Astro2020 Science White Paper

Mid-Frequency-Band Space Gravitational Wave Observations for the 2020 Decade

Thematic Areas: ☒Formation and Evolution of Compact Objects
☒ Cosmology and Fundamental Physics
☒Galaxy Evolution
☒Multi-Messenger Astronomy and Astrophysics

Principal Author:

Name: Peter F. Michelson
Institution: Stanford University
Email: peterm@stanford.edu
Phone: (650) 723-3004 (office)

Co-authors: (names and institutions)

Robert L. Byer (Stanford University)
Saps (Sasha) Buchman (Stanford University)
John A. Lipa (Stanford University)
Shally Saraf (Stanford University)
Ilya Mandel (Monash University)

Mid-Frequency-Band Space Gravitational Wave Observations for the 2020 Decade

Peter F. Michelson[1], Robert L. Byer[1], Sasha Buchman[1], John A. Lipa[1], Shally Saraf[1]
Ilya Mandel[2]

[1]*Stanford University, Stanford, California 94305 United States*
[2]*Monash University, Wellington Rd, Clayton VIC 3800, Australia*

Introduction

We make the science case for the early development of a **M**id-**F**requency-**B**and (MFB) gravitational waves (GW) observatory for the frequency band 10 mHz to 1 Hz, thus bridging between LIGO[1,2]/VIRGO[3] and the milli-hertz band of LISA[4]- with useable sensitivity extending to 10 Hz. We argue that this band will enable the timely development of this game-changing field of astrophysics, with observations of medium mass BBH and BNS sources prior to their mergers in the LIGO frequency range as well as EMRIs and mergers of supermassive BBH within the main detection band.

A combination of high and low frequency GW observations, from ground and space-based detectors is highly desirable to achieve the next key breakthroughs in our understanding of the new and dark Universe hinted at by electromagnetic wave astronomy. An MFB observatory builds on LISA as well as LIGO and adds significant new sources and science to GW astronomy in a timely way.

The case for mid-frequency-band GW astrophysics and astronomy

The discovery of the abundance of BBH of tens of solar masses, the multi messenger astrophysics with BNS mergers[5] and the remarkable scientific results derived from the data solidify the case for GW astrophysics and astronomy. However, fundamental questions remain, including the lack of unification of General Relativity with the Standard Model (SM) and/or Grand Unified Theories[6], as well as the inconvenient fact that dark energy, dark matter and inflation, three fundamental elements of our cosmological model, are not part of the SM. mLISA's mid-frequency band has attracted significant attention from the GW community[7,8], particularly as the detections by LIGO/VIRGO[9] give estimated event-rates for mLISA of 10^3-10^6 per year[10,11,]. For similar SNR, these signals that require 5 years integration times for LISA are observable in a few months by mLISA[12,13]. We summarize the expected and potential astrophysical and astronomical results from mLISA observations in its 30 mHz to 1 Hz frequency band - new sources are likely to be also expected:

Enhanced BBH parameter estimation: mLISA observations will occur well before these chirping signals enter the LIGO/VIRGO band, resulting in precise source parameter estimations, thereby allowing "coherent tracking" across the entire frequency band and resulting in precise tests of the "no hair theorem" by measuring the space-time multipoles, as well as other GR tests in the strong-gravity regime[8].

Sky localization: Binary neutron star GW sources will have quasi-constant frequencies for many years over most of the MFB, thus allowing the antenna to use the 2 AU diameter of the solar orbit as the baseline for sky localization to an estimated few arcminutes[7]. Consequently, the host galaxies of the neutron-star binaries could be identified to distances of $r_{max} \lesssim 500$ Mpc, making possible the study of the environment of the binary well in advance of coalescence.

Type IA supernova progenitors: The question of the creation of type IA supernovae would be answered by an IA observation and the detection, or lack thereof, of a coincidental GW event[7].

Mergers in the presence of third bodies: Signals of GW mergers in the MFB will carry the imprint of nearby third bodies, such as massive black holes or centers of massive core-collapsed globular clusters[7].

