

Gravitational Wave

Observatories

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Who is this?

Picture by R.X.Adhikari @TIFR Mumbai



An experimental astrophysicist

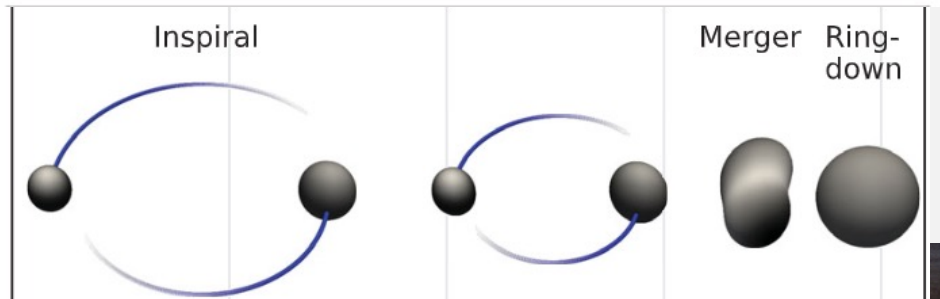
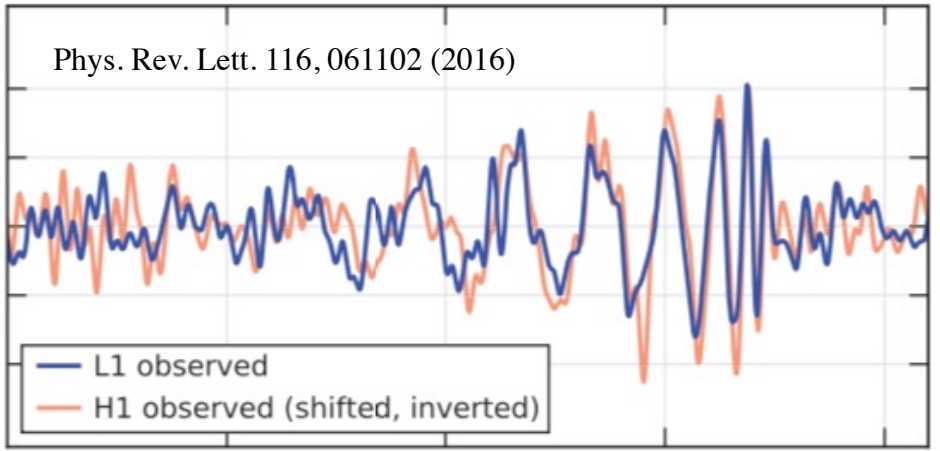


15+ years experience with gravitational wave observatories as an instrument scientist

- 2009-2017: LIGO Collaboration
- 2017-present: KAGRA collaboration
- 2018-present: LISA consortium
- 201X-present: DECIGO working group member

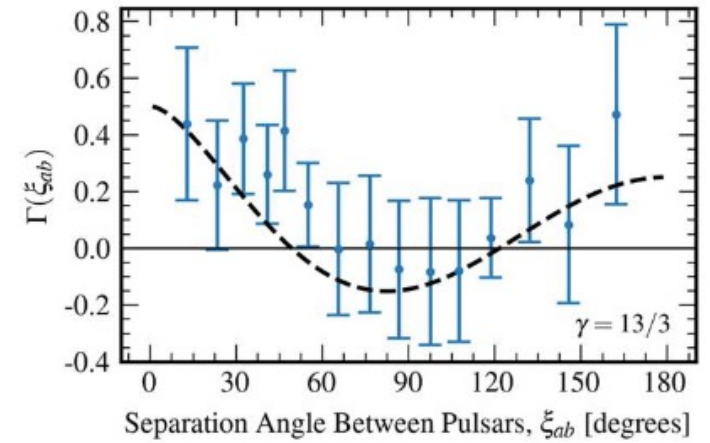
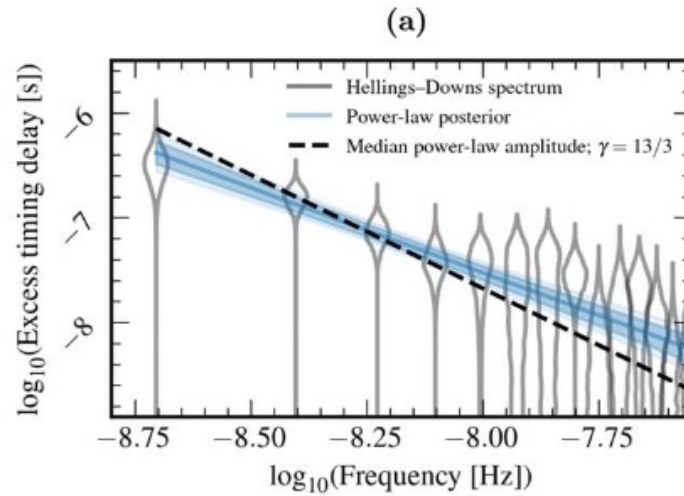
Gravitational wave astronomy marching on

First detection by LIGO (2015)



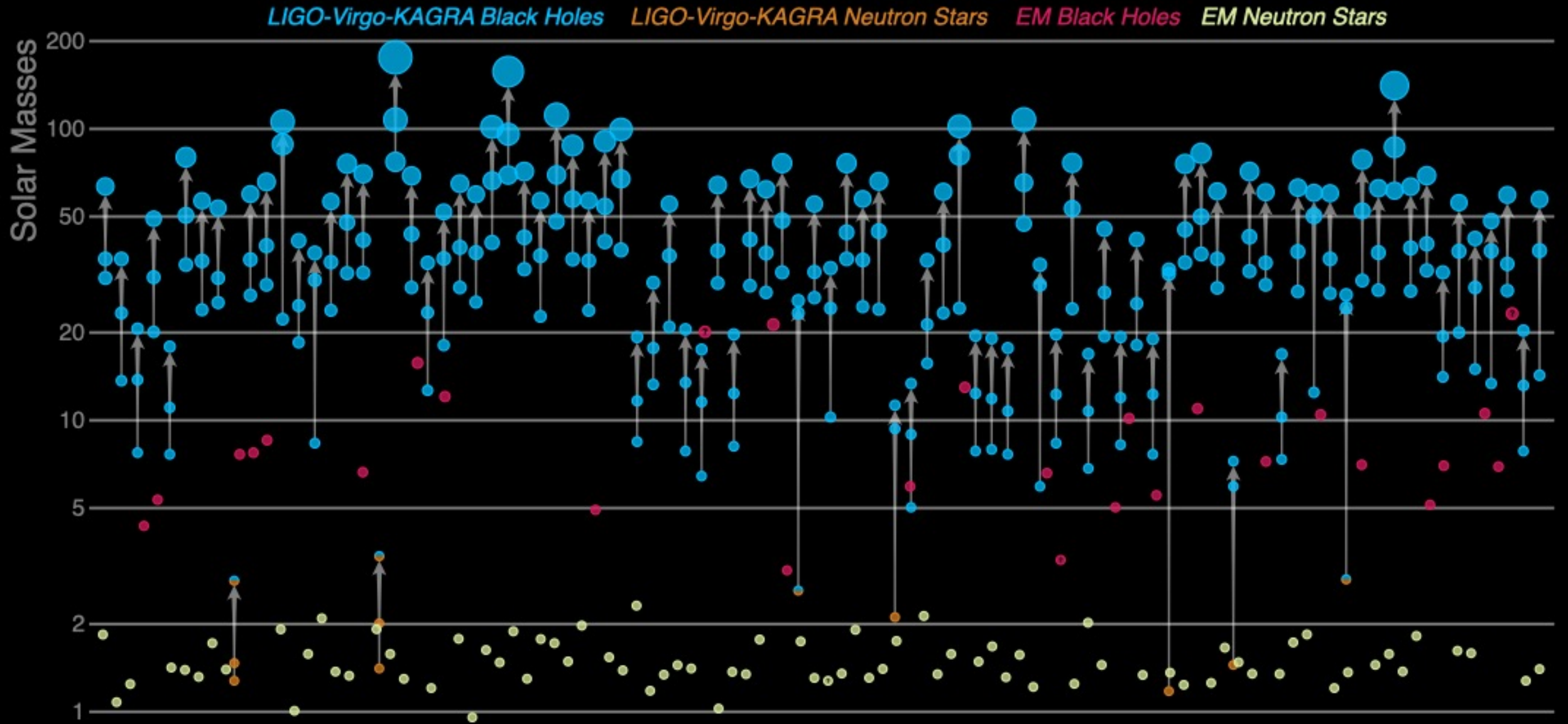
Recent discovery by the NANOGrav and IPTA

NANOGrav, APJ Lett. (2023)
(c)



A. Simonnet, NANOGrav Collab.

90 (and more) events



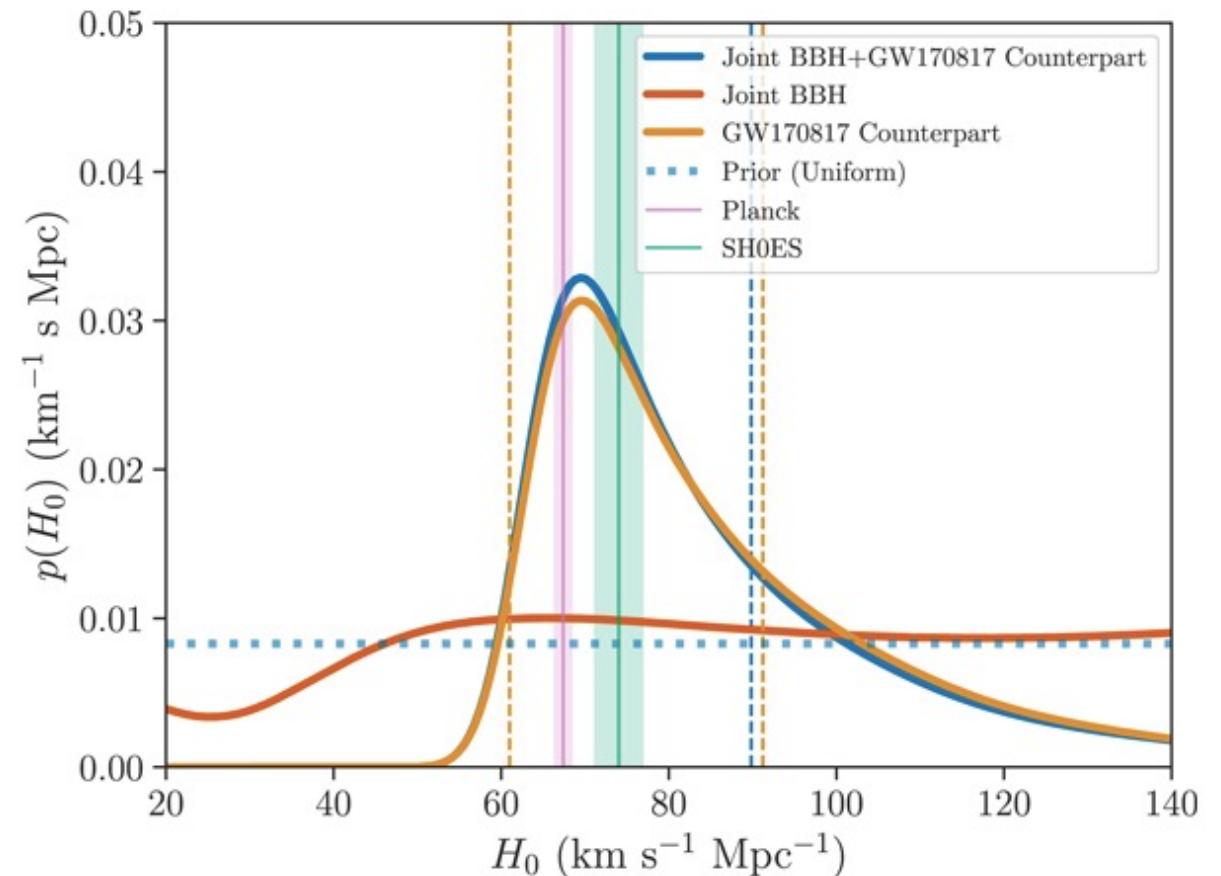
Science cases

<https://doi.org/10.1038/d41586-020-03047-0>

Astrophysical/cosmological contributions:

- Verification of GR
- Measuring Hubble constant
- Limiting EOS for NS
- Propagation speed of GWs
- Population of BH binaries
- ... etc.

