YKIS2018a Symposium

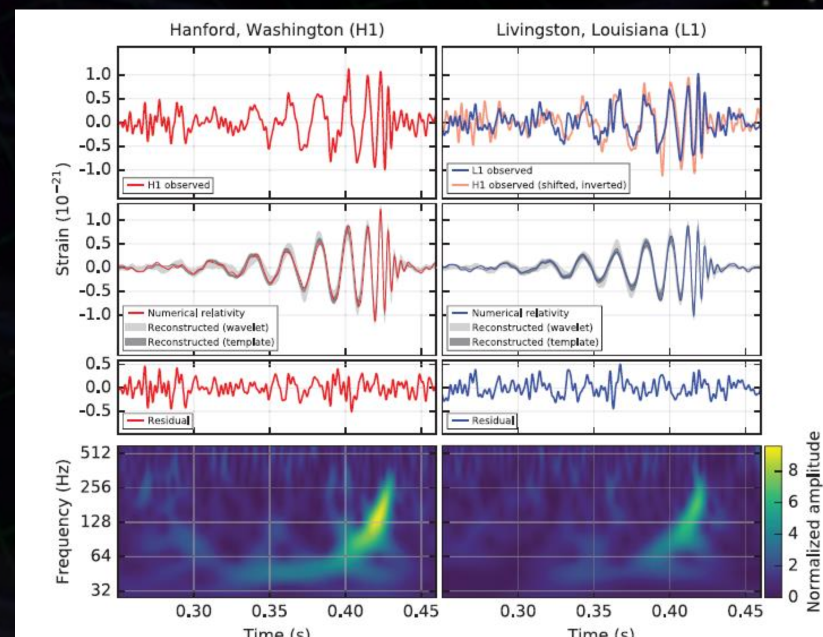
General Relativity - The Next Generation -

KAGRA and B-DECIGO

Masaki Ando (Univ. of Tokyo / NAOJ)

First Detection of GW

- On Feb. 11th, 2016, LIGO announced first detection of gravitational wave. The signal was from inspiral and merger of binary black hole at 410Mpc distance.
  - ⇨ Opens a new field of '<u>GW astronomy</u>'.

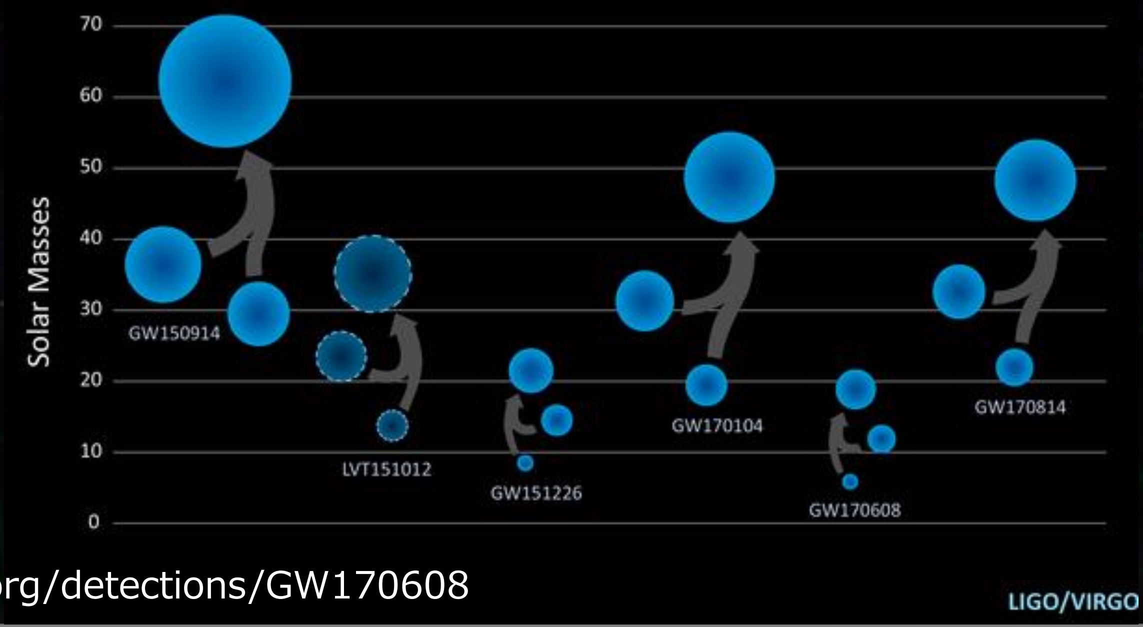


Courtesy Caltech/MIT/LIGO Laboratory

Mergers of Binary Black Hole

- 2nd: GW151226 (2016.6 announce)
- 3rd: GW170104 (2017.6.2 announce)
- 4th: GW170814 (2017.9.27 announce)
- 5th: GW170608 (2017.11.15 announce)

→ Mergers of binary black holes would be common events in the universe.

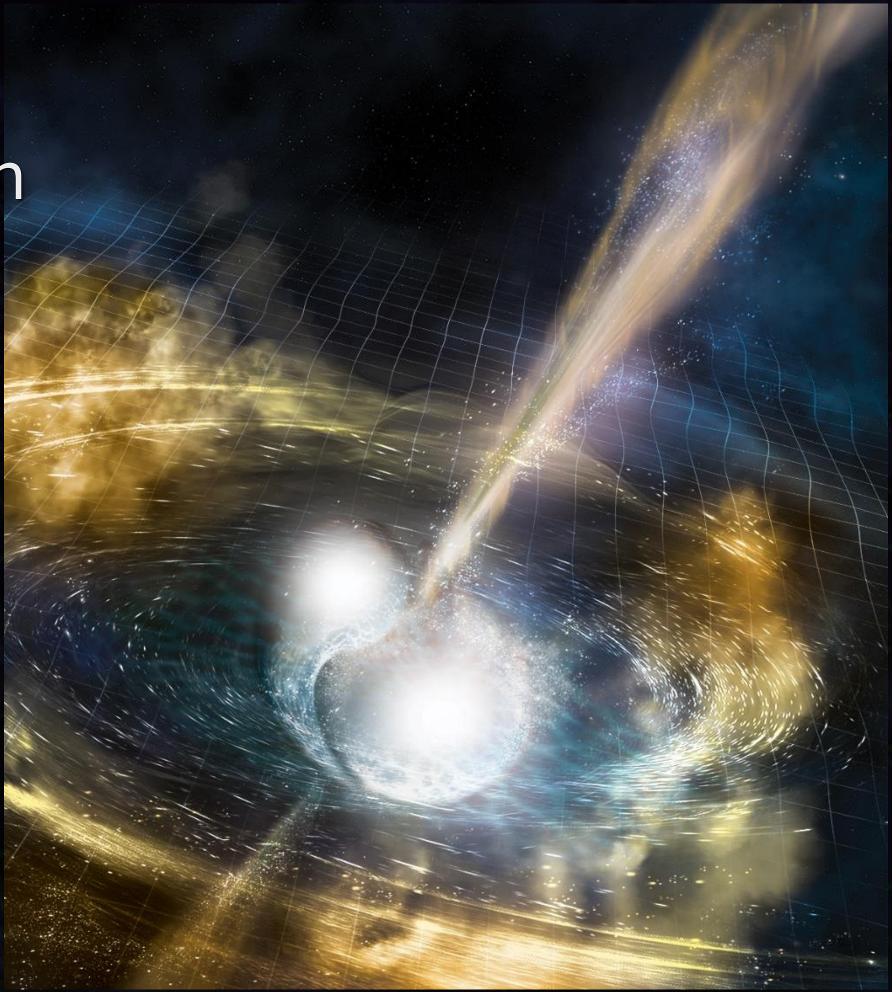


http://ligo.org/detections/GW170608

Merger of Binary Neutron Stars

- On Oct.16th, 2017, LIGO-VIRGO collaboration announced the first detection of gravitational-wave signal from merger of binary neutron stars

- The signal was detected on August 17th, 2017.
  → Named GW170817.
- Source Localization ~30deg^2



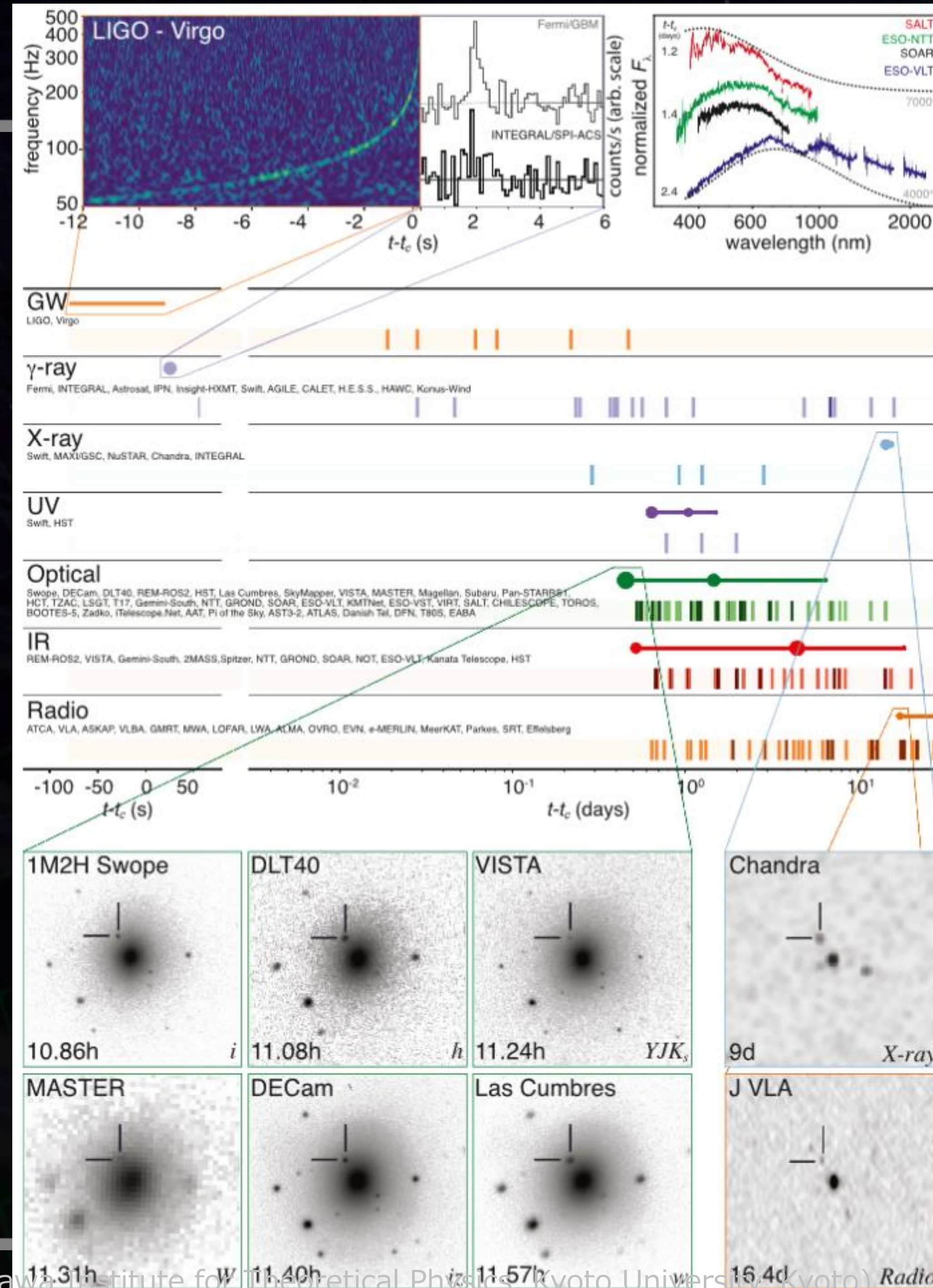
Courtesy Caltech/MIT/LIGO Laboratory

- EM counterpart was observed for the first time in GW170817.

⇩

- New knowledge
  - * Origin of SGRB.
  - * Origin of heavy elements in the universe.
  - * EoS of neutron star
  - * Fundamental physics and cosmology: speed of GW, Hubble's constant, ⋯.

ApJL 848 L12 (2017)



After the First Detections …

- The first GW (and EM counter part) detections demonstrated new possibilities by GW astronomy, and also showed new mysteries, such as the origin of heavier mass ($30M_{\odot}$) BBH.

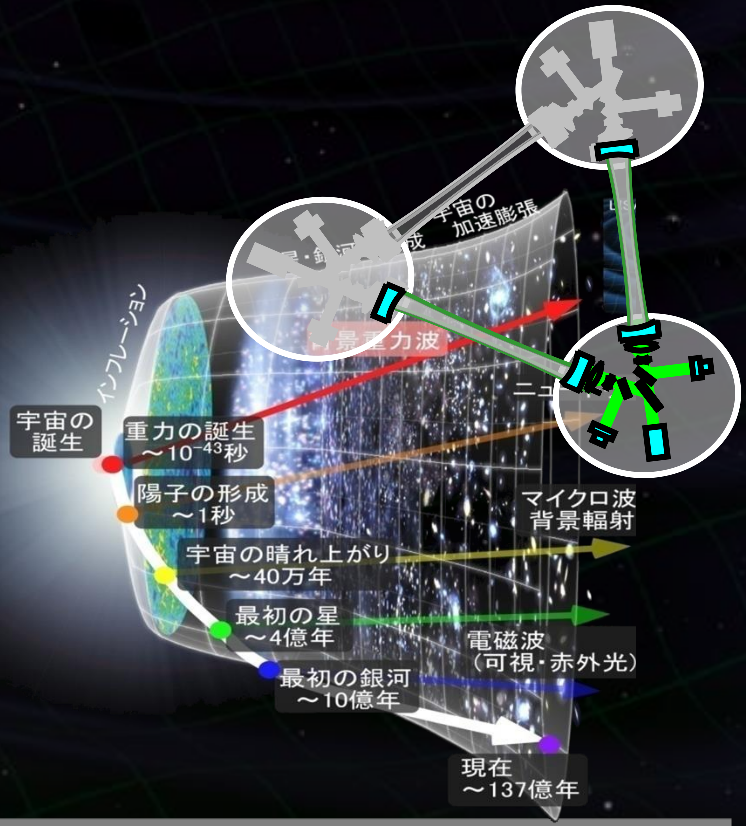
⇩

- 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,⋯).

KAGRA and DECIGO

KAGRA (~2019/20)
Terrestrial Detector
→ High frequency events
Target: GW detection

B-DECIGO (~2020s)
Space observatory
→ Low frequency sources
Target: GW astronomy



KAGRA (かぐら)

- Ground-based
  GW antenna in Japan-

KAGRA

KAGRA（かぐら）

Large-scale Cryogenic Gravitational-wave Telescope

2nd generation GW detector in Japan

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

Cryogenic interferometer
- Mirror temperature: 20K

Underground site
- Kamioka mine,
  1000m underground

KAGRA Collaboration

KAGRA collaboration:
~300 members from
~60 Universities or Institutes

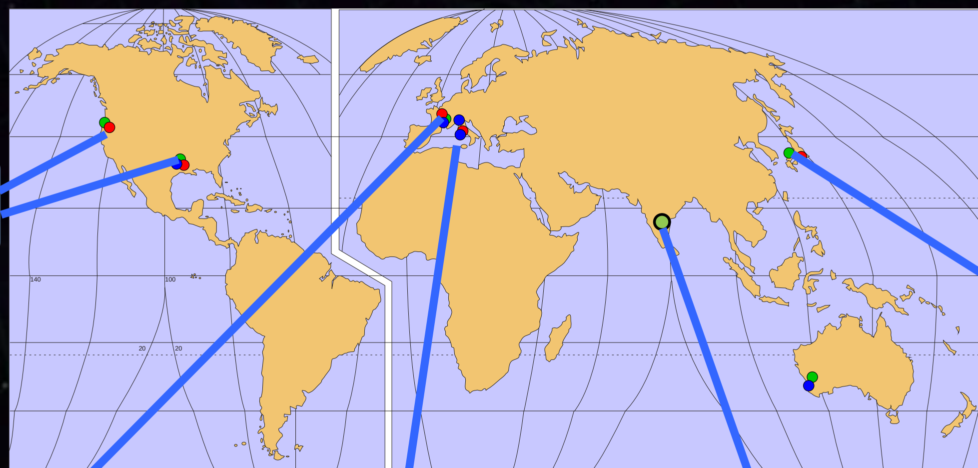
Designed by S. Miyoki

International GW Network

International network by 2nd–gen GW antennae.

