DECIGO

Seiji Kawamura on behalf of the DECIGO working group

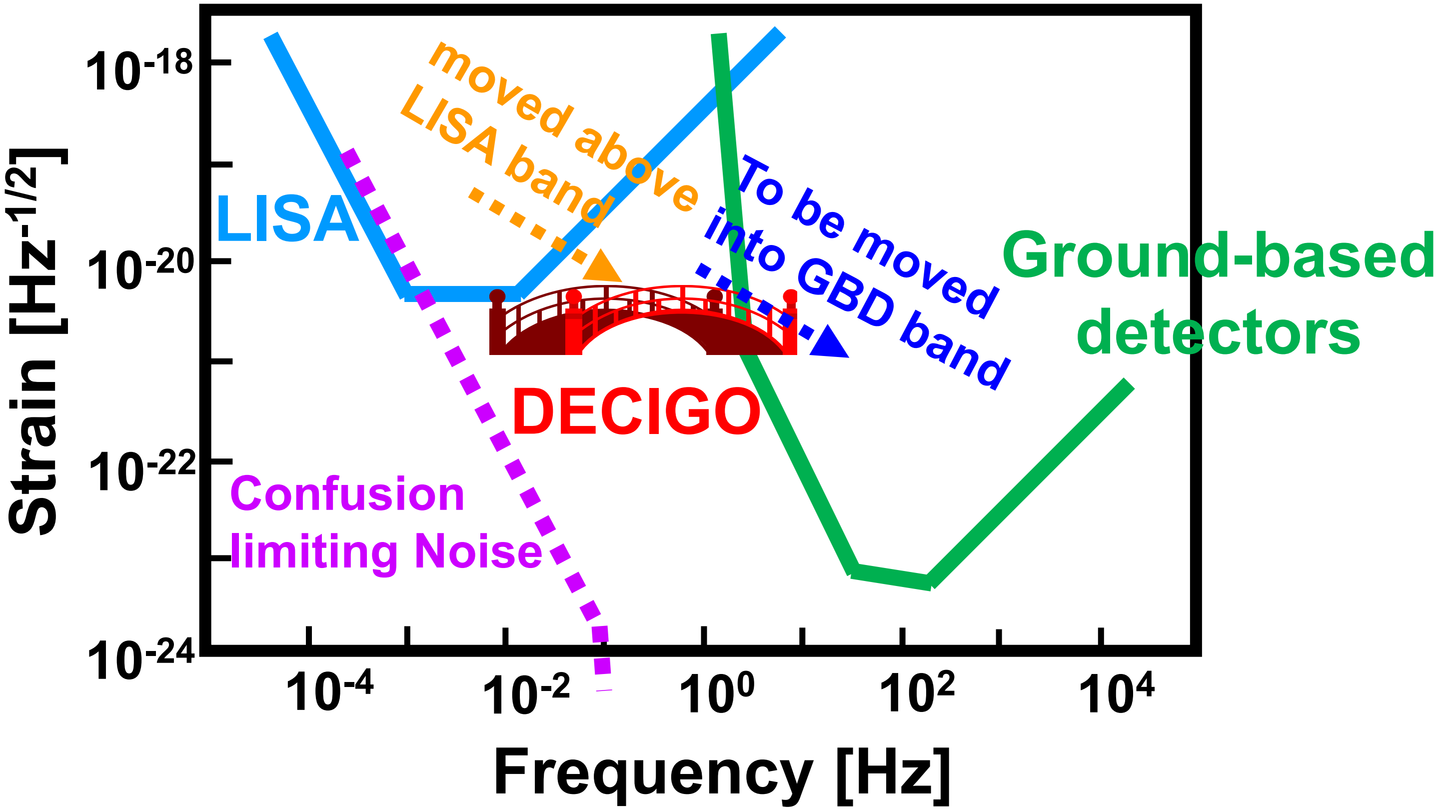
Gravitational wave detection at the Moon Workshop

Oct. 14, 2021

What is DECIGO?

***Deci**-hertz Interferometer **G**ravitational Wave **O**bservatory*

- **Bridges the gap between LISA and ground-based detectors**
  - **Follow-up for LISA, Predictor for ground-based detectors**
- **Low confusion limiting noise -> Extremely high sensitivity**



Possibility of Direct Measurement of the Acceleration of the Universe Using 0.1 Hz Band Laser Interferometer Gravitational Wave Antenna in Space

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It may be possible to construct a laser interferometer gravitational wave antenna in space with $h_{\rm rms} \sim 10^{-27}$ at $f \sim 0.1$ Hz in this century. Using this antenna, (1) typically 10^5 chirp signals of coalescing binary neutron stars per year may be detected with $S/N \sim 10^4$; (2) we can directly measure the acceleration of the universe by a 10 yr observation of binary neutron stars; and (3) the stochastic gravitational waves of $\Omega_{\rm GW} \gtrsim 10^{-20}$ predicted by the inflation may be detected by correlation analysis. Our formula for phase shift due to accelerating motion might be applied for binary sources of LISA.

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I. Introduction.—There are at least four methods to detect gravitational waves: (1) resonant type antenna covering ~kHz band; (2a) laser interferometers on the ground covering 10 Hz–kHz band; (2b) laser interferometers in space like LISA [1] covering 10^{-4}–10^{-2} Hz band; (3) residuals of pulsar timing covering $\sim 10^{-8}$ Hz band; (4) Doppler tracking of the spacecraft covering 10^{-4}–10^{-2} Hz band. It is quite interesting to note that little has been discussed on possible detectors in 10^{-2}–10 Hz band. In this Letter we consider the possible specification of such a detector, which we call DECIGO (Decihertz Interferometer Gravitational Wave Observatory). We argue that the direct measurement of the acceleration of the universe is possible using DECIGO.

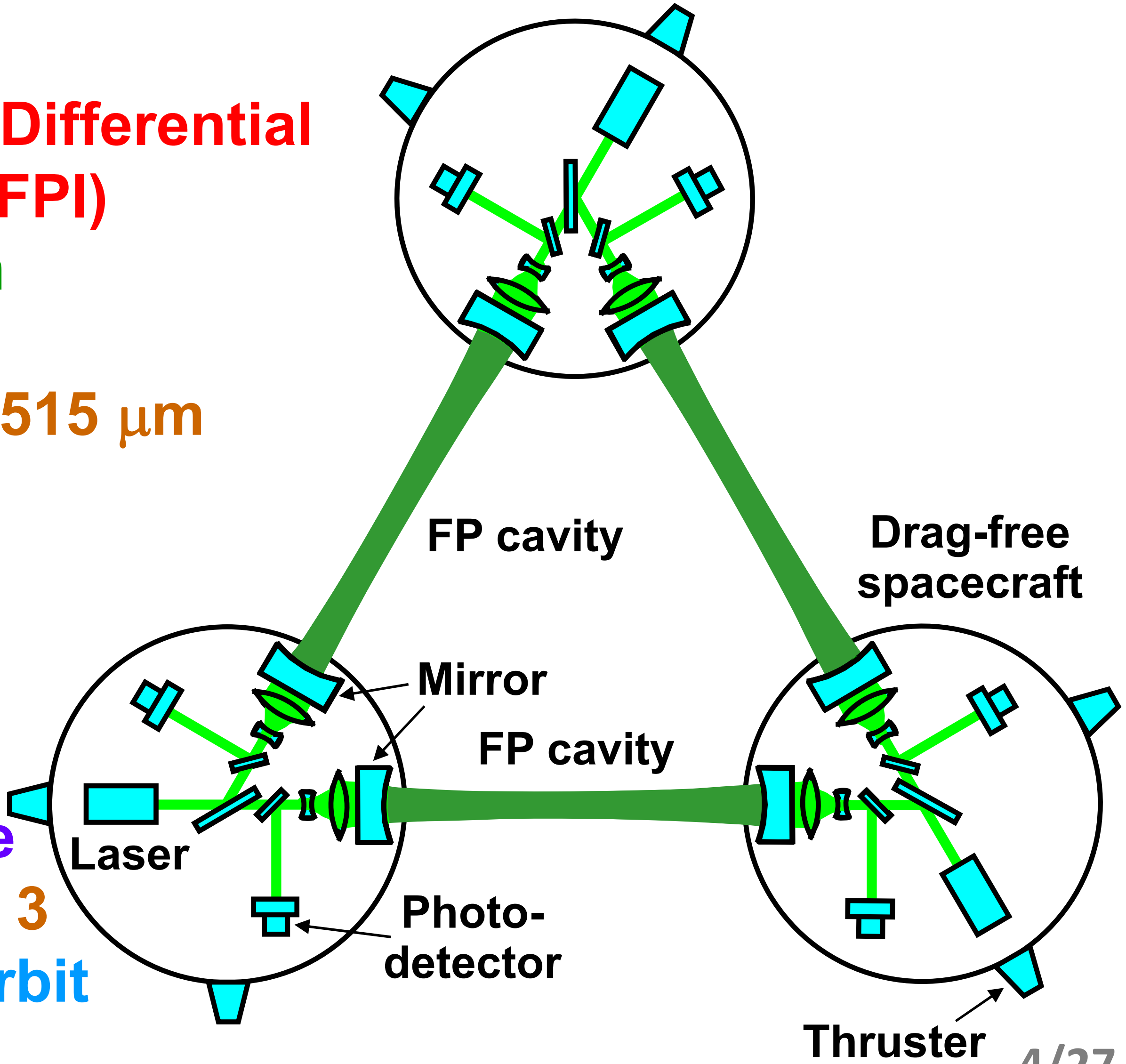
II. Specification of DECIGO.—The sensitivity of a space antenna with an arm length of 1/10 of LISA and yet the same assumption of the technology level, such

sooner. Note here that when the pioneering efforts to detect the gravitational waves started in the last century using resonant-type detectors as well as laser interferometers, few people expected the present achievement in resonant-type detectors such as IGEC (bar) [3] and in laser inteferometers such as TAMA300 [4], LIGO, GEO600, and VIRGO (for these detectors see [5]). Therefore all the experimentalists and the theorists on gravitational waves should not be restricted to the present levels of the detectors. Our point of view in this Letter is believing the proverb "Necessity is the mother of the invention" so that we argue why a detector like DECIGO is necessary to measure some important parameters in cosmology.

