

DECIGO

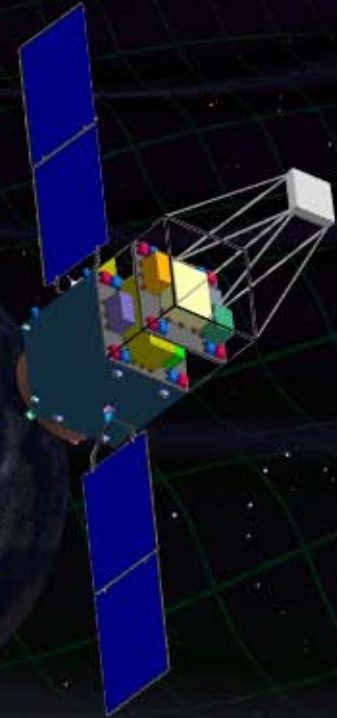
Masaki Ando

(Department of Physics, Kyoto University)

Original
Picture : Sora



Seiji Kawamura, Takashi Nakamura, Kimio Tsubono, Takahiro Tanaka, Ikkoh Funaki, Naoki Seto, Kenji Numata, Shuichi Sato, Nobuyuki Kanda, Takeshi Takashima, Kunihito Ioka, Kazuhiro Agatsuma, Tomotada Akutsu, Tomomi Akutsu, Koh-suke Aoyanagi, Koji Arai, Yuta Arase, Akito Araya, Hideki Asada, Yoichi Aso, Takeshi Chiba, Toshikazu Ebisuzaki, Motohiro Enoki, Yoshiharu Eriguchi, Masa-Katsu Fujimoto, Ryuichi Fujita, Mitsuhiro Fukushima, Toshifumi Futamase, Katsuhiko Ganzu, Tomohiro Harada, Tatsuaki Hashimoto, Kazuhiro Hayama, Wataru Hikida, Yoshiaki Himemoto, Hisashi Hirabayashi, Takashi Hiramatsu, Feng-Lei Hong, Hideyuki Horisawa, Mizuhiko Hosokawa, Kiyotomo Ichiki, Takeshi Ikegami, Kaiki T. Inoue, Koji Ishidoshiro, Hideki Ishihara, Takehiko Ishikawa, Hideharu Ishizaki, Hiroyuki Ito, Yousuke Itoh, Shogo Kamagasako, Nobuki Kawashima, Fumiko Kawazoe, Hiroyuki Kiriwaka, Naoko Kishimoto, Kenta Kiuchi, Shiho Kobayashi, Kazunori Kohri, Hiroyuki Koizumi, Yasufumi Kojima, Keiko Kokeyama, Wataru Kokuyama, Kei Kotake, Yoshihide Kozai, Hideaki Kudoh, Hiroo Kunimori, Hitoshi Kuninaka, Kazuaki Kuroda, Kei-ichi Maeda, Hideo Matsuhara, Yasushi Mino, Osamu Miyakawa, Shinji Miyoki, Mutsuko Y. Morimoto, Tomoko Morioka, Toshiyuki Morisawa, Shigenori Moriwaki, Shinji Mukohyama, Mitsuru Musha, Shigeo Nagano, Isao Naito, Noriyasu Nakagawa, Kouji Nakamura, Hiroyuki Nakano, Kenichi Nakao, Shinichi Nakasuka, Yoshinori Nakayama, Erina Nishida, Kazutaka Nishiyama, Atsushi Nishizawa, Yoshito Niwa, Masatake Ohashi, Naoko Ohishi, Masashi Ohkawa, Akira Okutomi, Kouji Onozato, Kenichi Oohara, Norichika Sago, Motoyuki Saijo, Masaaki Sakagami, Shin-ichiro Sakai, Shihori Sakata, Misao Sasaki, Takashi Sato, Masaru Shibata, Hisaaki Shinkai, Kentaro Somiya, Hajime Sotani, Naoshi Sugiyama, Yudai Suwa, Hideyuki Tagoshi, Kakuru Takahashi, Keitaro Takahashi, Tadayuki Takahashi, Hirotaka Takahashi, Ryuichi Takahashi, Ryutarō Takahashi, Takamori Akiteru, Tadashi Takano, Keisuke Taniguchi, Atsushi Taruya, Hiroyuki Tashiro, Mitsuru Tokuda, Masao Tokunari, Morio Toyoshima, Shinji Tsujikawa, Yoshiki Tsunesada, Ken-ichi Ueda, Masayoshi Utashima, Hiroshi Yamakawa, Kazuhiro Yamamoto, Toshitaka Yamazaki, Jun'ichi Yokoyama, Chul-Moon Yoo, Shijun Yoshida, Taizoh Yoshino



1. DECIGO

Overview and Science

Pre-conceptual Design

2. DECIGO Pathfinder

Overview and Science

Design and Status

3. Summary



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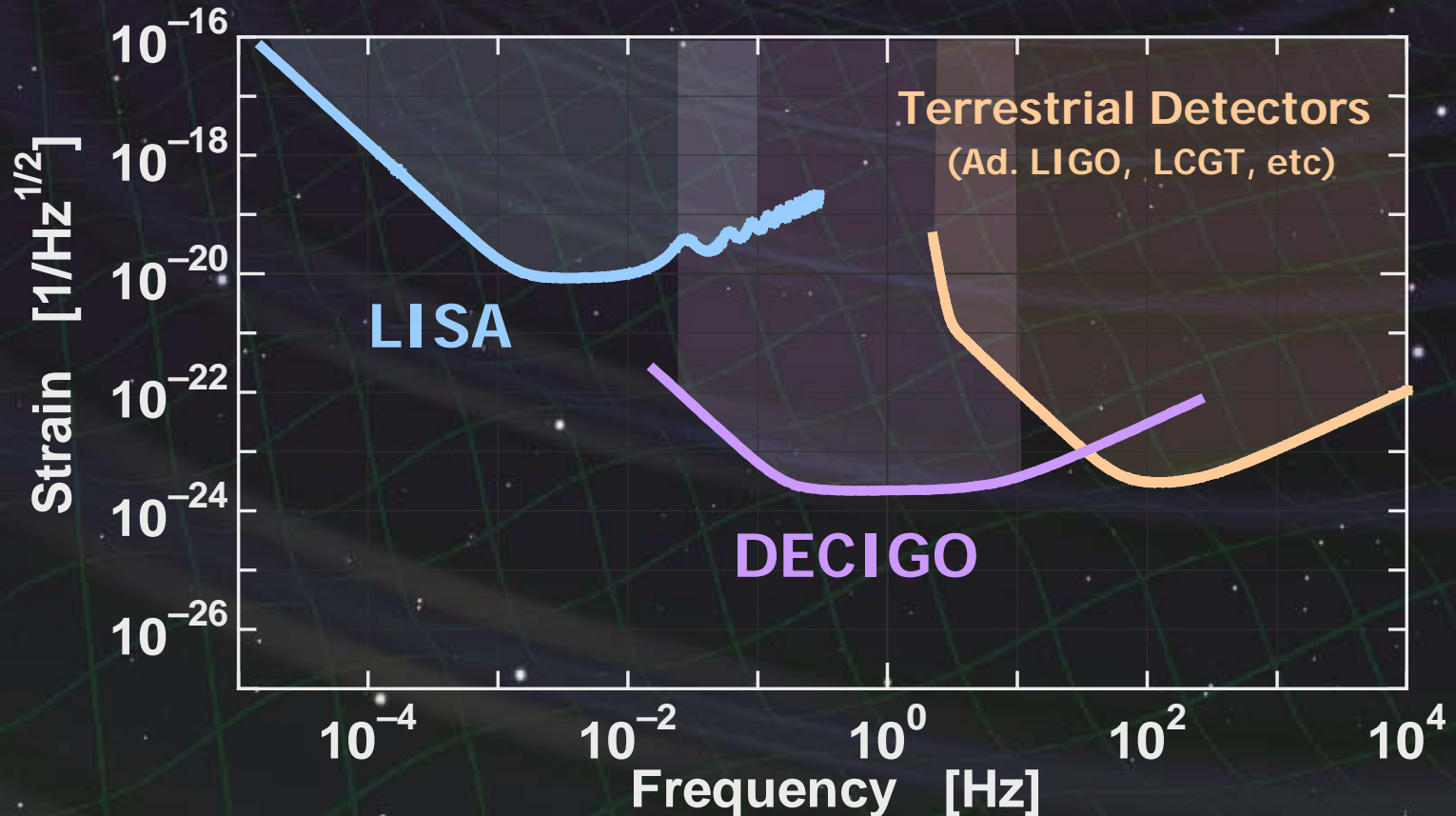
DECIGO

DECIGO (Deci-hertz interferometer Gravitational wave Observatory)

Space GW antenna ~2024
Obs. band around 0.1 Hz



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



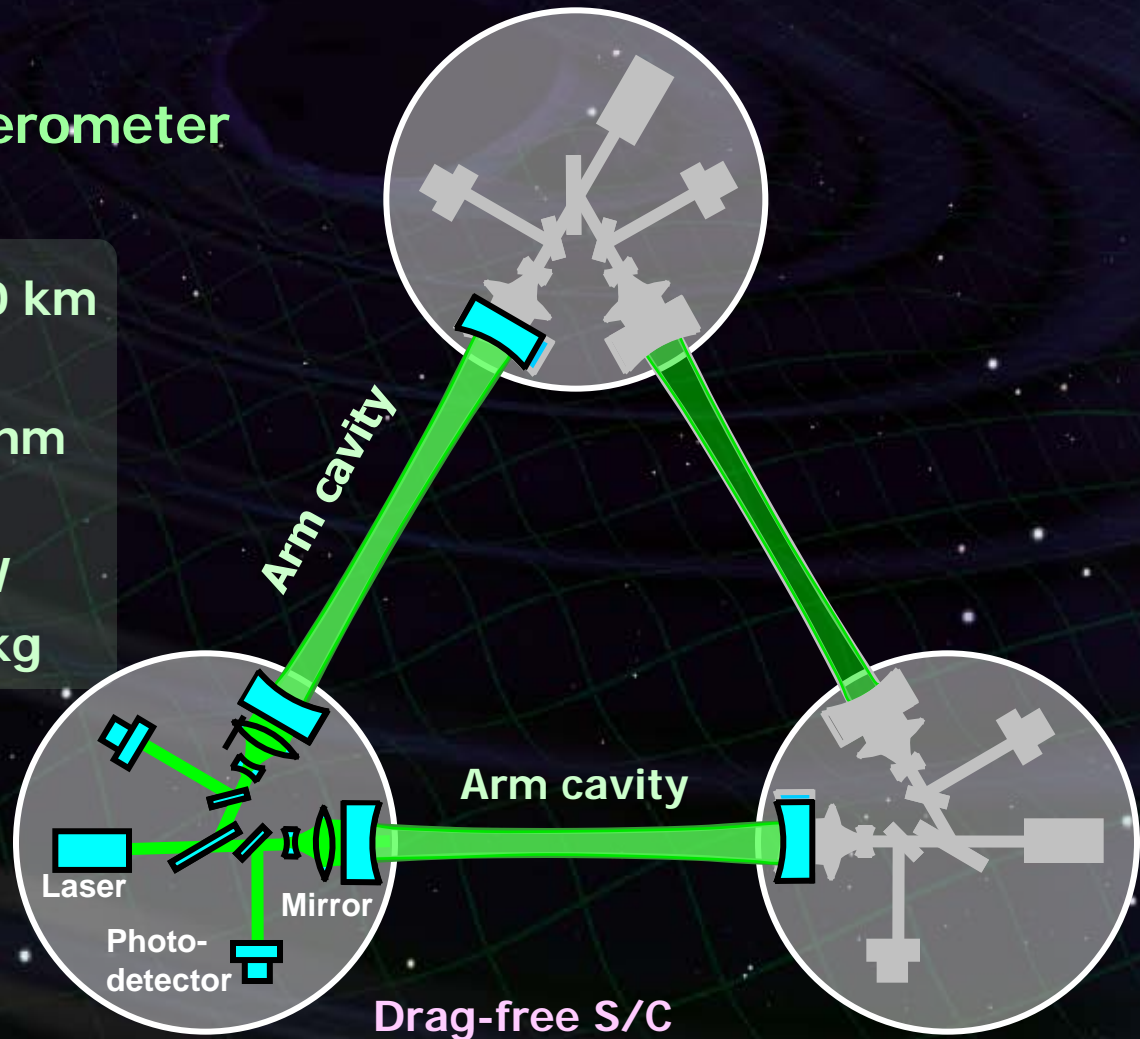
Pre-Conceptual Design

Interferometer Unit:

