Upper limits on a stochastic gravitational-wave background using LIGO and Virgo interferometers at 600-1000 Hz

J. Abadie
B. P. Abbott
R. Abbott
T. D. Abbott
M. Abernathy

See next page for additional authors

Follow this and additional works at: https://scholarworks.utrgv.edu/pa_fac
Part of the Astrophysics and Astronomy Commons

Recommended Citation
J. Abadie, et. al., (2012) Upper limits on a stochastic gravitational-wave background using LIGO and Virgo interferometers at 600-1000 Hz. Physical Review D - Particles, Fields, Gravitation and Cosmology 85:12. DOI: http://doi.org/10.1103/PhysRevD.85.122001

This Article is brought to you for free and open access by the College of Sciences at ScholarWorks @ UTRGV. It has been accepted for inclusion in Physics and Astronomy Faculty Publications and Presentations by an authorized administrator of ScholarWorks @ UTRGV. For more information, please contact justin.white@utrgv.edu, william.flores01@utrgv.edu.
Authors
J. Abadie, B. P. Abbott, R. Abbott, T. D. Abbott, M. Abernathy, T. Accadia, F. Acernese, C. Adams, R.
Adhikari, C. Affeldt, M. Agathos, K. Agatsuma, P. Ajith, B. Allen, E. Amador Ceron, D. Amariutei, S. B.
Anderson, W. G. Anderson, K. Arai, M. A. Arain, M. C. Araya, S. M. Aston, P. Astone, D. Atkinson, P. Aufmuth,
C. Aulbert, B. E. Aylott, S. Babak, P. Baker, and G. Ballardin

This article is available at ScholarWorks @ UTRGV: https://scholarworks.utrgv.edu/pa_fac/190
Upper limits on a stochastic gravitational-wave background using LIGO and Virgo interferometers at 600-1000 Hz

J. Abadie, B. P. Abbott, R. Abbott, T. D. Abbott, M. Abernathy, T. Accadia, F. Acernese, M. Adams, R. Adhikari, C. Affeldt, M. Agathos, K. Agatsuma, P. Ajith, B. Allen, E. Amador Ceron, D. Amariutei, S. B. Anderson, W. G. Anderson, K. Ariai, M. A. Arain, M. C. Araya, S. M. Ashton, P. Aston, D. Atkinson, P. Aufmuth, C. Aulbert, B. E. Aylott, S. Babak, P. Baker, G. Ballard, S. Ballmer, J. C. B. Barayoga, D. Barker, F. Barone, B. Barr, L. Barsotti, M.Barsuglia, M. A. Barton, I. Bartos, R. Bassiri, M. Bastarrika, A. Basti, J. Batch, J. Bauchwitz, Th. S. Bauer, M. Bebronne, D. Beck, B. Behnke, M. Bejger, M. G. Beker, A. S. Bell, A. Belletti, I. Belololpki, M. Benacquista, J. M. Berlinger, A. Bertolini, J. Betzwieser, N. Beveridge, P. T. Beyerdsdorff, I. A. Bilenko, G. Billingsley, J. Birch, R. Biswas, M. Bitossi, M. A. Bizouard, E. Black, J. K. Blackburn, J. Blackburn, D. Blair, B. Bland, M. Blom, O. Bock, T. P. Bodiya, C. Bogan, R. Bondarescu, F. Bondi, A. Bonnand, R. Bork, M. Born, V. Boschi, S. Bose, L. Bosi, B. Bouhon, S. Braccini, C. Bradaschia, P. P. Brady, V. Braginsky, M. Branschewski, J. E. Brau, J. Breyer, T. Briant, D. O. Bridges, A. Brillet, M. Brinkmann, V. Brissou, M.Britzer, A. F. Brooks, D. A. Brown, T. Bulik, H. J. Bulten, A. Buonanno, J. Burgert–Castelli, D. Buskulic, C. Buy, R. L. Byer, L. Cardonati, G. Cagnoli, E. Calloni, J. B. Camp, P. Campsie, J. Cannizzo, K. Cannon, B. Cameron, J. Cao, D. C. Capano, F. Carbognani, L. Carbone, S. Caride, S. Caudill, M. Cavaaggi, F. Cavalier, R. Cavalieri, G. Cella, C. Cepeda, E. Cesarini, O. Chaihi, T. Chalermsongsak, P. Charlton, E. Chassande-Mottin, S. Chelkowski, W. Chen, X. Chen, Y. Chen, A. Chincirri, A. Chiummo, H. Cho, J. Chow, N. Christensen, S. S. Y. Chua, C. T. Y. Chung, S. Chung, G. Ciani, D. E. Clark, J. Clark, J. H. Clayton, F. Cleva, E. Coccia, P.-F. Cohadon, C. N. Colacino, J. Colas, A. Colla, M. Colombini, A. Conte, D. Cook, T. R. Corbitt, M. Cordie, N. Cornish, A. Cori, C. A. Costa, M. Coughlin, J.-P. Coulon, P. Couvares, D. M. Coward, D. C. Coyne, J. D. E. Creighton, T. D. Creighton, A. M. Cruise, A. Cumming, L. Cunningham, E. Cuoco, R. M. Cutler, K. Dahl, S. L. Danilishin, R. Dannenberg, S. D’Antonio, K. Danzmann, V. Dattilo, B. Daudert, H. Daveloza, M. Davier, E. J. Daw, T. Day, T. Dayanga, N. De Rosa, D. Debra, G. Debreczeni, W. Del Pozzo, M. del Prete, T. Dent, V. Dergachev, R. DeRosa, R. DeSalvo, S. Dhurandhar, L. Di Fiore, A. Di Lieto, I. Di Palma, M. Di Paolo Emilio, N. Di Virgilio, M. Diaz, A. Dietz, F. Donovan, K. L. Dooley, M. Drago, R. W. P. Drever, J. C. Driggers, Z. Du, J. C. Dumas, S. Dwyer, T. Eberle, M. Edgar, R. Edwards, P. Effer, P. Ehrens, G. Endrodi, R. Engel, T. Etzel, K. Evans, M. Evans, T. Evans, M. Factourovich, V. Fanfoni, S. Fairhurst, Y. Fan, B. F. Farr, D. Fazio, H. Feirman, D. Feldbaum, F. Feroz, I. Ferrante, F. Fidecaro, L. S. Finn, I. Fiori, R. P. Fisher, R. Flaminio, M. Flanagan, S. Foley, E. Forsi, L. A. Forte, N. Fotopoulos, J.-D. Fournier, J. Franc, S. Frasca, F. Frasconi, M. Frede, Z. Frei, A. Freise, R. Frey, T. T. Fricke, D. Friederich, P. Fritschel, V. V. Frolov, M.-K. Fujimoto, P. J. Fulda, M. Fyffe, J. Gair, M. Galli, L. Gammaitoni, J. Garcia, F. Garufi, M. Gaspár, G. Gemme, R. Geng, E. Genin, A. Gennai, L. Á. Gergely, S. Ghosh, J. A. Giaime, S. Giampannis, K. D. Giardina, A. Giacchino, S. Gill, C. Gill, J. Gleason, B. Goetz, L. M. Goggin, G. González, M. L. Gorodetsky, S. Gófér, R. Gouaty, C. Graef, P. B. Graff, M. Granata, A. Grant, S. Gras, C. Gray, N. Gray, J. R. S. Gr оth ген h, A. M. Gretarsson, C. Greverie, R. Gross, H. Grote, S. Grunewald, G. M. Guidi, R. Gupta, E. K. Gustafson, R. Gustafson, T. Ha, J. M. Hallam, D. Hammel, G. Hammond, J. Hanks, C. Hanna, J. Hanson, J. Harms, G. M. Harry, I. W. Harry, E. D. Harstad, M. T. Hartman, K. Haught, J. Hayama, J.-F. Hayabu, J. Heefner, A. Heidmann, M. C. Heinzel, H. Heitmann, P. Hello, M. A. Hendry, I. S. Heng, A. W. Heptonstall, V. Herrera, M. Hewitson, S. Hild, D. Hoak, K. A. Hodges, K. Holm, M. Holtoft, T. Hong, S. Hooper, D. J. Hosken, J. Hough, E. J. Howell, B. Hughey, S. Husa, S. H. Huttner, R. Inta, T. Isogai, A. Ivanov, K. Izumi, M. Jacobson, E. James, Y. J. Jiang, P. Jaranauskas, E. Jesse, W. W. Johnson, D. I. Jones, G. J. Jones, R. Jones, L. Ju, P. Kalmus, V. Kalogera, S. Kandhasamy, G. Kang, J. B. Kanner, R. Kasturi, E. Katsavounidis, W. Katzman, H. Kaufer, K. Kawabe, S. Kawamura, F. Kawazoe, D. Kelley, W. Kells, D. G. Keppel, Z. Kerecsztes, A. Khalaidovskii, F. Y. Khalili, E. A. Khazanov, B. Kim.
L. Williams, B. Williams, B. Willke, L. Winkelmann, W. Winkler, C. C. Wipf, A. G. Wiseman, H. Wittel, G. Woan, R. Wooley, J. Worden, I. Yakushin, H. Yamamoto, K. Yamamoto, C. C. Yancey, H. Yang, D. Yeaton-Massey, S. Yoshida, P. Yu, M. Yvert, A. Zadrożny, M. Zanolin, J.-P. Zendri, F. Zhang, L. Zhang, W. Zhang, C. Zhao, N. Zotov, M. E. Zucker, and J. Zweizig.

