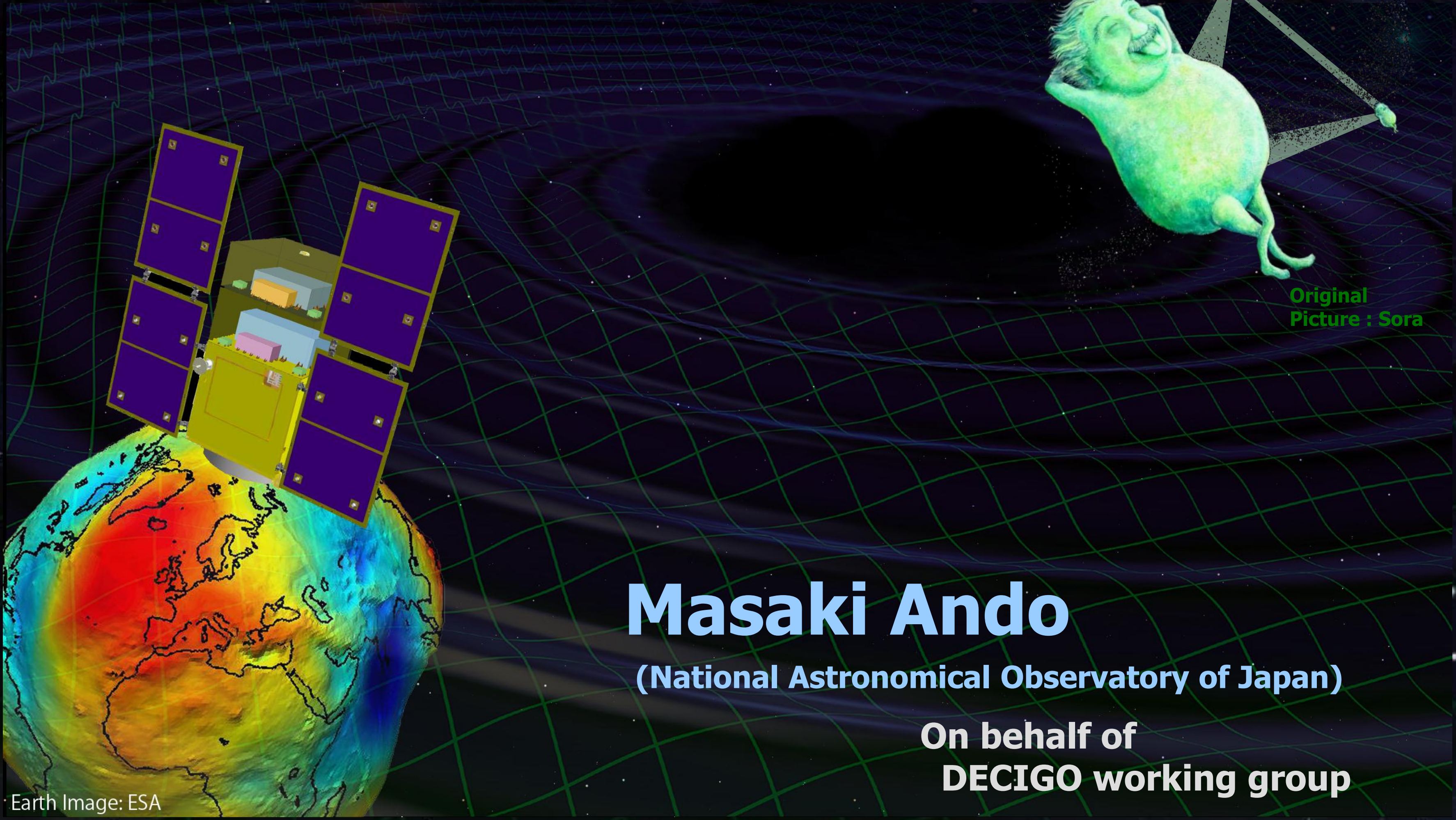
Space Gravitational-wave observatory: DECIGO



Masaki Ando

(National Astronomical Observatory of Japan)

**On behalf of
DECIGO working group**

The Fifth International ASTROD Symposium (July 12, 2012, Raman Research Institute, India)

DECIGO Working Group

Koh-suke Aoyanagi, Kazuhiro Agatsuma, 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, Masayoshi Utashima, Yumiko Ejiri, Motohiro Enoki, Toshikazu Ebisuzaki, Yoshiharu Eriguchi, Naoko Ohishi, Masashi Ohkawa, Masatake Ohashi, Kenichi Oohara, Yoshiyuki Obuchi, Kenshi Okada, Norio Okada, Nobuki Kawashima, Fumiko Kawazoe, Isao Kawano, Seiji Kawamura, Nobuyuki Kanda, Kenta Kiuchi, Naoko Kishimoto, Hitoshi Kuninaka, Hiroo Kunimori, Kazuaki Kuroda, Hiroyuki Koizumi, Feng-Lei Hong, Kazunori Kohri, Wataru Kokuyama, Keiko Kokeyama, Yoshihide Kozai, Yasufumi Kojima, Kei Kotake, Shiho Kobayashi, Motoyuki Saijo, Ryo Saito, Shin-ichiro Sakai, Masaaki Sakagami, Shihori Sakata, Norichika Sago, Misao Sasaki, Shuichi Sato, Takashi Sato, Masaru Shibata, Hisaaki Shinkai, 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, Keisuke Taniguchi, Atsushi Taruya, Takeshi Chiba, 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, 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, Chul-Moon Yoo, Jun'ichi Yokoyama, Shijun Yoshida, Taizoh Yoshino, Yaka Wakabayashi, Tomotada Akutsu, Nobuyuki Matsumoto, Ayaka Shoda, Yuta Michimura, Nobuyuki Tanaka, Sachiko Kuroyanagi, Dan Chen, Satoshi Eguchi, Rina Gondo, Kazunori Shibata, Takafumi Ushiba,

- **DECIGO**
- **DECIGO Pathfinder**
- **SWIM**
- **Summary**

DECIGO

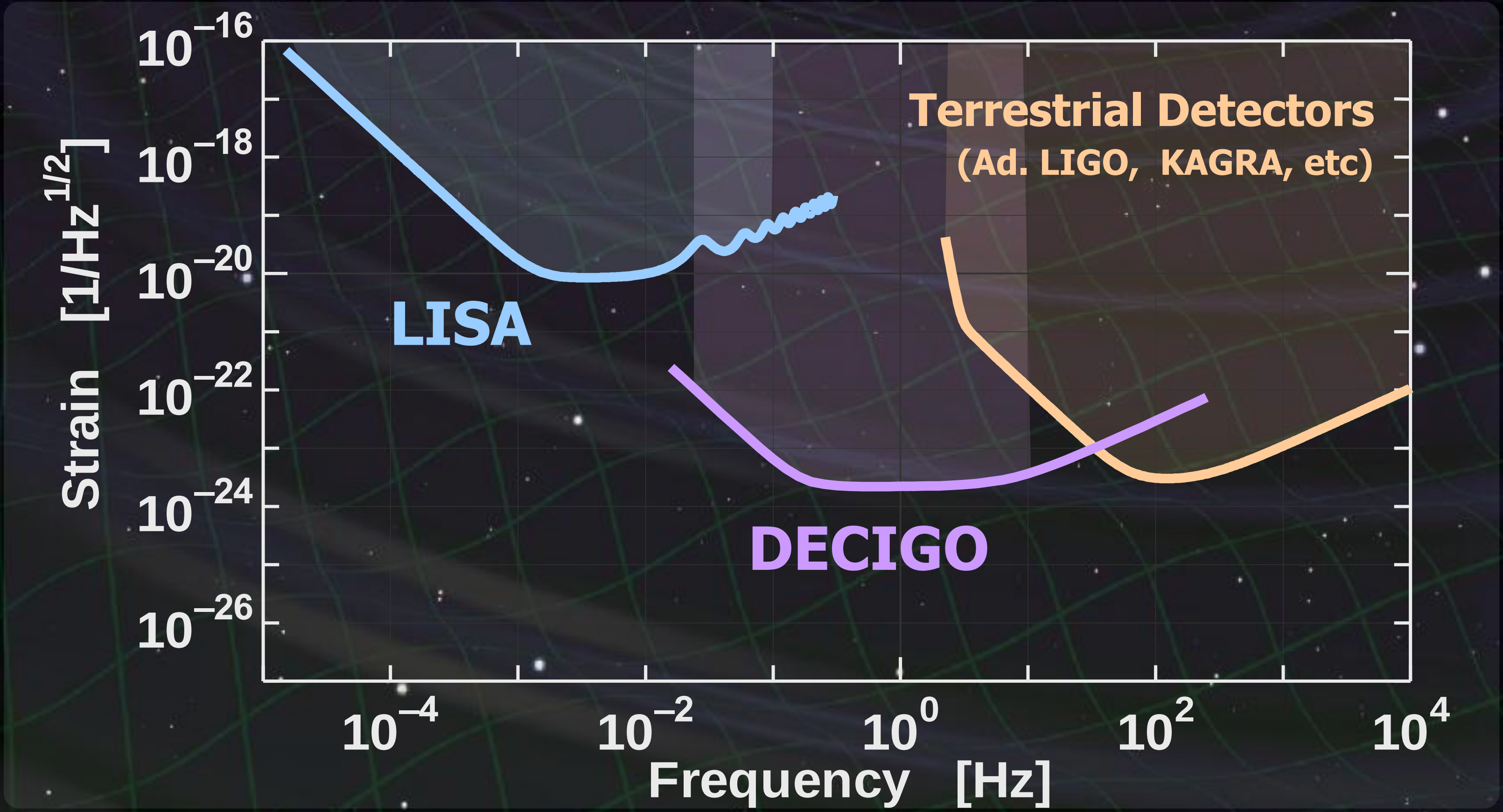
DECIGO

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



DECIGO Interferometer

Interferometer Unit:

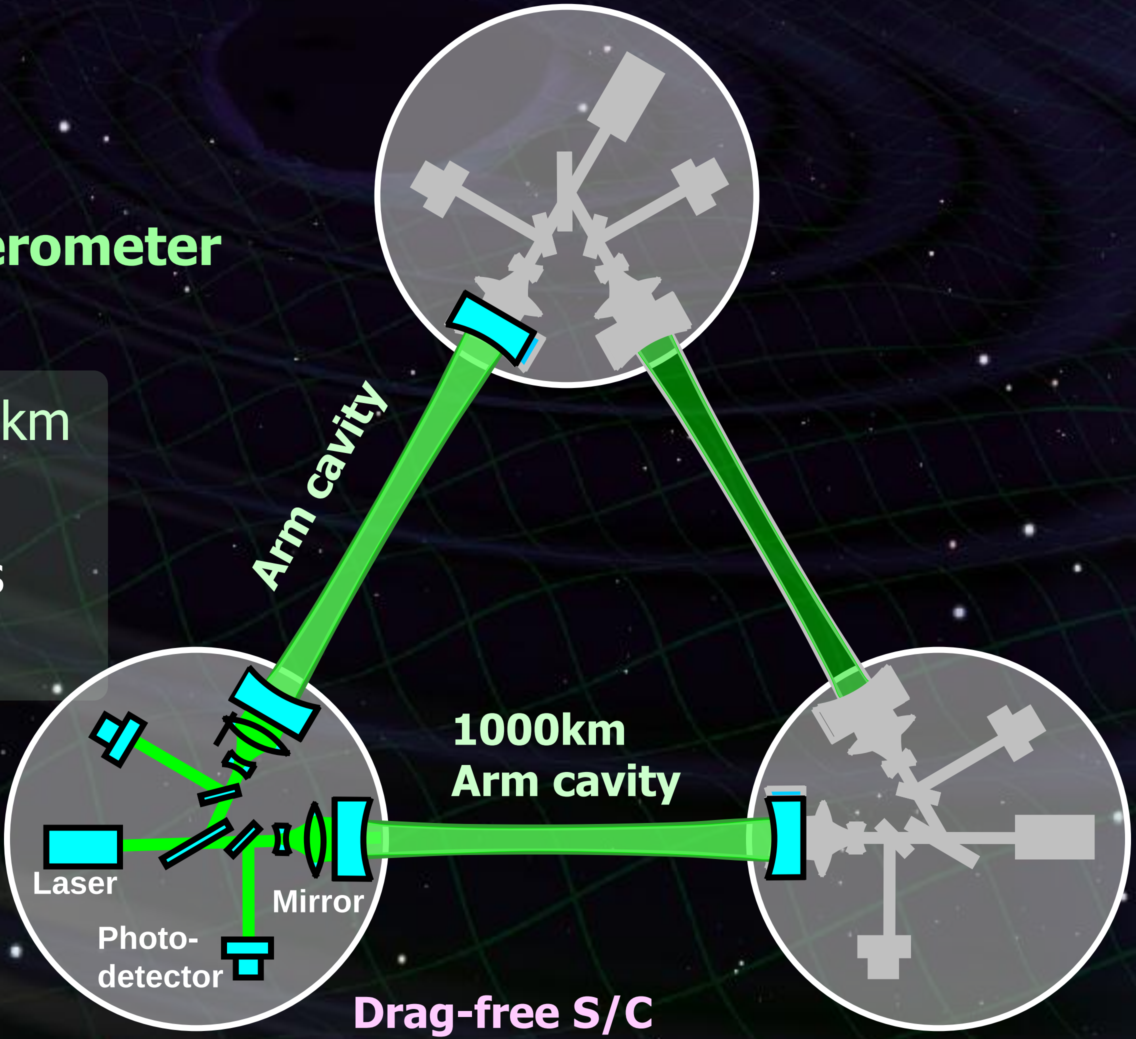
Differential FP interferometer

Baseline length: 1000 km

3 S/C formation flight

3 FP interferometers

Drag-free control

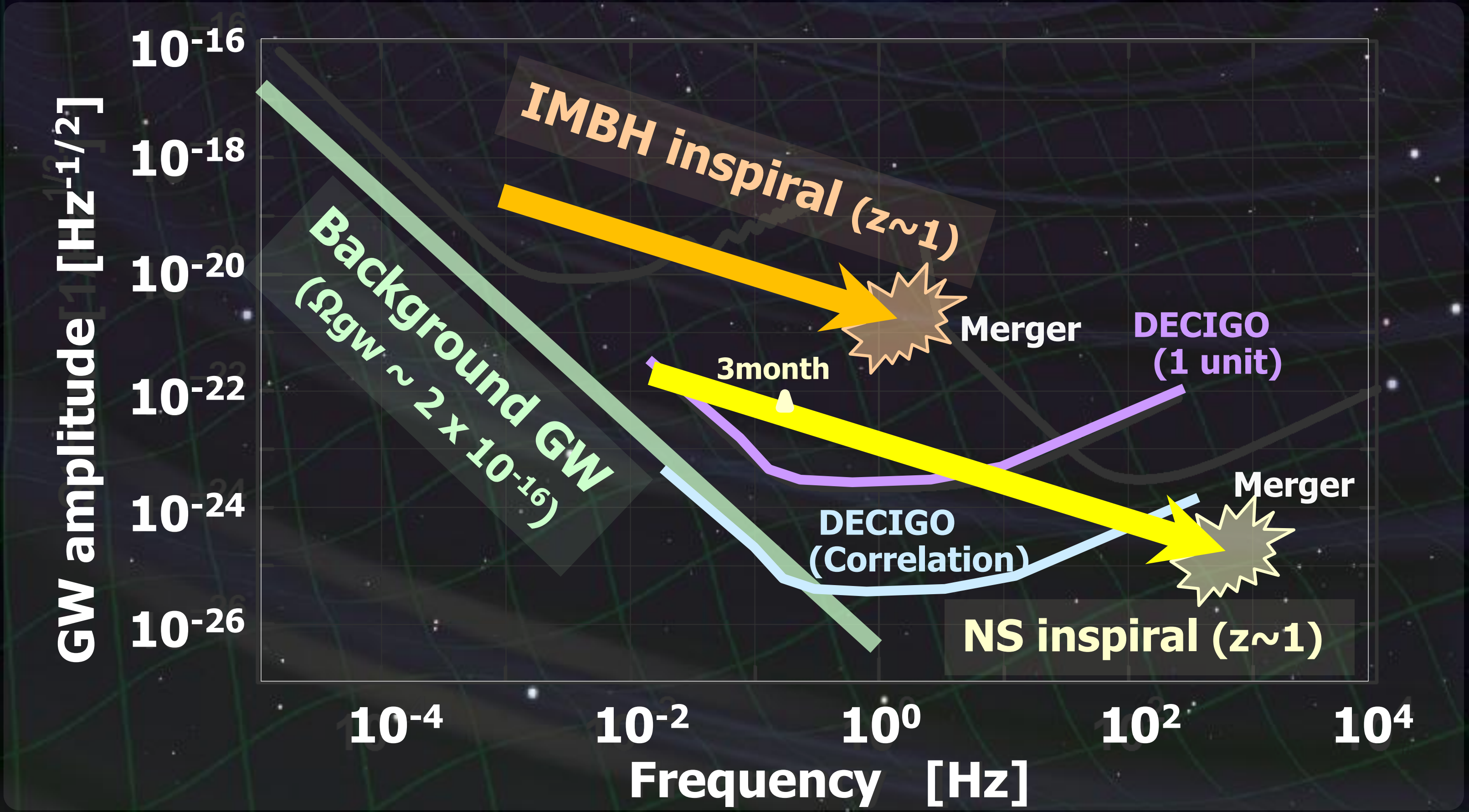


Targets and Science

IMBH binary inspiral
NS binary inspiral
Stochastic background

⇨

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



Astronomy and Cosmology

- **Verification of the alternative theories of gravity**

  Test Brans-Dicke theory by NS/BH binary evolution

  → Stronger constraint by 10^4 times

  K. Yagi and T. Tanaka, Prog. Theor. Phys. 123, 1069 (2010)

- **Black hole dark matter**

  Gravitational collapse of the primordial density fluctuations

  → Primordial black holes (PBHs)

  as a candidate of dark matter

  R. Saito and J. Yokoyama, Phys. Rev. Lett. 102 161101 (2009)

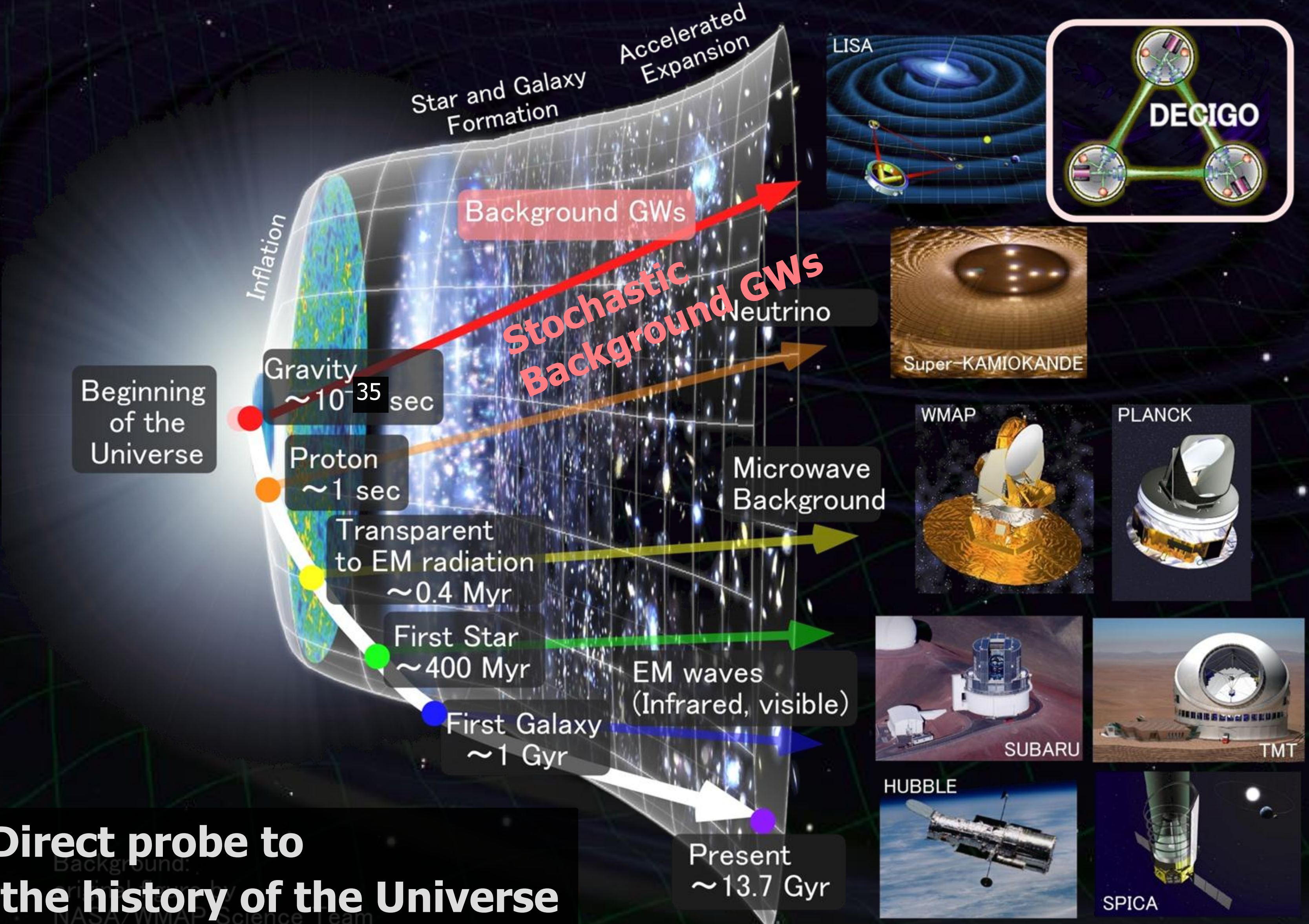
- **Neutron-star physics**

  Determine masses of 10^5 NSs per year

  → Constrain the EoS of NS

  Formation process of NS from the spectrum

Characterization of inflation



Direct probe to the history of the Universe

Pre-Conceptual Design

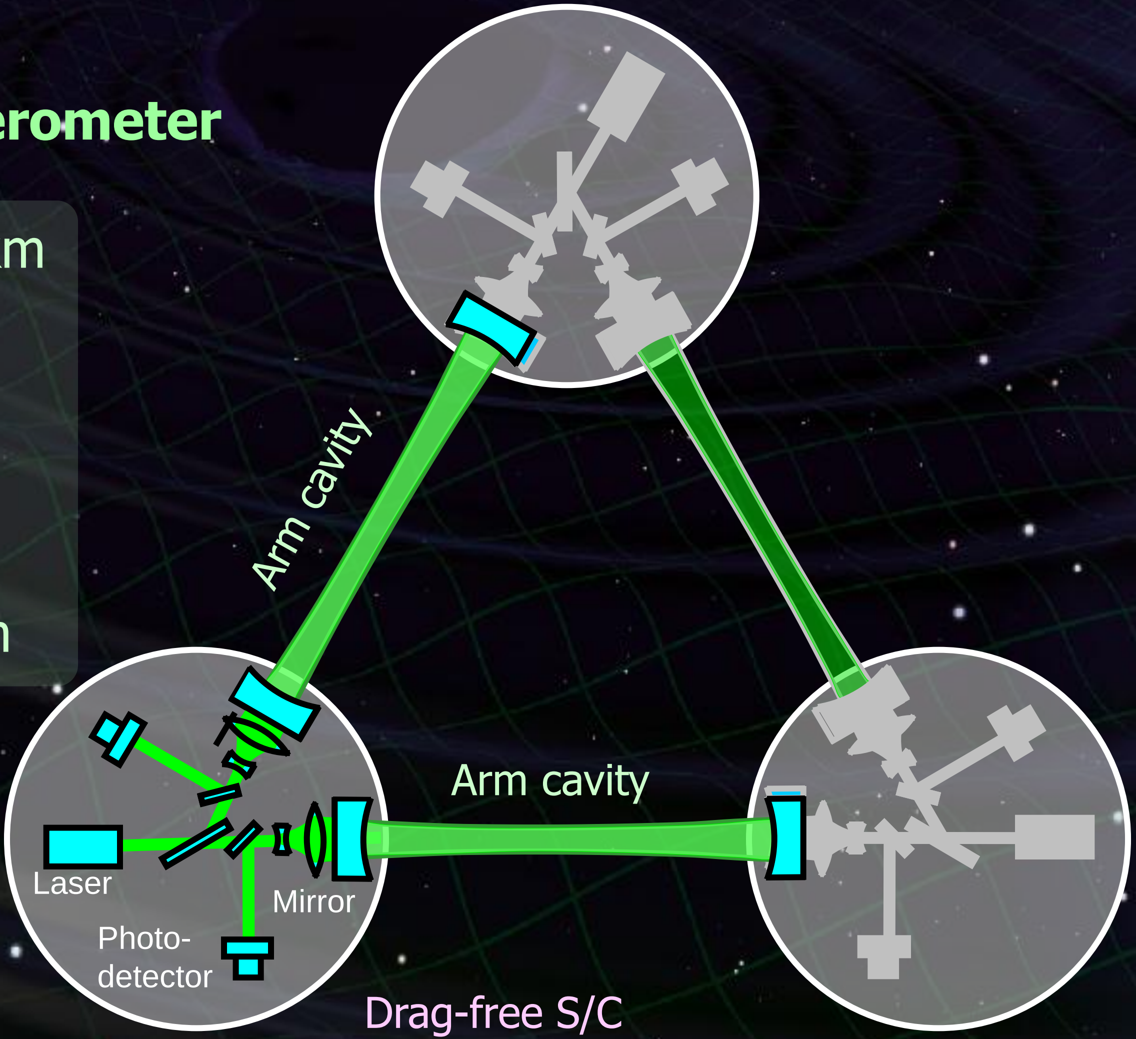
Interferometer Unit:

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

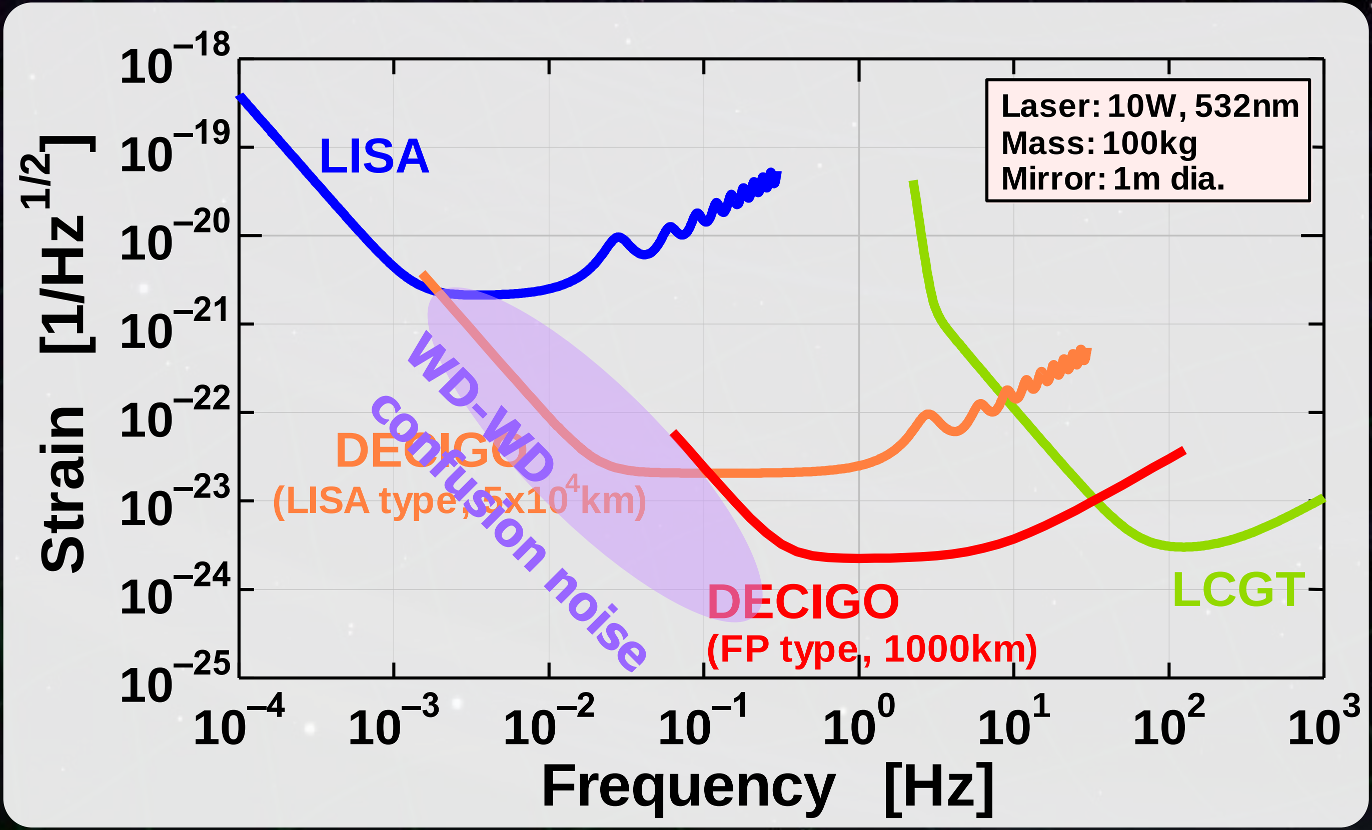


Interferometer Design

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

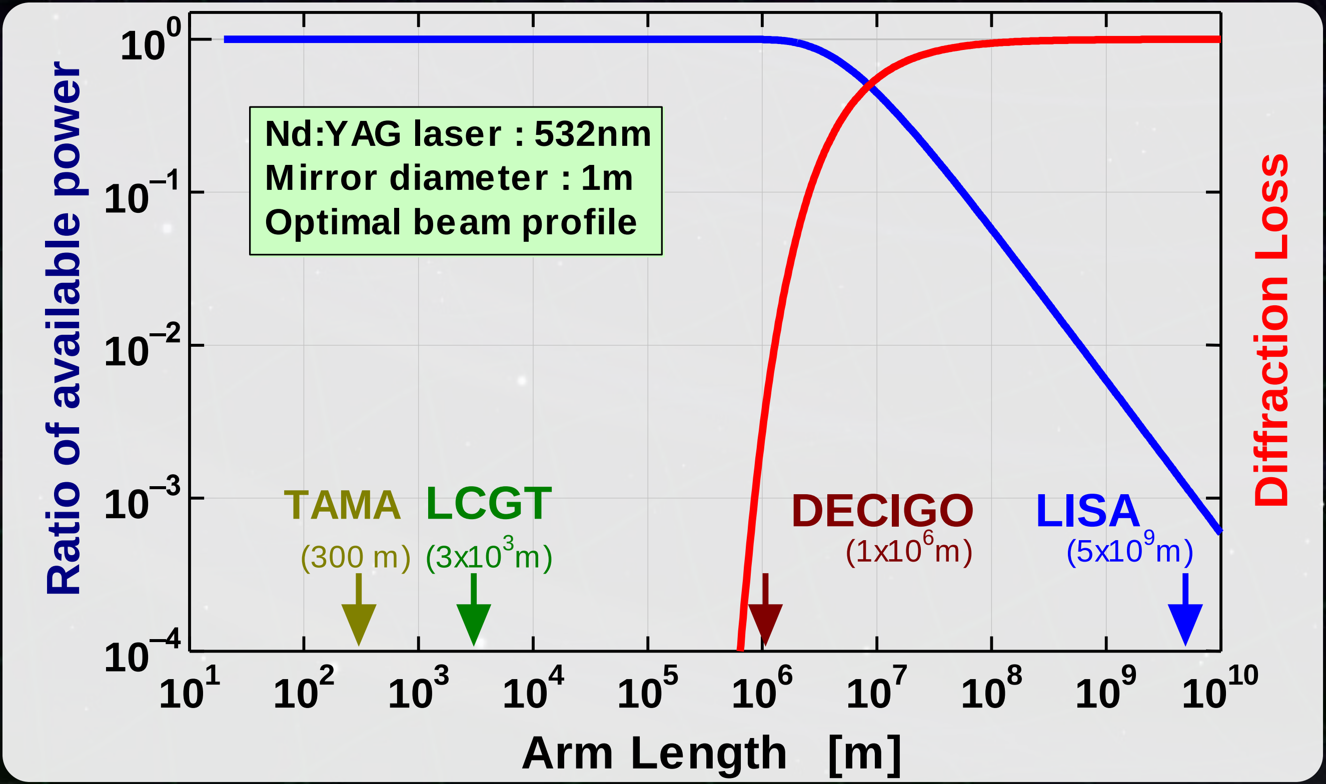
Effective reflectivity (TEM_{00} → TEM_{00})

Laser wavelength : 532nm

Mirror diameter: 1m

Optimal beam size

⇨ 1000 km is almost max.



Cavity and S/C control

Cavity length change

PDH error signal → Mirror position (and Laser frequency)

Relative motion between mirror and S/C

Local sensor → S/C thruster

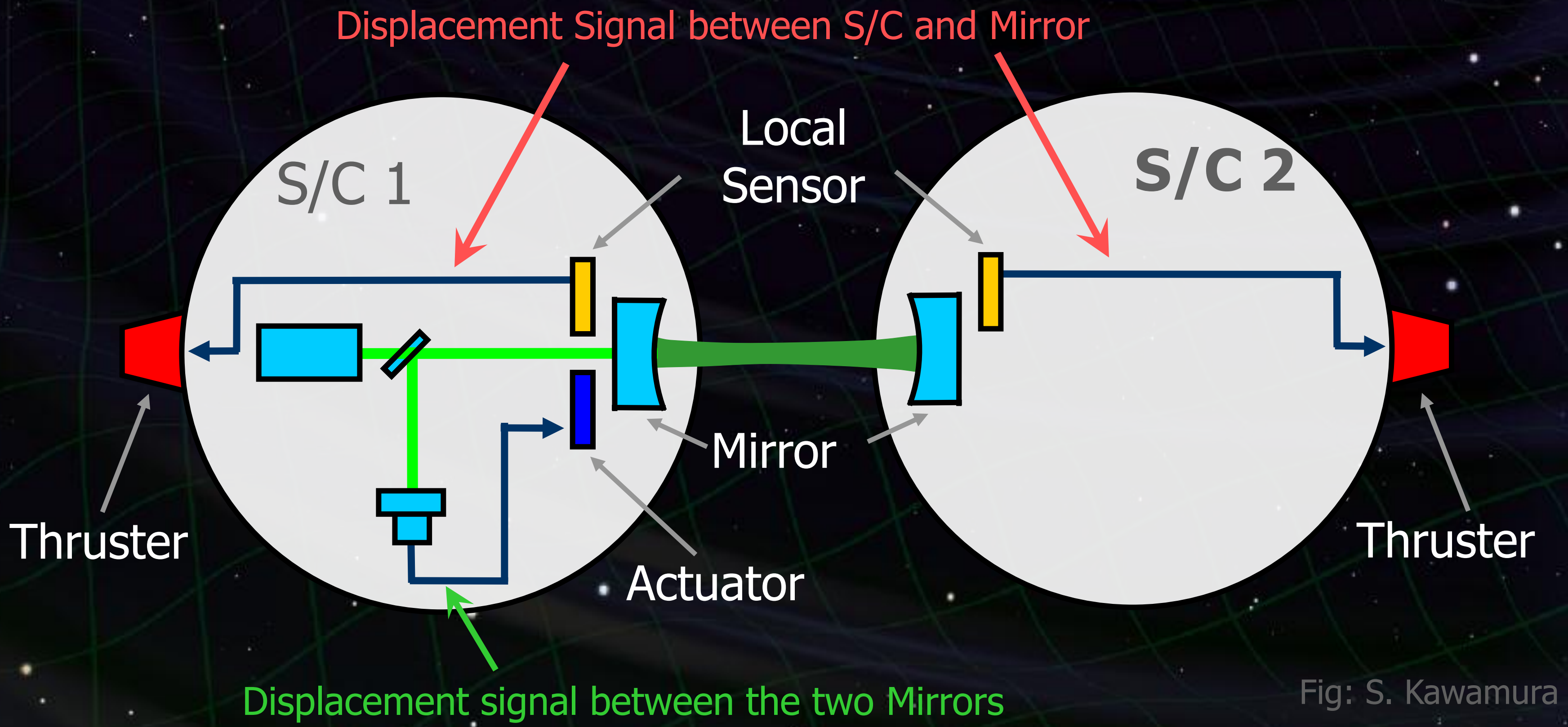


Fig: S. Kawamura

Requirements

Sensor 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

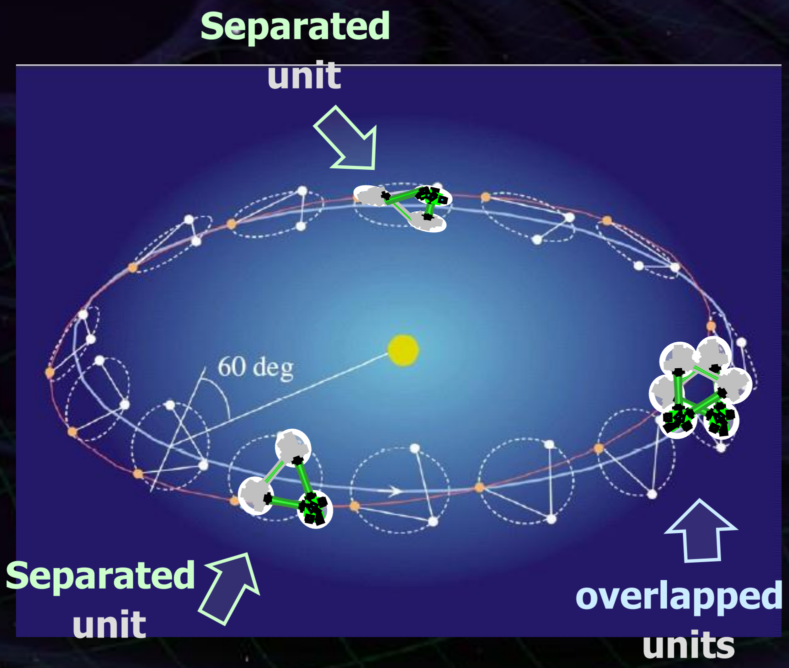
(Mirror force $\sim10^{-9}$ N)

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
$\sim 10^5$ NS binaries

⇨ Foreground for GWB

In principle, possible
to remove them.

