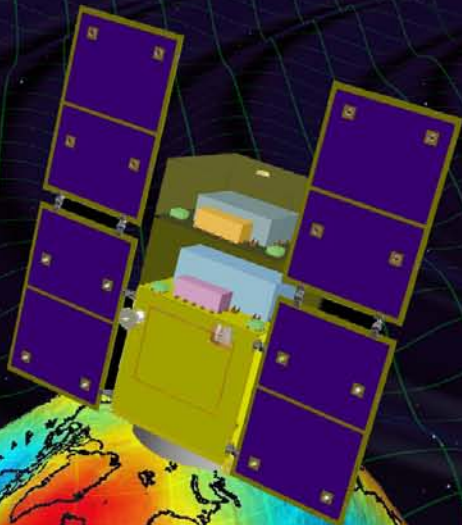


# DECIGO and DECIGO Pathfinder



Original  
Picture : Sora



Earth Image: ESA

**Masaki Ando**

(Department of Physics, Kyoto University)

On behalf of  
DECIGO working group

# **1. DECIGO**

Overview and Science

Pre-conceptual Design

# **2. DECIGO Pathfinder**

Overview and Science

Design and Status

Space Demonstration

# **3. Summary**



# **1. DECIGO**

Overview and Science

Pre-conceptual Design

# **2. DECIGO Pathfinder**

Overview and Science

Design and Status

Space Demonstration

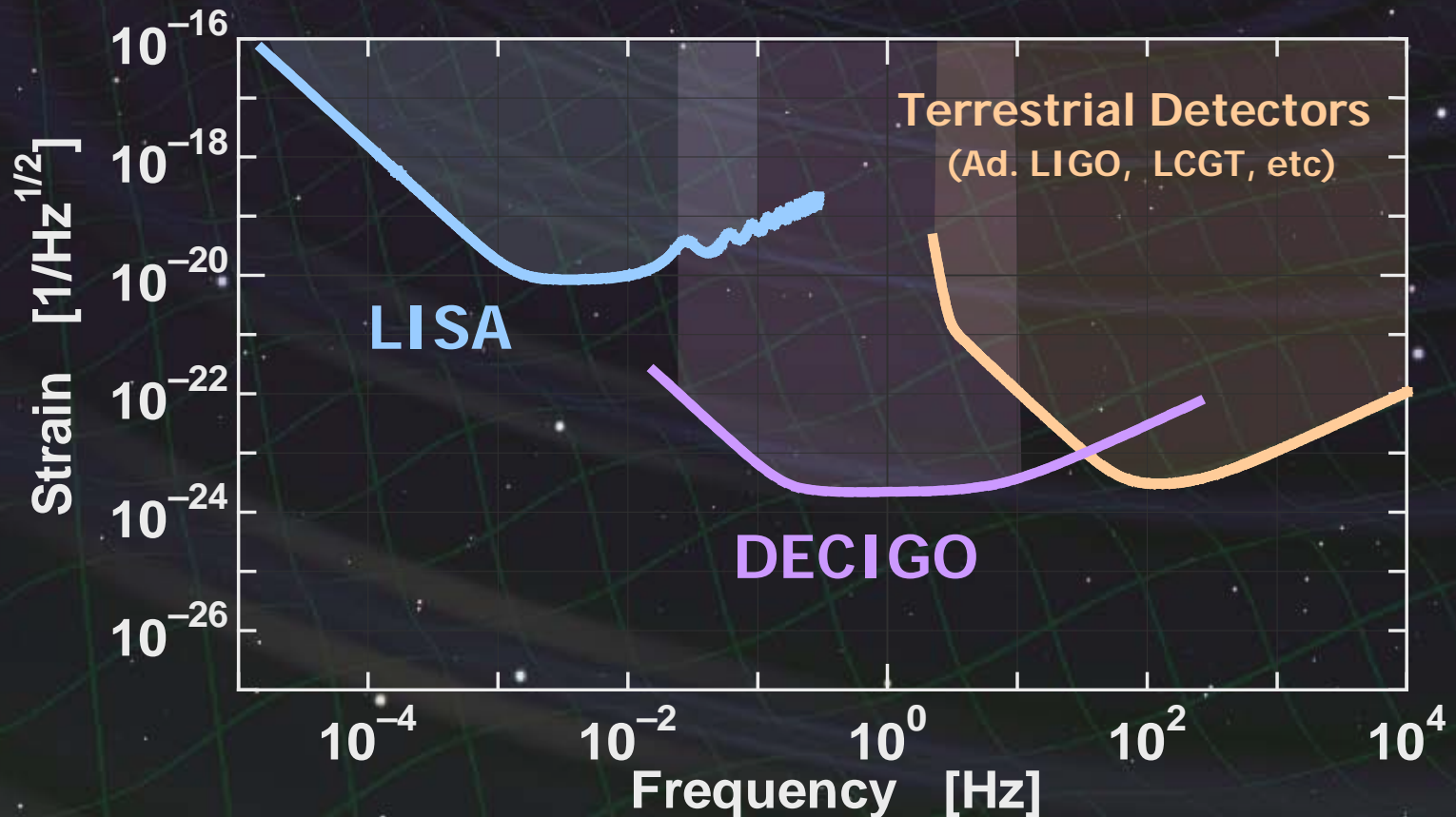
# **3. Summary**

**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**

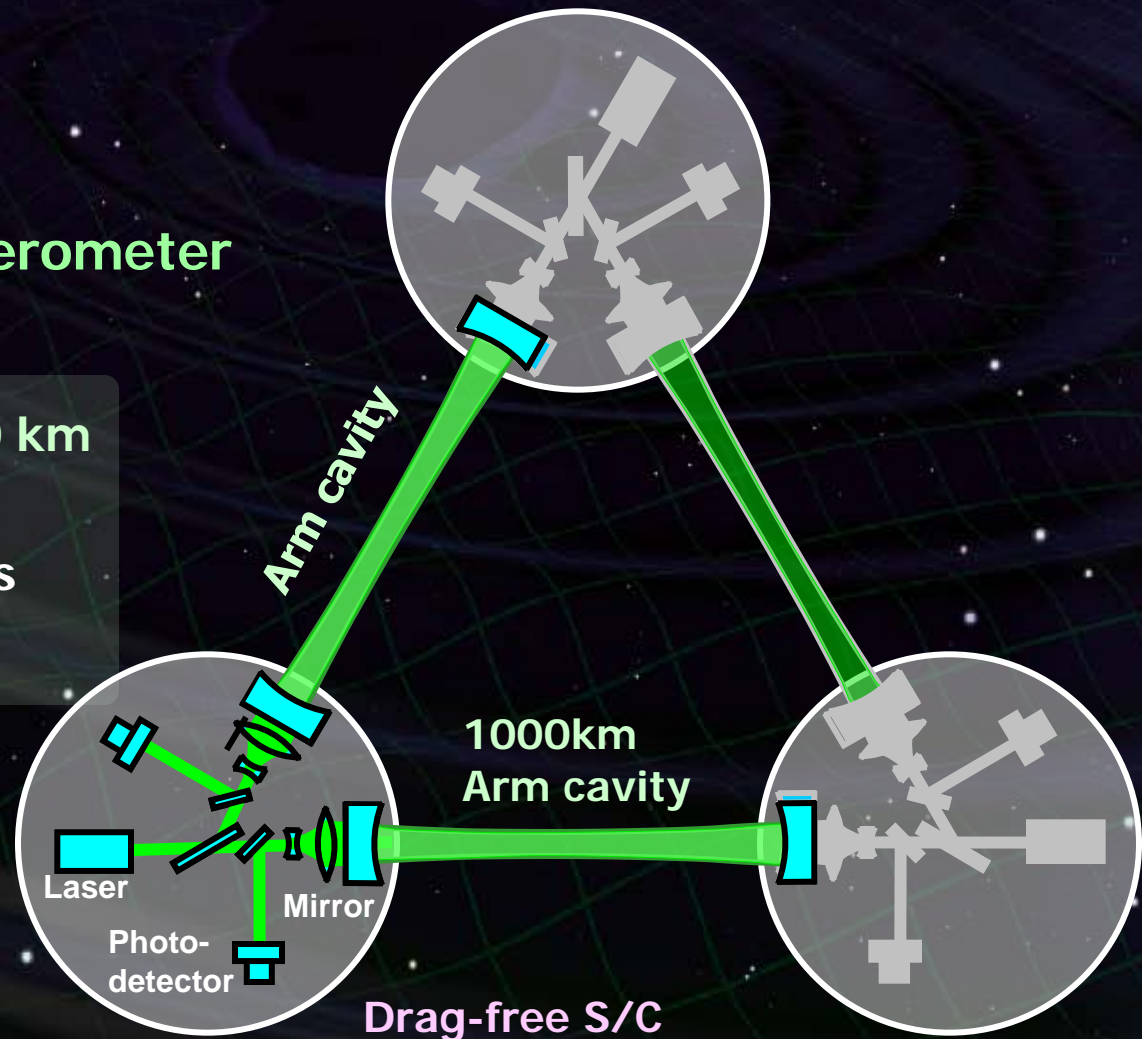


# DECIGO Interferometer



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

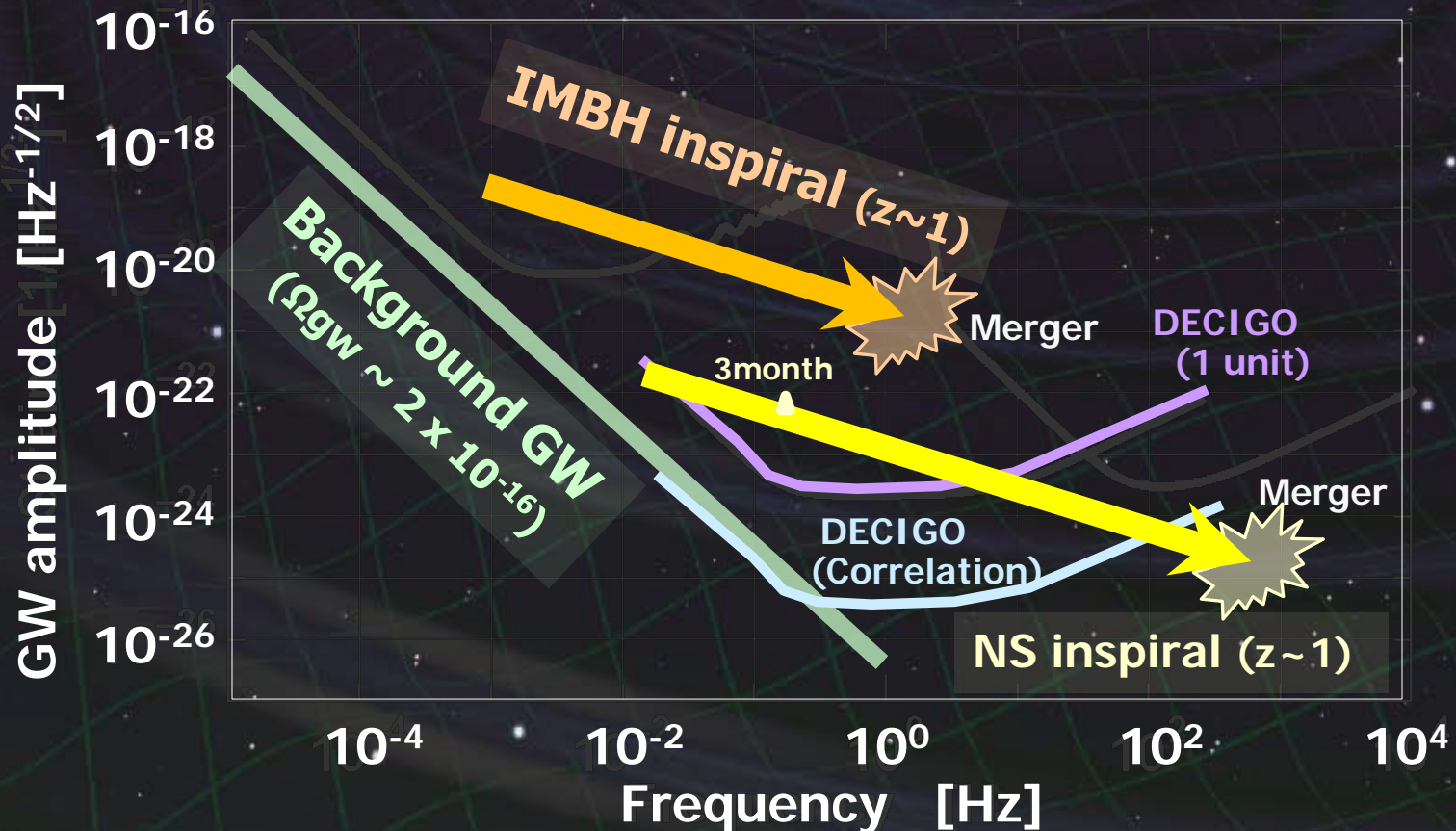
**Stochastic background**



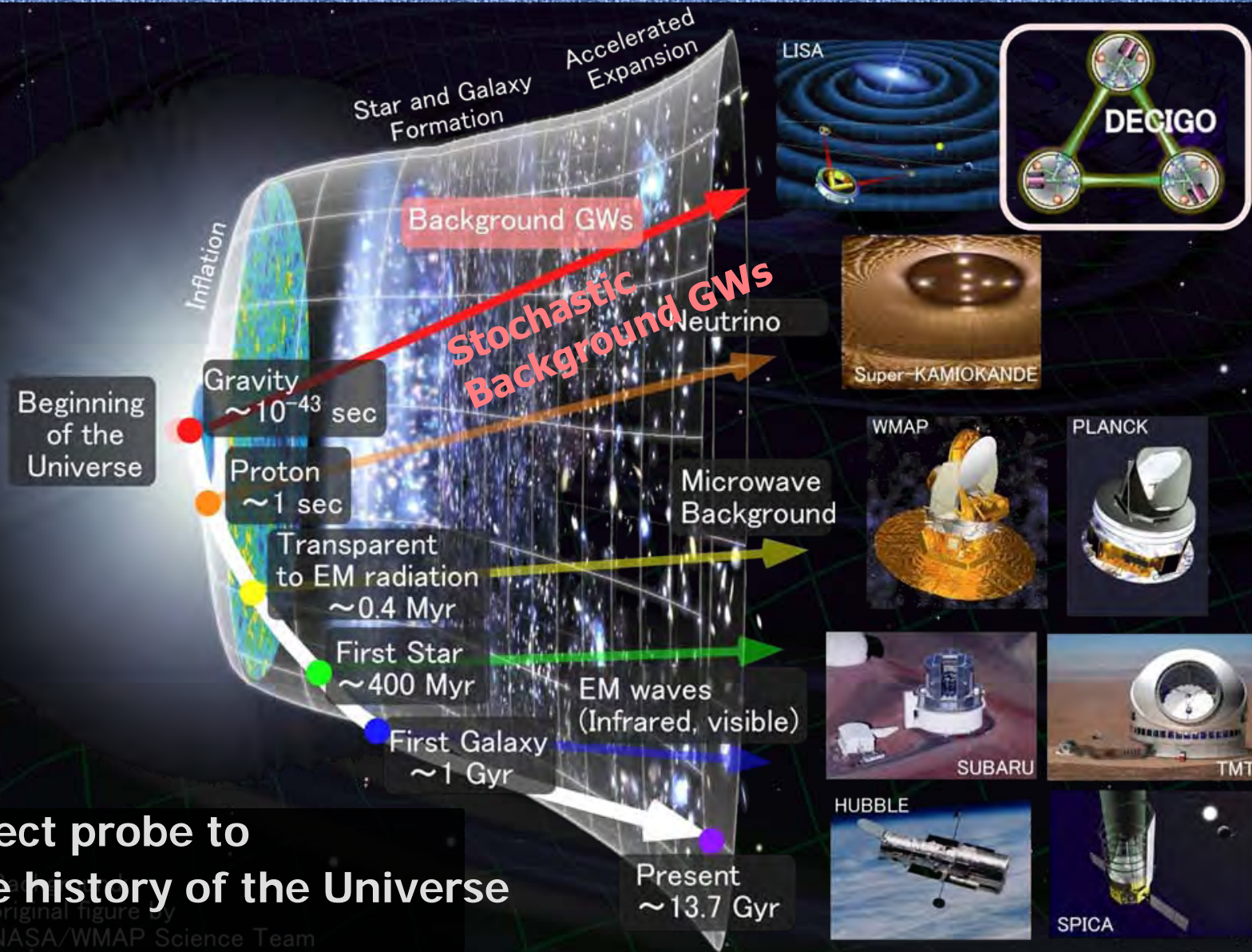
Galaxy formation (Massive BH)

Cosmology (Inflation, Dark energy)

Fundamental physics



# Characterization of inflation



**Direct probe to  
the history of the Universe**

