Gravitational-wave observatories: LCGT and DECIGO

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On behalf of
LCGT Collaboration and
DECIGO working group

The 20th workshop on General Relativity and Gravitation (JGRG20, Sept. 23, 2010, YITP, Kyoto)

1. Introduction
2. LCGT
3. DECIGO
4. Summary

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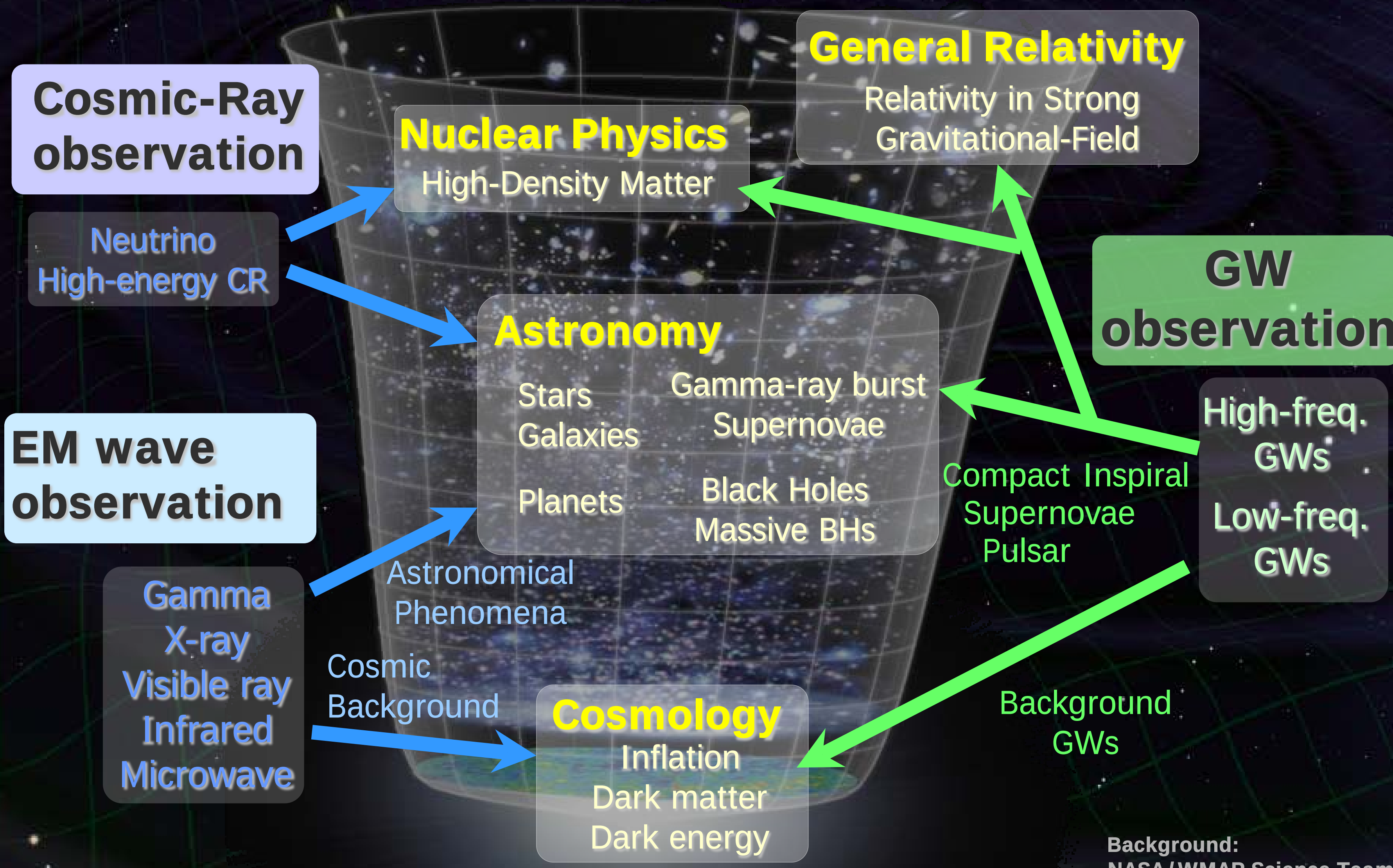
Observation of the Universe



Background:
NASA / WMAP Science Team

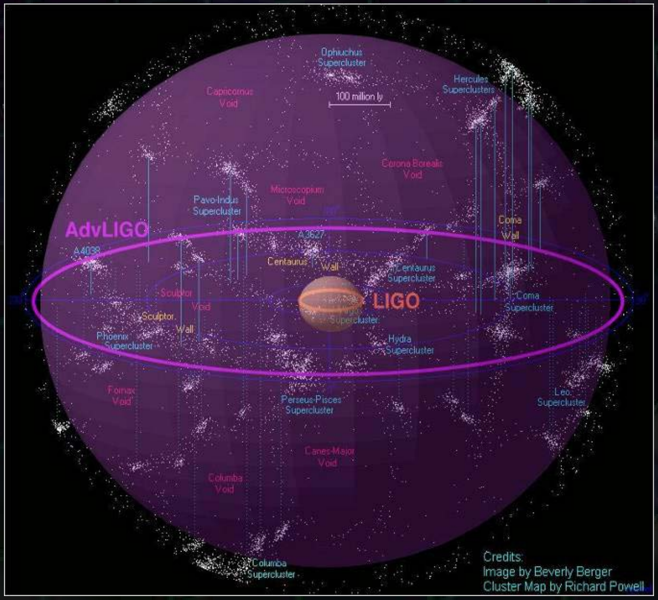
Expanding the Horizon

Current GW detectors : <20Mpc obs. range

However… we can expect only rare events (10^{-5}-10^{-3} event/yr)

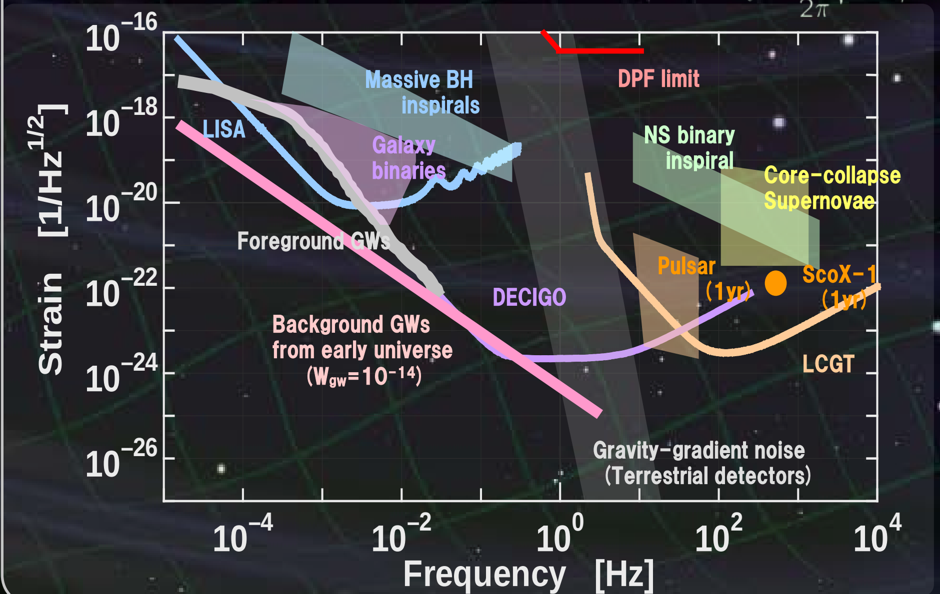
⇨ Next generation detectors

Better sensitivity to cover more galaxies



Wider observation band for various sources

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



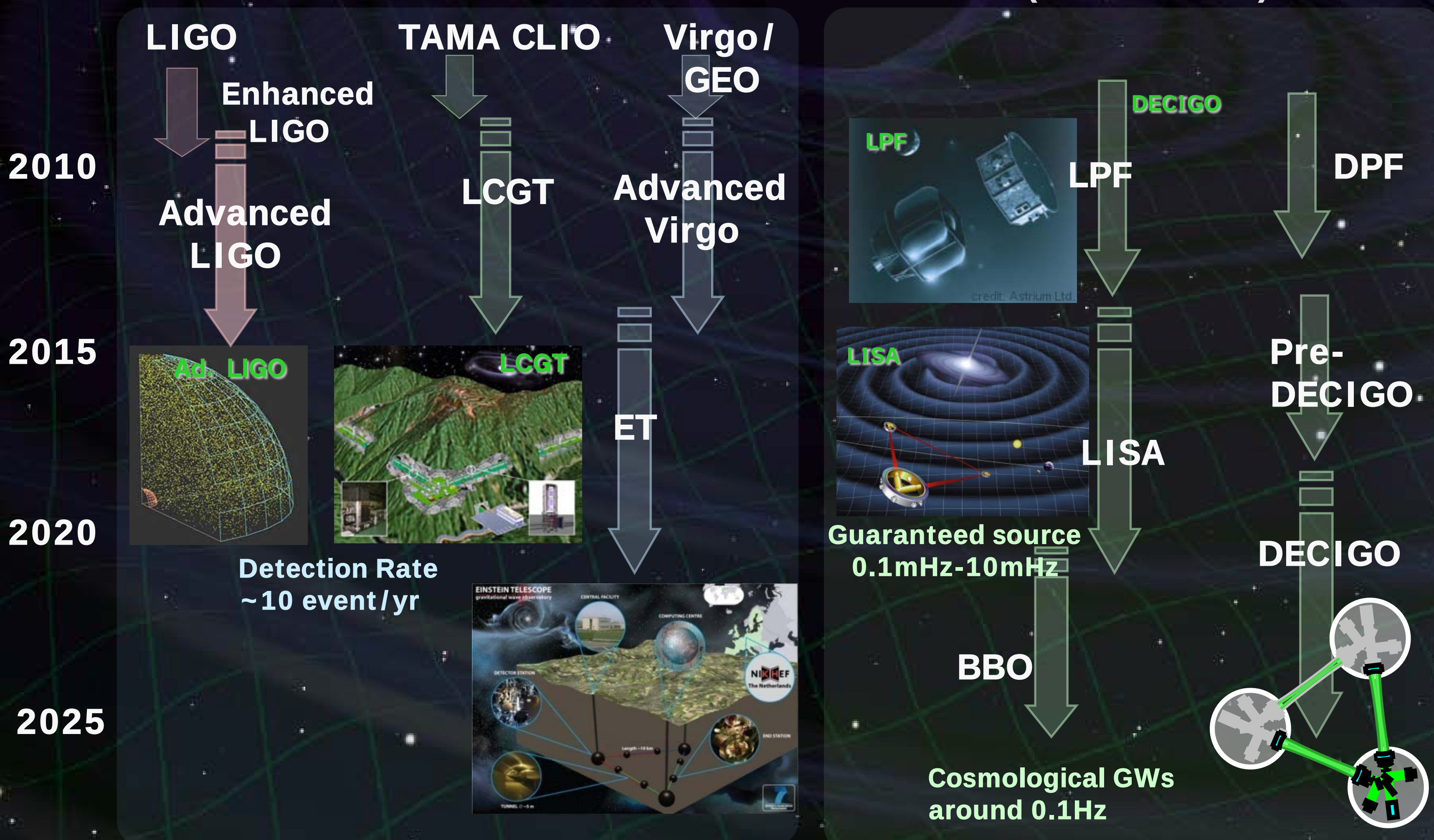
Roadmap of GW detectors

Ground based detectors

Improved sensitivities (10-1kHz)

Space-borne detectors

Low-frequency sources
(0.1mHz – 1Hz)



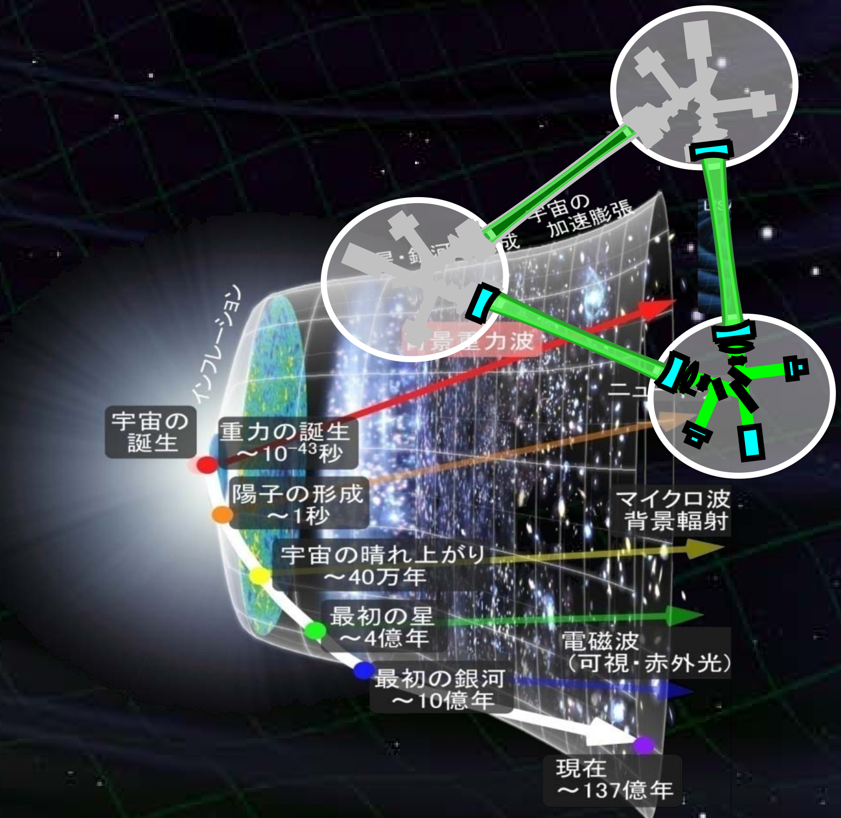
LCGT and DECIGO

LCGT (~2017)
Terrestrial Detector
→ High frequency events

Target: GW detection

DECIGO (~2027)
Space observatory
→ Low frequency sources

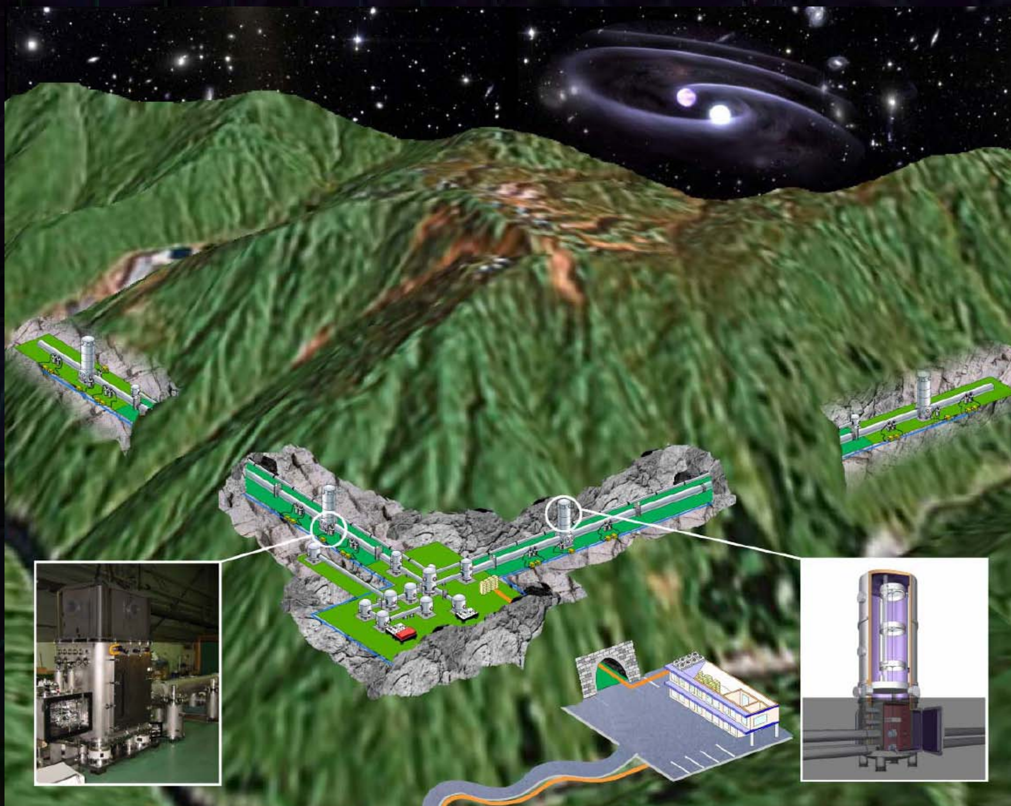
Target: GW astronomy



LCGT

LCGT (Large-scale Cryogenic Gravitational-wave Telescope)

Next-generation GW detector in Japan



Large-scale Detector
- Baseline length: 3km
- High-power Interferometer

Cryogenic interferometer
- Mirror temperature: 20K

Underground site
- Kamioka mine,
  1000m underground

Recent News

- LCGT project was selected by
  the 'Facility for the advanced researches'
  program of MEXT.

