



# A Joint Fermi-GBM and Swift-BAT Analysis of Gravitational-wave Candidates from the Third Gravitational-wave Observing Run

C. Fletcher<sup>1</sup> , J. Wood<sup>2</sup> , R. Hamburg<sup>3,4,5</sup> , P. Veres<sup>3,4</sup> , C. M. Hui<sup>2</sup> , E. Bissaldi<sup>6,7</sup> , M. S. Briggs<sup>3,4</sup> , E. Burns<sup>8</sup> ,  
W. H. Cleveland<sup>1</sup> , M. M. Giles<sup>9</sup> , A. Goldstein<sup>1</sup> , B. A. Hristov<sup>10</sup> , D. Kocevski<sup>2</sup> , S. Lesage<sup>4,11</sup> , B. Mailyan<sup>12</sup> ,  
C. Malacaria<sup>13</sup> , S. Poolakkil<sup>3,4</sup> , A. von Kienlin<sup>14</sup> , C. A. Wilson-Hodge<sup>2</sup>

Fermi Gamma-Ray Burst Monitor Team,  
and

M. Crnogorčević<sup>15,16,17</sup> , J. DeLaunay<sup>18,19,20</sup> , A. Tohuvavohu<sup>21</sup> , R. Caputo<sup>22</sup> , S. B. Cenko<sup>22,23</sup> , S. Laha<sup>16,24,25</sup> ,  
T. Parsotan<sup>16,24,25</sup> , R. Abbott<sup>26</sup> , H. Abe<sup>27</sup> , F. Acernese<sup>28,29</sup> , K. Ackley<sup>30</sup> , N. Adhikari<sup>31</sup> , R. X. Adhikari<sup>26</sup> ,  
V. K. Adkins<sup>32</sup> , V. B. Adya<sup>33</sup> , C. Affeldt<sup>34,35</sup> , D. Agarwal<sup>36</sup> , M. Agathos<sup>37,38</sup> , K. Agatsuma<sup>39</sup> , N. Aggarwal<sup>40</sup> ,  
O. D. Aguiar<sup>41</sup> , L. Aiello<sup>42</sup> , A. Ain<sup>43</sup> , P. Ajith<sup>44</sup> , T. Akutsu<sup>45,46</sup> , S. Albanesi<sup>47,48</sup> , R. A. Alfaldi<sup>49</sup> , A. Allocca<sup>29,50</sup> ,  
P. A. Altin<sup>33</sup> , A. Amato<sup>51</sup> , C. Anand<sup>30</sup> , S. Anand<sup>26</sup> , A. Ananyeva<sup>26</sup> , S. B. Anderson<sup>26</sup> , W. G. Anderson<sup>31</sup> , M. Ando<sup>52,53</sup> ,  
T. Andrade<sup>54</sup> , N. Andres<sup>55</sup> , M. Andrés-Carcasona<sup>56</sup> , T. Andrić<sup>57</sup> , S. V. Angelova<sup>58</sup> , S. Ansoldi<sup>59,60</sup> , J. M. Antelis<sup>61</sup> ,  
S. Antier<sup>62,63</sup> , T. Apostolatos<sup>64</sup> , E. Z. Appavuravther<sup>65,66</sup> , S. Appert<sup>26</sup> , S. K. Apple<sup>67</sup> , K. Arai<sup>26</sup> , A. Araya<sup>68</sup> ,  
M. C. Araya<sup>26</sup> , J. S. Areeda<sup>69</sup> , M. Arène<sup>70</sup> , N. Aritomi<sup>45</sup> , N. Arnaud<sup>5,71</sup> , M. Arogeti<sup>72</sup> , S. M. Aronson<sup>32</sup> , K. G. Arun<sup>73</sup> ,  
H. Asada<sup>74</sup> , Y. Asali<sup>75</sup> , G. Ashton<sup>76</sup> , Y. Aso<sup>77,78</sup> , M. Assiduo<sup>79,80</sup> , S. Assis de Souza Melo<sup>71</sup> , S. M. Aston<sup>81</sup> , P. Astone<sup>82</sup> ,  
F. Aubin<sup>80</sup> , K. AultONeal<sup>61</sup> , C. Austin<sup>32</sup> , S. Babak<sup>70</sup> , F. Badaracco<sup>83</sup> , M. K. M. Bader<sup>84</sup> , C. Badger<sup>85</sup> , S. Bae<sup>86</sup> ,  
Y. Bae<sup>87</sup> , A. M. Baer<sup>88</sup> , S. Bagnasco<sup>48</sup> , Y. Bai<sup>26</sup> , J. Baird<sup>70</sup> , R. Bajpai<sup>89</sup> , T. Baka<sup>90</sup> , M. Ball<sup>91</sup> , G. Ballardini<sup>71</sup> , S. W. Ballmer<sup>92</sup> ,  
A. Balsamo<sup>88</sup> , G. Baltus<sup>93</sup> , S. Banagiri<sup>40</sup> , B. Banerjee<sup>57</sup> , D. Bankar<sup>36</sup> , J. C. Barayoga<sup>26</sup> , C. Barbieri<sup>94,95,96</sup> , B. C. Barish<sup>26</sup> ,  
D. Barker<sup>97</sup> , P. Barneo<sup>54</sup> , F. Barone<sup>29,98</sup> , B. Barr<sup>49</sup> , L. Barsotti<sup>99</sup> , M. Barsuglia<sup>70</sup> , D. Barta<sup>100</sup> , J. Bartlett<sup>97</sup> ,  
M. A. Barton<sup>49</sup> , I. Bartos<sup>101</sup> , S. Basak<sup>44</sup> , R. Bassiri<sup>102</sup> , A. Basti<sup>43,103</sup> , M. Bawaj<sup>65,104</sup> , J. C. Bayley<sup>49</sup> , M. Bazzan<sup>105,106</sup> ,  
B. R. Becher<sup>107</sup> , B. Bécsy<sup>108</sup> , V. M. Bedakihalé<sup>109</sup> , F. Beirnaert<sup>110</sup> , M. Bejger<sup>111</sup> , I. Belahcene<sup>5</sup> , V. Benedetto<sup>112</sup> ,  
D. Beniwal<sup>113</sup> , M. G. Benjamin<sup>114</sup> , T. F. Bennett<sup>115</sup> , J. D. Bentley<sup>39</sup> , M. BenYaala<sup>58</sup> , S. Bera<sup>36</sup> , M. Berbel<sup>116</sup> ,  
F. Bergamin<sup>34,35</sup> , B. K. Berger<sup>102</sup> , S. Bernuzzi<sup>38</sup> , C. P. L. Berry<sup>49</sup> , D. Bersanetti<sup>117</sup> , A. Bertolini<sup>84</sup> , J. Betzwieser<sup>81</sup> ,  
D. Beveridge<sup>118</sup> , R. Bhandare<sup>119</sup> , A. V. Bhandari<sup>36</sup> , U. Bhardwaj<sup>63,84</sup> , R. Bhatt<sup>26</sup> , D. Bhattacharjee<sup>120</sup> , S. Bhaumik<sup>101</sup> ,  
A. Bianchi<sup>84,121</sup> , I. A. Bilenko<sup>122</sup> , G. Billingsley<sup>26</sup> , S. Bini<sup>123,124</sup> , R. Birney<sup>125</sup> , O. Birnholtz<sup>126</sup> , S. Biscans<sup>26,99</sup> , M. Bischl<sup>79,80</sup> ,  
S. Biscoveanu<sup>99</sup> , A. Bisht<sup>34,35</sup> , B. Biswas<sup>36</sup> , M. Bitossi<sup>43,71</sup> , M.-A. Bizouard<sup>62</sup> , J. K. Blackburn<sup>26</sup> , C. D. Blair<sup>118</sup> ,  
D. G. Blair<sup>118</sup> , R. M. Blair<sup>97</sup> , F. Bobba<sup>127,128</sup> , N. Bode<sup>34,35</sup> , M. Boër<sup>62</sup> , G. Bogaert<sup>62</sup> , M. Boldrin<sup>82,129</sup> , G. N. Bolingbroke<sup>113</sup> ,  
L. D. Bonavena<sup>105</sup> , F. Bondu<sup>130</sup> , E. Bonilla<sup>102</sup> , R. Bonnand<sup>55</sup> , P. Booker<sup>34,35</sup> , B. A. Boom<sup>84</sup> , R. Bork<sup>26</sup> , V. Boschi<sup>43</sup> ,  
N. Bose<sup>131</sup> , S. Bose<sup>36</sup> , V. Bossilkov<sup>118</sup> , V. Boudart<sup>93</sup> , Y. Bouffanais<sup>105,106</sup> , A. Bozzi<sup>71</sup> , C. Bradaschia<sup>43</sup> , P. R. Brady<sup>31</sup> ,  
A. Bramley<sup>81</sup> , A. Branch<sup>81</sup> , M. Branchesi<sup>57,132</sup> , J. E. Brau<sup>91</sup> , M. Breschi<sup>38</sup> , T. Briant<sup>133</sup> , J. H. Briggs<sup>49</sup> , A. Brillet<sup>62</sup> ,  
M. Brinkmann<sup>34,35</sup> , P. Brockill<sup>31</sup> , A. F. Brooks<sup>26</sup> , J. Brooks<sup>71</sup> , D. D. Brown<sup>113</sup> , S. Brunett<sup>26</sup> , G. Bruno<sup>83</sup> , R. Bruntz<sup>88</sup> ,  
J. Bryant<sup>39</sup> , F. Bucci<sup>80</sup> , T. Bulik<sup>134</sup> , H. J. Bulten<sup>84</sup> , A. Buonanno<sup>135,136</sup> , K. Burtnyk<sup>97</sup> , R. Buscicchio<sup>39</sup> , D. Buskulic<sup>55</sup> ,  
C. Buy<sup>137</sup> , R. L. Byer<sup>102</sup> , G. S. Cabourn Davies<sup>76</sup> , G. Cabras<sup>59,60</sup> , R. Cabrera<sup>83</sup> , L. Cadonati<sup>72</sup> , M. Caesar<sup>138</sup> ,  
G. Cagnoli<sup>51</sup> , C. Cahillane<sup>97</sup> , J. Calderón Bustillo<sup>139</sup> , J. D. Callaghan<sup>49</sup> , T. A. Callister<sup>140,141</sup> , E. Calloni<sup>29,50</sup> , J. Cameron<sup>118</sup> ,  
J. B. Camp<sup>142</sup> , M. Canepa<sup>117,143</sup> , S. Canevarolo<sup>90</sup> , M. Cannavacciuolo<sup>127</sup> , K. C. Cannon<sup>53</sup> , H. Cao<sup>113</sup> , Z. Cao<sup>144</sup> ,  
E. Capocasa<sup>45,70</sup> , E. Capote<sup>92</sup> , G. Carapella<sup>127,128</sup> , F. Carbognani<sup>71</sup> , M. Carlassara<sup>34,35</sup> , J. B. Carlin<sup>145</sup> , M. F. Carney<sup>40</sup> ,  
M. Carpinelli<sup>71,146,147</sup> , G. Carrillo<sup>91</sup> , G. Carullo<sup>43,103</sup> , T. L. Carver<sup>42</sup> , J. Casanueva Diaz<sup>71</sup> , C. Casentini<sup>148,149</sup> , G. Castaldi<sup>150</sup> ,  
S. Caudill<sup>84,90</sup> , M. Cavaglia<sup>120</sup> , F. Cavalier<sup>5</sup> , R. Cavalieri<sup>71</sup> , G. Cella<sup>43</sup> , P. Cerdá-Durán<sup>151</sup> , E. Cesarini<sup>149</sup> , W. Chaibi<sup>62</sup> ,  
S. Chalachadka Subrahmanya<sup>152</sup> , E. Champion<sup>153</sup> , C.-H. Chan<sup>154</sup> , C. Chan<sup>53</sup> , C. L. Chan<sup>155</sup> , K. Chan<sup>155</sup> , M. Chan<sup>156</sup> ,  
K. Chandra<sup>131</sup> , I. P. Chang<sup>154</sup> , P. Chanial<sup>71</sup> , S. Chao<sup>154</sup> , C. Chapman-Bird<sup>49</sup> , P. Charlton<sup>157</sup> , E. A. Chase<sup>40</sup> ,  
E. Chassande-Mottin<sup>70</sup> , C. Chatterjee<sup>118</sup> , Debarati Chatterjee<sup>36</sup> , Deep Chatterjee<sup>31</sup> , M. Chaturvedi<sup>119</sup> , S. Chaty<sup>70</sup> ,  
C. Chen<sup>154,158</sup> , D. Chen<sup>77</sup> , H. Y. Chen<sup>99</sup> , J. Chen<sup>154</sup> , K. Chen<sup>159</sup> , X. Chen<sup>118</sup> , Y.-B. Chen<sup>160</sup> , Y.-R. Chen<sup>154</sup> , Z. Chen<sup>42</sup> ,  
H. Cheng<sup>101</sup> , C. K. Cheong<sup>155</sup> , H. Y. Cheung<sup>155</sup> , H. Y. Chia<sup>101</sup> , F. Chiadini<sup>128,161</sup> , C.-Y. Chiang<sup>162</sup> , G. Chiarini<sup>106</sup> ,  
R. Chierici<sup>163</sup> , A. Chincarini<sup>117</sup> , M. L. Chiofalo<sup>43,103</sup> , A. Chiummo<sup>71</sup> , R. K. Choudhary<sup>118</sup> , S. Choudhary<sup>36</sup> ,  
N. Christensen<sup>62</sup> , Q. Chu<sup>118</sup> , Y.-K. Chu<sup>162</sup> , S. S. Y. Chua<sup>33</sup> , K. W. Chung<sup>85</sup> , G. Ciani<sup>105,106</sup> , P. Cieciulag<sup>111</sup> ,  
M. Cieřlar<sup>111</sup> , M. Cifaldi<sup>148,149</sup> , A. A. Ciobanu<sup>113</sup> , R. Ciolfi<sup>106,164</sup> , F. Cipriano<sup>62</sup> , F. Clara<sup>97</sup> , J. A. Clark<sup>26,72</sup> ,  
P. Clearwater<sup>165</sup> , S. Clesse<sup>166</sup> , F. Cleva<sup>62</sup> , E. Coccia<sup>57,132</sup> , E. Codazzo<sup>57</sup> , P.-F. Cohadon<sup>133</sup> , D. E. Cohen<sup>5</sup> , M. Colleoni<sup>167</sup> ,  
C. G. Collette<sup>168</sup> , A. Colombo<sup>94,95</sup> , M. Colpi<sup>94,95</sup> , C. M. Compton<sup>97</sup> , M. Constancio, Jr.<sup>41</sup> , L. Conti<sup>106</sup> , S. J. Cooper<sup>39</sup> ,  
P. Corban<sup>81</sup> , T. R. Corbitt<sup>32</sup> , I. Cordero-Carrión<sup>169</sup> , S. Corezzi<sup>65,104</sup> , K. R. Corley<sup>75</sup> , N. J. Cornish<sup>108</sup> , D. Corre<sup>5</sup> , A. Corsi<sup>170</sup> ,  
S. Cortese<sup>71</sup> , C. A. Costa<sup>41</sup> , R. Cotesta<sup>136</sup> , R. Cottingham<sup>81</sup> , M. W. Coughlin<sup>171</sup> , J.-P. Coulon<sup>62</sup> , S. T. Countryman<sup>75</sup> ,  
B. Cousins<sup>172</sup> , P. Couvares<sup>26</sup> , D. M. Coward<sup>118</sup> , M. J. Cowart<sup>81</sup> , D. C. Coyne<sup>26</sup> , R. Coyne<sup>173</sup> , J. D. E. Creighton<sup>31</sup> ,  
T. D. Creighton<sup>114</sup> , A. W. Criswell<sup>171</sup> , M. Croquette<sup>133</sup> , S. G. Crowder<sup>174</sup> , J. R. Cudell<sup>93</sup> , T. J. Cullen<sup>32</sup> , A. Cumming<sup>49</sup> ,  
R. Cummings<sup>49</sup> , L. Cunningham<sup>49</sup> , E. Cuoco<sup>43,71,175</sup> , M. Curylo<sup>134</sup> , P. Dabadie<sup>51</sup> , T. Dal Canton<sup>5</sup> , S. Dall’Osso<sup>57</sup>

G. Dályá<sup>110,176</sup>, A. Dana<sup>102</sup>, B. D'Angelo<sup>117,143</sup>, S. Danilishin<sup>84,177</sup>, S. D'Antonio<sup>149</sup>, K. Danzmann<sup>34,35</sup>,  
C. Darsow-Fromm<sup>152</sup>, A. Dasgupta<sup>109</sup>, L. E. H. Datrier<sup>49</sup>, Sayak Datta<sup>36</sup>, Sayantani Datta<sup>73</sup>, V. Dattilo<sup>71</sup>, I. Dave<sup>119</sup>,  
M. Davier<sup>5</sup>, D. Davis<sup>26</sup>, M. C. Davis<sup>138</sup>, E. J. Daw<sup>178</sup>, R. Dean<sup>138</sup>, D. DeBra<sup>102</sup>, M. Deenadayalan<sup>36</sup>, J. Degallaix<sup>179</sup>,  
M. De Laurentis<sup>29,50</sup>, S. Deléglise<sup>133</sup>, V. Del Favero<sup>153</sup>, F. De Lillo<sup>83</sup>, N. De Lillo<sup>49</sup>, D. Dell'Aquila<sup>146</sup>, W. Del Pozzo<sup>43,103</sup>,  
L. M. DeMarchi<sup>40</sup>, F. De Matteis<sup>148,149</sup>, V. D'Emilio<sup>42</sup>, N. Demos<sup>99</sup>, T. Dent<sup>139</sup>, A. Depasse<sup>83</sup>, R. De Pietri<sup>180,181</sup>,  
R. De Rosa<sup>29,50</sup>, C. De Rossi<sup>71</sup>, R. DeSalvo<sup>150,182</sup>, R. De Simone<sup>161</sup>, S. Dhurandhar<sup>36</sup>, M. C. Díaz<sup>114</sup>, N. A. Didio<sup>92</sup>,  
T. Dietrich<sup>136</sup>, L. Di Fiore<sup>29</sup>, C. Di Fronzo<sup>39</sup>, C. Di Giorgio<sup>127,128</sup>, F. Di Giovanni<sup>151</sup>, M. Di Giovanni<sup>57</sup>,  
T. Di Girolamo<sup>29,50</sup>, A. Di Lieto<sup>43,103</sup>, A. Di Michele<sup>104</sup>, B. Ding<sup>168</sup>, S. Di Pace<sup>82,129</sup>, I. Di Palma<sup>82,129</sup>,  
F. Di Renzo<sup>43,103</sup>, A. K. Divakarla<sup>101</sup>, A. Dmitriev<sup>39</sup>, Z. Doctor<sup>40</sup>, L. Donahue<sup>183</sup>, L. D'Onofrio<sup>29,50</sup>, F. Donovan<sup>99</sup>,  
K. L. Dooley<sup>42</sup>, S. Doravari<sup>36</sup>, M. Drago<sup>82,129</sup>, J. C. Driggers<sup>97</sup>, Y. Drori<sup>26</sup>, J.-G. Ducoin<sup>5</sup>, P. Dupej<sup>49</sup>, U. Dupletsa<sup>57</sup>,  
O. Durante<sup>127,128</sup>, D. D'Urso<sup>146,147</sup>, P.-A. Duverne<sup>5</sup>, S. E. Dwyer<sup>97</sup>, C. Eassa<sup>97</sup>, P. J. Easter<sup>30</sup>, M. Ebersold<sup>184</sup>, T. Eckhardt<sup>152</sup>,  
G. Eddolls<sup>49</sup>, B. Edelman<sup>91</sup>, T. B. Edo<sup>26</sup>, O. Edy<sup>76</sup>, A. Effler<sup>81</sup>, S. Eguchi<sup>156</sup>, J. Eichholz<sup>33</sup>, S. S. Eikenberry<sup>101</sup>,  
M. Eisenmann<sup>45,55</sup>, R. A. Eisenstein<sup>99</sup>, A. Ejlli<sup>42</sup>, E. Engelby<sup>69</sup>, Y. Enomoto<sup>52</sup>, L. Errico<sup>29,50</sup>, R. C. Essick<sup>185</sup>, H. Estellés<sup>167</sup>,  
D. Estevez<sup>186</sup>, Z. Etienne<sup>187</sup>, T. Etzel<sup>26</sup>, M. Evans<sup>99</sup>, T. M. Evans<sup>81</sup>, T. Evstafyeva<sup>37</sup>, B. E. Ewing<sup>172</sup>, F. Fabrizi<sup>79,80</sup>,  
F. Faedi<sup>80</sup>, V. Fafone<sup>57,148,149</sup>, H. Fair<sup>92</sup>, S. Fairhurst<sup>42</sup>, P. C. Fan<sup>183</sup>, A. M. Farah<sup>188</sup>, S. Farinon<sup>117</sup>, B. Farr<sup>91</sup>,  
W. M. Farr<sup>140,141</sup>, E. J. Fauchon-Jones<sup>42</sup>, G. Favaro<sup>105</sup>, M. Favata<sup>189</sup>, M. Fays<sup>93</sup>, M. Fazio<sup>190</sup>, J. Feicht<sup>26</sup>, M. M. Fejer<sup>102</sup>,  
E. Fenyvesi<sup>100,191</sup>, D. L. Ferguson<sup>192</sup>, A. Fernandez-Galiana<sup>99</sup>, I. Ferrante<sup>43,103</sup>, T. A. Ferreira<sup>41</sup>, F. Fidecaro<sup>43,103</sup>,  
P. Figura<sup>134</sup>, A. Fiori<sup>43,103</sup>, I. Fiori<sup>71</sup>, M. Fishbach<sup>40</sup>, R. P. Fisher<sup>88</sup>, R. Fittipaldi<sup>128,193</sup>, V. Fiumara<sup>128,194</sup>,  
R. Flamini<sup>45,55</sup>, E. Floden<sup>171</sup>, H. K. Fong<sup>53</sup>, J. A. Font<sup>151,195</sup>, B. Fornal<sup>182</sup>, P. W. F. Forsyth<sup>33</sup>, A. Franke<sup>152</sup>, S. Frasca<sup>82,129</sup>,  
F. Frasconi<sup>43</sup>, J. P. Freed<sup>61</sup>, Z. Frei<sup>176</sup>, A. Freise<sup>84,121</sup>, O. Freitas<sup>196</sup>, R. Frey<sup>91</sup>, P. Fritschel<sup>99</sup>, V. V. Frolov<sup>81</sup>,  
G. G. Fronze<sup>48</sup>, Y. Fujii<sup>197</sup>, Y. Fujikawa<sup>198</sup>, Y. Fujimoto<sup>199</sup>, P. Fulda<sup>101</sup>, M. Fyffe<sup>81</sup>, H. A. Gabbard<sup>49</sup>, W. E. Gabella<sup>200</sup>,  
B. U. Gadre<sup>136</sup>, J. R. Gair<sup>136</sup>, J. Gais<sup>155</sup>, S. Galadage<sup>30</sup>, R. Gamba<sup>38</sup>, D. Ganapathy<sup>99</sup>, A. Ganguly<sup>36</sup>, D. Gao<sup>201</sup>,  
S. G. Gaonkar<sup>36</sup>, B. Garaventa<sup>117,143</sup>, C. García Núñez<sup>125</sup>, C. García-Quirós<sup>167</sup>, F. Garufi<sup>29,50</sup>, B. Gateley<sup>97</sup>, V. Gayathri<sup>101</sup>,  
G.-G. Ge<sup>201</sup>, G. Gemme<sup>117</sup>, A. Gennai<sup>43</sup>, J. George<sup>119</sup>, O. Gerberding<sup>152</sup>, L. Gergely<sup>202</sup>, P. Gewecke<sup>152</sup>,  
S. Ghonge<sup>72</sup>, Abhirup Ghosh<sup>136</sup>, Archisman Ghosh<sup>110</sup>, Shaon Ghosh<sup>189</sup>, Shrobona Ghosh<sup>42</sup>, Tathagata Ghosh<sup>36</sup>,  
B. Giacomazzo<sup>94,95,96</sup>, L. Giacoppo<sup>82,129</sup>, J. A. Giaime<sup>32,81</sup>, K. D. Giardino<sup>81</sup>, D. R. Gibson<sup>125</sup>, C. Gier<sup>58</sup>, M. Giesler<sup>203</sup>,  
P. Giri<sup>43,103</sup>, F. Gissi<sup>112</sup>, S. Gkaitatzis<sup>43,103</sup>, J. Glanzer<sup>32</sup>, A. E. Gleckl<sup>69</sup>, P. Godwin<sup>172</sup>, E. Goetz<sup>204</sup>, R. Goetz<sup>101</sup>,  
N. Gohlke<sup>34,35</sup>, J. Golomb<sup>26</sup>, B. Goncharov<sup>57</sup>, G. González<sup>32</sup>, M. Gosselin<sup>71</sup>, R. Gouaty<sup>55</sup>, D. W. Gould<sup>33</sup>, S. Goyal<sup>44</sup>,  
B. Grace<sup>33</sup>, A. Grado<sup>29,205</sup>, V. Graham<sup>49</sup>, M. Granata<sup>179</sup>, V. Granata<sup>127</sup>, A. Grant<sup>49</sup>, S. Gras<sup>99</sup>, P. Grassia<sup>26</sup>, C. Gray<sup>97</sup>,  
R. Gray<sup>49</sup>, G. Greco<sup>65</sup>, A. C. Green<sup>101</sup>, R. Green<sup>42</sup>, A. M. Gretarsson<sup>61</sup>, E. M. Gretarsson<sup>61</sup>, D. Griffith<sup>26</sup>, W. L. Griffiths<sup>42</sup>,  
H. L. Griggs<sup>72</sup>, G. Grignani<sup>65,104</sup>, A. Grimaldi<sup>123,124</sup>, E. Grimes<sup>61</sup>, S. J. Grimm<sup>57,132</sup>, H. Grote<sup>42</sup>, S. Grunewald<sup>136</sup>,  
P. Gruning<sup>5</sup>, A. S. Gruson<sup>69</sup>, D. Guerra<sup>151</sup>, G. M. Guidi<sup>79,80</sup>, A. R. Guimaraes<sup>32</sup>, G. Guixé<sup>54</sup>, H. K. Gulati<sup>109</sup>, A. M. Gunny<sup>99</sup>,  
H.-K. Guo<sup>182</sup>, Y. Guo<sup>84</sup>, Anchal Gupta<sup>26</sup>, Anuradha Gupta<sup>206</sup>, I. M. Gupta<sup>172</sup>, P. Gupta<sup>84,90</sup>, S. K. Gupta<sup>131</sup>, R. Gustafson<sup>207</sup>,  
F. Guzman<sup>208</sup>, S. Ha<sup>209</sup>, I. P. W. Hadiputrawan<sup>159</sup>, L. Haegel<sup>70</sup>, S. Haino<sup>162</sup>, O. Halim<sup>60</sup>, E. D. Hall<sup>99</sup>, E. Z. Hamilton<sup>184</sup>,  
G. Hammond<sup>49</sup>, W.-B. Han<sup>210</sup>, M. Haney<sup>184</sup>, J. Hanks<sup>97</sup>, C. Hanna<sup>172</sup>, M. D. Hannam<sup>42</sup>, O. Hannuksela<sup>84,90</sup>, H. Hansen<sup>97</sup>,  
T. J. Hansen<sup>61</sup>, J. Hanson<sup>81</sup>, T. Harder<sup>62</sup>, K. Haris<sup>84,90</sup>, J. Harms<sup>57,132</sup>, G. M. Harry<sup>67</sup>, I. W. Harry<sup>76</sup>, D. Hartwig<sup>152</sup>,  
K. Hasegawa<sup>211</sup>, B. Haskell<sup>111</sup>, C.-J. Haster<sup>99</sup>, J. S. Hathaway<sup>153</sup>, K. Hattori<sup>212</sup>, K. Haughian<sup>49</sup>, H. Hayakawa<sup>213</sup>, K. Hayama<sup>156</sup>,  
F. J. Hayes<sup>49</sup>, J. Healy<sup>153</sup>, A. Heidmann<sup>133</sup>, A. Heidt<sup>34,35</sup>, M. C. Heintze<sup>81</sup>, J. Heinze<sup>34,35</sup>, J. Heinzl<sup>99</sup>, H. Heitmann<sup>62</sup>,  
F. Hellman<sup>214</sup>, P. Hello<sup>5</sup>, A. F. Helmling-Cornell<sup>91</sup>, G. Hemming<sup>71</sup>, M. Hendry<sup>49</sup>, I. S. Heng<sup>49</sup>, E. Hennes<sup>84</sup>,  
J. Hennig<sup>215</sup>, M. H. Hennig<sup>215</sup>, C. Henshaw<sup>72</sup>, A. G. Hernandez<sup>115</sup>, F. Hernandez Vivanco<sup>30</sup>, M. Heurs<sup>34,35</sup>, A. L. Hewitt<sup>216</sup>,  
S. Higginbotham<sup>42</sup>, S. Hild<sup>84,177</sup>, P. Hill<sup>58</sup>, Y. Himemoto<sup>217</sup>, A. S. Hines<sup>208</sup>, N. Hirata<sup>45</sup>, C. Hirose<sup>198</sup>, T.-C. Ho<sup>159</sup>,  
S. Hochheim<sup>34,35</sup>, D. Hofman<sup>179</sup>, J. N. Hohmann<sup>152</sup>, D. G. Holcomb<sup>138</sup>, N. A. Holland<sup>33</sup>, I. J. Hollows<sup>178</sup>, Z. J. Holmes<sup>113</sup>,  
K. Holt<sup>81</sup>, D. E. Holz<sup>188</sup>, Q. Hong<sup>154</sup>, J. Hough<sup>49</sup>, S. Hourihane<sup>26</sup>, E. J. Howell<sup>118</sup>, C. G. Hoy<sup>42</sup>, D. Hoyland<sup>39</sup>,  
A. Hreibi<sup>34,35</sup>, B.-H. Hsieh<sup>211</sup>, H.-F. Hsieh<sup>154</sup>, C. Hsiung<sup>158</sup>, Y. Hsu<sup>154</sup>, H.-Y. Huang<sup>162</sup>, P. Huang<sup>201</sup>, Y.-C. Huang<sup>154</sup>,  
Y.-J. Huang<sup>162</sup>, Yiting Huang<sup>174</sup>, Yiwen Huang<sup>99</sup>, M. T. Hübner<sup>30</sup>, A. D. Huddart<sup>218</sup>, B. Hughey<sup>61</sup>, D. C. Y. Hui<sup>219</sup>,  
V. Hui<sup>55</sup>, S. Husa<sup>167</sup>, S. H. Huttner<sup>49</sup>, R. Huxford<sup>172</sup>, T. Huynh-Dinh<sup>81</sup>, S. Ide<sup>220</sup>, B. Idzkowski<sup>134</sup>, A. Iess<sup>148,149</sup>,  
K. Inayoshi<sup>221</sup>, Y. Inoue<sup>159</sup>, P. Iosif<sup>222</sup>, M. Isi<sup>99</sup>, K. Isleif<sup>152</sup>, K. Ito<sup>223</sup>, Y. Itoh<sup>199,224</sup>, B. R. Iyer<sup>44</sup>,  
V. JaberianHamedan<sup>118</sup>, T. Jacqmin<sup>133</sup>, P.-E. Jaquet<sup>133</sup>, S. J. Jadhav<sup>225</sup>, S. P. Jadhav<sup>36</sup>, T. Jain<sup>37</sup>, A. L. James<sup>42</sup>,  
A. Z. Jan<sup>192</sup>, K. Jani<sup>200</sup>, J. Janquart<sup>84,90</sup>, K. Janssens<sup>62,226</sup>, N. N. Jantalar<sup>225</sup>, P. Jaranowski<sup>227</sup>, D. Jariwala<sup>101</sup>,  
R. Jaume<sup>167</sup>, A. C. Jenkins<sup>85</sup>, K. Jenner<sup>113</sup>, C. Jeon<sup>228</sup>, W. Jia<sup>99</sup>, J. Jiang<sup>101</sup>, H.-B. Jin<sup>229,230</sup>, G. R. Johns<sup>88</sup>, R. Johnston<sup>49</sup>,  
A. W. Jones<sup>118</sup>, D. I. Jones<sup>231</sup>, P. Jones<sup>39</sup>, R. Jones<sup>49</sup>, P. Joshi<sup>172</sup>, L. Ju<sup>118</sup>, A. Jue<sup>182</sup>, P. Jung<sup>87</sup>, K. Jung<sup>209</sup>, J. Junker<sup>34,35</sup>,  
V. Juste<sup>186</sup>, K. Kaihotsu<sup>223</sup>, T. Kajita<sup>232</sup>, M. Kakizaki<sup>212</sup>, C. V. Kalaghatgi<sup>42,84,90,233</sup>, V. Kalogera<sup>40</sup>, B. Kamai<sup>26</sup>,  
M. Kamiizumi<sup>213</sup>, N. Kanda<sup>199,224</sup>, S. Kandhasamy<sup>36</sup>, G. Kang<sup>234</sup>, J. B. Kanner<sup>26</sup>, Y. Kao<sup>154</sup>, S. J. Kapadia<sup>44</sup>,  
D. P. Kapasi<sup>33</sup>, C. Karathanasis<sup>56</sup>, S. Karki<sup>120</sup>, R. Kashyap<sup>172</sup>, M. Kasprzak<sup>26</sup>, W. Kastaun<sup>34,35</sup>, T. Kato<sup>211</sup>,  
S. Katsanevas<sup>71</sup>, E. Katsavounidis<sup>99</sup>, W. Katzman<sup>81</sup>, T. Kaur<sup>118</sup>, K. Kawabe<sup>97</sup>, K. Kawaguchi<sup>211</sup>, F. Kéfélian<sup>62</sup>, D. Keitel<sup>167</sup>,  
J. S. Key<sup>235</sup>, S. Khadka<sup>102</sup>, F. Y. Khalili<sup>122</sup>, S. Khan<sup>42</sup>, T. Khanam<sup>170</sup>, E. A. Khazanov<sup>236</sup>, N. Khetan<sup>57,132</sup>,  
M. Khurshed<sup>119</sup>, N. Kijbunchoo<sup>33</sup>, A. Kim<sup>40</sup>, C. Kim<sup>228</sup>, J. C. Kim<sup>237</sup>, J. Kim<sup>238</sup>, K. Kim<sup>228</sup>, W. S. Kim<sup>87</sup>,