original figure by  
NASA/WMAP Science Team

DECIGO will observe

$5 \times 10^4$  NS binaries for  $z < 1$

↳ Precise 'clock' at cosmological distance

## 'Standard Siren'

Relationship between  
distance and redshift

Distance: chirp waveform

Redshift: host galaxy

→ Information on **acceleration**  
of expansion of the universe



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

Determine cosmological parameters

**Absolute and independent measurement**

Angular resolution

$\sim 10 \text{ arcmin}^2$  (1 detector)

$\sim 10 \text{ arcsec}^2$  (3 detectors)

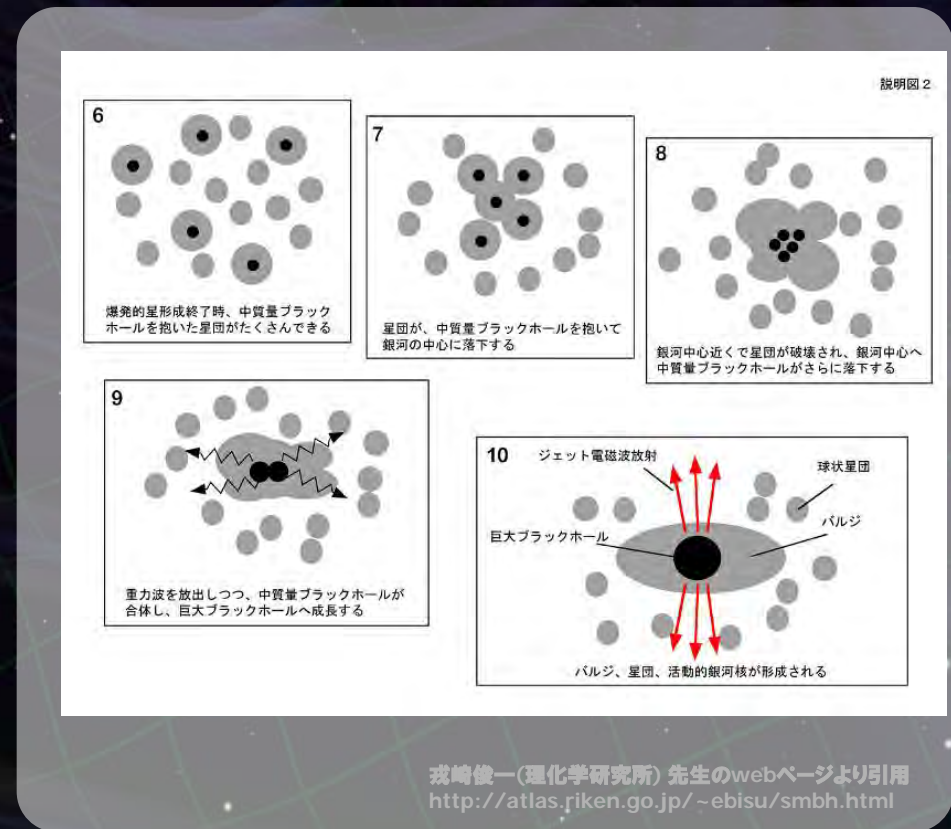
at  $z=1$



DECIGO will observe  
Intermediate-mass BH (IMBH)  
binary merger with  
 $\text{SNR} > 10^3$  for  $z \sim 10$  source



Information on the  
formation of  
Supermassive BHs  
at the center of galaxies



- **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 mass of  $10^5$  NSs per year  
→ Constrain the **EOS of NS**  
Formation process of NS from the spectrum

