Science and Design of DECIGO and B-DECIGO

Masaki Ando (Univ. of Tokyo / NAOJ)

On behalf of DECIGO Working Group

Credit: S.Sato

DECIGO Members

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(On April 1st, 2016)

After the First Detection …

DECIGO

- New mysteries and issues after the first detection:
  - Origin of heavier mass ($30M_{\odot}$) BBH.
  - Other GW sources: BNS, SN, Pulsar,⋯.
  - Sky localization and EM Follow-up observations.
  - Test of GR, Cosmology.

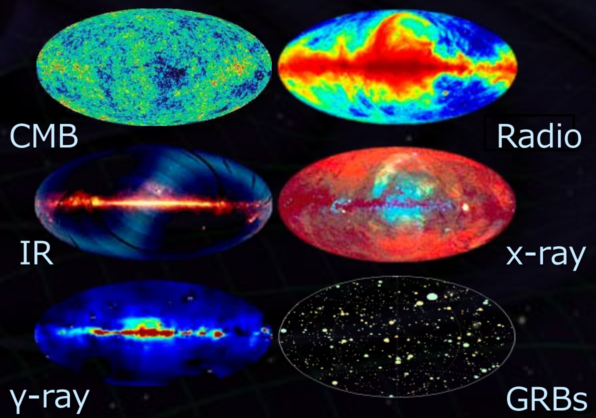
⇩

- Network of 2nd-gen. GW antennae (aLIGO, AdVIRGO, KAGRA, LIGO-India) will be formed in several years.
- Two ways after that for Astronomy and Cosmology:
  - 3rd–gen. ground-based GW antennae (ET, CE).
  - Space GW antennae (LISA, DECIGO, ASTROD,⋯).

Multiple-band Observation

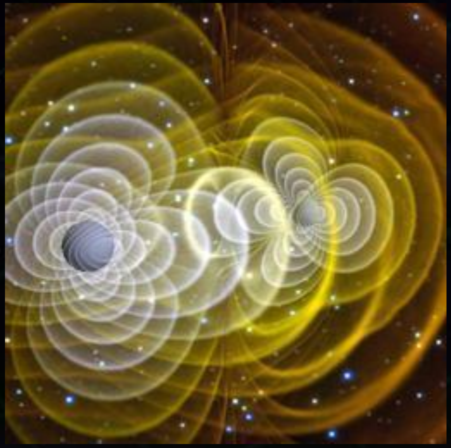
- Electro-Magnetic Observations :

  Multiple-band observations
  (Radio, Optical/IR, X-ray, γ-ray)
  → Variety of knowledge corr. to
  the <u>Energy and Temperature</u>
  of the target.



- Gravitational-wave Observations :

  Frequency of radiated GW
  ~ 1/ (Time scale of source motion)
  → Variety of knowledge corr. to
  the <u>Time scale and Mass</u> of sources.



GW Science at Low Frequency

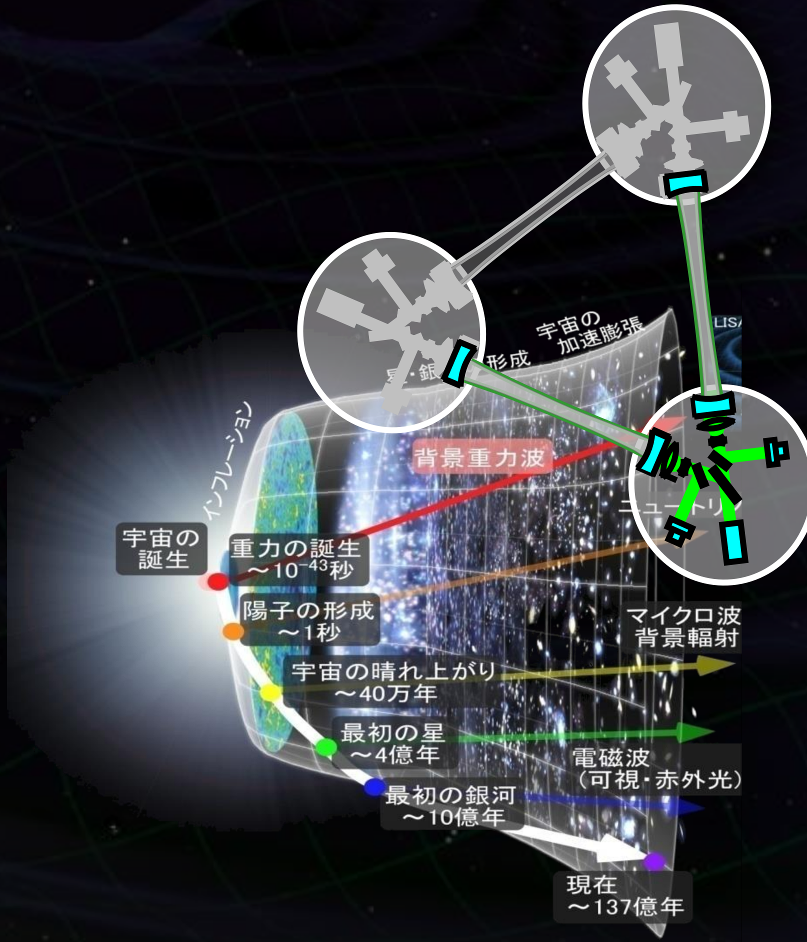
DECIGO

- Low-Freq. (~0.1Hz) GW antennae
  will provide original sciences:
  - * Mass and orbital parameters of binaries,
  - * Intermediate-Mass Black Hole binaries,
  - * Stochastic background GW.

⇩

- Fruitful sciences by space-borne GW antennae
  B-DECIGO: $h \sim 10^{-23}\ \mathrm{Hz}^{-1/2}$ (0.1Hz).
- Cosmological Observation by
  DECIGO : $h \sim 10^{-24}\ \mathrm{Hz}^{-1/2}$ (0.1Hz).

DECIGO



宇宙の
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～10^{-43}秒
陽子の形成
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宇宙の晴れ上がり
～40万年
最初の星
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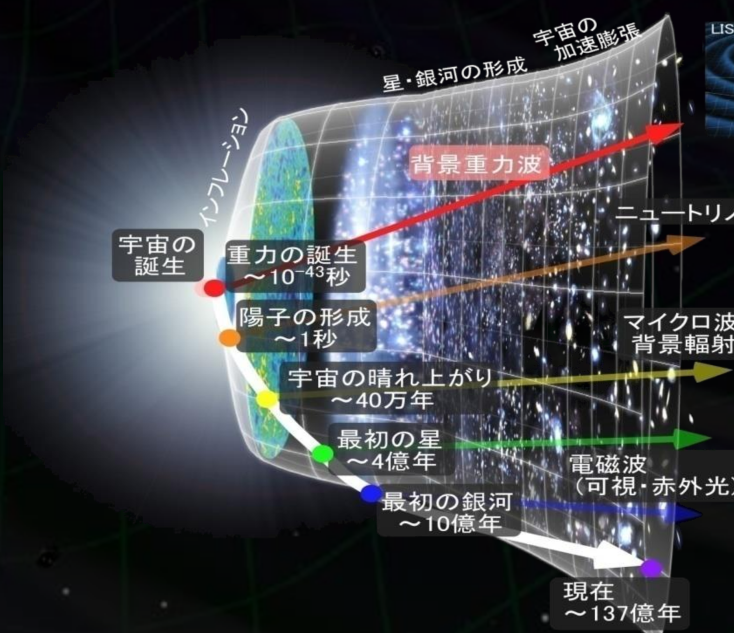
電磁波
（可視・赤外光）
最初の銀河
～10億年
現在
～137億年

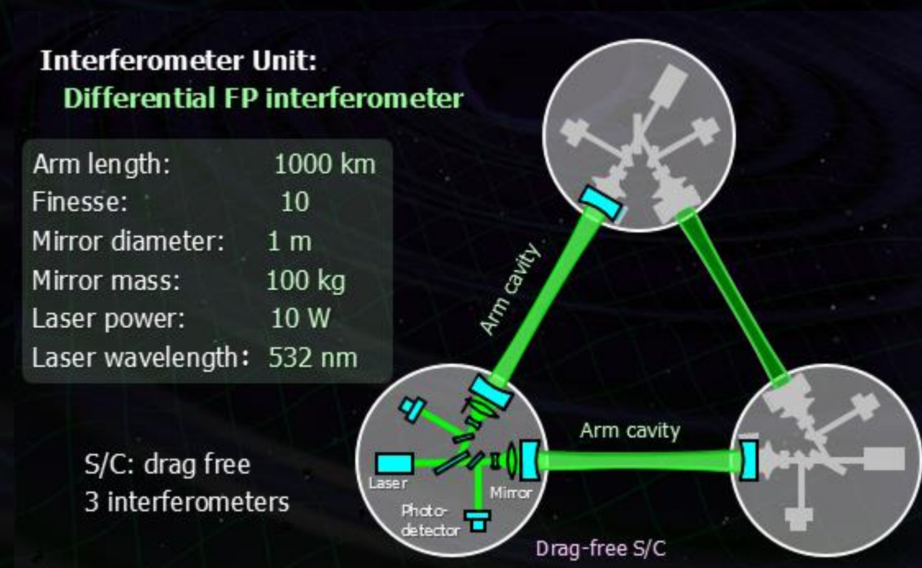
Space GW Antenna DECIGO

DECIGO (DECI-hertz interferometer Gravitational wave Observatory)

Purpose: To Obtain Cosmological Knowledge.

Direct observation of the origin of space-time and matter in Big-bang Universe.

