Observing the Universe with Gravitational Waves

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Plan of the talk

• Introduction to gravitational waves
• Gravitational wave signals
• Gravitational wave detectors
• Gravitational wave data analysis
• Main GW discoveries by LIGO and Virgo projects
• Overview of observations in O1, O2, and O3 data
• Physical and astrophysical significance of GW observations
Gravitational waves
(solutions of Einstein’s equations)

Linearized E. eqs. (Einstein 1916):
\[ g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \]

\[ \bar{h}_{\mu\nu} = \frac{16\pi G}{c^4} T_{\mu\nu} \]

\[ G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \]

- General relativity predicts gravitational waves as propagating oscillations of spacetime:
  - Propagate at the speed of light.
  - Generated by quadrupolar mass movements:
  \[ h_{jk} = \frac{G}{c^4} \frac{2}{r} \frac{d^2}{dt^2} Q_{jk} \]
  - Two transverse polarizations: "+" and "\times".

- Ring of free particles
  - Responding to GW propagating along z-axis:

- Gravitational wave acts as a strain:
  \[ h \approx \frac{2\Delta L}{L} \]
Gravitational wave sources

- **Periodic sources**
  - Binary Pulsars, Spinning neutron stars, Low mass X-ray binaries

- **Coalescing compact binaries**
  - Classes of objects: NS-NS, NS-BH, BH-BH
  - Physics regimes: Inspiral, merger, ringdown
  - Numerical relativity will be essential to interpret GW waveforms

- **Burst events**
  - e.g. Supernovae with asymmetric collapse

- **Stochastic background**
  - Primordial Big Bang \( t = 10^{-22} \) sec
  - Continuum of sources
    - The Unexpected!
Precision Interferometry

\[ h \sim \frac{\lambda}{L} \]

\[ x \frac{1}{N_{\text{roundtrip}}} \]

\[ x \sqrt{\frac{1}{N_{\text{photons}} \tau_{\text{storage}}}} \]

Putting in numbers:

\[ h \sim 10^{-21} \]

\[ \lambda = 1.06 \, \mu\text{m} \]

\[ L = 4000 \, \text{m} \]

\[ N_{\text{roundtrip}} = 40 \]
Detector sensitivity

GEO-LIGO-Virgo gravitational-wave strain

https://www.gw-openscience.org/detector_status/day/20190628/
Network of gravitational wave detectors

Advanced LIGO Hanford
Advanced Virgo
GEO600
Advanced LIGO Livingston
LIGO-India
KAGRA

Operating 2019
2025

Beyond 19, 1-5 July 2019, Warsaw
Observing timeline

Binary Neutron Star Range

Figure 2 from B. P. Abbott et al., Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA, 2018, Living Rev. Relativity 21

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Signal detection in noise

*Fundamental lemma of Neyman and Pearson:*
Test that maximizes probability of detection subject to fixed false alarm probability is likelihood ratio test


**N-P test:** Compare $\Lambda = p_1(x)/p_0(x)$ to a threshold

**additive noise:** $x(t) = n(t) + s(t)$

**Gaussianity:**
\[
\ln \Lambda = (x|s) - \frac{1}{2} (s|s)
\]

**stationarity:**
\[
(x|s) = 4\Re \int_{0}^{\infty} \tilde{x}(f) \tilde{s}^*(f) \frac{df}{S(f)}
\]
Searching for Compact Binary Coalescences

This source:
Binary BH-BH system

Produces this waveform:
“Chirp” waveform

Buried in this noise stream:

Matched templates to pull signal from the noise:

SNR(t)

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On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory (LIGO) caught the first gravitational-wave signal.

2017 Nobel prize in physics for decisive contributions to the LIGO detector and the observation of gravitational waves.
2017: Advanced Virgo joins the network

14th August 2017

- 3-detector network:
  - LIGO Hanford
  - LIGO Livingston
  - Virgo

- 14 August:
  First observation of a gravitational wave signal by LIGO and Virgo together

- Demonstration of dramatically improved sky localization with a three detector network

LIGO+Virgo, PRL 118, 221101 (2017)
Black hole masses

- Chirp mass is best measured. Individual masses can be better measured if merger is observed, because total mass is measured at merger.
Black hole spins

GW150914 (measurements @ 25Hz)

\[ \chi_{\text{eff}} = \frac{c}{GM} \left( \frac{S_1}{m_1} + \frac{S_2}{m_2} \right) \cdot \frac{L}{|L|}. \] (constant through 2PN order)

- BHs’ spins not maximal, and for GW151226 one BH’s spin larger than 0.2 at 99% confidence.

