Space Gravitational wave

Experiments

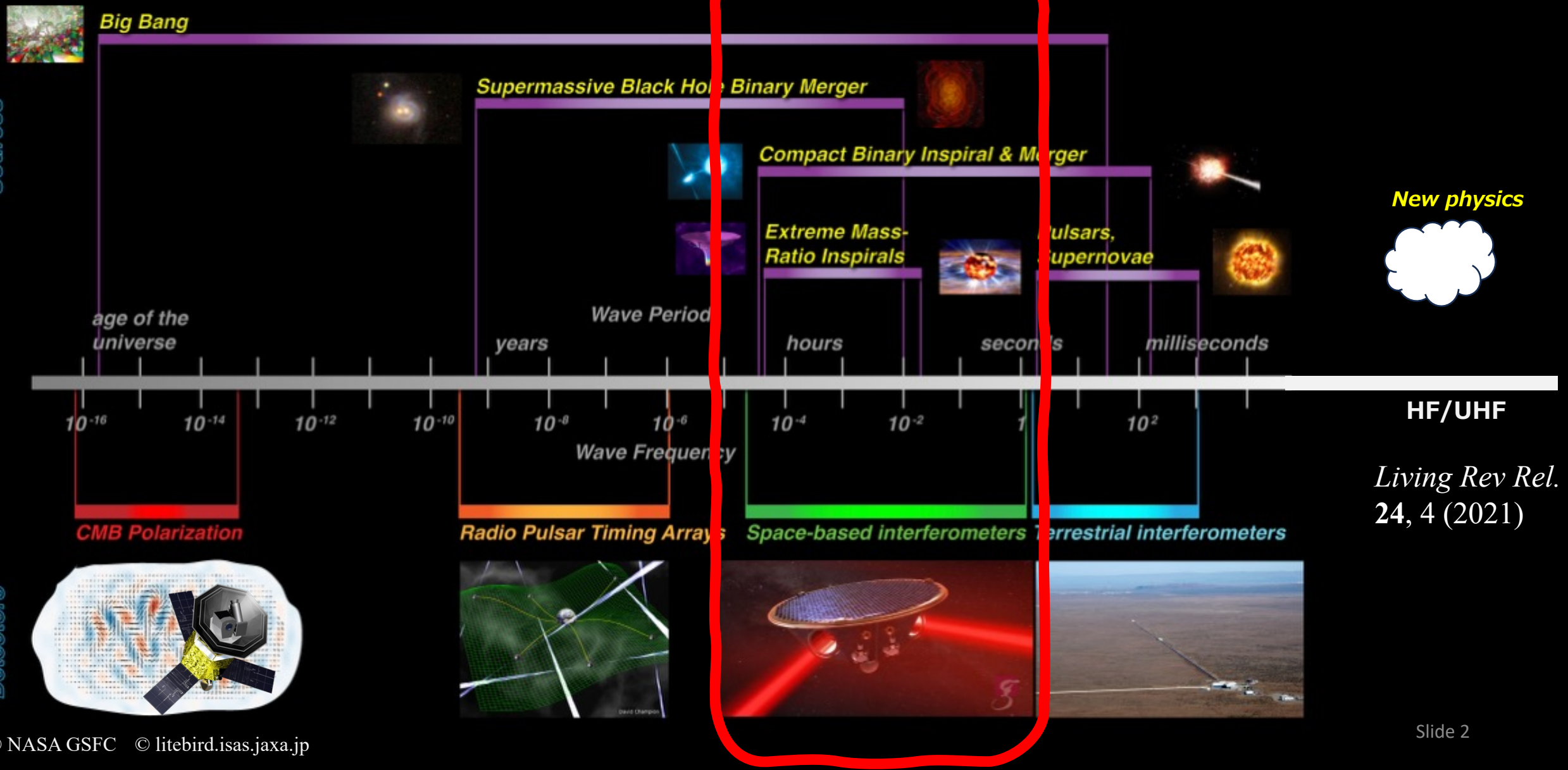
Kiwamu Izumi
(ISAS/JAXA)

Q-eyes, Tsukuba Japan, 2025/Dec/10

Talk plan

- Astrophysical capability of space GW detectors
- Instrumentation activities in our lab
- Some advanced topics

Gravitational wave spectrum



Living Rev Rel. **24**, 4 (2021)

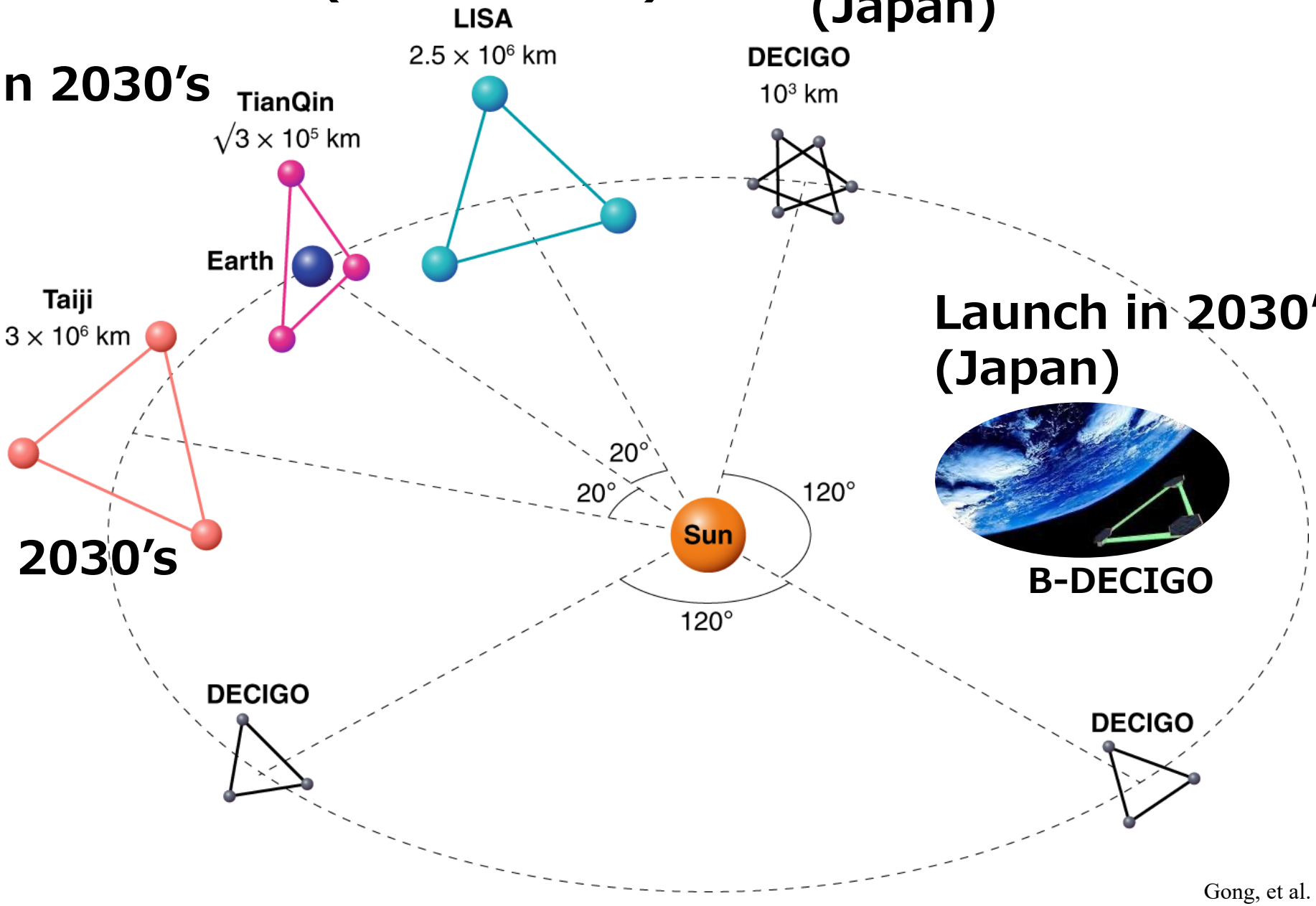
Launch in 2035 (ESA + NASA)

Launch in 2040's or beyond? (Japan)

Launch in 2030's (China)

Launch in 2030's (Japan)

Launch in 2030's (China)

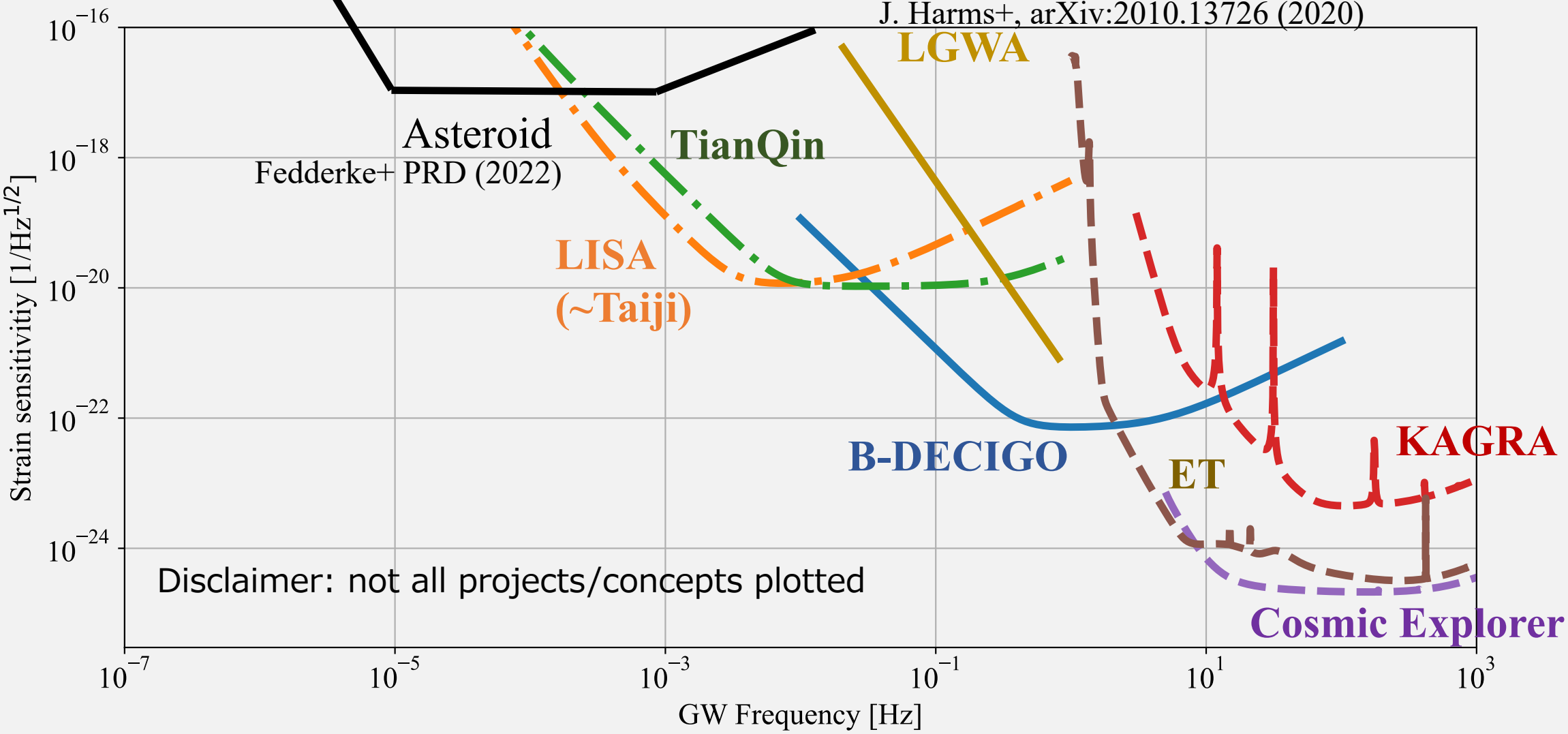


B-DECIGO

Gong, et al. Nature Astron. (2021)