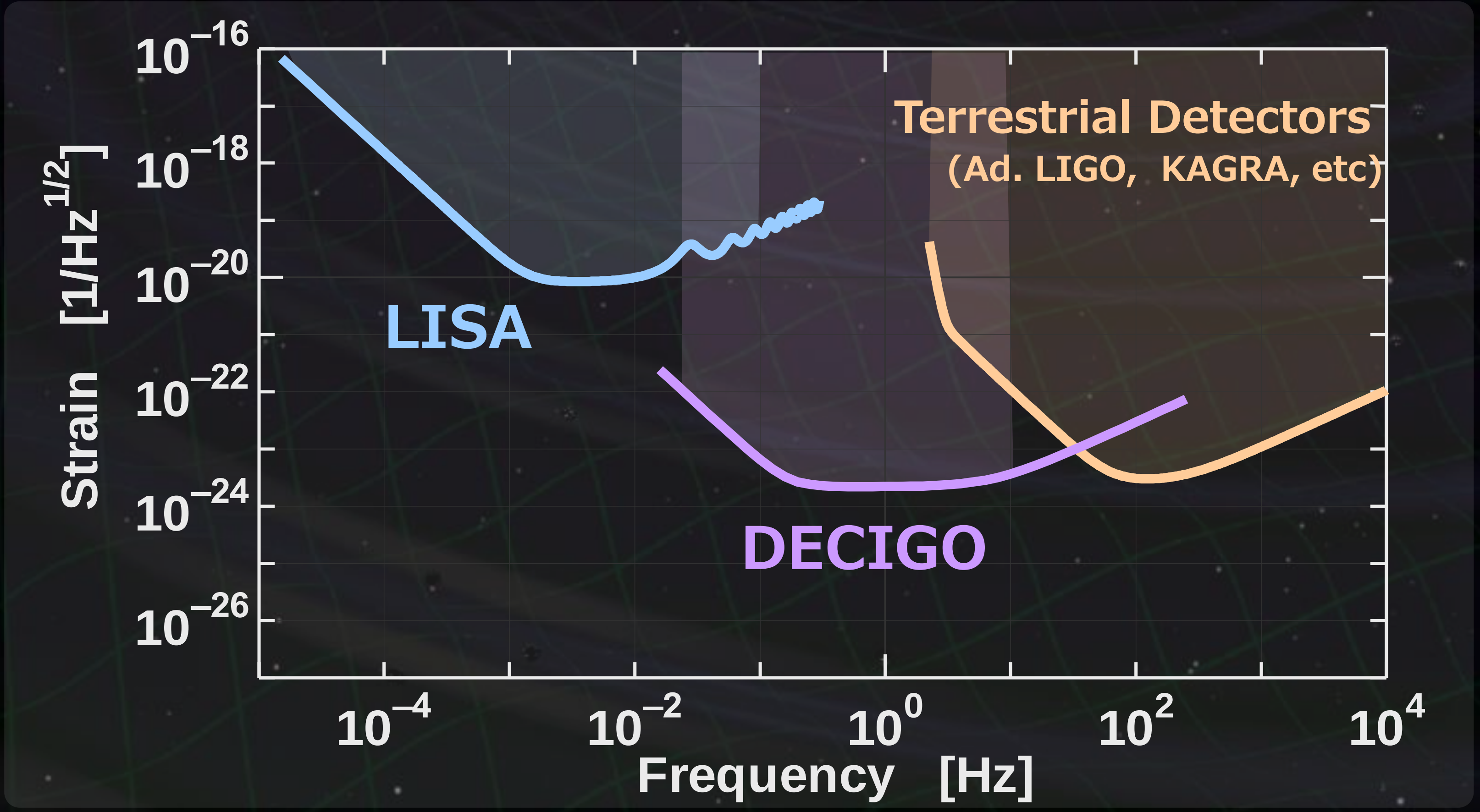




DECIGO Observation Band

Space GW antenna
Obs. band around 0.1 Hz

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

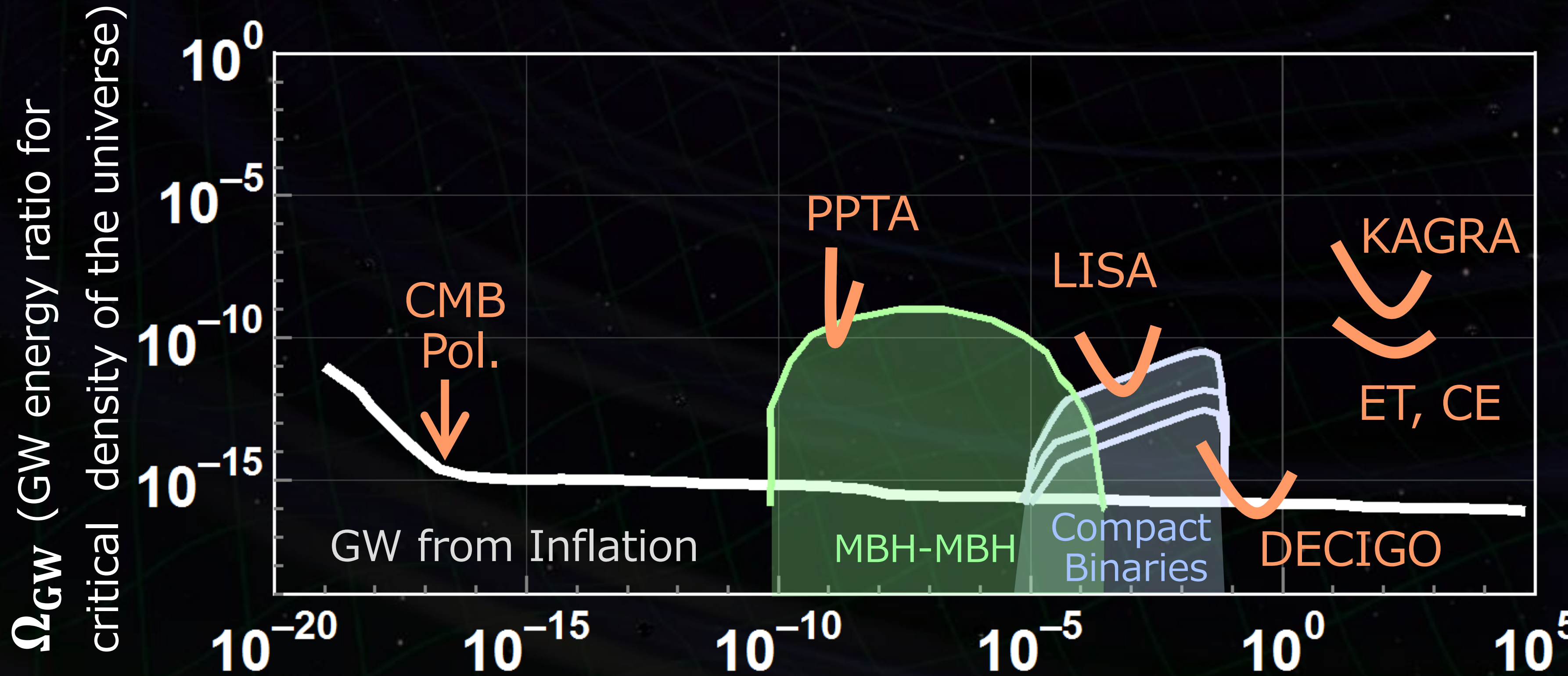


Observation of the Early Universe

Background:
original figure by
NASA/WMAP Science Team

‘Window’ for the Early Universe

DECIGO band is open window for direct observation of the early universe.



Kuroyanagi+, PRD (2009)

Pablo, PRD (2011)

GW Energy Density and Amplitude

- GW energy density ratio

GW energy density

$$\Omega_{\mathrm{GW}}(f) = \frac{1}{\rho_c} \frac{d\rho_{\mathrm{GW}}(f)}{d \ln f}$$

Critical energy density of the universe

Equivalent GW Amplitude

Hubble's constant

$$\tilde{h}^2_{\mathrm{GW}}(f) = \frac{3H_0^2}{10\pi^2 f^3}\Omega_{\mathrm{GW}}(f)$$

GW Energy Density and Amplitude

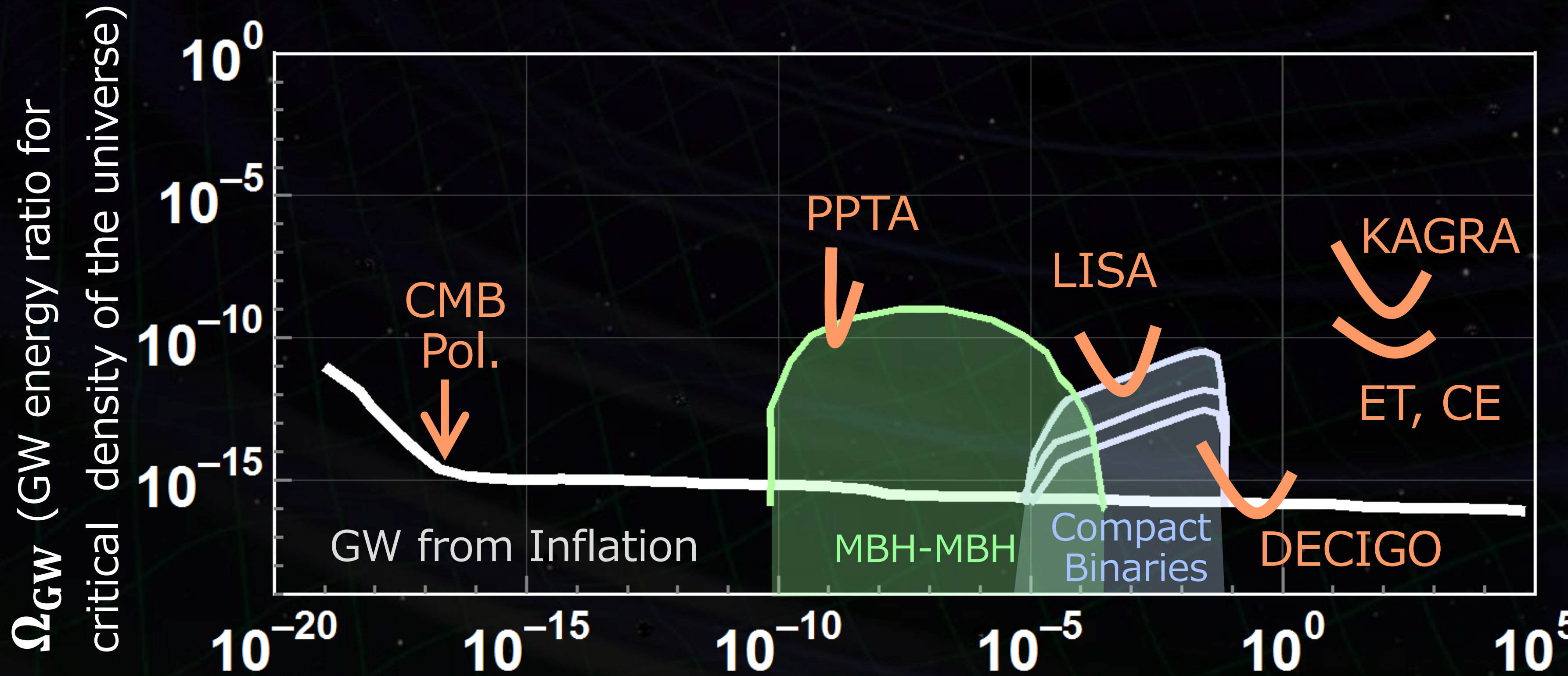
$$\tilde{h}_{GW}^2(f) = \frac{3H_0^2}{10\pi^2 f^3}\Omega_{GW}(f)$$

Smaller amplitude in high freq.

‘Window’ for the Early Universe

DECIGO

DECIGO band is open window for direct observation of the early universe.



Kuroyanagi+, PRD (2009)

Pablo, PRD (2011)

Observation of GW from Inflation

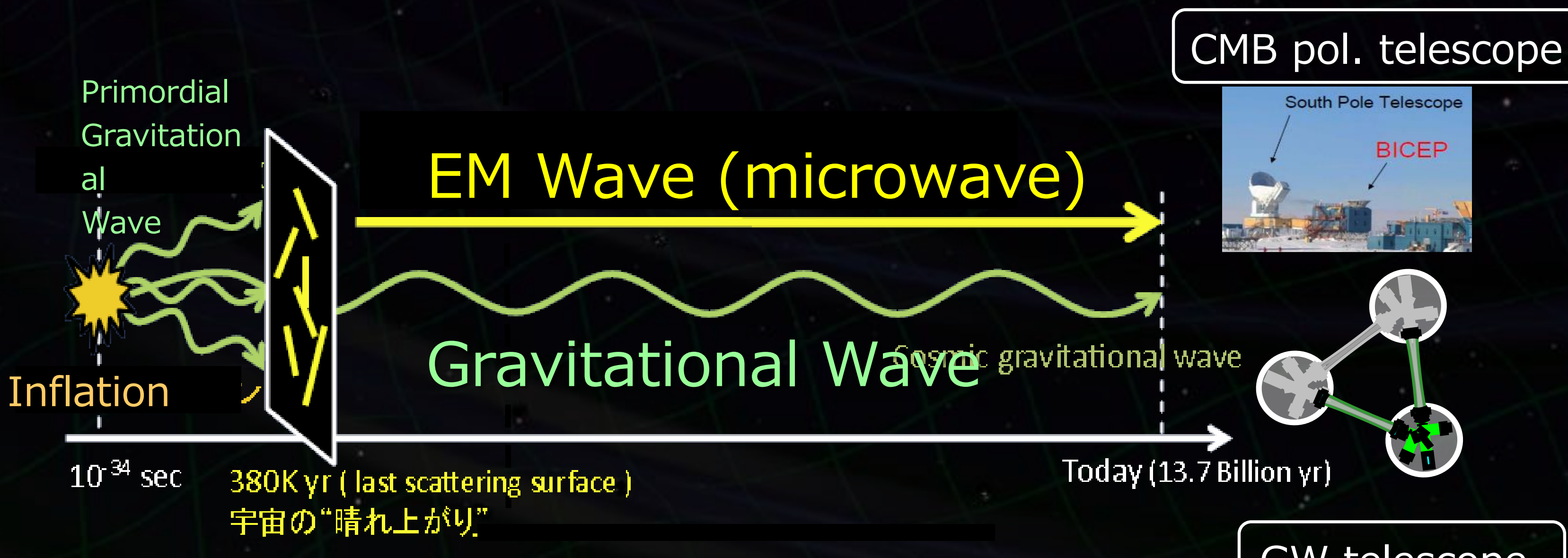
DECIGO

BICEP2, (POLARBEAR,･･･)

CMB B-mode polarization observation by micro-wave telescope.

DECIGO, (KAGRA, aLIGO,･･･)

GWB observation by GW telescope.

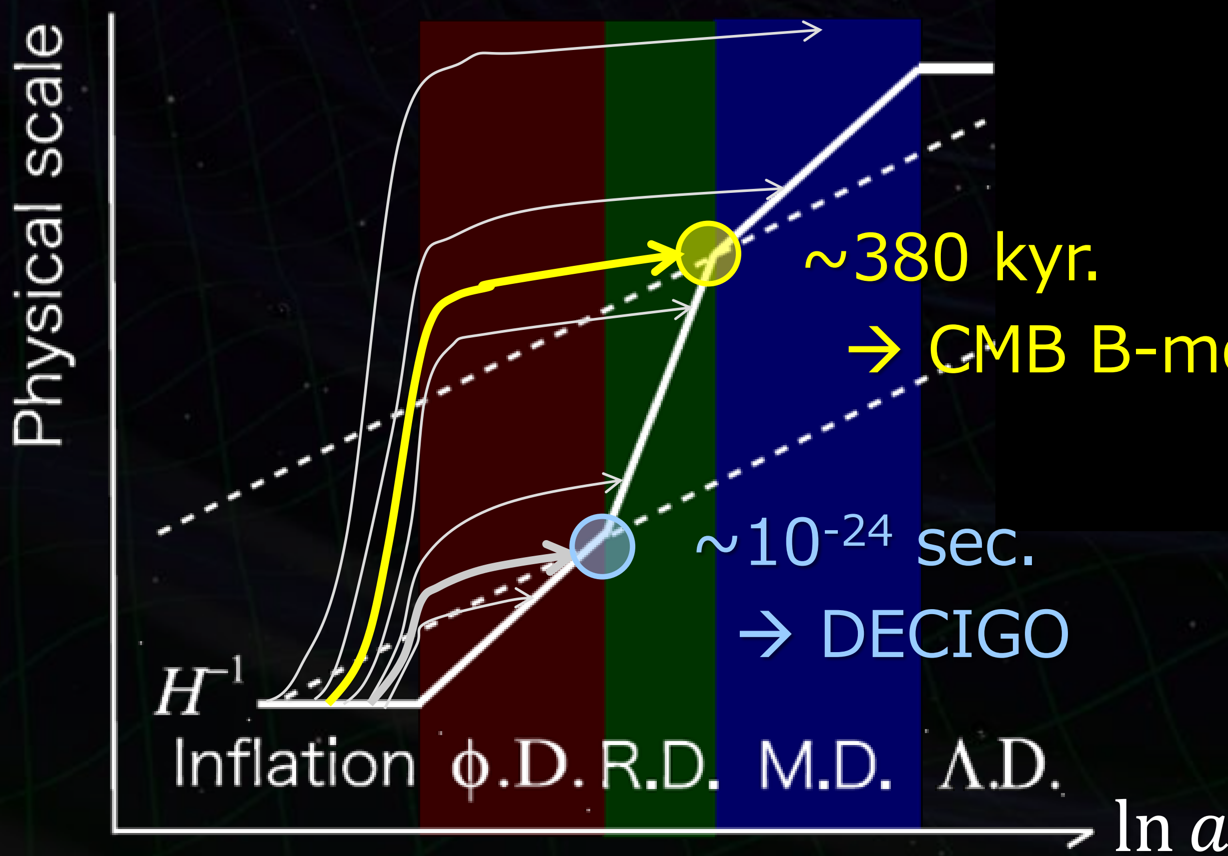


Original figure by Tajima (Kyoto 2011)

GW from Inflation

Stochastic background GWs by quantum fluctuation

→ Earlier-generated GWs in inflation period entered later into the horizon of the universe.



