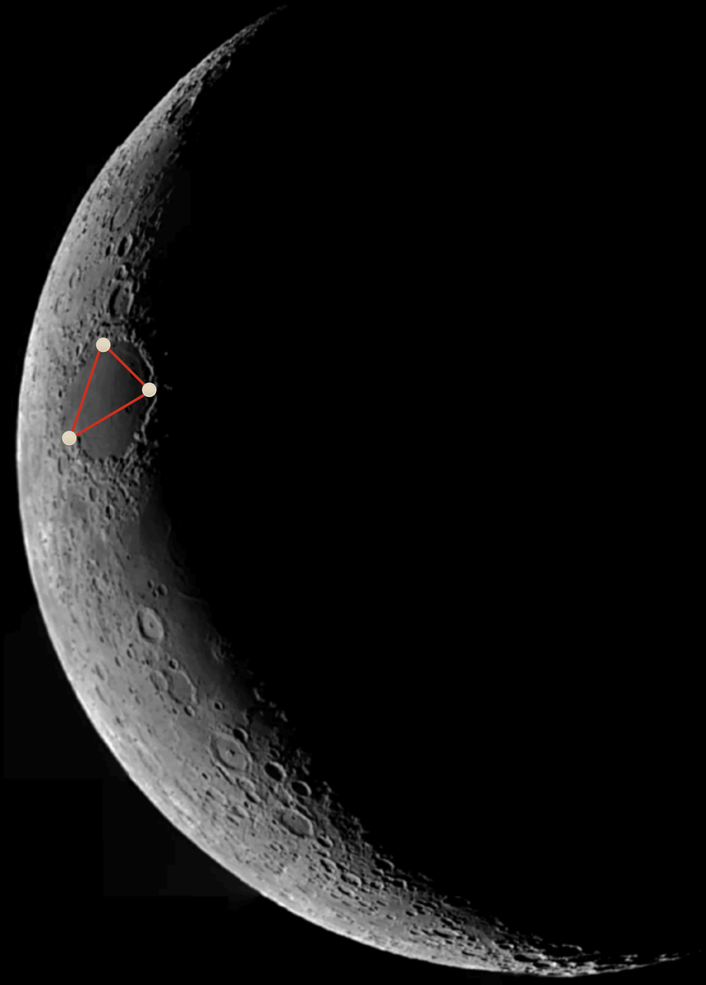
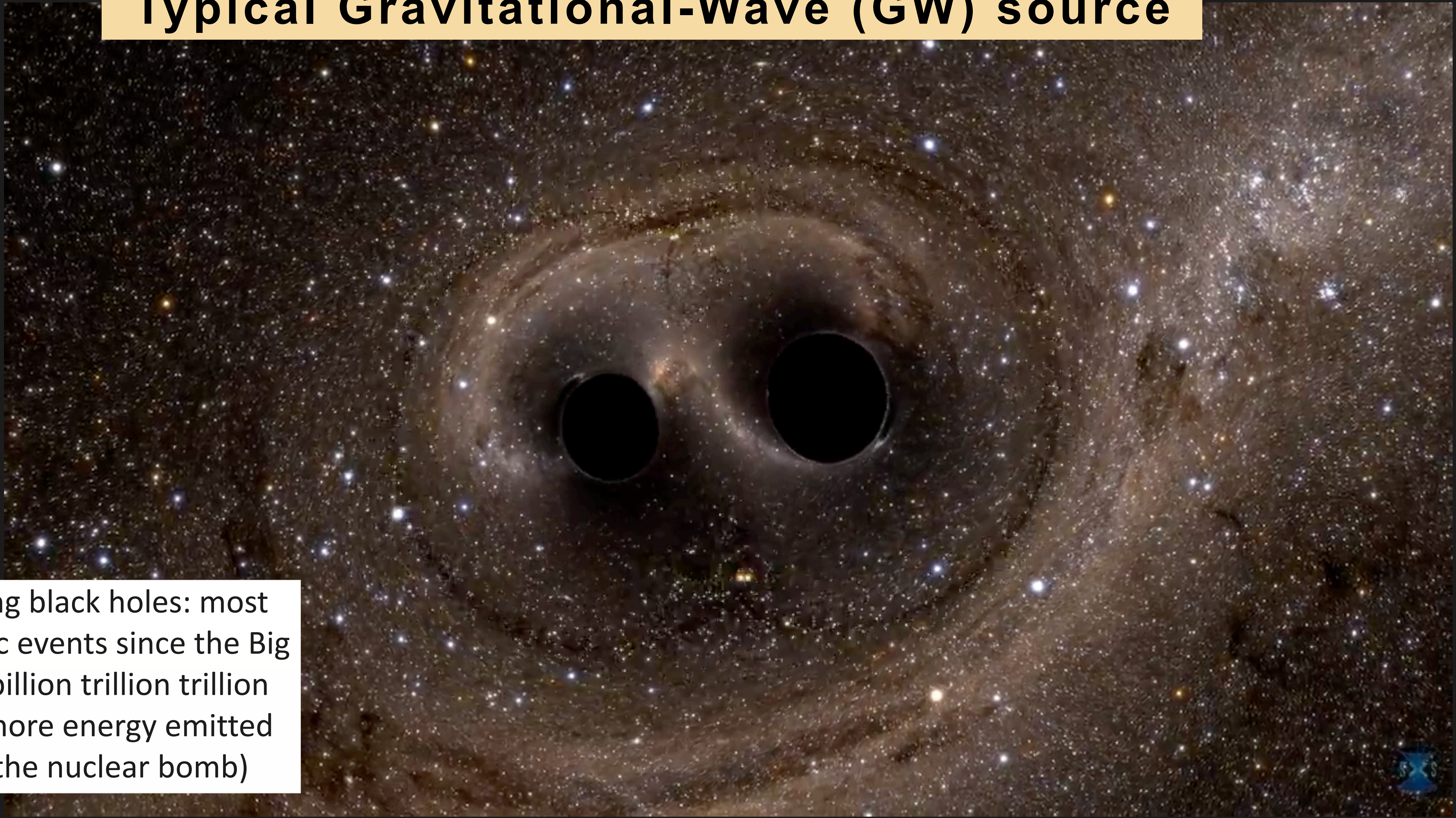
Gravitational-wave detectors: past, present and future

Prof. Karan Jani, Vanderbilt

VIPER Summer School @ Vanderbilt
Nashville, TN
July 8, 2024



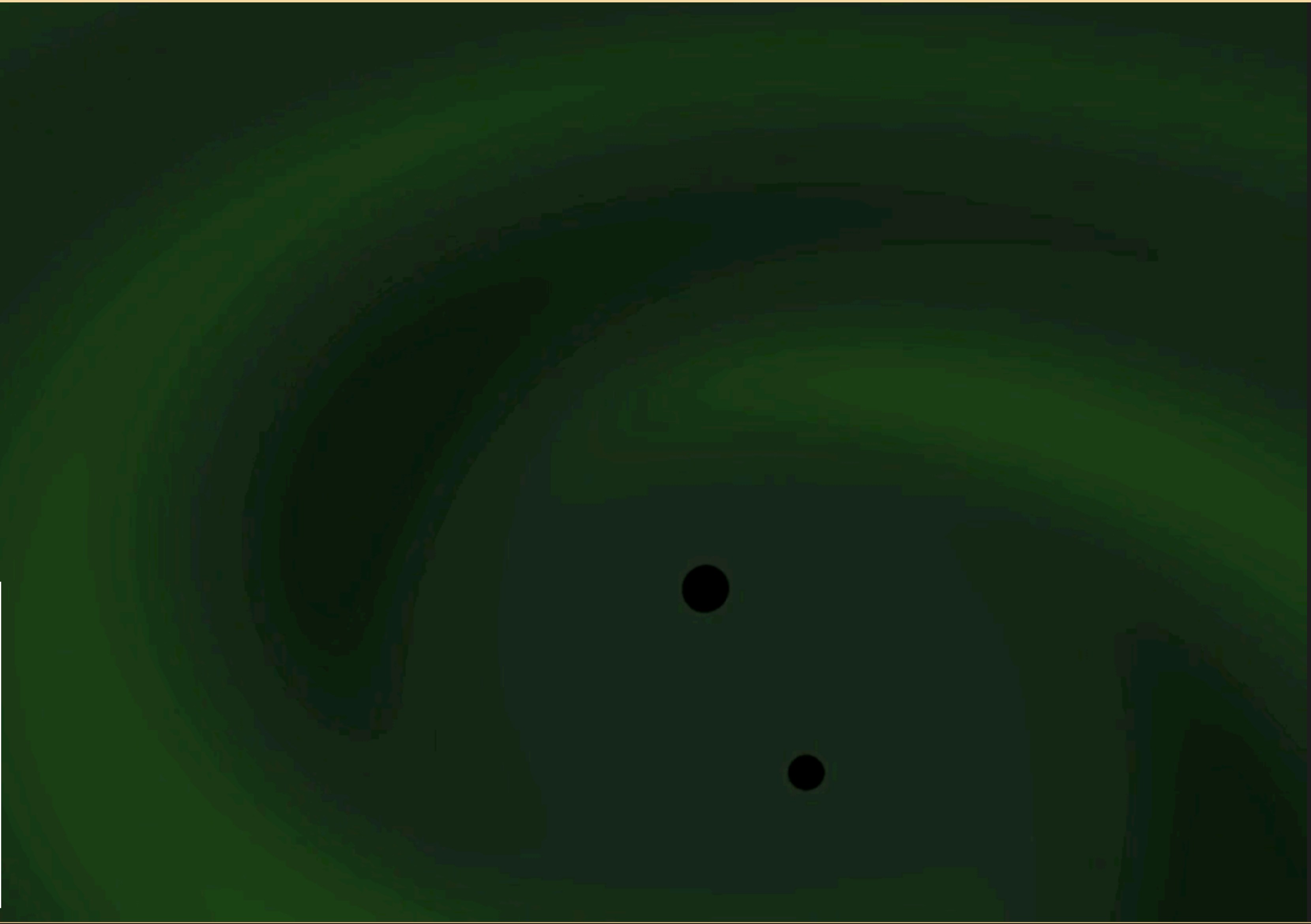
Typical Gravitational-Wave (GW) source



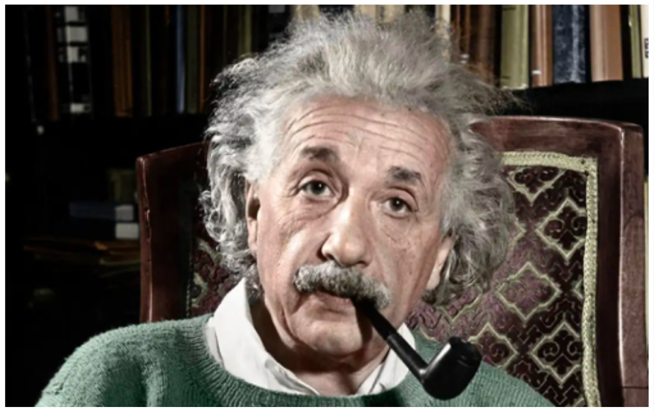
Colliding black holes: most energetic events since the Big Bang (billion trillion trillion times more energy emitted than the nuclear bomb)

Video: SXS Collaboration

GW = ripples on the fabric of spacetime

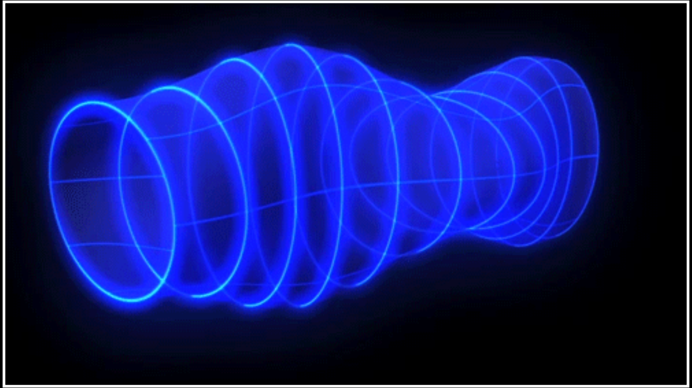


Predicted in 1916



Video: LIGO Labs

Effect of GW passing through matter



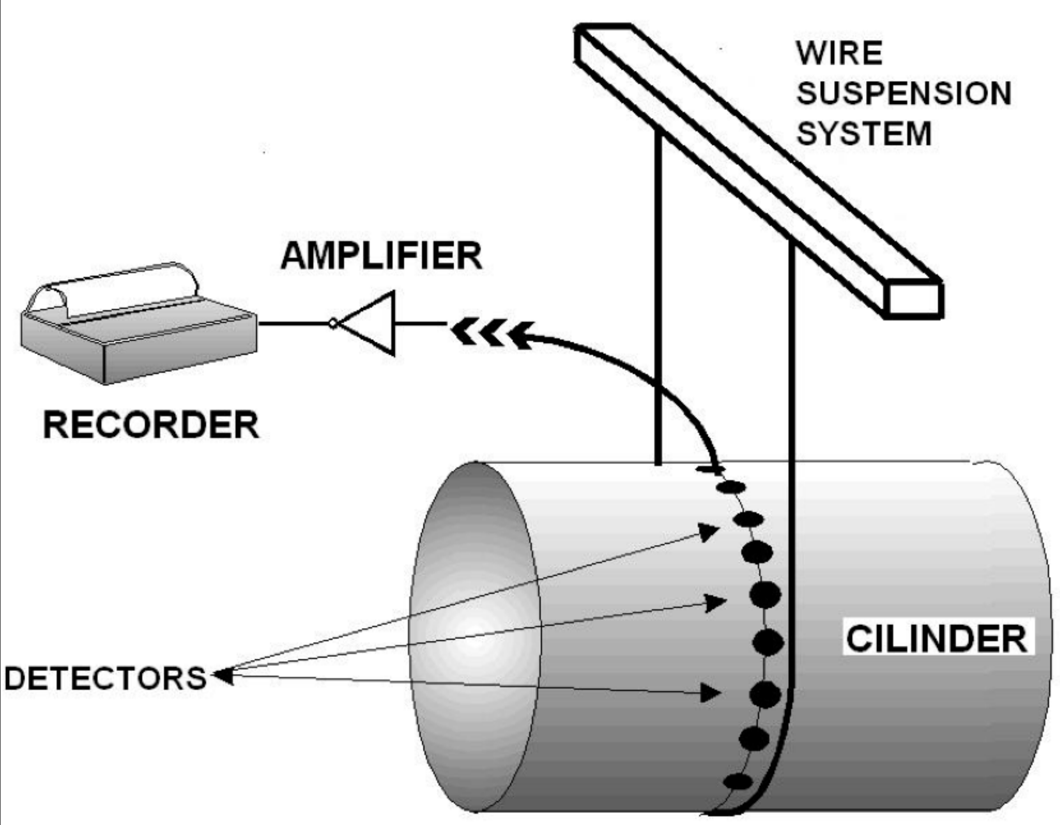
Video: LIGO Labs

Outline of the lecture

1. Past (pre-1990s)
    - Bar detectors
2. Present (2000-now)
    - LIGO-Virgo-KAGRA, PTA
3. Future (2030s)
    - LISA, Cosmic Explorer, Einstein Telescope
4. Distant future (20xx)
    - Lunar GW, detectors in deci-Hertz, micro-Hertz

DALL-E-3: “Gravitational-wave observatory”

Weber Bar (1960s): First GW detector



From: Cervantes-Cota, Galindo-Uribarri and Smoot; Universe 2016, 2(3), 22

1969: Claim of first “direct detection” of GW

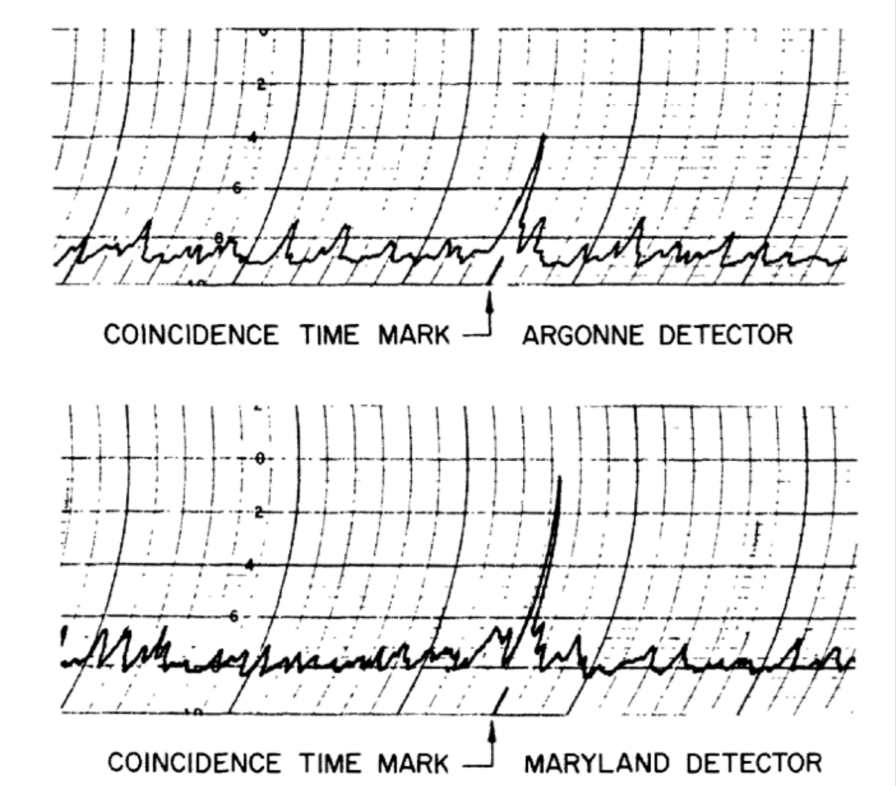
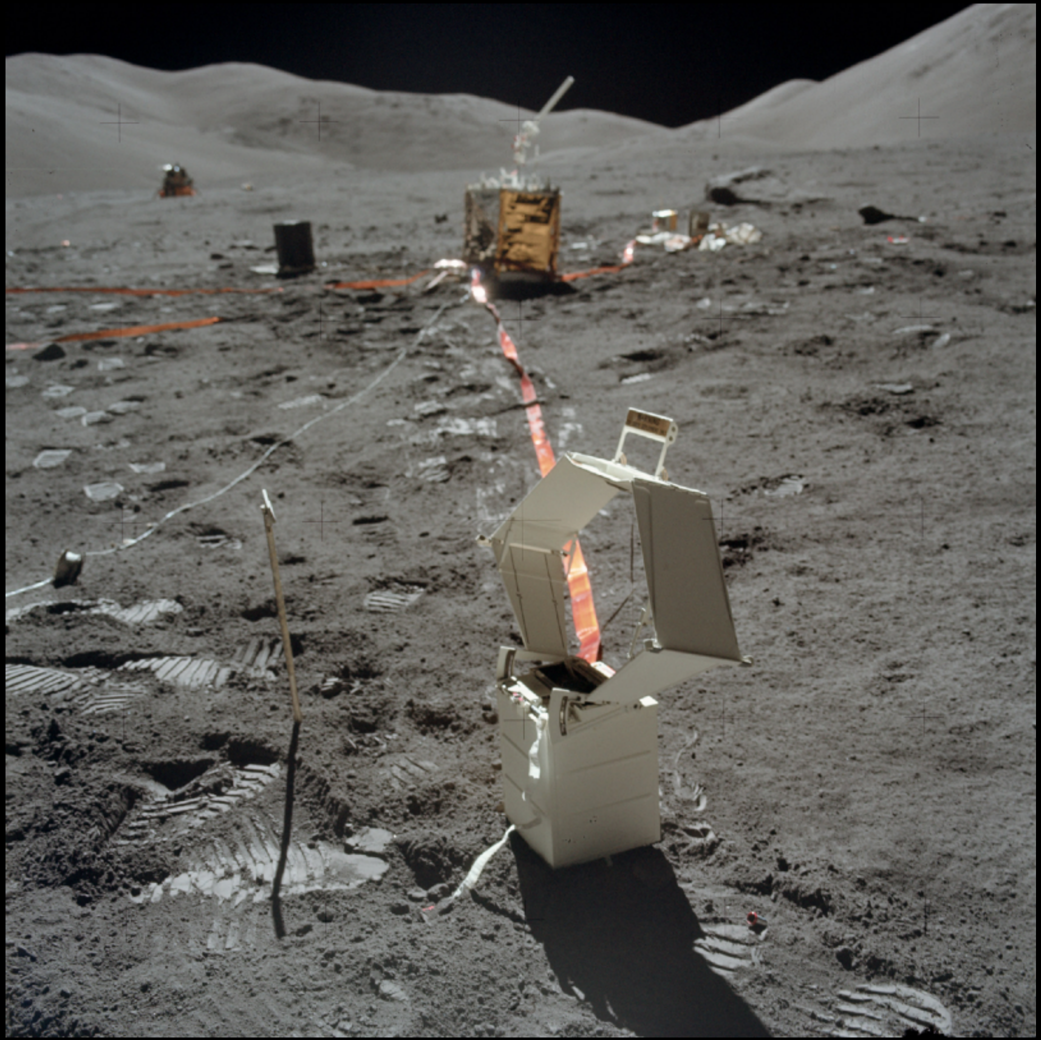


FIG. 2. Argonne National Laboratory and University of Maryland detector coincidence.

