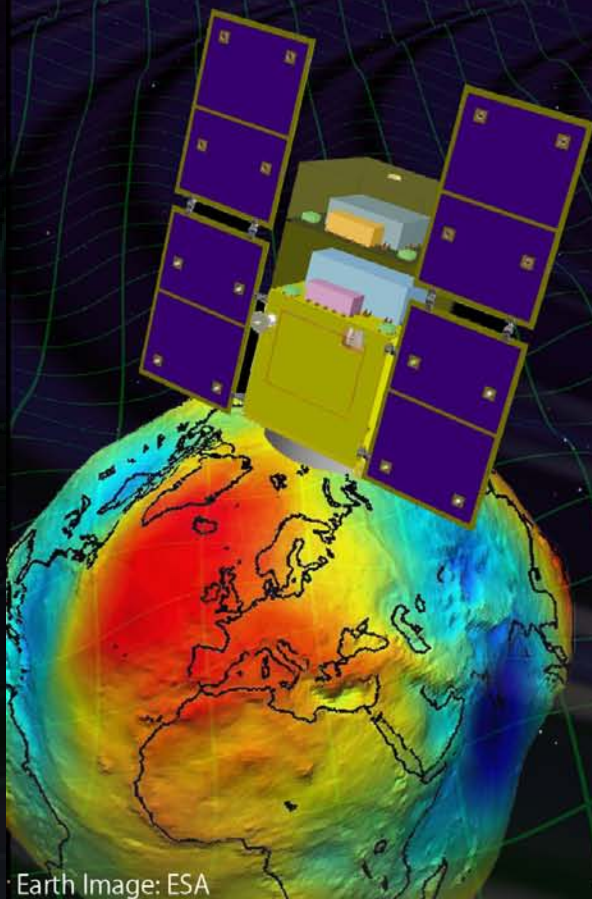
DECIGO Pathfinder



Original
Picture : Sora

Masaki Ando

(Department of Physics, Kyoto University)

On behalf of
DECIGO working group

(May 30, 2010)

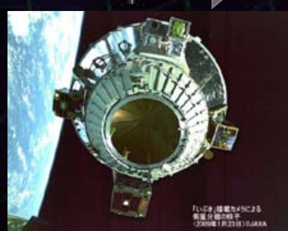
Roadmap

Figure: S.Kawamura

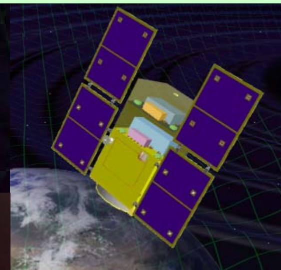
2010 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29

Mission

R&D
Fabrication

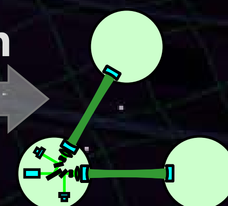


SDS-1 / SWIM



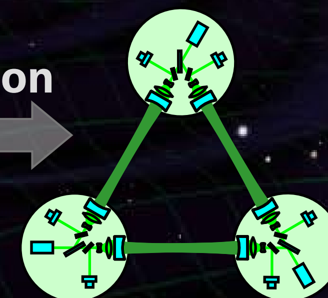
DECIGO
Pathfinder
(DPF)

R&D
Fabrication



Pre-DECIGO

R&D
Fabrication



DECIGO

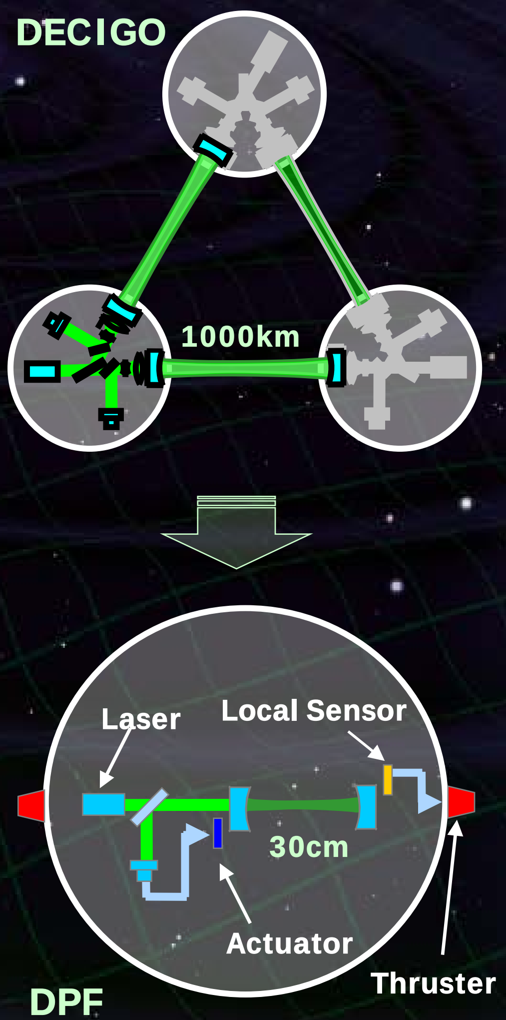
	SDS-1 / SWIM, DPF	Pre-DECIGO	DECIGO
Objective	Space test of key tech. GW observation	Detect GW with min. spec FP between S/C	GW astronomy
Design	Single small satellite Short FP interferometer	3 S/C 1 interferometer unit	3 S/C x 3-4 units

(May 30, 2010)

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 satellite

DPF Payload

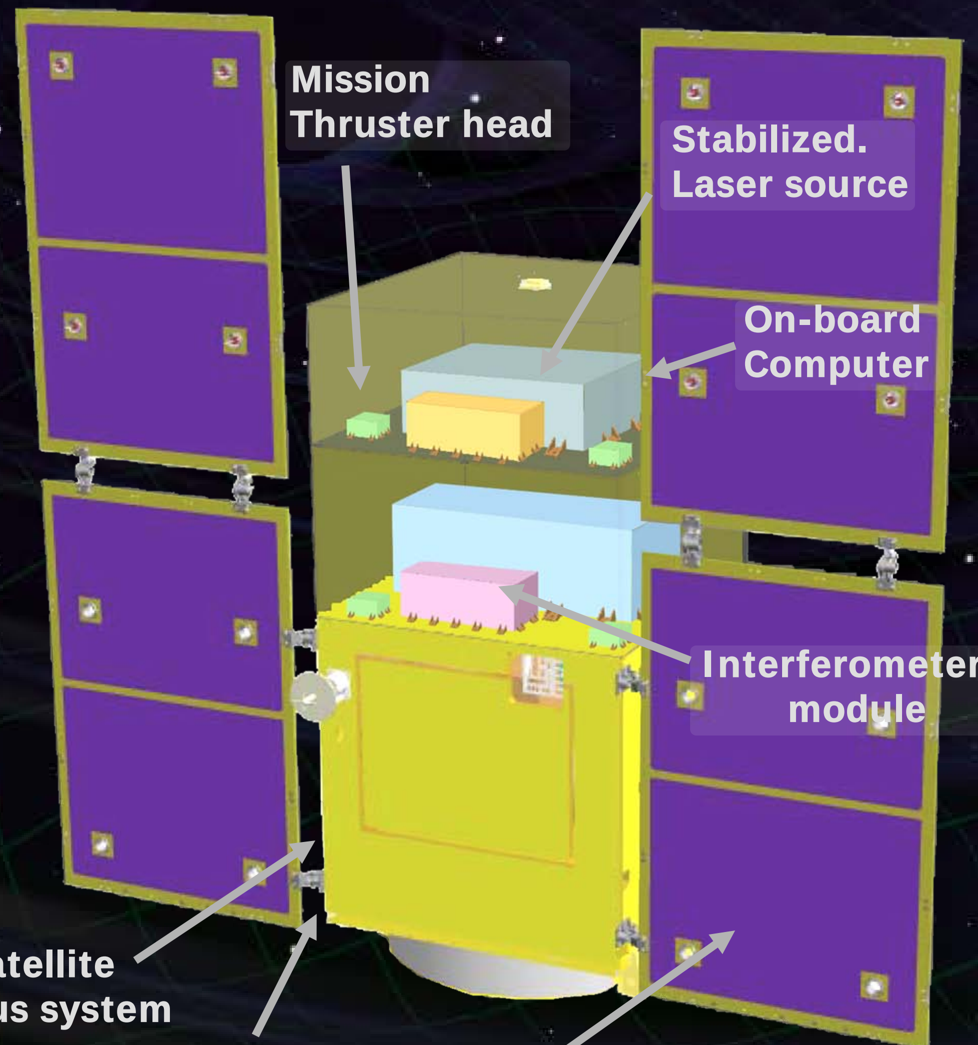
Size : 950mm cube
Weight : 150kg
Power : 130W
Data Rate: 800kbps
Mission thruster x12

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



(May 30, 2010)

Orbit and attitude

DECIGO

Satellite Orbit

Low-earth orbit

Altitude 500km, Inclination 98 deg

Eccentricity < 10^{-3} (accuracy of the launcher)

Orbital period ~100min

Sun-synchronous, dusk-dawn orbit for thermal stability

(eclipse ~100days/yr, 25 min max)

Satellite Attitude (under discussion)

Sun and Earth synchronous attitude

IFO optical axis parallel to the earth-vertical line

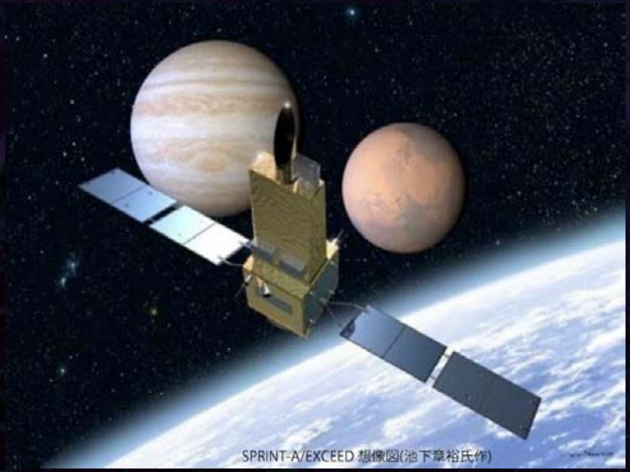
DPF mission status

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 (~2013/14) : ERG
DPF survived until final two
3rd mission (~2015/16) : TBD

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

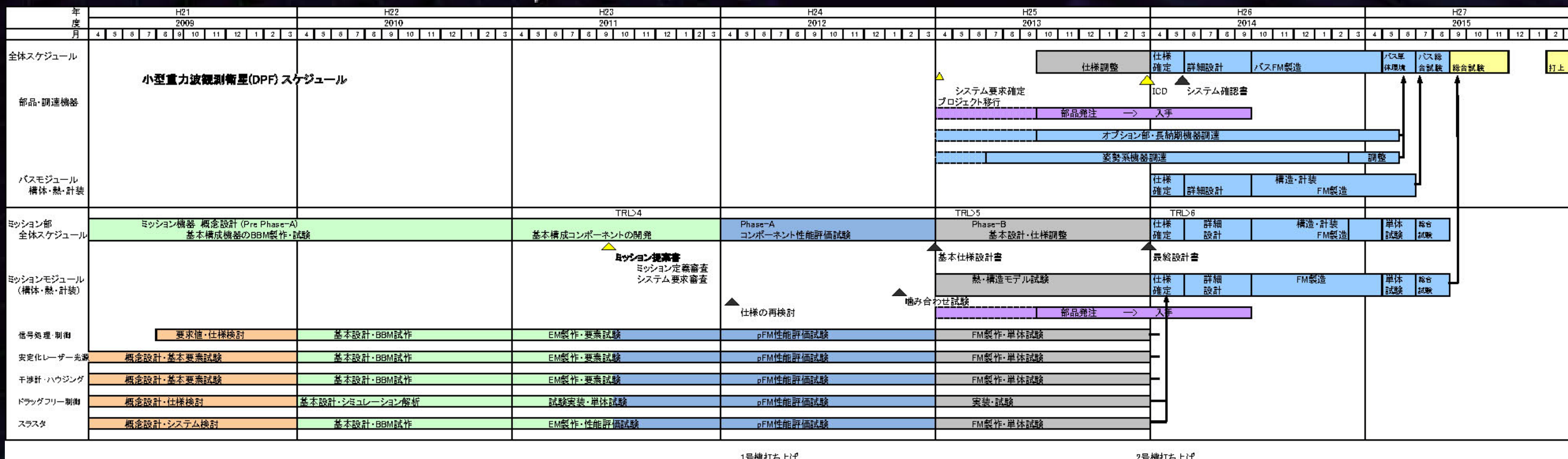


SPRINT-A /EXCEED
UV telescope mission


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

DPF Schedule

2009 2010 2011 2012 2013 2014 2015



Conceptual design | BBM | EM / pFM | Component FM | Satellite FM | Tests and Launch

Mission proposal
Require >TRL 4

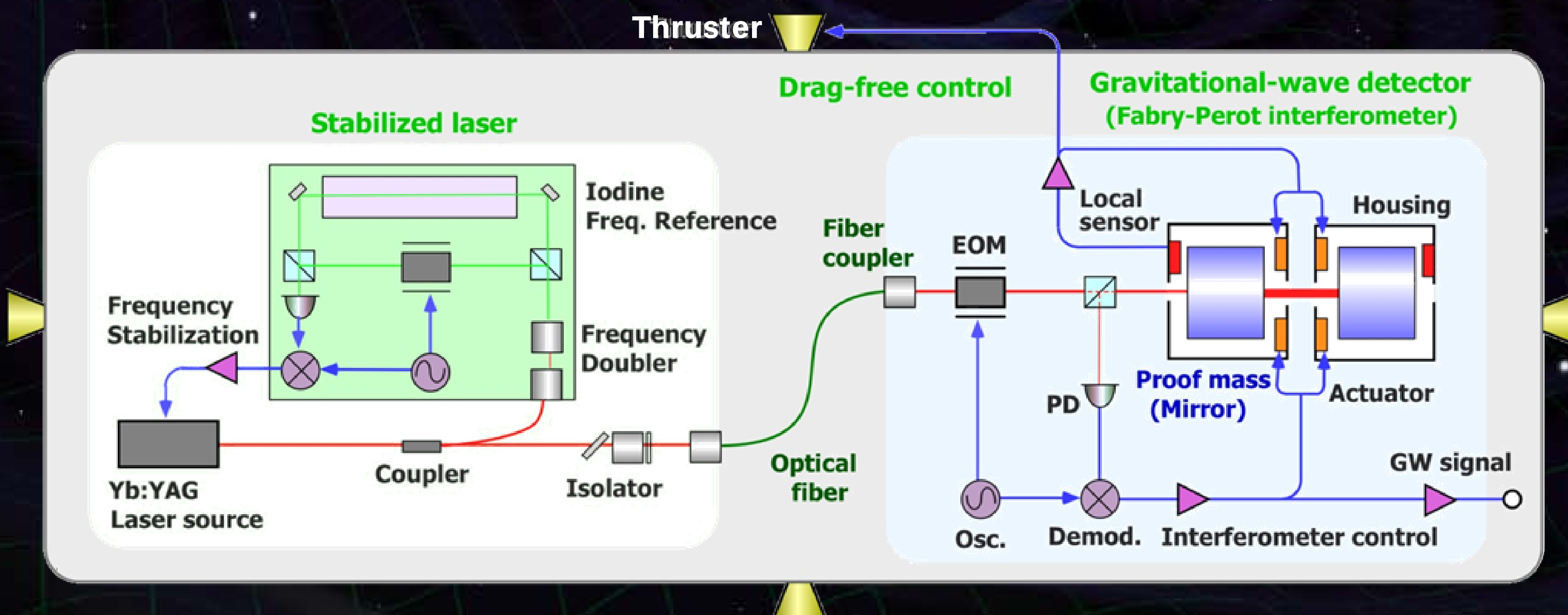
Complete component FM

(May 30, 2010)

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

(May 30, 2010)

