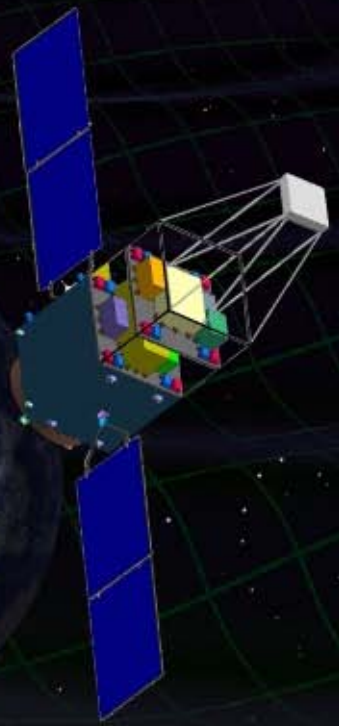
DECIGO and Pathfinder Missions

Original Picture : Sora

Masaki Ando

(Department of Physics, Kyoto University)



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 Kirihara, 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, Kakeru Takahashi, Keitaro Takahashi, Tadayuki Takahashi, Hirotaka Takahashi, Ryuichi Takahashi, Ryutaro 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

8th Edoardo Amaldi Conference on Gravitational Waves (June 24, 2009, New York, USA)

1. DECIGO

- Overview and Science
- Pre-conceptual Design

2. DECIGO Pathfinder

- Overview and Science
- Design and Status

3. Summary

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Overview and Science

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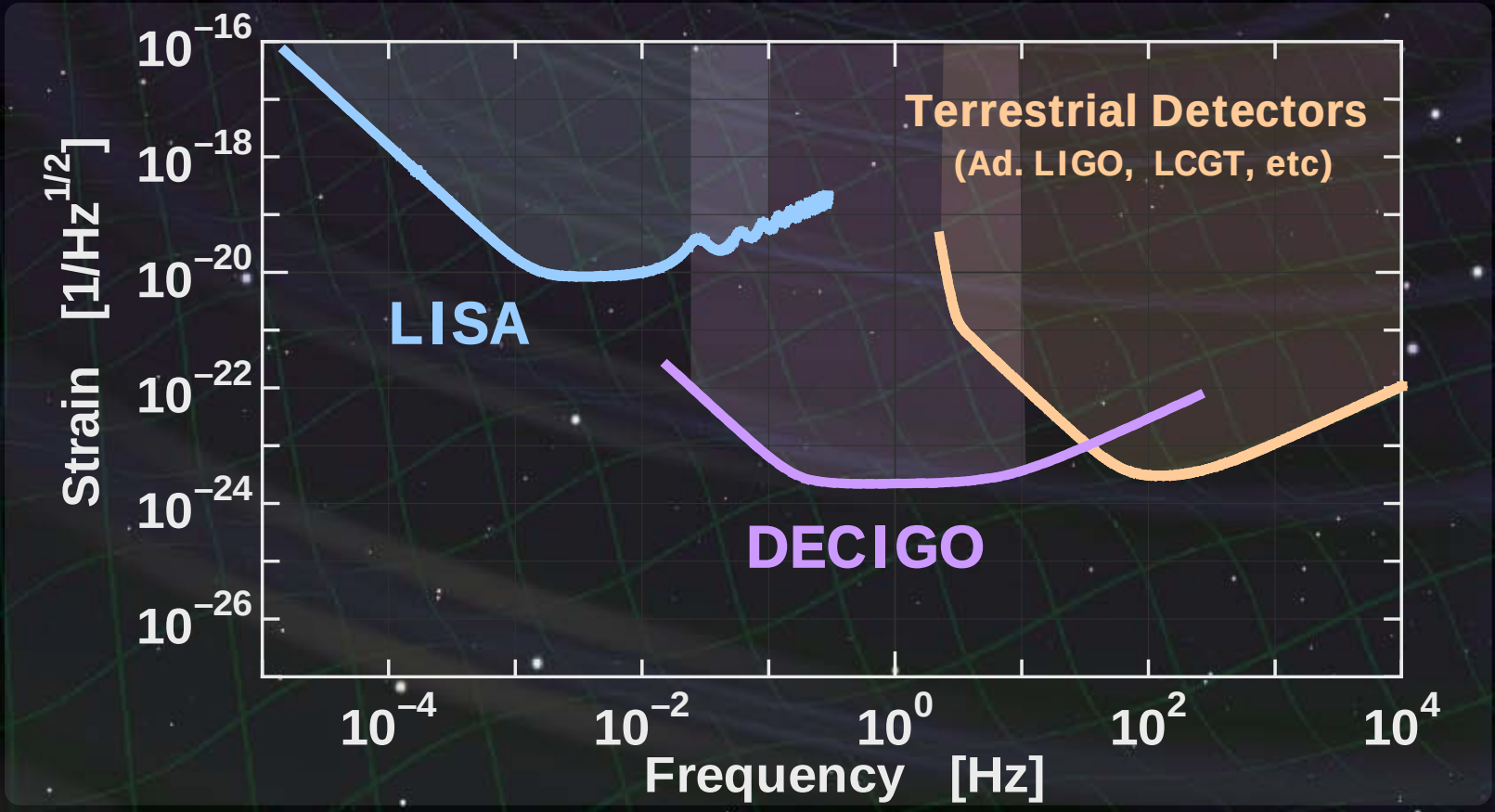
DECIGO

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

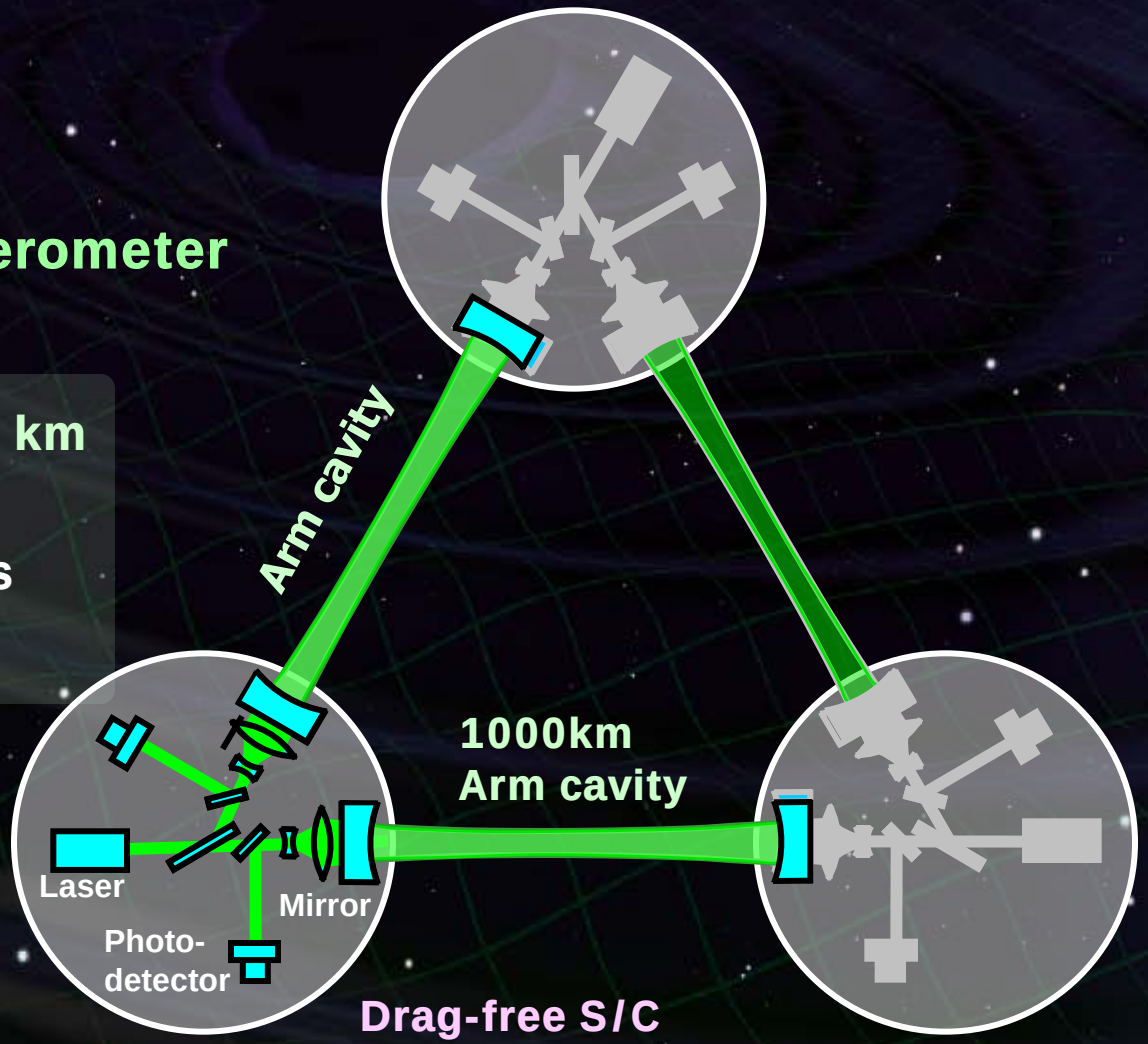


DECIGO Interferometer

Interferometer Unit:

Differential FP interferometer

Baseline length: 1000 km
3 S/C formation flight
3 FP interferometers
Drag-free control