More sophisticated bar detectors were built in CERN, in Italy, in Louisiana, in Netherlands. None of them saw any such signal at any time :(

 Images from: Saulson (2014) and Larson (2015)

Apollo 17 (1972): First GW detector outside earth



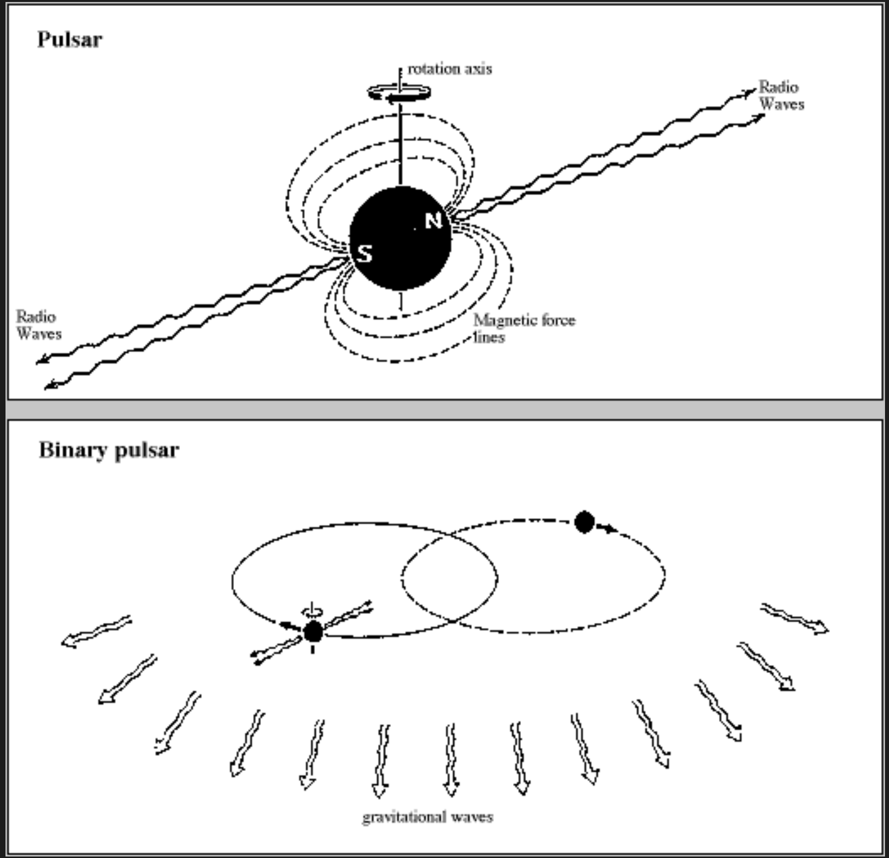
Lunar Surface Gravimeter

NSSDCA ID: 1972-096C-09

Mission Name: Apollo 17 Lunar Module /ALSEP
Principal Investigator: Prof. Joseph Weber

The primary objective of the lunar surface gravimeter (LSG) is to use the Moon as an instrumented antenna (refs. 12-1 to 12-8) to detect gravitational waves predicted by Einstein's general relativity theory. A secondary objective is to measure tidal deformation of the Moon. Einstein's theory describes gravitation as propagating with the speed of light. Gravitational waves carry energy, momentum, and information concerning changes in the configuration of their source. In these respects, such waves are similar to electromagnetic waves; however, electromagnetic waves only interact with electric charges and electric currents. Gravitational waves are predicted to interact with all forms of energy.

By 1980s, there were "indirect evidence" of GW. But a "direct detection" remained controversial



Nobel Prize Physics for 1993 to Hulse & Taylor

"The good agreement between the observed value and the theoretically calculated value of the orbital path can be seen as an indirect proof of the existence of gravitational waves. <u>We will probably have to wait until next century for a direct demonstration</u> of their existence" - Press Release, Nobel Prize (1993)

"Weber lived a long and active life, until 2000. He never agreed that his results were wrong. He kept making observations and announcing detections. (He "saw" SN1987a, e.g.) His continual presence reminded us that <u>our field was born in controversy</u>.

Without any formal closure (in particular, any agreement on what had gone wrong), it was hard to leave that episode in the past; in effect, we replayed the Weber affair all the time."

- Peter Saulson, 2014 (LIGO-G1400715)

2014: Another false claim of “direct evidence” of GW

Caltech

Menu

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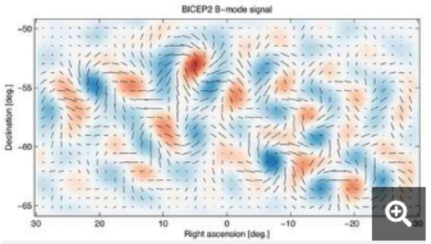
BICEP2 Discovers First Direct Evidence of Inflation and Primordial Gravitational Waves

March 17, 2014

Astronomers announced today that they have acquired the first direct evidence that gravitational waves rippled through our infant universe during an explosive period of growth called inflation. This is the strongest confirmation yet of cosmic inflation theories, which say the universe expanded by 100 trillion trillion times in less than the blink of an eye.



Gravitational waves from inflation generate a faint but distinctive twisting pattern in the polarization of the CMB, known as a "curl" or B-mode pattern. Shown here is the actual B-mode pattern

BICEP2 (Background Imaging of Cosmic Extragalactic Polarization), March 2014

nature

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Published: 30 January 2015

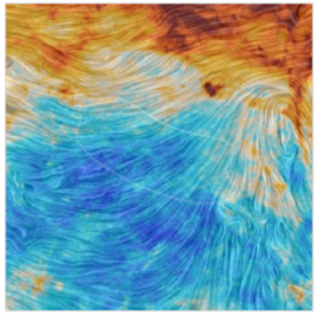
Gravitational waves discovery now officially dead

Ron Cowen

Nature (2015) | Cite this article

1546 Accesses | 4 Citations | 681 Altmetric | Metrics

Combined data from South Pole experiment BICEP2 and Planck probe point to Galactic dust as confounding signal.



Nature, January 2015

MIT 1972: Laser interferometer GW concept

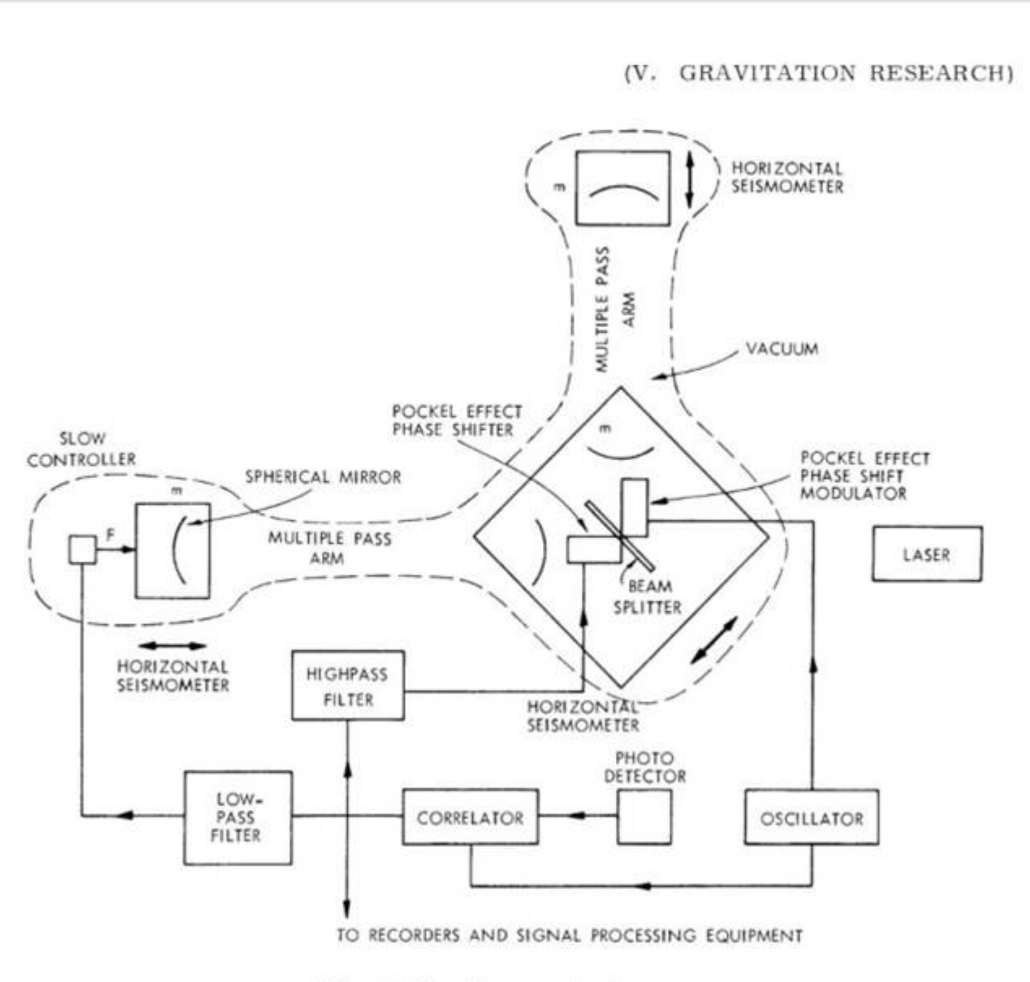
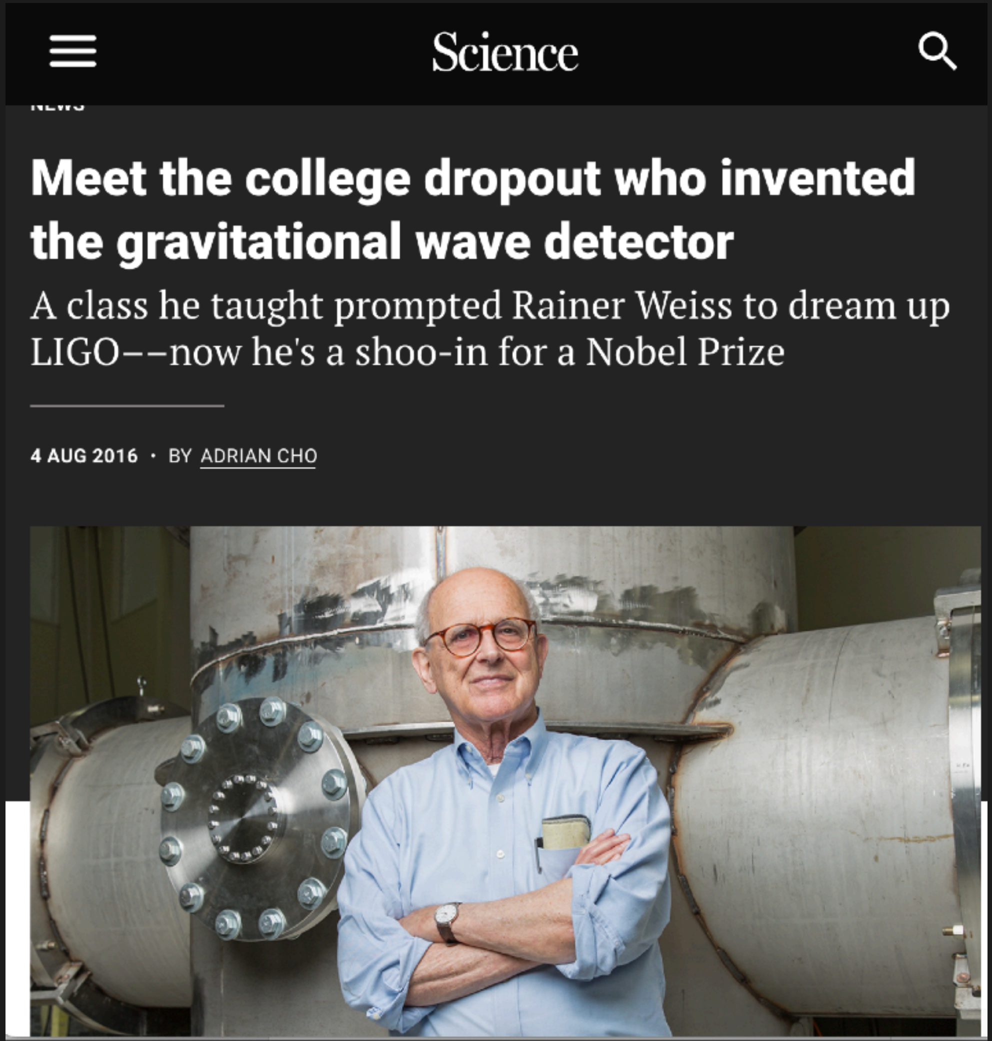
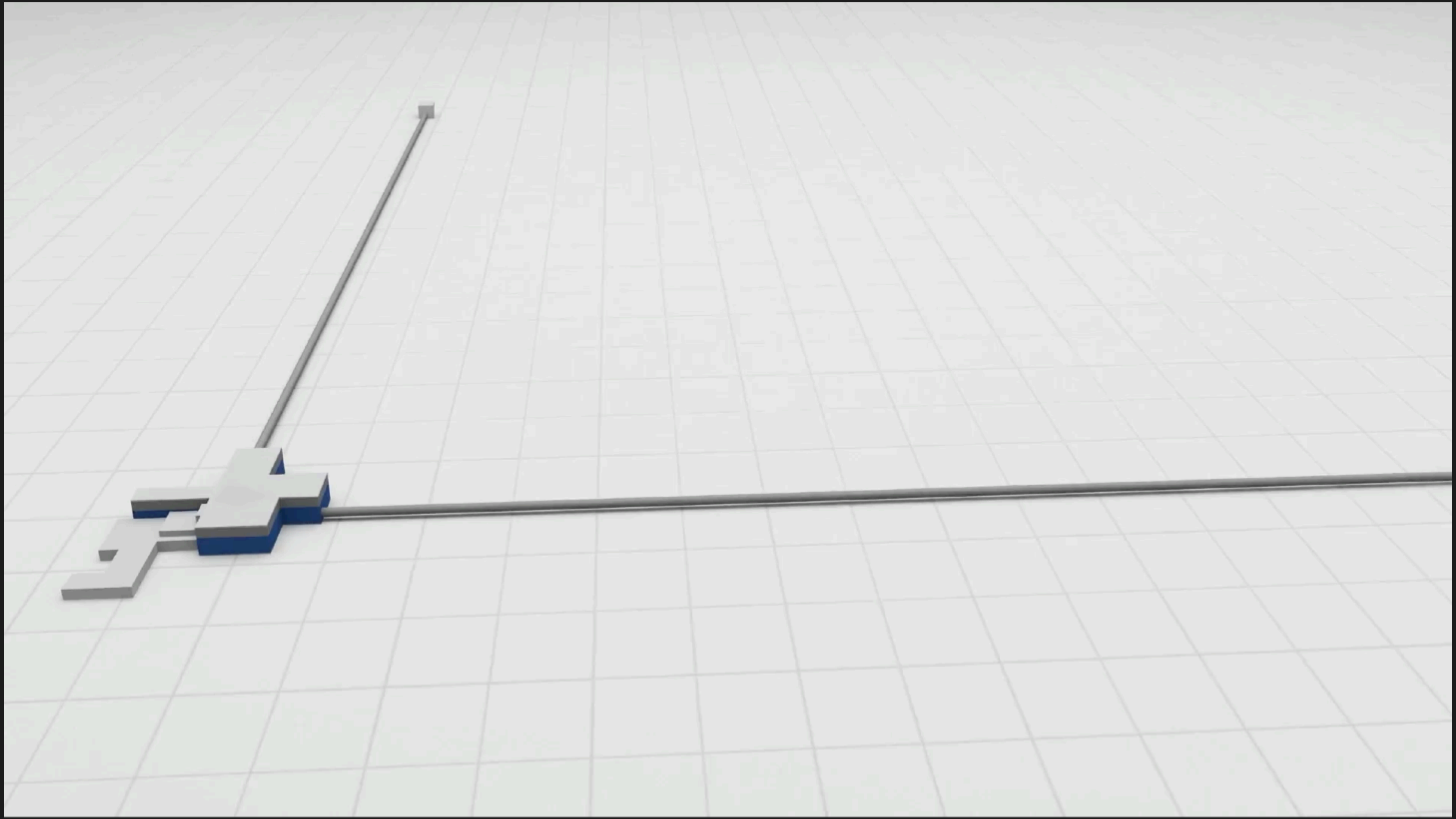


Fig. V-20. Proposed antenna.



