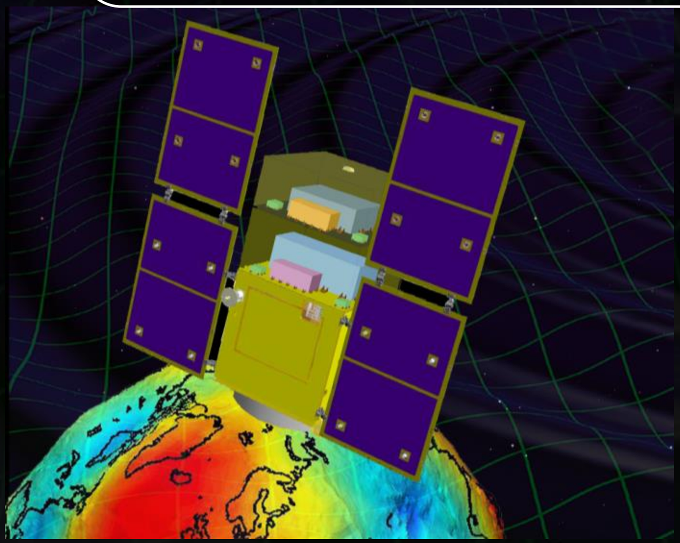
DECIGO: Space Gravitational-wave Antenna



Masaki Ando

(Dept. of Physics, Univ. of Tokyo / National Astronomical Observatory Japan)

- **KAGRA**
- **DECIGO**
- **DECIGO Pathfinder**

A little about

KAGRA Status

Gravitational-Wave Telescope

KAGRA (かぐら)

2nd Generation Large-scale Gravitational-Wave Telescope at Kamioka underground site

(Funded 2010-, Obs. : 2017-)

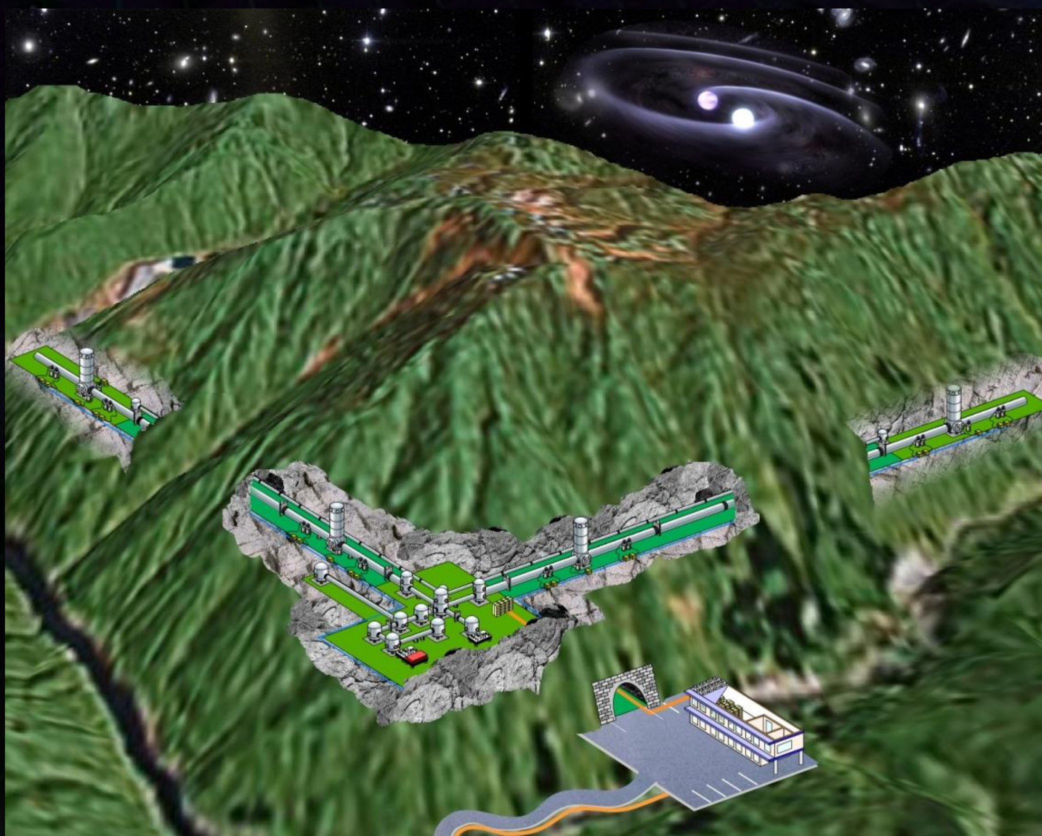
⇩

Open a new field of 'Gravitational-Wave Astronomy'

KAGRA Collaborations

219 Collaborators from more than 60 institutes

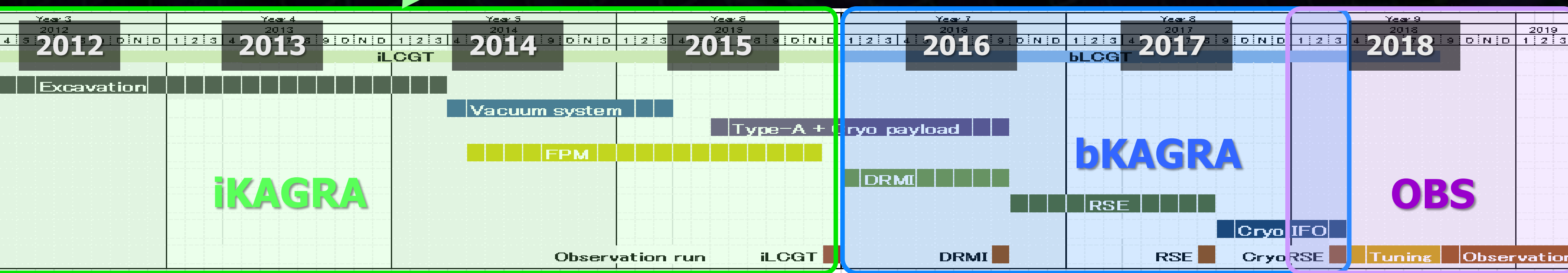
※ on April 2013



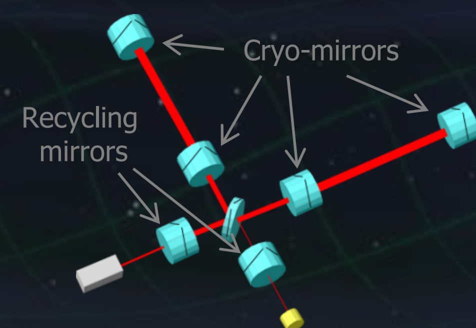
- Host:
  ICRR/U-Tokyo
- Co-host :
  NAOJ and KEK
- Collaborations
  U-Tokyo, ERI/U-Tokyo, Osaka-CU, TITEC, Osaka-U, Kyoto-U, NICT, AIST, UEC, Hosei-U, Ochanomizu-U, Niigata-U, Kyusyu-U, Nihon-U, Toyama-U, Caltech, MPQ, UWA, LSU, …

KAGRA Schedule

- **iKAGRA** (2010.10 – 2015.12)
  3-km FPM interferometer
  - Baseline 3km room temp.
  - Operation of total system with simplified IFO and VIS.



- **bKAGRA** (2016.1 – 2018.3)
  Operation with full config.
  - Final IFO+VIS configuration
  - Cryogenic operation.



Current Status of KAGRA

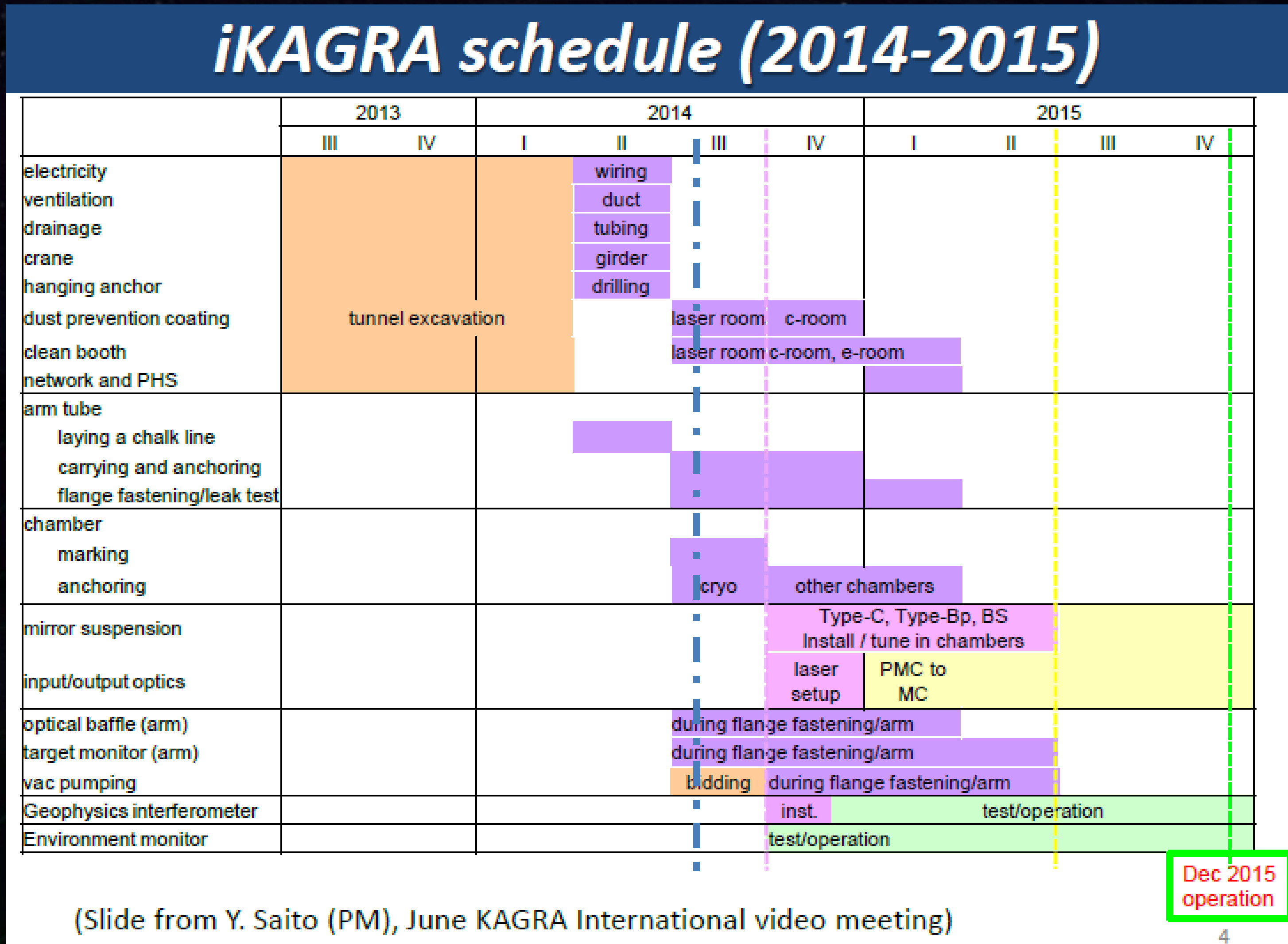
Tunnel excavation completed!

At the end of March 2014, the excavation of the KAGRA tunnel has been completed.

July 4, 2014: KAGRA tunnel visit.

From presentation file by
T.Kajita, KAGRA face-to-face Meeting (July 31th, Toyama)

Current Status of KAGRA



From presentation file by
T.Kajita, KAGRA face-to-face Meeting (July 31th, Toyama)

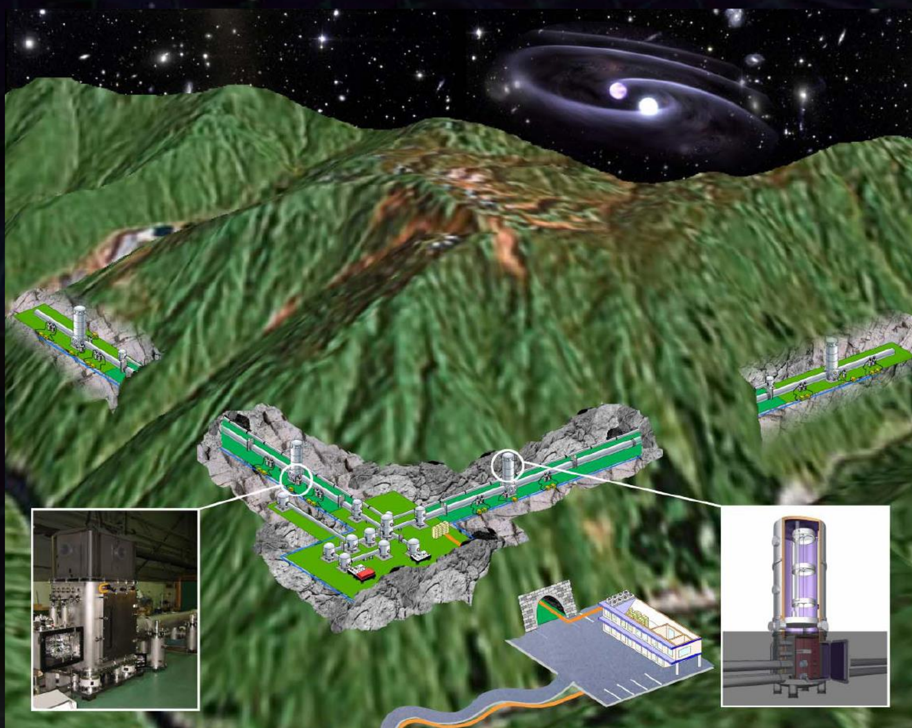
KAGRA and DECIGO

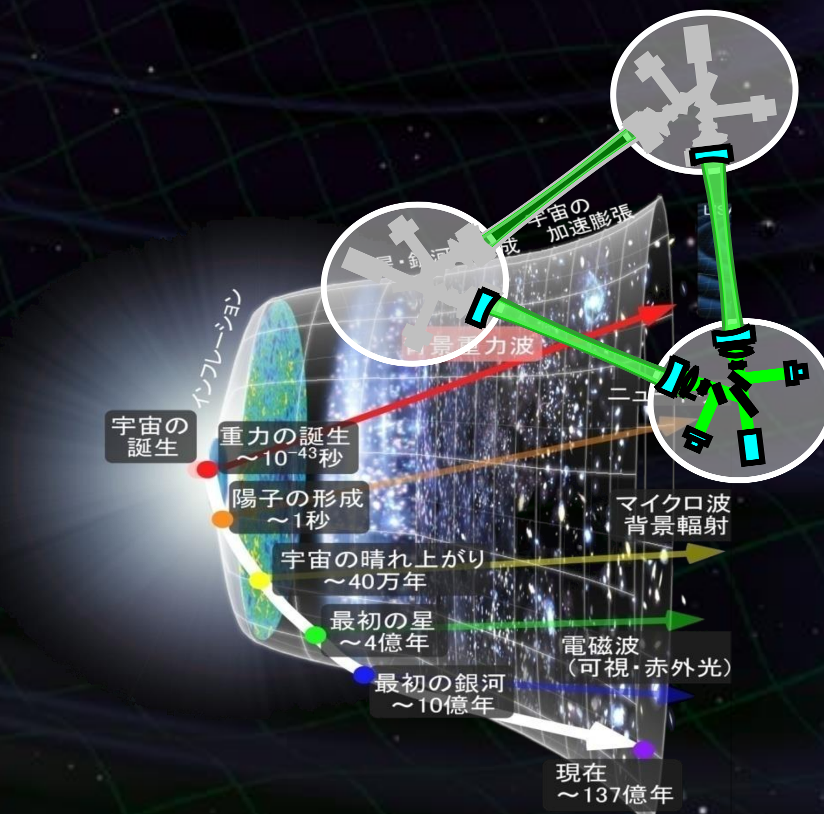
KAGRA (~2017)
Ground-based Detector
→ High-freq. GW events

Target : Detection, Astrophysics

DECIGO (~2027)
Space observatory
→ Low-freq. GW

Target : Cosmology





DECIGO

Space GW Antenna DECIGO

DECIGO (DECI-hertz interferometer Gravitational wave Observatory)

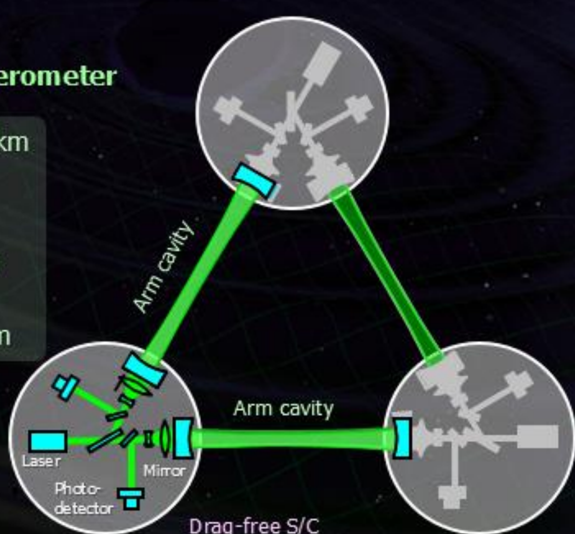
Purpose: To Obtain Cosmological Knowledge.

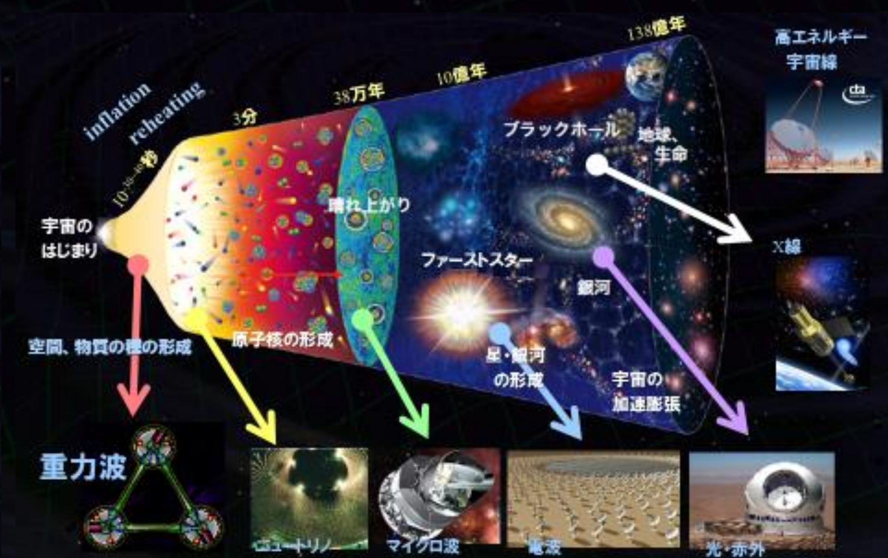
Direct observation of the origin of space-time and matter in Big-bang Universe.

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





背景画: 福井康雄監修「宇宙史を物理学で読み解く
-素粒子から物質・生命まで」(名古屋大学出版会)より

DECIGO Members

Koh-suke Aoyanagi, Kazuhiro Agatsuma, Tomotada Akutsu, Hideki Asada, Yoichi Aso, Koji Arai, Akito Araya, Masaki Ando, Kunihito Ioka, Takeshi Ikegami, Takehiko Ishikawa, Hideharu Ishizaki, Hideki Ishihara, Kiwamu Izumi, Kiyotomo Ichiki, Hiroyuki Ito, Yousuke Itoh, Kaiki T. Inoue, Akitoshi Ueda, Ken-ichi Ueda, Takafumi Ushiba, Masayoshi Utashima, Satoshi Eguchi, Yumiko Ejiri, Motohiro Enoki, Toshikazu Ebisuzaki, Yoshiharu Eriguchi, Naoko Ohishi, Masashi Ohkawa, Masatake Ohashi, Kenichi Oohara, Yoshiyuki Obuchi, Kenshi Okada, Norio Okada, Koki Okutomi, Nobuki Kawashima, Fumiko Kawazoe, Isao Kawano, Seiji Kawamura, Nobuyuki Kanda, Kenta Kiuchi, Naoko Kishimoto, Hitoshi Kuninaka, Hiroo Kunimori, Kazuaki Kuroda, Sachiko Kuroyanagi, Hiroyuki Koizumi, Feng-Lei Hong, Kazunori Kohri, WataruKokuyama, Keiko Kokeyama, Yoshihide Kozai, Yasufumi Kojima, Kei Kotake, Shiho Kobayashi, Rina Gondo, Motoyuki Saijo, Ryo Saito, Shin-ichiro Sakai, Masaaki Sakagami, Shihori Sakata, Norichika Sago, Misao Sasaki, Shuichi Sato, Takashi Sato, Masaru Shibata, Kazunori Shibata, Ayaka Shoda, Hisaaki Shinkai, Aru Suemasa, Naoshi Sugiyama, Rieko Suzuki, Yudai Suwa, Naoki Seto, Kentaro Somiya, Hajime Sotani, Takeshi Takashima, Tadashi Takano, Kakeru Takahashi, Keitaro Takahashi, Tadayuki Takahashi, Hirotaka Takahashi, Fuminobu Takahashi, Ryuichi Takahashi, Ryutaro Takahashi, Takamori Akiteru, Hideyuki Tagoshi, Hiroyuki Tashiro, Takahiro Tanaka, Nobuyuki Tanaka, Keisuke Taniguchi, Atsushi Taruya, Takeshi Chiba, Dan Chen, Shinji Tsujikawa, Yoshiki Tsunesada, Kimio Tsubono, Morio Toyoshima, Yasuo Torii, Kenichi Nakao, Kazuhiro Nakazawa, Shinichi Nakasuka, Hiroyuki Nakano, Shigeo Nagano, Kouji Nakamura, Takashi Nakamura, Yoshinori Nakayama, Atsushi Nishizawa, Erina Nishida, Kazutaka Nishiyama, Yoshito Niwa, Kenji Numata, Taiga Noumi, Tatsuaki Hashimoto, Kazuhiro Hayama, Tomohiro Harada, Wataru Hikida, Yoshiaki Himemoto, Hisashi Hirabayashi, Takashi Hiramatsu, Mitsuhiro Fukushima, Ryuichi Fujita, Masa-Katsu Fujimoto, Toshifumi Futamase, Ikkoh Funaki, Mizuhiko Hosokawa, Hideyuki Horisawa, Kei-ichi Maeda, Hideo Matsuhara, Nobuyuki Matsumoto, Yuta Michimura, Osamu Miyakawa, Umpei Miyamoto, Shinji Miyoki, Shinji Mukohyama, Mitsuru Musha, Toshiyuki Morisawa, Mutsuko Y. Morimoto, Shigenori Moriwaki, Kent Yagi, Hiroshi Yamakawa, Toshitaka Yamazaki, Kazuhiro Yamamoto, Jun'ichi Yokoyama, Shijun Yoshida, Taizoh Yoshino, Chul-Moon Yoo, Yaka Wakabayashi

(On February 28th, 2014)

GWs from Early Universe

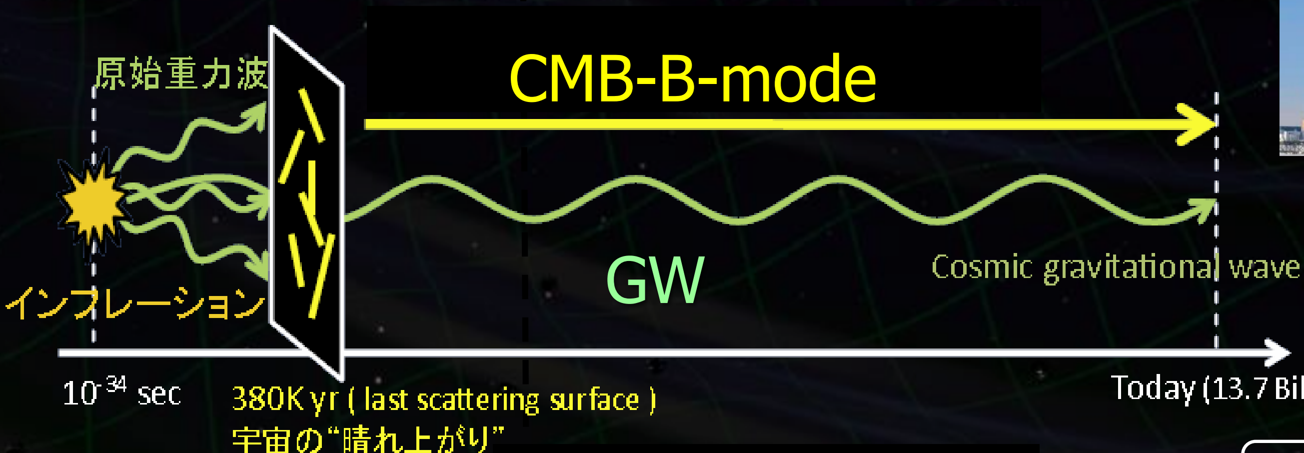
DECIGO

BICEP2, (WMAP, Planck,…)

Observation of
CMB B-mode Polarization
with radio telescope.

DECIGO, (KAGRA, aLIGO,…)

Observation of
Gravitational-wave background
with GW telescope.



