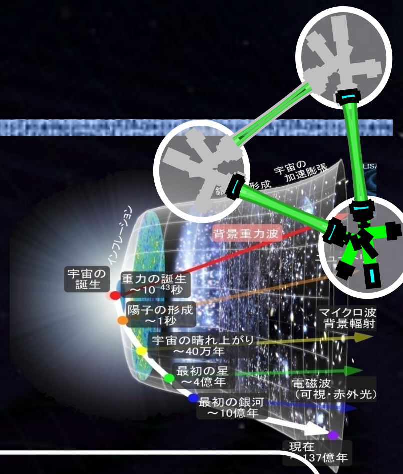


Space Gravitational-Wave Antenna: DECIGO and Pre-DECIGO

Masaki Ando (Univ. of Tokyo / NAOJ)
On behalf of DECIGO Working Group

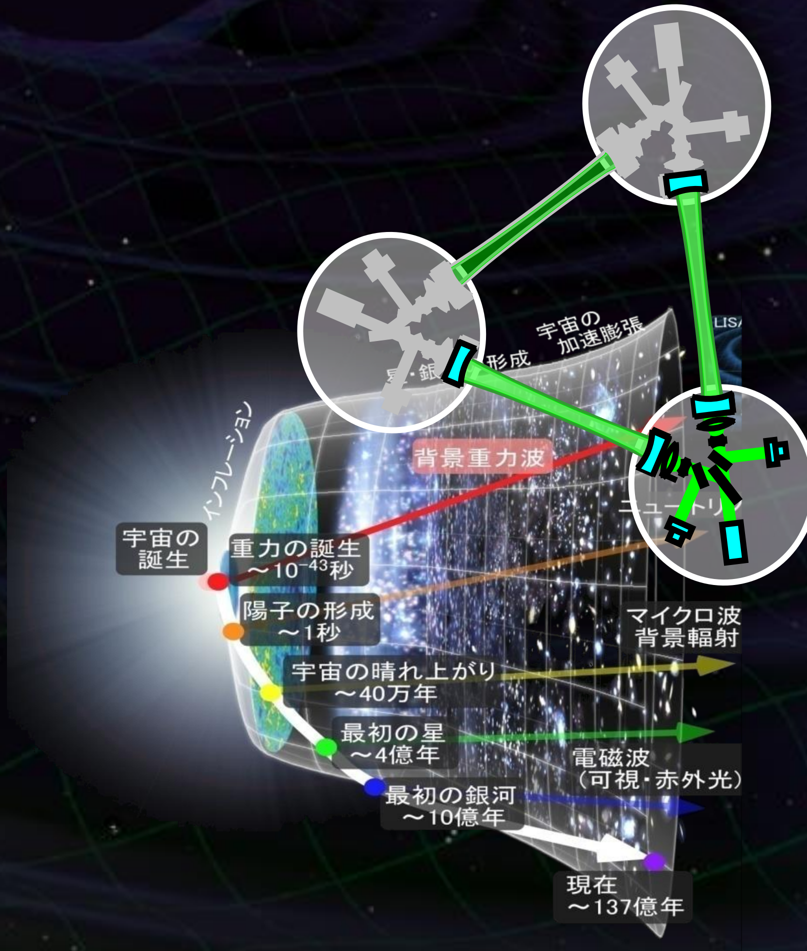
DECIGO Members

Masaki Ando, Seiji Kawamura, Naoki Seto, Takashi Nakamura, Kimio Tsubono, Shuichi Sato, Takahiro Tanaka, Ikkoh Funaki, Kenji Numata, Nobuyuki Kanda, Kunihito Ioka, Takeshi Takashima, Jun'ichi Yokoyama, Tomotada Akutsu, Mitsuru Musha, Akitoshi Ueda, Koh-suke Aoyanagi, Kazuhiro Agatsuma, Hideki Asada, Yoichi Aso, Koji Arai, Akito Araya, Takeshi Ikegami, Takehiko Ishikawa, Hideharu Ishizaki, Hideki Ishihara, Kiwamu Izumi, Kiyotomo Ichiki, Hiroyuki Ito, Yousuke Itoh, Kaiki T. Inoue, Ken-ichi Ueda, Takafumi Ushiba, Masayoshi Utashima, Satoshi Eguchi, Yumiko Ejiri, Motohiro Enoki, Toshikazu Ebisuzaki, Yoshiharu Eriguchi, Naoko Ohishi, Masashi Ohkawa, Masatake Ohashi, Kenichi Oohara, Yoshiyuki Obuchi, Kenshi Okada, Norio Okada, Koki Okutomi, Nobuki Kawashima, Fumiko Kawazoe, Isao Kawano, Kenta Kiuchi, Naoko Kishimoto, Hitoshi Kuninaka, Hiroo Kunimori, Kazuaki Kuroda, Sachiko Kuroyanagi, Hiroyuki Koizumi, Feng-Lei Hong, Kazunori Kohri, Wataru Kokuyama, Keiko Kokeyama, Yoshihide Kozai, Yasufumi Kojima, Kei Kotake, Shiho Kobayashi, Rina Gondo, Motoyuki Saijo, Ryo Saito, Shin-ichiro Sakai, Masaaki Sakagami, Shihori Sakata, Norichika Sago, Misao Sasaki, Takashi Sato, Masaru Shibata, Kazunori Shibata, Ayaka Shoda, Hisaaki Shinkai, Aru Suemasa, Naoshi Sugiyama, Rieko Suzuki, Yudai Suwa, Kentaro Somiya, Hajime Sotani, Tadashi Takano, Kakeru Takahashi, Keitaro Takahashi, Hirotaka Takahashi, Fuminobu Takahashi, Ryuichi Takahashi, Ryutaro Takahashi, Takamori Akiteru, Hideyuki Tagoshi, Hiroyuki Tashiro, Nobuyuki Tanaka, Keisuke Taniguchi, Atsushi Taruya, Takeshi Chiba, Dan Chen, Shinji Tsujikawa, Yoshiki Tsunesada, Morio Toyoshima, Yasuo Torii, Kenichi Nakao, Kazuhiro Nakazawa, Shinichi Nakasuka, Hiroyuki Nakano, Shigeo Nagano, Kouji Nakamura, Yoshinori Nakayama, Atsushi Nishizawa, Erina Nishida, Yoshito Niwa, Taiga Noumi, Tatsuaki Hashimoto, Kazuhiro Hayama, Tomohiro Harada, Wataru Hikida, Yoshiaki Himemoto, Hisashi Hirabayashi, Takashi Hiramatsu, Mitsuhiro Fukushima, Ryuichi Fujita, Masa-Katsu Fujimoto, Toshifumi Futamase, Mizuhiko Hosokawa, Hideyuki Horisawa, Kei-ichi Maeda, Hideo Matsuhara, Nobuyuki Matsumoto, Yuta Michimura, Osamu Miyakawa, Umpei Miyamoto, Shinji Miyoki, Shinji Mukohyama, Toshiyuki Morisawa, Mutsuko Y. Morimoto, Shigenori Moriwaki, Kent Yagi, Hiroshi Yamakawa, Toshitaka Yamazaki, Kazuhiro Yamamoto, Shijun Yoshida, Taizoh Yoshino, Chul-Moon Yoo, Yaka Wakabayashi

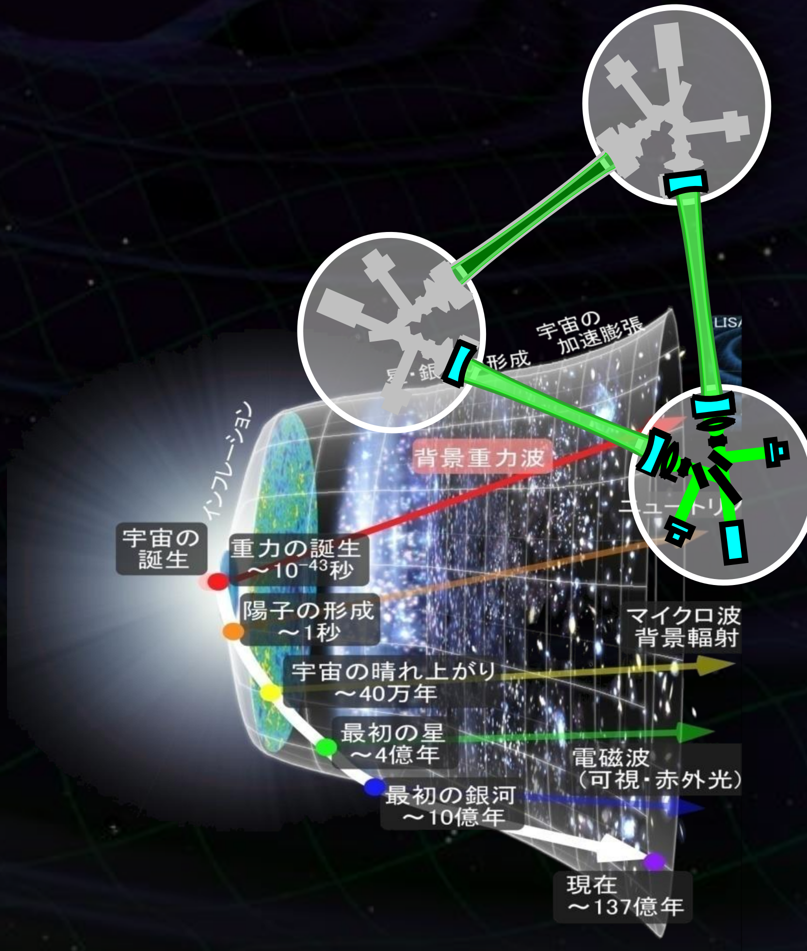
(On June 18th, 2015)

Outline

- DECIGO
- Pre-DECIGO



DECIGO



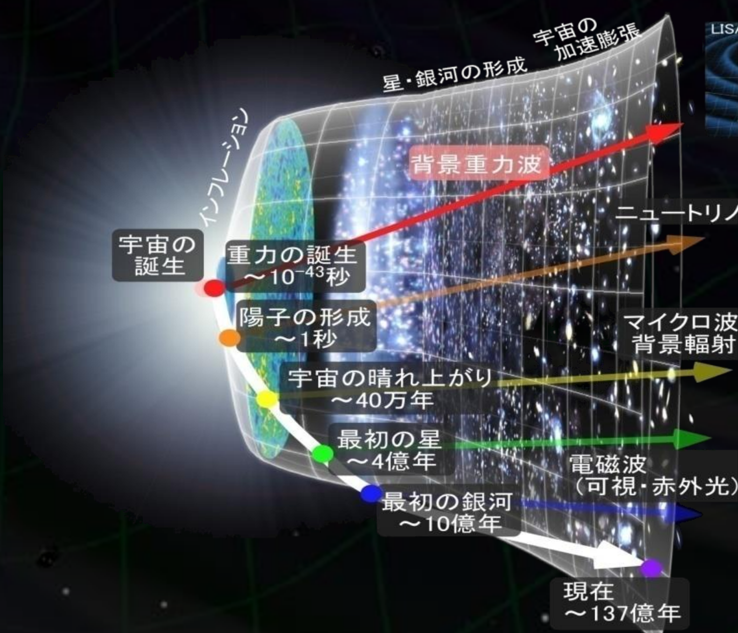
宇宙の
加速膨張
インフレーション
背景重力波
宇宙の
誕生
重力の誕生
～10^{-43}秒
陽子の形成
～1秒
マイクロ波
背景輻射
宇宙の晴れ上がり
～40万年
最初の星
～4億年
電磁波
（可視･赤外光）
最初の銀河
～10億年
現在
～137億年

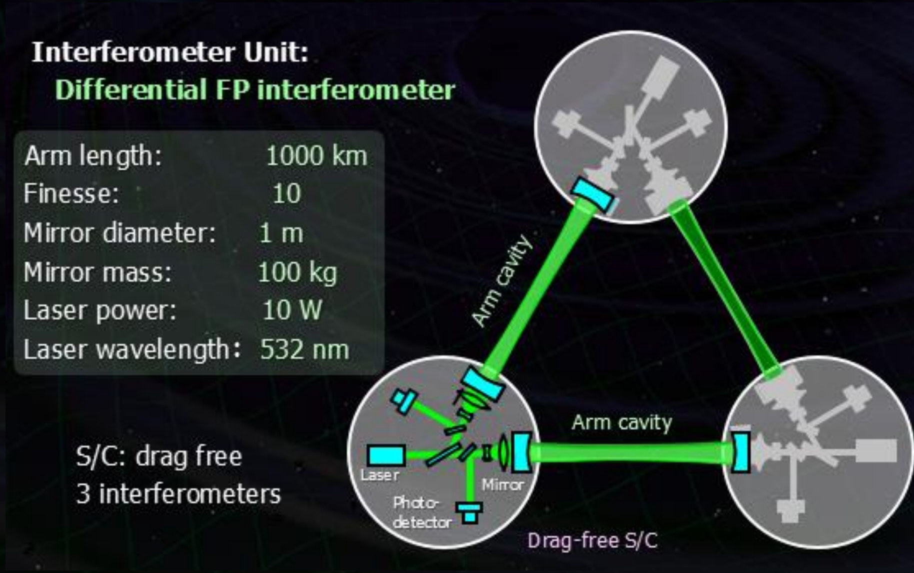
Space GW Antenna DECIGO

DECIGO (DECI-hertz interferometer Gravitational wave Observatory)

Purpose: To Obtain Cosmological Knowledge.