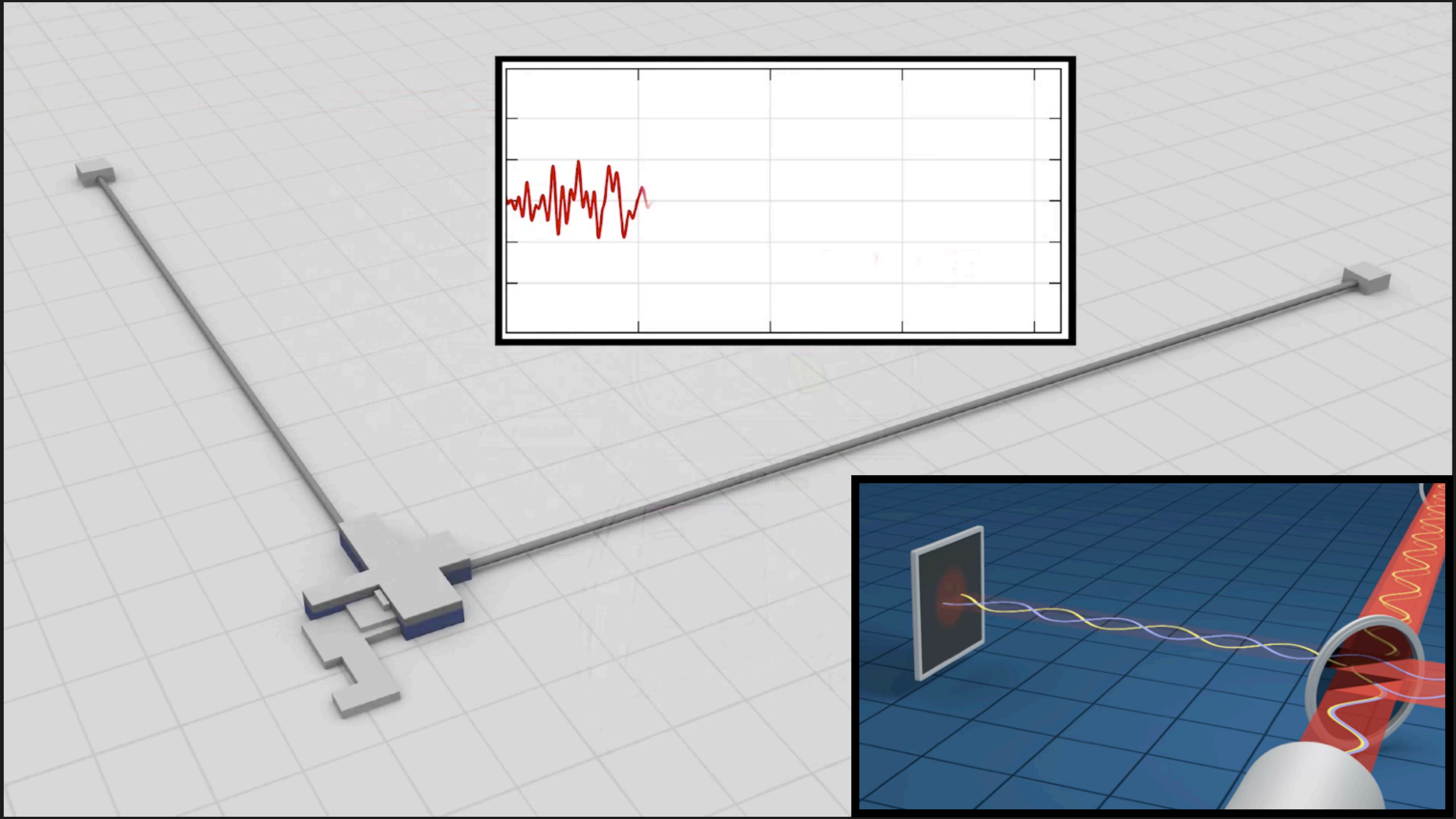
LIGO

Laser interferometer GW concept



Video: Kai Staas

Laser interferometer GW concept



Video: Kai Staas

LIGO (Laser Interferometer Gravitational-wave Observatory)

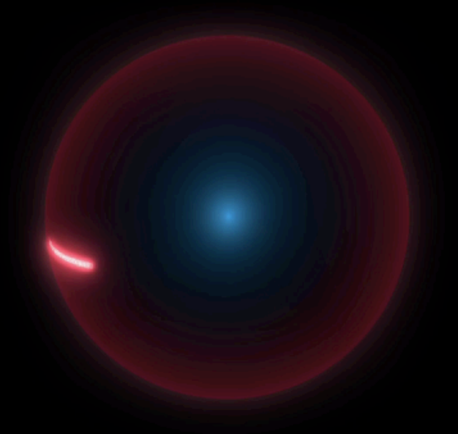
Operating since 2000

Arm-length 4 km

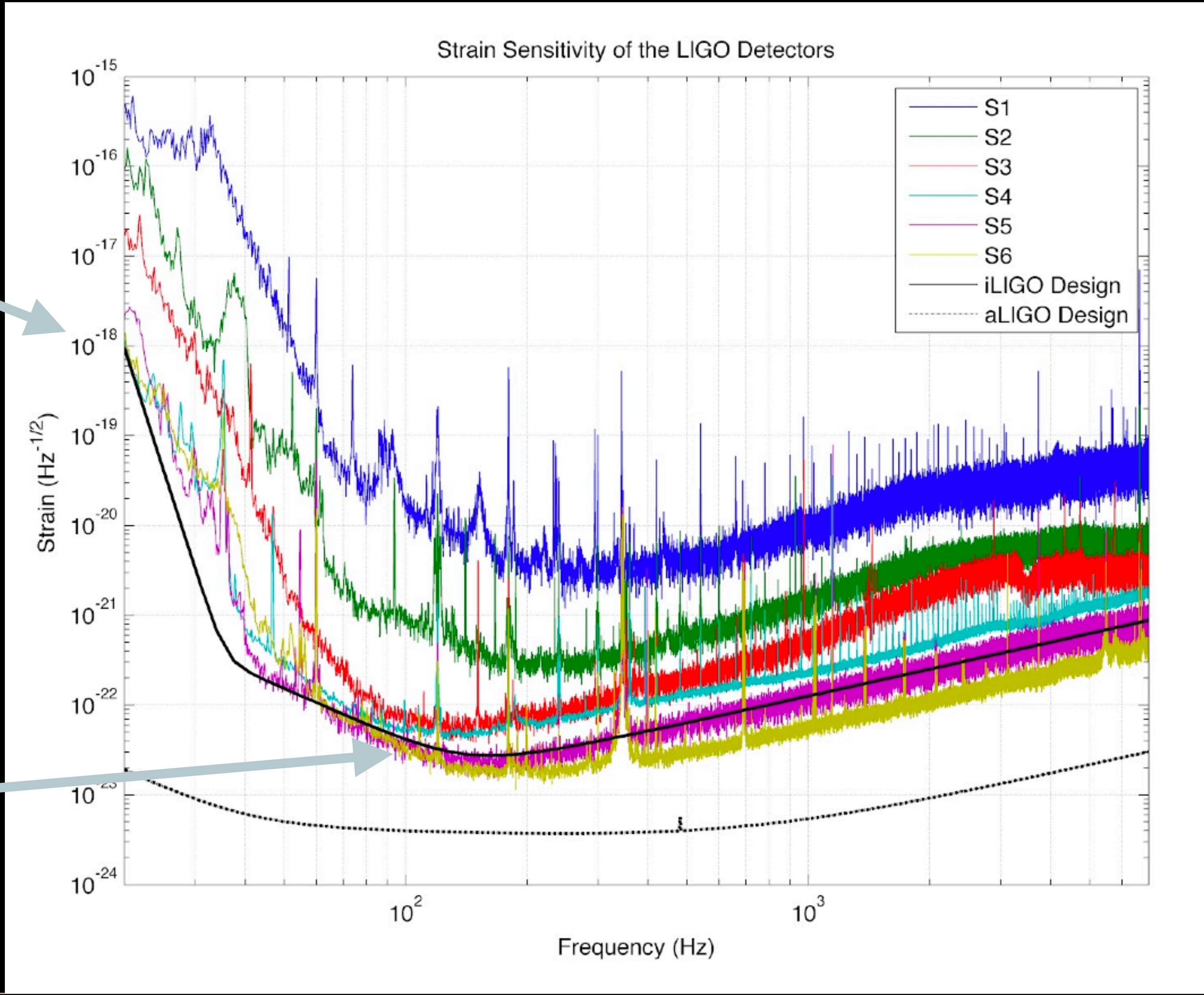
Current earth-based GW network

Sensitivity of Initial LIGO (2000-2010)

Change in arm-length from incoming GW = dL / L

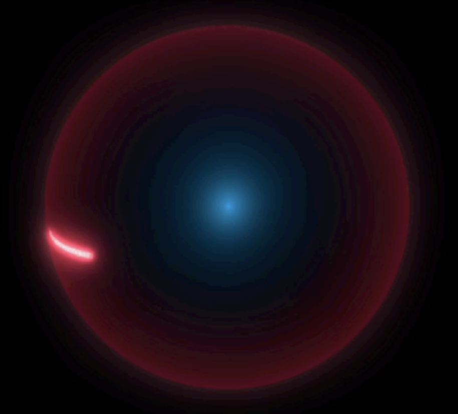


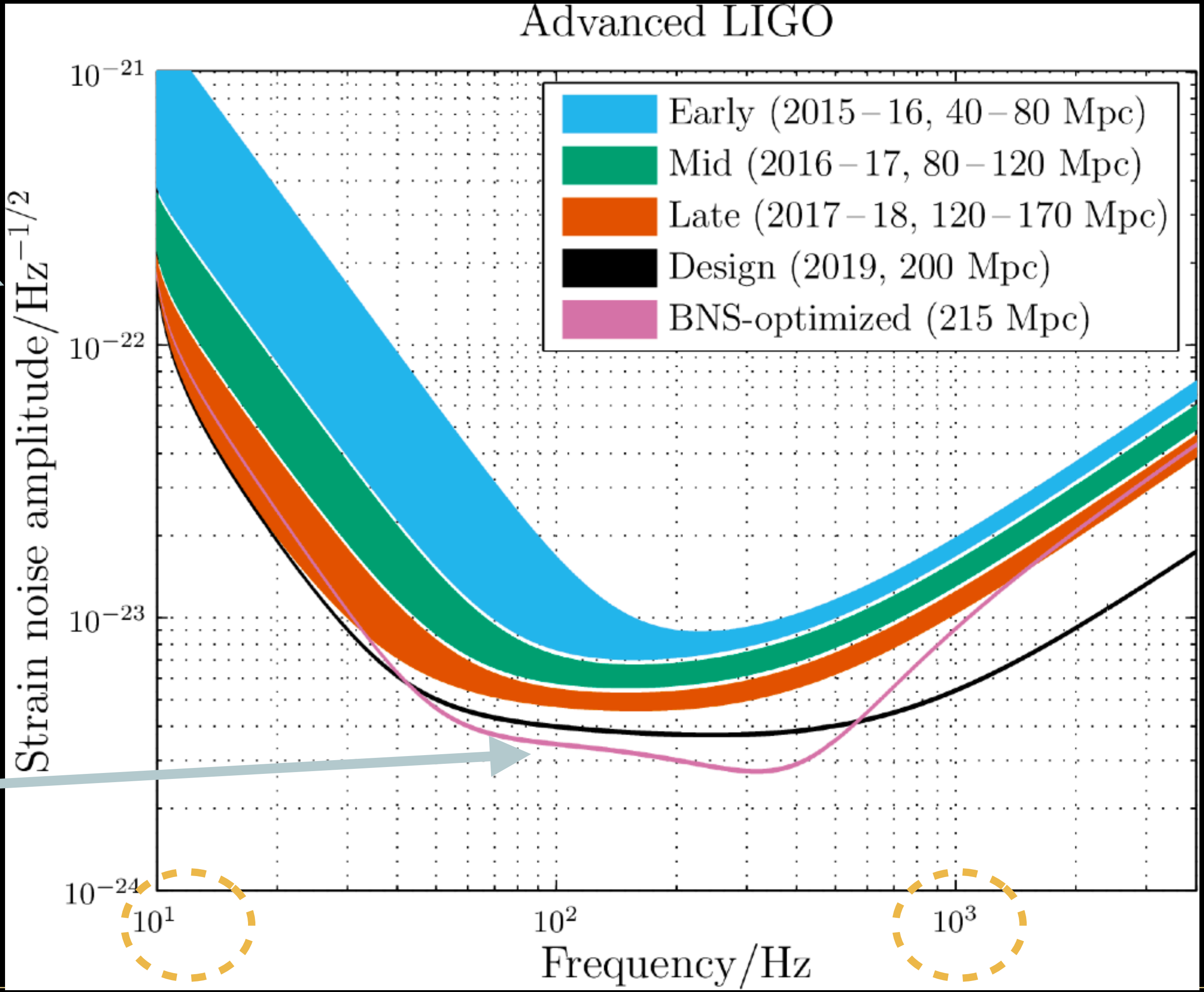
Diameter of proton = 1e-15
iLIGO peak sensitivity dL/L = 1e-21



Sensitivity of Advanced LIGO (2015 - present)

Change in arm-length from
incoming GW = dL / L

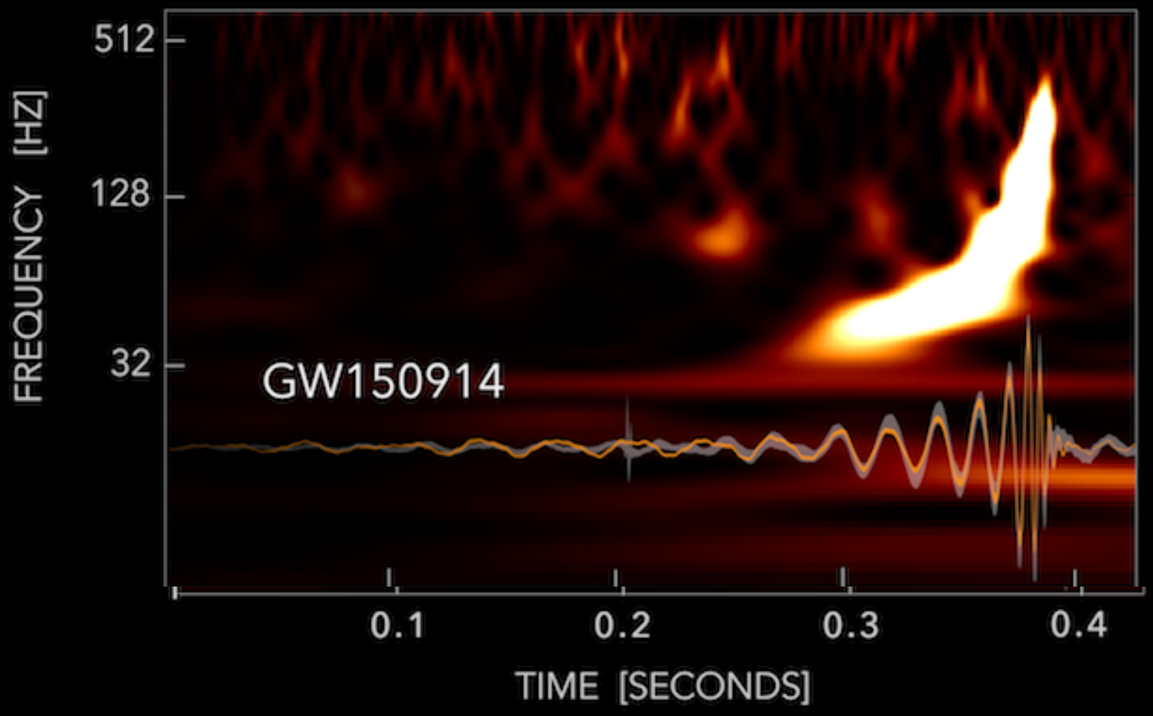




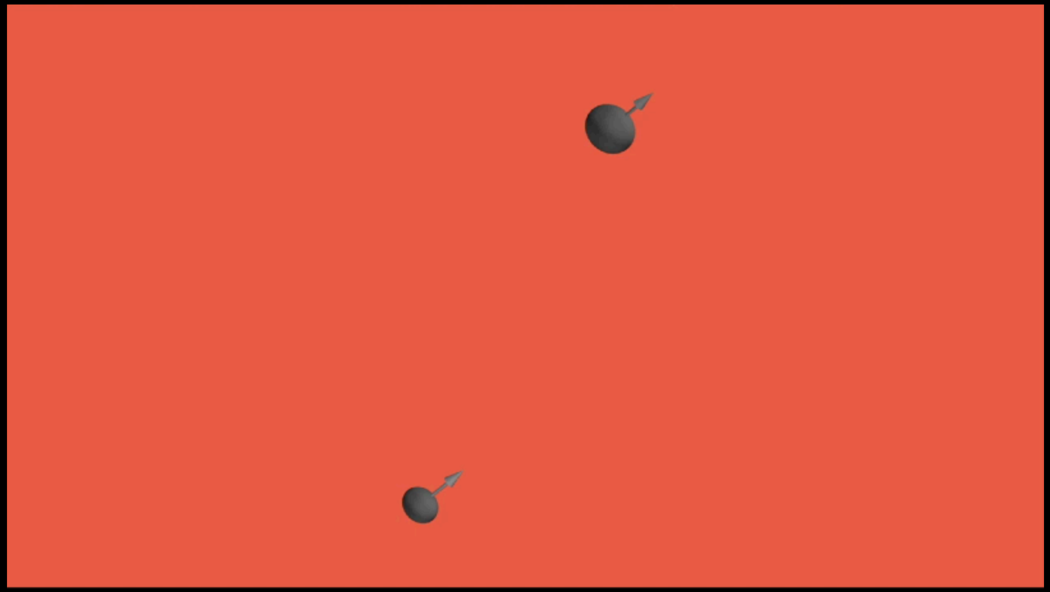
Diameter of proton = 1e-15
aLIGO peak sensitivity dL/L = 1e-23

First Direct Detection of GW (Sept. 14, 2015): 461 Mondays ago

LIGO detection of gravitational waves & binary black hole Inspiral-Merger-Ringdown