Y.-M. Kim<sup>209</sup>, C. Kimball<sup>40</sup>, N. Kimura<sup>213</sup>, M. Kinley-Hanlon<sup>49</sup>, R. Kirchoff<sup>34,35</sup>, J. S. Kissel<sup>97</sup>, S. Klimenko<sup>101</sup>, T. Klinger<sup>37</sup>, A. M. Knee<sup>204</sup>, T. D. Knowles<sup>187</sup>, N. Knust<sup>34,35</sup>, E. Knyazev<sup>99</sup>, Y. Kobayashi<sup>199</sup>, P. Koch<sup>34,35</sup>, G. Koekoek<sup>84,177</sup>, K. Kohri<sup>239</sup>, K. Kokeyama<sup>240</sup>, S. Koley<sup>57</sup>, P. Kolitsidou<sup>42</sup>, M. Kolstein<sup>56</sup>, K. Komori<sup>99</sup>, V. Kondrashov<sup>26</sup>, A. K. H. Kong<sup>154</sup>, A. Kontos<sup>107</sup>, N. Koper<sup>34,35</sup>, M. Korobko<sup>152</sup>, M. Kovalam<sup>118</sup>, N. Koyama<sup>198</sup>, D. B. Kozak<sup>26</sup>, C. Kozakai<sup>77</sup>, V. Kringel<sup>34,35</sup>, N. V. Krishnendu<sup>34,35</sup>, A. Królak<sup>241,242</sup>, G. Kuehn<sup>34,35</sup>, F. Kuei<sup>154</sup>, P. Kuijper<sup>84</sup>, S. Kulkarni<sup>206</sup>, A. Kumar<sup>225</sup>, Prayush Kumar<sup>44</sup>, Rahul Kumar<sup>97</sup>, Rakesh Kumar<sup>109</sup>, J. Kume<sup>53</sup>, K. Kuns<sup>99</sup>, Y. Kuromiya<sup>223</sup>, S. Kuroyanagi<sup>243,244</sup>, K. Kwak<sup>209</sup>, G. Lacaille<sup>49</sup>, P. Lagabbe<sup>55</sup>, D. Laghi<sup>137</sup>, E. Lalande<sup>245</sup>, M. Lalleman<sup>226</sup>, T. L. Lam<sup>155</sup>, A. Lamberts<sup>62,246</sup>, M. Landry<sup>97</sup>, B. B. Lane<sup>99</sup>, R. N. Lang<sup>99</sup>, J. Lange<sup>192</sup>, B. Lantz<sup>102</sup>, I. La Rosa<sup>55</sup>, A. Lartaux-Vollard<sup>5</sup>, P. D. Lasky<sup>30</sup>, M. Laxen<sup>81</sup>, A. Lazzarini<sup>26</sup>, C. Lazzaro<sup>105,106</sup>, P. Leaci<sup>82,129</sup>, S. Leavey<sup>34,35</sup>, S. LeBohec<sup>182</sup>, Y. K. Lecoecuche<sup>204</sup>, E. Lee<sup>211</sup>, H. M. Lee<sup>247</sup>, H. W. Lee<sup>237</sup>, K. Lee<sup>248</sup>, R. Lee<sup>154</sup>, I. N. Legred<sup>26</sup>, J. Lehmann<sup>34,35</sup>, A. Lemâitre<sup>249</sup>, M. Lenti<sup>80,250</sup>, M. Leonardi<sup>45</sup>, E. Leonova<sup>63</sup>, N. Leroy<sup>5</sup>, N. Letendre<sup>55</sup>, C. Levesque<sup>245</sup>, Y. Levin<sup>30</sup>, J. N. Leviton<sup>207</sup>, K. Leyde<sup>70</sup>, A. K. Y. Li<sup>26</sup>, B. Li<sup>154</sup>, J. Li<sup>40</sup>, K. L. Li<sup>251</sup>, P. Li<sup>252</sup>, T. G. F. Li<sup>155</sup>, X. Li<sup>160</sup>, C.-Y. Lin<sup>253</sup>, E. T. Lin<sup>154</sup>, F.-K. Lin<sup>162</sup>, F.-L. Lin<sup>254</sup>, H. L. Lin<sup>159</sup>, L. C.-C. Lin<sup>251</sup>, F. Linde<sup>84,233</sup>, S. D. Linker<sup>115,150</sup>, J. N. Linley<sup>49</sup>, T. B. Littenberg<sup>255</sup>, G. C. Liu<sup>158</sup>, J. Liu<sup>118</sup>, K. Liu<sup>154</sup>, X. Liu<sup>31</sup>, F. Llamas<sup>114</sup>, R. K. L. Lo<sup>26</sup>, T. Lo<sup>154</sup>, L. T. London<sup>63,99</sup>, A. Longo<sup>256</sup>, D. Lopez<sup>184</sup>, M. Lopez Portilla<sup>90</sup>, M. Lorenzini<sup>148,149</sup>, V. Lorientte<sup>257</sup>, M. Lormand<sup>81</sup>, G. Losurdo<sup>43</sup>, T. P. Lott<sup>72</sup>, J. D. Lough<sup>34,35</sup>, C. O. Lousto<sup>153</sup>, G. Lovelace<sup>69</sup>, J. F. Lucaccioni<sup>258</sup>, H. Lück<sup>34,35</sup>, D. Lumaca<sup>148,149</sup>, A. P. Lundgren<sup>76</sup>, L.-W. Luo<sup>162</sup>, J. E. Lynam<sup>88</sup>, M. Ma'arif<sup>159</sup>, R. Macas<sup>76</sup>, J. B. Machtinger<sup>40</sup>, M. MacInnis<sup>99</sup>, D. M. Macleod<sup>42</sup>, I. A. O. MacMillan<sup>26</sup>, A. Macquet<sup>62</sup>, I. Magaña Hernandez<sup>31</sup>, C. Magazzù<sup>43</sup>, R. M. Magee<sup>26</sup>, R. Maggiore<sup>39</sup>, M. Magnozzi<sup>117,143</sup>, S. Mahesh<sup>187</sup>, E. Majorana<sup>82,129</sup>, I. Maksimovic<sup>257</sup>, S. Maliakal<sup>26</sup>, A. Malik<sup>119</sup>, N. Man<sup>62</sup>, V. Mandic<sup>171</sup>, V. Mangano<sup>82,129</sup>, G. L. Mansell<sup>97,99</sup>, M. Manske<sup>31</sup>, M. Mantovani<sup>71</sup>, M. Mapelli<sup>105,106</sup>, F. Marchesoni<sup>65,66,259</sup>, D. Marín Pina<sup>54</sup>, F. Marion<sup>55</sup>, Z. Mark<sup>160</sup>, S. Márka<sup>75</sup>, Z. Márka<sup>75</sup>, C. Markakis<sup>37</sup>, A. S. Markosyan<sup>102</sup>, A. Markowitz<sup>26</sup>, E. Maros<sup>26</sup>, A. Marquina<sup>169</sup>, S. Marsat<sup>70</sup>, F. Martelli<sup>79,80</sup>, I. W. Martin<sup>49</sup>, R. M. Martin<sup>189</sup>, M. Martinez<sup>56</sup>, V. A. Martinez<sup>101</sup>, V. Martinez<sup>51</sup>, K. Martinovic<sup>85</sup>, D. V. Martynov<sup>39</sup>, E. J. Marx<sup>99</sup>, H. Masalehdan<sup>152</sup>, K. Mason<sup>99</sup>, E. Massera<sup>178</sup>, A. Masserot<sup>55</sup>, M. Masso-Reid<sup>49</sup>, S. Mastrogiovanni<sup>70</sup>, A. Matas<sup>136</sup>, M. Mateu-Lucena<sup>167</sup>, F. Matichard<sup>26,99</sup>, M. Matushechkina<sup>34,35</sup>, N. Mavalvala<sup>99</sup>, J. J. McCann<sup>118</sup>, R. McCarthy<sup>97</sup>, D. E. McClelland<sup>33</sup>, P. K. McClincy<sup>172</sup>, S. McCormick<sup>81</sup>, L. McCuller<sup>99</sup>, G. I. McGhee<sup>49</sup>, S. C. McGuire<sup>81</sup>, C. McIsaac<sup>76</sup>, J. McIver<sup>204</sup>, T. McRae<sup>33</sup>, S. T. McWilliams<sup>187</sup>, D. Meacher<sup>31</sup>, M. Mehmet<sup>34,35</sup>, A. K. Mehta<sup>136</sup>, Q. Meijer<sup>90</sup>, A. Melatos<sup>145</sup>, D. A. Melchor<sup>69</sup>, G. Mendell<sup>97</sup>, A. Menendez-Vazquez<sup>56</sup>, C. S. Menoni<sup>190</sup>, R. A. Mercer<sup>31</sup>, L. Mereni<sup>179</sup>, K. Merfeld<sup>91</sup>, E. L. Merilh<sup>81</sup>, J. D. Merritt<sup>91</sup>, M. Merzougui<sup>62</sup>, S. Meshkov<sup>26,313</sup>, C. Messenger<sup>49</sup>, C. Messick<sup>99</sup>, P. M. Meyers<sup>145</sup>, F. Meylahn<sup>34,35</sup>, A. Mhaske<sup>36</sup>, A. Miani<sup>123,124</sup>, H. Miao<sup>39</sup>, I. Michaloliakos<sup>101</sup>, C. Michel<sup>179</sup>, Y. Michimura<sup>52</sup>, H. Middleton<sup>145</sup>, D. P. Mihaylov<sup>136</sup>, L. Milano<sup>50,314</sup>, A. L. Miller<sup>83</sup>, A. Miller<sup>115</sup>, B. Miller<sup>63,84</sup>, M. Millhouse<sup>145</sup>, J. C. Mills<sup>42</sup>, E. Milotti<sup>60,260</sup>, Y. Minenkov<sup>149</sup>, N. Mio<sup>261</sup>, Ll. M. Mir<sup>56</sup>, M. Miravet-Tenés<sup>151</sup>, A. Mishkin<sup>101</sup>, C. Mishra<sup>262</sup>, T. Mishra<sup>101</sup>, T. Mistry<sup>178</sup>, S. Mitra<sup>36</sup>, V. P. Mitrofanov<sup>122</sup>, G. Mitselmakher<sup>101</sup>, R. Mittleman<sup>99</sup>, O. Miyakawa<sup>213</sup>, K. Miyo<sup>213</sup>, S. Miyoki<sup>213</sup>, Geoffrey Mo<sup>99</sup>, L. M. Modafferi<sup>167</sup>, E. Moguel<sup>258</sup>, K. Mogushi<sup>120</sup>, S. R. P. Mohapatra<sup>99</sup>, S. R. Mohite<sup>31</sup>, I. Molina<sup>69</sup>, M. Molina-Ruiz<sup>214</sup>, M. Mondin<sup>115</sup>, M. Montani<sup>79,80</sup>, C. J. Moore<sup>39</sup>, J. Moragues<sup>167</sup>, D. Moraru<sup>97</sup>, F. Morawski<sup>111</sup>, A. More<sup>36</sup>, C. Moreno<sup>61</sup>, G. Moreno<sup>97</sup>, Y. Mori<sup>223</sup>, S. Morisaki<sup>31</sup>, N. Morisue<sup>199</sup>, Y. Moriwaki<sup>212</sup>, B. Mours<sup>186</sup>, C. M. Mow-Lowry<sup>84,121</sup>, S. Mozzon<sup>76</sup>, F. Muciaccia<sup>82,129</sup>, Arunava Mukherjee<sup>263</sup>, D. Mukherjee<sup>172</sup>, Soma Mukherjee<sup>114</sup>, Subroto Mukherjee<sup>109</sup>, Suvodip Mukherjee<sup>63,185</sup>, N. Mukund<sup>34,35</sup>, A. Mullavey<sup>81</sup>, J. Munch<sup>113</sup>, E. A. Muñoz<sup>92</sup>, P. G. Murray<sup>49</sup>, R. Musenich<sup>117,143</sup>, S. Muusse<sup>113</sup>, S. L. Nadji<sup>34,35</sup>, K. Nagano<sup>264</sup>, A. Nagar<sup>48,265</sup>, K. Nakamura<sup>45</sup>, H. Nakano<sup>266</sup>, M. Nakano<sup>211</sup>, Y. Nakayama<sup>223</sup>, V. Napolano<sup>71</sup>, I. Nardecchia<sup>148,149</sup>, H. Narola<sup>90</sup>, L. Naticchioni<sup>82</sup>, B. Nayak<sup>115</sup>, R. K. Nayak<sup>267</sup>, B. F. Neil<sup>118</sup>, J. Neilson<sup>112,128</sup>, A. Nelson<sup>208</sup>, T. J. N. Nelson<sup>81</sup>, M. Nery<sup>34,35</sup>, P. Neubauer<sup>258</sup>, A. Neunzert<sup>235</sup>, K. Y. Ng<sup>99</sup>, S. W. S. Ng<sup>113</sup>, C. Nguyen<sup>70</sup>, P. Nguyen<sup>91</sup>, T. Nguyen<sup>99</sup>, L. Nguyen Quynh<sup>268</sup>, J. Ni<sup>171</sup>, W.-T. Ni<sup>154,201,229</sup>, S. A. Nichols<sup>32</sup>, T. Nishimoto<sup>211</sup>, A. Nishizawa<sup>53</sup>, S. Nissanke<sup>63,84</sup>, E. Nitoglia<sup>163</sup>, F. Nocera<sup>71</sup>, M. Norman<sup>42</sup>, C. North<sup>42</sup>, S. Nozaki<sup>212</sup>, G. Nurbek<sup>114</sup>, L. K. Nuttall<sup>76</sup>, Y. Obayashi<sup>211</sup>, J. Oberling<sup>97</sup>, B. D. O'Brien<sup>101</sup>, J. O'Dell<sup>218</sup>, E. Oelker<sup>49</sup>, W. Ogaki<sup>211</sup>, G. Oganessian<sup>57,132</sup>, J. J. Oh<sup>87</sup>, K. Oh<sup>219</sup>, S. H. Oh<sup>87</sup>, M. Ohashi<sup>213</sup>, T. Ohashi<sup>199</sup>, M. Ohkawa<sup>198</sup>, F. Ohme<sup>34,35</sup>, H. Ohta<sup>53</sup>, M. A. Okada<sup>41</sup>, Y. Okutani<sup>220</sup>, C. Olivetto<sup>71</sup>, K. Oohara<sup>211,269</sup>, R. Oram<sup>81</sup>, B. O'Reilly<sup>81</sup>, R. G. Ormiston<sup>171</sup>, N. D. Ormsby<sup>88</sup>, R. O'Shaughnessy<sup>153</sup>, E. O'Shea<sup>203</sup>, S. Oshino<sup>213</sup>, S. Ossokine<sup>136</sup>, C. Osthelder<sup>26</sup>, S. Otabe<sup>27</sup>, D. J. Ottaway<sup>113</sup>, H. Overmier<sup>81</sup>, A. E. Pace<sup>172</sup>, G. Pagano<sup>43,103</sup>, R. Pagano<sup>32</sup>, M. A. Page<sup>118</sup>, G. Pagliaroli<sup>57,132</sup>, A. Pai<sup>131</sup>, S. A. Pai<sup>119</sup>, S. Pal<sup>267</sup>, J. R. Palamos<sup>91</sup>, O. Palashov<sup>236</sup>, C. Palomba<sup>82</sup>, H. Pan<sup>154</sup>, K.-C. Pan<sup>154</sup>, P. K. Panda<sup>225</sup>, P. T. H. Pang<sup>84,90</sup>, C. Pankow<sup>40</sup>, F. Pannarale<sup>82,129</sup>, B. C. Pant<sup>119</sup>, F. H. Panther<sup>118</sup>, F. Paoletti<sup>43</sup>, A. Paoli<sup>71</sup>, A. Paolone<sup>82,270</sup>, G. Pappas<sup>222</sup>, A. Parisi<sup>158</sup>, H. Park<sup>31</sup>, J. Park<sup>271</sup>, W. Parker<sup>81</sup>, D. Pascucci<sup>84,110</sup>, A. Pasqualetti<sup>71</sup>, R. Passaquieti<sup>43,103</sup>, D. Passuello<sup>43</sup>, M. Patel<sup>88</sup>, M. Pathak<sup>113</sup>, B. Patricelli<sup>43,71</sup>, A. S. Patron<sup>32</sup>, S. Paul<sup>91</sup>, E. Payne<sup>30</sup>, M. Pedraza<sup>26</sup>, R. Pedurand<sup>128</sup>, M. Pegoraro<sup>106</sup>, A. Pele<sup>81</sup>, F. E. Peña Arellano<sup>213</sup>, S. Penano<sup>102</sup>, S. Penn<sup>272</sup>, A. Perego<sup>123,124</sup>, A. Pereira<sup>51</sup>, T. Pereira<sup>273</sup>, C. J. Perez<sup>97</sup>, C. Péroigois<sup>55</sup>, C. C. Perkins<sup>101</sup>, A. Perreca<sup>123,124</sup>, S. Perriès<sup>163</sup>, D. Pesios<sup>222</sup>, J. Petermann<sup>152</sup>, D. Petterson<sup>26</sup>, H. P. Pfeiffer<sup>136</sup>, H. Pham<sup>81</sup>, K. A. Pham<sup>171</sup>, K. S. Phukon<sup>84,233</sup>, H. Phurailatpam<sup>155</sup>, O. J. Piccinni<sup>82</sup>, M. Pichot<sup>62</sup>, M. Piendibene<sup>43,103</sup>, F. Piergiovanni<sup>79,80</sup>, L. Pierini<sup>82,129</sup>, V. Pierro<sup>112,128</sup>, G. Pillant<sup>71</sup>, M. Pillas<sup>5</sup>, F. Pilo<sup>43</sup>, L. Pinard<sup>179</sup>, C. Pineda-Bosque<sup>115</sup>, I. M. Pinto<sup>112,128,274</sup>



M. Pinto<sup>71</sup>, B. J. Piotrkowski<sup>31</sup>, K. Piotrkowski<sup>83</sup>, M. Pirello<sup>97</sup>, M. D. Pitkin<sup>216</sup>, A. Placidi<sup>65,104</sup>, E. Placidi<sup>82,129</sup>, M. L. Planas<sup>167</sup>, W. Plastino<sup>256,275</sup>, C. Pluchar<sup>276</sup>, R. Poggiani<sup>43,103</sup>, E. Polini<sup>55</sup>, D. Y. T. Pong<sup>155</sup>, S. Ponrathnam<sup>36</sup>, E. K. Porter<sup>70</sup>, R. Poulton<sup>71</sup>, A. Poverman<sup>107</sup>, J. Powell<sup>165</sup>, M. Pracchia<sup>55</sup>, T. Pradier<sup>186</sup>, A. K. Prajapati<sup>109</sup>, K. Prasai<sup>102</sup>, R. Prasanna<sup>225</sup>, G. Pratten<sup>39</sup>, M. Principe<sup>112,128,274</sup>, G. A. Prodi<sup>124,277</sup>, L. Prokhorov<sup>39</sup>, P. Proposito<sup>148,149</sup>, L. Prudenzi<sup>136</sup>, A. Puecher<sup>84,90</sup>, M. Punturo<sup>65</sup>, F. Puosi<sup>43,103</sup>, P. Puppò<sup>82</sup>, M. Pürer<sup>136</sup>, H. Qi<sup>42</sup>, N. Quartey<sup>88</sup>, V. Quetschke<sup>114</sup>, P. J. Quinonez<sup>61</sup>, R. Quitzow-James<sup>120</sup>, F. J. Raab<sup>97</sup>, G. Raaijmakers<sup>63,84</sup>, H. Radkins<sup>97</sup>, N. Radulesco<sup>62</sup>, P. Raffai<sup>176</sup>, S. X. Rail<sup>245</sup>, S. Raja<sup>119</sup>, C. Rajan<sup>119</sup>, K. E. Ramirez<sup>81</sup>, T. D. Ramirez<sup>69</sup>, A. Ramos-Buades<sup>136</sup>, J. Rana<sup>172</sup>, P. Rapagnani<sup>82,129</sup>, A. Ray<sup>31</sup>, V. Raymond<sup>42</sup>, N. Raza<sup>204</sup>, M. Razzano<sup>43,103</sup>, J. Read<sup>69</sup>, L. A. Rees<sup>67</sup>, T. Regimbau<sup>55</sup>, L. Rei<sup>117</sup>, S. Reid<sup>58</sup>, S. W. Reid<sup>88</sup>, D. H. Reitze<sup>26,101</sup>, P. Relton<sup>42</sup>, A. Renzini<sup>26</sup>, P. Rettigno<sup>47,48</sup>, B. Revenu<sup>70</sup>, A. Reza<sup>84</sup>, M. Rezac<sup>69</sup>, F. Ricci<sup>82,129</sup>, D. Richards<sup>218</sup>, J. W. Richardson<sup>278</sup>, L. Richardson<sup>208</sup>, G. Riemenschneider<sup>47,48</sup>, K. Riles<sup>207</sup>, S. Rinaldi<sup>43,103</sup>, K. Rink<sup>204</sup>, N. A. Robertson<sup>26</sup>, R. Robie<sup>26</sup>, F. Robinet<sup>5</sup>, A. Rocchi<sup>149</sup>, S. Rodriguez<sup>69</sup>, L. Rolland<sup>55</sup>, J. G. Rollins<sup>26</sup>, M. Romanelli<sup>130</sup>, R. Romano<sup>28,29</sup>, C. L. Romel<sup>97</sup>, A. Romero<sup>56</sup>, I. M. Romero-Shaw<sup>30</sup>, J. H. Romie<sup>81</sup>, S. Ronchini<sup>57,132</sup>, L. Rosa<sup>29,50</sup>, C. A. Rose<sup>31</sup>, D. Rosińska<sup>134</sup>, M. P. Ross<sup>279</sup>, S. Rowan<sup>49</sup>, S. J. Rowlinson<sup>39</sup>, S. Roy<sup>90</sup>, Santosh Roy<sup>36</sup>, Soumen Roy<sup>280</sup>, D. Rozza<sup>146,147</sup>, P. Ruggi<sup>71</sup>, K. Ruiz-Rocha<sup>200</sup>, K. Ryan<sup>97</sup>, S. Sachdev<sup>172</sup>, T. Sadecki<sup>97</sup>, J. Sadiq<sup>139</sup>, S. Saha<sup>154</sup>, Y. Saito<sup>213</sup>, K. Sakai<sup>281</sup>, M. Sakellariadou<sup>85</sup>, S. Sakon<sup>172</sup>, O. S. Salafia<sup>94,95,96</sup>, F. Salces-Carcoba<sup>26</sup>, L. Salconi<sup>71</sup>, M. Saleem<sup>171</sup>, F. Salemi<sup>123,124</sup>, A. Samajdar<sup>95</sup>, E. J. Sanchez<sup>26</sup>, J. H. Sanchez<sup>69</sup>, L. E. Sanchez<sup>26</sup>, N. Sanchis-Gual<sup>282</sup>, J. R. Sanders<sup>283</sup>, A. Sanuy<sup>54</sup>, T. R. Saravanan<sup>36</sup>, N. Sarin<sup>30</sup>, B. Sassolas<sup>179</sup>, H. Satari<sup>42,118</sup>, O. Sauter<sup>101</sup>, R. L. Savage<sup>97</sup>, V. Savant<sup>36</sup>, T. Sawada<sup>199</sup>, H. L. Sawant<sup>36</sup>, S. Sayah<sup>179</sup>, D. Schaetzl<sup>26</sup>, M. Scheel<sup>160</sup>, J. Scheuer<sup>40</sup>, M. G. Schiworski<sup>113</sup>, P. Schmidt<sup>39</sup>, S. Schmidt<sup>90</sup>, R. Schnabel<sup>152</sup>, M. Schneewind<sup>34,35</sup>, R. M. S. Schofield<sup>91</sup>, A. Schönbeck<sup>152</sup>, B. W. Schulte<sup>34,35</sup>, B. F. Schutz<sup>34,35,42</sup>, E. Schwartz<sup>42</sup>, J. Scott<sup>49</sup>, S. M. Scott<sup>33</sup>, M. Seglar-Arroyo<sup>55</sup>, Y. Sekiguchi<sup>284</sup>, D. Sellers<sup>81</sup>, A. S. Sengupta<sup>280</sup>, D. Sentenac<sup>71</sup>, E. G. Seo<sup>155</sup>, V. Sequino<sup>29,50</sup>, A. Sergeev<sup>236</sup>, Y. Setyawati<sup>34,35,90</sup>, T. Shaffer<sup>97</sup>, M. S. Shahriar<sup>40</sup>, M. A. Shaikh<sup>44</sup>, B. Shams<sup>182</sup>, L. Shao<sup>221</sup>, A. Sharma<sup>57,132</sup>, P. Sharma<sup>119</sup>, P. Shawhan<sup>135</sup>, N. S. Shcheblanov<sup>249</sup>, A. Sheela<sup>262</sup>, Y. Shikano<sup>285,286</sup>, M. Shikauchi<sup>53</sup>, H. Shimizu<sup>287</sup>, K. Shimode<sup>213</sup>, H. Shinkai<sup>288</sup>, T. Shishido<sup>78</sup>, A. Shoda<sup>45</sup>, D. H. Shoemaker<sup>99</sup>, D. M. Shoemaker<sup>192</sup>, S. ShyamSundar<sup>119</sup>, M. Sieniawska<sup>83</sup>, D. Sigg<sup>97</sup>, L. Silenzi<sup>65,66</sup>, L. P. Singer<sup>142</sup>, D. Singh<sup>172</sup>, M. K. Singh<sup>44</sup>, N. Singh<sup>134</sup>, A. Singha<sup>84,177</sup>, A. M. Sintes<sup>167</sup>, V. Sipala<sup>146,147</sup>, V. Skliris<sup>42</sup>, B. J. J. Slagmolen<sup>33</sup>, T. J. Slaven-Blair<sup>118</sup>, J. Smetana<sup>39</sup>, J. R. Smith<sup>69</sup>, L. Smith<sup>49</sup>, R. J. E. Smith<sup>30</sup>, J. Soldateschi<sup>80,250,289</sup>, S. N. Somala<sup>290</sup>, K. Somiya<sup>27</sup>, I. Song<sup>154</sup>, K. Soni<sup>36</sup>, S. Soni<sup>99</sup>, V. Sordini<sup>163</sup>, F. Sorrentino<sup>117</sup>, N. Sorrentino<sup>43,103</sup>, R. Soulard<sup>62</sup>, T. Souradeep<sup>36,291</sup>, E. Sowell<sup>170</sup>, V. Spagnuolo<sup>84,177</sup>, A. P. Spencer<sup>49</sup>, M. Spera<sup>105,106</sup>, P. Spinicelli<sup>71</sup>, A. K. Srivastava<sup>109</sup>, V. Srivastava<sup>92</sup>, K. Staats<sup>40</sup>, C. Stachie<sup>62</sup>, F. Stachurski<sup>49</sup>, D. A. Steer<sup>70</sup>, J. Steinlechner<sup>84,177</sup>, S. Steinlechner<sup>84,177</sup>, N. Stergioulas<sup>222</sup>, D. J. Stops<sup>39</sup>, M. Stover<sup>258</sup>, K. A. Strain<sup>49</sup>, L. C. Strang<sup>145</sup>, G. Stratta<sup>82,292</sup>, M. D. Strong<sup>32</sup>, A. Strunk<sup>97</sup>, R. Sturani<sup>273</sup>, A. L. Stuver<sup>138</sup>, M. Suchenek<sup>111</sup>, S. Sudhagar<sup>36</sup>, V. Sudhir<sup>99</sup>, R. Sugimoto<sup>264,293</sup>, H. G. Suh<sup>31</sup>, A. G. Sullivan<sup>75</sup>, T. Z. Summerscales<sup>294</sup>, L. Sun<sup>33</sup>, S. Sunil<sup>109</sup>, A. Sur<sup>111</sup>, J. Suresh<sup>53</sup>, P. J. Sutton<sup>42</sup>, Takamasa Suzuki<sup>198</sup>, Takanori Suzuki<sup>27</sup>, Toshikazu Suzuki<sup>211</sup>, B. L. Swinkels<sup>84</sup>, M. J. Szczepańczyk<sup>101</sup>, P. Szewczyk<sup>134</sup>, M. Tacca<sup>84</sup>, H. Tagoshi<sup>211</sup>, S. C. Tait<sup>49</sup>, H. Takahashi<sup>295</sup>, R. Takahashi<sup>45</sup>, S. Takano<sup>52</sup>, H. Takeda<sup>52</sup>, M. Takeda<sup>199</sup>, C. J. Talbot<sup>58</sup>, C. Talbot<sup>26</sup>, K. Tanaka<sup>296</sup>, Taiki Tanaka<sup>211</sup>, Takahiro Tanaka<sup>297</sup>, A. J. Tanasijczuk<sup>83</sup>, S. Tanioka<sup>213</sup>, D. B. Tanner<sup>101</sup>, D. Tao<sup>26</sup>, L. Tao<sup>101</sup>, R. D. Tapia<sup>172</sup>, E. N. Tapia San Martín<sup>84</sup>, C. Taranto<sup>148</sup>, A. Taruya<sup>298</sup>, J. D. Tasson<sup>183</sup>, R. Tenorio<sup>167</sup>, J. E. S. Terhune<sup>138</sup>, L. Terkowski<sup>152</sup>, M. P. Thirugnanasambandam<sup>36</sup>, M. Thomas<sup>81</sup>, P. Thomas<sup>97</sup>, E. E. Thompson<sup>72</sup>, J. E. Thompson<sup>42</sup>, S. R. Thondapu<sup>119</sup>, K. A. Thorne<sup>81</sup>, E. Thrane<sup>30</sup>, Shubhanshu Tiwari<sup>184</sup>, Srishti Tiwari<sup>36</sup>, V. Tiwari<sup>42</sup>, A. M. Toivonen<sup>171</sup>, A. E. Tolley<sup>76</sup>, T. Tomaru<sup>45</sup>, T. Tomura<sup>213</sup>, M. Tonelli<sup>43,103</sup>, Z. Tornasi<sup>49</sup>, A. Torres-Forne<sup>151</sup>, C. I. Torrie<sup>26</sup>, I. Tosta e Melo<sup>147</sup>, D. Töyrä<sup>33</sup>, A. Trapananti<sup>65,66</sup>, F. Travasso<sup>65,66</sup>, G. Traylor<sup>81</sup>, M. Trevor<sup>135</sup>, M. C. Tringali<sup>71</sup>, A. Tripathee<sup>207</sup>, L. Troiano<sup>128,299</sup>, A. Trovato<sup>70</sup>, L. Trozzo<sup>29,213</sup>, R. J. Trudeau<sup>26</sup>, D. Tsai<sup>154</sup>, K. W. Tsang<sup>84,90,300</sup>, T. Tsang<sup>301</sup>, J.-S. Tsao<sup>254</sup>, M. Tse<sup>99</sup>, R. Tso<sup>160</sup>, S. Tsuchida<sup>199</sup>, L. Tsukada<sup>172</sup>, D. Tsuna<sup>53</sup>, T. Tsutsui<sup>53</sup>, K. Turbang<sup>226,302</sup>, M. Turconi<sup>62</sup>, D. Tuyenbayev<sup>199</sup>, A. S. Ubhi<sup>39</sup>, T. Uchiyama<sup>213</sup>, R. P. Udall<sup>26</sup>, A. Ueda<sup>303</sup>, T. Uehara<sup>304,305</sup>, K. Ueno<sup>53</sup>, G. Ueshima<sup>306</sup>, C. S. Unnikrishnan<sup>307</sup>, A. L. Urban<sup>32</sup>, T. Ushiba<sup>213</sup>, A. Utina<sup>84,177</sup>, G. Vajente<sup>26</sup>, A. Vajpeyi<sup>30</sup>, G. Valdes<sup>208</sup>, M. Valentini<sup>123,124,206</sup>, V. Valsan<sup>31</sup>, N. van Bakel<sup>84</sup>, M. van Beuzekom<sup>84</sup>, M. van Dael<sup>84,308</sup>, J. F. J. van den Brand<sup>84,121,177</sup>, C. Van Den Broeck<sup>84,90</sup>, D. C. Vander-Hyde<sup>92</sup>, H. van Haevermaet<sup>226</sup>, J. V. van Heijningen<sup>83</sup>, M. H. P. M. van Putten<sup>309</sup>, N. van Remortel<sup>226</sup>, M. Vardaro<sup>84,233</sup>, A. F. Vargas<sup>145</sup>, V. Varma<sup>136</sup>, M. Vasúth<sup>100</sup>, A. Vecchio<sup>39</sup>, G. Vedovato<sup>106</sup>, J. Veitch<sup>49</sup>, P. J. Veitch<sup>113</sup>, J. Venneberg<sup>34,35</sup>, G. Venugopalan<sup>26</sup>, D. Verkindt<sup>55</sup>, P. Verma<sup>242</sup>, Y. Verma<sup>119</sup>, S. M. Vermeulen<sup>42</sup>, D. Veske<sup>75</sup>, F. Vetrano<sup>79</sup>, A. Vicere<sup>79,80</sup>, S. Vidyant<sup>92</sup>, A. D. Viets<sup>310</sup>, A. Vijaykumar<sup>44</sup>, V. Villa-Ortega<sup>139</sup>, J.-Y. Vinet<sup>62</sup>, A. Virtuoso<sup>60,260</sup>, S. Vitale<sup>99</sup>, H. Vocca<sup>65,104</sup>, E. R. G. von Reis<sup>97</sup>, J. S. A. von Wrangel<sup>34,35</sup>, C. Vorvick<sup>97</sup>, S. P. Vyatchanin<sup>122</sup>, L. E. Wade<sup>258</sup>, M. Wade<sup>258</sup>, K. J. Wagner<sup>153</sup>, R. C. Walet<sup>84</sup>, M. Walker<sup>88</sup>, G. S. Wallace<sup>58</sup>, L. Wallace<sup>26</sup>, J. Wang<sup>201</sup>, J. Z. Wang<sup>207</sup>, W. H. Wang<sup>114</sup>, R. L. Ward<sup>33</sup>, J. Warner<sup>97</sup>, M. Was<sup>55</sup>, T. Washimi<sup>45</sup>, N. Y. Washington<sup>26</sup>, J. Watchi<sup>168</sup>, B. Weaver<sup>97</sup>, C. R. Weaving<sup>76</sup>, S. A. Webster<sup>49</sup>, M. Weinert<sup>34,35</sup>, A. J. Weinstein<sup>26</sup>, R. Weiss<sup>99</sup>, C. M. Weller<sup>279</sup>, R. A. Weller<sup>200</sup>, F. Wellmann<sup>34,35</sup>, L. Wen<sup>118</sup>, P. Weßels<sup>34,35</sup>, K. Wette<sup>33</sup>, J. T. Whelan<sup>153</sup>, D. D. White<sup>69</sup>, B. F. Whiting<sup>101</sup>, C. Whittle<sup>99</sup>, D. Wilken<sup>34,35</sup>, D. Williams<sup>49</sup>, M. J. Williams<sup>49</sup>, A. R. Williamson<sup>76</sup>, J. L. Willis<sup>26</sup>, B. Willke<sup>34,35</sup>, D. J. Wilson<sup>276</sup>, C. C. Wipf<sup>26</sup>

T. Wlodarczyk<sup>136</sup>, G. Woan<sup>49</sup>, J. Woehler<sup>34,35</sup>, J. K. Wofford<sup>153</sup>, D. Wong<sup>204</sup>, I. C. F. Wong<sup>155</sup>, M. Wright<sup>49</sup>, C. Wu<sup>154</sup>,  
 D. S. Wu<sup>34,35</sup>, H. Wu<sup>154</sup>, D. M. Wysocki<sup>31</sup>, L. Xiao<sup>26</sup>, T. Yamada<sup>287</sup>, H. Yamamoto<sup>26</sup>, K. Yamamoto<sup>212</sup>,  
 T. Yamamoto<sup>213</sup>, K. Yamashita<sup>223</sup>, R. Yamazaki<sup>220</sup>, F. W. Yang<sup>182</sup>, K. Z. Yang<sup>171</sup>, L. Yang<sup>190</sup>, Y.-C. Yang<sup>154</sup>,  
 Y. Yang<sup>311</sup>, Yang Yang<sup>101</sup>, M. J. Yap<sup>33</sup>, D. W. Yeeles<sup>42</sup>, S.-W. Yeh<sup>154</sup>, A. B. Yelikar<sup>153</sup>, M. Ying<sup>154</sup>, J. Yokoyama<sup>52,53</sup>,  
 T. Yokozawa<sup>213</sup>, J. Yoo<sup>203</sup>, T. Yoshioka<sup>223</sup>, Hang Yu<sup>160</sup>, Haocun Yu<sup>99</sup>, H. Yuzurihara<sup>211</sup>, A. Zadrożny<sup>242</sup>, M. Zanolin<sup>61</sup>,  
 S. Zeidler<sup>312</sup>, T. Zelenova<sup>71</sup>, J.-P. Zeng<sup>106</sup>, M. Zevin<sup>188</sup>, M. Zhan<sup>201</sup>, H. Zhang<sup>254</sup>, J. Zhang<sup>118</sup>, L. Zhang<sup>26</sup>,  
 R. Zhang<sup>101</sup>, T. Zhang<sup>39</sup>, Y. Zhang<sup>208</sup>, C. Zhao<sup>118</sup>, G. Zhao<sup>168</sup>, Y. Zhao<sup>45,211</sup>, Yue Zhao<sup>182</sup>, R. Zhou<sup>214</sup>, Z. Zhou<sup>40</sup>,  
 X. J. Zhu<sup>30</sup>, Z.-H. Zhu<sup>144,252</sup>, A. B. Zimmerman<sup>192</sup>, M. E. Zucker<sup>26,99</sup>, and J. Zweizig<sup>26</sup>

The LIGO Scientific Collaboration, the Virgo Collaboration, and the KAGRA Collaboration

<sup>1</sup> Science and Technology Institute, Universities Space Research Association, Huntsville, AL 35805, USA

<sup>2</sup> NASA Marshall Space Flight Center, Huntsville, AL 35812, USA

<sup>3</sup> Department of Space Science, University of Alabama in Huntsville, Huntsville, AL 35899, USA

<sup>4</sup> Center for Space Plasma and Aeronomic Research, University of Alabama in Huntsville, Huntsville, AL 35899, USA

<sup>5</sup> Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France

<sup>6</sup> Dipartimento Interateneo di Fisica, Politecnico di Bari, Via E. Orabona 4, 70125, Bari, Italy

<sup>7</sup> INFN—Sezione di Bari, Via E. Orabona 4, 70125, Bari, Italy

<sup>8</sup> Department of Physics & Astronomy, Louisiana State University, Baton Rouge, LA 70803, USA

<sup>9</sup> Jacobs Space Exploration Group, Huntsville, AL 35806, USA

<sup>10</sup> Center for Space Plasma and Aeronomic Research, The University of Alabama in Huntsville, Huntsville, AL 35899, USA

<sup>11</sup> Department of Space Science, University of Alabama in Huntsville, 320 Sparkman Drive, Huntsville, AL 35899, USA

<sup>12</sup> Department of Aerospace, Physics and Space Sciences, Florida Institute of Technology, Melbourne, FL 32901, USA

<sup>13</sup> International Space Science Institute (ISSI), Hallerstrasse 6, 3012 Bern, Switzerland

<sup>14</sup> Max-Planck-Institut für extraterrestrische Physik, Giessenbachstrasse 1, D-85748 Garching, Germany

<sup>15</sup> Department of Astronomy, University of Maryland, College Park, MD 20742, USA

<sup>16</sup> Center for Research and Exploration in Space Science and Technology, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

<sup>17</sup> Stockholm University and The Oskar Klein Centre for Cosmoparticle Physics, Alba Nova, 10691 Stockholm, Sweden

<sup>18</sup> Department of Physics and Astronomy, University of Alabama, Tuscaloosa, AL 35487, USA

<sup>19</sup> Department of Physics, Pennsylvania State University, University Park, PA 16802, USA

<sup>20</sup> Center for Multimessenger Astrophysics, Institute for Gravitation and the Cosmos, Pennsylvania State University, University Park, PA 16802, USA

<sup>21</sup> Department of Astronomy & Astrophysics, University of Toronto, Toronto, Ontario, M5S 1A1, Canada

<sup>22</sup> Astrophysics Science Division, NASA Goddard Space Flight Center, MC 661, Greenbelt, MD 20771, USA

<sup>23</sup> Joint Space-Science Institute, University of Maryland, College Park, MD 20742, USA

<sup>24</sup> Astrophysics Science Division, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

<sup>25</sup> Center for Space Science and Technology, University of Maryland Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250, USA

<sup>26</sup> LIGO Laboratory, California Institute of Technology, Pasadena, CA 91125, USA

<sup>27</sup> Graduate School of Science, Tokyo Institute of Technology, Meguro-ku, Tokyo 152-8551, Japan

<sup>28</sup> Dipartimento di Farmacia, Università di Salerno, I-84084 Fisciano, Salerno, Italy

<sup>29</sup> INFN, Sezione di Napoli, Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy

<sup>30</sup> OzGrav, School of Physics & Astronomy, Monash University, Clayton 3800, Victoria, Australia

<sup>31</sup> University of Wisconsin-Milwaukee, Milwaukee, WI 53201, USA

<sup>32</sup> Louisiana State University, Baton Rouge, LA 70803, USA

<sup>33</sup> OzGrav, Australian National University, Canberra, Australian Capital Territory 0200, Australia

<sup>34</sup> Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-30167 Hannover, Germany

<sup>35</sup> Leibniz Universität Hannover, D-30167 Hannover, Germany

<sup>36</sup> Inter-University Centre for Astronomy and Astrophysics, Pune 411007, India

<sup>37</sup> University of Cambridge, Cambridge, CB2 1TN, UK

<sup>38</sup> Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universität Jena, D-07743 Jena, Germany

<sup>39</sup> University of Birmingham, Birmingham, B15 2TT, UK

<sup>40</sup> Northwestern University, Evanston, IL 60208, USA

<sup>41</sup> Instituto Nacional de Pesquisas Espaciais, São José dos Campos, São Paulo 12227-010, Brazil

<sup>42</sup> Cardiff University, Cardiff, CF24 3AA, UK

<sup>43</sup> INFN, Sezione di Pisa, I-56127 Pisa, Italy

<sup>44</sup> International Centre for Theoretical Sciences, Tata Institute of Fundamental Research, Bengaluru 560089, India

<sup>45</sup> Gravitational Wave Science Project, National Astronomical Observatory of Japan (NAOJ), Mitaka City, Tokyo 181-8588, Japan

<sup>46</sup> Advanced Technology Center, National Astronomical Observatory of Japan (NAOJ), Mitaka City, Tokyo 181-8588, Japan

<sup>47</sup> Dipartimento di Fisica, Università degli Studi di Torino, I-10125 Torino, Italy

<sup>48</sup> INFN Sezione di Torino, I-10125 Torino, Italy

<sup>49</sup> SUPA, University of Glasgow, Glasgow, G12 8QQ, UK

<sup>50</sup> Università di Napoli “Federico II,” Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy

<sup>51</sup> Université de Lyon, Université Claude Bernard Lyon 1, CNRS, Institut Lumière Matière, F-69622 Villeurbanne, France

<sup>52</sup> Department of Physics, The University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan

<sup>53</sup> Research Center for the Early Universe (RESCEU), The University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan

<sup>54</sup> Institut de Ciències del Cosmos (ICCUB), Universitat de Barcelona, C/ Martí i Franquès 1, Barcelona, 08028, Spain

<sup>55</sup> Univ. Savoie Mont Blanc, CNRS, Laboratoire d’Annecy de Physique des Particules—IN2P3, F-74000 Annecy, France

<sup>56</sup> Institut de Física d’Altes Energies (IFAE), Barcelona Institute of Science and Technology, and ICREA, E-08193 Barcelona, Spain

<sup>57</sup> Gran Sasso Science Institute (GSSI), I-67100 L’Aquila, Italy

<sup>58</sup> SUPA, University of Strathclyde, Glasgow, G1 1XQ, UK

<sup>59</sup> Dipartimento di Scienze Matematiche, Informatiche e Fisiche, Università di Udine, I-33100 Udine, Italy

<sup>60</sup> INFN, Sezione di Trieste, I-34127 Trieste, Italy

<sup>61</sup> Embry-Riddle Aeronautical University, Prescott, AZ 86301, USA

<sup>62</sup> Artemis, Université Côte d’Azur, Observatoire de la Côte d’Azur, CNRS, F-06304 Nice, France

<sup>63</sup> GRAPPA, Anton Pannekoek Institute for Astronomy and Institute for High-Energy Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, Netherlands

- <sup>64</sup> National and Kapodistrian University of Athens, School of Science Building, 2nd floor, Panepistimiopolis, 15771 Ilissia, Greece
- <sup>65</sup> INFN, Sezione di Perugia, I-06123 Perugia, Italy
- <sup>66</sup> Università di Camerino, Dipartimento di Fisica, I-62032 Camerino, Italy
- <sup>67</sup> American University, Washington, DC 20016, USA
- <sup>68</sup> Earthquake Research Institute, The University of Tokyo, Bunkyo-ku, Tokyo 113-0032, Japan
- <sup>69</sup> California State University Fullerton, Fullerton, CA 92831, USA
- <sup>70</sup> Université de Paris, CNRS, Astroparticule et Cosmologie, F-75006 Paris, France
- <sup>71</sup> European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy
- <sup>72</sup> Georgia Institute of Technology, Atlanta, GA 30332, USA
- <sup>73</sup> Chennai Mathematical Institute, Chennai 603103, India
- <sup>74</sup> Department of Mathematics and Physics, Graduate School of Science and Technology, Hirosaki University, 3 Bunkyo-cho, Hirosaki, Aomori 036-8561, Japan
- <sup>75</sup> Columbia University, New York, NY 10027, USA
- <sup>76</sup> University of Portsmouth, Portsmouth, PO1 3FX, UK
- <sup>77</sup> Kamioka Branch, National Astronomical Observatory of Japan (NAOJ), Kamioka-cho, Hida City, Gifu 506-1205, Japan
- <sup>78</sup> The Graduate University for Advanced Studies (SOKENDAI), Mitaka City, Tokyo 181-8588, Japan
- <sup>79</sup> Università degli Studi di Urbino “Carlo Bo,” I-61029 Urbino, Italy
- <sup>80</sup> INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Firenze, Italy
- <sup>81</sup> LIGO Livingston Observatory, Livingston, LA 70754, USA
- <sup>82</sup> INFN, Sezione di Roma, I-00185 Roma, Italy
- <sup>83</sup> Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium
- <sup>84</sup> Nikhef, Science Park 105, 1098 XG Amsterdam, Netherlands
- <sup>85</sup> King’s College London, University of London, London, WC2R 2LS, UK
- <sup>86</sup> Korea Institute of Science and Technology Information, Daejeon 34141, Republic of Korea
- <sup>87</sup> National Institute for Mathematical Sciences, Daejeon 34047, Republic of Korea
- <sup>88</sup> Christopher Newport University, Newport News, VA 23606, USA
- <sup>89</sup> School of High Energy Accelerator Science, The Graduate University for Advanced Studies (SOKENDAI), Tsukuba City, Ibaraki 305-0801, Japan
- <sup>90</sup> Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University, Princetonplein 1, 3584 CC Utrecht, Netherlands
- <sup>91</sup> University of Oregon, Eugene, OR 97403, USA
- <sup>92</sup> Syracuse University, Syracuse, NY 13244, USA
- <sup>93</sup> Université de Liège, B-4000 Liège, Belgium
- <sup>94</sup> Università degli Studi di Milano-Bicocca, I-20126 Milano, Italy
- <sup>95</sup> INFN, Sezione di Milano-Bicocca, I-20126 Milano, Italy
- <sup>96</sup> INAF, Osservatorio Astronomico di Brera sede di Merate, I-23807 Merate, Lecco, Italy
- <sup>97</sup> LIGO Hanford Observatory, Richland, WA 99352, USA
- <sup>98</sup> Dipartimento di Medicina, Chirurgia e Odontoiatria “Scuola Medica Salernitana,” Università di Salerno, I-84081 Baronissi, Salerno, Italy
- <sup>99</sup> LIGO Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
- <sup>100</sup> Wigner RCP, RMKI, H-1121 Budapest, Konkoly Thege Miklós út 29-33, Hungary
- <sup>101</sup> University of Florida, Gainesville, FL 32611, USA
- <sup>102</sup> Stanford University, Stanford, CA 94305, USA
- <sup>103</sup> Università di Pisa, I-56127 Pisa, Italy
- <sup>104</sup> Università di Perugia, I-06123 Perugia, Italy
- <sup>105</sup> Università di Padova, Dipartimento di Fisica e Astronomia, I-35131 Padova, Italy
- <sup>106</sup> INFN, Sezione di Padova, I-35131 Padova, Italy
- <sup>107</sup> Bard College, Annandale-On-Hudson, NY 12504, USA
- <sup>108</sup> Montana State University, Bozeman, MT 59717, USA
- <sup>109</sup> Institute for Plasma Research, Bhat, Gandhinagar 382428, India
- <sup>110</sup> Universiteit Gent, B-9000 Gent, Belgium
- <sup>111</sup> Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, 00-716, Warsaw, Poland
- <sup>112</sup> Dipartimento di Ingegneria, Università del Sannio, I-82100 Benevento, Italy
- <sup>113</sup> OzGrav, University of Adelaide, Adelaide, South Australia 5005, Australia
- <sup>114</sup> The University of Texas Rio Grande Valley, Brownsville, TX 78520, USA
- <sup>115</sup> California State University, Los Angeles, Los Angeles, CA 90032, USA
- <sup>116</sup> Departament de Matemàtiques, Universitat Autònoma de Barcelona, Edificio C Facultad de Ciencias 08193 Bellaterra (Barcelona), Spain
- <sup>117</sup> INFN, Sezione di Genova, I-16146 Genova, Italy
- <sup>118</sup> OzGrav, University of Western Australia, Crawley, Western Australia 6009, Australia
- <sup>119</sup> RRCAT, Indore, Madhya Pradesh 452013, India
- <sup>120</sup> Missouri University of Science and Technology, Rolla, MO 65409, USA
- <sup>121</sup> Vrije Universiteit Amsterdam, 1081 HV Amsterdam, Netherlands
- <sup>122</sup> Lomonosov Moscow State University, Moscow 119991, Russia
- <sup>123</sup> Università di Trento, Dipartimento di Fisica, I-38123 Povo, Trento, Italy
- <sup>124</sup> INFN, Trento Institute for Fundamental Physics and Applications, I-38123 Povo, Trento, Italy
- <sup>125</sup> SUPA, University of the West of Scotland, Paisley, PA1 2BE, UK
- <sup>126</sup> Bar-Ilan University, Ramat Gan, 5290002, Israel
- <sup>127</sup> Dipartimento di Fisica “E.R. Caianiello,” Università di Salerno, I-84084 Fisciano, Salerno, Italy
- <sup>128</sup> INFN, Sezione di Napoli, Gruppo Collegato di Salerno, Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy
- <sup>129</sup> Università di Roma “La Sapienza,” I-00185 Roma, Italy
- <sup>130</sup> Univ Rennes, CNRS, Institut FOTON—UMR6082, F-35000 Rennes, France
- <sup>131</sup> Indian Institute of Technology Bombay, Powai, Mumbai 400 076, India
- <sup>132</sup> INFN, Laboratori Nazionali del Gran Sasso, I-67100 Assergi, Italy
- <sup>133</sup> Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France, F-75005 Paris, France
- <sup>134</sup> Astronomical Observatory Warsaw University, 00-478 Warsaw, Poland
- <sup>135</sup> University of Maryland, College Park, MD 20742, USA
- <sup>136</sup> Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-14476 Potsdam, Germany
- <sup>137</sup> L2IT, Laboratoire des 2 Infinis—Toulouse, Université de Toulouse, CNRS/IN2P3, UPS, F-31062 Toulouse Cedex 9, France
- <sup>138</sup> Villanova University, Villanova, PA 19085, USA
- <sup>139</sup> IGFAE, Universidad de Santiago de Compostela, 15782 Spain

- <sup>140</sup> Stony Brook University, Stony Brook, NY 11794, USA
- <sup>141</sup> Center for Computational Astrophysics, Flatiron Institute, New York, NY 10010, USA
- <sup>142</sup> NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
- <sup>143</sup> Dipartimento di Fisica, Università degli Studi di Genova, I-16146 Genova, Italy
- <sup>144</sup> Department of Astronomy, Beijing Normal University, Beijing 100875, People's Republic of China
- <sup>145</sup> OzGrav, University of Melbourne, Parkville, Victoria 3010, Australia
- <sup>146</sup> Università degli Studi di Sassari, I-07100 Sassari, Italy
- <sup>147</sup> INFN, Laboratori Nazionali del Sud, I-95125 Catania, Italy
- <sup>148</sup> Università di Roma Tor Vergata, I-00133 Roma, Italy
- <sup>149</sup> INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy
- <sup>150</sup> University of Sannio at Benevento, I-82100 Benevento, Italy and INFN, Sezione di Napoli, I-80100 Napoli, Italy
- <sup>151</sup> Departamento de Astronomía y Astrofísica, Universitat de València, E-46100 Burjassot, València, Spain
- <sup>152</sup> Universität Hamburg, D-22761 Hamburg, Germany
- <sup>153</sup> Rochester Institute of Technology, Rochester, NY 14623, USA
- <sup>154</sup> National Tsing Hua University, Hsinchu City, 30013 Taiwan, Republic of China
- <sup>155</sup> The Chinese University of Hong Kong, Shatin, NT, Hong Kong
- <sup>156</sup> Department of Applied Physics, Fukuoka University, Jonan, Fukuoka City, Fukuoka 814-0180, Japan
- <sup>157</sup> OzGrav, Charles Sturt University, Wagga Wagga, New South Wales 2678, Australia
- <sup>158</sup> Department of Physics, Tamkang University, Danshui Dist., New Taipei City 25137, Taiwan
- <sup>159</sup> Department of Physics, Center for High Energy and High Field Physics, National Central University, Zhongli District, Taoyuan City 32001, Taiwan
- <sup>160</sup> CaRT, California Institute of Technology, Pasadena, CA 91125, USA
- <sup>161</sup> Dipartimento di Ingegneria Industriale (DIIN), Università di Salerno, I-84084 Fisciano, Salerno, Italy
- <sup>162</sup> Institute of Physics, Academia Sinica, Nankang, Taipei 11529, Taiwan
- <sup>163</sup> Université Lyon, Université Claude Bernard Lyon 1, CNRS, IP2I Lyon / IN2P3, UMR 5822, F-69622 Villeurbanne, France
- <sup>164</sup> INAF, Osservatorio Astronomico di Padova, I-35122 Padova, Italy
- <sup>165</sup> OzGrav, Swinburne University of Technology, Hawthorn VIC 3122, Australia
- <sup>166</sup> Université libre de Bruxelles, Avenue Franklin Roosevelt 50-1050 Bruxelles, Belgium
- <sup>167</sup> IAC3-IEEC, Universitat de les Illes Balears, E-07122 Palma de Mallorca, Spain
- <sup>168</sup> Université Libre de Bruxelles, Brussels 1050, Belgium
- <sup>169</sup> Departamento de Matemáticas, Universitat de València, E-46100 Burjassot, València, Spain
- <sup>170</sup> Texas Tech University, Lubbock, TX 79409, USA
- <sup>171</sup> University of Minnesota, Minneapolis, MN 55455, USA
- <sup>172</sup> The Pennsylvania State University, University Park, PA 16802, USA
- <sup>173</sup> University of Rhode Island, Kingston, RI 02881, USA
- <sup>174</sup> Bellevue College, Bellevue, WA 98007, USA
- <sup>175</sup> Scuola Normale Superiore, Piazza dei Cavalieri, 7-56126 Pisa, Italy
- <sup>176</sup> Eötvös University, Budapest 1117, Hungary
- <sup>177</sup> Maastricht University, P.O. Box 616, 6200 MD Maastricht, Netherlands
- <sup>178</sup> The University of Sheffield, Sheffield S10 2TN, UK
- <sup>179</sup> Université Lyon, Université Claude Bernard Lyon 1, CNRS, Laboratoire des Matériaux Avancés (LMA), IP2I Lyon / IN2P3, UMR 5822, F-69622 Villeurbanne, France
- <sup>180</sup> Dipartimento di Scienze Matematiche, Fisiche e Informatiche, Università di Parma, I-43124 Parma, Italy
- <sup>181</sup> INFN, Sezione di Milano Bicocca, Gruppo Collegato di Parma, I-43124 Parma, Italy
- <sup>182</sup> The University of Utah, Salt Lake City, UT 84112, USA
- <sup>183</sup> Carleton College, Northfield, MN 55057, USA
- <sup>184</sup> University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland
- <sup>185</sup> Perimeter Institute, Waterloo, ON N2L 2Y5, Canada
- <sup>186</sup> Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
- <sup>187</sup> West Virginia University, Morgantown, WV 26506, USA
- <sup>188</sup> University of Chicago, Chicago, IL 60637, USA
- <sup>189</sup> Montclair State University, Montclair, NJ 07043, USA
- <sup>190</sup> Colorado State University, Fort Collins, CO 80523, USA
- <sup>191</sup> Institute for Nuclear Research, Bem tér 18/c, H-4026 Debrecen, Hungary
- <sup>192</sup> University of Texas, Austin, TX 78712, USA
- <sup>193</sup> CNR-SPIN, c/o Università di Salerno, I-84084 Fisciano, Salerno, Italy
- <sup>194</sup> Scuola di Ingegneria, Università della Basilicata, I-85100 Potenza, Italy
- <sup>195</sup> Observatori Astronòmic, Universitat de València, E-46980 Paterna, València, Spain
- <sup>196</sup> Centro de Física das Universidades do Minho e do Porto, Universidade do Minho, Campus de Gualtar, PT-4710-057 Braga, Portugal
- <sup>197</sup> Department of Astronomy, The University of Tokyo, Mitaka City, Tokyo 181-8588, Japan
- <sup>198</sup> Faculty of Engineering, Niigata University, Nishi-ku, Niigata City, Niigata 950-2181, Japan
- <sup>199</sup> Department of Physics, Graduate School of Science, Osaka City University, Sumiyoshi-ku, Osaka City, Osaka 558-8585, Japan
- <sup>200</sup> Vanderbilt University, Nashville, TN 37235, USA
- <sup>201</sup> State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Innovation Academy for Precision Measurement Science and Technology (APM), Chinese Academy of Sciences, Xiao Hong Shan, Wuhan 430071, People's Republic of China
- <sup>202</sup> University of Szeged, Dóm tér 9, Szeged 6720, Hungary
- <sup>203</sup> Cornell University, Ithaca, NY 14850, USA
- <sup>204</sup> University of British Columbia, Vancouver, BC V6T 1Z4, Canada
- <sup>205</sup> INAF, Osservatorio Astronomico di Capodimonte, I-80131 Napoli, Italy
- <sup>206</sup> The University of Mississippi, University, MS 38677, USA
- <sup>207</sup> University of Michigan, Ann Arbor, MI 48109, USA
- <sup>208</sup> Texas A&M University, College Station, TX 77843, USA
- <sup>209</sup> Ulsan National Institute of Science and Technology, Ulsan 44919, Republic of Korea
- <sup>210</sup> Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, People's Republic of China
- <sup>211</sup> Institute for Cosmic Ray Research (ICRR), KAGRA Observatory, The University of Tokyo, Kashiwa City, Chiba 277-8582, Japan
- <sup>212</sup> Faculty of Science, University of Toyama, Toyama City, Toyama 930-8555, Japan

- <sup>213</sup> Institute for Cosmic Ray Research (ICRR), KAGRA Observatory, The University of Tokyo, Kamioka-cho, Hida City, Gifu 506-1205, Japan
- <sup>214</sup> University of California, Berkeley, CA 94720, USA
- <sup>215</sup> Maastricht University, 6200 MD, Maastricht, Netherlands
- <sup>216</sup> Lancaster University, Lancaster, LA1 4YW, UK
- <sup>217</sup> College of Industrial Technology, Nihon University, Narashino City, Chiba 275-8575, Japan
- <sup>218</sup> Rutherford Appleton Laboratory, Didcot, OX11 0DE, UK
- <sup>219</sup> Department of Astronomy & Space Science, Chungnam National University, Yuseong-gu, Daejeon 34134, Republic of Korea
- <sup>220</sup> Department of Physical Sciences, Aoyama Gakuin University, Sagami-hara City, Kanagawa 252-5258, Japan
- <sup>221</sup> Kavli Institute for Astronomy and Astrophysics, Peking University, Haidian District, Beijing 100871, People's Republic of China
- <sup>222</sup> Aristotle University of Thessaloniki, University Campus, 54124 Thessaloniki, Greece
- <sup>223</sup> Graduate School of Science and Engineering, University of Toyama, Toyama City, Toyama 930-8555, Japan
- <sup>224</sup> Nambu Yoichiro Institute of Theoretical and Experimental Physics (NITEP), Osaka City University, Sumiyoshi-ku, Osaka City, Osaka 558-8585, Japan
- <sup>225</sup> Directorate of Construction, Services & Estate Management, Mumbai 400094, India
- <sup>226</sup> Universiteit Antwerpen, Prinsstraat 13, 2000 Antwerpen, Belgium
- <sup>227</sup> University of Białystok, 15-424 Białystok, Poland
- <sup>228</sup> Ewha Womans University, Seoul 03760, Republic of Korea
- <sup>229</sup> National Astronomical Observatories, Chinese Academy of Sciences, Chaoyang District, Beijing 100107, People's Republic of China
- <sup>230</sup> School of Astronomy and Space Science, University of Chinese Academy of Sciences, Chaoyang District, Beijing 100107, People's Republic of China
- <sup>231</sup> University of Southampton, Southampton, SO17 1BJ, UK
- <sup>232</sup> Institute for Cosmic Ray Research (ICRR), The University of Tokyo, Kashiwa City, Chiba 277-8582, Japan
- <sup>233</sup> Institute for High-Energy Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, Netherlands
- <sup>234</sup> Chung-Ang University, Seoul 06974, Republic of Korea
- <sup>235</sup> University of Washington Bothell, Bothell, WA 98011, USA
- <sup>236</sup> Institute of Applied Physics, Nizhny Novgorod, 603950, Russia
- <sup>237</sup> Inje University Gimhae, South Gyeongsang 50834, Republic of Korea
- <sup>238</sup> Department of Physics, Myongji University, Yongin 17058, Republic of Korea
- <sup>239</sup> Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research Organization (KEK), Tsukuba City, Ibaraki 305-0801, Japan
- <sup>240</sup> School of Physics and Astronomy, Cardiff University, Cardiff, CF24 3AA, UK
- <sup>241</sup> Institute of Mathematics, Polish Academy of Sciences, 00656 Warsaw, Poland
- <sup>242</sup> National Center for Nuclear Research, 05-400 Świerk-Otwock, Poland
- <sup>243</sup> Instituto de Física Teórica, 28049 Madrid, Spain
- <sup>244</sup> Department of Physics, Nagoya University, Chikusa-ku, Nagoya, Aichi 464-8602, Japan
- <sup>245</sup> Université de Montréal/Polytechnique, Montreal, Quebec H3T 1J4, Canada
- <sup>246</sup> Laboratoire Lagrange, Université Côte d'Azur, Observatoire Côte d'Azur, CNRS, F-06304 Nice, France
- <sup>247</sup> Seoul National University, Seoul 08826, Republic of Korea
- <sup>248</sup> Sungkyunkwan University, Seoul 03063, Republic of Korea
- <sup>249</sup> NAVIER, École des Ponts, Univ Gustave Eiffel, CNRS, Mame-la-Vallée, France
- <sup>250</sup> Università di Firenze, Sesto Fiorentino I-50019, Italy
- <sup>251</sup> Department of Physics, National Cheng Kung University, Tainan City 701, Taiwan
- <sup>252</sup> School of Physics and Technology, Wuhan University, Wuhan, Hubei, 430072, People's Republic of China
- <sup>253</sup> National Center for High-performance computing, National Applied Research Laboratories, Hsinchu Science Park, Hsinchu City 30076, Taiwan
- <sup>254</sup> Department of Physics, National Taiwan Normal University, sec. 4, Taipei 116, Taiwan
- <sup>255</sup> NASA Marshall Space Flight Center, Huntsville, AL 35811, USA
- <sup>256</sup> INFN, Sezione di Roma Tre, I-00146 Roma, Italy
- <sup>257</sup> ESPCI, CNRS, F-75005 Paris, France
- <sup>258</sup> Kenyon College, Gambier, OH 43022, USA
- <sup>259</sup> School of Physics Science and Engineering, Tongji University, Shanghai 200092, People's Republic of China
- <sup>260</sup> Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy
- <sup>261</sup> Institute for Photon Science and Technology, The University of Tokyo, Bunkyo-ku, Tokyo 113-8656, Japan
- <sup>262</sup> Indian Institute of Technology Madras, Chennai 600036, India
- <sup>263</sup> Saha Institute of Nuclear Physics, Bidhannagar, West Bengal 700064, India
- <sup>264</sup> Institute of Space and Astronautical Science (JAXA), Chuo-ku, Sagami-hara City, Kanagawa 252-0222, Japan
- <sup>265</sup> Institut des Hautes Etudes Scientifiques, F-91440 Bures-sur-Yvette, France
- <sup>266</sup> Faculty of Law, Ryukoku University, Fushimi-ku, Kyoto City, Kyoto 612-8577, Japan
- <sup>267</sup> Indian Institute of Science Education and Research, Kolkata, Mohanpur, West Bengal 741252, India
- <sup>268</sup> Department of Physics, University of Notre Dame, Notre Dame, IN 46556, USA
- <sup>269</sup> Graduate School of Science and Technology, Niigata University, Nishi-ku, Niigata City, Niigata 950-2181, Japan
- <sup>270</sup> Consiglio Nazionale delle Ricerche—Istituto dei Sistemi Complessi, Piazzale Aldo Moro 5, I-00185 Roma, Italy
- <sup>271</sup> Korea Astronomy and Space Science Institute (KASI), Yuseong-gu, Daejeon 34055, Republic of Korea
- <sup>272</sup> Hobart and William Smith Colleges, Geneva, NY 14456, USA
- <sup>273</sup> International Institute of Physics, Universidade Federal do Rio Grande do Norte, Natal RN 59078-970, Brazil
- <sup>274</sup> Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi," I-00184 Roma, Italy
- <sup>275</sup> Dipartimento di Matematica e Fisica, Università degli Studi Roma Tre, I-00146 Roma, Italy
- <sup>276</sup> University of Arizona, Tucson, AZ 85721, USA
- <sup>277</sup> Università di Trento, Dipartimento di Matematica, I-38123 Povo, Trento, Italy
- <sup>278</sup> University of California, Riverside, Riverside, CA 92521, USA
- <sup>279</sup> University of Washington, Seattle, WA 98195, USA
- <sup>280</sup> Indian Institute of Technology, Palaj, Gandhinagar, Gujarat 382355, India
- <sup>281</sup> Department of Electronic Control Engineering, National Institute of Technology, Nagaoka College, Nagaoka City, Niigata 940-8532, Japan
- <sup>282</sup> Departamento de Matemática da Universidade de Aveiro and Centre for Research and Development in Mathematics and Applications, Campus de Santiago, 3810-183 Aveiro, Portugal
- <sup>283</sup> Marquette University, Milwaukee, WI 53233, USA
- <sup>284</sup> Faculty of Science, Toho University, Funabashi City, Chiba 274-8510, Japan
- <sup>285</sup> Graduate School of Science and Technology, Gunma University, Maebashi, Gunma 371-8510, Japan
- <sup>286</sup> Institute for Quantum Studies, Chapman University, Orange, CA 92866, USA
- <sup>287</sup> Accelerator Laboratory, High Energy Accelerator Research Organization (KEK), Tsukuba City, Ibaraki 305-0801, Japan



- <sup>288</sup> Faculty of Information Science and Technology, Osaka Institute of Technology, Hirakata City, Osaka 573-0196, Japan
- <sup>289</sup> INAF, Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, I-50125 Firenze, Italy
- <sup>290</sup> Indian Institute of Technology Hyderabad, Sangareddy, Khandi, Telangana 502285, India
- <sup>291</sup> Indian Institute of Science Education and Research, Pune, Maharashtra 411008, India
- <sup>292</sup> Istituto di Astrofisica e Planetologia Spaziali di Roma, Via del Fosso del Cavaliere, 100, 00133 Roma RM, Italy
- <sup>293</sup> Department of Space and Astronautical Science, The Graduate University for Advanced Studies (SOKENDAI), Sagami-hara City, Kanagawa 252-5210, Japan
- <sup>294</sup> Andrews University, Berrien Springs, MI 49104, USA
- <sup>295</sup> Research Center for Space Science, Advanced Research Laboratories, Tokyo City University, Setagaya, Tokyo 158-0082, Japan
- <sup>296</sup> Institute for Cosmic Ray Research (ICRR), Research Center for Cosmic Neutrinos (RCCN), The University of Tokyo, Kashiwa City, Chiba 277-8582, Japan
- <sup>297</sup> Department of Physics, Kyoto University, Sakyou-ku, Kyoto City, Kyoto 606-8502, Japan
- <sup>298</sup> Yukawa Institute for Theoretical Physics (YITP), Kyoto University, Sakyou-ku, Kyoto City, Kyoto 606-8502, Japan
- <sup>299</sup> Dipartimento di Scienze Aziendali—Management and Innovation Systems (DISA-MIS), Università di Salerno, I-84084 Fisciano, Salerno, Italy
- <sup>300</sup> Van Swinderen Institute for Particle Physics and Gravity, University of Groningen, Nijenborgh 4, 9747 AG Groningen, Netherlands
- <sup>301</sup> Faculty of Science, Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong
- <sup>302</sup> Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussel, Belgium
- <sup>303</sup> Applied Research Laboratory, High Energy Accelerator Research Organization (KEK), Tsukuba City, Ibaraki 305-0801, Japan
- <sup>304</sup> Department of Communications Engineering, National Defense Academy of Japan, Yokosuka City, Kanagawa 239-8686, Japan
- <sup>305</sup> Department of Physics, University of Florida, Gainesville, FL 32611, USA
- <sup>306</sup> Department of Information and Management Systems Engineering, Nagaoka University of Technology, Nagaoka City, Niigata 940-2188, Japan
- <sup>307</sup> Tata Institute of Fundamental Research, Mumbai 400005, India
- <sup>308</sup> Eindhoven University of Technology, Postbus 513, 5600 MB Eindhoven, Netherlands
- <sup>309</sup> Department of Physics and Astronomy, Sejong University, Gwangjin-gu, Seoul 143-747, Republic of Korea
- <sup>310</sup> Concordia University Wisconsin, Mequon, WI 53097, USA
- <sup>311</sup> Department of Electrophysics, National Yang Ming Chiao Tung University, Hsinchu 30010, Taiwan
- <sup>312</sup> Department of Physics, Rikkyo University, Toshima-ku, Tokyo 171-8501, Japan
- Received 2023 August 18; revised 2023 September 15; accepted 2023 September 30; published 2024 March 27

## Abstract

We present Fermi Gamma-ray Burst Monitor (Fermi-GBM) and Swift Burst Alert Telescope (Swift-BAT) searches for gamma-ray/X-ray counterparts to gravitational-wave (GW) candidate events identified during the third observing run of the Advanced LIGO and Advanced Virgo detectors. Using Fermi-GBM onboard triggers and subthreshold gamma-ray burst (GRB) candidates found in the Fermi-GBM ground analyses, the Targeted Search and the Untargeted Search, we investigate whether there are any coincident GRBs associated with the GWs. We also search the Swift-BAT rate data around the GW times to determine whether a GRB counterpart is present. No counterparts are found. Using both the Fermi-GBM Targeted Search and the Swift-BAT search, we calculate flux upper limits and present joint upper limits on the gamma-ray luminosity of each GW. Given these limits, we constrain theoretical models for the emission of gamma rays from binary black hole mergers.

*Unified Astronomy Thesaurus concepts:* [Gamma-ray bursts \(629\)](#); [Gravitational waves \(678\)](#)

## 1. Introduction

The detection of GW170817 (Abbott et al. 2017b) coincident with the short gamma-ray burst GRB 170817A (Goldstein et al. 2017; Savchenko et al. 2017) was a groundbreaking discovery for the multimessenger era. Not only was it the first binary neutron star (BNS) merger detected by the gravitational-wave (GW) instruments Advanced LIGO (Aasi et al. 2015) and Advanced Virgo (Acernese et al. 2014), it was also the first, and to date only, GW detection with a confirmed electromagnetic (EM) counterpart. Since then, the search for EM emission from more of these extreme events has been at the forefront of multimessenger astronomy, particularly in the gamma-ray energy band, since GRB 170817A demonstrated that BNS mergers are a progenitor of short gamma-ray bursts (GRBs; Abbott et al. 2017a). GWs have also been observed from the mergers of other compact objects, such as binary black hole (BBH) and neutron star–black hole (NSBH)

systems (Abbott et al. 2019, 2021a, 2021c, 2023); however, no additional EM counterparts have been confirmed, as they have been inconclusive (Connaughton et al. 2016; LSC and Virgo and Fermi-GBM Team 2019a, 2019b) or are still under debate (De Paolis et al. 2020; Graham et al. 2020; Ashton et al. 2021; Bustillo et al. 2021; Palmese et al. 2021).

GRB 170817A was first reported by the Fermi Gamma-ray Burst Monitor (GBM; Meegan et al. 2009), a space-based gamma-ray instrument sensitive from 8 keV to 40 MeV. This wide energy range of Fermi-GBM combined with its large field of view (FOV) and rapid alert abilities make it an ideal platform to search for gamma-ray counterparts to GWs in real time. Fermi-GBM also provides continuous time-tagged event (CTTE) data with a 6 hr latency that enables sensitive searches for short GRBs on the ground. Two of these searches are the Untargeted Search, a blind search of Fermi-GBM data for short GRBs, and the Targeted Search, which uses an external time to search for a short GRB (Blackburn et al. 2015; Goldstein et al. 2019). Both were previously used to look for subthreshold GRBs coincident with GWs from the first two LIGO–Virgo observing runs.

Additionally, the Burst Alert Telescope (BAT; Barthelmy et al. 2005) on board the Neil Gehrels Swift Observatory (hereafter referred to as Swift) provides excellent sensitivity to detecting hard X-ray and gamma-ray transients (Gehrels et al. 2004).

<sup>313</sup> Deceased, 2020 August.

<sup>314</sup> Deceased, 2021 April.



Swift-BAT primarily runs in a survey mode that continuously evaluates photon rate increases and potential GRB triggers. An increase in the observed photon rate can trigger the onboard image-processing algorithms, which can yield  $\sim$ arcminute GRB localizations.

Ideally, Swift-BAT would detect and localize a GRB produced by a binary merger independently of the GW detection. If a GRB does not trigger an onboard detection, continuous count-rate light curves are still available for offline ground searches. Although Swift-BAT has been used to search for public and subthreshold GWs during the LIGO–Virgo observing runs, this work presents the first systematic search of Swift-BAT data from a LIGO–Virgo observing run.

The first observing run (O1) operated from 2015 September to 2016 January, producing the first detection of GWs from a BBH merger (GW150914; Abbott et al. 2016). Burns et al. (2019) used the Fermi-GBM Targeted Search to identify both triggered and subthreshold GRB candidates in coincidence with GW candidates from O1. The most significant gamma-ray candidate found by the search was within 0.4 s of GW150914; however, it could not be confirmed as a counterpart, due to its weak signal and poor localization (Connaughton et al. 2016, 2018; Greiner et al. 2016).

The second observing run (O2) took place from 2016 November to 2017 August, resulting in the detections of GW170817, GRB 170817A, and the kilonova AT2017gfo (Chornock et al. 2017; Cowperthwaite et al. 2017; Nicholl et al. 2017; Soares-Santos et al. 2017; Tanvir et al. 2017; Margutti & Chornock 2021). Following O2, the LIGO Scientific and Virgo Collaboration published its first catalog of GW signals, called the Gravitational-Wave Transient Catalog 1 (GWTC-1; Abbott et al. 2019), using a reanalysis of data from both O1 and O2. Hamburg et al. (2020) searched for GRBs coincident to the GWs reported in GWTC-1, using Fermi-GBM triggers as well as subthreshold GRB candidates from the Untargeted and Targeted Searches, but found no additional counterparts beyond GRB 170817A.

The third observing run (O3) occurred from 2019 April to 2020 March, with a month-long commissioning break during 2019 October. It benefited from improvements to the sensitivity and duty cycle of the GW detectors made after O2 (Acerese et al. 2019; Buikema et al. 2020; Abbott et al. 2021a). This observing run provided 56 public GW candidates in real time with information from their preliminary analysis. More detailed analyses were published by the LIGO, Virgo, and KAGRA (LVK) Collaboration in a series of GWTCs (GWTC-2—Abbott et al. 2021a; GWTC-2.1—Abbott et al. 2021c; and GWTC-3—Abbott et al. 2023), with GWTC-3 providing a cumulative list of 79 GW signals from O3 with a probability of astrophysical origin ( $p_{\text{astro}} > 0.5$ )—an eightfold increase relative to O2. Among these candidates was the detection of a second confident signal classified as a BNS merger, GW190425, whose total mass is larger than that known from Galactic neutron star binaries (Abbott et al. 2020c).

Additionally, GW191219\_163120 and GW200115\_042309 provided the first detections of NSBH systems with  $p_{\text{astro}} > 0.5$ . Another possible NSBH, GW200105\_162426, fell just outside the  $p_{\text{astro}} > 0.5$  criterion in the GWTC-3 analysis (Abbott et al. 2021b). There were also two confident detections with ambiguous classifications, GW190814 (Abbott et al. 2020b) and GW200210\_092254, which represent a black hole merging with either a light black hole or a heavy neutron star. An

overwhelming majority of the remaining candidates are most likely BBHs in origin.

In this paper, we search Fermi-GBM and Swift-BAT data for short-GRB counterparts to GW candidates from O3, discussed in Section 2.1. Section 2.2 provides an overview of the Fermi-GBM Untargeted Search as well as improvements made to the Fermi-GBM Targeted Search. Section 2.3 describes the Swift-BAT subthreshold search. We present the results of the search with Fermi-GBM triggers and the Untargeted Search in Section 3.1; with the Fermi-GBM Targeted Search, including a new joint ranking statistic that takes the spatial coincidence into account, in Section 3.2; and with the Swift-BAT subthreshold search in Section 3.3. Section 3.4 presents the results from both Fermi-GBM and Swift-BAT for the marginal GWs identified in Section 2.1. Furthermore, Section 4 divides the discussion of GWs with  $p_{\text{astro}} > 0.5$  into two groups, depending on their estimated secondary component mass  $m_2$ . For mergers with a possible neutron star component, we present the flux and isotropic-equivalent luminosity upper limits from both Fermi-GBM and Swift-BAT (Section 4.1). For the BBH mergers, we compare the lack of observed gamma-ray emission to that predicted by theoretical models (Section 4.2). We discuss upper limits to the marginal GWs in Section 4.3. Finally, in Section 5, we summarize our results and discuss future plans for using the subthreshold searches for GWs.

## 2. Method

In this section, we summarize the set of GW signals that we analyze from O3. We also present the search methods used to find coincident gamma-ray and hard X-ray emission with Fermi-GBM and Swift-BAT.

### 2.1. GW Trigger Selection

The analysis reported here focuses on GW candidates identified during O3. These were selected by four separate analysis pipelines—i.e., GstLAL, Multi-Band Template Analysis, PyCBC, and cWB—and published in GWTC-3 (Abbott et al. 2023). Each pipeline calculates both a false-alarm rate (FAR) from a background noise hypothesis and a  $p_{\text{astro}}$  for each candidate, assuming a compact binary coalescence source. Candidate signals with  $p_{\text{astro}} > 0.5$  in any pipeline are selected for detailed analysis, with a full estimation of the potential astrophysical source parameters. The one exception is GW candidates identified by the minimally modeled cWB pipeline, which requires a time-matched confirmation with  $p_{\text{astro}} > 0.1$  in one of the other pipelines in order to ensure they originated from a compact binary coalescence. In total, there were 79 GWs identified with  $p_{\text{astro}} > 0.5$  during O3. Table 1 shows the candidate identifier, date, time, and  $p_{\text{astro}}$  for these GWs.

The remaining subset of GW signals with a FAR below  $2 \text{ yr}^{-1}$  and  $p_{\text{astro}} \leq 0.5$  in a given pipeline are considered marginal GW candidates. As of GWTC-3, there are six marginal candidates that cannot be attributed to instrumental or environmental causes (Table 2). We exclude these candidates from our main analysis; however, since the existence of a gamma-ray counterpart could potentially prove an astrophysical origin, we perform separate searches around each marginal candidate.