Direct observation of the origin of space-time and matter in Big-bang Universe.

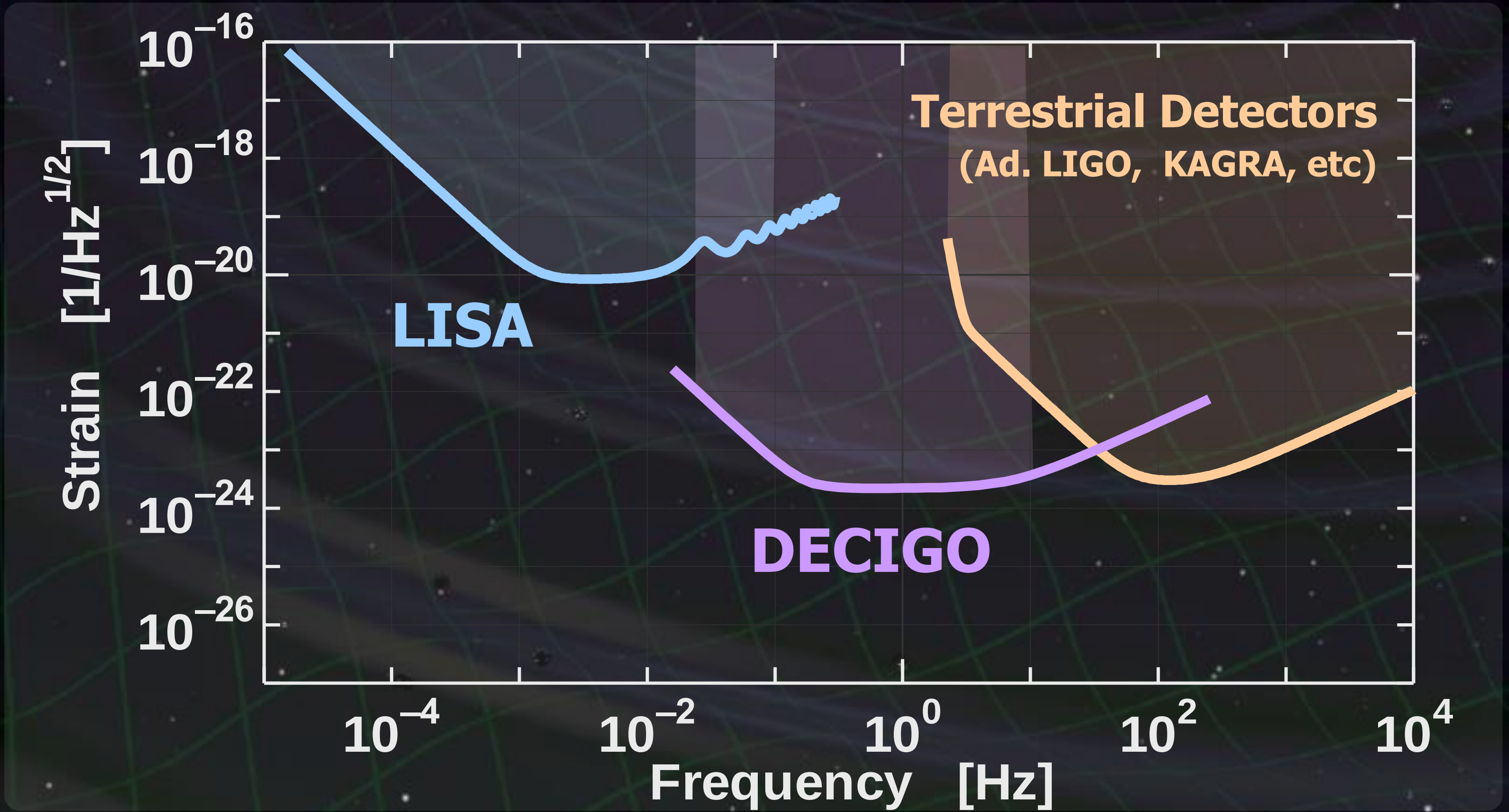




DECIGO Observation Band

Space GW antenna
Obs. band around 0.1 Hz

⇨ 'Bridge' the obs.gap between
LISA and Terrestrial detectors

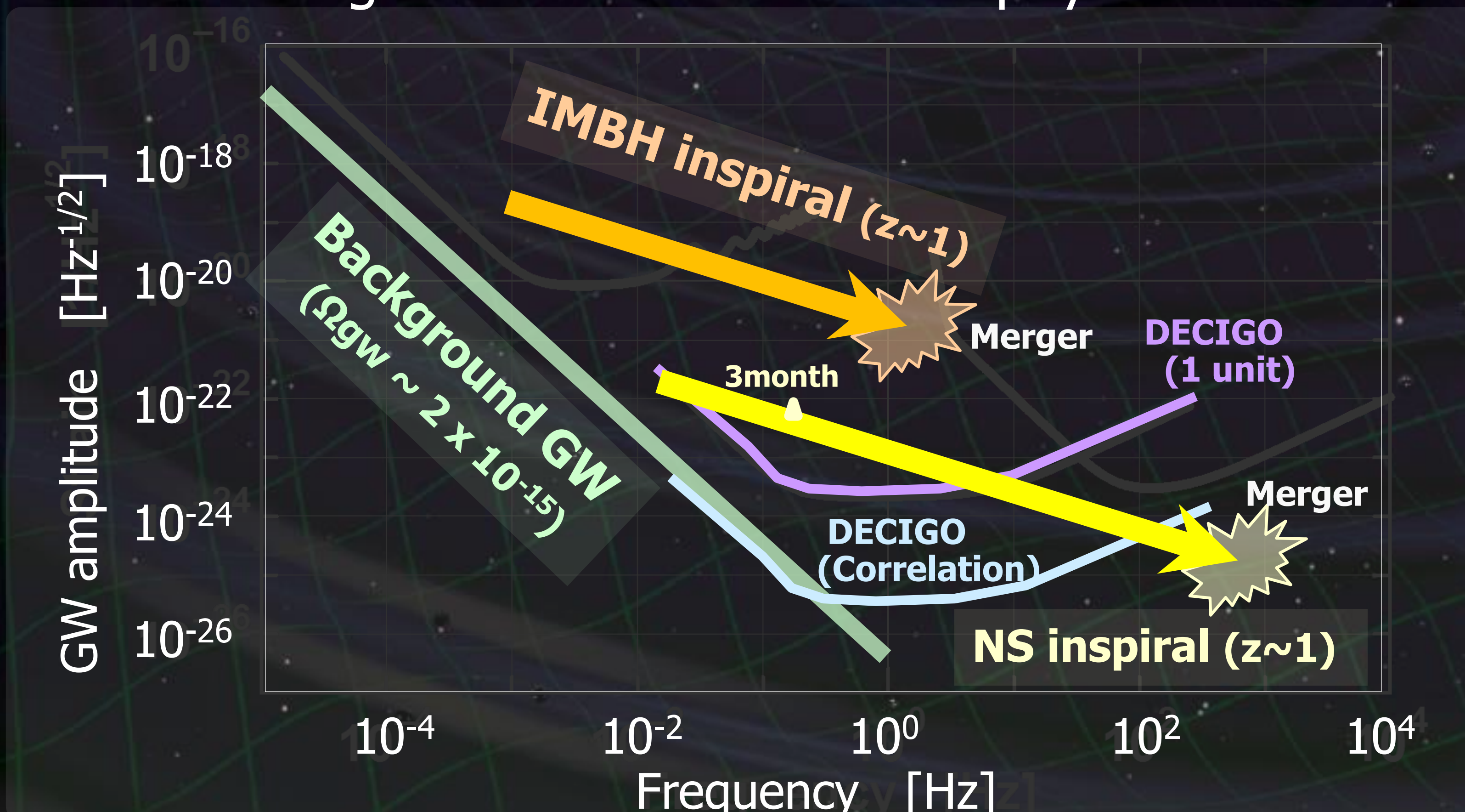


Targets and Science

IMBH binary inspiral
NS binary inspiral
Stochastic background

⇨

Galaxy formation (Massive BH)
Cosmology (Inflation, Dark energy)
Fundamental physics



Observation of GW from Inflation

DECIGO

BICEP2, (POLARBEAR,...)

CMB B-mode polarization observation by micro-wave telescope.

DECIGO, (KAGRA, aLIGO,...)

GWB observation by GW telescope.

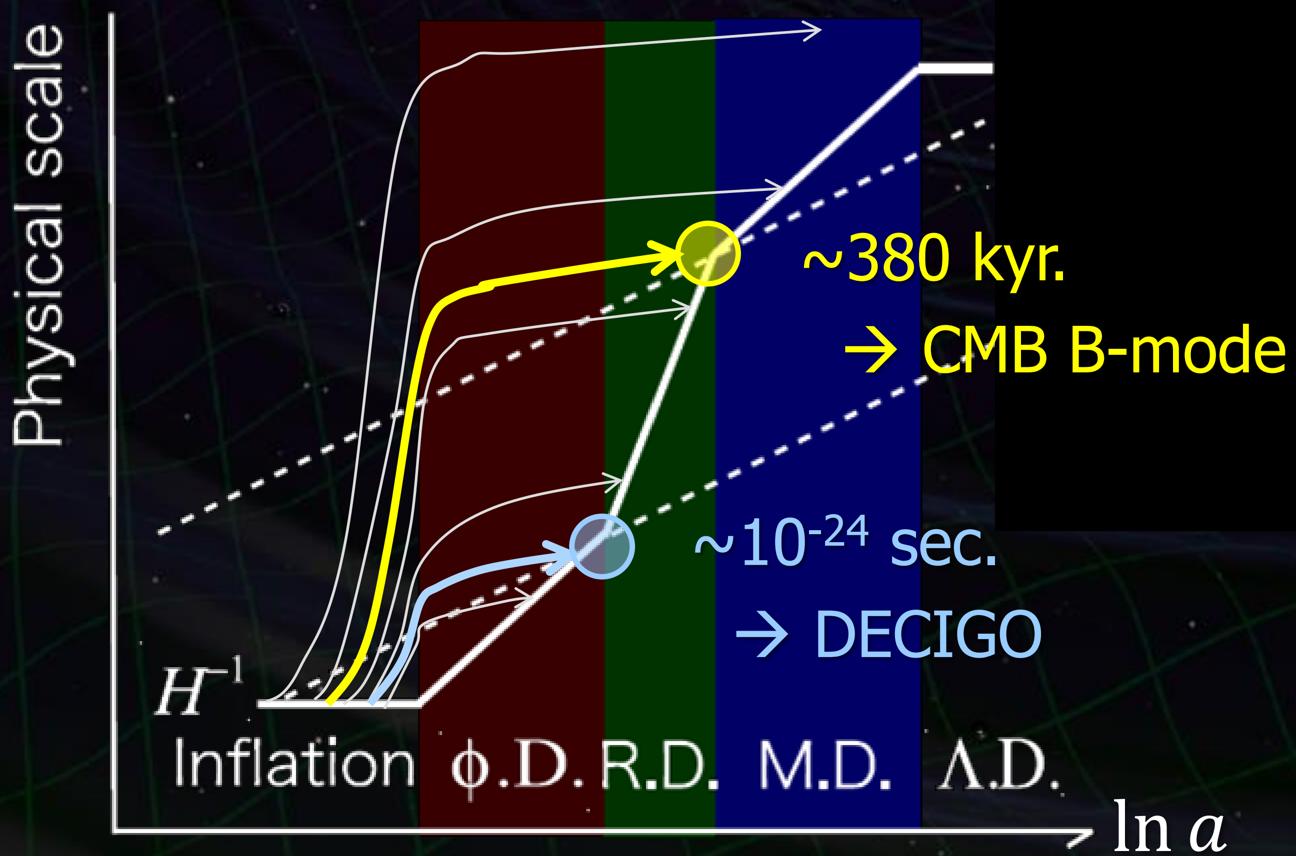
Original figure by Tajima (Kyoto 2011)

GW from Inflation

DECIGO

Stochastic background GWs by quantum fluctuation

→ Earlier-generated GWs in inflation period entered later into the horizon of the universe.