Nakayama+, Journal of Cosmology and Astroparticle Physics 06 (2008) 020.

Probing the Early Universe by GW

DECIGO

- GWs will carry direct information on the early universe.

- Spectrum : Initial fluctuation + Evolution history

Depends on r (tensor-to-scalar ratio), which may be also pinned-down by CMB B-mode polarization observation.

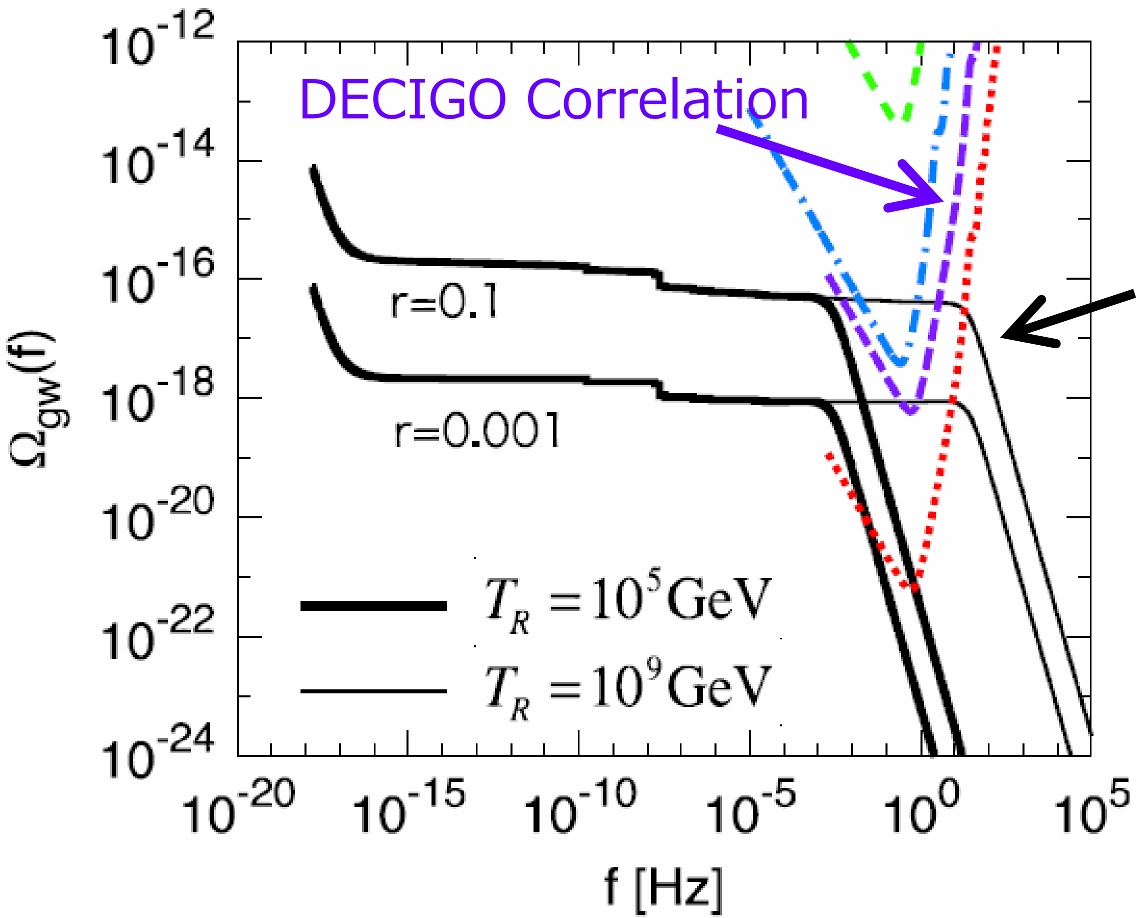
Different age in different freq.
Higher freq. → Earlier universe
- Reheating temperature
- Thermal history of the universe

….

GW from Inflation

Energy density ∝ Tensor-Scalar Ratio (r).

Power spectrum : Evolution history of the Universe.



- Spectrum Power.
  → Energy scale of inflation
- Cut-off freq.
  → Energy scale of Reheating

Nakayama+, Journal of Cosmology and Astroparticle Physics 06 (2008) 020.

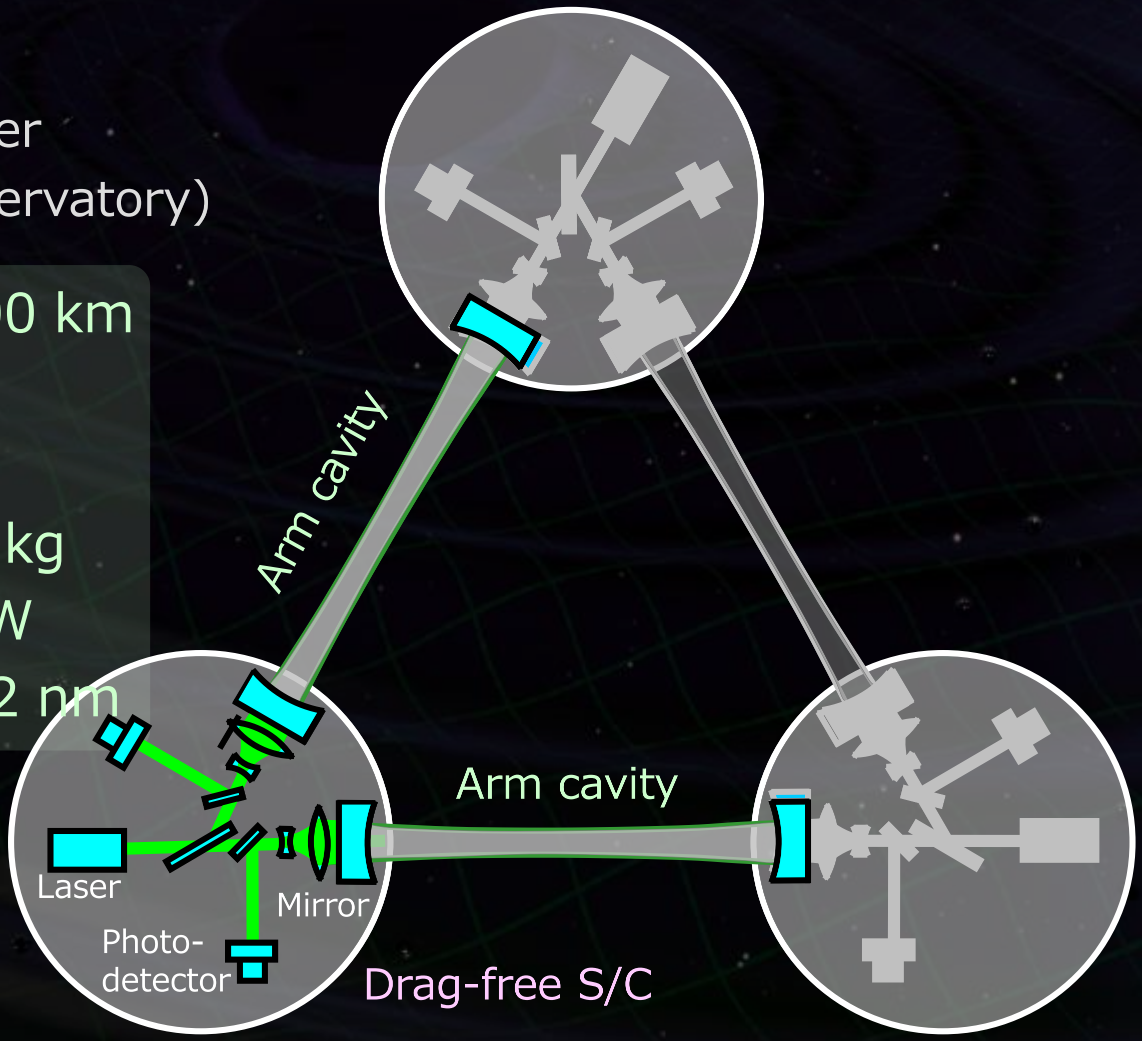
Conceptual Design

DECIGO

(DECI-hertz interferometer
Gravitational wave Observatory)

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

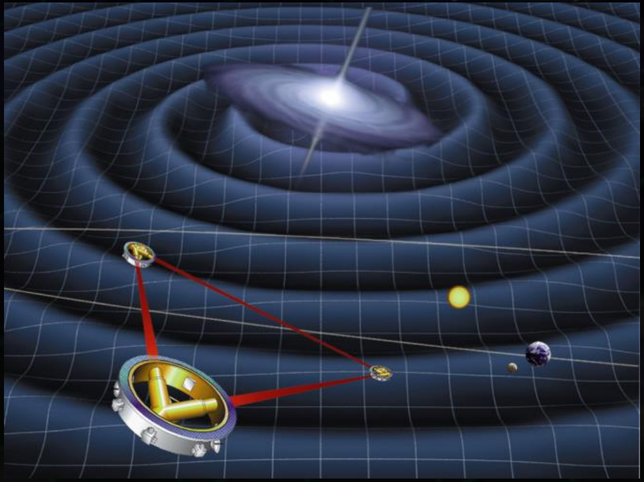
S/C: drag free
3 interferometers



Space GW antenna

LISA
(Laser Interferometer Space Antenna)

- Target: SMBH, Binaries.
  GWs around 1mHz.
- Baseline : 1-5M km.
  Constellation flight by 3 S/C
- Optical transponder.



DECIGO
(Deci-hertz Interferometer Gravitational Wave Observatory)

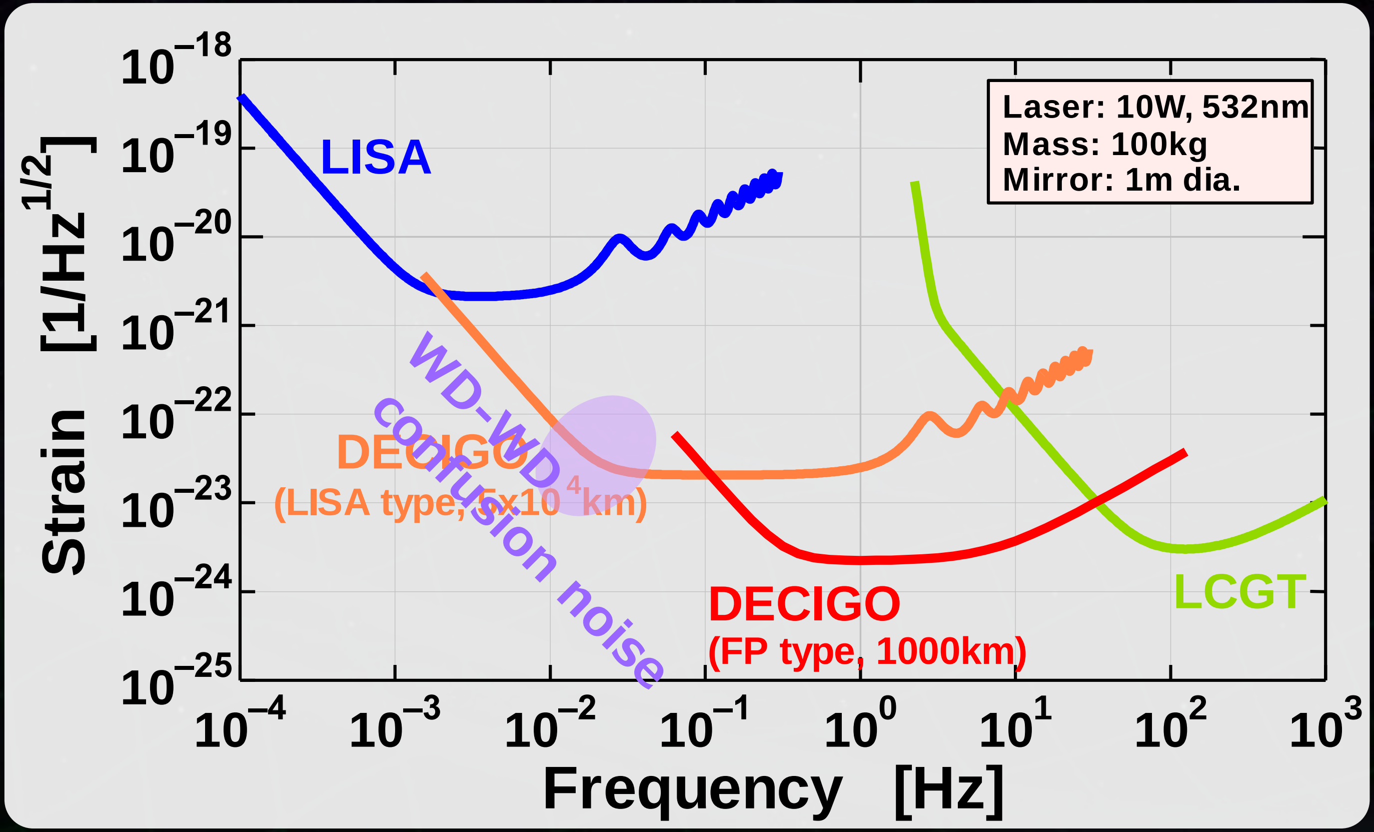
- Target: IMBH, NS binaries.
  GWs around 0.1Hz.
- Baseline : 1000 km.
  Formation flight by 3 S/C.
- Fabry-Perot interferometer.

