GRAVITATIONAL WAVE DETECTION WITH ATOMIC INTERFEROMETRY

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ABSTRACT

With large scale gravitational wave detectors like LIGO and VIRGO taking highly successful data runs, some detectors just coming online and more detectors of similar scale on the way like IndIGO (LIGO-India), we can easily say that gravitational waves are an excellent medium to probe general relativity and take census of hence-forth unseen objects. Given the rich spectrum of electromagnetic radiation we have exploited to understand our universe, it stands to reason that the spectrum of gravitational radiation will be equally interesting. Large detectors like LIGO probe a highly useful frequency space, but this paper will discuss longer wavelengths that aim to be probed by atomic interferometers like MAGIS-100. It will review the principles behind atomic interferometry and gravitational wave (GW) detection, the physics interesting to us at these scales, and a larger discussion of what relevant and exciting new measurements might be made with mid-band detectors spanning 0.1 - 10 Hz.

***K*eywords** Atomic Interferometry · Gravitational Radiation · General Relativity

Contents

1 Introduction

With the first two detections of gravitational wave events published by the LIGO collaboration in 2016, a new and promising mode of observation opened up to astronomers. Many other laser interferometer schemes were swiftly proposed and with decades of work, began to come online. Among those proposed for the next wave of science are space-based observatories like LISA, TianQin, DECIGO, BBO, and AMIGO [1]. LIGO and other earth-based detectors of their corresponding size and methodology were limited to frequency ranges above 10 Hz. It is evident that we have only just begun to examine a scientifically rich spectrum that will help to probe some of the deepest, and thus far, even inaccessible, problems facing astronomy and cosmology.

This paper examines the expansion of gravitational wave detectors into new, lower and mid-band frequencies, both as a summary of some of the proposed observatories and as a brief review on gains atomic interferometry has made in recent decades. We will first discuss the simple construction of gravitational waves as a vacuum solution to Einstein's equations, then move into principles of detection and atomic interferometry, the motivations for mid-band detectors and the sources it is uniquely posed to examine, and finally a look at promising recent experiments and those proposed to come.

1.1 Gravitational Waves as a Vacuum Solution to Einstein's Equations

A brief outline of the general relativistic formulation for gravitational radiation will be discussed here, to frame the conversation on detection. Much of this is drawn from *Gravity: Newtonian, Post-Newtonian, and Relativistic* [2] and some is drawn from *Modern Classical Physics* [3] to develop a full but brief picture. In the context of linear theory, gravitational radiation can be viewed as a small perturbation, h, of the Minkowsi (or flat) spacetime metric, η, such that $|h_{\mu\nu}| << 1$.

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \tag{1}$$

We could similarly work through a solution that perturbs some curved spacetime, but approximating with flat space is sufficient for the simple didactic example here.

With the stress energy tensor, $T^{\mu\nu}$, being set to zero everywhere, a vacuum condition to Einstein's equations can be used to constrain h. Additionally, several gauge conditions can be leveraged to determine the unique components of h. If we have a wave propagating in the z direction, a convenient gauge to use is the *transverse traceless gauge*, or TT. This choice is convenient for several reasons, chiefly that there are only two unique non-zero components for our z wave case. Additionally, we find that

$$h_{xx} = -h_{yy}, \quad h_{xy} = h_{yx} \tag{2}$$

as a consequence of the Lorentz gauge condition.

The metric perturbation is only spatial here - there is no temporal component - and it lies in the perpendicular plane to the wave's motion. These unique components are typically written as follows, in terms of 'polarization states' $+$ and $\times$.

$$h^{TT}_{xx} = h_+(t-z), \;\; h^{TT}_{xy} = h_\times(t-z) \tag{3}$$

It seems highly evident within this language that measuring length scales to ultimate accuracy and precision is paramount, if spatial strains are to be detected in line with this argument. Another clear consequence rests on the two polarization states, that perpendicular axes are required to fully characterize a given signal.

2 Atomic Interferometry

In about twenty years of development, atomic interferometers (AIs) have been used in various precision measurement experiments, ranging from measurement of the fine structure constant, testing the weak equivalence principle to 10^{-8}, and measuring the Newtonian Gravitational constant [1].

Here I will explain some of the basic elements of atomic interferometry, which leverages our ability to split atomic wavefunctions and superimpose them again. Over the past decades, AI has dramatically advanced, and only now is it truly viable for gravitational wave detection given the extraordinary strains that must be measured (on the order of 10^{-21}) with extreme precision.

