Gravitational Waves in the Mid-band with Atom Interferometry

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The direct detection of gravitational waves by LIGO is the beginning of a new era in astronomy [1–3]. Gravitational wave astronomy can provide information about astrophysical systems and cosmology that is difficult or impossible to acquire by other methods. Just like with electromagnetic waves, there is a wide spectrum of gravitational wave signals that must be explored to fully take advantage of this new source of information about the universe. LIGO and other terrestrial detectors are sensitive to gravitational waves between about 10 Hz and 1 kHz [4, 5] while LISA is targeted at the 1 mHz - 50 mHz range [6]. However the "mid-band" between these two ($\sim$ 30 mHz to 10 Hz) is also scientifically rich. There is an opportunity to fill this gap using atomic sensors. Here we focus mainly on the science possibilities in the mid-band. However to quantify estimates of the observable signals we use the specific proposal for an Atomic Gravitational Wave Interferometric Sensor (MAGIS) [7]. The discovery potential of such instrumentation appears exciting, ranging from observation of new astrophysical and cosmological sources, as well as searches for ultralight dark matter.

I.   Mid-band Science

The gravitational wave (GW) spectrum between $\sim$ 0.03 Hz and 10 Hz appears to be scientifically rich [8]. The lower end of this range would allow observation of white dwarf (WD) binary mergers, while the higher frequency region ($\sim$ 1 Hz) is potentially a valuable region for searching for cosmological sources such as inflation. There are also sources that may be observed both in this band and in the LIGO or LISA bands. For example, sources such as black hole (BH) or neutron star (NS) binaries may be observed in this band, and then observed later by LIGO once they pass into higher frequencies. Such joint observation would be a powerful new source of information, giving a prediction of the time and location of a merger event in LIGO which would allow narrow-field high sensitivity optical, x-ray, gamma ray, and other telescopes to repoint to observe the prompt emission during the actual merger.

Since the sources generally live a long time in this mid-frequency band, they can be localized on the sky even by a single-baseline detector since the detector will change orientation and position significantly during the time spent observing a single source. In the mid-band this angular resolution can be very good [9]. This additionally enables a great deal of important science. For example the improved angular resolution can greatly improve the ability to use BH binaries as standard sirens (see e.g. [10, 11]). This can lead to powerful probes of cosmology, and thus the mid-band could for example significantly improve measurements of the Hubble constant and dark energy equation of state (see e.g. [12–14]).

As described in detail below, the mid-band thus appears very promising since it allows:

- Good angular resolution for inspiraling BH's.
- Alerting EM telescopes to observe the NS merger event itself
- Observation of WD mergers
- BH standard siren measurements for cosmology (dark energy equation of state, etc.)
- Searches for novel sources such as intermediate mass black holes
- Searches for ultralight dark matter (axions, hidden photons, etc)
- Improved information on LIGO sources (e.g. BH spin measurements)
- Searches for cosmological sources (e.g. inflation, reheating, cosmic strings,...)

The detector proposed here could operate either in broadband [16] or resonant mode [17]. In the resonant mode the resonance frequency can be chosen anywhere in the range roughly 0.03 Hz to 3 Hz. Switching between the different modes or different resonant frequencies
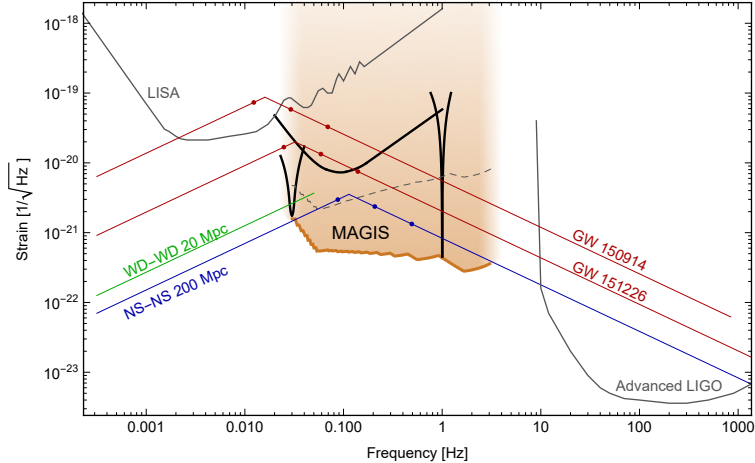
FIG. 1. MAGIS GW sensitivity. Broadband mode and two example resonant sensitivity curves are shown in solid, thick black. The envelope of the possible resonant curves is shown by the lower brown line (appropriate for discovery of longer-lived sources such as WD and NS binaries). The dashed gray curve is the appropriate curve for the discoverability (but not the ultimate SNR) of shorter-lived LIGO BH binaries. The LISA [6, 15] and AdvLIGO design sensitivity [5] are shown. Two LIGO BH merger events are shown in red. A WD-WD binary at 20 Mpc (with masses $0.5M_\odot$) is shown in green. A NS-NS binary at 200 Mpc (with masses $1.4M_\odot$) is shown in blue. The dots on the source curves indicate remaining lifetimes of 10 yrs, 1 yr and 0.1 yrs. See [7] for more details.