LIGO-Virgo Collaboration



Ferguson, Jani+ MAYA Collaboration

LIGO GW detections since 2015 to present: ~200

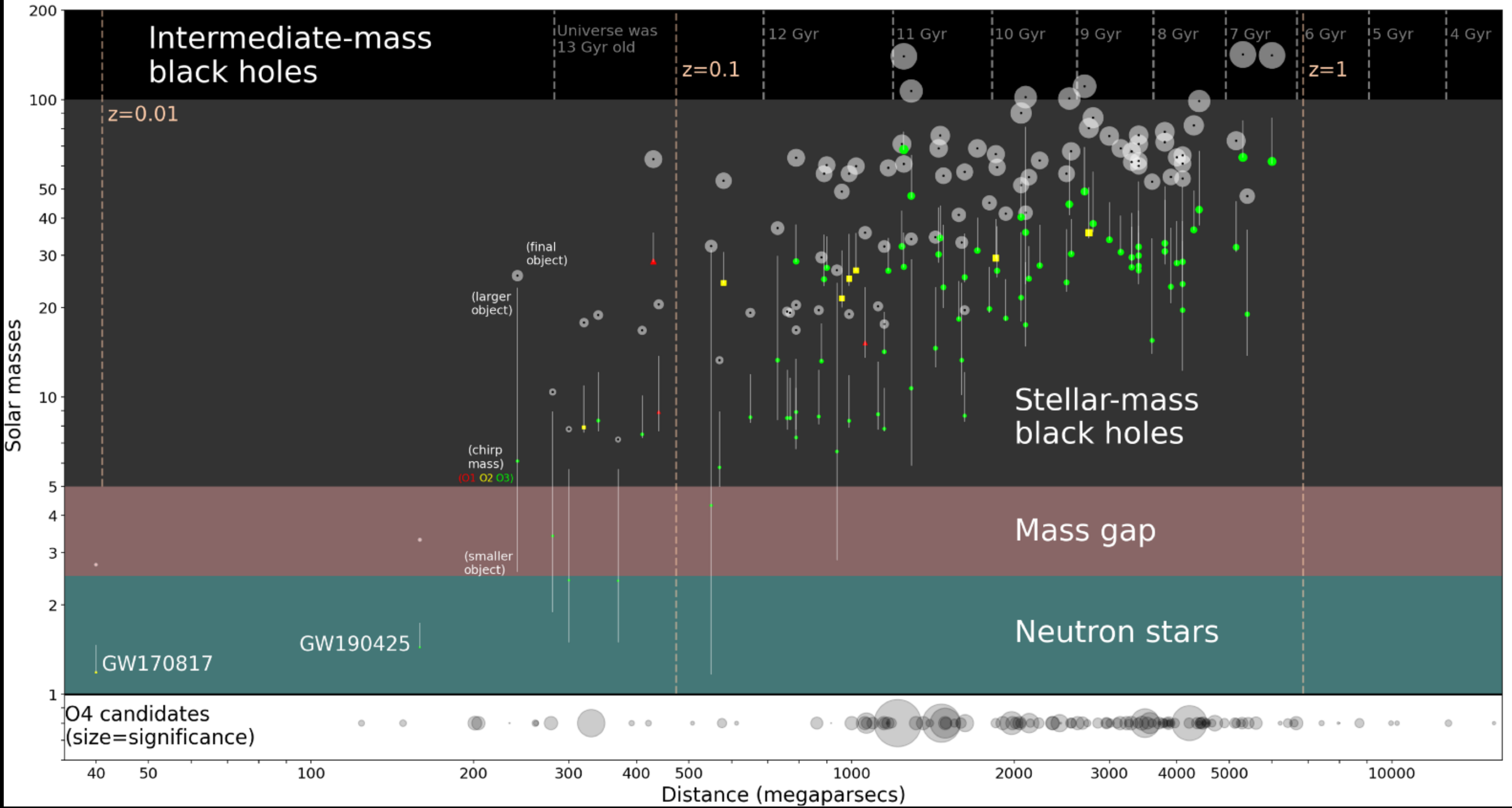
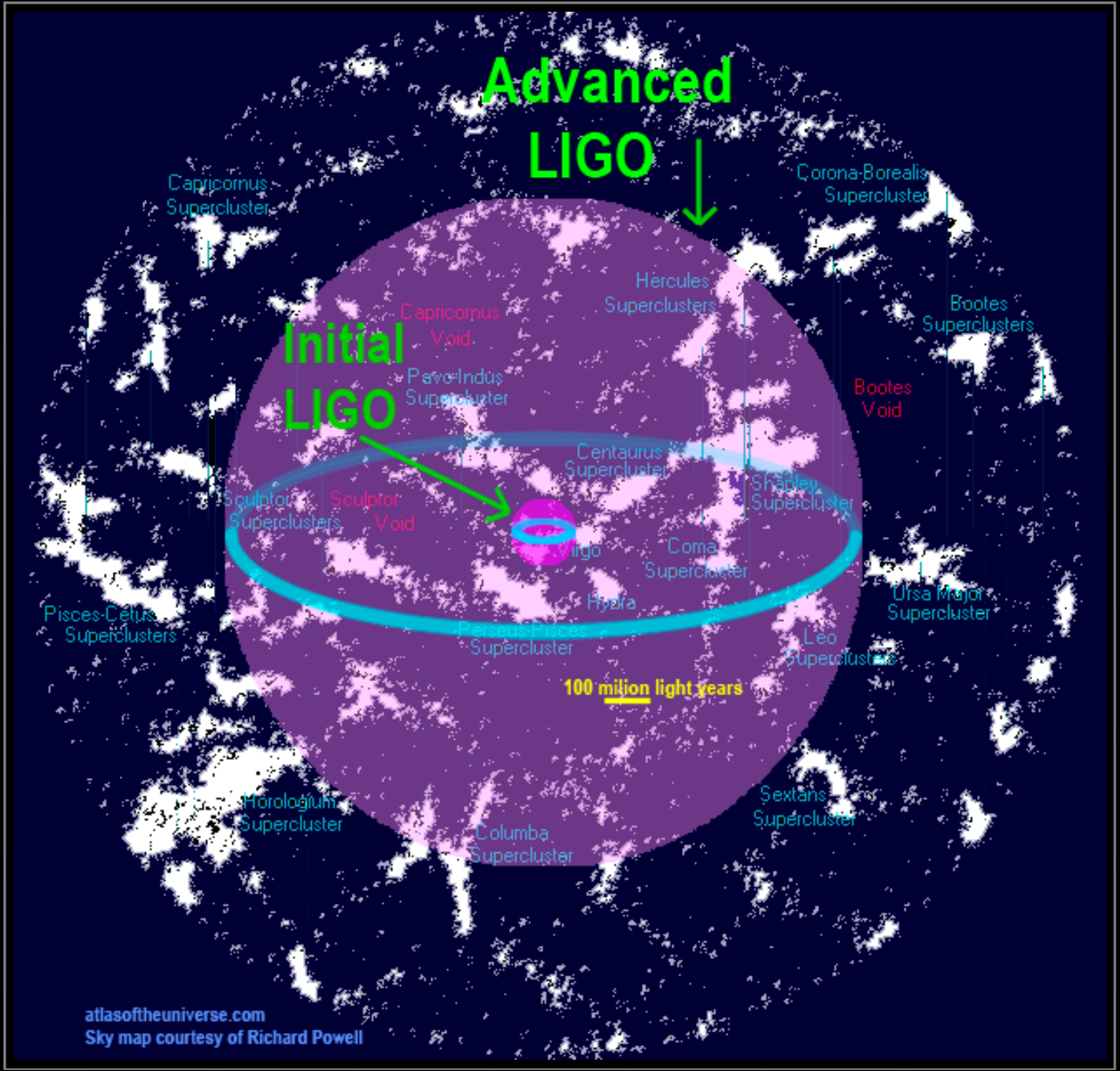


Image: Wikipedia

Why LIGO could not detect GW before 2015?



- Increase in sensitivity by a 10x
  = Increase in search volume of the universe by a (10x)^3

- Sources of strong GW emissions (like black hole collisions) are <u>extremely rare</u> in the universe.

- Estimate for stellar black hole collisions
  = ~10 per cubic Gpc per year
  = ~1 in billion years within the Milky Way

- In contrast, 100 million to billion stellar black hole <u>exist right now</u> within the Milky Way, but not colliding!

What sources in the universe LIGO can(not) detect?

LIGO frequency window = 10 Hz to a few kilo Hz

Frequency of GW during the last inner circular orbit of the binary (just before the collision)

$$f_{GW} \approx 2.2\mathrm{kHz} \left(\frac{M_\odot}{M} \right)$$

Total mass of the binary

- f_GW for binary with neutron stars (1.4 solar mass each) = ____ Hz
- f_GW for binary with stellar black holes (30 solar mass each) = ____ Hz
- f_GW for binary with Milky Way-like SMBHs (4 million solar mass each) = ____ Hz
- f_GW for binary with M87-like SMBHs (6 billion solar mass each) = ____ Hz

What sources in the universe LIGO can(not) detect?

LIGO frequency window = 10 Hz to a few kilo Hz

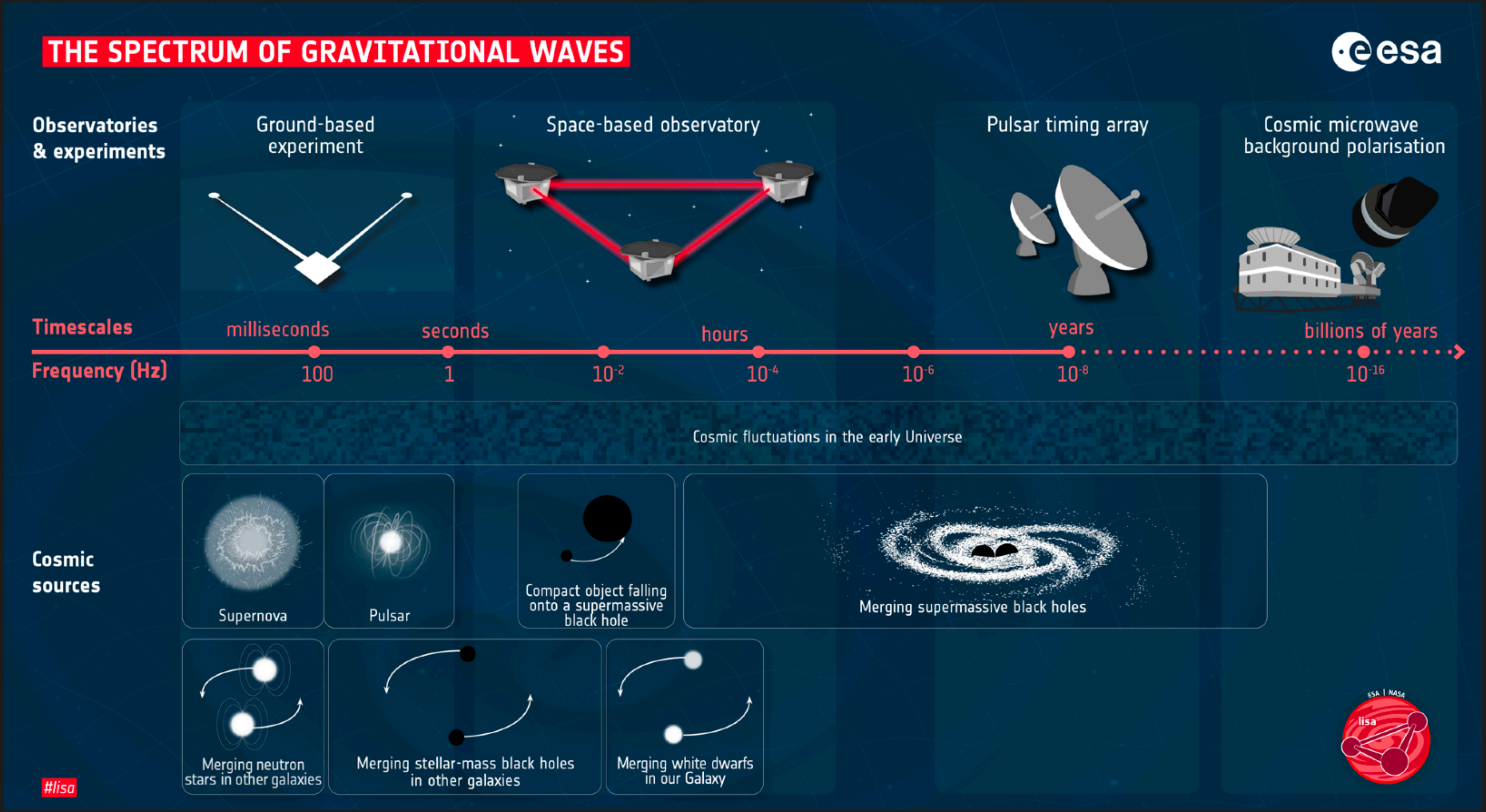
Frequency of GW during the last inner circular orbit of the binary (just before the collision)

$$f_{GW} \approx 2.2\text{kHz}\left(\frac{M_\odot}{M}\right)$$

Total mass of the binary

- f_GW for binary with neutron stars (1.4 solar mass each) = 780 Hz
- f_GW for binary with stellar black holes (30 solar mass each) = 36 Hz
- f_GW for binary with Milky Way-like SMBHs (4 million solar mass each) = 0.2 milli-Hz
- f_GW for binary with M87-like SMBHs (6 billion solar mass each) = 180 nano-Hz

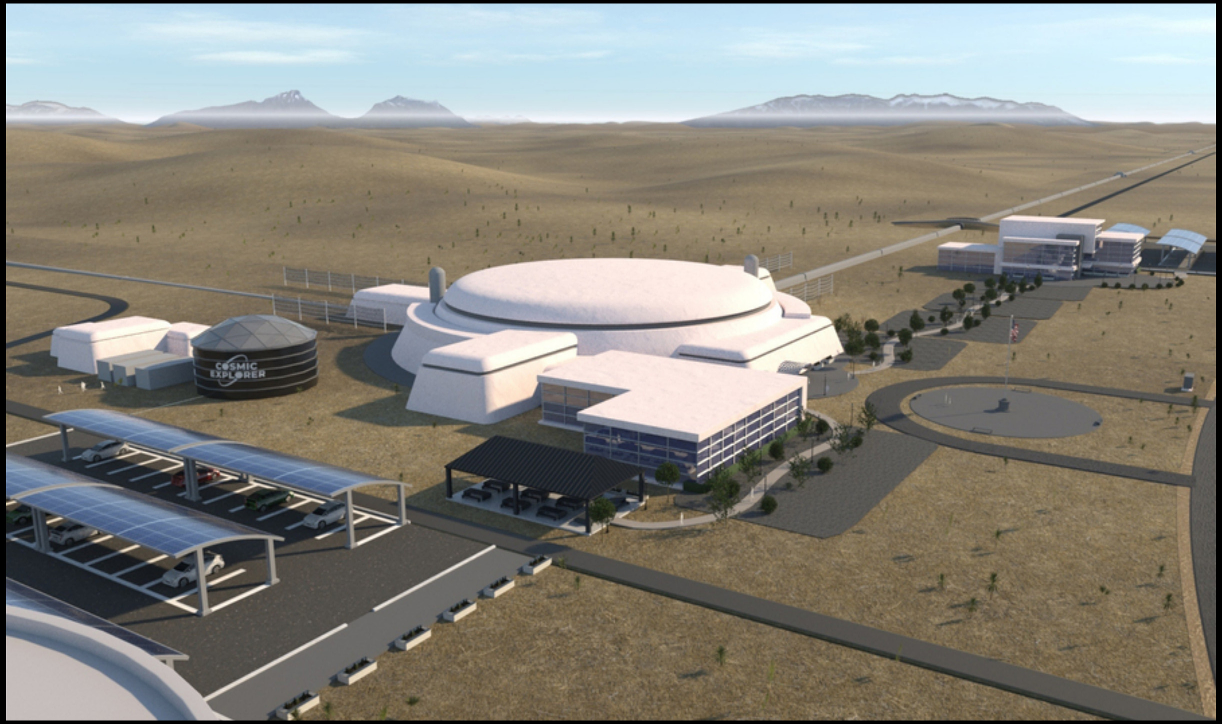
The need to go beyond LIGO



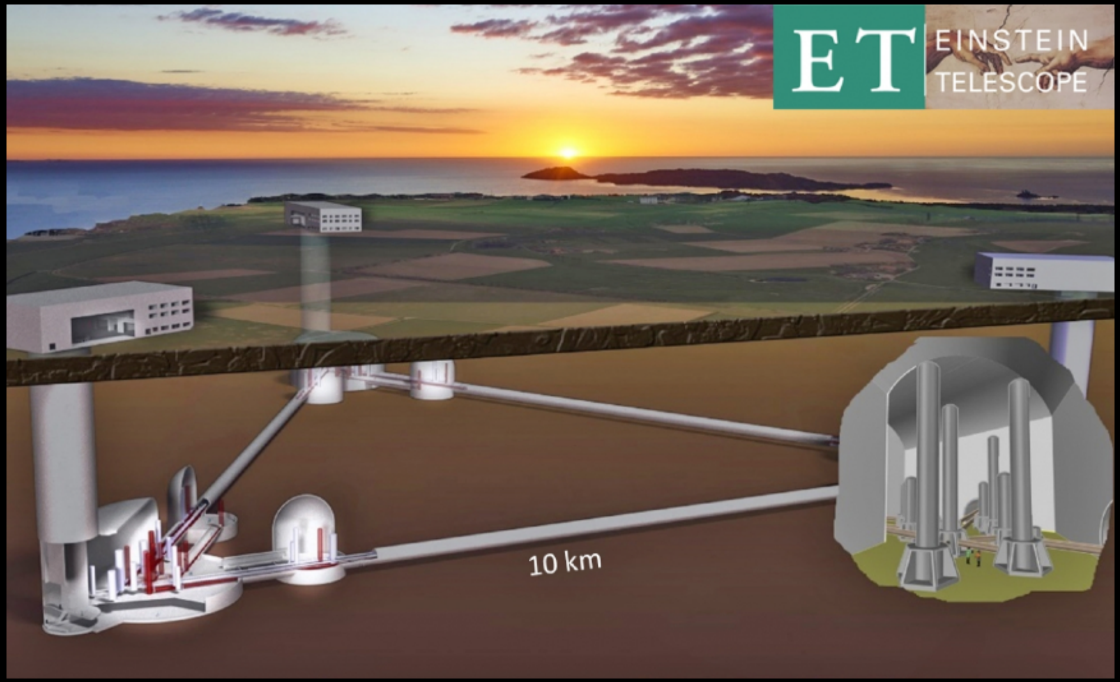
Laser Interferometer Space Antenna (LISA): milli-Hz regime

LISA Pathfinder at L1
(Successful in 2016)