Differential FP interferometer

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

S/C: drag free
3 interferometers

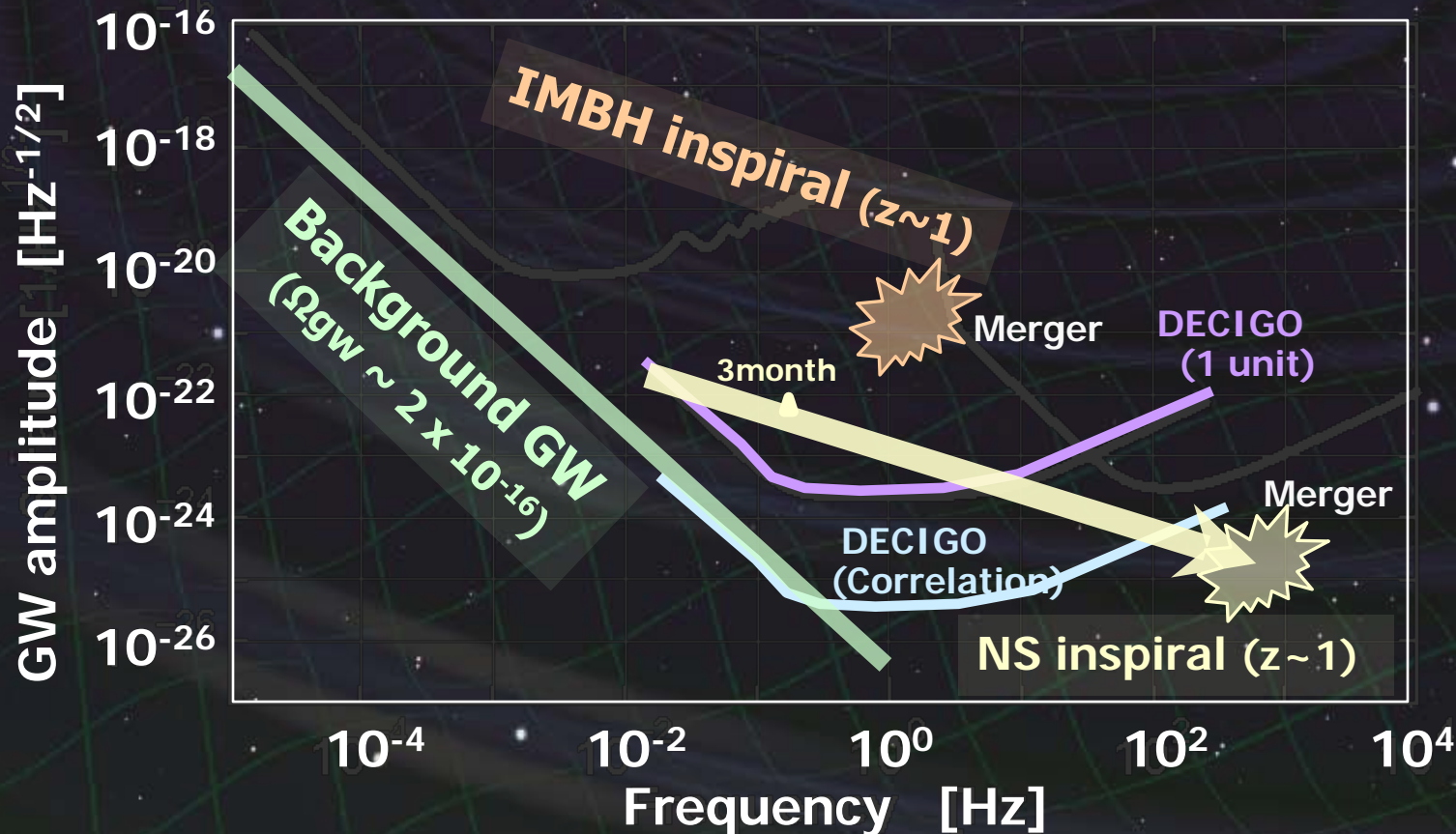


Targets and Science

IMBH binary inspiral
NS binary inspiral
Stochastic background



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



Constraint on dark energy

DECIGO will observe

10^{4-5} NS binaries at $z \sim 1$

↳ Precise 'clock' at cosmological distance

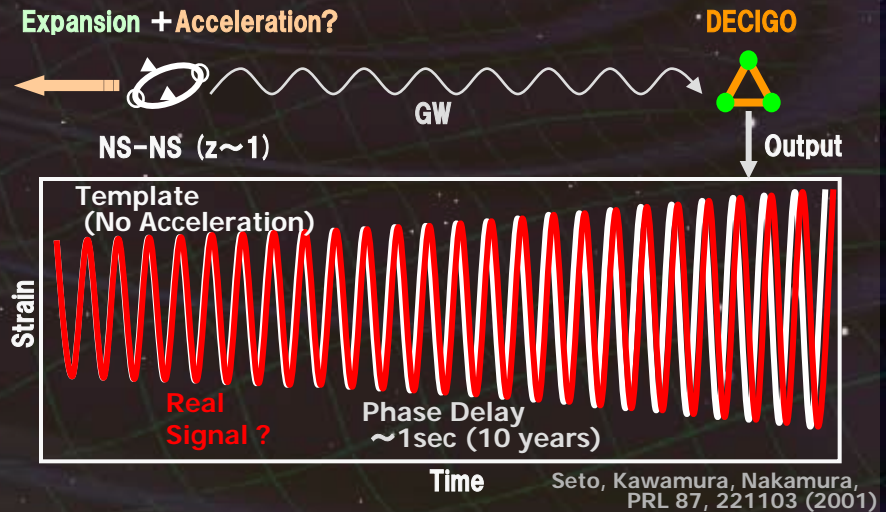
'Standard Siren'

Relationship between distance and redshift

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

Distance: chirp waveform

Redshift: host galaxy



Determine cosmological parameters

$$\Delta\Omega_m, \Delta\Omega_w, \Delta w \approx 1\%$$

Absolute and independent measurement

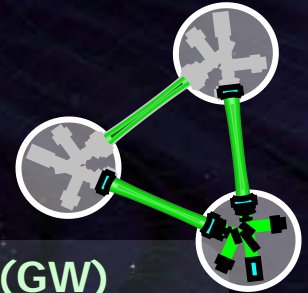
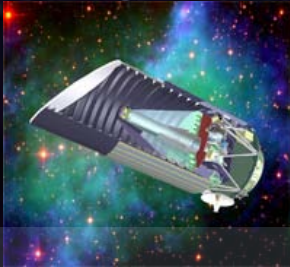
Angular resolution

$\sim 10\text{arcmin}$ (1 detector)
 $\sim 10\text{arcsec}$ (3 detectors)

at $z=1$

Standard Sources

Fig. from
SNAP
web page



Supernova (EM wave)
'Standard Candle'

Neutron-star binary (GW)
'Standard Siren'

**Absolute power
or amplitude**

Extrapolated from
nearby events

<

General Relativity

Event rate

2000/yr (SNAP)

<

10^{4-5} /yr (DECIGO)

Error in distance

~10%

≈

10% at $z=1$

**Identification
of host galaxy**

Easy?

>

Require multiple detectors
or statistics

Others

Uncertainty by
dust absorption

<

Negligible interaction
with matters

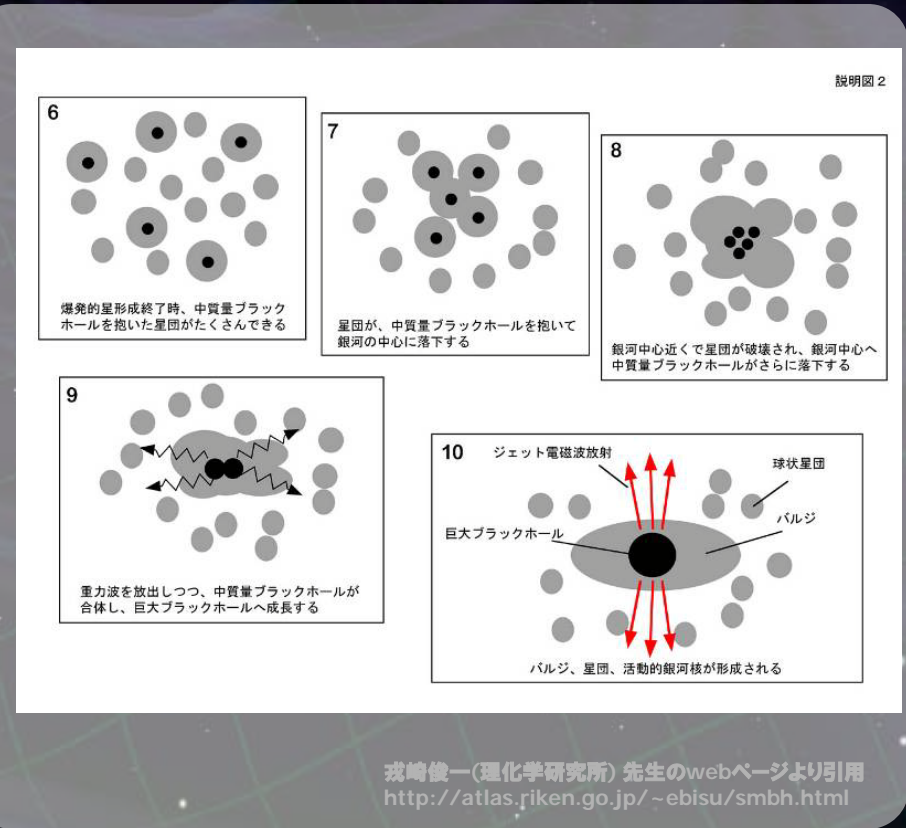
R.Takahashi (2006)

