Exploring Astrophysics and Cosmology with Decihertz Gravitational Wave Detectors

Term Paper Presentation

Santhiya P. S. and Vinay Kumar, 24 May 2023

Outline

- Detector Design
  - TianGO
  - DECIGO
  - LGWA

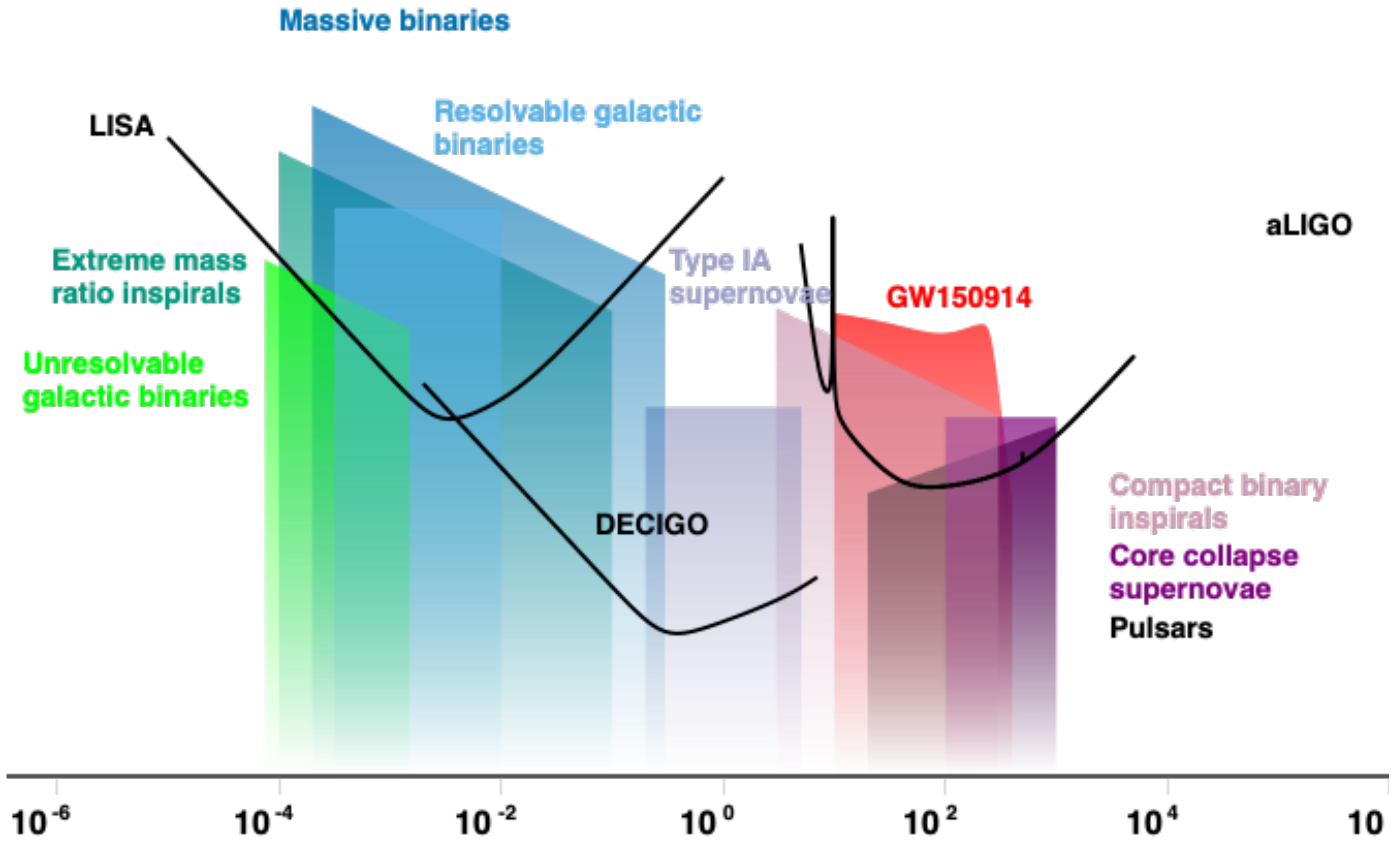
- Science Probes
  - BNS Mergers and EM counterparts
  - Type 1a Supernovae progenitors
  - Intermediate mass blackholes
  - Core collapse supernovae
  - Hubble tension
  - Acceleration of the universe

Detector Design

Detector Design

Advantages

- Ground based detectors - audio frequency range
- The proposed decihertz detectors - based outside earth
    - Longer arms⟶greater sensitivity to GW
    - Low noise⟶calmer environment⟶ detection of low frequency events in the mHz to decihertz range
    - Bridge gap between LISA and aLIGO

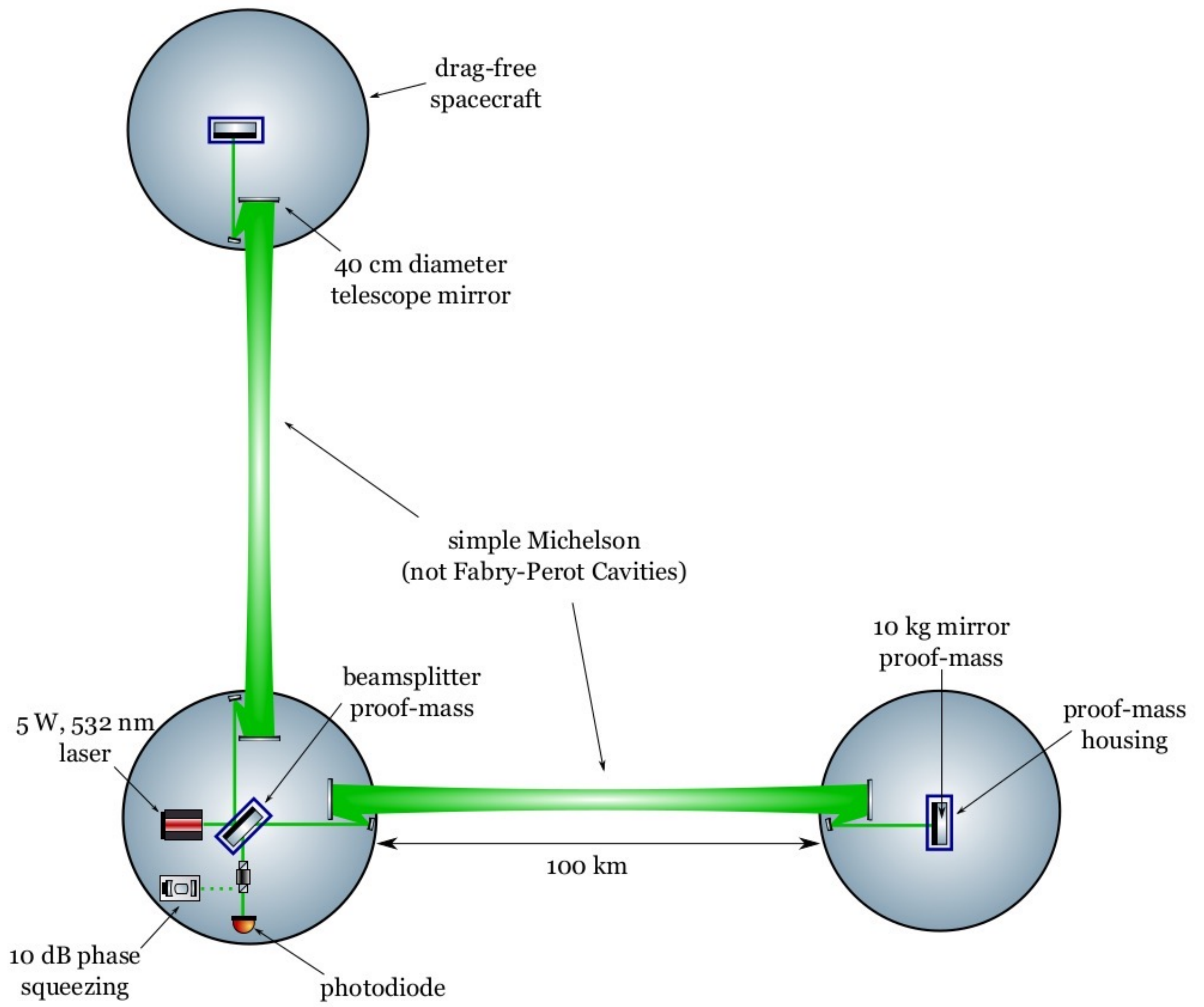


TianGO

- Space based - frequency range (0.1 to 10 Hz)
- Michelson interferometer
- Triangular constellation of three spacecrafts - 100 km arm length
- Corner spacecraft - laser and beam splitter
- Other spacecrafts carry mirrors - proof masses