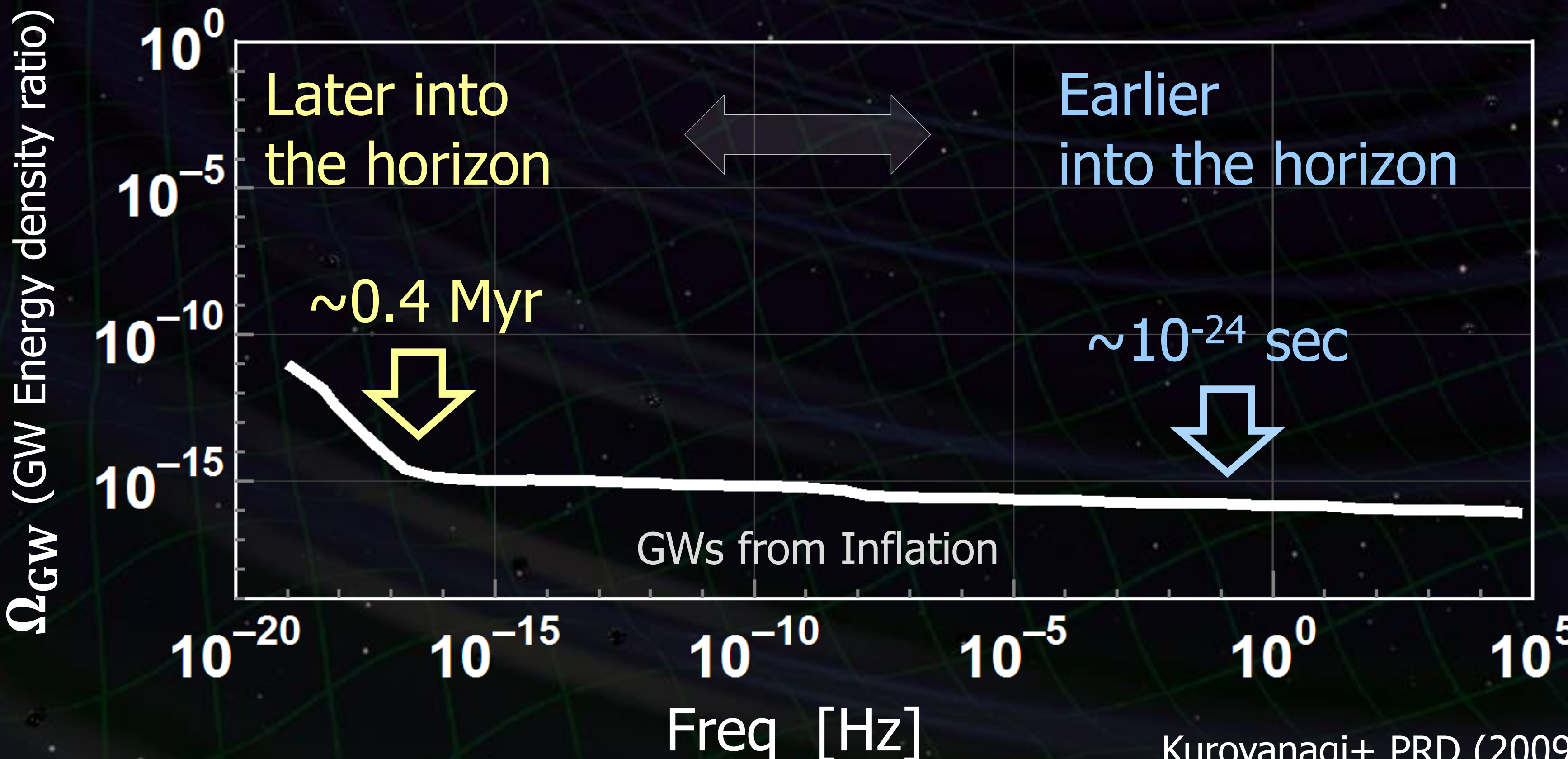


Nakayama+, Journal of Cosmology and Astroparticle Physics 06 (2008) 020.

GWs from Inflation

DECIGO

Enter the horizon earlier → High frequency GW.



Kuroyanagi+ PRD (2009)

Probing the Early Universe by GW

DECIGO

- GWs will carry direct information on the early universe.
- Spectrum : Initial fluctuation + Evolution history

Depends on r (tensor-to-scalar ratio), which may be also pinned-down by CMB B-mode polarization observation.

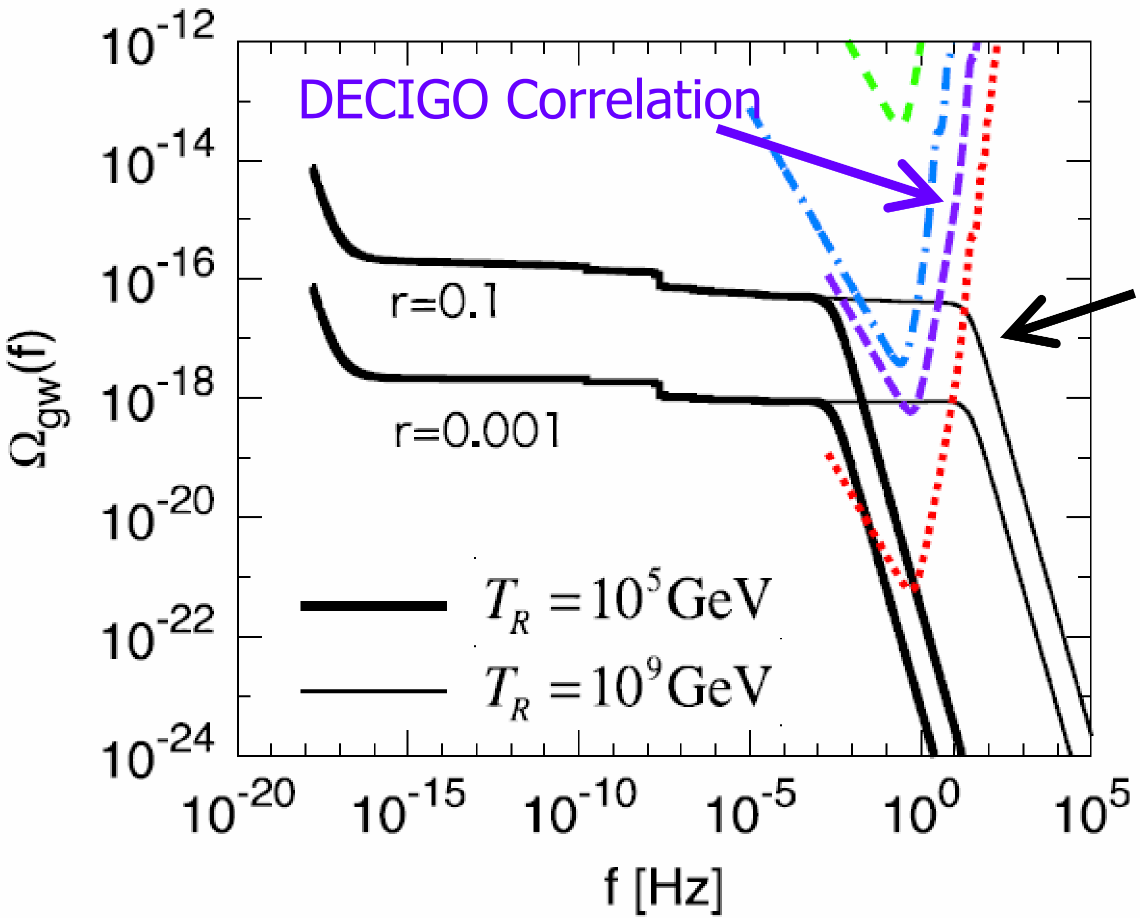
Different age in different freq.
Higher freq. → Earlier universe
- Reheating temperature
- Thermal history of the universe

....

GW from Inflation

Energy density ∝ Tensor-Scalar Ratio (r).

Power spectrum : Evolution history of the Universe.



- Spectrum Power.
  → Energy scale of inflation
- Cut-off freq.
  → Energy scale of Reheating

Nakayama+, Journal of Cosmology and Astroparticle Physics 06 (2008) 020.

Amplitude and Energy Density Ratio

DECIGO

Equivalent GW amplitude [Hz$^{-1/2}$]

GW energy density ratio [Dimensionless]

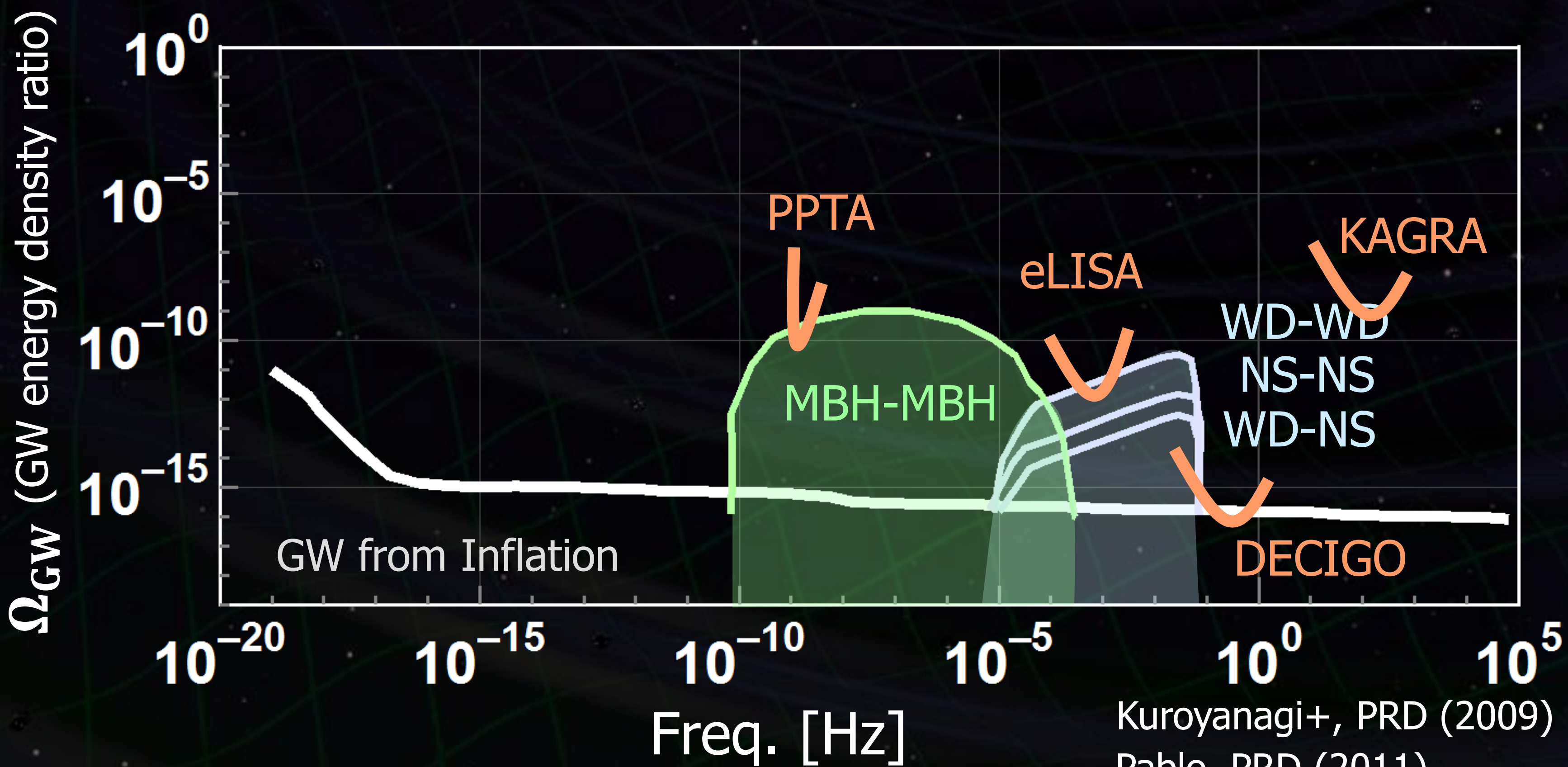
$$\tilde{h}^2_{GW}(f) = \frac{3H_0^2}{10\pi^2 f^3}\Omega_{GW}(f)$$

Larger amplitude in low-freq.

