

**Search for Gravitational Waves from Low Mass Compact Binary Coalescence in 186 Days of  
LIGO's Fifth Science Run  
LIGO-P0900009-v8**

B. P. Abbott,<sup>17</sup> R. Abbott,<sup>17</sup> R. Adhikari,<sup>17</sup> P. Ajith,<sup>2</sup> B. Allen,<sup>2,60</sup> G. Allen,<sup>35</sup> R. S. Amin,<sup>21</sup> S. B. Anderson,<sup>17</sup> W. G. Anderson,<sup>60</sup> M. A. Arain,<sup>47</sup> M. Araya,<sup>17</sup> H. Armandula,<sup>17</sup> P. Armor,<sup>60</sup> Y. Aso,<sup>17</sup> S. Aston,<sup>46</sup> P. Aufmuth,<sup>16</sup> C. Aulbert,<sup>2</sup> S. Babak,<sup>1</sup> P. Baker,<sup>24</sup> S. Ballmer,<sup>17</sup> C. Barker,<sup>18</sup> D. Barker,<sup>18</sup> B. Barr,<sup>48</sup> P. Barriga,<sup>59</sup> L. Barsotti,<sup>20</sup> M. A. Barton,<sup>17</sup> I. Bartos,<sup>10</sup> R. Bassiri,<sup>48</sup> M. Bastarrika,<sup>48</sup> B. Behnke,<sup>1</sup> M. Benacquista,<sup>42</sup> J. Betzwieser,<sup>17</sup> P. T. Beyersdorf,<sup>31</sup> I. A. Bilenko,<sup>25</sup> G. Billingsley,<sup>17</sup> R. Biswas,<sup>60</sup> E. Black,<sup>17</sup> J. K. Blackburn,<sup>17</sup> L. Blackburn,<sup>20</sup> D. Blair,<sup>59</sup> B. Bland,<sup>18</sup> T. P. Bodiya,<sup>20</sup> L. Bogue,<sup>19</sup> R. Bork,<sup>17</sup> V. Boschi,<sup>17</sup> S. Bose,<sup>61</sup> P. R. Brady,<sup>60</sup> V. B. Braginsky,<sup>25</sup> J. E. Brau,<sup>53</sup> D. O. Bridges,<sup>19</sup> M. Brinkmann,<sup>2</sup> A. F. Brooks,<sup>17</sup> D. A. Brown,<sup>36</sup> A. Brummit,<sup>30</sup> G. Brunet,<sup>20</sup> A. Bullington,<sup>35</sup> A. Buonanno,<sup>49</sup> O. Burmeister,<sup>2</sup> R. L. Byer,<sup>35</sup> L. Cadonati,<sup>50</sup> J. B. Camp,<sup>26</sup> J. Cannizzo,<sup>26</sup> K. C. Cannon,<sup>17</sup> J. Cao,<sup>20</sup> C. D. Capano,<sup>36</sup> L. Cardenas,<sup>17</sup> S. Caride,<sup>51</sup> G. Castaldi,<sup>56</sup> S. Caudill,<sup>21</sup> M. Cavaglia,<sup>39</sup> C. Cepeda,<sup>17</sup> T. Chalmersongsak,<sup>17</sup> E. Chalkley,<sup>48</sup> P. Charlton,<sup>9</sup> S. Chatterji,<sup>17</sup> S. Chelkowski,<sup>46</sup> Y. Chen,<sup>1,6</sup> N. Christensen,<sup>8</sup> C. T. Y. Chung,<sup>38</sup> D. Clark,<sup>35</sup> J. Clark,<sup>7</sup> J. H. Clayton,<sup>60</sup> T. Cokelaer,<sup>7</sup> C. N. Colacino,<sup>12</sup> R. Conte,<sup>55</sup> D. Cook,<sup>18</sup> T. R. C. Corbitt,<sup>20</sup> N. Cornish,<sup>24</sup> D. Coward,<sup>59</sup> D. C. Coyne,<sup>17</sup> J. D. E. Creighton,<sup>60</sup> T. D. Creighton,<sup>42</sup> A. M. Cruise,<sup>46</sup> R. M. Culter,<sup>46</sup> A. Cumming,<sup>48</sup> L. Cunningham,<sup>48</sup> S. L. Danilishin,<sup>25</sup> K. Danzmann,<sup>2,16</sup> B. Daudert,<sup>17</sup> G. Davies,<sup>7</sup> E. J. Daw,<sup>40</sup> D. DeBra,<sup>35</sup> J. Degallaix,<sup>2</sup> V. Dergachev,<sup>51</sup> S. Desai,<sup>37</sup> R. DeSalvo,<sup>17</sup> S. Dhurandhar,<sup>15</sup> M. Díaz,<sup>42</sup> A. Dietz,<sup>7</sup> F. Donovan,<sup>20</sup> K. L. Dooley,<sup>47</sup> E. E. Doomes,<sup>34</sup> R. W. P. Drever,<sup>5</sup> J. Dueck,<sup>2</sup> I. Duke,<sup>20</sup> J. -C. Dumas,<sup>59</sup> J. G. Dwyer,<sup>10</sup> C. Echols,<sup>17</sup> M. Edgar,<sup>48</sup> A. Effler,<sup>18</sup> P. Ehrens,<sup>17</sup> G. Ely,<sup>8</sup> E. Espinoza,<sup>17</sup> T. Etzel,<sup>17</sup> M. Evans,<sup>20</sup> T. Evans,<sup>19</sup> S. Fairhurst,<sup>7</sup> Y. Faltas,<sup>47</sup> Y. Fan,<sup>59</sup> D. Fazi,<sup>17</sup> H. Fehrmann,<sup>2</sup> L. S. Finn,<sup>37</sup> K. Flasch,<sup>60</sup> S. Foley,<sup>20</sup> C. Forrest,<sup>54</sup> N. Fotopoulos,<sup>60</sup> A. Franzen,<sup>16</sup> M. Frede,<sup>2</sup> M. Frei,<sup>41</sup> Z. Frei,<sup>12</sup> A. Freise,<sup>46</sup> R. Frey,<sup>53</sup> T. Fricke,<sup>19</sup> P. Fritschel,<sup>20</sup> V. V. Frolov,<sup>19</sup> M. Fyffe,<sup>19</sup> V. Galdi,<sup>56</sup> J. A. Garofoli,<sup>36</sup> I. Gholami,<sup>1</sup> J. A. Giaime,<sup>21,19</sup> S. Giampanis,<sup>2</sup> K. D. Giardino,<sup>19</sup> K. Goda,<sup>20</sup> E. Goetz,<sup>51</sup> L. M. Goggin,<sup>60</sup> G. González,<sup>21</sup> M. L. Gorodetsky,<sup>25</sup> S. Goßler,<sup>2</sup> R. Gouaty,<sup>21</sup> A. Grant,<sup>48</sup> S. Gras,<sup>59</sup> C. Gray,<sup>18</sup> M. Gray,<sup>4</sup> R. J. S. Greenhalgh,<sup>30</sup> A. M. Gretarsson,<sup>11</sup> F. Grimaldi,<sup>20</sup> R. Grosso,<sup>42</sup> H. Grote,<sup>2</sup> S. Grunewald,<sup>1</sup> M. Guenther,<sup>18</sup> E. K. Gustafson,<sup>17</sup> R. Gustafson,<sup>51</sup> B. Hage,<sup>16</sup> J. M. Hallam,<sup>46</sup> D. Hammer,<sup>60</sup> G. D. Hammond,<sup>48</sup> C. Hanna,<sup>17</sup> J. Hanson,<sup>19</sup> J. Harms,<sup>52</sup> G. M. Harry,<sup>20</sup> I. W. Harry,<sup>7</sup> E. D. Harstad,<sup>53</sup> K. Haughian,<sup>48</sup> K. Hayama,<sup>42</sup> J. Heefner,<sup>17</sup> I. S. Heng,<sup>48</sup> A. Heptonstall,<sup>17</sup> M. Hewitson,<sup>2</sup> S. Hild,<sup>46</sup> E. Hirose,<sup>36</sup> D. Hoak,<sup>19</sup> K. A. Hodge,<sup>17</sup> K. Holt,<sup>19</sup> D. J. Hosken,<sup>45</sup> J. Hough,<sup>48</sup> D. Hoyland,<sup>59</sup> B. Hughey,<sup