GWADW2021
(Gravitational Wave Advanced Detector Workshop)

Space GW Antennae: DECIGO/B-DECIGO

Masaki Ando (Univ. of Tokyo)

Outline

- Introduction
- DECIGO
- B-DECIGO
- Summary

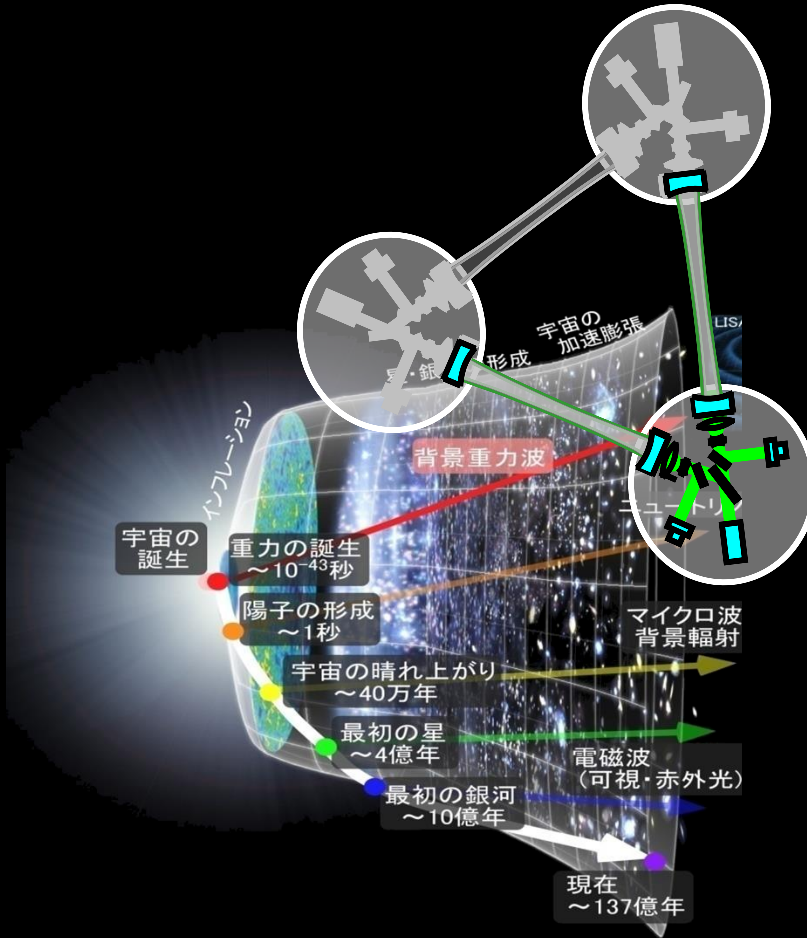
Introduction

- The first GW (and EM counter part) detections demonstrated new possibilities by GW astronomy.
  → More events, More precise parameter estimation.
- As for BNS, we need more events, sky localization, higher SNR for astrophysics and nuclear physics.

⇩

- Network of 2nd-gen. GW antennae (aLIGO, AdVIRGO, KAGRA, LIGO-India) is being formed.
- Two ways after that for Astronomy and Cosmology:
  - 3rd–gen. ground-based GW antennae (ET, CE).
  - Space GW antennae (LISA, DECIGO/B-DECIGO, …).

DECIGO



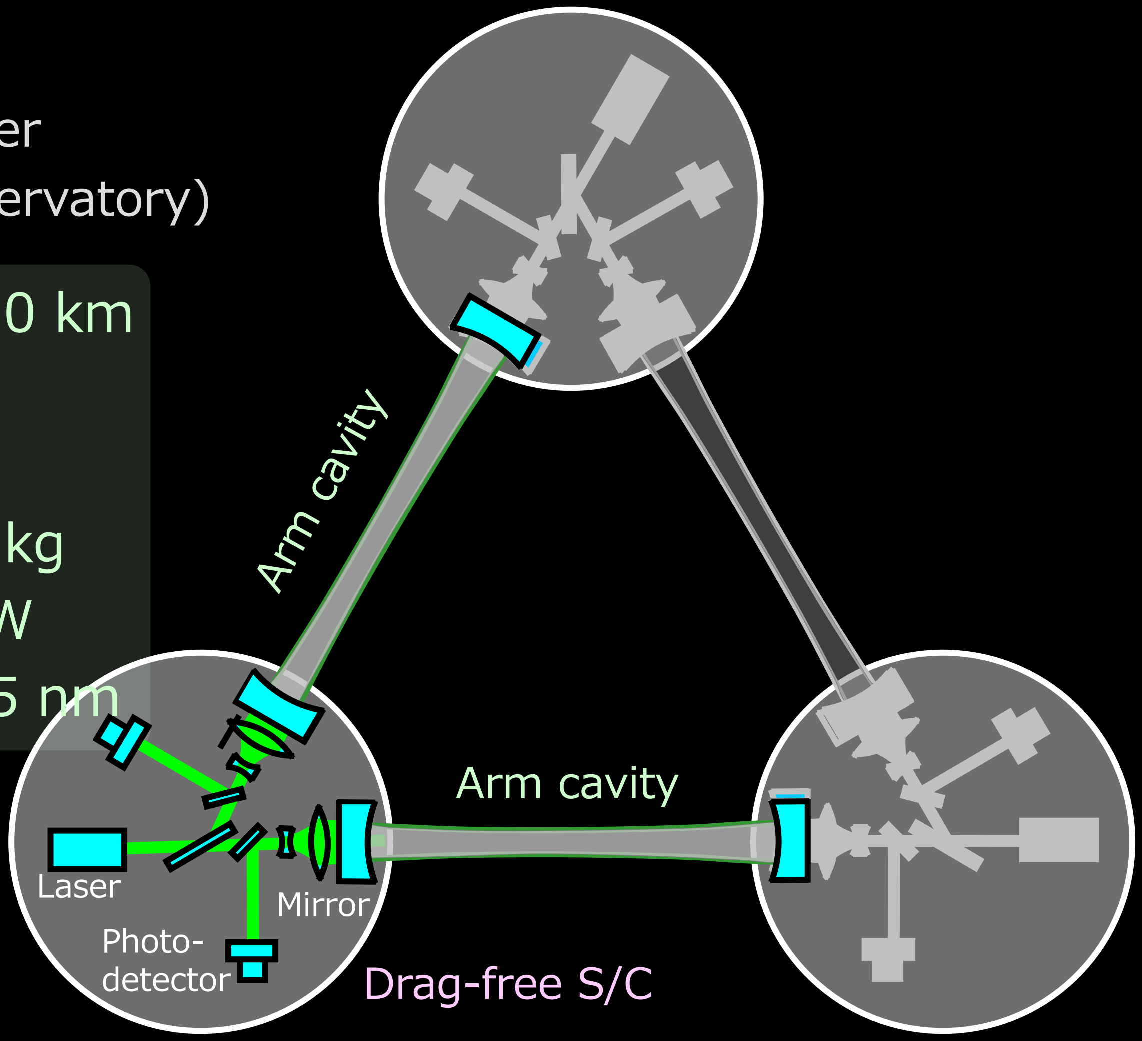
宇宙の
加速膨張
形成
LISA
背景重力波
インフレーション
宇宙の
誕生
重力の誕生
～10^{-43}秒
陽子の形成
～1秒
マイクロ波
背景輻射
宇宙の晴れ上がり
～40万年
最初の星
～4億年
電磁波
（可視・赤外光）
最初の銀河
～10億年
現在
～137億年

Conceptual Design

DECIGO

(DECI-hertz interferometer
Gravitational wave Observatory)

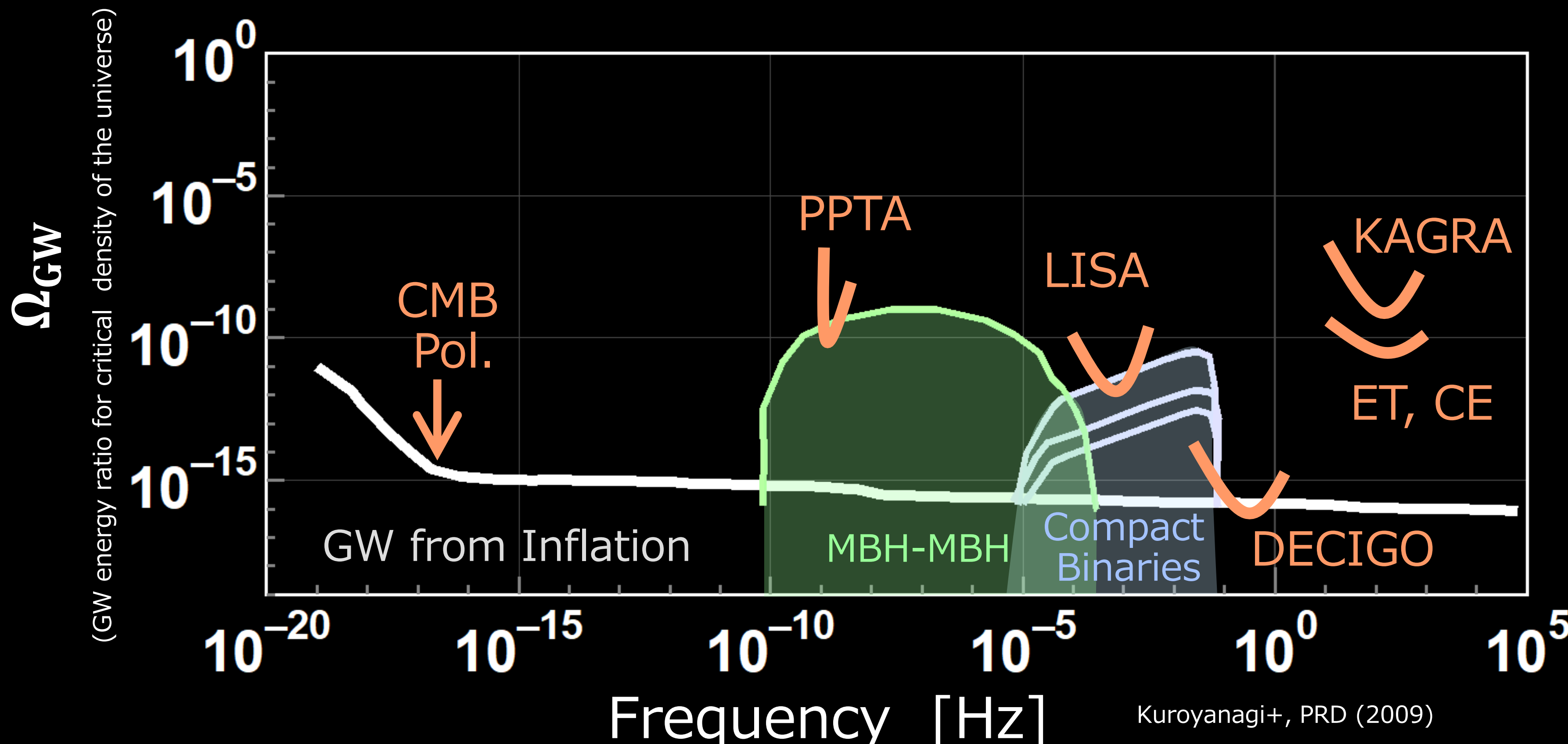
Arm length:	1000 km
Finesse:	10
Mirror diameter:	1 m
Mirror mass:	100 kg
Laser power:	10 W
Laser wavelength :	515 nm



S/C: drag free
3 interferometers

'Window' for the Early Universe

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



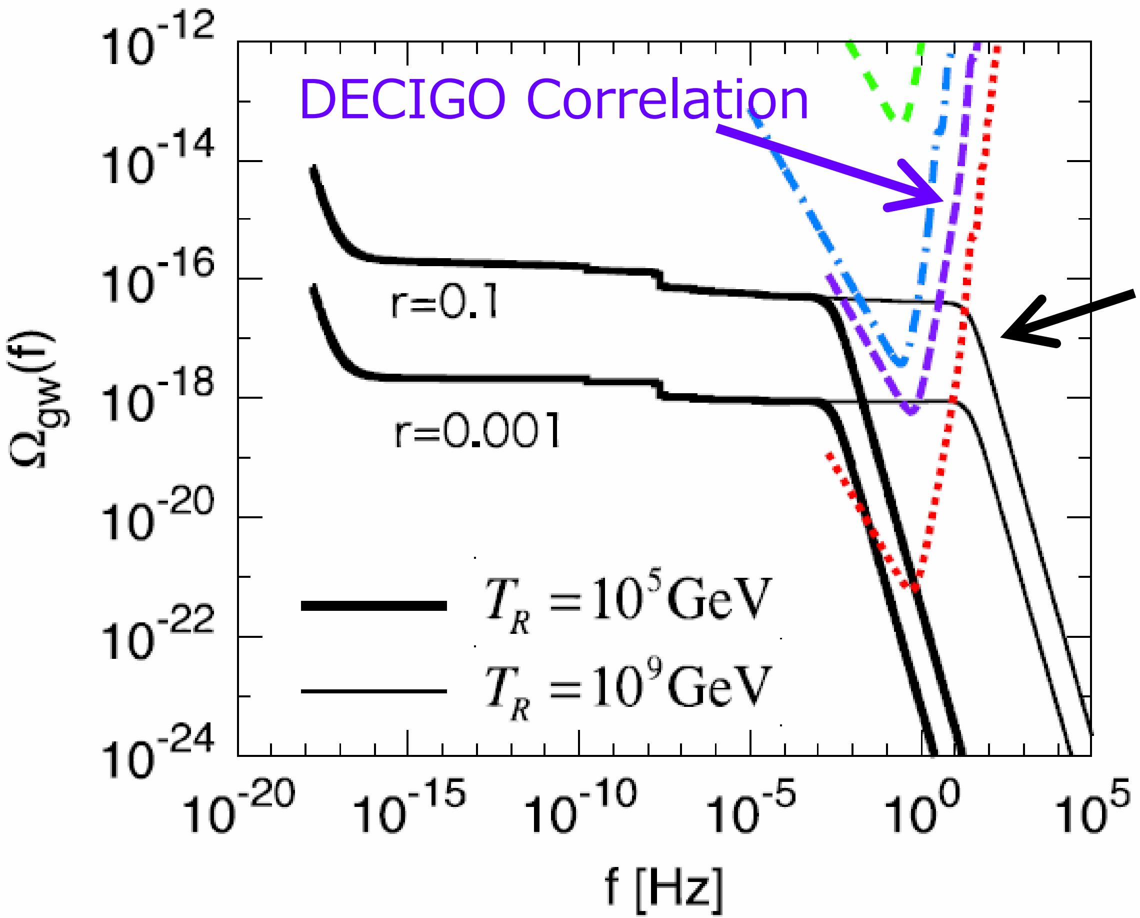
Kuroyanagi+, PRD (2009)

Pablo, PRD (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.

