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Astro2020 Science White Paper: Tests of General Relativity and Fundamental Physics with Space-based Gravitational Wave Detectors

Emanuele Berti,^{1,2,*} Enrico Barausse,^{3,4} Ilias Cholis,⁵ Juan García-Bellido,^{6,7} Kelly Holley-Bockelmann,^{8,9} Scott A. Hughes,¹⁰ Bernard Kelly,^{11,12,13} Ely D. Kovetz,¹ Tyson B. Littenberg,¹⁴ Jeffrey Livas,¹¹ Guido Mueller,¹⁵ Priya Natarajan,¹⁶ David H. Shoemaker,¹⁷ Deirdre Shoemaker,¹⁸ Jeremy D. Schnittman,^{11,13} Michele Vallisneri,¹⁹ and Nicolás Yunes²⁰

¹*Department of Physics and Astronomy, Johns Hopkins University,
3400 N. Charles Street, Baltimore, MD 21218, USA*

²*Department of Physics and Astronomy, The University of Mississippi, University, MS 38677, USA*

³*CNRS, UMR 7095, Institut d'Astrophysique de Paris, 98 bis Bd Arago, 75014 Paris, France*

⁴*Sorbonne Universités, UPMC Université Paris 6, UMR 7095,
Institut d'Astrophysique de Paris, 98 bis Bd Arago, 75014 Paris, France*

⁵*Department of Physics, Oakland University, Rochester, MI 48309 USA*

⁶*Instituto de Física Teórica UAM-CSIC, Universidad
Autónoma de Madrid, Cantoblanco, 28049 Madrid, Spain*

⁷*CERN, Theoretical Physics Department, 1211 Geneva, Switzerland*

⁸*Department of Physics and Astronomy, Vanderbilt University,
2301 Vanderbilt Place, Nashville, TN 37235, USA*

⁹*Department of Physics, Fisk University, 1000 17th Ave. N, Nashville, TN 37208, USA*

¹⁰*Department of Physics and MIT Kavli Institute, Cambridge, MA 02139*

¹¹*Gravitational Astrophysics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA*

¹²*CRESST, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA*

¹³*Department of Physics, University of Maryland,
Baltimore County, Baltimore, MD 21250, USA*

¹⁴*NASA Marshall Space Flight Center, Huntsville AL 35812, USA*

¹⁵*University of Florida, Gainesville, FL 32611, USA*

¹⁶*Department of Astronomy, Yale University,
52 Hillhouse Avenue, New Haven, CT 06511*

¹⁷*LIGO, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

¹⁸*Center for Relativistic Astrophysics and School of Physics,
Georgia Institute of Technology, Atlanta, GA 30332, USA*

¹⁹*Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109, USA*

²⁰*eXtreme Gravity Institute, Department of Physics,
Montana State University, Bozeman, Montana 59717, USA*

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Low-frequency gravitational-wave astronomy can perform precision tests of general relativity and probe fundamental physics in a regime previously inaccessible. A space-based detector will be a formidable tool to explore gravity's role in the cosmos, potentially telling us if and where Einstein's theory fails and providing clues about some of the greatest mysteries in physics and astronomy, such as dark matter and the origin of the Universe.

* email: berti@jhu.edu, phone: 410-516-2535

Einstein’s theory of gravity, general relativity (GR), has been a triumph of theoretical physics, having passed numerous observational tests – from the perihelion precession of Mercury’s orbit around the Sun, to the Nobel Prize winning discoveries of the Hulse-Taylor pulsar [1] and of gravitational waves (GWs) from black hole (BH) binary mergers [2]. Nonetheless, there are strong theoretical reasons – which relate to the origin of the Universe and physics beyond the Standard Model – to suspect that a deeper theory will emerge upon closer scrutiny.