B. P. Abbott *et al* 2021 *ApJ* **909** 218

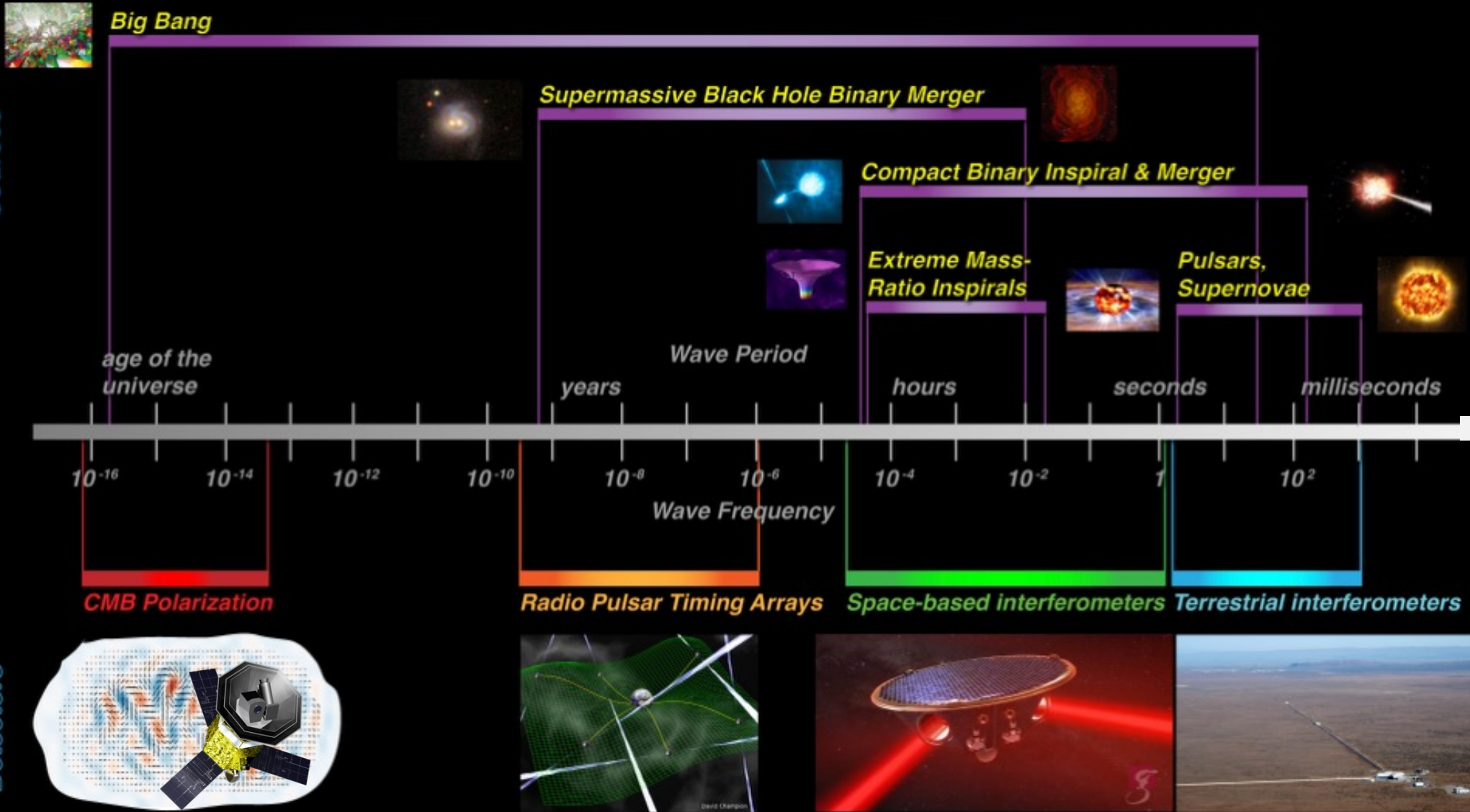


Where are we heading towards?

Multi-wavelength observations!



Gravitational wave spectrum



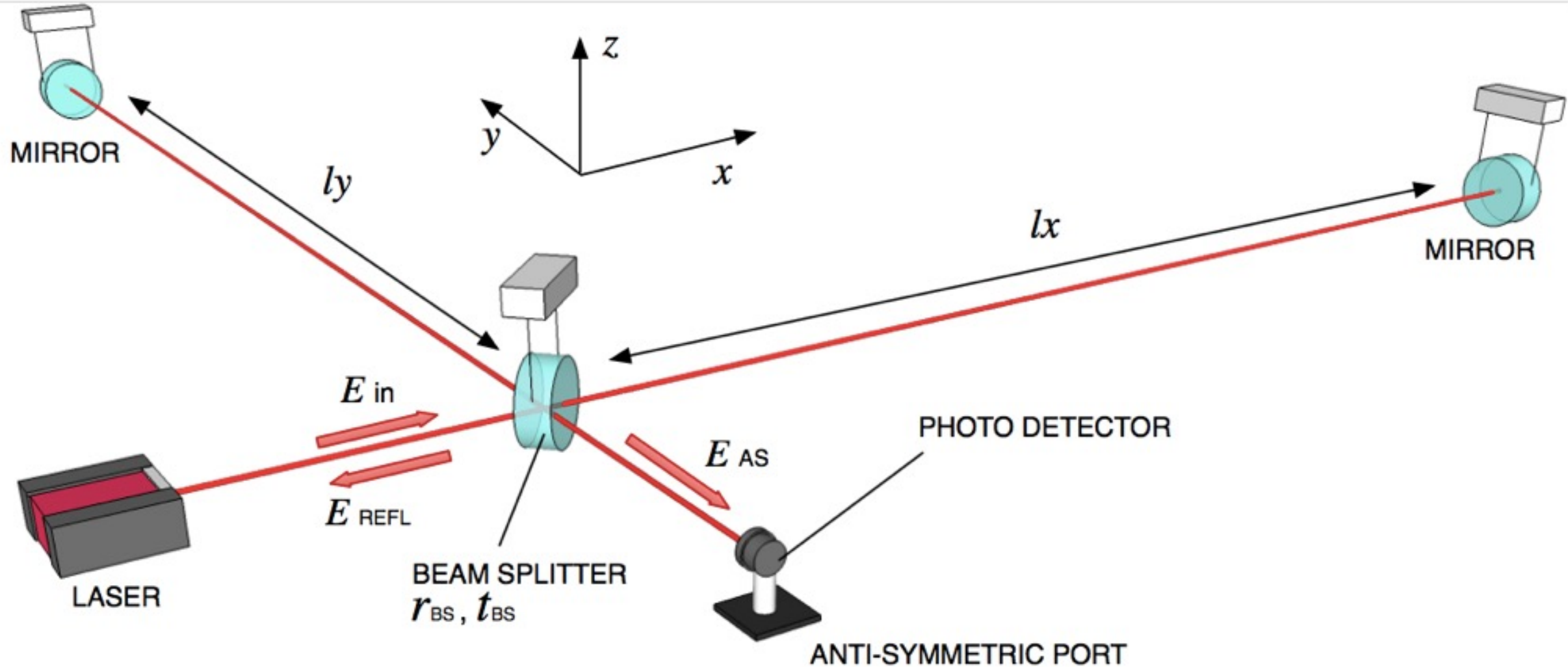
New physics

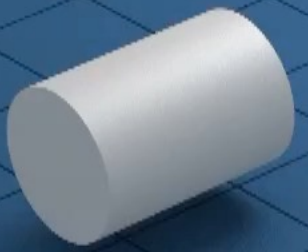


And..
HF/UHF
Living Rev Rel.
 24, 4 (2021)

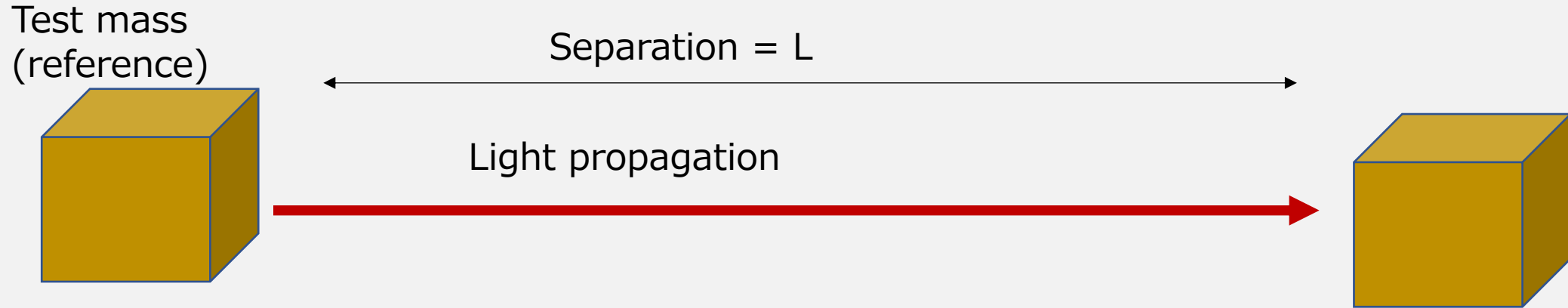
Detectors

Laser interferometer





Working principle



Optical phase (measurement quantity)