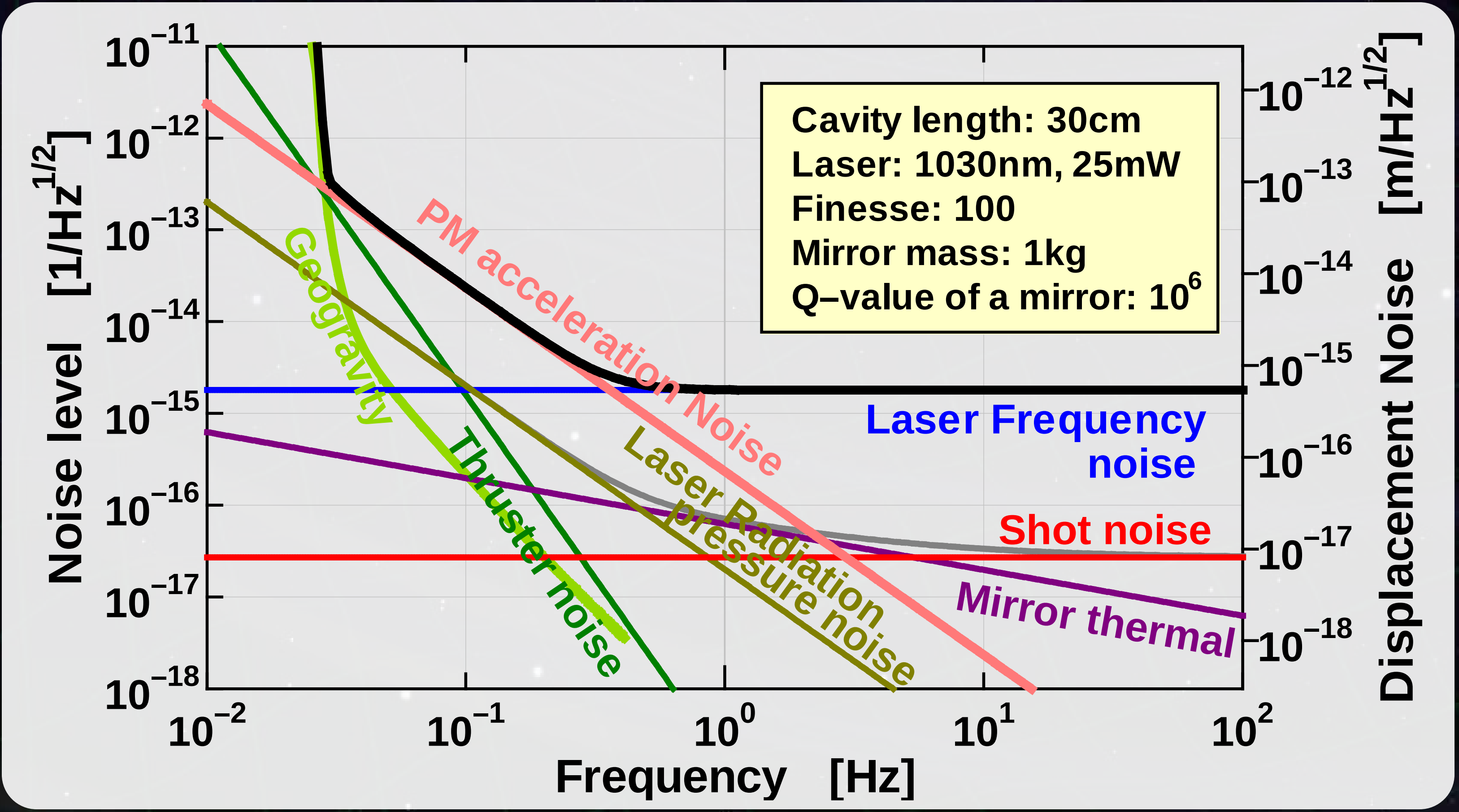
DPF Sensitivity

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)



(May 30, 2010)

Requirements

DECIGO

Sensor Noise

Disp. noise 6×10^{-16} m/Hz$^{1/2}$ (0.1 Hz)

⇨ x 200 of DECIGO in disp. noise

Other noises

Laser freq. noise: 0.5 Hz/Hz$^{1/2}$ (1Hz)

Acceleration Noise

Force noise 1×10^{-15} m/s^2/Hz$^{1/2}$ (0.1 Hz)

⇨ x 250 of DECIGO

Satellite motion

Disp. noise 1×10^{-9} m/Hz$^{1/2}$ (0.1 Hz)

External force sources

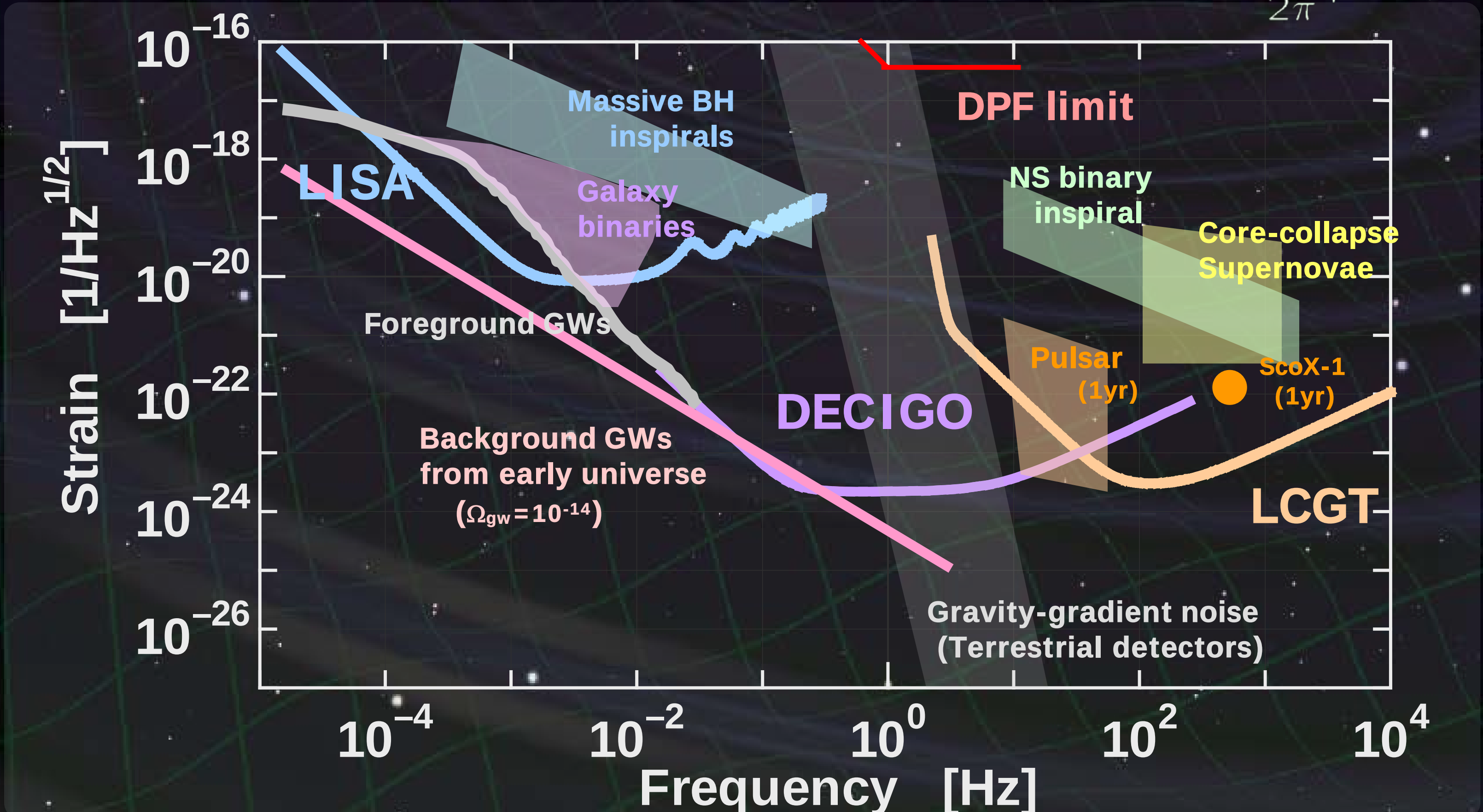
Fluctuation of magnetic field, electric field, gravitational field, temperature, pressure, etc.

DPF sensitivity

DPF sensitivity *h* ~ 2×10^{-15} $Hz^{1/2}$

(x10 of quantum noises)

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



(May 30, 2010)

GW target of DPF

Blackholes events in our galaxy

IMBH inspiral and merger

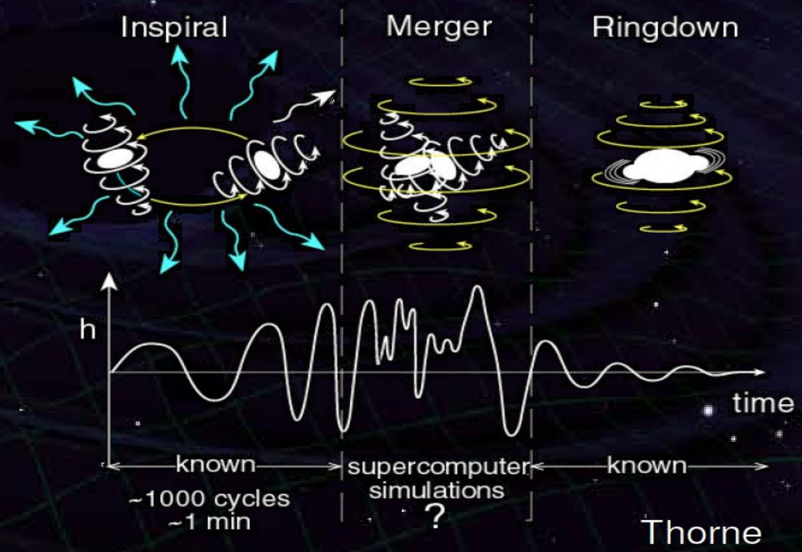
$h \sim 10^{-15}$, $f \sim$ 4 Hz
Distance 10kpc, $m = 10^3\ M_{sun}$
Obs. Duration (~1000sec)

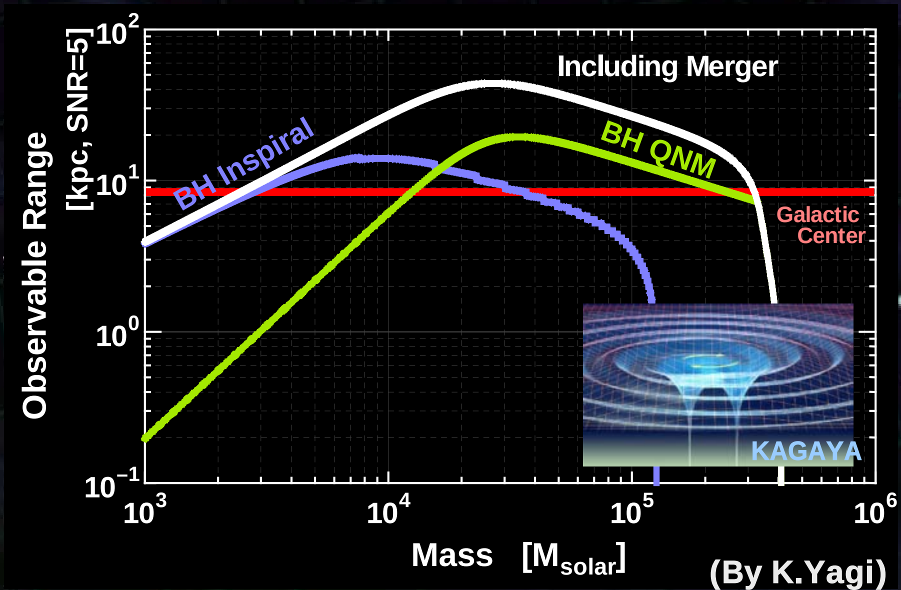
BH QNM

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

Observable range covers our Galaxy (SNR~5)

Hard to access by others → Original observation

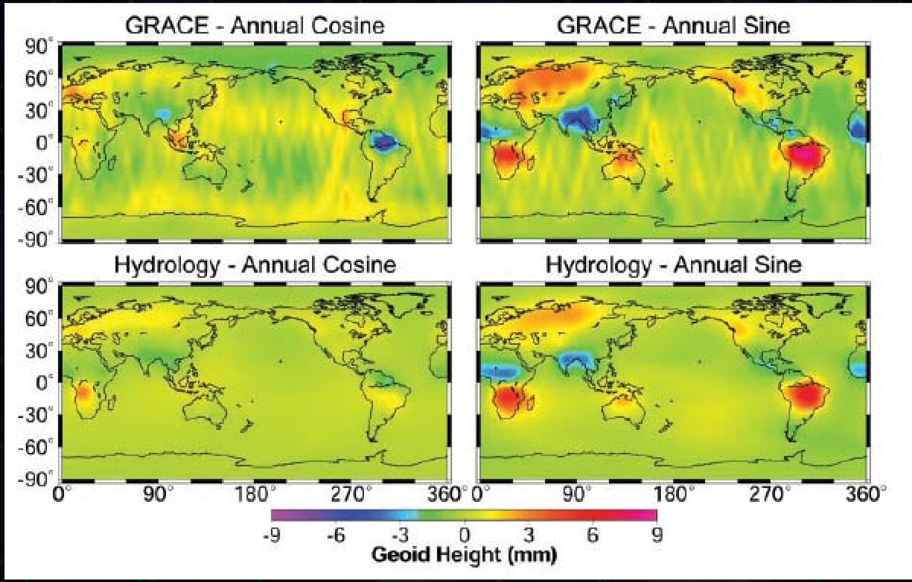




(May 30, 2010)

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

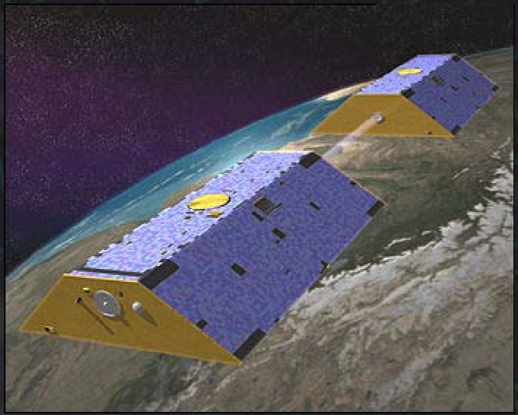
Satellite-to Satellite tracking High-Low

- 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 Gradient

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

GOCE (ESA, 2009-)

Results and plans

CHAMP,GRACE, GOCE in operation

- Shape of the Earth
  Coefficients up to 2190 orders
  (GRACE etc., 2008)
  ⇨ Earth standard with high precision and resolution
- Changes in time
  Seasonal movement of waters
  Crust deformation by earthquakes
  (Sumatera 2004)

Will be ended by around 2012

GRACE-FO (NASA)

Based on GRACE,
Add laser interferometer
To be launched in2016


The Future of Satellite Gravimetry

Report from the

Workshop on The Future of Satellite Gravimetry

12-13 April 2007, ESTEC, Noordwijk, The Netherlands

Radboud Koop and Reiner Rummel (Eds.)

IAS

Earth Gravity model

Describe gravity potential by
Spherical harmonic functions

$$U(r,\lambda,\phi) = \frac{GM}{r}\sum_{l=0}^{\infty}\sum_{m=0}^{n}\left(\frac{R}{r}\right)^{l} P_{lm}(\sin\phi) \times [C_{lm}\cos(m\lambda) + S_{lm}\sin(m\lambda)]$$

$G,\ M,\ R$: **Grav. Const., Mass and radius of the Earth**

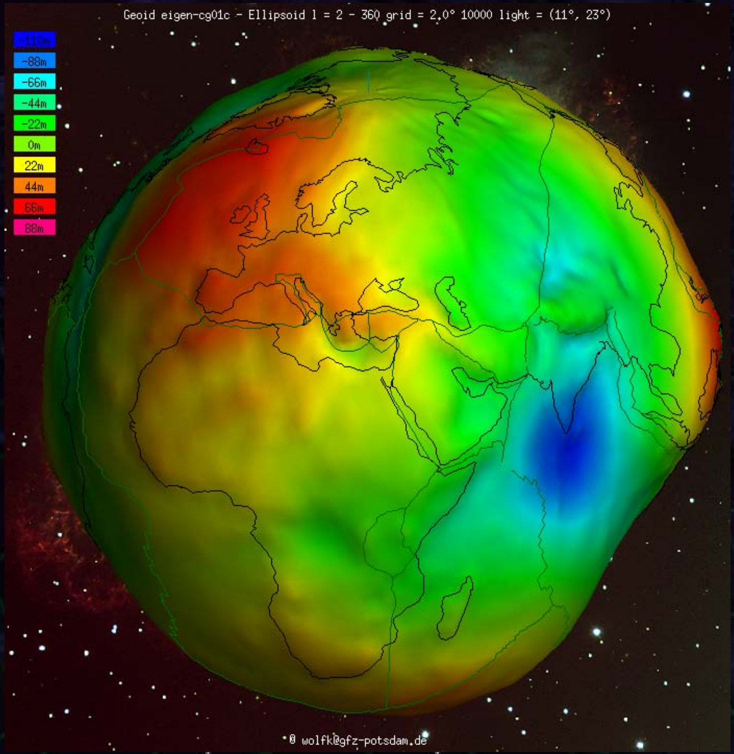
$r,\ \lambda,\ \phi$: **Orbital radius, longitude, altitude**

P_{lm} : **Associated Legendre functions**

Coefficients C_{lm}, S_{lm} **:**

Describe the mass distribution

Determined by satellite missions, etc.



