Improved Upper Limits on the Stochastic Gravitational-Wave Background from 2009–2010 LIGO and Virgo Data

J. Aasi,[1] B. P. Abbott,[1] R. Abbott,[1] T. Abbott,[2] M. R. Abernathy,[1] T. Accadia,[3] F. Acernese,[4,5] K. Ackley,[6] C. Adams,[7] T. Adams,[8] P. Addesso,[5] R. X. Adhikari,[1] C. Affeldt,[9] M. Agathos,[10] N. Aggarwal,[11] O. D. Aguiar,[12] A. Ain,[13] P. Ajith,[14] A. Alemic,[15] B. Allen,[9,16,17] A. Allocca,[18,19] D. Amariutei,[6] M. Andersen,[20] R. Anderson,[1] S. B. Anderson,[1] W. G. Anderson,[16] K. Arai,[1] M. C. Araya,[1] C. Arceneaux,[21] J. Areeda,[22] S. M. Aston,[7] P. Astone,[23] P. Aufmuth,[17] C. Aulbert,[9] L. Austin,[1] B. E. Aylott,[24] S. Babak,[25] P. T. Baker,[26] G. Ballardin,[27] S. W. Ballmer,[15] J. C. Barayoga,[1] M. Barbet,[6] B. C. Barish,[1] D. Barker,[28] F. Barone,[4,5] B. Barr,[29] L. Barsotti,[11] M. Barsuglia,[30] M. A. Barton,[28] I. Bartos,[31] R. Bassiri,[20] A. Basti,[18,32] J. C. Batch,[28] J. Bauchrowitz,[9] Th. S. Bauer,[10] B. Behnke,[25] M. Bejger,[33] M. G. Beker,[10] C. Belczynski,[34] A. S. Bell,[29] C. Bell,[29] G. Bergmann,[9] D. Bersanetti,[35,36] A. Bertolini,[10] J. Betzwieser,[7] P. T. Beyersdorf,[37] I. A. Bilenko,[38] G. Billingsley,[1] J. Birch,[7] S. Biscans,[11] M. Bitossi,[18] M. A. Bizouard,[39] E. Black,[1] J. K. Blackburn,[1] L. Blackburn,[40] D. Blair,[41] S. Bloemen,[42,10] M. Blom,[10] O. Bock,[9] T. P. Bodiya,[11] M. Boer,[43] G. Bogaert,[43] C. Bogan,[9] C. Bond,[24] F. Bondu,[44] L. Bonelli,[18,32] R. Bonnand,[45] R. Bork,[1] M. Born,[9] V. Boschi,[18] Sukanta Bose,[46,13] L. Bosi,[47] C. Bradaschia,[18] P. R. Brady,[16] V. B. Braginsky,[38] M. Branchesi,[48,49] J. E. Brau,[50] T. Briant,[51] D. O. Bridges,[7] A. Brillet,[43] M. Brinkmann,[9] V. Brisson,[39] A. F. Brooks,[1] D. A. Brown,[15] D. D. Brown,[24] F. Brückner,[24] S. Buchman,[20] T. Bulik,[34] H. J. Bulten,[10,52] A. Buonanno,[53] R. Burman,[41] D. Buskulic,[3] C. Buy,[30] L. Cadonati,[54] G. Cagnoli,[45] J. Calderón Bustillo,[55] E. Calloni,[4,56] J. B. Camp,[40] P. Campsie,[29] K. C. Cannon,[57] B. Canuel,[27] J. Cao,[58] C. D. Capano,[53] F. Carbognani,[27] L. Carbone,[24] S. Caride,[59] A. Castiglia,[60] S. Caudill,[16] M. Cavaglià,[21] F. Cavalier,[39] R. Cavalieri,[27] C. Celerier,[20] G. Cella,[18] C. Cepeda,[1] E. Cesarini,[61] R. Chakraborty,[1] T. Chalermsongsak,[1] S. J. Chamberlin,[16] S. Chao,[62] P. Charlton,[63] E. Chassande-Mottin,[30] X. Chen,[41] Y. Chen,[64] A. Chincarini,[35] A. Chiummo,[27] H. S. Cho,[65] J. Chow,[66] N. Christensen,[67] Q. Chu,[41] S. S. Y. Chua,[66] S. Chung,[41] G. Ciani,[6] F. Clara,[28] J. A. Clark,[54] F. Cleva,[43] E. Coccia,[68,69] P.-F. Cohadon,[51] A. Colla,[23,70] C. Collette,[71] M. Colombini,[47] L. Cominsky,[72] M. Constancio, Jr.,[12] A. Conte,[23,70] D. Cook,[28] T. R. Corbitt,[2] M. Cordier,[37] N. Cornish,[26] A. Corpuz,[73] A. Corsi,[74] C. A. Costa,[12] M. W. Coughlin,[75] S. Coughlin,[76] J.-P. Coulon,[43] S. Countryman,[31] P. Couvares,[15] D. M. Coward,[41] M. Cowart,[7] D. C. Coyne,[1] R. Coyne,[74] K. Craig,[29] J. D. E. Creighton,[16] S. G. Crowder,[77,*] A. Cumming,[29] L. Cunningham,[29] E. Cuoco,[27] K. Dahl,[9] T. Dal Canton,[9] M. Damjanic,[9] S. L. Danilishin,[41] S. D'Antonio,[61] K. Danzmann,[17,9] V. Dattilo,[27] H. Daveloza,[78] M. Davier,[39] G. S. Davies,[29] E. J. Daw,[79] R. Day,[27] T. Dayanga,[46] G. Debreczeni,[80] J. Degallaix,[45] S. Deléglise,[51] W. Del Pozzo,[10] T. Denker,[9] T. Dent,[9] H. Dereli,[43] V. Dergachev,[1] R. De Rosa,[4,56] R. T. DeRosa,[2] R. DeSalvo,[81] S. Dhurandhar,[13] M. Díaz,[78] L. Di Fiore,[4] A. Di Lieto,[18,32] I. Di Palma,[9] A. Di Virgilio,[18] A. Donath,[25] F. Donovan,[11] K. L. Dooley,[9] S. Doravari,[7] S. Dossa,[67] R. Douglas,[29] T. P. Downes,[16] M. Drago,[82,83] R. W. P. Drever,[1] J. C. Driggers,[1] Z. Du,[58] S. Dwyer,[28] T. Eberle,[9] T. Edo,[79] M. Edwards,[8] A. Effler,[2] H. Eggenstein,[9] P. Ehrens,[1] J. Eichholz,[6] S. S. Eikenberry,[6] G. Endrőczi,[80] R. Essick,[11] T. Etzel,[1] M. Evans,[11] T. Evans,[7] M. Factourovich,[31] V. Fafone,[61,69] S. Fairhurst,[8] Q. Fang,[41] S. Farinon,[35] B. Farr,[76] W. M. Farr,[24] M. Favata,[84] H. Fehrmann,[9] M. M. Fejer,[20] D. Feldbaum,[6,7] F. Feroz,[75] I. Ferrante,[18,32] F. Ferrini,[27] F. Fidecaro,[18,32] L. S. Finn,[85] I. Fiori,[27] R. P. Fisher,[15] R. Flaminio,[45] J.-D. Fournier,[43] S. Franco,[39] S. Frasca,[23,70] F. Frasconi,[18] M. Frede,[9] Z. Frei,[86] A. Freise,[24] R. Frey,[50] T. T. Fricke,[9] P. Fritschel,[11] V. V. Frolov,[7] P. Fulda,[6] M. Fyffe,[7] J. Gair,[75] L. Gammaitoni,[47,87] S. Gaonkar,[13] F. Garufi,[4,56] N. Gehrels,[40] G. Gemme,[35] E. Genin,[27] A. Gennai,[18] S. Ghosh,[42,10,46] J. A. Giaime,[7,2] K. D. Giardina,[7] A. Giazotto,[18] C. Gill,[29] J. Gleason,[6] E. Goetz,[9] R. Goetz,[6] L. Gondan,[86] G. González,[2] N. Gordon,[29] M. L. Gorodetsky,[38] S. Gossan,[64] S. Goßler,[9] R. Gouaty,[3] C. Gräf,[29] P. B. Graff,[40] M. Granata,[45] A. Grant,[29] S. Gras,[11] C. Gray,[28] R. J. S. Greenhalgh,[88] A. M. Gretarsson,[73] P. Groot,[42] H. Grote,[9] K. Grover,[24] S. Grunewald,[25] G. M. Guidi,[48,49] C. Guido,[7] K. Gushwa,[1] E. K. Gustafson,[1] R. Gustafson,[59] D. Hammer,[16] G. Hammond,[29] M. Hanke,[9] J. Hanks,[28] C. Hanna,[89] J. Hanson,[7] J. Harms,[1] G. M. Harry,[90] I. W. Harry,[15] E. D. Harstad,[50] M. Hart,[29] M. T. Hartman,[6] C.-J. Haster,[24] K. Haughian,[29] A. Heidmann,[51] M. Heintze,[6,7] H. Heitmann,[43] P. Hello,[39] G. Hemming,[27] M. Hendry,[29] I. S. Heng,[29] A. W. Heptonstall,[1] M. Heurs,[9] M. Hewitson,[9] S. Hild,[29] D. Hoak,[54] K. A. Hodge,[1] K. Holt,[7] S. Hooper,[41] P. Hopkins,[8] D. J. Hosken,[91] J. Hough,[29] E. J. Howell,[41] Y. Hu,[29] E. Huerta,[15] B. Hughey,[73] S. Husa,[55] S. H. Huttner,[29] M. Huynh,[16] T. Huynh-Dinh,[7] D. R. Ingram,[28] R. Inta,[85] T. Isogai,[11] A. Ivanov,[1] B. R. Iyer,[92] K. Izumi,[28] M. Jacobson,[1] E. James,[1] H. Jang,[93] P. Jaranowski,[94] Y. Ji,[58] F. Jiménez-Forteza,[55] W. W. Johnson,[2] D. I. Jones,[95] R. Jones,[29] R. J. G. Jonker,[10] L. Ju,[41] Haris K.,[96] P. Kalmus,[1] V. Kalogera,[76] S. Kandhasamy,[21] G. Kang,[93] J. B. Kanner,[1] J. Karlen,[54] M. Kasprzack,[27,39] E. Katsavounidis,[11] W. Katzman,[7] H. Kaufer,[17] K. Kawabe,[28] F. Kawazoe,[9] F. Kéfélian,[43] G. M. Keiser,[20] D. Keitel,[9] D. B. Kelley,[15] W. Kells,[1] A. Khalaidovski,[9] F. Y. Khalili,[38] E. A. Khazanov,[97] C. Kim,[98,93] K. Kim,[99] N. Kim,[20]

