An Overview of

Space Gravitational wave Observations

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Who is this?

An experimental astrophysicist

- 2017-present: JAXA
- 2012-2017: Postdoc at LIGO Hanford
- Scientific interests
  - Laser interferometry
  - Gravitational waves
  - Early Universe

What are gravitational waves?

Ripples of space-time, radiated from accelerated masses

General relativity

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

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

$$\left(-\frac{1}{c^2} \frac{\partial^2}{\partial t^2} + \frac{\partial^2}{\partial x_i^2} \right) h_{\mu\nu} = 0$$

Gravitational waves

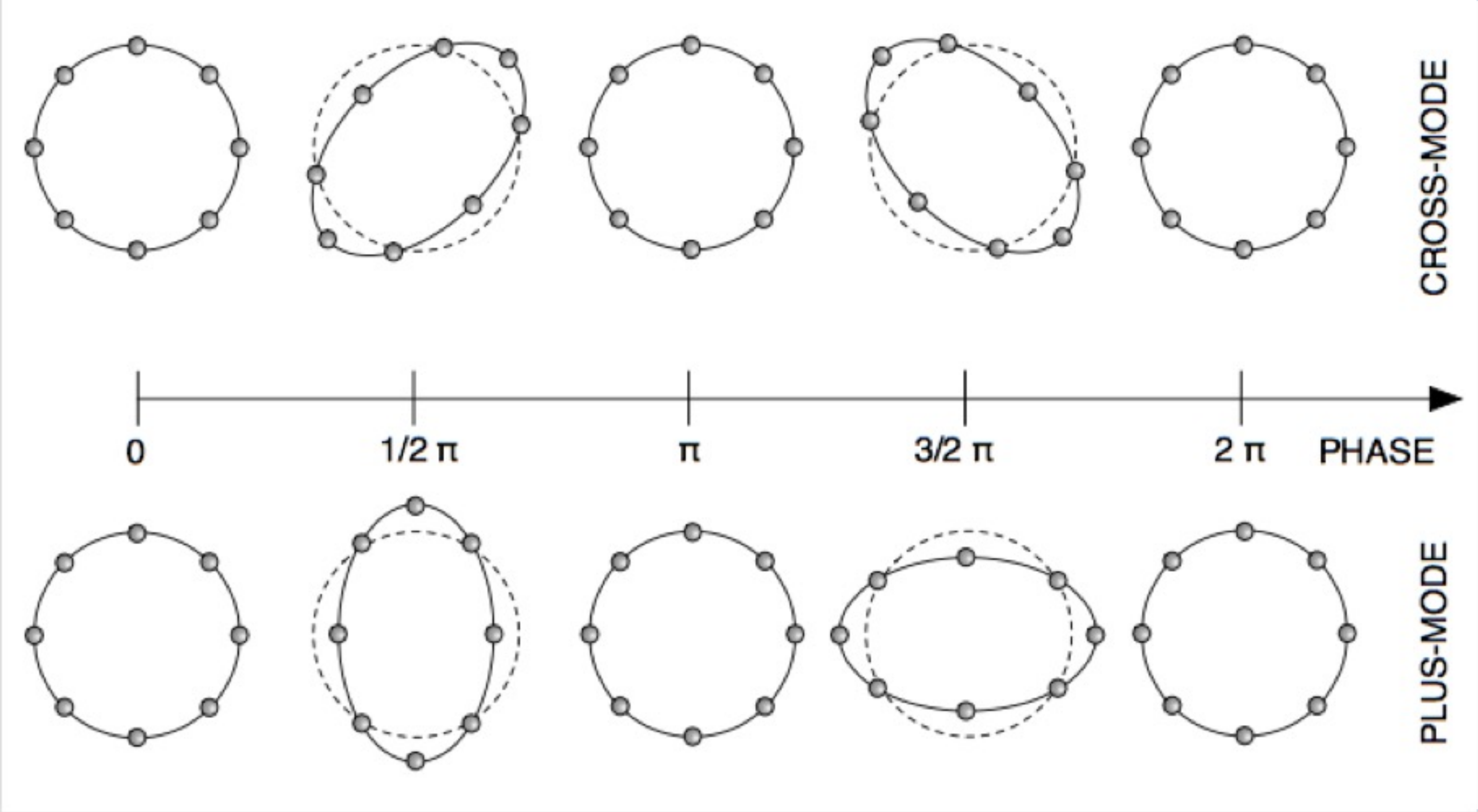
Newtonian Gravity

$$\Delta \phi = 4 \pi G \rho$$

Give some perturbation

Information propagates immediately

Two polarization states



Astrophysical sources

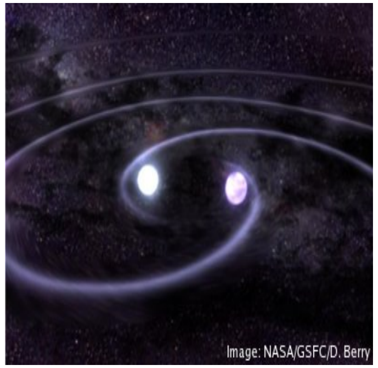
	Short Duration	*Long Duration*
Modeled	Compact Binary Coalescences	Non-Spherical, Rotating Compact Objects
Unmodeled	Bursts from Supernova and other Unmodeled Sources	Stochastic Background

Compact Binary Coalescences

$$h_{CBC} \approx 10^{-21}$$

$$f_{CBC} \approx 100 \text{ Hz}$$

$$R_{CBC} \approx 100 \text{ Mpc}^{-3}\text{Myr}^{-1}$$



J Abadie *et al* 2010 *Class. Quantum Grav.* **27** 173001

Non-Spherical, Rotating Compact Objects

$$h_{Pulsar} \approx 10^{-27} - 10^{-24}$$

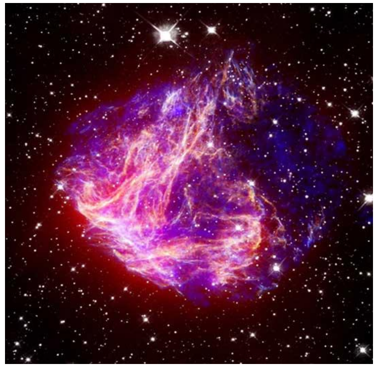
$$f_{Pulsar} \approx 2 f_{rotation}$$

L. Bildsten 1998 *ApJ* **501** L89

Bursts from Supernova and other Unmodeled Sources

$$h_{CC\ SNe} \approx 10^{-23} - 10^{-20}$$

$$f_{CC\ SNe} \approx 1000 \text{ Hz}$$

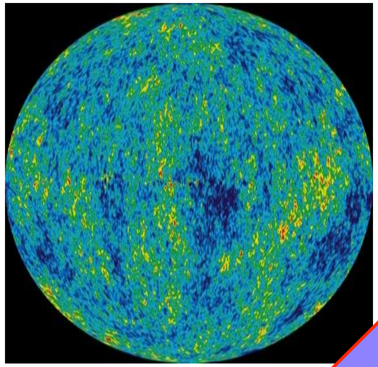


C. D. Ott *et al* 2004 *ApJ* **600** 834

Stochastic Background

$$h \approx 10^{-24}$$

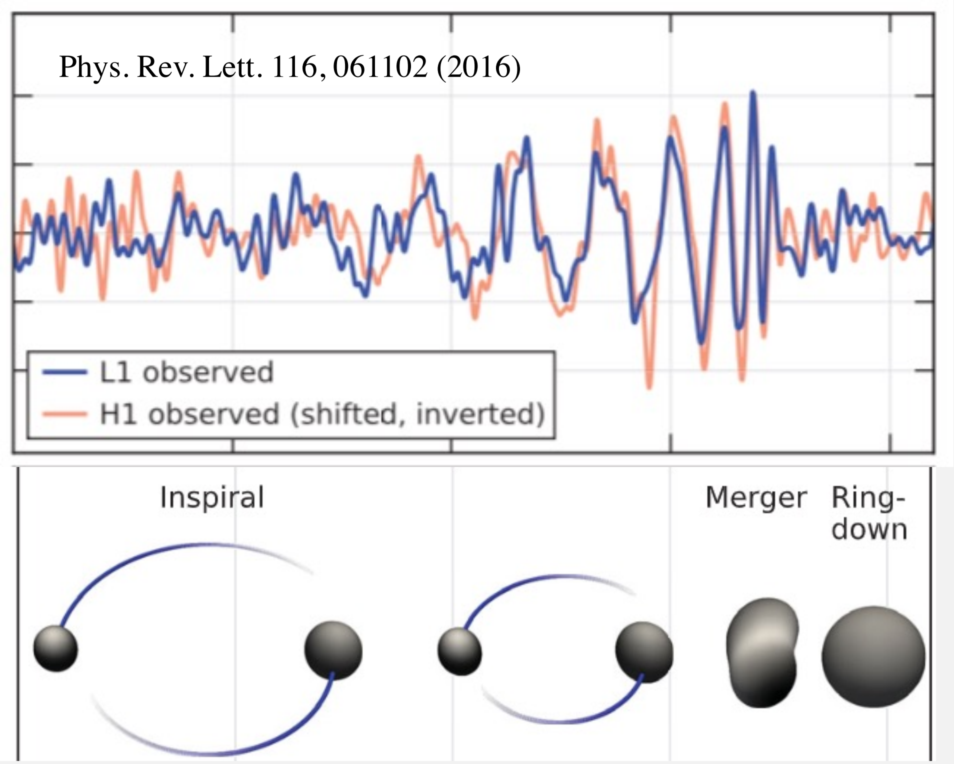
$$\text{for } f_{Stoch} \approx 50 - 150 \text{ Hz}$$



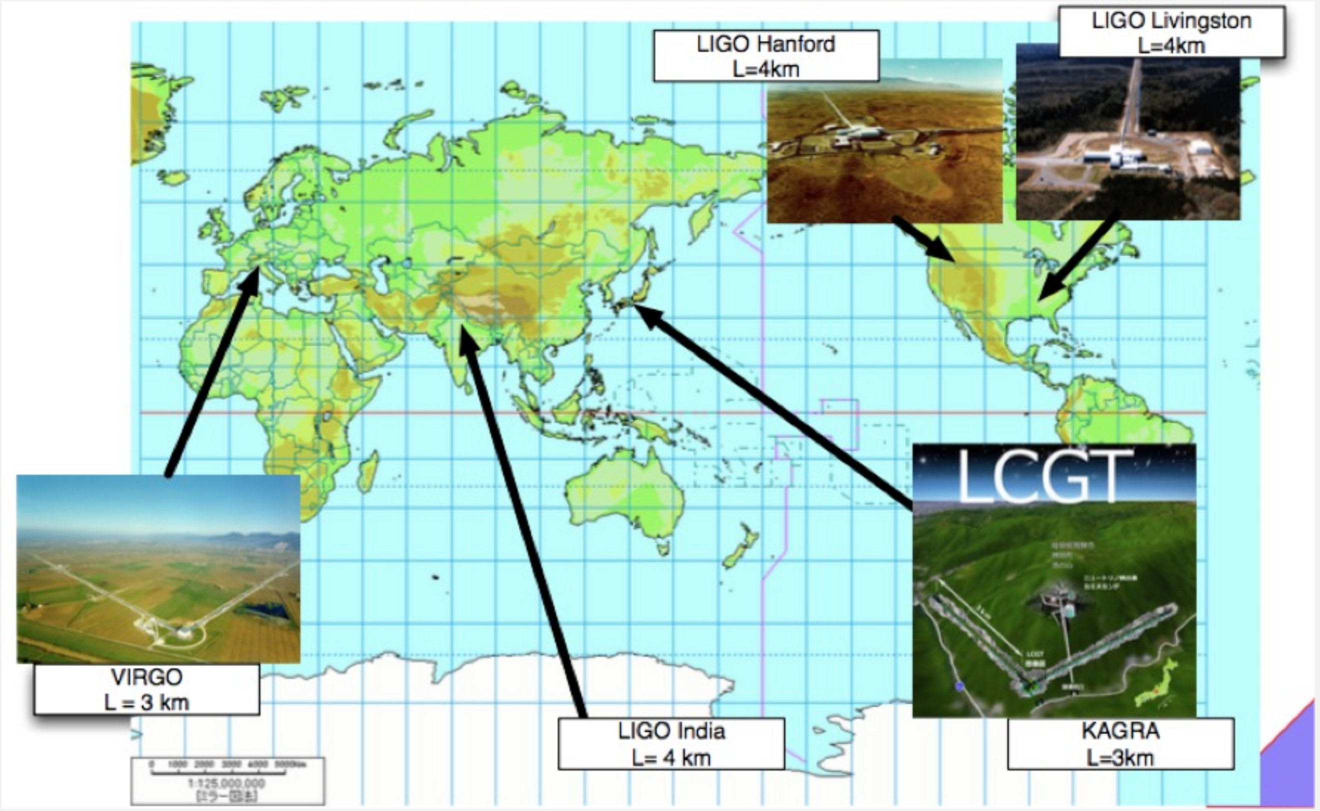
B. Allen 1996 *arXiv:gr- qc/96040*

Gravitaitonal wave astronomy

Use of gravitational waves as an observation tool

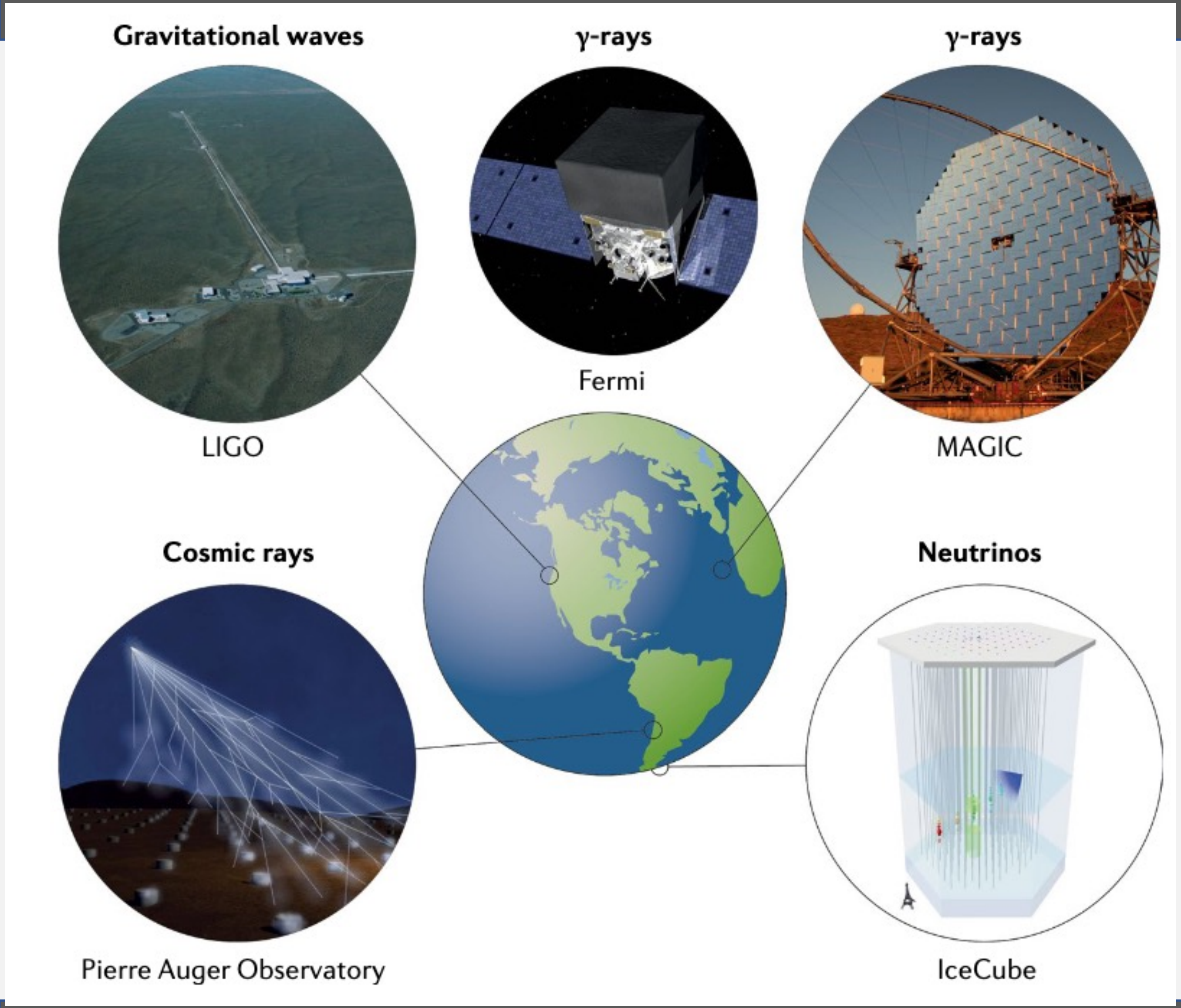


Ground-based observatories leading GW astronomy



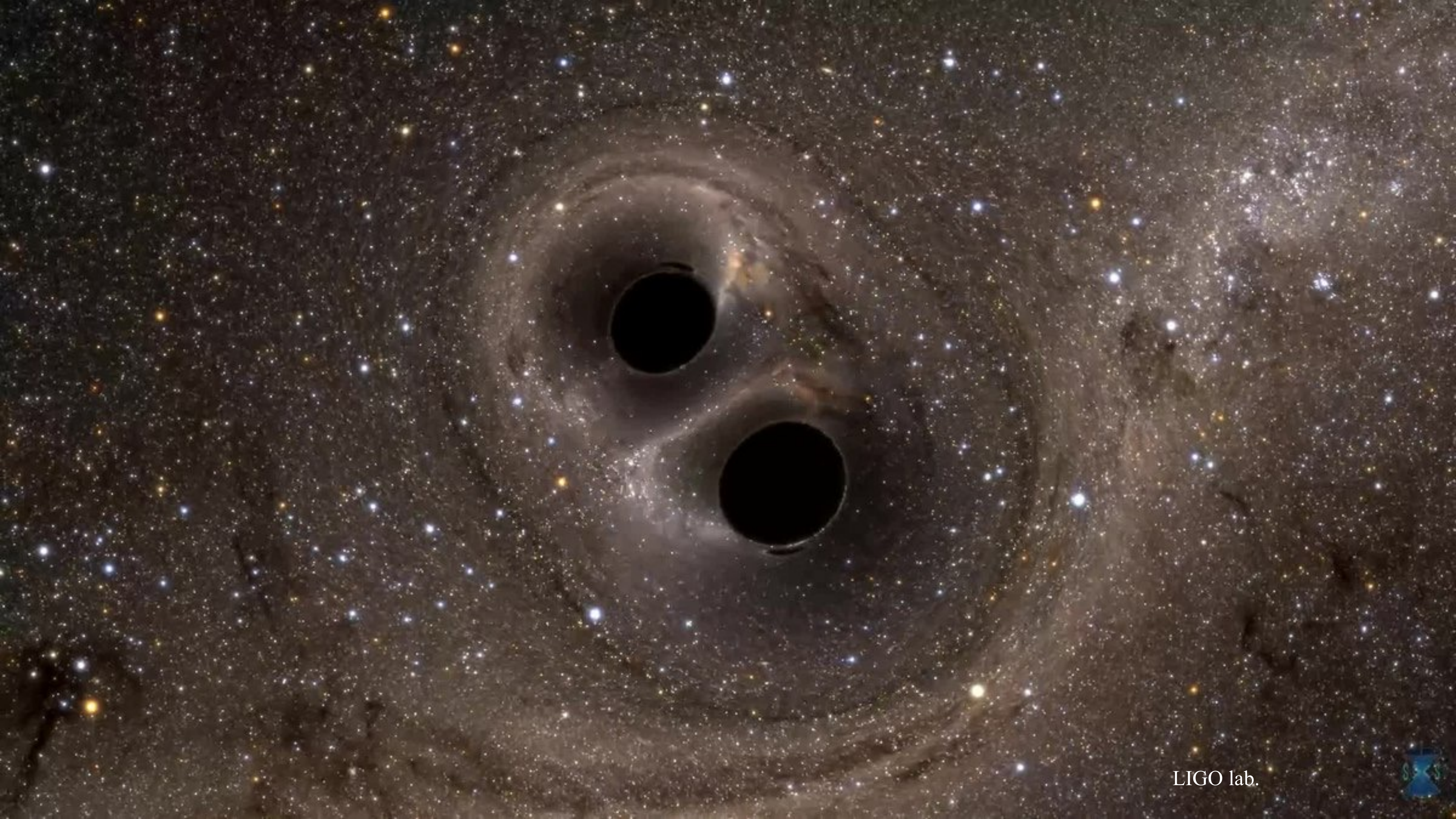
- ❖ Compact star coalescence events
  - ○ Stellar mass BH and NS

Multi-messenger astronomy



Gravitational wave astronomy forms a branch of Multi-messenger astronomy

Nature Reviews Physics 1, 585 (2019)



LIGO lab.