The sensitivity of DECIGO, which is optimized at 0.1 Hz, is assumed to be limited only by radiation pressure noise below 0.1 Hz and shot noise above 0.1 Hz. The contributions of the two noise sources are equal to each

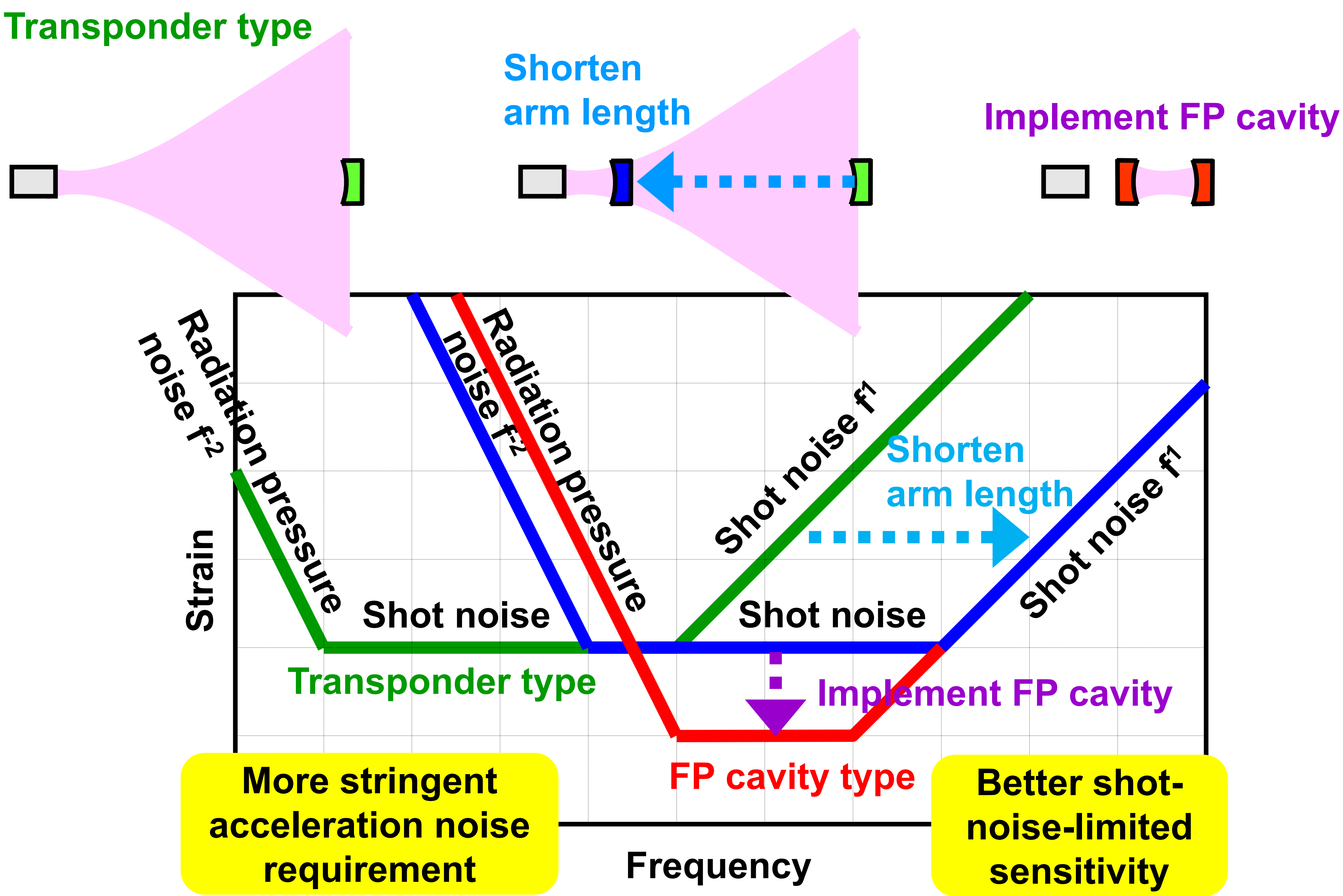
Pre-conceptual design

- Interferometer type: Differential FP interferometer (DFPI)
- Arm length: 1000 km
- Mirror diameter: 1 m
- Laser wavelength : 0.515 μm
- Finesse: 10
- Laser power: 10 W
- Mirror mass: 100 kg

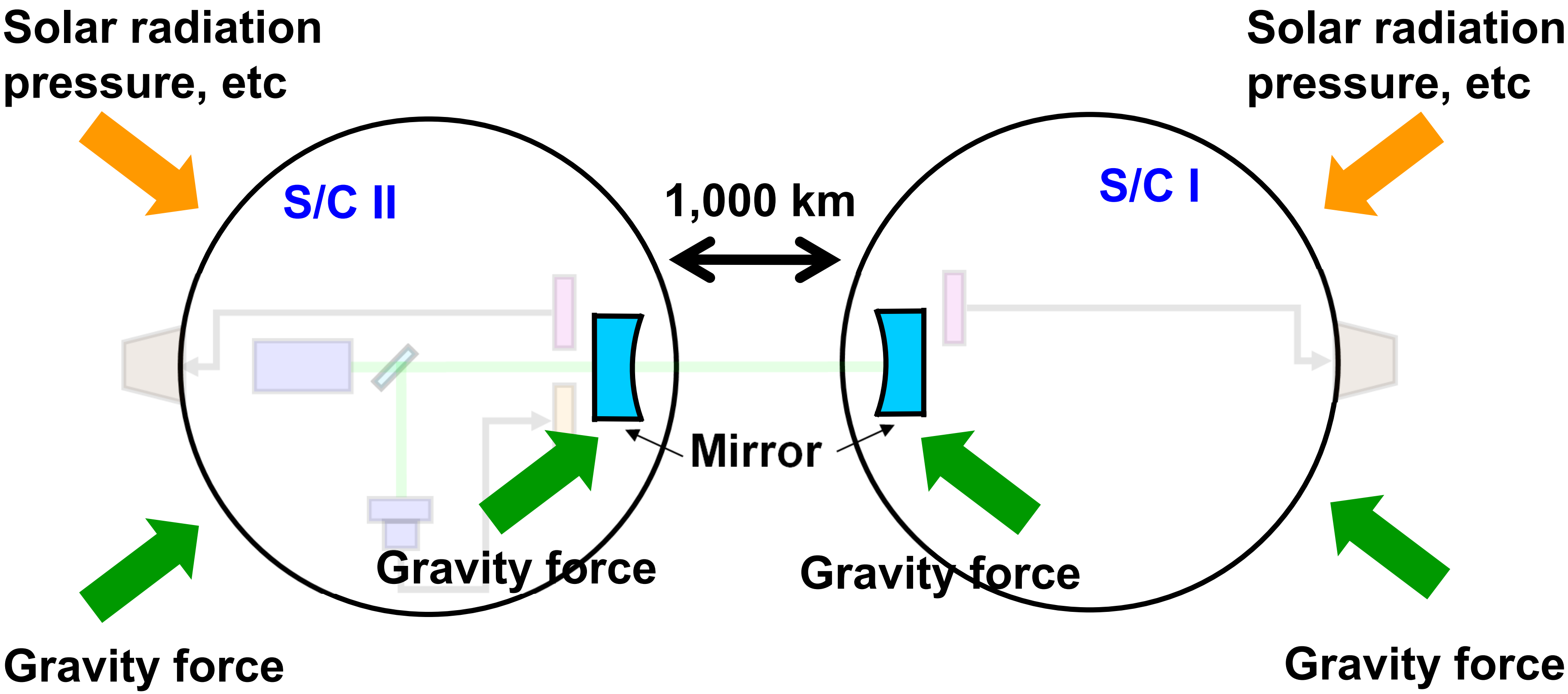


- Spacecraft: drag free
- # of interferometers: 3
- Orbit: Heliocentric orbit
- # of clusters: 4