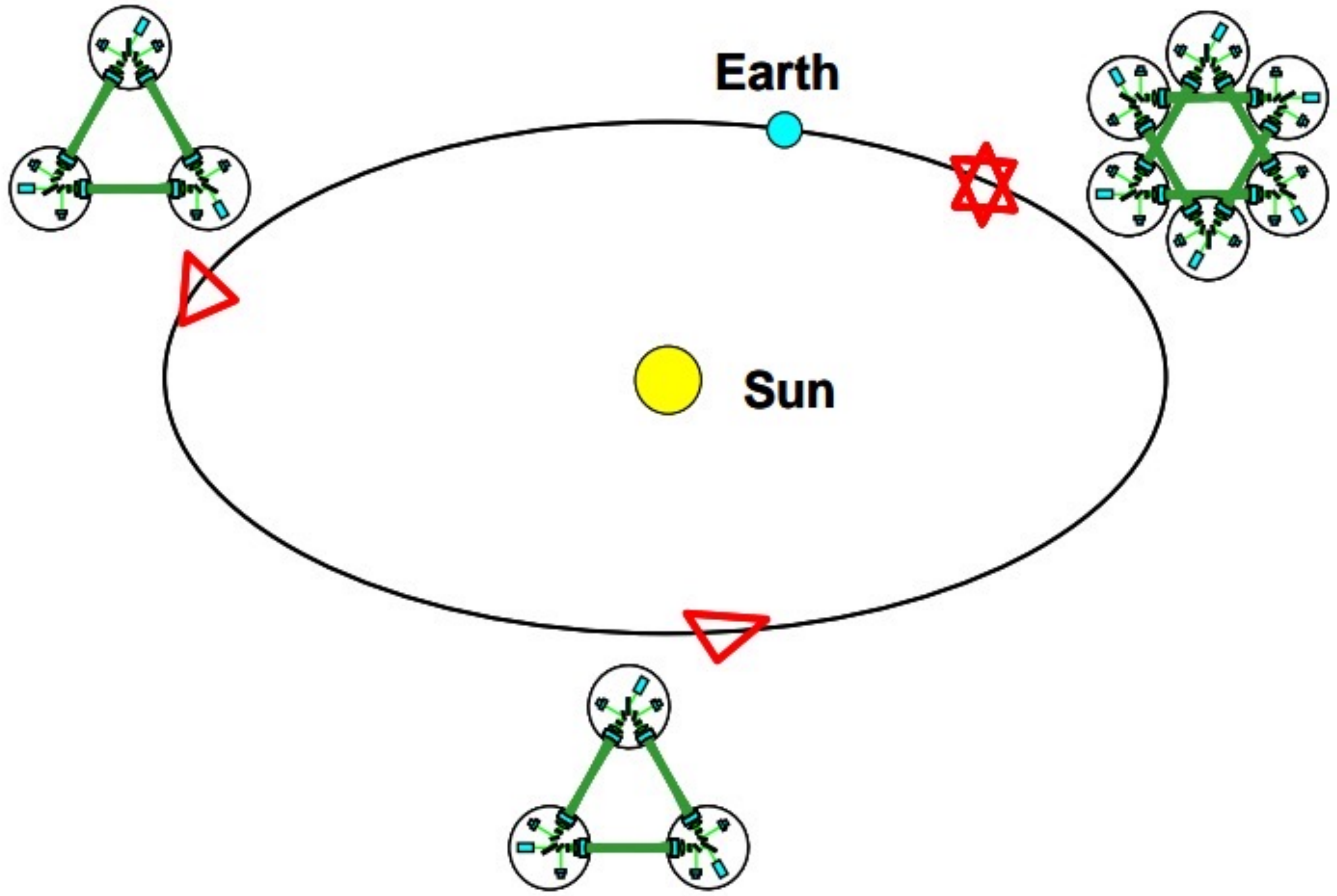
} Drag free flight

- Heliocentric orbit



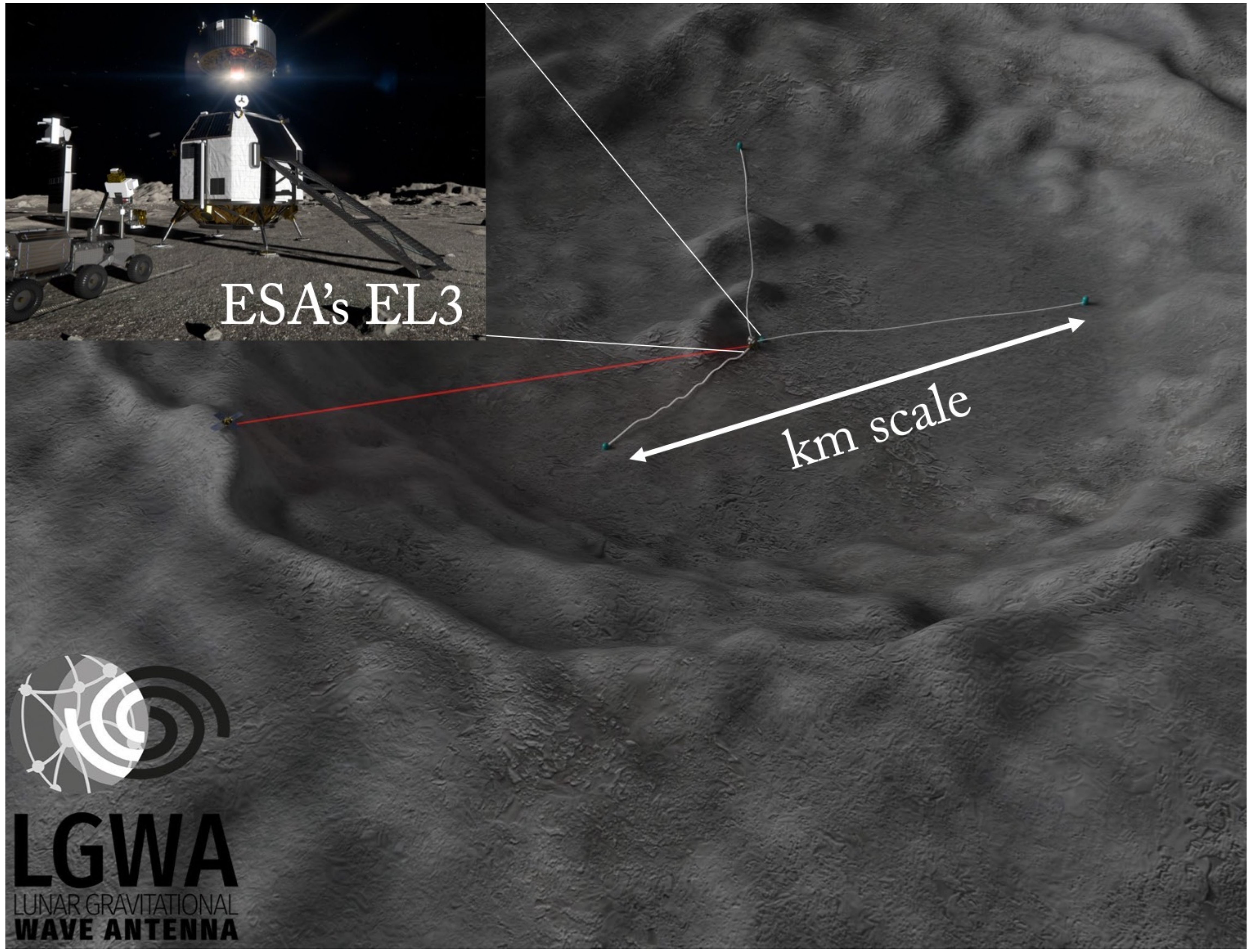
DECIGO

- Space based - co-earth orbit
- Four clusters
  - Two closely placed
  - Two are distributed elsewhere in the orbit
- Each cluster has three spacecrafts - equilateral triangle(1000 kms arm length)
- Proof masses - mirrors in drag free state
- Differential FP Michelson interferometer



