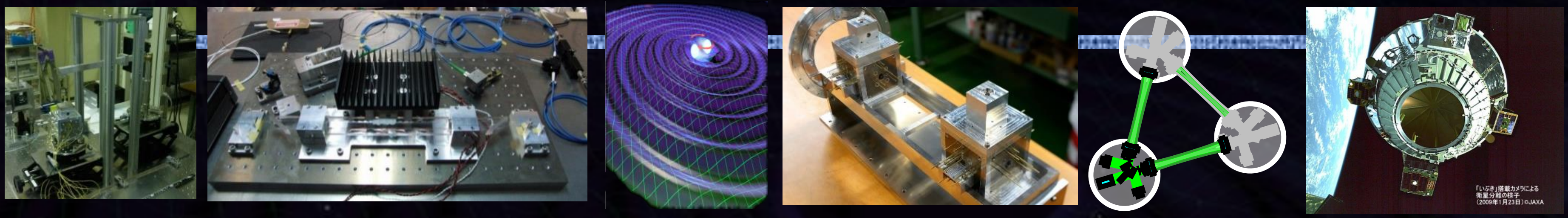


「いぶき」搭載カメラによる
衛星分離の様子
（2009年1月23日）©JAXA

Possibility of contribution to ESA L3 from Japan

※ This is not an officially qualified report form JAXA. This is presented from Ando’s personal viewpoint as a representative of the Japanese space GW community.

Masaki Ando (Univ. of Tokyo / NAOJ)

※ Previous JGWC chairperson, DPF WG leader,
Member of JAXA space science committee

ESA L3 GOAT#5 (September 17th, 2015, Noordijk, NL)

Summary

- JAXA-ISAS encourages international collaboration in general.
  - Sending person to ESA L1-L3 discussions.

- Informal discussion with Saku Tsuneta (Director General of JAXA-ISAS) on possibility to join ESA L3 (July 31th).
  → - Encourages bottom-up proposals from the community.
  - Suggested a presentation from community view points in GOAT #5.

- Japanese space GW community has been working on DECIGO and its precursor missions. Redefined the strategy in 2014. → Possibility to be a LISA Junior partner.

- JAXA Mission Opportunities
- Activities in Japan
- Conclusion

JAXA-ISAS Mission Opportunities

- Three categories in JAXA's
  'Space Science and Exploration program' (2014)

(1) Medium-scale missions
(Astro-H, Solar-C, Hayabusa2, ESA JUICE, ATHENA, …)
- Cost ~$300M, Development term 5-7 years.
- AO every 4 years.

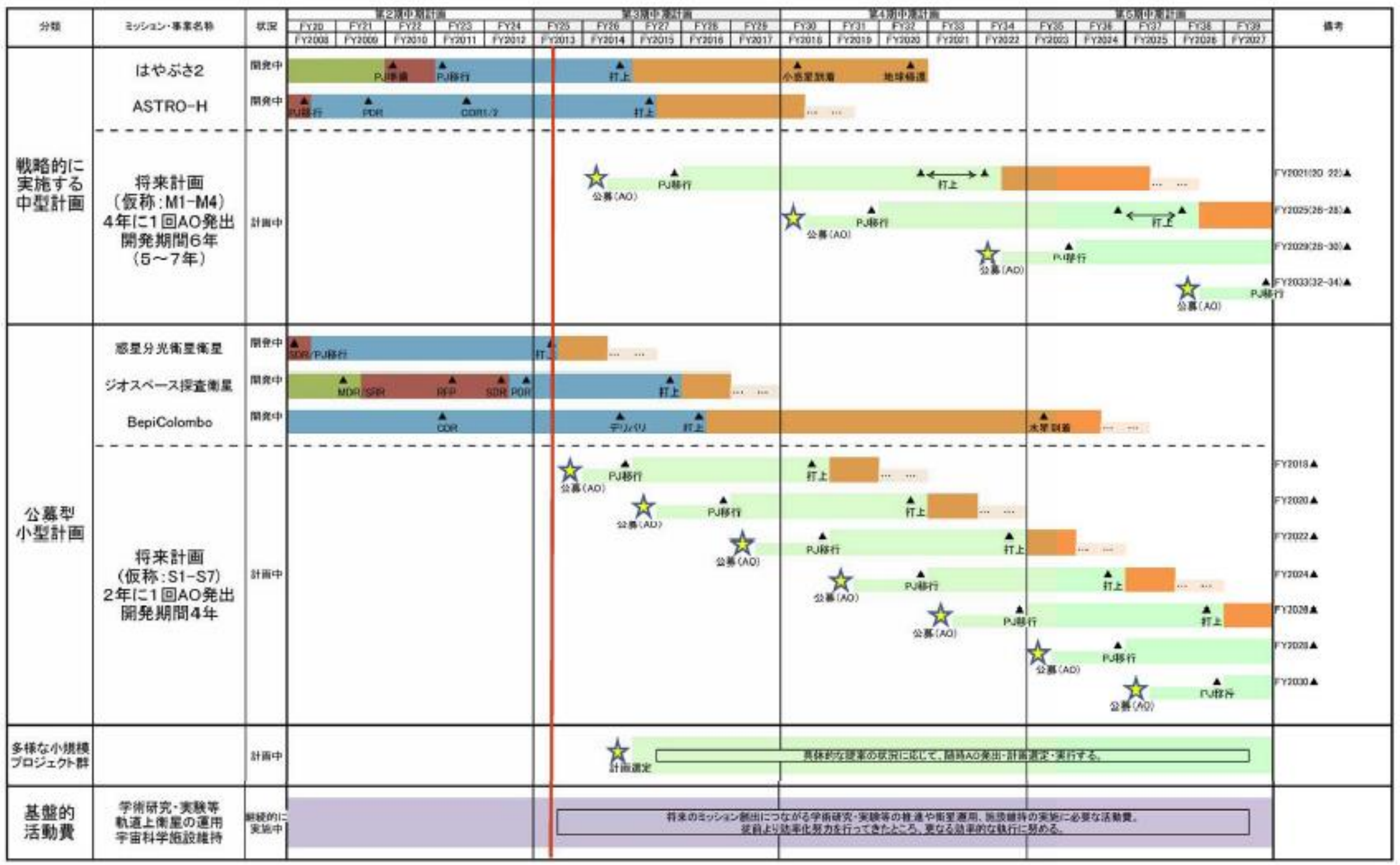
(2) Small-scale missions (Hisaki, ERG, …)
- Cost $100M~$150M, Development term 4 years.
- AO every 2 years.

(3) Various small projects
- Small rocket, Balloon, International Junior partner, Science mission using ISS, …
- ~$10M/year.

Mission Plan by JAXA

From file submitted to the government by ISAS/JAXA

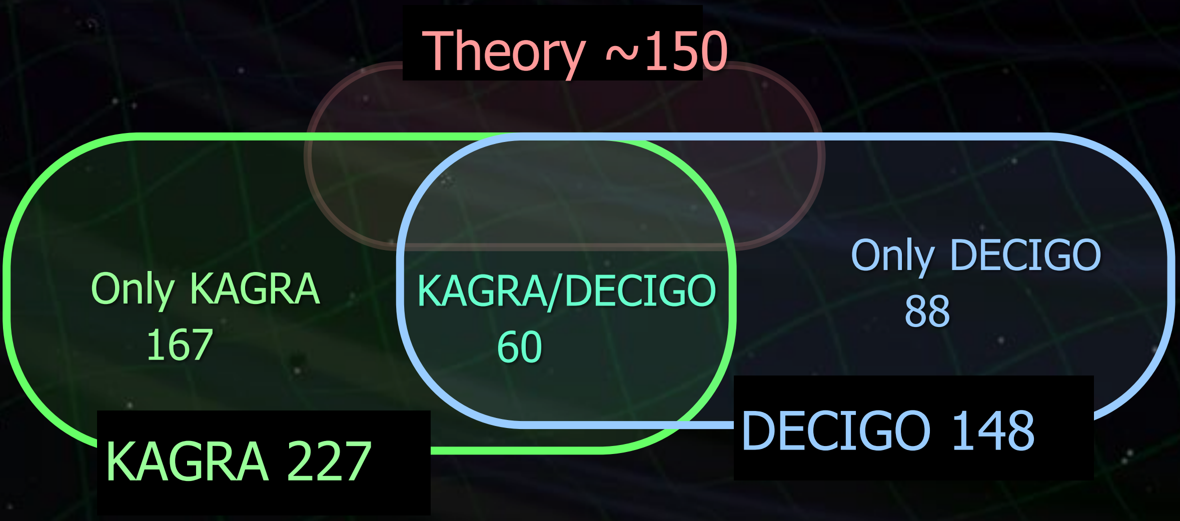
(内閣府・宇宙政策委員会・宇宙科学・探査部会 2013年9月19日).



- **JAXA Mission Opportunities**
- **Activities in Japan**
- **Conclusion**

Japanese GW Community

- JGWC (Japan Gravitational Wave Community) :
  - 325 members (in 2014)
  - Information exchange
    (conferences, announcement of new position, …)
  - Discuss future strategy



KAGRA and DECIGO

KAGRA **(~2017)**

Ground-based Detector

→ High-freq. (100Hz) GW event

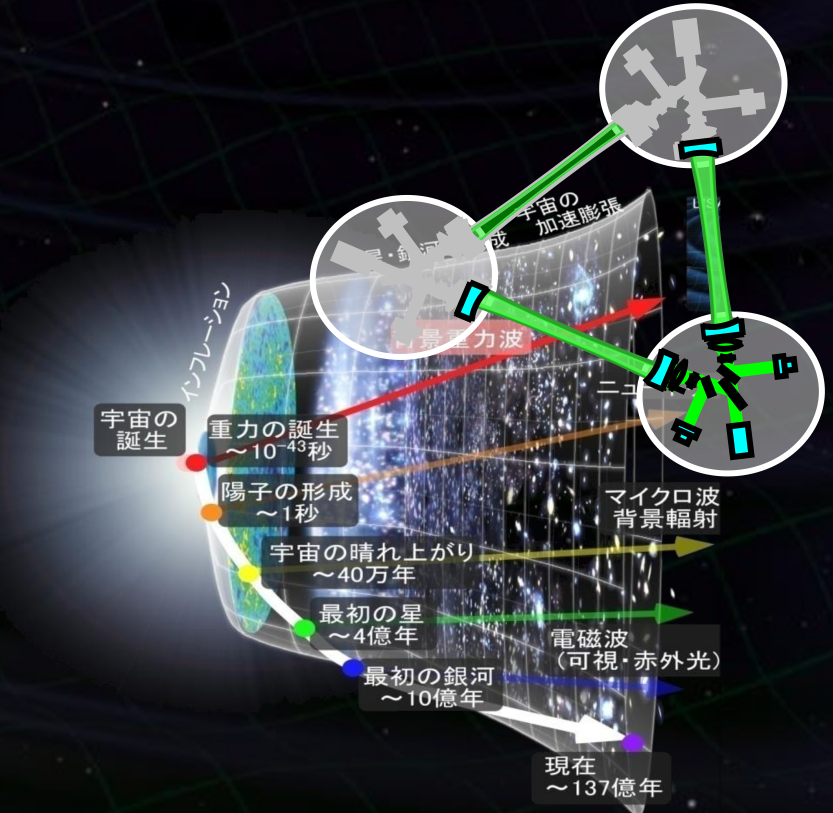
Target: Detection and Astronomy

DECIGO **(~2030)**

Space observatory

→ Low-freq. (0.1Hz) GW signal

Target: Cosmology



Space GW Antenna DECIGO

DECIGO (DECI-hertz interferometer Gravitational wave Observatory)

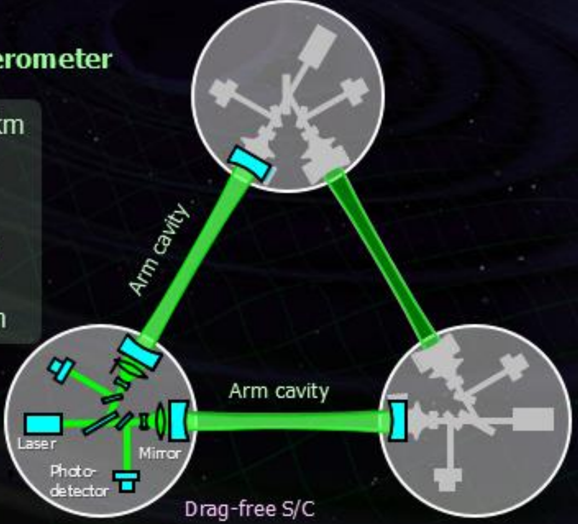
Purpose: To Obtain Cosmological Knowledge.

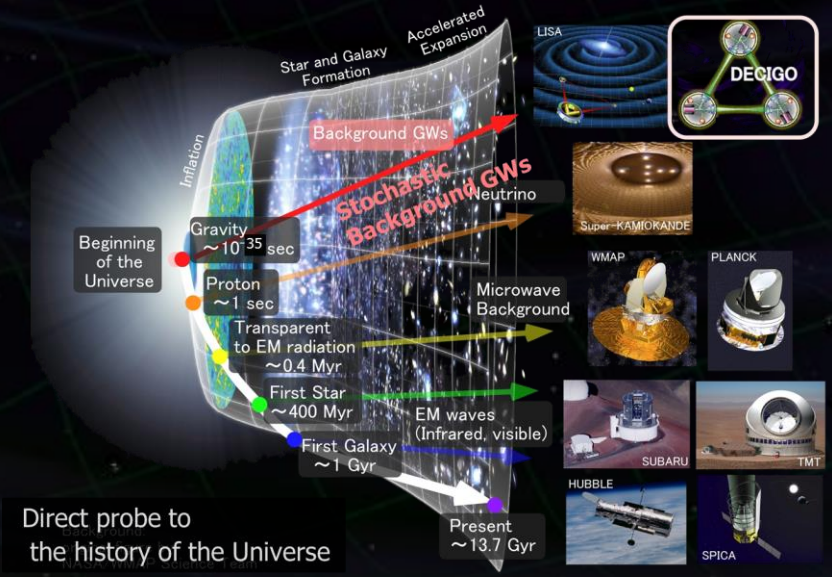
Direct observation of the origin of space-time and matter in Big-bang Universe.