CMB Polarization telescope

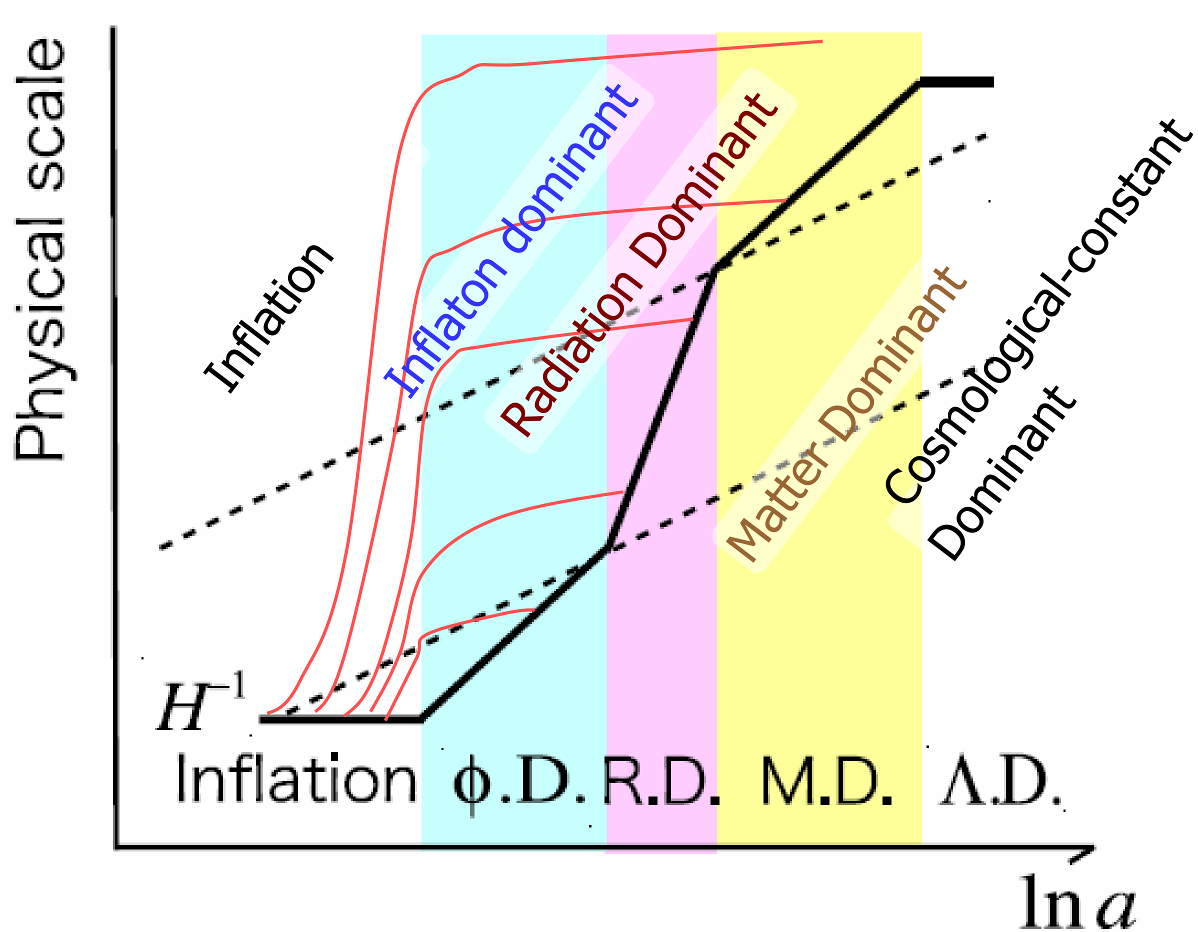
GW telescope

図: 田島氏談話会資料より(2011 京都大学)

GW from Inflation

DECIGO

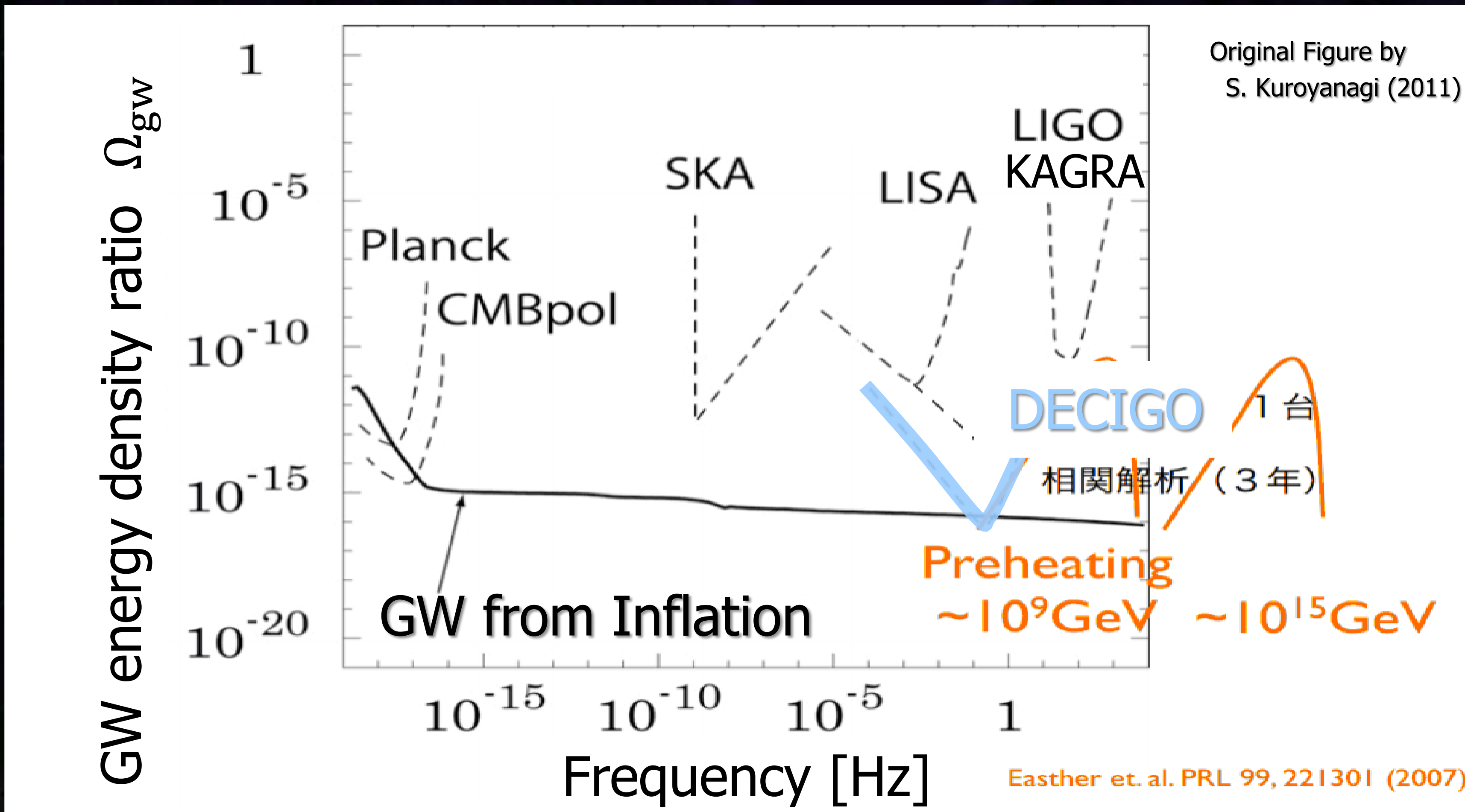
GWs in early phase of inflation → Expanded more in inflation and re-enter to the horizon later → Lower freq. GWs.



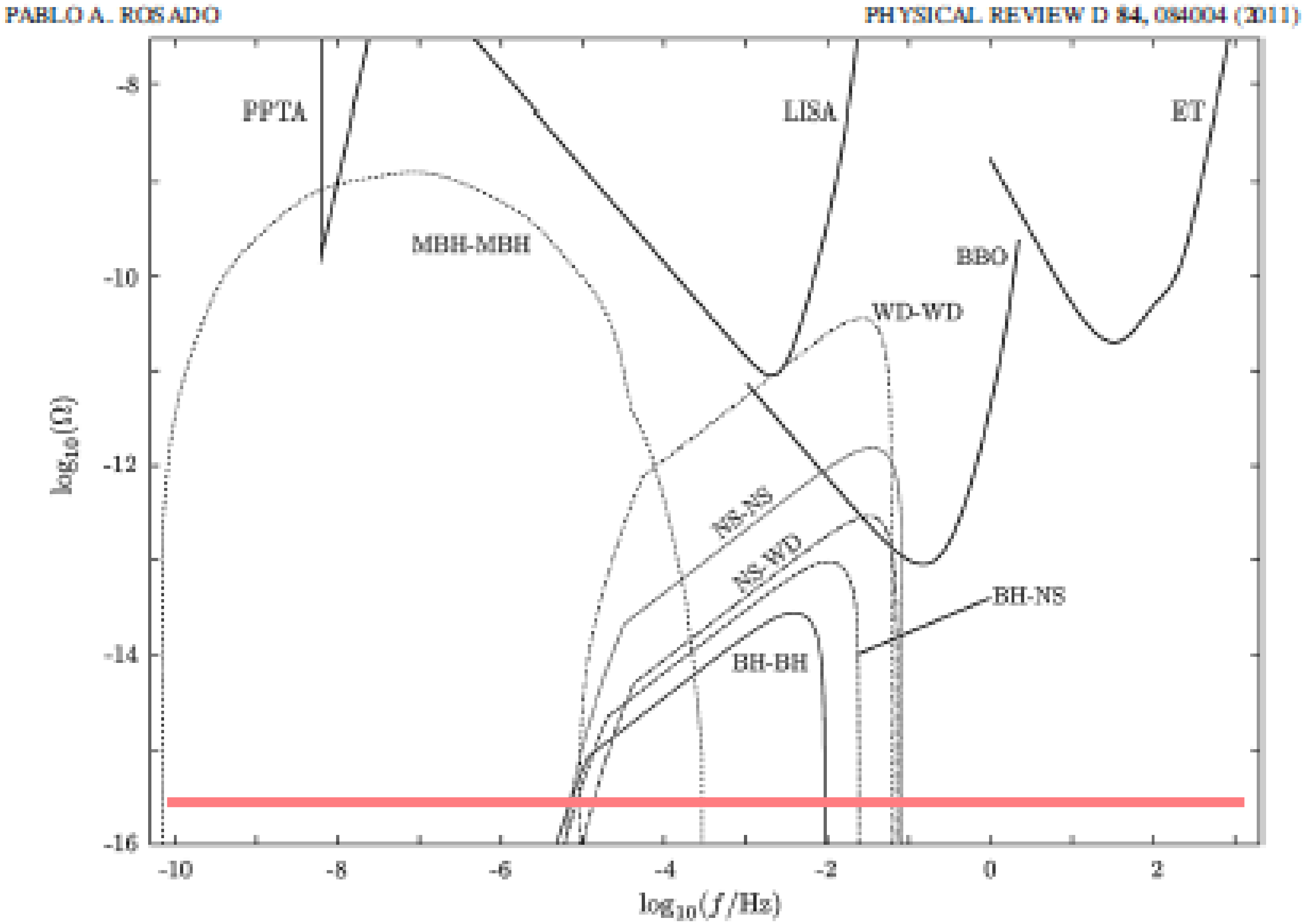
Nakayama+, Journal of Cosmology and Astroparticle Physics 06 (2008) 020.

Primordial GW

Earlier universe → Smaller horizon scale → High GW freq.



GW Foreground

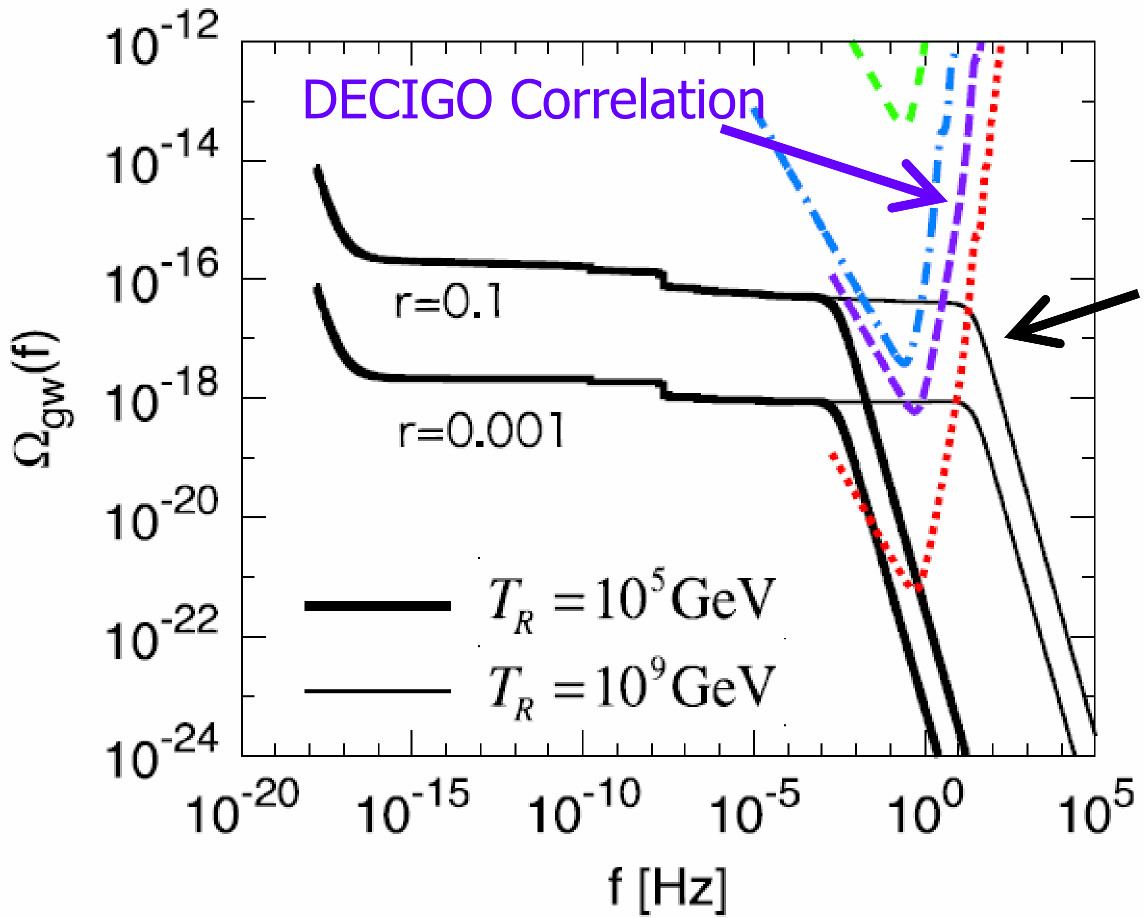


PABLO A. ROSADO PHYSICAL REVIEW D 84, 084004 (2011)

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

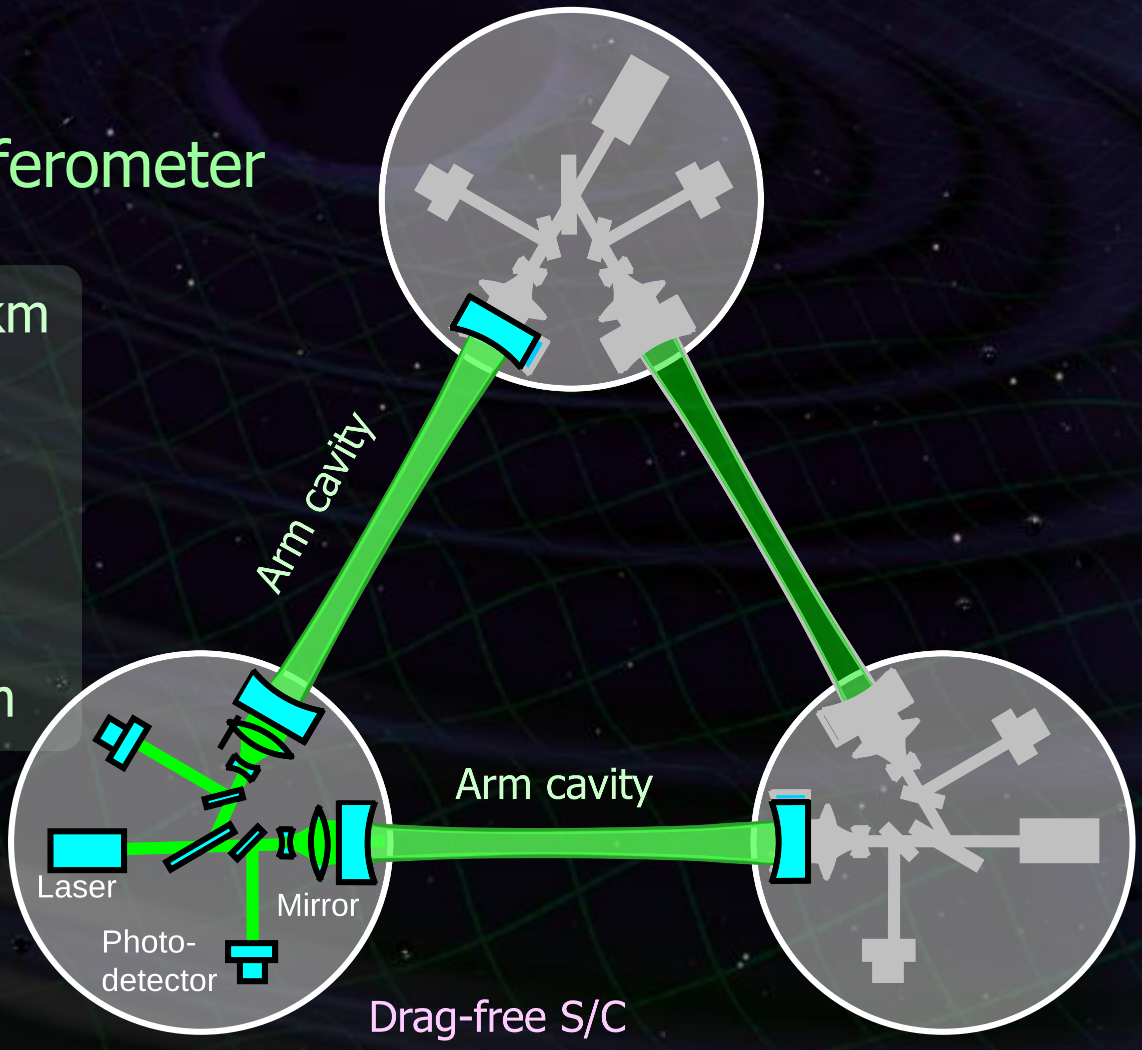
Interferometer Unit:

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

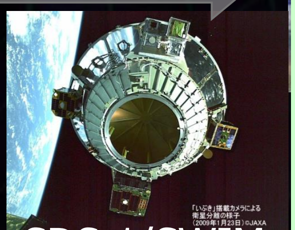
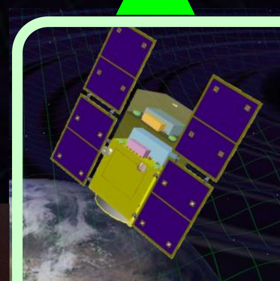
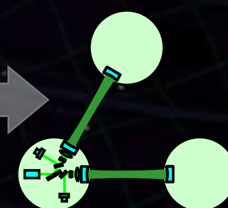
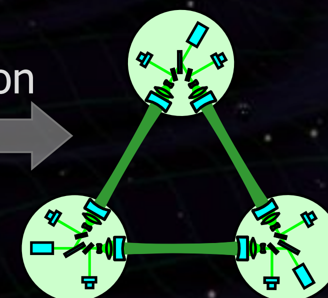
S/C: drag free

3 interferometers



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

DECIGO Pathfinder

Technical Steps for DECIGO

- Key technologies for DECIGO

  (1) Precise measurement by laser interferometer.

  Operation of Fabry-Perot interferometer in Space environment and Drag-free control.

  ⇨ Demonstration by DPF

  (2) Long-baseline formation flight.

  Realization of precise formation flight with more than km scale

  ⇨ Demonstration by Pre-DECIGO

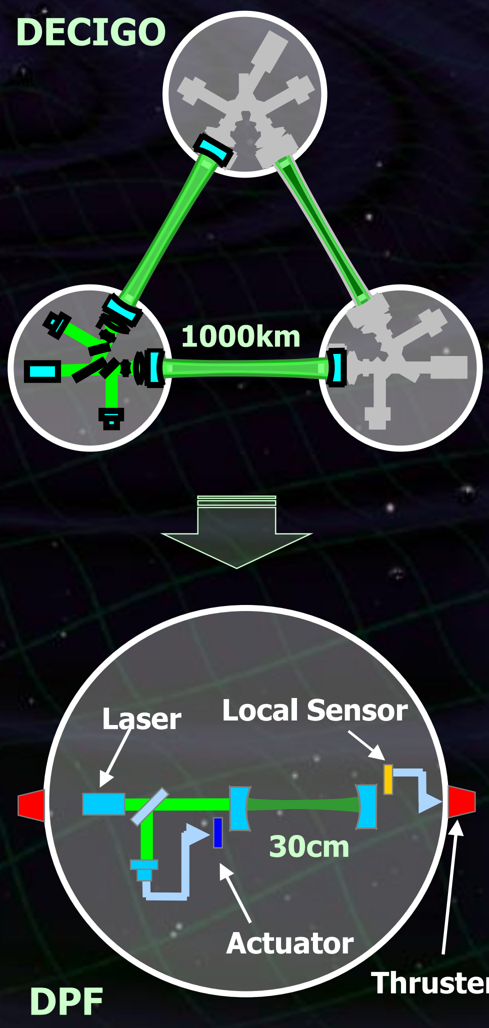
DECIGO-PF

DECIGO Pathfinder (DPF)

First milestone mission for DECIGO

Shrink arm cavity

DECIGO 1000km → DPF 30cm



Purpose

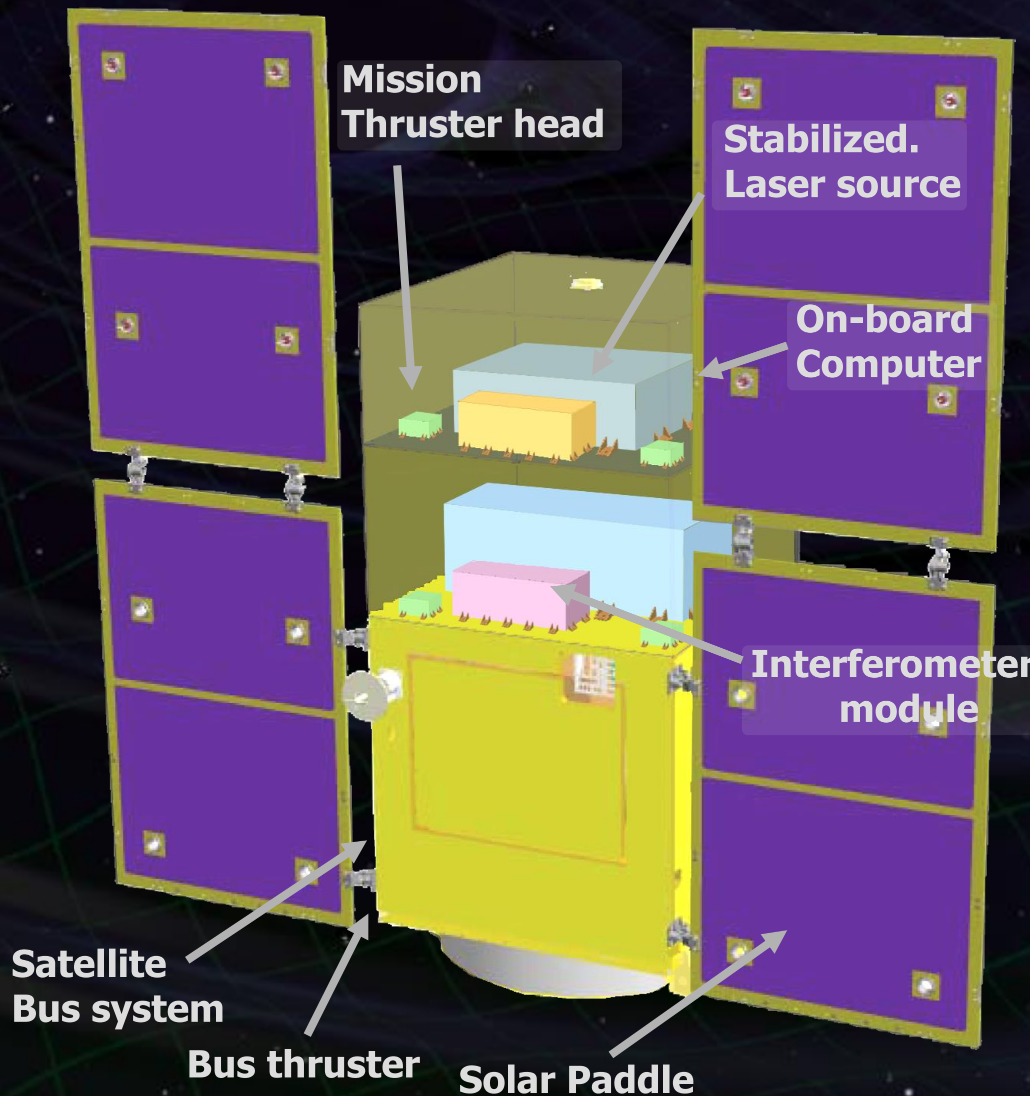
- FP interferometer in space
- Stabilized laser source
- Drag-free control
- Continuous data-processing

DPF satellite

DPF Payload
Size : 950mm cube
Weight : 200kg
Power : 130W
Data Rate: 800kbps
Mission thruster x10

Power Supply
SpW Comm.