Foreground GWs

Unresolvable GWs from too many binaries

⇨ GW Foregrounds at 10^{-10} – 0.1 Hz freq. band.



Kuroyanagi+, PRD (2009)
Pablo, PRD (2011)

‘Window’ Band for Primordial GWs

DECIGO

- Large amplitude GWs expected at low-frequency
- Foreground GWs below 0.1Hz

⇩

Freq. band of 0.1 -1 Hz is advantageous for observation of GWs from inflation

$$\Omega_{\mathrm{GW}} \sim 10^{-16} - 10^{-15}$$

$$\rightarrow \tilde{h}_{\mathrm{GW}} \sim 10^{-24}\ \mathrm{Hz}^{-1/2}\ (@\ 0.1\mathrm{Hz})$$

Pre-Conceptual Design

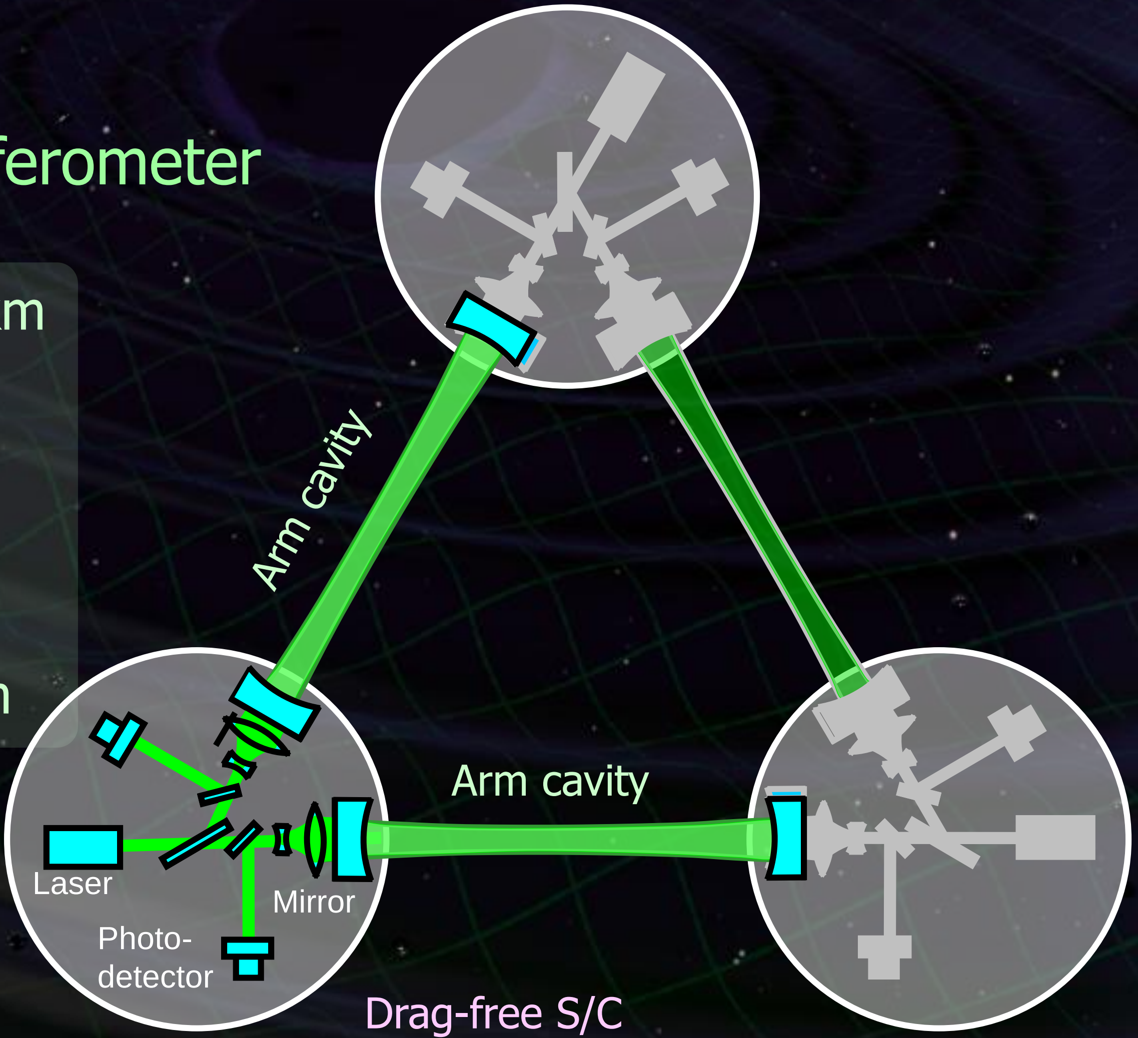
Interferometer Unit:

Differential FP interferometer

Arm length:	1000 km
Finesse:	10
Mirror diameter:	1 m
Mirror mass:	100 kg
Laser power:	10 W
Laser wavelength:	532 nm

S/C: drag free

3 interferometers

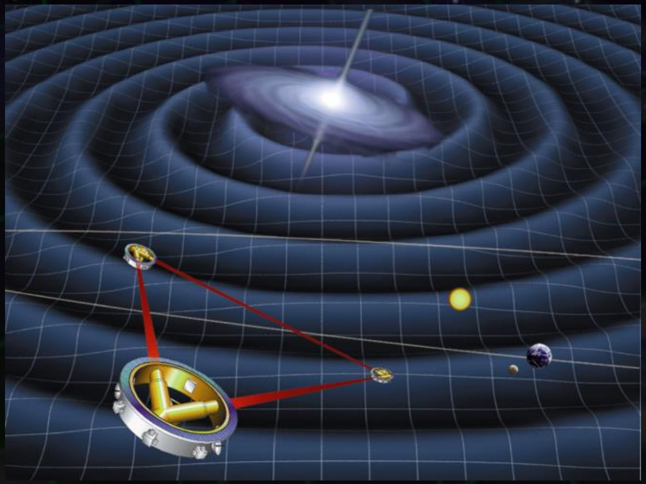


Space GW antenna

eLISA

(Laser Interferometer Space Antenna)

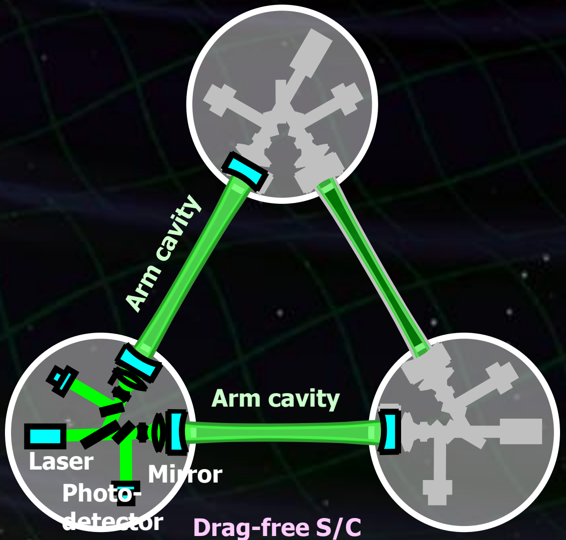
- Target: SMBH, Binaries.
  GWs around 1mHz.
- Baseline : 1-5M km.
  Constellation flight by 3 S/C
- Optical transponder.



DECIGO

(Deci-hertz Interferometer Gravitational Wave Observatory)

- Target: IMBH, NS binaries.
  GWs around 0.1Hz.
- Baseline : 1000 km.
  Formation flight by 3 S/C.
- Fabry-Perot interferometer.