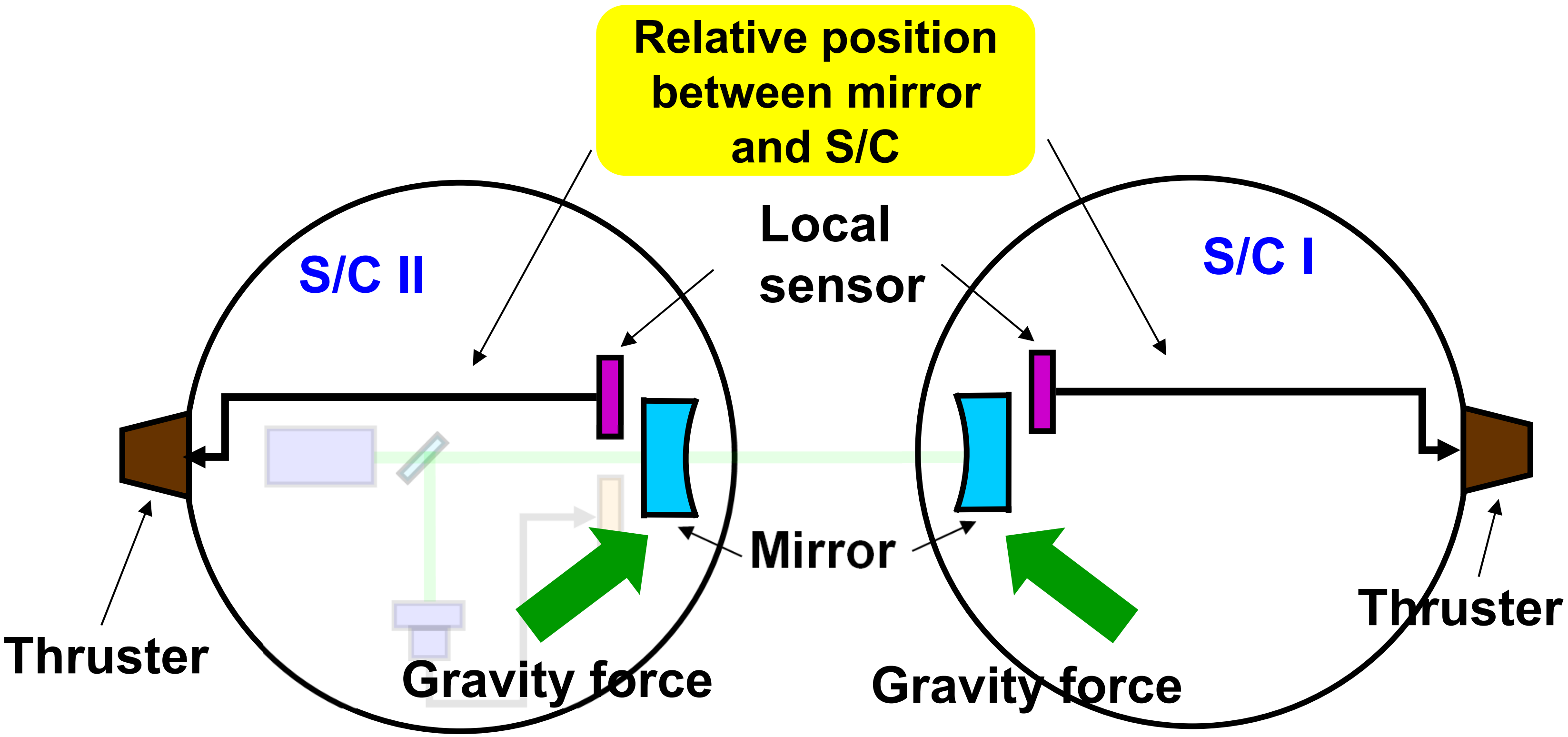
Why short? Why FP cavity?



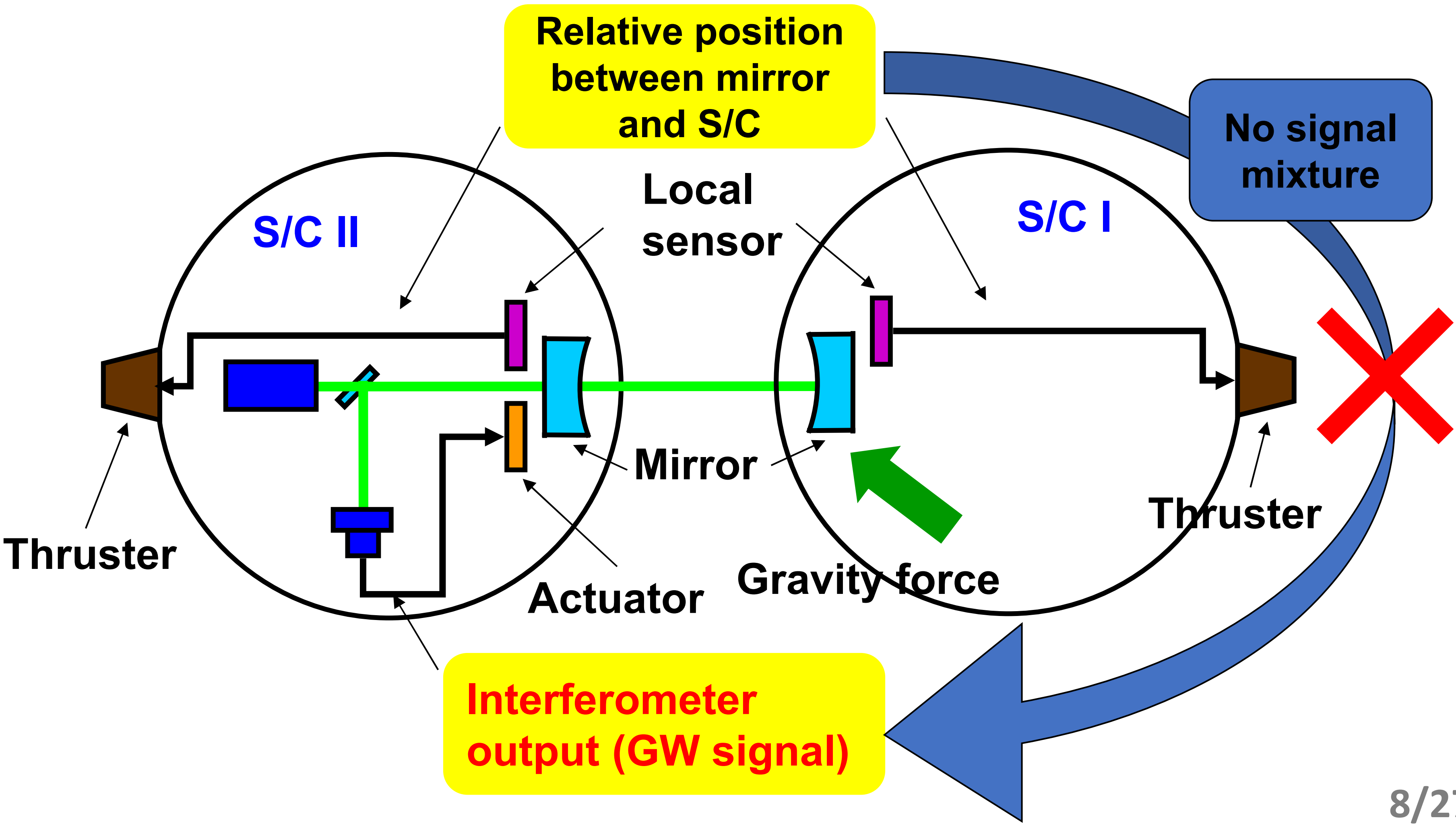
Drag free and FP cavity: compatible?