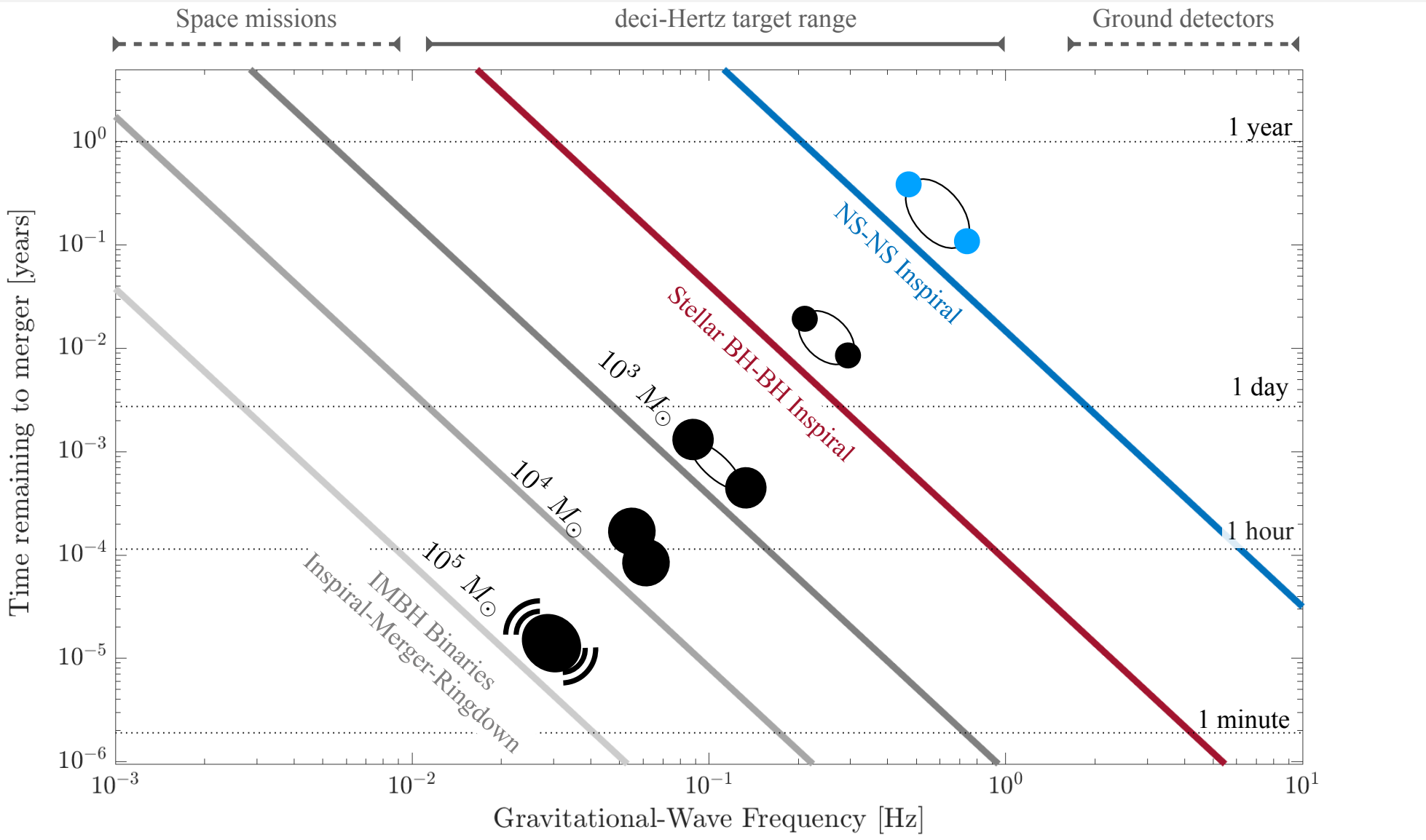
A future landscape

PTAs



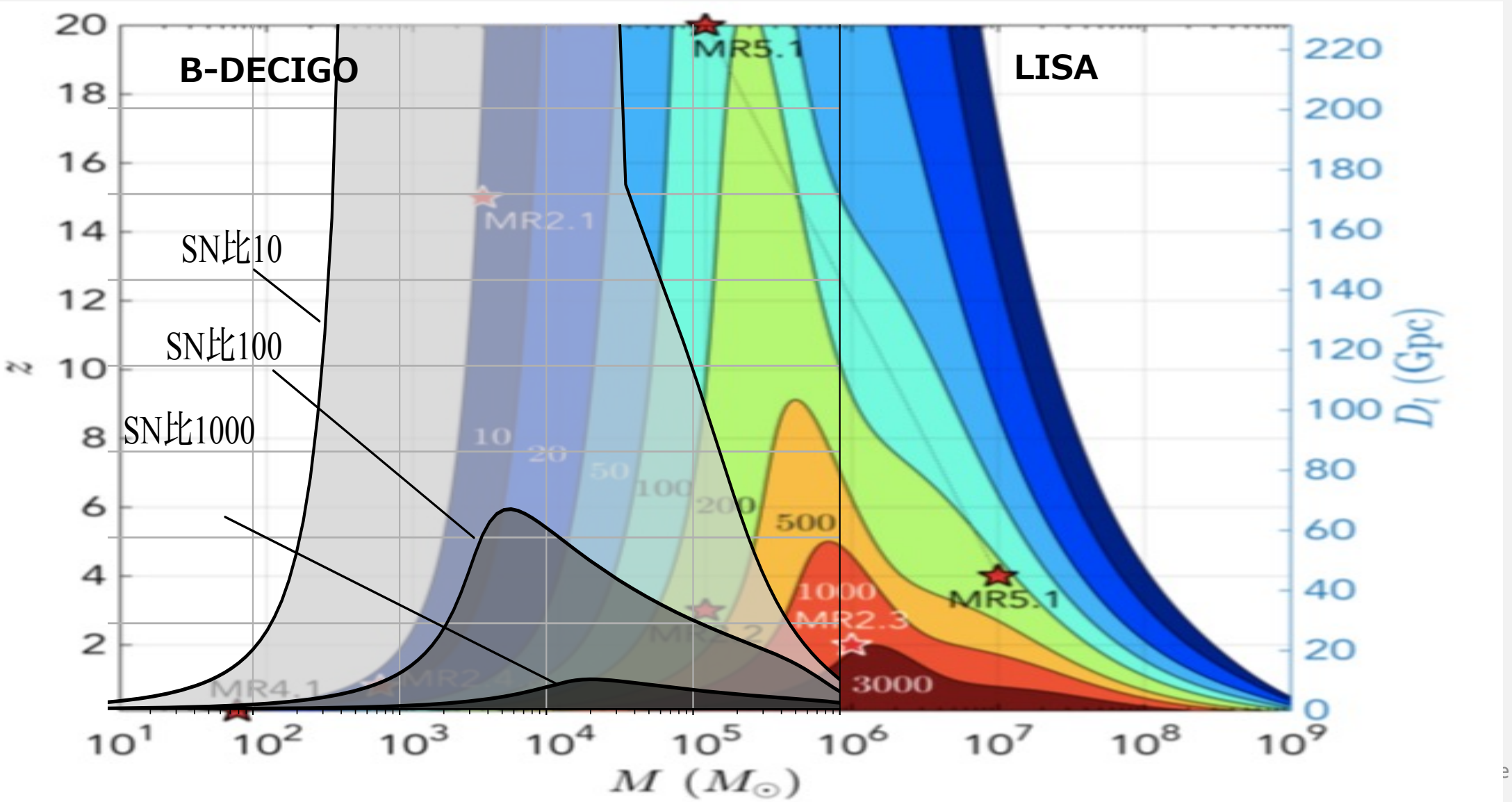
Binary sources

KI and K. Jani, Springer (2022)



Astrophysical reach

Caveat: unofficial



Proactive MMA

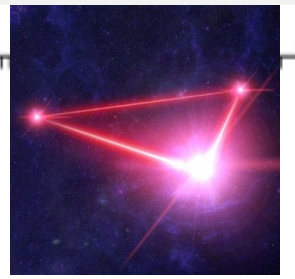
- **Early alert for BNS merger**

B-DECIGO can predict the sky position for BNS@z=0.1 with $\Delta\Omega = 1\text{x}10^{-3}$ [deg^2] before merger

- **One can plan ahead**

Predicting host galaxies
Simultaneous observation campaign

Plot from Isoyama+, PTEP (2018)