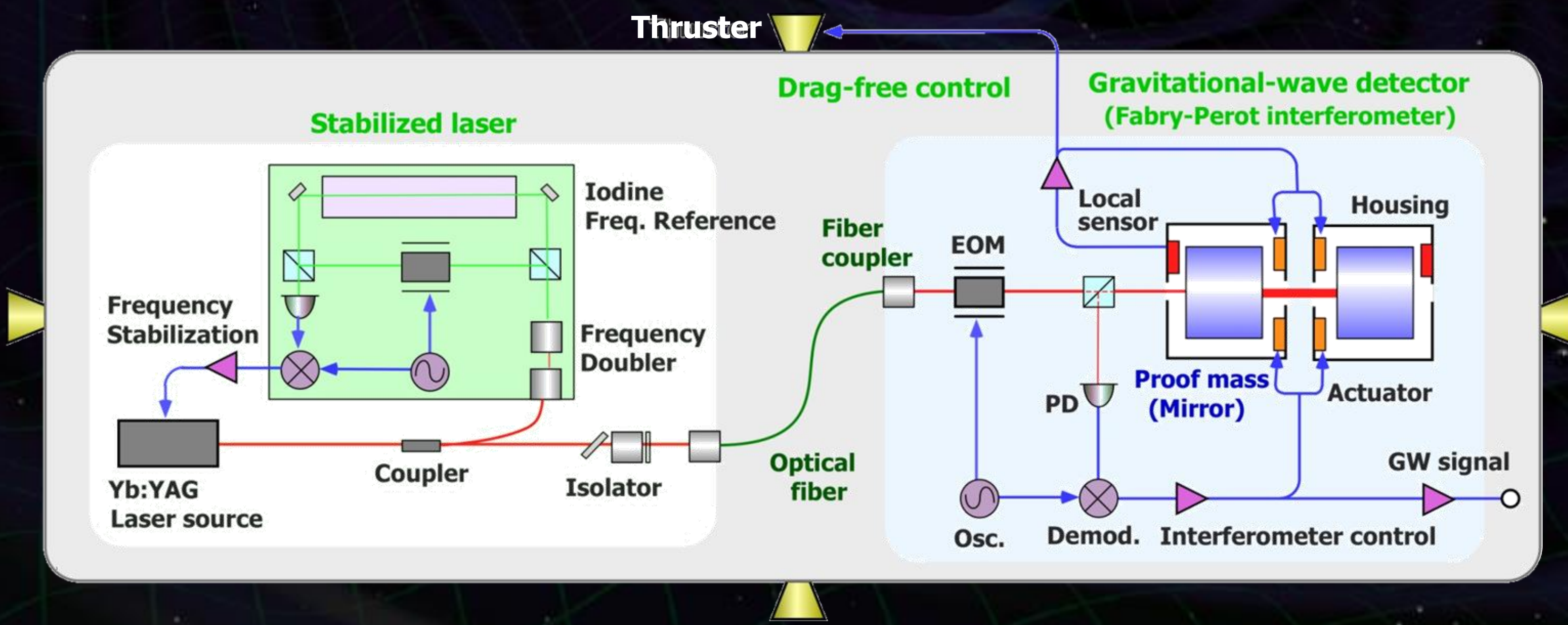
Satellite Bus
('Standard bus' system)
Size :
950x950x1100mm
Weight : 250kg
SAP : 960W
Battery: 50AH
Downlink : 2Mpbs
DR: 1GByte
3N Thrusters x 4



DPF mission payload

Mission weight : ~200kg
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

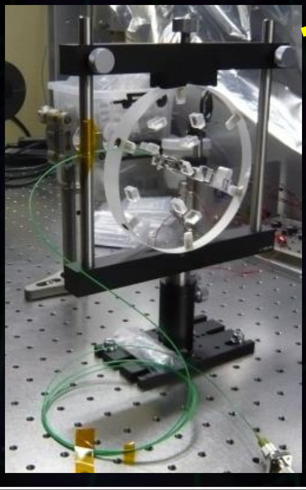
Fabry-Perot interferometer
Finesse : 100
Length : 30cm
Test mass : ~a few kg
Signal extraction by PDH

Interferometer Module

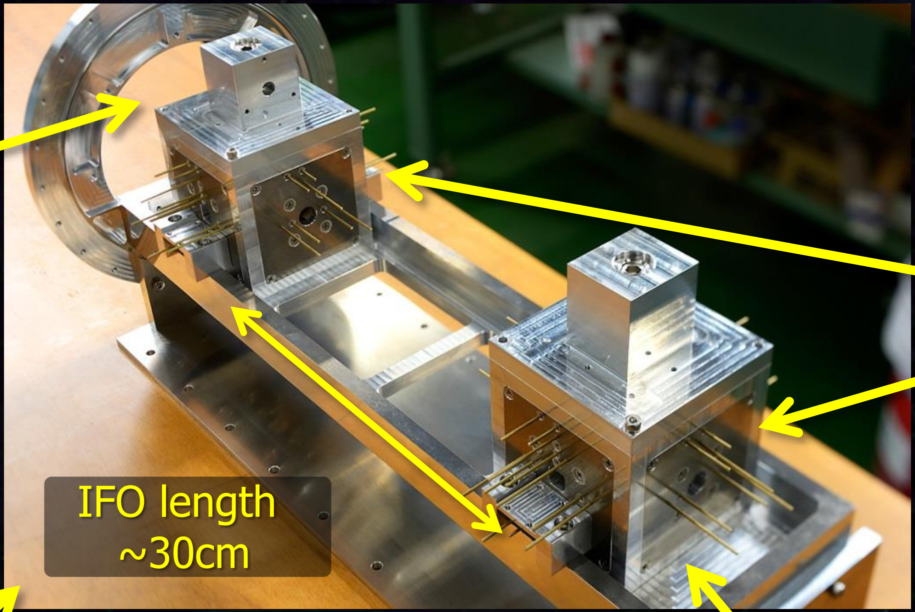
DECIGO

IO Optics

Monolithic opt. bench by silicate bonding

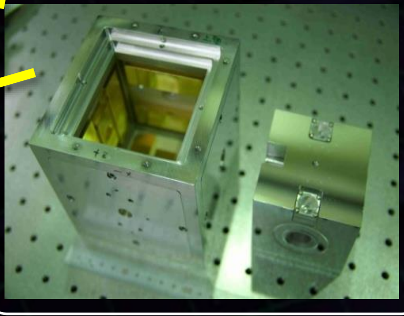


Interferometer Module



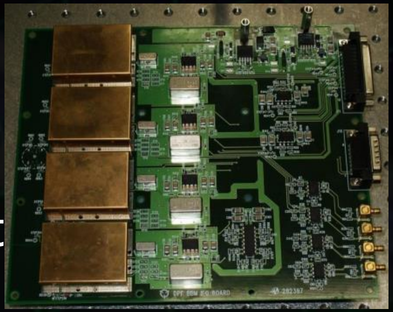
Test mass module

TM, Capacitive Sensor/Actuator, Launch lock



Quad-RFPD

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

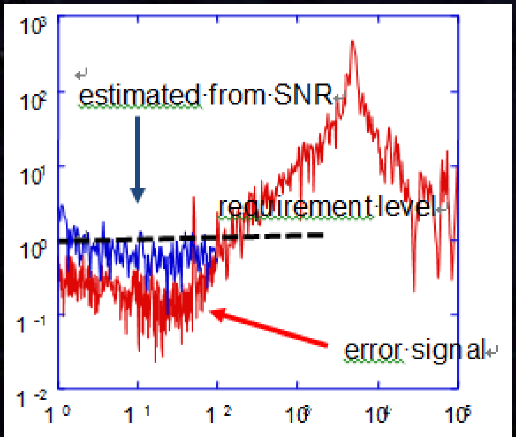


SpW signal-processing board

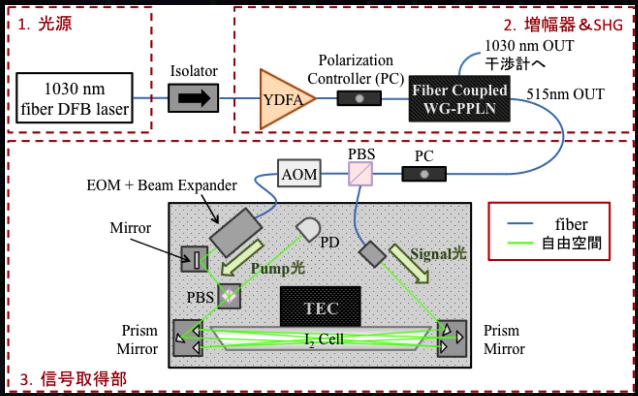
SpW FPGA + 16bit AD/DA

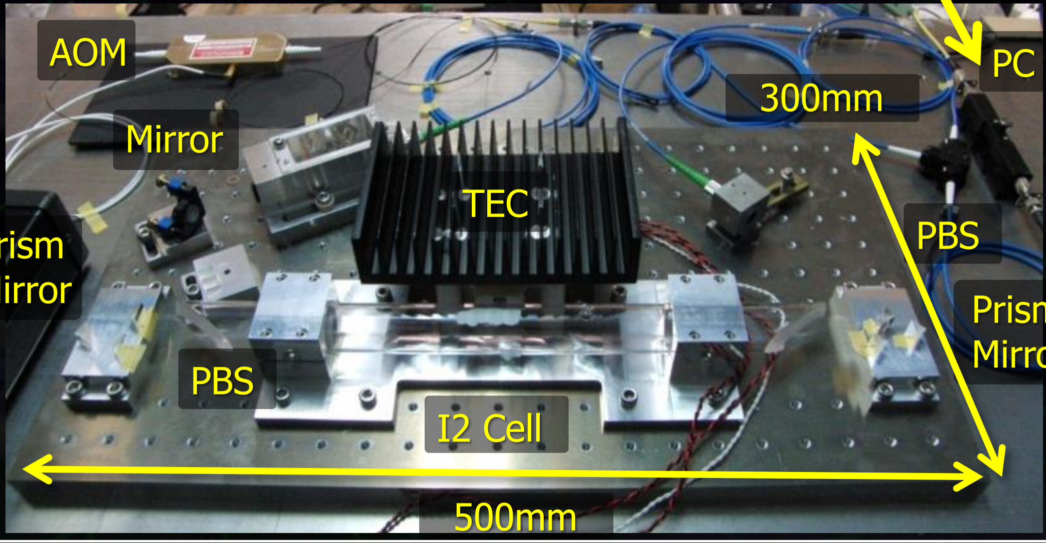
Frequency Stabilization Module

- 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





DPF mission status

DPF : One of the candidate of
JAXA's small satellite program

↑

~150M$ -scale mission opportunity
Standard Bus + Epsilon rocket

SPRINT-A /EXCEED UV telescope mission

1st mission (2012): SPRINT-A/EXCEED
2nd mission (~2015) : SPRINT-B/ERG
DPF survived until final two
3rd mission (~2019) : TBD
Call for proposal : 2014
↑ DPF proposal submitted

Epsilon rocket Fig. by JAXA

Mission Selection Result

DECIGO

- AO from JAXA (December 2013)
  for small science mission using epsilon rocket.
  - The program framework was changed:
    ~10 M$ payload mission → ~150 M$ mission
  - Deadline : End of February.
  - 7 mission proposals including DPF.

⇨ DPF was dropped in the first down-selection (May)

- Started discussions on the next strategy.

Restructure of Space Program

DECIGO

- ISAS/JAXA decided a new plan for space science and exploration program (2014)
  - Three categories
    - * Strategic medium-scale missions (~300 M$)
      Hayabusa-2, ASTRO-H
    - * Small-scale missions (100 - 150 M$)
      AO in every two years
      HISAKI, ERG, …
    - * Various small projects (~10 M$/year)
      ISS missions, International collaboration,
      Small rocket, Balloon, …

⇨ 'Small-scale' mission became core program in JAXA

Summary

Summary

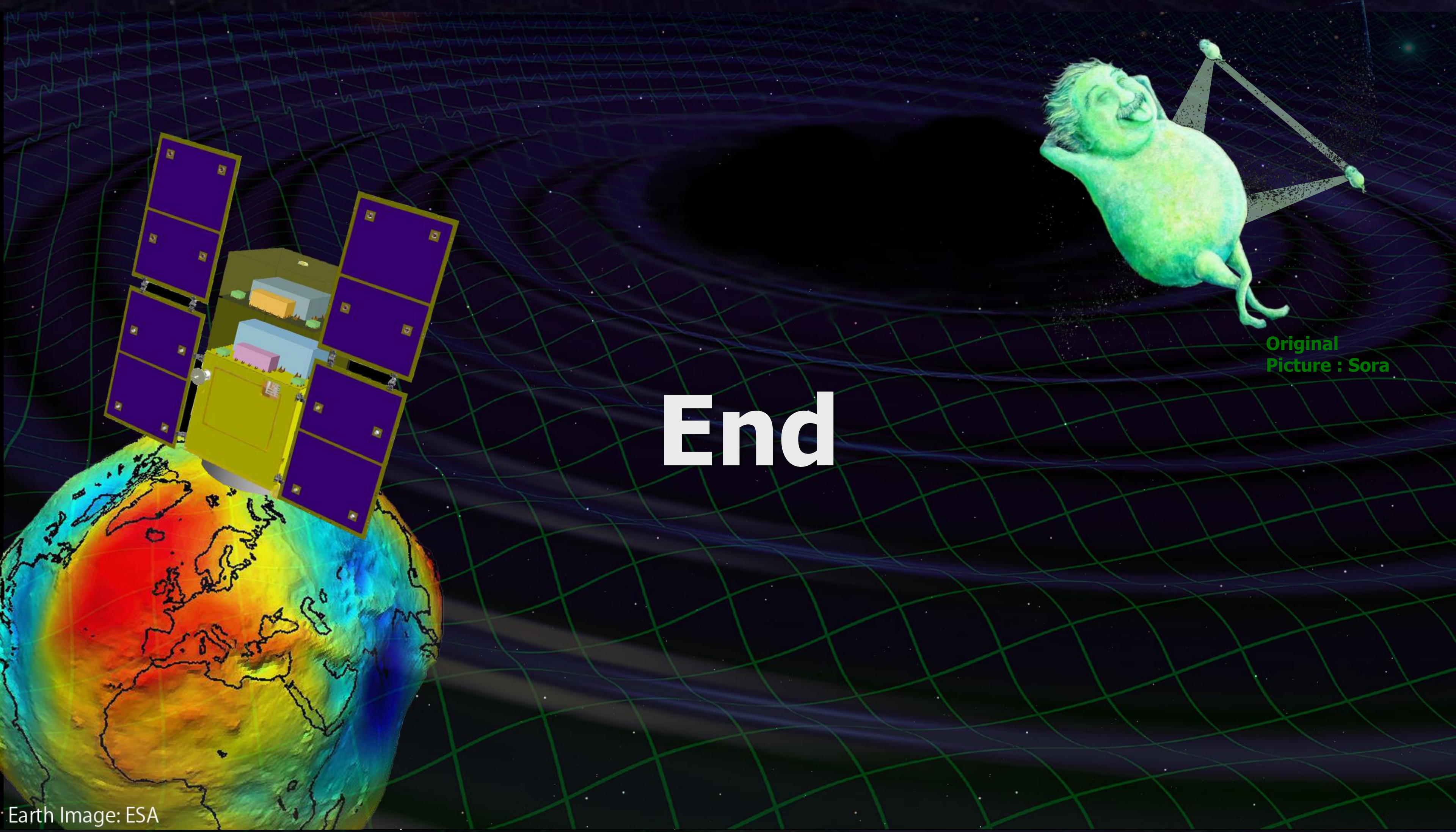
DECIGO : Fruitful Sciences

Very beginning of the Universe
Dark energy, Dark matter
Galaxy formation
→ Will be realized at last.

DECIGO Pathfinder

Submitted mission proposal,
but failed in the selection.
→ Start discussions on the next strategy.

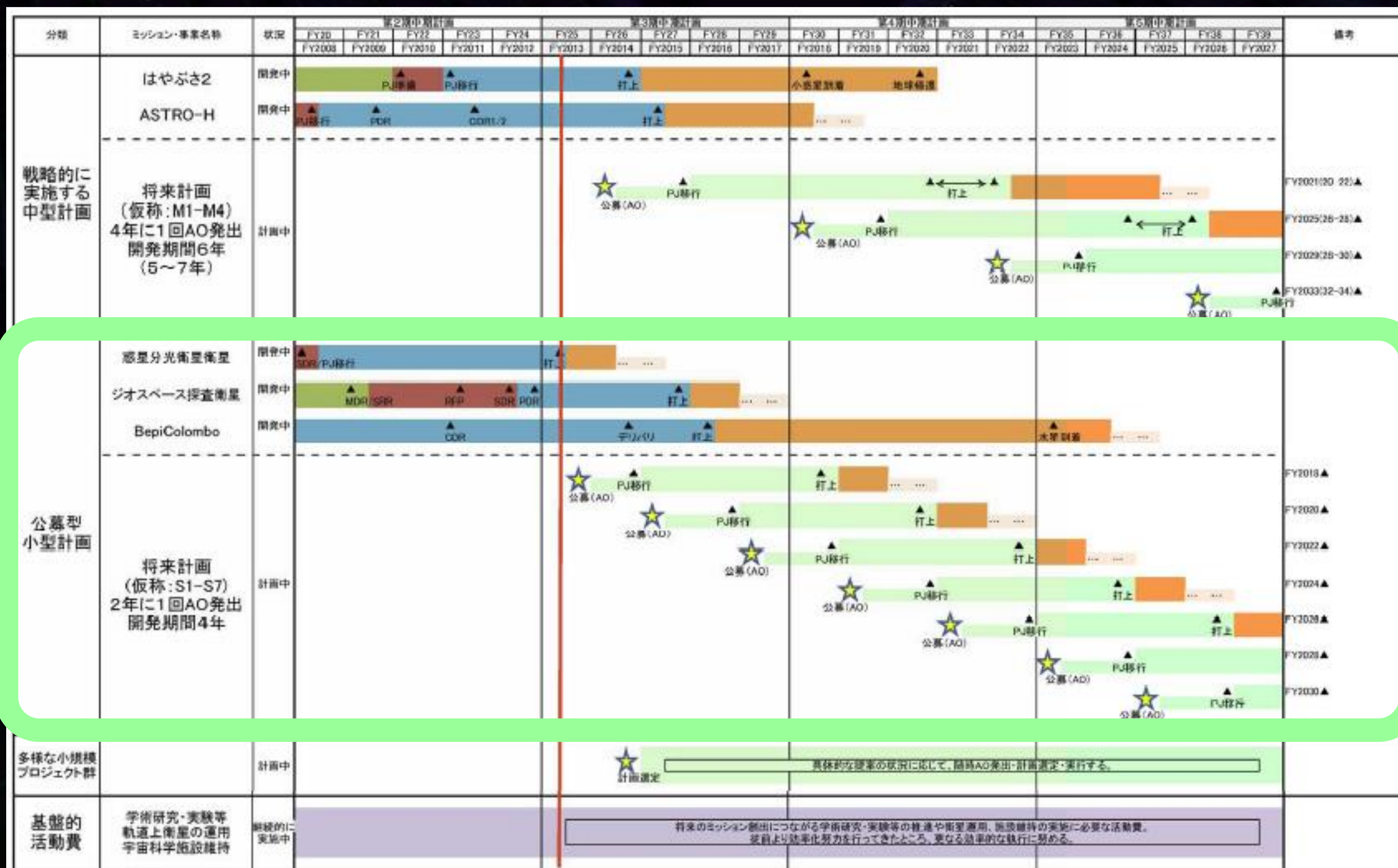
End



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).

