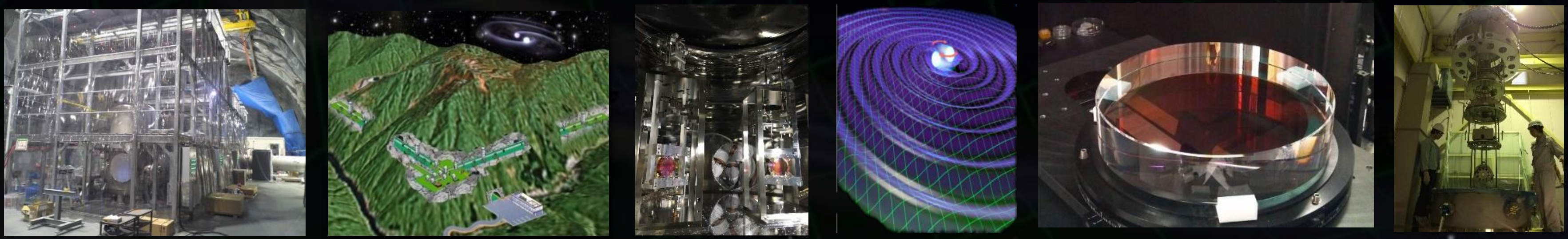
Observation of Gravitational Waves

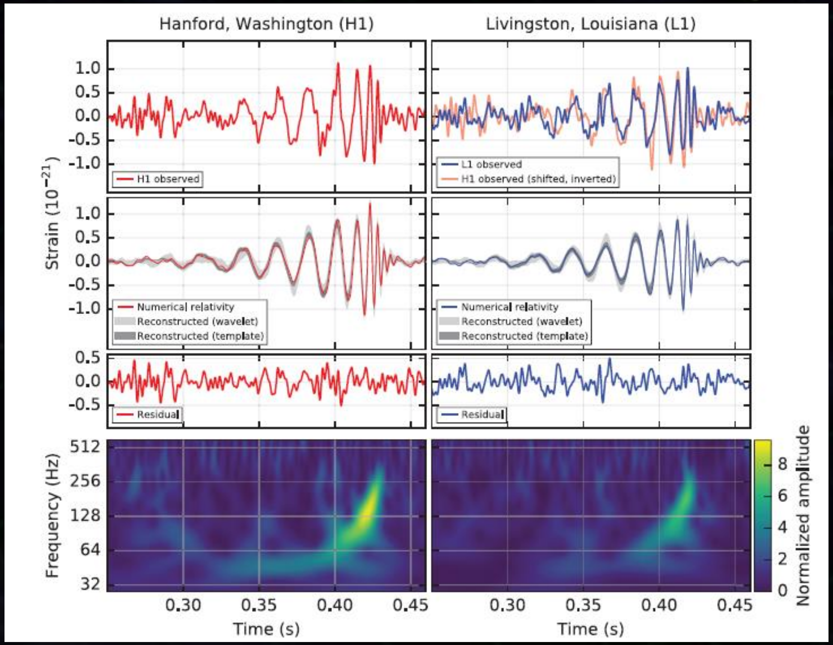
Masaki Ando (Univ. of Tokyo / NAOJ)



Physics in LHC and the Early Universe (Jan. 10th, 2017, The University of Tokyo, Tokyo)

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

Impacts of the First Detection

(1) The First Direct Observation of GW.

GW was directly observed for the first time 100 years after theoretical prediction by GR. The waveform was well-matched with the prediction.

→ Solved the 'Einstein's final homework'.

(2) Opening of a new field of GW Astronomy.

We obtained a completely new method to observe the universe. There already are new discoveries: existence of heavier-mass BHs around $30\ M_{\odot}$, and binary of them. Such a system cannot be found by conventional EM observations.

Current Status and the Next Steps

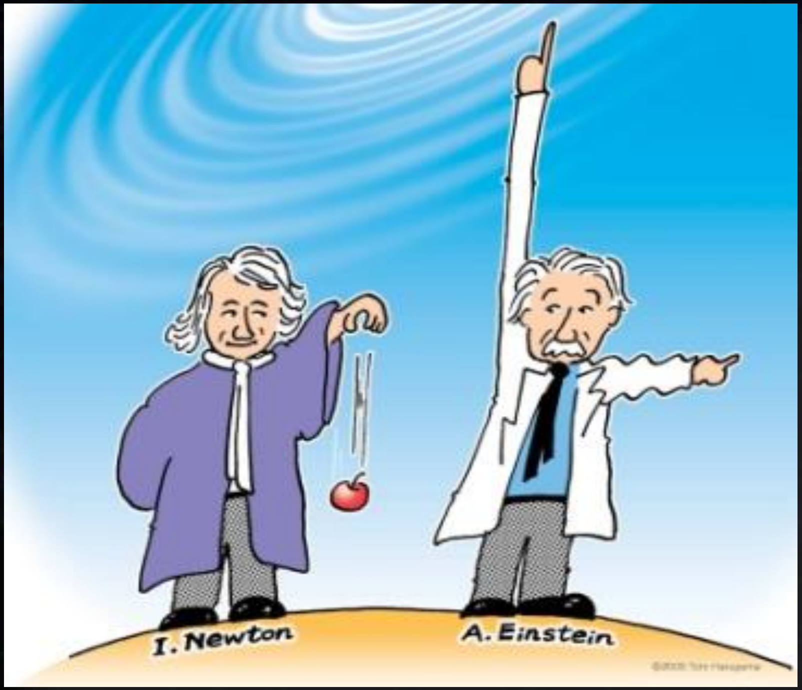
- Observation Runs by 2nd-generation GW antennae:
  - *aLIGO has started O2 from December 2016.
  - *AdV and KAGRA will join the network soon.
    - → ~100 events/year expected.
- Proposals for 3rd-generation GW antennae:
  - *ET (Einstein Telescope) in Europe.
  - *CE (Cosmic Explorer) in USA.
    - → 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.

Outline

- Introduction to GW Observation
- First Detection of GW by LIGO
- Current and Future Steps
- Space Missions
- Summary

Einstein’s the ‘Last Homework’

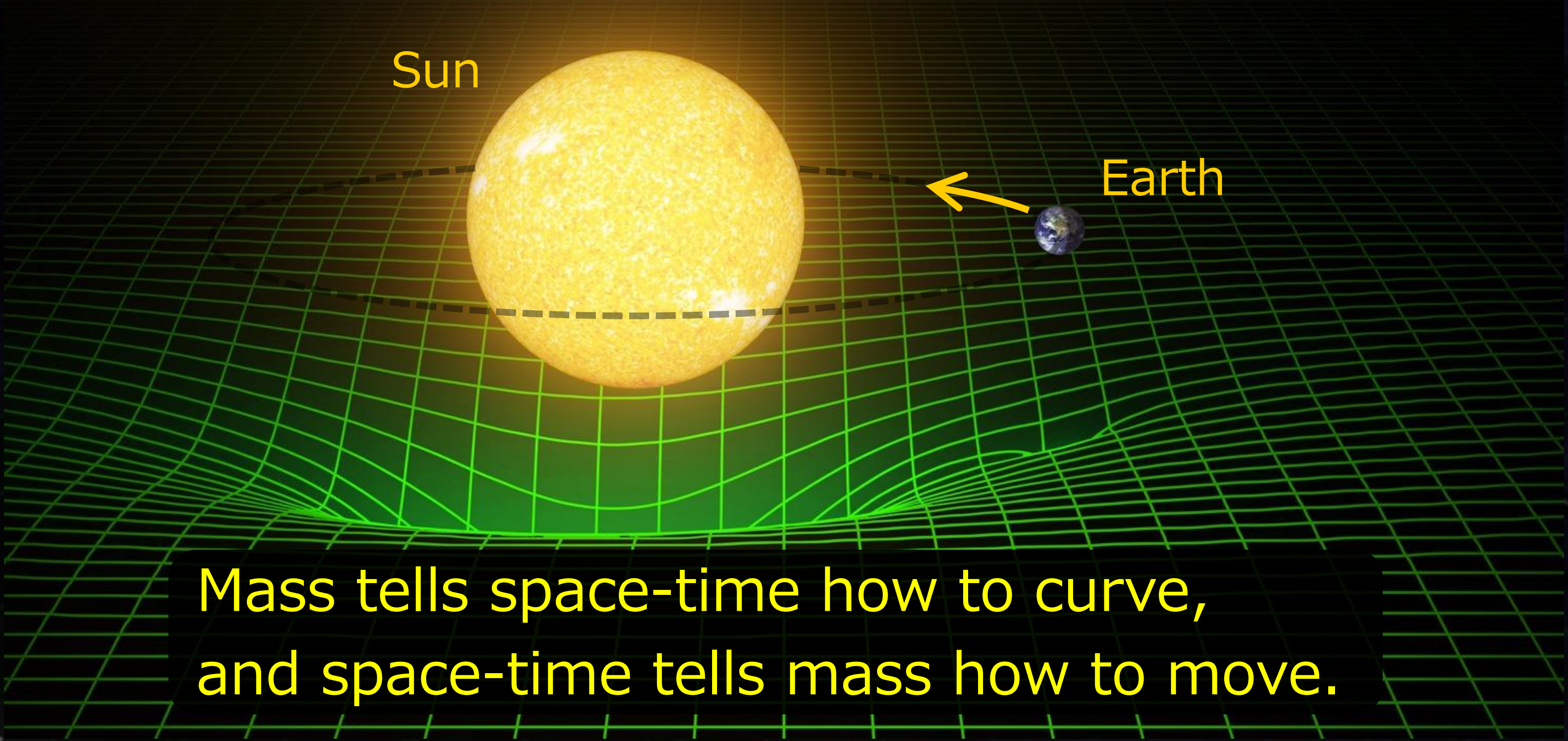
- Brief introduction to General relativity and Gravitational Waves -



イラスト：Tom Haruyama

Gravity in General Relativity

In the theory of General Relativity, gravity is interpreted as a nature of space-time.



Mass tells space-time how to curve, and space-time tells mass how to move.

Courtesy Caltech/MIT/LIGO Laboratory

Gravitational Wave

Rapid motion of mass will cause ripples of space time, which propagate at the speed of light.

⇨ **Gravitational Wave**

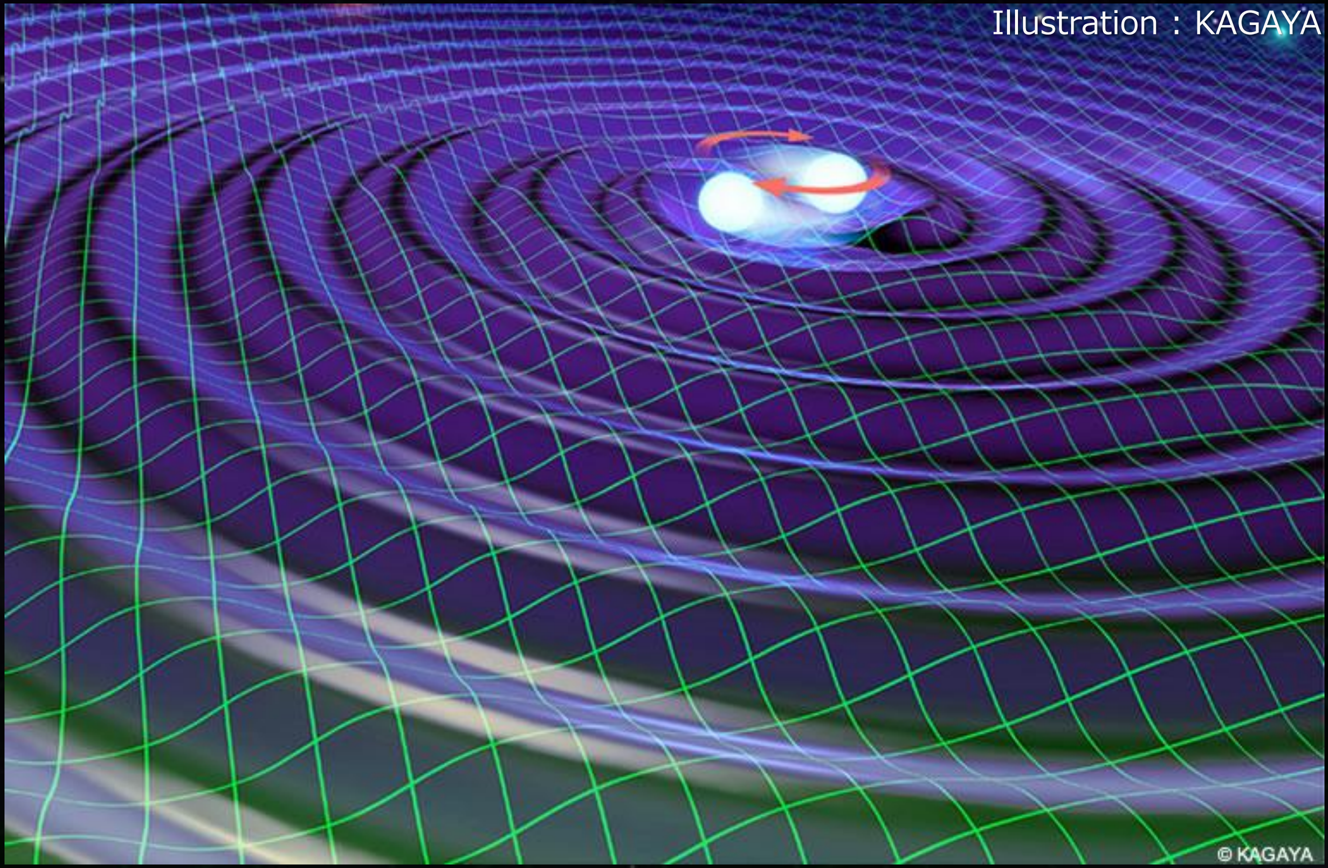


Illustration : KAGAYA

Effect of GW

Effect of GW :