Next-generation "LIGO"-like GW detectors on Earth

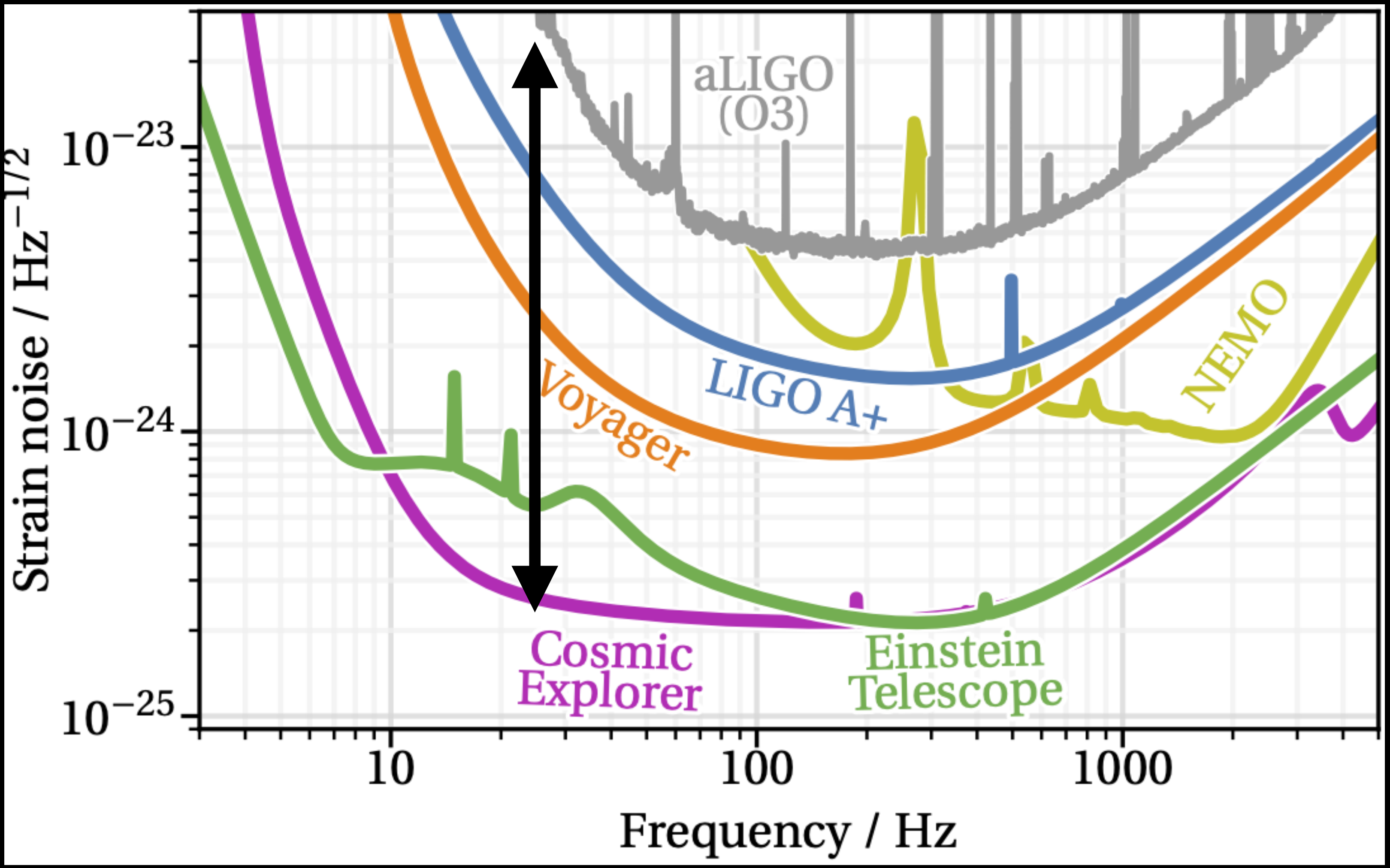


Cosmic Explorer (USA): 40 km x 40 km



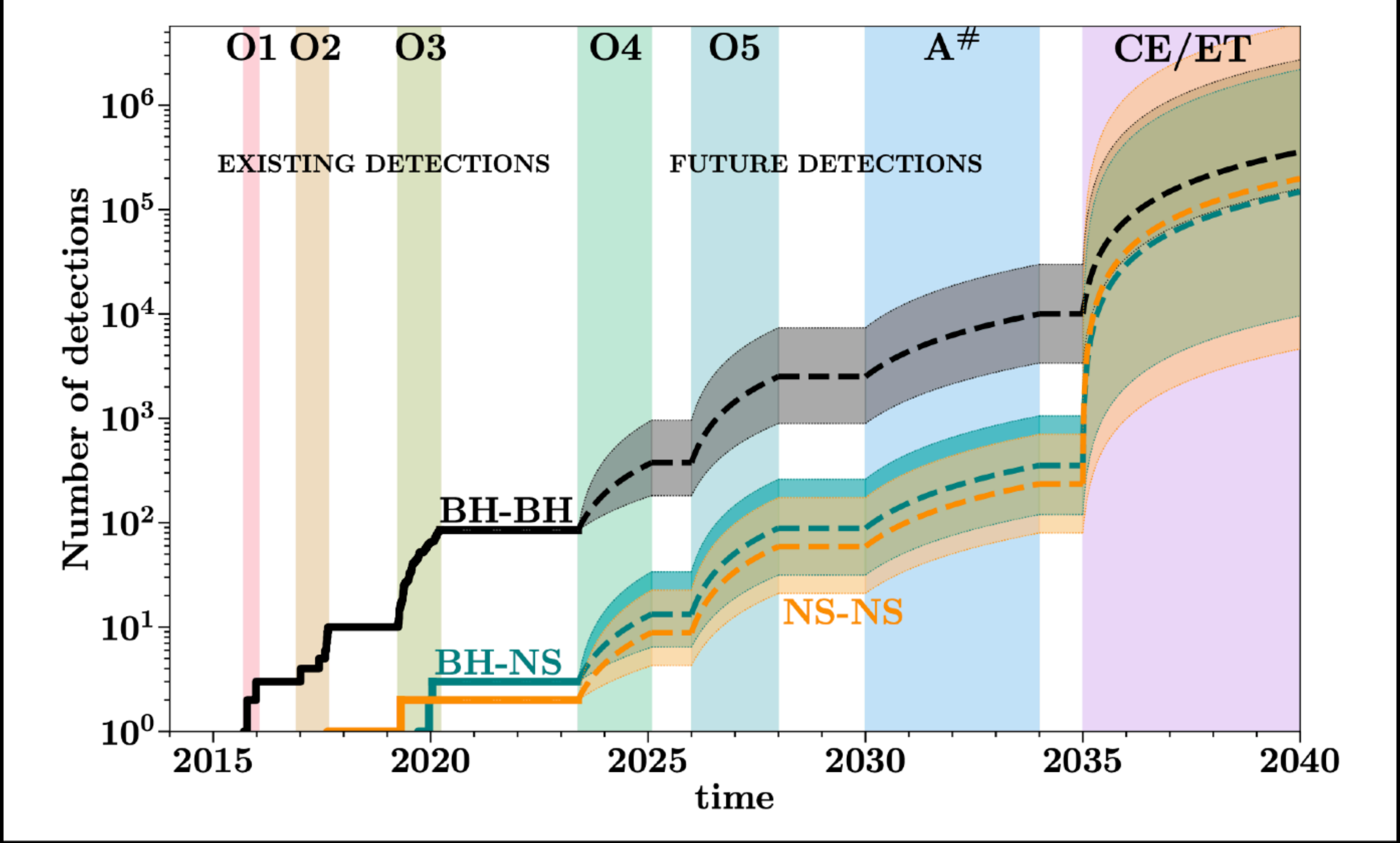
Einstein Telescope (Europe)

Next-generation "LIGO"-like GW detectors on Earth



- Next-generation GW detectors = 100x improvement over the current LIGO-Virgo-KAGRA detectors
- Several technology development challenges (may take till late 2040s to reach optimal sensitivity)
- However, frequency window remains nearly same (few Hz to kilo Hz)

By 2040s: million GW events from stellar binaries!



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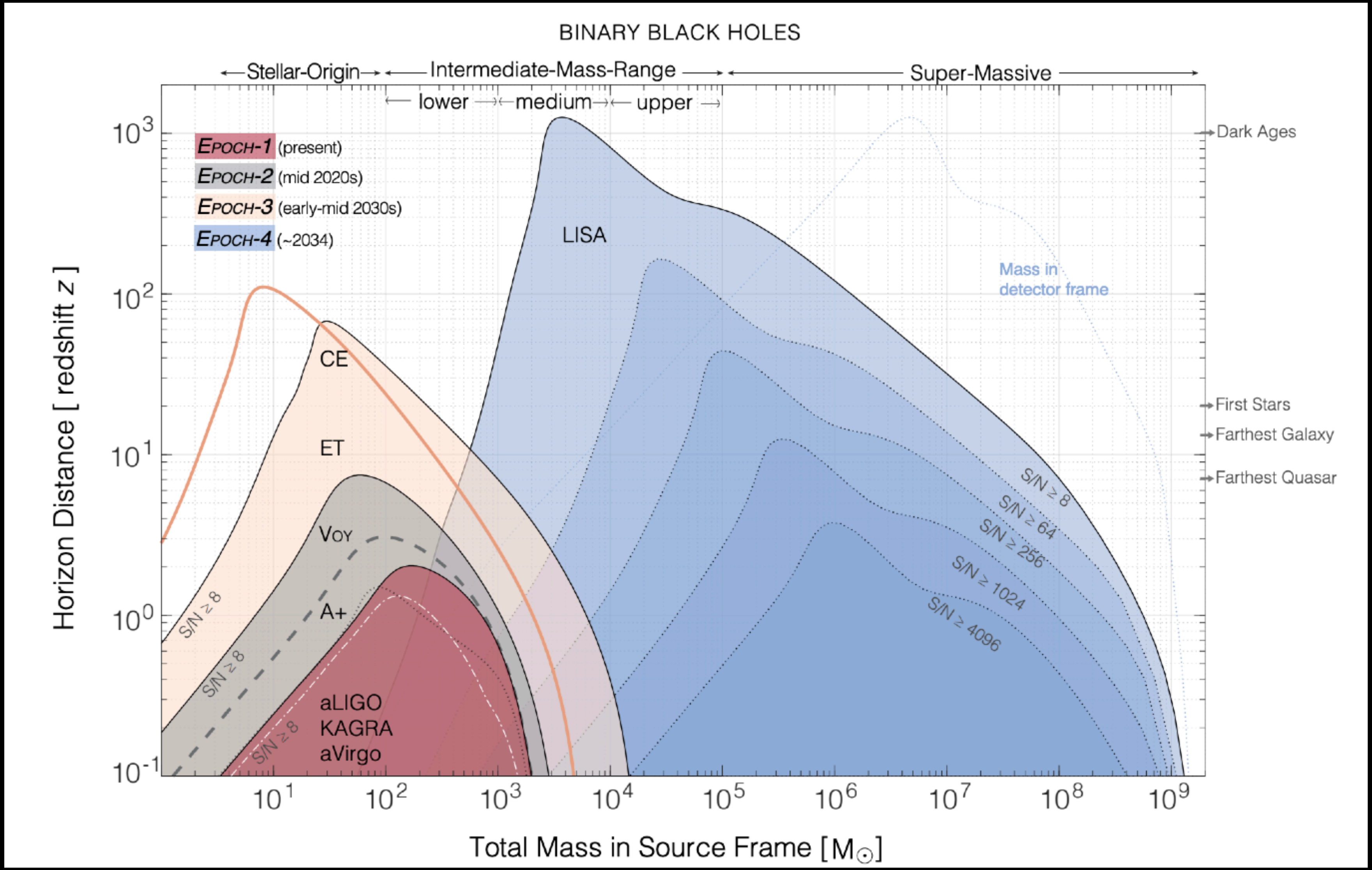
Broekgaarden + 2024

By 2040s: Survey of colliding black holes across universe



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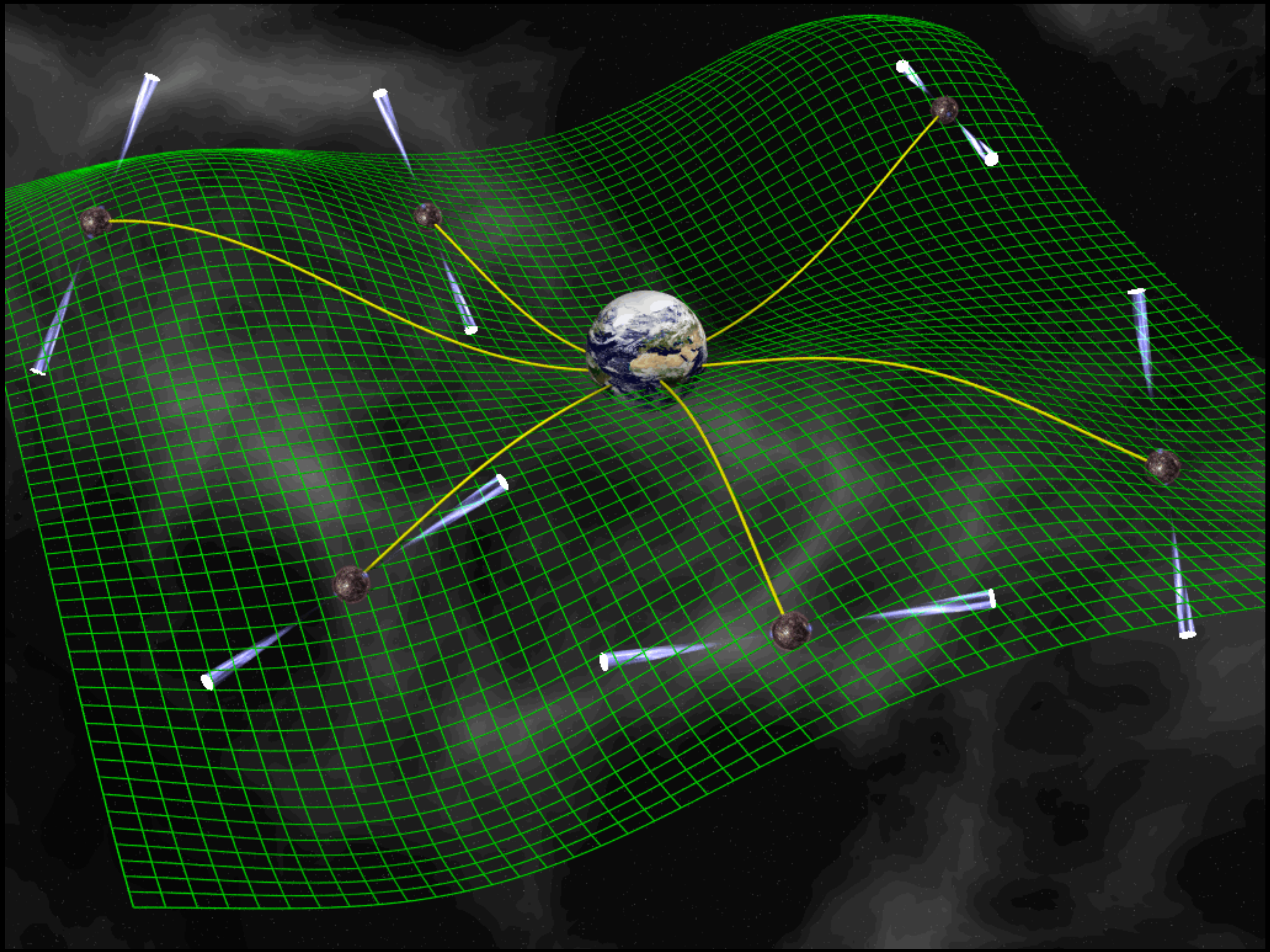
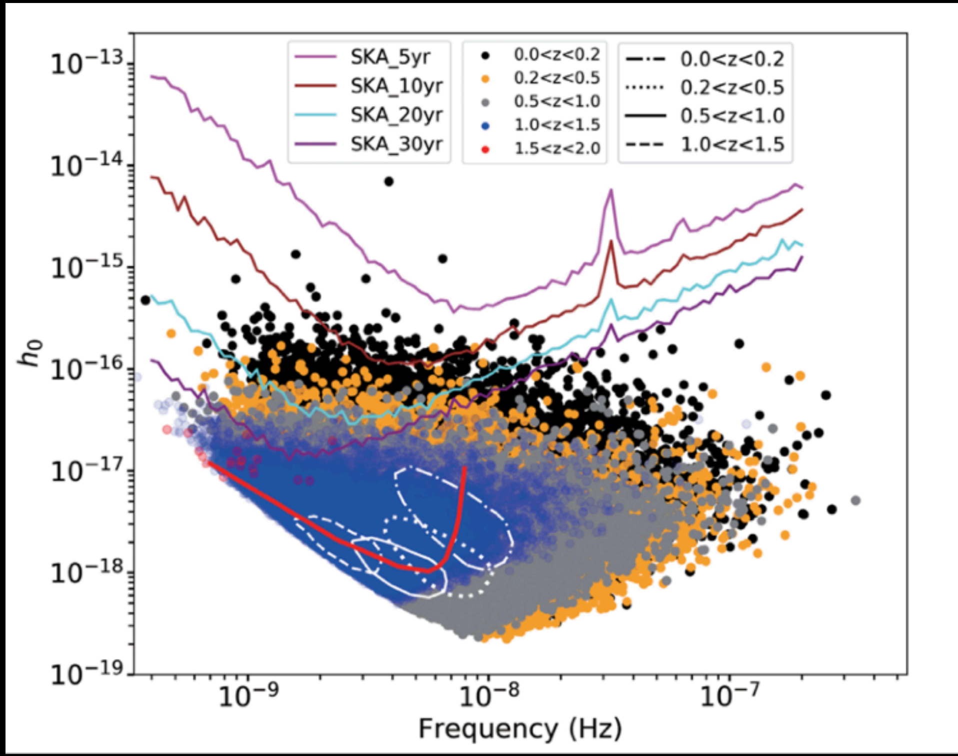
Jani+ 2020

Pulsar Timing Array = the nano-Hertz regime





Feng+ 2020

Merger time of a binary in a GW detector

$$\tau_c = \frac{5}{256}\frac{c^5}{G^{\frac{5}{3}}}\frac{(\pi f_s)^{-\frac{8}{3}}}{\mathcal{M}^{\frac{5}{3}}},$$

Leong Chan et al. (2018)

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

- First Multi-Messenger Discovery: GW170817 (1.4 + 1.4 solar mass)
  - At f_start = 10 Hz (lowest f detectable by LIGO), time to merge = _____
  - At f_start = 1 Hz (inaccessible by any GW detector), time to merge = _____
  - At f_start = 0.1 Hz (max f detectable by LISA), time to merge = ______

Merger time of a binary in a GW detector

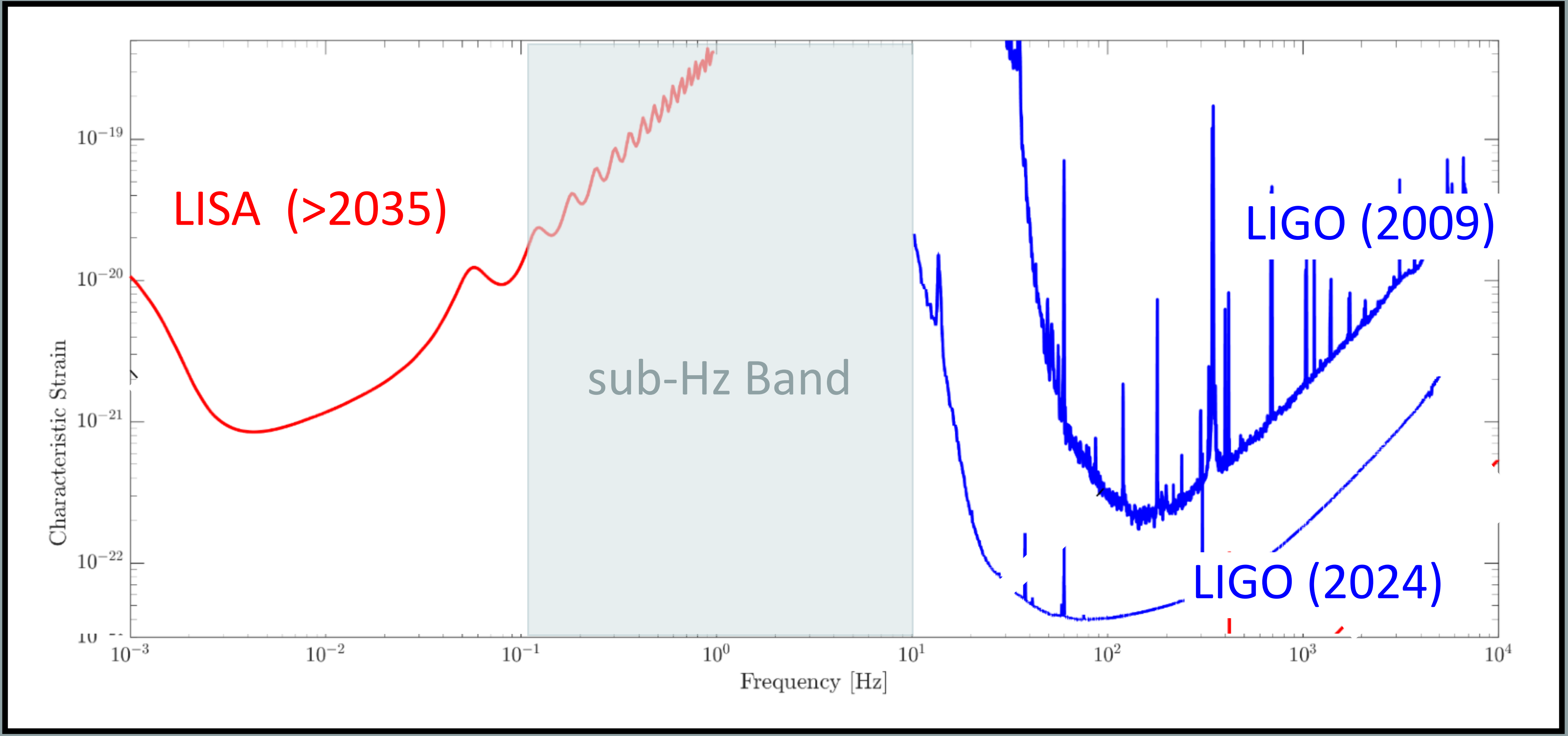
$$\tau_c = \frac{5}{256}\frac{c^5}{G^{\frac{5}{3}}}\frac{(\pi f_s)^{-\frac{8}{3}}}{\mathcal{M}^{\frac{5}{3}}},$$