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

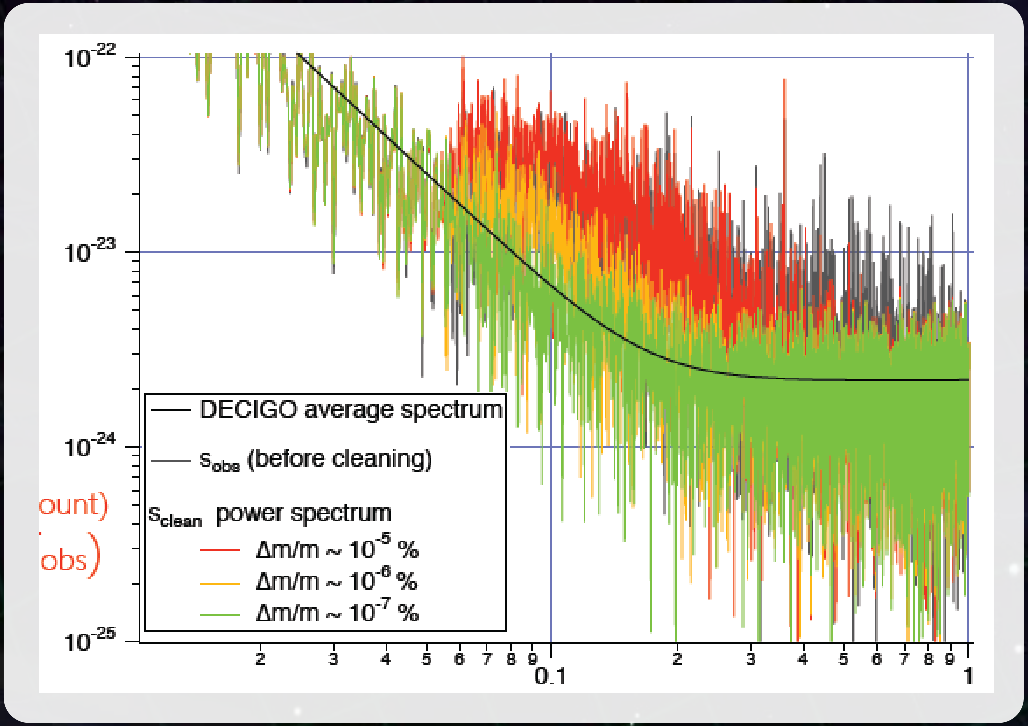
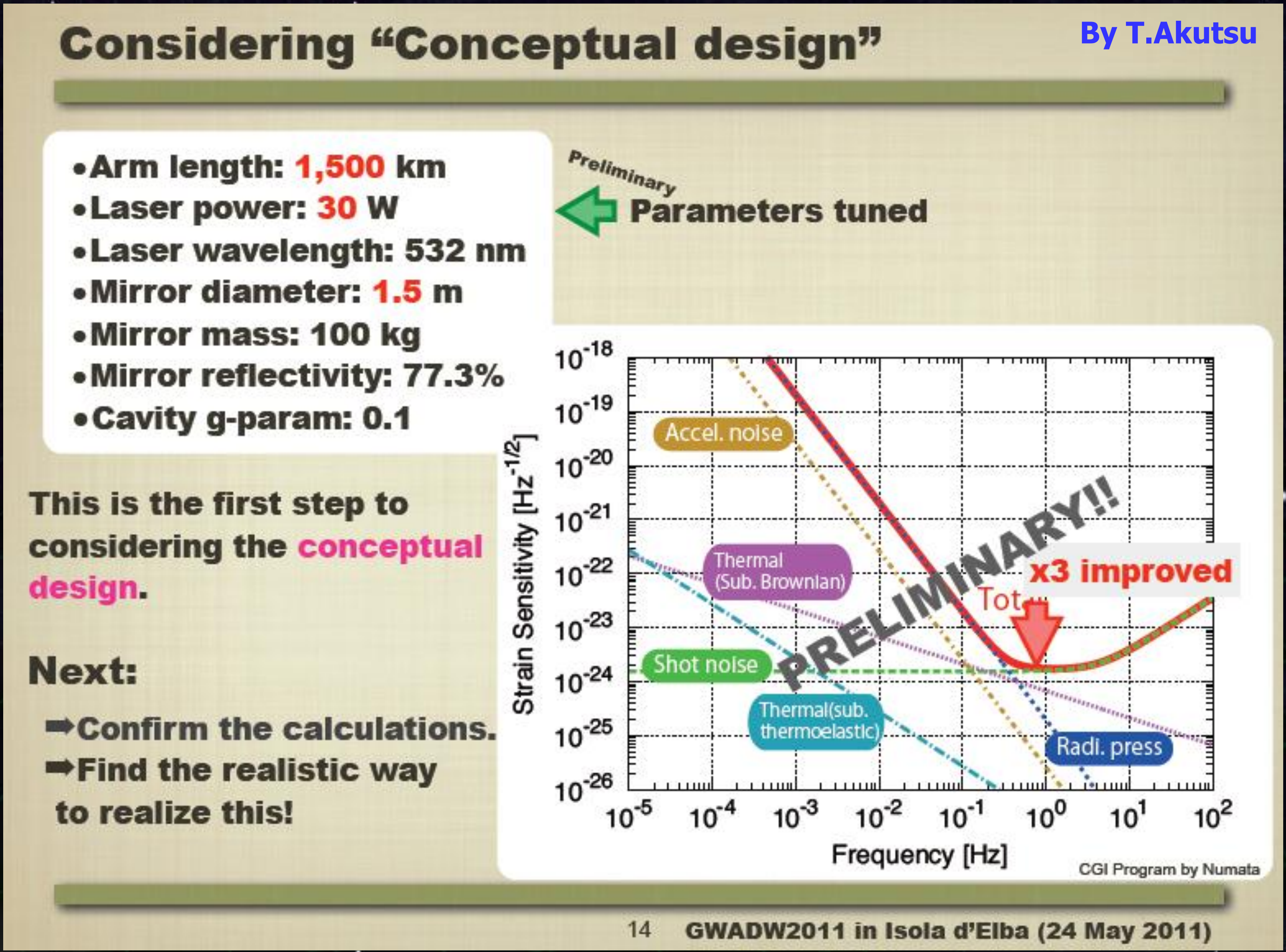


Fig: N. Kanda

Design Update



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!

CGI Program by Numata

GW observation roadmap

Ground-based Observatory

Better sensitivity (10Hz-1kHz)

2010

2015

2020

2025

LIGO

Enhanced LIGO

Advanced LIGO

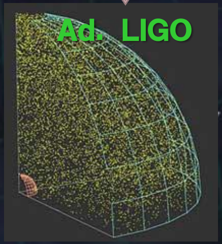
TAMA CLIO

LCGT

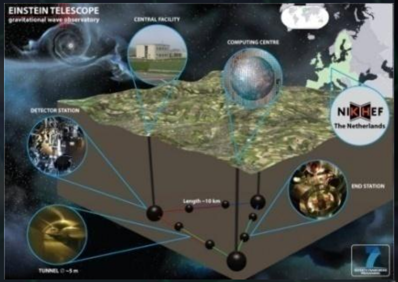
Virgo

Advanced Virgo

ET



Detection rate
~10 event/yr



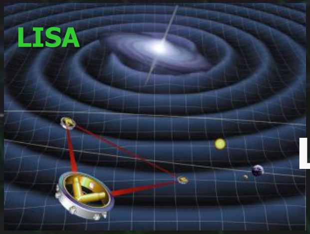
Space-borne observatory

Low-freq. observation (<1Hz)

DECIGO

LPF

DPF



LISA

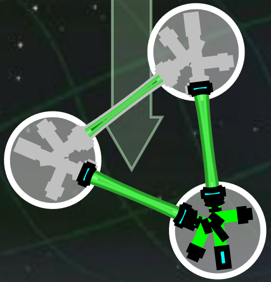
0.1mHz-10mHz
Guaranteed
sources

Pre-DECIGO

DECIGO

BBO

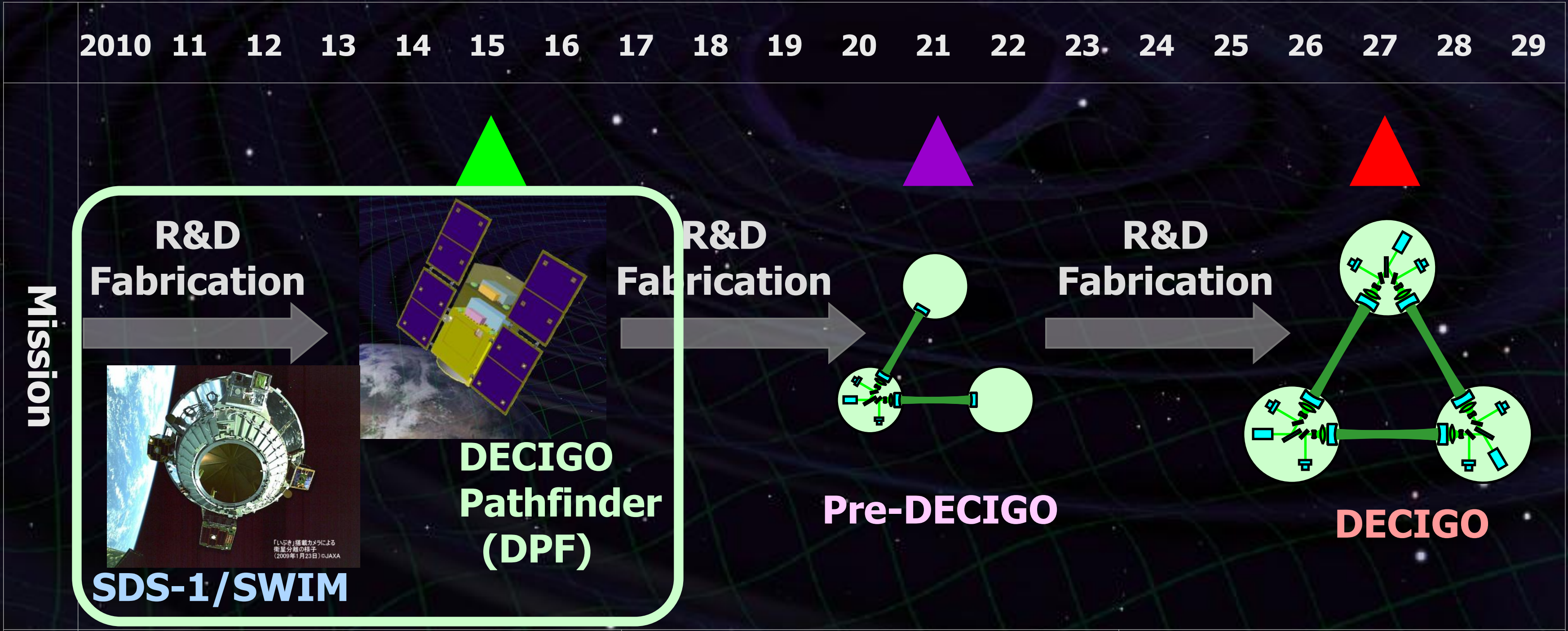
0.1Hz band
Cosmological GWs



The Fifth International ASTROD Symposium (July 12, 2012, Raman Research Institute, India)

Roadmap

Figure: S.Kawamura



2010 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29

Mission

R&D
Fabrication

「いぶき」搭載カメラによる
衛星分離の様子
（2009年1月23日）©JAXA

SDS-1/SWIM

DECIGO
Pathfinder
(DPF)

R&D
Fabrication

Pre-DECIGO

R&D
Fabrication

DECIGO

Objective	Space test of key tech. GW observation	Detect GW with min. spec FP between S/C	GW astronomy
Design	Single small satellite Short FP interferometer	3 S/C 1 interferometer unit	3 S/C x 3-4 units

DECIGO Pathfinder

DECIGO-PF

DECIGO Pathfinder (DPF)

First milestone mission for DECIGO

Shrink arm cavity

DECIGO 1000km → DPF 30cm

Single satellite

(Payload ~1m^3 , 350kg)

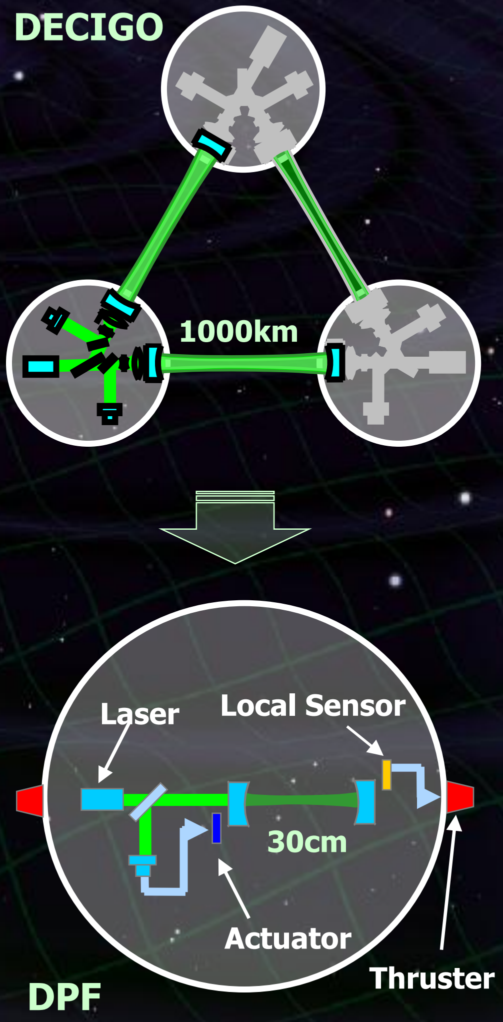
Low-earth orbit

(Altitude 500km, sun synchronous)

30cm FP cavity with 2 test masses

Stabilized laser source

Drag-free control



DPF satellite

DPF Payload

Size : 950mm cube

Weight : 150kg

Power : 130W

Data Rate: 800kbps

Mission thruster x12

Power Supply
SpW Comm.