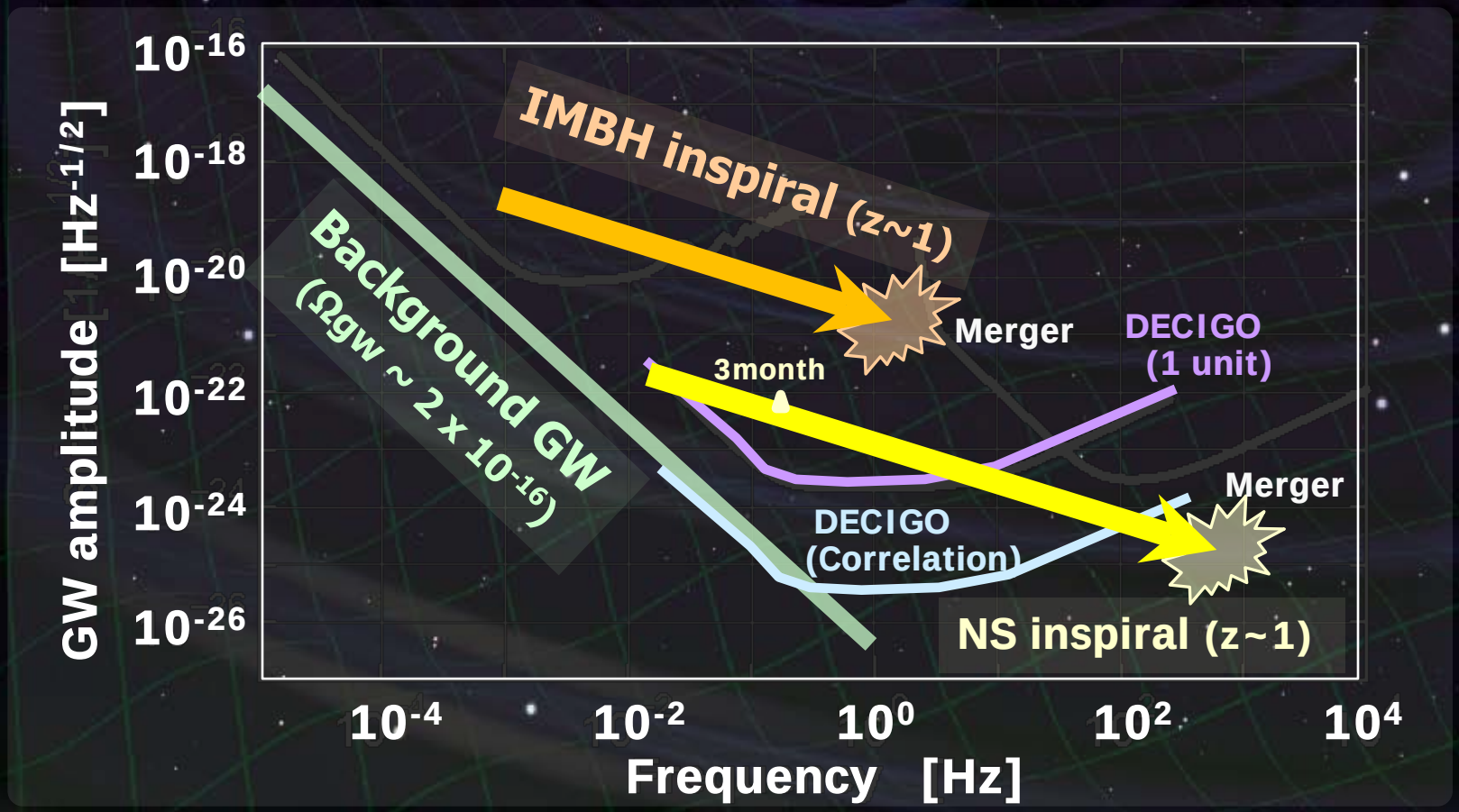


Targets and Science

IMBH binary inspiral
NS binary inspiral
Stochastic background

⇨

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



Constraint on dark energy

DECIGO will observe

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

↳ Precise 'clock' at cosmological distance

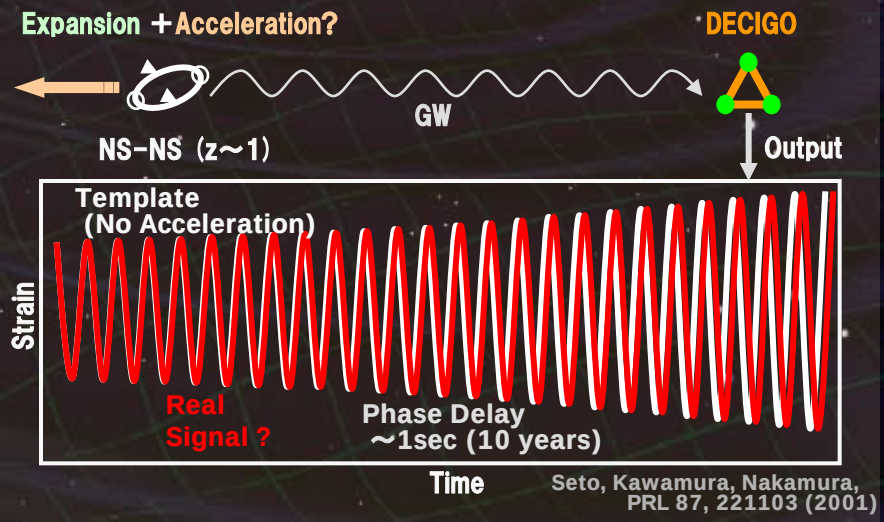
'Standard Siren'

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)

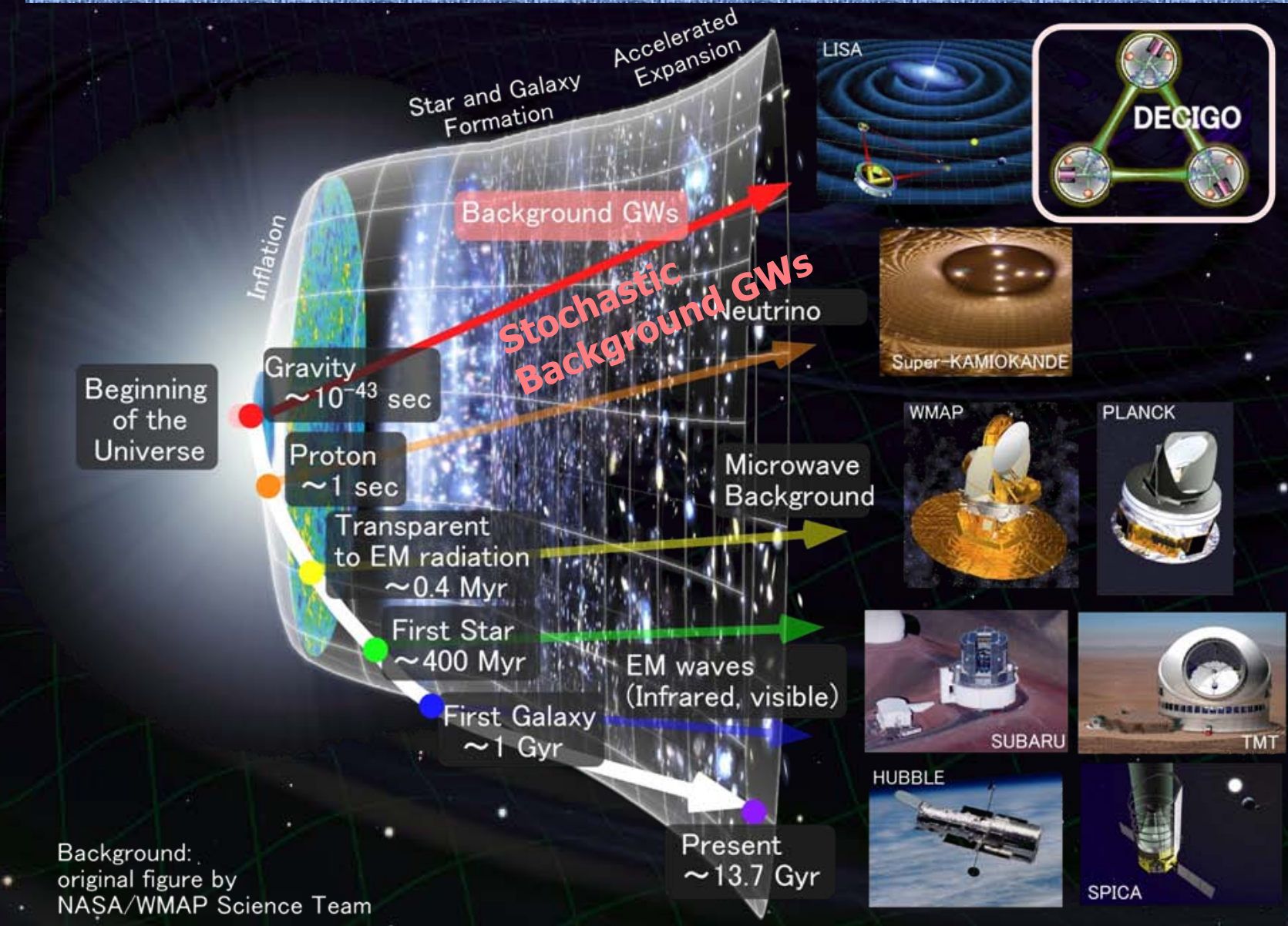
Determine cosmological parameters

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

Absolute and independent measurement

Angular resolution
~10arcmin (1 detector)
~10arcsec (3 detectors)
at z=1

Stochastic Background GWs



1. DECIGO

Overview and Science

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Pre-Conceptual Design

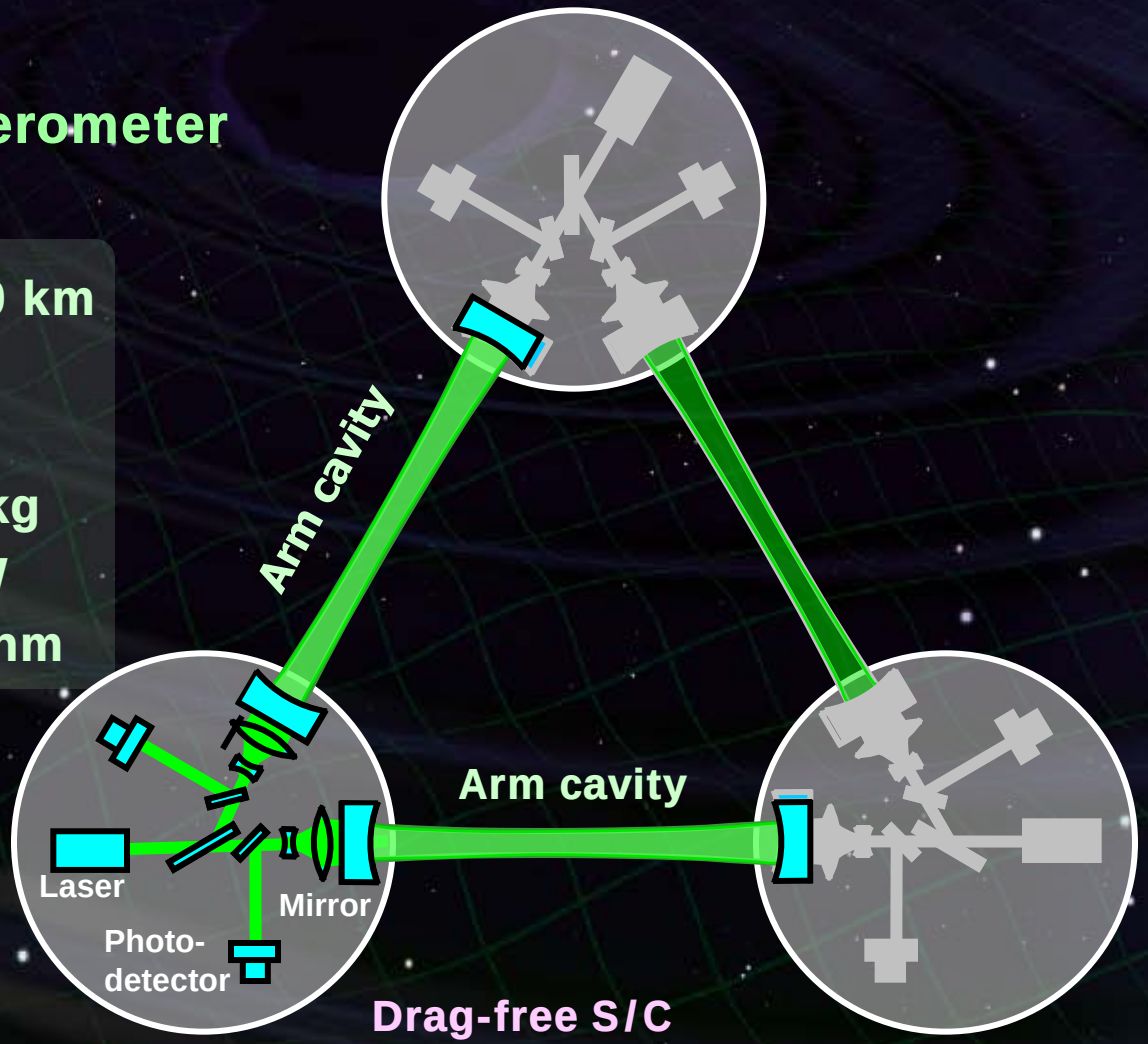
Interferometer Unit:

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

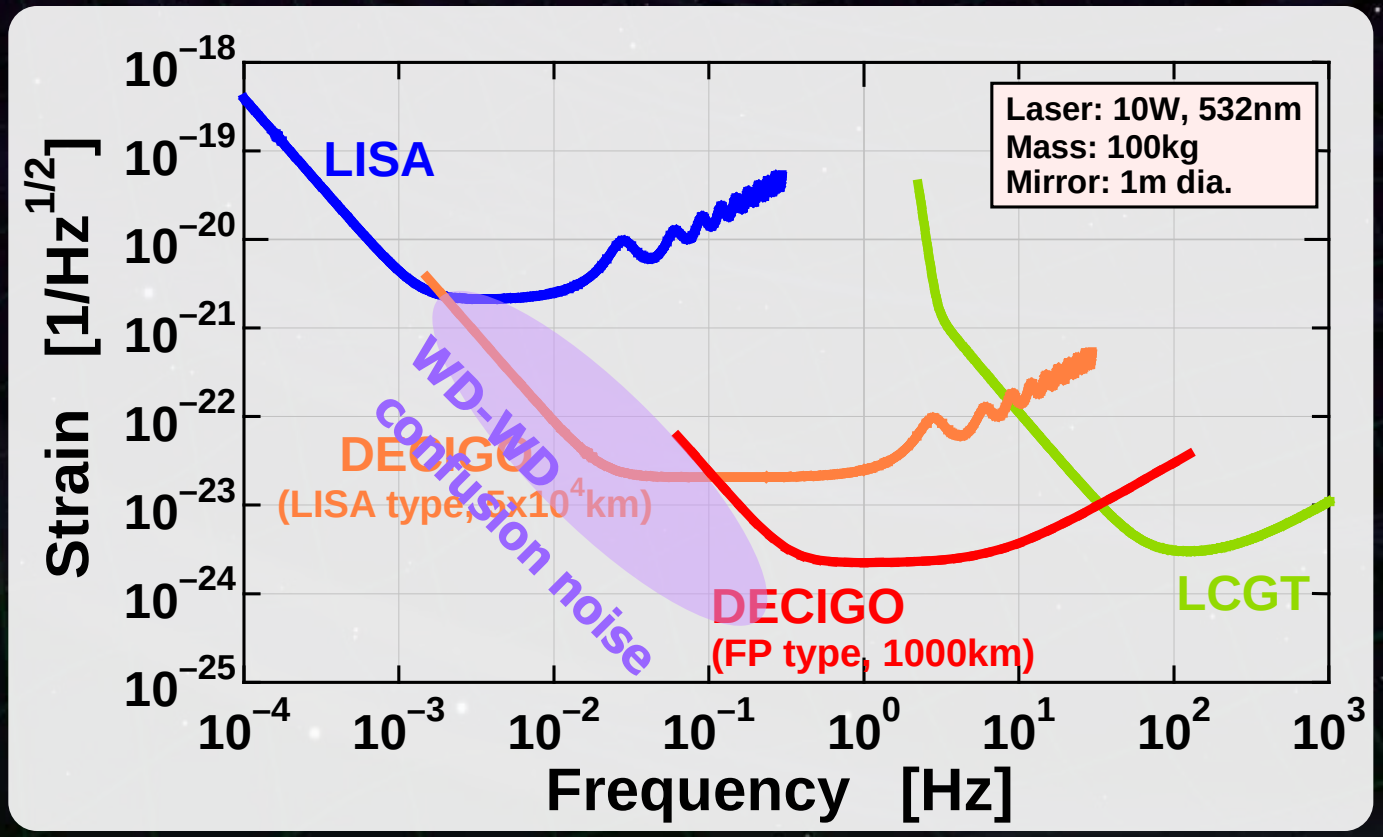


Interferometer Design

Transponder type vs **Direct-reflection type**

Compare : Sensitivity curves and Expected Sciences

⇨ Decisive factor: **Binary confusion noise**



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

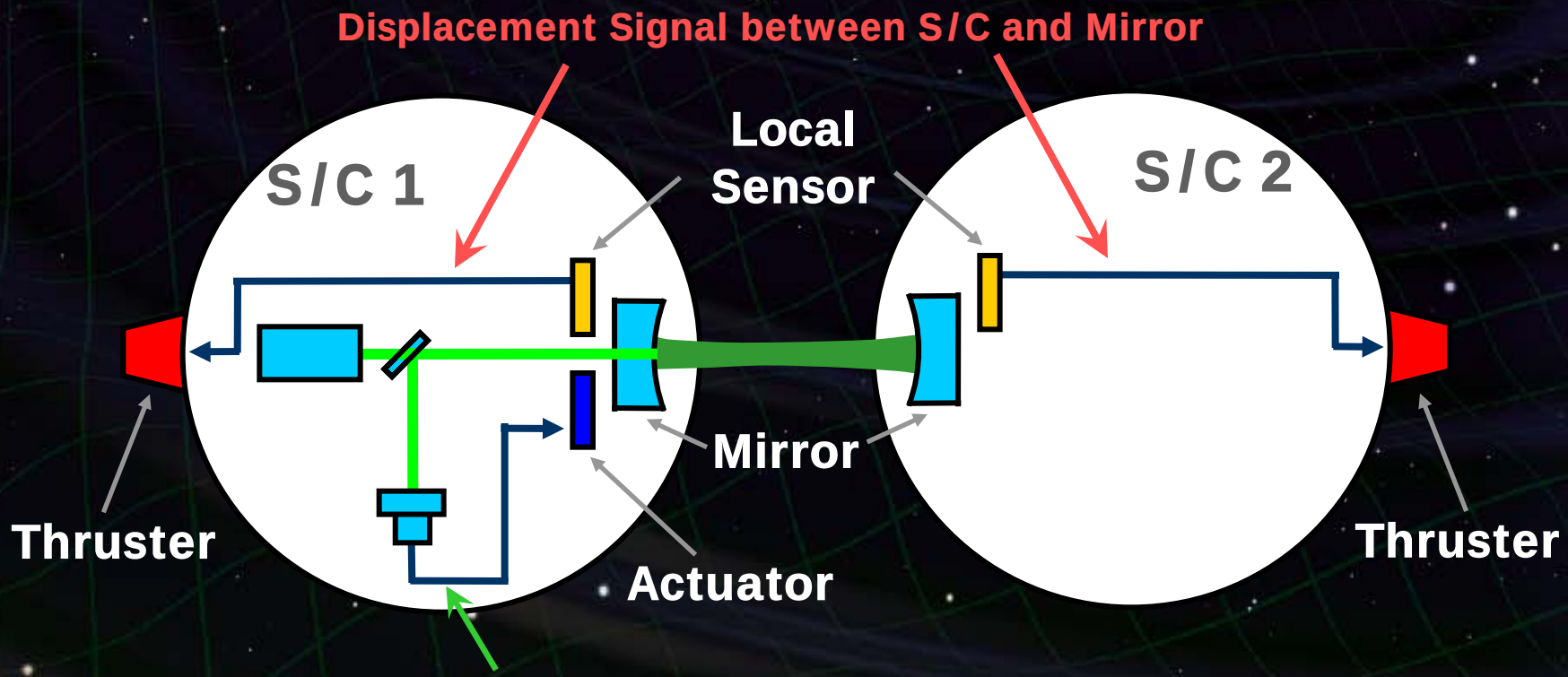


Fig: S. Kawamura

Requirements

Sensor Noise

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

⇨ x 10 of 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

Candidate of orbit:

Record-disk orbit around the Sun

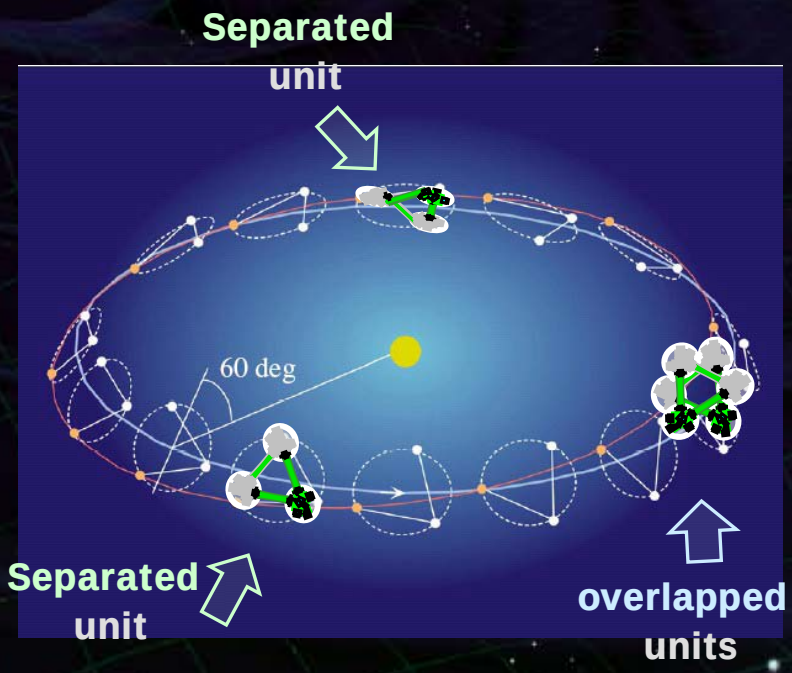
Relative acc. 4×10^{-12} m/s^2

(Mirror force ~10^{-9} N)

Halo orbit around L2 (or L1)

Relative acc. 4×10^{-7} m/s^2

(Mirror force ~10^{-4} N)



Constellation

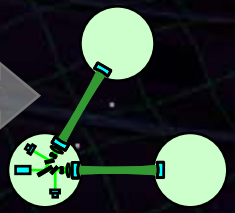
4 interferometer units

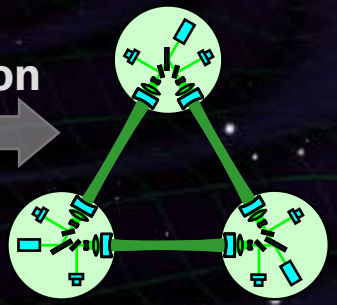
2 overlapped units → Cross correlation

2 separated units → Angular resolution

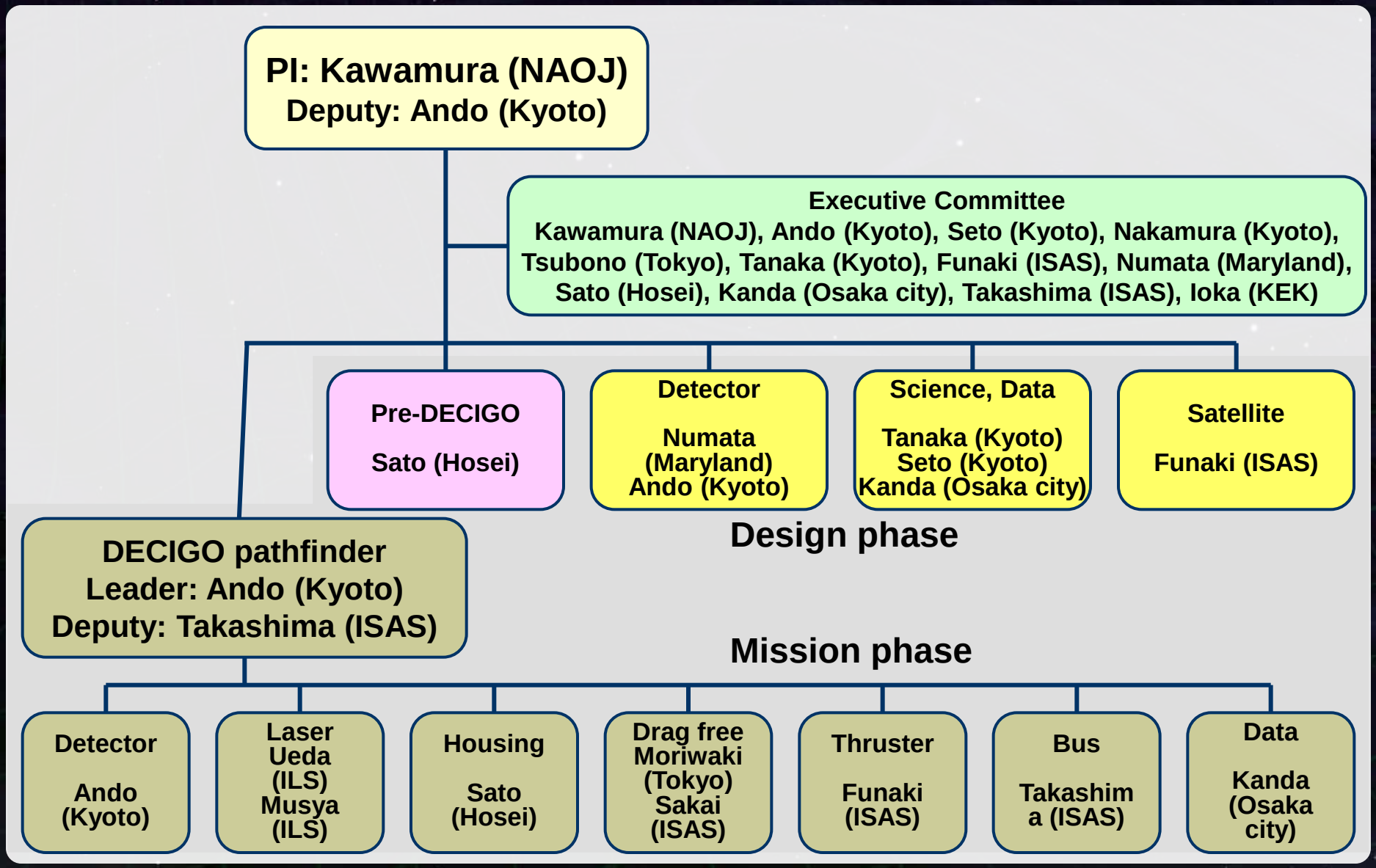
Roadmap

Figure: S.Kawamura

	2007 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26		
Mission	R&D Fabrication →  SDS-1/SWIM	 DECIGO Pathfinder (DPF)	R&D Fabrication →  Pre-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

