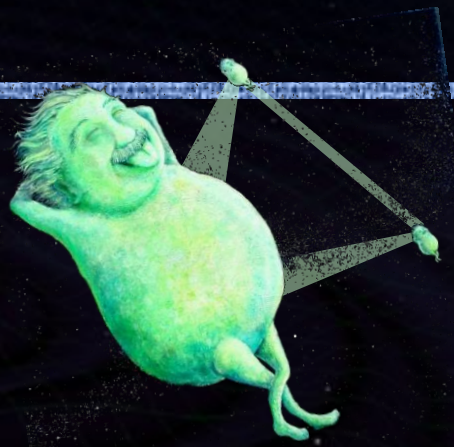
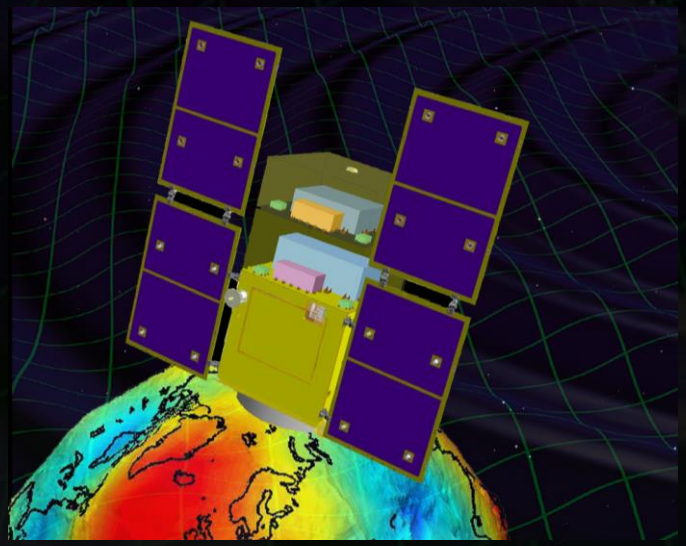


DECIGO and DECIGO Pathfinder



Masaki Ando

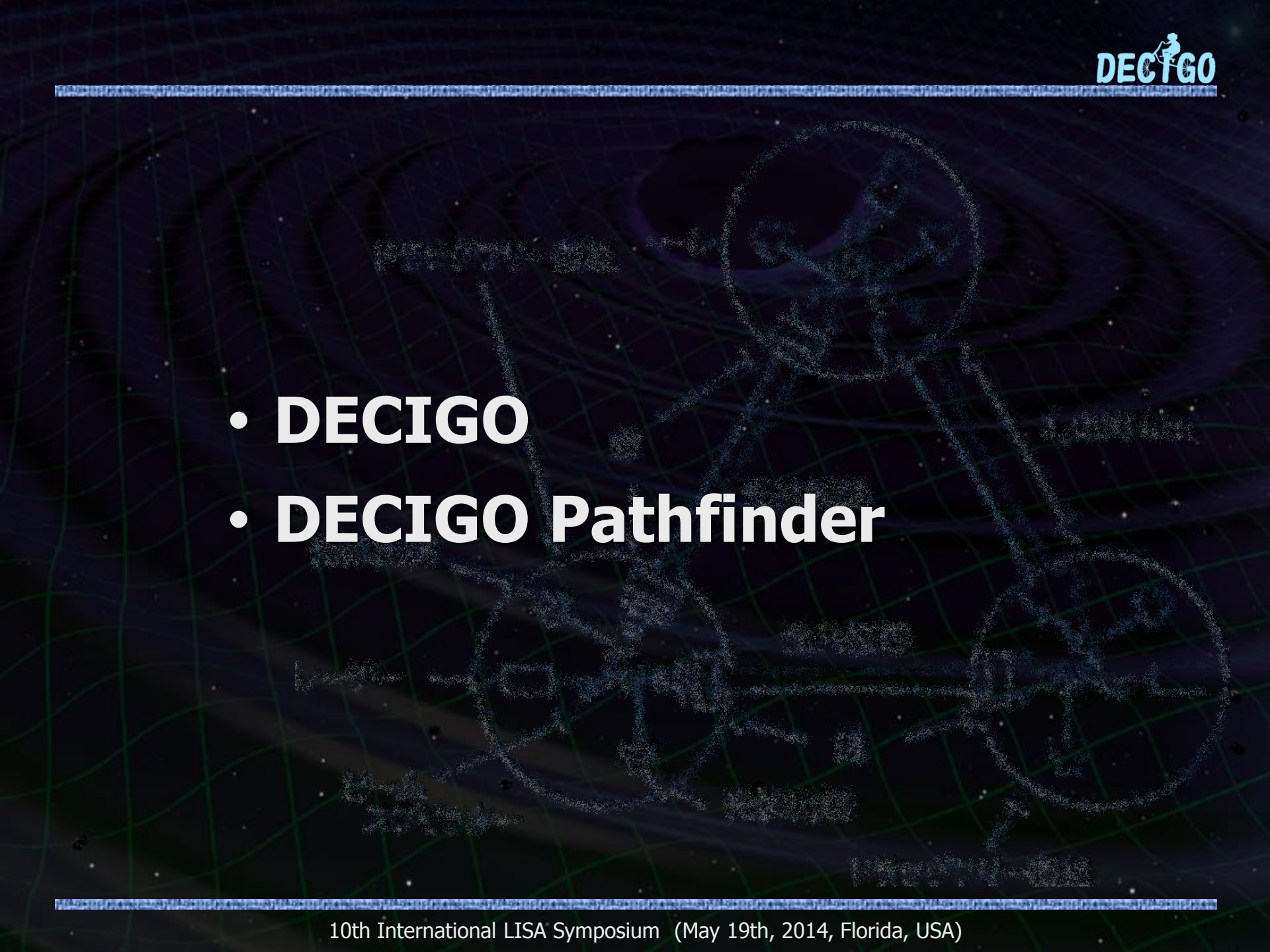
(Dept. of Physics, Univ. of Tokyo /
National Astronomical Observatory Japan)

10th International LISA Symposium (May 19th, 2014, Florida, USA)

DECIGO Members

Koh-suke Aoyanagi, Kazuhiro Agatsuma, Tomotada Akutsu, Hideki Asada, Yoichi Aso, Koji Arai, Akito Araya, Masaki Ando, Kunihito Ioka, Takeshi Ikegami, Takehiko Ishikawa, Hideharu Ishizaki, Hideki Ishihara, Kiwamu Izumi, Kiyotomo Ichiki, Hiroyuki Ito, Yousuke Itoh, Kaiki T. Inoue, Akitoshi Ueda, 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, Seiji Kawamura, Nobuyuki Kanda, Kenta Kiuchi, Naoko Kishimoto, Hitoshi Kuninaka, Hiroo Kunimori, Kazuaki Kuroda, Sachiko Kuroyanagi, Hiroyuki Koizumi, Feng-Lei Hong, Kazunori Kohri, WataruKokuyama, 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, Shuichi Sato, Takashi Sato, Masaru Shibata, Kazunori Shibata, Ayaka Shoda, Hisaaki Shinkai, Aru Suemasa, Naoshi Sugiyama, Rieko Suzuki, Yudai Suwa, Naoki Seto, Kentaro Somiya, Hajime Sotani, Takeshi Takashima, Tadashi Takano, Kakeru Takahashi, Keitaro Takahashi, Tadayuki Takahashi, Hirotaka Takahashi, Fuminobu Takahashi, Ryuichi Takahashi, Ryutaro Takahashi, Takamori Akiteru, Hideyuki Tagoshi, Hiroyuki Tashiro, Takahiro Tanaka, Nobuyuki Tanaka, Keisuke Taniguchi, Atsushi Taruya, Takeshi Chiba, Dan Chen, Shinji Tsujikawa, Yoshiki Tsunesada, Kimio Tsubono, Morio Toyoshima, Yasuo Torii, Kenichi Nakao, Kazuhiro Nakazawa, Shinichi Nakasuka, Hiroyuki Nakano, Shigeo Nagano, Kouji Nakamura, Takashi Nakamura, Yoshinori Nakayama, Atsushi Nishizawa, Erina Nishida, Kazutaka Nishiyama, Yoshito Niwa, Kenji Numata, 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, Ikkoh Funaki, Mizuhiko Hosokawa, Hideyuki Horisawa, Kei-ichi Maeda, Hideo Matsuhara, Nobuyuki Matsumoto, Yuta Michimura, Osamu Miyakawa, Umpei Miyamoto, Shinji Miyoki, Shinji Mukohyama, Mitsuru Musha, Toshiyuki Morisawa, Mutsuko Y. Morimoto, Shigenori Moriwaki, Kent Yagi, Hiroshi Yamakawa, Toshitaka Yamazaki, Kazuhiro Yamamoto, Jun'ichi Yokoyama, Shijun Yoshida, Taizoh Yoshino, Chul-Moon Yoo, Yaka Wakabayashi

(On February 28th, 2014)



- **DECIGO**
- **DECIGO Pathfinder**

DECIGO

Space GW Antenna DECIGO

DECIGO (DECI-hertz interferometer Gravitational wave Observatory)

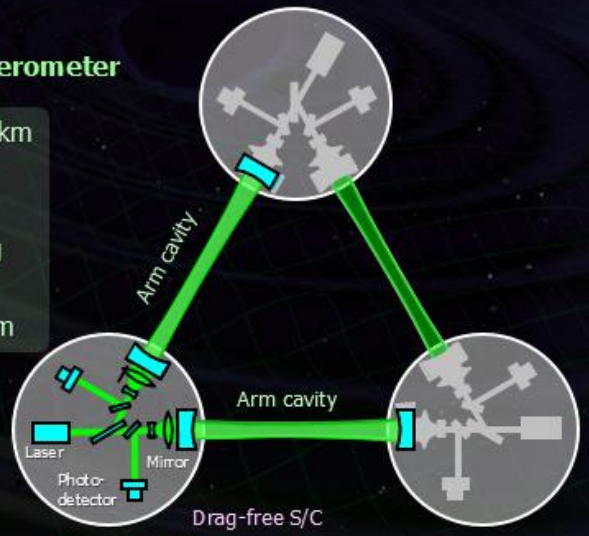
Purpose: To Obtain Cosmological Knowledge.

