Gravitational Wave

Observatories

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Who is this?

Picture by R.X.Adhikari @TIFR Mumbai

An experimental astrophysicist

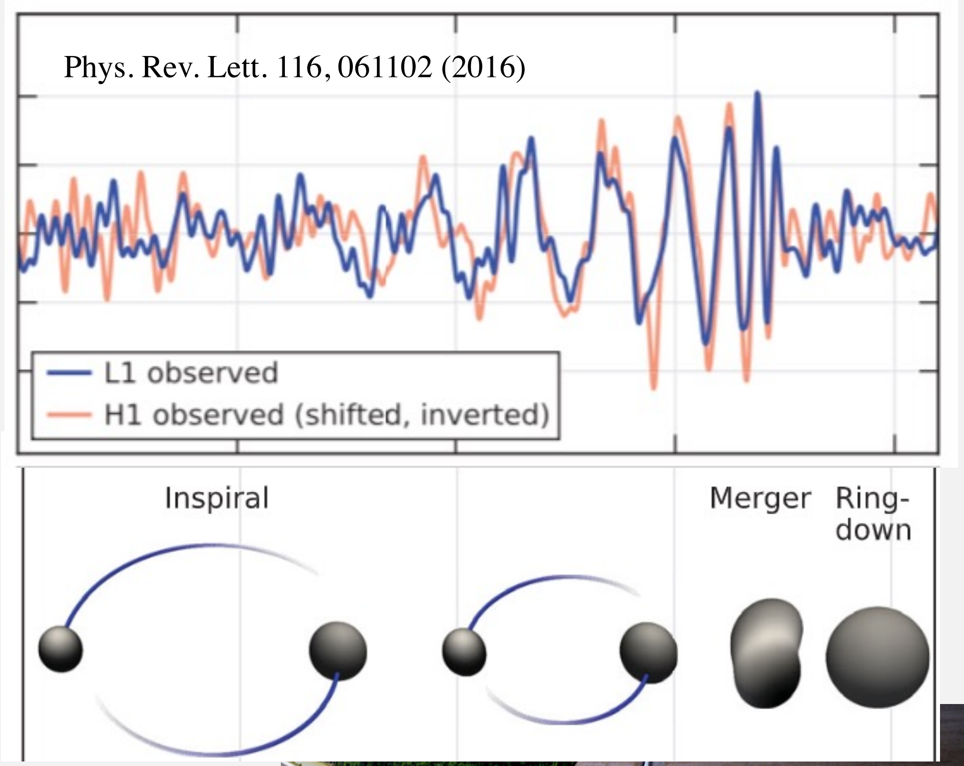
JAXA

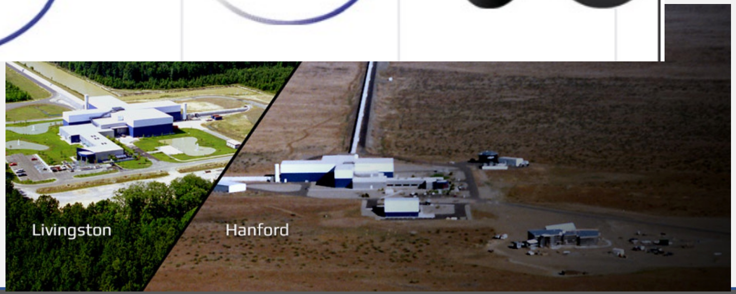
15+ years experience with gravitational wave observatories as an instrument scientist

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

Gravitaitonal wave astronomy marching on

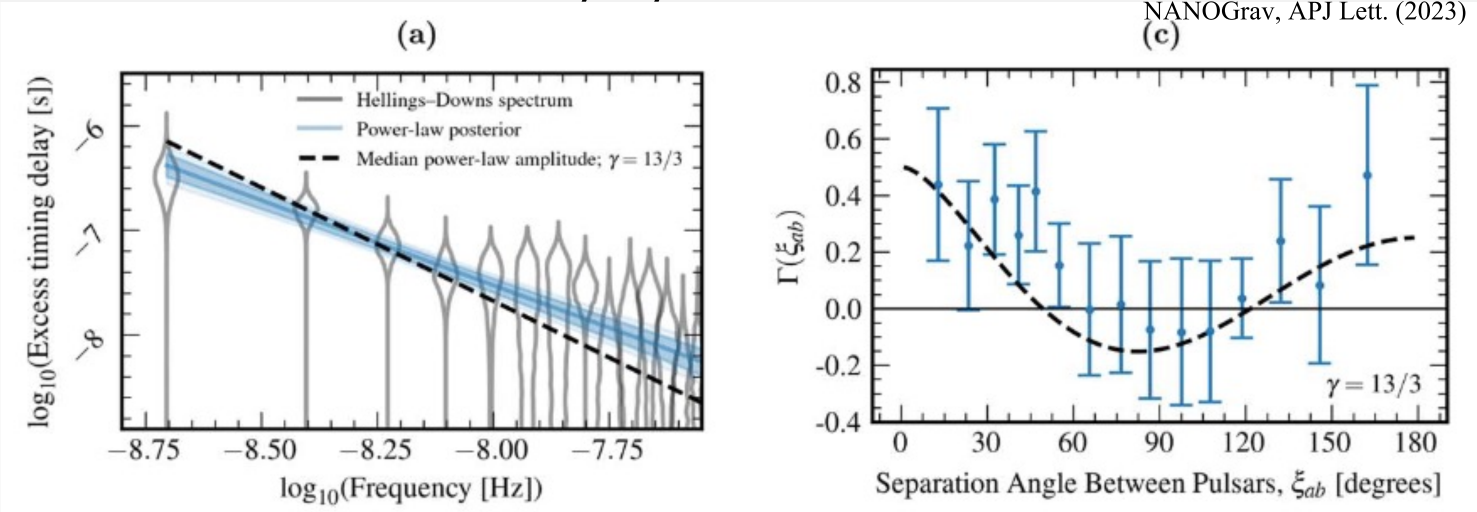
First detection by LIGO (2015)





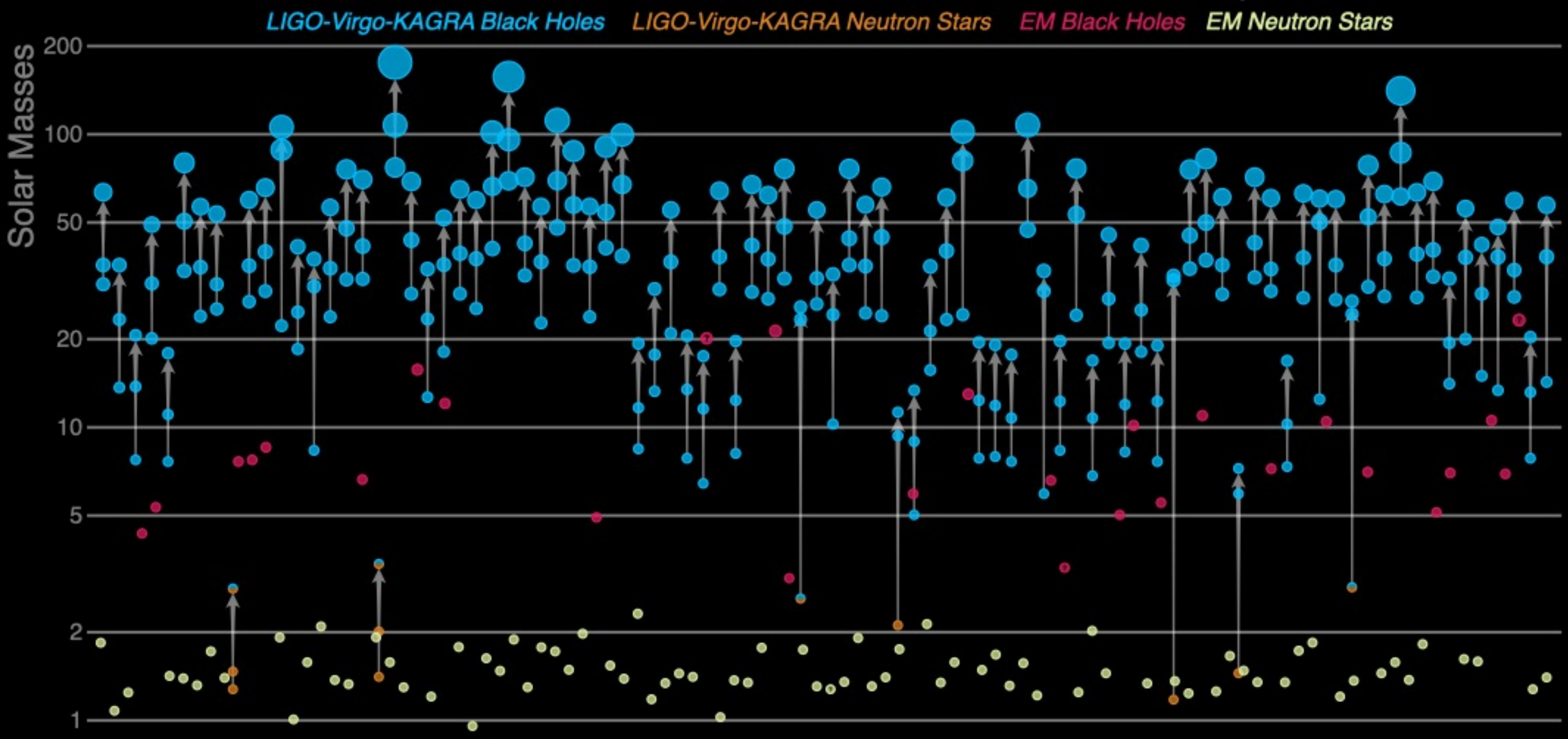
Recent discovery by the NANOGrav and IPTA

NANOGrav, APJ Lett. (2023)



A. Simonnet, NANOGrav Collab.

90 (and more) events



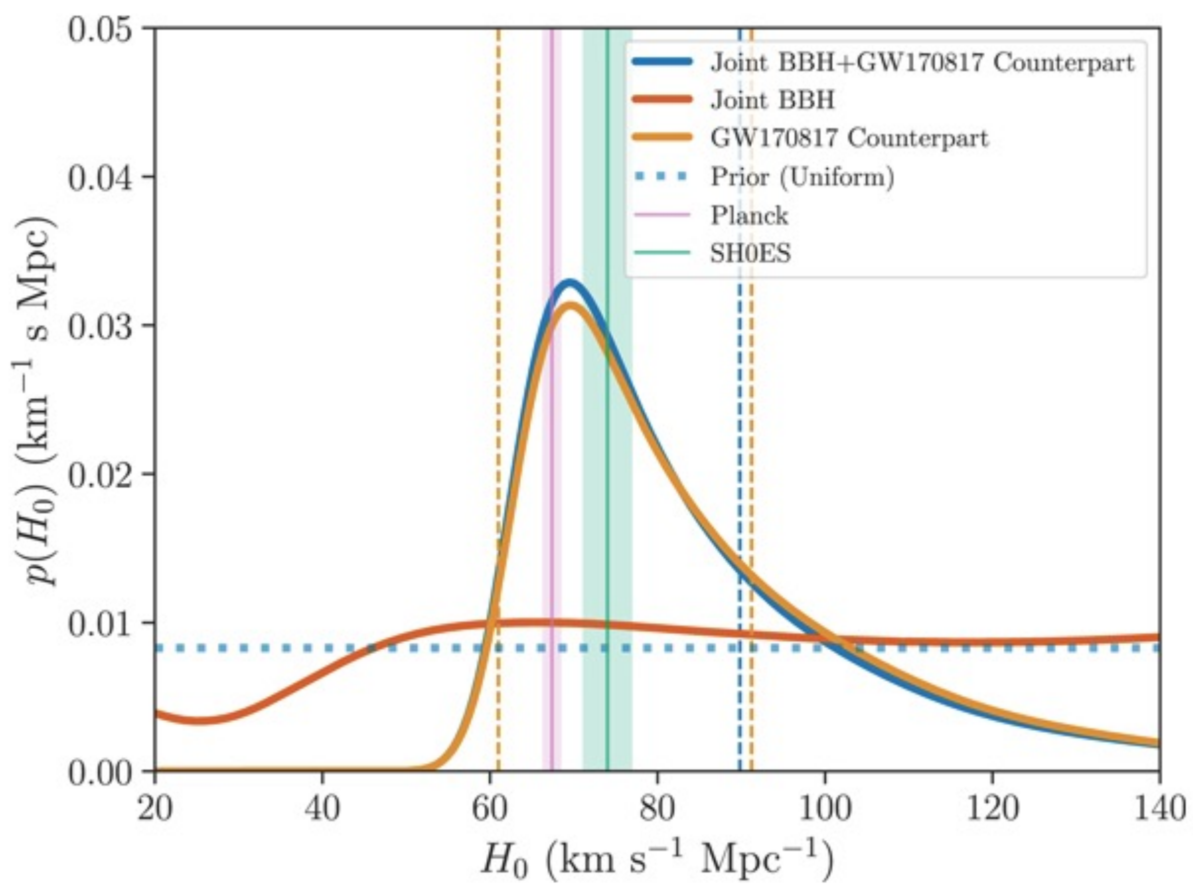
Science cases

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

Astrophysical/cosmological contributions:

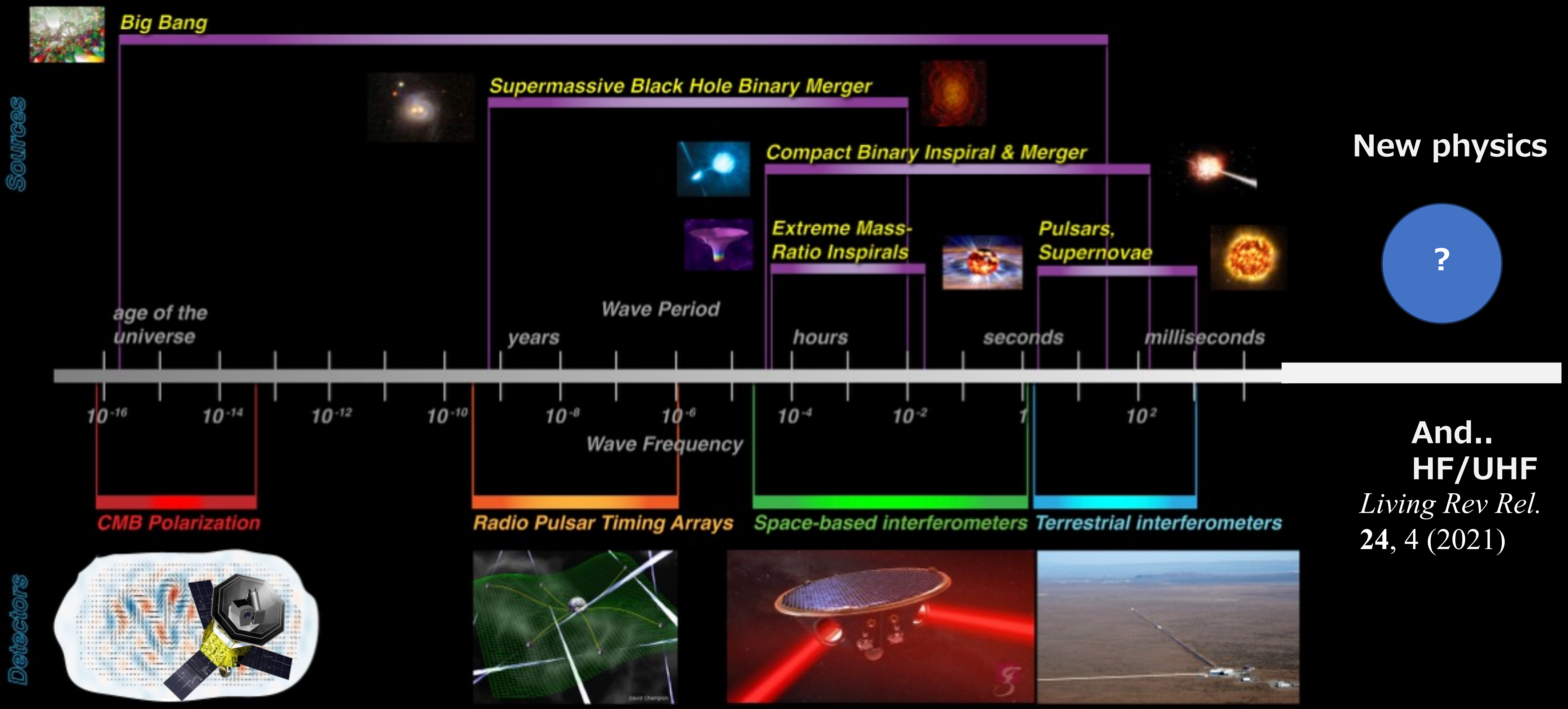
B. P. Abbott *et al* 2021 *ApJ* **909** 218

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

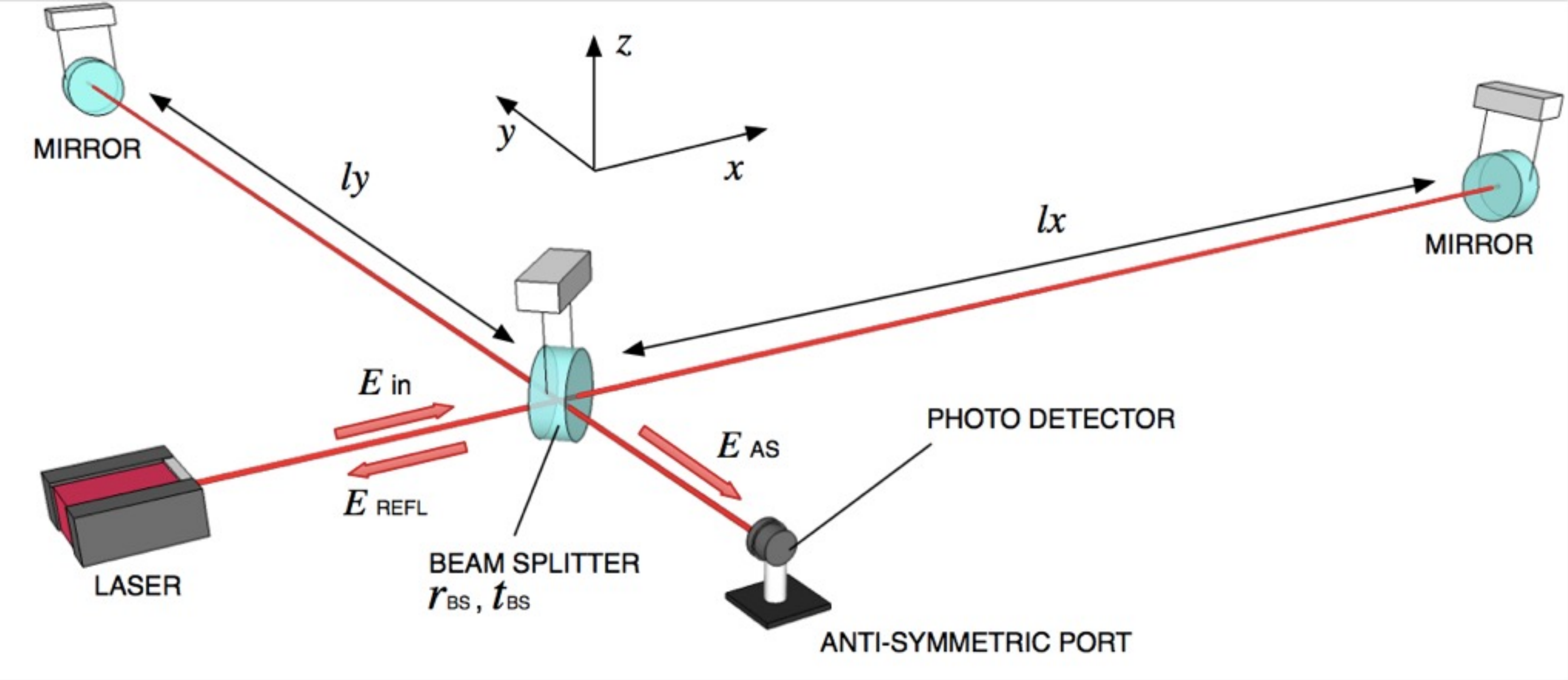


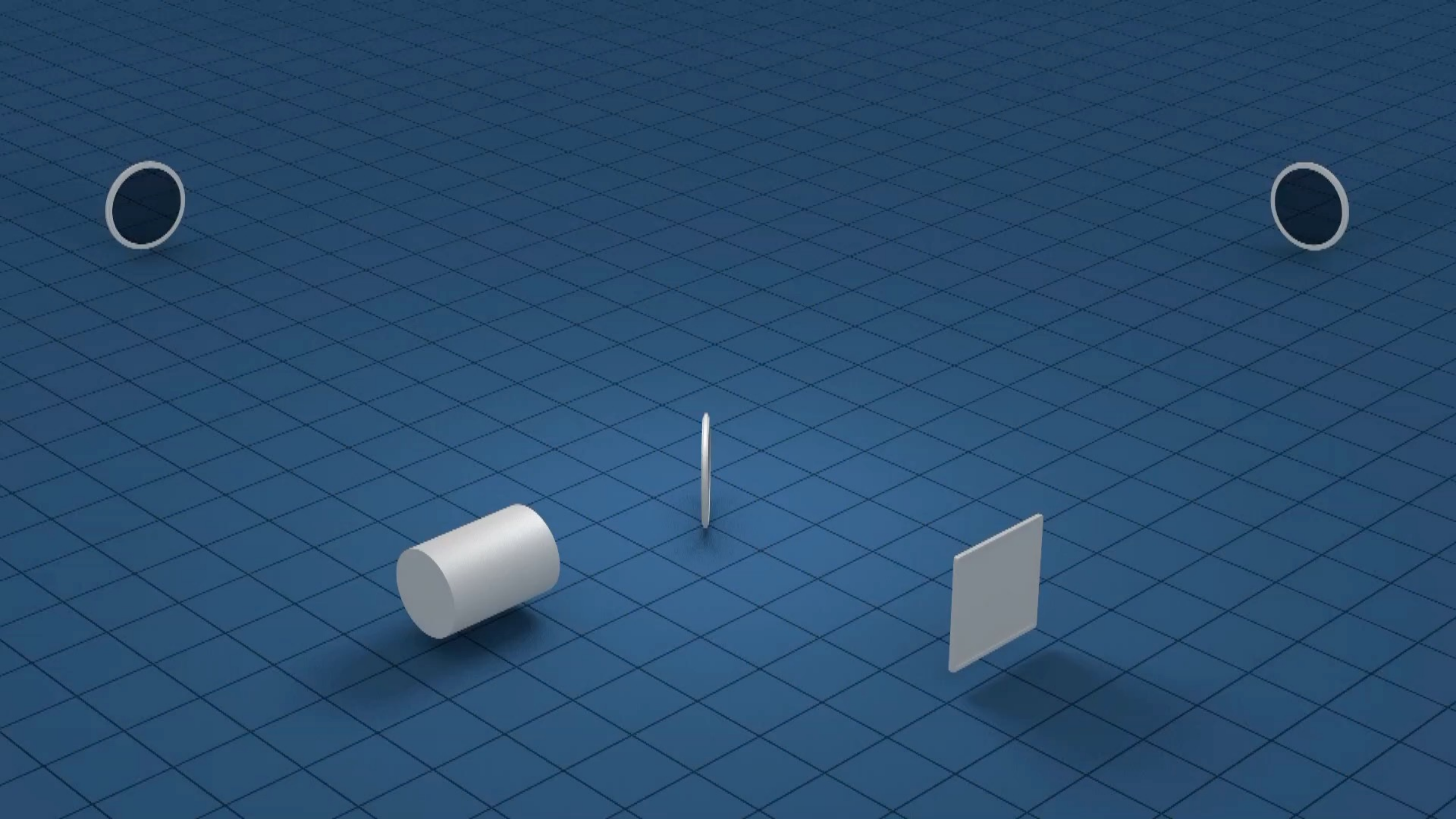

Where are we heading towards?
Multi-wavelength observations!
LIGO lab.