→ GW astronomy (Detection, Parameter estimation, ···)

aLIGO (USA)
4km x 2



KAGRA (JPN)
baseline 3km

GEO-HF (GER-UK)
baseline 600m

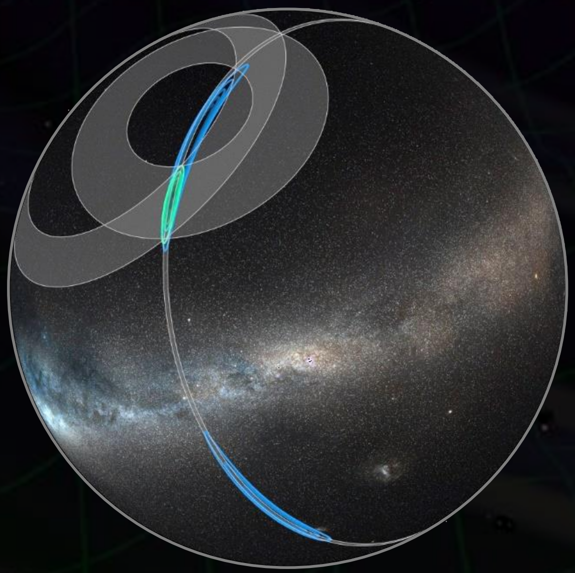
Adv.VIRGO (ITA-FRA)
baseline 3km

LIGO-India
project approved

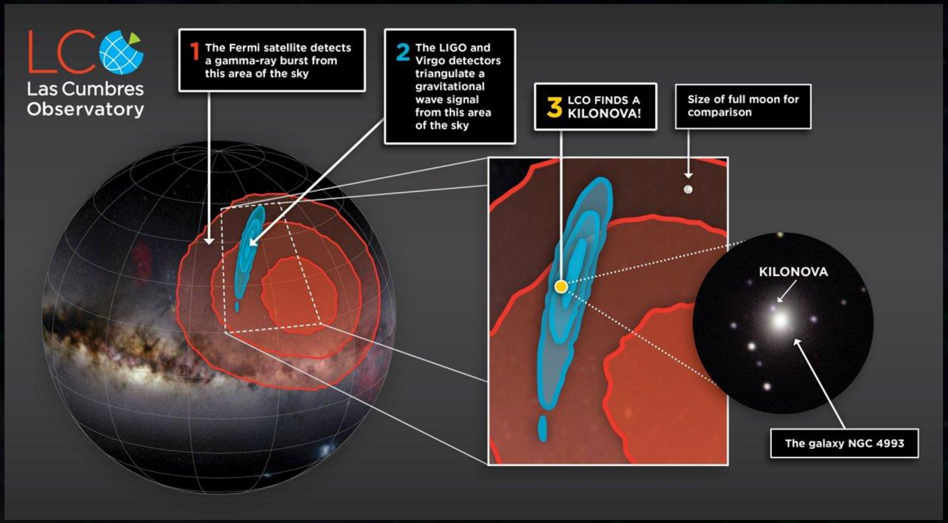
indigo

Importance of Sky Localization

- For GW astronomy, parameter estimation of the source is important. In particular, sky localization is critical for identification of EM counterapart.
- In GW170817, the sky position was localized with ~30deg^2 error by 2 LIGO + 1 VIRGO detectors. ~20 galaxies in this region.

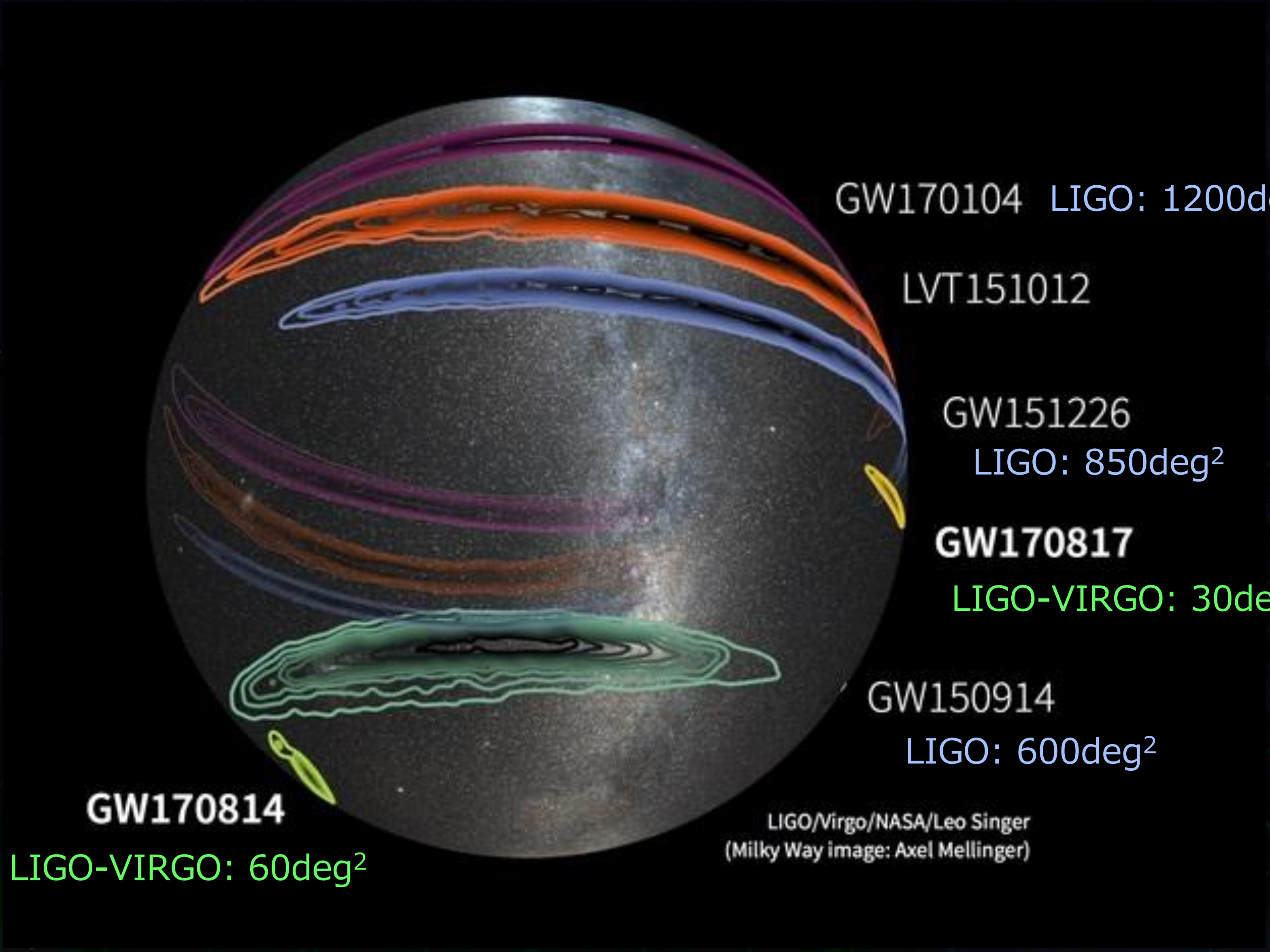


Credit: LIGO/Virgo/NASA/Leo Singer
(Milky Way Image: Alex Mellinger)



Credit: Sarah Wilkinson / LCO
(Taken from https://youtu.be/wnwMhvdDcfI)

Source Localization



Antenna Pattern of GW Detector

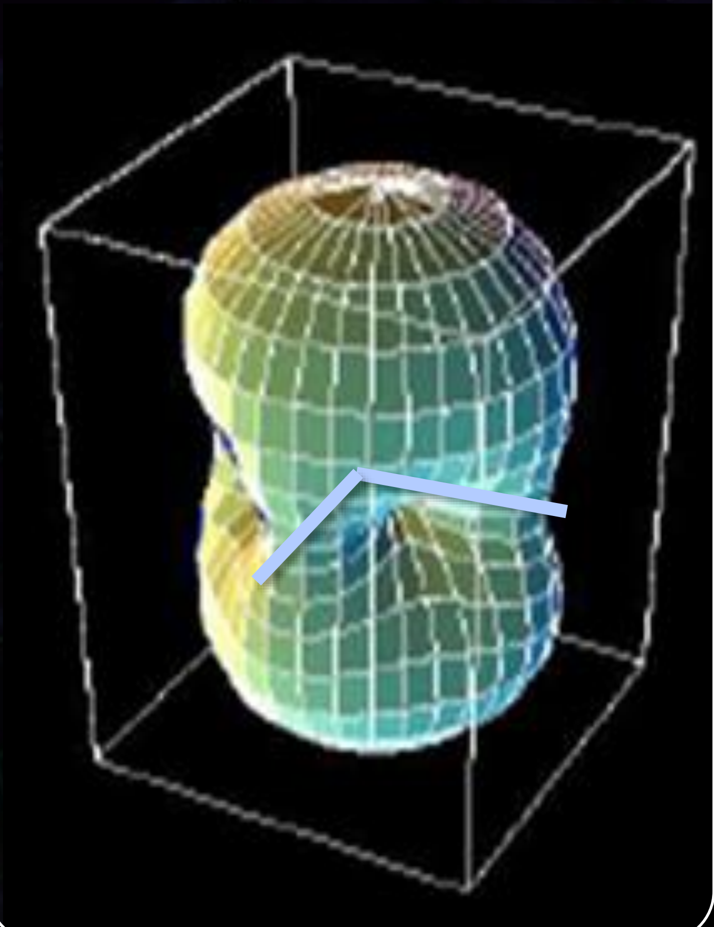
An Interferometric GW antenna has …

* Good sky coverage
* Poor angular resolution

⇩

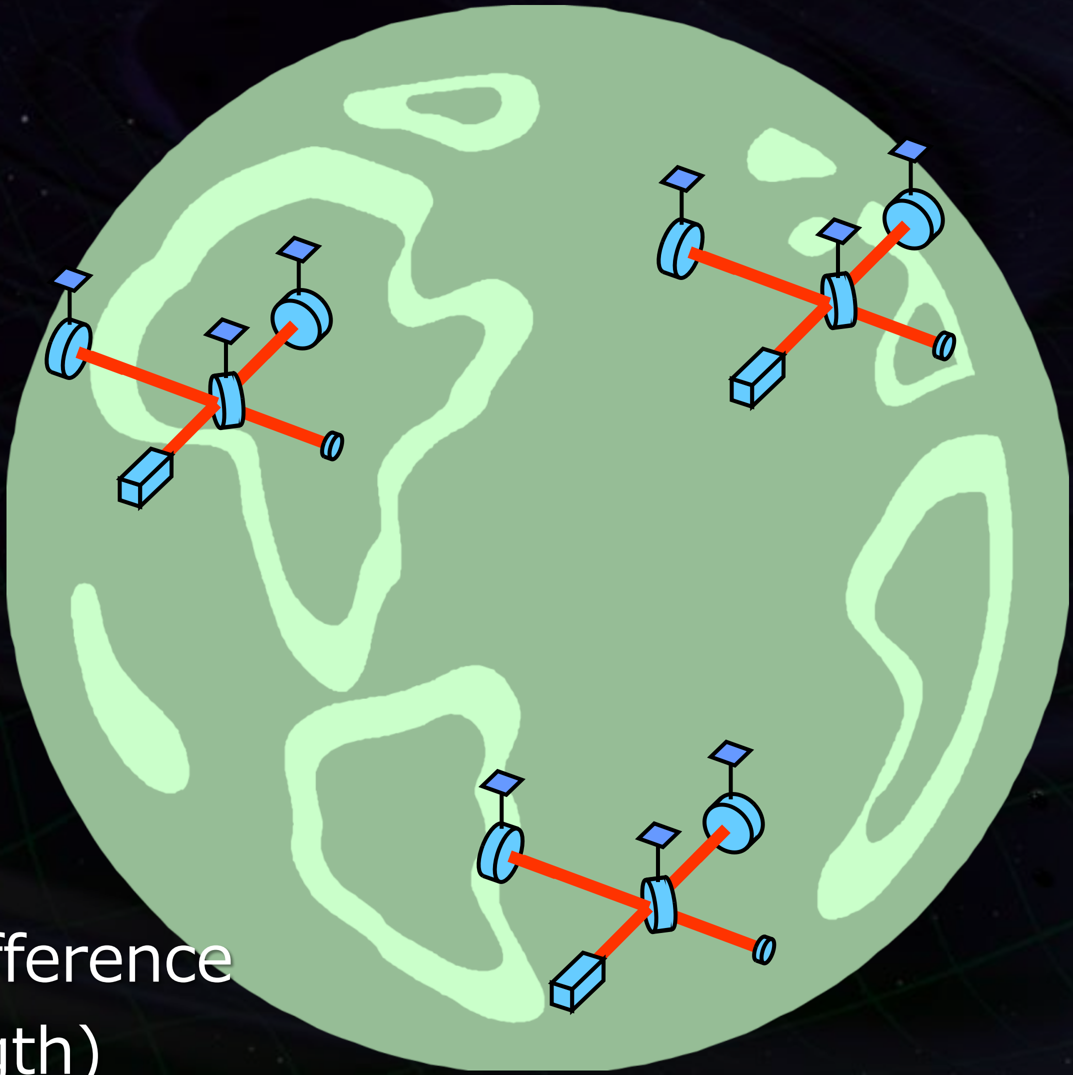
Difficult to determine the source sky position with single antenna.

Antenna Pattern



International Network for Astronomy

Animation :
S. Kawamura (ICRR)



Multiple Detector

⇩

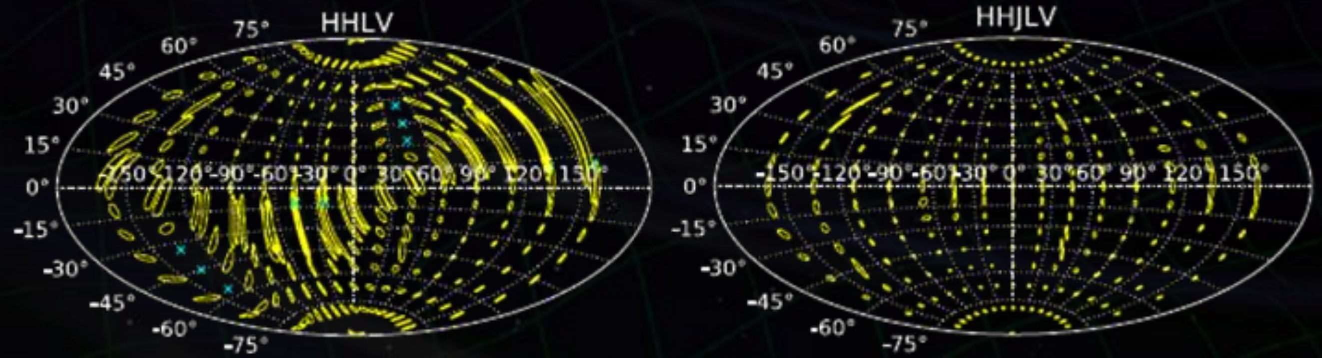
Identify the source
by the arrival-time difference
(and also signal strength)

Sky Localization

NS-NS coalescence @180Mpc (95%CI)		
(1.4,1.4)Msun	LHV	LHVK
median of δΩ [Deg^2]	30.25	9.5

H: LIGO--Hanford
L: LIGO--Livingston
V: Virgo,
K: KAGRA
I: LIGO-Indea

From presentation by H. Tagoshi
J.Veitch+, PRD85, 104045 (2012)
Tagoshi+ (2014)



S.Fairhaurst
CQG 28(2011)
105021

Adding KAGRA to the network (aLIGO + adv. VIRGO)
→ Improvement of angular resolution by 3-4 times.