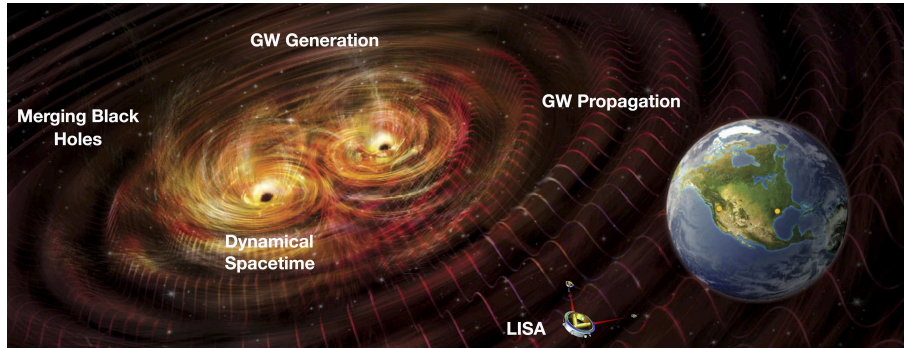
Until recently, our picture of the Universe was mostly assembled using traditional electromagnetic telescopes in every waveband, from gamma rays to radio. Although this picture revealed wonders, it has so far lacked highly precise information about objects where gravity is extremely strong such as BHs, or where gravity is dynamical and speeds are relativistic. The missing pieces of the puzzle will be provided by GW detectors, such as LIGO [3], Virgo [4], and future ground-based detectors; Pulsar Timing Arrays [5]; and the planned future space-based interferometers such as LISA [6]. Unlike light, GWs are not easily absorbed by matter, allowing us to peer beyond interstellar gas, beyond intervening galaxies, beyond accretion disks of massive BHs, and into the hearts of strong-gravity objects. This white paper concerns the theme *Cosmology and Fundamental Physics*, and specifically addresses tests of gravity and fundamental physics. Another white paper, *Cosmology with a space-based gravitational wave observatory* by Caldwell et al., focuses on the exciting opportunities provided by mHz GW observations for understanding the early Universe.

Space-based GW observatories are sensitive to gravitational wavelengths inaccessible to their ground-based counterparts [3]. Current detectors operate at frequencies $\gtrsim 10$ Hz and detect binaries with masses $\lesssim 10^2 M_\odot$ in the “local” Universe. This includes BH merger events lasting minutes or less, with typical signal-to-noise ratio (SNRs) of a few tens. Space-based missions such as LISA [6, 7] will operate at frequencies ~ 1 mHz and target very different source populations, including the merger of massive BHs in galactic centers. Events can last weeks, months or years with SNRs in the hundreds to thousands, allowing us to probe a much larger volume of the Universe. Space-based observatories will measure $\sim 10^4$ – 10^5 GW cycles from massive BH mergers and extreme mass-ratio inspirals (EMRIs), encoding information from which we will draw exquisitely precise astrophysical measurements and perform stringent tests of GR in the strong gravity regime.

The science case for space-based GW detectors as fundamental physics experiments is outstanding. Compared to binary pulsar and ground-based observations, these detectors will provide high-SNR observations of completely different source populations, potentially revealing novel phenomena and probing gravity at very different frequencies, and hence different source masses and energy scales. Some GR modifications affect gravity only in the strong field, while simultaneously passing all binary pulsar, cosmology and Solar System tests [8–10]. Space-based GW detectors have an unprecedented potential to carry out *precision tests* in this mostly unexplored strong gravity regime [11]. **A single space-based detection should allow for precision tests of GR at the sub 0.1% level, a factor of 100–1000 better than current ground-based detections.**

Schematically, modifications of GR can affect: **(a) GW generation, (b) GW propagation, (c) BH spacetimes, and/or (d) BH dynamics.** Modifications to GW generation can, for example, lead to violations of the strong equivalence principle. Modifications to the propagation of GWs can be thought of as changes in their dispersion relation, e.g. due to gravitational Lorentz symmetry breaking. Modifications to the astrophysical expectation that rotating BHs are described by the Kerr metric arise in various gravity theories, such as those containing high-order curvature terms in the action. Finally, the relaxation of the remnant after a BH collision is encoded in its oscillation spectrum (the so-called “ringdown” [12]), which is also typically corrected in modified theories of gravity. Different GW sources targeted by space-based GW detectors are better at probing different

classes of modifications of GR. Massive BH mergers are excellent at probing (a), (b), and (d). The inspiral of a small compact object into a massive BH (a so-called extreme mass-ratio inspiral, or EMRI) will be very good for (b) and has the unique ability to probe (c), as discussed below.



Probing gravitational wave generation and propagation. Inferences drawn from GWs can be divided into two classes, depending on the sector of the theory they constrain: (a) *generation* and (b) *propagation*. The generation sector deals with the way GWs (and any additional degree of freedom) are produced, and how they evolve in time and backreact on the evolution of the source (say, a binary system). The propagation sector deals with how GWs travel away from the source.

