MULTI-MESSENGER ASTRONOMY EFFORTS IN KOREA:
GRAVITATIONAL-WAVE EM COUNTERPART KOREAN OBSERVATORY (GECKO)

Originally, KU collaboration

Myungshin Im (SNU)

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¹. Seoul National University, 2. KASI, 3. KIAS, 4. EWU, 5. KHU
GW170817: NS-NS MERGER
MULTI-MESSENGER ASTRONOMY

- 2017-08-17 GW event marked the start of MMA using GW and EMW signals
- 3700 (39@Korea, 45 countries, 900+ institutions, 80 facilities), 59 page ApJL paper
ANSWERS TO KEY QUESTIONS

• Binary neutron star merger ➔ short GRB-like event? **YES, but off-axis or cocoon?**

• EM counterpart = Kilonova? **YES, but is this typical?**
  - blue or red? **Both**
  - Brightness? **17 mag in the beginning**

• Environment of NS merger? **Massive elliptical galaxy, near center, but it looks strange**

Gold! (200 $M_E$)

$H_0$ from GW (but need more)
GW EM COUNTERPART KOREAN OBSERVATORY (GECKO)

Korea: SNU 0.6, 1.0m SOAO 0.6m DOAO 1.0m

Maidanak: 1.5m Telescope

Hawaii: UKIRT, Gemini-N

US: LOAO 1-m

US: McDonald 2.1-m, 0.8m, 0.25m

Chile: Gemini-S, KMTNet, KCT/RASA36 (0.4m)

Australia: LSGT 0.43m (SSO), KMTNet

Yellow: Spectroscopy

Light yellow: medium-band
KOREA MICROLENSING TELESCOPE NETWORK (KMTNET)

• Three 1.6m telescopes at southern hemisphere
• FOV: 4 deg$^2$
• Limiting mag: 23 AB mag (5-σ) in 6 min
• 24 hr coverage
• 100 deg$^2$ in a few hrs
• 1/3 O4 EM counterparts may be uncovered by KMTNet
FOV OF GECKO TELESCOPES

- HST
- SAO 1 m: 21' x 21'
- KHAO 0.8 m: 23' x 23'
- KHAO 0.4 m: 21' x 16'
- DOAO 1 m: 13' x 13'
- LSGT 0.4 m: 16' x 16'
- LOAO 1 m: 28' x 28'
- KCT 0.4 m: 24' x 18'
- KMTNet 1.6 m X 3 2.0d x 2.0d
- WIT 0.4 m 2.3d x 2.3d
- RASA 0.36 m 2.7d x 2.7d
- CBNUO 0.6 m 1.2d x 1.2d
THREE CHALLENGES FOR EM COUNTERPART IDENTIFICATION

1. Wide localization area

2. Faint, fast-declining transient (kilonova)

3. Many transients/artificial signals
1. LOCALIZATION AREA
10’S TO 1000’S DEG$^2$

- GW localization area: too wide to cover
- HST ACS FoV: 10 arcmin$^2$
- ~1/4 million HST ACS fields to cover 700 deg$^2$ (GW200115)

GW170817 70 deg$^2$

GW200115 7000 deg$^2$

GW200105 700 deg$^2$
2. KILONOVAE ARE FAINT AND BECOME FAINTER FAST

- Peak luminosity $R \sim -16$ mag
- Peak apparent mag: $17 - 22.5$ mag
- Becomes a few mag fainter in several days

→ Rapid identification is essential

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Paek, Im+ 2021, in prep
The 8th KAGRA International Workshop
3. MANY TRANSIENTS/FAKE SIGNALS IN WIDE FOV

- Transients
  100/10 deg$^2$ (Kim+21)
- Variable sources
  700/10 deg$^2$ (Sesar+07)
- 100,000s artifacts

Need spectrum to select a kilonova
SPECTRUM CAN TELL WHICH TRANSIENT IS KILONOVA

Comparison of KN and SN spectra

Kilonova

Kilonova
GECKO OBSERVATION

METHODS

1. Wide-field observation
   - Observation of a wide area to catch EM counterpart
   - Wide-field telescopes

2. Target galaxy observation
   - Observation of individual galaxies in the order of priority
   - Narrow-field telescope
PRIORITIZATION

1. Position on the skymap

2. Distance

3. Host galaxy property

More massive host galaxy

Larger BNS merger rate

$L_K \propto M_*$

From presentation by G. Paek
APPLICATION TO GW170817

Strategy

From presentation by G. Paek
Prioritization method works well for GW170817
Strategy

**FOLLOW-UP OBSERVATION**

1. Automated system for GW signal

2. Transient search

3. Distinguish KN

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From presentation by G. Paek

The 8th KAGRA International Workshop
FIRST KOREAN OBSERVATION

- At 2017-8-18, about 21 hours after the GW detection, the GW EM counterpart was detected by LSGT (0.43m telescope!)