KAGRA Features

- Large laser interferometer : Baseline 3km
- Underground site : stable environment.
- Cryogenic mirrors : thermal noise reduction

Original advanced technologies in KAGRA, which also gives prospects for 3G detectors

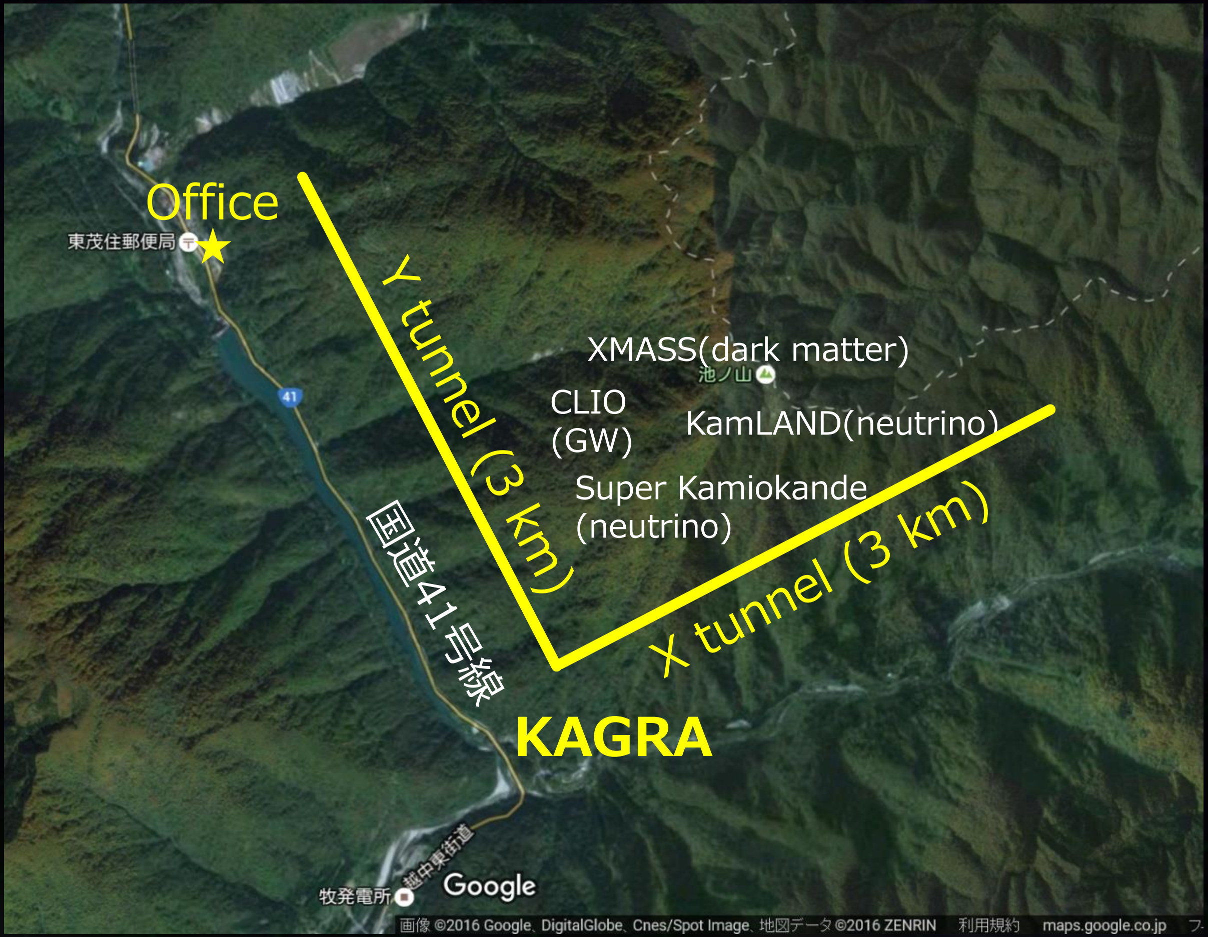
KAGRA Site

Underground site at Kamioka, Gifu prefecture

Facility of the Institute of Cosmic-Ray Research (ICRR), Univ. of Tokyo.

Map by Google

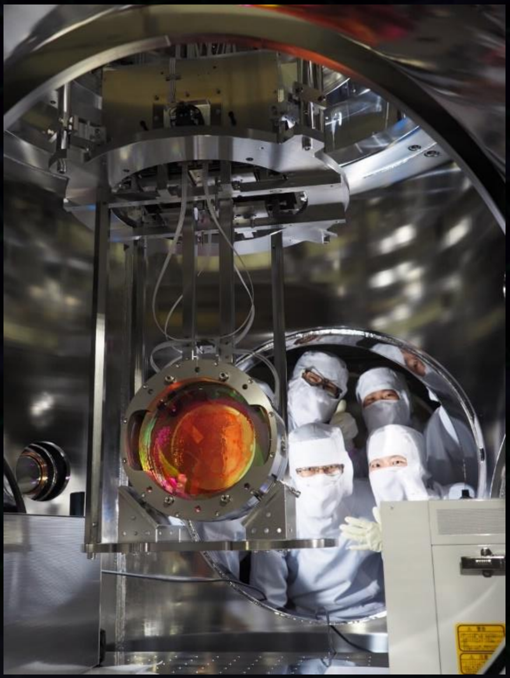
KAGRA Photos



iKAGRA Installation and Test Run

- Tunnel and Facility are almost ready.
  → iKAGRA (simple Michelson configuration) test run for 3weeks in spring 2016.
- Currently, upgrading for full configuration.

3-km Tunnel and Beam Duct (Photo by S. Miyoki)

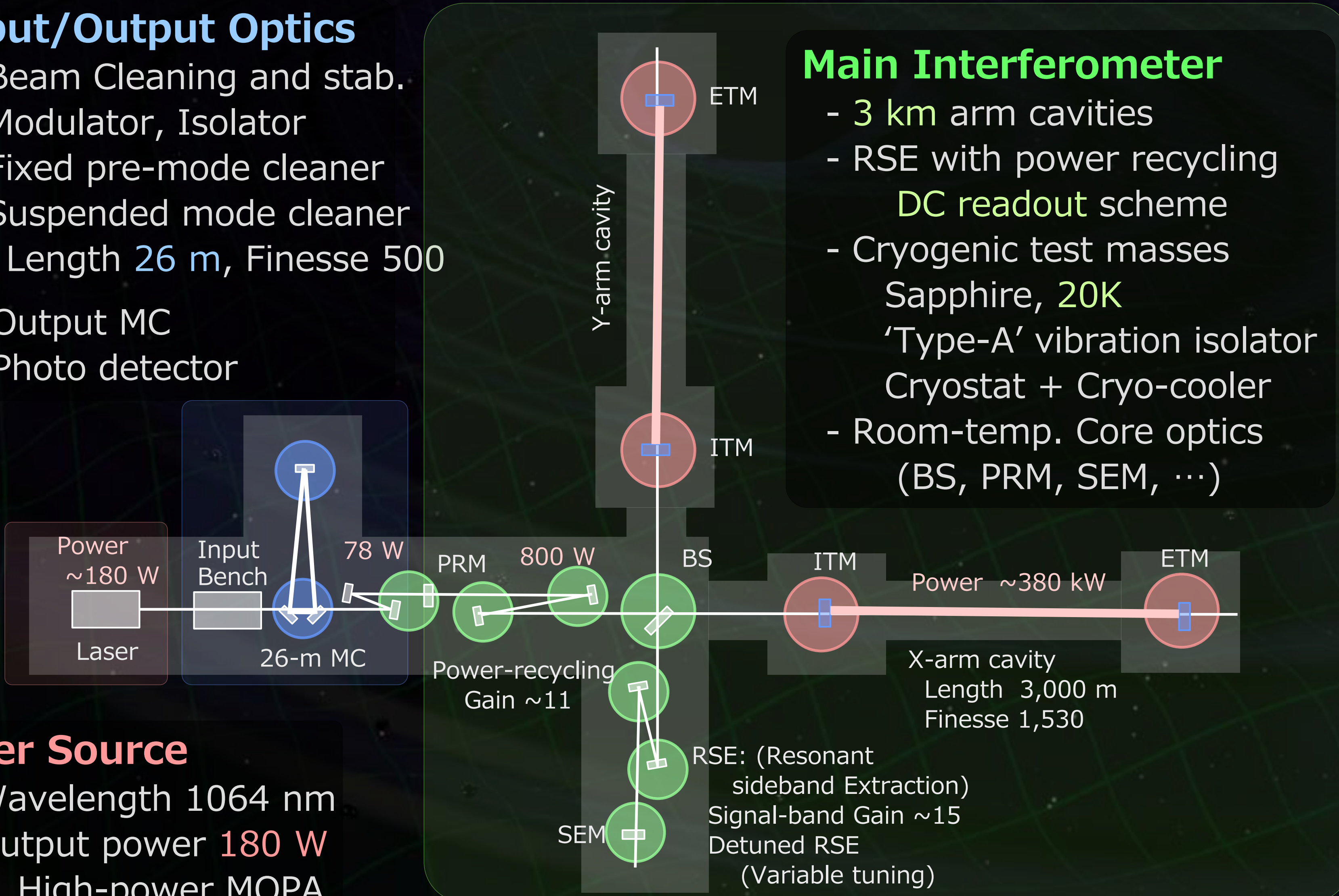


Type-Bp' suspension for PR3 (Feb. 25th, 2016)

KAGRA Optical Design

Input/Output Optics
- Beam Cleaning and stab.
- Modulator, Isolator
- Fixed pre-mode cleaner
- Suspended mode cleaner
  Length 26 m, Finesse 500
- Output MC
- Photo detector

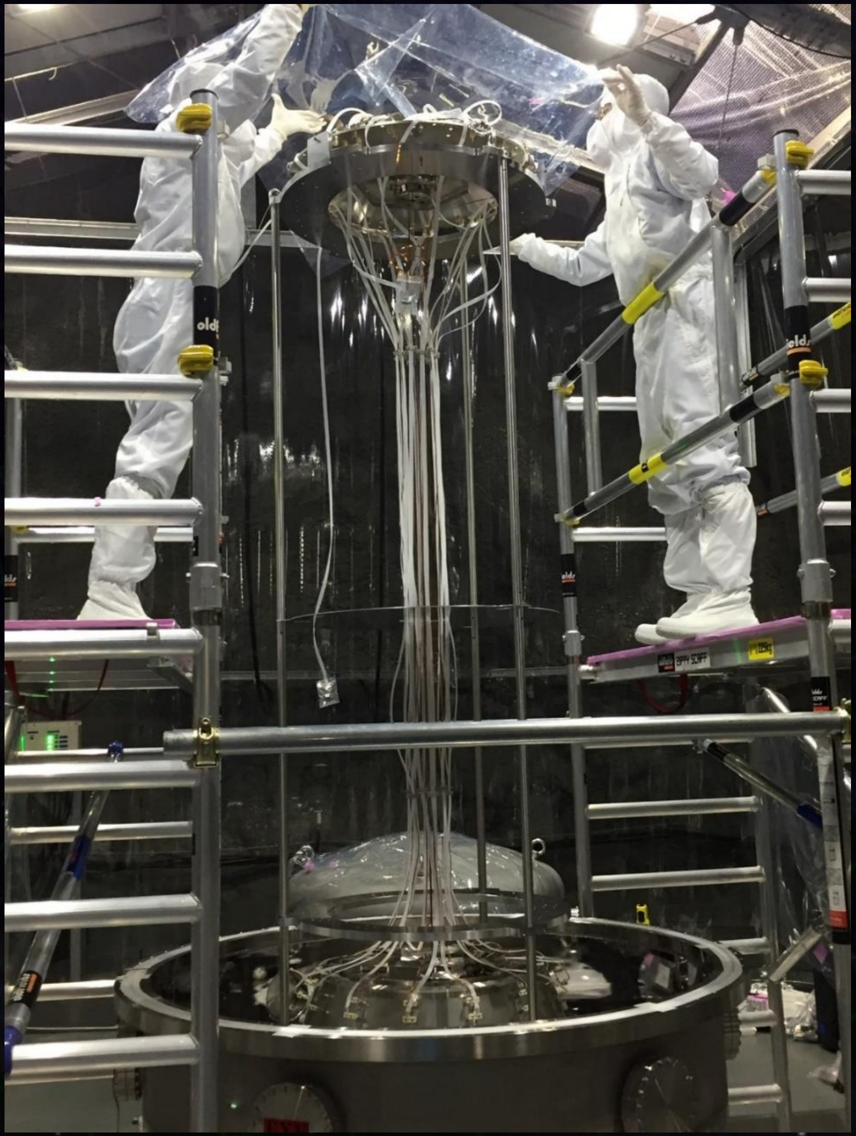
Main Interferometer
- 3 km arm cavities
- RSE with power recycling
  DC readout scheme
- Cryogenic test masses
  Sapphire, 20K
  'Type-A' vibration isolator
  Cryostat + Cryo-cooler
- Room-temp. Core optics
  (BS, PRM, SEM, …)