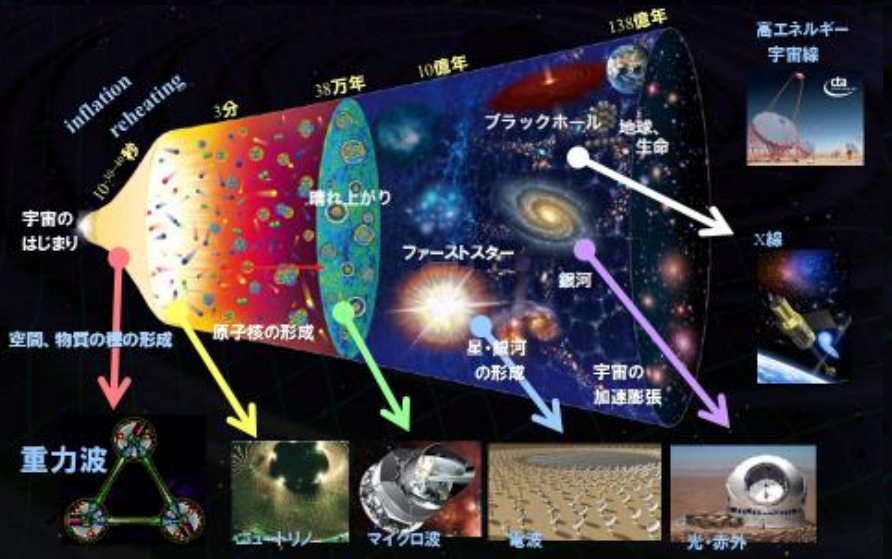
Direct observation of the origin of space-time and matter in Big-bang Universe.

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





背景画：福井康雄監修「宇宙史を物理学で読み解く -素粒子から物質・生命まで」(名古屋大学出版会)より

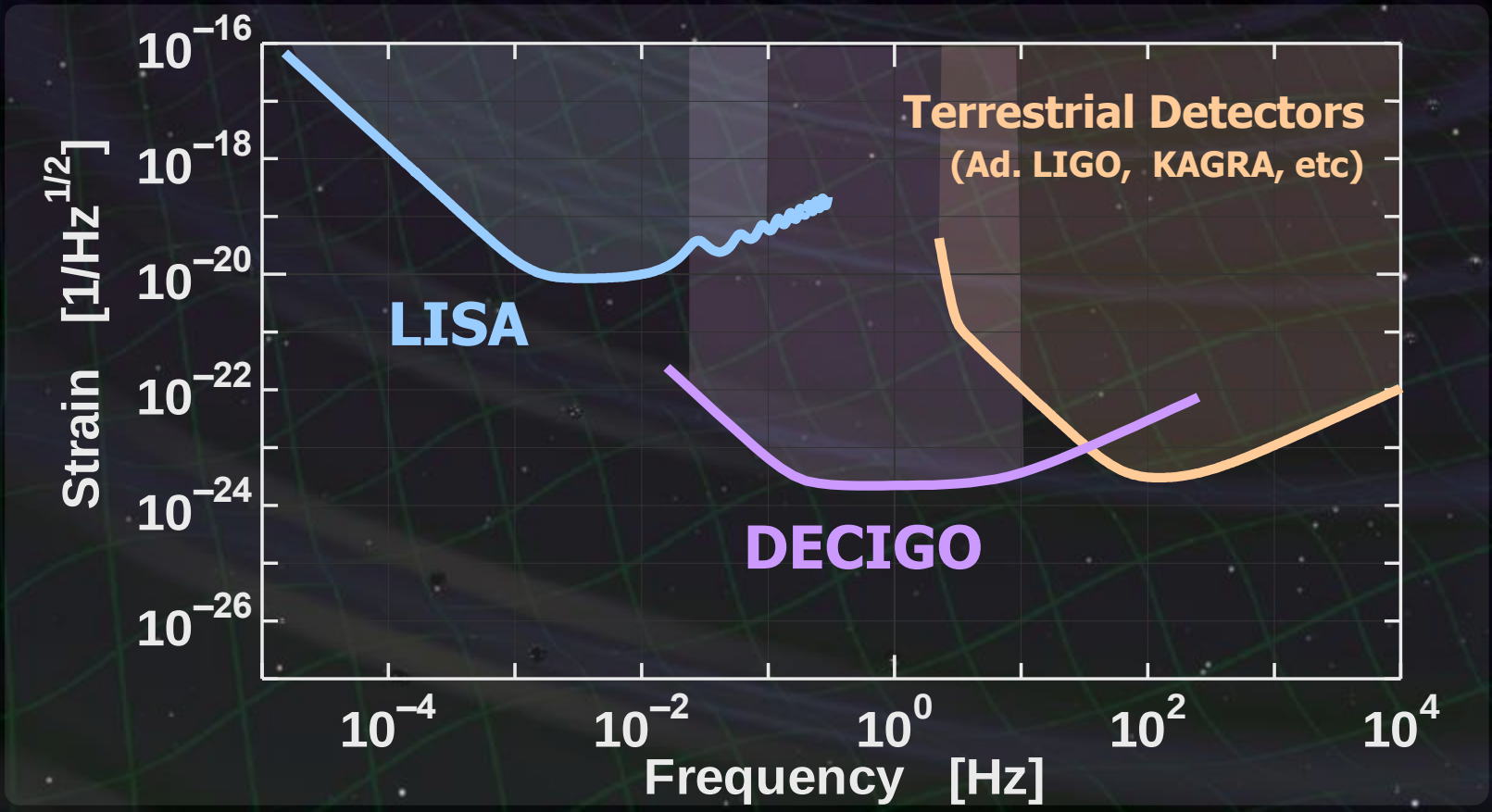
DECIGO

DECIGO (Deci-hertz interferometer Gravitational wave Observatory)