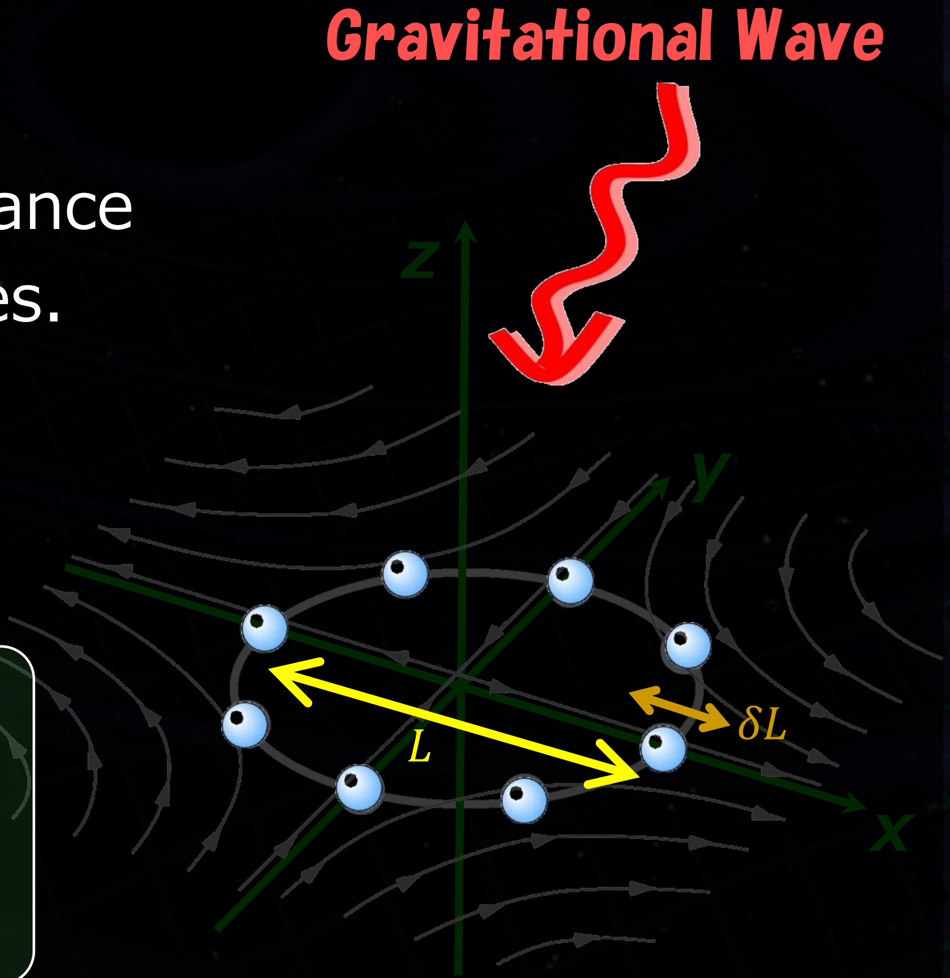
Change in the proper distance between separated masses.

Amplitude of GW is described by strain ‘h’ .

$h \sim \delta L / L$

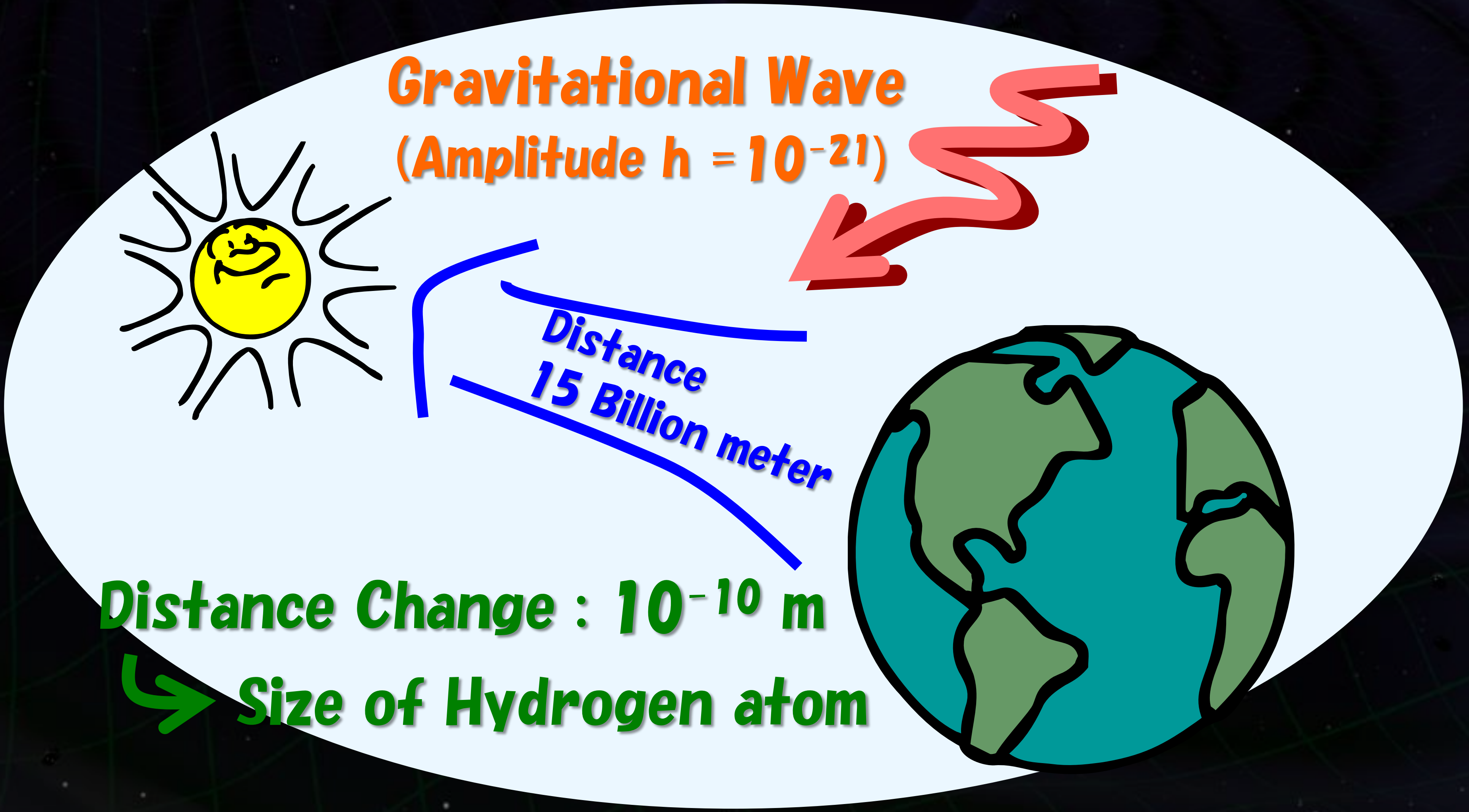
δL : Change in distance

L : Original separation



Example of GW Effect

GW effect is Extremely Tiny



Gravitational Wave
(Amplitude $h = 10^{-21}$)

Distance
15 Billion meter

Distance Change : 10^{-10} m

→ **Size of Hydrogen atom**

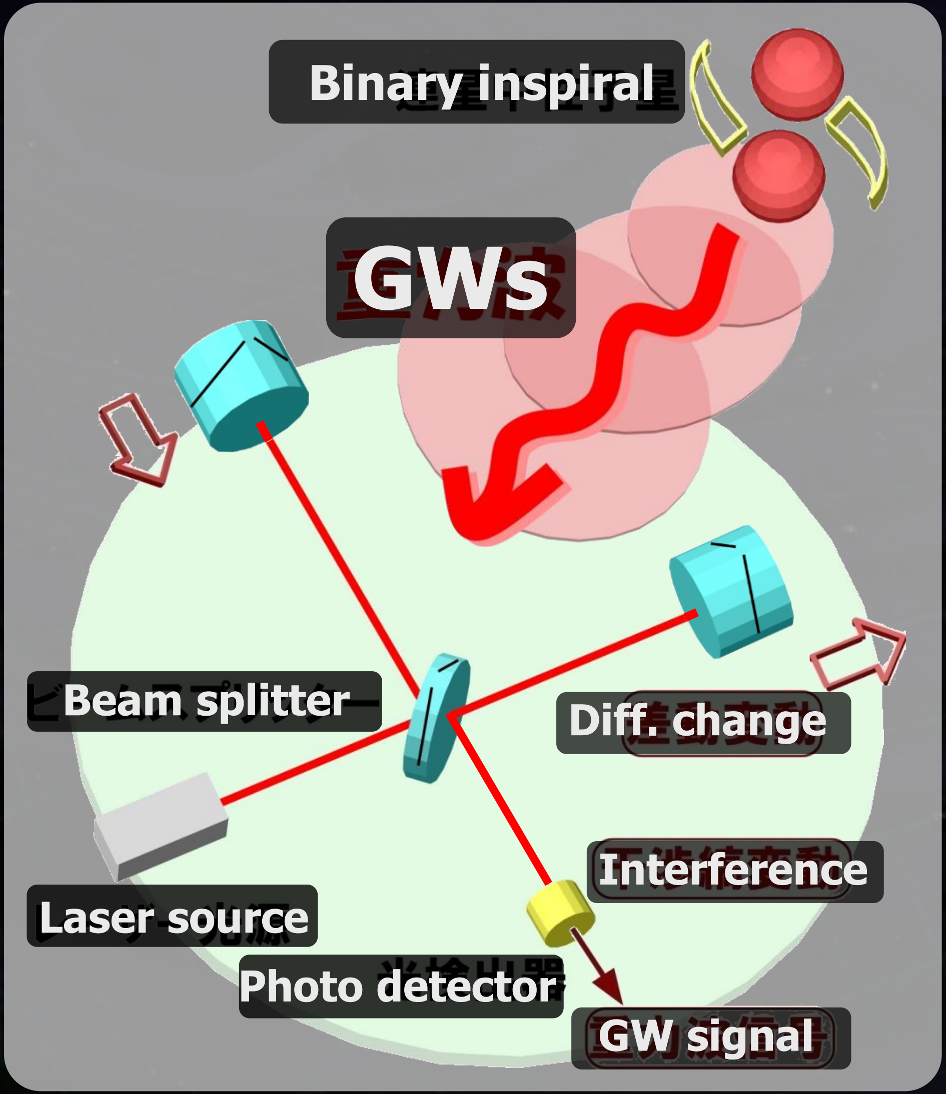
Principle of GW Antenna

Laser Interferometer
(Michelson Interferometer)

GW will cause differential length change in two arms

⇩

GW is observed from the light-power change on the photo detector.



First detection of GW by LIGO

- What was observed and what we know from the signal -

Courtesy Caltech/MIT/LIGO Laboratory

LIGO

- LIGO (Laser Interferometer Gravitational-Wave Observatory) : GW observatory with two 4-km laser interferometric antennae placed at Hanford and Livingston sites, separated by about 3,000km from each other.
- Project approved in 1992. Start construction in 1994. First obs. run in 2002 (Initial LIGO). Upgrade to aLIGO (Advanced LIGO) from 2008.

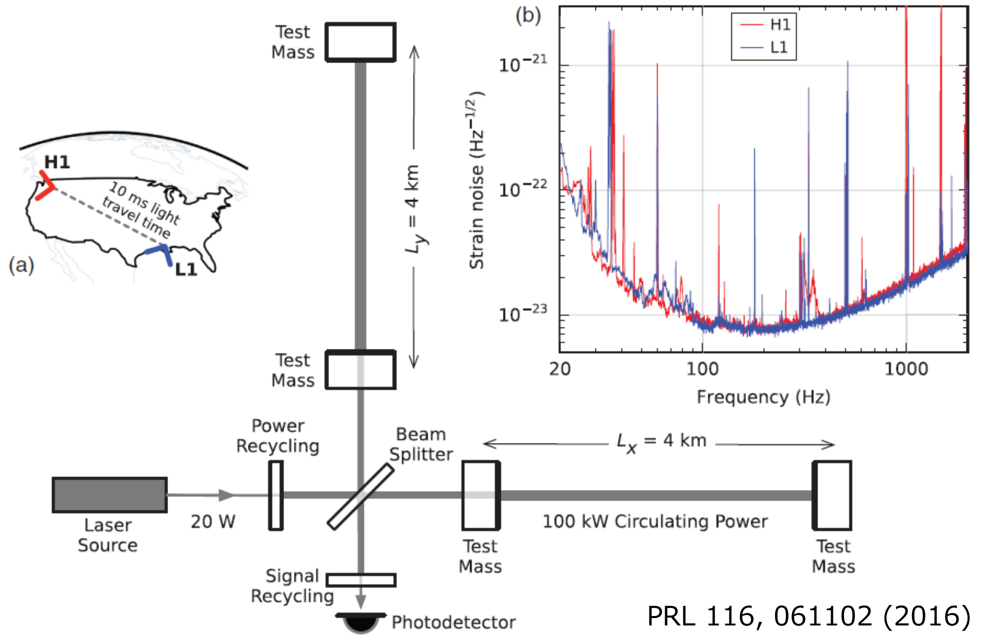
Courtesy Caltech/MIT/LIGO Laboratory

LIGO Hanford Observatory (LHO)

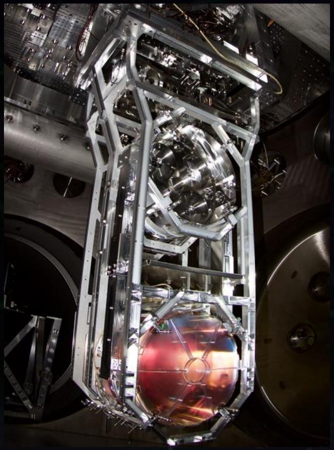
LIGO Livingston Observatory (LLO)

LIGO Configuration and Sensitivity

- First observation run (O1) by aLIGO
  from Mid.-Sept. 2015 to Jan. 2016.
- Sensitivities of 2 LIGO antennae : $h \sim 10^{-22}$ at 100Hz.
- Records ~200,000 auxiliary channels to monitor environment and antenna status.