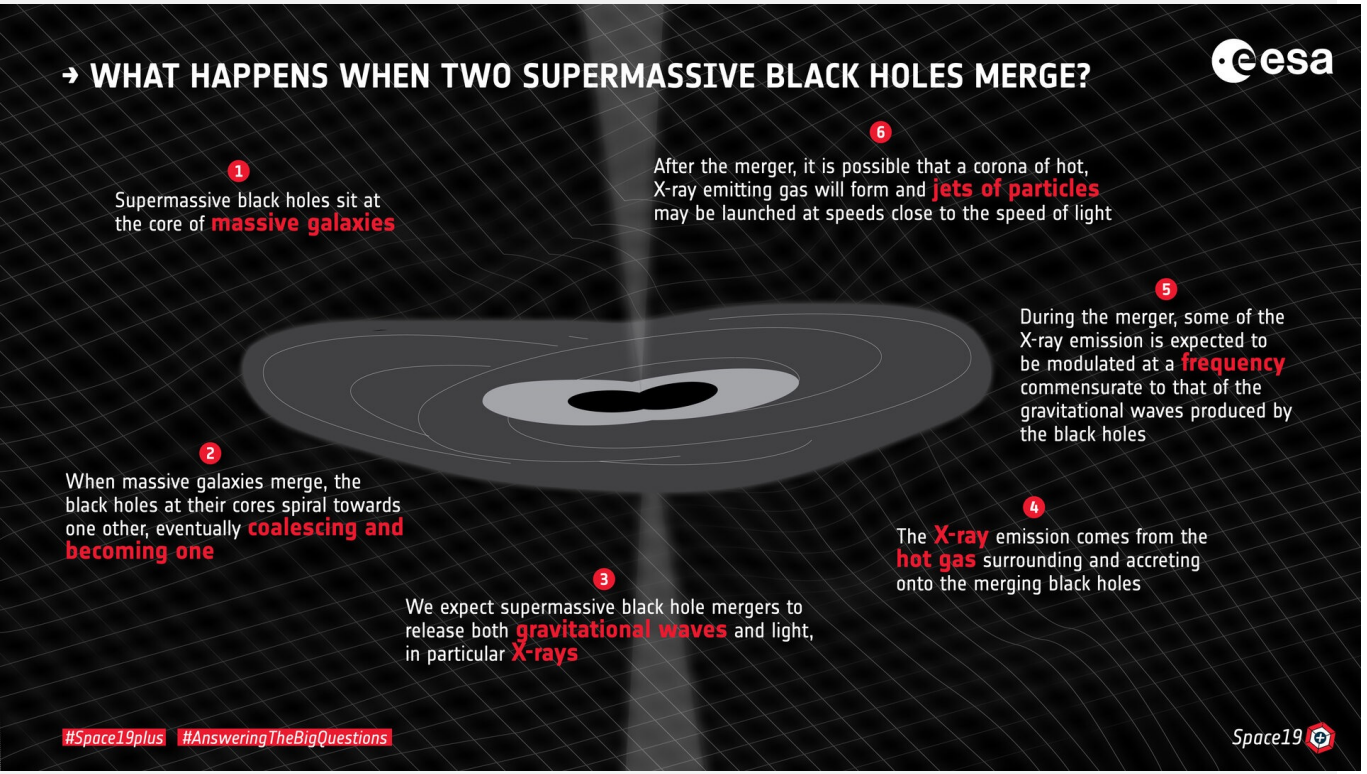
© LISA/ESA

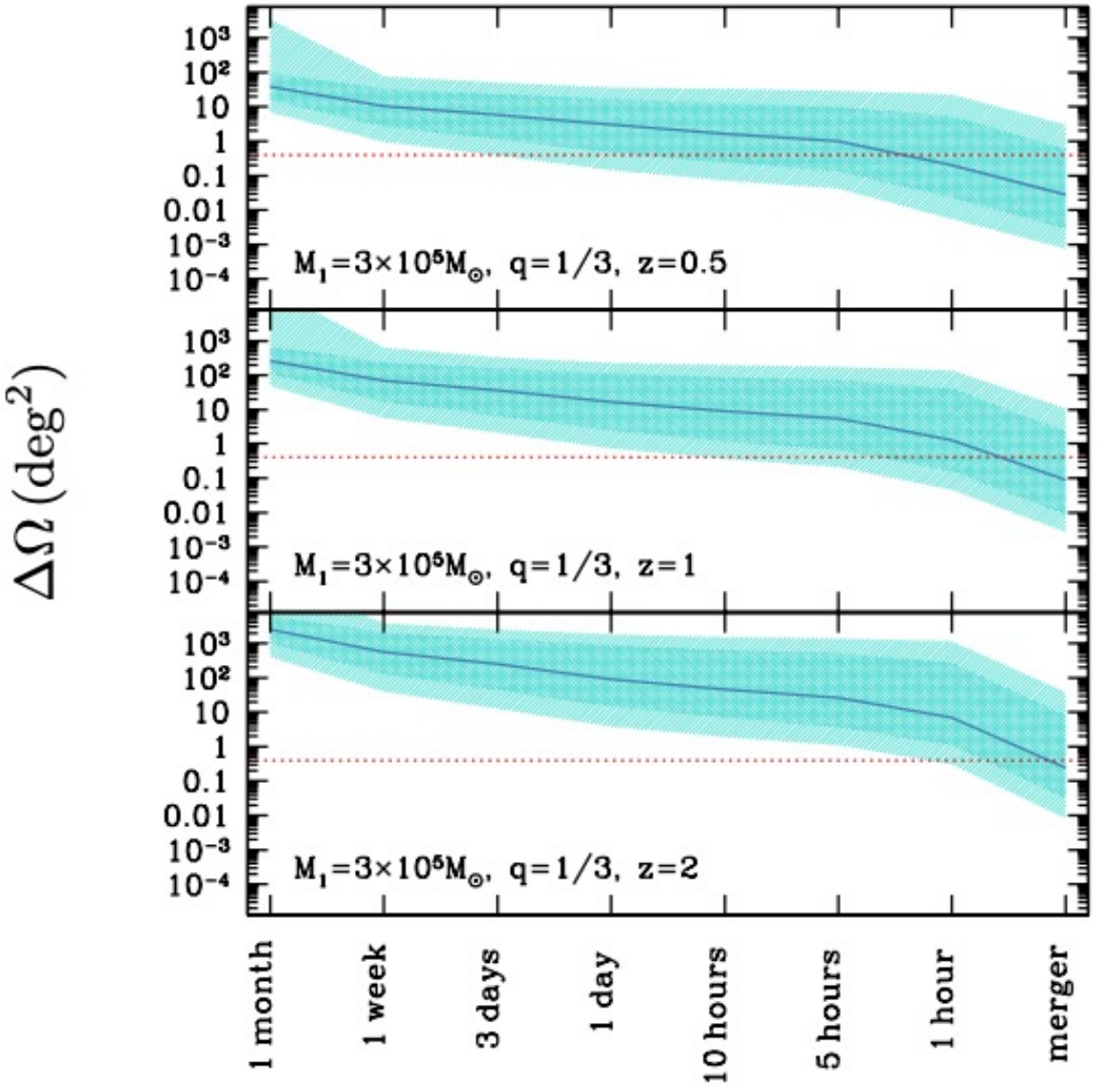
© B-DECIGO

SMBH merger with GW+X-ray

M. Colpi+, Athena-LISA Synergies (2019)

- LISA identifies SMBH, estimating the sky position
- X-ray telescope (Athena) looks for it in FOV 0.4 deg^2





Probing inflationary Universe

- Reheating energy scale provides hints for inflatons
  - Thermal history of early Universe
- Reheating energy scale changes the transfer function
  - Resulting in different PGW spectra [1]
- Complementary to ongoing CMB experiments
  - LiteBIRD, ground-based CMB expreiments
- Additionally a variety of experiments
  - Parity violation [2]
  - Searches for vector and/or scalar modes [3]

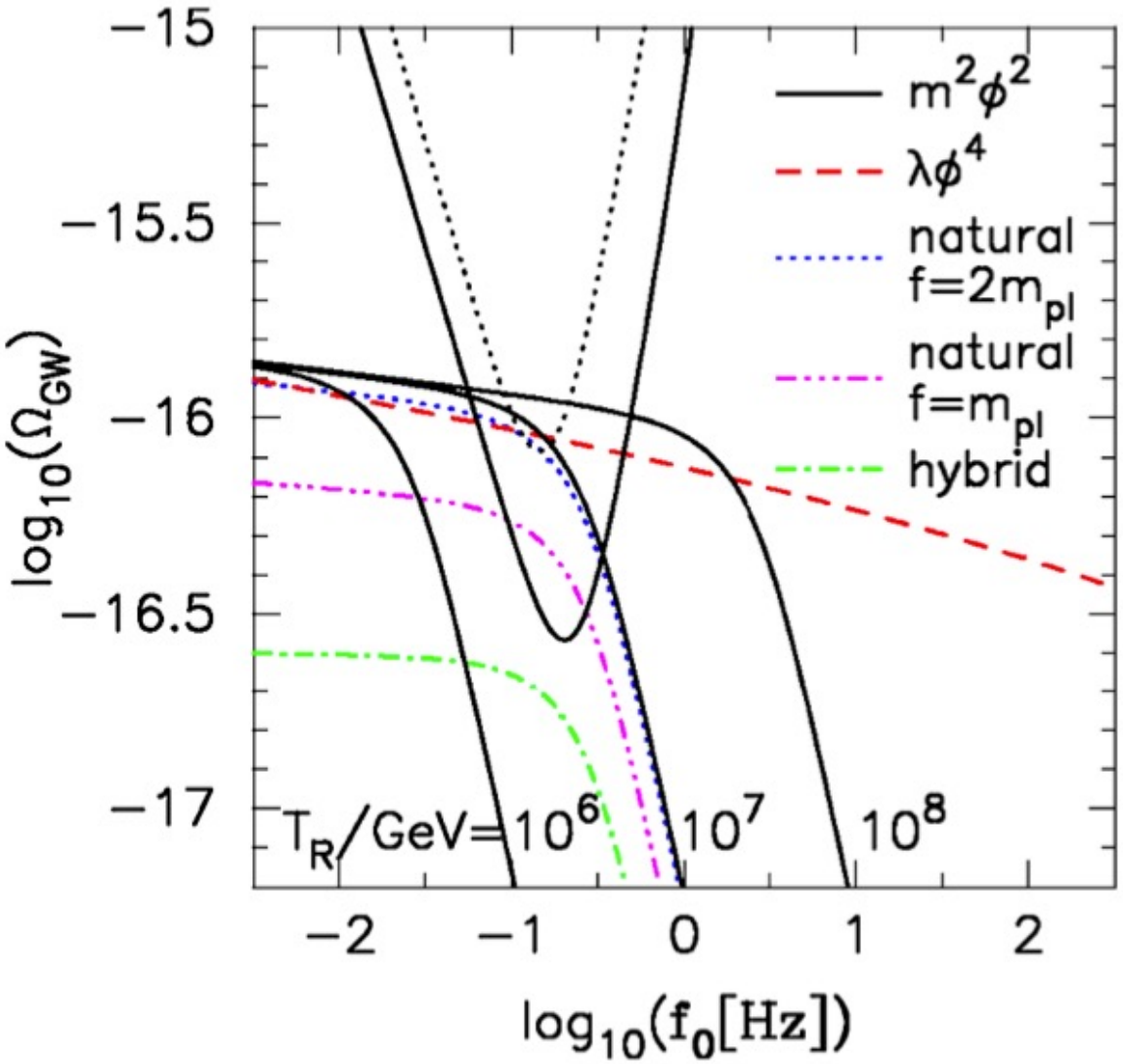


Figure Kuroyanagi+, Phys. Rev. D 83, 043514 (2011)

[1] Nakayama+ JCAP 2009
[2] Seto 2007
[3] Nshizawa+, 2010

Cosmology with high angular resolution

Credit: Claire Lamman/DESI collaboration
https://newscenter.lbl.gov/2025/03/19/new-desi-results-strengthen-hints-that-dark-energy-may-evolve/

Binary signal gives the luminosity distance d_L

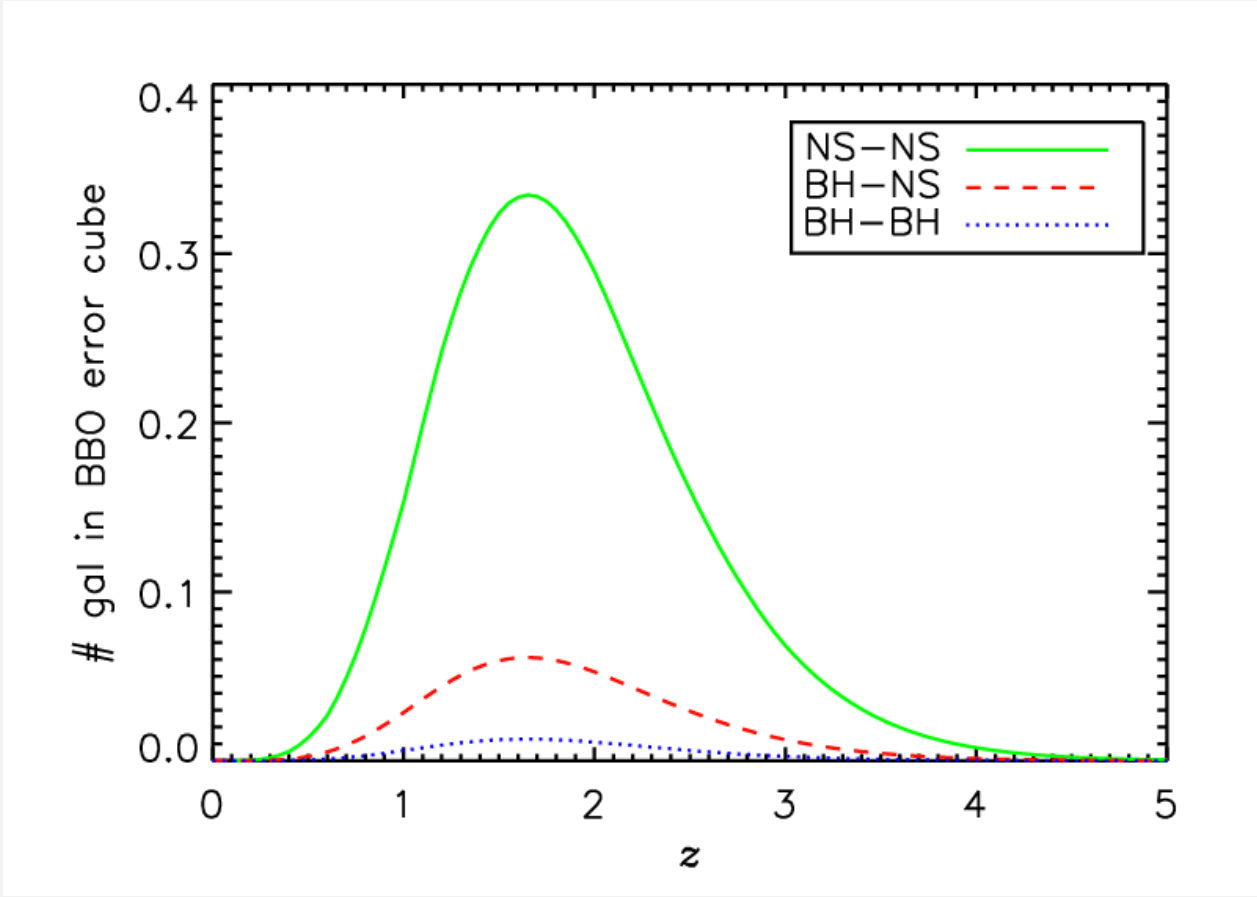
$$h \propto \frac{G}{c^4 d_L} \frac{d^2 Q}{dt^2}$$

Q: quadrupole moment

In case of DECIGO or similar, the angular resolution is high enough to identify the host galaxy

Yet another observation tool for cosmology

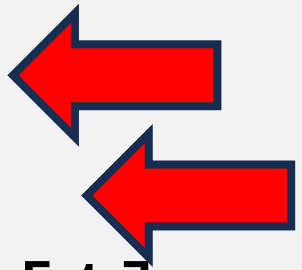
Phys. Rev. D, 80, 104009 (2009)



Instrument activities

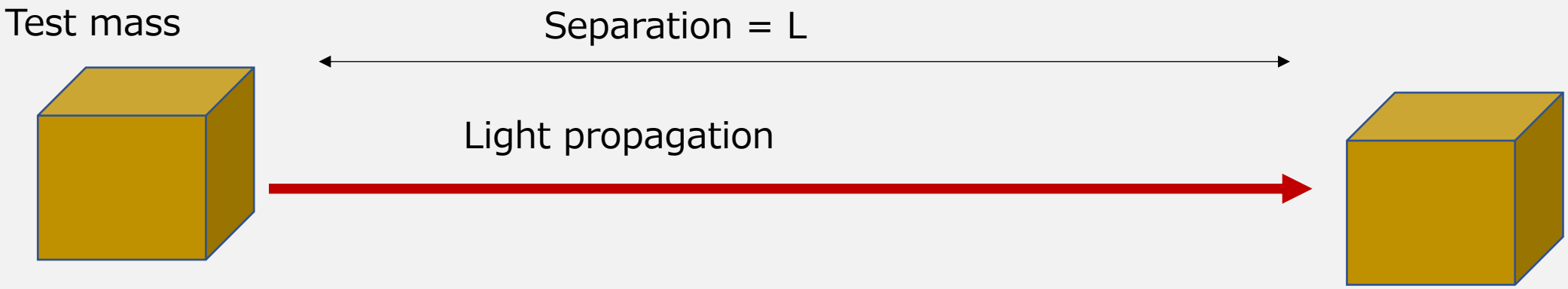
Instrument activities

- Formation flying mission: SILVIA
- SORAC: inertial reference sensor
- Small force measurement on ground [1]
- Back-linked Fabry-Perot interferometer [2,3]
- etc



[1] Okuma+, Phys. Rev. D **111**, 082006 (2025)
[2] KI and M.K. Fujimoto, PTEP (2021)
[3] R. Sugimoto+, Phys. Rev. D **109**, 022003 (2024)