2.1 Why Use Atoms?

In the context of gravitational radiation, and with large kilometer-scale detectors in mind, it might seem counter intuitive to examine such small particles when expected strains are so minuscule. On the contrary, atoms are excellent test particles, when neutral, that follow geodesics in free fall. They also conveniently take up much less space and are flexible in terms of operation. It will be discussed much later, but while LIGO requires a shared infrastructure across the globe to attempt localization, atomic interferometry only requires a single baseline to achieve the same if not better results [4].

2.2 How it Works

The principle for atomic interferometry is similar to that of LIGO, though as LIGO splits coherent light and allows it to run down different axes before examining the interference fringe, atomic interferometry leverages the fact that matter also exhibits wave-like properties. Laser pulses can "kick" atoms into quantum superpositions by triggering Bragg or Raman transitions and those matterwaves can be directed and recombined at the end of the experiment to measure the corresponding interference pattern, however this is done with clouds of atoms and the fringe manifests as population differences between final momentum states [5].

A novel variant of the Mach-Zender interferometer will be discussed more in depth here, which is only sensitive to the phase of the laser at the time photons are transferred. The laser is much like a ruler in this case, telling us exactly how fast the nuclei are accelerating which is invaluable in terms of measuring gravitational radiation [5].

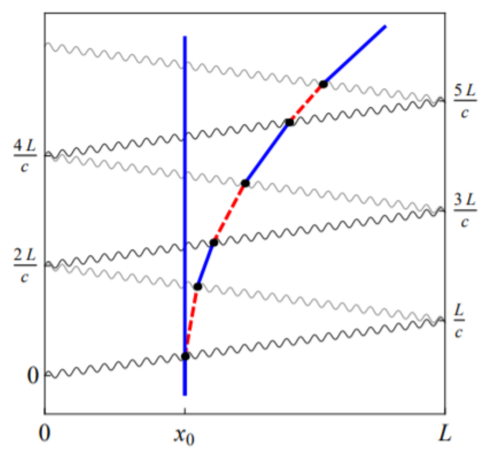

Figure 1: A spacetime diagram of the novel atomic interferometric detector's beamsplitter with $N = 3$. Blue lines indicate ground state atoms, and red, excited. Gray lines indicate light pulses that interact with the atom at the intersections [4].

As seen in Fig. 1, the beamsplitter for an interferometer is interrogated by laser pulses moving across a null geodesic (diagonally in the figure), sending the atom from the neutral state (blue) to the excited state (red). Some initial pulse splits the wavefunction in two, and after this pulse reaches a distance L, a secondary laser fires a pulse that is Doppler tuned to only interact with the originally excited half of the wavefunction. For a large momentum transfer (LMT), more sequences of π pulses are sent to the excited state, imbuing it with momentum $2N\hbar k$ for some wave-vector k [4].

A key principle is that the atom will accumulate phase faster in the excited state. If the atom accelerates and time dilation is present, the phase shift that is observed is proportional to the acceleration. If there is no acceleration, there is no phase difference. When the distribution of atoms is read off, there is an additional way to minimize noise. The aim is to make the measurement differential, that is, by having two spatially separated interferometers operating on the same laser pulses. While the math will not be described explicitly, the gravitational wave signal will be proportional to the phase difference between the two interferometers [4].

The most important thing to note here is that the interferometers are more or less measuring the light traveled time across them, and do not rely on the laser as a phase reference or clock (since both are interrogated by the same pulse). This is the main distinguishing factor between this novel proposed detector and previous iterations and greatly reduces noise [4].

2.3 Relevant Backgrounds

In contrast to optics with stringent mechanical constraints, this approach directly avoids laser frequency noise and naturally mitigates mechanical noise sources. Since it measures the relative acceleration between two inertial atom clouds with a high energy atomic transition (as a time reference), the laser is not used as a clock. Unlike other atomic interferometer schemes, laser frequency noise is therefore not a factor. This is primarily due to the fact that the phase of a laser pulse does not evolve during propagation in a vacuum, and both interferometers therefore experience the same intrinsic laser noise (via phase noise or frequency jitter) [4].

Additionally, since neutral atoms are great test particles and have uniform structure, environmental perturbations do not pose a significant threat to sensitivity. The reduced need for laser and platform stability is one of the major reasons a single baseline detector is feasible with this technology.

