Recent results of gravitational wave

Masaki Ando (Univ. of Tokyo / NAOJ) on behalf of the DECIGO collaboration
Fundamental Law of the Universe

High-energy Physics

Astrophysics

Cosmology
• Recent Results
• B-DECIGO
• DECIGO
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’.
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 $\sim 30$ deg$^2$.  

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, ….
Fundamental Physics

• Speed of GW
  - In GR prediction, GW propagates at the speed of light.
  - GW-EM arrival time difference was 1.7 sec.
  - Source distance 40Mpc (1.2×10^{24} m).

  → Upper limit \( \frac{c_{GW} - c_{EM}}{c_{EM}} < 3 \times 10^{-15} \).

• Cosmological Parameter
  - GW amplitude → Source distance.
  - EM counter part → Redshift

Hubble parameter:

\[ H_0 = 70^{+12.0}_{-8.0} \text{ km/s/Mpc} \]

→ Consistent with other results.

Independent measurement.

Hubble parameter by CMB measurement (Planck):
\[ H_0 = 67.90 \pm 0.55 \text{ km/s/Mpc} \]

doi:10.1038/nature24471
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, origins of heavy elements...

- 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, DECIGO, ...).
B - DECIGO
Space GW Observatory: B-DECIGO

Si We changed the name: Pre-DECIGO \( \rightarrow \) B-DECIGO

- **B-DECIGO**
  - Space-borne GW antenna formed by three S/C
  - Target Sensitivity for GW: \( 2 \times 10^{-23} \text{ Hz}^{-1/2} \) at 0.1Hz.

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

Target: JAXA Strategic Medium-scale mission (2020s).
B-DECIGO Design (Preliminary)

- **Mission Requirement**
  - Strain sensitivity of $2 \times 10^{-23} \text{ Hz}^{-1/2}$ 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 $\sim 120$min (Preliminary).
Sensitivity Curves

(1) Inspiral of Compact binaries
- High rate \( \sim 10^5 \) binaries/yr.
- Estimation of binary parameters and merger time.
  \( \rightarrow \) Astronomy by GW only and GW-EM observations.

(2) Inspirals and mergers of IMBHs
- Cover most of the universe.
  \( \rightarrow \) Formation history of SMBH and galaxies.

(3) Foreground understandings for DECIGO
- 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. $\rightarrow$ B-DECIGO**
  - Mass, Position, Time, …

- **High.-freq. $\rightarrow$ Ground based**
  - Astrophysics, EoS of NS
Sensitivity Curves


- LISA
- 2nd-gen GW antennae (aLIGO, AdVIRGO, KAGRA, …)
- 3rd-gen. (ET, CE)
- DECIGO
- B-DECIGO
- 30M⊙BBH at 1Gpc
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.
Observable Range

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


SNR ~100
Localization~0.1 deg
Distance error~3%
Merger time ~1 sec
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.
- Range for **BNS** is $\sim 2\text{Gpc} \rightarrow \sim 100$ 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 larger cycle number ($\sim 10^5$):
    * Localization, Merger time $\rightarrow$ Alerts for GW-EM.
    * Mass, Distance, Spin $\rightarrow$ Origin and nature of BBH.

⇒ **Fundamental physics, Cosmology**
In future DECIGO, unresolvable GWs by many binaries can be a foreground for primordial GW obs. 

Gain understandings with >100 binaries.
### Updated Roadmap for DECIGO

**Figure: S.Kawamura**

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<thead>
<tr>
<th>Year</th>
<th>Mission</th>
<th>Purpose</th>
<th>Design</th>
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<tbody>
<tr>
<td>2014</td>
<td>R&amp;D Fabrication</td>
<td>Demonstration and test of space IFO technique</td>
<td>Micro-g experiment FP cavity + Drag-free</td>
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<td>2018</td>
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<td>Sciences by GW observation</td>
<td>3 S/C, 3 arms.</td>
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**Ground test + Piggy-back opportunity**

**SDS-1/SWIM**

**B-DECIGO**

**DECIGO**

**GW Astronomy and Cosmology**

**FF with 3 S/C 3-4 IFO units**

Higgs Couplings 2018 (Nov. 28, 2018, KFC Hall & Rooms, Ryogoku, Tokyo)
**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.
DECI-GO

(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

Drag-free S/C

Higgs Couplings 2018 (Nov. 28, 2018, KFC Hall & Rooms, Ryogoku, Tokyo)
Observation of the Early Universe

Background:

original figure by NASA/WMAP Science Team
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)
‘Window’ for the Early Universe

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

\( \Omega_{\text{GW}} \) (GW energy ratio for critical density of the universe)

- CMB Pol.
- GW from Inflation
- MBH-MBH Compact Binaries
- DECIGO

Kuroyanagi+, PRD (2009)
Pablo, PRD (2011)

Higgs Couplings 2018  (Nov. 28, 2018, KFC Hall & Rooms, Ryogoku, Tokyo)
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. $\rightarrow$ Earlier universe
  - Reheating temperature
  - Thermal history of the universe
  ...

GW from Inflation

Energy density $\propto$ Tensor-Scalar Ratio ($r$).

Power spectrum: Evolution history of the Universe.

- Spectrum Power.
  $\rightarrow$ Energy scale of inflation
- Cut-off freq.
  $\rightarrow$ Energy scale of Reheating

DECIGO Correlation

Summary
Summary

• First direct detection of GW was achieved by LIGO.
• GW from binary NS merger was detected. A lot of outcomes obtained together with EM follow-ups.
• New field of ‘Gravitational-wave astrophysics’ has started. We obtained a new prove to the universe.
• More range and more statistics are necessary.
  ➔ Better sensitivity and 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.