IMBH inspiral and Merger

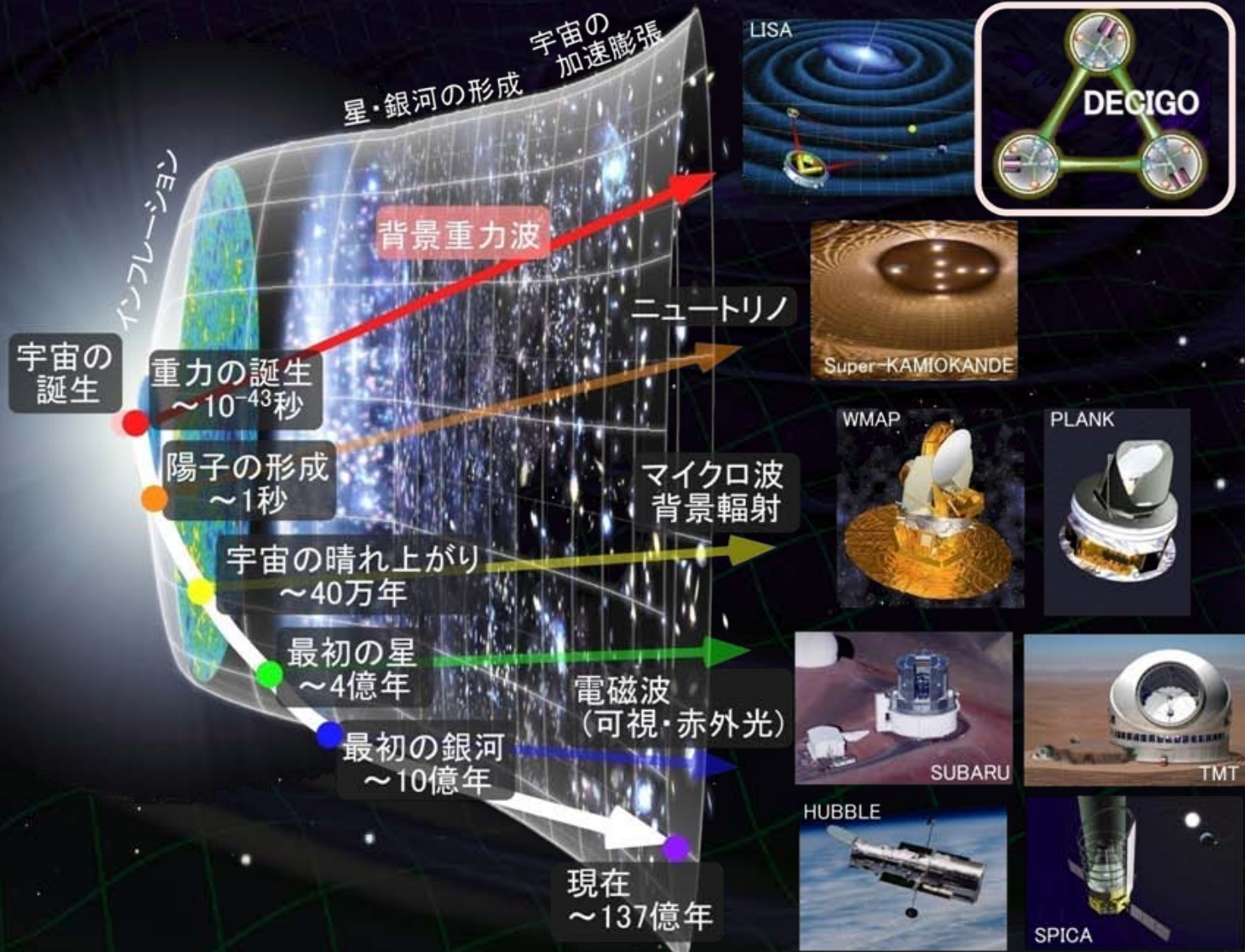
DECIGO will observe
Intermediate-mass BH (IMBH)
binary merger with
SNR > 6000 for $z \sim 1$ source



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



Stochastic Background GWs



LCGT and DECIGO

LCGT (~2014)

Terrestrial Detector

→ High frequency events

Target: GW detection

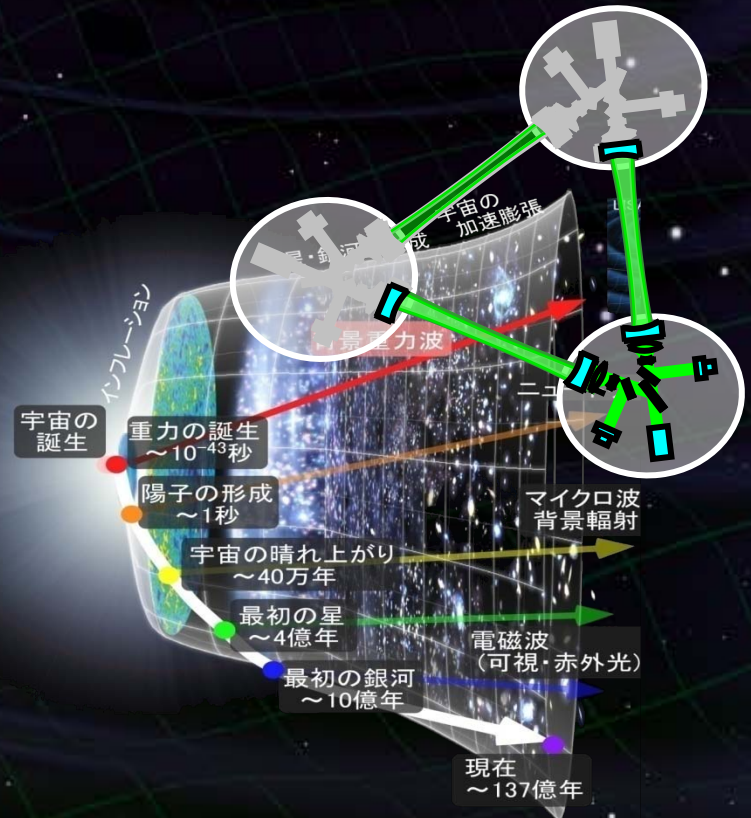


DECIGO (~2024)

Space observatory

→ Low frequency sources

Target: GW astronomy



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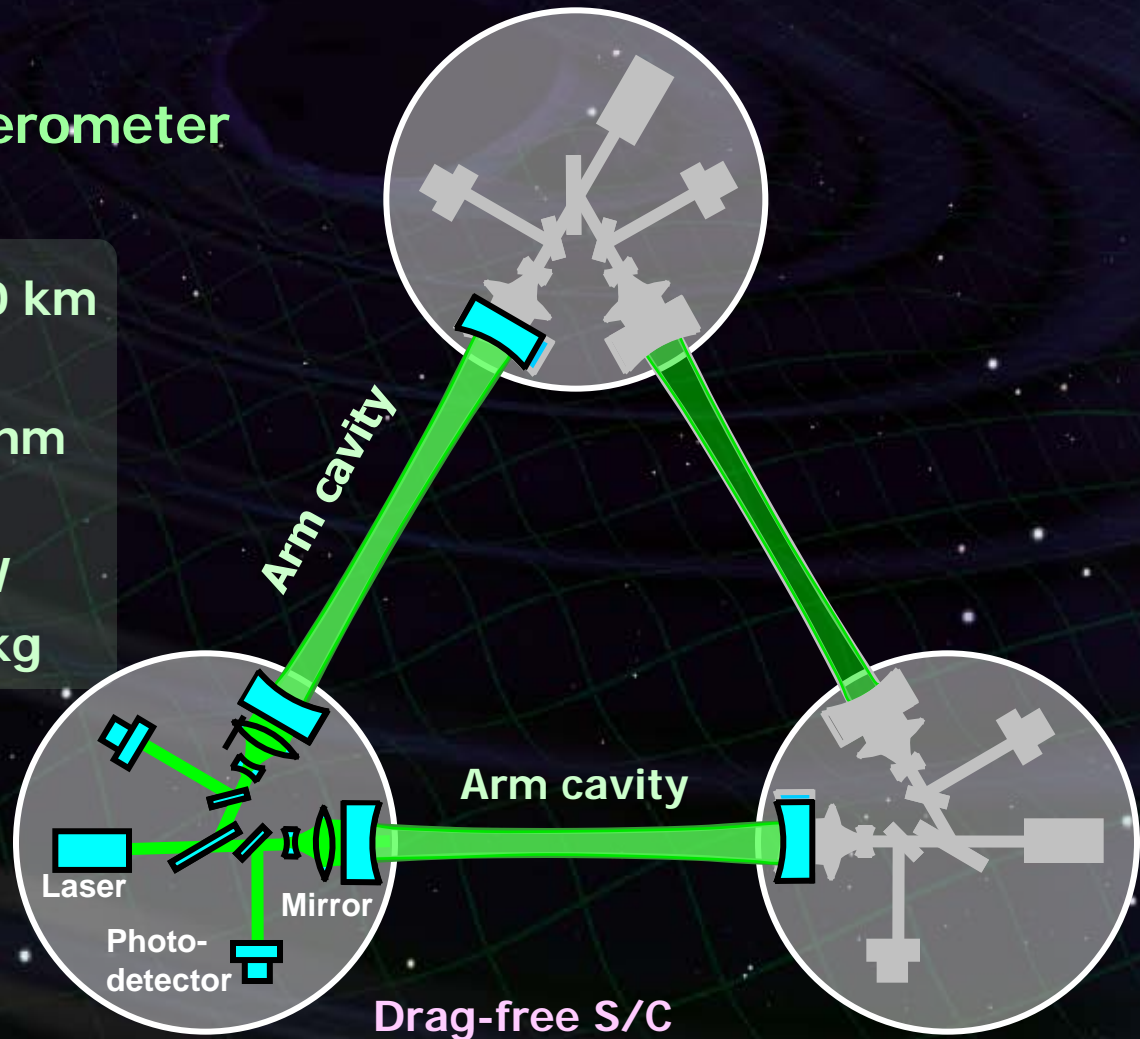
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3 interferometers