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





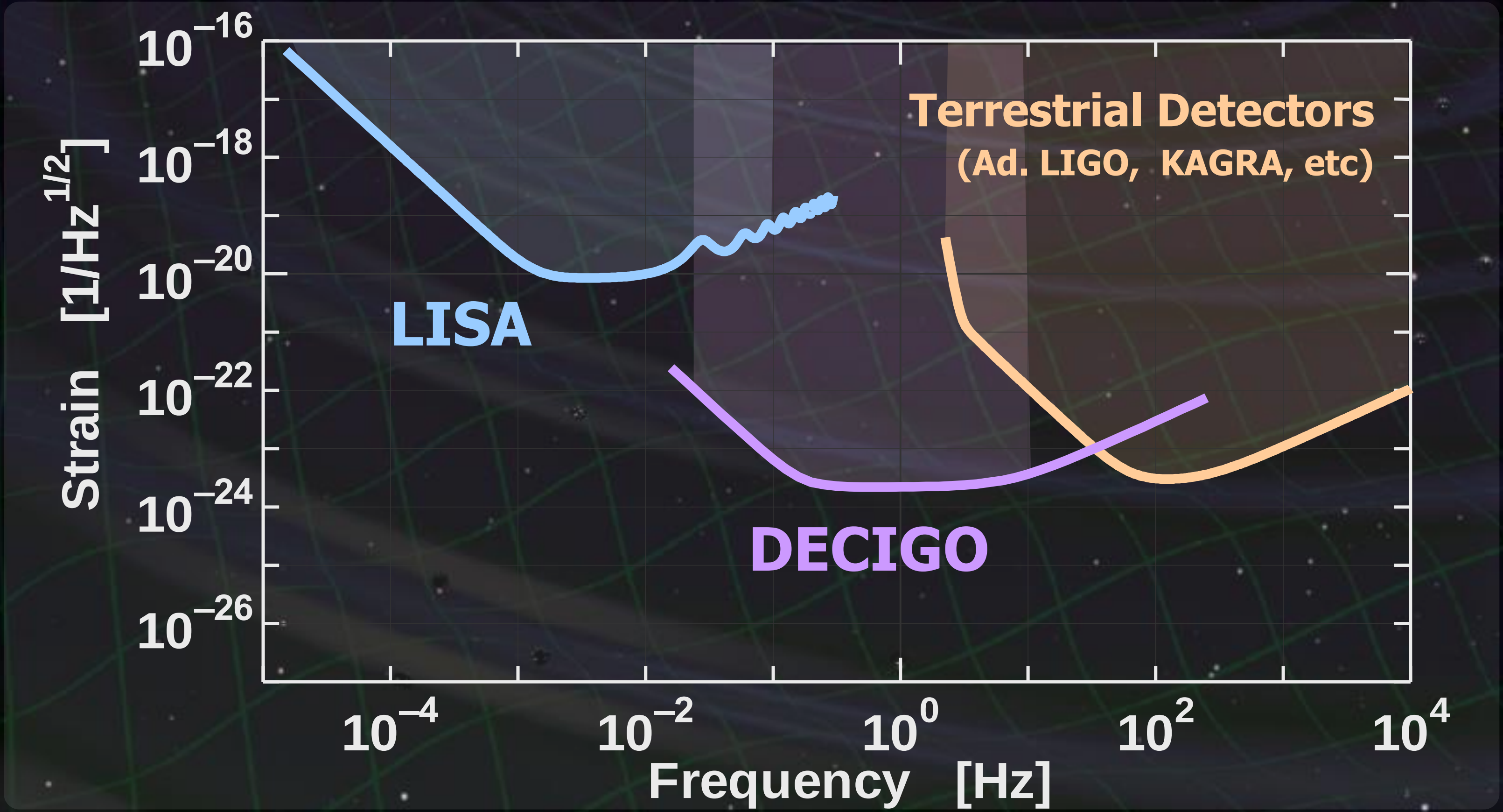
Direct probe to the history of the Universe

DECIGO

DECIGO (Deci-hertz interferometer Gravitational wave Observatory)

Space GW antenna (~2030)
Obs. band around 0.1 Hz

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



LISA and DECIGO

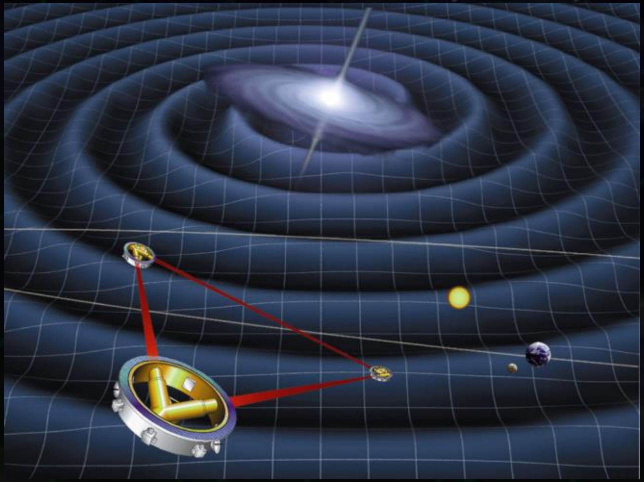
eLISA

(Laser Interferometer Space Antenna)

- Target: SMBH, Binaries.

  ~1mHz GW signals.
- Baseline : 100-500 Mkm.

  Constellation of 3 S/C.
- Config.: Optical transponder.



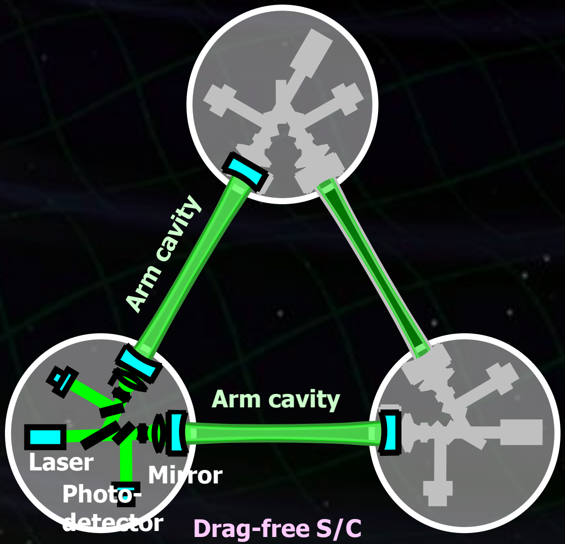
DECIGO

(Deci-hertz Interferometer
Gravitational Wave Observatory)

- Target: IMBH, NS, GW Background.

  ~0.1Hz GW signals.
- Baseline : 1000 km.

  Formation Flight by 3 S/C.
- Config.: FP Interferometer.

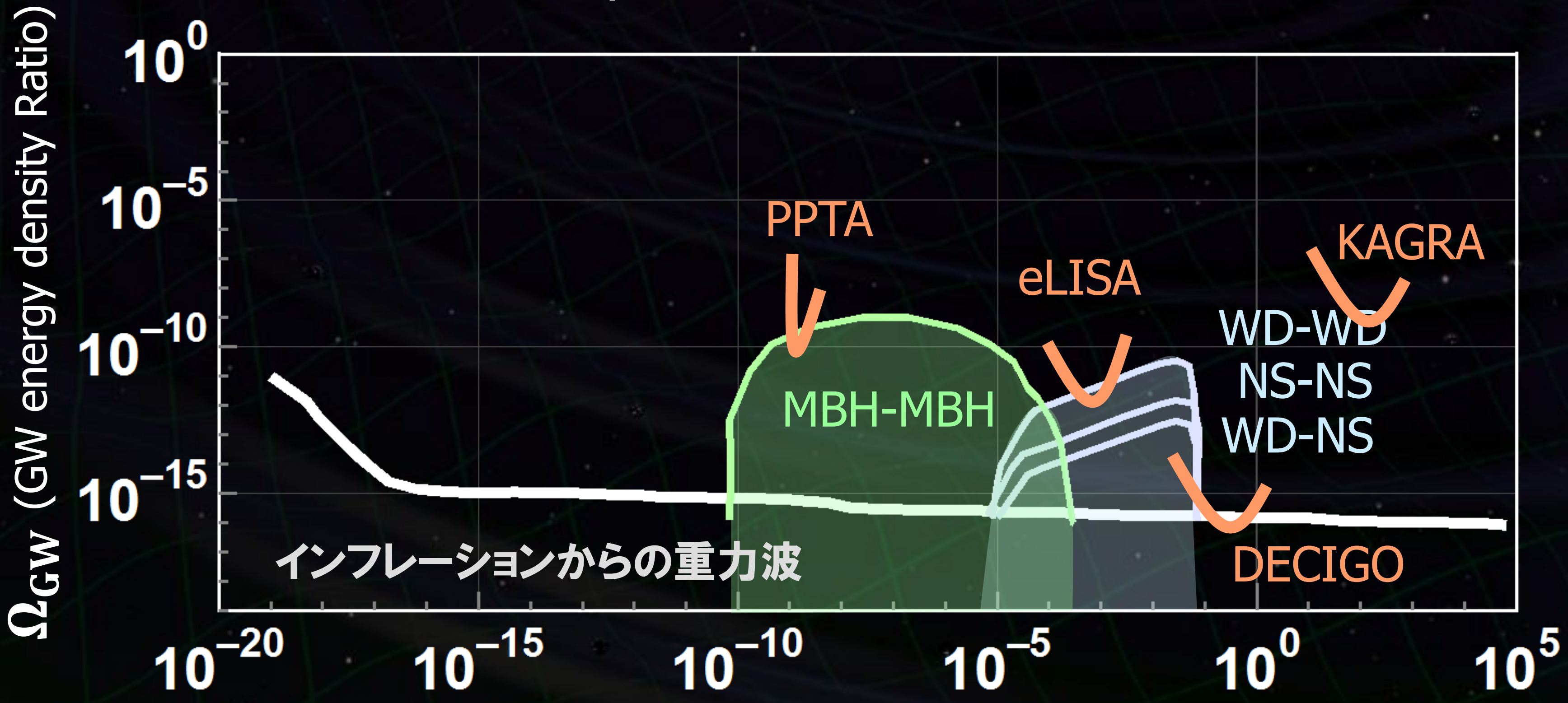


Foreground GW

GWs from many binaries → Unresolvable noises.

⇨ Foreground noise for primordial GW observation

at freq. bands 10^{-10} – 0.1 Hz,



Kuroyanagi+, PRD (2009)
Pablo, PRD (2011)

History of the DECIGO team

- Activity for DECIGO and DPF.

  * 2001 First proposal paper on DECIGO.

  * 2005 Establishment of the first roadmap.

  DPF → Pre-DECIGO → DECIGO

  * 2007 DPF working group approved by JAXA-ISAS.

  * 2009 DPF Mission proposal → Fail (in final two).

  (2010 the KAGRA project started)

  * 2014 DPF Mission proposal → Fail (in the first stage).

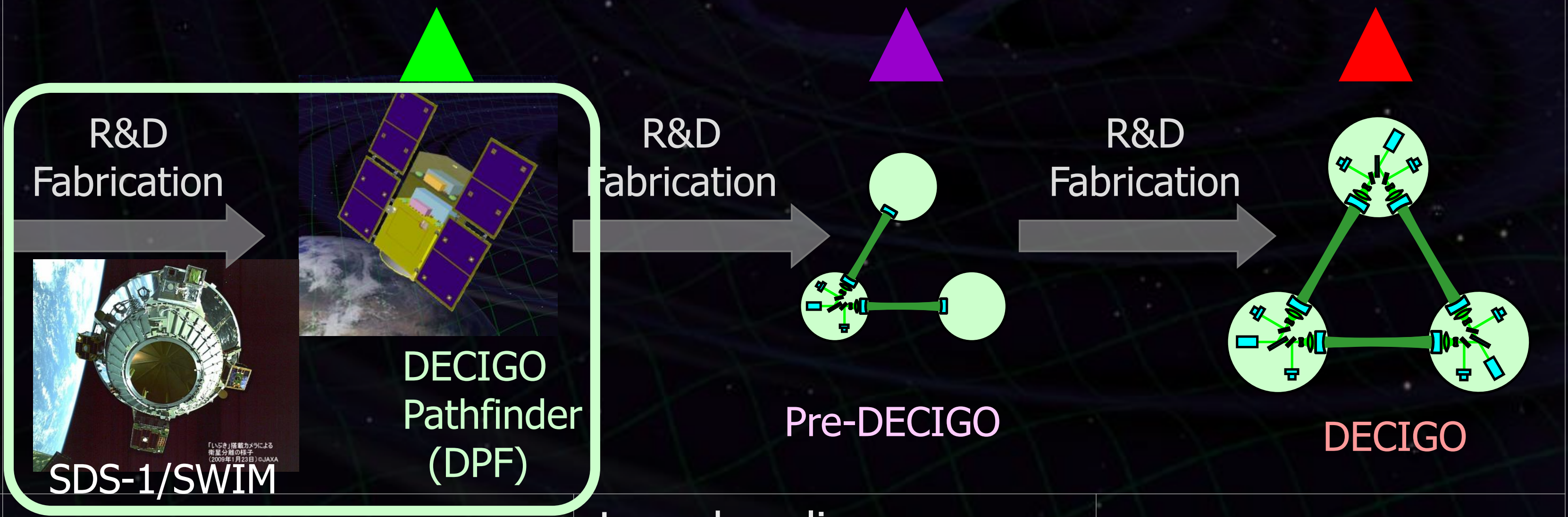
- 2014 Revision of the DECIGO roadmap.
  - Ground test/Piggy back → Pre-DECIGO → DECIGO
  - Pre-DECIGO mission design development of key tech.
  - Possibility of international collaboration

Previous 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

DECIGO
Pathfinder
(DPF)

R&D
Fabrication

Pre-DECIGO

R&D
Fabrication

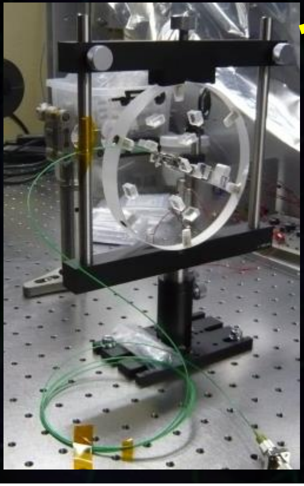
DECIGO

Purpose	Interferometer in Space (Obs. Of GW and Earth Gravity)	Long-baseline Precise Formation Flight (GW Observation)	GW Astronomy and Cosmology
Design	One Small Satellite Short FP cavity + Drag-free	FF with 3 S/C 1 IFO unit	FF with 3 S/C 3-4 IFO units

