RESCEU summer school 2020

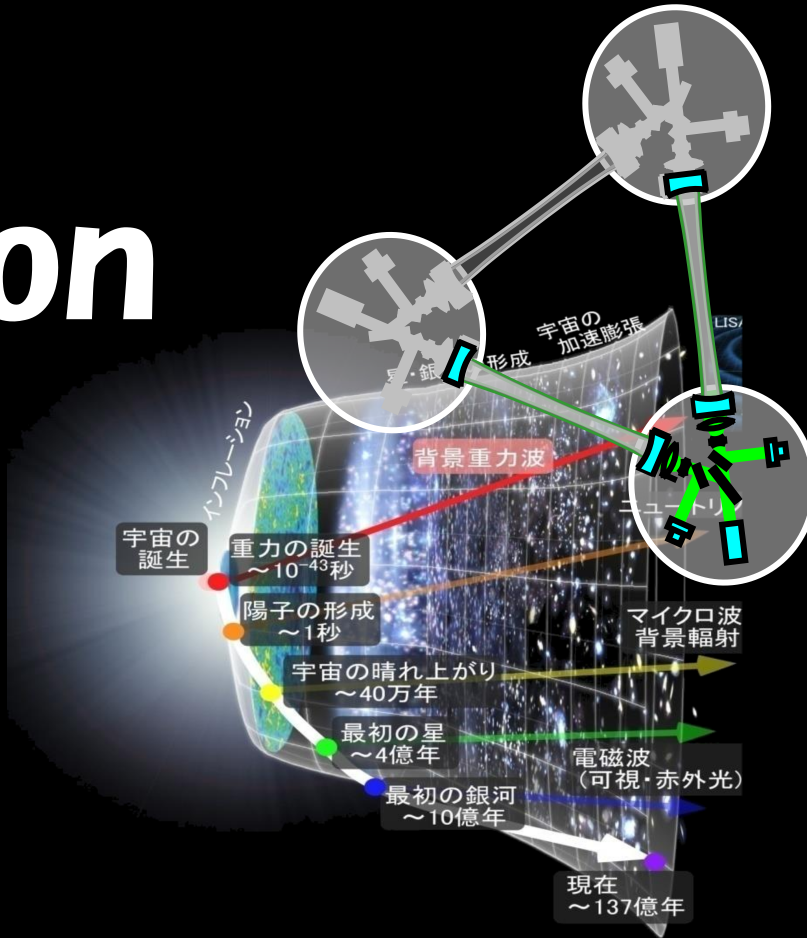
Observation of Gravitational-Wave in Space

Masaki Ando (Univ. of Tokyo)

Lecture Plan

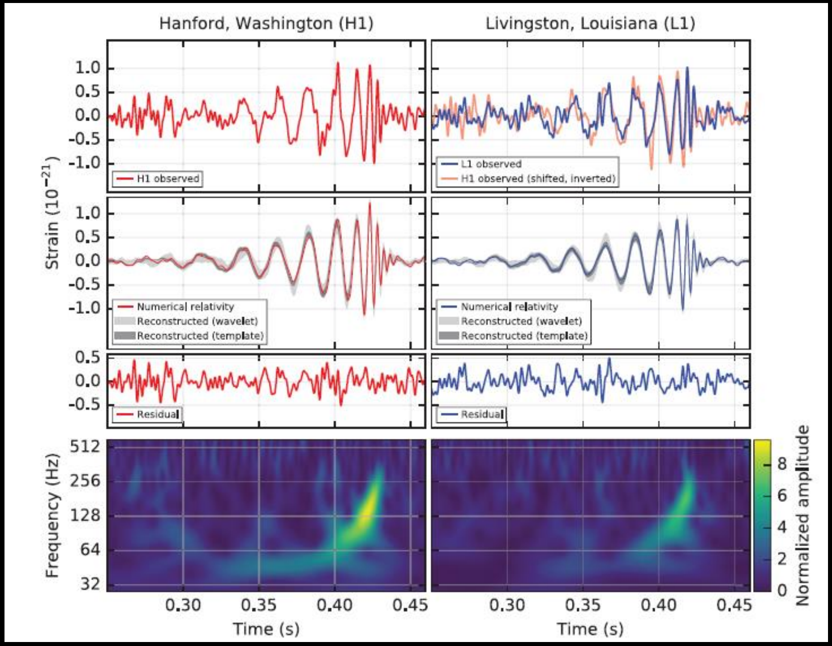
- Introduction
- B-DECIGO
- DECIGO

Introduction



First Detection of GW

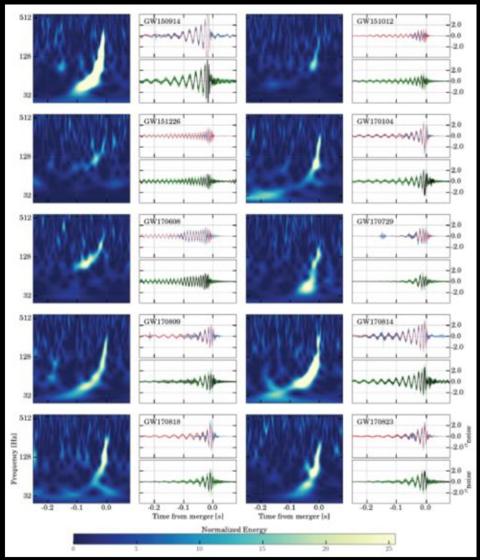
- On Feb. 11th, 2016, LIGO announced first detection of gravitational wave. The signal was from inspiral and merger of binary black hole.
  - ⇨ Opens a new field of 'GW astronomy'.



Courtesy Caltech/MIT/LIGO Laboratory

Mergers of Binary Black Hole

arXiv:1811.12907 (Nov. 30, 2018)



- Publications after the first event.

  *2nd: GW151226 (reported in 2016.6)
  *3rd: GW170104 (reported on 2017.6.2)
  *4th: GW170814 (reported on 2017.9.27)
  *5th: GW170608 (reported on 2017.11.15)
  *6-10th: GW151012, GW170729, GW170809, GW170818, GW170823 (reported on 2018.11.30)

⇨ LIGO/VIRGO GWTC-1 [Phys. Rev. X 9, 031040, (2019)]

3 BBH events in O1 (Sept. 2015 – Jan. 2016)

7 BBH events in O2 (Nov. 2016 – Aug. 2017)

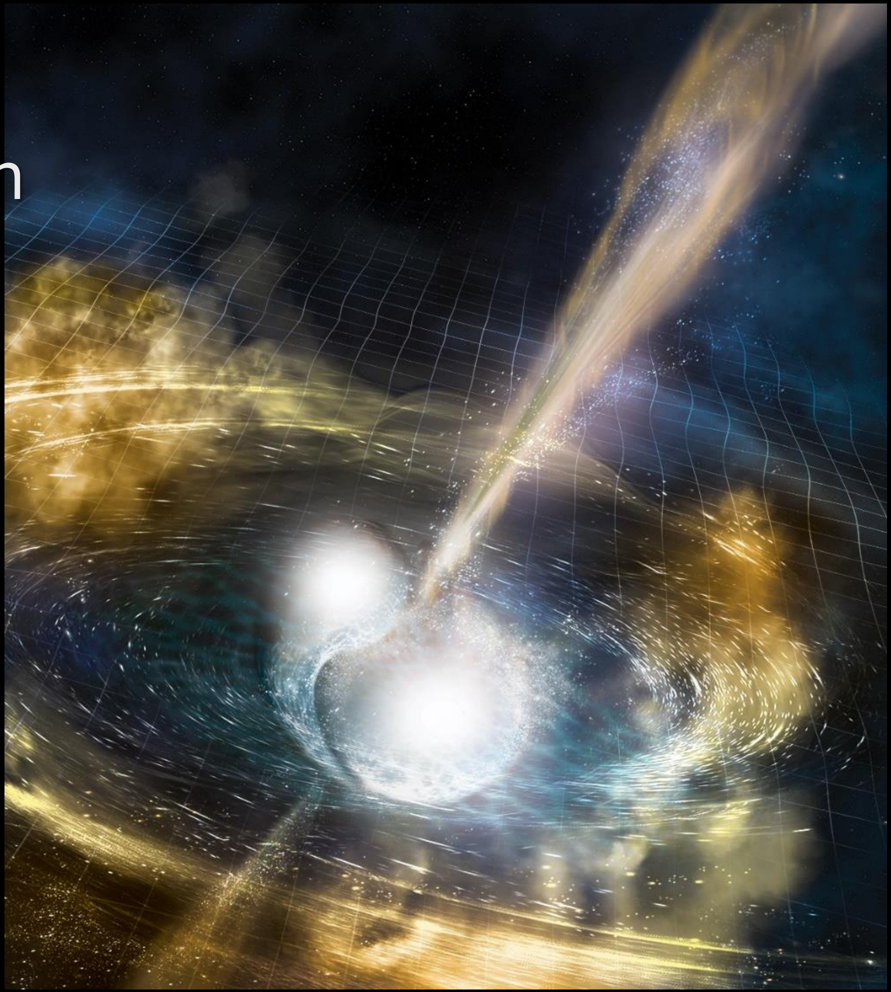
- 56 Public alerts in O3 (April 2019 – Mar. 2020)

→ BBH mergers are common events in the universe.

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

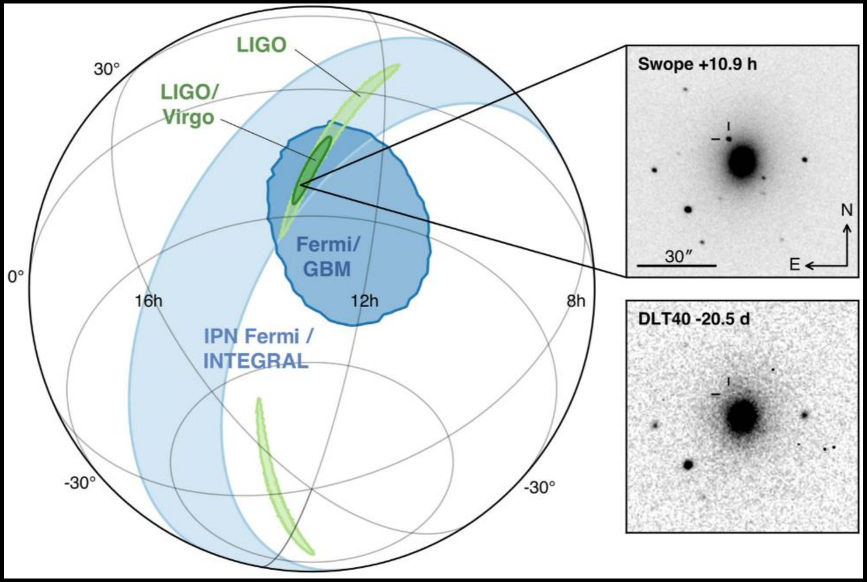


Courtesy Caltech/MIT/LIGO Laboratory

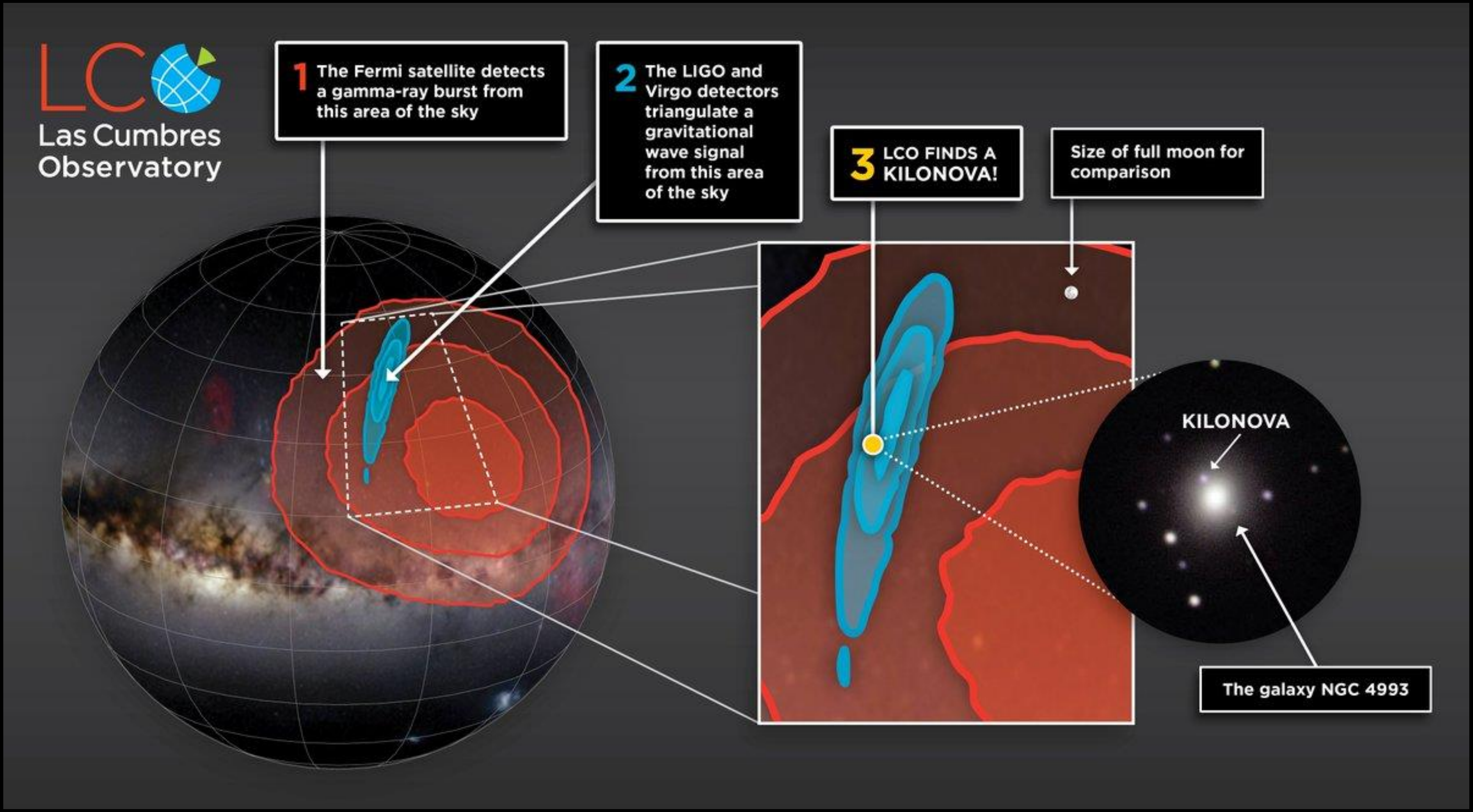
EM Follow-up Observations

- Detection by Advanced LIGO: SNR of 32.4.
- Advanced Virgo contribution for sky localization: from 190 deg^2 to 30 deg^2 .
- Prompt EM (gamma-ray) observation by Fermi, 1.7sec after GW.
- Obs. by ~70 EM telescopes. EM counterpart was detected by X-ray, UV, Optical, IR, and Radio.

ApJL 848 L12 (2017)



Discovery of the EM Counterpart

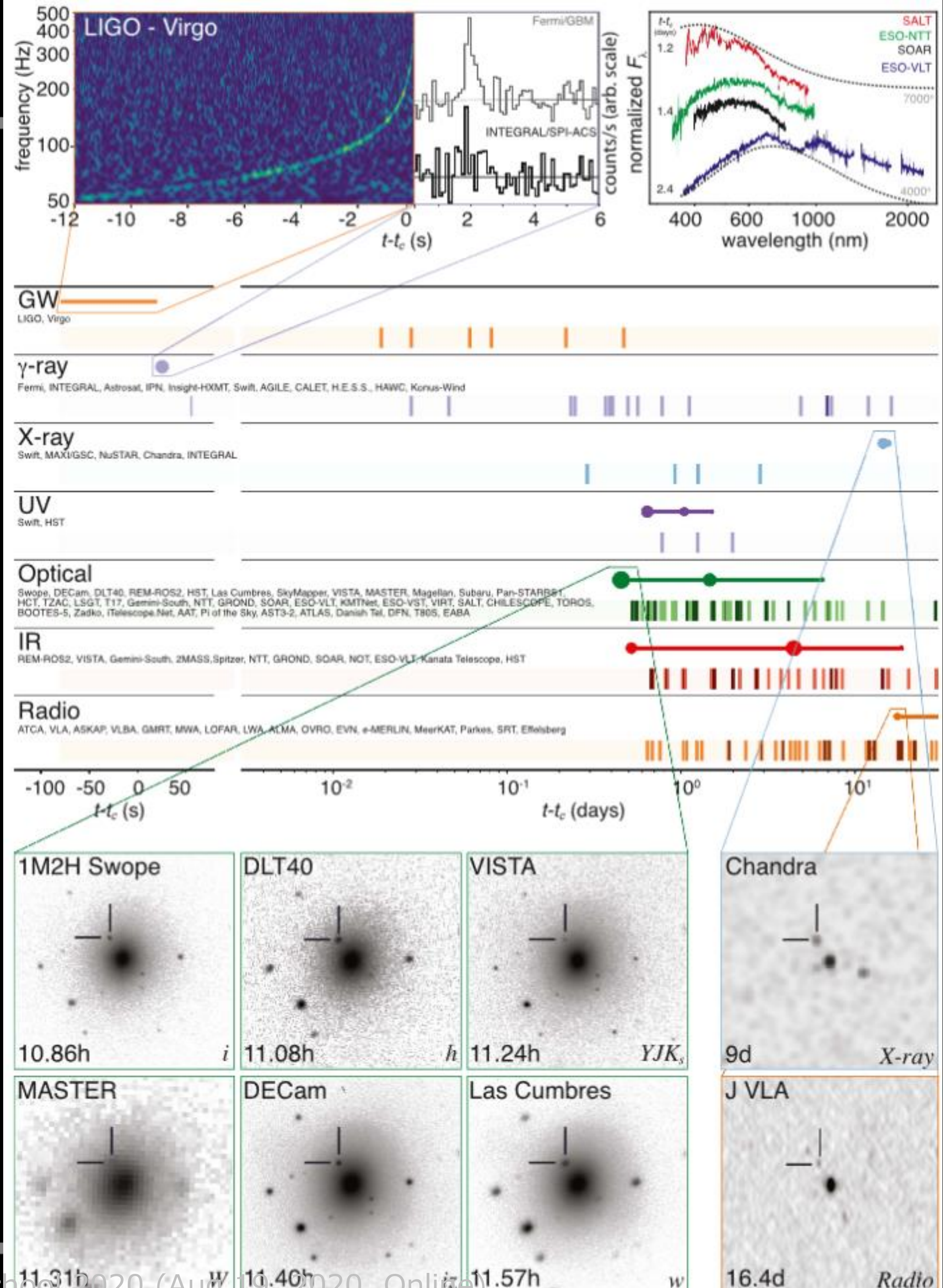


Credit: Sarah Wilkinson / LCO (Taken from https://youtu.be/wnwMhvdDcfI)

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

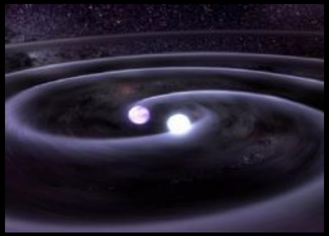
⇩

- 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)

BNS Merger Rate



- Estimation from pulsar observations

Galaxy event rate:

$$\mathcal{R} = 118^{+174}_{-79} [\text{events/Myr}]$$

V. Kalogera et.al., ApJ, 601 L179 (2004)

Number density of galaxies:

$$\rho = 1.2 \times 10^{-2} \quad [\text{Mpc}^{-3}]$$

R. K. Kopparapu et.al., ApJ. 675 1459 (2008)

⇨ BNS merger rate: $1400^{+2100}_{-950}\ \mathrm{Gpc^{-3}yr^{-1}}$

- Estimation from GW observation (GW170817)

BNS merger rate: $1540^{+3200}_{-1220}\ \mathrm{Gpc^{-3}yr^{-1}}$

LIGO and VIRGO, PRL (2017)

Fundamental Physics: Speed of GW

- Test of GR : Propagation speed of GW.
- GW (GW170817) and EM (GRB170817A) from the same BNS merger
  - * False coincidence rate (direction and time): 5×10^{-8}
  - * Arrival time difference 1.74 ± 0.05 sec
  - * Source distance : 40Mpc (1.2×10^{24} m).

→ Stringent limit on the speed of GW

$$-3 \times 10^{-15} \leq \frac{v_{\mathrm{GW}}}{v_{\mathrm{EM}}} - 1 \leq 7 \times 10^{-16}.$$

※ Note: Dependent on GRB source model. Here, GW and EM radiation-time difference is assumed to be less than 10 sec from the source. There are more exotic models, which will be tested by more events to be observed.

Fundamental Physics

- Cosmological Parameter

Use BNS merger as a 'Standard Siren'

- GW amplitude → Source distance.
- EM counter part → Redshift

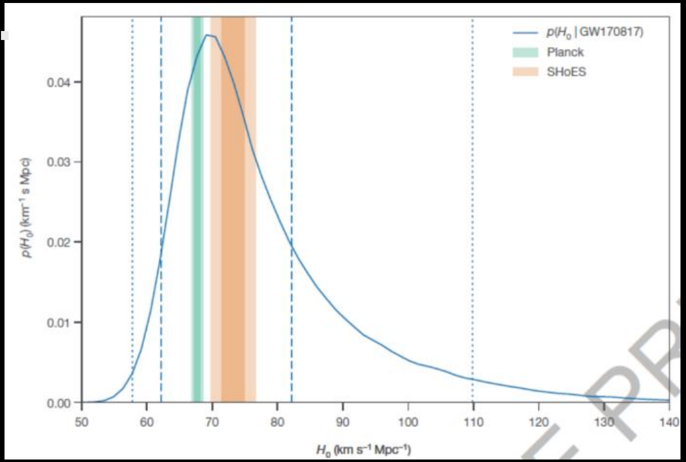
Hubble parameter:

⇨ $H_0 = 70^{+12.0}_{-8.0}$ km/s/Mpc

Consistent with other results.

Independent measurement.