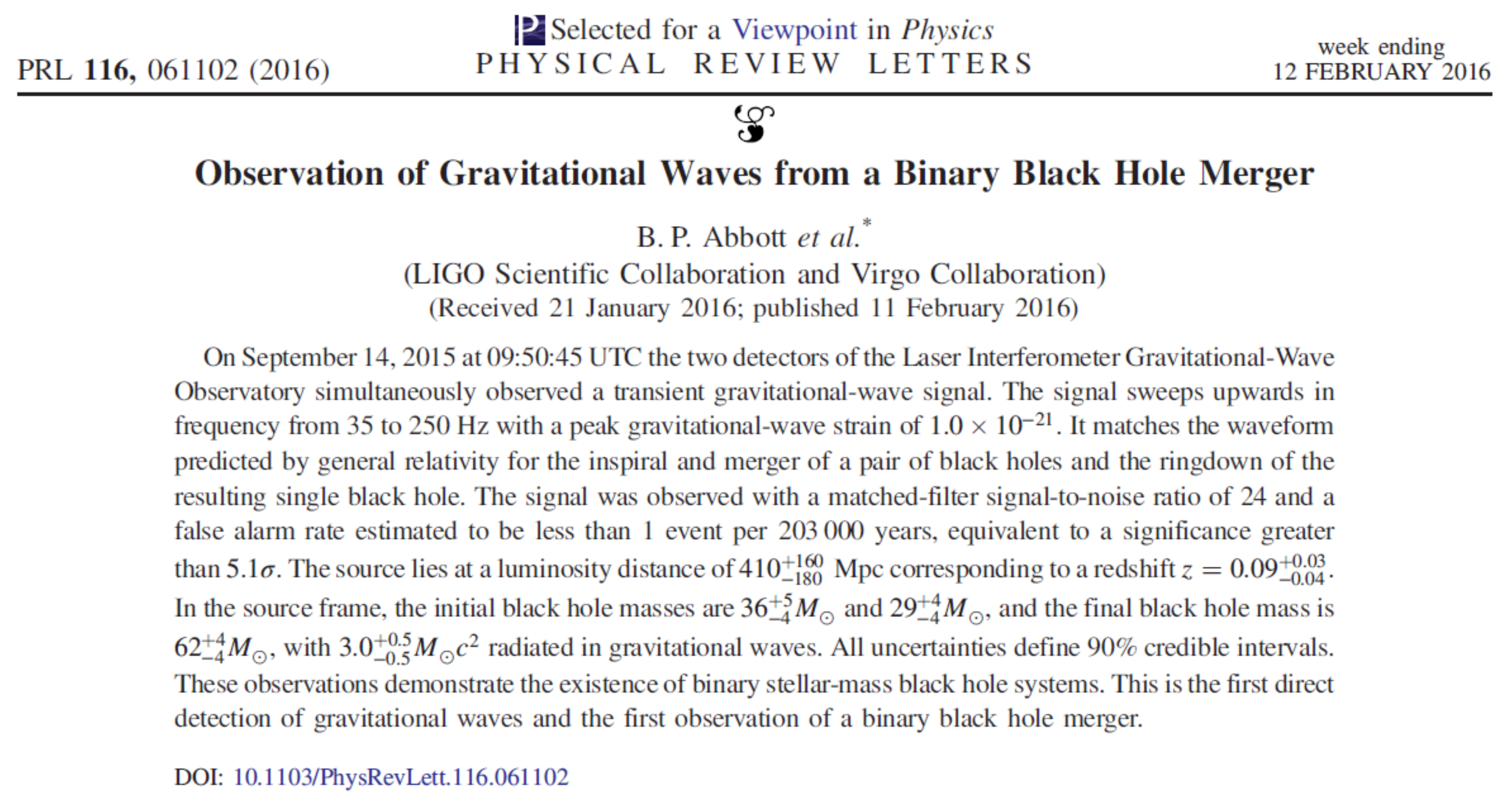


PRL 116, 061102 (2016)



First Detection of GW by LIGO

- On Sept. 14th, 2015, LIGO observed a GW signal from a binary black hole merger.
  → The event was named 'GW150914'.



PRL **116,** 061102 (2016)

Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS

week ending
12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)

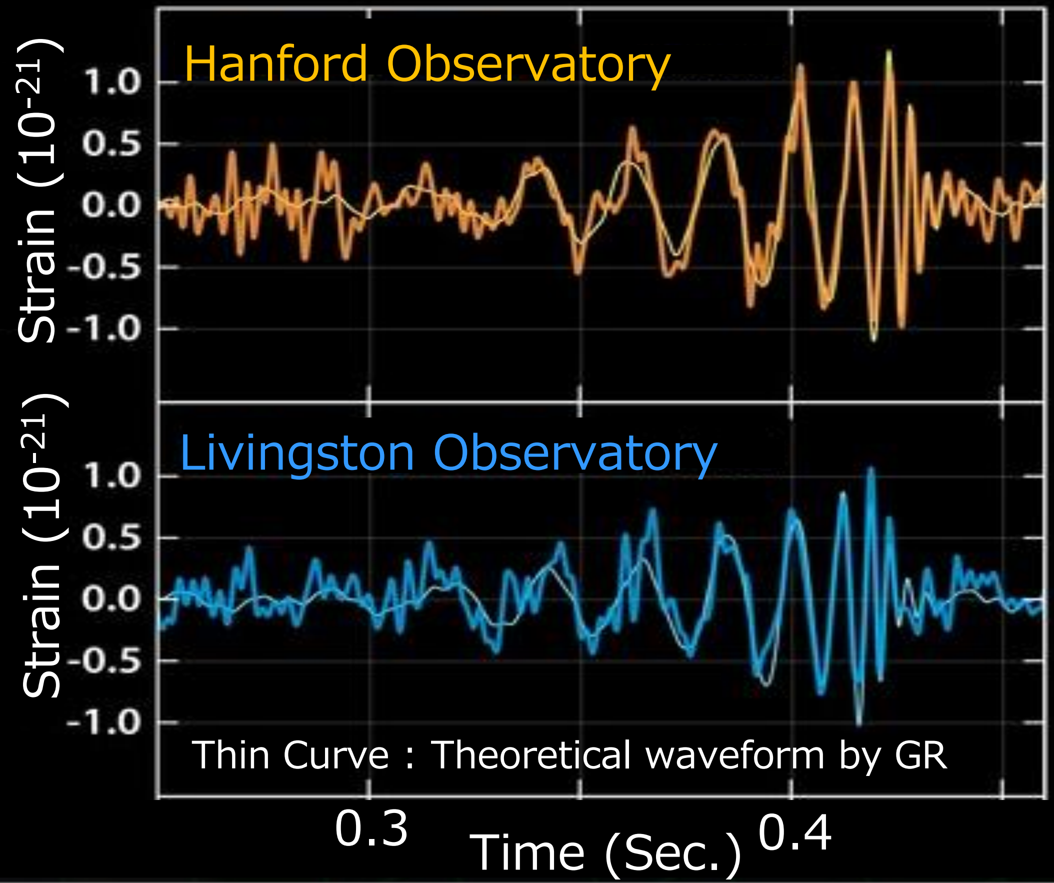
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

Observed Signal by LIGO : GW150914

- LIGO observed large and clear waveform with an amplitude of $h \sim 10^{-21}$, SNR~24 (FAR 1/200,000yr).
- Good coincidence (Δt~7msec). Similar waveform.



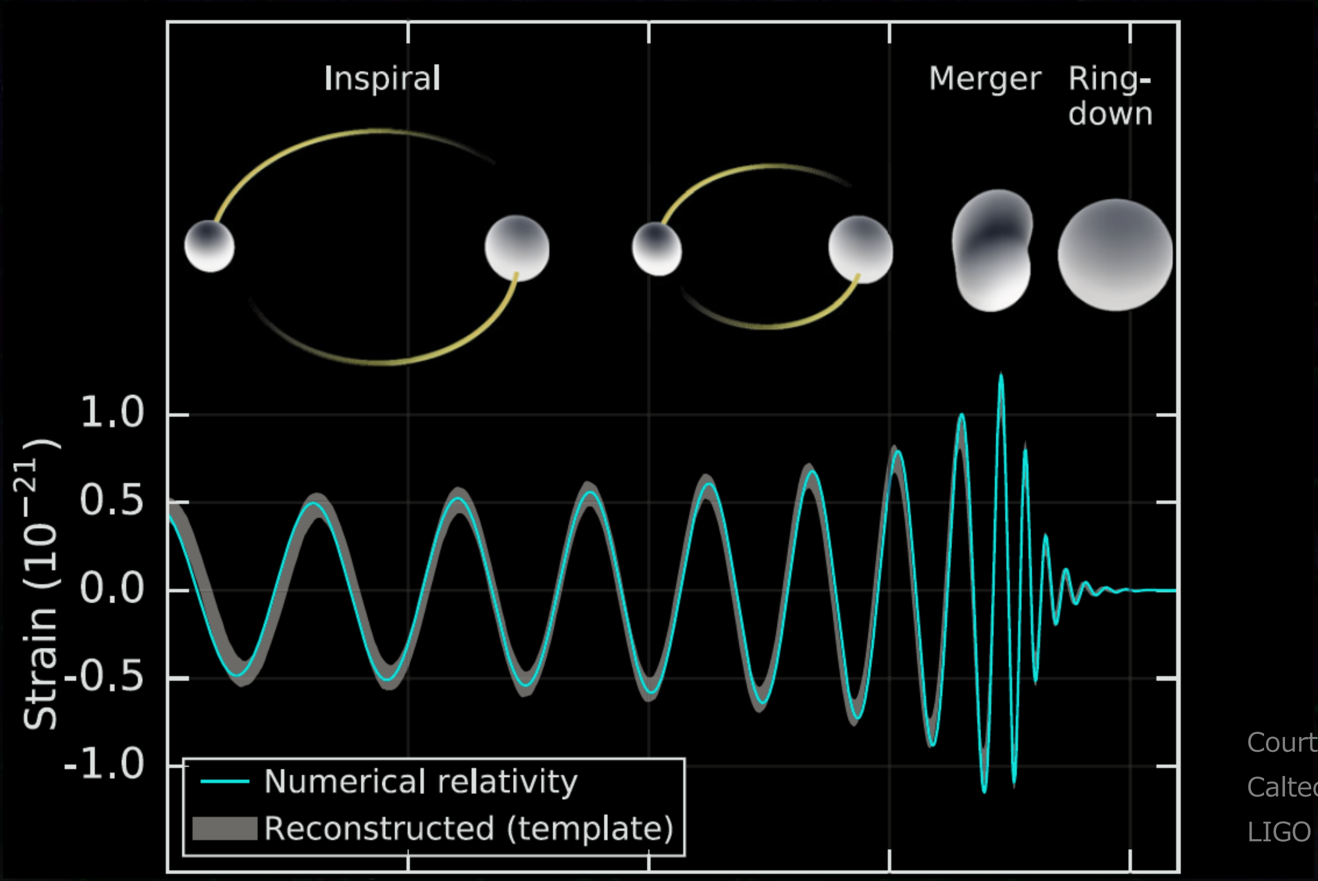
Thin Curve : Theoretical waveform by GR

※ Simple signal processing:
Band-pass 35-350Hz
+ Line cleaning.

Created using materials in LIGO Web
(Courtesy Caltech/MIT/LIGO Laboratory)

The Origin of the Signal

- The signal matches well with the waveform predicted by GR for the inspiral and merger of a pair black hole and ringdown of the resulting single black hole.