(The LIGO Scientific Collaboration and The Virgo Collaboration)

1 LIGO - California Institute of Technology, Pasadena, CA 91125, USA
2 California State University Fullerton, Fullerton CA 92831 USA
3 SUPA, University of Glasgow, Glasgow, G12 8QQ, United Kingdom
4 Laboratoire d'Annecy-le-Vieux de Physique des Particules (LAPP), Université de Savoie, CNRS/IN2P3, F-74941 Annecy-Le-Vieux, France
5 INFN, Sezione di Napoli; Università di Napoli Federico II; Compleso Universitario di Monte S. Angela, I-80126 Napoli; Università di Salerno, Fisciano, I-84084 Salerno, Italy
6 LIGO - Livingston Observatory, Livingston, LA 70754, USA
7 Albert-Einstein-Institut, Max-Planck-Institut für Gravitationsphysik, D-30167 Hannover, Germany
8 Leibniz Universität Hannover, D-30167 Hannover, Germany
9 Nikhef, Science Park, Amsterdam, the Netherlands; VU University Amsterdam, De Boelelaan 1081, 1081 HV Amsterdam, the Netherlands
10 National Astronomical Observatory of Japan, Tokyo 181-8588, Japan
11 University of Wisconsin–Milwaukee, Milwaukee, WI 53201, USA
12 University of Florida, Gainesville, FL 32611, USA
13 University of Birmingham, Birmingham, B15 2TT, United Kingdom
14 INFN, Sezione di Roma; Università 'La Sapienza', I-00185 Roma, Italy
15 LIGO - Hanford Observatory, Richland, WA 99352, USA
16 Albert-Einstein-Institut, Max-Planck-Institut für Gravitationsphysik, D-14476 Golm, Germany
17 Montana State University, Bozeman, MT 59717, USA
18 European Gravitational Observatory (EGO), I-56021 Cascina (PI), Italy
19 Syracuse University, Syracuse, NY 13244, USA
20 LIGO - Massachusetts Institute of Technology, Cambridge, MA 02139, USA
21 Laboratoire Astroparticule et Cosmologie (APC) Université Paris Diderot, CNRS: IN2P3, CEA: DSM/IRFU, Observatoire de Paris, 10 rue A. Domon et L. Duquet, 75013 Paris - France
22 Columbia University, New York, NY 10027, USA
23 INFN, Sezione di Pisa; Università di Pisa; Università di Siena, I-53100 Siena, Italy
24 Stanford University, Stanford, CA 94305, USA
25 IM-PAN 00-956 Warszawa; Astronomical Observatory Warsaw University 00-478 Warszawa; CAMK-PAN 00-716 Warszawa; Białystok University 15-424 Białystok; IPJ 05-400 Świecie-OTwok; Institute of Astronomy 65-265 Zielona Góra, Poland
26 The University of Texas at Brownsville and Texas Southmost College, Brownsville, TX 78520, USA
27 San Jose State University, San Jose, CA 95192, USA
28 Moscow State University, Moscow, 119992, Russia
29 LAL, Université Paris-Sud, IN2P3/CNRS, F-91898 Orsay; ESPCI, CNRS, F-75005 Paris, France
30 NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA
31 University of Western Australia, Crawley, WA 6009, Australia
32 The Pennsylvania State University, University Park, PA 16802, USA
33 Université Nice-Sophia-Antipolis, CNRS, Observatoire de la Côte d’Azur, F-06304 Nice; Institut de Physique de Rennes, CNRS, Université de Rennes 1, 35042 Rennes, France
34 Laboratoire des Matériaux Avancés (LMA), IN2P3/CNRS, F-69622 Villeurbanne, Lyon, France
35 Washington State University, Pullman, WA 99164, USA
36 INFN, Sezione di Perugia; Università di Perugia, I-06123 Perugia, Italy
37 INFN, Sezione di Firenze, I-50019 Sesto Fiorentino; Università degli Studi di Urbino 'Carlo Bo', I-61029 Urbino, Italy
38 University of Oregon, Eugene, OR 97403, USA
39 Laboratoire Kastler Brossel, ENS, CNRS, UPMC, Université Pierre et Marie Curie, 4 Place Jussieu, F-75005 Paris, France
40 University of Maryland, College Park, MD 20742 USA
41 University of Massachusetts - Amherst, Amherst, MA 01003, USA
42 Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, Ontario, M5S 3H8, Canada
43 Tsinghua University, Beijing 100084, China
44 University of Michigan, Ann Arbor, MI 48109, USA
45 Louisiana State University, Baton Rouge, LA 70803, USA
46 The University of Mississippi, University, MS 38677, USA
47 Charles Sturt University, Wagga Wagga, NSW 2678, Australia
A stochastic background of gravitational waves is expected to arise from a superposition of unresolvable gravitational-wave signals of astrophysical or cosmological origin. This background is a target for the current generation of ground-based detectors. In this article we present the first joint search for a stochastic background using data from the LIGO and Virgo interferometers. In a frequency band of 600-1000 Hz, we obtained a 95% upper limit on the amplitude of $\Omega_{GW}(f) = \Omega_0 (f/900\text{Hz})^3$, of $\Omega_0 < 0.32$, assuming a value of the Hubble parameter of $h_{100} = 0.71$. These new limits are a factor of seven better than the previous best in this frequency band.