# 1. DECIGO

Overview and Science

Pre-conceptual Design



# 2. DECIGO Pathfinder

Overview and Science

Design and Status

Space Demonstration

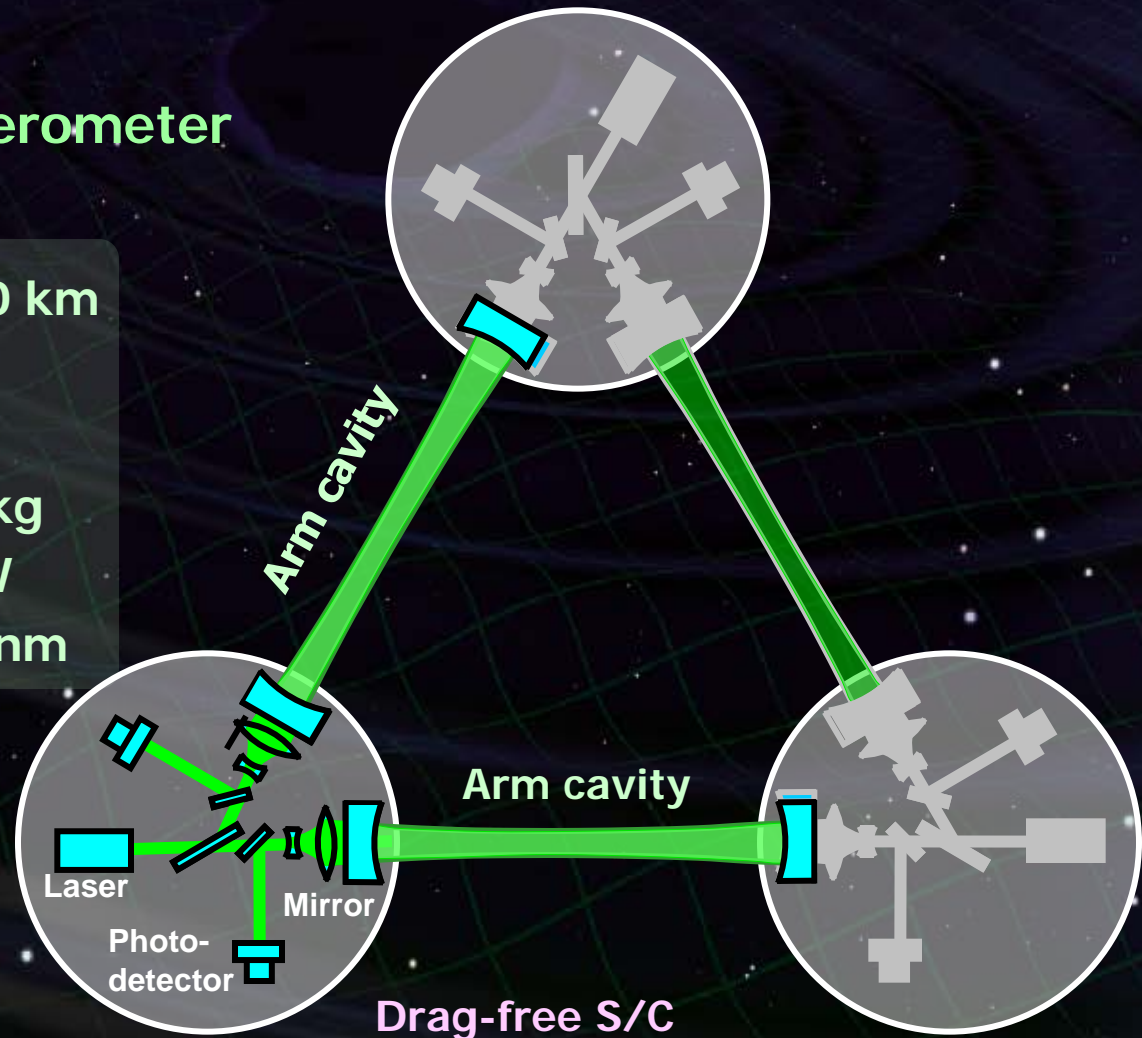
# 3. Summary

## 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

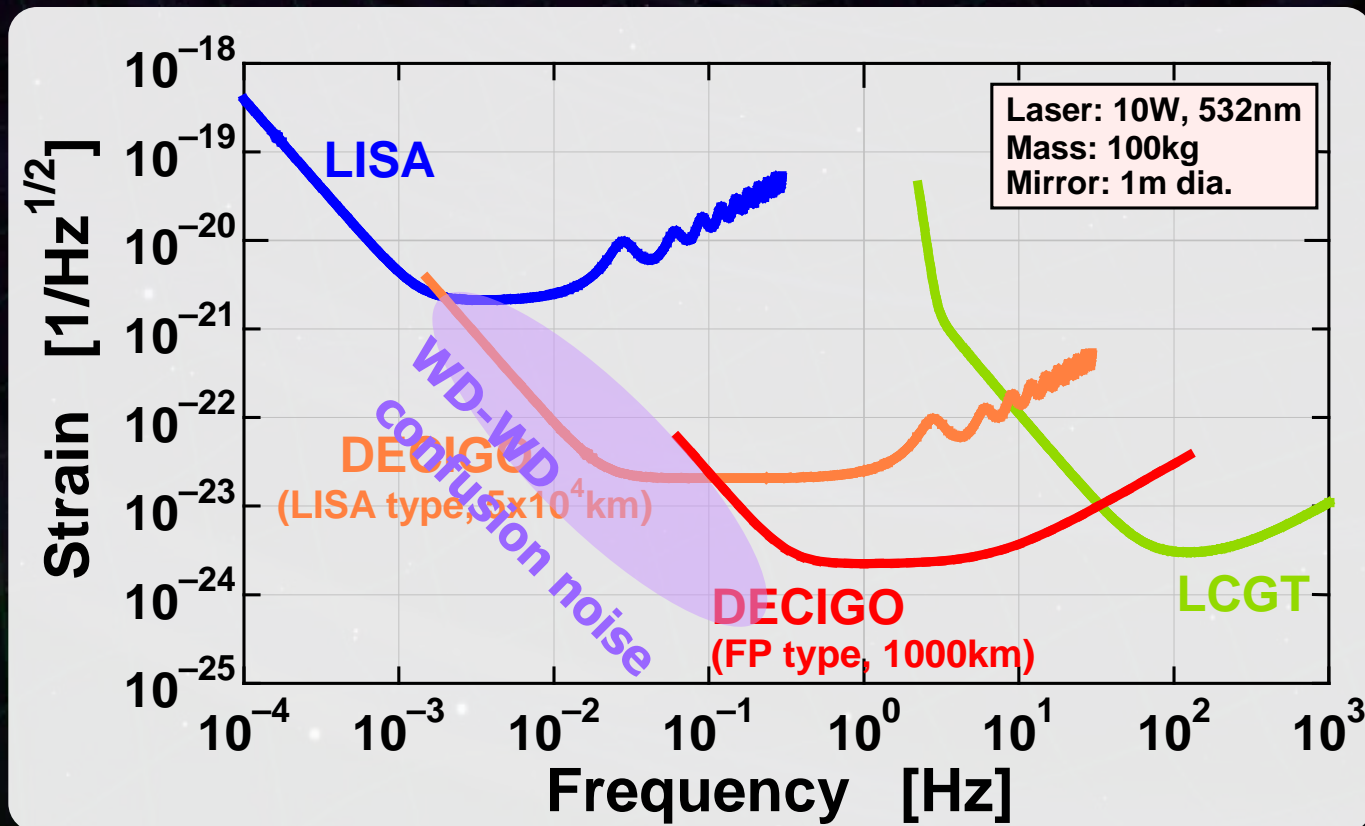


# Interferometer Design

## 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 ( $TEM_{00} \rightarrow TEM_{00}$ )

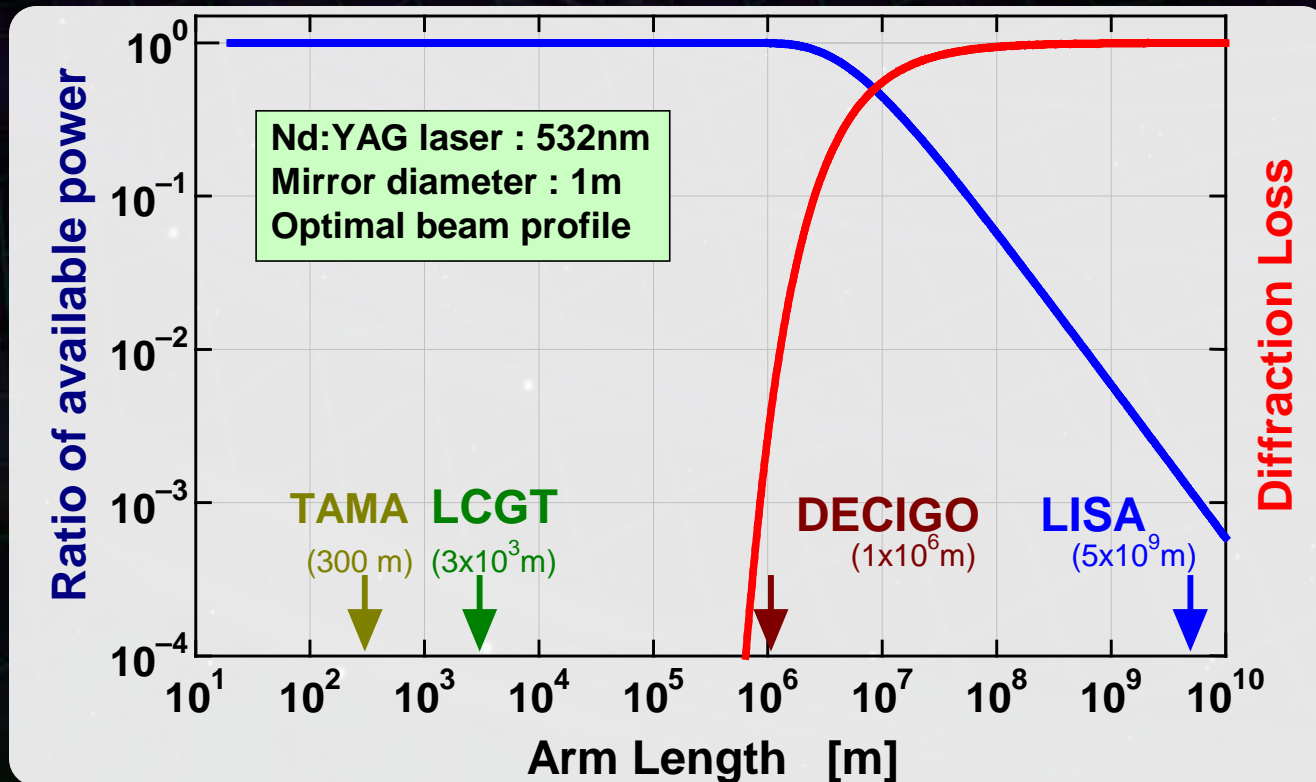
Laser wavelength : 532nm

Mirror diameter: 1m

Optimal beam size



1000 km  
is almost max.



# 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  
→  $\Delta m/m < \sim 10^{-7} \%$

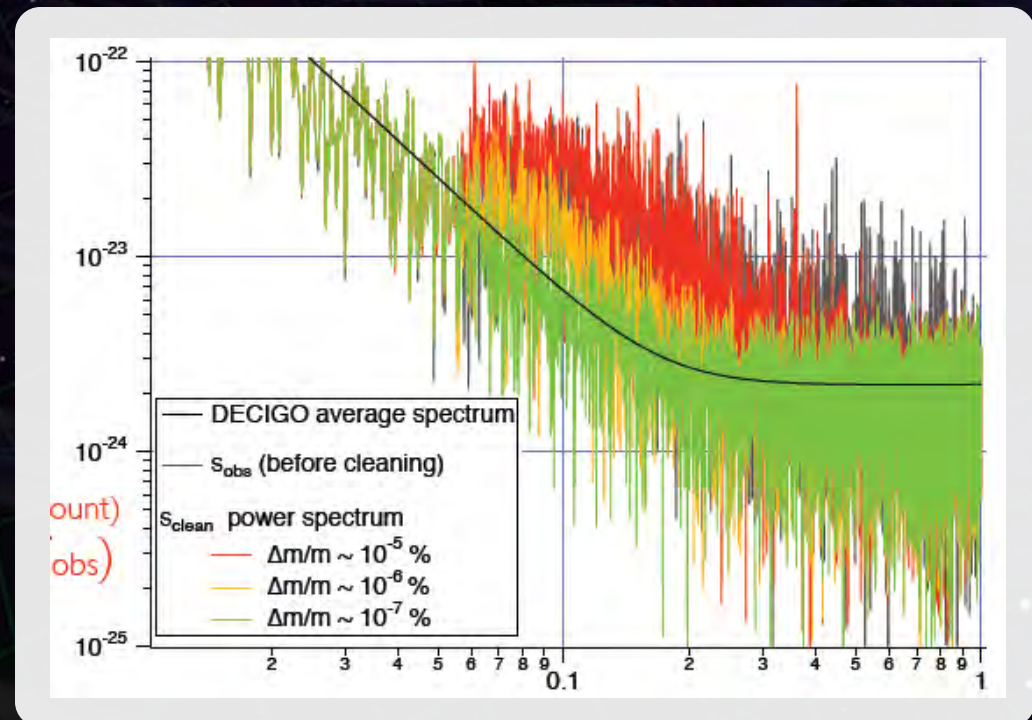


Fig: N. Kanda

# Cavity and S/C control

## Cavity length change

PDH error signal  $\rightarrow$  Mirror position (and Laser frequency)

Relative motion between mirror and S/C

Local sensor  $\rightarrow$  S/C thruster

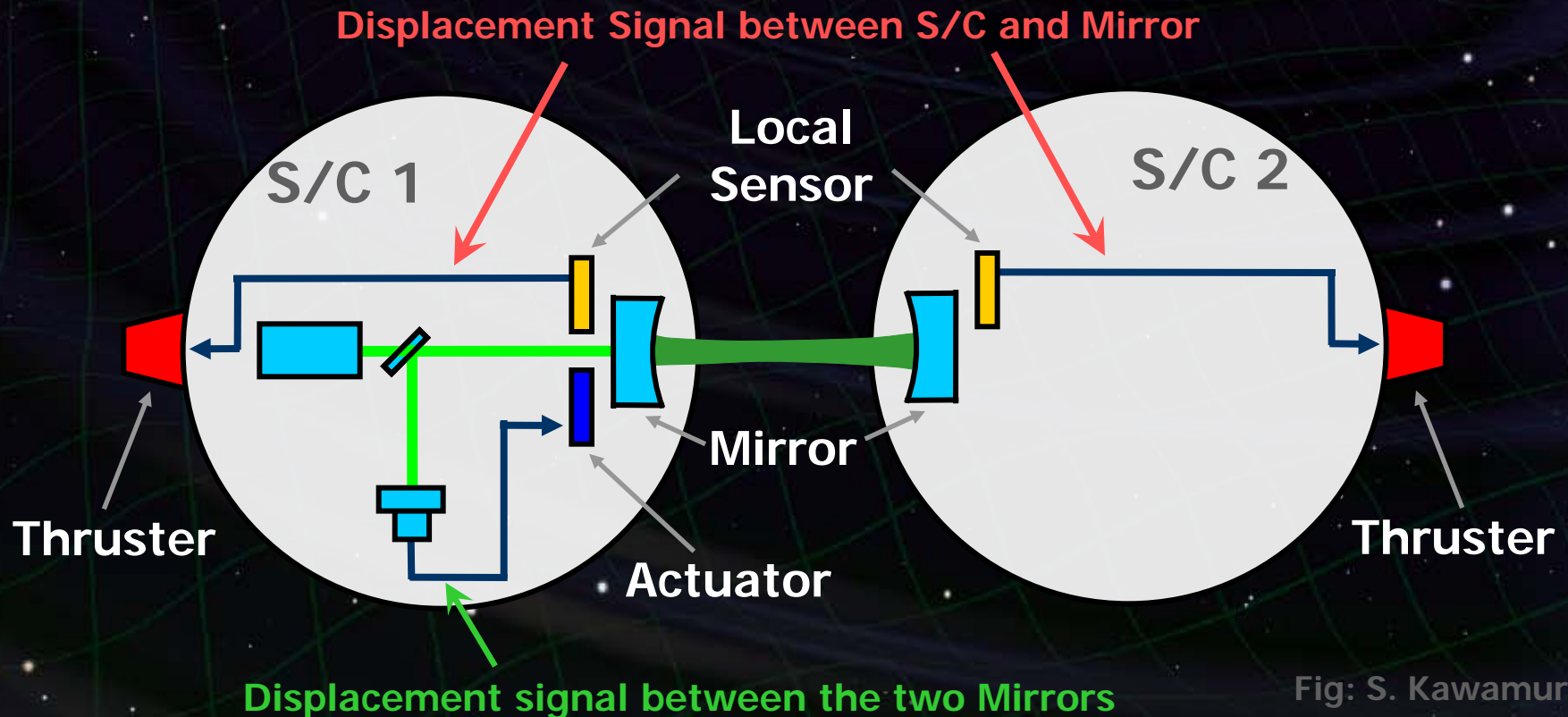


Fig: S. Kawamura



# Requirements

## Sensor Noise

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

⇒ x 10 of LCGT in phase noise

Other noises should be well below the shot noise

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

Stab. Gain  $10^5$ , CMRR  $10^5$

## Acceleration Noise

Force noise  $4 \times 10^{-17} \text{ N/Hz}^{1/2}$  (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.  $4 \times 10^{-12} \text{ m/s}^2$

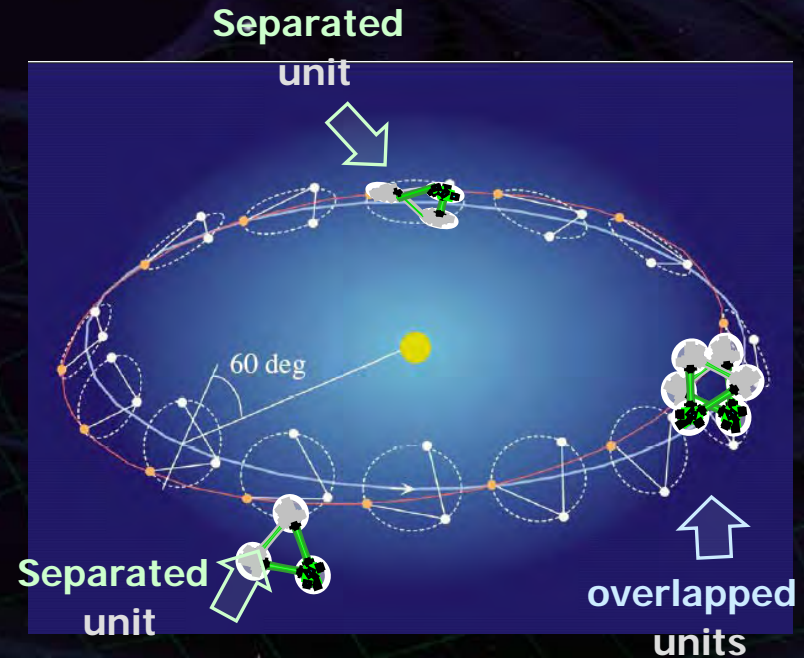
(Mirror force  $\sim 10^{-9} \text{ N}$ )