Evolutionary history of compact object binaries: MFB observatory will expand the frequency spectrum coverage for BBH and NBH events, thus improving the understanding of the evolution and formation of these objects[7].

Stochastic background: Detections at MFB frequencies could possibly allow the observation of the cosmological GW background[14,15].

Primordial black hole (PBH) formation: PBHs are theorized to have been generated by various models[16,17,18,19] of the early Universe, resulting in a wide range of PBH masses - from the Plank mass to orders of magnitude above $M_\odot$[20]. mLISA's numerous GW detections, with accurate parameter estimation, will allow to differentiate between these models.

Element formation: Additional detections of NBH or NS mergers will improve the understanding of the formation of heavy elements[21,22].

Massive and Supermassive Black Holes: mLISA will characterize the parameters of coalescing BBHs with masses in the 10^3-10^8 $M_\odot$ range[23], with precisions comparable or better than LISA - the larger amplitude modulation due to the diurnal rotation of the array should compensate for a lower SNR[24].

Massive Black Hole Formation: MFB will search for mergers leading to the creation of the massive black holes inhabiting the centers of galaxies, thus validating or negating different proposed scenarios for their formation[25]. For the MFB sensitivity band, the potential nuclei for mergers would be in the range of 10^2-10^3 $M_\odot$ and would have been generated by first generation stars[7]. This would help establish the distribution of black hole seeds from population III stars and thus probe the formation of galactic structure.

Intermediate Mass Black Holes (IMBH): mLISA has the optimal band for IMBH, ~10^3 $M_\odot$, detection; observable as either mergers or inspirals of compact stellar mass objects[7]. Under the assumption that IMBHs are central to globular clusters[26], observations of their mergers would help the understanding of the dynamics of the globular clusters[7,8].

EMRI: MFB will observe with good SNRs the spiraling of small black-holes (a few to 10 $M_\odot$) into larger (10^2 - 10^6 $M_\odot$) holes, the so called Extreme and Intermediate Mass Ratio Inspiral (EMRI/IMRI) binary systems[27]. These astrophysical objects are expected to radiate predominantly in the region of the GW band where LISA and MFB achieve their best sensitivities.

Improved measurements of the Hubble constant, H_0 [28]: Detections GW170817[29] and GRB 170817A [30,31] give a 'GW Hubble constant'[32] $H_0^{GW} = 70.0\,^{+12.0}_{-8.0}\,\frac{\mathrm{km}}{\mathrm{s \cdot Mpc}}$. mLISA's high event-rates will allow (with ~100 mergers) a determination of H_0^{GW} to ≤ 5% and over a much larger volume[33].

Galactic Binary Calibrators: MFB will also study known galactic binaries containing stellar-mass objects whose physical properties and sky locations have already been identified through optical observations (the so called "calibrators"). In relation to stellar-mass binary systems, in particular white-dwarf binaries, it should be said that the hundreds of millions of such systems in our own galaxy, forming a "noise background" in the LISA data, will not degrade the MFB data because of its poorer sensitivity in the GW frequency band where this background radiates.

The MFB concept

The MFB concept envisions a geocentric spacecraft formation with arm length between 73,000 km (*gLISA*[34] in geosynchronous orbit) to 629,000 km (*Lagrange*[35] at Earth-lunar 3, 4, 5 Lagrange points). MFB's concept and technology have been studied for the past ten years at Stanford University, the Jet Propulsion Laboratory, the National Institute for Space Research, and at Space Systems Loral resulting in a 2020 decade launch date, while using a conventional program development plan, at a cost comparable to medium scale observatories launched by NASA in the previous decade. Similar to LISA, MFB will exchange coherent laser beams along its three arms[36] and synthesize interferometric combinations that are highly sensitive to gravitational radiation by applying Time-Delay Interferometry (TDI) to its heterodyne measurements[37]. Figure 1 shows the characteristic strain sensitivities of MFB compared to aLIGO and LISA, the detected GW sources by aLIGO, and the expected sources for a MFB and LISA.