Gravitational wave spectrum

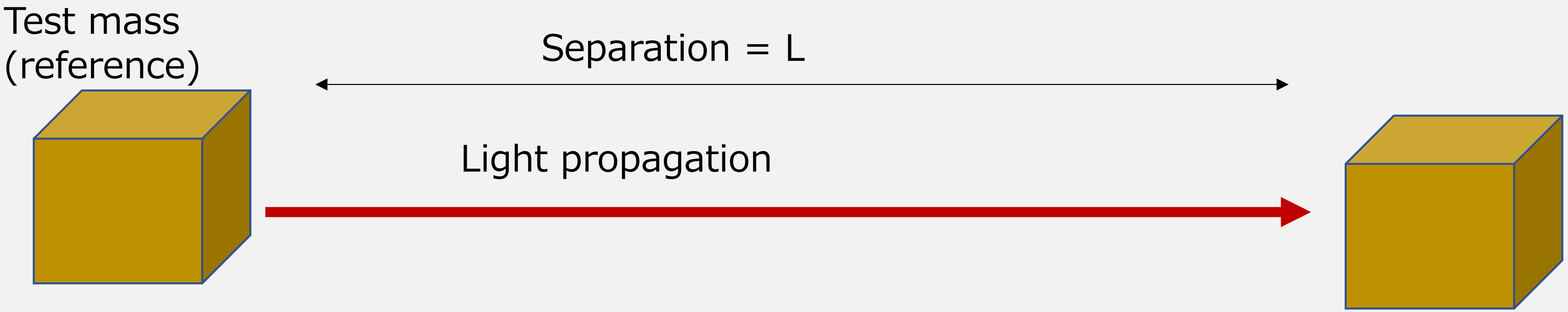


Laser interferometer





Working principle



Optical phase (measurement quantity)

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

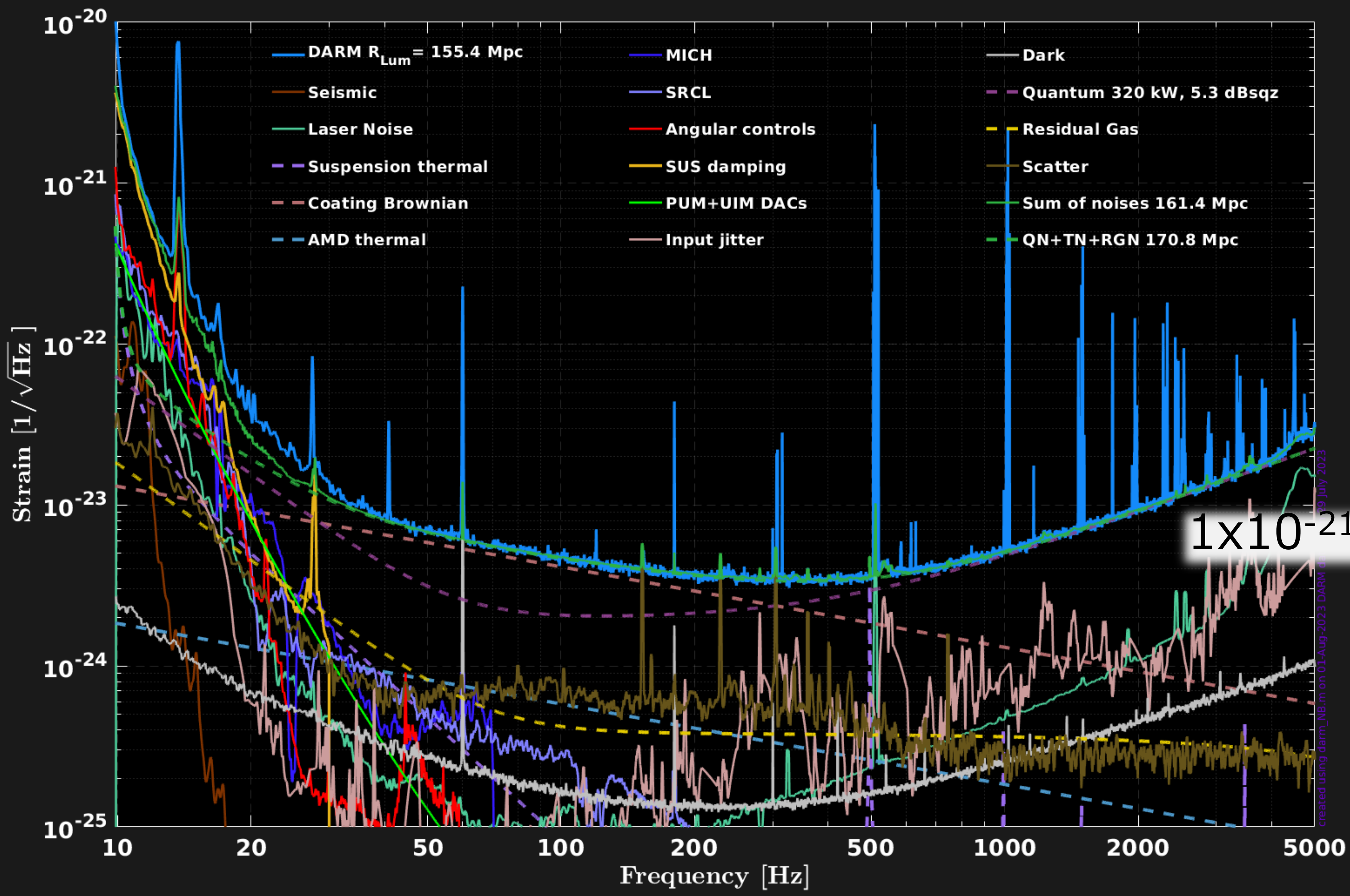
$$\approx k\,L - \boxed{k\,Lh(t)/2}$$

h: GW amplitude
k: wavenumber of light field

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

Sensitivity on ground

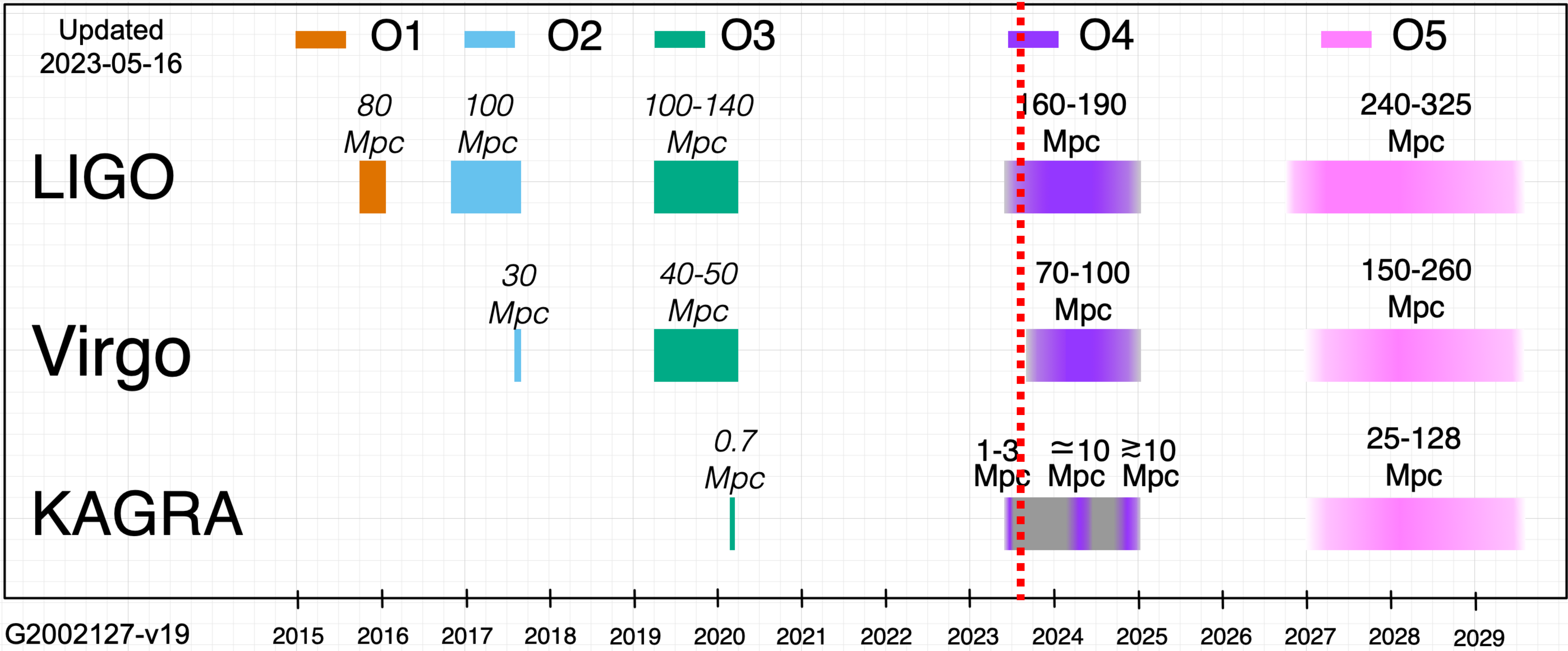
LIGO Livingston alog 66532 (2023/Aug/1)
Credit: A. Effler and V. Frolov