Satellite Bus

('Standard bus' system)

Size :

950x950x1100mm

Weight : 200kg

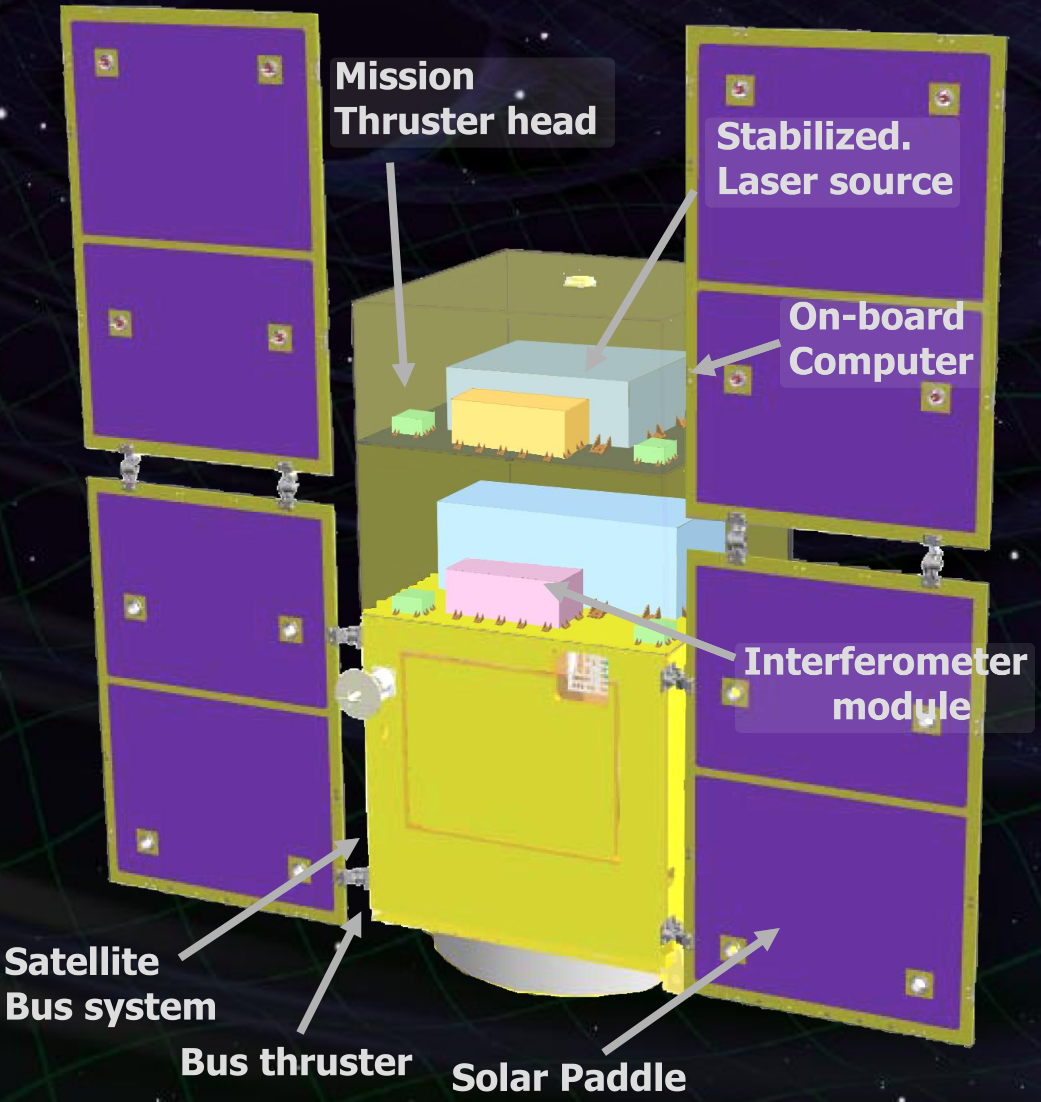
SAP : 960W

Battery: 50AH

Downlink : 2Mpbs

DR: 1GByte

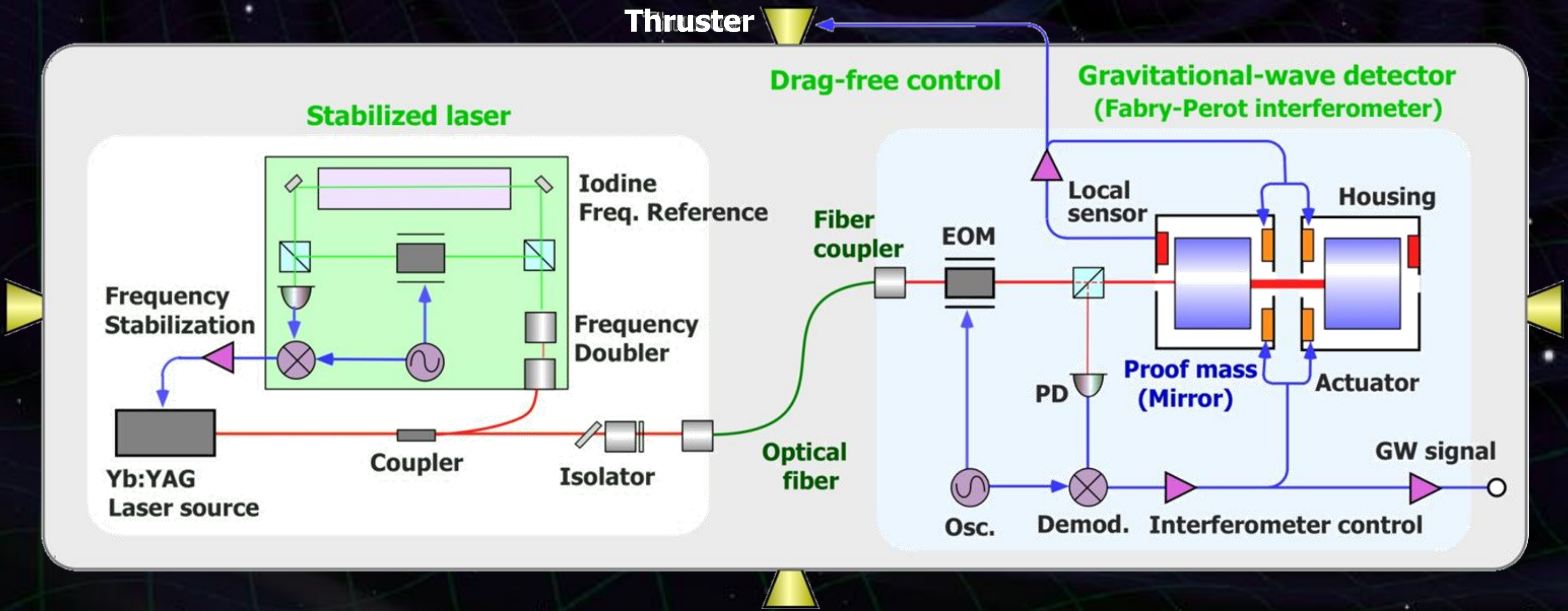
3N Thrusters x 4



DPF mission payload

Mission weight : ~150kg
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

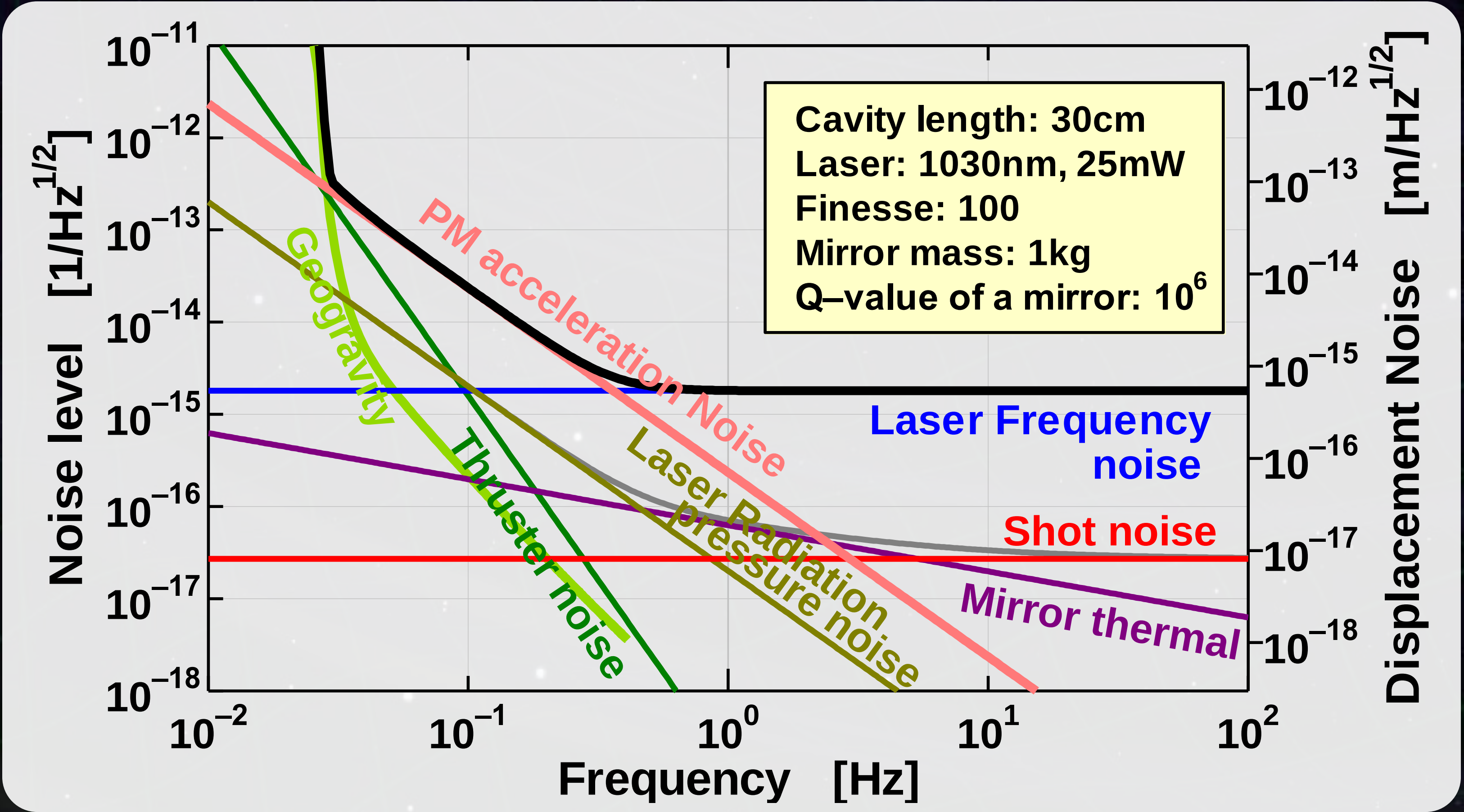
Fabry-Perot interferometer
Finesse : 100
Length : 30cm
Test mass : ~a few kg
Signal extraction by PDH

DPF Sensitivity

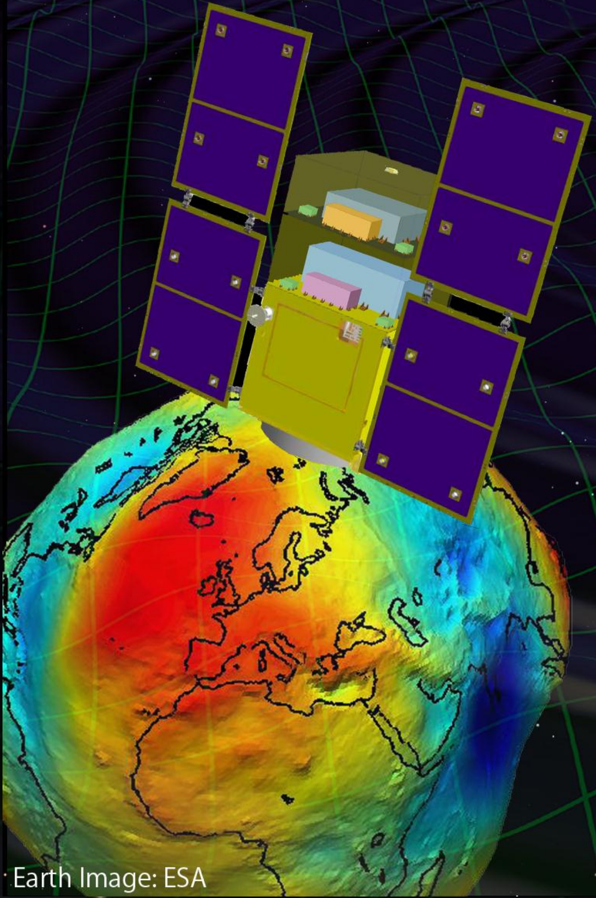
Laser source : 1030nm, 25mW
IFO length : 30cm
Finesse : 100, Mirror mass : 1kg
Q-factor : 10^5, Substrate: TBD
Temperature : 293K

Satellite mass : 350kg, Area: $2m^2$
Altitude: 500km
Thruster noise: $0.1\mu N/Hz^{1/2}$

(Preliminary parameters)



Targets of DPF


Earth Image: ESA

Scientific observations

Gravitational Waves form BH mergers

→ BH formation mechanism

Gravity of the Earth

→ Geophysics, Earth environment

Science technology

Space demonstration for DECIGO

→ Most tech. with single satellite
(IFO, Laser, Drag-free)

Precision measurement in orbit

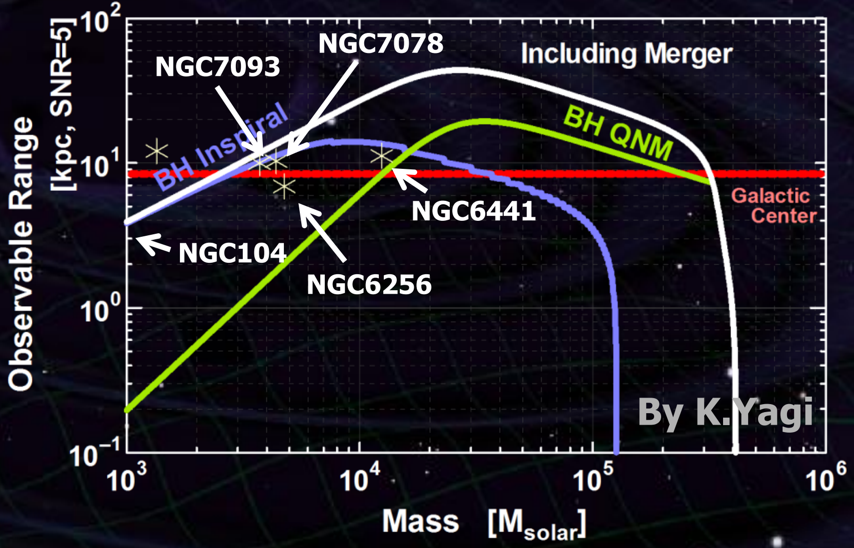
→ IFO measurement
under stable zero-gravity