R&D Fabrication →  DECIGO

Organization



Collaboration and support

- Supports from LISA
  - Technical advises from LISA/LPF experiences
  - Support Letter for DECIGO/DPF
  - LISA-DECIGO workshop (2008.11)

- Collab. with Stanford univ. group
  - Drag-free control of DECIGO/DPF
  - UV LED Charge Management System for DPF

- 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-)

- Collab. with UNISEC (University Space Engineering Consortium)
  - Call for active young engineers

1. DECIGO

Overview and Science

Pre-conceptual Design

⇨ 2. DECIGO Pathfinder

Overview and Science

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3. Summary

Roadmap

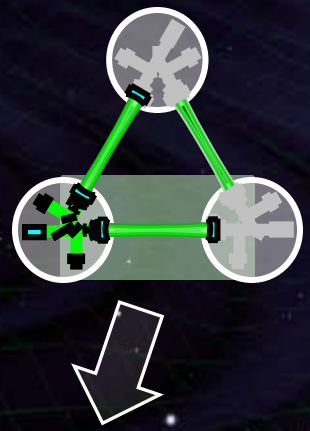
Figure: S.Kawamura

	2007 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26		
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



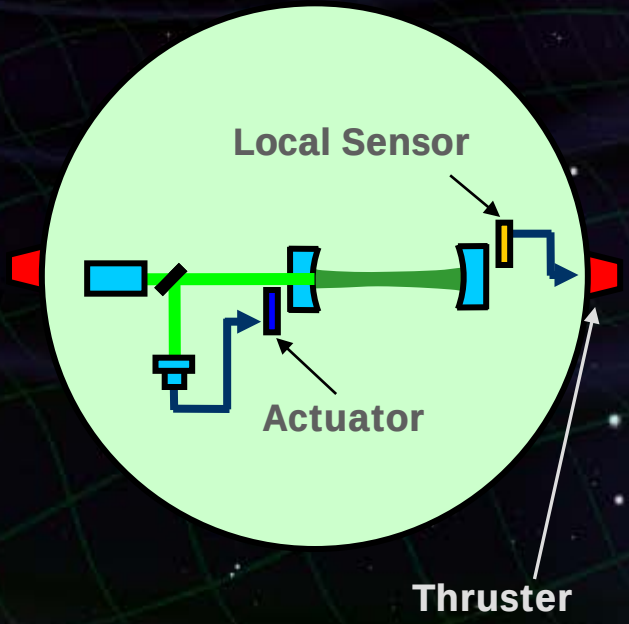
Single satellite
(Payload ~1m^3 , 350kg)

Low-earth orbit
(Altitude 500km, sun synchronous)

30cm FP cavity with 2 test masses

Stabilized laser source

Drag-free control



DPF satellite

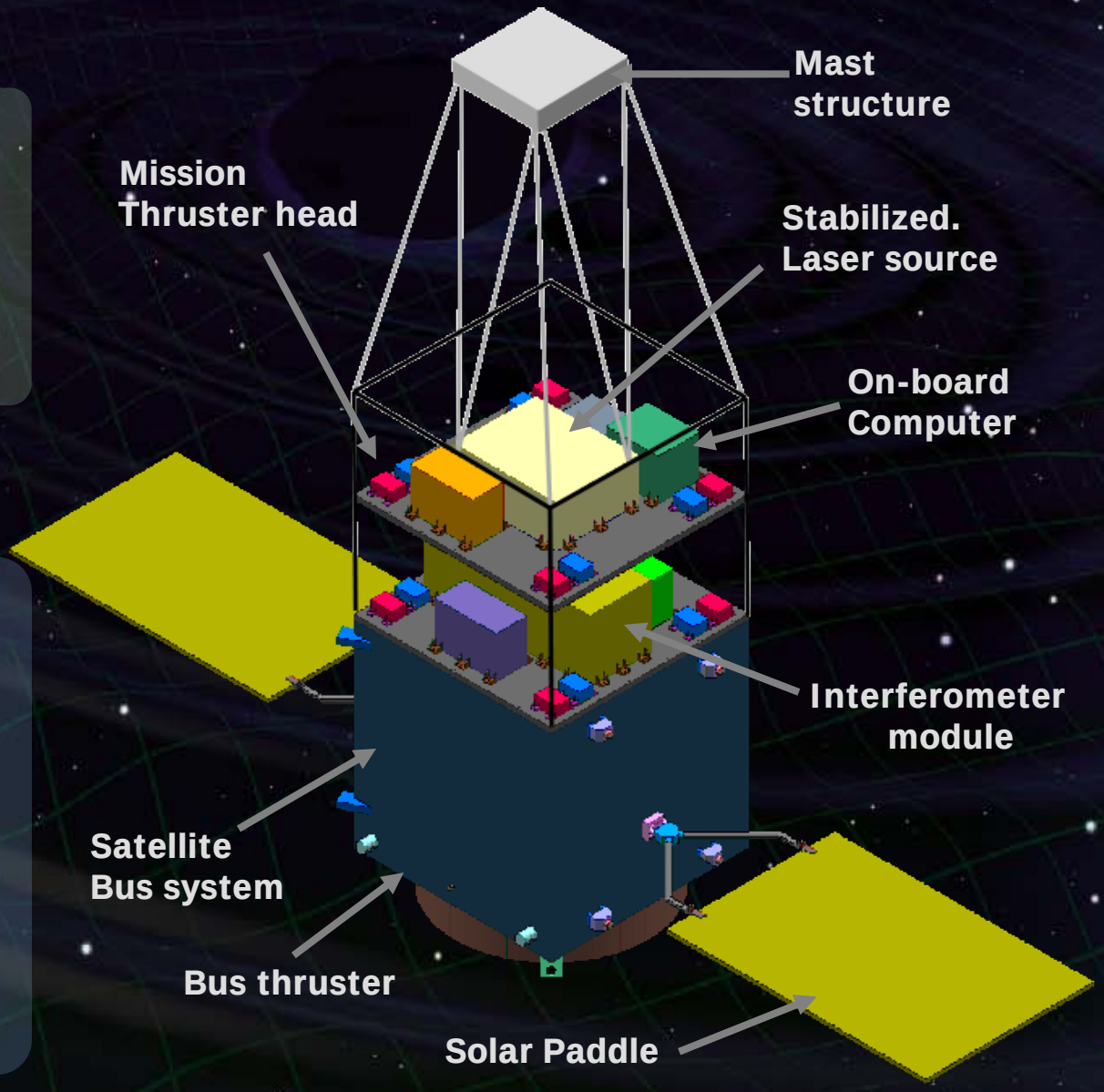
DPF Payload

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

Power Supply
SpW Comm.

Satellite Bus

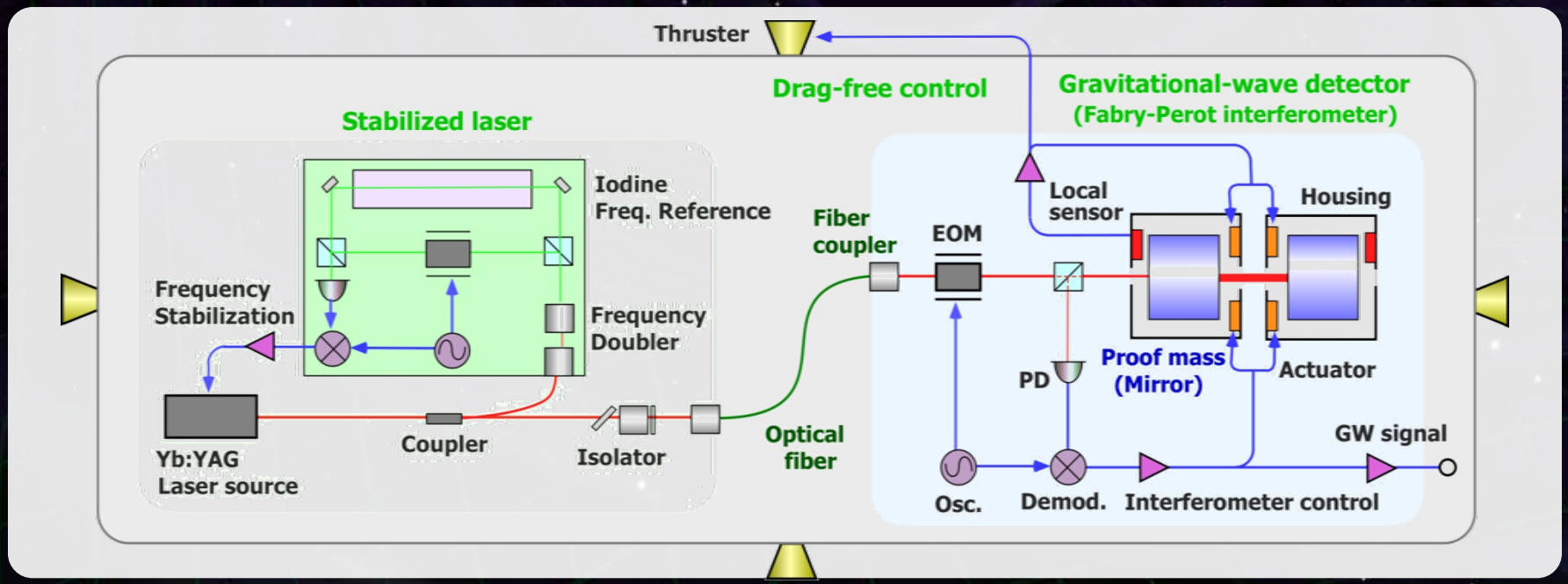
('Standard bus' system)
Size :
950x950x1100mm
Weight : 200kg
SAP : 960W
Battery: 50AH
Downlink : 2Mpbs
DR: 1GByte
3N Thrusters x 4



DPF mission payload

Mission weight : ~150kg
Mission space : ~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

