Gravitational wave electromagnetic counterpart searching

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Why EM follow-up are interesting?

- Precise (arcsec) sky localization – e.g. link to EM event
- Energetics – e.g. EM emission (beamed and isotropic)
- Host galaxy – e.g. Redshift, Environment (stellar populations, dynamics..) where the EM counterparts are generated and evolve
- Nucleosynthesis of elements
- Cosmology
- Fundamental physics – e.g. speed of photons and gravitational waves (GW)
- Constraint models of GW+EM emitters
ASTROPHYSICAL SOURCES emitting transient GW signals detectable by LIGO and Virgo (10-1000 Hz)

Coalescence of binary system of neutron stars (NS) and/or stellar-mass black-hole (BH) \(10^{-2}M_\odot c^2\)

Core-collapse supernova \(10^{-8} \sim 10^{-5} M_\odot c^2\)

Isolated NSs instabilities \(10^{-16} \sim 10^{-5} M_\odot c^2\)

For CC SN: uncertain GW waveforms

GW: Milky Way  \quad Ott et al. 2012
Optimistic models: few Mpc Fryer&New 2011

\(~2\) per century in Milky way  \quad Li 2011
\(~2\) per year within 20 Mpc  \quad Li 2011

Range

197 Mpc for BNS
410 Mpc for NS–BH
968 Mpc for BBH

Rate

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>(\dot{N}_{\text{low}})</th>
<th>(\dot{N}_{\text{re}})</th>
<th>(\dot{N}_{\text{high}})</th>
<th>(\dot{N}_{\text{max}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS–NS</td>
<td>0.4</td>
<td>40</td>
<td>400</td>
<td>1000</td>
</tr>
<tr>
<td>NS–BH</td>
<td>0.2</td>
<td>10</td>
<td>300</td>
<td>1000</td>
</tr>
<tr>
<td>BH–BH</td>
<td>0.4</td>
<td>20</td>
<td>1000</td>
<td></td>
</tr>
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Abadie et al. 2010
EM emission

BNS/NS-BH

Jet–ISM shock (afterglow)
Optical (hours–days)
Radio (weeks–years)

Ejecta–ISM shock
Radio (years)

Merger ejecta
Tidal tail and disk wind
ν ~ 0.1–0.3 c

Kilonova
Optical (∼ 1 day)

iGRB
X, UV:
minutes-days
optical:
weeks-months
radio:
years

Credit by NSF

Metzger & Berger et al 2011

Isotropic
sGRB(gamma)
afterglow(radio)
kilonova(optical, IR)

Isolated NS instabilities

gamma
X
radio

BBH emission?

BBH emission?

Jets
Particles inside the jets
Tenuous plasma
Accretion disk
Black holes
Black hole trajectories

courtesy of Science
Expected optical light curves from BNS

Fast transient: Challenge for follow-up and identification time domain astronomy

Courtesy of G. Stratta
Optical GW follow-up: fast, wide, deep.

1. ‘blind search strategy’: wide-field tilling search on high probability GW region
e.g. **GRAWITA**

2. ‘targeting search strategy’: pointed search of selected galaxies in high probability GW region
   e.g. **DLT40**

~100-1000 square degrees (H+L)

~10 square degrees (H+L+V)

Future? LIGO-India, KAGRA…
triangle localization
1. Tiling

- 90 sq. degrees
- 90 pointings

2. Observations

- GW150914 VST field P50 epoch 1
- Number of images: ≥ 200 images (~18000×18000 px to map 1 deg²)
- Image size: ~1.5 GB / image
- Calibration time: ~ 8.5 hrs for a set of ~ 200 images (Grado & WG2: VST center)

3. Search

- Ph-pipe: candidates detection
- Image extraction
- Classical photometry
- Image comparison with existing catalogues
- Search for variable stars

4. Characterization and follow-up

- Telescopes: LBT / NTT / TNG / NOT / Asiago
- Collaborations: IPPT and PanSTARRS/PESSTO

See Grado talk for more details

1. Ranking algorithm for hotpants and sextractor parameters
2. Machine learning for image and light curve
Distance Less Than 40 Mpc = DLT40

‘DLT40 normal run’:
- Prompt 5(search) + LCOGT/FLOYDS···(spectroscopy)

1. Aim: Search for SNe in nearby galaxies with 1 day cadence, which is the time when we can learn the most on the physics of the explosion
2. Fast, well designed for GW, GRB, neutrino··· follow-up. Follow LIGO trigger from O2 period

1. 0.4m telescope with 10*10 arcmin FoV in Chile
2. 0.4m in Australia

Automatically pipeline
Decrease Delay time between explosion and data collected
Distance Less Than 40 Mpc = DLT40