International Centre for Global Earth Models (ICGEM)
http://icgem.gfz-potsdam.de/ICGEM/ICGEM.html

(May 30, 2010)

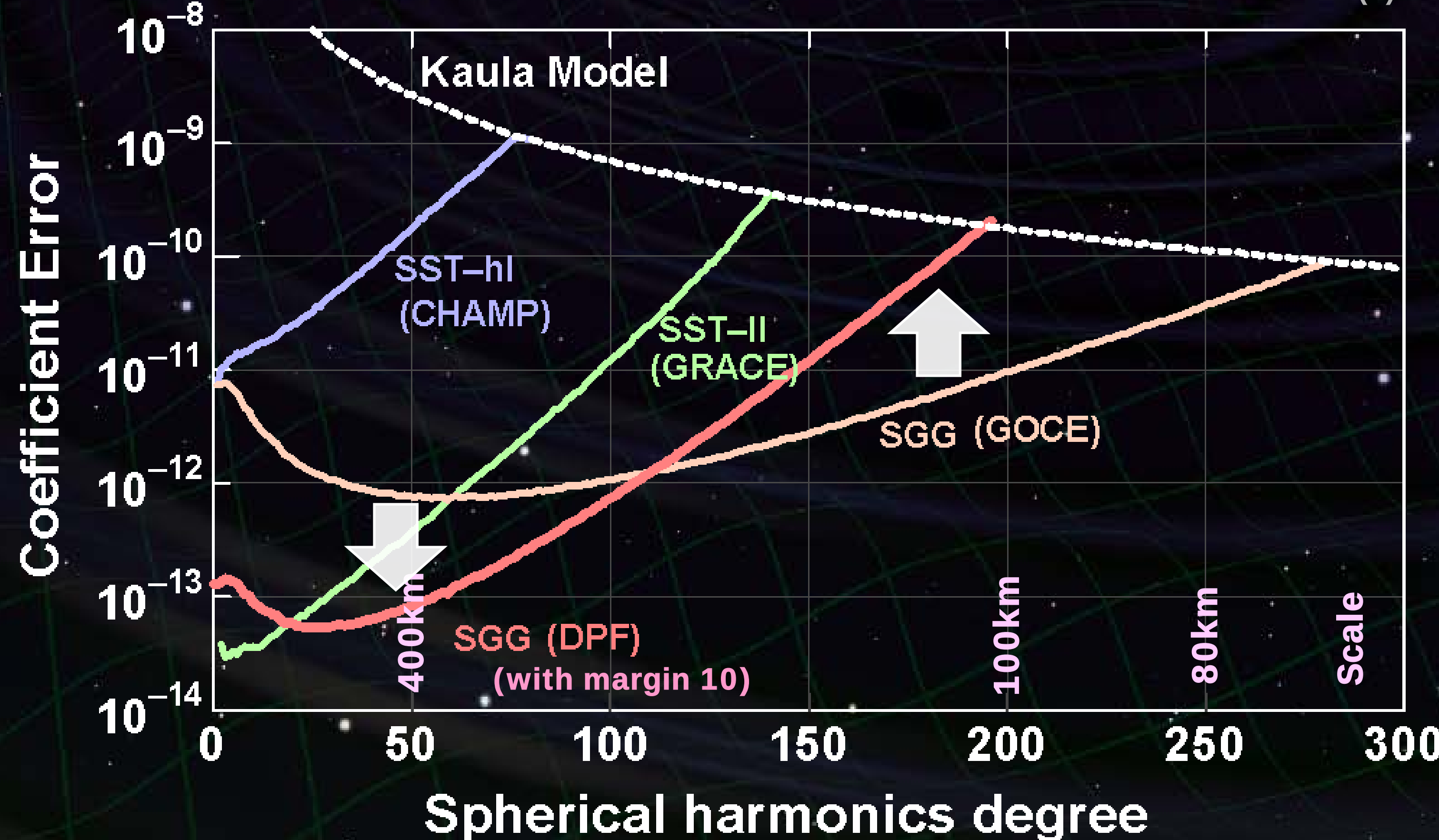
DPF sensitivity

Comparison of sensitivities

Better in low orders (large scale) ← Sensors

Worse in high orders (small scale) ← Altitude

Report for Mission Selection
Gravity Field and Steady-State
Ocean Circulation Mission
ESA SP-1233(1) July 1999.

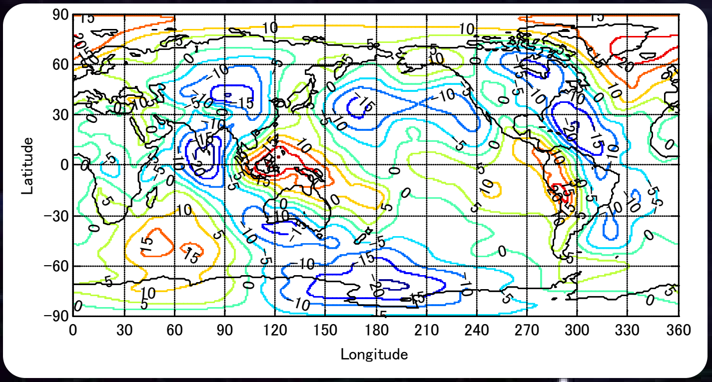


Acceleration spectrum

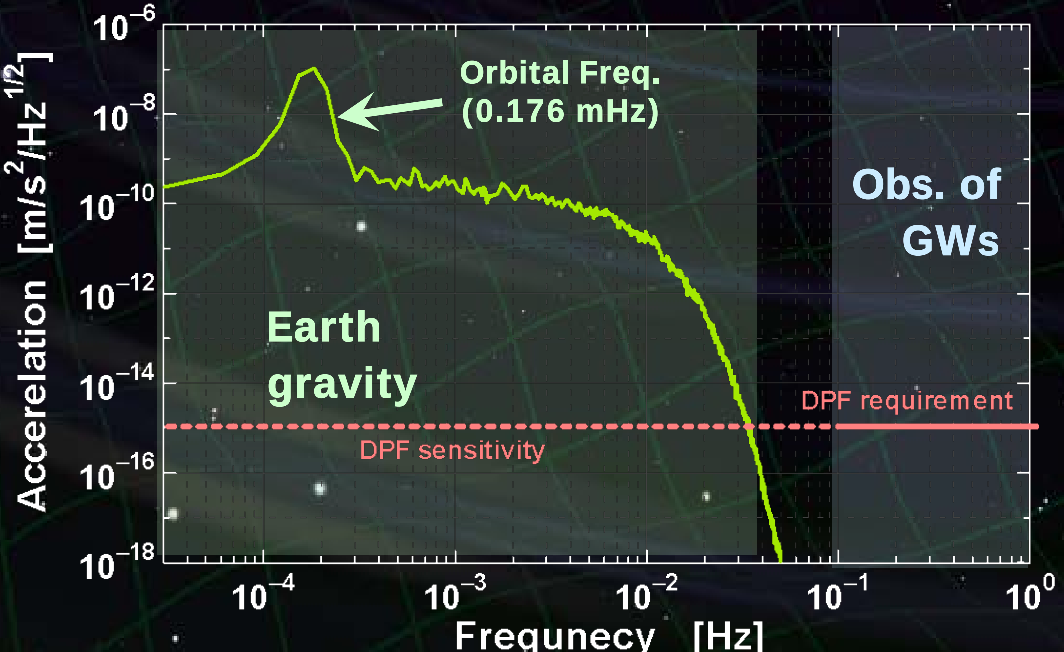
DECIGO

Estimation of observed acceleration

EGM2008 (order 2190) data
→ Calculate potential
DPF orbit
altitude 500km, polar-orbit
→ Estimate observed acceleration



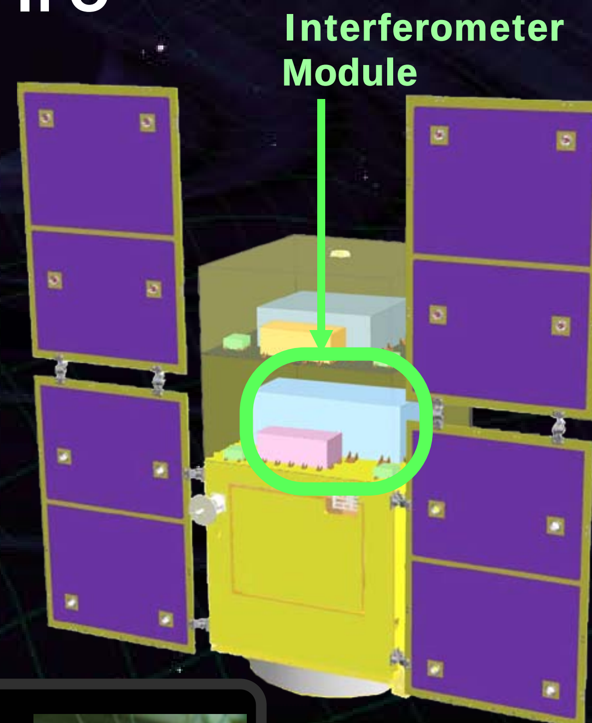
Gravity acceleration in mgal
(l>2 500km altitude)



(May 30, 2010)

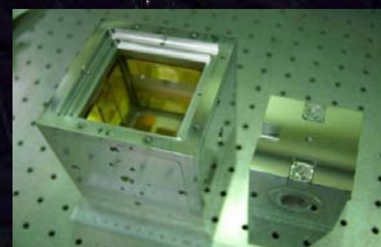
Interferometer Module

Interferometer Module : Test mass + IFO



Test-mass module
→ Gravity reference

- BBM of Module, Sensor, Actuator, Clump/Release
- μ-Grav. Exp.



Hosei, NAOJ, Ochanomizu, Stanford

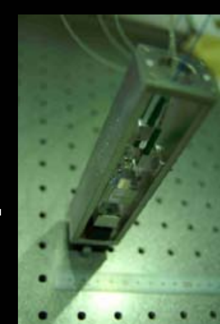
Interferometer
→ GW, Gravity observation

- 30cm IFO BBM Digital control
- Packaging
- Monolithic Opt.

NAOJ, U-Tokyo

Laser sensor
→ Small MI

- BBM test
- Sensitivity meas.



ERI, U-Tokyo

Interferometer Module

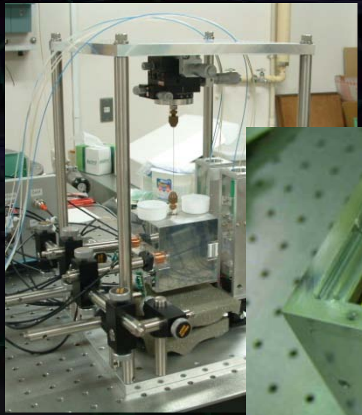
By
M.Michimura

Main interferometer

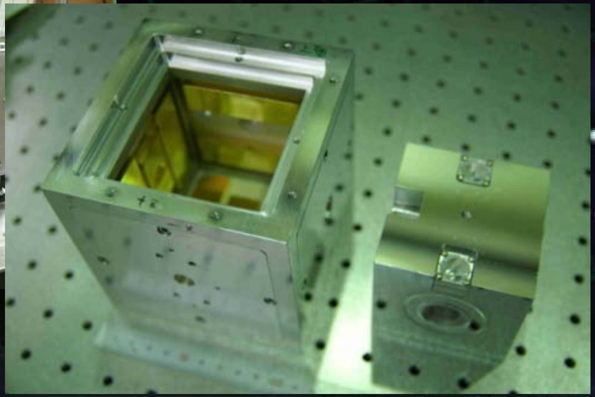
30cm Fabry-Perot interferometer
Finesse ~100, Two test masses
Monolithic input bench
PDH and WFS for length and
alignment signal extraction

Test-mass module

Reference for geodesy
Test mass ~1kg ~50mm cubic
Mirrors will be glued
ES sensor-and-actuators
Laser sensors
Launch lock, clump/release
Discharge with UV LED



By
A.Araya



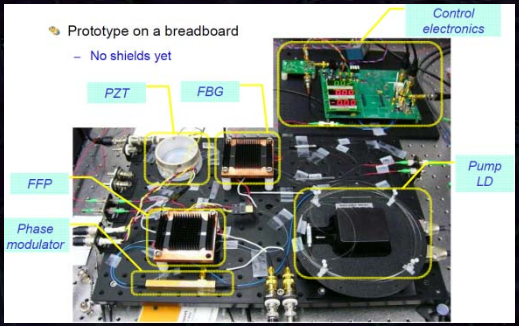
By
S.Sato

Stabilized Laser Module

Stabilized Laser : Laser source + Stabilization system

Yb:YAG (NPRO or Fiber laser)
→ Laser source

- BBM development

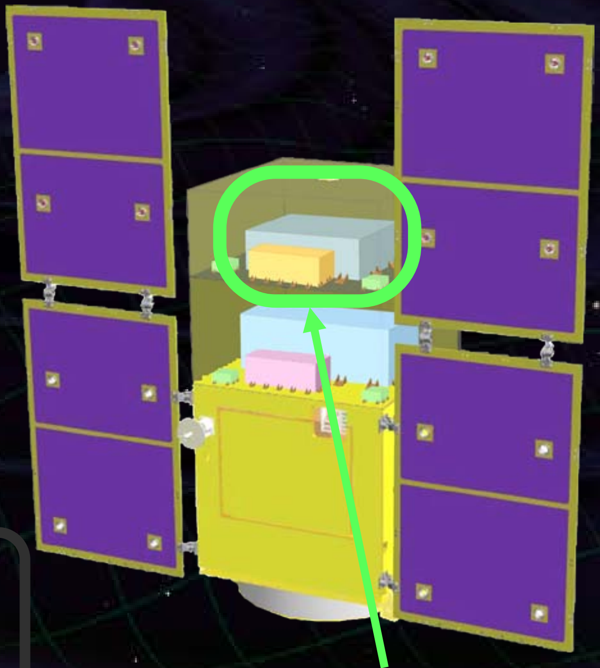


UEC, NASA/GSFC

I_2 absorption line
→ Frequency reference

- BBM development
- Stability meas.

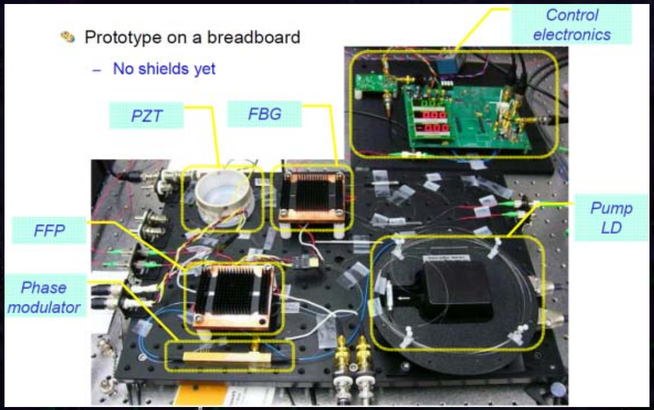
UEC, NICT



Stabilized Laser Module

Stabilized Laser Module

Laser source
- Yb:YAG laser
  - wavelength 1030nm
  - output 100mW
- Candidates
  - NPRO, fiber laser



By K.Numata

Stabilization
- Freq. Stabilization
  - by Saturated absorption with I_2
  - Requirement: 0.5 Hz/Hz$^{1/2}$
  - Required freq.-doubled beam (515nm)
  - Multi-path in 40cm-length cell
- Option: monolithic reference cavity

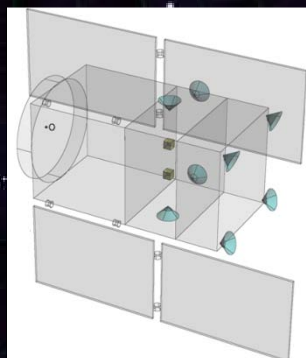
- Intensity stabilization
  - Requirement: 10^{-8} Hz$^{-1/2}$

By M.Musha

Attitude and Drag-free control

Attitude and Drag-free control : Structure, Thrusters, Control

Structure, thermal stability

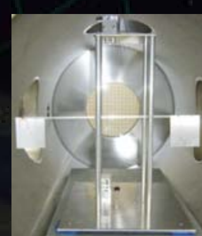


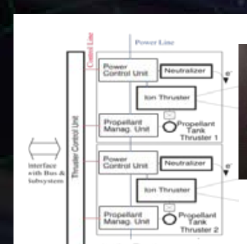
- Passive attitude stability
- Drag-free control

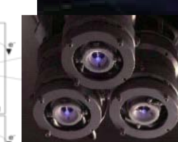
U-Tokyo, JAXA

Low-noise Thruster

→ Actuators for satellite control

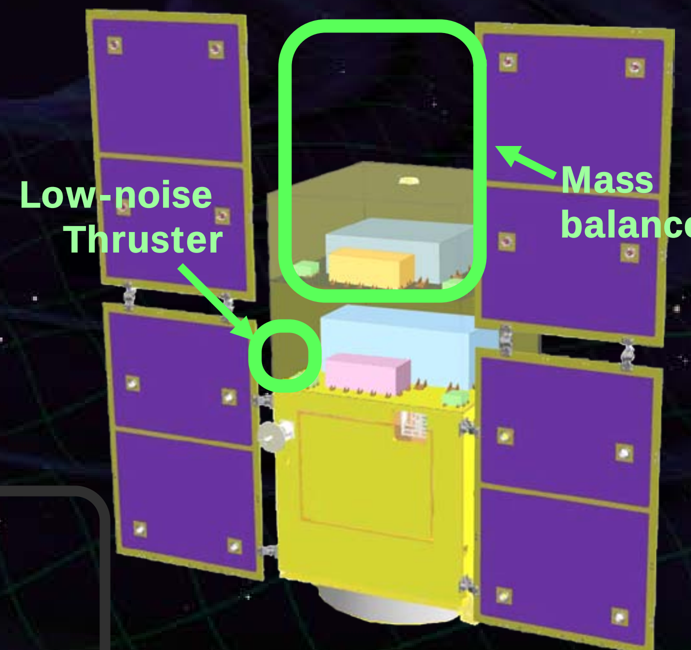






- BBM and system design

JAXA, NDAJ, Tokai-U



Attitude and Drag-free control

DECIGO

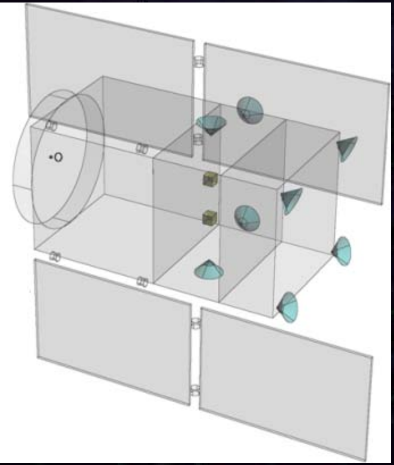
Attitude control and Drag-free

Satellite structure (mass distribution)