LGWA

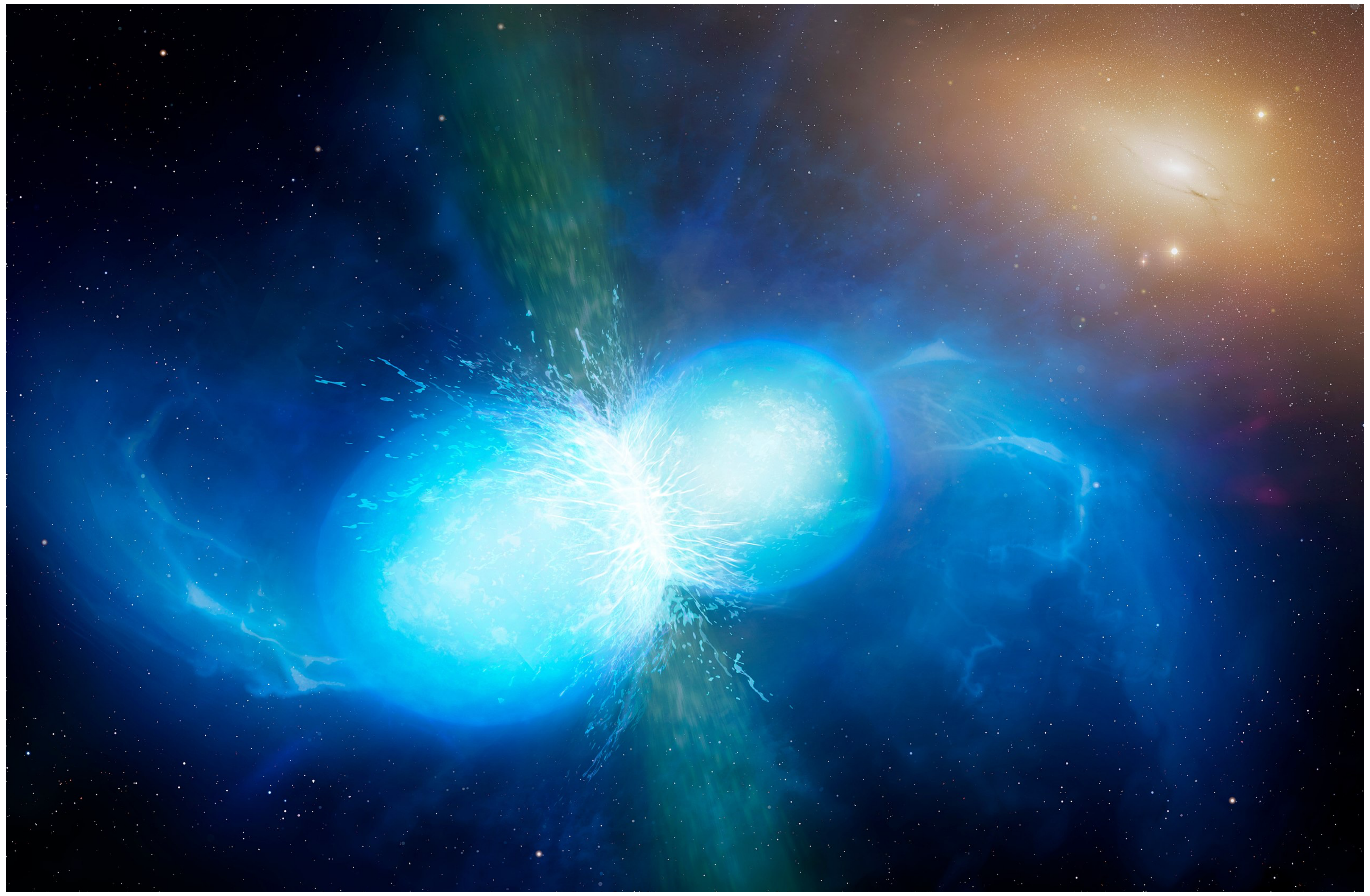
- Array of seismometers on moon
  - Closest celestial object
  - Substantial size-increased sensitivity
  - Reduced seismic activity
- Frequency range - 1 mHz to 1 Hz, sensitivity peaks in decihertz range
- Inertial sensors in permanently shadowed region
- Kilometre scale array



Science Probes

BNS Mergers and EM Counterparts

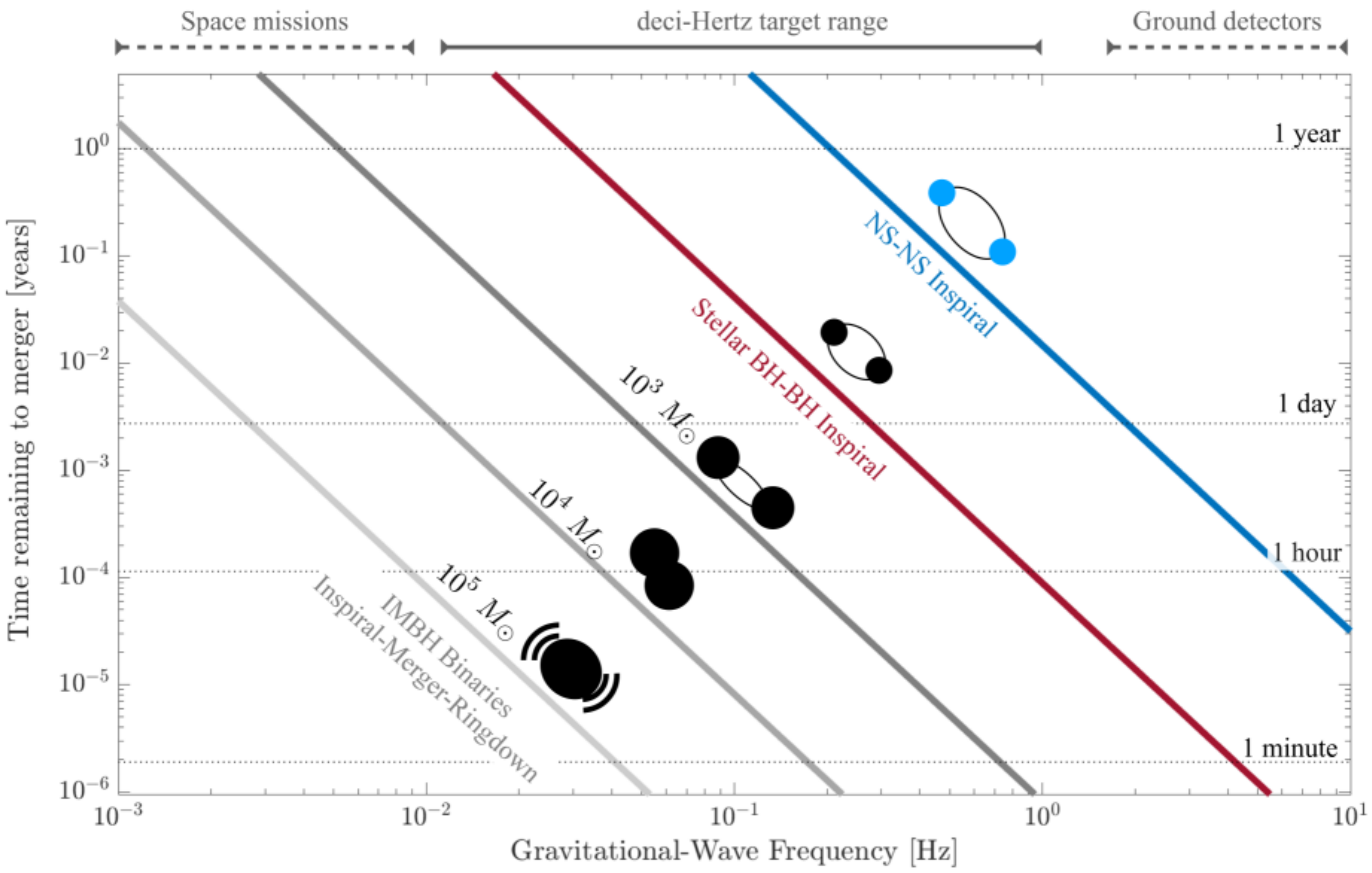
- GW170817 - EM counterpart seen
- GW190425 - EM counterpart not seen
- Could be because LVC
  - Poor early warning ~ minutes
  - Poor sky localisation ~ 10 deg



BNS Mergers and EM Counterparts

Early Warning and Sky Localization

- Time to coalescence ~ $f^{-8/3}$
- Low frequency - more time spent
- For BNS system, $1.4\ M_{\odot}$, $T_c \sim 5$ yrs
- In 5 yrs, detectors traverse solar orbit
- Effective baseline ~ 2 AU
- Angular sky localization ~ 0.001 rad



BNS Mergers and EM Counterparts

Astrophysics

- If EM counterpart
  - Measure arrival time diff b/w GW and EM
  - Test if GW travel at light speed
  - Constrain massive graviton theories
- If still No EM counterpart
  - Study environments of BNS
  - Composition of host galaxy