Space GW antenna (~2027)
Obs. band around 0.1 Hz

⇨

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

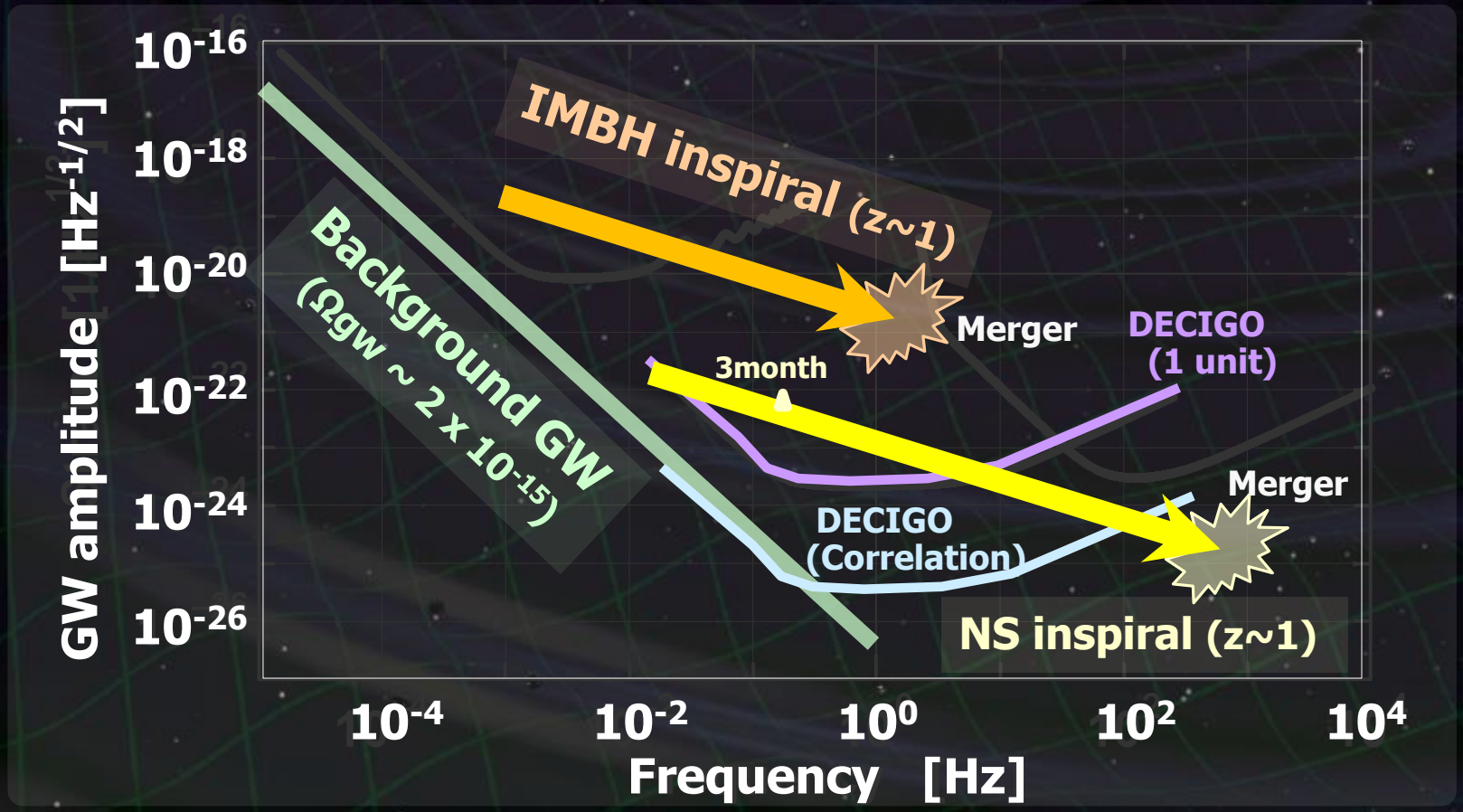


Targets and Science

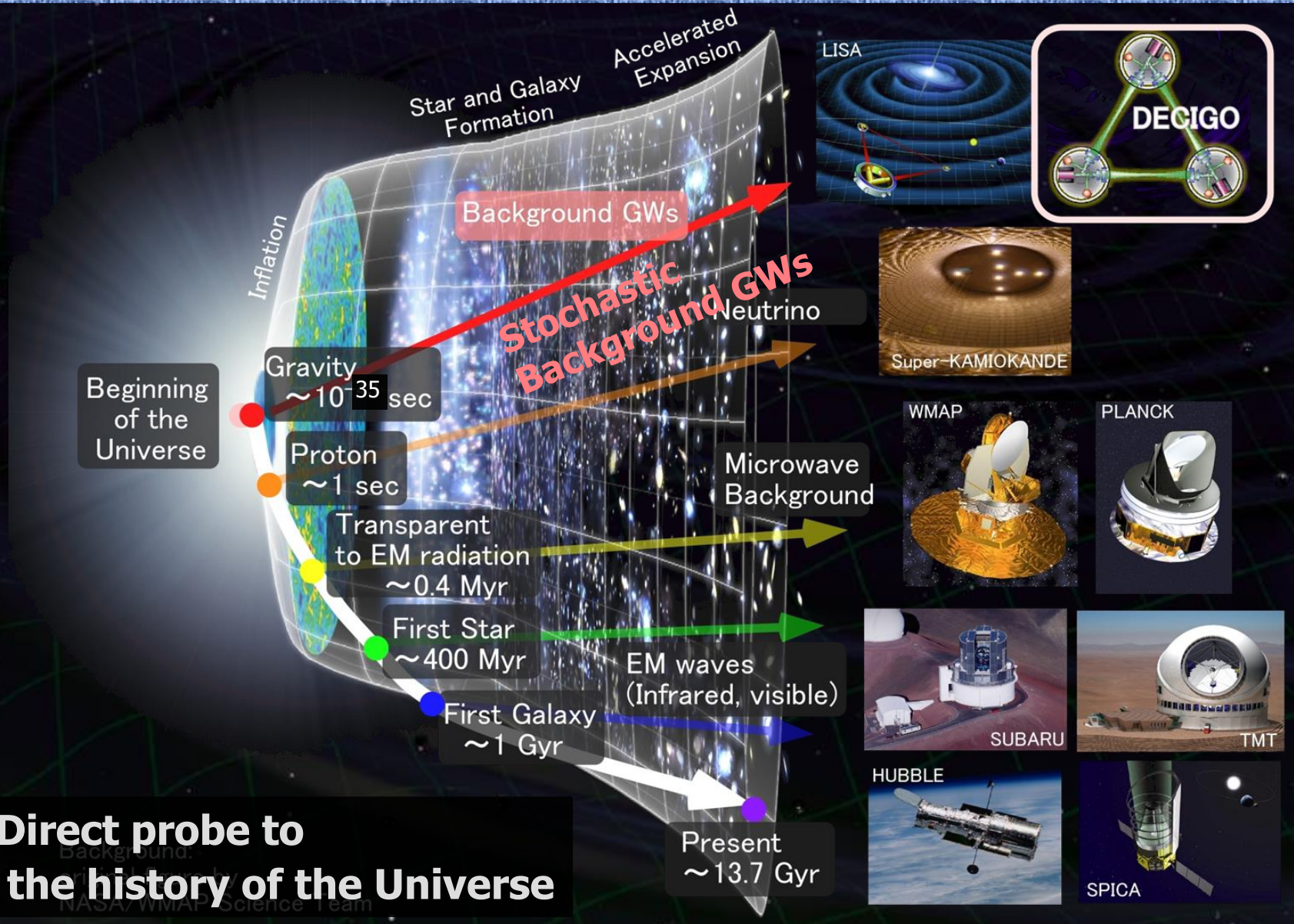
IMBH binary inspiral
NS binary inspiral
Stochastic background