It took the gravity theory community approximately 50 years to obtain a model of the GWs emitted in the inspiral and merger of compact binaries in GR accurate enough for LIGO/Virgo observations. Given the plethora of proposed modified gravity models and the extreme difficulty in constructing sufficiently accurate GW models for data analysis, it is not very useful to carry out similar calculations on a theory-by-theory basis. It is much more appealing to develop generic tests of Einstein’s theory given the available data. In the context of Solar System observations one can expand the Einstein equations in powers of v/c around their Newtonian limit. This idea led to the development of the widely used “parameterized post-Newtonian” (ppN) framework of Will and Nordtvedt [13–16]. A similar proposal to carry out generic tests was implemented in the analysis of LIGO BH merger observations [17], and it consists of verifying the post-Newtonian structure of the GW phase [18]. In the parameterized post-Einsteinian (ppE) approach [19], Bayesian inference on the data decides the posteriors for the magnitude of “GR correction” parameters, which can then be mapped to posteriors on coupling parameters of specific theories [9, 20].

Such theory-agnostic approaches allow us to answer the question: **what new physics can be probed with space-based GW detectors?** Any order-of-magnitude improvement in our understanding of the behavior of strong, dynamical gravity can lead to potential breakthroughs. As an illustration of the dangers of extrapolating physical theories, note that the gravitational potential at the Earth’s surface (where Newtonian gravity is extremely successful) is only 4 orders of magnitude smaller than the gravitational potential at the Sun’s surface, where relativistic effects are relevant (as shown by the classical Solar System tests of GR). Going beyond gravity, a very successful theory such as quantum electrodynamics cannot be extrapolated from atomic to nuclear energy scales, where the strong interaction dominates; again, these two scales are separated by just 6 orders of magnitude. Therefore it is not unreasonable to expect that **LISA may provide breakthroughs in our understanding of gravity** when one considers that multi-wavelength observations with space- and ground-based instruments will allow for constraints on violations of the strong equivalence principle that are 8 orders of magnitude more stringent than all current bounds [21]. Single observations with future instruments will yield constraints on the size of a large extra-dimension (in Randall-Sundrum type models) that are 5 orders of magnitude more stringent than current bounds with LIGO; constraints on the temporal variability of Newton’s gravitational constant that are 12

orders of magnitude more stringent than the best current bounds with LIGO; and constraints on the mass of the graviton from propagation effects that are about 5 orders of magnitude better than current bounds [22], beginning to approach the natural value of the mass of the graviton in eV that one would expect if such a mass is connected to a solution to the dark energy problem.

In conclusion, space-based detectors will be exceptional tools to test the generation and propagation of GWs. **They are generally 2–4 orders of magnitude better than current GW detectors at probing the generation of GWs** from binaries for theories that produce effects at negative PN order: these include scalar-tensor theory, Einstein-dilaton-Gauss Bonnet and dynamical Chern-Simons gravity, theories that violate Lorentz symmetry, theories with extra dimensions, and theories with a time-varying gravitational constant. Space-based and third-generation Earth-based detectors [23] can observe merging BH binaries at cosmological distances, and their longer longer baseline will yield **tighter bounds on the propagation of GWs**.

Probing black hole spacetimes and dynamics. Observational evidence for massive BHs at the centers of galaxies has been garnered by electromagnetic radiation emitted as stars and gas interact with the BH’s gravitational potential. Arguably the best evidence comes from the center of our own Galaxy, where the mapping of stars orbiting a dark, compact object of mass $4 \times 10^6 M_\odot$ within 100 AU has become so accurate that it was used to detect gravitational redshift by the GRAVITY collaboration [24]. Space-based detectors will map BH spacetimes down to **length scales $\sim 10^4$ times smaller**, probing regions on the size of the horizon through the observation of EMRIs.

Orbiting compact objects, such as stellar-mass BHs and neutron stars, can probe the dark region close to the horizon of massive BHs. These compact objects emit mHz GWs as they inspiral into the central, massive BH. The frequencies of the GWs emitted during the inspiral are mostly determined by the mass of the central BH. Space-based detectors will be sensitive to capture events from 10^5 – $10^7 M_\odot$ BHs. EMRI signals provide opportunities to test GR that are beyond the reach of GRAVITY or ground-based detectors. The white paper *The unique potential of extreme mass-ratio inspirals for gravitational-wave astronomy* by Berry et al. describes the science enabled by these sources. According to current estimates, detection rates will range from a few up to a few thousand EMRIs per year, with SNRs in the hundreds for the strongest sources [25].