>20</sup> S. H. Huttner,<sup>48</sup> D. R. Ingram,<sup>18</sup> T. Isogai,<sup>8</sup> M. Ito,<sup>53</sup> A. Ivanov,<sup>17</sup> B. Johnson,<sup>18</sup> W. W. Johnson,<sup>21</sup> D. I. Jones,<sup>57</sup> G. Jones,<sup>7</sup> R. Jones,<sup>48</sup> L. Ju,<sup>59</sup> P. Kalmus,<sup>17</sup> V. Kalogera,<sup>28</sup> S. Kandhasamy,<sup>52</sup> J. Kanner,<sup>49</sup> D. Kasprzyk,<sup>46</sup> E. Katsavounidis,<sup>20</sup> K. Kawabe,<sup>18</sup> S. Kawamura,<sup>27</sup> F. Kawazoe,<sup>2</sup> W. Kells,<sup>17</sup> D. G. Keppel,<sup>17</sup> A. Khalaidovski,<sup>2</sup> F. Y. Khalili,<sup>25</sup> R. Khan,<sup>10</sup> E. Khazanov,<sup>14</sup> P. King,<sup>17</sup> J. S. Kissel,<sup>21</sup> S. Klimenko,<sup>47</sup> K. Kokeyama,<sup>27</sup> V. Kondrashov,<sup>17</sup> R. Kopparapu,<sup>37</sup> S. Koranda,<sup>60</sup> D. Kozak,<sup>17</sup> B. Krishnan,<sup>1</sup> R. Kumar,<sup>48</sup> P. Kwee,<sup>16</sup> P. K. Lam,<sup>4</sup> M. Landry,<sup>18</sup> B. Lantz,<sup>35</sup> A. Lazzarini,<sup>17</sup> H. Lei,<sup>42</sup> M. Lei,<sup>17</sup> N. Leindeferger,<sup>35</sup> I. Leonor,<sup>53</sup> C. Li,<sup>6</sup> H. Lin,<sup>47</sup> P. E. Lindquist,<sup>17</sup> T. B. Littenberg,<sup>24</sup> N. A. Lockerbie,<sup>58</sup> D. Lodhia,<sup>46</sup> M. Longo,<sup>56</sup> M. Lormand,<sup>19</sup> P. Lu,<sup>35</sup> M. Lubinski,<sup>18</sup> A. Lucianetti,<sup>47</sup> H. Lück,<sup>2,16</sup> A. P. Lundgren,<sup>36</sup> B. Machenschalk,<sup>1</sup> M. MacInnis,<sup>20</sup> M. Mageswaran,<sup>17</sup> K. Mailand,<sup>17</sup> I. Mandel,<sup>28</sup> V. Mandic,<sup>52</sup> S. Márka,<sup>10</sup> Z. Márka,<sup>10</sup> A. Markosyan,<sup>35</sup> J. Markowitz,<sup>20</sup> E. Maros,<sup>17</sup> I. W. Martin,<sup>48</sup> R. M. Martin,<sup>47</sup> J. N. Marx,<sup>17</sup> K. Mason,<sup>20</sup> F. Matichard,<sup>21</sup> L. Matone,<sup>10</sup> R. A. Matzner,<sup>41</sup> N. Mavalvala,<sup>20</sup> R. McCarthy,<sup>18</sup> D. E. McClelland,<sup>4</sup> S. C. McGuire,<sup>34</sup> M. McHugh,<sup>23</sup> G. McIntyre,<sup>17</sup> D. J. A. McKechnan,<sup>7</sup> K. McKenzie,<sup>4</sup> M. Mehmet,<sup>2</sup> A. Melatos,<sup>38</sup> A. C. Melissinos,<sup>54</sup> D. F. Menéndez,<sup>37</sup> G. Mendell,<sup>18</sup> R. A. Mercer,<sup>60</sup> S. Meshkov,<sup>17</sup> C. Messenger,<sup>2</sup> M. S. Meyer,<sup>19</sup> J. Miller,<sup>48</sup> J. Minelli,<sup>37</sup> Y. Mino,<sup>6</sup> V. P. Mitrofanov,<sup>25</sup> G. Mitselmakher,<sup>47</sup> R. Mittleman,<sup>20</sup> O. Miyakawa,<sup>17</sup> B. Moe,<sup>60</sup> S. D. Mohanty,<sup>42</sup> S. R. P. Mohapatra,<sup>50</sup> G. Moreno,<sup>18</sup> T. Morioka,<sup>27</sup> K. Mors,<sup>2</sup> K. Mossavi,<sup>2</sup> C. MowLowry,<sup>4</sup> G. Mueller,<sup>47</sup> H. Müller-Ebhardt,<sup>2</sup> D. Muhammad,<sup>19</sup> S. Mukherjee,<sup>42</sup> H. Mukhopadhyay,<sup>15</sup> A. Mullavey,<sup>4</sup> J. Munch,<sup>45</sup> P. G. Murray,<sup>48</sup> E. Myers,<sup>18</sup> J. Myers,<sup>18</sup> T. Nash,<sup>17</sup> J. Nelson,<sup>48</sup> G. Newton,<sup>48</sup> A. Nishizawa,<sup>27</sup> K. Numata,<sup>26</sup> J. O'Dell,<sup>30</sup> B. O'Reilly,<sup>19</sup> R. O'Shaughnessy,<sup>37</sup> E. Ochsner,<sup>49</sup> G. H. Ogin,<sup>17</sup> D. J. Ottaway,<sup>45</sup> R. S. Ottens,<sup>47</sup> H. Overmier,<sup>19</sup> B. J. Owen,<sup>37</sup> Y. Pan,<sup>49</sup> C. Pankow,<sup>47</sup> M. A. Papa,<sup>1,60</sup> V. Parameshwaraiah,<sup>18</sup> P. Patel,<sup>17</sup> M. Pedraza,<sup>17</sup> S. Penn,<sup>13</sup> A. Perraca,<sup>46</sup> V. Pierro,<sup>56</sup> I. M. Pinto,<sup>56</sup> M. Pitkin,<sup>48</sup> H. J. Pletsch,<sup>2</sup> M. V. Plissi,<sup>48</sup> F. Postiglione,<sup>55</sup> M. Principe,<sup>56</sup> R. Prix,<sup>2</sup> L. Prokhorov,<sup>25</sup> O. Punken,<sup>2</sup> V. Quetschke,<sup>47</sup> F. J. Raab,<sup>18</sup> D. S. Rabeling,<sup>4</sup> H. Radkins,<sup>18</sup> P. Raffai,<sup>12</sup> Z. Raics,<sup>10</sup> N. Rainer,<sup>2</sup> M. Rakhmanov,<sup>42</sup> V. Raymond,<sup>28</sup> C. M. Reed,<sup>18</sup> T. Reed,<sup>22</sup> H. Rehbein,<sup>2</sup> S. Reid,<sup>48</sup> D. H. Reitze,<sup>47</sup> R. Riesen,<sup>19</sup> K. Riles,<sup>51</sup> B. Rivera,<sup>18</sup> P. Roberts,<sup>3</sup> N. A. Robertson,<sup>17,48</sup> C. Robinson,<sup>7</sup> E. L. Robinson,<sup>1</sup> S. Roddy,<sup>19</sup> C. Röver,<sup>2</sup> J. Rollins,<sup>10</sup> J. D. Romano,<sup>42</sup> J. H. Romie,<sup>19</sup> S. Rowan,<sup>48</sup> A. Rüdiger,<sup>2</sup> P. Russell,<sup>17</sup> K. Ryan,<sup>18</sup> S. Sakata,<sup>27</sup> L. Sancho de la Jordana,<sup>44</sup> V. Sandberg,<sup>18</sup> V. Sannibale,<sup>17</sup> L. Santamaría,<sup>1</sup> S. Saraf,<sup>32</sup> P. Sarin,<sup>20</sup> B. S. Sathyaprakash,<sup>7</sup> S. Sato,<sup>27</sup> M. Satterthwaite,<sup>4</sup> P. R. Saulson,<sup>36</sup> R. Savage,<sup>18</sup> P. Savov,<sup>6</sup> M. Scanlan,<sup>22</sup> R. Schilling,<sup>2</sup> R. Schnabel,<sup>2</sup> R. Schofield,<sup>53</sup> B. Schulz,<sup>2</sup> B. F. Schutz,<sup>1,7</sup> P. Schwinberg,<sup>18</sup>