**Table 1**  
GW Candidates from O3 with  $p_{\text{astro}} > 0.5$  (Abbott et al. 2023)

Event Name	Date	Time (UTC)	$p_{\text{astro}}$	Event Name	Date	Time (UTC)	$p_{\text{astro}}$
GW190403_051519	04-03-2019	05:15:19	0.60	GW191103_012549	11-03-2019	01:25:49	0.94
GW190408_181802	04-08-2019	18:18:02	>0.99	GW191105_143521	11-05-2019	14:35:21	>0.99
GW190412	04-12-2019	05:30:44	>0.99	GW191109_010717	11-09-2019	01:07:17	>0.99
GW190413_052954	04-13-2019	05:29:54	0.92	GW191113_071753	11-13-2019	07:17:53	0.68
GW190413_134308	04-13-2019	13:43:08	0.99	GW191126_115259	11-26-2019	11:52:59	0.70
GW190421_213856	04-21-2019	21:38:56	>0.99	GW191127_050227	11-27-2019	05:02:27	0.74
GW190425	04-25-2019	08:18:05	0.69	GW191129_134029	11-29-2019	13:40:29	>0.99
GW190426_190642	04-26-2019	19:06:42	0.73	GW191204_110529	12-04-2019	11:05:29	0.74
GW190503_185404	05-03-2019	18:54:04	>0.99	GW191204_171526	12-04-2019	17:15:26	>0.99
GW190512_180714	05-12-2019	18:07:14	>0.99	GW191215_223052	12-15-2019	22:30:52	>0.99
GW190513_205428	05-13-2019	20:54:28	>0.99	GW191216_213338	12-16-2019	21:33:38	>0.99
GW190514_065416	05-14-2019	06:54:16	0.75	GW191219_163120	12-19-2019	16:31:20	0.82
GW190517_055101	05-17-2019	05:51:01	>0.99	GW191222_033537	12-22-2019	03:35:37	>0.99
GW190519_153544	05-19-2019	15:35:44	>0.99	GW191230_180458	12-30-2019	18:04:58	0.96
GW190521	05-21-2019	03:02:29	>0.99	GW200112_155838	01-12-2020	15:58:38	>0.99
GW190521_074359	05-21-2019	07:43:59	>0.99	GW200115_042309	01-15-2020	04:23:09	>0.99
GW190527_092055	05-27-2019	09:20:55	0.83	GW200128_022011	01-28-2020	02:20:11	>0.99
GW190602_175927	06-02-2019	17:59:27	>0.99	GW200129_065458	01-29-2020	06:54:58	>0.99
GW190620_030421	06-20-2019	03:04:21	0.99	GW200202_154313	02-02-2020	15:43:13	>0.99
GW190630_185205	06-30-2019	18:52:05	>0.99	GW200208_130117	02-08-2020	13:01:17	>0.99
GW190701_203306	07-01-2019	20:33:06	>0.99	GW200208_222617	02-08-2020	22:26:17	0.70
GW190706_222641	07-06-2019	22:26:41	>0.99	GW200209_085452	02-09-2020	08:54:52	0.97
GW190707_093326	07-07-2019	09:33:26	>0.99	GW200210_092254	02-10-2020	09:22:54	0.54
GW190708_232457	07-08-2019	23:24:57	>0.99	GW200216_220804	02-16-2020	22:08:04	0.77
GW190719_215514	07-19-2019	21:55:14	0.91	GW200219_094415	02-19-2020	09:44:15	>0.99
GW190720_000836	07-20-2019	00:08:36	>0.99	GW200220_061928	02-20-2020	06:19:28	0.62
GW190725_174728	07-25-2019	17:47:28	0.96	GW200220_124850	02-20-2020	12:48:50	0.83
GW190727_060333	07-27-2019	06:03:33	>0.99	GW200224_222234	02-24-2020	22:22:34	>0.99
GW190728_064510	07-28-2019	06:45:10	>0.99	GW200225_060421	02-25-2020	06:04:21	>0.99
GW190731_140936	07-31-2019	14:09:36	0.83	GW200302_015811	03-02-2020	01:58:11	0.91
GW190803_022701	08-03-2019	02:27:01	0.97	GW200306_093714	03-06-2020	09:37:14	0.81
GW190805_211137	08-05-2019	21:11:37	0.95	GW200308_173609	03-08-2020	17:36:09	0.86
GW190814	08-14-2019	21:10:39	>0.99	GW200311_115853	03-11-2020	11:58:53	>0.99
GW190828_063405	08-28-2019	06:34:05	>0.99	GW200316_215756	03-16-2020	21:57:56	>0.99
GW190828_065509	08-28-2019	06:55:09	>0.99	GW200322_091133	03-22-2020	09:11:33	0.62
GW190910_112807	09-10-2019	11:28:07	>0.99				
GW190915_235702	09-15-2019	23:57:02	>0.99				
GW190916_200658	09-16-2019	20:06:58	0.62				
GW190917_114630	09-17-2019	11:46:30	0.74				
GW190924_021846	09-24-2019	02:18:46	>0.99				
GW190925_232845	09-25-2019	23:28:45	0.99				
GW190926_050336	09-26-2019	05:03:36	0.51				
GW190929_012149	09-29-2019	01:21:49	0.86				
GW190930_133541	09-30-2019	13:35:41	>0.99				

**Table 2**  
Marginal GWs from O3 without Clear Instrumental or Environmental Causes (Abbott et al. 2021c, 2023)

Event Name	Date	Time (UTC)	$p_{\text{astro}}$
GW190426_152155	04-26-2019	15:21:55	0.14
GW190531_023648	05-31-2019	02:36:48	0.28
GW191118_212859	11-18-2019	21:28:59	0.05
GW200105_162426	01-05-2020	16:24:26	0.36
GW200201_203549	02-01-2020	20:35:49	0.12
GW200311_103121	03-11-2020	10:31:21	0.19

## 2.2. Fermi-GBM Searches

Fermi-GBM has 12 sodium iodide (NaI) and 2 bismuth germanate detectors that are strategically positioned to cover the full sky, unocculted by the Earth (Meegan et al. 2009). The flight software on board Fermi-GBM triggers on an event when

there is an influx of gamma rays at a level greater than  $4.5\sigma$  above the background rate in at least two NaI detectors (Paciesas et al. 2012). Additionally, the downlink of CTTE data enables searches for GRBs below Fermi-GBM’s onboard triggering threshold using ground-based computing resources. With  $2 \mu\text{s}$  timing resolution and full coverage of the unocculted sky over the energy range from 8 keV to 40 MeV, CTTE data have significantly expanded the sensitivity of the Fermi-GBM instrument and its subthreshold searches.

### 2.2.1. Untargeted Search

The Fermi-GBM Untargeted Search is a blind search that automatically scans the CTTE data for significant count-rate increases in at least two NaI detectors. The algorithm was originally developed for detecting terrestrial gamma-ray flashes (Briggs et al. 2013) and has since been adapted to search for short GRBs with fluxes below the onboard triggering threshold.



The Untargeted Search runs through 18 timescales ranging from 64 ms to 31 s and five energy bins from 27 to 985 keV, and short-GRB candidates are identified when at least two detectors exceed  $2.5\sigma$  and  $1.25\sigma$  above the background rate. Each candidate is given a reliability score based on whether the geometry of the detectors with significant flux is consistent with the observation of a distant astrophysical source. Currently, short-GRB candidates with durations less than 2.8 s and reliability classifications of low, medium, and high are publicly distributed via GCN.<sup>315</sup>

In this work, we combine short-GRB candidates detected by the Untargeted Search with GBM-triggered GRBs and examine their temporal offsets from the GWs listed in Table 1. Theoretical models predict the temporal offset between merger time and the production of gamma rays to range from 0.01 s to 10 s, depending on the conditions producing the gamma-ray emission (Zhang 2019). For GRB 170817A, the only known short GRB associated with a GW, the temporal offset was 1.7 s, with a duration ( $T_{90}$ ) over which 5%–95% of the GRB flux (50–300 keV) was detected of 2 s (Abbott et al. 2017a). This is consistent with a range of physically viable scenarios (e.g., Lin et al. 2018; Salafia et al. 2018; Zhang et al. 2018) where the temporal offset is correlated with the burst duration. We therefore choose to subtract the burst duration timescale from the temporal offset when performing our analysis. Doing so increases the observed significance of the simulated short-GRB counterparts and yields no loss in detection sensitivity at the  $3\sigma$  level in alternative scenarios where the temporal offset is the same for all simulated GRBs.

After calculating the time offsets for each GW–GRB pair minus the burst duration, the smallest resulting time offset for each GW is taken. For GBM-triggered GRBs, we use the  $T_{90}$  as a measure of the duration. For GRB candidates from the Untargeted Search, we use the most significant timescale over which the GRB candidate was detected, which scales linearly with  $T_{90}$  for onboard-triggered GRBs. A background distribution is produced in the same way, by replacing the observed GW times with random times during which there are no reported GW signals. This yields a distribution of temporal offsets minus the burst duration between unrelated GWs and the GRB sample. In both the search and background samples, positive and negative time offsets are allowed, with no maxima imposed. GW triggers occurring during Fermi’s passage through the South Atlantic Anomaly (SAA) are also included. See the results presented in Section 3.1 for a comparison of the cumulative signal and background distributions.

### 2.2.2. GBM Targeted Search

The Fermi-GBM Targeted Search was developed for multi-messenger follow-up observations (Blackburn et al. 2015). It uses CTTE data to scan around an external trigger time for gamma-ray emission typical of a short GRB. For follow-up of the GWs in Table 1, we search from  $-1$  s to  $+30$  s around the GW time, to ensure we do not miss unexpectedly delayed gamma-ray emission from a counterpart short GRB, even after accounting for temporal offsets up to 10 s relative to the GW time. Starting 1 s before the GW time provides a comfortable buffer for the fact that the trigger times can vary by a few milliseconds for GW signals that are identified by multiple pipelines. The scan is repeated for eight characteristic emission

timescales that increase by factors of 2 from 64 ms to 8.192 s. Each emission timescale begins the search centered at the start of the scan window and then advances until the end using a fixed time-step size. Emission timescales greater than 256 ms use a time step equal to one-eighth of the total emission duration. The remaining emission timescales use a 64 ms step size to limit both the additional trials and the additional computational time associated with the shorter emission timescales.

The Targeted Search achieves greater sensitivity than the onboard triggering algorithm by processing the data from all 14 detectors coherently, rather than focusing on significant signals present in detector pairs. This allows for the detection of weaker signals below the Fermi-GBM onboard triggering threshold (Kocevski et al. 2018). To do this, three spectral templates representing spectrally hard, normal, and soft GRBs (Table 3) are folded through the GBM detector responses to produce an expected count rate for a given astrophysical source location and flux. This expected count rate is then compared to the observed counts through a log-likelihood ratio,

$$\mathcal{L}_j(d, s) = \sum_i \left[ \ln \frac{\sigma_{n_i}}{\sigma_{d_i}} + \frac{\tilde{d}_i^2}{2\sigma_{n_i}^2} - \frac{(\tilde{d}_i - r_{i,j}s)^2}{2\sigma_{d_i}^2} \right], \quad (1)$$

where  $\tilde{d}_i$  represents the background-subtracted measurements in each detector,  $\sigma_n$  is the standard deviation of the background measurement,  $\sigma_d$  is the standard deviation of the expected data (background+signal),  $r_{i,j}$  is the location-dependent instrumental response for the spectrum denoted by index  $j$ , and  $s$  is the intrinsic source photon flux at the Earth. See Blackburn et al. (2015) for a full derivation.

The log-likelihood ratio quantifies the probability that an astrophysical source is present versus a background-only hypothesis. It is first computed separately for each point on the sky and spectral template at a given time and emission duration. During this process, we estimate the best-fit photon flux for each spectral template by finding the value  $s_{\text{best}}$  that maximizes the log-likelihood ratio. Since the best-fit photon flux maximizes the likelihood, which is effectively a product of Gaussian distributions, the variance on this photon flux equals the variance of the likelihood:

$$\sigma_{\mathcal{L}_j}^2 = \frac{1}{\sum_i r_{i,j}^2 / \sigma_{d_i}^2}, \quad (2)$$

where  $\sigma_{d_i}$  includes both background and source contributions, with the latter evaluated at  $s_{\text{best}}$ . Signal injection studies using the normal spectral template have demonstrated that this formulation yields the expected error coverage levels for true source fluxes near  $1 \times 10^{-7}$  erg cm $^{-2}$  s $^{-1}$  and below, which is the relevant flux range for this subthreshold analysis in Fermi-GBM.

We marginalize the log-likelihood ratio over all possible source amplitudes using a modified power-law prior designed to both avoid divergence and to produce a luminosity distribution for the observed source flux that is invariant with respect to source distance (Blackburn et al. 2015):

$$P(s) = \left[ 1 - e^{-(s/2.5\sigma_L)^{-1}} \right] s^{-1}. \quad (3)$$

The net result is a hypothesis test formulation following Bayes’ theorem.

<sup>315</sup> [https://gcn.gsfc.nasa.gov/fermi\\_gbm\\_subthresh\\_archive.html](https://gcn.gsfc.nasa.gov/fermi_gbm_subthresh_archive.html)



**Table 3**  
Spectral Templates Used by the Fermi-GBM Targeted Search

Template	Type	Parameters
Hard	Cutoff power law (Goldstein et al. 2016)	$E_{\text{peak}} = 1500$ keV, $\alpha = -1.5$
Normal	Band (Band et al. 1993)	$E_{\text{peak}} = 230$ keV, $\alpha = -1.0$ , $\beta = -2.3$
Soft	Band (Band et al. 1993)	$E_{\text{peak}} = 70$ keV, $\alpha = -1.9$ , $\beta = -3.7$

The amplitude-marginalized log-likelihood ratios for individual spectral templates,  $\mathcal{L}'_j(d)$ , at each time and duration are then averaged over all sky positions and templates, using a uniform prior to formulate the full marginal log-likelihood ratio,

$$\Lambda = \sum_{j=1}^3 \frac{1}{3} \int \frac{\mathcal{L}'_j(d)}{4\pi} d\Omega, \quad (4)$$

where the sum over  $j$  covers the hard, normal, and soft spectral templates. The marginal results from all scanned times and durations are then sorted according to the largest value of  $\Lambda$  after filtering out known detector effects.

Localization maps estimating the probability of finding the true source location at each point on the sky are produced for the top-ranking candidates using the log-likelihood ratio of the best-fitting spectrum for each candidate. This is done by noting that the log-likelihood ratio asymptotically approaches the behavior of a  $\chi^2$  distribution according to Wilks' theorem (Wilks 1938), with a statistical probability given by

$$P \propto \exp[\mathcal{L}'_j(d)]. \quad (5)$$

The statistical probability is then convolved with Gaussian kernels to account for systematic errors, which are predominantly induced by the difference between the true source spectrum and the three spectral templates, imperfect knowledge of the detector response, and whether atmospheric scattering is taken into account for a given spacecraft rocking angle. As a final step, we set the region blocked by the Earth in Fermi-GBM to zero and renormalize the map to account for the fact that gamma-ray sources are not visible through the Earth and an implicit assumption that the signal has a nonterrestrial origin.

The Targeted Search method was previously used to search for subthreshold counterparts to GWs identified during the O1 and O2 observing runs (Hamburg et al. 2020). A number of improvements were made to it in preparation for O3 (Goldstein et al. 2019):

1. The removal of the lowest 4–12 keV energy channel in the NaI detector data helped remove detector noise as well as Galactic transients.
2. Better background fitting during the approach and exit from the SAA. This reduces the local particle background triggers that were present in about 1% of searches and formed the dominant non-GRB background in the high log-likelihood ratio parameter space.
3. Better detector response models with a more complete treatment of the effects from the backscattering of high-energy gamma-ray photons off the Earth's atmosphere. The atmospheric scattering effects are currently applied when the zenith of Fermi-GBM is within  $\pm 5^\circ$  of its nominal rocking angle of  $130^\circ$  with respect to the Earth's geocenter, which occurs for  $\sim 70\%$  of measurements.

4. Decreasing the resolution from  $1^\circ$  to  $5^\circ$  for the grid of sky positions analyzed during the search. This provided an order of magnitude improvement in execution time, with no notable loss in sensitivity or degradation of localization capability.

These changes necessitated a recalculation of the estimated systematic uncertainty applied to the localization maps generated for the top-ranking search candidates. An initial study of 34 subthreshold short-GRB detections modeled this uncertainty as a  $2.7^\circ$  Gaussian systematic (Goldstein et al. 2019). A more detailed model was developed for this work using a larger sample of 3000 simulated short-GRB detections. It consists of a weighted pair of Gaussian shapes normalized over the sky with the standard deviation  $\sigma_1$  of the first Gaussian always smaller than that of the second Gaussian,  $\sigma_2$ . The parameters of each Gaussian were determined as functions of the most probable zenith angle for each candidate and the spacecraft rocking angle relative to the Earth. They range from  $1.6^\circ$  to  $6.0^\circ$  for  $\sigma_1$  and  $6.4^\circ$  to  $60.4^\circ$  for  $\sigma_2$ , with the fractional contribution of the first Gaussian spanning 0.42–0.77.

### 2.2.3. GBM Targeted Search Ranking Statistic

We use a ranking statistic  $R$  to characterize the significance of a coincidence between the GW candidates from the catalog and the short-GRB candidates found by the Targeted Search. Following the formulation in Hamburg et al. (2020), the statistic takes into account the probability of the astronomical origin of the GW,  $p_{\text{astro}}$ ; the fraction of the GW localization not occulted by the Earth for Fermi-GBM,  $p_{\text{visible}}$ ; the time offset of the GRB candidate from the GW time,  $\Delta t$ ; and the FAR from the best-fitting spectral template of the GRB candidate,  $\text{FAR}_{\text{GBM}}$ . We update the formulation to include the spatial association probability  $p_{\text{assoc}}$  and the duration  $D$  of the gamma-ray emission:

$$R = \frac{p_{\text{astro}} \times p_{\text{visible}} \times p_{\text{assoc}}}{|\Delta t - D| \times \text{FAR}_{\text{GBM}}}. \quad (6)$$

The spatial association probability  $p_{\text{assoc}}$  quantifies whether the localizations of a subthreshold gamma-ray candidate and GW are consistent with being produced by the same source. It is computed according to

$$S = \int \rho_{\text{GBM}} \rho_{\text{GW}} d\Omega, \quad B = \int \rho_{\text{GBM}} \rho_{\text{uniform}} d\Omega, \quad (7)$$

$$p_{\text{assoc}} = \frac{S}{S + B}, \quad (8)$$

where  $S$  represents a signal hypothesis with both localizations produced by the same source and  $B$  denotes a background hypothesis where the localizations are unrelated. Both  $S$  and  $B$  are constructed from integrals over all sky positions. In this context,  $\rho_{\text{GBM}}$  is the probability density per unit area reported by the localization maps produced for gamma-ray candidates identified by the Targeted Search. Likewise,  $\rho_{\text{GW}}$  is the

probability density of the localization maps produced for each GW and  $\rho_{\text{uniform}} = 1/4\pi$  is the unit density of a uniform spatial distribution on the sky.

The duration of gamma-ray emission  $D$  is incorporated into the temporal weight,

$$\frac{1}{|\Delta t - D|}, \quad (9)$$

where  $\Delta t$  is the temporal offset between the GW time and the start of the candidate gamma-ray emission identified by the Targeted Search and  $D$  is the candidate emission timescale. As discussed in Section 2.2.1, this is designed to account for scenarios where the observed temporal offset scales with the burst duration, which is expected from a broad range of models describing the observations of GW170817/GRB 170817A. The best-fit value of  $D$ , given by the candidate with the largest value of  $\Lambda$ , is a good proxy for burst duration because it scales proportionally with  $T_{90}$  when the Targeted Search is applied to confirmed short GRBs in Fermi-GBM.

We enforce a minimum value of  $|\Delta t - D| = 1$  ms to avoid divergence and account for the millisecond-scale uncertainty between the GW merger times of signals identified by multiple pipelines. We also apply a minimum value of  $\text{FAR}_{\text{GBM}} = 6.43 \times 10^{-6}$  Hz. This is equal to observing a single GRB candidate over the length of the background sample used to compute  $\text{FAR}_{\text{GBM}}$ .

We tested the impact of these updates on the ranking statistic by using the Fermi-GBM response generator<sup>316</sup> to inject short GRBs into CTTE data from the locations of modeled BNS mergers in Abbott et al. (2020a). The start time of each GRB was offset from the GW time using the duration of each burst, as given by  $T_{90}$ . We then applied the Targeted Search to this data set and ranked the candidates according to Equation (6) as well as the older method from Hamburg et al. (2020). Doing so resulted in a factor of 1.7 increase in the number of joint detections relative to the ranking statistic formulation from our older method.

Since the true time offset model is not known, we repeated the GRB injection study using the following alternative models for the start time of the injected GRB relative to the GW:

1. An offset of half  $T_{90}$  to test a scaling factor less than the total burst duration.
2. No time offset to bound emission scenarios where the GRB occurs a few milliseconds after the GW (Zhang 2019).
3. A fixed offset of 0.5 s assuming most gamma-ray counterparts have a characteristic time delay that is half the median  $T_{90}$  of the short GRBs observed in Fermi-GBM.

These models were chosen with a bias toward testing time offsets shorter than the typical duration of a short GRB, since the inclusion of  $D$  in the updated temporal weight naturally performs better at longer time offsets than the  $1/|\Delta t|$  weight used in Hamburg et al. (2020). The updated ranking statistic outperformed the older method in all scenarios, albeit with a smaller increase in the relative number of joint detections

compared to the scenario where the temporal offset scales with burst duration.

#### 2.2.4. Fermi-GBM Flux Upper Limits

For GW signals without a significant counterpart detection in Fermi-GBM, we compute the gamma-ray flux upper limits as a function of sky position using the Targeted Search, because it is the most sensitive analysis method employed by Fermi-GBM. To do this, we use the normal spectral template from Table 3 and the 1 s gamma-ray emission duration from the Targeted Search, since they are characteristic of typical short GRBs (von Kienlin et al. 2020; Poolakkil et al. 2021). This results in a set of upper limits for each sky position at times ranging from  $-1$  s to  $+30$  s around the GW time. We then choose the maximum observed upper-limit measurement for each sky position, guaranteeing that the specified confidence level of the upper limit applies over the entire search period.

We construct the upper limits from the best-fit photon flux amplitude  $s_{\text{best}}$  and its Gaussian error  $\sigma_{\mathcal{L}}$ , discussed in Section 2.2.2, according to

$$S_{\text{UL}} = s_{\text{best}} + N \times \sigma_{\mathcal{L}}, \quad (10)$$

where  $N$  is the significance level of the upper limit. We use a  $3\sigma$  upper-limit level for reporting upper limits over the full 10–1000 keV energy range of standard GRB flux measurements in Fermi-GBM, following the convention established in Goldstein et al. (2019). We also compute a second  $5\sigma$  upper limit over a 15–350 keV range to match the convention used by Swift-BAT (see Section 2.3.3) when combining the upper limits from both instruments.

### 2.3. Swift-BAT Searches

Swift-BAT is a coded-aperture, large-FOV (2.2 sr at 10% coding fraction), hard X-ray instrument on board Swift. Its detector plane contains 32,768 CZT detector elements, positioned under a coded-aperture mask and a graded-Z fringe shield that helps lower the background rate (Barthelmy et al. 2005). The BAT covers an energy range from 15 to 350 keV and monitors large portions of the sky with the goal of detecting GRBs. Once triggered, the BAT can localize a GRB to  $1'$ – $3'$  accuracy, prompting the Swift spacecraft to slew and point its two narrowfield instruments—the X-ray Telescope (Burrows et al. 2005) and the Ultraviolet/Optical Telescope (Roming et al. 2005)—for follow-up observations. The BAT's localization accuracy is quantified by the instrument's partial coding fraction, i.e., the fraction of detectors exposed to an event at a given time and sky position. If the coding fraction for a given trigger is 0%, then the BAT will not be able to localize the event. The BAT averages  $\sim 90$  GRB onboard triggers per year, among which  $\sim 10\%$  are short in duration (Gehrels et al. 2009). The onboard GRB triggers are complemented by subsequent on-ground rates and image data processing, in turn allowing for dedicated searches for GRB emission. With no GWs from Table 1 triggering an onboard BAT detection, we conduct an offline follow-up analysis from the ground to search for the corresponding hard X-ray counterpart emission.

#### 2.3.1. Swift-BAT Rate Data Search

The BAT flight software continuously assesses the signal-to-noise ratio ( $S/N$ ) of the observed count rates. If an  $S/N$

<sup>316</sup> <https://fermi.gsfc.nasa.gov/ssc/data/analysis/rmfit/DOCUMENTATION.html>

exceeds the given threshold value determined by a number of rate trigger criteria (Fenimore et al. 2004), the triggering algorithm subsequently checks the corresponding image data for the final confirmation and localization of the potential burst. The detection is confirmed only if the image S/N threshold is surpassed ( $\gtrsim 6.5$ ) and no other sources have been previously reported at the event localization. For every confirmed detection, the BAT records event data containing the counts' arrival times, locations on the detector plane, and energy. With its large effective area ( $\sim 2600 \text{ cm}^2$  for 100 keV photon detection at launch), the event data volume collected by the BAT is too big to be stored on board and, due to the limitations of the Swift downlink bandwidth, it is not possible to transfer all the event data to the ground. As such, until recently, the only way to conduct an offline, on-ground, follow-up analysis of untriggered and subthreshold events relied upon the rates' light curves in four energy channels (15–25, 25–50, 50–100, and 100–350 keV) with three time binnings (64 ms, 1 s, and 1.6 s) and their corresponding 64 s images in a single energy bin (15–50 keV). The recently developed Gamma-ray Urgent Archiver for Novel Opportunities (GUANO) technique circumvents this issue by retrieving BAT event data extending to  $\sim 200$  s long windows surrounding the trigger times from various astrophysical events (e.g., GWs, GRBs, fast radio bursts, neutrinos, etc.; Tohuvavohu et al. 2020). However, in this paper, we do not use the GUANO technique, since a significant number of the considered GW triggers were detected prior to the GUANO deployment in 2019 December. Instead, we conduct the analysis using the regular rate data from the BAT and leave the analogous study using the GUANO data for the future GW observing runs.

To conduct the untriggered and subthreshold search for hard X-ray counterparts coincident with the LVK triggers in Table 1, we developed a code analogous to Lien et al. (2014). The search process begins by extracting the raw light curves from within the central region of the BAT FOV, binned in 64 ms, 1 s, and 1.6 s time intervals. We opt to use the 1 s binned data to calculate the average background rate and standard deviation,  $\sigma_{\text{bg}}$ , starting at  $-1$  s before the GW trigger time and extending to  $+30$  s after. Using the raw light curves, we compute the average background rate,  $r_{\text{bg}}$ , spanning a time window outside the signal interval and spanning  $\sim 800$  s (excluding instrument slews or the SAA). The signal significance,  $S$ , is then computed from  $\sigma_{\text{bg}}$ , using

$$S = (r_{\text{sig}} - r_{\text{bg}}) / \sigma_{\text{bg}}, \quad (11)$$

where  $r_{\text{sig}}$  is the threshold signal rate. The background uncertainty is estimated as  $\sigma_{\text{bg}} = \sqrt{\frac{1}{N} \sum_{i=1}^N (r_{\text{bg},i} - \bar{r}_{\text{bg}})^2}$ , where  $N$  is the number of data points in the considered portion of the light curve,  $r_{\text{bg},i}$  is the  $i$ th background rate measurement, and  $\bar{r}_{\text{bg}}$  is the mean background rate over the considered time interval. Furthermore, we visually inspect each light curve to ensure that no peaks originate from detector noise. Once this is done, we check whether there are any potential counterparts to the GW, defined as a  $\geq 5\sigma$  detection above background.

### 2.3.2. Non-Imaging Transient Reconstruction And TEmporal Search Response Functions

To produce the BAT instrument response functions appropriate for converting from photon counts to a source flux in the rate data domain, we use the Non-Imaging Transient

Reconstruction And TEmporal Search (NITRATES; DeLaunay & Tohuvavohu 2022). The NITRATES response modeling takes into account both coded and uncoded parts of the detector, and thus includes responses appropriate for all counts recorded in the rate data. In addition, these responses allow for potential GRB detection from outside the BAT's coded FOV, as well as higher sensitivity across the entire FOV. The instrument responses were created by simulating photon beams onto the Swift Mass Model using GEANT4, a particle interaction simulator software toolkit (Allison et al. 2016). We produce Detector Response Matrices for 31 different incident directions, covering the  $\sim 2.2$  sr sky area (corresponding to the 10% coding fraction) where the responses are well calibrated. For a complete description of the BAT instrument response modeling, see Section 5 and Appendix A of DeLaunay & Tohuvavohu (2022).

### 2.3.3. Swift-BAT Flux Upper Limits

For GWs without a  $5\sigma$  detection above background in Swift-BAT, we estimate the flux upper limit from the observed photon counts. We compute these limits for each time bin in the search by calculating the necessary number of counts that would result in a  $5\sigma$  detection at that time from the estimated background uncertainty  $\sigma_{\text{bg}}$ , assuming a 1 s emission duration. We then select the largest count value obtained in the search bins for each GW, since this is guaranteed to satisfy the  $5\sigma$  criteria over the full search window. We convert the photon counts to flux upper limits within the partially coded BAT FOV, over a 15–350 keV energy range as a function of sky position, by applying the NITRATES instrument response functions using the normal spectral template (Table 3) employed for upper limits computed with the Fermi-GBM Targeted Search in Section 2.2.4. This is done over 31 locations in a grid covering the  $\sim 2.2$  sr BAT FOV.

### 2.4. Combined and Marginal Flux Upper Limits

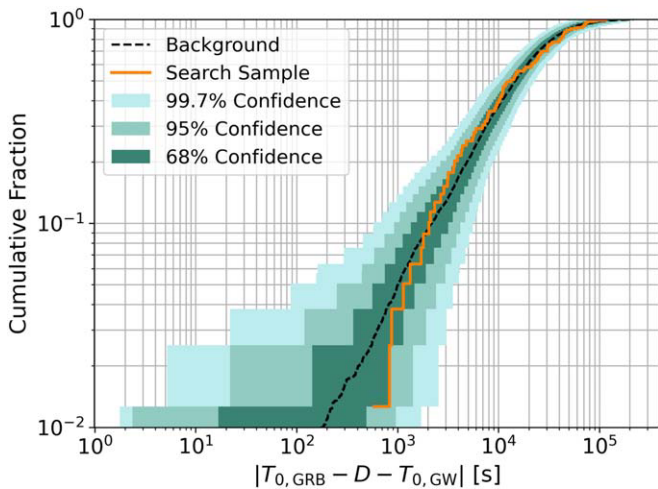
For GWs without a detected counterpart in Fermi-GBM or Swift-BAT, we combine the  $5\sigma$  confidence level flux upper limits described in Sections 2.2.4 and 2.3.3 to produce joint flux upper limits as a function of sky position using both instruments. We do this by selecting the more constraining upper limit at each position, since the individual limits result from independent measurements. This allows us to provide a single upper-limit map for each GW that simultaneously leverages the wide FOV provided by Fermi-GBM as well as the additional coverage and enhanced sensitivity of Swift-BAT.

We also provide marginalized flux upper limits ( $S_{\text{UL,marg}}$ ) that we compute by integrating the upper limits over the sky using the probability density of the GW localization as a prior,

$$S_{\text{UL,marg}} = \int S_{\text{UL}} \tilde{\rho}_{\text{GW}} d\Omega, \quad (12)$$

where  $S_{\text{UL}}$  is the position-dependent upper limit at a given confidence level and  $\tilde{\rho}_{\text{GW}}$  is the probability density of the GW localization normalized over the visible portion of the sky. This reduces the set of upper limits for each GW to a single, characteristic upper limit that accounts for the most likely location of the GW source.





**Figure 1.** The cumulative distribution for the minimum time offsets between the O3 GW triggers and GRBs found by either the GBM onboard triggering algorithms or the Untargeted Search. The confidence intervals for the search sample were determined by Monte Carlo sampling of the background.

### 2.5. Isotropic-equivalent Luminosity Upper Limits

We compute upper limits on the isotropic-equivalent gamma-ray luminosity  $L_{\text{iso}}$  in the cosmological rest-frame energy range of 1 keV–10 MeV for GWs without a detected counterpart in Fermi-GBM or Swift-BAT according to

$$L_{\text{iso}} = 4\pi D_L^2 S_{\text{UL,marg}}, k, \quad (13)$$

where  $D_L$  is the median luminosity distance of the GW,  $S_{\text{UL,marg}}$  is the marginalized confidence level flux upper limit described in Section 2.4, and  $k$  is the standard bolometric correction factor given by

$$k \equiv \frac{\int_{1 \text{ keV}/(1+z)}^{10 \text{ MeV}/(1+z)} E \frac{dN}{dE}(E) dE}{\int_{15 \text{ keV}}^{350 \text{ keV}} E \frac{dN}{dE}(E) dE}, \quad (14)$$

where  $z$  is the redshift inferred from  $D_L$ . In this case,  $\frac{dN}{dE}(E)$  represents the normal spectral shape from Table 3, which is used to generate the marginalized flux upper limit. We chose to use the median  $D_L$  and the marginalized flux upper limit for each GW, rather than marginalizing  $L_{\text{iso}}$  from the values estimated at each sky position, in order to exclude the low-likelihood modes of the distance luminosity posteriors for GW200308\_173609 and GW200322\_091133, as discussed in Abbott et al. (2023). All other GWs yield similar values for  $L_{\text{iso}}$  regardless of whether we use the individual or median values for  $D_L$  in the calculation.

## 3. Results

This section presents the results for the searches from Fermi-GBM and Swift-BAT for coincident gamma-ray emission to the GW candidates presented in Tables 1 and 2.

### 3.1. Triggered and Untargeted Search Results

We compare the distribution of temporal offsets between the GWs listed in Table 1 and the closest gamma-ray signal in

Fermi-GBM, minus its burst duration, shown in Figure 1. The GRB sample here comprises 214 GRBs, both long and short, triggered by Fermi-GBM during O3 and 479 short-GRB candidates detected by the Untargeted Search. The background distribution was composed by choosing  $\sim 10^4$  random times in O3 during which there were no reported GWs. Confidence intervals for the search sample were determined empirically by Monte Carlo sampling of the background distribution.

There are no significant deviations from the background, with the search sample lying largely within the 68% confidence interval. The shortest temporal offset given by the sample distribution is approximately 10 minutes and is within the 95% confidence interval. Such large offsets are not expected for on-axis prompt emission from GRBs associated with binary mergers (Vedrenne & Atteia 2009; Zhang 2019); therefore, we find no further evidence for a GW/gamma-ray association.

### 3.2. Targeted Search Results

We ran the Targeted Search on the 79 GWs shown in Table 1. Fermi-GBM was in the SAA for 15 of those times, therefore the detectors were turned off and no data were obtained. Figure 2 shows the cumulative rate above a given value of the marginalized log-likelihood ratio  $\Lambda$  separated according to the best-fitting spectral template. The background distribution is determined by randomly selecting times during the O3 livetime without known GW triggers. This represents the FAR of the search and describes the frequency of the expected false positives as a function of  $\Lambda$ . No significant gamma-ray signals were found in coincidence with GWs.

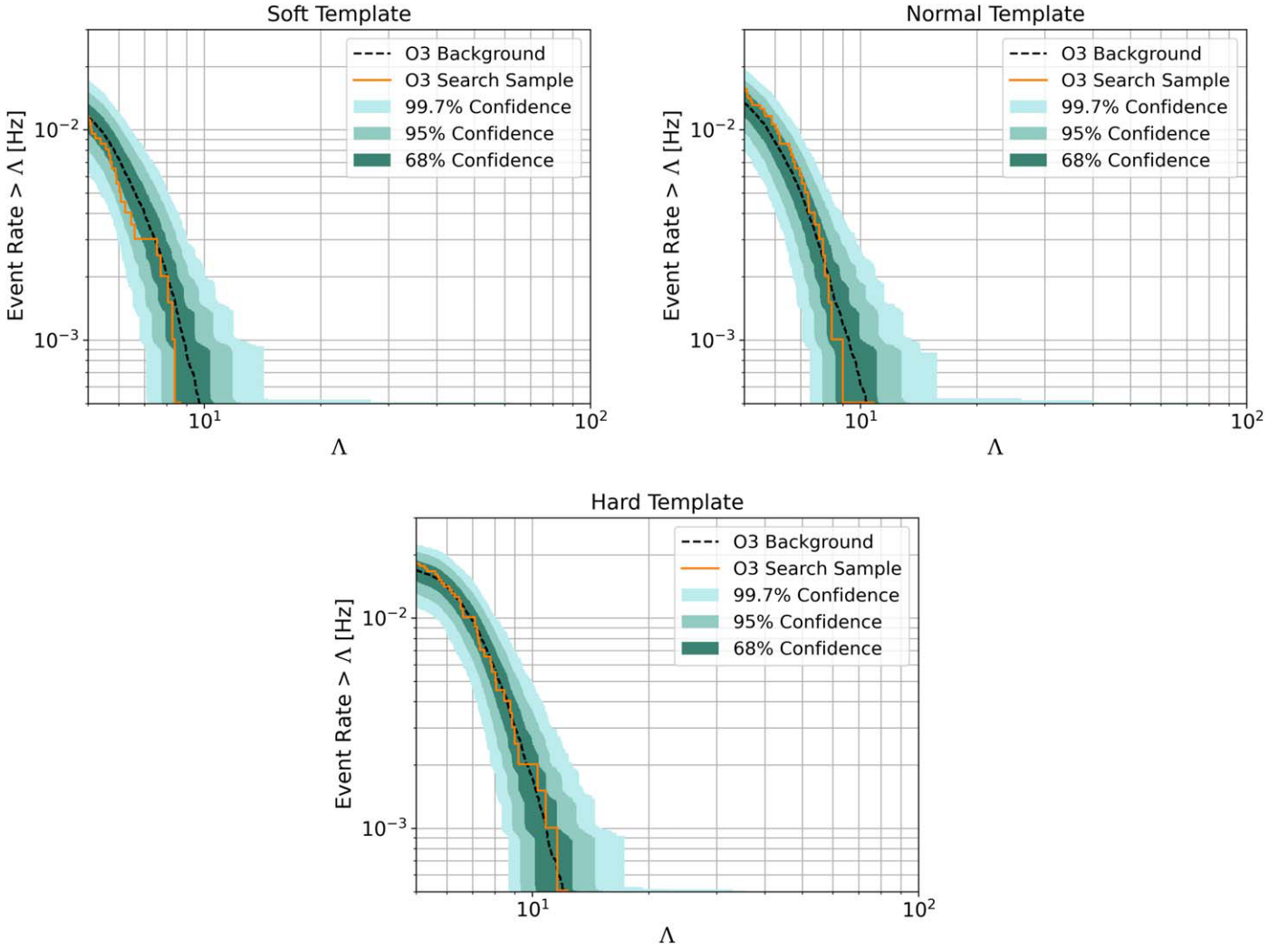
Figure 3 shows the ranking statistic  $R$  from Section 2.2.3 mapped to a  $p$ -value, defined as the number of more highly ranked background candidates as compared to the total number of background candidates or  $p_i = N(R > R_i)/N$ , where  $N$  is the number of background gamma-ray candidates and  $i$  is the candidate index within the search sample. The plots show no significant deviations from background, yielding no evidence for a GRB counterpart to the GW signals.