Interferometer Design

Transponder type vs Direct-reflection type

Compare : Sensitivity curves and Expected Sciences

⇨ Decisive factor: Binary confusion noise



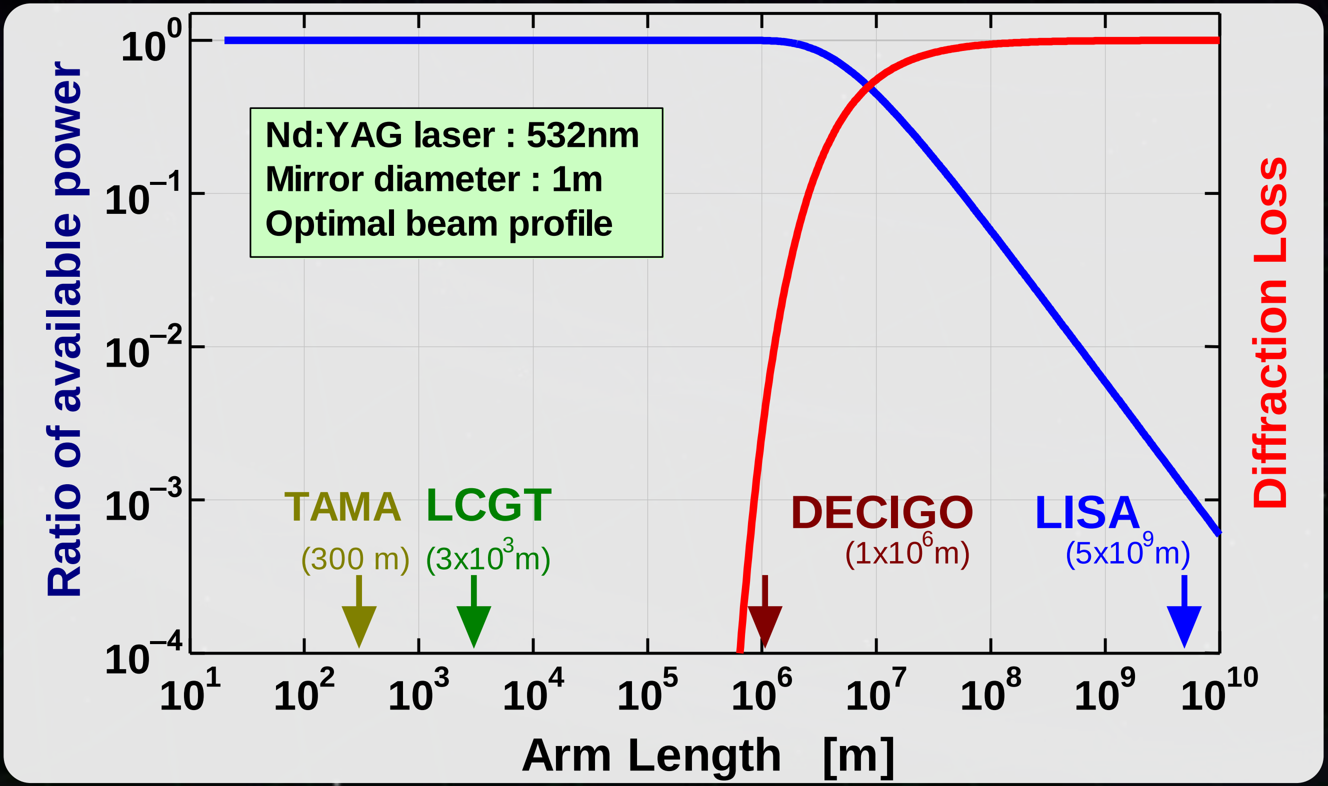
Arm length

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 (+Laser freq.)

Relative motion between mirror and S/C

Local sensor → S/C thruster

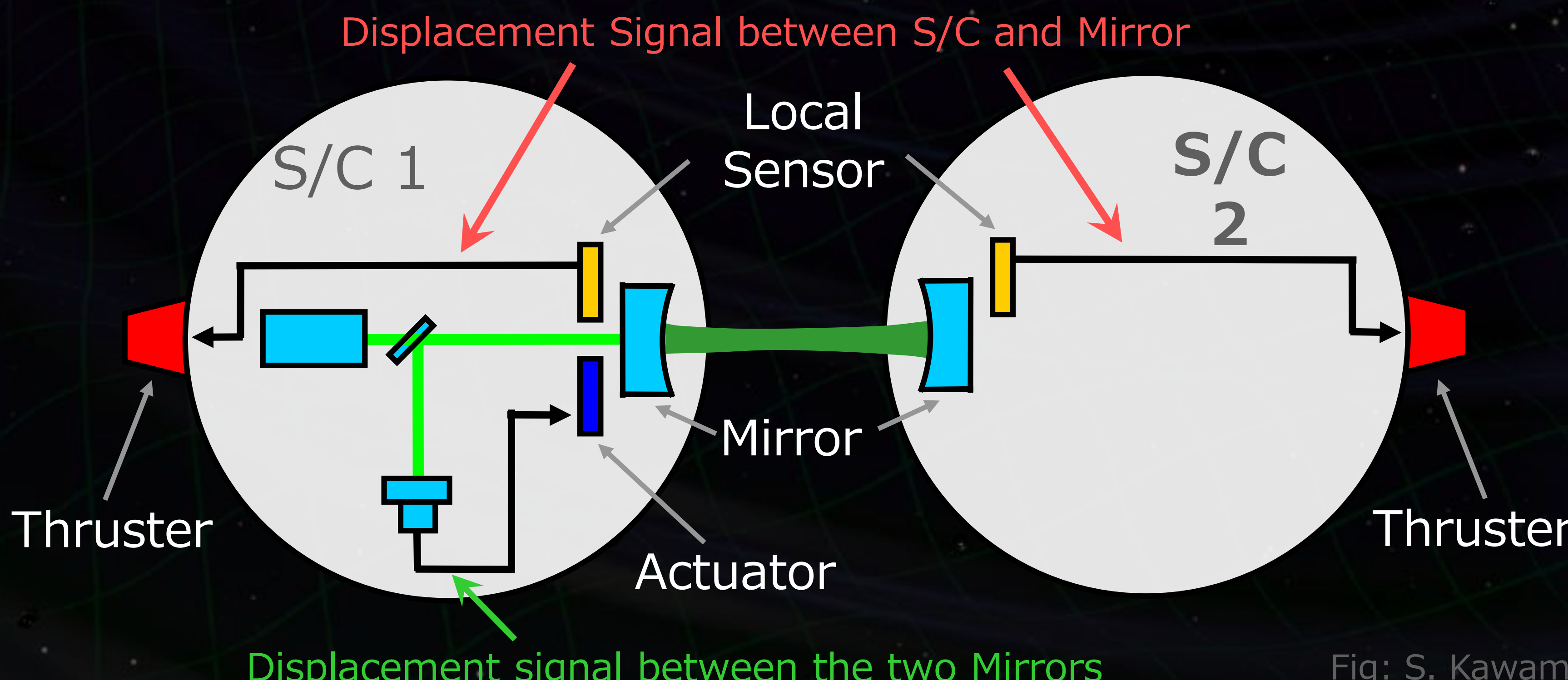


Fig: S. Kawamura

Requirements

DECIGO

Displacement Noise

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

⇨ x 10 of KAGRA 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

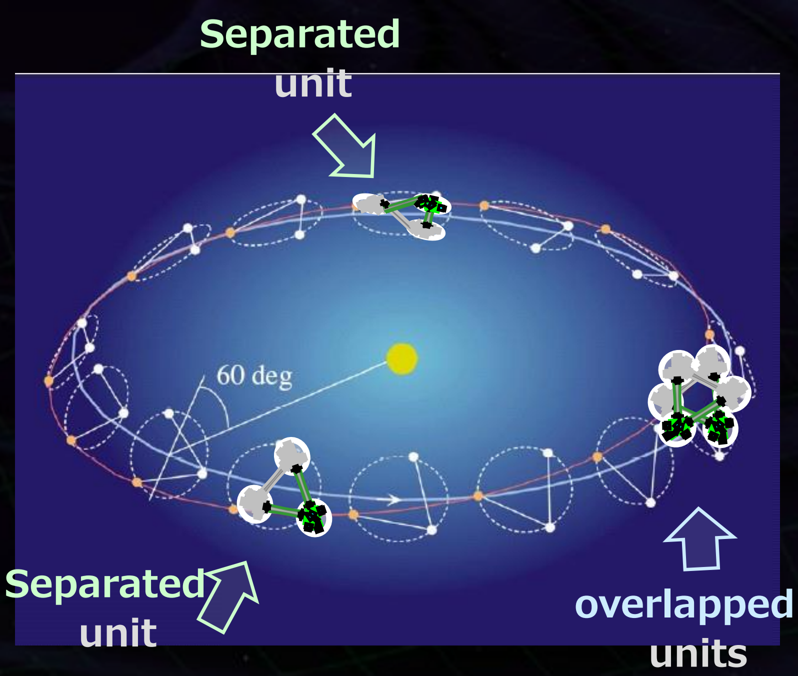
DECIGO

Candidate of orbit:

Record-disk orbit around the Sun

Relative acc. 4×10^{-12} m/s^2

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

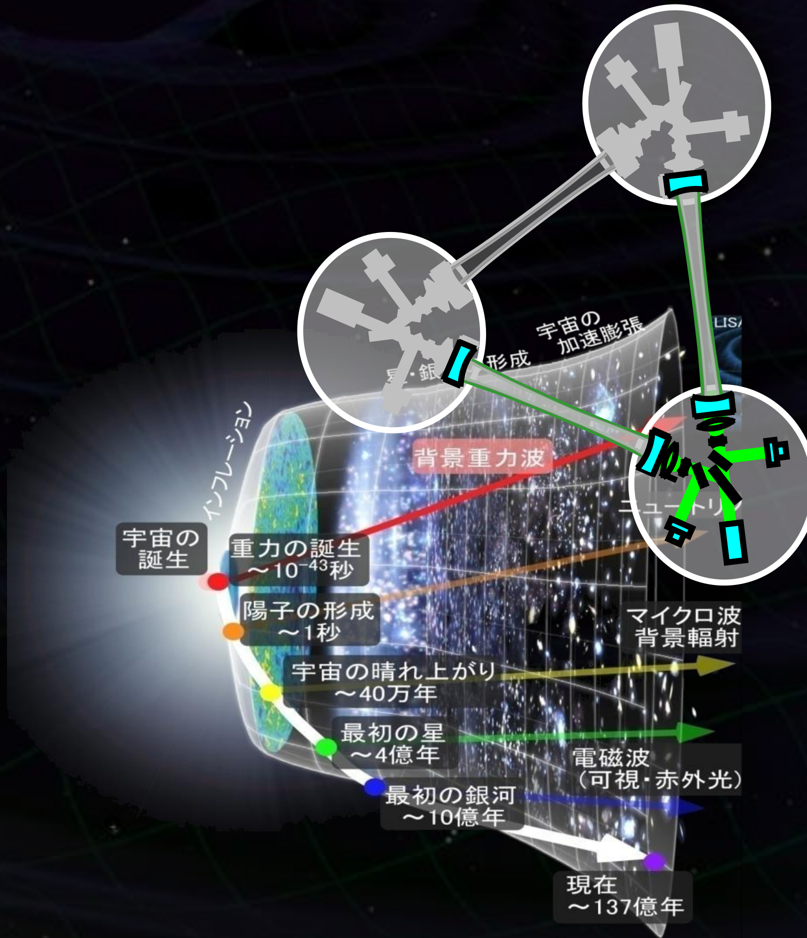


Constellation

4 interferometer units

2 overlapped units → Cross correlation
2 separated units → Angular resolution

B-DECIGO



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マイクロ波
背景輻射
電磁波
（可視・赤外光）
現在
～137億年

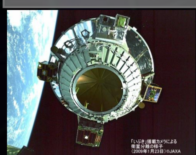
Updated Roadmap for DECIGO

Figure: S.Kawamura

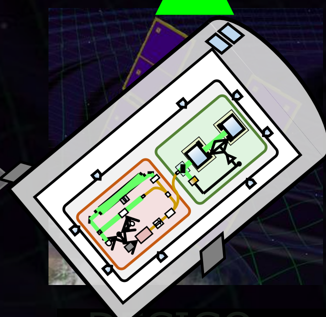
	2014	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33

Mission

R&D Fabrication

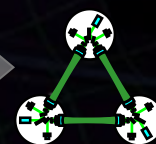


SDS-1/SWIM



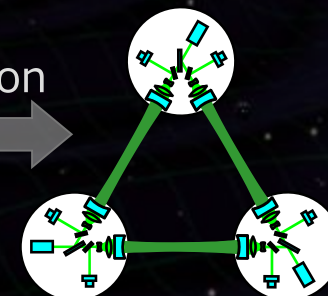
Ground test + Piggy-back opportunity.

R&D Fabrication



B-DECIGO

R&D Fabrication



DECIGO

Purpose	Demonstration and test of space IFO technique	Sciences by GW observation	GW Astronomy and Cosmology
Design	Micro-g experiment FP cavity + Drag-free	3 S/C , 3 arms.	FF with 3 S/C 3-4 IFO units

Space GW Observatory: B-DECIGO

※ We changed the name: Pre-DECIGO → B-DECIGO

- B-DECIGO
  - Space-borne GW antenna formed by three S/C
  - Target Sensitivity for GW : 2×10^{-23} $Hz^{-1/2}$ at 0.1Hz.