Construction cost is partially approved:
9.8 BYen for first 3-year construction.
(Original request: 15.5 BYen for 7 years.)

Baseline design is not changed:
Requesting the additional cost for
full construction of LCGT.

⇨ This talk is mainly on the baseline design.

LCGT interferometer

LCGT baseline design

- Arm length of 3km, Underground site of Kamioka
- Cryogenic mirror and suspension

High-power RSE interferometer with cryogenic mirrors

Resonant-Sideband Extraction

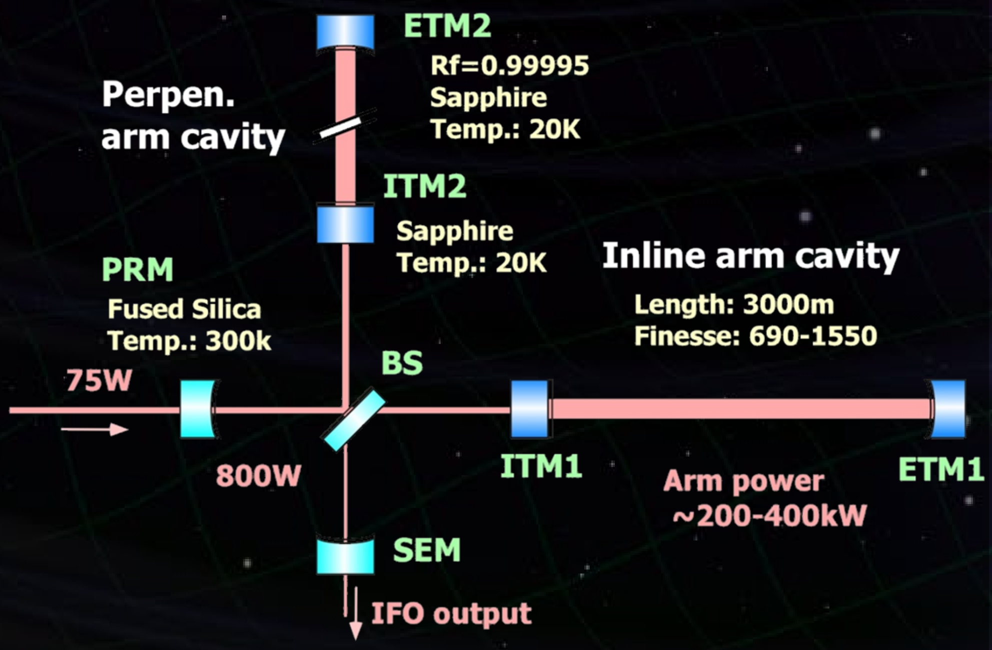
- Input carrier power : 75W
- DC readout

Main IFO mirror

- 20K, 30kg (Φ250mm, t150mm)
- Mech. Loss : 10^{-8}
- Opt. Absorption 20ppm/cm

Suspension

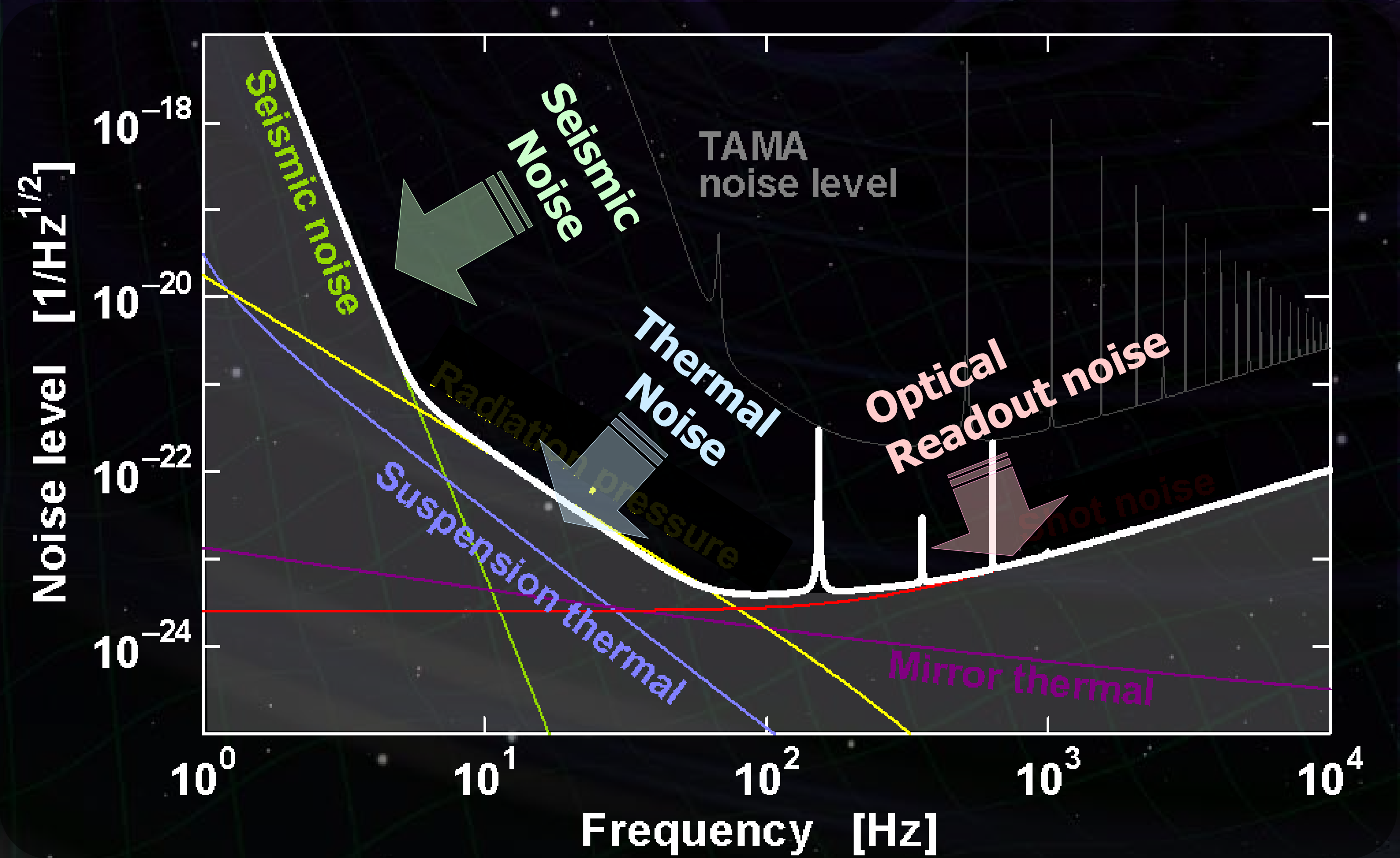
- Sapphire fiber 16K
- Mech. Loss : 2×10^{-8}



Sensitivity Curve

Comparable with Ad.LIGO Ad.VIRGO

→ Global network observation



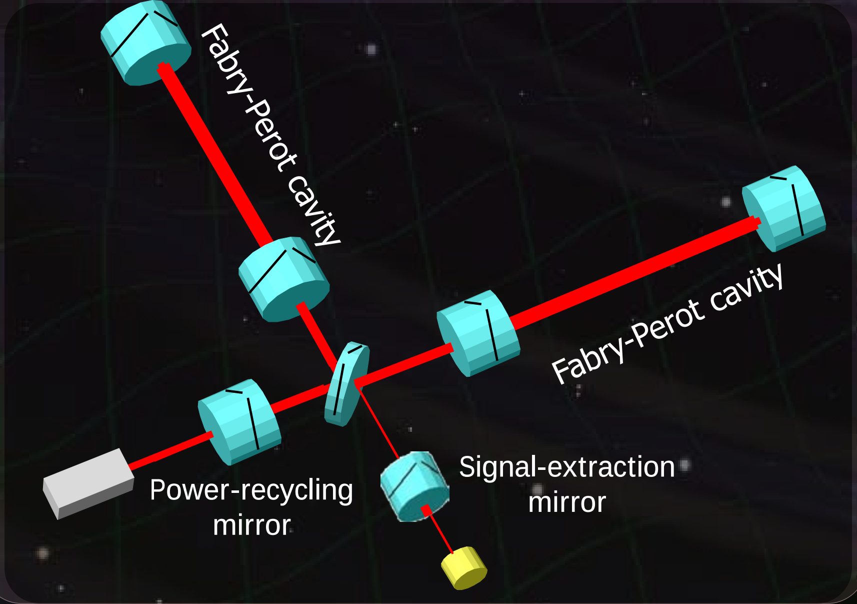
Readout-noise reduction

High-freq. (> 100 Hz) improvement

Shot noise reduction by high power in arm cavities

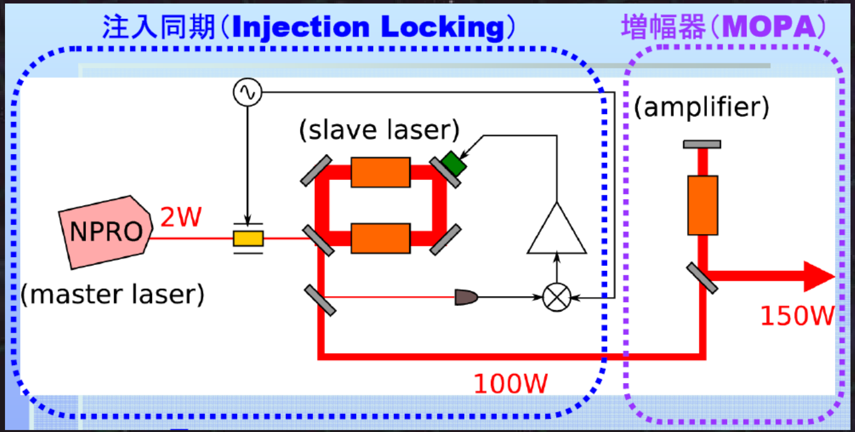
Optical configuration

Fabry-Perot Michelson interferometer with RSE (Resonant-Sideband Extraction)



High-power laser source

Nd:YAG laser source with 150W output power



Low-loss mirror

Less than 45ppm by reflection

Thermal-noise reduction

Mid.-freq. (around 100 Hz) improvement

Cryogenics

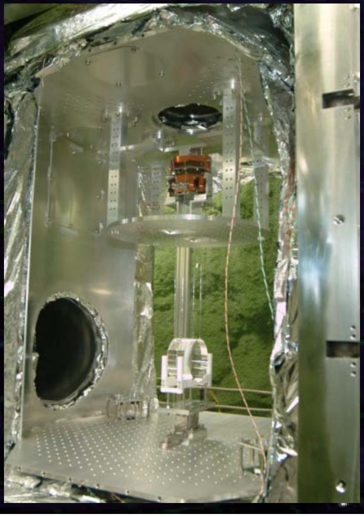
Mirror ~20K
Suspension ~16K

Sapphire mirror
→ High mechanical Q-value at low temperature

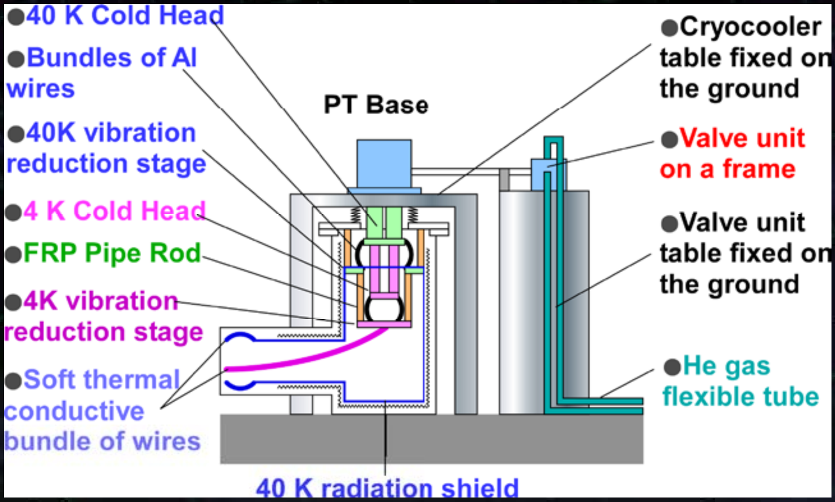
$$\text{Thermal noise} \propto \sqrt{\frac{T}{Q}}$$

⇨ Cryogenic is a straight-forward way to reduce thermal noise.

