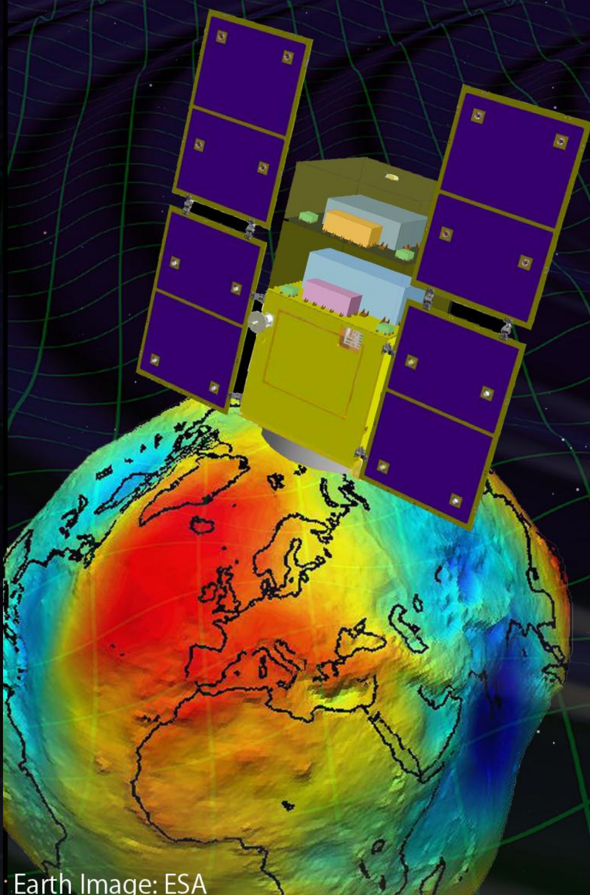
Plan of Lectures

Lecture (I) Ground-based detector : LCGT

Lecture (II) Space-borne detector : DECIGO

Lecture (III) Novel type detector : TOBA

Space-borne detector : DECIGO



Earth Image: ESA

Original
Picture : Sora

Masaki Ando
(Department of Physics, Kyoto University)

On behalf of
DECIGO working group

APCTP2011 (August 2, 2011, Pohang, Korea)

1. Introduction
2. DECIGO
3. DECIGO Pathfinder
4. SWIM
5. Summary

Introduction

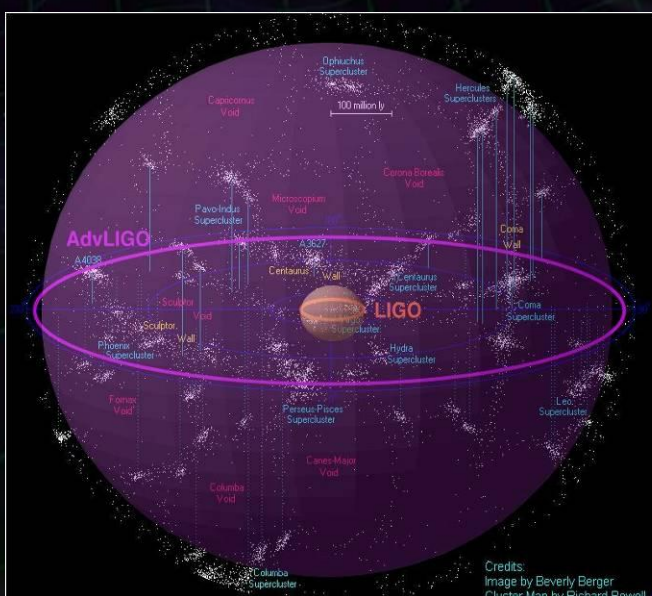
Expanding the Horizon

First-gen. GW detectors : ~ 20Mpc obs. range

However… we can expect only rare events (10^{-4}-10^{-2} event/yr)

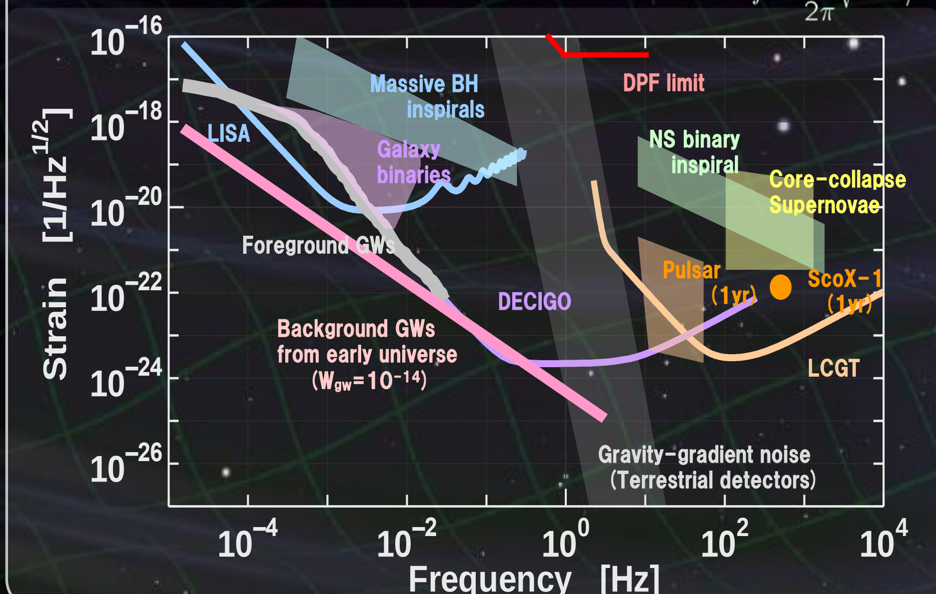
⇨ **Next generation detectors**

Better sensitivity
to cover more galaxies



Wider observation band
for various sources

$$f \sim \frac{1}{2\pi}\sqrt{GM/R^3}$$



Expanding the observation band

DECIGO

GW frequency ~ 1/ (time scale of the source)

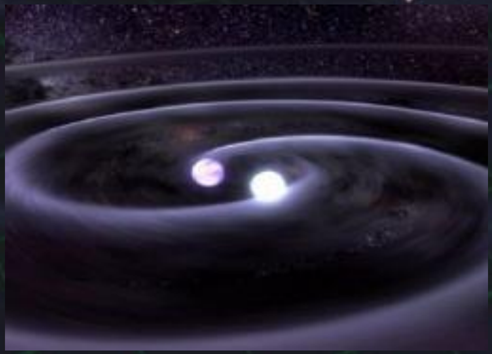
Observation at low frequency
- Larger-mass events → larger amplitude GW
- (Almost) stationary source → Do not have to wait for 'events'

➡ **Different or complementary science**

(Example) GW from compact binary inspiral

$$h \sim \frac{4G^2}{c^4 r} \frac{m_1 m_2}{R} \qquad f \sim \frac{1}{2\pi}\sqrt{\frac{G(m_1+m_2)}{R^3}}$$

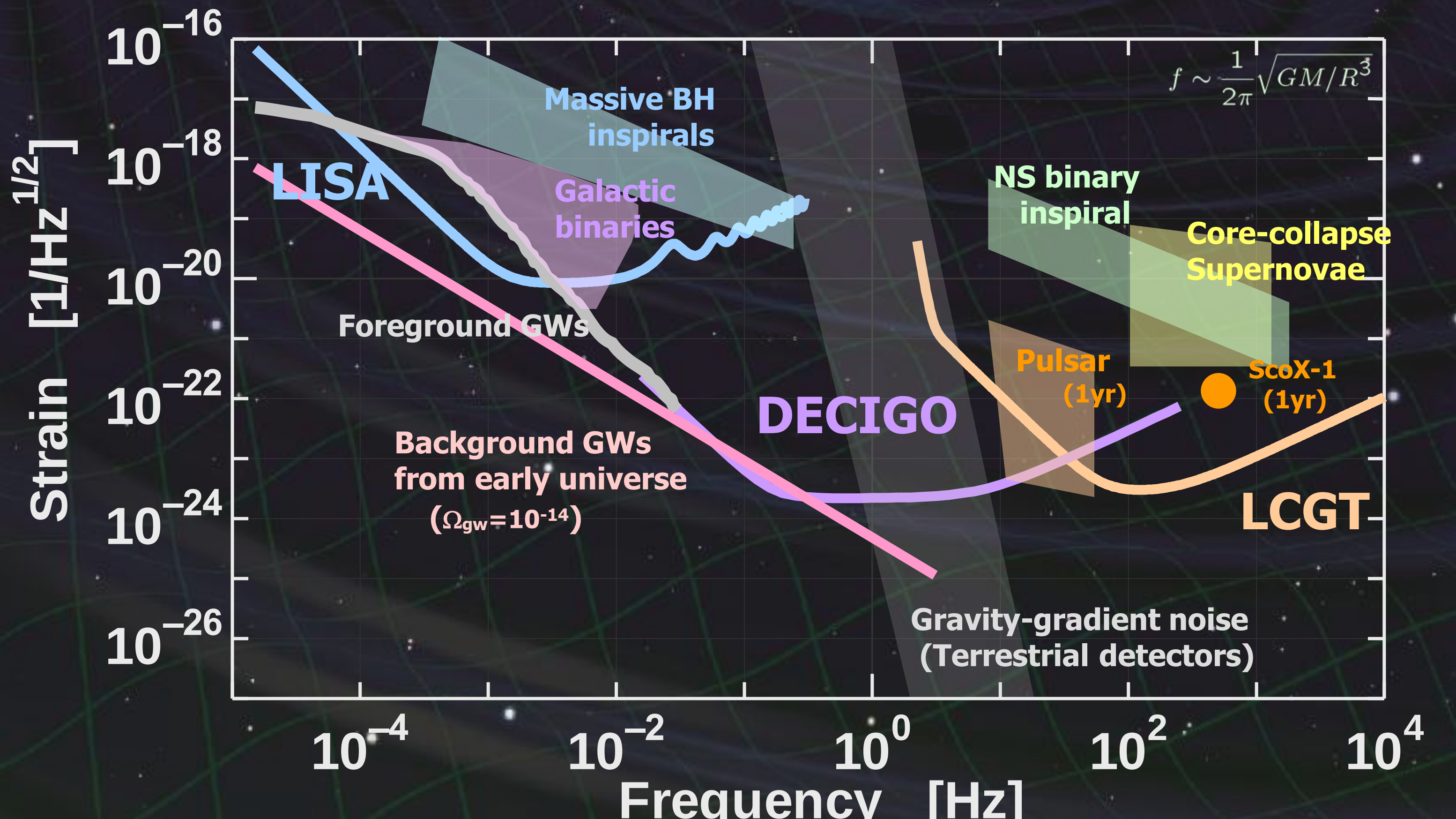
Separation (R) Mass ($m_1 m_2$)



- Large separation
  → stationary, low-freq. GWs
- Just before merger ($R_{\rm ISCO} \propto M$)
  → Large mass, large amplitude GWs at low freq.

Sources and detectors

Ground-based detectors : 10Hz - 1kHz → Neutron star, Supernova, ...
DECIGO/BBO : 0.1 - 1Hz → IMBH, Background GWs, ...
LISA : 1mHz – 0.1Hz → SMBH, Compact binary,...



Space GW detector

DECIGO

Advantages of a space detector for low-freq. observation

- Free from noises by the earth
    Seismic noise, gravity-gradient noise

- Longer baseline
    Observation freq. band
        ∝ 1 / (Beam storage time) ∝ Baseline length

    Suppression of displacement noise
        Strain sensitivity ~ (disp. noise) / (Baseline length)

Disadvantages of a space detector

- Cost, Development time
- Maintenance and upgrade are almost impossible after launch

Space-borne observatories

LISA (Laser Interferometer Space Antenna)

Obs. band around 1mHz

~Million km baseline length

Recent change : ESA/NASA → ESA mission

Design updates underway

→ changing name to

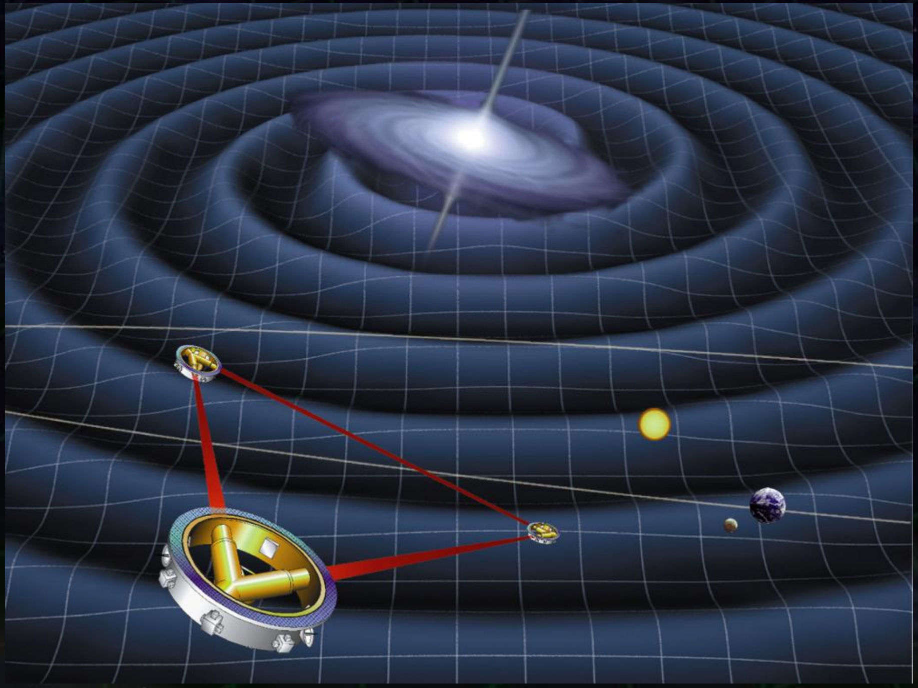
NGO (New Gravitational-wave Observatory)