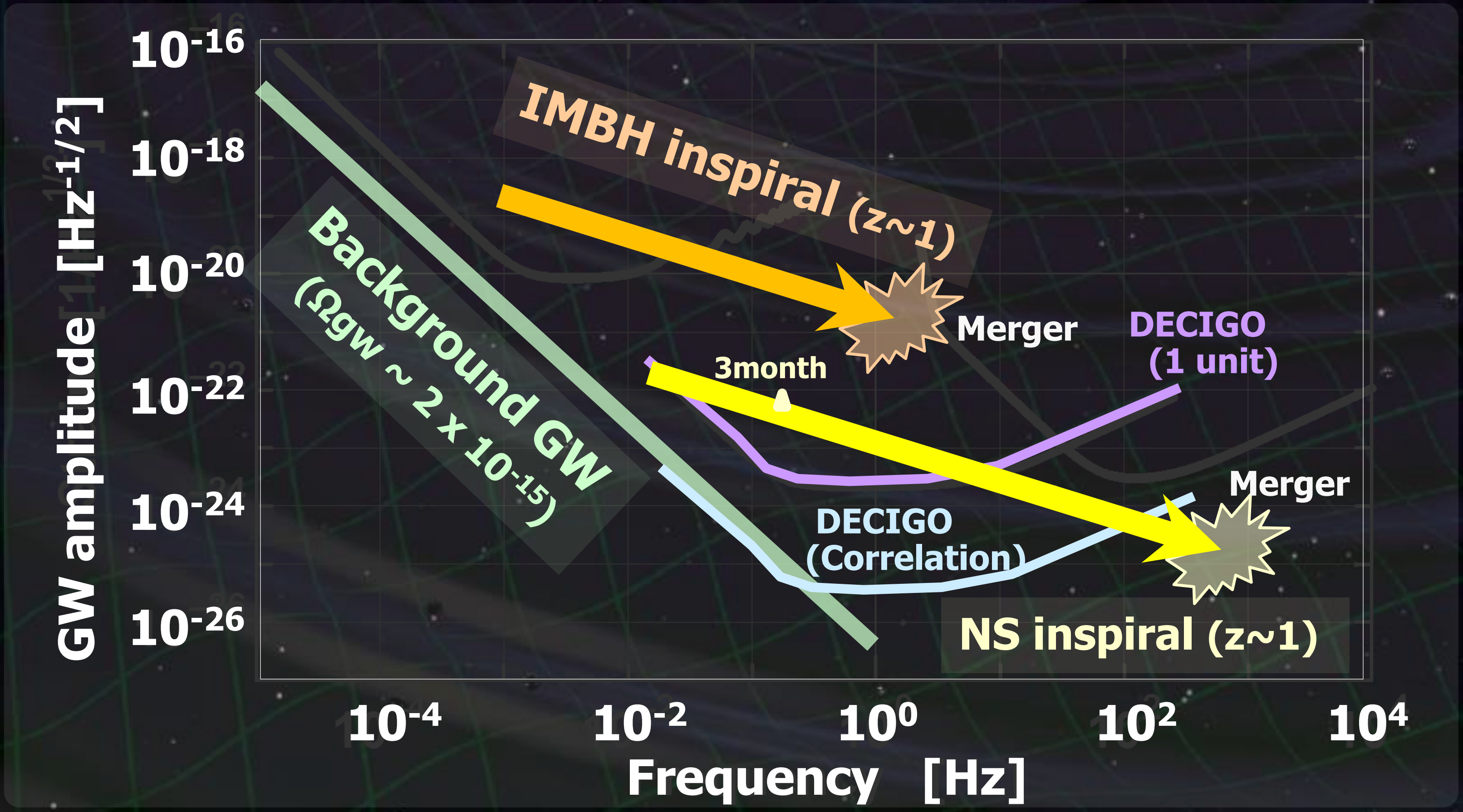


Targets and Science

IMBH binary inspiral
NS binary inspiral
Stochastic background

⇨

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

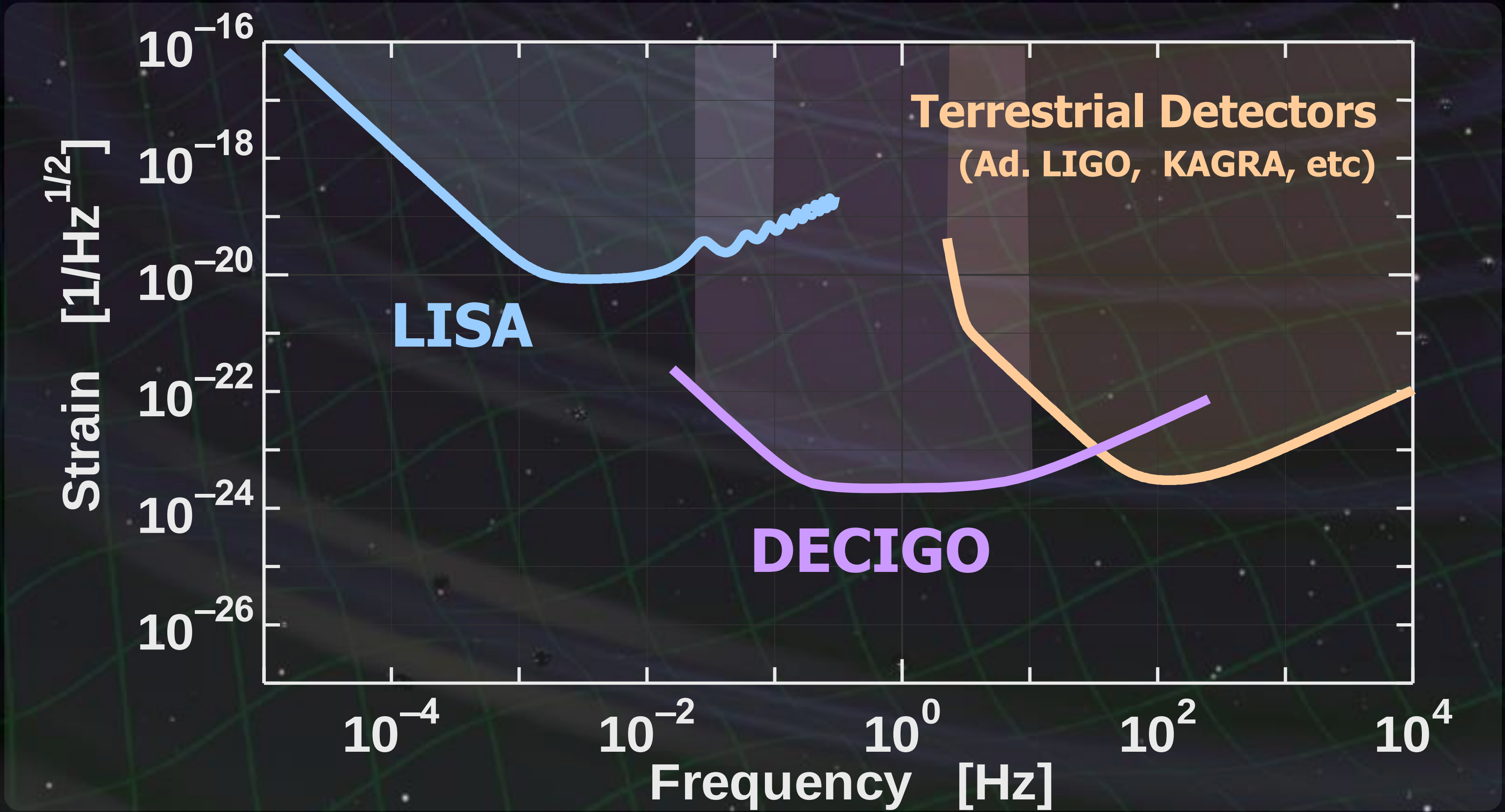


DECIGO

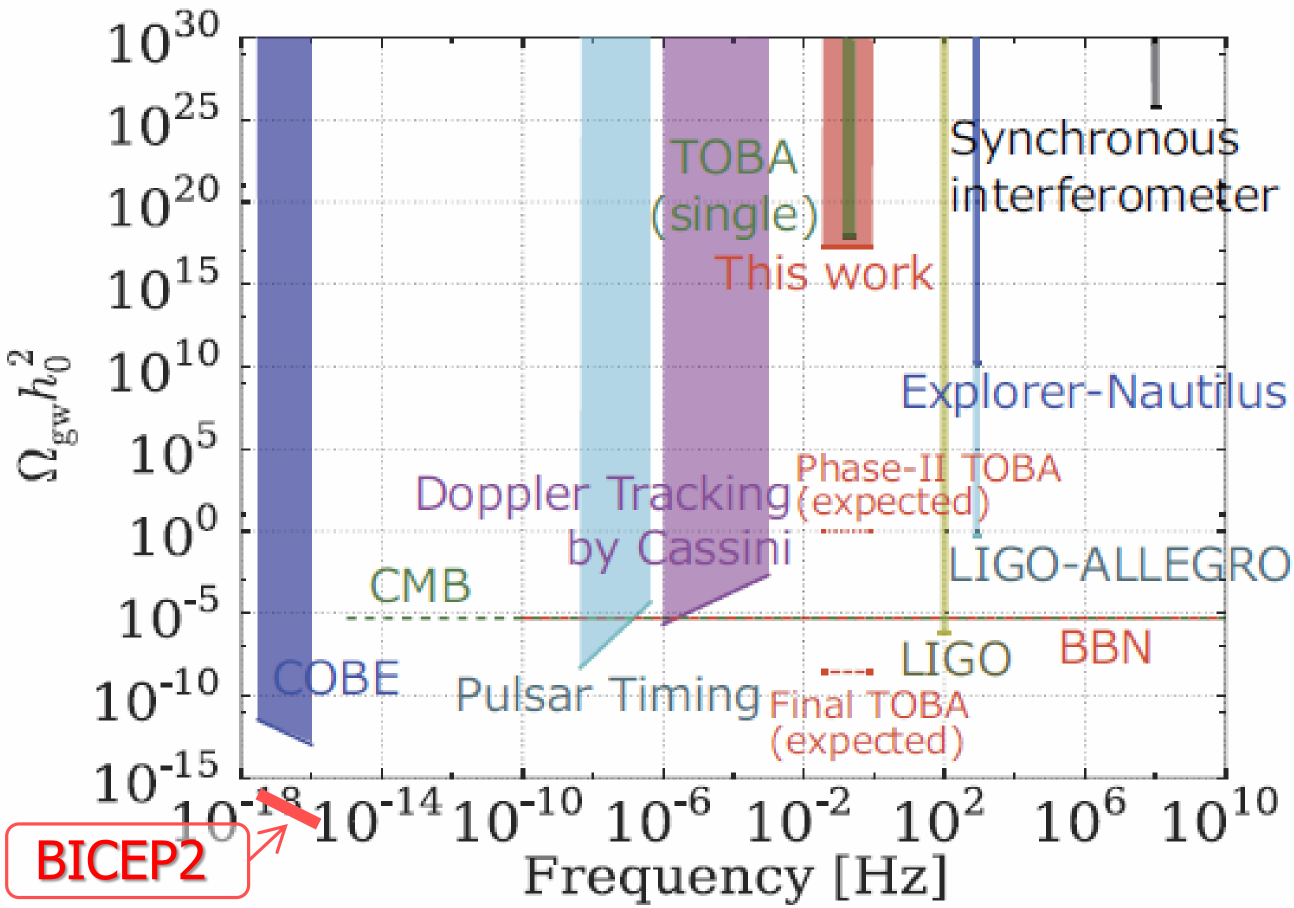
DECIGO (**Deci-hertz interferometer Gravitational wave Observatory**)

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

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



背景重力波探査の現状



Shoda+, PRD D 89, 027101.

Technical Steps for DECIGO

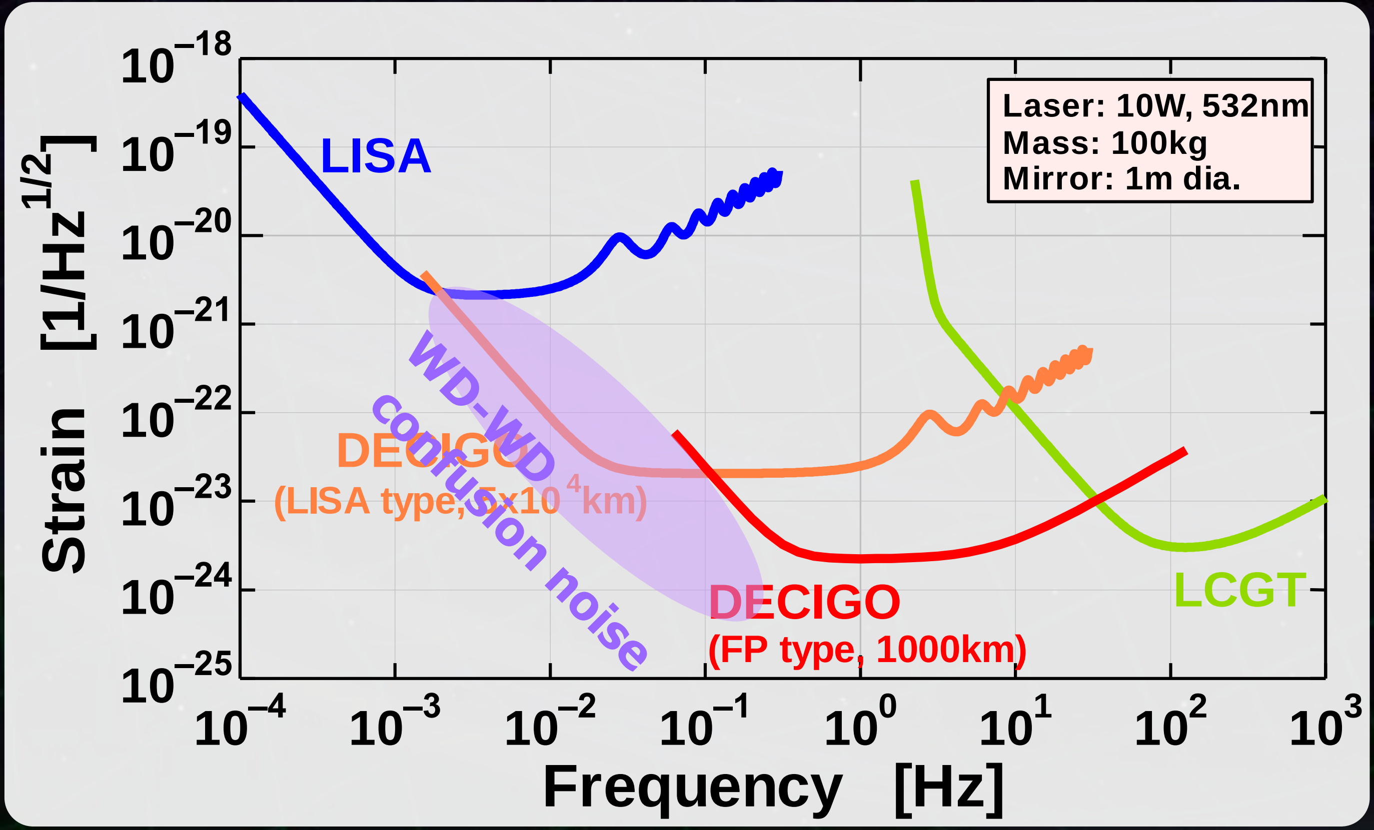
	DPF target	Pre-DECIGO target	DECIGO Requirement
Space FP	First demonstration of FP cavity (30cm) in space. Disp. noise ~10^{-16}m/Hz$^{1/2}$, Acc. Noise 10^{-15} N/Hz$^{1/2}$.	FP operation with long-base line (100km). Disp. noise 10^{-17}m/Hz$^{1/2}$ Acc. noise 10^{-16} N/Hz$^{1/2}$.	Disp. 3x10^{-18} m/Hz$^{1/2}$. Acc. 10^{-17} N/Hz$^{1/2}$. Baseline length 1000km.
Stab. Laser source	Freq. stability of 0.5Hz/Hz$^{1/2}$ in space environment. Output pow. : 100mW.	Freq. stability of 0.5Hz/Hz$^{1/2}$. Output pow. : 1W.	Freq. Stab. of 0.5Hz/Hz$^{1/2}$. Output pow. : 10W.
Drag-free Control and FF	Realize all DoF drag-free control with 1x10^{-9} m/Hz$^{1/2}$.	All DoF DF control 1x10^{-9} m/Hz$^{1/2}$. Long-baseline Formation Flight 100km.	All DoF DF control 1x10^{-9} m/Hz$^{1/2}$. Long-baseline FF 1000km.

DECIGO

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

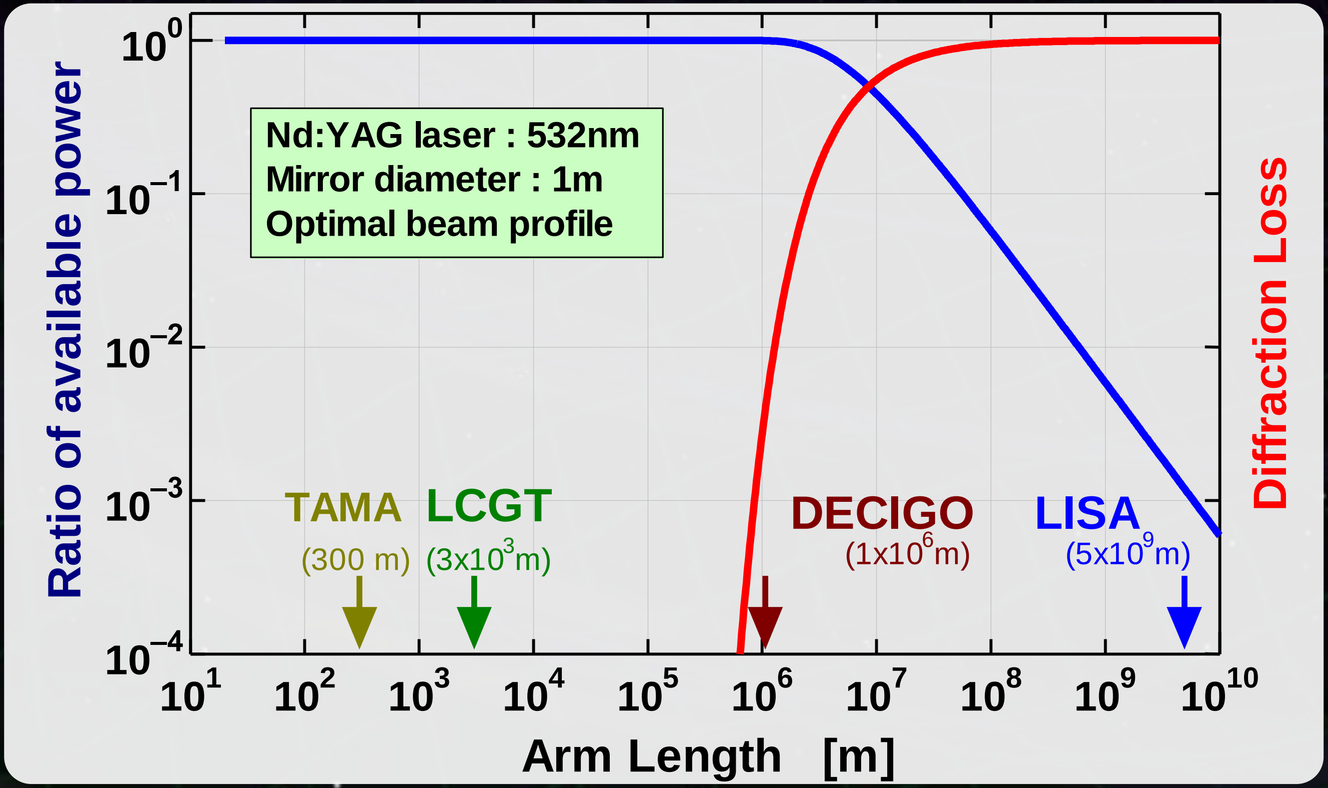
Effective reflectivity (TEM_{00} → TEM_{00})

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

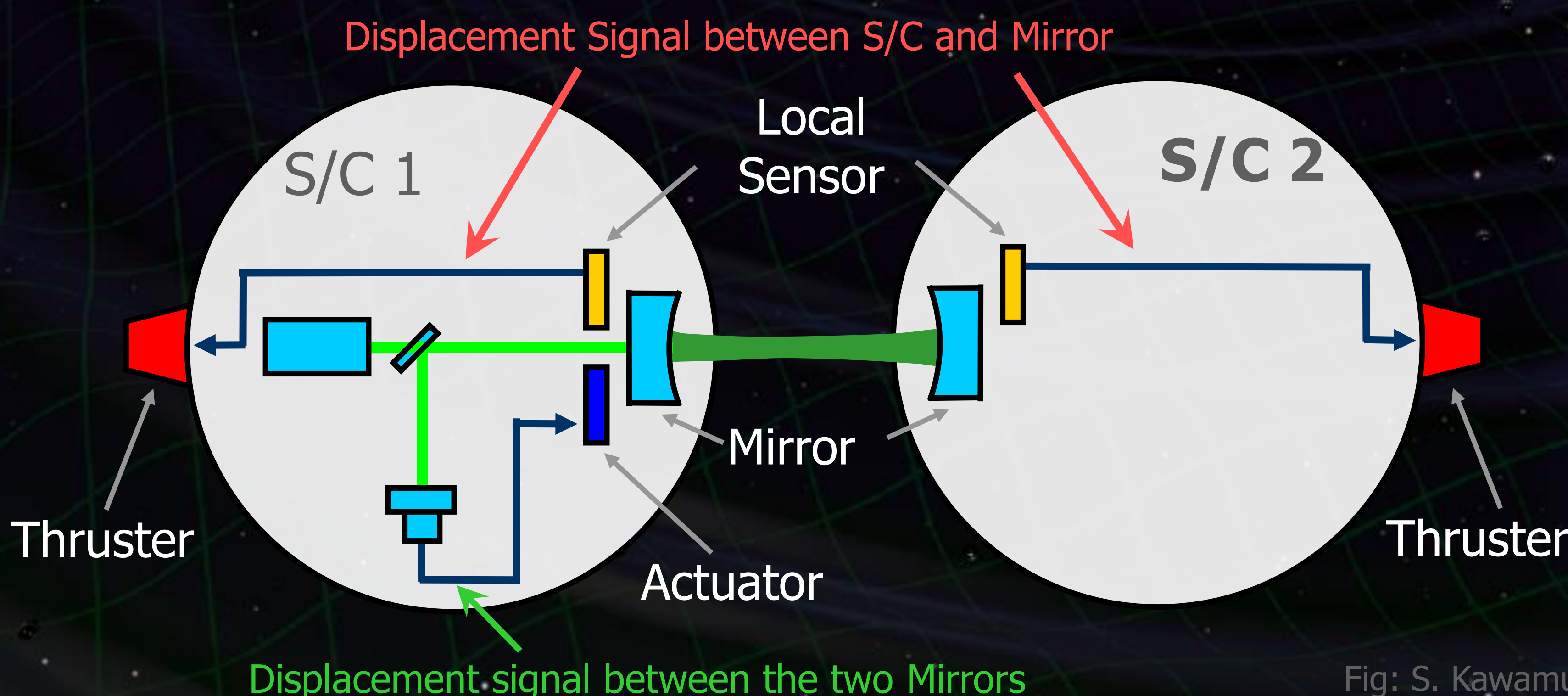


Fig: S. Kawamura

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

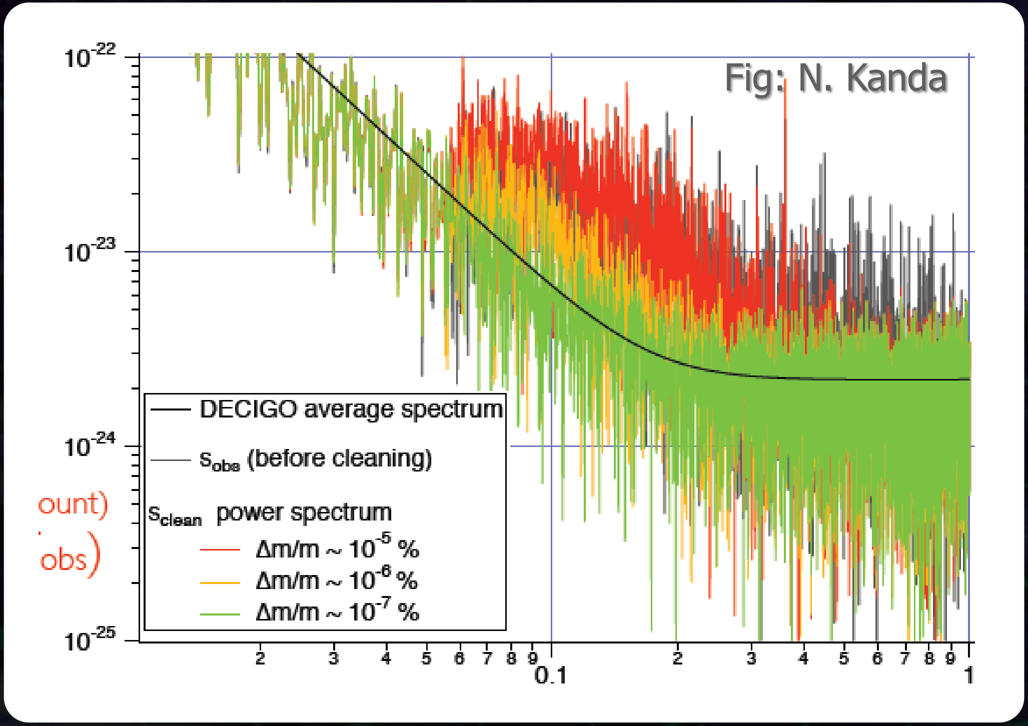
DECIGO obs. band: free from WD binary foreground
→ Open for cosmological observation

DECIGO will watch
~ 10^5 NS binaries

⇨ Foreground for GWB

In principle, possible
to remove them.

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



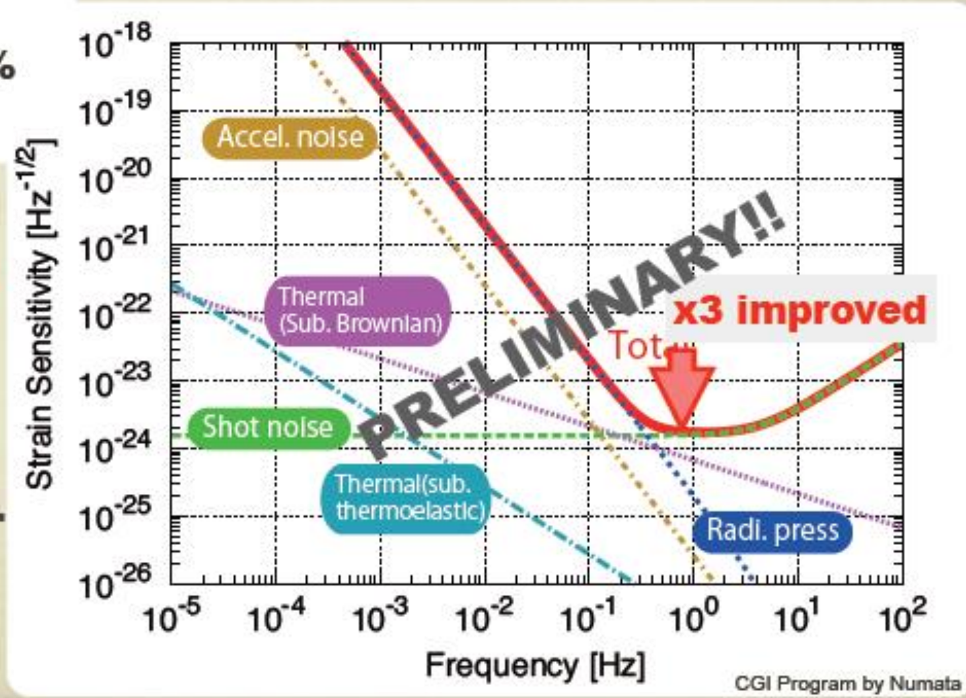
Design Update

By T.Akutsu

Considering "Conceptual design"

- 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



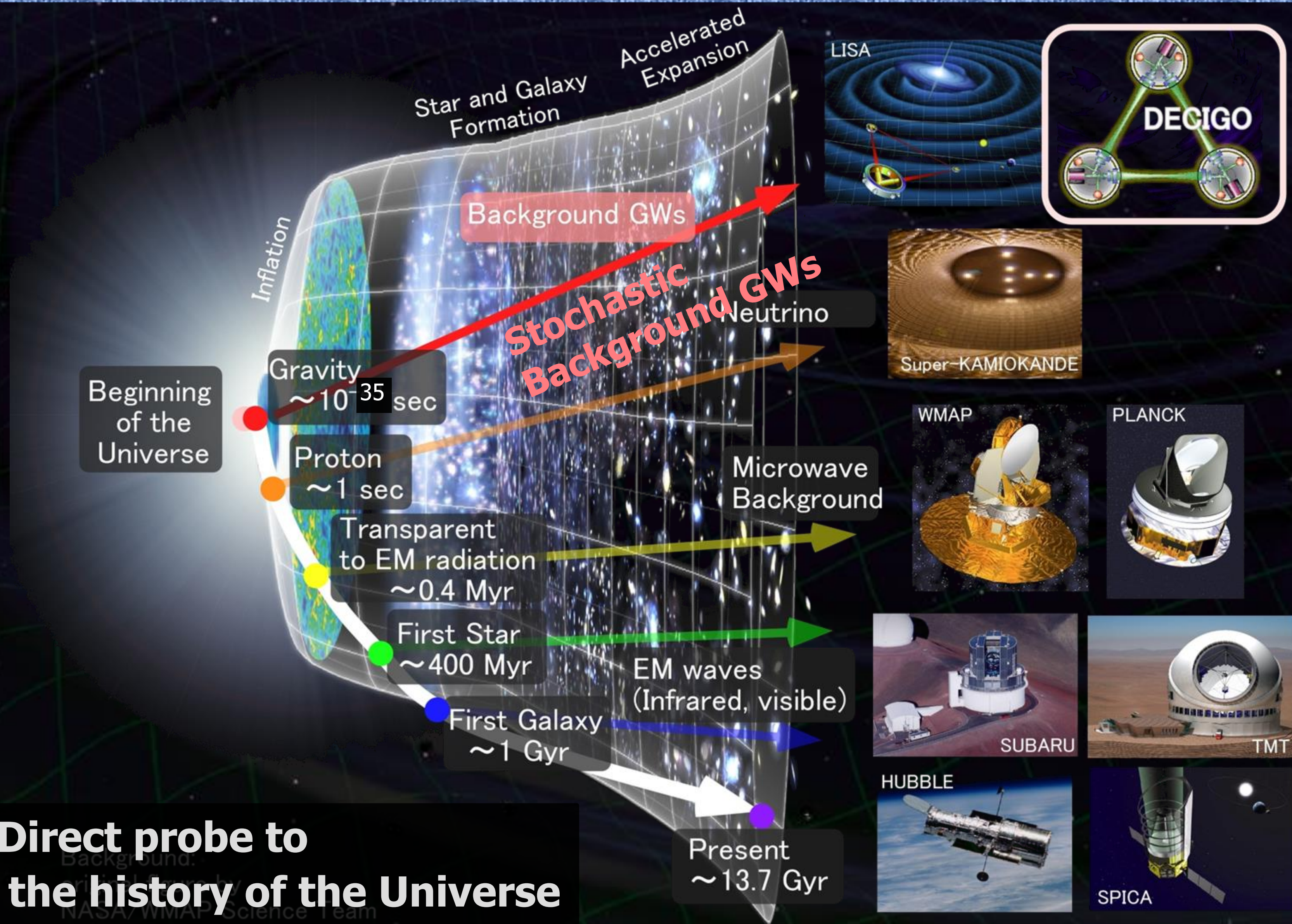
This is the first step to considering the conceptual design.