Passive attitude stabilization by gravity gradient

Thruster position and control topology: under consideration

By S.Moriwaki



Thruster (tentative)

12 (TBD) mission thrusters

Low-noise small thruster

Max. thrust 10μN (tunable)

Noise 0.1 $\mu N/Hz^{1/2}$

>10Hz response

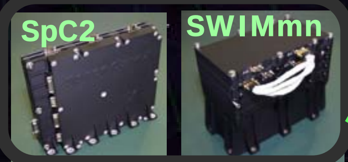
- FEEP system, Gas jet backup

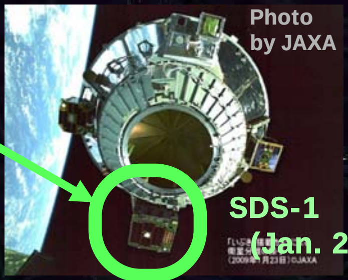
By I.Funaki

Signal processing and Control

Signal Processing and Control : SpaceWire-based system

SpC2 + SpW system
→ Signal processing and install. ctrl



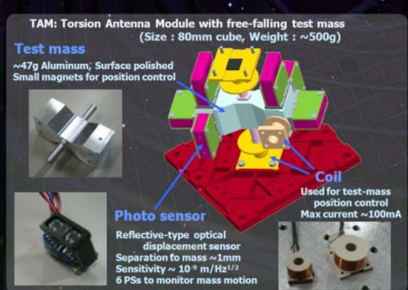


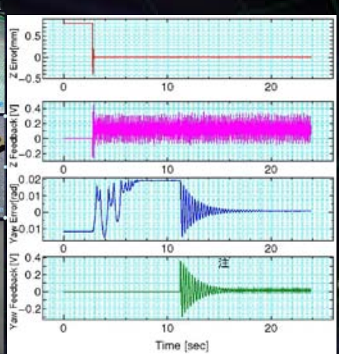
SDS-1
(Jan. 2009)

Space demonstration
bySDS-1/SWIM

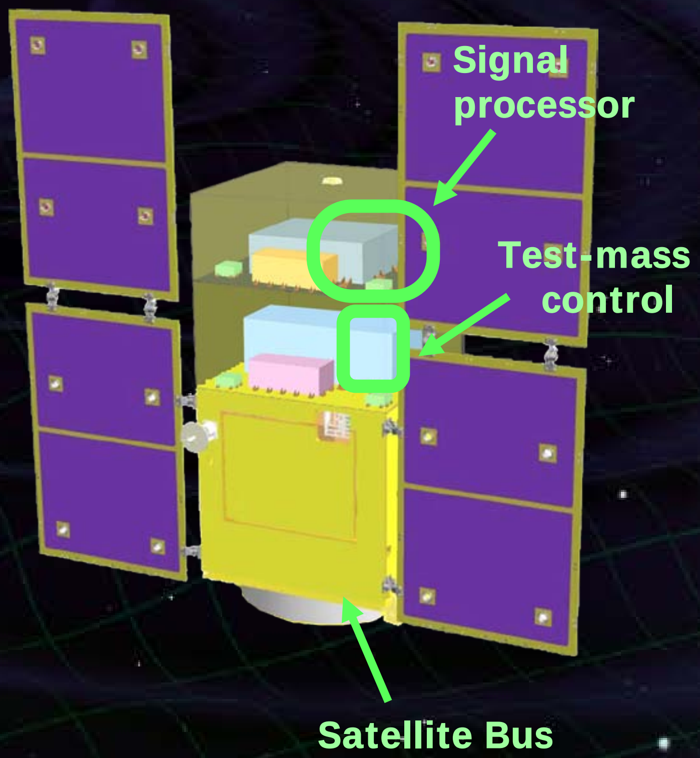
JAXA, U-Tokyo, Kyoto

SWIMmn demonstration
→ Test mass control in orbit





JAXA, U-Tokyo, Kyoto



SWIM launch

Test of signal processing
and control system

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

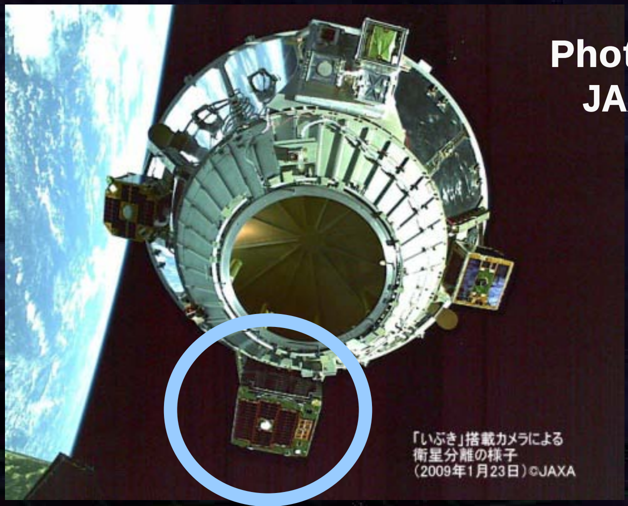


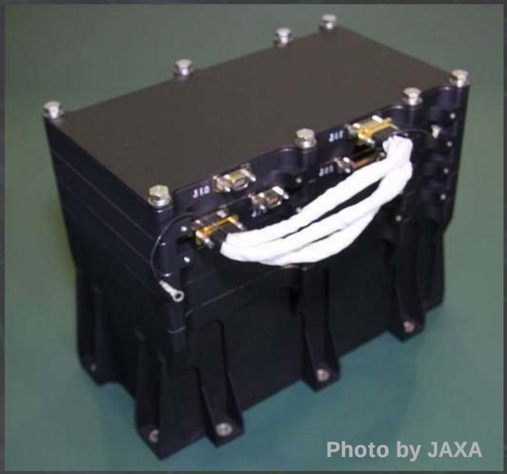
Photo: JAXA

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

SWIMμν : 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

SWIMμν

DECIGO

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

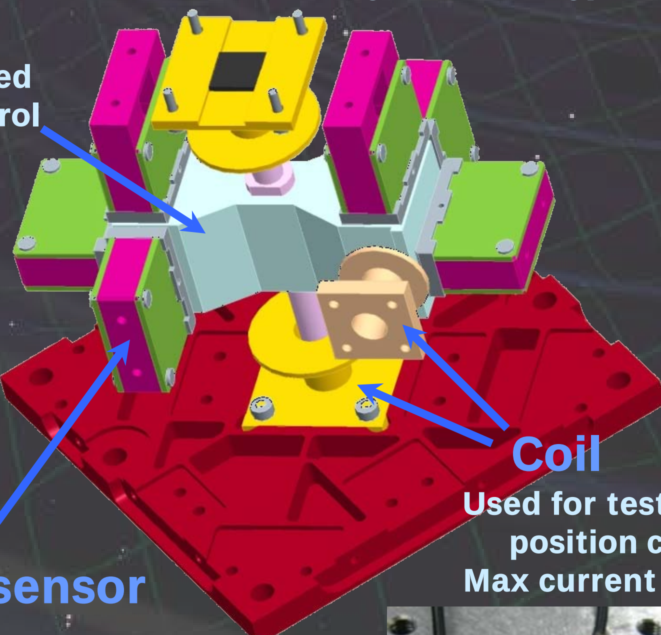
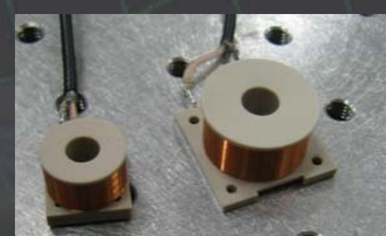


Photo sensor

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

Coil

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



(May 30, 2010)

Successful control

SWIM

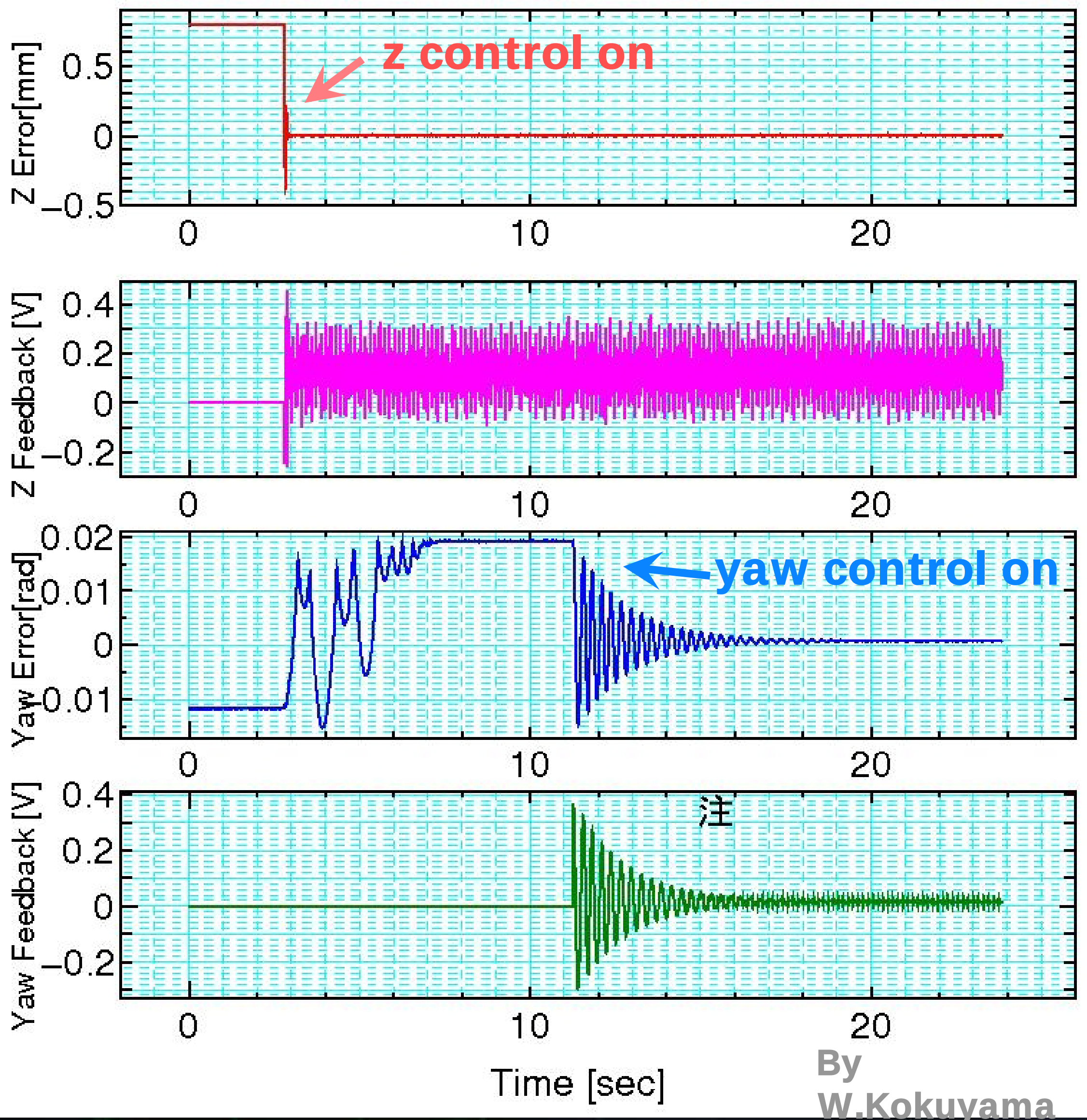
In-orbit operation

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



By W.Kokuyama

Summary

DECIGO

DECIGO : Fruitful Sciences

Very beginning of the Universe

Dark energy

Galaxy formation

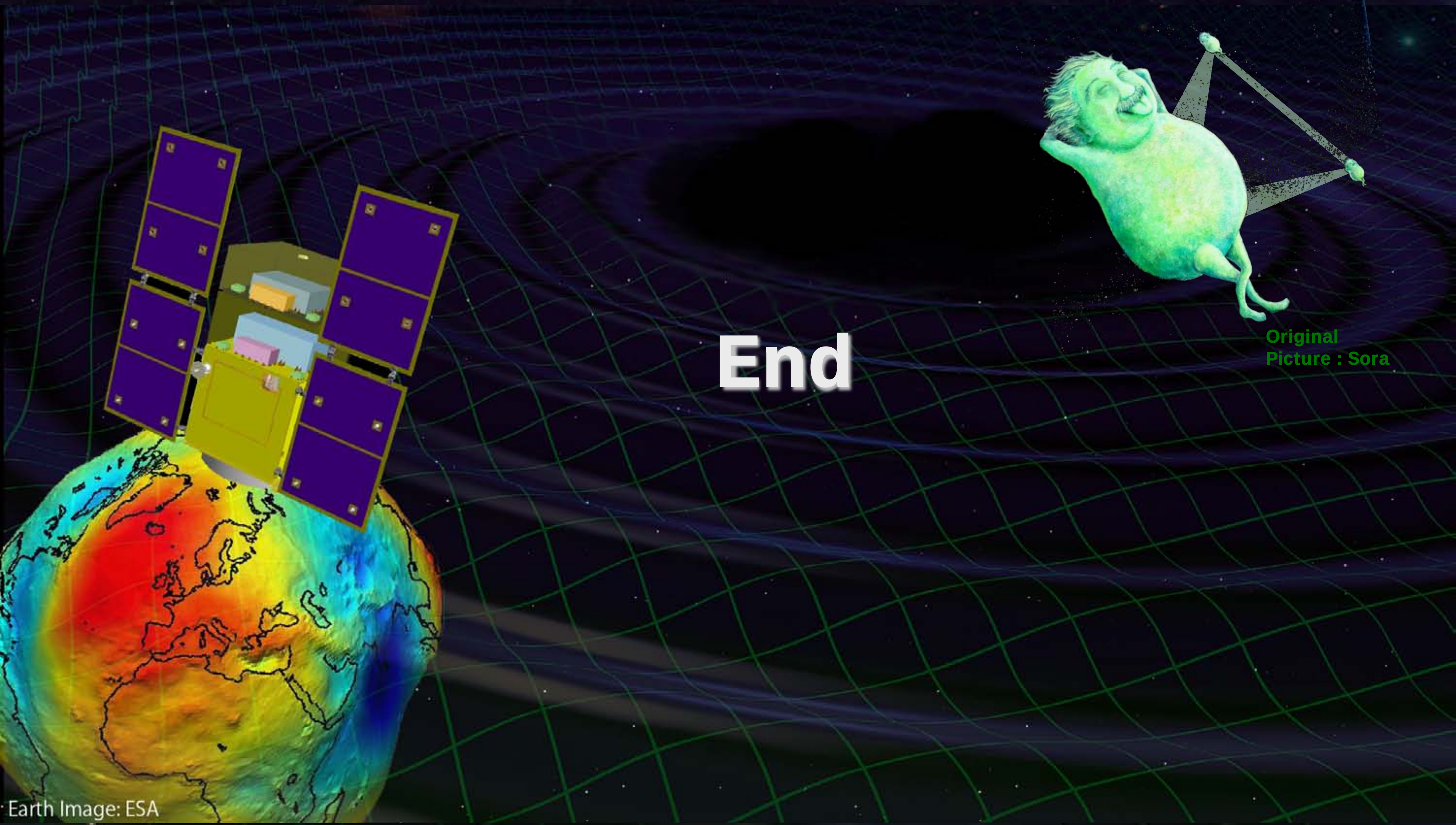
DECIGO Pathfinder

Important milestone for DECIGO

Strong candidate of JAXA's satellite series

SWIM – under operation in orbit

first precursor to space!



End

球状星団のブラックホール

中心付近の星の速度分布の観測

Core velocity dispersions for 25 Galactic and 10 old Magellanic globular clusters?

Pierre Dubath et al.,

Astron. Astrophys. 324, 505–522 (1997)

Table 6. Radial velocities and core velocity dispersions for all Galactic globular clusters in our sample.