PACS numbers: 95.85.Sz, 04.80.Nn, 04.30.Db, 07.05.Kf

I. INTRODUCTION

A major science goal of current and future generations of gravitational-wave detectors is the detection of a stochastic gravitational wave background (SGWB) – a superposition of unresolvable gravitational-wave signals of astrophysical and/or cosmological origin. An astrophysical background is expected to be comprised of signals originating from astrophysical objects, for example binary neutron stars [1], spinning neutron stars [2], magnetars [3] or core-collapse supernovae [4]. A cosmological
The gravitational wave signal has a power spectrum, \( S_{GW}(f) \), which is related to \( \Omega_{GW}(f) \) by [19]

\[
S_{GW}(f) = \frac{3H_0^2}{10\pi^2} \frac{\Omega_{GW}(f)}{f^3}.
\]

Our signal model is a power law spectrum,

\[
\Omega_{GW}(f) = \Omega_\alpha \left(\frac{f}{f_R}\right)^\alpha,
\]

where \( \alpha \) is the spectral index, and \( f_R \) a reference frequency, such that \( \Omega_\alpha = \Omega_{GW}(f_R) \). For this analysis we create a filter using a model which corresponds to a white strain amplitude spectrum and choose a reference frequency of 900 Hz, such that

\[
\Omega_{GW}(f) = \Omega_3 \left(\frac{f}{900\text{Hz}}\right)^3.
\]

We choose this spectrum as it is expected that some astrophysical backgrounds will have a rising \( \Omega_{GW}(f) \) spectrum in the frequency band we are investigating [2–4]. In fact, different models predict different values of the spectral index \( \alpha \) in our frequency band, so we quote upper limits for several values.

For a pair of detectors, with interferometers labelled by \( i \) and \( j \), we calculate the cross-correlation statistic in...
the frequency domain
\[
\dot{Y} = \int_{-\infty}^{+\infty} df \ Y(f) = \int_{-\infty}^{+\infty} df \int_{-\infty}^{+\infty} d f' \ \delta_T(f-f') \ \hat{s}_i(f) \ \hat{s}_j(f') \ \hat{Q}_{ij}(f'),
\]
where \(\hat{s}_i(f)\) and \(\hat{s}_j(f)\) are the Fourier transforms of the strain time-series of two interferometers, \(\hat{Q}_{ij}(f)\) is a filter function and \(\delta_T\) is a finite-time approximation to the Dirac delta function, [13]
\[
\delta_T(f) := \int_{-T/2}^{T/2} df \ e^{-i2\pi ft} = \frac{\sin(\pi fT)}{\pi f}.
\]

We assume the detector noise is Gaussian, stationary, uncorrelated between the two interferometers and much larger than the signal. Under these assumptions, the variance of the estimator \(\hat{Y}\) is
\[
\sigma_Y^2 = \int_{0}^{+\infty} df \ \sigma_Y^2(f) \approx \frac{T}{2} \int_{0}^{+\infty} df \ P_i(f) P_j(f) |\hat{Q}_{ij}(f)|^2,
\]
where \(P_i(f)\) is the one-sided power spectral density of interferometer \(i\) and \(T\) is the integration time. By maximizing the expected signal-to-noise ratio (SNR) for a chosen model of \(\Omega_{GW}(f)\), we find the optimal filter function,
\[
\hat{Q}_{ij}(f) = N \frac{\gamma_{ij}(f) f^{\alpha-3}}{f^2 P_i(f) P_j(f)},
\]
where \(\gamma_{ij}(f)\) is the overlap reduction function (ORF) of the two interferometers and \(N\) is a normalisation factor. We choose the normalisation such that the cross-correlation statistic is an estimator of \(\Omega_x\), with expectation value \(\langle \hat{Y} \rangle = \Omega_x\). It follows that the normalisation is
\[
N = \frac{\int_0^{2\alpha} df \ \left( \frac{10\pi^2}{3H_0^2} \right) \left[ \int_0^{+\infty} df \ f^{2\alpha-6} \gamma_{ij}^2(f) \right]^{-1}}\]
\[
= \left( \int_0^{+\infty} df |\hat{I}(f)| \right)^{-1} \frac{f^2}{8T} \left( \frac{10\pi^2}{3H_0^2} \right)^2 \left( \int_0^{+\infty} df \ f^{2\alpha-6} \gamma_{ij}^2(f) \right)^{-1}.
\]

Using this filter function and normalisation gives an optimal SNR of [13]
\[
\text{SNR} \approx \frac{3H_0^2}{10\pi^2} \sqrt{2T} \left[ \int_0^{+\infty} df \ f^{2\alpha-6} \gamma_{ij}^2(f) \right]^{1/2}.
\]