Next:

➡Confirm the calculations.
➡Find the realistic way to realize this!

14 GWADW2011 in Isola d'Elba (24 May 2011)

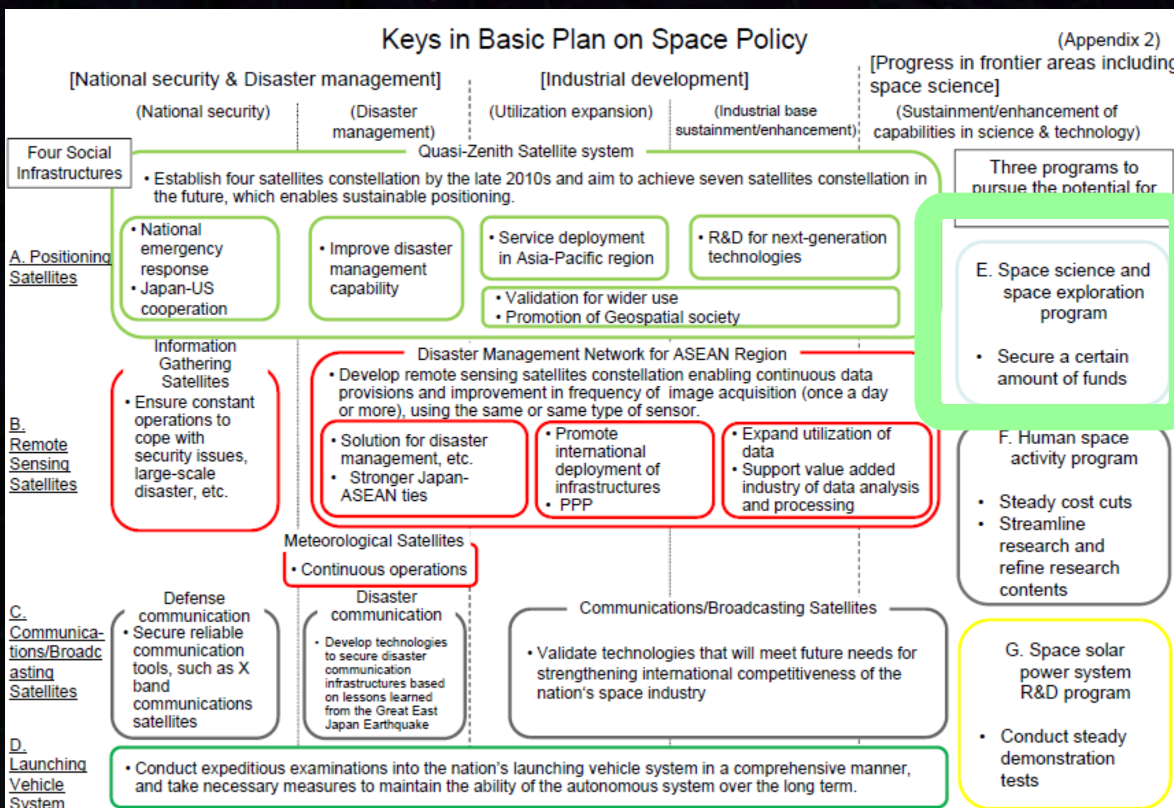
Characterization of inflation



Direct probe to the history of the Universe

Restructure of space sections

- Restructure of space sections in Japan (2008)
  Based on a new law : Basic Plan on Space Policy
  ISAS/JAXA : MEXT → Cabinet Office (CAO)

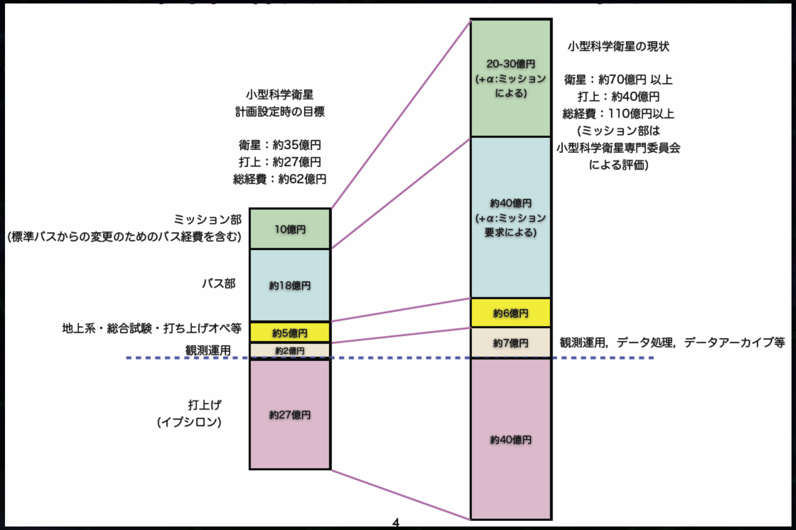


Space Science and space exploration program

From CAO Web Page :http://www8.cao.go.jp/space/plan/plan-eng.pdf

小型科学衛星シリーズ

- 小型科学衛星シリーズの位置づけが見直された.
  - 小型科学衛星プログラムは「特徴ある宇宙科学ミッションを迅速かつ高頻度に実現する」目的で進められた.
  - しかし, 2011年にERG（小型科学衛星2号機）の想定資金からの大幅超過をきっかけとして, 小型科学衛星シリーズとしてのプロジェクトは Termination された.
  - 小型科学衛星専門委員会によるコスト評価, および, SE推進室の評価.
    → 検討中のWGのミッション実現には, マージン無しで70から120億円の衛星コスト（当初想定の1.7から3.4倍）が必要であることが示唆された.
  - これまで: ミッション部 10億円以内
    → 今後 ミッション部 20~30+α億円.

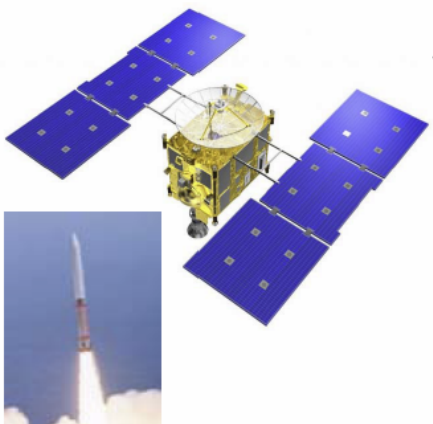


宇宙科学・探査ロードマップ

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。

Collaboration and support

DECIGO

- **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 , Earth's gravity observation
- **Collab. with JAXA Trajectory and Navigation group**
  - → Formation flight of DECIGO, DPF drag-free control
- **Geophysics group (Kyoto, ERI, UEC, NAOJ)**
- **Advanced technology center (ATC) of NAOJ**
- **JAXA's fund for small satellite development**
- **Research Center for the Early Universe (RESCEU), Univ. of Tokyo**

Astronomy and Cosmology

DECIGO

- **Verification of the alternative theories of gravity**

  Test Brans-Dicke theory by NS/BH binary evolution

  → Stronger constraint by 10^4 times

  K. Yagi and T. Tanaka, Prog. Theor. Phys. 123, 1069 (2010)

- **Black hole dark matter**

  Gravitational collapse of the primordial density fluctuations

  → Primordial black holes (PBHs) as a candidate of dark matter

  R. Saito and J. Yokoyama, Phys. Rev. Lett. 102 161101 (2009)

- **Neutron-star physics**

  Determine masses of 10^5 NSs per year

  → Constrain the EoS of NS

  Formation process of NS from the spectrum

GW observation roadmap

DECIGO

Ground-based Observatory

Better sensitivity (10Hz-1kHz)

LIGO → Enhanced LIGO → Advanced LIGO

TAMA CLIO → KAGRA

Virgo → Advanced Virgo

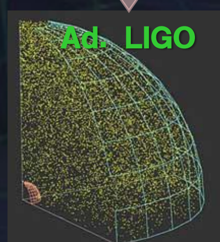
ET

2010

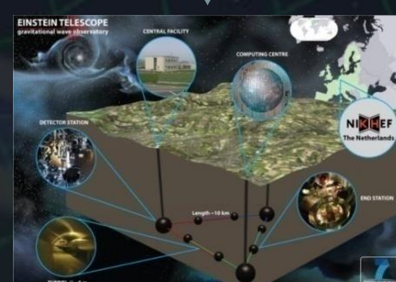
2015

2020

2025



Detection rate
~10 event/yr

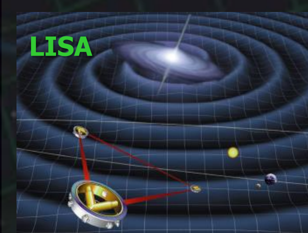


Space-borne observatory

Low-freq. observation (<1Hz)

LPF

DPF



LISA

Pre-DECIGO

0.1mHz-10mHz
Guaranteed
sources

DECIGO

BBO

0.1Hz band
Cosmological GWs

インフレーションの重力波観測

DECIGO

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.

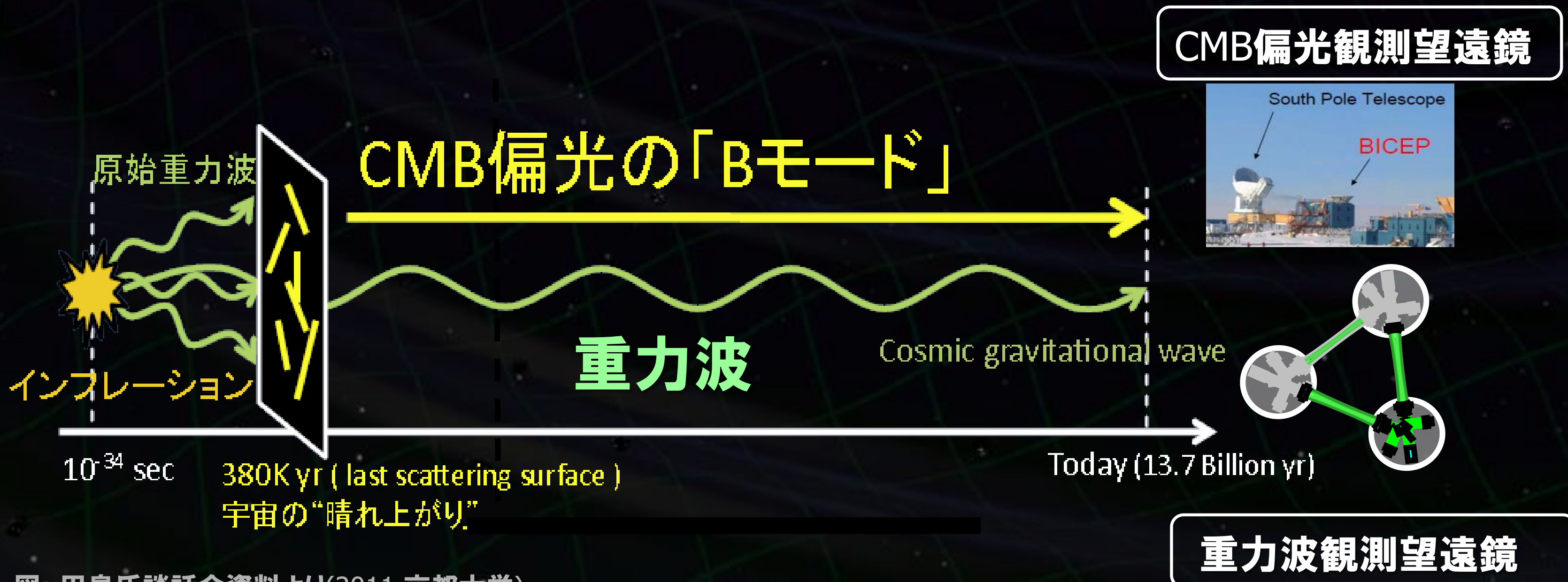
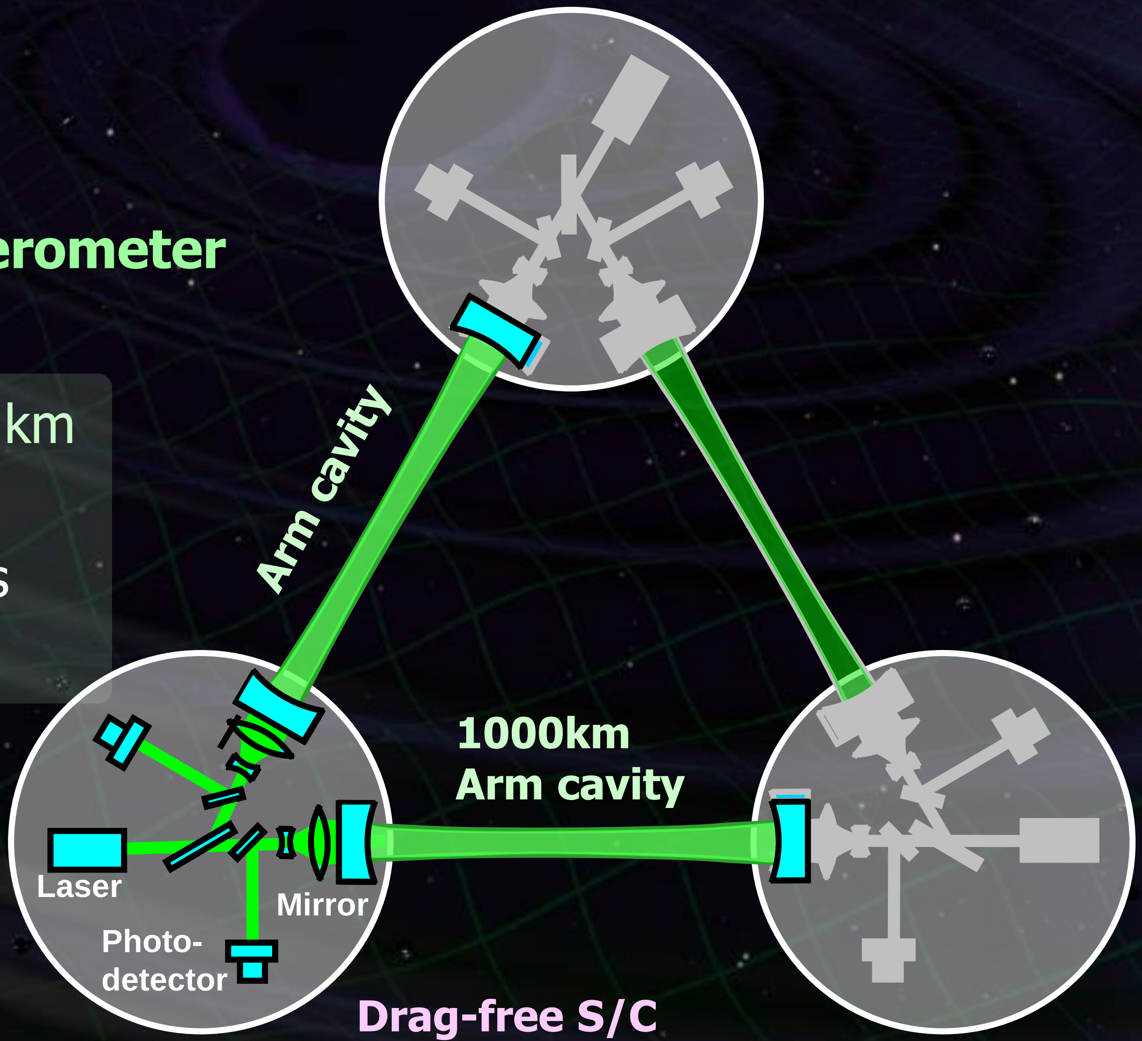


図: 田島氏談話会資料より(2011 京都大学)

DECIGO Interferometer

Interferometer Unit:
Differential FP interferometer

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



Organization

DECIGO

PI: Nakamura (Kyoto)
Deputy: Ando (Tokyo),Seto (Kyoto)

Executive Committee
Kawamura (ICRR), Ando (Tokyo), Seto (Kyoto), Nakamura (Kyoto), Tsubono (Waseda), Tanaka (Kyoto), Funaki (ISAS), Numata (Maryland), Sato (Hosei), Kanda (Osaka city), Takashima (ISAS), Ioka (KEK), Yokoyama (Tokyo), Akutsu (NAOJ)

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 (Tokyo)

Mission phase

Detector
Sato (Hosei)
Akutsu (NAOJ)
Ueda (NAOJ)
Aso (Tokyo)

Laser
Musha (ILS)
Ueda (ILS)

Drag free
Sato (Hosei)

Thruster
Funaki (ISAS)

Satellite
Sato (Hosei)

Data
Kanda (Osaka city)

Orbit and Constellation

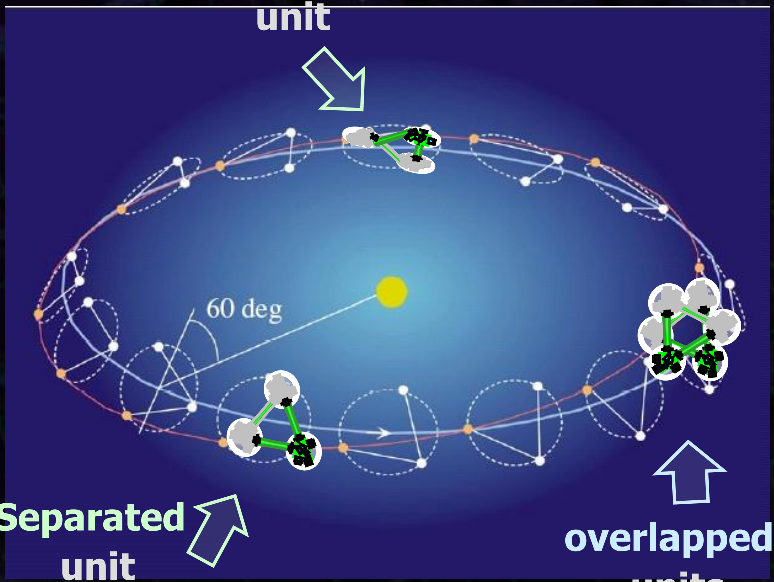
DECIGO

Candidate of orbit:

Record-disk orbit around the Sun

Relative acc. 4×10^{-12} m/s^2

(Mirror force $\sim 10^{-9}$ N)



Constellation

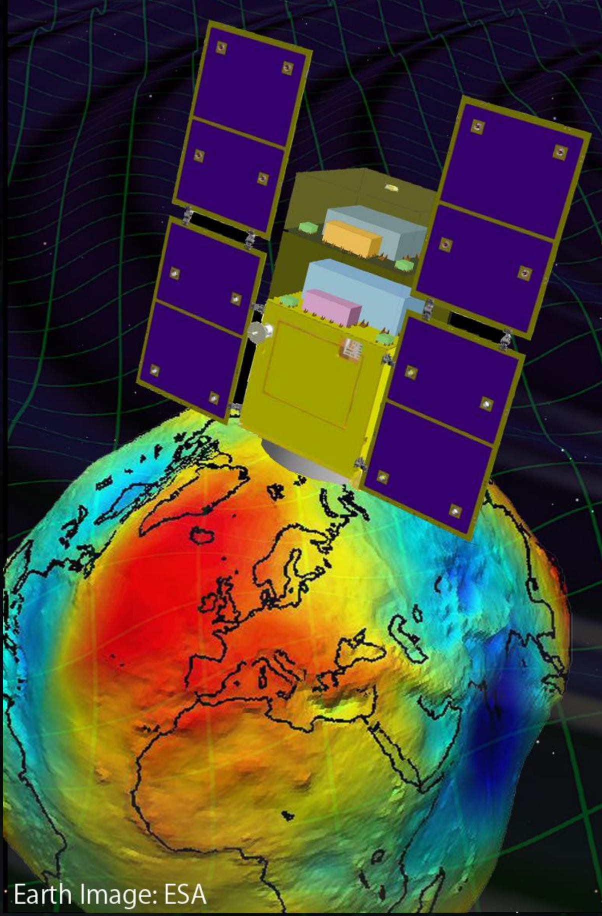
4 interferometer units

2 overlapped units → Cross correlation

2 separated units → Angular resolution

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

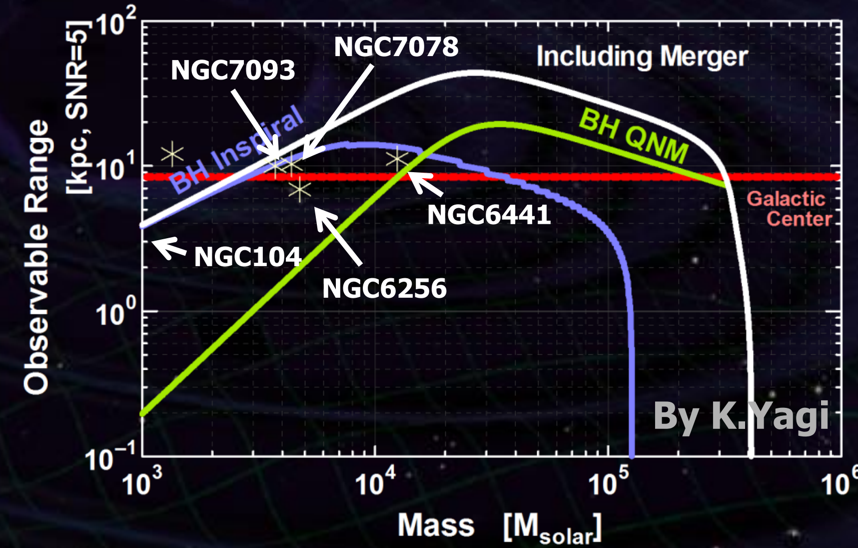
→ IFO measurement under stable zero-gravity

DPF Science

Astronomical observation

GW from merger of IMBHs
→ Formation mechanism of supermassive BHs

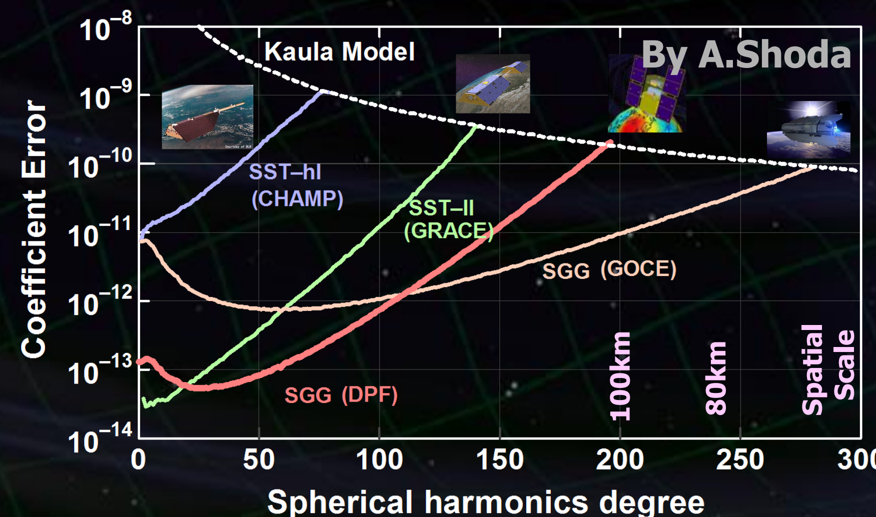
~30 GCs within DPF range



Observation of the earth

Gravitational potential
→ Shape of the earth
Environment monitor

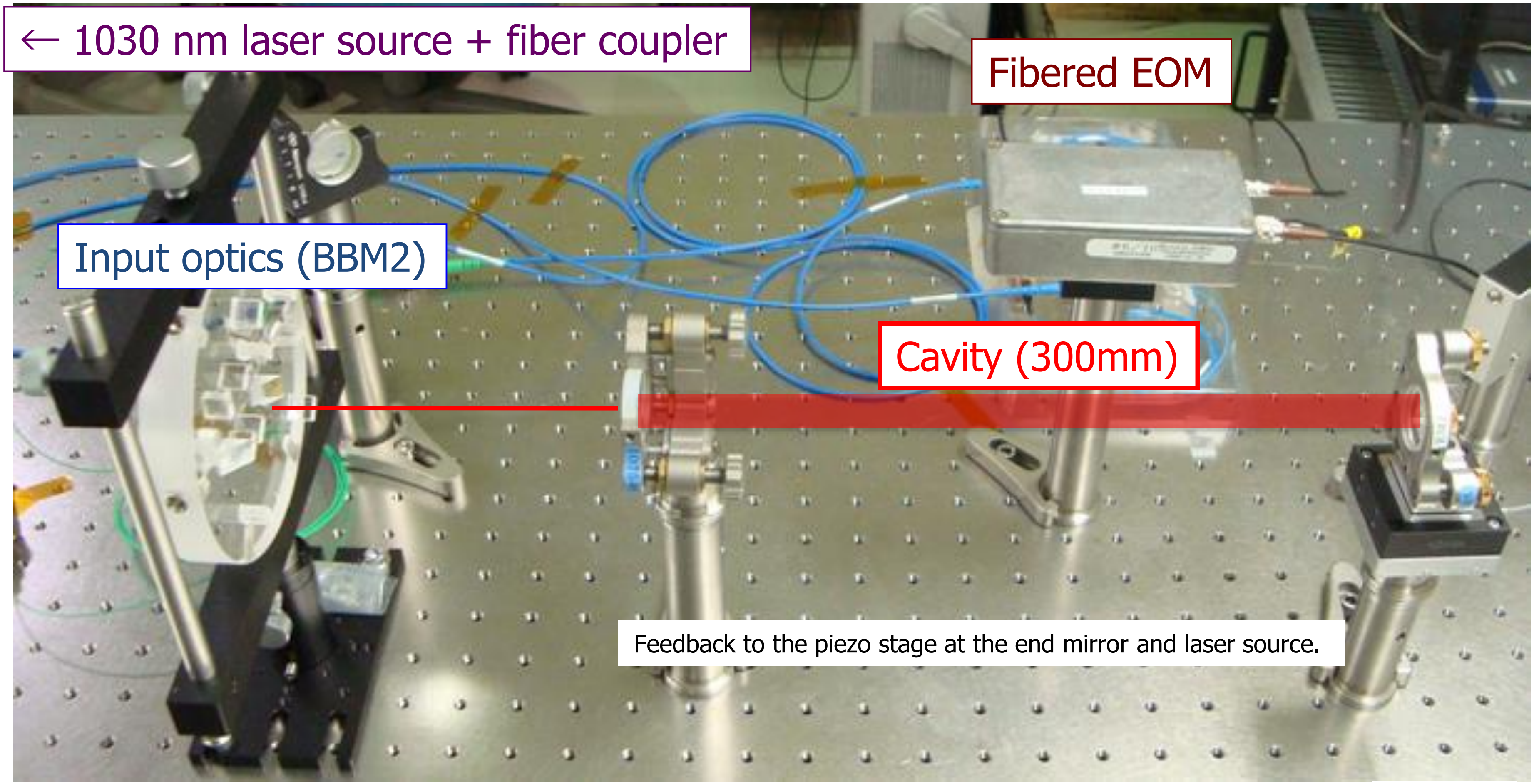
Comparable sensitivity with other missions