## Constellation

4 interferometer units

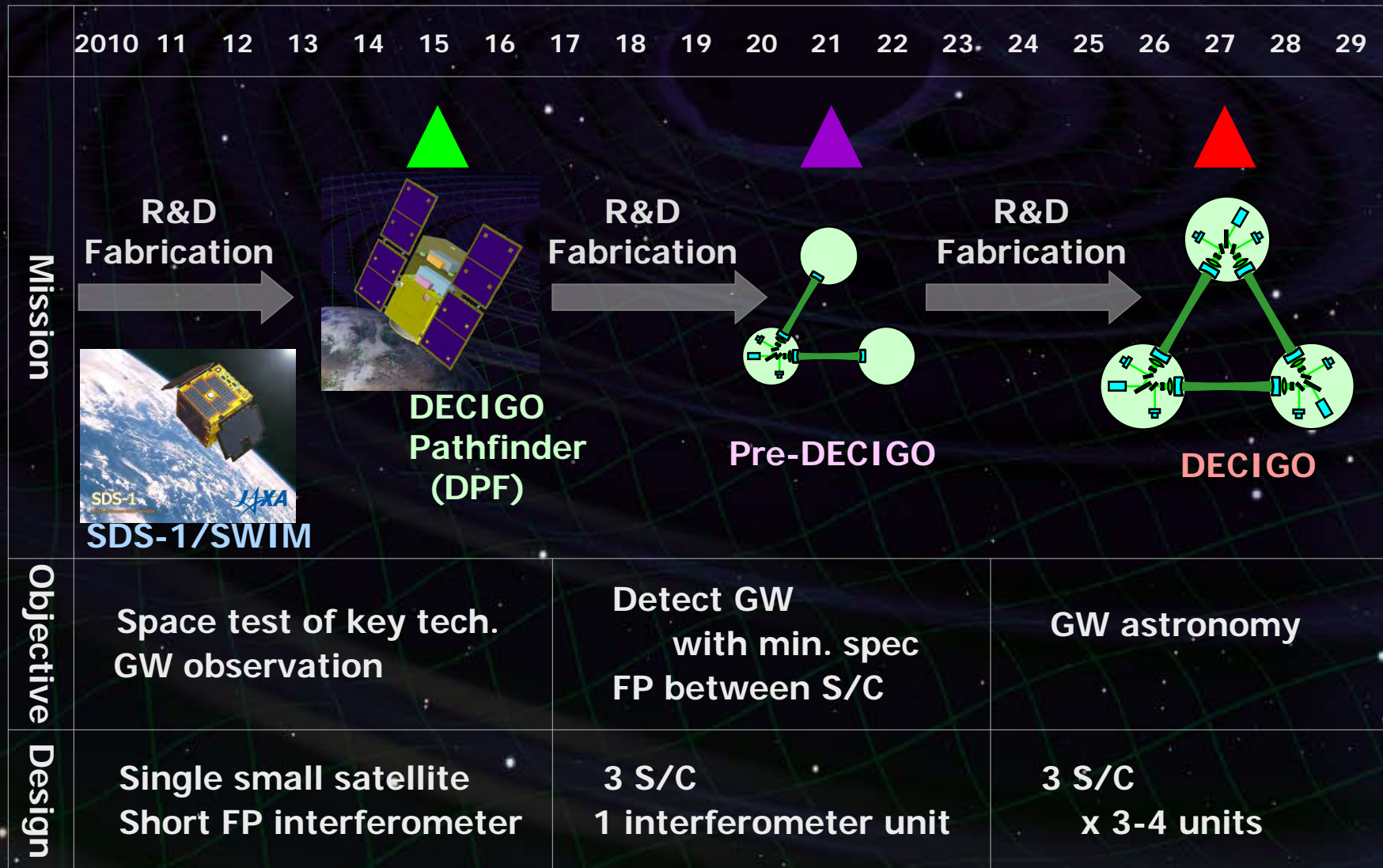
2 overlapped units  $\rightarrow$  Cross correlation

2 separated units  $\rightarrow$  Angular resolution



# Roadmap

Figure: S.Kawamura



# Organization



**PI: Kawamura (NAOJ)**  
**Deputy: Ando (Kyoto)**

**Executive Committee**  
Kawamura (NAOJ), Ando (Kyoto), Seto (Kyoto), Nakamura (Kyoto), Tsubono (Tokyo), Tanaka (Kyoto), Funaki (ISAS), Numata (Maryland), Sato (Hosei), Kanda (Osaka city), Takashima (ISAS), Ioka (KEK), Yokoyama (Tokyo)

**Pre-DECIGO**  
Sato (Hosei)

**Detector**  
Akutsu (NAOJ)  
Numata (Maryland)

**Science, Data**  
Tanaka (Kyoto)  
Seto (Kyoto)  
Kanda (Osaka city)

**Satellite**  
Funaki (ISAS)

## Design phase

**DECIGO pathfinder**  
**Leader: Ando (Kyoto)**

## Mission phase

**Detector**  
Sato (Hosei)  
Ueda (NAOJ)  
Aso (Tokyo)

**Laser**  
Musha (ILS)  
Ueda (ILS)

**Drag free**  
Moriwaki (Tokyo)  
Sakai (ISAS)

**Thruster**  
Funaki (ISAS)

**Bus**  
Takashima (ISAS)

**Data**  
Kanda (Osaka city)

- 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 , started discussion
- Collab. with **JAXA navigation-control section**  
→ formation flight of DECIGO, DPF drag-free control
- Research Center for the Early Universe (**RESCEU**), Univ. of Tokyo  
Support DECIGO as ones of main projects (2009.4-)
- Advanced technology center ( **ATC**) of **NAOJ**  
Will make it a main nucleus of DPF

# LCGT and DECIGO

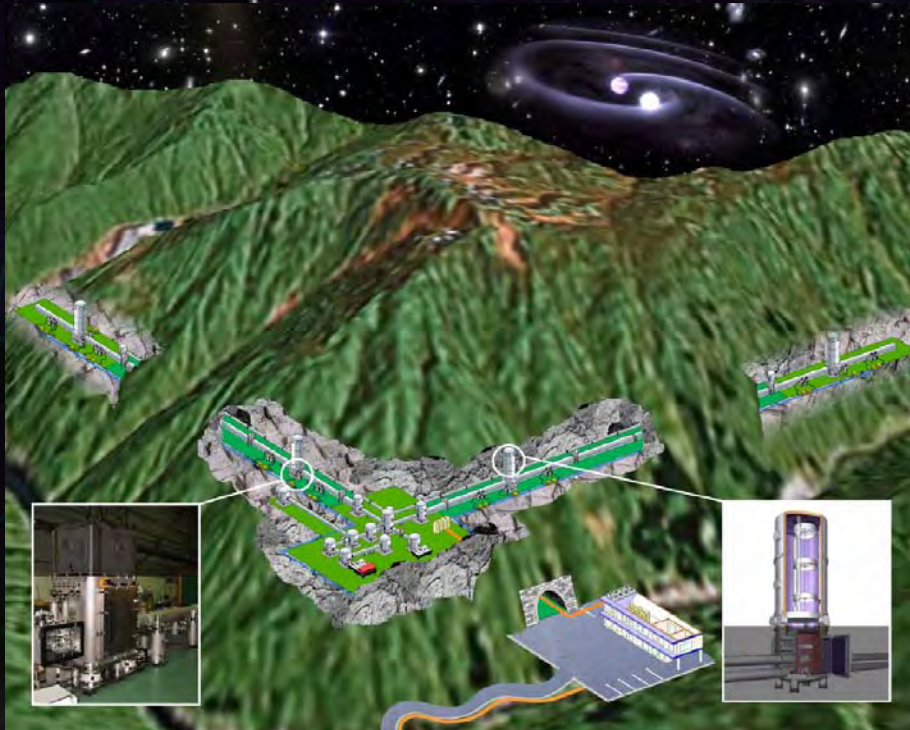


**LCGT** (~2016)

Terrestrial Detector

→ High frequency events

Target: GW detection

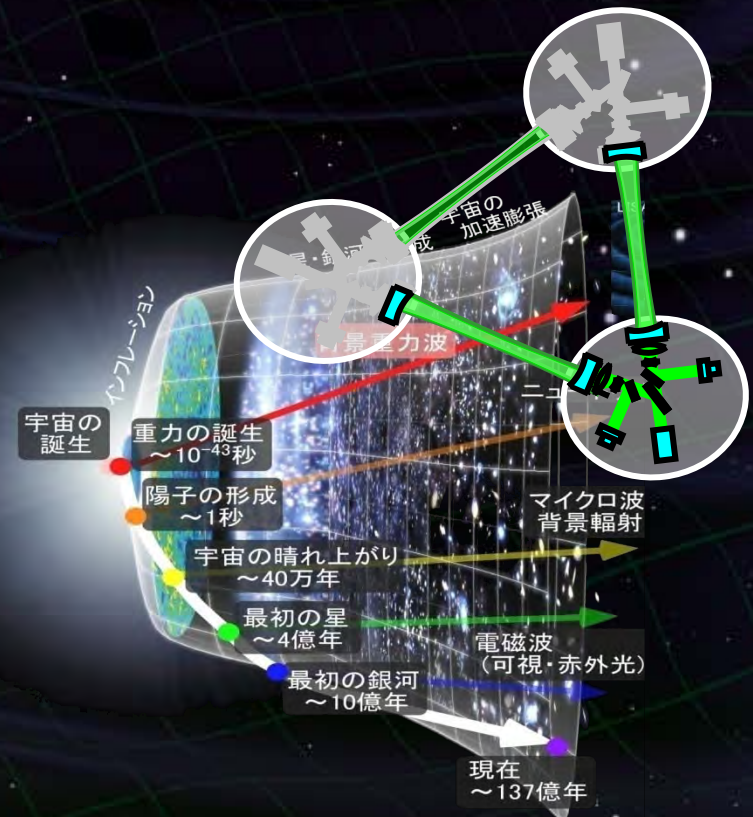


**DECIGO** (~2027)

Space observatory

→ Low frequency sources

Target: GW astronomy



# 1. DECIGO

Overview and Science  
Pre-conceptual Design



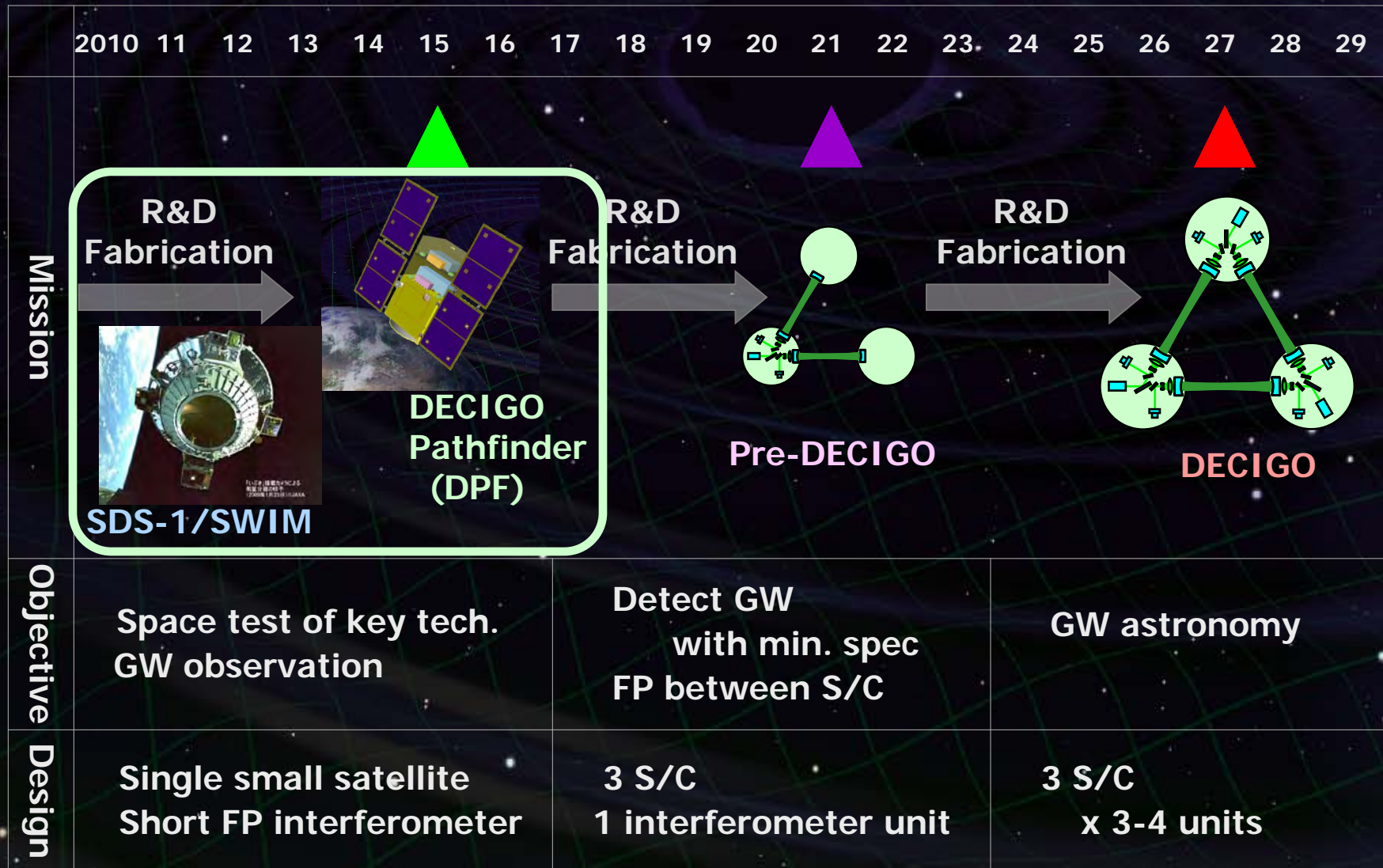
# 2. DECIGO Pathfinder

Overview and Science  
Design and Status  
Space Demonstration

# 3. Summary

# Roadmap

Figure: S.Kawamura





## DECIGO Pathfinder (DPF)

First milestone mission for DECIGO

Shrink arm cavity

DECIGO 1000km  $\rightarrow$  DPF 30cm

**Single satellite**

(Payload  $\sim 1\text{m}^3$ , 350kg)