Laser Source
- Wavelength 1064 nm
- Output power 180 W
  High-power MOPA

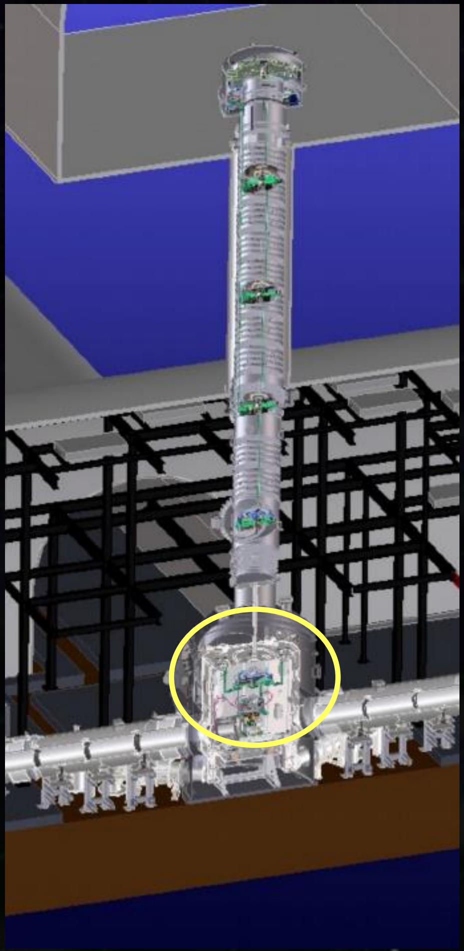
KAGRA Photos

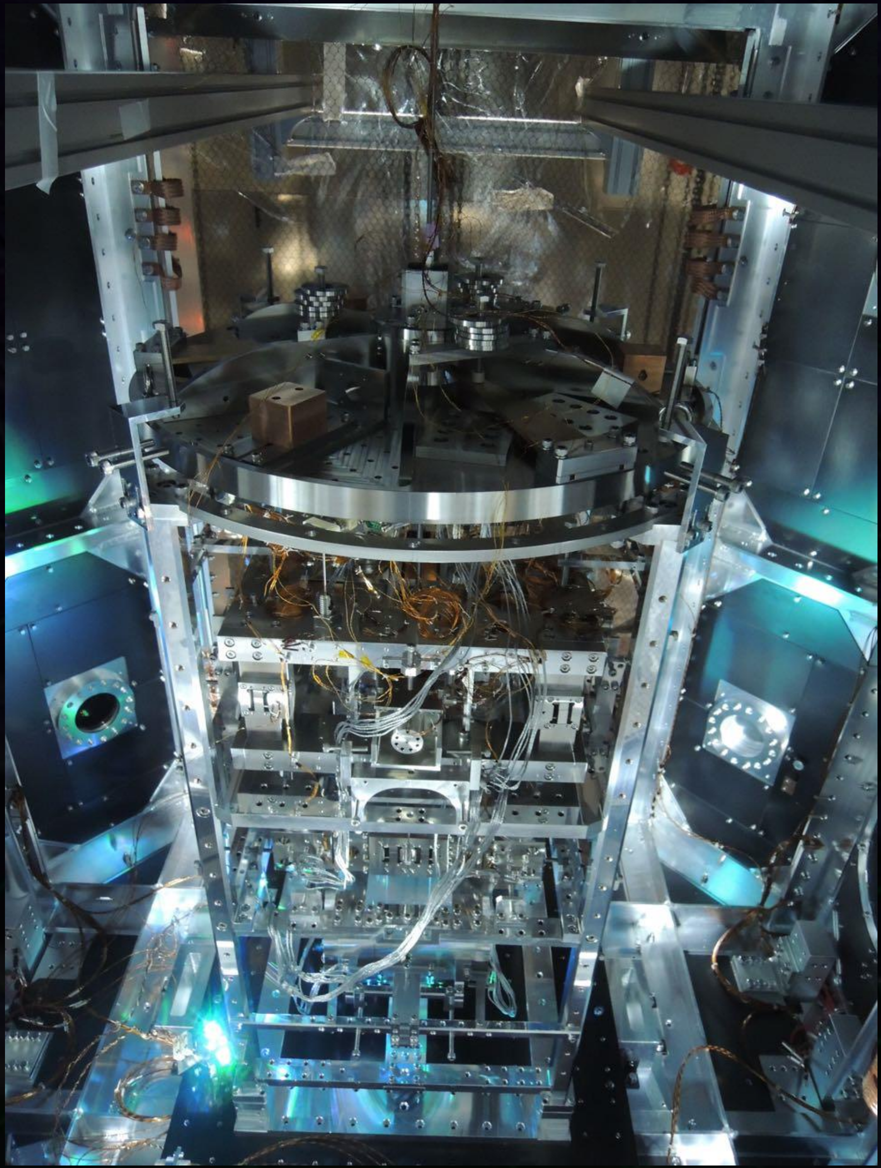
Vibration Isolation



KAGRA Photos

Cryogenic Suspension

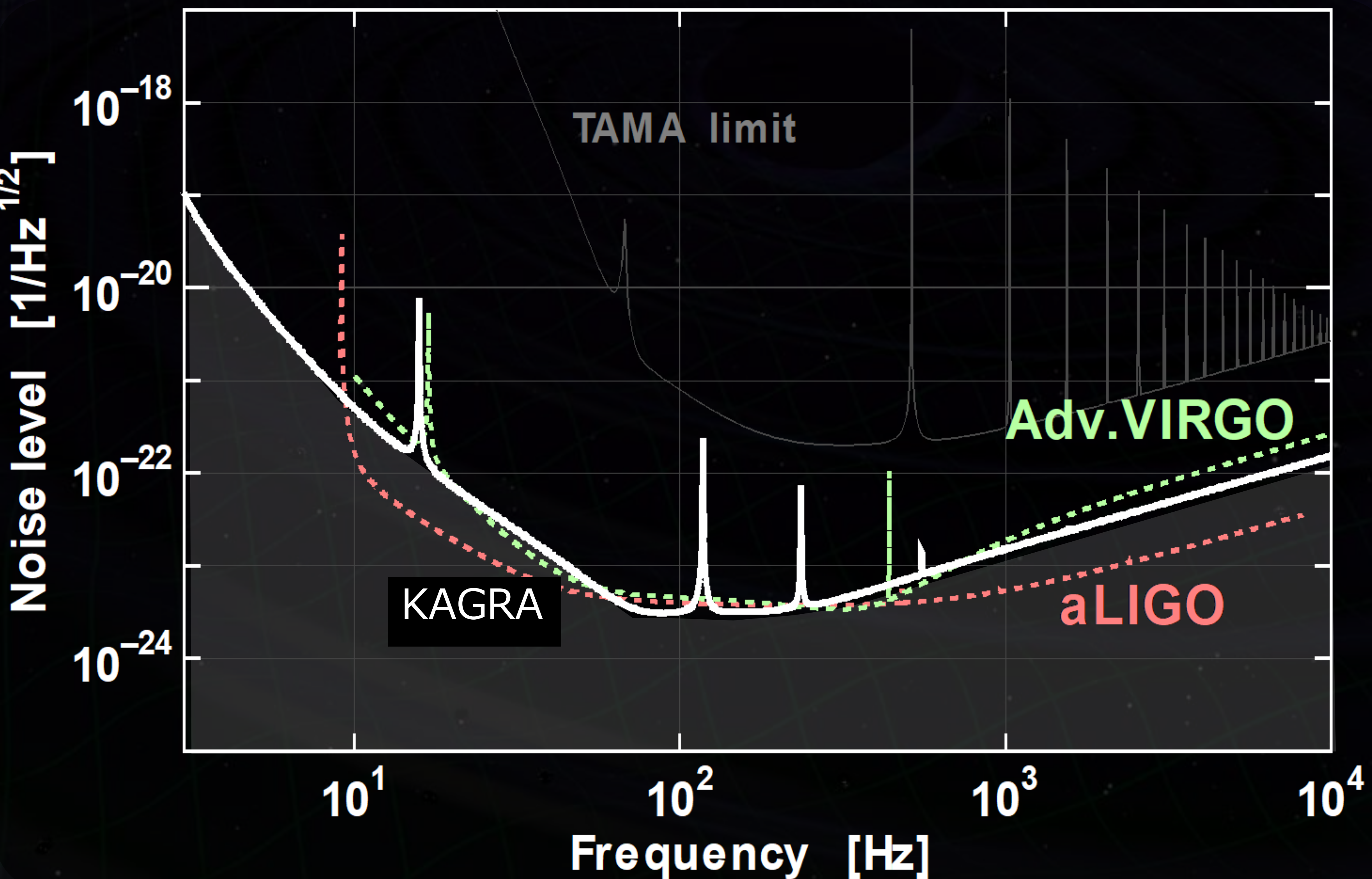




KAGRA Photos

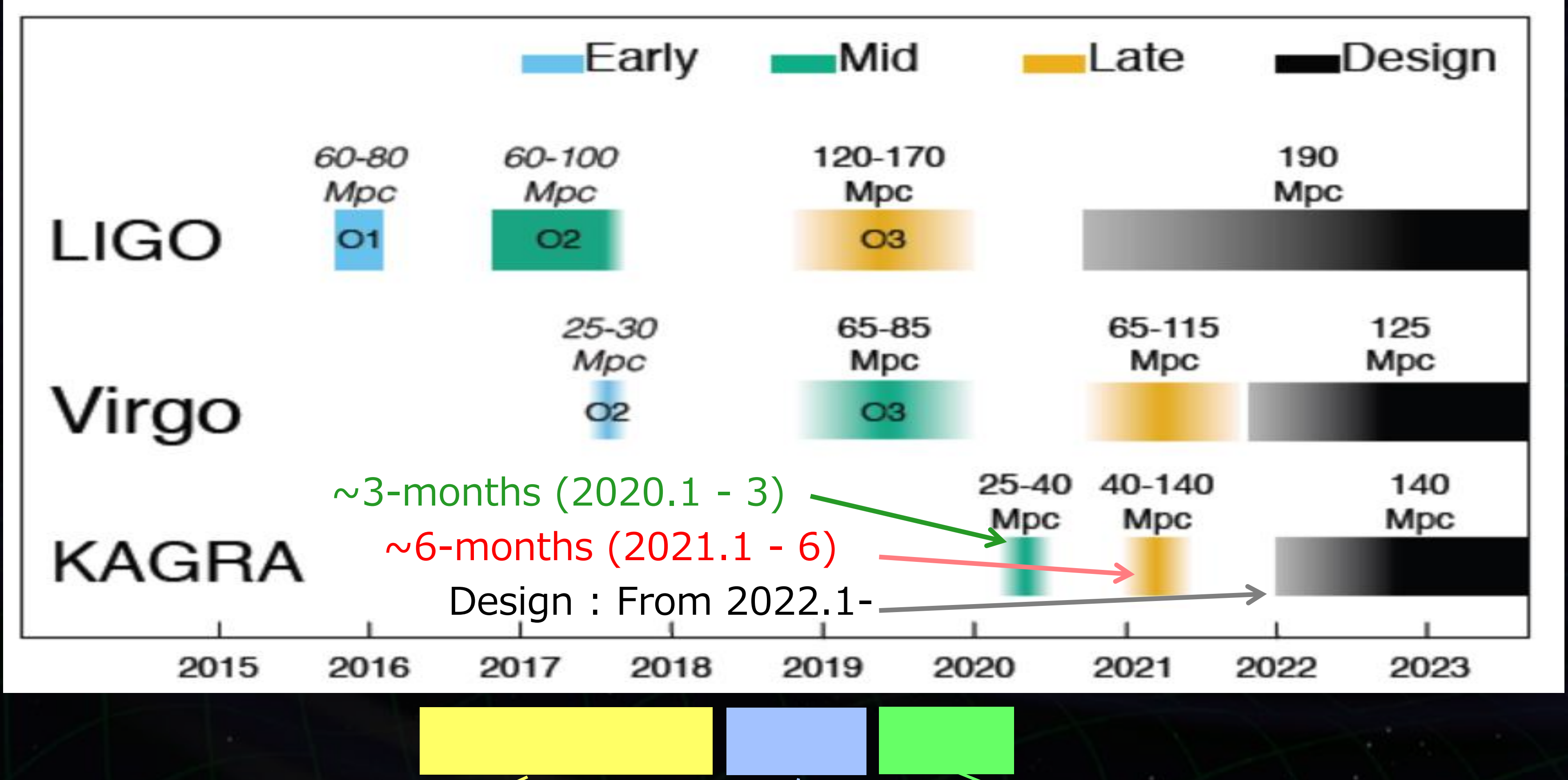
Sapphire Mirror: Diameter 22cm, Thickness 15cm

Sensitivity Comparison



Observation Scenario

KAGRA Collaboration, LIGO Scientific Collaboration and Virgo Collaboration: arXiv:1304.0670, Submitted to LLR (2017)



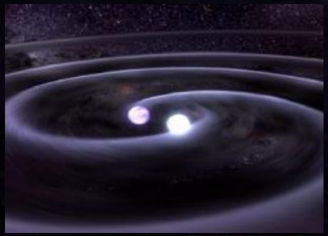
Phase-1
Cryogenic (PR)MI
No sensitivity goal

Phase-2
Cryogenic RSE
No sensitivity goal

Phase-3
Cryogenic RSE, 1-yr commissioning after the first full operation

BNS Detection Rate

- Detection rate of GW signal from BNS
  - BNS merger rate: $1540^{+3200}_{-1220}\ \mathrm{Gpc^{-3}yr^{-1}}$
  - KAGRA observable range ~140 Mpc (SNR>8, Sky average) from the design sensitivity

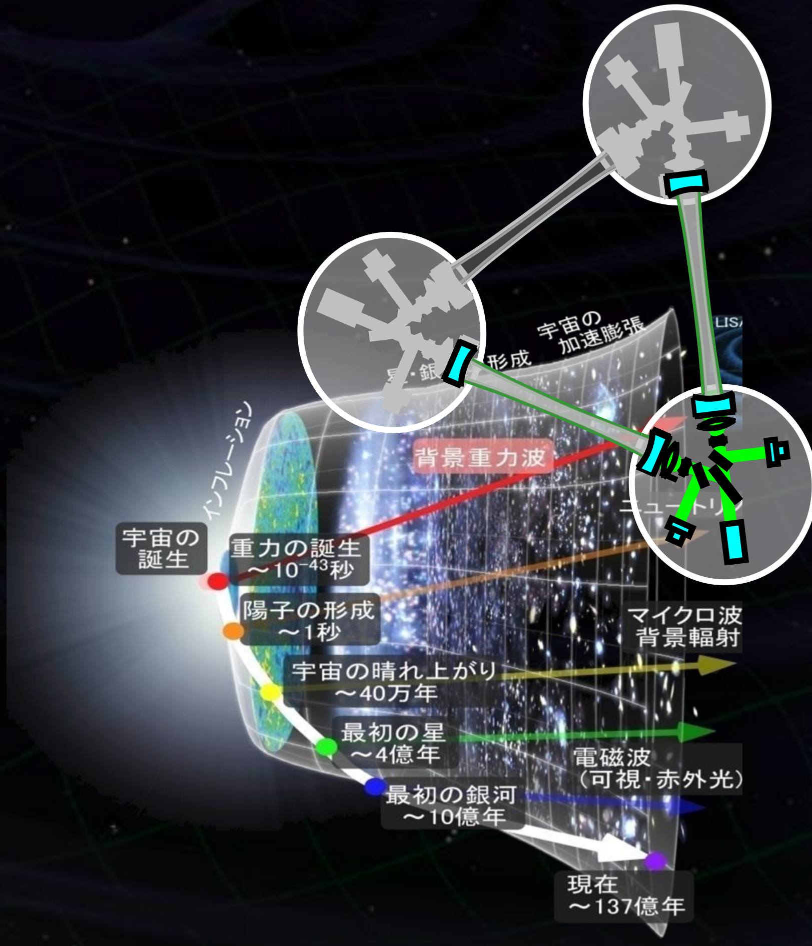


⇨ KAGRA Detection rate ~10 events/yr

※ Detection rate of ~1 event/yr when Obs. Range is ~60 Mpc

※ More BBH detection rate is expected;
BBH rate $103^{+110}_{-63}\ \mathrm{Gpc^{-3}yr^{-1}}$ (PRL 118 221101 (2017))
Detector range is roughly proportional to the target mass.

B-DECIGO

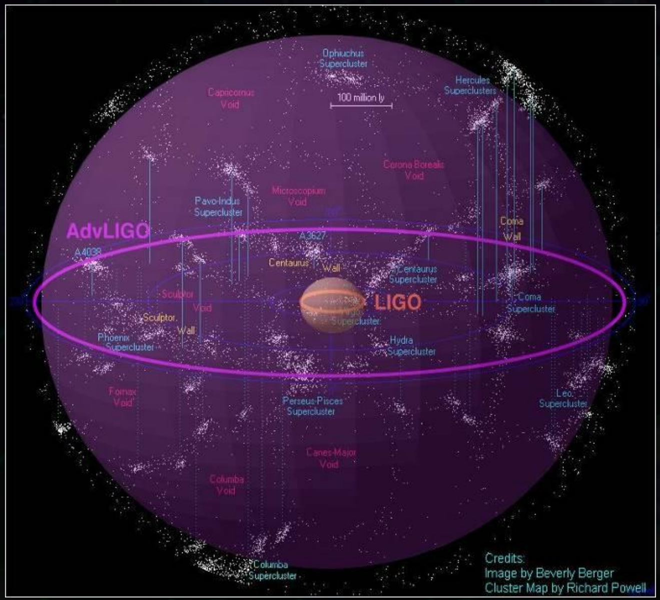


宇宙の
加速膨張
インフレーション
背景重力波
宇宙の
誕生
重力の誕生
～10^{-43}秒
陽子の形成
～1秒
マイクロ波
背景輻射
宇宙の晴れ上がり
～40万年
最初の星
～4億年
電磁波
（可視・赤外光）
最初の銀河
～10億年
現在
～137億年

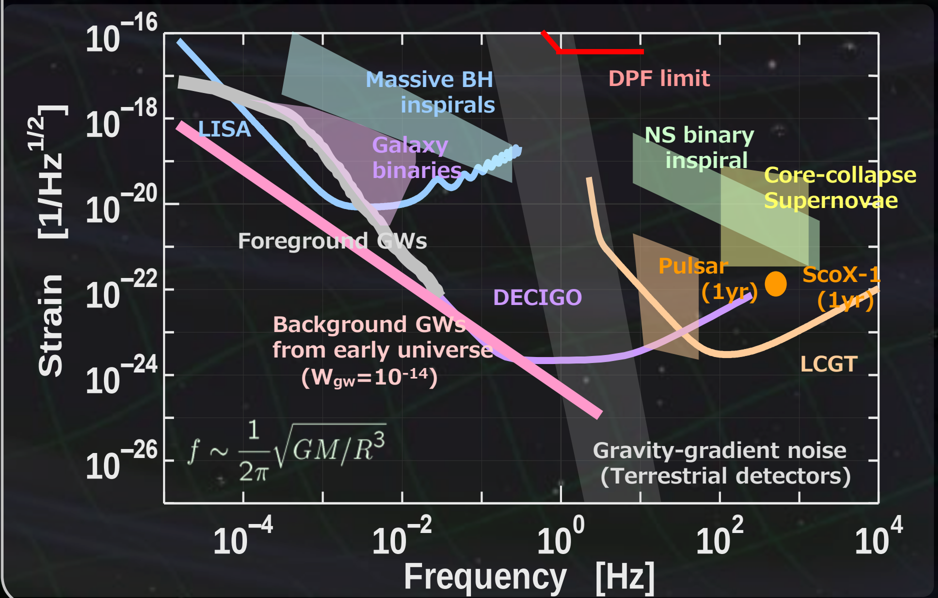
Future Possibilities

Observation network by 2nd-gen antennae (aLIGO, AdVIRGO, KAGRA, LIGO-India) will be formed in several years ⇨ What will be the next step?