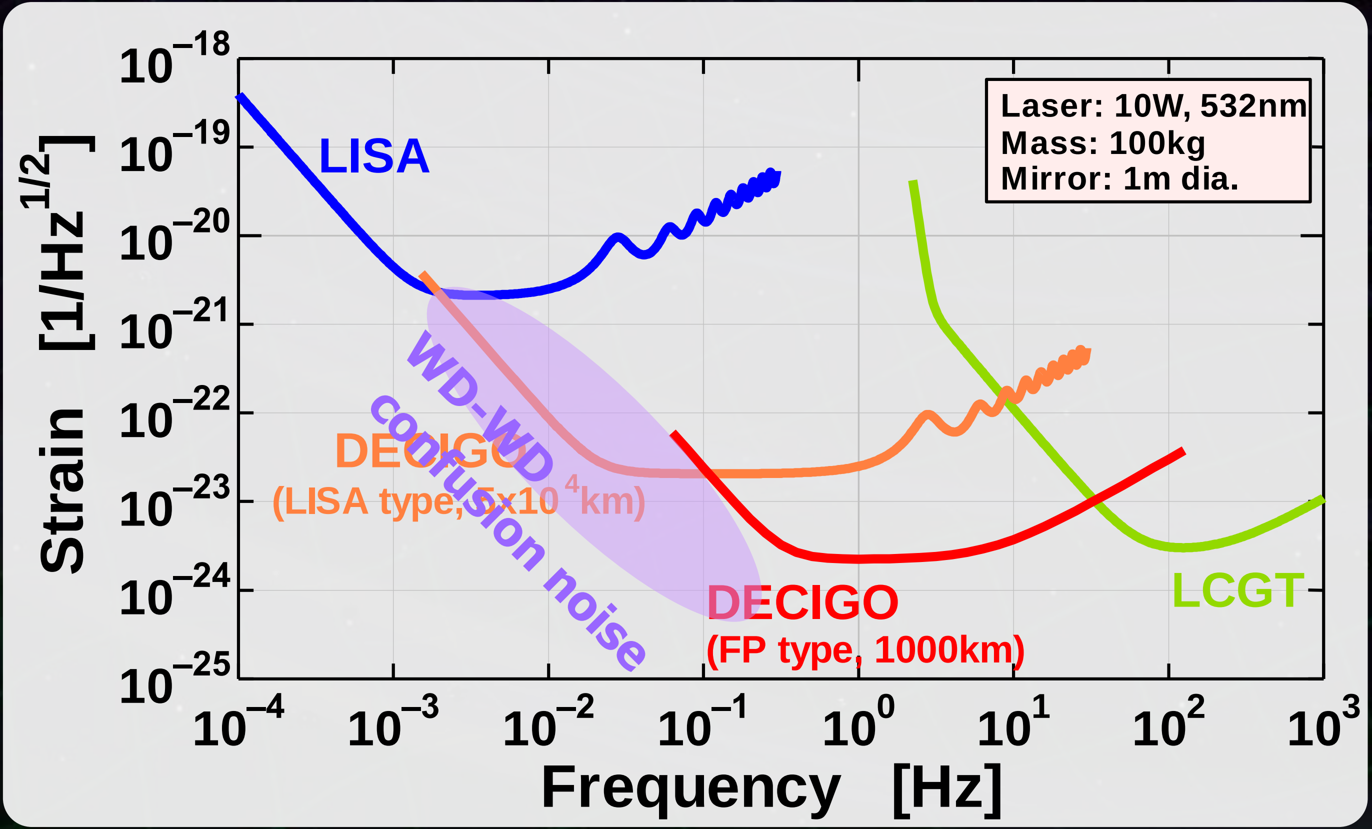
Interferometer Design

DECIGO

Transponder type vs Direct-reflection type

Compare : Sensitivity curves and Expected Sciences

⇨ Decisive factor: Binary confusion noise



Arm length

Cavity arm length : Limited by diffraction loss

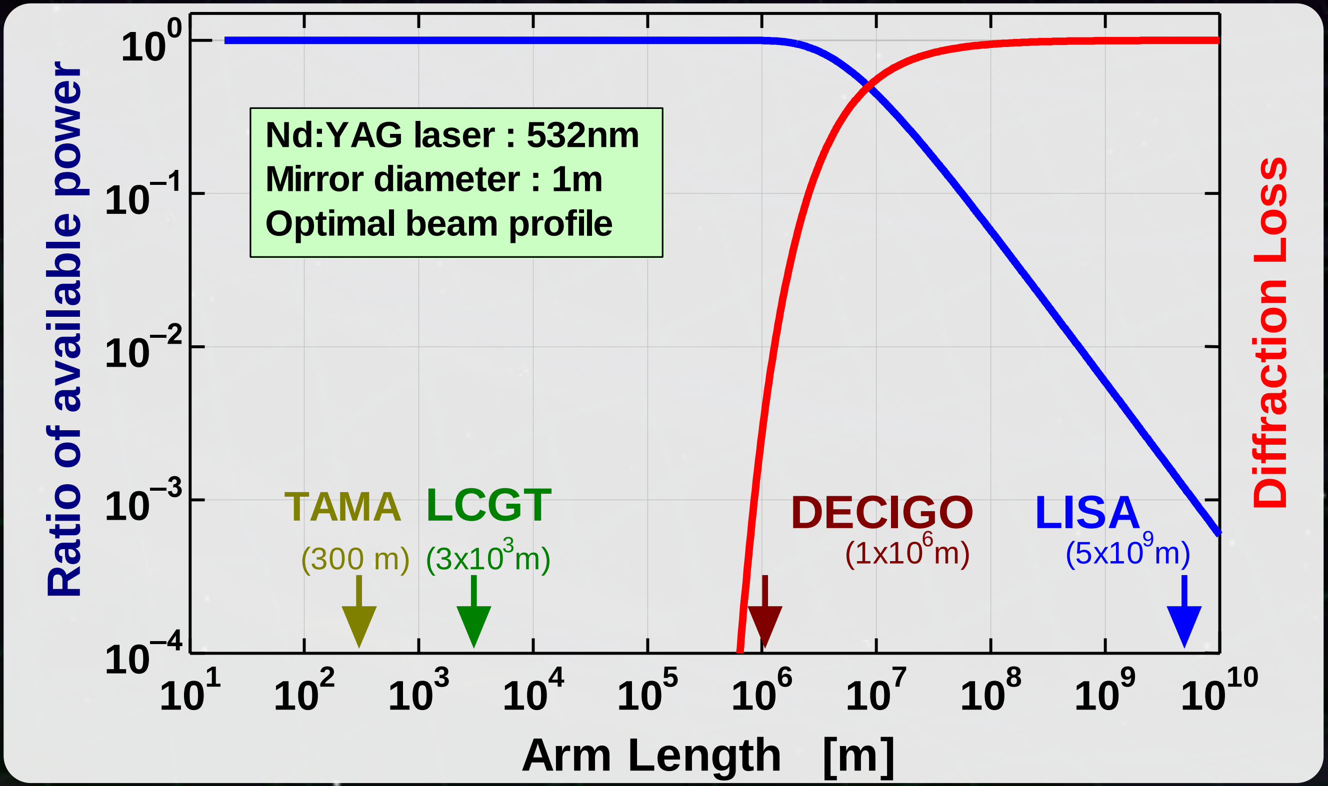
Effective reflectivity ($TEM_{00} \rightarrow TEM_{00}$)

Laser wavelength : 532nm

Mirror diameter: 1m

Optimal beam size

⇨ 1000 km is almost max.



Cavity and S/C control

Cavity length change

PDH error signal → Mirror position (+Laser freq.)

Relative motion between mirror and S/C

Local sensor → S/C thruster

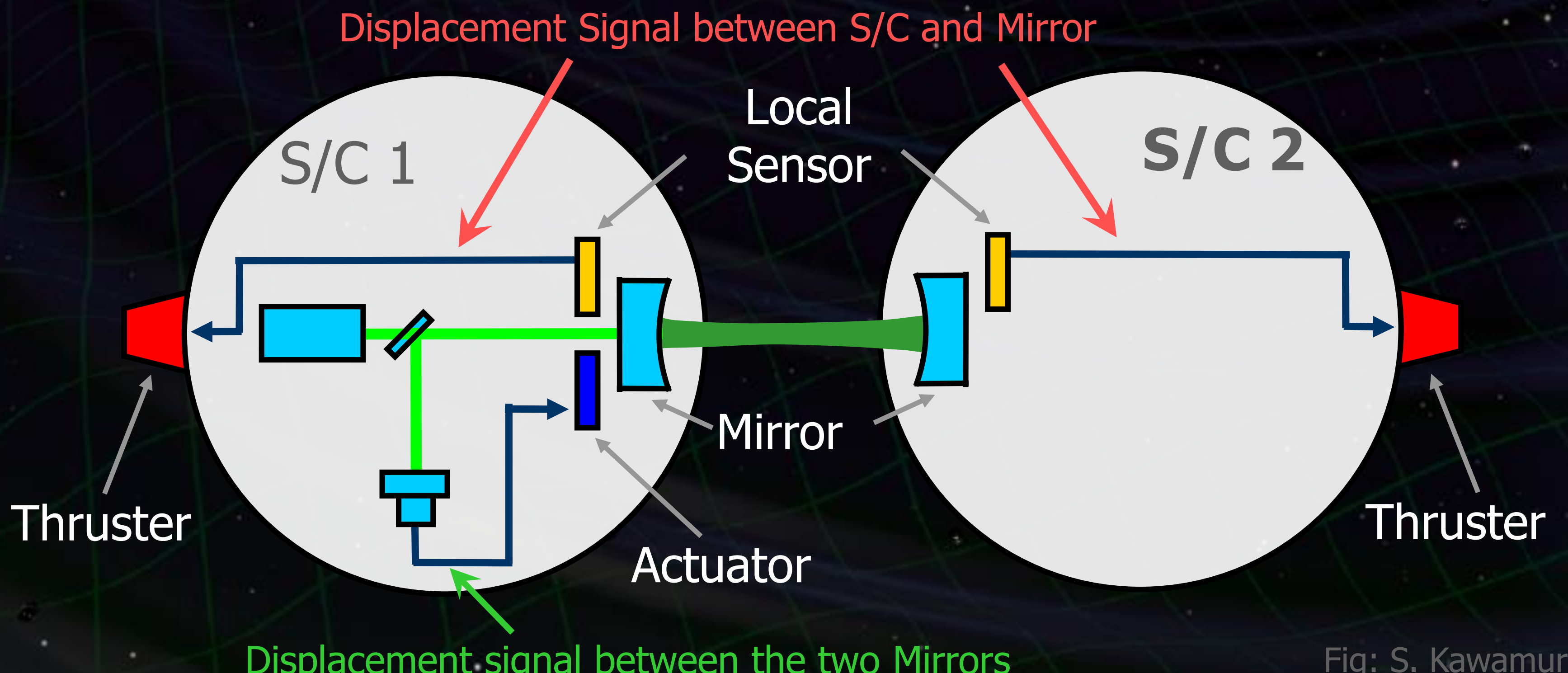


Fig: S. Kawamura

Requirements

Displacement Noise

Shot noise 3×10^{-18} m/Hz$^{1/2}$ (0.1 Hz)

⇨ x 10 of KAGRA in phase noise

Other noises should be well below the shot noise

Laser freq. noise: 1 Hz/Hz$^{1/2}$ (1Hz)

Stab. Gain 10^5, CMRR 10^5

Acceleration Noise

Force noise 4×10^{-17} N/Hz$^{1/2}$ (0.1 Hz)

⇨ x 1/50 of LISA

External force sources

Fluctuation of magnetic field, electric field, gravitational field, temperature, pressure, etc.

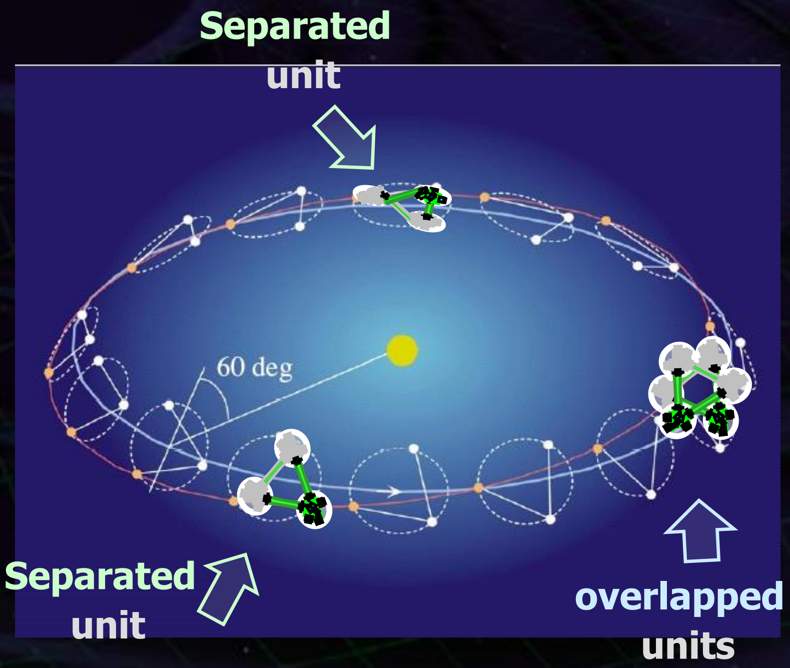
Orbit and Constellation

Candidate of orbit:

Record-disk orbit around the Sun

Relative acc. 4×10^{-12} m/s^2

(Mirror force $\sim10^{-9}$ N)



Constellation

4 interferometer units

2 overlapped units → Cross correlation

2 separated units → Angular resolution

Foreground Cleaning

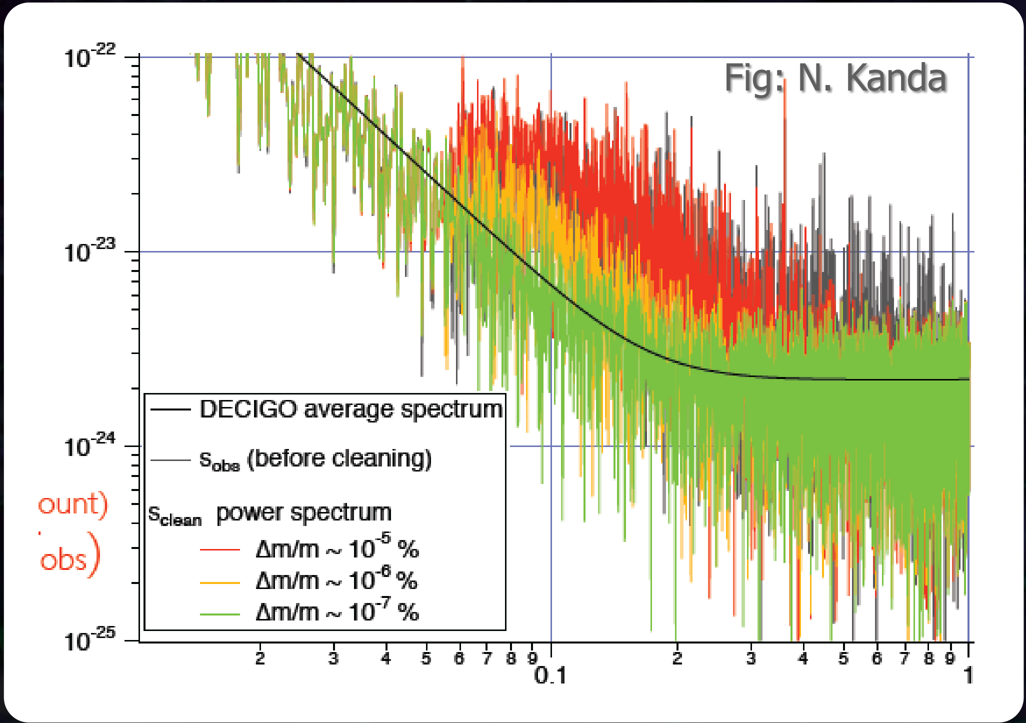
DECIGO obs. band: free from WD binary foreground
→ Open for cosmological observation

DECIGO will watch
~ 10^5 NS binaries

⇨ Foreground for GWB

In principle, possible
to remove them.