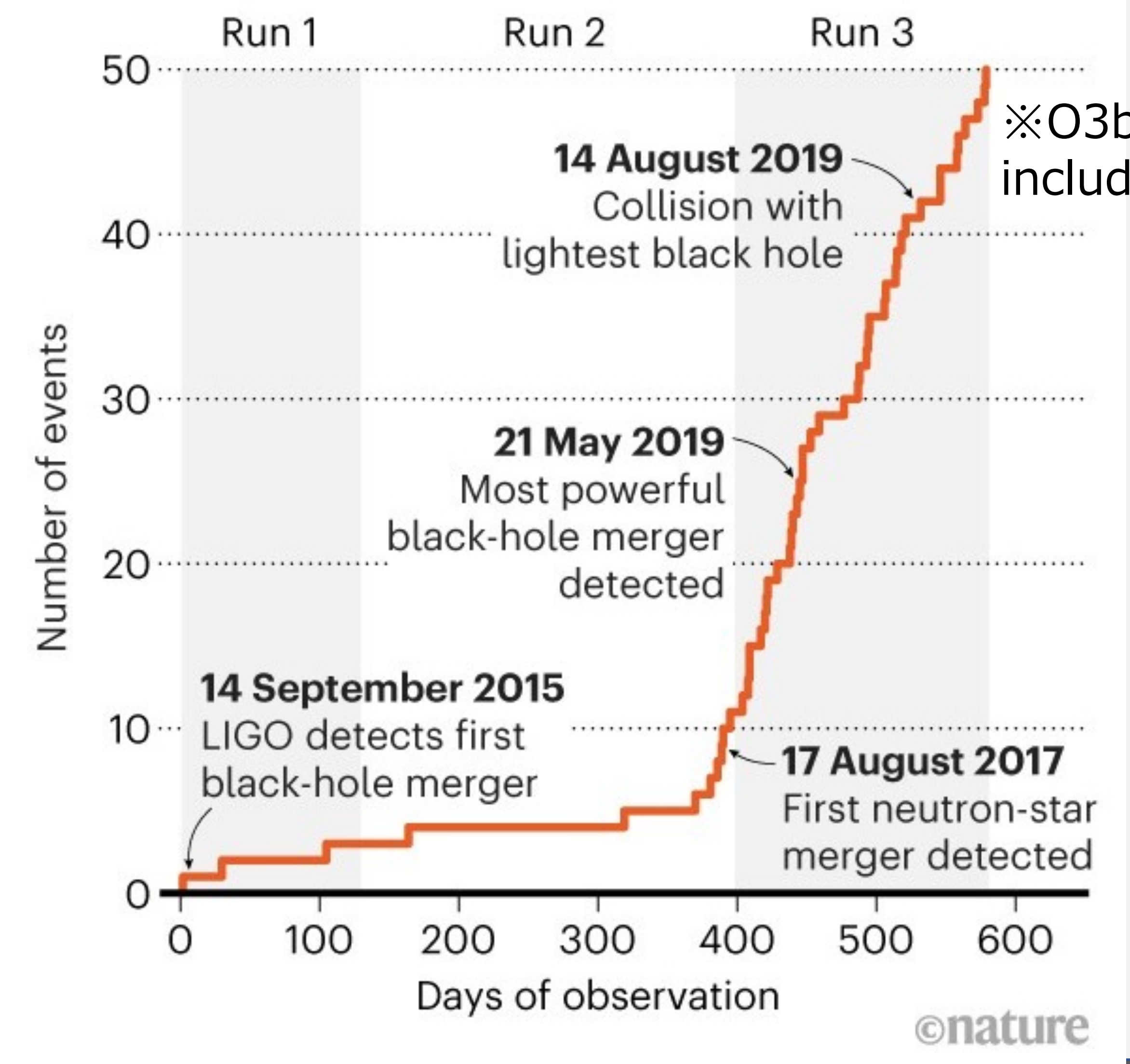
Cosmic Clashes

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

90 compact binary coalescence events observed

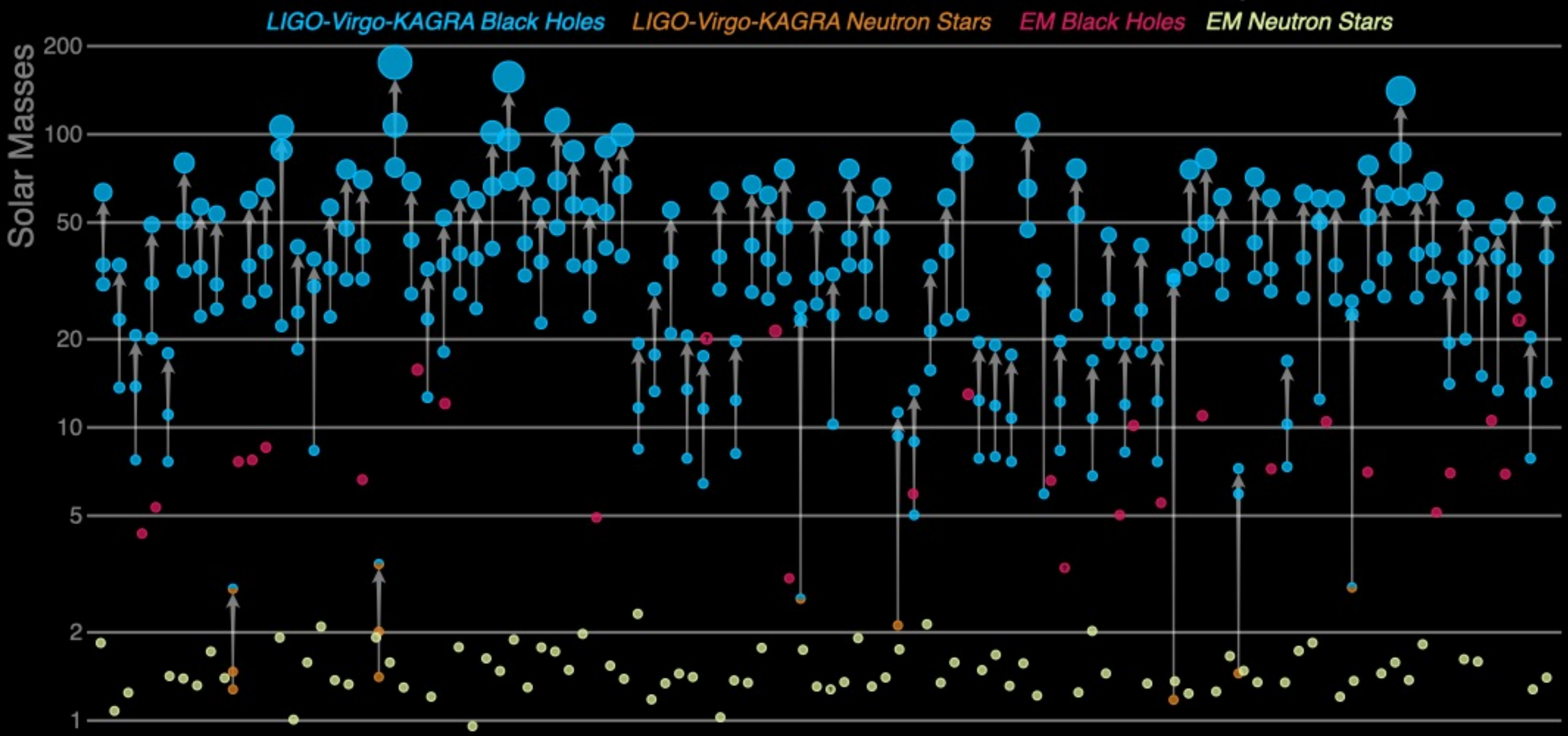
Astrophysical/cosmological contributions:

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

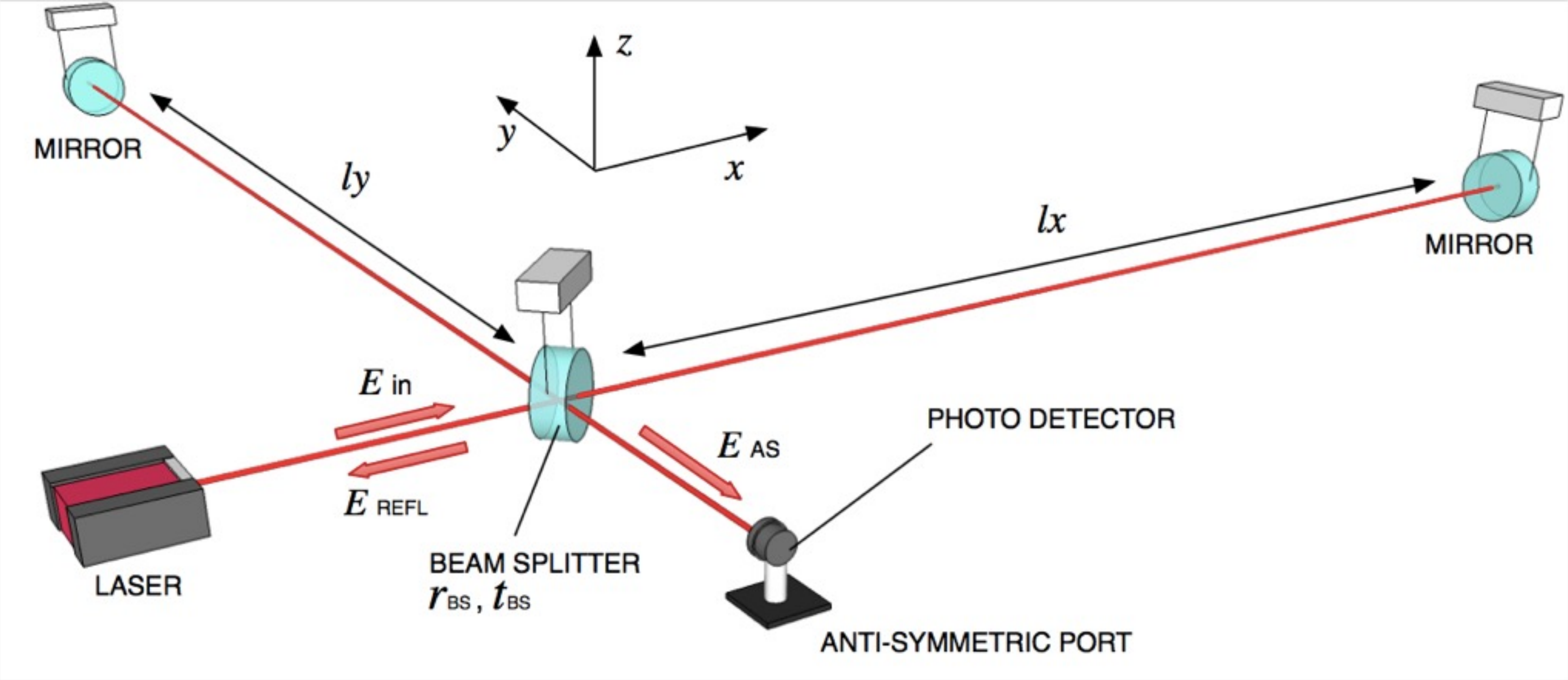


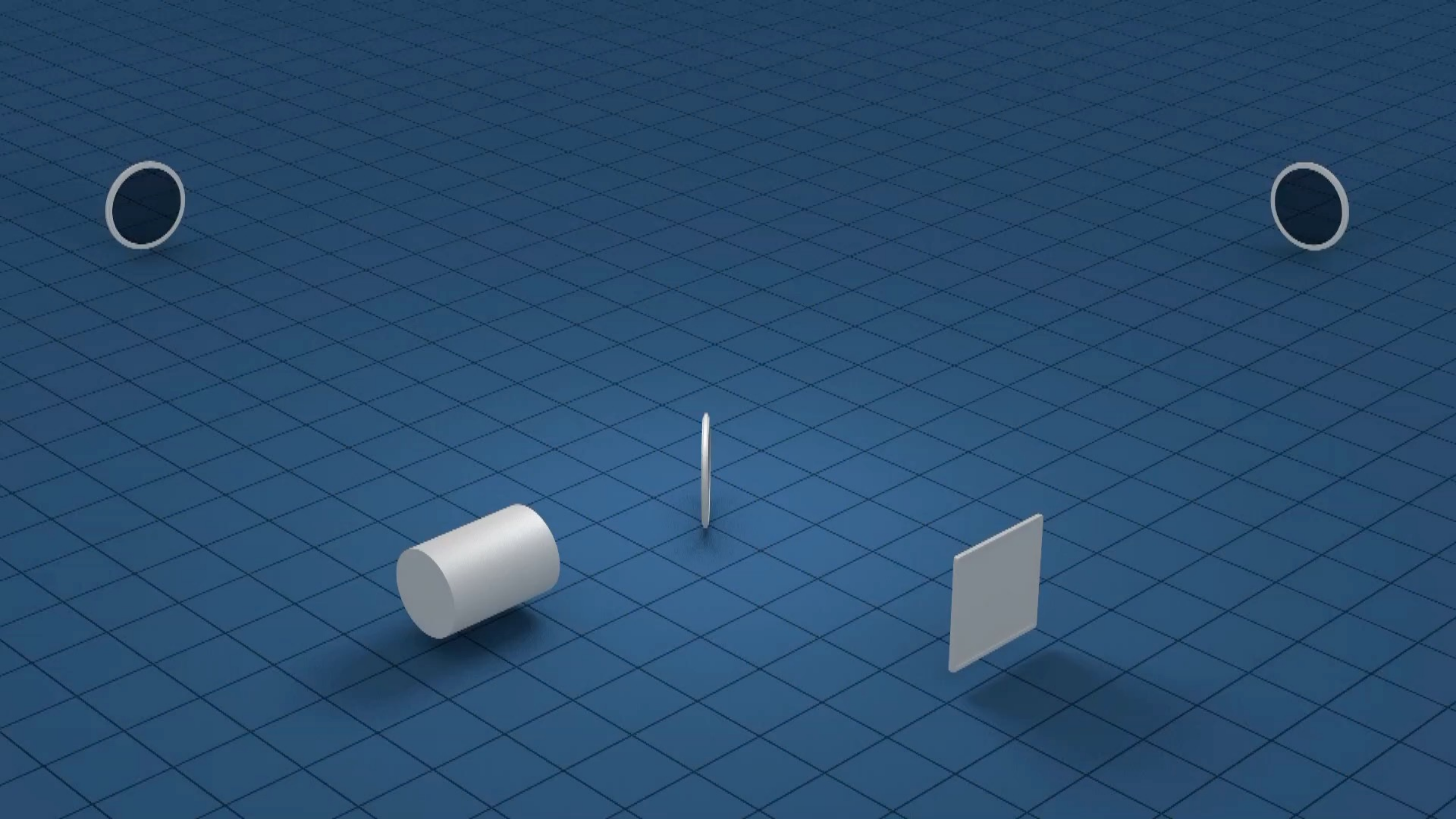
※O3b not included

90 events to date

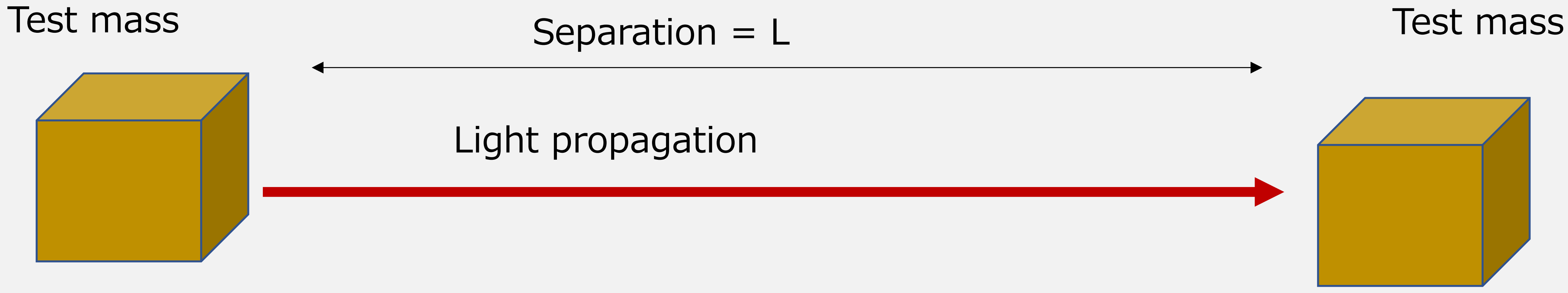


Laser interferometer





Working principle of Laser interferometer



Optical phase (measurement quantity)

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

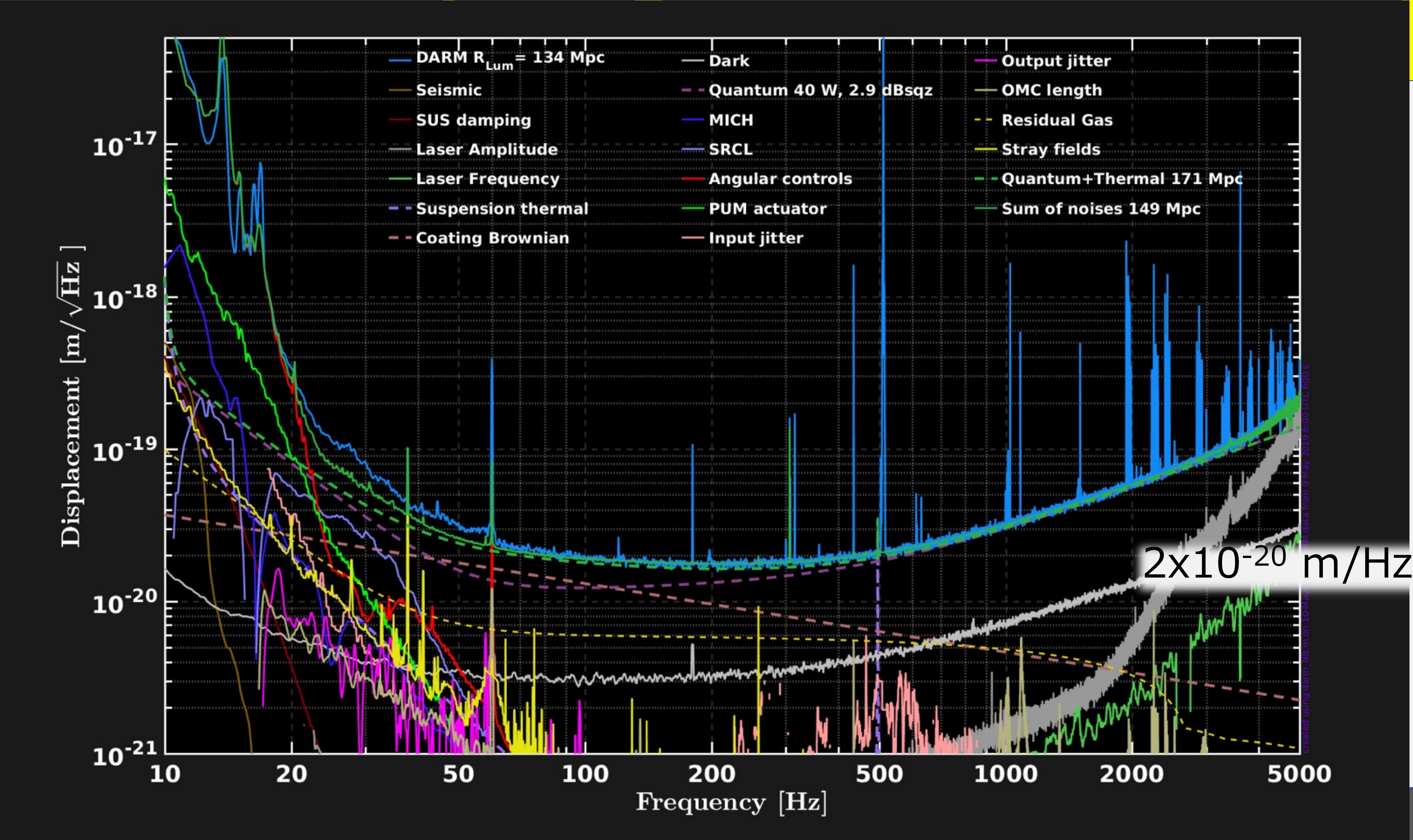
$$\approx k\,L - \underline{k\,Lh(t)/2}$$

h: GW amplitude
k: wavenumber of light field

►Sensitivity proportional to interferometer length

Sensitivity on ground

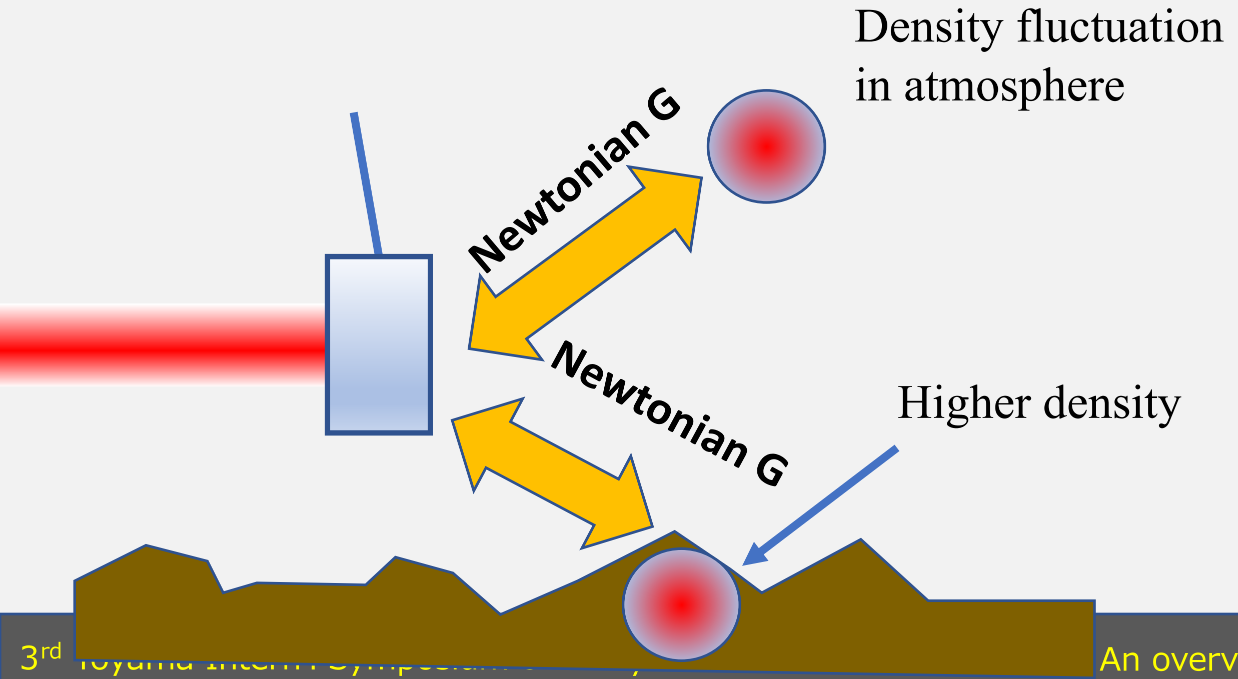
LIGO Livingston alog 45851 (2019)
Credit: V. Frolov