Lee Sang Gak Telescope (Siding Spring Observatory)

Optical counterpart detection by LSGT

2017-08-18 10:08:01 (UT)

GW170817 (AT2017gfo)

NGC 4993
• Blue → Red evolution
COMPARISON WITH KILONOVA MODEL

- $M_{\text{ej}} \approx 0.01 \text{ Msun}$
- Off-axis GRB/Wind model

Troja, E. et al. (2017, Nature)
NGC 4993 STUDY

• E with $M^* \sim 10^{10-11} \, M_\odot$

• Old ($t > 3$ Gyr), but too old?

• GW event at $\sim R_{\text{eff}}$, but too close to center?

• $D_L \sim 40$ Mpc (FP + GC)

Lee, Kang, & Im, 2018, ApJL
<table>
<thead>
<tr>
<th>Name</th>
<th>Classification</th>
<th>Primary/2nd ary (Msun)</th>
<th>Distance (Mpc)</th>
<th>50%/90% CR (deg²)</th>
<th>FAR (1/yr)</th>
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<tr>
<td>GW190408</td>
<td>BBH</td>
<td>24.5/18.3</td>
<td>1548+-302</td>
<td>25/139</td>
<td>1/1.1e10yr</td>
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<td>GW190412</td>
<td>BBH</td>
<td>30/8.3</td>
<td>734+-93</td>
<td>3/21</td>
<td>1/1.88e19yr</td>
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<td>BNS</td>
<td>2/1.4</td>
<td>157+-43</td>
<td>2400/9881</td>
<td>1/7e4yr</td>
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<td>?</td>
<td>5.7/1.5</td>
<td>337+-107</td>
<td>221/1393</td>
<td>1/1.63yr</td>
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<td>BBH</td>
<td>42.9/28.5</td>
<td>1527+-411</td>
<td>26/94</td>
<td>1/19.37yr</td>
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<td>S190510g</td>
<td>BNS/Terrestrial</td>
<td>-</td>
<td>227+-98</td>
<td>31/1166</td>
<td>1/3.59</td>
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<td>BBH</td>
<td>53.6/40.8</td>
<td>2152+-466</td>
<td>14/45</td>
<td>1/1.65</td>
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<td>GW190814</td>
<td>NSBH or BBH</td>
<td>23.2/2.59</td>
<td>241+-26</td>
<td>4/19</td>
<td>1/1e25</td>
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<tr>
<td>S190822c</td>
<td>Retracted</td>
<td>Retracted</td>
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<tr>
<td>S191213g</td>
<td>BNS(77%)</td>
<td>-</td>
<td>195+-59</td>
<td>852/4480</td>
<td>1/1.12</td>
</tr>
<tr>
<td>S200114f</td>
<td>NSBH(&gt;99%)?</td>
<td>?</td>
<td>?</td>
<td>37/403</td>
<td>1/25.8</td>
</tr>
<tr>
<td>S200213t</td>
<td>BNS(63%)</td>
<td>-</td>
<td>201+-80</td>
<td>129/2326</td>
<td>1/1.8</td>
</tr>
</tbody>
</table>
GW190425 (BNS)

- Follow-up from 90 min to 6 days after trigger
- Covered 610/5419 (~10%) kinds of host galaxy candidate
- Covered ~29% score
- Find no EM counterpart to S190425z

The first BNS merger event in 03 run

| Trigger time | 2019-04-25 09:40:17 UTC |
| Detectors    | LIGO Livingston & Virgo (2 of 3) |
| FAR          | ~1/70,000 year |
| GW luminosity distance | 156 ± 41 Mpc |
| 90% confidence localization area | 7461 deg² |
GW190425

INTERESTING CANDIDATE

GECKO 190427a

Host galaxy SED fitting

$z(\text{phot}) = 0.15$ ($D_L = 700$ Mpc)
NS-BH Merger Events in O3b: Not Observed By GECKO

Events with < 700 deg² are doable for optical follow-up
GECKO DEPTHS

- Sensitive enough for ~300 Mpc events

Paek, G. et al. in prep
NEED ACCURATE LOCALIZATION MAP

- Optical observation may miss the true localization area due to inaccurate map

Kim, Im, et al. 2021
OBSERVATION EFFICIENCY

- GECKO observation starts: < 1 hr from GW event

- Coverage speed: 40 deg$^2$/hr (R ~ 22.5 mag at 5-σ) or 700 deg$^2$ in 17.5 hrs or one night observation at two KMTNet sites