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

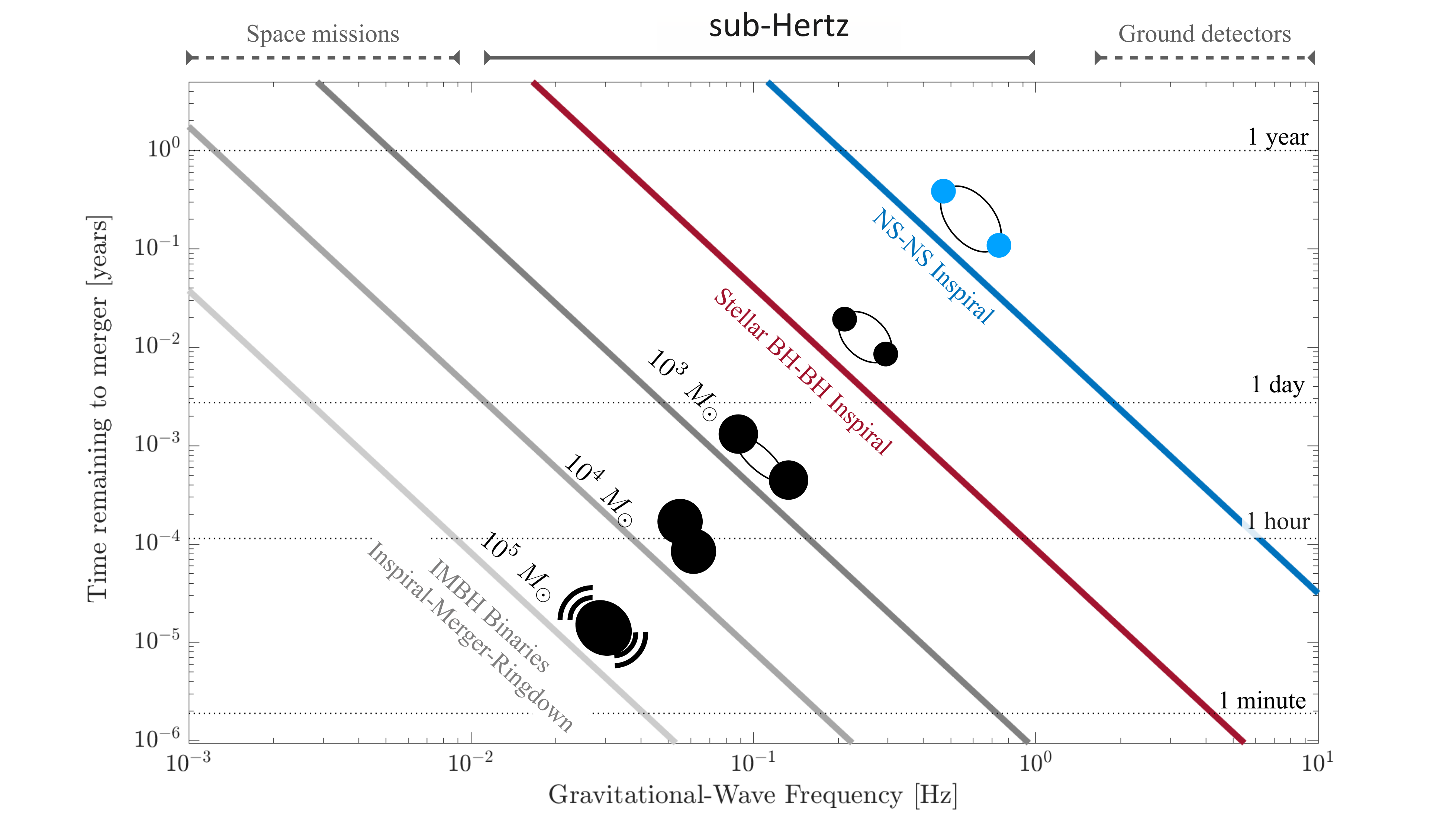
Leong Chan et al. (2018)

- First Multi-Messenger Discovery: GW170817 (1.4 + 1.4 solar mass)
  - At f_start = 10 Hz (lowest f detectable by LIGO), time to merge = 15 minutes
  - At f_start = 1 Hz (inaccessible by any GW detector), time to merge = ~ 5 days
  - At f_start = 0.1 Hz (max f detectable by LISA), time to merge = ~ 6 years

0.1-10 Hz: the missing sub-Hz band in GW spectrum



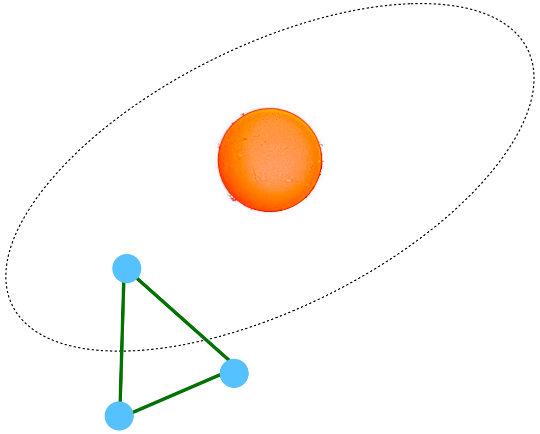
0.1-10 Hz: the missing sub-Hz band in GW spectrum



Izumi & Jani, 2021

Next Generation sub-Hz GW detector concepts

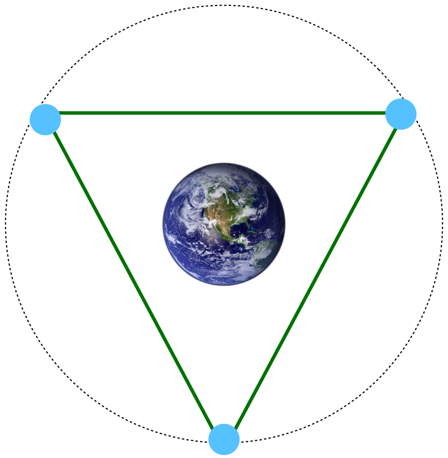
Large Space Missions (Heliocentric)



Decihertz Observatory
Arca Sedda, Berry, **KJ**+ (CQG 2020);
Submitted to ESA's Voyage 2050

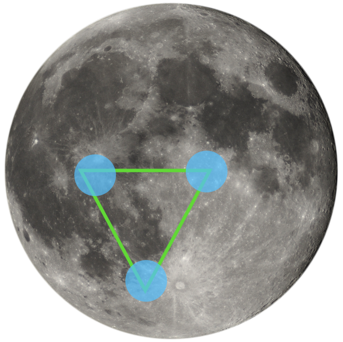
DECIGO Kawamura S et al. (CQG 2011)

Small Space Missions (Geocentric)



SAGE
Lacour+ (with **KJ**)
(CQG 2019)

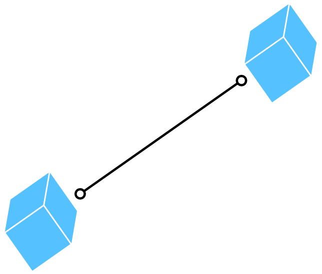
Lunar-based Experiments



GLOC / LILA
(Jani+ 2020, 2021)

LGWA
(Harms+, 2021, 2024)

Atom Interferometry

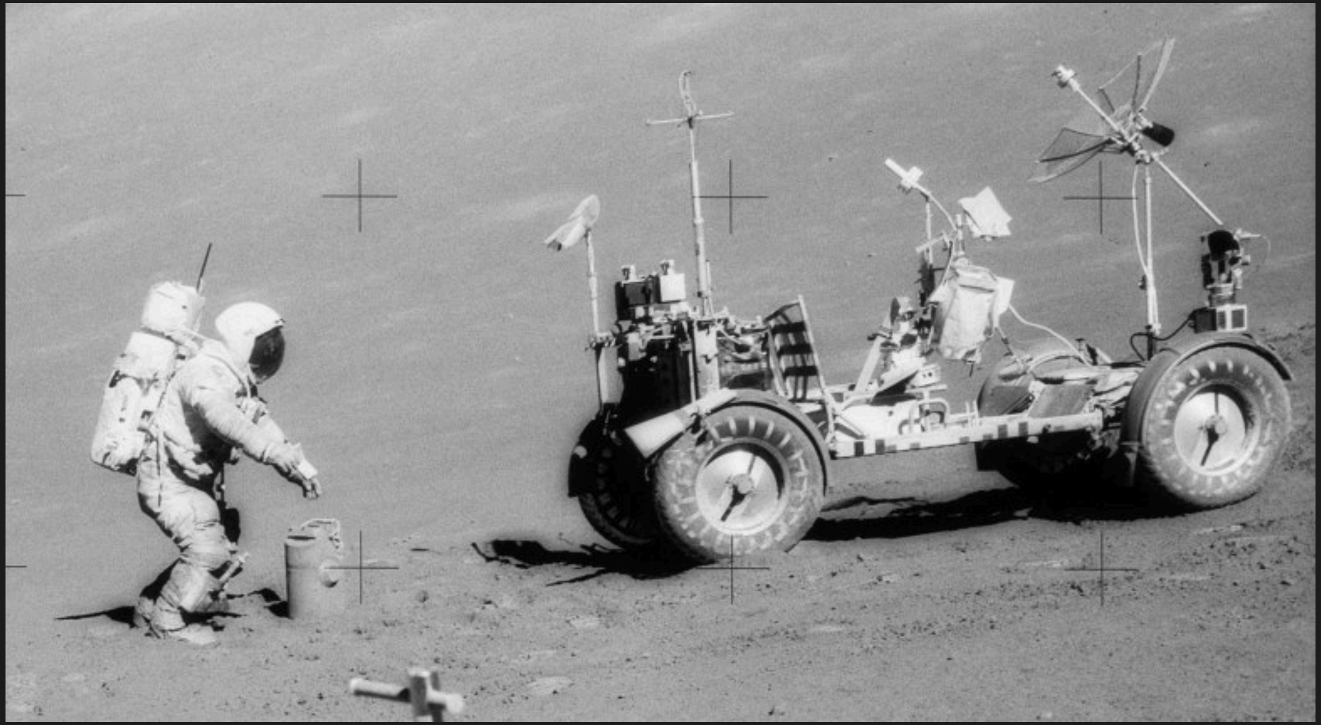


MAGIS
Graham+ (2017)

AEDGE
El-Neaj+(2020)

Izumi & Jani, 2021

Why build a laser interferometer on the Moon?



Our Moon is >10,000x quieter than on Earth at frequencies in “Missing band”

Natural vacuum on the lunar surface is >100x better than ultra-high vacuum of LIGO

No environmental or human noise!

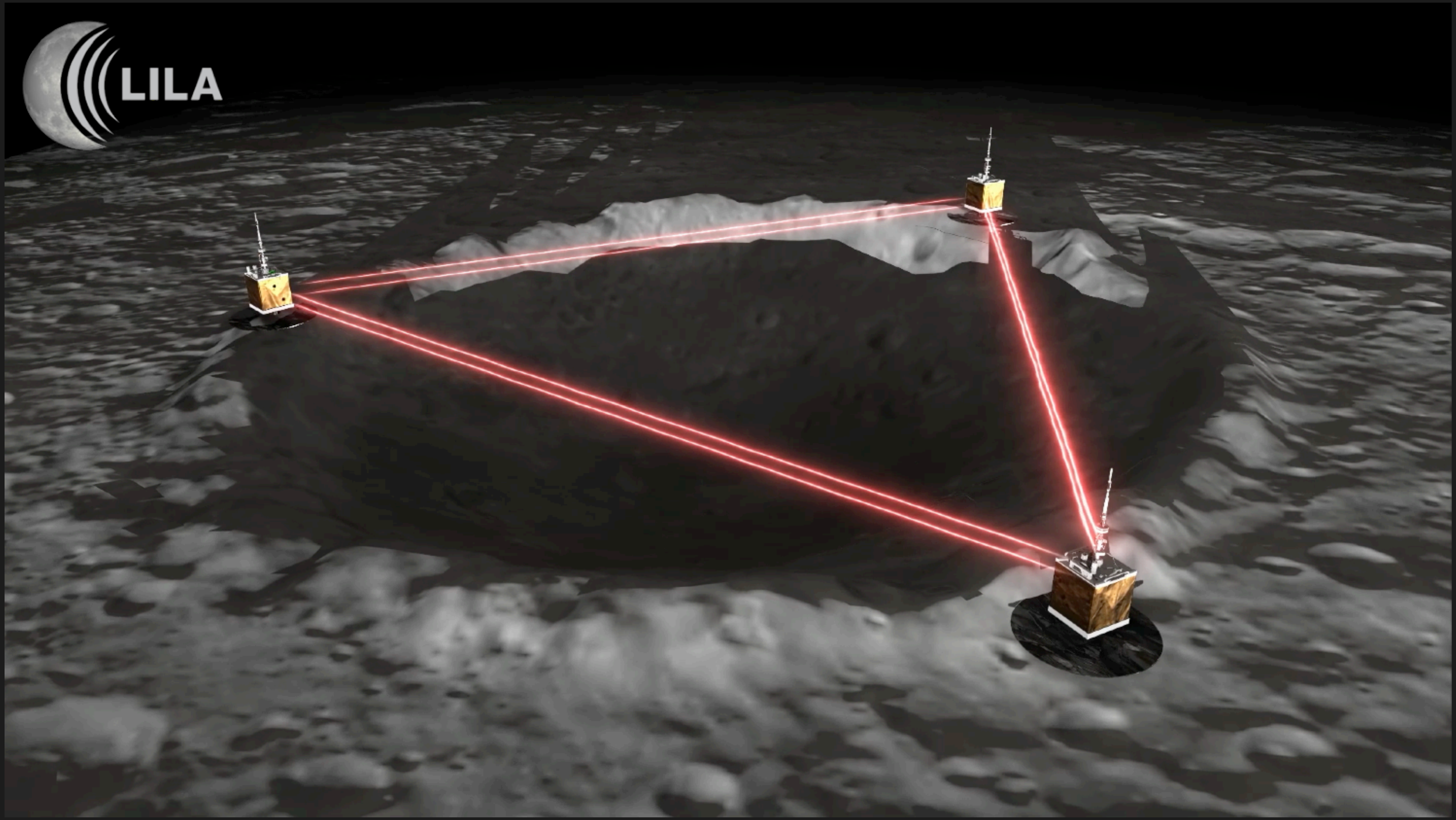
A Lunar Gravitational Wave Antenna Using a Laser Interferometer

R. T. Stebbins and P. L. Bender*

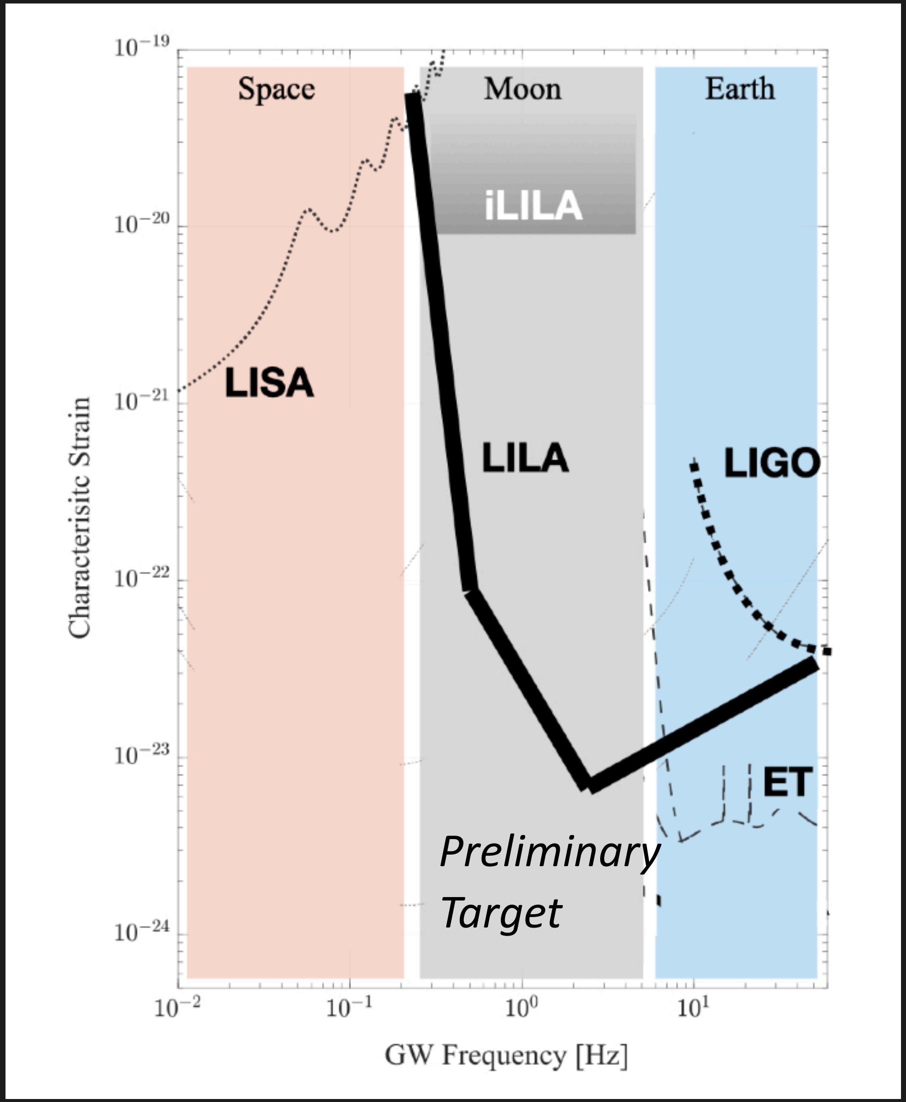
GRAVITATIONAL RADIATION OBSERVATIONS ON THE MOON