⇨

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



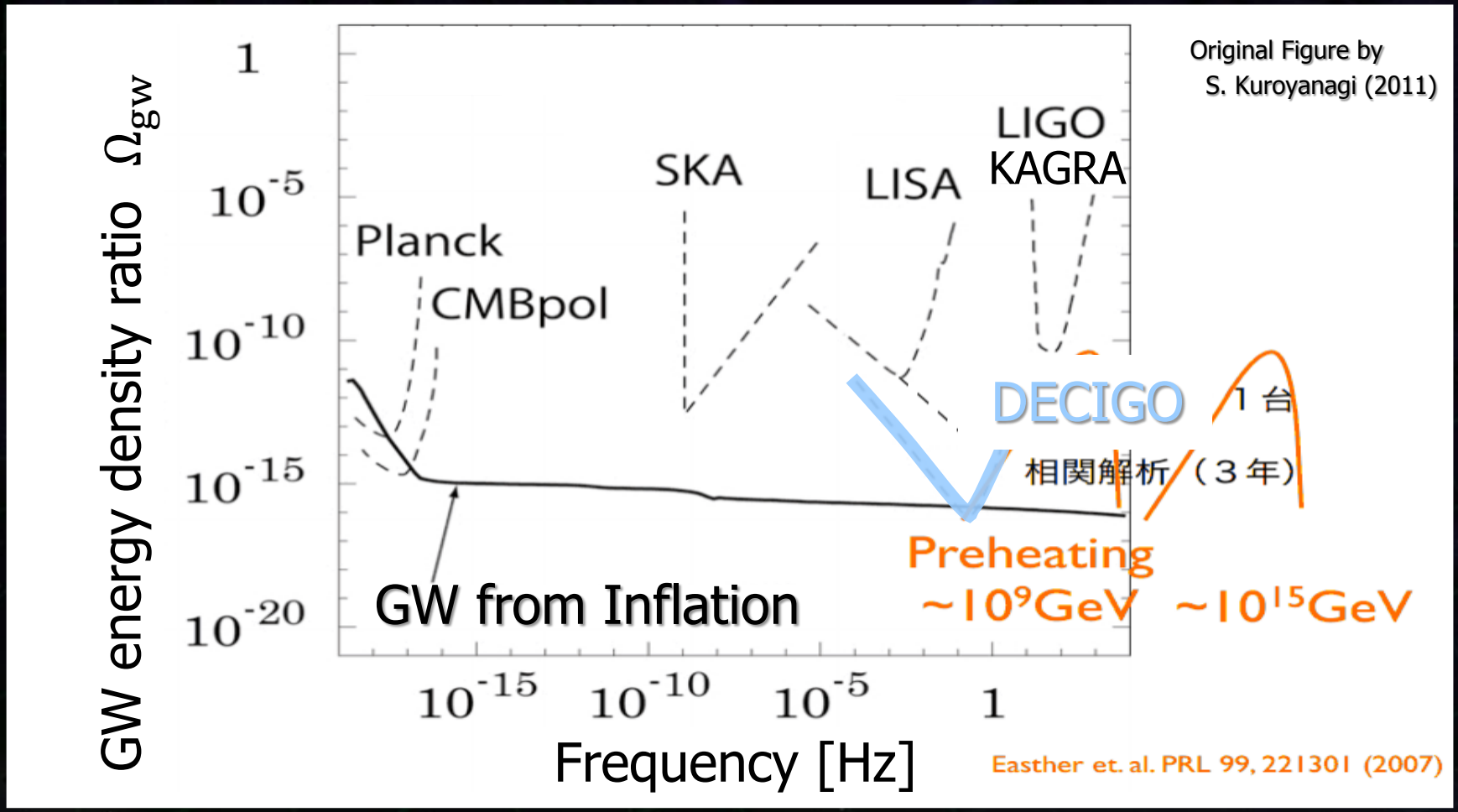
Characterization of inflation



Direct probe to the history of the Universe

Primordial GW

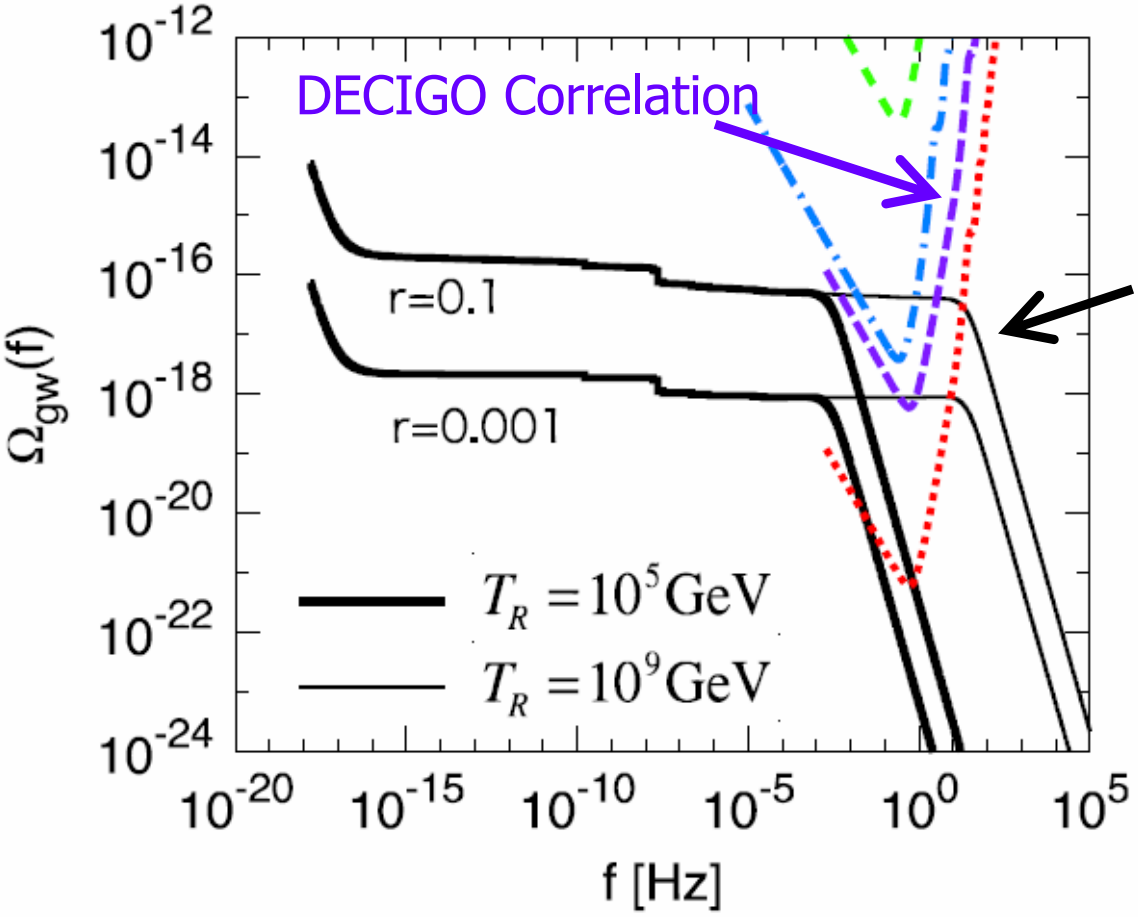
Earlier universe → Smaller horizon scale → High GW freq.



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
  'Age of Big-bang'.

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

Pre-Conceptual Design

DECIGO

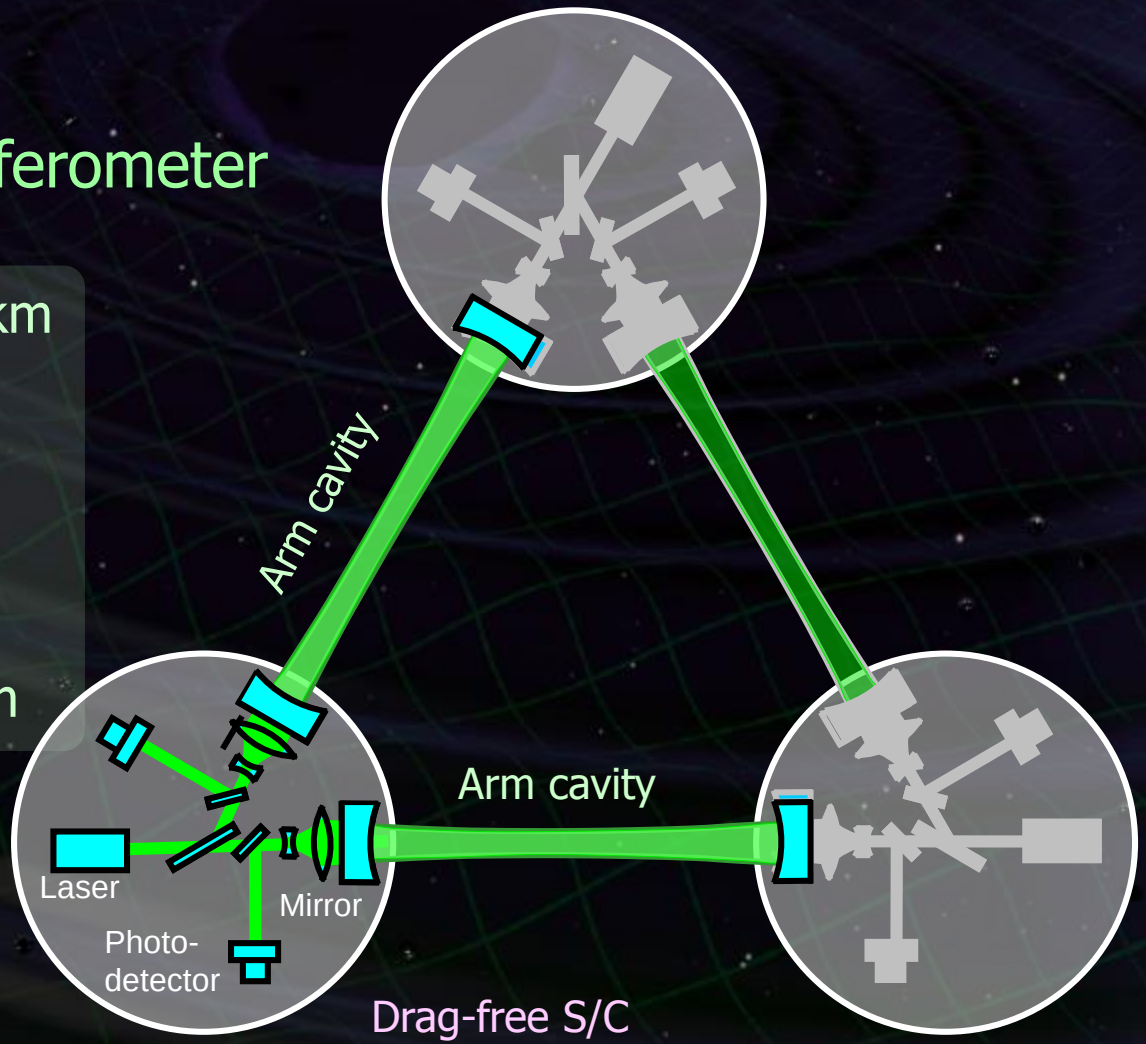
Interferometer Unit:

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



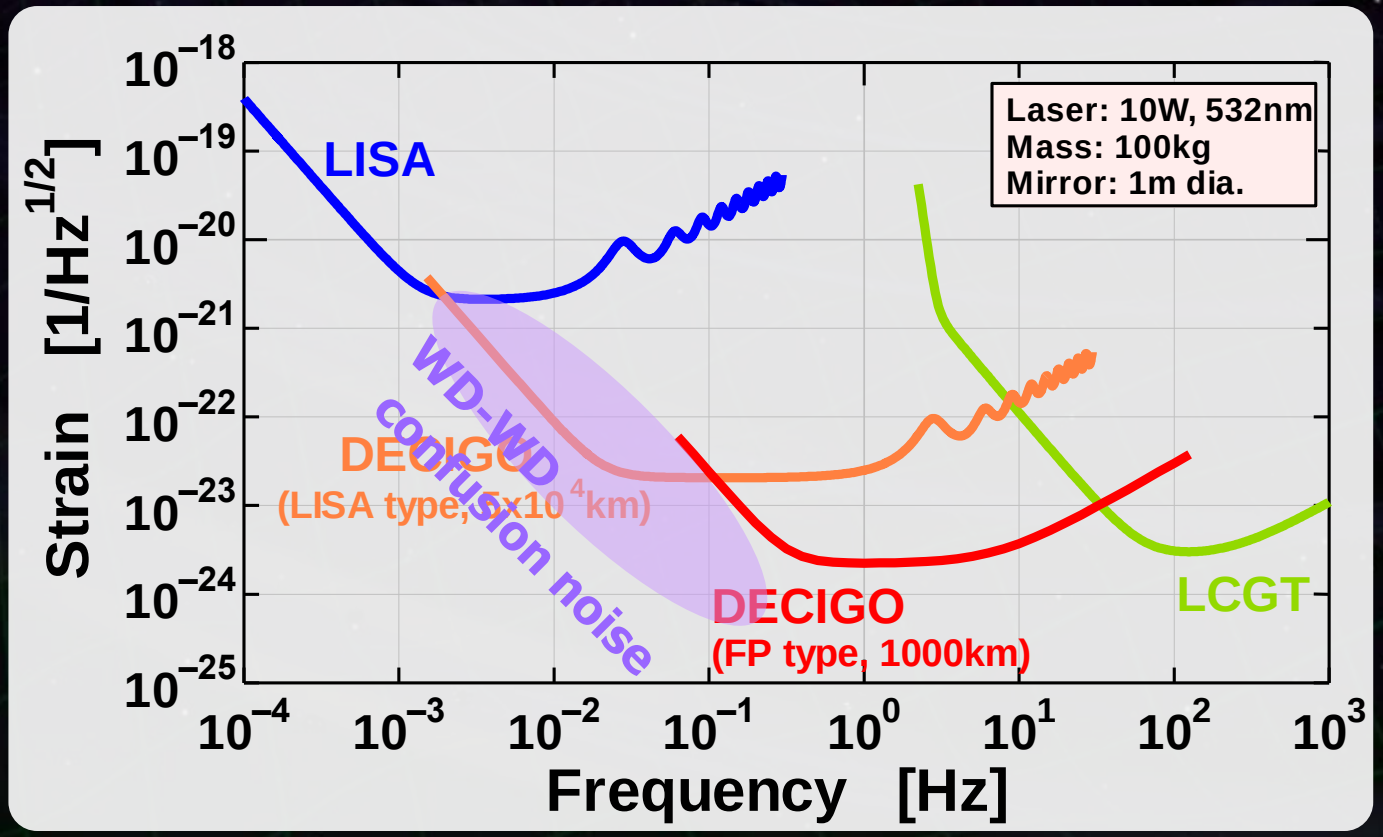
Interferometer Design

DECIGO

Transponder type vs Direct-reflection type

Compare : Sensitivity curves and Expected Sciences

Decisive factor: Binary confusion noise



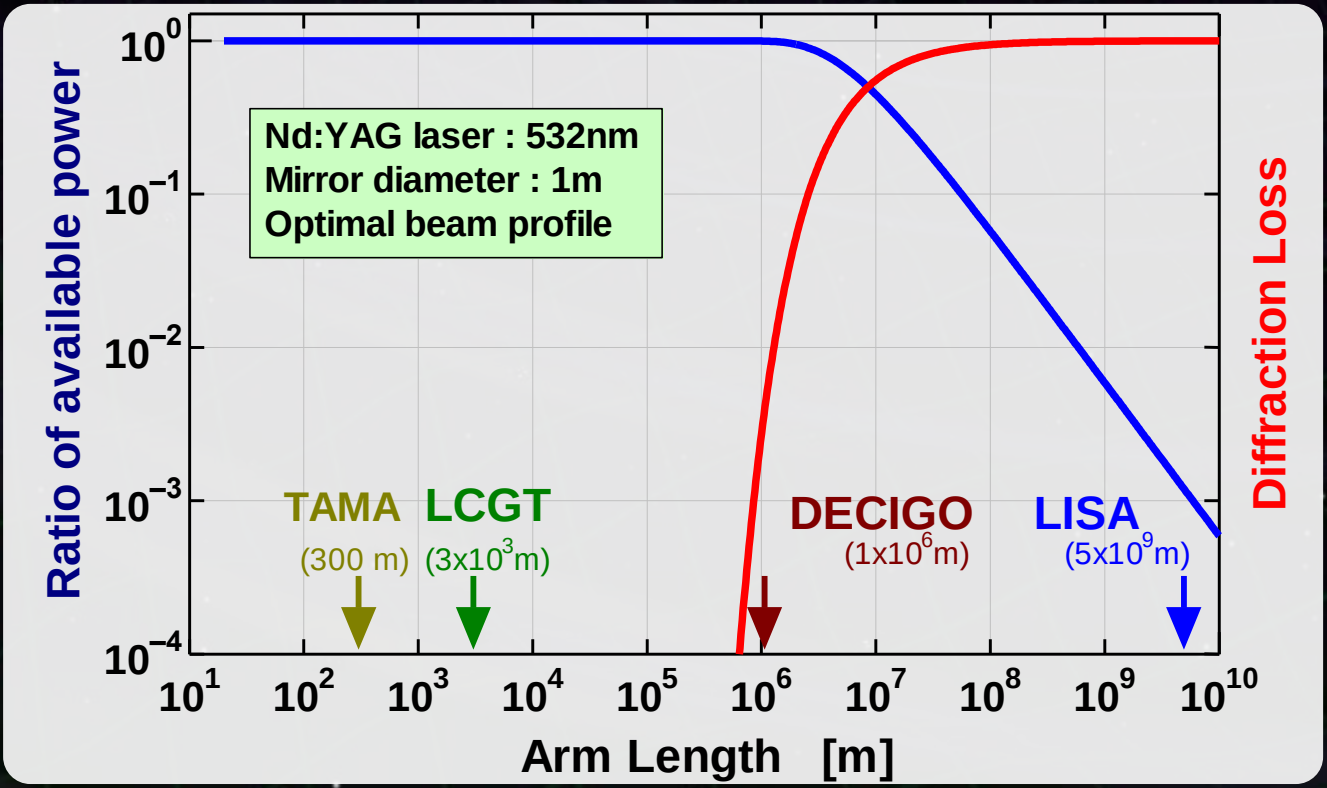
Arm length

Cavity arm length : Limited by diffraction loss

Effective reflectivity (TEM_{00} → TEM_{00})

- Laser wavelength : 532nm
- Mirror diameter: 1m
- Optimal beam size

⇨ 1000 km is almost max.



Cavity and S/C control

DECIGO

Cavity length change

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

Relative motion between mirror and S/C

Local sensor → S/C thruster

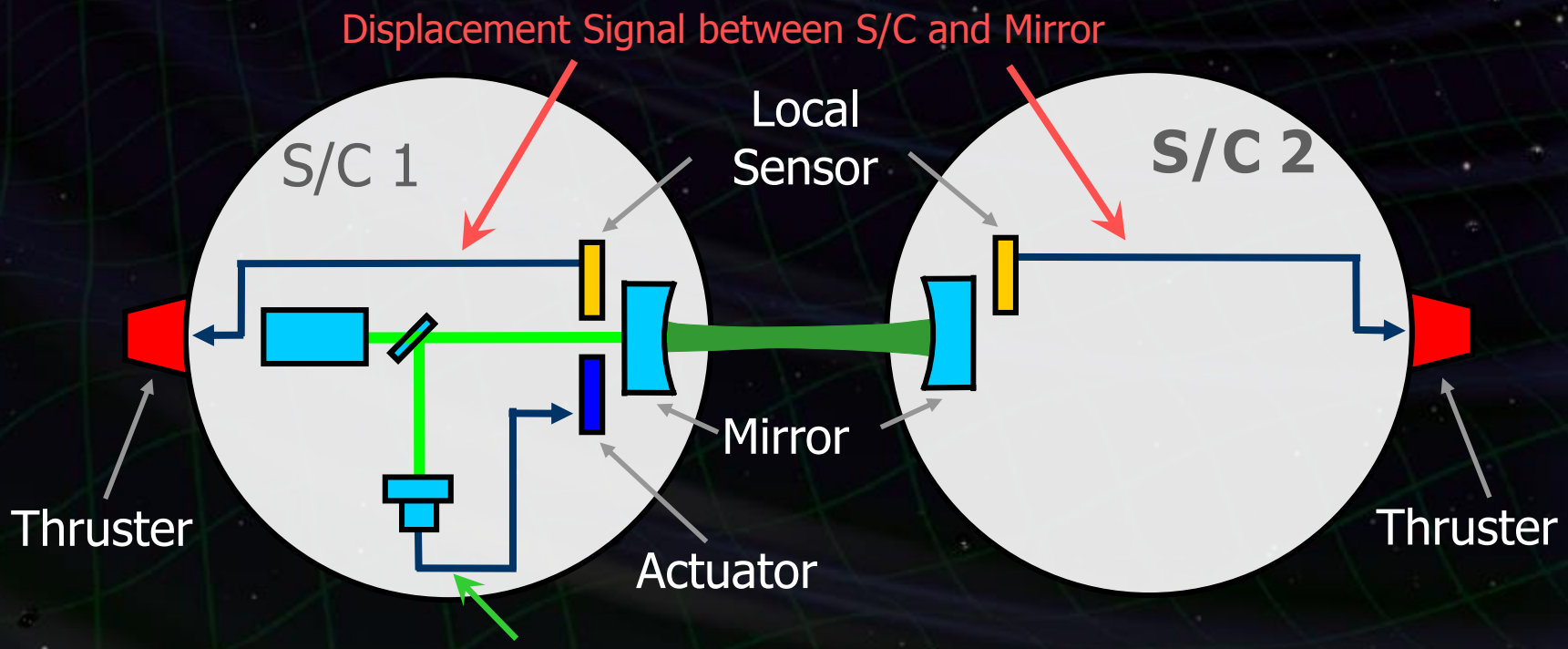


Fig: S. Kawamura

Requirements

DECIGO

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.

Foreground Cleaning

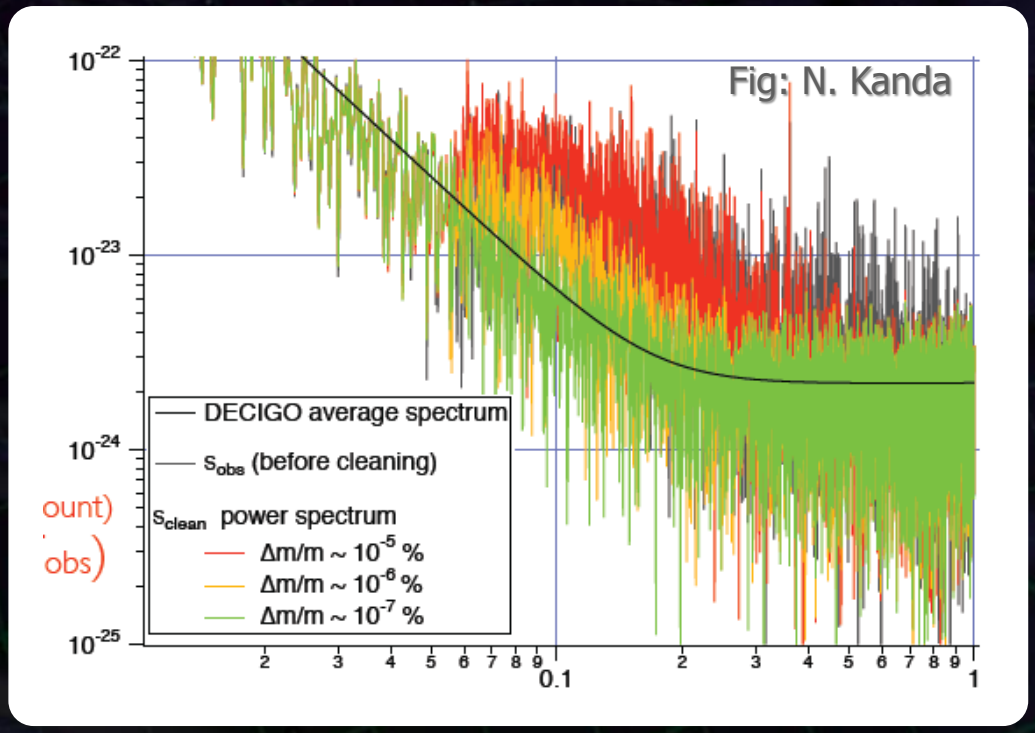
DECIGO obs. band: free from WD binary foreground
→ Open for cosmological observation