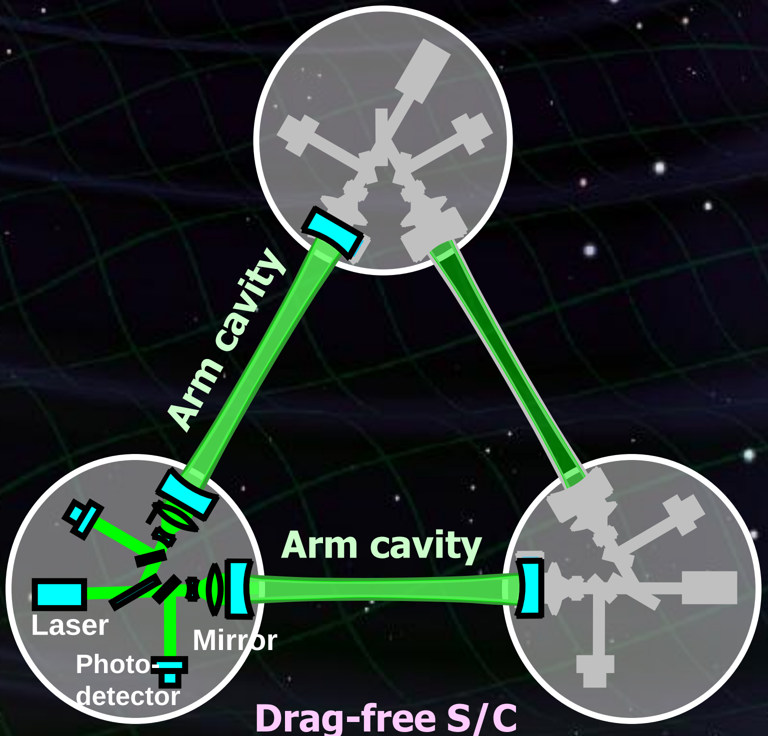
DECIGO

(Deci-hertz Interferometer Gravitational Wave Observatory)

Obs. Band around 0.1Hz

1000km baseline length



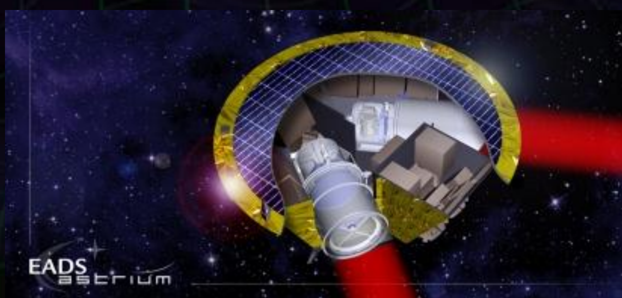


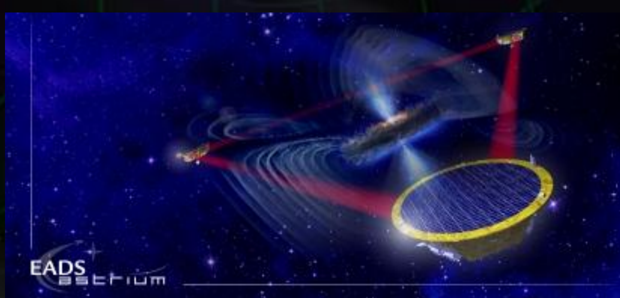
NGO (LISA) Interferometry

Interferometer design

- Optical transponder configuration
  Long baseline (~1 million km) →power loss by diffraction
  Each S/C has laser source →Phase-lock to incoming beam

LISA web page : http://sci.esa.int/lisa





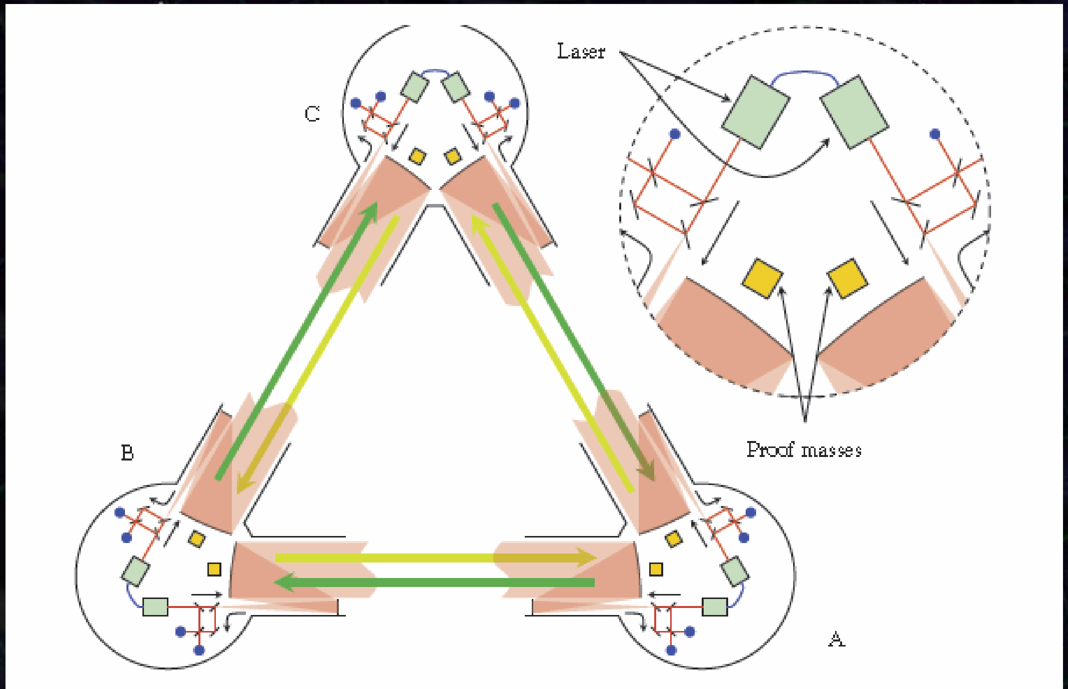


Figure 3.2.: A constellation of three identical LISA spacecraft constitutes the science instrument. There are six identical, send/receive laser ranging terminals (two per S/C) with associated test masses and a comparison of signals at each apex. The sketch leaves out the test mass interferometers for clarity.

LISA assessment study report (Yellow Book), ESA/SRE (2011) 3, February 2011

LISA Pathfinder

LISA Pathfinder

- Technical test for LISA
  Obtain the best geodesic motion possible
  Differential acceleration of the two TMs
  3×10^{-14} m s^{-2} at 1 mHz
  Determine best configuration by experiments
  Develop a noise model of the system
  Allows the projection of the performance of technologies to LISA

- Status
  Most of the hardware is there.
  Awaiting thrusters and launch lock.
  Most of the experiments are already defined.
- Launch in 2014

M Hewitson for the LPF team, AMALDI, July 15th 2011

GW observation roadmap

Ground-based Observatory

Better sensitivity (10Hz-1kHz)

LIGO → Enhanced LIGO → Advanced LIGO

TAMA CLIO → LCGT

Virgo → Advanced Virgo

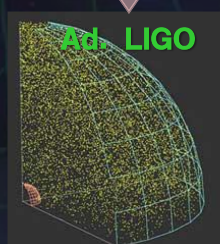
ET

2010

2015

2020

2025



Detection rate
~10 event/yr

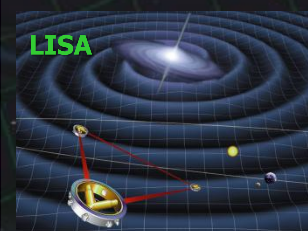
Space-borne observatory

Low-freq. observation (<1Hz)