Courtesy
Caltech/MIT/
LIGO Laboratory

Parameter Estimation

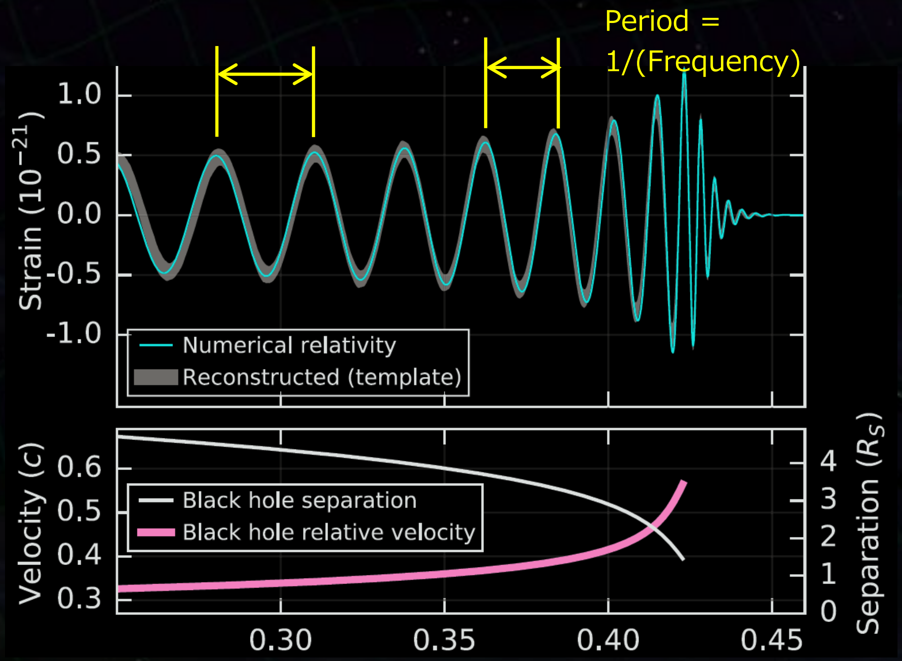
- Parameter estimation only from the GW waveform.
  - * Freq., Freq. change → Masses, Separation, ⋯
  - * Amplitude → Distance to the binary. Inclination,⋯
  - * Ringdown after merger → Mass and Spin of new BH.

- Binary BH masses :

  $36^{+5}_{-4}\,M_\odot$ and $29^{+4}_{-4}\,M_\odot$
- BH mass after merger:

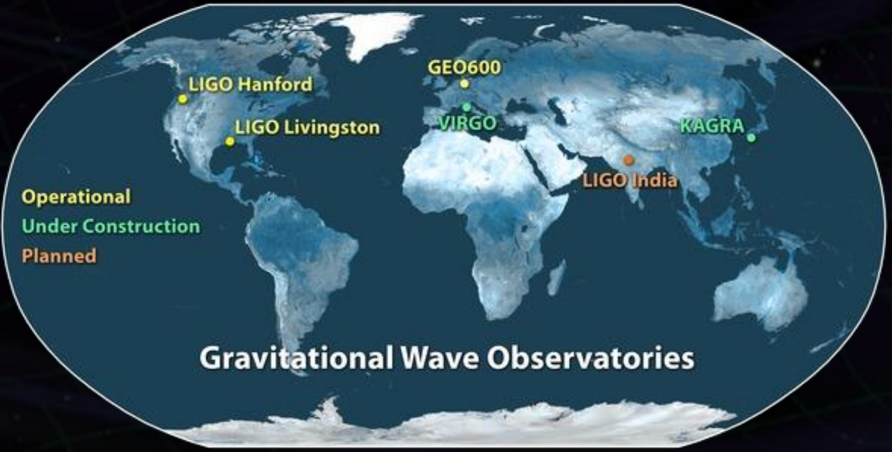
  $62^{+4}_{-4}\,M_\odot$.
- Distance to the source:

  $410^{+160}_{-180}\,M_\odot$ Mpc.



Current and the next steps

- New mystery and follow-up activities -



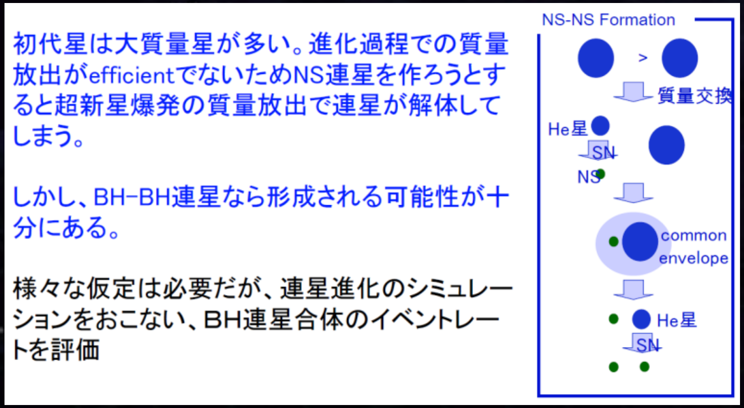
Courtesy Caltech/MIT/LIGO Laboratory

New Mystery

- The result arises new mysteries:
  - *Origin of a 30$M_\odot$ BH binary.
    Several possibilities:
    - (1) First stars (Pop-III).
    - (2) Pop-II stars
    - (3) Primordial BHs
    - (4) Binary formation
      by dynamic friction.

    …
  - *Population and merger rate
    of such a binary system.

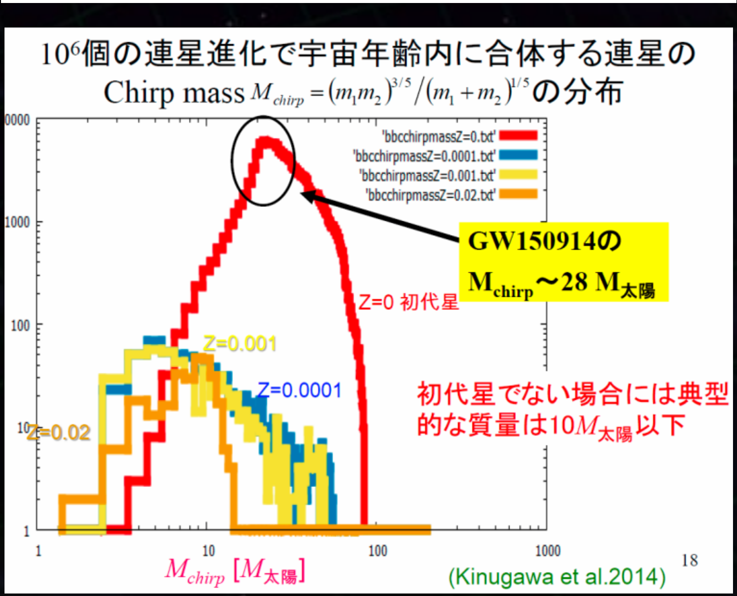
By T. Tanaka (JPS meeting 2016.3.22)



初代星は大質量星が多い。進化過程での質量放出がefficientでないためNS連星を作ろうとすると超新星爆発の質量放出で連星が解体してしまう。

しかし、BH–BH連星なら形成される可能性が十分にある。

様々な仮定は必要だが、連星進化のシミュレーションをおこない、BH連星合体のイベントレートを評価



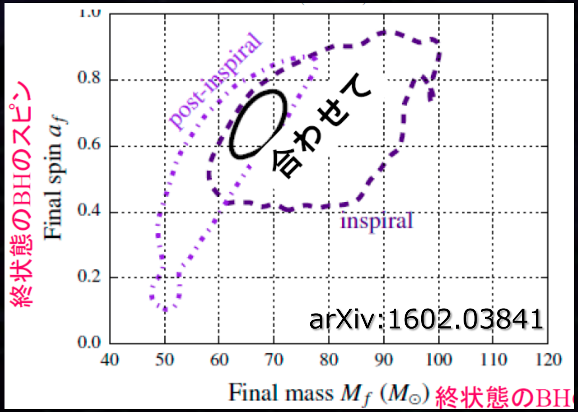
10⁶個の連星進化で宇宙年齢内に合体する連星のChirp mass $M_{chirp} = (m_1 m_2)^{3/5} / (m_1 + m_2)^{1/5}$ の分布

初代星でない場合には典型的な質量は10$M_{太陽}$以下

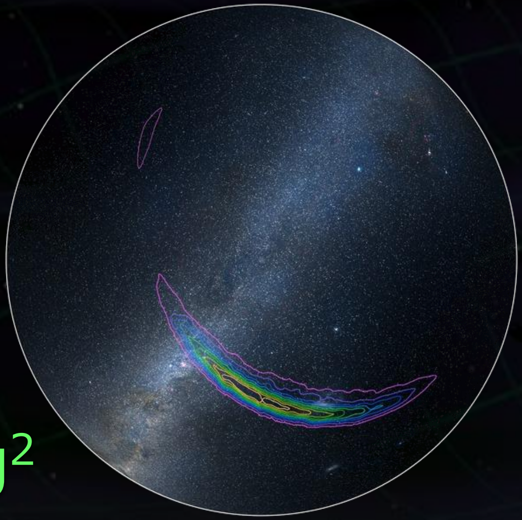
(Kinugawa et al.2014)

Poorly Estimated Parameters

- What was NOT identified well by GW150914
  - * **Spin** : spins at inspiral phase and ringdown phase (after merger) are estimated from waveforms.
    → Consistent, but no more than that because of large error.



  - * **Source position** :
    Time difference observed by 2 LIGO antennae was 7msec. Including the antenna pattern gains a little for localization. → Position Error : **590deg^2**