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

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

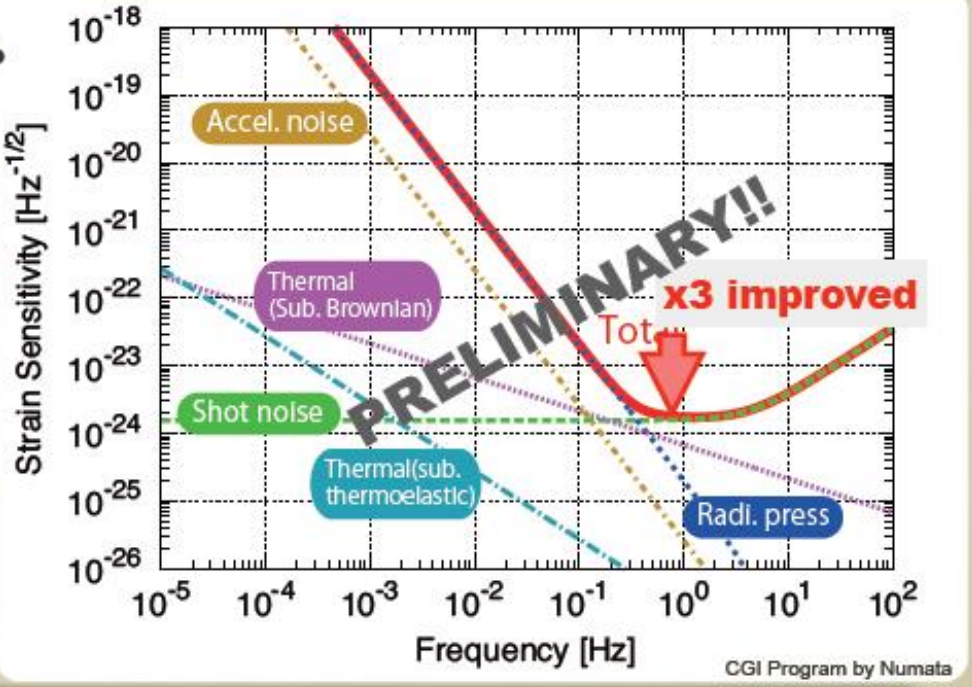
⇦ Parameters tuned

This is the first step to considering the conceptual design.

Next:

➡Confirm the calculations.

➡Find the realistic way to realize this!



DECIGO Pathfinder

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 → 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

Technical Steps for DECIGO

- Key technologies for DECIGO

(1) Precise measurement by laser interferometer.

Operation of Fabry-Perot interferometer in Space environment and Drag-free control.

⇨ Demonstration by DPF

(2) Long-baseline formation flight.

Realization of precise formation flight with more than km scale

⇨ Demonstration by Pre-DECIGO

Technical Steps for DECIGO

	DPF target	Pre-DECIGO target	DECIGO Requirement
Space FP	First demonstration of FP cavity (30cm) in space. Disp. noise ~10^{-16}m/Hz$^{1/2}$, Acc. Noise 10^{-15} N/Hz$^{1/2}$.	FP operation with long-base line (100km). Disp. noise 10^{-17}m/Hz$^{1/2}$ Acc. noise 10^{-16} N/Hz$^{1/2}$.	Disp. 3×10^{-18} m/Hz$^{1/2}$. Acc. 10^{-17} N/Hz$^{1/2}$. Baseline length 1000km.
Stab. Laser source	Freq. stability of 0.5Hz/Hz$^{1/2}$ in space environment. Output pow. : 100mW.	Freq. stability of 0.5Hz/Hz$^{1/2}$. Output pow. : 1W.	Freq. Stab. of 0.5Hz/Hz$^{1/2}$. Output pow. : 10W.
Drag-free Control and FF	Realize all DoF drag-free control with 1×10^{-9} m/Hz$^{1/2}$.	All DoF DF control 1×10^{-9} m/Hz$^{1/2}$. Long-baseline Formation Flight 100km.	All DoF DF control 1×10^{-9} m/Hz$^{1/2}$. Long-baseline FF 1000km.

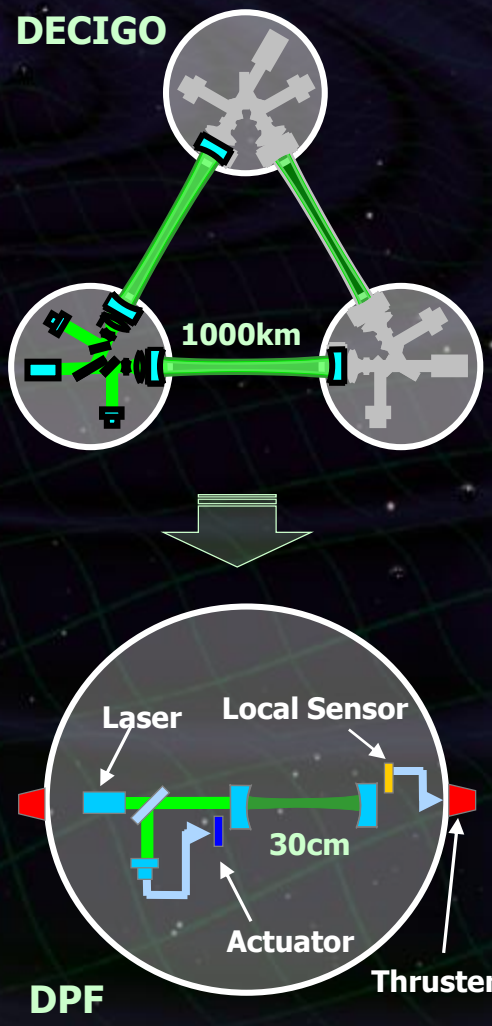
DECIGO-PF

DECIGO Pathfinder (DPF)

First milestone mission for DECIGO

Shrink arm cavity

DECIGO 1000km → DPF 30cm



Purpose

- FP interferometer in space
- Stabilized laser source
- Drag-free control
- Continuous data-processing

DPF satellite

DECIGO

DPF Payload

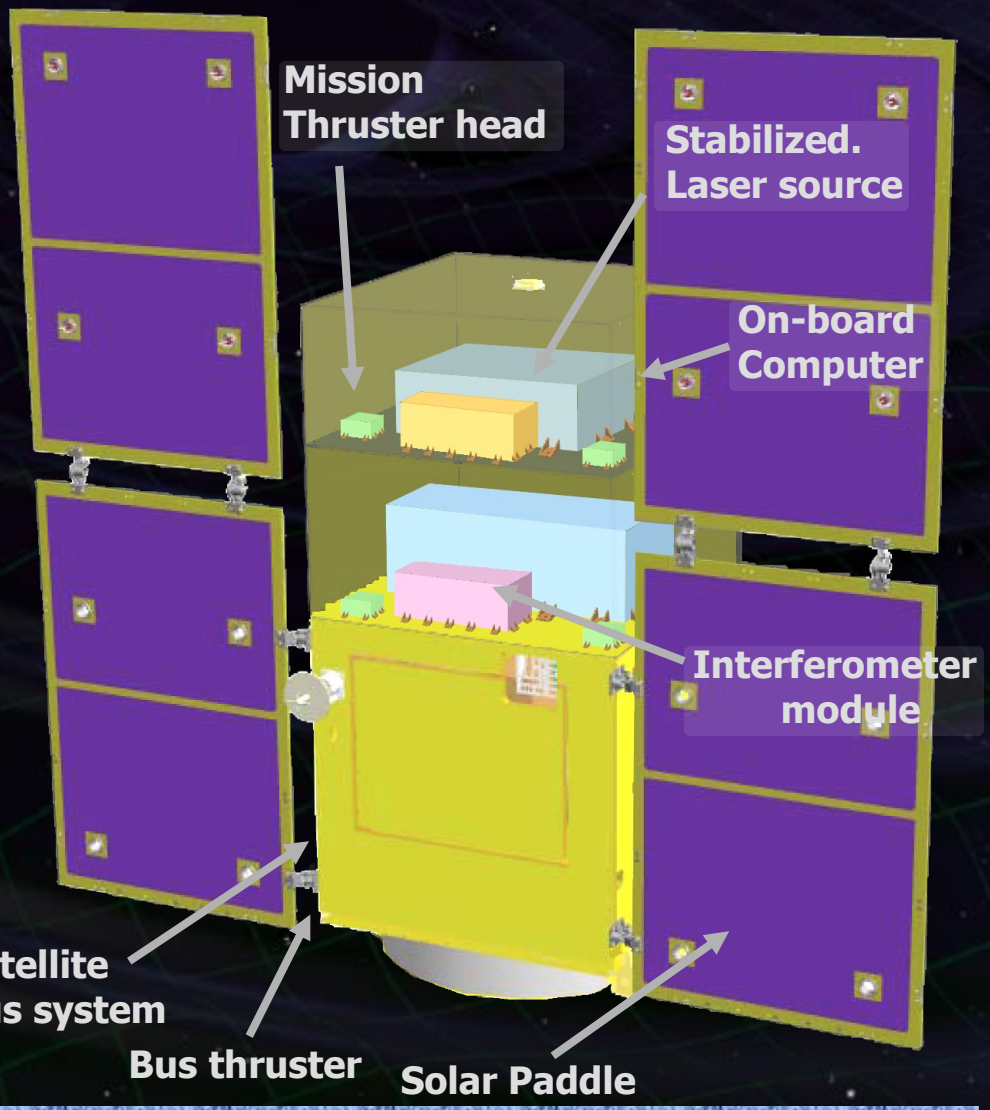
Size : 950mm cube
Weight : 200kg
Power : 130W
Data Rate: 800kbps
Mission thruster x10

Power Supply
SpW Comm.