DPF Science

Astronomical observation

GW from merger of IMBHs
→ Formation mechanism
of supermassive BHs

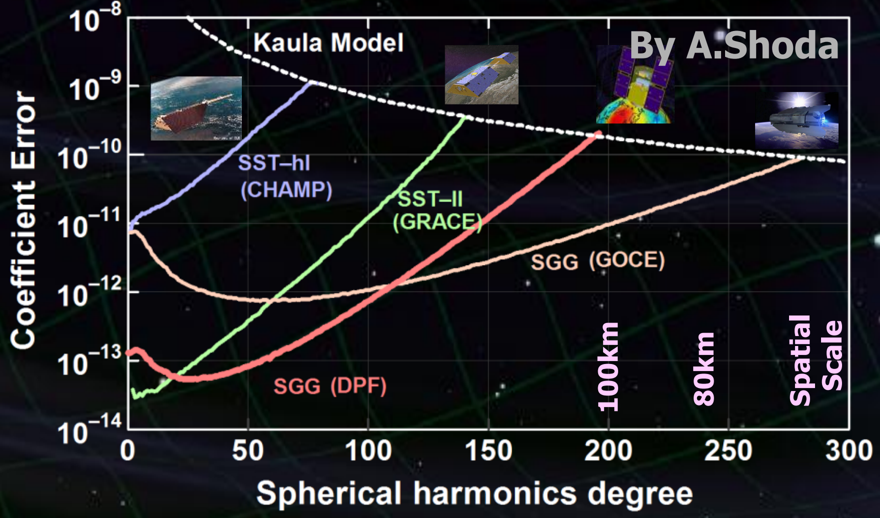
~30 GCs within DPF range



Observation of the earth

Gravitational potential
→ Shape of the earth
Environment monitor

Comparable sensitivity with other missions



GW target of DPF

Black hole events
in our galaxy

IMBH inspiral and merger

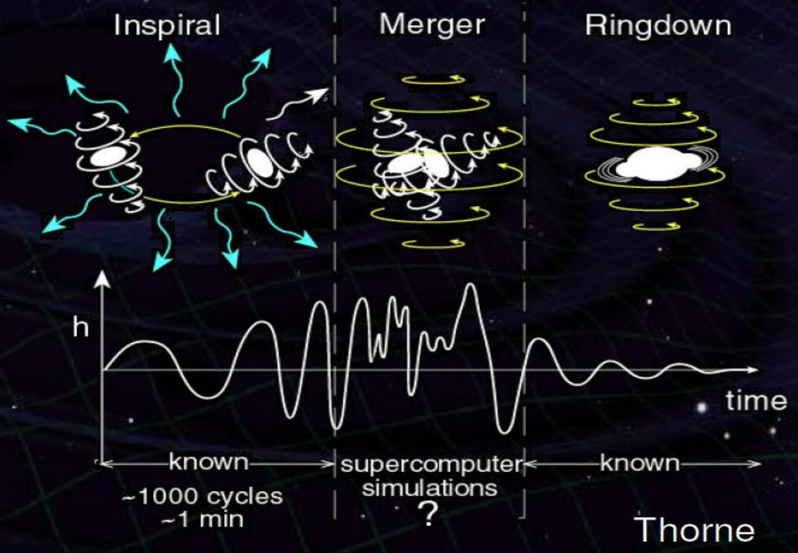
Obs. Distance 40kpc,
for $m = 2\ \mathrm{x}10^4\ M_{\mathrm{sun}}$

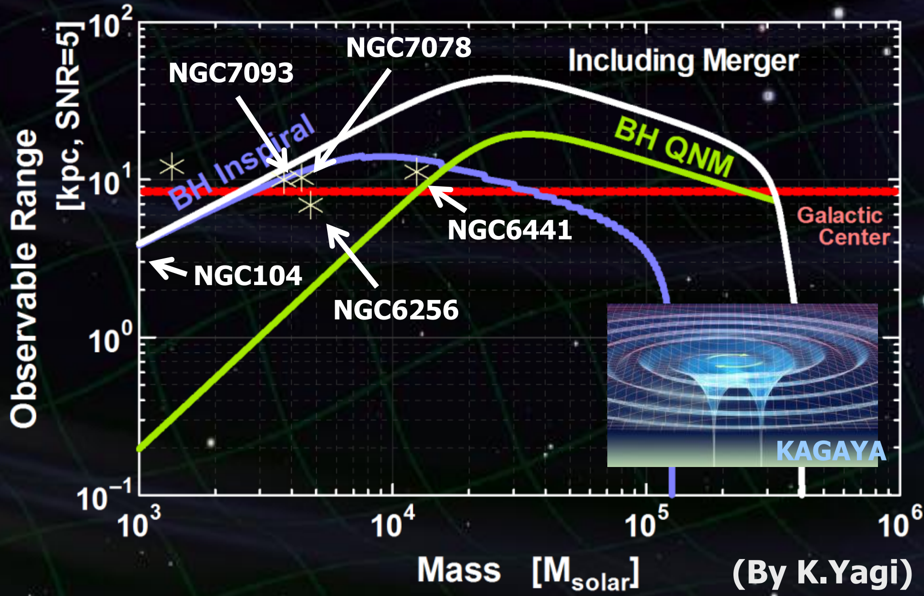
Obs. Duration (~1000sec)

Observable range covers
our Galaxy (SNR~5)

There may be IMBH at GCs
DPF covers ~30 GCs

Hard to access by others
→ Original observation





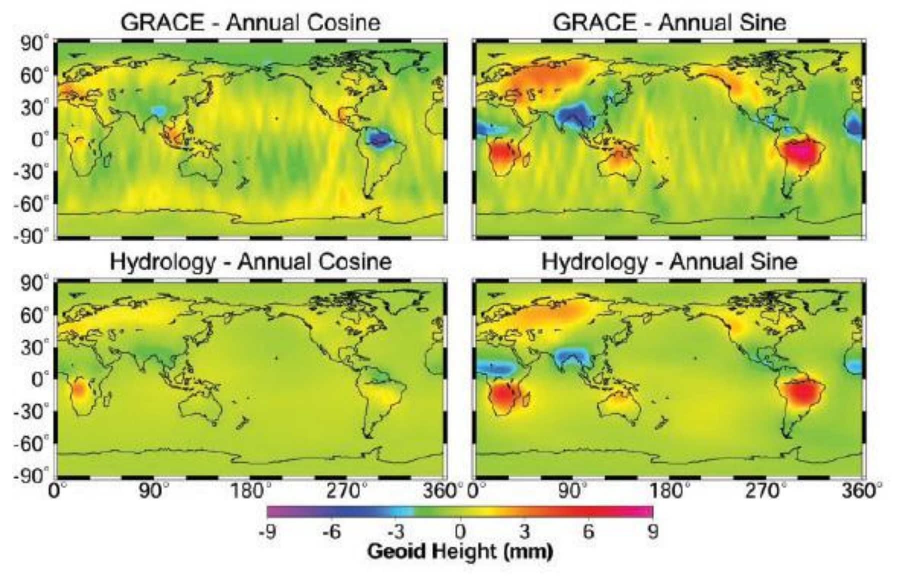
(By K.Yagi)

Earth’s Gravity Observation

Measure gravity field of the Earth

from Satellite Orbits, and gravity-gradiometer

⇨ comprehensive and homogeneous-quality data



Seasonal change of the gravitational potential
observed by GRACE

Determine global gravity field

→ Basis of the shape of the Earth (Geoid)

Monitor of change in time

→ Result of Earth’s dynamics

Ground water motion

Strains in crusts by earthquakes and volcanoes

Satellite Gravity missions

3-types of satellite gravity missions

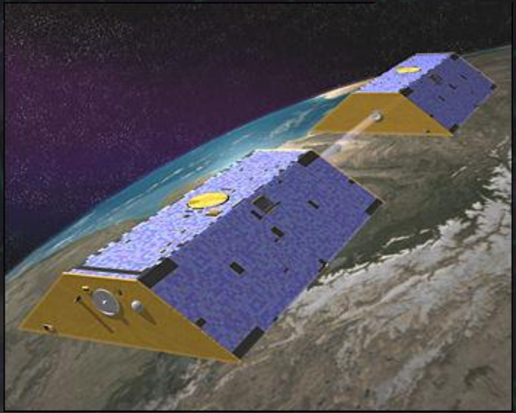
Satellite-to Satellite tracking High-Low

- Observe satellite orbit by global positioning system (GPS,…)
- Cancel drag-effects by accelerometer

CHAMP (GFZ, 2000-)

Satellite-to Satellite tracking Low-Low

- Distance meas. by along-track satellites
- Cancel drag-effects by accelerometer



GRACE (NASA, 2002-)

Satellite Gravity Gradiometry

- Observe potential by gravity gradiometer
- Drag-free control for cancellation of drags

GOCE (ESA, 2009-)

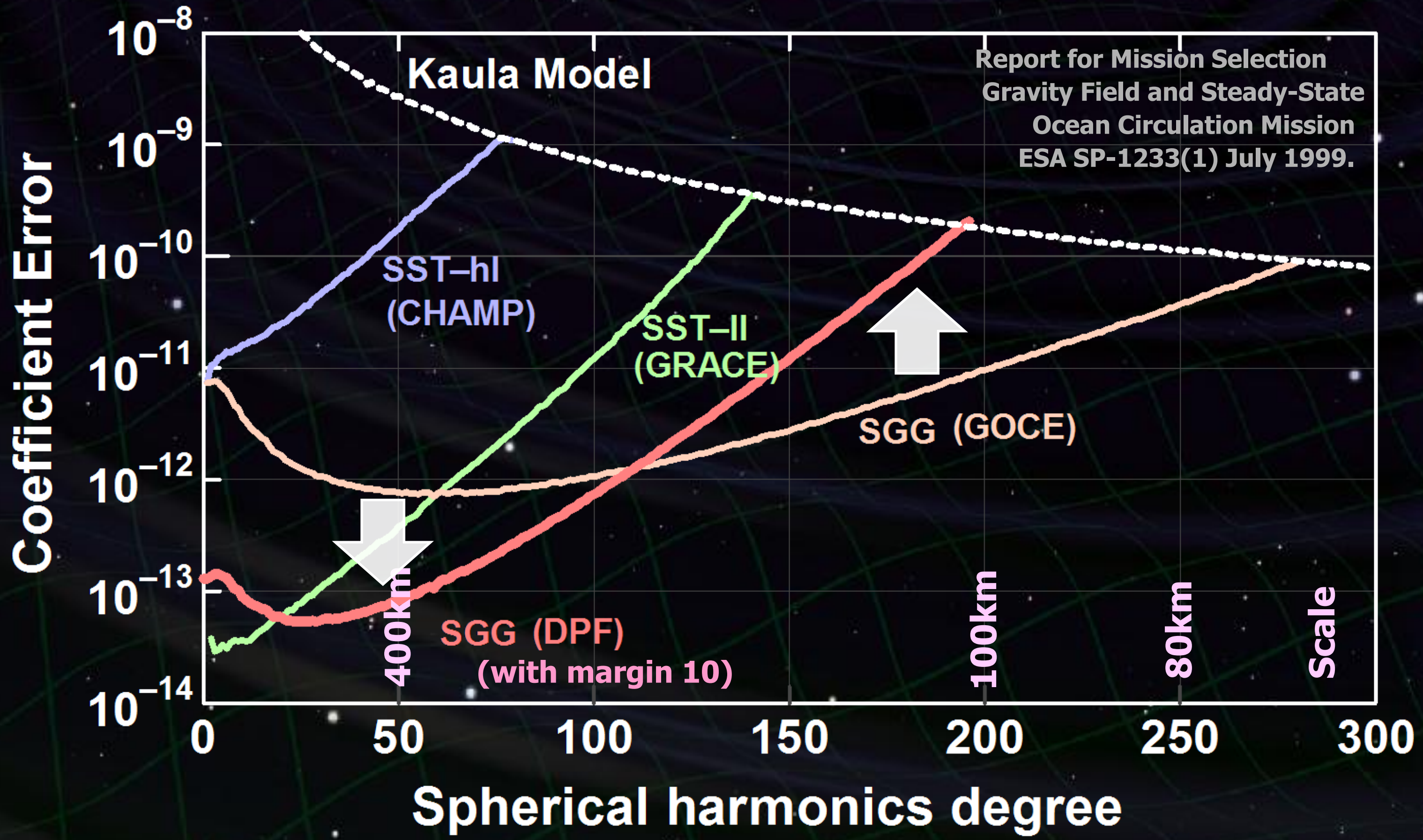
The Fifth International ASTROD Symposium (July 12, 2012, Raman Research Institute, India)

