The 15th International Symposium on

Origin of Matter and Evolution of Galaxies

Gravitational-wave observation
- Recent results and prospects -

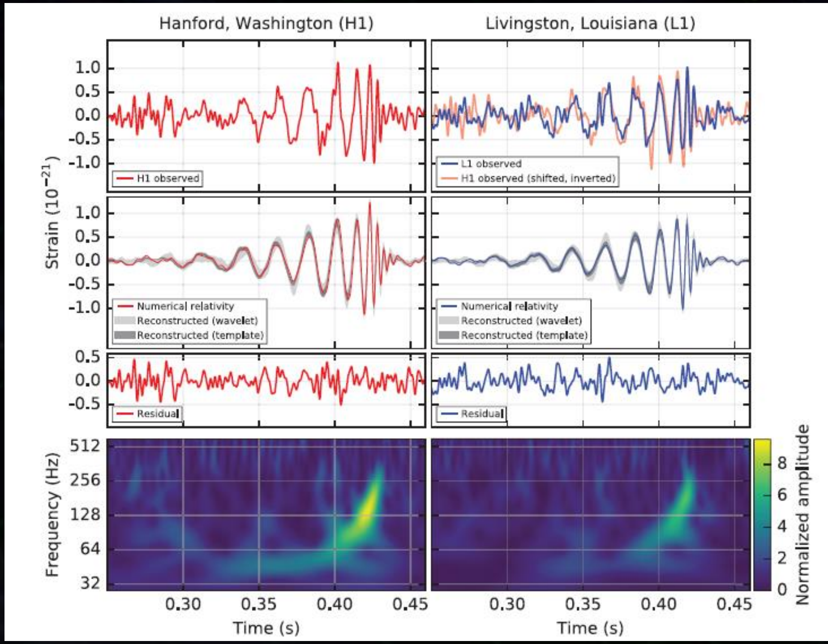
Masaki Ando (Univ. of Tokyo)

Outline

- Introduction : GW observations
- Ground-based Antennae and KAGRA
- Space GW antenna : B-DECIGO
- Summary

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

- Publications after the first event.

  *2nd: GW151226 (reported in 2016.6)

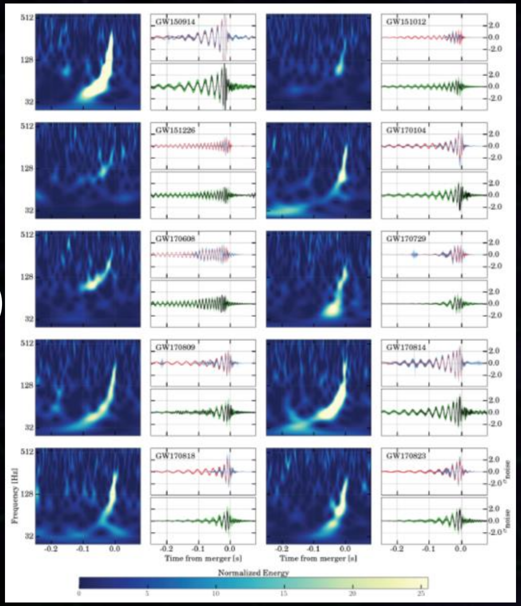
  *3rd: GW170104 (reported on 2017.6.2)

  *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)

arXiv:1811.12907 (Nov. 30, 2018)



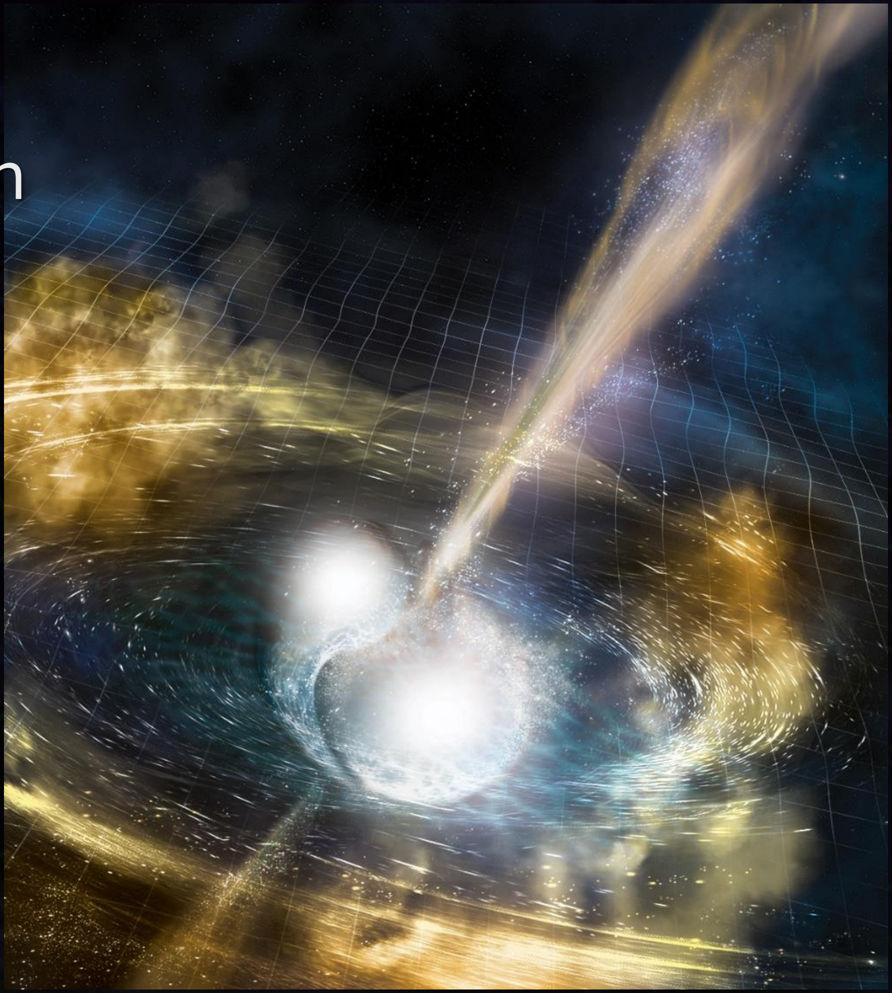
- Public alerts in O3 (2019.April-) : 18 alerts so far.

→ 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 ~30deg²

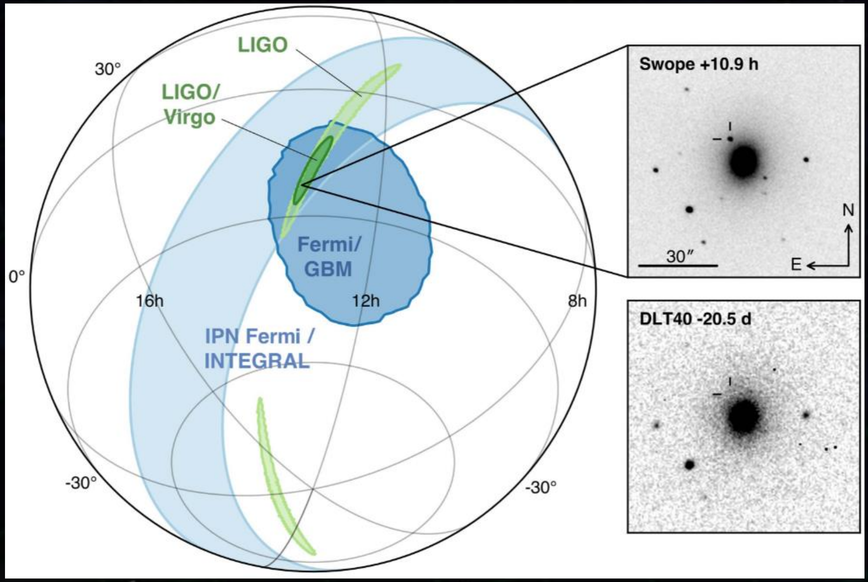


Courtesy Caltech/MIT/LIGO Laboratory

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)

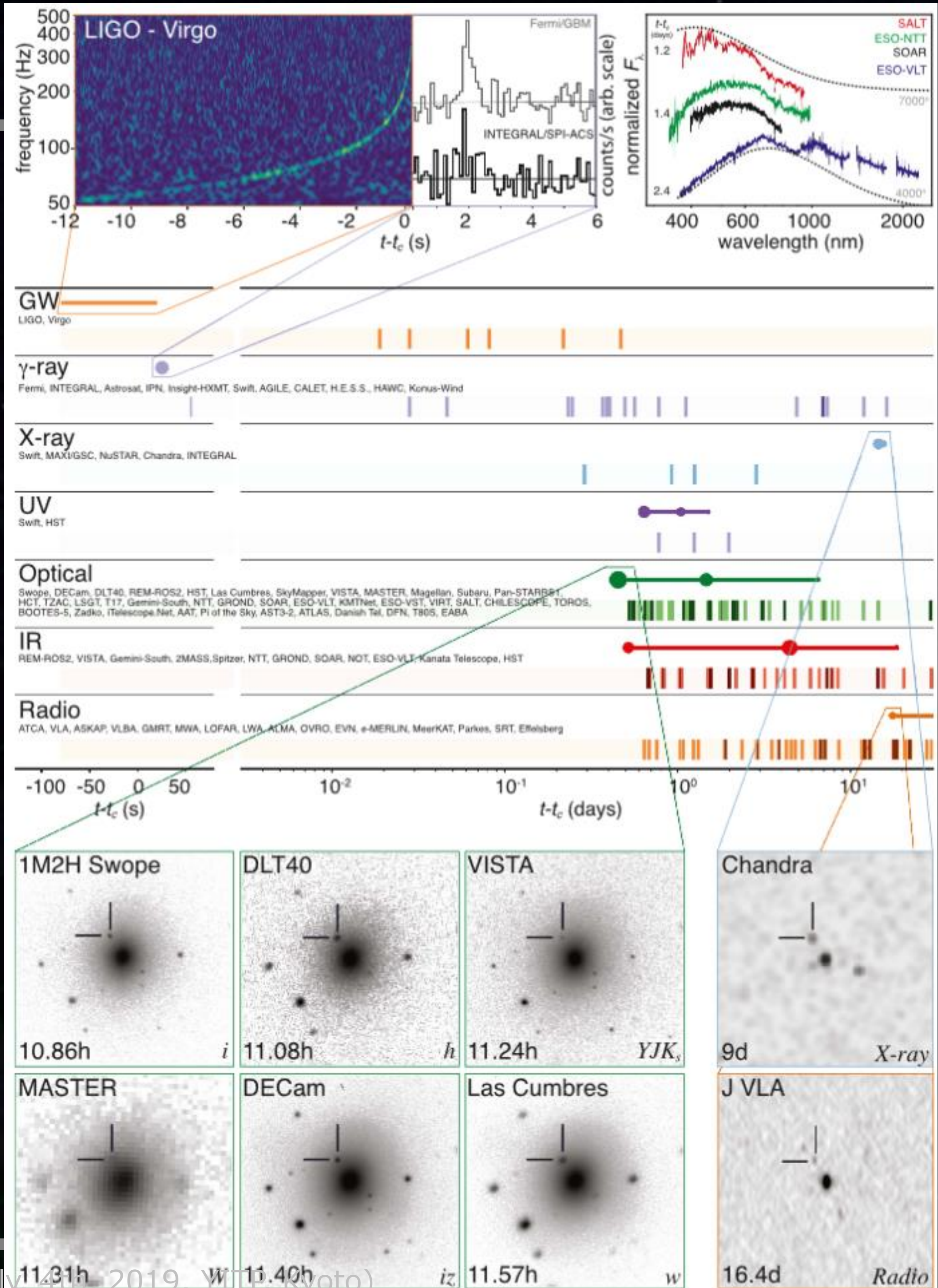


- EM counterpart was observed for the first time in GW170817.

