

# Snowmass2021 - Letter of Interest

## *Multi-messenger Probes of Cosmology and Fundamental Physics using Gravitational Waves*

**Thematic Areas:** (check all that apply ☐/☒)

- (CF1) Dark Matter: Particle Like
- (CF2) Dark Matter: Wavelike
- (CF3) Dark Matter: Cosmic Probes
- (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
- (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
- (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
- (CF7) Cosmic Probes of Fundamental Physics
- (TF09) Astro-particle Physics & Cosmology

**Contact Information:**

Suvodip Mukherjee (Universty of Amsterdam)[s.mukherjee@uva.nl]  
Antonella Palmese (Fermi National Accelerator Laboratory) [palmese@fnal.gov]  
Tessa Baker (Queen Mary University of London) [t.baker@qmul.ac.uk]  
Thomas D. P. Edwards (Stockholm University) [thomas.edwards@fysik.su.se]  
Zoltán Haiman (Columbia University)[zoltan@astro.columbia.edu]  
Robert Caldwell (Dartmouth College)[robert.r.caldwell@dartmouth.edu]

**Authors:** (Listed after the references)

**Abstract:** Multi-frequency electromagnetic and gravitational wave signals are two independent avenues to explore the Universe over a vast range of redshifts and length scales. The synergy between these two probes opens a new *multi-messenger* frontier, capable of studying several aspects of fundamental physics and cosmology. With the aid of multi-frequency observations from these probes, we will be able to obtain an independent measurement of the expansion history of the Universe, which will provide a robust measurement of Hubble constant and the dark energy (DE) equation of state (EoS). The multi-wavelength nature of electromagnetic and gravitational wave signals also makes it possible to make decisive tests of the theory of General Relativity on cosmological scales through gravitational wave propagation and lensing. Multi-messenger probes will also open a new window to probe fundamental particles in the Universe and can unveil the nature of dark matter. The exploration of multi-messenger cosmology requires coordination between missions operating in different frequency bands of the electromagnetic and gravitational wave spectrum.

**Motivation:** Cosmological probes using electromagnetic (EM) observations of the cosmic microwave background (CMB), large-scale structure (LSS), and supernovae (SNe) have played a key role in constructing the standard model of cosmology. Since the seminal direct detection of Gravitational Waves<sup>1</sup> (GWs), we have been exploiting new avenues to explore the cosmos and the fundamental laws of physics which govern it. GW signals span a wide range of frequencies and are detectable above a few tens Hz by the Hanford-Livingston-Virgo-KAGRA-LIGO-India (HLVKI) detectors<sup>2-5</sup>. Future measurements from the Pulsar Timing Array (PTA)<sup>6,7</sup>, Laser Interferometer Space Antenna (LISA)<sup>8</sup>, TianQin<sup>9</sup>, Cosmic Explorer (CE)<sup>10</sup>, and the Einstein Telescope (ET)<sup>11</sup> will detect GWs at lower frequencies. Proposed experiments that are capable of observing other GW frequency ranges offer opportunities to further open this window on the Cosmic Frontier<sup>12,13</sup>. By combining this new avenue with the traditional EM probes, a new paradigm of observational cosmology using *multi-messenger* probes is possible. We briefly describe a few key topics related to cosmology and fundamental physics, which will be explored using GWs and EM probes.

**Hubble constant measurement:** Recently, two main probes of the Hubble constant  $H_0$  have come into significant tension: the latest measurement from the Cepheids and SNe Ia distance ladder and from the *Planck* observations of the CMB are discrepant at the  $4.4\sigma$  level. An independent, new probe of  $H_0$  such as GW standard sirens<sup>14-16</sup> (StSs) could help clarify this tension. StSs are ideal for this purpose as they are “self-calibrating” distance indicators, i.e., unlike SNe, they do not require a distance ladder. While the GW signal can provide a luminosity distance measurement, the mass-redshift degeneracy requires external information to derive a redshift, and thus to probe  $H_0$  and other cosmological parameters through the distance-redshift relation. Here we focus on multi-messenger StSs that require EM observations (i.e. the EM counterpart and/or host galaxies) alongside the GW data. The constraining power of StSs on  $H_0$  is most prominent for low redshift ( $z \lesssim 0.1$ ) sources with an identified unique host galaxy<sup>17</sup>. This specific case can be exploited with sustained follow-up campaigns of GW events<sup>18</sup>. On the other hand, LISA should be able to measure the luminosity distance to massive black hole (BH) binary inspirals up to redshift  $z \sim 10$ , well prior to the onset of DE domination and well beyond what SNe can probe. Successful coordination with EM observatories will enable a high redshift probe of the evolution of  $H(z)$ <sup>19</sup>. Where EM counterparts cannot be identified (e.g. as expected for most scenarios of stellar origin binary BH mergers) StSs can still provide competitive constraints on  $H_0$  through cross-correlation with galaxy catalogs<sup>14,20-25</sup>.

**Dark Energy and cosmological parameters:** Multiple analyses from observations of CMB, LSS (e.g. with baryon acoustic oscillation) and SNe have indicated the presence of DE, which is the dominant part of the energy density of the Universe. However, the true nature of DE remains to be validated from observations. GWs at higher redshifts ( $z \gtrsim 0.1$ ) bring an independent avenue to test the presence of DE and explore its EoS. It is possible to measure the DE EoS  $w(z)$  by measuring simultaneously the luminosity distances and the counterpart redshifts of GW sources since the relationship between these two numbers depends on  $w(z)$ . With the aid of cross-correlation of gravitational wave sources with the galaxy distribution identified from photometric or spectroscopic redshift surveys<sup>24</sup>, or by identifying host galaxies from concomitant EM signals, we can measure the nature of DE up to high redshift using GW probes. This will shed light on various models of DE and its coupling with matter<sup>26</sup> in an independent way than the traditional EM probes. The high redshifts reached by the gravitational wave sources possible from LISA ( $z \lesssim 10$ ), ET and CE ( $z \lesssim 2$  for binary neutron stars and  $z \lesssim 10$  for binary BHs) will reveal the expansion history up to high redshift. In addition, nearby ( $z \lesssim 0.3$ ) GW sources with counterparts can probe the peculiar velocity field of the LSS and enable precision measurements of cosmological parameters governing the growth of structure<sup>27</sup>.