Cryogenic mirror and suspension of CLIO 100-m interferometer



Low-vibration Cryo-cooler design



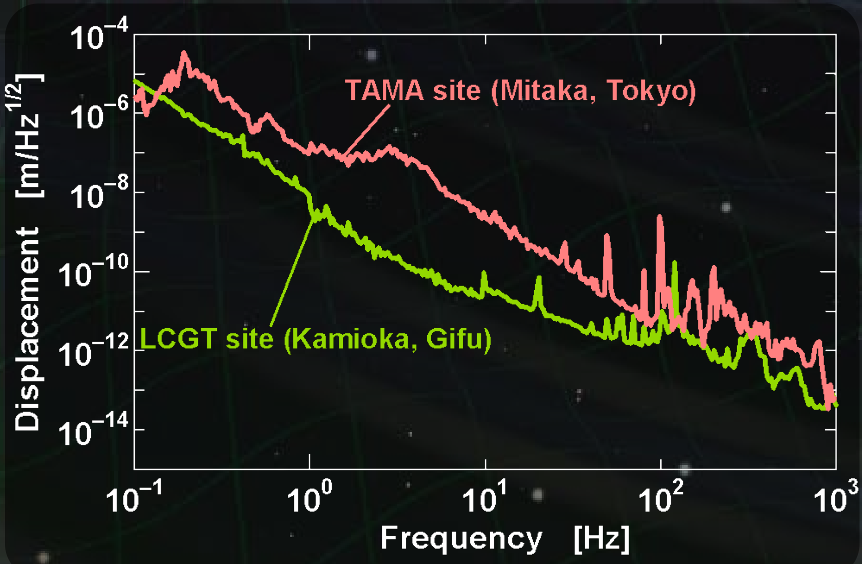
Seismic-noise reduction

Low-freq. (< 100 Hz) improvement

Quiet site

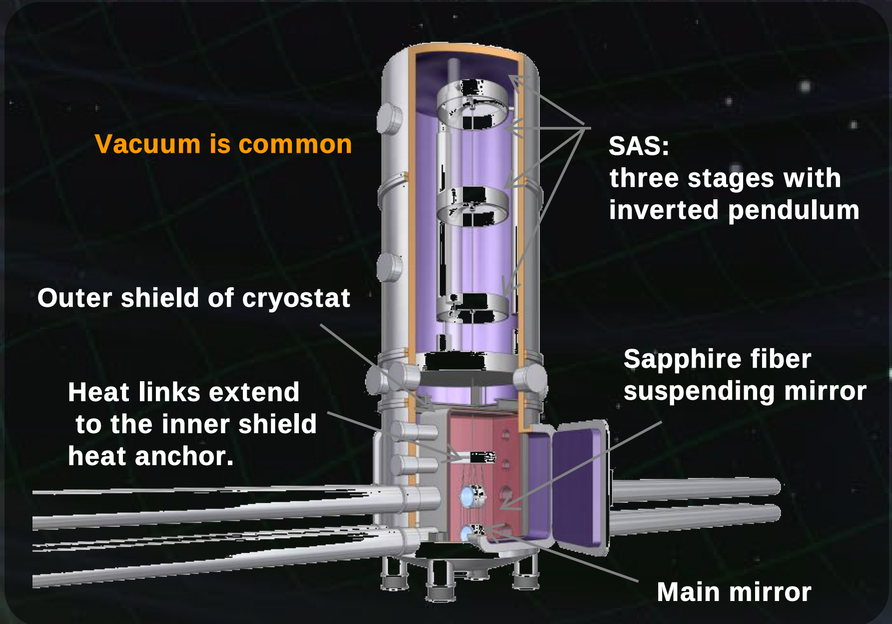
Kamioka underground site
(~1000km underground)

Lower seismic disturbance
by **2-3 orders**



Better Isolation system

Multi-stage and Low-freq.
vibration isolation system



1. Introduction

2. LCGT

Overview and design

⇨ Observable range

R&D by CLIO

3. DECIGO

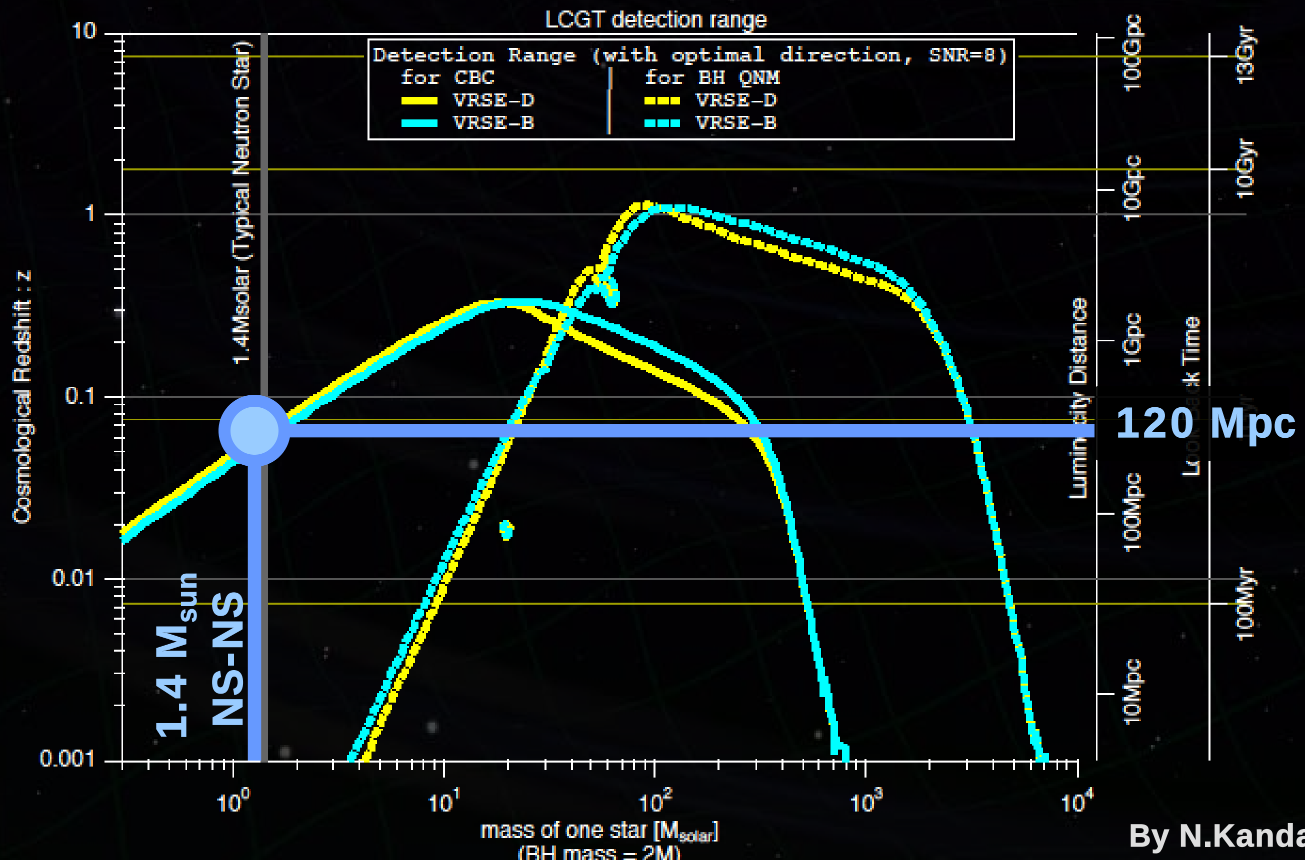
4. Summary

Observable range

Primary purpose of LCGT : Detection of GW

→ **First target : Neutron-star binary inspirals**

⇨ **Obs. Range 120Mpc** (SNR=8, Avg. over sky pos. an pol.)



By N.Kanda

Detection rate of LCGT

Neutron-star binary inspirals events

Observable range

sensitivity curve → 120 Mpc

Galaxy number density :

$$\rho = 1.2 \times 10^{-2} \quad [\mathrm{Mpc}^{-3}]$$

R. K. Kopparapu et.al., ApJ. 675 1459 (2008)

Event rate :

$$\mathcal{R} = 83.0^{+209.1}_{-66.1} [\mathrm{events/Myr}]$$

V. Kalogera et.al., ApJ, 601 L179 (2004)

⇨ **Detection rate 6.9 events/yr**

Detection probability

Probability to detect
at least one event
in one-year observation

⇨ Success probability
of the LCGT project

99.9 %

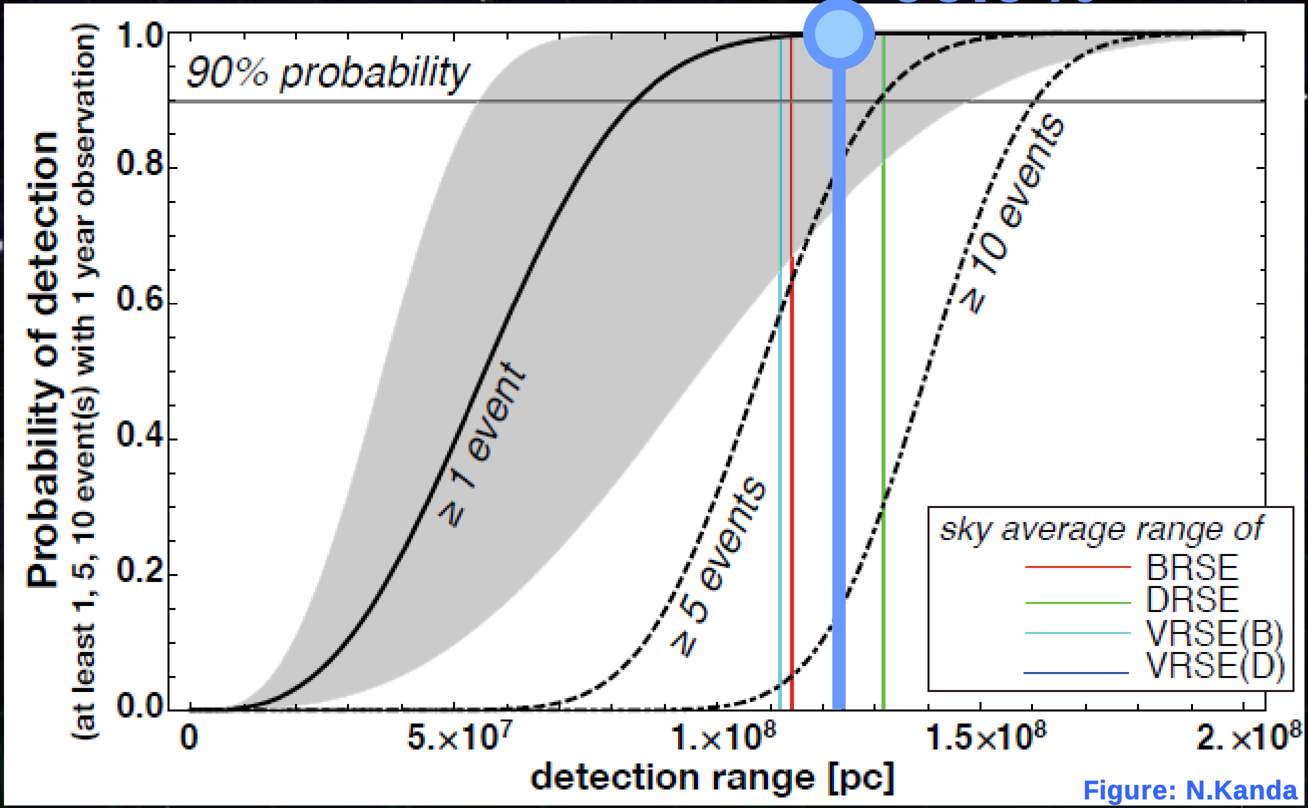


Figure: N.Kanda

Assume
Poisson distribution

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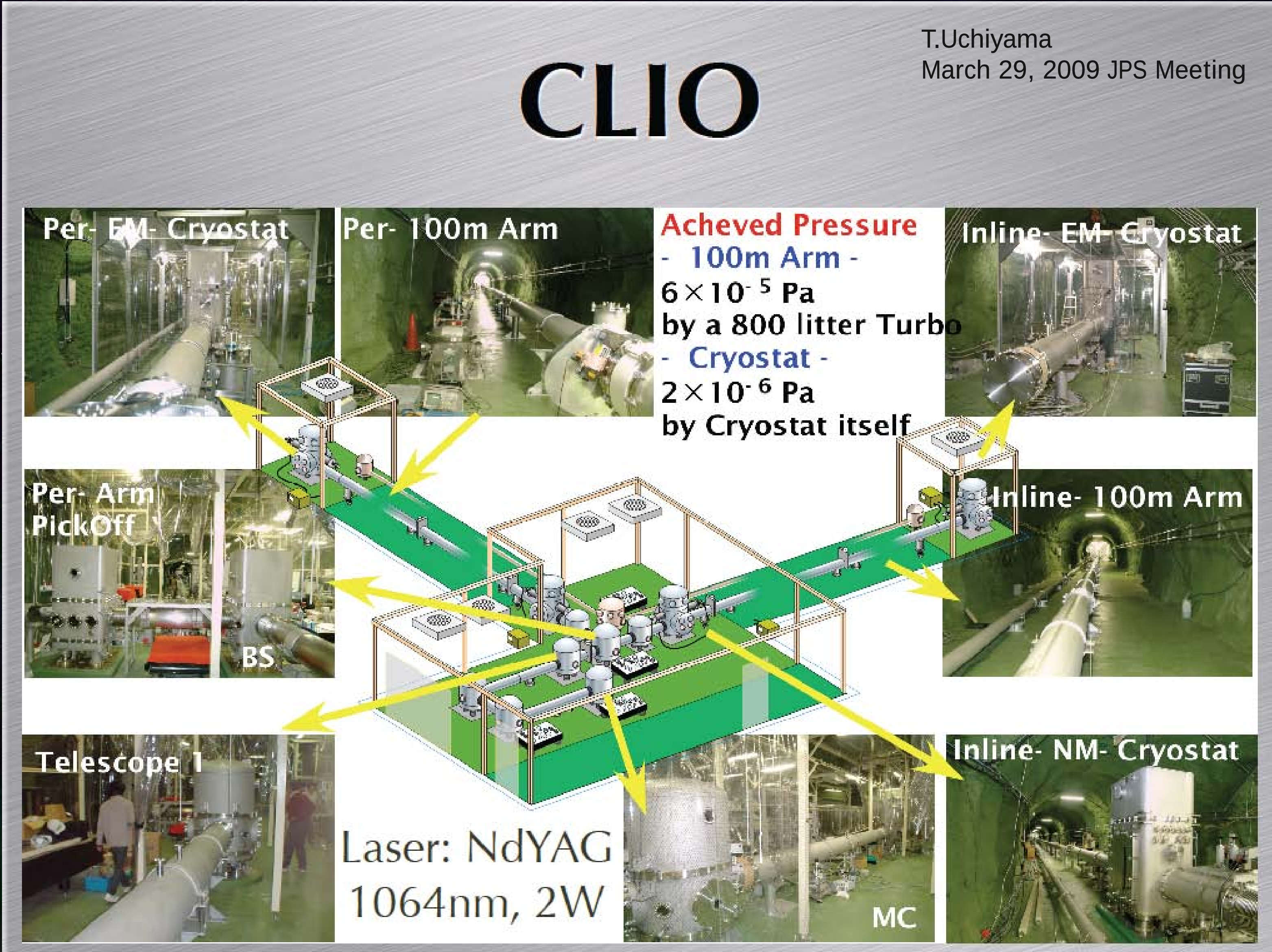
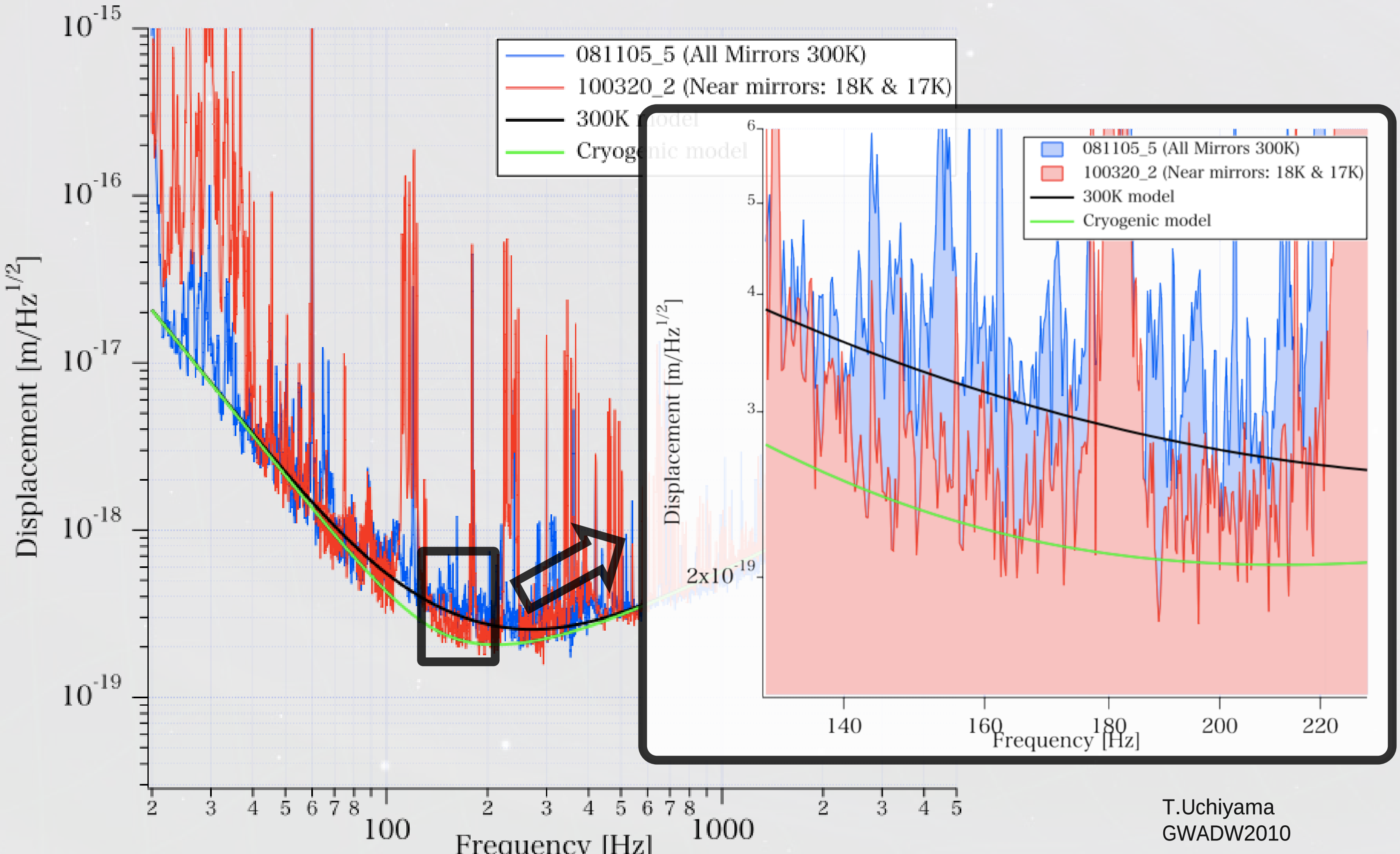
CLIO