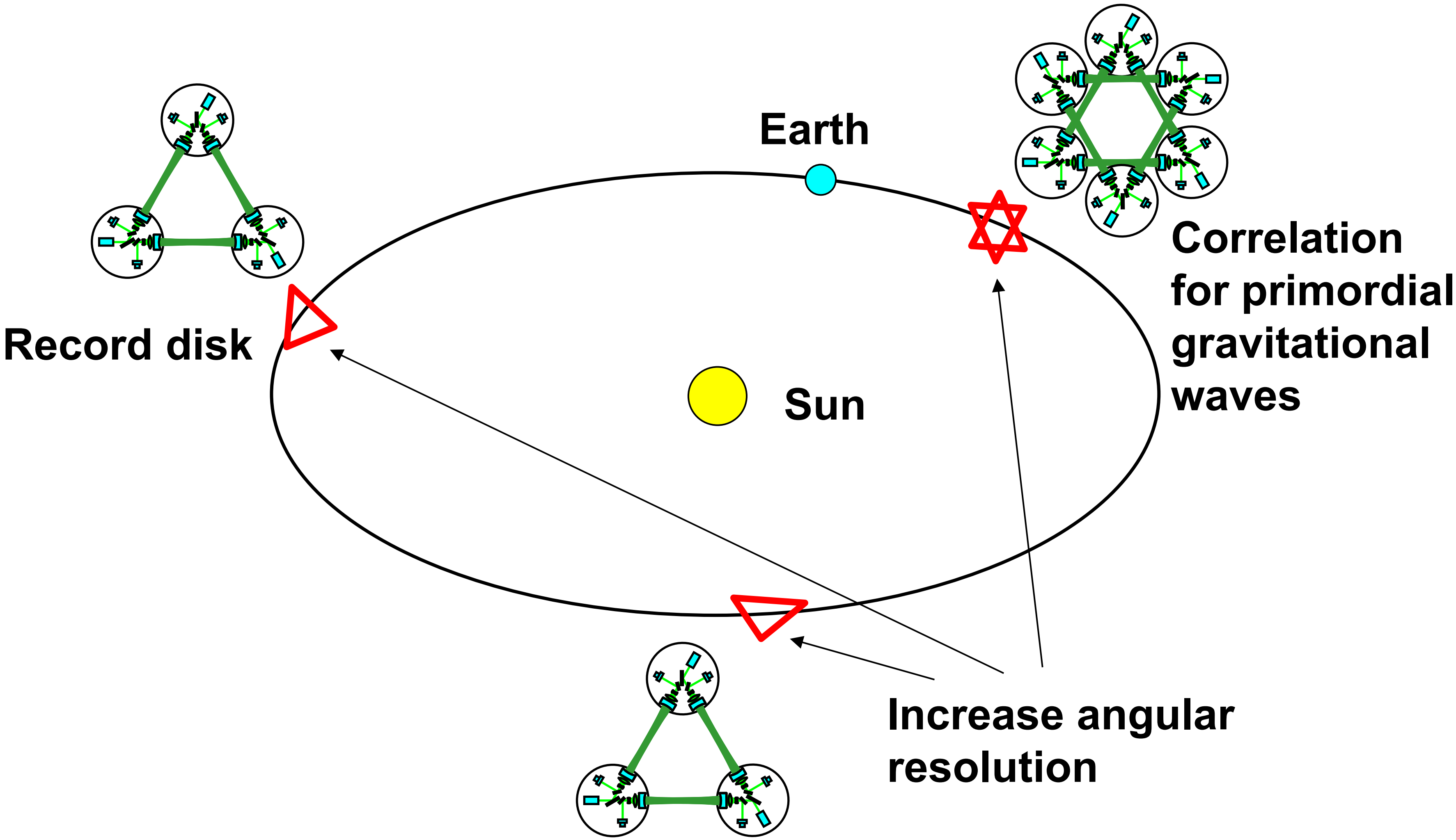
FP cavity and drag free : compatible?



Drag free and FP cavity: compatible?



Orbit and constellation (preliminary)



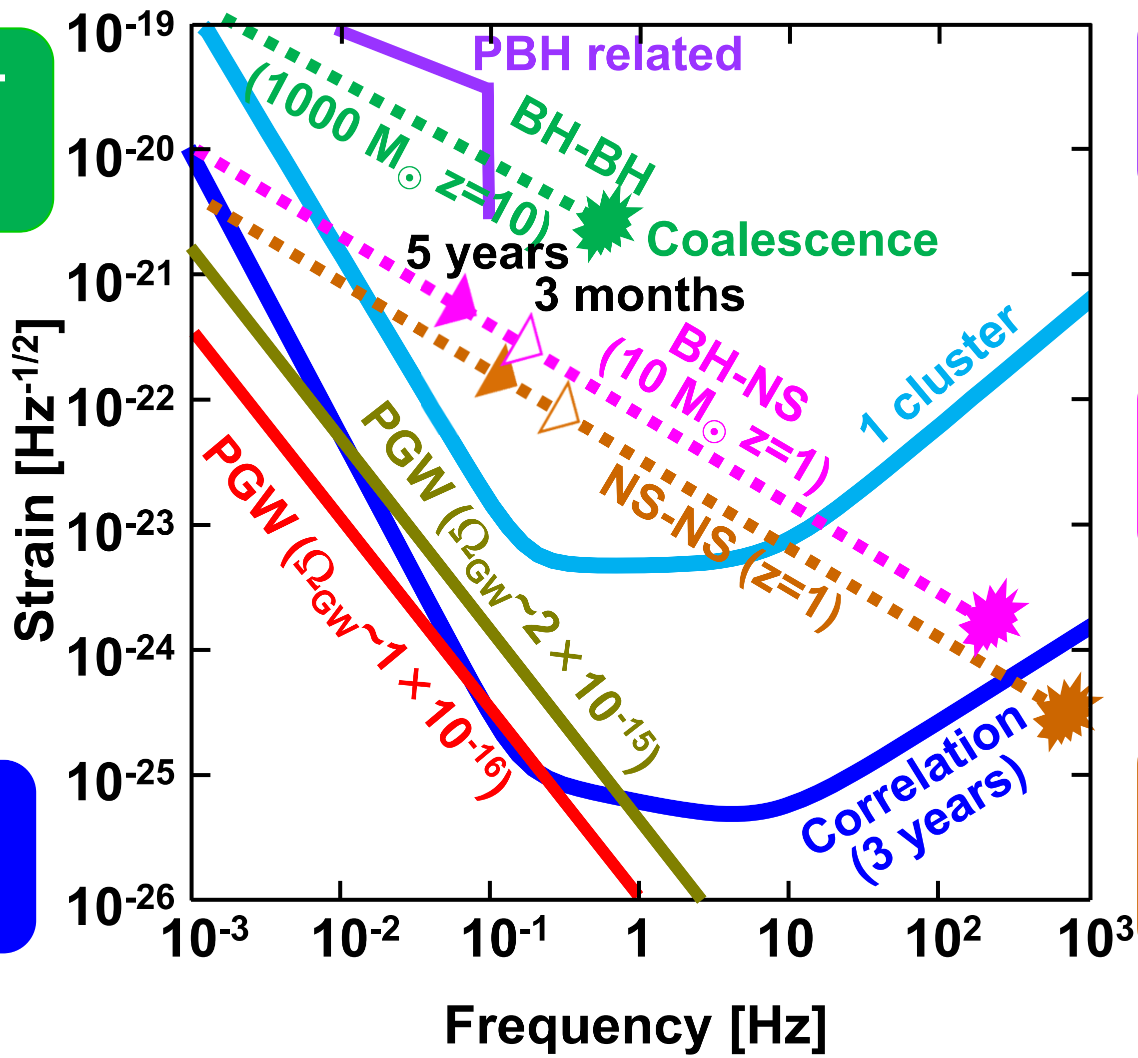
Target sensitivity and science

Intermediate-mass black hole (BH)

Prediction of binary neutron star (BNS) coalescence

Takahashi, Nakamura 2003

Primordial gravitational wave (PGW)



Dark Matter

Saito, Yokoyama 2009, 2011

General relativity

Yagi, Tanaka 2010

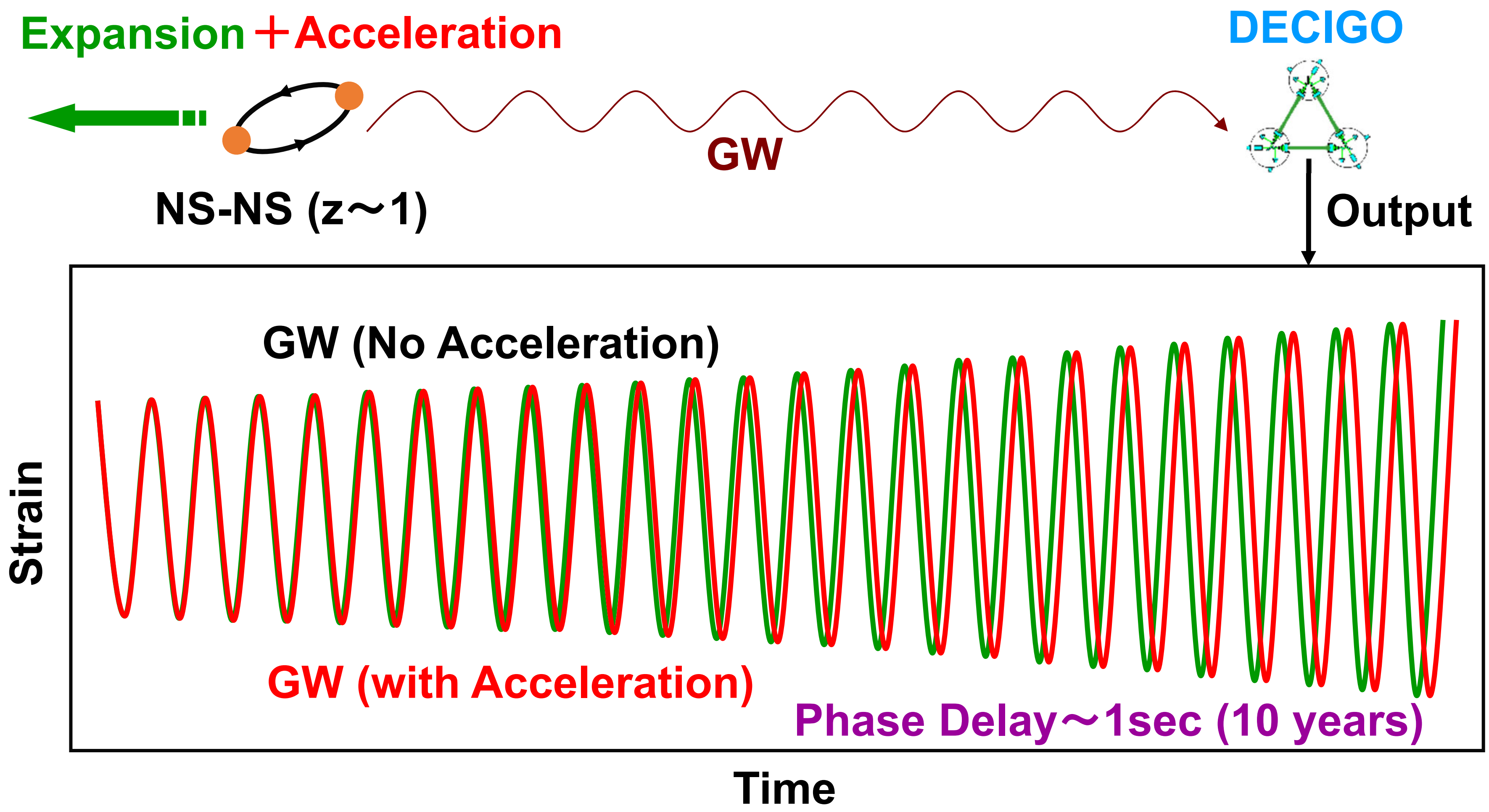
Acceleration of expansion of Universe

Seto, Kawamura, Nakamura 2001

Primordial GW

- Direct observation of primordial GWs from inflation
  - Whether Inflation really happened?
  - Which inflation model is correct?
  - Parity violation? （Clockwise and counterclockwise GW）
    - Seto 2007
  - Separation of Tensor, Vector, scalar mode
    - Nishizawa, Taruya, Kawamura 2010