can be done rapidly by simply changing the sequence of laser pulses used, without changing hardware or satellite configuration. The question of the optimal observing strategy for such a resonant detector is non-trivial and requires additional study. For the purpose of this study, we will assume a simple observation strategy, and give numbers for sources observable with that strategy (with SNR of 3). However there may well be a better strategy: the strategy chosen depends on the type of source one wants to search for, so it could be re-optimized for different sources. The example observing strategy we chose to consider here, motivated by searching for the BH binaries visible in LIGO as well as merging WD binaries, is to sit at a frequency around 0.05 Hz (with a resonant $Q \sim 10$) in 'discovery mode', waiting for a source to enter the band. Once a source is discovered it can be tracked for longer by sweeping the detector frequency up to follow the source. This allows a significant improvement in SNR beyond discovery, improving measurement of source parameters and angular localization.

MAGIS' ability to provide advanced space-time localization (small angular error ellipses and precise chirp dates) of NS binary, NS-BH and typical stellar BH-BH mergers is a key feature of the mission, since it enables simultaneous E-M observations. A preliminary study of MAGIS' ability to localize the space-time position of inspiral events has been made [9], but more detailed studies are needed to explore all the deliverables. Degree and $\sim 10^5$ s -scale localization can be achieved for bright sources, enabling wide-field contemporaneous E-M study w/ e.g. LSST, WFIRST and SKA. With resonant observing, some sources may also be localized within 10-20 arcmin [9], enabling observations from the VLA, 10m-class telescopes and Chandra-type X-ray studies, enabling exquisite probes of the source.

White Dwarf Binaries - A double WD binary with secondary mass $M_2 M_\odot$ ends its inspiral at $\sim 0.06 M_2$ Hz. Thus while a typical WD-WD radiates in the LISA band, the most

interesting double WD, the candidate Type Ia progenitors with $M_1 + M_2 > 1.4M_\odot$ reach the mid-band. In fact, such WD-WD mergers could only be seen with such a mid-band detector[18]. Using the rates in [19] we expect a few such systems in the Milky Way, where high S/N allows us to measure departures from pure GR evolution, probing dissipative effects. With ~ 150 WD-WD Ia progenitors visible to Virgo group, we expect that a low-frequency MAGIS scan can measure the population of double degenerate (WD-WD) Ia progenitors. Lower mass WD-WD binaries are more common and a low frequency MAGIS search could detect several thousand sources, with $\sim 1/y$ passing from the GR-dominated regime. The relevant sensitivity is shown by the brown line in Figure 1, where narrow band sensitivity increases greatly toward 0.03 Hz. Measuring the high frequency population of the WD-WD spectrum thus tests the efficacy of this channel in producing Ia supernovae.

Rapidly spinning, nearby ($d < $kpc) WD in close binaries, such as HD 49798 ($f_{GW} = 0.15$Hz) and AE Aq ($f_{GW} = 0.06$Hz), provide a second class of WD sources for MAGIS. These are measurable with S/N$\sim$10 in 30d resonant searches (after orbital de-modulation) if the WD quadrupole moment is $Q \sim 10^{47}$g cm^2. Measuring the detailed waveforms (and quadrupole moments of spinning WD) probes the interior structure and merger dynamics.