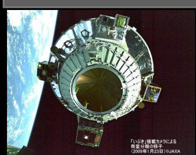
Roadmap for DECIGO

Original figure: S.Kawamura

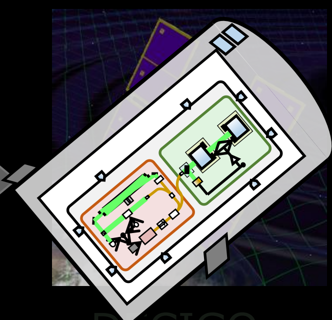
2009 ~2030

Mission

R&D Fabrication



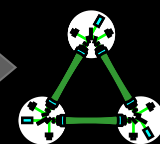
SDS-1/SWIM



DECIGO Pathfinder (DPF)

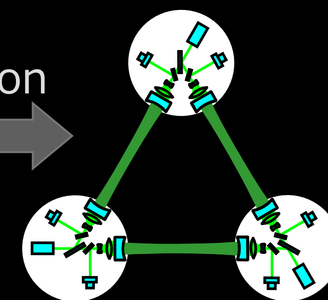
Ground test + Space demonstration.

R&D Fabrication



B-DECIGO

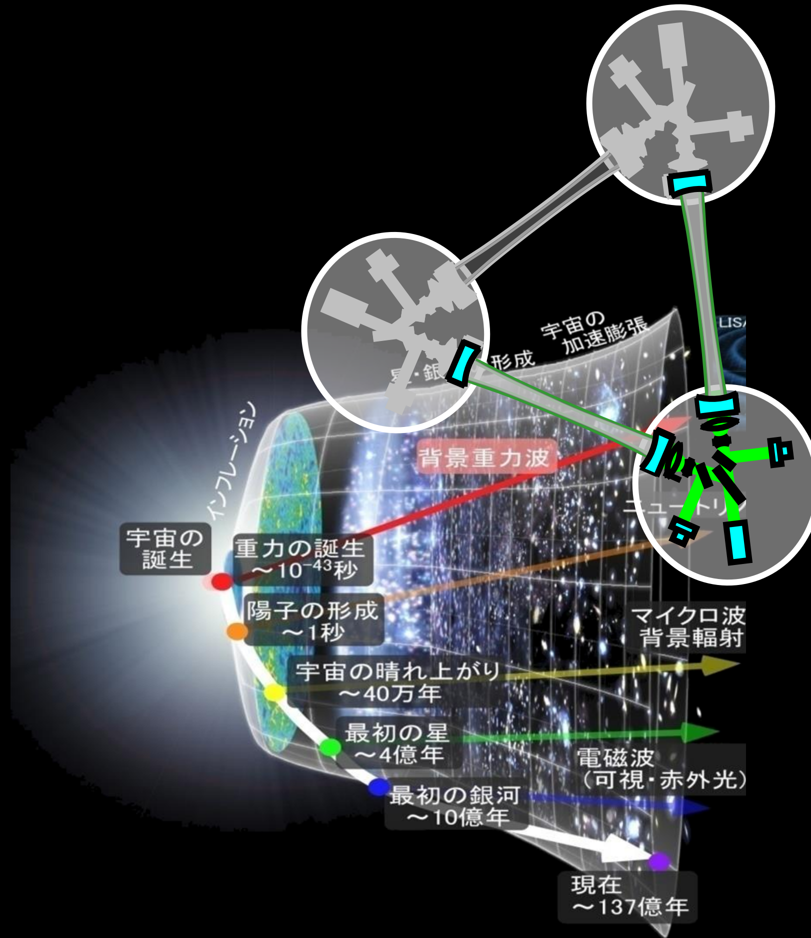
R&D Fabrication



DECIGO

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

B-DECIGO



宇宙の
加速膨張
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背景重力波
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（可視・赤外光）
最初の銀河
～10億年
現在
～137億年

Space GW Observatory: B-DECIGO

※ Renamed in 2016: 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.

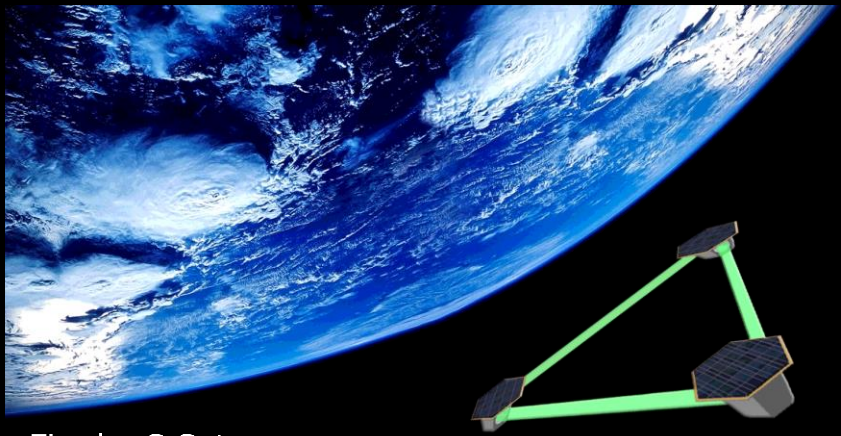


Fig. by S.Sato

Target: JAXA Strategic Medium-scale mission (~2030).

B-DECIGO Design (Preliminary)

Mission requirement:

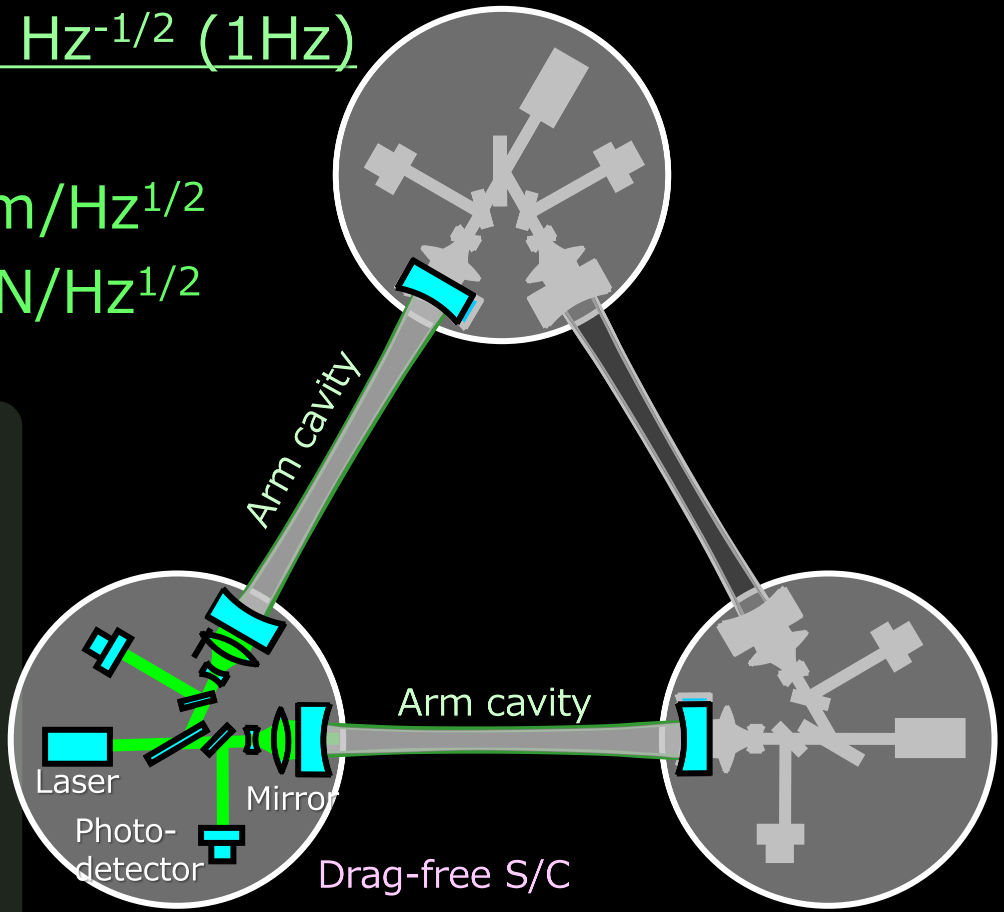
Strain sensitivity 2×10^{-23} $Hz^{-1/2}$ (1Hz)

⇩

* Disp. noise : 1×10^{-18} $m/Hz^{1/2}$
* Force noise : 1×10^{-16} $N/Hz^{1/2}$

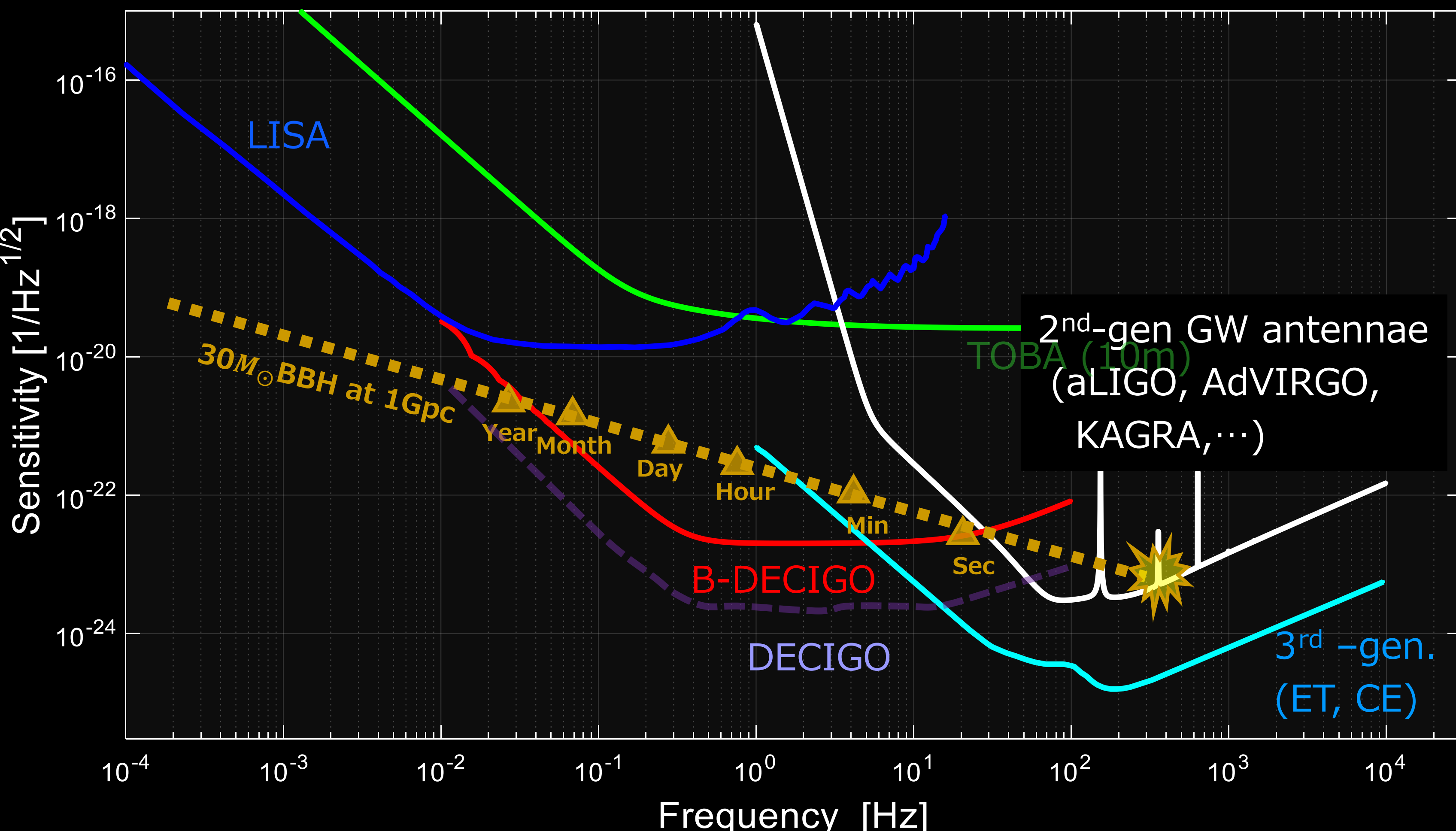
Arm length:	100 km
Finesse:	100
Mirror diameter:	30 cm
Mirror mass:	30 kg
Laser power:	1 W
Laser wavelength :	515 nm

Orbit : TBD
(Record-disk around the Earth?)



Sensitivity Curves

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



Sciences by B-DECIGO

(1) Inspiral of Compact binaries [‘Promised’ target]

- High rate ~10^5 binaries/yr.
- Estimation of binary parameters and merger time.

→ Astronomy by GW and GW-EM observations.

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

- Cover most of the universe.