Acceleration of Expansion of the Universe



Seto, Kawamura, Nakamura, PRL 87, 221103 (2001)

DECIGO and gamma-ray burst (GRB)

- Prediction of NS-NS coalescence
  - z<5; 5 years before coalescence
  - Expected event rate: 10^6 /year (300 /day)
  - Angular accuracy：1 arcsec
- Assuming short GRB comes from NS-NS coalescence
  - Assuming 1/30 of short GRB can be detected (beaming effect)
  - Expected event rate: 10 /day

⇩

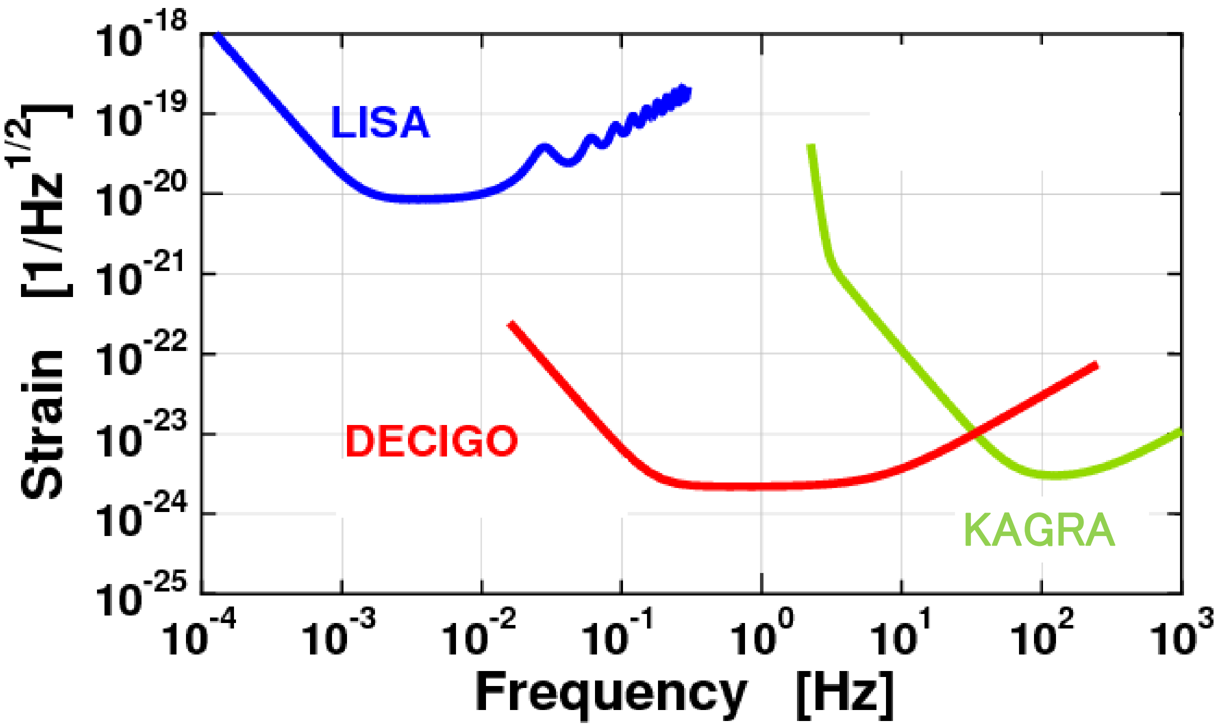
- Frequent and detailed observation of GRB by electro-magnetic waves

Other science targets

- Thermal history of the Universe
  - Kuroyanagi, Chiba, Sugiyama, 2015
- Planet around neutron star
  - Seto, 2008
- Prediction of SGB
  - Takahashi, Nakamura, 2003
- Higgs Sector
  - Kakizaki, Kanemura, Matsui, 2015
- Gravitational lens for GW
  - Hou, Biesiada, et al., 2021, Piórkowska-Kurpas, Biesiada, et al., 2021

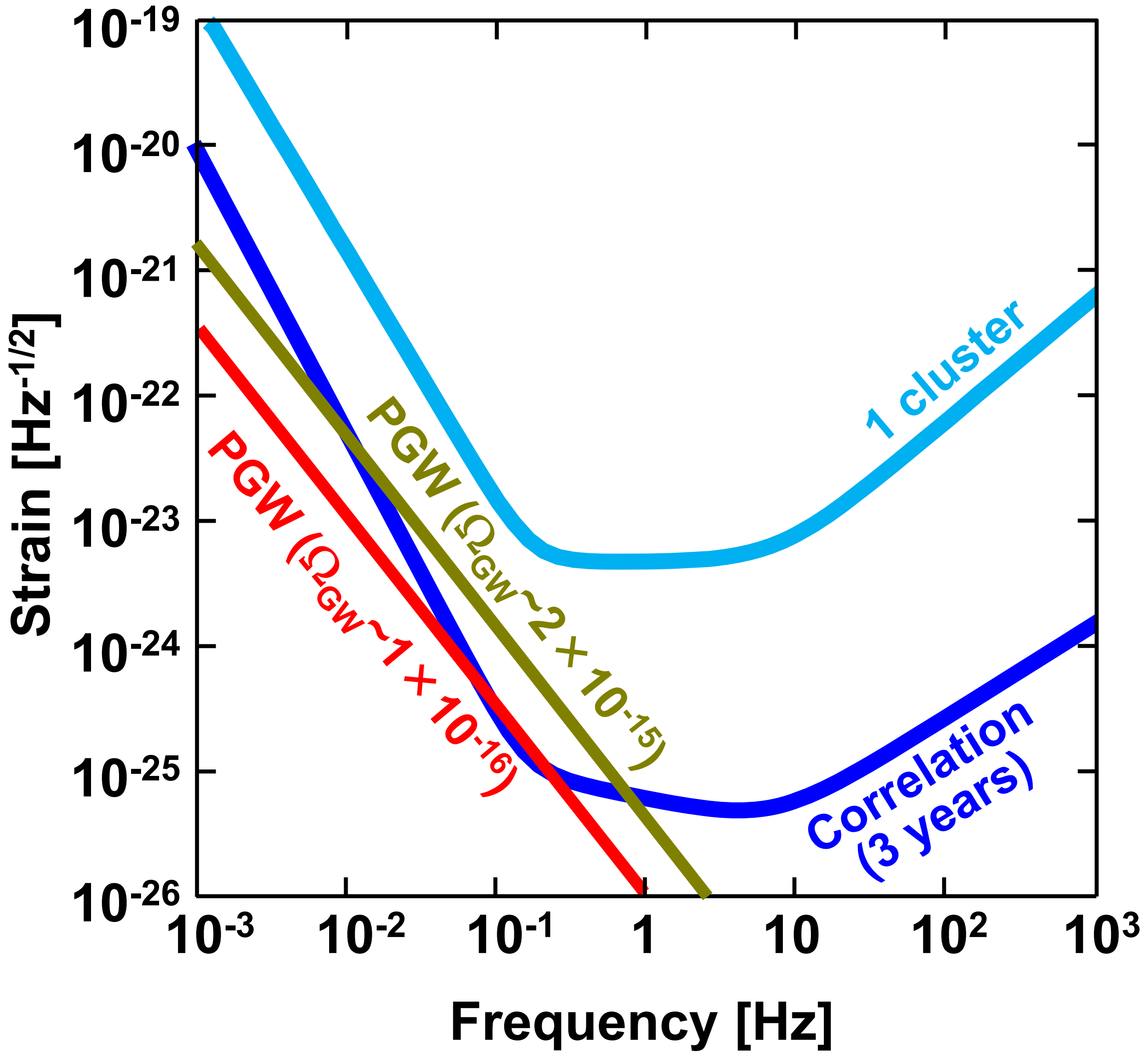
Requirements

- Force noise: 25 times more stringent than LISA
  - Comparable in terms of strain; distance: 1/2500, mirror mass: 100
- Sensor noise: 30 times looser than KAGRA
  - Comparable in terms of strain; storage time 30)



Update of PGW

- The upper limit of PGW has been reduced by consideration of the Planck observation results



Improvement of target sensitivity (1)

- The target sensitivity of DECIGO should be improved to ensure detection of PGW.
- Since the target sensitivity is limited by quantum noise, the quantum noise should be reduced.
- We are investigating optimization of the design parameters for the quantum noise.