⇩

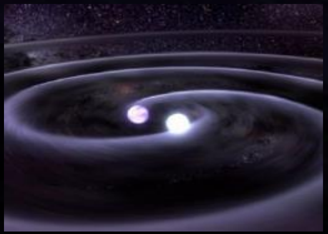
- New knowledge
 * Origin of SGRB.
 * Origin of heavy elements in the universe.
 * EoS of neutron star
 * Fundamental physics and cosmology: speed of GW, Hubble's constant, ⋯.

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.

NS EoS: Tidal deformability

- Tidal deformation in formation from GW waveform

  * Tidal deformability λ :

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

Quadrupole moment

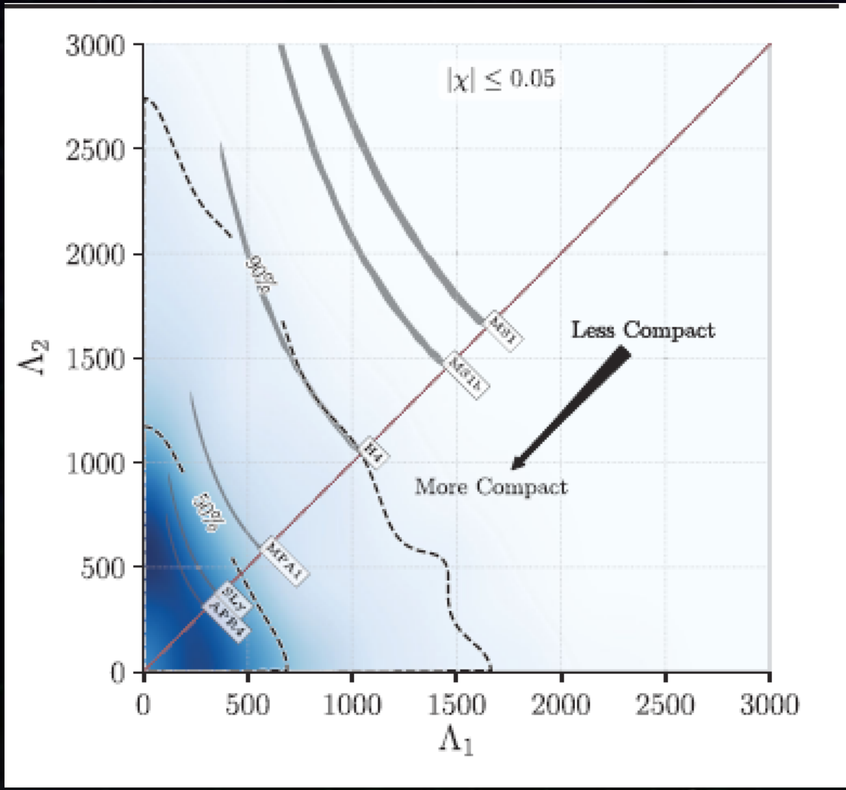
Tidal force from companion object

  * Dimensionless parameter

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

Hard EoS → Large diameter

→ Large Λ



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.

⇩

- 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, B-DECIGO, ⋯).

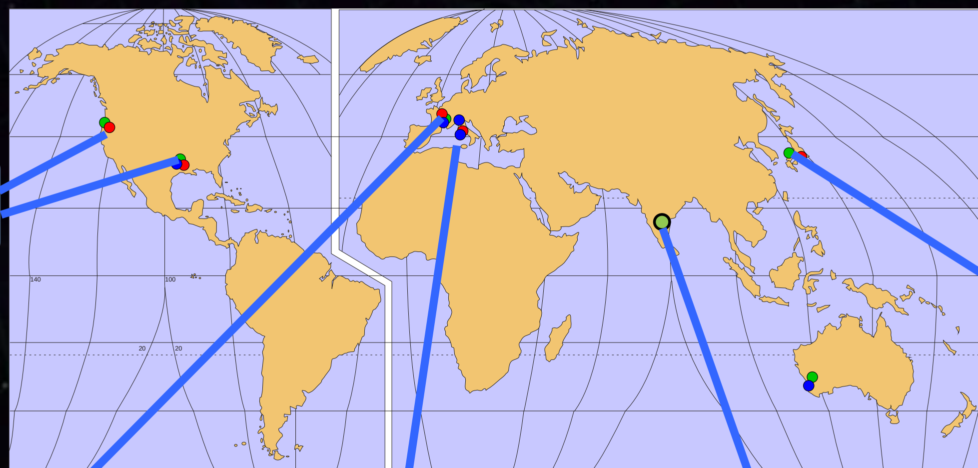
Ground-based GW Antennae

International GW Network

International network by 2nd−gen GW antennae.

→ GW astronomy (Detection, Parameter estimation, ⋯)