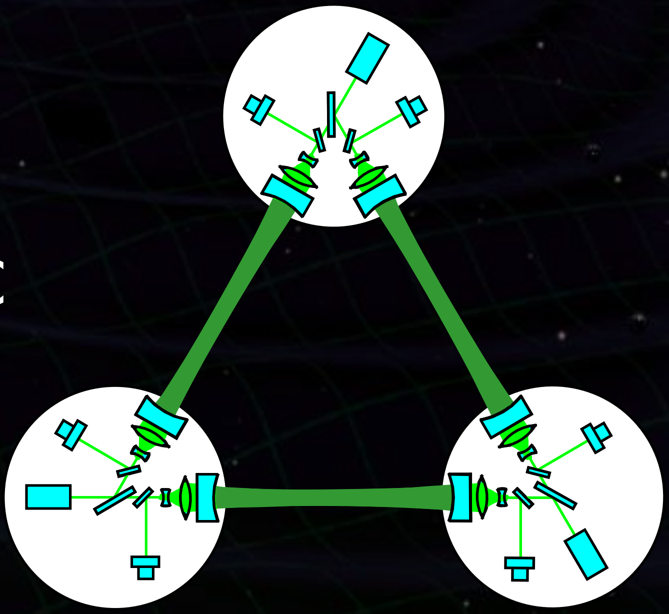
- Sciences of B-DECIGO
  (1) Compact binaries.
  (2) IMBH merger.
  (3) Info. of foregrounds for DECIGO.

Fig. by S.Sato

Target: JAXA Strategic Medium-scale mission (2020s).

B-DECIGO Design (Preliminary)

- Mission Requirement
  - Strain sensitivity of 2×10^{-23} $Hz^{-1/2}$ at 0.1Hz.
  - >3-years observation period.



- Conceptual Design
  - Laser interferometer by 3 S/C
  - Baseline : 100 km
    Laser source : 1W, 515nm
    Mirror : 300mm, 30kg
  - Drag-free and Formation flight.
  - Record-disk orbit around the earth:
    Altitude 2000km, Period ~120min (Preliminary).

Sciences by B-DECIGO

(1) Inspiral of Compact binaries ['Promised' target]

- High rate ~10^6 binaries/yr.
- Estimation of binary parameters and merger time.

→ Astronomy by GW only and GW-EM observations.

(2) Inspirals and mergers of IMBHs [Original science]

- Cover most of the universe.

→ Formation history of SMBH and galaxies.

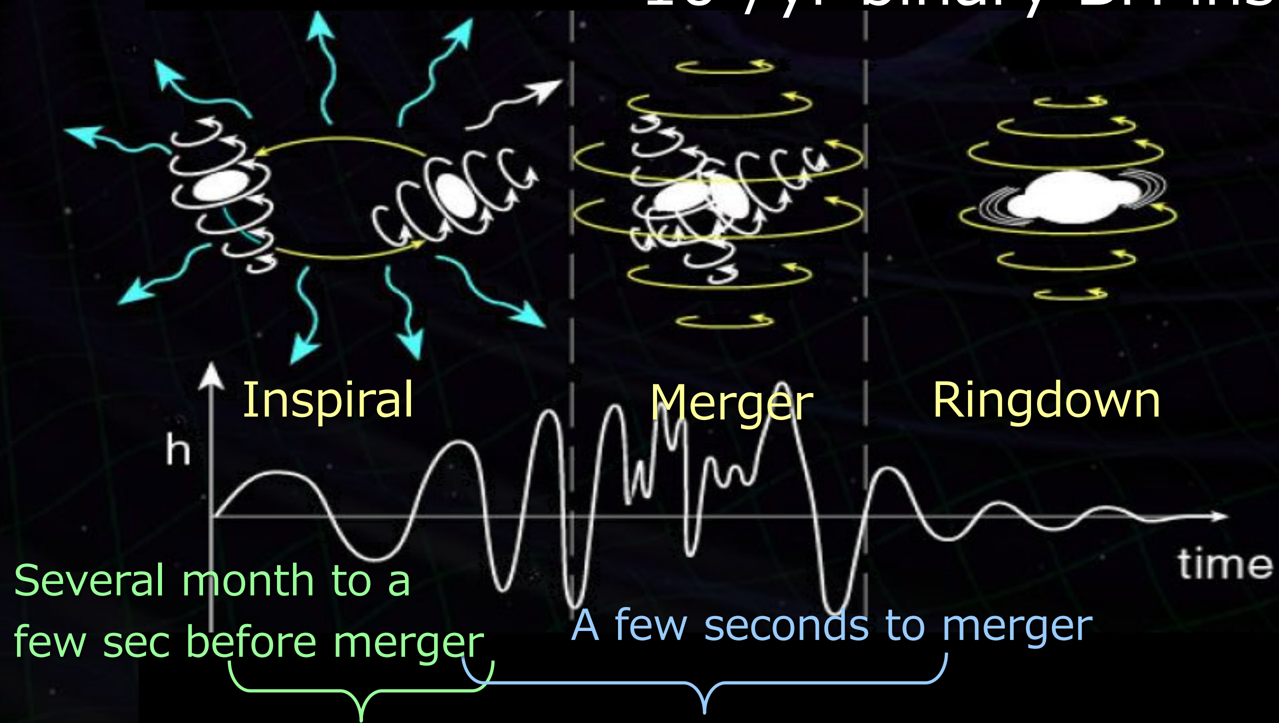
(3) Foreground understandings for DECIGO [Cosmology]

- Parameter estimation and subtraction of binaries.
- Characteristics of foreground.
- Is the any eccentric binaries?

Target (1) : Compact Binaries

B-DECIGO will observe >100/yr binary NS inspirals.

$\sim 10^6$/yr binary BH inspirals.

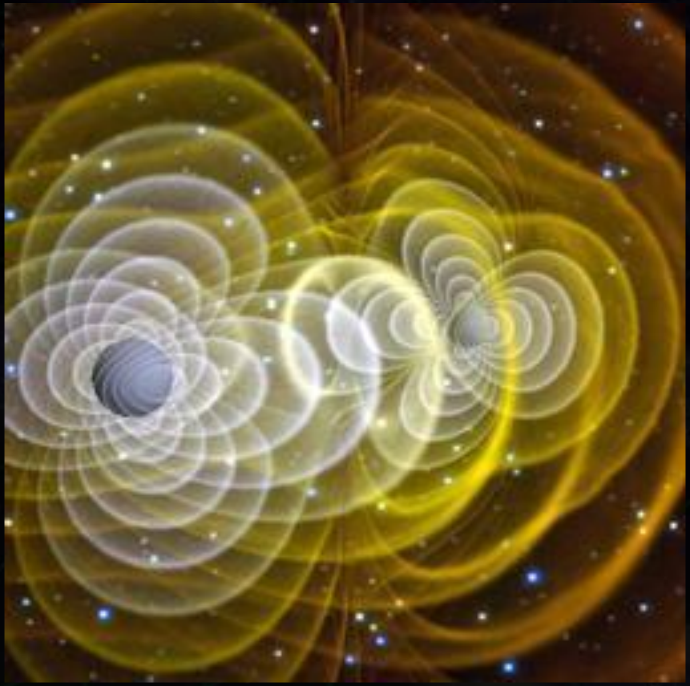


Low.-freq. → B-DECIGO
Mass, Position, Time,⋯

High-freq. → Ground based
Astrophysics, EoS of NS

Target (2) : Intermediate-mass BH Merger

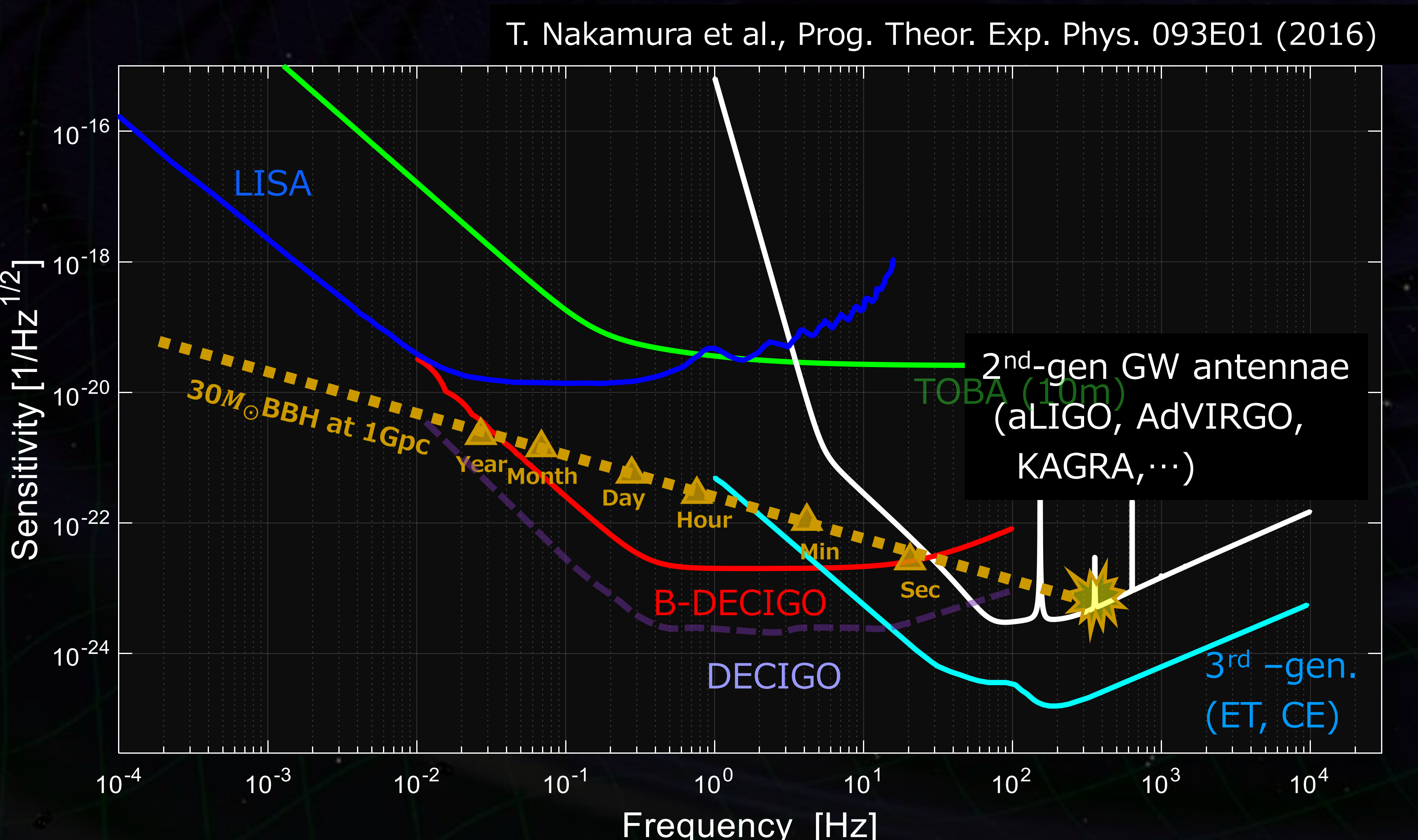
B-DECIGO will see almost the whole Universe.



The mystery on the history of SMBH at the center of Galaxies:
(A) Large BH + Accretion
(B) Hierarchical merger

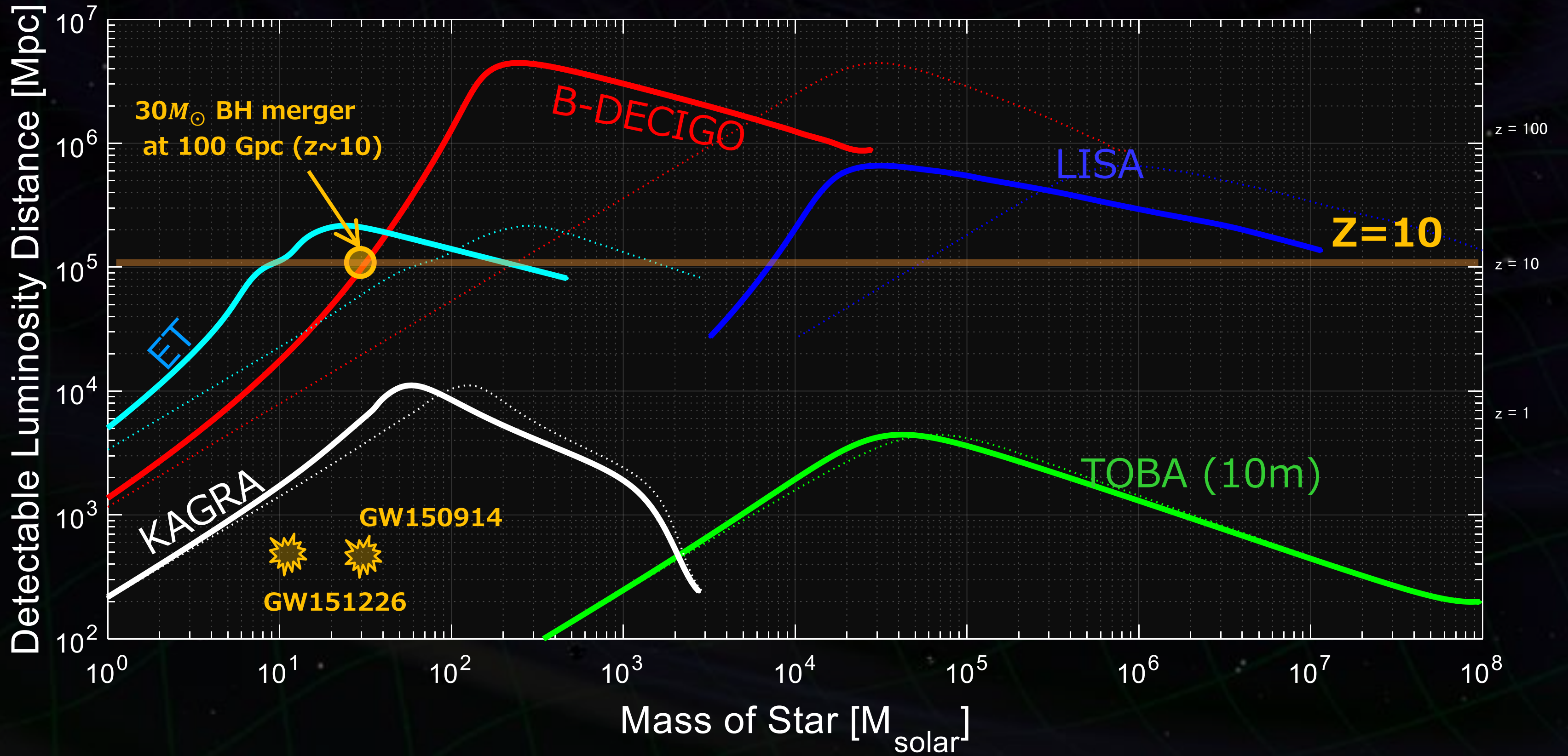
- B-DECIGO can pin-down the story.
- Original observation.