$$\Delta\Phi(t) = kc \int_{t-L/c}^t (1 + h(t))^{-1/2} dt$$

$$\approx kL - \boxed{kLh(t)/2}$$

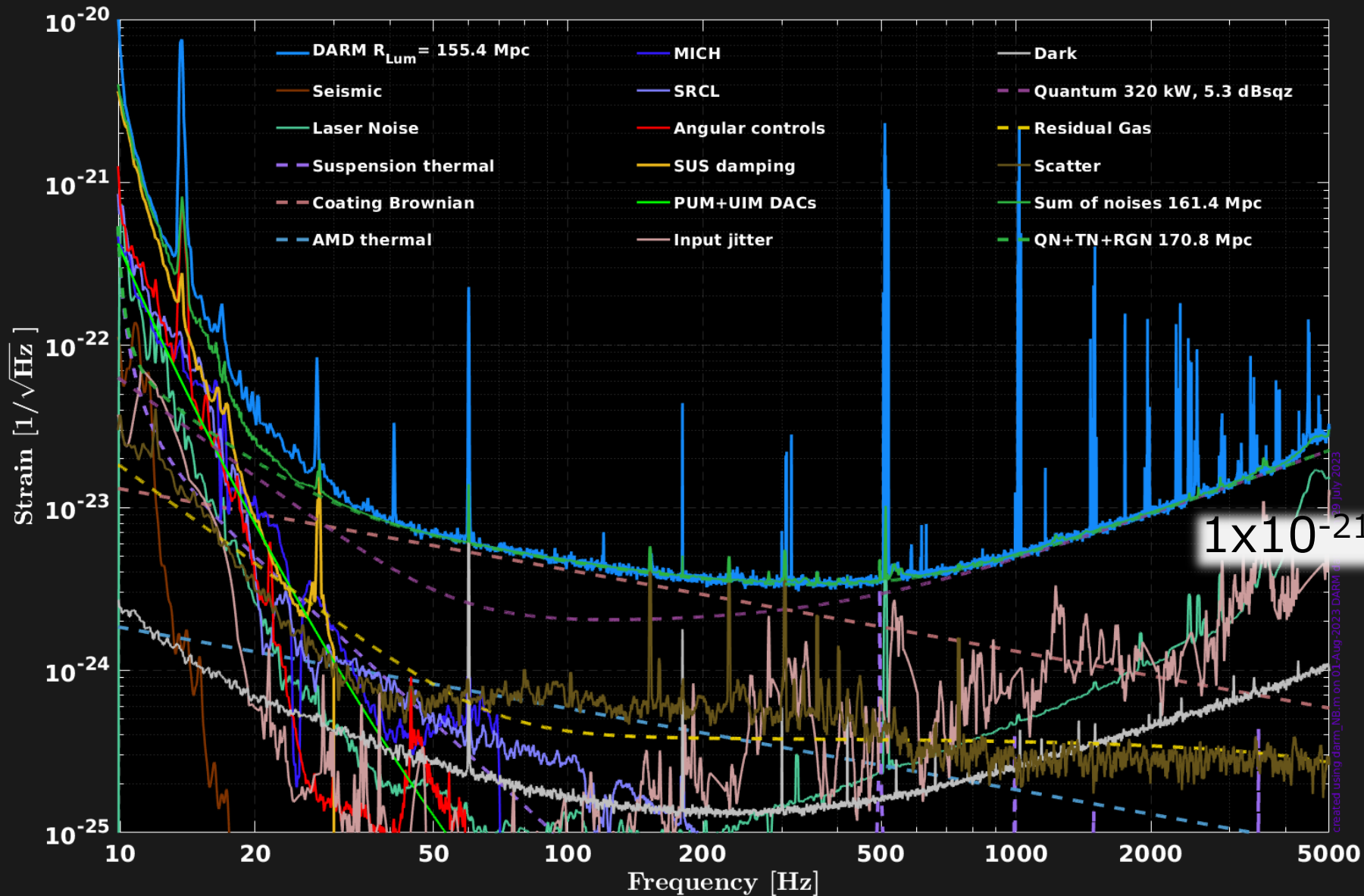
h : GW amplitude
 k : wavenumber of light field

- ▶ Sensitivity increases as L
- ▶ Increasing L loses observation bandwidth

Sensitivity on ground

LIGO Livingston alog 66532 (2023/Aug/1)