Obs No. (1)	NGC No. (2)	V_r (km s^{-1}) (3)	σ_{CCF} (km s^{-1}) (4)	D (%) (5)	S/N (6)	ε (km s^{-1}) (7)	σ_{ref} (km s^{-1}) (8)	σ_p^{obs}(core) (km s^{-1}) (9)	stat err (km s^{-1}) (10)	σ_p(core) (km s^{-1}) (11)
1	104	−19.4±1.6	11.8±0.2	0.110	13.0	0.12	7.2±0.15	$9.3^{+0.4}_{-0.4}$	$^{+4.8}_{-2.6}$:	$10.0^{+4.8}_{-2.6}$:
2	"	−19.9±1.6	11.5±0.2	0.107	13.0	0.12	6.8±0.10	$9.3^{+0.3}_{-0.3}$	...	...
3	362	223.3±1.6	8.9±0.1	0.171	14.0	0.07	6.8±0.10	$5.7^{+0.3}_{-0.3}$	$^{+3.0}_{-1.6}$:	$6.2^{+3.0}_{-1.6}$:
4	1851	320.3±0.8	13.8±0.2	0.071	59.8	0.04	9.0±0.20	$10.5^{+0.4}_{-0.5}$	$^{+2.5}_{-1.7}$	$11.3^{+2.5}_{-1.8}$
5	1904	200.6±0.9	9.7±0.3	0.050	15.4	0.19	9.0±0.20	$3.6^{+1.1}_{-1.6}$	$^{+1.9}_{-1.0}$:	$3.9^{+2.2}_{-1.9}$:
6	5272	−146.3±1.6	8.1±0.3	0.112	5.0	0.30	6.8±0.10	$4.4^{+0.7}_{-0.8}$	$^{+2.3}_{-1.2}$:	$4.8^{+2.4}_{-1.4}$:
7	5286	57.2±1.7	10.8±0.7	0.050	5.0	0.67	7.2±0.15	$8.0^{+1.0}_{-1.1}$	$^{+4.2}_{-2.2}$:	$8.6^{+4.3}_{-2.5}$:
8	5694	−142.7±1.7	8.8±0.5	0.053	6.4	0.49	6.8±0.10	$5.6^{+0.9}_{-1.0}$	$^{+1.3}_{-1.3}$	$6.1^{+1.3}_{-1.3}$
9	5824	−26.0±1.6	12.6±0.3	0.037	16.0	0.28	6.8±0.10	$10.6^{+0.4}_{-0.4}$	$^{+1.6}_{-1.6}$	$11.1^{+1.6}_{-1.6}$
10	5904	54.7±1.6	9.1±0.3	0.084	6.0	0.33	6.8±0.10	$6.0^{+0.6}_{-0.7}$	$^{+3.1}_{-1.7}$:	$6.5^{+3.2}_{-1.8}$:
11	5946	129.1±1.9	8.1±1.1	0.101	1.5	1.10	7.2±0.15	$3.7^{+2.2}_{-2.7}$	$^{+1.9}_{-1.0}$:	$4.0^{+2.9}_{-2.9}$:
12	6093	7.8±1.7	15.0±0.5	0.037	10.0	0.45	6.8±0.10	$13.4^{+0.6}_{-0.6}$	$^{+7.0}_{-3.8}$:	$14.5^{+7.0}_{-3.8}$:
13	6256	−104.6±3.1	9.5±2.6	0.081	0.8	2.57	6.8±0.10	$6.6^{+3.4}_{-6.0}$	$^{+3.4}_{-1.8}$:	...
14	6266	−71.8±1.6	16.0±0.3	0.067	10.0	0.25	7.2±0.15	$14.3^{+0.4}_{-0.4}$	$^{+7.4}_{-4.0}$:	$15.4^{+7.4}_{-4.0}$:
15	6284	27.5±1.7	9.3±0.4	0.134	3.0	0.42	6.8±0.10	$6.3^{+0.7}_{-0.8}$	$^{+3.3}_{-1.8}$:	$6.8^{+3.4}_{-2.0}$:
16	6293	−147.9±1.8	10.5±0.8	0.037	5.5	0.82	7.2±0.15	$7.6^{+1.2}_{-1.4}$	$^{+4.0}_{-2.1}$:	$8.2^{+4.2}_{-2.5}$:
17	6325	31.0±1.8	9.0±0.8	0.157	1.4	0.76	6.8±0.10	$5.9^{+1.2}_{-1.4}$	$^{+3.1}_{-1.7}$:	$6.4^{+3.3}_{-2.2}$:
18	6342	118.0±1.6	8.3±0.3	0.172	3.2	0.30	6.8±0.10	$4.8^{+0.7}_{-0.7}$	$^{+2.5}_{-1.3}$:	$5.2^{+2.6}_{-1.5}$:
19	6397	15.1±1.6	7.5±0.3	0.045	13.0	0.28	7.2±0.15	$2.1^{+1.3}_{-2.1}$	$^{+1.1}_{-0.6}$:	...
20	"	15.0±1.6	7.4±0.4	0.050	10.0	0.33	7.2±0.15	$1.7^{+1.5}_{-1.7}$	...	...
21	6441	14.6±1.6	19.3±0.2	0.098	12.0	0.14	6.8±0.10	$18.1^{+0.2}_{-0.2}$	$^{+9.4}_{-5.1}$:	$19.5^{+9.4}_{-5.1}$:
22	6522	−10.3±1.6	9.6±0.3	0.133	4.3	0.29	6.8±0.10	$6.8^{+0.5}_{-0.6}$	$^{+3.5}_{-1.9}$:	$7.3^{+3.5}_{-2.0}$:
23	6558	−198.8±1.6	7.5±0.2	0.168	5.6	0.18	6.8±0.10	$3.2^{+0.6}_{-0.8}$	$^{+1.7}_{-0.9}$:	$3.5^{+1.8}_{-1.2}$:
24	6681	223.4±1.6	11.5±0.3	0.092	7.4	0.24	6.8±0.10	$9.3^{+0.4}_{-0.4}$	$^{+4.8}_{-2.6}$:	$10.0^{+4.8}_{-2.6}$:
25	6752	−32.0±1.6	8.5±0.2	0.082	21.0	0.10	7.2±0.15	$4.5^{+0.5}_{-0.6}$	$^{+2.3}_{-1.3}$:	$4.9^{+2.4}_{-1.4}$:
26	7078	−111.3±1.6	15.6±0.2	0.015	54.0	0.21	6.8±0.10	$14.0^{+0.3}_{-0.3}$	$^{+5.0}_{-3.0}$	$15.1^{+5.0}_{-3.0}$
27	7099	−180.7±1.8	8.2±0.8	0.022	11.0	0.83	6.8±0.10	$4.6^{+1.5}_{-2.0}$	$^{+2.8}_{-1.5}$:	$5.8^{+2.9}_{-1.7}$:
28	"	−181.1±1.8	8.6±0.9	0.020	11.0	0.91	6.8±0.10	$5.3^{+1.5}_{-1.9}$	...	...
29	"	−183.6±2.2	8.9±1.5	0.017	8.0	1.47	6.8±0.10	$5.7^{+2.2}_{-3.0}$	...	...
30	"	−185.1±1.7	8.9±0.5	0.031	14.4	0.45	6.8±0.10	$5.7^{+0.8}_{-0.9}$	...	...
31	"	−182.9±2.7	8.2±2.2	0.017	5.4	2.18	6.8±0.10	$4.6^{+3.3}_{-3.6}$	...	...

中心付近の星の速度分布と BH質量の関係

GEMINI AND HUBBLE SPACE TELESCOPE EVIDENCE FOR AN INTERMEDIATE-MASS BLACK HOLE IN ω CENTAURI

Eva Noyola et al., ApJ 676 (2008) 1008Y1015

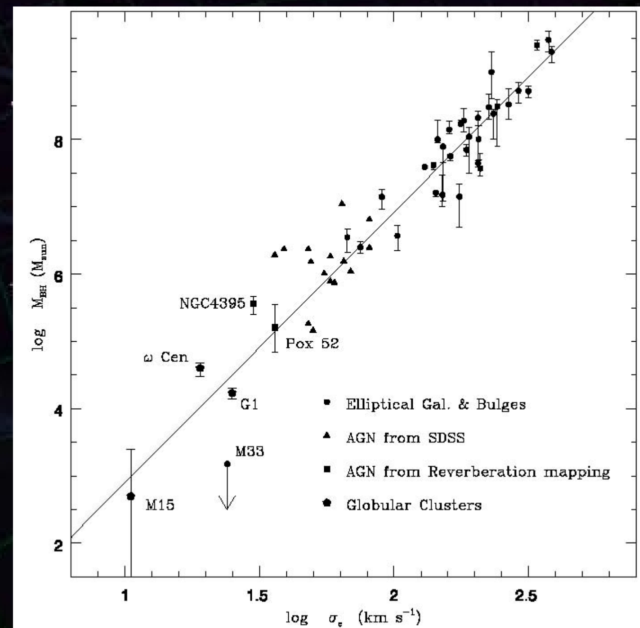


FIG. 9.—$M_\bullet$-σ_{vel} relation for elliptical galaxies and bulges. The solid line is the relation in Tremaine et al. (2002). ω Cen lies on the low-mass extrapolation and suggests a similarity between it and the galaxies. Different types of systems such as star clusters and low-luminosity AGNs appear to populate the low-mass end of the diagram.

(May 30, 2010)

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

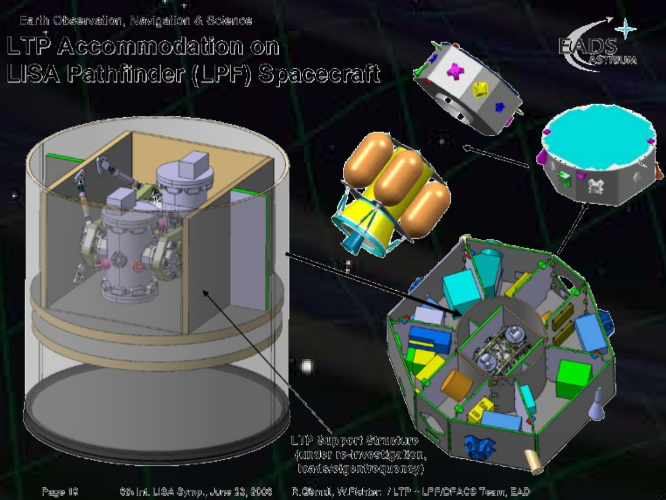
(~150 Globular Clusters in our Galaxy)

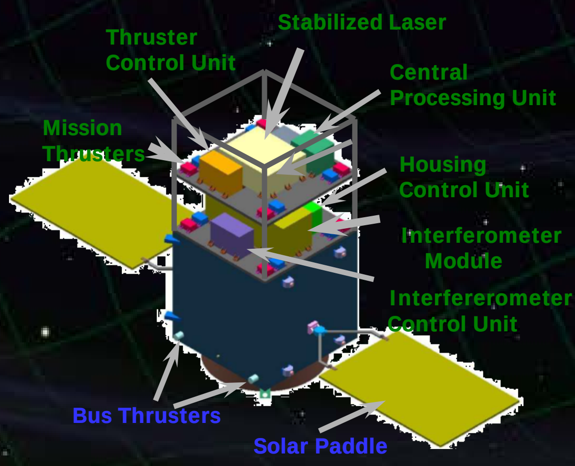
NGC#	BH質量 [Msun]	距離 [kpc]	SNR (同質量)	SNR (1:1/3)	SNR +100Msun	速度分散 [km/sec]
6441	12423.8	11.2	36.4	22.2	3.7	19.5
6256	4753.6	6.9	26.6	16.2	4.3	15.4
7078	4387.8	10.3	16.6	10.2	2.8	15.1
6093	3720.3	10.0	14.9	9.1	2.7	14.5
104	820.0	4.5	9.4	5.7	3.6	10
1851	1348.5	12.1	5.3	3.2	1.6	11.3
6681	820.0	9.0	4.7	2.9	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 Dedicated launcher (Vega)	~2015 Dedicated launcher (M-V follow-on)
Weight	1,900 kg	350 kg
Orbit	Halo orbit around L1 Drag-free attitude control	SSO altitude 500km 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)





(May 30, 2010)

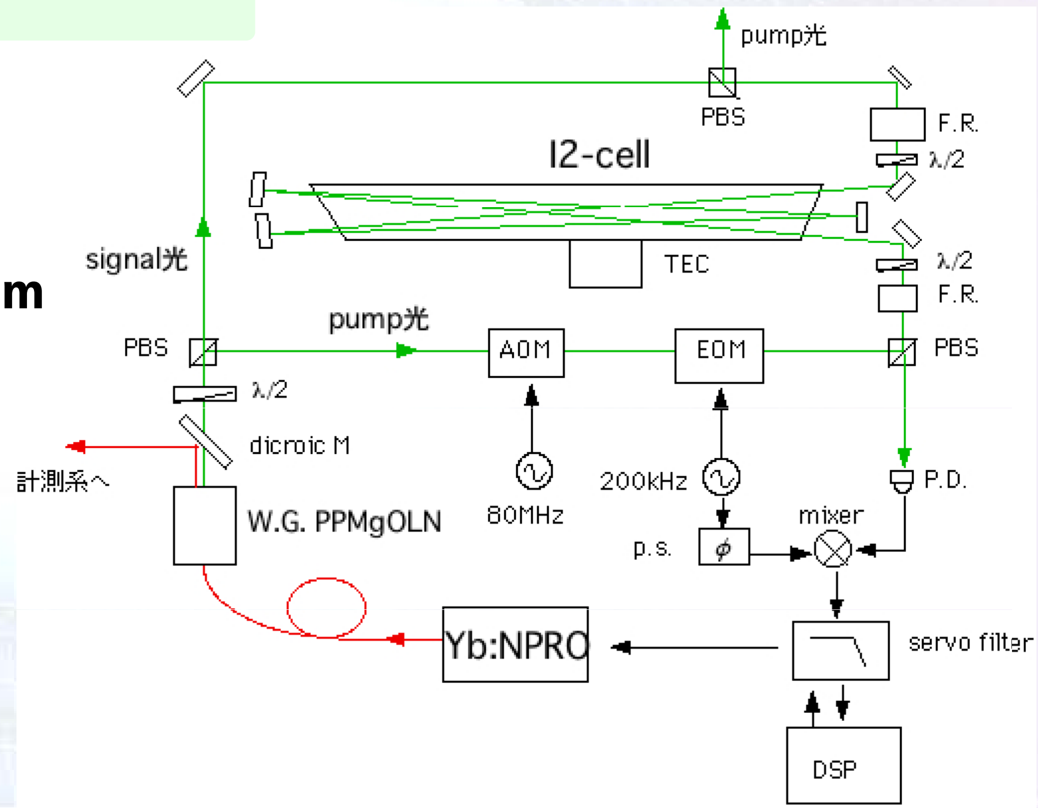
Stabilized laser

Laser source

Yb:YAG laser (1030nm)
Power : 25mW
Freq. stab. by Iodine absorption line
→ 0.5 Hz/Hz$^{1/2}$ (at 0.1Hz)

Comparable stability with that by a reference cavity at 0.1Hz

Narrow absorption line at 515nm



Advantage of I_2 stabilization

- Less affected by environment
- Easier ground-base tests
  - Moderate vibration isolation
  - No vacuum system

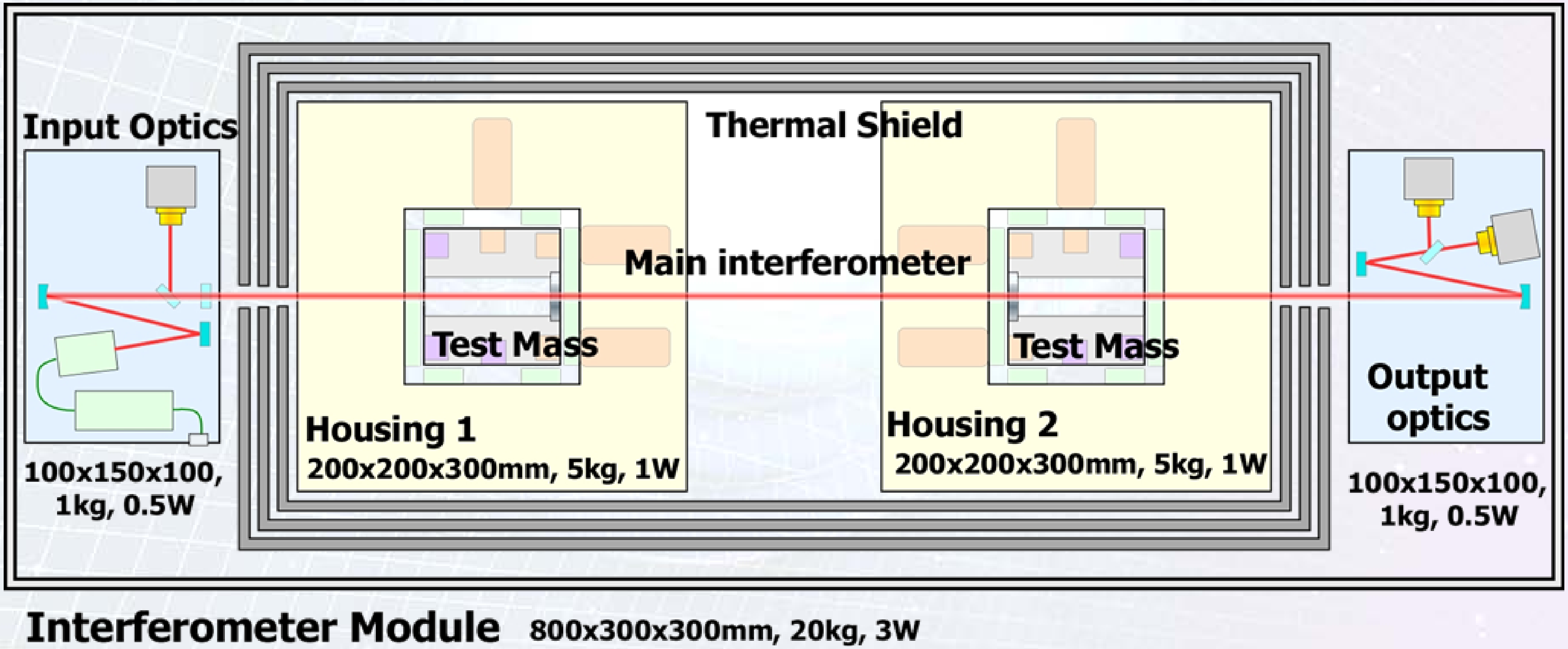
Disadvantages

- Less experience

Main interferometer

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

Test-mass module
- Keeps a test inside
- Local sensor / actuator
- Launch-lock system
- Interferometer sensors for fine measurement