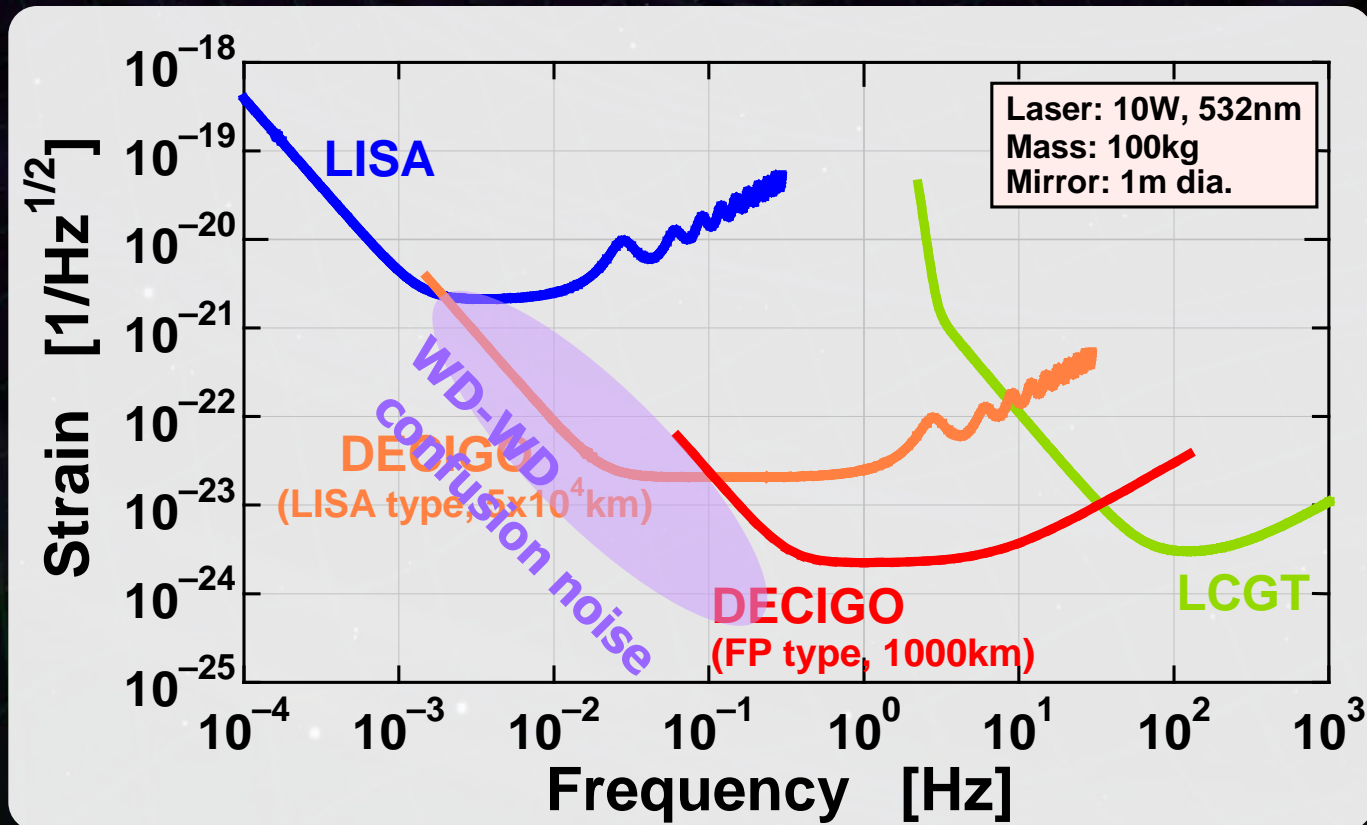


Interferometer Design

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

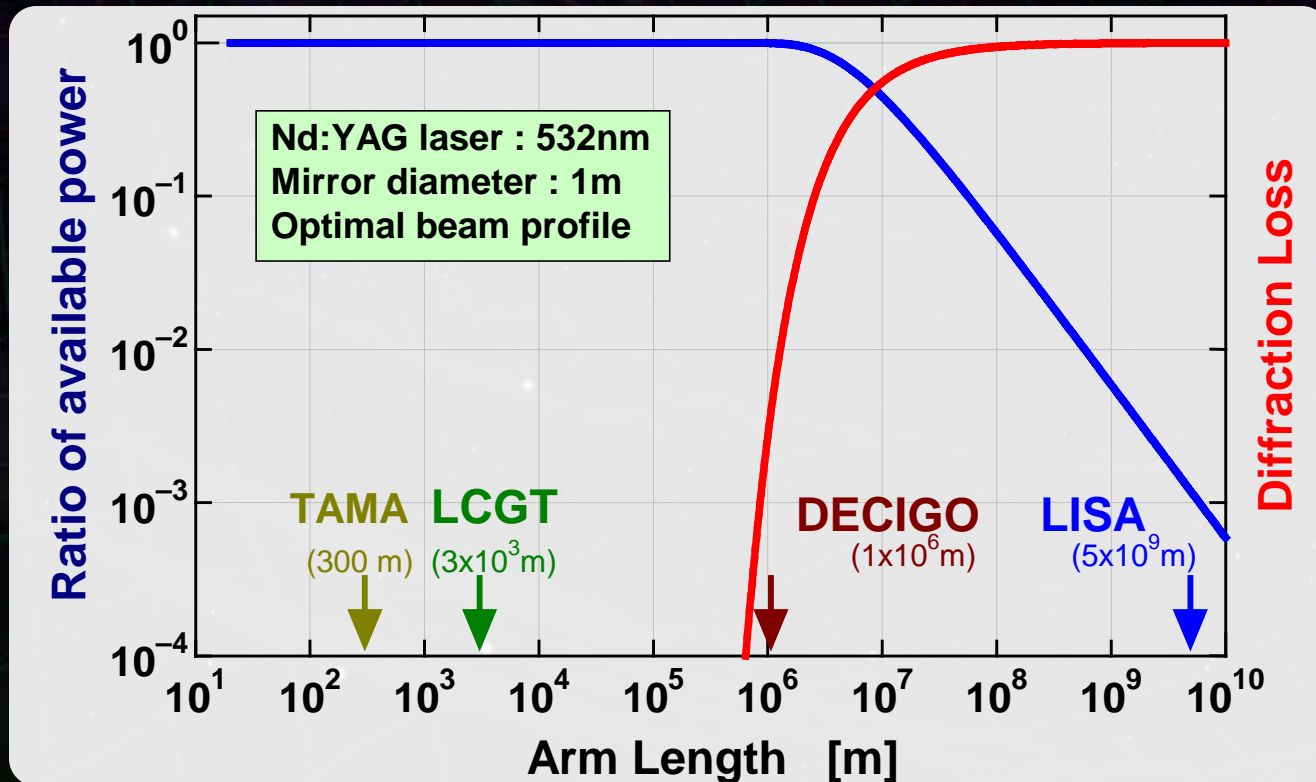
Laser wavelength : 532nm

Mirror diameter: 1m

Optimal beam size



1000 km
is almost max.



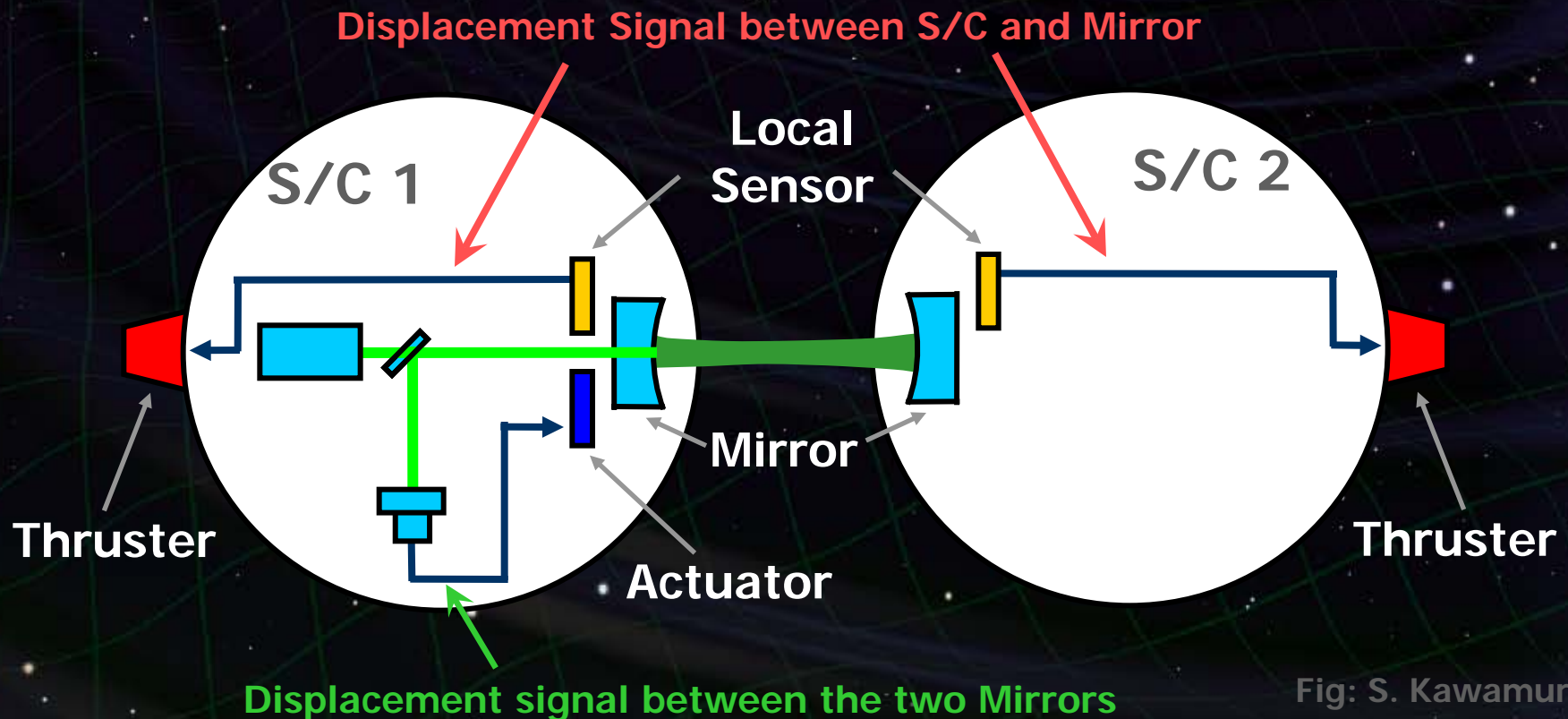
Cavity and S/C control

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



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

Halo orbit around L2 (or L1)

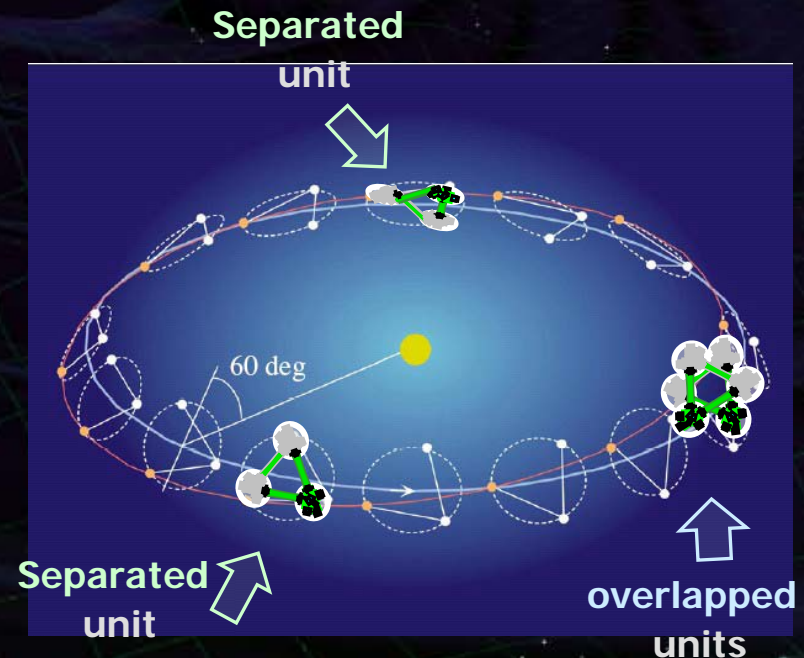
Relative acc. $4 \times 10^{-7} \text{ m/s}^2$
(Mirror force $\sim 10^{-4} \text{ N}$)

Constellation

4 interferometer units

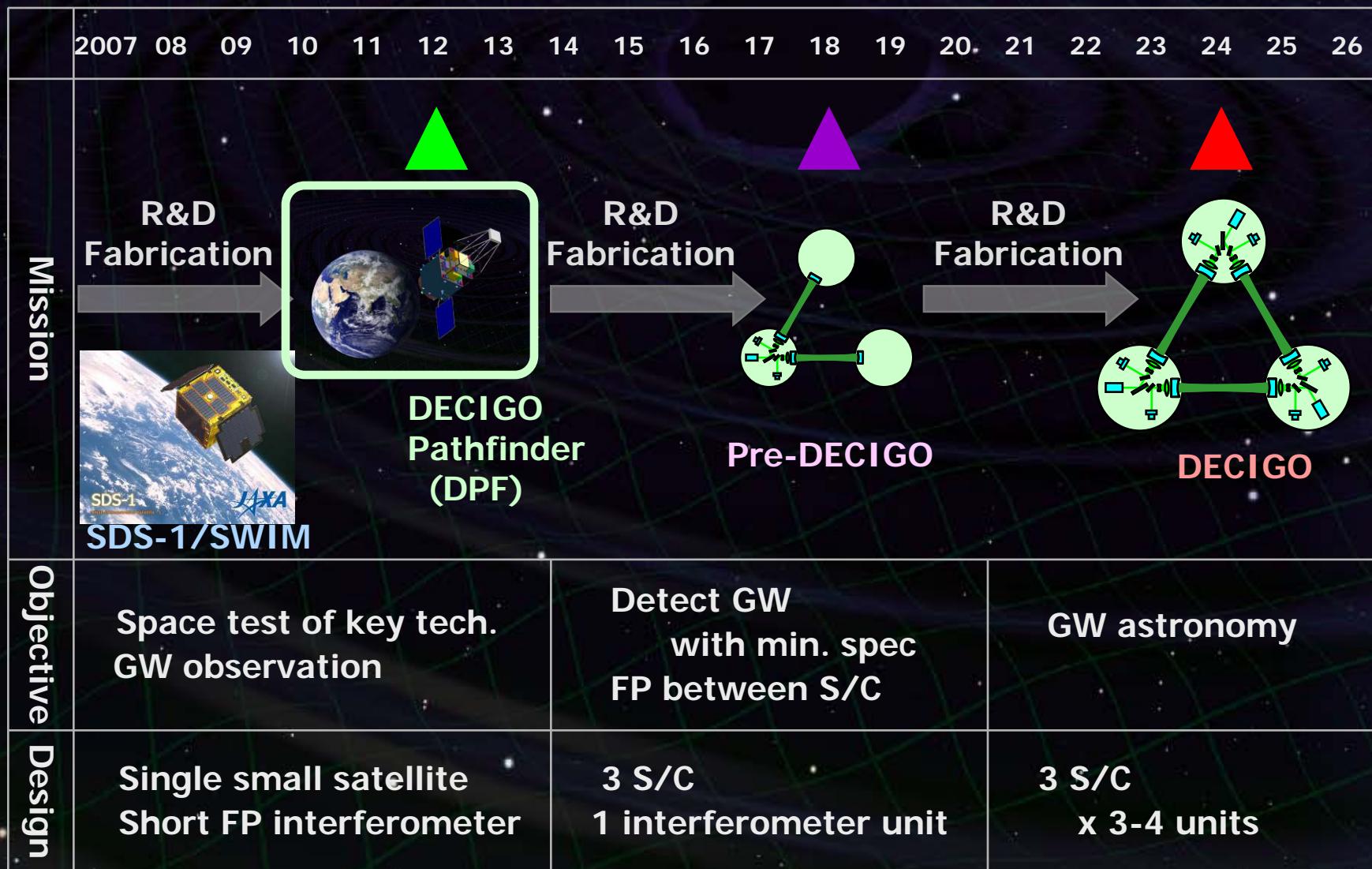
2 overlapped units \rightarrow Cross correlation