Credit: A. Effler and V. Frolov

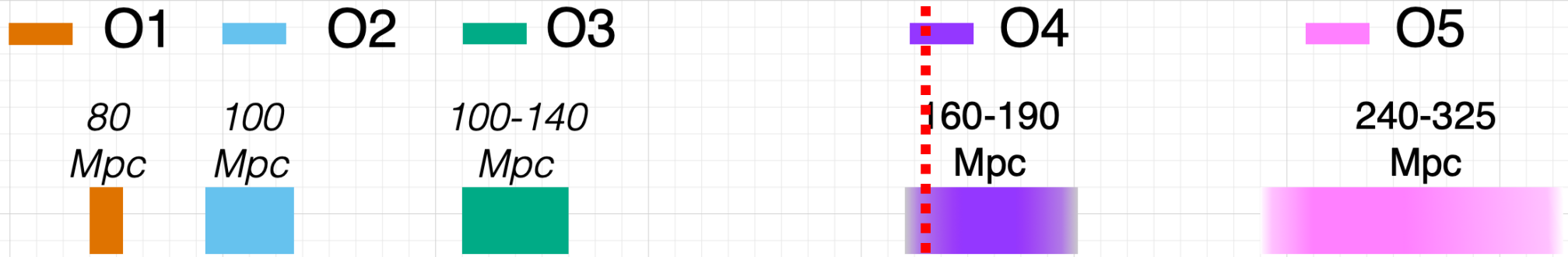


Observing plans

IGWN
<https://observing.docs.ligo.org/plan/>



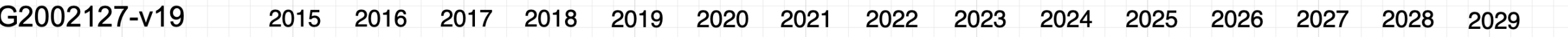
Updated
2023-05-16



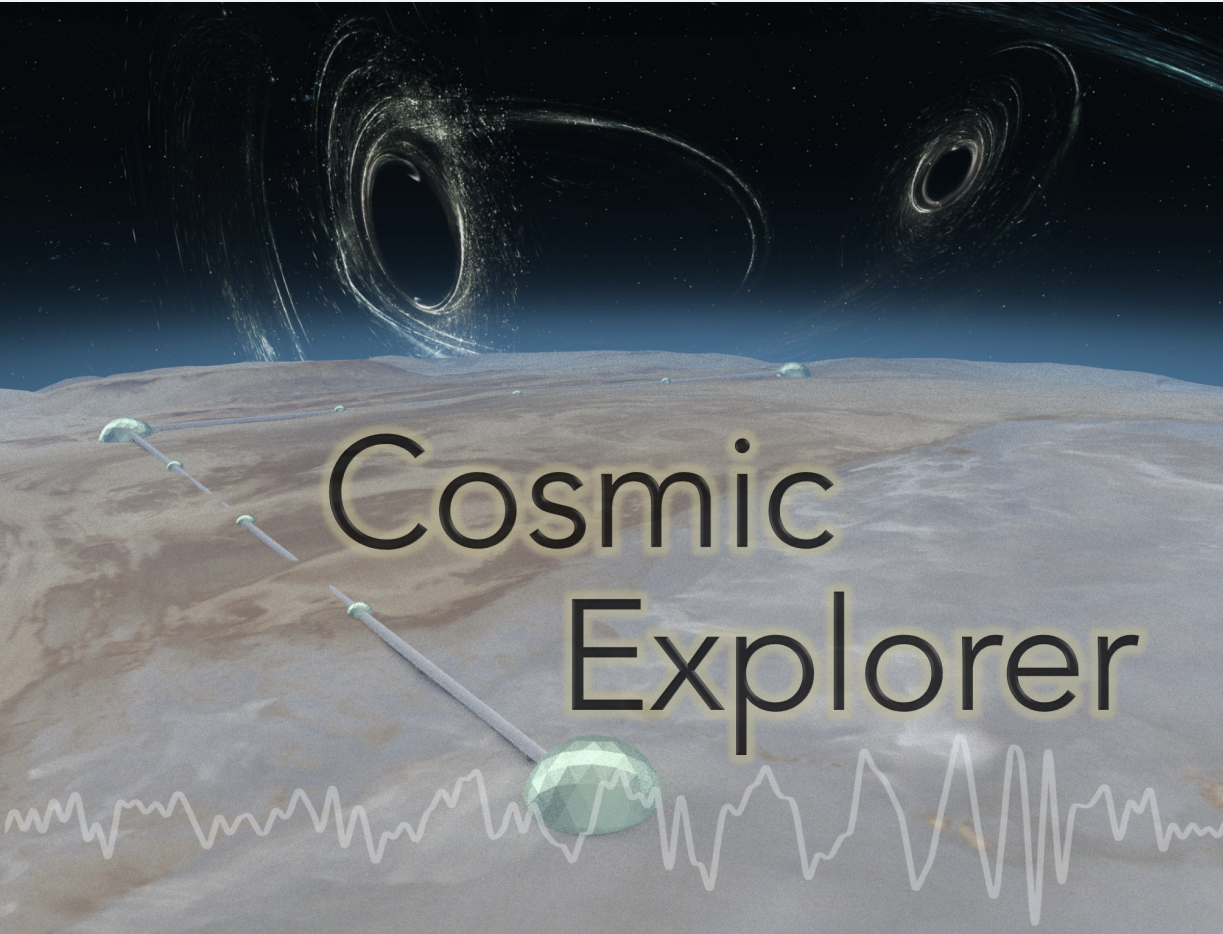
LIGO

Virgo

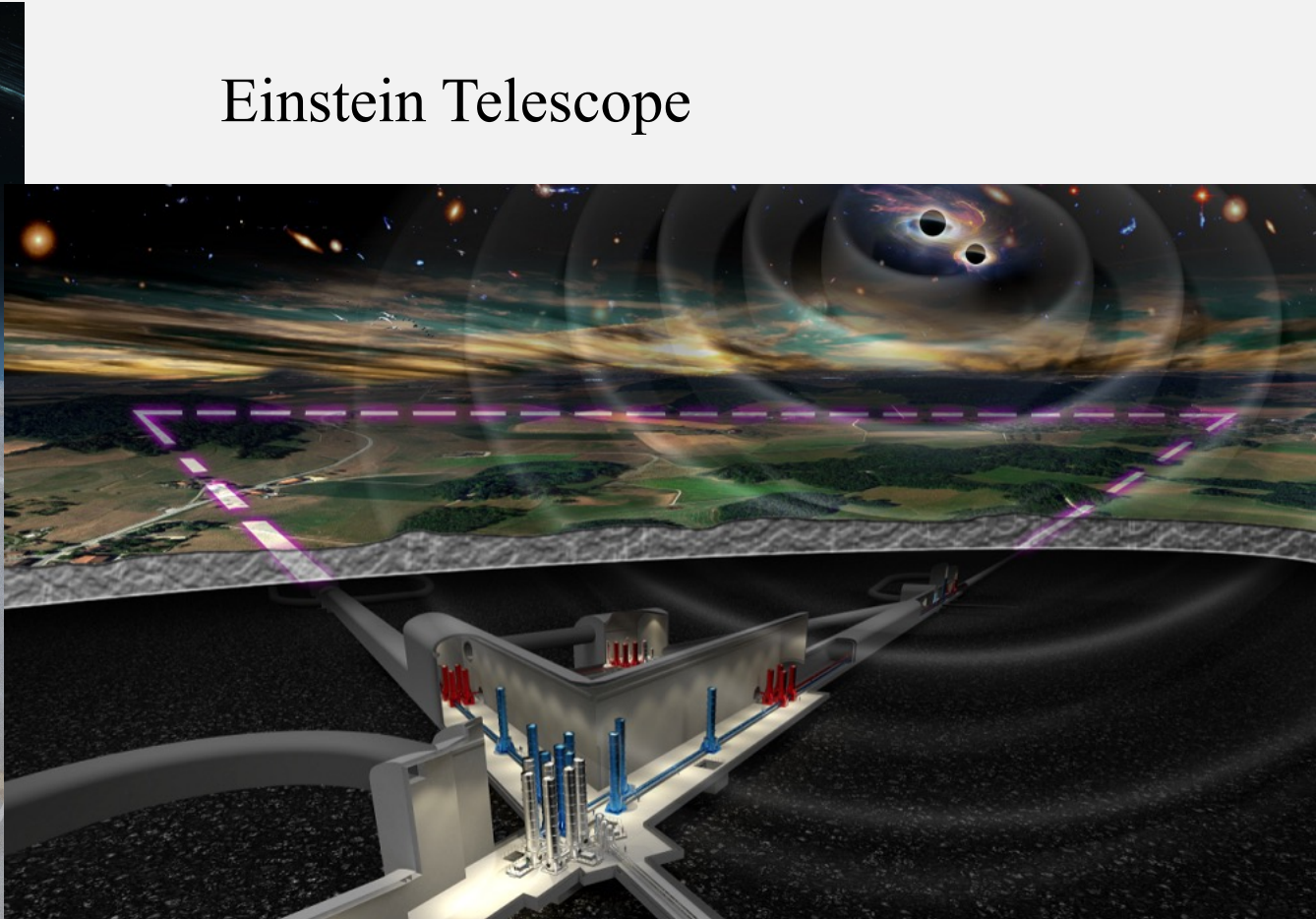
KAGRA



Future plans a.k.a. 3G detectors in 2030's

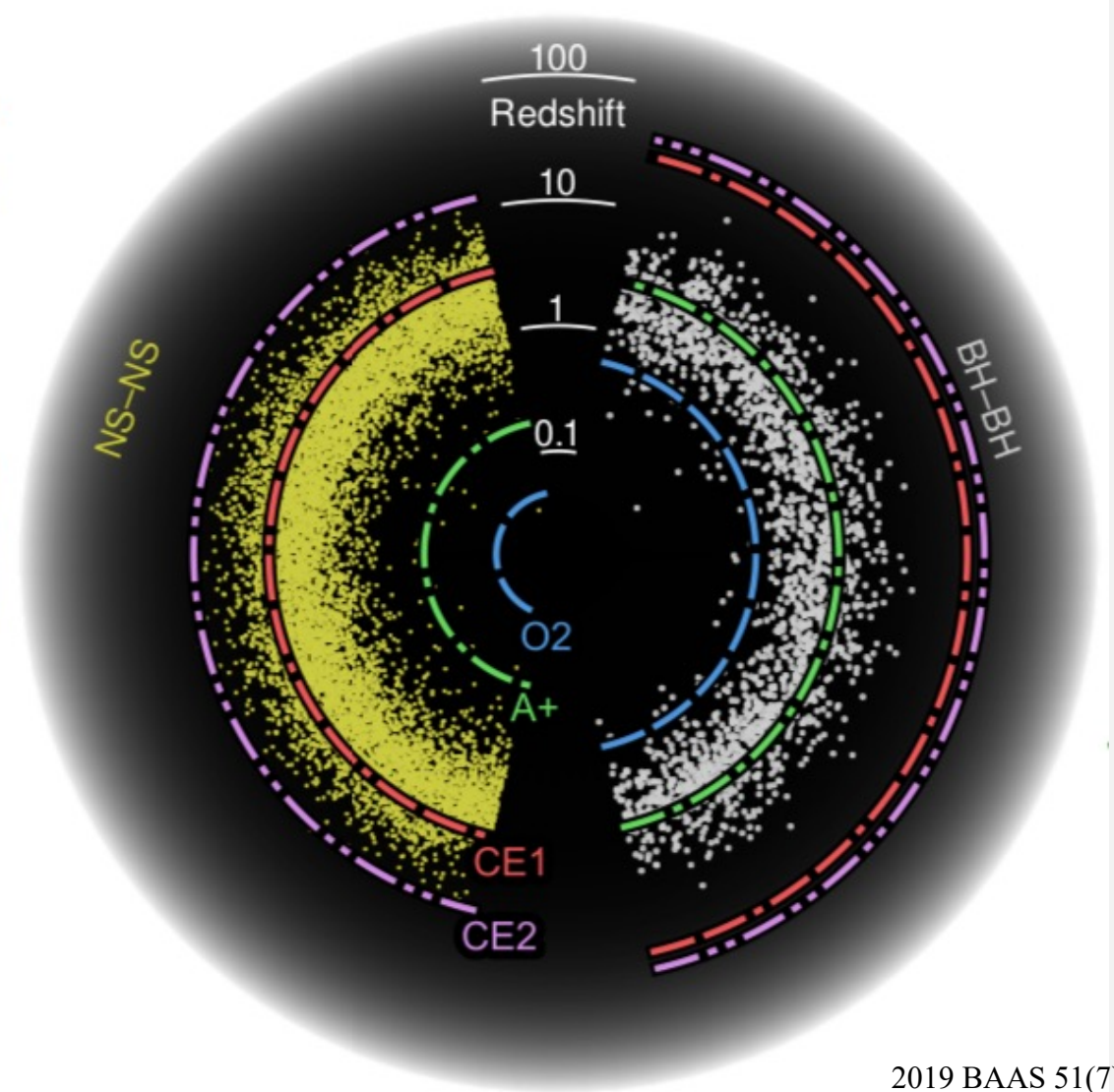
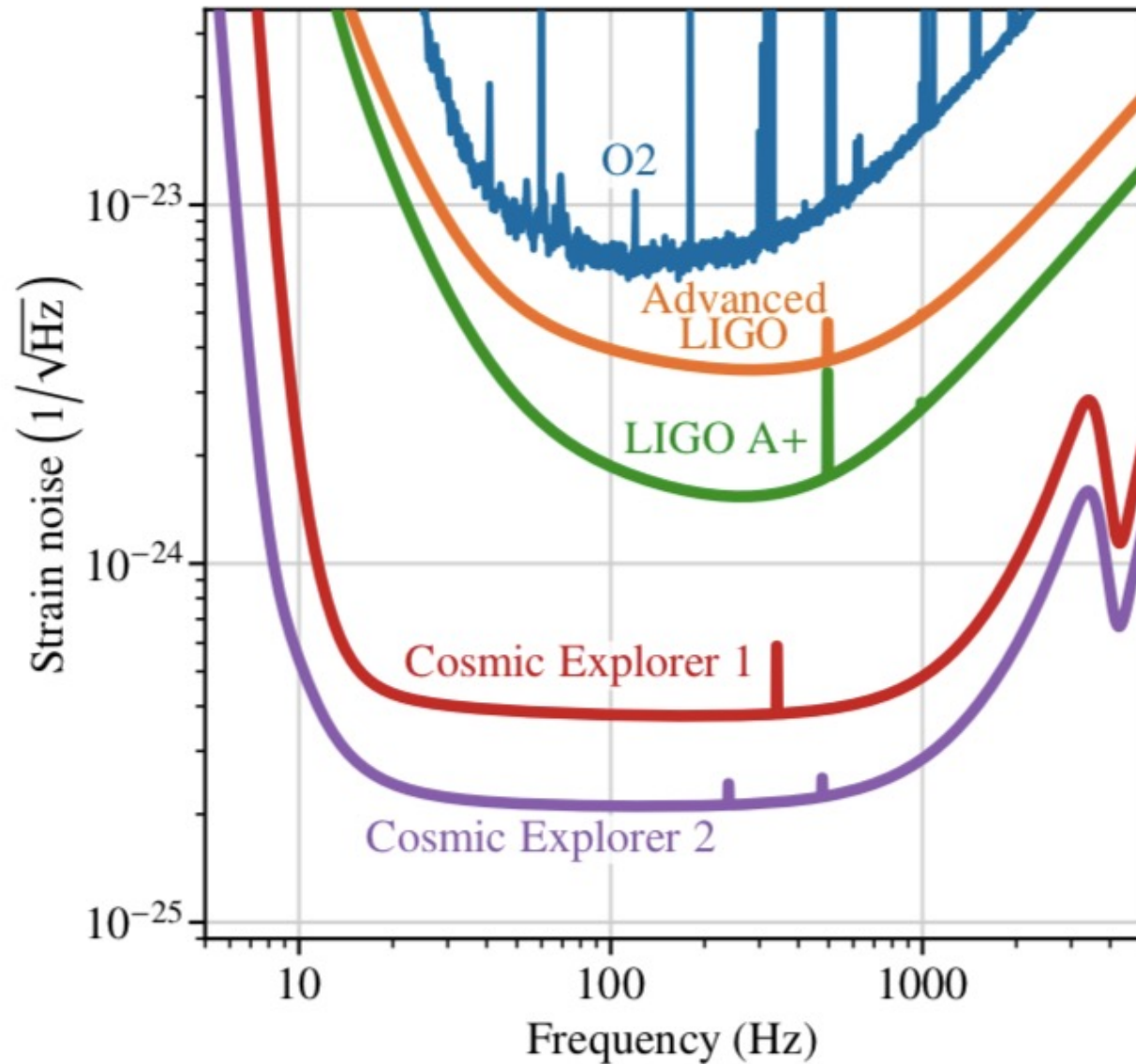


US-lead project, 40 km



European project, 10 km, triangular shape, underground

Astrophysical reach of 3G detectors



Into space



Advantages

- ▶ Reduced seismic noises
- ▶ Long laser interferometer lengths
- ▶ Vacuum tubes not required
- ▶ Low-freq. GW sources

Gravitational wave spectrum



Big Bang

Sources

Supermassive Black Hole Binary Merger

Compact Binary Inspiral & Merger

Extreme Mass-Ratio Inspirals

Pulsars, Supernovae

New physics



age of the universe

years

Wave Period

hours

seconds

milliseconds



Wave Frequency

And.. HF/UHF

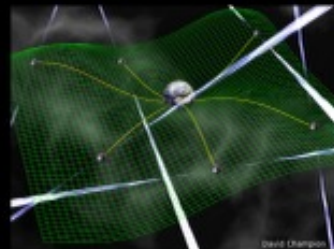
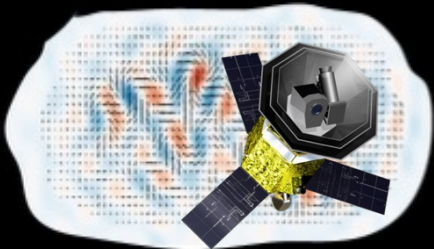
CMB Polarization