Hubble parameter by CMB measurement (Planck): $H_0 = 67.90 \pm 0.55$ km/s/Mpc

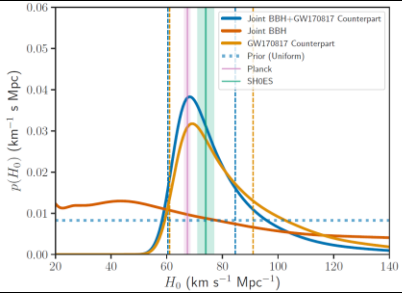


doi:10.1038/nature24471

※ Update using BBH results

Hubble parameter: $H_0 = 68^{+14.0}_{-7.0}$ km/s/Mpc

[arXiv:1908.06060v2 (Aug. 2019)]



NS EoS: Tidal deformability

- Tidal deformation in formation from GW waveform

  * Tidal deformability λ :

$$Q_{ij} = -\lambda E_{ij}$$

↑ Quadrupole moment

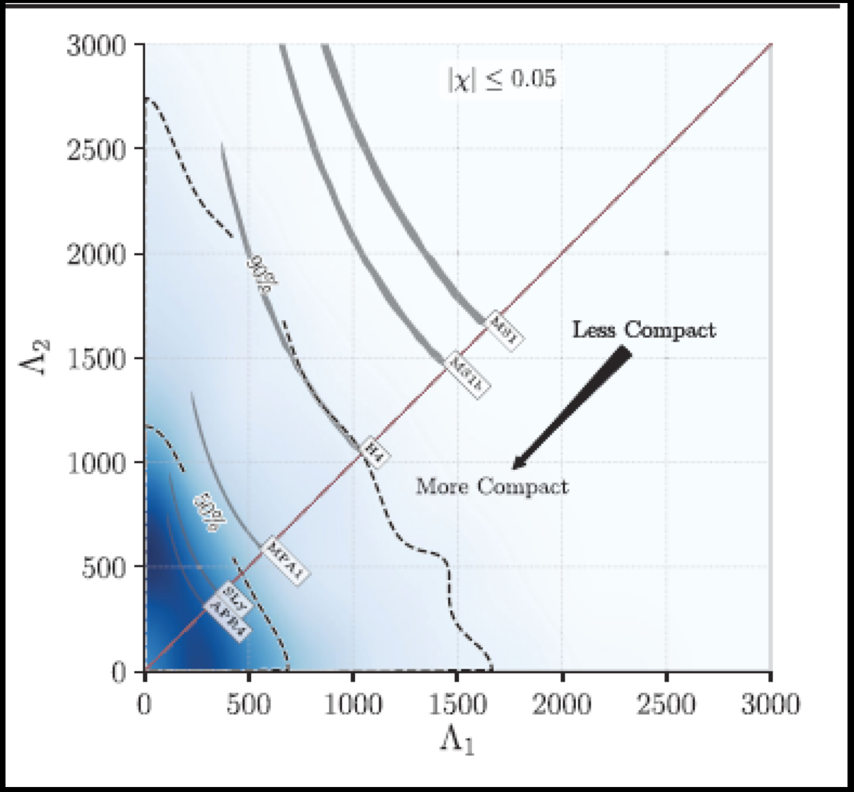
↖ Tidal force from companion object

  * Dimensionless parameter

$$\Lambda = \frac{G}{c^5 R^5}\lambda,\ C = \frac{GM}{c^2 R}$$

Hard EoS → Large diameter

→ Large Λ



Detection Papers from O3

- GW190425 : BNS with large chirp mass.

  Component mass of $1.12 - 2.52\ M_\odot$ [ApJ. Letters 892 L3 (2020)]

- GW190412 : BBH with large mass ratio of $0.28^{+0.12}_{-0.06}$

  Evidence of higher-multipole emission

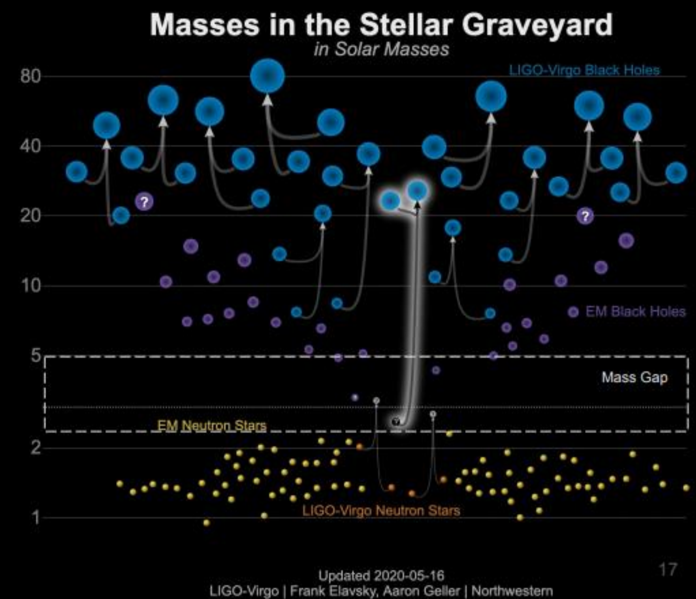
  [arxiv.org/abs/2004.08342, Accepted by PRD on June 30, 2020]

- GW190814 : 'Mass gap' event

  Most unequal mass ratio of $0.112^{+0.008}_{-0.009}$ ($\sim 23.2\ M_\odot$ and $\sim 2.59\ M_\odot$)

  The nature (BH or NS) of the secondary is unknown.

  [ApJ. Letters 896:L44 (2020)]



KAGRA

KAGRA（かぐら)

2nd generation GW Antenna. in Japan

LCGT (Large-scale Cryogenic Gravitational-wave Telescope)

Project started in 2010, >300 Collaborators, from >100 Groups in 14 Regions

KAGRA GW Detector

- KAGRA as a 2nd generation GW detector

Large-scale Detector
- Baseline : 3km
- Intra-cavity power ~400kW

Cryogenic interferometer
- Mirror temperature: 20K

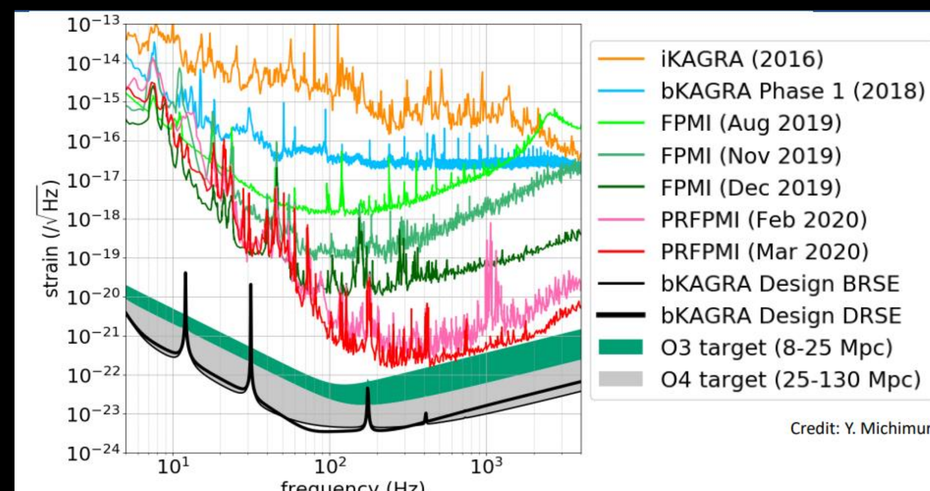
Underground site :
- 1000m underground at Kamioka, Gifu

* International GW network with LIGO/VIRGO
* Advanced technologies: cryogenic and underground

KAGRA Observation Run

- KAGRA started observation run in 2019
  - * KAGRA solo : 2 weeks (Feb. 25 – Mar. 10)
  - * O3GK : 2 weeks (Apr. 7 – Apr. 21)
  - * Science-mode duty factor 53.2%
  - * Typical binary range ~600 kpc (Best ~970 kpc)

From KAGRA web site (Feb 25, 2020)



✓The best sensitivity has reached 970 kpc (~1Mpc)!

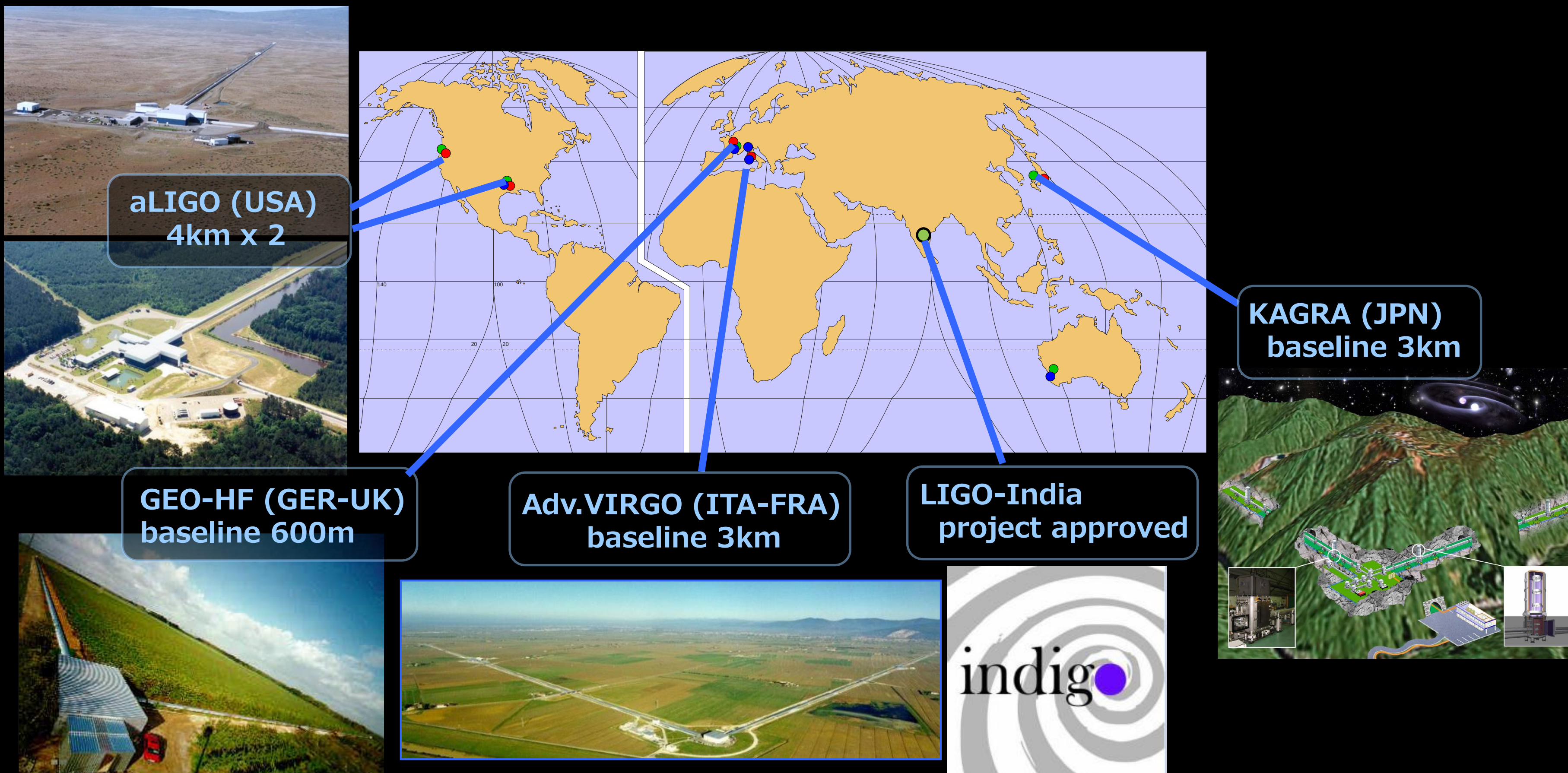
✓4 orders of magnitude improvement between Aug. 2019 and March 2020 @300Hz!

From presentation by T.Kajita (May 27, 2020)

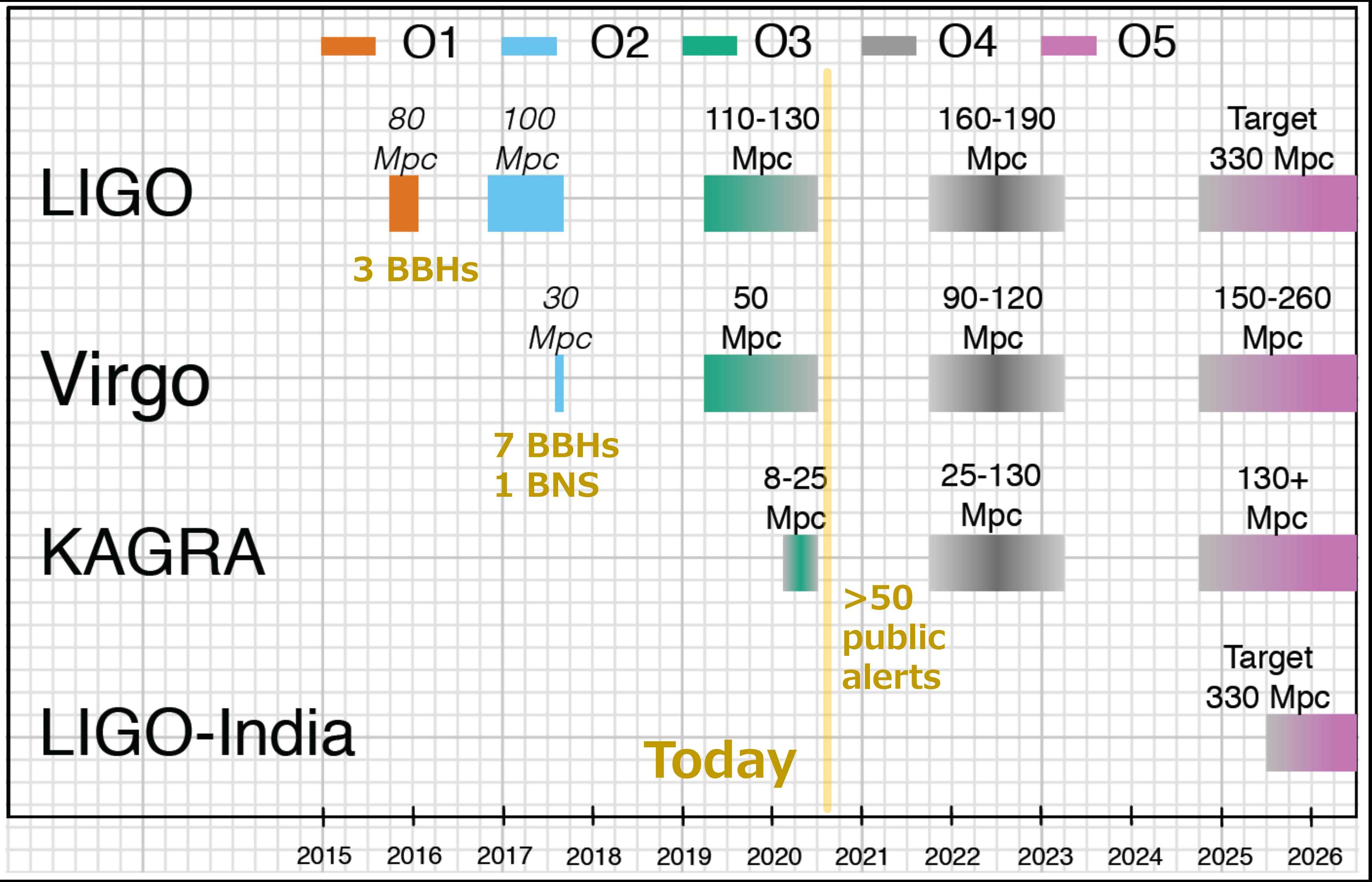
International GW Network

International network by 2nd–gen GW antennae.

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



Observation Scenario



Living Reviews in Relativity 21, 3 (2018); Updated version to be submitted.

Next Steps …

- 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.

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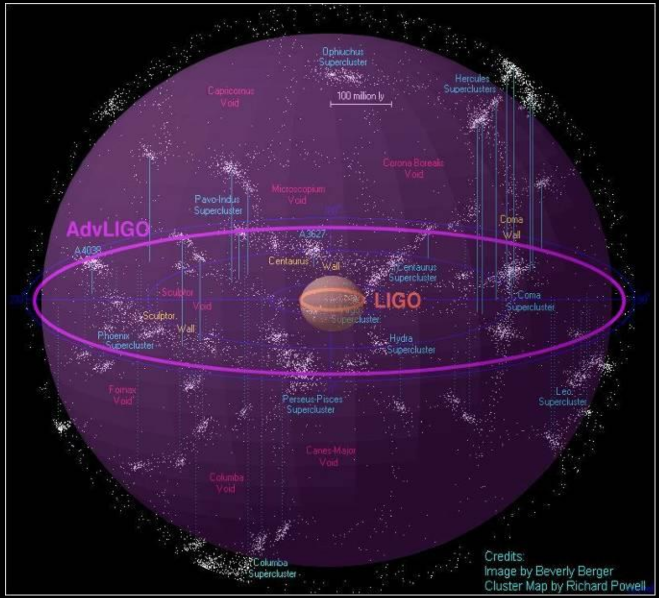
- Network of 2nd-gen. GW antennae (aLIGO, AdVIRGO, KAGRA, LIGO-India) is being formed.
- Two ways after that for Astronomy and Cosmology:
  - 3rd–gen. ground-based GW antennae (ET, CE).
  - Space GW antennae (LISA, B-DECIGO, ⋯).

Future Possibilities

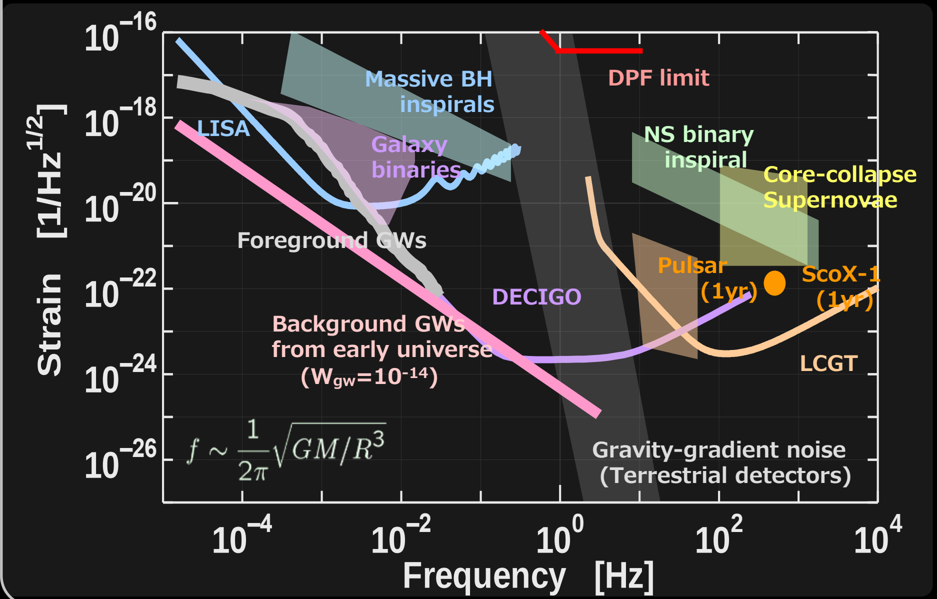
3rd generation ground-based antennae

Sensitivity Improvement to cover more galaxies.



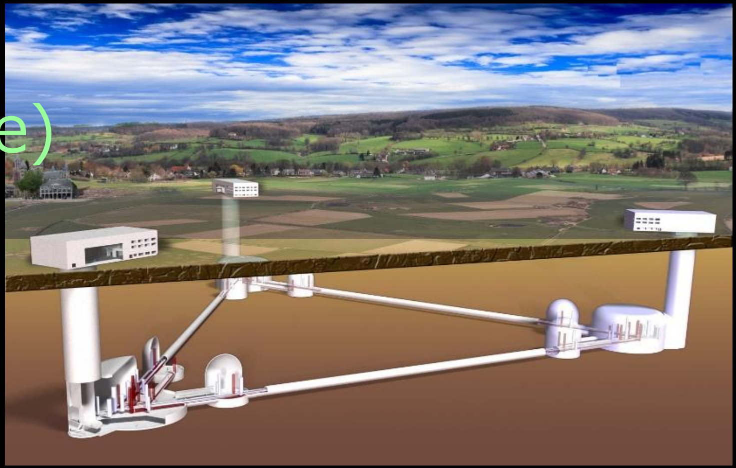
Space-borne Antennae

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



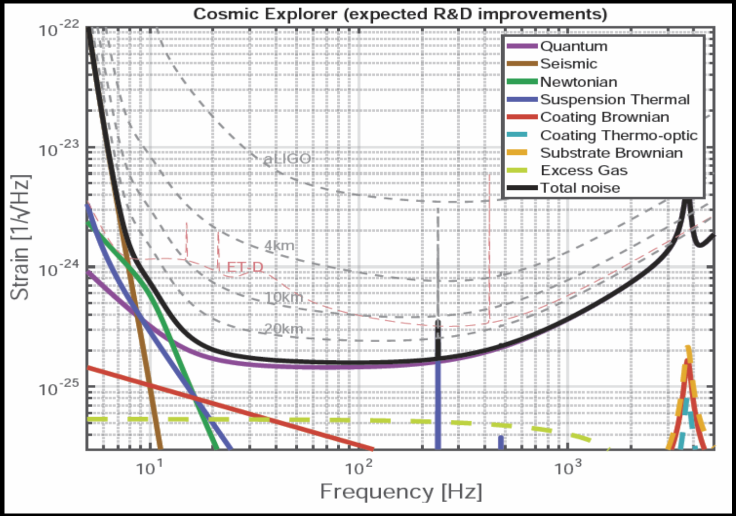
Next Generation GW Antennae

3rd Generation GW Antennae (~2030)



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

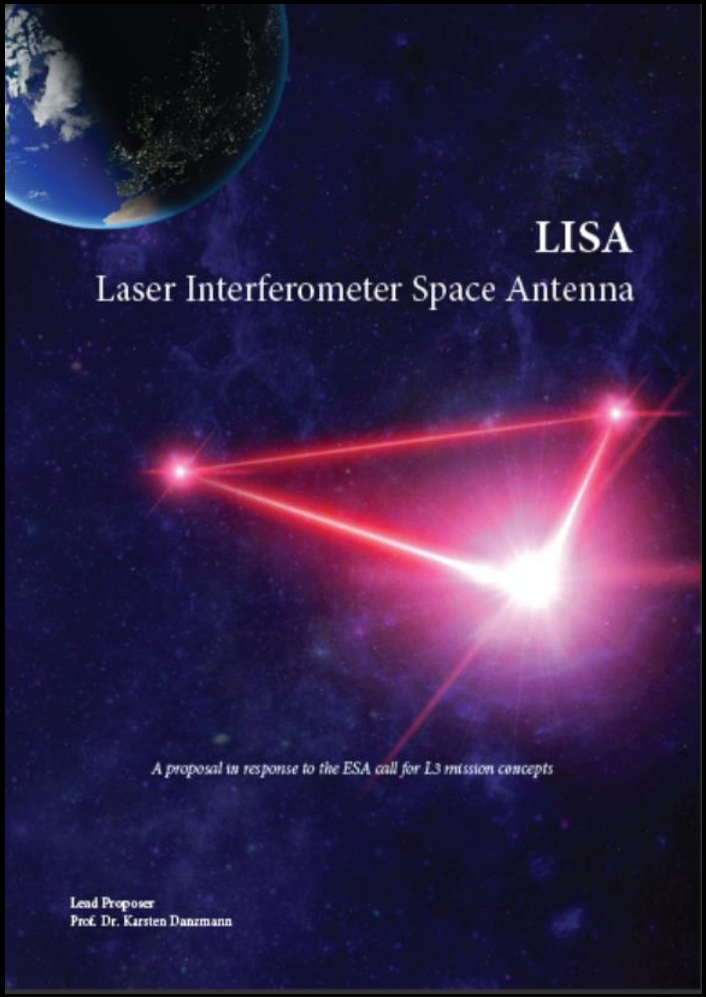
* USA: CE (Cosmic Explorer)
  x10 sensitivity,
  Long baseline ~40km,
  Surface site, Cryogenic (?)