2 separated units \rightarrow Angular resolution



Roadmap

Figure: S.Kawamura



Organization

PI: Kawamura (NAOJ)
Deputy: Ando (Tokyo)

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

Pre-DECIGO
Sato (Hosei)

Detector
Numata
(Maryland)
Ando (Kyoto)

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

Satellite
Funaki (ISAS)

DECIGO pathfinder
Leader: Ando (Tokyo)
Deputy: Takashima (ISAS)

Design phase
Mission phase

Detector
Ando
(Kyoto)

Laser
Ueda
(ILS)
Musya
(ILS)

Housing
Sato
(Hosei)

Drag free
Moriwaki
(Tokyo)
Sakai
(ISAS)

Thruster
Funaki
(ISAS)

Bus
Takashim
a (ISAS)

Data
Kanda
(Osaka
city)

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DECIGO-PF

DECIGO Pathfinder (DPF)

First milestone mission for DECIGO

Shrink arm cavity

DECIGO 1000km → DPF 30cm

Single satellite

(Payload ~ 1m³ , 350kg)

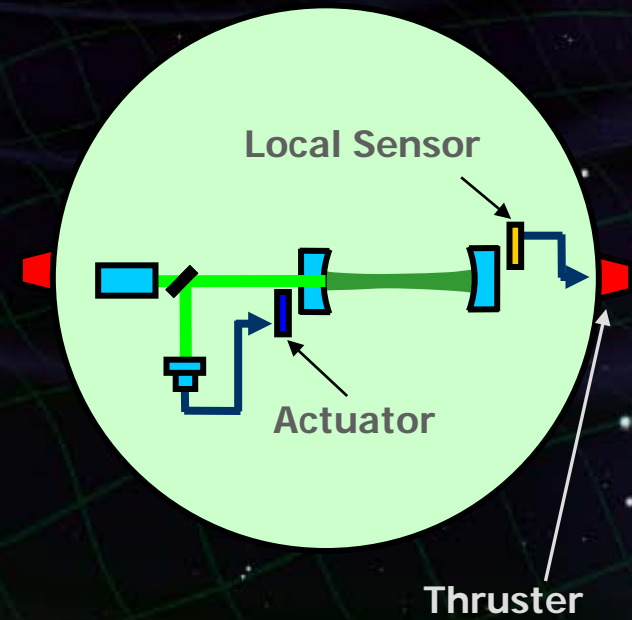
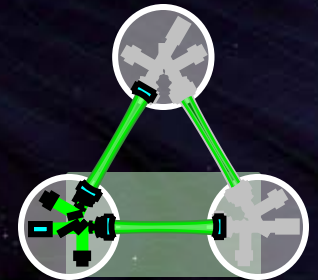
Low-earth orbit

(Altitude 500km, sun synchronous)

30cm FP cavity with 2 test masses

Stabilized laser source

Drag-free control



DPF and DECIGO

DPF requirements

Precise meas.
by IFO



Disp. noise
 $6 \times 10^{-16} \text{ m/Hz}^{1/2}$

$4 \times 10^{-18} \text{ m/Hz}^{1/2}$

Force noise
 $10^{-14} \text{ N/Hz}^{1/2}$

$10^{-17} \text{ N/Hz}^{1/2}$

Stab. Laser



Freq. Stability
 $0.5 \text{ Hz/Hz}^{1/2}$

$1 \text{ Hz/Hz}^{1/2}$

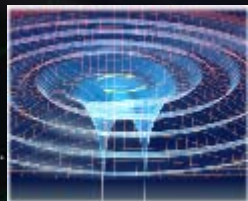
Drag-free
control



Satellite disp.
 $10^{-9} \text{ m/Hz}^{1/2}$

Thruster noise
 $10^{-7} \text{ N/Hz}^{1/2}$

GW Obs.



0.1 Hz band
Observation and
Data analysis

DECIGO requirements

1000km FP cavity
IFO control in space
Low external force
Large optics

Ultra stable Laser
Stabilization of source
Stabilization by long arm

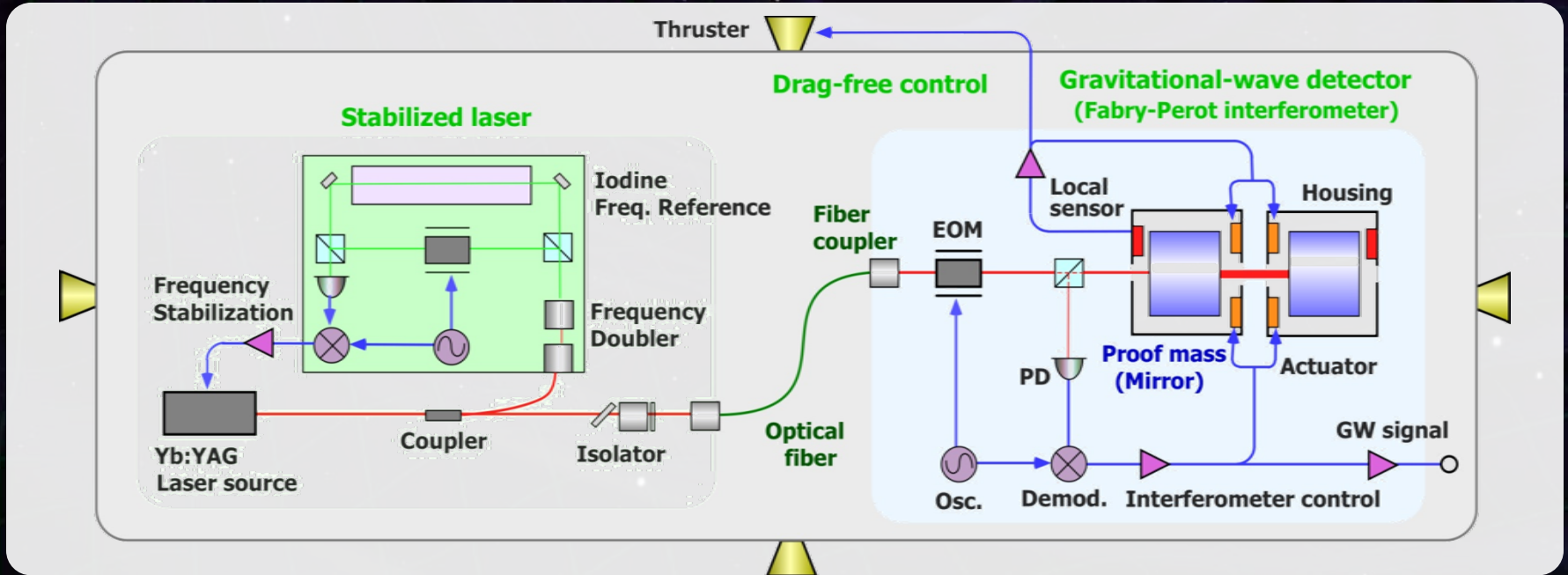
Formation flight
Stable orbit
Inter S/C Ranging
Drag-free control
Low-noise thruster

Observation
Data procession
Data analysis
Triggered search

DPF mission payload

Mission weight : ~150kg
Mission space : ~90 x 90 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

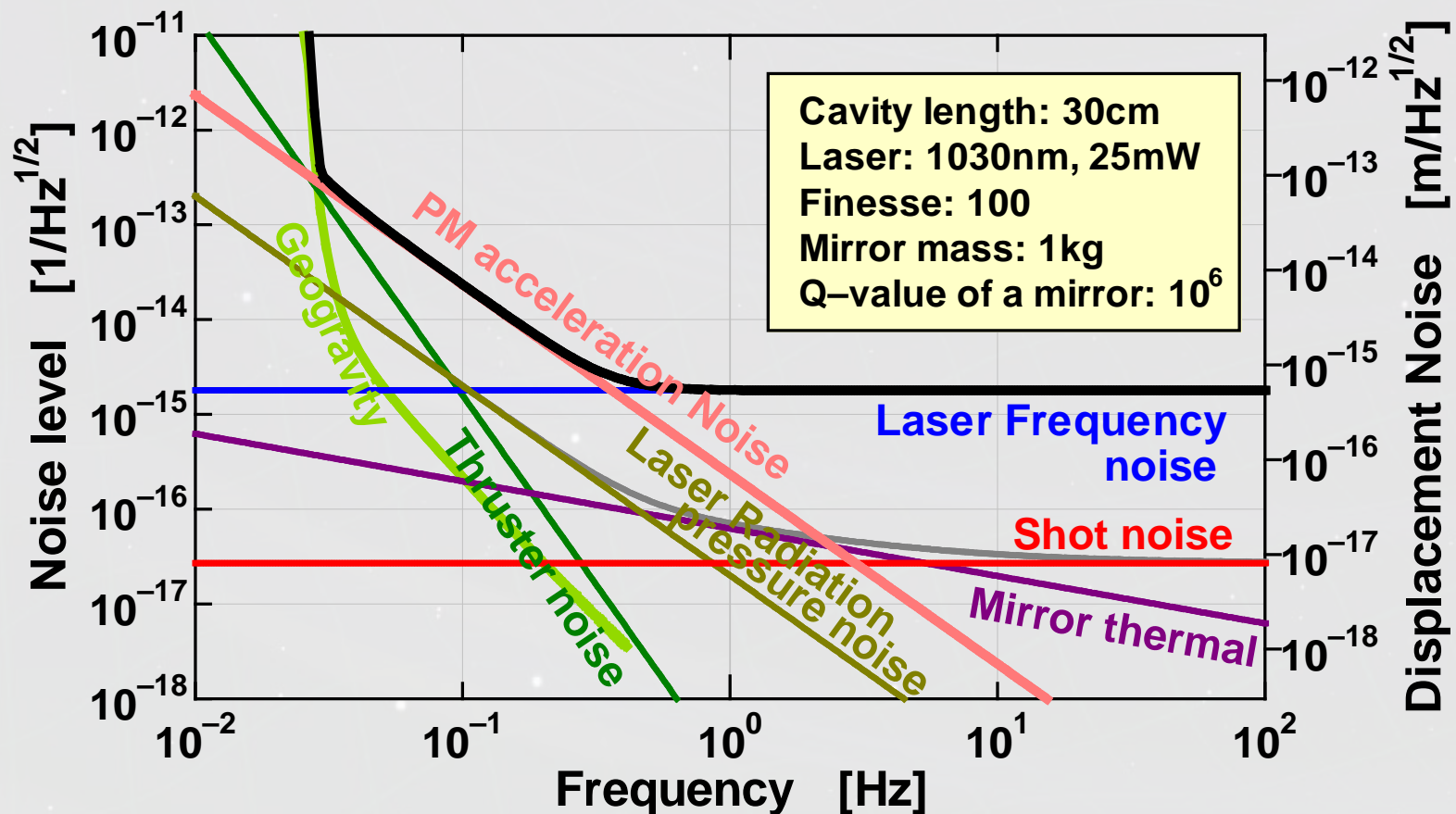
Finesse : 100
Length : 30cm
Test mass : 1kg
Signal extraction by PDH

DPF Sensitivity

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

Satellite mass : 350kg, Area: 2m²
Altitude: 500km
Thruster noise: $0.1\mu\text{N}/\text{Hz}^{1/2}$

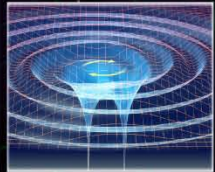
(Preliminary parameters)



Objectives of DPF

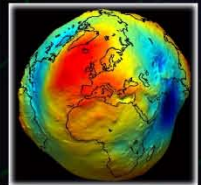
Observation

Gravitational wave

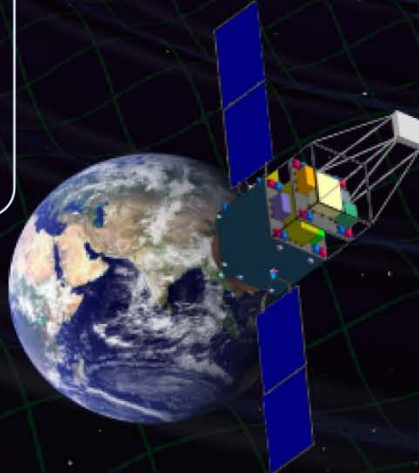


Intermediate-mass
inspiral and merger

Earth gravity



Environ. monitor
Geoid resolution
 $\sim 1\text{mm}$.