Radio Pulsar Timing Arrays

Space-based interferometers

Terrestrial interferometers

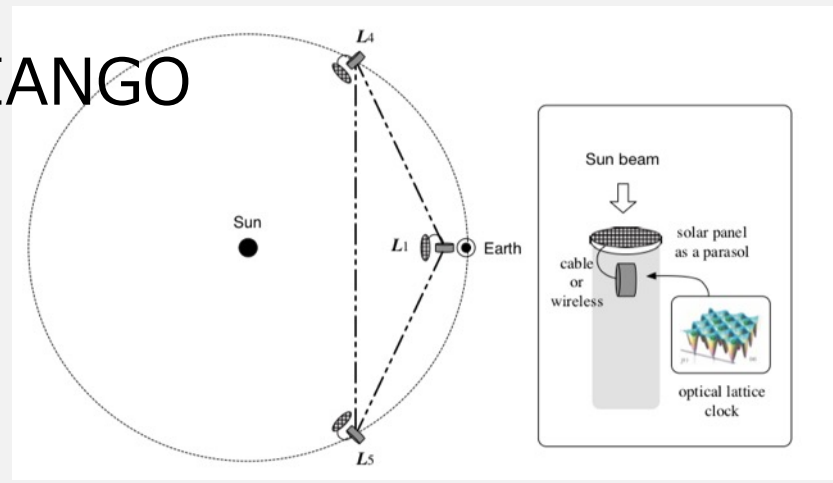
Detectors



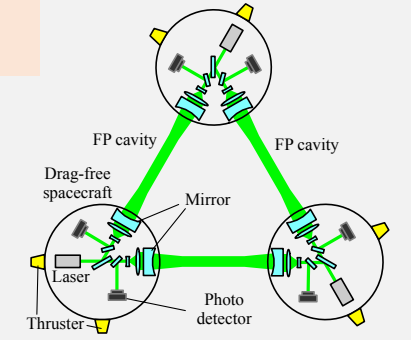
Space-based detectors

A number of concepts exist today

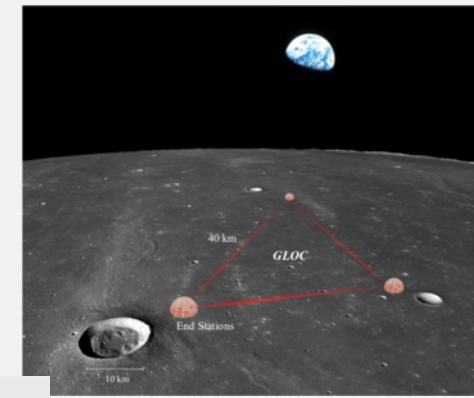
- ▶ Laser interferometers
 - ▶ LISA, DECIGO, TianQin, Taiji, TIANGO
- ▶ Atom interferometers
 - ▶ AEDGE [1]
- ▶ Precision clocks
 - ▶ INO[2], DOCS[3]
- ▶ Lunar-based detectors
 - ▶ GLOC[4], LGWA[5], LSGA[6], LION [7]



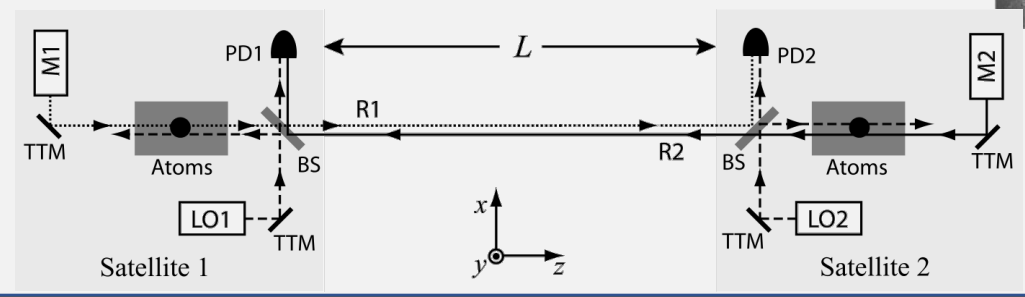
INO



DECIGO



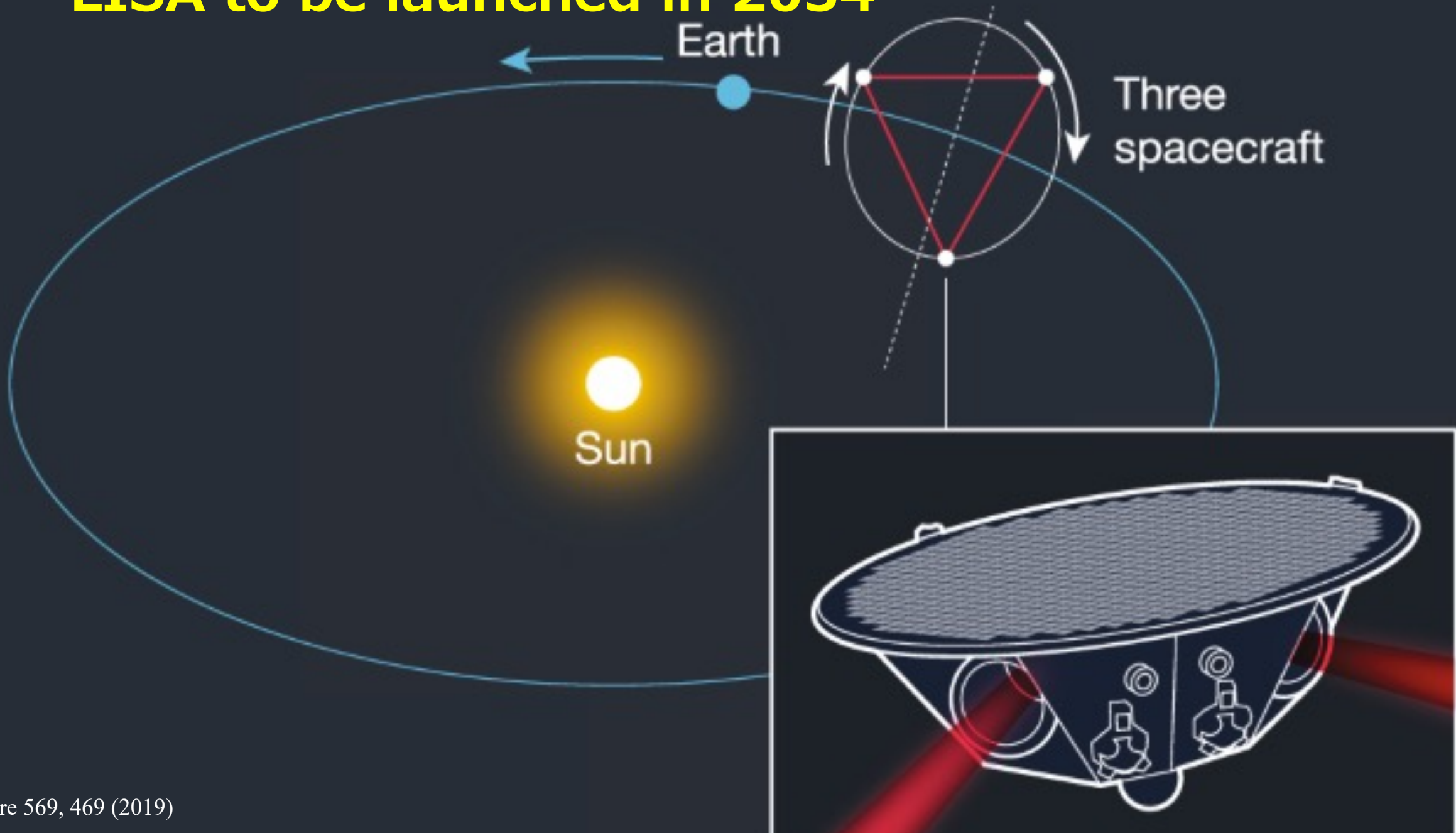
GLOC



AEDGE

[1] Y. A. El-Neaj+ EPJ Quantum Tech. (2020)
 [2] T. Ebisuzaki+, Intn'l J. Mod. Phys. D (2020)
 [3] J. Su+, Class. Quantum Grav. (2018)
 [4] K. Jani+, arXiv:2007.085502 (2020)
 [5] J. Harms+, arXiv:2010.13726 (2020)
 [6] S. Katsanevas+, ESA (2020)
 [7] P. Amaro-Seoane+, Class. Quantum Grav. (2021)

LISA to be launched in 2034



Taiji and TianQin, aiming 2030's launch

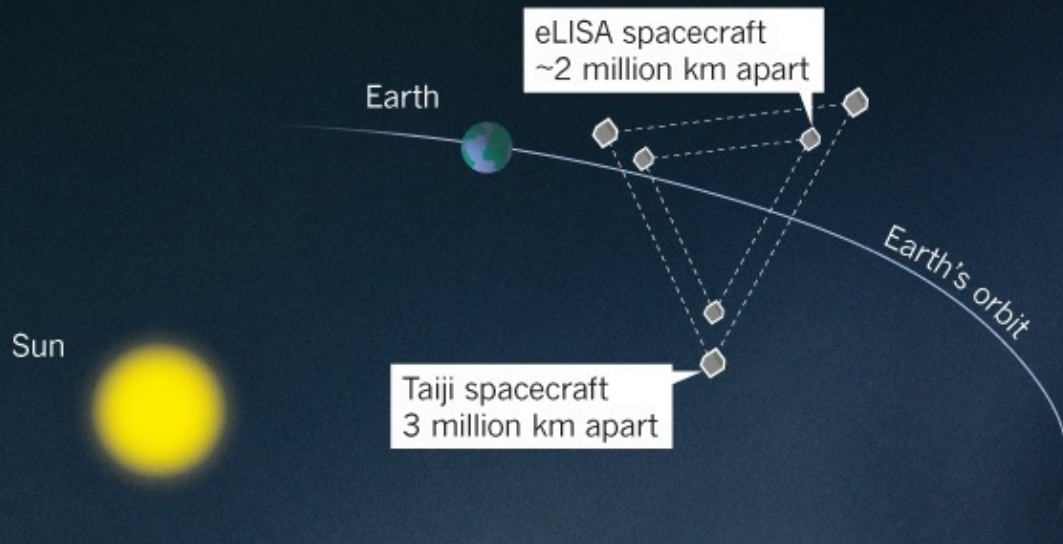
- Two Chinese space gw mission concepts are independently being developed

CHINA'S CHOICES

Chinese researchers have proposed several ways to detect gravitational waves in space.