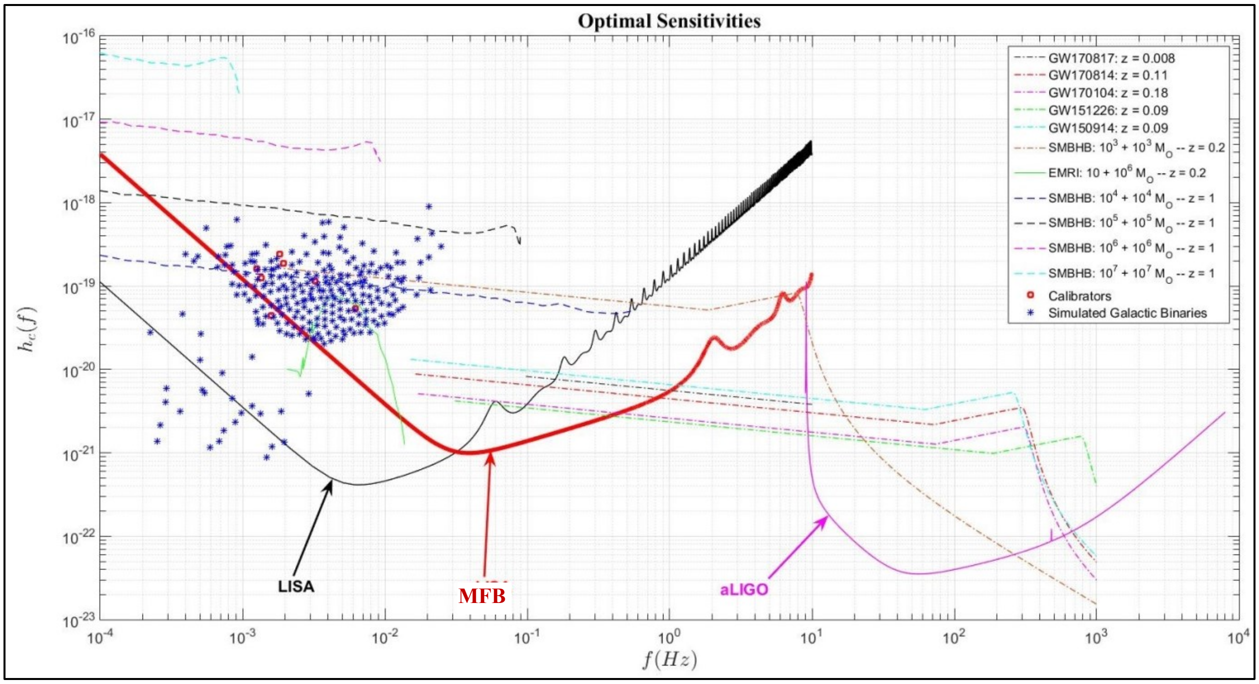

Figure 1. The characteristic strain of MFB, LISA and aLIGO averaged over sources randomly distributed over the sky and the polarization states. Each of these curves is uniquely determined by the TDI *A*, *E*, and *T* data combinations associated with the data from each mission (see ref 38). For completeness we have included the amplitude of the events detected by aLIGO, as a function of the Fourier frequency *f* and other potential sources

Conclusions

a) A mid-band GW detector will achieve the most important science goals of LISA listed in the 2010 astrophysics decadal survey, "New Worlds, New Horizons"[39].
b) Measurements of black hole mass and spin from MBHB will be important for understanding the significance of mergers in the building of galaxies.
c) An equally powerful test will be provided by the mergers of MBHB by comparing actual GW forms to the highly detailed numerical simulations performed by modern general relativistic hydrodynamics codes with dynamical space-time evolution[40].
d) Potential for discovery of waves from unanticipated or exotic sources, such as backgrounds produced during the earliest moments of the universe, dark energy signals or cusps associated with cosmic strings.
e) MFB observations will complement the scientific capabilities of both LISA and LIGO/VIRGO and meet the GW science objectives stated in the NASA's Astrophysics Visionary Roadmap[41] and Science Plan[42].