Space GW Antennae

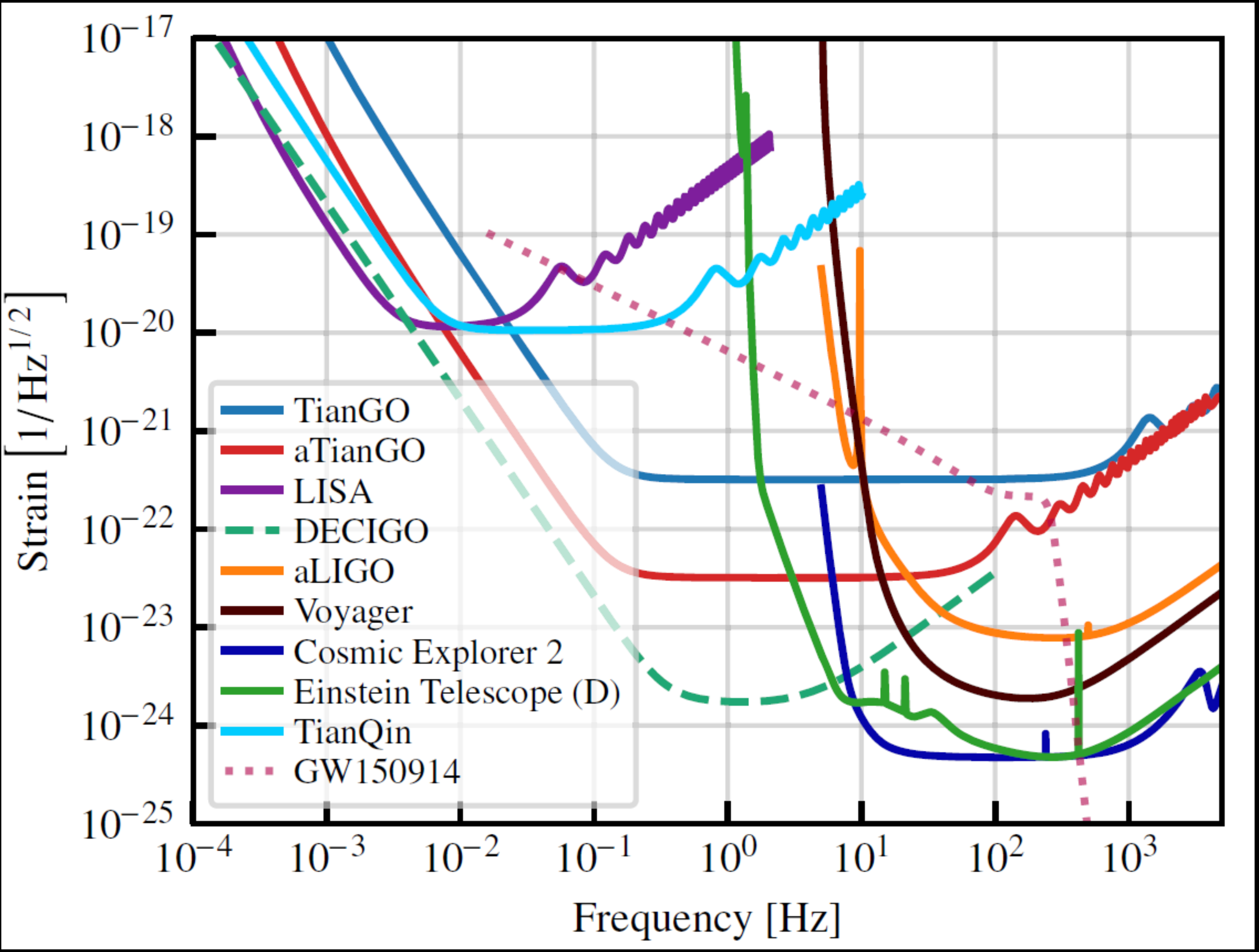
- Space GW antenna
  *Observation at low-frequency with long baseline by avoiding seismic disturbances

*LISA: selected as ESA L3 (2034)
*2 mission proposals (Taiji and TianQin) in China
*DECIGO/B-DECIGO in Japan
*TianGO proposal by USA group



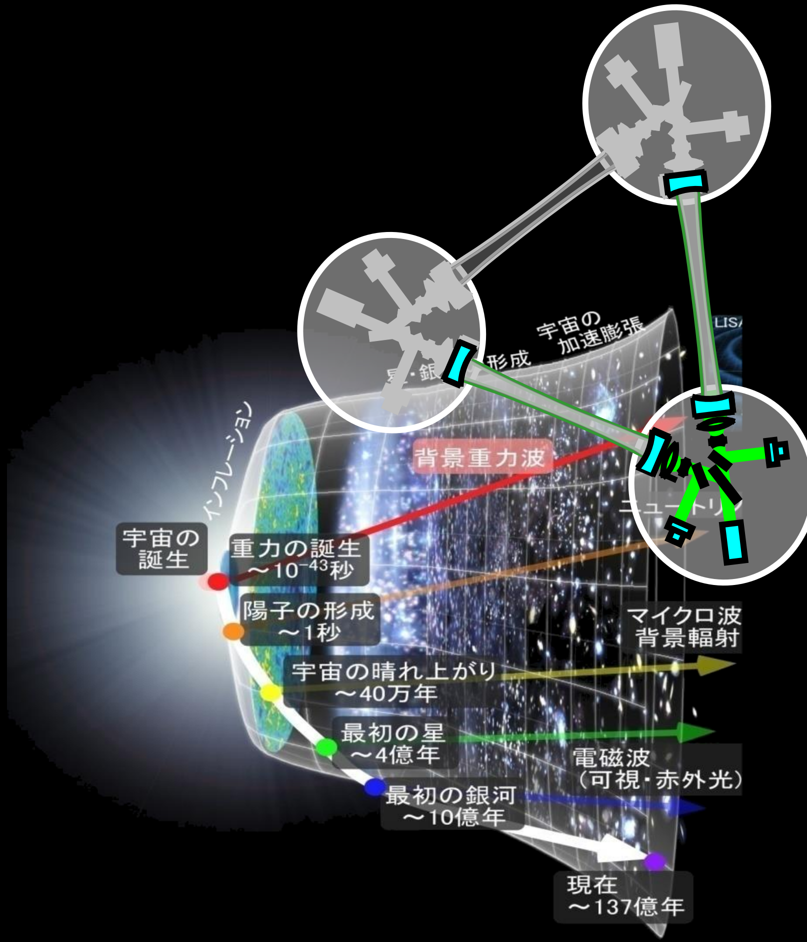
https://www.elisascience.org/articles/elisa-mission/lisa-mission-proposal-l3

Space GW Antennae



Phys. Rev. D 102, 043001 (2020)

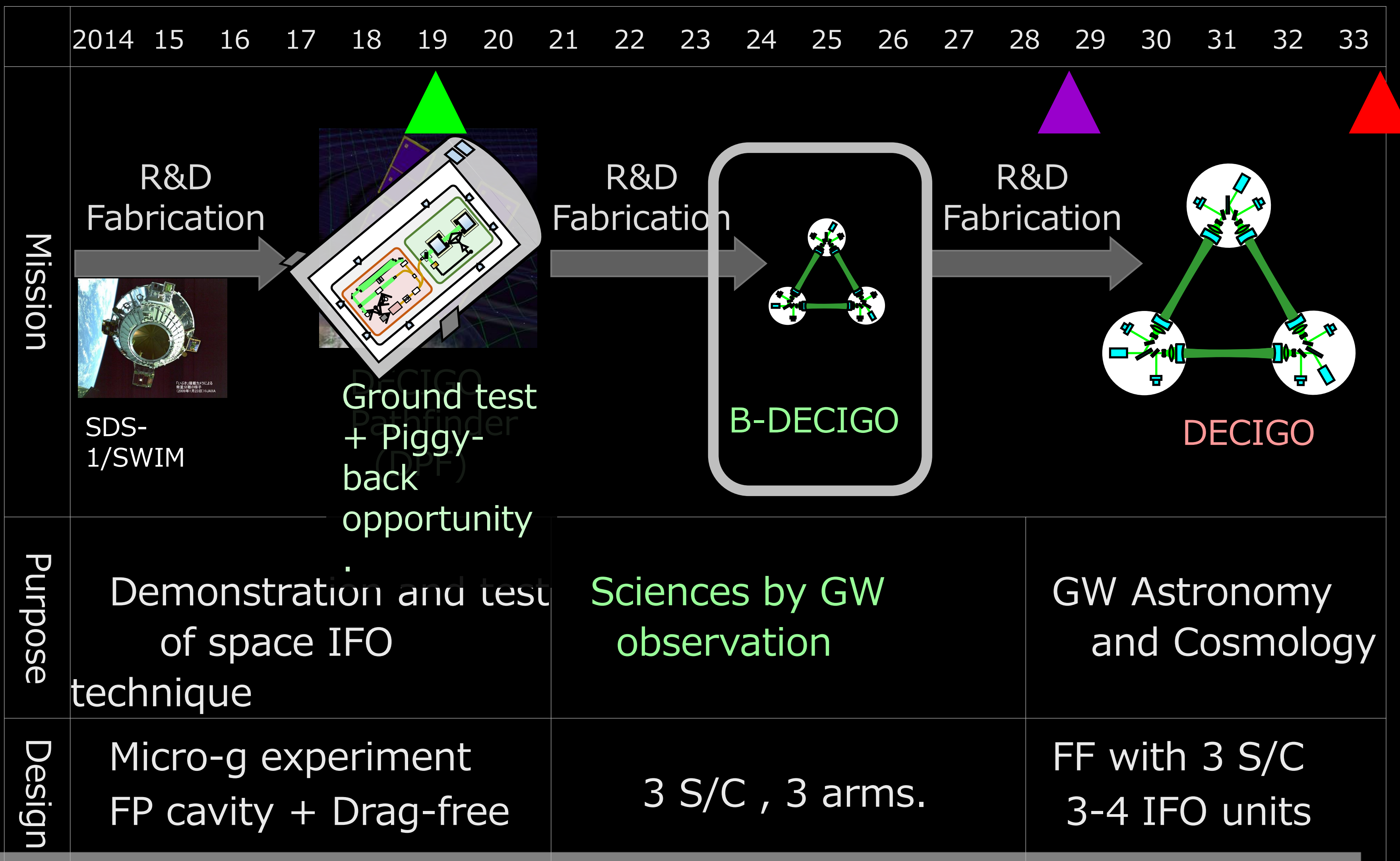
B-DECIGO



宇宙の
加速膨張
形成
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

Updated Roadmap for DECIGO

Figure: S.Kawamura



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 : $2 \times 10^{-23}\ \mathrm{Hz}^{-1/2}$ at 0.1Hz.

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

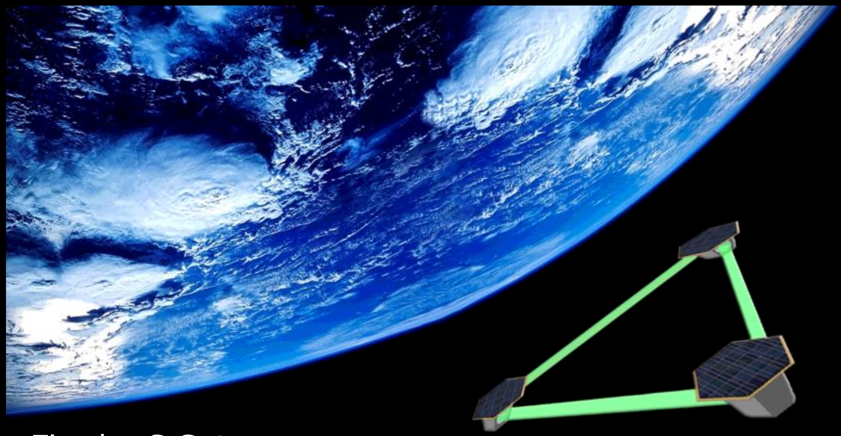


Fig. by S.Sato

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

B-DECIGO Design (Preliminary)

Mission requirement:

Strain sensitivity 2×10^{-23} $Hz^{-1/2}$ (0.1Hz)

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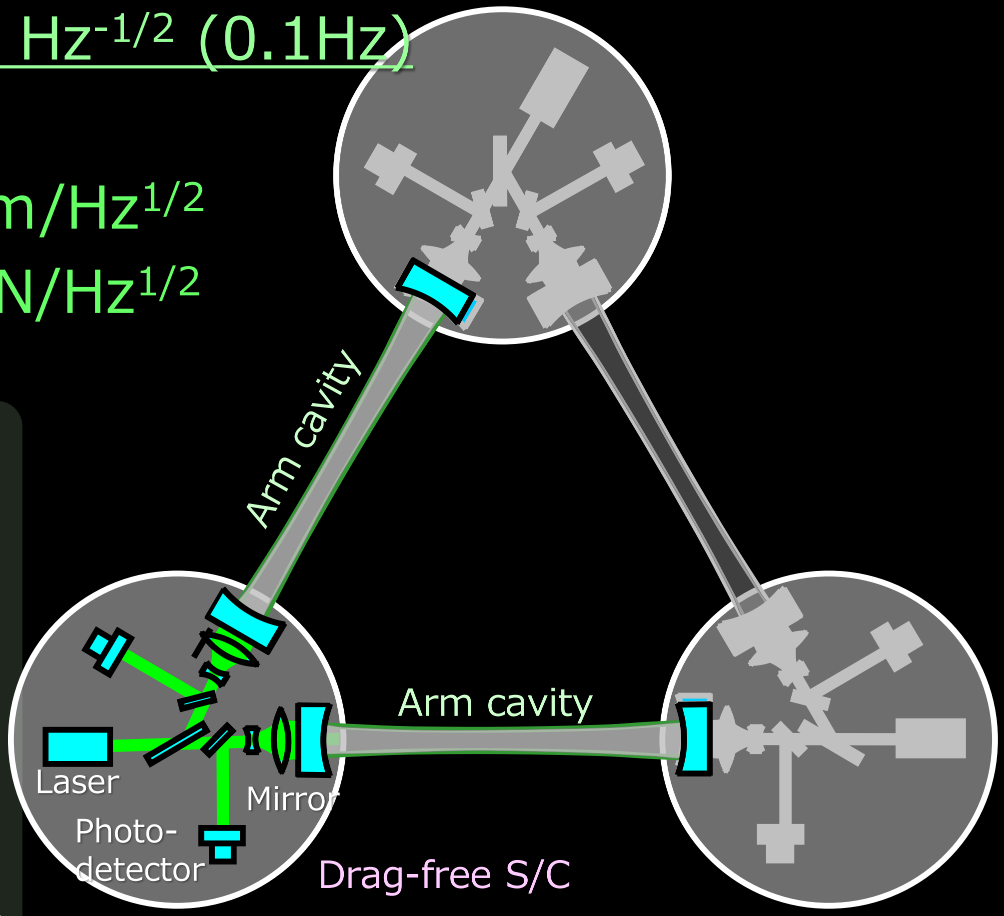
* Disp. noise : 2×10^{-18} $m/Hz^{1/2}$
* Force noise : 1×10^{-16} $N/Hz^{1/2}$

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

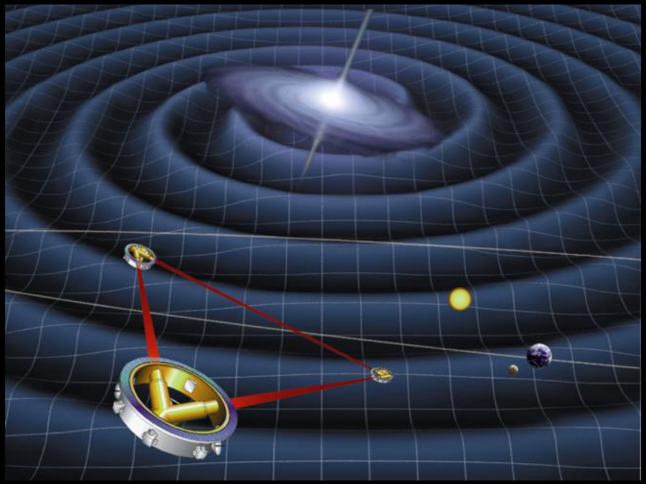
Orbit : TBD
(Record-disk around the Earth?)



Space GW antenna

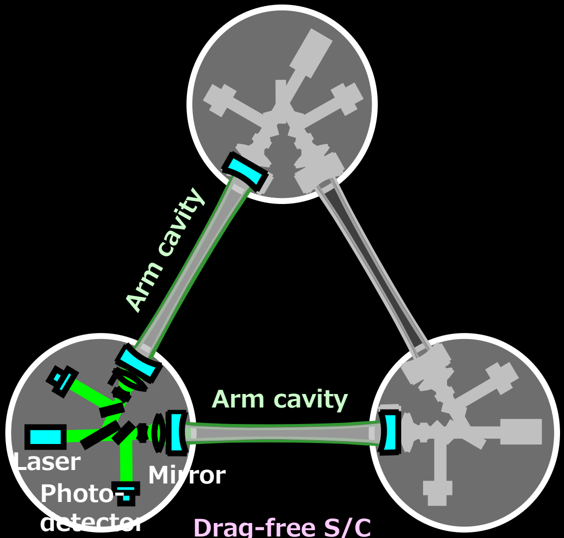
LISA
(Laser Interferometer Space Antenna)

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

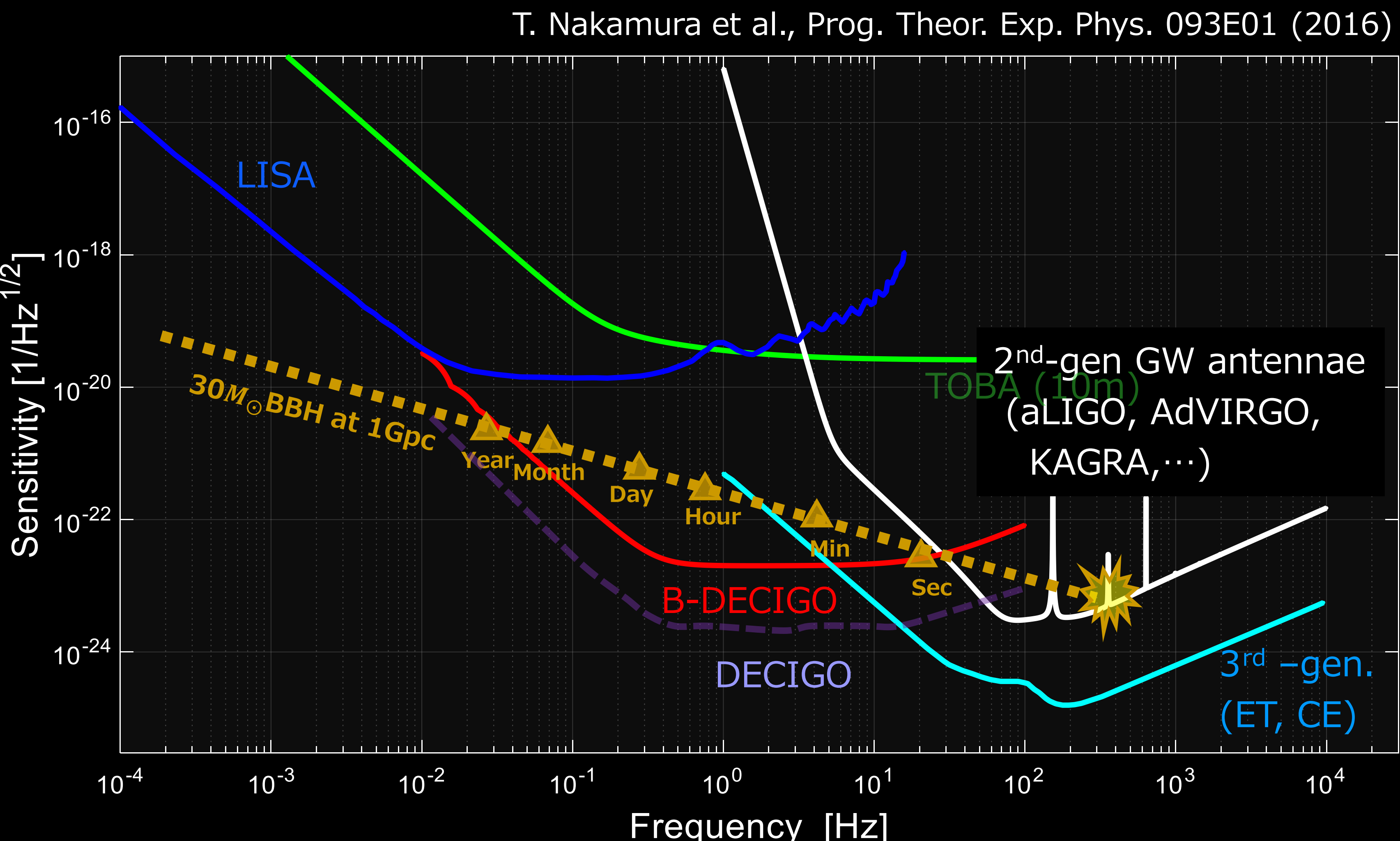


B-DECIGO
(Deci-hertz Interferometer Gravitational Wave Observatory)

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



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.