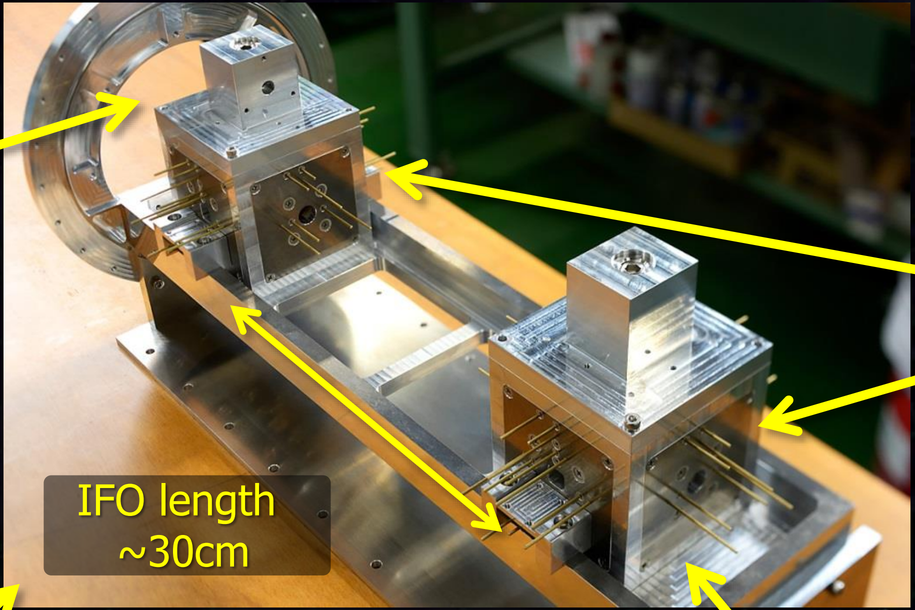
Interferometer Module

IO Optics

Monolithic opt. bench by silicate bonding

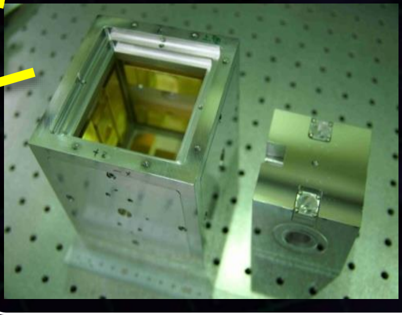


Interferometer Module



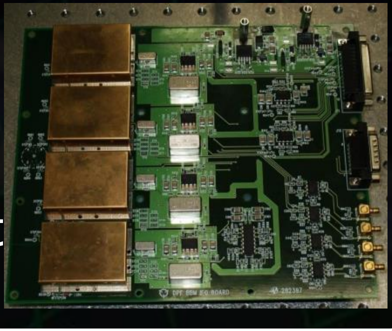
Test mass module

TM, Capacitive Sensor/Actuator, Launch lock



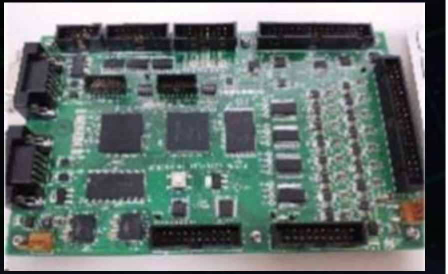
Quad-RFPD

Quadrant PD + Demod. circuits for length and alignment control signals



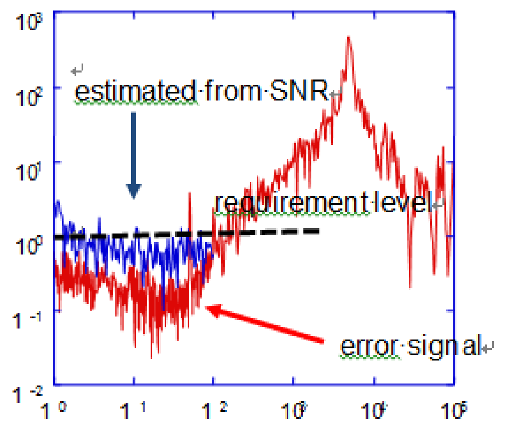
SpW signal-processing board

SpW FPGA + 16bit AD/DA

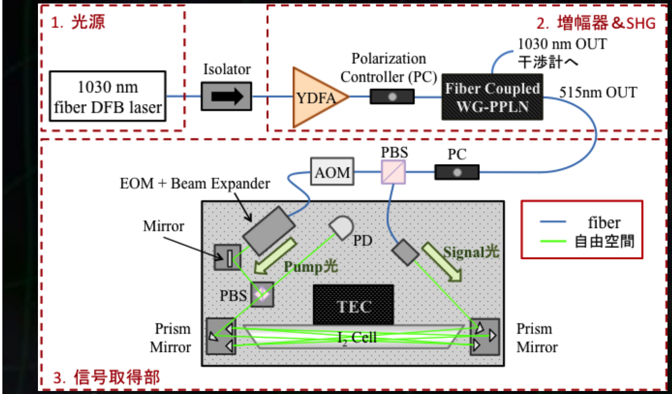


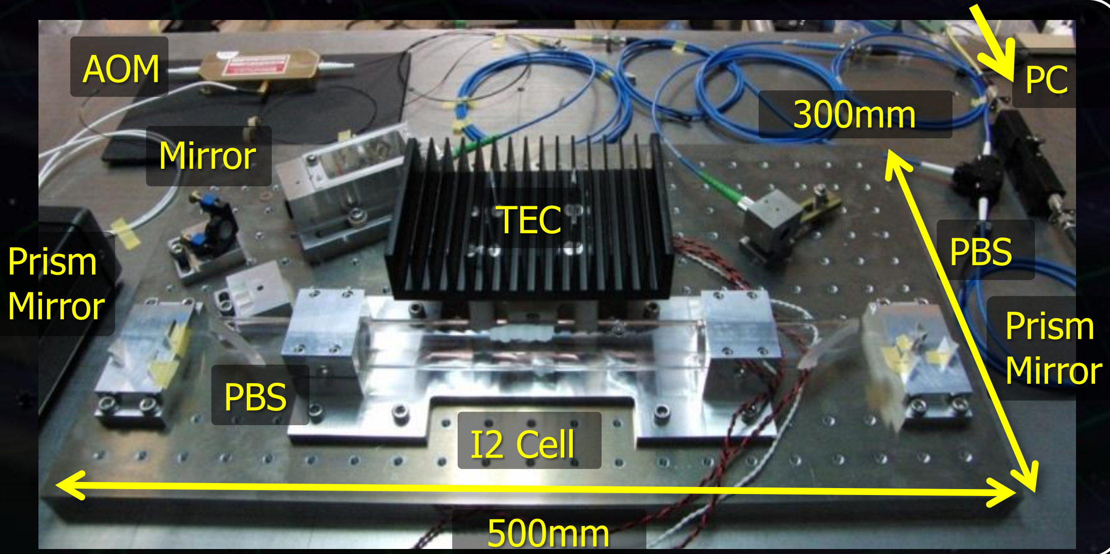
Frequency Stabilization Module

- Frequency Stabilization module BBM2 (at UEC)
  - Use absorption line of Iodine molecule.
  - Satisfy requirement (0.5 Hz/Hz$^{1/2}$) in error-signal measurement.
  - Preparing one-more module for relative stability evaluation.



Freq. Stab module





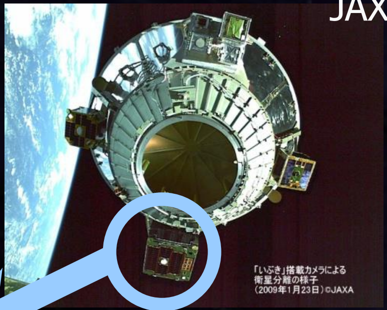
Space Demonstration by SWIM

SWIM (Space wire demonstration module) on SDS-1

Launched in Jan. 2009, 1.5 yr operation.

⇨ First demonstration of a space GW detector

Photo: JAXA



SpaceCube2: Space-qualified Computer

Photo by JAXA

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

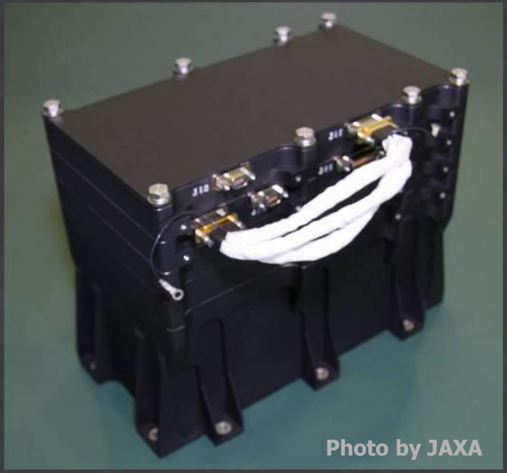


Photo by JAXA

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

SDS-1
Bus System

Power +28V
RS422 for CMD/TLM
GPS signal

Power ±15V, +5V
SpW x2 for CMD/TLM

Rotating TOBA : SWIM$_{\mu\nu}$

Small Module SWIM$_{\mu\nu}$ on SDS-1

Launched Jan. 2009, Terminated Sept. 2010

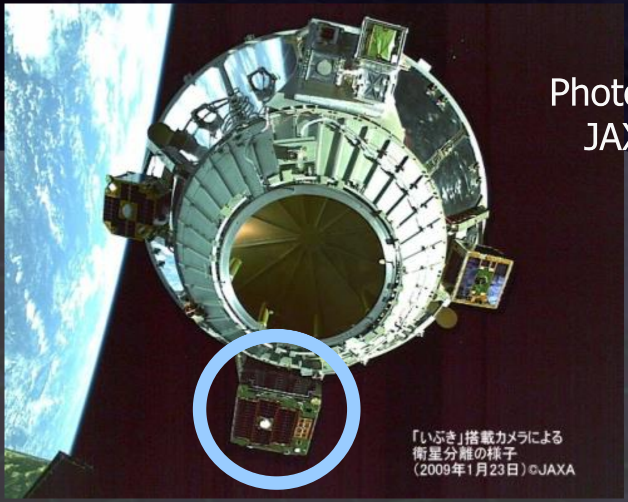
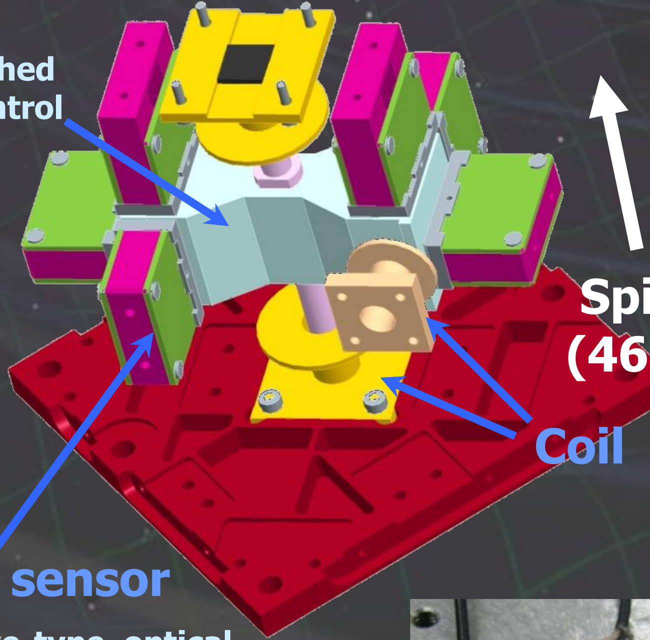


Photo: JAXA

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

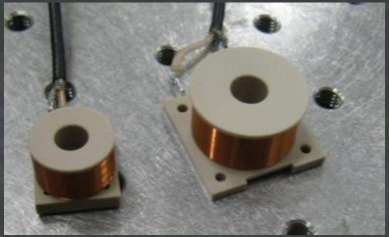


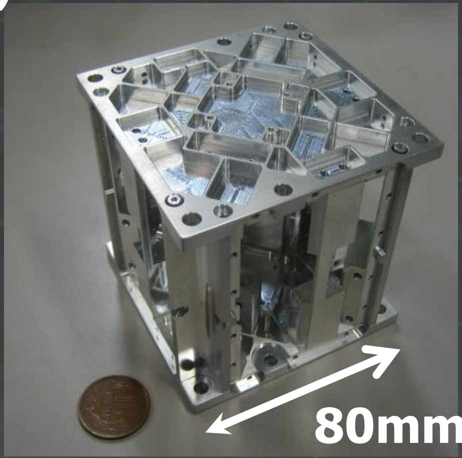
Spin Axis (46.5mHz)