The ORF encodes the separation and orientations of the detectors and is defined as [13, 20]
\[
\gamma_{ij}(f) := \frac{5}{8\pi} \sum_A \int d\Omega \ e^{i2\pi f\Omega t} \Delta_x/v F_i^A(\Omega) F_j^A(\Omega),
\]
where \(\hat{\Omega}\) is a unit vector specifying a direction on the two-sphere, \(\Delta_x = \hat{x}_i - \hat{x}_j\) is the separation of the two interferometers and
\[
F_i^A(\Omega) = e_{ab}^A(\Omega) d_{a_b}^i
\]
is the response of the \(i\)th detector to the \(A = +, x\) polarisation, where \(e_{ab}^A\) are the transverse traceless polarisation tensors. The geometry of each interferometer is described by a response tensor,
\[
d_{a_b}^i = \frac{1}{2}(\hat{x}^a \hat{x}^b - \hat{y}^a \hat{y}^b),
\]
which is constructed from the two unit vectors that point along the arms of the interferometer, \(\hat{x}\) and \(\hat{y}\) [20, 21]. At zero frequency, the ORF is determined solely by the relative orientations of the two interferometers. The LIGO interferometers are oriented in such a way as to maximize the amplitude of the ORF at low frequency, while the relative orientations of the LIGO-Virgo pairs are poor. Thus at low frequency the amplitude of the ORF between the Hanford and Livingston interferometers, \(\gamma_{HL}(f)\), is larger than that of the overlap between Virgo and any of the LIGO interferometers, \(\gamma_{HV}(f)\) or \(\gamma_{LV}(f)\) (note that the ‘HL’ and ‘HV’ overlap reduction functions hold for both H1 and H2 as they are colocated). However, at high frequency the ORF behaves as a sinc function of the frequency multiplied by the light travel time between the interferometers. As the LIGO interferometers are closer to each other than to Virgo, their ORF \(\gamma_{HL}(f)\) oscillates less, but decays more rapidly with frequency than the ORFs of the LIGO-Virgo pairs. Fig. 1 shows the ORFs between the LIGO Hanford, LIGO Livingston and Virgo sites.

We define the “sensitivity integrand”, \(I(f)\), by inserting Eq. 9 and Eq. 10 into Eq. 8, giving
\[
\sigma_Y^2 = \left( \int_0^{+\infty} df I(f) \right)^{-1} \frac{f^2}{8T} \left( \frac{10\pi^2}{3H_0^2} \right)^2 \left( \int_0^{+\infty} df \ f^{2\alpha-6} \gamma_{ij}^2(f) \right)^{-1}.
\]

This demonstrates the contribution to the inverse of the variance at each frequency. The sensitivity of each pair is dependent on the noise power spectra of the two interferometers, as well as the observing geometry, described by \(\gamma_{ij}(f)\). For interferometers operating at design sensitivity, this means that for frequencies above \(\sim 200\) Hz the LIGO-Virgo pairs make the dominant contribution to the sensitivity [22]. During its first science run Virgo was closest to design sensitivity at frequencies above several hundred Hz, which informed our decision to use the 600-1000 Hz band.

The procedure by which we analysed the data is as follows. For each pair of interferometers, labelled by \(I\), the coincident data were divided into segments, labelled by \(J\), of length \(T = 60s\). The data from each segment are Hann windowed in order to minimize spectral leakage. In order not to reduce the effective observation time, the segments are therefore overlapped by 50%. For each segment, the data from both interferometers were Fourier transformed then coarse-grained to a resolution of 0.25 Hz. The data from the adjacent segments were then used
to calculate power spectral densities (PSDs) with Welch’s method. The Fourier transformed data and the PSDs were used to calculate the estimator on $\Omega$ with frequency, but fall off more slowly, due to the larger light-travel time between the USA and Europe.

Figure 1: Plot of the overlap reduction function (ORF) for the pairs of sites used in this analysis. The dashed curve is the ORF for the two LIGO sites (HL), the solid curve is for the Hanford-Virgo sites (HV) and the dashed-dotted curve is for Livingston-Virgo (LV). We see that the LIGO orientations have been optimized for low frequency searches, around 10–100 Hz. However, this ORF falls off rapidly with frequency, such that at frequencies over $\sim 500$ Hz, the amplitude of the ORF of the HL pair is smaller than that of the Virgo pairs. The LV and HV overlap reduction functions oscillate more with frequency, but fall off more slowly, due to the larger light-travel time between the USA and Europe.

A. Data Quality

Data quality cuts were made to eliminate data that was too noisy or non-stationary, or that had correlated noise between detectors. Time segments that were known to contain large noise transients in one interferometer were removed from the analysis. We also excluded times when the digitizers were saturated, times with particularly high noise and times when the calibration was unreliable. This also involved excluding the last thirty seconds before the loss of lock in the interferometers, as they are known to have an increase in noise in this period. Additionally, we ensured that the data were approximately stationary over a period of three minutes, as the PSD estimates, $P_i(f)$, used in calculating the optimal filter and standard deviation in each segment are obtained from data in the immediately adjacent segments. This was achieved by calculating a measure of stationarity,

$$\Delta \sigma_{IJ} = \frac{|\sigma_{IJ} - \sigma'_{IJ}|}{\sigma_{IJ}},$$

for each segment, where $\sigma_{IJ}$ was calculated (following Eq. 8) using the PSDs estimated from the adjacent segments, and $\sigma'_{IJ}$ was calculated using the PSDs estimated using data from the segment itself. To ensure stationarity, we set a threshold value, $\zeta$, and all segments with values of $\Delta \sigma_{IJ} > \zeta$ are discarded. The threshold was tuned by analysing the data with unphysical time offsets between the interferometers; a value of $\zeta = 0.1$ as this ensures that the remaining data are Gaussian.

In order to exclude correlations between the instruments caused by environmental factors we excluded certain frequencies from our analysis. The frequency bins to be removed were identified in two ways. Some correlations between the interferometers were known to exist a priori, e.g. there are correlations at multiples of 60 Hz between the interferometers located in the USA due to the frequency of the power supply [19]. These were removed from the analysis, but in order to ensure that all coherent bins were identified, we also calculated the coherence,

$$\Gamma(f) = \frac{|s_1^*(f)\tilde{s}_2(f)|^2}{P_1(f)P_2(f)},$$

which is the ratio of the cross-spectrum to the product of the two power spectral densities, averaged over the whole run. This value was calculated first at a resolution of 0.1 Hz, then at 1 mHz to investigate in more detail the frequency distribution of the coherence. Several frequencies showed excess coherence; some had been identified a priori but two had not, so these were also removed from the analysis. The calculations of the power spectra and the cross-correlation were carried out at a resolution of 0.25 Hz, so we removed the corresponding 0.25 Hz bin from our analysis. Excess coherence was defined as coherence exceeding a threshold of $\Gamma(f) = 5 \times 10^{-3}$. This threshold was also chosen after analysing the data with unphysical time offsets. The excluded bins for each interferometer can be seen in Table I.