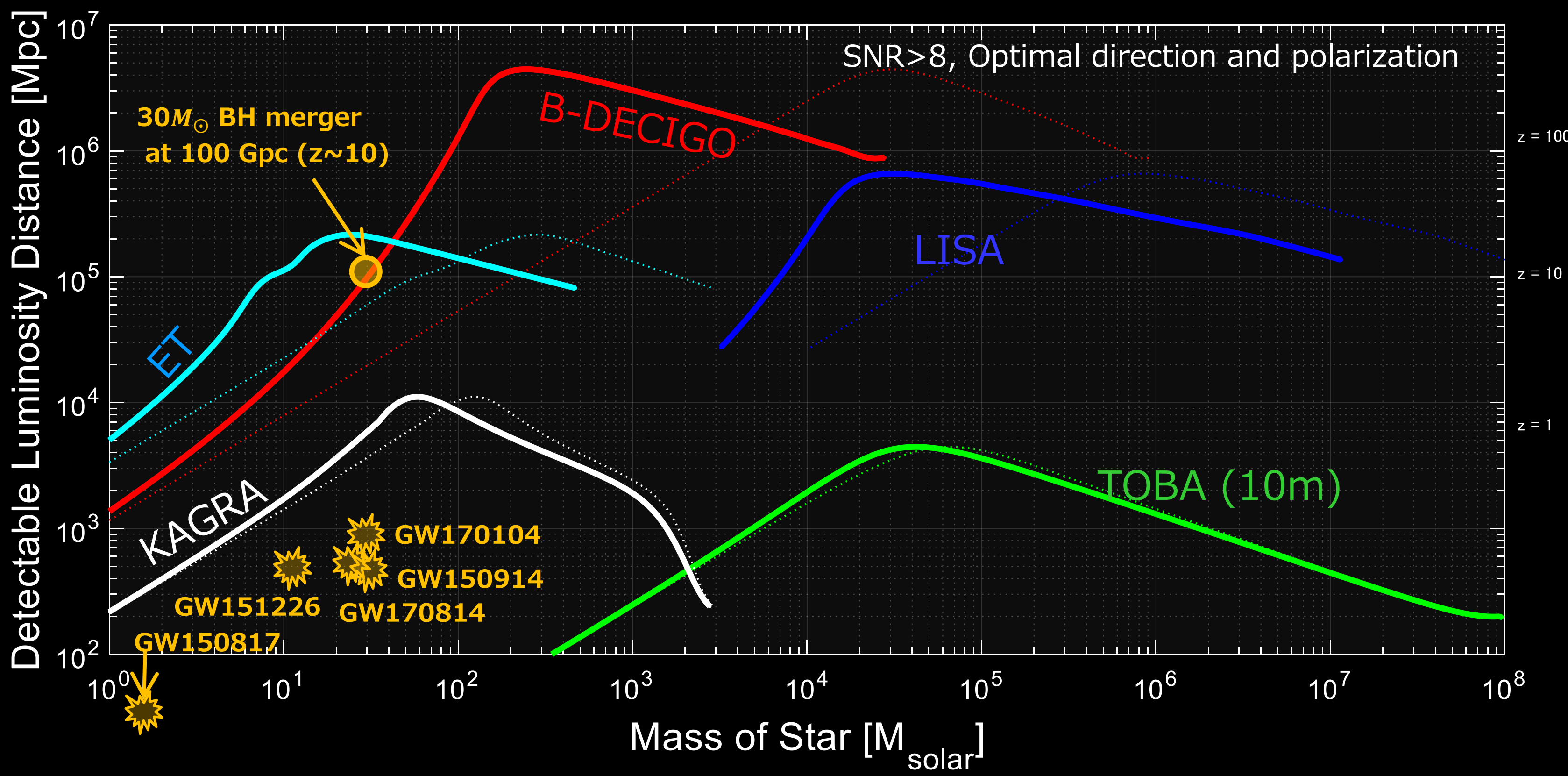
→ Formation history of SMBH and galaxies.

(3) Foreground understandings for DECIGO [Cosmology]

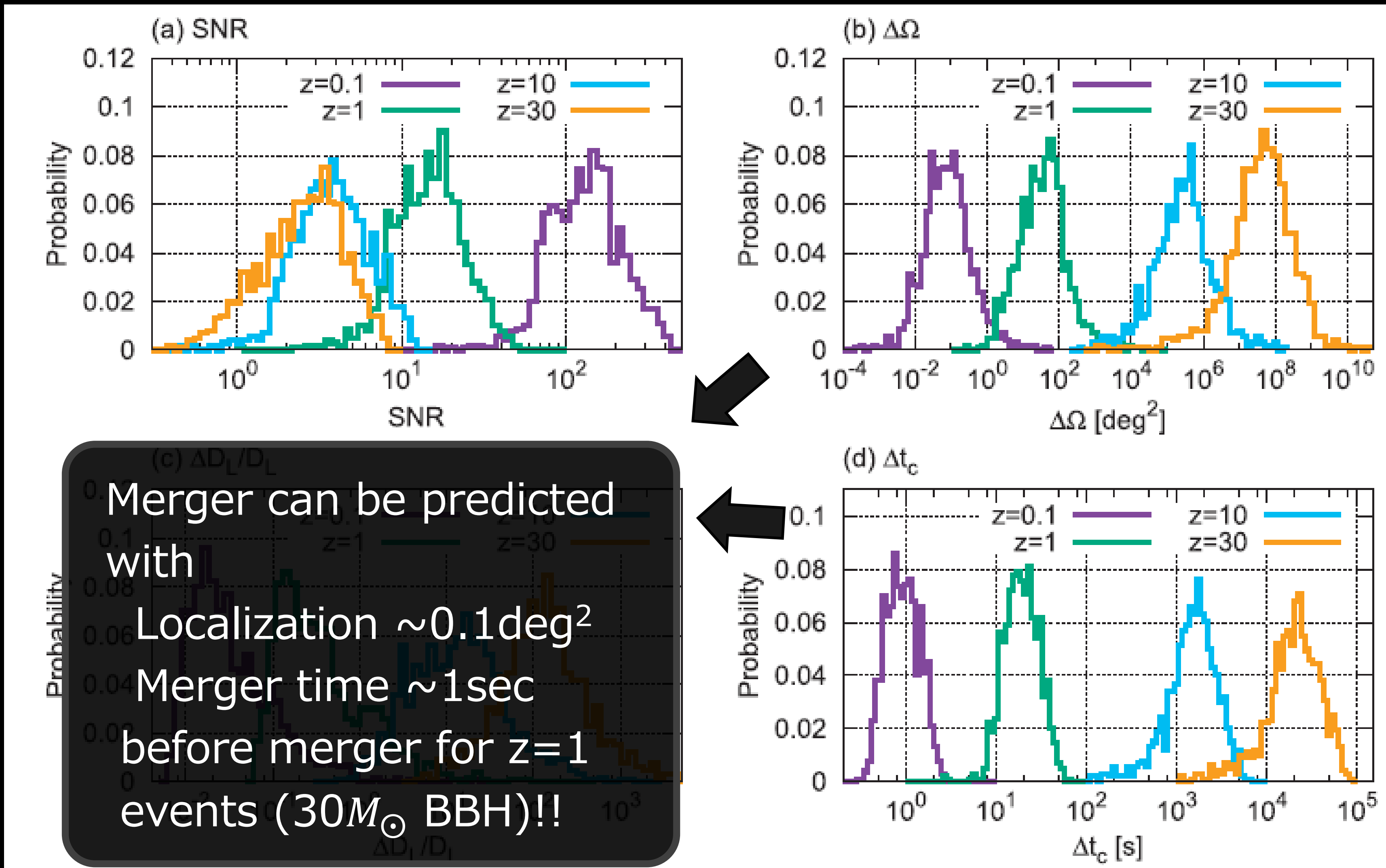
- Parameter estimation and subtraction of binaries.
- Characteristics of foreground.
- Is the any eccentric binaries?

Observable Range

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



Parameter Estimation Accuracy



Merger can be predicted with

Localization ~0.1deg^2

Merger time ~1sec

before merger for z=1 events ($30M_\odot$ BBH)!!

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

B-DECIGO Sciences for CBC

- 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 → ~ 100 events/yr .
- 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 (~10^5) :
  * Localization, Merger time → Alerts for GW-EM.
  * Mass, Distance, Spin → Origin and nature of binaries.

Sciences by B-DECIGO

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

- High rate ~10^5 binaries/yr.
- Estimation of binary parameters and merger time.

→ Astronomy by GW and GW-EM observations.

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

- Cover most of the universe.

→ Formation history of SMBH and galaxies.

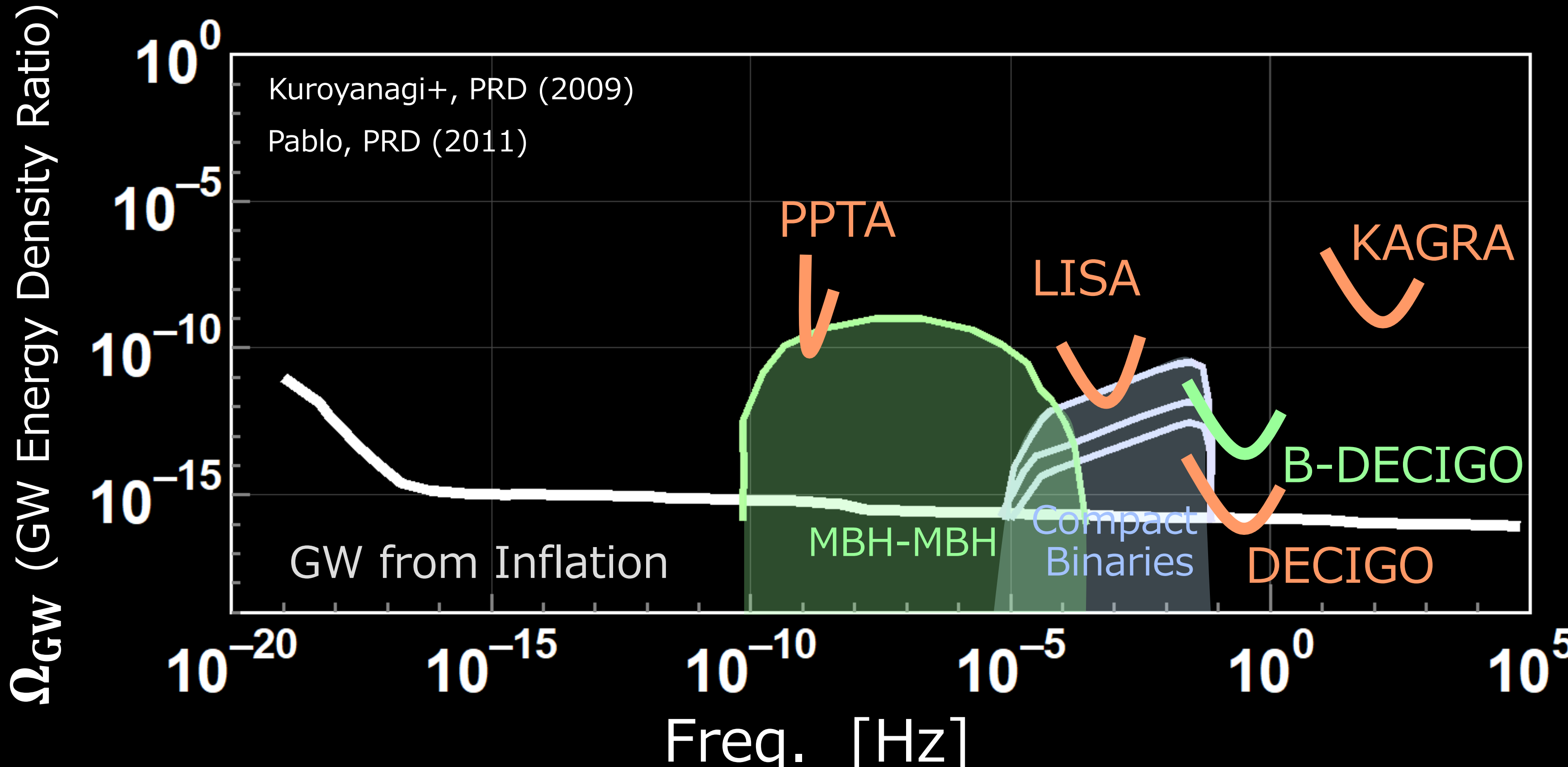
⇨(3) Foreground understandings for DECIGO [Cosmology]

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

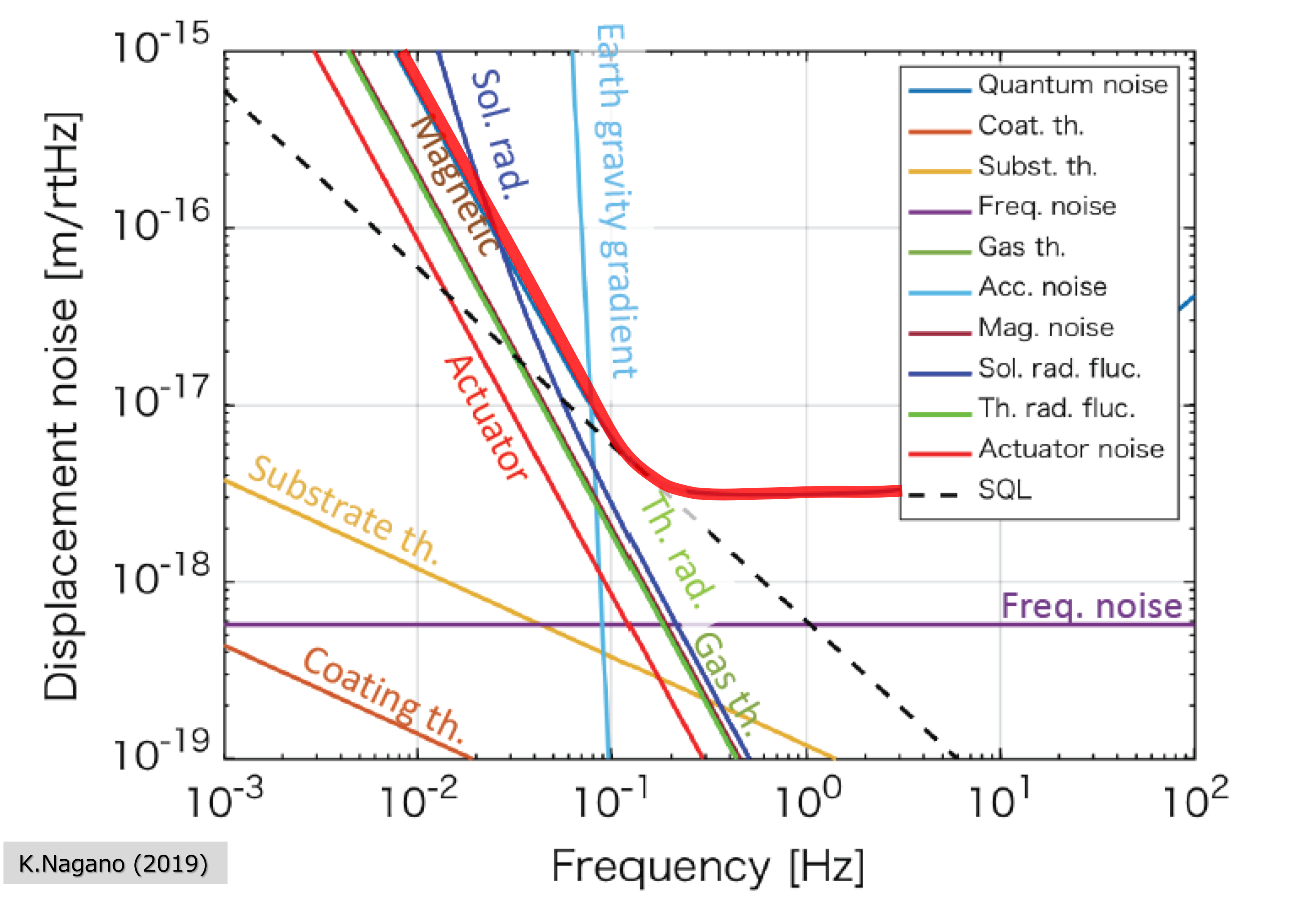
Target (3) : Foreground Understandings

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

⇨ Gain understandings with >100 binaries.