Sensitivity Improvement to cover more galaxies.



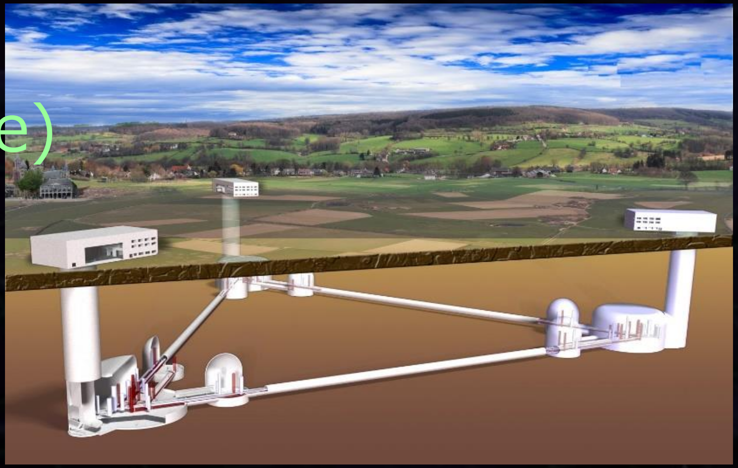
Expansion of obs. Band for variety of sources and cosmology.



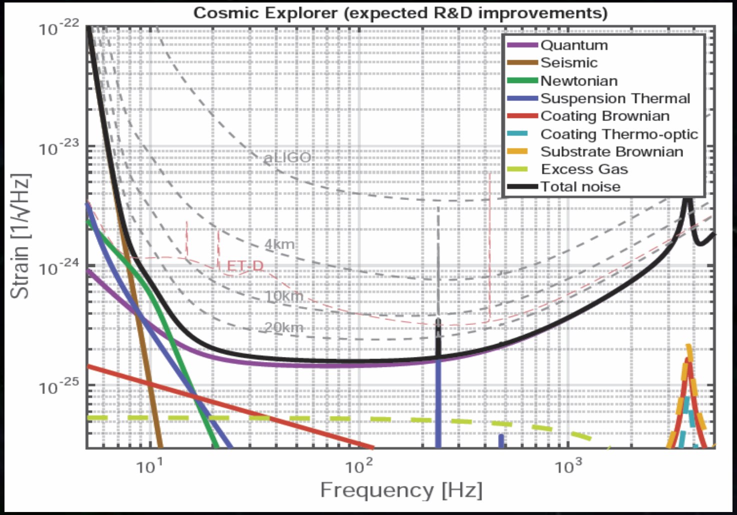
Next Generation GW Antennae

3rd Generation GW Antennae (~2030)

* Europe: ET (Einstein Telescope)
  x10 sensitivity,
  Long baseline ~10km,
  Underground, Cryogenic

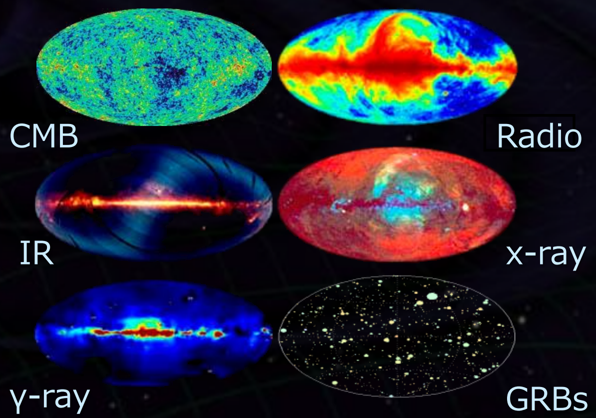


* USA: CE (Cosmic Explorer)
  x10 sensitivity,
  Long baseline ~40km,
  Surface site, Cryogenic (?)

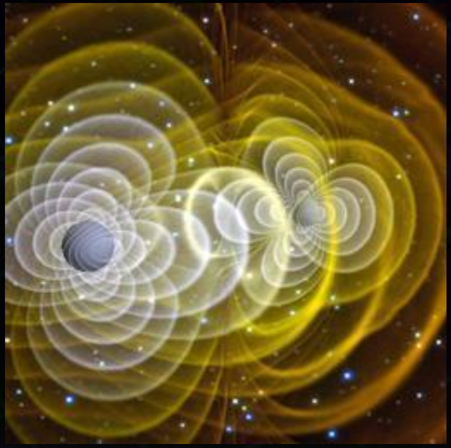


Multiple-band Observation

- Electro-Magnetic Observations :
  Multiple-band observations
  (Radio, Optical/IR, X-ray, γ-ray)
  → Variety of knowledge corr. to
  the Energy and Temperature
  of the target.



- Gravitational-wave Observations :
  Frequency of radiated GW
  ~ 1/ (Time scale of source motion)
  → Variety of knowledge corr. to
  the Time scale and Mass of sources.



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)

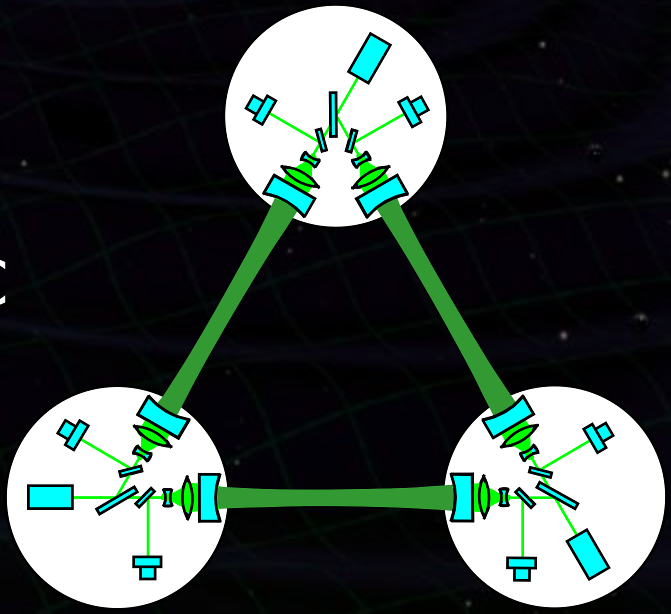
- Mission Requirement
  - Strain sensitivity of 2×10^{-23} $Hz^{-1/2}$ at 0.1Hz.
  - >3-years observation period.

- 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).

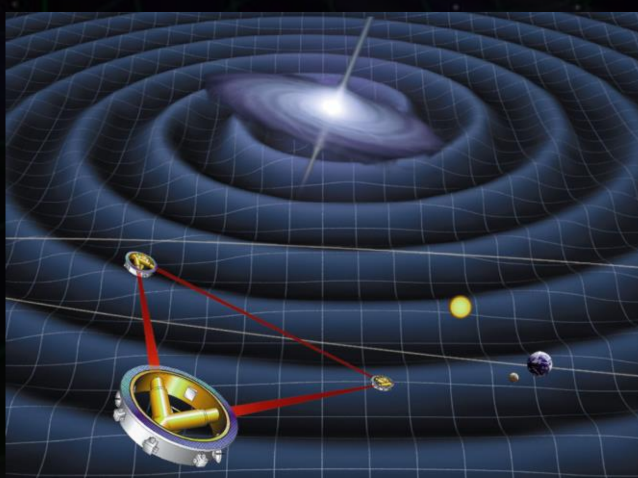


Space GW antenna

LISA

(Laser Interferometer
Space Antenna)

- Target: SMBH, Binaries.
  GWs around 1mHz.
- Baseline : 2.5M km.
  Constellation flight by 3 S/C
- Optical transponder.



B-DECIGO

(Deci-hertz Interferometer
Gravitational Wave Observatory)

- Target: IMBH, BBH, BNS.
  GWs around 0.1Hz.
- Baseline : 100 km.
  Formation flight by 3 S/C.
- Fabry-Perot interferometer.

Interferometer Configurations

- Optical transponder

  * Phase locking of laser sources in each S/C.

  * Long baseline is possible.

  → Better Acc. Noise

  Doppler tracking using laser beam

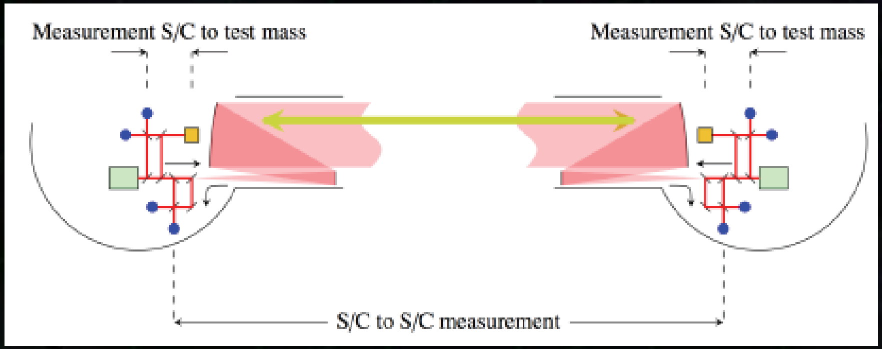
- Fabry-Perot cavity

  * Direct reflection.

  * Large laser power accumulated in cavity.

  → Better Shot noise

  Similar config.to ground-based GW antennae



M Hewitson (ASTROD WS 2017)

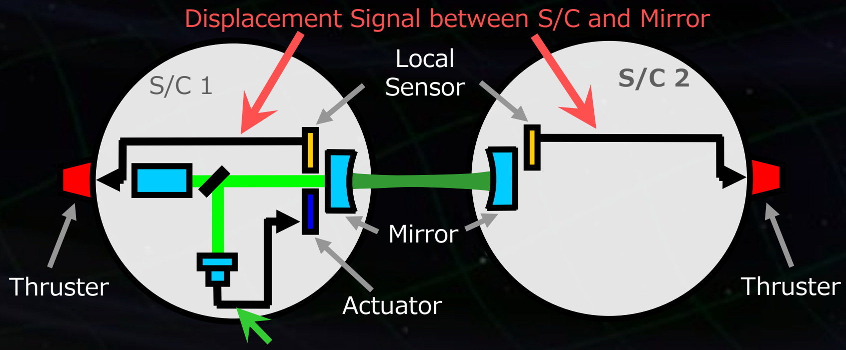
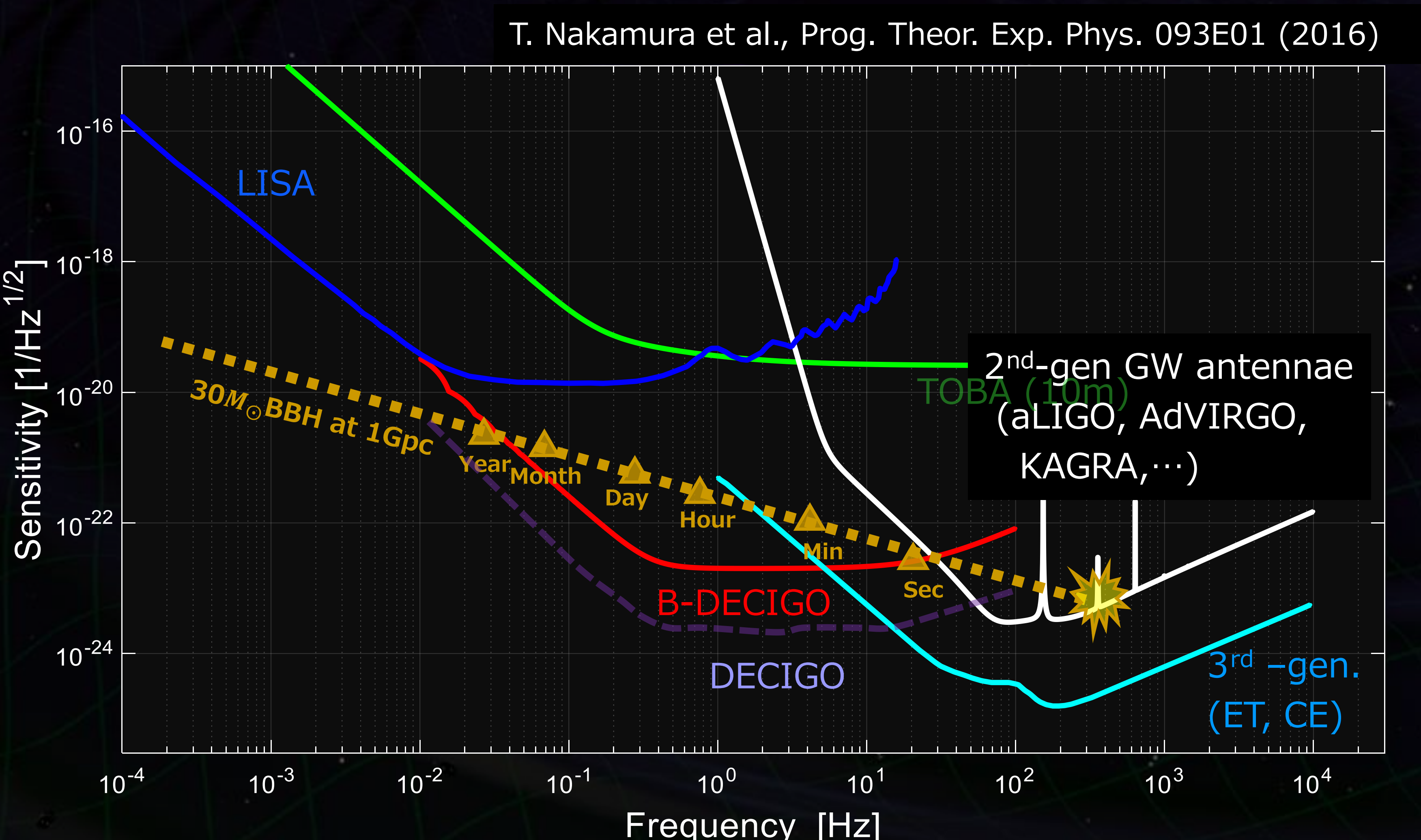


Fig: S. Kawamura

Sensitivity Curves



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 only and GW-EM observations.

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

- Cover most of the universe.

→ Formation history of SMBH and galaxies.

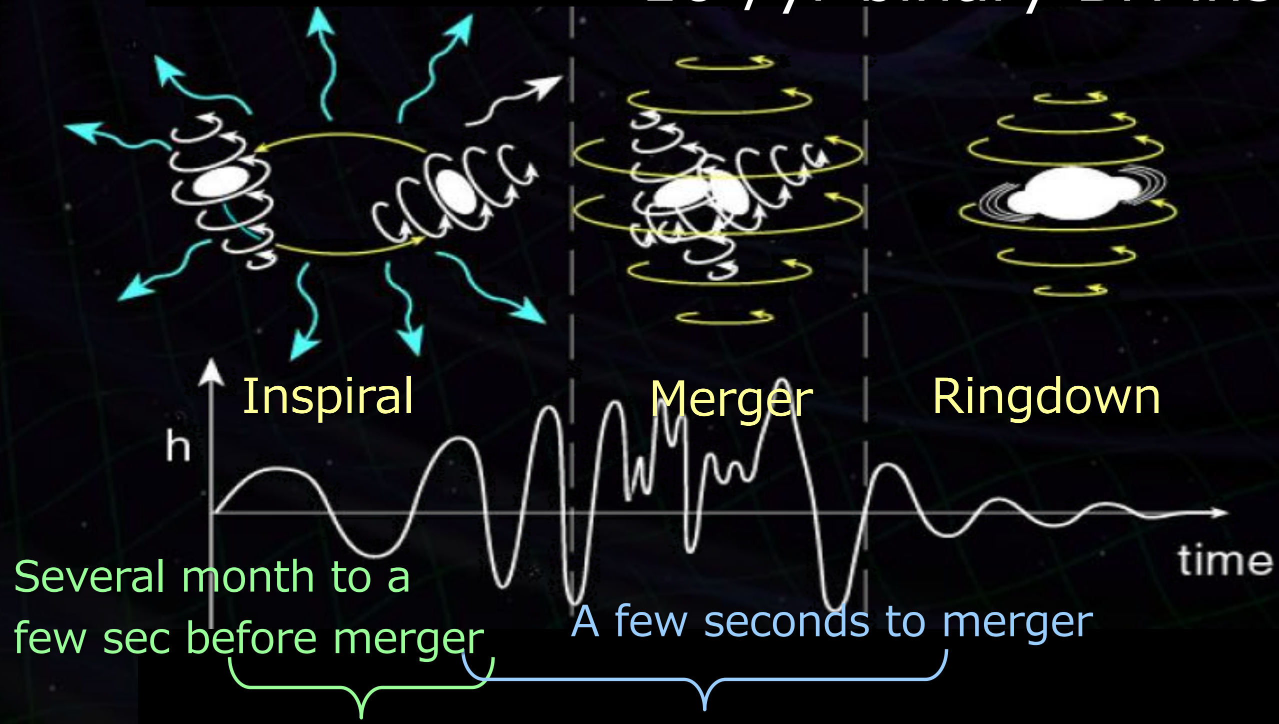
(3) Foreground understandings for DECIGO [Cosmology]

- 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.