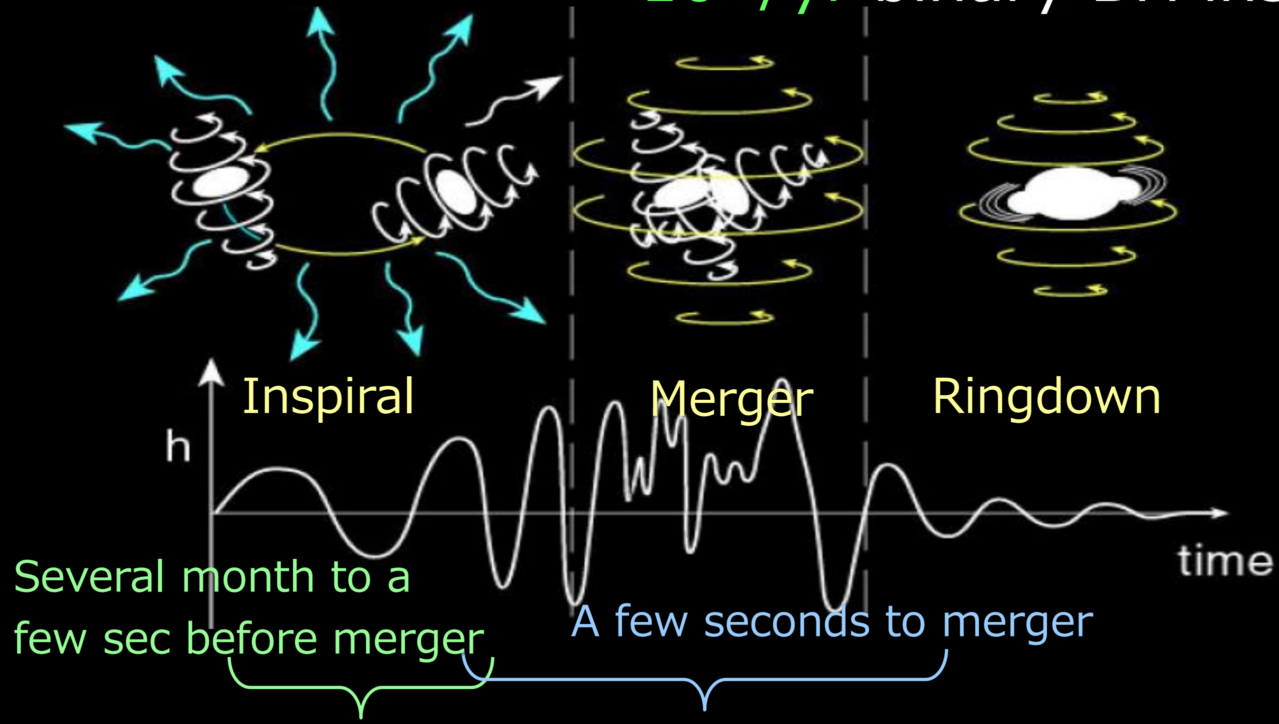
(3) Foreground understandings for DECIGO [Cosmology]

- 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.

$\sim 10^5$ /yr binary BH inspirals.



Low.-freq. → B-DECIGO Mass, Position, Time,···	High-freq. → Ground based Astrophysics, EoS of NS

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.

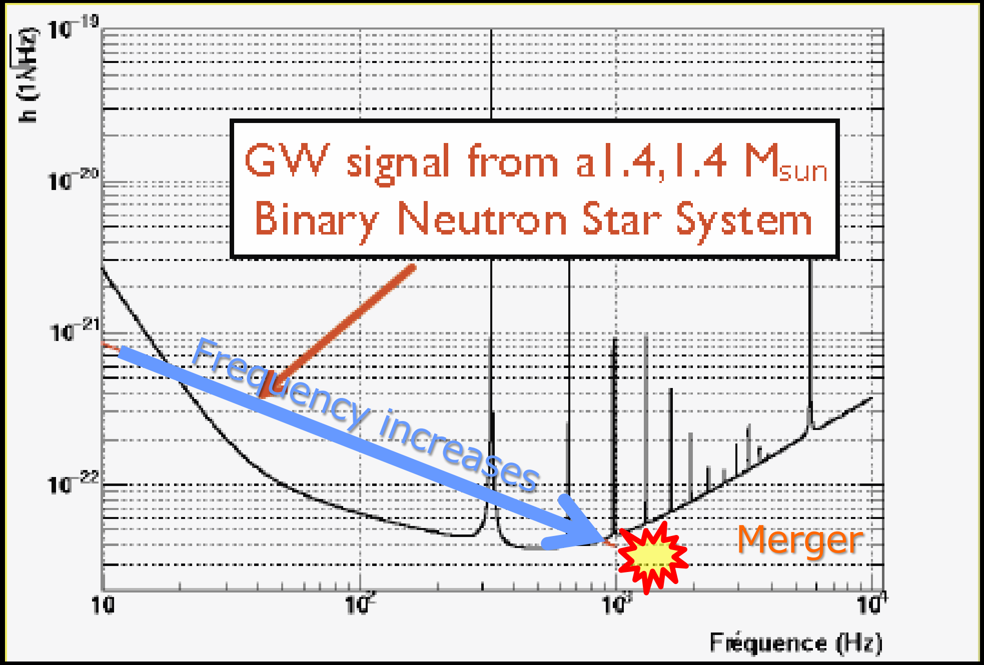
- Some basics in observation of compact binaries
    1. Observable range
    2. Number of cycles, Time to merger
    3. Parameter estimation

Observable Distance

- Signal waveform and amplitude + Detector noise
  → Signal-to-Noise ratio (SNR) can be estimated.

$$\left(\frac{S}{N}\right)^2_{max} = \int_0^\infty \frac{|\tilde{h}(f)|^2}{S_n(f)} df$$

(Matched filtering is assumed.)



Example of BNS merger (by Marion 2011)

Signal amplitude is inverse-proportional to the source distance.

⇩

Observable range is Estimated for given SNR threshold.

Post-Newtonian Approximation

- Chirp waveform by analytical calculation : Order expansion by (v/c).

Restricted Post-Newtonian Approximation (Blanchet+ 1995)

$$h_+(t) = \frac{2\mathcal{M}_\mathrm{c}}{D_\mathrm{L}}[\pi \mathcal{M}_\mathrm{c} f(t)]^{2/3}(1+\cos^2\iota)\cos\Phi(t)$$

$$h_\times(t) = \frac{2\mathcal{M}_\mathrm{c}}{D_\mathrm{L}}[\pi \mathcal{M}_\mathrm{c} f(t)]^{2/3}(-2\cos\iota)\ \sin\Phi(t)$$

$$\frac{df}{dt} = \frac{96}{5}\pi^{8/3}\mathcal{M}_\mathrm{c} f^{11/3}\left[1 - \left(\frac{743}{336}+\frac{11}{4}\eta\right)(\pi\mathcal{M}_\mathrm{c} f)^{2/3} + (4\pi)(\pi\mathcal{M}_\mathrm{c} f) + \left(\frac{34103}{18144}+\frac{13661}{2016}\eta+\frac{59}{18}\eta^2\right)(\pi\mathcal{M}_\mathrm{c} f)^{4/3} + (2.5\mathrm{PN}) + \cdots\right]$$

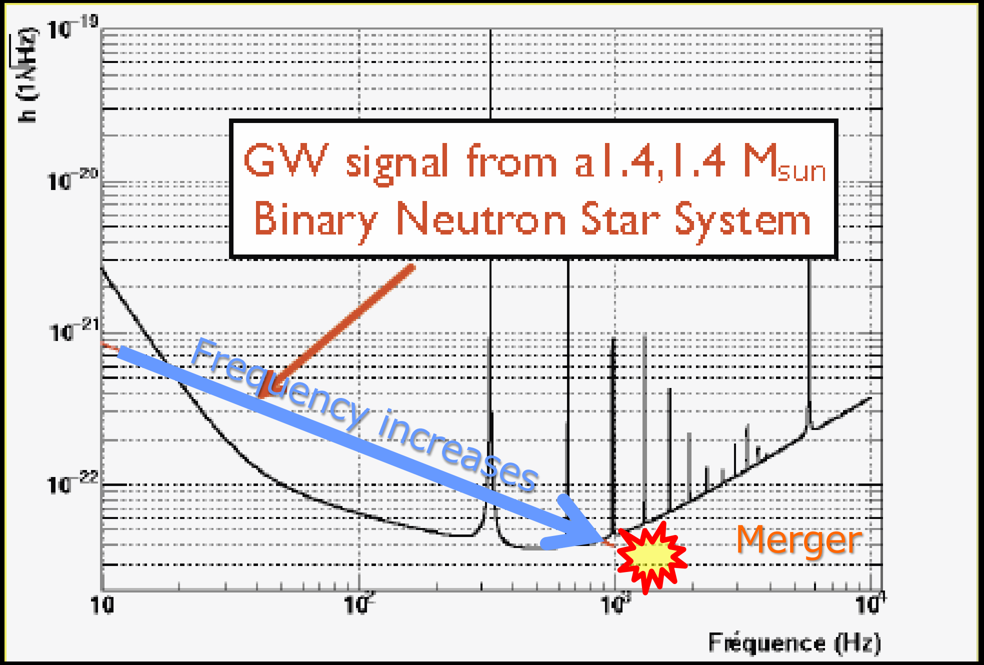
Chirp mass	$\mathcal{M}_\mathrm{c} = (m_1 \cdot m_2)^{3/5}/(m_1+m_2)^{1/5}$
Reduced mass ratio	$\eta = \mu/M = (m_1 \cdot m_2)/(m_1+m_2)^2$
Luminosity distance	D_L
Inclination angle	ι
Phase	$\Phi(t) = 2\pi\int f(t')dt' = 2\pi\int \frac{f}{(df/dt)}df$

Spectrum of Chirp wave

- Fourier transformation $\tilde{h}_+(f) \equiv \int_{-\infty}^{\infty} e^{2\pi i f t}\, h(t)\, dt$

$$\tilde{h}_+(f) = \sqrt{\frac{5}{96}}\,\frac{\pi^{-2/3}\mathcal{M}_{\mathrm{c}}^{5/6}}{D_{\mathrm{L}}}\,\frac{(1+\cos^2\iota)}{2}\, f^{-7/6}\, e^{i\Psi(f)}$$

$$\Psi(f) = 2\pi f t_{\mathrm{c}} - \Phi_{\mathrm{c}} - \frac{\pi}{4} + \frac{3}{128}(\pi\mathcal{M}_{\mathrm{c}} f)^{-5/3} + \cdots$$



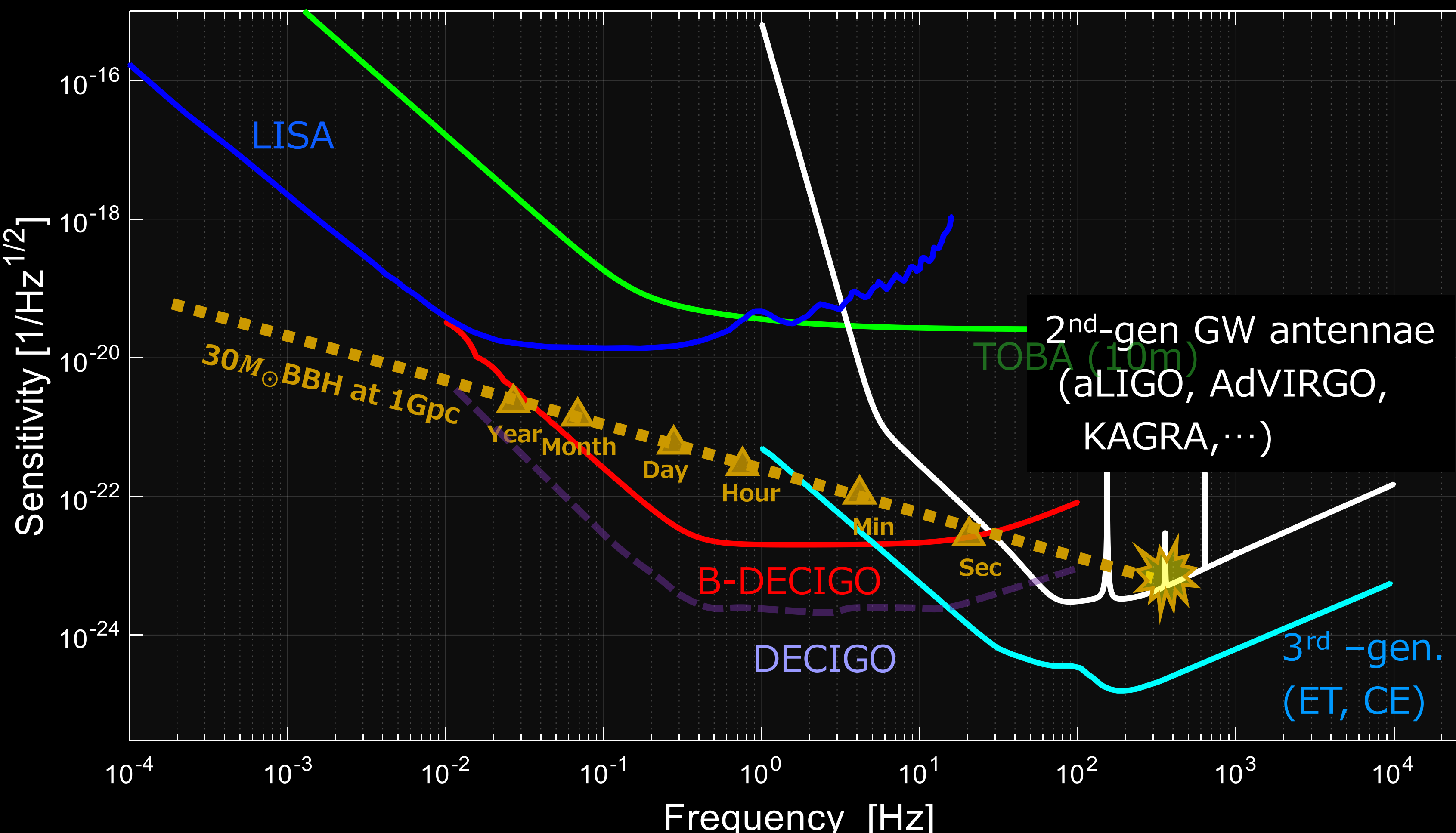
Example of BNS merger (by Marion 2011)

Fourier amplitude

$\propto (f)^{-7/6}$

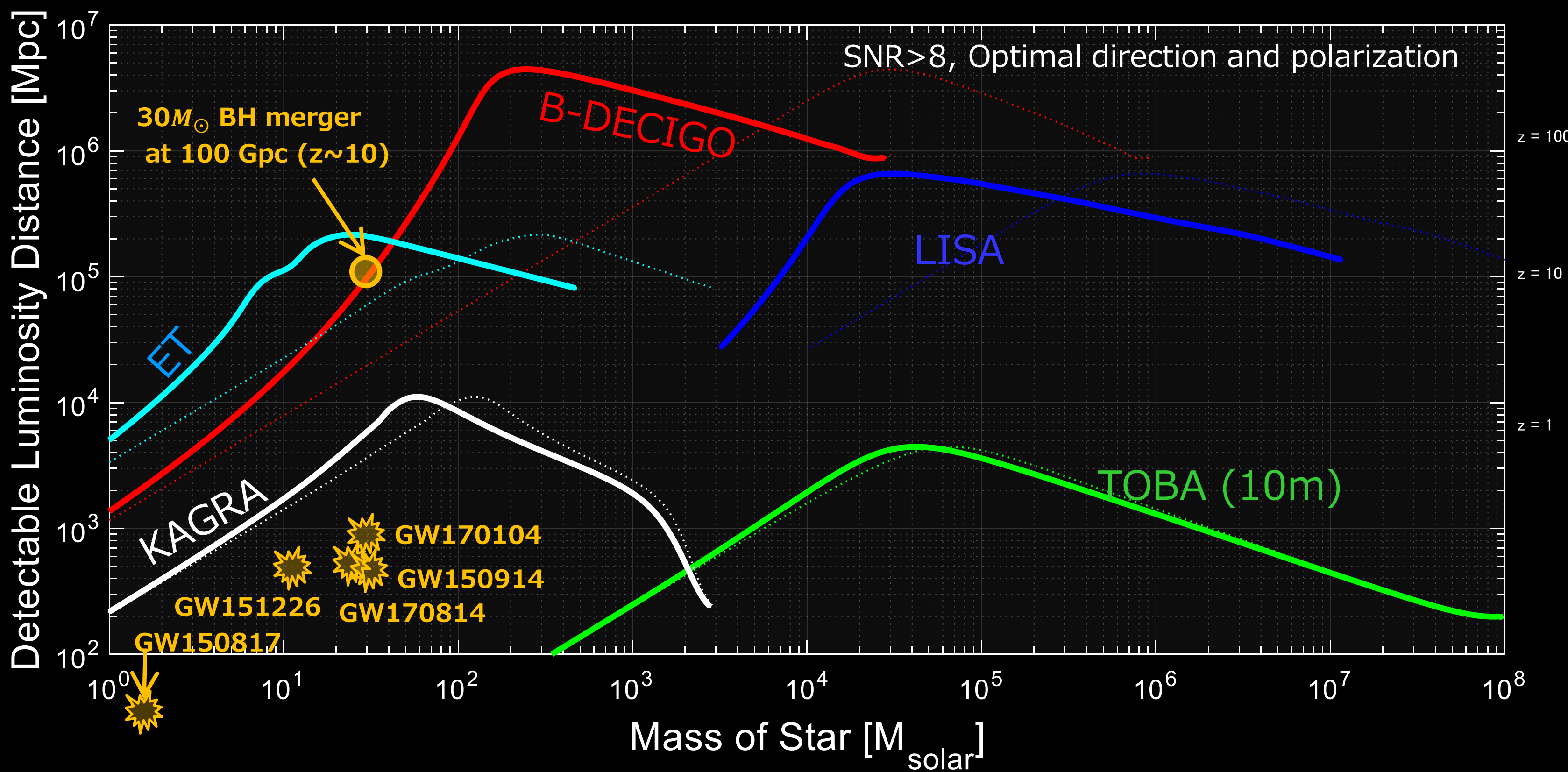
Sensitivity Curves

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



Observable Range

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



- Some Basics in observation of compact binaries
    1. Observable range
    2. Number of cycles, Time to merger
    3. Parameter estimation

Quadruple Formula

- GW Amplitude: $h_{ij}^{\mathrm{TT}}(t, \boldsymbol{x}) = \frac{2\mathrm{G}}{c^4\, r}\, \ddot{Q}_{ij}^{TT}(t - \boldsymbol{r}/c)$

(Quadrupole Moment:

$$Q_{ij}^{\mathrm{TT}} = \int dV\, \rho\, (x^i x^j - \frac{1}{3} r^2 \delta_{ij})$$
)

※ $\ddot{Q}_{ij}^{TT}$ has a dimension of Energy

$$\ddot{Q}_{ij}^{TT} \sim \frac{(\text{Mass}) \times (\text{System Scale})^2}{(\text{System Transit Time})^2}$$

$$\sim (\text{Quadrupole Kinetic Energy})$$

Quadruple Formula

- Energy Radiation Rate (luminosity):

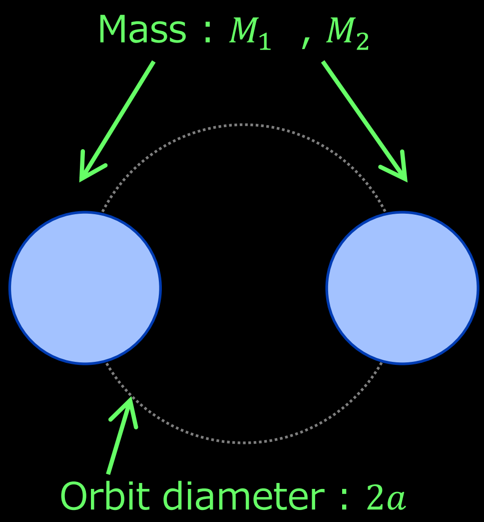
$$\frac{dE_{\mathrm{GW}}}{dt} = \frac{c^3 r^2}{32\pi G} \int d\Omega \left\langle \dot{h}_{ij}^{TT} \dot{h}_{ij}^{TT} \right\rangle = \frac{G}{5c^5} \left\langle \dddot{Q}_{ij} \dddot{Q}_{ij} \right\rangle$$

※ $\dddot{Q}_{ij}$ and $\frac{c^5}{G}$ has a dimension of energy rate

$$L_0 \equiv \frac{c^5}{G} = 2 \times 10^5 \ \ M_{\odot} c^2/s$$

⇨ Soler-mass scale and near-light-speed motion are required for significant GW radiation.