J. Scott,<sup>48</sup> S. M. Scott,<sup>4</sup> A. C. Searle,<sup>17</sup> B. Sears,<sup>17</sup> F. Seifert,<sup>2</sup> D. Sellers,<sup>19</sup> A. S. Sengupta,<sup>17</sup> A. Sergeev,<sup>14</sup> B. Shapiro,<sup>20</sup> P. Shawhan,<sup>49</sup> D. H. Shoemaker,<sup>20</sup> A. Sibley,<sup>19</sup> X. Siemens,<sup>60</sup> D. Sigg,<sup>18</sup> S. Sinha,<sup>35</sup> A. M. Sintes,<sup>44</sup> B. J. J. Slagmolen,<sup>4</sup> J. Slutsky,<sup>21</sup> J. R. Smith,<sup>36</sup> M. R. Smith,<sup>17</sup> N. D. Smith,<sup>20</sup> K. Somiya,<sup>6</sup> B. Sorazu,<sup>48</sup> A. Stein,<sup>20</sup> L. C. Stein,<sup>20</sup> S. Steplewski,<sup>61</sup> A. Stochino,<sup>17</sup> R. Stone,<sup>42</sup> K. A. Strain,<sup>48</sup> S. Strigin,<sup>25</sup> A. Stroer,<sup>26</sup> A. L. Stuver,<sup>19</sup> T. Z. Summerscales,<sup>3</sup> K. -X. Sun,<sup>35</sup> M. Sung,<sup>21</sup> P. J. Sutton,<sup>7</sup> G. P. Szokoly,<sup>12</sup> D. Talukder,<sup>61</sup> L. Tang,<sup>42</sup> D. B. Tanner,<sup>47</sup> S. P. Tarabrin,<sup>25</sup> J. R. Taylor,<sup>2</sup> R. Taylor,<sup>17</sup> J. Thacker,<sup>19</sup> K. A. Thorne,<sup>19</sup> K. S. Thorne,<sup>6</sup> A. Thüring,<sup>16</sup> K. V. Tokmakov,<sup>48</sup> C. Torres,<sup>19</sup> C. Torrie,<sup>17</sup> G. Traylor,<sup>19</sup> M. Trias,<sup>44</sup> D. Ugolini,<sup>43</sup> J. Ulmen,<sup>35</sup> K. Urbanek,<sup>35</sup> H. Vahlbruch,<sup>16</sup> M. Vallisneri,<sup>6</sup> C. Van Den Broeck,<sup>7</sup> M. V. van der Sluys,<sup>28</sup> A. A. van Veggel,<sup>48</sup> S. Vass,<sup>17</sup> R. Vaulin,<sup>60</sup> A. Vecchio,<sup>46</sup> J. Veitch,<sup>46</sup> P. Veitch,<sup>45</sup> C. Veltkamp,<sup>2</sup> A. Villar,<sup>17</sup> C. Vorvick,<sup>18</sup> S. P. Vyachanin,<sup>25</sup> S. J. Waldman,<sup>20</sup> L. Wallace,<sup>17</sup> R. L. Ward,<sup>17</sup> A. Weidner,<sup>2</sup> M. Weinert,<sup>2</sup> A. J. Weinstein,<sup>17</sup> R. Weiss,<sup>20</sup> L. Wen,<sup>6,59</sup> S. Wen,<sup>21</sup> K. Wette,<sup>4</sup> J. T. Whelan,<sup>1,29</sup> S. E. Whitcomb,<sup>17</sup> B. F. Whiting,<sup>47</sup> C. Wilkinson,<sup>18</sup> P. A. Willems,<sup>17</sup> H. R. Williams,<sup>37</sup> L. Williams,<sup>47</sup> B. Willke,<sup>2,16</sup> I. Wilmot,<sup>30</sup> L. Winkelmann,<sup>2</sup> W. Winkler,<sup>2</sup> C. C. Wipf,<sup>20</sup> A. G. Wiseman,<sup>60</sup> G. Woan,<sup>48</sup> R. Wooley,<sup>19</sup> J. Worden,<sup>18</sup> W. Wu,<sup>47</sup> I. Yakushin,<sup>19</sup> H. Yamamoto,<sup>17</sup> Z. Yan,<sup>59</sup> S. Yoshida,<sup>33</sup> M. Zanolin,<sup>11</sup> J. Zhang,<sup>51</sup> L. Zhang,<sup>17</sup> C. Zhao,<sup>59</sup> N. Zotov,<sup>22</sup> M. E. Zucker,<sup>20</sup> H. zur Mühlen,<sup>16</sup> and J. Zweizig<sup>17</sup>