DECIGO

LPF

DPF



LISA

Pre-DECIGO

0.1mHz-10mHz
Guaranteed sources

DECIGO

BBO

0.1Hz band
Cosmological GWs

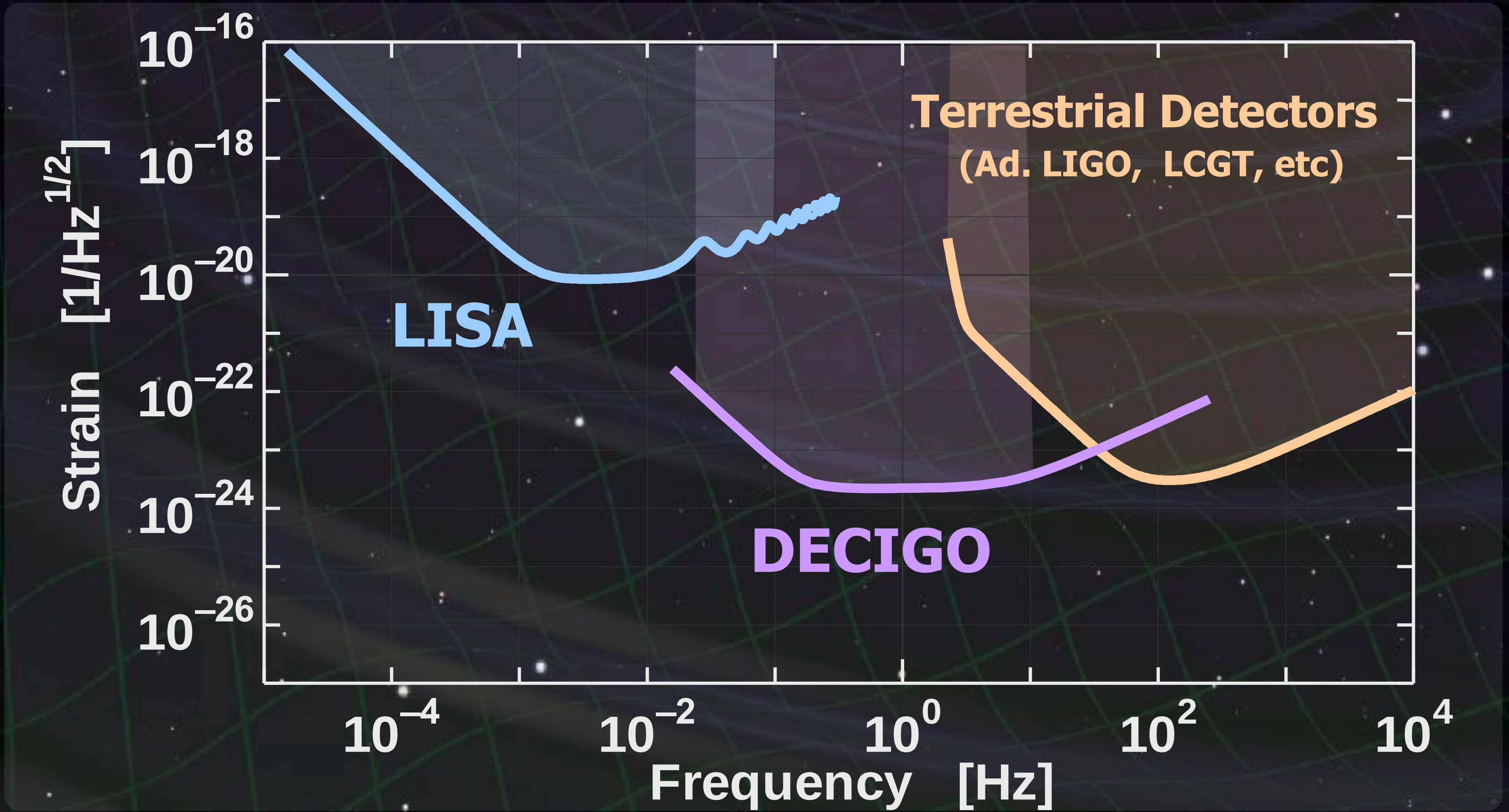
DECIGO

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



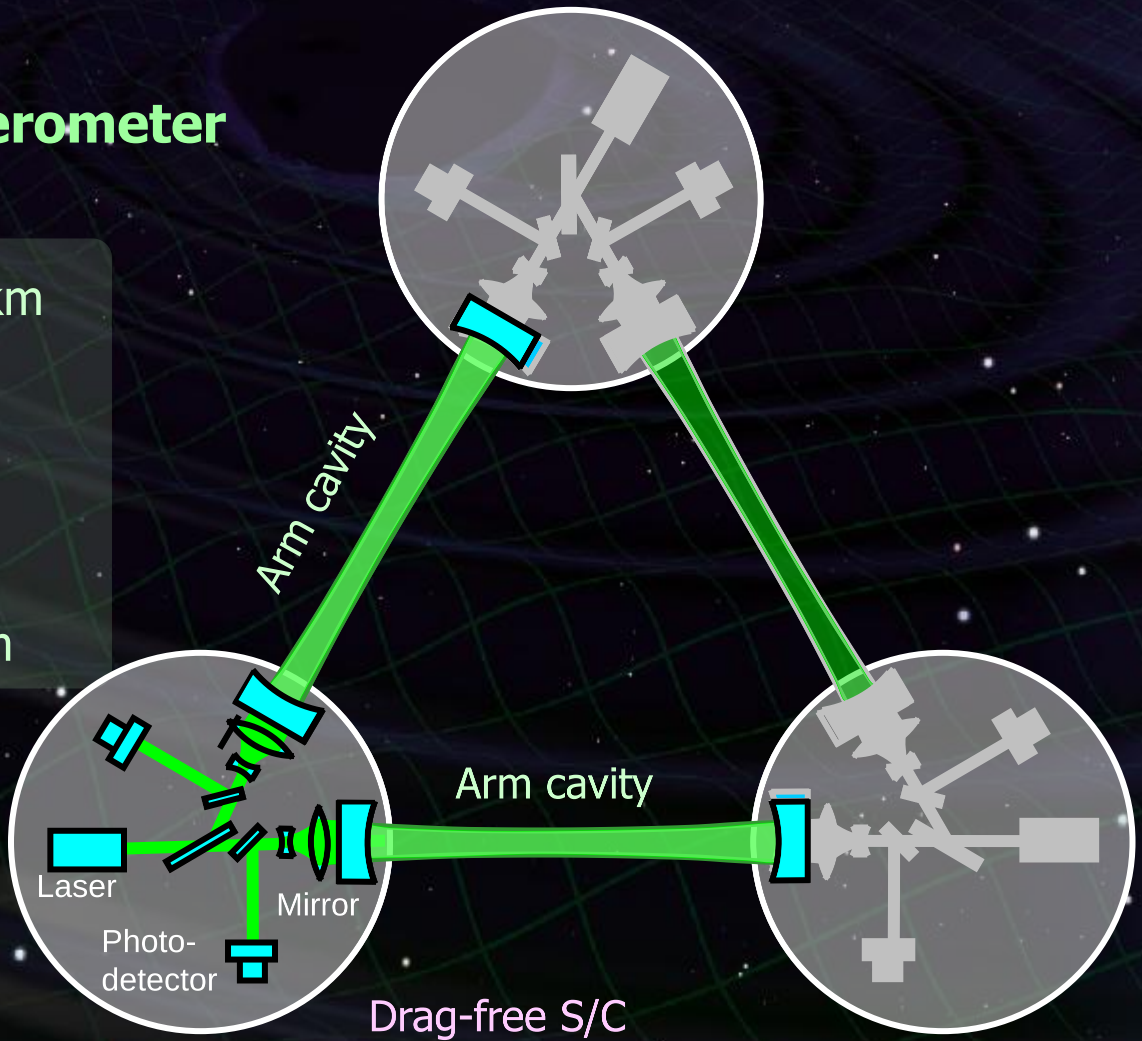
Pre-Conceptual Design

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



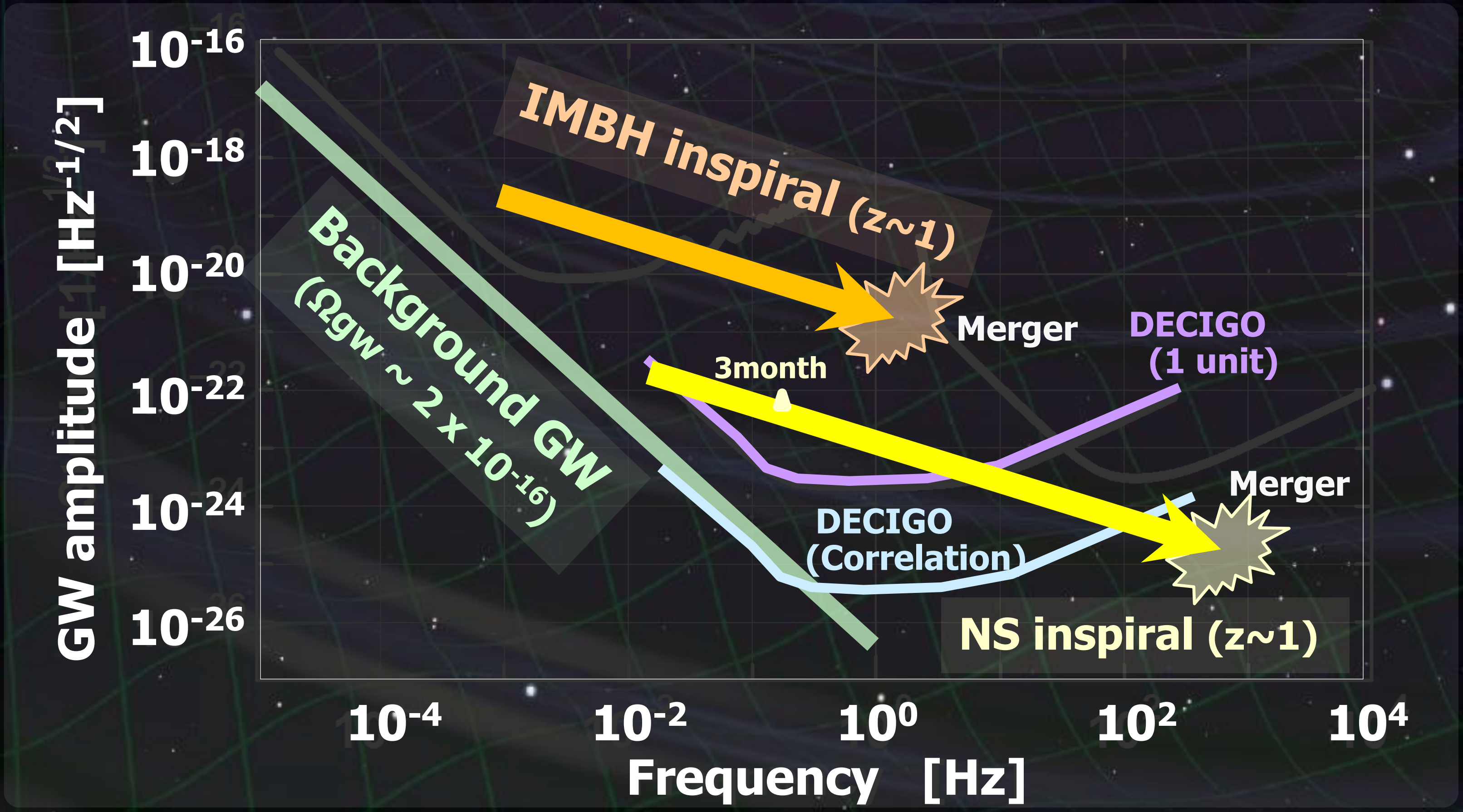
Targets and Science

DECIGO

IMBH binary inspiral
NS binary inspiral
Stochastic background

⇨

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



Astronomy and Cosmology

DECIGO

- **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**

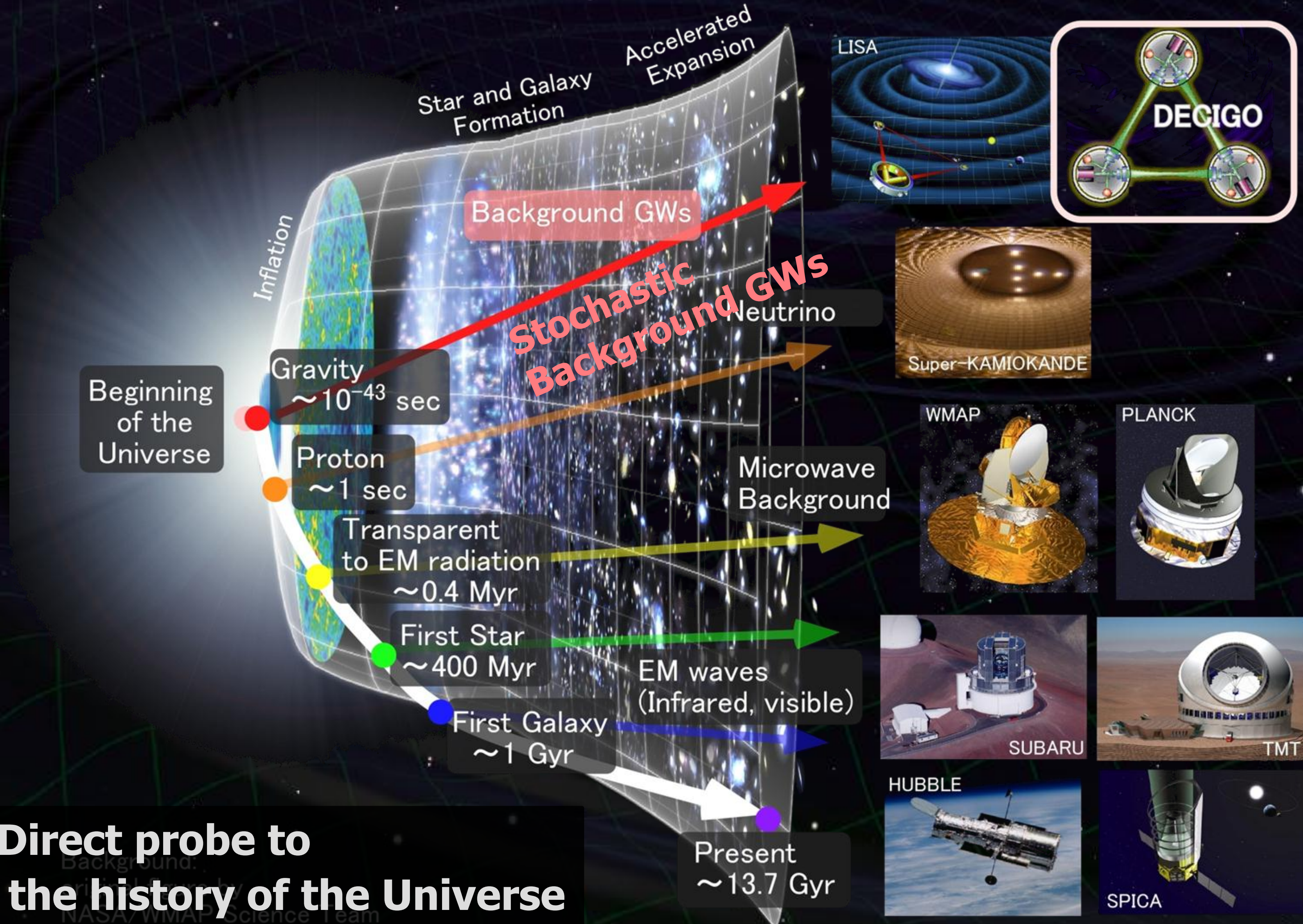
  Determine masses of 10^5 NSs per year

  → Constrain the EoS of NS

  Formation process of NS from the spectrum

Characterization of inflation

DECIGO



Direct probe to the history of the Universe

DECIGO Interferometer

Interferometer Unit:

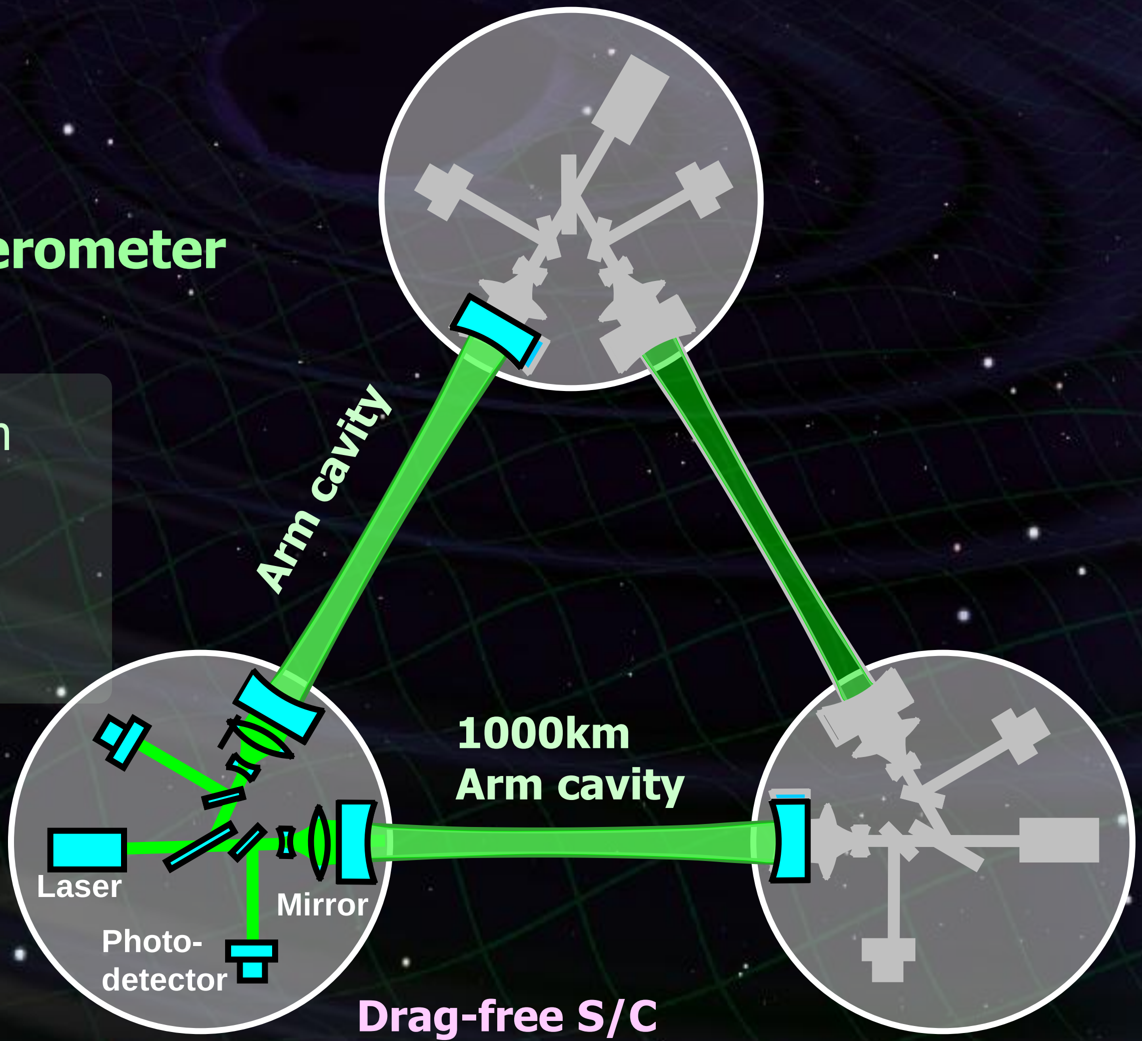
Differential FP interferometer

Baseline length: 1000 km

3 S/C formation flight

3 FP interferometers

Drag-free control

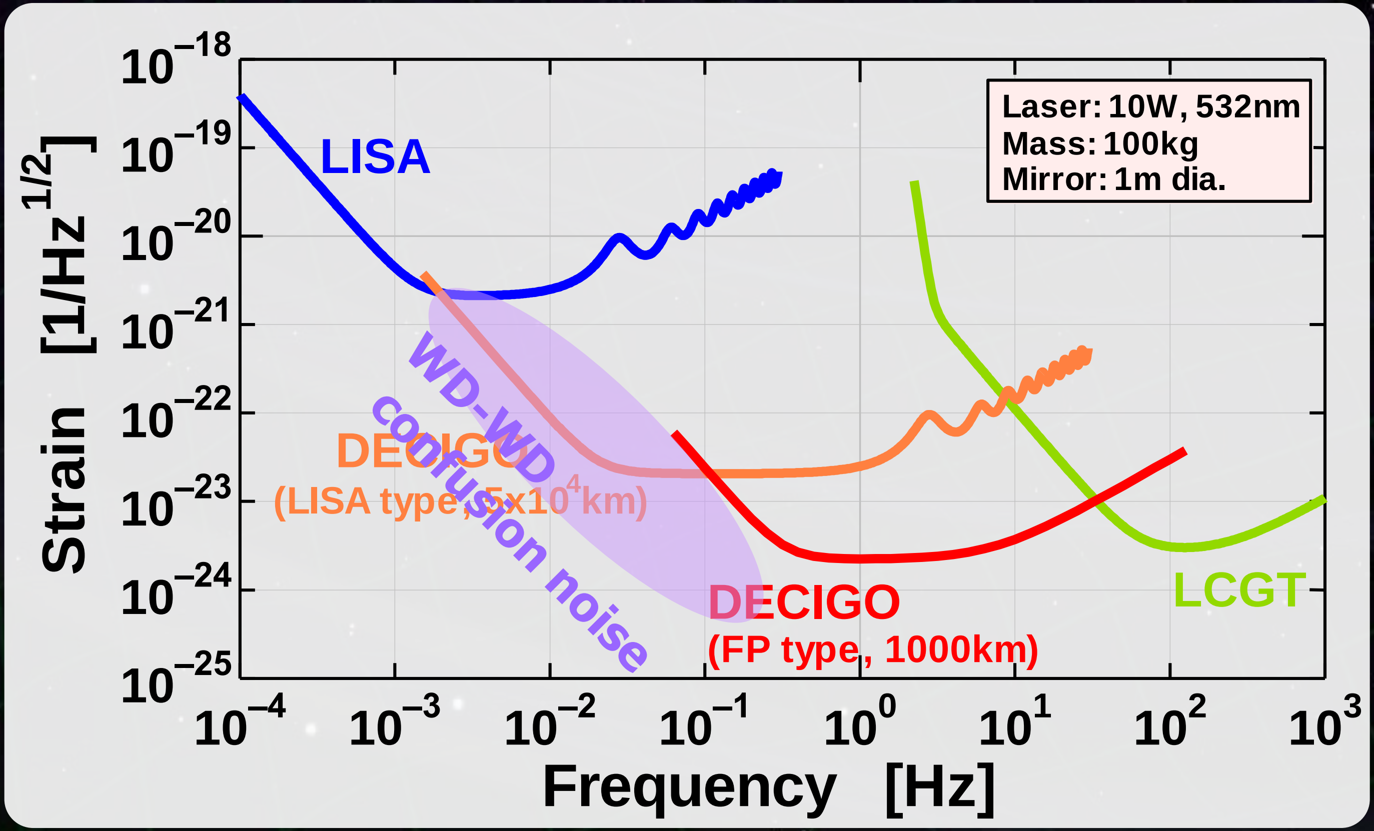


Interferometer Design

Transponder type vs Direct-reflection type

Compare : Sensitivity curves and Expected Sciences

⇨ Decisive factor: Binary confusion noise



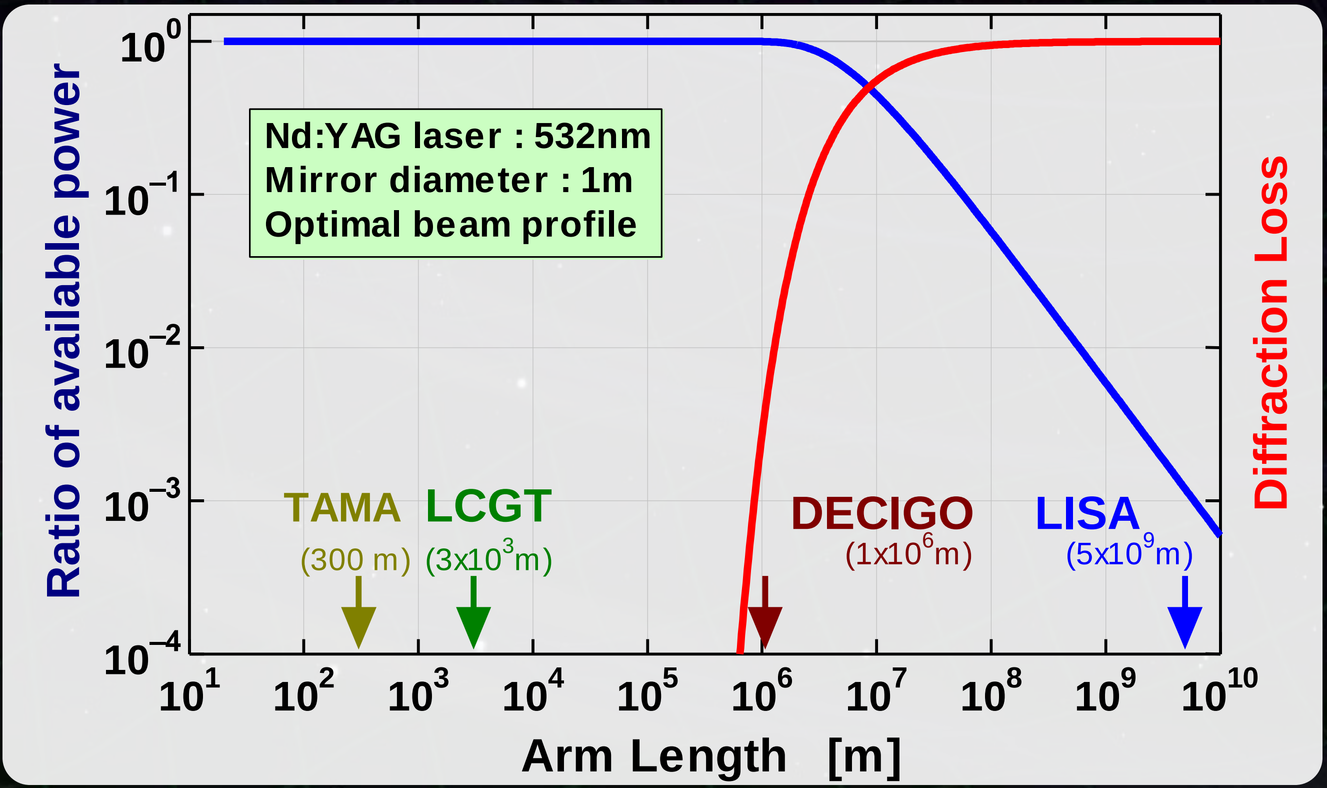
Arm length

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

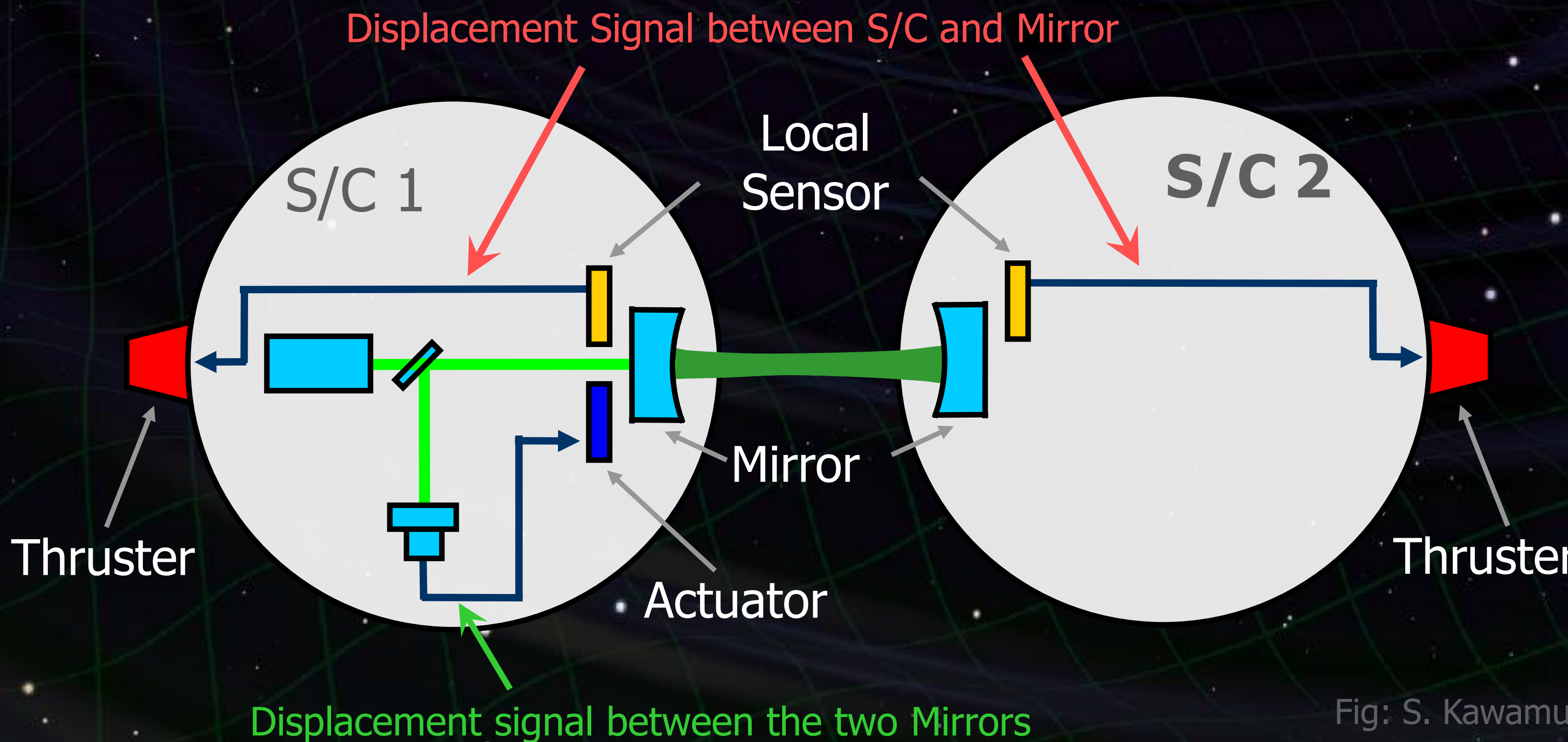


Fig: S. Kawamura

Requirements

DECIGO

Sensor Noise

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

⇨ **x 10 of LCGT 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

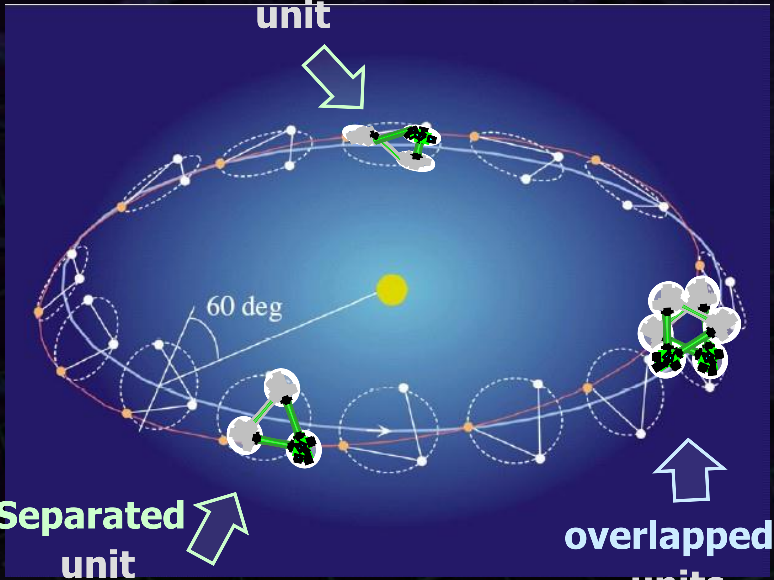
DECIGO

Candidate of orbit:

Record-disk orbit around the Sun

Relative acc. 4×10^{-12} m/s^2

(Mirror force ~10^{-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 accurate waveform
→ $\Delta m/m < \sim 10^{-7}$ %

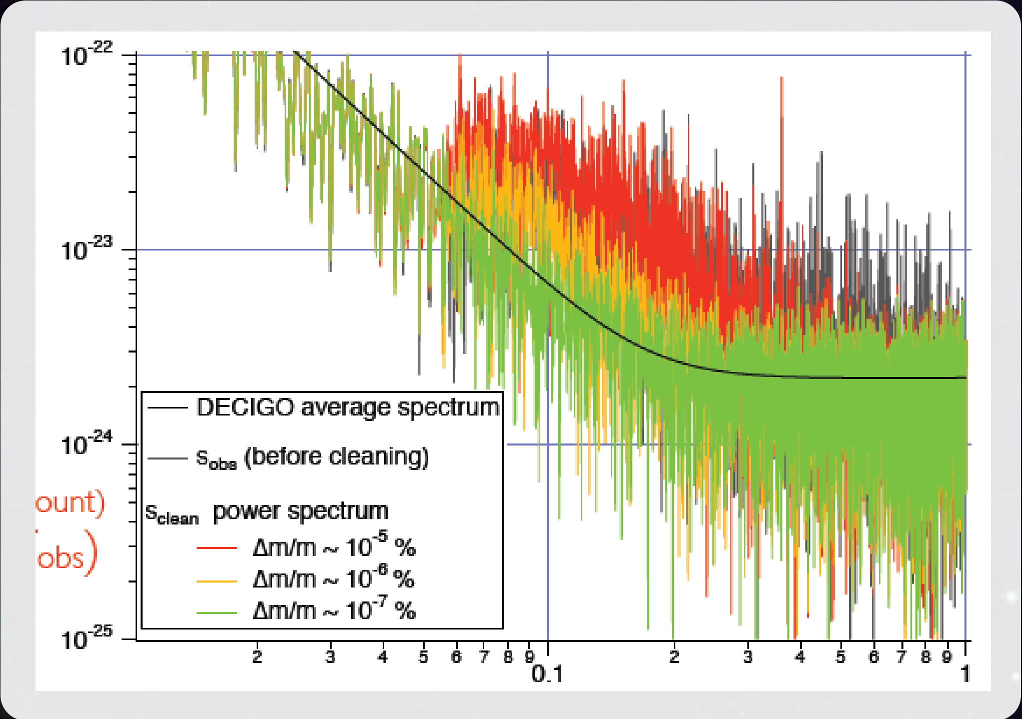


Fig: N. Kanda

Design Update

DECIGO

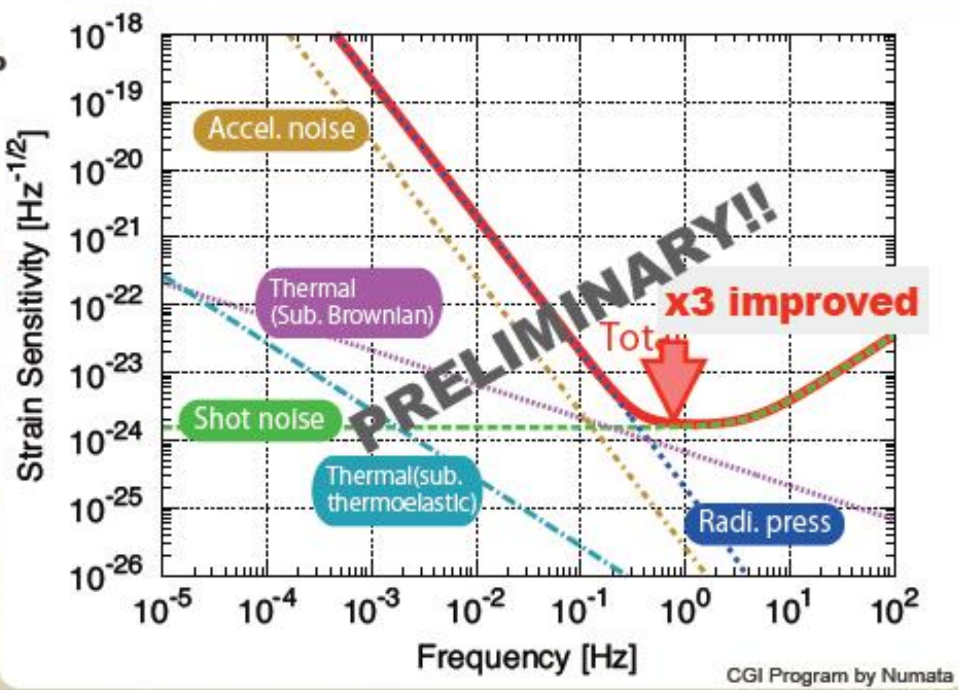
Considering "Conceptual design"

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

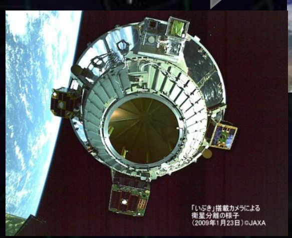
Roadmap

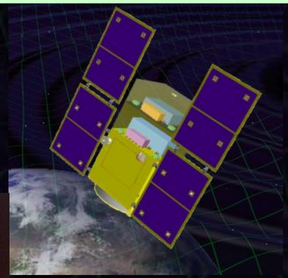
Figure: S.Kawamura

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

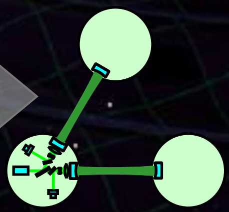
Mission

R&D
Fabrication

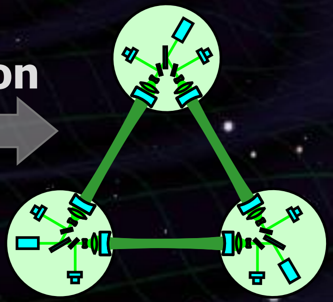

SDS-1/SWIM


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-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

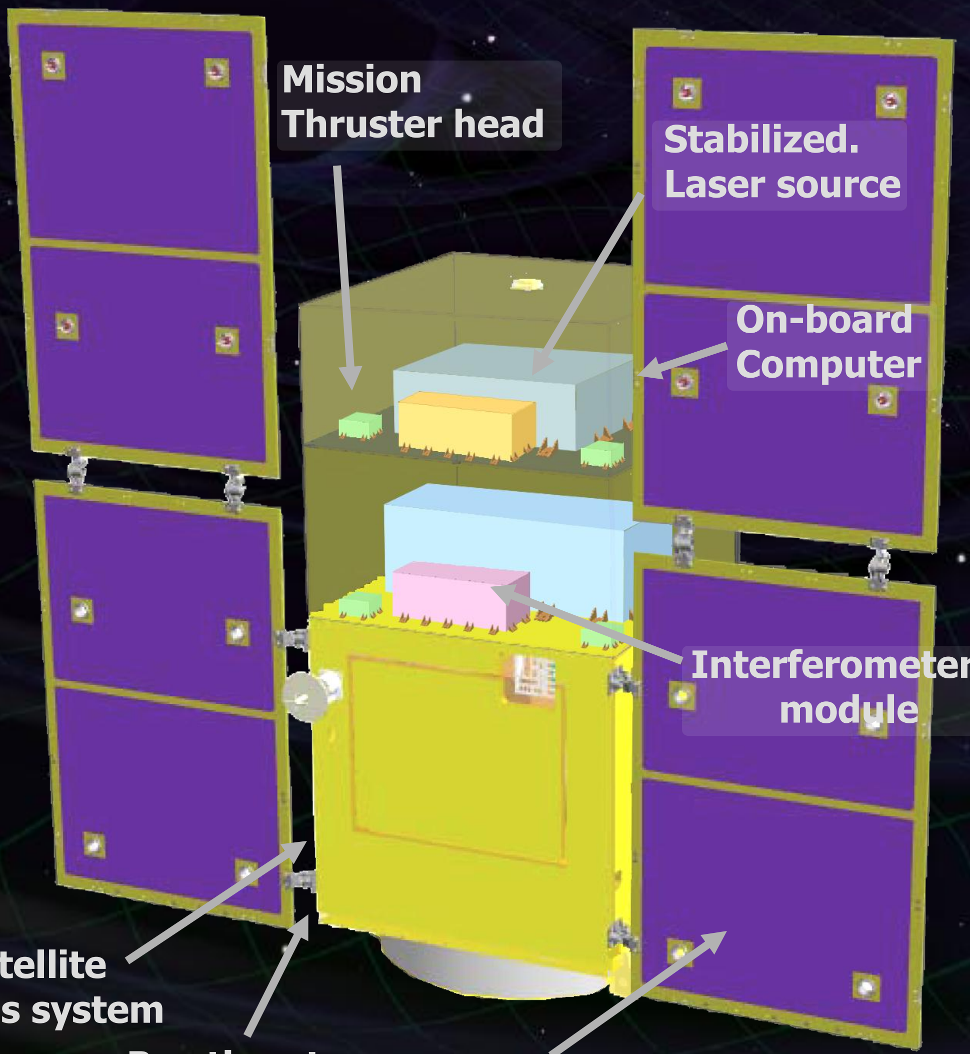
DPF Payload

- Size : 950mm cube
- Weight : 150kg
- Power : 130W
- Data Rate: 800kbps
- Mission thruster x12

Power Supply
SpW Comm.

Satellite Bus
('Standard bus' system)

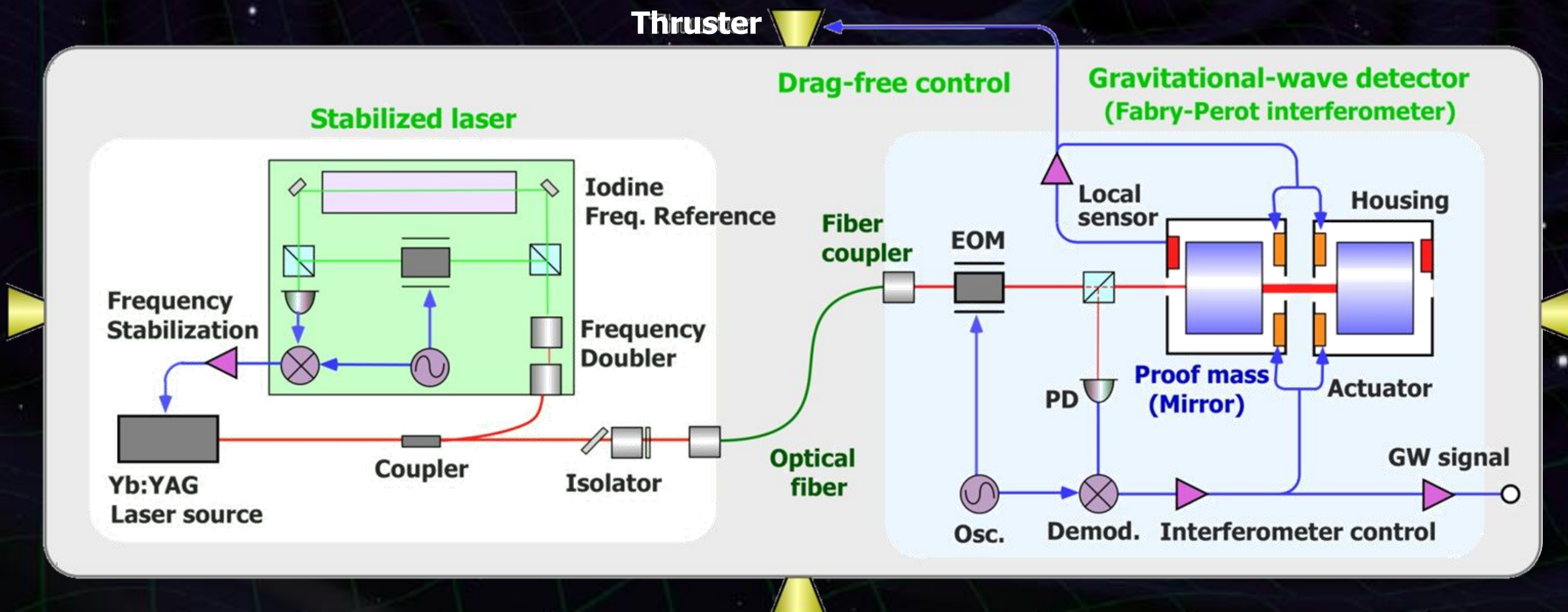
- Size : 950x950x1100mm
- Weight : 200kg
- SAP : 960W
- Battery: 50AH
- Downlink : 2Mpbs
- DR: 1GByte
- 3N Thrusters x 4