Antenna Pattern of GW Detector

An Interferometric GW antenna has …

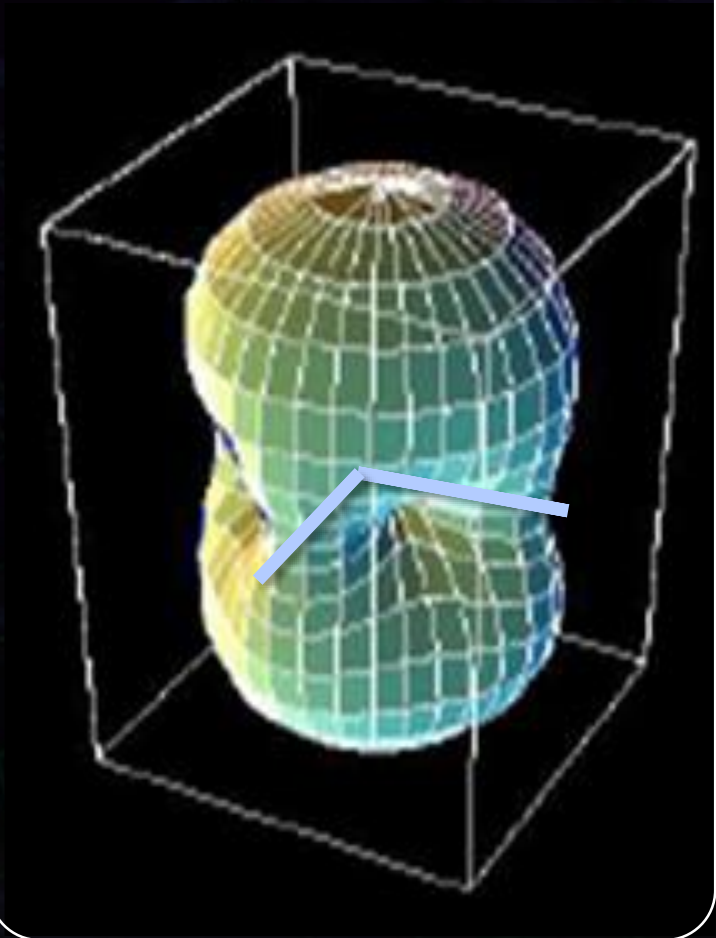
* Good sky coverage

* Poor angular resolution

⇩

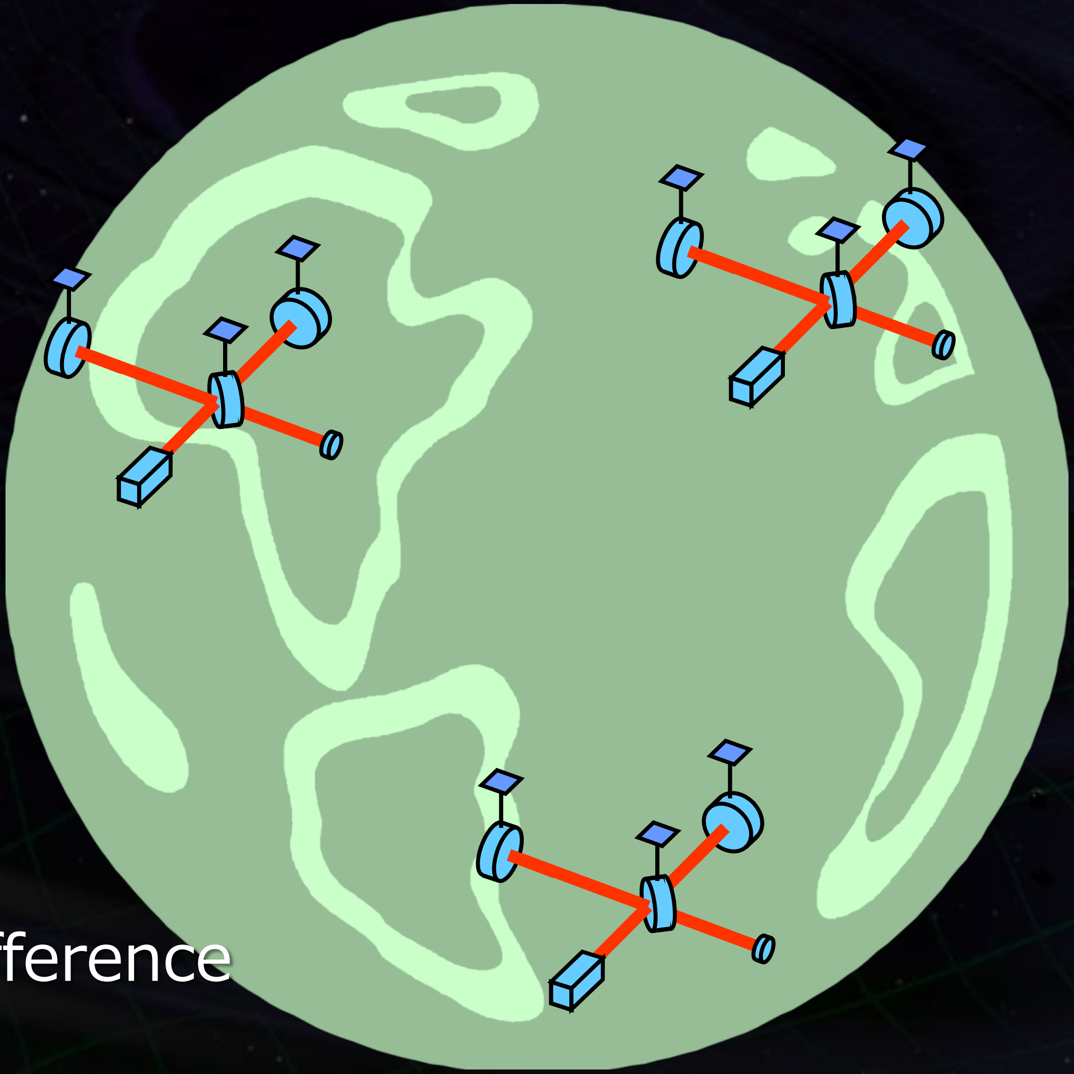
Difficult to determine the source sky position with single antenna.

Antenna Pattern



International Network for Astronomy

Animation :
S. Kawamura (ICRR)



Multiple Detector

⇩

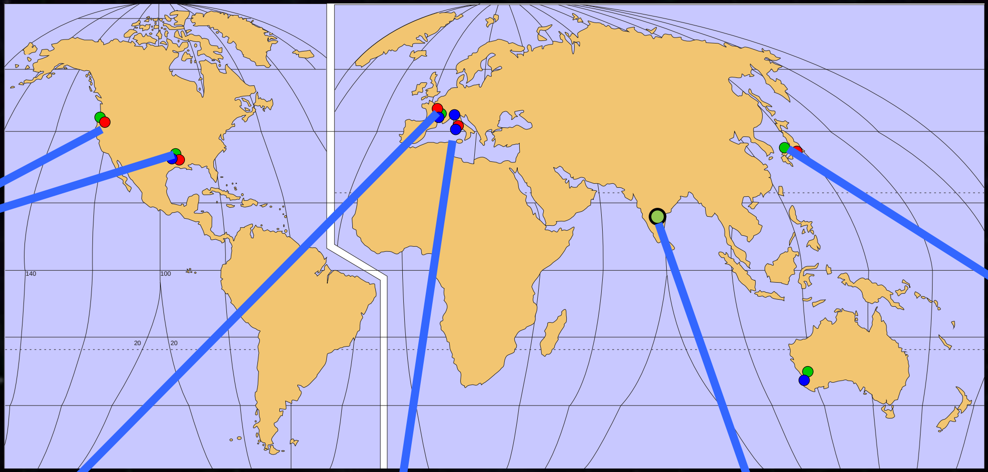
Identify the source
by the arrival-time difference

International GW Network

International network by 2nd–gen GW antennae.

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

aLIGO (USA)
4km x 2



GEO-HF (GER-UK)
baseline 600m

Adv.VIRGO (ITA-FRA)
baseline 3km

LIGO-India
project approved

KAGRA (JPN)
baseline 3km

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

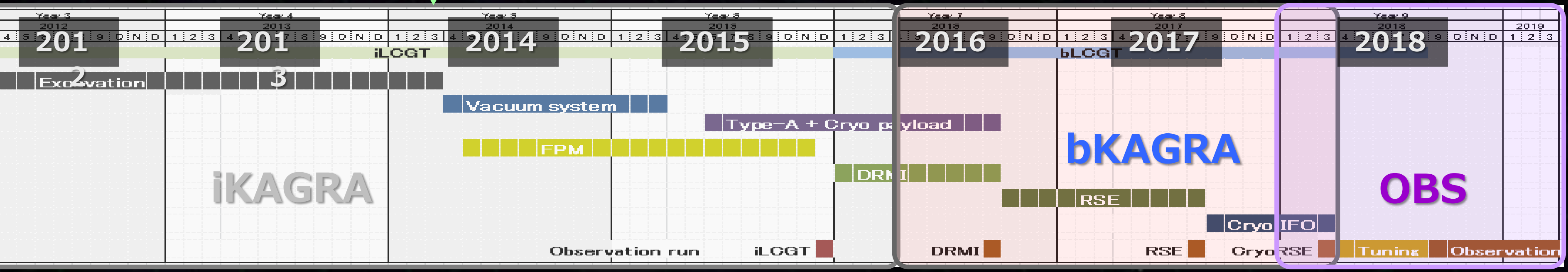
Underground site

Kamioka mine,

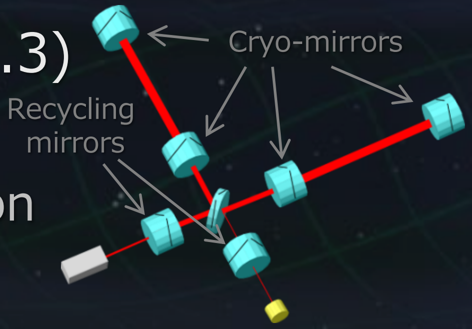
1000m underground

KAGRA Overall Schedule

- **iKAGRA** (2010.10 – 2016.3)
  Michelson interferometer
  - Baseline 3km room temp.
  - Operation of total system with simplified IFO and VIS.



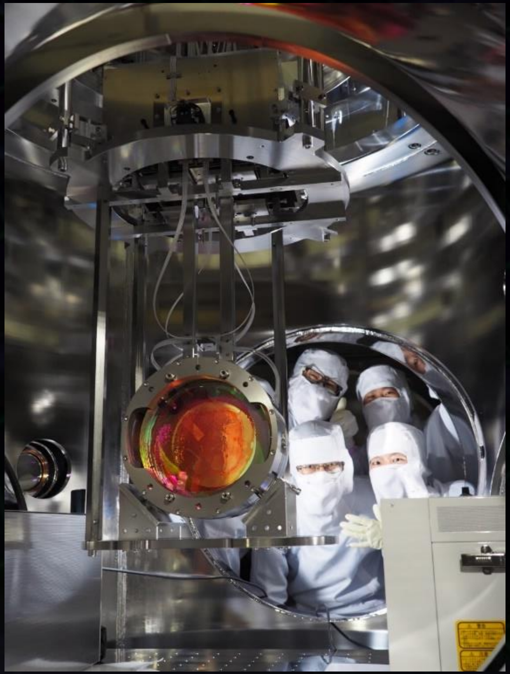
- **bKAGRA** (2016.4 – 2018.3)
  Operation with full config.
  - Final IFO+VIS configuration
  - Cryogenic operation.



iKAGRA Installation and Test Run

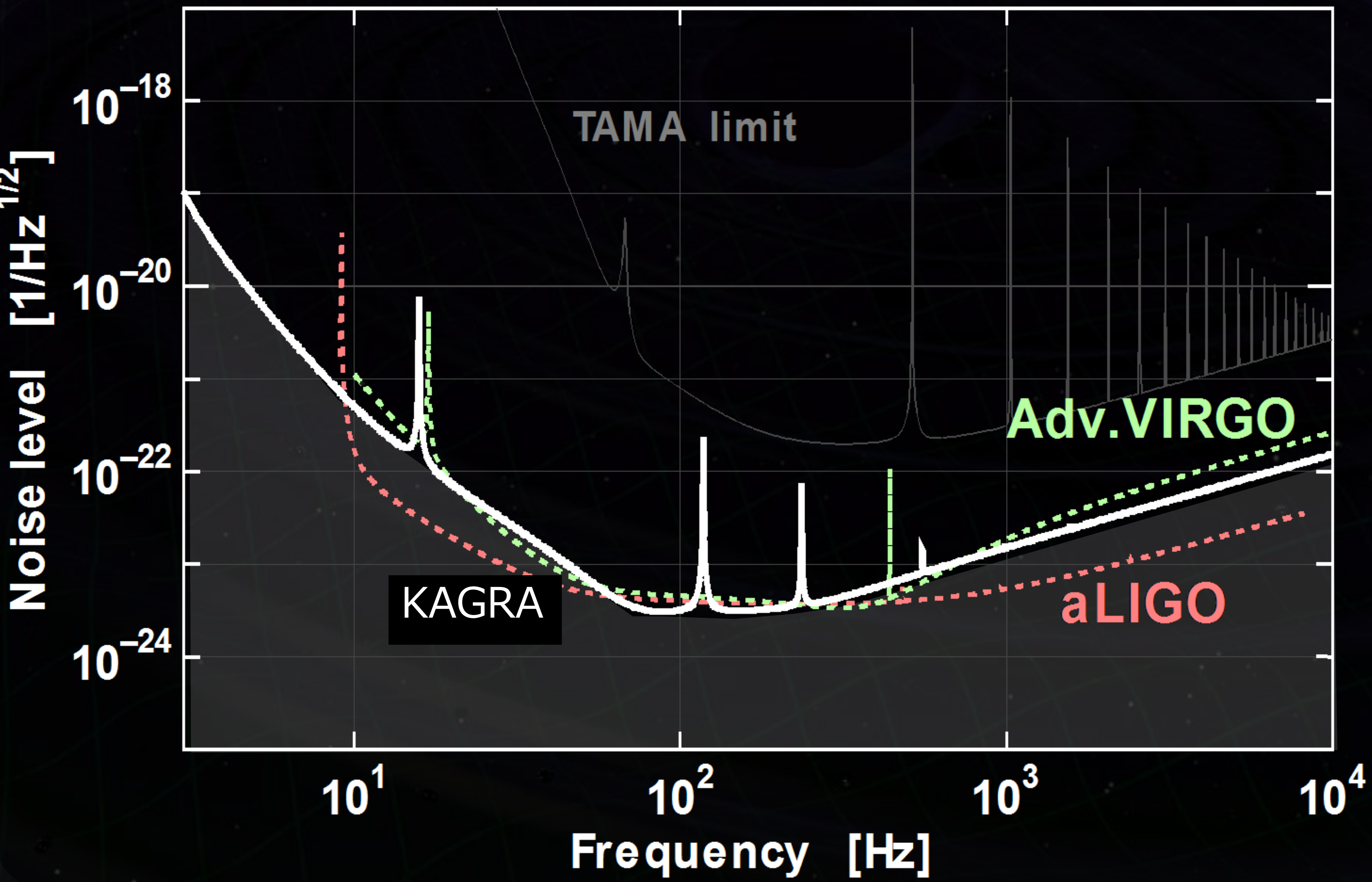
- Tunnel and Facility are almost ready.
- iKAGRA Interferometer and Data system are ready.
- iKAGRA test run for 3weeks in spring 2016
- Operation with full configuration in 2018.

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



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

Sensitivity Comparison



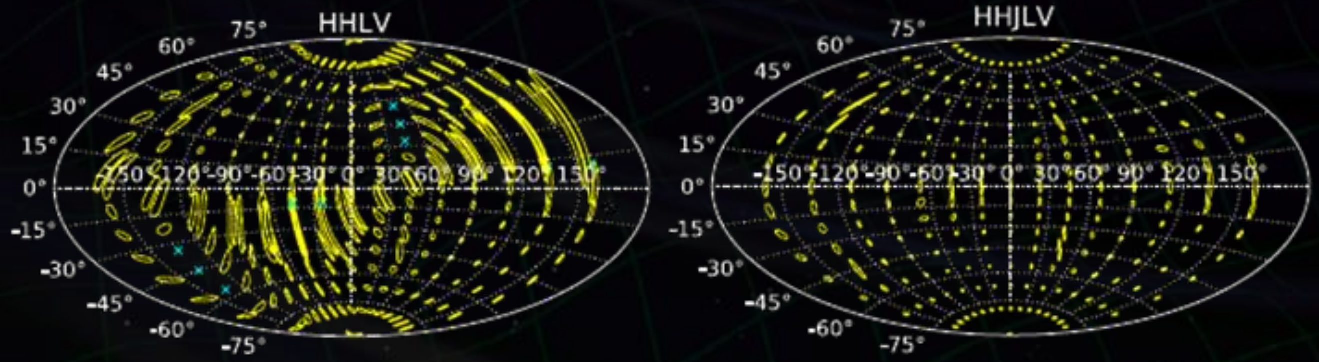
Sky Localization

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

NS-NS coalescence @180Mpc (95%CI)

(1.4,1.4)Msun	LHV	LHVK
median of $\delta\Omega$ $[\mathrm{Deg}^2]$	30.25	9.5

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.

