Gravitational-wave lensing within ground-based gravitational-wave detectors

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Virtual Seminar at Institut d'astrophysique de Paris
Gravitational Waves

- Predicted by Einstein in 1916

Properties:
- Travels at the speed of light
- Two polarizations
- Passes through matter unimpeded

\[ G_{\mu\nu} = 8\pi T_{\mu\nu} \]
Gravitational-Wave Generation

Credits: LIGO/Virgo, SXS
Gravitational-Wave Detection

Credits: LIGO/Virgo, SXS
## O1/O2 detections

<table>
<thead>
<tr>
<th>Event</th>
<th>UTC Time</th>
<th>PyCBC</th>
<th>FAR [y^{-1}]</th>
<th>cWB</th>
<th>PyCBC</th>
<th>Network SNR</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>PyCBC</td>
<td>GSTLAL</td>
<td></td>
<td>cWB</td>
<td>PyCBC</td>
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<tr>
<td>GW150914</td>
<td>09:54:45.4</td>
<td>&lt; 1.53 × 10^{-5}</td>
<td>&lt; 1.00 × 10^{-7}</td>
<td>&lt; 1.63 × 10^{-4}</td>
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<td>24.4</td>
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<td>13.1</td>
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<td>10.8</td>
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<td>2.08 × 10^{-4}</td>
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<td>2.14 × 10^{-3}</td>
<td>11.1</td>
<td>11.5</td>
</tr>
</tbody>
</table>
Rate of Lensing

![Graph showing the rate of lensing events.](image)

Gravitational Lensing

Gwave source

$D_{OS}$

galaxy lens

$D_{LS}$ $D_{OL}$

ESA/Hubble & NASA
NASA, ESA & STScI
Oguri et al.
Strong Lensing Magnification

\[(1 + z)m_i = (1 + z_L)m_i^L,\]

\[D_L = D/\sqrt{\mu}\]
Strong Lensing Magnification

\[(1 + z)m_i = (1 + z_L)m_i^L,\]

\[D_L = D/\sqrt{\mu} \]
Strong Lensing Magnification

Credits: LIGO/Virgo

GWTC-1: Strong Lensing Magnification

Heavy neutron stars (e.g. GW190425)
Heavy neutron stars (e.g. GW190425)

- Binary neutron stars (BNSs) offer tidal measurements that would not be biased by lensing magnification
- Thus, a lensed BNS would appear as a massive BNS with a tidal deformability of a lower-mass BNS.
- Given an equation of state, we might rule out/confirm lensing for BNSs.
Heavy neutron stars (e.g. GW190425)

- Methodology could be used to confirm/rule out lensing.
- No evidence of GW lensing magnification for GW190425
- Future detections with better tidal measurements will likely yield better constraints
Why study magnification?

Example work:

- High-redshift BBH probes (Dai et al. 2017)

- Primordial black hole probes (Dai et al. 2017)

- Wave effects (Diego et al. 2019)

- Combined with tidal measurements, could allow for evidence of lensing for binaries with EM counterparts (Pang et al. 2020)
Strong Lensing Multi-Images

Multiple image signals are possible!
Strong Lensing Multi-Images

Strong Lensing Multi-Images

$$B_U^L := \frac{Z_L}{Z_U} = \int d\theta \frac{P(\theta|d_1) \cdot P(\theta|d_2)}{P(\theta)}$$

$$R_U^L = \frac{P(\Delta t_0|\mathcal{H}_L)}{P(\Delta t_0|\mathcal{H}_U)}$$

GWTC-1: Strong Lensing Multi-Images

\[ B^L_U := \frac{Z_L}{Z_U} = \int d\theta \frac{P(\theta|d_1) P(\theta|d_2)}{P(\theta)} \]

\[ R^L_U = \frac{P(\Delta t_0|H_L)}{P(\Delta t_0|H_U)} \]
GWTC-1: Strong Lensing Multi-Images

GW170814-GW170809:
- Apparent overlap in chirp masses, spins

However, likely caused by correlations between parameters

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Why study multi-images

Example work:


- Strong lensing cosmography (Baker & Trodden 2017, Liao et al. 2017)

- Hubble constant measurements (Liao et al. 2017)

- Polarization tests (Wong et al., in prep)
Polarization tests (preliminary)

Credits: Apollo 17  
Wong et al. (in prep)
Polarization tests (preliminary)

- Because multiple images arrive at a time-delay and thus different detector orientation, it allows for tests with effectively larger number of detectors.
Microlensing
Microlensing
Microlensing

Point mass lens

![Graph showing microlensing effects with frequency on the x-axis and strain on the y-axis. The graph includes labels for source, lens, and observer at different cosmic distances (680 Mpc and 380 Mpc).]
Microlensing: intermediate-mass black holes

Above 100 solar masses

Implementation within LSC-developed LALSuite

GWTC-1: Microlensing
Microlensing: Macromodels

Microlensing: Macromodels
Microlensing: Outlook

- Framework for generic microlensing configurations

- Waveform generation and analysis by lensingGW

Pagano et al., in prep.
Microlensing: Outlook

- Framework for generic microlensing configurations
- Waveform generation and analysis by lensingGW

Pagano et al., in prep.
Why study microlensing?

Example work:

- Study primordial black hole dark matter (Jung et al., 2019)
- Search for intermediate-mass black holes (Lai et al., 2017)
- Possibly smoking-giun evidence of strong lensing (Diego et al., 2019)
- Gravitational waves could allow for study of wave diffraction effects
Gravitational-wave lensing

- Gravitational waves, like light, can be gravitationally lensed

- Strong lensing would cause the signal to be magnified and split into multiple images

- If the wave travels through substructures, it could experience microlensing

- Thus far, we have not found compelling evidence of Gravitational-wave lensing

- However, future analyses and detector upgrades allow for better sensitivity and improved searches