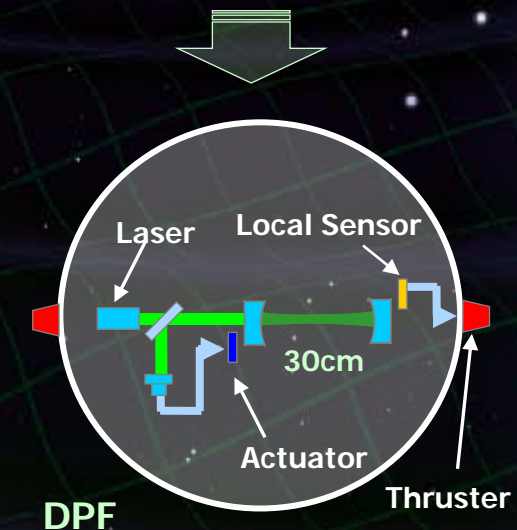
**Low-earth orbit**

(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

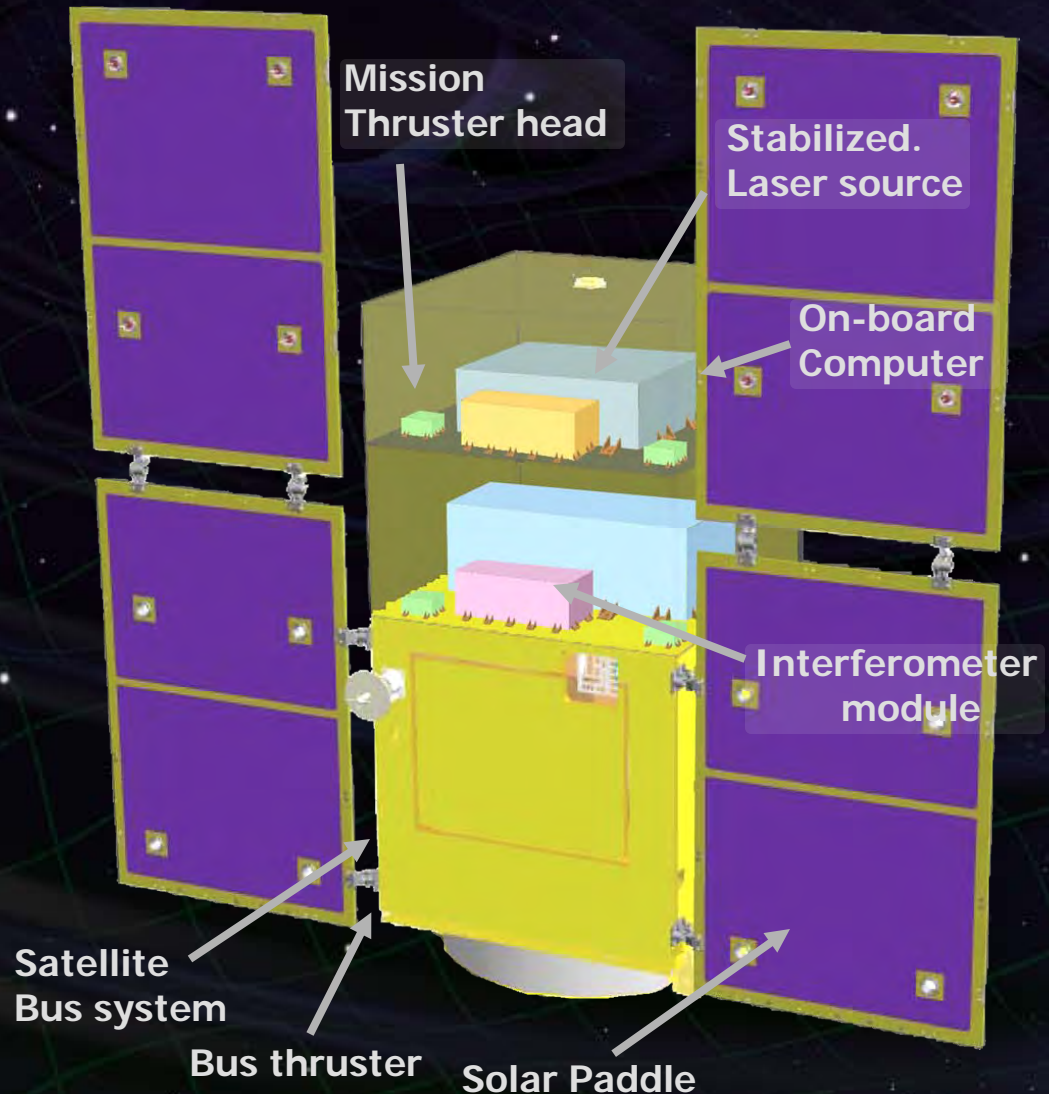
Power Supply  
SpW Comm.



## Satellite Bus

('Standard bus' system)

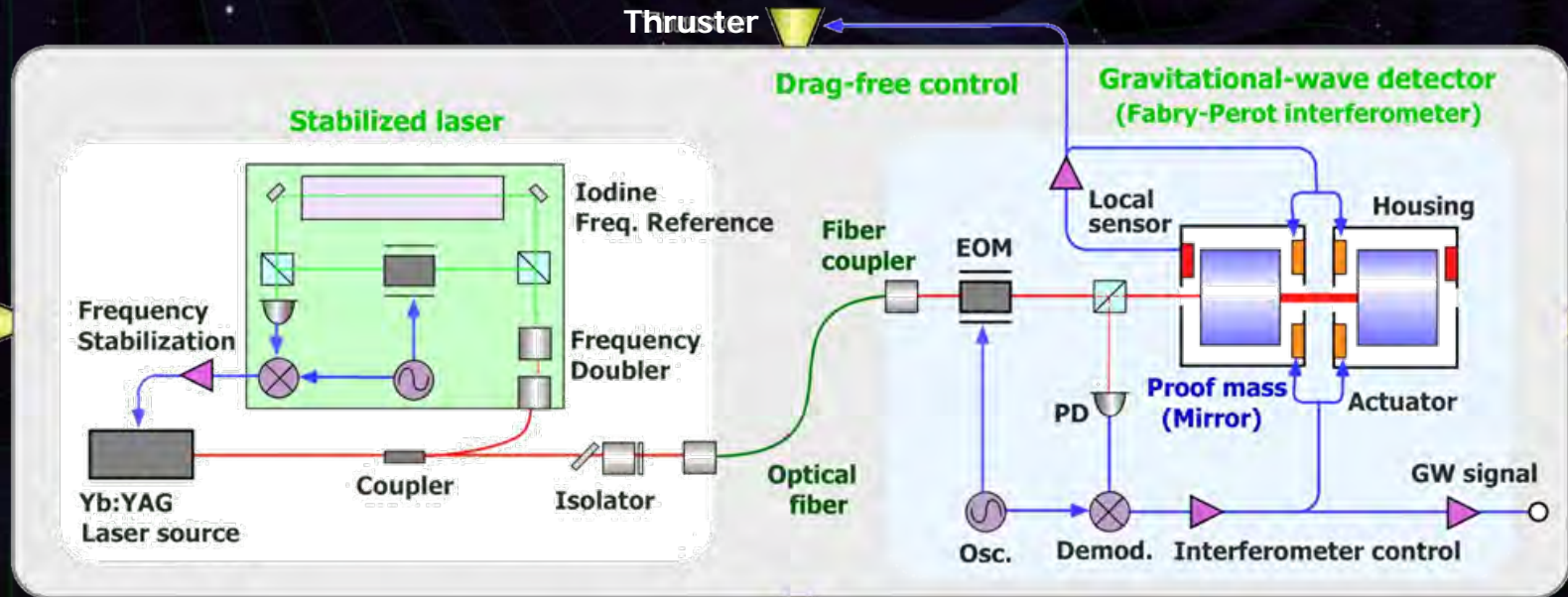
Size :  
950x950x1100mm  
Weight : 200kg  
SAP : 960W  
Battery: 50AH  
Downlink : 2Mbps  
DR: 1GByte  
3N Thrusters x 4



# 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

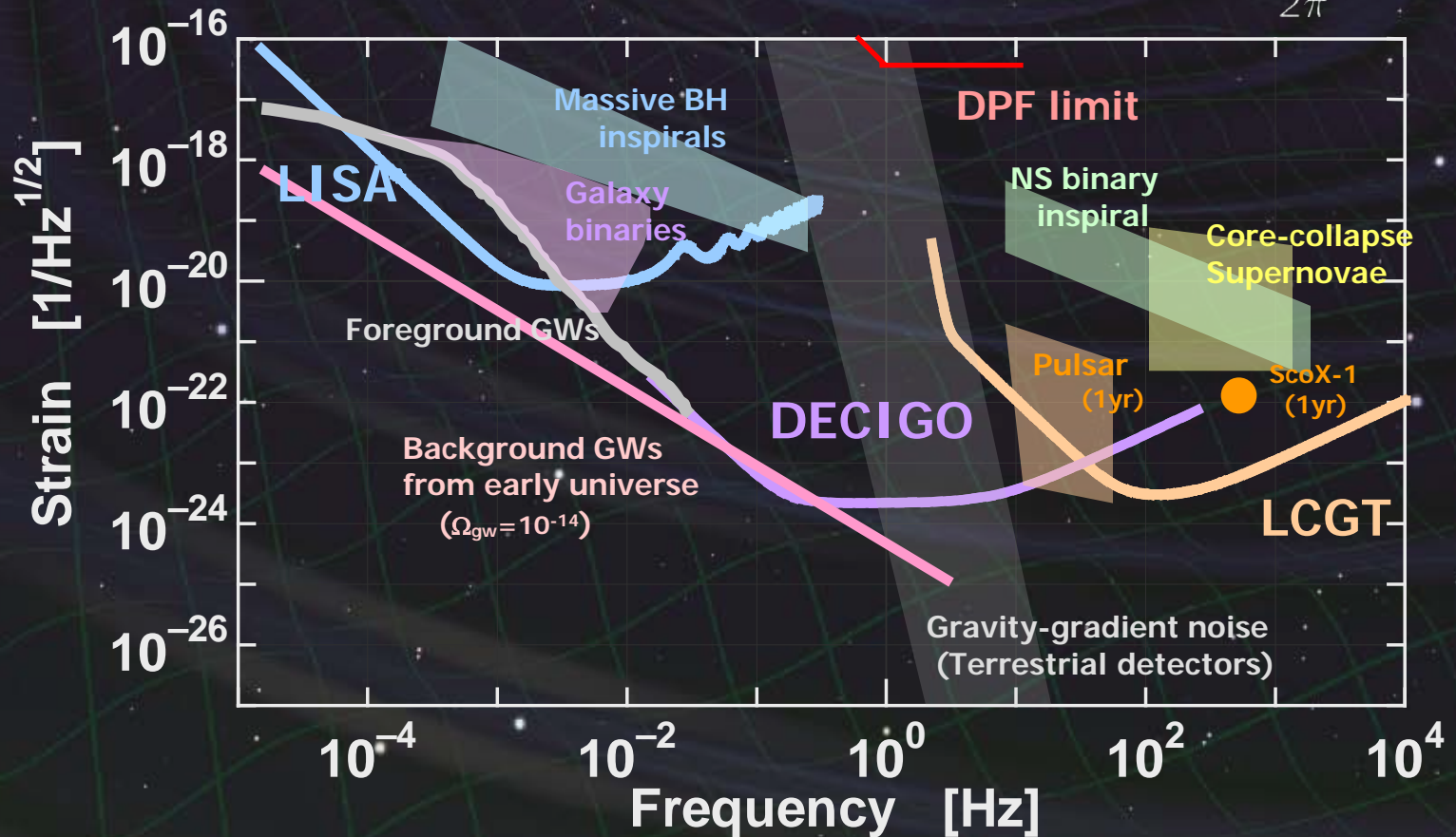
## Fabry-Perot interferometer

Finesse : 100  
Length : 30cm  
Test mass : ~ 1kg  
Signal extraction by PDH

# DPF sensitivity

DPF sensitivity  $h \sim 2 \times 10^{-15} \text{ Hz}^{1/2}$   
 (x10 of quantum noises)