Satellite Bus

('Standard bus' system)

Size :
950x950x1100mm
Weight : 250kg
SAP : 960W
Battery: 50AH
Downlink : 2Mpbs
DR: 1GByte
3N Thrusters x 4

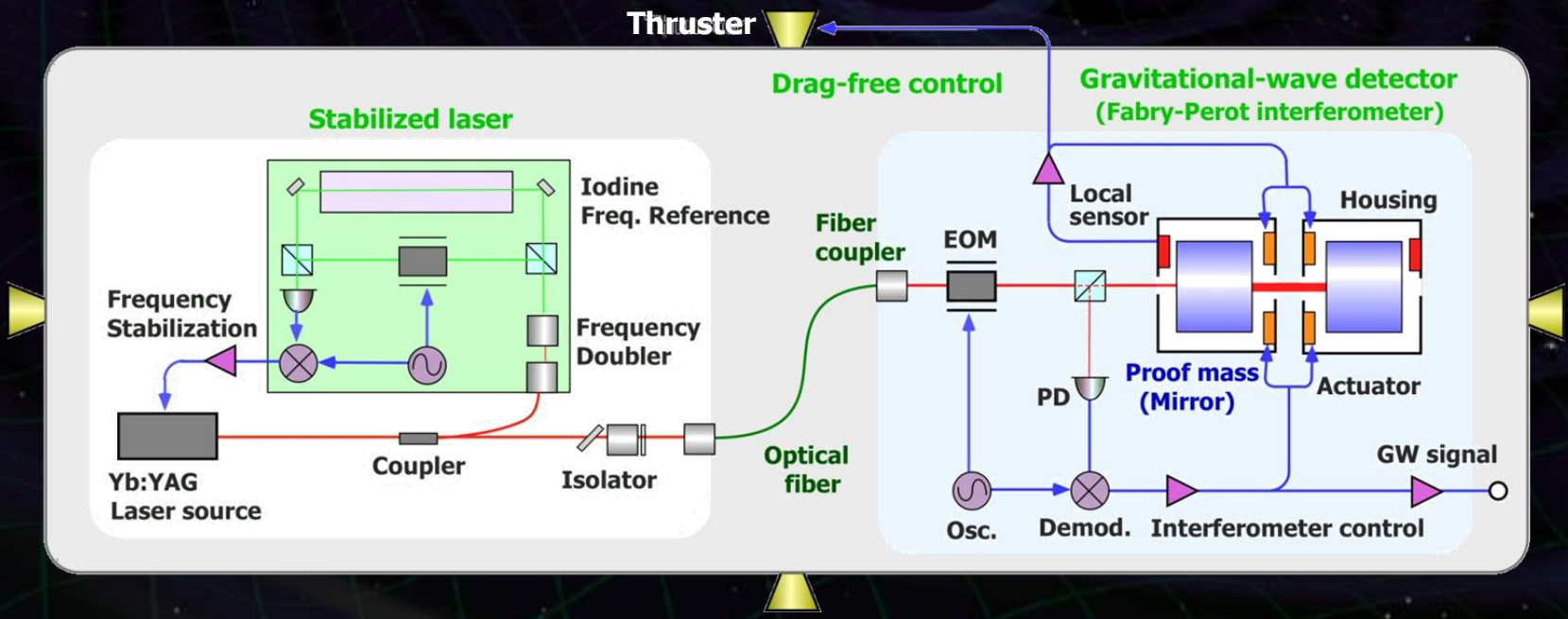


DPF mission payload

DECIGO

Mission weight : ~200kg
Mission space : ~95 x 95 x 90 cm

Drag-free control
Local sensor signal
→ Feedback to thrusters



Laser source
Yb:YAG laser (1030nm)
Power : 25mW
Freq. stab. by Iodine abs. line

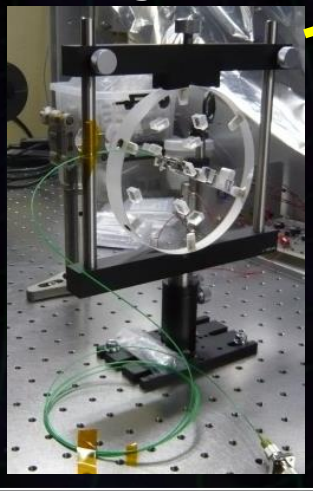
Fabry-Perot interferometer
Finesse : 100
Length : 30cm
Test mass : ~a few kg
Signal extraction by P**DH**