Thermal backgrounds require temperature stability on the order of 3 mK, which is quite feasible, though depends on the choice of atomic candidate. Alkaline earth-like atoms are preferred due to long excited state lifetime and their manageable sensitivity to other backgrounds, like magnetic fields (which affect Zeeman transitions).

3 Why Do We Need a Mid-Band Detector?

Gravitational waves carry the imprint of near and far activity, and thus their generators span the age of the universe. The spectrum, like the electromagnetic spectrum we've observed for millennia, is rich with scientific merit and artefacts of the universe's past. Splitting it into various bands, I discuss some of the astrophysical sources expected to produce signals here.

In extreme low frequency bands, the largest wavelength waves would result from quantum fluctuations in the very early universe, the Planck era. Frequencies from $10^{-9} - 10^{-7}$ Hz can probe both distant supermassive black hole mergers but also energetic, early universe processes [3]. Less cosmological in nature, frequencies up to 0.1 Hz can examine both astrophysical mergers like in-galaxy binary systems and phase transitions in the early universe. As described in Fig. 2 we can see how the period of the waves relate to source type, frequency, and mode of detection.
Mid-band, as per this paper, can generally be understood to cover 0.03-30 Hz. This range fortuitously avoids a large portion of the foreground noise generated by double white dwarfs which is expected to be a large source of confusion-limited noise for LISA at higher frequencies [7]. Additionally, the mid-band range is low enough to access cosmological sources like gravitational waves from inflation and reheating, phase transitions at scales above the weak scale, and models of axion inflation. With a 1000 meter baseline, many of these signals would be detectable [8].

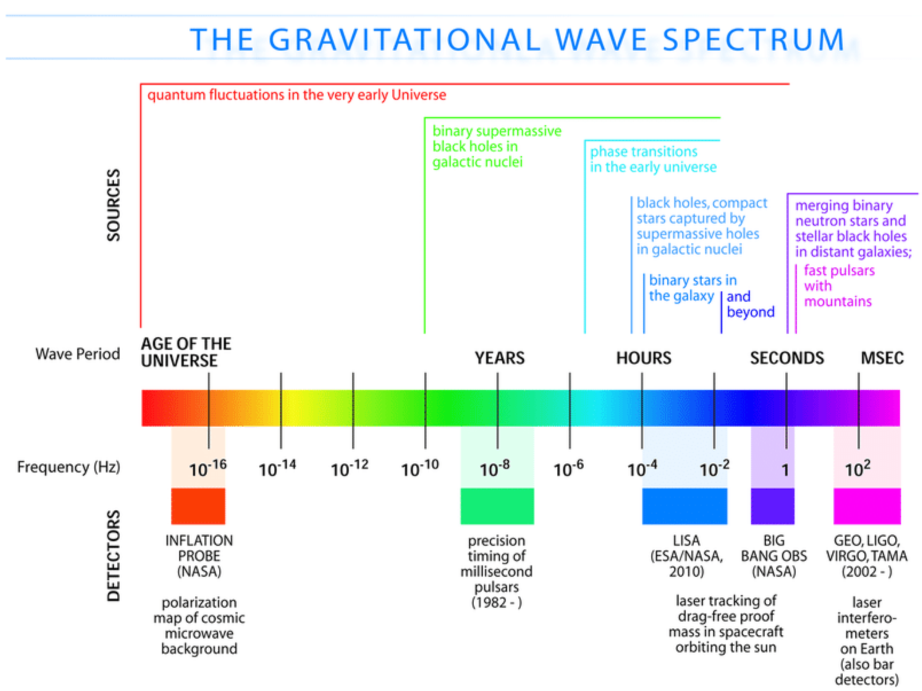

Figure 2: The gravitational wave spectrum paired with some relevant detectors, though not inclusive of atomic interferometry, is displayed here. We can see detectors like LIGO miss many cosmological signals in lieu of astrophysical ones [6].