T.Uchiyama
March 29, 2009 JPS Meeting
CLIO
Per- EM- Cryostat
Per- 100m Arm
Acheved Pressure
- 100m Arm -
6×10-5 Pa
by a 800 litter Turbo
- Cryostat -
2×10-6 Pa
by Cryostat itself
Inline- EM- Cryostat
Per- Arm PickOff
BS
Inline- 100m Arm
Telescope 1
Laser: NdYAG
1064nm, 2W
MC
Inline- NM- Cryostat

CLIO sensitivity

Sensitivity improvement with cryogenic operation



T.Uchiyama
GWADW2010

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⇨ 3. DECIGO

Overview and design

DECIGO Pathfinder

Space demonstration by SWIM

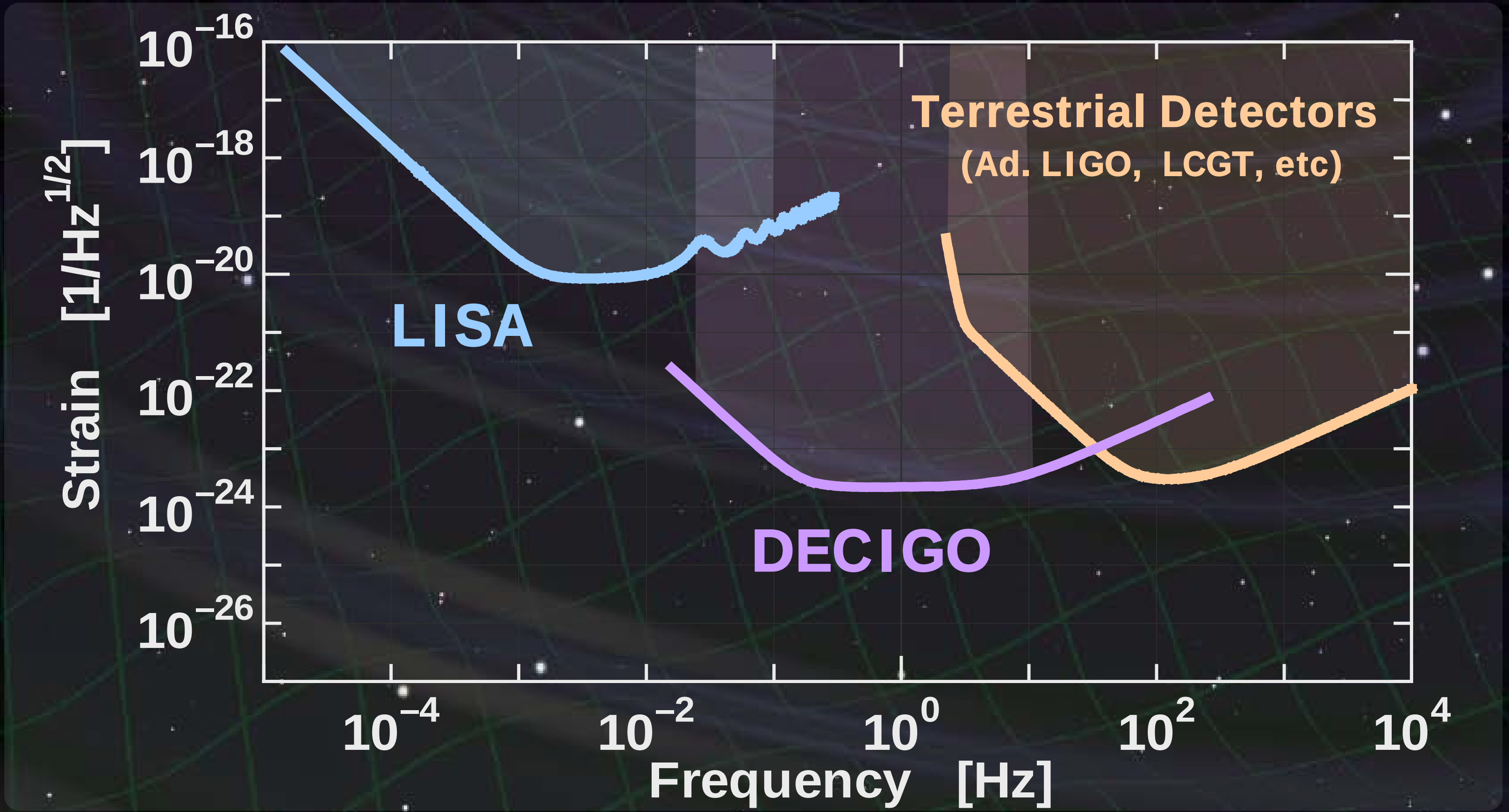
4. Summary

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



DECIGO Interferometer

Interferometer Unit:

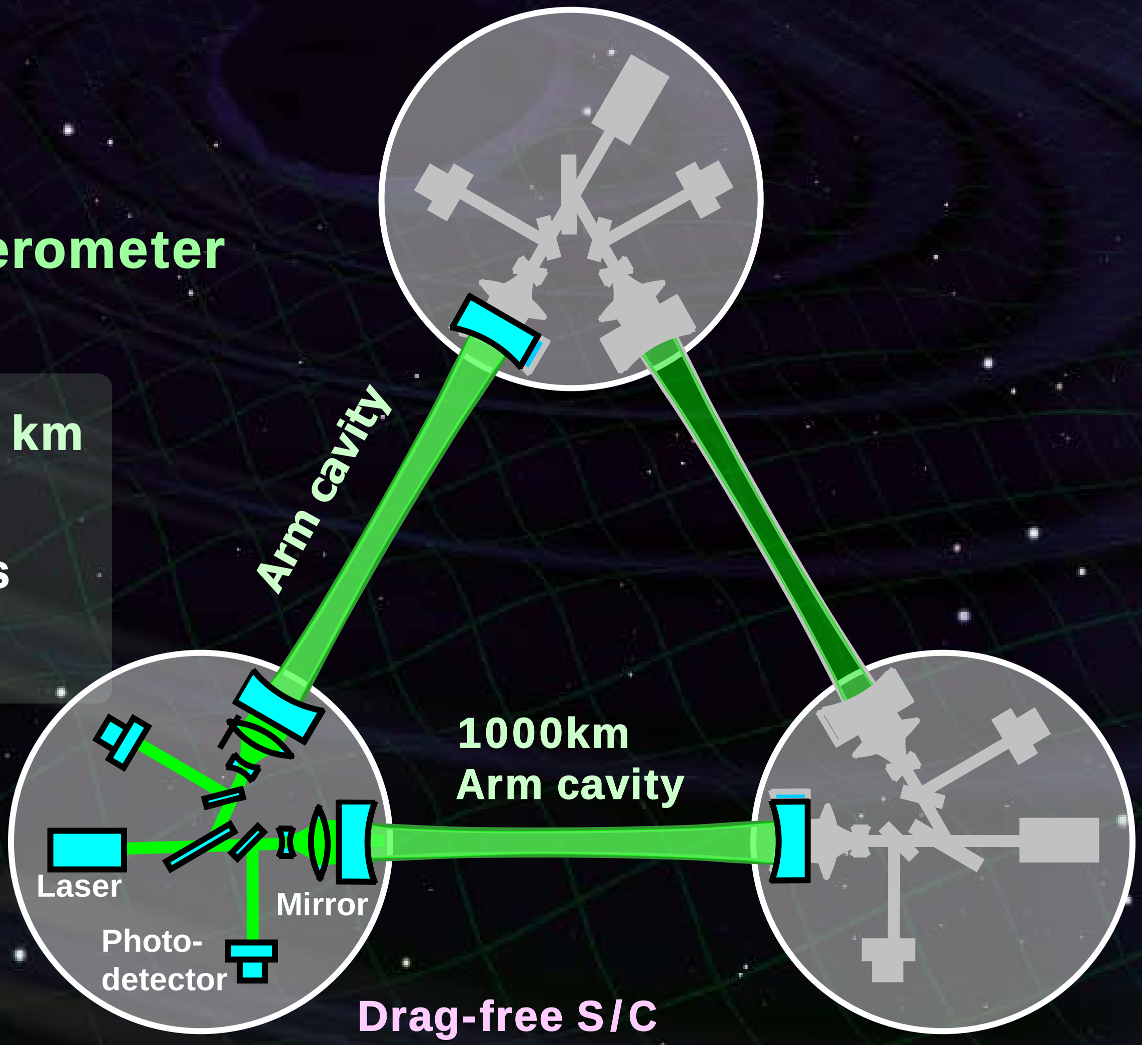
Differential FP interferometer

Baseline length: 1000 km

3 S/C formation flight

3 FP interferometers

Drag-free control



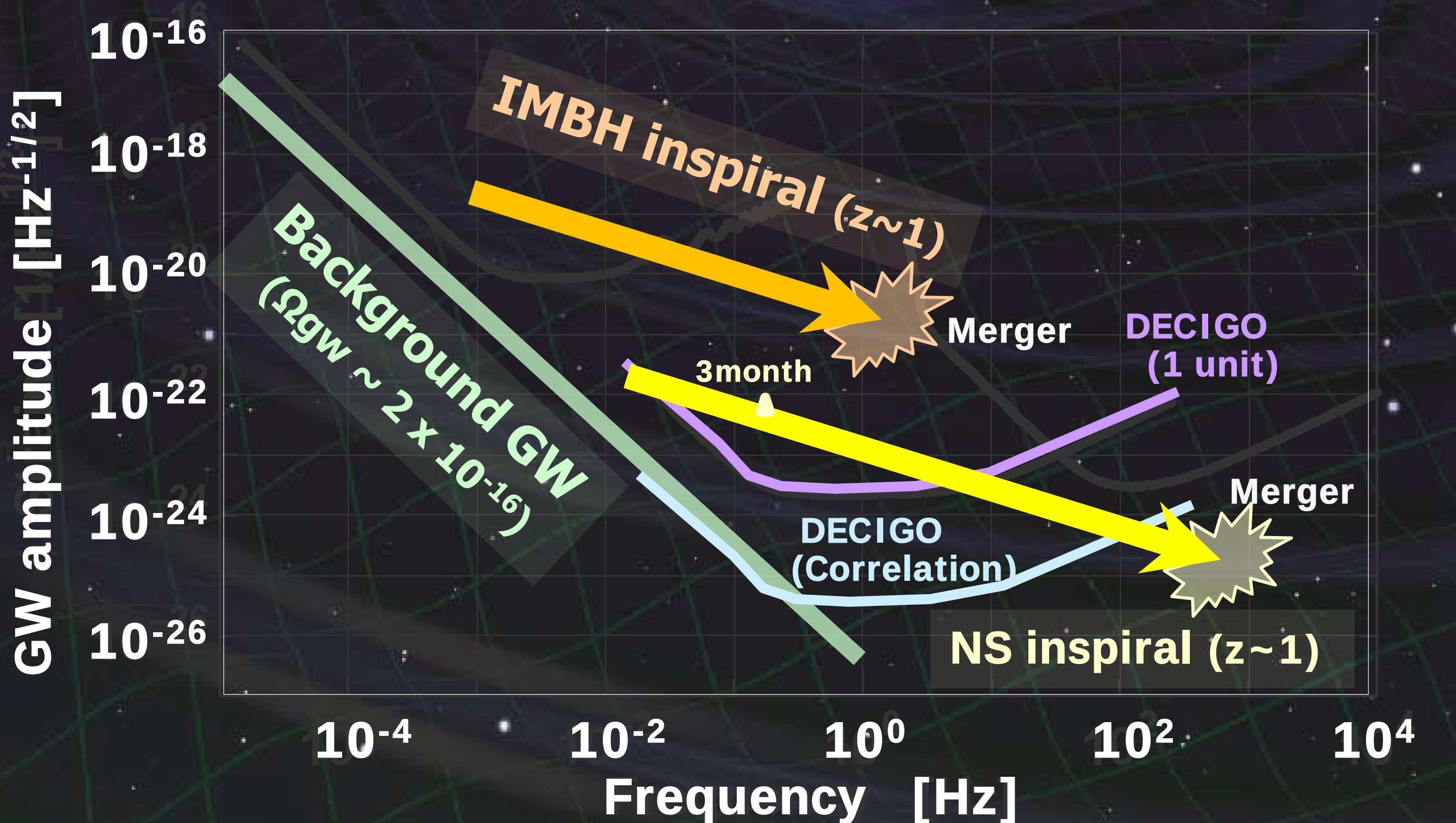
Targets and Science

DECIGO

IMBH binary inspiral
NS binary inspiral
Stochastic background

⇒

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

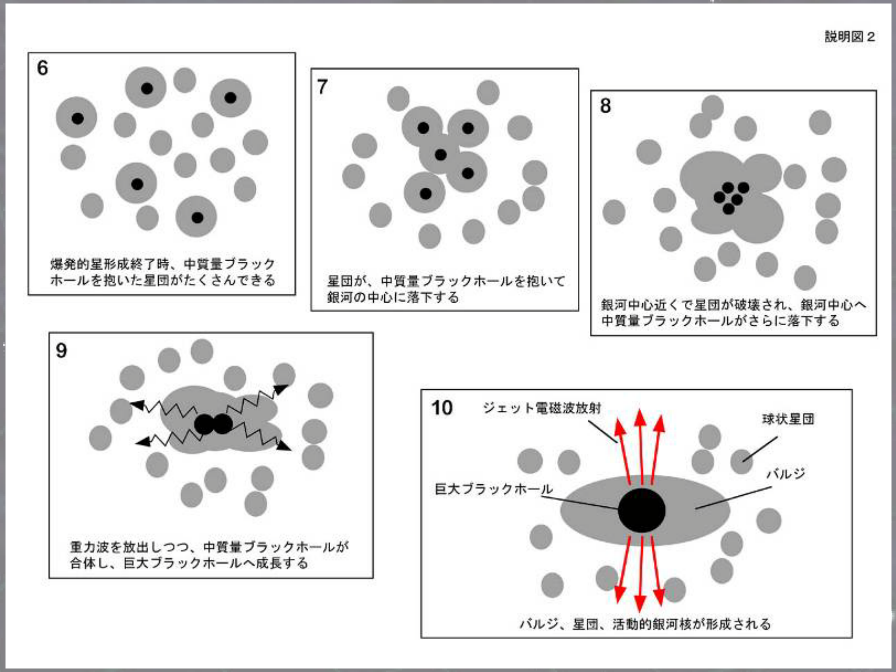


IMBH inspiral and Merger

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

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

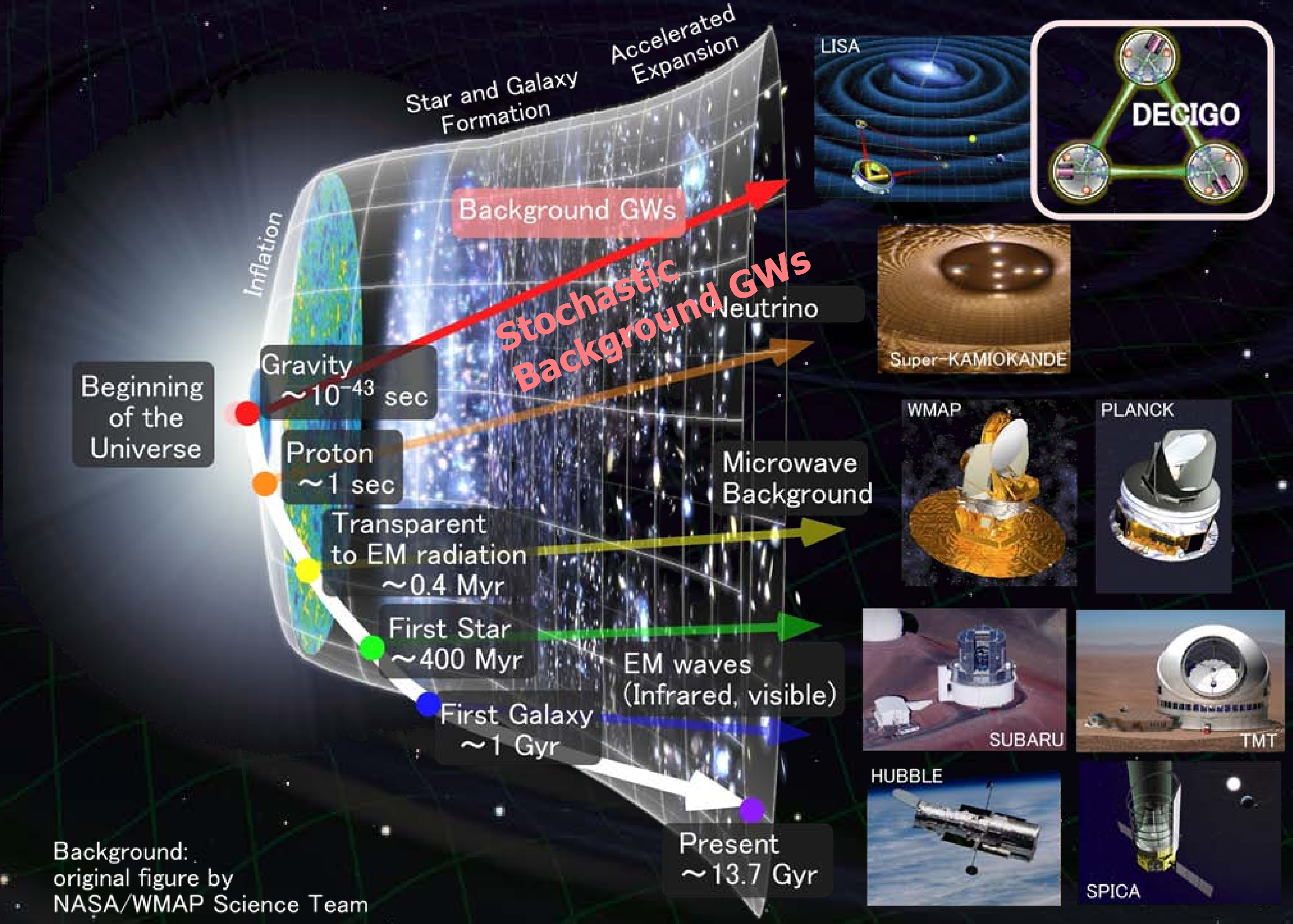
Seto, Kawamura, Nakamura, PRL 87, 221103 (2001)

Determine cosmological parameters

Absolute and independent measurement

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

Stochastic Background GWs



Pre-Conceptual Design

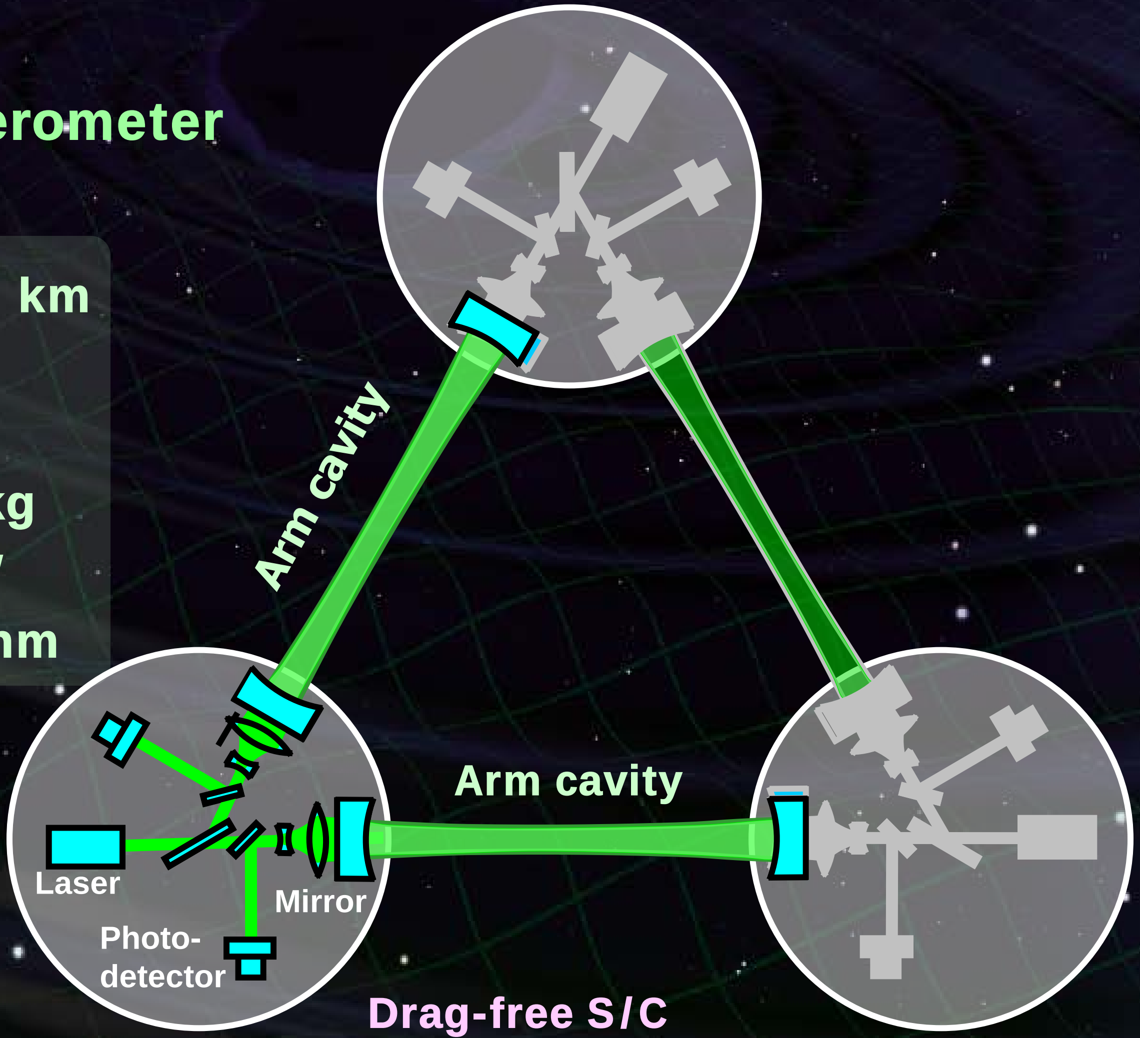
Interferometer Unit:

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

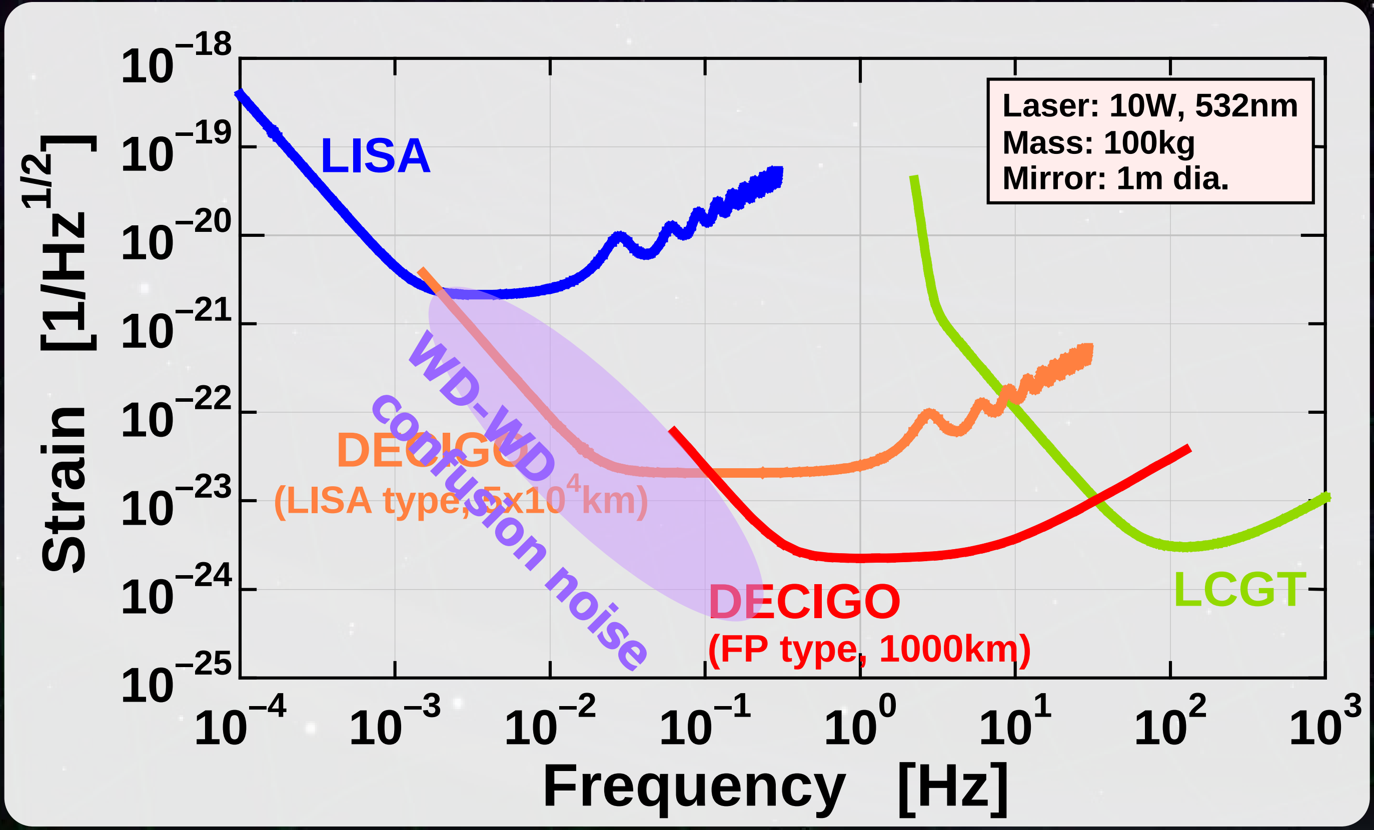


Interferometer Design

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

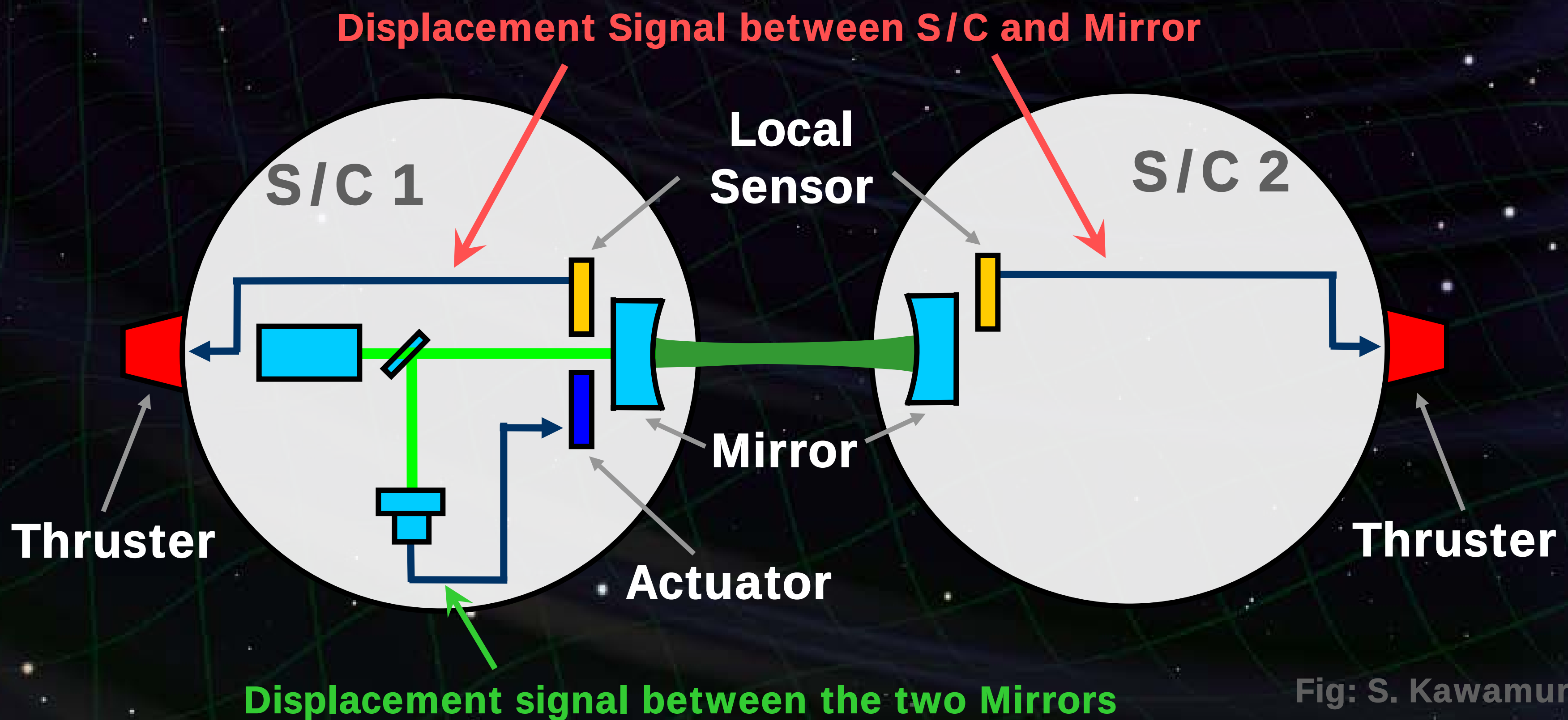


Fig: S. Kawamura

Requirements

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

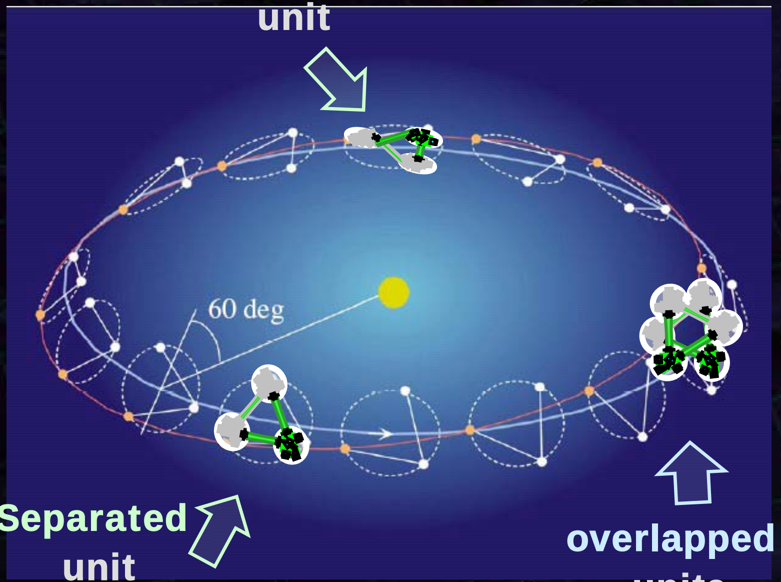
Relative acc. 4×10^{-12} m/s^2

(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

DECIGO

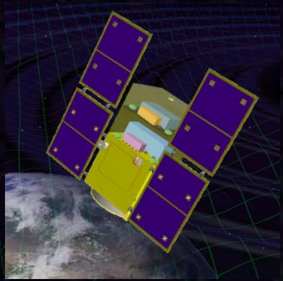
Figure: S.Kawamura

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

Mission

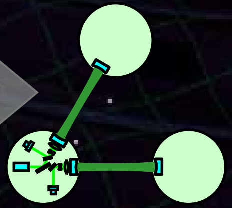
R&D
Fabrication

SDS-1/SWIM



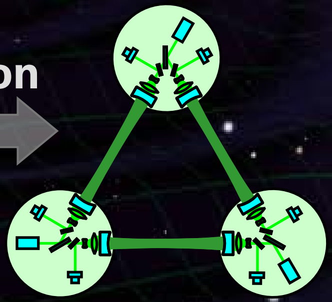
DECIGO
Pathfinder
(DPF)

R&D
Fabrication



Pre-DECIGO

R&D
Fabrication



DECIGO

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

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Overview and design

⇨ DECIGO Pathfinder

Space demonstration by SWIM

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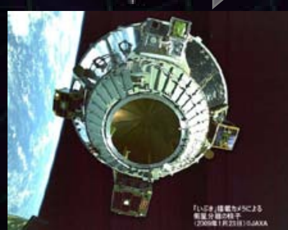
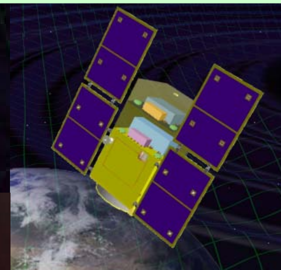
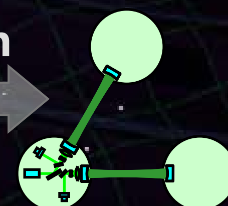
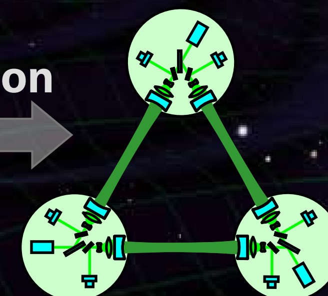
Roadmap

Figure: S.Kawamura

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

	2010–2016	2017–2022	2023–2029
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

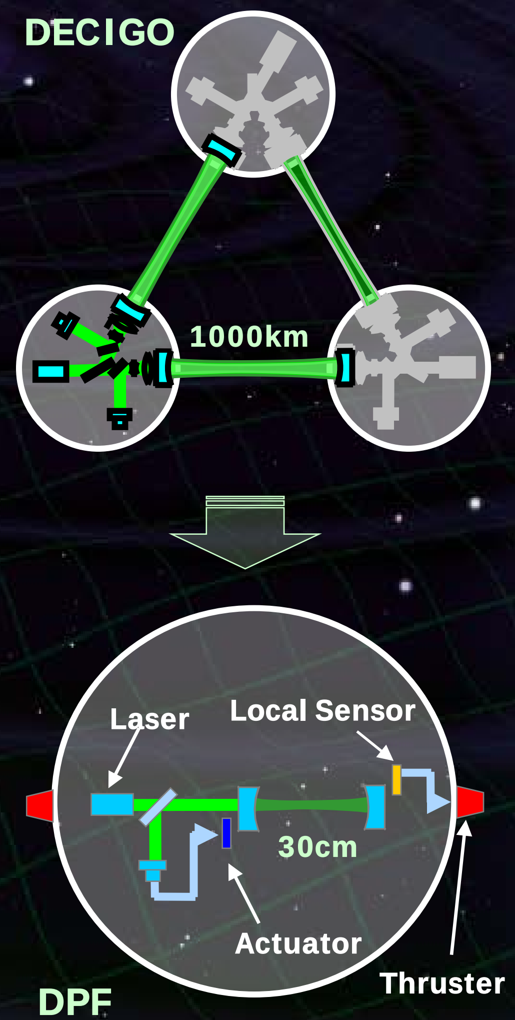
DECIGO-PF

DECIGO Pathfinder (DPF)

First milestone mission for DECIGO

Shrink arm cavity

DECIGO 1000km → DPF 30cm



Single satellite

(Payload ~1m³ , 350kg)

Low-earth orbit

(Altitude 500km, sun synchronous)

30cm FP cavity with 2 test masses

Stabilized laser source

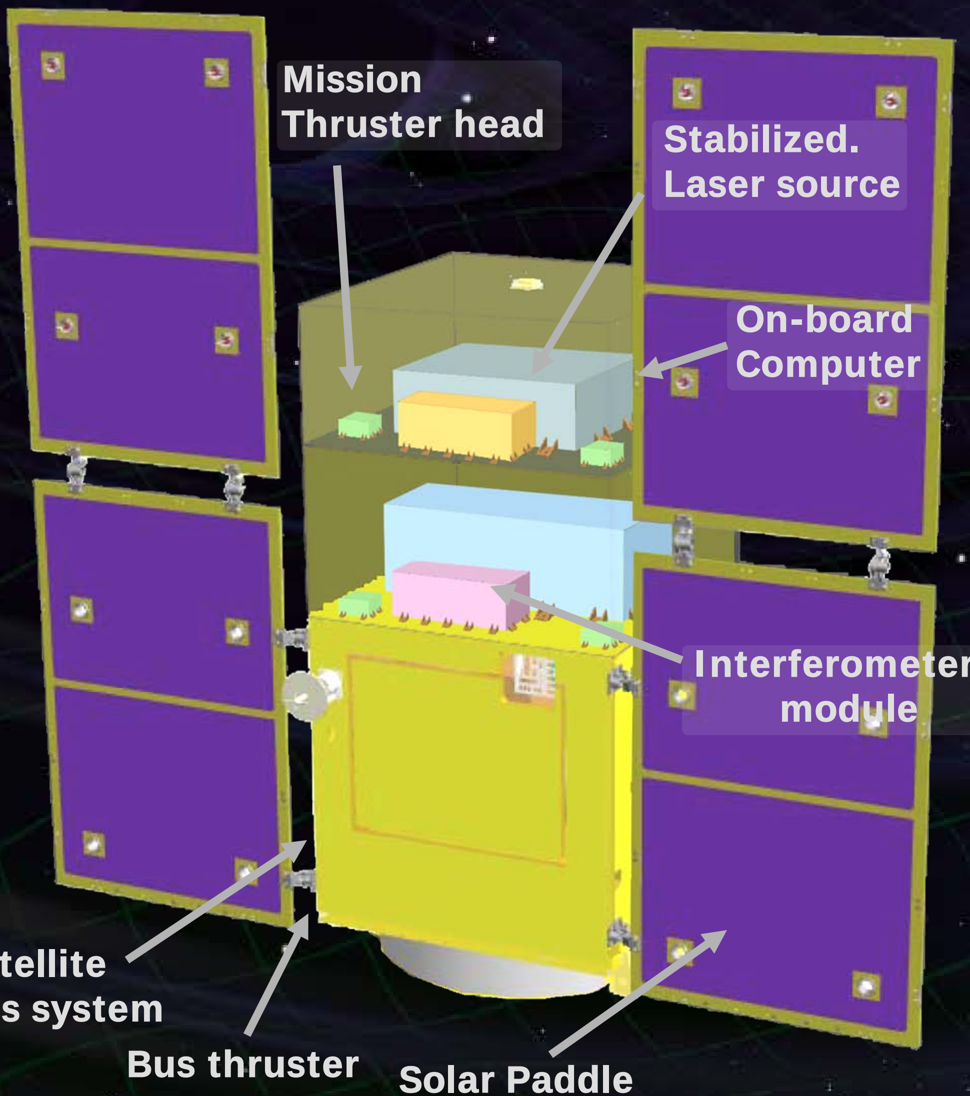
Drag-free control

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

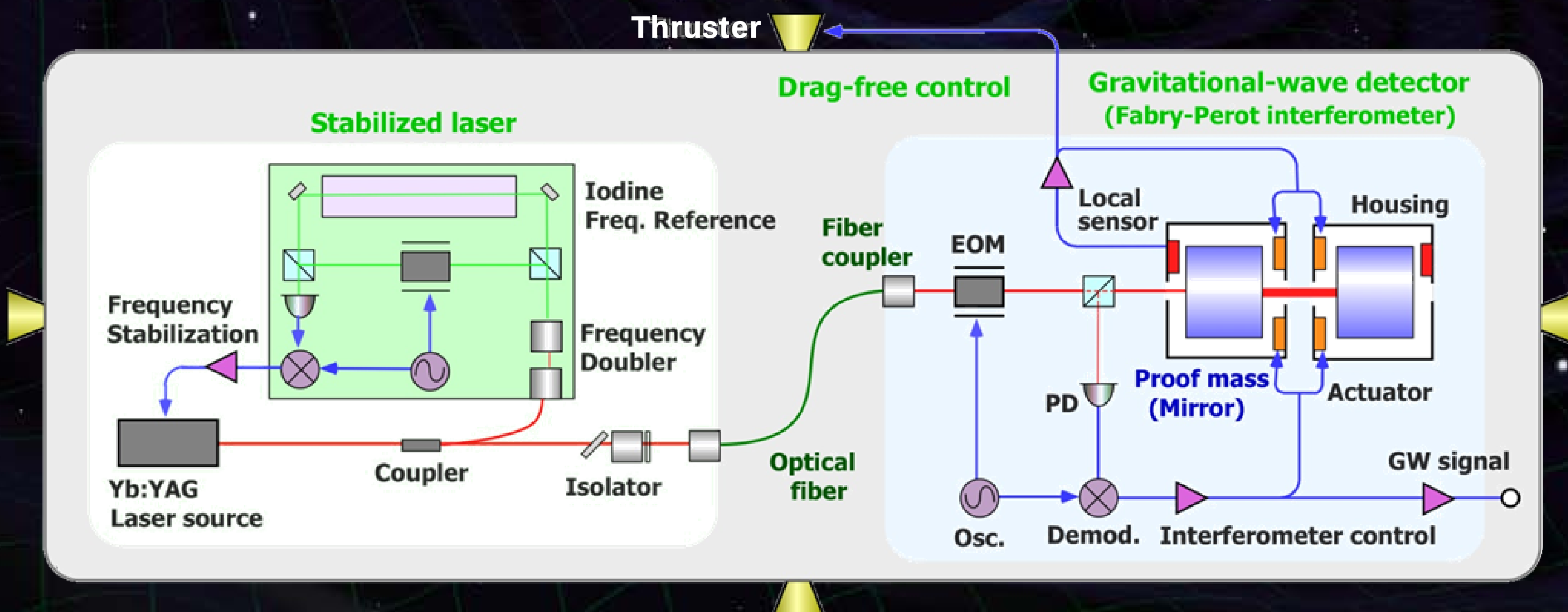


DPF mission payload

DECIGO

Mission weight : ~150kg
Mission space : ~95 x 95 x 90 cm

Drag-free control
Local sensor signal
→ Feedback to thrusters

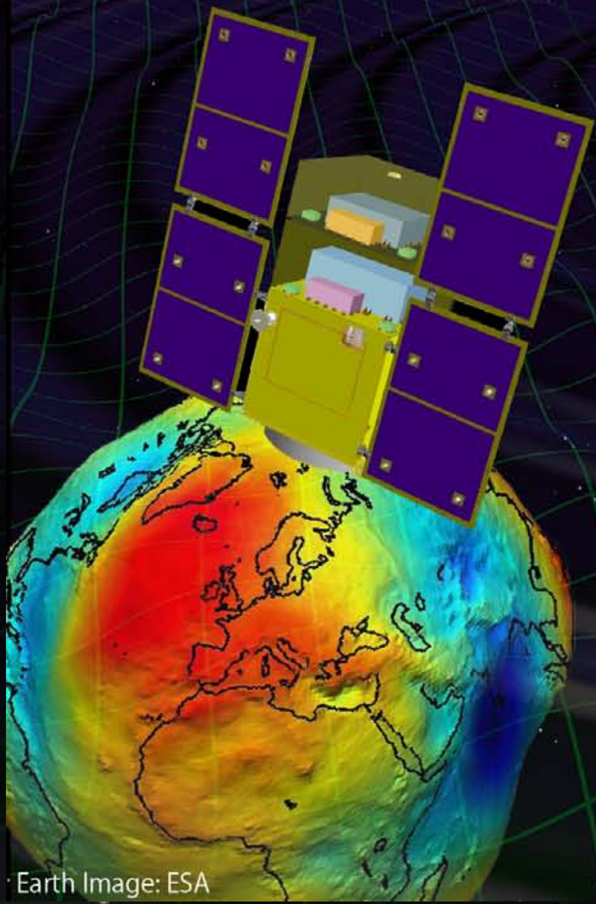


Laser source
Yb:YAG laser (1030nm)
Power : 25mW
Freq. stab. by Iodine abs. line

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

Targets of DPF

DECIGO



Scientific observations

Gravitational Waves form BH mergers

→ BH formation mechanism

Gravity of the Earth

→ Geophysics, Earth environment

Science technology

Space demonstration for DECIGO

→ Most tech. with single satellite

(IFO, Laser, Drag-free)