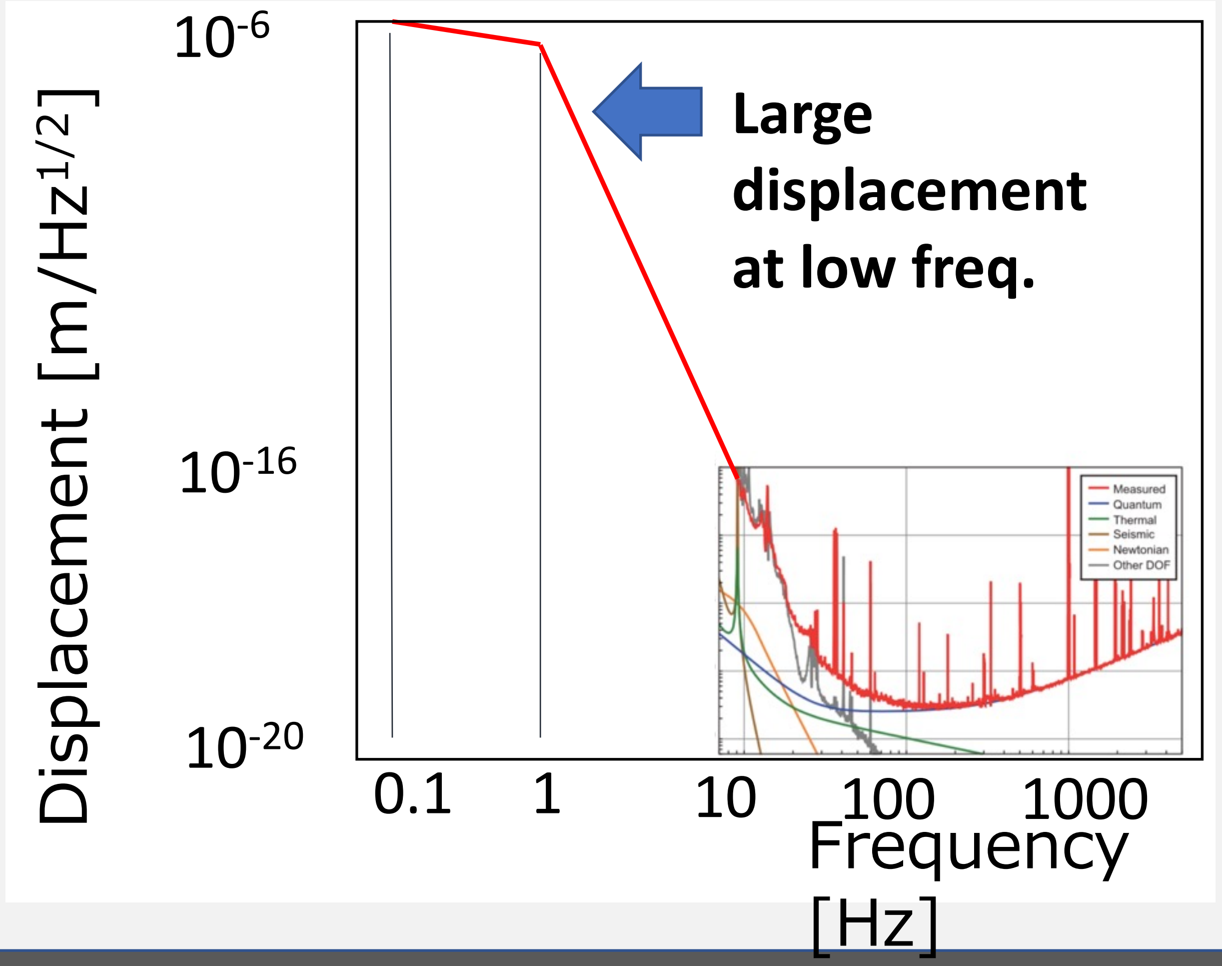


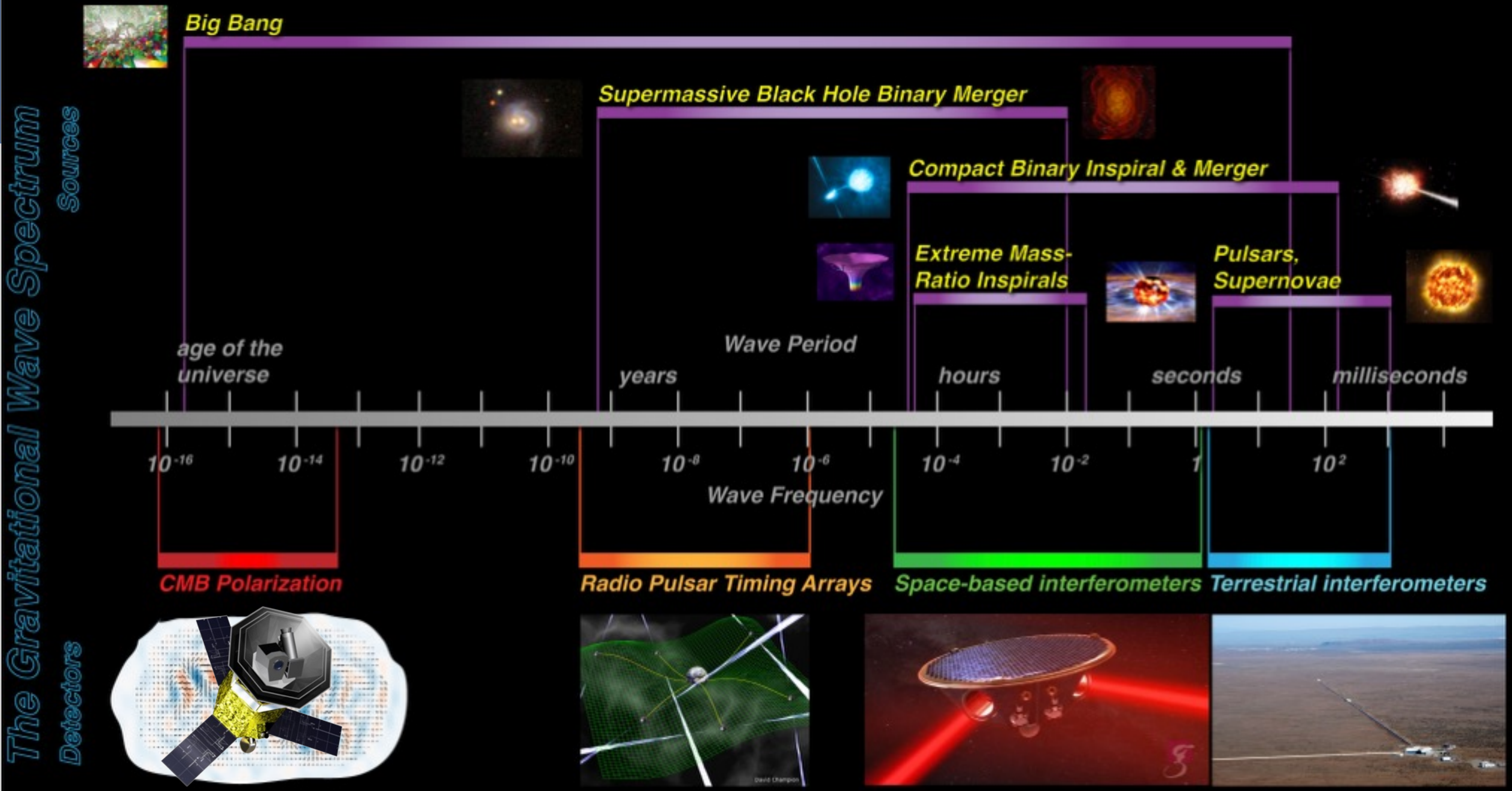
2×10^{-20} m/Hz$^{1/2}$@100Hz

Low frequency noise limited by terrestrial seismic noises

- ▶Contamination by seismic noises below 10 Hz
- ▶Gravity gradient noise can not be reduced by vibration isolation system






The Gravitational Wave Spectrum
Sources
Detectors
Big Bang
Supermassive Black Hole Binary Merger
Compact Binary Inspiral & Merger
Extreme Mass-Ratio Inspirals
Pulsars, Supernovae
Wave Period
age of the universe
years
hours
seconds
milliseconds
10^-16
10^-14
10^-12
10^-10
10^-8
10^-6
10^-4
10^-2
1
10^2
Wave Frequency
CMB Polarization
Radio Pulsar Timing Arrays
Space-based interferometers
Terrestrial interferometers

Into space

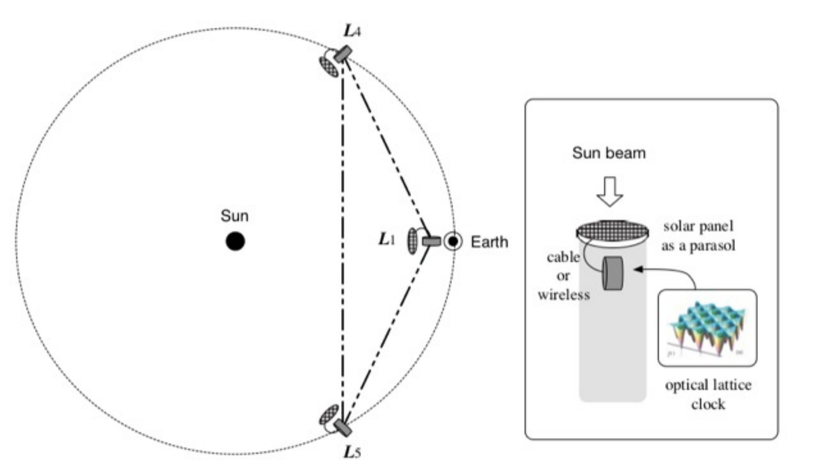
Merits for putting the detectors in space

- ► Almost no seismic noises
- ► Long laser interferometer lengths
- ► Vacuum tubes not required
- ► Different GW sources

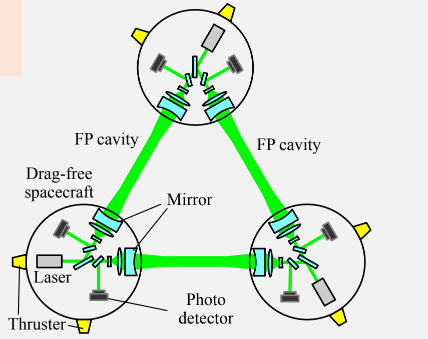
Space-based detectors

A number of concepts exist today

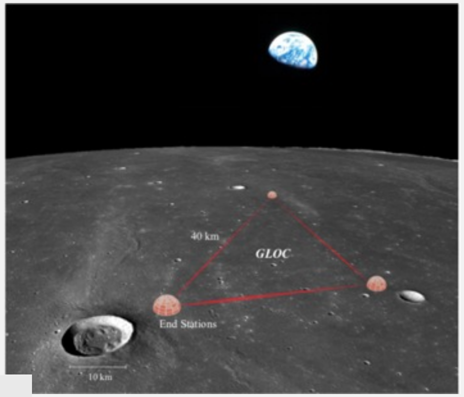
- ►Laser interferometers
  - ► LISA, DECIGO, TianQin, Taiji
- ►Atom interferometers
  - ► AEDGE [1]
- ►Precision clocks
  - ►INO[2] ,DOCS[3]
- ►Lunar-based interferometers
  - ►GLOC[4], LGWA[5],LSGA[6], LION [7]



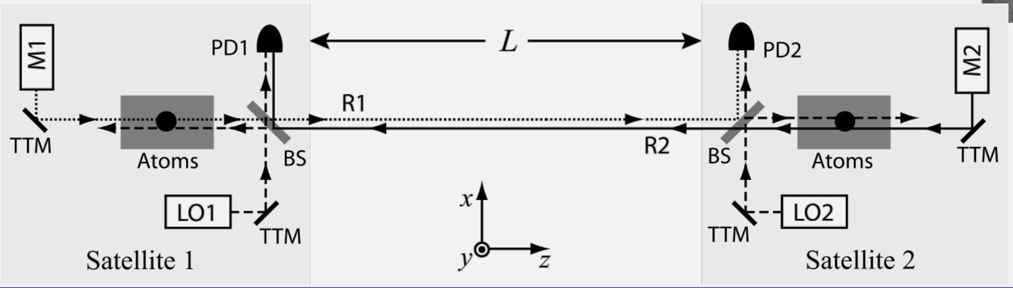
INO



DECIGO



GLOC



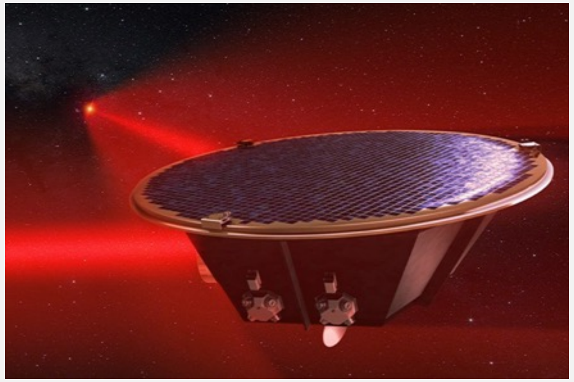
AEDGE

[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)

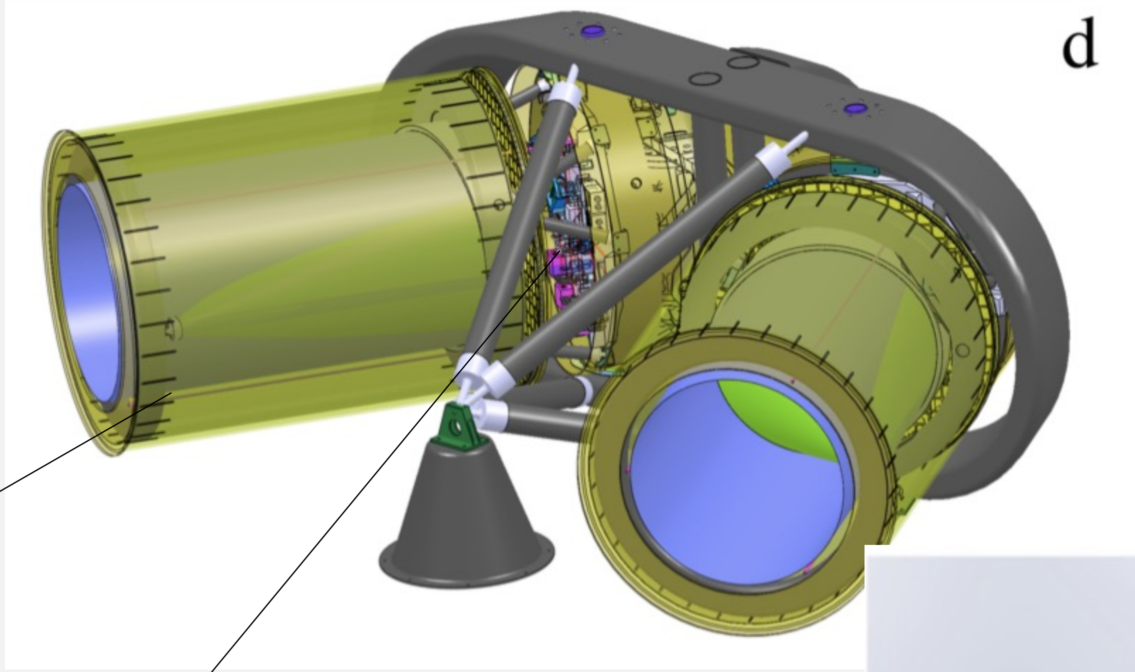
LISA

- ►LISA: **L**aser **I**nterferometer **S**pace **A**ntenna
  space GW mission, to be launched in 2035
- ►Development underway, lead by ESA
  Selected as the Cosmic Vision L3 (2017)
- ►Targeting 1mHz -100mHz low frequency band
- ►3S/C deployed in equilateral triangular constellation
  Different concept than the ground-based
  (long laser links, transponder, drag-free and etc.)
- ►Two groups participating from Japan
  - ►Japanese working group for LISA science
  - ►Japan instrument group

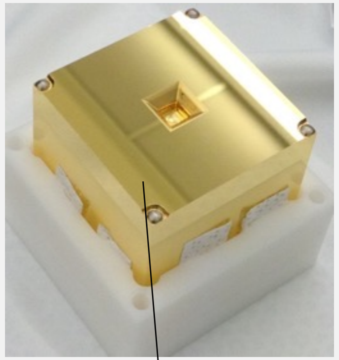
How it looks like



Inside



Test mass

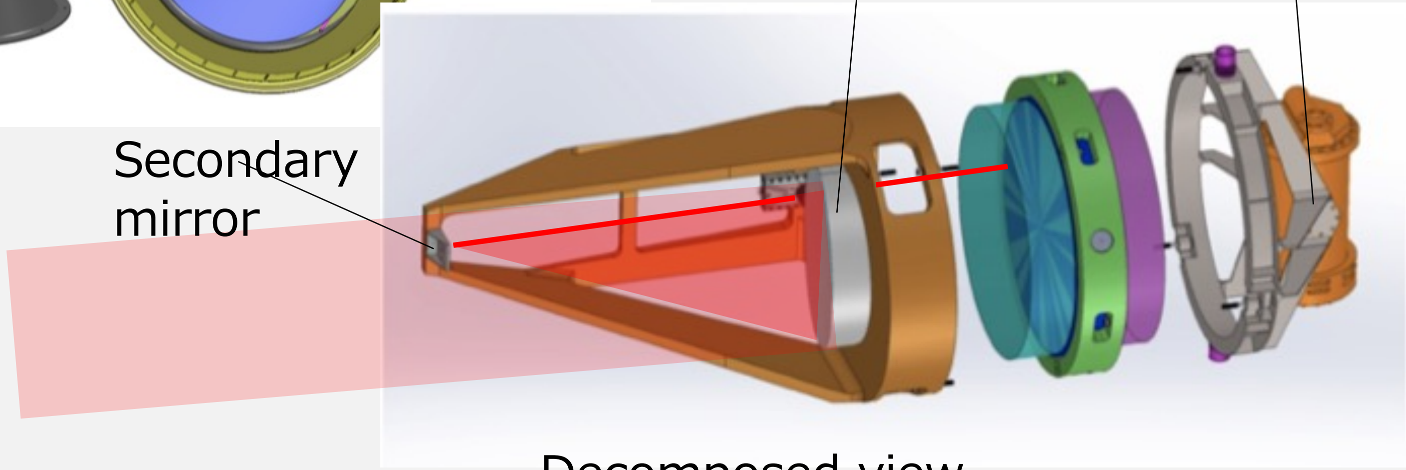


Primary mirror

Telscope Thermal shroud

Optical bench

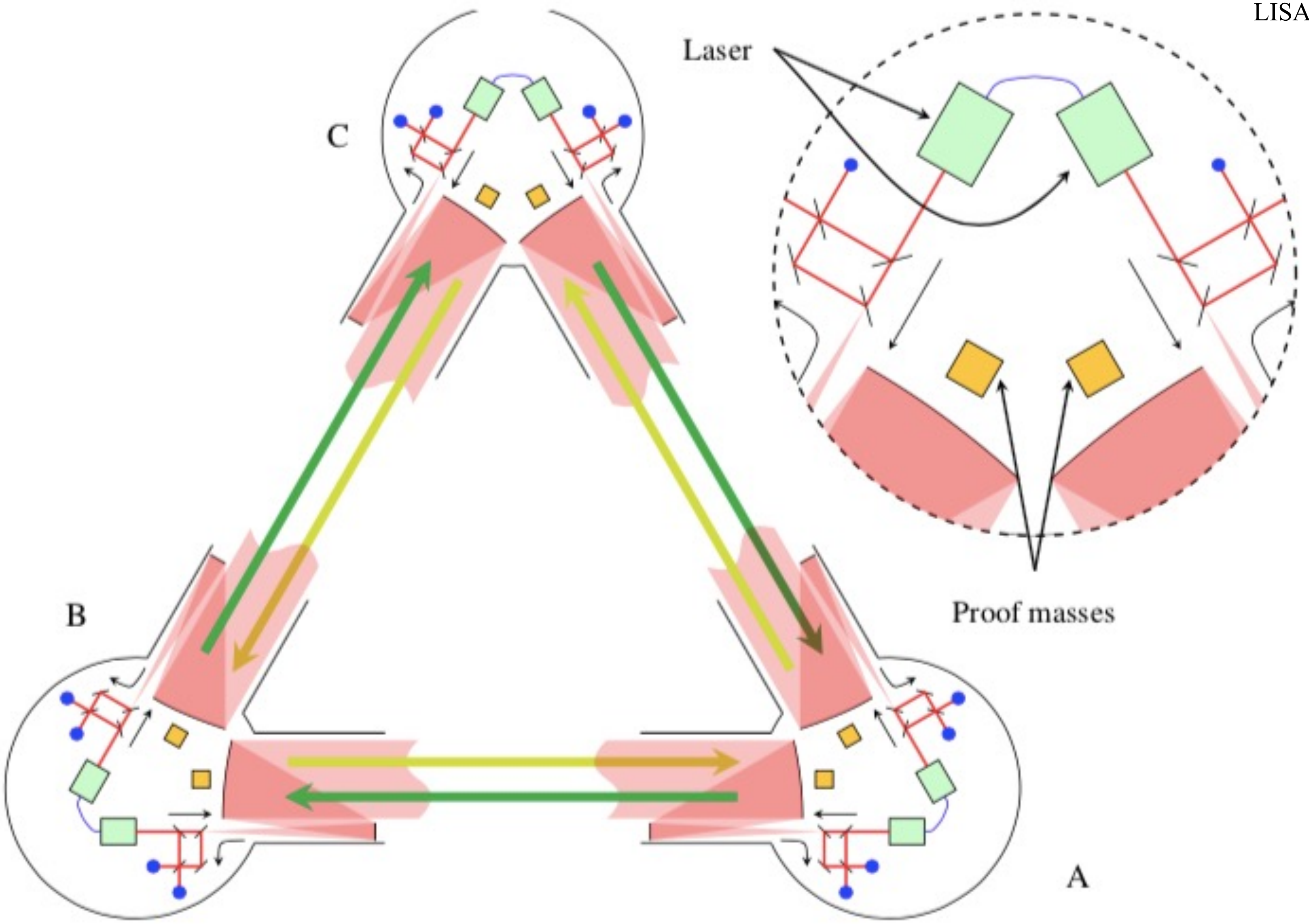
Secondary mirror



Decomposed view

Figures:ESA-SRE-2011-3

A closer look



LISA assessment study report, ESA/SRE(2011)3

Arm length: 2,500,000 km
Three satellites
Six lasers (lambda=1064 nm)
Six laser links
Six test masses
Drag-free control
Optical transponder
time-delay interferometry
6.5 yrs mission duration (10 max.)

Science goals/objectives of LISA

Two key questions

(1) How, when and where do the first massive black holes form, grow and assemble, and what is the connection with galaxy formation?
(2) What is the nature of gravity near the horizons of black holes and on cosmological scales?

LISA L3 proposal document

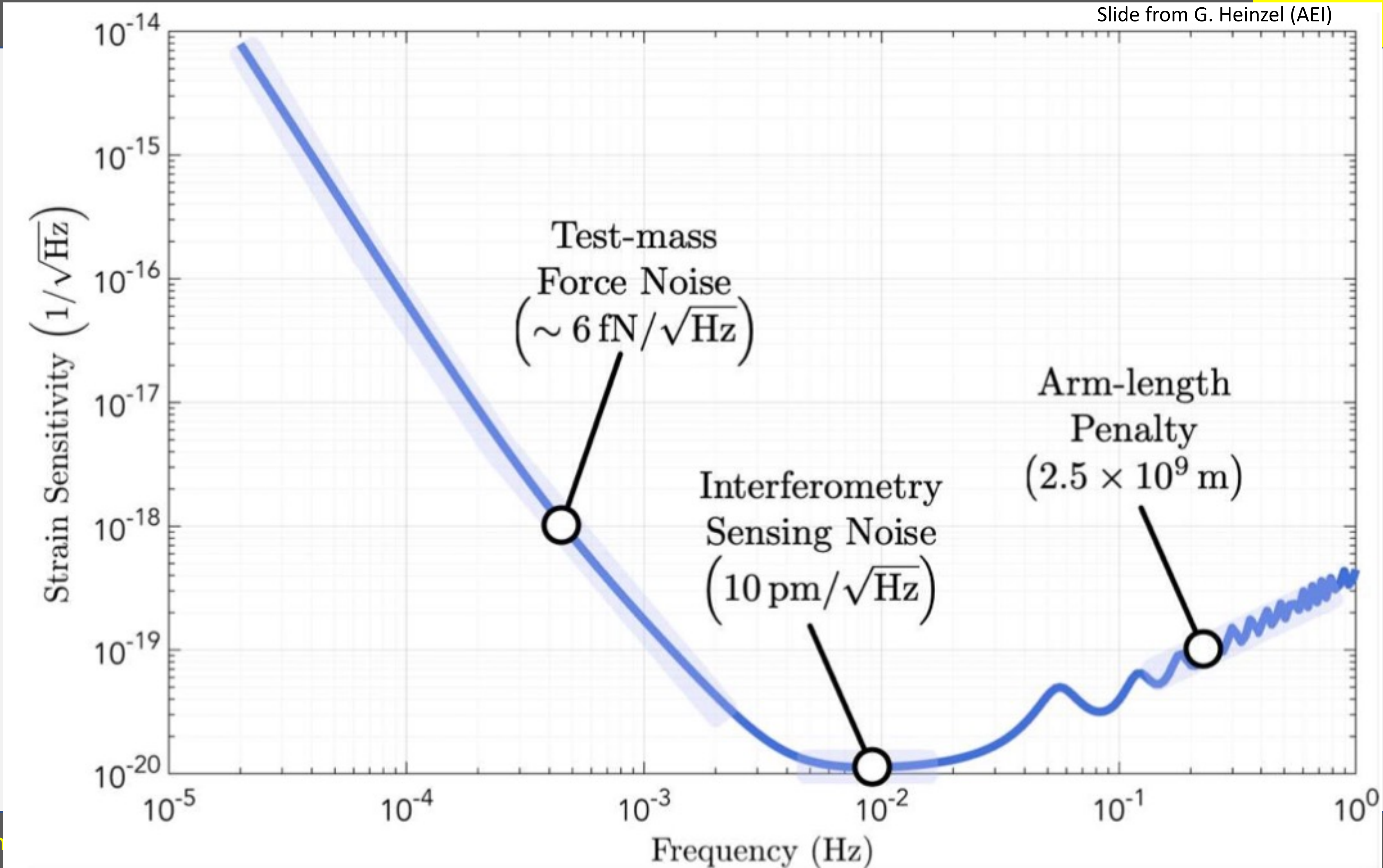
Science objectives

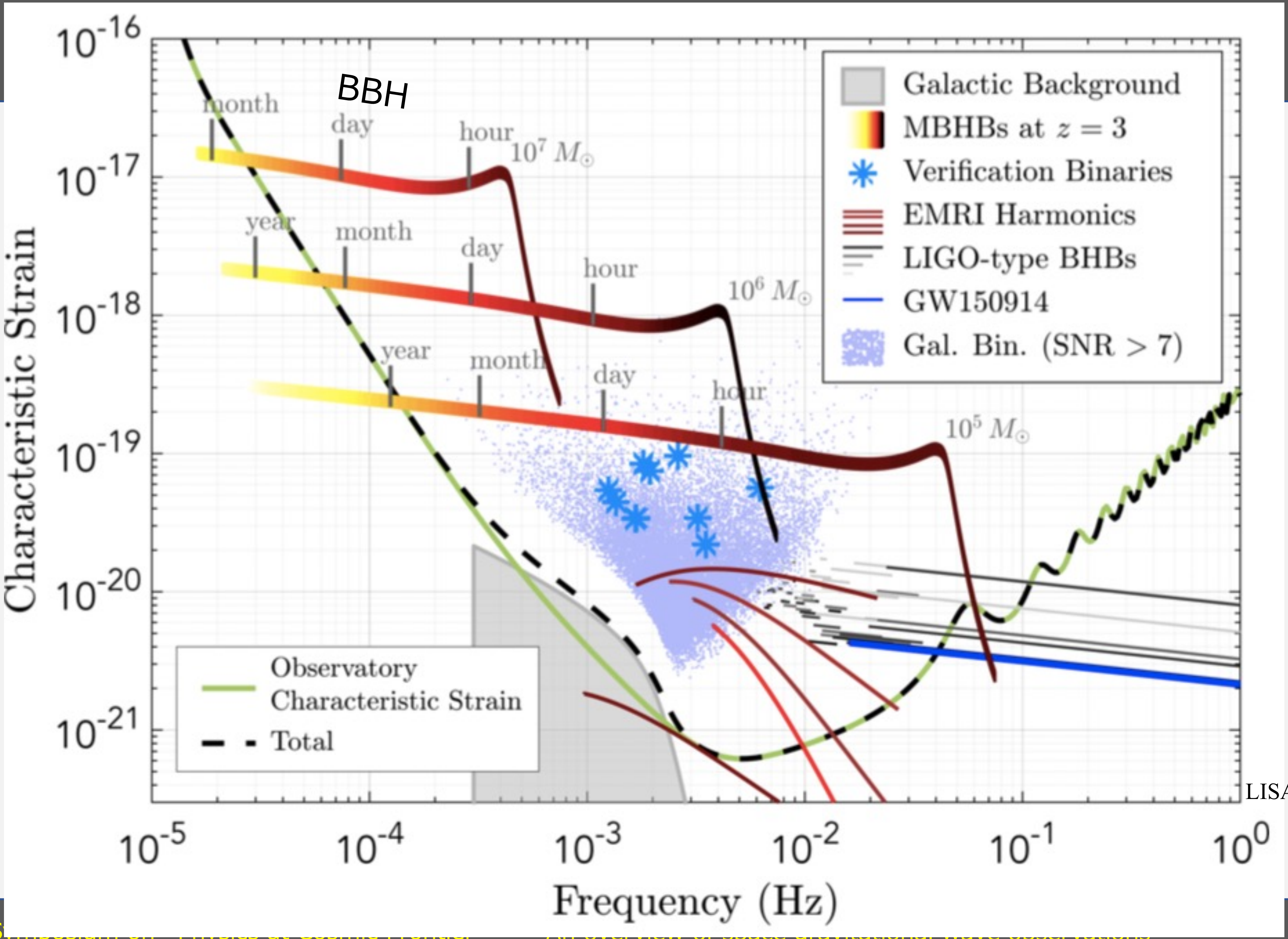
SO 1: Study the formation & evolution of compact binary stars in the Milky Way
SO 2: Trace the origin, growth & merger history of MBHs
SO 3: Probe the dynamics of dense nuclear clusters using EMRIs
SO 4: Understand the astrophysics of stellar origin black holes
SO 5: Explore the fundamental nature of gravity & black holes
SO 6: Probe the rate of expansion of the Universe
SO 7: Understand stochastic GW backgrounds & their implications for the early Universe and TeV-scale particle physics
SO 8: Search for GW bursts and un- foreseen sources