### 3.3. Swift Results

We ran the pipeline described in Section 2.3 on the 1 s binned light curves from Swift-BAT for the 79 candidates listed in Table 1. The goal of the pipeline is to examine whether any emission surpasses the  $5\sigma$  threshold above the observed background rate level. We visually inspect each light curve to ensure that no detector noise or malfunction affects the reported results. We identify detector noise as a fast-duration peak seen only in some of the energy channels. Once identified, the detector noise is subtracted down to the level of the average background rate. There are 14 GWs for which the data are either unavailable or background-dominated, because they occurred during either the Swift-BAT SAA passage or a slew. Separately, 13 GWs were within the BAT FOV ( $>10\%$  partial coding) and had image survey data available at the time of interest. We report no significant hard X-ray detection in the Swift-BAT rate data coincident with the reported GW triggers at the  $5\sigma$  level. We also ran the standard BAT analysis on the survey data (longer timescales,  $\sim 300$  s) for the 13 inside-BAT-FOV candidates and also report no excess X-ray emission.<sup>317</sup>

<sup>317</sup> <https://heasarc.gsfc.nasa.gov/ftools/caldb/help/batsurvey.html>





**Figure 2.** The cumulative rate above a given value of the marginalized log-likelihood ratio  $\Lambda$ , separated into three plots according to the best-fitting spectral template, found in the Targeted Search. The orange line is the foreground distribution of GRB candidates found with the Targeted Search around the given GW merger time. The black dotted line is the randomly selected background sample and the green shading represents the 68%, 95%, and 99.7% confidence intervals around it.

### 3.4. Results for Marginal GW Candidates

The Fermi-GBM and Swift-BAT searches were applied separately to the six marginal GW signals from Table 2 in an effort to identify EM counterparts that could prove an astrophysical origin. The closest time offset from the GBM Triggered and Untargeted Searches was observed for GW191118\_212859, which occurred 42 minutes before the onboard trigger of GRB 191118A and corresponds to a  $p$ -value of 0.1. The most significant Targeted Search candidate was found for GW200105\_162426, using the hard spectral template. It has a pretrial  $p$ -value of 0.1, as estimated by the ranking statistic distribution for background described in Section 2.2.3. Applying a trials factor of 3 to account for the three spectral templates used by the Targeted Search increases the  $p$ -value to 0.3. No  $5\sigma$  detections were found for any marginal candidates using the Swift-BAT rate data search.

## 4. Science Discussion

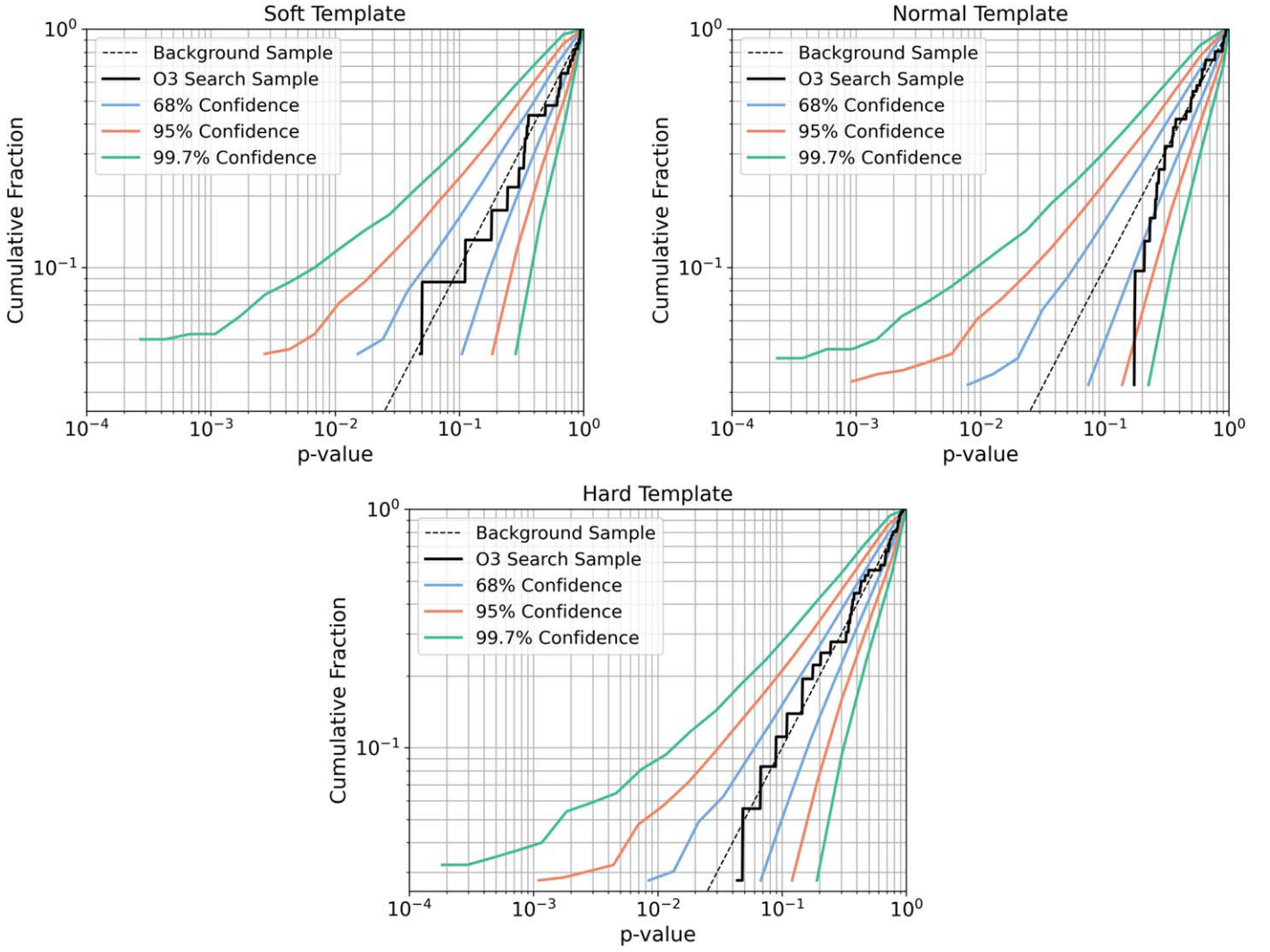
Compact binary mergers containing a neutron star component are likely candidates for gamma-ray emission, particularly if the inspiral process results in tidal disruption of the neutron star (Burns 2020). In contrast, BBH mergers are not

expected to produce gamma rays outside of a few exotic scenarios (e.g., Loeb 2016; Perna et al. 2016; Zhang 2016; Dai et al. 2017). Therefore, using the standard convention of  $m_1 > m_2$ , we divide our discussion into two sections, based on the secondary component mass  $m_2$ :

1. Mergers with a possible neutron star:  $m_2 \leq 3 M_\odot$  (5% credible level); and
2. Probable BBH mergers:  $m_2 > 3 M_\odot$  (95% credible level).

The cut  $m_2 \leq 3 M_\odot$  was chosen to include all systems with at least one neutron star component up to the maximal allowed neutron star mass of 2.16–3.0  $M_\odot$  (Bombaci 1996; Kalogera & Baym 1996; Margalit & Metzger 2017; Rezzolla et al. 2018). It may include a few ambiguous BBH mergers, due to the uncertainty on the maximum allowed neutron star mass. We favor this approach over a stricter cut due to the limited number of systems in O3 with light secondary component masses. Additionally, the discussion of possible BBH mergers does not suffer from the loss of a few ambiguous candidates, particularly given the large number of systems with  $m_2 > 3 M_\odot$ .

In Section 4.1, we discuss the absence of GRB detections in coincidence with the six GWs classified with a possible neutron star component and present flux upper limits from Fermi-GBM

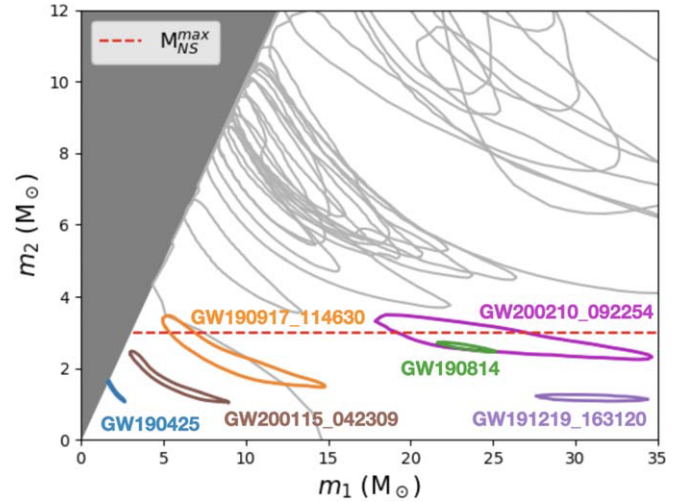


**Figure 3.** Cumulative fraction vs.  $p$ -value of the updated ranking statistic  $R$ . The solid black line is the foreground distribution of GRB candidates found with the Targeted Search around the given GW merger time. The dashed black line is the randomly selected background sample and the blue, green and orange lines represent the 68%, 95% and 99.7% confidence intervals for background, respectively.

and Swift-BAT. In Section 4.2, we discuss the BBH mergers, providing flux upper limits and exploring how these limits may rule out certain theoretical models.

#### 4.1. Possible Neutron Star in the System

There are six GWs—i.e., GW190425, GW190814, GW190917\_114630, GW191219\_163120, GW200115\_042309, and GW200210\_092254—where  $\geq 5\%$  of posterior probability lies below the dashed red line in Figure 4. GW190425 is the least massive system from O3 and the second BNS merger detected by LIGO–Virgo. It has a primary mass of  $m_1 = 2.1^{+0.5}_{-0.4} M_\odot$  and a secondary mass of  $m_2 = 1.3^{+0.3}_{-0.2} M_\odot$  (Abbott et al. 2020c, 2021c). GW190814 has a low-mass secondary component, estimated at  $m_2 = 2.6^{+0.1}_{-0.1} M_\odot$ , while its primary component has an estimated mass of  $m_1 = 23.3^{+1.4}_{-1.4} M_\odot$ . It is unclear whether this source is a BBH or an NSBH merger, since the secondary component could either be a light black hole or a heavy neutron star (Abbott et al. 2021c). GW190917\_114630 was identified as a BBH merger by the GstLAL pipeline, but its secondary component mass of  $m_2 = 2.1^{+1.1}_{-0.4} M_\odot$  is a strong indicator for an NSBH origin



**Figure 4.** The inferred 90% credible regions of the component masses for all GWs with  $p_{\text{astro}} > 0.5$  from O3 are shown in gray (Abbott et al. 2021a, 2021c, 2023). The red dashed line marks the upper bound of  $m_2$  allowed for our classification of systems with a possible neutron star component, which are marked by colored contours.

**Table 4**  
Flux Upper Limits for the Six GWs from O3 with  $p_{\text{astro}} > 0.5$  That Are Classified with a Possible Neutron Star Component

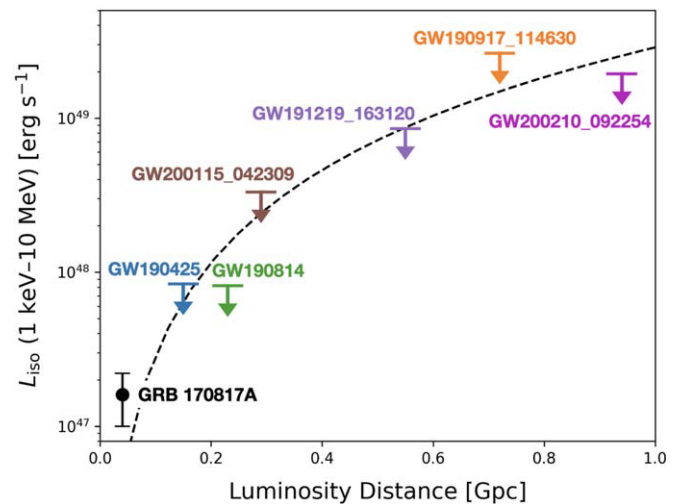
Event Name	Coverage (%)			$3\sigma$ Flux U.L. (erg s <sup>-1</sup> cm <sup>-2</sup> )			$5\sigma$ Flux U.L. (erg s <sup>-1</sup> cm <sup>-2</sup> )		
	GBM	BAT	Combined	10–1000 keV			15–350 keV		
				Min	Max	Marginal	Min	Max	Marginal
GW190425	56.70	10.81	57.81	$1.37 \times 10^{-7}$	$2.47 \times 10^{-7}$	$1.66 \times 10^{-7}$	$6.12 \times 10^{-8}$	$2.31 \times 10^{-7}$	$1.51 \times 10^{-7}$
GW190814	100.00	100.00	100.00	$1.17 \times 10^{-7}$	$1.26 \times 10^{-7}$	$1.21 \times 10^{-7}$	$4.71 \times 10^{-8}$	$7.64 \times 10^{-8}$	$6.26 \times 10^{-8}$
GW190917_114630	88.92	6.56	95.07	$1.48 \times 10^{-7}$	$4.33 \times 10^{-7}$	$2.33 \times 10^{-7}$	$5.26 \times 10^{-8}$	$3.83 \times 10^{-7}$	$2.08 \times 10^{-7}$
GW191219_163120	61.06	N/A	61.06	$1.03 \times 10^{-7}$	$2.36 \times 10^{-7}$	$1.20 \times 10^{-7}$	$1.00 \times 10^{-7}$	$2.27 \times 10^{-7}$	$1.15 \times 10^{-7}$
GW200115_042309	96.26	4.80	96.26	$1.31 \times 10^{-7}$	$2.83 \times 10^{-7}$	$1.78 \times 10^{-7}$	$8.53 \times 10^{-8}$	$2.56 \times 10^{-7}$	$1.60 \times 10^{-7}$
GW200210_092254	61.79	50.55	65.85	$1.28 \times 10^{-7}$	$3.13 \times 10^{-7}$	$2.01 \times 10^{-7}$	$4.41 \times 10^{-8}$	$1.47 \times 10^{-7}$	$9.00 \times 10^{-8}$

**Note.** The  $3\sigma$  upper limits are computed for the 10–1000 keV energy range over the FOV of Fermi-GBM. The  $5\sigma$  upper limits are computed for the combined coverage of Fermi-GBM and Swift-BAT, with both instruments matched to the 15–350 keV energy range of Swift-BAT. The columns labeled “Min” and “Max” correspond, respectively, to the minimum and maximum upper limits obtained for points within the 90% credible region of the GW localization. The “Marginal” upper limit is computed by integrating the upper limits produced at individual locations over the full sky, using the GW localization as a weighted prior, normalized to the visible portion of the sky. Also shown is the visible coverage percentage of the full GW localization for Fermi-GBM alone, Swift-BAT alone, and the combined FOV from both instruments.

(Abbott et al. 2021c). GW191219\_163120 has a large primary component mass of  $m_1 = 31.1_{-2.8}^{+2.2} M_{\odot}$  and the lowest secondary component mass  $m_2 = 1.17_{-0.06}^{+0.07} M_{\odot}$  of all the GWs with a possible neutron star (Abbott et al. 2023); it represents a potential NSBH merger. GW200115\_042309 has a primary mass of  $m_1 = 5.9_{-2.5}^{+2.0} M_{\odot}$ , suggesting a low-mass black hole, and a secondary mass of  $m_2 = 1.44_{-0.29}^{+0.85} M_{\odot}$ , which is consistent with a neutron star (Abbott et al. 2023). GW200210\_092254 possesses a primary component mass of  $m_1 = 24.1_{-4.6}^{+7.5} M_{\odot}$  and a secondary component mass of  $m_2 = 2.83_{-0.42}^{+0.47} M_{\odot}$  that could either be a light black hole or a heavy neutron star (Abbott et al. 2023). It is unclear if this source is a BBH or NSBH merger.

All GWs except GW191219\_163120 were observable by both Fermi-GBM and Swift-BAT (Table 4). GW191219\_163120 was observed by Fermi-GBM, but no Swift-BAT data are available due to a slewing behavior of the spacecraft at the GW time. Neither instrument detected an EM counterpart to these GWs. Therefore, we compute flux upper limits for each GW using the methods described in Section 2. Table 4 presents the minimum and maximum flux upper limits from Fermi-GBM and Swift-BAT over the 90% credible regions of the GW localizations, as well as sky-marginalized flux upper limits. Incorporating the combined measurements from Fermi-GBM and Swift-BAT, we also use the sky-marginalized  $5\sigma$  flux limits to generate upper limits on the isotropic-equivalent luminosity (Figure 5). The combined  $5\sigma$  flux upper limits over the 15–350 keV energy range can be seen in Figure 6.

The lack of a gamma-ray counterpart to BNS merger GW190425 has three plausible explanations. First, the combined coverage of  $\sim 60\%$  of the total GW localization implies that the GW source may not have been visible to Fermi-GBM and Swift-BAT. Second, GW190425 has an estimated luminosity distance of  $D_L = 0.15_{-0.06}^{+0.08}$  Gpc, which is four times larger than that to GW170817 (Abbott et al. 2019). At this distance, the luminosity of GW170817 would fall well below the upper limit for GW190425<sup>318</sup> (Fletcher et al. 2019; Figure 5), indicating that a counterpart similar to the one for GW170817 would have been unobservable to



**Figure 5.** The  $5\sigma$  upper limits on the isotropic-equivalent luminosity  $L_{\text{iso}}$  for the six GWs in O3 identified with a possible neutron star component and  $p_{\text{astro}} > 0.5$ . The black data point is the measured  $L_{\text{iso}}$  from GRB 170817A and the black dashed line is the approximate lower bound for  $L_{\text{iso}}$  of the GRBs detected on board Fermi-GBM (Abbott et al. 2017a).

Fermi-GBM or Swift-BAT. Finally, the inclination angle of this GW is poorly constrained, with the 90% credible level extending to a viewing angle of  $70^\circ$  with respect to the jet axis. This encompasses scenarios where the observed off-axis flux would be below the detection limits, even if the central engine of GW190425 was powerful enough to be detected on-axis by Fermi-GBM and Swift-BAT at its measured distance.

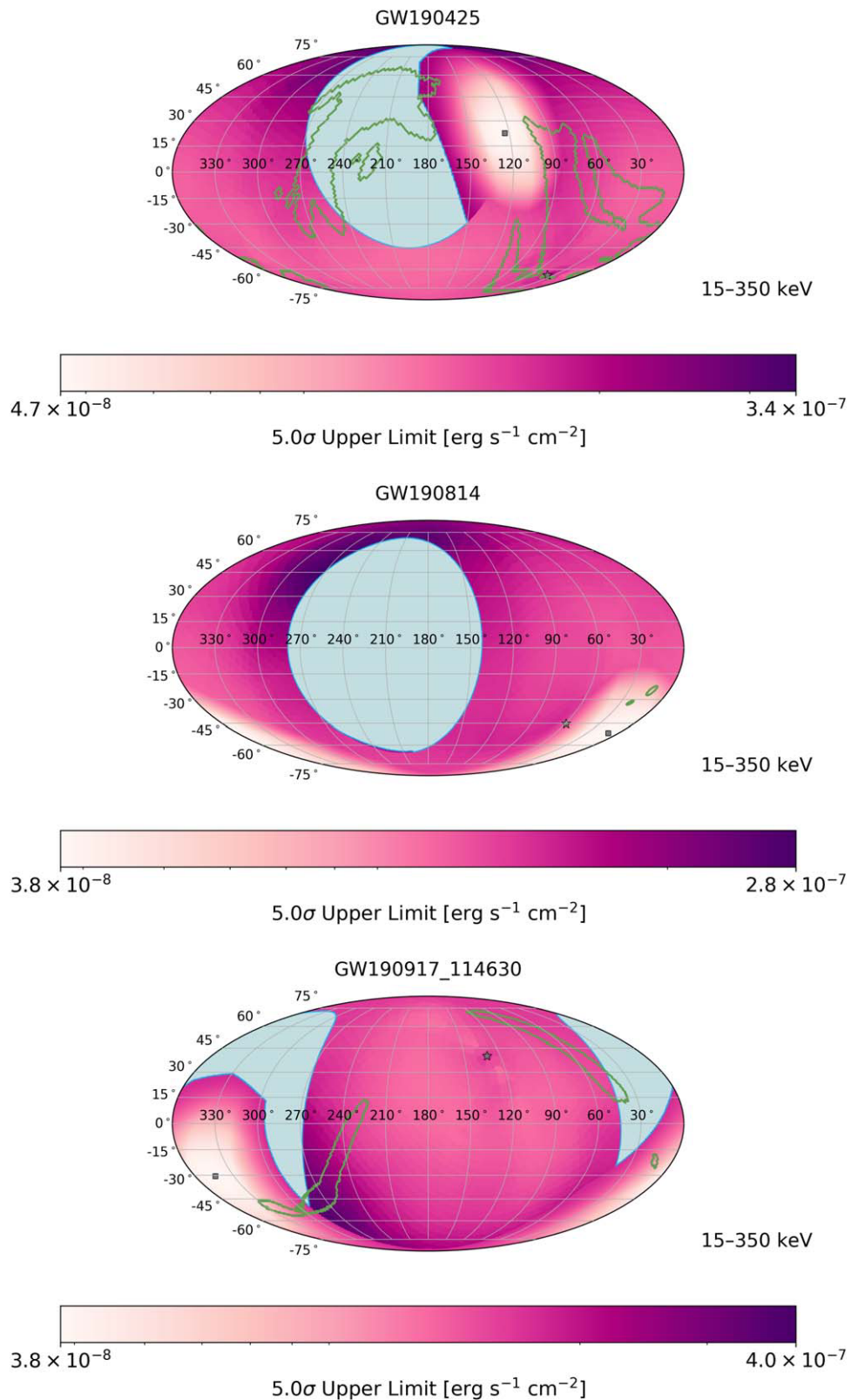
#### 4.2. Probable BBH Mergers

There are a total of 73 GWs with the criterion of  $m_2 > 3 M_{\odot}$  in  $> 95\%$  of the posterior probability. All of these have estimated primary and secondary component masses much larger than the maximum expected neutron star mass of  $3 M_{\odot}$ . Therefore, they are most likely GW signals from BBH mergers.

Of these GWs, 10 occurred during the SAA for Fermi-GBM, but had data from Swift-BAT. Likewise, Swift-BAT does not have data for nine GWs, either because Swift-BAT was in the SAA or slewing, but data are available from Fermi-GBM. Finally, there are five GWs that do not have data from either Fermi-GBM or Swift-BAT, due to being in the SAA and/or

<sup>318</sup> Note that the luminosity upper limit for GW190425 is also consistent with that found in Hosseinzadeh et al. (2019), which uses preliminary Fermi-GBM flux upper limits reported during the O3 online analysis.





**Figure 6.** The  $5\sigma$  flux upper limit as a function of sky position for the six GWs from O3 identified with a possible neutron star component and  $p_{\text{astro}} > 0.5$ . The purple gradient represents the combined Fermi-GBM and Swift-BAT flux upper limits for source positions at each point on the sky. The star symbol represents the zenith direction of Fermi-GBM, the square symbol represents the center of the Swift-BAT FOV, and the green contour represents the 90% credible area of the LVK localization. The blue region is the nonvisible portion of the sky that is occulted by the Earth for Fermi-GBM and outside the Swift-BAT FOV.

slewing. Neither instrument identified an EM counterpart for the GWs with data coverage. As a result, we compute flux upper limits for each GW according to the methods described

in Section 2. Table 5 presents the minimum and maximum upper limits over the 90% credible region of the GW localization as well as the marginalized flux upper limits. Joint



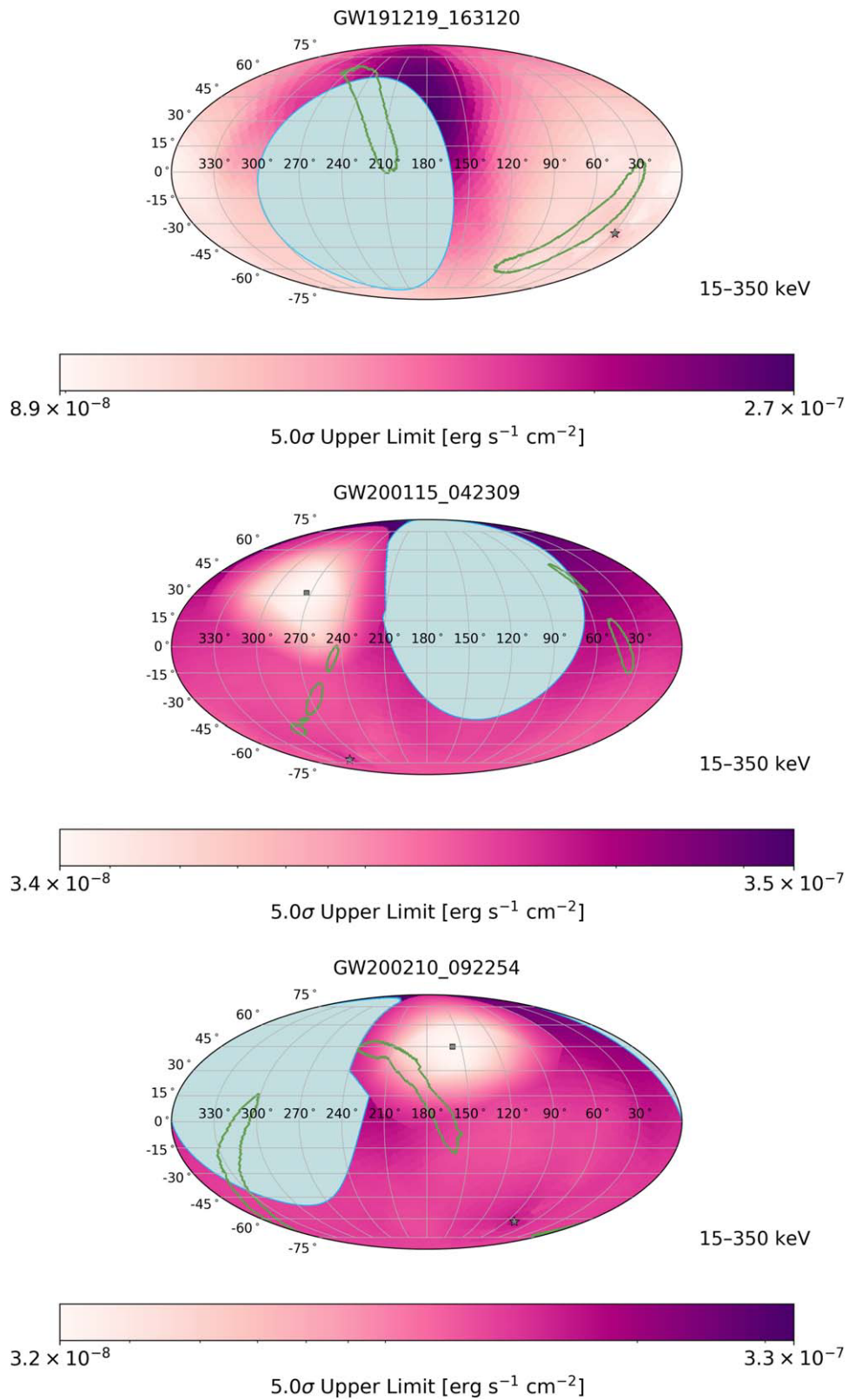


Figure 6. (Continued.)

flux upper limits as a function of sky position and the corresponding isotropic-equivalent luminosity limits for the GWs that have data coverage are provided in a separate data release in Zenodo, at doi:[10.5281/zenodo.8101645](https://doi.org/10.5281/zenodo.8101645). For the

GWs with Fermi-GBM data, we look into constraining theoretical models of gamma-ray emission from BBHs using the 3-sigma flux upper limits, as they provide broad spectral coverage over the 10–1000 keV energy range.

**Table 5**  
 Flux Upper Limits for Possible EM Counterparts to Probable BBH Candidates Detected During O3 with  $p_{\text{astro}} > 0.5$

Event Name	Coverage (%)			$3\sigma$ Flux U.L. (erg s $^{-1}$ cm $^{-2}$ )			$5\sigma$ Flux U.L. (erg s $^{-1}$ cm $^{-2}$ )		
	GBM	BAT	Combined	10–1000 keV			15–350 keV		
				Min	Max	Marginal	Min	Max	Marginal
GW190403_051519	76.61	24.76	82.91	$1.07 \times 10^{-7}$	$3.09 \times 10^{-7}$	$1.78 \times 10^{-7}$	$3.67 \times 10^{-8}$	$2.80 \times 10^{-7}$	$1.50 \times 10^{-7}$
GW190408_181802	SAA	0.00	0.00	...	...	...	...	...	$3.50 \times 10^{-7}$
GW190412	97.27	3.45	99.80	$1.00 \times 10^{-7}$	$1.22 \times 10^{-7}$	$1.11 \times 10^{-7}$	$9.81 \times 10^{-8}$	$1.15 \times 10^{-7}$	$1.07 \times 10^{-7}$
GW190413_052954	33.38	0.05	33.42	$1.21 \times 10^{-7}$	$1.97 \times 10^{-7}$	$1.36 \times 10^{-7}$	$1.15 \times 10^{-7}$	$2.12 \times 10^{-7}$	$1.28 \times 10^{-7}$
GW190413_134308	SAA	6.94	6.94	...	...	...	$7.40 \times 10^{-8}$	$2.10 \times 10^{-7}$	$1.25 \times 10^{-7}$
GW190421_213856	65.97	40.81	99.97	$1.38 \times 10^{-7}$	$1.58 \times 10^{-7}$	$1.44 \times 10^{-7}$	$5.02 \times 10^{-8}$	$2.04 \times 10^{-7}$	$1.30 \times 10^{-7}$
GW190426_190642	88.70	SAA	88.70	$1.10 \times 10^{-7}$	$2.48 \times 10^{-7}$	$1.34 \times 10^{-7}$	$1.09 \times 10^{-7}$	$2.29 \times 10^{-7}$	$1.31 \times 10^{-7}$
GW190503_185404	96.59	SAA	96.59	$1.32 \times 10^{-7}$	$1.36 \times 10^{-7}$	$1.33 \times 10^{-7}$	$1.25 \times 10^{-7}$	$1.28 \times 10^{-7}$	$1.26 \times 10^{-7}$
GW190512_180714	30.95	0.00	30.95	$1.65 \times 10^{-7}$	$1.79 \times 10^{-7}$	$1.76 \times 10^{-7}$	$1.54 \times 10^{-7}$	$1.66 \times 10^{-7}$	$1.64 \times 10^{-7}$
GW190513_205428	84.97	0.00	84.97	$1.07 \times 10^{-7}$	$1.31 \times 10^{-7}$	$1.13 \times 10^{-7}$	$1.06 \times 10^{-7}$	$1.19 \times 10^{-7}$	$1.09 \times 10^{-7}$
GW190514_065416	83.33	68.64	83.75	$1.09 \times 10^{-7}$	$3.03 \times 10^{-7}$	$1.35 \times 10^{-7}$	$3.89 \times 10^{-8}$	$2.79 \times 10^{-7}$	$8.77 \times 10^{-8}$
GW190517_055101	6.81	4.07	10.57	$1.32 \times 10^{-7}$	$1.35 \times 10^{-7}$	$1.34 \times 10^{-7}$	$4.41 \times 10^{-8}$	$1.26 \times 10^{-7}$	$1.02 \times 10^{-7}$
GW190519_153544	40.53	0.00	40.53	$1.13 \times 10^{-7}$	$1.61 \times 10^{-7}$	$1.26 \times 10^{-7}$	$1.06 \times 10^{-7}$	$1.54 \times 10^{-7}$	$1.18 \times 10^{-7}$
GW190521	58.61	61.27	99.98	$1.64 \times 10^{-7}$	$3.54 \times 10^{-7}$	$2.19 \times 10^{-7}$	$4.20 \times 10^{-8}$	$3.20 \times 10^{-7}$	$1.35 \times 10^{-7}$
GW190521_074359	100.00	0.00	100.00	$1.20 \times 10^{-7}$	$1.61 \times 10^{-7}$	$1.51 \times 10^{-7}$	$1.16 \times 10^{-7}$	$1.48 \times 10^{-7}$	$1.40 \times 10^{-7}$
GW190527_092055	72.51	0.05	72.51	$1.14 \times 10^{-7}$	$3.30 \times 10^{-7}$	$1.91 \times 10^{-7}$	$1.10 \times 10^{-7}$	$2.96 \times 10^{-7}$	$1.74 \times 10^{-7}$
GW190602_175927	65.84	SAA	65.84	$1.53 \times 10^{-7}$	$2.08 \times 10^{-7}$	$1.89 \times 10^{-7}$	$1.51 \times 10^{-7}$	$1.92 \times 10^{-7}$	$1.76 \times 10^{-7}$
GW190620_030421	SAA	4.10	4.10	...	...	...	$8.21 \times 10^{-8}$	$1.79 \times 10^{-7}$	$1.39 \times 10^{-7}$
GW190630_185205	78.32	SAA	78.32	$1.17 \times 10^{-7}$	$2.16 \times 10^{-7}$	$1.30 \times 10^{-7}$	$1.08 \times 10^{-7}$	$1.97 \times 10^{-7}$	$1.20 \times 10^{-7}$
GW190701_203306	100.00	99.51	100.00	$1.27 \times 10^{-7}$	$1.33 \times 10^{-7}$	$1.28 \times 10^{-7}$	$1.01 \times 10^{-7}$	$1.20 \times 10^{-7}$	$1.15 \times 10^{-7}$
GW190706_222641	66.90	12.80	73.80	$1.03 \times 10^{-7}$	$2.95 \times 10^{-7}$	$1.63 \times 10^{-7}$	$4.66 \times 10^{-8}$	$2.79 \times 10^{-7}$	$1.53 \times 10^{-7}$
GW190707_093326	42.31	SAA	42.31	$1.38 \times 10^{-7}$	$2.34 \times 10^{-7}$	$1.60 \times 10^{-7}$	$1.30 \times 10^{-7}$	$2.12 \times 10^{-7}$	$1.48 \times 10^{-7}$
GW190708_232457	56.01	SAA	56.01	$1.28 \times 10^{-7}$	$4.24 \times 10^{-7}$	$1.93 \times 10^{-7}$	$1.22 \times 10^{-7}$	$3.77 \times 10^{-7}$	$1.75 \times 10^{-7}$
GW190719_215514	74.97	15.00	89.79	$1.17 \times 10^{-7}$	$3.74 \times 10^{-7}$	$1.85 \times 10^{-7}$	$3.65 \times 10^{-8}$	$3.40 \times 10^{-7}$	$1.60 \times 10^{-7}$
GW190720_000836	87.90	SAA	87.90	$1.08 \times 10^{-7}$	$2.64 \times 10^{-7}$	$1.19 \times 10^{-7}$	$1.01 \times 10^{-7}$	$2.46 \times 10^{-7}$	$1.12 \times 10^{-7}$
GW190725_174728	SAA	SAA	...	...	...	...	...	...	...
GW190727_060333	61.20	0.01	61.20	$1.61 \times 10^{-7}$	$1.93 \times 10^{-7}$	$1.74 \times 10^{-7}$	$1.49 \times 10^{-7}$	$1.72 \times 10^{-7}$	$1.58 \times 10^{-7}$
GW190728_064510	74.03	71.13	74.03	$1.07 \times 10^{-7}$	$2.36 \times 10^{-7}$	$1.21 \times 10^{-7}$	$6.33 \times 10^{-8}$	$2.28 \times 10^{-7}$	$9.27 \times 10^{-8}$
GW190731_140936	61.08	3.17	61.08	$1.20 \times 10^{-7}$	$1.99 \times 10^{-7}$	$1.40 \times 10^{-7}$	$1.13 \times 10^{-7}$	$1.88 \times 10^{-7}$	$1.32 \times 10^{-7}$
GW190803_022701	SAA	47.43	47.43	...	...	...	$7.34 \times 10^{-8}$	$1.47 \times 10^{-7}$	$1.16 \times 10^{-7}$
GW190805_211137	91.07	7.64	98.63	$1.15 \times 10^{-7}$	$1.60 \times 10^{-7}$	$1.43 \times 10^{-7}$	$4.04 \times 10^{-8}$	$1.48 \times 10^{-7}$	$1.27 \times 10^{-7}$
GW190828_063405	90.53	24.93	90.53	$1.34 \times 10^{-7}$	$2.01 \times 10^{-7}$	$1.81 \times 10^{-7}$	$8.58 \times 10^{-8}$	$1.83 \times 10^{-7}$	$1.56 \times 10^{-7}$
GW190828_065509	12.79	8.82	12.79	$1.60 \times 10^{-7}$	$2.98 \times 10^{-7}$	$2.00 \times 10^{-7}$	$5.19 \times 10^{-8}$	$2.67 \times 10^{-7}$	$1.32 \times 10^{-7}$
GW190910_112807	SAA	34.37	34.37	...	...	...	$3.85 \times 10^{-8}$	$1.77 \times 10^{-7}$	$8.11 \times 10^{-8}$
GW190915_235702	94.82	76.04	94.87	$1.59 \times 10^{-7}$	$2.15 \times 10^{-7}$	$1.86 \times 10^{-7}$	$5.59 \times 10^{-8}$	$1.74 \times 10^{-7}$	$1.13 \times 10^{-7}$
GW190916_200658	56.57	0.00	56.57	$1.20 \times 10^{-7}$	$1.61 \times 10^{-7}$	$1.31 \times 10^{-7}$	$1.12 \times 10^{-7}$	$1.42 \times 10^{-7}$	$1.21 \times 10^{-7}$
GW190924_021846	100.00	92.40	100.00	$1.39 \times 10^{-7}$	$1.61 \times 10^{-7}$	$1.47 \times 10^{-7}$	$4.25 \times 10^{-8}$	$1.43 \times 10^{-7}$	$8.43 \times 10^{-8}$
GW190925_232845	SAA	SAA	...	...	...	...	...	...	...
GW190926_050336	60.68	0.02	60.68	$1.53 \times 10^{-7}$	$2.84 \times 10^{-7}$	$2.10 \times 10^{-7}$	$1.43 \times 10^{-7}$	$2.57 \times 10^{-7}$	$1.88 \times 10^{-7}$
GW190929_012149	73.05	34.84	73.05	$1.35 \times 10^{-7}$	$2.25 \times 10^{-7}$	$1.75 \times 10^{-7}$	$4.79 \times 10^{-8}$	$2.14 \times 10^{-7}$	$1.59 \times 10^{-7}$
GW190930_133541	63.05	0.56	63.05	$1.55 \times 10^{-7}$	$2.87 \times 10^{-7}$	$2.39 \times 10^{-7}$	$1.46 \times 10^{-7}$	$2.71 \times 10^{-7}$	$2.25 \times 10^{-7}$
GW191103_012549	76.96	56.21	97.35	$1.57 \times 10^{-7}$	$3.60 \times 10^{-7}$	$1.98 \times 10^{-7}$	$1.25 \times 10^{-7}$	$3.24 \times 10^{-7}$	$1.65 \times 10^{-7}$
GW191105_143521	77.45	8.05	80.39	$1.35 \times 10^{-7}$	$2.01 \times 10^{-7}$	$1.69 \times 10^{-7}$	$1.06 \times 10^{-7}$	$1.91 \times 10^{-7}$	$1.58 \times 10^{-7}$
GW191109_010717	89.38	29.05	89.38	$1.29 \times 10^{-7}$	$2.22 \times 10^{-7}$	$1.55 \times 10^{-7}$	$1.25 \times 10^{-7}$	$2.05 \times 10^{-7}$	$1.47 \times 10^{-7}$
GW191113_071753	72.98	2.27	73.00	$1.53 \times 10^{-7}$	$2.27 \times 10^{-7}$	$1.72 \times 10^{-7}$	$1.45 \times 10^{-7}$	$2.08 \times 10^{-7}$	$1.61 \times 10^{-7}$
GW191126_115259	59.81	7.88	59.81	$1.12 \times 10^{-7}$	$2.09 \times 10^{-7}$	$1.36 \times 10^{-7}$	$7.09 \times 10^{-8}$	$1.96 \times 10^{-7}$	$1.25 \times 10^{-7}$
GW191127_050227	89.03	77.16	89.04	$1.12 \times 10^{-7}$	$2.42 \times 10^{-7}$	$1.40 \times 10^{-7}$	$3.94 \times 10^{-8}$	$2.23 \times 10^{-7}$	$8.96 \times 10^{-8}$
GW191129_134029	SAA	SAA	...	...	...	...	...	...	...
GW191204_110529	48.10	25.20	66.23	$1.09 \times 10^{-7}$	$2.77 \times 10^{-7}$	$1.42 \times 10^{-7}$	$3.10 \times 10^{-8}$	$1.43 \times 10^{-7}$	$1.07 \times 10^{-7}$
GW191204_171526	SAA	87.15	87.15	...	...	...	$2.02 \times 10^{-7}$	$9.13 \times 10^{-7}$	$3.97 \times 10^{-7}$
GW191215_223052	51.87	21.09	51.87	$1.41 \times 10^{-7}$	$1.69 \times 10^{-7}$	$1.53 \times 10^{-7}$	$4.40 \times 10^{-8}$	$1.55 \times 10^{-7}$	$1.29 \times 10^{-7}$
GW191216_213338	94.70	1.76	94.76	$1.40 \times 10^{-7}$	$1.64 \times 10^{-7}$	$1.48 \times 10^{-7}$	$1.26 \times 10^{-7}$	$1.50 \times 10^{-7}$	$1.33 \times 10^{-7}$
GW191222_033537	SAA	0.89	0.89	...	...	...	$1.84 \times 10^{-7}$	$1.92 \times 10^{-7}$	$1.89 \times 10^{-7}$
GW191230_180458	40.80	0.00	40.80	$1.09 \times 10^{-7}$	$1.72 \times 10^{-7}$	$1.39 \times 10^{-7}$	$1.09 \times 10^{-7}$	$1.60 \times 10^{-7}$	$1.33 \times 10^{-7}$
GW200112_155838	SAA	SAA	...	...	...	...	...	...	...
GW200128_022011	45.58	23.04	45.58	$1.22 \times 10^{-7}$	$3.08 \times 10^{-7}$	$1.42 \times 10^{-7}$	$3.29 \times 10^{-8}$	$2.83 \times 10^{-7}$	$1.07 \times 10^{-7}$
GW200129_065458	1.36	1.16	1.36	...	...	$1.42 \times 10^{-7}$	...	...	$6.49 \times 10^{-8}$
GW200202_154313	99.99	SAA	99.99	$1.18 \times 10^{-7}$	$1.26 \times 10^{-7}$	$1.21 \times 10^{-7}$	$1.10 \times 10^{-7}$	$1.18 \times 10^{-7}$	$1.14 \times 10^{-7}$
GW200208_130117	99.70	0.00	99.70	$1.33 \times 10^{-7}$	$1.36 \times 10^{-7}$	$1.36 \times 10^{-7}$	$1.22 \times 10^{-7}$	$1.25 \times 10^{-7}$	$1.25 \times 10^{-7}$
GW200208_222617	SAA	5.85	5.85	...	...	...	$6.09 \times 10^{-8}$	$1.77 \times 10^{-7}$	$1.06 \times 10^{-7}$
GW200209_085452	61.47	7.05	61.63	$1.27 \times 10^{-7}$	$1.69 \times 10^{-7}$	$1.35 \times 10^{-7}$	$3.71 \times 10^{-8}$	$1.28 \times 10^{-7}$	$1.17 \times 10^{-7}$
GW200216_220804	SAA	38.42	38.42	...	...	...	$8.98 \times 10^{-8}$	$1.71 \times 10^{-7}$	$1.47 \times 10^{-7}$