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

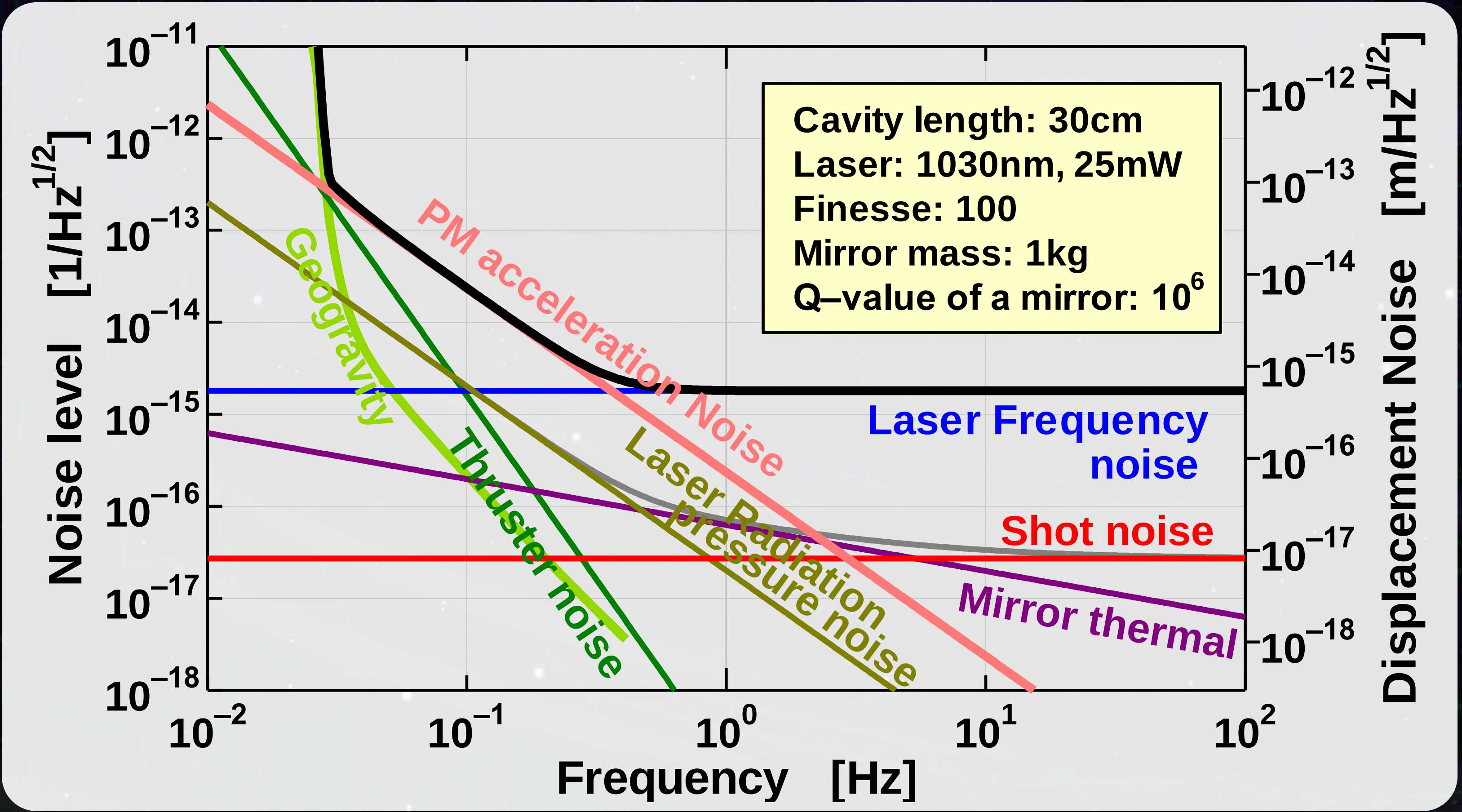
DPF Sensitivity

DECIGO

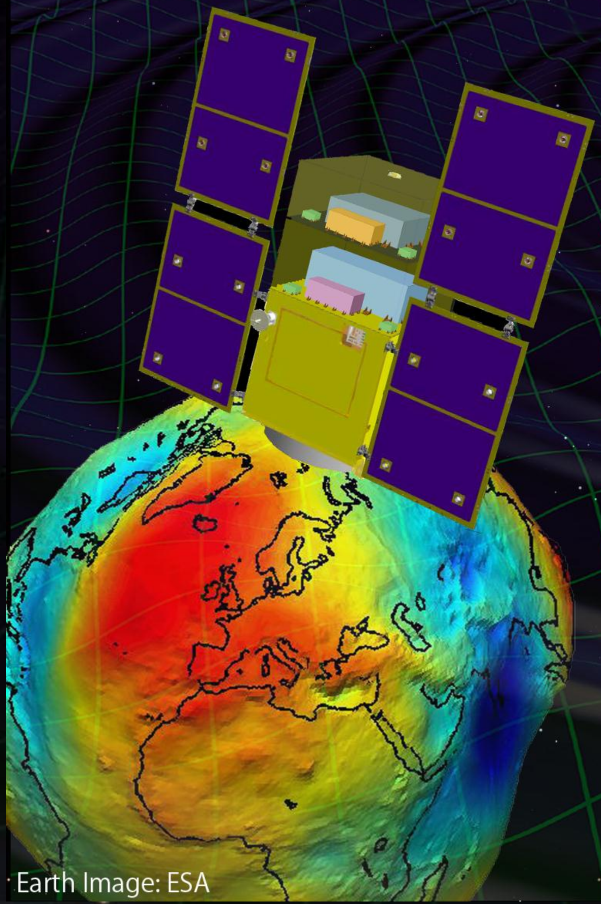
Laser source : 1030nm, 25mW
IFO length : 30cm
Finesse : 100, Mirror mass : 1kg
Q-factor : 10^5, Substrate: TBD
Temperature : 293K

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

(Preliminary parameters)



Targets of DPF



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

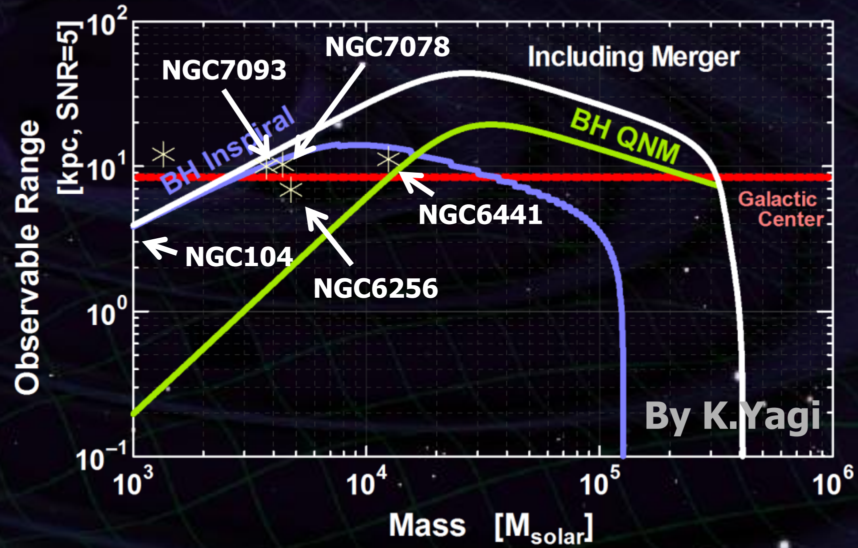
→ IFO measurement
under stable zero-gravity

DPF Science

Astronomical observation

GW from merger of IMBHs
→ Formation mechanism of supermassive BHs

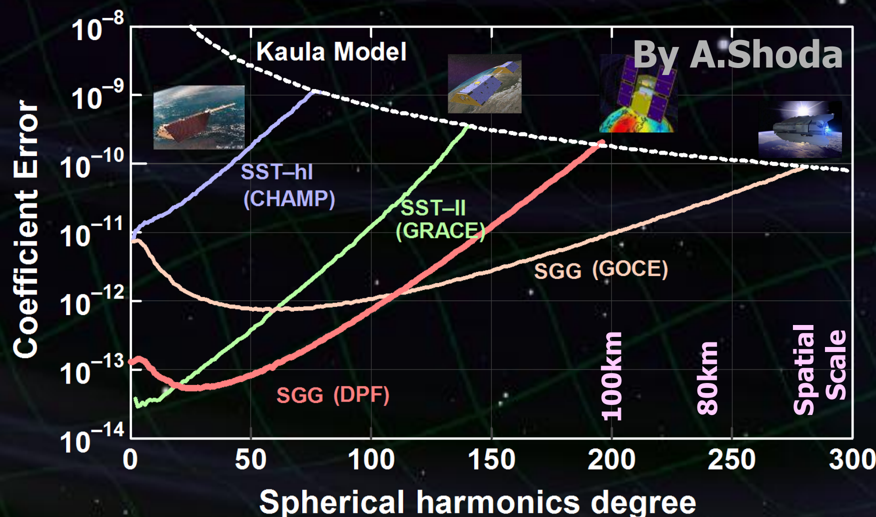
~30 GCs within DPF range



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

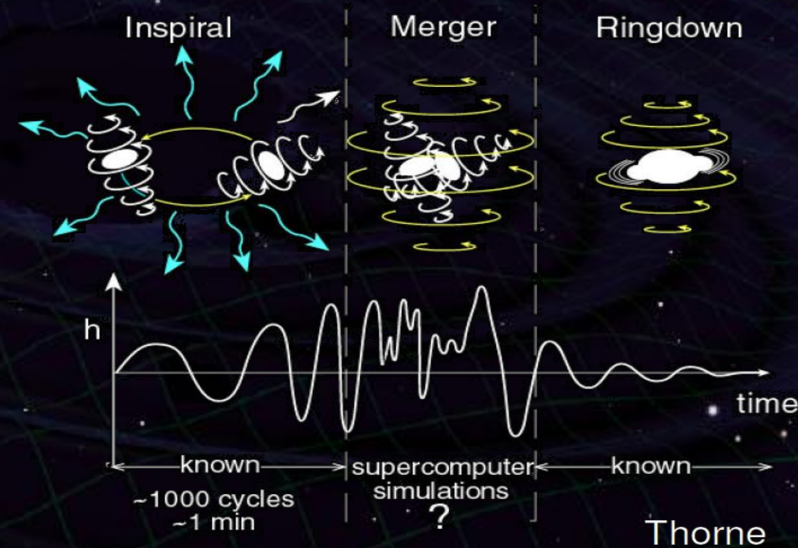
Obs. Distance 40kpc,
for $m = 2 \times 10^4 M_{sun}$

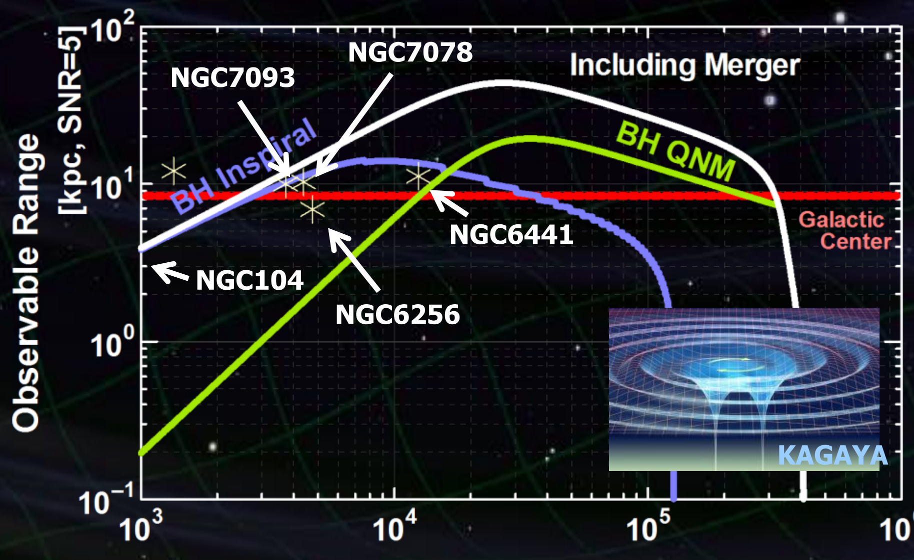
Obs. Duration (~1000sec)

Observable range covers our Galaxy (SNR~5)