Estimated Noise Sources



Technical Challenges

- Long-baseline Interferometry (Disp. <1×10^{-18} m/Hz$^{1/2}$)
  - Optical configuration for IFO, and laser source.
  - 100km Fabry-Perot cavity (Large RoC, Distortion).
  - Initial 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.
- Mission Design
  - Orbital Design, Initial Mission sequence.
  - Resource distribution, Launcher, Cost estimation.

B-DECIGO Study

- B-DECIGO System Design

→ Feasibility study by a company

- Mass, Power, Thermal, Communication, Launch/Orbit, S/C control, S/C design,…

→ Confirmation of feasibility (Preliminary)

[S/C mass ~430kg, power ~450 W]

- Cost estimation

→ Possibility to be within JAXA mission’s cost cap.

B-DECIGO R&D

・<u>Technical Survey</u> as the first step of trade-off studies.

カテゴリ	番号	サーベイ項目
1	1	干渉計方式, 制御トポロジー
1	2	光学系実装
1	3	光学設計
2	1	レーザー光源
2	2	光源安定化方式
3	1	鏡・テストマスモジュール
3	2	ローカルセンサ・アクチュエータ
3	3	帯電除去
3	4	ローンチロック・クランプリリース
3	5	真空系・脱ガス対策
3	6	熱変動・勾配・温度安定化
4	1	ドラッグフリー・衛星変動抑圧
4	2	スラスタ
5	1	電気-光学コンポーネント
5	2	変復調・位相検波回路
5	3	デジタル/アナログIF (ADC/DAC)
5	3	制御系実装
6	1	初期捕捉方式
6	2	展開
6	3	リンクアクイジション
6	4	共振器ロックアクイジション
6		姿勢制御方式・コンポーネント
7	1	軌道選択
8	1	衛星取り付け・輸送方式
9	1	熱設計
10	1	システム設計
11	1	運用方式・地上とのデータ通信・衛星間通信
12	1	衛星地上試験・検証
13		冗長性の考え方、宇宙コンポーネントの知識
14		重力波検出器としての絶対キャリブレーション方法の検討

・<u>Space demonstration</u> in cooperation with the Formation-Flight Working Group of JAXA aerospace engineering committee.

→ SILVIA (<u>S</u>pace <u>I</u>nterferometer <u>L</u>aboratory <u>V</u>oyaging towards <u>I</u>nnovative <u>A</u>pplications) was selected as Pre-Phase A1b by JAXA/ISAS in FY2019.

「2019年度公募型小型計画・宇宙科学ミッションコンセプト提案」の結果について

2019年10月10日に公募を開始した「2019年度公募型小型計画・宇宙科学ミッションコンセプト提案」は、2020年2月5日の締切までに7件の応募がありました。宇宙科学研究所は提案の評価を宇宙理学委員会と宇宙工学委員会に依頼し、2つの委員会は合同で「公募型小型・評価審査小委員会」を設置しました。

宇宙科学プログラム室は、希望のあったワーキンググループに対し、提案書作成に向けた調整、支援を行いました。小委員会では、応募のあった全テーマについて2020年3月に一次ヒアリングを行った後、4テーマについて2020年5月に二次ヒアリングを実施し、最終的に1テーマを選定しました。小委員会の選定結果は2020年8月3日の臨時宇宙理工学合同委員会に報告され、そこでの審議を経て承認されました。

次のフェーズに進むことのできる提案は、新時代の高精度天体観測手法である宇宙干渉計の実現に必須となる、超高精度フォーメーションフライト技術とドラッグフリー技術の軌道上実証を行い、将来の重力波望遠鏡や赤外線干渉計等のミッション実現に向けた技術を獲得することを目指すSILVIA (Space Interferometer Laboratory Voyaging towards Innovative Applications) 計画の1件であります。

今後、この提案に対してアイデア実現加速プロセス (Pre-PhaseA1b) を実施し、適切な時期にミッション定義フェーズ (Pre-Phase A2) に進むための審査(プリプロジェクト候補選定審査) を実施していく予定です。その後本提案は、公募型小型計画5号機あるいは6号機の候補の一つとして活動していくことになります。

公募型小型・評価審査小委員会および木村 真一委員長には、大変な労力をかけて厳正なる審査をしていただきました。小委員会委員および小委員会から評価を委託された外部委員の皆様に深く感謝いたします。

（佐藤 英一）

「ISAS News」 2020.8
http://www.isas.jaxa.jp/outreach/isas_news/files/ISASnews473.pdf

Developments

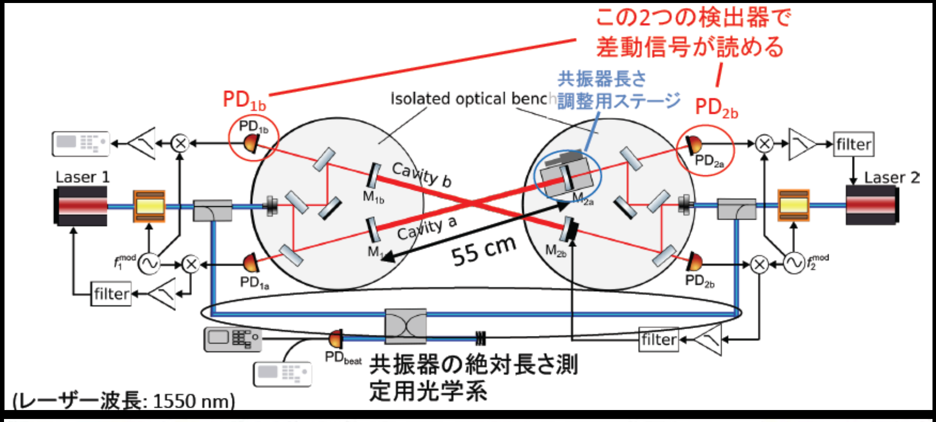
- Developments in
  - Interferometer prototype
  - Laser source and stabilization
  - Drag-free control
  - Thruster test
  - Formation flight simulation

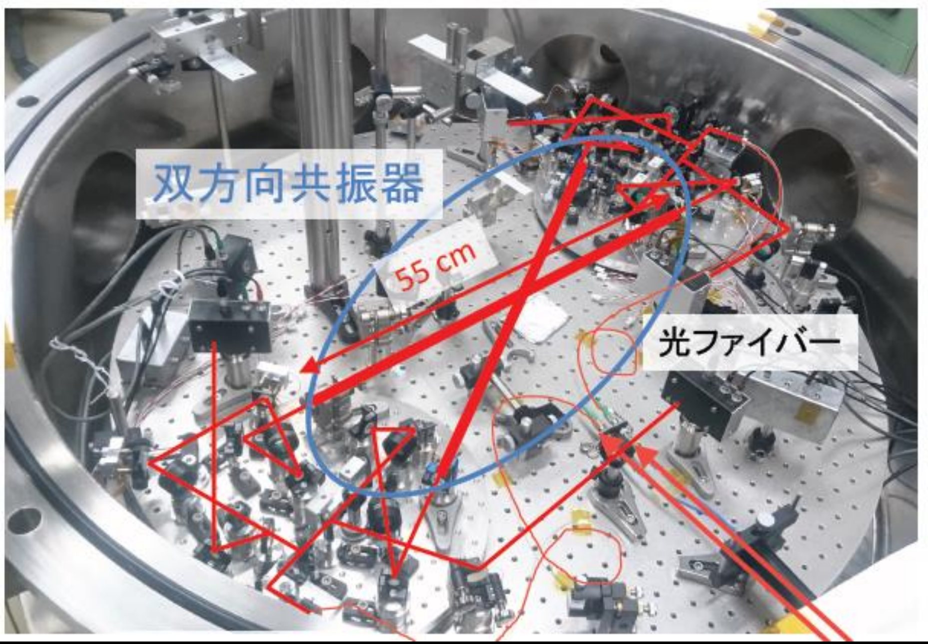
- Related presentation:

  #57 (Poster presentation)

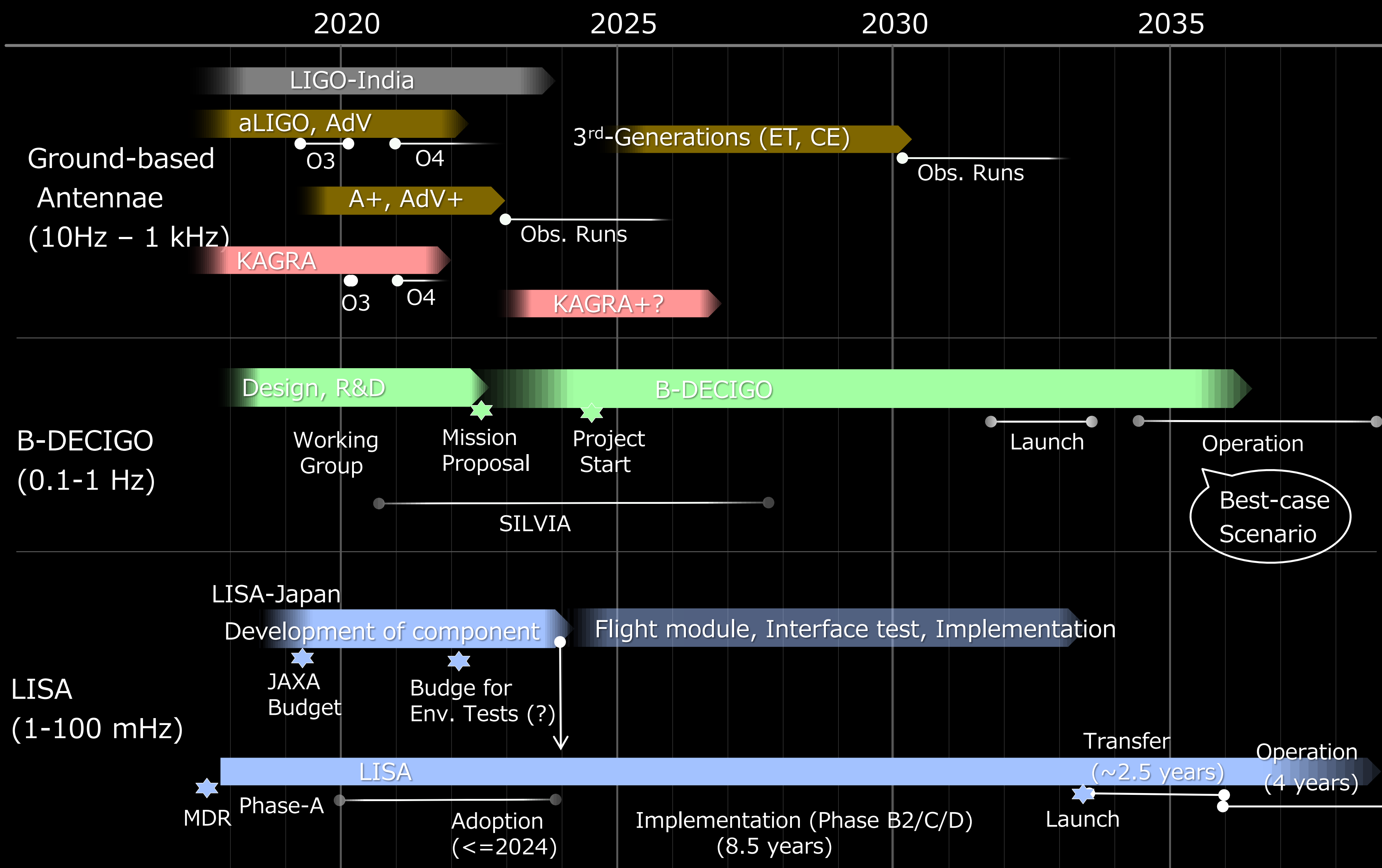
  ‘Demonstration of a dual-pass differential Fabry–Perot interferometer for future interferometric space gravitational wave antennas: DECIGO and B-DECIGO’

  by Koji Nagano





Roadmap


2020
2025
2030
2035
LIGO-India
aLIGO, AdV
O3
O4
Ground-based Antennae (10Hz – 1 kHz)
3rd-Generations (ET, CE)
Obs. Runs
A+, AdV+
Obs. Runs
KAGRA
O3
O4
KAGRA+?
Design, R&D
B-DECIGO
B-DECIGO (0.1-1 Hz)
Working Group
Mission Proposal
Project Start
Launch
Operation
Best-case Scenario
SILVIA
LISA-Japan
Development of component
Flight module, Interface test, Implementation
JAXA Budget
Budge for Env. Tests (?)
LISA (1-100 mHz)
Transfer (~2.5 years)
Operation (4 years)
LISA
MDR
Phase-A
Adoption (<=2024)
Implementation (Phase B2/C/D) (8.5 years)
Launch

Summary

Summary

- First direct detection of GW was achieved by LIGO 100 years after the theoretical prediction by A. Einstein by General Relativity.
- It opens the new field of 'Gravitational-wave astronomy'. We obtained a new prove to understand the universe.
- The field will be expanded by antennae with better sensitivity, and with different frequencies.