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N. G. Kim,[93] Y.-M. Kim,[65] E. J. King,[91] P. J. King,[1] D. L. Kinzel,[7] J. S. Kissel,[28] S. Klimenko,[6] J. Kline,[16] S. Koehlenbeck,[9] K. Kokeyama,[2] V. Kondrashov,[1] S. Koranda,[16] W. Z. Korth,[1] I. Kowalska,[34] D. B. Kozak,[1] A. Kremin,[77] V. Kringel,[9] A. Królak,[100,101] G. Kuehn,[9] A. Kumar,[102] P. Kumar,[15] R. Kumar,[29] L. Kuo,[62] A. Kutynia,[101] P. Kwee,[11] M. Landry,[28] B. Lantz,[20] S. Larson,[76] P. D. Lasky,[103] C. Lawrie,[29] A. Lazzarini,[1] C. Lazzaro,[104] P. Leaci,[25] S. Leavey,[29] E. O. Lebigot,[58] C.-H. Lee,[65] H. K. Lee,[99] H. M. Lee,[98] J. Lee,[11] M. Leonardi,[82,83] J. R. Leong,[9] A. Le Roux,[7] N. Leroy,[39] N. Letendre,[3] Y. Levin,[105] B. Levine,[28] J. Lewis,[1] T. G. F. Li,[10,1] K. Libbrecht,[1] A. Libson,[11] A. C. Lin,[20] T. B. Littenberg,[76] V. Litvine,[1] N. A. Lockerbie,[106] V. Lockett,[22] D. Lodhia,[24] K. Loew,[73] J. Logue,[29] A. L. Lombardi,[54] M. Lorenzini,[61,69] V. Loriette,[107] M. Lormand,[7] G. Losurdo,[48] J. Lough,[15] M. J. Lubinski,[28] H. Lück,[17,9] E. Luijten,[76] A. P. Lundgren,[9] R. Lynch,[11] Y. Ma,[41] J. Macarthur,[29] E. P. Macdonald,[8] T. MacDonald,[20] B. Machenschalk,[9] M. MacInnis,[11] D. M. Macleod,[2] F. Magana-Sandoval,[15] M. Mageswaran,[1] C. Maglione,[108] K. Mailand,[1] E. Majorana,[23] I. Maksimovic,[107] V. Malvezzi,[61,69] N. Man,[43] G. M. Manca,[9] I. Mandel,[24] V. Mandic,[77] V. Mangano,[23,70] N. Mangini,[54] M. Mantovani,[18] F. Marchesoni,[47,109] F. Marion,[3] S. Márka,[31] Z. Márka,[31] A. Markosyan,[20] E. Maros,[1] J. Marque,[27] F. Martelli,[48,49] I. W. Martin,[29] R. M. Martin,[6] L. Martinelli,[43] D. Martynov,[1] J. N. Marx,[1] K. Mason,[11] A. Masserot,[3] T. J. Massinger,[15] F. Matichard,[11] L. Matone,[31] R. A. Matzner,[110] N. Mavalvala,[11] N. Mazumder,[96] G. Mazzolo,[17,9] R. McCarthy,[28] D. E. McClelland,[66] S. C. McGuire,[111] G. McIntyre,[1] J. McIver,[54] K. McLin,[72] D. Meacher,[43] G. D. Meadors,[59] M. Mehmet,[9] J. Meidam,[10] M. Meinders,[17] A. Melatos,[103] G. Mendell,[28] R. A. Mercer,[16] S. Meshkov,[1] C. Messenger,[29] P. Meyers,[77] H. Miao,[64] C. Michel,[45] E. E. Mikhailov,[112] L. Milano,[4,56] S. Milde,[25] J. Miller,[11] Y. Minenkov,[61] C. M. F. Mingarelli,[24] C. Mishra,[96] S. Mitra,[13] V. P. Mitrofanov,[38] G. Mitselmakher,[6] R. Mittleman,[11] B. Moe,[16] P. Moesta,[64] M. Mohan,[27] S. R. P. Mohapatra,[15,60] D. Moraru,[28] G. Moreno,[28] N. Morgado,[45] S. R. Morriss,[78] K. Mossavi,[9] B. Mours,[3] C. M. Mow-Lowry,[9] C. L. Mueller,[6] G. Mueller,[6] S. Mukherjee,[78] A. Mullavey,[2] J. Munch,[91] D. Murphy,[31] P. G. Murray,[29] A. Mytidis,[6] M. F. Nagy,[80] D. Nanda Kumar,[6] I. Nardecchia,[61,69] L. Naticchioni,[23,70] R. K. Nayak,[113] V. Necula,[6] G. Nelemans,[42,10] I. Neri,[47,87] M. Neri,[35,36] G. Newton,[29] T. Nguyen,[66] A. Nitz,[15] F. Nocera,[27] D. Nolting,[7] M. E. N. Normandin,[78] L. K. Nuttall,[16] E. Ochsner,[16] J. O'Dell,[88] E. Oelker,[11] J. J. Oh,[114] S. H. Oh,[114] F. Ohme,[8] P. Oppermann,[9] B. O'Reilly,[7] R. O'Shaughnessy,[16] C. Osthelder,[1] D. J. Ottaway,[91] R. S. Ottens,[6] H. Overmier,[7] B. J. Owen,[85] C. Padilla,[22] A. Pai,[96] O. Palashov,[97] C. Palomba,[23] H. Pan,[62] Y. Pan,[53] C. Pankow,[16] F. Paoletti,[18,27] R. Paoletti,[18,19] H. Paris,[28] A. Pasqualetti,[27] R. Passaquieti,[18,32] D. Passuello,[18] M. Pedraza,[1] S. Penn,[115] A. Perreca,[15] M. Phelps,[1] M. Pichot,[43] M. Pickenpack,[9] F. Piergiovanni,[48,49] V. Pierro,[81,35] L. Pinard,[45] I. M. Pinto,[81,35] M. Pitkin,[29] J. Poeld,[9] R. Poggiani,[18,32] A. Poteomkin,[97] J. Powell,[29] J. Prasad,[13] S. Premachandra,[105] T. Prestegard,[77] L. R. Price,[1] M. Prijatelj,[27] S. Privitera,[1] G. A. Prodi,[82,83] L. Prokhorov,[38] O. Puncken,[78] M. Punturo,[47] P. Puppo,[23] J. Qin,[41] V. Quetschke,[78] E. Quintero,[1] G. Quiroga,[108] R. Quitzow-James,[50] F. J. Raab,[28] D. S. Rabeling,[10,52] I. Rácz,[80] H. 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Shah,[42,10] M. S. Shahriar,[76] M. Shaltev,[9] B. Shapiro,[20] P. Shawhan,[53] D. H. Shoemaker,[11] T. L. Sidery,[24] K. Siellez,[43] X. Siemens,[16] D. Sigg,[28] D. Simakov,[9] A. Singer,[1] L. Singer,[1] R. Singh,[2] A. M. Sintes,[55] B. J. J. Slagmolen,[66] J. Slutsky,[9] J. R. Smith,[22] M. Smith,[1] R. J. E. Smith,[1] N. D. Smith-Lefebvre,[1] E. J. Son,[114] B. Sorazu,[29] T. Souradeep,[13] L. Sperandio,[61,69] A. Staley,[31] J. Stebbins,[20] J. Steinlechner,[9] S. Steinlechner,[9] B. C. Stephens,[16] S. Steplewski,[46] S. Stevenson,[24] R. Stone,[78] D. Stops,[24] K. A. Strain,[29] N. Straniero,[45] S. Strigin,[38] R. Sturani,[120,48,49] A. L. Stuver,[7] T. Z. Summerscales,[121] S. Susmithan,[41] P. J. Sutton,[8] B. Swinkels,[27] M. Tacca,[30] D. Talukder,[50] D. B. Tanner,[6] S. P. Tarabrin,[9] R. Taylor,[1] A. P. M. ter Braack,[10] M. P. Thirugnanasambandam,[1] M. Thomas,[7] P. Thomas,[28] K. A. Thorne,[7] K. S. Thorne,[64] E. Thrane,[1] V. Tiwari,[6] K. V. Tokmakov,[106] C. Tomlinson,[79] A. Toncelli,[18,32] M. Tonelli,[18,32] O. Torre,[18,19] C. V. Torres,[78] C. I. Torrie,[1,29] F. Travasso,[47,87] G. Traylor,[7] M. Tse,[31,11] D. Ugolini,[122] C. S. Unnikrishnan,[14] A. L. Urban,[16] K. Urbanek,[20] H. Vahlbruch,[17] G. Vajente,[18,32] G. Valdes,[78] M. Vallisneri,[64] J. F. J. van den Brand,[10,52] C. Van Den Broeck,[10] S. van der Putten,[10] M. V. van der Sluys,[42,10] J. van Heijningen,[10] A. A. van Veggel,[29] S. Vass,[1] M. Vasúth,[80] R. Vaulin,[11] A. Vecchio,[24] G. Vedovato,[104] J. Veitch,[10] P. J. Veitch,[91] K. Venkateswara,[123] D. Verkindt,[3] S. S. Verma,[41] F. Vetrano,[48,49] A. Viceré,[48,49] R. Vincent-Finley,[111] J.-Y. Vinet,[43] S. Vitale,[11] T. Vo,[28] H. Vocca,[47,87] C. Vorvick,[28] W. D. Vousden,[24] S. P. Vyachanin,[38] A. Wade,[66] L. Wade,[16] M. Wade,[16] M. Walker,[2] L. Wallace,[1] M. Wang,[24] X. Wang,[58] R. L. Ward,[66] M. Was,[9] B. Weaver,[28] L.-W. Wei,[43] M. Weinert,[9] A. J. Weinstein,[1] R. Weiss,[11] T. Welborn,[7] L. Wen,[41] P. Wessels,[9] M. West,[15] T. Westphal,[9] K. Wette,[9] J. T. Whelan,[60] D. J. White,[79] B. F. Whiting,[6] K. Wiesner,[9] C. Wilkinson,[28] K. Williams,[111] L. Williams,[6] R. Williams,[1] T. Williams,[124] A. R. Williamson,[8] J. L. Willis,[125] B. Willke,[17,9] M. Wimmer,[9] W. Winkler,[9] C. C. Wipf,[11] A. G. Wiseman,[16] H. Wittel,[9] G. Woan,[29] J. Worden,[28] J. Yablon,[76] I. Yakushin,[7] H. Yamamoto,[1] C. C. Yancey,[53] H. Yang,[64] Z. Yang,[58] S. Yoshida,[124] M. Yvert,[3] A. Zadrożny,[101] M. Zanolin,[73] J.-P. Zendri,[104] Fan Zhang,[11,58] L. Zhang,[1] C. Zhao,[41] X. J. Zhu,[41] M. E. Zucker,[11] S. Zuraw,[54] and J. Zweizig[1]