(The LIGO Scientific Collaboration, <http://www.ligo.org>)

<sup>1</sup>Albert-Einstein-Institut, Max-Planck-Institut für Gravitationsphysik, D-14476 Golm, Germany

<sup>2</sup>Albert-Einstein-Institut, Max-Planck-Institut für Gravitationsphysik, D-30167 Hannover, Germany

<sup>3</sup>Andrews University, Berrien Springs, MI 49104 USA

<sup>4</sup>Australian National University, Canberra, 0200, Australia

<sup>5</sup>California Institute of Technology, Pasadena, CA 91125, USA

<sup>6</sup>Caltech-CaRT, Pasadena, CA 91125, USA

<sup>7</sup>Cardiff University, Cardiff, CF24 3AA, United Kingdom

<sup>8</sup>Carleton College, Northfield, MN 55057, USA

<sup>9</sup>Charles Sturt University, Wagga Wagga, NSW 2678, Australia

<sup>10</sup>Columbia University, New York, NY 10027, USA

<sup>11</sup>Embry-Riddle Aeronautical University, Prescott, AZ 86301 USA

<sup>12</sup>Eötvös University, ELTE 1053 Budapest, Hungary

<sup>13</sup>Hobart and William Smith Colleges, Geneva, NY 14456, USA

<sup>14</sup>Institute of Applied Physics, Nizhny Novgorod, 603950, Russia

<sup>15</sup>Inter-University Centre for Astronomy and Astrophysics, Pune - 411007, India

<sup>16</sup>Leibniz Universität Hannover, D-30167 Hannover, Germany

<sup>17</sup>LIGO - California Institute of Technology, Pasadena, CA 91125, USA

<sup>18</sup>LIGO - Hanford Observatory, Richland, WA 99352, USA

<sup>19</sup>LIGO - Livingston Observatory, Livingston, LA 70754, USA

<sup>20</sup>LIGO - Massachusetts Institute of Technology, Cambridge, MA 02139, USA

<sup>21</sup>Louisiana State University, Baton Rouge, LA 70803, USA

<sup>22</sup>Louisiana Tech University, Ruston, LA 71272, USA

<sup>23</sup>Loyola University, New Orleans, LA 70118, USA

<sup>24</sup>Montana State University, Bozeman, MT 59717, USA

<sup>25</sup>Moscow State University, Moscow, 119992, Russia

<sup>26</sup>NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA

<sup>27</sup>National Astronomical Observatory of Japan, Tokyo 181-8588, Japan

<sup>28</sup>Northwestern University, Evanston, IL 60208, USA

<sup>29</sup>Rochester Institute of Technology, Rochester, NY 14623, USA

<sup>30</sup>Rutherford Appleton Laboratory, HSIC, Chilton, Didcot, Oxon OX11 0QX United Kingdom

<sup>31</sup>San Jose State University, San Jose, CA 95192, USA

<sup>32</sup>Sonoma State University, Rohnert Park, CA 94928, USA

<sup>33</sup>Southeastern Louisiana University, Hammond, LA 70402, USA

<sup>34</sup>Southern University and A&M College, Baton Rouge, LA 70813, USA

<sup>35</sup>Stanford University, Stanford, CA 94305, USA

<sup>36</sup>Syracuse University, Syracuse, NY 13244, USA

<sup>37</sup>The Pennsylvania State University, University Park, PA 16802, USA

<sup>38</sup>The University of Melbourne, Parkville VIC 3010, Australia

<sup>39</sup>The University of Mississippi, University, MS 38677, USA

<sup>40</sup>The University of Sheffield, Sheffield S10 2TN, United Kingdom

<sup>41</sup>The University of Texas at Austin, Austin, TX 78712, USA

<sup>42</sup>The University of Texas at Brownsville and Texas Southmost College, Brownsville, TX 78520, USA

<sup>43</sup>Trinity University, San Antonio, TX 78212, USA

<sup>44</sup>Universitat de les Illes Balears, E-07122 Palma de Mallorca, Spain

<sup>45</sup>University of Adelaide, Adelaide, SA 5005, Australia

<sup>46</sup>University of Birmingham, Birmingham, B15 2TT, United Kingdom

<sup>47</sup>University of Florida, Gainesville, FL 32611, USA

<sup>48</sup>University of Glasgow, Glasgow, G12 8QQ, United Kingdom

<sup>49</sup>University of Maryland, College Park, MD 20742 USA

<sup>50</sup>University of Massachusetts - Amherst, Amherst, MA 01003, USA

<sup>51</sup>University of Michigan, Ann Arbor, MI 48109, USA

<sup>52</sup>University of Minnesota, Minneapolis, MN 55455, USA

<sup>53</sup>University of Oregon, Eugene, OR 97403, USA

<sup>54</sup>University of Rochester, Rochester, NY 14627, USA

<sup>55</sup>University of Salerno, 84084 Fisciano (Salerno), Italy

<sup>56</sup>University of Sannio at Benevento, I-82100 Benevento, Italy

<sup>57</sup>University of Southampton, Southampton, SO17 1BJ, United Kingdom

<sup>58</sup>University of Strathclyde, Glasgow, G1 1XQ, United Kingdom

<sup>59</sup>University of Western Australia, Crawley, WA 6009, Australia

<sup>60</sup>University of Wisconsin-Milwaukee, Milwaukee, WI 53201, USA

<sup>61</sup>Washington State University, Pullman, WA 99164, USA

(RCS Id: s5-2yr-12to18-lowcbc.tex,v 1.109 2009/05/19 06:51:15 mckechan Exp ; compiled 22 May 2009)