aLIGO (USA)
4km x 2



KAGRA (JPN)
baseline 3km

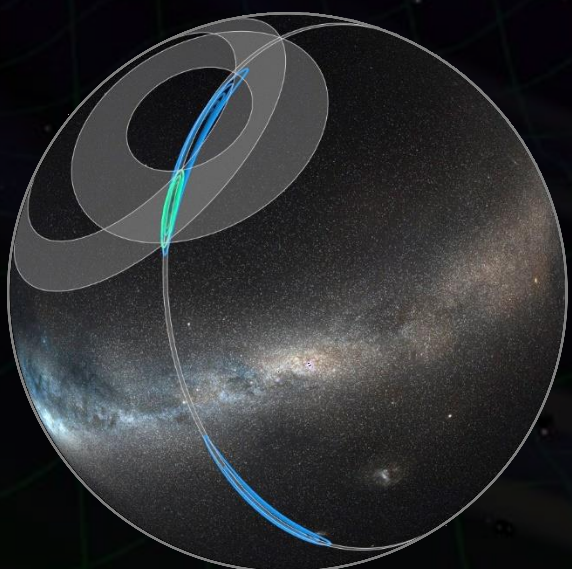
GEO-HF (GER-UK)
baseline 600m

Adv.VIRGO (ITA-FRA)
baseline 3km

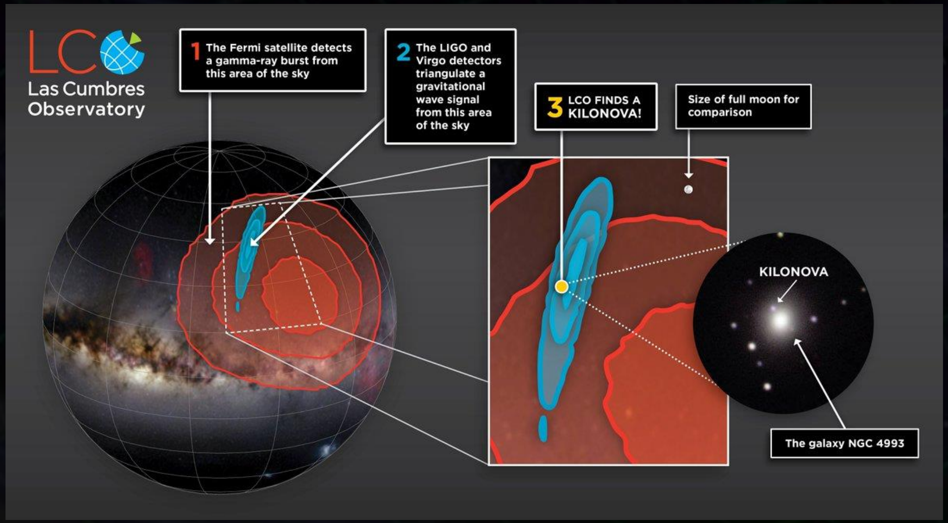
LIGO-India
project approved

Importance of Sky Localization

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

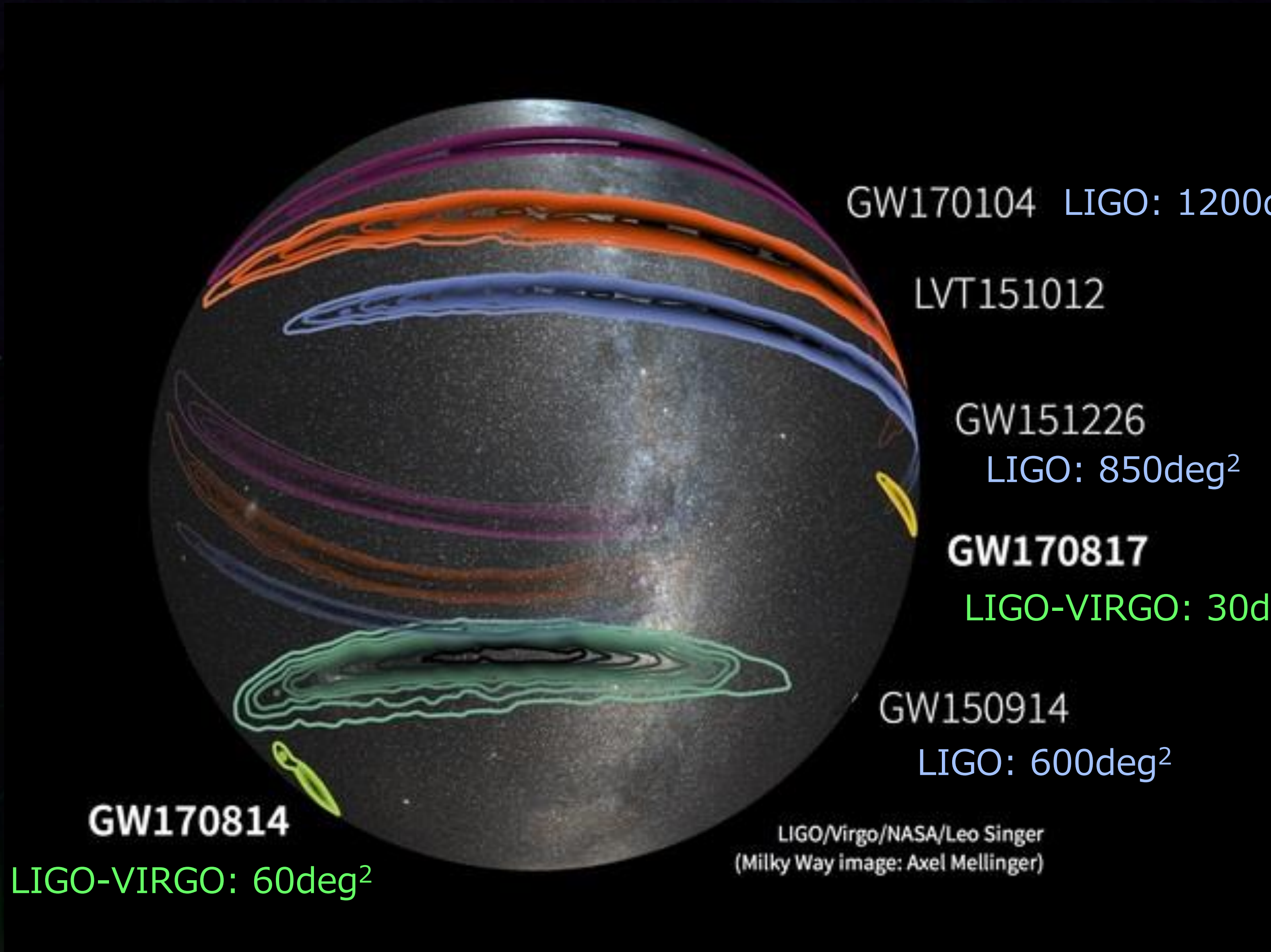


Credit: LIGO/Virgo/NASA/Leo Singer
(Milky Way Image: Alex Mellinger)



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

Source Localization



Antenna Pattern of GW Detector

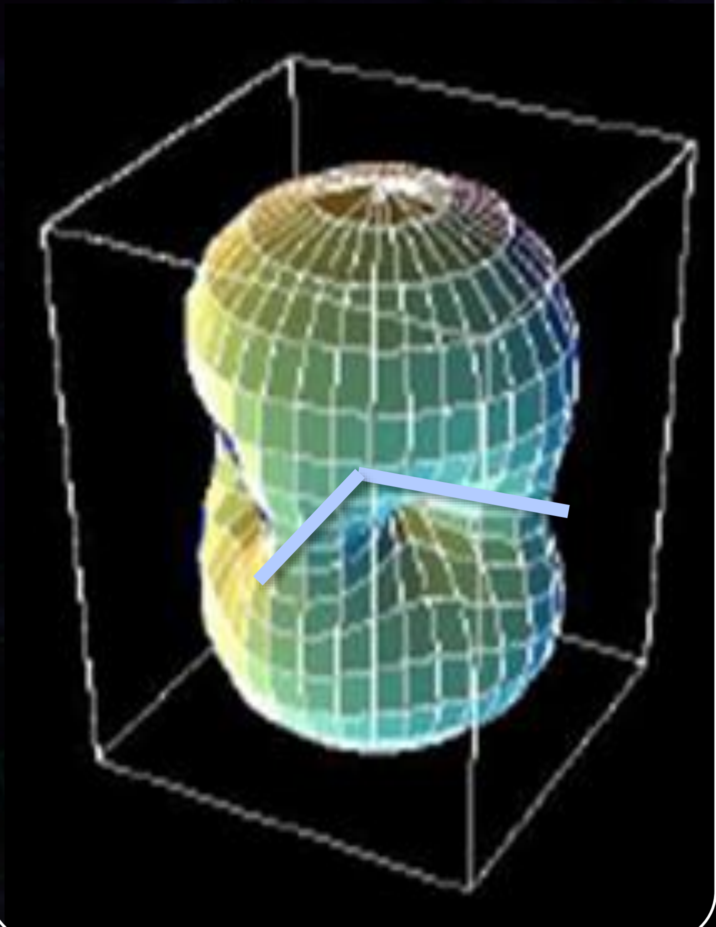
An Interferometric GW antenna has ⋯

* Good sky coverage
* Poor angular resolution

⇩

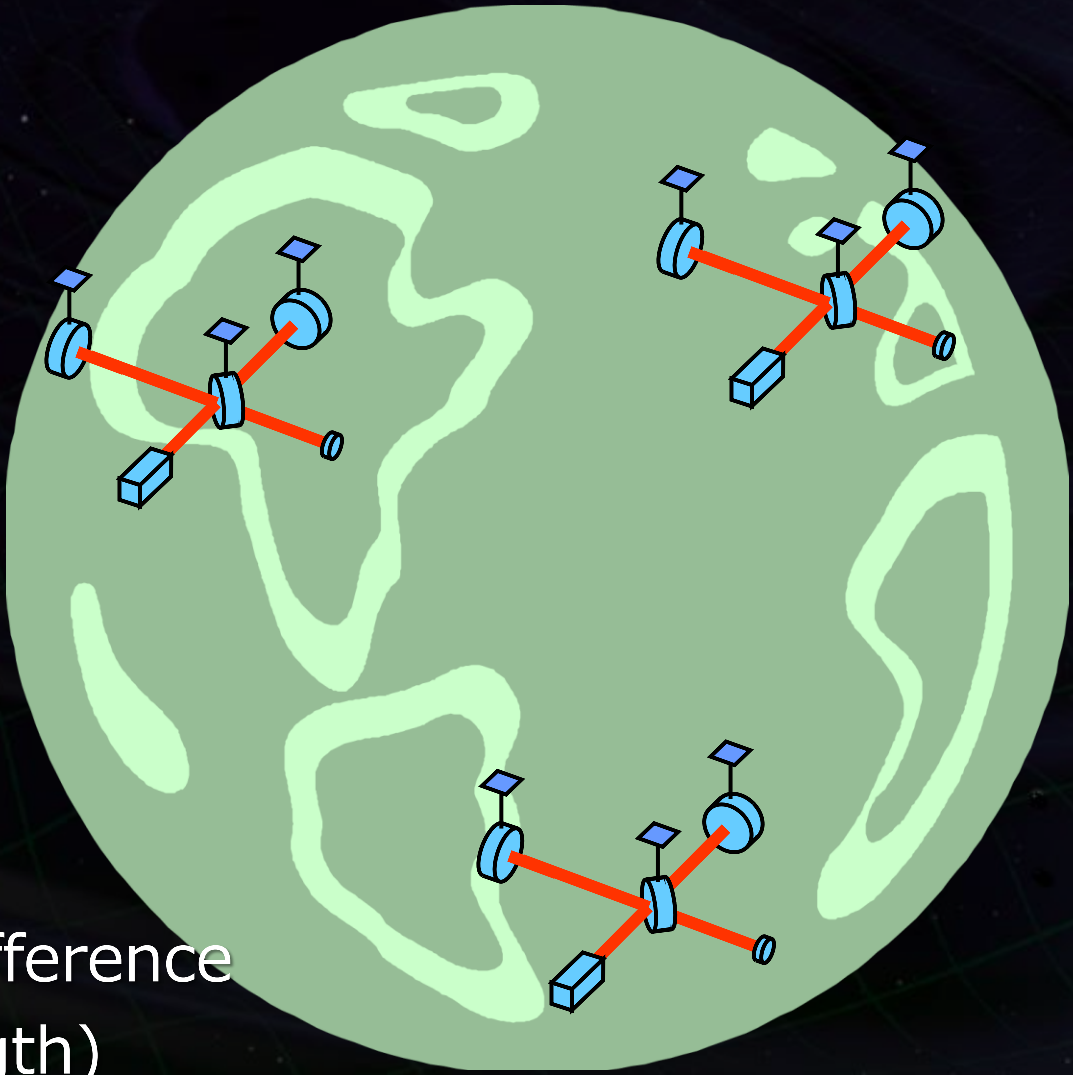
Difficult to determine the source sky position with single antenna.

Antenna Pattern



International Network for Astronomy

Animation :
S. Kawamura (ICRR)