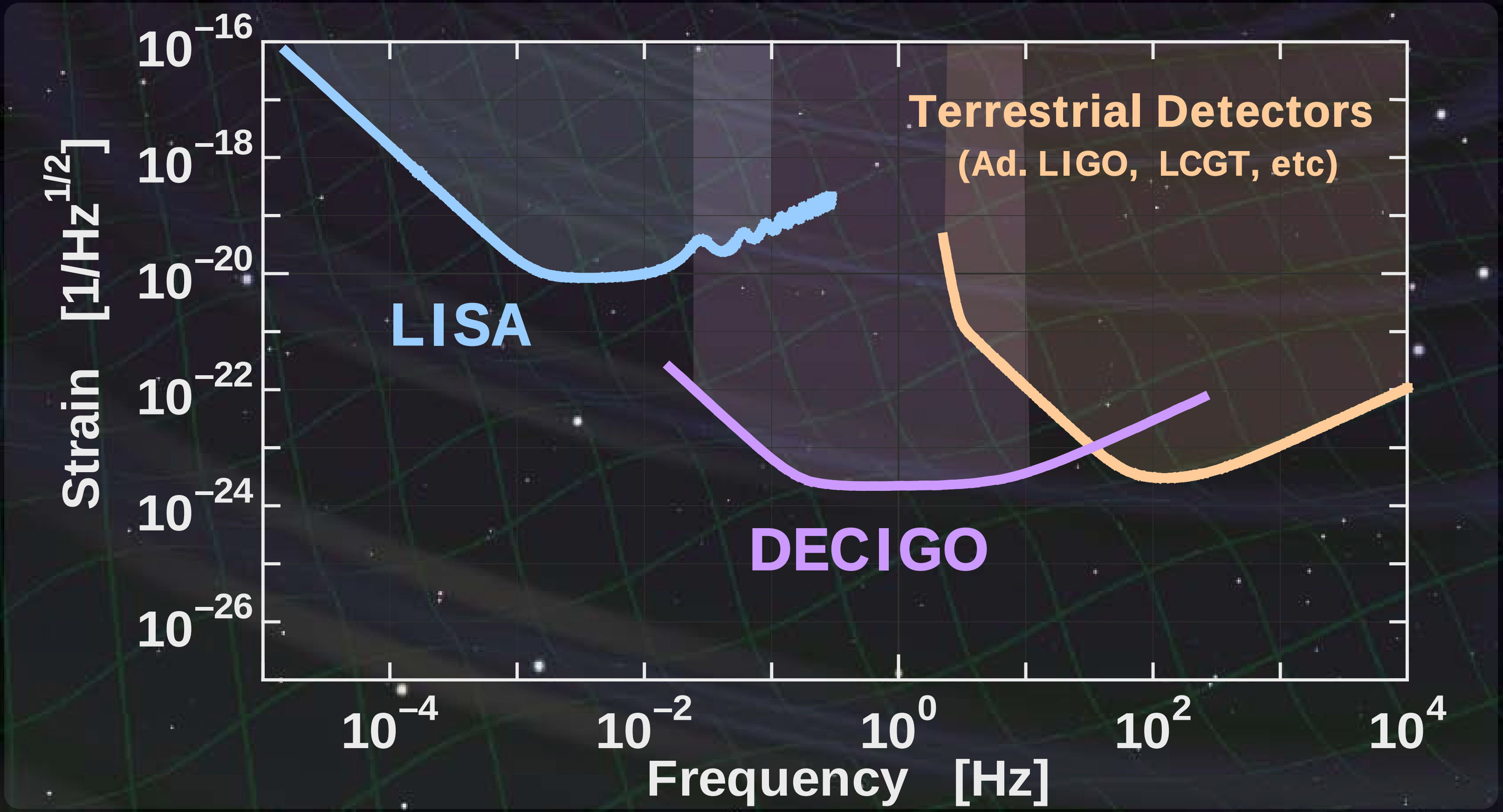
DECIGO

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

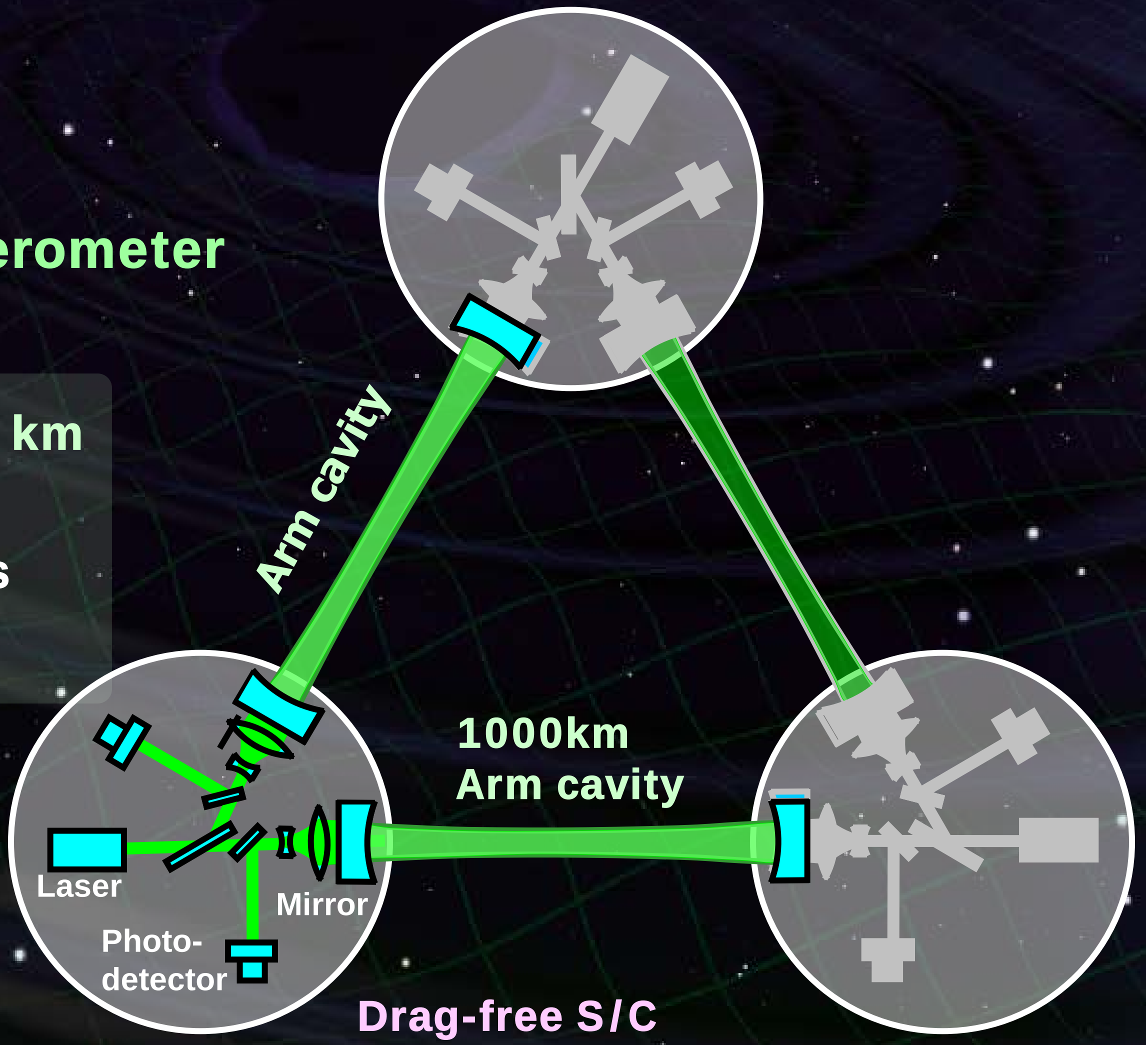


(May 30, 2010)

DECIGO Interferometer

Interferometer Unit:
Differential FP interferometer

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



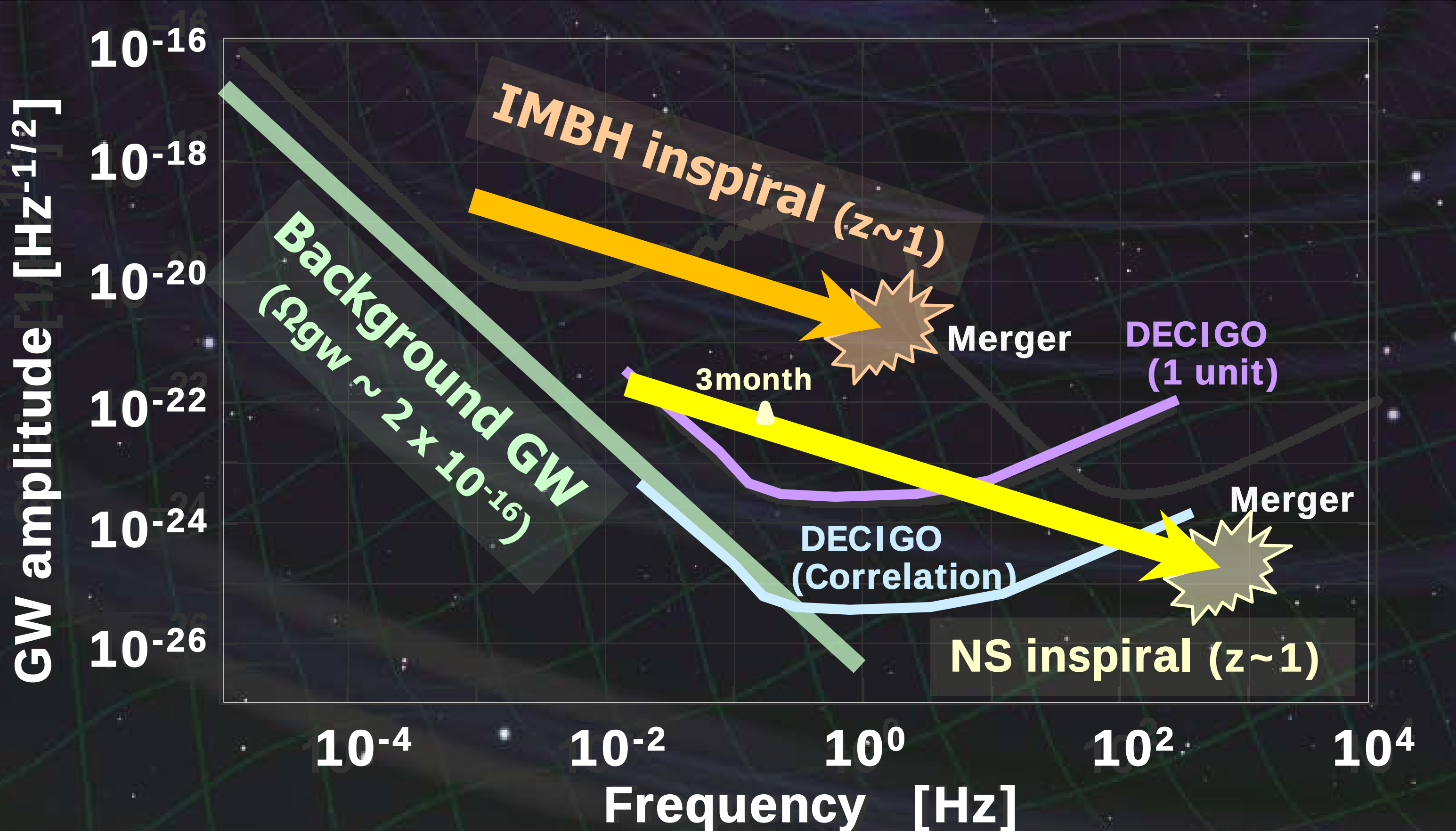
Targets and Science

DECIGO

IMBH binary inspiral
NS binary inspiral
Stochastic background

⇨

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



(May 30, 2010)

Constraint on dark energy

DECIGO

DECIGO will observe

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

Precise 'clock' at cosmological distance

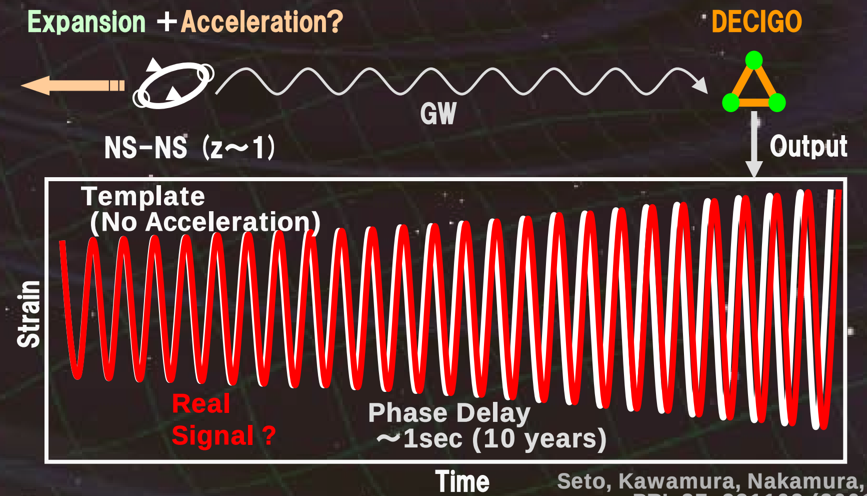
'Standard Siren'

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)

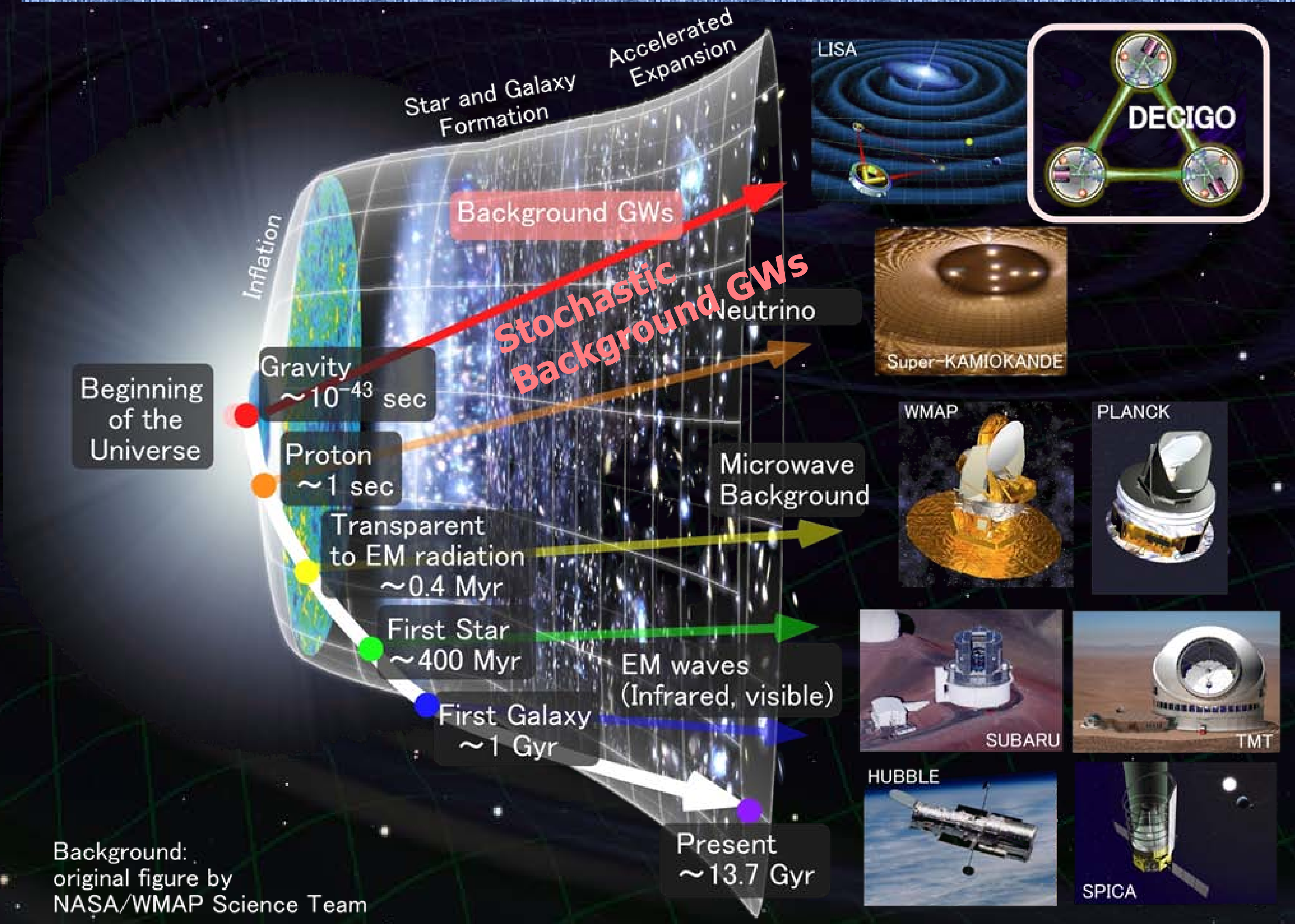
Determine cosmological parameters

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

Absolute and independent measurement

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

Stochastic Background GWs



(May 30, 2010)