(LIGO and Virgo Collaboration)

[1]*LIGO - California Institute of Technology, Pasadena, California 91125, USA*
[2]*Louisiana State University, Baton Rouge, Louisiana 70803, USA*
[3]*Laboratoire d'Annecy-le-Vieux de Physique des Particules (LAPP), Université de Savoie, CNRS/IN2P3, F-74941 Annecy-le-Vieux, France*
[4]*INFN, Sezione di Napoli, Complesso Universitario di Monte Sant'Angelo, I-80126 Napoli, Italy*
[5]*Università di Salerno, Fisciano, I-84084 Salerno, Italy*
[6]*University of Florida, Gainesville, Florida 32611, USA*
[7]*LIGO - Livingston Observatory, Livingston, Los Angeles 70754, USA*
[8]*Cardiff University, Cardiff CF24 3AA, United Kingdom*
[9]*Albert-Einstein-Institut, Max-Planck-Institut für Gravitationsphysik, D-30167 Hannover, Germany*
[10]*Nikhef, Science Park, 1098 XG Amsterdam, The Netherlands*
[11]*LIGO - Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[12]*Instituto Nacional de Pesquisas Espaciais, 12227-010 São José dos Campos, São Paulo, Brazil*
[13]*Inter-University Centre for Astronomy and Astrophysics, Pune 411007, India*
[14]*Tata Institute for Fundamental Research, Mumbai 400005, India*
[15]*Syracuse University, Syracuse, New York 13244, USA*
[16]*University of Wisconsin–Milwaukee, Milwaukee, Wisconsin 53201, USA*
[17]*Leibniz Universität Hannover, D-30167 Hannover, Germany*
[18]*INFN, Sezione di Pisa, I-56127 Pisa, Italy*
[19]*Università di Siena, I-53100 Siena, Italy*
[20]*Stanford University, Stanford, California 94305, USA*
[21]*The University of Mississippi, University, Mississippi 38677, USA*
[22]*California State University Fullerton, Fullerton, California 92831, USA*
[23]*INFN, Sezione di Roma, I-00185 Roma, Italy*
[24]*University of Birmingham, Birmingham B15 2TT, United Kingdom*
[25]*Albert-Einstein-Institut, Max-Planck-Institut für Gravitationsphysik, D-14476 Golm, Germany*
[26]*Montana State University, Bozeman, Montana 59717, USA*
[27]*European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy*
[28]*LIGO - Hanford Observatory, Richland, Washington 99352, USA*
[29]*SUPA, University of Glasgow, Glasgow G12 8QQ, United Kingdom*
[30]*APC, AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/Irfu, Observatoire de Paris, Sorbonne Paris Cité, 10, rue Alice Domon et Léonie Duquet, F-75205 Paris Cedex 13, France*
[31]*Columbia University, New York, New York 10027, USA*
[32]*Università di Pisa, I-56127 Pisa, Italy*
[33]*CAMK-PAN, 00-716 Warsaw, Poland*
[34]*Astronomical Observatory Warsaw University, 00-478 Warsaw, Poland*
[35]*INFN, Sezione di Genova, I-16146 Genova, Italy*
[36]*Università degli Studi di Genova, I-16146 Genova, Italy*
[37]*San Jose State University, San Jose, California 95192, USA*
[38]*Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia*
[39]*LAL, Université Paris-Sud, IN2P3/CNRS, F-91898 Orsay, France*
[40]*NASA/Goddard Space Flight Center, Greenbelt, Maryland 20771, USA*
[41]*University of Western Australia, Crawley, Western Australia 6009, Australia*
[42]*Department of Astrophysics/IMAPP, Radboud University Nijmegen, P.O. Box 9010, 6500 GL Nijmegen, The Netherlands*
[43]*Université Nice-Sophia-Antipolis, CNRS, Observatoire de la Côte d'Azur, F-06304 Nice, France*
[44]*Institut de Physique de Rennes, CNRS, Université de Rennes 1, F-35042 Rennes, France*
[45]*Laboratoire des Matériaux Avancés (LMA), IN2P3/CNRS, Université de Lyon, F-69622 Villeurbanne, Lyon, France*
[46]*Washington State University, Pullman, Washington 99164, USA*
[47]*INFN, Sezione di Perugia, I-06123 Perugia, Italy*
[48]*INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Firenze, Italy*