Measurement principle



Optical phase (measurement quantity)

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

$$\approx kL - kLh(t)/2$$

Laser Noise

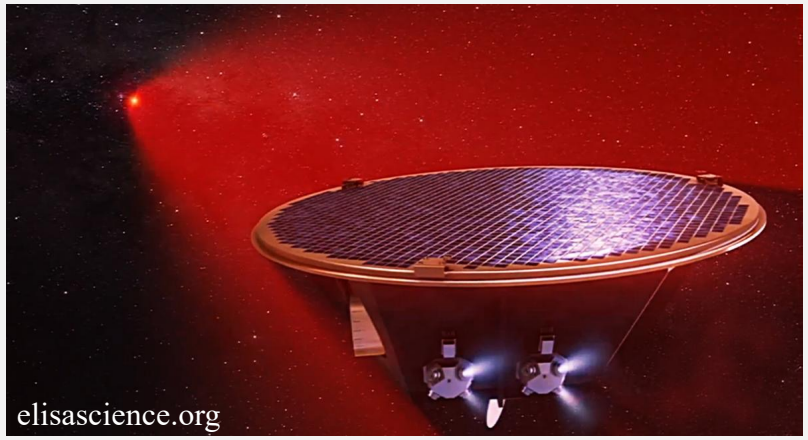
Test mass noise

Signal

h: GW amplitude
k: wavenumber of light field

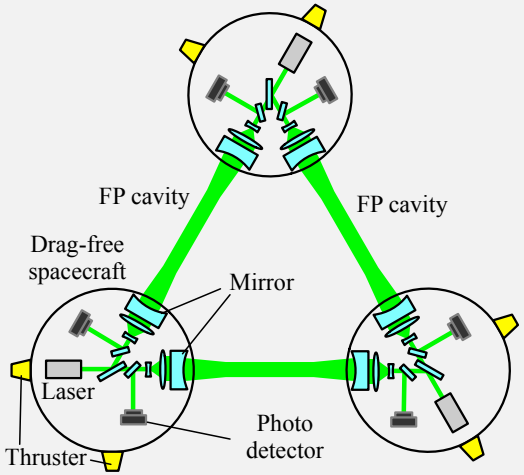
Two interferometer approaches

▶ Transponder laser interferometer



LISA, TianQin and Taiji.
Small portion of light is sampled, similarly to radio wave communication.
No need for precision formation flying

▶ Fabry-Perot laser interferometer



DECIGO

B-DECIGO and DECIGO
Similar to ground-based interferometers
Precision formation flying (better than 1 um) required.

SILVIA

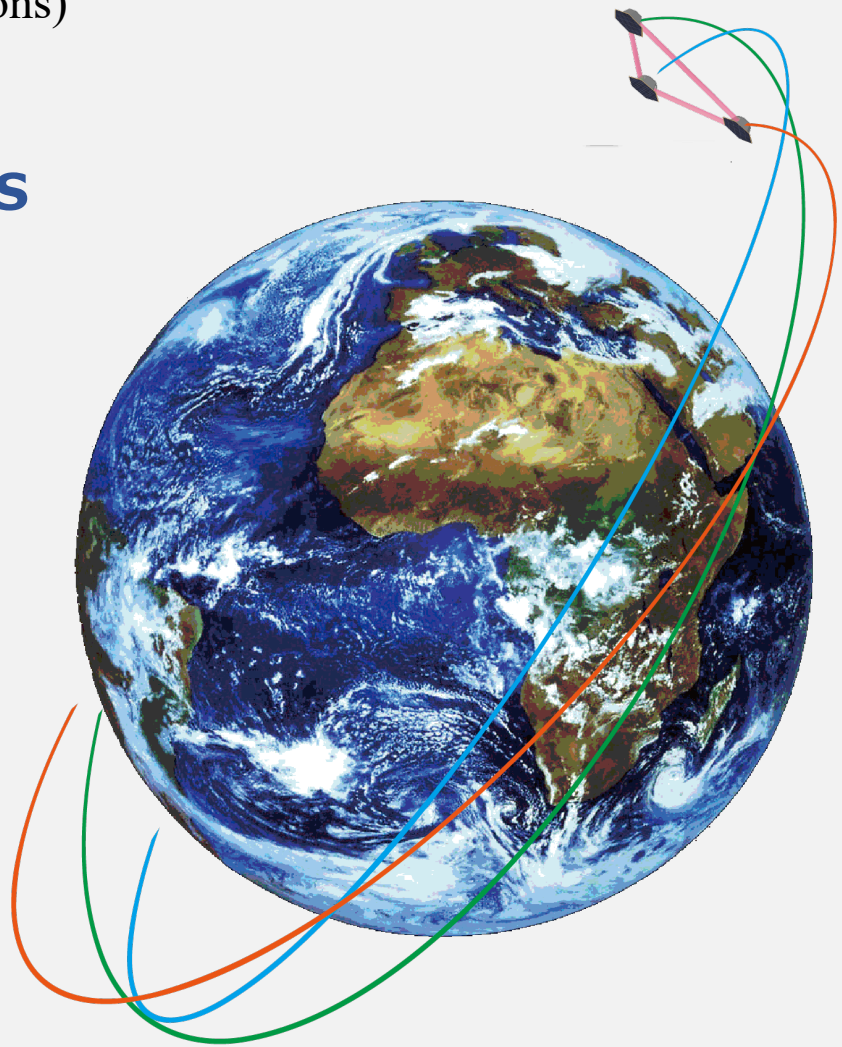
T. Ito+, PASJ (2025)

(**S**pace **I**nterferometer **L**aboratory **V**oyaging towards **I**nnovative **A**pplications)

In-orbit demonstration of technologies necessary for formation flying (FF) satellites

- **Proposed for JAXA's M-class mission**
  - Proposed in 2020
  - Use of Epsilon rocket
- **Engineering demonstration**
  - Ultra-precision FF
  - Intersatellite laser interferometer

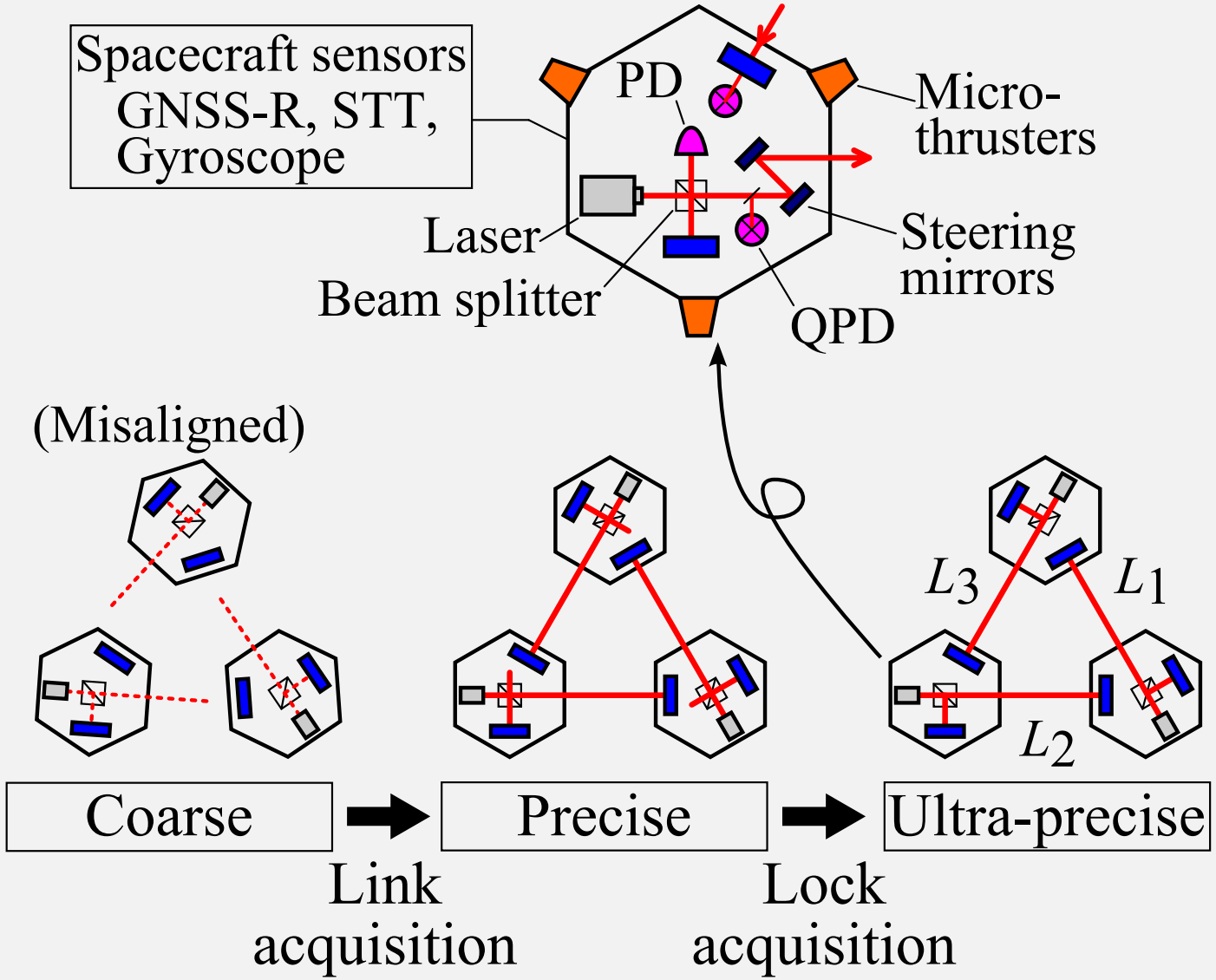
Target launch in early 2030's



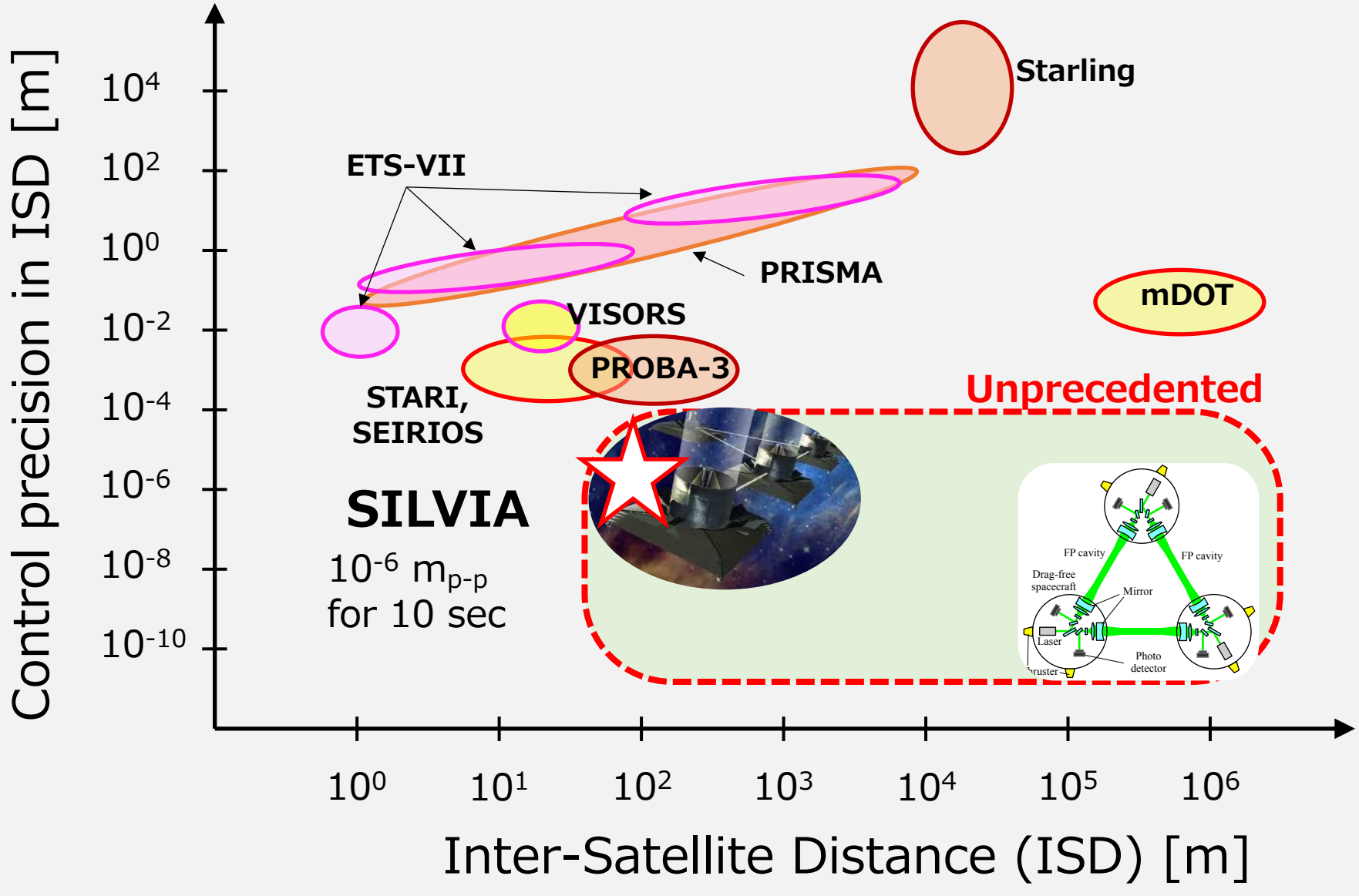
© S. Sato (Hosei U.)