- File transfer (reduced image): < 1 hr from the observation

- Transient search: ~ days to weeks
OUTLOOK FOR EVENTS IN 2021~ 2022 ~

- LIGO
  - O1: 80 Mpc
  - O2: 100 Mpc
  - O3: 110-130 Mpc
  - O4: 160-190 Mpc
  - O5: Target 330 Mpc

- Virgo
  - 30 Mpc

- KAGRA
  - 50 Mpc
  - 8-25 Mpc
  - 25-130 Mpc

- LIGO-India
  - Target 330 Mpc

KMTNet next phase

Arxiv1304.0670
**O4 예상치 (2022 – 2023)**

- **BNS rate** – $[4-80] \sim \sqrt{4\times80} = 18$ per year
- **CR:** $\sim 3$ with $5 \text{ deg}^2$, $\sim 15$ with $< 20 \text{ deg}^2$

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**GW150914**

$1000 \text{ deg}^2 \rightarrow 10 \text{ deg}^2$

**Arxiv1304.0670**

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<tbody>
<tr>
<td>Planned run duration</td>
<td>4 months</td>
<td>9 months</td>
<td>12 months</td>
<td>40 – 70</td>
<td>05</td>
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<tr>
<td>LIGO Expected burst range/Mpc</td>
<td>40 – 60</td>
<td>60 – 75</td>
<td>75 – 90</td>
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<td>Virgo</td>
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**Estimated BNS detections**

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**Estimated BNS detections**

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<tr>
<th>90% CR</th>
<th>% within 5 deg^2</th>
<th>% within 20 deg^2</th>
<th>median/deg^2</th>
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<tr>
<td>3 – 7</td>
<td>23 – 30</td>
<td>62 – 67</td>
<td>9 – 12</td>
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<tr>
<td>14 – 22</td>
<td>65 – 73</td>
<td>110 – 180</td>
<td>9 – 12</td>
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<tr>
<td>44 – 52</td>
<td>87 – 90</td>
<td>44 – 52</td>
<td>87 – 90</td>
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</table>

**Searched area**

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<th>90% CR</th>
<th>% within 5 deg^2</th>
<th>% within 20 deg^2</th>
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MMA WITH KMTNET (2020-2023)

- TOO of GW/neutrino sources to identify and characterize their nature
- 168 hrs per site per year (total 504 hrs per year) – 3 year program
- 22 researchers from SNU, KASI, NIMS, Ewha, NYSC, KIAA

**KMTNet Proposal (2020-10-01 to 2023-09-30)**

**Title: Multi-Messenger Astronomy with KMTNet**

**Research Team**

P.I. Myungshin Im (Seoul National University)

Co.I. Chung-Uk Lee (KASI), Seung-Lee Kim (KASI), Hyung Mok Lee (KASI), Sung-Chul Yoon (SNU), Joonho Kim (SNU), Gregory S. H. Paek (SNU), Sophia Kim (SNU), Sungyong Hwang (SNU), Gu Lim (SNU), Changsu Choi (SNU), Seong-Kook Lee (SNU), Yongmin Yoon (SNU), Yongjung Kim (SNU), Dohyeong Kim (KIAA), Wonseok Kang (NYSC), Taewoo Kim (NYSC), Hyun-II Sung (KASI), Z. Lucas Uhm (KASI), Soojong Pak (KHU), Chunglee Kim (Ewha Womans Univ.), Sanghoon Oh (NIMS)
**KMT SYNOPTIC SURVEY OF SOUTHERN SKY (KS4)**

- Wide-field imaging survey of Southern Sky (~7000 deg²)
- 2020~2023
- Reference image for optical follow-ups
- 37 Co-Is from Korea, Australia, South Africa

<table>
<thead>
<tr>
<th>Filter</th>
<th>AB mag (5-σ)</th>
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<tr>
<td>B</td>
<td>23.5</td>
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<tr>
<td>V</td>
<td>23.2</td>
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<tr>
<td>R</td>
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SMANGNET: SMALL TELESCOPE NETWORK OF KOREA
소형망원경 네트워크(소망넷)

- 5 domestic, 5 oversea telescopes
- Aperture size: 0.25 m – 1.0 m
EXPECTED RESULTS

• Fast identification of GW EM counterpart: 1/3 from GECKO?

• Kilonova/BBH EM counterpart nature (> 10 events)

• Cosmological application

• Compact merger environment study (> 10 hosts)
THE END

• GW-EM MMA: New frontier of Astronomy

• Be ready, and get lucky

Thank you