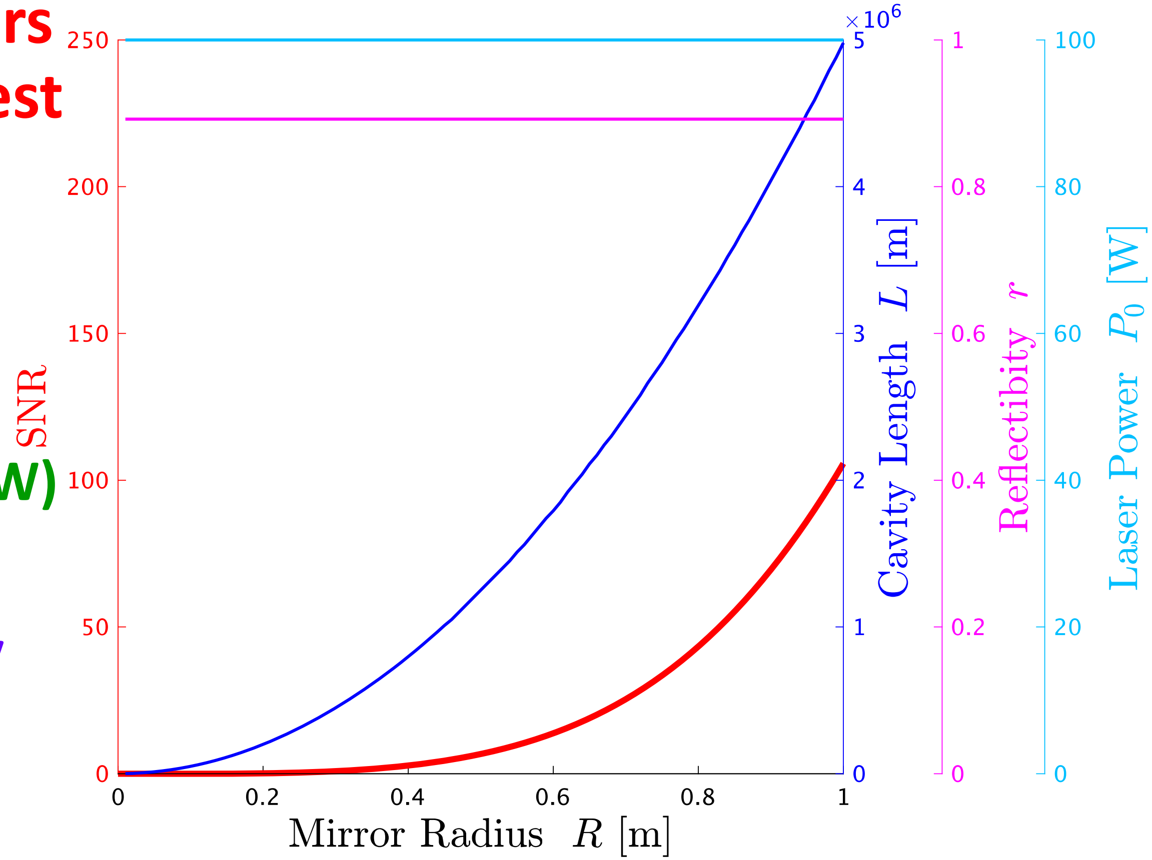
  Step 1: Only quantum noise has been considered with a frequency band between 0.1 Hz and 10 Hz.

  Step 2: Other noise sources (thermal noise, confusion limiting noise, etc.) will be considered.

  Step 3: Practical feasibility will be considered.

Dependence of signal-to-noise ratio (SNR) for PGW on mirror radius

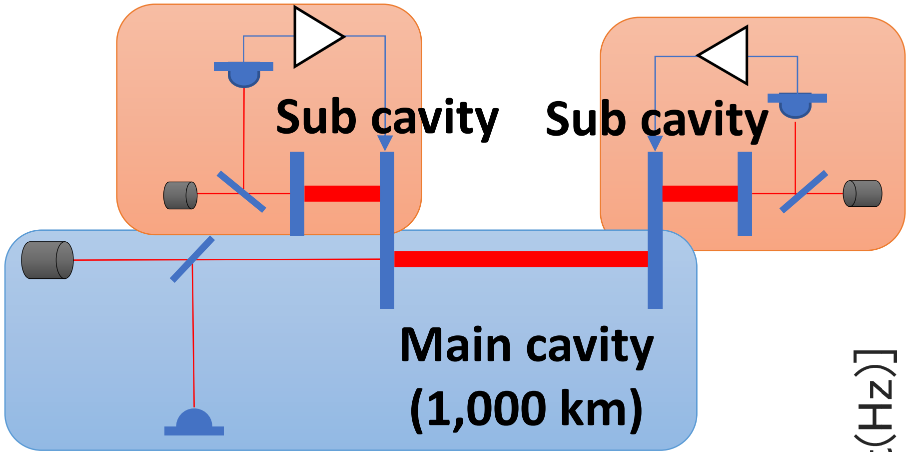
- The following parameters are optimized for the best SNR for a given mirror radius
  - Cavity length
  - Reflectivity of mirror
  - Laser power (up to 100 W)
- Considering optical diffraction loss properly
- Constant mirror mass is assumed



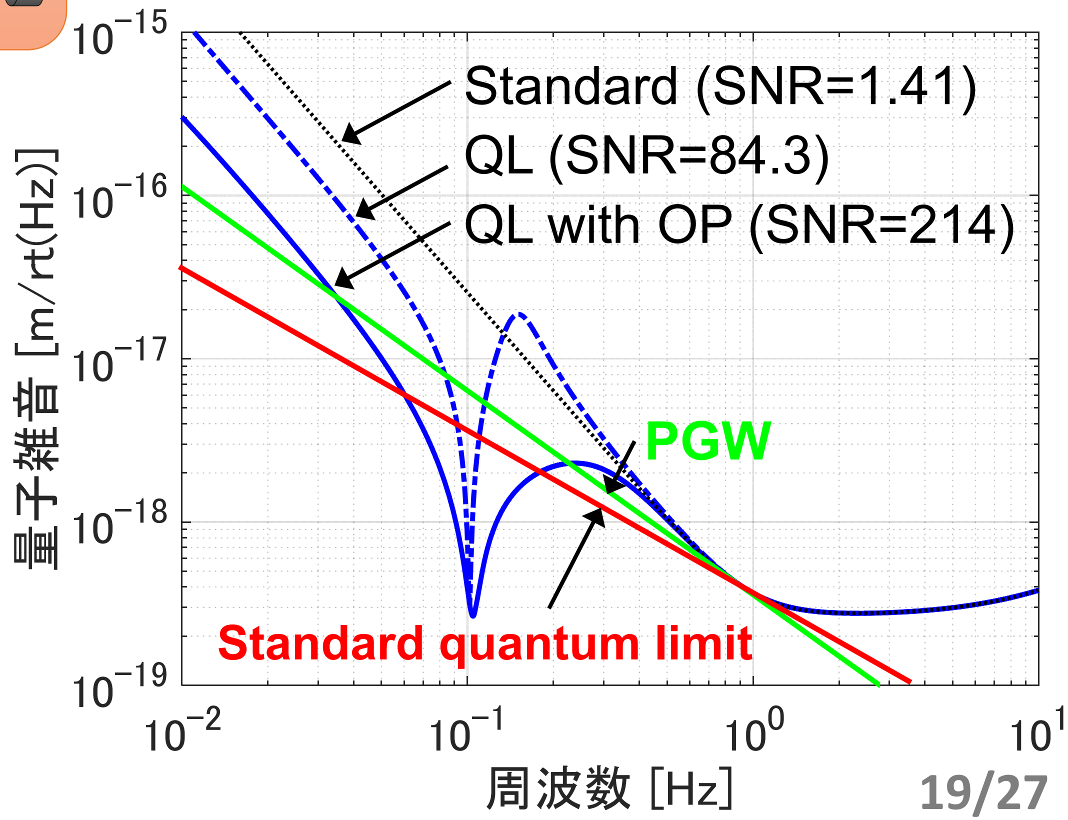
- Shoki Iwaguchi, et al., Galaxies **9** (2021) 9010009
- Tomohiro Ishikawa, et al., Galaxies **9** (2021) 9010014

Improvement of target sensitivity (2)

- **We are also investigating the possibility of implementing quantum locking (QL) with an optical spring (OP) for DECIGO.**



- **Only quantum noise is considered with a frequency band 0.1 to 10 Hz.**
- **Perfect ponderomotive squeezing is assumed.**
- **Laser power of 100 W is assumed.**



- Rika Yamada, et al., Phys. Lett. A 384 (2020) 126626
- Rika Yamada, et al., Phys. Lett. A 402 (2021) 127365