Science Technology

Space interferometer

Precise meas. in space

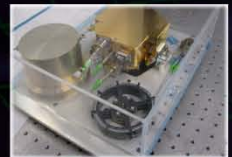
$6 \times 10^{-16} \text{ m/Hz}^{1/2}$



Stabilized laser

High stability in Space

$0.5 \text{ Hz/Hz}^{1/2}$



Drag-free control

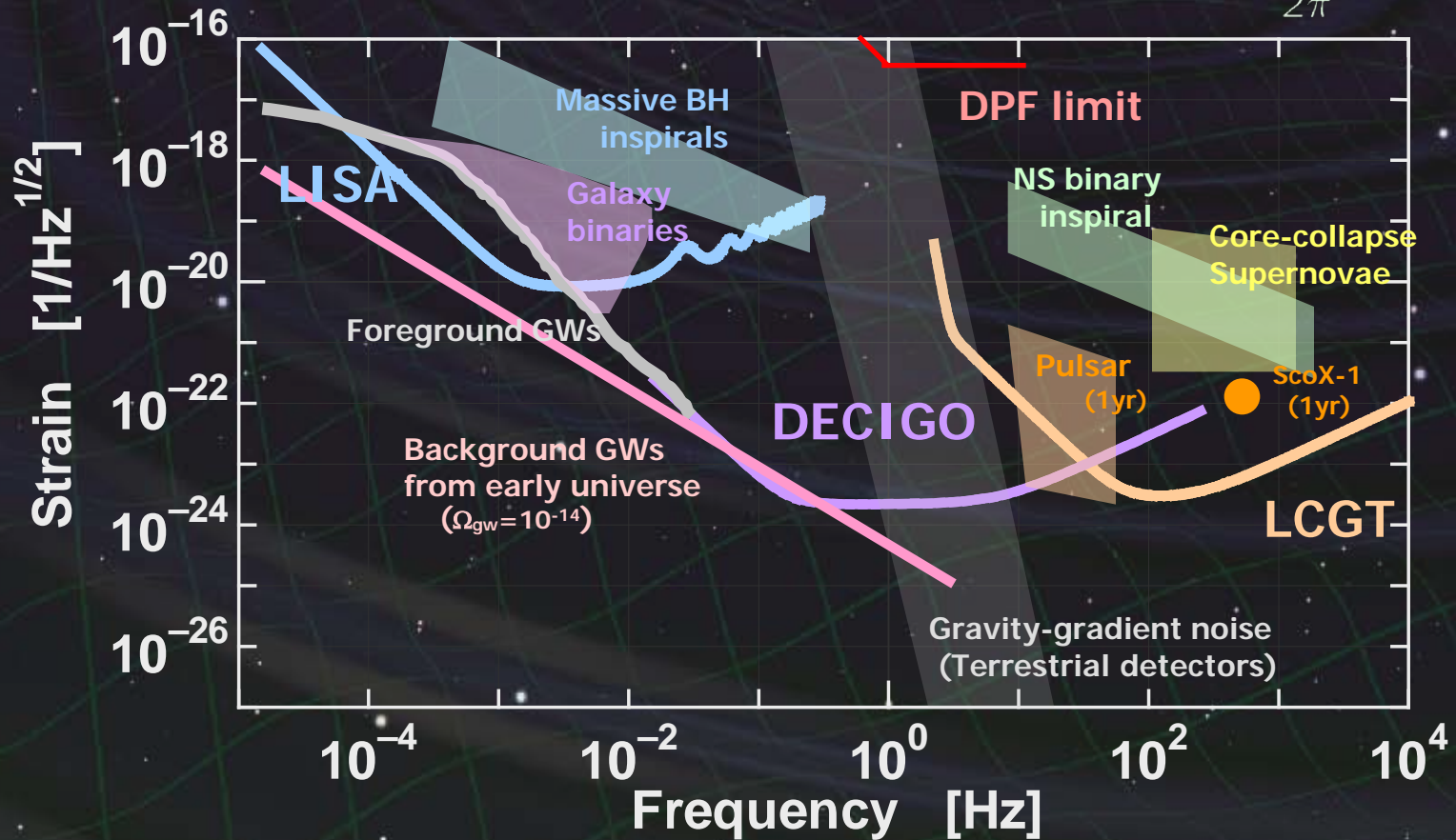
Low-noise control
with passive stab.



DPF sensitivity

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

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



GW target of DPF

Blackholes events in our galaxy

IMBH inspiral and merger

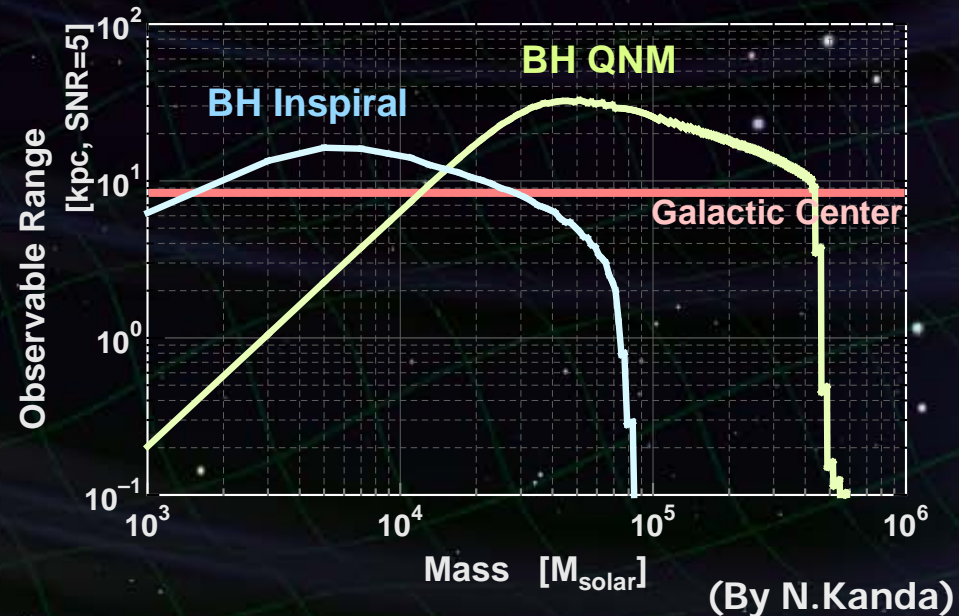
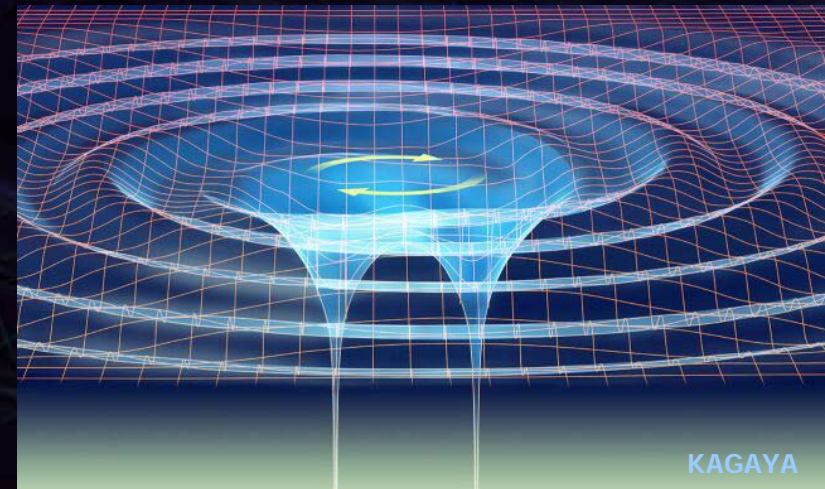
$h \sim 10^{-15}$, $f \sim 4$ Hz
Distance 10kpc, $m = 10^3 M_{\text{sun}}$
Obs. Duration (~ 1000 sec)

BH QNM

$h \sim 10^{-15}$, $f \sim 0.3$ Hz
Distance 1Mpc, $m = 10^5 M_{\text{sun}}$

Observable range reaches
the Galactic center (SNR ~ 5)

Hard to access by others
→ Original observation



DPF targets

BHs in Globular clusters

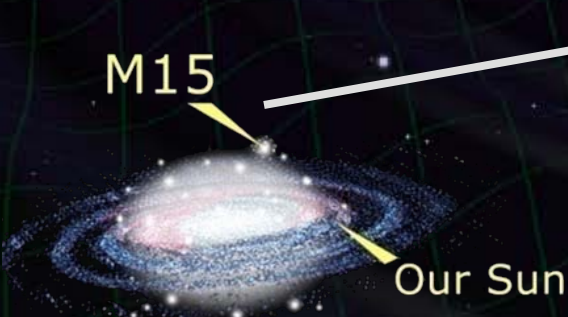
BH masses estimated from star motion

⇒ Estimate SNR of GW signals

Equal mass, Mass ratio 1:1/3, 100Msun BH capture

Credit: NASA, STScI

Globular clusters known to have black holes



Milky Way Galaxy
(artist's concept)

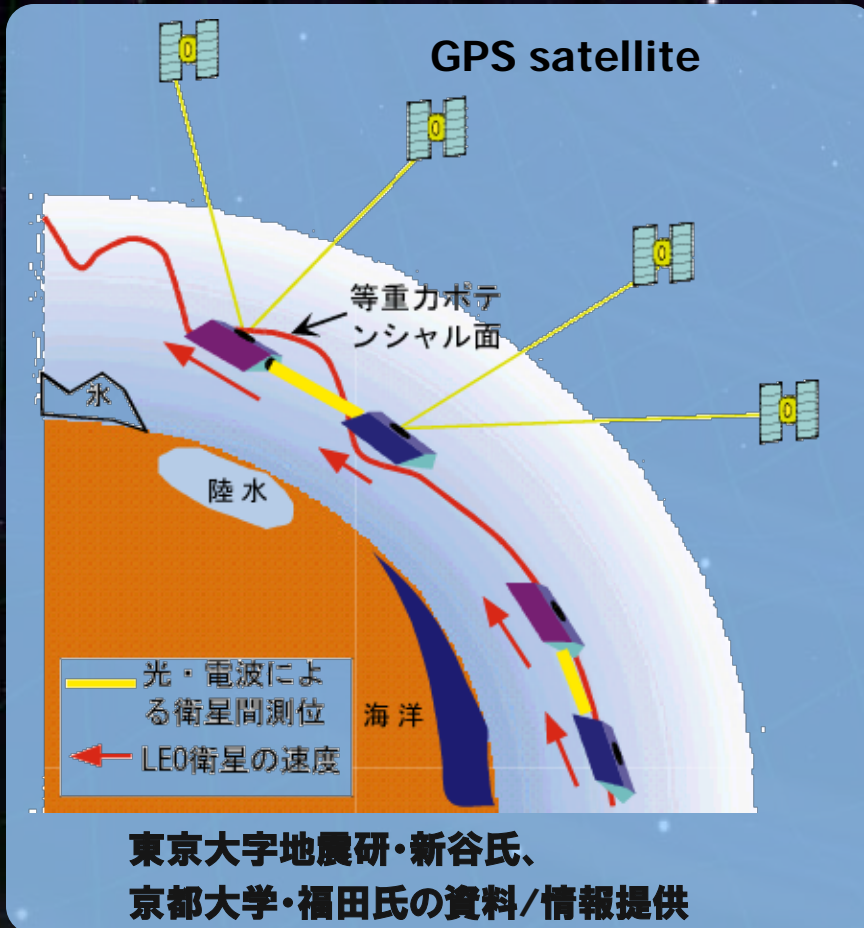
(~ 150 Globular Clusters
in our Galaxy)