**Dark Matter:** The particle nature of dark matter (DM) is one of the biggest mysteries of modern physics. Although we know little about DM, GWs may offer a new window into this dark side of our Universe. In particular, the equivalence principle states that all forms of matter must gravitate, dark or not. This offers the intriguing possibility that dynamical friction, caused by an accreted DM density spike, could affect the phase

evolution of intermediate mass ratio systems<sup>28–30</sup>. If this spike is formed from axion DM and the binary partner is a neutron star, it is possible that a radio counterpart could also be observed<sup>31</sup>. Ultra-light particle candidates can potentially solve several outstanding issues in astrophysics<sup>32</sup> and particle theory<sup>33;34</sup>. If these particles exist, BHs that are spinning sufficiently quickly may induce superradiant instabilities that lead to the growth of a *boson cloud* surrounding the central BH — the growth of boson clouds is also sensitive to the agreement between the Compton wavelength of the particle and the size of the BH. These clouds produce continuous GW emission when in isolation<sup>35–40</sup> but can also perturb the evolution of a binary system<sup>41;42</sup>. Measuring GW emission from BHs with masses across ten orders of magnitude, using both space-based and ground-based detectors, allows us to probe a similarly wide range of particle masses. In addition, multiband observations can potentially be used in tandem to further constrain these light particles<sup>43</sup>.

**Modified Gravity:** The propagation of EM waves and GWs through space-time is identical according to Einstein’s Theory of General Relativity. However, alternative theories of gravity, invoked to explain the present-day cosmic acceleration, predict deviations in the propagation of GWs<sup>44–50</sup>, and modifications in the gravitational interaction between matter and GWs through gravitational lensing<sup>51–54</sup>. These theories can lead to measurable effects on (i) the mass of graviton (as probed by the GW dispersion relation<sup>55</sup>), (ii) the difference in speed of propagation between GWs and photons<sup>56–61</sup>, (iii) the evolution of the cosmological perturbations (particularly as a function of scale)<sup>62–65</sup>, (iv) the relation between matter density and gravitational potential<sup>62–65</sup>, (v) the running of the effective Planck mass<sup>66–68</sup>, and (vi) the presence of additional GW polarizations<sup>69</sup>. Multi-messenger observations bring a unique opportunity to test the theory of gravity by testing the equivalence between the gravitational wave propagation and EM wave propagation<sup>52;53;68;70</sup>. We can test this equivalence by bounding deviations from the  $\Lambda$ CDM predictions for the luminosity distance and phase of a GW signal<sup>71</sup>, analyzing the data for additional polarization modes, and measuring the delay between photon and GW arrival times. Furthermore, GW observables often have a different sensitivity to parameters of modified gravity theories than EM probes such as the matter power spectrum or CMB. Alongside their different sources of systematic error, this empowers the combination of GW and EM probes to break degeneracies in key parameters. By using multi-band GW analyses, one can test the idea that deviations of GR are a function of scale, frequency or energy, for example, reducing to GR at tens of Hz but deviating from GR in the mHz regime<sup>72</sup>. Measuring time-delays between photons and gravitons at mHz frequencies with LISA has the advantages that the EM versus GW chirp signals arise from the same orbital motion and can be phased in a robust way without modeling the astrophysical source<sup>73;74</sup>; it also provides a higher sensitivity due to the longer distances reached by LISA. The frequency-dependence of the time delay would further probe Lorentz-violating theories<sup>75–77</sup>.

**Future outlook:** Vast science goals advancing the Cosmic Frontier are achievable from multi-messenger probes. Successful realization of these goals requires coordination between the ongoing/upcoming gravitational wave facilities and the observatories covering a wide frequency range of the EM spectrum. The tactical designs of these future missions concerning cadence, frequency bands, depth and sky coverage will be crucial to gain maximum results. In particular, we recommend that upcoming/proposed future imaging and spectroscopic<sup>78</sup> dark energy experiments (e.g. Rubin Observatory<sup>79</sup>, DESI-II<sup>80</sup>, MSE<sup>81</sup>, LS4<sup>82</sup>) allocate a significant amount of time and resources to GW follow-up in order to enable the aforementioned probes. Wide-field optical searches are paramount for counterpart discovery over the GW localization regions, and further deep multi-wavelength observations from ground and space would enable characterization of the candidate sources. We stress the importance for space missions (e.g. Athena<sup>83</sup> in X-ray, Roman Space Telescope<sup>84</sup> in infrared) to follow-up GW counterparts, in particular quick UV and deep IR measurements to observe the kilonova emission where it is hardly observable from the ground. Precision photometry of the EM light curve could in fact significantly improve cosmological constraints from StSs<sup>85</sup>. Along with the synergy between the EM and GW sector, neutrino measurements are also going to bring a new direction to the multi-messenger exploration capable of unveiling the sources of high-energy neutrinos.

## References

- [1] B. P. Abbott et al. Observation of gravitational waves from a binary black hole merger. *Phys. Rev. Lett.*, 116:061102, Feb 2016.
- [2] B.P. Abbott et al. Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA. *Living Rev. Rel.*, 21(1):3, 2018.
- [3] J. Aasi et al. Advanced LIGO. *Class. Quant. Grav.*, 32:074001, 2015.
- [4] F. Acernese, M. Agathos, K. Agatsuma, et al. Advanced virgo: a second-generation interferometric gravitational wave detector. *Classical and Quantum Gravity*, 32(2):024001, dec 2014.
- [5] LIGO-India. <https://dcc.ligo.org/LIGO-M1100296/public>.
- [6] Xavier Siemens, Jeffrey S. Hazboun, Paul T. Baker, Sarah Burke-Spolaor, Dustin Madison, Chiara Mingarelli, Joseph Simon, and Tristan Smith. Physics Beyond the Standard Model With Pulsar Timing Arrays. *arXiv e-prints*, page arXiv:1907.04960, July 2019.
- [7] Chiara M. F. Mingarelli. Probing supermassive black hole binaries with pulsar timing. *Nature Astronomy*, 3:8–10, January 2019.
- [8] Pau Amaro-Seoane, Heather Audley, Stanislav Babak, et al. Laser Interferometer Space Antenna. *arXiv e-prints*, page arXiv:1702.00786, February 2017.
- [9] Jianwei Mei et al. The TianQin project: current progress on science and technology. *PTEP*, 8 2020.
- [10] David Reitze et al. Cosmic Explorer: The U.S. Contribution to Gravitational-Wave Astronomy beyond LIGO. *Bull. Am. Astron. Soc.*, 51:035, 7 2019.
- [11] M. Punturo et al. The Einstein Telescope: A third-generation gravitational wave observatory. *Class. Quant. Grav.*, 27:194002, 2010.
- [12] Guglielmo M. Tino et al. SAGE: A Proposal for a Space Atomic Gravity Explorer. *Eur. Phys. J. D*, 73(11):228, 2019.
- [13] Yousef Abou El-Neaj et al. AEDGE: Atomic Experiment for Dark Matter and Gravity Exploration in Space. *EPJ Quant. Technol.*, 7:6, 2020.
- [14] B. F. Schutz. Determining the Hubble constant from gravitational wave observations. *Nature*, 323:310, September 1986.
- [15] B.P. Abbott et al. A gravitational-wave standard siren measurement of the Hubble constant. *Nature*, 551(7678):85–88, 2017.
- [16] B.P. Abbott et al. A gravitational-wave measurement of the Hubble constant following the second observing run of Advanced LIGO and Virgo. 8 2019.
- [17] Hsin-Yu Chen, Maya Fishbach, and Daniel E. Holz. A two per cent Hubble constant measurement from standard sirens within five years. *Nature*, 562:545–547, Oct 2018.
- [18] Antonella Palmese, Or Graur, James T. Annis, et al. Gravitational wave cosmology and astrophysics with large spectroscopic galaxy surveys. *BAAS*, 51(3):310, May 2019.