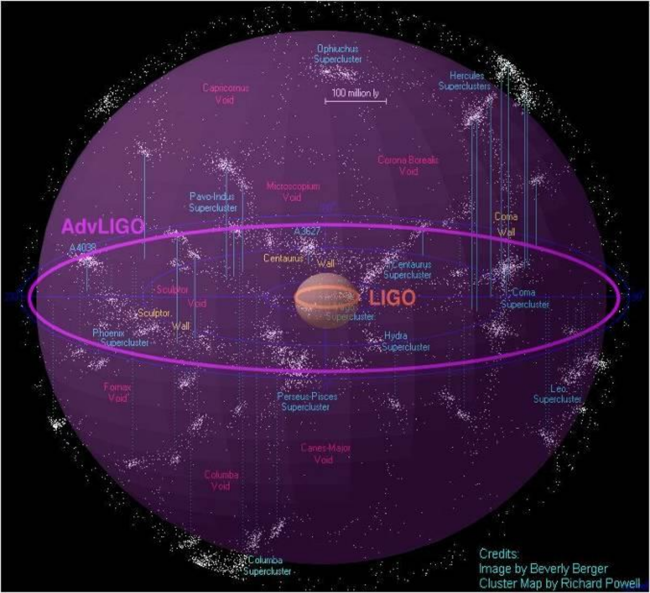
Listen to the Universe by Gravitational Waves

- Future prospects of sciences by GW astronomy -

Future Possibilities

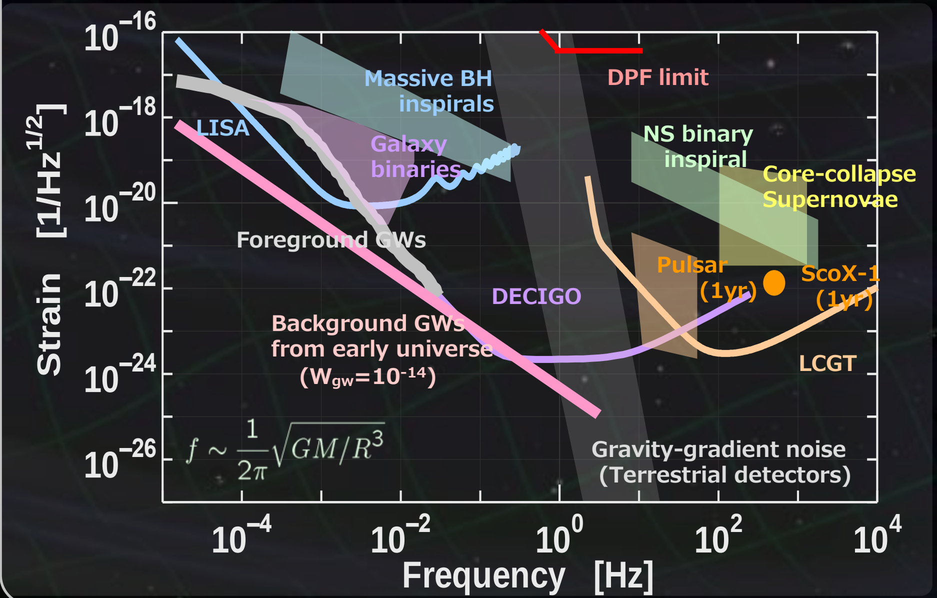
Observation network by 2nd-gen antennae (aLIGO, AdVIRGO, KAGRA, LIGO-India) will be formed in several years ⇨ What will be the next step?

Sensitivity Improvement to cover more galaxies.



Credits:
Image by Beverly Berger
Cluster Map by Richard Powell

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

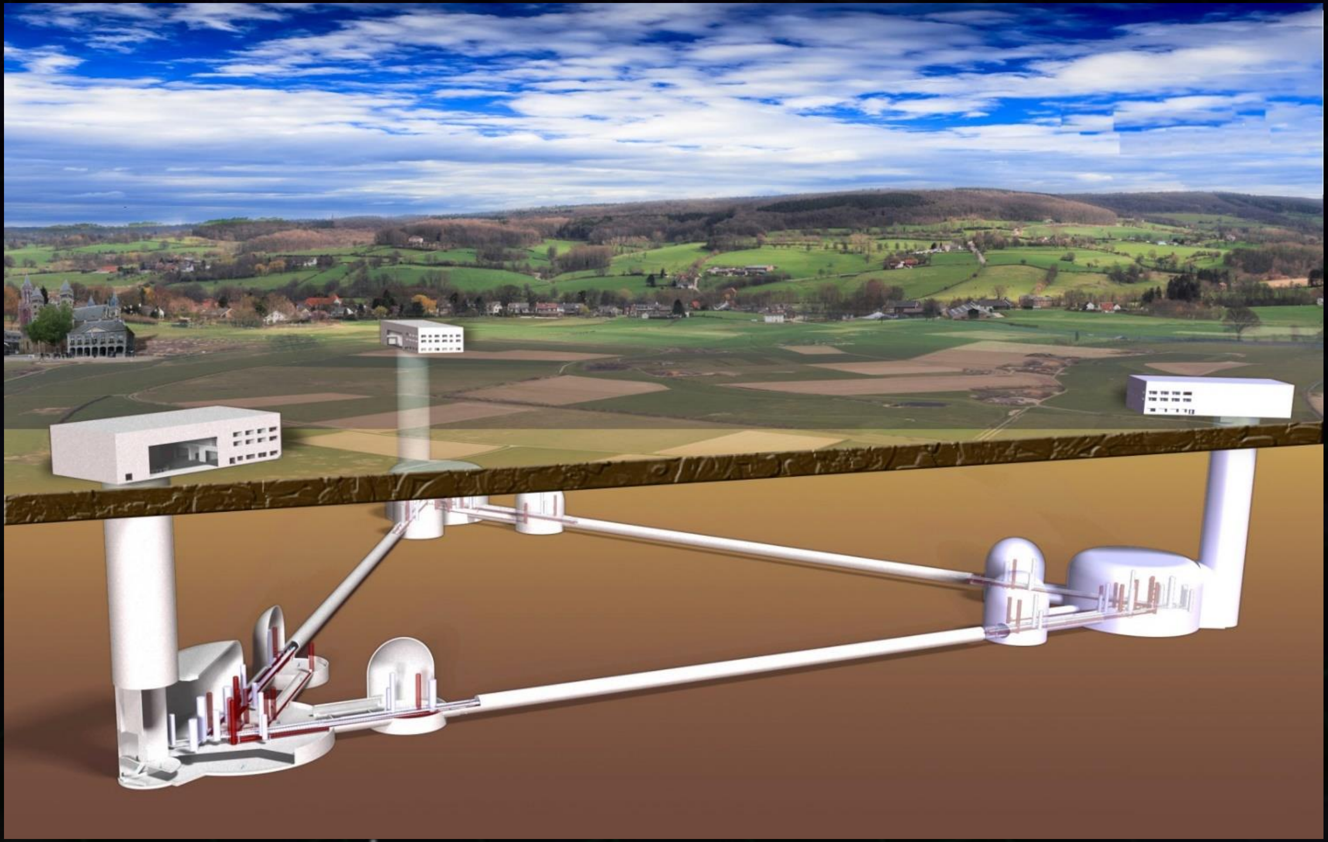


Third generation detectors

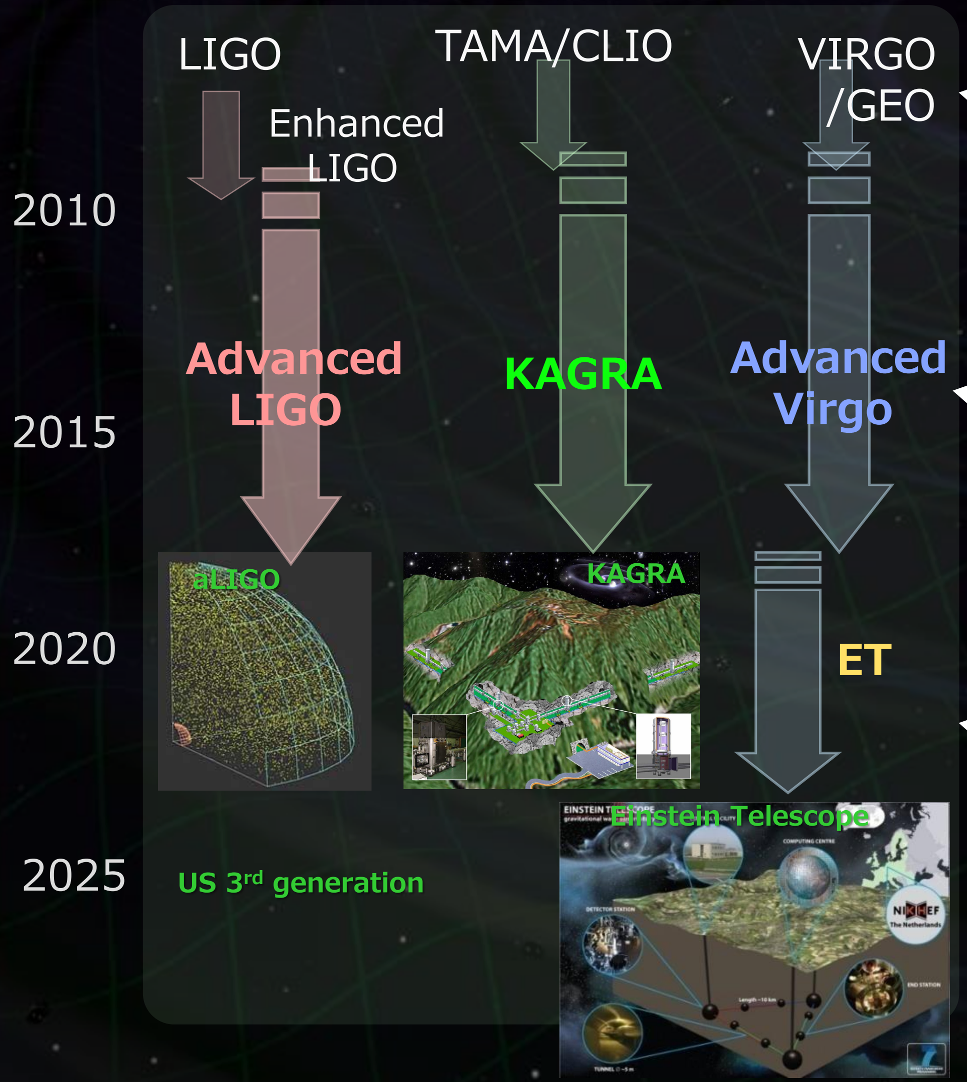
ET (Einstein Telescope)

Sensitivity : x 10 improvement form 2nd-gen ones.

Longer baseline, Underground site, Cryogenic mirrors



Roadmap for Ground-based Antennae



- **1st Generation detector**
  Obs. range: ~20Mpc
  Rate: 10^{-4} – 10^{-2} ev/yr
  → Lucky event, Upper limit

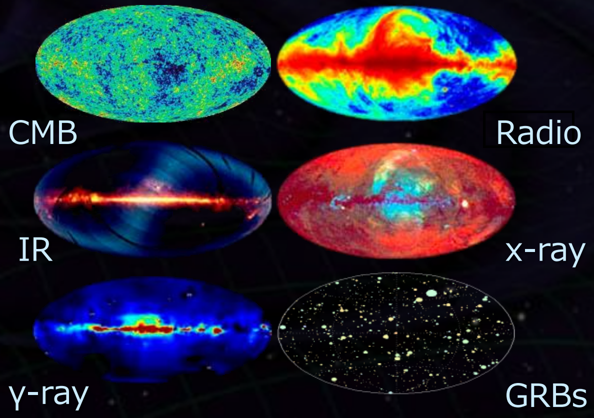
- **2nd Generation detector**
  Obs. Range: ~300Mpc
  Rate: ~10 event/yr
  → Detection, GW astronomy

- **3rd Generation detector**
  Obs. Range ~3 Gpc
  Dairy detection
  → Statistics, Cosmology

Multiple-band Observation

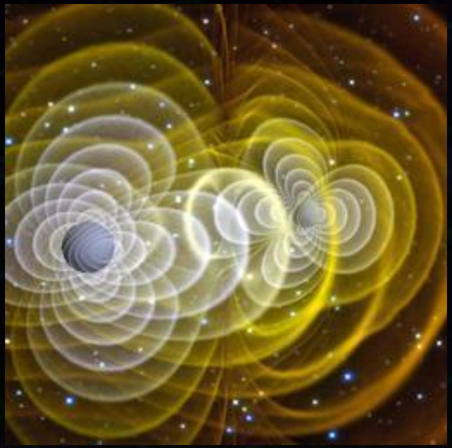
- Electro-Magnetic Observations :