Multiple Detector

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

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

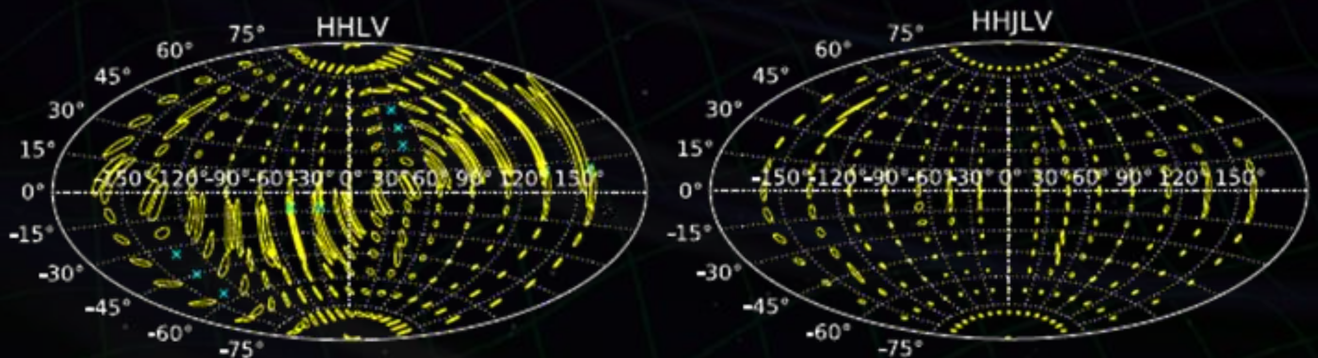
Designed by S. Miyoki

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

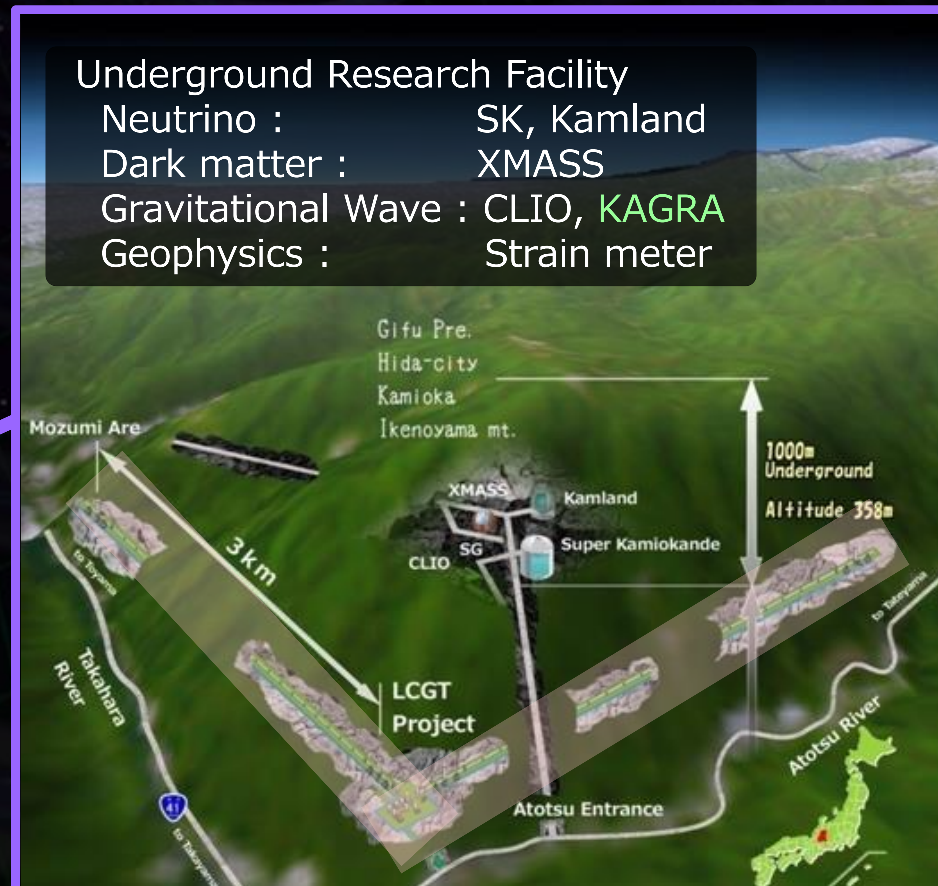
Original advanced technologies in KAGRA, which also gives prospects for 3G detectors

KAGRA Site

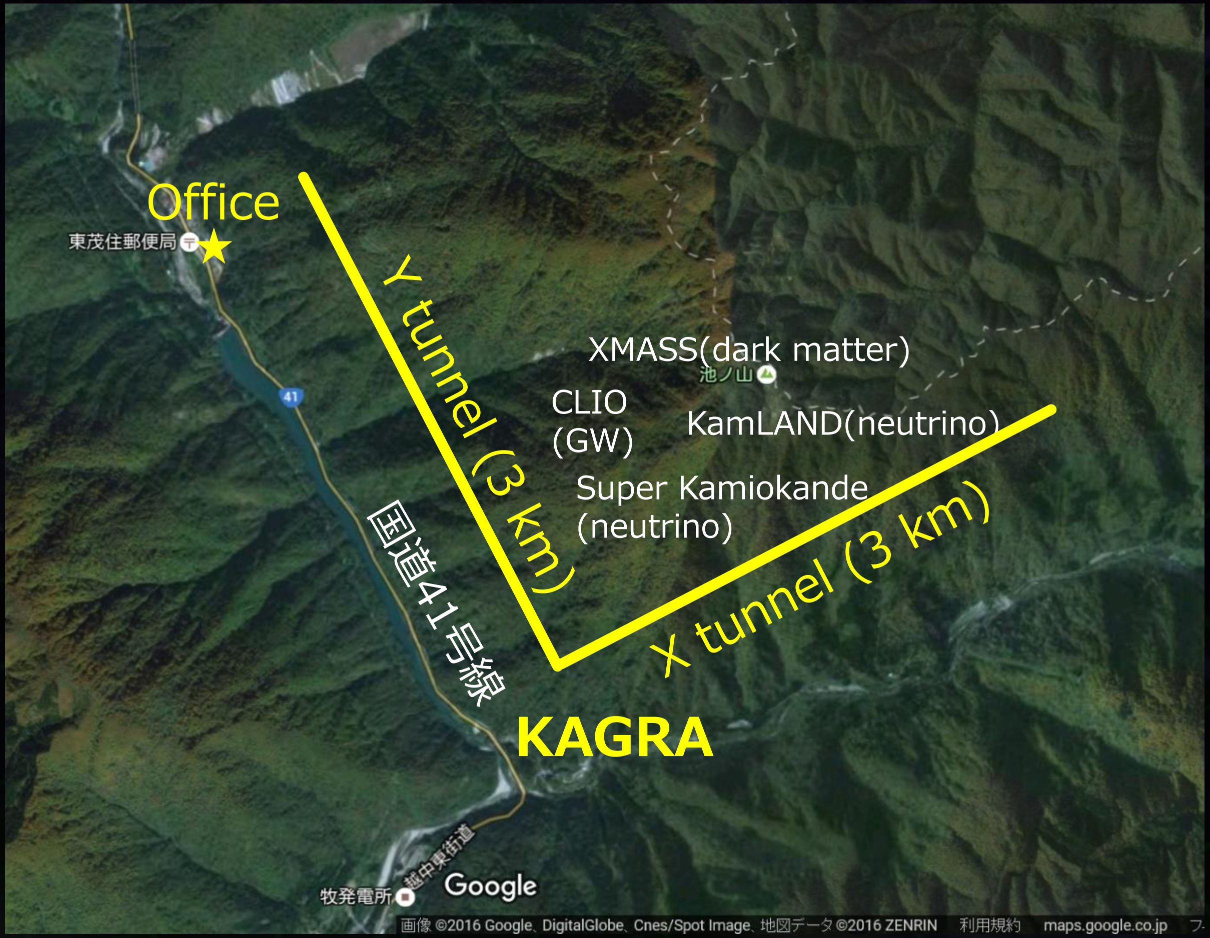
Underground site at Kamioka, Gifu prefecture