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



## Scientific observations

Gravitational Waves from BH mergers

→ BH formation mechanism

Gravity of the Earth

→ Geophysics, Earth environment

## Science technology

Space demonstration for DECIGO

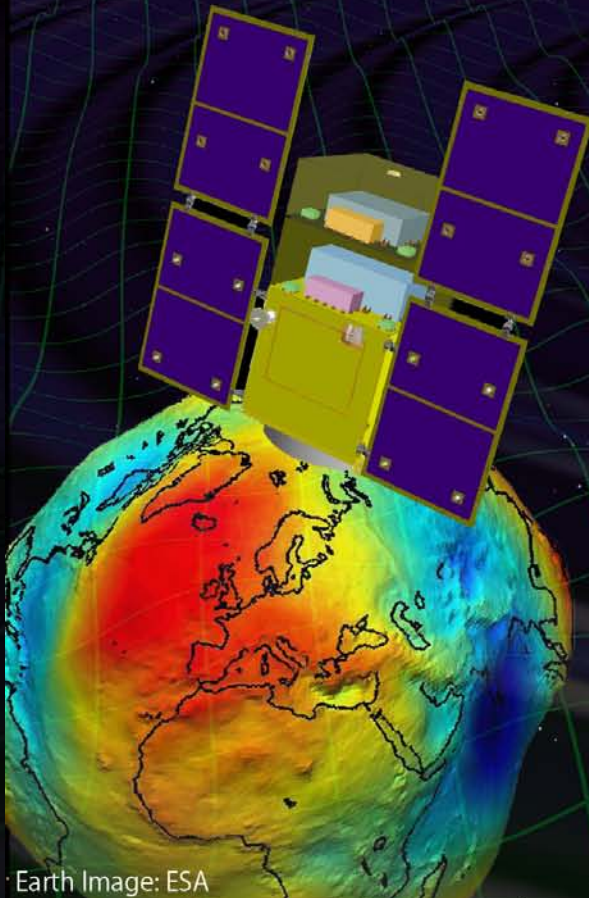
→ Most tech. with single satellite

(IFO, Laser, Drag-free)

Precision measurement in orbit

→ IFO measurement

under stable zero-gravity



Earth Image: ESA

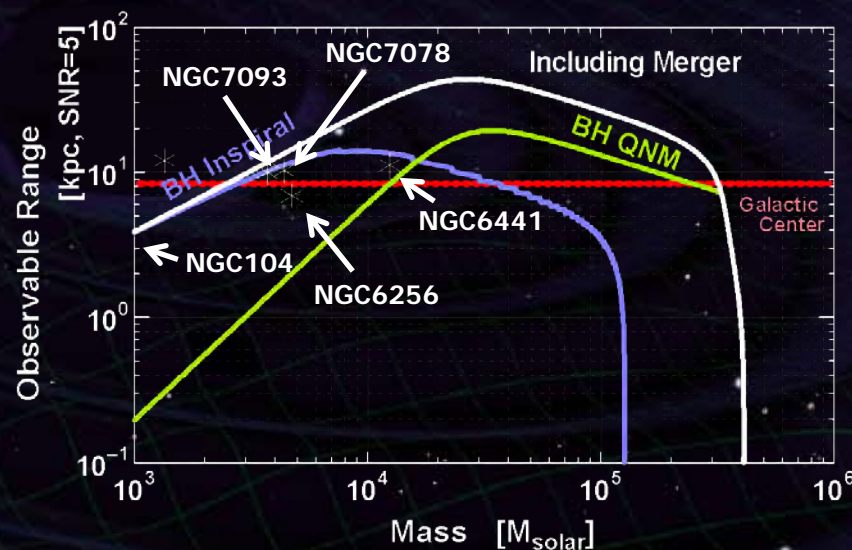
# DPF Targets

## Astronomical observation

GW from merger of IMBHs

→ Formation mechanism  
of supermassive BHs

~30 GCs within DPF range



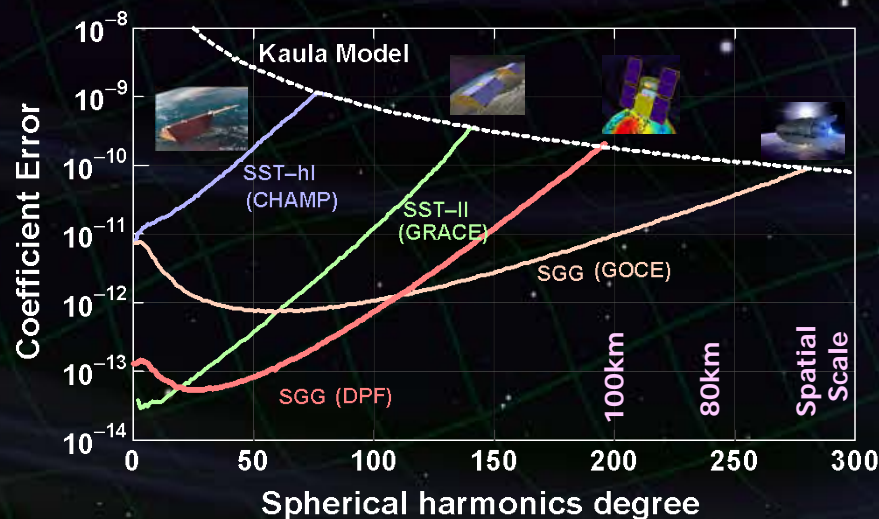
## Observation of the earth

Gravitational potential

→ Shape of the earth

Environment monitor

Comparable sensitivity  
with other missions



# 1. DECIGO

Overview and Science  
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# 2. DECIGO Pathfinder

Overview and Science  
**Design and Status**  
Space Demonstration



# 3. Summary

# 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

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

2<sup>nd</sup> mission (~2013/14) : ERG  
DPF survived until final two

3<sup>rd</sup> mission (~2015/16) : TBD

DPF is one of the strongest  
candidates of the 3<sup>rd</sup> mission



SPRINT-A/EXCEED 想像図(池下章裕氏作)

SPRINT-A /EXCEED  
UV telescope mission



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



# 1. DECIGO

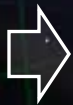
Overview and Science  
Pre-conceptual Design

# 2. DECIGO Pathfinder

Overview and Science  
Design and Status

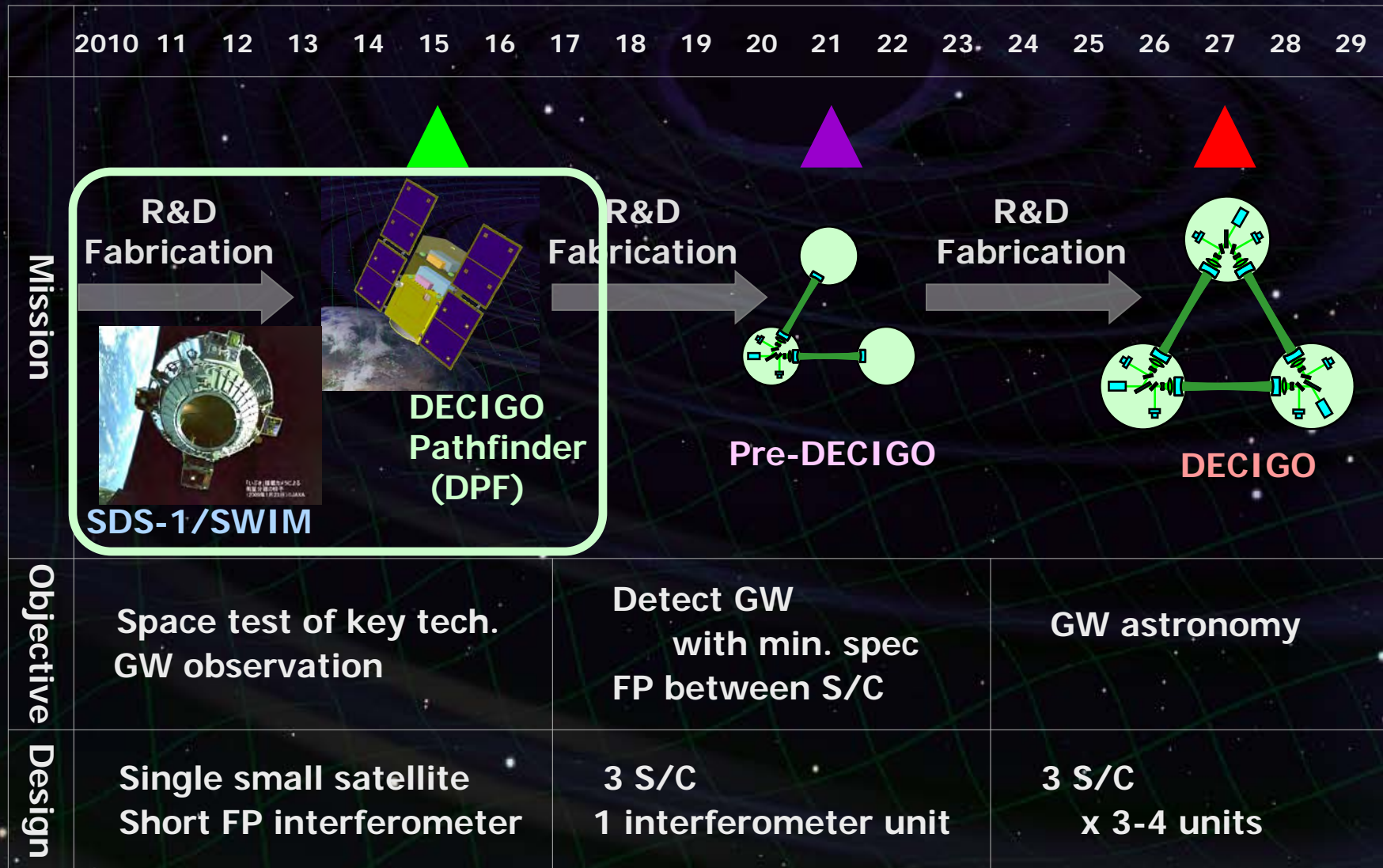
Space Demonstration

# 3. Summary



# Roadmap

Figure: S.Kawamura



# SWIM launch and operation



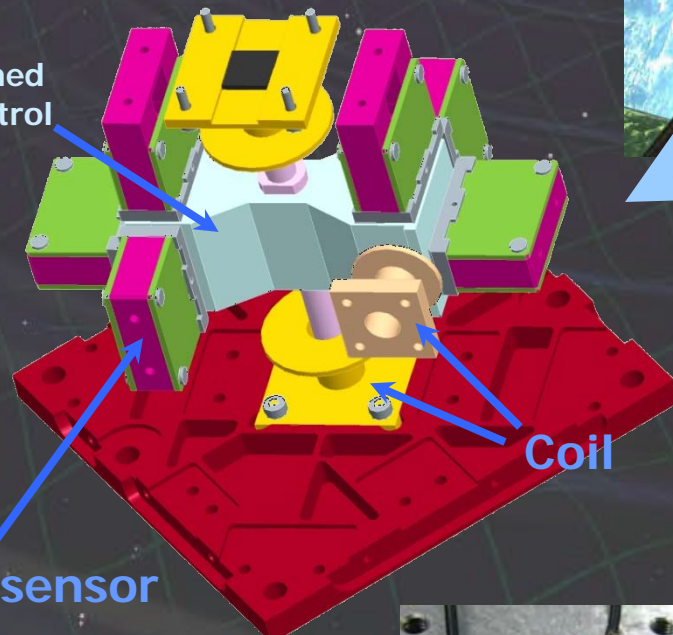
Tiny GW detector module  
Launched in Jan. 23, 2009

⇒ In-orbit operation

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<sup>1/2</sup>  
6 PSs to monitor mass motion

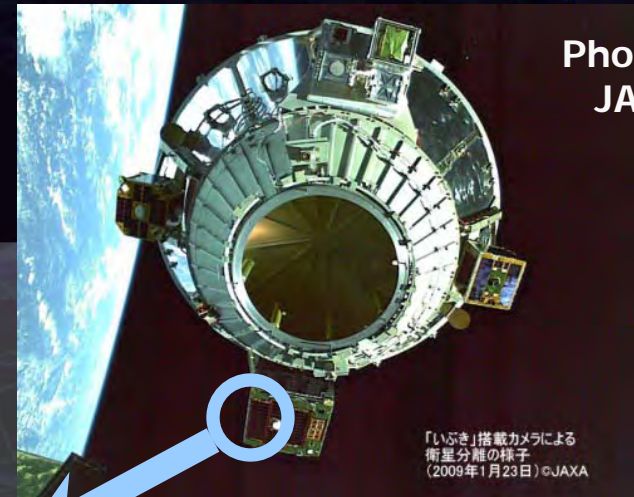
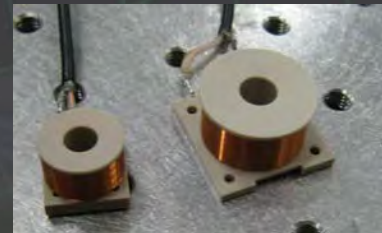