EMRI orbits exhibit complicated behavior, and this complexity can be used – in analogy to geodesy – to provide exquisite measurements of the multipolar structure of the central object’s spacetime. For rotating (Kerr) BHs in GR, all multipoles depend on just two parameters: the mass M and dimensionless spin χ of the BH. This means that EMRIs can be used to identify any deviations of the spacetime from the Kerr metric predicted by general relativity [11, 26, 27]. For example, every EMRI detection will provide a constraint on **deviations of the quadrupole moment from the value predicted by the Kerr solution at the level of 0.01–1 %** [25, 28].

Other ideas have been put forth to draw inferences on the nature of BHs. The dynamics of hypothetical BH alternatives in binary systems are driven by their so-called “tidal Love numbers,” which encode the deformability of a self-gravitating object immersed in a tidal environment. In GR, the tidal Love numbers of black holes are exactly zero. Recent work computed the tidal Love numbers of exotic compact objects (such as boson stars, gravastars and wormholes) as well as BHs in various theories of modified gravity [29]. Space-based detectors could distinguish even extremely compact exotic objects from BHs [30].

The large number of orbits of a small object inspiraling into a massive BH can reveal the nature of the central BH with great precision. The final phase of a BH merger also provides rich ground for testing GR. The BH remnant of a binary BH merger is highly distorted, and it radiates away these distortions by vibrating like a ringing bell in a discrete set of damped oscillation frequencies called

“quasinormal modes.” One can then imagine treating BHs as “gravitational atoms,” and viewing their GW oscillation spectrum as a unique fingerprint of spacetime dynamics (in analogy with atomic spectra). This is usually called “BH spectroscopy” [31]. In general, a binary BH merger signal will contain several ringdown modes, although one expects the weaker modes to be hard to resolve if their amplitude is low and/or if the detector’s noise is large. In GR the mode frequencies and damping times depend only on the Kerr BH mass and dimensionless spin (M, χ) . Therefore the dominant mode can be used to identify the two numbers necessary to specify the Kerr metric; then the detection of *any* subdominant mode is a test of GR, because all complex frequencies are uniquely determined by (M, χ) . BH spectroscopy provides important tests of the degree to which the assumptions that go into the mathematical “no-hair” theorems of GR are violated in astrophysical BH mergers [32], where the spacetime is highly dynamical and non-stationary.

One of the biggest puzzles in physics is the so-called “information loss paradox”: if a BH evaporates away and disappears, as Hawking predicted, it destroys the information that fell in. This violates unitarity, a foundational principle of quantum mechanics. Among proposed solutions to the paradox there are scenarios (including “firewall” and “fuzzball” proposals) that predict quantum modifications at the horizon scale [33]. If a merger remnant does not possess an event horizon, the standard ringdown signal could be followed by quasiperiodic bursts of radiation (“echoes”) that carry information about near-horizon structures, which are conjectured to exist in some models of quantum gravity [34, 35]. Measurements of post-merger radiation [36] and of stochastic GW backgrounds [37] with Earth- or space-based interferometers could constrain these scenarios.

A range of GW detectors could detect the quasinormal modes of a BH. However, third-generation ground-based detectors (like the Einstein Telescope and Cosmic Explorer) are needed to match the SNR of space-based detectors and to perform BH spectroscopy [38]. An important difference between Earth- and space-based detectors is that **a very large fraction of BH spectroscopy tests will occur at cosmological redshift in space-based (but not in Earth-based) detectors**. Even third-generation detectors like Einstein Telescope would be limited to $z \lesssim 3$, and only 40-km detectors, such as Cosmic Explorer [39], would be able to do spectroscopy at $z \approx 10$. By contrast, BH merger SNRs in space are so large that we could detect several modes and do BH spectroscopy out to $z \approx 5$, 10, or even 20, depending only on uncertainties in astrophysical BH formation models [38, 40]. This would allow simultaneous constraints of the large-scale dynamics of gravity (which may differ from the standard Λ CDM scenario if, say, cosmological expansion is due to gravitational degrees of freedom that evolve with redshift) and of the strong field, highly dynamical regime. As a corollary of this kind of analysis, GW detectors in space will produce an exquisitely accurate redshift survey of BH masses and spins which is of enormous value to astronomy (beyond its intrinsic theoretical physics interest). Quite remarkably, BH mass and spin measurements can also be used to probe dark matter, as we discuss below.