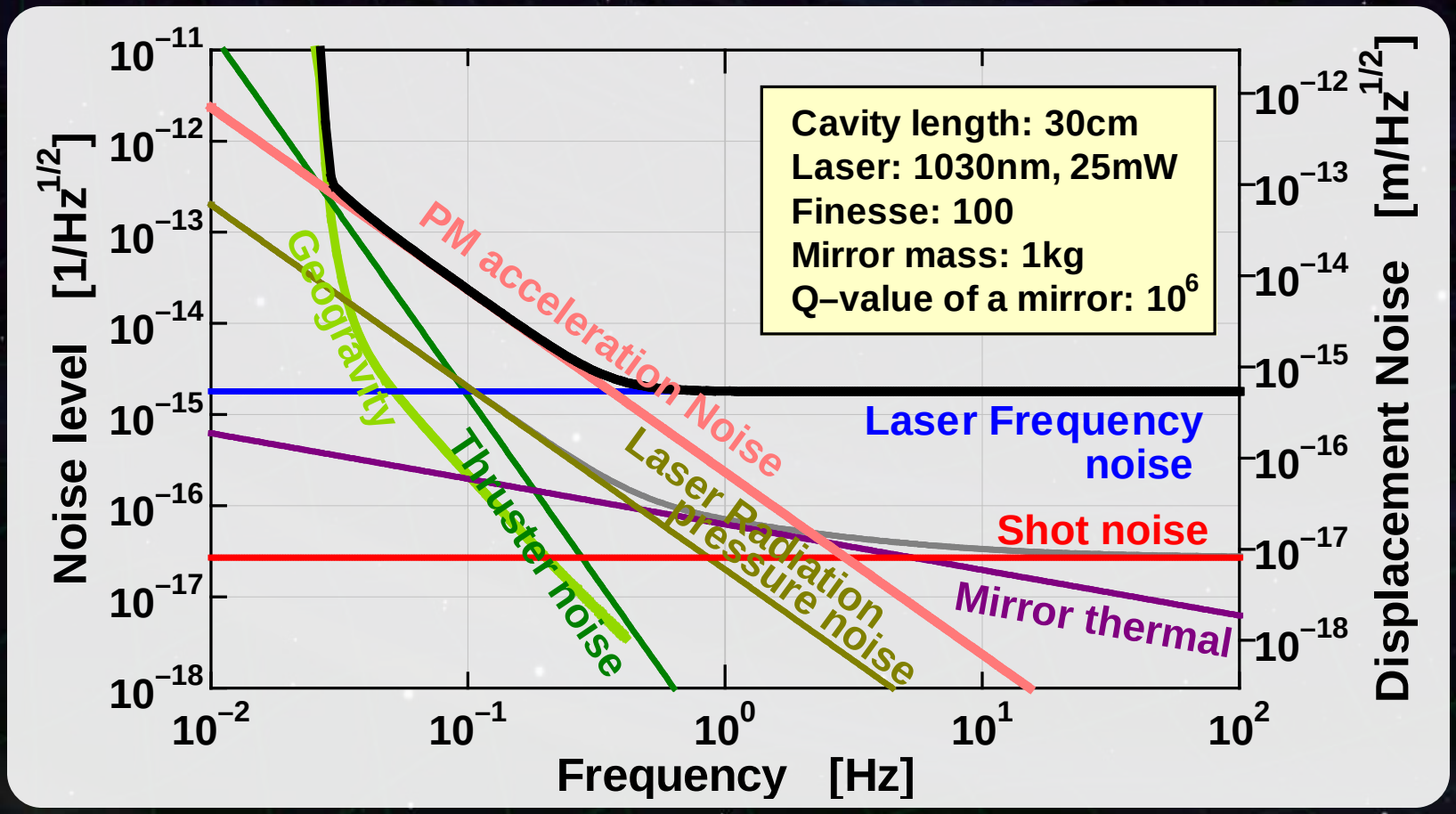
Fabry-Perot interferometer
Finesse : 100
Length : 30cm
Test mass : 1kg
Signal extraction by PDH

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: $2m^2$
Altitude: 500km
Thruster noise: $0.1\mu N/Hz^{1/2}$

(Preliminary parameters)

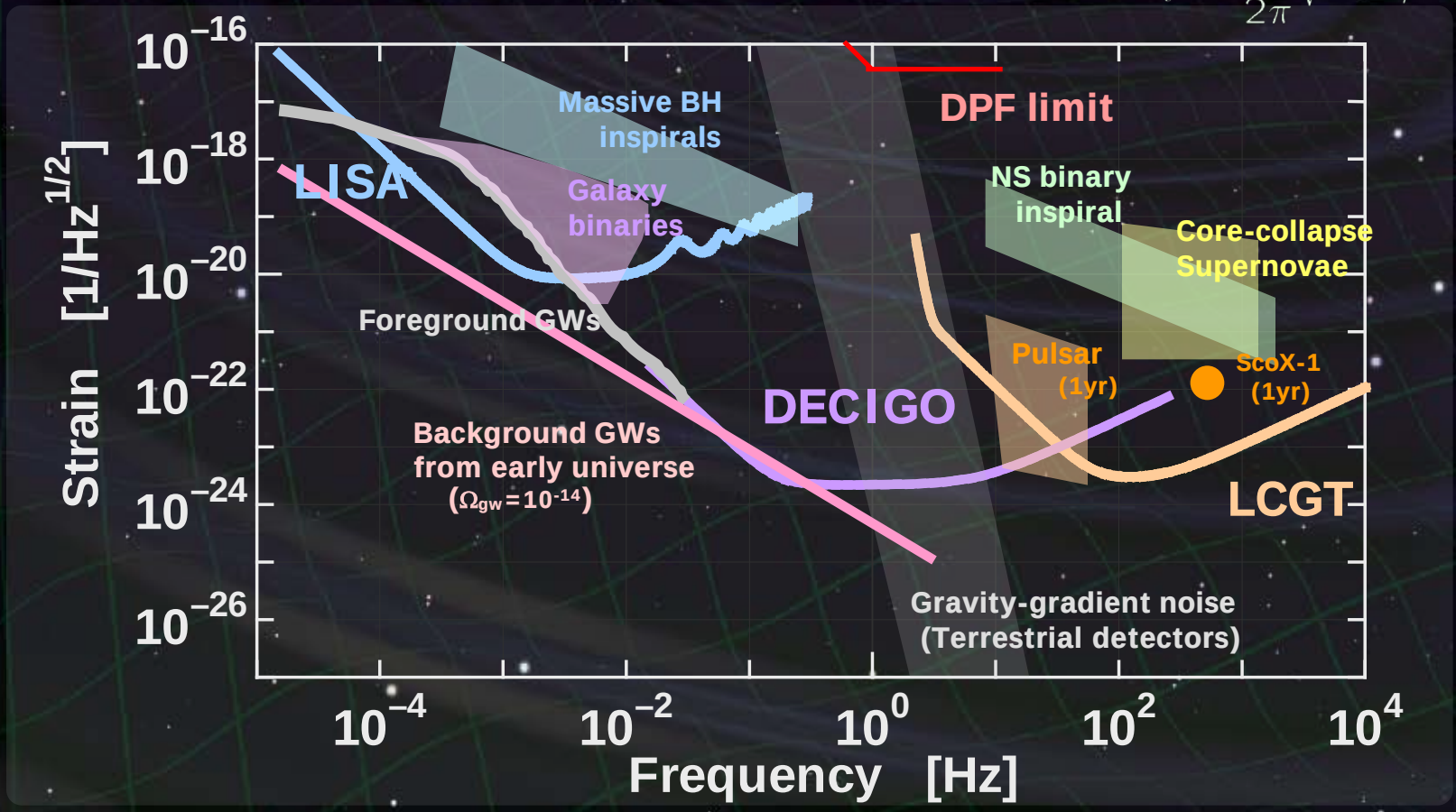


DPF sensitivity

DPF sensitivity $h \sim 2\times10^{-15}\ \mathrm{Hz}^{1/2}$

(x10 of quantum noises)

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



GW target of DPF

Blackholes events in our galaxy

IMBH inspiral and merger

$h \sim 10^{-15}$, $f \sim$ 4 Hz

Distance 10kpc, $m = 10^3 M_{sun}$

Obs. Duration (~1000sec)

BH QNM

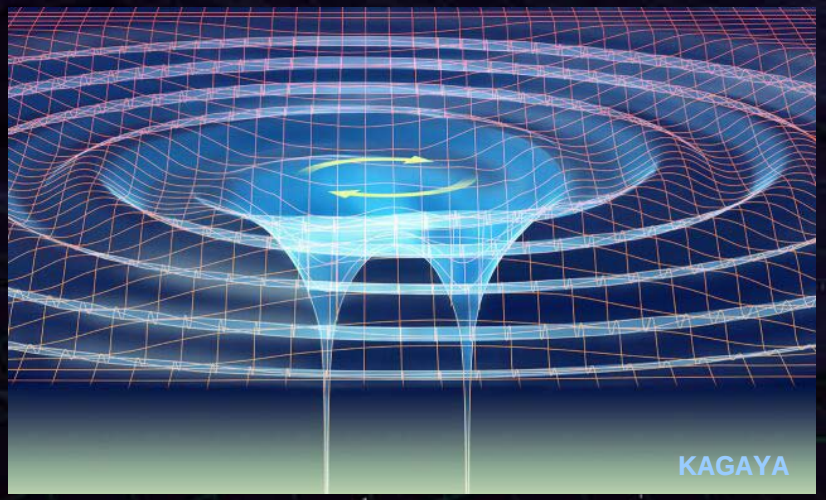
$h \sim 10^{-15}$, $f \sim$ 0.3 Hz

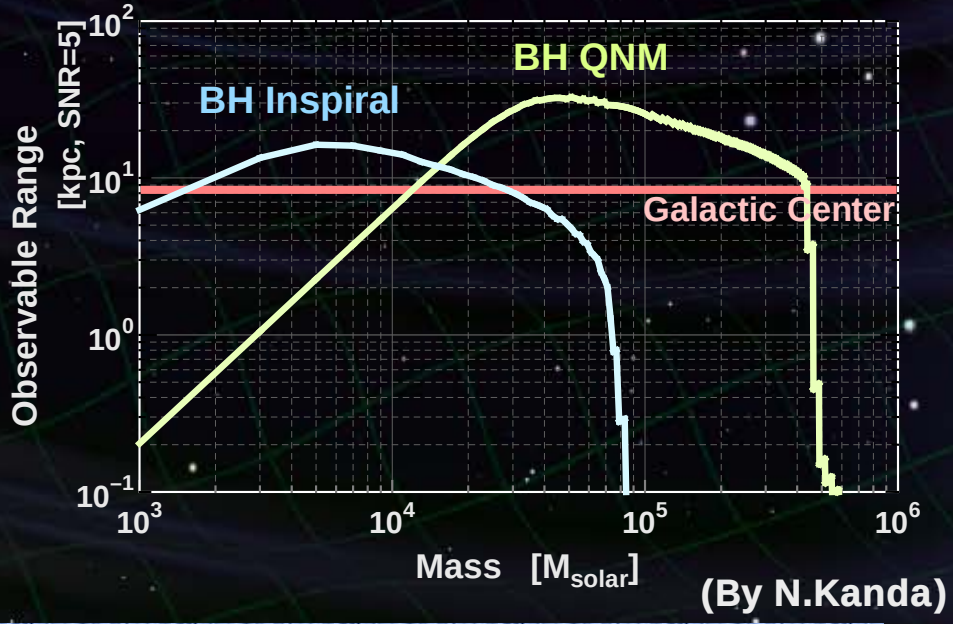
Distance 1Mpc, $m = 10^5 M_{sun}$

Observable range reaches the Galactic center (SNR~5)