干渉計モジュールについて

光学系部品だけでの動作テスト

この状態でのFabry-Perot光共振器の動作は確認済み。

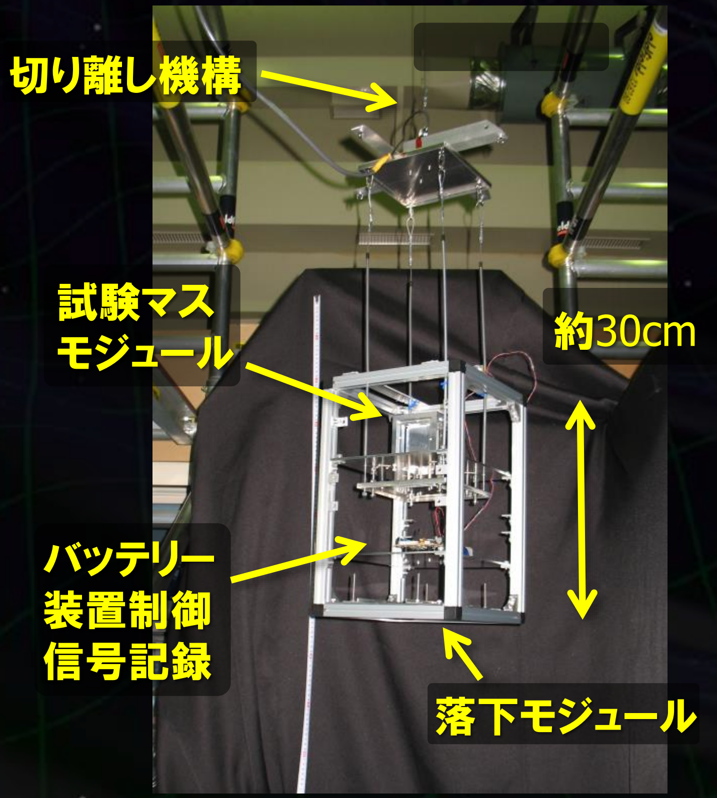


The cavity can be operated.

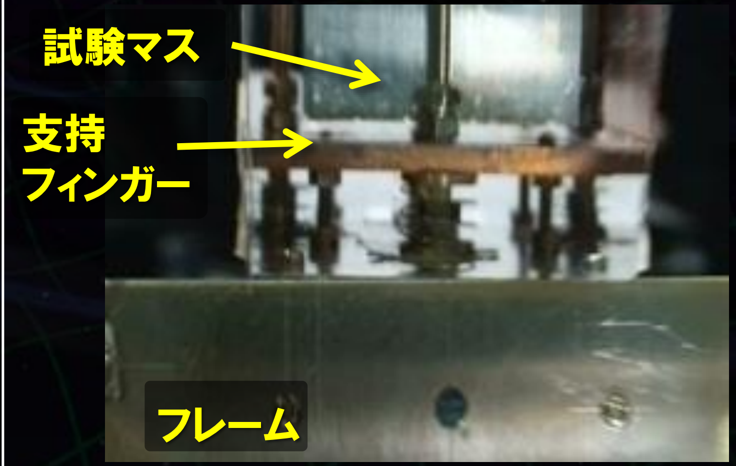
by Kasuga

自由落下試験

- 無重力下での試験マス制御デモンストレーション (国立天文台)
  - 落下モジュール (構造, 電源, センサ,ロガーなど)
  - ~3m落下設備　(足場, 切り離し機構, クッションなど)



自由落下時の様子



無重力下で試験マス浮上を確認

今後,静電S/Aによる制御をめざす.

SWIMによる宇宙実証

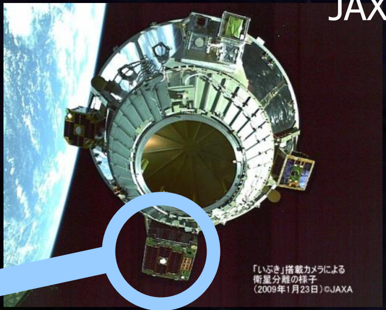
DECIGO

Photo：
JAXA

SDS-1搭載のSWIM (Space wire demonstration module)

2009年1月打ち上げ，2010年9月運用停止

⇨ 世界で最初の 宇宙重力波検出器

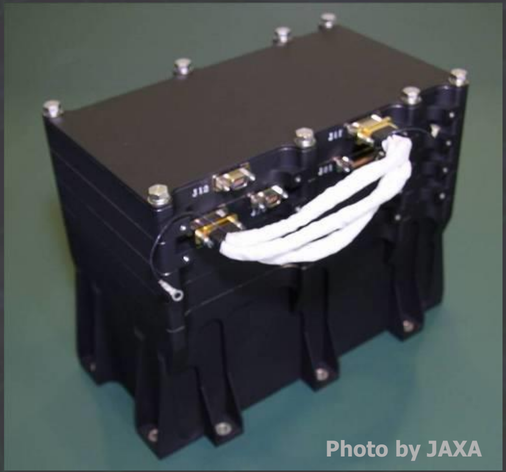


SpaceCube2: Space-qualified Computer

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

SDS-1 Bus System

Power +28V
RS422 for CMD/TLM
GPS signal

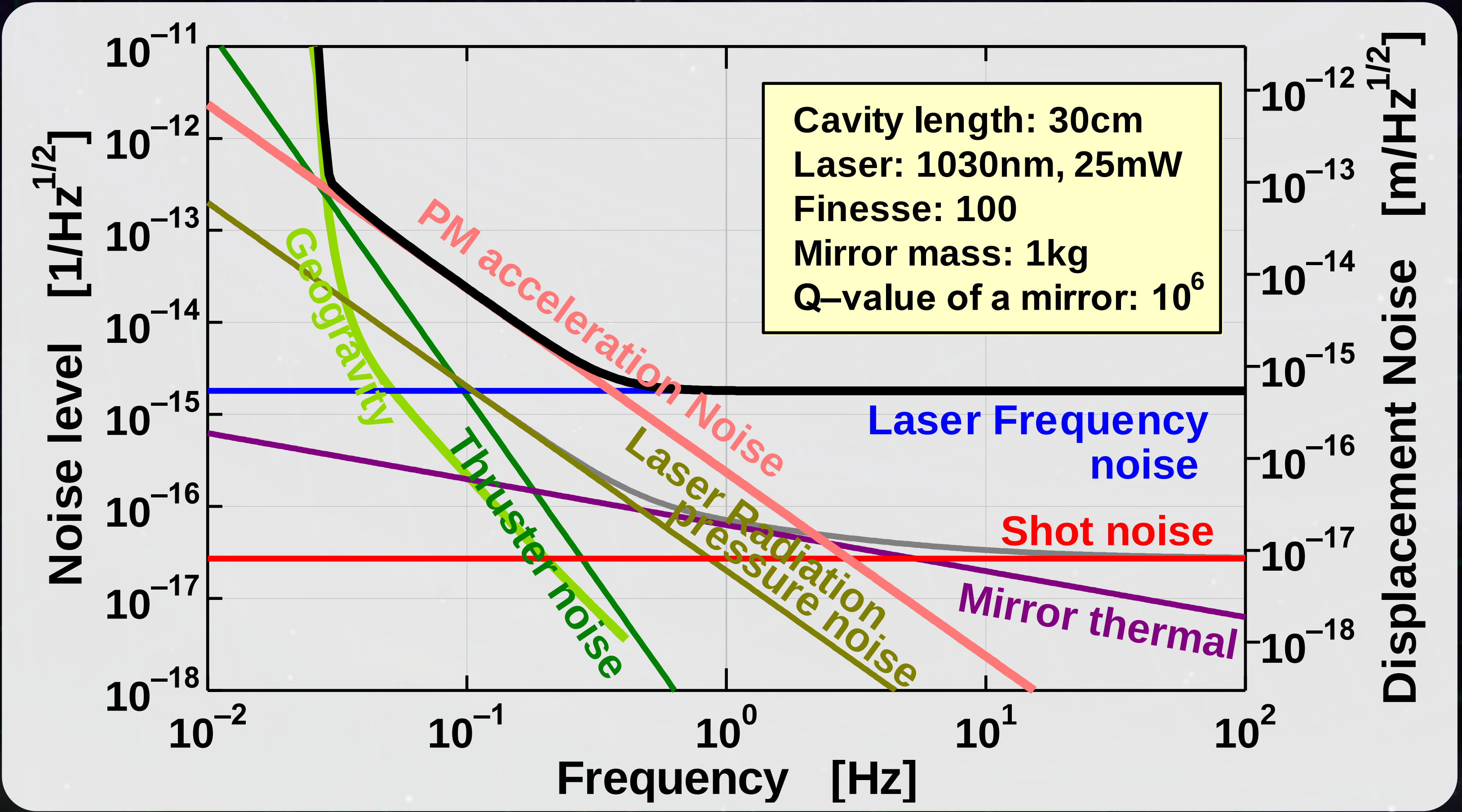
Power ±15V, +5V
SpW x2 for CMD/TLM

DPF Sensitivity

Laser source : 1030nm, 25mW
IFO length : 30cm
Finesse : 100, Mirror mass : 1kg
Q-factor : 10^5, Substrate: TBD
Temperature : 293K

Satellite mass : 350kg, Area: $2m^2$
Altitude: 500km
Thruster noise: $0.1\mu N/Hz^{1/2}$

(Preliminary parameters)

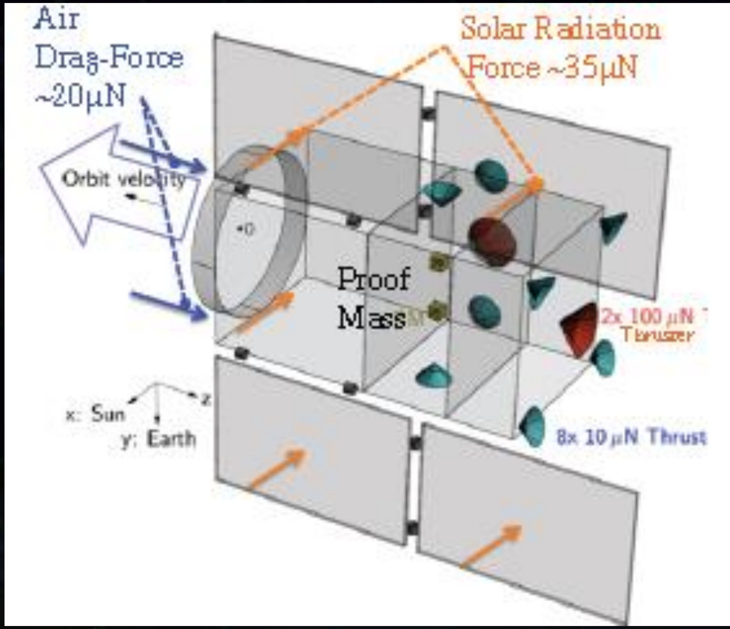


ミッションスラスタ構成

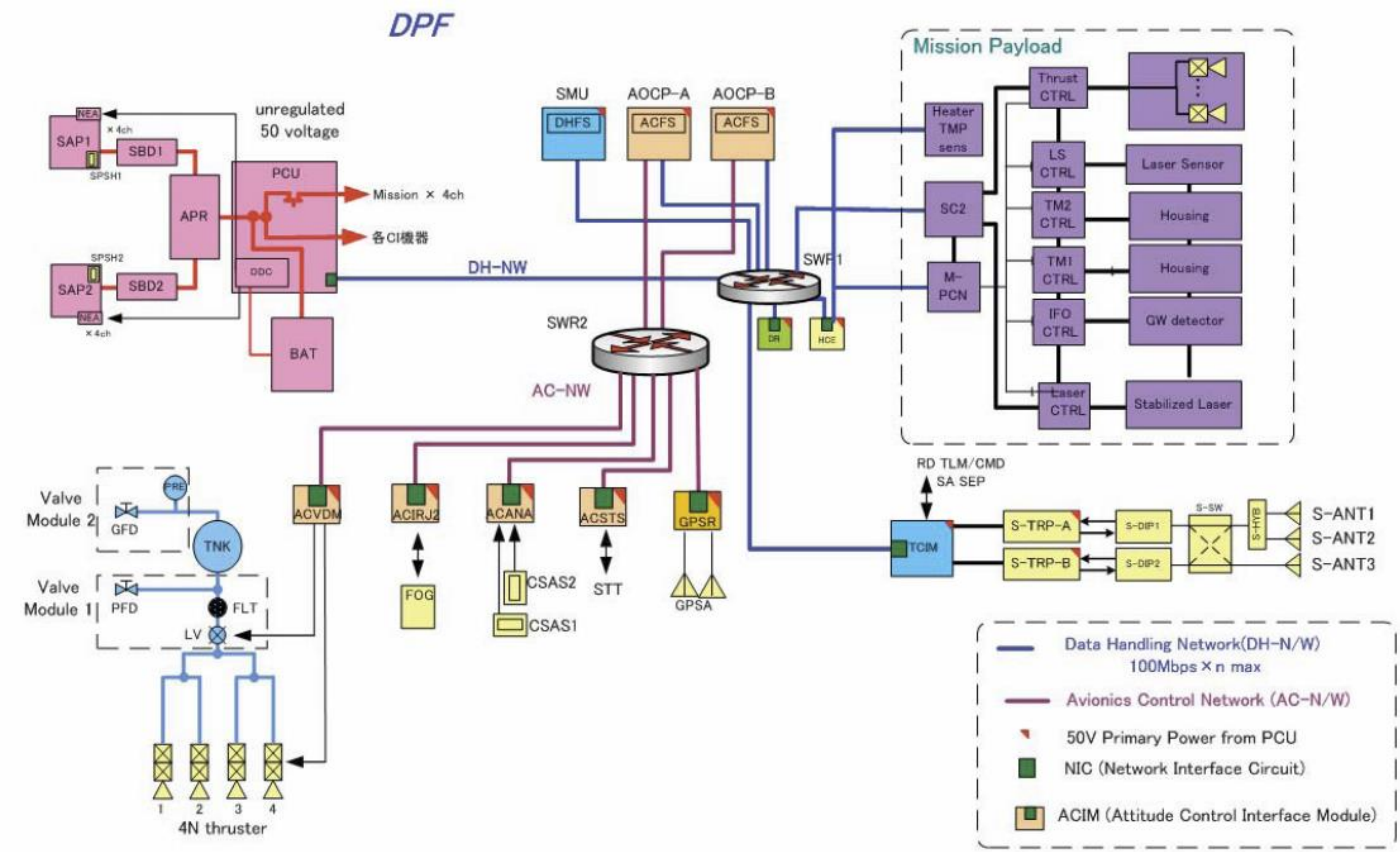
- ミッションスラスタ構成
  - 準定常成分 100 μNスラスタ 2台
    大気ドラッグ, 太陽輻射圧
  - 変動成分 10 μNスラスタ 8台
    大気圧変動, 太陽輻射変動

ミッションスラスタ仕様

推力	0.5-100 μN x2 (可変)
	0.5-10 μN x 8 (可変)
分解能	0.1 μN
推力雑音	0.1 μN/Hz$^{1/2}$
制御応答	>10Hz
Isp	TBD
電力・質量	<40W, <40kg
運用寿命	4,300 時間



DPFシステムブロック図



DPFシステム概念検討（これまで）

補足

- 検討ベースラインの整理
  - ミッション要求とシステム仕様
- 衛星システム諸元の整理
  - 課題の検討（SANT，CSAS，G
  - 衛星システムブロック図
  - 質量配分
  - 電力配分、電力解析
  - 衛星コンフィギュレーション
- 課題
  - 熱検討
  - 受動安定姿勢検討
  - システム検討

である。

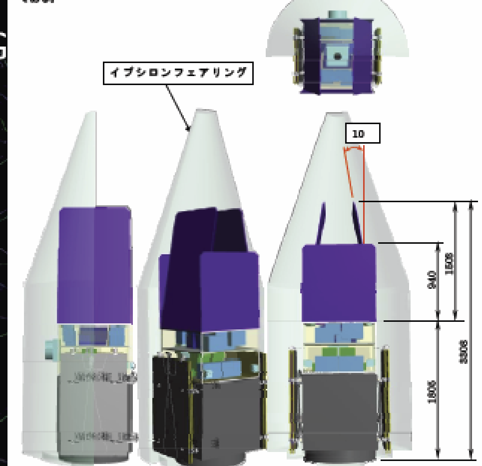
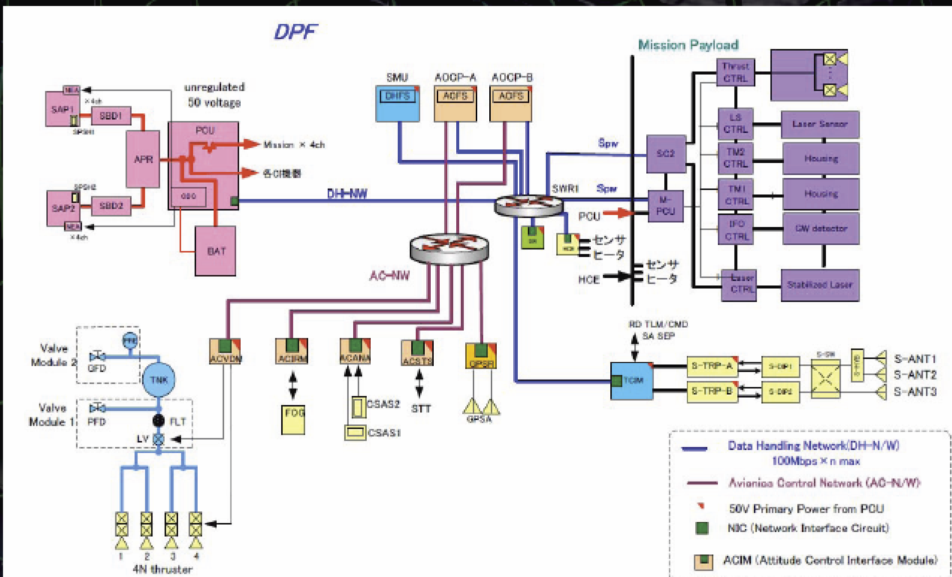
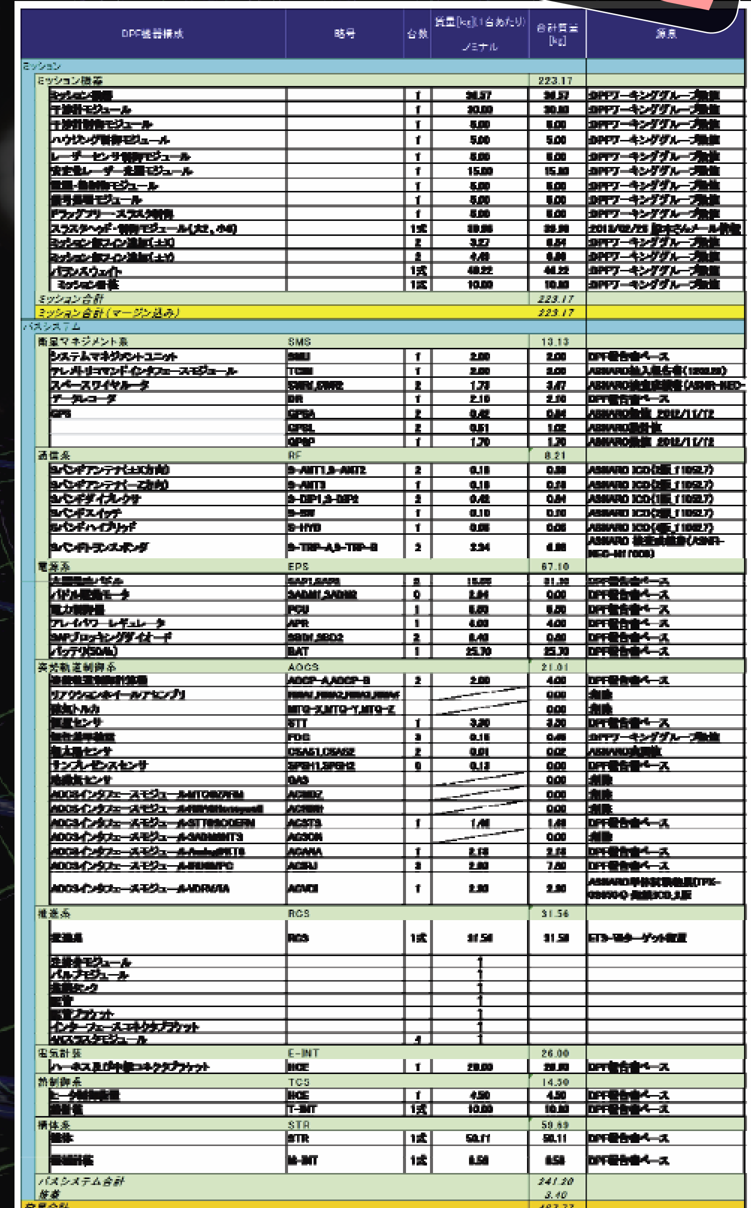