GW from a Compact Binary



- GWs from a compact binary

  * Amplitude: $h = \frac{4G}{c^4}\frac{\mu a^2 \omega_b^2}{r}$

  * Energy rate: $\frac{dE_{\rm GW}}{dt} = \frac{32G}{5c^5}\mu^2 a^4 \omega_b^6$

Total mass: $M = m_1 + m_2$

Reduced mass ratio: $\mu = \frac{m_1 m_2}{M}$

Radius of the orbit: a

Orbital period: P_b

(Rotation frequency: $f_{\rm b} = 1/P_b$, $\omega_{\rm b} = 2\pi f_b$)

GW frequency : $f_{\rm GW} = 2 f_b$

GW from a Compact Binary

- Kepler's Law: $GM = \omega_b^2 a^3$

→ $h = \frac{4G^{5/3}}{c^4} \frac{M_c^{5/3} \omega_b^{2/3}}{r}$, $\frac{dE_{\mathrm{GW}}}{dt} = \frac{32G^{7/3}}{5c^5} M_c^{10/3} \omega_b^{10/3}$

Here, Chirp mass : $M_c \equiv \mu^{3/5} M^{2/5}$

$(= q^{3/5}/M \ , \ q = \mu/M)$

※ In case of equal mass ($m_1 = m_2 = m$),
chirp mass is $M_c \simeq 2^{-1/5}\, m \simeq 0.87\, m$

Chirp Waveform

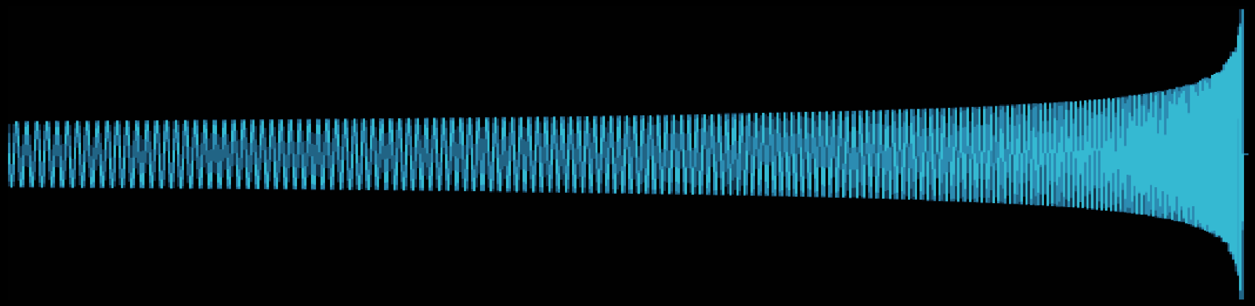
・Conservation of the orbital energy
(kinetic energy + potential energy by gravity)

$$E = -GM\mu/2a \quad \Rightarrow \quad \frac{dE}{dt} = \frac{GM\mu}{2a^2}\frac{da}{dt}$$

・GW radiation → Loss of orbital energy

⇒ Orbital decay: $\frac{da}{dt} = -\frac{64G^3}{5c^5}\frac{\mu M^2}{a^3}$

Increase in frequency: $\frac{df_b}{dt} = \frac{48G^{5/3}}{5\pi c^5} M_c^{5/3}\ \omega_b^{11/3}$



Chirp Waveform

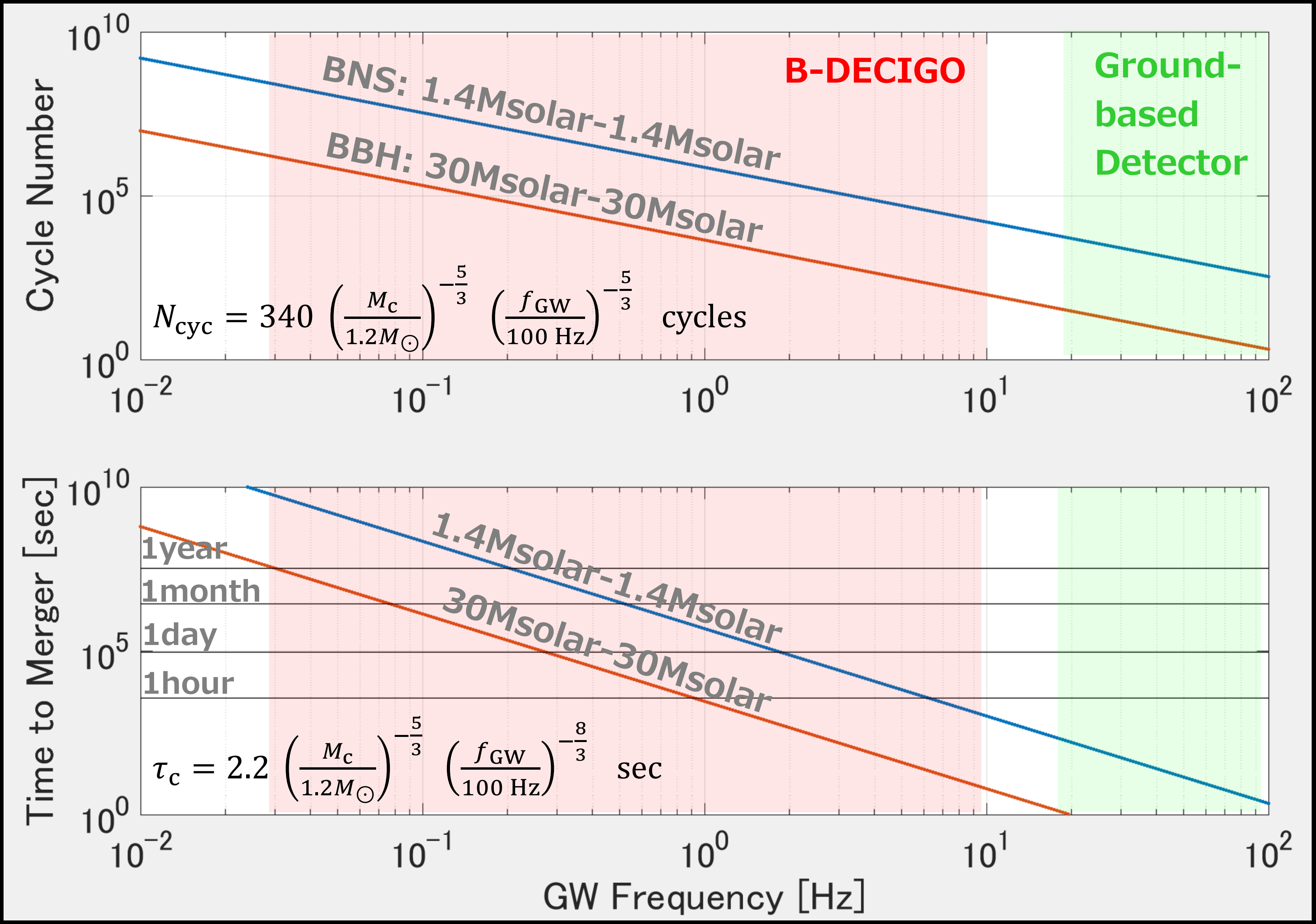
- Cycle number (until ISCO):

$$N_{\mathrm{cyc}} = 340 \left(\frac{M_{\mathrm{c}}}{1.2 M_{\odot}}\right)^{-\frac{5}{3}} \left(\frac{f_{\mathrm{GW}}}{100\ \mathrm{Hz}}\right)^{-\frac{5}{3}} \ \mathrm{cycles}$$

- Time to merger (until ISCO):

$$\tau_{\mathrm{c}} = 2.2 \left(\frac{M_{\mathrm{c}}}{1.2 M_{\odot}}\right)^{-\frac{5}{3}} \left(\frac{f_{\mathrm{GW}}}{100\ \mathrm{Hz}}\right)^{-\frac{8}{3}} \ \mathrm{sec}$$

Obs. Freq. vs Time to Merger



- Some Basics in observation of compact binaries
  1. Observable range
  2. Number of cycles, Time to merger
  3. Parameter estimation

Parameter for Chirp waveform

- Source parameter : 5

  Chirp mass $\mathcal{M}_c = (m_1 \cdot m_2)^{3/5}/(m_1 + m_2)^{1/5}$

  Reduced mass ratio $\eta = \mu/M = (m_1 \cdot m_2)/(m_1 + m_2)^2$

  Coalescence time t_c

  Spins χ_1, χ_2

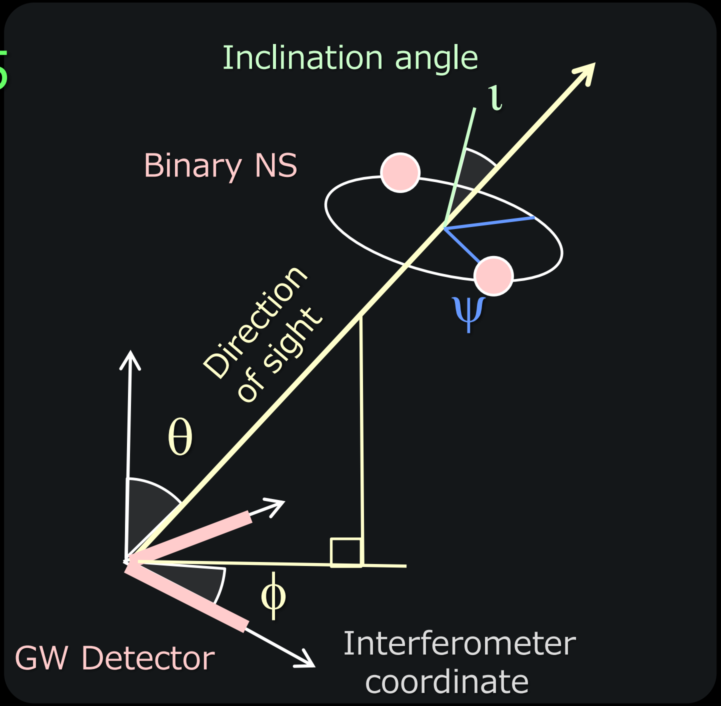
- Source and detector geometry: 5

  Luminosity distance D_L

  Inclination angle ι

  Source sky position $\theta, \ \phi$

  Polarization angle Ψ



- Signal timing : 2

  Initial phase ϕ_0

  Initial frequency f_0

Parameter Estimation Accuracy

PTEP

Prog. Theor. Exp. Phys. **2015**, 00000 (18 pages)
DOI: 10.1093/ptep/0000000000

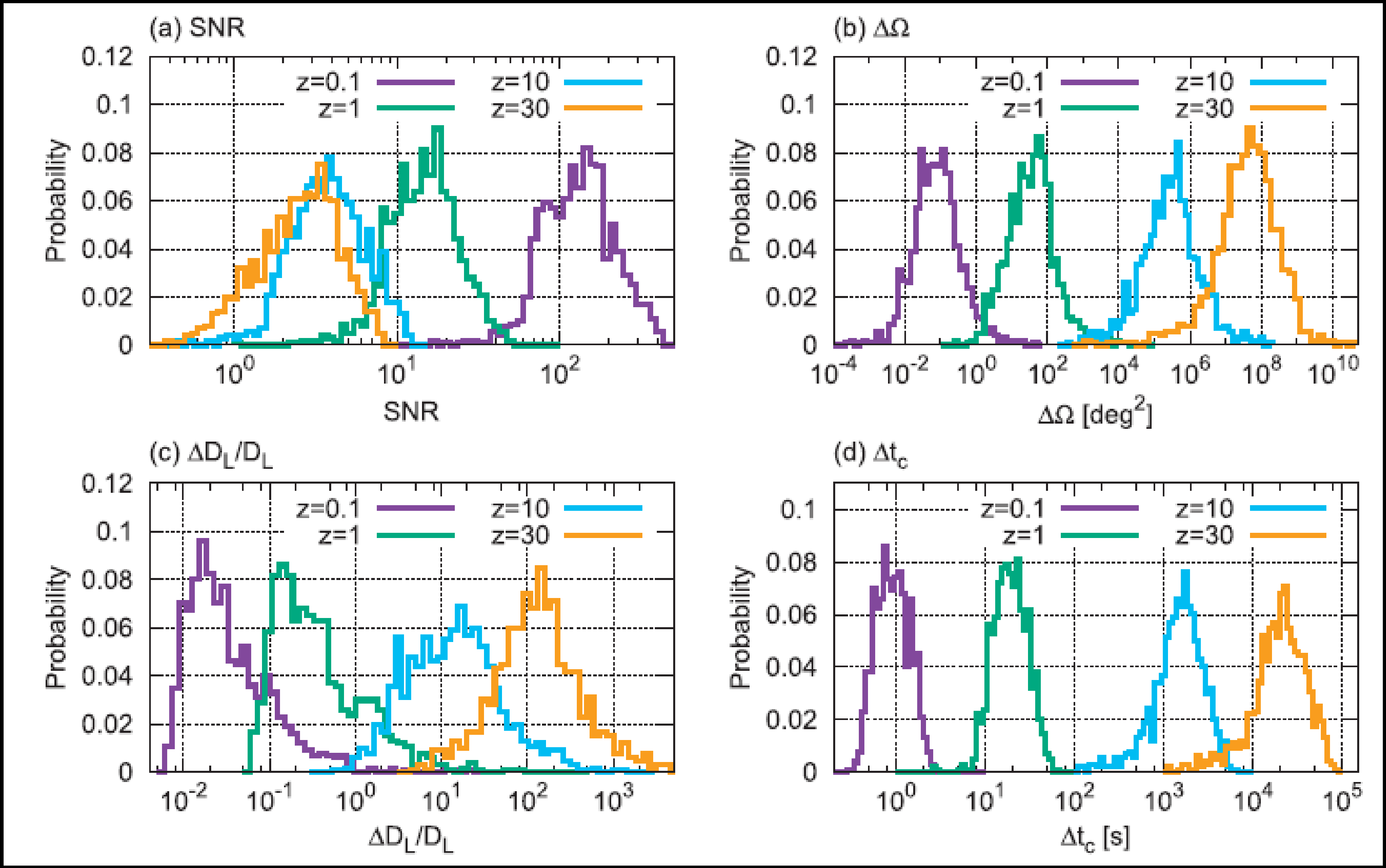
Pre-DECIGO can get the smoking gun to decide the astrophysical or cosmological origin of GW150914-like binary black holes

Takashi Nakamura[1], Masaki Ando[2,3,5], Tomoya Kinugawa[4], Hiroyuki Nakano[1], Kazunari Eda[2,5], Shuichi Sato[6], Mitsuru Musha[7], Tomotada Akutsu[3], Takahiro Tanaka[1,8], Naoki Seto[1], Nobuyuki Kanda[9], Yousuke Itoh[5]

[1] *Department of Physics, Kyoto University, Kyoto 606-8502, Japan*
[2] *Department of Physics, The University of Tokyo, Tokyo 113-0033, Japan*
[3] *National Astronomical Observatory of Japan, Tokyo 181-8588, Japan*
[4] *Institute for Cosmic Ray Research, The University of Tokyo, Chiba 277-8582, Japan*
[5] *Research Center for the Early Universe (RESCEU), The University of Tokyo, Tokyo 113-0033, Japan*
[6] *Department of Advanced Sciences, Hosei University, Tokyo 184-8584 Japan*
[7] *Institute for Laser Science, University of Electro-Communications, Tokyo 182-8585, Japan*
[8] *Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan*
[9] *Department of Physics, Osaka City University, Osaka 558-8585, Japan*

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

Parameter Estimation Accuracy



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

Parameter Estimation Accuracy

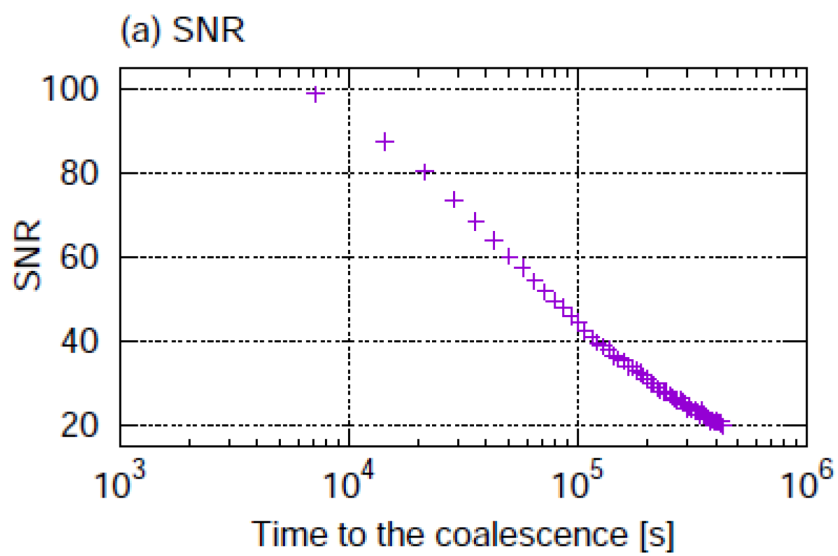
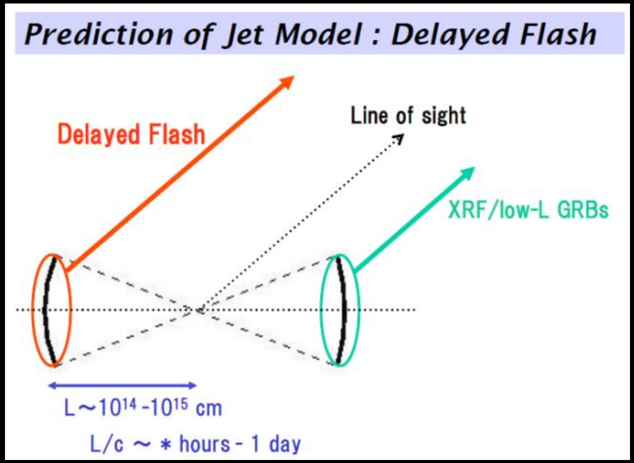


Fig. 11 Time evolution for (a) SNR and (b) angular resolution of GWs from $30M_\odot$ equal-mass BH binaries at the distance of $z = 0.1$. We assume $\alpha = \delta = 1.0\,\mathrm{rad}$, $\psi = 0.5\,\mathrm{rad}$, and $\cos\iota = 0.5$.

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

On-time EM Counterpart Observations

New astrophysical possibilities:
Position and time before merger
→ Enables EM observation of
BNS/GRB/Kilonova at merger.



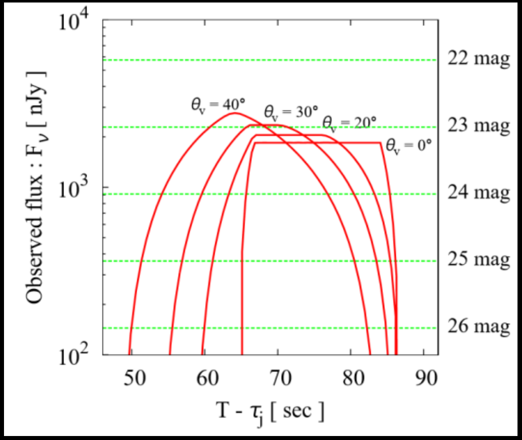
(Ex1) Light curve/Spectrum obs.
before/just after merger.

(Ex2) Delayed Flash from GRB.

Yamazaki et al. : https://arxiv.org/abs/1711.06856

(Ex3) Fast Radio Bursts from BNS
(1msec after merger).

Totani: https://arxiv.org/abs/1710.02302



山崎氏 講演資料 (2017.11.21) より
https://arxiv.org/abs/1711.06856

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.

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.

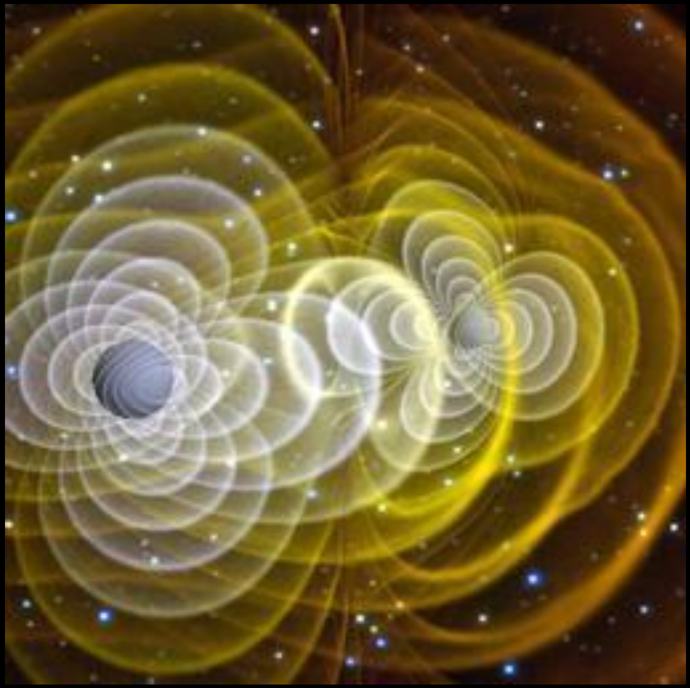
→ Formation history of SMBH and galaxies.

(3) Foreground understandings for DECIGO [Cosmology]

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

Target (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 mergers

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

Mystery of SMBH

- How supermassive BH were formed?
  - Initial massive BH formation.
  - Glow-up process (Gas accretion of Mergers?)