[49]Università degli Studi di Urbino 'Carlo Bo', I-61029 Urbino, Italy
[50]University of Oregon, Eugene, Oregon 97403, USA
[51]Laboratoire Kastler Brossel, ENS, CNRS, UPMC, Université Pierre et Marie Curie, F-75005 Paris, France
[52]VU University Amsterdam, 1081 HV Amsterdam, The Netherlands
[53]University of Maryland, College Park, Maryland 20742, USA
[54]University of Massachusetts - Amherst, Amherst, Massachusetts 01003, USA
[55]Universitat de les Illes Balears, E-07122 Palma de Mallorca, Spain
[56]Università di Napoli 'Federico II', Complesso Universitario di Monte Sant'Angelo, I-80126 Napoli, Italy
[57]Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, Ontario M5S 3H8, Canada
[58]Tsinghua University, Beijing 100084, China
[59]University of Michigan, Ann Arbor, Michigan 48109, USA
[60]Rochester Institute of Technology, Rochester, New York 14623, USA
[61]INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy
[62]National Tsing Hua University, Hsinchu Taiwan 300
[63]Charles Sturt University, Wagga Wagga, New South Wales 2678, Australia
[64]Caltech-CaRT, Pasadena, California 91125, USA
[65]Pusan National University, Busan 609-735, Korea
[66]Australian National University, Canberra, Australian Capital Territory 0200, Australia
[67]Carleton College, Northfield, Minnesota 55057, USA
[68]INFN, Gran Sasso Science Institute, I-67100 L'Aquila, Italy
[69]Università di Roma Tor Vergata, I-00133 Roma, Italy
[70]Università di Roma 'La Sapienza', I-00185 Roma, Italy
[71]University of Brussels, Brussels 1050, Belgium
[72]Sonoma State University, Rohnert Park, California 94928, USA
[73]Embry-Riddle Aeronautical University, Prescott, Azusa 86301, USA
[74]The George Washington University, Washington, DC 20052, USA
[75]University of Cambridge, Cambridge CB2 1TN, United Kingdom
[76]Northwestern University, Evanston, Illinois 60208, USA
[77]University of Minnesota, Minneapolis, Minnesota 55455, USA
[78]The University of Texas at Brownsville, Brownsville, Texas 78520, USA
[79]The University of Sheffield, Sheffield S10 2TN, United Kingdom
[80]Wigner RCP, RMKI, H-1121 Budapest, Konkoly Thege Miklósút 29-33, Hungary
[81]University of Sannio at Benevento, I-82100 Benevento, Italy
[82]INFN, Gruppo Collegato di Trento, I-38050 Povo Trento, Italy
[83]Università di Trento, I-38050 Povo, Trento, Italy
[84]Montclair State University, Montclair, New Jersey 07043, USA
[85]The Pennsylvania State University, University Park, Pennsylvania 16802, USA
[86]MTA Eötvös University, 'Lendulet' Astrophysics Research Group, Budapest 1117, Hungary
[87]Università di Perugia, I-06123 Perugia, Italy
[88]Rutherford Appleton Laboratory, HSIC, Chilton, Didcot, Oxon OX11 0QX, United Kingdom
[89]Perimeter Institute for Theoretical Physics, Ontario N2L 2Y5, Canada
[90]American University, Washington, DC 20016, USA
[91]University of Adelaide, Adelaide, South Australia 5005, Australia
[92]Raman Research Institute, Bangalore, Karnataka 560080, India
[93]Korea Institute of Science and Technology Information, Daejeon 305-806, Korea
[94]Biał ystok University, 15-424 Biał ystok, Poland
[95]University of Southampton, Southampton, SO17 1BJ, United Kingdom
[96]IISER-TVM, CET Campus, Trivandrum Kerala 695016, India
[97]Institute of Applied Physics, Nizhny Novgorod 603950, Russia
[98]Seoul National University, Seoul 151-742, Korea
[99]Hanyang University, Seoul 133-791, Korea
[100]IM-PAN, 00-956 Warsaw, Poland
[101]NCBJ, 05-400 Świerk-Otwock, Poland
[102]Institute for Plasma Research, Bhat, Gandhinagar 382428, India
[103]The University of Melbourne, Parkville, Victoria 3010, Australia
[104]INFN, Sezione di Padova, I-35131 Padova, Italy
[105]Monash University, Victoria 3800, Australia
[106]SUPA, University of Strathclyde, Glasgow G1 1XQ, United Kingdom
[107]ESPCI, CNRS, F-75005 Paris, France
[108]Argentinian Gravitational Wave Group, Cordoba, Cordoba 5000, Argentina

[109]*Università di Camerino, Dipartimento di Fisica, I-62032 Camerino, Italy*
[110]*The University of Texas at Austin, Austin, Texas 78712, USA*
[111]*Southern University and A&M College, Baton Rouge, Los Angeles 70813, USA*
[112]*College of William and Mary, Williamsburg, Virginia 23187, USA*
[113]*IISER-Kolkata, Mohanpur, West Bengal 741252, India*
[114]*National Institute for Mathematical Sciences, Daejeon 305-390, Korea*
[115]*Hobart and William Smith Colleges, Geneva, New York 14456, USA*
[116]*RRCAT, Indore, Madhya Pradesh 452013, India*
[117]*SUPA, University of the West of Scotland, Paisley PA1 2BE, United Kingdom*
[118]*Institute of Astronomy, 65-265 Zielona Góra, Poland*
[119]*Indian Institute of Technology, Gandhinagar, Ahmedabad, Gujarat 382424, India*
[120]*Instituto de Física Teórica, Universidade Estadual Paulista/International Center for Theoretical Physics-South American Institue for Research, São Paulo, São Paulo 01140-070, Brazil*
[121]*Andrews University, Berrien Springs, Michigan 49104, USA*
[122]*Trinity University, San Antonio, Texas 78212, USA*
[123]*University of Washington, Seattle, Washington 98195, USA*
[124]*Southeastern Louisiana University, Hammond, Los Angeles 70402, USA*
[125]*Abilene Christian University, Abilene, Texas 79699, USA*

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Gravitational waves from a variety of sources are predicted to superpose to create a stochastic background. This background is expected to contain unique information from throughout the history of the Universe that is unavailable through standard electromagnetic observations, making its study of fundamental importance to understanding the evolution of the Universe. We carry out a search for the stochastic background with the latest data from the LIGO and Virgo detectors. Consistent with predictions from most stochastic gravitational-wave background models, the data display no evidence of a stochastic gravitational-wave signal. Assuming a gravitational-wave spectrum of $\Omega_{\rm GW}(f) = \Omega_\alpha (f/f_{\rm ref})^\alpha$, we place 95% confidence level upper limits on the energy density of the background in each of four frequency bands spanning 41.5–1726 Hz. In the frequency band of 41.5–169.25 Hz for a spectral index of $\alpha = 0$, we constrain the energy density of the stochastic background to be $\Omega_{\rm GW}(f) < 5.6 \times 10^{-6}$. For the 600–1000 Hz band, $\Omega_{\rm GW}(f) < 0.14(f/900\ {\rm Hz})^3$, a factor of 2.5 lower than the best previously reported upper limits. We find $\Omega_{\rm GW}(f) < 1.8 \times 10^{-4}$ using a spectral index of zero for 170–600 Hz and $\Omega_{\rm GW}(f) < 1.0(f/1300\ {\rm Hz})^3$ for 1000–1726 Hz, bands in which no previous direct limits have been placed. The limits in these four bands are the lowest direct measurements to date on the stochastic background. We discuss the implications of these results in light of the recent claim by the BICEP2 experiment of the possible evidence for inflationary gravitational waves.

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Introduction.—The stochastic gravitational-wave background (SGWB) has great potential to be a rich area of study since it is expected to include contributions from a superposition of astrophysical and/or cosmological sources. Astrophysical contributions to the background might very well dominate in the LIGO and Virgo frequency band. These contributions may include compact binary coalescences [1–5], rotating neutron stars [6–8], magnetars [9–11], and supernovae [12–15]. Many mechanisms for generating cosmological contributions to the stochastic background have been postulated as well, such as inflationary models [16–23] and cosmic strings [24–27]. The recent observation of B-mode polarization in the cosmic microwave background claimed by the BICEP2 experiment [28], when using common dust emission models, suggests the presence of gravitational waves produced by primordial vacuum modes amplified by inflation (although the lack of public dust emission maps means BICEP2 could not empirically exclude dust emission as being wholly responsible for the excess B-mode polarization, and recent analyses reinforce this [29,30]). The energy density of these gravitational waves in the LIGO and Virgo frequency band is several orders of magnitude weaker than typical predictions for astrophysical contributions and 6 orders of magnitude weaker than what Advanced LIGO [31] and Advanced Virgo [32] detectors are expected to achieve. However, nonstandard inflationary models [19,20] might surpass even the predicted astrophysical contributions at the LIGO and Virgo frequencies, thereby facilitating detection with Advanced LIGO and Advanced Virgo to which the BICEP2 measurement is not sensitive. Current alternative theories of inflation, predicting a high-frequency background detectable with Advanced LIGO and Advanced Virgo, remind us that many details of inflation are still unknown, and reality may be more complicated than predicted by simple slow-roll models. Other cosmological backgrounds, e.g., from cosmic (super) strings, may be detectable as well [27].