NGC#	BH質量 [Msun]	距離 [kpc]	SNR (同質量)	SNR (1:1/3)	SNR +100Msun	速度分散 [km/sec]
6441	12423.8	11.2	36.4	22.2	3.7	19.5
6256	4753.6	6.9	26.6	16.2	4.3	15.4
7078	4387.8	10.3	16.6	10.2	2.8	15.1
6093	3720.3	10.0	14.9	9.1	2.7	14.5
104	820.0	4.5	9.4	5.7	3.6	10
1851	1348.5	12.1	5.3	3.2	1.6	11.3
6681	820.0	9.0	4.7	2.9	1.8	10
6293	365.6	8.8	2.5	1.5	1.4	8.2
5286	443.8	11.0	2.3	1.4	1.2	8.6
6522	227.8	7.8	1.9	1.1	1.3	7.3
5904	142.0	7.5	1.3	0.8	1.1	6.5
6325	133.3	8.0	1.2	0.7	1.0	6.4
6752	45.0	4.0	0.9	0.6	1.3	4.9
7099	89.3	8.0	0.8	0.5	0.9	5.8
6284	170.7	15.3	0.7	0.5	0.6	6.8

(By N.Seto)

Gravity of the Earth

Measure gravity field of the Earth for Satellite Orbits



Determine global gravity field
→ Density distribution
Monitor of change in time
Ground water motion
Strains in crusts by
earthquakes and volcanoes

Observation Gap
between GRACE and GRACE-FO
(2012-16)
→ DPF contribution
in international network

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DPF satellite

DPF Payload

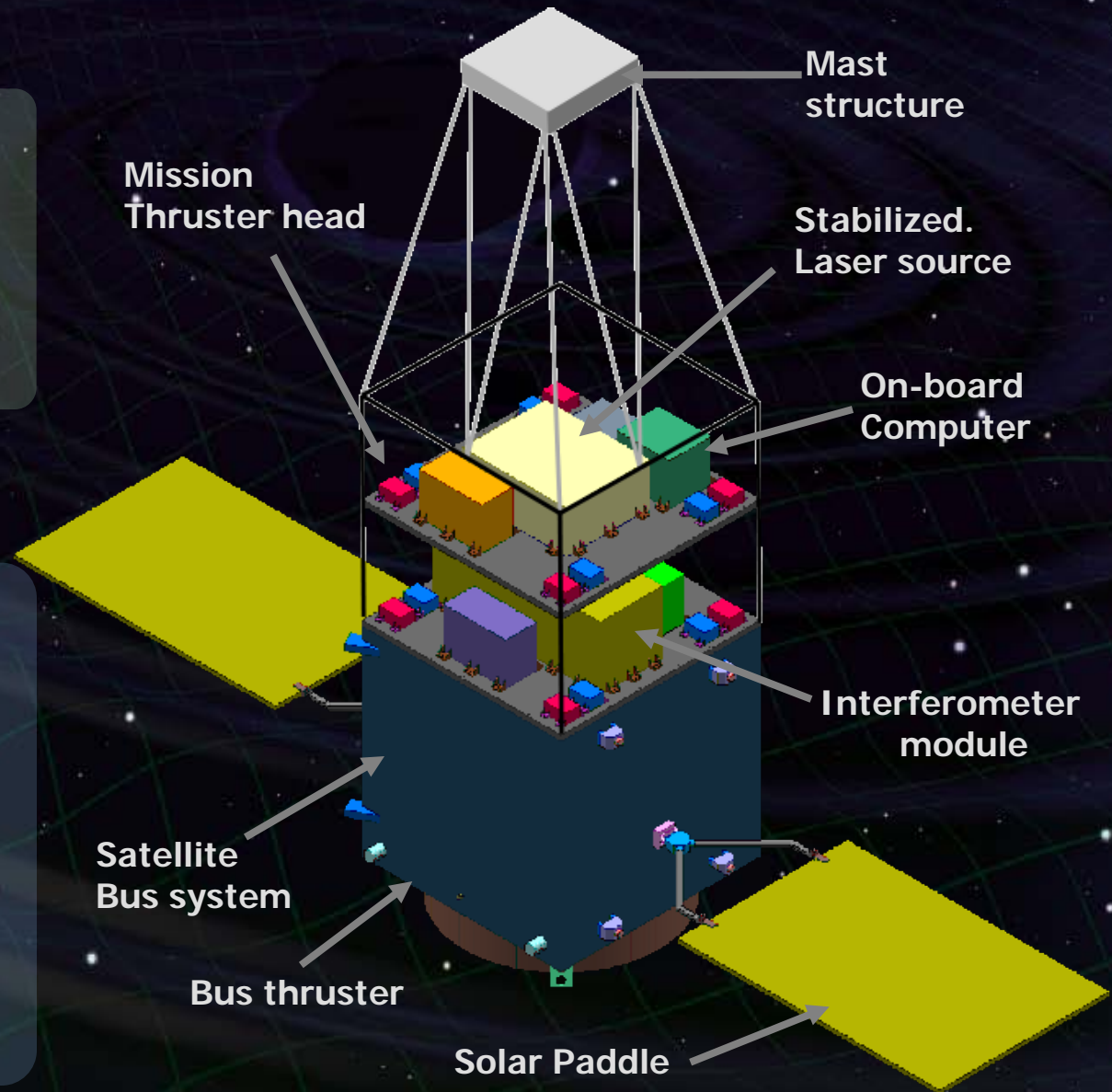
Size : 950mm cube
Weight : 150kg
Power : 130W
Data Rate: 800kbps
Mission thruster x12

Power Supply
SpW Comm.

Satellite Bus

('Standard bus' system)

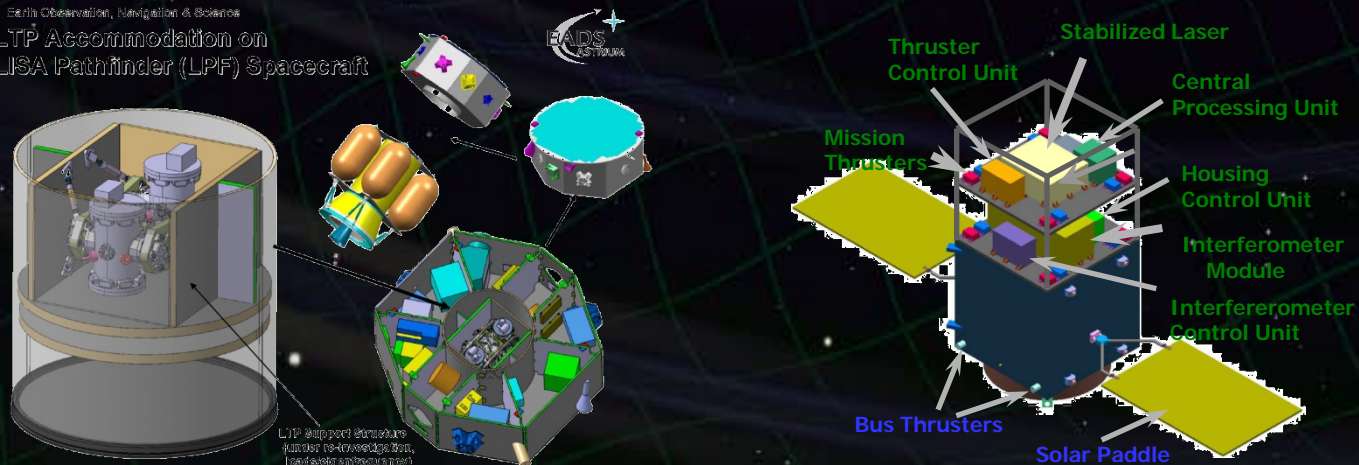
Size :
950x950x1100mm
Weight : 200kg
SAP : 960W
Battery: 50AH
Downlink : 2Mbps
DR: 1GByte
3N Thrusters x 4



Comparison with LPF

	LPF (LISA Pathfinder)	DPF (DECIGO Pathfinder)
Purpose	Demonstration for LISA	Demonstration for DECIGO GW observation
Launch	2010	~2013
Weight	Dedicated launcher (Vega)	Dedicated launcher (M-V follow-on)
Orbit	1,900 kg	350 kg
Test Mass	Halo orbit around L1	SSO altitude 500km
Laser source	Drag-free attitude control	Drag-free attitude control
Interferometer	Au-Pt alloy x2	TBD x2
Sensitivity	Nd:YAG (1064nm)	Yb:YAG (1030nm)
	Mach-Zehnder	Fabry-Perot
	$3 \times 10^{-14} \text{ m/s}^2/\text{Hz}^{1/2}$ (1mHz)	$1 \times 10^{-15} \text{ m/s}^2/\text{Hz}^{1/2}$ (0.1Hz)

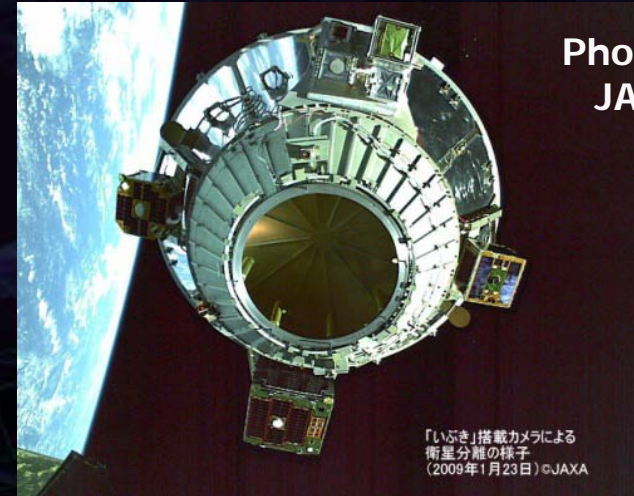
Earth Observation, Navigation & Science
LTP Accommodation on
LISA Pathfinder (LPF) Spacecraft



SWIM launch

Test of signal processing
and control system

SWIM (Space-wire Demonstration module)
on **SDS-1** satellite
Launched in Jan. 23, 2009



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



SWIM μ v : 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



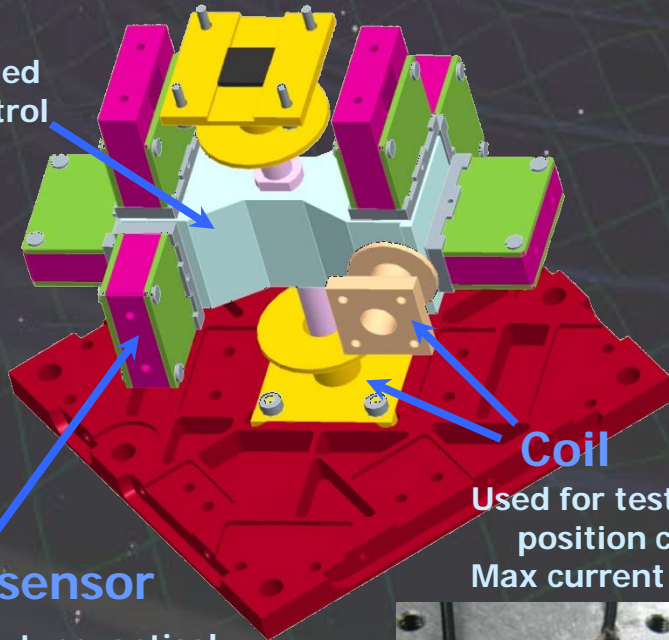
SWIM μ v

Tiny GW detector ~47g test masses inside
→ Levitated control in space

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

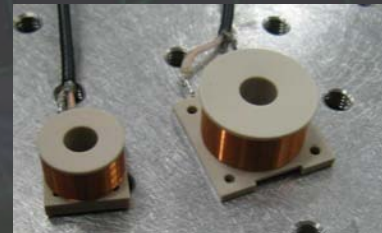


Coil

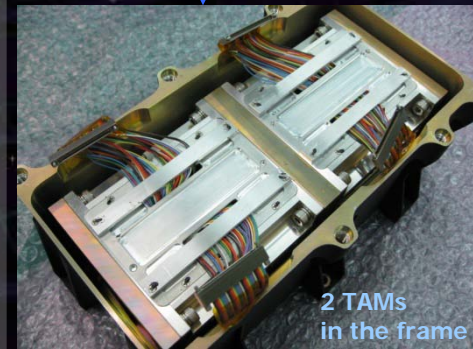
Used for test-mass
position control
Max current ~100mA