- [19] Nicola Tamanini, Chiara Caprini, Enrico Barausse, Alberto Sesana, Antoine Klein, and Antoine Petiteau. Science with the space-based interferometer eLISA. III: Probing the expansion of the Universe using gravitational wave standard sirens. *JCAP*, 04:002, 2016.
- [20] Daniel E. Holz and Scott A. Hughes. Using gravitational-wave standard sirens. *Astrophys. J.*, 629:15–22, 2005.
- [21] The DES Collaboration, The LIGO Scientific Collaboration, and The Virgo Collaboration. First measurement of the Hubble constant from a dark standard siren using the Dark Energy Survey galaxies and the LIGO/Virgo binary-black-hole merger GW170814. *arXiv e-prints*, January 2019.
- [22] A. Palmese, J. deVicente, M. E. S. Pereira, et al. A statistical standard siren measurement of the Hubble constant from the LIGO/Virgo gravitational wave compact object merger GW190814 and Dark Energy Survey galaxies. *arXiv:2006.14961 e-prints*, page arXiv:2006.14961, June 2020.
- [23] Rachel Gray, Ignacio Magaña Hernandez, Hong Qi, Ankan Sur, Patrick R. Brady, Hsin-Yu Chen, Will M. Farr, Maya Fishbach, Jonathan R. Gair, Archisman Ghosh, Daniel E. Holz, Simone Mastroianni, Christopher Messenger, Danièle A. Steer, and John Veitch. Cosmological inference using gravitational wave standard sirens: A mock data analysis. *Phys. Rev. D*, 101:122001, Jun 2020.
- [24] Suvodip Mukherjee, Benjamin D. Wandelt, Samaya M. Nissanke, and Alessandra Silvestri. Accurate and precision Cosmology with redshift unknown gravitational wave sources. *arXiv:2007.02943 e-prints*, 7 2020.
- [25] Sayantani Bera, Divya Rana, Surhud More, and Sukanta Bose. Incompleteness be damned: Inference of  $H_0$  from BBH-galaxy cross-correlations. *arXiv:2007.04271 e-prints*, 7 2020.
- [26] Jaewon Yoo and Yuki Watanabe. Theoretical Models of Dark Energy. *International Journal of Modern Physics D*, 21(12):1230002, December 2012.
- [27] Antonella Palmese and Alex G. Kim. Probing gravity and growth of structure with gravitational waves and galaxies’ peculiar velocity. *arXiv e-prints*, May 2020.
- [28] Bradley J. Kavanagh, David A. Nichols, Gianfranco Bertone, and Daniele Gaggero. Detecting dark matter around black holes with gravitational waves: Effects of dark-matter dynamics on the gravitational waveform. *arXiv e-prints*, 2 2020.
- [29] Kazunari Eda, Yousuke Itoh, Sachiko Kuroyanagi, and Joseph Silk. Gravitational waves as a probe of dark matter minispikes. *Phys. Rev. D*, 91(4):044045, 2015.
- [30] Enrico Barausse, Vitor Cardoso, and Paolo Pani. Can environmental effects spoil precision gravitational-wave astrophysics? *Phys. Rev. D*, 89(10):104059, 2014.
- [31] Thomas D.P. Edwards, Marco Chianese, Bradley J. Kavanagh, Samaya M. Nissanke, and Christoph Weniger. Unique Multimessenger Signal of QCD Axion Dark Matter. *Phys. Rev. Lett.*, 124(16):161101, 2020.
- [32] Lam Hui, Jeremiah P. Ostriker, Scott Tremaine, and Edward Witten. Ultralight scalars as cosmological dark matter. *Phys. Rev. D*, 95(4):043541, 2017.
- [33] R. D. Peccei and Helen R. Quinn. CP Conservation in the Presence of Instantons. *Phys. Rev. Lett.*, 38:1440–1443, 1977.