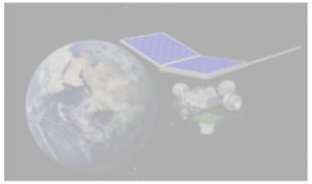
Roadmap

Now updating the roadmap

Mission

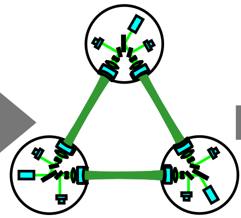
R&D
Fabrication

SWIM



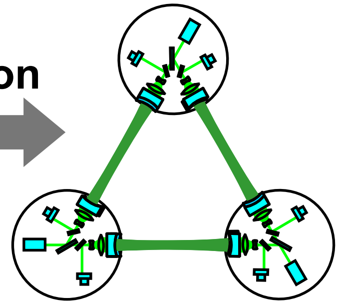
DICIGO Pathfinder

R&D
Fabrication



B-DECIGO

R&D
Fabrication

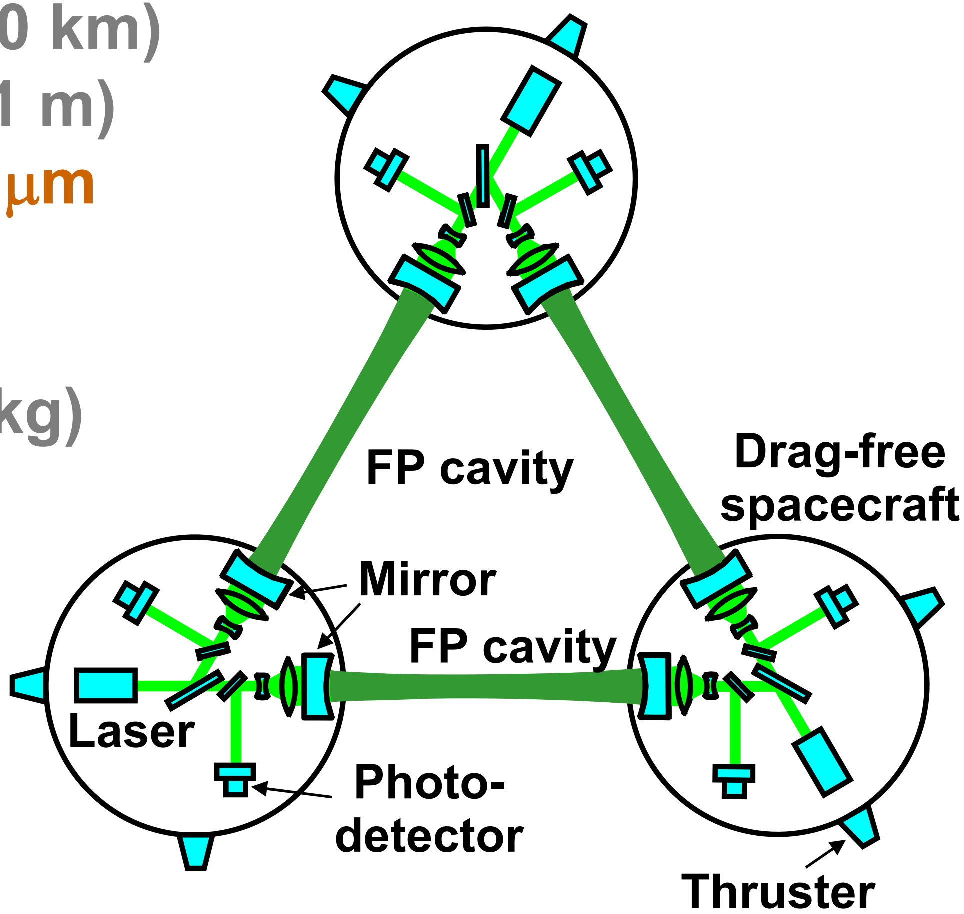


DECIGO

Objectives	Test of key technologies	Detection of GW w/ minimum spec. Test FP cavity between S/C	Full GW astronomy
Scope	1 S/C 1 arm	3 S/C 3 interferometer	3 S/C, 3 interferometers 4 clusters

B-DECIGO: Conceptual design

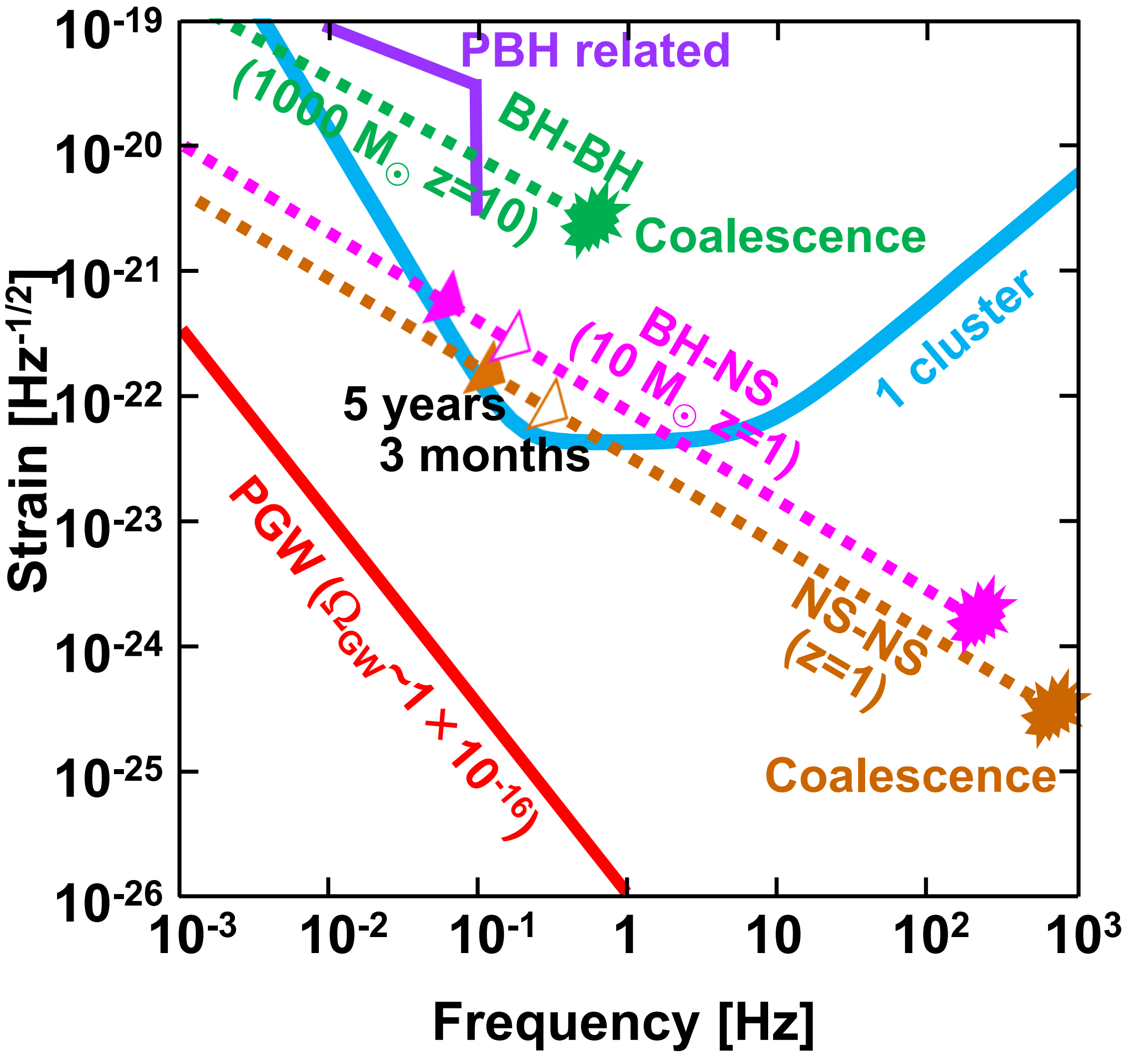
- Interferometer type: DFPI
- Arm length: 100 km (1000 km)
- Mirror diameter: 30 cm (1 m)
- Laser wavelength : 0.515 μm
- Finesse: 100 (10)
- Laser power: 1 W (10 W)
- Mirror mass: 30 kg (100 kg)
- S/C: drag free
- # of interferometers: 3
- Orbit: TBD
  (Heliocentric orbit)
- # of clusters: 1 (4)



* (DECIGO parameter if different)

B-DECIGO: Target sensitivity and objectives

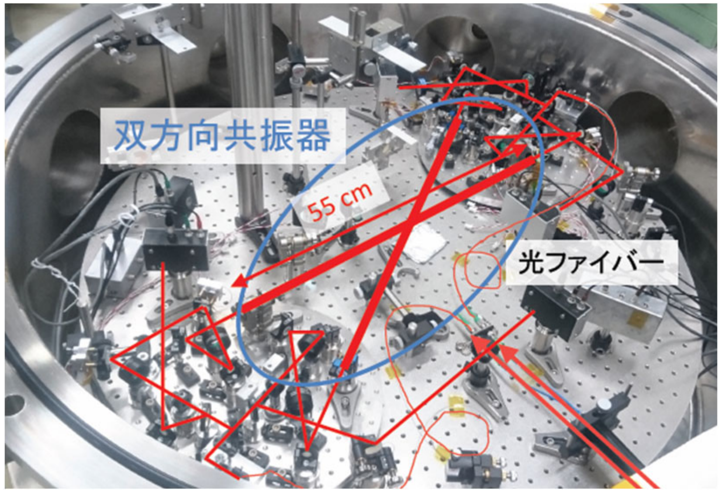
- Observation of NS-NS (BH) binary
  - Prediction of timing of NS-NS (BH) coalescence
  - 100 /year
- Revelation of origin of ~30 M BBH (Nakamura+ 2016)
- Much better parameter estimation of binaries (Isoyama+ 2018)
- Removal of foreground for DECIGO
- Verification of technologies for DECIGO