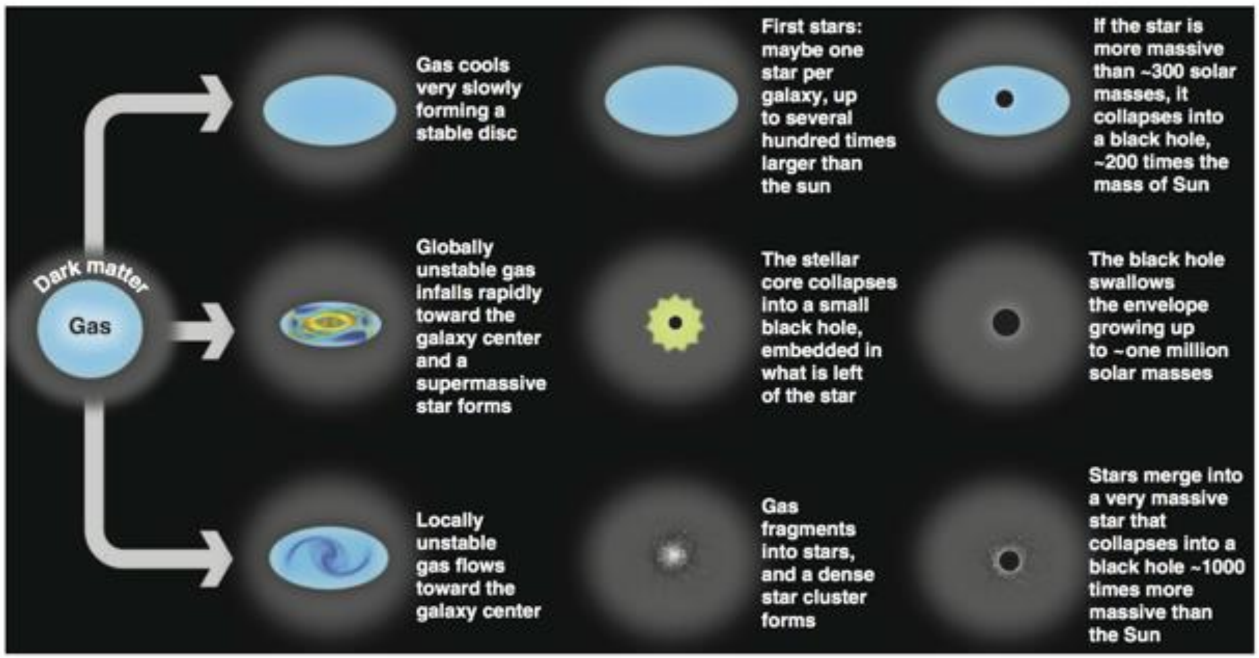
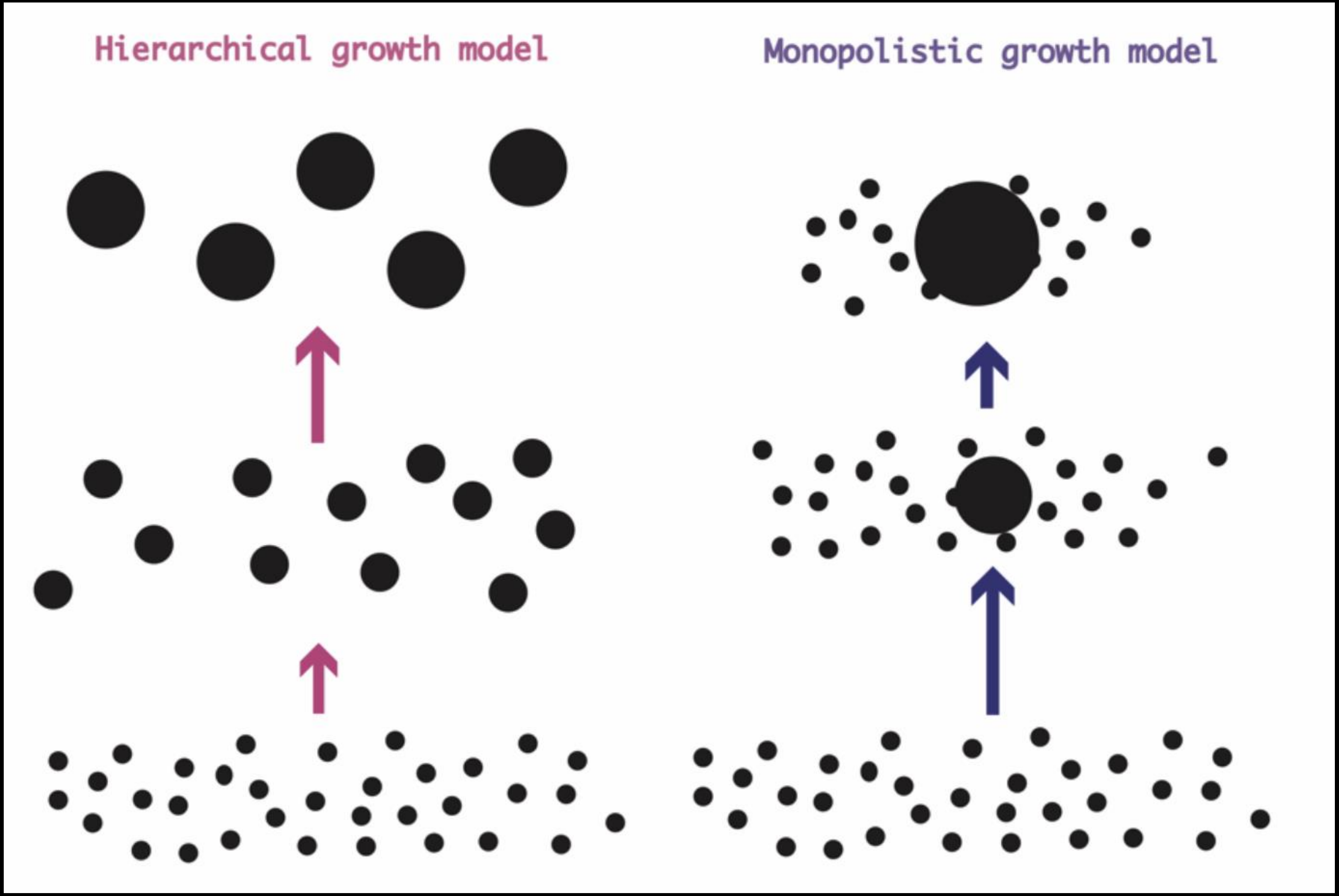


Fig. 1. Illustration showing three pathways to MBH formation that can occur in a distant galaxy (*56*). The starting point is a primeval galaxy, composed of a dark matter halo and a central condensation of gas. Most of this gas will eventually form stars and contribute to making galaxies as we know them. However, part of this gas has also gone into making a MBH, probably following one of these routes.

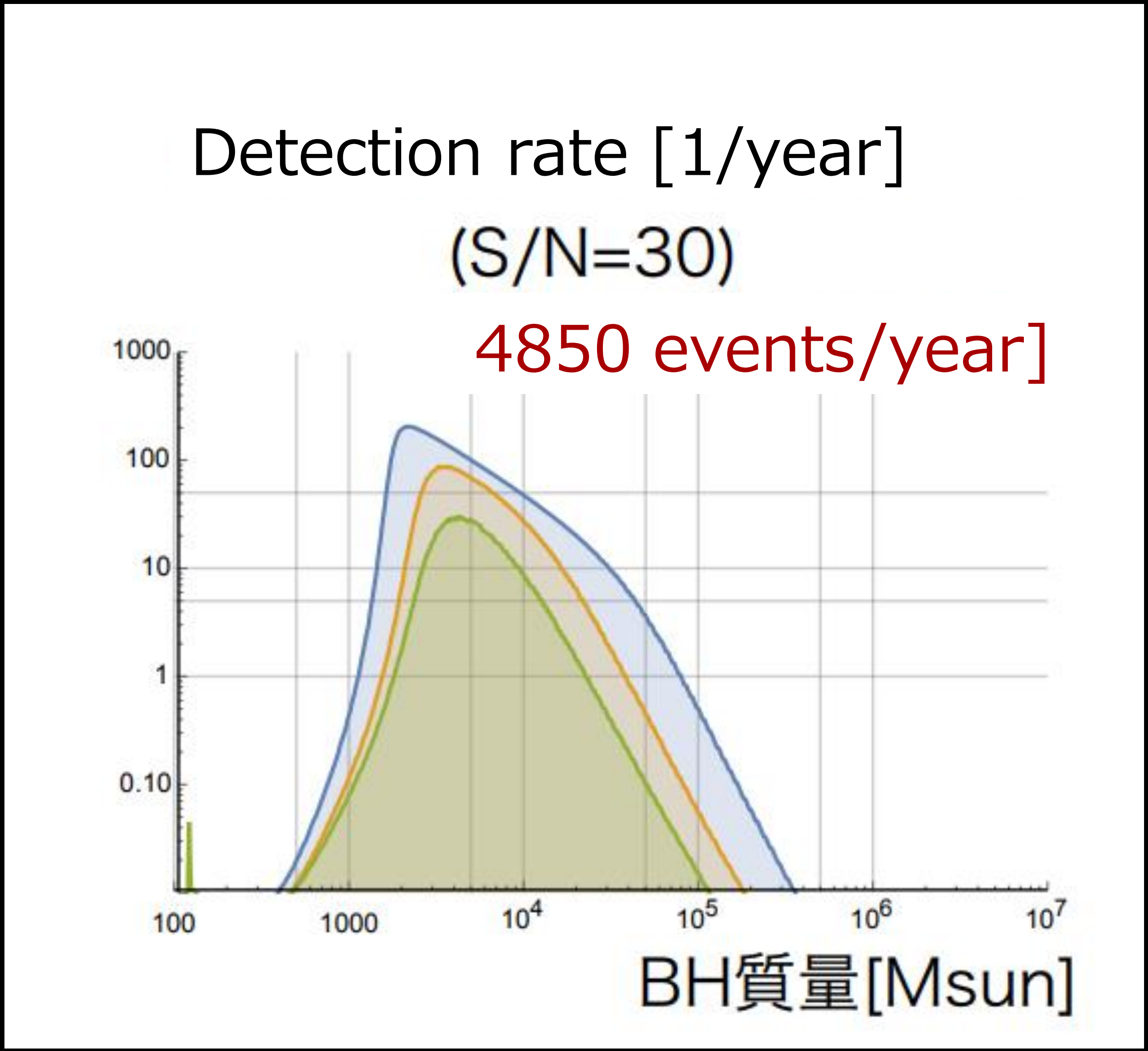
Volonteri, Science 337 (2012) 544

SMBH formation by Mergers



真貝寿明 セミナー資料 (2017年) より

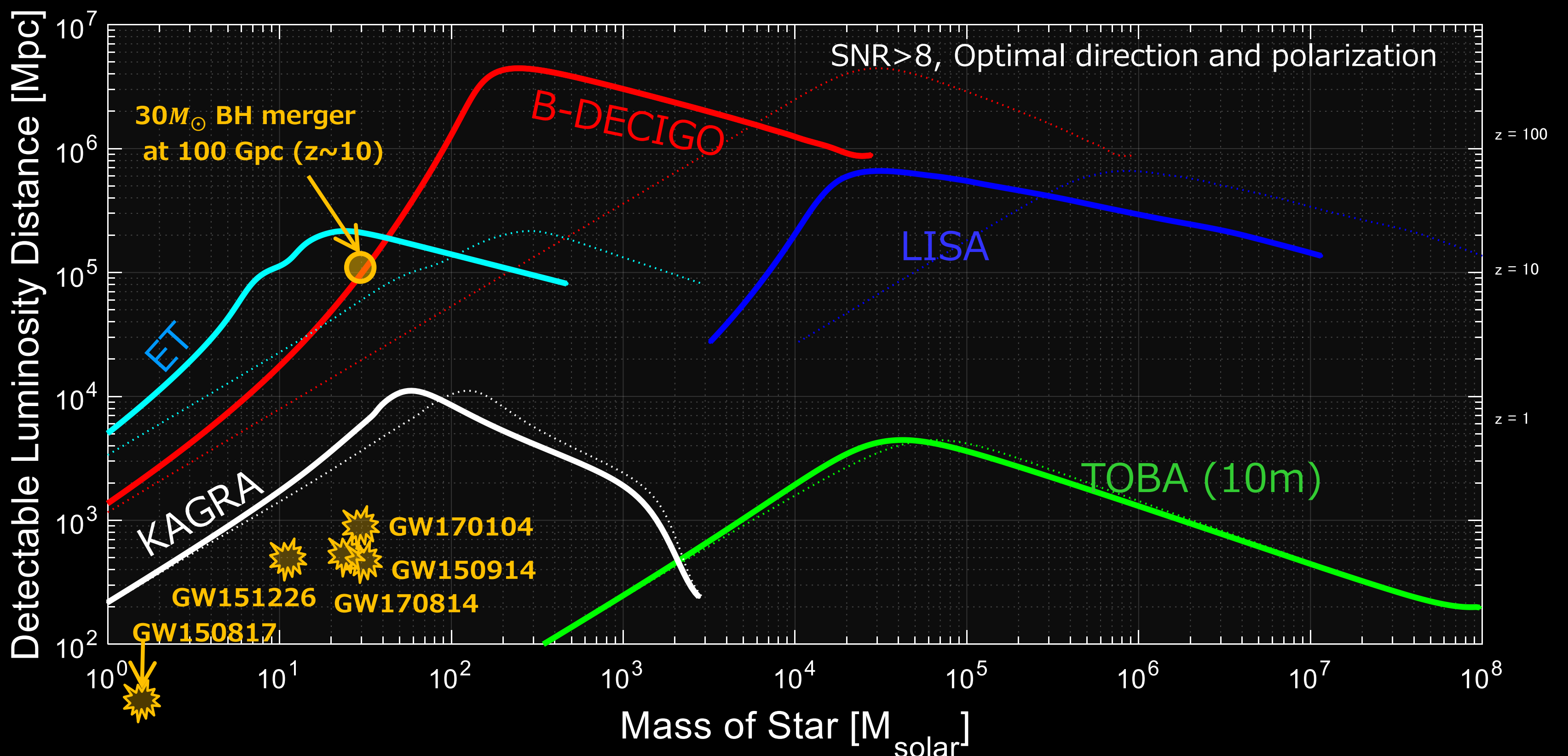
IMBH Merger Event Rate



Hisaaki Shinkai (Seminar 2017)

Observable Range

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



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.

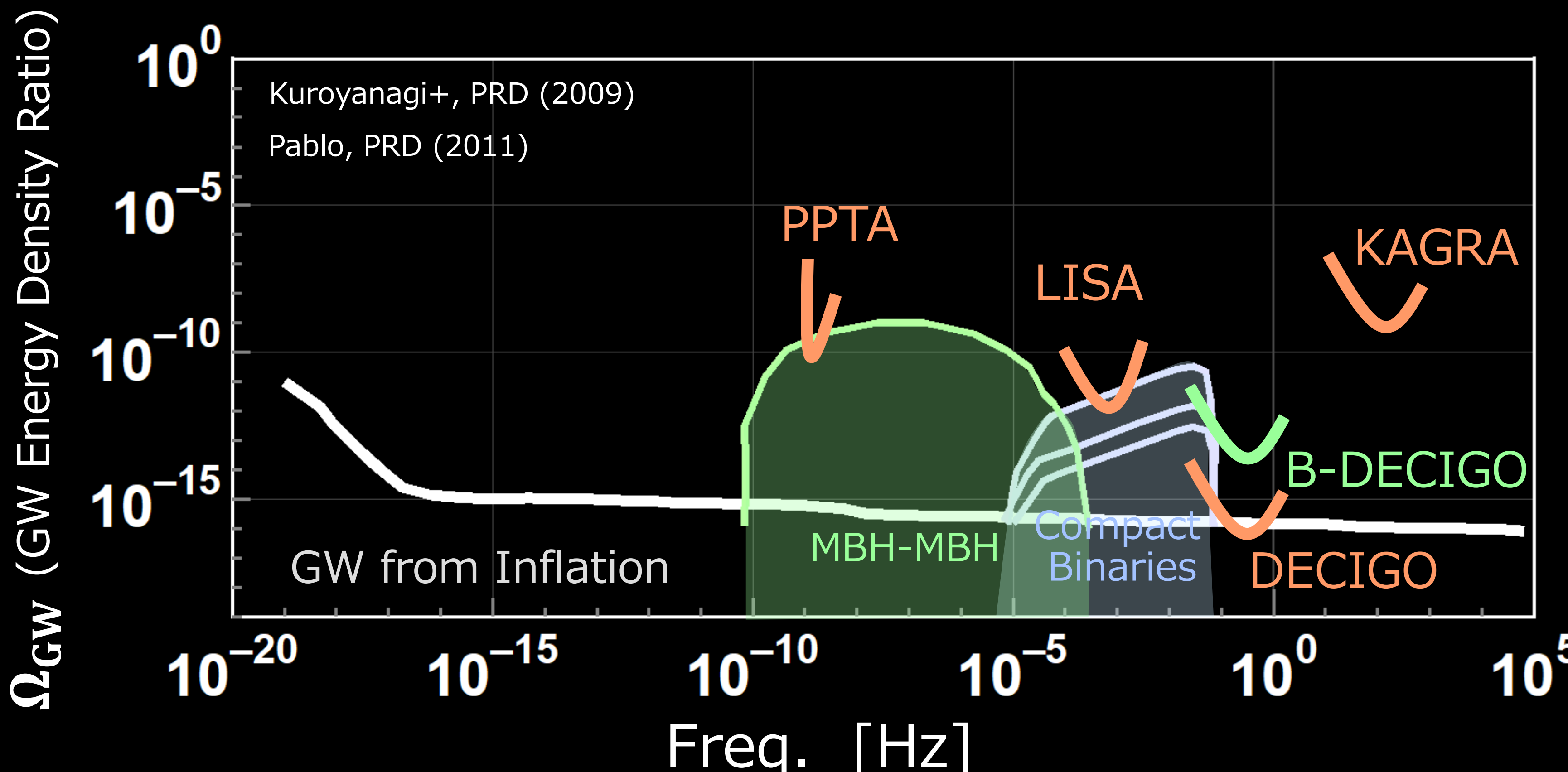
(3) Foreground understandings for DECIGO [Cosmology]

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

Target (3) : Foreground Understandings

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

⇨ Gain understandings with >100 binaries.



Binary Confusion Noise

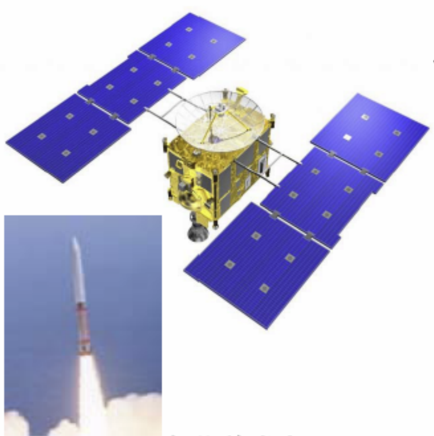
- There are lot of compact binaries in the Universe.
  → Binary confusion noise.
- In observation, frequency resolution $\Delta f \simeq 1/T_{\mathrm{obs}}$
  (1 year observation → $\Delta f \sim 3 \times 10^{-8}$ Hz).
  If multiple signal exist at the same $\sim 10\Delta f$ band,
  they cannot be distinguished.
- Since the signal sweeps up rather rapidly, signals can be separated in higher frequency band.
  → Confusion noise will be around
  * 10^{-10} – 10^{-4} Hz: from Massive BH binaries.
  * 10^{-5} – 10^{-1} Hz: from NS or WD binaries.
  However, there is no direct observation.