- B-DECIGO will provide fruitful sciences. Future DECIGO will be one of the dream of science; it will be able to observe the early universe directly.

End

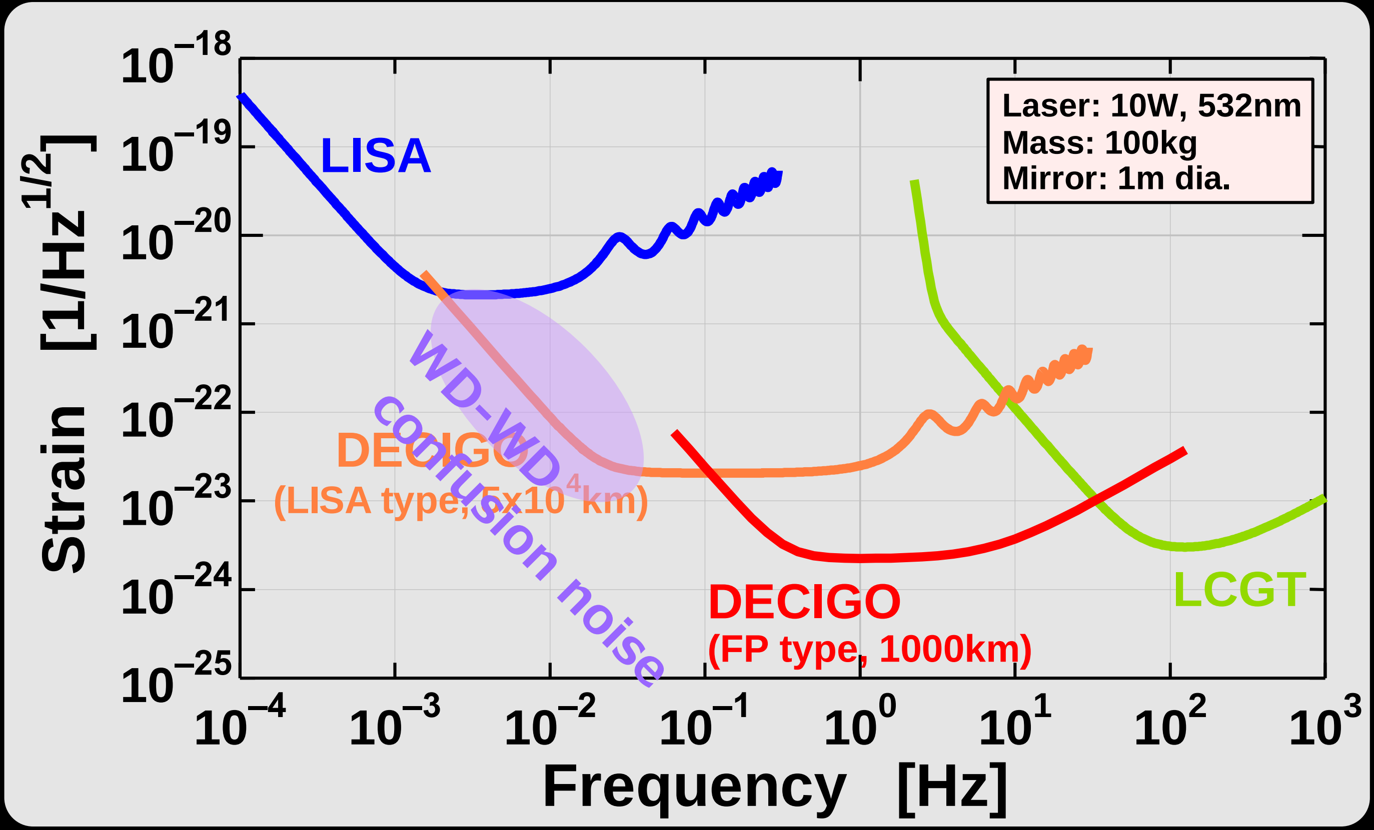
Back-Up Slides

Interferometer Design

Transponder type vs Direct-reflection type

Compare : Sensitivity curves and Expected Sciences

⇨ Decisive factor: Binary confusion noise



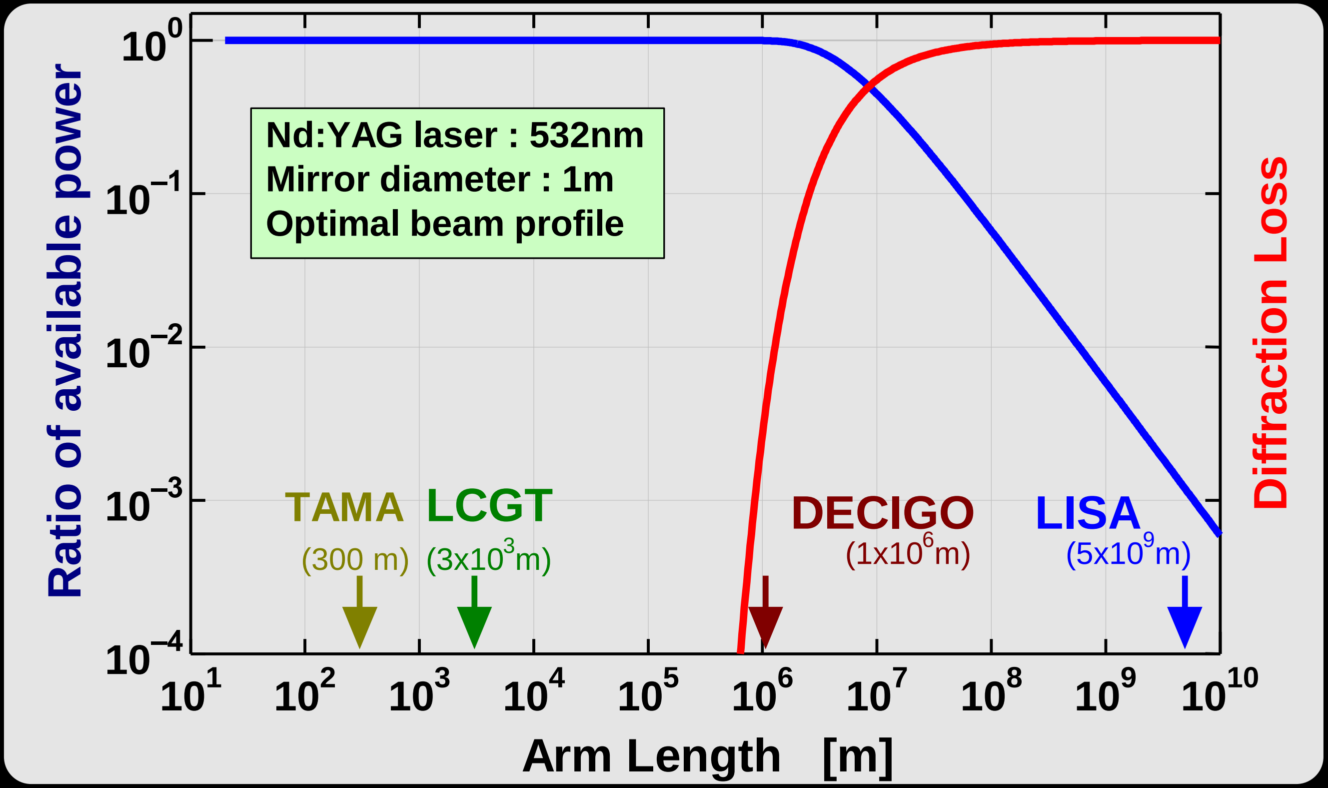
Arm length

Cavity arm length : Limited by diffraction loss

Effective reflectivity ($TEM_{00} \rightarrow TEM_{00}$)

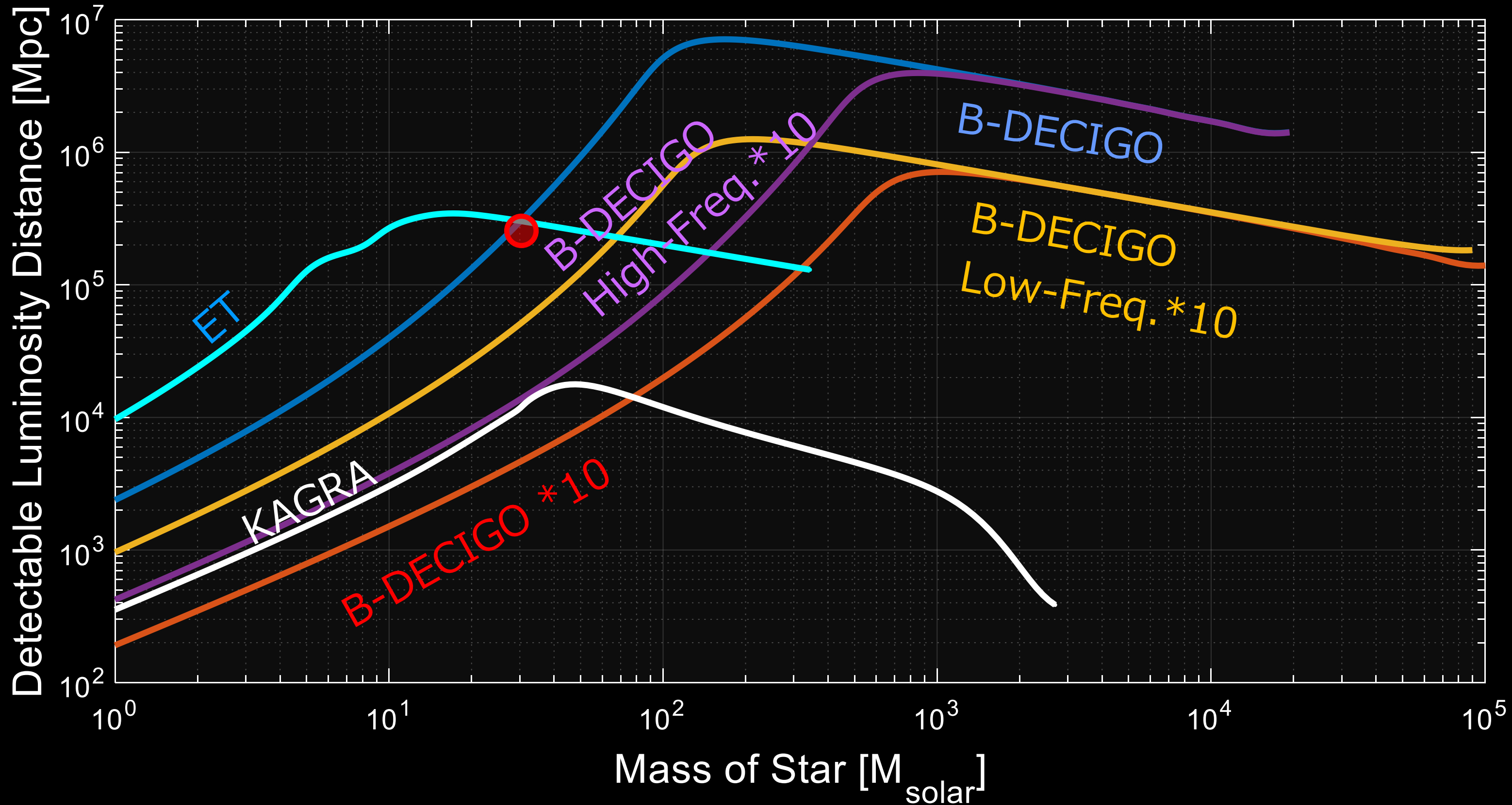
- Laser wavelength : 532nm
- Mirror diameter: 1m
- Optimal beam size

⇨ 1000 km is almost max.



Trade-off Study for Descope

What happens if we degrade the target sensitivity.



Low-freq. noise (Acc. noise) → Degrade overall range.

High-freq. noise (Shot noise) → Degrade for lighter mass.