- [34] R. D. Peccei and Helen R. Quinn. Constraints Imposed by CP Conservation in the Presence of Instantons. *Phys. Rev.*, D16:1791–1797, 1977.
- [35] Asimina Arvanitaki and Sergei Dubovsky. Exploring the String Axiverse with Precision Black Hole Physics. *Phys. Rev. D*, 83:044026, 2011.
- [36] Richard Brito, Shrobona Ghosh, Enrico Barausse, Emanuele Berti, Vitor Cardoso, Irina Dvorkin, Antoine Klein, and Paolo Pani. Gravitational wave searches for ultralight bosons with ligo and lisa. *Phys. Rev. D*, 96:064050, Sep 2017.
- [37] C. Palomba, S. D’Antonio, P. Astone, S. Frasca, G. Intini, I. La Rosa, P. Leaci, S. Mastrogiovanni, A. L. Miller, F. Muciaccia, O. J. Piccinni, L. Rei, and F. Simula. Direct constraints on the ultralight boson mass from searches of continuous gravitational waves. *Phys. Rev. Lett.*, 123:171101, Oct 2019.
- [38] Maximiliano Isi, Ling Sun, Richard Brito, and Andrew Melatos. Directed searches for gravitational waves from ultralight bosons. *Phys. Rev. D*, 99:084042, Apr 2019.
- [39] Ling Sun, Richard Brito, and Maximiliano Isi. Search for ultralight bosons in Cygnus X-1 with Advanced LIGO. *Phys. Rev. D*, 101(6):063020, March 2020.
- [40] The LVK Collaboration. Snowmass 2021 Letter of Interest: Search for gravitational waves from ultralight boson clouds around black holes. 2020.
- [41] Daniel Baumann, Horng Sheng Chia, and Rafael A. Porto. Probing Ultralight Bosons with Binary Black Holes. *Phys. Rev. D*, 99(4):044001, 2019.
- [42] Daniel Baumann, Horng Sheng Chia, Rafael A. Porto, and John Stout. Gravitational Collider Physics. *Phys. Rev. D*, 101(8):083019, 2020.
- [43] Ken K.Y. Ng, Maximiliano Isi, Carl-Johan Haster, and Salvatore Vitale. Multiband gravitational-wave searches for ultralight bosons. *arXiv:2007.12793 e-prints*, 7 2020.
- [44] Vitor Cardoso, Oscar J. C. Dias, and Jose P. S. Lemos. Gravitational radiation in D-dimensional spacetimes. *Phys. Rev.*, D67:064026, 2003.
- [45] Ippocratis D. Saltas, Ignacy Sawicki, Luca Amendola, and Martin Kunz. Anisotropic Stress as a Signature of Nonstandard Propagation of Gravitational Waves. *Phys. Rev. Lett.*, 113(19):191101, 2014.
- [46] Lucas Lombriser and Andy Taylor. Breaking a Dark Degeneracy with Gravitational Waves. *JCAP*, 1603(03):031, 2016.
- [47] Lucas Lombriser and Nelson A. Lima. Challenges to Self-Acceleration in Modified Gravity from Gravitational Waves and Large-Scale Structure. *Phys. Lett.*, B765:382–385, 2017.
- [48] Enis Belgacem, Yves Dirian, Stefano Foffa, and Michele Maggiore. Gravitational-wave luminosity distance in modified gravity theories. *Phys. Rev. D*, 97(10):104066, 2018.
- [49] Atsushi Nishizawa. Generalized framework for testing gravity with gravitational-wave propagation. I. Formulation. *Phys. Rev.*, D97(10):104037, 2018.
- [50] Enis Belgacem, Yves Dirian, Stefano Foffa, and Michele Maggiore. Modified gravitational-wave propagation and standard sirens. *Phys. Rev. D*, 98(2):023510, 2018.

- [51] Giuseppe Congedo and Andy Taylor. Joint cosmological inference of standard sirens and gravitational wave weak lensing. *Phys. Rev. D*, 99(8):083526, 2019.
- [52] Suvodip Mukherjee, Benjamin D. Wandelt, and Joseph Silk. Probing the theory of gravity with gravitational lensing of gravitational waves and galaxy surveys. *Mon. Not. Roy. Astron. Soc.*, 494(2):1956–1970, 2020.
- [53] Suvodip Mukherjee, Benjamin D. Wandelt, and Joseph Silk. Multimessenger tests of gravity with weakly lensed gravitational waves. *Phys. Rev. D*, 101(10):103509, 2020.
- [54] Jose María Ezquiaga, Wayne Hu, and Macarena Lagos. Apparent Superluminality of Lensed Gravitational Waves. *Phys. Rev. D*, 102(2):023531, 2020.
- [55] B.P. Abbott, R. Abbott, T.D. Abbott, S. Abraham, F. Acernese, K. Ackley, C. Adams, R.X. Adhikari, V.B. Adya, C. Affeldt, and et al. Tests of general relativity with the binary black hole signals from the ligo-virgo catalog gwtc-1. *Physical Review D*, 100(10), Nov 2019.
- [56] T. Baker, E. Bellini, P. G. Ferreira, M. Lagos, J. Noller, and I. Sawicki. Strong Constraints on Cosmological Gravity from GW170817 and GRB 170817A. *Physical Review Letters*, 119(25):251301, December 2017.
- [57] Jose María Ezquiaga and Miguel Zumalacárregui. Dark Energy After GW170817: Dead Ends and the Road Ahead. *Phys. Rev. Lett.*, 119(25):251304, 2017.
- [58] P. Creminelli and F. Vernizzi. Dark Energy after GW170817 and GRB170817A. *Physical Review Letters*, 119(25):251302, December 2017.
- [59] Jeremy Sakstein and Bhuvnesh Jain. Implications of the Neutron Star Merger GW170817 for Cosmological Scalar-Tensor Theories. *Phys. Rev. Lett.*, 119(25):251303, 2017.
- [60] S. Boran, S. Desai, E.O. Kahya, and R.P. Woodard. GW170817 Falsifies Dark Matter Emulators. *Phys. Rev. D*, 97(4):041501, 2018.
- [61] Yashar Akrami, Philippe Brax, Anne-Christine Davis, and Valeri Vardanyan. Neutron star merger gw170817 strongly constrains doubly coupled bigravity. *Physical Review D*, 97(12), Jun 2018.
- [62] Rachel Bean, David Bernat, Levon Pogosian, Alessandra Silvestri, and Mark Trodden. Dynamics of Linear Perturbations in  $f(R)$  Gravity. *Phys. Rev.*, D75:064020, 2007.
- [63] Wayne Hu and Ignacy Sawicki. A Parameterized Post-Friedmann Framework for Modified Gravity. *Phys. Rev.*, D76:104043, 2007.
- [64] Fabian Schmidt. Weak Lensing Probes of Modified Gravity. *Phys. Rev.*, D78:043002, 2008.
- [65] Alessandra Silvestri, Levon Pogosian, and Roman V. Buniy. Practical approach to cosmological perturbations in modified gravity. *Phys. Rev.*, D87(10):104015, 2013.
- [66] Enis Belgacem, Gianluca Calcagni, Marco Crisostomi, et al. Testing modified gravity at cosmological distances with LISA standard sirens. *JCAP*, 2019(7):024, Jul 2019.
- [67] Macarena Lagos, Maya Fishbach, Philippe Landry, and Daniel E. Holz. Standard sirens with a running planck mass. *Phys. Rev. D*, 99:083504, Apr 2019.