図 8.1-1　打上げ時コンフィギュレーション





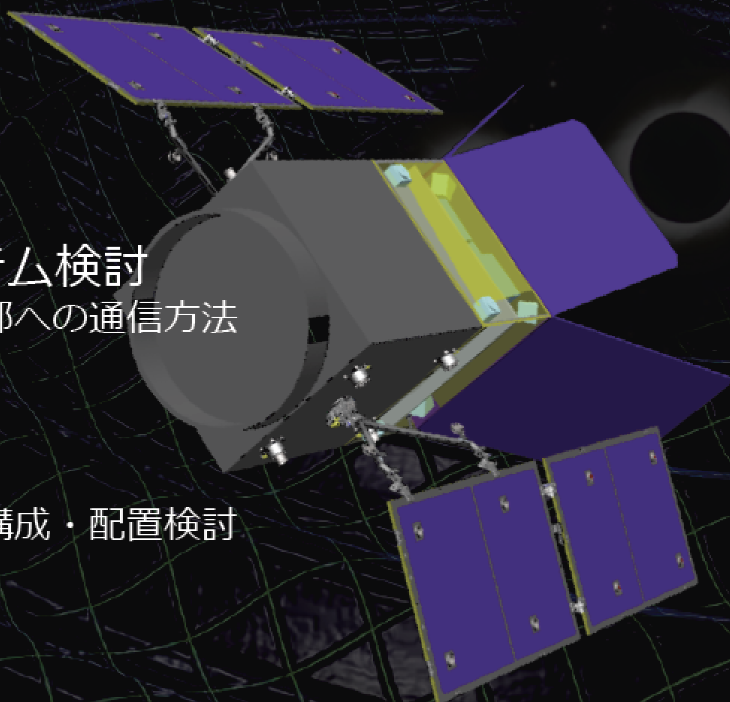
DPF機器構成	略号	台数	質量[kg](1台あたり) ノミナル	合計質量[kg]	備考
ミッション					
ミッション機器				223.17	
ミッション機器		1	36.57	36.57	DPFワーキンググループ推定
干渉計モジュール		1	30.00	30.00	DPFワーキンググループ推定
干渉計制御モジュール		1	5.00	5.00	DPFワーキンググループ推定
ハウジング制御モジュール		1	5.00	5.00	DPFワーキンググループ推定
レーザーセンサ制御モジュール		1	5.00	5.00	DPFワーキンググループ推定
安定化レーザー光源モジュール		1	15.00	15.00	DPFワーキンググループ推定
電源・制御モジュール		1	5.00	5.00	DPFワーキンググループ推定
信号処理モジュール		1	5.00	5.00	DPFワーキンググループ推定
ドラッグフリースラスタ制御		1	5.00	5.00	DPFワーキンググループ推定
スラスタヘッド・制御モジュール(大2，小4)		1式	[illegible]	[illegible]	2013/02/25 [illegible]さんメール情報
ミッション部フイン追加(上X)		2	3.27	6.54	DPFワーキンググループ推定
ミッション部フイン追加(上Y)		2	4.40	[illegible]	DPFワーキンググループ推定
バランスウェイト		1式	40.22	40.22	DPFワーキンググループ推定
ミッション余裕		1式	10.00	10.00	DPFワーキンググループ推定
ミッション合計				223.17	
ミッション合計(マージン込み)				223.17	
バスシステム					
衛星マネジメント系	SMS			13.13	
システムマネジメントユニット	SMU	1	2.00	2.00	DPF報告書ベース
テレメトリコマンドインタフェースモジュール	TCIM	1	2.00	2.00	ASNARO納入報告書([illegible])
スペースワイヤルータ	SWR1,SWR2	2	1.73	3.47	ASNARO検査成績書(ASNR-NEC-
データレコーダ	DR	1	2.10	2.10	DPF報告書ベース
GPS	GPSA	2	0.42	0.84	ASNARO実績 2012/11/12
	GPSL	2	0.51	1.02	ASNARO推定値
	GPSP	1	1.70	1.70	ASNARO実績 2012/11/12
通信系	RF			8.21	
Sバンドアンテナ(上X方向)	S-ANT1,S-ANT2	2	0.18	[illegible]	ASNARO ICD([illegible]_f1052.7)
Sバンドアンテナ(−Z方向)	S-ANT3	1	0.18	0.18	ASNARO ICD([illegible]_f1052.7)
Sバンドダイプレクサ	S-DIP1,S-DIP2	2	0.42	0.84	ASNARO ICD([illegible]_f1052.7)
Sバンドスイッチ	S-SW	1	0.10	0.10	ASNARO ICD([illegible]_f1052.7)
Sバンドハイブリッド	S-HYD	1	[illegible]	[illegible]	ASNARO ICD([illegible]_f1052.7)
Sバンドトランスポンダ	S-TRP-A,S-TRP-B	2	2.34	[illegible]	ASNARO 検査成績書(ASNR-NEC-M1008)
電源系	EPS			67.10	
太陽電池パドル	SAP1,SAP2	2	[illegible]	31.30	DPF報告書ベース
パドル駆動モータ	SADM1,SADM2	0	2.84	0.00	DPF報告書ベース
電力制御器	PCU	1	[illegible]	[illegible]	DPF報告書ベース
アレイパワーレギュレータ	APR	1	4.00	4.00	DPF報告書ベース
SAPブロッキングダイオード	SBD1,SBD2	2	0.40	0.80	DPF報告書ベース
バッテリ(50Ah)	BAT	1	25.70	25.70	DPF報告書ベース
姿勢軌道制御系	AOCS			21.01	
姿勢軌道制御計算機	AOCP-A,AOCP-B	2	2.00	4.00	DPF報告書ベース
リアクションホイールアセンブリ	RWA1,RWA2,RWA3,RWA4			0.00	削除
磁気トルカ	MTQ-X,MTQ-Y,MTQ-Z			0.00	削除
恒星センサ	STT	1	3.20	3.20	DPF報告書ベース
[illegible]	FOG	3	0.15	[illegible]	DPFワーキンググループ推定
粗太陽センサ	CSAS1,CSAS2	2	0.01	0.02	ASNARO実績値
サンプレゼンスセンサ	SPSH1,SPSH2	0	0.12	0.00	DPF報告書ベース
地磁気センサ	GAS			0.00	削除
AOCSインタフェースモジュール-[illegible]	[illegible]			0.00	削除
AOCSインタフェースモジュール-[illegible]	[illegible]			0.00	削除
AOCSインタフェースモジュール-STT(SODERN)	ACSTS	1	1.48	1.48	DPF報告書ベース
AOCSインタフェースモジュール-[illegible]	ACSON			0.00	削除
AOCSインタフェースモジュール-[illegible]	ACANA	1	2.18	2.18	DPF報告書ベース
AOCSインタフェースモジュール-[illegible]	[illegible]	3	2.60	7.80	DPF報告書ベース
AOCSインタフェースモジュール-[illegible]	[illegible]	1	2.30	2.30	ASNARO単体試験結果(TPK-[illegible])
推進系	RCS			31.56	
推進系	RCS	1式	31.56	31.56	[illegible]
推進薬モジュール			↑		
バルブモジュール			↑		
推進薬タンク			↑		
配管			↑		
配管ブラケット			↑		
インターフェースコネクタブラケット			↑		
[illegible]モジュール		4	↑		
電気計装	E-INT			26.00	
ハーネス及び中継コネクタブラケット	HCE	1	26.00	26.00	DPF報告書ベース
熱制御系	TCS			14.50	
ヒータ制御装置	HCE	1	4.50	4.50	DPF報告書ベース
熱制御材	T-INT	1式	10.00	10.00	DPF報告書ベース
構体系	STR			59.69	
構体	STR	1式	50.11	50.11	DPF報告書ベース
機械計装	M-INT	1式	[illegible]	[illegible]	DPF報告書ベース
バスシステム合計				241.20	
推薬				3.40	
衛星合計				467.77	

図 2.5.3-1　質量配分

DPFシステム概念検討（これまで）

補足

- 熱設計検討
  - 熱的要求条件
  - 設計方針
  - 排熱検討
- SpW信号処理系システム検討
  - バス部からミッション部への通信方法
- 受動安定姿勢の検討
  - 日照時安定姿勢の改善
  - ミッションスラスタの構成・配置検討



©NEC

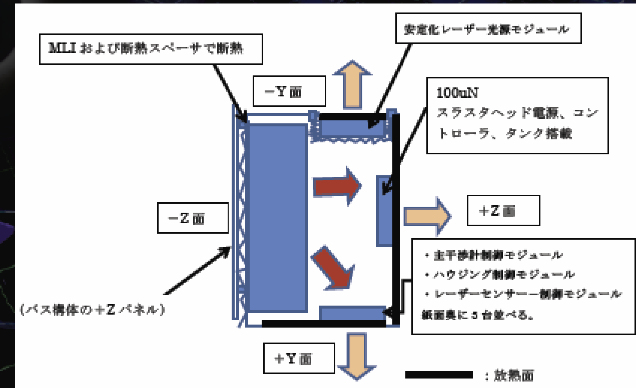
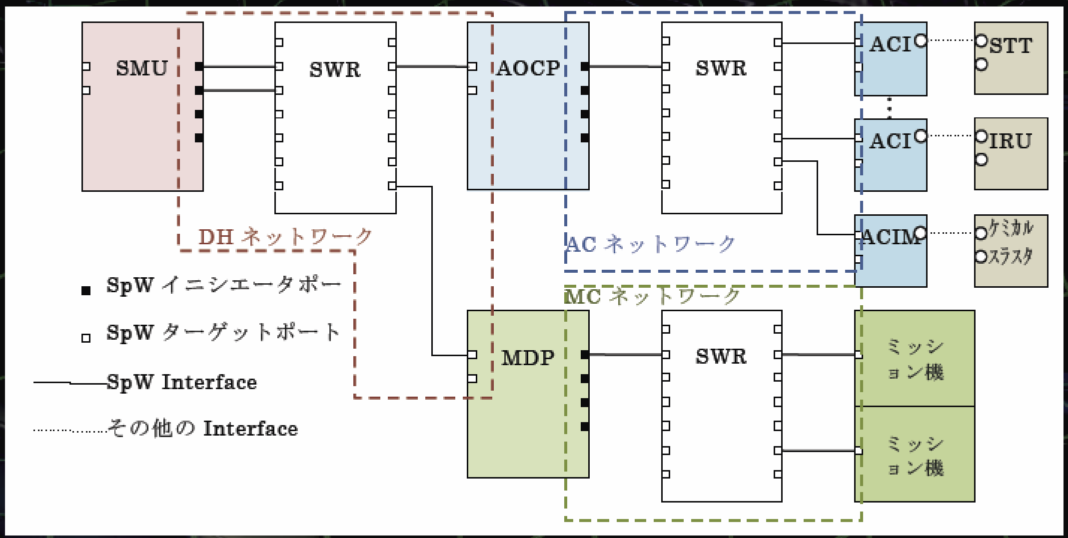


表 2-3　バス機器許容温度および発生熱量

搭載パネル	機器名称	動作時許容温度			発熱（定常観測＋伝送）	備考
+X 独立熱制御	BAT-L	20	～	30	−	
	BAT-H	20	～	30	−	
−X	SWR2	−25	～	50	10.3	SPRINT-A CDR設計値
	PCU	−30	～	60	17.2	SPRINT-A CDR設計値
	ACSDN	−30	～	50	3.5	SPRINT-A CDR設計値
	ACIRM	−30	～	50	9.5	SPRINT-A CDR設計値
	ACANA	−30	～	50	10.5	SPRINT-A CDR設計値
	HCE	−20	～	50	9.6	SPRINT-A CDR設計値
	−Xパネル合計				60.6	
+Y	APR	−25	～	65	68	SPRINT-A CDR設計値
	ACSTS	−30	～	50	7	SPRINT-A CDR設計値
	SWR1	−25	～	50	10.3	SPRINT-A CDR設計値
	SBD	−30	～	60	11	SPRINT-A CDR設計値
	SADM	−30	～	60	1.5	SPRINT-A CDR設計値
	+Yパネル合計				97.8	
−Y	S-TRP-A	−20	～	55	10	SPRINT-A CDR設計値
	S-TRP-B	−20	～	55	27.6	SPRINT-A CDR設計値
	AOCP-B	−25	～	50	1	SPRINT-A CDR設計値
	AOCP-A	−25	～	50	13	SPRINT-A CDR設計値
	SMU	−25	～	50	19	SPRINT-A CDR設計値
	TCIM	−30	～	50	14	SPRINT-A CDR設計値
	DR	−25	～	55	6.5	SPRINT-A CDR設計値
	SADM	−30	～	60	1.5	SPRINT-A CDR設計値
	SBD	−30	～	60	11	SPRINT-A CDR設計値
	−Yパネル合計				103.6	
+Z	FOG	−10	～	50	6.9	IKAROS搭載品
	S-SW	−20	～	50	0.2	SPRINT-A CDR設計値
	S-DIP1	−20	～	55	0.1	SPRINT-A CDR設計値
	S-DIP2	−20	～	55	0.1	SPRINT-A CDR設計値
	GAS	−30	～	60	1.0	SPRINT-A CDR設計値
	S-HYB	−20	～	55	1.6	SPRINT-A CDR設計値
ミッション側からの熱入力					20	仮定
	+Zパネル合計				29.9	
−Z	RCS用ヒータ				5.2	ASNARO実績
	−Zパネル合計				5.2	
+Z 独立熱制御	STT	−30	～	60	7.2	SPRINT-A CDR設計値
	バス合計				304.3	

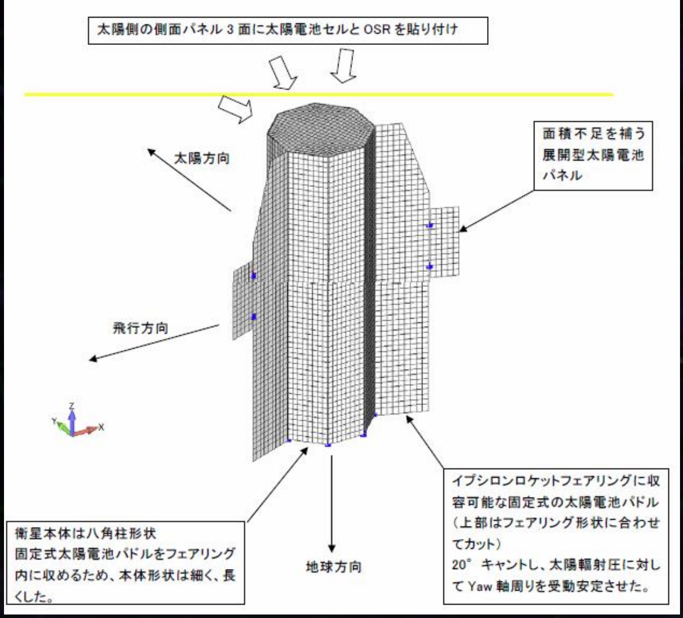


受動安定姿勢のための検討

- 衛星構造のオプション案の検討

  問題意識: 衛星構造(特にSAP)の共振など剛性を高めた構成の検討.
  従来は衛星バスの制約から検討外であったが、ミッションの
  枠組み変更に伴い検討を開始.
  (SE室との相談でもencourageされた)

  結果: 成立する可能性があることを示唆.
  - 最低共振周波数
    従来 1~2Hz → 今回 26.8 Hzに向上.
  - 質量評価 → これまでとほぼ同等.
  - SAP面積 従来 4.3 m^2 → 2.8 m^2.
  - 要検討事項:
    搭載機器配置, 質量バランス, 電力,
    排熱面設定, ミッションスラスタ配置,
    受動姿勢安定, コスト など.



GW target of DPF

Black hole events in our galaxy

IMBH inspiral and merger

Obs. Distance 40kpc, for $m = 2 \times 10^4 M_{sun}$

Obs. Duration (~1000sec)

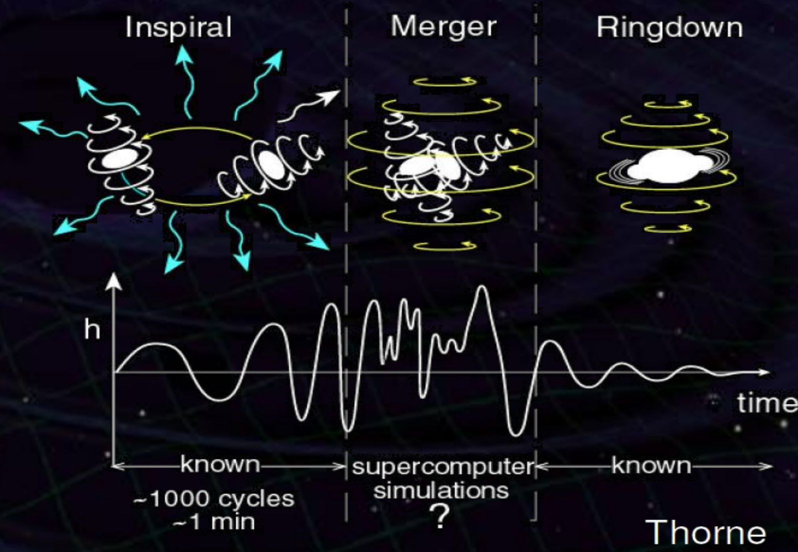
Observable range covers our Galaxy (SNR~5)

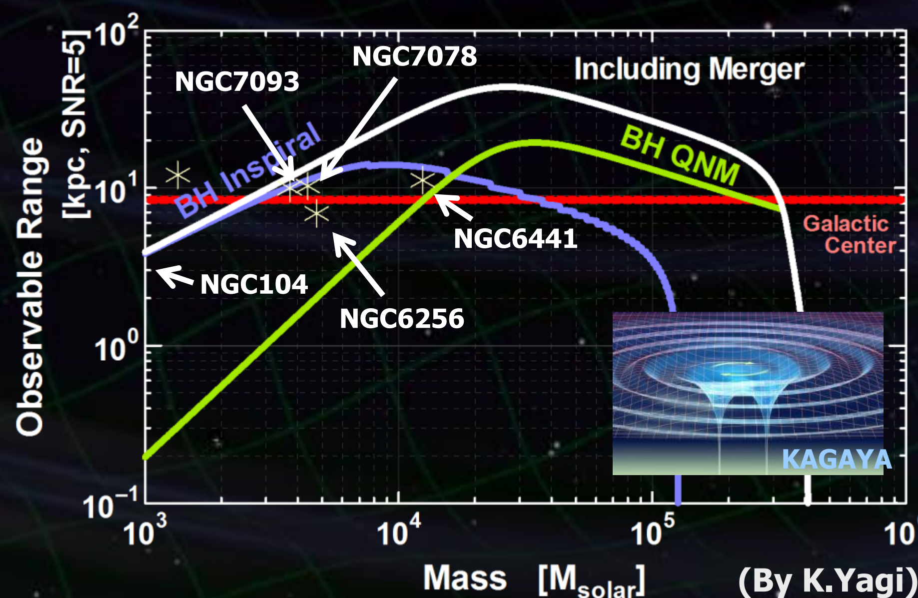
There may be IMBH at GCs

DPF covers ~30 GCs

Hard to access by others

→ Original observation

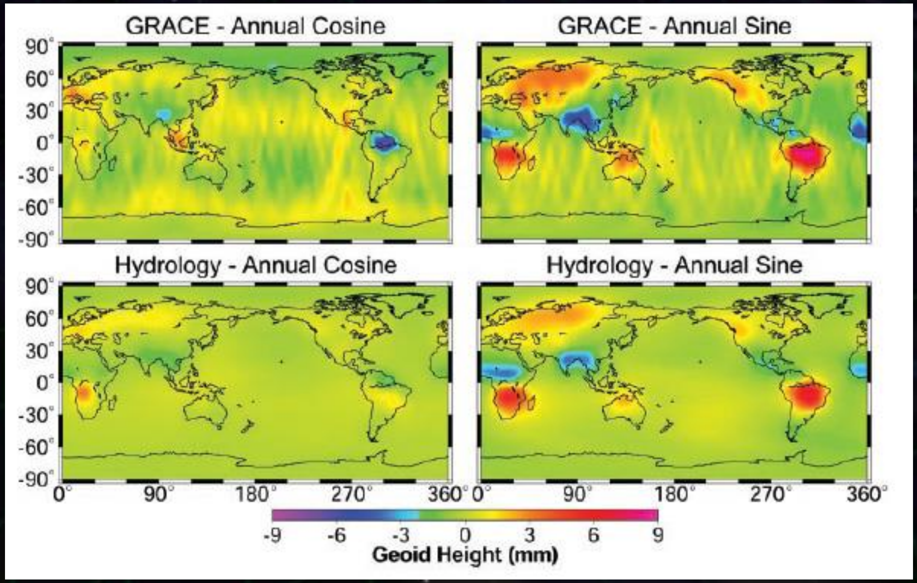




Earth's Gravity Observation

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

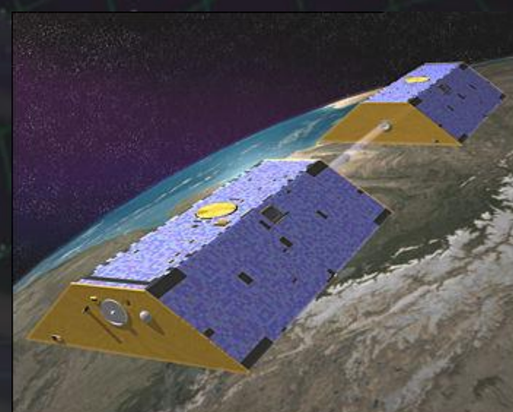
Satellite-to Satellite tracking High-Low

- 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

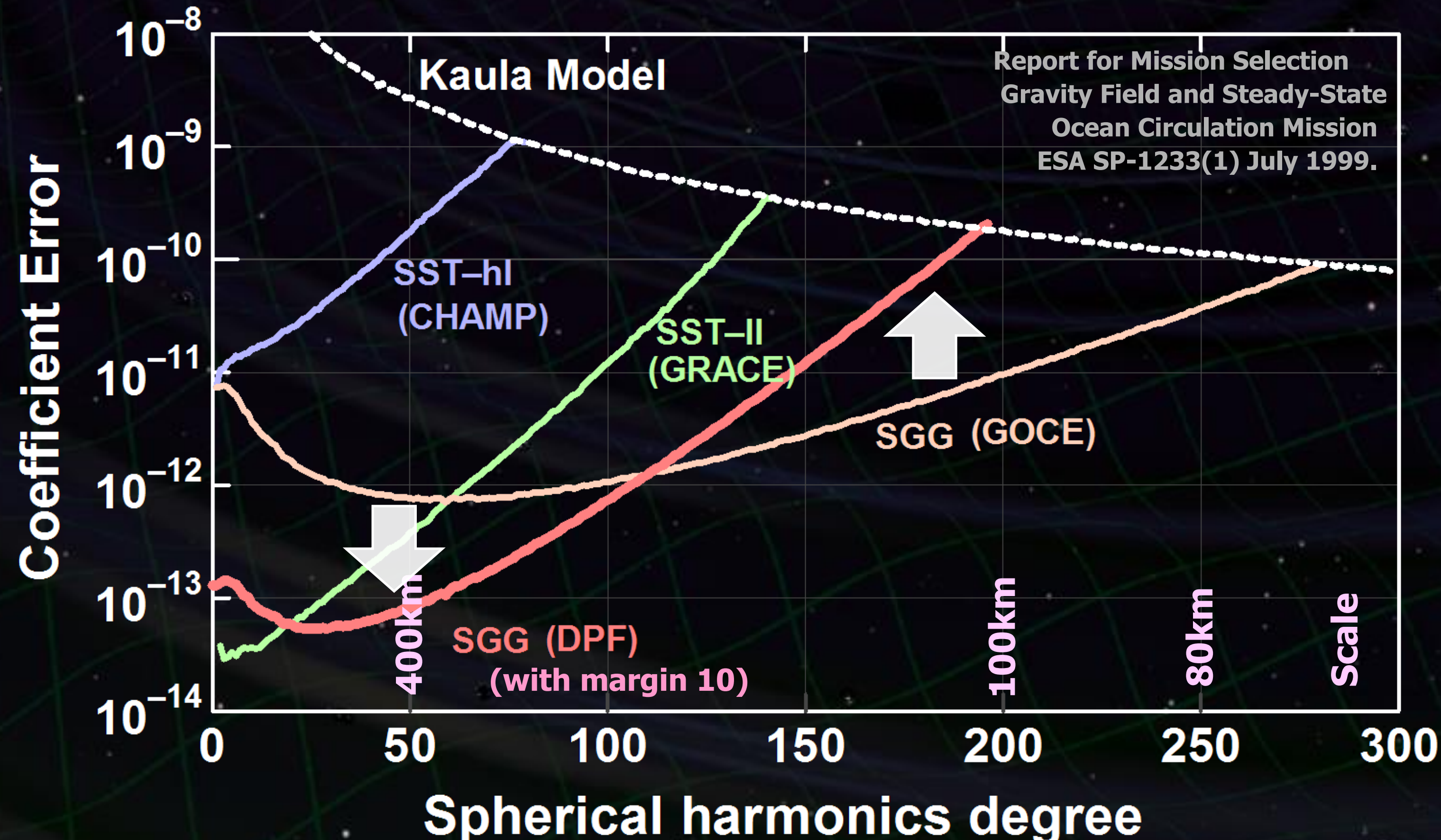
GOCE (ESA, 2009-)

DPF sensitivity

Comparison of sensitivities

Better in low orders (large scale) ← Sensors

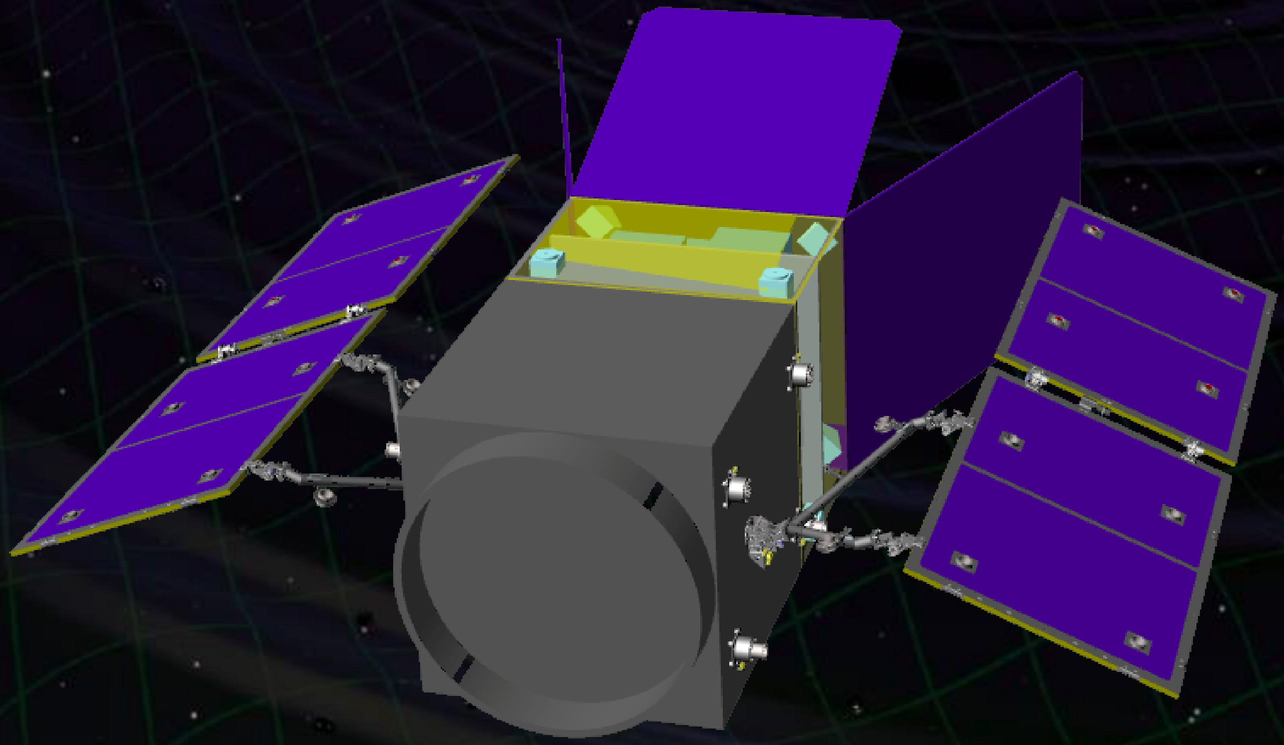
Worse in high orders (small scale) ← Altitude