Coil

Photo sensor

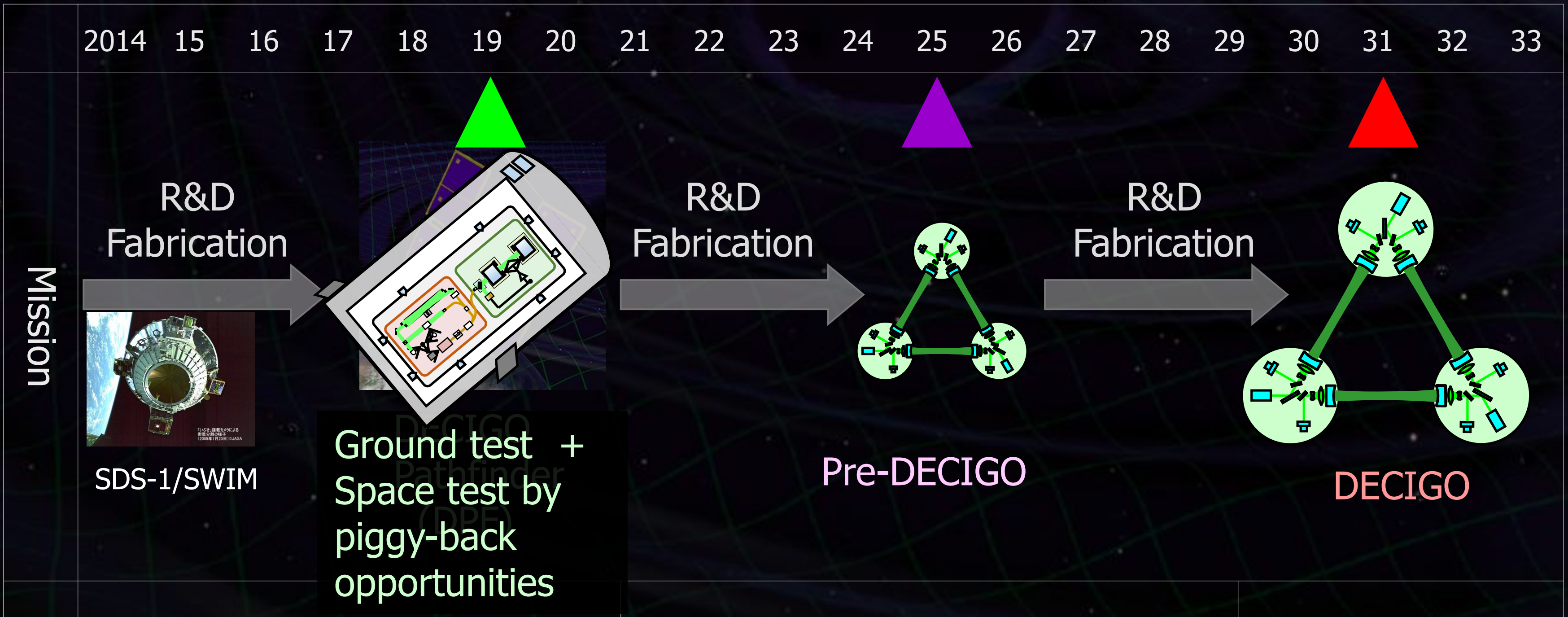
Reflective-type optical displacement sensor
Separation to mass ~1mm
Sensitivity ~ 10^{-9} m/Hz$^{1/2}$
6 PSs to monitor mass motion





DECIGO Roadmap (Revised in 2014)

Figure: S.Kawamura



R&D
Fabrication

SDS-1/SWIM

Ground test +
Space test by
piggy-back
opportunities

R&D
Fabrication

Pre-DECIGO

R&D
Fabrication

DECIGO

Target	Development of Critical components.	GW observation at 0.1Hz. (IMBH, NS binary, WD foreground	GW cosmology
Config.	Ground-based tests. Space qualification by piggy.	3 S/C, FP interferometer, 100km baseline	3 S/C 1000 km baseline 3-4 IFO units

- **JAXA Mission Opportunities**
- **Activities in Japan**
- **Conclusion**

Summary from Community PoV (1/2)

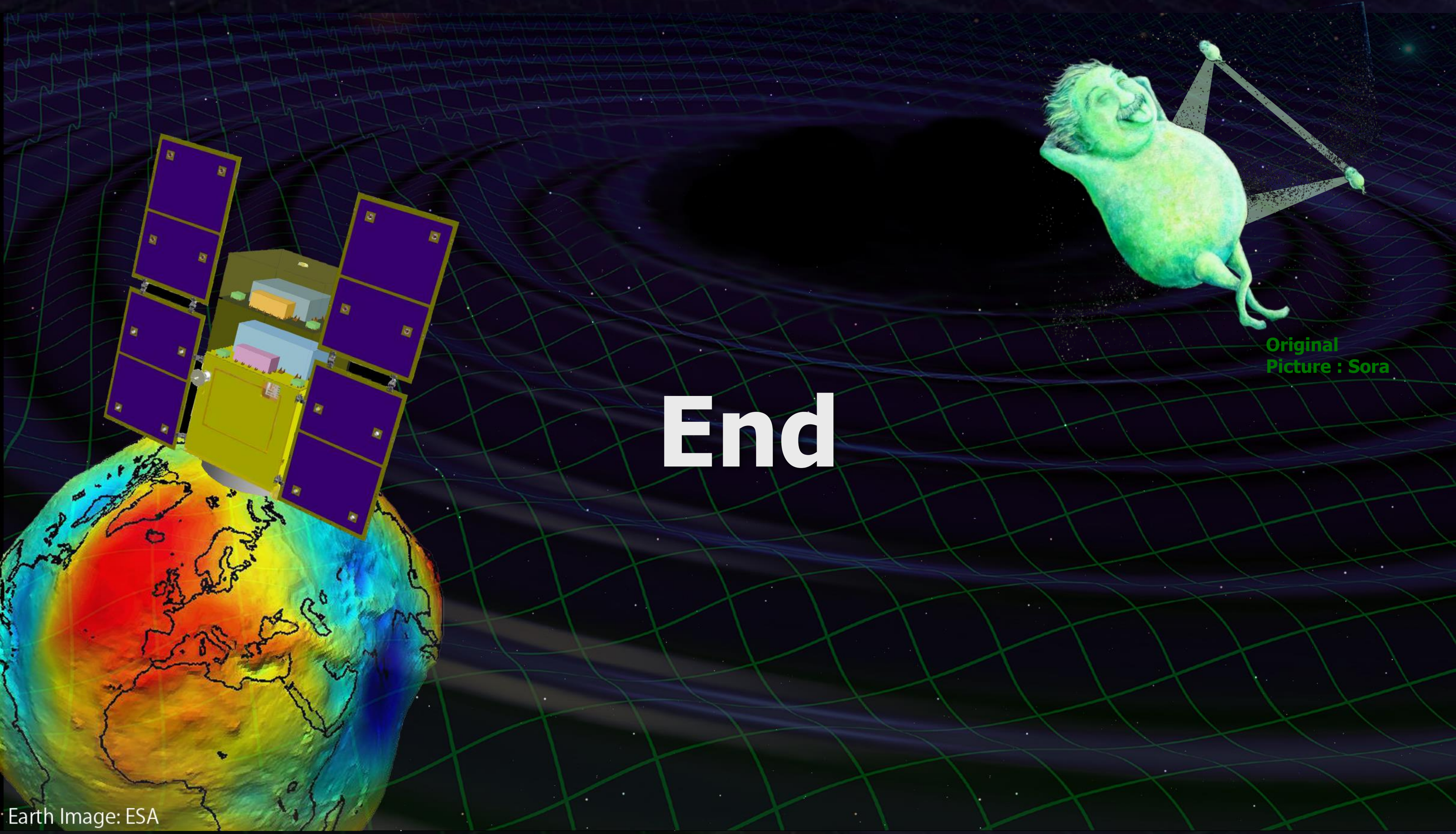
- GW community in Japan has ~45 years experiences on ground-based GW detectors, and ~15 years activities for space GW antenna. It also have a little experiences on space missions.

- Current first priority in Japanese GW community is KAGRA, and space GW antenna is the next step. Since JAXA highly requires first-priority support from the community, there will be a small chance to be selected as medium/small-scale mission. However there will be a chance in the 'Various small project' category in an international framework.

Summary from Community PoV (2/2)

- Since DECIGO will provide fruitful science which never obtained by EM observations, it will be realized at last. Pre-DECIGO will have a lot of original science, different from and complementary with those of LISA. It is important to keep the (minimum) activities: system design study and development of key components.

- Contribution to LISA will be a good opportunity to make solid basis for the space GW community in Japan. Junior partner will be a realistic choice. Candidates: Laser source, Freq. stabilization, Part of Interferometer, Data analysis, …



End

Original Picture : Sora

Earth Image: ESA

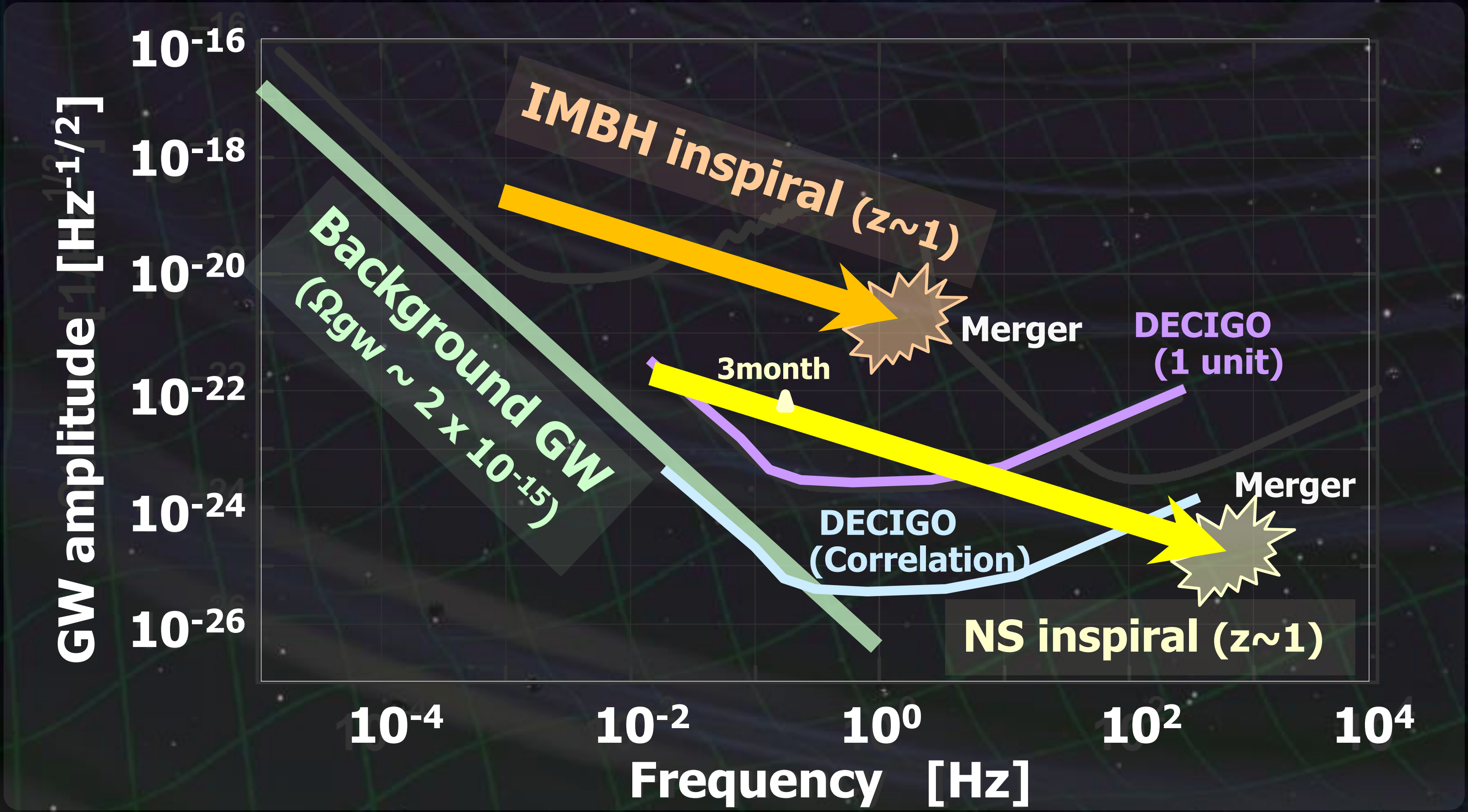
Supplementary Slides

Targets and Science

IMBH binary inspiral
NS binary inspiral
Stochastic background

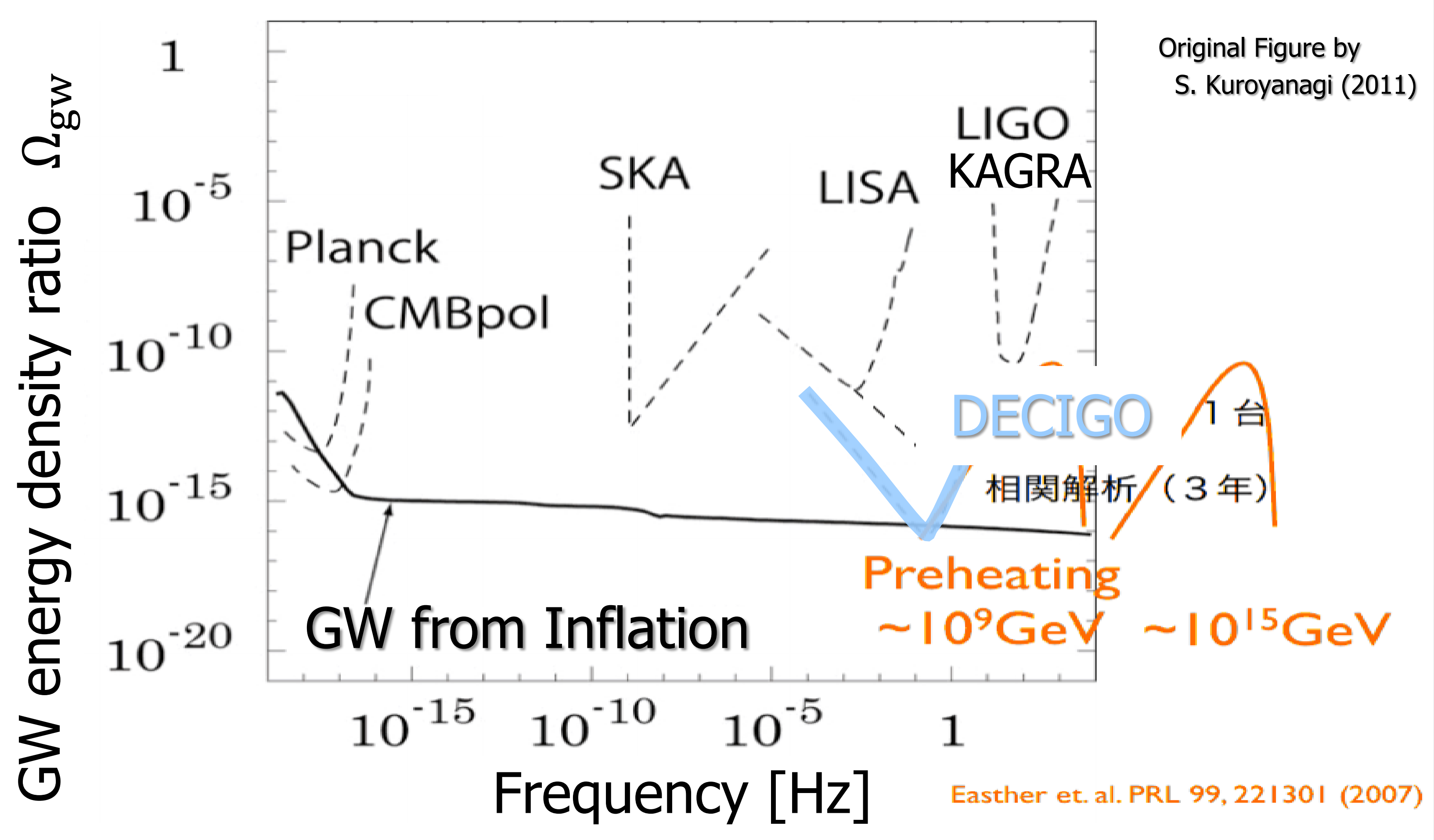
⇨

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



Primordial GW

Earlier universe → Smaller horizon scale → High GW freq.