Use of asymmetric Michelson

T. Ito+, PASJ (2025)



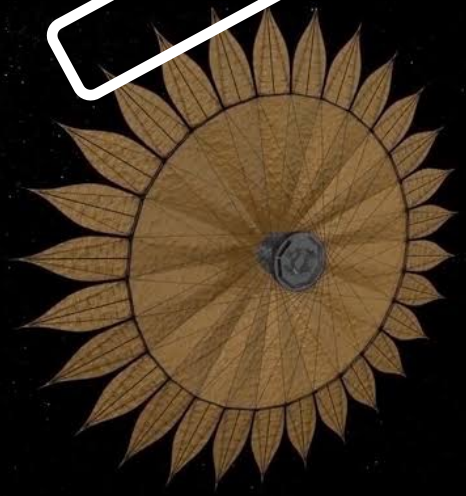
Into ultra-precision



Broader impacts of FF

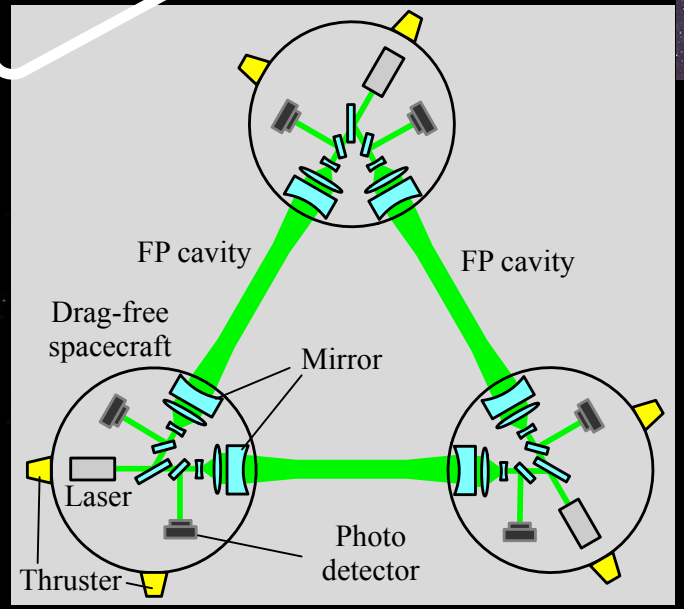
Your idea goes here (Tell us!)

Occulter



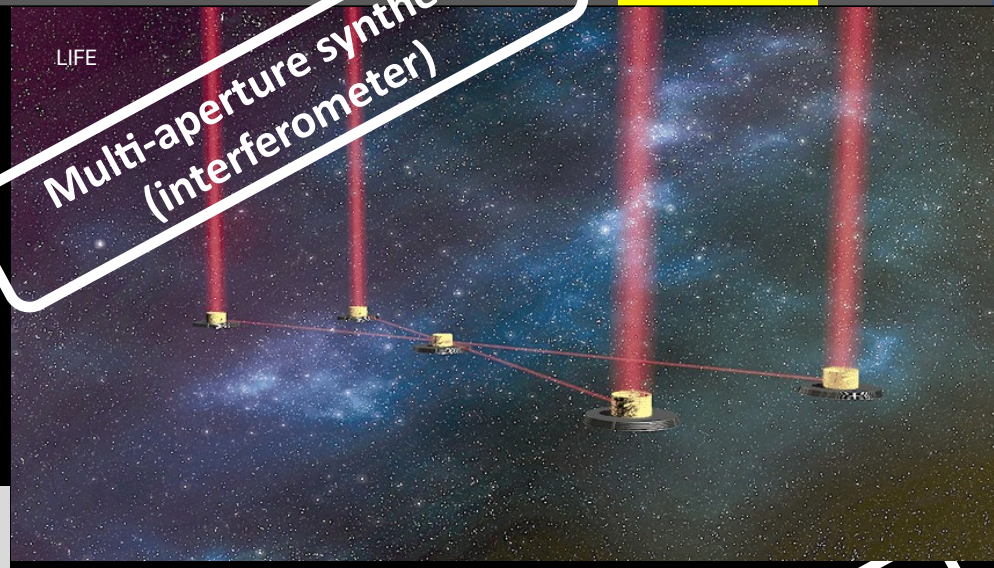
Starshade (NASA)

Gravitational wave observatories



B-DECIGO/DECIGO (Japan)

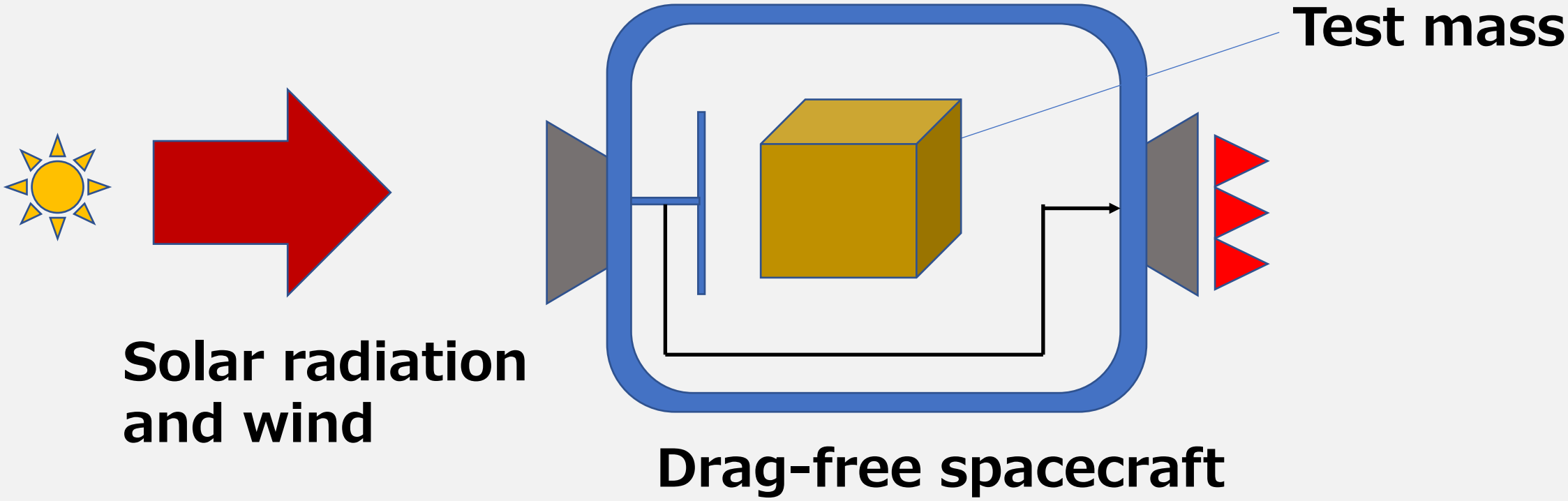
Multi-aperture synthesis (interferometer)



Long focal length

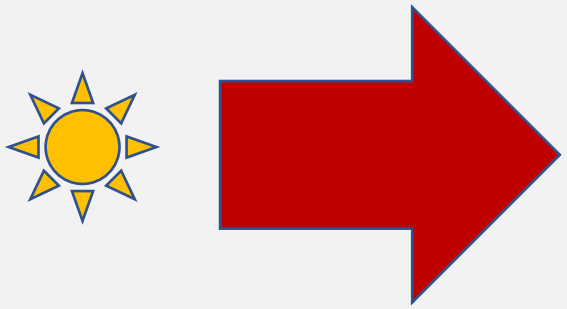
Inertial reference sensor

- ►Floating mass serves as an inertial reference
- ►Shielding necessary to keep TM from external disturbances
- ►Drag free necessary not to introduce the vibration of spacecraft to TM

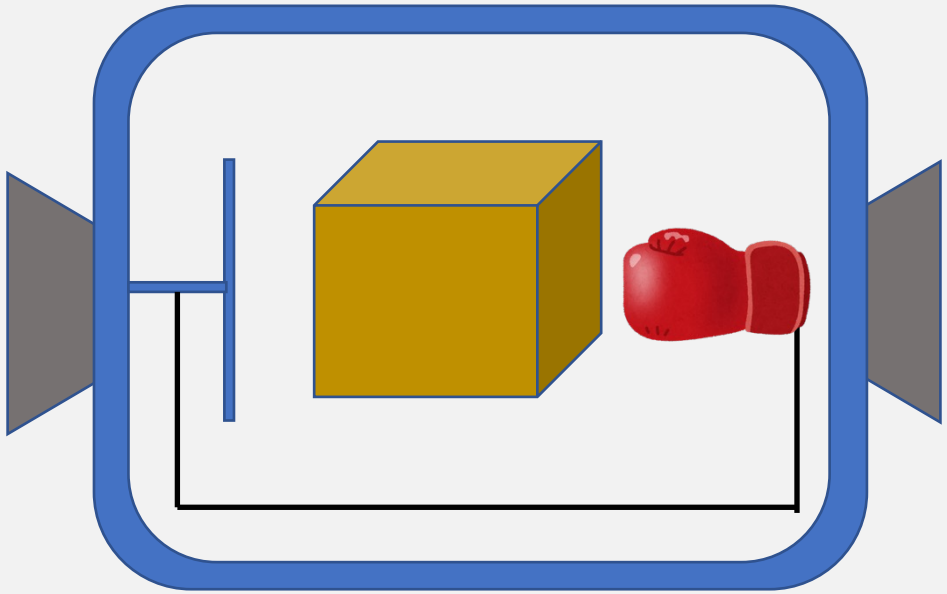


Accelerometer

- ►Instead, feeding the signal back to TM
- ►Feedback force directly tells acceleration acting on spacecraft