REFERENCES

[1] R. Weiss, Quarterly Progress Report of RLE, MIT **105,** 54 (1972)
[2] LIGO Caltech
[3] VIRGO
[4] O. Jennrich, *et al.* NGO assessment study report (Yellow Book) 〈hal-00730260〉(2012)
[5] B. P. Abbott, *et al.* Astrophys. J. Lett. **848(2),** L12 (2017)
[6] C. M. Will, Living Rev. Relativity, **9** (2006)
[7] I. Mandel, A. Sesana and A. Vecchio, Classical Quant. Grav., **35(5)**, 054004 (2018)
[8] P.W. Graham *et al*. arxiv: 1711.02225v1 (2017)
[9] B. P. Abbott *et al.* arXiv:1811.12907v2. (2018).
[10] K. Belczynski, *et al.* Astrophysical J. **819(2)**, 108 (2016)
[11] K. Belczynski *et al.* Nature, **534**, 512 (2016)
[12] A. Sesana, Phys. Rev. Lett. **116**, 231102 (2016)
[13] M. Tinto, and J.C.N de Araujo, Phys. Rev. D, **94**, 081101(R) (2016)
[14] V. Mandic *et al*. Phys. Rev. Lett, **109**, 171102 (2012)
[15] T. Callister *et al*., Phys. Rev. X, **6**, 031018 (2016)
[16] S. Clesse and J. Garcìa-Bellido, Phys. Rev. D **92**, 023524 (2015)
[17] K. Jedamzik and J.C. Niemeyer, Phys. Rev. D **59**, 124014 (1999)
[18] J. Garriga and A. Vilenkin, Phys. Rev. D **47**, 3265 (1993)
[19] J. Garriga, A. Vilenkin and J. Zhang, J. Cosmol. Astropart. Phys. **02**, 064 (2016)
[20] H. Deng and A. Vilenkin, J. Cosmol. Astropart. Phys. **12,** 044 (2017)
[21] D. Kasen *et al*. Nature, **551**, 80 (2017)
[22] F.-K. Thielemann *et al*. Annu. Rev. Nucl. Part. S. **67**, 253 (2017)
[23] K. Belczynski *et al*. Astrophysical J. **789(2)**, 120 (2014)
[24] S.T. McWilliams "Optimal orbits for eLISA science", 10th LISA Symposium Florida, (2014).
[25] M. Volonteri, Astron. Astrophys. Rev. **18(3),** 279 (2010)
[26] C-J. Haster *et al.* Astrophysical J. **832(2),** 192 (2016)
[27] P. Amaro-Seoane *et al*. Classical Quant. Grav. **29**, 12 (2012)
[28] The LIGO Scientific Collaboration *et al*. Nature **551**, 85 (2017)
[29] B. P. Abbott *et al*. Phys. Rev. Lett. **119**,161101 (2017)
[30] A. Goldstein, *et al.* Astrophys. J. Lett. **848(2),** L14 (2017)
[31] B. P. Abbott, *et al.* Astrophys. J. Lett. **848(2),** L13 (2017)
[32] B.F. Schutz, Nature **323**, 310 (1986)
[33] W. Del Pozzo, Phys. Rev. D, **86**, 043011 (2012)
[34] M. Tinto, *et al*. Rev. Sci. Instrum. **86**, 014501, (2015)
[35] J W Conklin, *et al.* arXiv:1111.5264v2 (2011)
[36] M. Tinto, *et al.* Classical Quant. Grav. **32**, 185017 (2015)
[37] M. Tinto and S.V. Dhurandhar, Living Rev. Relativity, **17**, 6 (2014)
[38] T.A. Prince *et al.* Phys. Rev. D, **66**, 122002 (2002)
[39] Committee for a Decadal Survey of Astronomy and Astrophysics (2010)
[40] B. Zink, *et al*, Phys. Rev. Lett. **96**, 161101 (2006)
[41] NASA Astrophysics Visionary Roadmap (2013)
[42] NASA Science Plan (2014)