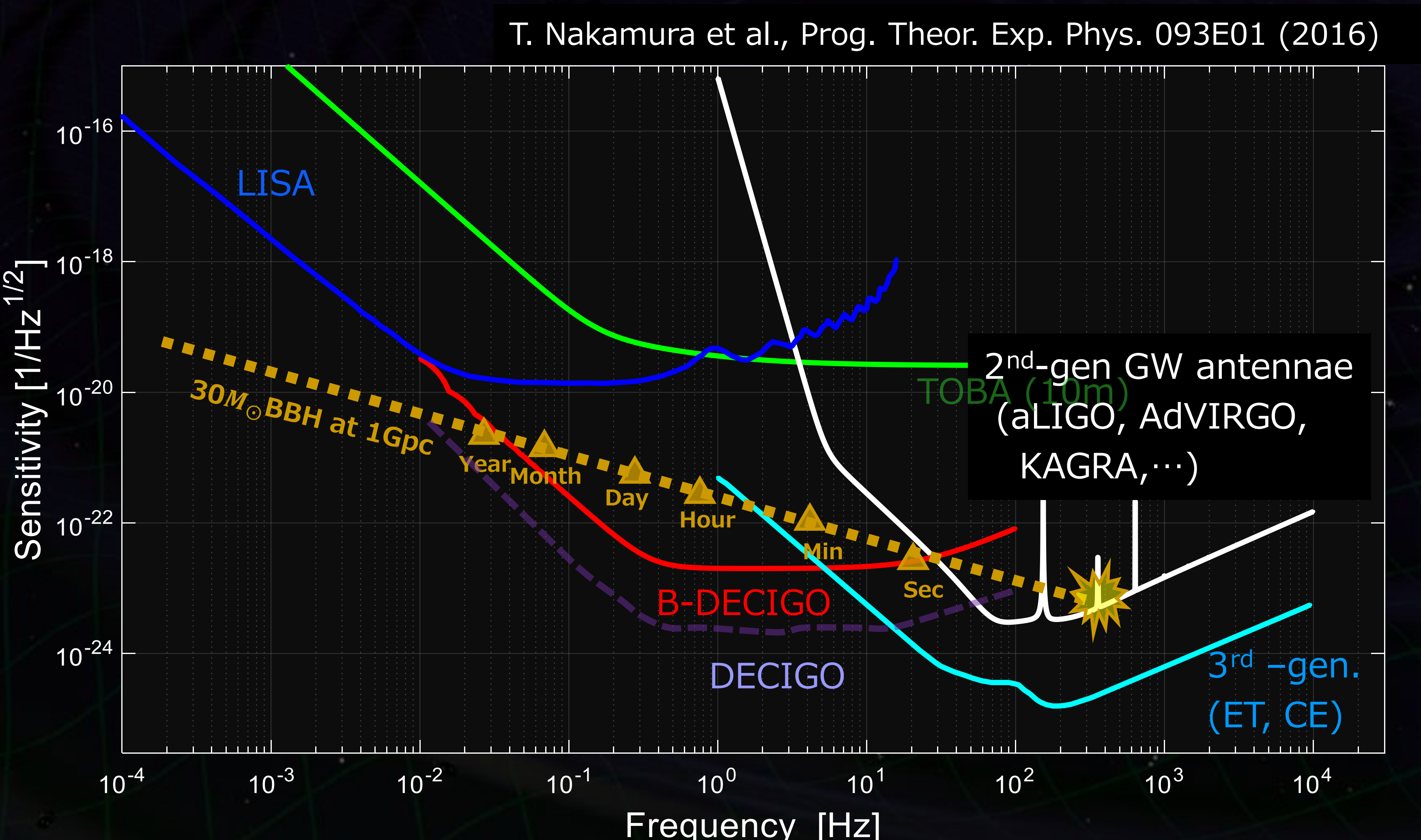
~10^5/yr binary BH inspirals.



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

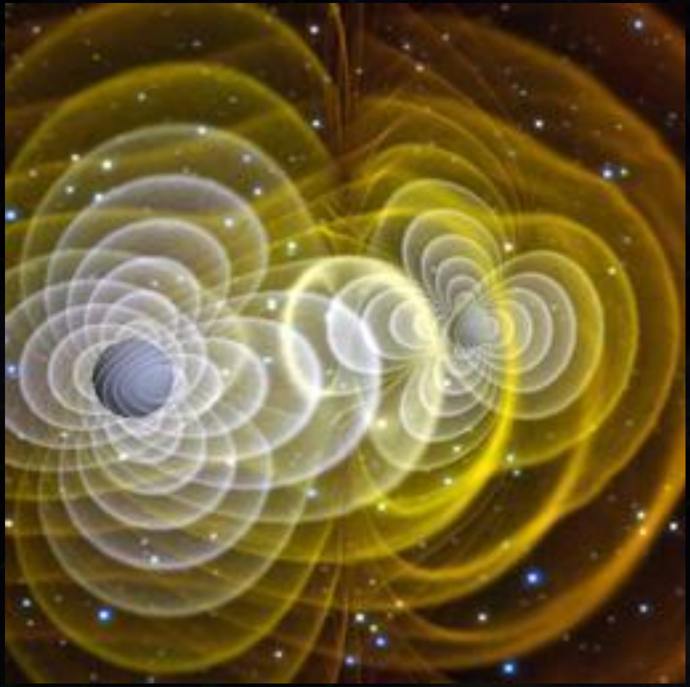
High-freq. → Ground based
Astrophysics, EoS of NS

Sensitivity Curves



Target (2) : Intermediate-mass BH Merger

B-DECIGO will see almost the whole Universe.



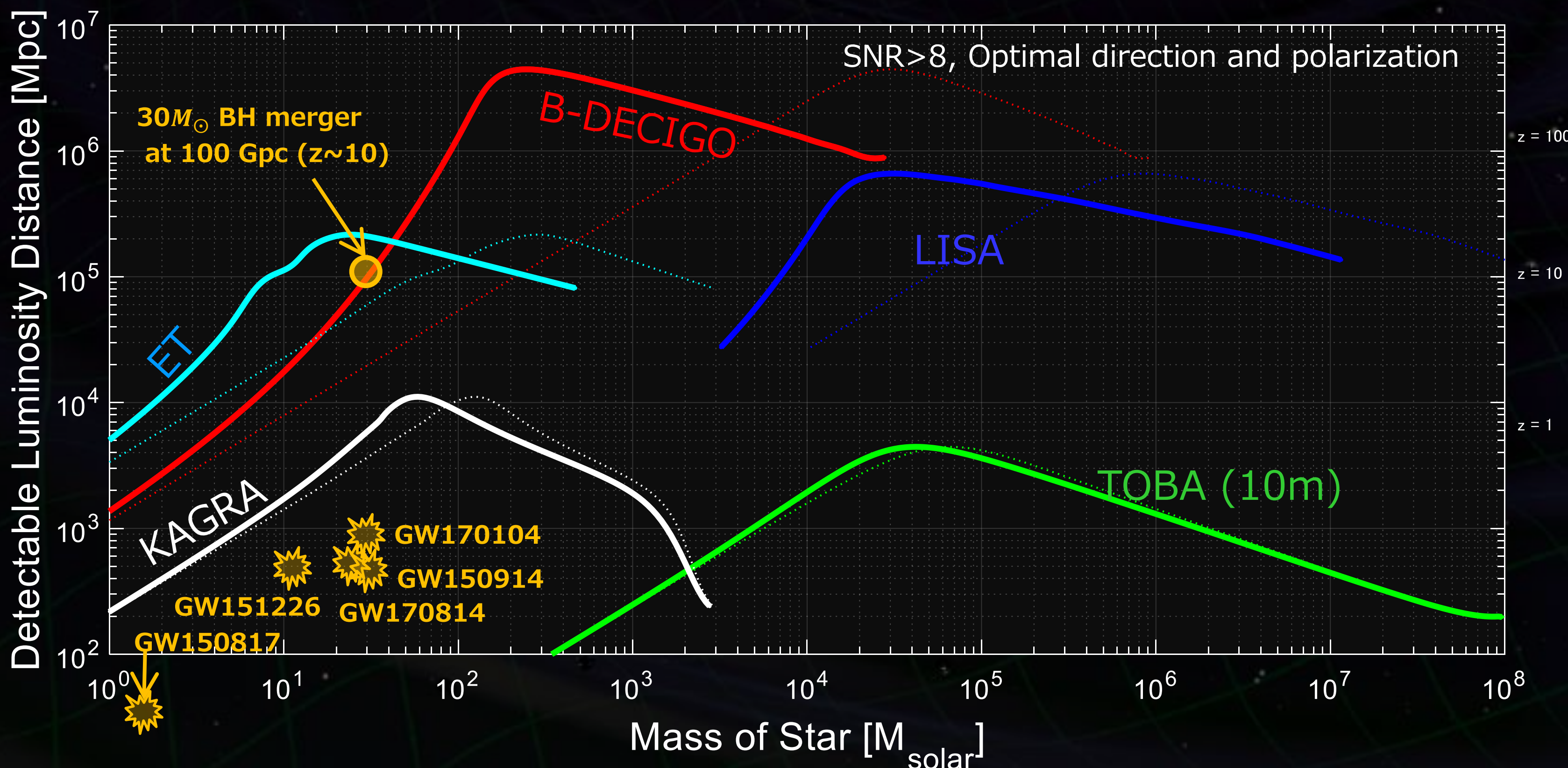
The mystery on the history of SMBH at the centers of Galaxies:

(A) Large BH + Accretion
(B) Hierarchical merger

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

Observable Range

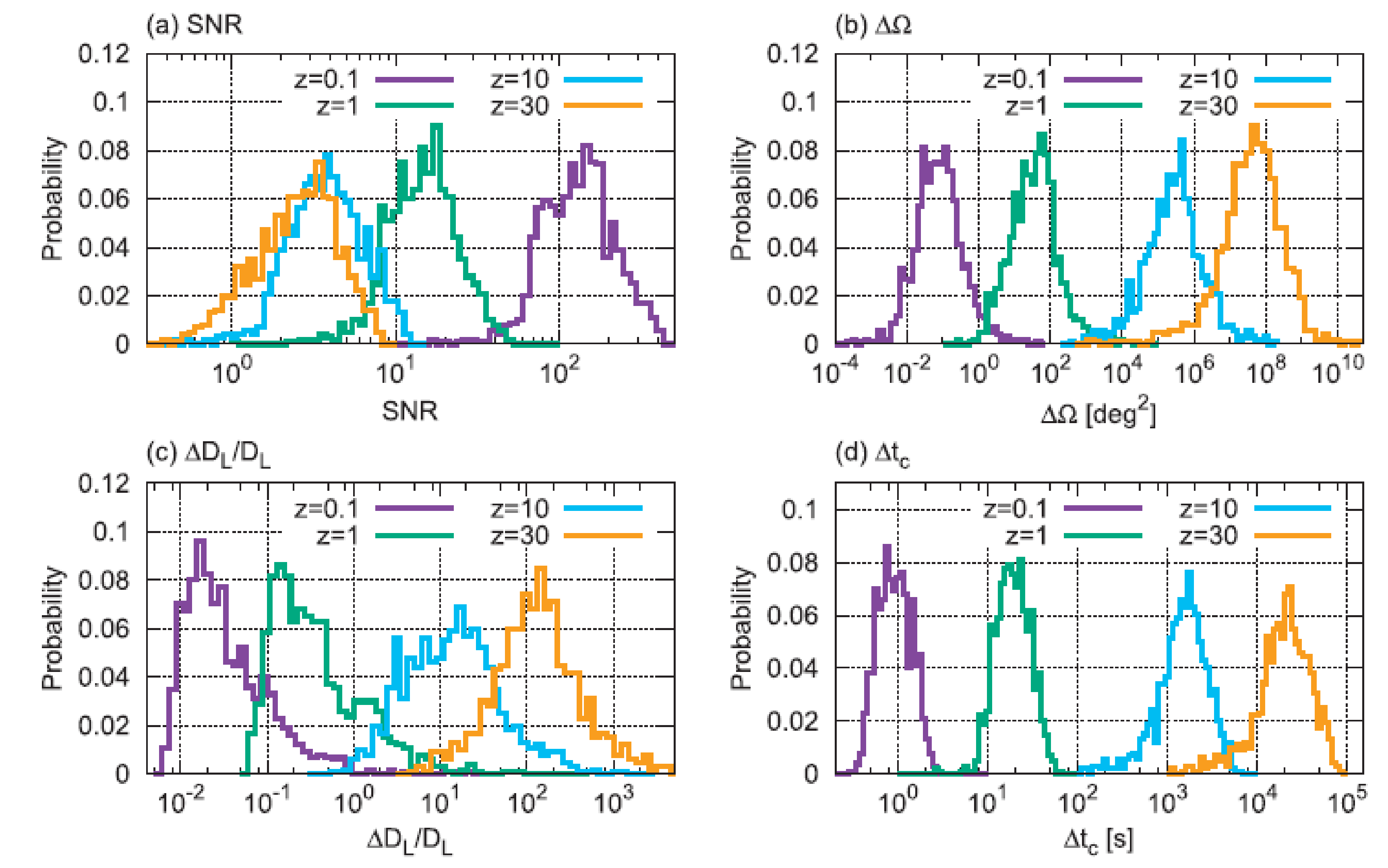
$30M_\odot$ BBH Merger : 100 Gpc (z>10) range
with SNR~8 (optimal direction/polarization).



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 ($\sim 10^5$) :
  * Localization, Merger time → Alerts for GW-EM.
  * Mass, Distance, Spin → Origin and nature of BBH.