DPF sensitivity

Comparison of sensitivities

Better in low orders (large scale) ← Sensors

Worse in high orders (small scale) ← Altitude



DPF-WG activities

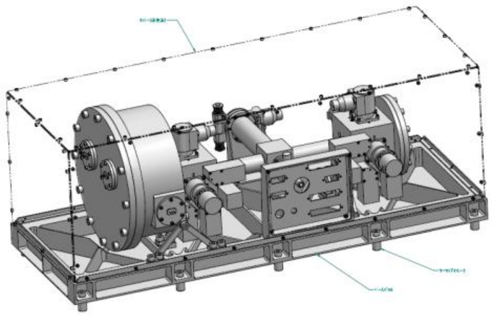
Mission design

- Structure and thermal modeling
- Drag-free control design

DPF-WG activities

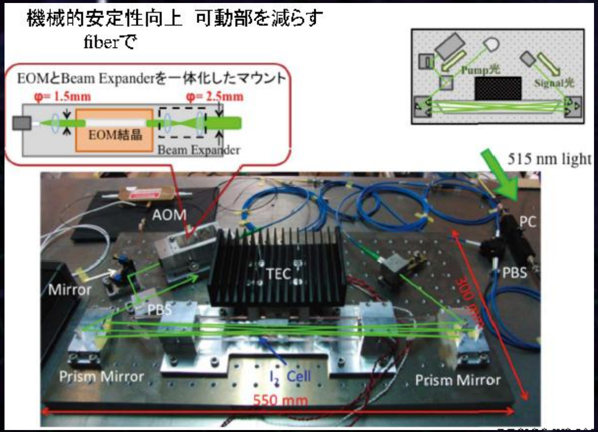
BBMs (Bread-board model) for Core components

Interferometer module



Univ. of Tokyo、NAOJ

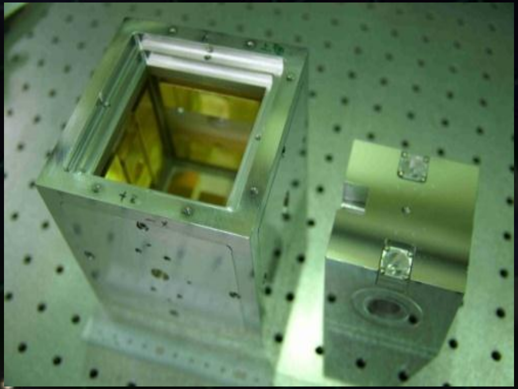
Laser stabilization module



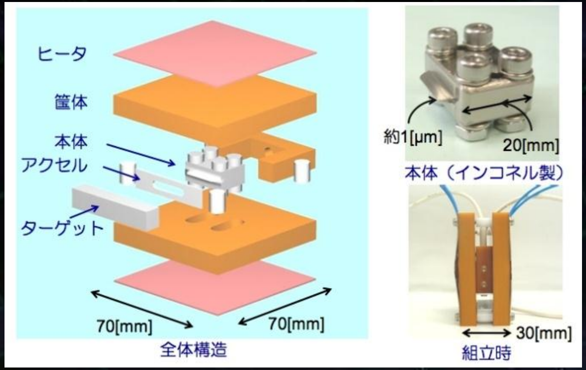
UEC, NICT, NASA/GSFC

Test-mass module

NAOJ, Hosei Univ.



Low-noise thruster module



JAXA

DPF mission status

DPF : One of the candidate of JAXA's small satellite series

↑

At least 3 satellite in 5 years with
Standard Bus + M-V follow-on rocket

1st mission (2012): SPRINT-A/EXCEED

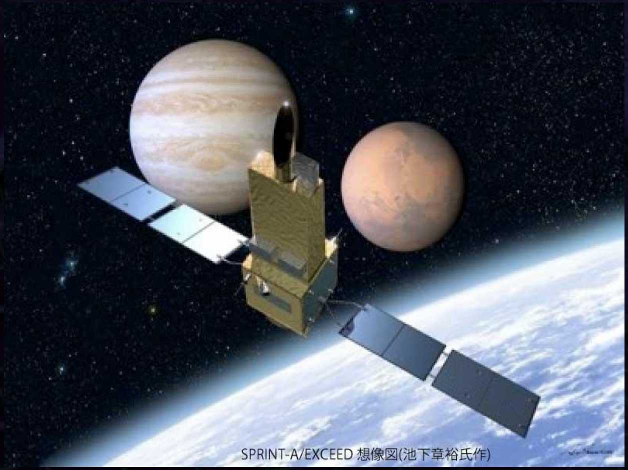
2nd mission (~2015) : SPRINT-B/ERG

DPF survived until final two

3rd mission (~2016/17) : TBD

Call for proposal : 2012

DPF is one of the strongest candidates of the 3rd mission



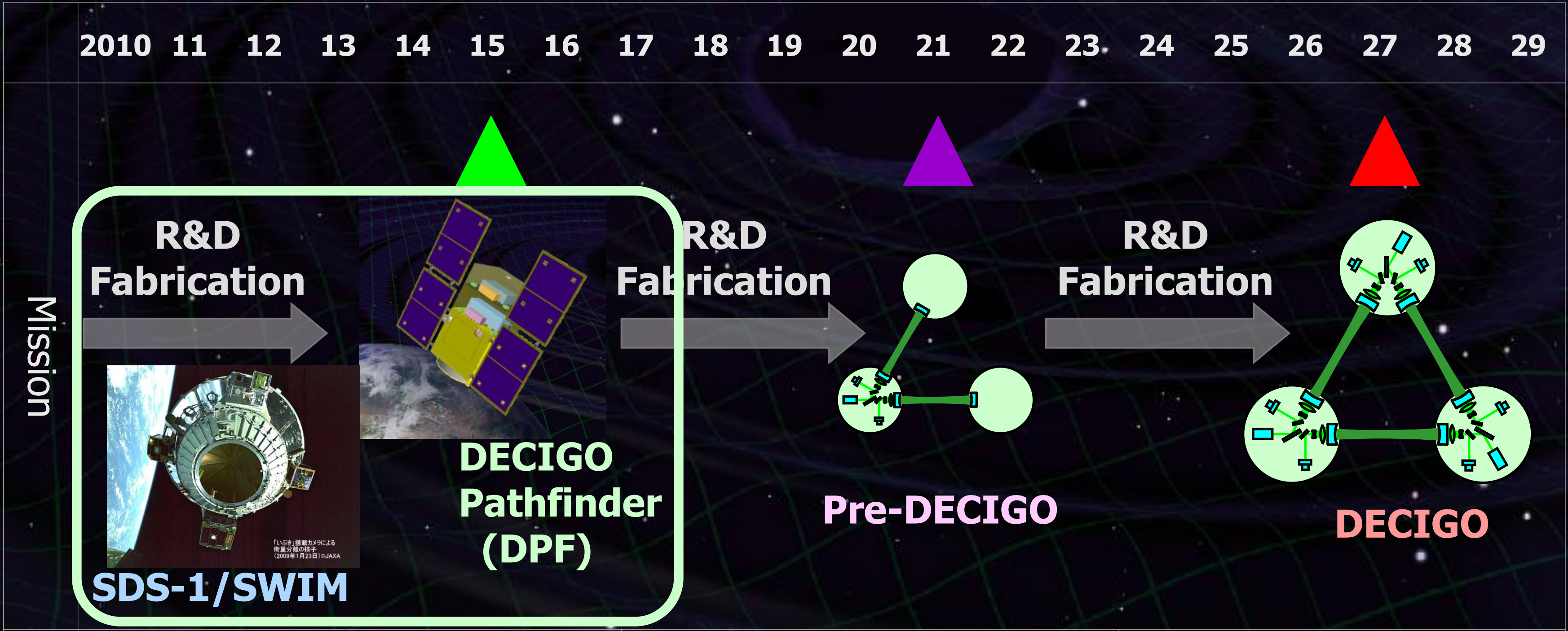
**SPRINT-A /EXCEED
UV telescope mission**

**Next-generation
Solid rocket booster (M-V FO)
Fig. by JAXA**

SWIM

Roadmap

Figure: S.Kawamura



Objective	Space test of key tech. GW observation	Detect GW with min. spec FP between S/C	GW astronomy
Design	Single small satellite Short FP interferometer	3 S/C 1 interferometer unit	3 S/C x 3-4 units

Rotating TOBA : SWIMμν

DECIGO

Small Module SWIMμν on SDS-1

Launched Jan. 2009, Terminated Sept. 2010

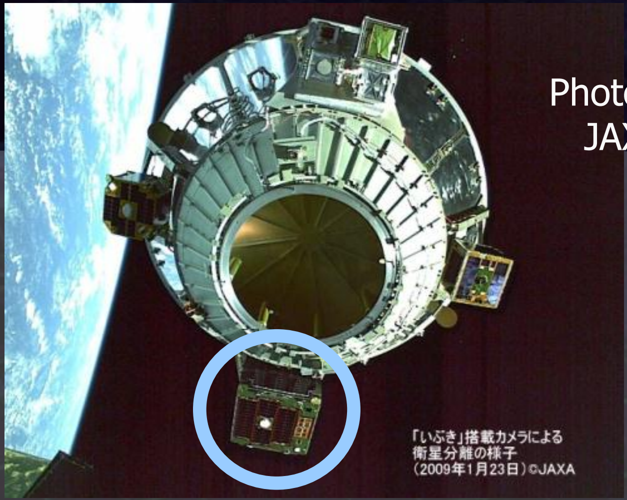
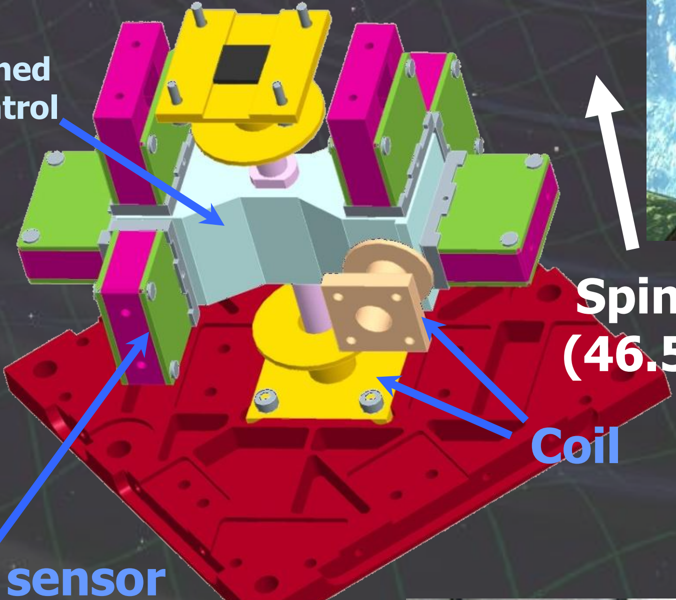


Photo: JAXA

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



Test mass

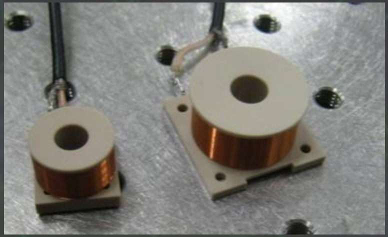
~47g Aluminum, Surface polished
Small magnets for position control

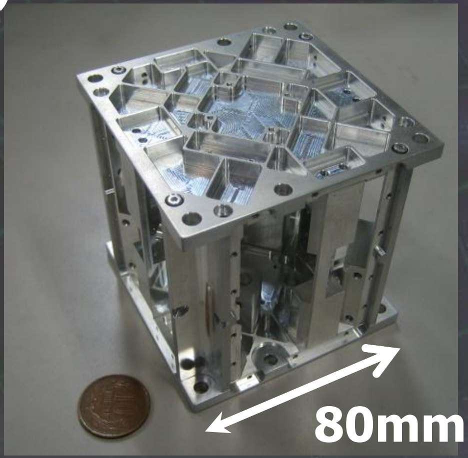
Spin Axis (46.5mHz)