Parameter Estimation Accuracy

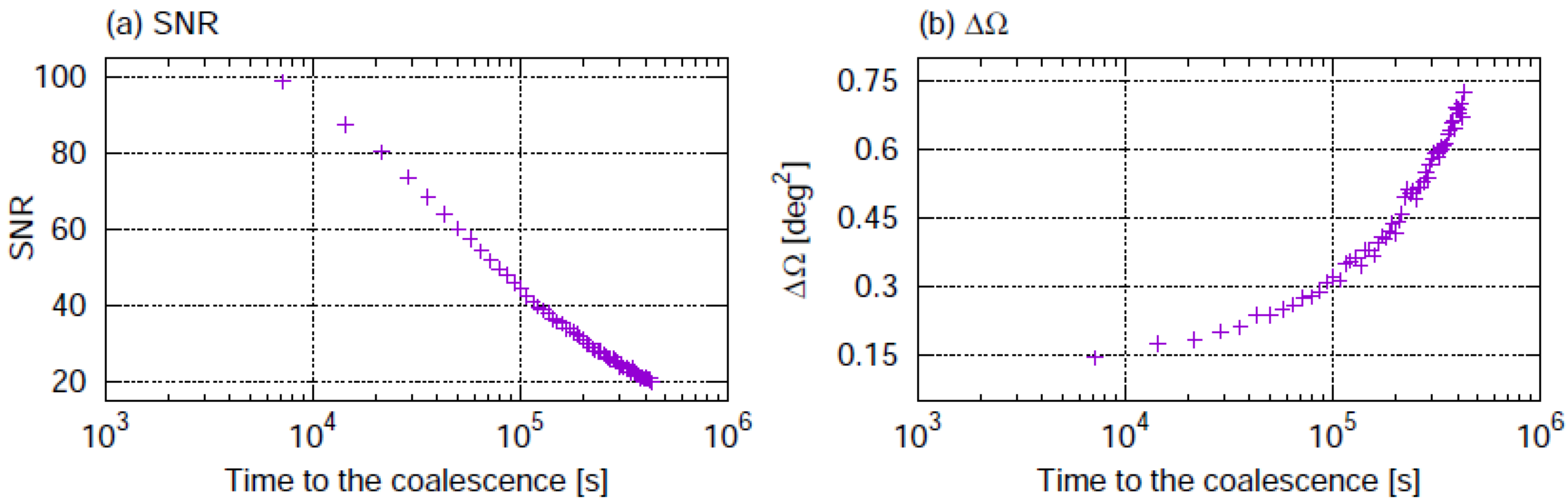
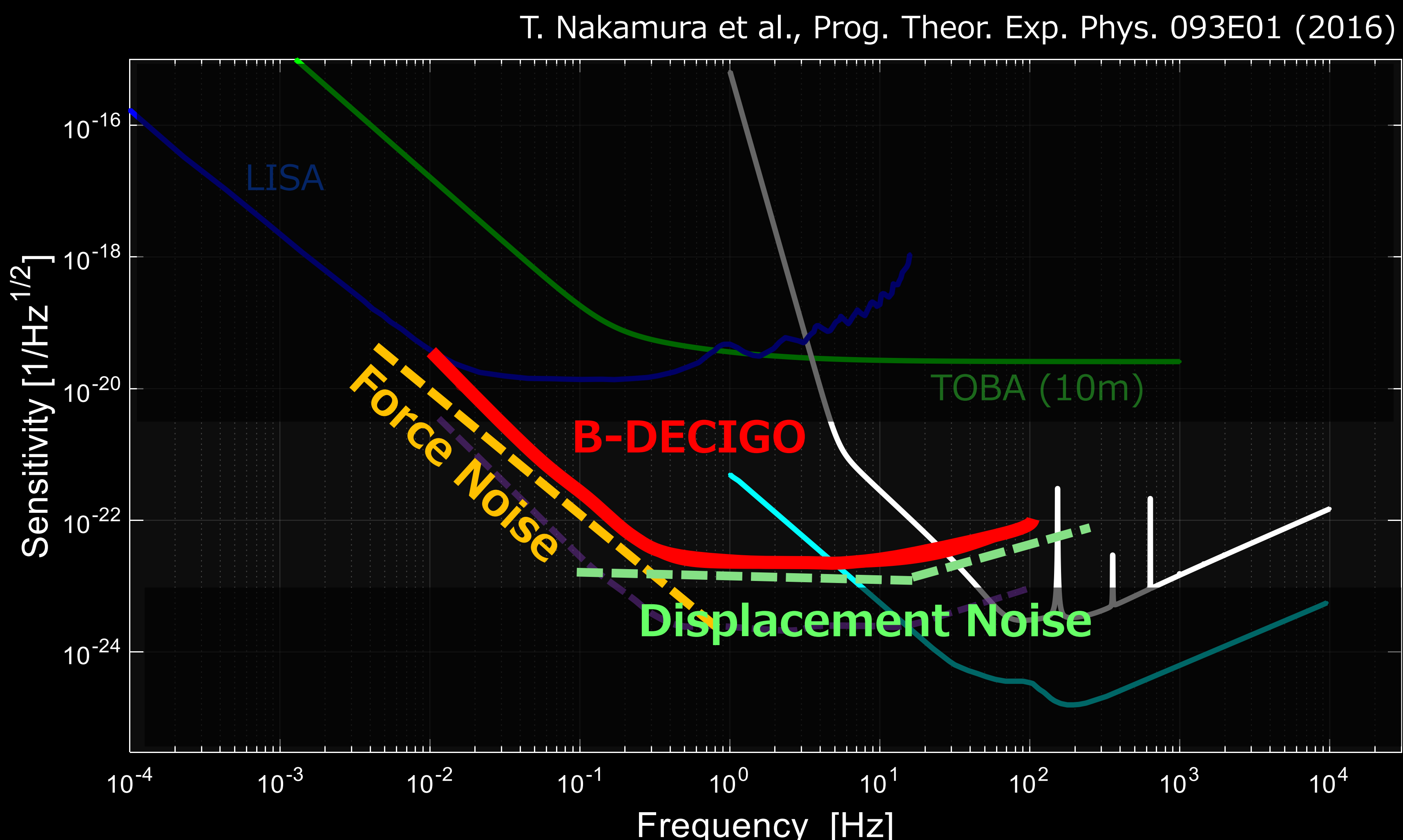


Fig. 11 Time evolution for (a) SNR and (b) angular resolution of GWs from $30M_\odot$ equal-mass BH binaries at the distance of $z = 0.1$. We assume $\alpha = \delta = 1.0\,\mathrm{rad}$, $\psi = 0.5\,\mathrm{rad}$, and $\cos\iota = 0.5$.

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

Sensitivity Curves



B-DECIGO Requirements

Displacement Noise

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

⇨ ~ x10 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

Force (Acceleration) Noise

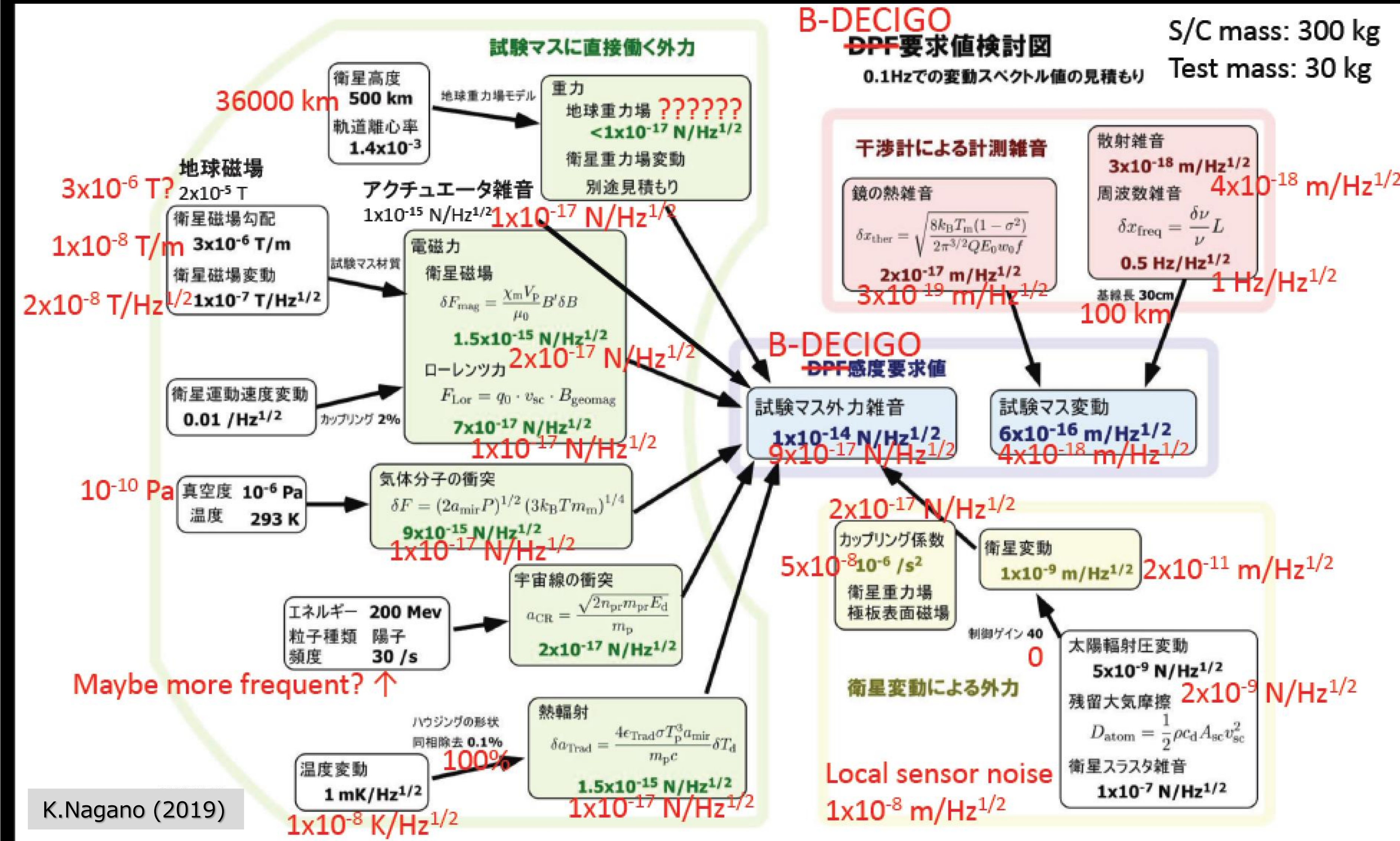
Force noise 1×10^{-16} N/Hz$^{1/2}$ (0.1 Hz)

⇨ x 1/60 of LISA

External force sources

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

Basic Requirements



Force Noise Requirements (1)

	DPF	B-DECIGO
Magnetic noise		
Magnetic fluctuation, δB [T/rtHz]	1e-7	2e-8
Magnetic gradient, B' [T/m]	3e-6	1e-8
Residual gas thermal		
Pressure [Pa]	1e-6	1e-9
Solar radiation pressure noise		
Solar radiation fluctuation [N/rtHz]	4e-10	4e-10
Local sensor sensitivity [m/rtHz]	1e-10	1e-13
Thruster noise, Fth [N/rtHz]	1e-7	1e-7
Coupling, α [1/s^2]	1e-6	1e-6
Actuator noise		
Actuator noise, Fact [N/rtHz]	1e-15	1e-17

K.Nagano (2019)

Force Noise Requirements (2)

	DPF	B-DECIGO
Thermal radiation fluctuation		
Temperature fluctuation, δT [K/rtHz]	1e-3	1e-6
Common mode rejection	1e-3	1
Shield	1	1e-2
Frequency noise		
Frequency noise [Hz/rtHz]	0.5	1
Control gain	?	3e8
Thermal noise		
Substrate loss angle		1e-7
Costing loss angle (SiO_2, Ta_2O_5)		0.5e-4, 2e-4
Beam radius [cm]		14

K.Nagano (2019)

Formation Flight

- Formation flight is achieved by 2 steps.
  * TM-TM: Length measurement and control by the laser interferometer.
  * TM-S/C: Control by local sensor and thruster

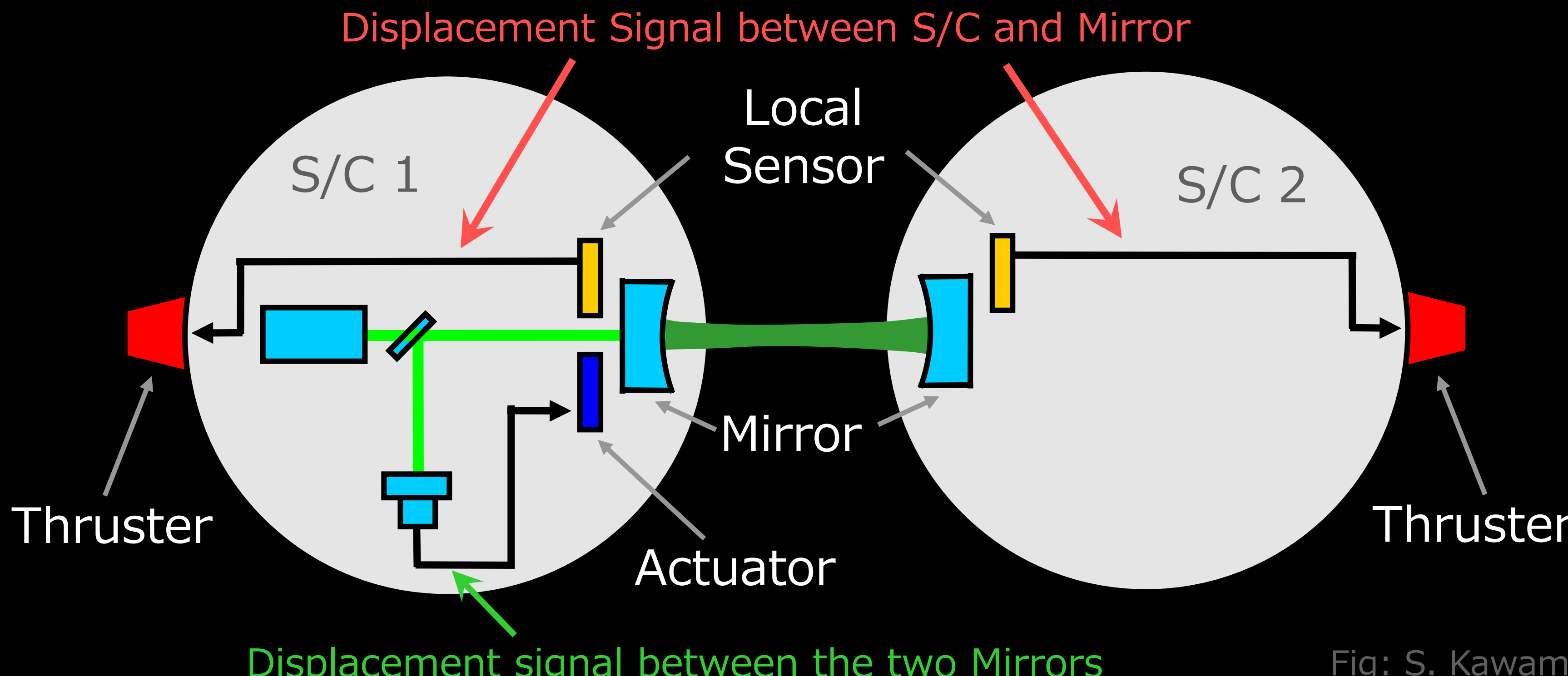


Fig: S. Kawamura

Formation Flight Requirements

- TM (mirror): untouched from S/C for reduction of FN.
- Laser interferometer ranging.