- [68] Tessa Baker and Ian Harrison. Constraining Scalar-Tensor Modified Gravity with Gravitational Waves and Large Scale Structure Surveys. *arXiv:2007.13791 e-prints*, July 2020.
- [69] Srashti Goyal, K. Haris, Ajit Kumar Mehta, and Parameswaran Ajith. Testing the nature of gravitational-wave polarizations using strongly lensed signals. *arXiv:2008.07060 e-prints*.
- [70] B.P. Abbott et al. Gravitational Waves and Gamma-rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A. *Astrophys. J. Lett.*, 848(2):L13, 2017.
- [71] S. Mastrogiovanni, D. A. Steer, and M. Barsuglia. Probing modified gravity theories and cosmology using gravitational-waves and associated electromagnetic counterparts. *Phys. Rev. D*, 102:044009, Aug 2020.
- [72] Claudia de Rham and Scott Melville. Gravitational Rainbows: LIGO and Dark Energy at its Cutoff. *Phys. Rev. Lett*, 121(22):221101, November 2018.
- [73] Zoltán Haiman. Electromagnetic chirp of a compact binary black hole: A phase template for the gravitational wave inspiral. *Phys. Rev. D*, 96(2):023004, July 2017.
- [74] Yike Tang, Zoltán Haiman, and Andrew MacFadyen. The late inspiral of supermassive black hole binaries with circumbinary gas discs in the LISA band. *MNRAS*, 476(2):2249–2257, May 2018.
- [75] Bence Kocsis, Zoltán Haiman, and Kristen Menou. Premerger Localization of Gravitational Wave Standard Sirens with LISA: Triggered Search for an Electromagnetic Counterpart. *ApJ*, 684(2):870–887, September 2008.
- [76] Zoltán Haiman, Bence Kocsis, and Kristen Menou. The Population of Viscosity- and Gravitational Wave-driven Supermassive Black Hole Binaries Among Luminous Active Galactic Nuclei. *ApJ*, 700(2):1952–1969, August 2009.
- [77] Saeed Mirshekari, Nicolás Yunes, and Clifford M. Will. Constraining lorentz-violating, modified dispersion relations with gravitational waves. *Phys. Rev. D*, 85:024041, Jan 2012.
- [78] R. Morgan, A. Garcia, and The DESGW Collaboration. Snowmass 2021 Letter of Interest: Probing Dark Energy with Gravitational Wave Standard Sirens in the HEP Experimental Cosmic Frontier . 2020.
- [79] Rubin Observatory. <https://www.lsst.org>.
- [80] The DESI Collaboration. Snowmass 2021 Letter of Interest: Next-generation Spectroscopic Surveys with DESI. 2020.
- [81] The MSE Science Team. The detailed science case for the maunakea spectroscopic explorer, 2019 edition. *arXiv:1904.04907 e-prints*, 2019.
- [82] P. Nugent et al. Snowmass 2021 Letter of Interest: La Silla Schmidt Southern Survey. 2020.
- [83] Athena X-ray Observatory. <https://www.the-athena-x-ray-observatory.eu>.
- [84] Roman Space Telescope. <https://roman.gsfc.nasa.gov>.
- [85] S. Dhawan, M. Bulla, A. Goobar, A. Sagués Carracedo, and C. N. Setzer. Constraining the Observer Angle of the Kilonova AT2017gfo Associated with GW170817: Implications for the Hubble Constant. *ApJ*, 888(2):67, January 2020.



## Authors:

Ana Achúcarro (Leiden University) [achucar@lorentz.leidenuniv.nl]  
Michalis Agathos (University of Cambridge) [magathos@damtp.cam.ac.uk]  
Özgür Akarsu (Istanbul Technical University) [akarsuo@itu.edu.tr]  
Yashar Akrami (École Normale Supérieure, Paris) [akrami@ens.fr]  
Lorenzo Amati (INAF - OAS Bologna, Italy) [lorenzo.amati@inaf.it]  
Mustafa A. Amin (Rice University) [mustafa.a.amin@rice.edu]  
Manuel, Arca Sedda (Astronomisches Rechen Institut-Zentrum für Astronomie der Universität Heidelberg) [m.arcasedda@gmail.com]  
Pia Astone (INFN, Roma) [pia.astone@roma1.infn.it]  
Dimitry Ayzenberg (University of Tübingen) [dimitry.ayzenberg@mnf.uni-tuebingen.de]  
Anastasios Avgoustidis (University of Nottingham) [Anastasios.Avgoustidis@nottingham.ac.uk]  
Tristan Bachmann (University of Chicago) [tgbachmann@uchicago.edu]  
David Bacon (University of Portsmouth) [david.bacon@port.ac.uk]  
Vishal Baibhav (Johns Hopkins University) [vbaibha1@jh.edu]  
Tessa Baker (Queen Mary University of London) [t.baker@qmul.ac.uk]  
Enrico Barausse (SISSA Scuola Internazionale Superiore di Studi Avanzati) [barausse@sissa.it]  
Nicola Bartolo (University of Padova, Italy) [nicola.bartolo@pd.infn.it]  
Imre Bartos (University of Florida) [imrebartos@ufl.edu]  
Daniel Baumann (University of Amsterdam) [dbaumann@uva.nl]  
Michał Bejger (Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences) [bejger@camk.edu.pl]  
Emilio Bellini (University of Oxford) [emilio.bellini@physics.ox.ac.uk]  
Nicola Bellomo (University of Barcelona) [nicola.bellomo@icc.ub.edu]  
Ido Ben-Dayan (Ariel University) [idobd@ariel.ac.il],  
Segev BenZvi (University of Rochester) [sbenzvi@ur.rochester.edu],  
Daniele Bertacca (University of Padova and INFN Sezione di Padova, Italy) [daniele.bertacca@pd.infn.it]  
Emanuele Berti (Johns Hopkins University) [berti@jhu.edu]  
Gianfranco Bertone (U. of Amsterdam) [g.bertone@uva.nl]  
Ofek Birnholtz (Bar-Ilan University) [ofek.birnholtz@biu.ac.il]  
Clecio Bom (Centro Brasileiro de Pesquisas Físicas, Brazil) [debom@cbpf.br]  
Béatrice Bonga (Radboud University Nijmegen) [bbonga@science.ru.nl]  
Sukanta Bose (IUCAA & Washington State University) [sukanta@iucaa.in]  
Marica Branchesi (Gran Sasso Science Institute) [marica.branchesi@gssi.it]  
Richard Brito (Sapienza University of Rome) [richard.brito@roma1.infn.it]  
Marco Bruni (University of Portsmouth, UK, , and INFN Sezione di Trieste, Italy) [marco.bruni@port.ac.uk]  
Alessandra Buonanno (Max Planck Institute for Gravitational Physics) [alessandra.buonanno@aei.mpg.de]  
Robert Caldwell (Dartmouth College) [robert.r.caldwell@dartmouth.edu]  
Pedro R. Capelo (University of Zurich) [pcapelo@physik.uzh.ch]  
Laurentiu Caramete (Institute of Space Science, Romania) [lcaramete@spacescience.ro]  
Alejandro Cárdenas-Avendaño (Fundacion Universitaria Konrad Lorenz) [alejandro.cardenas@konradlorenz.edu.co]  
Carmelita Carbone (Istituto di Astrofisica Spaziale e Fisica cosmica Milano and INFN Sezione di Milano, Italy) [carmelita.carbone@inaf.it],  
Vitor Cardoso (Instituto Superior Técnico, Lisbon) [vitor.cardoso@ist.utl.pt]  
Peter Cameron (Brookhaven National Lab - retired) [electronGaugeGroup@gmail.com]  
Chiara Caprini (CNRS, APC Paris) [caprini@apc.in2p3.fr]  
Marco Cavaglia (Missouri University of Science and Technology) [cavagliam@mst.edu]  
Jose A. R. Cembranos (Universidad Complutense de Madrid) [cembra@fis.ucm.es]  
Sukanya Chakrabarti (RIT) [chakrabarti@astro.rit.edu]