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

Map by Google



KAGRA Photos



KAGRA 3-km Tunnel and Duct

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

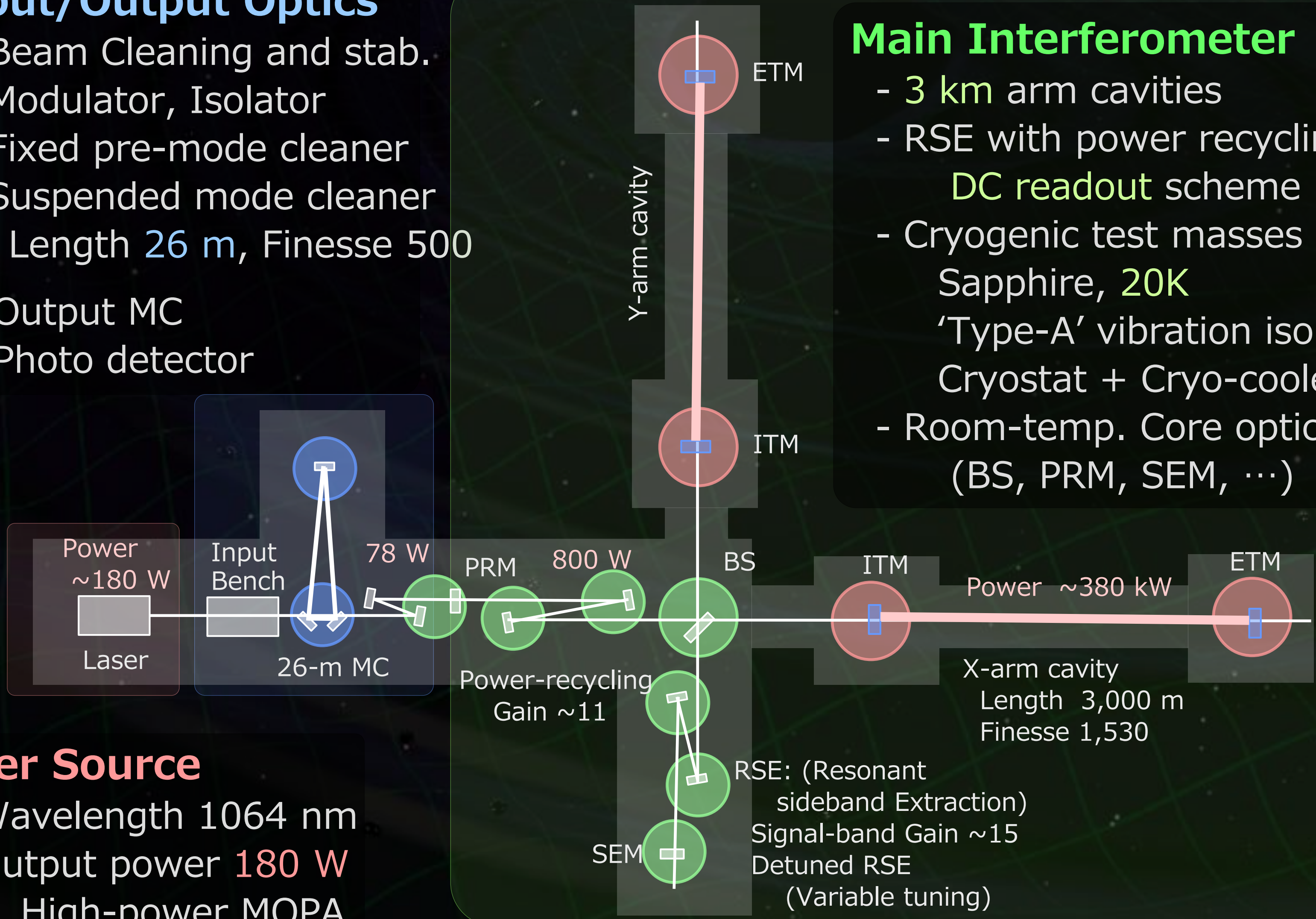
KAGRA Optical Design

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

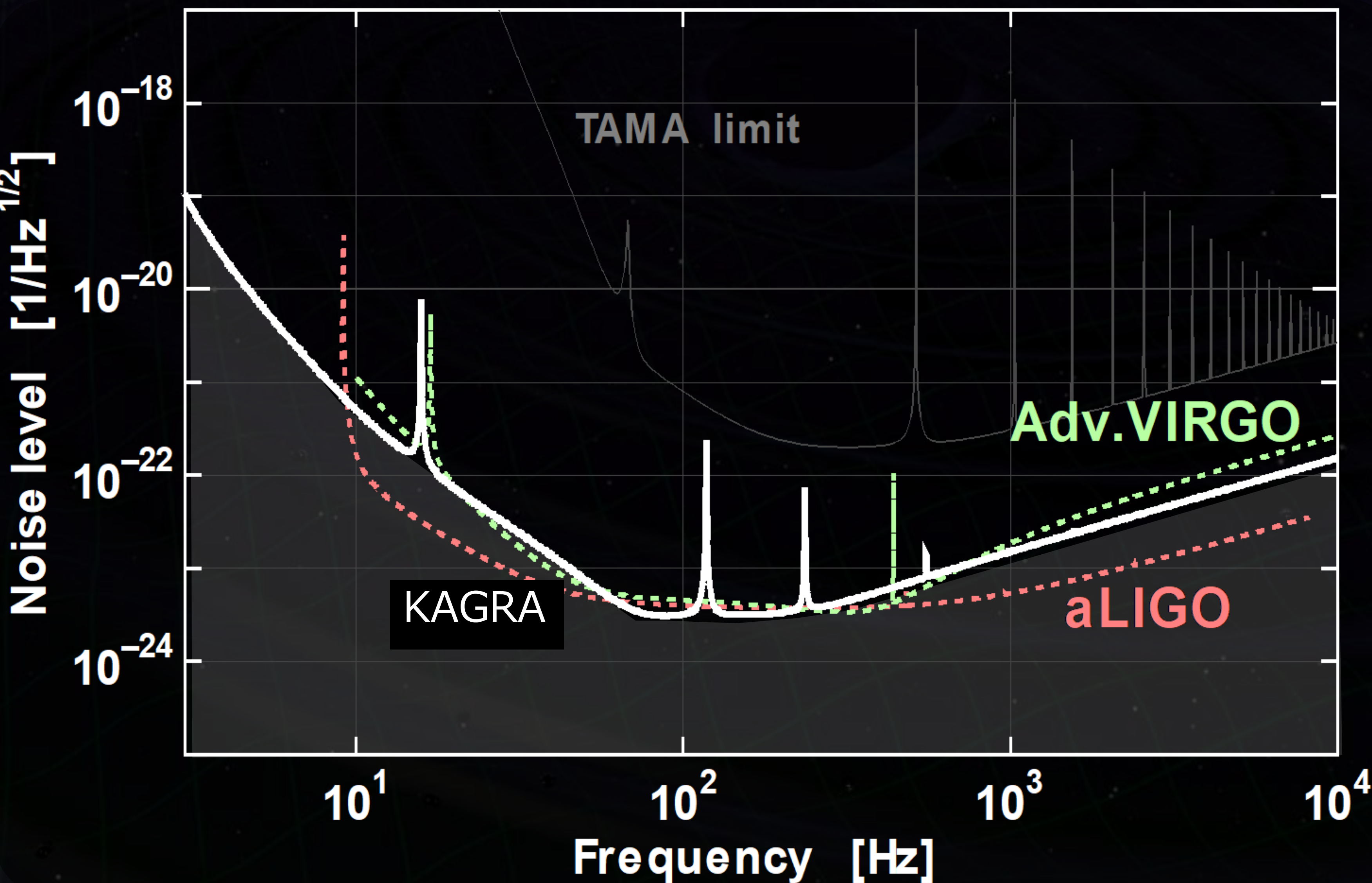
- 3 km arm cavities
- RSE with power recycling
  DC readout scheme
- Cryogenic test masses
  Sapphire, 20K
  'Type-A' vibration isolator
  Cryostat + Cryo-cooler
- Room-temp. Core optics
  (BS, PRM, SEM, …)



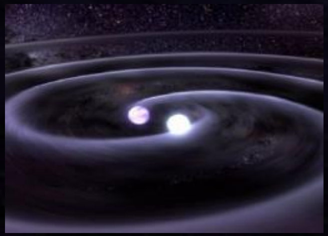
Laser Source

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

Sensitivity Comparison



BNS Detection Rate



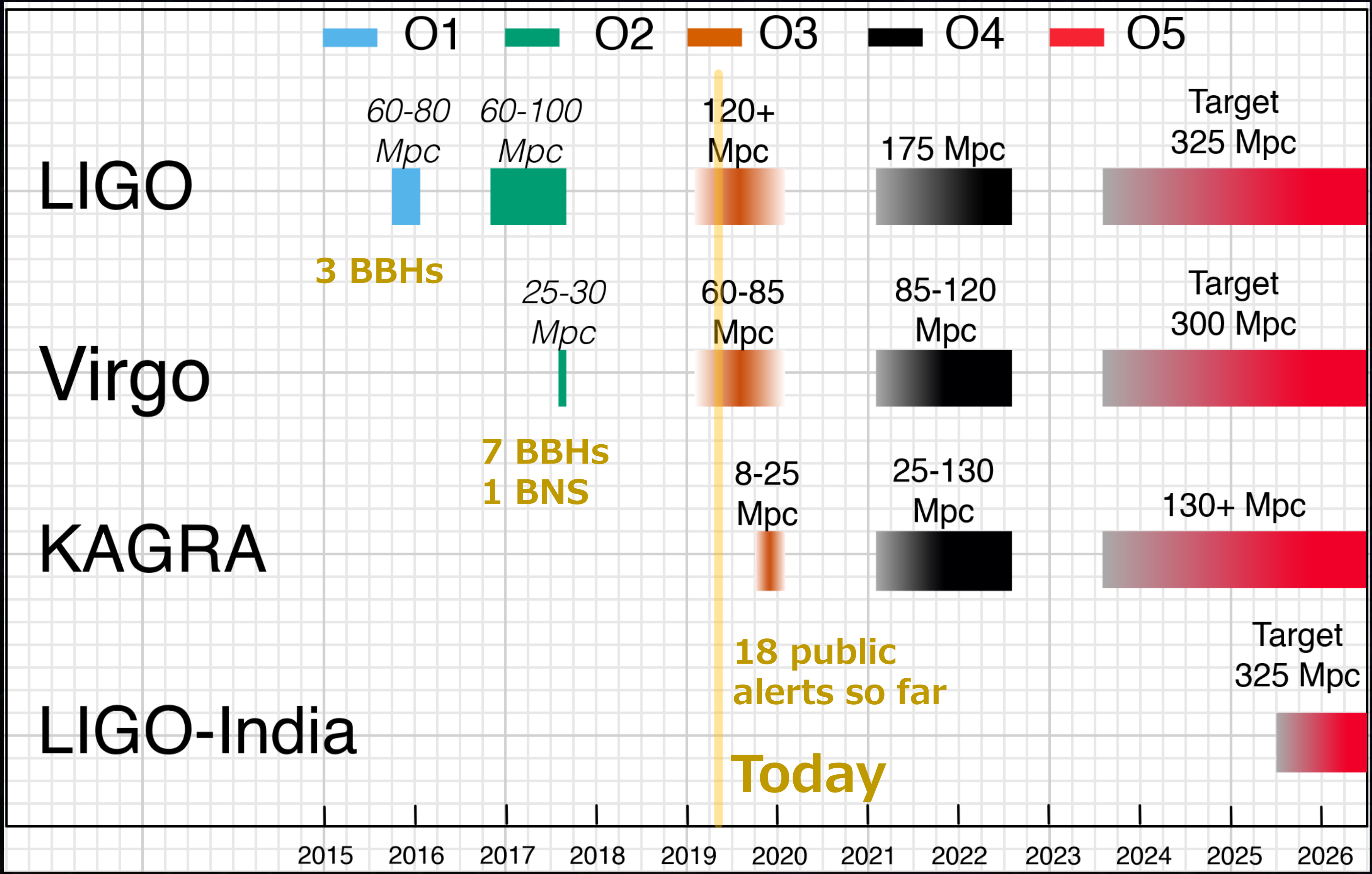
- Detection rate of GW signal from BNS
  - BNS merger rate: $1540^{+3200}_{-1220}\ \mathrm{Gpc^{-3}yr^{-1}}$
  - KAGRA observable range ~140 Mpc (SNR>8, Sky average) from the design sensitivity

⇨ 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.

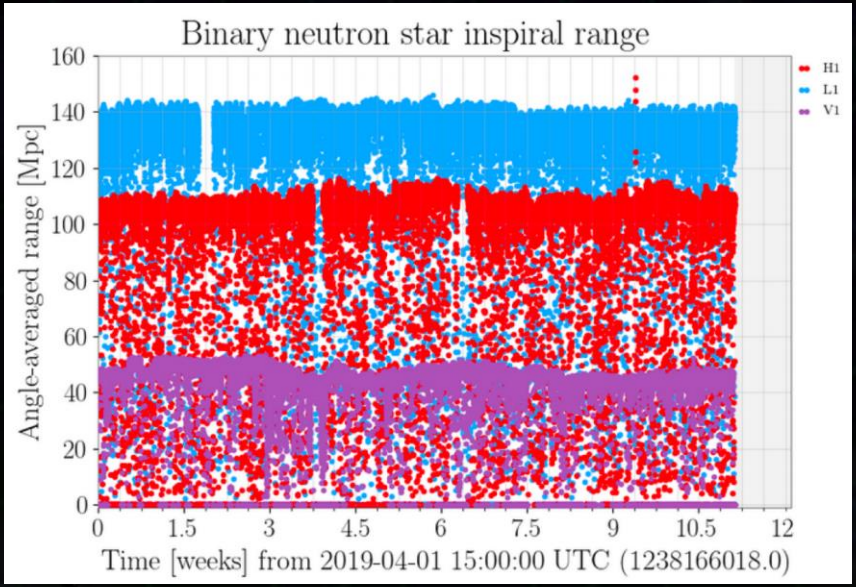
Observation Scenario

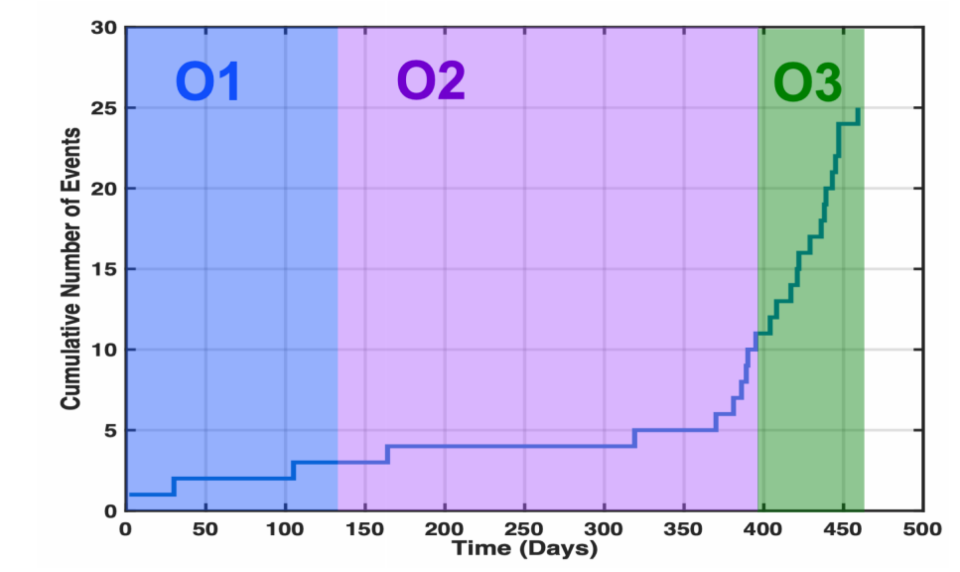


Living Reviews in Relativity 21, 3 (2018); Updated version to be submitted.