Interferometer Module

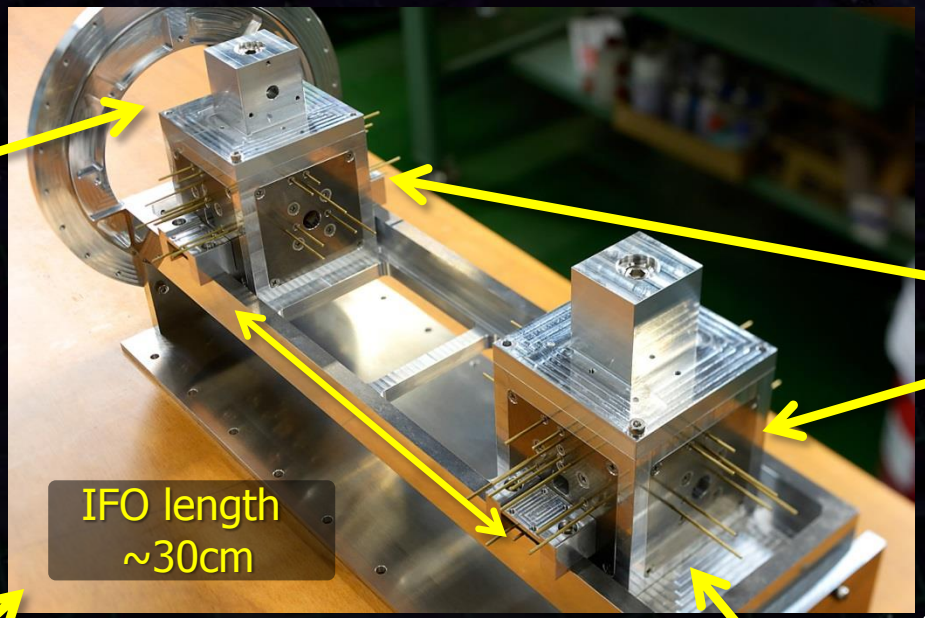
DECIGO

IO Optics

Monolithic opt. bench by silicate bonding

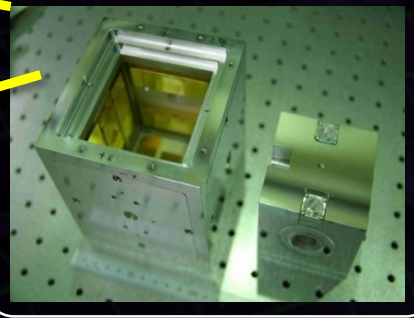


Interferometer Module



Test mass module

TM, Capacitive Sensor/Actuator, Launch lock



Quad-RFPD

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

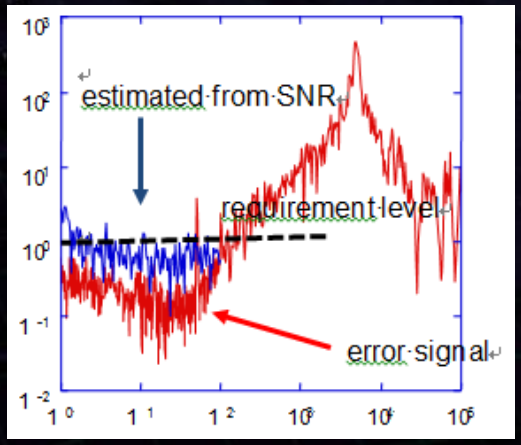
SpW signal-processing board

SpW FPGA + 16bit AD/DA

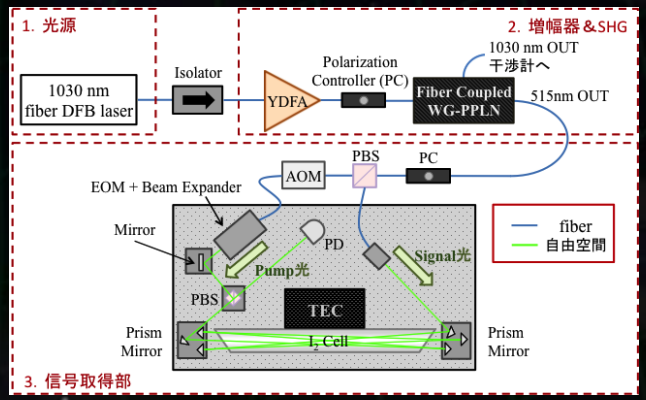
Frequency Stabilization Module

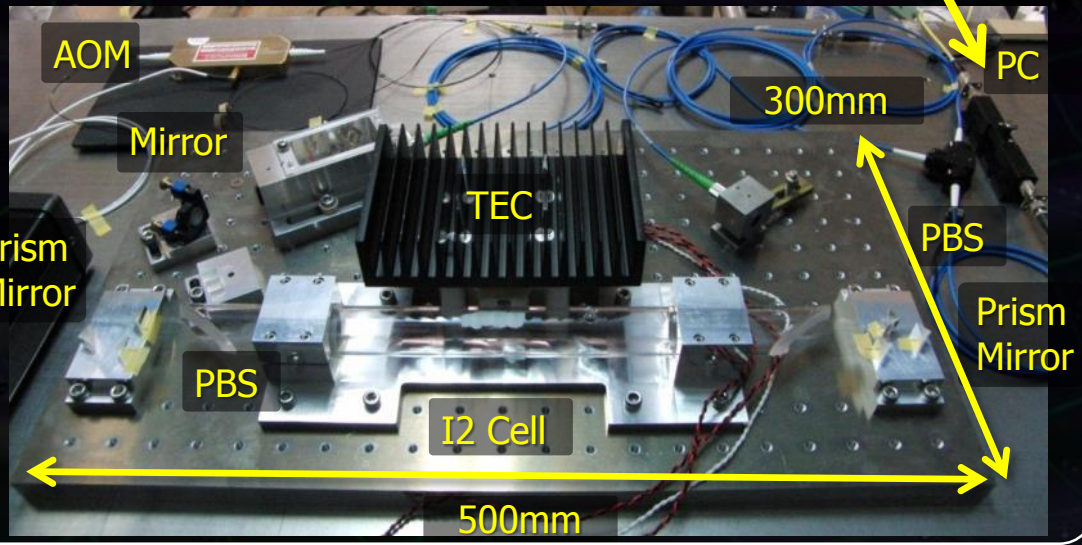
DECIGO

- 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





Mission Selection Result

DECIGO

- AO from JAXA (December 2013)
  for small science mission using epsilon rocket.
  - The program framework was changed:
    ~10 M$ payload mission → ~150 M$ mission
  - Deadline : End of February.
  - 7 mission proposals including DPF.

⇨ DPF was dropped in the first down-selection (May)

- Started discussions on the next strategy.

Restructure of Space Program

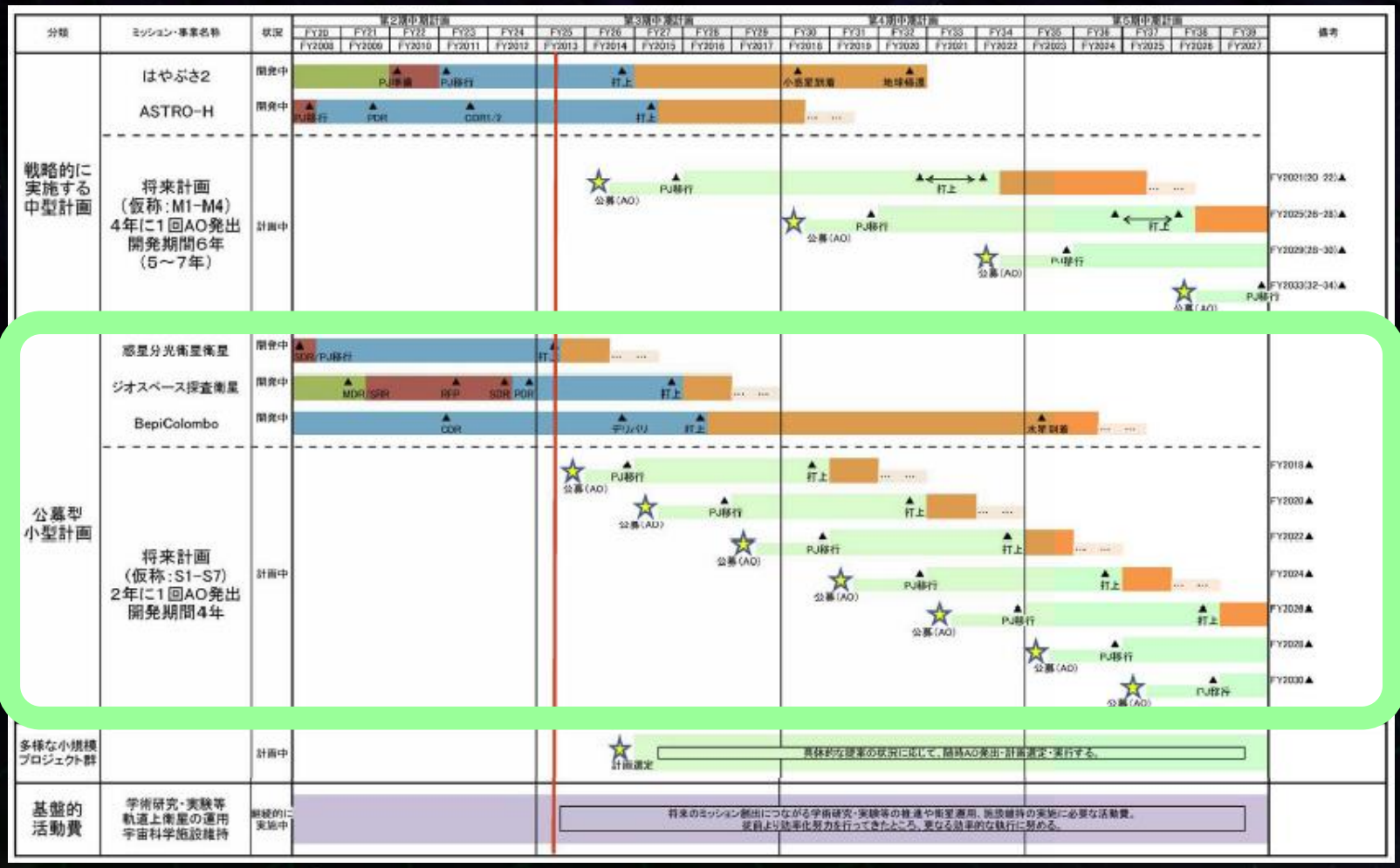
DECIGO

- ISAS/JAXA decided a new plan for space science and exploration program (2014)
  - Three categories
    - * Strategic medium-scale missions (~300 M$)
      Hayabusa-2, ASTRO-H
    - * Small-scale missions (100 - 150 M$)
      AO in every two years
      HISAKI, ERG, …
    - * Various small projects (~10 M$/year)
      ISS missions, International collaboration,
      Small rocket, Balloon, …

⇨ 'Small-scale' mission became core program in JAXA

Mission Plan by JAXA

From file submitted to the government by ISAS/JAXA
(**内閣府・宇宙政策委員会・宇宙科学・探査部会** 2013年9月19日).



Summary

Summary

DECIGO : Fruitful Sciences

Very beginning of the Universe

Dark energy, Dark matter

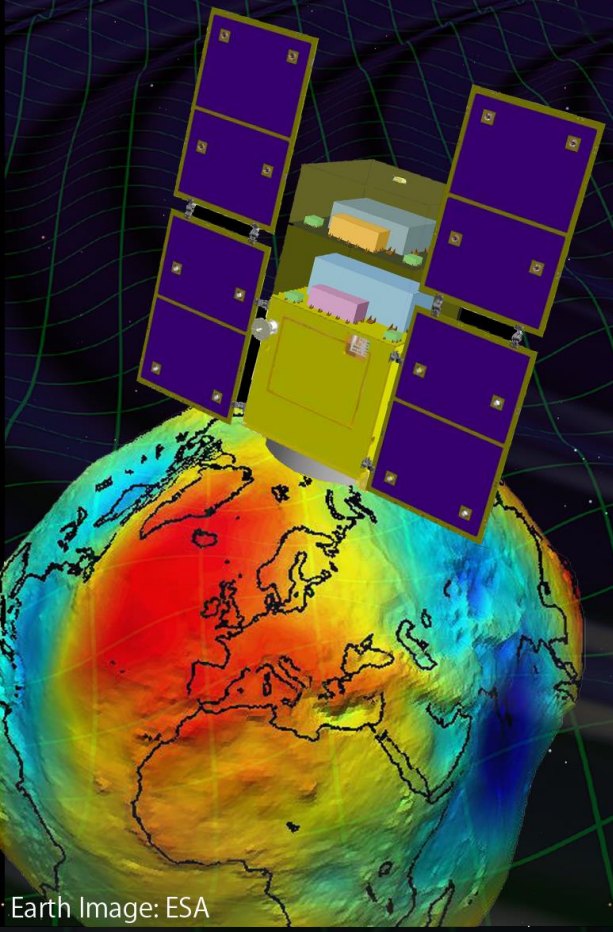
Galaxy formation

→ Will be realized at last.

DECIGO Pathfinder

Submitted mission proposal,
but failed in the selection.

→ Start discussions on the next strategy.



Earth Image: ESA

Original
Picture : Sora

End