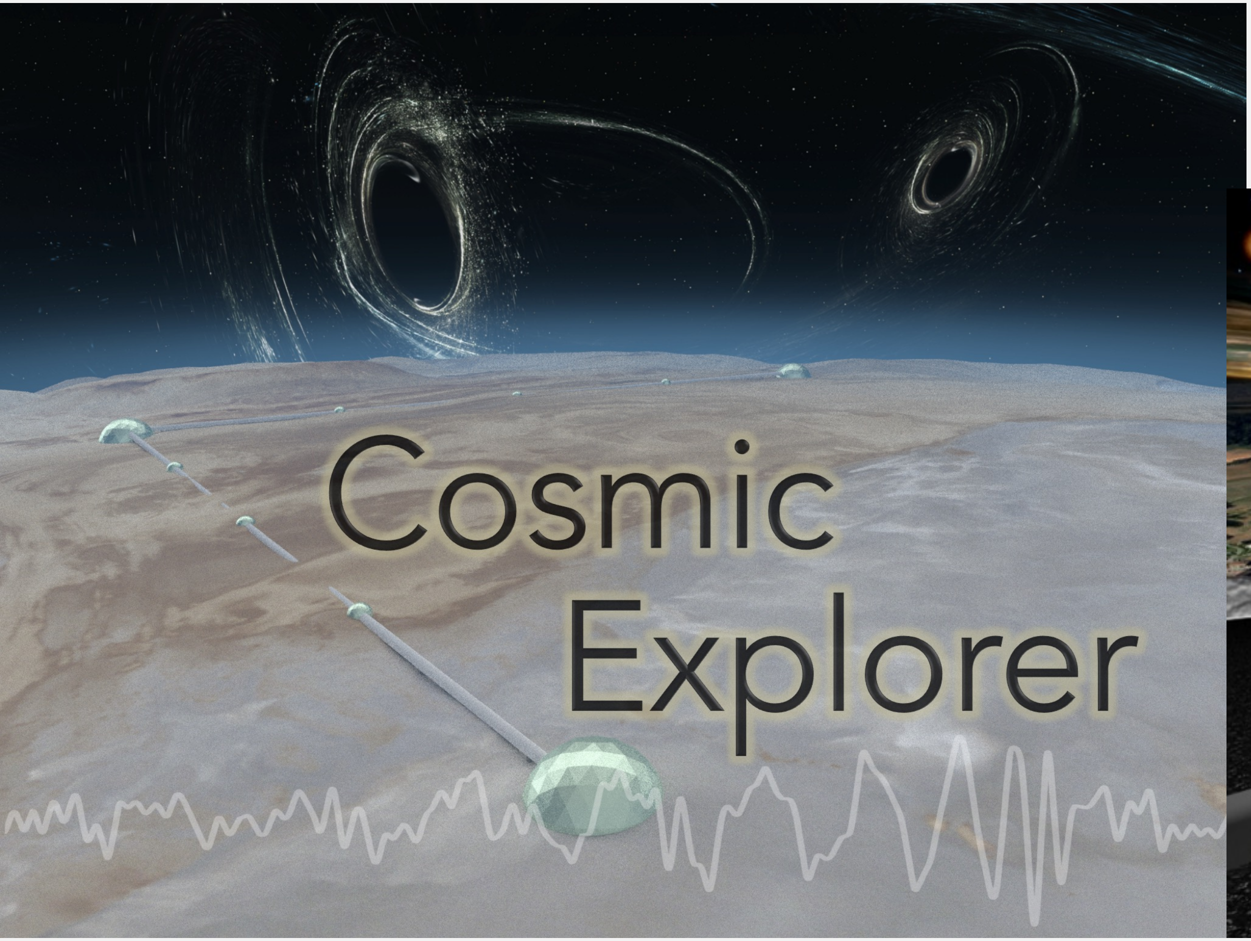
$1x10^{-21}$ m/$Hz^{1/2}$@200Hz

Observing plans

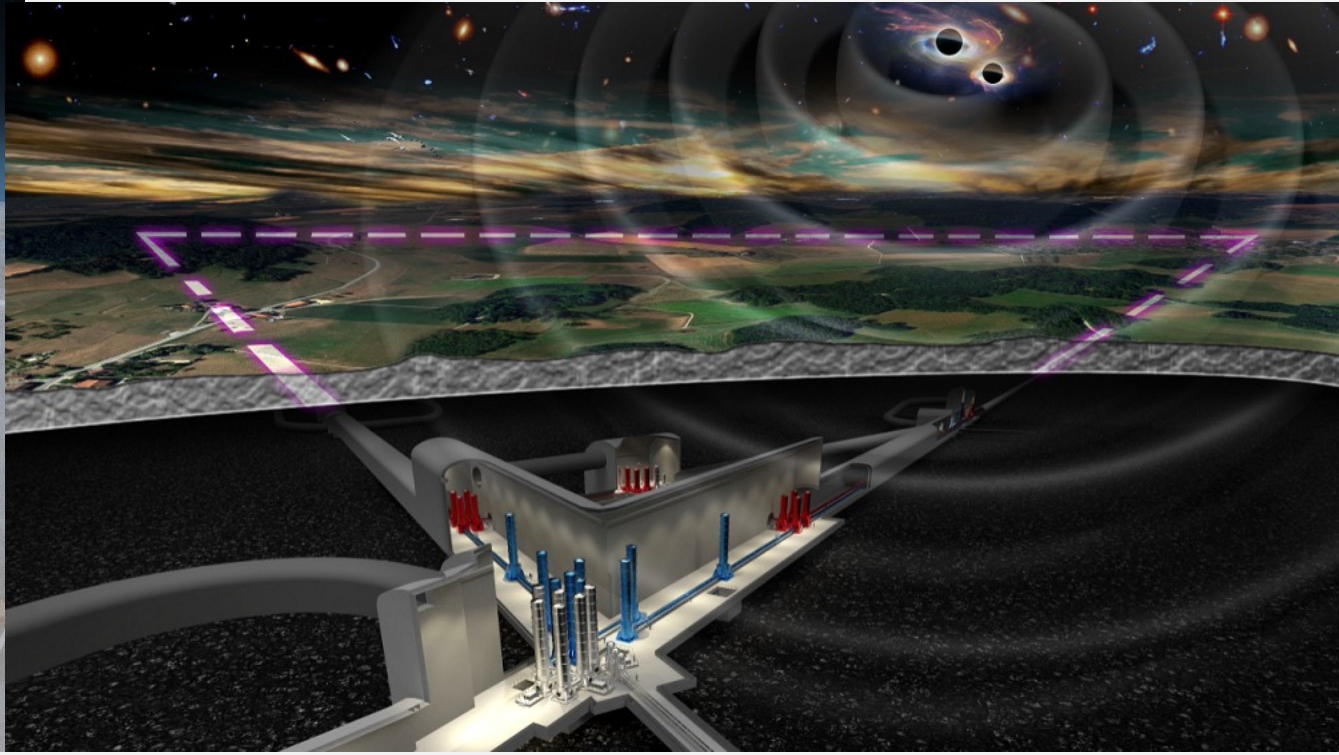
IGWN
https://observing.docs.ligo.org/plan/