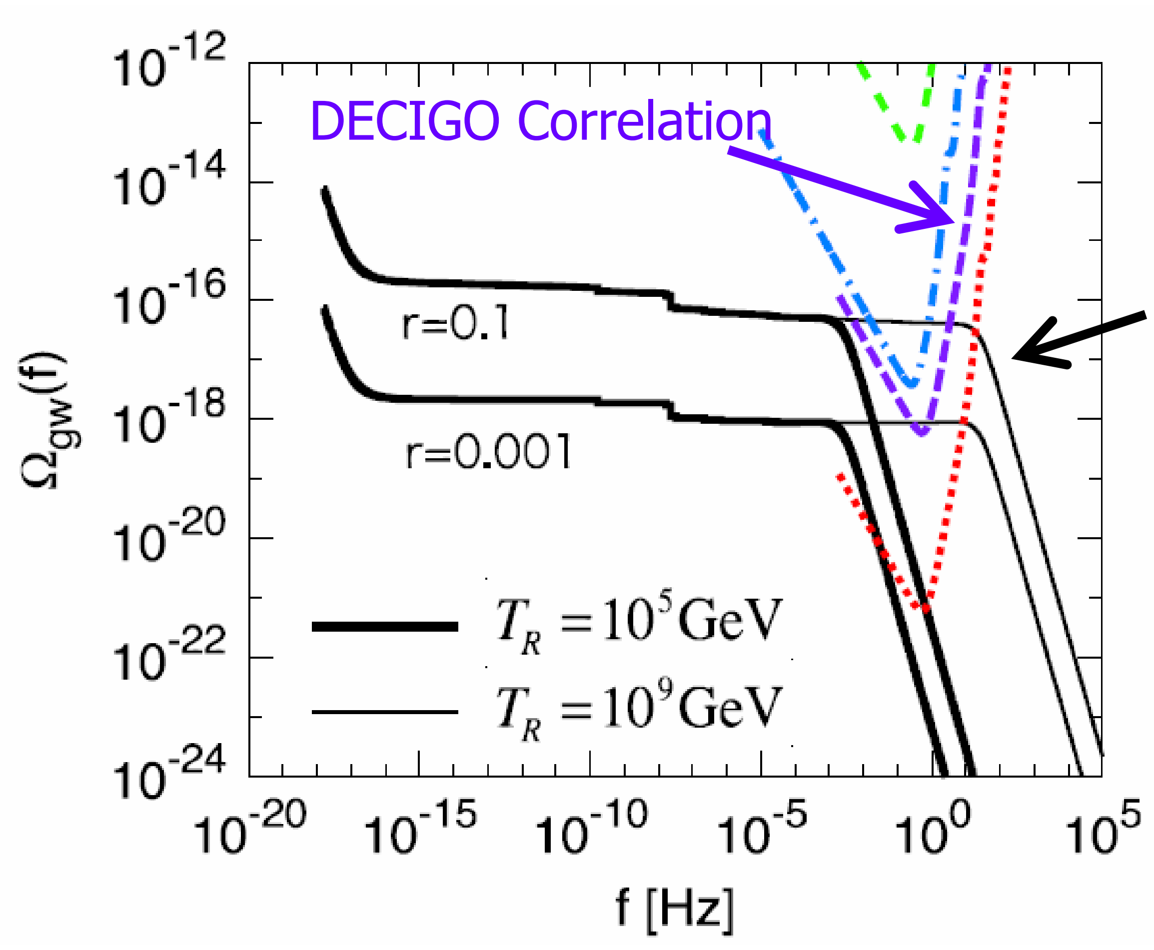
Original Figure by S. Kuroyanagi (2011)

Easther et. al. PRL 99, 221301 (2007)

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.

Pre-Conceptual Design

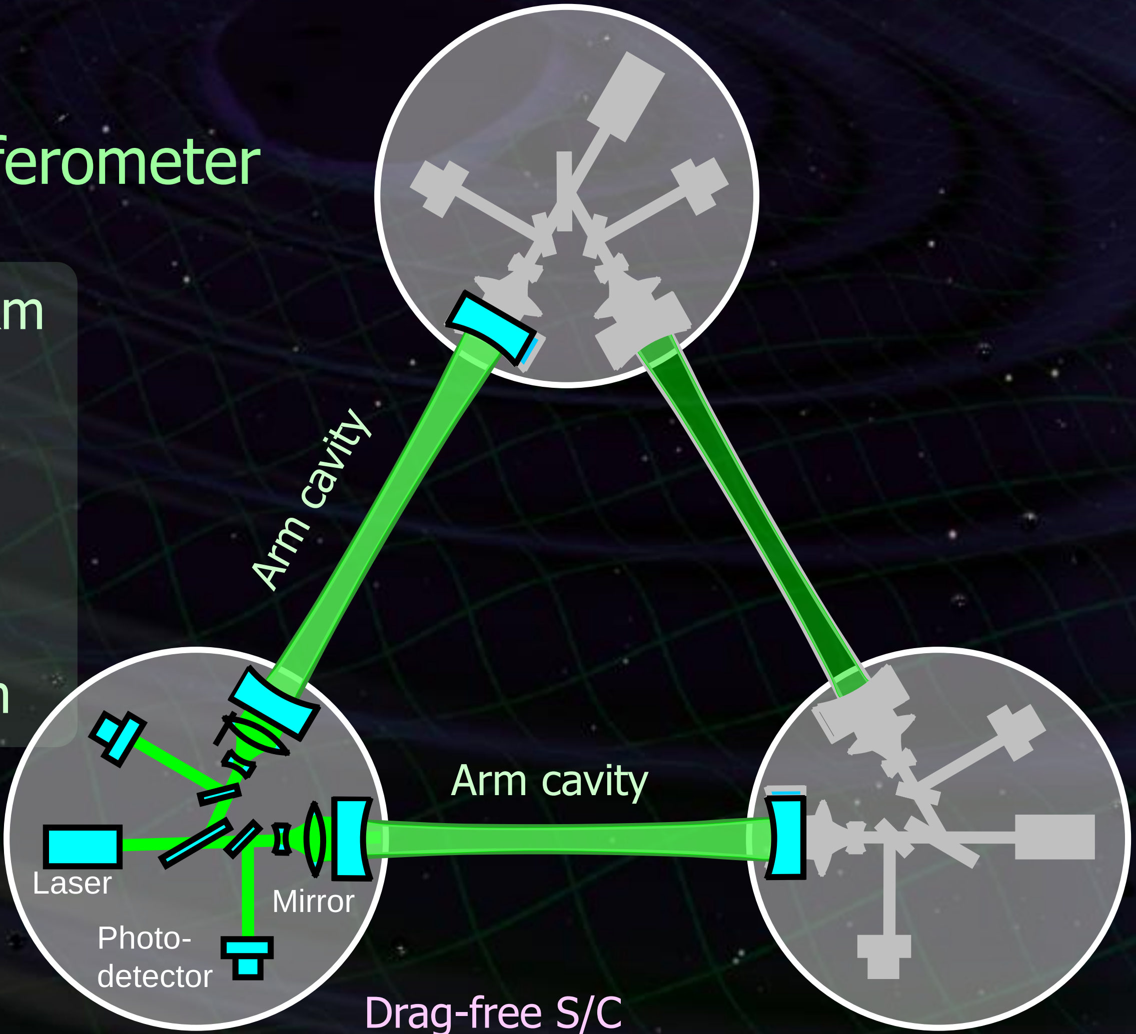
Interferometer Unit:

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

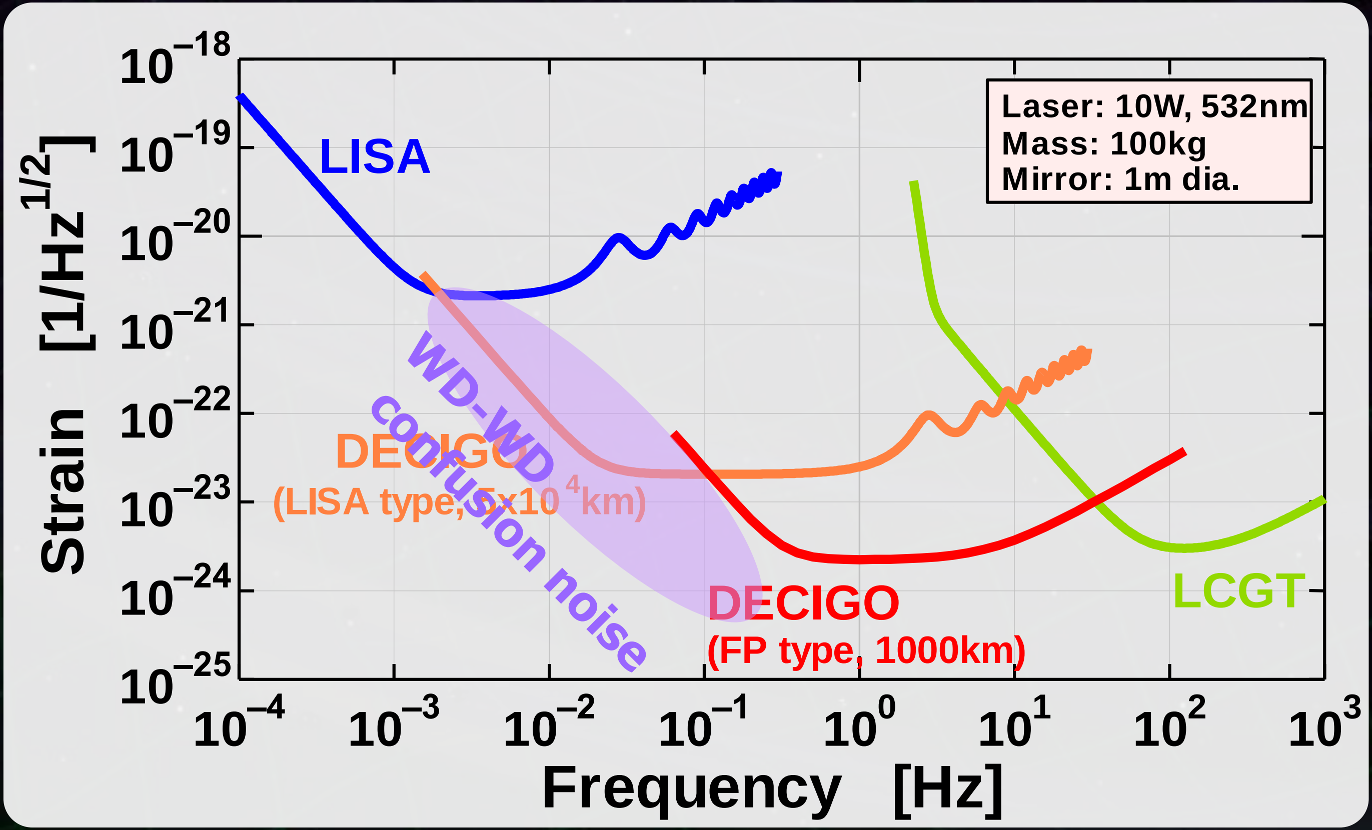


Interferometer Design

Transponder type vs Direct-reflection type

Compare : Sensitivity curves and Expected Sciences

⇨ Decisive factor: Binary confusion noise



Arm length

Cavity arm length : Limited by diffraction loss

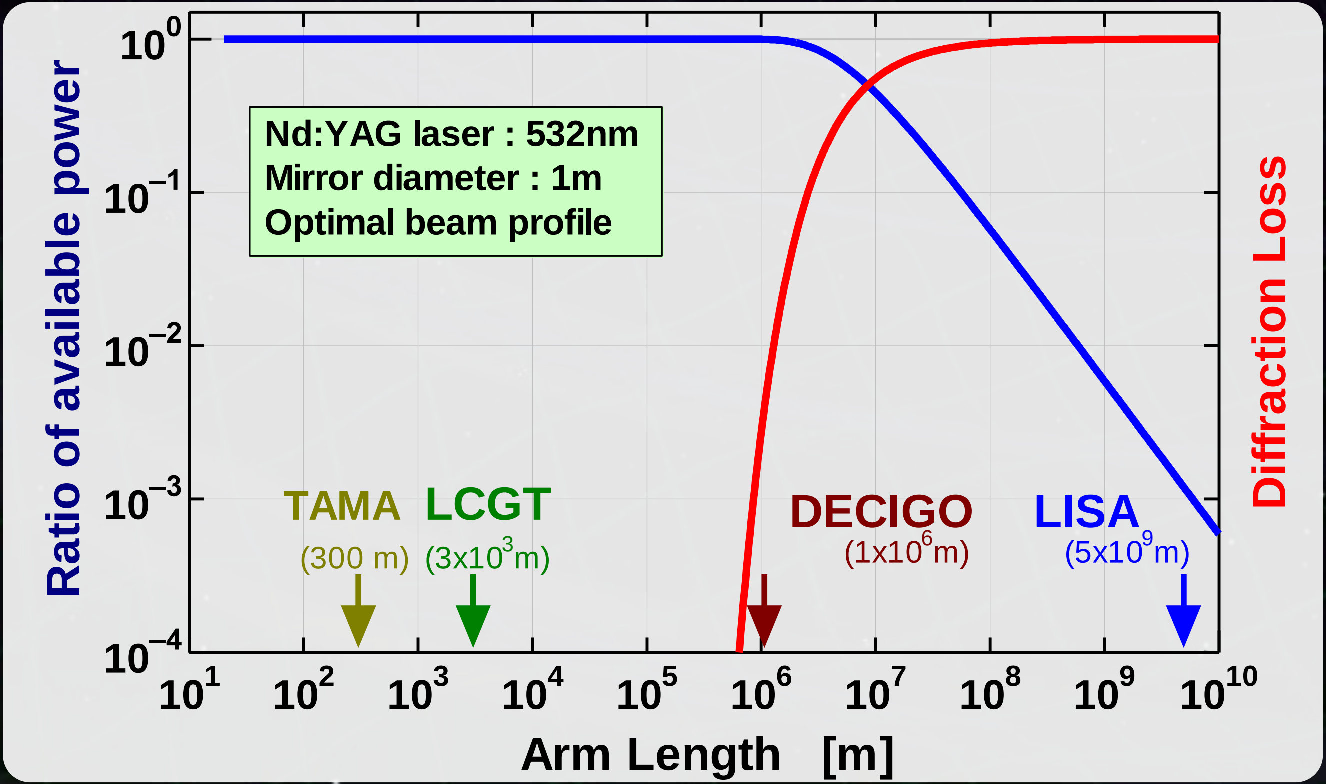
Effective reflectivity (TEM_{00} → TEM_{00})