Precision measurement in orbit

→ IFO measurement

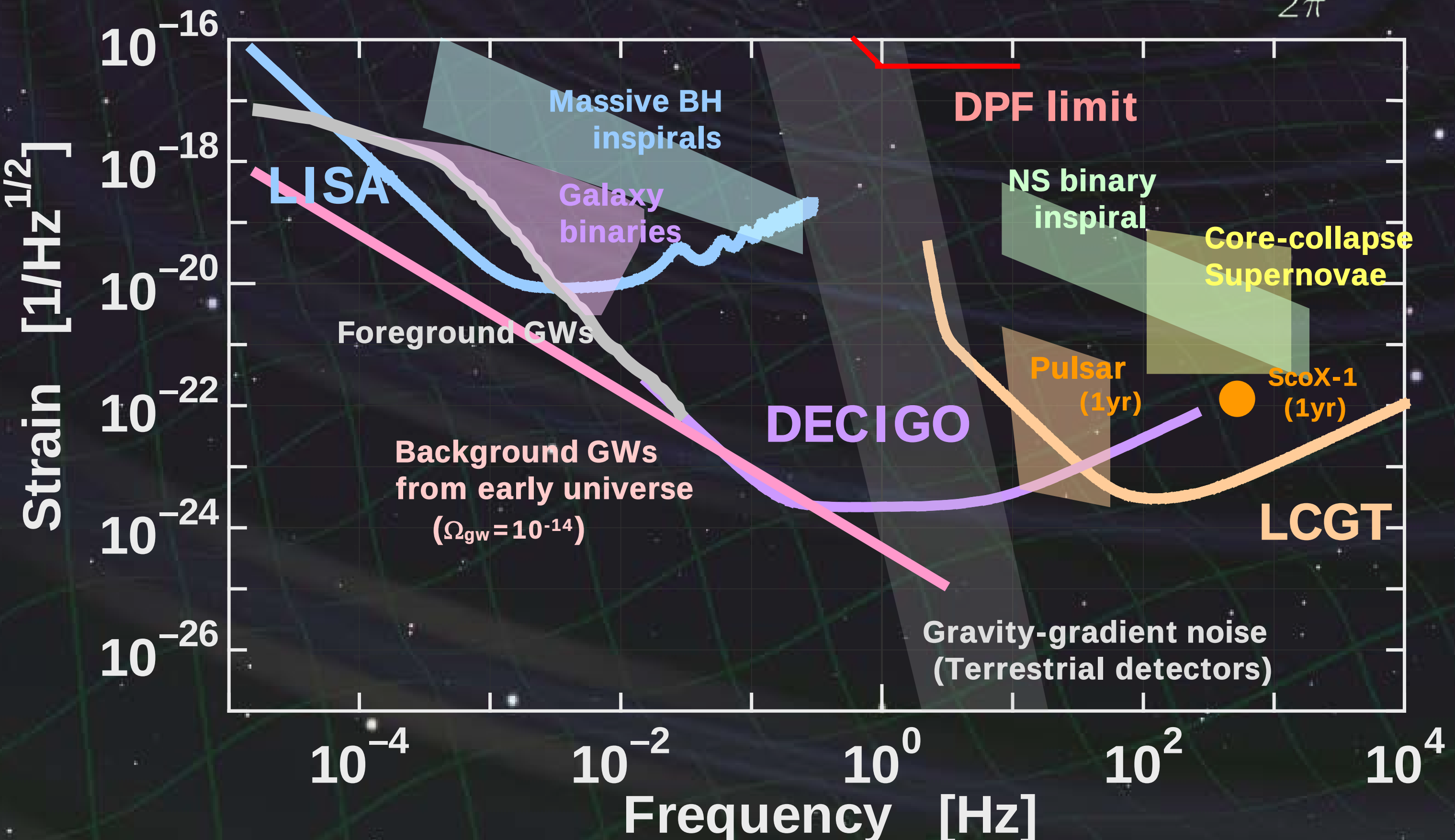
under stable zero-gravity

DPF 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

DECIGO

Blackholes events in our galaxy

IMBH inspiral and merger

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

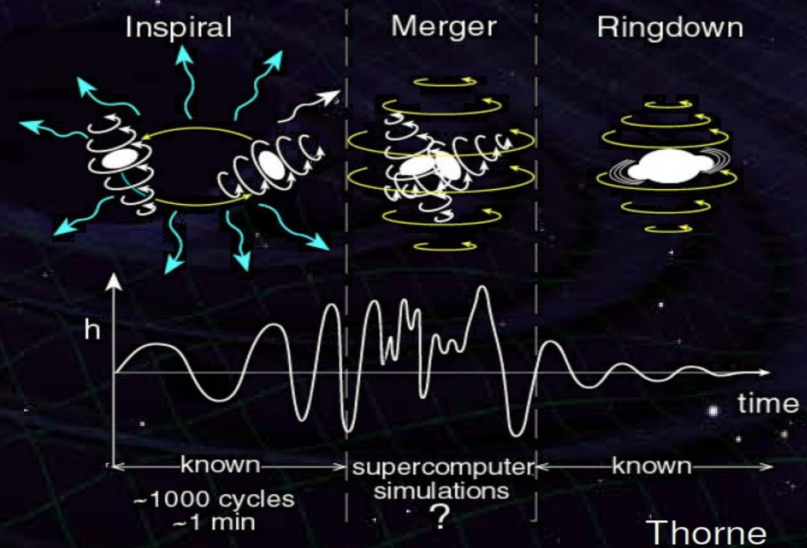
Distance 10kpc, $m = 10^3 M_{sun}$

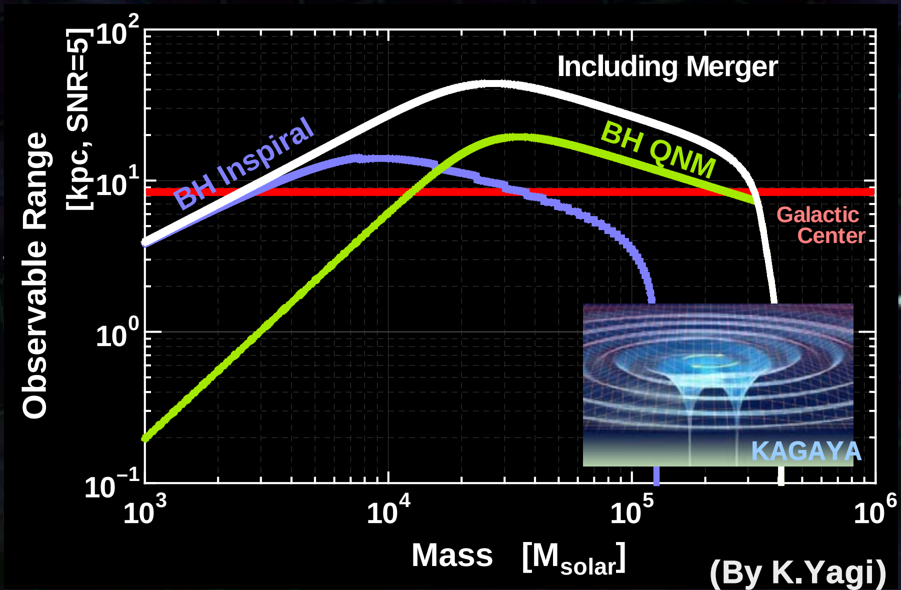
Obs. Duration (~1000sec)

BH QNM

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

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





(By K.Yagi)

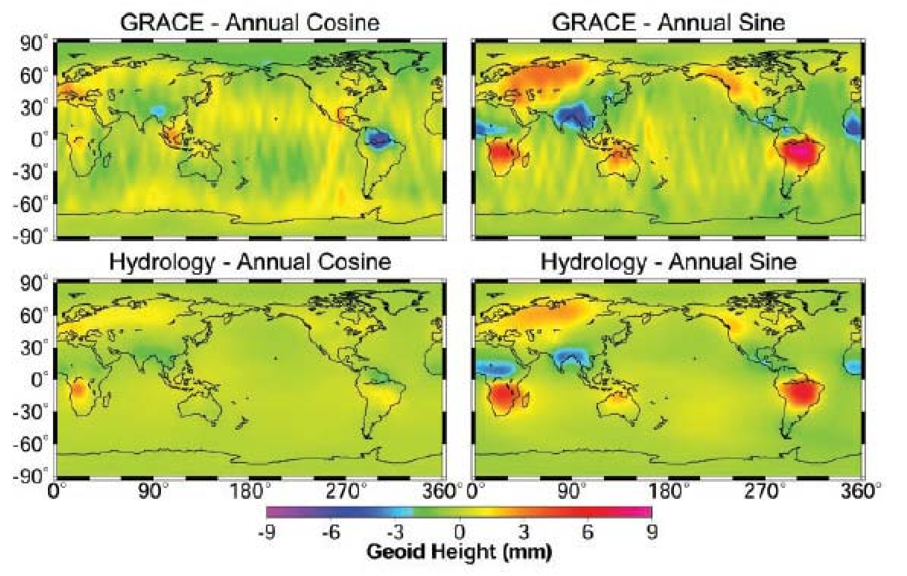
Observable range covers our Galaxy (SNR~5)

Hard to access by others → Original observation

Earth's Gravity Observation

Measure gravity field of the Earth
from Satellite Orbits, and gravity-gradiometer

⇨ comprehensive and homogeneous-quality data



Seasonal change of the gravitational potential observed by GRACE

Determine global gravity field
→ Basis of the shape of the Earth (Geoid)

Monitor of change in time
→ Result of Earth's dynamics
Ground water motion
Strains in crusts by earthquakes and volcanoes

Satellite Gravity missions

3-types of satellite gravity missions

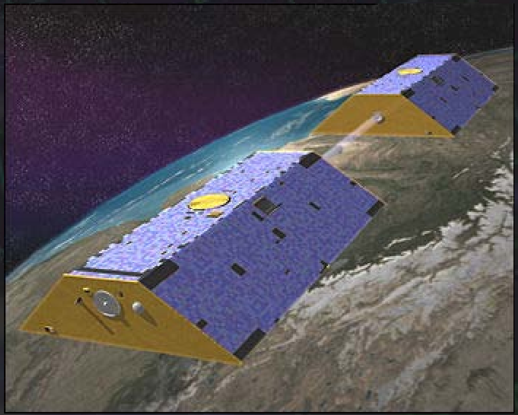
Satellite-to Satellite tracking High-Low

- Observe satellite orbit by global positioning system (GPS,…)
- Cancel drag-effects by accelerometer

CHAMP (GFZ, 2000-)

Satellite-to Satellite tracking Low-Low

- Distance meas. by along-track satellites
- Cancel drag-effects by accelerometer



GRACE (NASA, 2002-)

Satellite Gravity Gradiometry

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

GOCE (ESA, 2009-)

DPF sensitivity

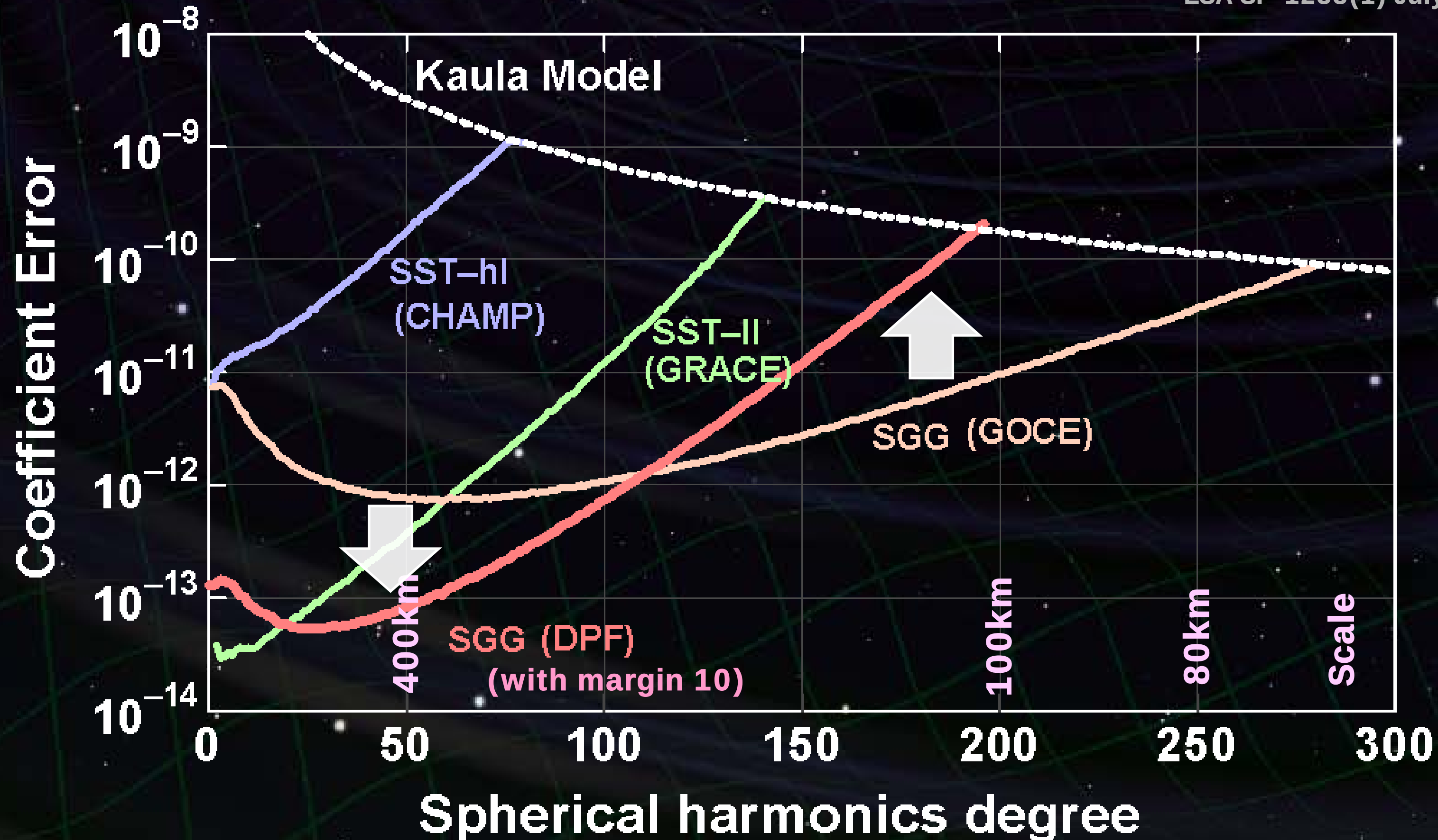
DECIGO

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.