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



Einstein Telescope

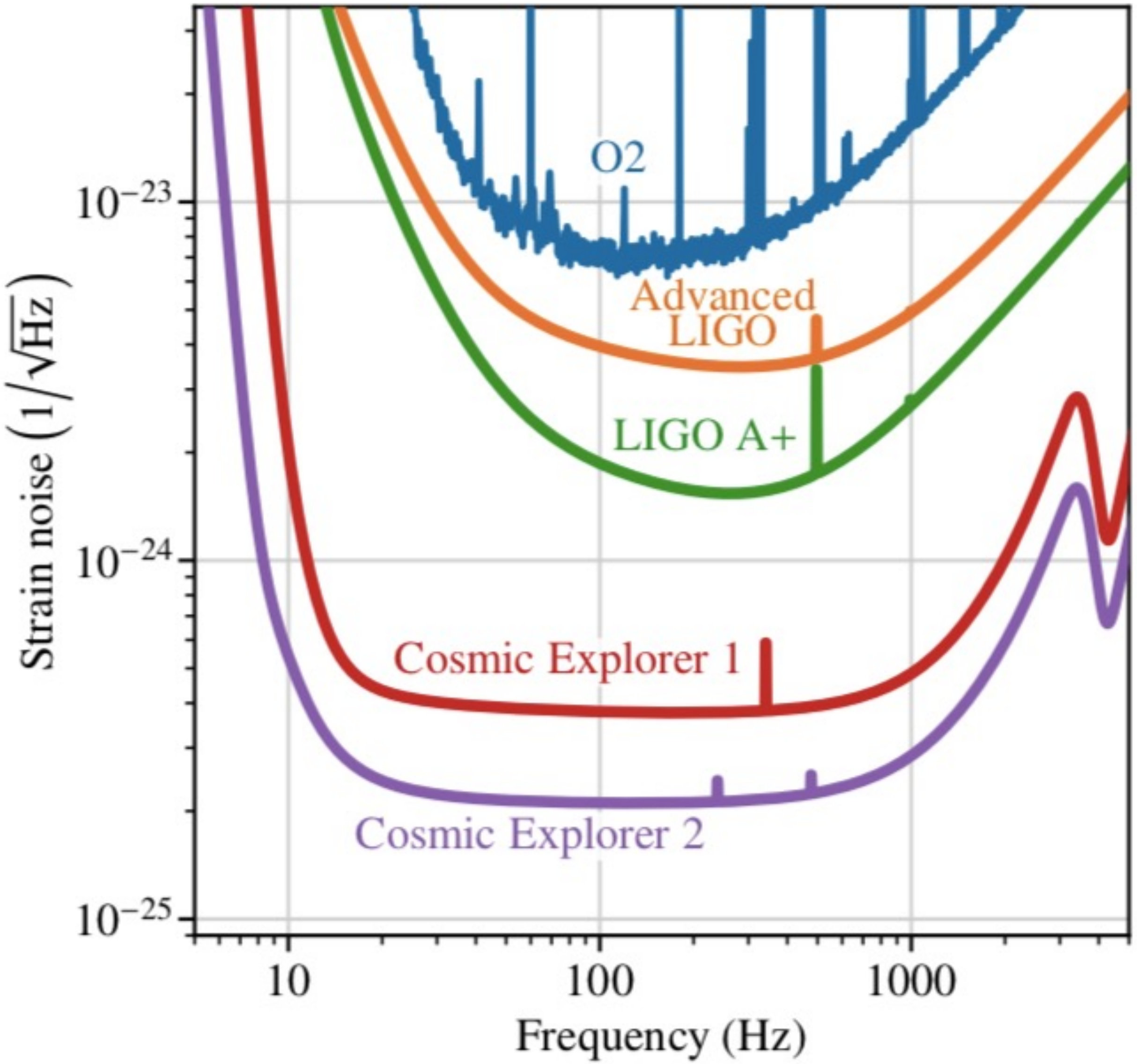


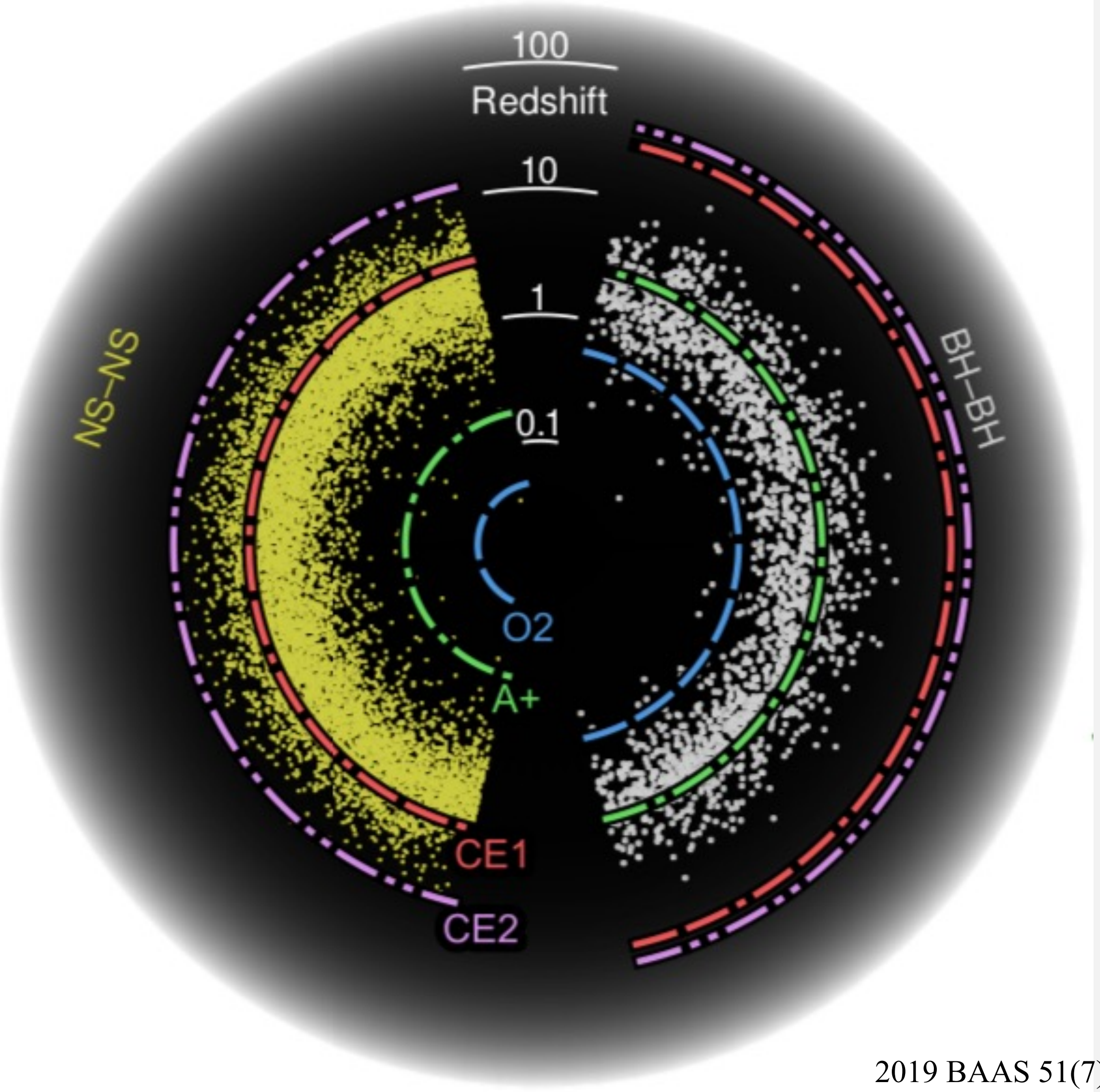
US-lead project, 40 km

Europian project, 10 km, triangular shape, underground

https://cosmicexplorer.org http://www.et-gw.eu

Astrophysical reach of 3G detectors





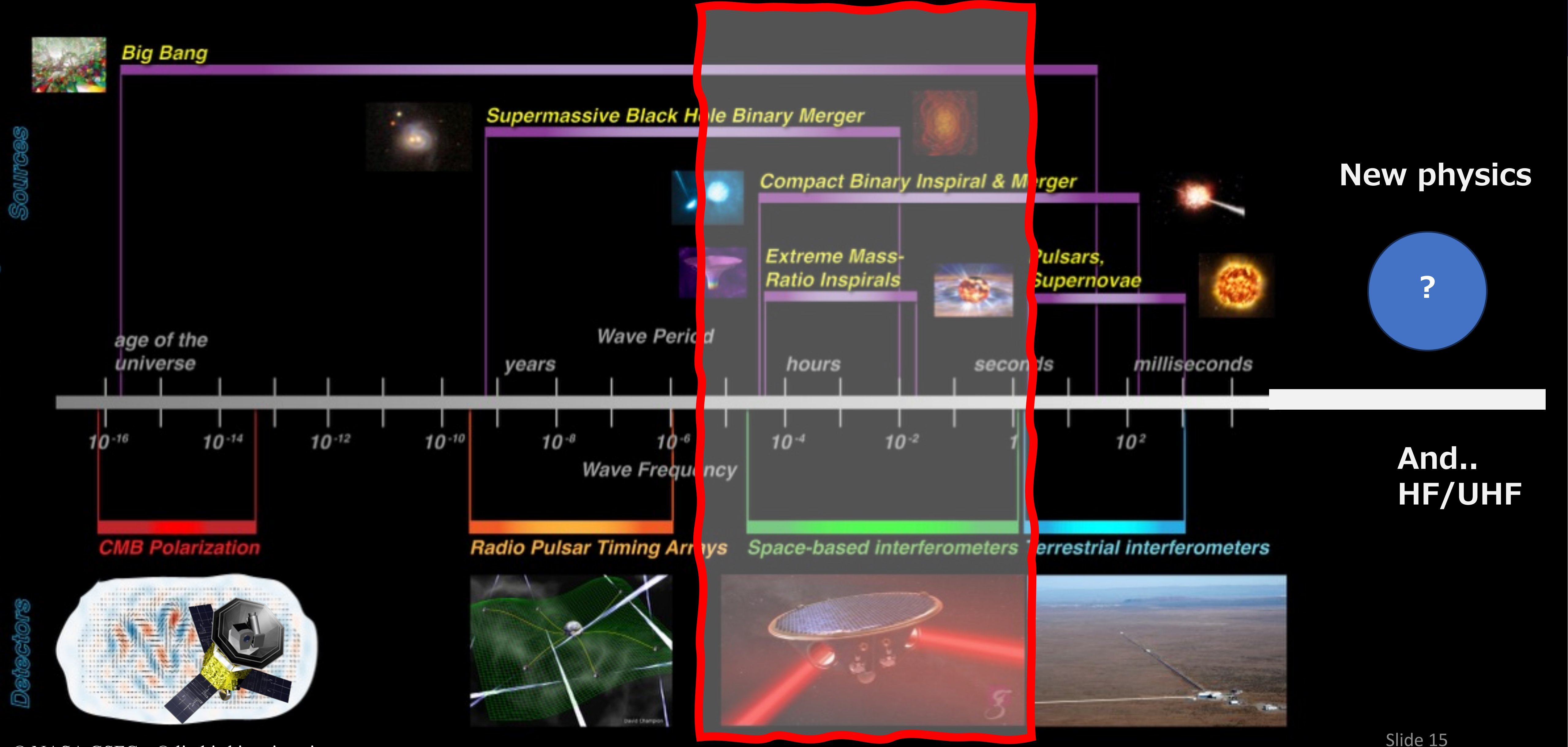
2019 BAAS 51(7) 035

Into space

Advantages

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

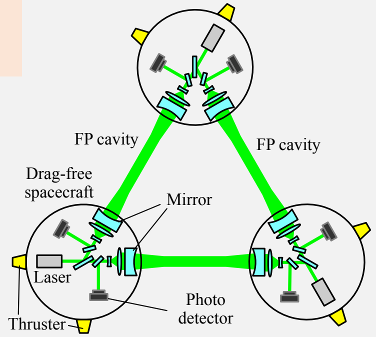
Gravitational wave spectrum



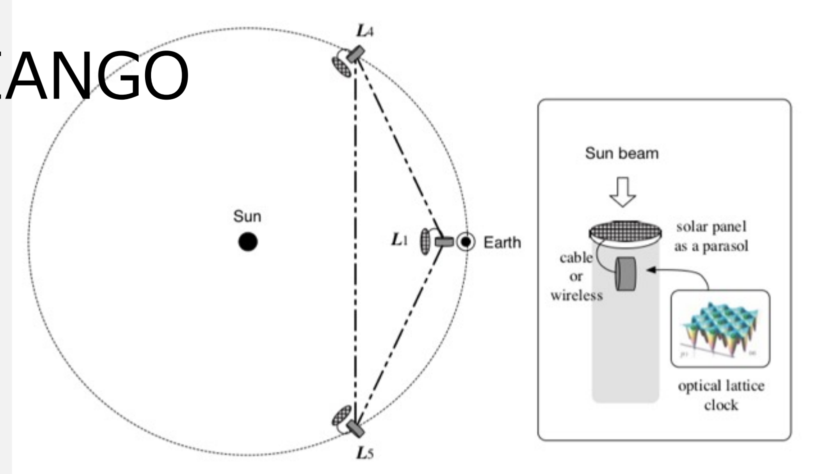
Space-based detectors

A number of concepts exist today

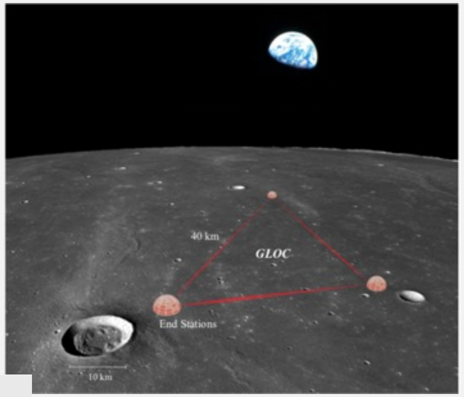
- ► Laser interferometers
  - ► LISA, DECIGO, TianQin, Taiji, TIANGO
- ► Atom interferometers
  - ► AEDGE [1]
- ► Precision clocks
  - ► INO[2] ,DOCS[3]
- ► Lunar-based detectors
  - ► GLOC[4], LGWA[5],LSGA[6], LION [7]



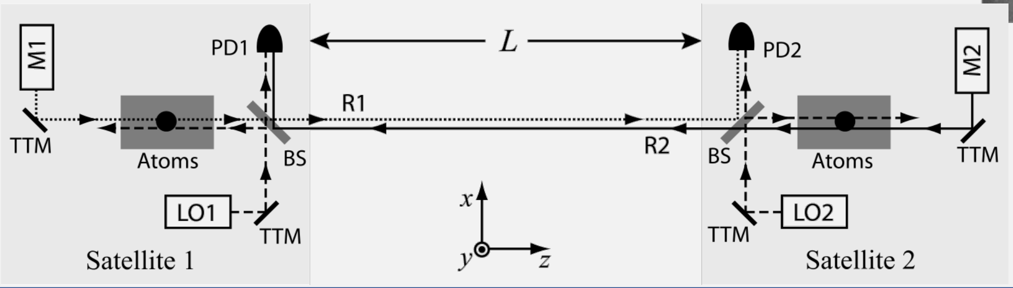
DECIGO



INO



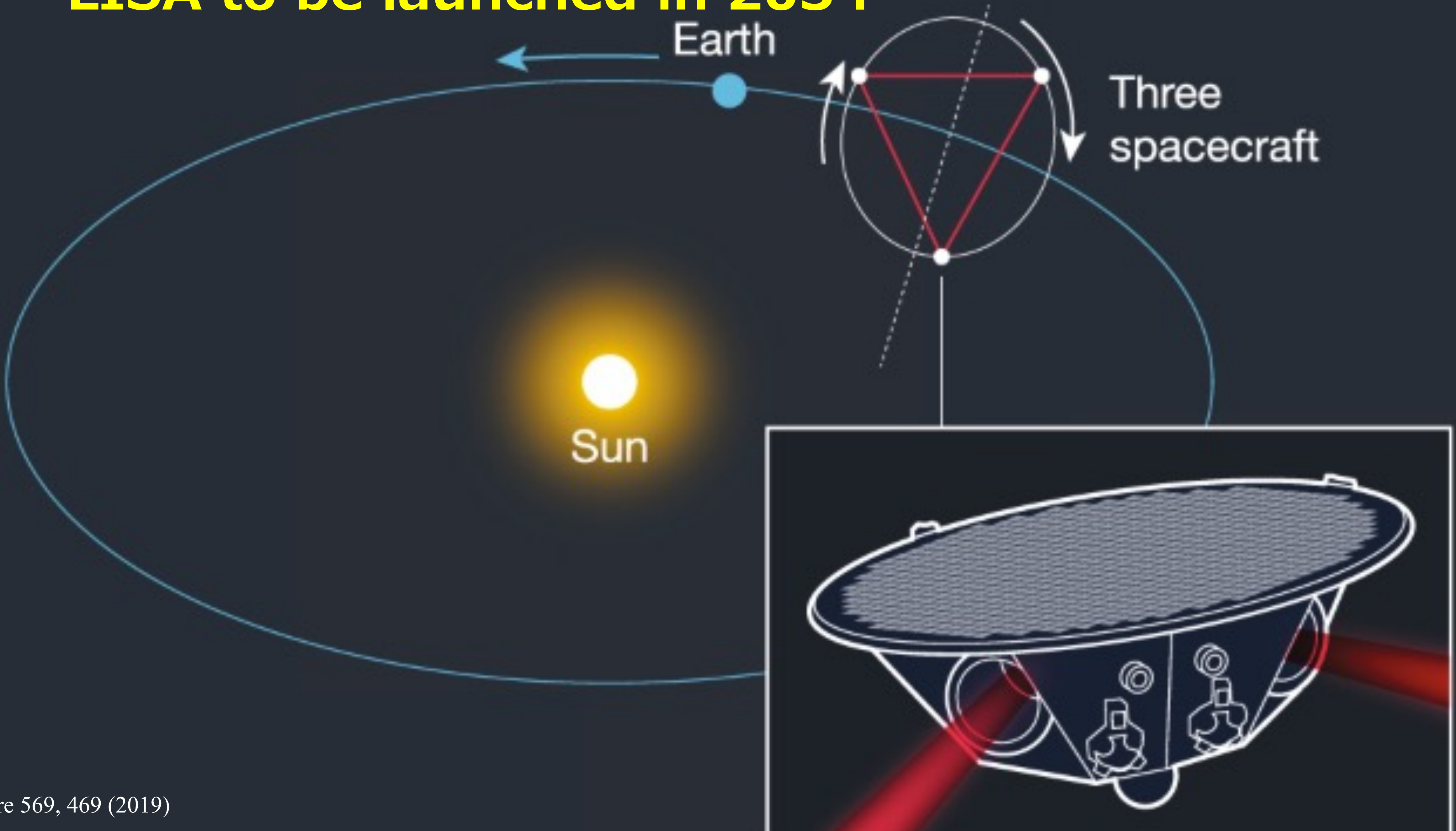
GLOC



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)