DPF-WG activities

Mission design

- Structure and thermal modeling
- Drag-free control design

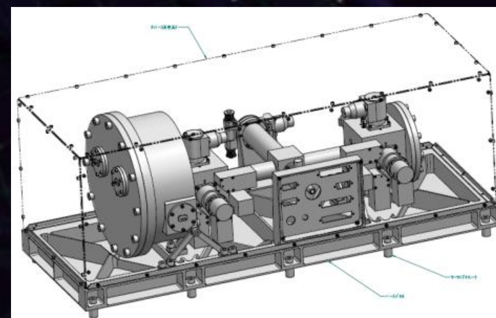


Design : NEC

DPF-WG activities

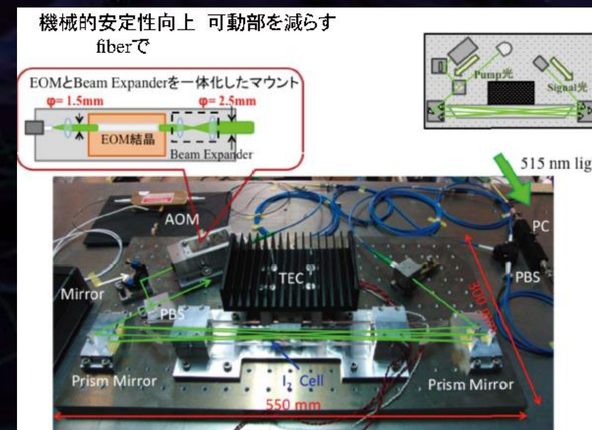
BBMs (Bread-board model) for Core components

Interferometer module



Univ. of Tokyo,NAOJ

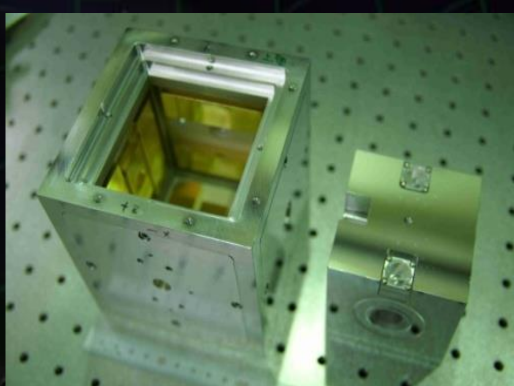
Laser stabilization module

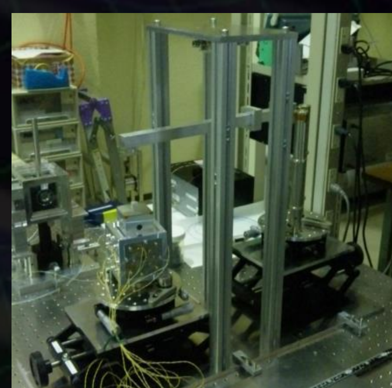


UEC, NICT, NASA/GSFC

Test-mass module

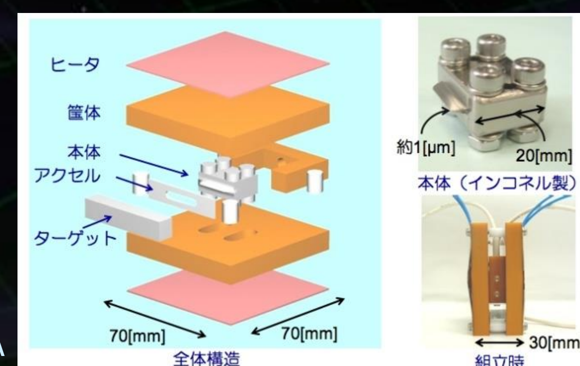
NAOJ, Hosei Univ.





Low-noise thruster module

JAXA



SWIM

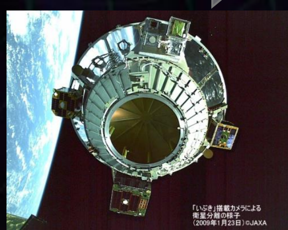
Roadmap

Figure: S.Kawamura

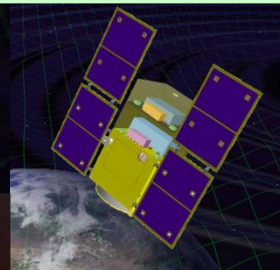
	2010	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29

Mission

R&D Fabrication

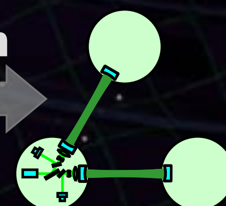


SDS-1/SWIM



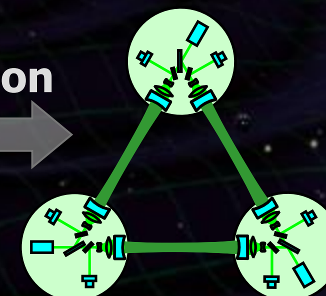
DECIGO Pathfinder (DPF)

R&D Fabrication



Pre-DECIGO

R&D Fabrication



DECIGO

	SDS-1/SWIM, DECIGO Pathfinder (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

Rotating TOBA : SWIMμν

Small Module SWIMμν on SDS-1

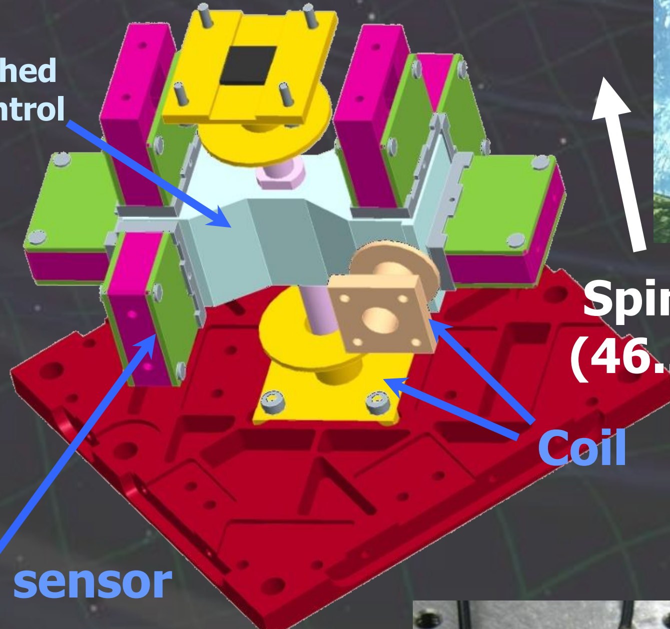
Launched Jan. 2009, Terminated Sept. 2010

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

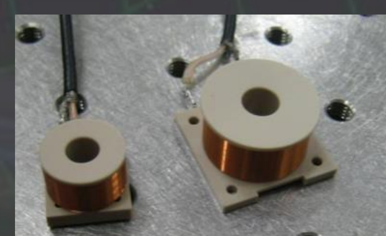


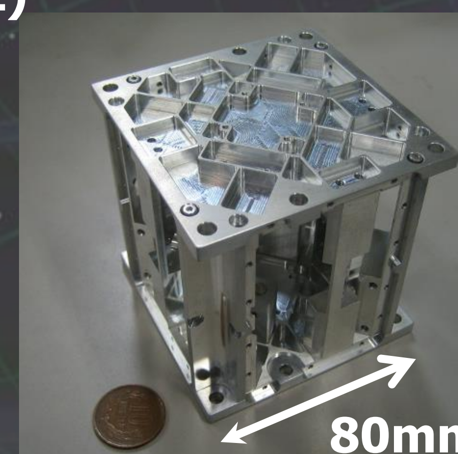
Spin Axis (46.5mHz)

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

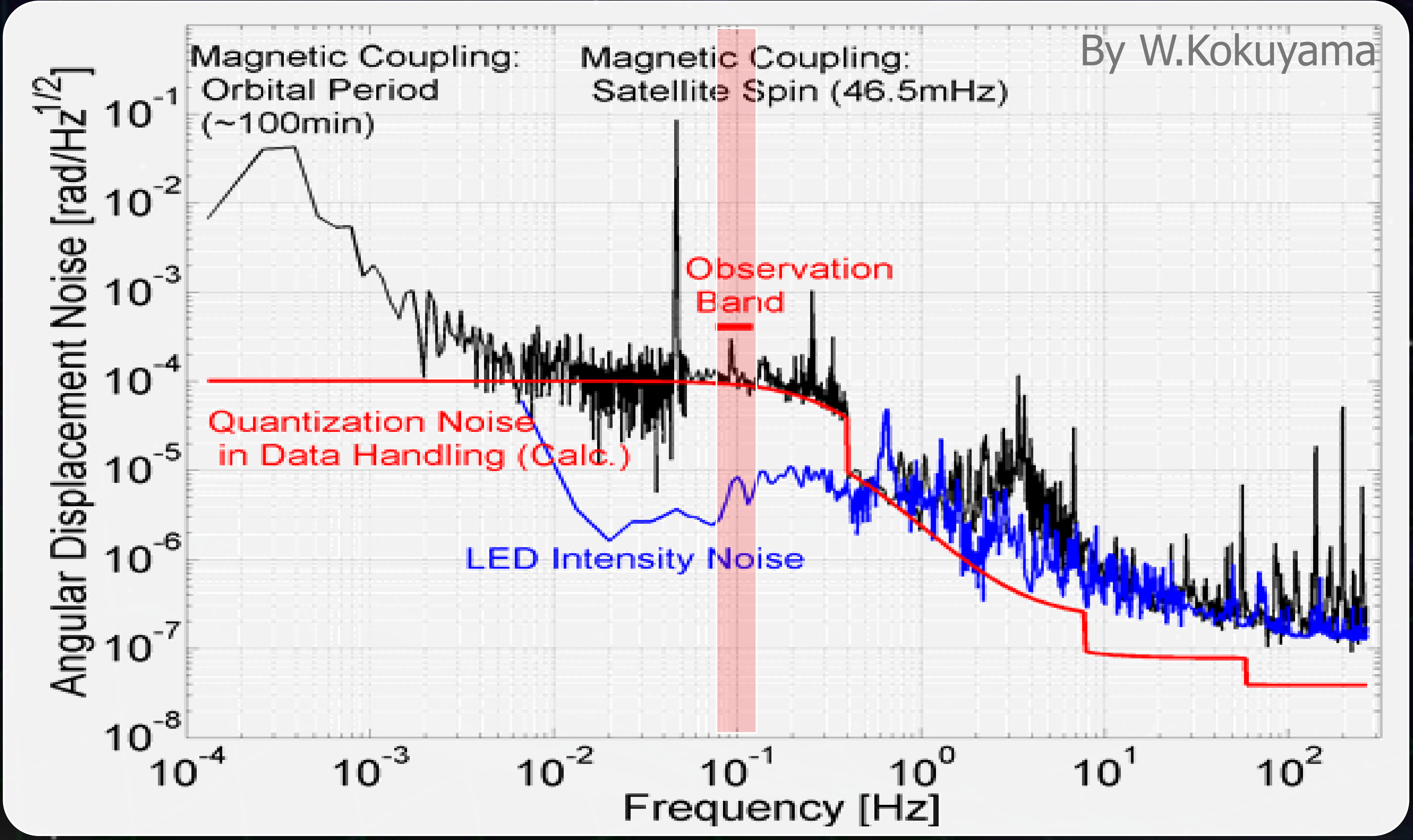




80mm

Sensitivity

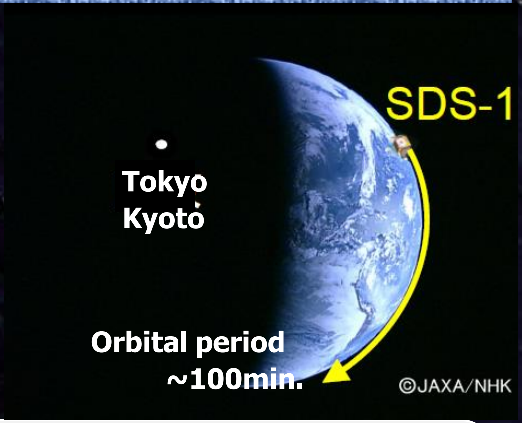
Though limited by non-fundamental noises, best as a space-borne GW detector.

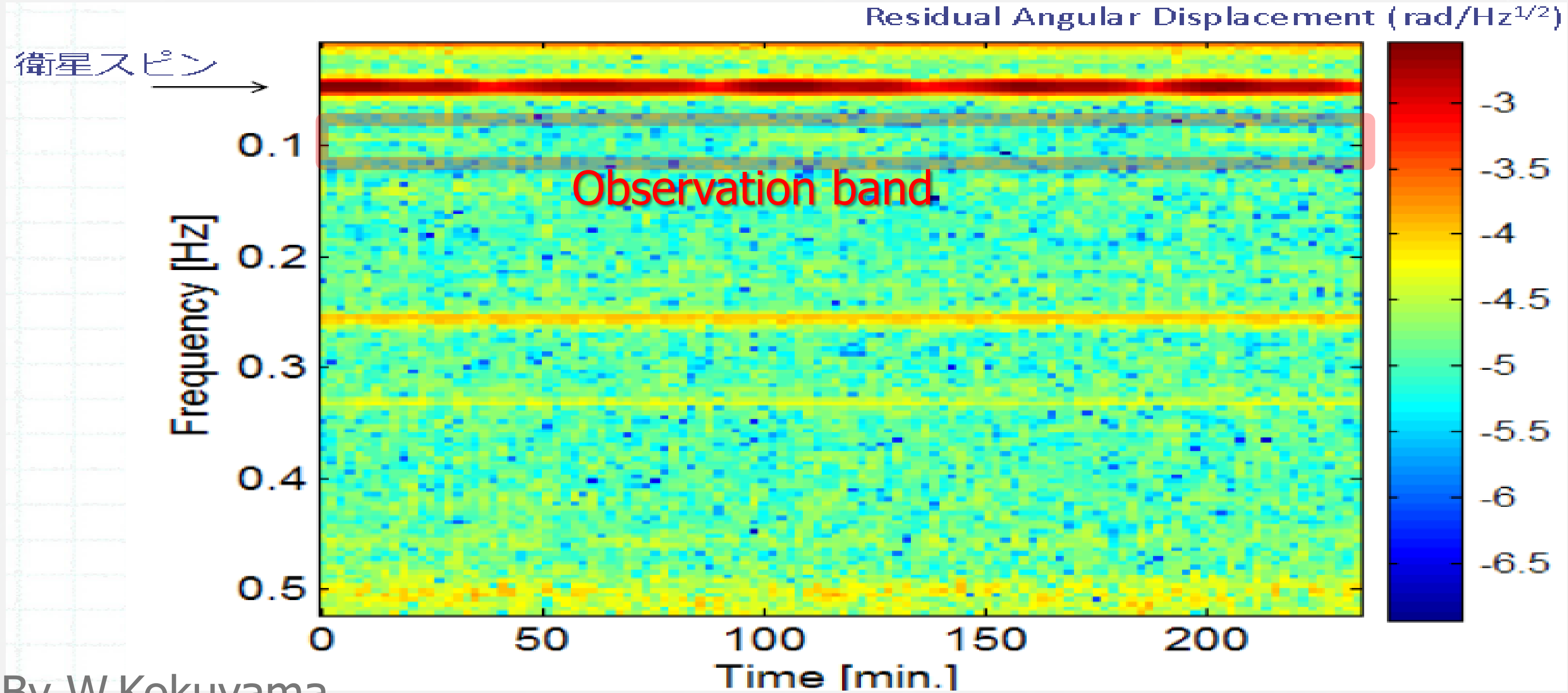


Observation by SWIM

Continuous data taking

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





By W.Kokuyama

Upper Limit on GWB

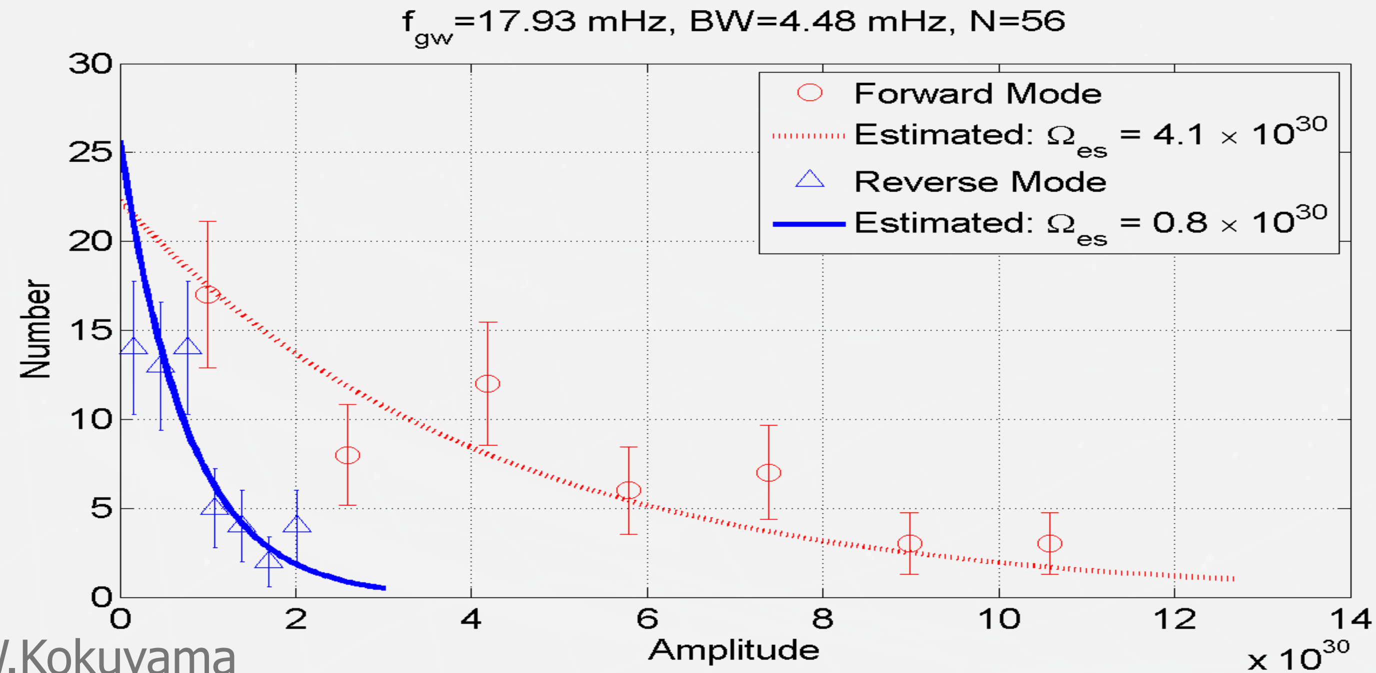
DECIGO

Upper Limit at two frequencies (two polarizations)

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

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

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



By W.Kokuyama

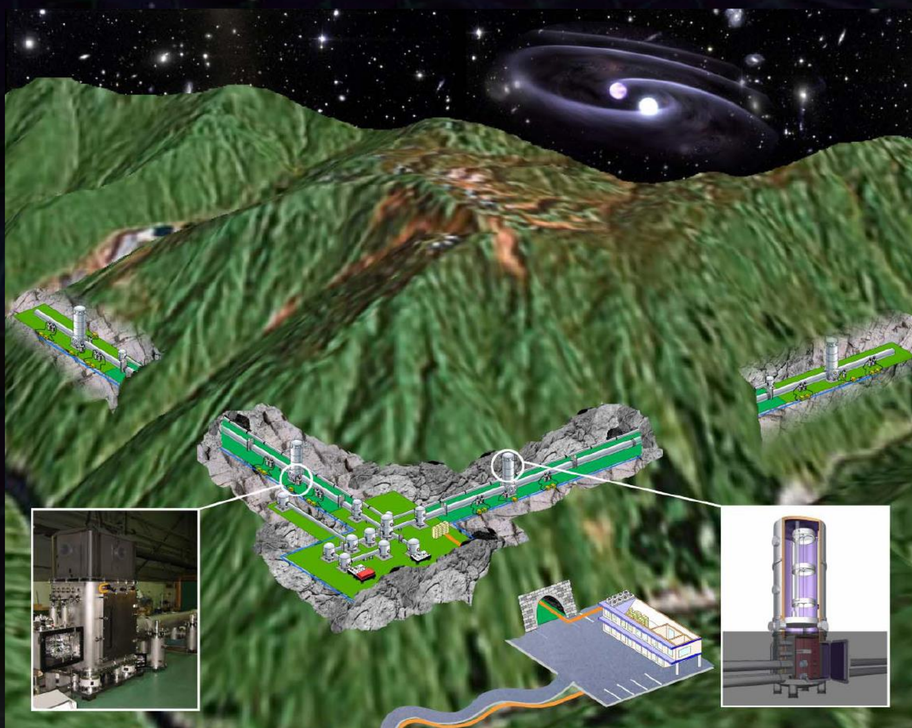
KAGRA and DECIGO

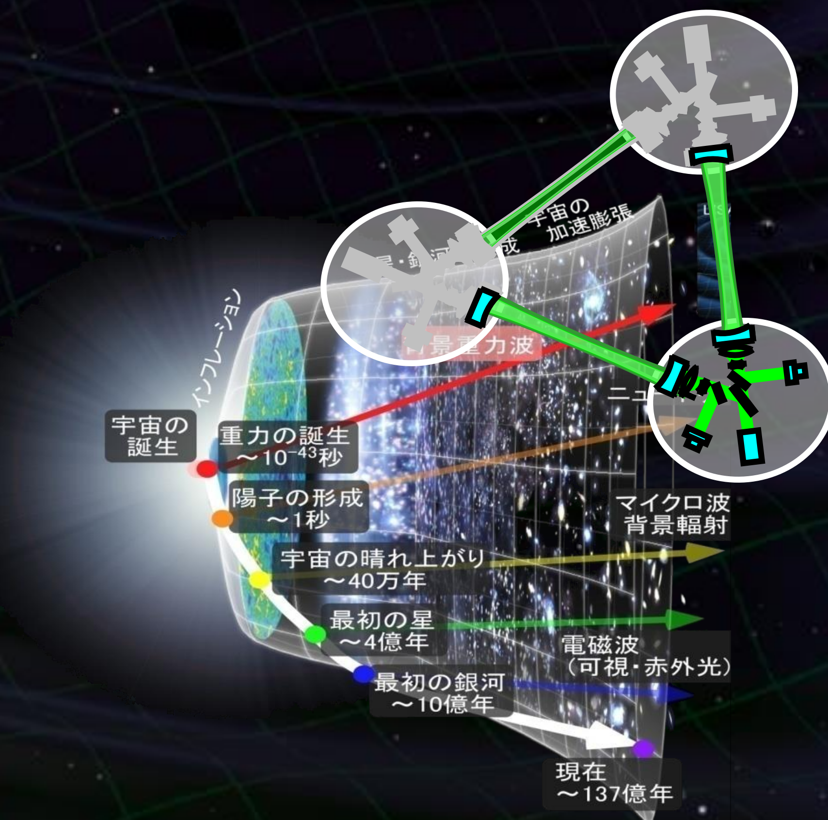
KAGRA (~2016)
Terrestrial Detector
→ High frequency events

Target: GW detection

DECIGO (~2027)
Space observatory
→ Low frequency sources

Target: GW astronomy





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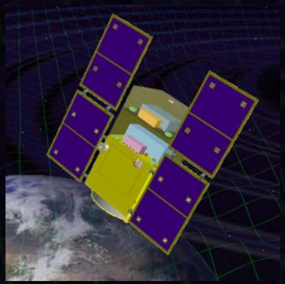
Mission

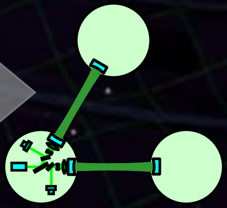
R&D
Fabrication

SDS-1/SWIM



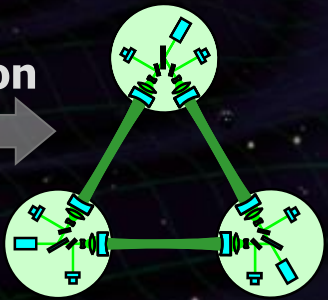
DECIGO
Pathfinder
(DPF)

R&D
Fabrication



Pre-DECIGO

R&D
Fabrication



DECIGO

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