Require waveform
Accuracy $\Delta m/m < \sim 10^{-7}$ %



Design Update Possibility

DECIGO

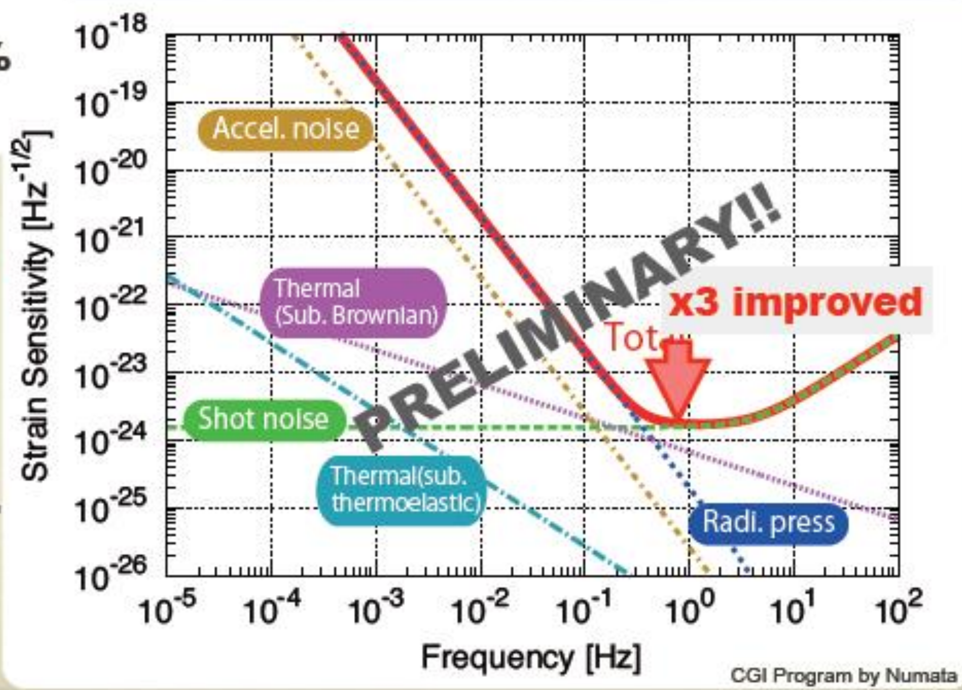
Considering "Conceptual design"

By T.Akutsu

- Arm length: **1,500** km
- Laser power: **30** W
- Laser wavelength: 532 nm
- Mirror diameter: **1.5** m
- Mirror mass: 100 kg
- Mirror reflectivity: 77.3%
- Cavity g-param: 0.1

Preliminary

Parameters tuned



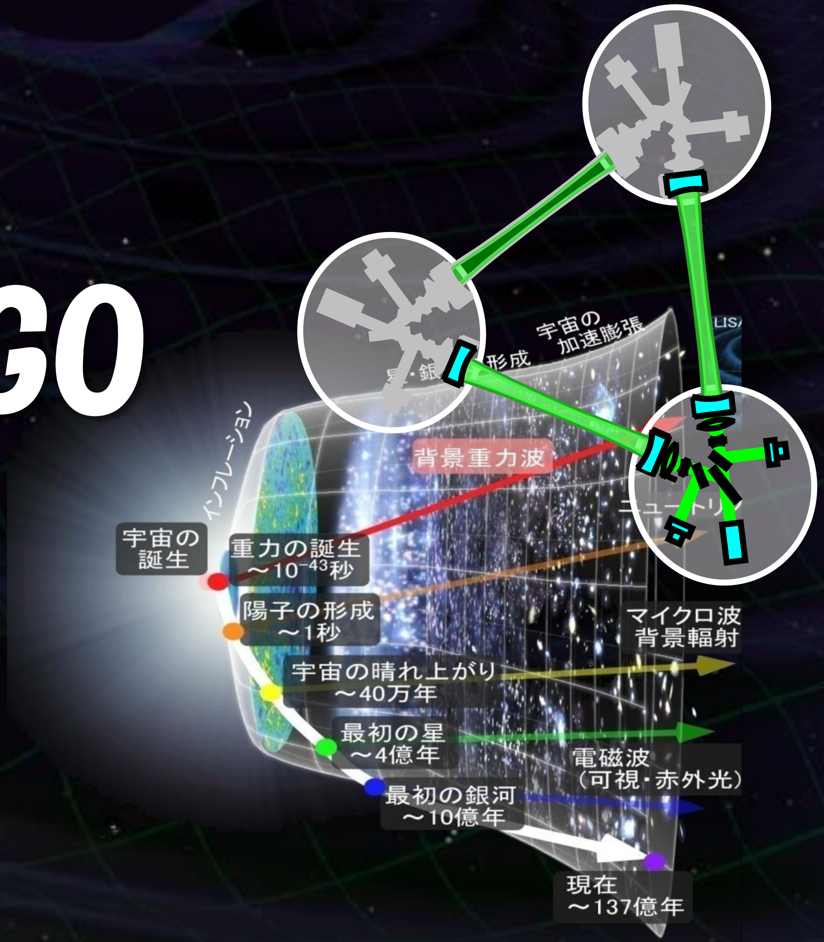
This is the first step to considering the **conceptual design**.

Next:

➡Confirm the calculations.

➡Find the realistic way to realize this!

Pre-DECIGO


宇宙の
加速膨張
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（可視・赤外光）
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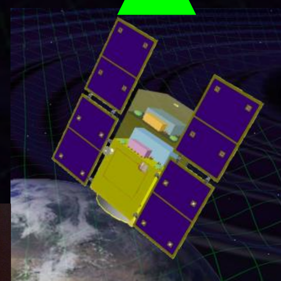
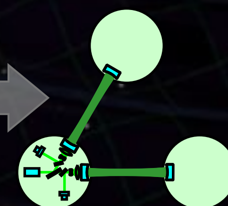
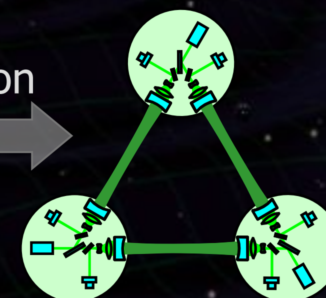
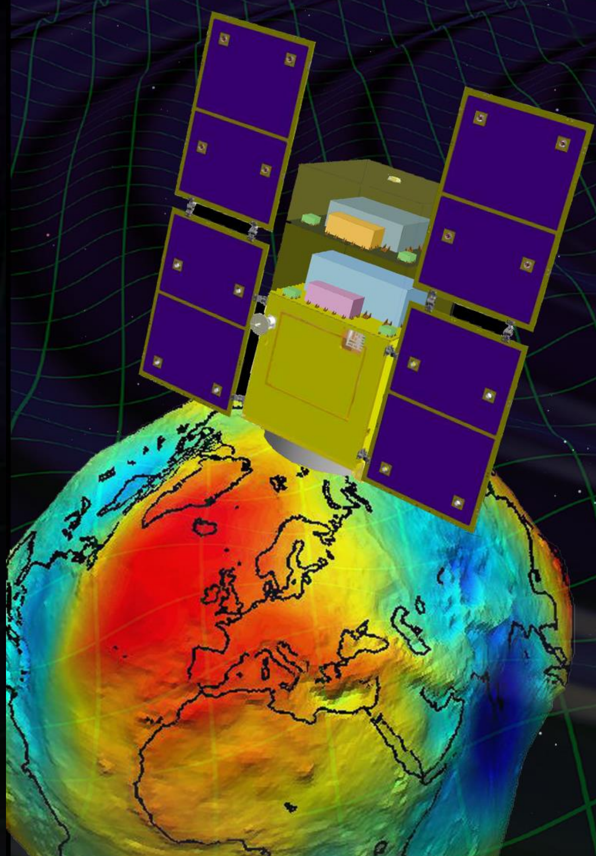
～10億年
現在
～137億年

Previous Roadmap for DECIGO

Figure: S.Kawamura

	2014–17	18–20	21–24	25	26–29	30–33
	2014 15 16 17	18 19 20	21 22 23 24	25	26 27 28 29	30 31 32 33
Mission	R&D Fabrication →  SDS-1/SWIM	 DECIGO Pathfinder (DPF)	R&D Fabrication →	 Pre-DECIGO	R&D Fabrication →	 DECIGO
Purpose	Interferometer in Space (Obs. Of GW and Earth Gravity)		Long-baseline Precise Formation Flight (GW Observation)		GW Astronomy and Cosmology	
Design	One Small Satellite Short FP cavity + Drag-free		FF with 3 S/C 1 IFO unit		FF with 3 S/C 3-4 IFO units	

DECIGO Pathfinder



Earth Image: ESA

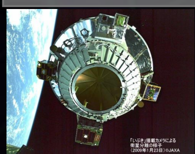
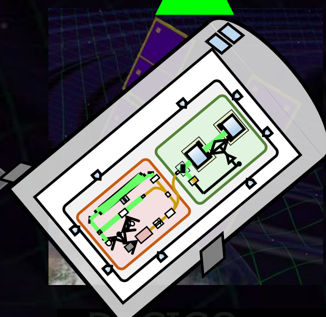
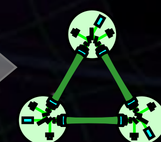
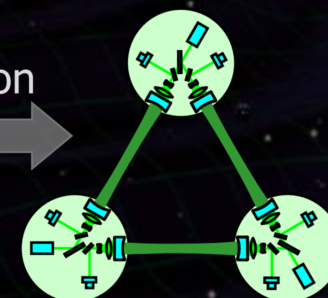
DECIGO Pathfinder (DPF)

- Space demonstration satellite for Pre-DECIGO and DECIGO.
- Working group since 2005.
- Has been a candidate of 'Small Mission by Epsilon' in JAXA.
- Mission proposal submitted in Feb. 2014.

→ Failed in the selection

Updated Roadmap for DECIGO

Figure: S.Kawamura

	2014 15 16 17 18 19 20	21 22 23 24 25 26 27	28 29 30 31 32 33
Mission	R&D Fabrication  SDS-1/SWIM  Ground test + Piggy-back opportunity.	R&D Fabrication  Pre-DECIGO	R&D Fabrication  DECIGO
Purpose	Demonstration and test of space IFO technique	Sciences by GW observation	GW Astronomy and Cosmology
Design	Micro-g experiment FP cavity + Drag-free	3 S/C , 3 arms.	FF with 3 S/C 3-4 IFO units

Sciences by Pre-DECIGO

DECIGO

(1) Inspiral of NS-NS binaries ['Promised' target]

- ~10 binaries/yr.
- Estimation of binary parameters and merger time a few month before merger.

→ Key role in multi-messenger astronomy.

(2) Inspirals and mergers of IMBHs [Original science]

- Cover most of the universe.

→ Formation history of SMBH and galaxies.