There may be IMBH at GCs
DPF covers ~30 GCs

Hard to access by others
→ Original observation



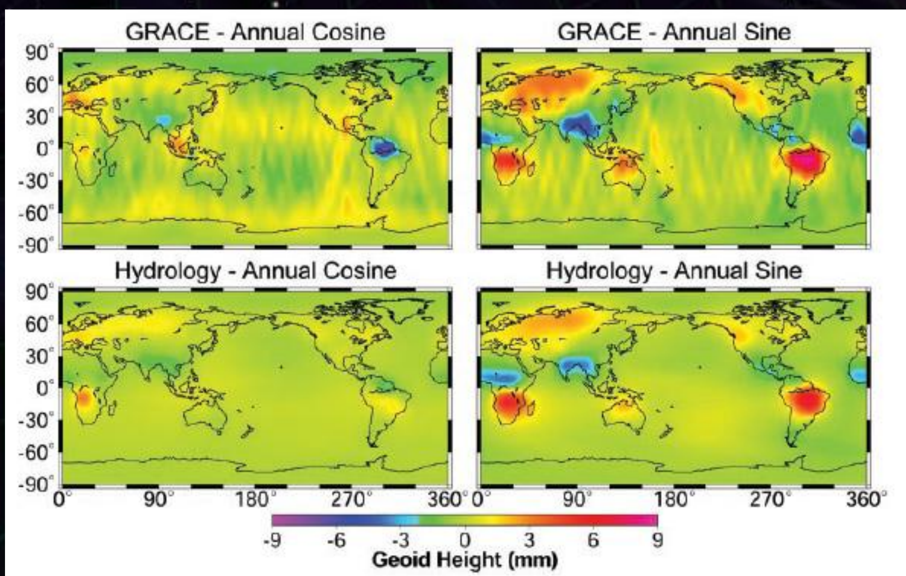


(By K.Yagi)

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

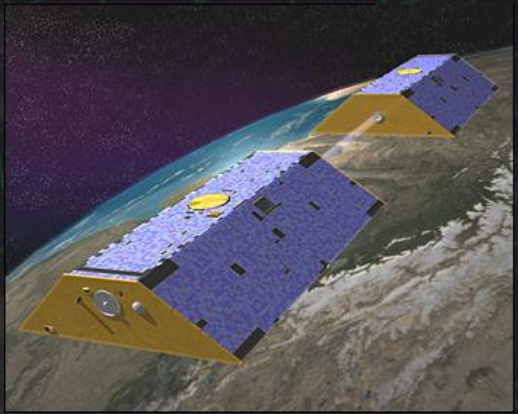
Satellite-to Satellite tracking High-Low

- 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

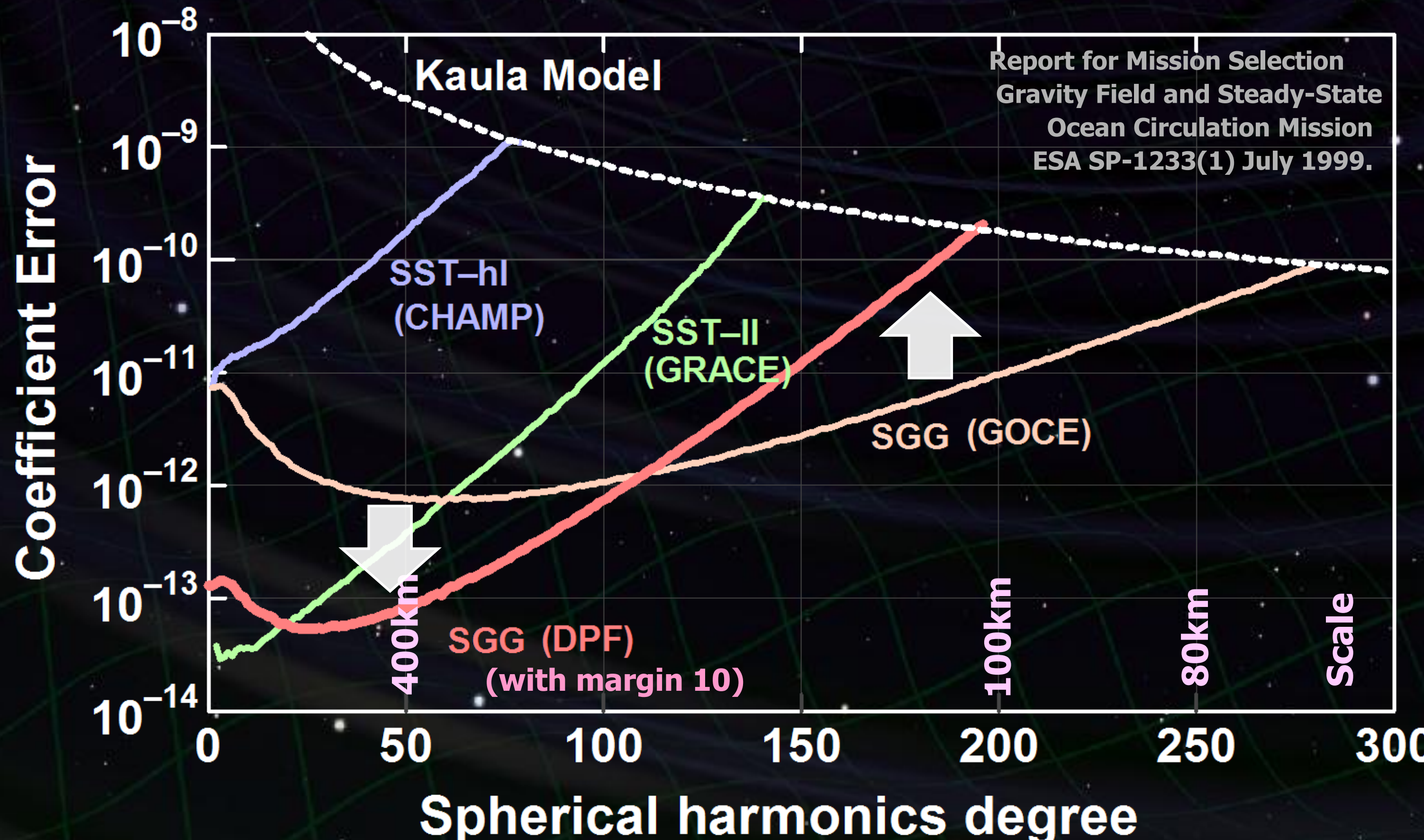
GOCE (ESA, 2009-)

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

BBMs (Bread-board model) for Core components

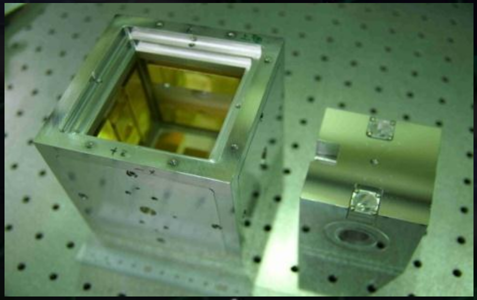
Interferometer module

Univ. of Tokyo
NAOJ

Laser stabilization module

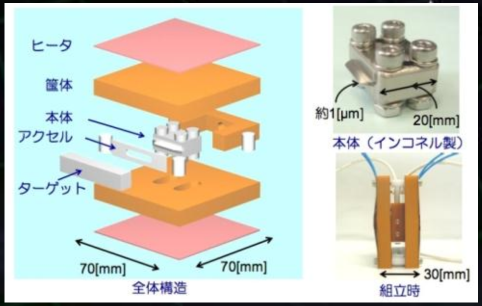
UEC, NICT
NASA/GSFC

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 (~2014/15) : 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

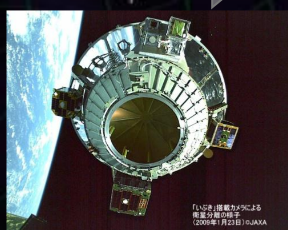
Roadmap

Figure: S.Kawamura

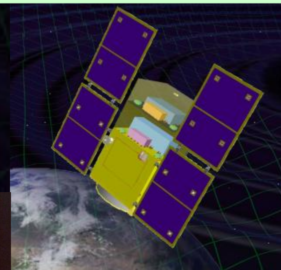
2010 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29

Mission

R&D
Fabrication

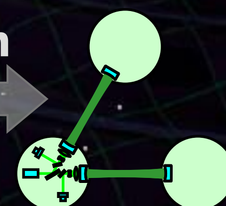


SDS-1/SWIM



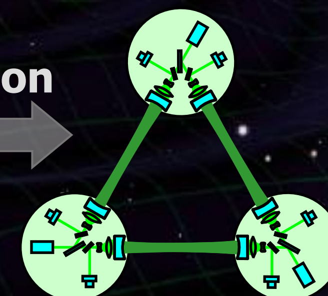
DECIGO
Pathfinder
(DPF)

R&D
Fabrication



Pre-DECIGO

R&D
Fabrication



DECIGO

	SDS-1/SWIM, DPF	Pre-DECIGO	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

SWIM launch and operation

DECIGO

Tiny GW detector module

Launched in Jan. 23, 2009

⇨ In-orbit operation

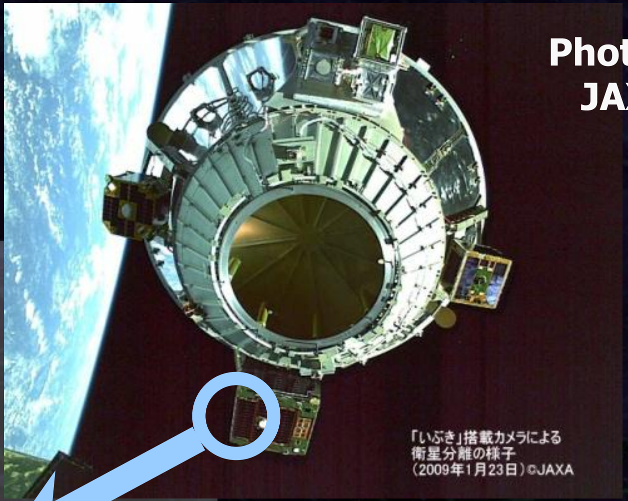
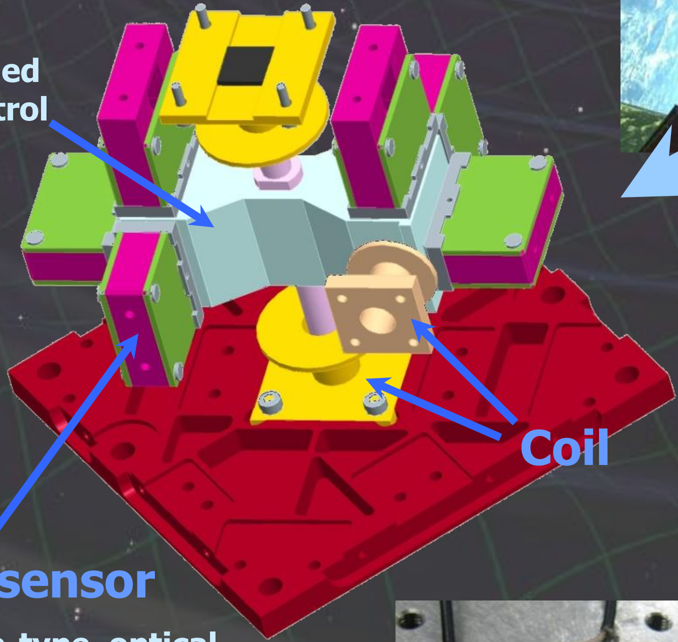


Photo: JAXA

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

Test mass

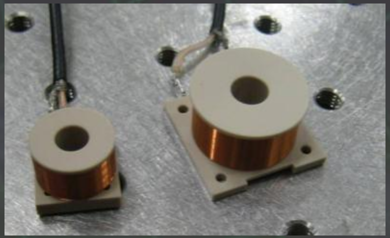
~47g Aluminum, Surface polished
Small magnets for position control