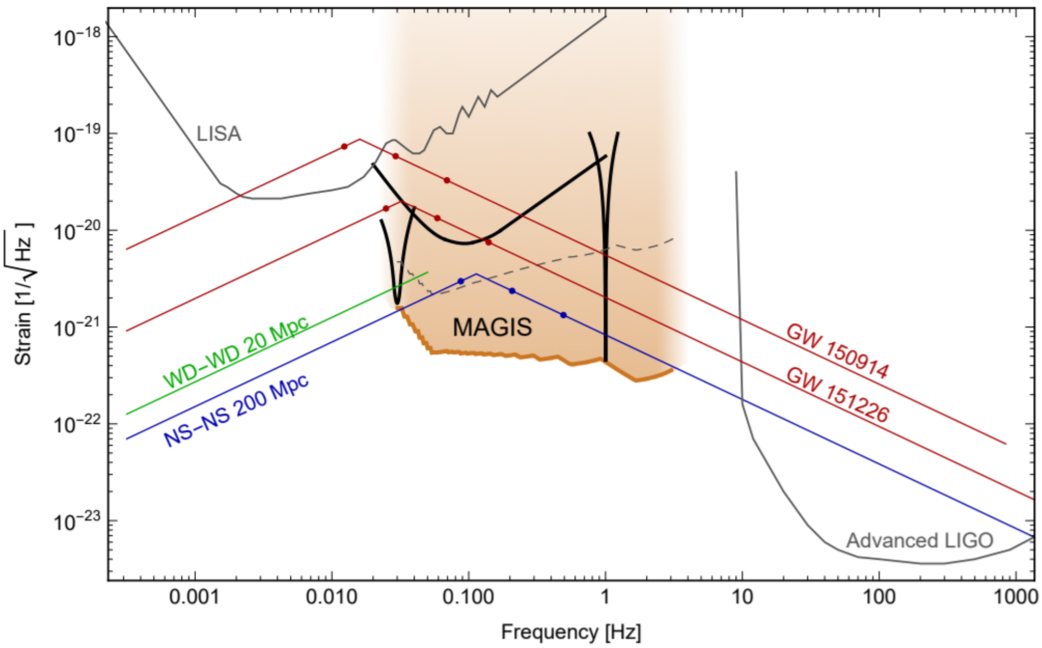

Figure 3: A depiction of proposed sensitivity of a mid-band detector, MAGIS, sitting between the domains of LISA and LIGO with BH merger signals as detected by LIGO in red. Nearby white dwarf mergers (WD-WD) can be seen to partially intrude on the lower frequency end of the band [9].

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Valuable science that would be expected at this band includes the following astrophysical sources as binary mergers [9].

- **White dwarfs**
- **Black holes**: including intermediate mass mergers
- **Neutron stars**

An interesting note on binary black hole or neutron star mergers, is that they are also observable at higher frequencies in LIGO or LISA bands. Joint observations temporally separated would greatly assist efforts to follow up detection with multi-messenger astronomy among various telescopes and electromagnetic bands.

Since sources are long-lived in this band, a single detector rotating about the Earth and spinning about the sun produces a good localization due to changing orientation during observation. The Doppler shift from the detector's motion assists with this process, and the effect is maximized at these frequencies, where the mid-band covers the largest frequencies for the longest-lived signal [10]. Thus the science is not merely interesting on its own, but as part of a larger collaboration of astronomers.

Meanwhile, there is another avenue for more "speculative" cosmological sources, among them inflation, reheating, and dark matter direct detection [9].

4 Proposed Experiments

4.1 MAGIS 100/1000

Of all projects discussed in this paper, MAGIS-100 is the most imminent. Following initial proof-of-concept for these detectors, the Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS-100) is a proposed mid-band detector to be built at Fermilab. It will have the capability to probe dark matter, test quantum mechanics at new distance scales, and will be a stepping stone to the development of a 1000 meter baseline detector [8]. The basis of the project is to connect two 50 meter interferometers across a vertical baseline of 100 meters to achieve uprecedented macroscopic superpositions. An existing access shaft at Fermilab for Neutrinos at the Main Injector (NuMI) will be leveraged as seen in Fig. 4.