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。



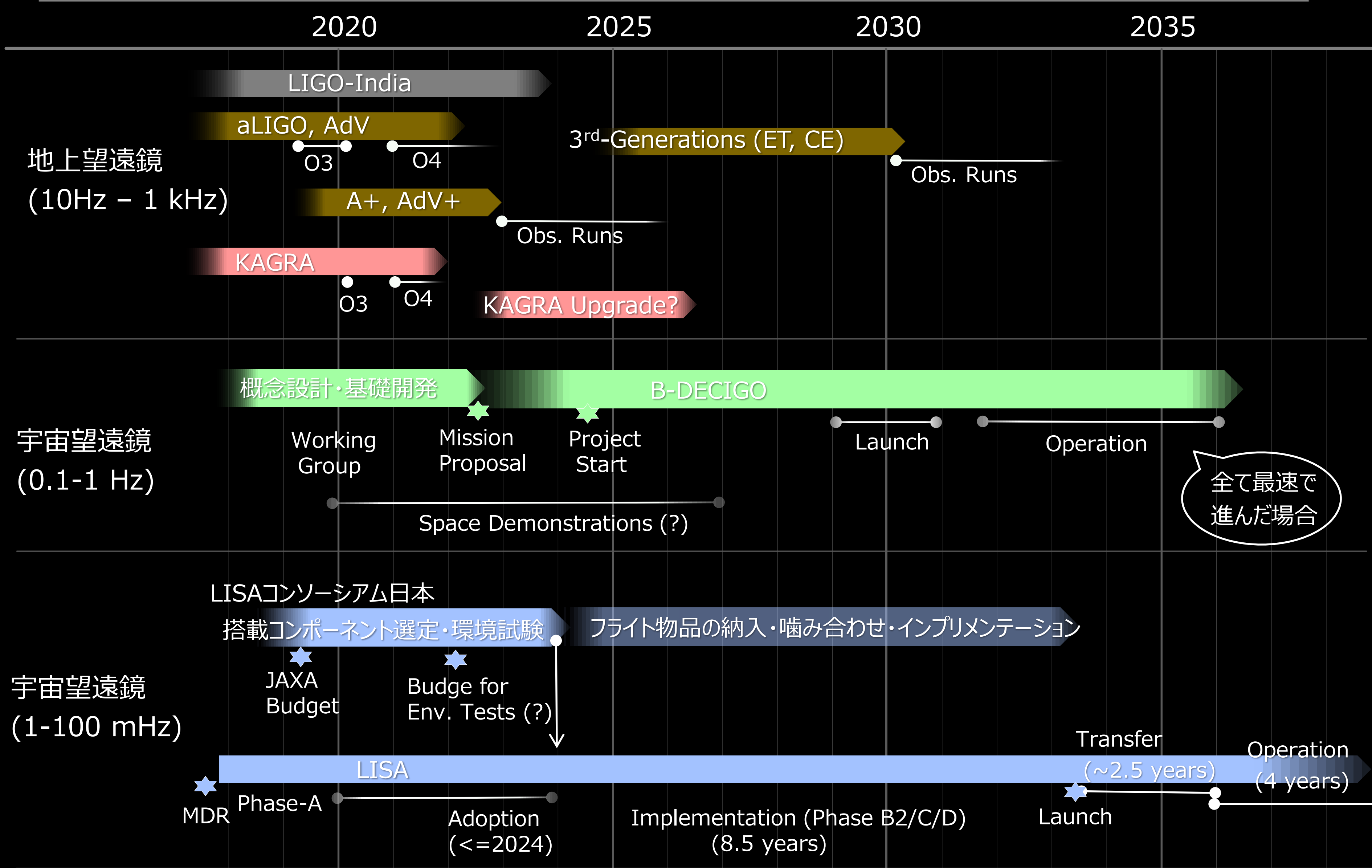
2000年代前半までの
典型的な科学衛星ミッション
M-Vロケットによる打ち上げ

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。

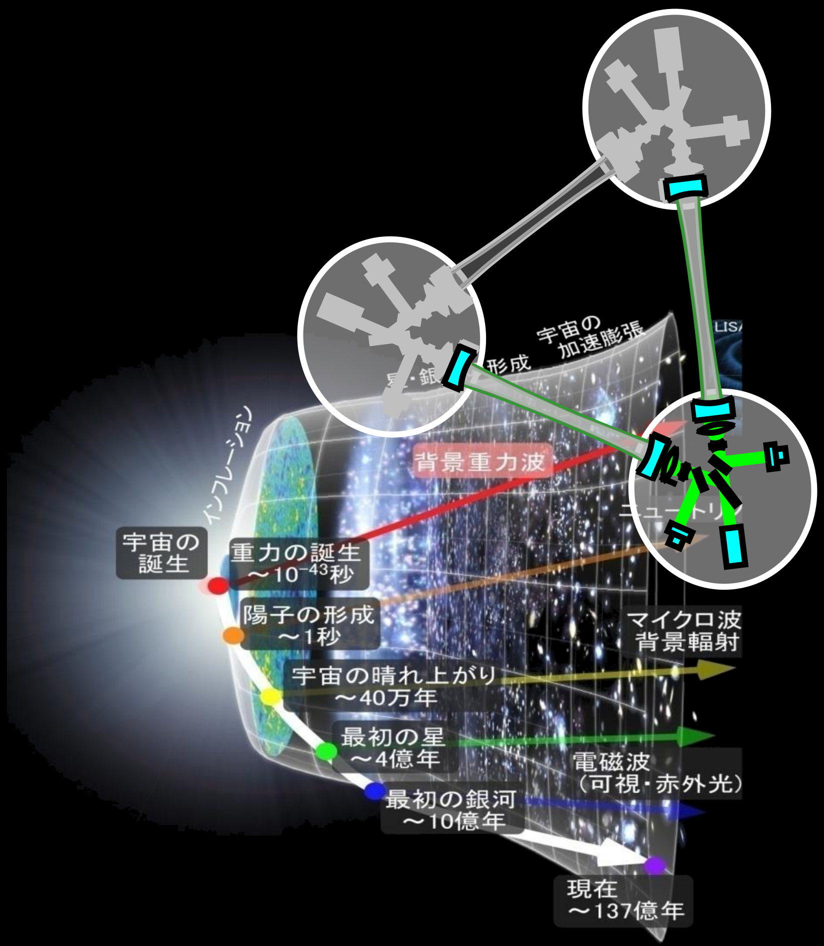
多様な小規模プロジェクト群（10億/年程度）
海外ミッションへのジュニアパートナとしての参加、海外も含めた衛星・小型ロケット・気球など飛翔機会への参加、小型飛翔機会の創出、ISSを利用した科学研究など、多様な機会を最大に活用し成果創出を最大化する。

Roadmap



2020
2025
2030
2035
LIGO-India
aLIGO, AdV
O3
O4
3rd-Generations (ET, CE)
Obs. Runs
地上望遠鏡
(10Hz – 1 kHz)
A+, AdV+
Obs. Runs
KAGRA
O3
O4
KAGRA Upgrade?
概念設計・基礎開発
B-DECIGO
Working Group
Mission Proposal
Project Start
Launch
Operation
宇宙望遠鏡
(0.1-1 Hz)
全て最速で進んだ場合
Space Demonstrations (?)
LISAコンソーシアム日本
搭載コンポーネント選定・環境試験
フライト物品の納入・噛み合わせ・インプリメンテーション
JAXA Budget
Budge for Env. Tests (?)
宇宙望遠鏡
(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

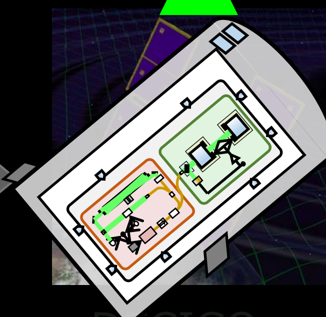
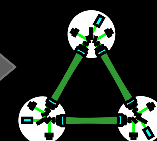
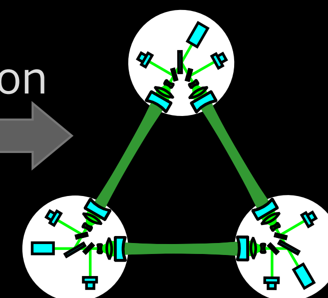
DECIGO



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

Updated Roadmap for DECIGO

Figure: S.Kawamura

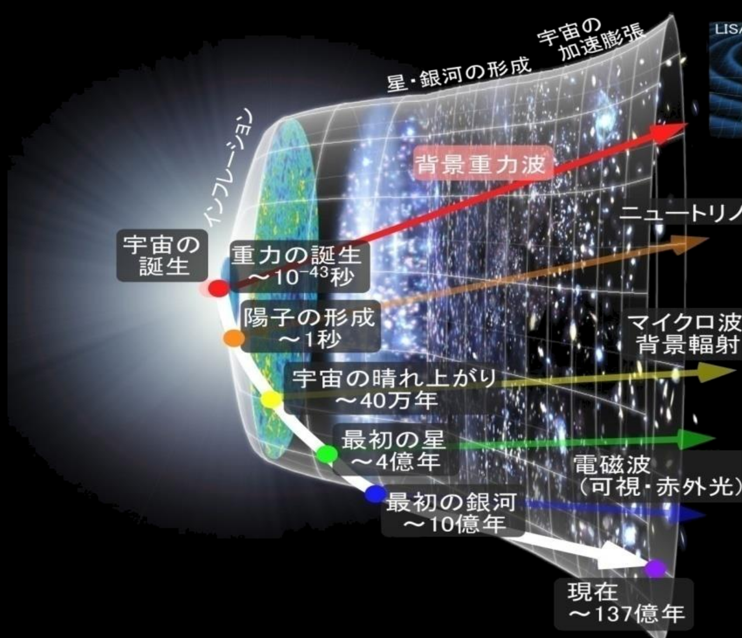
	2014 15 16 17 18 19 20	21 22 23 24 25 26 27 28	29 30 31 32 33
Mission	R&D Fabrication  SDS-1/SWIM  DECIGO Pathfinder (DPF) Ground test + Piggy-back opportunity.	R&D Fabrication  B-DECIGO	R&D Fabrication  DECIGO
Purpose	Demonstration and test of space IFO technique	Sciences by GW observation	GW Astronomy and Cosmology
Design	Micro-g experiment FP cavity + Drag-free	3 S/C , 3 arms.	FF with 3 S/C 3-4 IFO units

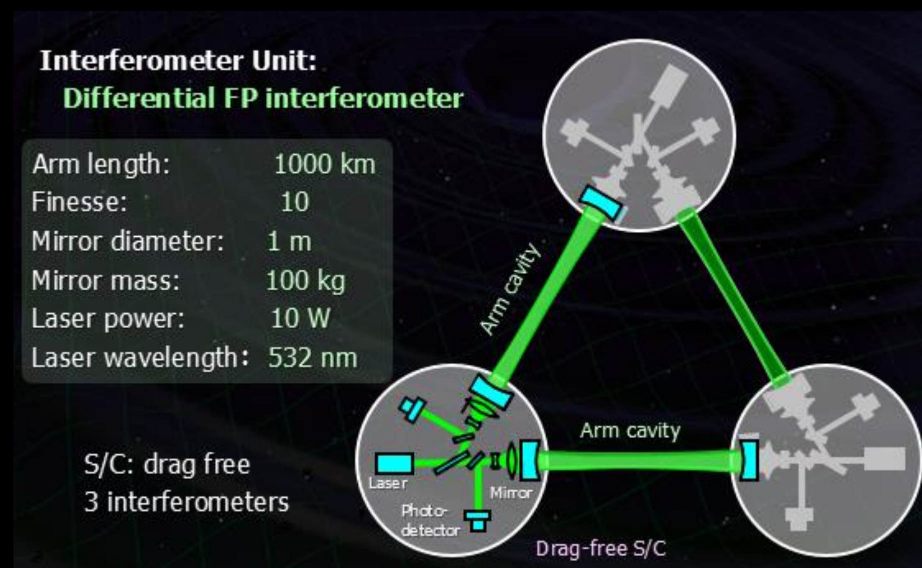
Space GW Antenna DECIGO

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.





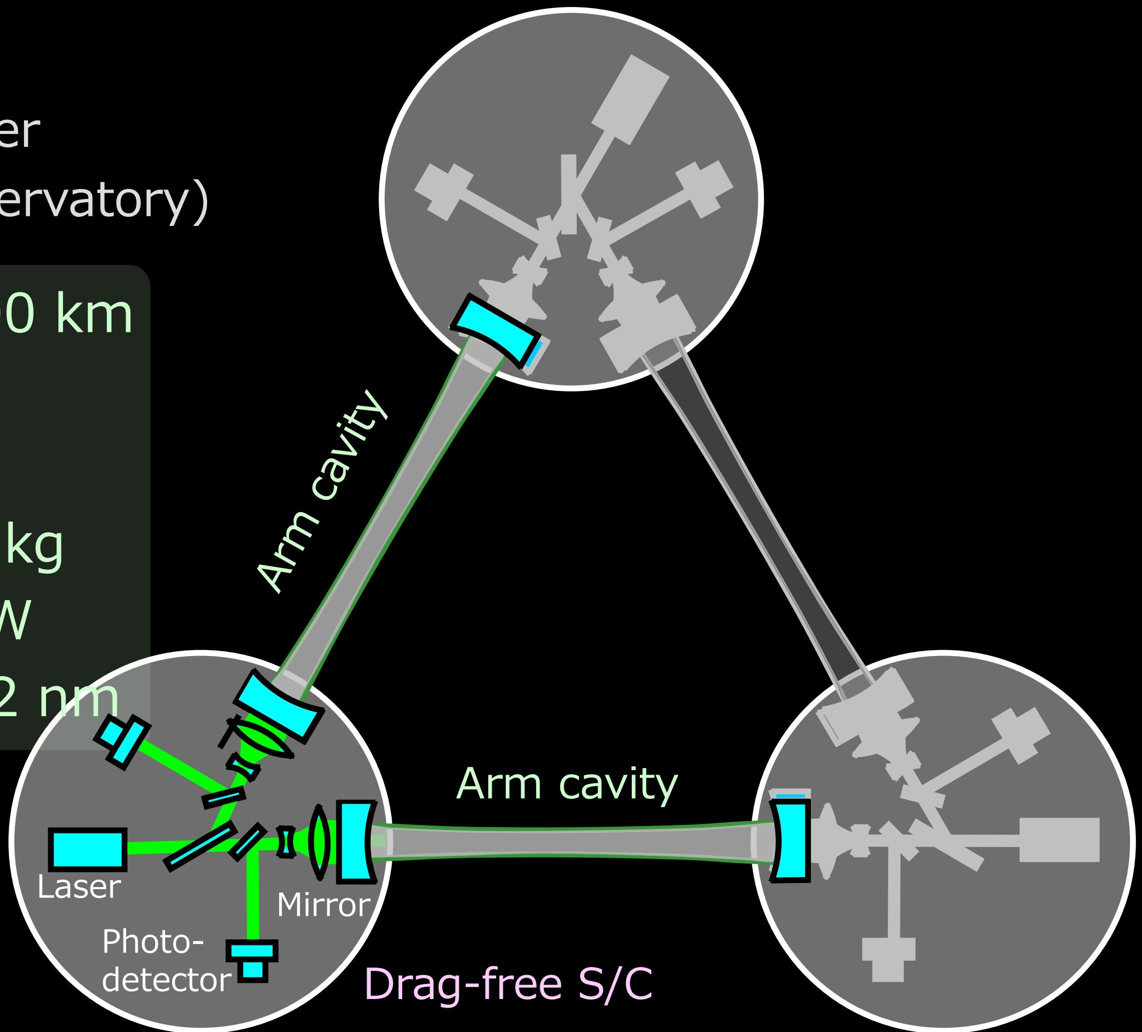
Conceptual Design

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

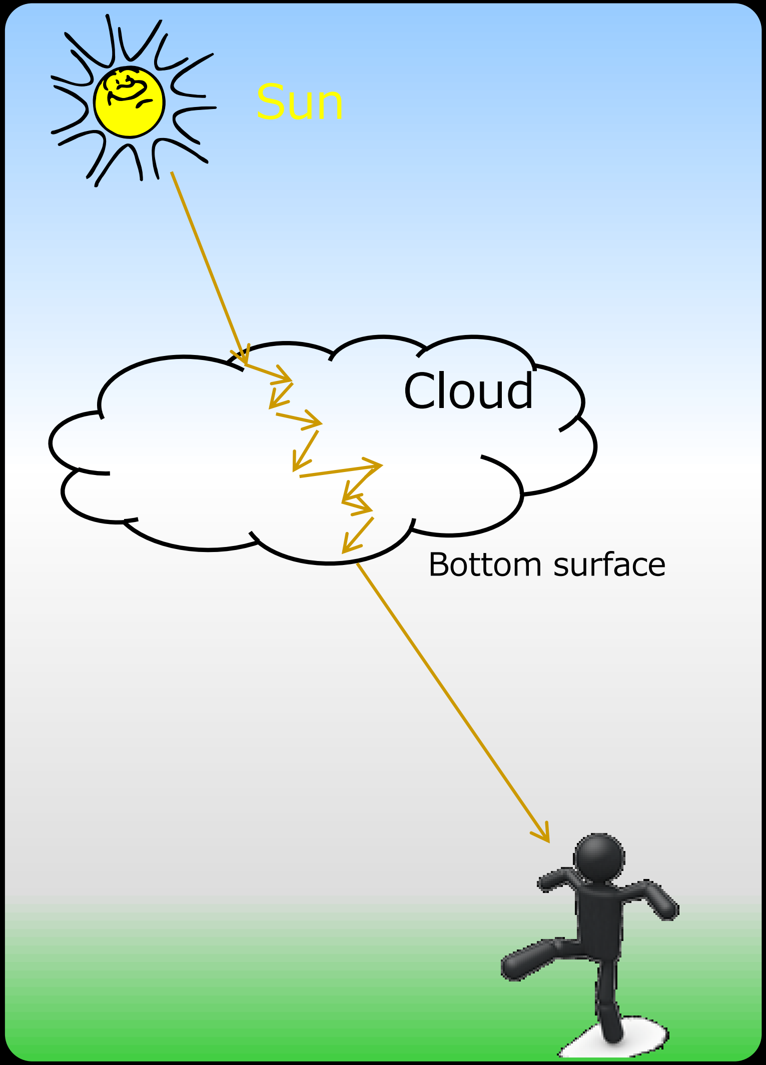


Observation of the Early Universe

Background:
original figure by
NASA/WMAP Science Team

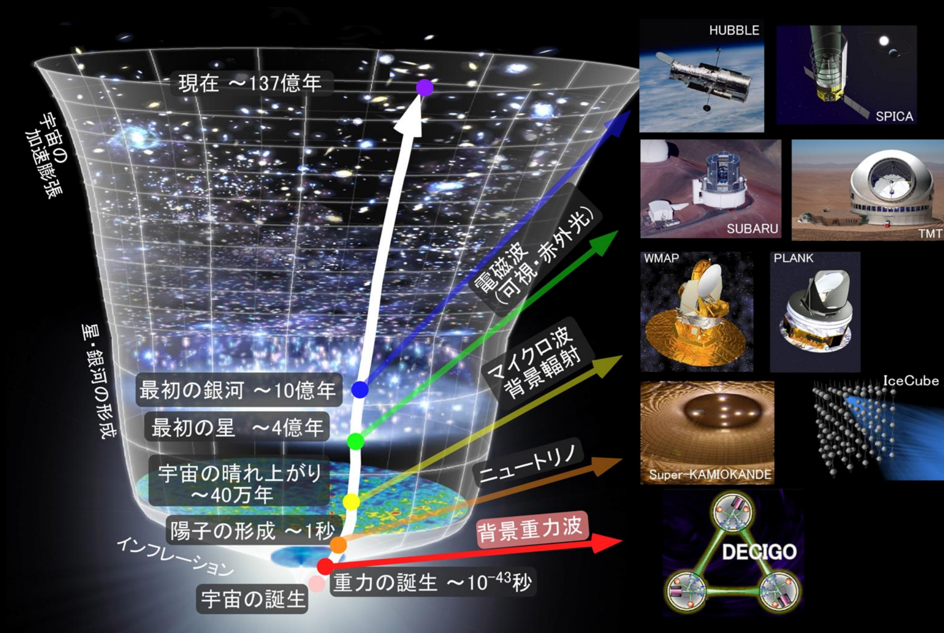
Scattering of Light (EM wave)

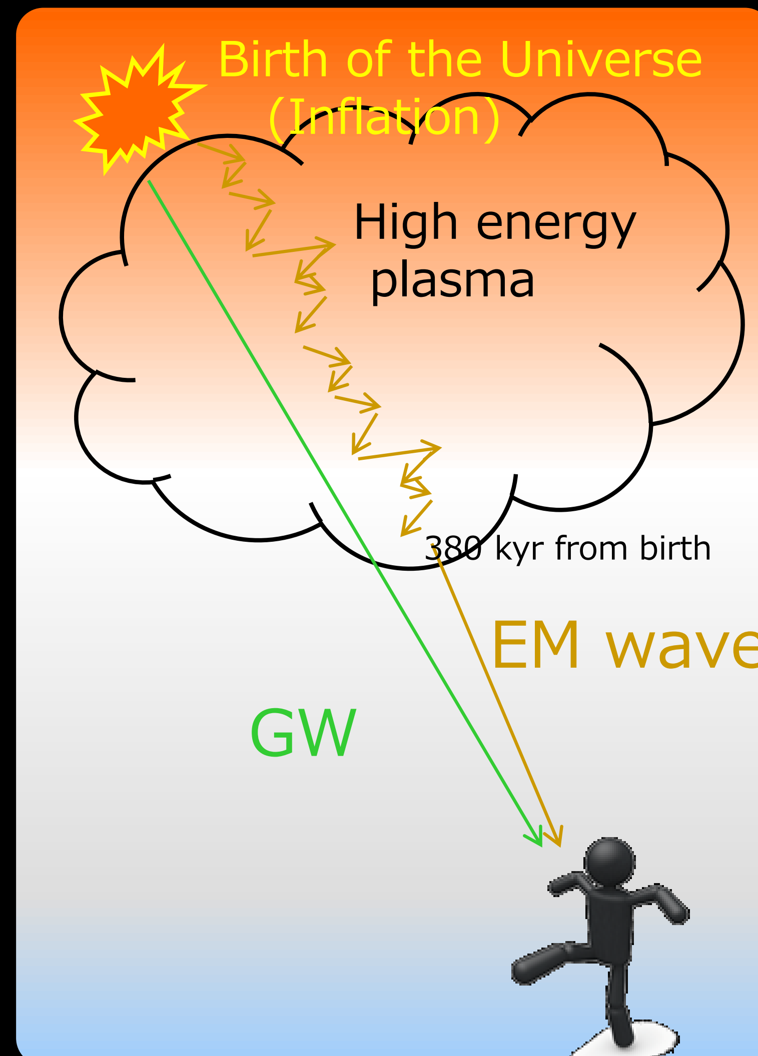
Light from the Sun is scattered in the cloud. It loses original information (shape of the Sun).



Observation of the Early Universe

Very early universe can be observed by GW.





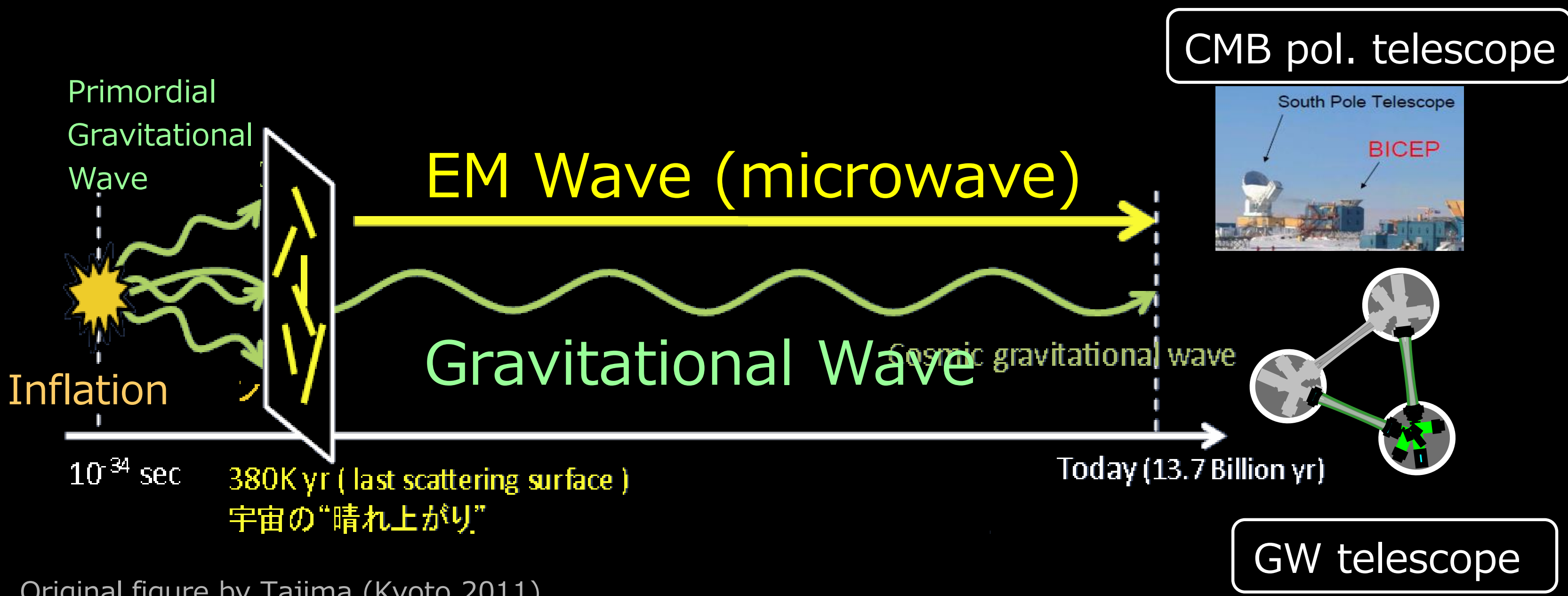
Observation of GW from Inflation

BICEP2 (LiteBIRD,⋯)

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

DECIGO (KAGRA, aLIGO,⋯)

GWB observation by GW telescope.