Solar radiation and wind

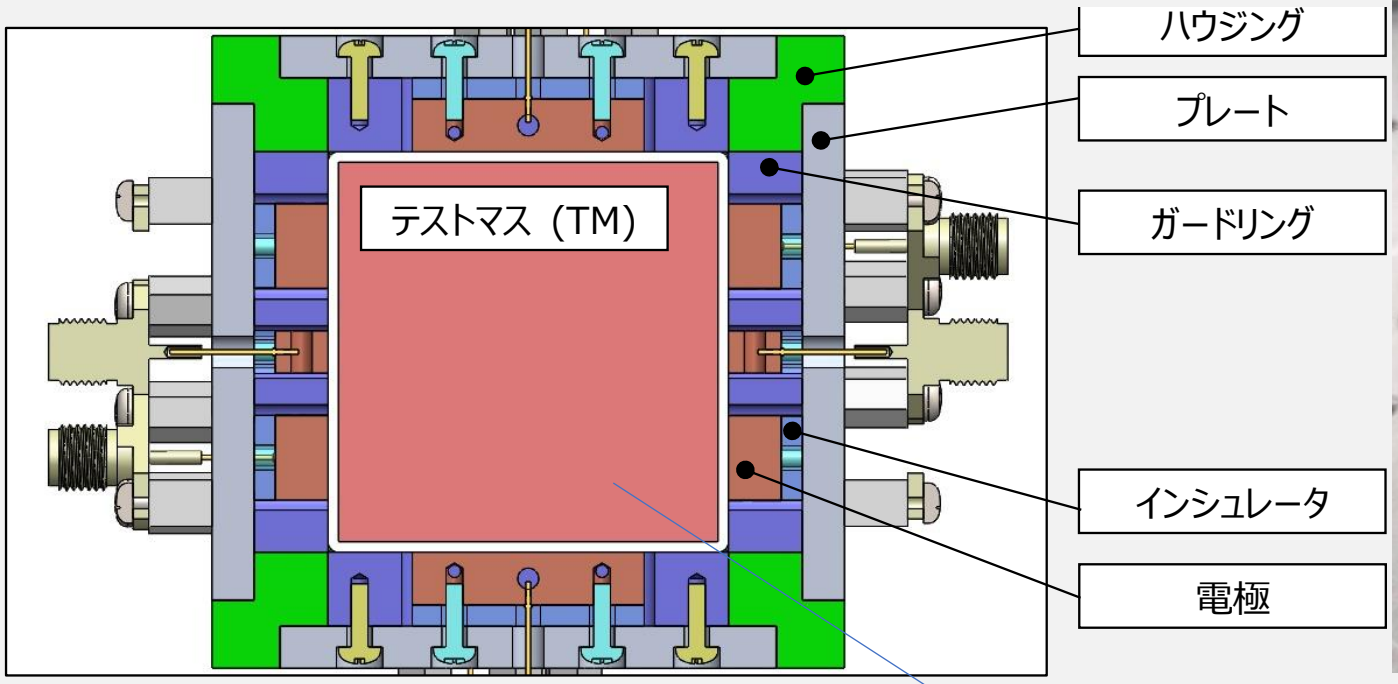


TM is forced to follow spacecraft

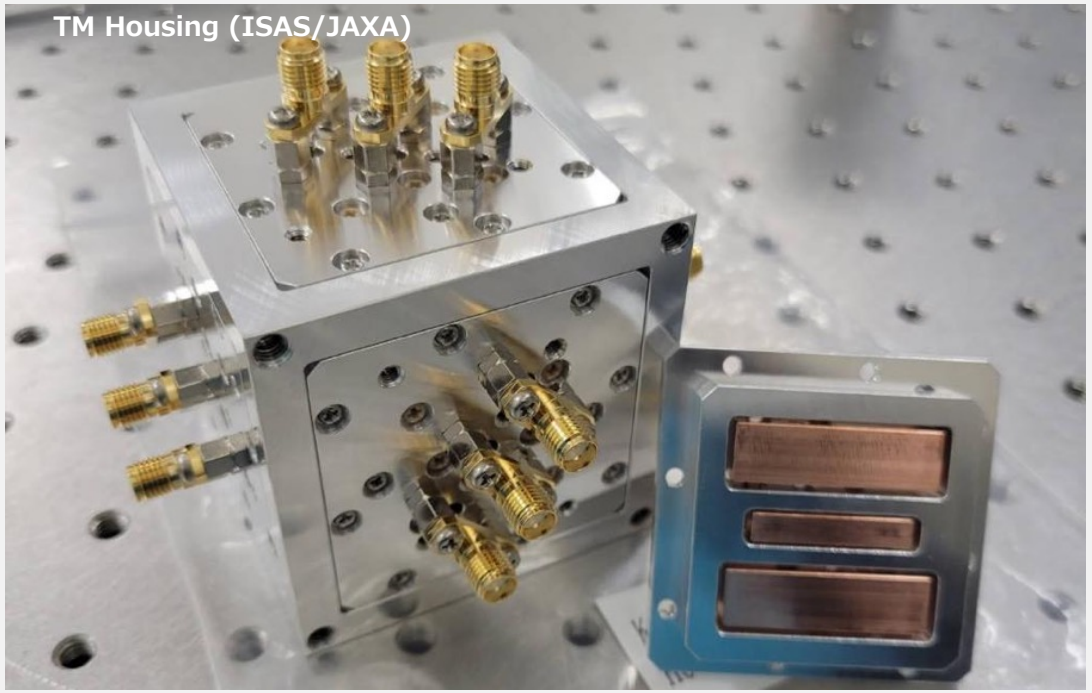
Space accelerometer: SORAC

As a technology development step, our lab chose to go for the development of space accelerometer, specific for monitoring the solar radiation pressure

- Use of capacitve sensors and electrostatic actuators, 3 axes
- Goal sensitivity :10^{-10} m/s^2 (for 10-100 sec in Allan dev.)
- Improving the automous navigation accuracy and GNSS

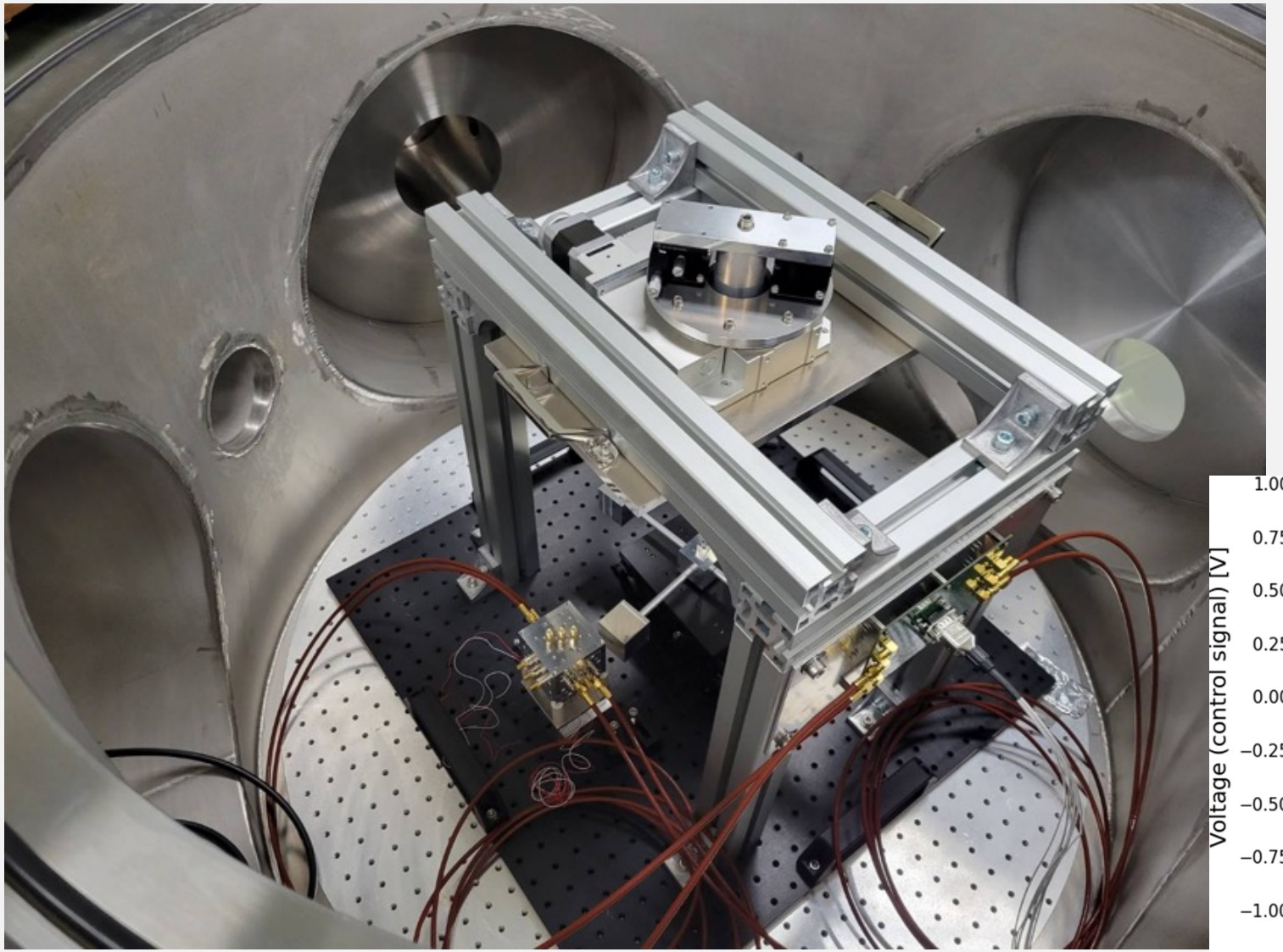


Schematical view (ISAS/JAXA)

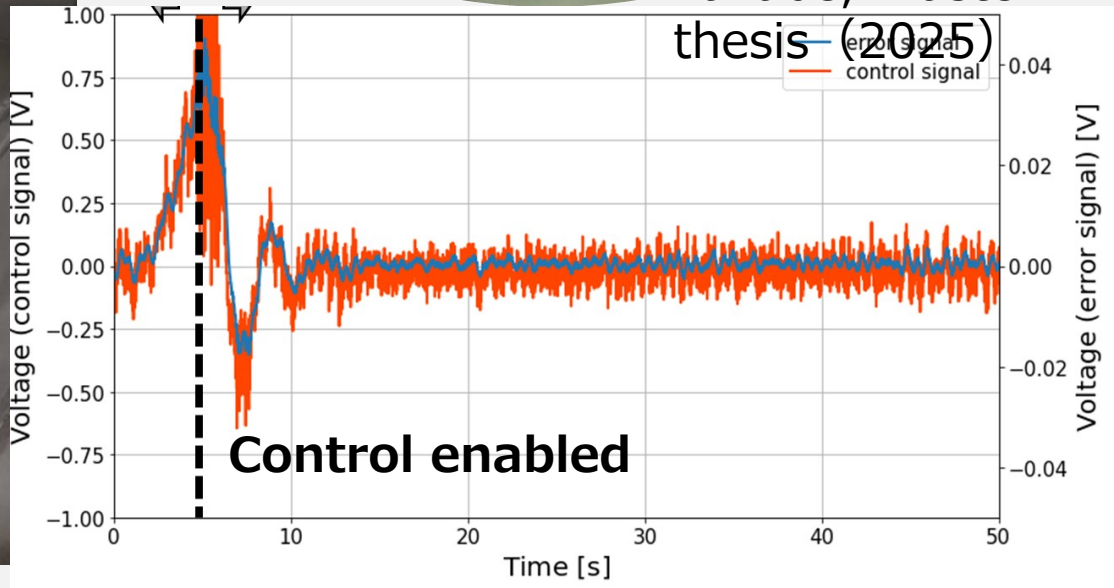


36^3 mm^3 Test mass

Control test package underway

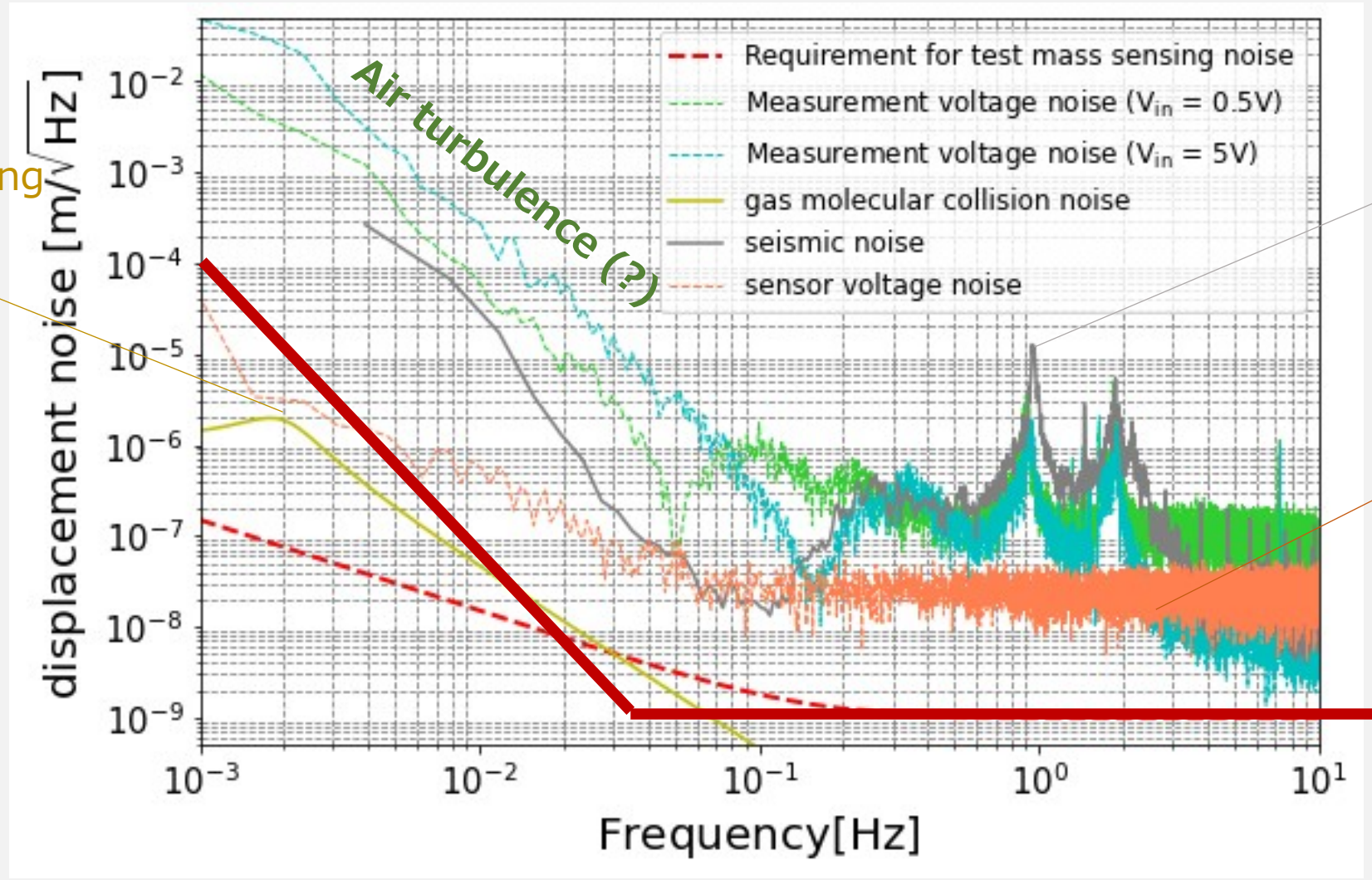


Yakabe, master thesis (2025)