Type 1a Supernovae

Formation Channels

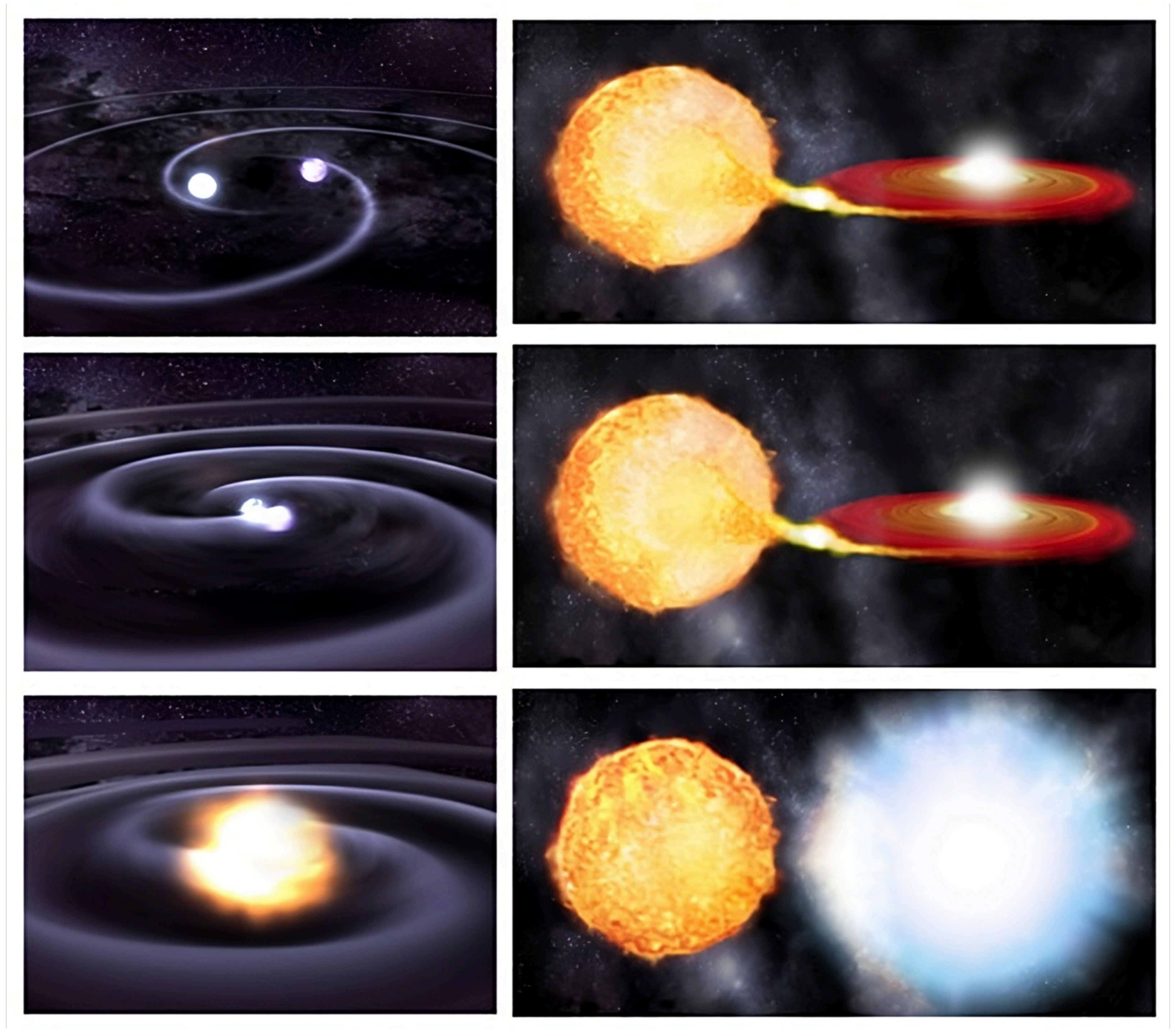
Double Degenerate

White Dwarf Binary

Inspiral and merger

Massive, Explodes

GW in dHz band



Single Degenerate

White Dwarf and Big Star

WD feeds on Star

Massive, Explodes

GW in low freq

Type 1a Supernovae

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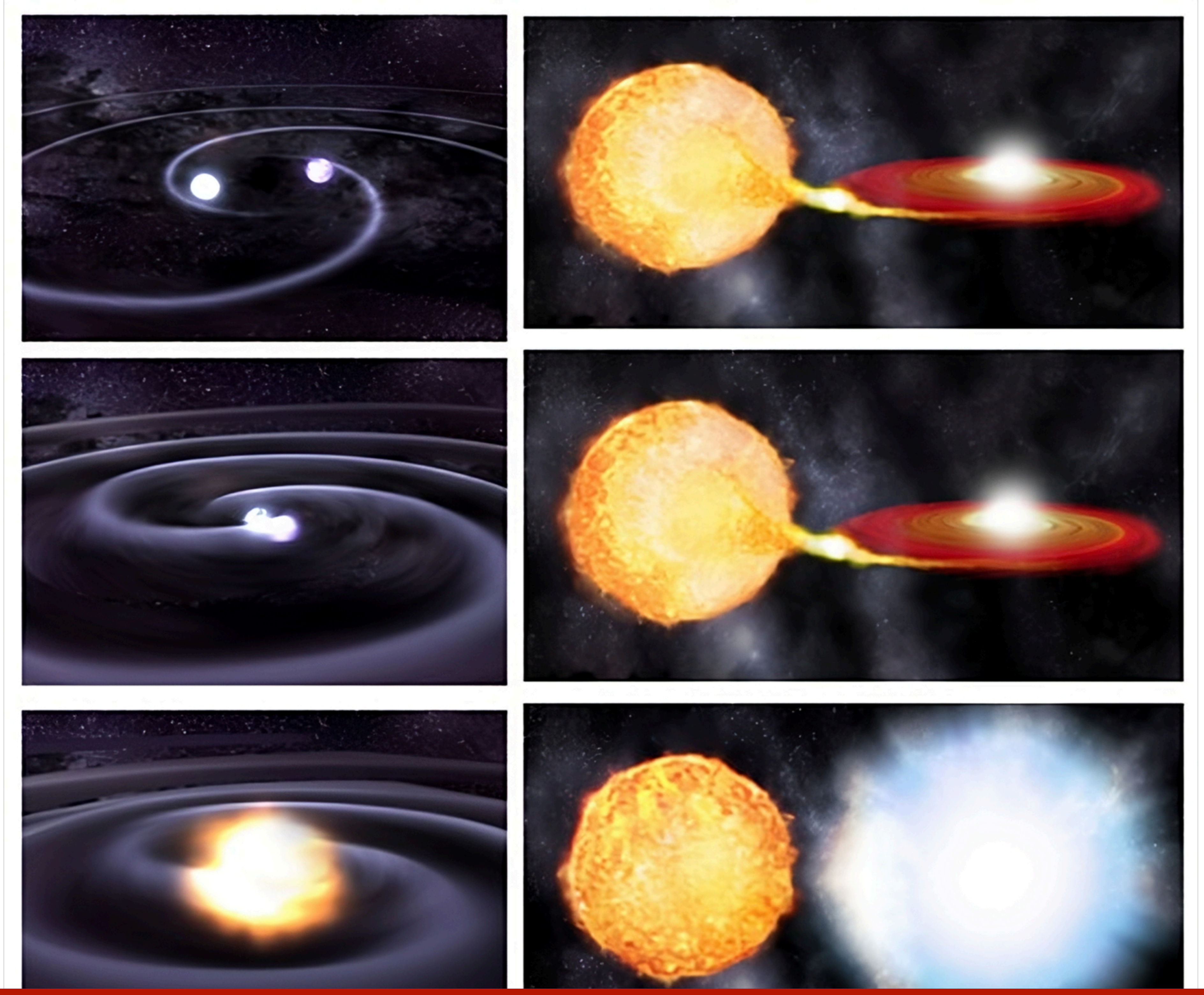

Single Degenerate

White Dwarf and Big Star

WD feeds on Star

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Early Warning + Sky Localization Beneficial

Intermediate Mass Blackholes

- IMBHs emit GW in decihertz range

  as they form a binary with WD / IMBH / NS

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Intermediate Mass Blackholes

- IMBHs emit GW in decihertz range $\longrightarrow$ $f_{ISCO} \approx \dfrac{c^3}{\pi G M 6^{3/2}}$

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$$\approx 4.3\ Hz$$

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  EM Counterpart

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$$\approx 4.3\ Hz$$

EM Counterpart

- provides essential insights into accretion physics, super-Eddington flows
- standard sirens for cosmography

Intermediate Mass Blackholes

- Non-observation of signal $\longrightarrow$constrain the existence of IMBH$\longrightarrow$Gives insights on the formation channel of massive BHs

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Massive seeds

IMBH mergers

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Massive seeds ~~IMBH mergers~~

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- Non-observation of signal ⟶constrain the existence of IMBH⟶Gives insights on the formation channel of massive BHs

Massive seeds ~~IMBH mergers~~

- Stellar evolution and dynamics of the globular cluster in which they reside.

Core Collapse Supernovae

- Main mechanisms: explosive nuclear burning or by the gravitational collapse of the stellar core (CCSNe)