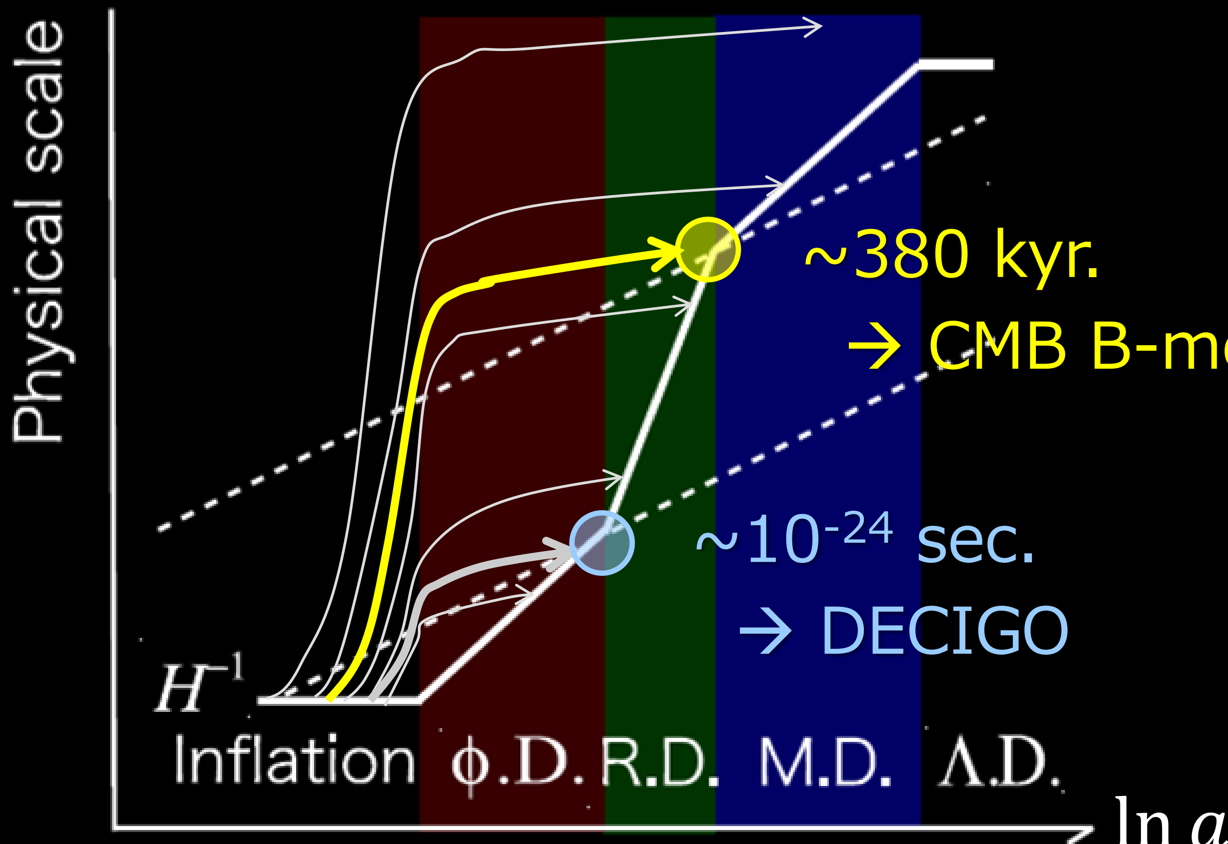


Original figure by Tajima (Kyoto 2011)

GW from Inflation

Stochastic background GWs by quantum fluctuation

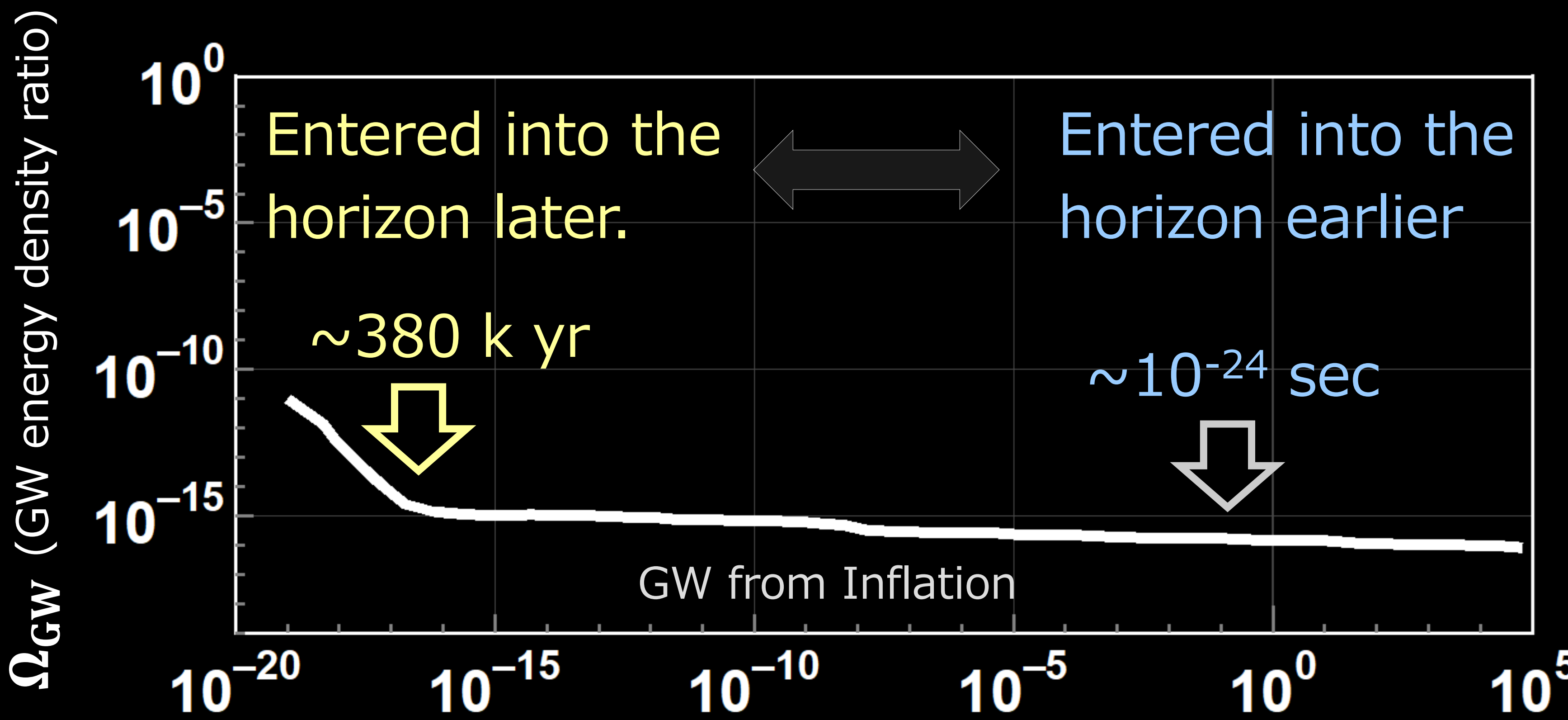
→ Earlier-generated GWs in inflation period entered later into the horizon of the universe.



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

GW from Inflation

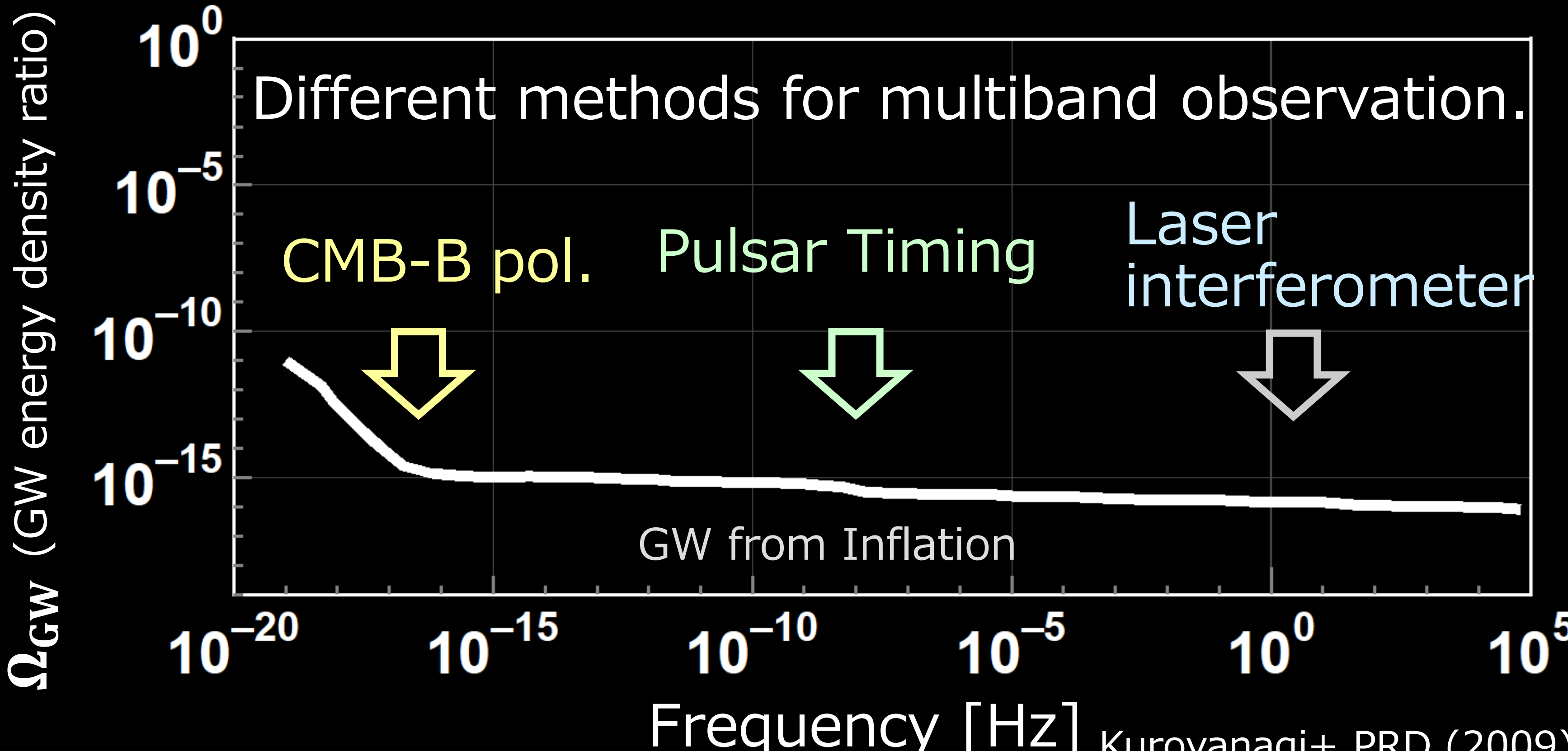
Frequency corresponds to
when the GW entered into the horizon.



Kuroyanagi+ PRD (2009) など

Observation of GWB

GW amplitude changes according to the evolution of the Universe. → Spectrum has information of history of the Universe.



Kuroyanagi+ PRD (2009) など

GW Energy Density and Amplitude

- GW energy density ratio

GW energy density

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

Critical energy density of the universe

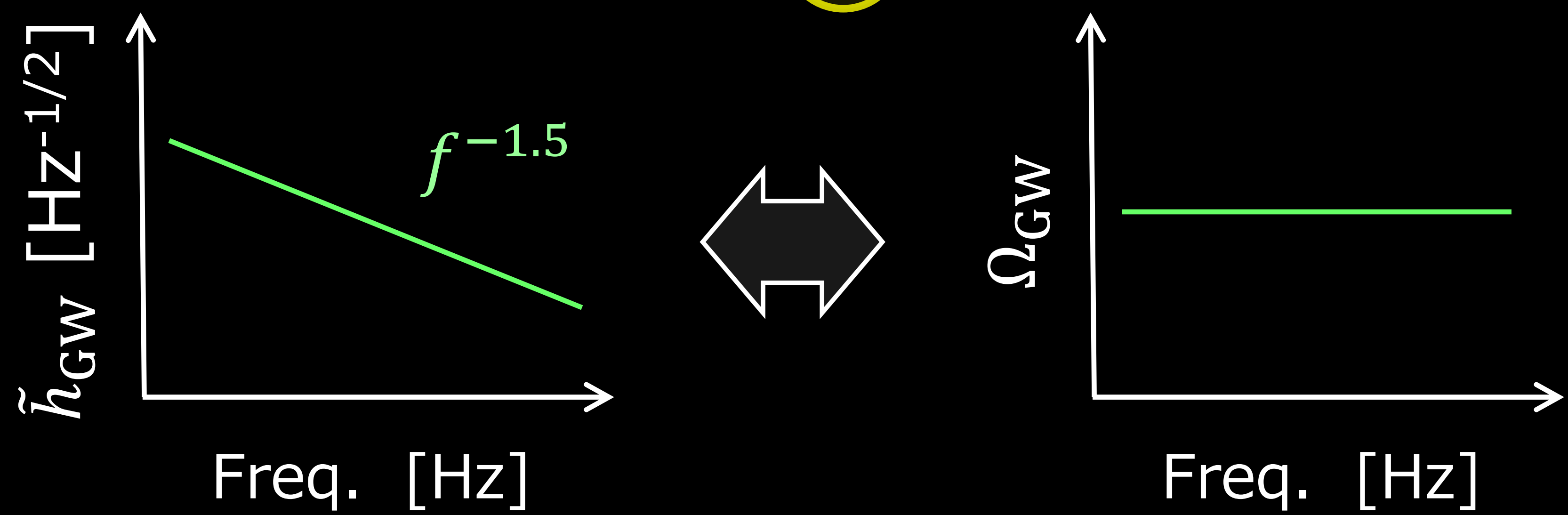
Equivalent GW Amplitude

Hubble's constant

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

GW Energy Density and Amplitude

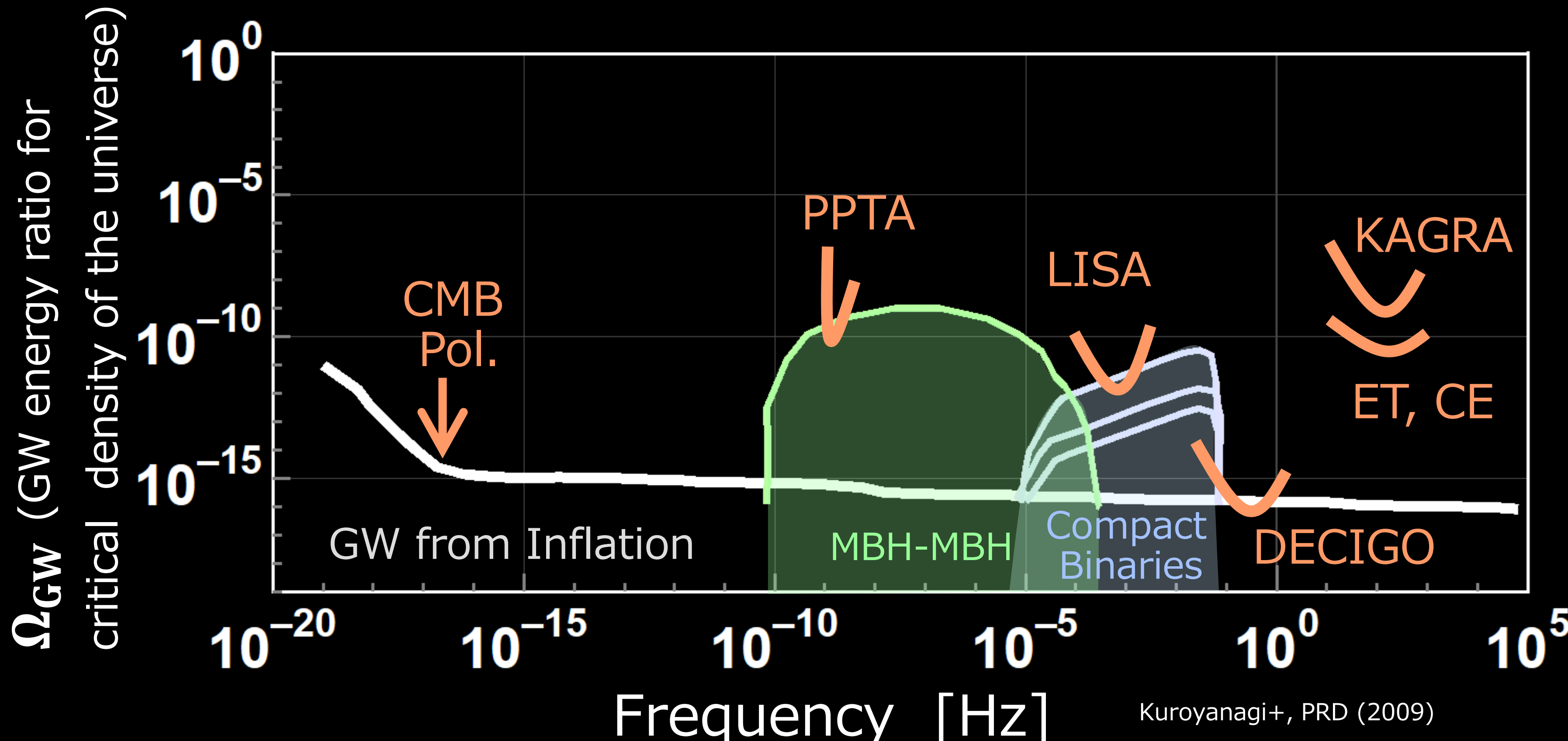
$$\tilde{h}^2_{\mathrm{GW}}(f) = \frac{3H_0^2}{10\pi^2 f^3}\Omega_{\mathrm{GW}}(f)$$



Smaller amplitude in high freq.

‘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

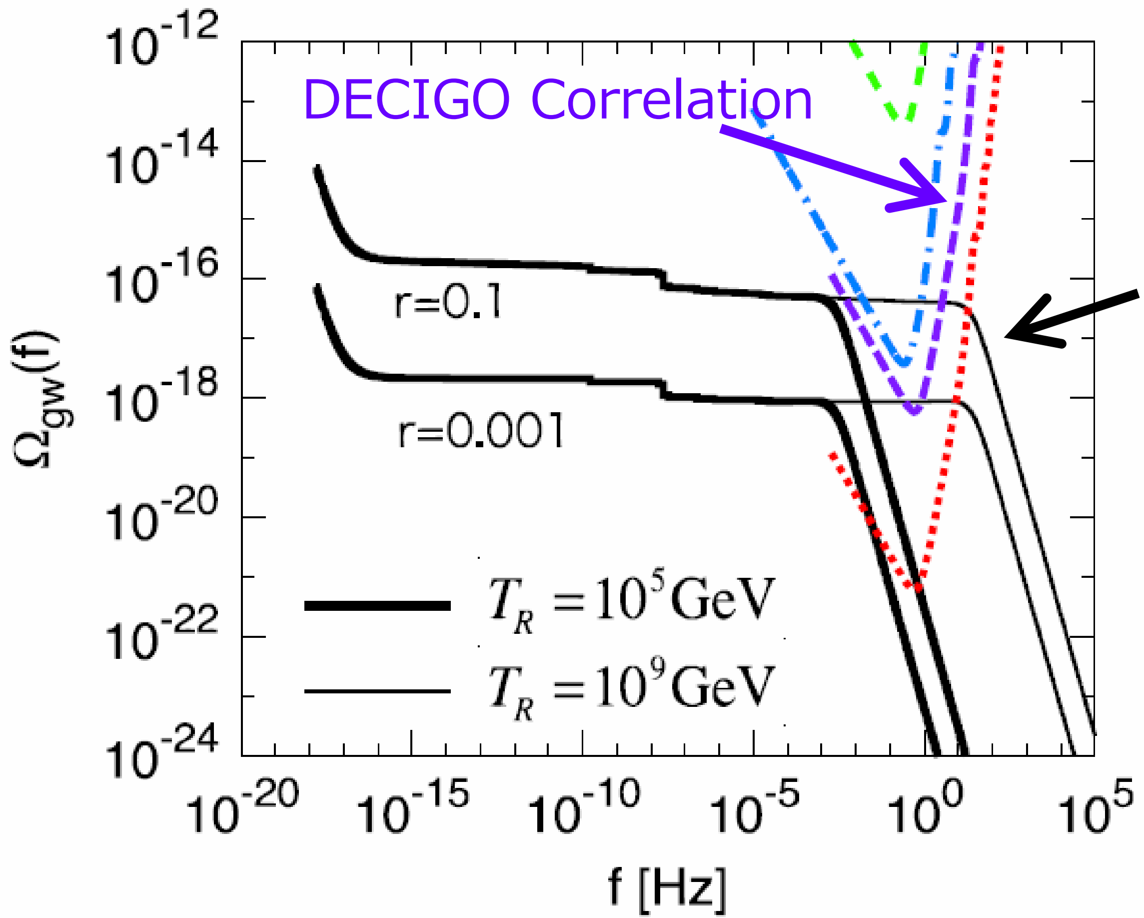
Depends on r (tensor-to-scalar ratio), which may be also pinned-down by CMB B-mode polarization observation.

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.

- 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