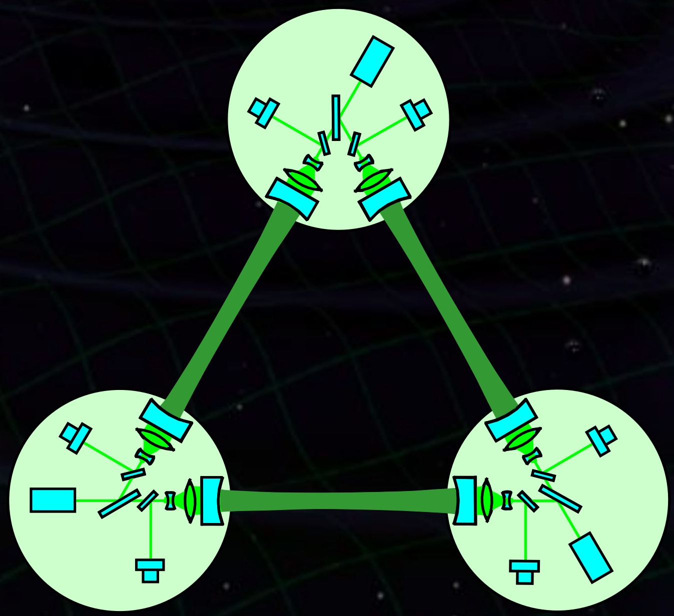
(3) Foreground understandings for DECIGO [for Cosmology]

- Parameter estimation and subtraction of binaries.
- Characteristics of foreground.
- Is the any eccentric binaries?

Pre-DECIGO Design (Preliminary)

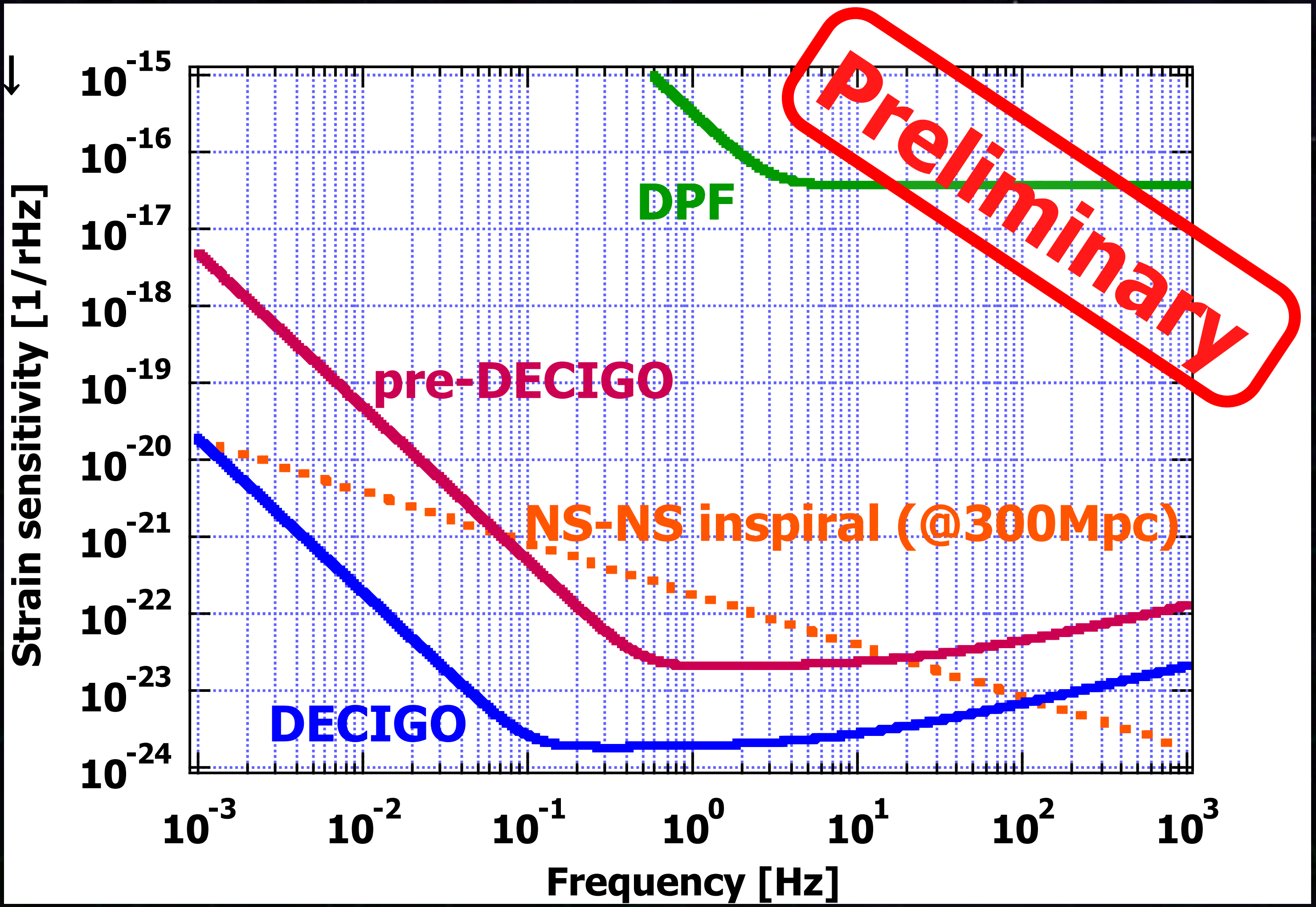
- Mission Requirement
  - Strain sensitivity of 2×10^{-23} $Hz^{-1/2}$ at 0.1Hz.
  - >3-years observation period.

- Conceptual Design
  - Laser interferometer by 3 S/C
  - Baseline : 100 km
    Laser source : 1W, 515nm
    Mirror : 300mm, 30kg
  - Drag-free and Formation flight.
  - Record-disk Orbit around the earth??



Sensitivity of Pre-DECIGO

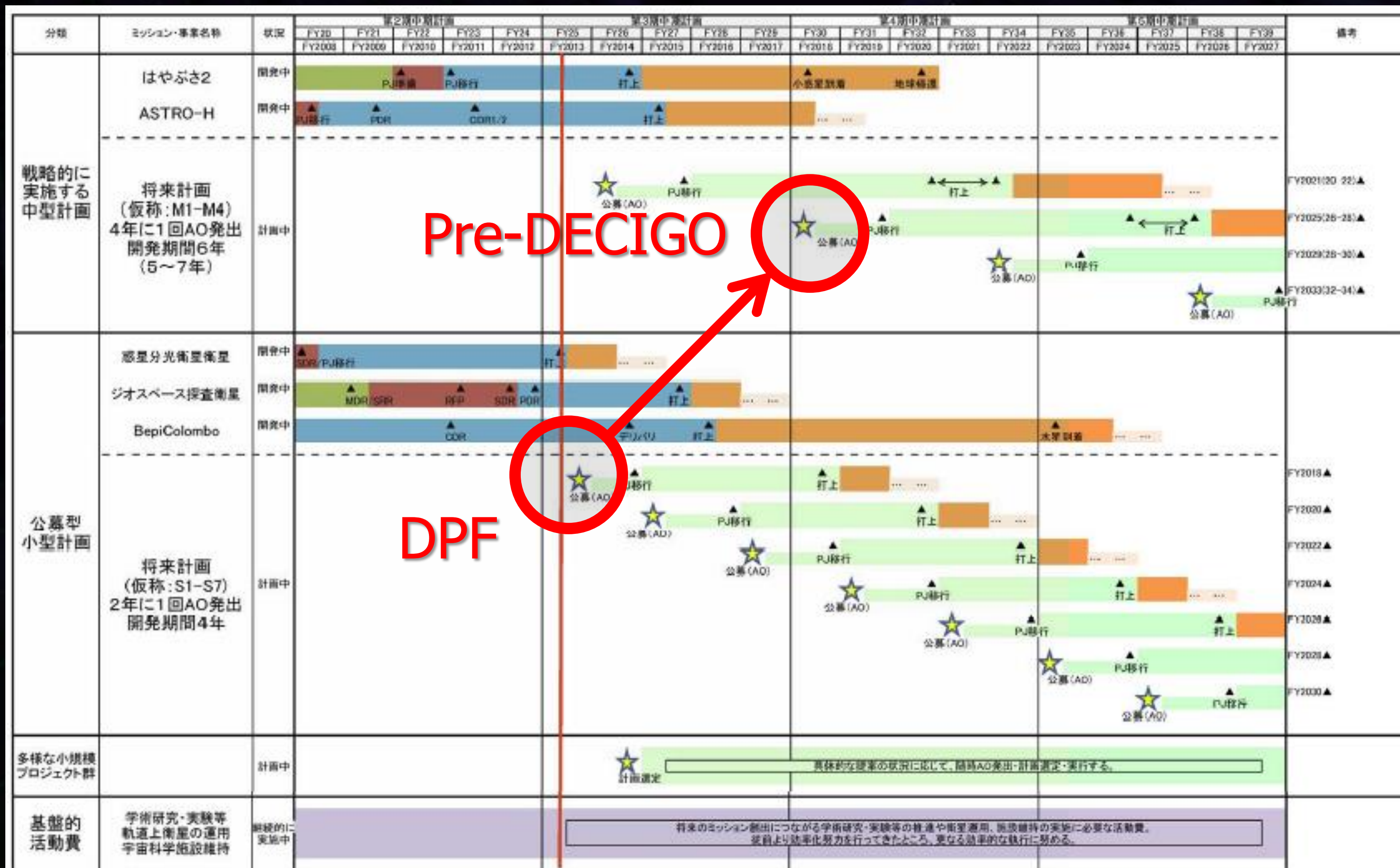
By S.Sato



Mission Opportunities (JAXA Roadmap)

DECIGO

From file submitted to the government by ISAS/JAXA (Sept. 19th 2013)