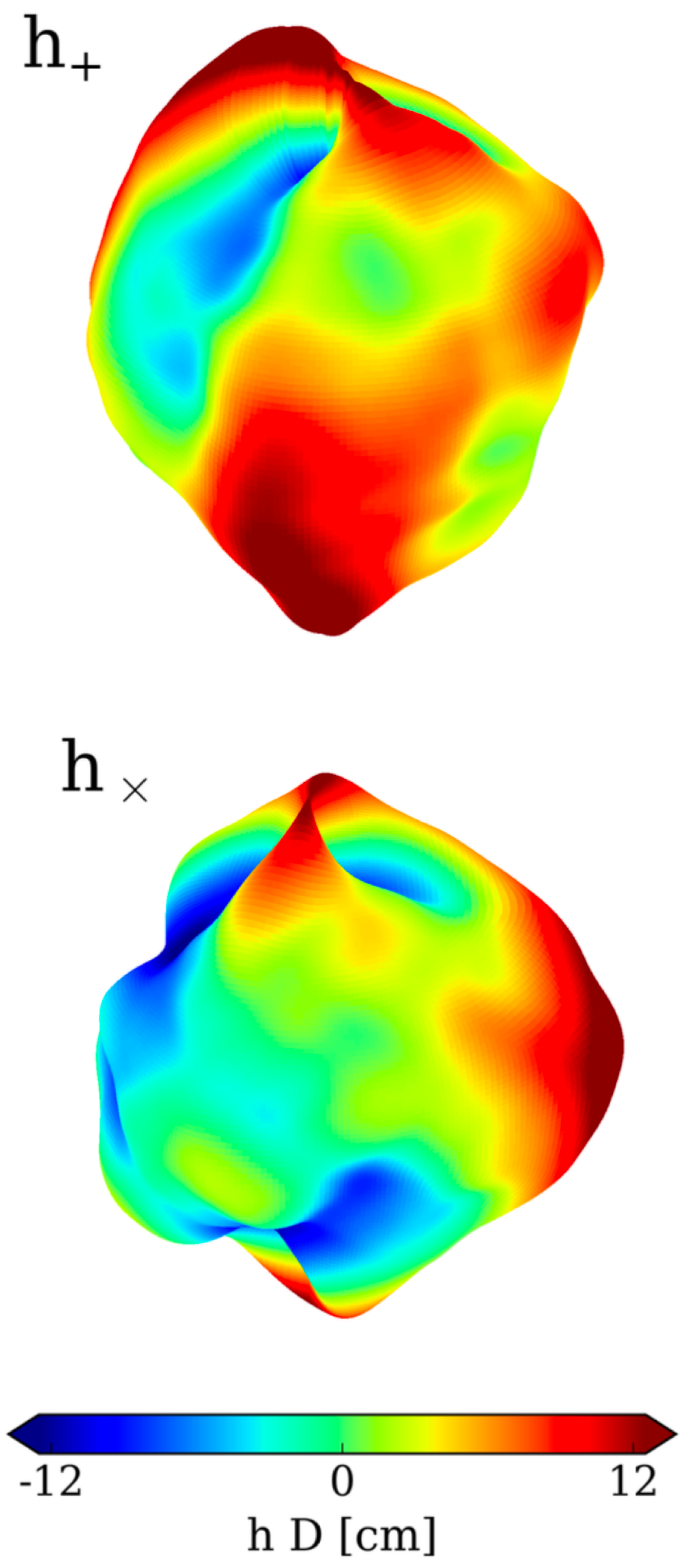
- GWs emitted

  - $10^2 - 10^3\ Hz \longrightarrow$ SN explosion

  - $0.1 - 1\ Hz \longrightarrow$ Anisotropic emission of neutrinos and matter

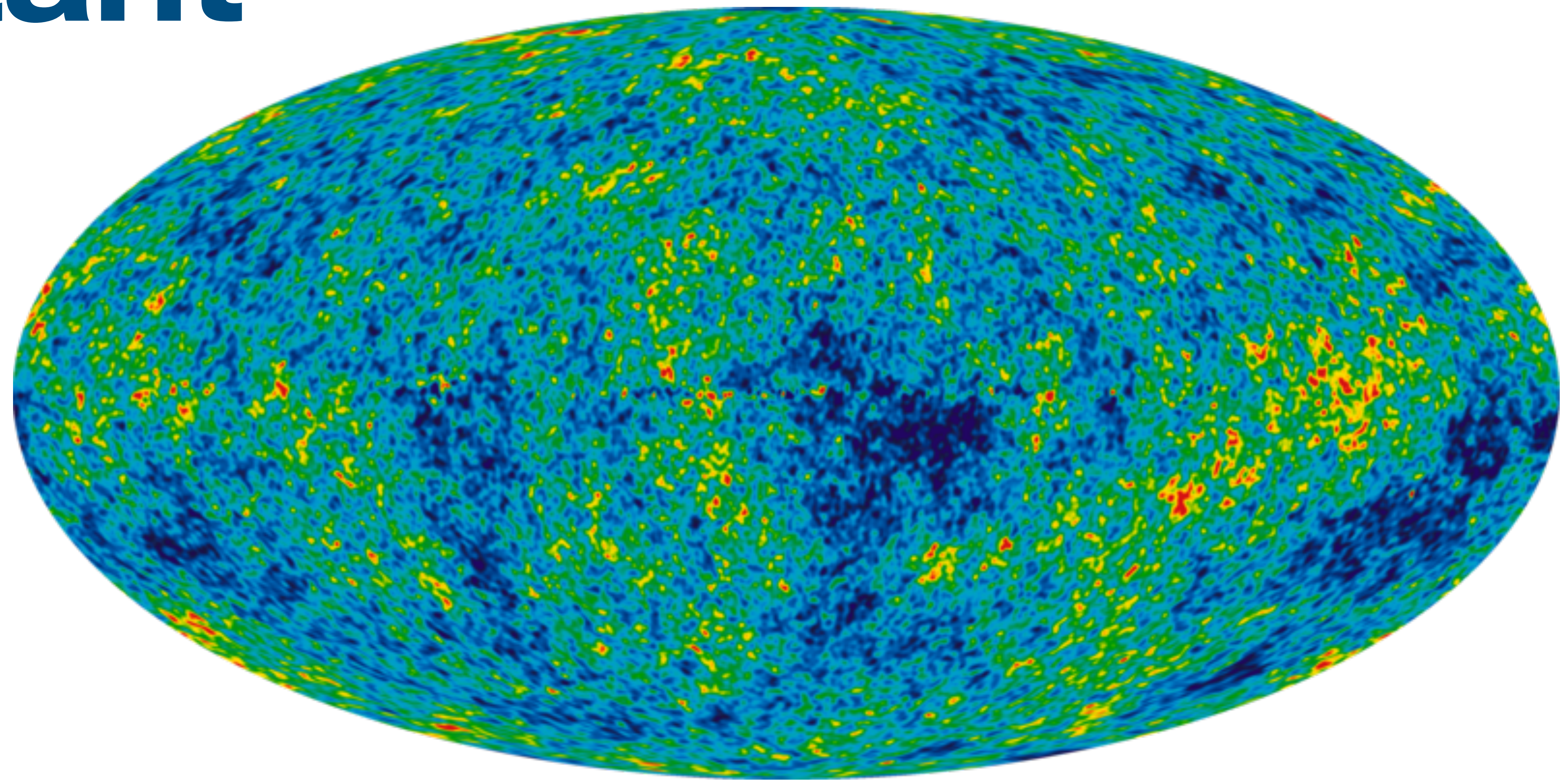
  - Significant role in the overall GW signature of supernova explosions.

- Dynamics and characteristics of the supernova event and mechanisms that drive the explosion



Measuring Hubble Constant

Current Methods of Estimation



- CMB -
  - Anisotropies
  - Temperature fluctuations
  - Acoustic power spectrum
- Supernovae
  - Standard candles
  - Apparent vs Intrinsic Luminosity