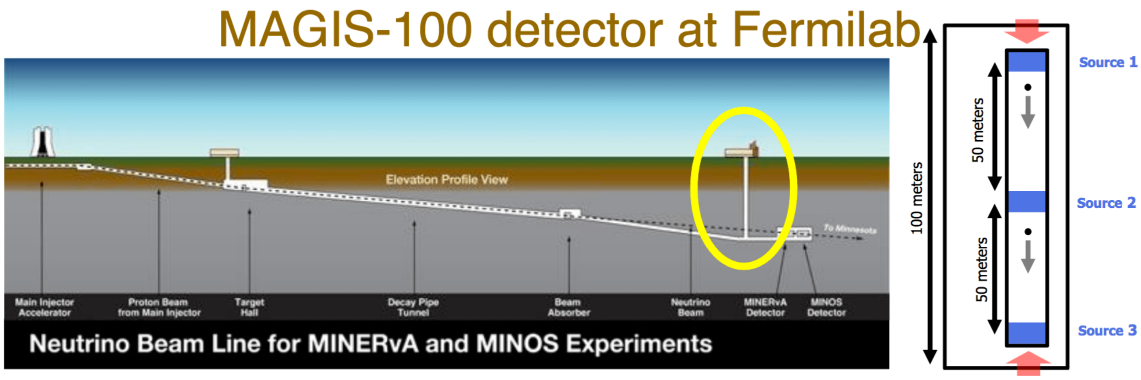

Figure 4: A depiction of the NuMI shaft at Fermilab to be used for MAGIS-100 [8]

The basis of MAGIS was used to illustrate prior sections of this paper on atomic interferometry, so much of the fundamental principles will not be discussed here. While MAGIS-100 will in some degree be sensitive to the hypothetical ultralight dark matter and improve on current detection bounds by some two orders of magnitude, this paper will not go into depth on this subject. Instead we look deeper at the 0.1-10 Hz frequency range for gravitational wave detection - between the Advanced LIGO and proposed LISA (space based observatory) experiment sensitivities [8].

MAGIS-1000 as an expansion of this experiment would be ideally suited to the SURF laboratory in South Dakota. The proposal suggests that such a detector would be able to access "the highest energy scales in the very early universe" [8]. And for the reasons described in Section 3, it would generate a highly desirable data pool to probe the early universe, improving upon 100 meter results by a full order of magnitude.

4.2 MAGIS

Not to be confused with MAGIS-100, the Mid-band Atomic Gravitational Wave Interferometric Sensor (MAGIS) is a proposed space based observatory, rather than a fixed baseline on Earth. The radiation is sensed through precise measurement of the light flight time between two distantly separated atomic inertial references in medium earth orbit (MEO) [9]. Ultra-cold Strontium atoms would serve as both clocks and precise inertial references using interferometry. Similar to LISA and GRACE-FO technology, a phase meter and differential wave front sensor will help compare phases for laser beams passing between the two satellites.

This observatory would have the capability to operate in two primary modes, broadband or resonant simply by adjusting the sequence of laser pulses used. Resonant modes at specific frequencies are depicted with solid black lines in Fig. 3, and such adjustments might be made to sensitivity to target different sources over the course of an observing run [9]. While we've discussed the benefits of localization in this band, this detector specifically would be expected to measure source position on the sky to sub-degree accuracy, and with resonant observing on the order of 10 arcminutes, which would mean rapid and easy follow up with an electromagnetic counterpart [10].

4.3 AIGSO

While MAGIS has been well fleshed out, other proposed mid-band detectors exist. One of which is supported by the National Key Research Program of China among other funding agencies, known as the Atomic Interferometric Gravitational-Wave Space Observatory (AIGSO). This program would use three satellites orbiting the Earth, with some strain sensitivity of $10^{-20}/\sqrt{Hz}$ in the 0.1 - 10 Hz band. The phase shift of AIGSO would be dominated by the Sagnac effect of gravitational waves, which is directly proportional to the area enclosed, the frequency, and wave amplitude. AIGSO opts to use standing light waves to split reflect and recombine a variety of atomic beams, similar to MAGIS in that the atoms will remain in the same internal state independent of laser fluctuation [1].

The primary difference between the two is that AIGSO uses true atomic matter waves, where MAGIS opts to use the atoms as sensitive inertial test masses. Integration time for this detector should be on the order of several days, thanks to high atomic flux intensity over a smaller baseline [1].

5 Conclusions

In conclusion the future holds promise for mid-band gravitational wave detectors, and atomic interferometry is the leading candidate to fill the void. Several promising ground based and space based observatories have been proposed, and some are in the early stages of testing and design.

With novel interferometric techniques that dramatically reduce environmental and laser noise, we may be poised to probe compact objects and high energy mergers in a more complete and holistic way than ever before, with swift localization and coordination among other observatories. We also stand on the precipice of examining some of the earliest gravitational relics in our universe when mid-band detectors come online, and a great deal of new physics might suprise us when they do.

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