Hard to access by others

→ Original observation

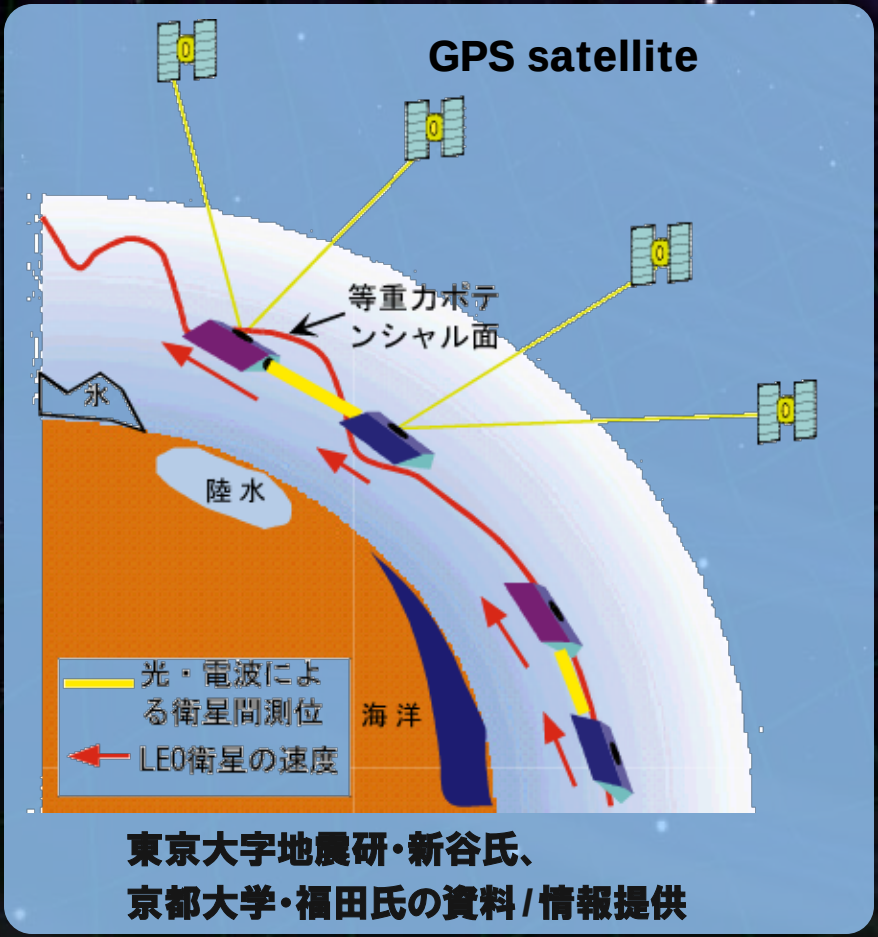




(By N.Kanda)

Gravity of the Earth

Measure gravity field of the Earth for Satellite Orbits



東京大学地震研・新谷氏、
京都大学・福田氏の資料/情報提供

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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R&D for DPF (1)

Stabilized Laser

- BBM development
  - Yb:YAG (NPRO) source
  - Saturated absorption by I_2
  - → Stability test, Packaging

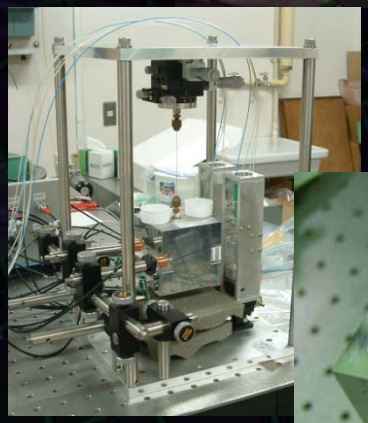
By M.Musha

IFO and housing

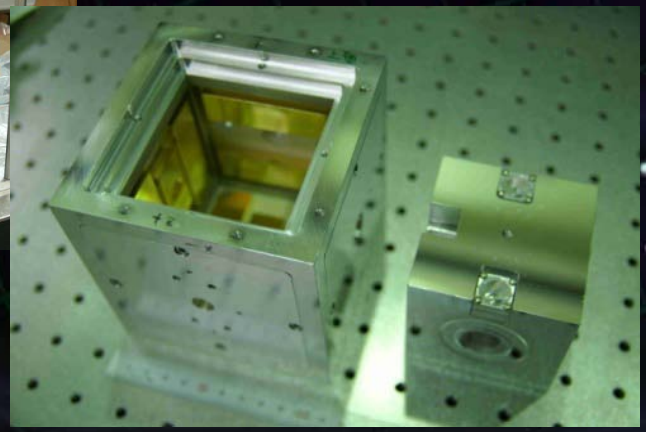
- BBM-EM development
  - → Test of concepts
  - + Earth gravity sensors

S.Sato's talk
(P. Session #2, Today)

Y.Wakabayashi's poster



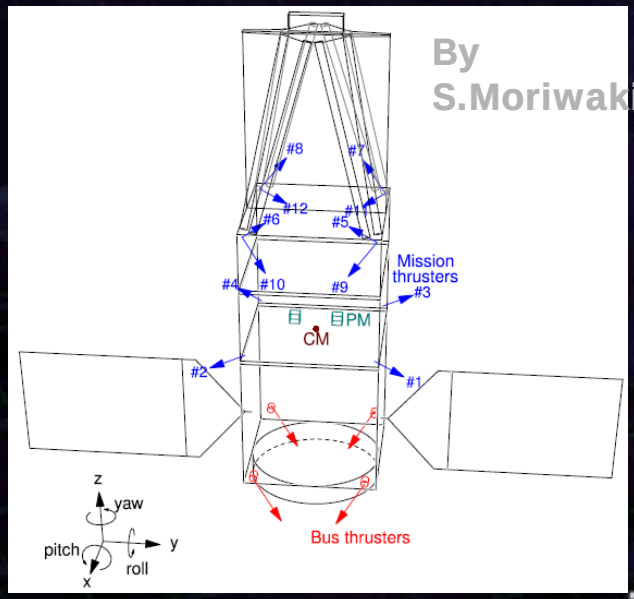
By S.Sato



By A.Araya

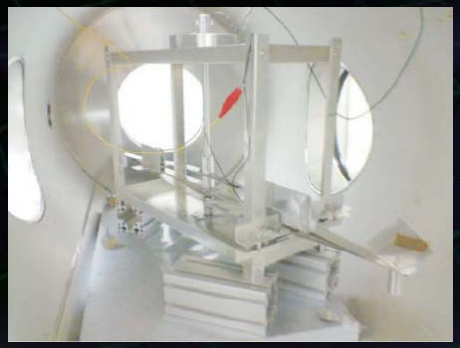
R&D for DPF (2)

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 FEEP

By I.Funaki



SWIM launch and operation

Tiny GW detector module
Launched in Jan. 23, 2009

⇨ **In-orbit operation**

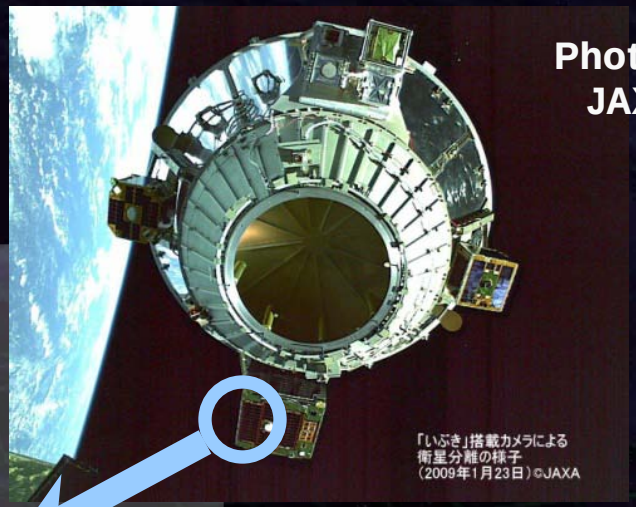


Photo: JAXA

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

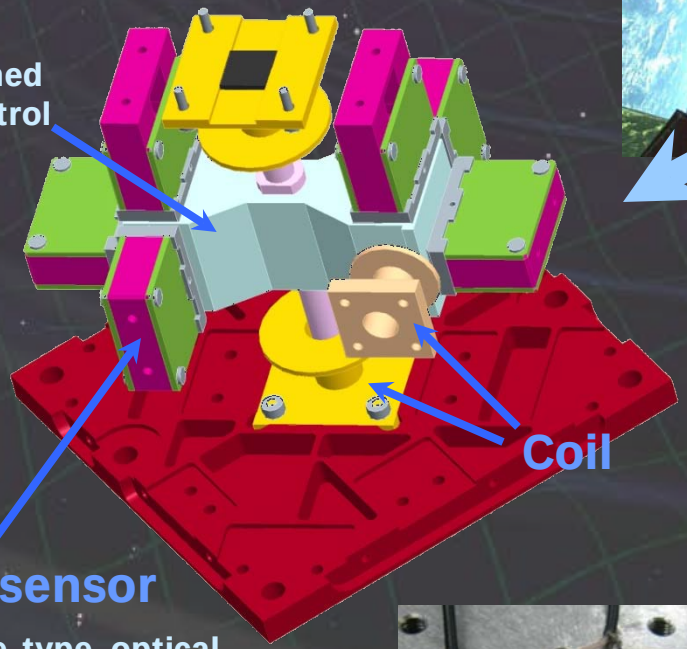
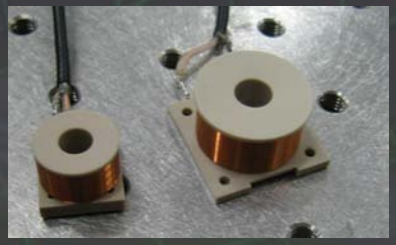


Photo sensor

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



W.Kokuyama's talk (P. Session #2, Today)

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 (~2013) in selection

Candidates: 2 missions (ERG, DPF)

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

Decision in this month

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Summary

DECIGO : Fruitful Sciences

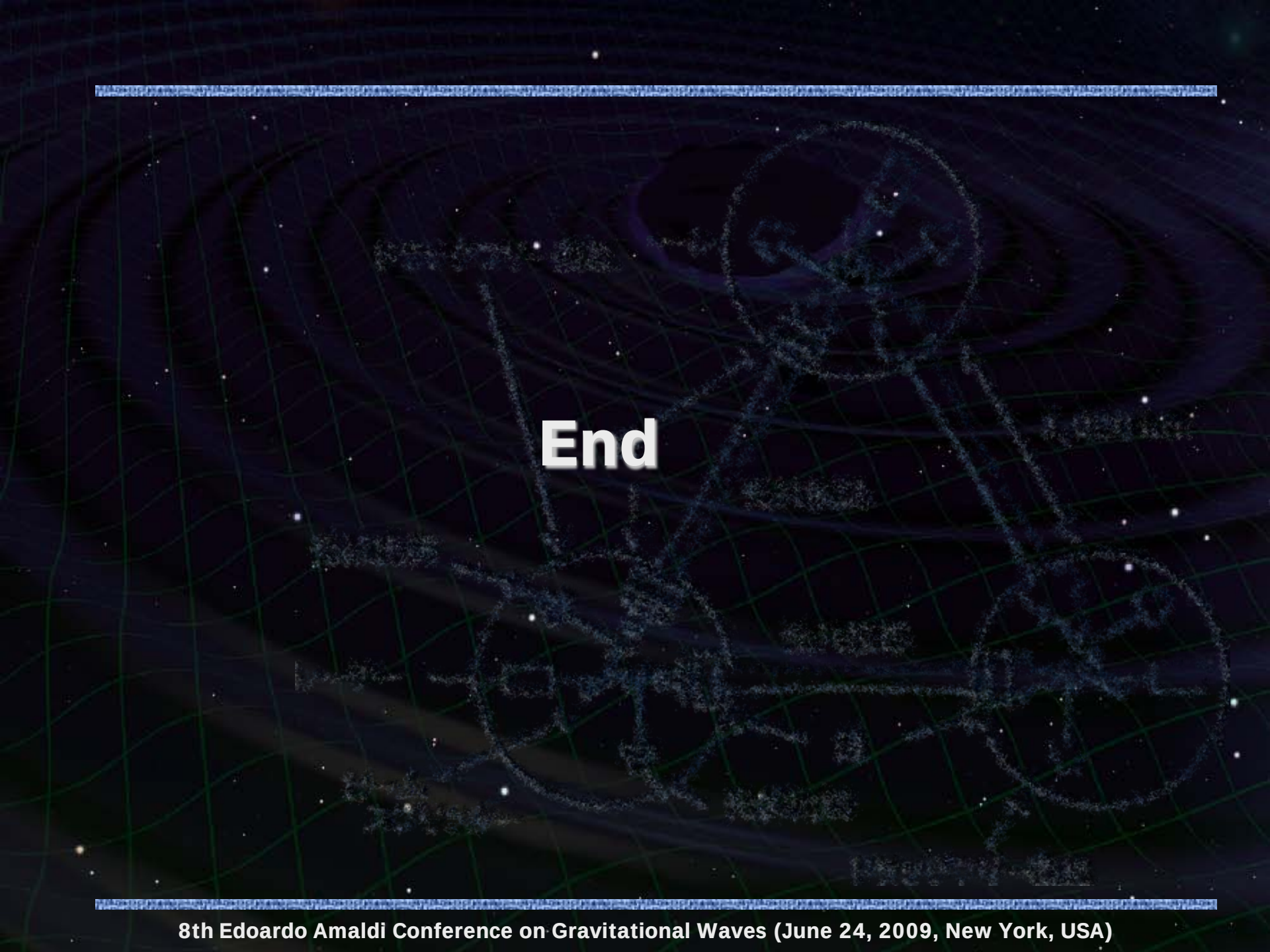
- Very beginning of the Universe
- Dark energy
- Galaxy formation

DECIGO Pathfinder

- Important milestone for DECIGO
- Strong candidate of JAXA's satellite series

SWIM – under operation in orbit

first precursor to space!