Chia-Feng Chang (University of California-Riverside) [chiafeng.chang@email.ucr.edu]  
 Eric Chassande-Mottin (CNRS/IN2P3 Université de Paris, AstroParticule et Cosmologie) [ecm@apc.in2p3.fr]  
 Hsin-Yu Chen (MIT) [himjiu@mit.edu]  
 Jens Chluba (University of Manchester) [jens.chluba@manchester.ac.uk]  
 Sebastien Clesse (University of Louvain) [sebastien.clesse@uclouvain.be]  
 Katy Clough (University of Oxford) [katy.clough@physics.ox.ac.uk]  
 Lucas Gardai Collodel (University of Tübingen) [lucas.gardai-collodel@uni-tuebingen.de]  
 Monica Colpi (University of Milano Bicocca) [monica.colpi@unimib.it]  
 Geoffrey Compère (Université Libre de Bruxelles) [gcompere@ulb.ac.be]  
 Giuseppe Congedo (University of Edinburgh) [giuseppe.congedo@ed.ac.uk]  
 Carlo R. Contaldi (Imperial College London) [c.contaldi@imperial.ac.uk]  
 Michael Coughlin (University of Minnesota) [cough052@umn.edu]  
 Bryce Cousins (Pennsylvania State University) [bfc5288@Psu.edu]  
 Djuna Croon (TRIUMF) [dcroon@triumf.ca]  
 Yanou Cui (University of California- Riverside) [yanou.cui@ucr.edu]  
 Saurya Das (University of Lethbridge) [saurya.das@uleth.ca]  
 Sayak Datta (Inter-University Centre for Astronomy and Astrophysics) [skdatta@iucaa.in]  
 Andrea Derdzinski (University of Zurich) [andrea@ics.uzh.ch]  
 Shantanu Desai (IIT Hyderabad) [shantanud@phy.iith.ac.in]  
 Kyriakos Destounis, University of Tübingen, kyriakos.destounis@uni-tuebingen.de  
 Biprateep Dey (University of Pittsburgh) [biprateep@pitt.edu]  
 Tristano Di Girolamo (University of Naples "Federico II") [tristano.digirolamo@na.infn.it]  
 Eleonora Di Valentino (University of Manchester, UK) [eleonora.divalentino@manchester.ac.uk]  
 Tim Dietrich (University of Potsdam) [tim.dietrich@uni-potsdam.de]  
 Daniela Doneva (University of Tübingen) [daniela.doneva@uni-tuebingen.de]  
 Sorin Dragomir (Università degli Studi della Basilicata, Dipartimento di Matematica, Informatica ed Economia, Potenza, Italy), [sorin.dragomir@unibas.it]  
 Ruth Durrer (University of Geneva) [ruth.durrer@unige.ch]  
 Anne Ealet (Claude Bernard Lyon 1 University - IP2I) [ealet@ip2i.in2p3.fr]  
 Thomas D. P. Edwards (Stockholm University) [thomas.edwards@fysik.su.se]  
 Stephanie Escoffier (Aix-Marseille University - CPPM) [escoffier@cppm.in2p3.fr]  
 Jose M. Ezquiaga (University of Chicago) [ezquiaga@uchicago.edu]  
 JiJi Fan (Brown University) [jiji\_fan@brown.edu]  
 Matteo Fasiello (ICG Portsmouth) [matteo.fasiello@port.ac.uk]  
 Pedro G. Ferreira (University of Oxford) [pedro.ferreira@physics.ox.ac.uk]  
 Giacomo Fragione (Northwestern University) [giacomo.fragione@northwestern.edu]  
 Tassos Fragos (University of Geneva) [anastasios.fragkos@unige.ch]  
 Noemi Frusciante (Instituto de Astrofísica e Ciências do Espaço, Universidade de Lisboa) [nfrusciante@fc.ul.pt]  
 Juan García-Bellido (Universidad Autónoma de Madrid) [juan.garciabellido@uam.es]  
 László Árpád Gergely (University of Szeged, Hungary) [laszlo.a.gergely@gmail.com]  
 Davide Gerosa (University of Birmingham) [d.gerosa@bham.ac.uk]  
 Archisman Ghosh (Ghent University) [archisman.ghosh@ugent.be]  
 Leonardo Gualtieri (Sapienza University of Rome) [leonardo.gualtieri@roma1.infn.it]  
 Mandeep S. S. Gill (Stanford University) [msgill@slac.stanford.edu]  
 Aniello Grado (INAF, Naples, Italy) [aniello.grado@inaf.it]  
 Salman Habib (Argonne National Laboratory) [habib@anl.gov]  
 Leïla Haegel (University of Paris, CNRS, Astroparticles and Cosmology) [leila.haegel@apc.in2p3.fr]  
 ChangHoon Hahn (Lawrence Berkeley National Laboratory) [changhoonhahn@lbl.gov]