Photo:  
JAXA

# SWIM observation

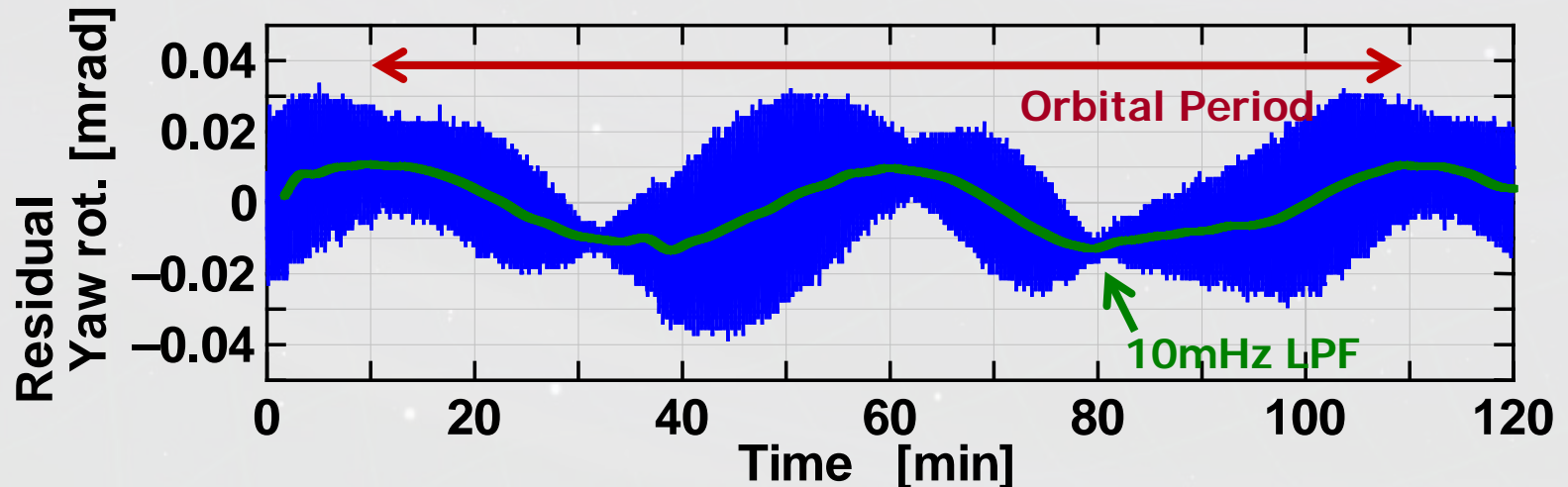
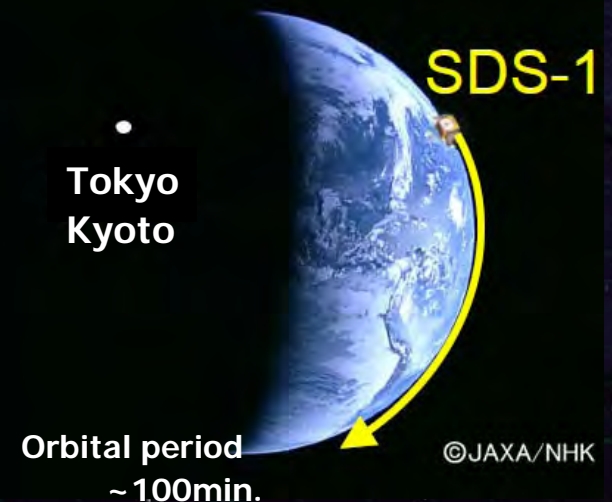
## Observation by SWIM

Jun 17, 2010 ~120 min. operation

July 15, 2010 ~240 min. operation

Ground-based detectors were operated at the same period.

⇒ Data analysis



# Supplementary topic



## TOBA : Torsion-Bar Antenna

Two test-mass bars  
Monitor differential  
angular fluctuation

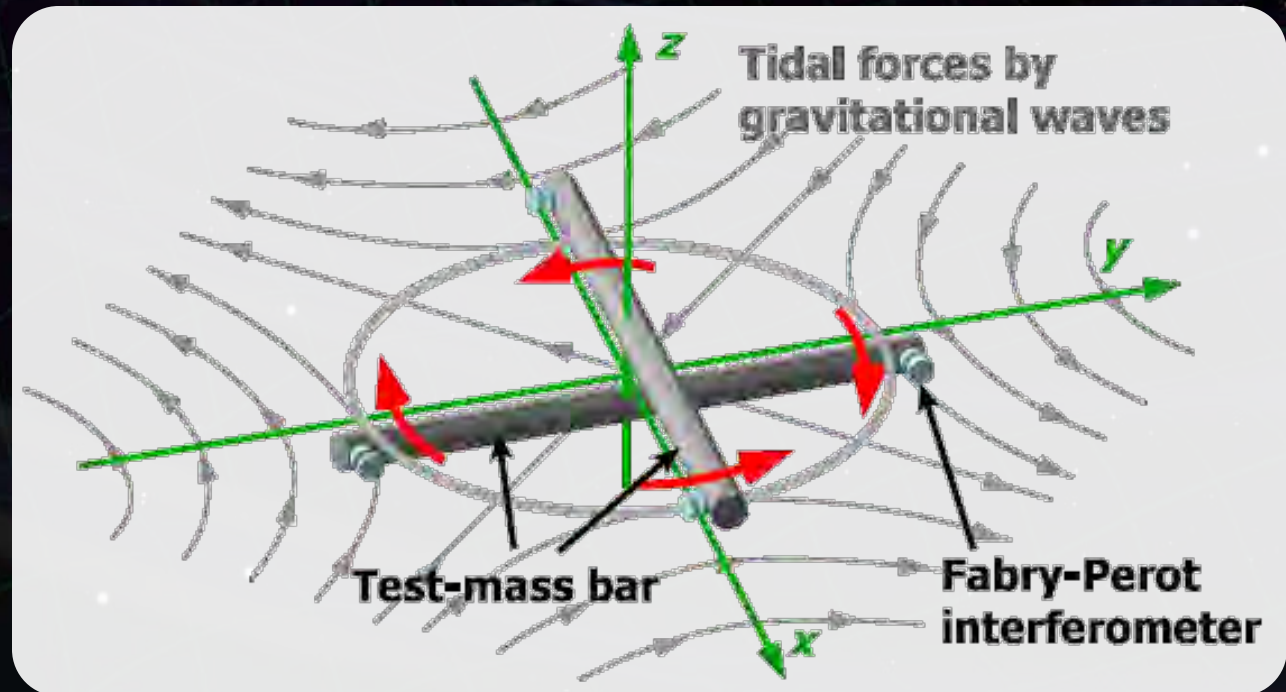


Sensitive to low-freq. GWs  
even with ground-based config.  
Much better in space

Current Issue!



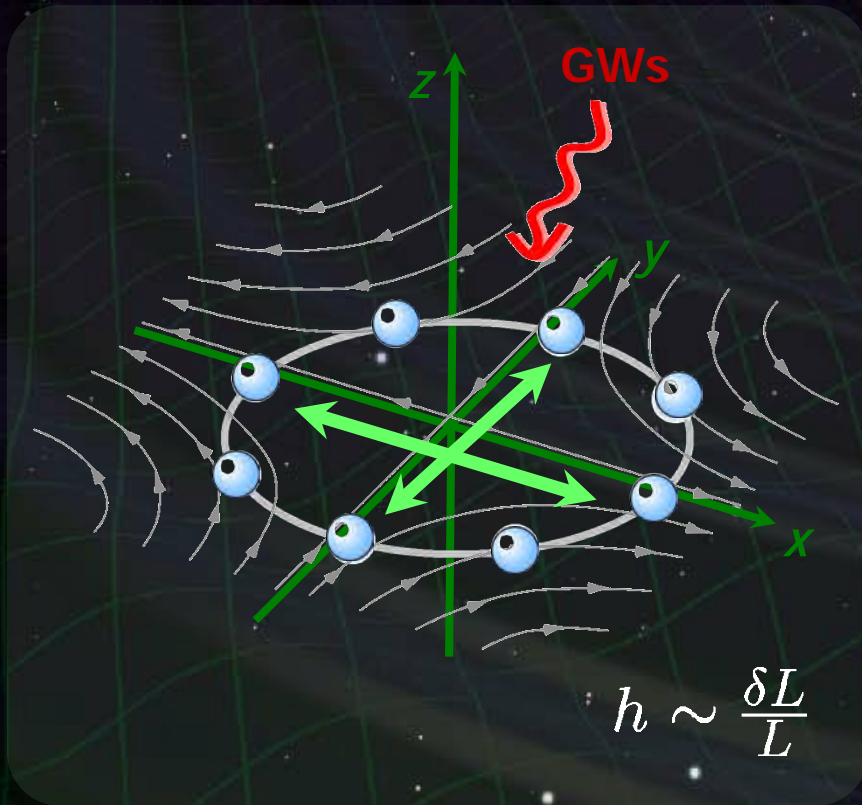
M.Ando, et. al,  
Phys. Rev. Lett.  
105, 161101 (2010)



# Strain and Torsion

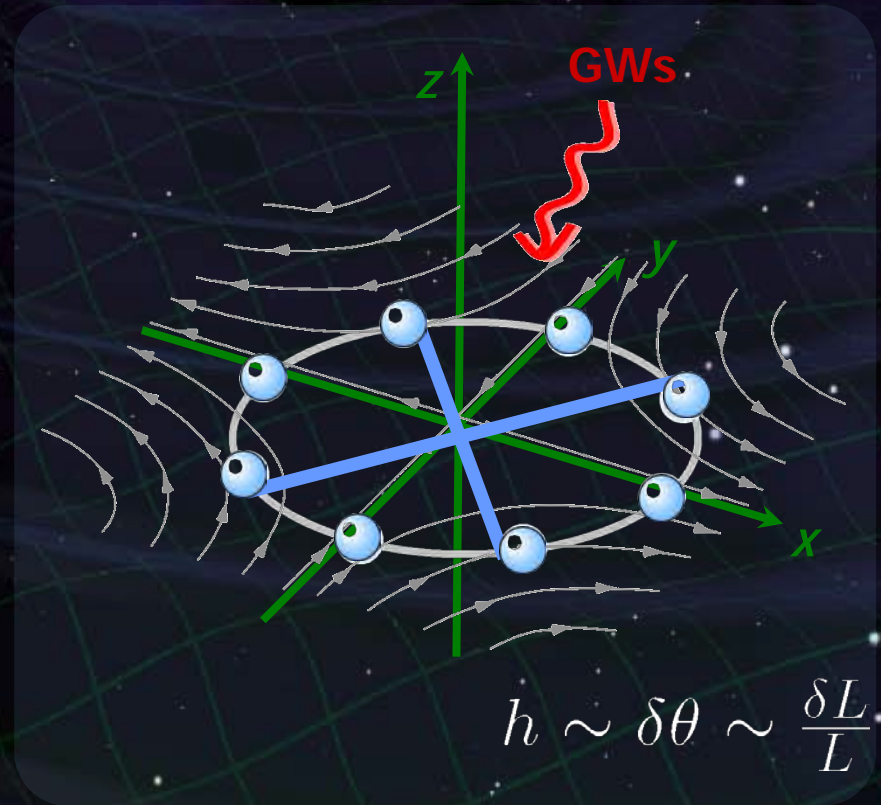
## Conventional IFO antenna

Detect differential length change



## Torsion-bar antenna

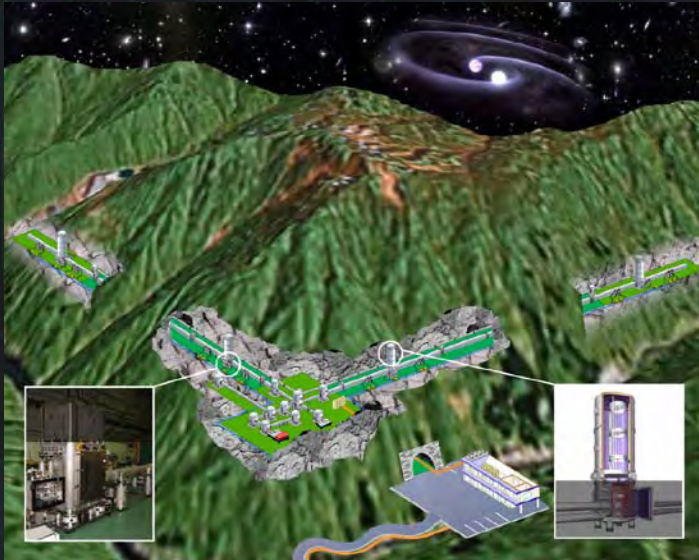
Detect differential rotation



Observe change in tidal forces using free test masses

## Conventional IFO

Obs. band 10Hz-1kHz

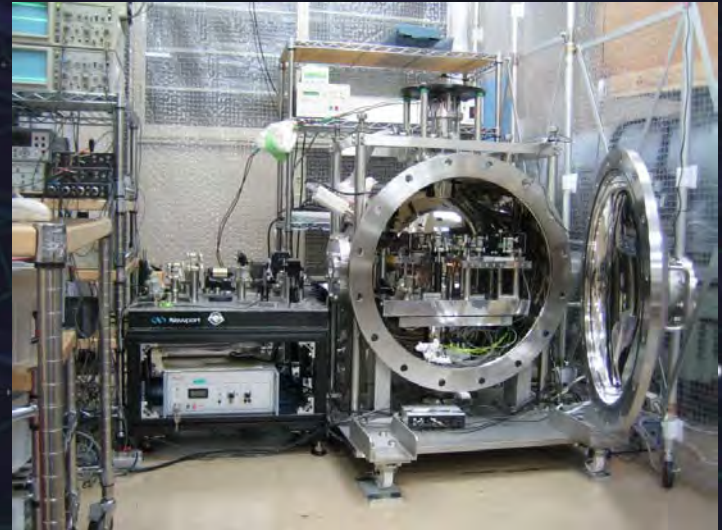


Suspended as pendulum  
(Res. Freq.  $\sim 1\text{Hz}$ )