arXiv:1907.064802

Probing the mHz band

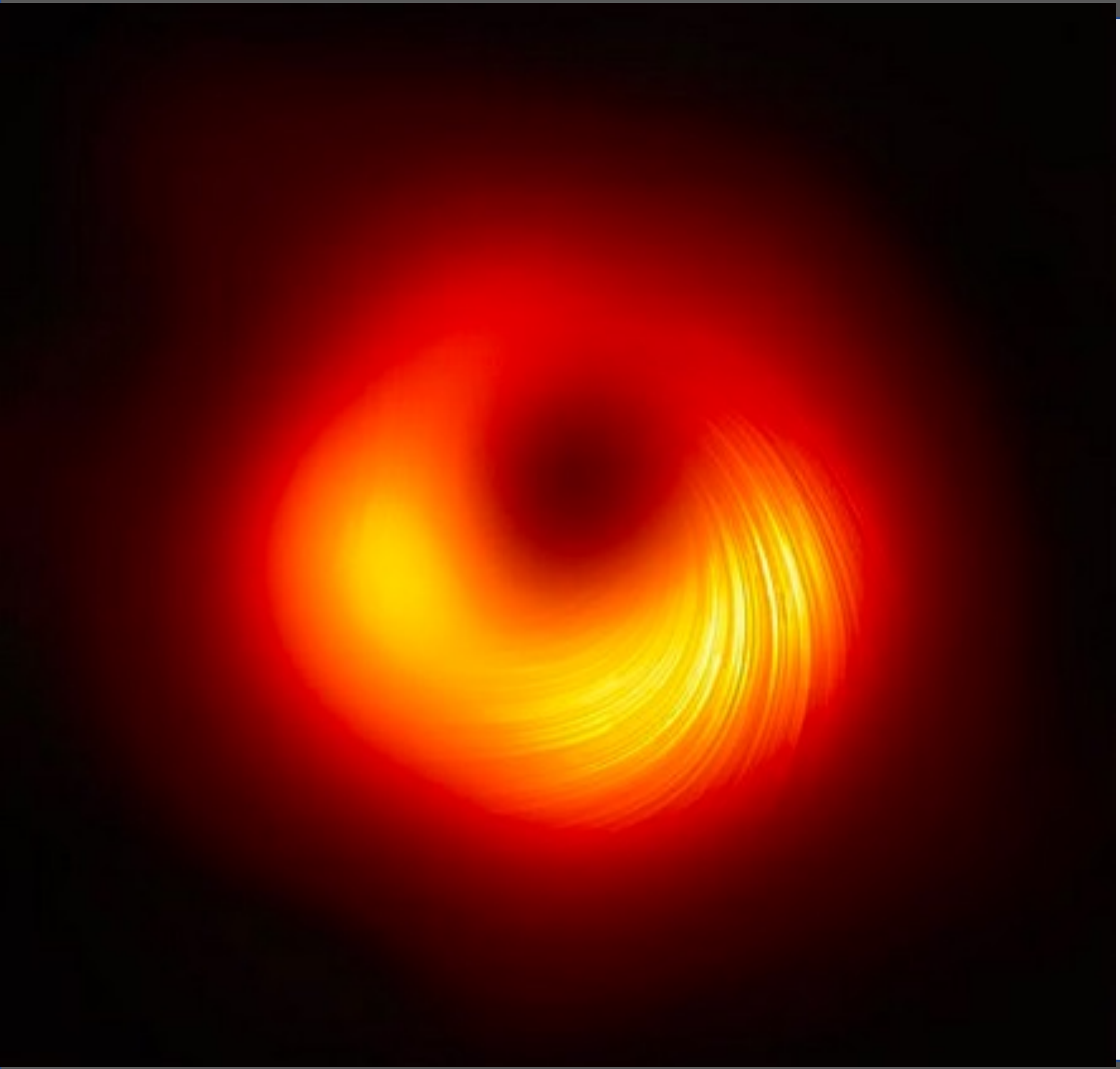
Sky and polarization averaged





LISA L3 proposal document (2017)

Super Massive Black Holes



SMBH at the center of M87
(C) EHT collaboration

Furthest SMBH confirmed today:
$8 \times 10^8\ M_\odot$ at $z = 7.5$ [1]

[1] E. Banados+, Nature (2017)

How did they grow?

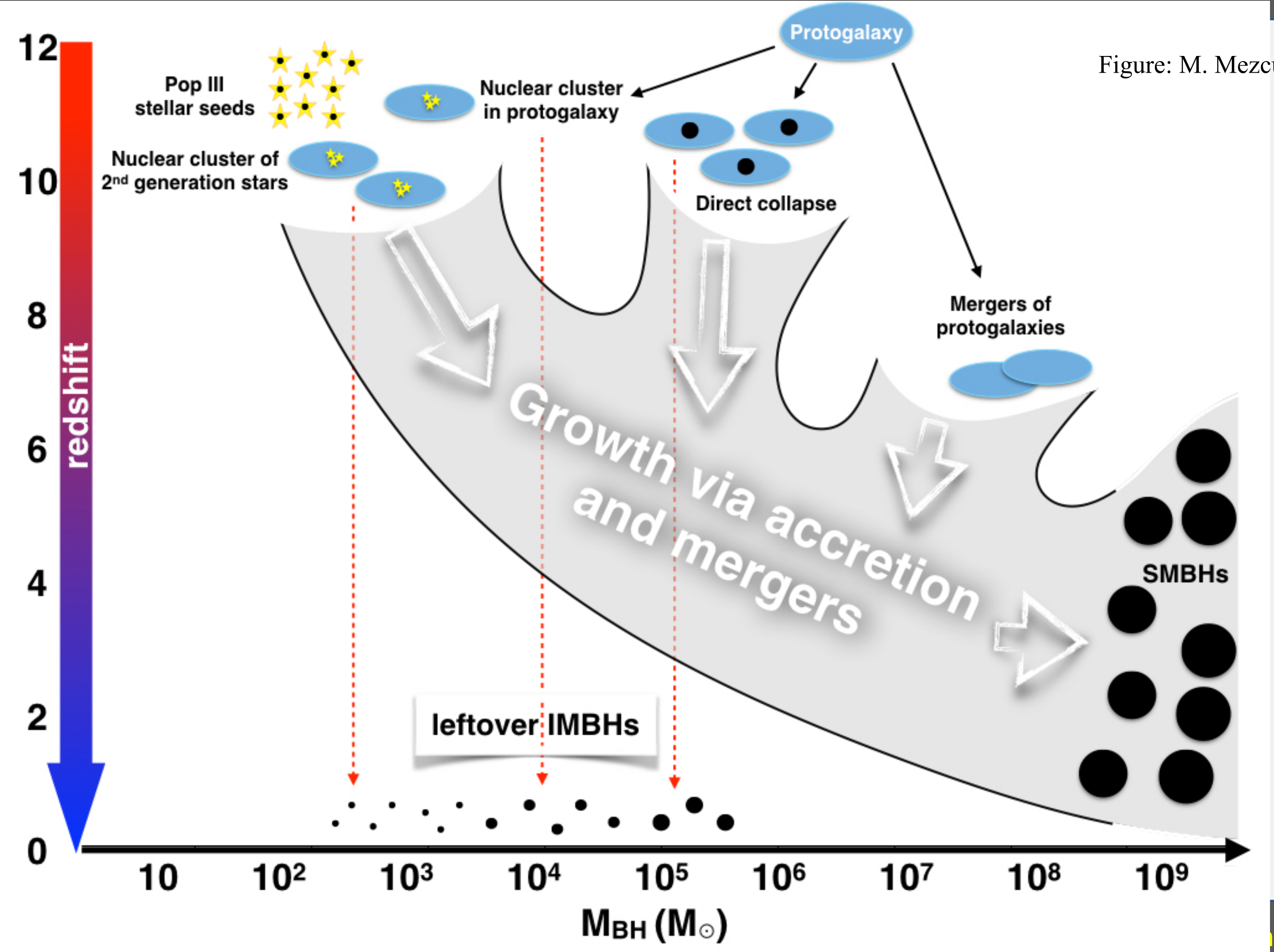


Figure: M. Mezcua, Int. J. Mod. Phys. 26, 11, 1730021 (2017)

Hierarchical merger tree

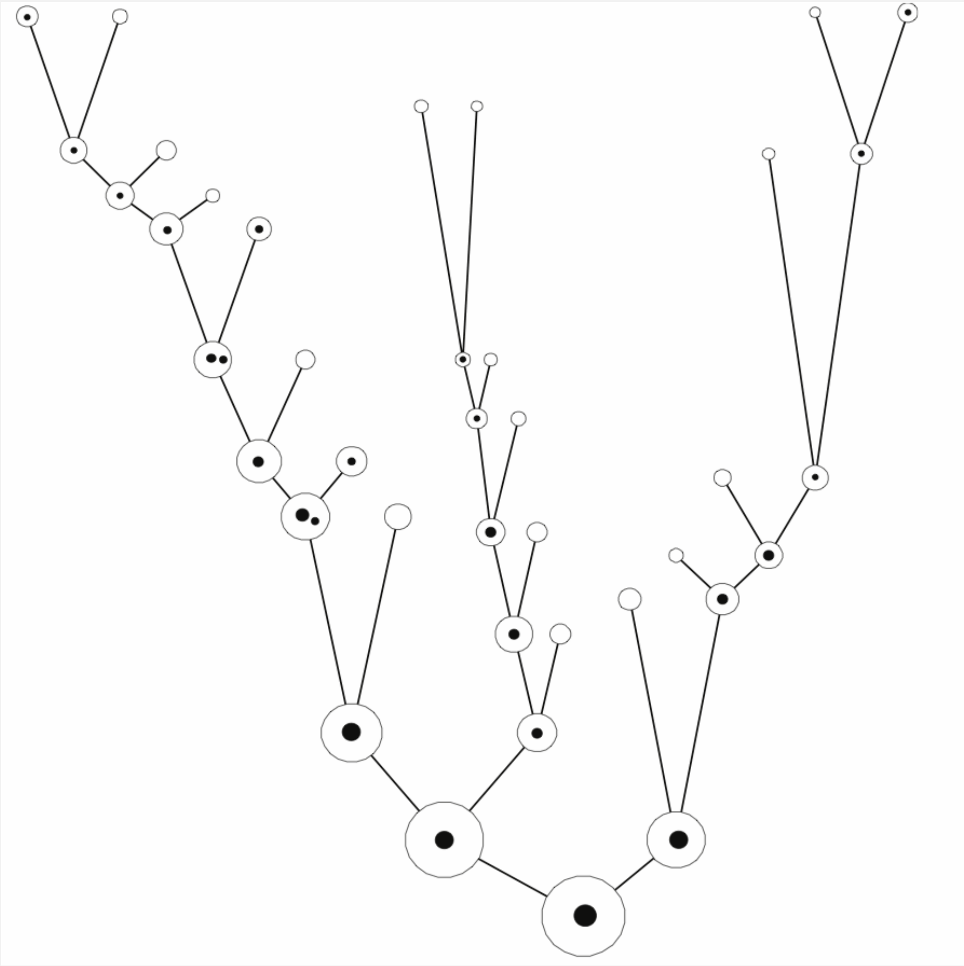
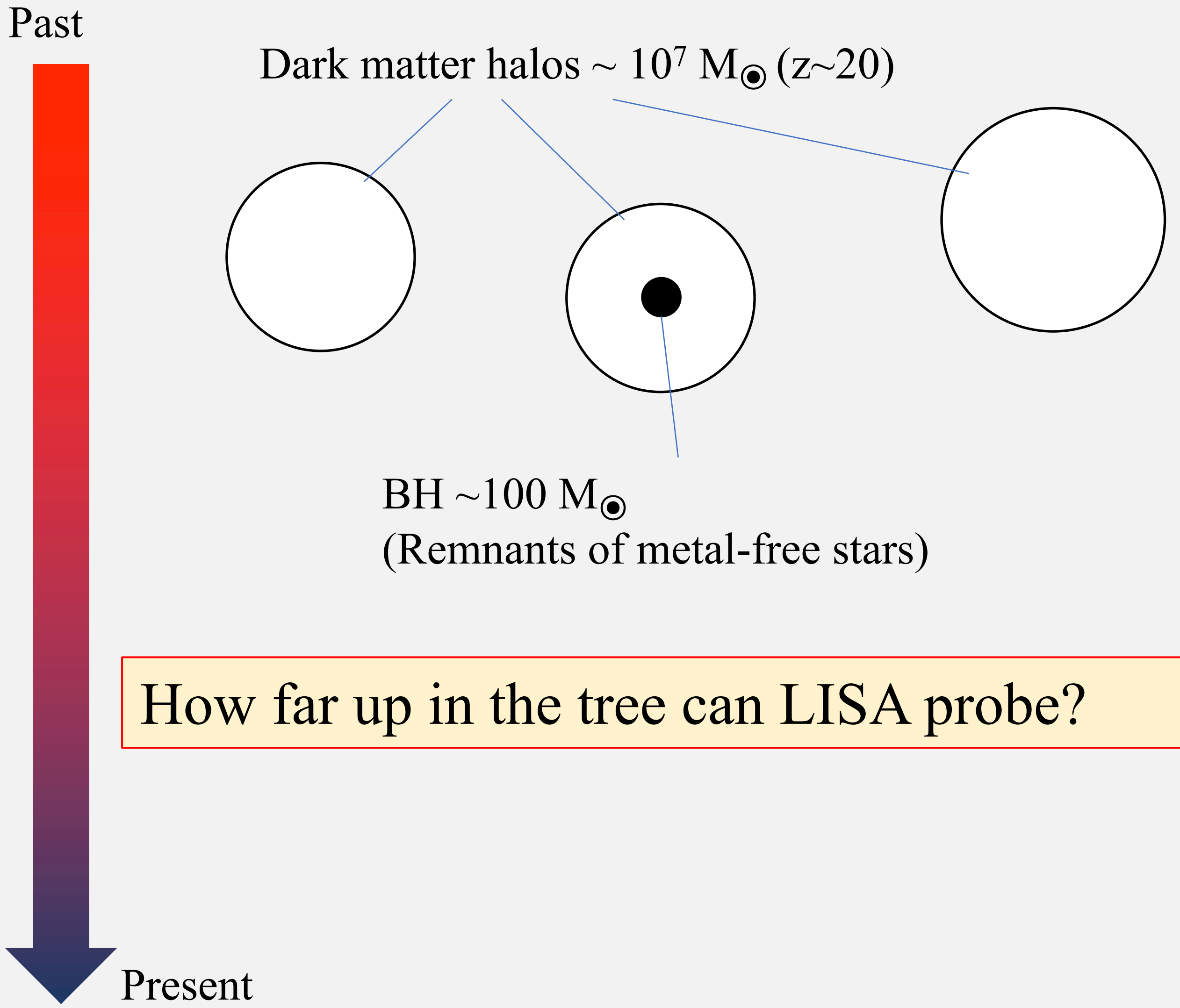


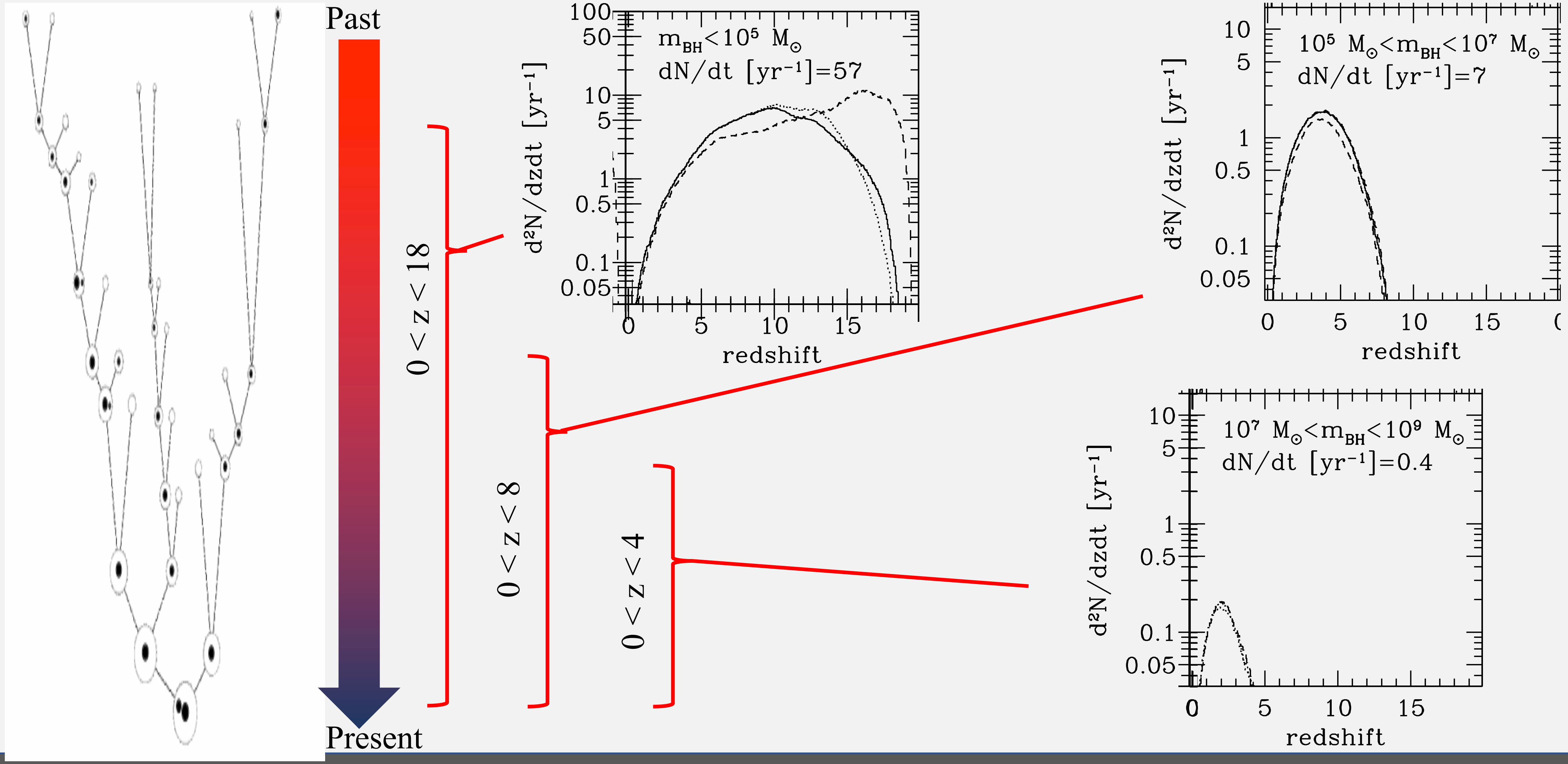
Figure: http://www2.iap.fr/users/volonter/BHdynamics.html



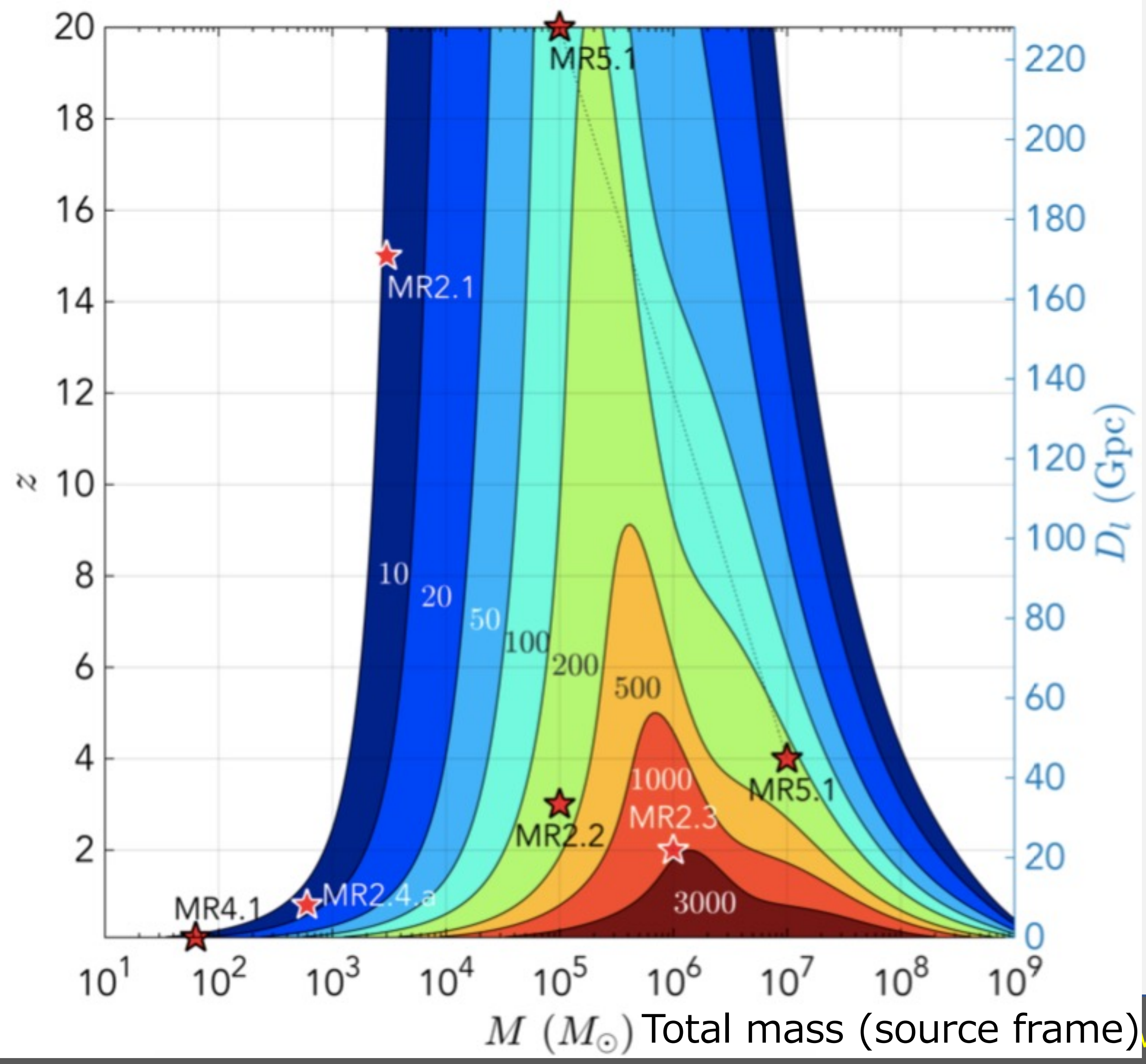
How far up in the tree can LISA probe?