Probing dark matter. One of the most extraordinary features of massive, rotating BHs is that they can act as particle detectors, and therefore confirm or rule out the existence of light bosonic fields, which have been proposed as dark matter candidates [41, 42], in the Universe. **Observations of rotating BHs with space-based GW detectors could therefore constrain or detect certain dark matter candidates, even in the absence of a direct detection of stochastic GWs of cosmological origin.** The reason is that ultralight bosonic fields around spinning BHs can trigger a superradiant instability that Press and Teukolsky called a “BH bomb” [43], forming a long-lived bosonic “cloud” outside the horizon. The superradiant instability spins the BH down, transferring up to a few percent of the BH’s mass and angular momentum to the cloud [44–51]. The condensate is then dissipated through the emission of GWs with frequency $f \sim m_s/\hbar$, where m_s is the mass of the field.

This explosive mechanism is most effective when the boson’s Compton wavelength is comparable to the BH’s gravitational radius [52]. Strong motivation to investigate this possibility comes e.g. from “string axiverse” scenarios in particle theory (where axion-like particles arise over a broad range of masses in string theory compactifications as Kaluza–Klein zero modes of antisymmetric tensor fields [53]) and from “fuzzy dark matter” scenarios (which require axions with masses $\approx 10^{-22}$ eV [42]). Current Earth-based detectors can probe boson masses $m_s \sim 10^{-13}$ – 10^{-11} eV, while **a space-based detector can detect or rule out bosons of mass $m_s \sim 10^{-19}$ – 10^{-15} eV** [54–58]. While axions in the “standard” mass range proposed to solve the strong CP problem of QCD could be tested by GW interferometers on Earth [46, 49, 54], LISA could test a broad range of masses relevant to string axiverse scenarios, as well as some candidates for fuzzy dark matter.

The range of allowed boson masses m_s can also be constrained by LISA measurements of the spins of BHs in binary systems. For a given m_s , spinning BHs should not exist when the BH spin χ is large enough to trigger superradiant instabilities. Instability windows in the BH spin versus mass plane, for selected values of m_s , can be obtained by requiring that the instability acts on timescales shorter than known astrophysical processes, such as accretion and mergers. Roughly speaking, continuum fitting or Iron $K\alpha$ measurements of supermassive BH spins probe the existence of bosons in the mass range $m_s \sim 10^{-19}$ – 10^{-17} eV. For stellar-mass BHs, the relevant mass range is $m_s \sim 10^{-12}$ – 10^{-11} eV. BH spin measurements with a space-based GW detector can rule out light dark matter particles in the intermediate mass range (roughly $m_s \sim 10^{-16}$ – 10^{-13} eV) inaccessible to electromagnetic observations of stellar and massive BHs. **Space-based GW detectors can probe the existence of light scalar fields in a large mass range that is not probed by other BH spin measurement methods, or even measure m_s with $\sim 10\%$ accuracy if scalars in the mass range $[10^{-17}, 10^{-13}]$ eV exist in nature** [55]. Spin-one and spin-two fields (i.e., hypothetical dark photons or massive gravitons) would trigger even stronger superradiant instabilities, so a space-based detector could either detect them or set strong constraints on their existence [51, 59, 60].

Another interesting candidate for dark matter are primordial BHs (PBHs) [61]. In particular, PBHs in the stellar-mass range may contribute a non-negligible fraction of dark matter [62–65]. PBHs can dynamically form binaries, typically resulting in highly eccentric orbits at formation [66]. GWs are a direct probe of the self-interaction of PBH dark matter [67]. With its access to earlier stages of the inspiral, a space-based detector can be invaluable in distinguishing the PBH binary formation channel from stellar-origin formation channels through measurements of the spin and eccentricity [68], as well as the mass spectrum [69]. Another source of unique information is through the stochastic background. The PBH merger rate at high redshift is not limited by the star formation rate, and so the stochastic background from these events should extend to lower frequencies (and higher redshifts) than for traditional binary BH sources [70, 71]. Meanwhile, if PBHs are to form from the collapse of overdense regions deep in the radiation domination era, the required $\mathcal{O}(1)$ fluctuations in the primordial curvature power spectrum will provide a second-order source of primordial GWs [72–74]. The characteristic frequency of these GWs is directly related to the PBH mass. Interestingly, **one of the least constrained mass windows for PBH dark matter – $10^{-13} M_\odot$ to $10^{-11} M_\odot$ – corresponds precisely to the mHz frequency window of LISA** [75–77]. LISA will be able to test the PBH dark matter scenario in this mass window through the two-point and three-point correlations of the GW signal [78, 79].

In conclusion, space-based interferometers usher in the promise of mHz GW astronomy and, with it, the power to test our understanding of gravitational physics, from modifications of GR to hints at the true nature of dark matter. Space-based GW detectors will dramatically advance, and potentially revolutionize, our understanding of fundamental physics and astrophysics.

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