Sensitivity Curves



Observable Range

$30M_\odot$ BBH Merger : 100 Gpc (z>10) range
with SNR~8 (optimal direction/polarization).

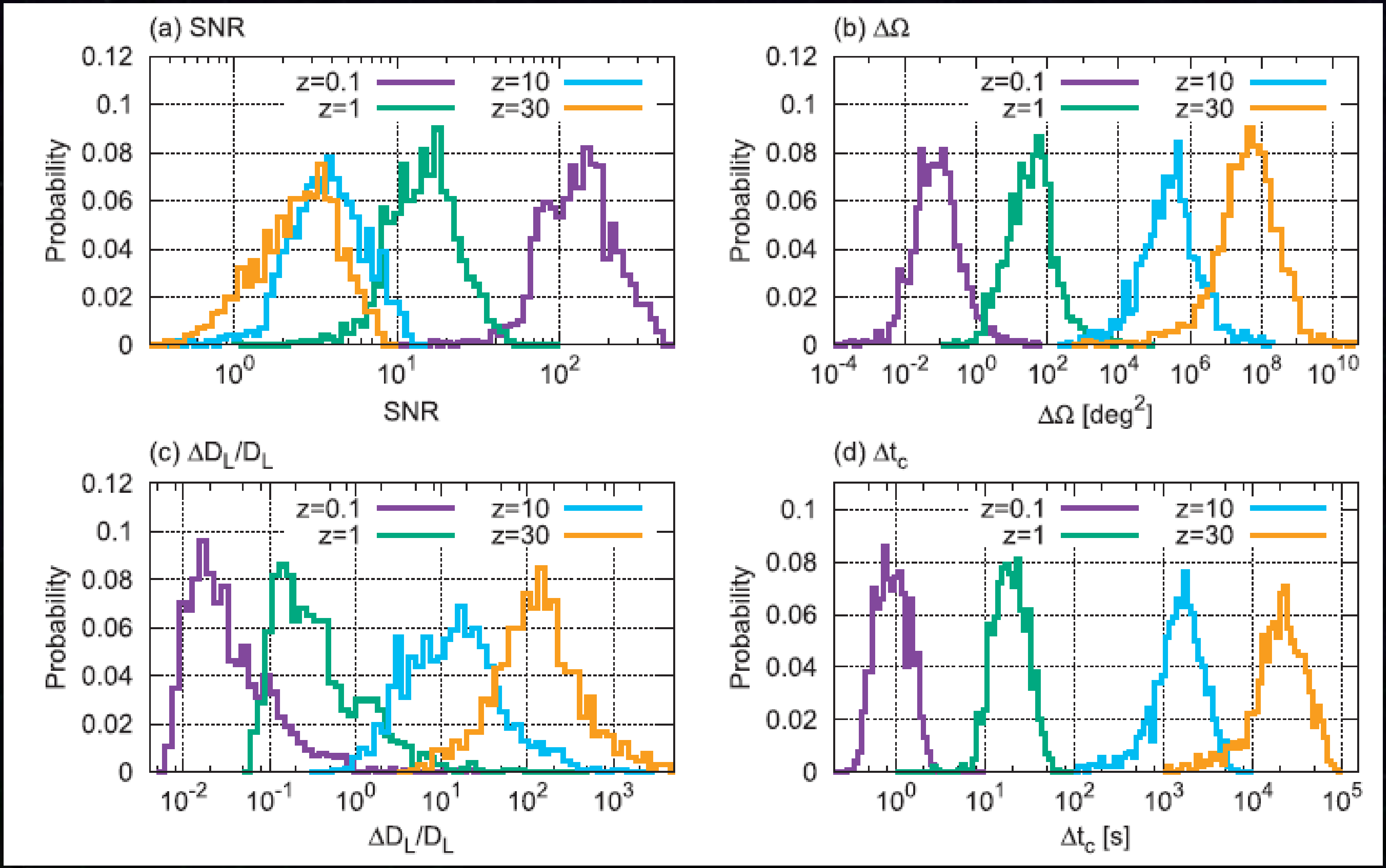


B-DECIGO Sciences for CBC

DECIGO

- With its BBH observable range, in B-DECIGO
  Detection Rate will be $\sim 4 \times 10^4 - 10^6$ events/yr .
  → Possible to identify the origin of BBH :
  Pop-III, Pop-I/II, or Primordial BH.
- Range for BNS is ~2Gpc → Higher rate expected.
- With low-freq. GW observations, longer observation time is expected; in $30M_{\odot}$ BBH merger case, the signal is at 0.1Hz in 15days before merger.
  → Improved parameter estimation accuracy with lager cycle number ($\sim 10^5$) :
  * Localization, Merger time → Alerts for GW-EM.
  * Mass, Distance, Spin → Origin and nature of BBH.

Parameter Estimation Accuracy

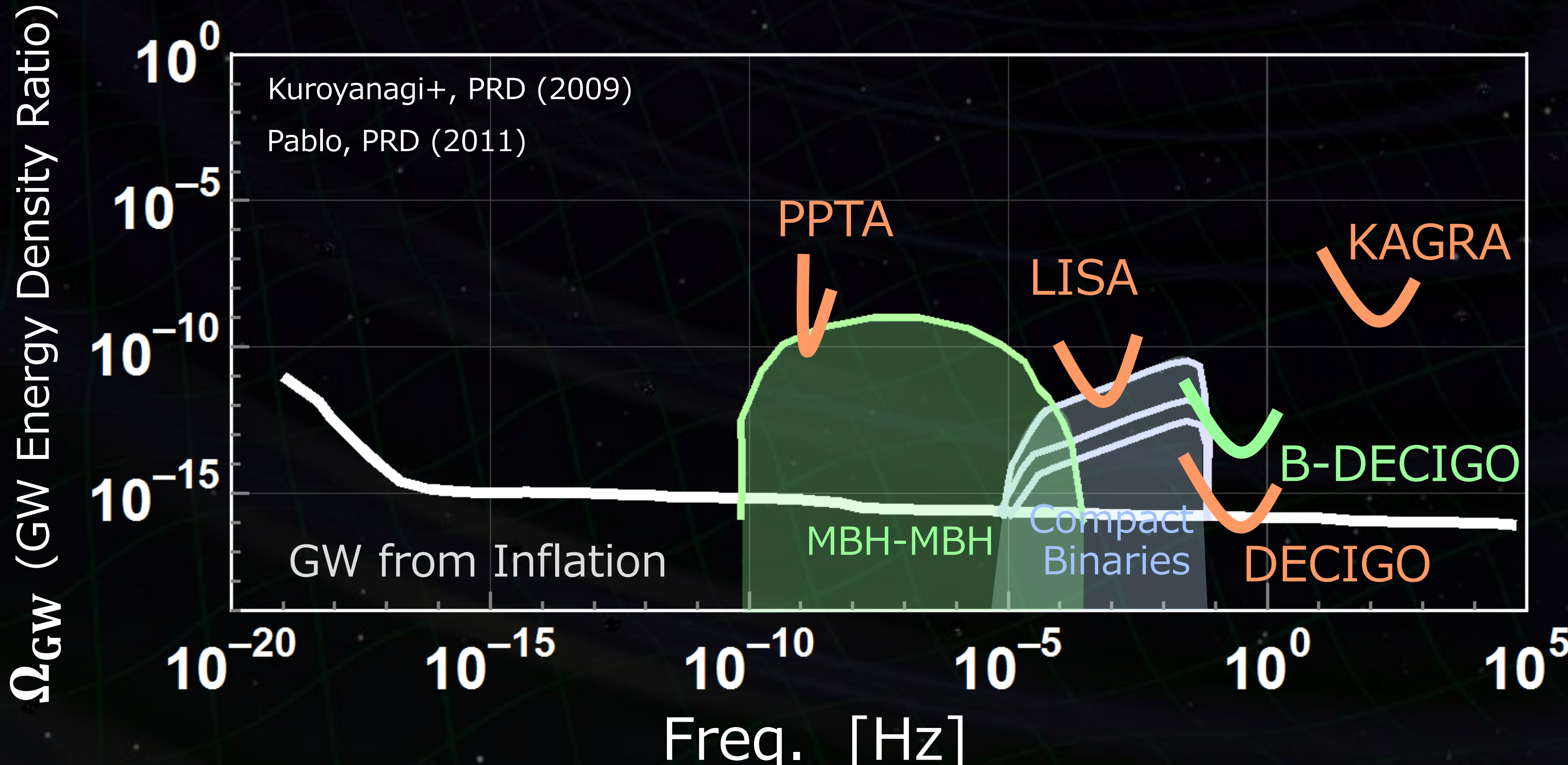


T. Nakamura et al., Prog. Theor. Exp. Phys. 093E01 (2016)

Target (3) : Foreground Understandings

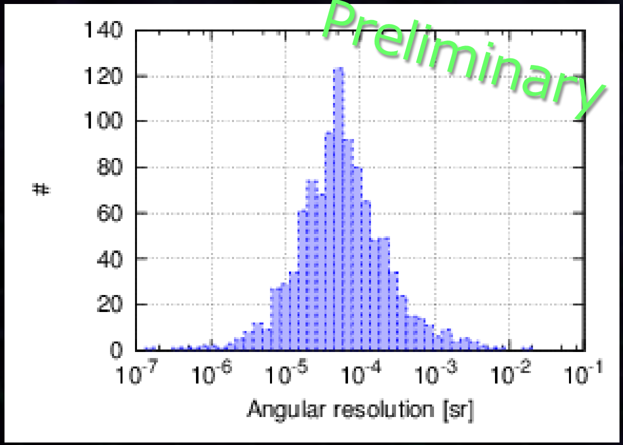
In future DECIGO, unresolvable GWs by many binaries can be a foreground for primordial GW obs.

⇨ Gain understandings with >100 binaries.



Current Issues on B-DECIGO

- Parameter estimation accuracy.
  Quantitative evaluation of the B-DECIGO performance:
  Mass, Sky position, Merger time, Inclination, Distance, Spin,….



Preliminary results by K.Eda

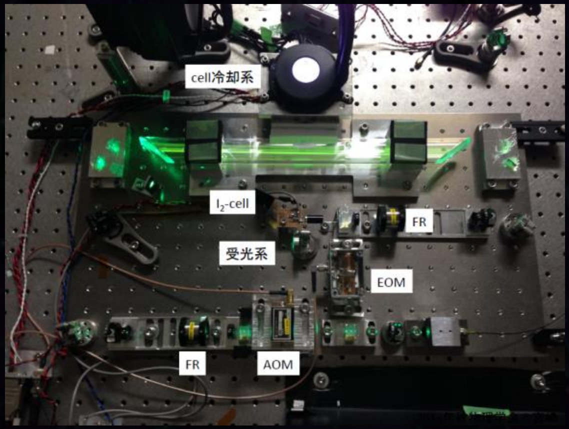
- Data analysis scheme:
  Parameter estimation and subtraction,⋯.
- Antenna Design:
  Orbit, Interferometer design, Acceleration noise, Formation flight and Control Scheme, ⋯

Technical Challenges

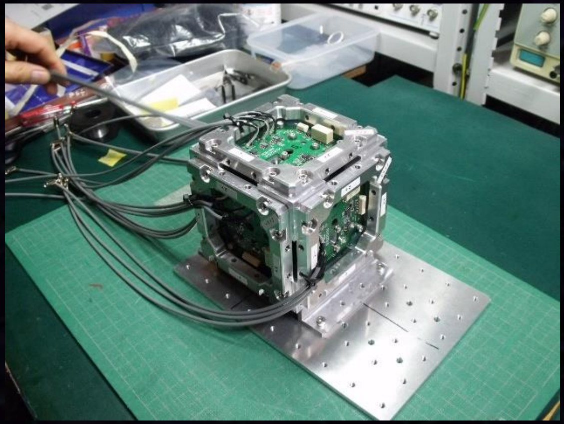
- Long-baseline Interferometry (Disp. < 2×10^{-18} m/Hz$^{1/2}$)
  - Optical configuration for IFO, and laser source.
  - 100km Fabry-Perot cavity (Large RoC, Distortion).
  - Initial attitude acquisition.
- Force Noise (Force noise < 1×10^{-16} N/Hz$^{1/2}$)
  - Gravity, EM force, Residual gas, thermal radiation, Cosmic ray, control noise, etc..
- Satellite control
  - Drag-free, Low-noise thruster, Signal processing.
- Satellite System Design
  - Orbital Design, Initial Mission sequence.
  - Resource distribution, Launcher, Cost estimation.