Coalescence event rate prediction v.s. merger tree

Figures: Sesana+, ApJ (2004)



Covering almost all the epoch in merger tree

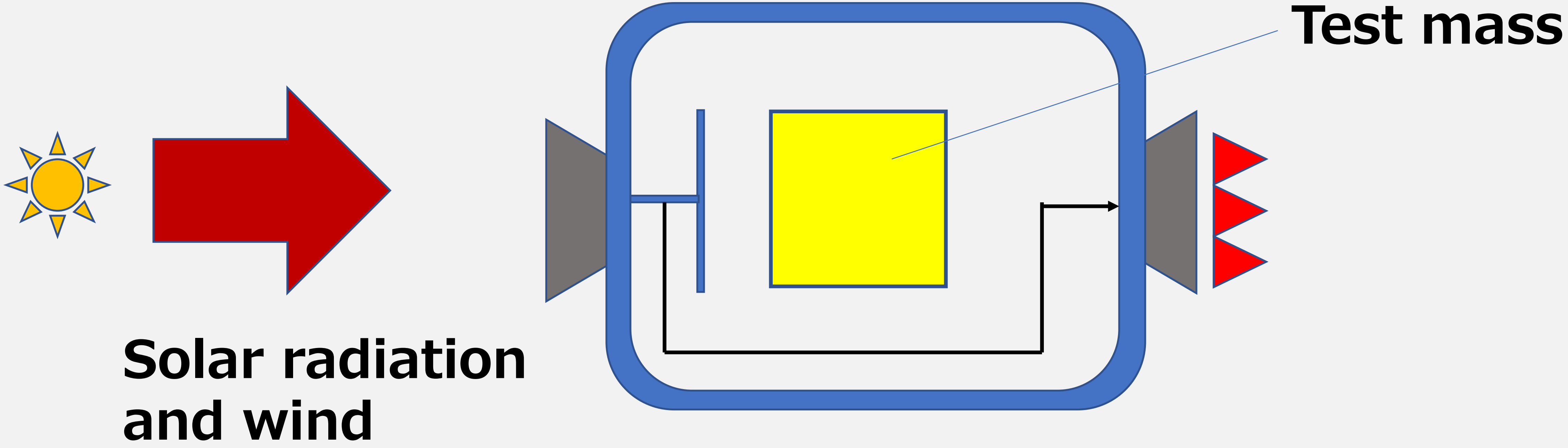


- ► $10^3\,M_\odot < M < 10^7\,M_\odot$
- ► Beyond z = 10

LISA L3 proposal document (2017)

Drag free control

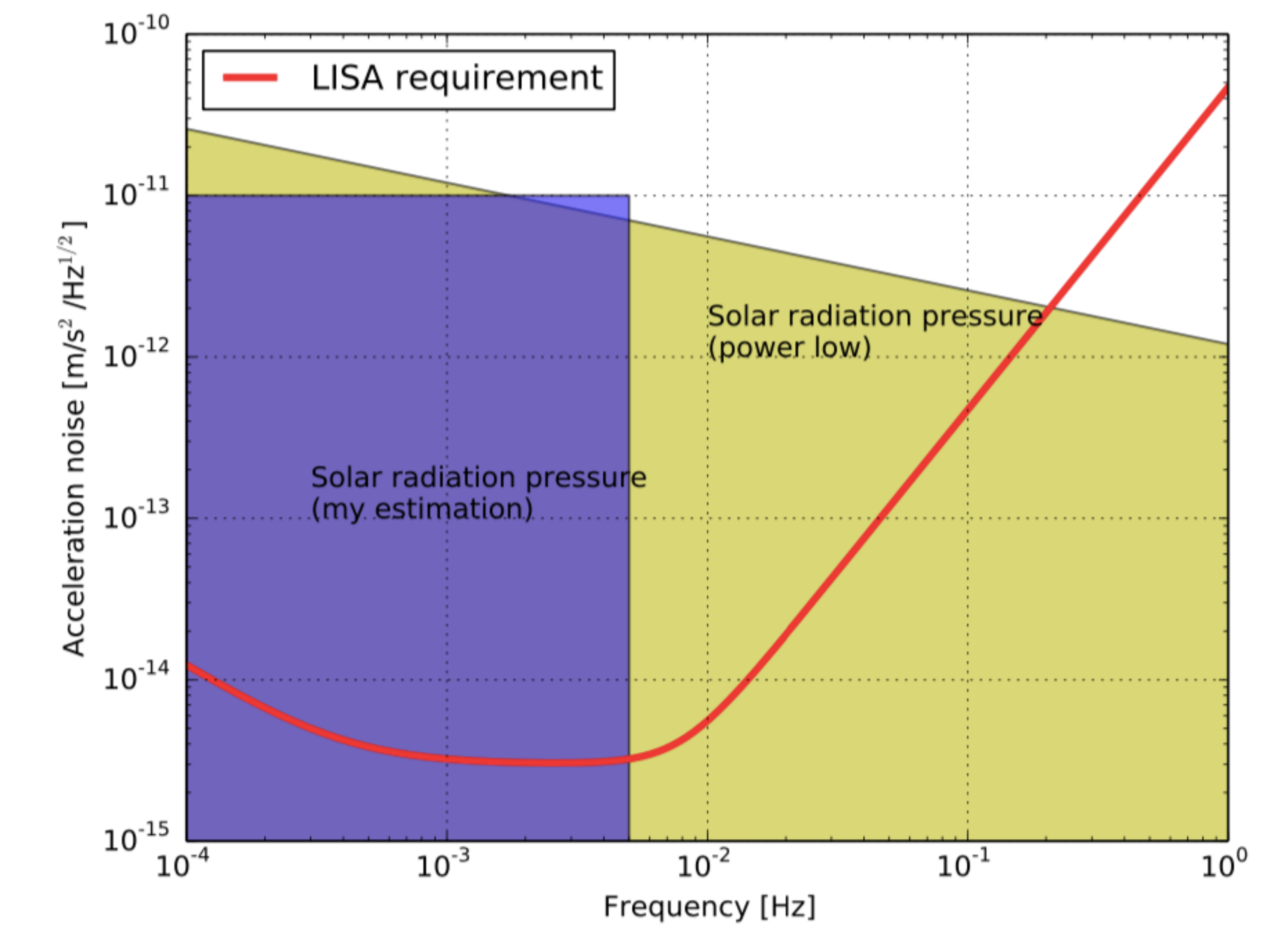
- ►Floating mass available in orbit
- ►Shielding necessary to keep TM from external disturbances



Drag free very necessary

► Solar radiation model at 1 AU

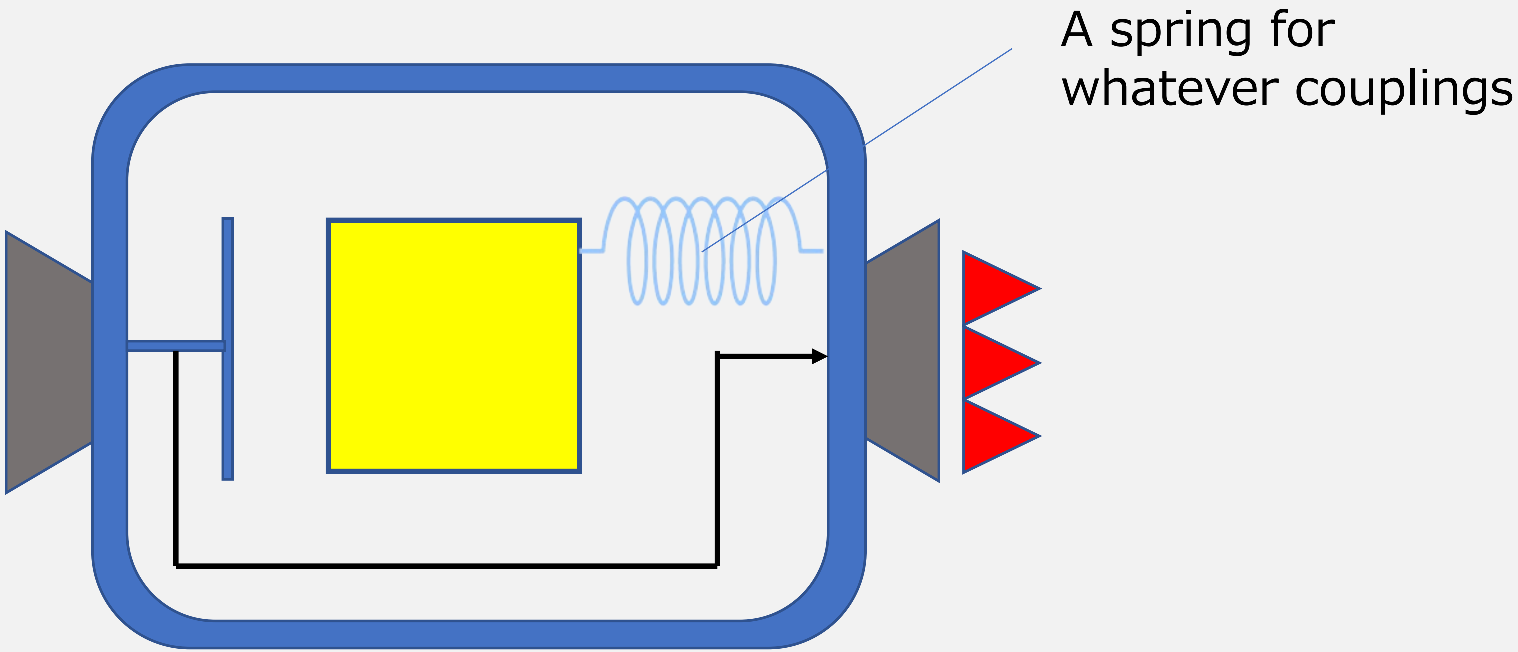
$$\frac{\delta W}{W_0} \approx 1.3 \times 10^{-3} \left(\frac{1\,\mathrm{mHz}}{\nu}\right)^{1/3} /\sqrt{\mathrm{Hz}}$$



Noise introduction in D.F.

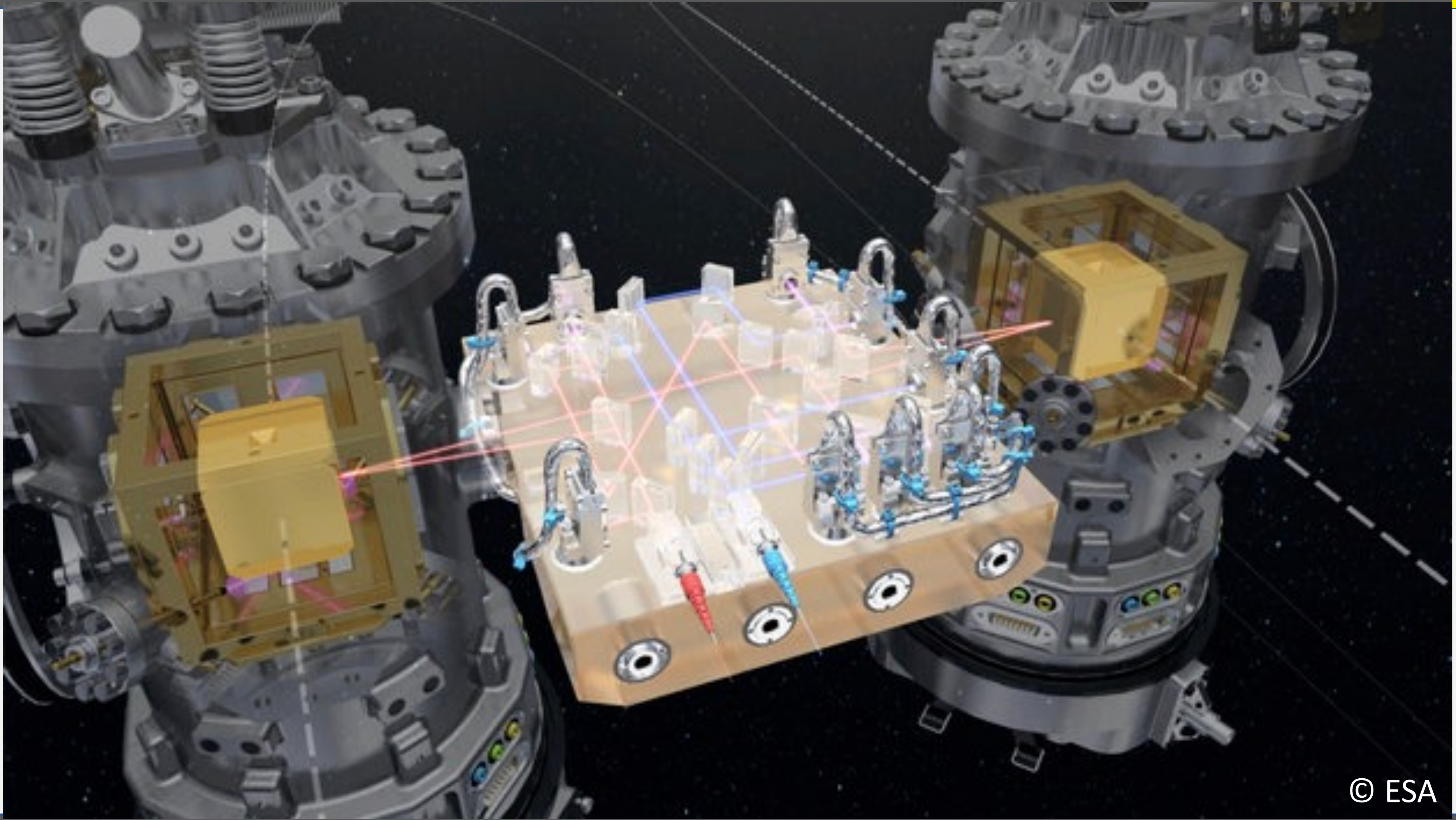
However

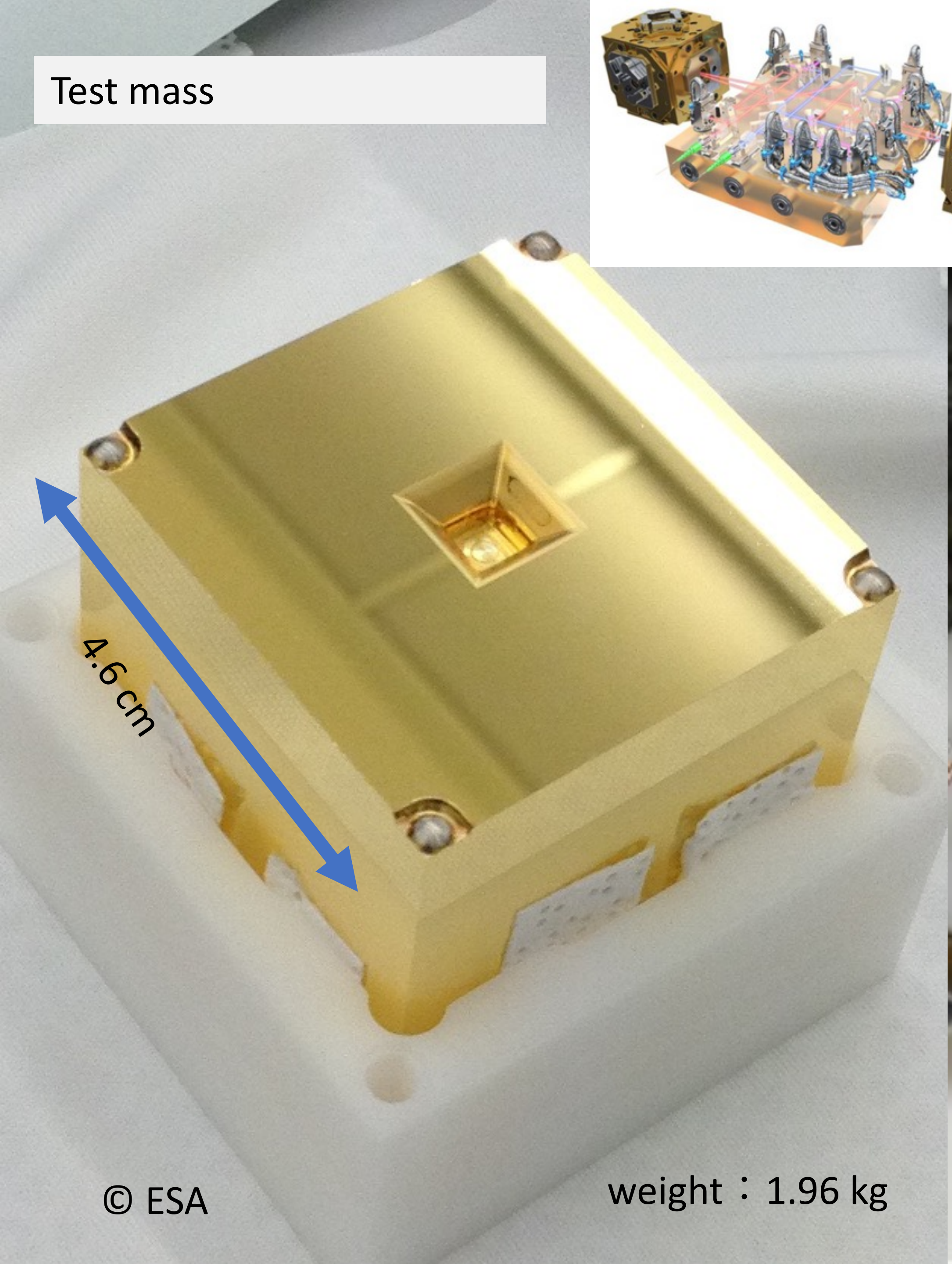
- Relative displacement of S/C then exerts force to test mass
  - Via gravitational and electro-magnetic and other couplings
- Necessary to precisely control S/C at ~nm/Hz$^{1/2}$
  - Low-noise thrusters (uN thrusters), precision local sensors

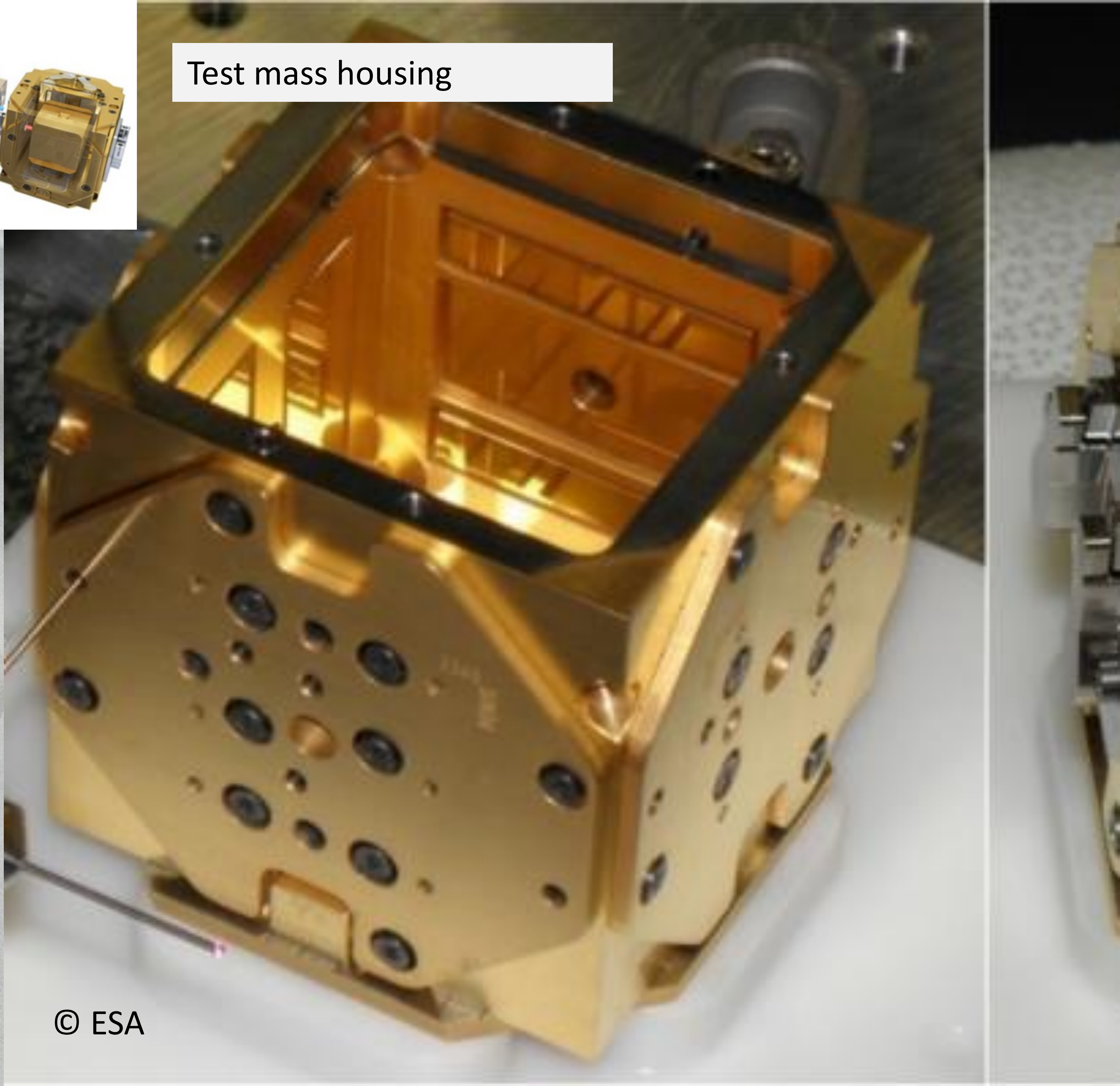


LISA Pathfinder

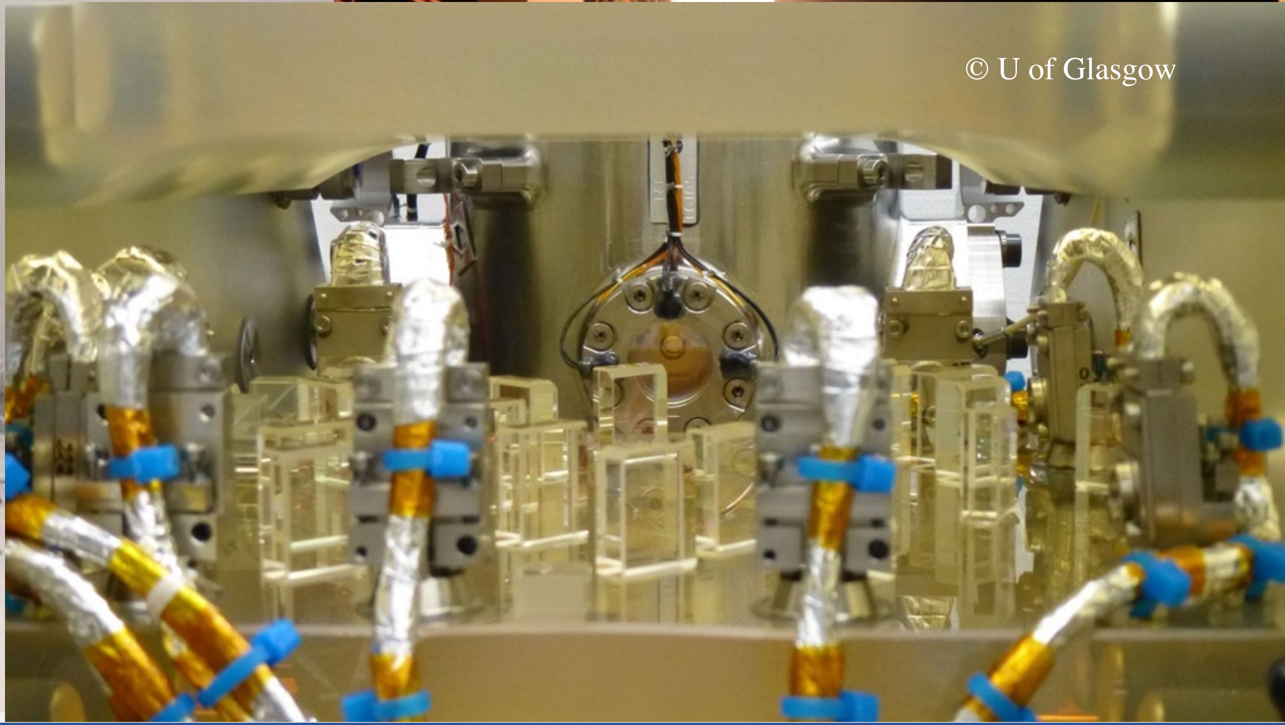
- ❖ 2015/Dec.: Launched (SE, L1)
- ❖ 2017/June.: Mission complete