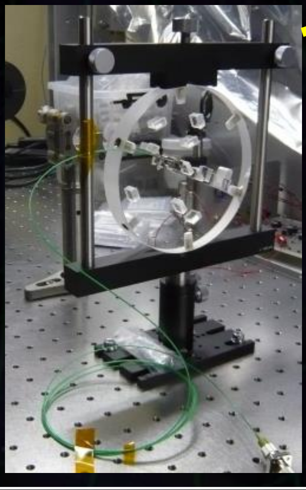


Interferometer Module

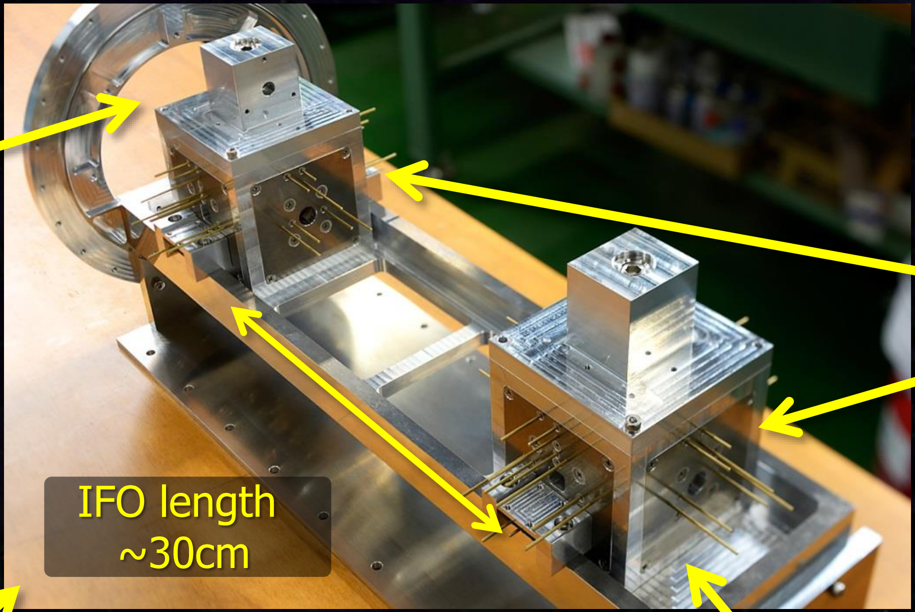
DECIGO

IO Optics

Monolithic opt. bench by silicate bonding

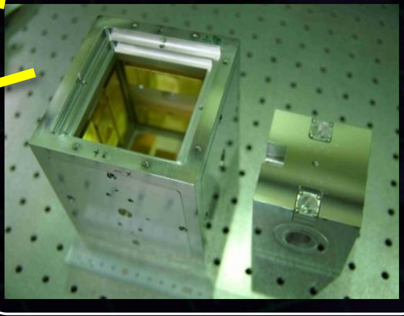


Interferometer Module



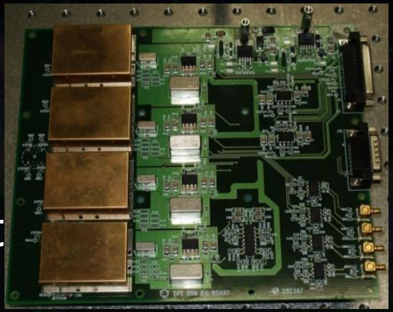
Test mass module

TM, Capacitive Sensor/Actuator, Launch lock



Quad-RFPD

Quadrant PD + Demod. circuits for length and alignment control signals

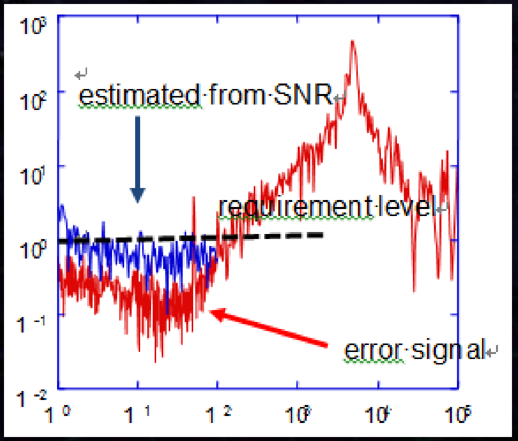


SpW signal-processing board

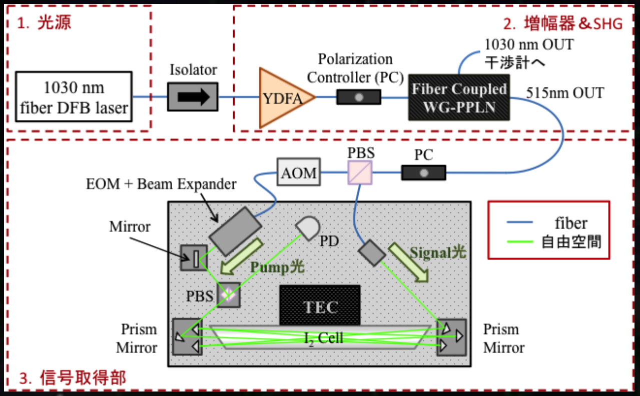
SpW FPGA + 16bit AD/DA

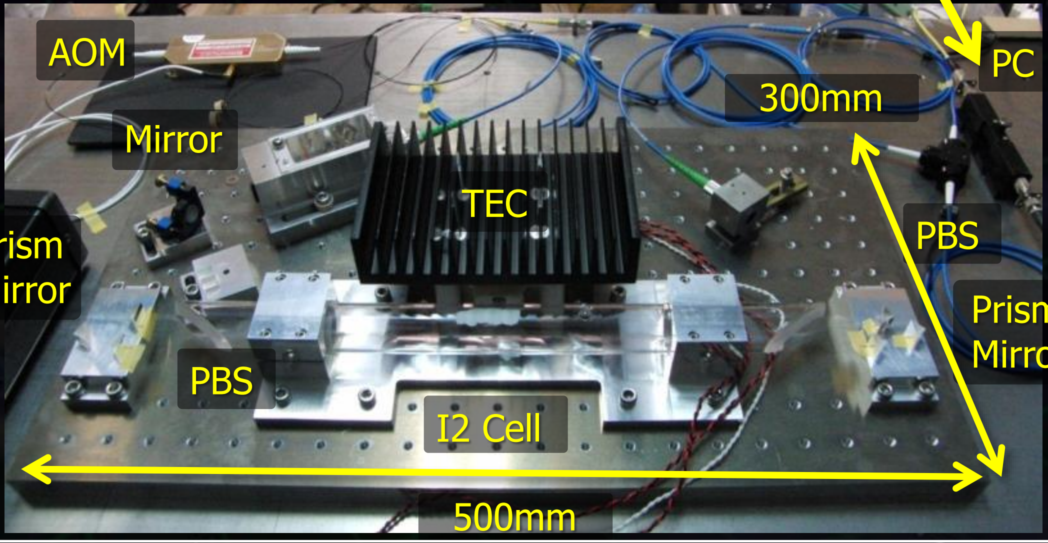
Frequency Stabilization Module

- Frequency Stabilization module BBM2 (at UEC)
  - Use absorption line of Iodine molecule.
  - Satisfy requirement (0.5 Hz/Hz$^{1/2}$) in error-signal measurement.
  - Preparing one-more module for relative stability evaluation.



Freq. Stab module





Space Demonstration by SWIM

DECIGO

Photo: JAXA

SWIM (Space wire demonstration module) on SDS-1 satellite

Launched in Jan. 2009, 1.5 years operation

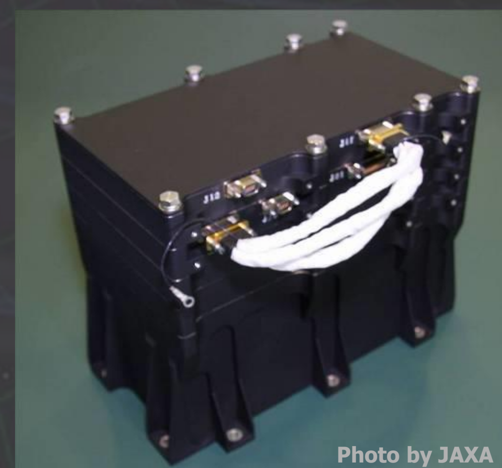
⇨ Successful as a tiny space GW detector

SpaceCube2: Space-qualified Computer

CPU: HR5000
(64bit, 33MHz)
System Memory:
2MB Flash Memory
4MB Burst SRAM
4MB Asynch. SRAM
Data Recorder:
1GB SDRAM
1GB Flash Memory
SpW: 3ch

Size: 71 x 221 x 171
Weight: 1.9 kg
Power: 7W

SWIMμν : User Module



Processor test board
GW+Acc. sensor
FPGA board
DAC 16bit x 8 ch
ADC 16bit x 4 ch
→ 32 ch by MPX
Torsion Antenna x2
~47g test mass

Data Rate : 380kbps
Size: 124 x 224 x 174
Weight: 3.5 kg
Power: ~7W

SDS-1 Bus System

Power +28V
RS422 for CMD/TLM
GPS signal

Power ±15V, +5V
SpW x2 for CMD/TLM

Space GW detector : SWIMμν

Small freely-floating test mass
→ Space demonstration of
control and data processing

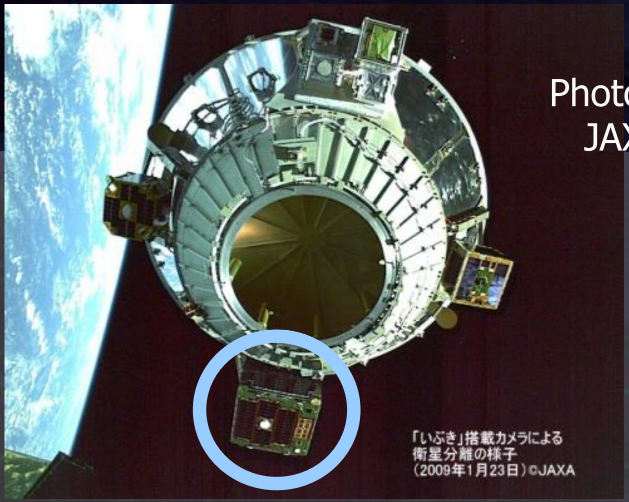
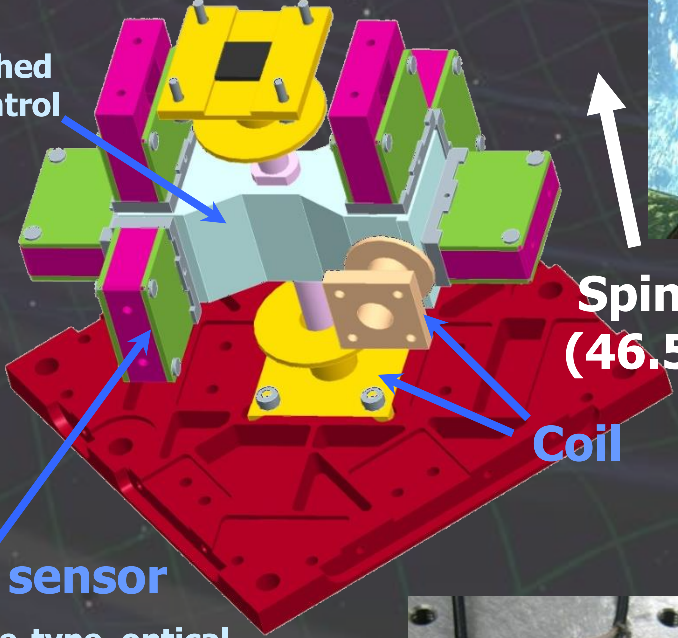


Photo: JAXA

TAM: Torsion Antenna Module with free-falling test mass
(Size : 80mm cube, Weight : ~500g)

Test mass

~47g Aluminum, Surface polished
Small magnets for position control

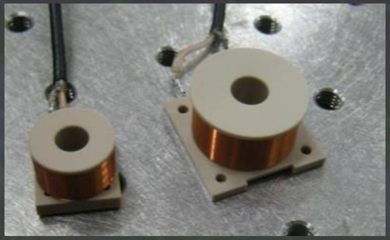


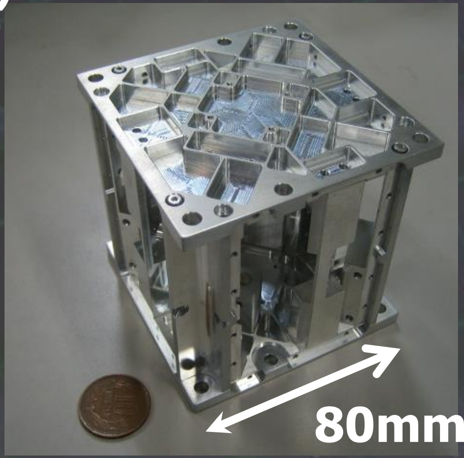
Spin Axis (46.5mHz)

Coil

Photo sensor

Reflective-type optical displacement sensor
Separation to mass ~1mm
Sensitivity ~ 10^{-9} m/$Hz^{1/2}$
6 PSs to monitor mass motion





Summary

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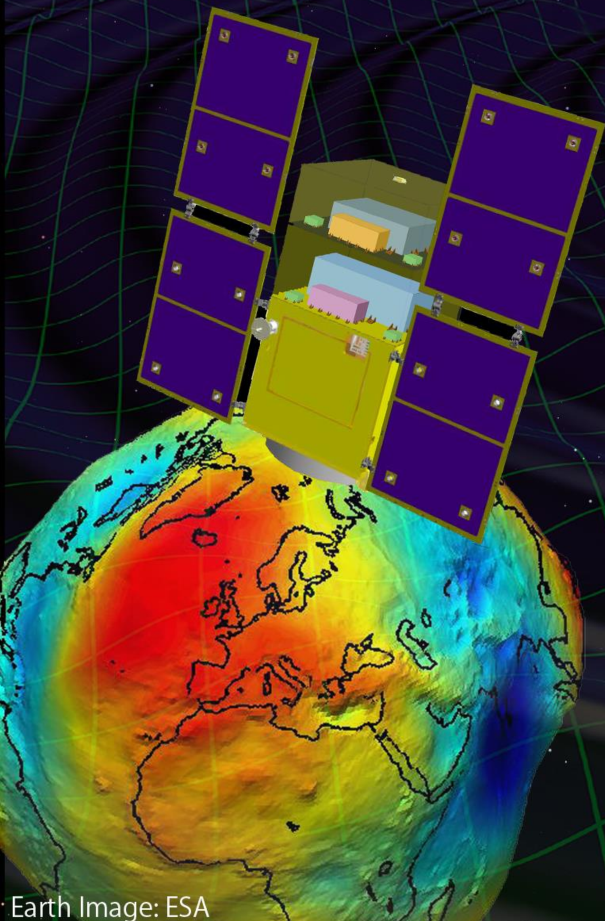
DECIGO : Fruitful Sciences

Very beginning of the Universe
Dark energy, Dark matter
Galaxy formation
→ Will be realized at last.

Pre-DECIGO : Original Sciences

Key role for multi-messenger astoronomy.
Information on SMBH and galaxy formation.
Prospects for future mission : DECIGO.

End



Earth Image: ESA

Original Picture : Sora