We report on a search for gravitational waves from coalescing compact binaries using LIGO observations between November 14, 2006 and May 18, 2007. This search targeted binaries with total mass between 2 and  $35 M_{\odot}$  and a minimum component mass of  $1 M_{\odot}$ . No gravitational-wave signals were detected during our observations and so we report upper limits on the rate of compact binary coalescence as a function of the binary’s mass. Assuming a compact binary object population with a Gaussian mass distribution representing binary neutron star systems, binary black hole systems and black hole–neutron star binary systems, we find the 90%-confidence upper limit on the rate of coalescences to be  $1.4 \times 10^{-2} \text{ yr}^{-1} L_{10}^{-1}$ ,  $7.3 \times 10^{-4} \text{ yr}^{-1} L_{10}^{-1}$ , and  $3.6 \times 10^{-3} \text{ yr}^{-1} L_{10}^{-1}$  respectively, where  $L_{10}$  is  $10^{10}$  times the blue solar luminosity.

PACS numbers: 95.85.Sz, 04.80.Nn, 07.05.Kf, 97.60.Jd, 97.60.Lf, 97.80.-d

## I. INTRODUCTION

In November 2005 the three first-generation detectors of the Laser Interferometer Gravitational-wave Observatory (LIGO) reached design sensitivity and began a two-year period of observations (known as the fifth science run, or S5) which concluded in October 2007 [1]. One of the most promising sources of gravitational-waves for LIGO is a compact binary coalescence (CBC); the inspiral and merger of binary neutron stars (BNS), binary black holes (BBH), or a black hole–neutron star binary (BHNS) [2–7]. These systems spiral together as they emit energy in the form of gravitational waves, finally merging to form a single object, which then settles down to equilibrium. Ground-based gravitational-wave detectors are most sensitive to waves with frequencies between  $\sim 40$ –1000 Hz, corresponding to the late stages of inspiral and merger. In this paper we report the results of search for gravitational-waves from binaries with total mass between 2 and  $35 M_{\odot}$  and a minimum component mass of  $1 M_{\odot}$  in LIGO observations between November 14, 2006 and May 18, 2007. The results of a search for these systems in data taken from November 4, 2005 to November 14, 2006 were reported in Ref. [7]. From May–October 2007, the Virgo gravitational-wave detector operated in coincidence with the LIGO detectors [8] and the LIGO data from this period is being analyzed together with the Virgo data. Since this joint analysis requires significant modifications to our analysis pipeline, results of this search will be reported in a subsequent publication. In contrast, the results presented here were obtained with substantially the same analysis pipeline used in Ref. [7].

No gravitational-wave signals were observed during this search and so we report upper limits on CBC rates using the upper limits of Ref. [7] as prior rate distributions. In Sec. II we

summarize the analysis procedure and in Sec. III we present the search results and upper limits on CBC rates derived from LIGO observations in the period November 4, 2005 to May 18, 2007.

## II. THE DATA ANALYSIS PIPELINE

Since the data-analysis pipeline used in this search is fundamentally the same as that of Ref. [7], here we only describe the major components and highlight differences to the previous search, referring to Refs. [6, 7] for details. The most substantial change in this analysis is a modification to the way in which the significance of candidate events are compared to instrumental noise background. In previous searches, the noise background was computed *using the entire observation period* by introducing an artificial time-shift between data recorded at the two LIGO observatories. Since the instrumental behavior varied over the course of the S5 run, here we split the observation period into six four-week segments and one 18 day segment (referred to as “months”) and measure the instrumental background *independently in each month*. Candidate triggers are therefore compared to a background that better reflects the instrumental behavior at the time of the candidate. Each month was searched independently for gravitational-wave candidates and in the absence of detections, the results from the months are combined (together with the results from Ref. [7]) to set an upper limit on the CBC rate.

We search for gravitational-wave signals when at least two of the LIGO detectors were operational. This comprised a total of 0.28 yr when all three detectors (the 4 km and 2 km Hanford detectors, denoted H1 and H2 respectively, and the 4 km Livingston detector, denoted L1) were operational (H1H2L1

coincident data), 0.10 yr of H1H2 coincident data, 0.02 yr of H1L1 coincident data, and 0.01 yr of H2L1 coincident data. Noise correlations between the co-located H1 and H2 detectors cause our method of estimating the instrumental background using time-shifted data to fail, and so we do not search data when only the H1H2 detectors are operating. Approximately 10% of data is designated *playground* and used for tuning our search pipeline.

Since post-Newtonian (PN) theory accurately models the waves from our target sources [9–16] we use matched filtering to search for signals. We construct template banks [17] of restricted second order PN waveforms in the frequency domain [10, 18, 19] such that no more than 3% of the signal-to-noise ratio (SNR) is lost due to the discreteness of the bank [20]. A “trigger” is generated if the matched-filter SNR of the the strain data filtered against the template exceeds a threshold of 5.5 [21]. We demand that triggers are coincident in time of arrival and mass [22] in at least two of the three LIGO detectors. When all three detector are operating we can obtain (in principle) four possible types of coincidence: H1H2L1 triple coincident triggers and three different double coincident types: H1H2, H1L1 and H2L1. We discard H1H2 double coincident triggers, due to the problems estimating the background for these triggers and discard H2L1 triggers when the H1 detector is operating nominally (since the 4 km H1 detector is more sensitive than the 2 km H2 detector). Coincident triggers are subjected to consistency checks using signal-based vetoes [23–25]. Times of poor detector data quality are flagged using environmental and auxiliary data; triggers from these times are also vetoed [7]. We construct two categories of data-quality vetoes depending on the severity of the instrumental artifact being flagged. In our primary search and upper limit computation we veto coincident triggers that fall in times from either category. We also consider detection candidates in data with only the most severe category applied in case a loud signal is present that may otherwise be vetoed. Surviving triggers are clustered in time and ranked by an effective SNR statistic, which is computed from the trigger’s matched-filter SNR and the value of the  $\chi^2$  signal-based veto for that trigger [6]. After discarding playground data and times in both veto categories, a total of 0.21 yr of triple coincident data (H1H2L1), 0.02 yr of H1L1 coincident data, and 0.01 yr of H2L1 coincident data remain. In the absence of a detection, these data are used to compute upper limits on the CBC rate.