B. Timing accuracy

In order to be sure that the cross-correlation is a measure of the gravitational-wave signal present in both detectors in a pair, we must be sure that the data collected in both detectors are truly coincident. Calibration studies were carried out to determine the timing offset, if any, between the detectors and to estimate the error on this offset. These studies are described in more detail in reference [24], but we summarize them here.
Table I: Table of the the frequency bins excluded from the analysis for each interferometer. The bins at 640 Hz and 961 Hz were identified using coherence tests, while the others were excluded a priori. Also excluded were harmonics of the power line frequency at multiples of 60 Hz for the LIGO detectors and multiples of 50 Hz for Virgo. Each excluded bin is centred at the frequency listed above and has a width of 0.25 Hz.

| IFO | Notched frequencies (Hz) |
|-----|--------------------------|
| H1  | 786.25, 961             |
|     | Harmonic of calibration line |
| H2  | 640, 814.5, 961         |
|     | Excess noise, Harmonic of calibration line |
| L1  | 793.5, 961             |
|     | Harmonic of calibration line |
| V1  | 706, 710, 714, 718     |
|     | Harmonics of calibration lines |

The output of each interferometer is recorded at a rate of 16384 Hz. Each data point has an associated time-stamp and we need to ensure that data taken with identical time stamps are indeed coincident measurements of the strain, to within the calibration errors of the instruments. No offset between the instruments was identified, but several possible sources of timing error were investigated. First, approximations in our models of the interferometers can introduce phase errors. For the measurement of strain, we model the interferometers using the long-wavelength approximation (i.e. we assume that the wavelengths of the gravitational waves that we measure are much longer than the arm-lengths of the interferometers). We also make an approximation in the transfer function of the Fabry-Perot cavity; the exact function has several poles or singularities, but we use an approximation which includes only the lowest frequency pole [25]. The errors that these two approximations introduce largely cancel, with a residual error of $\sim 2\mu s$ or $\sim 1^\circ$ at 1kHz [24].

Secondly, there is some propagation time between strain manifesting in the detectors and the detector output being recorded in a frame file. This is well understood for all detectors and is accounted for (to within calibration errors) when the detector outputs are converted to strain. The time-stamp associated with each data point is therefore taken to be the GPS time at which the differential arm length occurs, to within calibration errors [24].

Thirdly, the GPS time recorded at each site has some uncertainty. The timing precision of the GPS system is $\sim 30$ ns, which corresponds with the stated location accuracy of $\sim 10$ m. Each site necessarily uses its own GPS receiver, so the relative accuracy of these receivers has been checked, by taking a Virgo GPS receiver to a LIGO site and comparing the outputs. The relative accuracy was found to be better than $1\mu s$. The receivers have also been checked against Network Time Protocol (NTP) and were found to have no offset [24]. The total error in GPS timing is far smaller than the instrumental phase calibration errors in the 600-1000 Hz frequency band (see Table II).

These investigations concluded that the timing offset between the instruments is zero for all pairs, with errors on these values that are smaller than the error in the phase calibration of each instrument. The phase calibration errors of the instruments are negligible in this analysis as their inclusion would produce a smaller than 1% change in the results at this sensitivity, and therefore the relative timing error is negligible.

C. Combination of multiple pairs

We performed an analysis of all of the available data from LIGO’s fifth science run and Virgo’s first science run. However, we excluded the H1-H2 pair as two instruments were built inside the same vacuum system, and so may have significant amounts of correlated noise. There is an ongoing investigation into identifying and removing these correlations [26], and for the present analysis, we consider only the five remaining pairs. As described above, the output of each pair yields an estimator, $Y_i$, with a standard deviation, $\sigma_i$, where $I = 1 \ldots 5$ labels the detector pair.

Using the estimators $Y_i$ and their associated error bars, $\sigma_i$, we construct a Bayesian posterior probability density function (PDF) on $\Omega_3$. Bayes theorem says that the posterior PDF of a set of unknown parameters, $\hat{\theta}$, given a set of data, $D$, is given by

$$p(\hat{\theta} | D) = \frac{p(\hat{\theta}) p(D | \theta)}{p(D)}, \quad (18)$$

where $p(\hat{\theta})$ is the prior PDF on the unknown parameters – representing the state of knowledge before the experiment – $p(D | \theta)$ is the likelihood function and $p(D)$ is a normalisation factor. In this case, the unknown parameters, $\hat{\theta}$, are the value of $\Omega_3$ and the amplitude calibration factors of the instruments, which will be discussed below. The data set, $D$, is the set of five estimators, $\{Y_i\}$, we obtain from the five pairs of instruments.

In forming this posterior, we must consider the errors in the calibration of the strain data obtained by the interferometers. In the data from one interferometer, labelled by $i$, there may be an error on the calibration of both the amplitude and the phase, such that the value we measure is

$$\tilde{s}_i(f) = e^{A_i + i\phi_i} s_i^0(f), \quad (19)$$

where $s_i^0(f)$ is the “true” value that would be measured if the interferometer were perfectly calibrated. The phase calibration errors given in Table II are negligible, and the studies described in Section II B have shown that there is no significant relative timing error between the interferometers, so we can simply assume that $\phi_i = 0$. However,
the amplitude calibration errors are not negligible, and the calibration factors take the values \( \Lambda_i = 0 \pm \epsilon_{\Lambda,i} \), where \( \epsilon_{\Lambda,i} \) are the fractional amplitude calibration errors of the instruments, which are quoted in Table II.

| Instrument | Amplitude error (%) | Phase error (deg) |
|------------|---------------------|------------------|
| HI         | 10.2                | 4.3              |
| H2         | 10.3                | 3.4              |
| L1         | 13.4                | 2.3              |
| V1         | 6.0                 | 4.0              |

Table II: Table of values of the errors in the calibration of amplitude and phase for each of the LIGO [27] and Virgo [28] instruments used in this analysis. The errors are valid over the whole 600-1000 Hz band.

The calibration factors combine such that the estimator for a pair \( I \) is

\[
\hat{Y}_I = e^{\Lambda_{I,1}} + \Lambda_{I,2} \tilde{Y}_I^t,
\]

where \( \tilde{Y}_I^t \) is the “true” value that would be measured with perfectly calibrated instruments and \( \Lambda_{I,1} \) and \( \Lambda_{I,2} \) are the calibration factors of the two instruments in pair \( I \). The likelihood function for a single estimator is given by

\[
p(\hat{Y}_I | \Omega_3, \sigma_I, \Lambda_I) = \frac{1}{\sigma_I \sqrt{2\pi}} \exp \left( -\frac{(\hat{Y}_I - e^{\Lambda_I} \Omega_3)^2}{2\sigma_I^2} \right),
\]

where we have used \( \Lambda_I = \Lambda_{I,1} + \Lambda_{I,2} \). The joint likelihood function on all the data is the product over all pairs of Equation 21

\[
p(\{\hat{Y}_I\} | \Omega_3, \{\sigma_I\}, \{\Lambda_I\}) = \prod_{I=1}^{n_{\text{IFO}}} p(\hat{Y}_I | \Omega_3, \sigma_I, \Lambda_I).
\]

In order to form a posterior PDF, we define priors on the calibration factors of the individual interferometers, \( \{\Lambda_i\} \). The calibration factors are assumed to be Gaussian distributed, with variance given by the square of the calibration errors quoted in Table II, such that

\[
p(\{\Lambda_i\}|\{\epsilon_{\Lambda,i}\}) = \prod_{i=1}^{n_{\text{IFO}}} \frac{1}{\epsilon_{\Lambda,i} \sqrt{2\pi}} \exp \left( -\frac{\Lambda_i^2}{2\epsilon_{\Lambda,i}^2} \right),
\]

where \( n_{\text{IFO}} \) is the number of interferometers we are using, in this case four. The prior on \( \Omega_3 \) is a top hat function

\[
p(\Omega_3) = \begin{cases} 
\frac{1}{\Omega_{\text{max}}} & \text{for } 0 \leq \Omega < \Omega_{\text{max}} \\
0 & \text{otherwise}
\end{cases}
\]

We choose a flat prior on \( \Omega_3 \) because, although there has been analysis in this band previously, it did not include data from the whole of the frequency band and an uninformative flat prior is conservative. We chose \( \Omega_{\text{max}} = 10 \), which is two orders of magnitude greater than the estimators and their standard deviations, such that the prior is essentially unconstrained.