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

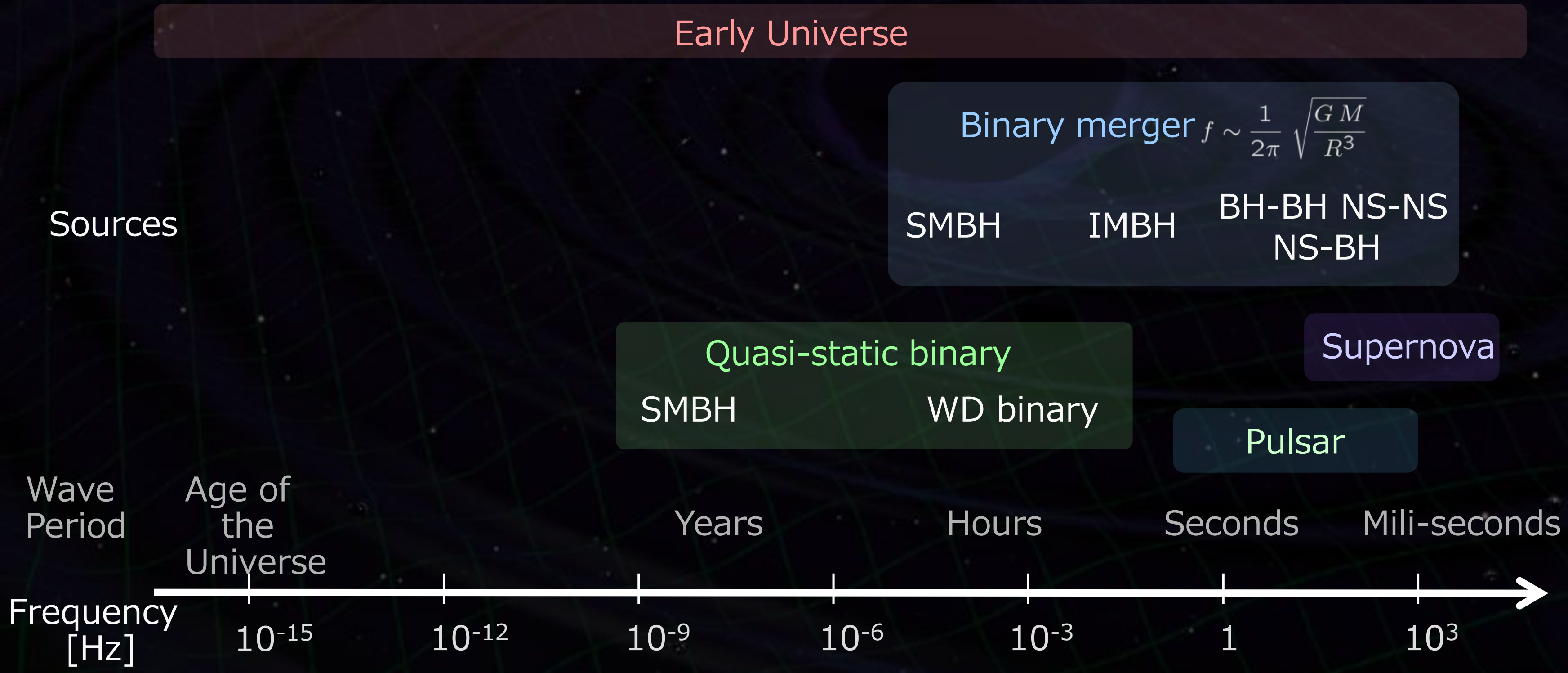


- Gravitational-wave Observations :

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



Source and Detectors



Early Universe

Binary merger $f \sim \frac{1}{2\pi}\sqrt{\frac{G\,M}{R^3}}$

Sources

SMBH

IMBH

BH-BH NS-NS
NS-BH

Quasi-static binary

SMBH

WD binary

Supernova

Pulsar

Wave Period

Age of the Universe

Years

Hours

Seconds

Mili-seconds

Frequency [Hz]

10^{-15}

10^{-12}

10^{-9}

10^{-6}

10^{-3}

1

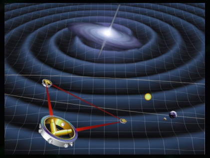
10^{3}

Detectors

CMB
B-mode

Pulsar
timing

Doppler
tracking



Space
interferometer

Ground-based
Interferometer

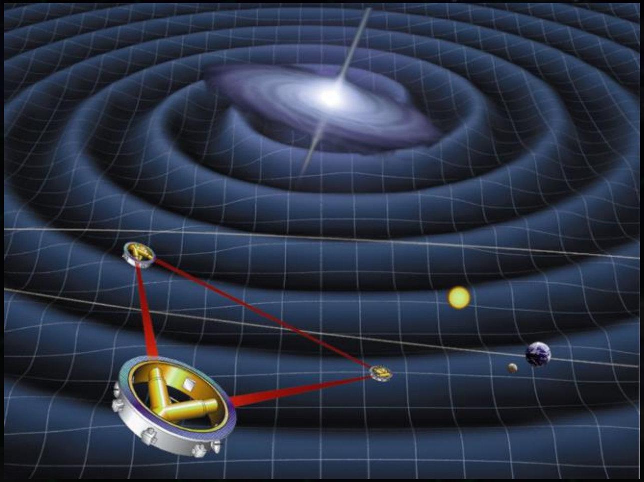
Resonant bar

Space GW antenna

LISA

(Laser Interferometer Space Antenna)

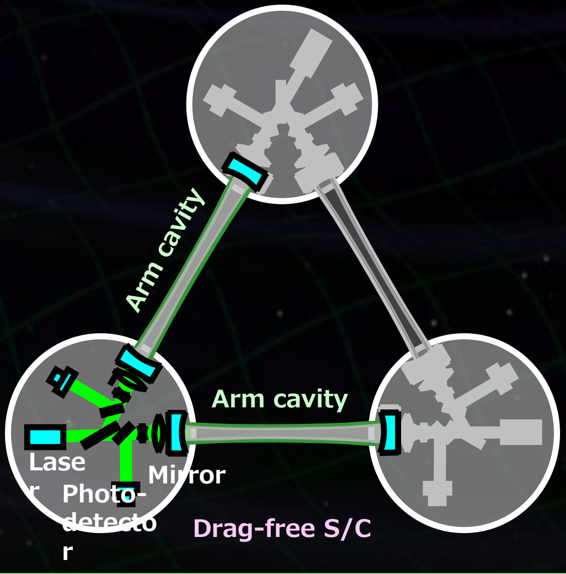
- Target: SMBH, Binaries. GWs around 1mHz.
- Baseline : 1-5M km. Constellation flight by 3 S/C
- Optical transponder.



B-DECIGO

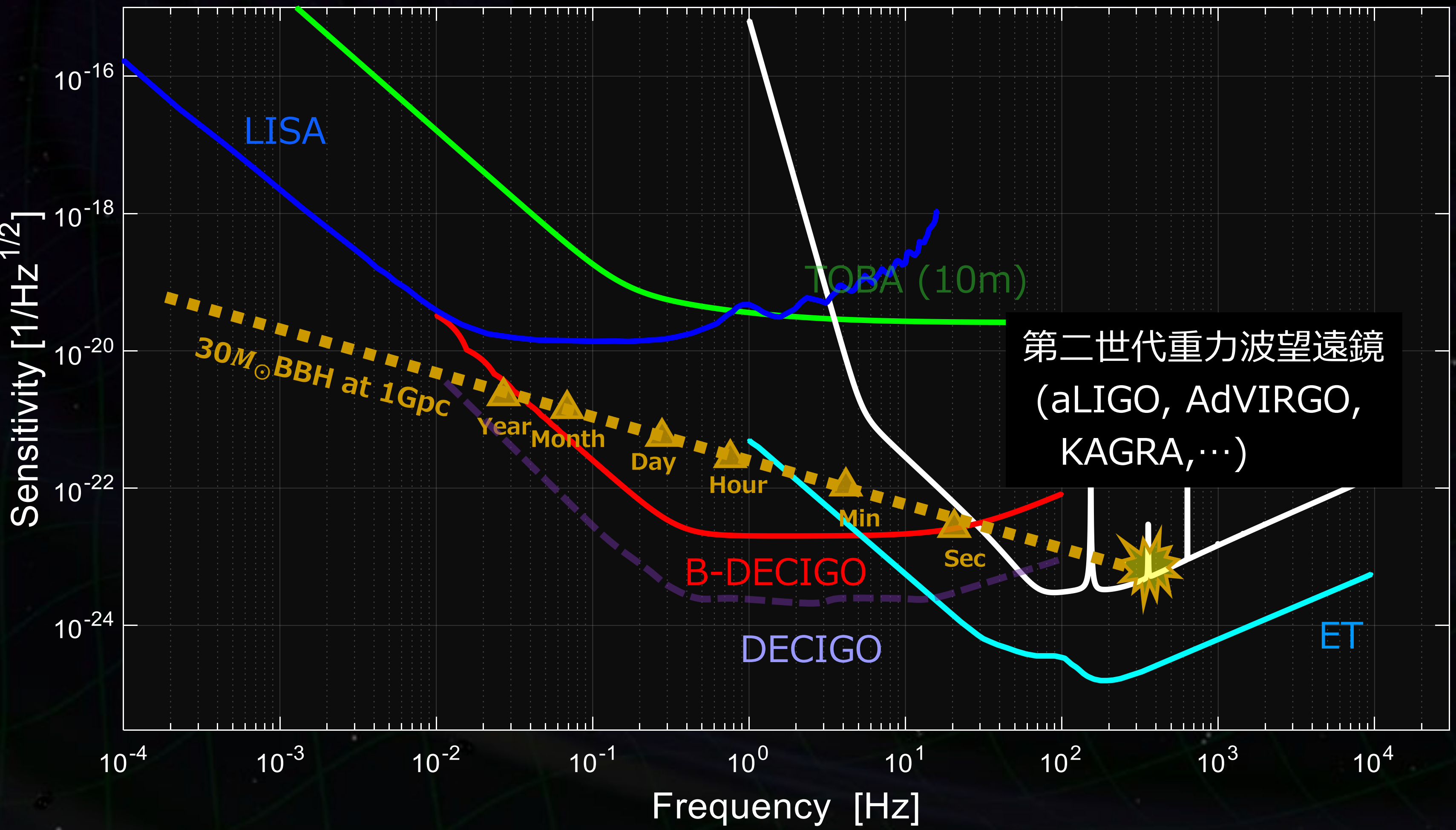
(Deci-hertz Interferometer Gravitational Wave Observatory)

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



Sensitivity Curves of GW Antennae

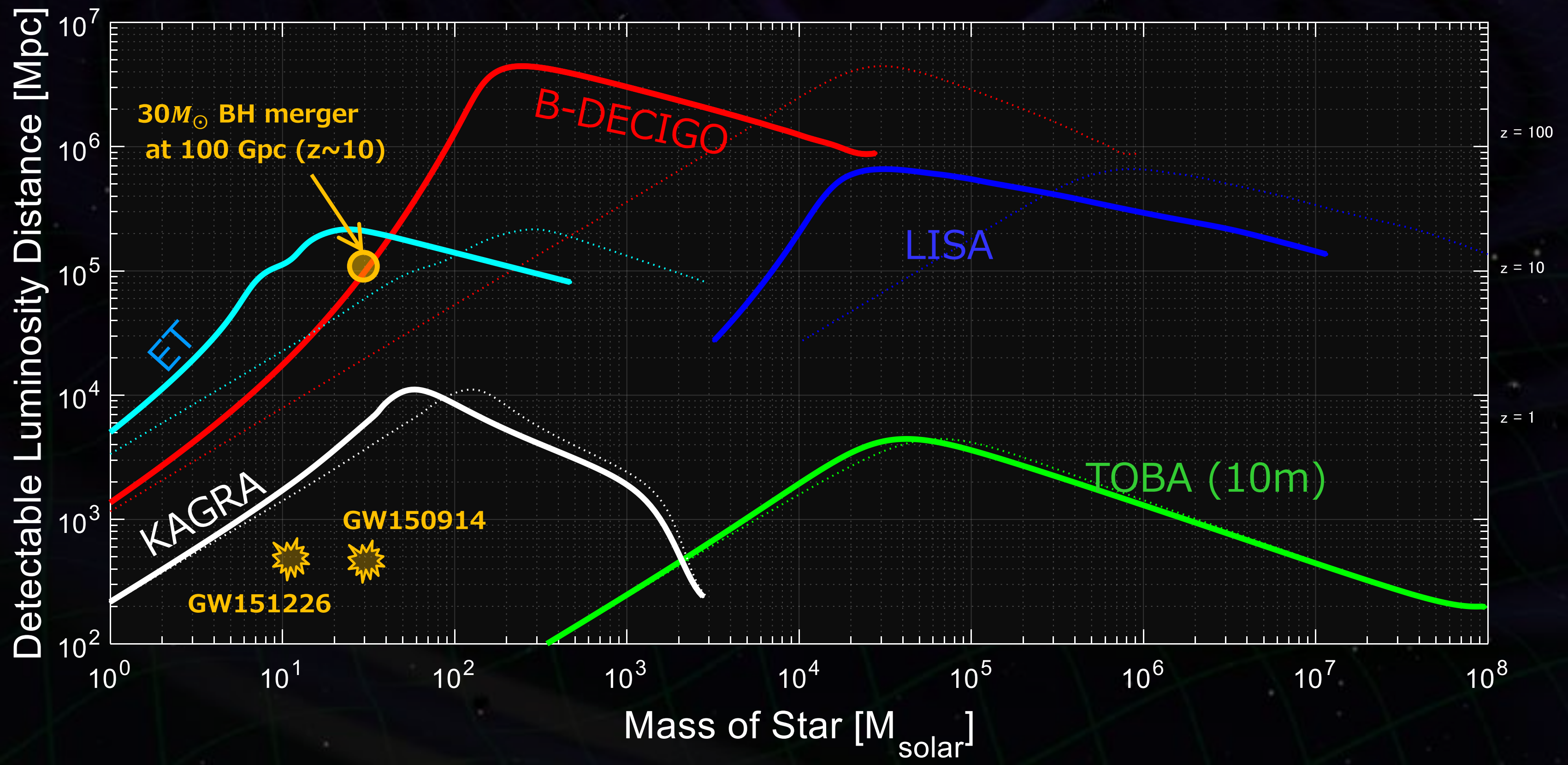
T. Nakamura et al., Prog. Theor. Exp. Phys. 093E01 (2016)



Observable Range

Observable range for binary mergers:

Estimated from waveform and sensitivity curve.