LIGO+VIRGO (+KAGRA) O3

- O3 began on April 1st, 2019.
  - * H-L-V three-way coincidence duty factor ~45%, "no interferometer" state of the network ~ 2.7%.
  - * Released public alerts for 18 event candidates.
- KAGRA will join the network in 2019 (or early 2020).





From presentation by K.Kawabe (G1901130 LVEM Forum 20 Jun 2019)

KAGRA Schedule and Status for O3

- Installation is completed (expect for small components).
  * All optics, Vibration isolation system are installed.
  * Mirrors are already cooled down.
  * Interferometer is under commissioning phase
    Arm cavities, Central IFO, → Full operation.

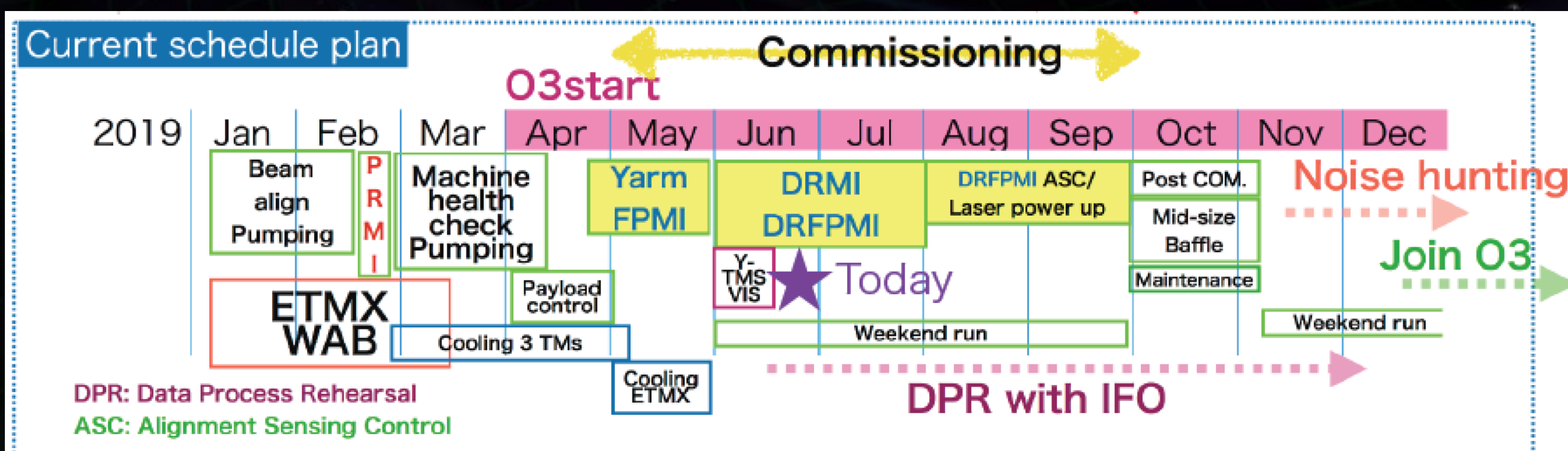


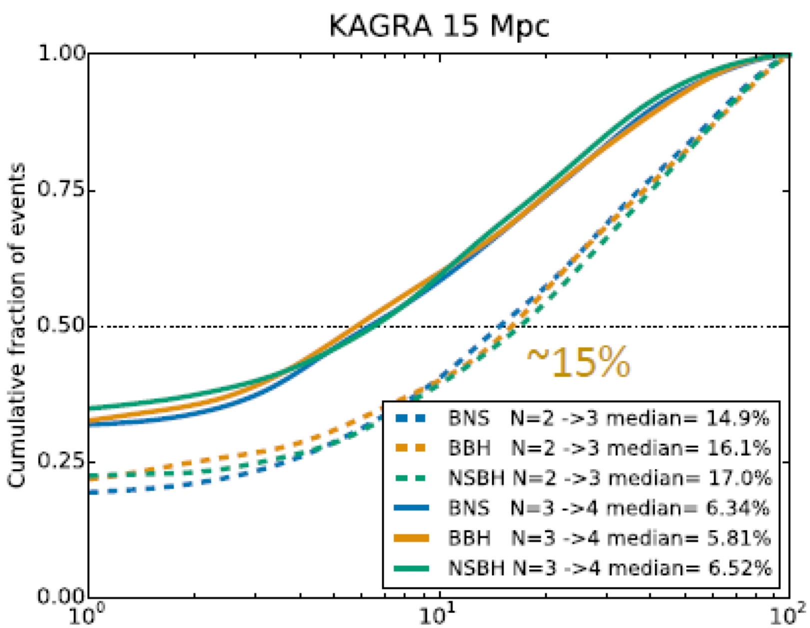
Figure by T. Uchiyama

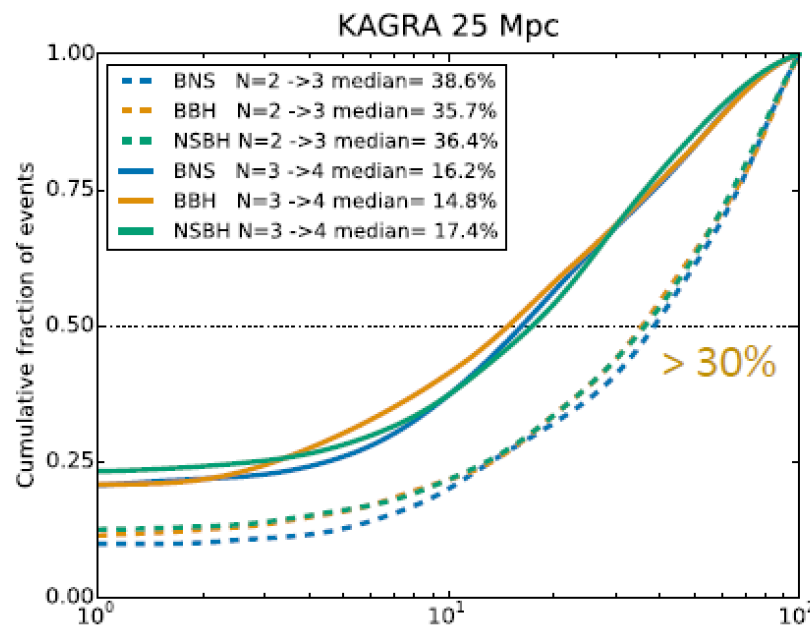
KAGRA’s Contribution Study for O3

JGW-G1910299, JGW-T1910330, JGW-G1910190
https://git.ligo.org/sadakazu.haino/o3-simulation-for-kagra

In N=2(HL,LV,HV) -> 3(+K) cases,

- >30% improvement with 25 Mpc
- ~15% improvement even with 15 Mpc



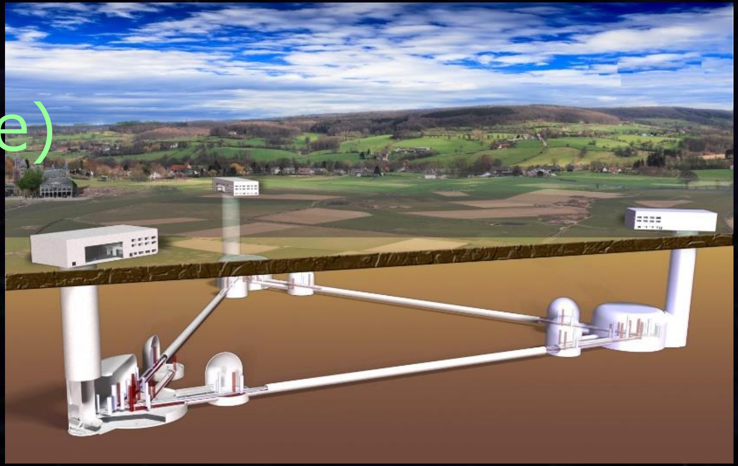


From presentation by Haino (KIW6, June 2019)

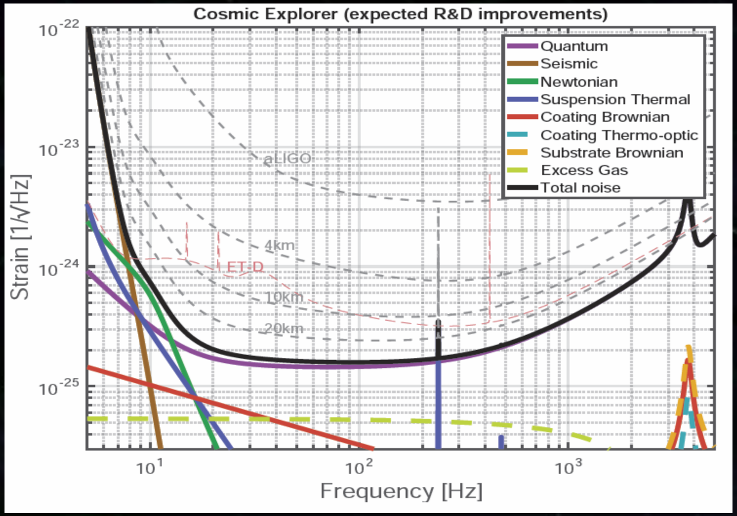
Next Generation GW Antennae

3rd Generation GW Antennae (~2030)