The multitude of astrophysical and cosmological sources potentially contributing to a stochastic background offers an opportunity to study many aspects of the Universe that are not accessible through standard electromagnetic astrophysical observations [33]. With the possible observation of a gravitational-wave (GW) imprint on the cosmic microwave background (CMB) [28], we enter an exciting new phase in GW cosmology in which it appears plausible to study the physics of very early times and very high energies.

In this Letter we report on a search for the isotropic stochastic background using data gathered in 2009–2010 by the LIGO and Virgo detectors. For the search, we cross-correlated data streams from different detectors to look for a correlated stochastic signal. Most SGWB models predict backgrounds much lower than these data were capable of detecting. However, this work sets the stage for the Advanced LIGO and Advanced Virgo detectors, which are expected to achieve 4 orders of magnitude improvement in sensitivity to the GW energy density at 100 Hz and be sensitive to frequencies down to 10 Hz. Having found no statistically significant evidence of a stochastic gravitational-wave signal, we present the best constraints to date on the energy density of the SGWB from the LIGO and Virgo detectors.

Data.—Previous to this analysis, the best limits on the SGWB from LIGO and Virgo data were obtained using 2005—2007 data [34–36]. For this study, we use data from the LIGO observatories in Hanford, Washington, (H1) and Livingston Parish, Louisiana, (L1) [37] as well as the Virgo observatory in Cascina, Italy (V1) [38]. The H2 observatory in Hanford was decommissioned before these data were collected. LIGO data ran from July 2009 to October 2010. Virgo data spanned July 2009 to January 2010 and July 2010 to October 2010.

Method.—The SGWB energy density spectrum is defined as

$$\Omega_{\rm GW}(f) = \frac{f}{\rho_{\rm c}}\frac{d\rho_{\rm GW}}{df}, \tag{1}$$

where f is frequency, $\rho_{\rm c}$ is the critical (closure) energy density of the Universe, and $d\rho_{\rm GW}$ is the gravitational radiation energy density contained in the range f to $f + df$ [39]. For the LIGO and Virgo frequency bands, most theoretical models are characterized by a power law spectrum, so we assume the gravitational-wave spectrum to be [35,39,40]

$$\Omega_{\rm GW}(f) = \Omega_\alpha\left(\frac{f}{f_{\rm ref}}\right)^\alpha. \tag{2}$$

Here, $f_{\rm ref}$ is an arbitrary reference frequency (see Table I). Ω_α is a constant characterizing the amplitude of the SGWB in a given frequency band. Following the precedent of Refs. [34–36], we consider two spectral index values: $\alpha = 0$ (cosmologically motivated) and $\alpha = 3$ (astrophysically motivated).

We employ a cross-correlation method optimized for detecting an isotropic SGWB using pairs of detectors [39]. This method defines a cross-correlation estimator,

$$\hat{Y} = \int_{-\infty}^{\infty} df \int_{-\infty}^{\infty} df' \delta_T(f - f')\tilde{s}_1^*(f)\tilde{s}_2(f')\tilde{Q}(f'), \tag{3}$$

and its variance,

$$\sigma_Y^2 \approx \frac{T}{2}\int_0^\infty df P_1(f)P_2(f)|\tilde{Q}(f)|^2, \tag{4}$$

where $\delta_T(f - f')$ is the finite-time approximation to the Dirac delta function, $\tilde{s}_1$ and $\tilde{s}_2$ are Fourier transforms of time-series strain data from two interferometers, T is the coincident observation time, and P_1 and P_2 are one-sided strain power spectral densities from the two interferometers. The filter function $\tilde{Q}$ is given by

$$\tilde{Q}(f) = \lambda\frac{\gamma(f)\Omega_{\rm GW}(f)H_0^2}{f^3 P_1(f)P_2(f)}, \tag{5}$$

where λ is a normalization constant chosen such that $\langle\hat{Y}\rangle = \Omega_\alpha$, $\gamma(f)$ is the overlap reduction function arising from the combined antenna patterns of differing detector locations and orientations [42], and H_0 is the present best estimate of the Hubble constant, 68 km s^{-1} Mpc^{-1} [41].

To combine the measured $\hat{Y}$ for each of the H1L1, H1V1, and L1V1 detector pairs, we follow Ref. [39] and average results from detector pairs weighted by their variances. The optimal estimator is thus given by

TABLE I. Results of the stochastic analysis of 2009–2010 LIGO and Virgo data. Note that the previous limits are scaled to the current best estimate of H_0 [41].

Frequency (Hz)	$f_{\rm ref}$ (Hz)	α	Ω_α	95% C.L. upper limit	Previous limits
41.5–169.25	…	0	$(-1.8 \pm 4.3) \times 10^{-6}$	5.6×10^{-6}	7.7×10^{-6}
170–600	⋯	0	$(9.6 \pm 4.3) \times 10^{-5}$	1.8×10^{-4}	⋯
600–1000	900	3	0.026 ± 0.052	0.14	0.35
1000–1726	1300	3	-0.077 ± 0.53	1.0	⋯

$$\hat{Y}_{\mathrm{tot}} = \frac{\sum_l \hat{Y}_l \sigma_l^{-2}}{\sum_l \sigma_l^{-2}}, \qquad (6)$$

where l sums over detector pairs. The total variance σ_{tot}^2 is

$$\sigma_{\mathrm{tot}}^{-2} = \sum_l \sigma_l^{-2}. \qquad (7)$$

Analysis.—Following Refs. [34–36], we divide the strain time series data, down-sampled to 4096 Hz, into 50% overlapping 60 s segments that are Hann windowed and high-pass filtered with a sixth-order Butterworth filter with knee frequency 32 Hz. The data are coarse grained to obtain a frequency resolution of 0.25 Hz.

We include in the analysis only those times when a detector pair has both detectors in a low noise science mode. Excluded times fall into two different categories. We exclude data (i) from times when detector operation is unstable and (ii) from times associated with hardware injections, where simulated signals are induced by coherent movement of interferometer mirrors. These cuts cause $< 2\%$ reduction in coincident data for each detector pair. Additionally, we exclude data segments that deviate from the assumption that the power spectra of the detector noise are stationary with time [34]. Depending on the frequency band, this process excludes up to 4.7% of data segments. Combining the above effects, the cuts leave ~117 days of live time for the H1L1 detector pair, ~74 days for H1V1, and ~59 days for L1V1.