  $< 1\times10^{-18}\ \mathrm{m/Hz^{1/2}}$ (0.1Hz)

  Length accuracy < 0.5%

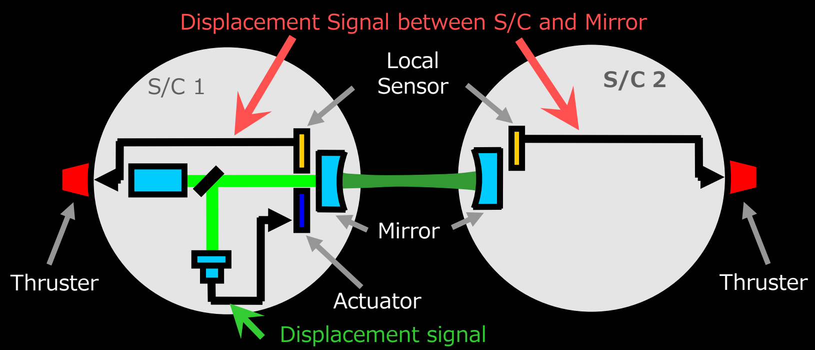


Fig: S. Kawamura

- Force noise from S/C motion.
  - Drag-free (Control S/C to follow TM)

    $< 2\times10^{-11}\ \mathrm{m/Hz^{1/2}}$ (0.1Hz)
  - Coupling between S/C-TM < $5\times10^{-8}\ /\mathrm{s}^2$
- Initial acquisition.
  - High-dynamic range scanning to find relative position.
  - Switch to the final now-noise sensor/actuator.

Drag-Free Requirements

- Drag-Free Control: Suppress in-band S/C motion.
  - Keep the relative position within linear range of the local sensor/actuator.
    TM-S/C RMS motion < 0.1mm
  - Signal communication between Bus – Mission comp.
  - Drag-free: Gain > ~40 (0.1Hz), Band > ~10Hz
- Low-noise thruster: Suppress solar radiation noise.
  - Max force > 100 μN (tunable force)
  - Thrust noise < 10^{-7} N/Hz$^{1/2}$ (100Hz)
- Selection of the orbit:
  - Tidal force on TM ⇔ Range of control actuator.
  - Trade-off with Duty factor, Mission lifetime.

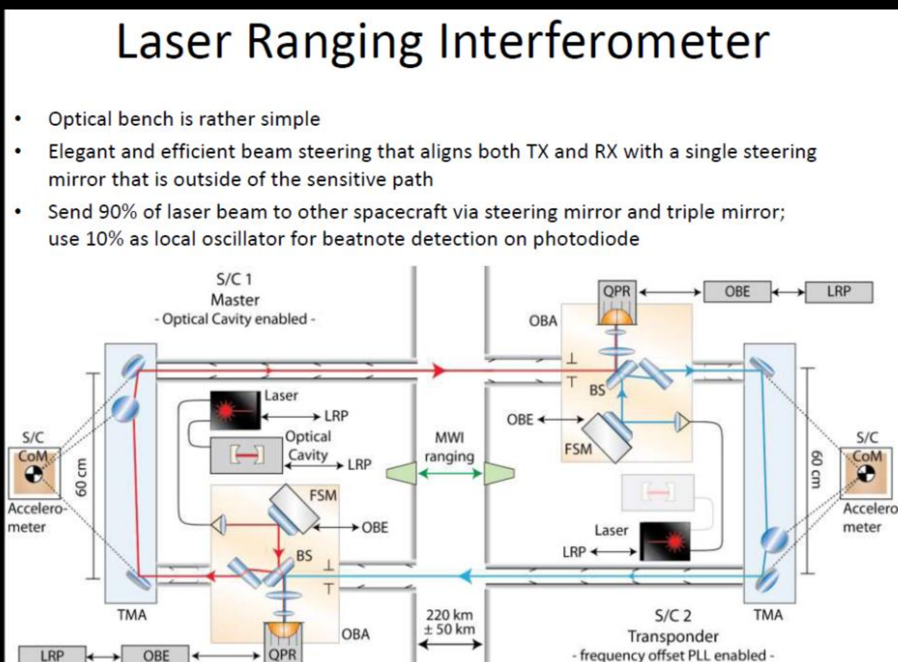
Initial Acquisition

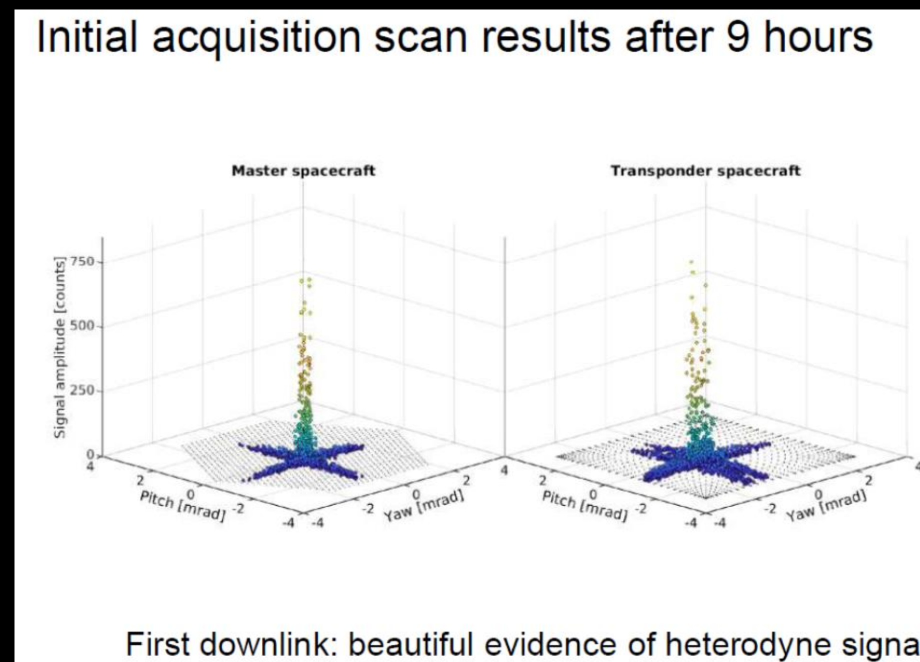
- 3 steps for Initial lock acquisition:
  - (1) Launch and introduction to the reference orbit, by S/C tracking from the earth.
  - (2) Find the laser beam from each other, by on-board instruments.
    - Accuracy : ~10cm mirror diameter, 100km separation → 10^{-6} rad is required.
    - Reasonable scanning time <~hours.
  - (3) Fine alignment using the main beam.
    - Length sensing by the main FP interferometer.
    - Wave front sensing by the main beam.

Initial Acquisition of GRACE-FO

- Laser Ranging Interferometer (LRI) of GRACE-FO
  - Baseline length ~250km, Mirror diameter ~3cm
  - Scan the beam by a steering mirror.

  → Initial acquisition was achieved by 9-hour scan.

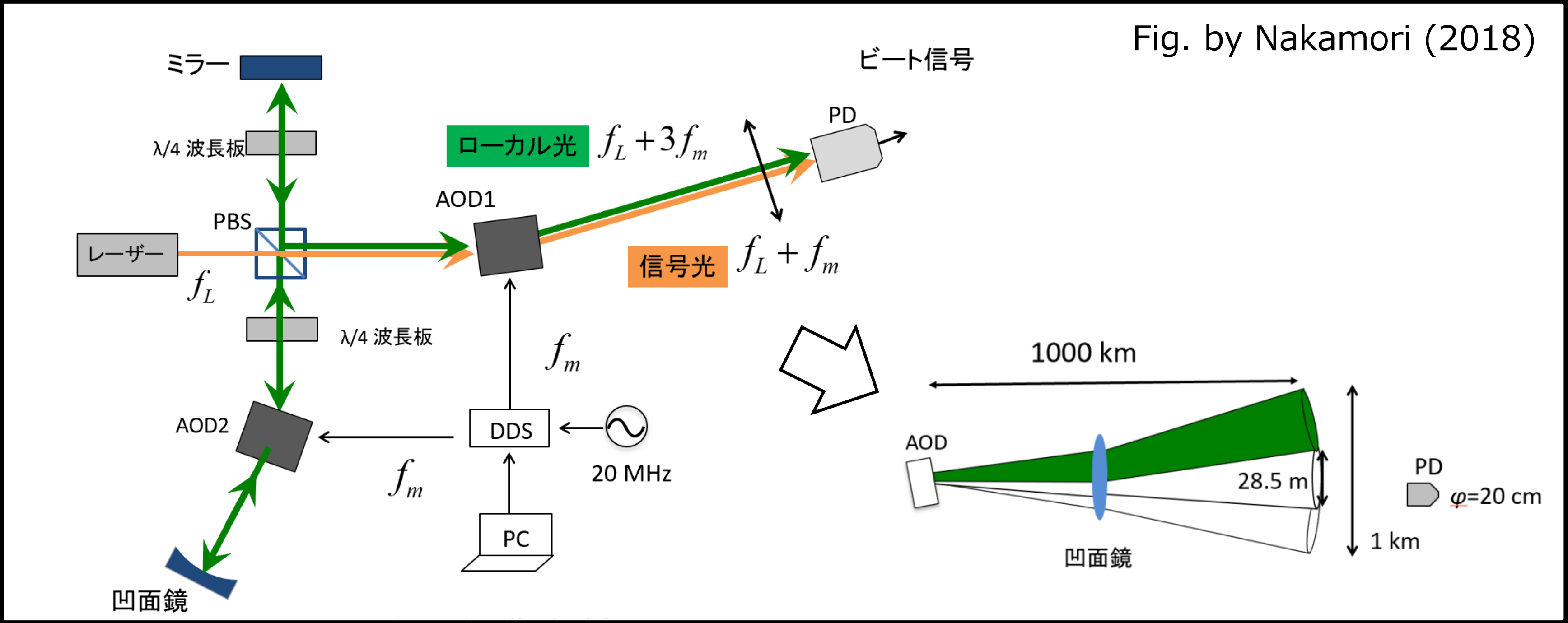




G.Heinzel (KIW6, June, 2019)

Idea of Initial Acquisition

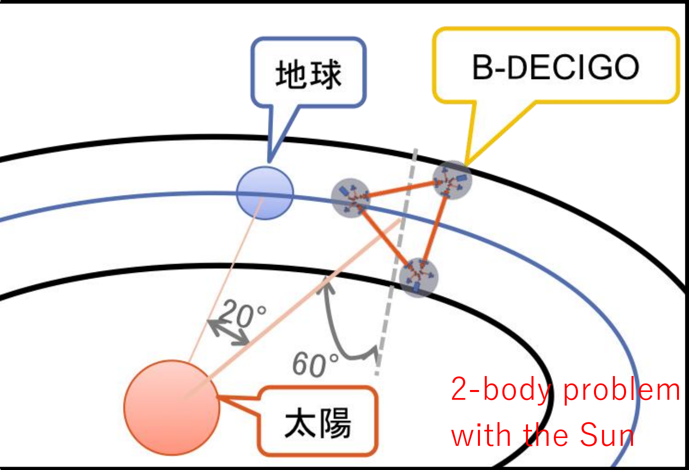
- Idea to use beam scan by AOD (Acousto-optic deflector)
  - Good spatial resolution.
  - Quick scanning without mechanical actuator.
  - Less affected by laser frequency and intensity drift.
  - 100mW laser source, 3sec for 1km scan.



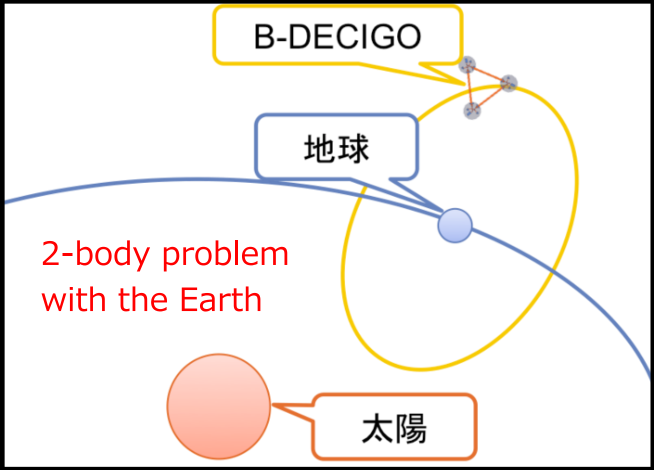
B-DECIGO Orbit

- Selection of orbit
  - Low relative acceleration for free-falling TM.
  - Stable orbit even without length control.
  - Trade-off with launch cost and tele-communication.