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

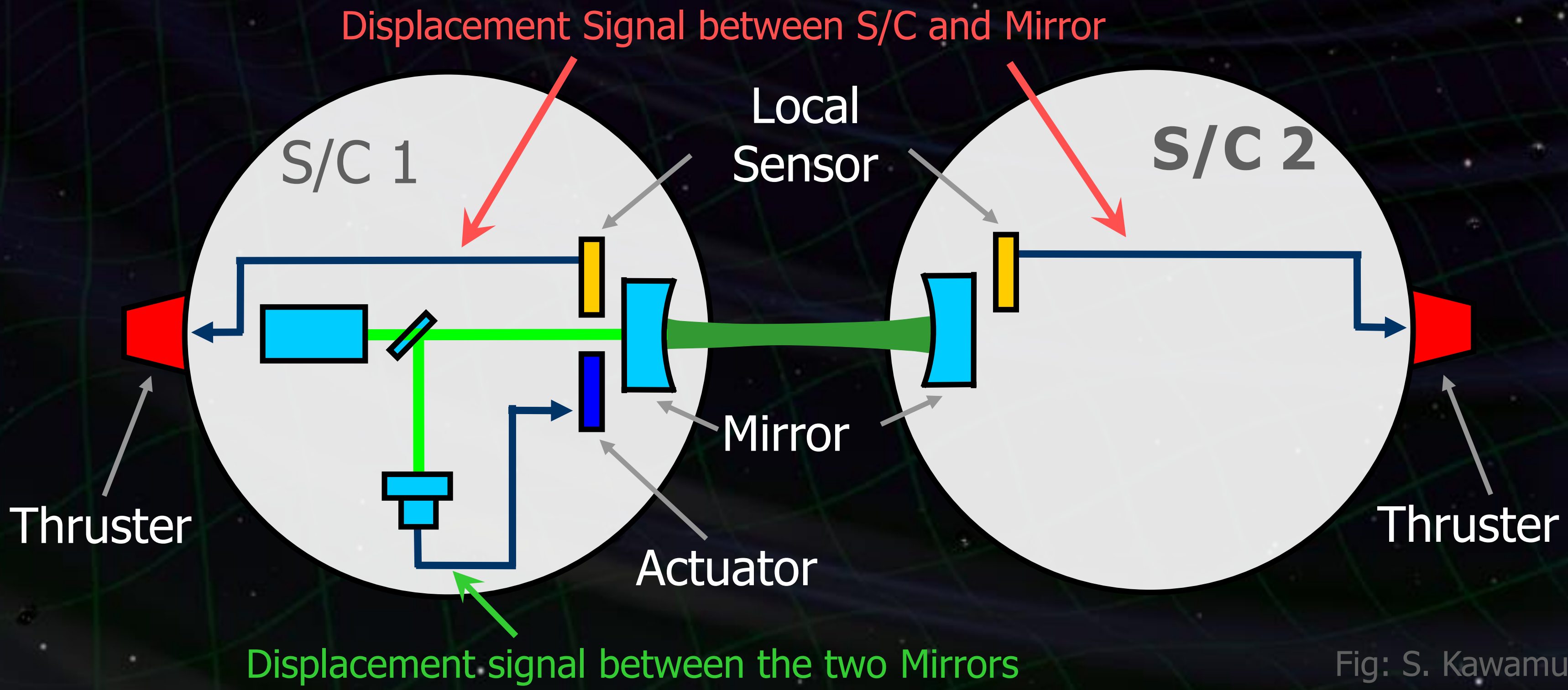


Fig: S. Kawamura

Requirements

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.

Foreground Cleaning

DECIGO obs. band: free from WD binary foreground
→ Open for cosmological observation

DECIGO will watch
~ 10^5 NS binaries

⇨ Foreground for GWB

In principle, possible
to remove them.

Require waveform
Accuracy $\Delta m/m < \sim 10^{-7}$ %

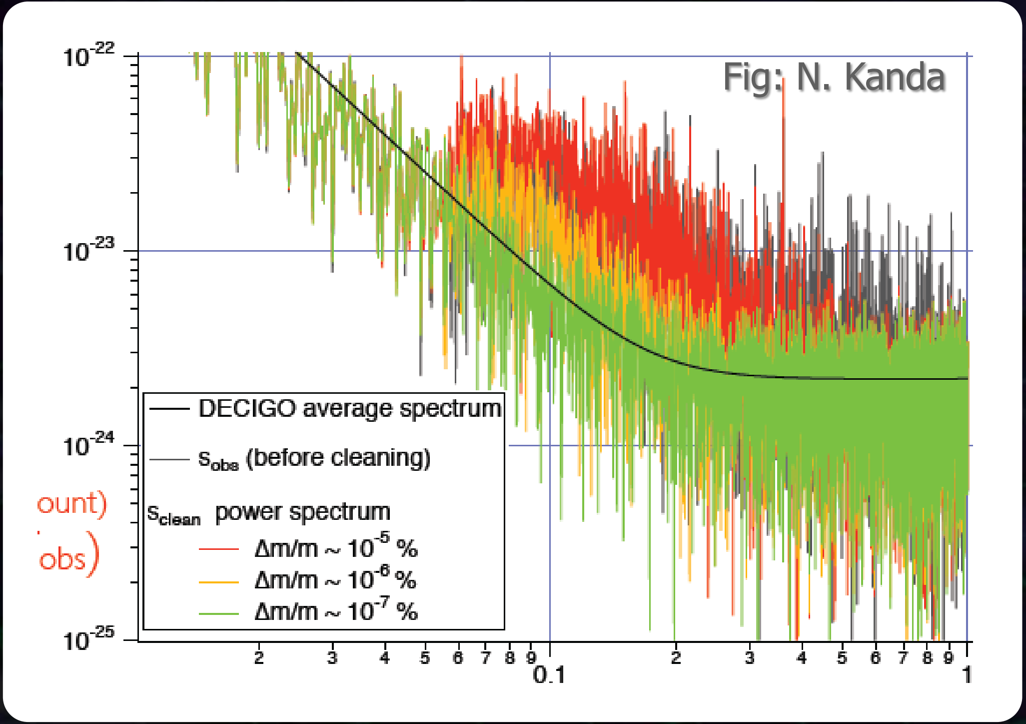
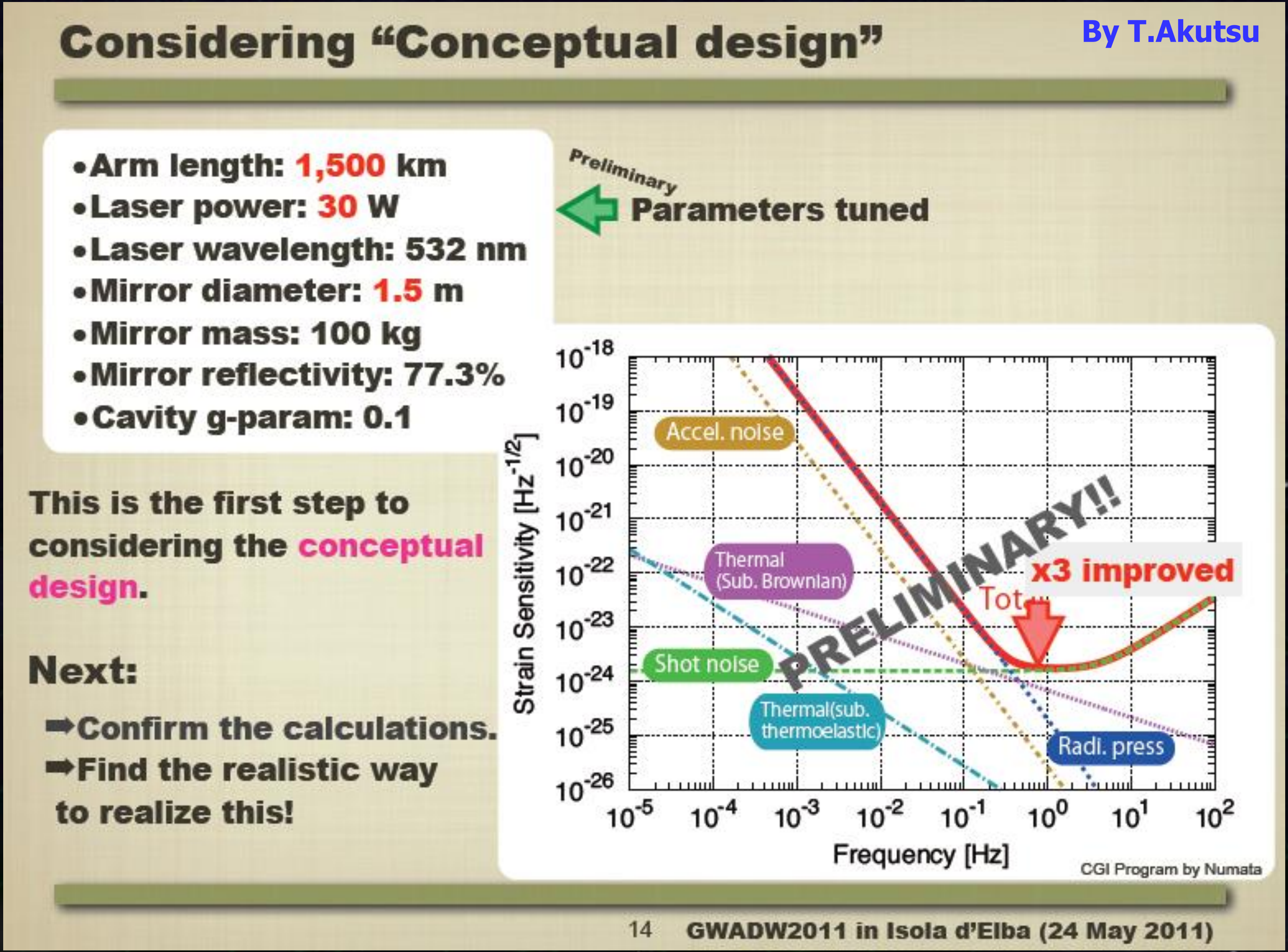


Fig: N. Kanda

Design Update



Considering "Conceptual design"

By T.Akutsu

- Arm length: 1,500 km
- Laser power: 30 W
- Laser wavelength: 532 nm
- Mirror diameter: 1.5 m
- Mirror mass: 100 kg
- Mirror reflectivity: 77.3%
- Cavity g-param: 0.1

Preliminary

Parameters tuned

This is the first step to considering the conceptual design.

Next:

➡Confirm the calculations.

➡Find the realistic way to realize this!

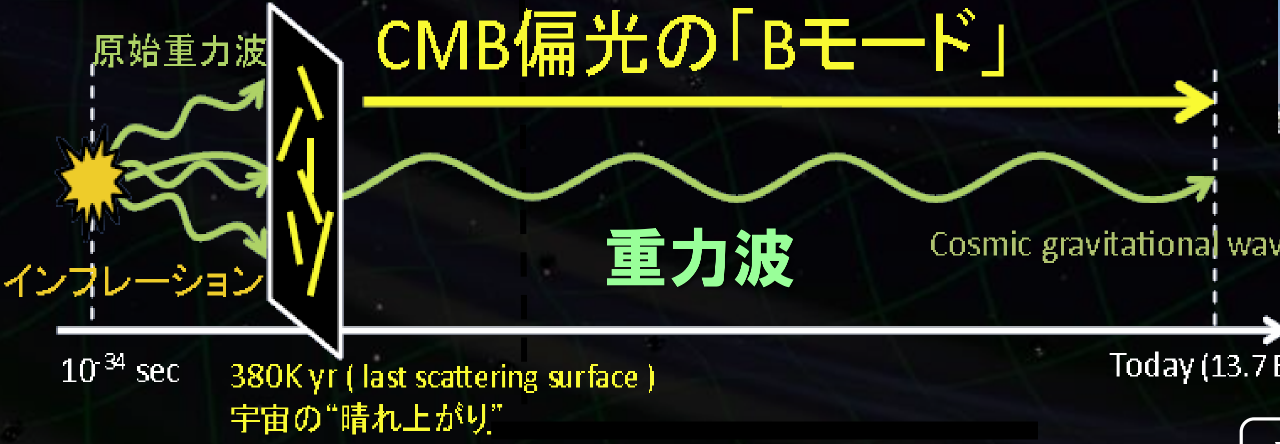
初期宇宙からの重力波観測

BICEP2, (POLARBEAR,...)

マイクロ波望遠鏡を用いた
宇宙背景放射 B-mode偏光
成分の観測.

DECIGO, (KAGRA, aLIGO,...)

重力波望遠鏡を用いた
宇宙背景重力波の観測.