**Table 5**  
(Continued)

Event Name	Coverage (%)			$3\sigma$ Flux U.L. (erg s <sup>-1</sup> cm <sup>-2</sup> )			$5\sigma$ Flux U.L. (erg s <sup>-1</sup> cm <sup>-2</sup> )		
	GBM	BAT	Combined	10–1000 keV			15–350 keV		
				Min	Max	Marginal	Min	Max	Marginal
GW200219_094415	20.36	SAA	20.36	$1.37 \times 10^{-7}$	$1.73 \times 10^{-7}$	$1.52 \times 10^{-7}$	$1.29 \times 10^{-7}$	$1.58 \times 10^{-7}$	$1.41 \times 10^{-7}$
GW200220_061928	99.63	0.05	99.65	$1.33 \times 10^{-7}$	$2.12 \times 10^{-7}$	$1.65 \times 10^{-7}$	$1.22 \times 10^{-7}$	$1.87 \times 10^{-7}$	$1.48 \times 10^{-7}$
GW200220_124850	63.37	21.46	80.25	$1.10 \times 10^{-7}$	$2.34 \times 10^{-7}$	$1.28 \times 10^{-7}$	$3.07 \times 10^{-8}$	$2.18 \times 10^{-7}$	$1.10 \times 10^{-7}$
GW200224_222234	SAA	98.76	98.76	...	...	...	$1.13 \times 10^{-7}$	$1.40 \times 10^{-7}$	$1.27 \times 10^{-7}$
GW200225_060421	87.61	1.30	87.61	$1.37 \times 10^{-7}$	$3.32 \times 10^{-7}$	$2.36 \times 10^{-7}$	$1.28 \times 10^{-7}$	$3.10 \times 10^{-7}$	$2.23 \times 10^{-7}$
GW200302_015811	67.41	23.35	67.92	$1.04 \times 10^{-7}$	$3.40 \times 10^{-7}$	$1.62 \times 10^{-7}$	$3.27 \times 10^{-8}$	$1.77 \times 10^{-7}$	$1.19 \times 10^{-7}$
GW200306_093714	72.37	30.46	90.36	$1.18 \times 10^{-7}$	$2.54 \times 10^{-7}$	$1.46 \times 10^{-7}$	$5.38 \times 10^{-8}$	$2.40 \times 10^{-7}$	$1.33 \times 10^{-7}$
GW200308_173609	70.53	4.40	70.89	$1.19 \times 10^{-7}$	$3.39 \times 10^{-7}$	$1.92 \times 10^{-7}$	$8.13 \times 10^{-8}$	$3.20 \times 10^{-7}$	$1.77 \times 10^{-7}$
GW200311_115853	SAA	N/A	...	...	...	...	...	...	...
GW200316_215756	15.69	13.49	15.69	$1.14 \times 10^{-7}$	$1.51 \times 10^{-7}$	$1.34 \times 10^{-7}$	$1.09 \times 10^{-7}$	$1.36 \times 10^{-7}$	$1.22 \times 10^{-7}$
GW200322_091133	75.18	13.82	89.00	$1.06 \times 10^{-7}$	$3.70 \times 10^{-7}$	$1.54 \times 10^{-7}$	$4.49 \times 10^{-8}$	$3.38 \times 10^{-7}$	$1.39 \times 10^{-7}$

**Note.** The  $3\sigma$  upper limits are computed for the 10–1000 keV energy range over the FOV of Fermi-GBM. The  $5\sigma$  upper limits are computed for the combined coverage of Fermi-GBM and Swift-BAT, with both instruments matched to the 15–350 keV energy range of Swift-BAT. The columns labeled “Min” and “Max” correspond, respectively, to the minimum and maximum upper-limit values obtained for points within the 90% credible level of the GW localization. The “Marginal” upper limit is computed by integrating the upper limits produced at individual locations over the full sky, using the GW localization as a weighted prior, normalized to the visible portion of the sky.

#### 4.2.1. Constraining Gamma-Ray Emission Models from BBH Mergers

EM radiation from BBH mergers is not expected, due to the challenges associated with forming an accretion disk during the merger process. Nevertheless, Connaughton et al. (2016) reported GW150914-GBM, a weak gamma-ray signal following the first LIGO–Virgo detection of BBH GW150914 (Abbott et al. 2016), and, more recently, the Zwicky Transient Facility identified a potential EM counterpart to GW190521 (Graham et al. 2020). While the associations between these detections and the corresponding GWs remain nebulous (Connaughton et al. 2018; De Paolis et al. 2020; Ashton et al. 2021; Bustillo et al. 2021; Palmese et al. 2021), a wide spectrum of models has been developed to invoke EM emission from BBH mergers, all with non-negligible difficulties (e.g., Loeb 2016; Perna et al. 2016, 2018; Zhang 2016).

To test the association between GW150914 and GW150914-GBM, Veres et al. (2019) assumed some of these BBH emission models and derived a model-dependent BBH-to-GRB ratio that represents the expected number of BBH mergers to be detected by LVK before a gamma-ray counterpart might be observed by Fermi-GBM. These models consider gamma-ray counterparts similar to GW150914-GBM for all BBH mergers. Since the number of LVK BBH merger detections has reached the BBH-to-GRB ratio for a few models reported by Veres et al. (2019), we attempt to constrain them by computing gamma-ray flux upper limits for each model and examining the implications with respect to individual BBH mergers.

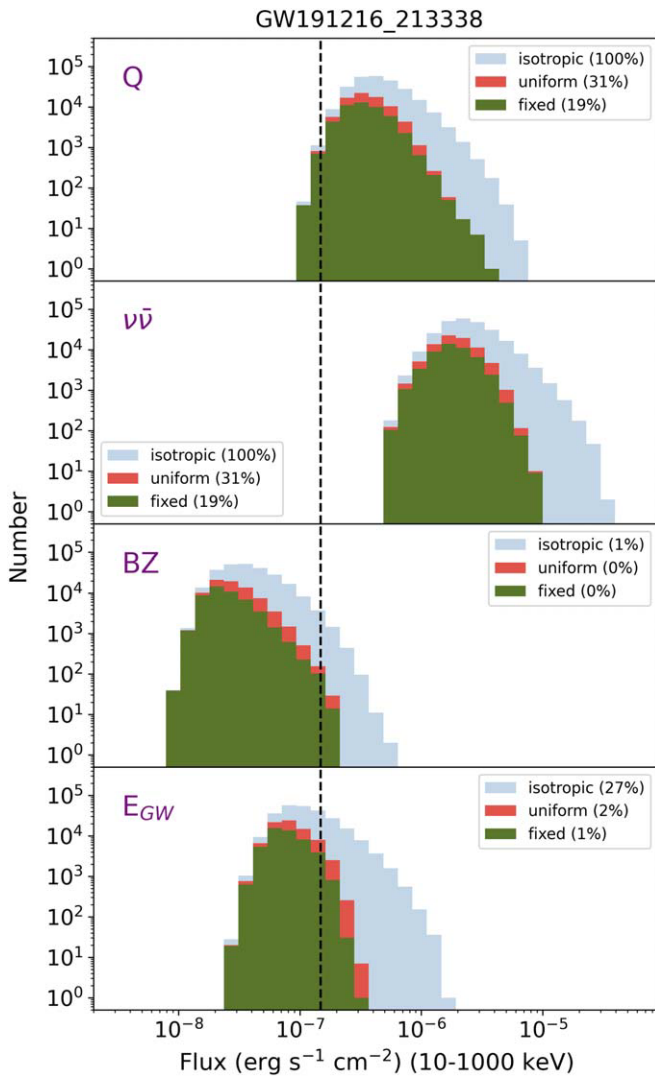
We consider four models for relating potential gamma-ray emission to the energy present in BBH mergers: a neutrino–antineutrino annihilation powered jet mechanism ( $\nu\bar{\nu}$ ; Ruffert & Janka 1998), a charged black hole (Q; Zhang 2016), the Blandford–Znajek mechanism (BZ; Blandford & Znajek 1977), and a model where the gamma-ray energy is proportional to the emitted GW energy ( $E_{\text{GW}}$ ). A detailed summary of these models and their parameters can be found in Veres et al. (2019). We note that all of the above scenarios suffer from nontrivial critiques, but are used here to be widely inclusive of the broad spectrum of proposed mechanisms for gamma-ray

production. The intrinsic properties of each model (e.g., magnetic field strength, charge of the black hole, etc.) are determined by setting them to values consistent with the observed luminosity of GW150914-GBM (Connaughton et al. 2016).

For each GW, we use the posterior distributions of the BBH parameters (e.g., final mass, distance, inclination, rotation parameter, etc.) from GWTC-3 and derive a distribution of gamma-ray fluxes for the different models. We then compare the distribution of fluxes to the  $3\sigma$  marginalized flux upper limit from Fermi-GBM, shown in Table 5. This is performed for three GRB jet geometries: an isotropic emitter (i.e., an opening angle of  $90^\circ$ ), an opening angle distributed uniformly between  $10^\circ$  and  $40^\circ$ , and a fixed  $20^\circ$  opening angle. All jets are assumed to have a top-hat angular structure and are assigned pointing directions by sampling from the inclination posterior of each GW. Due to relativistic beaming, emission is strongly suppressed for GRBs with jet opening angles smaller than the viewing angle. In order to simplify the treatment of such cases, we assign zero flux to jets whose inclination is larger than the opening angle.

Figure 7 shows an example of the flux distribution for the four different models and the three jet geometries compared to the GBM upper limits for GW191216\_213338. There is a dearth of jetted cases (green and red) compared to isotropic emission (light blue) at higher fluxes. This is explained by the inclination angle–distance degeneracy of the GW parameter estimation. Point estimates with smaller distances and thus higher flux will preferentially have jets pointed away from our line of sight. When we impose a jet opening angle  $\lesssim 40^\circ$  on such systems, they will not include the observer within their aperture in most of the cases. Conversely, the point estimates with largest distances point preferentially toward the observer, thus there will be no strong differences between the jetted and isotropic cases at low flux values.

We classify GW191216\_213338 as noteworthy because the predicted gamma-ray flux distribution from at least one model violates the GBM flux upper limit by more than 10%. The 10%



**Figure 7.** Examples of the gamma-ray flux expected for the four different models: Q, the neutrino–antineutrino annihilation powered jet model ( $\nu\bar{\nu}$ ), BZ, and the gamma-ray energy as a fraction of GW energy ( $E_{GW}$ ) in the case of GW191216\_213338. The  $3\sigma$  (10–1000 keV) marginalized flux upper limit is indicated by the vertical line. The legend contains the fraction of all cases above the  $3\sigma$  upper limit after accounting for the visibility of the jet geometry. Note that this is limited to the fraction of visible jets when all expected fluxes exceed the GBM upper limit; cases with zero expected flux are not shown in the plot. Here the limit is violated in 100% and  $>99\%$  of cases for the  $\nu\bar{\nu}$  and Q models, respectively (assuming isotropic emission).

limit in the rest of this section refers to the isotropic emission model. Of the 58 probable BBH mergers with Fermi-GBM data coverage described in Section 4.2, 18 are considered noteworthy according to this criterion. The remaining 40 did not yield the necessary number of cases above the GBM flux upper limit in any of the models.

Out of the four models considered here, the  $\nu\bar{\nu}$  model violates the Fermi-GBM flux upper limit in most of the cases. Of the noteworthy GWs (denoted by the asterisks in Table 7, in the Appendix), 15 exceed the GBM limit in more than 10% of cases for this model. In particular, GW190924\_021846, GW191216\_213338 (Figure 7), and GW200202\_154313 exceed the GBM limit in {100, 30, 20}%, {100, 31, 19}%, and {100, 36, 24}% of the cases, respectively (the three numbers represent the three different opening angle choices).

Interestingly, for these three events, in the isotropic emission scenario the  $\nu\bar{\nu}$  can be ruled out, and the nondetection in gamma rays can constrain the jet geometry. This is due to GW191216\_213338 and GW200202\_154313 being the two closest BBH signals observed during O3 with luminosity distances of  $0.34^{+0.12}_{-0.13}$  Gpc and  $0.41^{+0.15}_{-0.16}$  Gpc, respectively (Abbott et al. 2023). In addition to being nearby (luminosity distance of  $0.55 \pm 0.22$  Gpc), GW190924\_021846 has a relatively low final mass ( $13.9^{+2.8}_{-0.9} M_{\odot}$ ), which leads to higher flux in the  $\nu\bar{\nu}$  model.

For the Q model, the most constraining GWs are also GW191216\_213338 and GW200202\_154313. They violate the GBM flux upper limit for the different jet geometries in {100, 31, 19}% and {96, 33, 22}% of cases, respectively. In total, 12 of the probable BBH mergers have larger than 10% of their flux estimates above the upper limit for this model.

GW191109\_010717 is the most constraining for the BZ scenario. It violates the gamma-ray upper limit in {26,  $<0.1$ ,  $<0.1$ }% of cases for the three different opening angle choices. It has the fourth-highest total mass  $M = 112^{+20}_{-16} M_{\odot}$  in O3 and is reasonably close at  $D_L = 1.29^{+1.13}_{-0.65}$  Gpc (Abbott et al. 2023). The only other GW with more than 10% of the flux estimates above the upper limit for the BZ mechanism is GW190521\_074359.

For the  $E_{GW}$  scenario, GW191216\_213338 is again the most constrained. It violates the gamma-ray upper limit in {27, 1.8, 0.7}% of the cases for the three jet opening angle choices. There are three GWs with 10% of the flux estimates from this model above the GBM flux upper limit (Table 7, in the Appendix).

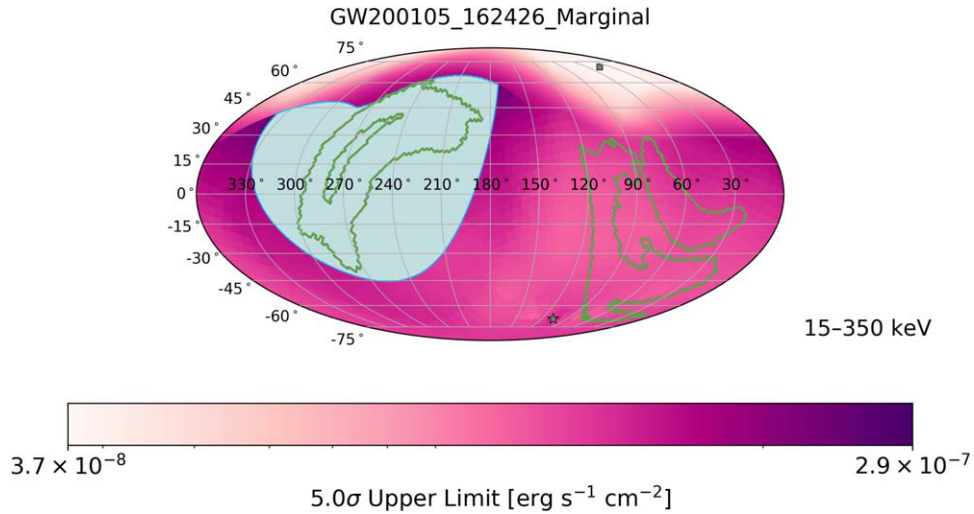
In summary, we provide constraints on theoretical models of gamma-ray emission from BBH mergers using the flux upper limits from Fermi-GBM. We find that for most BBH mergers, the models considered here do not predict gamma-ray flux over the upper limit. Under our model assumptions, this can be understood as a consequence of the larger average distance of BBH mergers during O3 compared to that of GW150914. We also find that the  $\nu\bar{\nu}$  model is the most constrained. This model has the lowest BBH-to-GRB ratio in Veres et al. (2016) and, indeed, observations reveal that 18 out of 58 cases for the  $\nu\bar{\nu}$  model yield an appreciable flux above the upper limit. The expected flux in this model is inversely proportional with the final mass; the average BBH merger in O3 was less massive than GW150914, resulting in larger predicted gamma-ray flux.

### 4.3. Marginal GWs

Although all six marginal GWs from Table 2 have  $p_{\text{astro}} < 0.5$ , they are of interest for EM follow-up. This is because GW200311\_103121 may have a possible BNS origin and the remaining five candidates have possible NSBH origins (Abbott et al. 2021c, 2023). In particular, the possible NSBH merger GW200105\_162426 was noted as a clear outlier from experimental backgrounds, despite not satisfying the  $p_{\text{astro}} > 0.5$  criterion used to identify GW signals with a likely astrophysical origin. It also has the highest observed  $p_{\text{astro}}$  of all the marginal GWs.

The five marginal GWs with possible NSBH origins were visible to Fermi-GBM, while the remaining one, GW200311\_103121, occurred when Fermi-GBM was in the SAA. None of the marginal GWs have appreciable coverage in Swift-BAT. No significant counterparts were found. As with GW190425, this may be due to unfavorable viewing angles





**Figure 8.** The  $5\sigma$  upper limits as a function of sky position for GW200105\_162426, the marginal GW with the highest  $p_{\text{astro}}$ . The purple gradient represents the combined Fermi-GBM and Swift-BAT flux upper limits for source positions at each point on the sky. The star symbol represents the zenith direction of Fermi-GBM, the square symbol represents the center of the Swift-BAT FOV, and the green contour represents the 90% credible area of the LVK localization. The blue region is the nonvisible portion of the sky that is occulted by the Earth for Fermi-GBM and outside the Swift-BAT FOV.

**Table 6**  
Flux Upper Limits for Possible EM Counterparts to Marginal GW Candidates with ( $\text{FAR} < 2 \text{ yr}^{-1}$ ,  $p_{\text{astro}} < 0.5$ )

Event Name	Coverage (%)			$3\sigma$ Flux U.L. (erg s $^{-1}$ cm $^{-2}$ )			$5\sigma$ Flux U.L. (erg s $^{-1}$ cm $^{-2}$ )		
	GBM	BAT	Combined	10–1000 keV			15–350 keV		
				Min	Max	Marginal	Min	Max	Marginal
GW190426_152155	100.00	SAA	100.00	$1.03 \times 10^{-7}$	$1.65 \times 10^{-7}$	$1.30 \times 10^{-7}$	$1.00 \times 10^{-7}$	$1.53 \times 10^{-7}$	$1.21 \times 10^{-7}$
GW190531_023648	86.90	0.03	86.91	$1.35 \times 10^{-7}$	$2.63 \times 10^{-7}$	$1.74 \times 10^{-7}$	$1.26 \times 10^{-7}$	$2.42 \times 10^{-7}$	$1.60 \times 10^{-7}$
GW191118_212859	93.63	SAA	93.63	$1.07 \times 10^{-7}$	$2.93 \times 10^{-7}$	$1.19 \times 10^{-7}$	$1.05 \times 10^{-7}$	$2.71 \times 10^{-7}$	$1.13 \times 10^{-7}$
GW200105_162426	53.57	3.01	54.36	$1.13 \times 10^{-7}$	$1.53 \times 10^{-7}$	$1.26 \times 10^{-7}$	$1.06 \times 10^{-7}$	$1.69 \times 10^{-7}$	$1.18 \times 10^{-7}$
GW200201_203549	86.01	SAA	86.01	$1.17 \times 10^{-7}$	$1.80 \times 10^{-7}$	$1.31 \times 10^{-7}$	$1.09 \times 10^{-7}$	$1.64 \times 10^{-7}$	$1.22 \times 10^{-7}$
GW200311_103121	SAA	0.01	0.01	...	...	...	...	...	$1.09 \times 10^{-7}$

**Note.** The  $3\sigma$  upper limits are computed for the 10–1000 keV energy range over the FOV of Fermi-GBM. The  $5\sigma$  upper limits are computed for the combined coverage of Fermi-GBM and Swift-BAT, with both instruments matched to the 15–350 keV energy range of Swift-BAT. The columns labeled “Min” and “Max” correspond, respectively, to the minimum and maximum upper limits obtained for points within the 90% credible level of the GW candidate localization. The “Marginal” upper limit is computed by integrating the upper limits produced at individual locations over the full sky using the GW localization as a weighted prior, normalized to the visible portion of the sky. Also shown is the visible coverage percentage of the full GW localization for Fermi-GBM alone, Swift-BAT alone, and the combined FOV from both instruments.

with respect to the jet axis, larger observational distances, such as the  $0.27^{+0.12}_{-0.11}$  Gpc distance to GW200105\_162426 (Abbott et al. 2023), and partial sky coverage for candidates other than GW190426\_152155. It therefore remains ambiguous as to whether these signals are real compact binary coalescences. Nevertheless, we provide in Table 6 the flux upper limits for each marginal GW, calculated according to the same methods described in Section 4.1, since they may provide emission model constraints if future analyses can identify an astrophysical progenitor with a favorable viewing angle with respect to the jet axis. Figure 8 displays the  $5\sigma$  confidence level flux upper-limit map for GW200105\_162426, since it is the marginal GW with the highest probability of having an astrophysical origin. The marginalized  $5\sigma$  flux upper limit of GW200105\_162426 yields an isotropic-equivalent luminosity upper limit of  $L_{\text{iso}} = 2.1 \times 10^{48}$  erg s $^{-1}$  when combined with its 0.27 Gpc distance. The data release (Wood et al. 2023) associated with this work provides flux upper limits as a function of sky position for the remaining marginal GWs.

## 5. Summary and Future Directions

Using the 79 GW candidates with  $p_{\text{astro}} > 0.5$  from O3 that were reported in GWTC-3, we searched for coincident EM counterparts with Fermi-GBM and Swift-BAT. This represents the most comprehensive follow-up to date of the O3 run in the hard X-ray and gamma-ray regime. We found no significant counterparts in either instrument. For the one BNS merger, GW190425, with  $p_{\text{astro}} > 0.5$ , there are several possible reasons for the nondetection of a counterpart:

1. The combined Fermi-GBM and Swift-BAT coverage of the GW localization area was  $\sim 60\%$ , meaning that the GW source may have been outside the FOV for both instruments.
2. The distance to GW190425 was four times larger than the estimated distance for GW170817, causing the observed flux to be below the detection threshold in both instruments if it had the same intrinsic luminosity and viewing angle as GW170817.

3. The viewing angle may have been too far away from the jet axis to detect emission under scenarios with a clean or structured jet.

GW190425 is therefore unconstrained by our observations.

In contrast to GW190425, the large number of BBH detections in this sample allowed us to begin placing constraints on certain models of gamma-ray emission from BBH mergers, despite the larger average distance for this class compared to the BNS mergers. The most constrained model was the  $\nu\bar{\nu}$  model, where two GWs, GW191216\_213338 and GW200202\_154313, were predicted to produce an observable flux in Fermi-GBM. With the number of GWs from BBH mergers set to increase in the fourth LVK observing run (O4), we expect this model to become more constrained and ruled out as a potential explanation of EM emission from BBH mergers.

With O4 having begun on 2023 May 24, we expect an increase in GW detections by a factor of 5 (Abbott et al. 2018; Petrov et al. 2022) and a bountiful regime of EM follow-up data. Although the median luminosity distance for these GWs will also increase by a factor of 2 relative to O3 (Petrov et al. 2022), meaning that not all of these events will be detectable to Fermi-GBM and Swift-BAT, there will still be at least a doubling of events within the observable distance of O3, based on observing time alone. This increases the need for further instantaneous, wide-FOV gamma-ray/X-ray observations in order to detect the EM counterparts to these GWs and localize them, especially given the absence of a counterpart detection during O3. Toward this end, the Fermi-GBM Targeted Search updates presented in this paper will be used in future LVK observing runs. In the absence of detections, flux upper limits, both marginalized and as a function of sky position, will be provided to the community. Additionally, Swift-BAT GUANO and NITRATES will be used during the next observing run.

### Acknowledgments

The USRA coauthors gratefully acknowledge NASA funding through contract 80MSFC17M0022. R.H. acknowledges funding from the European Union’s Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No. 945298-ParisRegionFP. The UAH coauthors gratefully acknowledge NASA funding from co-operative agreement 80MSFC22M0004. The NASA authors gratefully acknowledge NASA funding through the Fermi-GBM project. This research also made use of Astropy, a community-developed core Python package for Astronomy (Astropy Collaboration et al. 2013, 2018, 2022); NumPy (Harris et al. 2020); SciPy (Virtanen et al. 2020), and matplotlib, a Python library for publication-quality graphics (Hunter 2007).

The Swift authors acknowledge the use of public data from the Swift data archive. M.C. acknowledges support from NASA under award number 80GSFC21M0002 and from Vetenskapsrådet through project number 31004019. J.D. acknowledges support by the NSF under award numbers PHY-1913607 and PHY-2209445.

This material is based upon work supported by NSF’s LIGO Laboratory, which is a major facility fully funded by the National Science Foundation. The authors also gratefully acknowledge the support of the Science and Technology Facilities Council (STFC) of the United Kingdom, the Max-Planck-Society (MPS), and the State of Niedersachsen/

Germany for supporting the construction of Advanced LIGO and the construction and operation of the GEO 600 detector. Additional support for Advanced LIGO was provided by the Australian Research Council. The authors gratefully acknowledge the Italian Istituto Nazionale di Fisica Nucleare (INFN), the French Centre National de la Recherche Scientifique (CNRS), and the Netherlands Organization for Scientific Research (NWO) for the construction and operation of the Virgo detector and the creation and support of the EGO consortium. The authors also gratefully acknowledge research support from these agencies as well as from the Council of Scientific and Industrial Research of India, the Department of Science and Technology, India, the Science & Engineering Research Board (SERB), India, the Ministry of Human Resource Development, India, the Spanish Agencia Estatal de Investigación (AEI), the Spanish Ministerio de Ciencia e Innovación and Ministerio de Universidades, the Conselleria de Fons Europeus, Universitat i Cultura and the Direcció General de Política Universitaria i Recerca del Govern de les Illes Balears, the Conselleria d’Innovació Universitats, Ciència i Societat Digital de la Generalitat Valenciana and the CERCA Programme Generalitat de Catalunya, Spain, the National Science Centre of Poland and the European Union—European Regional Development Fund; the Foundation for Polish Science (FNP), the Swiss National Science Foundation (SNSF), the Russian Foundation for Basic Research, the Russian Science Foundation, the European Commission, the European Social Funds (ESF), the European Regional Development Funds (ERDF), the Royal Society, the Scottish Funding Council, the Scottish Universities Physics Alliance, the Hungarian Scientific Research Fund (OTKA), the French Lyon Institute of Origins (LIO), the Belgian Fonds de la Recherche Scientifique (FRS-FNRS), Actions de Recherche Concertées (ARC) and Fonds Wetenschappelijk Onderzoek—Vlaanderen (FWO), Belgium, the Paris Île-de-France Region, the National Research, Development and Innovation Office Hungary (NKFIH), the National Research Foundation of Korea, the Natural Science and Engineering Research Council Canada, the Canadian Foundation for Innovation (CFI), the Brazilian Ministry of Science, Technology, and Innovations, the International Center for Theoretical Physics South American Institute for Fundamental Research (ICTP-SAIFR), the Research Grants Council of Hong Kong, the National Natural Science Foundation of China (NSFC), the Leverhulme Trust, the Research Corporation, the National Science and Technology Council (NSTC), Taiwan, the United States Department of Energy, and the Kavli Foundation. The authors gratefully acknowledge the support of the NSF, STFC, INFN, and CNRS for the provision of computational resources.

This work was supported by MEXT, the JSPS Leading-edge Research Infrastructure Program, JSPS Grant-in-Aid for Specially Promoted Research 26000005, JSPS Grant-in-Aid for Scientific Research on Innovative Areas 2905: JP17H06358, JP17H06361, and JP17H06364, JSPS Core-to-Core Program A. Advanced Research Networks, JSPS Grant-in-Aid for Scientific Research (S) 17H06133 and 20H05639, JSPS Grant-in-Aid for Transformative Research Areas (A) 20A203: JP20H05854, the joint research program of the Institute for Cosmic Ray Research, University of Tokyo, the National Research Foundation (NRF), the Computing Infrastructure Project of the Global Science experimental Data hub

Center (GSDC) at KISTI, the Korea Astronomy and Space Science Institute (KASI), the Ministry of Science and ICT (MSIT) in Korea, Academia Sinica (AS), the AS Grid Center (ASGC) and the National Science and Technology Council (NSTC) in Taiwan under grants including the Rising Star Program and Science Vanguard Research Program, the Advanced Technology Center (ATC) of NAOJ, and the Mechanical Engineering Center of KEK.

Additional LSC–Virgo–KAGRA acknowledgments for the support of individual authors may be found in the following document: <https://dcc.ligo.org/LIGO-M2300033/public>.

## Appendix Flux Upper Limits for Probable BBH Mergers

In Table 7, we present the sky-marginalized  $3\sigma$  flux upper limits for the probable BBH mergers described in Section 4.2, as well as the 0.95 percentile fluxes for the different models of BBH emission. The upper limits are constructed over a 10–1000 keV energy range according to the method in Section 2. They assume the spectral shape of the potential emission follows the normal spectral template from Table 3, with a 1 s emission duration.