‘DLT40 normal run’:
- Prompt 5(search) + LCO/FLOYDS⋯(spectroscopy)
- 400-600 galaxy every night, ~2000 in total (sub-catalogue from GWGC)

Galaxy samples construction:
1. rec. velocity < 3000 km/s
2. MB < −18 mag
3. E_MW(B−V) < 0.5 mag
‘DLT40 normal run’:
- Prompt 5(search) + LCO/FLOYDS⋯(spectroscopy)
- 400-600 galaxy every night, ~2000 in total (sub-catalogue from GWGC)
- Reach to r=19 mag on average
‘DLT40 normal run’:
- Prompt 5(search) + LCO/FLOYDS⋯(spectroscopy)
- 400-600 galaxy every night, ~2000 in total (sub-catalogue from GWGC)
- Reach to $r=19$ mag on average
- ~30 nearby SN in the last 2 years
Distance Less Than 40 Mpc = DLT40

‘DLT40 GW run’:
- Prompt 5(search) + LCO/FLOYDS ...(spectroscopy)
- 400-600 galaxy every night, ~2000 in total (sub-catalogue from GWGC)
- Reach to r=19 mag on average
- ~30 nearby SN in the last 2 years
- high priority would be given to LIGO galaxies if any

1. Galaxy selection for GW151226
2. Spatial and luminosity cut would be employed if needed
BNS at 40 Mpc !!

GW170817: 2017/08/17 UT:12:41:04.445710
GRB170817a: ~2 sec later

LIGO-Virgo

Fermi

INTEGRAL
**GW170817:** 2017/08/17 UT: 12:41:04.445710
**GRB170817a:** ~2 sec later
**2017fgo/sss17a/DLT17ck:** ~11 hours later, optical kilonova in NGC4993

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**DLT17ck**
On 2017 August 17 23:49:55 UT (11.08 hours after GW170817)

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Valenti et al, 2017
Multi-messenger astronomy has truly begun!

GW
Gamma
X
UV
Optical
IR
Radio
DLT17ck light curve

DLT17ck lc is comparable to the fast kilonova model.
Cooling down fast.
Kilonova identification - GRAWITA spectrum

These data revealed signatures of the radioactive decay of r-process nucleosynthesis providing the first spectral identification of the kilonova emission.

Cooling down very fast

See Cappellaro talk for more details.
DLT17ck is unique, first kilonova

1. Identification: cadence
daily cadence search & multi-messenger search

2. Rate: time
Detecting a kilonova with a survey like DLT40 (independently on the LIGO trigger) will take ~18.4 years!
Future – pointed search

Success of the pointed search and small telescopes, but future?

Galaxy catalogue incompleteness

GLADE: the best public galaxy catalogue

Dálya+ 2016 (GLADE document)

Complete up to 73 Mpc
**Future - EM in LIGO O3**

- **BNS? NS-BH?**
- **galactic SN?**
- **BBH?**

‘pointed’: Nearby bright transient
**Pro:**
- high cadence
**Con:**
1. Galaxy completeness
2. Distance limited

‘tiling’: distant faint transient
**Pro:**
- go further
**Con:**
1. Time consumed for image processing
2. Real/bogus candidate classification

<table>
<thead>
<tr>
<th></th>
<th>DLT40</th>
<th>exptime</th>
<th>limit magnitude</th>
<th>Number of galaxies</th>
<th>Distance</th>
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</thead>
<tbody>
<tr>
<td>O2</td>
<td></td>
<td>45s</td>
<td>19</td>
<td>400-600</td>
<td>70 Mpc</td>
</tr>
<tr>
<td>O3</td>
<td></td>
<td>100s</td>
<td>19.5</td>
<td>230</td>
<td>85 Mpc</td>
</tr>
</tbody>
</table>

**Legend:**
- Early: 60-80 Mpc
- Mid: 60-100 Mpc
- Late: 120-170 Mpc
- 190 Mpc

**LIGO:**
- O1: 25-30 Mpc
- O2: 65-85 Mpc
- O3: 65-115 Mpc
- O4: 125 Mpc

**Virgo:**
- O2: 25-40 Mpc
- O3: 40-140 Mpc
- O4: 140 Mpc

**KAGRA:**
- 2015-2023
Future – prepare for multi-messenger era & big data astronomy era

1. Multi-messenger search: GW, neutrino…

2. Multi-wavelength search: GRB, FRB…

3. Fast identification: machine learning - scikit-learn/tensorflow

4. Test facility:
   Asiago Schmidt telescope/PROMPT/REM
Thanks for attention!