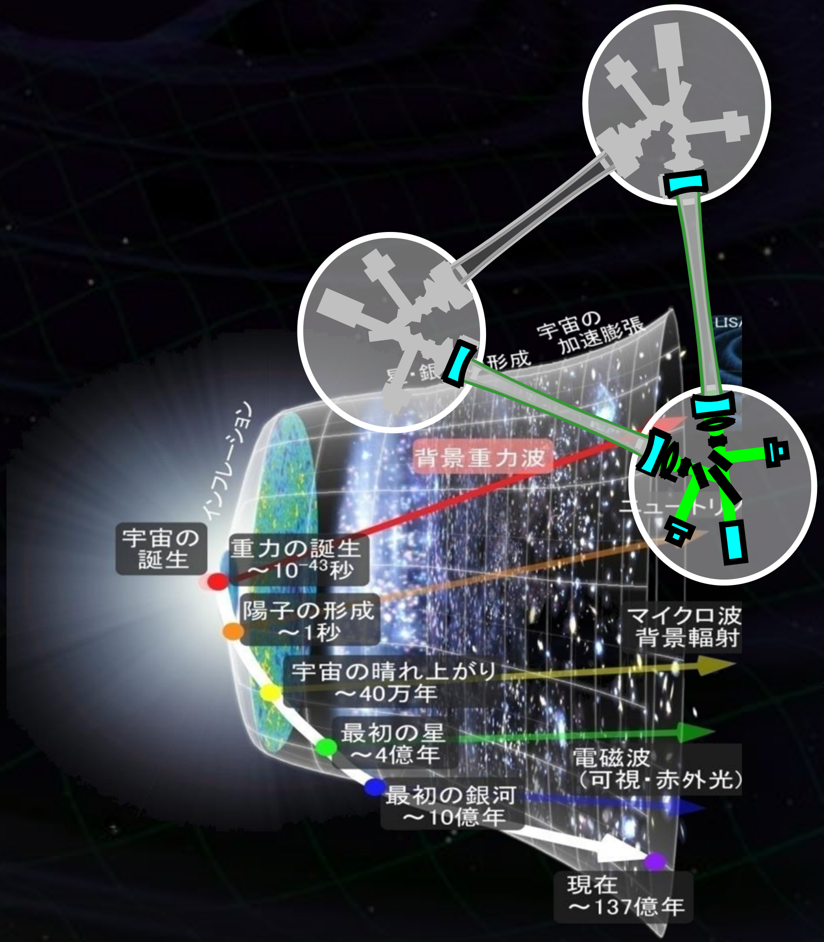
* Europe: ET (Einstein Telescope)
x10 sensitivity,
Long baseline ~10km,
Underground, Cryogenic



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



B-DECIGO



宇宙の
加速膨張
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

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} $\mathrm{Hz}^{-1/2}$ 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 Large-scale mission (~2030).

Target (1) : Compact Binaries

B-DECIGO will observe >100/yr binary NS inspirals.

~10^5/yr binary BH inspirals.

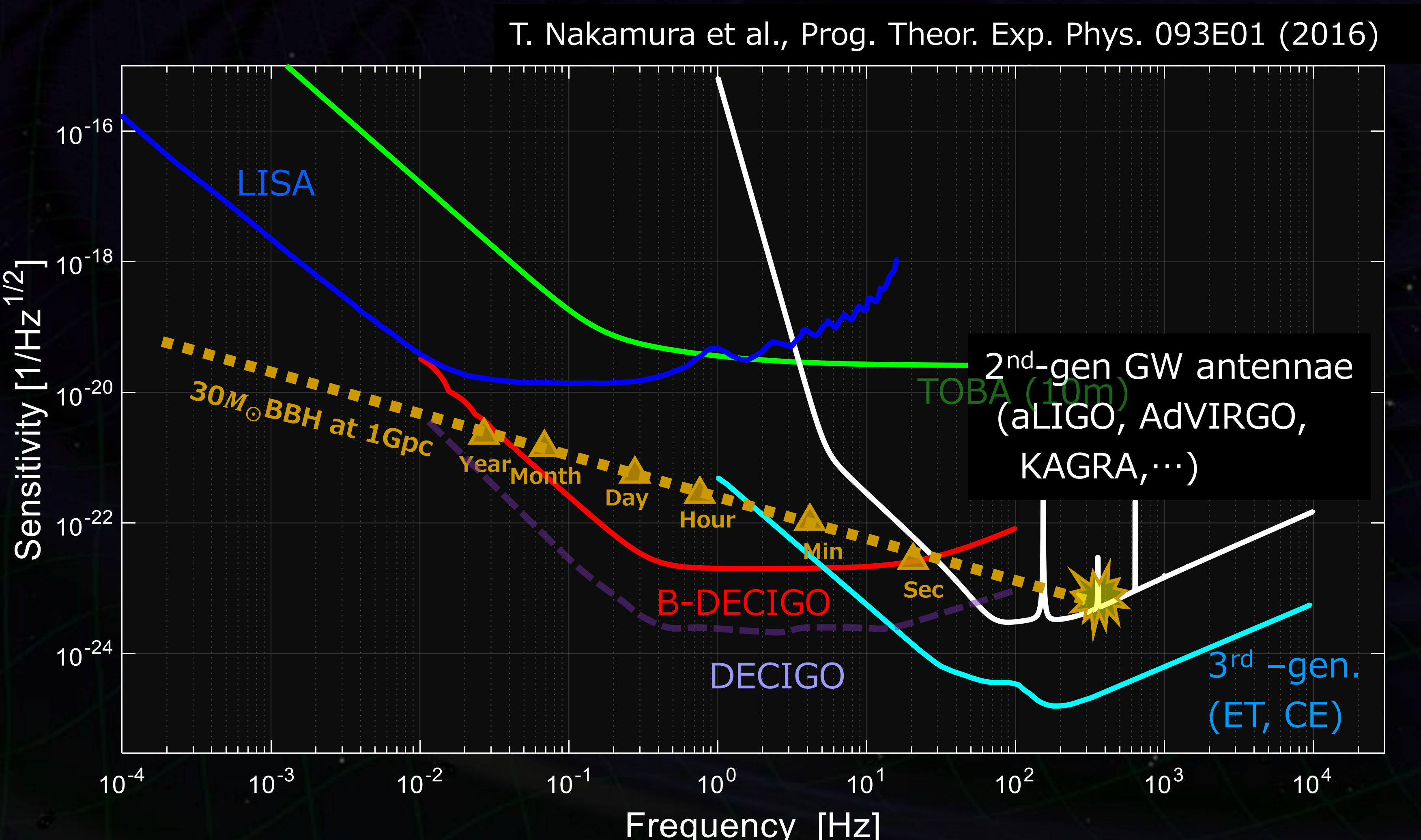
Several month to a
few sec before merger

A few seconds to merger

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

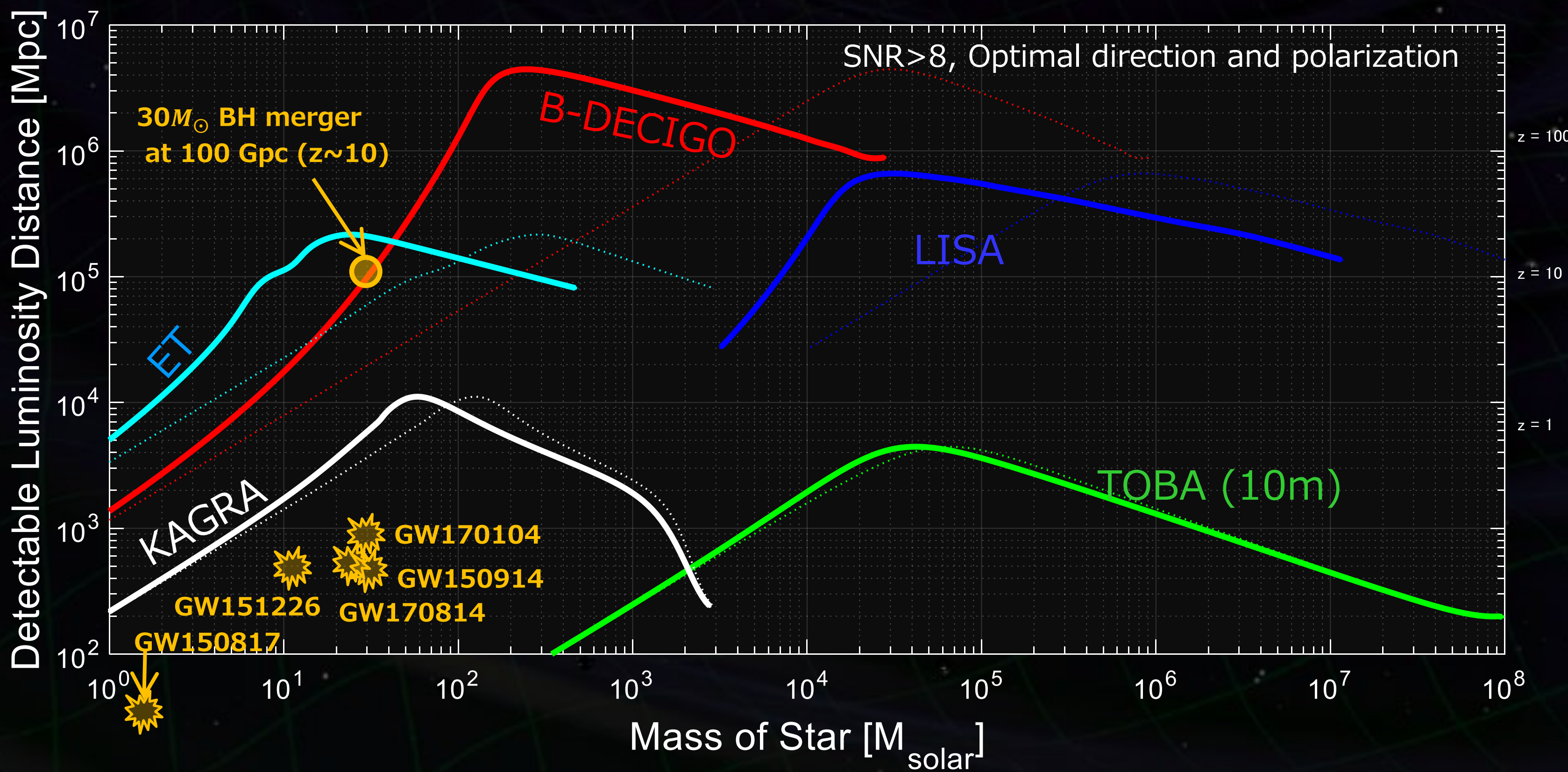
High-freq. → Ground based
Astrophysics, EoS of NS