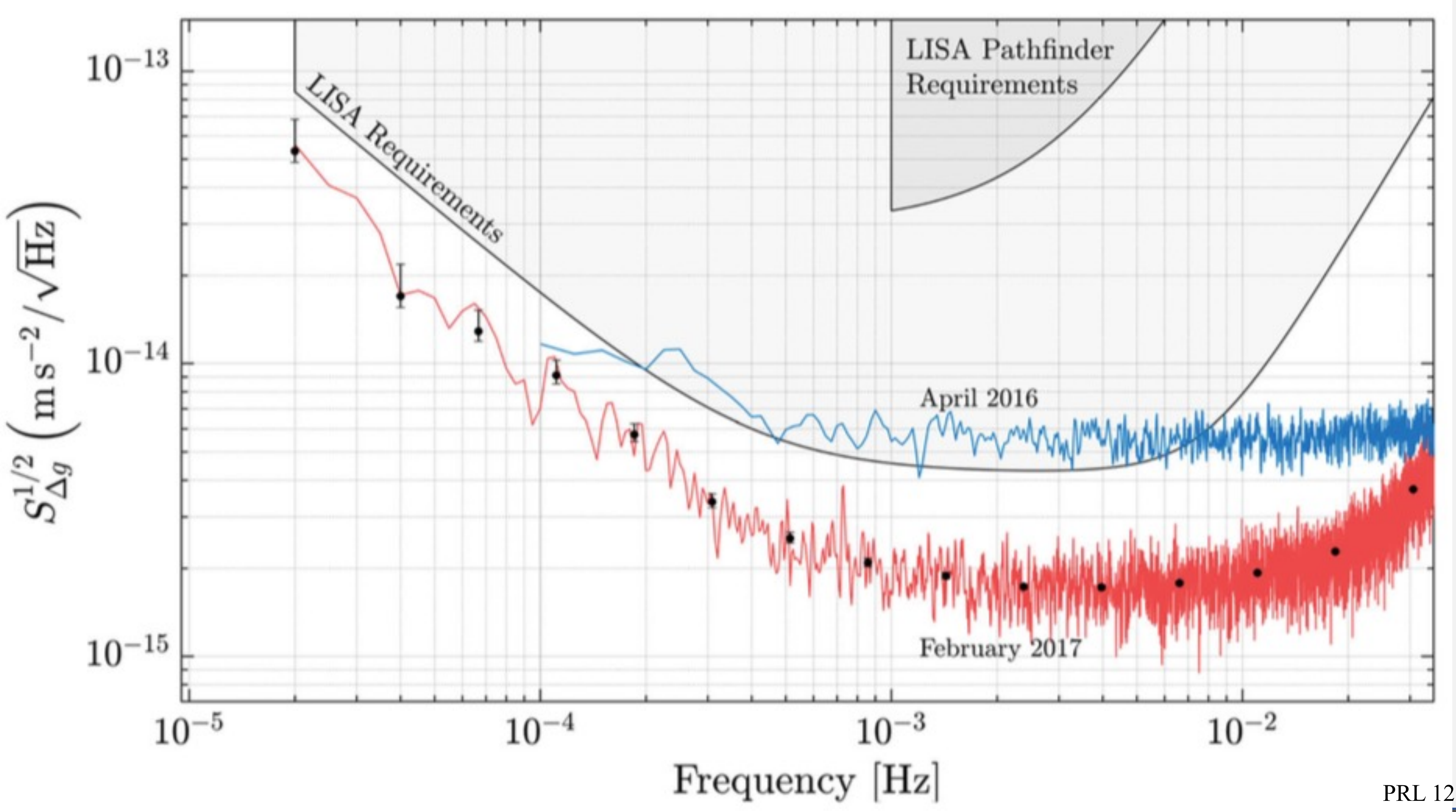

Test mass
4.6 cm
© ESA
weight：1.96 kg


Test mass housing
© ESA

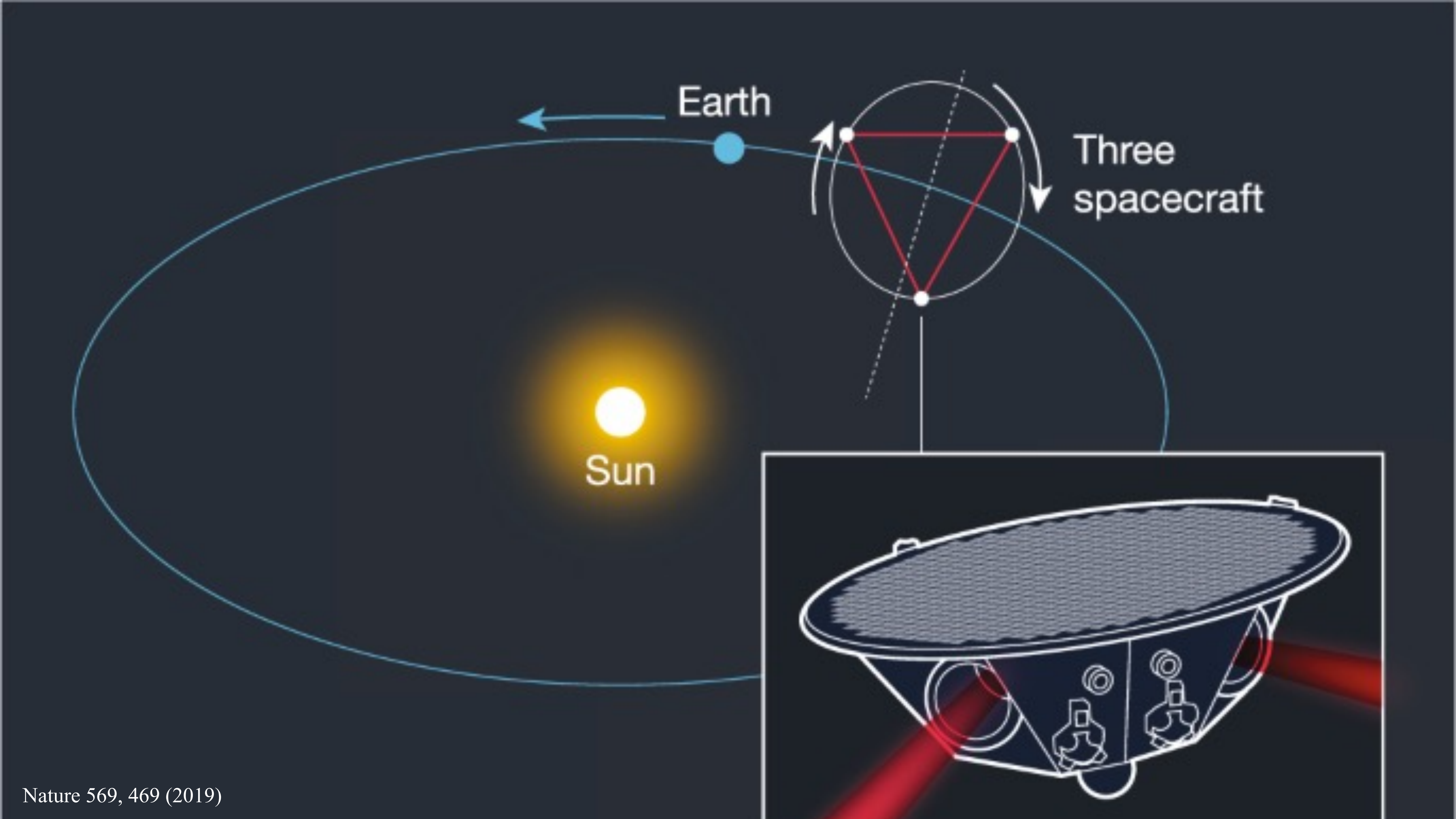
LPF pictures



Demonstration by LISA Pathfinder



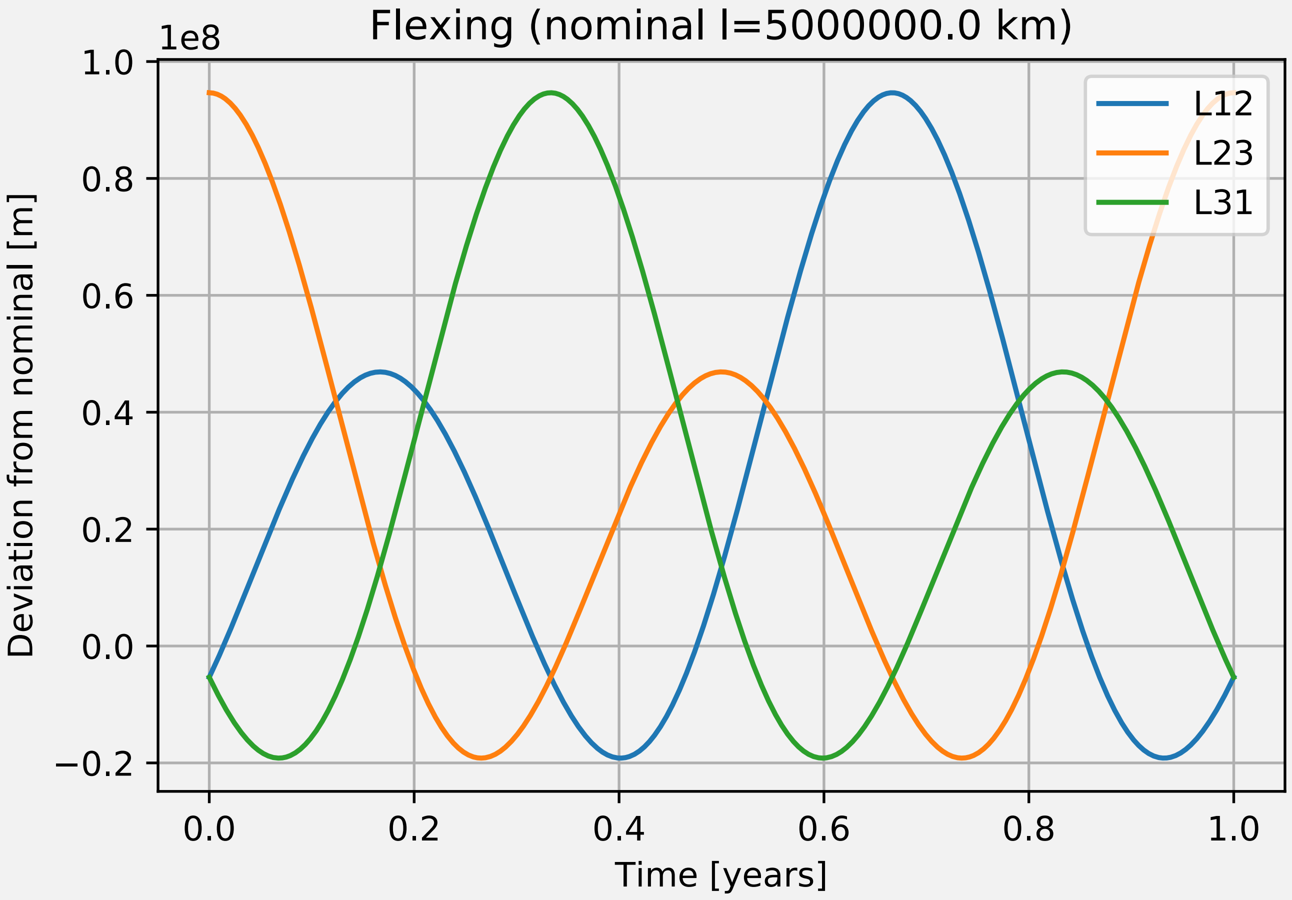
PRL 120, 061101 (2018)

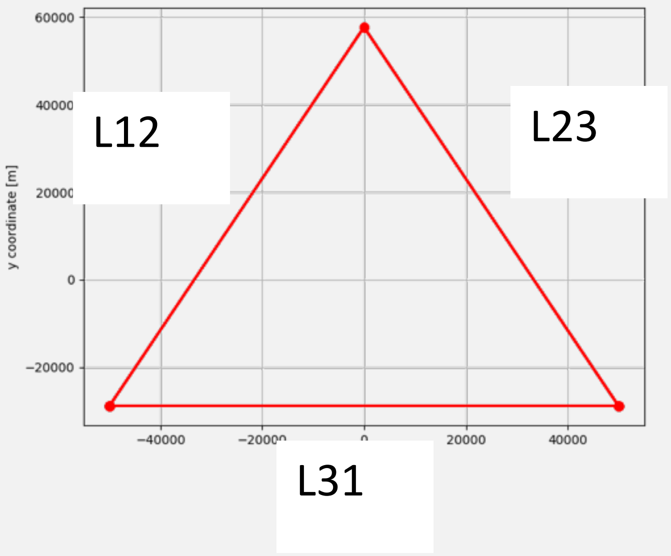


Nature 569, 469 (2019)

Constellation flying

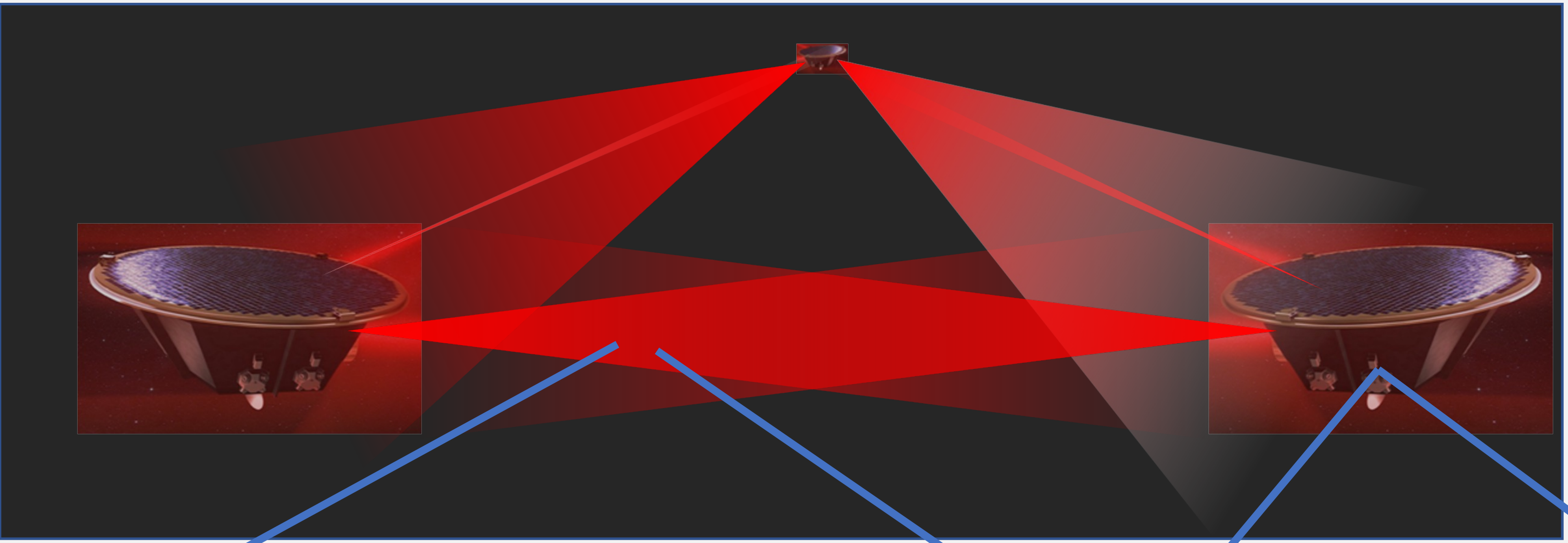
The distances between S/C vary as function of time in LISA





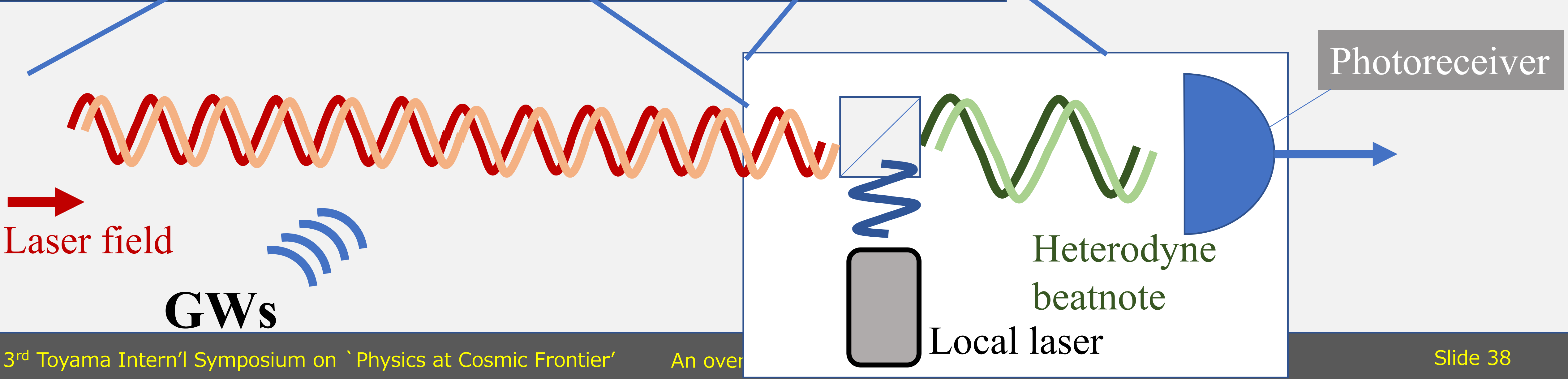
e.g.,
K Rajesh Nayak+, 2006 Class. Quantum Grav. 23 1763

Heterodyne interferometry



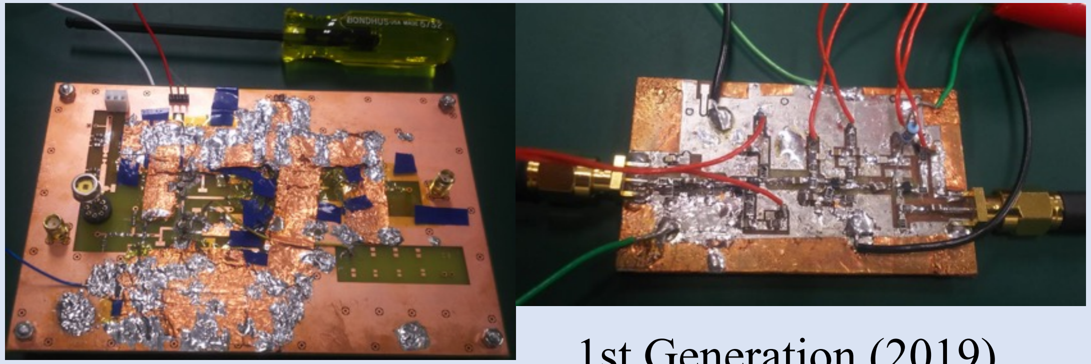
※Wavelength: 1064 nm

Equivalent to length measurement at ~ 10^{-12}m level precision

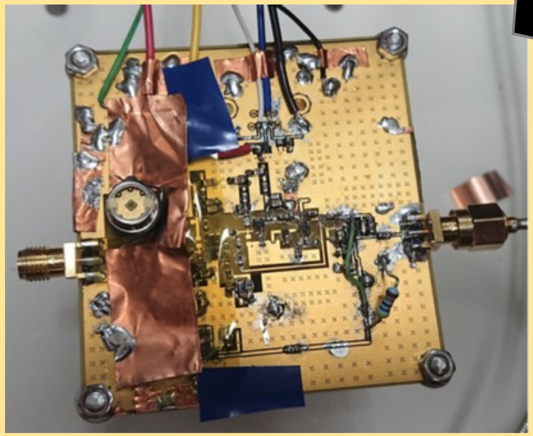


Photoreceiver development BBM study completed

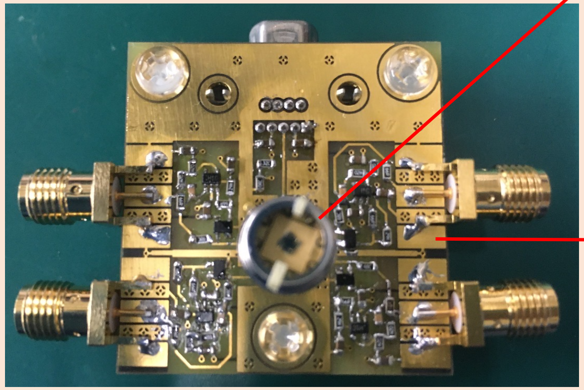
M. Kobayashi+, JPS meeting 17aK16-3 (2020)
KI+, Prog. Theor. Exp. Phys. (2020)
H. Okasaka+, JPS meeting 14pW3-7 (2021)
K. Komori+, JPS meeting 14aW3-9 (2021)



1st Generation (2019)



2nd Generation (2020)