**Table 7**  
Table Showing the 0.95 Percentile Fluxes from Different Models of BBH Emission

Name	Waveform (Visible Frac.)	$F_Q$	$F_{DP}$	$F_{BZ}$	$F_{GW}$	UL
GW190403_051519	IMRPhenomXPHM (49, 36)	74, 70, 67	7.3, 6.7, 6.4	7.3, 5.8, 5.6	2.5, 1.8, 1.7	178
GW190403_051519	SEOBNRv4PHM (39, 30)	44, 35, 35	5.0, 4.0, 3.8	6.5, 4.6, 4.5	3.4, 1.9, 1.7	178
GW190412	IMRPhenomXPHM (6, 0)	*137, 83, 95	*299, 165, 173	59, 30, 25	64, 28, 22	111
GW190412	SEOBNRv4PHM (12, 4)	*148, 85, 82	*356, 178, 172	48, 25, 23	70, 29, 25	111
GW190413_052954	IMRPhenomXPHM (30, 19)	11, 5.8, 5.2	10, 5.7, 5.2	10, 4.4, 4.0	10, 4.2, 3.6	136
GW190421_213856	IMRPhenomXPHM (23, 14)	21, 8.1, 7.5	14, 6.1, 5.8	36, 13, 12	27, 10, 9.6	144
GW190426_190642	IMRPhenomXPHM (22, 14)	32, 31, 29	2.7, 2.3, 2.1	75, 24, 22	26, 8.0, 7.1	134
GW190503_185404	IMRPhenomXPHM (30, 20)	50, 20, 18	38, 16, 15	68, 29, 28	54, 20, 18	133
GW190503_185404	SEOBNRv4PHM (25, 16)	42, 22, 21	32, 17, 16	53, 25, 24	44, 19, 18	133
GW190512_180714	IMRPhenomXPHM (27, 17)	49, 24, 24	107, 55, 54	20, 7.2, 6.6	28, 10, 9.2	176
GW190512_180714	SEOBNRv4PHM (22, 13)	45, 18, 17	104, 46, 43	18, 6.1, 5.2	28, 9.5, 8.2	176
GW190513_205428	IMRPhenomXPHM (31, 19)	42, 24, 23	35, 21, 20	16, 9.2, 8.4	17, 8.2, 7.5	113
GW190513_205428	SEOBNRv4PHM (30, 19)	52, 26, 24	36, 20, 19	15, 8.3, 7.9	17, 8.0, 7.0	113
GW190514_065416	IMRPhenomXPHM (24, 15)	12, 5.1, 4.8	7.8, 3.8, 3.7	21, 8.7, 7.3	14, 6.0, 5.4	135
GW190514_065416	SEOBNRv4PHM (21, 13)	12, 6.9, 6.1	7.5, 4.4, 4.2	17, 8.0, 7.8	12, 6.0, 5.5	135
GW190517_055101	IMRPhenomXPHM (10, 5)	*485, 198, 173	*202, 85, 74	48, 10, 7.9	60, 18, 14	134
GW190517_055101	SEOBNRv4PHM (14, 8)	*360, 171, 145	*142, 70, 62	29, 9.3, 7.6	53, 16, 14	134
GW190519_153544	IMRPhenomXPHM (6, 3)	49, 19, 19	14, 6.1, 5.8	47, 12, 9.7	32, 7.1, 5.5	126
GW190519_153544	SEOBNRv4PHM (5, 2)	49, 21, 17	12, 6.3, 4.9	38, 17, 14	26, 9.6, 7.7	126
GW190521_074359	IMRPhenomXPHM (7, 3)	*222, 58, 49	142, 44, 38	*259, 76, 69	*228, 65, 57	151
GW190521_074359	SEOBNRv4PHM (25, 14)	*99, 51, 47	62, 31, 29	*94, 37, 35	*87, 35, 31	151
GW190521	IMRPhenomXPHM (19, 11)	15, 3.4, 3.2	2.9, 0.77, 0.72	121, 21, 18	38, 6.9, 5.9	219
GW190527_092055	IMRPhenomXPHM (21, 13)	44, 16, 15	31, 14, 13	27, 13, 12	23, 9.5, 8.7	191
GW190527_092055	SEOBNRv4PHM (22, 14)	34, 16, 15	29, 15, 14	23, 10, 9.7	24, 10, 10	191
GW190602_175927	IMRPhenomXPHM (31, 20)	24, 14, 13	6.8, 4.2, 3.9	61, 33, 32	29, 13, 12	189
GW190630_185205	IMRPhenomXPHM (21, 14)	*225, 75, 70	*215, 78, 73	145, 56, 51	167, 56, 51	130
GW190630_185205	SEOBNRv4PHM (26, 18)	*195, 93, 88	*185, 89, 83	131, 56, 53	145, 60, 57	130
GW190701_203306	IMRPhenomXPHM (32, 20)	20, 11, 10	10, 6.0, 5.5	51, 26, 24	31, 15, 13	128
GW190701_203306	SEOBNRv4PHM (35, 23)	21, 14, 14	9.7, 6.9, 6.7	48, 29, 26	29, 16, 15	128
GW190706_222641	IMRPhenomXPHM (20, 12)	53, 37, 34	11, 8.4, 8.2	63, 43, 40	31, 19, 18	163
GW190706_222641	SEOBNRv4PHM (19, 10)	41, 27, 29	9.1, 6.9, 7.5	62, 44, 46	33, 22, 23	163
GW190707_093326	IMRPhenomXPHM (37, 26)	174, 114, 109	*961, 632, 602	21, 13, 12	63, 38, 35	160
GW190707_093326	SEOBNRv4PHM (31, 20)	151, 76, 70	*821, 429, 389	20, 9.8, 8.9	57, 27, 24	160
GW190708_232457	IMRPhenomXPHM (39, 26)	152, 96, 91	*415, 260, 248	35, 20, 18	70, 39, 36	193
GW190708_232457	SEOBNRv4PHM (36, 25)	125, 74, 72	*338, 203, 197	37, 19, 19	64, 34, 34	193
GW190719_215514	IMRPhenomXPHM (25, 16)	51, 29, 28	25, 13, 13	16, 10, 9.2	14, 7.2, 6.4	185
GW190720_000836	IMRPhenomXPHM (44, 32)	*261, 234, 266	*1054, 759, 785	19, 12, 12	54, 28, 26	119
GW190720_000836	SEOBNRv4PHM (35, 24)	*194, 126, 119	*852, 555, 515	19, 11, 10	51, 28, 26	119
GW190727_060333	IMRPhenomXPHM (30, 19)	23, 11, 10	14, 7.8, 7.3	16, 6.8, 6.1	15, 6.1, 5.4	174
GW190727_060333	SEOBNRv4PHM (25, 16)	21, 12, 11	12, 7.8, 7.3	14, 6.8, 6.3	14, 6.1, 5.6	174
GW190728_064510	IMRPhenomXPHM (32, 21)	*253, 125, 125	*1130, 462, 459	21, 8.4, 7.6	58, 17, 15	121
GW190728_064510	SEOBNRv4PHM (30, 19)	*208, 79, 75	*1015, 408, 388	17, 6.0, 5.6	54, 18, 16	121
GW190731_140936	IMRPhenomXPHM (28, 18)	20, 11, 10	12, 7.4, 6.8	24, 11, 10	19, 9.3, 8.7	140
GW190731_140936	SEOBNRv4PHM (27, 18)	26, 17, 16	13, 9.4, 9.1	24, 12, 10	20, 11, 9.9	140
GW190805_211137	IMRPhenomXPHM (22, 14)	28, 13, 12	8.7, 4.8, 4.6	7.4, 2.2, 1.9	7.3, 2.2, 1.9	143
GW190805_211137	SEOBNRv4PHM (18, 11)	21, 13, 13	6.6, 4.7, 4.8	7.9, 2.6, 2.2	6.9, 2.4, 2.3	143
GW190828_063405	IMRPhenomXPHM (31, 21)	58, 25, 23	48, 22, 21	27, 7.7, 6.8	33, 9.9, 8.5	181
GW190828_065509	IMRPhenomXPHM (22, 12)	43, 19, 18	103, 48, 44	16, 6.4, 5.4	23, 7.6, 6.3	200
GW190915_235702	IMRPhenomXPHM (18, 10)	39, 17, 14	37, 18, 16	28, 11, 10	29, 11, 10	186
GW190915_235702	SEOBNRv4PHM (20, 12)	42, 25, 24	39, 23, 22	31, 12, 10	32, 13, 11	186
GW190916_200658	IMRPhenomXPHM (28, 18)	13, 6.6, 6.2	6.8, 3.5, 3.2	8.4, 4.0, 3.6	6.7, 2.3, 2.0	131

**Table 7**  
(Continued)

Name	Waveform (Visible Frac.)	$F_Q$	$F_D$	$F_{BZ}$	$F_{GW}$	UL
GW190916_200658	SEOBNRv4PHM (25, 16)	12, 6.1, 6.0	6.1, 3.4, 3.4	8.4, 4.9, 4.2	5.9, 2.4, 2.2	131
GW190924_021846	IMRPhenomXPHM (32, 22)	*351, 258, 281	*3217, 1887, 1884	21, 12, 12	78, 31, 28	147
GW190924_021846	SEOBNRv4PHM (25, 16)	*317, 131, 120	*3158, 1364, 1253	17, 6.4, 5.8	75, 28, 25	147
GW190926_050336	IMRPhenomXPHM (10, 6)	14, 2.9, 2.6	11, 3.3, 3.0	21, 3.9, 3.5	13, 2.5, 2.2	210
GW190929_012149	IMRPhenomXPHM (9, 5)	12, 2.8, 2.6	4.9, 1.5, 1.4	34, 14, 12	14, 4.3, 3.7	175
GW190930_133541	IMRPhenomXPHM (34, 23)	*363, 236, 252	*1483, 790, 776	23, 12, 12	69, 26, 23	239
GW190930_133541	SEOBNRv4PHM (32, 21)	*264, 141, 136	*1086, 566, 534	24, 11, 11	60, 26, 24	239
GW191103_012549	IMRPhenomXPHM (34, 23)	*332, 234, 230	*1349, 831, 801	15, 9.3, 8.6	53, 27, 24	198
GW191103_012549	SEOBNRv4PHM (27, 18)	*303, 164, 158	*1355, 764, 710	16, 8.6, 8.3	58, 28, 26	198
GW191105_143521	IMRPhenomXPHM (35, 24)	86, 43, 42	*509, 262, 247	8.5, 3.5, 3.3	26, 10, 9.5	169
GW191105_143521	SEOBNRv4PHM (27, 17)	84, 35, 31	*509, 229, 208	8.3, 3.0, 2.7	26, 9.8, 8.6	169
GW191109_010717	IMRPhenomXPHM (5, 2)	169, 11, 10	43, 5.5, 5.0	*437, 54, 43	217, 27, 22	155
GW191109_010717	SEOBNRv4PHM (16, 10)	47, 24, 22	16, 10.0, 9.5	*198, 113, 102	89, 50, 43	155
GW191113_071753	IMRPhenomXPHM (15, 8)	35, 20, 20	86, 53, 51	25, 8.3, 7.3	16, 5.9, 5.3	172
GW191113_071753	SEOBNRv4PHM (15, 9)	74, 42, 35	118, 72, 62	17, 8.6, 8.0	14, 6.3, 5.7	172
GW191126_115259	IMRPhenomXPHM (36, 25)	103, 68, 68	*394, 252, 244	5.6, 2.9, 2.7	18, 9.1, 8.4	136
GW191126_115259	SEOBNRv4PHM (28, 18)	104, 58, 52	*419, 234, 214	6.5, 3.1, 2.7	21, 9.8, 8.8	136
GW191127_050227	IMRPhenomXPHM (29, 19)	59, 58, 61	15, 11, 11	48, 44, 41	11, 8.8, 8.8	140
GW191127_050227	SEOBNRv4PHM (17, 10)	32, 15, 16	16, 7.4, 7.1	20, 10, 11	13, 4.8, 4.5	140
GW191204_110529	IMRPhenomXPHM (22, 13)	107, 56, 51	118, 68, 64	46, 26, 25	57, 32, 30	142
GW191204_110529	SEOBNRv4PHM (15, 9)	119, 78, 70	121, 84, 82	42, 29, 31	55, 35, 36	142
GW191215_223052	IMRPhenomXPHM (15, 8)	34, 14, 11	54, 22, 18	19, 5.2, 4.1	25, 6.5, 5.4	153
GW191215_223052	SEOBNRv4PHM (14, 8)	31, 13, 12	49, 21, 19	17, 4.9, 4.3	22, 6.7, 5.8	153
GW191216_213338	IMRPhenomXPHM (31, 19)	*1097, 696, 684	*5893, 3599, 3466	96, 60, 54	*287, 152, 140	148
GW191216_213338	SEOBNRv4PHM (25, 15)	*1180, 586, 545	*6516, 3304, 3024	93, 45, 40	*311, 150, 135	148
GW191230_180458	IMRPhenomXPHM (21, 13)	10, 3.2, 2.9	4.6, 1.8, 1.7	18, 5.5, 4.9	11, 3.5, 3.1	139
GW191230_180458	SEOBNRv4PHM (23, 14)	8.4, 4.2, 4.1	3.8, 2.1, 2.1	14, 5.1, 4.5	9.3, 3.5, 3.0	139
GW200128_022011	IMRPhenomXPHM (20, 12)	35, 13, 11	18, 8.1, 7.0	32, 11, 9.8	27, 9.5, 8.3	142
GW200128_022011	SEOBNRv4PHM (26, 15)	36, 29, 21	15, 13, 9.6	26, 18, 11	23, 17, 10	142
GW200129_065458	IMRPhenomXPHM (33, 18)	*220, 149, 145	170, 108, 105	113, 64, 59	128, 62, 57	142
GW200129_065458	SEOBNRv4PHM (18, 9)	*235, 108, 103	211, 96, 88	165, 60, 59	188, 75, 71	142
GW200202_154313	IMRPhenomXPHM (37, 25)	*666, 364, 350	*4383, 2342, 2214	50, 23, 21	*174, 78, 71	121
GW200202_154313	SEOBNRv4PHM (32, 21)	*703, 330, 300	*4700, 2248, 2051	50, 22, 20	*185, 80, 72	121
GW200208_130117	IMRPhenomXPHM (31, 20)	18, 9.3, 8.4	16, 8.7, 7.9	25, 11, 9.6	21, 9.3, 7.8	136
GW200208_130117	SEOBNRv4PHM (31, 20)	17, 11, 11	14, 9.8, 9.2	22, 11, 10	19, 10, 9.0	136
GW200209_085452	IMRPhenomXPHM (22, 13)	21, 4.4, 4.0	16, 4.6, 4.3	25, 4.8, 4.2	21, 4.4, 4.0	135
GW200209_085452	SEOBNRv4PHM (22, 14)	10, 5.7, 5.6	8.4, 4.9, 4.8	12, 4.5, 3.9	10, 4.0, 3.7	135
GW200219_094415	IMRPhenomXPHM (18, 11)	11, 3.1, 2.7	8.9, 3.1, 2.8	16, 3.6, 3.2	13, 3.2, 2.7	152
GW200219_094415	SEOBNRv4PHM (22, 14)	10, 4.9, 4.6	7.7, 3.9, 3.7	11, 4.1, 3.8	9.7, 3.4, 3.2	152
GW200220_061928	IMRPhenomXPHM (22, 14)	8.3, 3.3, 3.1	1.3, 0.63, 0.61	52, 11, 10	12, 4.1, 3.4	165
GW200220_061928	SEOBNRv4PHM (22, 14)	10, 6.2, 5.3	1.4, 0.88, 0.8	34, 12, 10	12, 4.6, 4.1	165
GW200220_124850	IMRPhenomXPHM (20, 13)	13, 4.4, 4.3	8.8, 3.6, 3.5	16, 6.3, 6.0	12, 5.0, 4.8	128
GW200220_124850	SEOBNRv4PHM (17, 12)	11, 4.8, 5.3	8.0, 3.8, 3.9	18, 6.2, 7.5	13, 4.9, 5.5	128
GW200225_060421	IMRPhenomXPHM (16, 8)	97, 45, 40	224, 114, 107	33, 16, 14	53, 26, 24	236
GW200225_060421	SEOBNRv4PHM (22, 13)	71, 43, 47	174, 97, 102	25, 12, 12	43, 18, 20	236
GW200302_015811	IMRPhenomXPHM (15, 8)	62, 27, 26	60, 29, 29	62, 27, 26	53, 23, 22	162
GW200302_015811	SEOBNRv4PHM (20, 12)	66, 35, 35	58, 30, 30	54, 22, 21	48, 20, 18	162
GW200306_093714	IMRPhenomXPHM (28, 18)	133, 73, 67	113, 60, 56	19, 10, 9.7	24, 9.9, 9.1	146
GW200306_093714	SEOBNRv4PHM (25, 16)	132, 86, 82	102, 63, 61	20, 9.3, 8.1	23, 10, 9.5	146
GW200308_173609	IMRPhenomXPHM (18, 11)	51, 55, 51	24, 24, 22	74, 19, 12	7.3, 2.2, 2.2	192
GW200308_173609	SEOBNRv4PHM (14, 8)	71, 66, 67	32, 26, 25	13, 2.8, 3.3	4.7, 2.1, 2.1	192
GW200316_215756	IMRPhenomXPHM (21, 11)	112, 68, 62	*482, 258, 237	13, 6.3, 5.3	29, 10, 9.2	134
GW200316_215756	SEOBNRv4PHM (24, 15)	103, 45, 41	*484, 223, 205	10, 3.6, 3.2	28, 10, 9.1	134
GW200322_091133	IMRPhenomXPHM (14, 9)	147, 476, 499	72, 58, 64	42, 26, 27	8.7, 3.3, 3.7	154
GW200322_091133	SEOBNRv4PHM (4, 4)	3.7, 3.3, 0.22	2.0, 0.45, 0.17	4.8, 0.48, 0.37	0.77, 0.27, 0.26	154

**Note.** The two numbers after the waveform names indicate the percentage of cases where the jet is pointing toward Earth in the uniform  $10^\circ$ – $40^\circ$  opening angle and in the fixed  $20^\circ$  opening angle cases, respectively. The flux units are  $10^{-9}$  erg  $\text{cm}^{-2}$   $\text{s}^{-1}$ . The three numbers in each cell represent the isotropic emission, the uniform-distributed jet opening angle, and the fixed jet opening angle. The upper limits (UL) are the  $3\sigma$ , 10–1000 keV range values from Table 5. The asterisks mark instances where the isotropic emission exceeds the UL in more than 10% of the cases.



## ORCID iDs

- C. Fletcher <https://orcid.org/0000-0002-0186-3313>  
 J. Wood <https://orcid.org/0000-0001-9012-2463>  
 R. Hamburg <https://orcid.org/0000-0003-0761-6388>  
 P. Veres <https://orcid.org/0000-0002-2149-9846>  
 C. M. Hui <https://orcid.org/0000-0002-0468-6025>  
 E. Bissaldi <https://orcid.org/0000-0001-9935-8106>  
 E. Burns <https://orcid.org/0000-0002-2942-3379>  
 W. H. Cleveland <https://orcid.org/0009-0003-3480-8251>  
 A. Goldstein <https://orcid.org/0000-0002-0587-7042>  
 B. A. Hristov <https://orcid.org/0000-0001-9556-7576>  
 S. Lesage <https://orcid.org/0000-0001-8058-9684>  
 B. Mailyan <https://orcid.org/0000-0002-2531-3703>  
 C. Malacaria <https://orcid.org/0000-0002-0380-0041>  
 S. Poolakkil <https://orcid.org/0000-0002-6269-0452>  
 A. von Kienlin <https://orcid.org/0000-0002-0221-5916>  
 C. A. Wilson-Hodge <https://orcid.org/0000-0002-8585-0084>  
 M. Crnogorčević <https://orcid.org/0000-0002-7604-1779>  
 J. DeLaunay <https://orcid.org/0000-0001-5229-1995>  
 A. Tohuvavohu <https://orcid.org/0000-0002-2810-8764>  
 R. Caputo <https://orcid.org/0000-0002-9280-836X>  
 S. Laha <https://orcid.org/0000-0003-2714-0487>  
 T. Parsotan <https://orcid.org/0000-0002-4299-2517>  
 K. Ackley <https://orcid.org/0000-0002-8648-0767>  
 N. Adhikari <https://orcid.org/0000-0002-4559-8427>  
 R. X. Adhikari <https://orcid.org/0000-0002-5731-5076>  
 M. Agathos <https://orcid.org/0000-0002-9072-1121>  
 K. Agatsuma <https://orcid.org/0000-0002-3952-5985>  
 O. D. Aguiar <https://orcid.org/0000-0002-2139-4390>  
 L. Aiello <https://orcid.org/0000-0003-2771-8816>  
 P. Ajith <https://orcid.org/0000-0001-7519-2439>  
 T. Akutsu <https://orcid.org/0000-0003-0733-7530>  
 A. Allocca <https://orcid.org/0000-0002-5288-1351>  
 P. A. Altin <https://orcid.org/0000-0001-8193-5825>  
 A. Amato <https://orcid.org/0000-0001-9557-651X>  
 S. B. Anderson <https://orcid.org/0000-0003-2219-9383>  
 W. G. Anderson <https://orcid.org/0000-0003-0482-5942>  
 N. Andres <https://orcid.org/0000-0002-5360-943X>  
 M. Andrés-Carcasona <https://orcid.org/0000-0002-8738-1672>  
 T. Andrić <https://orcid.org/0000-0002-9277-9773>  
 J. M. Antelis <https://orcid.org/0000-0003-3377-0813>  
 S. Antier <https://orcid.org/0000-0002-7686-3334>  
 K. Arai <https://orcid.org/0000-0001-8916-8915>  
 A. Araya <https://orcid.org/0000-0002-6884-2875>  
 M. C. Araya <https://orcid.org/0000-0002-6018-6447>  
 J. S. Areeda <https://orcid.org/0000-0003-0266-7936>  
 N. Aritomi <https://orcid.org/0000-0003-4424-7657>  
 N. Arnaud <https://orcid.org/0000-0001-6589-8673>  
 K. G. Arun <https://orcid.org/0000-0002-6960-8538>  
 H. Asada <https://orcid.org/0000-0001-9442-6050>  
 G. Ashton <https://orcid.org/0000-0001-7288-2231>  
 Y. Aso <https://orcid.org/0000-0002-1902-6695>  
 P. Astone <https://orcid.org/0000-0003-4981-4120>  
 F. Aubin <https://orcid.org/0000-0003-1613-3142>  
 K. AultONeal <https://orcid.org/0000-0002-6645-4473>  
 S. Babak <https://orcid.org/0000-0001-7469-4250>  
 F. Badaracco <https://orcid.org/0000-0001-8553-7904>  
 S. Bae <https://orcid.org/0000-0003-2429-3357>  
 S. Bagnasco <https://orcid.org/0000-0001-6062-6505>  
 R. Bajpai <https://orcid.org/0000-0003-0495-5720>  
 G. Baltus <https://orcid.org/0000-0002-0304-8152>  
 S. Banagiri <https://orcid.org/0000-0001-7852-7484>  
 B. Banerjee <https://orcid.org/0000-0002-8008-2485>  
 D. Bankar <https://orcid.org/0000-0002-6068-2993>  
 P. Barneo <https://orcid.org/0000-0002-8883-7280>  
 F. Barone <https://orcid.org/0000-0002-8069-8490>  
 B. Barr <https://orcid.org/0000-0002-5232-2736>  
 L. Barsotti <https://orcid.org/0000-0001-9819-2562>  
 M. Barsuglia <https://orcid.org/0000-0002-1180-4050>  
 D. Barta <https://orcid.org/0000-0001-6841-550X>  
 M. A. Barton <https://orcid.org/0000-0002-9948-306X>  
 R. Bassiri <https://orcid.org/0000-0001-8171-6833>  
 M. Bawaj <https://orcid.org/0000-0003-3611-3042>  
 J. C. Bayley <https://orcid.org/0000-0003-2306-4106>  
 B. Bécsy <https://orcid.org/0000-0003-0909-5563>  
 F. Beirnaert <https://orcid.org/0000-0002-4003-7233>  
 M. Beijger <https://orcid.org/0000-0002-4991-8213>  
 J. D. Bentley <https://orcid.org/0000-0002-4736-7403>  
 M. Berbel <https://orcid.org/0000-0001-6345-1798>  
 B. K. Berger <https://orcid.org/0000-0002-4845-8737>  
 S. Bernuzzi <https://orcid.org/0000-0002-2334-0935>  
 C. P. L. Berry <https://orcid.org/0000-0003-3870-7215>  
 D. Bersanetti <https://orcid.org/0000-0002-7377-415X>  
 J. Betzwieser <https://orcid.org/0000-0003-1533-9229>  
 D. Beveridge <https://orcid.org/0000-0002-1481-1993>  
 U. Bhardwaj <https://orcid.org/0000-0003-1233-4174>  
 D. Bhattacharjee <https://orcid.org/0000-0001-6623-9506>  
 S. Bhaumik <https://orcid.org/0000-0001-8492-2202>  
 G. Billingsley <https://orcid.org/0000-0002-4141-2744>  
 O. Birnholtz <https://orcid.org/0000-0002-7562-9263>  
 S. Biscoveanu <https://orcid.org/0000-0001-7616-7366>  
 B. Biswas <https://orcid.org/0000-0003-2131-1476>  
 M.-A. Bizouard <https://orcid.org/0000-0002-4618-1674>  
 J. K. Blackburn <https://orcid.org/0000-0002-3838-2986>  
 G. N. Bolingbroke <https://orcid.org/0000-0002-7350-5291>  
 E. Bonilla <https://orcid.org/0000-0002-6284-9769>  
 R. Bonnand <https://orcid.org/0000-0001-5013-5913>  
 V. Boschi <https://orcid.org/0000-0001-8665-2293>  
 V. Boudart <https://orcid.org/0000-0001-9923-4154>  
 P. R. Brady <https://orcid.org/0000-0002-4611-9387>  
 M. Branchesi <https://orcid.org/0000-0003-1643-0526>  
 J. E. Brau <https://orcid.org/0000-0003-1292-9725>  
 M. Breschi <https://orcid.org/0000-0002-3327-3676>  
 T. Briant <https://orcid.org/0000-0002-6013-1729>  
 A. F. Brooks <https://orcid.org/0000-0003-4295-792X>  
 R. Bruntz <https://orcid.org/0000-0002-0840-8567>  
 A. Buonanno <https://orcid.org/0000-0002-5433-1409>  
 R. Busicchio <https://orcid.org/0000-0002-7387-6754>  
 C. Buy <https://orcid.org/0000-0003-2872-8186>  
 G. S. Cabourn Davies <https://orcid.org/0000-0002-4289-3439>  
 G. Cabras <https://orcid.org/0000-0002-6852-6856>  
 R. Cabrera <https://orcid.org/0000-0003-0133-1306>  
 L. Cadonati <https://orcid.org/0000-0002-9846-166X>  
 G. Cagnoli <https://orcid.org/0000-0002-7086-6550>  
 K. C. Cannon <https://orcid.org/0000-0003-4068-6572>  
 Z. Cao <https://orcid.org/0000-0002-1932-7295>  
 E. Capocasa <https://orcid.org/0000-0003-3762-6958>  
 J. B. Carlin <https://orcid.org/0000-0001-5694-0809>  
 G. Carullo <https://orcid.org/0000-0001-9090-1862>  
 M. Cavaglia <https://orcid.org/0000-0002-3835-6729>  
 F. Cavalier <https://orcid.org/0000-0002-3658-7240>

- R. Cavaliere <https://orcid.org/0000-0001-6064-0569>  
 G. Cella <https://orcid.org/0000-0002-0752-0338>  
 E. Cesarini <https://orcid.org/0000-0001-9127-3167>  
 S. Chalathadka Subrahmanya <https://orcid.org/0000-0002-9207-4669>  
 E. Champion <https://orcid.org/0000-0002-7901-4100>  
 C. L. Chan <https://orcid.org/0000-0002-3377-4737>  
 P. Chaniel <https://orcid.org/0000-0003-1753-524X>  
 C. Chapman-Bird <https://orcid.org/0000-0002-2728-9612>  
 P. Charlton <https://orcid.org/0000-0002-4263-2706>  
 E. A. Chase <https://orcid.org/0000-0003-1005-0792>  
 E. Chassande-Mottin <https://orcid.org/0000-0003-3768-9908>  
 C. Chatterjee <https://orcid.org/0000-0001-8700-3455>  
 Debarati Chatterjee <https://orcid.org/0000-0002-0995-2329>  
 S. Chaty <https://orcid.org/0000-0002-5769-8601>  
 C. Chen <https://orcid.org/0000-0002-3354-0105>  
 D. Chen <https://orcid.org/0000-0003-1433-0716>  
 H. Y. Chen <https://orcid.org/0000-0001-5403-3762>  
 F. Chiadini <https://orcid.org/0000-0002-9339-8622>  
 A. Chincarini <https://orcid.org/0000-0003-4094-9942>  
 A. Chiummo <https://orcid.org/0000-0003-2165-2967>  
 S. Choudhary <https://orcid.org/0000-0003-0949-7298>  
 N. Christensen <https://orcid.org/0000-0002-6870-4202>  
 S. S. Y. Chua <https://orcid.org/0000-0001-8026-7597>  
 G. Ciani <https://orcid.org/0000-0003-4258-9338>  
 M. Cieřlar <https://orcid.org/0000-0001-8912-5587>  
 R. Ciolfi <https://orcid.org/0000-0003-3140-8933>  
 J. A. Clark <https://orcid.org/0000-0003-3243-1393>  
 E. Codazzo <https://orcid.org/0000-0001-7170-8733>  
 P.-F. Cohadon <https://orcid.org/0000-0003-3452-9415>  
 D. E. Cohen <https://orcid.org/0000-0002-0583-9919>  
 M. Colleoni <https://orcid.org/0000-0002-7214-9088>  
 A. Colombo <https://orcid.org/0000-0002-7439-4773>  
 L. Conti <https://orcid.org/0000-0003-2731-2656>  
 T. R. Corbitt <https://orcid.org/0000-0002-5520-8541>  
 I. Cordero-Carrion <https://orcid.org/0000-0002-1985-1361>  
 N. J. Cornish <https://orcid.org/0000-0002-7435-0869>  
 S. Cortese <https://orcid.org/0000-0002-6504-0973>  
 M. W. Coughlin <https://orcid.org/0000-0002-8262-2924>  
 B. Cousins <https://orcid.org/0000-0002-7026-1340>  
 P. Couvares <https://orcid.org/0000-0002-2823-3127>  
 D. C. Coyne <https://orcid.org/0000-0002-6427-3222>  
 R. Coyne <https://orcid.org/0000-0002-5243-5917>  
 J. D. E. Creighton <https://orcid.org/0000-0003-3600-2406>  
 A. W. Criswell <https://orcid.org/0000-0002-9225-7756>  
 M. Croquette <https://orcid.org/0000-0002-8581-5393>  
 J. R. Cudell <https://orcid.org/0000-0002-2003-4238>  
 R. Cummings <https://orcid.org/0000-0002-8042-9047>  
 T. Dal Canton <https://orcid.org/0000-0001-5078-9044>  
 S. Dall’Osso <https://orcid.org/0000-0003-4366-8265>  
 G. Dalya <https://orcid.org/0000-0003-3258-5763>  
 B. D’Angelo <https://orcid.org/0000-0001-9143-8427>  
 S. Danilishin <https://orcid.org/0000-0001-7758-7493>  
 C. Darsow-Fromm <https://orcid.org/0000-0001-9602-0388>  
 Sayantani Datta <https://orcid.org/0000-0001-9200-8867>  
 D. Davis <https://orcid.org/0000-0001-5620-6751>  
 M. C. Davis <https://orcid.org/0000-0001-7663-0808>  
 E. J. Daw <https://orcid.org/0000-0002-3780-5430>  
 J. Degallaix <https://orcid.org/0000-0002-1019-6911>  
 S. Deleglise <https://orcid.org/0000-0002-8680-5170>  
 F. De Lillo <https://orcid.org/0000-0003-4977-0789>  
 D. Dell’Aquila <https://orcid.org/0000-0001-5895-0664>  
 T. Dent <https://orcid.org/0000-0003-1354-7809>  
 A. Depasse <https://orcid.org/0000-0003-1014-8394>  
 R. De Pietri <https://orcid.org/0000-0003-1556-8304>  
 R. De Rosa <https://orcid.org/0000-0002-4004-947X>  
 R. DeSalvo <https://orcid.org/0000-0002-4818-0296>  
 M. C. Daz <https://orcid.org/0000-0002-7555-8856>  
 T. Dietrich <https://orcid.org/0000-0003-2374-307X>  
 C. Di Giorgio <https://orcid.org/0000-0003-2127-3991>  
 F. Di Giovanni <https://orcid.org/0000-0001-8568-9334>  
 T. Di Girolamo <https://orcid.org/0000-0003-2339-4471>  
 A. Di Lieto <https://orcid.org/0000-0002-4787-0754>  
 A. Di Michele <https://orcid.org/0000-0002-0357-2608>  
 S. Di Pace <https://orcid.org/0000-0001-6759-5676>  
 I. Di Palma <https://orcid.org/0000-0003-1544-8943>  
 F. Di Renzo <https://orcid.org/0000-0002-5447-3810>  
 A. Dmitriev <https://orcid.org/0000-0002-0314-956X>  
 L. D’Onofrio <https://orcid.org/0000-0001-9546-5959>  
 S. Doravari <https://orcid.org/0000-0001-8750-8330>  
 M. Drago <https://orcid.org/0000-0002-3738-2431>  
 J. C. Driggers <https://orcid.org/0000-0002-6134-7628>  
 D. D’Urso <https://orcid.org/0000-0002-8215-4542>  
 T. Eckhardt <https://orcid.org/0000-0002-1224-4681>  
 G. Eddolls <https://orcid.org/0000-0002-5895-4523>  
 B. Edelman <https://orcid.org/0000-0001-7648-1689>  
 O. Edy <https://orcid.org/0000-0001-9617-8724>  
 A. Effler <https://orcid.org/0000-0001-8242-3944>  
 S. Eguchi <https://orcid.org/0000-0003-2814-9336>  
 J. Eichholz <https://orcid.org/0000-0002-2643-163X>  
 A. Ejlli <https://orcid.org/0000-0002-4149-4532>  
 Y. Enomoto <https://orcid.org/0000-0001-6426-7079>  
 R. C. Essick <https://orcid.org/0000-0001-8196-9267>  
 D. Estevez <https://orcid.org/0000-0002-3021-5964>  
 M. Evans <https://orcid.org/0000-0001-8459-4499>  
 F. Fabrizi <https://orcid.org/0000-0002-3809-065X>  
 V. Fafone <https://orcid.org/0000-0003-1314-1622>  
 P. C. Fan <https://orcid.org/0000-0003-3988-9022>  
 A. M. Farah <https://orcid.org/0000-0002-6121-0285>  
 B. Farr <https://orcid.org/0000-0002-2916-9200>  
 W. M. Farr <https://orcid.org/0000-0003-1540-8562>  
 G. Favaro <https://orcid.org/0000-0002-0351-6833>  
 M. Favata <https://orcid.org/0000-0001-8270-9512>  
 M. Fays <https://orcid.org/0000-0002-4390-9746>  
 E. Fenyvesi <https://orcid.org/0000-0003-2777-3719>  
 D. L. Ferguson <https://orcid.org/0000-0002-4406-591X>  
 A. Fernandez-Galiana <https://orcid.org/0000-0002-8940-9261>  
 I. Ferrante <https://orcid.org/0000-0002-0083-7228>  
 F. Fidecaro <https://orcid.org/0000-0002-6189-3311>  
 P. Figura <https://orcid.org/0000-0002-8925-0393>  
 A. Fiori <https://orcid.org/0000-0003-3174-0688>  
 I. Fiori <https://orcid.org/0000-0002-0210-516X>  
 M. Fishbach <https://orcid.org/0000-0002-1980-5293>  
 J. A. Font <https://orcid.org/0000-0001-6650-2634>  
 B. Fornal <https://orcid.org/0000-0003-3271-2080>  
 F. Frasconi <https://orcid.org/0000-0003-4204-6587>  
 Z. Frei <https://orcid.org/0000-0002-0181-8491>  
 A. Freise <https://orcid.org/0000-0001-6586-9901>  
 R. Frey <https://orcid.org/0000-0003-0341-2636>  
 G. G. Fronze <https://orcid.org/0000-0003-0966-4279>  
 B. U. Gadre <https://orcid.org/0000-0002-1534-9761>  
 J. R. Gair <https://orcid.org/0000-0002-1671-3668>

- D. Ganapathy <https://orcid.org/0000-0003-3028-4174>  
 A. Ganguly <https://orcid.org/0000-0001-7394-0755>  
 D. Gao <https://orcid.org/0000-0002-1697-7153>  
 B. Garaventa <https://orcid.org/0000-0003-2490-404X>  
 F. Garufi <https://orcid.org/0000-0003-1391-6168>  
 G.-G. Ge <https://orcid.org/0000-0003-2601-6484>  
 G. Gemme <https://orcid.org/0000-0002-1127-7406>  
 A. Gennai <https://orcid.org/0000-0003-0149-2089>  
 O. Gerberding <https://orcid.org/0000-0001-7740-2698>  
 L. Gergely <https://orcid.org/0000-0003-3146-6201>  
 S. Ghonge <https://orcid.org/0000-0002-5476-938X>  
 Abhirup Ghosh <https://orcid.org/0000-0002-2112-8578>  
 Archisman Ghosh <https://orcid.org/0000-0003-0423-3533>  
 Shaon Ghosh <https://orcid.org/0000-0001-9901-6253>  
 Tathagata Ghosh <https://orcid.org/0000-0001-9848-9905>  
 B. Giacomazzo <https://orcid.org/0000-0002-6947-4023>  
 J. A. Giaime <https://orcid.org/0000-0002-3531-817X>  
 M. Giesler <https://orcid.org/0000-0003-2300-893X>  
 P. Giri <https://orcid.org/0000-0002-4628-2432>  
 S. Gkaitatzis <https://orcid.org/0000-0001-9420-7499>  
 E. Goetz <https://orcid.org/0000-0003-2666-721X>  
 R. Goetz <https://orcid.org/0000-0002-9617-5520>  
 B. Goncharov <https://orcid.org/0000-0003-3189-5807>  
 G. González <https://orcid.org/0000-0003-0199-3158>  
 A. Grado <https://orcid.org/0000-0002-0501-8256>  
 M. Granata <https://orcid.org/0000-0003-3275-1186>  
 R. Gray <https://orcid.org/0000-0002-5556-9873>  
 A. C. Green <https://orcid.org/0000-0002-6287-8746>  
 W. L. Griffiths <https://orcid.org/0000-0001-8366-0108>  
 H. L. Griggs <https://orcid.org/0000-0001-5018-7908>  
 A. Grimaldi <https://orcid.org/0000-0002-6956-4301>  
 H. Grote <https://orcid.org/0000-0002-0797-3943>  
 D. Guerra <https://orcid.org/0000-0003-0029-5390>  
 G. M. Guidi <https://orcid.org/0000-0002-3061-9870>  
 H.-K. Guo <https://orcid.org/0000-0002-3777-3117>  
 Anuradha Gupta <https://orcid.org/0000-0002-5441-9013>  
 F. Guzman <https://orcid.org/0000-0001-9136-929X>  
 L. Haegel <https://orcid.org/0000-0002-3680-5519>  
 O. Halim <https://orcid.org/0000-0003-1326-5481>  
 E. D. Hall <https://orcid.org/0000-0001-9018-666X>  
 W.-B. Han <https://orcid.org/0000-0002-2039-0726>  
 M. Haney <https://orcid.org/0000-0001-7554-3665>  
 J. Harms <https://orcid.org/0000-0002-7332-9806>  
 G. M. Harry <https://orcid.org/0000-0002-8905-7622>  
 I. W. Harry <https://orcid.org/0000-0002-5304-9372>  
 D. Hartwig <https://orcid.org/0000-0002-9742-0794>  
 C.-J. Haster <https://orcid.org/0000-0001-8040-9807>  
 J. Healy <https://orcid.org/0000-0002-5233-3320>  
 A. Heidmann <https://orcid.org/0000-0002-0784-5175>  
 J. Heinze <https://orcid.org/0000-0001-8692-2724>  
 H. Heitmann <https://orcid.org/0000-0003-0625-5461>  
 F. Hellman <https://orcid.org/0000-0002-9135-6330>  
 A. F. Hellmink-Cornell <https://orcid.org/0000-0002-7709-8638>  
 G. Hemming <https://orcid.org/0000-0001-5268-4465>  
 M. Hendry <https://orcid.org/0000-0001-8322-5405>  
 E. Hennes <https://orcid.org/0000-0002-2246-5496>  
 M. H. Hennig <https://orcid.org/0000-0003-1531-8460>  
 M. Heurs <https://orcid.org/0000-0002-5577-2273>  
 A. L. Hewitt <https://orcid.org/0000-0002-1255-3492>  
 D. G. Holcomb <https://orcid.org/0000-0001-5987-769X>  
 I. J. Hollows <https://orcid.org/0000-0002-3404-6459>  
 Z. J. Holmes <https://orcid.org/0000-0003-1311-4691>  
 D. E. Holz <https://orcid.org/0000-0002-0175-5064>  
 E. J. Howell <https://orcid.org/0000-0001-7891-2817>  
 C. G. Hoy <https://orcid.org/0000-0002-8843-6719>  
 H.-F. Hsieh <https://orcid.org/0000-0002-8947-723X>  
 H.-Y. Huang <https://orcid.org/0000-0002-1665-2383>  
 P. Huang <https://orcid.org/0000-0002-3812-2180>  
 Y.-C. Huang <https://orcid.org/0000-0001-8786-7026>  
 Y.-J. Huang <https://orcid.org/0000-0002-2952-8429>  
 M. T. Hübner <https://orcid.org/0000-0002-9642-3029>  
 D. C. Y. Hui <https://orcid.org/0000-0003-1753-1660>  
 V. Hui <https://orcid.org/0000-0002-0233-2346>  
 B. Idzkowski <https://orcid.org/0000-0001-5869-2714>  
 K. Inayoshi <https://orcid.org/0000-0001-9840-4959>  
 P. Iosif <https://orcid.org/0000-0003-1621-7709>  
 M. Isi <https://orcid.org/0000-0001-8830-8672>  
 Y. Itoh <https://orcid.org/0000-0003-2694-8935>  
 B. R. Iyer <https://orcid.org/0000-0002-4141-5179>  
 V. JaberianHamedan <https://orcid.org/0000-0003-3605-4169>  
 T. Jacqmin <https://orcid.org/0000-0002-0693-4838>  
 P.-E. Jacquet <https://orcid.org/0000-0001-9552-0057>  
 S. P. Jadhav <https://orcid.org/0000-0003-0554-0084>  
 A. L. James <https://orcid.org/0000-0001-9165-0807>  
 A. Z. Jan <https://orcid.org/0000-0003-2050-7231>  
 K. Janssens <https://orcid.org/0000-0001-8760-4429>  
 P. Jaranowski <https://orcid.org/0000-0001-8085-3414>  
 R. Jaume <https://orcid.org/0000-0001-8691-3166>  
 A. C. Jenkins <https://orcid.org/0000-0003-1785-5841>  
 J. Jiang <https://orcid.org/0000-0002-0154-3854>  
 H.-B. Jin <https://orcid.org/0000-0002-6217-2428>  
 A. W. Jones <https://orcid.org/0000-0002-0395-0680>  
 L. Ju <https://orcid.org/0000-0002-7951-4295>  
 P. Jung <https://orcid.org/0000-0003-2974-4604>  
 J. Junker <https://orcid.org/0000-0002-3051-4374>  
 T. Kajita <https://orcid.org/0000-0003-1207-6638>  
 M. Kakizaki <https://orcid.org/0000-0003-1430-3339>  
 V. Kalogera <https://orcid.org/0000-0001-9236-5469>  
 M. Kamiizumi <https://orcid.org/0000-0001-7216-1784>  
 N. Kanda <https://orcid.org/0000-0001-6291-0227>  
 S. Kandhasamy <https://orcid.org/0000-0002-4825-6764>  
 G. Kang <https://orcid.org/0000-0002-6072-8189>  
 D. P. Kapasi <https://orcid.org/0000-0001-8189-4920>  
 C. Karathanasis <https://orcid.org/0000-0002-0642-5507>  
 M. Kasprzak <https://orcid.org/0000-0003-4618-5939>  
 S. Katsanevas <https://orcid.org/0000-0003-0324-0758>  
 K. Kawaguchi <https://orcid.org/0000-0003-4443-6984>  
 D. Keitel <https://orcid.org/0000-0002-2824-626X>  
 J. S. Key <https://orcid.org/0000-0003-0123-7600>  
 F. Y. Khalili <https://orcid.org/0000-0001-7068-2332>  
 S. Khan <https://orcid.org/0000-0003-4953-5754>  
 N. Kijbunchoo <https://orcid.org/0000-0002-2874-1228>  
 C. Kim <https://orcid.org/0000-0003-3040-8456>  
 J. Kim <https://orcid.org/0000-0001-9145-0530>  
 K. Kim <https://orcid.org/0000-0003-1653-3795>  
 Y.-M. Kim <https://orcid.org/0000-0001-8720-6113>  
 M. Kinley-Hanlon <https://orcid.org/0000-0002-7367-8002>  
 R. Kirchhoff <https://orcid.org/0000-0003-0224-8600>  
 J. S. Kissel <https://orcid.org/0000-0002-1702-9577>  
 A. M. Knee <https://orcid.org/0000-0003-0703-947X>  
 K. Kokeyama <https://orcid.org/0000-0002-2896-1992>  
 S. Koley <https://orcid.org/0000-0002-5793-6665>