Technical Developments

Stabilized Laser Source

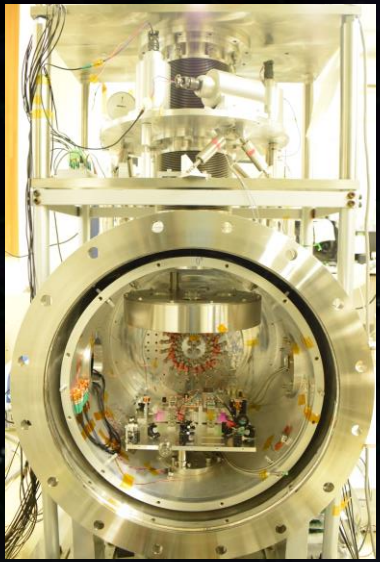


Test-mass Module

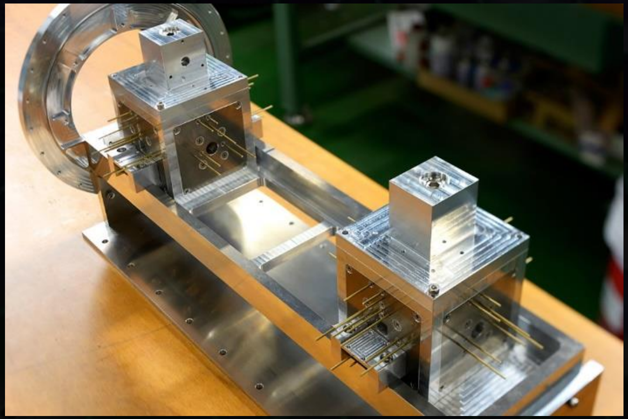


Drag-free demo.

Force Noise



Interferometer

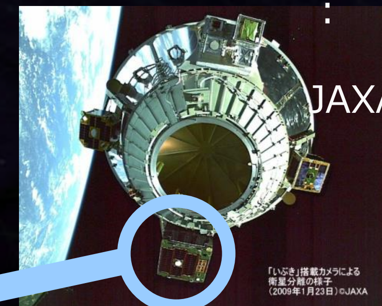


Thruster Noise

Space Demonstration by SWIM

DECIGO

Photo : JAXA



SDS-1/SWIM (Space wire demonstration module)

Launch in Jan. 2009, Terminated in Sept. 2010

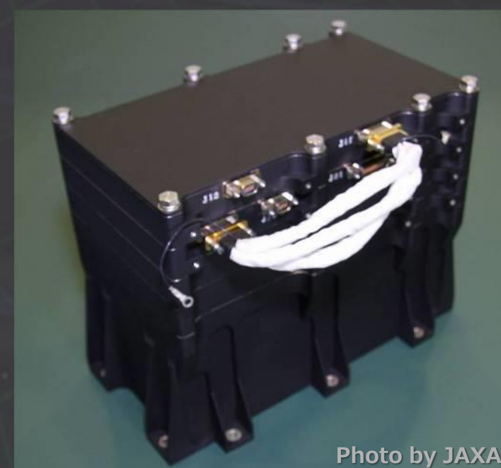
⇨ 1st Space GW antenna (?)

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

SWIMmn : 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

SDS-1 Bus System

Power +28V
RS422 for CMD/TLM
GPS signal

Power ±15V, +5V
SpW x2 for CMD/TLM

SWIMμν

DECIGO

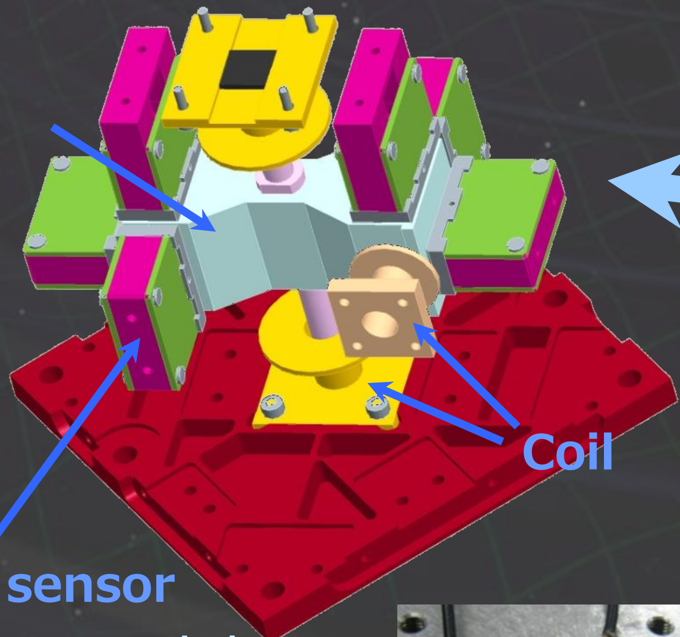
Tiny Space GW antenna (Torsion-bar antenna)

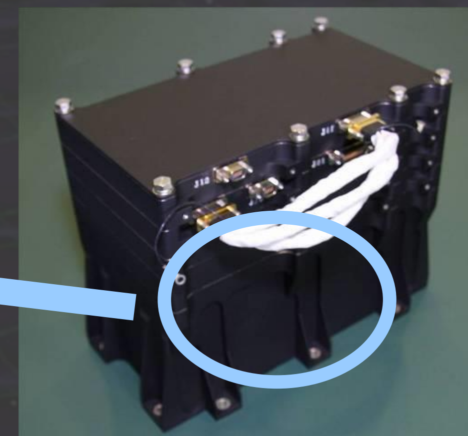
Photo : JAXA

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

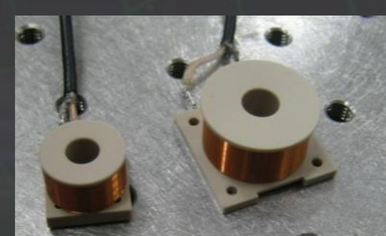




Coil

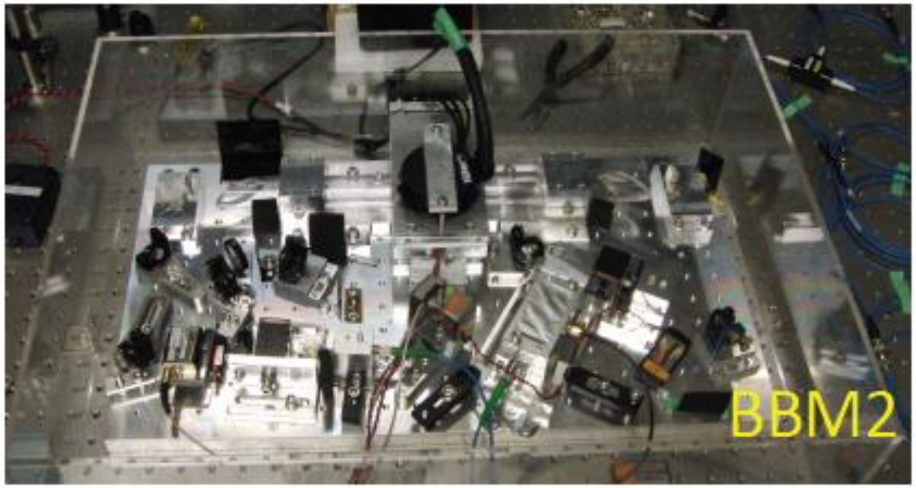
Photo sensor

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



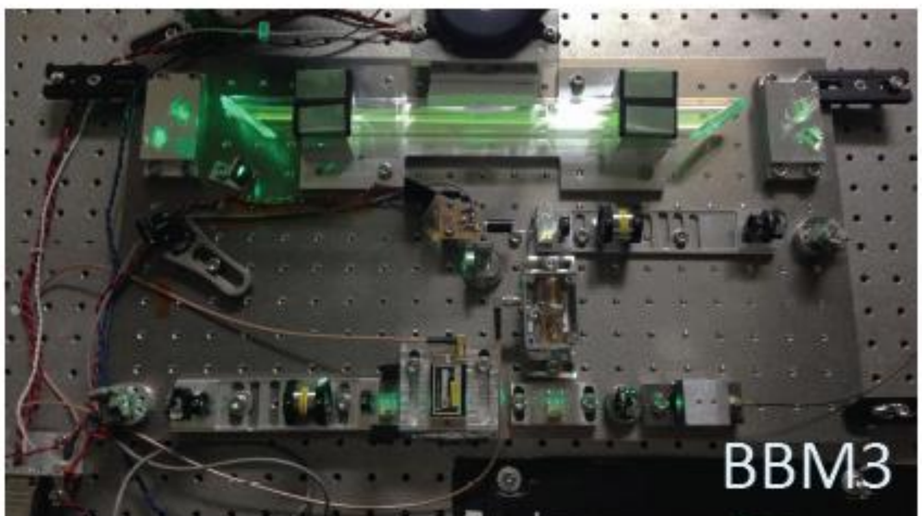
Stabilized Laser Source (1/3)

DECIGO



- Light source : Yb-fiber DFB laser (Koheras AdjusteK Y10)
- light source part consists of fiber components (inline PBS, inline PC)

Size : 550x300 mm (aluminum breadboard)

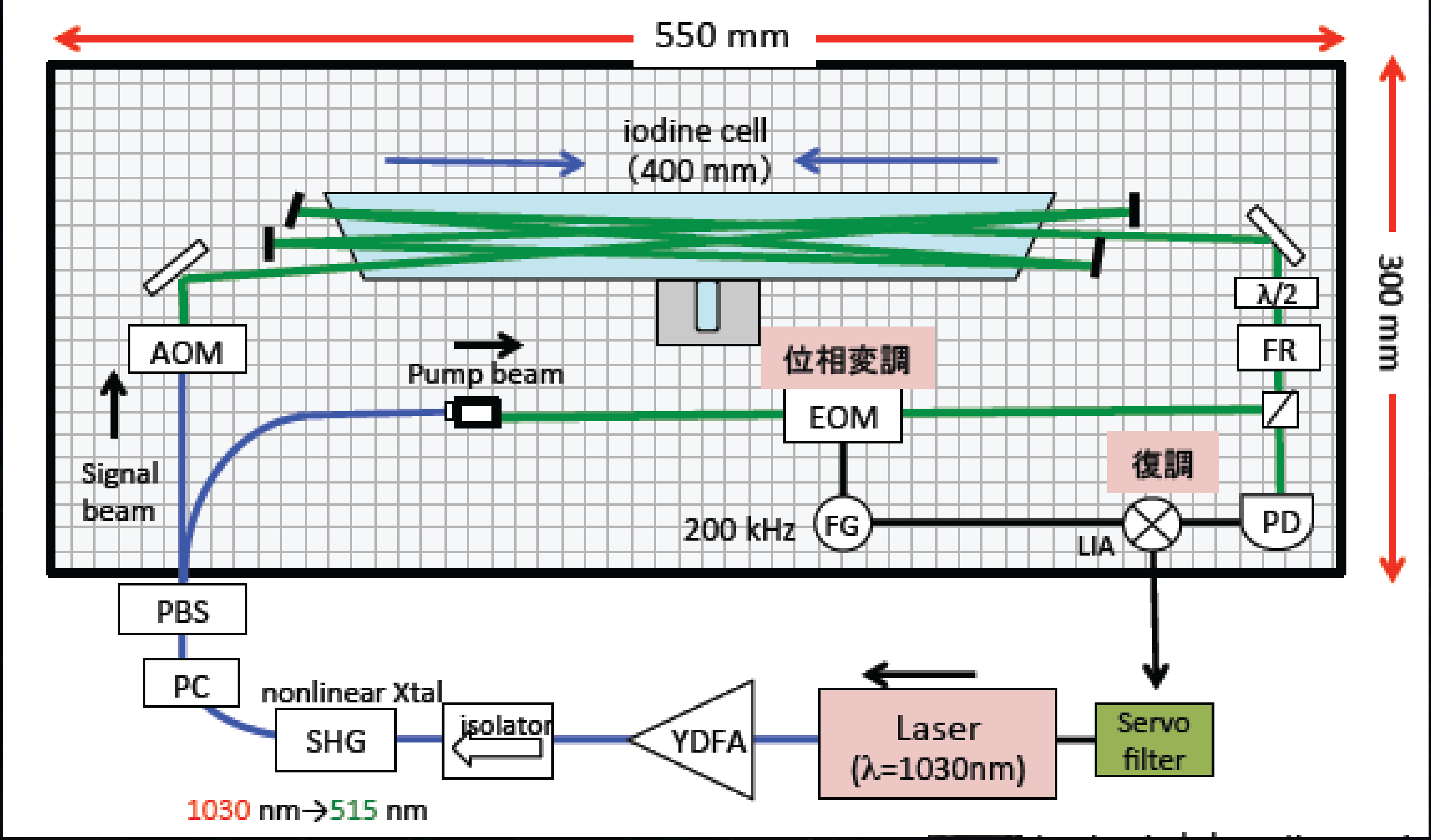


- Light source: Yb:fiber DFB laser (The Koheras BasiK^{TM} Y10)
- beam expander is mounted to suppress the TOF broadening effect
- monolithic optical bases is introduced

Stabilized Laser Source (2/3)

Stabilized Laser Source : BBM2

Fig. by A.Suemasa



Stabilized Laser Source (3/3)