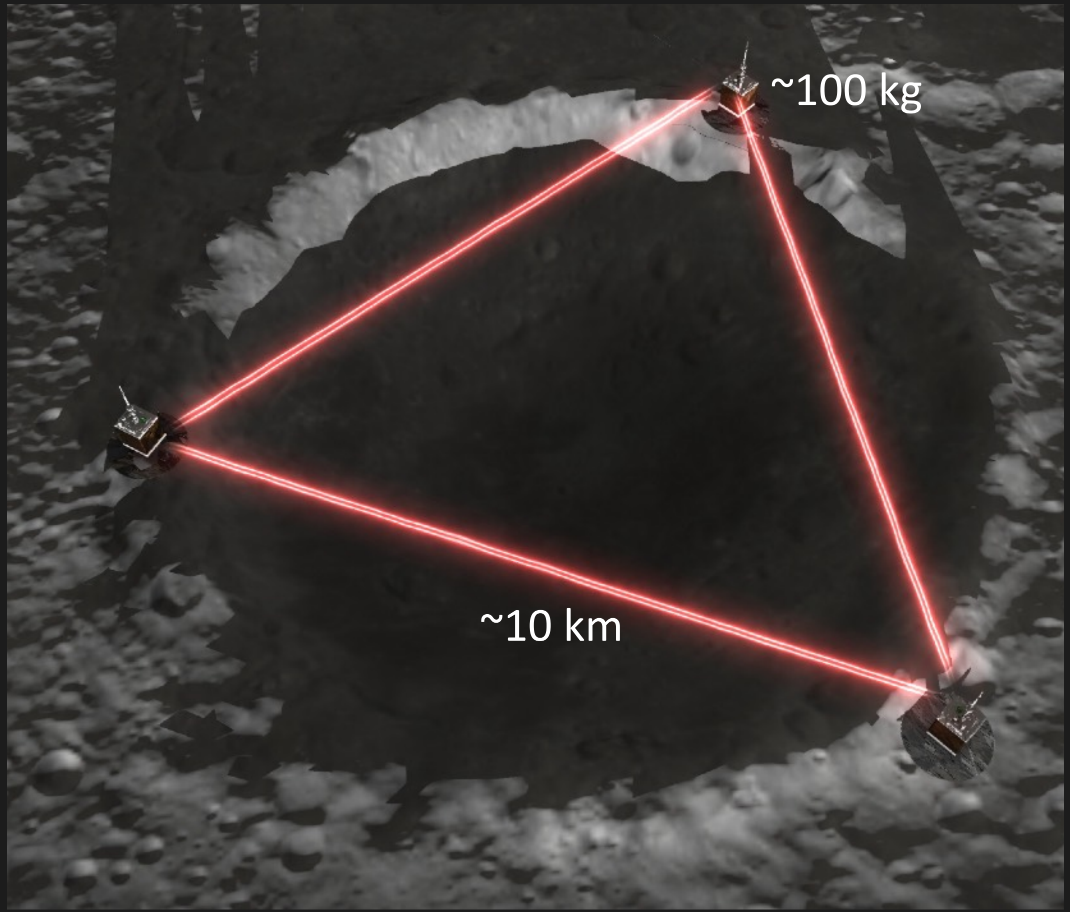
R. T. Stebbins,[a] J. W. Armstrong,[b] P. L. Bender,[a,d] R. W. P. Drever,[c] R. W. Hellings,[b] and P. R. Saulson[a]

LILA: Laser Interferometer Lunar Antenna (“lee-laa”)



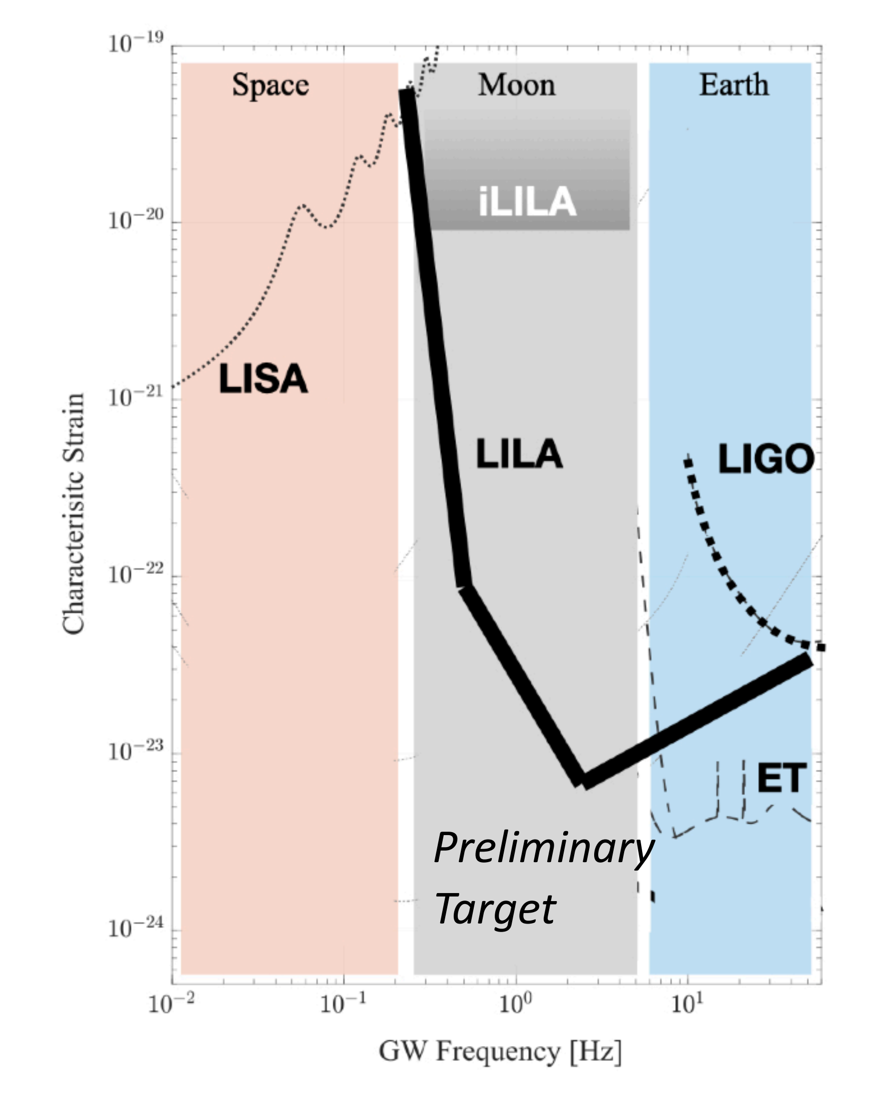
LILA Science: New Frequency Spectrum of GW

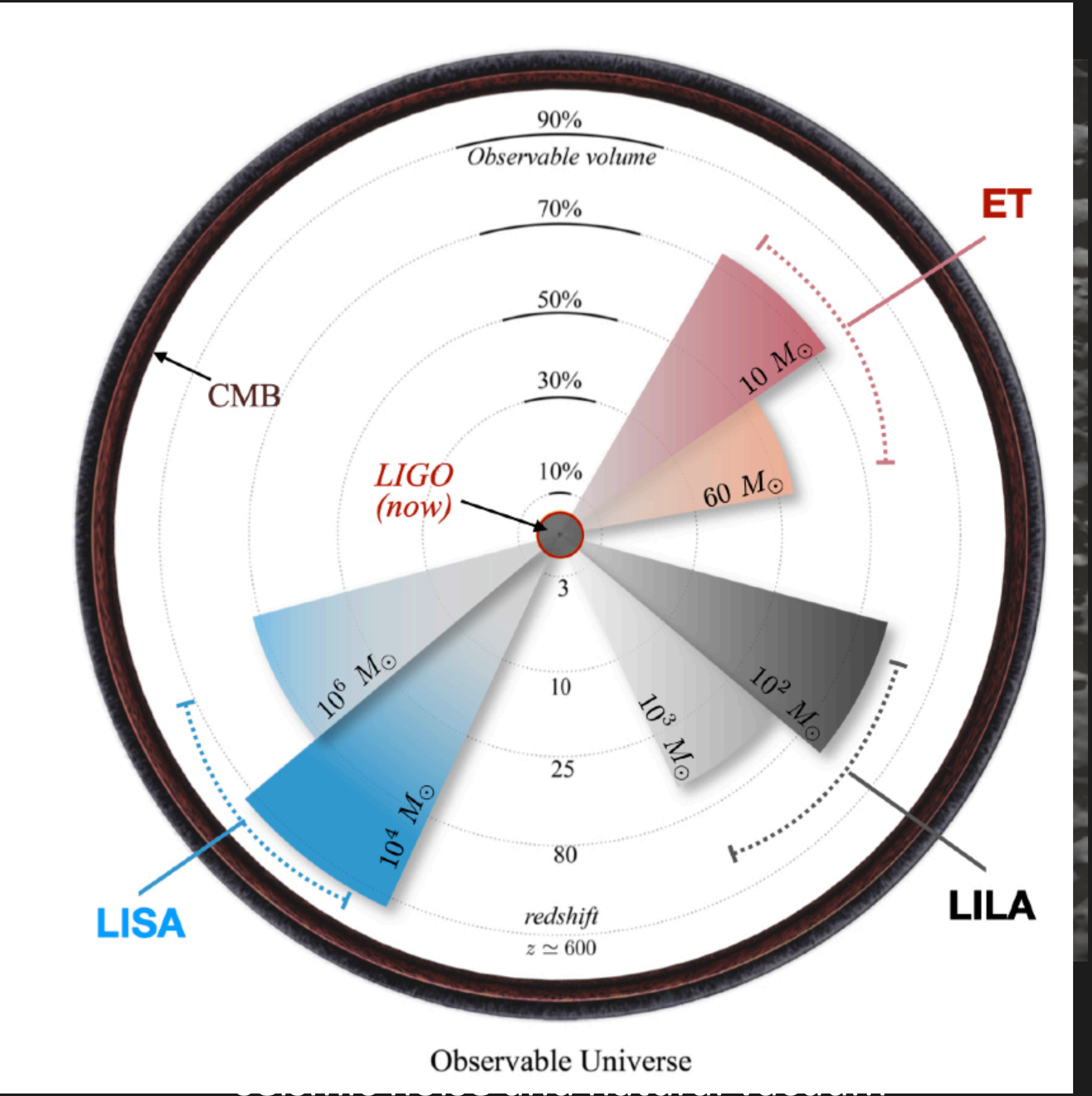




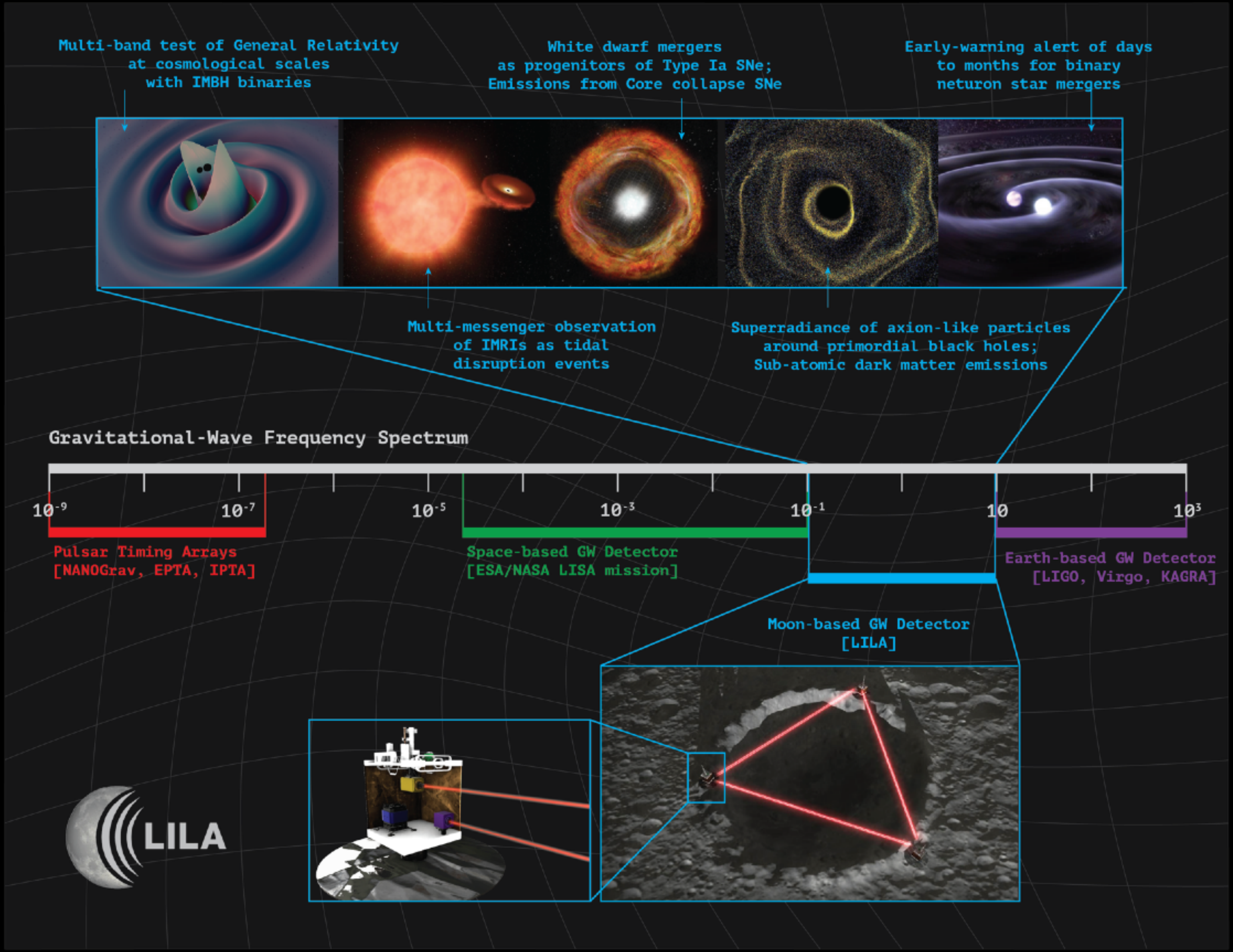
LILA sensitivity benefits from Moon's low seismic noise and natural vacuum

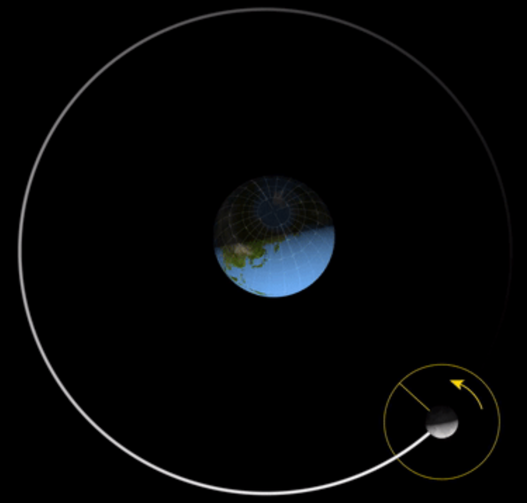
LILA Science: Cosmological survey of IMBH





LILA: Expanding the landscape of Multi-messenger

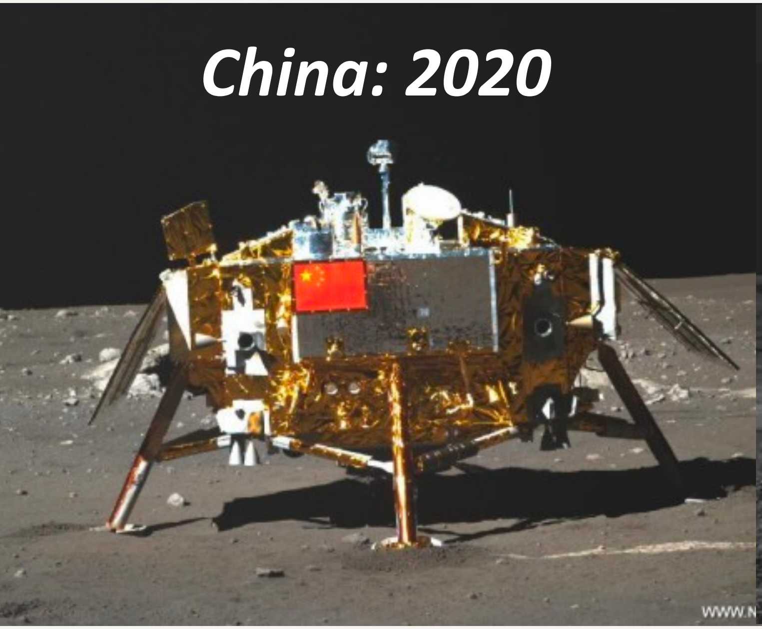


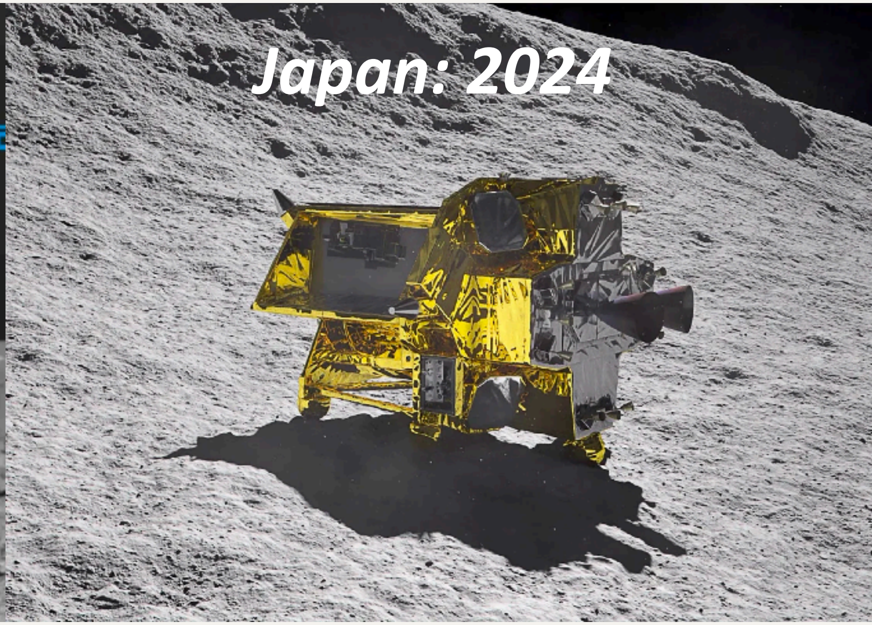


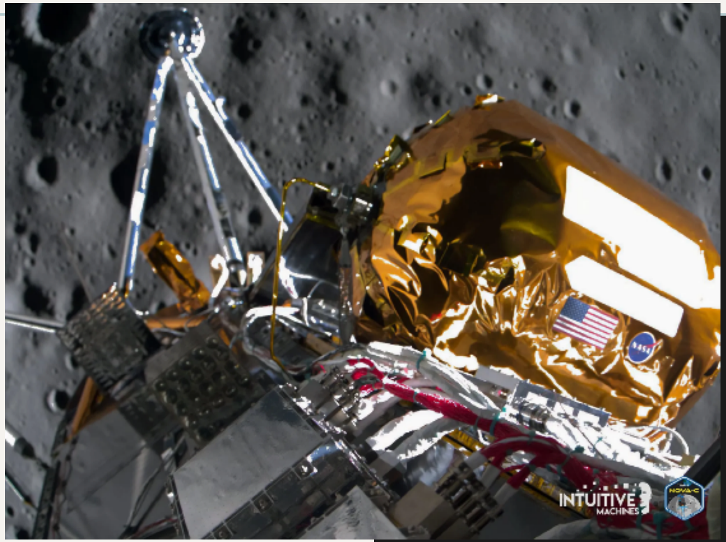
	LILA at 0.1 Hz	LILA at 0.5 Hz
GW170817 (BNS) early-alert	6 years	1 month