Long baseline  
→ Accumulation of signal,  
**High sensitivity**

## TOBA

Obs. band 10mHz-1Hz



Torsion pendulum  
(Res. freq  $\sim 1\text{mHz}$ )

Shorter length  
→ Simple config.  
**Common-mode rejection**



# TOBA Sensitivity



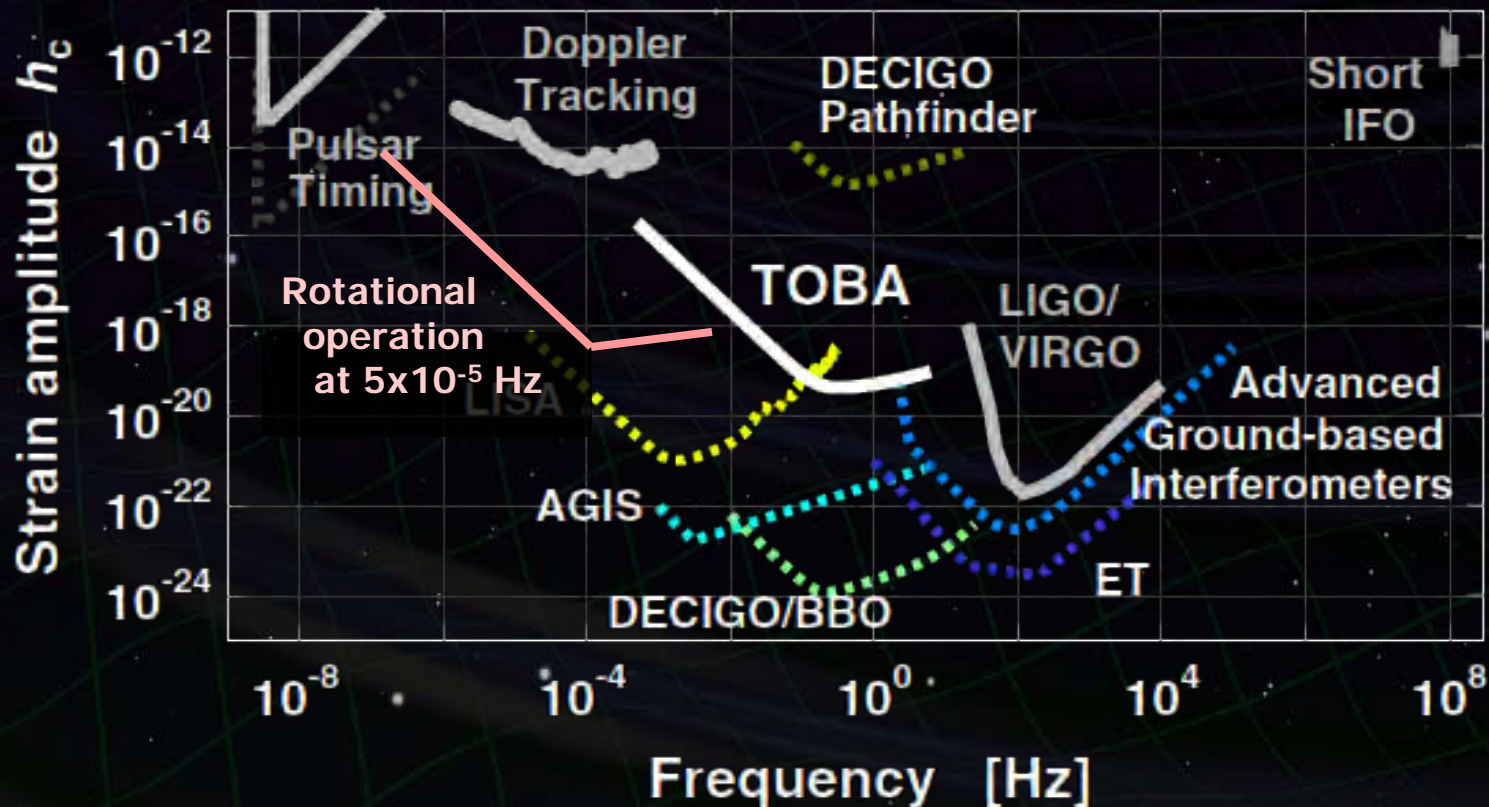
Assume realistic parameters

Test mass Aluminum 7,600kg, 10m

Laser source 10W

Temperature 4K

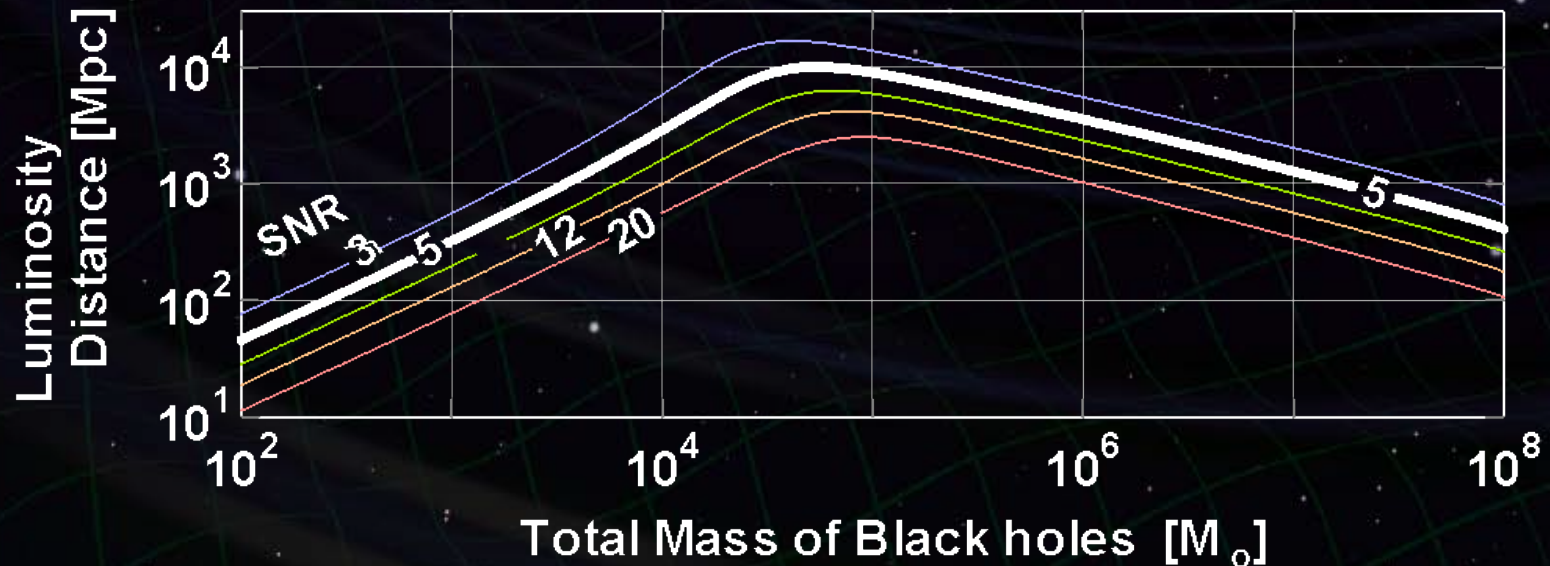
Bar length : 10m, Mass : 7600kg  
Laser source : 1064nm, 10W  
Cavity length : 1cm, Finesse : 100  
Bar Q-value :  $10^5$ , Temp: 4K  
Support Loss :  $10^{-10}$



# Observable range

## GWs from binary BH mergers

⇒ Obs. Range  $\sim 10\text{Gpc}$  ( $\sim 10^5 M_{\odot}$ , SNR = 5)



Calculation by K.Yagi

Observable GW  
energy density ratio

$$\Omega_{\text{gw}} \sim 10^{-7}$$

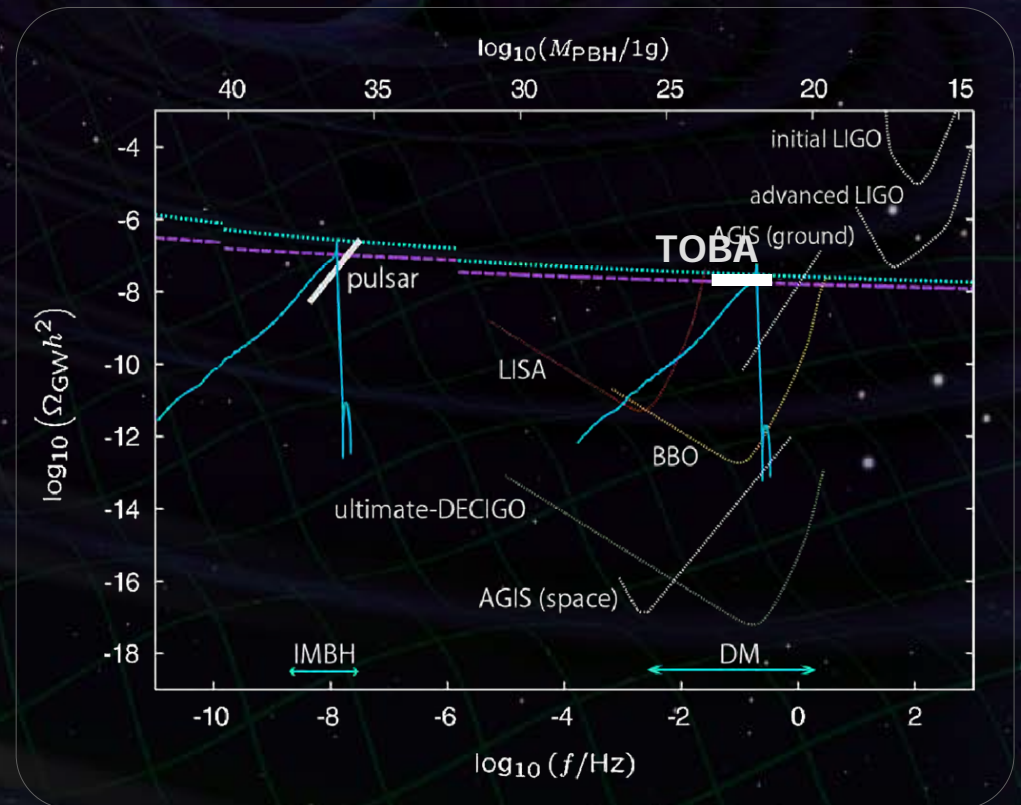
(1-yr observation)



Beat BBN upper limit

GW by primordial  
tensor perturbation

R.Saito and J.Yokoyama,  
PRL 102, 161101 (2009)



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Design and Status  
Space Demonstration



# 3. Summary

## **DECIGO : Fruitful Sciences**

**Very beginning of the Universe**

**Dark energy**

**Galaxy formation**

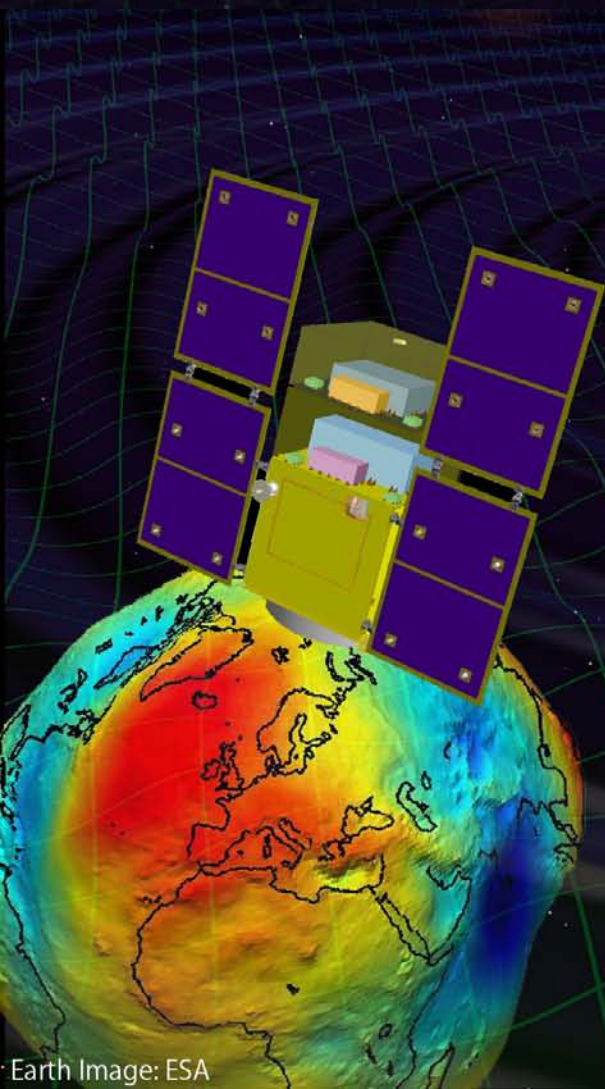
## **DECIGO Pathfinder**

**Important milestone for DECIGO**

**Strong candidate of JAXA's satellite series**

**SWIM – under operation in orbit**

**first precursor to space!**



Earth Image: ESA

End



Original  
Picture : Sora