The rate of instrumental noise artifacts is measured by time-shifting data from the Livingston and Hanford observatories (H1 and H2 data are kept fixed with respect to each other). Since the data is offset by more than the light-travel time between observatories, triggers which survive the pipeline are due to noise alone. We performed 100 such time-shifts to obtain a good estimate of the noise background in our search. Since CBC signals of higher-mass contain fewer gravitational-wave cycles in the sensitive band of our detectors, our signal-based vetoes are not as powerful. High-mass templates are therefore more sensitive to non-stationary noise transients and hence our false alarm rate (FAR) for these system is larger. In order to account for this mass-dependent behavior we compute the background for three different mass regions and com-

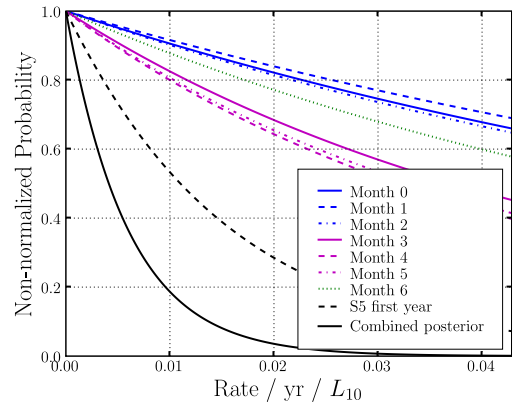


FIG. 1: The posterior distribution for the rate of BNS coalescences. The dashed black curve shows the rate computed in Ref. [7]. The solid black curve shows the result of this search using the previous analysis as a prior. The figure also shows the rate distributions for the individual months computed using a uniform prior. The improvement in latter months is due to increasing detector sensitivity during this search.

pare foreground and background within each of these ranges. Specifically, in each region we count the number of background triggers with effective SNR greater-than or equal to a given foreground trigger; dividing this number by the amount of background time analyzed gives us the FAR for that trigger. This allows us to define a single detection statistic for every trigger in each of the mass categories. The FAR can then be directly compared to obtain a ranking of the significance of the triggers, regardless of their mass [7].

### III. SEARCH RESULTS

The seven months of data were analyzed separately using the procedure described above. No gravitational wave candidates were observed with a FAR significantly above those expected from the noise background. The loudest trigger in this search was a triple coincident trigger with a FAR of 6 per year. This is consistent with the expected background, since we searched 0.21 yr of data. The second and third loudest triggers had FAR values of 10 and 11 per year respectively. Although we did not have any detection candidates, we exercised our follow-up procedures by examining any triggers with a FAR of less than 50 per year. This exercise prepares us for future detections and often identifies areas where our search pipeline can be improved to exclude noise transients.

In the absence of detection candidates, we use our observations to set an upper limit on the CBC rate. We follow the procedure described in [26–28] and use the results reported in Ref. [7] as prior information on the rates. We present five different classes of upper limits. The first three limits are placed on binaries of neutron stars and/or black holes assuming canonical mass distributions for BNS [ $m_1 = m_2 = (1.35 \pm 0.04) M_\odot$ ], BBH [ $m_1 = m_2 = (5 \pm 1) M_\odot$ ], and BHNS [ $m_1 = (5 \pm 1) M_\odot$ ,  $m_2 = (1.35 \pm 0.04) M_\odot$ ] sys-



tems. We also present upper limits as a function of the total mass of the binary and, for BHNS binaries, as a function of the black hole mass. We combine the results from each of the seven months, along with the prior results from the first year analysis, in a Bayesian manner, using the same procedure as described in [7].

We first calculate upper limits on BNS, BBH and BHNS systems assuming the objects have no spin, and summarize the results Tables I and II. The rate of binary coalescences in a galaxy is expected to be proportional to the blue light luminosity of the galaxy [29]. Therefore, we place limits on the rate per  $L_{10}$  per year, where  $L_{10}$  is  $10^{10}$  times the blue solar luminosity (the Milky Way contains  $\sim 1.7L_{10}$  [30]). To calculate the search sensitivity, the analysis was repeated numerous times adding simulated signals with a range of masses, distance and other astrophysical parameters to the data. Since sensitivity of gravitational wave detectors to coalescing binaries is often quoted in terms of the horizon distance—the distance at which an optimally oriented and located binary would produce an SNR of 8—we also give the horizon distances in Table II. There are a number of uncertainties which affect the upper limit calculation, including Monte Carlo statistics, detector calibration, distances and luminosities of galaxies listed in the galaxy catalog [29] and differences between the PN templates used to evaluate efficiency of the search and the actual waveforms. The effect of these errors on the cumulative luminosity are summarized for the BNS search in Table I. We marginalize over all of the uncertainties [26] to obtain a posterior distribution on the rate of binary coalescences.

In Fig. 1, we show the derived distribution of the rate of BNS coalescences. Since there are no detection candidates, the distribution is peaked at zero rate. We include the distribution for all searches previous to this one (which is our prior). In addition, we present the result that would be obtained from each month, were it analyzed independently of the others and of the previous searches. This provides an illustration of the amount that each month contributes to the final upper limit result and demonstrates the improvement in sensitivity of the detectors during the search. The upper limit is finally obtained by integrating the distribution from zero to  $\mathcal{R}_{90\%}$  so that 90% of the probability is contained in the interval. The results obtained in this way are  $\mathcal{R}_{90\%,\text{BNS}} = 1.4 \times 10^{-2} \text{ yr}^{-1} L_{10}^{-1}$ ,  $\mathcal{R}_{90\%,\text{BBH}} = 7.3 \times 10^{-4} \text{ yr}^{-1} L_{10}^{-1}$ , and  $\mathcal{R}_{90\%,\text{BHNS}} = 3.6 \times 10^{-3} \text{ yr}^{-1} L_{10}^{-1}$ .