Pre-Conceptual Design

DECIGO

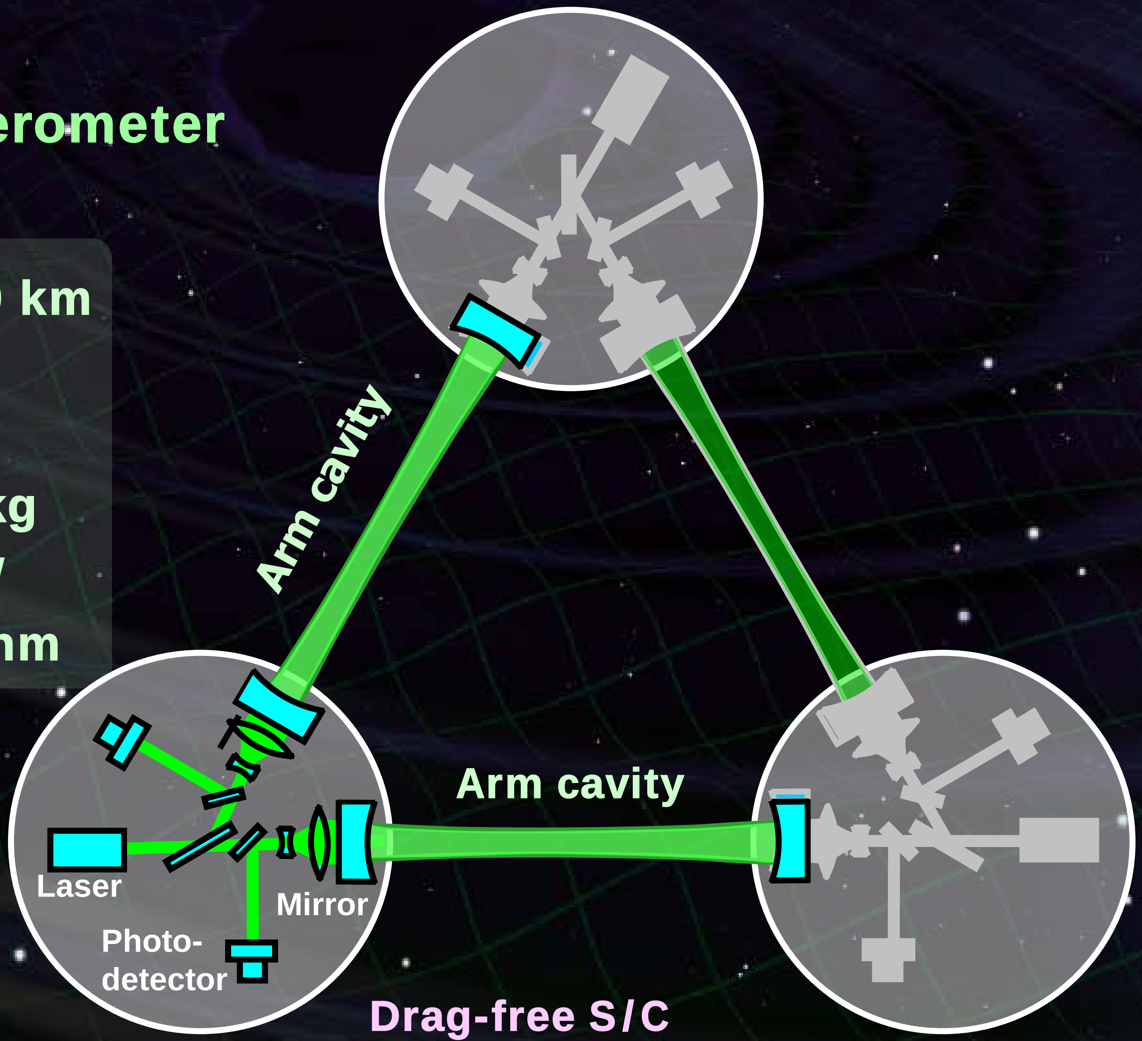
Interferometer Unit:

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



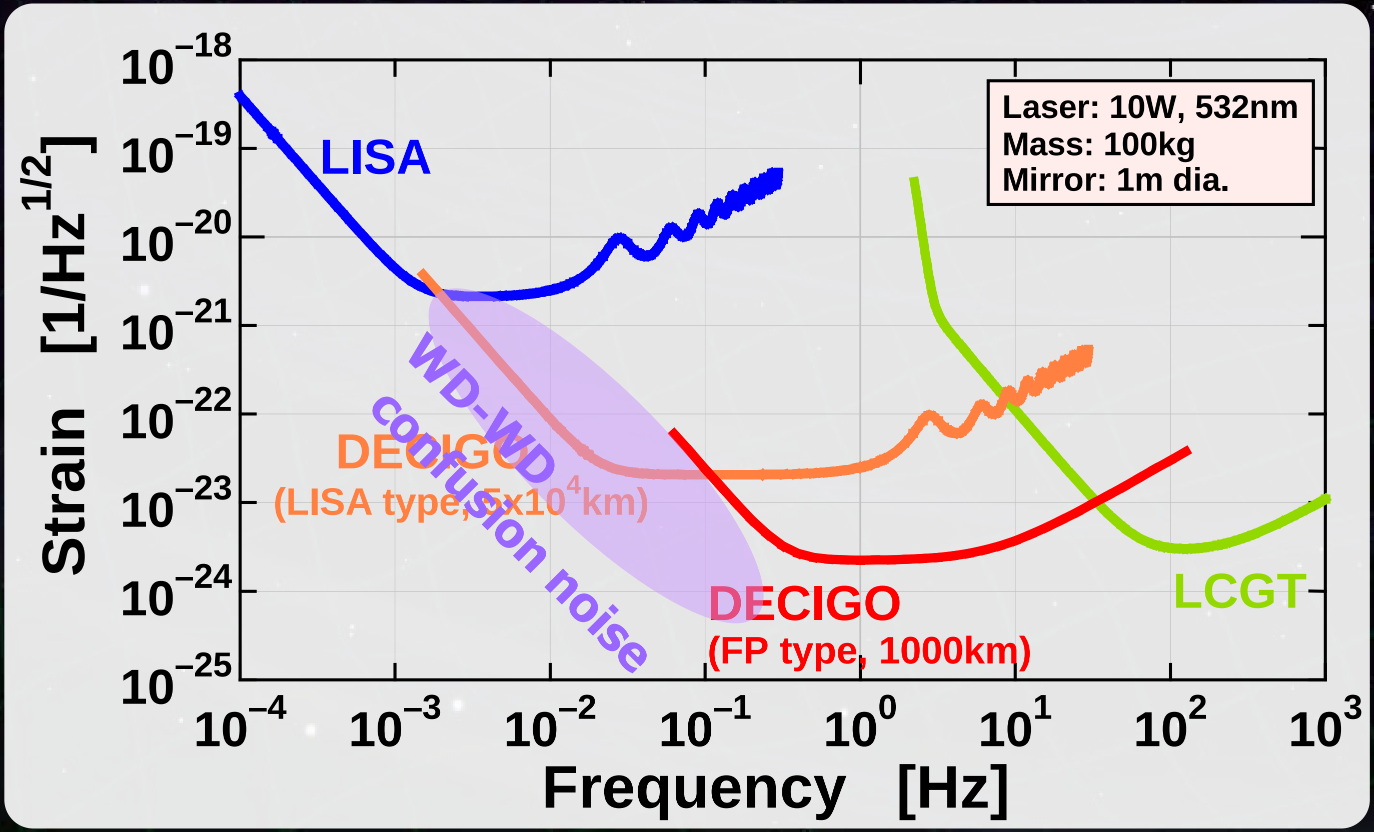
(May 30, 2010)

Interferometer Design

Transponder type vs Direct-reflection type

Compare : Sensitivity curves and Expected Sciences

Decisive factor: Binary confusion noise



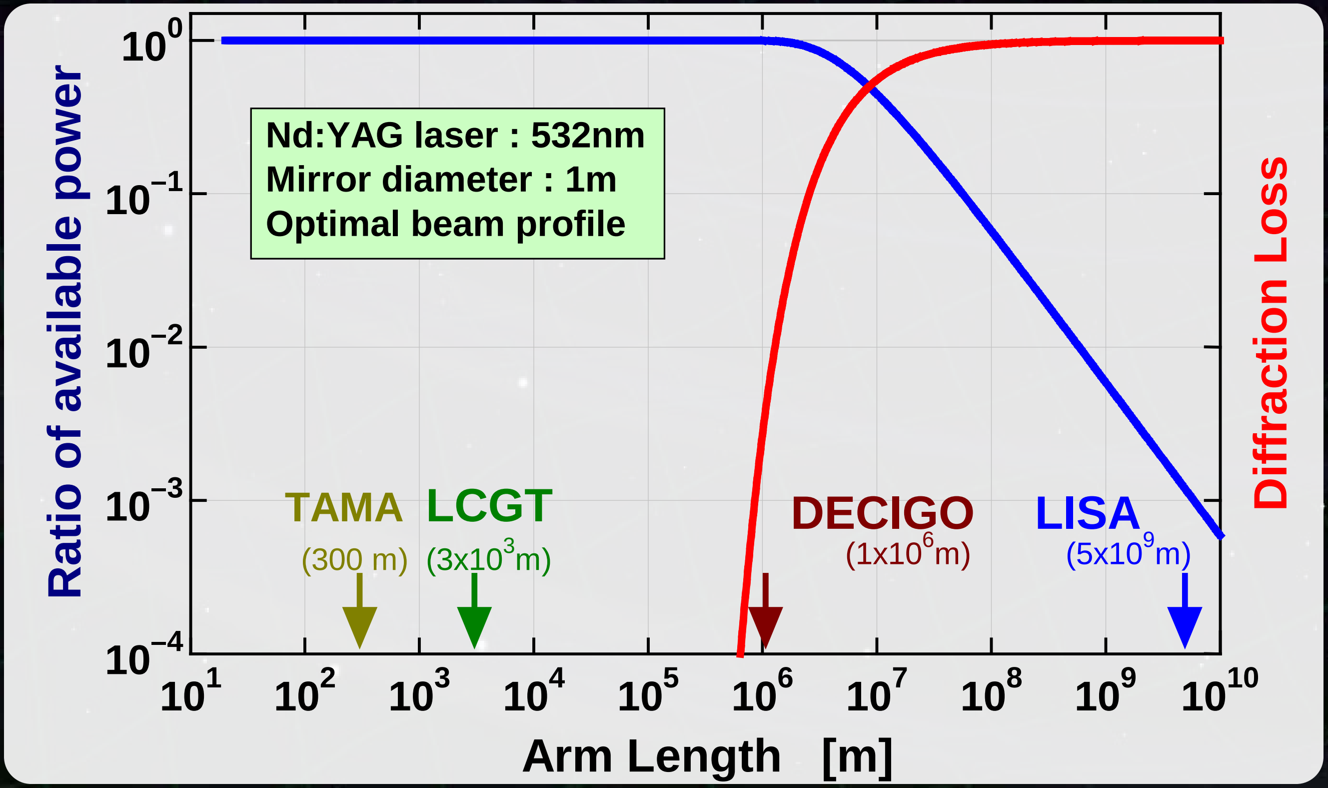
Arm length

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

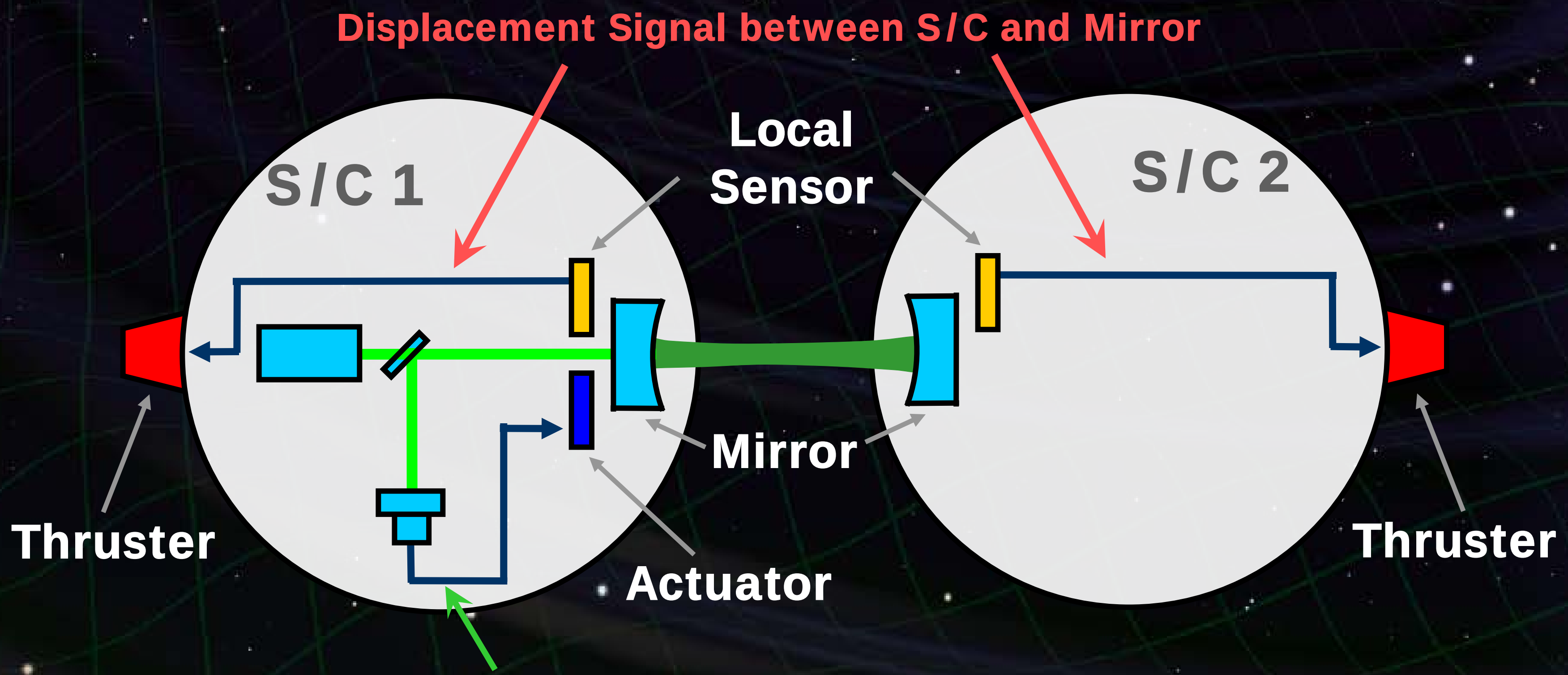


Fig: S. Kawamura

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

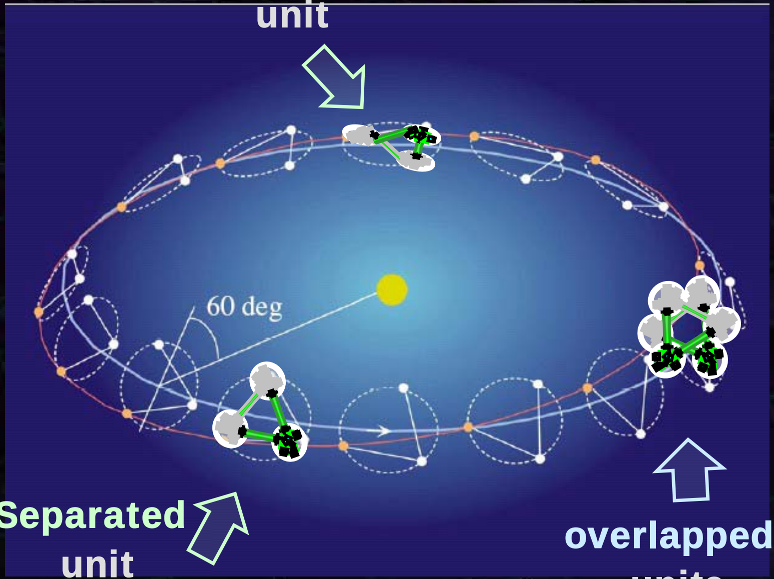
Relative acc. 4×10^{-12} m/s^2

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

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

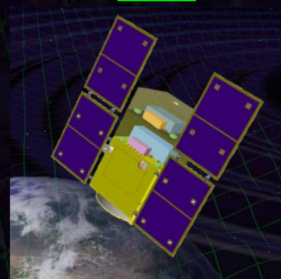
Figure: S.Kawamura

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

Mission

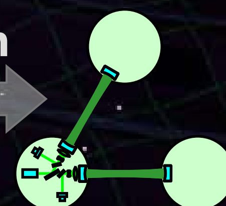
R&D
Fabrication

SDS-1/SWIM



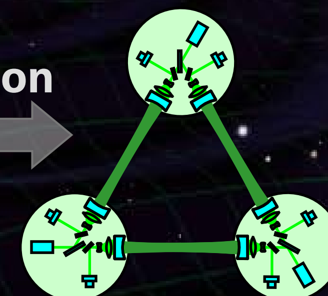
DECIGO Pathfinder (DPF)

R&D
Fabrication



Pre-DECIGO

R&D
Fabrication



DECIGO

	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

(May 30, 2010)

Organization

DECIGO

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)