Zoltán Haiman (Columbia University) [zoltan@astro.columbia.edu]  
 Fawad Hassan (Stockholm University) [fawad@fysik.su.se]  
 Carlos Herdeiro (Aveiro University) [herdeiro@ua.pt]  
 Kenneth Herner (Fermi National Accelerator Laboratory) [kherner@fnal.gov]  
 Tanja Hinderer (Utrecht University) [t.p.hinderer@uu.nl]  
 David Hobbs (Lund Observatory) [david@astro.lu.se]  
 Daniel Holz (University of Chicago) [qrs@uchicago.edu]  
 Yi-Ming Hu (Sun Yat-sen University) [huyiming@sysu.edu.cn]  
 Eliu A. Huerta (University of Illinois at Urbana-Champaign) [eliu@illinois.edu]  
 Scott A. Hughes (Massachusetts Institute of Technology) [sahughes@mit.edu]  
 Rajeev K. Jain (Indian Institute of Science, Bangalore, India) [rkjain@iisc.ac.in],  
 Philippe Jetzer (University of Zürich, Switzerland) [jetzer@physik.uzh.ch]  
 Cristian Joana (University of Louvain) [cristian.joana@uclouvain.be]  
 Emre Onur Kahya (Istanbul Technical University and MILA-Quebec AI Institute) [kahyaemr@mila.quebec]  
 Christos Karathanasis (High Energy Physics Institute, IFAE, Barcelona) [ckarathanasis@ifae.es]  
 Stavros Katsanevas (EGO) [stavros.katsanevas@ego-gw.it]  
 Bradley J. Kavanagh (IFCA, CSIC-UC) [kavanagh@ifca.unican.es]  
 Ryan Keeley (KASI) [rkeeley@kasi.re.kr]  
 David Keitel (Universitat de les Illes Balears) [david.keitel@ligo.org]  
 Shiho Kobayashi (Liverpool John Moores University) [S.Kobayashi@ljmu.ac.uk]  
 Albert Kong (National Tsing Hua University, Taiwan) [akong@gapp.nthu.edu.tw]  
 Savvas M. Koushiappas (Brown University) [koushiappas@brown.edu]  
 Alex G. Kim (LBNL) [agkim@lbl.gov]  
 Joachim Kopp (CERN) [jkopp@cern.ch]  
 Kazuya Koyama (University of Portsmouth) [Kazuya.Koyama@port.ac.uk]  
 Martin Kunz (Université de Genève) [martin.kunz@unige.ch],  
 Benjamin L'Huillier (Yonsei University) [blhuillier@yonsei.ac.kr],  
 Macarena Lagos (University of Chicago) [mlagos@kip.uchicago.edu]  
 Ofer Lahav (University College London) [o.lahav@ucl.ac.uk]  
 Ryan N. Lang (Massachusetts Institute of Technology) [rlang@mit.edu]  
 Kenny C. Y. Ng (The Chinese University of Hong Kong) [kcyng@phy.cuhk.edu.hk]  
 Lan Q. Nguyen (University of Notre Dame) [lnguyen3@nd.edu]  
 Paola Leaci (Sapienza University and Rome INFN) [paola.leaci@roma1.infn.it]  
 Benjamin V. Lehmann (University of California, Santa Cruz) [blehmann@ucsc.edu]  
 Eugene A. Lim (King's College London), [eugene.a.lim@gmail.com]  
 Xin Liu (University of Illinois at Urbana-Champaign) [xinliuxl@illinois.edu]  
 Giuseppe Lodato (Università degli Studi di Milano, Italy) [giuseppe.lodato@unimi.it]  
 Lucas Lombriser (University of Geneva) [lucas.lombriser@unige.ch]  
 Georgios Loukes-Gerakopoulos (Astronomical Institute of the Czech Academy of Sciences) [gglukes@asu.cas.cz]  
 Ignacio Magaña Hernandez (University of Wisconsin, Milwaukee) [maganah2@uwm.edu],  
 Michele Maggiore (University of Geneva, Switzerland) [michele.maggiore@unige.ch]  
 Elisabetta Maiorano (INAF-OAS, Bologna) [elisabetta.maiorano@inaf.it]  
 Ilya Mandel (Monash University) [ilya.mandel@monash.edu]  
 Vuk Mandic (University of Minnesota) [vuk@umn.edu]  
 Prado Martín-Moruno (Universidad Complutense de Madrid) [pradomm@ucm.es]  
 Andrea Maselli (Sapienza University of Rome, Italy) [andrea.maselli@roma1.infn.it]  
 Simone Mastrogiovanni (University of Paris, CNRS, Astroparticles and Cosmology) [mastrosi@apc.in2p3.fr]  
 Lucio Mayer (University of Zürich, Switzerland) [lmayer@physik.uzh.ch]

Sabino Matarrese (University of Padova and INFN Sezione di Padova, Italy) [sabino.matarrese@pd.infn.it]  
 Samuel D. McDermott (Fermilab) [sammcd00@fnal.gov]  
 Sean McGee (University of Birmingham) [smcgee@star.sr.bham.ac.uk]  
 Eugenio Megías (University of Granada, Spain) [emegias@ugr.es]  
 David F. Mota (University of Oslo, Norway) [mota@astro.uio.no]  
 Chiara M. F. Mingarelli (University of Connecticut and Flatiron Institute) [cmingarelli@flatironinstitute.org]  
 Edvard Mörtzell (Stockholm University) [edvard@fysik.su.se]  
 David F. Mota (Institute of Theoretical Astrophysics, University of Oslo) [mota@astro.uio.no]  
 Suvodip Mukherjee (University of Amsterdam) [s.mukherjee@uva.nl]  
 Sourabh Nampalliwar (University of Tübingen) [sourabh.nampalliwar@uni-tuebingen.de]  
 Germano Nardini (University of Stavanger) [germano.nardini@uis.no]  
 David Neilsen (Brigham Young University) [david.neilsen@byu.edu]  
 David Nichols (University of Virginia) [david.nichols@virginia.edu]  
 Samaya Nissanke (University of Amsterdam) [samaya.nissanke@uva.nl]  
 Nelson J. Nunes (Instituto de Astrofísica e Ciências do Espaço, Universidade de Lisboa) [njnunes@fc.ul.pt],  
 Vasilis K. Oikonomou (Aristotle University of Thessaloniki) [voikonomou@auth.gr]  
 Roberto Oliveri (CEICO, Institute of Physics of the Czech Academy of Sciences) [roliveri@fzu.cz]  
 Giorgio Orlando (University of Padova) [giorgio.orlando@phd.unipd.it]  
 Fabio Pacucci (Harvard University & SAO) [fabio.pacucci@cfa.harvard.edu]  
 Eliana Palazzi (INAF-OAS, Bologna) [eliana.palazzi@inaf.it]  
 Antonella Palmese (Fermi National Accelerator Laboratory) [palmese@fnal.gov]  
 Francesco Pannarale (Sapienza University of Rome) [francesco.pannarale@uniroma1.it]  
 George Pappas (Aristotle University of Thessaloniki) [gpappas@auth.gr]  
 Sohyun Park (CERN) [sohyun.park@cern.ch]  
 Vasileios Paschalidis (University of Arizona) [vpaschal@email.arizona.edu]  
 Pascal Paschos (University of Chicago) [paschos@uchicago.edu] Maria E. S. Pereira (Brandeis University) [mariaeli@brandeis.edu]  
 Elena Pian (INAF-OAS, Bologna) [elena.pian@inaf.it]  
 Ornella Juliana Piccinni (INFN Sezione di Roma) [ornella.juliana.piccinni@roma1.infn.it]  
 Tsvi Piran (Hebrew University, Jerusalem) [tsvi.piran@mail.huji.ac.il]  
 Khun Sang Phukon (Nikhef & University of Amsterdam) [k.s.phukon@nikhef.nl]  
 Nikodem Popławski (University of New Haven) [NPoplawski@newhaven.edu]  
 John Quenby (Imperial College) [j.quenby@imperial.ac.uk]  
 Marco Raveri (University of Pennsylvania) [mraveri@sas.upenn.edu]  
 Vivien Raymond (Cardiff University) [raymondv@cardiff.ac.uk],  
 Angelo Ricciardone (INFN Sezione di Padova and University of Padova, Italy) [angelo.ricciardone@pd.infn.it]  
 John Regan (Maynooth University, Ireland) [john.regan@mu.ie]  
 Sébastien Renaux-Petel (Institut d'Astrophysique de Paris) [renaux@iap.fr]  
 Keith Riles (University of Michigan) [kriles@umich.edu]  
 Andrea Rossi (INAF-OAS, Bologna) [andrea.rossi@inaf.it]  
 Stephan Rosswog (Stockholm University, Sweden) [stephan.rosswog@astro.su.se]  
 Milton Ruiz (University of Illinois at Urbana-Champaign) [ruizm@illinois.edu]  
 Ester Ruiz Morales (Universidad Politécnica de Madrid) [ester.ruiz.morales@upm.es]  
 Samanta Saha (BRAC University, Dhaka, Bangladesh) [samanta.saha@bracu.ac.bd]  
 Martin Sahlén (Uppsala University) [martin.sahlen@physics.uu.se]  
 Khaled Said (University of Queensland) [k.saidahmedsoliman@uq.edu.au]  
 Mairi Sakellariadou (King's College London) [mairi.sakellariadou@kcl.ac.uk]  
 Jeremy Sakstein (University of Hawai'i at Manoa)