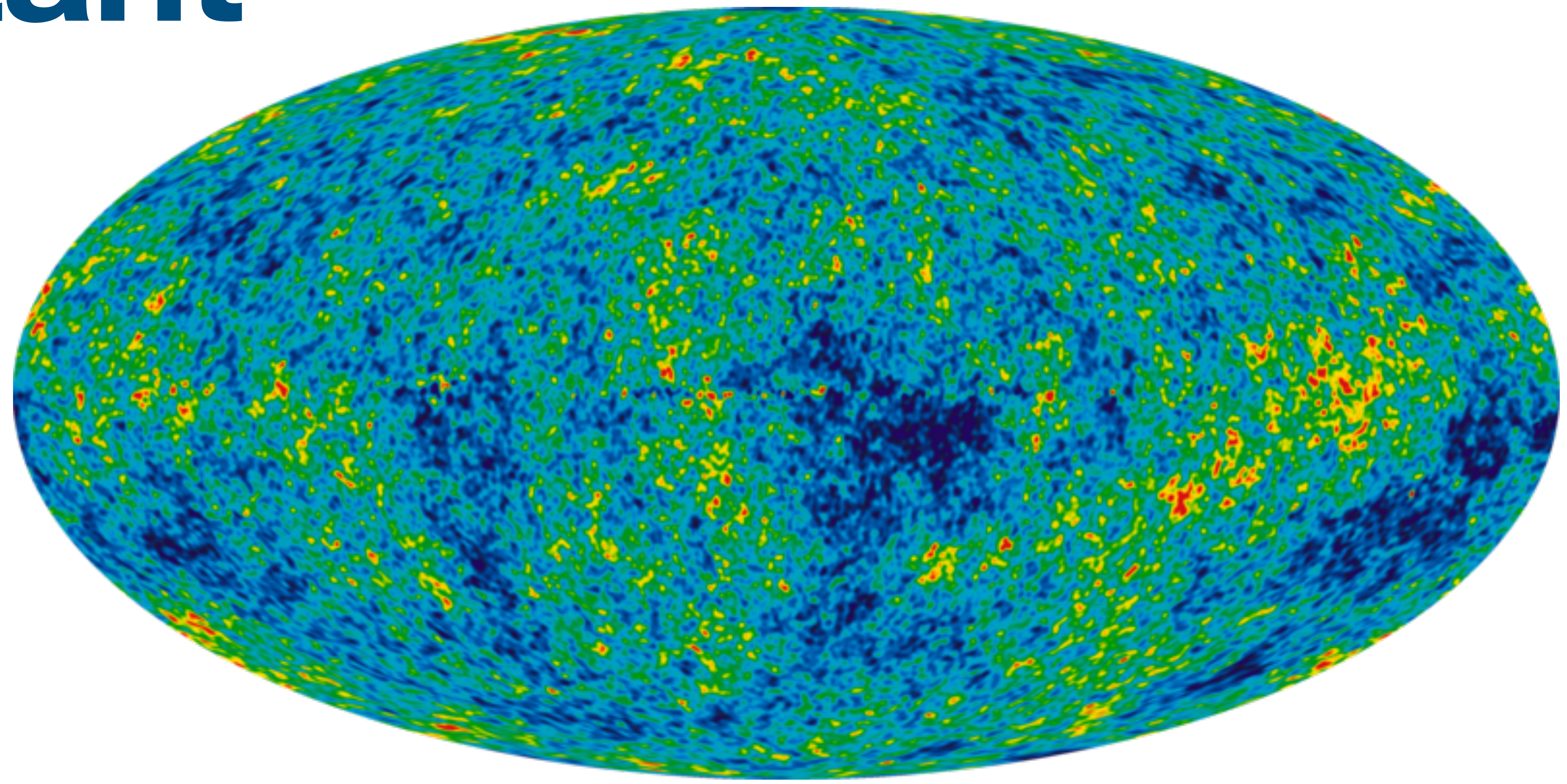
Measuring Hubble Constant

Current Methods of Estimation

$$H_0 = 67.5 \pm 0.5 \text{ km/s/Mpc}$$

Hubble Tension

$$H_0 = 73.8 \pm 2.4 \text{ km/s/Mpc}$$



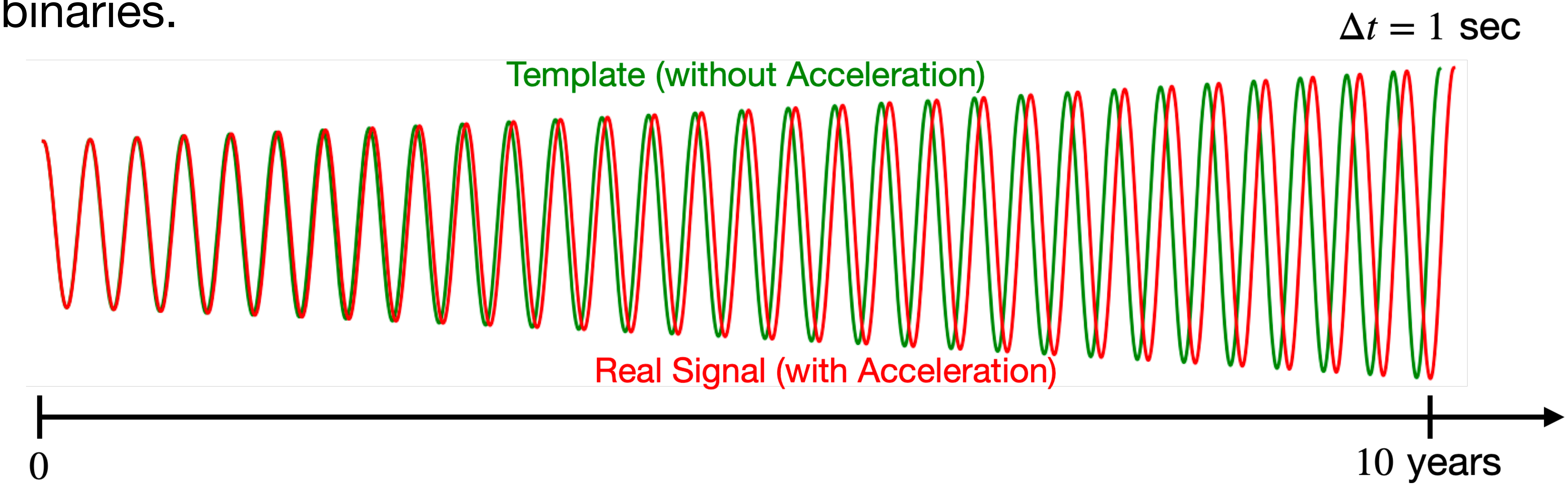
Measuring Hubble Constant

GW detectors

- Observing long-time inspirals - BNS
- Measure distance from GW waveform
- Identify host galaxy
  - Sky localization
  - EM counterpart
- Measure redshift from spectroscopy
- Find H_0 from distance and redshift

Acceleration of the Universe

- GWs will get differentially stretched at different times due to accelerated expansion.
- This shows up as an acquired phase delay. Can be detected for long lasting binaries.



Summary

- Brief overview of detector specifications.
- Science probes: BNS mergers, SNe progenitors, existence of IMBHs, CCSNe, Hubble Tension, Accelerated Universe.
- Further:
  - Stochastic GWs - binaries and primordial sources
  - Better parameter estimation - spin and alignment distribution
  - Explosive events like Jets

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Questions?

Exploring Astrophysics and Cosmology with Decihertz Gravitational Wave Detectors

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Multiple space-based decihertz gravitational wave detectors have been proposed and some are well into the developmental stages. We look at the schematics and specifications for a few of them, namely the DECIGO, the TianGO and the LGWA. We then present some astrophysical and cosmological insights that can be obtained using such detectors.

PACS numbers:
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I. INTRODUCTION

Gravitational waves, ripples in the fabric of spacetime, provide a unique window into the most energetic and cataclysmic events in the universe. Since the historic direct detection of gravitational waves in 2015, the field of gravitational wave astronomy has rapidly evolved, opening up new avenues for studying astrophysical phenomena. While ground-based detectors, such as LIGO and Virgo, have been successful in observing gravitational waves in the audio-frequency band, a relatively unexplored regime awaits discovery at even lower frequencies.

This paper focuses on the potential of decihertz gravitational wave detectors. We explore their design principles and distinctive characteristics in Section II. In section III, we examine the astrophysical and cosmological significance of employing decihertz detectors, encompassing phenomena like the dynamics of binary mergers, supernovae, and the evolution of the universe.

II. DETECTOR DESIGN

The proposed decihertz band gravitational wave detectors are all based outside the earth. This provides specific advantages over those stationed on the earth. Firstly, space based detectors have higher sensitivity to gravitational waves. The sensitivity to gravitational waves is proportional to the arm length of the detectors and it is easy to build detectors of longer arm length in space than on earth. Also, ground-based detectors have limitations on the low frequency detections due to seismic noise while the sky based detectors are in relatively 'calmer' environments, thus allowing for detection of low frequency events (0.001 Hz - 10 Hz). A brief description of the schematic design for three of the proposed detectors are given below.

A. TianGO

TianGO [1] is a space based detector which is sensitive to a frequency spectrum of range 0.1 to 1 Hz. At its core, it is a simple Michelson interferometer in space that works with a 5 W laser with wavelength, $\lambda = 532$ cm. It has three spacecrafts positioned at the vertices of a right triangle with 100 km long arms as shown in Figure 1.The corner spacecraft accommodates a laser and a beam splitter. The other two spacecrafts carry reflecting mirrors of 10 kg each. The beam splitter and mirrors are maintained under drag-free flight to make them as inertial as possible. This drag-free motion is sensed by the spacecrafts, which then follow the trajectories of the free-falling objects. The dispersion of the laser beams is minimized using telescopes housed in all the spacecrafts. This configuration is placed in a heliocentric orbit close to the earth.

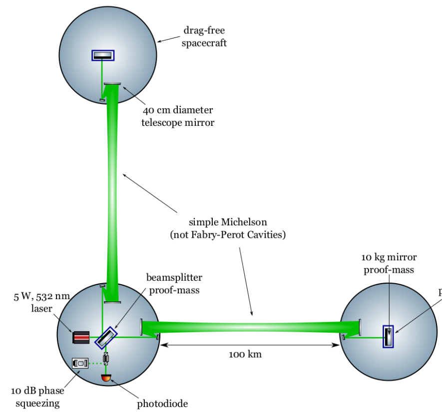

FIG. 1: Overview of the TianGO detector

B. DECIGO

The DECIGO constellation [2] is a sophisticated configuration consisting of four distinct clusters that are strategically placed in a heliocentric orbit. Two of these clusters are positioned in close proximity to each other, while the remaining two are distributed elsewhere along DECIGO's co-earth orbit. Within each cluster, three spacecrafts are arranged in an equilateral triangle formation, with sides of length 1000 km. These spacecraft are meticulously maintained in a drag-free state to ensure

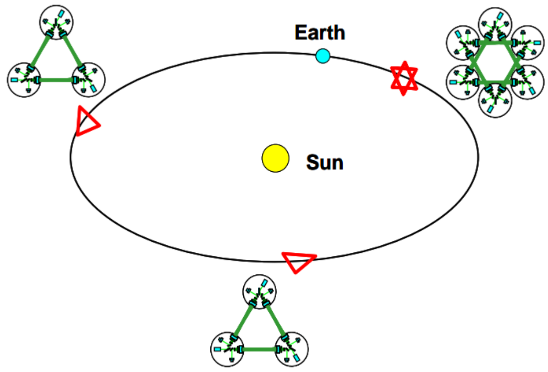

FIG. 2: Constellation of DECIGO in a heliocentric orbit.

accurate measurements.

Central to DECIGO's detection capabilities are the two floating mirrors housed within each spacecraft. These 100 kg mirrors serve as proof masses. By precisely quantifying the variations in distance between these mirrors, DECIGO is capable of detecting gravitational waves. To facilitate this measurement process, DECIGO employs a differential Fabry–Perot Michelson interferometer, known for its exceptional sensitivity and accuracy. A schematic diagram for this setup is shown in Figure 2.

C. The Lunar Gravitational-Wave Antenna

The Lunar Gravitational-Wave Antenna (LGWA) [3] utilizes an array of advanced seismometers deployed on the Moon to detect and study gravitational waves within the frequency range of 1 mHz to 1 Hz, with its sensitivity peaking in the decihertz range. The Moon's advantageous properties make it an ideal location for this detector: it is the closest celestial body to Earth, it has a substantial size that enhances sensitivity to gravitational wave signals, and it lacks an atmosphere and ocean, providing a stable environment with reduced seismic activity.