We combine the prior and likelihood functions to give a posterior PDF

\[
p(\Omega_3, \{\Lambda_i\}|\{\hat{Y}_I\}, \{\sigma_I\}, \{\epsilon_{\Lambda,i}\}) = p(\Omega_3)p(\{\Lambda_i\}|\{\epsilon_{\Lambda,i}\}) \times p(\{\hat{Y}_I\}|\Omega_3, \{\sigma_I\}, \{\Lambda_i\}).
\]

We marginalize this posterior analytically over all \( \Lambda_i \) to give us a posterior on \( \Omega_3 \) alone,

\[
p(\Omega_3|\{\hat{Y}_I\}, \{\sigma_I\}, \{\epsilon_{\Lambda,i}\}) = \int_{-\infty}^{\Omega_{\text{upper}}} d\Lambda_1 \int_{-\infty}^{\Omega_{\text{upper}}} d\Lambda_2 \cdots \int_{-\infty}^{\Omega_{\text{upper}}} d\Lambda_{n_{\text{IFO}}} p(\Omega_3, \{\Lambda_i\}|\{\hat{Y}_I\}, \{\sigma_I\}, \{\epsilon_{\Lambda,i}\}).
\]

Using this posterior PDF we calculate a 95% probability interval, \( (\Omega_{\text{lower}}, \Omega_{\text{upper}}) \) on \( \Omega_3 \). We calculate the values of \( \Omega_{\text{lower}} \) and \( \Omega_{\text{upper}} \) by finding the minimum-width interval that satisfies

\[
\int_{\Omega_{\text{lower}}}^{\Omega_{\text{upper}}} p(\Omega_3|\{\hat{Y}_I\}, \{\sigma_I\}, \{\epsilon_{\Lambda,i}\})d\Omega_3 = 0.95.
\]

If we find that \( \Omega_{\text{lower}} \) is equal to zero, then we have a null result, and we can simply quote the upper limit, \( \Omega_{\text{upper}} \).

The optimal estimator, \( \hat{Y} \), is given by the combination

\[
\hat{Y} = \frac{\sum_I e^{2\Lambda_i} \hat{Y}_I \sigma_I^{-2}}{\sum_I e^{2\Lambda_i} \sigma_I^{-2}}.
\]

It has a variance, \( \sigma \), given by

\[
\sigma^{-2} = \sum_I e^{2\Lambda_i} \sigma_I^{-2}.
\]

Under the assumption that the calibration factors \( \Lambda_i \) are all equal to zero, then the optimal way to combine the results from each pair is to perform a weighted average with weights \( 1/\sigma_I^2 \) (equivalently to combining results
from multiple, uncorrelated, time segments) \[22\]

\[
\hat{Y} = \frac{\sum_j \hat{Y}_j \sigma_j^{-2}}{\sum_j \sigma_j^{-2}} \quad (30)
\]

\[
\sigma^{-2} = \sum_j \sigma_j^{-2}. \quad (31)
\]

A combined sensitivity integrand can also be found by summing the integrands from each pair: \[22\]

\[
I(f) = \sum_j I_j(f) \quad (32)
\]

### III. RESULTS

We applied the analysis described in Section II to all of the available data from the LIGO and Virgo interferometers between November 2005 and September 2007 \[1\] and obtained estimators of \(\Omega_3\) from each of five pairs, which are listed in Table III along with their standard deviations. We also create the combined estimators and their standard deviations, using Equations 30 and 31, for the full network, and for the network including only the LIGO interferometers. We see that the addition of Virgo to the network reduces the size of the standard deviation by 23%.

| Network | Estimator \(\hat{Y}_I\) |
|---------|-------------------------|
| H1L1    | 0.11 ± 0.15             |
| H1V1    | 0.55 ± 0.21             |
| H2L1    | -0.14 ± 0.25            |
| H2V1    | -0.51 ± 0.40            |
| L1V1    | 0.18 ± 0.19             |
| LIGO    | 0.05 ± 0.13             |
| all     | 0.13 ± 0.10             |

Table III: Table of values of \(\hat{Y}_I\), the estimator of \(\Omega_3\), obtained by analysing the data taken during LIGO’s fifth science run and Virgo’s first science run, over a frequency band of 600-1000 Hz, along with the standard deviation, \(\sigma_I\), of each result.

Using the posterior PDF defined in Equation 26 and the calibration errors in Table II we found a 95% upper limit of \(\Omega_3 < 0.32\), assuming the Hubble constant to be \(h_{100} = 0.71\) \[29\] (see also \[30\]), while using only the LIGO instruments obtained an upper limit of \(\Omega_3 < 0.30\). Both of the lower limits were zero. The posterior PDFs obtained by the search are shown in Figure 2, while the sensitivity integrands, which show the contribution to the sensitivity of the search from each frequency bin, are shown in Figure 3. The upper limit corresponds to a strain sensitivity of \(8.5 \times 10^{-24}\text{Hz}^{-1/2}\) using just the LIGO interferometers, or \(8.7 \times 10^{-24}\text{Hz}^{-1/2}\) using both LIGO and Virgo. The LIGO-only upper limit is, in fact, lower than the upper limit using the whole data set, even though the sensitivity of the combined LIGO-Virgo analysis is better. This is not surprising because the addition of Virgo also increases the value of the estimator. The estimator will usually lie somewhere between 0 and 2 \(\sigma\) – in this case, the LIGO-only estimator was in the lower part of that range while the LIGO-Virgo estimator was not, but the two results are entirely consistent with each other. When we add Virgo, the likelihood excludes more of the parameter space below \(\Omega_3 = 0\), but this is a region we already exclude by setting the priors. Monte-Carlo simulations show that, in the absence of a signal, the probability of the combined LIGO-Virgo upper limit being at least this much larger than the LIGO-only upper limit is 4.3%. This probability is not so small as to indicate a non-null result and we therefore conclude that the LIGO-Virgo upper limit is larger due to statistical fluctuations.