Photo sensor

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



SWIMmn Module



2 TAMs
in the frame



Successful control

SWIM

In-orbit operation

Test mass controlled

Error signal \rightarrow zero

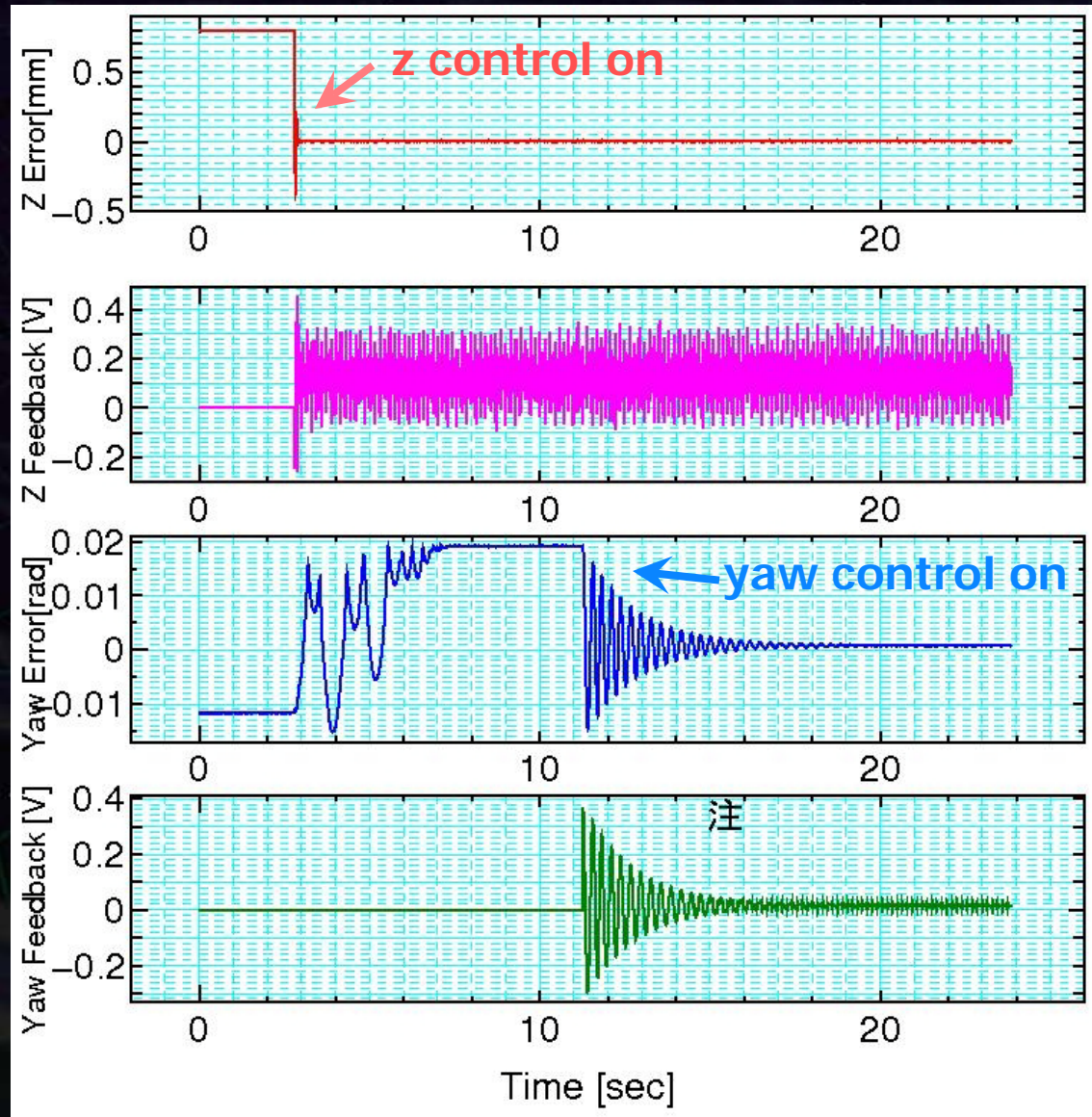
Damped oscillation
(in pitch DoF)

Free oscillation
in x and y DoF

Signal injection
 \rightarrow OL trans. Fn.

Operation: May 12, 2009

Downlink: ~ a week



R&D for DPF (1)

Stabilized Laser

BBM development

Yb:YAG (NPRO) source

Saturated absorption by I_2

→ Stability test, Packaging

By
M.Musha

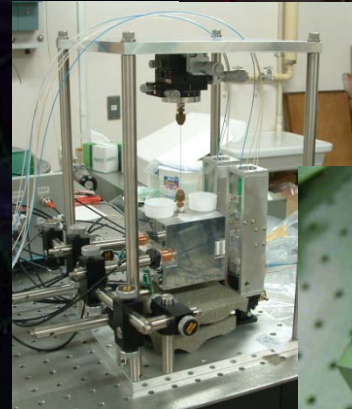


IFO and housing

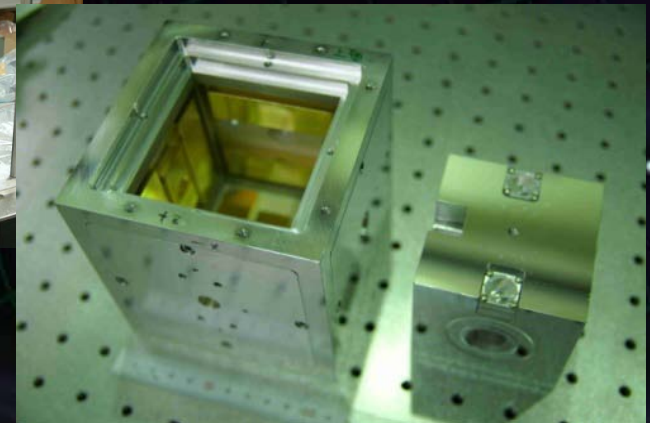
BBM-EM development

→ Test of concepts

+ Earth gravity sensors



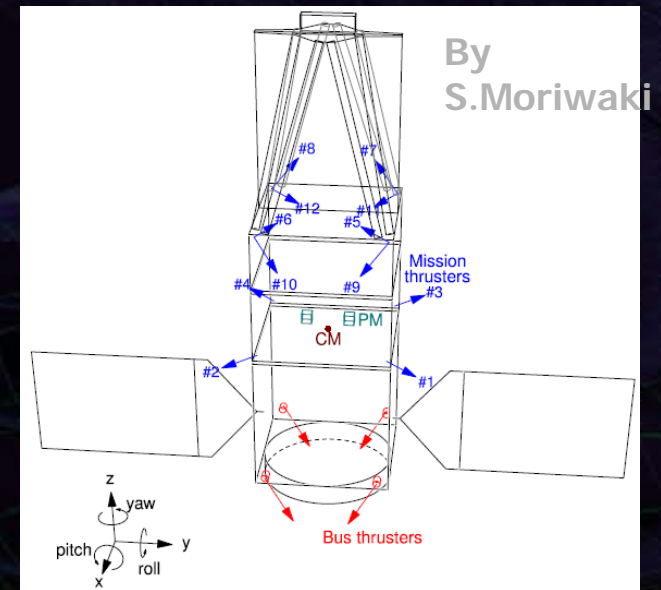
By
S.Sato



By
A.Araya

R&D for DPF (2)

Attitude control and Drag-free
Satellite structure (mass distribution)
Passive attitude stabilization
by gravity gradient
Mission thruster position
Control topology



Thruster
System design
with existing tech.
Noise meas. system
(thruster stand)
Development of Slit FEED

By
I.Funaki



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 (~20013) in selection

Candidates: 2 missions (ERG, **DPF**)



Hearing tomorrow!

1. DECIGO

Overview and Science

Pre-conceptual Design

2. DECIGO Pathfinder

Overview and Science

Design and Status



3. Summary

Summary

DECIGO : Fruitful Science

Very beginning of the Universe

Dark energy

Galaxy formation

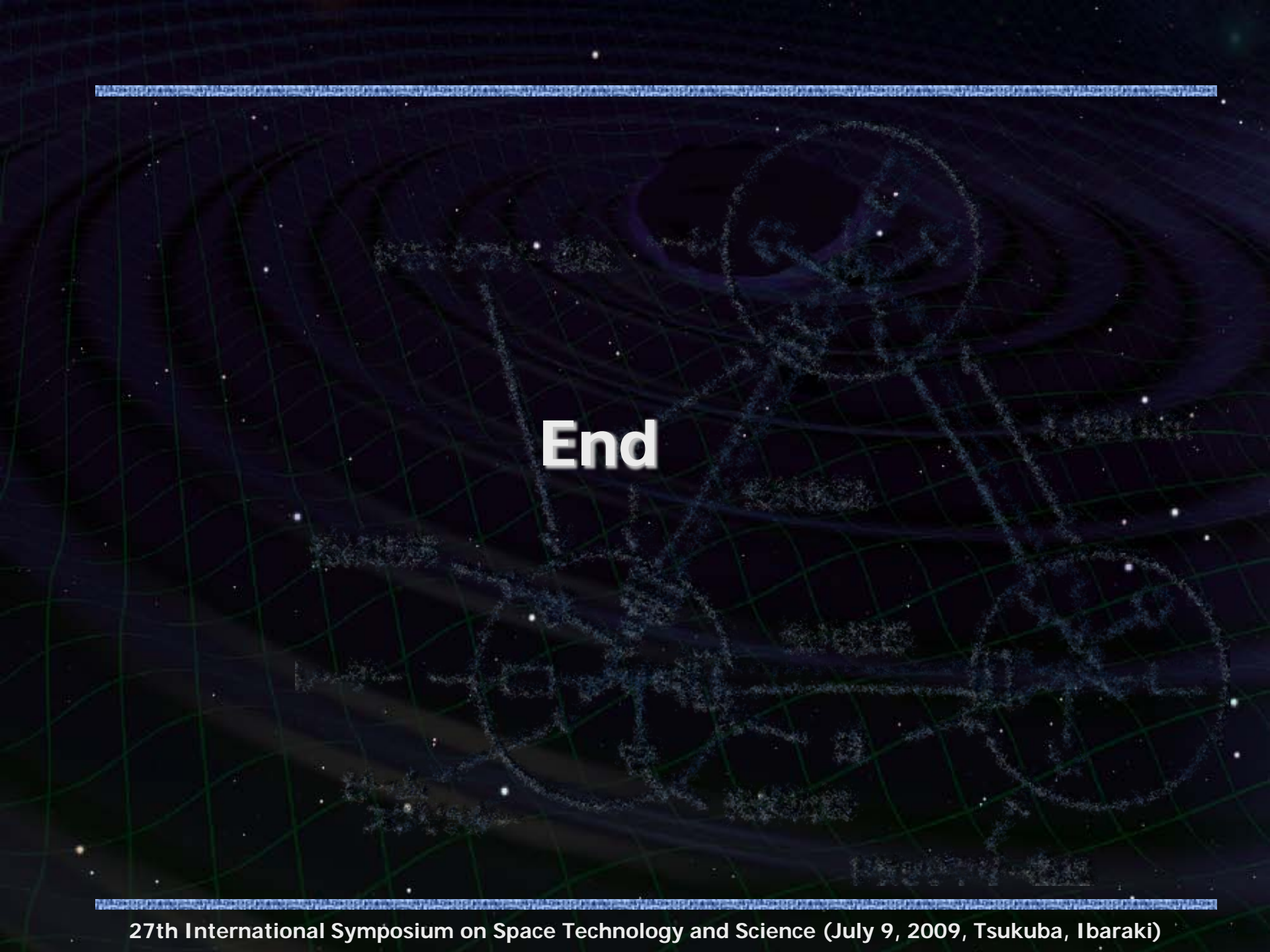
DECIGO Pathfinder

Important milestone for DECIGO

Preparing for the final selection

SWIM – under operation in orbit

first precursor to space!



End