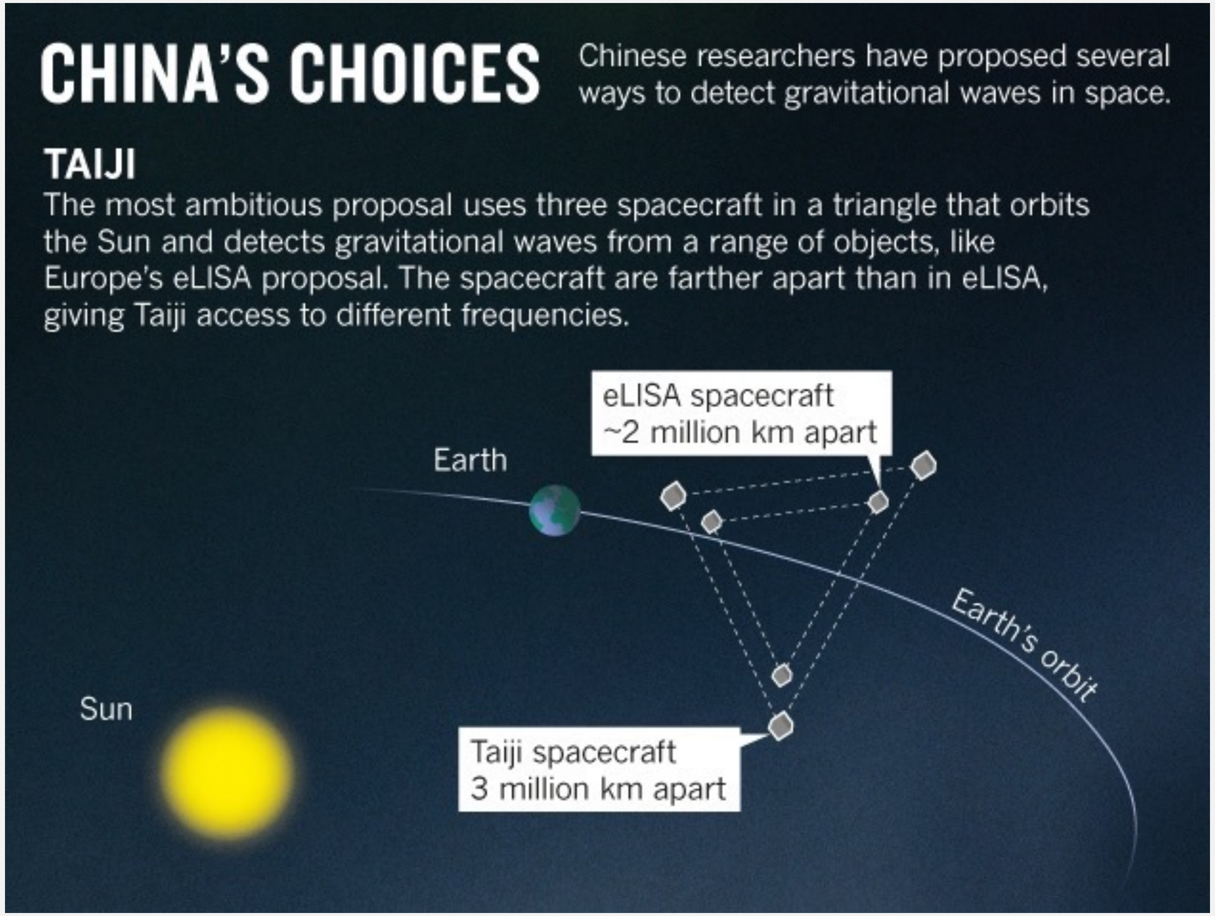
LISA to be launched in 2034

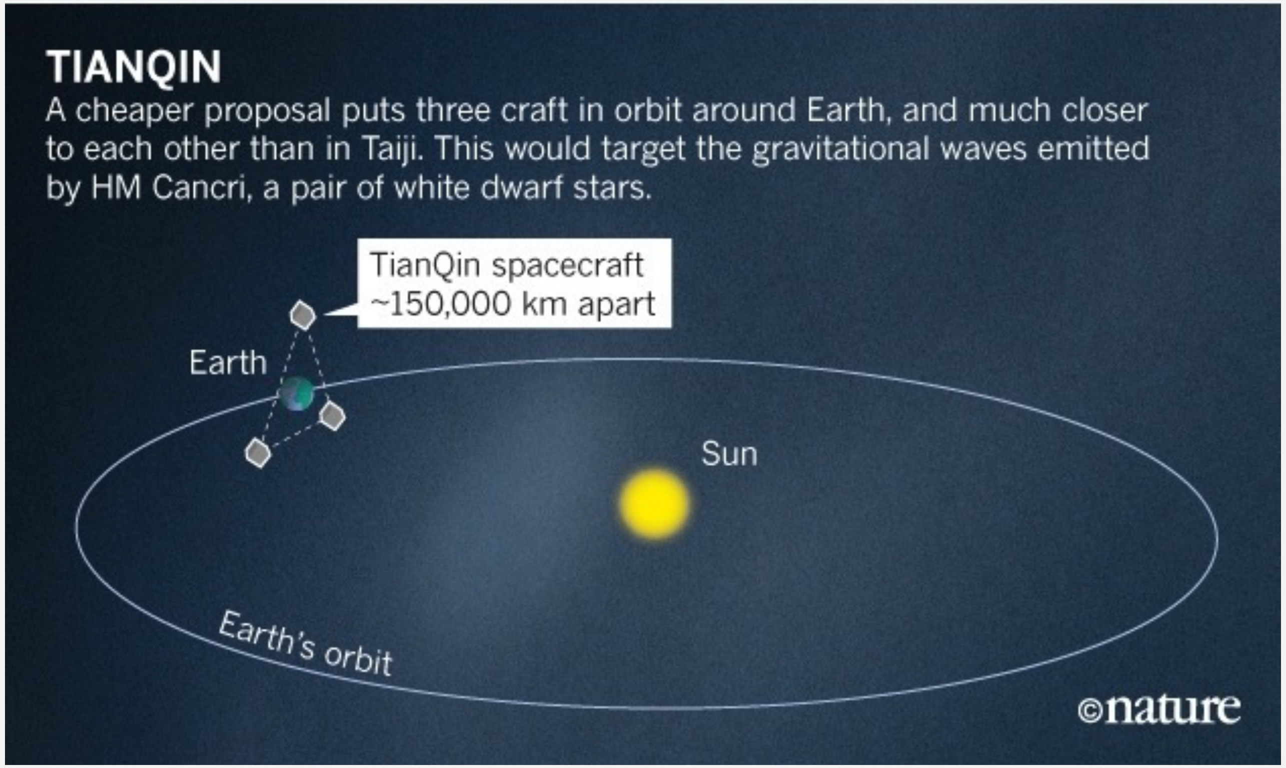


Nature 569, 469 (2019)

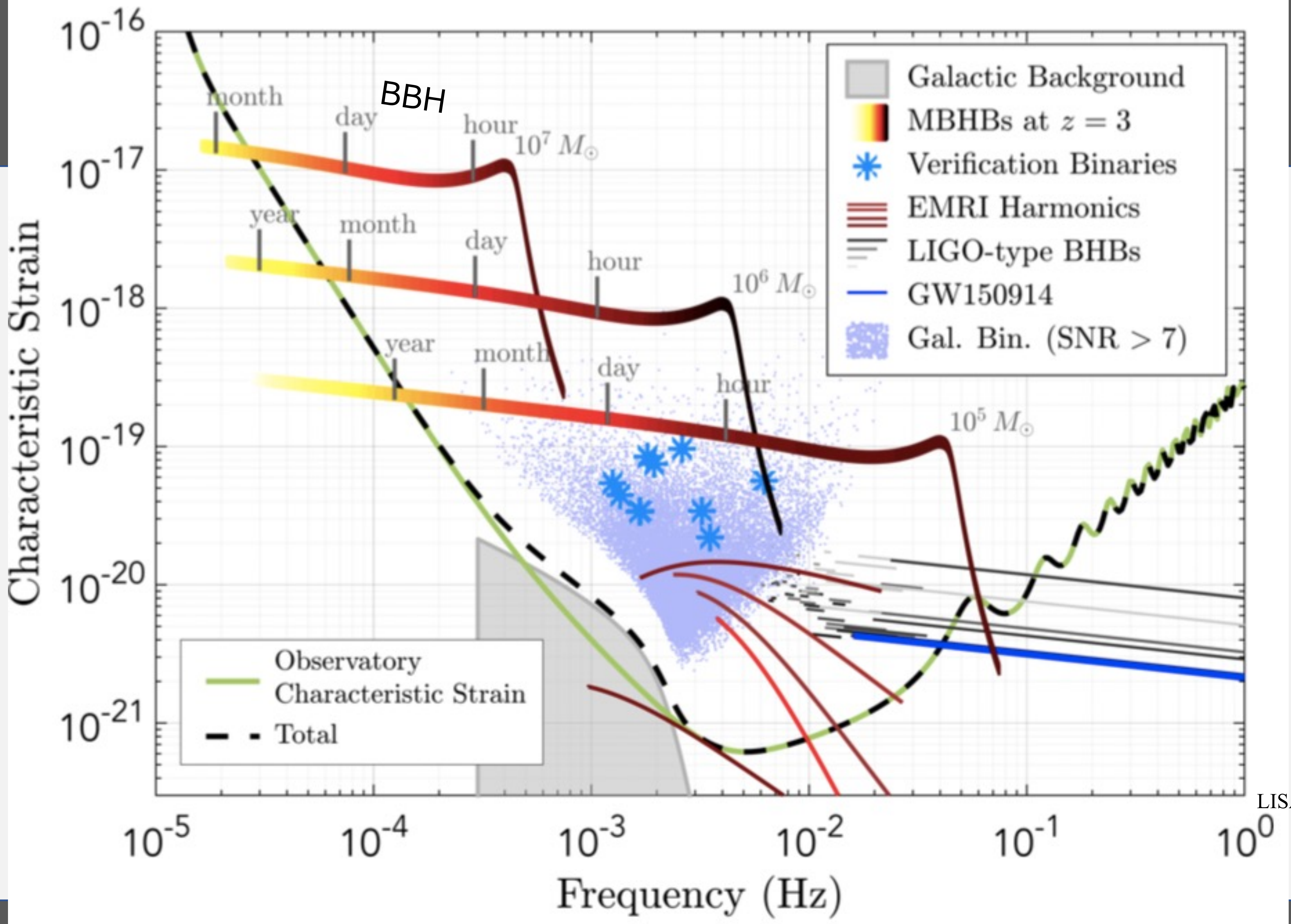
Taiji and TianQin, aiming 2030's launch

- Two Chinese space gw mission concepts are independently being developed



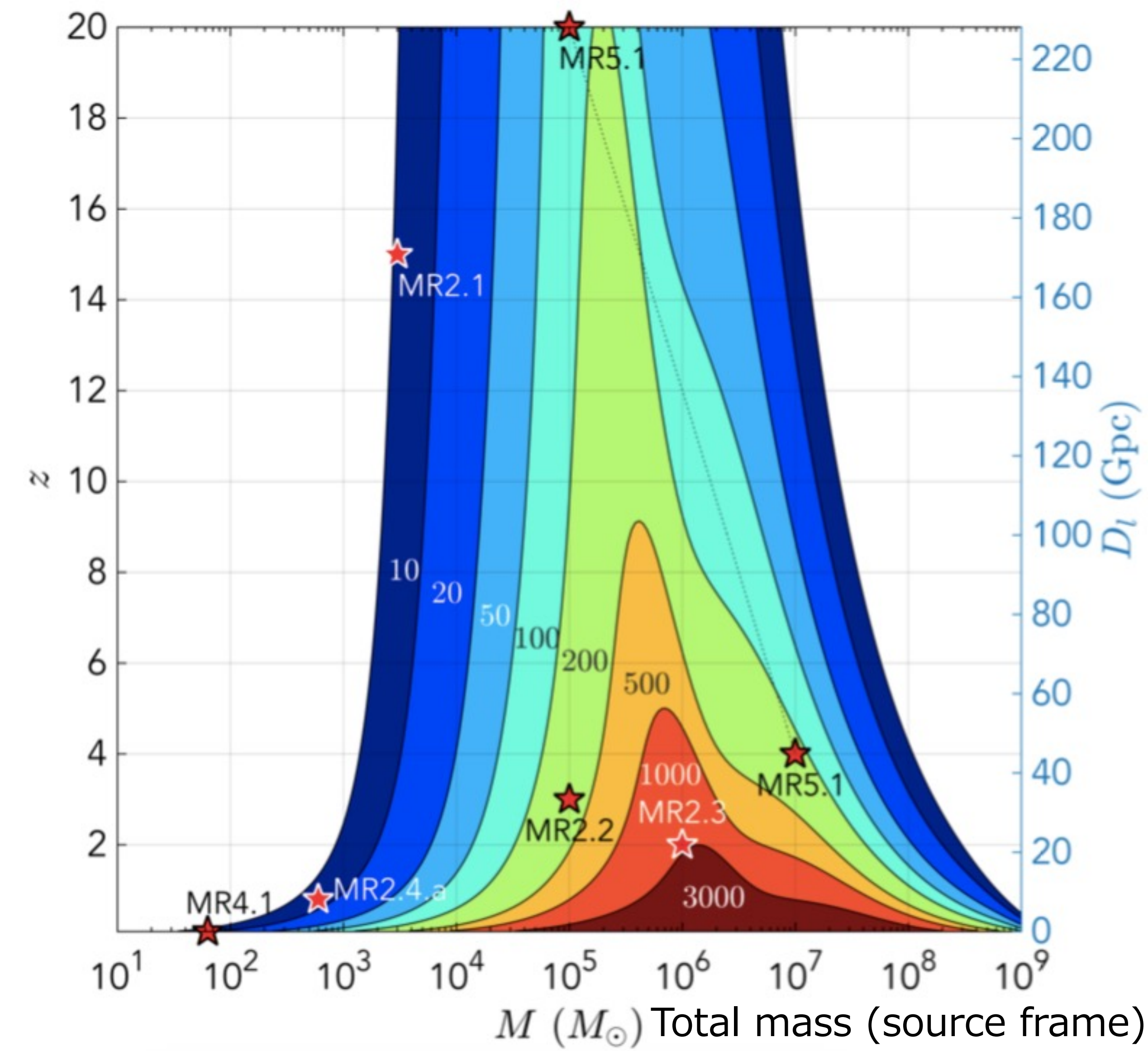


Nature **531**, 150–151 (2016)



LISA L3 proposal document (2017)