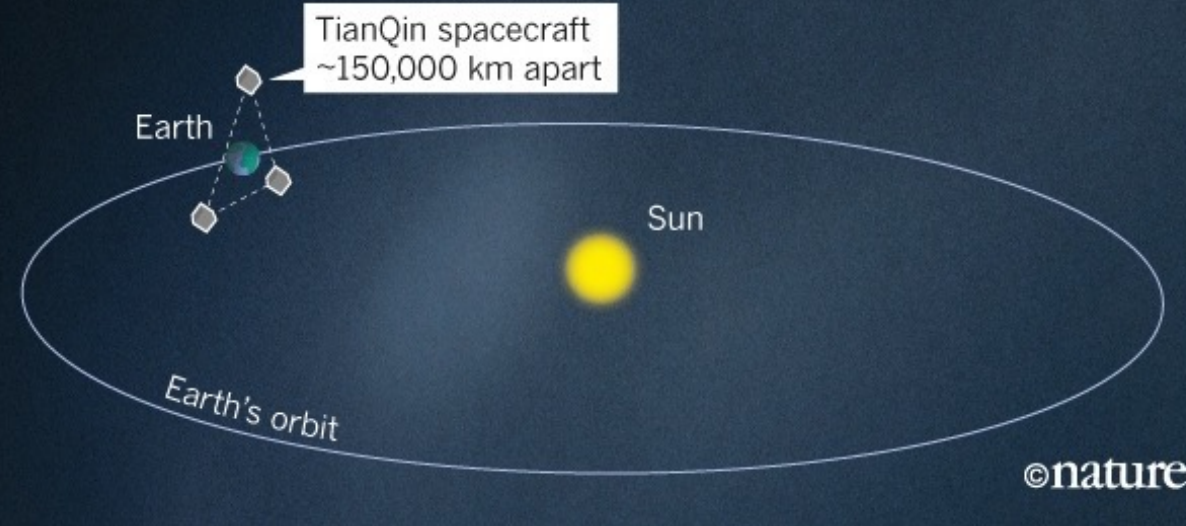
TAIJI

The most ambitious proposal uses three spacecraft in a triangle that orbits the Sun and detects gravitational waves from a range of objects, like Europe's eLISA proposal. The spacecraft are farther apart than in eLISA, giving Taiji access to different frequencies.

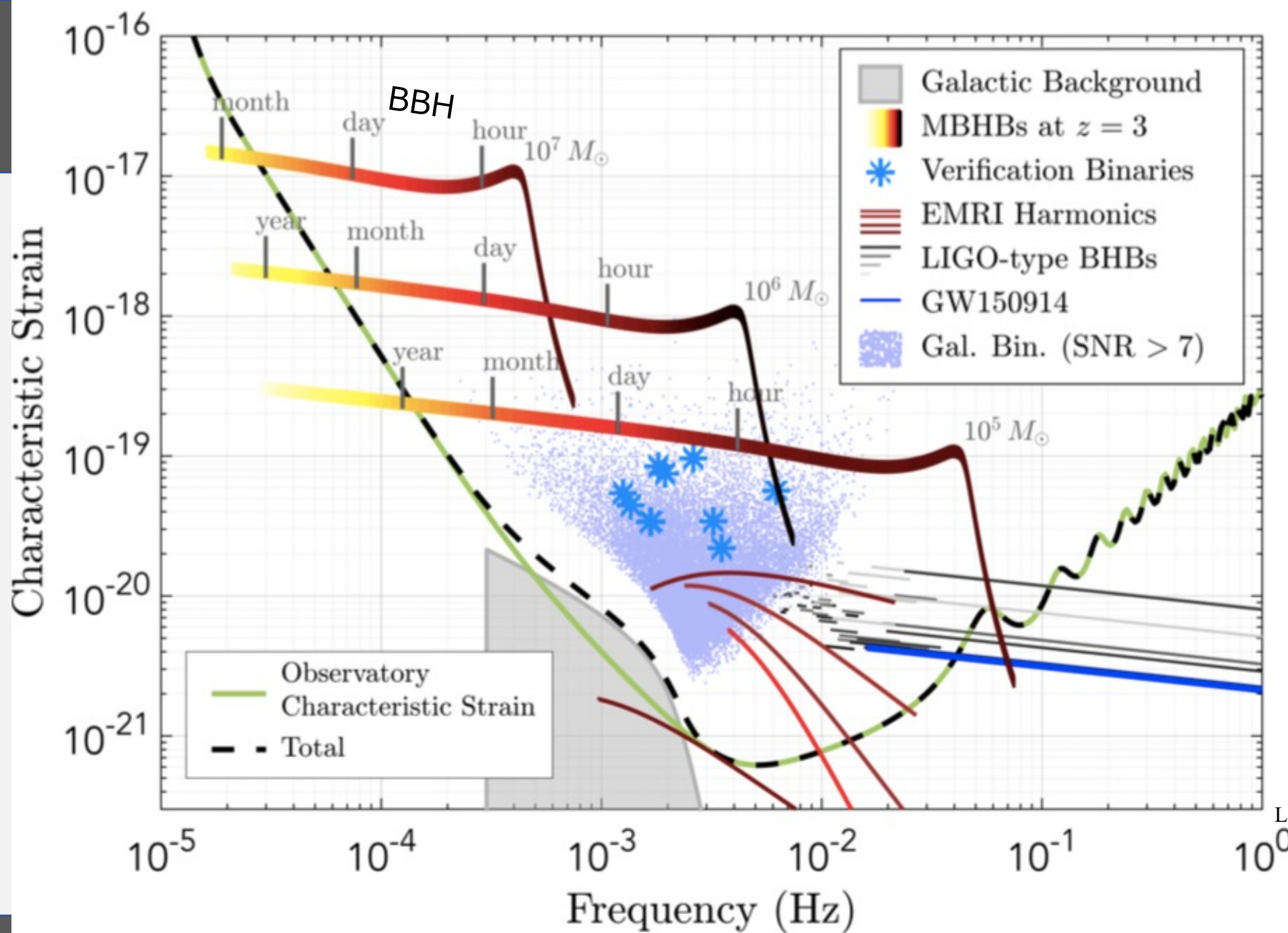


TIANQIN

A cheaper proposal puts three craft in orbit around Earth, and much closer to each other than in Taiji. This would target the gravitational waves emitted by HM Cancri, a pair of white dwarf stars.

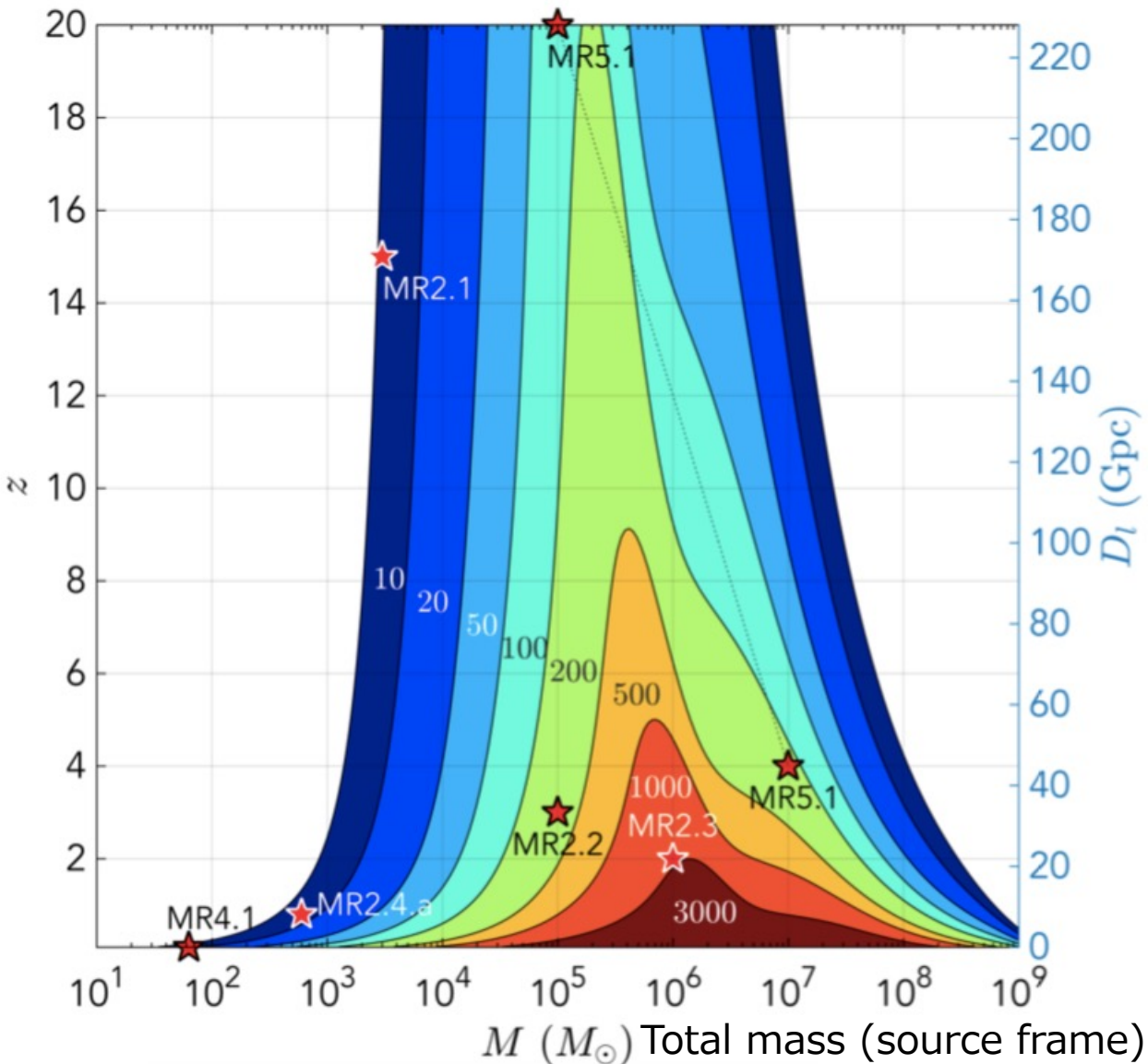


Nature **531**, 150–151 (2016)



LISA L3 proposal document (2017)