Parameter Estimation Accuracy

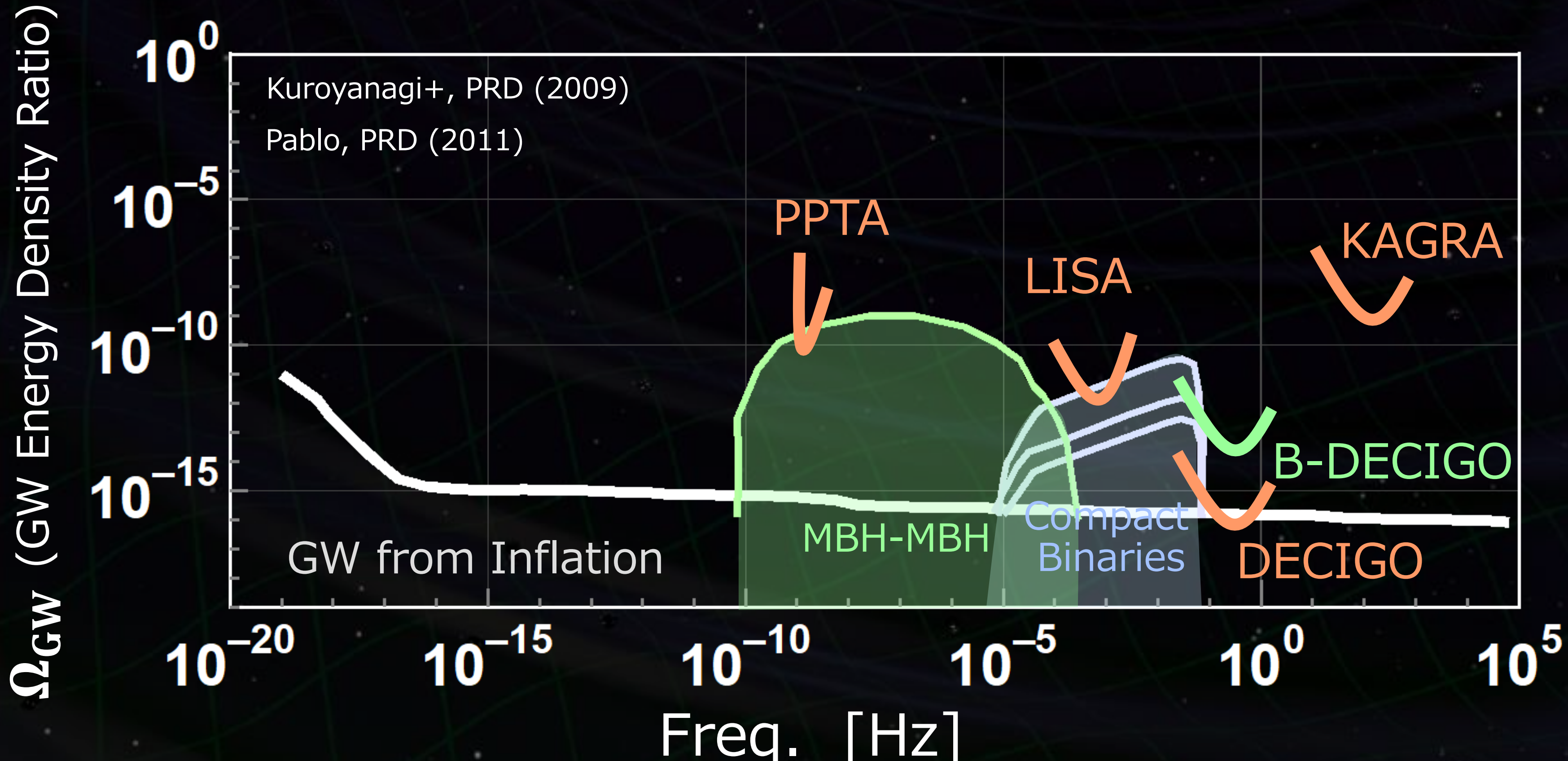


T. Nakamura et al., Prog. Theor. Exp. Phys. 093E01 (2016)

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.



Technical Challenges

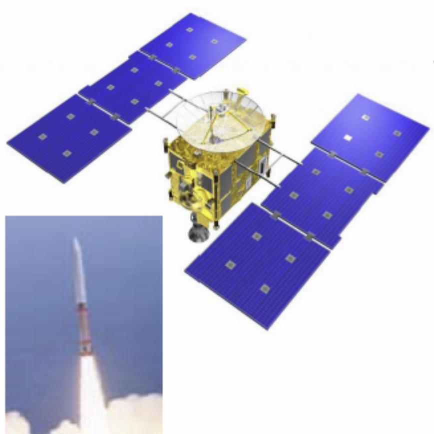
- Long-baseline Interferometry (Disp. <2×10^{-18} m/Hz$^{1/2}$)
  - Optical configuration for IFO, and laser source.
  - 100km Fabry-Perot cavity (Large RoC, Distortion).
  - Initial attitude acquisition.
- Force Noise (Force noise <1×10^{-16} N/Hz$^{1/2}$)
  - Gravity, EM force, Residual gas, thermal 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.

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

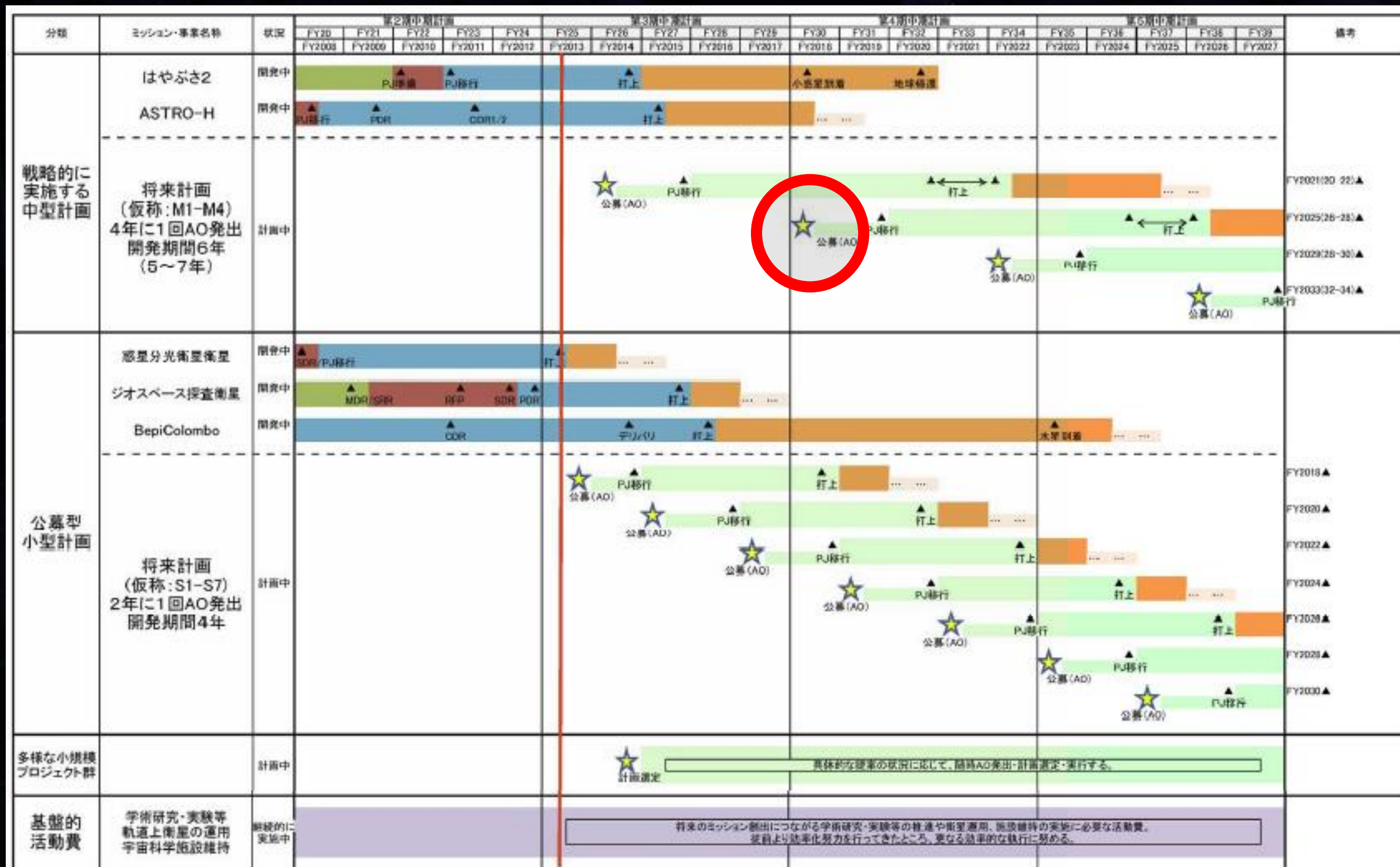
戦略的に実施する中型計画（300億程度）
世界第一級の成果創出を目指し、各分野のフラッグシップ的なミッションを日本がリーダとして実施する。多様な形態の国際協力を前提。

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).



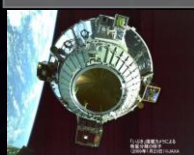
Updated Roadmap for DECIGO

Figure: S.Kawamura

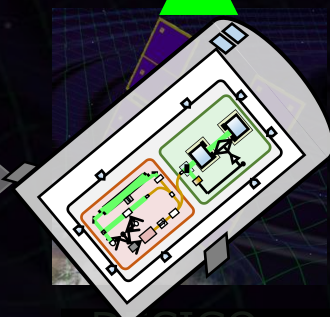
	2014	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33

Mission

R&D Fabrication

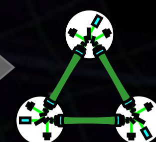


SDS-1/SWIM



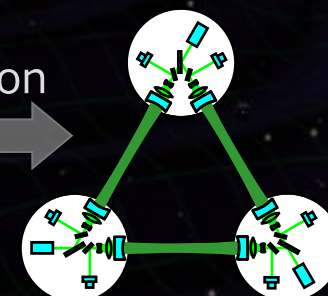
Ground test + Piggy-back opportunity.

R&D Fabrication



B-DECIGO

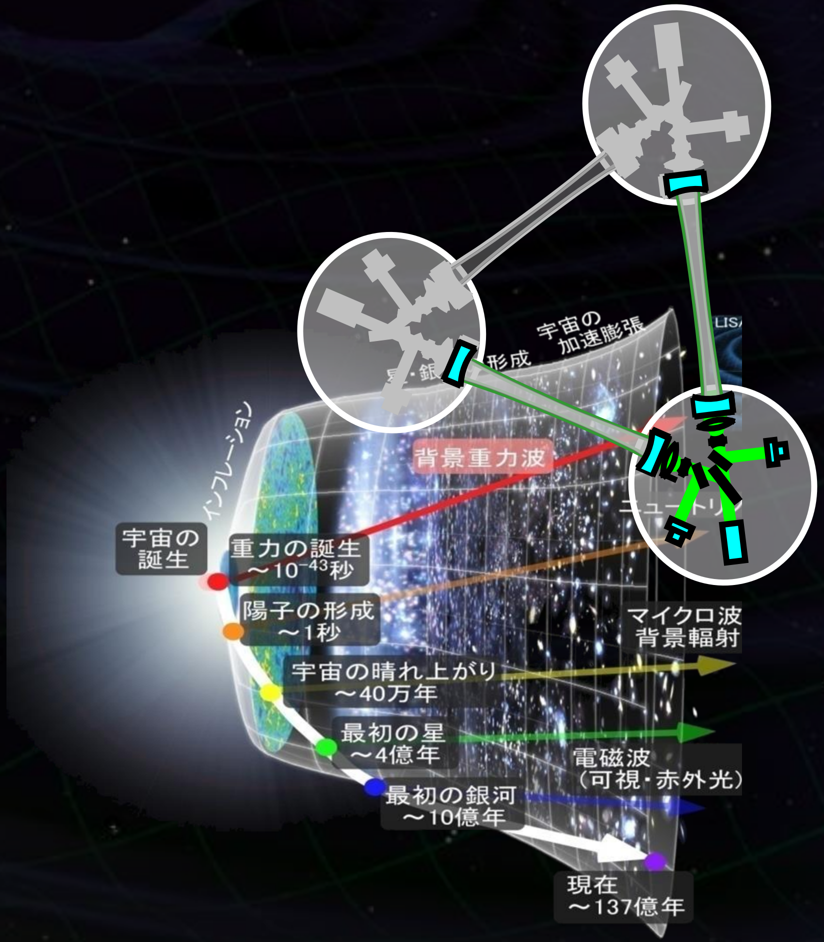
R&D Fabrication



DECIGO

	2014–20	21–28	29–33
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

DECIGO



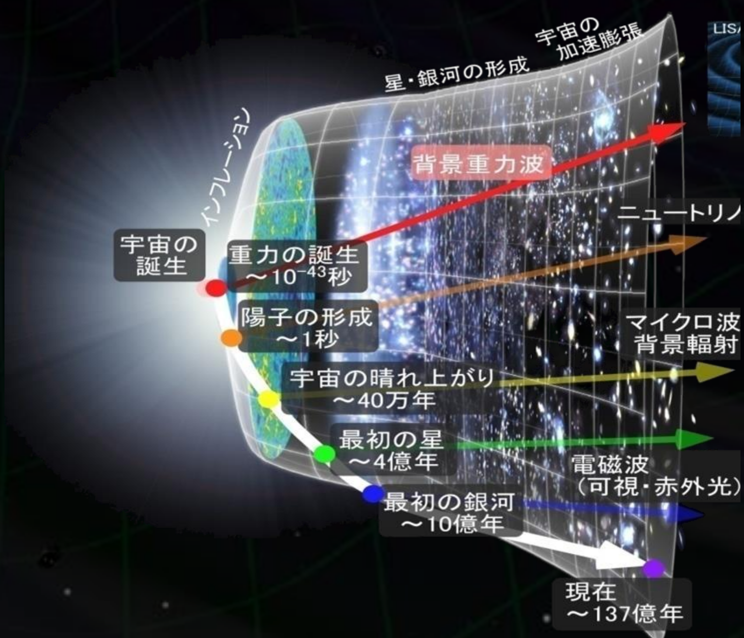
宇宙の
加速膨張
形成
背景重力波
インフレーション
宇宙の
誕生
重力の誕生
～10^{-43}秒
陽子の形成
～1秒
宇宙の晴れ上がり
～40万年
最初の星
～4億年
最初の銀河
～10億年
現在
～137億年
マイクロ波
背景輻射
電磁波
（可視・赤外光）

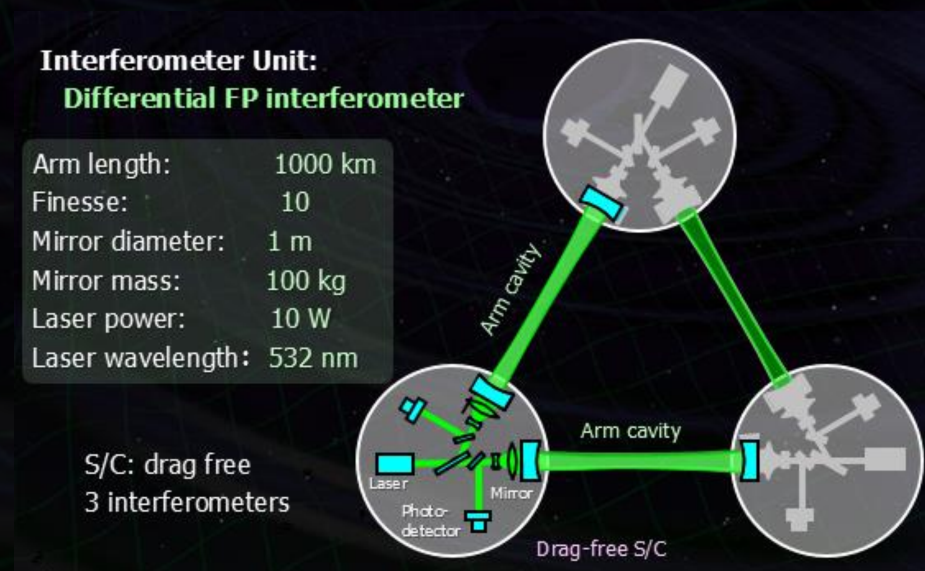
Space GW Antenna DECIGO

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.