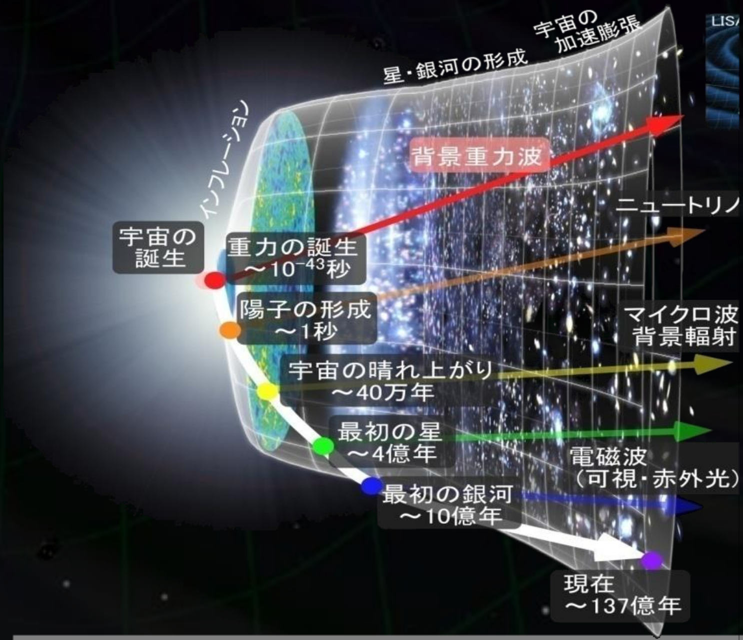
Long observation time → Better parameter estimation accuracy (mass, sky position, merger time,⋯).

Space GW Antenna DECIGO

DECIGO (DECI-hertz interferometer Gravitational wave Observatory)

Purpose: To Obtain Cosmological Knowledge.

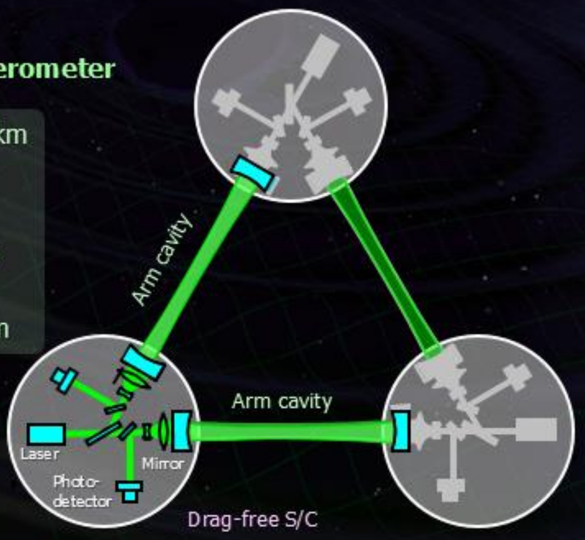
Direct observation of the origin of space-time and matter in Big-bang Universe.



Interferometer Unit:
Differential FP interferometer

Arm length:	1000 km
Finesse:	10
Mirror diameter:	1 m
Mirror mass:	100 kg
Laser power:	10 W
Laser wavelength:	532 nm

S/C: drag free
3 interferometers



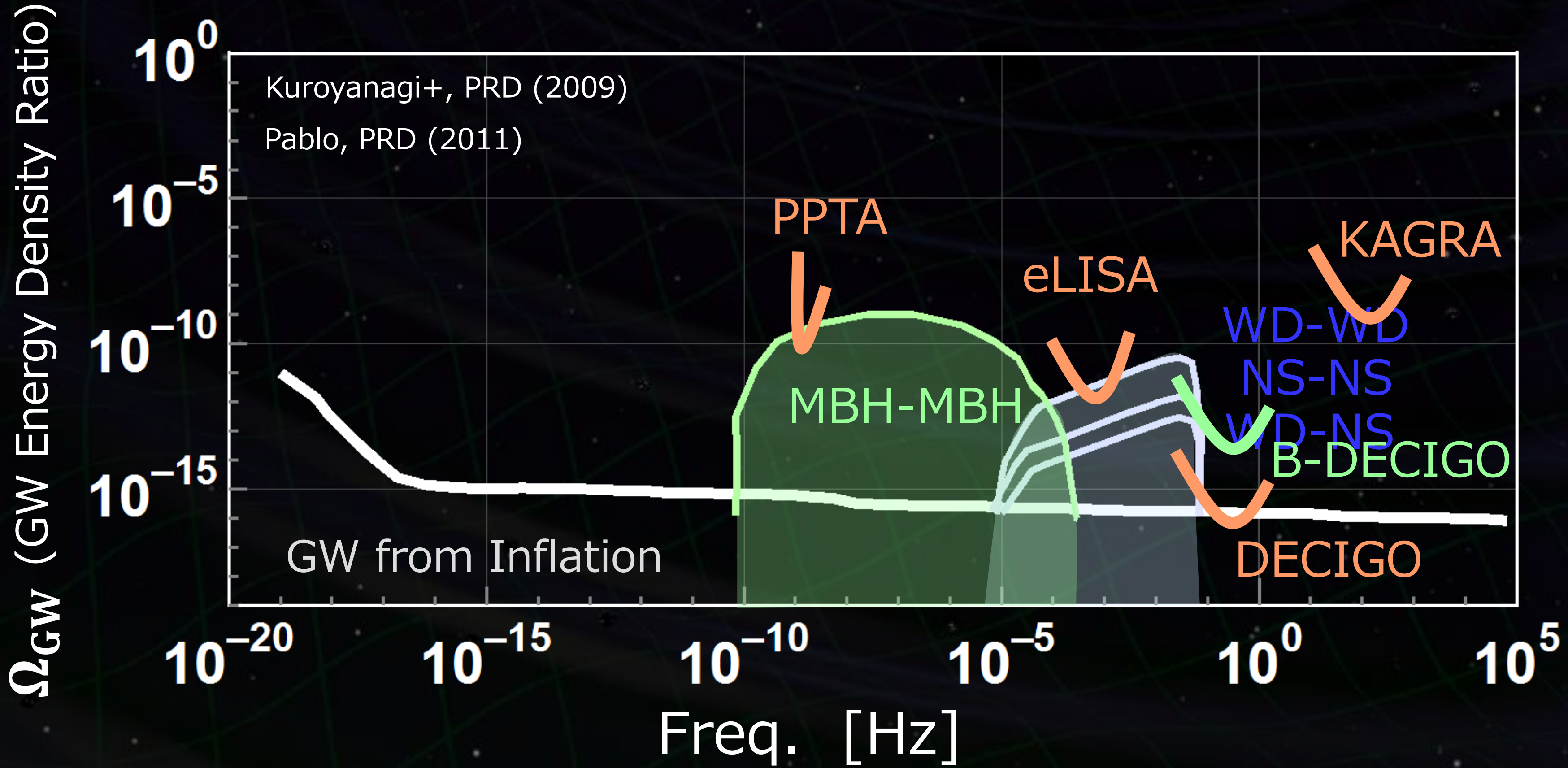
Observation of the Early Universe

Background:
original figure by
NASA/WMAP Science Team

GWB and Foreground

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

⇧ Foreground understandings by B-DECIGO.



Summary

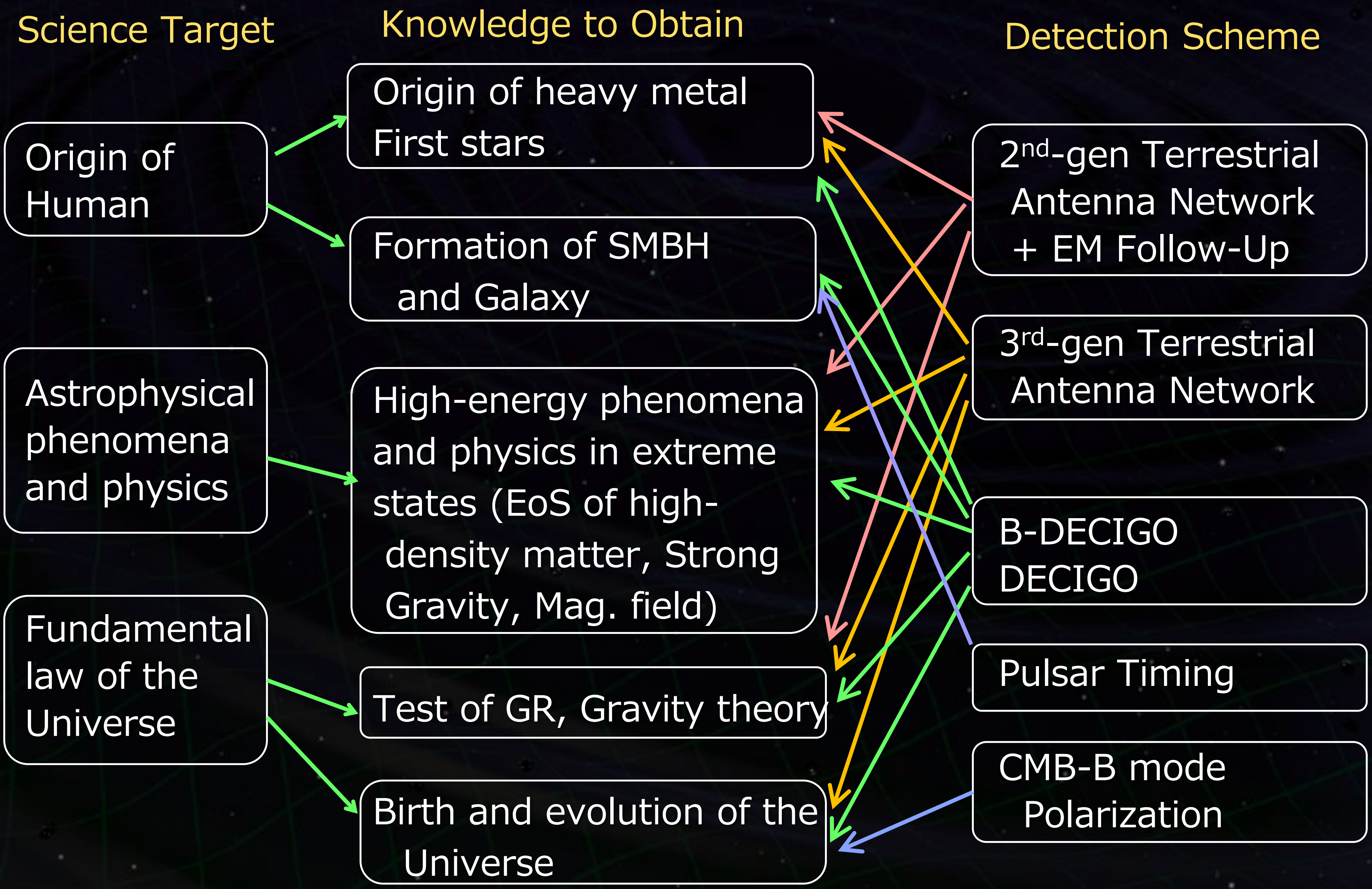
Future Prospects

- Ground-based Antennae (10 Hz - a few kHz)
  - *2015 : First detection by aLIGO.
  - *2016- : Join of AdVIRGO, KAGRA to the network
EM follow-up observation.
  - *2022 : LIGO-India operational.
  - *~2025 : Operation of 3rd-gen antenna (ET, CE).
- Space-borne antenna (0.1-10 Hz)
  - *2020s : GW observation by B-DECIGO.
  - *After that : Cosmology by DECIGO
- Space-borne antenna (0.1 – 100 mHz)
  - *2015 : Launch of LISA Pathfinder.
  - *2034 : Observation by eLISA.

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 is in progress and will join the network in 2018.
- 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.

Scientific Targets of GW Astronomy



Science Target

Origin of Human

Astrophysical phenomena and physics

Fundamental law of the Universe

Knowledge to Obtain

Origin of heavy metal
First stars

Formation of SMBH and Galaxy

High-energy phenomena and physics in extreme states (EoS of high-density matter, Strong Gravity, Mag. field)

Test of GR, Gravity theory

Birth and evolution of the Universe

Detection Scheme

2nd-gen Terrestrial Antenna Network + EM Follow-Up

3rd-gen Terrestrial Antenna Network

B-DECIGO
DECIGO

Pulsar Timing

CMB-B mode Polarization

End