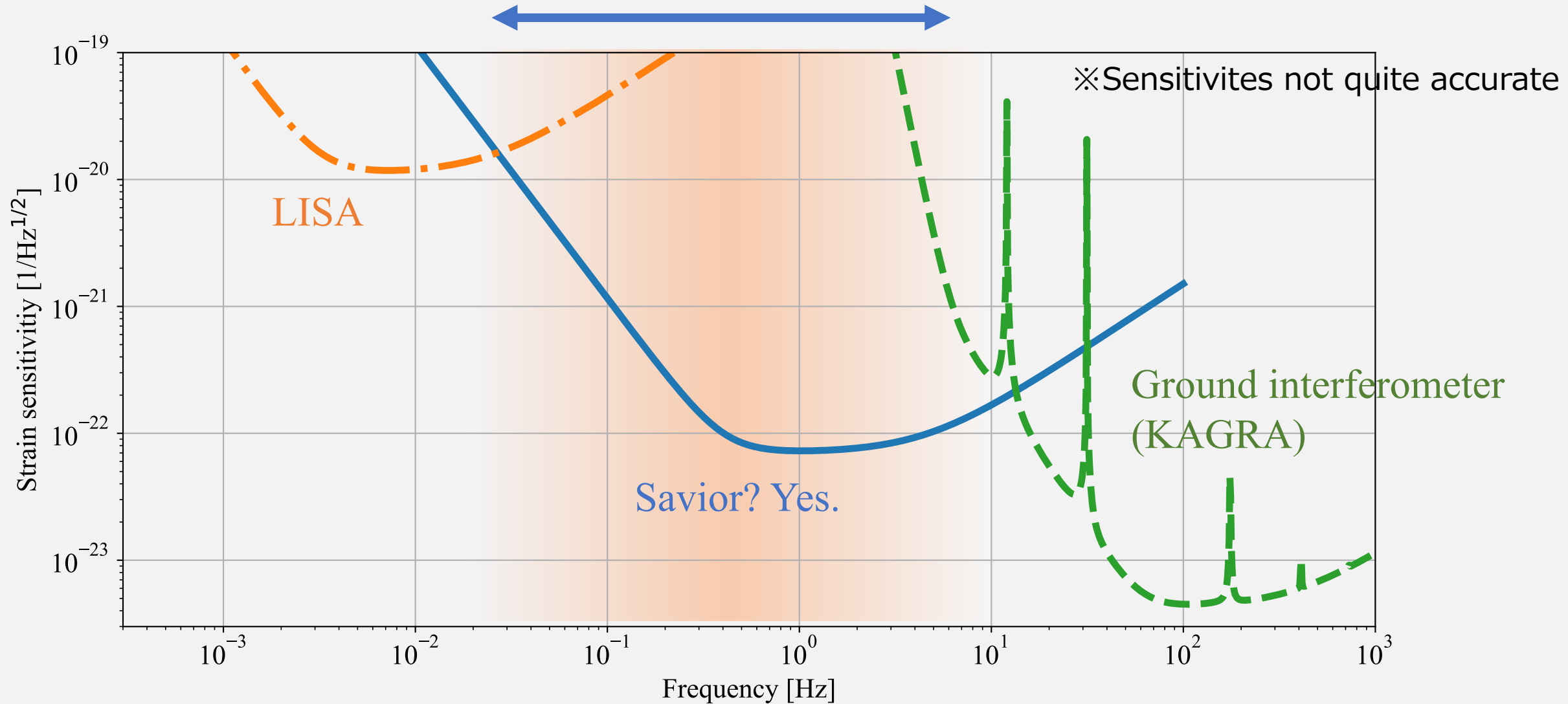
Covering almost all the epoch in merger tree



- ▶ $10^3 M_{\odot} < M < 10^7 M_{\odot}$
- ▶ Beyond $z = 10$

LISA L3 proposal document (2017)

Deci-Hertz band unexplored

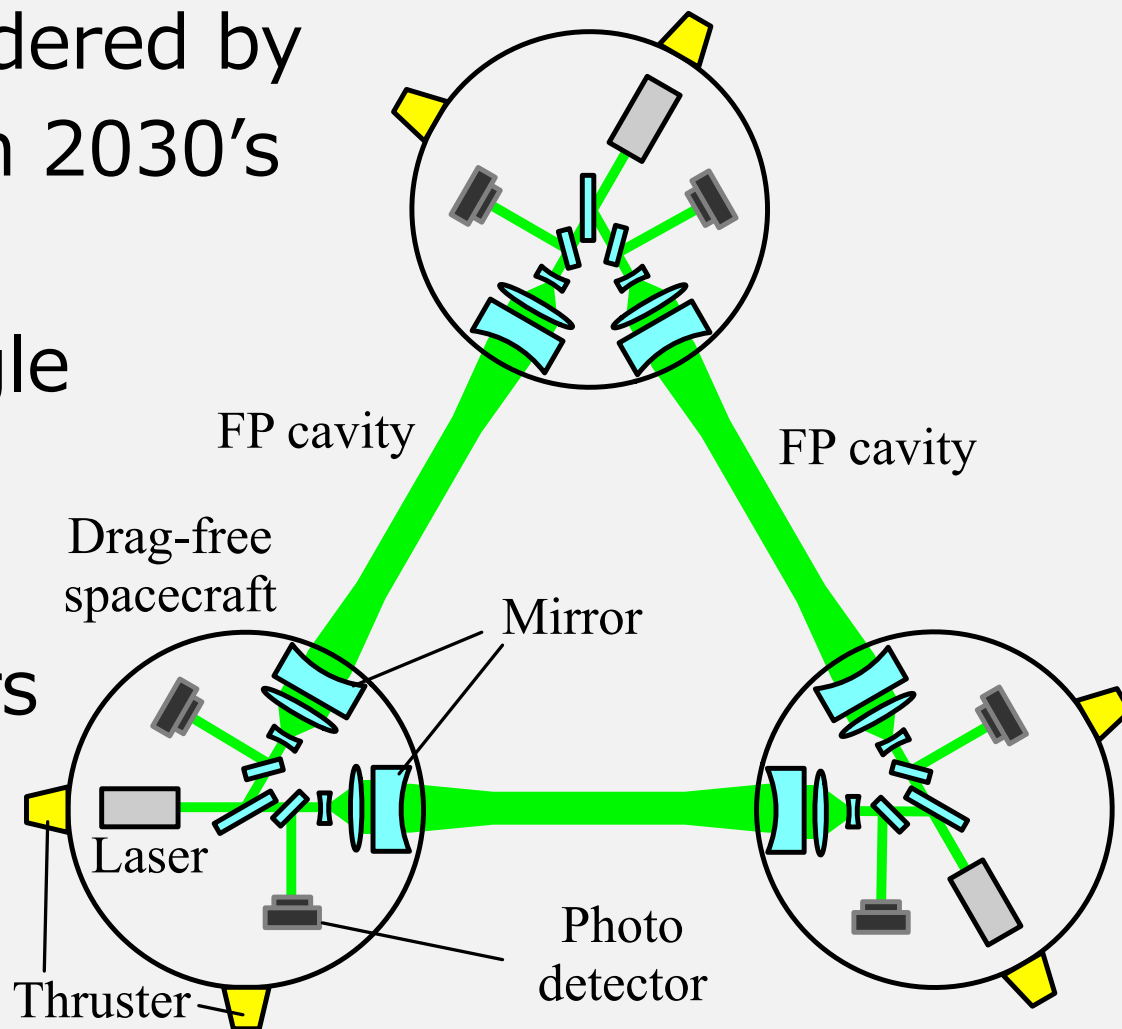




B-DECIGO

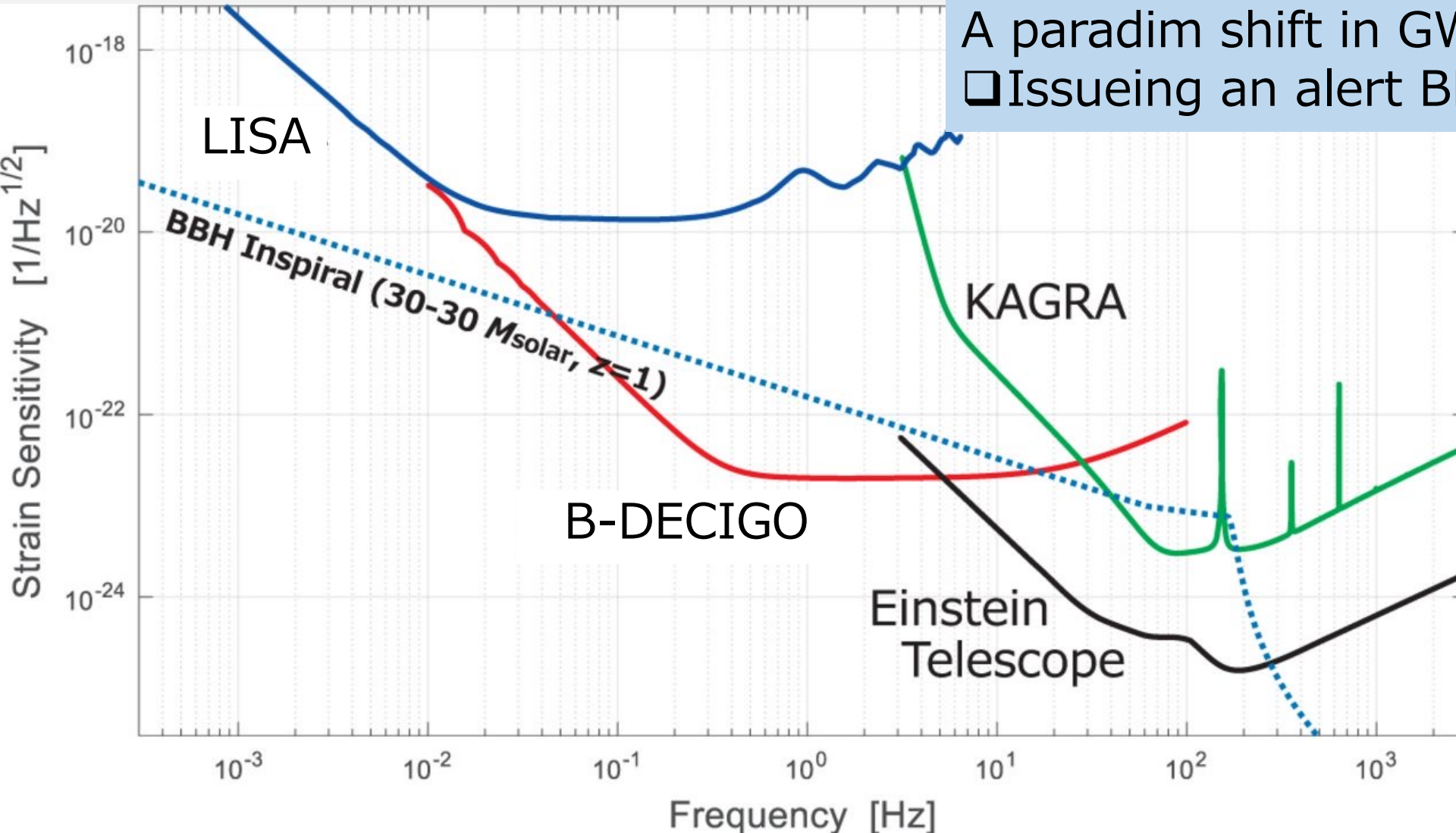
B-DECIGO

- ▶ A space-GW mission concept considered by a Japanese group, to be launched in 2030's
- ▶ Observing GWs in 0.1 Hz band
- ▶ 3 S/C deployed in equilateral triangle
- ▶ Orbit TBD
- ▶ S/C distance 100 km
- ▶ Intersatellite Fabry-Perot resonators