End

LCGT and DECIGO

LCGT (~2014)

Terrestrial Detector

→ High frequency events

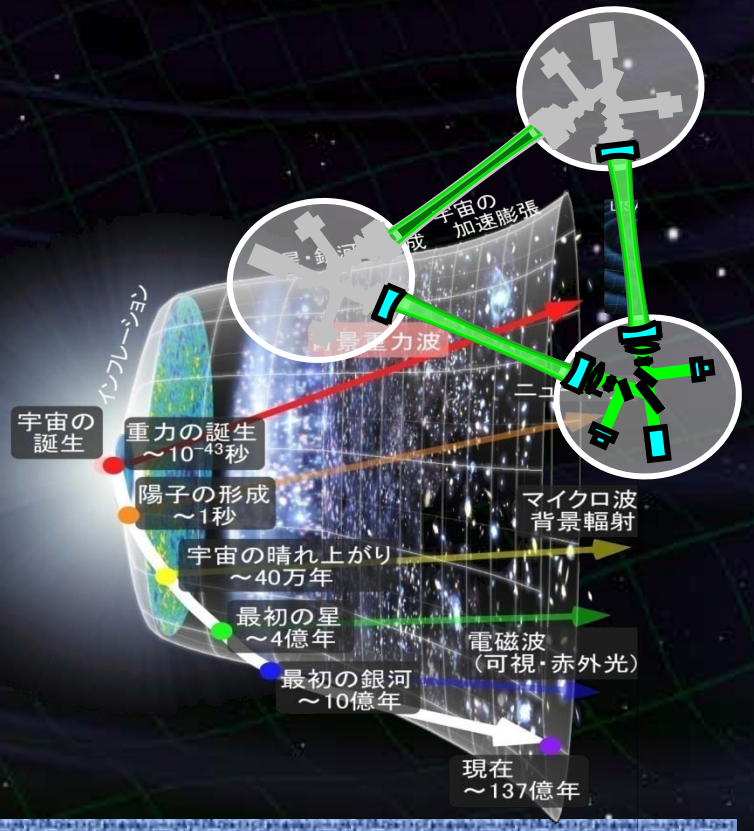
Target: GW detection

DECIGO (~2024)

Space observatory

→ Low frequency sources

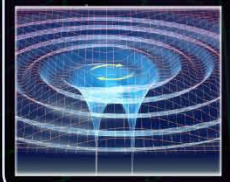
Target: GW astronomy



Objectives of DPF

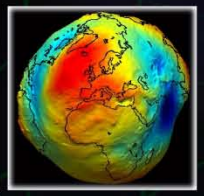
Observation

Gravitational wave



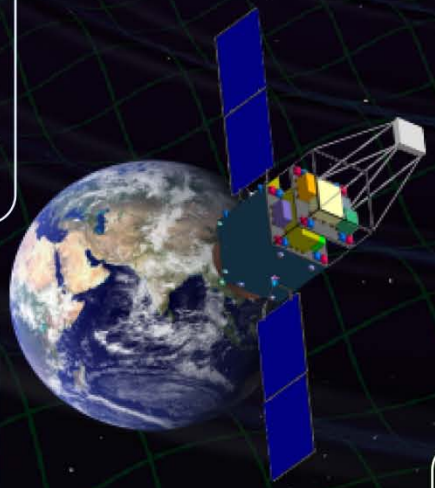
Intemedate-mass inspiral and merger

Earth gravity



Environ. monitor

Geoid resolusion ~1mm.



Science Technology

Space interferometer

Precise meas. in space

6×10^{-16} m/Hz$^{1/2}$

Stabilized laser

High stability in Space

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

Drag-free control

Low-noise control with passive stab.

DPF and DECIGO

DPF requirements

DECIGO requirements

Precise meas. by IFO

Disp. noise
6×10^{-16} m/Hz$^{1/2}$ → 4×10^{-18} m/Hz$^{1/2}$

Force noise
10^{-14} N/Hz$^{1/2}$ → 10^{-17} N/Hz$^{1/2}$

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

Stab. Laser

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

- Ultra stable Laser
- Stabilization of source
- Stabilization by long arm

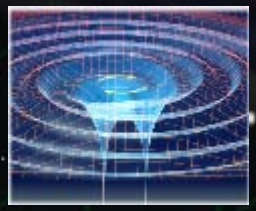
Drag-free control

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

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

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

GW Obs.



0.1 Hz band
Observation and
Data analysis

- Observation
- Data procession
- Data analysis
- Triggered search

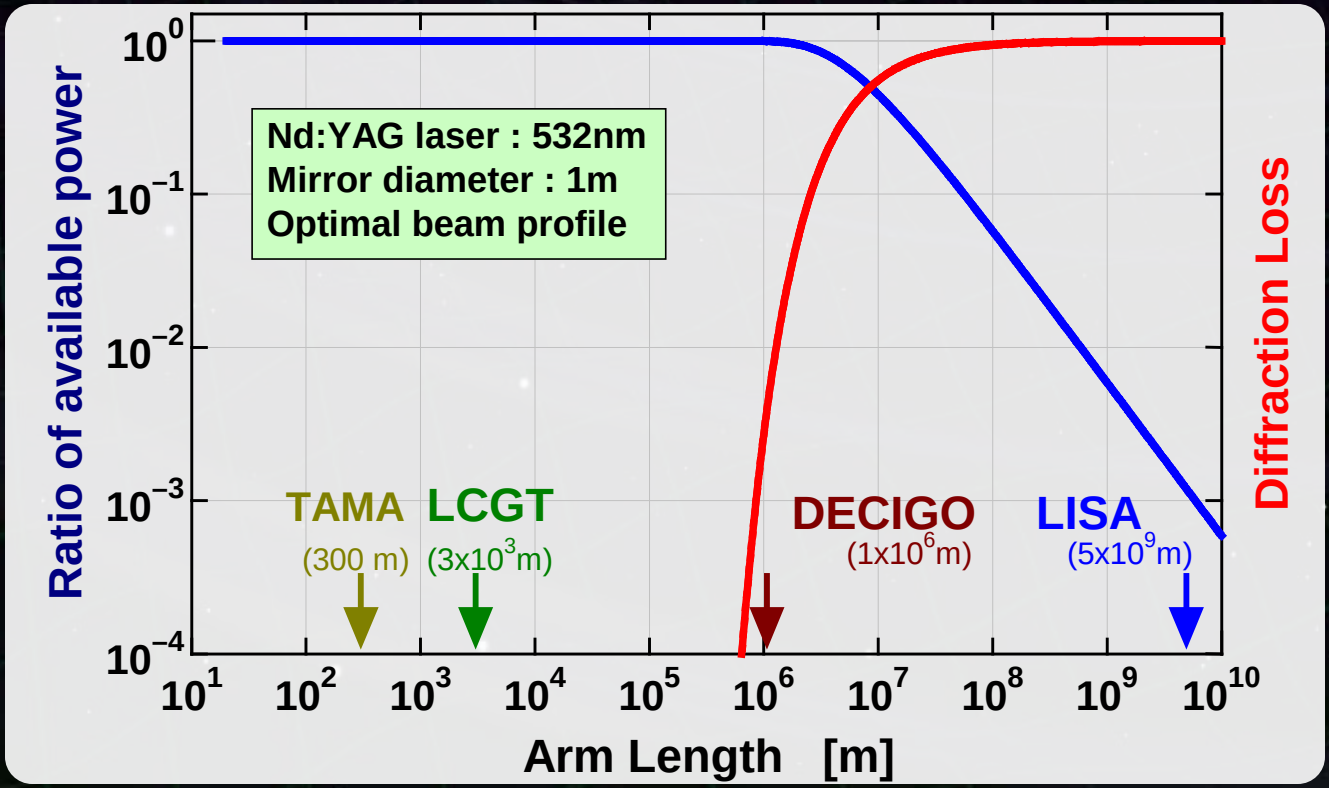
Arm length

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.**

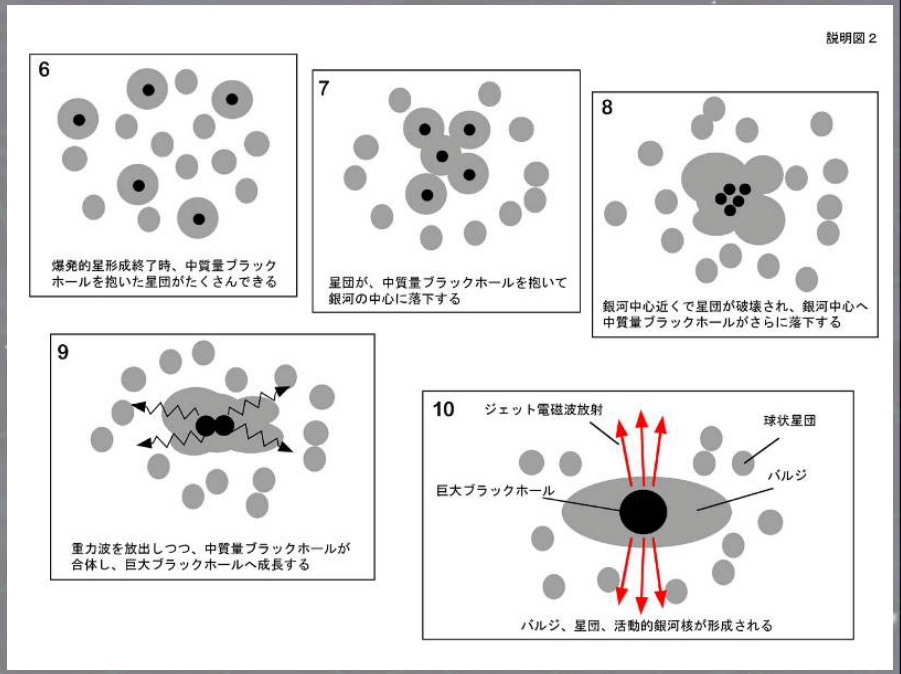


IMBH inspiral and Merger

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

⇩

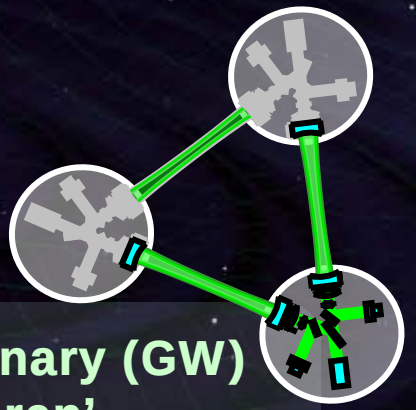
Information on the
formation of
Supermassive BHs
at the center of galaxies