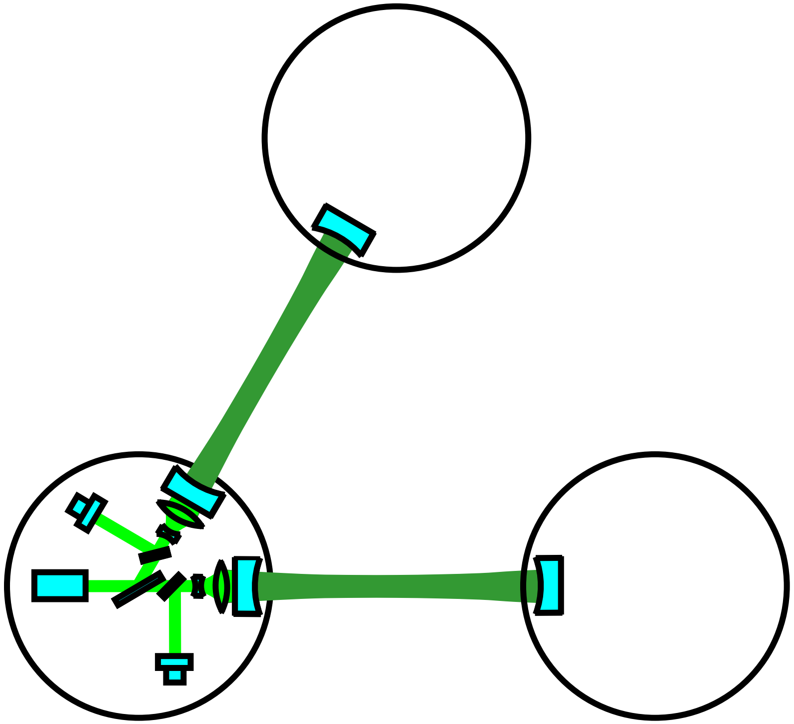
Data
Kanda (Osaka city)

(May 30, 2010)

Collaboration and support

- Supports from **LISA**
  Technical advices from LISA/LPF experiences
  Support Letter for DECIGO/DPF, Joint workshop (2008.11)
- Collab. with **Stanford univ. group**
  Drag-free control of DECIGO/DPF
  UV LED Charge Management System for DPF
- Collab. with **NASA/GSFC**
  Fiber Laser , 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

Pre-DECIGO

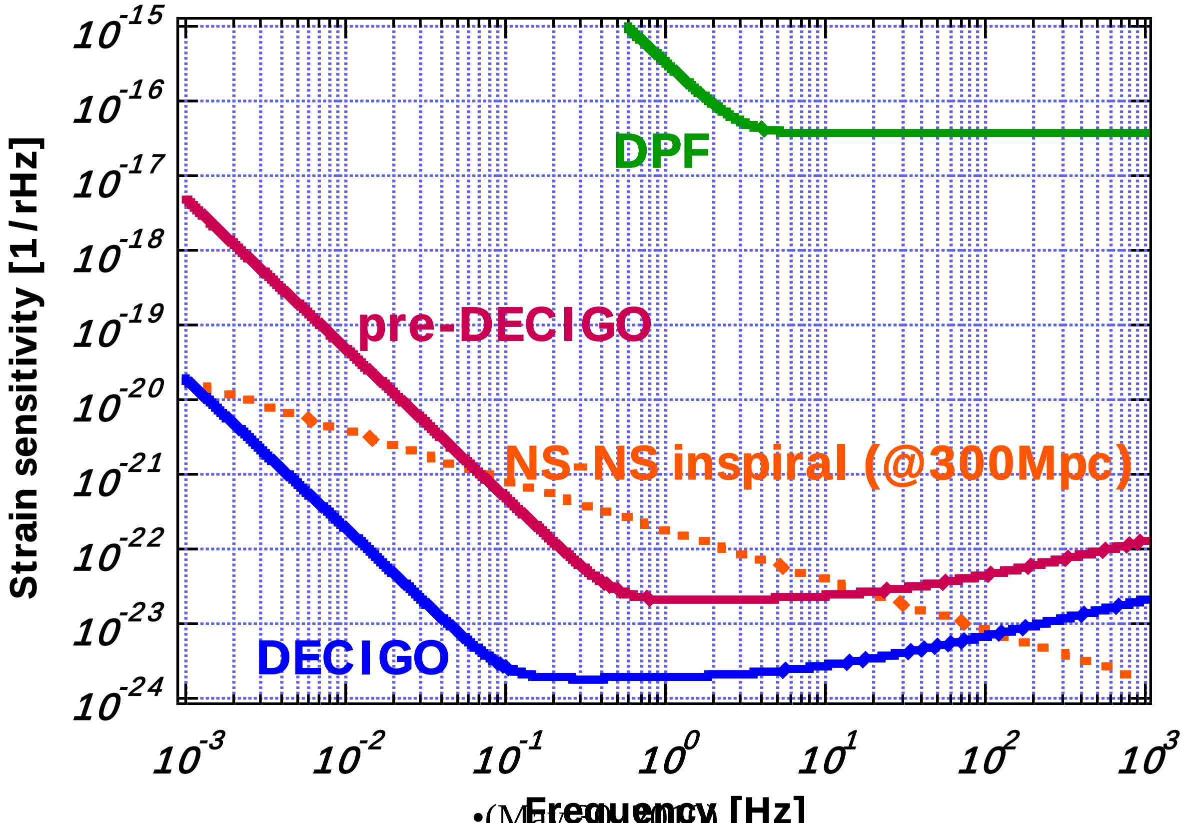


	Pre-DECIGO	DECIGO
Arm length	100 km	1000 km
Mirror diameter	30 cm	1 m
Laser wavelength	0.532 μm	0.532 μm
Finesse	30	10
Laser power	1 W	10 W
Mirror mass	30 kg	100 kg
# of interferometers in each cluster	1	3
# of clusters	1	4

•(May 30, 2010)

Sensitivity of Pre-DECIGO

•S/N~14 for NS-NS@300Mpc, 10-20 events/year



•(May 30, 2010)

LCGT and DECIGO

LCGT (~2014)

Terrestrial Detector

→ High frequency events

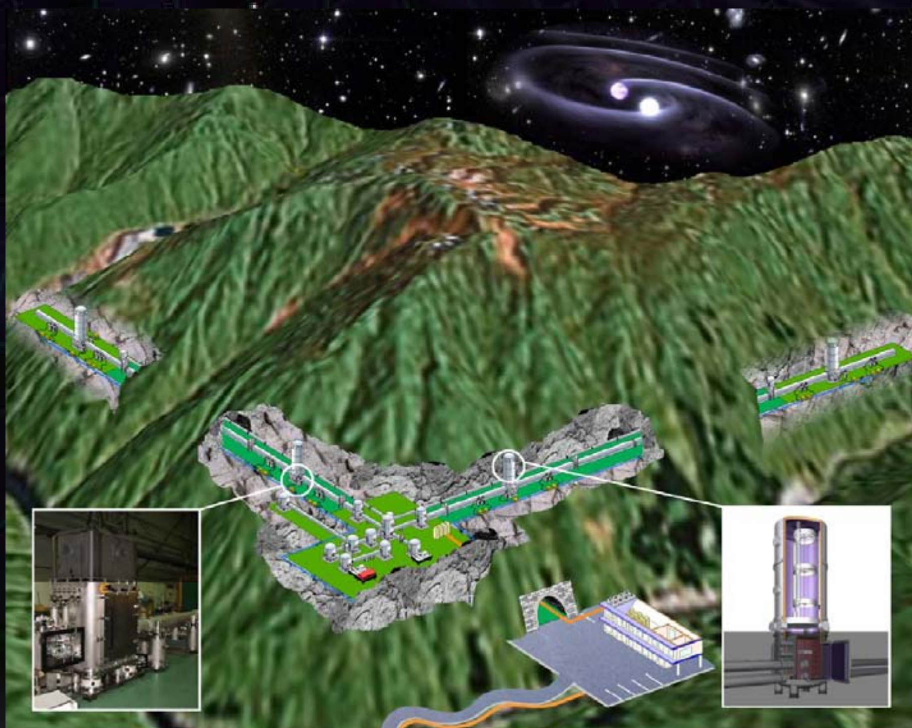
Target: GW detection

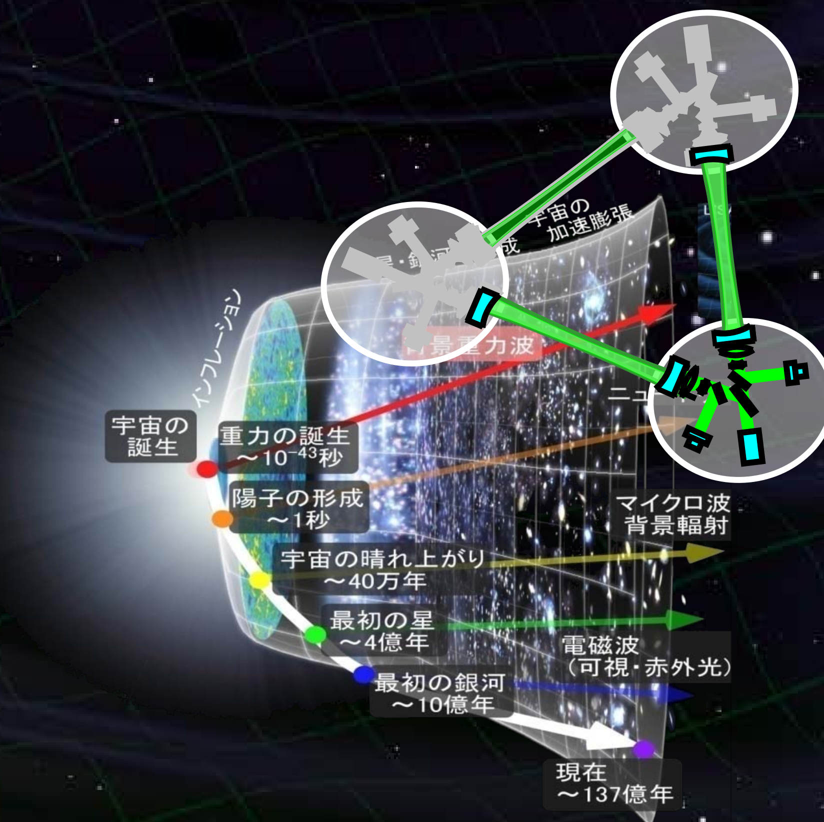
DECIGO (~2024)

Space observatory

→ Low frequency sources

Target: GW astronomy





(May 30, 2010)

SWIM launch and operation

DECIGO

Tiny GW detector module
Launched in Jan. 23, 2009
⇨ In-orbit operation

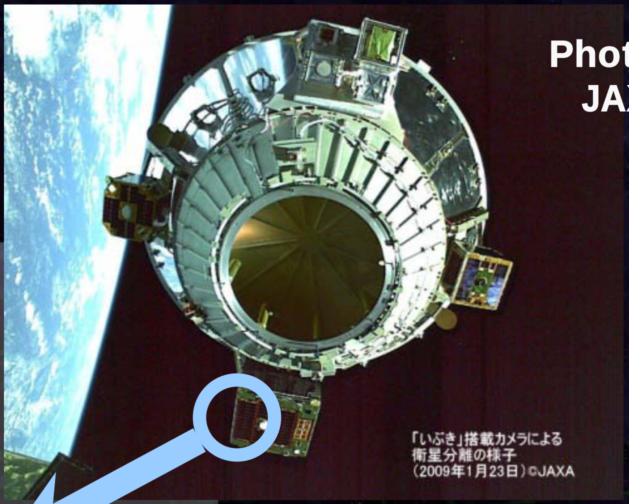
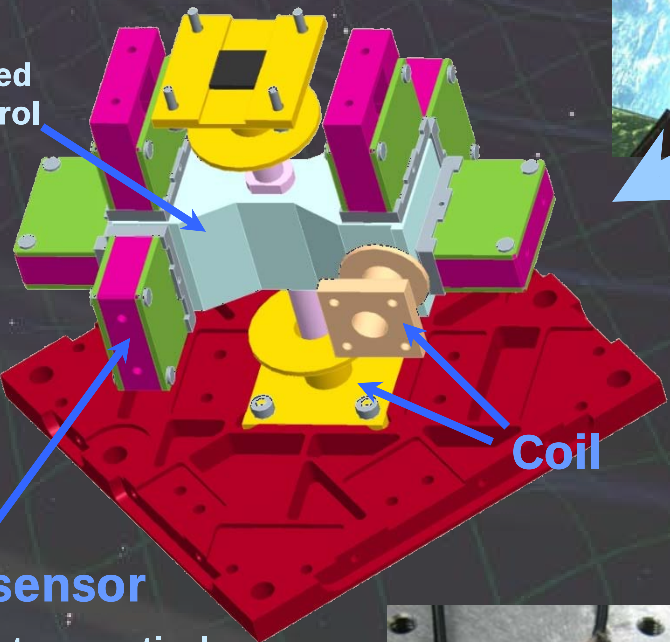


Photo: JAXA

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

Test mass

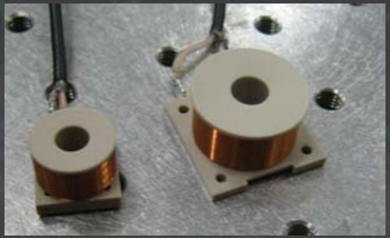
~47g Aluminum, Surface polished
Small magnets for position control



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

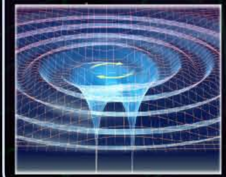


(May 30, 2010)

Objectives of DPF

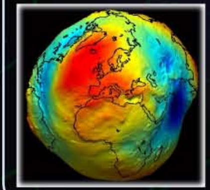
Observation

Gravitational wave



Intemedate-mass
inspiral and merger

Earth gravity



Environ. monitor
Geoid resolution
~1mm.

Science Technology

Space interferometer

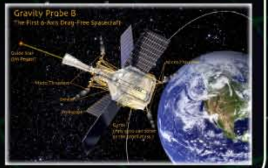
Precise meas. in space
$6\text{x}10^{-16}$ m/Hz$^{1/2}$

Stabilized laser

High stability in Space
0.5 Hz/Hz$^{1/2}$

Drag-free control

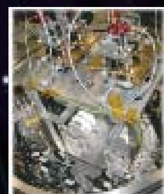
Low-noise control
with passive stab.



DPF and DECIGO

DPF requirements

Precise meas. by IFO



Disp. noise
6×10^{-16} m/Hz$^{1/2}$

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

→ 4×10^{-18} m/Hz$^{1/2}$, 10^{-17} N/Hz$^{1/2}$

Stab. Laser

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

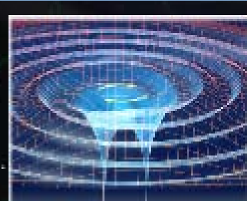
→ 1 Hz/Hz$^{1/2}$

Drag-free control

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

Thruster noise
10^{-7} 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

(May 30, 2010)

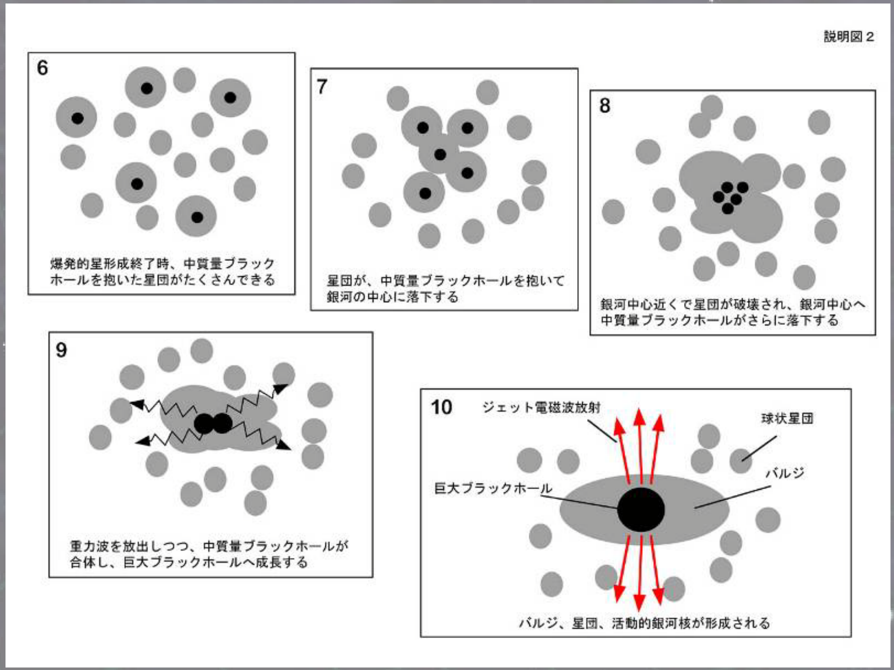
IMBH inspiral and Merger

DECIGO

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

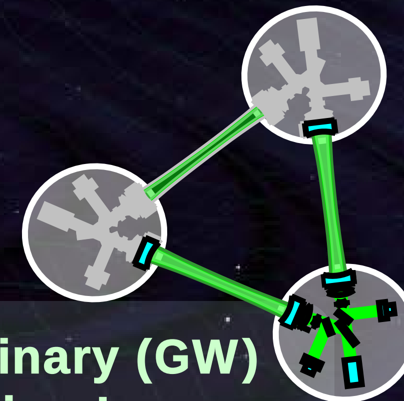


戎崎俊一(理化学研究所) 先生のwebページより引用
http://atlas.riken.go.jp/~ebisu/smbh.html

Standard Sources

DECIGO

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)