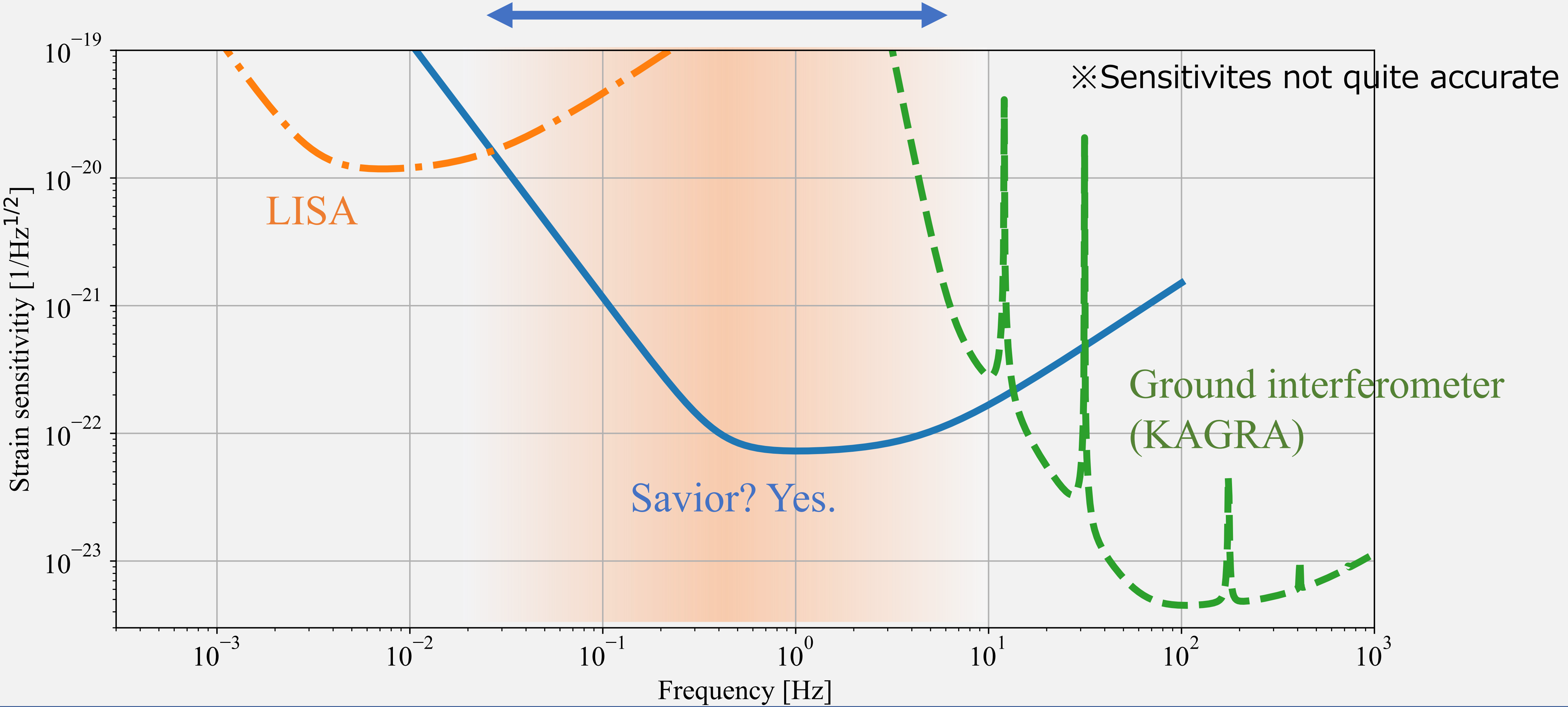
Covering almost all the epoch in merger tree



- ► $10^3\ M_\odot < M < 10^7\ M_\odot$
- ► Beyond z = 10

LISA L3 proposal document (2017)

Deci-Hertz band unexplored

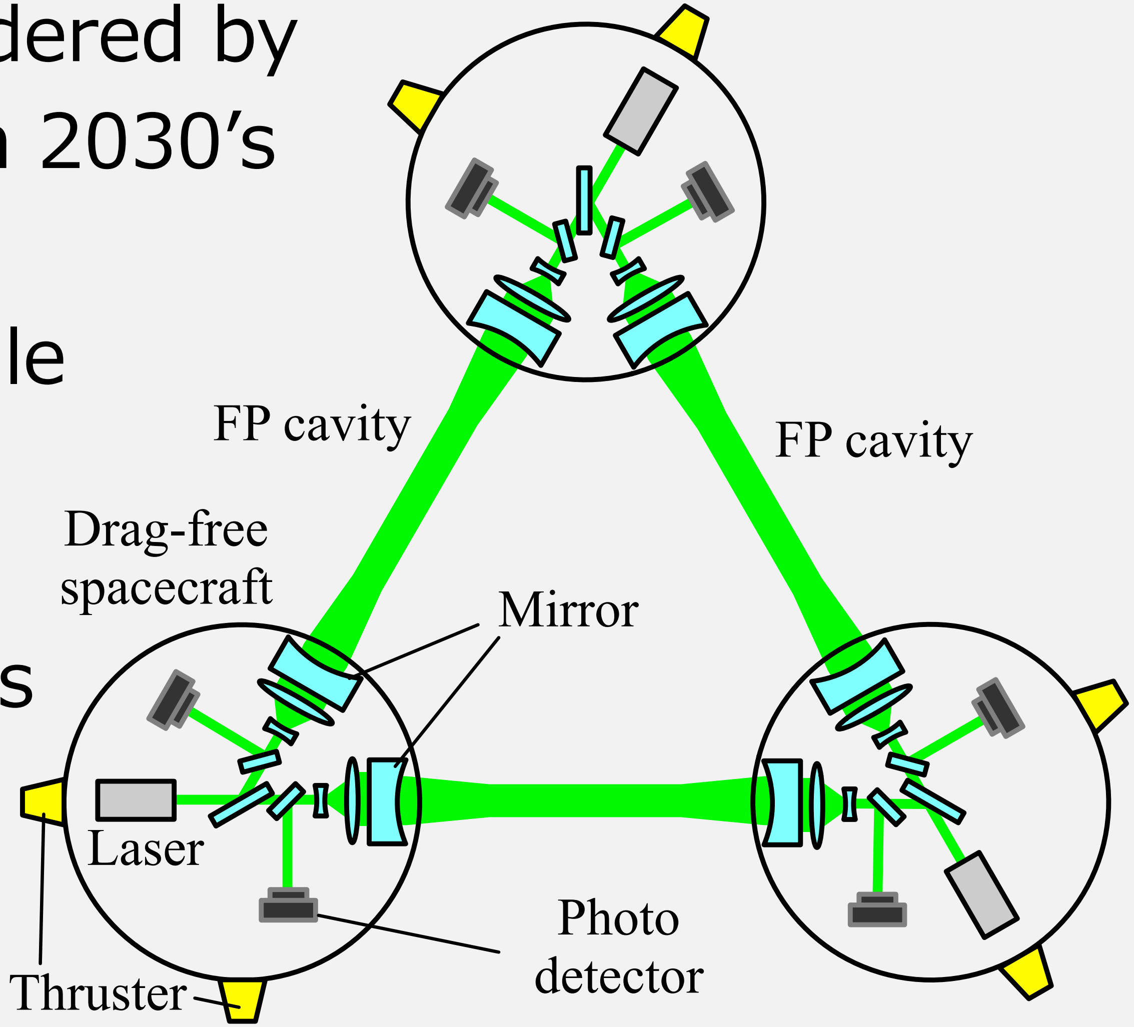


credit: B-DECIGO/S.Sato

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

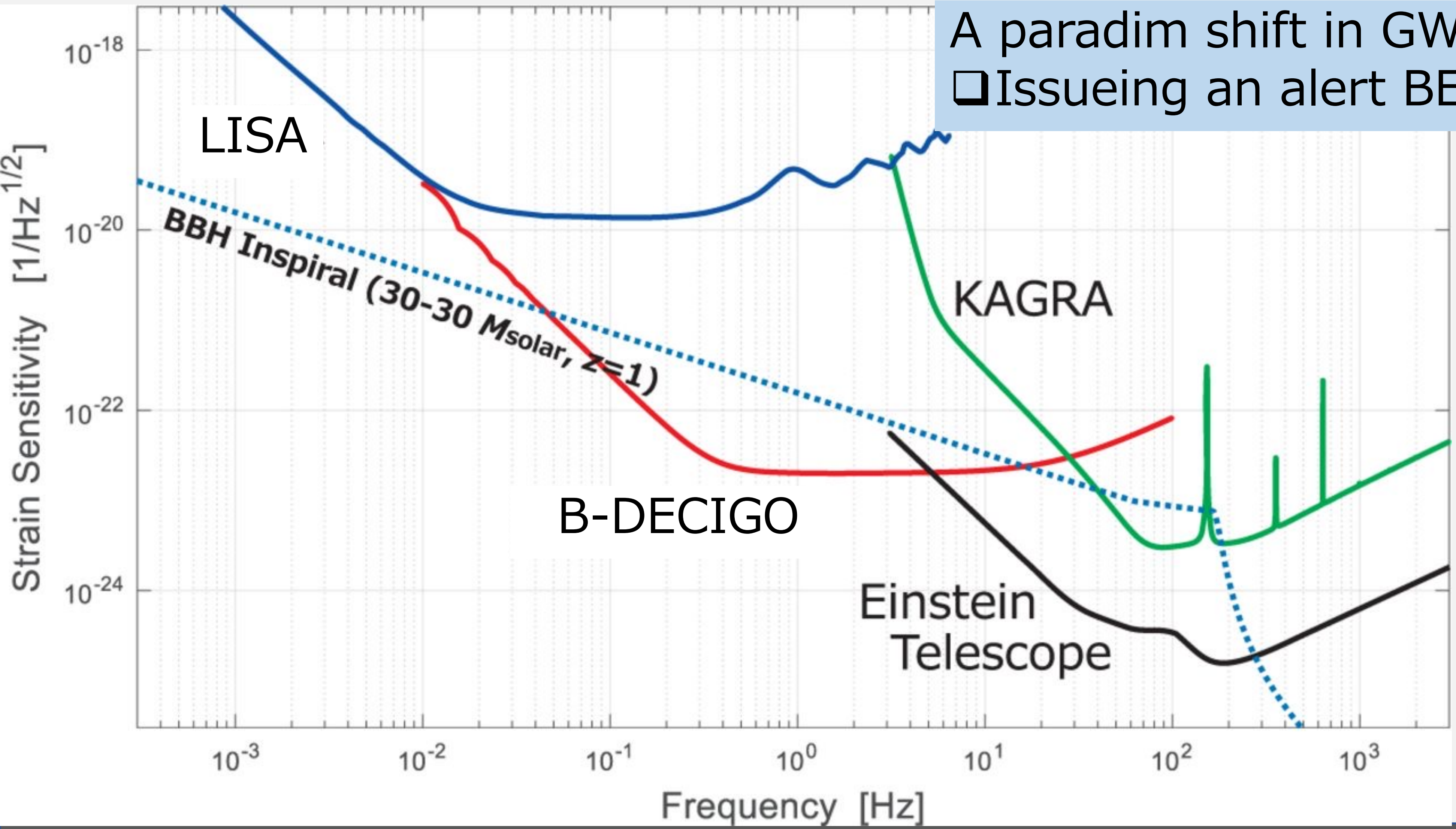


Multi-wavelength observation

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

A paradim shift in GW astronomy

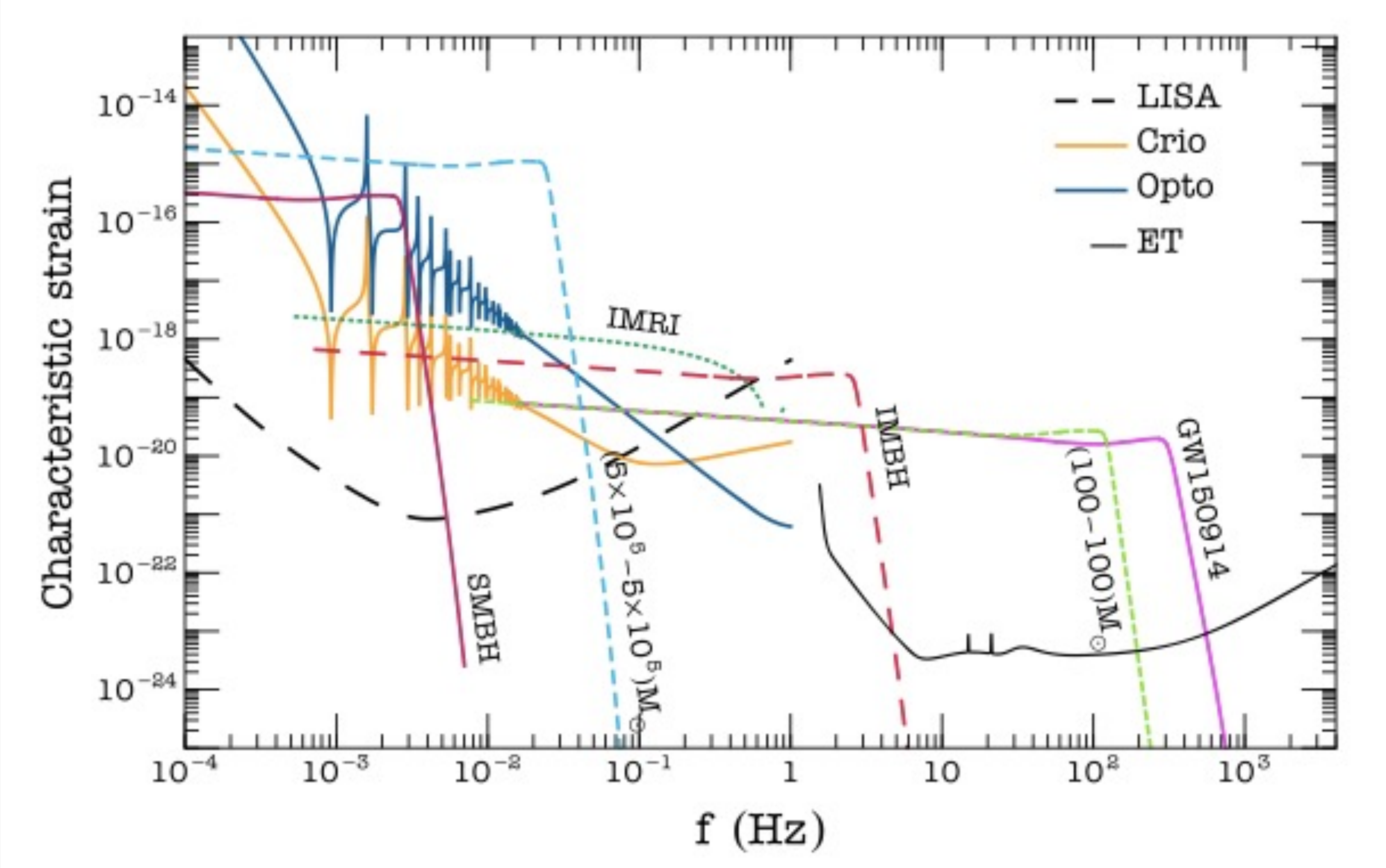
- Issueing an alert BEFORE they merge!