- P. Kolitsidou <https://orcid.org/0000-0002-6719-8686>  
M. Kolstein <https://orcid.org/0000-0002-5482-6743>  
A. K. H. Kong <https://orcid.org/0000-0002-5105-344X>  
A. Kontos <https://orcid.org/0000-0002-1347-0680>  
M. Korobko <https://orcid.org/0000-0002-3839-3909>  
C. Kozakai <https://orcid.org/0000-0003-2853-869X>  
N. V. Krishnendu <https://orcid.org/0000-0002-3483-7517>  
A. Królak <https://orcid.org/0000-0003-4514-7690>  
P. Kuijer <https://orcid.org/0000-0002-6987-2048>  
Prayush Kumar <https://orcid.org/0000-0001-5523-4603>  
K. Kuns <https://orcid.org/0000-0003-0630-3902>  
S. Kuroyanagi <https://orcid.org/0000-0001-6538-1447>  
K. Kwak <https://orcid.org/0000-0002-2304-7798>  
D. Laghi <https://orcid.org/0000-0001-7462-3794>  
R. N. Lang <https://orcid.org/0000-0002-4804-5537>  
B. Lantz <https://orcid.org/0000-0002-7404-4845>  
P. D. Lasky <https://orcid.org/0000-0003-3763-1386>  
M. Laxen <https://orcid.org/0000-0001-7515-9639>  
A. Lazzarini <https://orcid.org/0000-0002-5993-8808>  
P. Leaci <https://orcid.org/0000-0002-3997-5046>  
S. Leavey <https://orcid.org/0000-0001-8253-0272>  
Y. K. Lecoecue <https://orcid.org/0000-0002-9186-7034>  
H. M. Lee <https://orcid.org/0000-0003-4412-7161>  
H. W. Lee <https://orcid.org/0000-0002-1998-3209>  
K. Lee <https://orcid.org/0000-0003-0470-3718>  
R. Lee <https://orcid.org/0000-0002-7171-7274>  
M. Lenti <https://orcid.org/0000-0002-2765-3955>  
M. Leonardi <https://orcid.org/0000-0002-7641-0060>  
N. Leroy <https://orcid.org/0000-0002-2321-1017>  
K. L. Li <https://orcid.org/0000-0001-8229-2024>  
X. Li <https://orcid.org/0000-0002-3780-7735>  
C.-Y. Lin <https://orcid.org/0000-0002-7489-7418>  
E. T. Lin <https://orcid.org/0000-0002-0030-8051>  
F.-L. Lin <https://orcid.org/0000-0002-4277-7219>  
H. L. Lin <https://orcid.org/0000-0002-3528-5726>  
L. C.-C. Lin <https://orcid.org/0000-0003-4083-9567>  
G. C. Liu <https://orcid.org/0000-0001-5663-3016>  
J. Liu <https://orcid.org/0000-0001-6726-3268>  
R. K. L. Lo <https://orcid.org/0000-0003-1561-6716>  
A. Longo <https://orcid.org/0000-0003-4254-8579>  
M. Lorenzini <https://orcid.org/0000-0002-2765-7905>  
G. Losurdo <https://orcid.org/0000-0003-0452-746X>  
J. D. Lough <https://orcid.org/0000-0002-5160-0239>  
C. O. Lousto <https://orcid.org/0000-0002-6400-9640>  
D. Lumaca <https://orcid.org/0000-0002-3628-1591>  
L.-W. Luo <https://orcid.org/0000-0002-2761-8877>  
R. Macas <https://orcid.org/0000-0002-6096-8297>  
D. M. Macleod <https://orcid.org/0000-0002-1395-8694>  
I. A. O. MacMillan <https://orcid.org/0000-0002-6927-1031>  
C. Magazzù <https://orcid.org/0000-0002-9913-381X>  
R. M. Magee <https://orcid.org/0000-0001-9769-531X>  
R. Maggiore <https://orcid.org/0000-0001-5140-779X>  
M. Magnozzi <https://orcid.org/0000-0003-4512-8430>  
E. Majorana <https://orcid.org/0000-0002-2383-3692>  
V. Mandic <https://orcid.org/0000-0001-6333-8621>  
V. Mangano <https://orcid.org/0000-0001-7902-8505>  
M. Manske <https://orcid.org/0000-0002-7778-1189>  
M. Mantovani <https://orcid.org/0000-0002-4424-5726>  
M. Mapelli <https://orcid.org/0000-0001-8799-2548>  
D. Marín Pina <https://orcid.org/0000-0001-6482-1842>  
S. Márka <https://orcid.org/0000-0002-3957-1324>  
Z. Márka <https://orcid.org/0000-0003-1306-5260>  
S. Marsat <https://orcid.org/0000-0001-9449-1071>  
I. W. Martin <https://orcid.org/0000-0001-7300-9151>  
H. Masalehdan <https://orcid.org/0000-0002-4589-0815>  
M. Masso-Reid <https://orcid.org/0000-0001-6177-8105>  
S. Mastrogianni <https://orcid.org/0000-0003-1606-4183>  
M. Mateu-Lucena <https://orcid.org/0000-0003-4817-6913>  
M. Matushechikina <https://orcid.org/0000-0002-9957-8720>  
N. Mavalvala <https://orcid.org/0000-0003-0219-9706>  
D. E. McClelland <https://orcid.org/0000-0001-6210-5842>  
J. McIver <https://orcid.org/0000-0003-0316-1355>  
D. Meacher <https://orcid.org/0000-0001-5882-0368>  
M. Mehmet <https://orcid.org/0000-0001-9432-7108>  
C. S. Menoni <https://orcid.org/0000-0001-9185-2572>  
C. Messenger <https://orcid.org/0000-0001-7488-5022>  
P. M. Meyers <https://orcid.org/0000-0002-2689-0190>  
F. Meylahn <https://orcid.org/0000-0002-9556-142X>  
A. Miani <https://orcid.org/0000-0001-7737-3129>  
I. Michaloliakos <https://orcid.org/0000-0003-2980-358X>  
C. Michel <https://orcid.org/0000-0003-0606-725X>  
Y. Michimura <https://orcid.org/0000-0002-2218-4002>  
H. Middleton <https://orcid.org/0000-0001-5532-3622>  
D. P. Mihaylov <https://orcid.org/0000-0002-8820-407X>  
M. Miravet-Tenés <https://orcid.org/0000-0002-8766-1156>  
T. Mishra <https://orcid.org/0000-0002-7881-1677>  
S. Mitra <https://orcid.org/0000-0002-0800-4626>  
V. P. Mitrofanov <https://orcid.org/0000-0002-6983-4981>  
G. Mitselmakher <https://orcid.org/0000-0001-5745-3658>  
O. Miyakawa <https://orcid.org/0000-0002-9085-7600>  
K. Miyo <https://orcid.org/0000-0001-6976-1252>  
S. Miyoki <https://orcid.org/0000-0002-1213-8416>  
Geoffrey Mo <https://orcid.org/0000-0001-6331-112X>  
L. M. Modafferi <https://orcid.org/0000-0002-3422-6986>  
S. R. Mohite <https://orcid.org/0000-0003-1356-7156>  
M. Molina-Ruiz <https://orcid.org/0000-0003-4892-3042>  
A. More <https://orcid.org/0000-0001-7714-7076>  
C. Moreno <https://orcid.org/0000-0002-0496-032X>  
S. Morisaki <https://orcid.org/0000-0002-8445-6747>  
B. Mours <https://orcid.org/0000-0002-6444-6402>  
C. M. Mow-Lowry <https://orcid.org/0000-0002-0351-4555>  
S. Mozzon <https://orcid.org/0000-0002-8855-2509>  
D. Mukherjee <https://orcid.org/0000-0001-7335-9418>  
Suvodip Mukherjee <https://orcid.org/0000-0002-3373-5236>  
N. Mukund <https://orcid.org/0000-0002-8666-9156>  
E. A. Muñiz <https://orcid.org/0000-0001-8844-421X>  
P. G. Murray <https://orcid.org/0000-0002-8218-2404>  
R. Musenich <https://orcid.org/0000-0002-2168-5462>  
K. Nagano <https://orcid.org/0000-0001-6686-1637>  
K. Nakamura <https://orcid.org/0000-0001-6148-4289>  
H. Nakano <https://orcid.org/0000-0001-7665-0796>  
I. Nardecchia <https://orcid.org/0000-0001-5558-2595>  
L. Naticchioni <https://orcid.org/0000-0003-2918-0730>  
R. K. Nayak <https://orcid.org/0000-0002-6814-7792>  
S. W. S. Ng <https://orcid.org/0000-0001-5843-1434>  
C. Nguyen <https://orcid.org/0000-0001-8623-0306>  
L. Nguyen Quynh <https://orcid.org/0000-0002-1828-3702>  
W.-T. Ni <https://orcid.org/0000-0001-6792-4708>  
A. Nishizawa <https://orcid.org/0000-0003-3562-0990>  
E. Nitoglia <https://orcid.org/0000-0001-8906-9159>  
L. K. Nuttall <https://orcid.org/0000-0002-8599-8791>  
Y. Obayashi <https://orcid.org/0000-0001-8791-2608>  
E. Oelker <https://orcid.org/0000-0002-3916-1595>  
J. J. Oh <https://orcid.org/0000-0001-5417-862X>



- K. Oh <https://orcid.org/0000-0002-9672-3742>  
 S. H. Oh <https://orcid.org/0000-0003-1184-7453>  
 M. Ohashi <https://orcid.org/0000-0001-8072-0304>  
 M. Ohkawa <https://orcid.org/0000-0002-1380-1419>  
 F. Ohme <https://orcid.org/0000-0003-0493-5607>  
 K. Oohara <https://orcid.org/0000-0002-7518-6677>  
 B. O'Reilly <https://orcid.org/0000-0002-3874-8335>  
 R. O'Shaughnessy <https://orcid.org/0000-0001-5832-8517>  
 E. O'Shea <https://orcid.org/0000-0002-0230-9533>  
 S. Oshino <https://orcid.org/0000-0002-2794-6029>  
 S. Ossokine <https://orcid.org/0000-0002-2579-1246>  
 D. J. Ottaway <https://orcid.org/0000-0001-6794-1591>  
 C. Palomba <https://orcid.org/0000-0002-4450-9883>  
 K.-C. Pan <https://orcid.org/0000-0002-1473-9880>  
 F. Panarale <https://orcid.org/0000-0002-7537-3210>  
 F. Paoletti <https://orcid.org/0000-0001-8898-1963>  
 A. Parisi <https://orcid.org/0000-0003-0251-8914>  
 J. Park <https://orcid.org/0000-0002-7510-0079>  
 W. Parker <https://orcid.org/0000-0002-7711-4423>  
 D. Pascucci <https://orcid.org/0000-0003-1907-0175>  
 R. Passaquieti <https://orcid.org/0000-0003-4753-9428>  
 B. Patricelli <https://orcid.org/0000-0001-6709-0969>  
 S. Paul <https://orcid.org/0000-0002-4449-1732>  
 F. E. Peña Arellano <https://orcid.org/0000-0002-8516-5159>  
 S. Penn <https://orcid.org/0000-0003-4956-0853>  
 T. Pereira <https://orcid.org/0000-0003-1856-6881>  
 A. Perreca <https://orcid.org/0000-0002-6269-2490>  
 J. Petermann <https://orcid.org/0000-0002-8949-3803>  
 H. P. Pfeiffer <https://orcid.org/0000-0001-9288-519X>  
 K. A. Pham <https://orcid.org/0000-0002-7650-1034>  
 K. S. Phukon <https://orcid.org/0000-0003-1561-0760>  
 O. J. Piccinni <https://orcid.org/0000-0001-5478-3950>  
 M. Pichot <https://orcid.org/0000-0002-4439-8968>  
 L. Pierini <https://orcid.org/0000-0003-0945-2196>  
 V. Piero <https://orcid.org/0000-0002-6020-5521>  
 M. D. Pitkin <https://orcid.org/0000-0003-4548-526X>  
 A. Placidi <https://orcid.org/0000-0001-8032-4416>  
 M. L. Planas <https://orcid.org/0000-0001-8278-7406>  
 W. Plastino <https://orcid.org/0000-0002-5737-6346>  
 R. Poggiani <https://orcid.org/0000-0002-9968-2464>  
 E. Polini <https://orcid.org/0000-0003-4059-0765>  
 R. Poulton <https://orcid.org/0000-0003-2049-520X>  
 G. Pratten <https://orcid.org/0000-0003-4984-0775>  
 G. A. Prodi <https://orcid.org/0000-0001-5256-915X>  
 M. Punturo <https://orcid.org/0000-0001-8722-4485>  
 M. Pürer <https://orcid.org/0000-0002-3329-9788>  
 H. Qi <https://orcid.org/0000-0001-6339-1537>  
 P. Raffai <https://orcid.org/0000-0001-7576-0141>  
 K. E. Ramirez <https://orcid.org/0000-0003-2194-7669>  
 A. Ramos-Buades <https://orcid.org/0000-0002-6874-7421>  
 V. Raymond <https://orcid.org/0000-0003-0066-0095>  
 N. Raza <https://orcid.org/0000-0002-8549-9124>  
 M. Razzano <https://orcid.org/0000-0003-4825-1629>  
 L. Rei <https://orcid.org/0000-0002-8690-9180>  
 P. Relton <https://orcid.org/0000-0003-2756-3391>  
 P. Rettegno <https://orcid.org/0000-0001-8088-3517>  
 B. Revenu <https://orcid.org/0000-0002-7629-4805>  
 J. W. Richardson <https://orcid.org/0000-0002-1472-4806>  
 K. Riles <https://orcid.org/0000-0002-6418-5812>  
 S. Rinaldi <https://orcid.org/0000-0001-5799-4155>  
 K. Rink <https://orcid.org/0000-0002-1494-3494>  
 A. Rocchi <https://orcid.org/0000-0002-1382-9016>  
 L. Rolland <https://orcid.org/0000-0003-0589-9687>  
 J. G. Rollins <https://orcid.org/0000-0002-9388-2799>  
 A. Romero <https://orcid.org/0000-0003-2275-4164>  
 S. Ronchini <https://orcid.org/0000-0003-0020-687X>  
 M. P. Ross <https://orcid.org/0000-0002-8955-5269>  
 D. Rozza <https://orcid.org/0000-0002-7378-6353>  
 J. Sadiq <https://orcid.org/0000-0001-5931-3624>  
 S. Saha <https://orcid.org/0000-0002-3333-8070>  
 M. Sakellariadou <https://orcid.org/0000-0002-2715-1517>  
 O. S. Salafia <https://orcid.org/0000-0003-4924-7322>  
 F. Salces-Carcoba <https://orcid.org/0000-0001-7049-4438>  
 M. Saleem <https://orcid.org/0000-0002-3836-7751>  
 F. Salemi <https://orcid.org/0000-0002-9511-3846>  
 A. Samajdar <https://orcid.org/0000-0002-0857-6018>  
 N. Sanchis-Gual <https://orcid.org/0000-0001-5375-7494>  
 A. Sanuy <https://orcid.org/0000-0002-5767-3623>  
 O. Sauter <https://orcid.org/0000-0003-2293-1554>  
 R. L. Savage <https://orcid.org/0000-0003-3317-1036>  
 T. Sawada <https://orcid.org/0000-0001-5726-7150>  
 M. G. Schiworski <https://orcid.org/0000-0001-9298-004X>  
 P. Schmidt <https://orcid.org/0000-0003-1542-1791>  
 R. Schnabel <https://orcid.org/0000-0003-2896-4218>  
 E. Schwartz <https://orcid.org/0000-0001-8922-7794>  
 J. Scott <https://orcid.org/0000-0001-6701-6515>  
 S. M. Scott <https://orcid.org/0000-0002-9875-7700>  
 M. Seglar-Arroyo <https://orcid.org/0000-0001-8654-409X>  
 Y. Sekiguchi <https://orcid.org/0000-0002-2648-3835>  
 Y. Setyawati <https://orcid.org/0000-0003-3718-4491>  
 M. S. Shahriar <https://orcid.org/0000-0002-7981-954X>  
 M. A. Shaikh <https://orcid.org/0000-0003-0826-6164>  
 L. Shao <https://orcid.org/0000-0002-1334-8853>  
 P. Shawhan <https://orcid.org/0000-0002-8249-8070>  
 N. S. Shcheblanov <https://orcid.org/0000-0001-8696-2435>  
 Y. Shikano <https://orcid.org/0000-0003-2107-7536>  
 H. Shimizu <https://orcid.org/0000-0002-4221-0300>  
 K. Shimode <https://orcid.org/0000-0002-5682-8750>  
 H. Shinkai <https://orcid.org/0000-0003-1082-2844>  
 A. Shoda <https://orcid.org/0000-0002-0236-4735>  
 D. H. Shoemaker <https://orcid.org/0000-0002-4147-2560>  
 D. M. Shoemaker <https://orcid.org/0000-0002-9899-6357>  
 D. Sigg <https://orcid.org/0000-0003-4606-6526>  
 L. Silenzi <https://orcid.org/0000-0001-7316-3239>  
 L. P. Singer <https://orcid.org/0000-0001-9898-5597>  
 D. Singh <https://orcid.org/0000-0001-9675-4584>  
 M. K. Singh <https://orcid.org/0000-0001-8081-4888>  
 N. Singh <https://orcid.org/0000-0002-1135-3456>  
 A. Singha <https://orcid.org/0000-0002-9944-5573>  
 A. M. Sintes <https://orcid.org/0000-0001-9050-7515>  
 B. J. J. Slagmolen <https://orcid.org/0000-0002-2471-3828>  
 J. R. Smith <https://orcid.org/0000-0003-0638-9670>  
 R. J. E. Smith <https://orcid.org/0000-0001-8516-3324>  
 J. Soldateschi <https://orcid.org/0000-0002-5458-5206>  
 S. N. Somala <https://orcid.org/0000-0003-2663-3351>  
 K. Somiya <https://orcid.org/0000-0003-2601-2264>  
 I. Song <https://orcid.org/0000-0002-4301-8281>  
 K. Soni <https://orcid.org/0000-0001-8051-7883>  
 S. Soni <https://orcid.org/0000-0003-3856-8534>  
 N. Sorrentino <https://orcid.org/0000-0002-1855-5966>  
 A. P. Spencer <https://orcid.org/0000-0003-4418-3366>  
 M. Spera <https://orcid.org/0000-0003-0930-6930>  
 D. A. Steer <https://orcid.org/0000-0002-8781-1273>  
 S. Steinlechner <https://orcid.org/0000-0003-4710-8548>

- K. A. Strain <https://orcid.org/0000-0002-2066-5355>  
 G. Stratta <https://orcid.org/0000-0003-1055-7980>  
 A. L. Stuver <https://orcid.org/0000-0003-0324-5735>  
 S. Sudhagar <https://orcid.org/0000-0001-8578-4665>  
 V. Sudhir <https://orcid.org/0000-0002-5397-6950>  
 R. Sugimoto <https://orcid.org/0000-0001-6705-3658>  
 H. G. Suh <https://orcid.org/0000-0003-2662-3903>  
 A. G. Sullivan <https://orcid.org/0000-0002-9545-7286>  
 T. Z. Summerscales <https://orcid.org/0000-0002-4522-5591>  
 L. Sun <https://orcid.org/0000-0001-7959-892X>  
 A. Sur <https://orcid.org/0000-0001-6635-5080>  
 J. Suresh <https://orcid.org/0000-0003-2389-6666>  
 P. J. Sutton <https://orcid.org/0000-0003-1614-3922>  
 Takamasa Suzuki <https://orcid.org/0000-0003-3030-6599>  
 B. L. Swinkels <https://orcid.org/0000-0002-3066-3601>  
 M. J. Szczepańczyk <https://orcid.org/0000-0002-6167-6149>  
 S. C. Tait <https://orcid.org/0000-0003-0327-953X>  
 H. Takahashi <https://orcid.org/0000-0003-0596-4397>  
 R. Takahashi <https://orcid.org/0000-0003-1367-5149>  
 H. Takeda <https://orcid.org/0000-0001-9937-2557>  
 Takahiro Tanaka <https://orcid.org/0000-0001-8406-5183>  
 S. Tanioka <https://orcid.org/0000-0003-3321-1018>  
 L. Tao <https://orcid.org/0000-0003-4382-5507>  
 E. N. Tapia San Martín <https://orcid.org/0000-0002-4817-5606>  
 A. Taruya <https://orcid.org/0000-0002-4016-1955>  
 J. D. Tasson <https://orcid.org/0000-0002-4777-5087>  
 R. Tenorio <https://orcid.org/0000-0002-3582-2587>  
 J. E. S. Terhune <https://orcid.org/0000-0001-9078-4993>  
 L. Terkowski <https://orcid.org/0000-0003-4622-1215>  
 J. E. Thompson <https://orcid.org/0000-0002-0419-5517>  
 Shubhanshu Tiwari <https://orcid.org/0000-0003-1611-6625>  
 V. Tiwari <https://orcid.org/0000-0002-1602-4176>  
 A. E. Tolley <https://orcid.org/0000-0001-9841-943X>  
 T. Tomaru <https://orcid.org/0000-0002-8927-9014>  
 T. Tomura <https://orcid.org/0000-0002-7504-8258>  
 A. Torres-Forné <https://orcid.org/0000-0001-8709-5118>  
 I. Tosta e Melo <https://orcid.org/0000-0001-5833-4052>  
 A. Trapananti <https://orcid.org/0000-0001-7763-5758>  
 F. Travasso <https://orcid.org/0000-0002-4653-6156>  
 M. C. Tringali <https://orcid.org/0000-0001-5087-189X>  
 A. Tripathee <https://orcid.org/0000-0002-6976-5576>  
 A. Trovato <https://orcid.org/0000-0002-9714-1904>  
 L. Trozzo <https://orcid.org/0000-0002-8803-6715>  
 T. Tsang <https://orcid.org/0000-0003-3666-686X>  
 T. Tsutsui <https://orcid.org/0000-0002-2909-0471>  
 K. Turbang <https://orcid.org/0000-0002-9296-8603>  
 D. Tuyenbayev <https://orcid.org/0000-0002-4378-5835>  
 A. S. Ubhi <https://orcid.org/0000-0002-3240-6000>  
 T. Uchiyama <https://orcid.org/0000-0003-2148-1694>  
 T. Uehara <https://orcid.org/0000-0003-4375-098X>  
 K. Ueno <https://orcid.org/0000-0003-3227-6055>  
 T. Ushiba <https://orcid.org/0000-0002-5059-4033>  
 A. Utina <https://orcid.org/0000-0003-2975-9208>  
 G. Vajente <https://orcid.org/0000-0002-7656-6882>  
 G. Valdes <https://orcid.org/0000-0001-5411-380X>  
 M. Valentini <https://orcid.org/0000-0003-1215-4552>  
 M. van Beuzekom <https://orcid.org/0000-0002-0500-1286>  
 J. F. J. van den Brand <https://orcid.org/0000-0003-4434-5353>  
 H. van Haevermaet <https://orcid.org/0000-0003-2386-957X>  
 J. V. van Heijningen <https://orcid.org/0000-0002-8391-7513>  
 N. van Remortel <https://orcid.org/0000-0003-4180-8199>  
 V. Varma <https://orcid.org/0000-0002-9994-1761>  
 M. Vasúth <https://orcid.org/0000-0003-4573-8781>  
 A. Vecchio <https://orcid.org/0000-0002-6254-1617>  
 J. Veitch <https://orcid.org/0000-0002-6508-0713>  
 P. J. Veitch <https://orcid.org/0000-0002-2597-435X>  
 J. Venneberg <https://orcid.org/0000-0002-2508-2044>  
 G. Venugopalan <https://orcid.org/0000-0003-4414-9918>  
 D. Verkindt <https://orcid.org/0000-0003-4344-7227>  
 Y. Verma <https://orcid.org/0000-0003-4147-3173>  
 S. M. Vermeulen <https://orcid.org/0000-0003-4227-8214>  
 D. Veske <https://orcid.org/0000-0003-4225-0895>  
 A. Viceré <https://orcid.org/0000-0003-0624-6231>  
 A. D. Viets <https://orcid.org/0000-0002-4241-1428>  
 A. Vijaykumar <https://orcid.org/0000-0002-4103-0666>  
 V. Villa-Ortega <https://orcid.org/0000-0001-7983-1963>  
 S. Vitale <https://orcid.org/0000-0003-2700-0767>  
 C. Vorvick <https://orcid.org/0000-0003-1591-3358>  
 S. P. Vyatchanin <https://orcid.org/0000-0002-6823-911X>  
 M. Wade <https://orcid.org/0000-0002-5703-4469>  
 K. J. Wagner <https://orcid.org/0000-0002-7255-4251>  
 J. Wang <https://orcid.org/0000-0002-1830-8527>  
 M. Was <https://orcid.org/0000-0002-1890-1128>  
 T. Washimi <https://orcid.org/0000-0001-5792-4907>  
 J. Watchi <https://orcid.org/0000-0002-9154-6433>  
 A. J. Weinstein <https://orcid.org/0000-0002-0928-6784>  
 R. A. Weller <https://orcid.org/0000-0002-2280-219X>  
 K. Wette <https://orcid.org/0000-0002-4394-7179>  
 J. T. Whelan <https://orcid.org/0000-0001-5710-6576>  
 B. F. Whiting <https://orcid.org/0000-0002-8501-8669>  
 C. Whittle <https://orcid.org/0000-0002-8833-7438>  
 D. Williams <https://orcid.org/0000-0003-3772-198X>  
 M. J. Williams <https://orcid.org/0000-0003-2198-2974>  
 A. R. Williamson <https://orcid.org/0000-0002-7627-8688>  
 J. L. Willis <https://orcid.org/0000-0002-9929-0225>  
 B. Willke <https://orcid.org/0000-0003-0524-2925>  
 G. Woan <https://orcid.org/0000-0003-0381-0394>  
 J. K. Wofford <https://orcid.org/0000-0002-4301-2859>  
 I. C. F. Wong <https://orcid.org/0000-0003-2166-0027>  
 C. Wu <https://orcid.org/0000-0003-3191-8845>  
 D. S. Wu <https://orcid.org/0000-0003-2849-3751>  
 L. Xiao <https://orcid.org/0000-0003-2703-449X>  
 H. Yamamoto <https://orcid.org/0000-0001-6919-9570>  
 K. Yamamoto <https://orcid.org/0000-0002-3033-2845>  
 T. Yamamoto <https://orcid.org/0000-0002-0808-4822>  
 F. W. Yang <https://orcid.org/0000-0001-9873-6259>  
 K. Z. Yang <https://orcid.org/0000-0001-8083-4037>  
 L. Yang <https://orcid.org/0000-0002-8868-5977>  
 Y. Yang <https://orcid.org/0000-0002-3780-1413>  
 A. B. Yelikar <https://orcid.org/0000-0002-8065-1174>  
 J. Yokoyama <https://orcid.org/0000-0001-7127-4808>  
 Hang Yu <https://orcid.org/0000-0002-6011-6190>  
 Haocun Yu <https://orcid.org/0000-0002-7597-098X>  
 S. Zeidler <https://orcid.org/0000-0001-7949-1292>  
 M. Zevin <https://orcid.org/0000-0002-0147-0835>  
 J. Zhang <https://orcid.org/0000-0002-3931-3851>  
 R. Zhang <https://orcid.org/0000-0001-8095-483X>  
 C. Zhao <https://orcid.org/0000-0001-5825-2401>  
 Y. Zhao <https://orcid.org/0000-0003-2542-4734>  
 X. J. Zhu <https://orcid.org/0000-0001-7049-6468>

Z.-H. Zhu  <https://orcid.org/0000-0002-3567-6743>  
 A. B. Zimmerman  <https://orcid.org/0000-0002-7453-6372>  
 J. Zweizig  <https://orcid.org/0000-0002-1521-3397>

## References

- Aasi, J., Abbott, B. P., Abbott, R., et al. 2015, *CQGra*, **32**, 074001  
 Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016, *PhRvL*, **116**, 061102  
 Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017a, *ApJL*, **848**, L13  
 Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017b, *PhRvL*, **119**, 161101  
 Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2018, *LRR*, **21**, 3  
 Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2019, *PhRvX*, **9**, 031040  
 Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2020a, *LRR*, **23**, 3  
 Abbott, R., Abbott, T. D., Abraham, S., et al. 2020b, *ApJL*, **896**, L44  
 Abbott, R., Abbott, T. D., Abraham, S., et al. 2020c, *ApJL*, **892**, L3  
 Abbott, R., Abbott, T. D., Abraham, S., et al. 2021a, *PhRvX*, **11**, 021053  
 Abbott, R., Abbott, T. D., Abraham, S., et al. 2021b, *ApJL*, **915**, L5  
 Abbott, R., Abbott, T. D., Acernese, F., et al. 2023, *PhRvX*, **13**, 041039  
 Abbott, R., Abbott, T. D., Acernese, F., et al. 2021c, arXiv:2108.01045  
 Acernese, F., Agathos, M., Agatsuma, K., et al. 2014, *CQGra*, **32**, 024001  
 Acernese, F., Agathos, M., Aiello, L., et al. 2019, *PhRvL*, **123**, 231108  
 Allison, J., Amako, K., Apostolakis, J., et al. 2016, *NIMPA*, **835**, 186  
 Ashton, G., Ackley, K., Hernandez, I. M., & Piotrzkowski, B. 2021, *CQGra*, **38**, 235004  
 Astropy Collaboration, Price-Whelan, A. M., Lim, P. L., et al. 2022, *ApJ*, **935**, 167  
 Astropy Collaboration, Price-Whelan, A. M., Sipőcz, B. M., et al. 2018, *AJ*, **156**, 123  
 Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, *A&A*, **558**, A33  
 Band, D., Matteson, J., Ford, L., et al. 1993, *ApJ*, **413**, 281  
 Barthelmy, S. D., Barbier, L. M., Cummings, J. R., et al. 2005, *SSRv*, **120**, 143  
 Blackburn, L., Briggs, M. S., Camp, J., et al. 2015, *ApJS*, **217**, 8  
 Blandford, R. D., & Znajek, R. L. 1977, *MNRAS*, **179**, 433  
 Bombaci, I. 1996, *A&A*, **305**, 871  
 Briggs, M. S., Xiong, S., Connaughton, V., et al. 2013, *JGRA*, **118**, 3805  
 Buikema, A., Cahillane, C., Mansell, G. L., et al. 2020, *PhRvD*, **102**, 062003  
 Burns, E. 2020, *LRR*, **23**, 4  
 Burns, E., Goldstein, A., Hui, C. M., et al. 2019, *ApJ*, **871**, 90  
 Burrows, D. N., Hill, J. E., Nousek, J. A., et al. 2005, *SSRv*, **120**, 165  
 Bustillo, J. C., Leong, S. H. W., Chandra, K., McKernan, B., & Ford, K. E. S. 2021, arXiv:2112.12481  
 Chornock, R., Berger, E., Kasen, D., et al. 2017, *ApJL*, **848**, L19  
 Connaughton, V., Burns, E., Goldstein, A., et al. 2016, *ApJL*, **826**, L6  
 Connaughton, V., Burns, E., Goldstein, A., et al. 2018, *ApJL*, **853**, L9  
 Cowperthwaite, P. S., Berger, E., Villar, V. A., et al. 2017, *ApJL*, **848**, L17  
 Dai, L., McKinney, J. C., & Miller, M. C. 2017, *MNRAS Lett.*, **470**, L92  
 De Paolis, F., Nucita, A. A., Strafella, F., Licchelli, D., & Ingrassio, G. 2020, *MNRAS Lett.*, **499**, L87  
 DeLaunay, J., & Tohuvavohu, A. 2022, *ApJ*, **941**, 33  
 Fenimore, E. E., McLean, K., Palmer, D., et al. 2004, *BaltA*, **13**, 301  
 Fletcher, C. & Fermi-GBM Team 2019, GCN, **24185**, 1  
 Gehrels, N., Chincarini, G., Giommi, P., et al. 2004, *ApJ*, **611**, 1005  
 Gehrels, N., Ramirez-Ruiz, E., & Fox, D. 2009, *ARA&A*, **47**, 567  
 Goldstein, A., Burns, E., Hamburg, R., et al. 2016, arXiv:1612.02395  
 Goldstein, A., Hamburg, R., Wood, J., et al. 2019, arXiv:1903.12597  
 Goldstein, A., Veres, P., Burns, E., et al. 2017, *ApJL*, **848**, L14  
 Graham, M. J., Ford, K. E. S., McKernan, B., et al. 2020, *PhRvL*, **124**, 251102  
 Greiner, J., Burgess, J. M., Savchenko, V., & Yu, H.-F. 2016, *ApJL*, **827**, L38  
 Hamburg, R., Fletcher, C., Burns, E., et al. 2020, *ApJ*, **893**, 100  
 Harris, C. R., Millman, K. J., van der Walt, S. J., et al. 2020, *Natur*, **585**, 357  
 Hosseinzadeh, G., Cowperthwaite, P. S., Gomez, S., et al. 2019, *ApJL*, **880**, L4  
 Hunter, J. D. 2007, *CSE*, **9**, 90  
 Kalogera, V., & Baym, G. 1996, *ApJL*, **470**, L61  
 Kocevski, D., Burns, E., Goldstein, A., et al. 2018, *ApJ*, **862**, 152  
 Lien, A., Sakamoto, T., Gehrels, N., et al. 2014, *ApJ*, **783**, 24  
 Lin, D.-B., Liu, T., Lin, J., et al. 2018, *ApJ*, **856**, 90  
 Loeb, A. 2016, *ApJL*, **819**, L21  
 LSC and Virgo and Fermi-GBM Team 2019a, GCN, **25406**, 1  
 LSC and Virgo and Fermi-GBM Team 2019b, GCN, **25465**, 1  
 Margalit, B., & Metzger, B. D. 2017, *ApJL*, **850**, L19  
 Margutti, R., & Chornock, R. 2021, *ARA&A*, **59**, 155  
 Meegan, C., Lichti, G., Bhat, P. N., et al. 2009, *ApJ*, **702**, 791  
 Nicholl, M., Berger, E., Kasen, D., et al. 2017, *ApJL*, **848**, L18  
 Paciasas, W. S., Meegan, C. A., von Kienlin, A., et al. 2012, *ApJS*, **199**, 18  
 Palmese, A., Fishbach, M., Burke, C. J., Annis, J., & Liu, X. 2021, *ApJL*, **914**, L34  
 Perna, R., Chruslinska, M., Corsi, A., & Belczynski, K. 2018, *MNRAS*, **477**, 4228  
 Perna, R., Lazzati, D., & Giacomazzo, B. 2016, *ApJL*, **821**, L18  
 Petrov, P., Singer, L. P., Coughlin, M. W., et al. 2022, *ApJ*, **924**, 54  
 Poolakkil, S., Preece, R., Fletcher, C., et al. 2021, *ApJ*, **913**, 60  
 Rezzolla, L., Most, E. R., & Weih, L. R. 2018, *ApJL*, **852**, L25  
 Roming, P. W. A., Kennedy, T. E., Mason, K. O., et al. 2005, *SSRv*, **120**, 95  
 Ruffert, M., & Janka, H. T. 1998, *A&A*, **338**, 535  
 Salafia, O. S., Ghisellini, G., Ghirlanda, G., & Colpi, M. 2018, *A&A*, **619**, A18  
 Savchenko, V., Ferrigno, C., Kuulkers, E., et al. 2017, *ApJL*, **848**, L15  
 Soares-Santos, M., Holz, D. E., Annis, J., et al. 2017, *ApJL*, **848**, L16  
 Tanvir, N. R., Levan, A. J., González-Fernández, C., et al. 2017, *ApJL*, **848**, L27  
 Tohuvavohu, A., Kennea, J. A., DeLaunay, J., et al. 2020, *ApJ*, **900**, 35  
 Vedrenne, G., & Atteia, J.-L. 2009, *Gamma-Ray Bursts: The Brightest Explosions in the Universe* (Berlin: Springer), 385  
 Veres, P., Dal Canton, T., Burns, E., et al. 2019, *ApJ*, **882**, 53  
 Veres, P., Preece, R. D., Goldstein, A., et al. 2016, *ApJL*, **827**, L34  
 Virtanen, P., Gommers, R., Oliphant, T. E., et al. 2020, *NatMe*, **17**, 261  
 von Kienlin, A., Meegan, C. A., Paciasas, W. S., et al. 2020, *ApJ*, **893**, 46  
 Wilks, S. S. 1938, *Ann. Math. Stat.*, **9**, 60  
 Wood, J., Fletcher, C., Crnogorčević, M., Hamburg, R., & Veres, P. 2023, Fermi-GBM and Swift-BAT Data Release Related to Analysis of Gravitational-Wave Candidates from the Third Gravitational-wave Observing Run, v1, Zenodo, doi:10.5281/zenodo.8101645  
 Zhang, B. 2016, *ApJL*, **827**, L31  
 Zhang, B. 2019, *FrPhy*, **14**, 64402  
 Zhang, B., Zhang, B., Sun, H., et al. 2018, *NatCo*, **9**, 447