Ippocratis D. Saltas (CEICO, Institute of Physics, Prague) [saltas@fzu.cz]  
 Nicole Lloyd-Ronning (Los Alamos Lab; UNM, Los Alamos) [lloyd-ronning@lanl.gov]  
 Eusebio Sanchez (CIEMAT, Madrid) [eusebio.sanchez@ciemat.es]  
 B.S. Sathyaprakash (Pennsylvania State University) [bss25@psu.edu]  
 Pedro Schwaller (Johannes Gutenberg University Mainz) [pedro.schwaller@uni-mainz.de]  
 Olga Sergijenko (Taras Shevchenko National University of Kyiv) [olga.sergijenko.astro@gmail.com]  
 Christian N. Setzer (Stockholm University) [christian.setzer@fysik.su.se]  
 Lijing Shao (Peking University) [lshao@pku.edu.cn]  
 Peter Shawhan (University of Maryland) [pshawhan@umd.edu]  
 Joseph Silk (Institut d'Astrophysique de Paris) [silk@iap.fr]  
 Alessandra Silvestri (Lorentz Institute, Leiden University) [silvestri@lorentz.leidenuniv.nl]  
 Marcelle Soares-Santos (Michigan University) [mssantos@umich.edu]  
 Carlos F. Sopuerta (Institute of Space Sciences, CSIC and IEEC) [sopuerta@ice.csic.es],  
 Lorenzo Sorbo (University of Massachusetts, Amherst) [sorbo@physics.umass.edu]  
 Ulrich Sperhake (University of Cambridge) [U.Sperhake@damtp.cam.ac.uk]  
 Danièle Steer (APC, University of Paris, France) [steer@apc.univ-paris7.fr]  
 Nikolaos Stergioulas (Aristotle University of Thessaloniki) [niksterg@auth.gr]  
 Giulia Stratta (INAF-OAS, Bologna) [giulia.stratta@inaf.it]  
 Ling Sun (California Institute of Technology & Australian National University) [ling.sun@anu.edu.au],  
 Ankan Sur (Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences) [ankansur@camk.edu.pl]  
 Patrick J. Sutton (Cardiff University) [suttonpj1@cardiff.ac.uk]  
 Arthur Suvorov (University of Tübingen) [arthur.suvorov@tat.uni-tuebingen.de],  
 Volodymyr Takhistov (UCLA) [vtakhist@physics.ucla.edu] ,  
 Nicola Tamanini (Albert Einstein Institute) [nicola.tamanini@aei.mpg.de],  
 Tomas Tamfal (University of Zurich) [tomas.tamfal@uzh.ch],  
 Gianmassimo Tasinato (Swansea University) [g.tasinato2208@gmail.com],  
 Yu-Dai Tsai (Fermilab) [ytsai@fnal.gov],  
 Sergey Tsygankov (University of Turku) [sertsy@utu.fi],  
 Caner Unal (CEICO, Institute of Physics of the Czech Academy of Sciences) [unalx005@umn.edu]  
 Elias C. Vagenas (Kuwait University) [elias.vagenas@ku.edu.kw],  
 Maarten van de Meent (Max Planck Institute for Gravitational Physics) [mmeent@aei.mpg.de],  
 Valeri Vardanyan (Kavli Institute for the Physics and Mathematics of the Universe) [valeri.vardanyan@ipmu.jp]  
 Daniele Vernieri (University of Naples "Federico II", Italy) [daniele.vernieri@unina.it]  
 Filippo Vernizzi (Institut de Physique Théorique, CEA Saclay) [filippo.vernizzi@ipht.fr]  
 Salvatore Vitale (MIT) [svitale@mit.edu]  
 Benjamin D. Wandelt (IAP, Sorbonne Université) [bwandelt@iap.fr]  
 Barry Wardell (University College Dublin) [barry.wardell@ucd.ie]  
 Amanda Weltman (University of Cape Town) [amanda.weltman@uct.ac.za]  
 Andrew Williamson (University of Portsmouth) [andrew.williamson@port.ac.uk]  
 Helvi Witek (University of Illinois at Urbana-Champaign) [hwitek@illinois.edu]  
 Samuel J. Witte (IFIC, University of Valencia) [sam.witte@ific.uv.es]  
 Richard Woodard (University of Florida) [woodard@phys.ufl.edu]  
 Kadri Yakut (University of Ege) [kadri.yakut@ege.edu.tr],  
 Stoytcho Yazadjiev (University of Sofia) [yazad@phys.uni-sofia.bg],  
 Silvia Zane (Mullard Space Science Laboratory, University College London, UK) [s.zane@ucl.ac.uk]  
 Miguel Zumalacarregui (Max Planck Institute for Gravitational Physics) [miguel.zumalacarregui@aei.mpg.de]