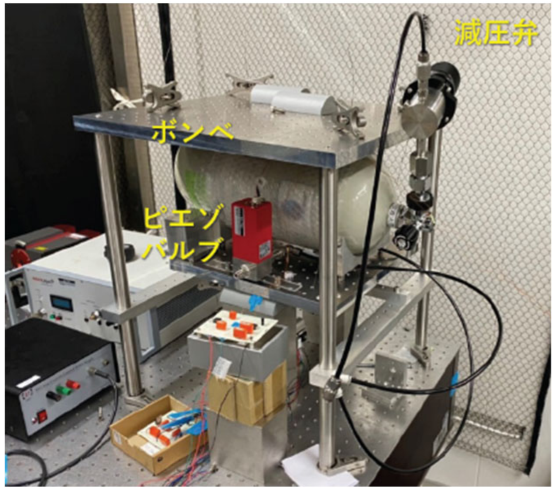
Progress on B-DECIGO

- Investigation and development of system
  - Feasibility study and cost estimation with an industrial partner (financial support by RESCEU)
  - Technology study meetings
  - Collaboration with ISAS/JAXA formation flying working group
  - Study of possibility of technology demonstration by super small spacecraft
- Application for B-DECIGO working group to ISAS/JAXA
  - In preparation
- Submission of letter of intent to master plan 2023

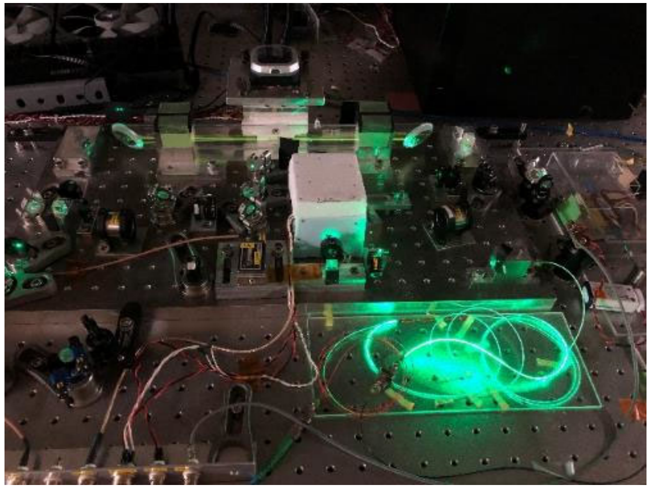
Progress on technologies for B-DECIGO

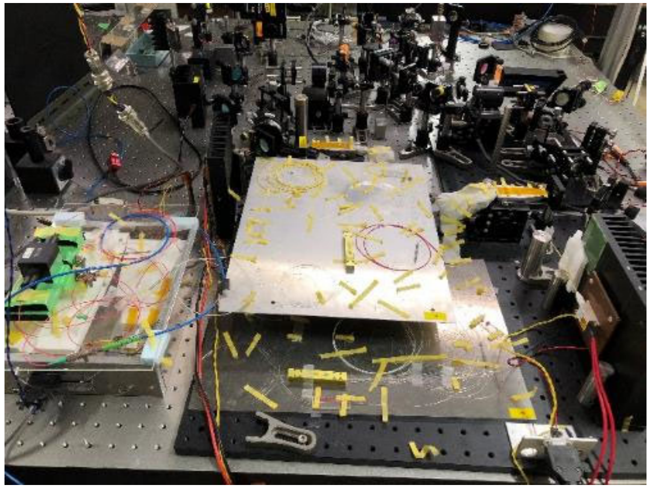


Bi-directional interferometer



Low-noise thruster



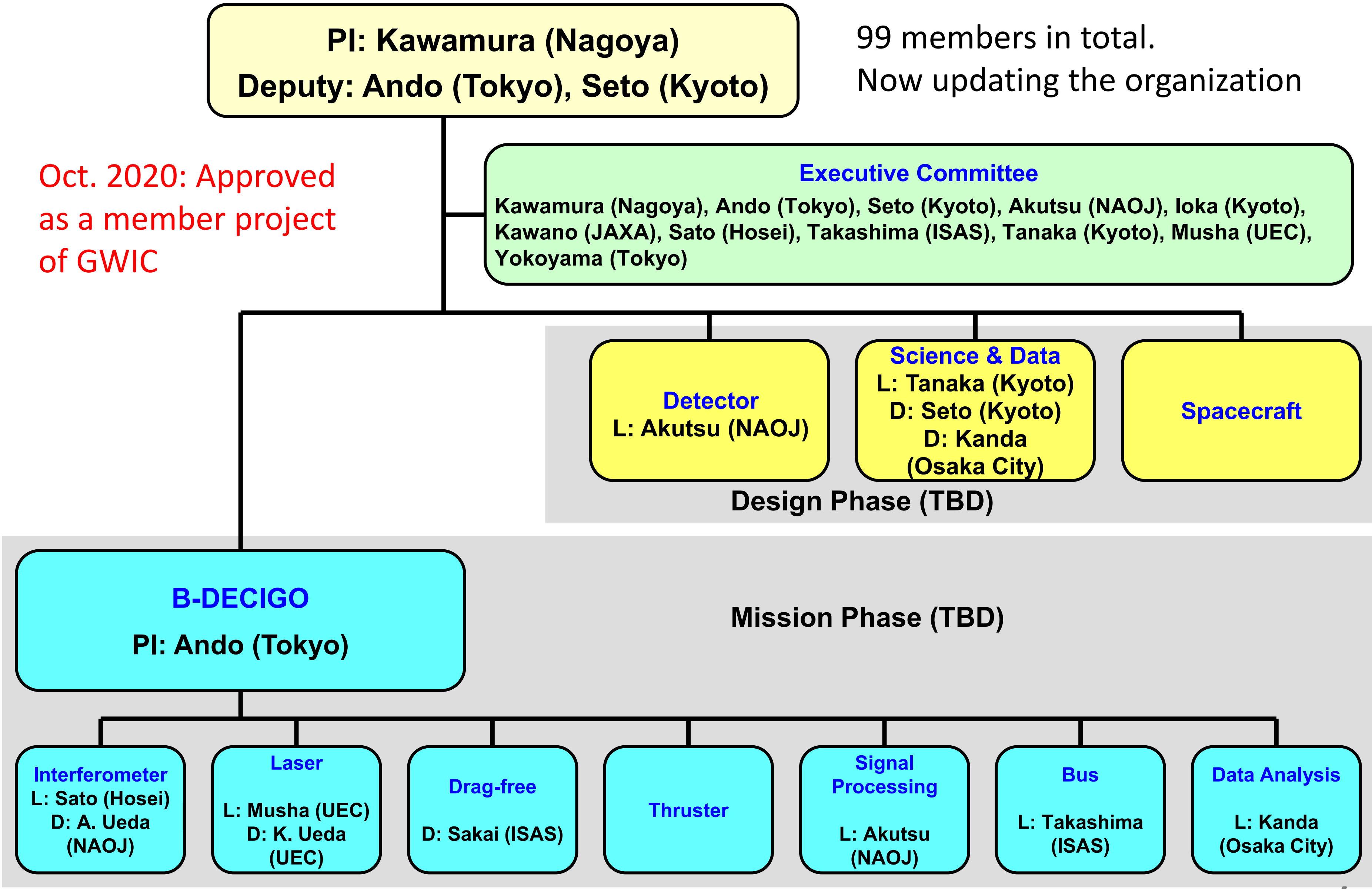


High-power stabilized laser

DECIGO Organization

99 members in total.
Now updating the organization

Oct. 2020: Approved as a member project of GWIC



L: Leader, D: Deputy

SILVIA (Space Interferometer Laboratory Voyaging towards Innovative Applications)

- Small satellite mission by formation flight official WG at ISAS/JAXA in collaboration with the DECIGO working group and infrared interferometer team (and possibly X-ray interferometer team)
- Objectives and scope
  - Demonstration of the following technologies
    - Formation flight among three (or two) spacecraft
    - Drag-free system
- Members
  - PI: I. Kawano, an executive member of the DECIGO working group
  - including many DECIGO members (Kawamura, Ando, …)
- Current status
  - Applied for a small satellite mission at ISAS/JAXA
  - Aug. 2020: Approved to proceed to Pre-Phase A1b (Idea implementation process)
    - Only SILVIA selected among seven missions that applied
  - Developing preliminary design for the review to judge for Pre-phase A2 (Mission definition)
    - If approved, SILVIA will become a candidate mission for the 5th or 6th small satellite mission

Summary

- DECIGO will accomplish a variety of outstanding sciences, including direct observation of PGWs.
- We are now investigating improvement of target sensitivity.
- B-DECIGO will not only accomplish a variety of important sciences but also establish the necessary technologies for DECIGO.
- SILVIA will establish the essential technologies for B-DECIGO and DECIGO.