Solar Orbit (LISA-like)



Earth Orbit
(2,000km, 36,000km)



Lagrange Point

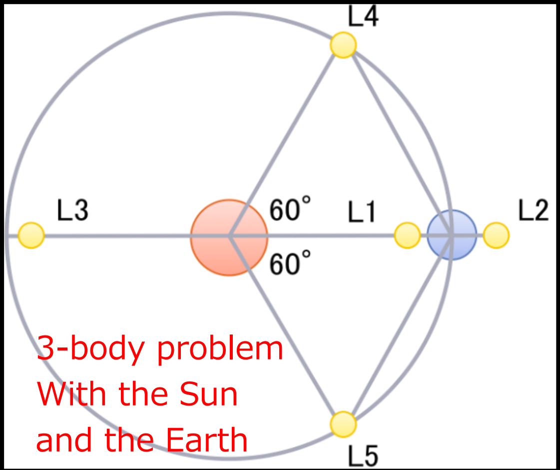
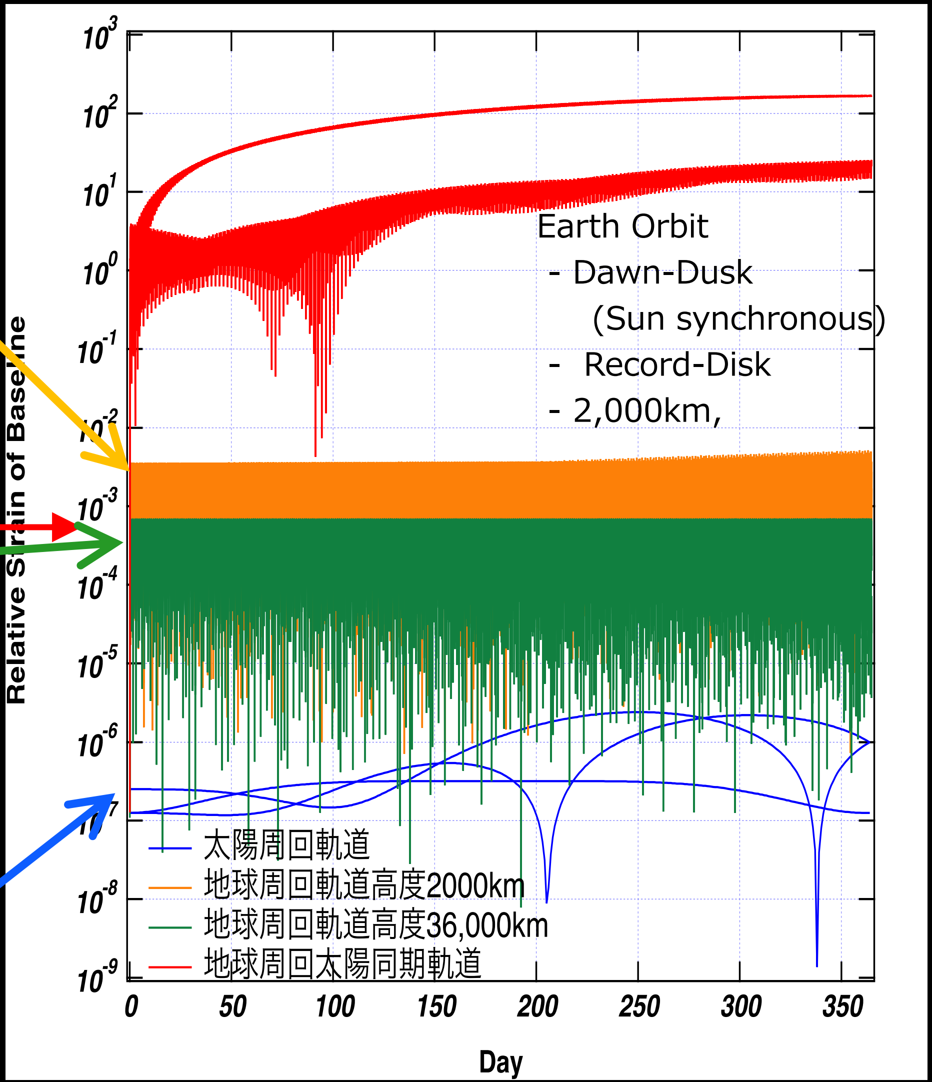


Figure by S.Sato

Numerical Simulation on Orbit (1)

- <u>Earth Orbit</u> (2,000km)
  - Thermal step
  - Orbital period ~2hour
  - Length change ~5×10^{-3}
- <u>Earth Orbit</u> (36,000km)
  - Thermal step
  - Orbital period :24hour
  - Length change ~7×10^{-4}
- <u>Solar Orbit</u> (LISA-like)
  - Thermally stable
  - Radius : 1AU
  - Orbital period: 1yr
  - Length change ~2×10^{-6}

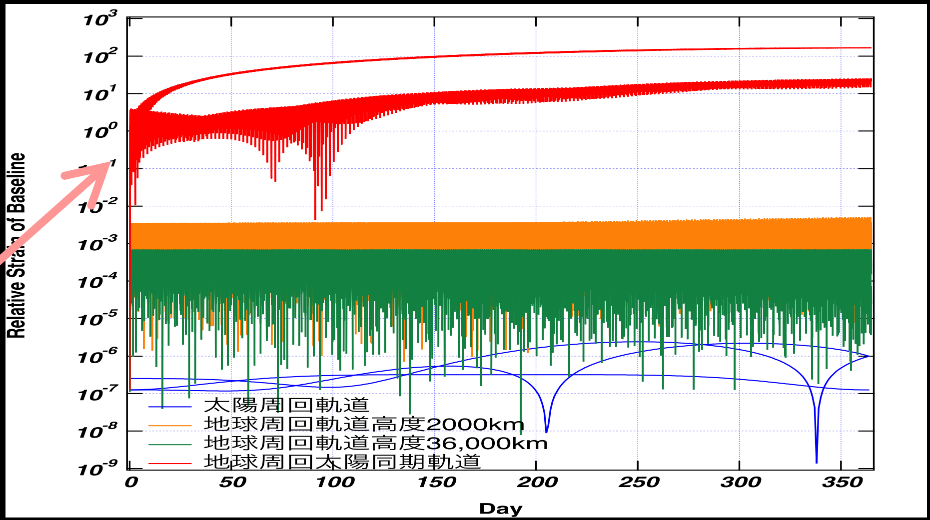
Figure by S.Sato



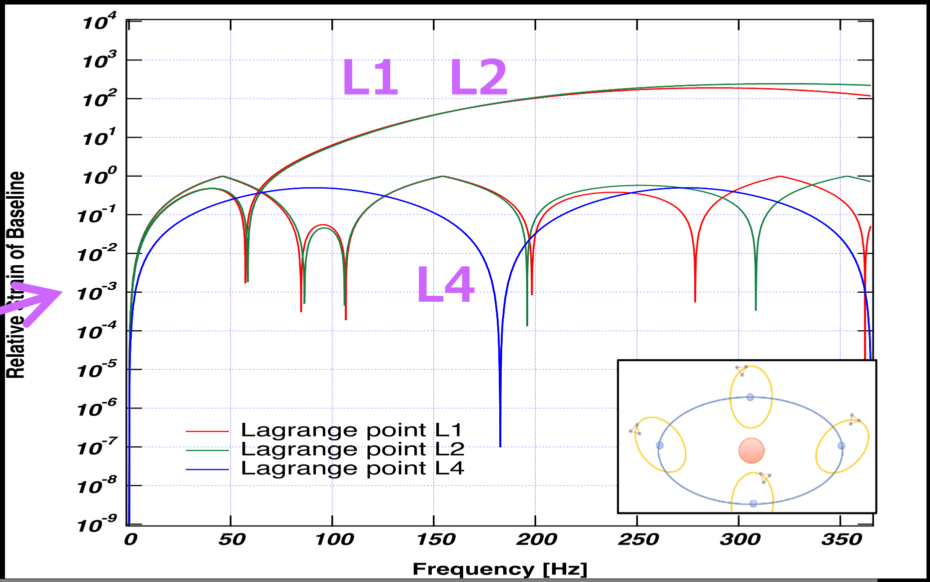
Numerical Simulation on Orbit (2)

Figure by S.Sato

- Earth Orbit (2,000km)
  - Dawn-Dusk
    (Sun synchronous)
    No thermal step
  - Record-Disk
  - Length change $\sim 2\times10^{2}$



- Lagrange Point
  - No thermal step
  - Orbital period ~2hour
  - Length change
    $\sim 2\times10^{2}$ - $\sim 5\times10^{-1}$



B-DECIGO Data Analysis

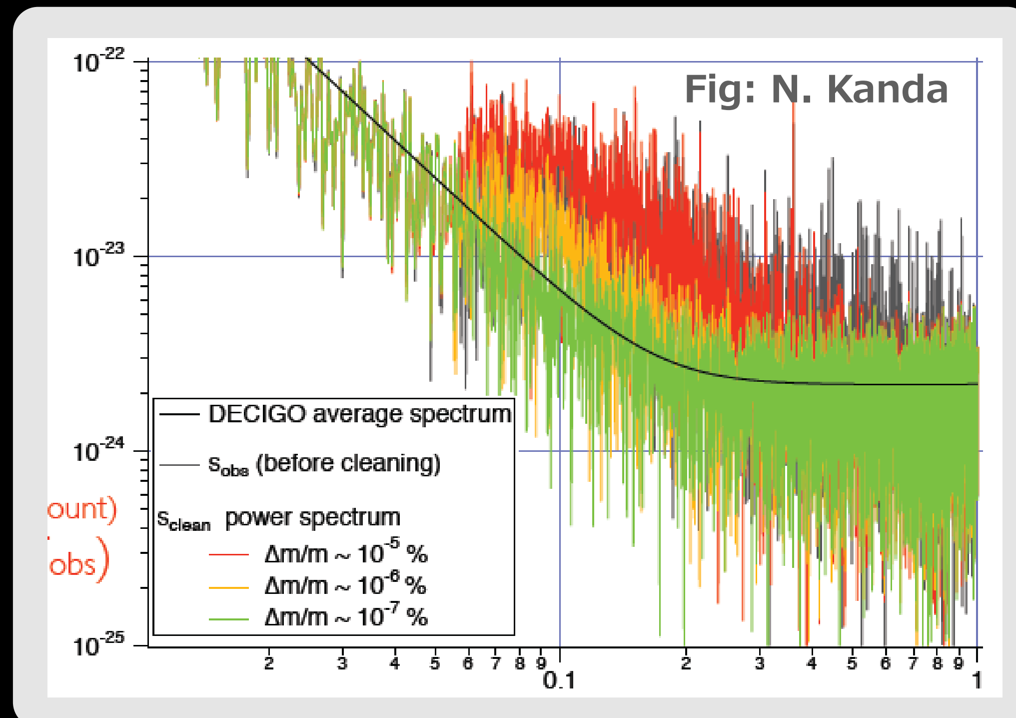
- Challenges in data analysis of B-DECIGO:
  - * Separation of many signals.
    Signal rate $\sim 10^5$ /yr → 1 event/5min.
    Basically, it is possible to separate them, by identifying and subtracting the waveform one by one from the largest SNR signals.
  - * Computational power.
    Orbital motion of B-DECIGO → signal modulation.
    - Critical for sky localization by single IFO unit.
    - May be a challenge in data analysis.
  - * Low-latency data processing and analysis.
    Data-processing strategy to send alerts of mergers.

Foreground Cleaning

- Preliminary demonstration of data analysis

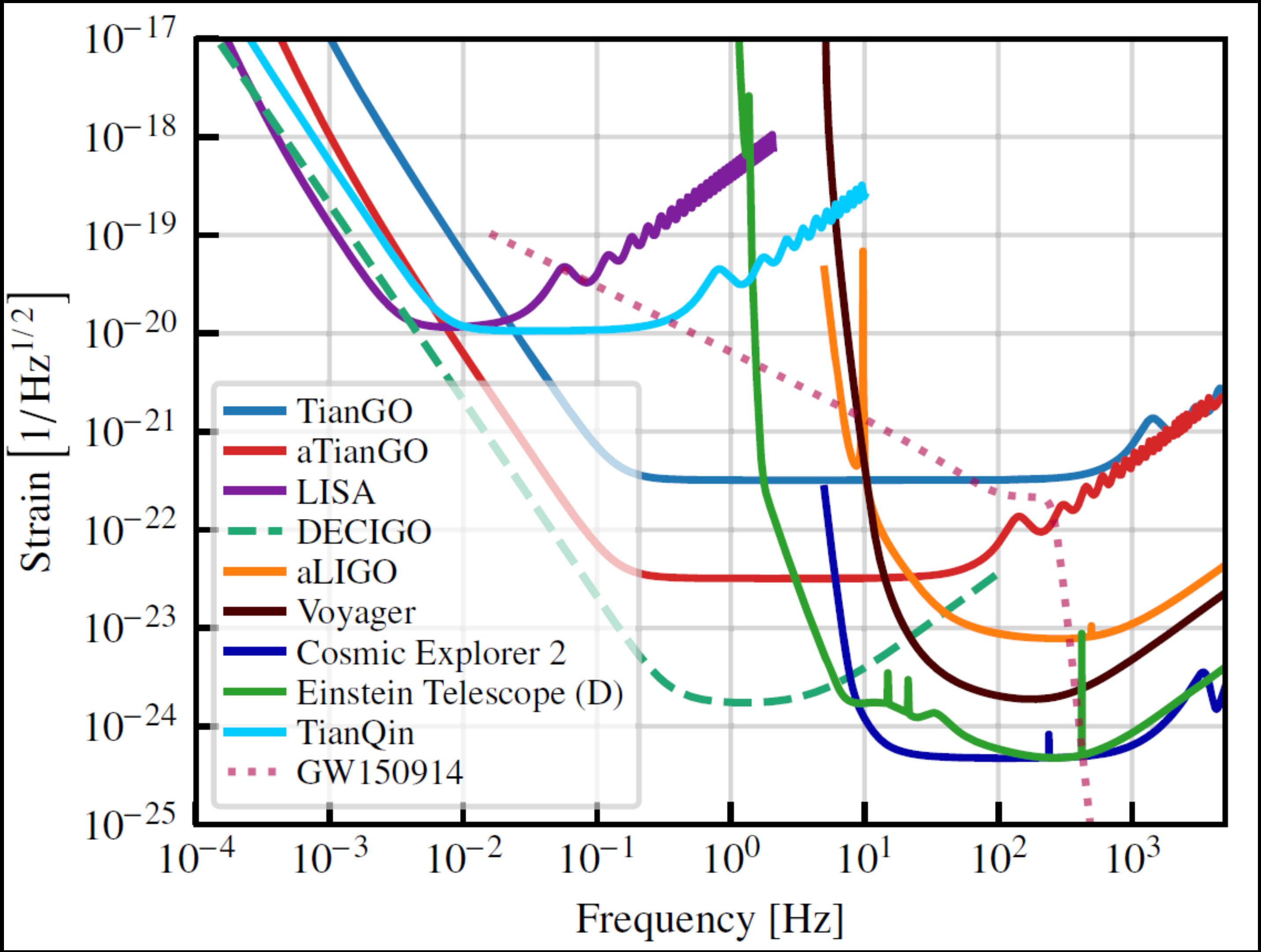
Inject ~ 10^5 NS binary waveform to simulated DECIGO noise.

Demonstration of identification and subtraction from largest signals



Successful. However, found that high parameter estimation accuracy is required → $\Delta m/m < \sim 10^{-7}$ %

Space GW Antennae



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