Additionally we calculate the upper limit for BBH systems as a function of the total mass of the binary, assuming a uniform distribution of the component masses. For BHNS systems, we construct an upper limit as a function of the black hole mass, assuming a fixed neutron star mass of  $m_{\text{NS}} = 1.35M_{\odot}$ . These upper limits are shown in Figure 2.

Finally, we present upper limits on coalescence rates where the spin of the components of the binary is taken into account. Astrophysical observations of neutron stars indicate that their spins will not be large enough to have a significant effect on the BNS waveform observed in the LIGO band [31, 32]. Theoretical considerations limit the magnitude of the spin,  $S$ , of a black hole to lie within the range  $0 \leq S \leq Gm^2/c$ . However, the astrophysical distribution of

Coincidence Time	H1H2L1	H1L1	H2L1
Observation Time (yr)	0.21	0.02	0.01
Cumulative Luminosity ( $L_{10}$ )	490	410	110
Calibration Error	23%	23%	26%
Monte Carlo Error	3%	7%	10%
Waveform Error	31%	32%	31%
Galaxy Distance Error	16%	16%	3%
Galaxy Magnitude Error	19%	19%	17%

TABLE I: Detailed results from the BNS search. The observation time is the time used in the upper limit analysis. The cumulative luminosity is the luminosity to which the search is sensitive above the loudest event for each coincidence time. The errors in this table are listed as one-sigma logarithmic error bars (expressed as percentages) in luminosity associated with each source error.

Component Masses ( $M_{\odot}$ )	1.35/1.35	5.0/5.0	5.0/1.35
$D_{\text{horizon}}$ (Mpc)	$\sim 30$	$\sim 100$	$\sim 60$
Cumulative Luminosity ( $L_{10}$ )	490	11000	2100
Non-spinning Upper Limit ( $\text{yr}^{-1} L_{10}^{-1}$ )	$1.4 \times 10^{-2}$	$7.3 \times 10^{-4}$	$3.6 \times 10^{-3}$
Spinning Upper Limit ( $\text{yr}^{-1} L_{10}^{-1}$ )	–	$9.0 \times 10^{-4}$	$4.4 \times 10^{-3}$

TABLE II: Overview of results from BNS, BBH and BHNS searches.  $D_{\text{horizon}}$  is the horizon distance averaged over the time of the search. The cumulative luminosity is the luminosity to which the search is sensitive above the loudest event for times when all three LIGO detectors were operational. The first set of upper limits are those obtained for binaries with non-spinning components. The second set of upper limits are produced using black holes with a spin uniformly distributed between zero and the maximal value of  $Gm^2/c$ .

black hole spins, and spin orientations, is not well constrained. Therefore, we provide a sample upper limit for spinning systems using a spin magnitude and orientation distributed uniformly within the allowed values. This gives upper limits on the rate of BBH and BHNS systems of  $\mathcal{R}_{90\%,\text{BBH}} = 9.0 \times 10^{-4} \text{ yr}^{-1} L_{10}^{-1}$  and  $\mathcal{R}_{90\%,\text{BHNS}} = 4.4 \times 10^{-3} \text{ yr}^{-1} L_{10}^{-1}$ . These rates are about 20% larger than the non-spinning rates.

#### IV. DISCUSSION

We have searched for gravitational waves from CBCs with total mass between 2–35  $M_{\odot}$  in LIGO observations between November 14, 2006 and May 18, 2007. No detection candidates with significance above that expected due to the background were found in the search. By combining this search with our previous results, we set a new upper limits on the CBC rate in the local universe which is approximately a factor of three lower than that reported in Ref. [7]. This improvement is significant, even though we searched only two thirds as much data as in Ref. [7]. It is due, in part, to improvements in detector sensitivity during S5 which increased the horizon distance. Moreover, the shorter analysis time and improved

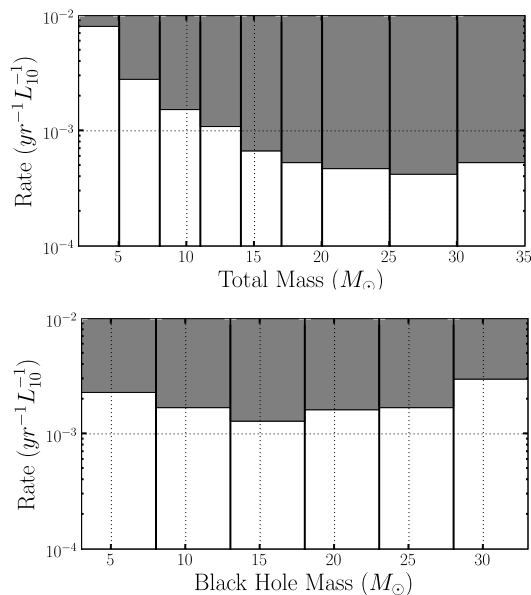


FIG. 2: The marginalized 90% rate upper limits as a function of mass. The upper plot shows limits for BBH systems as a function of the total mass of the system. The lower plot shows limits for BHNS systems as a function of the black hole mass, assuming a fixed neutron star mass of  $1.35M_{\odot}$ . Here the upper limits are calculated using only H1H2L1 data since the relatively small amount of H1L1 and H2L1 data makes it difficult to evaluate the cumulative luminosity in the individual mass bins.

stationarity of the data, led to many of the months having a less significant loudest event than in the previous search. Both of these effects increased the luminosity to which the search was sensitive, thereby improving the upper limit.

Astrophysical estimates for CBC rates depend on a number of assumptions and unknown model parameters, and are still uncertain at present. In the simplest models, the coalescence rates should be proportional to the stellar birth rate in nearby spiral galaxies, which can be estimated from their blue luminosity [29]. The optimistic, upper end of the plau-

sible rate range for BNS is  $5 \times 10^{-4} \text{ yr}^{-1} L_{10}^{-1}$  [33, 34] and  $6 \times 10^{-5} \text{ yr}^{-1} L_{10}^{-1}$  for BBH and BHNS [35, 36]. The upper limits reported here are  $\sim 1$ – $2$  orders of magnitude above the optimistic expected rates. With the next run starting in mid 2009, the Enhanced LIGO and Virgo detectors will begin operations with a factor of  $\sim 2$  increase in horizon distance. The total luminosity searched will increase by a factor of  $\sim 10$ , thereby bringing us close to the optimistic rates. The most confident BNS rate predictions are based on extrapolations from observed binary pulsars in our Galaxy; these yield realistic BNS rates of  $5 \times 10^{-5} \text{ yr}^{-1} L_{10}^{-1}$  [33, 34]. Rate estimates for BBH and BHNS are less well constrained, but realistic estimates are  $2 \times 10^{-6} \text{ yr}^{-1} L_{10}^{-1}$  for BHNS [35] and  $4 \times 10^{-7} \text{ yr}^{-1} L_{10}^{-1}$  for BBH [36]. Thus, the expected rates are  $\sim 2$ – $3$  orders of magnitude lower than the limits presented in this paper. The Advanced LIGO and Virgo detectors, currently under construction, will increase our horizon distance by an order of magnitude or more, allowing us to measure the rate of CBCs in the Universe.