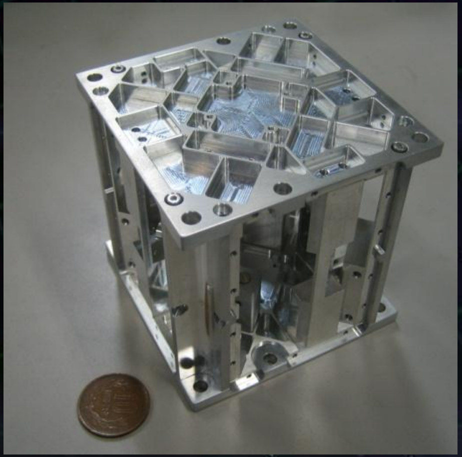


Coil

Photo sensor

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





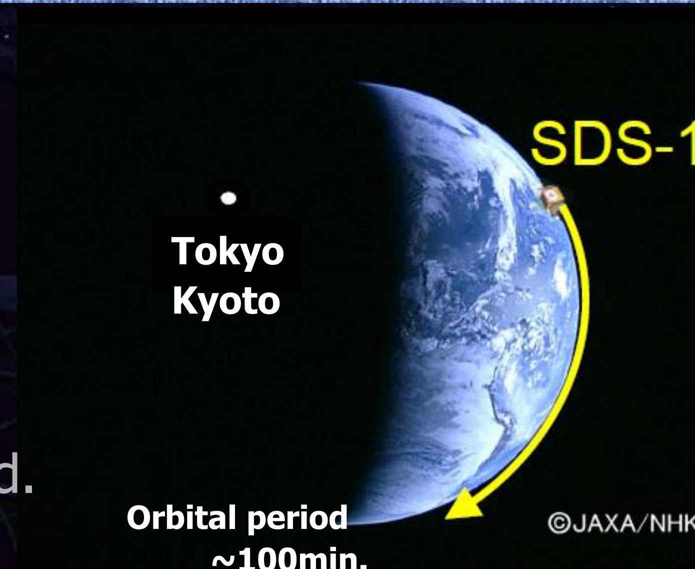
SWIM observation

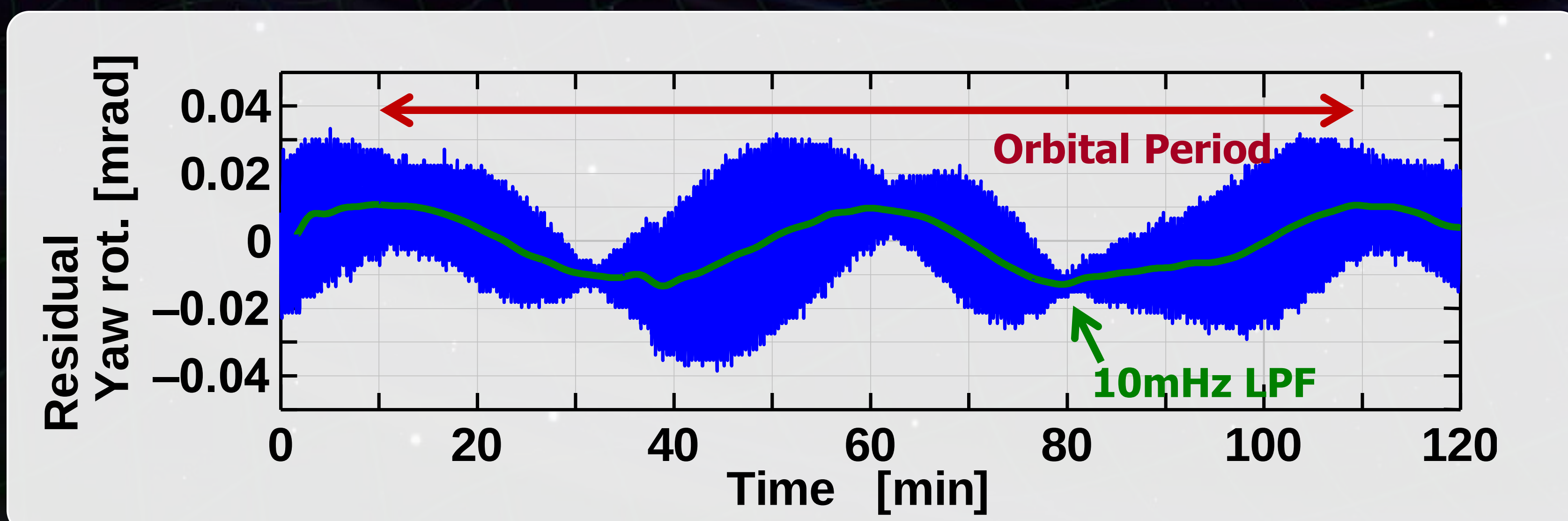
Observation by SWIM

Jun 17, 2010 ~120 min. operation

July 15, 2010 ~240 min. operation

Ground-based detectors were operated at the same period.

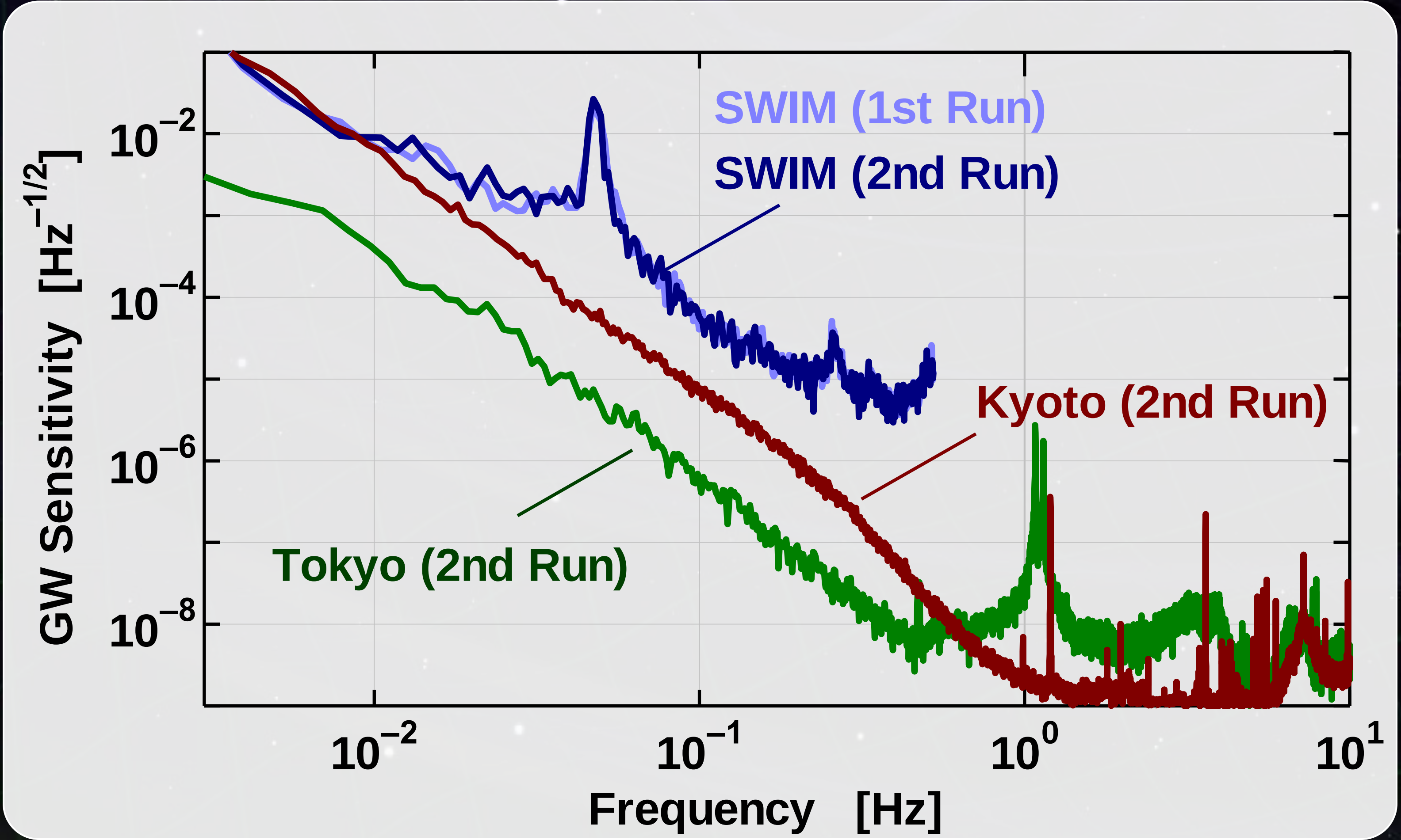




Sensitivity

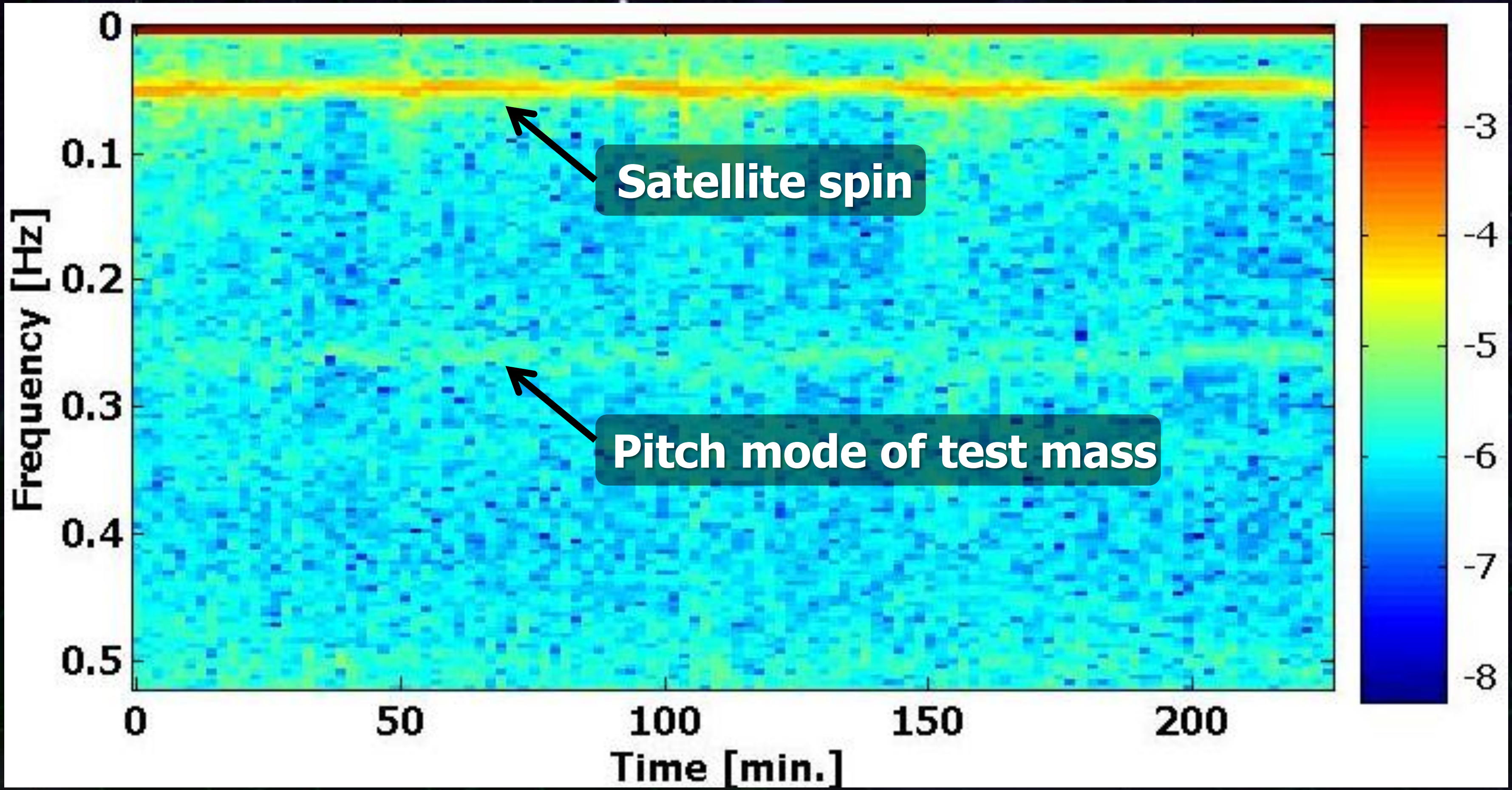
DECIGO

Observation by SWIM and ground-based detectors
1st run June 17 2010, 2nd run July15 2010



SWIM observation

SWIM observation (July 15, 2010 ~240 min.)



Summary

Summary

DECIGO

DECIGO : Fruitful Sciences

Very beginning of the Universe
Dark energy
Galaxy formation

DECIGO Pathfinder

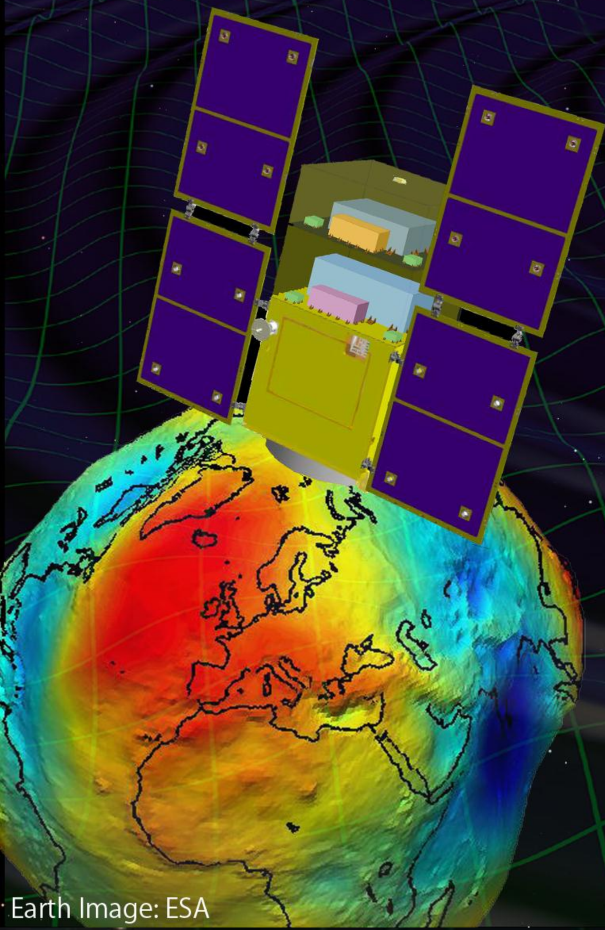
Important milestone for DECIGO
Observation of GWs and Earth's gravity
Strong candidate of JAXA's satellite series

SWIM – Operation in orbit
first precursor to space!

Collaboration and support

DECIGO

- **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 navigation-control section**
  - → 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**



End

Original
Picture : Sora

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