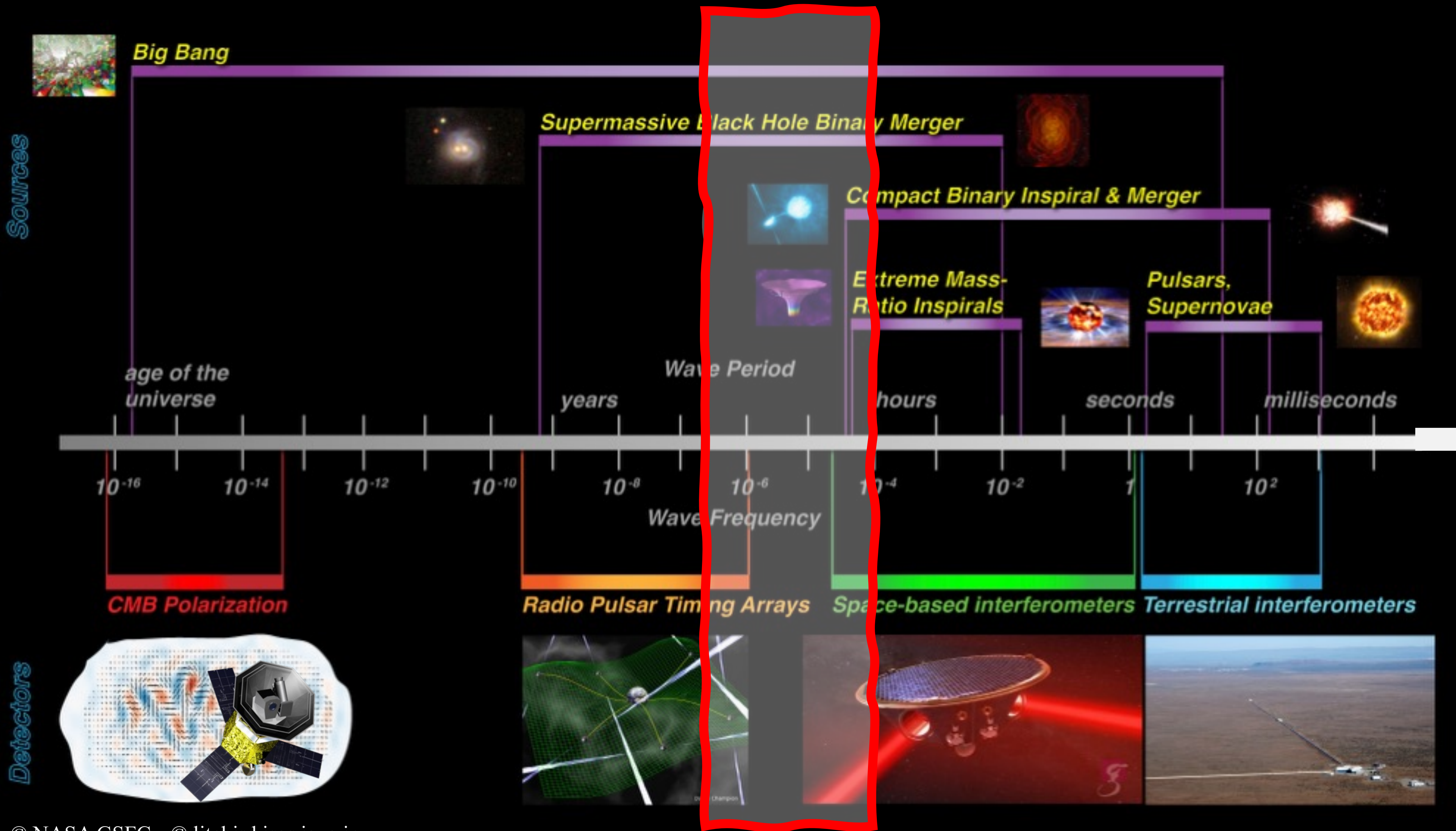
Other detectors at 0.1 Hz? Yes.

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

For example…



Gravitational wave spectrum



New physics

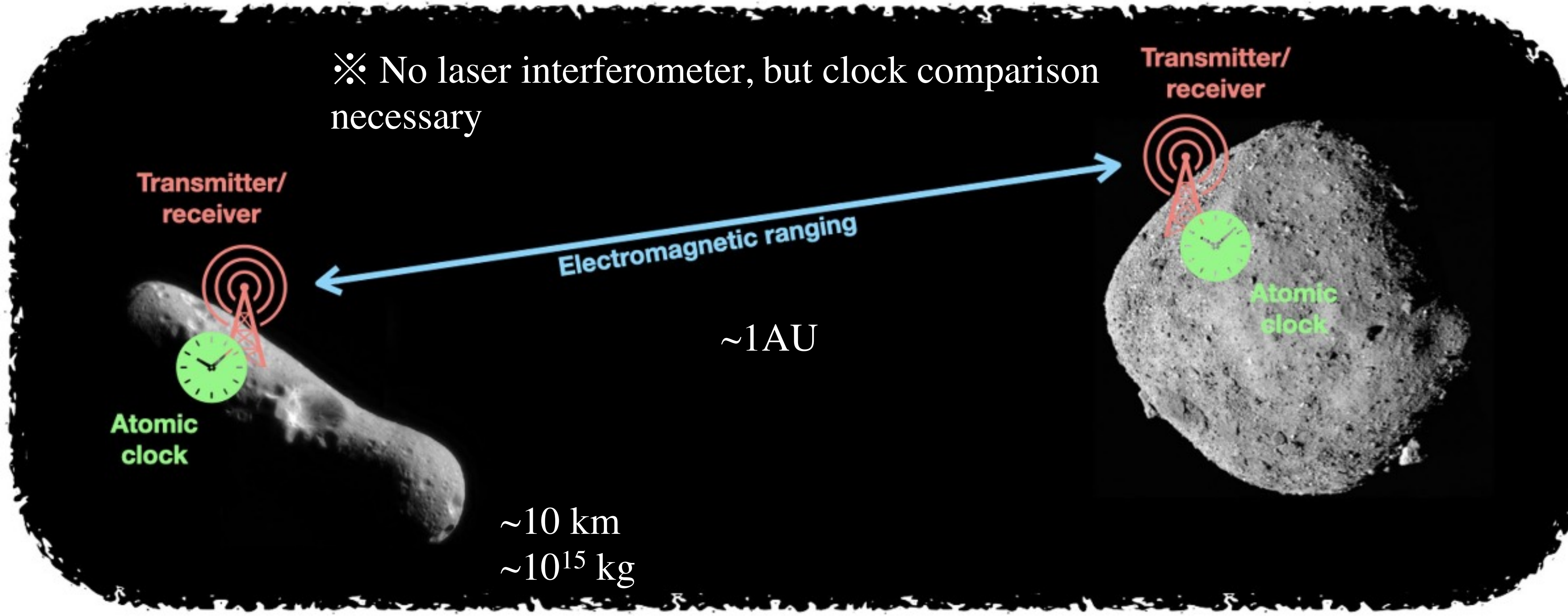
?

And..
HF/UHF

An example:
Asteroids as test masses

Fedderke+ PRD (2022)

※ No laser interferometer, but clock comparison necessary

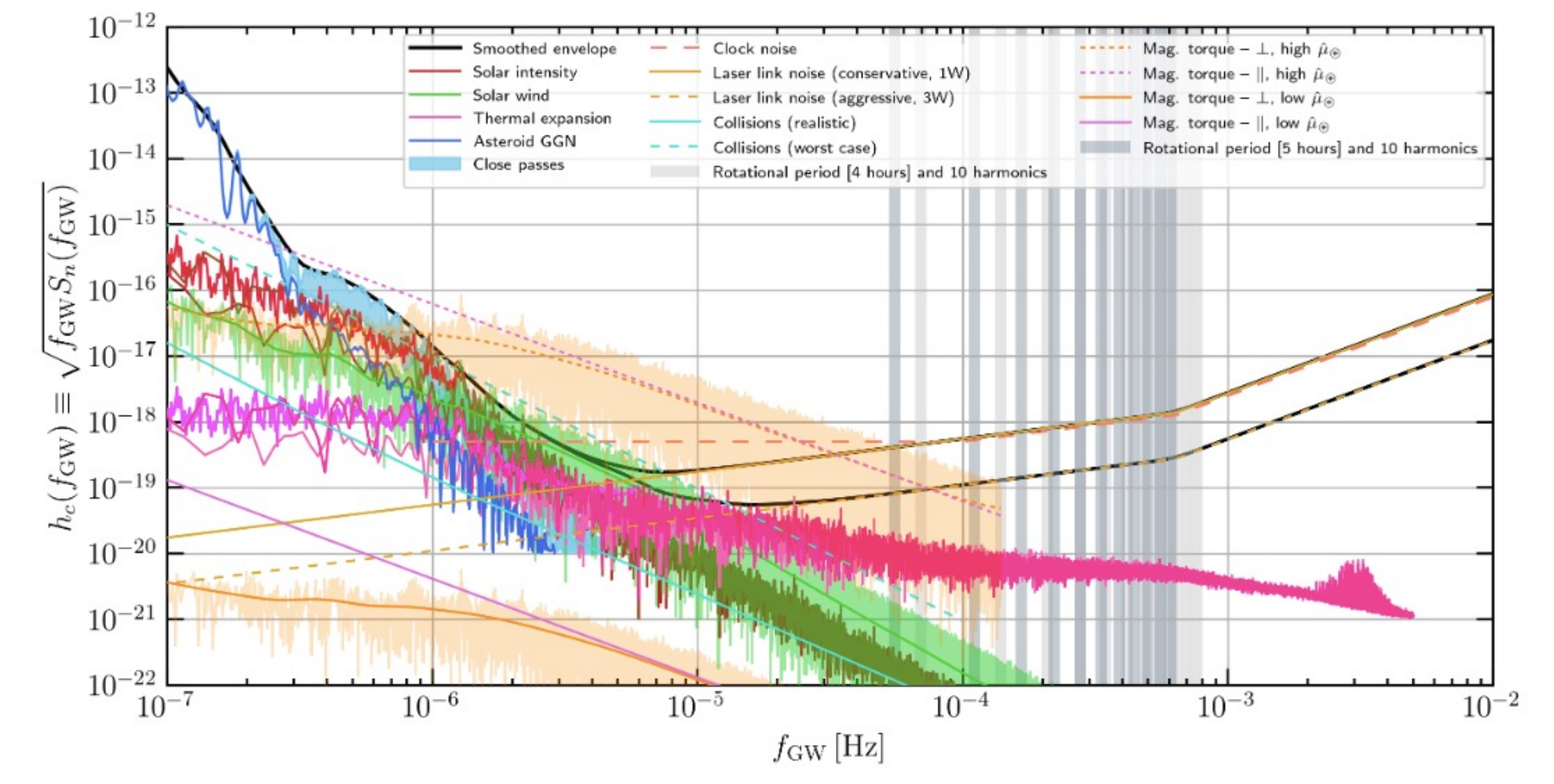


~1AU

~10 km
$\sim 10^{15}$ kg

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