## V. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of the United States National Science Foundation for the construction and operation of the LIGO Laboratory and the Science and Technology Facilities Council of the United Kingdom, the Max-Planck-Society, and the State of Niedersachsen/Germany for support of the construction and operation of the GEO600 detector. The authors also gratefully acknowledge the support of the research by these agencies and by the Australian Research Council, the Council of Scientific and Industrial Research of India, the Istituto Nazionale di Fisica Nucleare of Italy, the Spanish Ministerio de Educación y Ciencia, the Conselleria d’Economia, Hisenda i Innovació of the Govern de les Illes Balears, the Royal Society, the Scottish Funding Council, the Scottish Universities Physics Alliance, The National Aeronautics and Space Administration, the Carnegie Trust, the Leverhulme Trust, the David and Lucile Packard Foundation, the Research Corporation, and the Alfred P. Sloan Foundation.

- 
- [1] B. Abbott et al. (LIGO Scientific) (2007), 0711.3041.
  - [2] B. Abbott et al. (LIGO Scientific Collaboration), Phys. Rev. D **69**, 122001 (2004), gr-qc/0308069.
  - [3] B. Abbott et al. (LIGO Scientific Collaboration), Phys. Rev. D **72**, 082001 (2005), gr-qc/0505041.
  - [4] B. Abbott et al. (LIGO Scientific Collaboration), Phys. Rev. D **72**, 082002 (2005), gr-qc/0505042.
  - [5] B. Abbott et al. (LIGO Scientific Collaboration), Phys. Rev. D **73**, 062001 (2006), gr-qc/0509129.
  - [6] B. Abbott et al. (LIGO Scientific Collaboration), Phys. Rev. D **77**, 062002 (2008), arXiv:0704.3368 [gr-qc].
  - [7] B. Abbott et al. (LIGO Scientific) (2009), 0901.0302.
  - [8] F. Acernese et al., Classical and Quantum Gravity **23**, S635 (2006).
  - [9] L. Blanchet, B. R. Iyer, C. M. Will, and A. G. Wiseman, Class. Quant. Grav. **13**, 575 (1996).
  - [10] S. Droz, D. J. Knapp, E. Poisson, and B. J. Owen, Phys. Rev. D **59**, 124016 (1999).
  - [11] L. Blanchet, Living Rev. Rel. **4**, 3 (2002), gr-qc/0202016.
  - [12] A. Buonanno, G. B. Cook, and F. Pretorius, Phys. Rev. D **75**, 124018 (2007), gr-qc/0610122.
  - [13] M. Boyle et al., Phys. Rev. D **76**, 124038 (2007), 0710.0158.
  - [14] M. Hannam et al., Phys. Rev. D **77**, 044020 (2008), 0706.1305.
  - [15] Y. Pan et al., Phys. Rev. D **77**, 024014 (2008).
  - [16] M. Boyle, D. A. Brown, and L. Pekowsky (2009), 0901.1628.
  - [17] T. Cokelaer, Phys. Rev. D **76**, 102004 (2007), gr-qc/0706.4437.
  - [18] K. S. Thorne, in *Three hundred years of gravitation*, edited by S. W. Hawking and W. Israel (Cambridge University Press, Cambridge, 1987), chap. 9, pp. 330–458.
  - [19] B. S. Sathyaprakash and S. V. Dhurandhar, Phys. Rev. D **44**, 3819 (1991).
  - [20] B. J. Owen and B. S. Sathyaprakash, Phys. Rev. D **60**, 022002

- (1999).
- [21] B. A. Allen, W. G. Anderson, P. R. Brady, D. A. Brown, and J. D. E. Creighton (2005), gr-qc/0509116.
- [22] C. A. K. Robinson, B. S. Sathyaprakash, and A. S. Sengupta, *Physical Review D* **78**, 062002 (2008).
- [23] The LIGO Scientific Collaboration, Tech. Rep. LIGO-T070109-01 (2007), URL <http://www.ligo.caltech.edu/docs/T/T070109-01.pdf>.
- [24] B. Allen, *Phys. Rev. D* **71**, 062001 (2005).
- [25] A. Rodríguez, Master's thesis, Louisiana State University (2007).
- [26] P. R. Brady and S. Fairhurst, *Class. Quant. Grav.* **25**, 1050002 (2008), arXiv:0707.2410 [gr-qc].
- [27] P. R. Brady, J. D. E. Creighton, and A. G. Wiseman, *Class. Quant. Grav.* **21**, S1775 (2004).
- [28] R. Biswas, P. R. Brady, J. D. E. Creighton, and S. Fairhurst (2007), arXiv:0710.0465 [gr-qc].
- [29] R. K. Kopparapu, C. Hanna, V. Kalogera, R. O'Shaughnessy, G. Gonzalez, P. R. Brady, and S. Fairhurst, *Astrophys. J.* **675**, 1459 (2008).
- [30] V. Kalogera, R. Narayan, D. N. Spergel, and J. H. Taylor, *Astrophys. J.* **556**, 340 (2001).
- [31] R. N. Manchester, G. B. Hobbs, A. Teoh, and M. Hobbs, *Astronom. J.* **129**, 1993 (2005).
- [32] T. A. Apostolatos, C. Cutler, G. J. Sussman, and K. S. Thorne, *Phys. Rev. D* **49**, 6274 (1994).
- [33] V. Kalogera, C. Kim, D. R. Lorimer, M. Burgay, N. D'Amico, A. Possenti, R. N. Manchester, A. G. Lyne, B. C. Joshi, M. A. McLaughlin, et al., *Astrophys. J.* **601**, L179 (2004), erratum-ibid. 614 (2004) L137.
- [34] V. Kalogera et al., *Astrophys. J. Lett.* **614**, L137 (2004).
- [35] R. O'Shaughnessy, C. Kim, V. Kalogera, and K. Belczynski, *Astrophys. J.* **672**, 479 (2008).
- [36] R. O'Shaughnessy, C. Kim, T. Fragos, V. Kalogera, and K. Belczynski, *Astrophys. J.* **633**, 1076 (2005).