Noise on ground (in air)

Yakabe master thesis (2025)



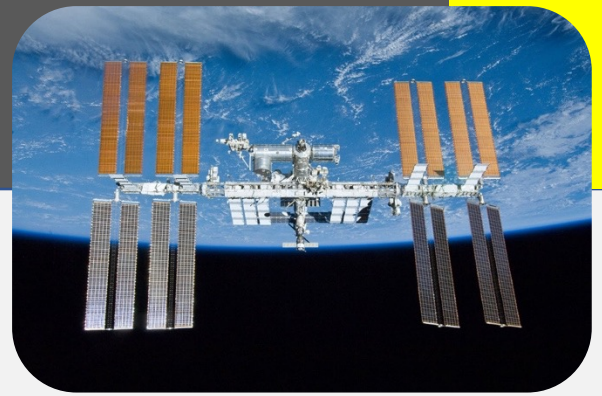
gas damping

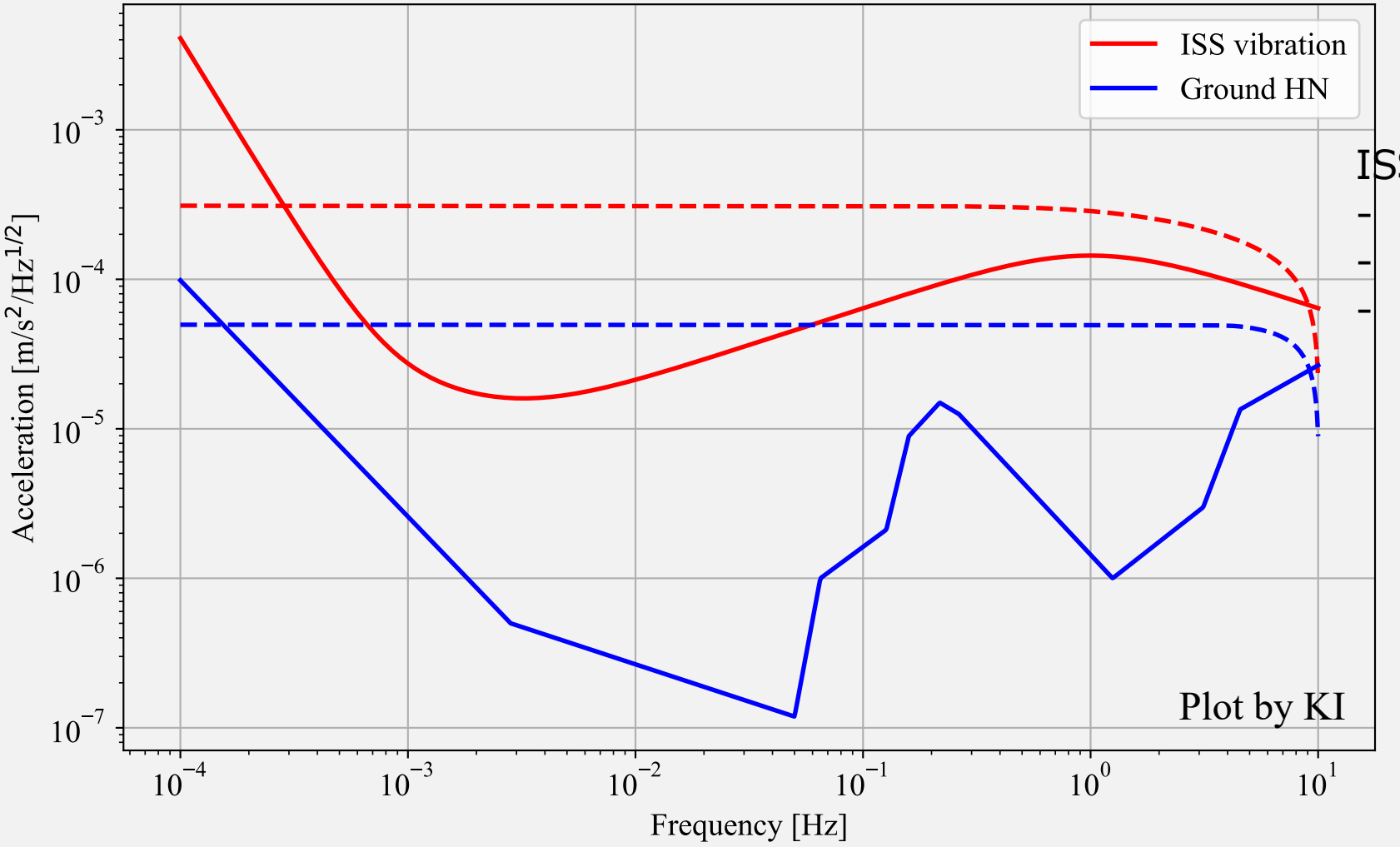
Seismic noise

Electronic noise

Goal sensitivity

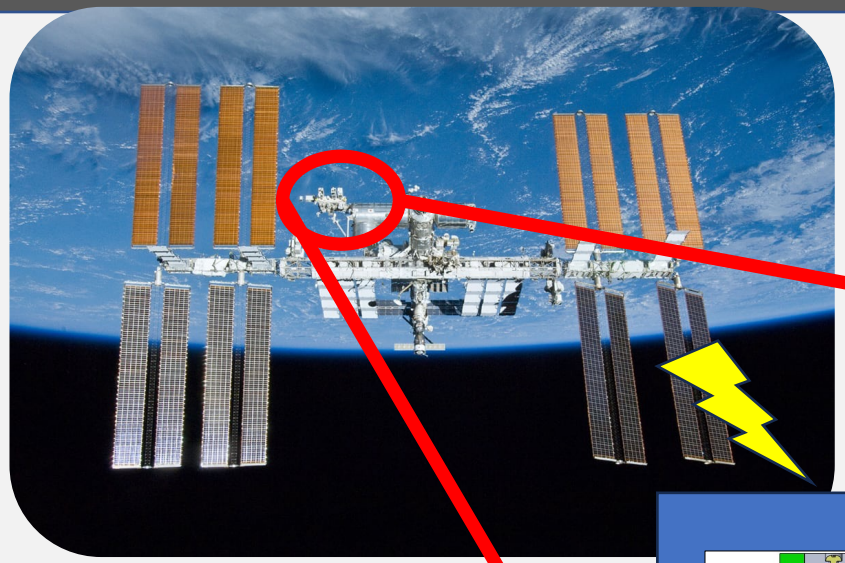
Noise test package in ISS



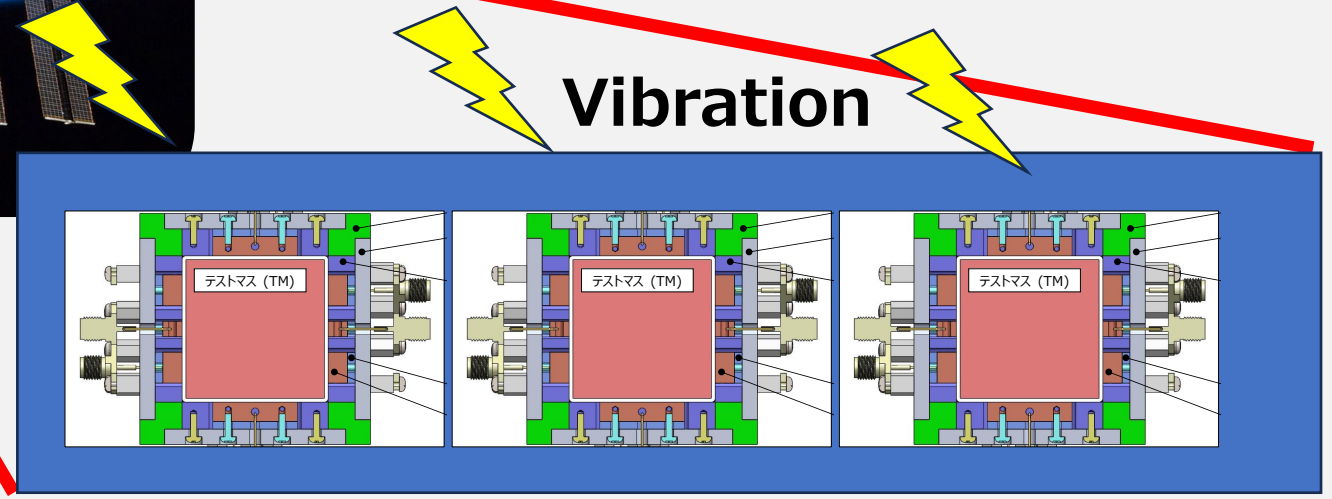


ISS
- Good for microgravity environment
- Free from seismic noise
- Not great for vibration

Denoising ISS vibration



Application of *three-channel corretion* [1] is being considered for suppressing the high vibration noise



Data downlink

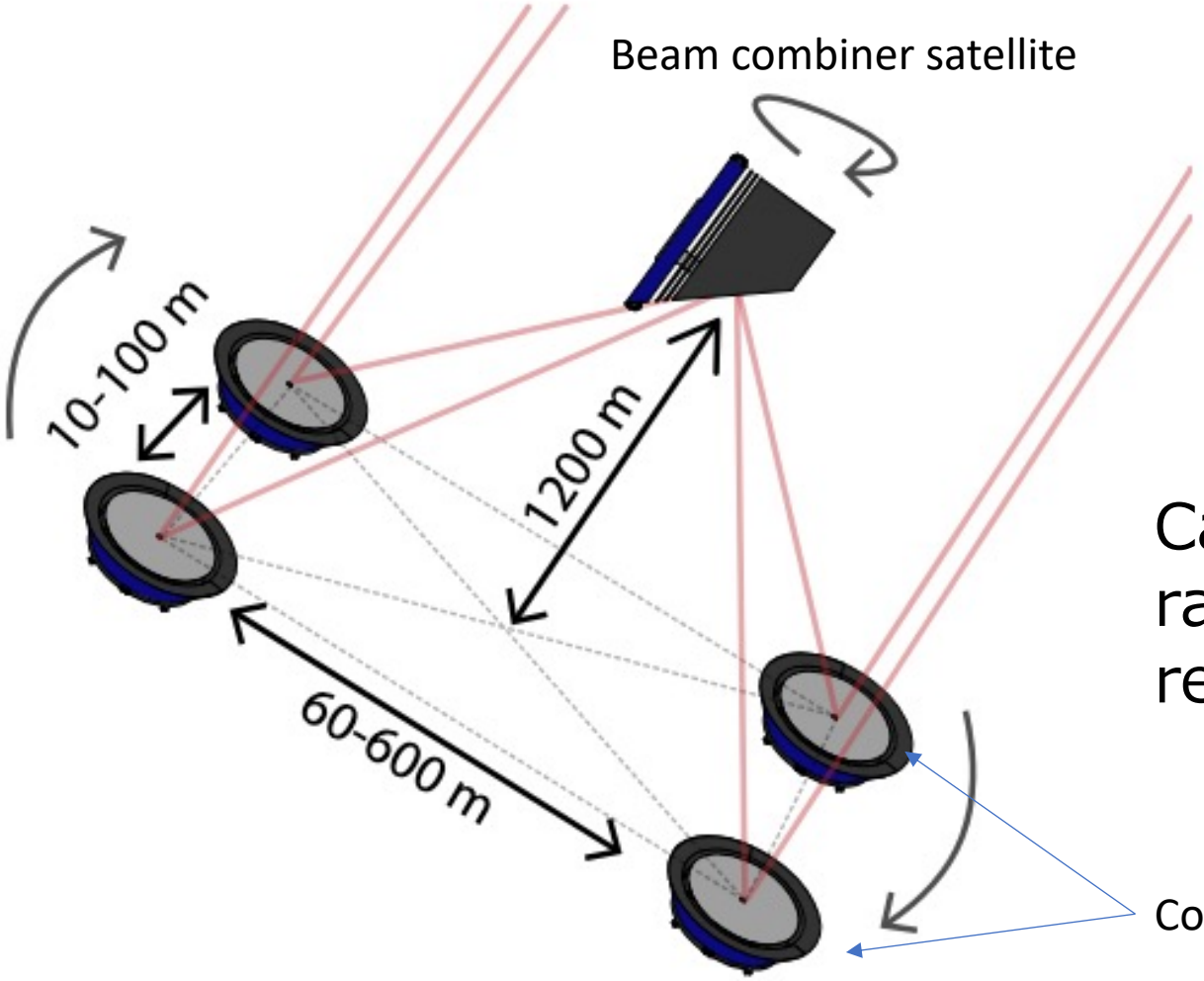
Relative alignment precision
~ 10^{-5} rad or better necessary