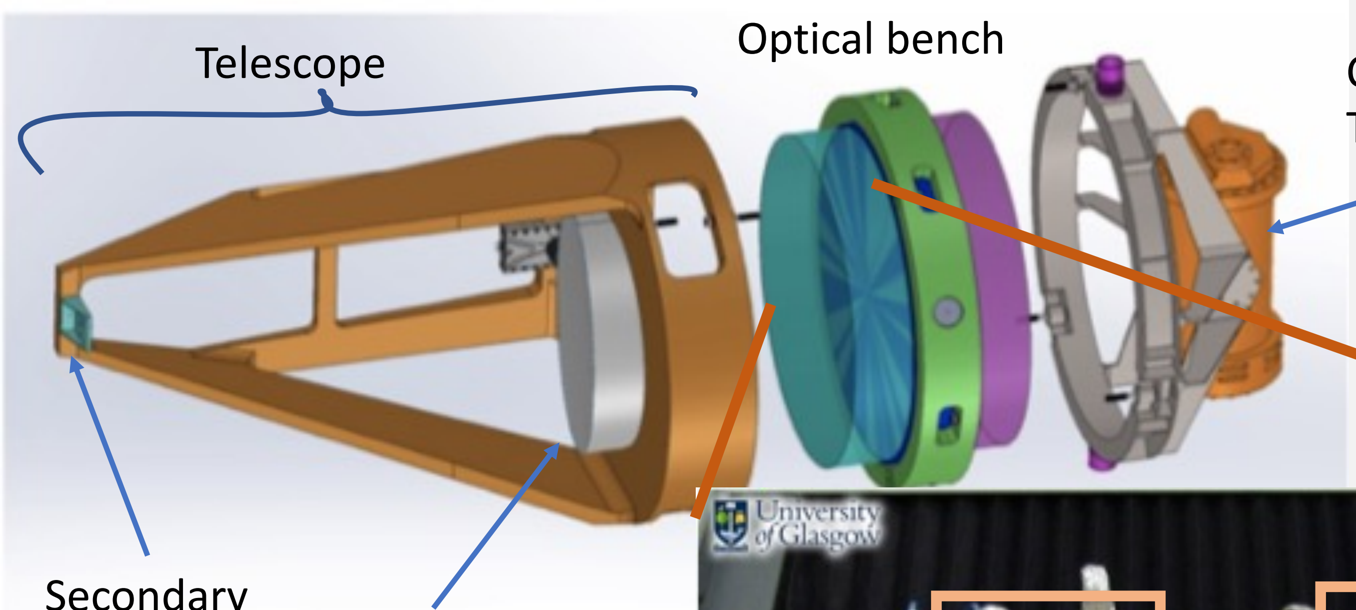
3rd Generation (2021)

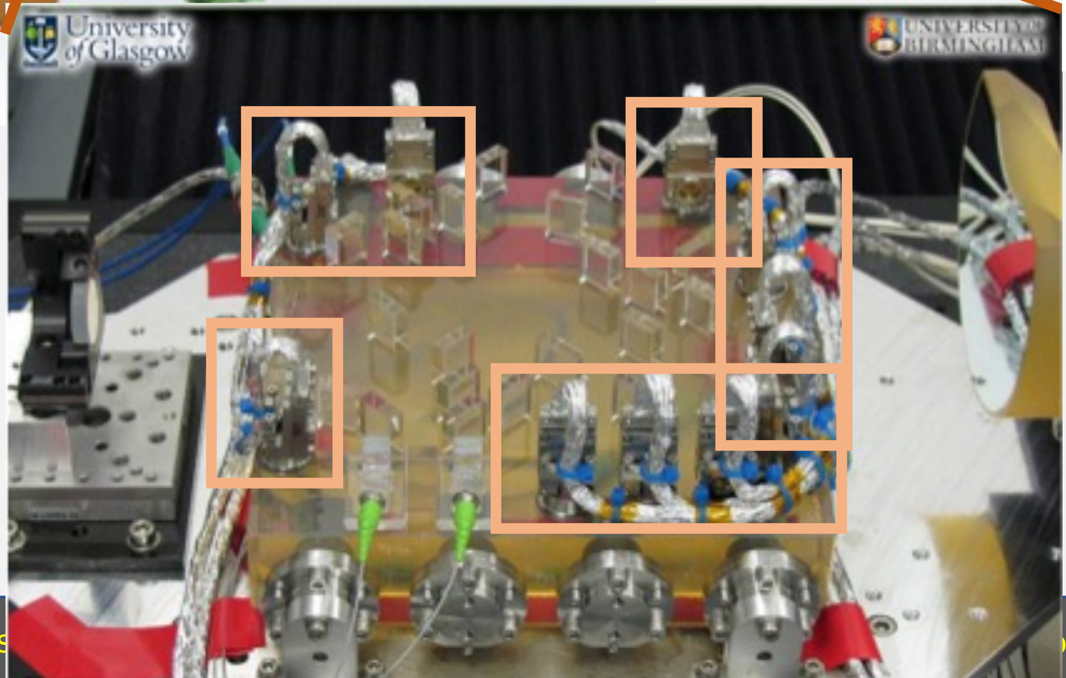
InGaAs PIN photodoide
Custom made by Hamamatsu Photonics
1.5mmφ, 4-segmented
Junction capacitance < 10 pF/seg

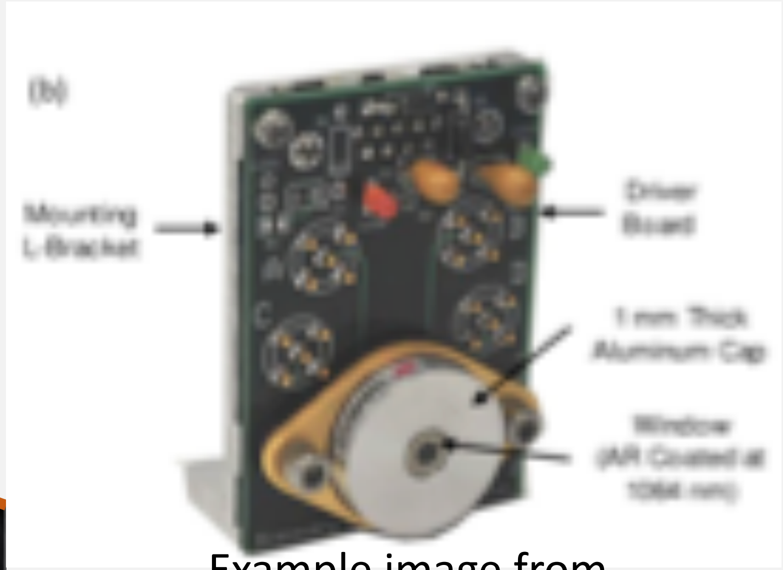
Low noise pre-amp
SiGe:C heterojunc. BJT
Bandwidth > 25 MHz
Power consump. ~20mW/seg
Size: ~ 40 mm x 40 mm

Ready for Engineering Model studies

Photoreceivers go here



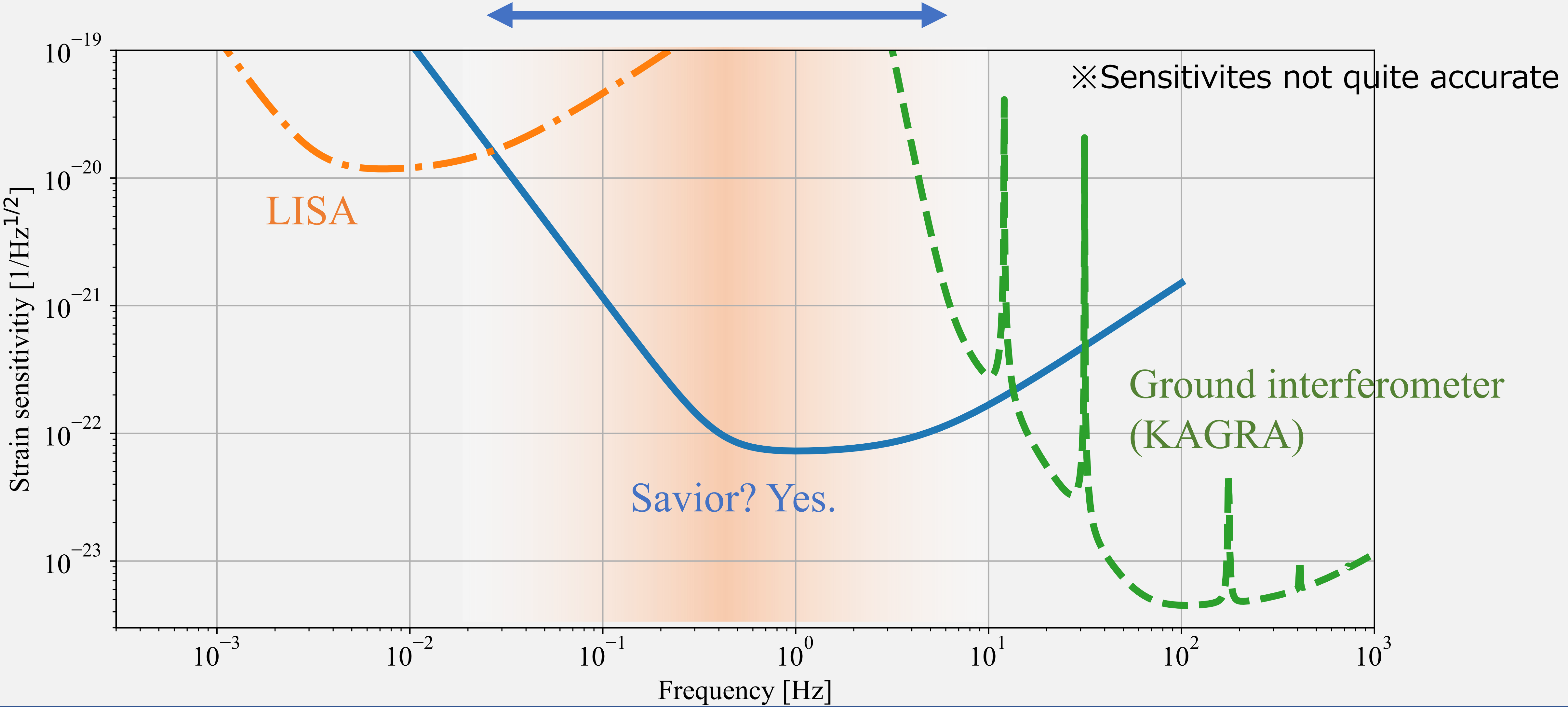




Example image from
Joshi et al., SPIE (2018)

100-200 of these are needed

Deci-Hertz band unexplored

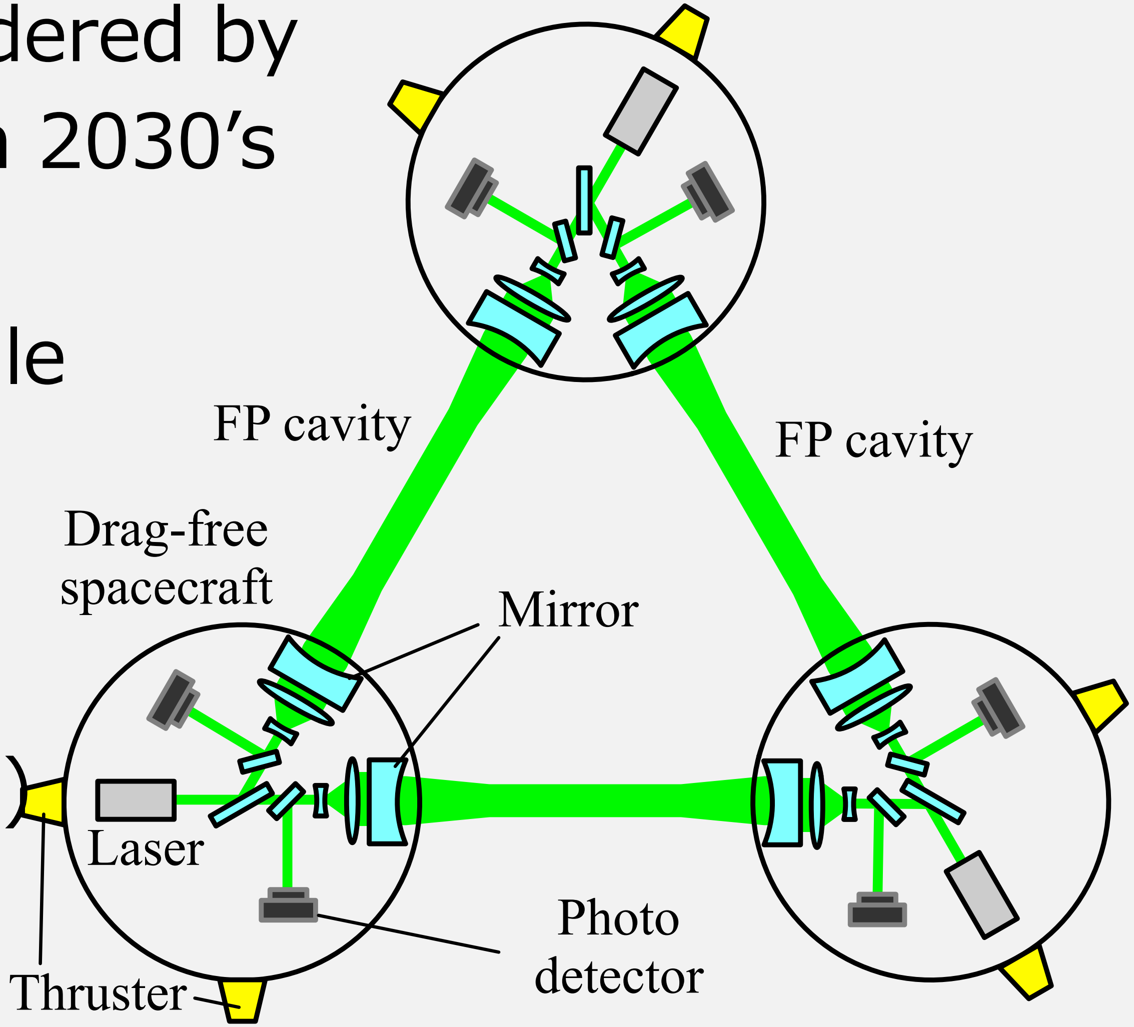


credit: B-DECIGO/S.Sato

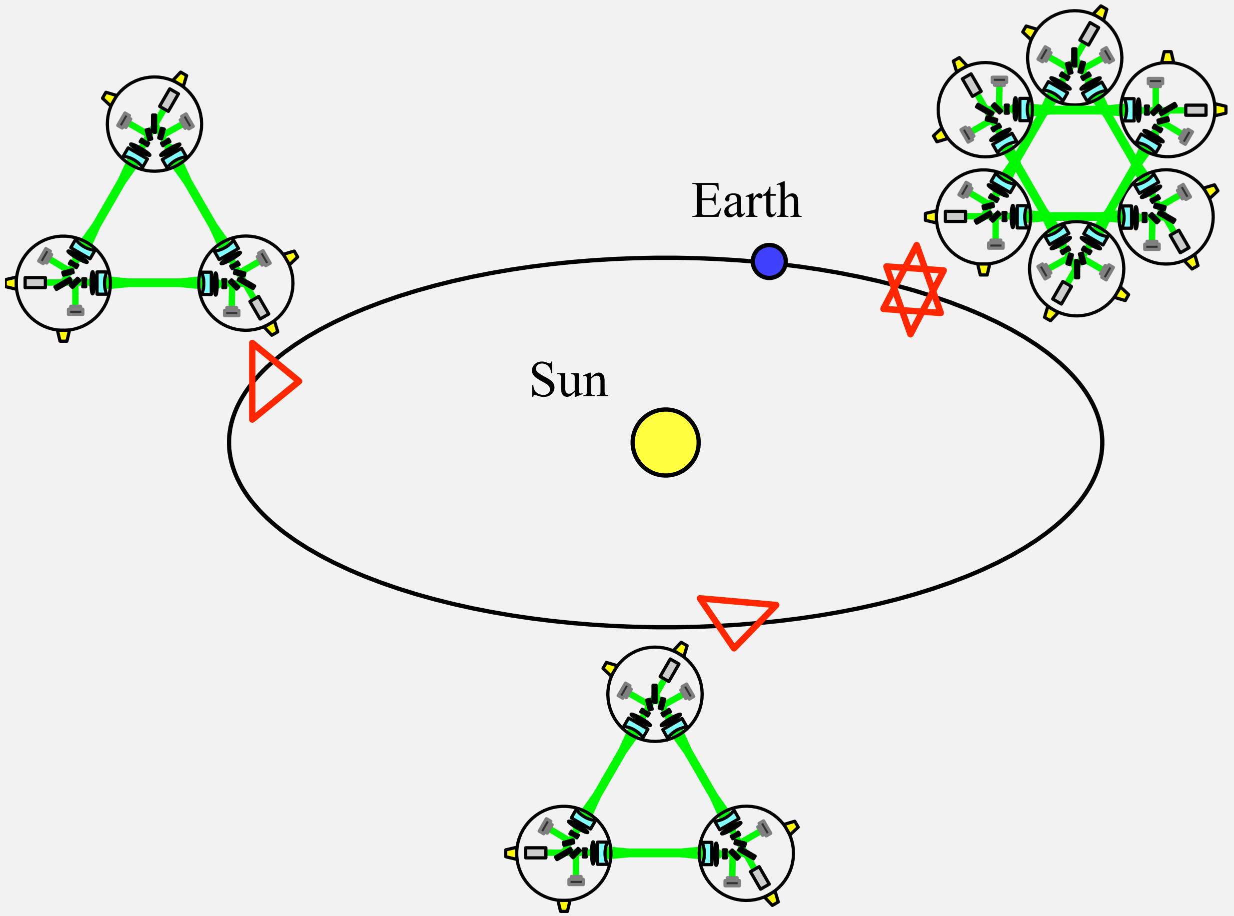
Here comes B-DECIGO

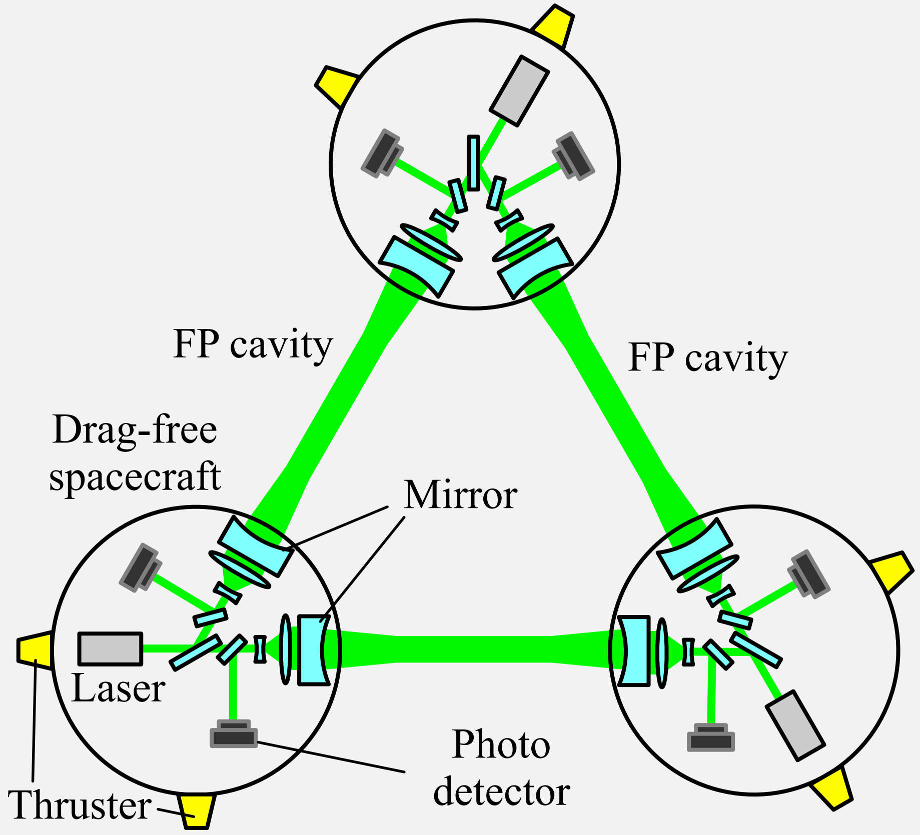
B-DECIGO

- ▶ 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
- ▶ Fabry-Perot resonators (requiring precision formation flying)



DECIGO: Japanese space mission concept





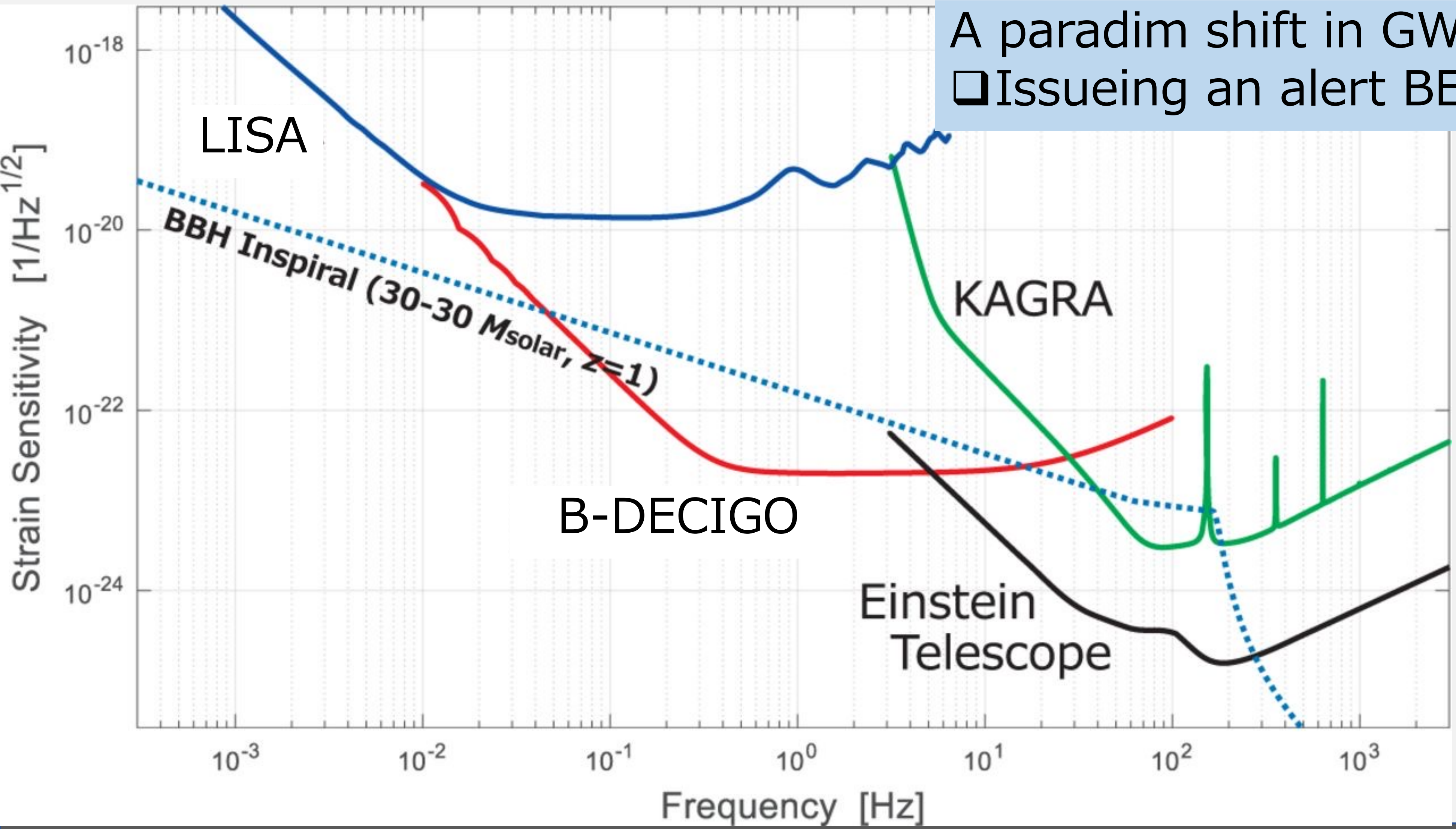
Pre-curser mission B-DECIGO, envisioned to launch in 2030s
Ultimate goal is direct detection of Primordial GW background at around 0.1 Hz

Multi-wavelength observation

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

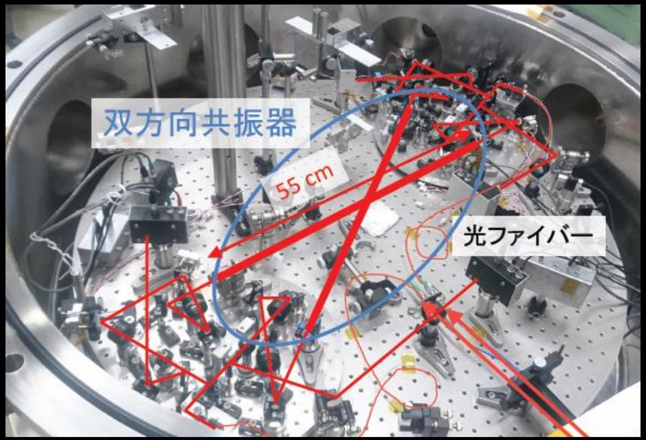
A paradim shift in GW astronomy

- ❑Issueing an alert BEFORE they merge!