DPF mission status

DECIGO

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

SPRINT-A /EXCEED
UV telescope mission

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

2nd mission (~2013/14) : ERG

DPF survived until final two

3rd mission (~2015/16) : TBD

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

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

1. Introduction

2. LCGT

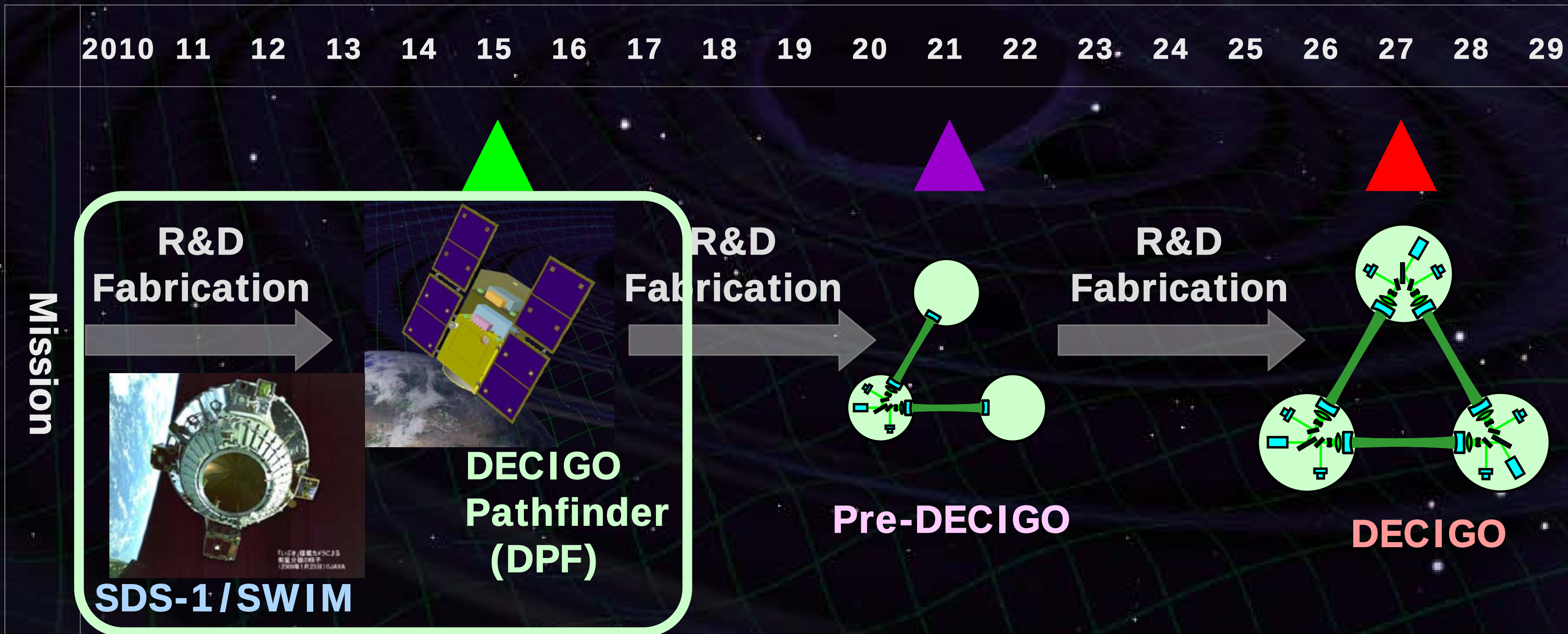
3. DECIGO

- Overview and design
- DECIGO Pathfinder
- ⇨ Space demonstration by SWIM

4. Summary

Roadmap

Figure: S.Kawamura



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

SWIM launch and operation

DECIGO

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

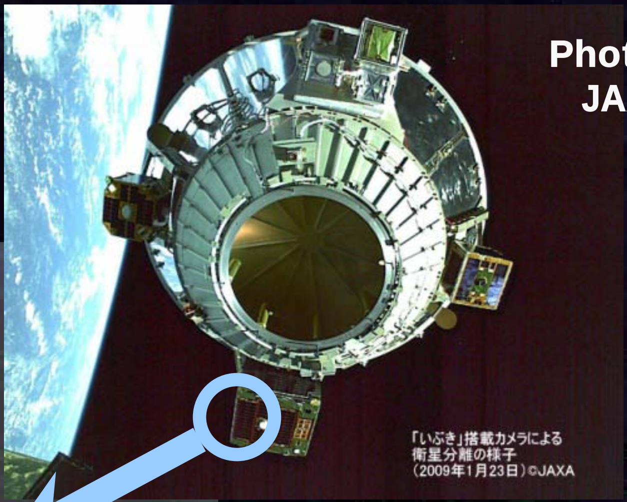
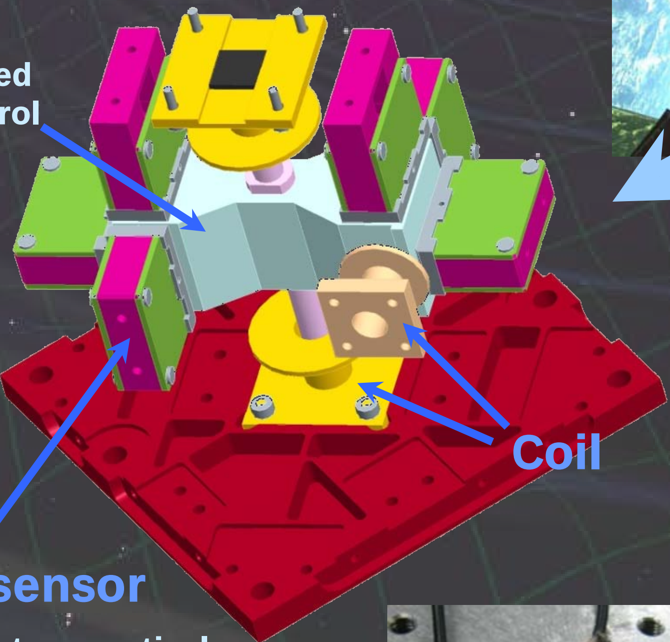


Photo: JAXA

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

Test mass

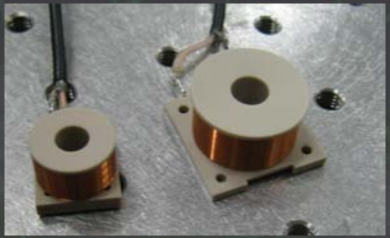
~47g Aluminum, Surface polished
Small magnets for position control



Coil

Photo sensor

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



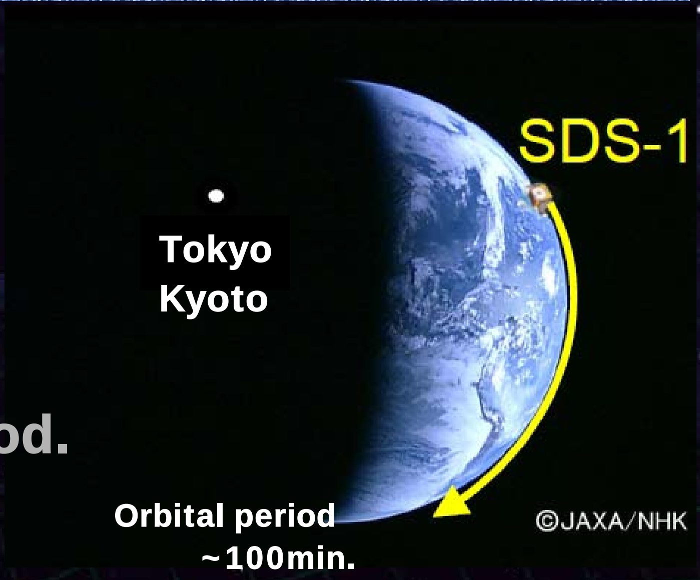
SWIM observation

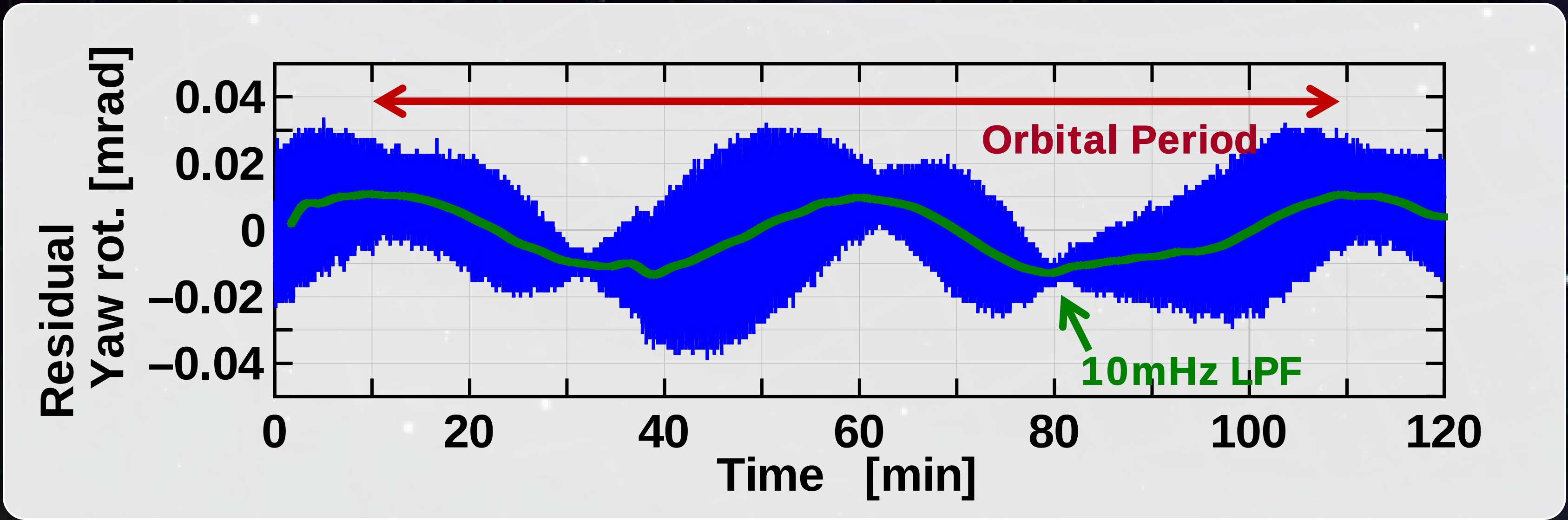
Observation by SWIM

Jun 17, 2010 ~120 min. operation
July 15, 2010 ~240 min. operation

Ground-based detectors were operated at the same period.

⇨ Data analysis





1. Introduction

2. LCGT

3. DECIGO

⇨ 4. Summary

Summary (1)

LCGT : Project started

Costs have been partially funded

Form global network

with Ad. LIGO and Ad. VIRGO

R&D and detailed design

CLIO: Improved sensitivity

at cryogenic temperature

Designs and developments underway

Summary (2)

DECIGO

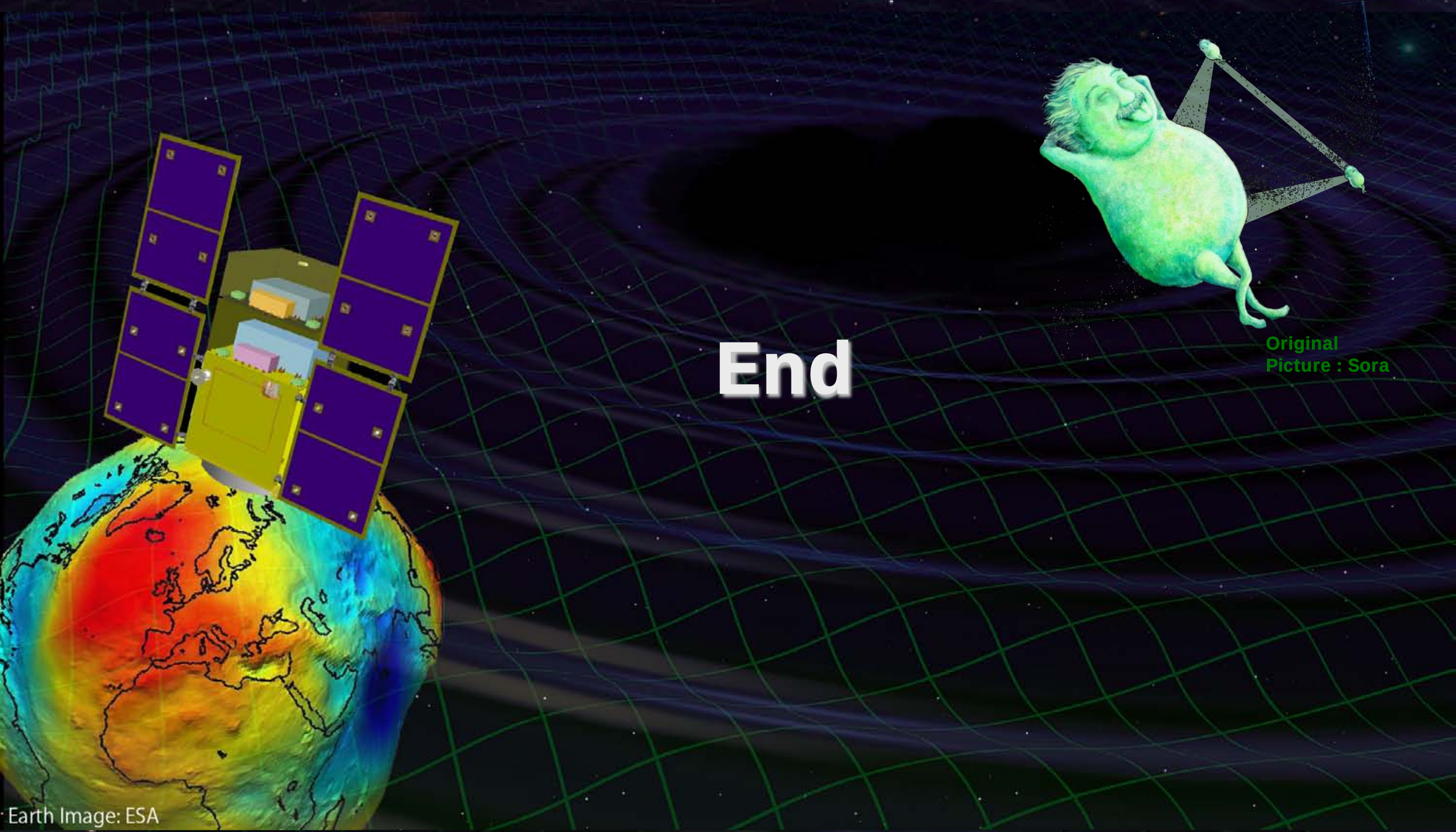
DECIGO : Fruitful Sciences

- 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!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Original
Picture : Sora
Earth Image: ESA