Offline three-channel correlation for denoising

[1] Sleeman+, ``Three-Channel Correlation Analysis: A New Technique to Measure Instrumental Noise of Digitizers and Seismic Sensors'' (2006)

Advanced topics

Application of formation flying



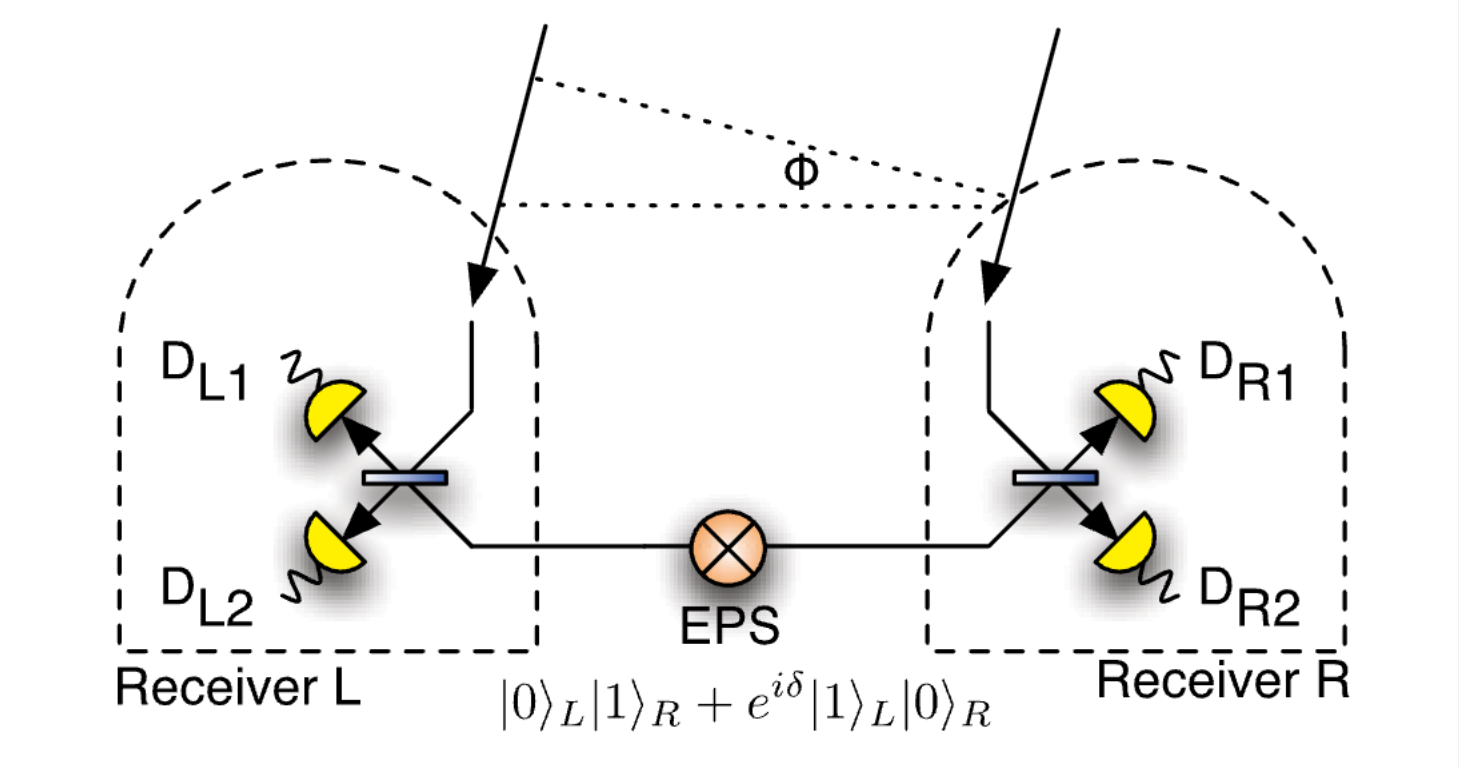
LIFE :
Mid infrared stellar light interferometer

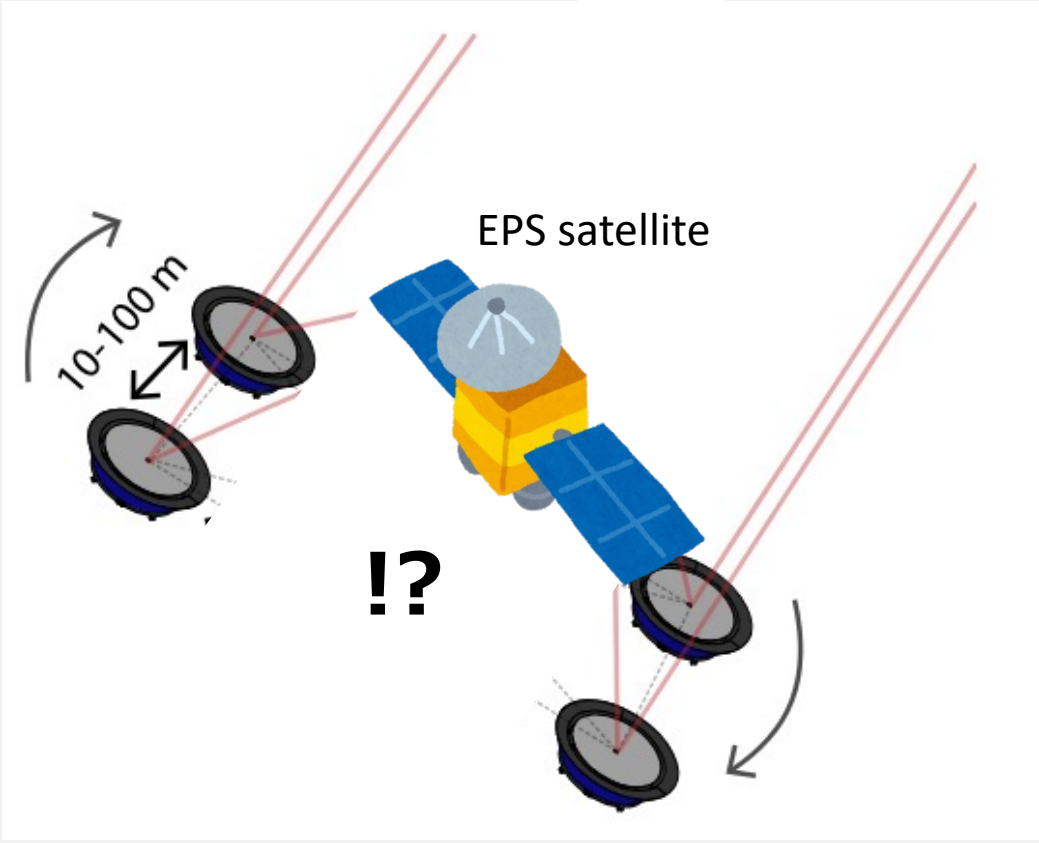
Can we do something similar to radio wave interferometer, i.e., receiving light at the collector satellites?

A. M. Galuser et al., SPIE (2024)

Quantum enhanced interferometry

Gottesman+, PRL 109, 070503 (2012)

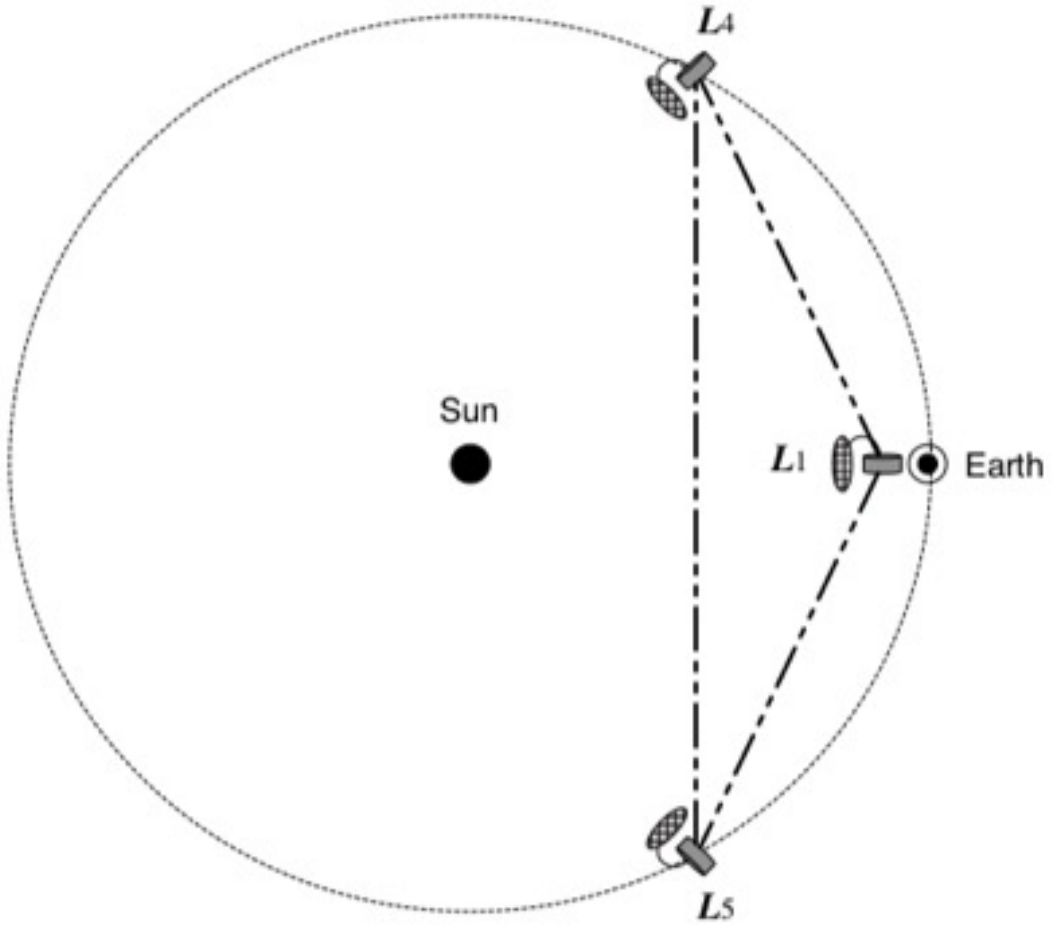


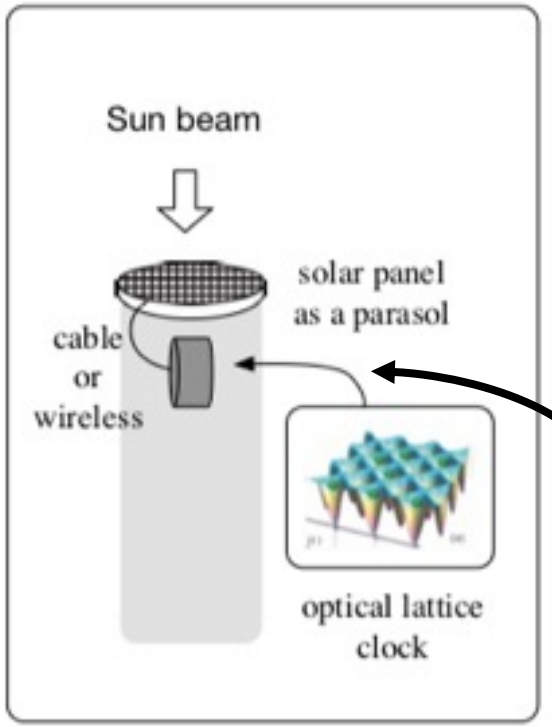


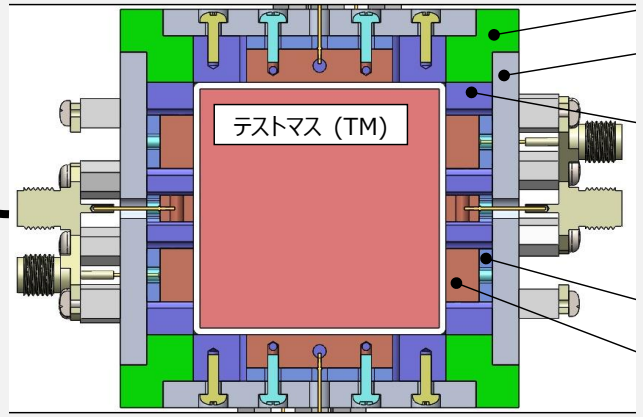
Avoids the shot noise problem

Application of accelerometer?

T. Ebisuzaki+, Intn'l J. Mod. Phys. D (2020)







GW detection using optical lattice clock

Additional monitor for
non-gravitational accelerations

Summary

- Space GW observations will open new window for astrophysics
- Development of several key concepts and components underway
- If you have any new ideas utilizing our experimental activities, please let us know!