To achieve its objectives, LGWA relies on two crucial components. The first component is the cryogenic inertial sensor concept, which enables LGWA to measure horizontal ground displacements with exceptional sensitivity at 1 Hz. By utilizing a permanently shadowed region (PSR) on the lunar surface, where temperatures are around 30 K, the cryogenic environment enhances the performance of the inertial sensors by eliminating thermal noise and minimizing seismic disturbances.

The second key component involves deploying a kilometer-scale array of LGWA-grade inertial sensors along with advanced noise-cancellation techniques. This array configuration, consisting of a minimum of four stations strategically positioned with each sensor surrounded by others in all directions, enables efficient noise

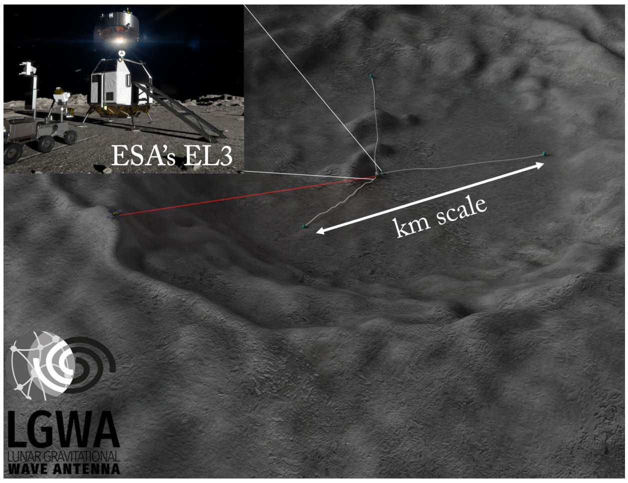

FIG. 3: Schematic design for the LGWA.

cancellation. It is crucial to include a PSR within the array deployment area to minimize interference and optimize the clarity of gravitational wave signals. Figure 3 shows the proposed design for the LGWA.

III. SCIENCE PROBES USING DECIHERTZ GW OBSERVATIONS

A. BNS Mergers and EM Counterparts

In the three observation runs conducted so far, the LIGO gravitational wave detectors have detected only two confirmed mergers of Binary Neutron Stars (BNS) [4]. Out of these two events, the accompanying electromagnetic (EM) counterpart, a Gamma Ray Burst (GRB), was confidently observed for only one of them [5]. To enhance the chances of detecting the electromagnetic signals accompanying BNS mergers, it is advantageous to employ space-based, decihertz band gravitational wave detectors. These detectors can identify BNS systems well in advance of their actual merger and provide enhanced sky localization compared to current ground-based detectors. This enables early warning to electromagnetic telescopes, allowing them to focus at expected space-time coordinates of the merger, thus significantly improving the likelihood of detection.

Early Warning Time. Figure 4 illustrates the distribution of time spent by various sources of gravitational waves across different frequency bands. This duration can be estimated as follows.

The separation between components of a binary system at a frequency, $f_{\rm GW}$ can be approximated using

$$a = \left[4\left(\frac{GM}{4\pi^2 f_{\rm GW}^2}\right)\right]^{1/3}, \tag{3.1}$$

where M is the total mass of the binary. The time for merger, once the system attains a separation a is given

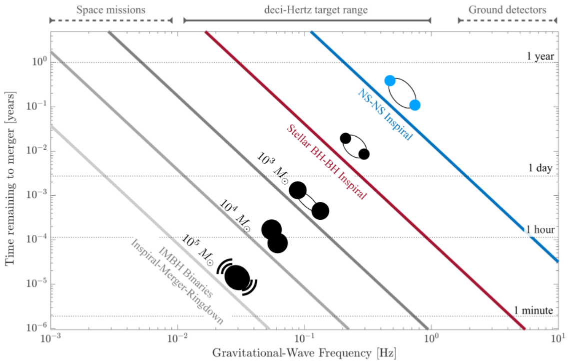

FIG. 4: Time remaining to merger for different GW sources.

by

$$T = \frac{a^4}{4\beta}, \tag{3.2}$$

with $\beta = \dfrac{16}{5}\dfrac{G^3M^3}{c^5}$, assuming initial circular orbit and identical component masses [6].

To estimate the time to coalescence for a BNS system with component masses of 1.4 $M_\odot$, which has a gravitational wave emission frequency of 0.1 Hz, we substitute $f_{\rm GW} = 0.1$ Hz in Equation 3.1 to obtain the corresponding separation. Using this value in Equation 3.2, we find that the BNS system will merge in approximately 4.3 years after entering the decihertz frequency band. During this period, the system will spend most of its time in the decihertz band. Careful analysis of the incoming signal would make it possible to forecast the merger, thus providing early warning to electromagnetic telescopes, enabling them to prepare and enhance the chances of successfully observing the EM counterpart.

Accurate Sky Localization. A space-based detector in a solar orbit would have completed several orbits around the Sun while observing the inspiral of a BNS system. By utilizing observations from this detector, we can achieve highly accurate localization of the gravitational wave source. This is possible because the detector effectively acts as multiple detectors positioned at different locations along its orbit, providing multiple long baselines. In this case, the largest baseline has a length, $b = 2$ AU, which is roughly equivalent to 1000 light seconds.

For a decihertz detector, an estimation of the timing accuracy (τ) is around 1 second [7]. In the optimal scenario, where the line of sight is perpendicular to the orbital plane, we can calculate the angular sky localization accuracy as follows:

$$\sigma = \tau\frac{c}{b} = 0.001 \text{ rad.}$$

The improved sky localization accuracy provided by a space-based detector in a solar orbit represents a significant advancement compared to the current capabilities. This advancement opens up the possibility of precisely pointing sensitive electromagnetic telescopes, which have a limited field of view, towards the gravitational wave source at the anticipated time of merger. As a result, it becomes feasible to observe the electromagnetic counterparts to the gravitational wave emissions.

These observations of electromagnetic counterparts serve as valuable tools to test the speed of gravitational wave propagation. By measuring the difference in the time of arrival of gravitational waves and the EM counterpart, we can examine whether gravitational waves travel at the speed of light. This testing allows us to scrutinize general relativity in comparison to alternative theories of gravity that incorporate massive gravitons.

Furthermore, if no electromagnetic counterpart is observed despite the precise localization achieved, this absence becomes a valuable piece of information for studying the environment surrounding these sources. It can help researchers investigate the factors or conditions that might be responsible for the absence of gamma-ray bursts during the merger event. This intriguing phenomenon presents an opportunity to delve into the mechanisms and circumstances that influence the emission or non-emission of GRBs in these particular scenarios.

B. Origins of Type IA Supernovae

Type Ia supernovae are powerful explosions that destroy white dwarf stars, releasing an enormous amount of energy. They exhibit a characteristic light curve, making them valuable as standard candles for cosmological distance measurements [8]. Understanding their formation mechanisms is crucial for interpreting their properties accurately.

There are two primary formation channels for Type Ia supernovae [9]. The first is the single-degenerate channel, where a white dwarf accretes matter from a companion star, typically a main-sequence or red giant star. As the accreted material accumulates on the white dwarf's surface, its mass gradually increases, eventually reaching the Chandrasekhar limit. At this point, the core of the white dwarf becomes hot and dense enough to initiate runaway nuclear fusion, resulting in a thermonuclear explosion that causes the supernova.

The second formation channel is the double-degenerate channel, involving the merger of two white dwarfs in a close binary system. When two white dwarfs are in a tight orbit, their orbits decay due to the emission of gravitational waves, leading to a spiral-in process. Eventually, the two white dwarfs collide and merge, triggering the ignition of a thermonuclear explosion.

Gravitational wave observations offer a promising avenue for determining the underlying channel involved in Type Ia supernovae. If we detect both gravitational waves and a supernova event simultaneously, it would strongly suggest the presence of the double degenerate channel. On the other hand, if we do not detect any gravitational waves preceding a nearby type IA supernova, it would indicate the single degenerate channel, as the lower frequency gravitational waves would have disrupted the companion star.

The frequency of gravitational waves emitted by a white dwarf binary can be approximated by inverting equation 3.1. This gives a gravitational wave frequency of

$$f_{\rm GW} \approx 2\sqrt{\left(\frac{GM}{4\pi^2 a^3}\right)}, \tag{3.3}$$

where M is the total mass of the binary and a is the separation. Subbing realistic values for $M \approx 2M_\odot$ and $a \approx 0.02R_\odot$ [10], we get a frequency $f_{\rm GW} \approx 0.1$ Hz. So, gravitational waves emitted by a white dwarf binary are in the decihertz band, thus requiring decihertz GW detectors to observe such emissions. The precise sky localization attained from these space based detectors would also aid in detecting the supernovae through electromagnetic observations. This makes space-based decihertz gravitational wave detectors instrumental in studying and pinning down the formation mechanisms of Type Ia supernovae.

C. Intermediate-Mass Black Holes

Intermediate-mass black holes (IMBHs) lie in the mass range of $10^2 - 10^5$ $M_\odot$, in between stellar and massive blackholes. Because of their small sphere of influence, only a few objects in close proximity exhibit clear and definitive signs of being influenced by an IMBH's dynamics, thus making it hard to find. The frequency of gravitational waves corresponding the innermost stable circular orbit of a stellar mass object around an IMBH of mass M is given by [7]

$$f_{\rm ISCO} \approx \frac{c^3}{6^{3/2}\pi GM}.$$

This is around 4.3 Hz, thus making decihertz range range detectors possibly one of the best means to observe them.