Instrumental artifacts can appear in the frequency domain. We identify high coherence bins using the same method as Ref. [34]. Lines of excess coherence are caused, for example, by power line harmonics and 16 Hz harmonics from H1 and L1 data acquisition systems. These frequency bins are excluded from the final analysis.

In order to have an end-to-end test of the detectors and the analysis pipeline, simulations of a stochastic signal are made in both the hardware and the software (by the addition of a stochastic signal to interferometer data). The successful recovery of hardware injections is described in Ref. [43]. We successfully recovered a software injection, which had $\Omega_0 = 1.2 \times 10^{-4}$ (corresponding to a signal-to-noise ratio of ≈ 10), in all three detector pairs using about one-third of the data.

Coherence studies have been made comparing data from magnetometers at the LIGO Hanford, LIGO Livingston, and Virgo observatories [44]. These studies report on the observations of correlated magnetic field noise between observatories and its potential coupling to GW detectors. While this may be a concern for future generations of detectors with their improved sensitivity, it does not affect the data used in the analysis presented in this Letter or previous results [34–36].

Results and discussion.—Applying the previously described search techniques and data-quality cuts, we obtain results in each of four frequency bands that together span 41.5—1726 Hz and are summarized in Table I. In Fig. 1 we plot the frequency-dependent contributions to Ω_α. We find no evidence for an isotropic gravitational-wave background and set direct upper limits on the energy density of the SGWB.

41.5–169.25 Hz band: We use a spectral index of $\alpha = 0$, a value motivated by cosmological models, following the precedent of Ref. [34]. Using the previous LIGO results [34] as a prior and marginalizing over detector calibration uncertainties [45], we determine the 95% confidence level (C.L.) upper limit to be $\Omega_0 < 5.6 \times 10^{-6}$. This is the first result using both LIGO and Virgo data in this frequency band and it is the best direct limit on the SGWB energy density at these frequencies. The previous S5 result in this band [34] set an upper limit of $\Omega_0 < 7.7 \times 10^{-6}$ (when scaled for the current best estimate of H_0 [41]). The limit here is a 38% improvement.

600–1000 Hz band: For this frequency band, we use a reference frequency of 900 Hz and a spectral index of $\alpha = 3$ (an astrophysically motivated value) following Ref. [35]. After taking detector calibration uncertainties into account and using the previous LIGO and Virgo results as a prior [35], we determine the 95% C.L. upper limit to be $\Omega_3 < 0.14$. Previous to this result, the best direct limit in this frequency band was from the combined results of LIGO and Virgo reported in Ref. [35] with $\Omega_3 < 0.35$ (using the present best estimate of H_0 [41]). Our limit is a factor of 2.5 lower than this result. This improvement comes from enhanced detector sensitivity at frequencies above 300 Hz in S6 and VSR2-3, despite a shorter observation time.

Additional frequency bands: We report additional frequency bands spanning 170–600 and 1000–1726 Hz. For the 170–600 Hz band, we measure the 95% C.L. upper limit to be 1.8×10^{-4}, assuming a flat prior from 0 to 1. We find the 95% C.L. upper limit to be 1.0 for the 1000–1726 Hz band, assuming a flat prior from 0 to 10. These are the first measurements of the SGWB in these bands. For the 170–600 Hz band, Ω_0 exceeds the single-sigma error bar by a factor of 2.2 which has a 10% chance of happening due to Gaussian noise given that we analyze four independent frequency bands.

Implications.—Figure 2 shows the upper limits from our measurement (solid black lines, denoted "LIGO-Virgo") in comparison with other bounds on the SGWB and several representative SGWB models. We include the indirect bound on the total GW energy density in the 10^{-10}–10^{10} Hz band derived from big bang nucleosynthesis and observations of the abundances of the lightest nuclei [33,46,47] ("BBN," dashed red line). We also include the similar indirect homogeneous bound from CMB and matter power spectra measurements [48] (dashed blue line). The bound due to millisecond pulsar timing measurements [49] is solid green ("Pulsar Limit"). The projected sensitivity of