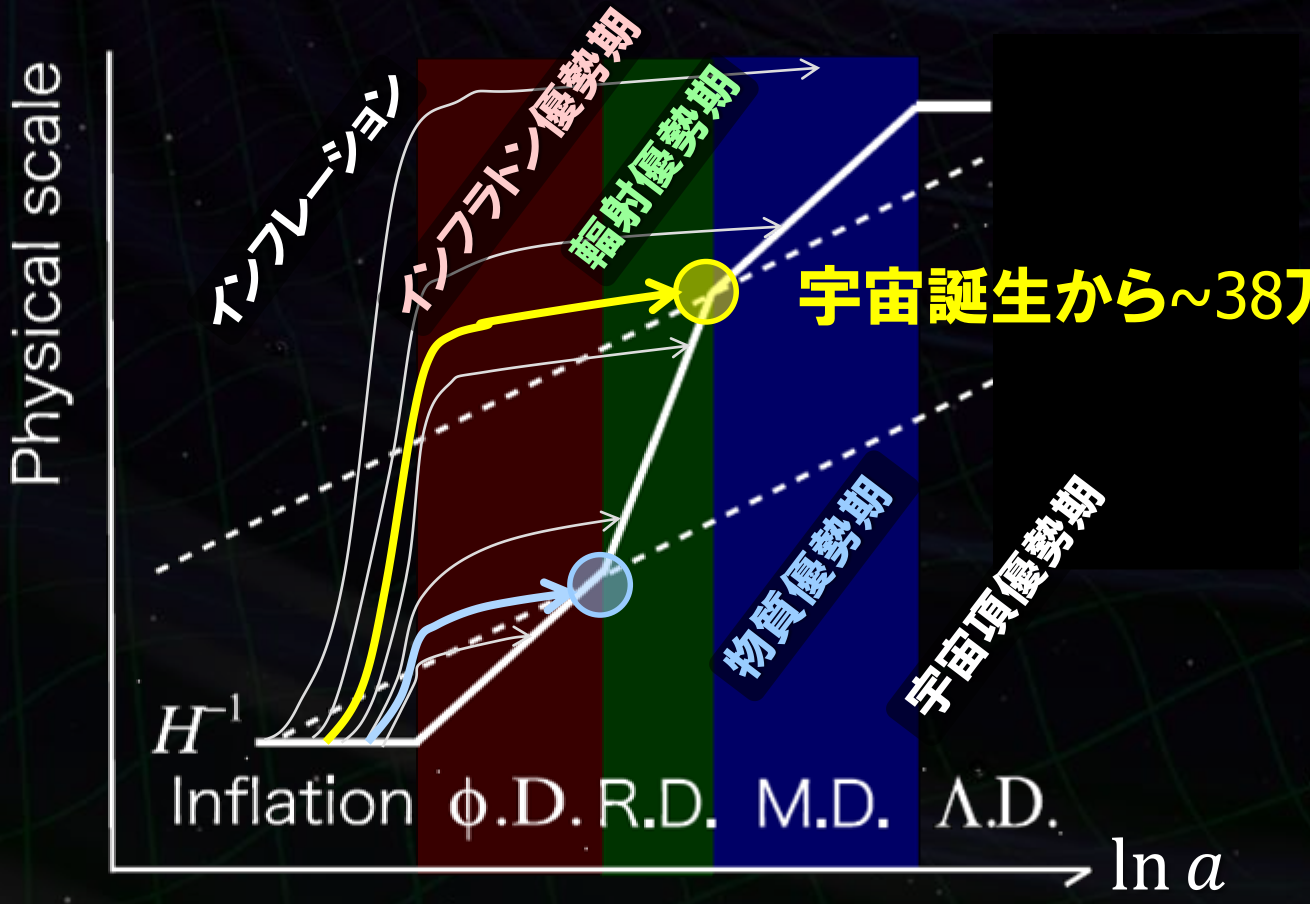
CMB偏光観測望遠鏡

重力波観測望遠鏡

図: 田島氏談話会資料より(2011 京都大学)

インフレーションからの重力波

計量の量子揺らぎとして生成 → 初期に生成された重力波ほど,
長くインフレーションで引き延ばされ, 最近に宇宙の地平線内へ.



宇宙誕生から~38万年後

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

重力波エネルギー密度比と振幅

重力波のエネルギー密度比

重力波のエネルギー密度

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

宇宙の臨界密度

⇨

等価な重力波振幅

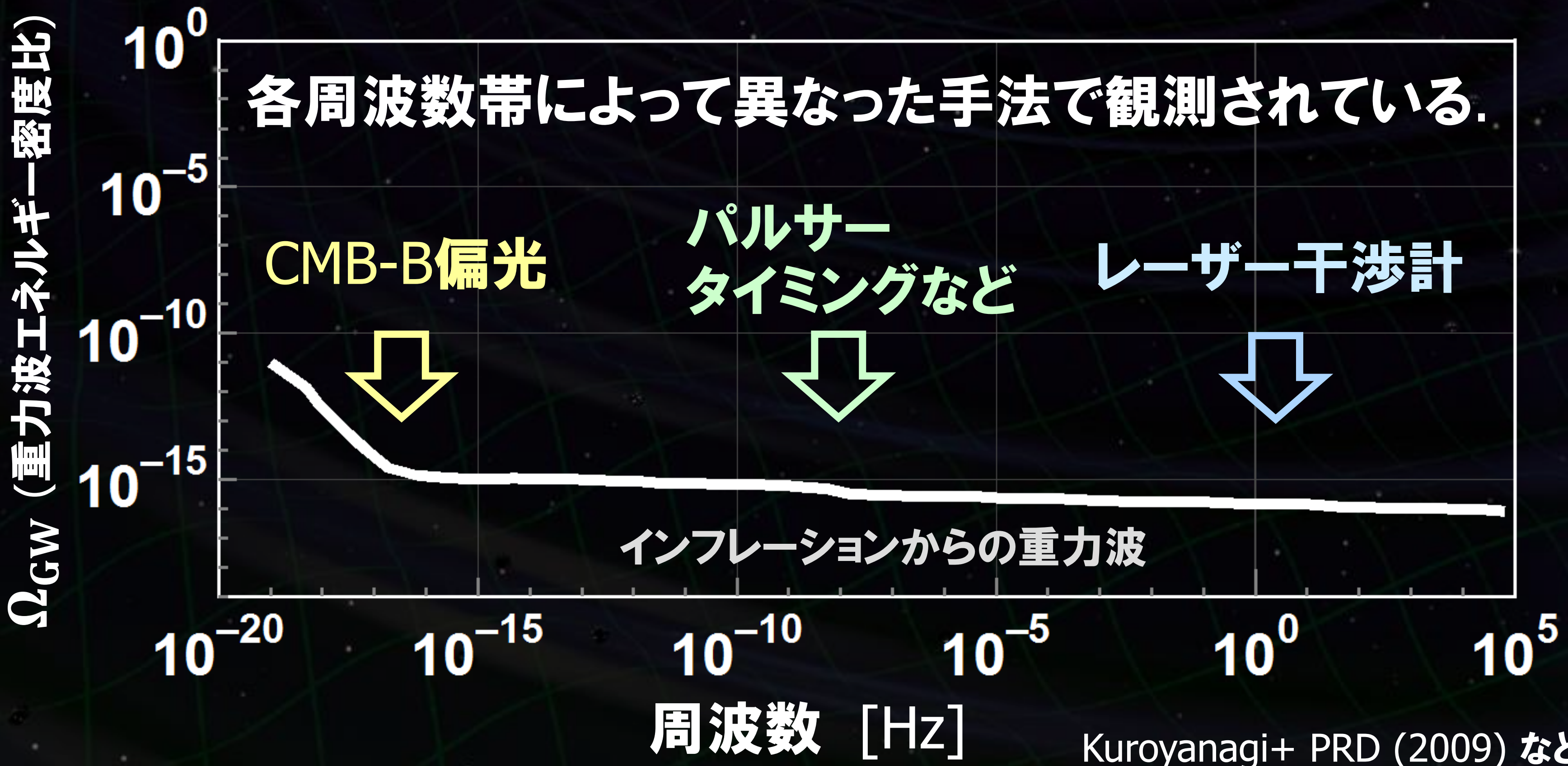
ハッブル定数

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

背景重力波の観測

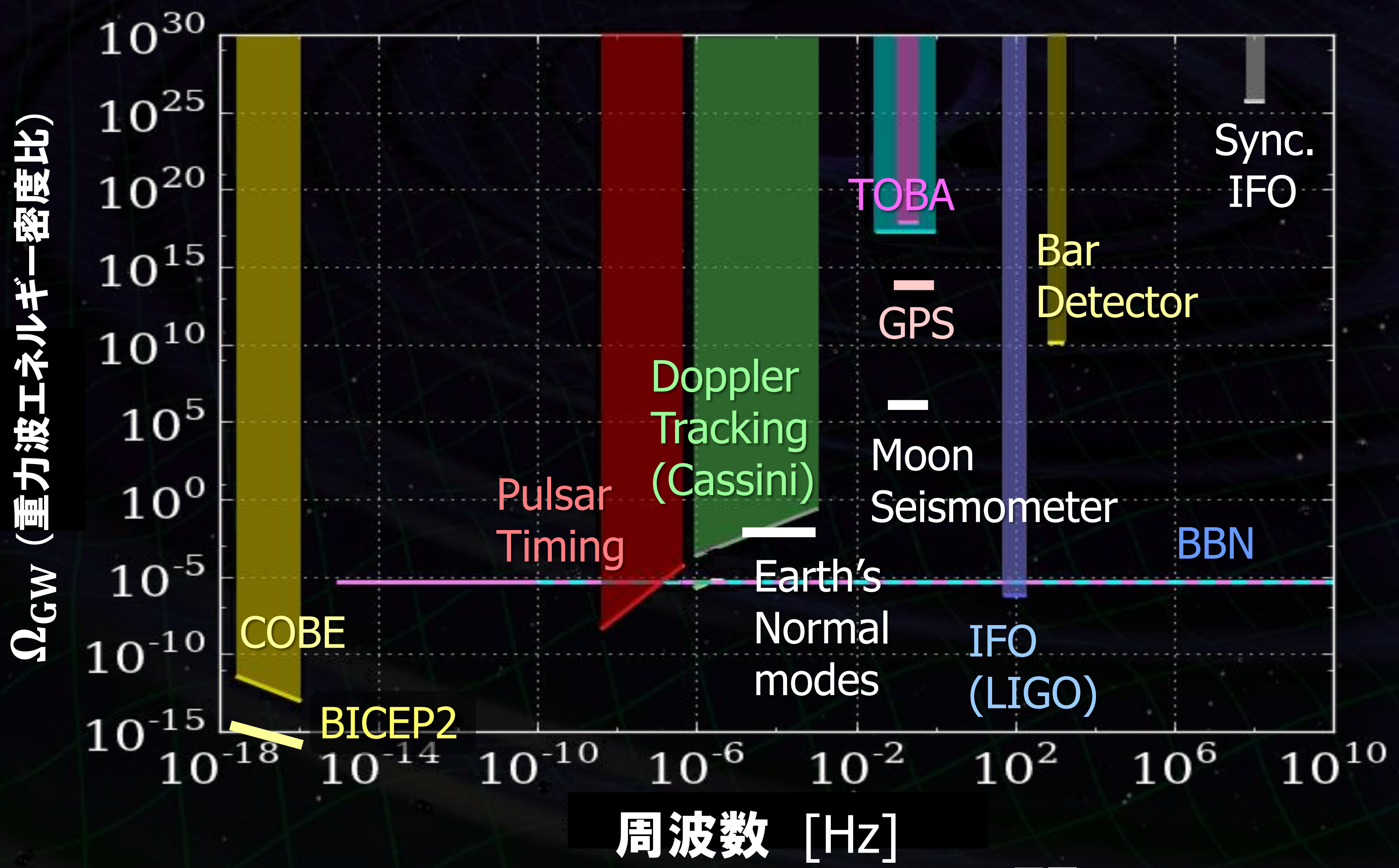
地平線内に入った重力波は, 宇宙膨張とともに発展.

→ スペクトルの形は、**宇宙進化の情報**を持っている.



Kuroyanagi+ PRD (2009) など

背景重力波探査の現状



原図：Shoda+, PRD (2013)

重力波エネルギー密度比と振幅

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

高周波数では振幅は小さくなる

原始重力波観測の「窓」

DECIGO

- さまざまな周波数帯で原始重力波観測を観測することで宇宙の進化の情報を得ることが可能.
- インフレーションからの重力波観測には低周波数が有利.
- 0.1Hz以下の周波数帯では, フォアグラウンド重力波が存在.

⇩

インフレーションからの重力波観測には,
0.1 -1 Hzの周波数帯が良い.

$$\Omega_{\mathrm{GW}} \sim 10^{-16} \; - \; 10^{-15}$$

→ $\tilde{h}_{\mathrm{GW}} \sim 10^{-24}$ Hz$^{-1/2}$ (@ 0.1Hz)

原始重力波観測の意義

- 重力波 – 強い透過力を持ち, 初期宇宙の情報を伝える.
- スペクトルの形 : 初期揺らぎ + 宇宙進化の歴史.

CMB Bモード偏光から
もある程度推定可能.