Coil

Photo sensor

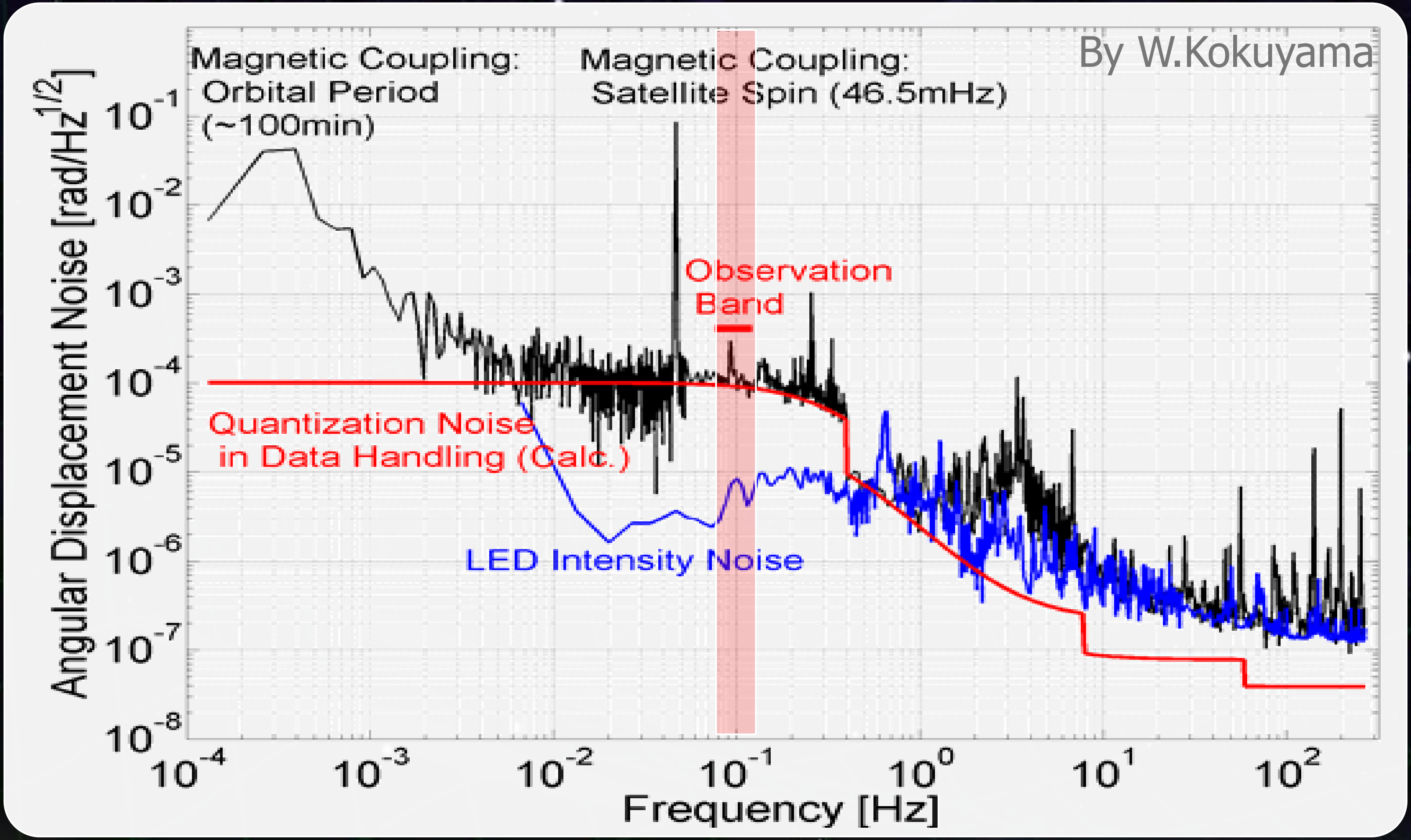
Reflective-type optical displacement sensor
Separation to mass ~1mm
Sensitivity ~ 10^{-9} m/Hz$^{1/2}$
6 PSs to monitor mass motion





Sensitivity

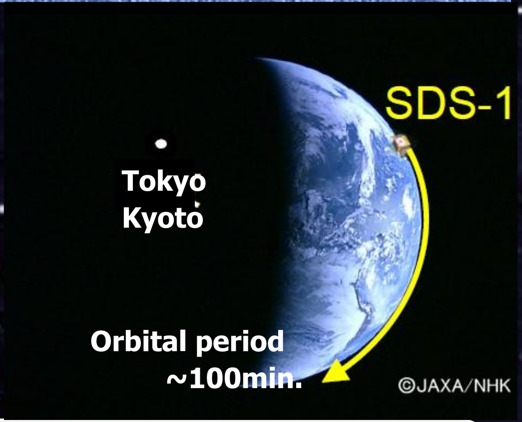
Though limited by non-fundamental noises,
best as a space-borne GW detector.



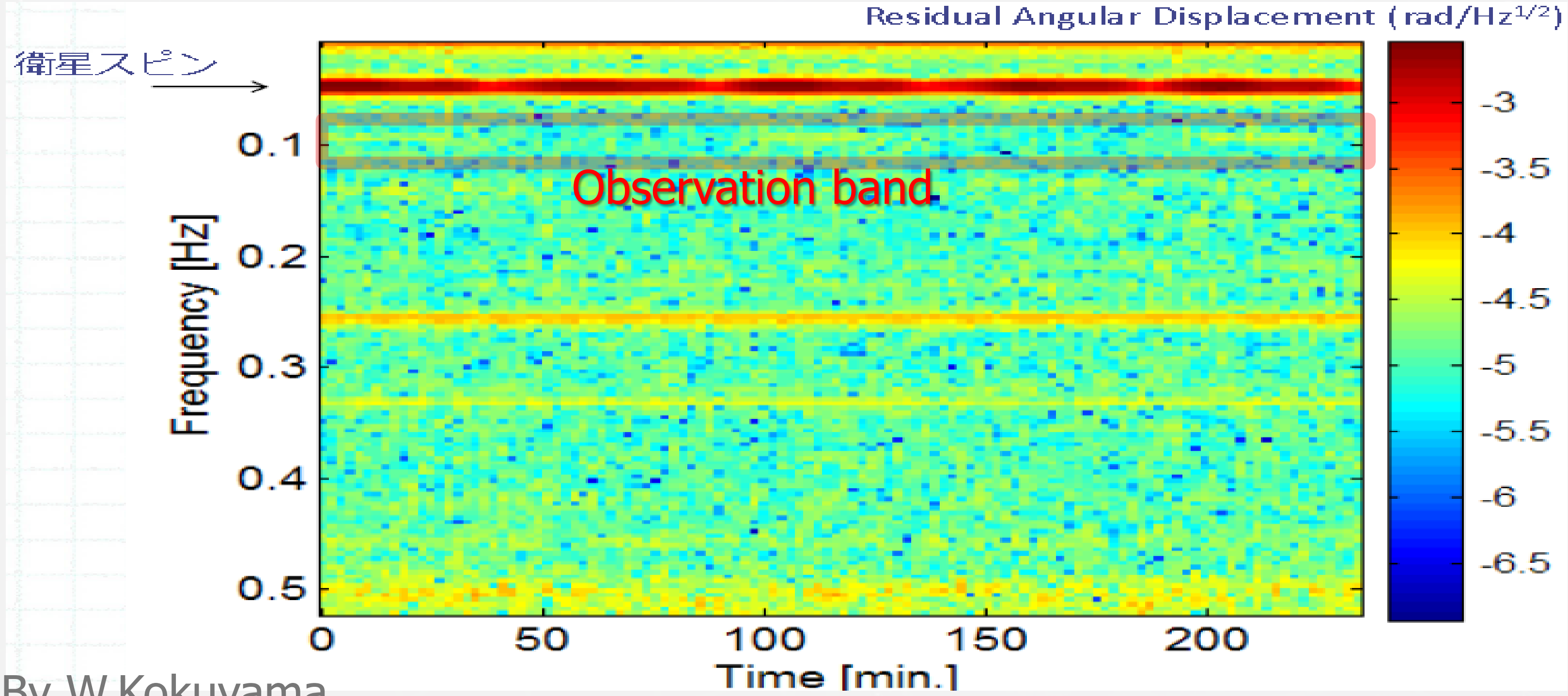
Observation by SWIM

Continuous data taking

Jun 17, 2010 ~120 min.
July 15, 2010 ~240 min.



©JAXA/NHK



By W.Kokuyama

Upper Limit on GWB

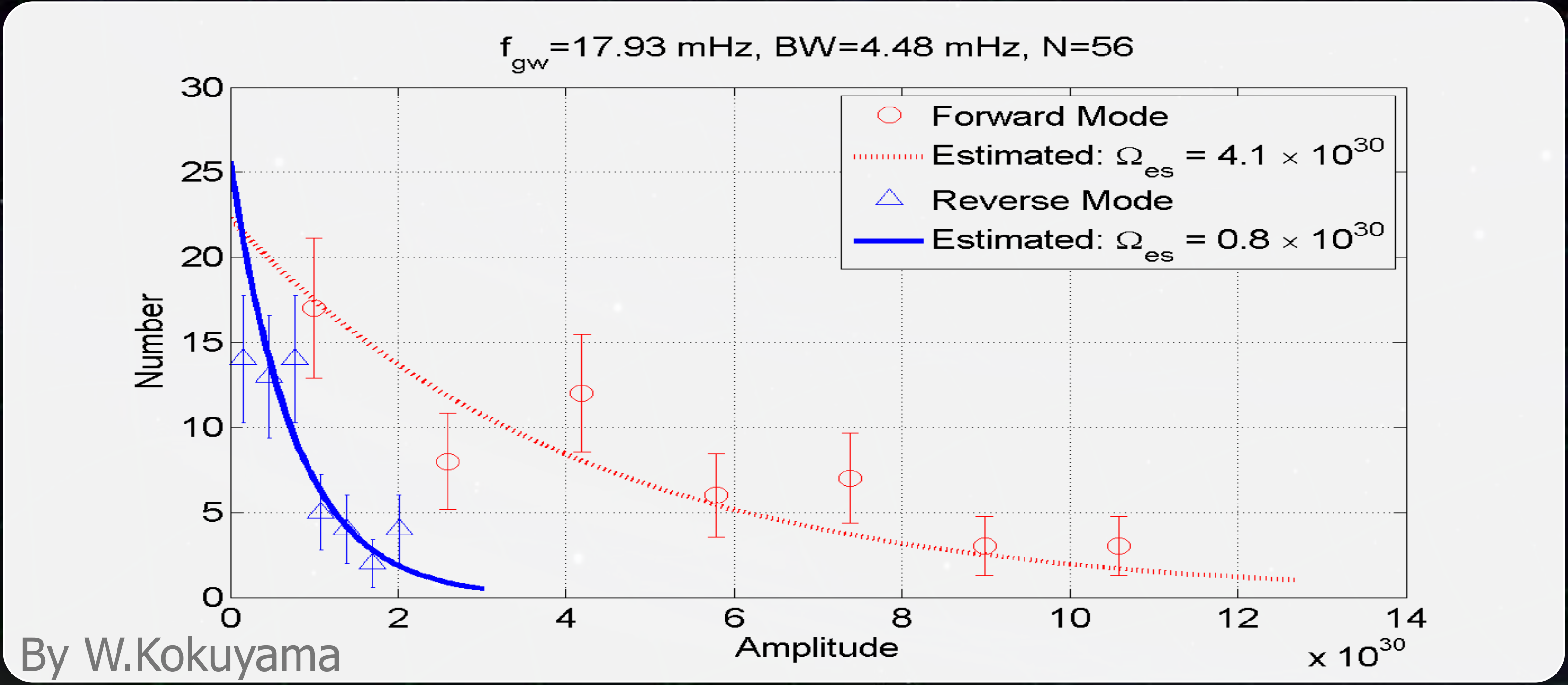
DECIGO

Upper Limit at two frequencies (two polarizations)

'Forward' mode $\Omega_{\mathrm{gw}}^{\mathrm{FW}} = 1.7 \times 10^{31}$

'Reverse' mode $\Omega_{\mathrm{gw}}^{\mathrm{RE}} = 3.1 \times 10^{30}$

(C.L. 95%, f0 18mHz, BW 4mHz)



By W.Kokuyama

Summary

Summary

DECIGO : Fruitful Sciences

Very beginning of the Universe

Dark energy

Galaxy formation

DECIGO Pathfinder

Important milestone for DECIGO

Observation of GWs and Earth's gravity

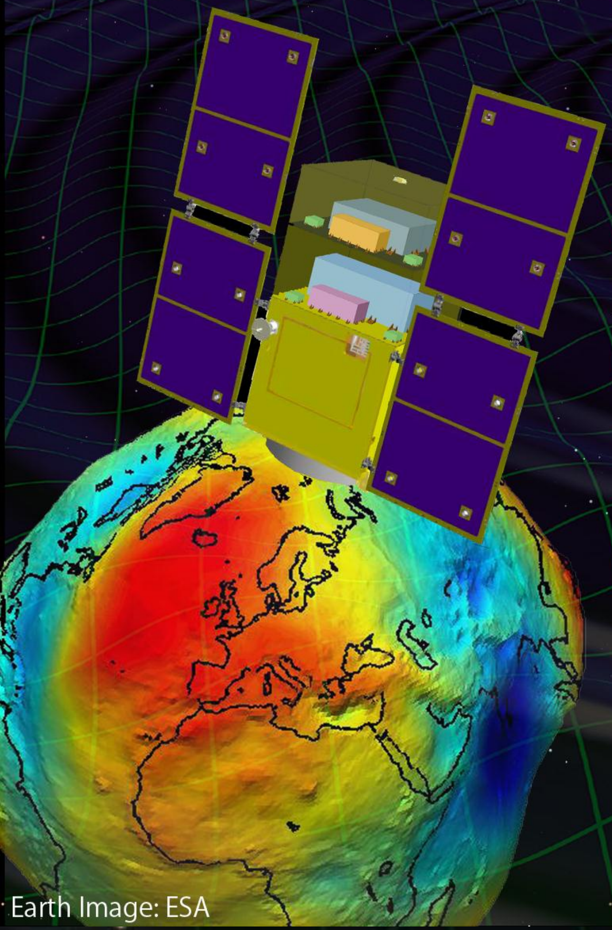
Strong candidate of JAXA's satellite series

SWIM – Operation in orbit

first precursor to space!

Collaboration and support

- **Supports from LISA**
  Technical advices from LISA/LPF experiences
  Support Letter for DECIGO/DPF, Joint workshop (2008.11)
- **Collab. with Stanford univ. group**
  Drag-free control of DECIGO/DPF
  UV LED Charge Management System for DPF
- **Collab. with NASA/GSFC**
  Fiber Laser , Earth's gravity observation
- **Collab. with JAXA Trajectory and Navigation group**
  → Formation flight of DECIGO, DPF drag-free control
- **Geophysics group (Kyoto, ERI, UEC, NAOJ)**
- **Advanced technology center (ATC) of NAOJ**
- **JAXA's fund for small satellite development**
- **Research Center for the Early Universe (RESCEU), Univ. of Tokyo**



Earth Image: ESA

End

Original Picture : Sora