戎崎俊一(理化学研究所) 先生のwebページより引用
http://atlas.riken.go.jp/~ebisu/smbh.html

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)	<	$10^{4\text{-}5}$/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)

DPF targets

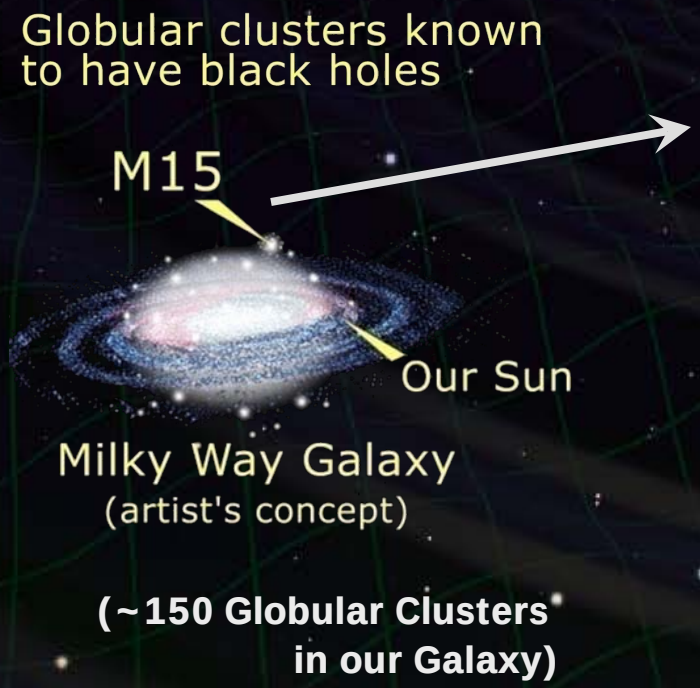
BHs in Globular clusters

BH masses estimated from star motion

⇨ Estimate SNR of GW signals

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

Credit: NASA, STScI



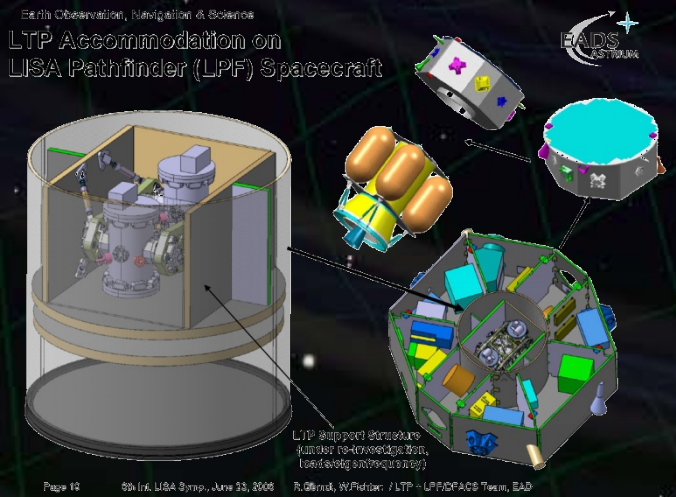
(~150 Globular Clusters in our Galaxy)

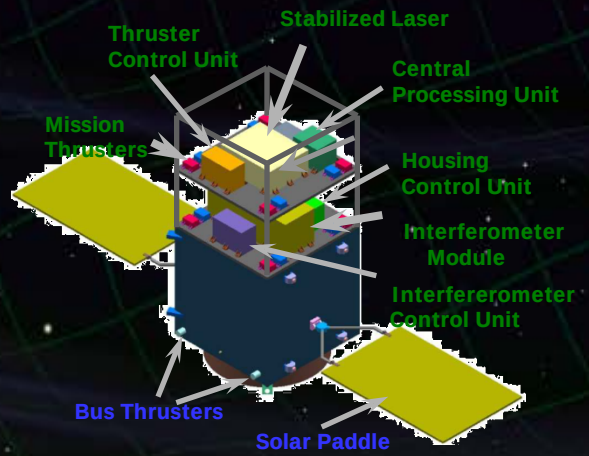
NGC#	BH質量 [Msun]	距離 [kpc]	SNR (同質量)	SNR (1:1/3)	SNR +100Msun	速度分散 [km/sec]
6441	12423.8	11.2	36.4	22.2	3.7	19.5
6256	4753.6	6.9	26.6	16.2	4.3	15.4
7078	4387.8	10.3	16.6	10.2	2.8	15.1
6093	3720.3	10.0	14.9	9.1	2.7	14.5
104	820.0	4.5	9.4	5.7	3.6	10
1851	1348.5	12.1	5.3	3.2	1.6	11.3
6681	820.0	9.0	4.7	2.9	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)

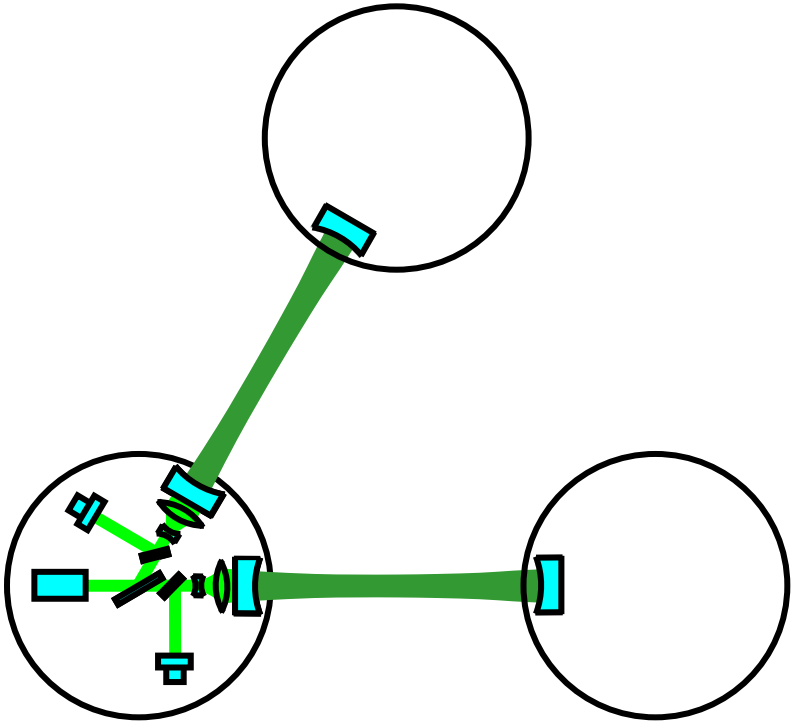
Comparison with LPF

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





Pre-DECIGO



	Pre-DECIGO	DECIGO
Arm length	100 km	1000 km
Mirror diameter	30 cm	1 m
Laser wavelength	0.532 μm	0.532 μm
Finesse	30	10
Laser power	1 W	10 W
Mirror mass	30 kg	100 kg
# of interferometers in each cluster	1	3
# of clusters	1	4

•8th Edoardo Amaldi Conference on Gravitational Waves (June 24, 2009, New York, USA)

SWIM launch

Test of signal processing and control system

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

Photo: JAXA

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

Photo by JAXA

SWIMμν : User Module

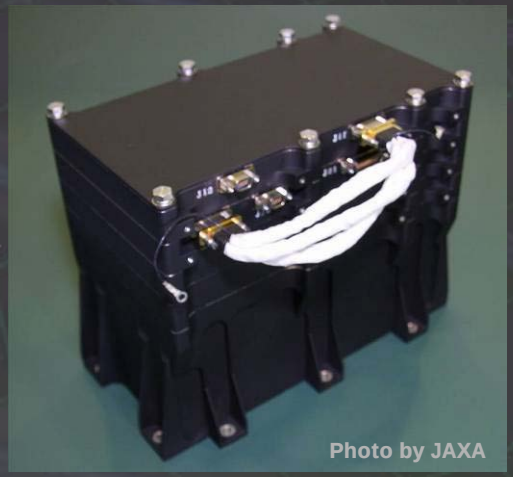


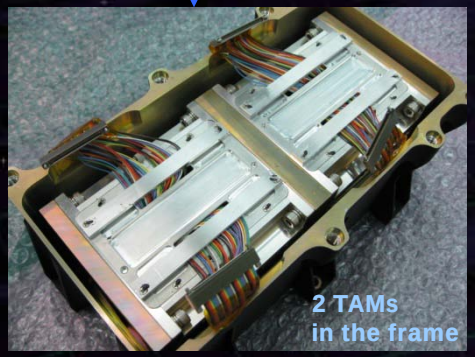
Photo by JAXA

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

SWIMμν

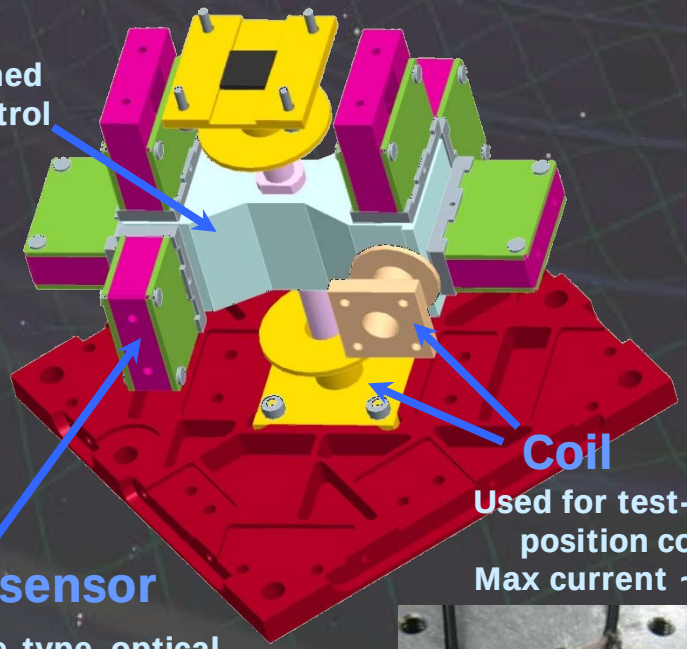
Tiny GW detector ~47g test masses inside
→ Levitated control in space



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

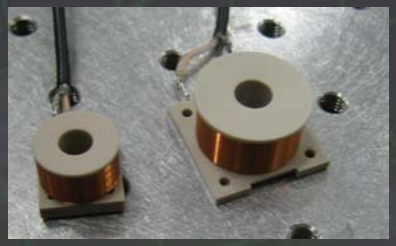


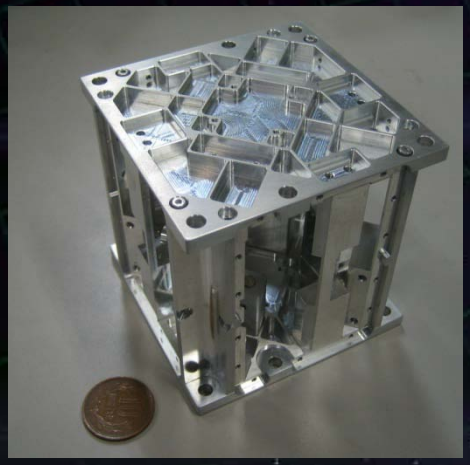
Coil

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





Successful control

SWIM
In-orbit operation

Test mass controlled

- Error signal → zero
- Damped oscillation (in pitch DoF)
- Free oscillation in x and y DoF
- Signal injection → OL trans. Fn.

Operation: May 12, 2009

Downlink: ~ a week