Binary Black Holes - The discoveries at Advanced LIGO show that the universe is rich in binary BH mergers [20] and encourages deeper exploration of the BH population. When operated in the discovery mode at a frequency ~ 0.05 Hz, MAGIS easily detects large chirp mass binaries such as the $\sim 26M_\odot$ GW150914 event. This event is detectable out to ~ 2 Gpc with SNR $\gtrsim 3$ (see Figure 1), in 'discovery mode.' This can be seen by comparing the source curve with the dashed gray line (since at these frequencies this source is relatively short-lived). More frequently MAGIS should also detect BH binaries with more typical $8M_\odot + 5M_\odot$ ($M_{chirp} = 5.5M_\odot$) at frequencies $\sim 0.03 - 0.06$ Hz. These would be discovered several years before the merger event, giving MAGIS the opportunity to pursue deeper studies using resonant sensitivity to predict the merger date in the Advanced LIGO band. For the louder sources, these predictions will include high quality pre-merger parameters, and degree-scale localization, allowing deep *targeted* radio/optical/X-ray searches for (presently unexpected) E-M signals during the merger events. Thus the MAGIS-AdvLIGO combination offers opportunities for powerful probes of the merger physics.

With a long lifetime in the MAGIS band, precise positions and pre-merger parameters of BH binaries can be obtained. For higher SNR events, study over many MAGIS orbits allows measurement of gravitational wave polarization and the orientation of the binary orbit. Together with AdvLIGO measurements of the chirp, this improves constraints on the initial spins. If precessional or eccentricity effects are seen in the pre-chirp signal, additional constraints may be extracted. Initial spins and eccentricity are important clues to the BHs' origin and can be used to probe several astrophysics and particle physics scenarios [21].

For source localization, consider an event like GW150914. This event can be detected by MAGIS with a SNR ~ 10 when operated in the discovery mode. Subsequent to discovery, the signal can be resonantly followed, permitting a total SNR ~ 50 which should allow degree scale localization. Further studies are necessary to optimize such measurement strategies.

Neutron Star Binaries - The recent detection of NS mergers by LIGO and VIRGO and the subsequent observation by many EM telescopes (see e.g. [3, 22–24]) has proven that NS binaries will be an exciting source of GWs. There is a great deal of information to extract from these events, for example better cosmological measurements of the Hubble constant [14]. It would be useful to have warning and angular localization of the object prior to merger, as

it allows probes of prompt (ms to hour) counterpart emission with E-M facilities, from X-ray space telescopes to large aperture gound-based telescopes with photometric, spectroscopic and polarization sensitivity. Such localization is difficult to achieve in the LIGO band.

As can be seen from Fig. 1, the mid-frequency band is an ideal range for discovering NS binaries. MAGIS could detect NS binaries out to roughly 300 Mpc (at SNR 3). Note that to find the SNR of these NS detections at the lower frequencies of 'discovery mode' one should compare the source curve in Figure 1 to the brown (not dashed gray) line. This would allow a valuable connection with Advanced LIGO which can observe NS-NS binary mergers out to about 200 Mpc, with an expected merger rate of 40 per year.

The best strategy for discovering a population suitable for joint MAGIS AdvLIGO band study is likely an early-mission deep resonant survey at $f \sim 0.15 - 0.3$ Hz where the detected sources will sweep into the AdvLIGO band in 1-5y. A suitable subset of sources can be identified and follow-on resonant observations can be scheduled into a mission plan that optimizes science from these key sources, while exploring other mission objectives. Optimized strategies need to be identified for using MAGIS broadband and resonant observation time to identify samples of NS-NS and NS-BH in-spirals and provide maximum precision on the position and in-spiral date as alerts to AdvLIGO and E-M facilities. Scheduling (months) simultaneous observations (optical, X-ray, gamma ray, etc.) for a sample of chirp events will be a game changer. The full astrophysics community can participate in the study of the expected E-M signals from precursor through ring-down, teasing out the NS equation of state, the relativistic MHD of the merger and the origin of r-process elements. Without MAGIS, we have only shallow, sky survey-type E-M observations of the prompt signal, with other telescopes observing the object a long time after merger, restricting studies.

Intermediate Mass Black Holes - If intermediate mass black holes (IMBH) exist (such as [25]), MAGIS should be able to discover inspirals of stellar mass compact objects (NS and BH) into $\sim 10^3 \, M_\odot$ primaries throughout much of the Hubble volume, with SNR ~ 5 when operating in the discovery mode around ~ 0.05 Hz. Little is known about this potential population, but at MAGIS sensitivities, estimates suggest ~ 1 event per year for both BH and NS inspirals [26]. These large mass-ratio events offer unique opportunity to probe BH spacetime [27]. Of course, if binary BH in the $10^3 - 10^5 M_\odot$ range exist they would be detectable to $z \sim 10$. Rate estimates are as high as $\mathcal{O}(10 - 100)$/year [28].