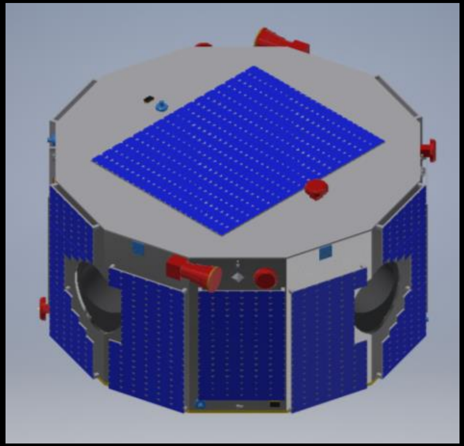


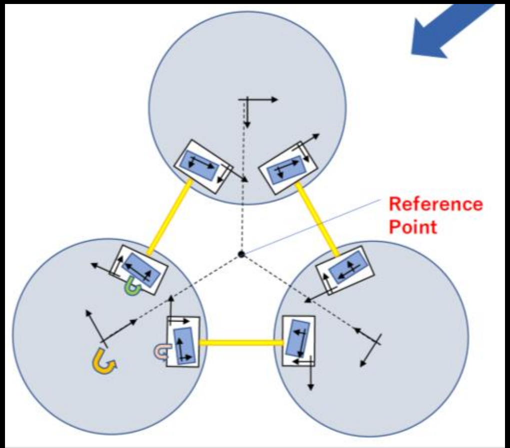
Technological studies

Credit: B-DECIGO/DECIGO collaboration

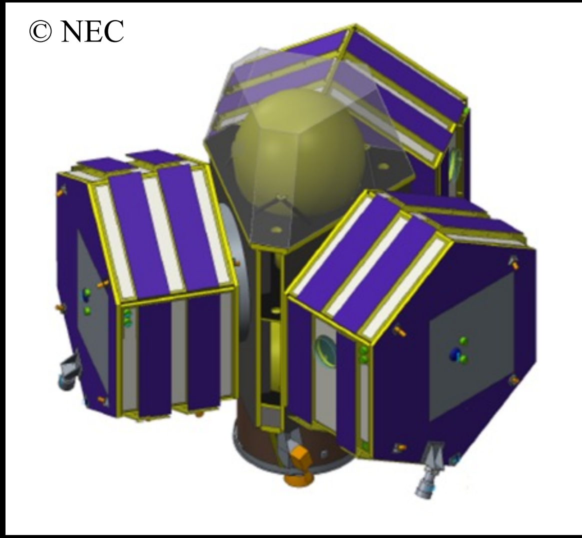


レーザー干渉計構成の動作実証 [東京大・理]

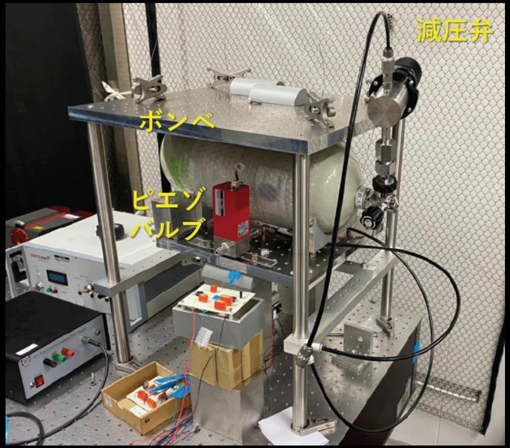




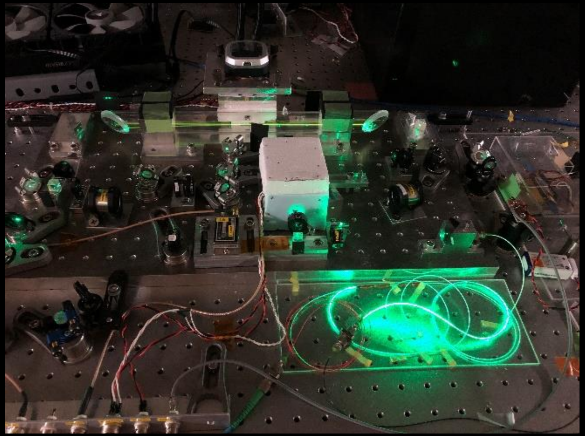
衛星システム・軌道・制御検討 [東京大・工, 法政大など]

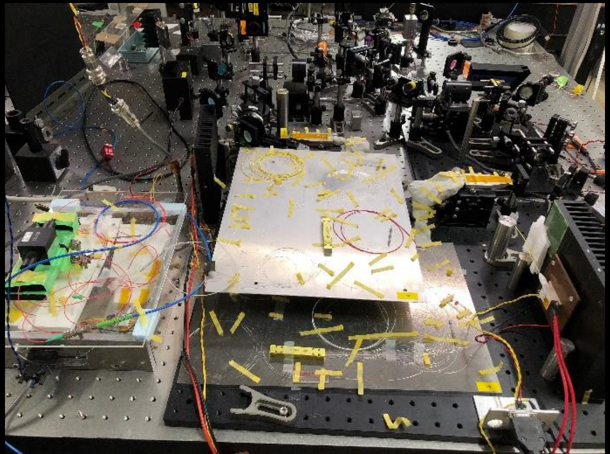


B-DECIGOのシステム検討
[NEC株式会社と協働]



低雑音スラスタの性能評価 [法政大]

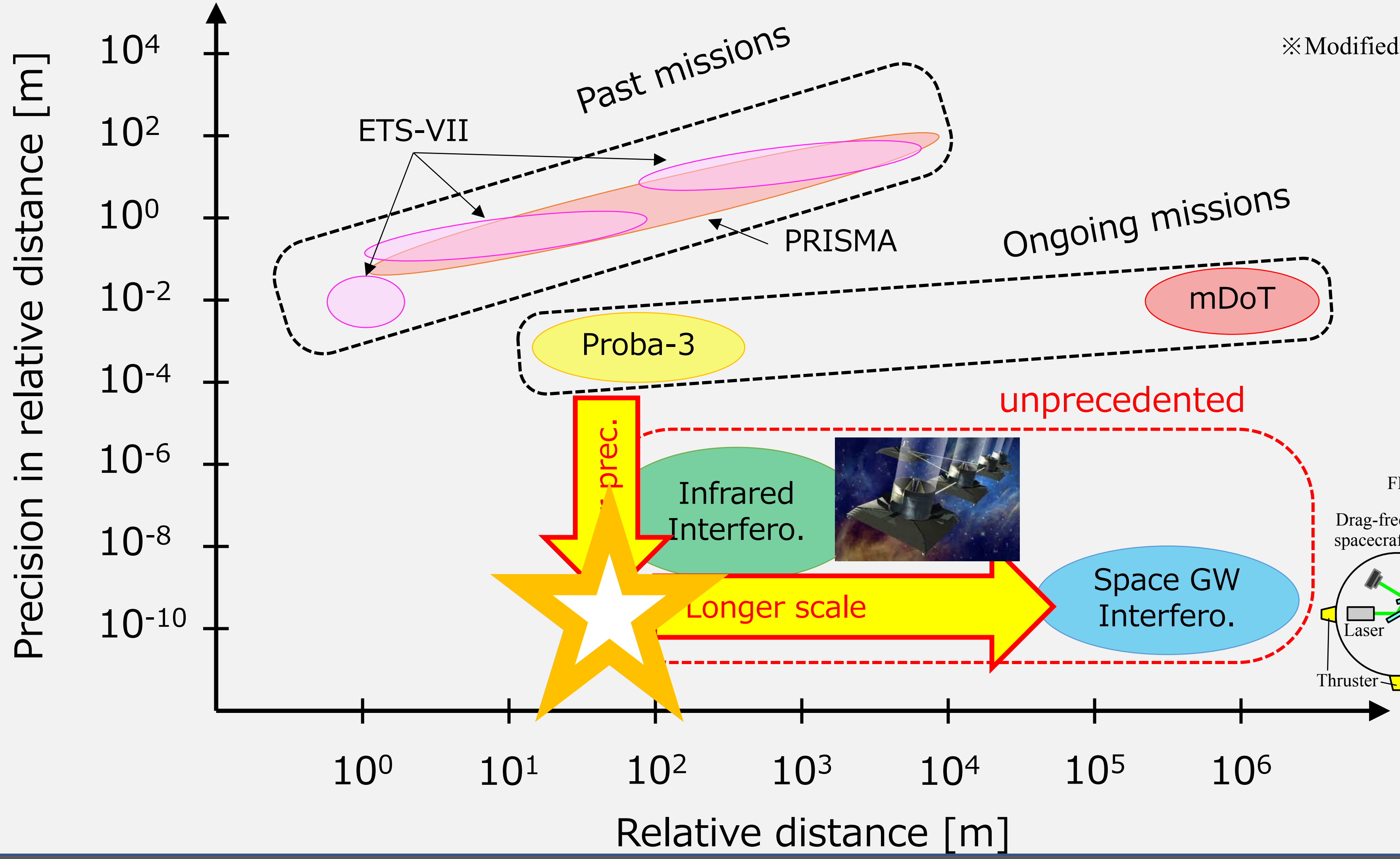


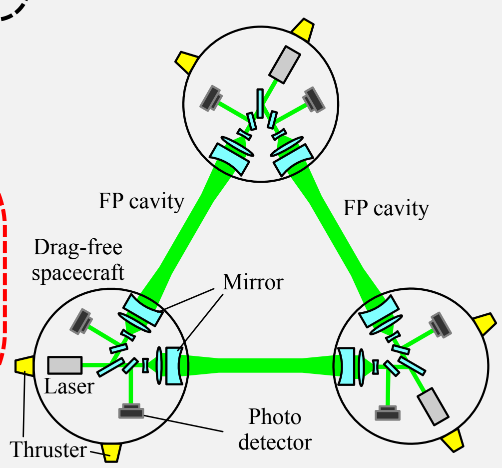


高出力・安定レーザー光源の開発 [電通大]

Another key: Formation Flying

※Modified from Formation Flying WG final report (2018)

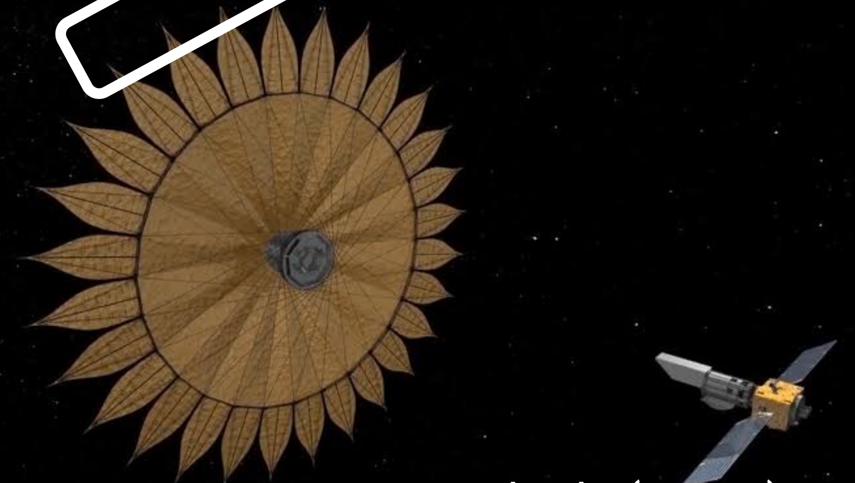




FF concepts to date

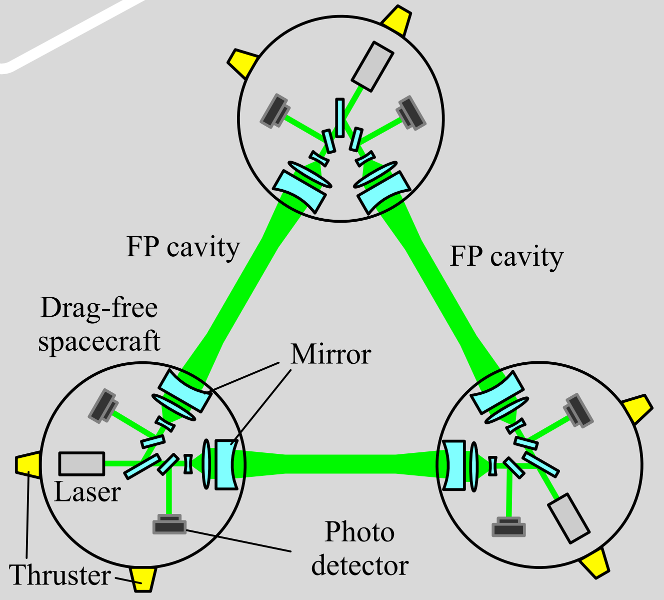
- A key for future space-based observatories

Occulter



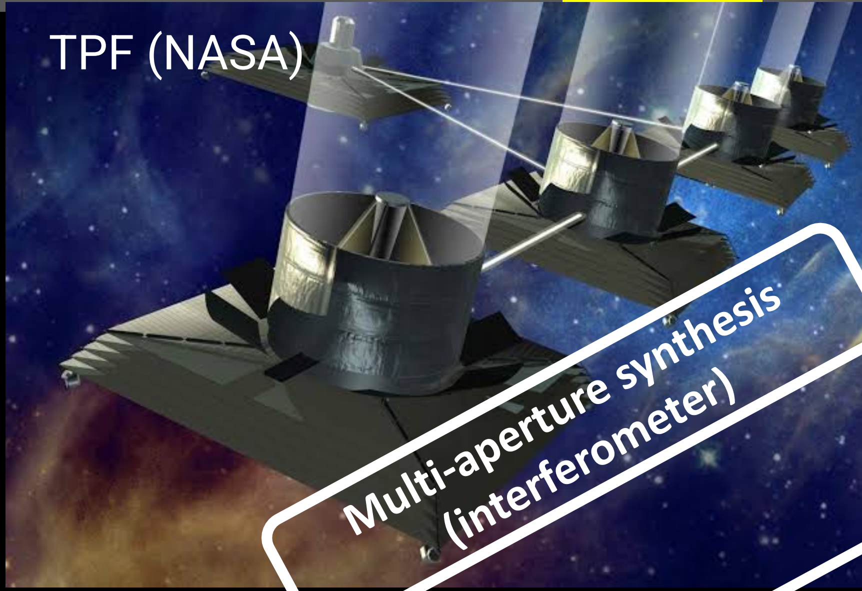
Starshade (NASA)

Gravitational wave observatories



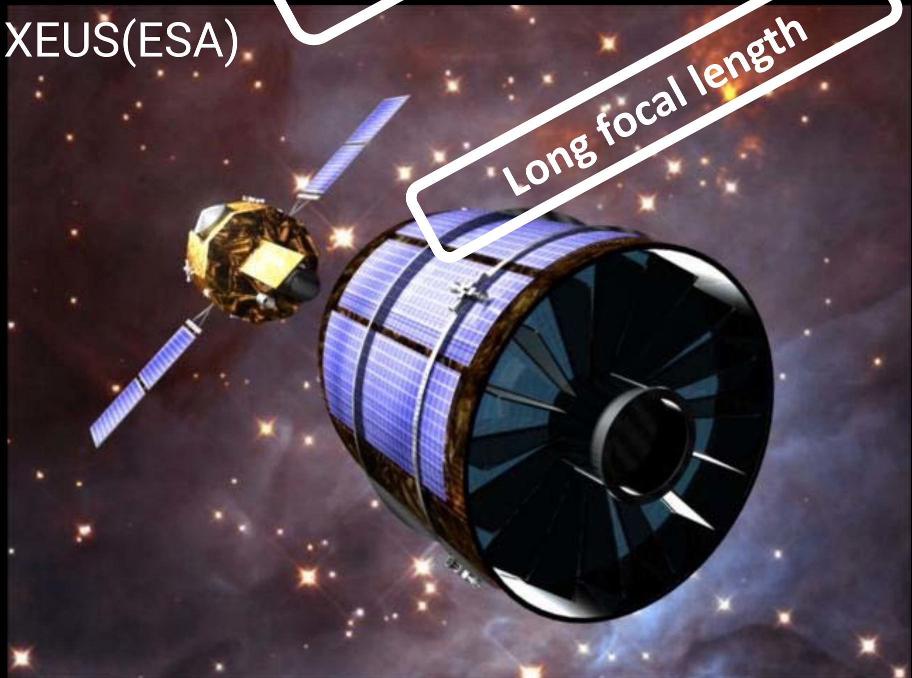
B-DECIGO/DECIGO (Japan)

TPF (NASA)



Multi-aperture synthesis (interferometer)

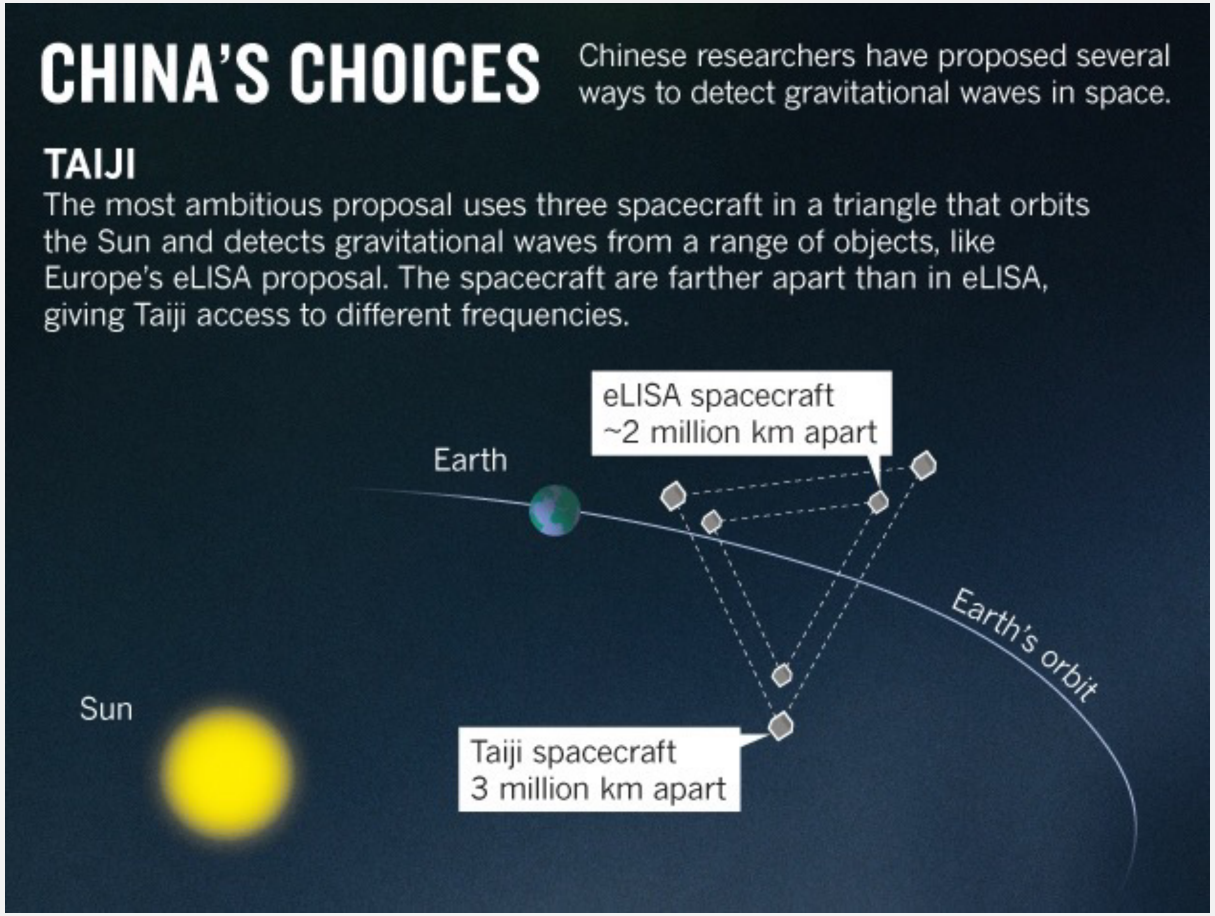
XEUS(ESA)

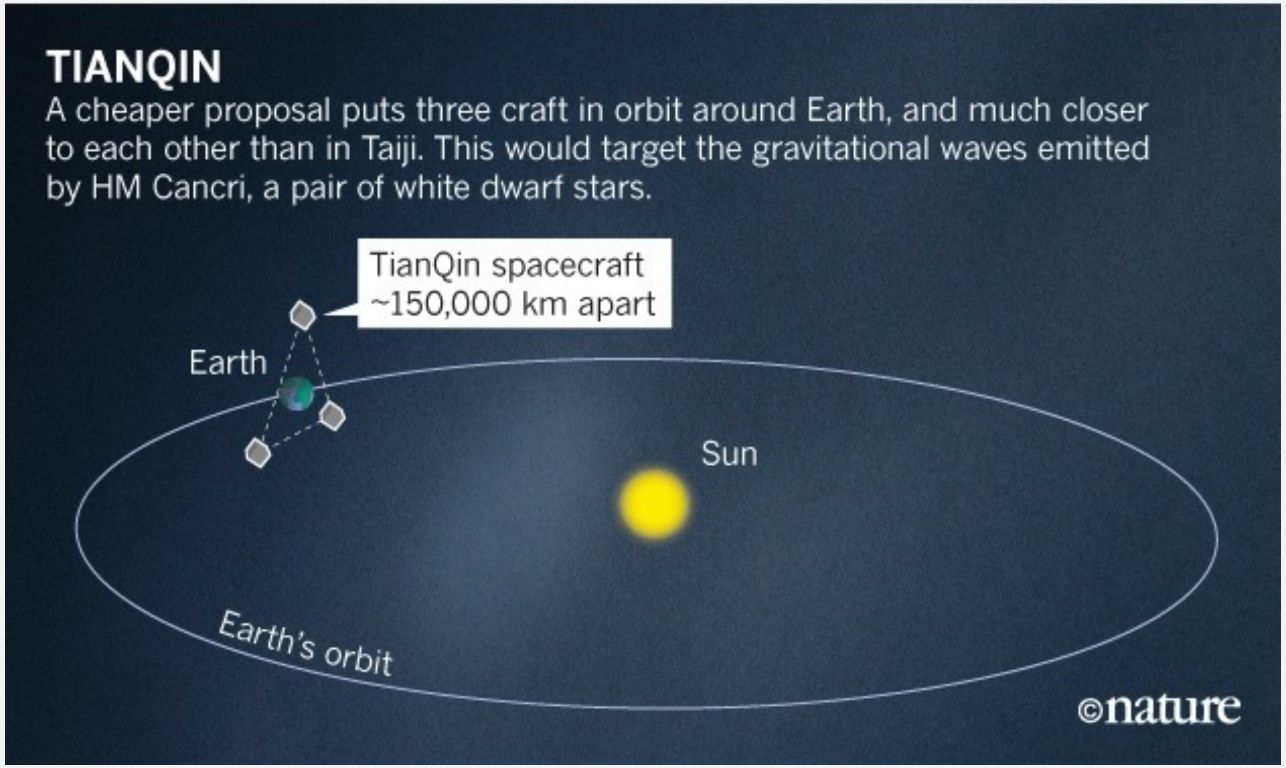


Long focal length

Rise of Chinese missions

- Two Chinese space gw mission concepts are independently being developed
- Aiming at launching in 2030's





Nature **531**, 150–151 (2016)

Summary

Observations of gravitational wave provide new insight into dark and relativistice universe.

Young researchers,
It is time to jump into the field of space gravitational wave observations

Inquiries should be sent to
kiwamu@astro.isas.jaxa.jp