BBM2 BBM3

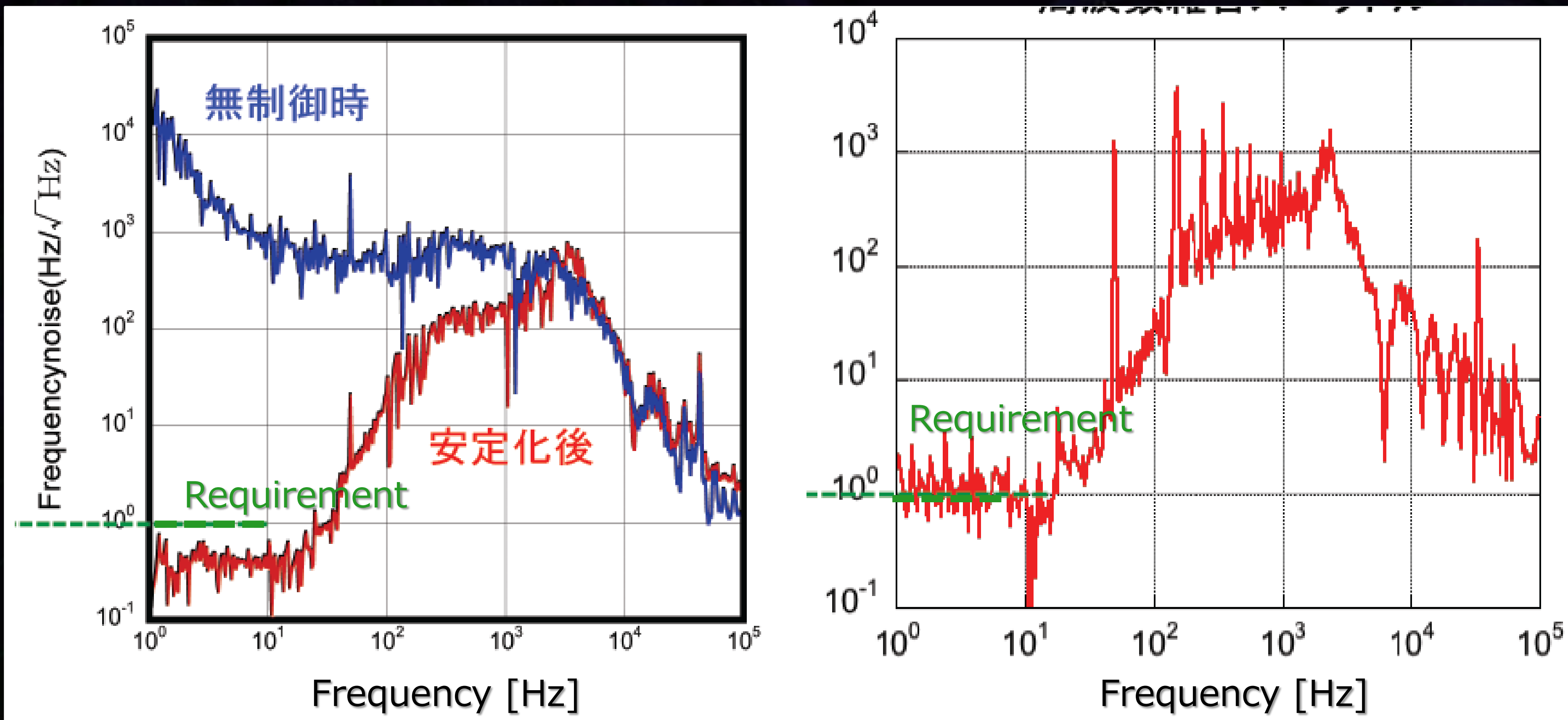


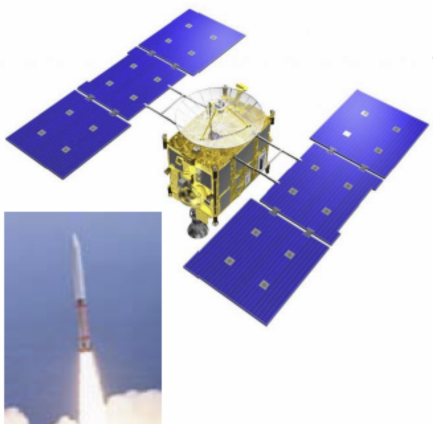
Fig. by A.Suemasa

JAXA Roadmap

内閣府・宇宙政策委員会・宇宙科学・探査部会 資料より (2013年9月19日).

Ⅲ. 今後の宇宙科学・探査プロジェクトの推進方策

宇宙科学における宇宙理工学各分野の今後のプロジェクト実行の戦略に基づき、厳しいリソース制約の中、従来目指してきた大型化の実現よりも、中型以下の規模をメインストリームとし、中型(H2クラスで打ち上げを想定)、小型(イプシロンで打ち上げを想定)、および多様な小規模プロジェクトの3クラスのカテゴリーに分けて実施する。



2000年代前半までの
典型的な科学衛星ミッション
M-Vロケットによる打ち上げ

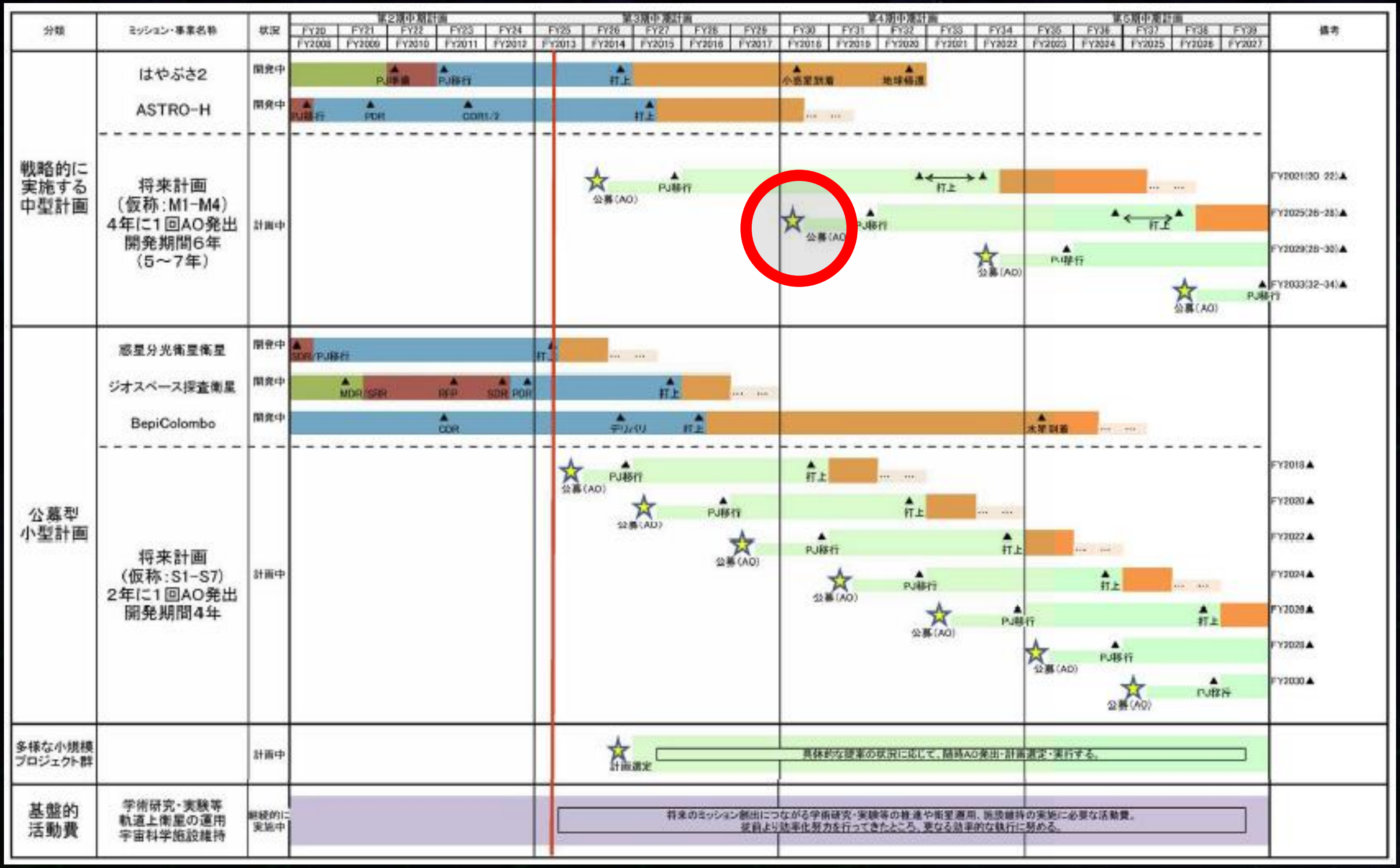
戦略的に実施する中型計画(300億程度)
世界第一級の成果創出を目指し、各分野のフラッグシップ的なミッションを日本がリーダとして実施する。
多様な形態の国際協力を前提。

公募型小型計画(100-150億規模)
高頻度な成果創出を目指し、機動的かつ挑戦的に実施する小型ミッション。地球周回/深宇宙ミッションを機動的に実施。現行小型衛星計画から得られた経験等を活かし、衛星・探査機の高度化による軽量高機能化に取り組む。等価な規模の多様なプロジェクトも含む。

多様な小規模プロジェクト群(10億/年程度)
海外ミッションへのジュニアパートナとしての参加、海外も含めた衛星・小型ロケット・気球など飛翔機会への参加、小型飛翔機会の創出、ISSを利用した科学研究など、多様な機会を最大に活用し成果創出を最大化する。

JAXA Roadmap

From file submitted to the government by ISAS/JAXA
(内閣府・宇宙政策委員会・宇宙科学・探査部会　2013年9月19日).



Summary

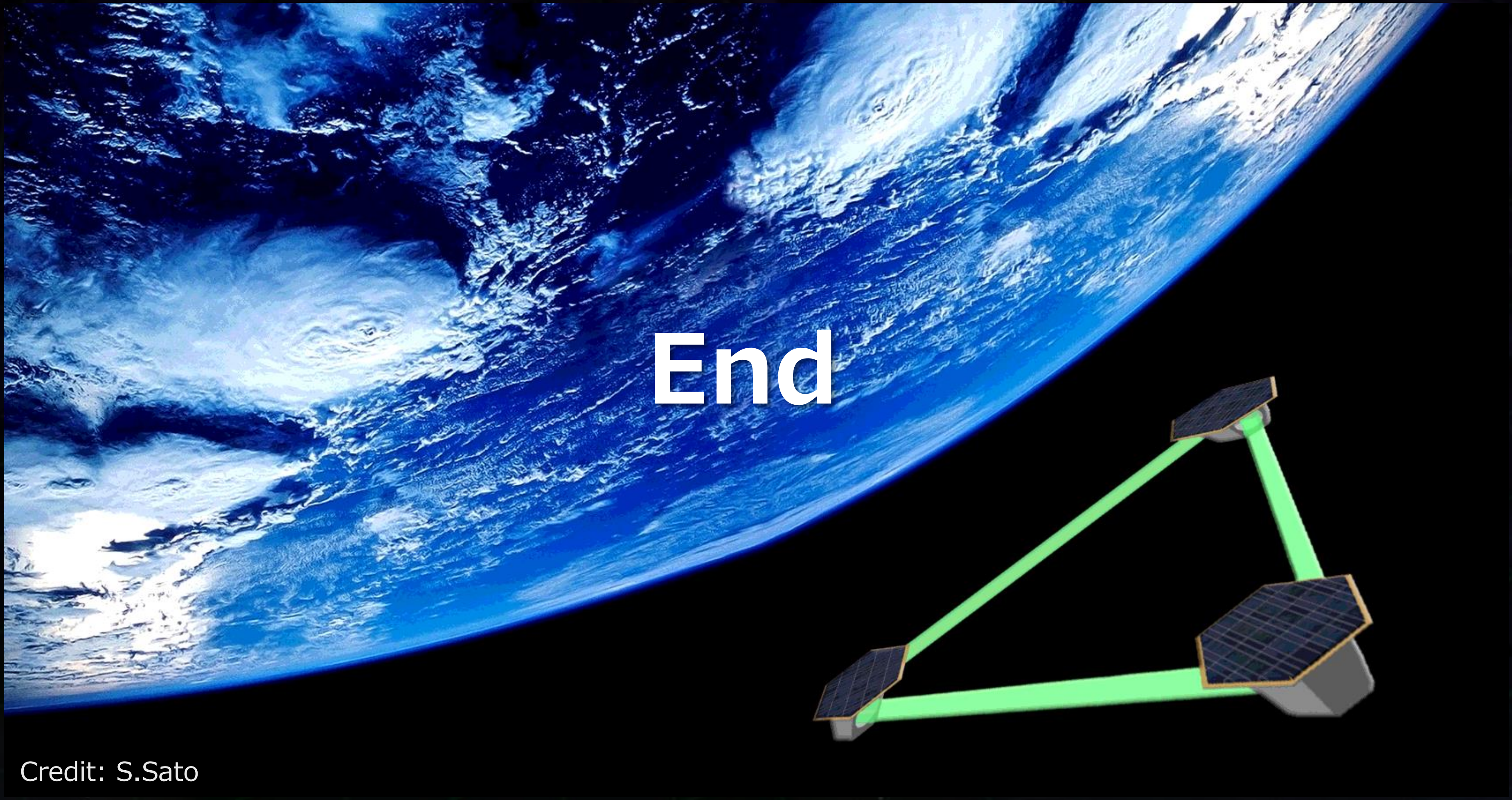
Summary

DECIGO : Huge Sciences

*Direct observation of very beginning of the Universe
*Dark energy, Dark matter
*Galaxy formation
→ Will be realized at last.

B-DECIGO : Fruitful and Original Sciences

*A lot of sciences on compact binaries:
GW150914-like events and BNS events.
*Observation of IMBH mergers.
*Understandings of foreground for DECIGO.


End
Credit: S.Sato