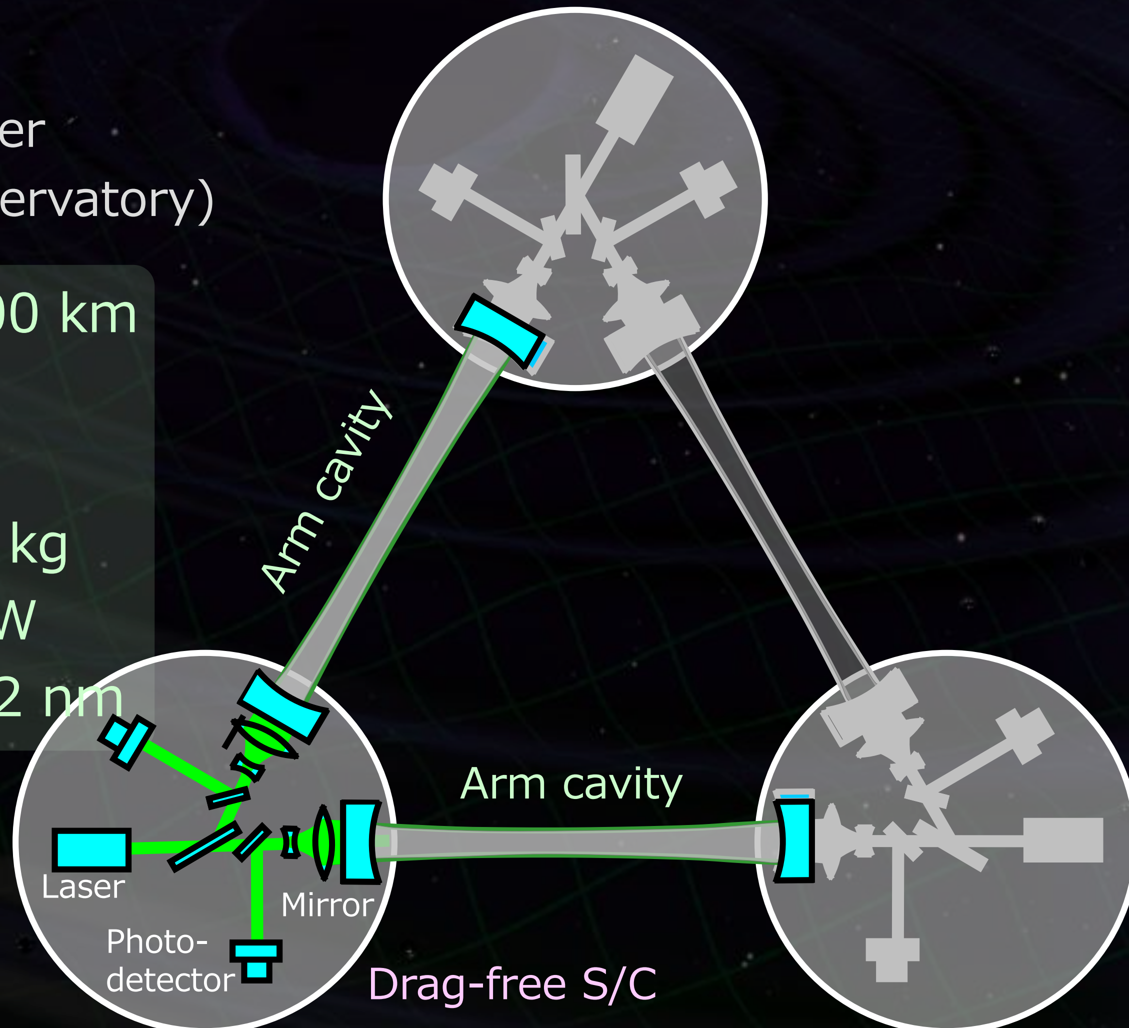
Conceptual Design

DECIGO

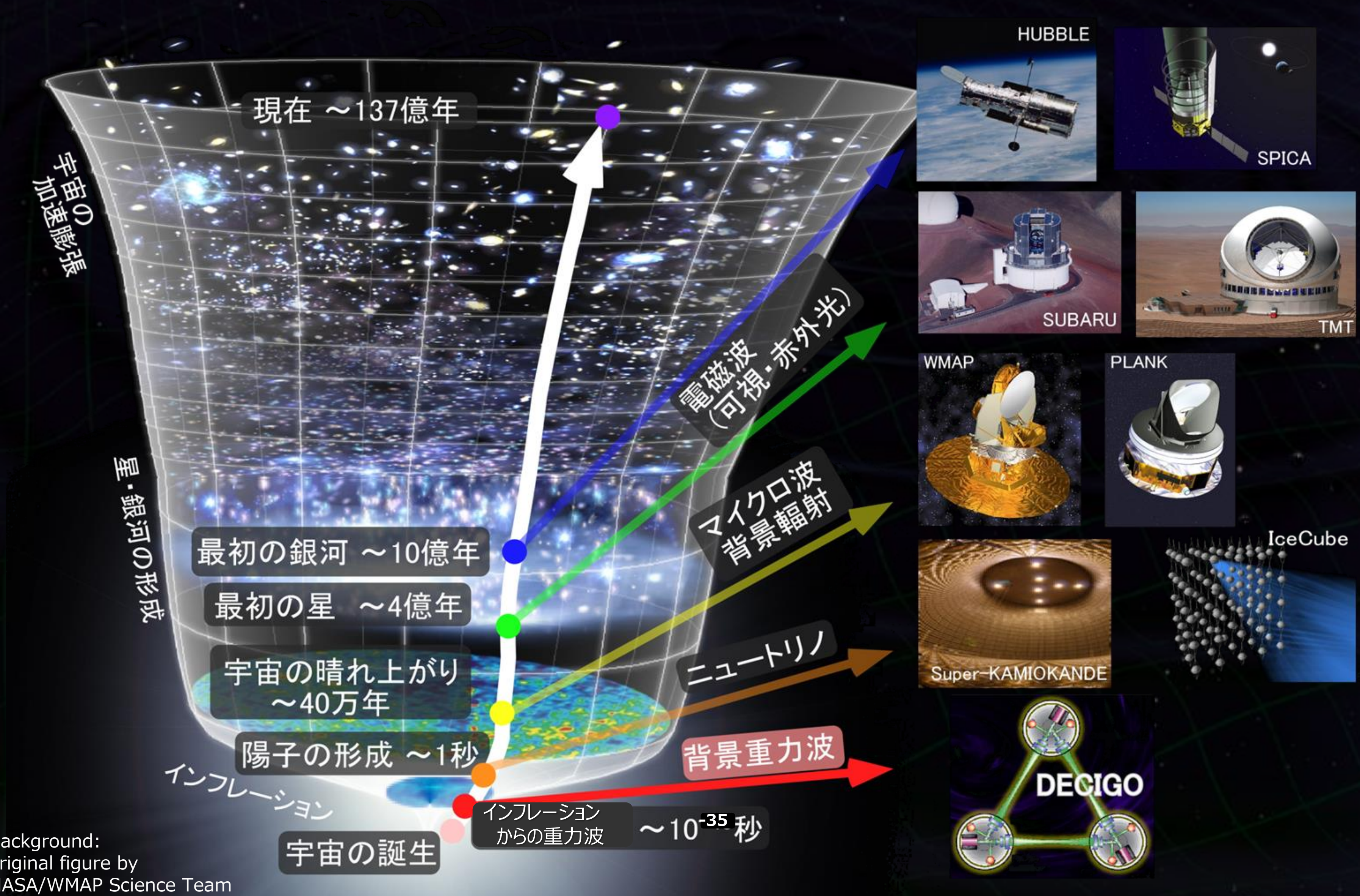
(DECI-hertz interferometer
Gravitational wave Observatory)

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



Observation of the Early Universe



Background:
original figure by
NASA/WMAP Science Team

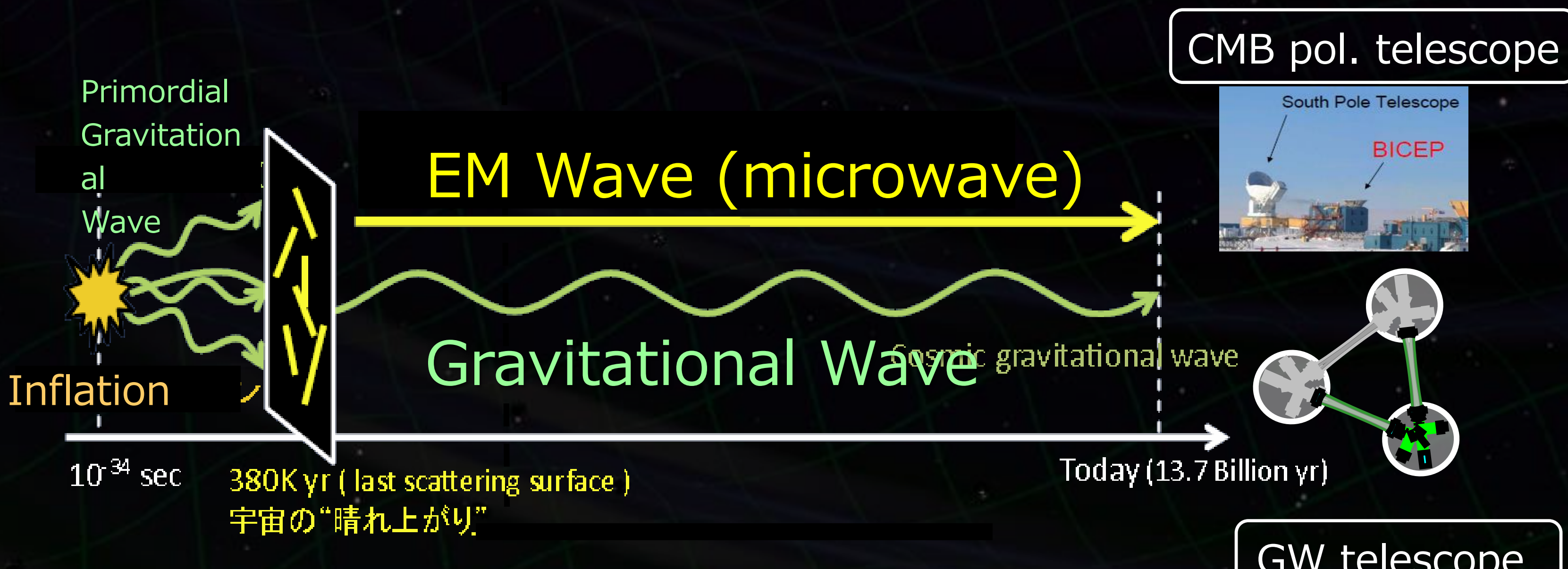
Observation of GW from Inflation

BICEP2, (POLARBEAR,···)

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

DECIGO, (KAGRA, aLIGO,···)

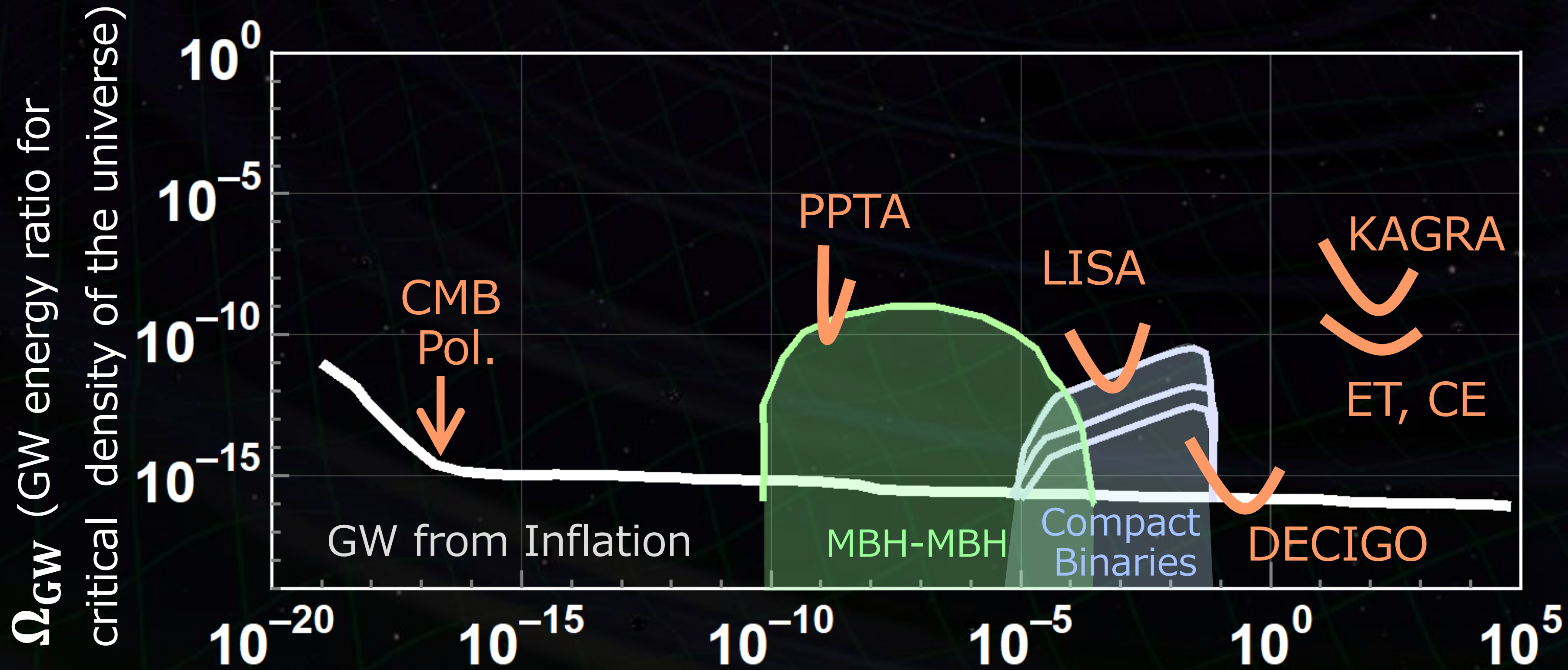
GWB observation by GW telescope.



Original figure by Tajima (Kyoto 2011)

'Window' for the Early Universe

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



Kuroyanagi+, PRD (2009)

Pablo, PRD (2011)

Probing the Early Universe by GW

- 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.

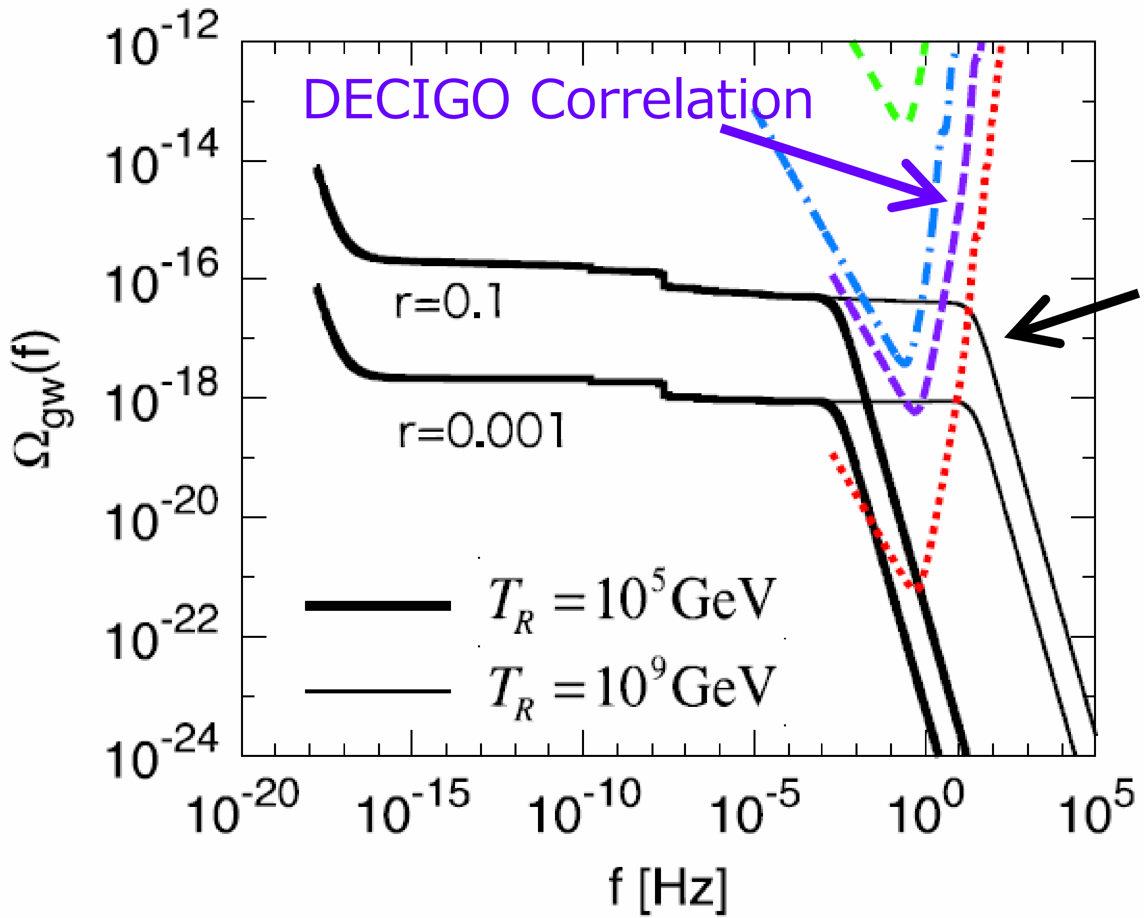
Different age in different freq.
Higher freq. → Earlier universe
- Reheating temperature
- Thermal history of the universe

…．

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.

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.
- Japanese KAGRA will improve the source parameter estimation accuracy. Best effort to join the network.
- 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