We also used the same data to calculate the 95% probability intervals for gravitational wave spectra with spectral indices ranging over \(-4 \leq \alpha \leq 4\), which correspond with different models of possible backgrounds in our frequency band. For example, a background of magnetar signals would be expected to have a spectral index of \(\alpha = 4\) \[3\]. Figure 4 shows the values of these upper limits. Note that they were all calculated using a reference frequency of 900 Hz, and Hubble parameter \(h_{100} = 0.71\).

---

\[1\] We initially analyzed only data from times after Virgo had begun taking data (May–September 2007). This preliminary analysis resulted in a marginal signal with a false-alarm probability of \(p=2\%\). To follow up, we extended the analysis to include all available LIGO data, yielding the results shown here, which are consistent with the null hypothesis.
Figure 3: Sensitivity integrands for the LIGO only result (dashed) and for the full LIGO-Virgo result (solid). We can see that the sensitivity is increased across the band by the addition of the Virgo interferometer to the search. The vertical lines correspond to frequency bins removed from the search.

Figure 4: 95% probability intervals on $\Omega_\alpha$, calculated using different values of $\alpha$. These upper limits were all calculated using the same data, with a band width of 600-1000 Hz and a reference frequency of 900 Hz. The dashed line shows the upper limit calculated using the LIGO interferometers only, while the solid line shows the upper limits calculated using all of the available data. The lower limits were all zero.

IV. VALIDATION OF RESULTS

In order to test our analysis pipeline, we created simulated signals and used software to add them to the data that had been taken during the first week of Virgo’s first science run (this week was then excluded from the full analysis). We generated frame files containing a simulated isotropic stochastic background, with $\Omega_{\text{GW}}(f) \propto f^3$. We were then able to scale this signal to several values of $\Omega_3$ and add it to the data taken from the instruments. We did not include H2 in this analysis, but used only H1, L1 and V1. Table IV shows the injected values of $\Omega_3$ and the recovered values and associated standard deviations, along with the SNR of the signal in the H1V1 pair. The recovered 95% probability intervals of the injections can be seen in Figure 5. The intervals all contain the injected value of $\Omega_3$.

It should be noted that, in order to have detectable signals in this short amount of data, the larger injections are no longer in the small signal limit. We usually make two assumptions based on this limit. The first is the approximation in Eq. 8, which only holds if the signal is much smaller than the noise, as we are ignoring terms that are first and second order in $\Omega_{\text{GW}}(f)$ \[13\]. The second assumption enters into the calculation of the noise PSDs, $P_i(f)$. We calculate these directly from the data, as in the small-signal limit we can assume $\langle |\tilde{s}_i(f)|^2 \rangle \approx \langle |\tilde{n}_i(f)|^2 \rangle$. The first assumption causes an over-estimation of the standard deviation, while the second causes our “optimal” filter to no longer be quite optimal. If we ignore these assumptions, we will underestimate the theoretical error bar, $\sigma_Y$, and the width of the posterior PDFs. However, we still find 95% probability intervals that are consistent with the injected signals.

V. COMPARISON WITH OTHER RESULTS

The previous most sensitive direct upper limit in this frequency band was $\Omega_{\text{GW}}(f) < 1.02$, obtained by the joint analysis of data from the LIGO Livingston interferometer and the ALLEGRO bar detector over a frequency band of $850 \text{ Hz} \leq f \leq 950 \text{ Hz}$ \[18\]. This result was obtained using a constant $\Omega_{\text{GW}}(f) = \Omega_0$, so should be compared with our upper limit for $\alpha = 0$. As can
Table IV: Table of values of $\Omega_3$ for software injections, along with the recovered values, the 95% probability interval and the expected SNR of each injection in the H1V1 pair. Note that the standard deviations presented in this table are underestimated, as the injections are not in the small signal limit, however we still recover the signals within the 95% probability intervals.

| Injected $\Omega_3$ | Estimator Y | 95% probability interval | SNR in H1V1 |
|---------------------|-------------|--------------------------|-------------|
| 2.0                 | 1.8±1.3     | (0.0, 4.1)               | 1.3         |
| 9.7                 | 9.1±1.5     | (5.7, 12.8)              | 6.3         |
| 20.2                | 19.3±1.8    | (14.2, 24.8)             | 13.3        |
| 95.1                | 91.1±3.7    | (72.3, 110.6)            | 62.3        |
| 203.1               | 194.1±6.2   | (154.9, 234.3)           | 133.1       |

be seen in Figure 4, our 95% upper limit for $\alpha = 0$ is $\Omega_0 < 0.16$ using all the available data, or $\Omega_0 < 0.15$ using just the LIGO interferometers, therefore our result has improved on the sensitivity of the LIGO-ALLEGRO result by a factor of $\approx 7$. The comparative strain sensitivity of the upper limits of the current search and the LIGO-ALLEGRO search can be seen in Figure 6.

The previous most sensitive direct limit at any frequency was the analysis of data from the three LIGO detectors in the fifth science run [17]. The analysis was carried out using the same data as the analysis presented in this paper, but was restricted to the frequency band $40 \text{Hz} \leq f \leq 500 \text{Hz}$. This included the most sensitive frequency band of the three detectors. The 95% upper limit on $\Omega_0$ in this band was given as $6.9 \times 10^{-6}$, which is a factor of $2 \times 10^4$ times smaller than our upper limit. They also found an upper limit on $\Omega_3$ of $7.1 \times 10^{-6}$. In order to compare that to our upper limit on $\Omega_3$, we must extend the spectrum to the frequency band analysed in this paper. The $40 \text{Hz} \leq f \leq 500 \text{Hz}$ upper limit would correspond to an upper limit at $900 \text{Hz}$ of $\Omega_3 < 0.0052$, which is a factor of $\approx 60$ smaller than the upper limit presented in this paper. The search at lower frequencies is significantly more sensitive and we would expect that in the advanced detector era the combined analysis of LIGO and Virgo detectors at low frequencies will improve even further on the previously published upper limits.

We can also compare our results with indirect upper limits on the stochastic gravitational wave background. In this band, the most stringent constraints come from Big Bang nucleosynthesis (BBN) and measurements of the cosmic microwave background (CMB). The BBN bound constrains the integrated energy density of gravitational waves over frequencies above $10^{-10} \text{Hz}$, based on observations of different relative abundances of light nuclei today. The BBN upper limit is [6]

$$\int \Omega_{\text{GW}}(f) d(\ln f) < 1.1 \times 10^{-5} (N_\nu - 3), \quad (33)$$

where $N_\nu$ is the effective number of neutrino species at the time of BBN. Recent constraints on $N_\nu$, obtained from CMB measurements, BBN modeling, and the observed abundances of light elements suggest that $3.5 \lesssim N_\nu \lesssim 4.4$ [31–34]. The CMB limit also constrains the integrated gravitational wave energy density, and is obtained from the observed CMB and matter power spectra, as these would be altered if there were a higher gravitational wave energy density at the time of decoupling. The CMB upper limit [35] is

$$\int \Omega_{\text{GW}}(f) d(\ln f) < 1.3 \times 10^{-5}. \quad (34)$$

Our upper limit is not sensitive enough to improve on these indirect upper limits, however, these indirect bounds only apply to a background of cosmological origin, whereas the bound presented here applies to astrophysical signals as well.