Multi-wavelength observation

T. Nakamura Prog. Theor. Exp. Phys 093E01 (2016)

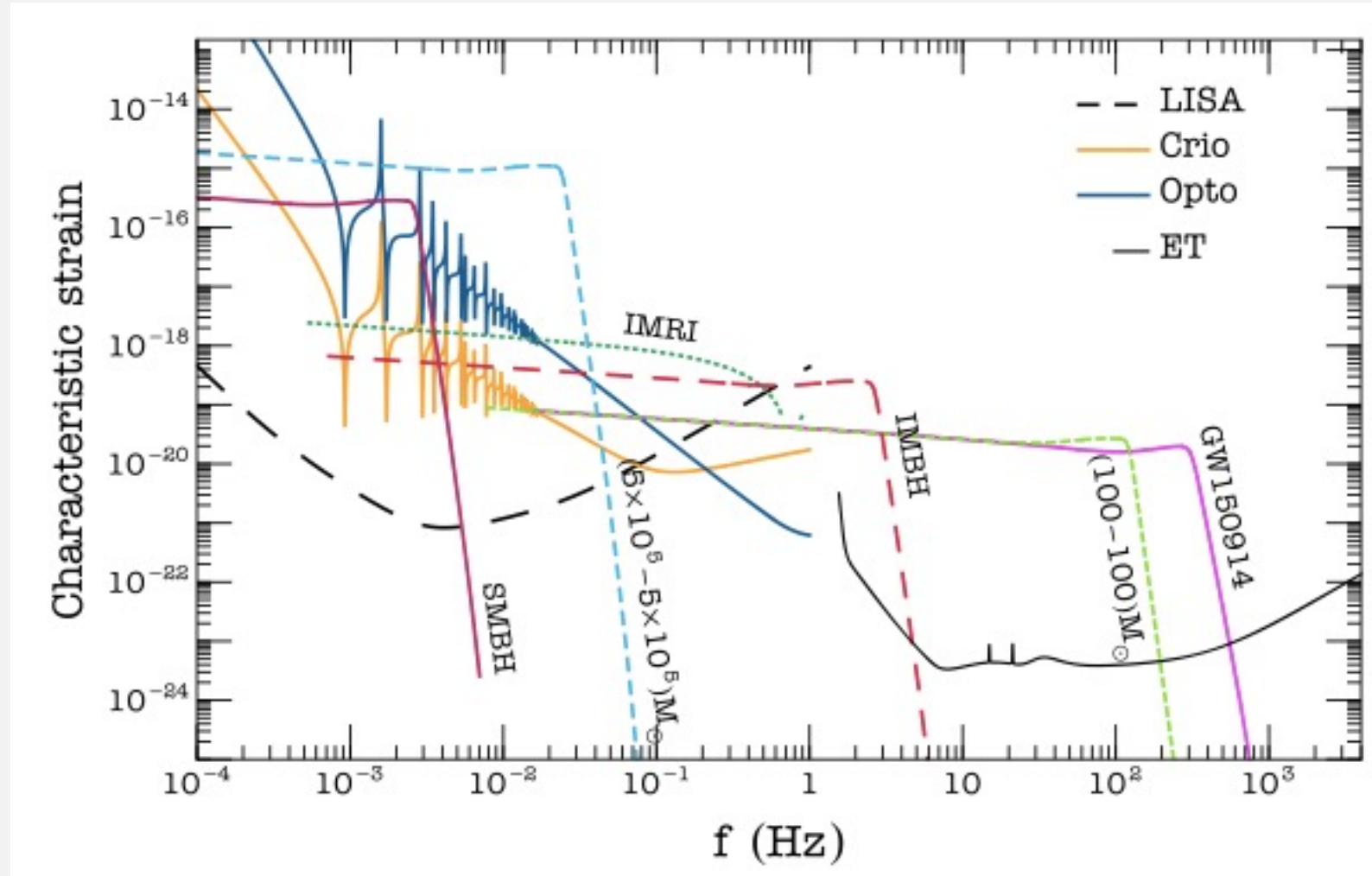


A paradigm shift in GW astronomy
□ Issuing an alert BEFORE they merge!

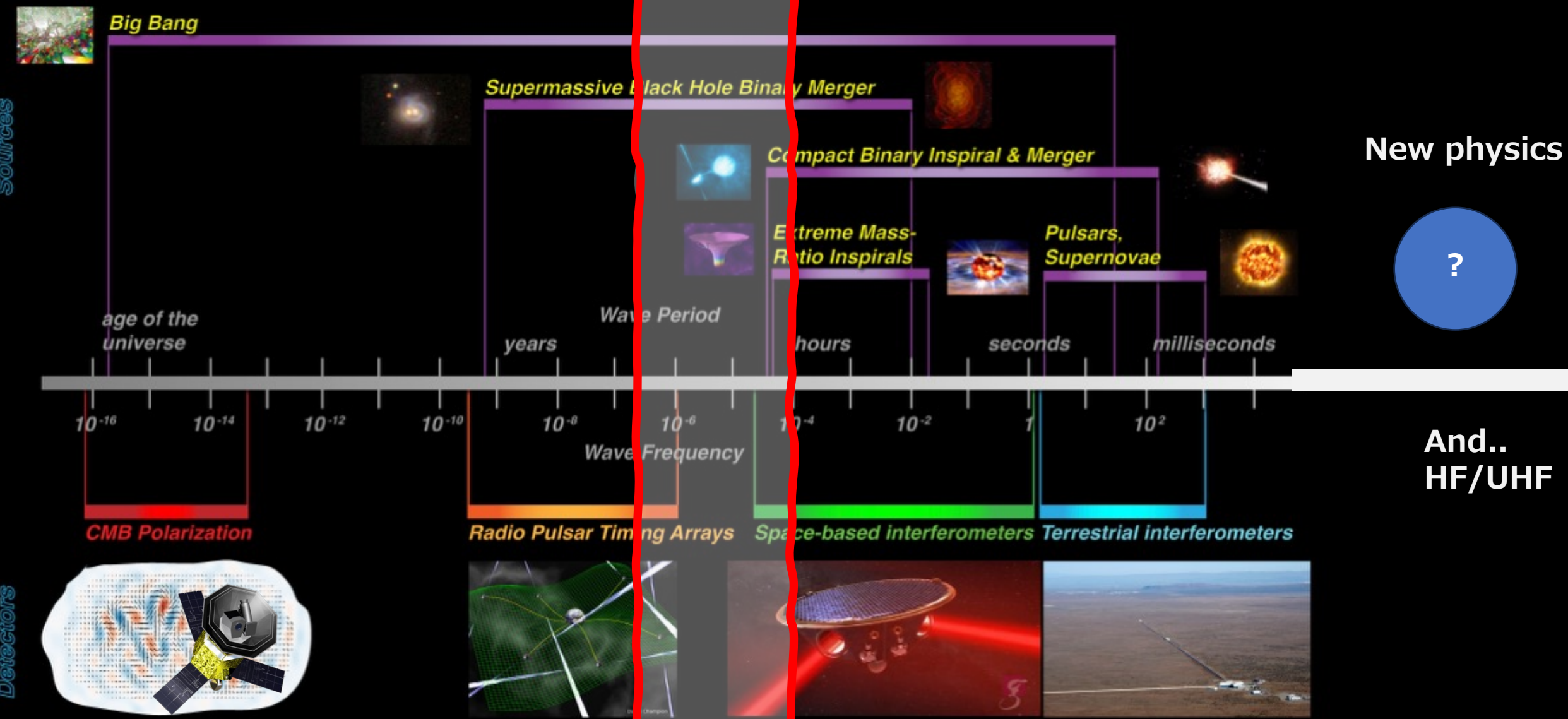
Other detectors at 0.1 Hz? Yes.

The Astrophysical Journal, 910:1 (22pp), 2021 March 20

For example...



Gravitational wave spectrum



An example: Asteroids as test masses

Fedderke+ PRD (2022)

⌘ No laser interferometer, but clock comparison necessary

Transmitter/
receiver



Atomic
clock

~10 km
~ 10^{15} kg

Electromagnetic ranging

~1AU

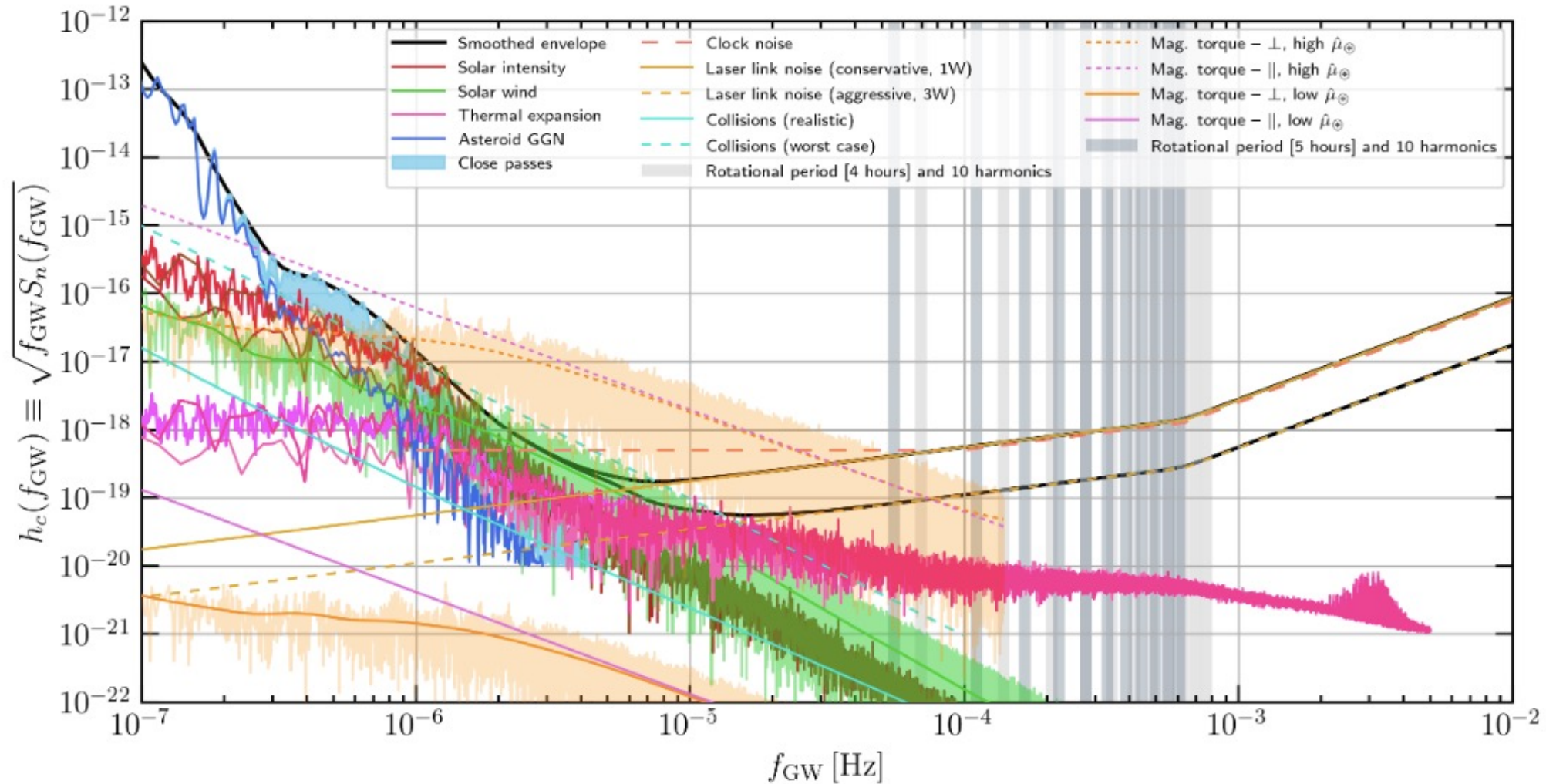
Transmitter/
receiver



Atomic
clock

Asteroids acting as test masses

Fedderke+ PRD (2022)



Summary

- ❖ Gravitational wave astronomy keeps evolving
 - ❖ Ground interferometers in O4, PTA's recent discovery
- ❖ Moving towards multi-wavelength observations
- ❖ Ground- and space-based observatories being considered

A future landscape

PTAs