Being the heaviest objects in the star cluster, it is highly likely that IMBHs form binaries and can be detected through gravitational wave emission either through the inspiral of compact objects of stellar mass (black holes, neutron stars, or white dwarfs) into IMBHs or the merger of two IMBHs.

The detection of IMBHs also gives insights about the formation channels of massive black holes in the universe. In the absence of detection of GW emission from the binaries involving IMBHs, we can constrain the existence of IMBHs. Ruling out the presence of IMBHs would provide compelling evidence for the origin of massive black holes from more massive seeds rather than them evolving from the mergers of stellar BHs. Gaining insights into the formation and growth mechanisms of massive black holes is crucial for comprehending the processes underlying the development of structure in the early Universe and the evolution of galaxies.

By observing IMBHs, we can gain valuable insights into stellar evolution and dynamics of the globular cluster in which they reside. These coalescences of IMBHs could offer the opportunity to detect electromagnetic counterparts if the compact object involved in the inspiral is a white dwarf, rather than a neutron star or blackhole. For instance, the inspiral of a white dwarf into an IMBH with a mass in the range of 10^4 solar masses could be potentially observable up to a redshift of approximately 0.5. This detection could be achieved with sufficiently sensitive decihertz detectors.

The detection of electromagnetic counterparts to tidal disruptions offers several significant advantages. Firstly, it provides essential insights into accretion physics, including the study of super-Eddington flows, with crucial details that can be influenced by the mass and spin of the accretor, which can be determined through gravitational wave observations. Secondly, it introduces another valuable category of standard sirens for cosmography. Thirdly, it enables precise localization of the event, facilitating a definitive connection between intermediate-mass black holes and globular clusters or dwarf galaxies.

D. Core Collapse Supernovae

Theoretical models suggest that supernova (SN) explosions can be fueled by two main mechanisms: explosive nuclear burning or by the gravitational collapse of the stellar core known as core-collapse supernovae (CCSNe). CCSNe is one of the most energetic explosions in the universe which mark the final stage of evolution for stars (≥ 8 $M_\odot$).

During a CCSNe, a significant amount of energy is released which can be detected in the form of gravitational waves. The majority of the gravitational wave energy emitted during a CCSN falls within the frequency range of approximately 10^2 to 10^3 Hz.

During the supernova explosion, in addition to the high-frequency gravitational wave emission, there are two notable low-frequency signals that contribute to the overall emission [11]. The first signal arises from the asymmetric ejection of material, generating gravitational waves in the frequency range of 0.1 to 1 Hz. This type of emission is expected not only for supernovae occurring in isolation but also for those that occur within close binary systems.

The second low-frequency signal originates from the asymmetric emission of neutrinos. As the outgoing neutrino shells exhibit asymmetry (Figure 5), they produce gravitational waves at frequencies ranging from approximately 0.1 to 10 Hz. This frequency range overlaps with the gravitational wave emission resulting from the matter ejected during the explosion.

These combined low-frequency signals, originating from both asymmetric matter ejection and neutrino emis-

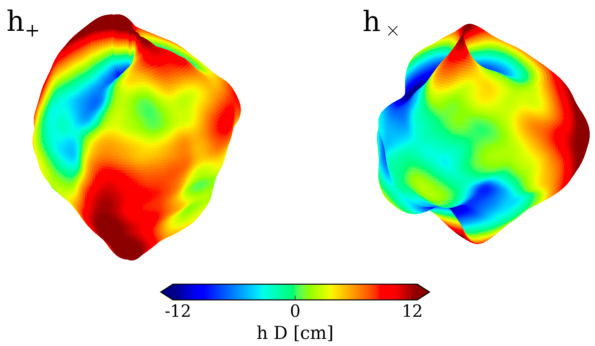

FIG. 5: Three-dimensional map illustrating the gravitational-wave strain h, multiplied by distance D, generated by neutrino emission anisotropies.

sion, play a significant role in the overall gravitational wave signature of supernova explosions. Understanding and detecting these low-frequency components provide crucial insights into the dynamics and characteristics of the supernova event, as well as the underlying mechanisms driving the explosion.

Therefore, the observation of higher-frequency gravitational wave emissions (from ground based detectors) with the low-frequency signals(from decihertz detectors) would shed light on the intricate interplay between neutrino emissions, matter ejection, and the underlying physics governing the mechanisms driving supernova explosions.

E. Resolving Hubble Tension

The Hubble tension refers to the discrepancy between different measurements of the Hubble constant H_0. The Hubble constant describes the current rate of expansion of the universe. Traditionally, the Hubble constant has been measured using two main approaches:

1. Observations of the Cosmic Microwave Background (CMB): The CMB is the remnant radiation from the early universe. It provides a snapshot of the universe when it was only about 380,000 years old. The Hubble constant can be inferred by analyzing the small temperature fluctuations in the CMB. Analyzing this 'early-time' information yields a value of $H_0 = 67.5 \pm 0.5$ km/s per Mpc [12].

2. Observations of Supernovae and Cepheid variable stars: Supernovae are exploding stars, and Cepheid variables are pulsating stars with a well-known relationship between their pulsation period and intrinsic brightness. By observing these objects in distant galaxies and measuring their redshift is another avenue for determining the Hubble constant. This analysis with 'late-time' observations indicates a higher value for H_0 of 73 km/s per Mpc [13].

The early-time and the late-time observations disagree with each other. The Hubble tension, which is the (non-zero) difference between these measurements, implies that there is a disagreement between the predictions of the standard cosmological model (based on the CMB) and the direct measurements of the expansion rate of the local universe (based on supernovae and Cepheids). Resolving the Hubble tension is crucial for our understanding of the fundamental properties of the universe and its evolution.

Gravitational waves provide an alternative way to measure the Hubble constant, thus making them useful in resolving the Hubble tension. If one could get accurate estimates of both, the distance to the source and the redshift, one could estimate the Hubble constant from these measurements. While gravitational wave detectors measure distances to the source, they do not determine the redshifts. However, from the arguments in the preceding sections, we know that space based gravitational wave detectors allow for excellent sky localization of the source binaries. This information can be used, either directly, or with the help of EM counterpart (if it exists), to ascertain the host galaxy of the source. Knowing the host galaxy, one could obtain the redshifts using spectroscopic techniques. This can then be used, in conjunction with the distance observed using gravitational waves, to estimate the Hubble constant, and possibly resolve the Hubble tension.

F. Measuring the Acceleration of the Universe

That the universe is accelerating, is supported by strong evidence from observations such as distant supernovae, the cosmic microwave background, and the large-scale structure of the universe [14]. The dominant driver of this acceleration is believed to be dark energy, a mysterious form of energy that continues to be a subject of active research and investigation.

Gravitational waves provide a valuable tool to investigate the acceleration of the universe. In an accelerating universe, gravitational waves experience phase delays as they propagate through space [15]. Current models suggest that these phase delays accumulate at a rate of approximately 1 second per 10 years. Binary neutron star systems may produce gravitational wave signals that persist in the decihertz frequency range for about 10 years. By precisely measuring the acquired phase delays using decihertz gravitational wave detectors with sufficient timing accuracy, it becomes possible to determine the acceleration of the universe and constrain the parameters of dark energy distribution models.

IV. DISCUSSION AND CONCLUSION

In conclusion, this paper has highlighted the significance of decihertz gravitational wave detectors in ad-

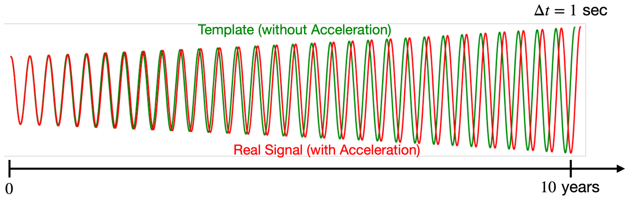

FIG. 6: Representative diagram showing the phase delay acquired by a gravitational wave due to the acceleration of the universe.

vancing our knowledge of astrophysics and cosmology. The design principles and characteristics of three notable decihertz detectors, namely TianGO, DECIGO, and the Lunar Gravitational-Wave Antenna (LGWA), have been discussed.

Moreover, the paper has explored the potential astrophysical and cosmological insights that can be gained through decihertz detectors. While focusing on this topic, it is important to acknowledge additional intriguing possibilities that were not extensively covered here. Decihertz detectors might have the ability to detect stochastic gravitational waves originating from binary systems and primordial sources like inflation, primordial black holes, phase transitions, and cosmic strings. Multi-band observations facilitated by these detectors hold the potential to yield a deeper understanding of the evolutionary history of various binaries, enabling precise determination of source parameters such as spin magnitudes and misalignment angles. In addition to binaries, comprehensive coverage of the frequency spectrum allows for the observation of gravitational waves emitted by catastrophic events like jets, which in turn provide opportunities to investigate the underlying physics.

Undoubtedly, the ongoing advancements in the development and deployment of future gravitational wave detectors will pave the way for exciting breakthroughs in our comprehension of the universe. The exploration of decihertz gravitational waves promises to unlock new realms of knowledge and contribute to our ever-growing understanding of astrophysics and cosmology.

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