VI. CONCLUSIONS

Data acquired by the LIGO and Virgo interferometers have been analysed to search for a stochastic background of gravitational waves. This is the first time that data from LIGO and Virgo have been used jointly for such a
search, and we have demonstrated that the addition of Virgo increases the sensitivity of the search significantly, reducing the error bar by 23% even though the length of time for which Virgo was taking data was approximately one fifth of the time of the LIGO run. The upper limit obtained with the LIGO interferometers only is the most sensitive direct result in this frequency band to date, improved on the previous best limit, set with the joint analysis of ALLEGRO and LIGO data, by a factor of \( \approx 7 \).

Adding Virgo improves the sensitivity across the frequency band, largely due to the addition of pairs which have different overlap reduction functions. This enables us to cover the frequency band more evenly, as well as effectively increasing the total observation time. We can see that the sensitivity of the search is much improved by adding Virgo by comparing the standard deviations in Table III. However, in this case, the increased sensitivity did not lead to a decreased upper limit, as the joint estimator of \( Q_2 \) obtained by the full LIGO-Virgo search was higher than the estimator obtained by the LIGO-only analysis.

As part of this analysis, we have also developed a method of marginalizing over the error on the amplitude calibration of several interferometers. The methods used in this paper will be useful for future analyses of data from the network of interferometers, which we expect to grow, eventually including not only interferometers in North America and Europe, but also hopefully around the world.

The authors gratefully acknowledge the support of the United States National Science Foundation for the construction and operation of the LIGO Laboratory, 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, and the Italian Istituto Nazionale di Fisica Nucleare and the French Centre National de la Recherche Scientifique for the construction and operation of the Virgo detector. The authors also gratefully acknowledge the support of the research by these agencies and by the Australian Research Council, the International Science Linkages program of the Commonwealth of Australia, 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 Foundation for Fundamental Research on Matter supported by the Netherlands Organisation for Scientific Research, the Polish Ministry of Science and Higher Education, the FOCUS Programme of Foundation for Polish Science, 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. This is LIGO document LIGO-P1000128.

[1] T. Regimbau and J. A. de Freitas Pacheco, Astrophys.J. 642, 455 (2006), arXiv:gr-qc/0512008.
[2] T. Regimbau and J. A. de Freitas Pacheco, Astron. Astrophys. 376, 381 (2001), arXiv:astro-ph/0105260.
[3] T. Regimbau and J. A. de Freitas Pacheco, Astron. Astrophys. 447, 1 (2006).
[4] V. Ferrari, S. Matarrese, and R. Schneider, MNRAS 303, 247 (1999), arXiv:astro-ph/9804259.
[5] L. Grishchuk, JETP Letters 23, 293 (1976).
[6] M. Maggiore, Phys. Rep. 331, 283 (2000), gr-qc/9909001.
[7] X. Siemens, V. Mandic, and J. Creighton, Phys. Rev. Lett. 98, 111101 (2007).
[8] R. Bar-Kana, Phys. Rev. D50, 1157 (1994), arXiv:astro-ph/9401050.
[9] A. A. Starobinsky, JETP Lett. 30, 682 (1979).
[10] R. Brustein et al., Phys. Lett. B361, 45 (1995), arXiv:hep-th/9507017.
[11] V. Mandic and A. Buonanno, Phys. Rev. D73, 063008 (2006), arXiv:astro-ph/0510341.
[12] R. Apreda et al., Nucl. Phys. B631, 342 (2002), arXiv:gr-qc/0107033.
[13] B. Allen and J. D. Romano, Phys. Rev. D59, 102001 (1999), arXiv:gr-qc/9710117.
[14] B. P. Abbott et al., Reports on Progress in Physics 72, 076901 (2009), arXiv:gr-qc/0711.3041.
[15] F. Acernese et al., Classical and Quantum Gravity 25, 114045 (2008).
[16] H. Grote for the LIGO Scientific Collaboration, Classical and Quantum Gravity 25, 114043 (2008).
[17] B. P. Abbott et al., Nature 460, 990 (2009), arXiv:astro-ph/0910.0772.
[18] B. Abbott et al., Phys. Rev. D76, 022001 (2007), arXiv:gr-qc/0703068.
[19] B. Abbott et al., Astrophys.J. 659, 918 (2007), arXiv:astro-ph/0608506.
[20] E. E. Flanagan, Phys. Rev. D 48, 2389 (1993), arXiv:astro-ph/9305029.
[21] N. Christensen, Phys. Rev. D 46, 5250 (1992).
[22] G. Cella et al., Classical and Quantum Gravity 24, 639 (2007), arXiv:gr-qc/0704.2983.
[23] A. Lazarrini and J. R. Romano, LIGO Technical Document T040089-00 (2004), URL https://dcc.ligo.org/cgi-bin/DocDB/ShowDocument?docid=t040089.
[24] W. Anderson et al., Tech. Rep. VIR-0416A-10 (2010), URL https://tds.ego-gw.it/ql/?c=7701.
[25] M. Rakhmanov, J. D. Romano, and J. T. Whelan, Classical and Quantum Gravity 25, 184017 (2008), arXiv:gr-qc/0808.3805.
[26] N. V. Fotopoulos for the LIGO Scientific Collaboration, Journal of Physics Conference Series 122, 012032 (2008), arXiv:gr-qc/0801.3429.
[27] J. Abadie et al., Nucl. Instrum. Meth. A 624, 223 (2010), arXiv:gr-qc/1007.3973.
[28] T. Accadia et al., J. Phys. Conf. Ser. 228, 012015 (2010), arXiv:gr-qc/1002.2329.
[29] WMAP, Wmap-recommended parameters constraints
(2012), URL http://lambda.gsfc.nasa.gov/product/map/current/best_params.cfm.

[30] A. G. Riess et al., ApJ 730, 119 (2011).

[31] G. Mangano and P. D. Sperico, Phys. Lett. B 701, 296 (2011).

[32] J. Hamann, S. Hannestad, G. G. Raffelt, and Y. Y. Y. Wong, JCAP 1109, 034 (2011).

[33] K. M. Nollett and G. P. Holder (2011), arxiv.org/1112.2683.

[34] R. H. Cyburt et al., Astropart. Phys. 23, 313 (2005), arXiv:astro-ph/0408033.

[35] T. L. Smith, E. Pierpaoli, and M. Kamionkowski, Phys. Rev. Lett. 97, 021301 (2006).