Sensitivity Curves



Observable Range

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



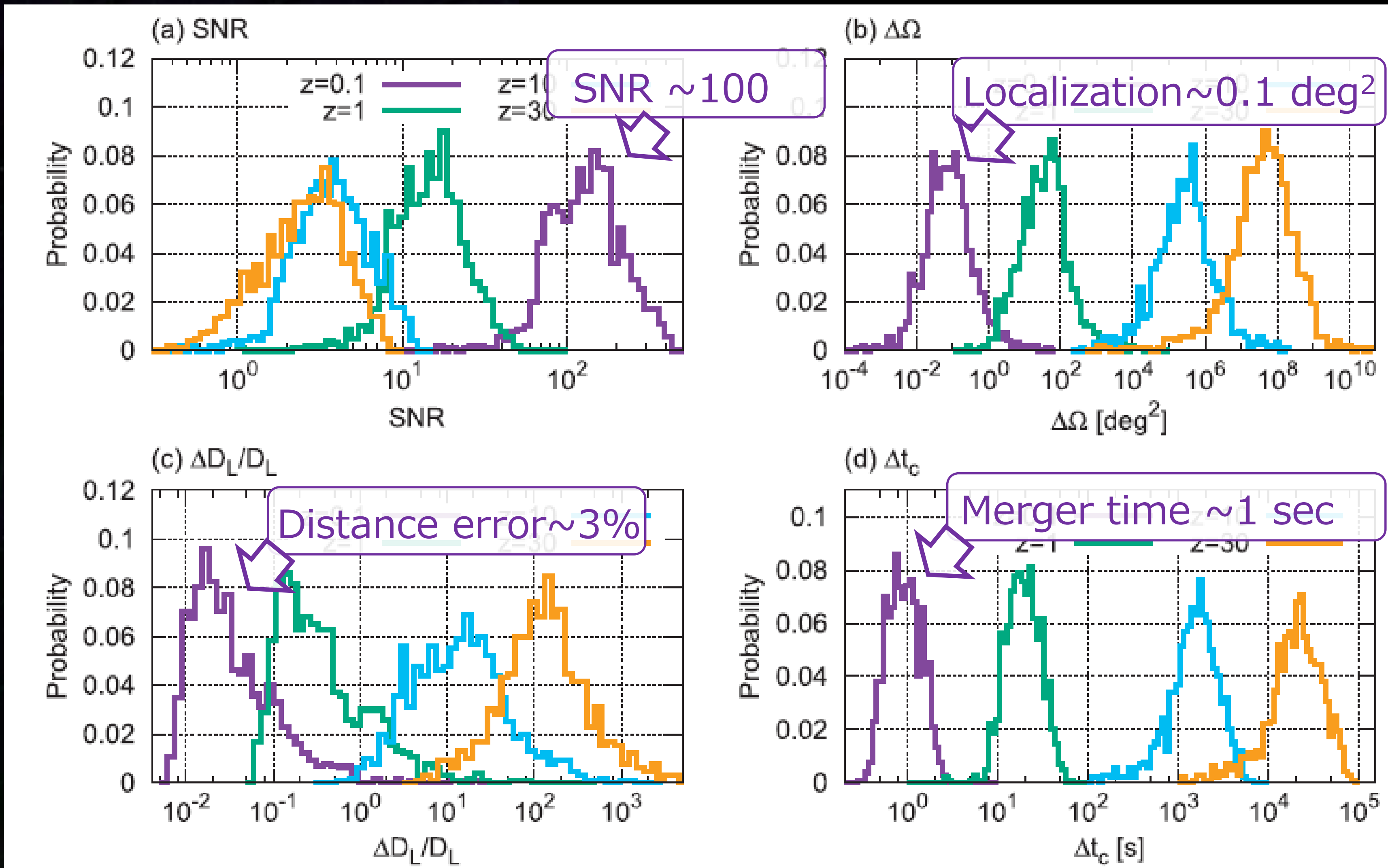
B-DECIGO Sciences for CBC

- With its <u>BBH</u> observable range, in B-DECIGO
  Detection Rate will be $\sim 4 \times 10^4 - 10^6$ events/yr .
- Range for <u>BNS</u> is ~2Gpc → ~ 100 events/yr .

- With low-freq. GW observations, <u>longer observation time</u> 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 → <u>Alerts for GW-EM</u>.
  * Mass, Distance, Spin → <u>Origin and nature of BBH</u>.

Parameter Estimation Accuracy

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



※ 30$M_\odot$ BBH merger case, the signal integration upto 15days before merger.

Summary

Summary

- First direct detection of GW opened 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, multiple detectors, and with different frequencies.
- Japanese KAGRA will improve the source parameter estimation accuracy. Best effort to join the network.
- Space mission B-DECIGO enables an alert before merger for EM counterpart search. Light curve can be observed just after merger. More event rate, higher SNR is expected.

End

中性子星の状態方程式に対する制限

GRBのモデル (形成された天体が BH or マグネター)と, 重力波観測から求められた質量から,中性子星の状態方程式に対する制限が与えられる (SHTやMS1モデルでは,BHはできなさそう).

THE ASTROPHYSICAL JOURNAL LETTERS, 848:L13 (27pp), 2017 October 20 Abbott et al.

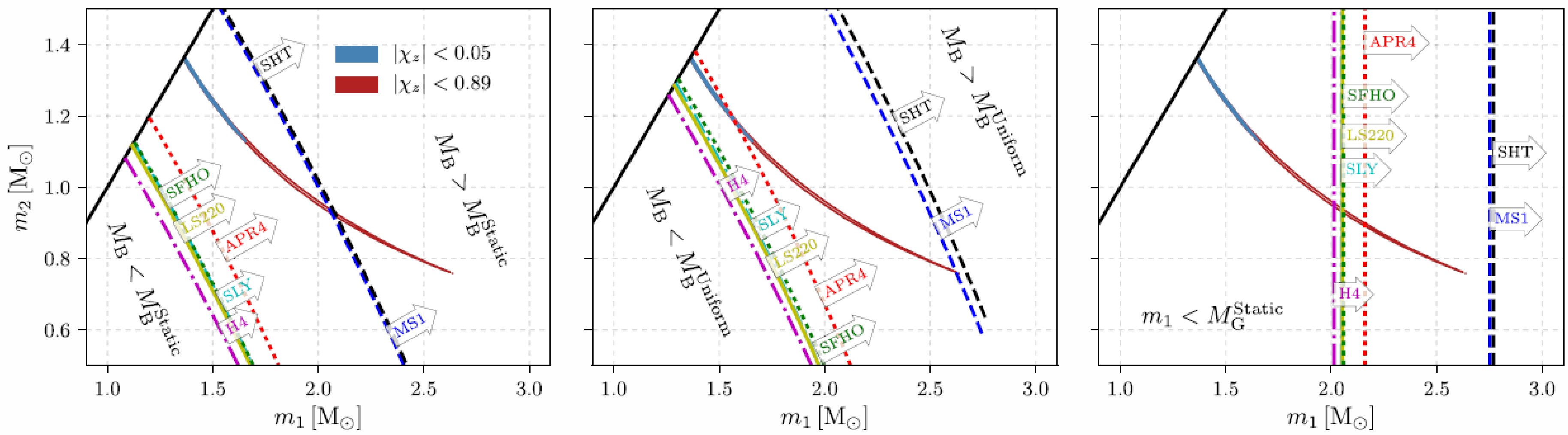
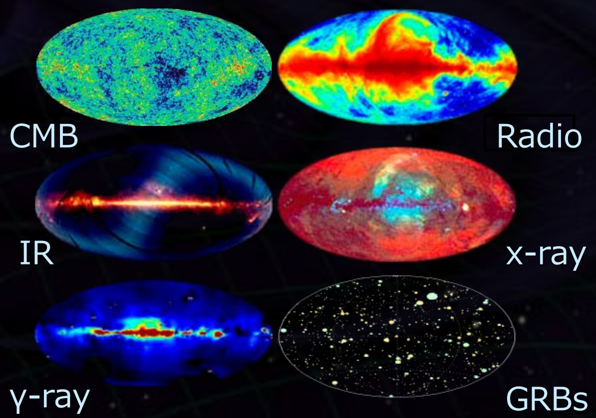


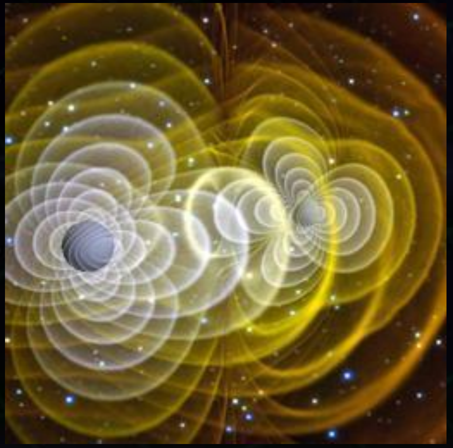
Figure 3. Critical mass boundaries for different EOSs in comparison with the 90% credible region of the gravitational masses inferred from GW170817 (prior limits on the spin magnitude, $|\chi_z|$, given in the legend). The slanted curves in the left panel and middle panel correspond to the maximum baryonic mass allowed for a single non-rotating NS (left) and for a uniformly rotating NS (middle). Arrows indicate for each EOS the region in the parameter space where the total initial baryonic mass exceeds the maximum mass for a single non-rotating or uniformly rotating NS, respectively. The right panel illustrates EOS-dependent cuts on the gravitational mass m_1 of the heavier star, with arrows indicating regions in which m_1 exceeds the maximum possible gravitational mass $M_G^{\rm Static}$ for non-rotating NSs. In all three panels the black solid line marks the $m_1 = m_2$ boundary, and we work in the $m_1 > m_2$ convention.

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.



Current Status and the Next Steps

- Observation Runs by 2nd-generation GW antennae:
  - *aLIGO and AdV has started observation runs.
  - *KAGRA and LIGO-India will join the network soon.
    - → 10~100 events/year expected.
- Proposals for 3rd-generation GW antennae:
  - *ET (Einstein Telescope) in Europe.
  - *CE (Cosmic Explorer) in USA.
    - → Obs. range of z>10 for compact binary mergers.
- Space GW antenna missions for low-freq. GWs:
  - *LISA for MBHs and stationary binaries.
  - *B-DECIGO and DECIGO for IMBH and GWB.
    - → Galaxy, Cosmology, and Fundamental physics.