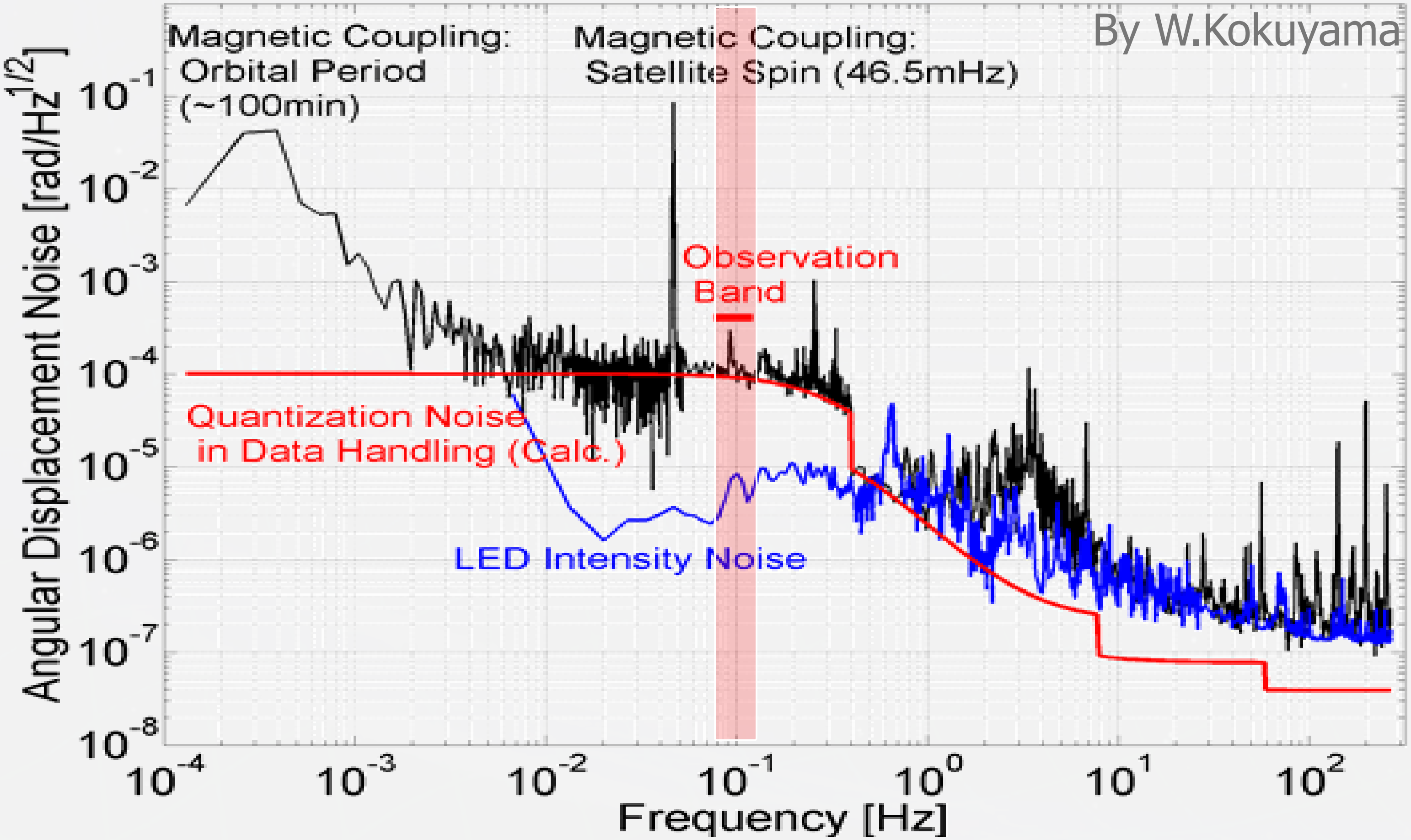
観測周波数と宇宙の時代が対応.
高周波数 → より初期宇宙の情報.
- Reheating温度(物質の種の形成)
- 宇宙の熱進化史 ….

DECIGOが目指す 0.1Hzの周波数帯 :
インフレーション期とBBN期の間の情報
→ CMB-B偏光観測と相補的な観測.

Sensitivity

DECIGO

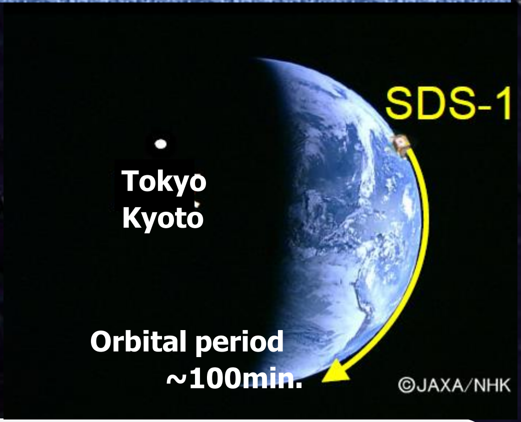
Though limited by non-fundamental noises,
best as a space-borne GW detector.

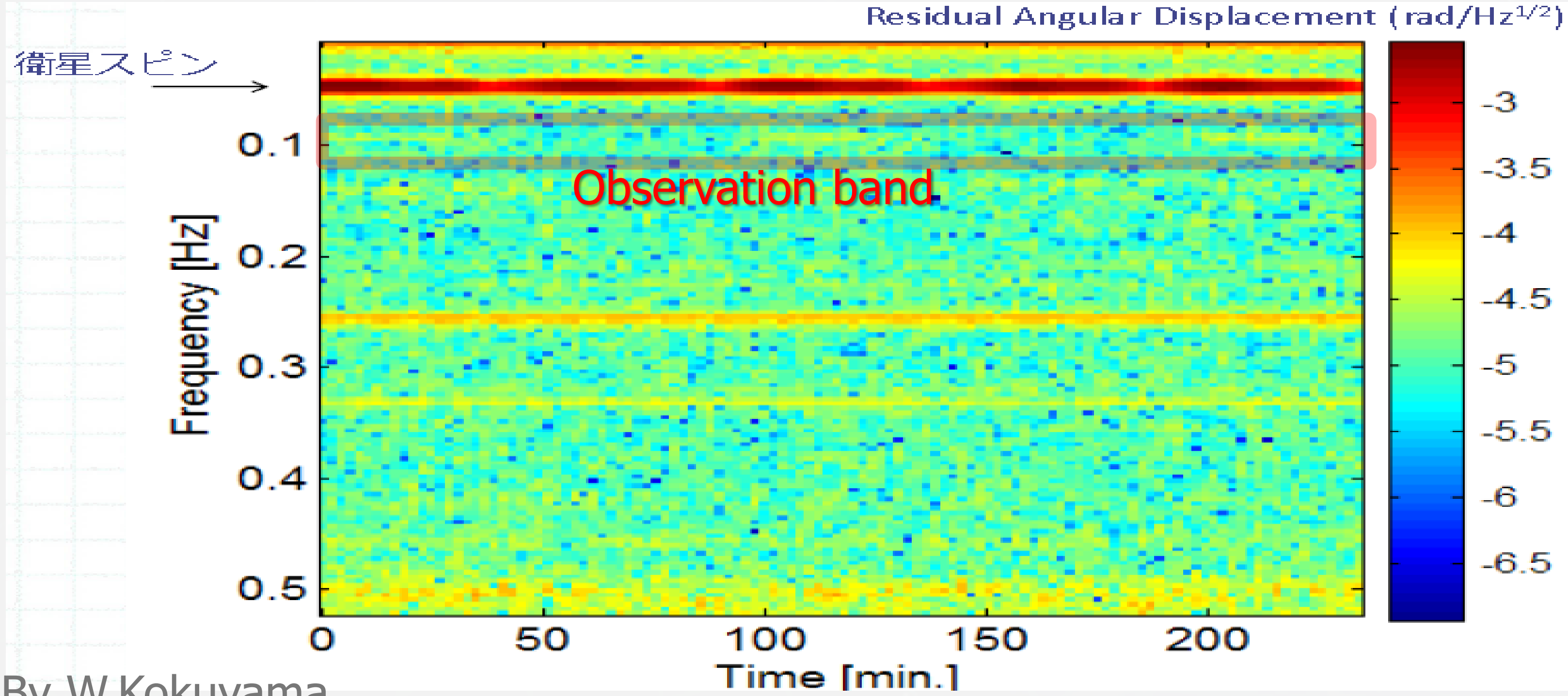


Observation by SWIM

Continuous data taking

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





By W.Kokuyama

Upper Limit on GWB

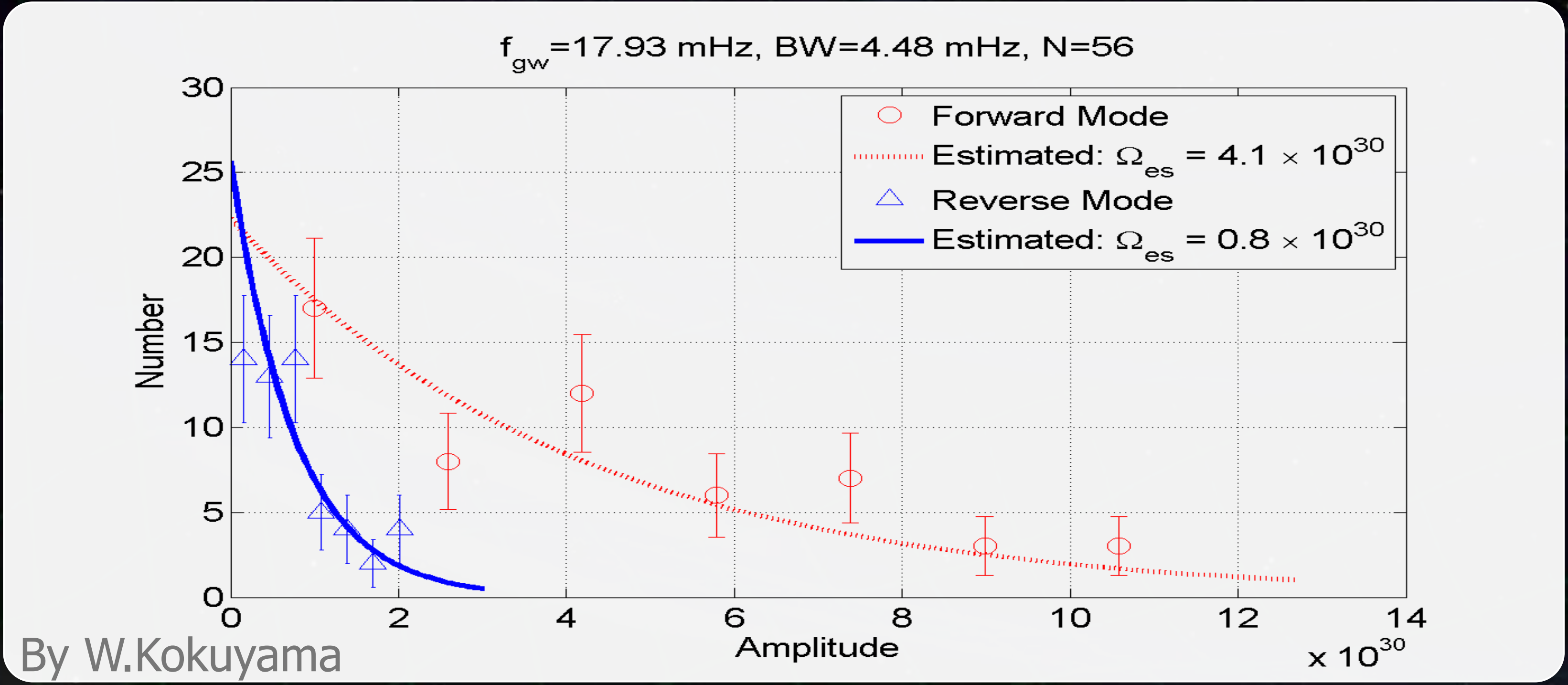
DECIGO

Upper Limit at two frequencies (two polarizations)

'Forward' mode $\Omega_{\mathrm{gw}}^{\mathrm{FW}} = 1.7 \times 10^{31}$

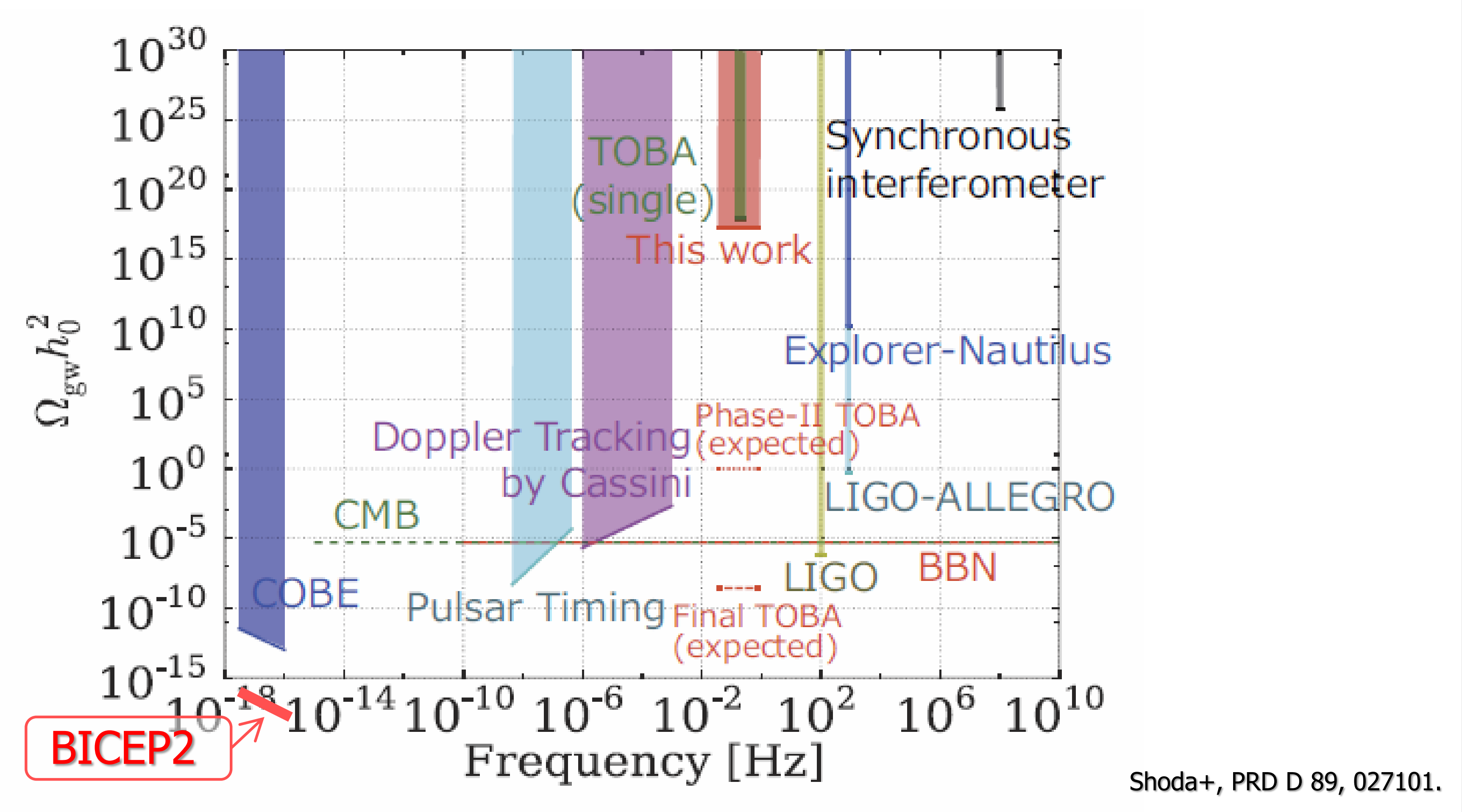
'Reverse' mode $\Omega_{\mathrm{gw}}^{\mathrm{RE}} = 3.1 \times 10^{30}$

(C.L. 95%, f0 18mHz, BW 4mHz)



By W.Kokuyama

背景重力波探査の現状



Shoda+, PRD D 89, 027101.