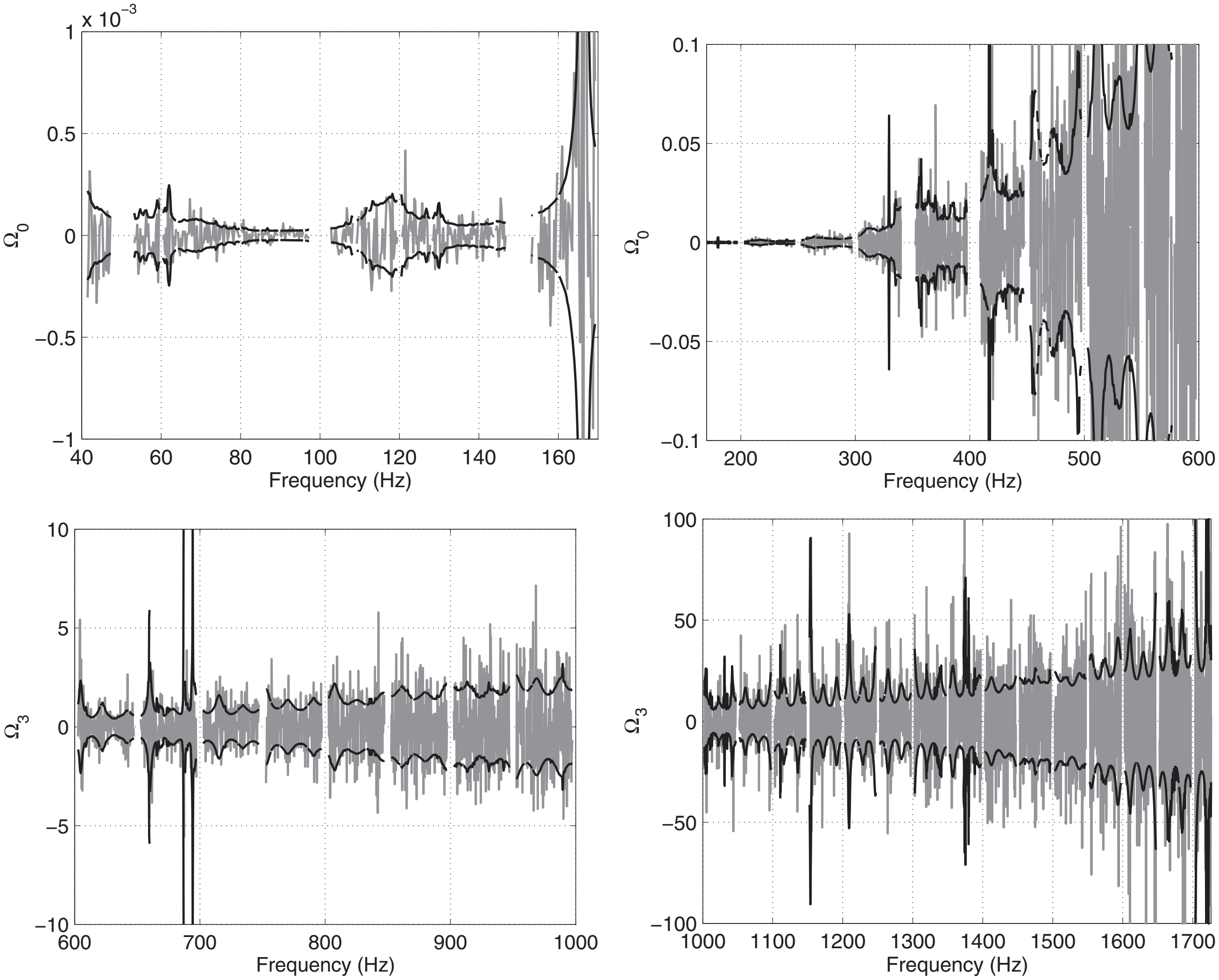

FIG. 1. Integrand of Eq. (3) multiplied by $df = 0.25$ Hz (gray) and the associated 1σ uncertainty (black). Though energy density is a positive quantity, its estimator can be either positive or negative due to noise. Fluctuations of the estimator around zero are consistent with the absence of a signal. The broadband results in Table I are obtained as a weighted average over each observing band following Ref. [39]. Each spectrum includes data from all available detector pairs in 2009–2010. The LIGO and Virgo detectors are most sensitive in the 41.5–169.25 Hz band.

the advanced GW detector network including Advanced LIGO [31], Advanced Virgo [32], and KAGRA [50] is solid blue ("AdvDet"). Recently, the BICEP2 Collaboration claimed observation of *B*-mode polarization in the CMB and considered an interpretation where the polarization signal is largely due to tensor modes [28]. A canonical slow-roll inflationary model with tensor-to-scalar ratio $r = 0.2$ (the BICEP2 best fit) yields the spectrum shown by the solid blue line ("Slow-Roll Inflation"), predicting $\Omega_{\mathrm{GW}} \sim 5 \times 10^{-16}$ in the frequency band of terrestrial GW detectors [22]. This signal is not within reach of the measurement described here, nor will it be within reach of the advanced detector network. Observation of this signal with GW detectors will require novel technology, possibly satellite based [51] or underground [52].

Future measurements of this inflationary signal by GW detectors, combined with the CMB *B*-mode polarization measurements, will constrain the tensor spectral index n_t, hence constraining inflationary models [53]. GW measurements hold great promise for probing the physics of inflation as well as for probing processes at the energy scales of 10^3–10^{10} GeV [54], well beyond those of the Large Hadron Collider. For example, the late stages of inflation could generate boosts in the GW spectrum at high frequencies, either through a preheating resonant phase [18,23] or via the backreaction of fields generated by the inflaton [19,20]. As shown in Fig. 2, the axion-inflaton model including backreaction (black line, "Axion Infl.") could produce a GW spectrum sufficiently strong to be observed by the advanced detector network. The evolution

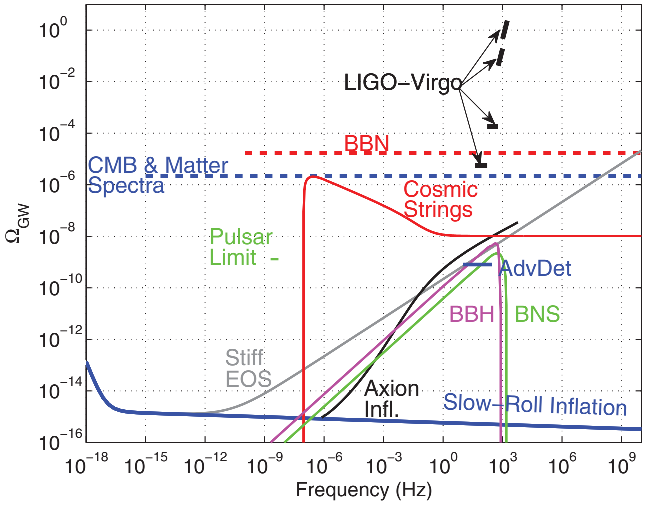

FIG. 2 (color). Normalized GW energy density versus frequency for experimental bounds and for several SGWB models (see text for detail). Note that the different experimental bounds shown in this figure constrain different quantities. The LIGO-Virgo upper limits are on Ω_α (for $\alpha = 0$, 3, see Table I), which are converted into bounds on $\Omega_{\rm GW}(f)$ as defined by Eq. (2). While "BBN" and "CMB & Matter Spectra" constrain the total GW energy density in the frequency bands indicated by their respective lines, "Pulsar Limit" is on $\Omega_{\rm GW}(f)$ at the specific frequency of $f = 2.8$ nHz.

of the Universe after inflation and before big bang nucleosynthesis is not well understood. The presence of a new "stiff" energy component at this time (with equation of state parameter $w > 1/3$) could also result in a significant high-frequency boost to the GW spectrum [55]. Figure 2 shows the example of $w = 0.6$ (denoted "Stiff EOS" for stiff equation of state), which may also be detectable by the advanced detector network. A cosmological background from cosmic strings ("Cosmic Strings") is potentially detectable as well [27].

It should also be noted that astrophysical GW foregrounds could mask the inflationary signal. Figure 2 shows the possible GW spectra from the stochastic superposition of all the binary neutron stars ("BNS," green line) and binary black holes ("BBH," magenta line) [3], which are too distant to be individually resolved with advanced detectors. Realistic binary rates may lead to a detectable stochastic signal in the advanced detector network. Other astrophysical models (including rotating neutron stars [6–8], magnetars [9–11], and others) may also contribute to the astrophysical foreground. Astrophysical sources are interesting in their own right. However, foreground subtraction may be necessary to reach a slow-roll inflationary signal. Such a subtraction will require detailed understanding of the foregrounds, which in turn may require multiple detectors operating in different frequency bands to disentangle different frequency and spatial contributions [56].

Conclusions.—The results presented above include data from both LIGO and Virgo detectors and span the frequency range of 41.5–1726 Hz. The upper limit placed on the low frequency 41.5–169.25 Hz band is 38% lower than previous direct measurements [34]. For the 600–1000 Hz band, the upper limit is a factor of 2.5 lower than previous direct measurements [35]. We also place the first upper limits over the remainder of the LIGO and Virgo frequency range: 170–600 and 1000–1726 Hz. Together, these are the lowest upper limits from direct measurements of the SGWB to date.

With Advanced LIGO and Advanced Virgo detectors on the horizon, the sensitivity of interferometers to the SGWB will improve substantially in the coming years. This will allow us to probe astrophysical sources such as binary black holes and cosmological sources such as axion inflation. We may also detect an unexpected source. To reach the SGWB generated by the standard slow-roll inflationary model, however, more sensitive gravitational wave detectors will be needed, likely deploying novel technologies.

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*sgwynne.crowder@ligo.org

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