GW170817 sky-localization with LILA: ~10 arc-second^2

Soft-landings on the Moon in the last few years

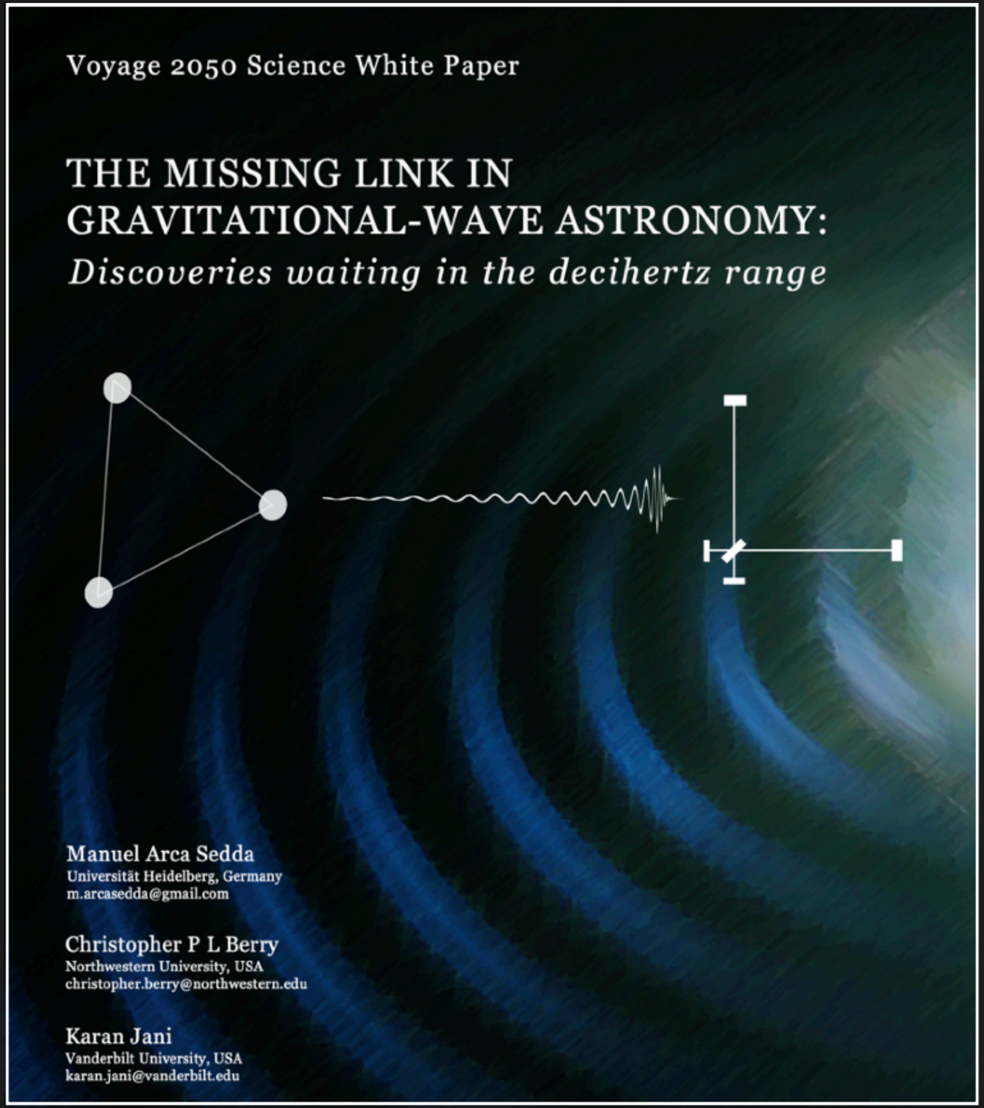


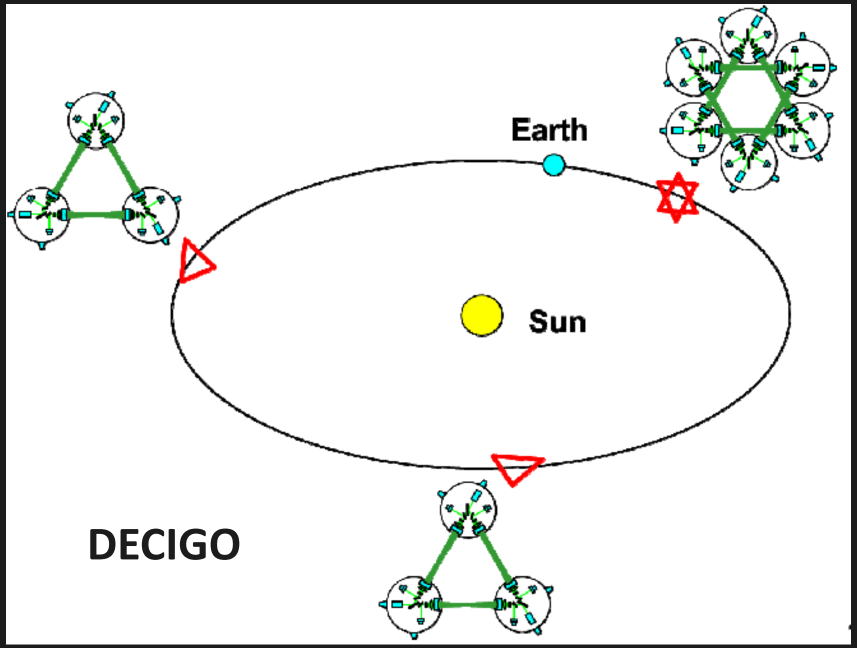




Initiative Machines, USA: 2024 (first soft-landing on the Moon by private company)

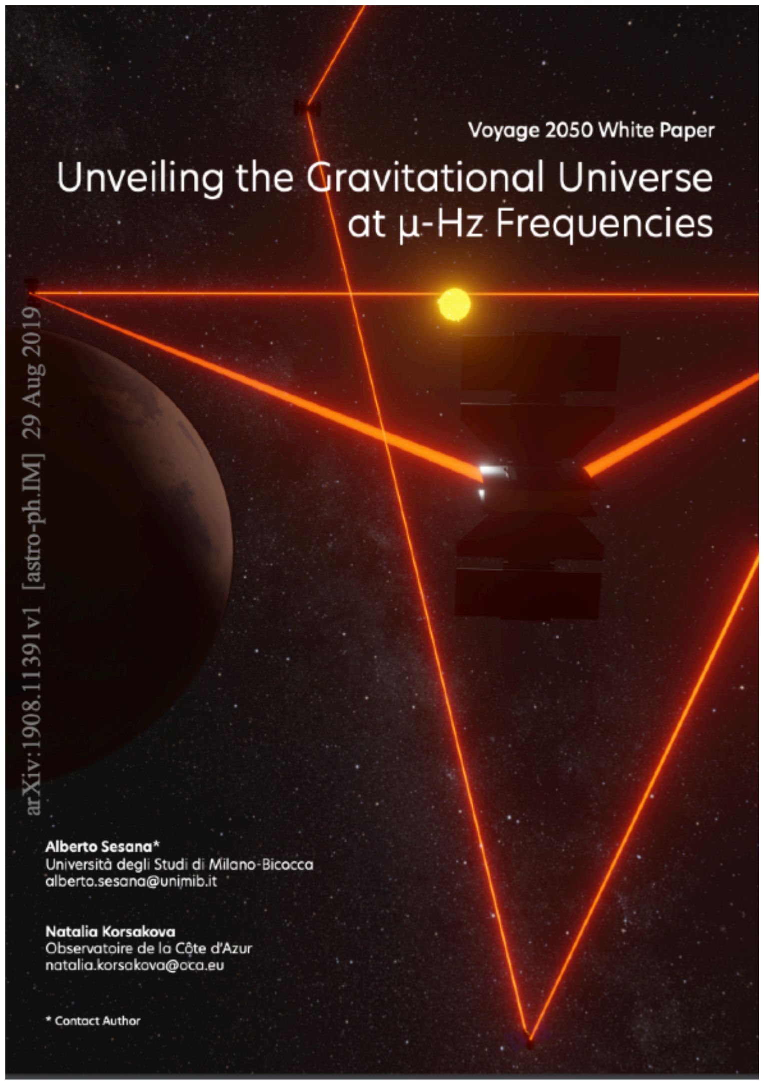
Alternative: space-based Sub-Hz GW detector

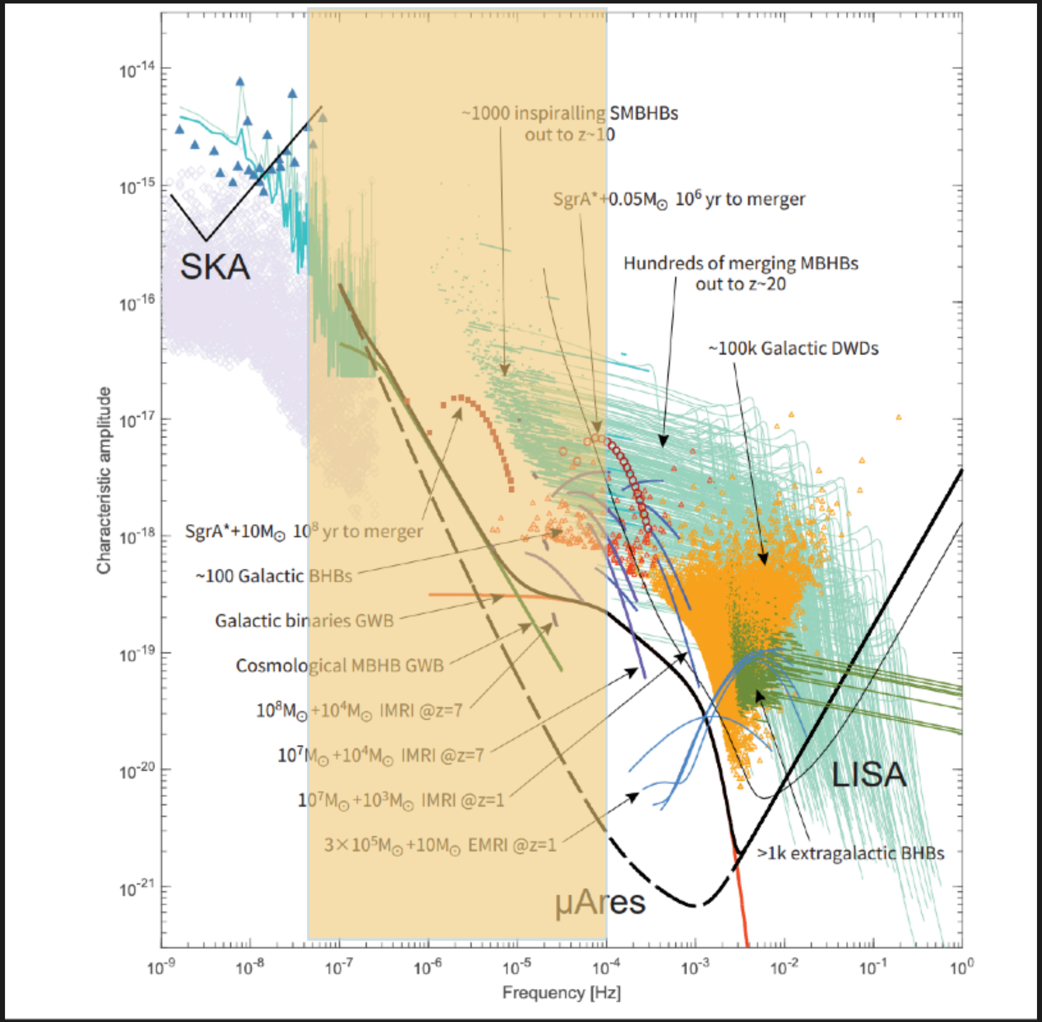




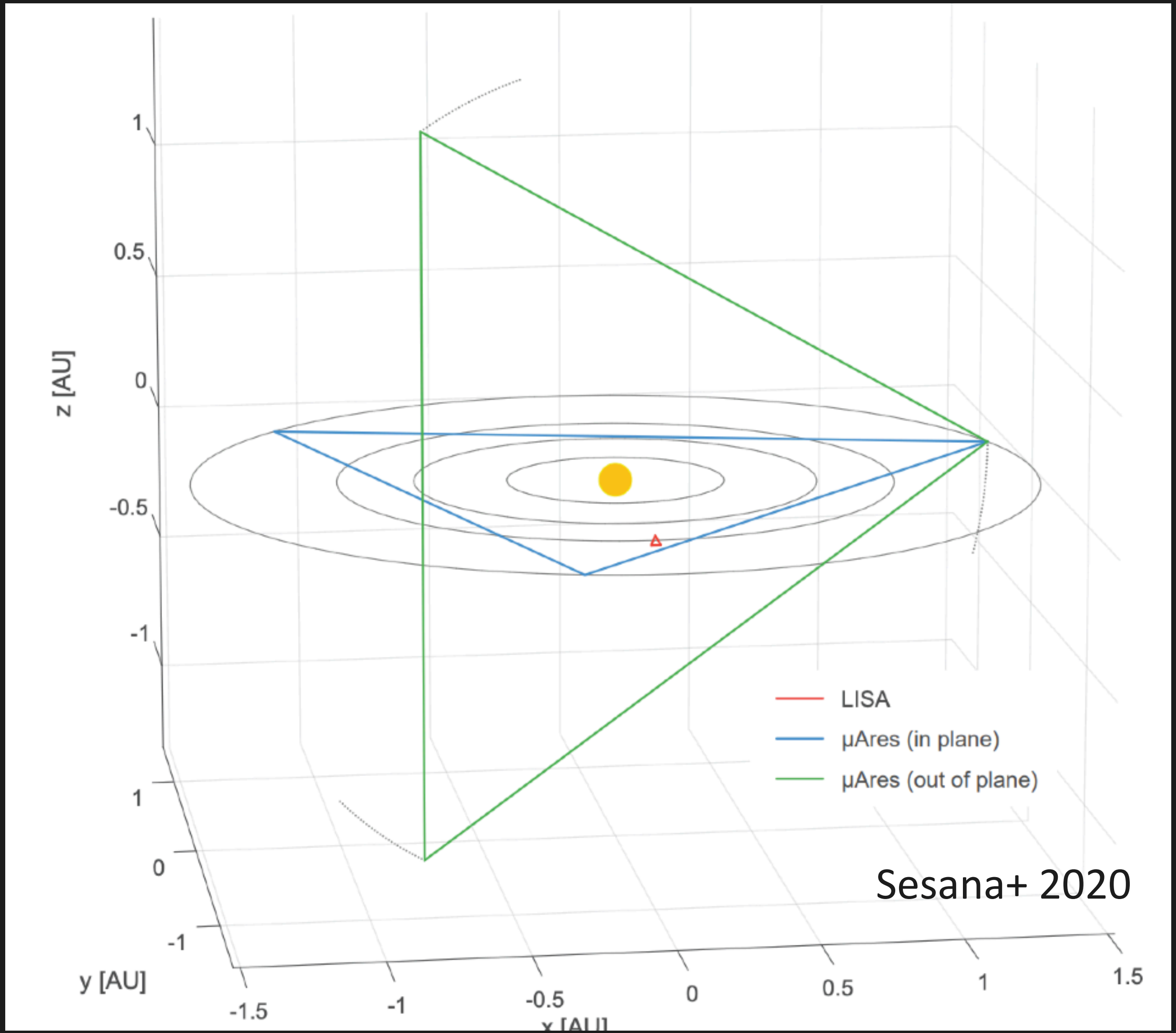
- Requires huge technology developments to go beyond the state-of-the-art LISA
- ESA Voyage 2050 studies: 100,000x lower displacement noise than LISA, 7x bigger telescope, 15x more laser power

micro-Hertz: the other missing band in GW spectrum

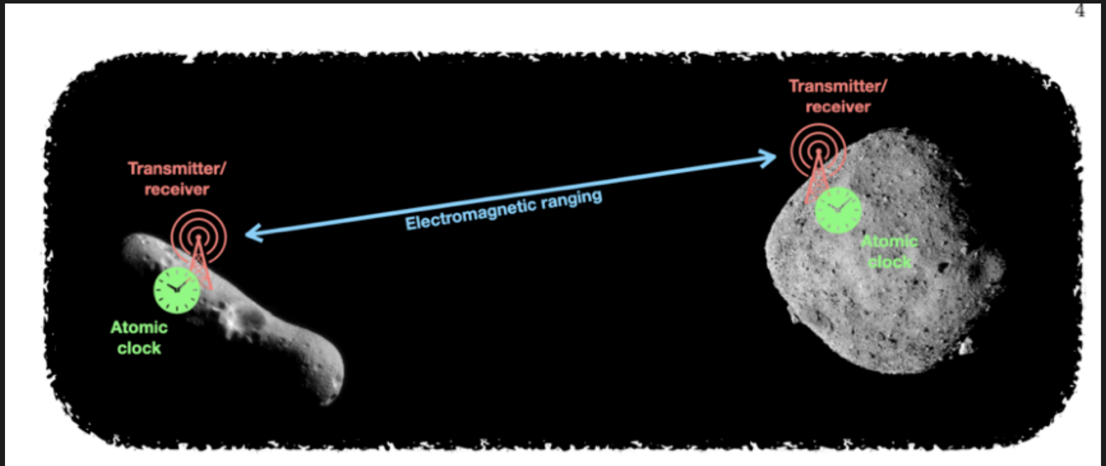




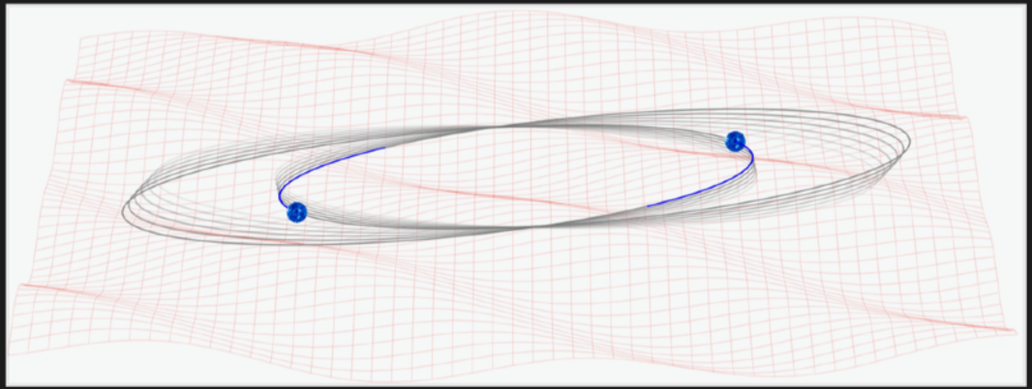
micro-Hertz detector concepts



Sesana+ 2020



Fedderke+ 2022



Blass & Jenkins 2022

Conclusions

- We live in an extraordinary time of GW detections across the spectrum!
- Right now: Earth-based detectors LIGO-Virgo-KAGRA will measure GW from 10 Hz to a few kilo-Hz from 100s of stellar black holes and neutron stars. PTA will measure stochastic GW at nano-Hz from potential supermassive black hole binaries.
- Near future: LISA will measure GW from around 0.1 mili-Hz to 10 mili-Hz, opening a new astrophysical window into super-massive black hole binaries, double white binaries.
- Distant future: Next-gen earth-based detectors Cosmic Explorer and Einstein Telescope will measure GW from a few Hz to a few kilo-Hz from across the observable universe. Millions of sources!
- Distant^2 future: New concepts on Moon / Solar System scales to fill the missing bands in GW spectrum from sub-Hertz (between LIGO & LISA) to micro-Hertz (between PTA & LISA)