Cosmological Sources - Conventional astrophysical sources, while representing extreme members of their object classes providing exceptional science yield, are relatively limited in number, especially in the upper half of the MAGIS band. Above 0.05 Hz we expect only a few Galactic rotating WD and WD-WD binaries, a few 10s of local group WD systems, and a few 100 NS-NS, NS-BH and BH-BH binaries. At frequencies above the irreducible LISA background of Galactic WD-WD binaries and below the 0.1-3 kHz AdvLIGO range rich with NS and BH chirp events, MAGIS sources will be relatively limited and, with multi-year evolution times, nearly monochromatic. This exciting, but resolvable foreground population enables searches for cosmological GWs in the mid-band [17].

It is well known that a detector around 1 Hz is ideal to search for inflationary GWs, a major scientific goal. The only known ways to search for these GWs are the CMB and direct GW detection around 1 Hz. This band probes a different part of the inflationary epoch (and potential) than the CMB. A detection in both the CMB and at 1 Hz would provide a powerful test of the scale-invariance of the spectrum over roughly 18 orders of magnitude in frequency, testing the core of inflation. Such a long lever-arm would allow

direct measurement of the inflationary potential. MAGIS does not have the sensitivity to detect GWs produced by typical inflation models that obey constraints imposed by the CMB. However, MAGIS probes the inflationary potential towards the end of inflation, which is observationally unconstrained and may feature enhanced GW production [29].

First order phase transitions at temperatures ~ 100 TeV may also produce GWs in the mid band. This scale emerges in new solutions to the hierarchy problem such as the relaxion [30, 31]. If discoveverd, GWs from the 100 TeV universe would revolutionize particle physics. MAGIS is also sensitive to GWs produced by cosmic strings with tension $G\mu \sim 10^{-16}$.

Dark Matter Direct Detection - The identification of the properties of dark matter (DM) is a major goal that has the potential to unveil new paradigms in astrophysics, cosmology and particle physics. Ultra-light scalars are a particularly well motivated class of DM. They emerge naturally in many theories of particle physics (e.g. string theory [32]), could explain facets of structure formation [33] and may solve the hierarchy problem [31].

Single baseline GW detectors have enhanced sensitivity to ultra-light scalar DM [34]. These candidates can cause temporal oscillations in fundamental constants with a frequency set by the DM mass, resulting in a modulation of atomic energies [31]. This is a narrow signal in frequency space, with a width 10^{-6} of the DM mass, set by the DM virial velocity. This spectral characteristic would distinguish it from backgrounds as well as GW signals. MAGIS can improve on current searches for electron-mass or electric-charge modulus DM by up to 10 orders of magnitude in coupling [34]. Through different modes of operation, the instrument can search for the precession of nuclear spin caused by axion-like DM and dark photons [35]. Scalar and vector DM can also be searched for through time-varying equivalence principle violations [36] or variations in the earth's gravitational field [37].

II. Instrument description

To access this frequency range we propose a Mid-band Atomic Gravitational Wave Interferometric Sensor (MAGIS). Motivated by ongoing gains in sensitivity in recent years, the prospect of using atom interferometers and atomic clocks for GW detection has been studied [17, 38–44]. The MAGIS concept [7, 16, 17] takes advantage of both clocks and atom interferometers to allow for a single baseline GW detector [40, 45, 46]. A 100 m baseline terrestrial pathfinder instrument, MAGIS-100, has recently been funded and has received preliminary approval as a Fermilab experiment. MAGIS-100 will retire risks for follow-on terrestrial and space-based detectors.

In the MAGIS detector design, dilute clouds of ultracold atoms at both ends of the baseline act as both inertial references and as clocks. Laser light propagates between the two atoms ensembles and interacts with the atoms, driving transitions between the ground and excited atomic clock levels. The timing of these transitions depends on the light travel time across the baseline, so a passing GW can result in a shift of the atomic state [40]. MAGIS will use Sr atoms, which are excellent clocks [47]. Since the atoms serve as precision laser frequency references, only two satellites operating along a single line-of-sight are required to sense GWs. In MEO orbits, the measurement baseline re-orients on a rapid time scale compared to the observation duration of the GW signals from many anticipated sources. This allows efficient determination of sky position and polarization information. The relatively short measurement baseline allows for excellent strain sensitivity in the 0.03 Hz to 3 Hz observation band, intermediate between the LISA and LIGO antenna responses, and suited to GW astronomy, cosmology and dark matter searches, as described above.

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