- **Spins < 0.7. No information about precession.**
GRB 170817A occurs (1.74 ± 0.05) seconds after GW170817

It was autonomously detected in-orbit by Fermi-GBM (GCN was issued 14s after GRB) and in the routine followup search for short transients by INTEGRAL SPI-ACS

Probability that GW170817 and GRB 170817A occurred this close in time and with location agreement by chance is 5.0x10^{-8} (Gaussian equivalent significance of 5.3σ)

BNS mergers are progenitors of (at least some) SGRBs

Approximate timeline:

GW170817 - August 17, 2017 12:41:04 UTC = $t_0$

GRB 170817A
$t_0 + 2$ sec

LIGO signal found
$t_0 + 6$ minutes

LIGO-Virgo GCN reporting BNS signal associated with the time of the GRB
$t_0 + 41$ minutes

SkyMap from LIGO-Virgo
$t_0 + 4$ hours

Optical counterpart found
$t_0 + 11$ hours

- The localisation region became observable to telescopes in Chile 10 hours after the event time (wait for nightfall!)
- Approximately 70 ground- and space- based observatories followed-up on this event
GW170817: A string of “firsts”

- First observation of a binary neutron star merger
  - Also loudest gravitational wave signal to date!
- Confirmation that short, hard gamma ray bursts are associated with binary neutron star mergers
  - Fermi/INTEGRAL GRB observation 1.74 seconds after gravitational waves
- Confirmation that the speed of gravity equals the speed of light
  - The same to within $\sim 1$ part in $10^{15}$
- Confirmation of the origin of heavy elements
  - Observation of “kilonova” in X-rays, UV, optical, infrared, radio
- First direct measurement of the neutron star equation of state
  - More compact neutron stars are favored
- A new measure of distances in the Universe
  - Distance can be inferred directly from the gravitational wave signal
GW measurement:
Luminosity distance $d_L$

Galaxy localization:
Redshift $z$

Hubble constant: $H_0$

**GW170817 measurement of $H_0$.**

*Marginalized posterior density* for $H_0$ (blue curve).

Properties of nuclear matter

NS equation of state (EOS) affects gravitational waveform during late inspiral, merger and postmerger.
Constraints on NS EOS

More compact <- Less compact

PDFs of the combined tidal parameter for the high-spin (left) and low-spin (right) priors.

\[ \Lambda = \frac{2}{3} k_2 [(c^2/G)(R/m)]^5 \]

\[ \hat{\Lambda} = \frac{16}{13} \frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5} \]

\[ \Lambda_1 \quad \Lambda_2 \quad : \text{Love numbers} \]

https://arxiv.org/abs/1805.11579

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Constraints on NS radius

Marginalized posterior for the mass $m$ and areal radius $R$ of each binary component using EOS-insensitive relations (left panel) and a parametrized EOS where we impose a lower limit on the maximum mass of $1.97 M$ (right panel).

https://arxiv.org/abs/1805.11581, accepted to PRL
Does the speed of gravity equal the speed of light?

• Gamma rays reached Earth 1.74 seconds after end of gravitational wave inspiral signal
• Consider two extremes:
  • The gamma rays were emitted at the same time as end of GW
    → Light moved slower than gravity
  • The gamma rays were emitted 10 seconds after the end of GW
    → Light moved faster than gravity
• Conservative lower bound on distance from GW signal: 26 Mpc

\[-3 \times 10^{-15} < \Delta v / v_{EM} < +7 \times 10^{-16}\]

What the LIGO-Virgo Detections Tell Us About the Validity of General Relativity

90% upper bounds on the absolute magnitude of the GR violating parameters $\delta \phi$

**Post-Newtonian Approximation to GR**

$$h(f) = A(f)e^{i\phi(f)}$$

$$\phi(f) = \phi_{\text{ref}} + 2\pi ft_{\text{ref}} + \phi_{\text{Newton}} (Mf)^{-5/3} + \phi_{0.5PN} (Mf)^{-4/3} + \phi_{1PN} (Mf)^{-1} + \phi_{1.5PN} (Mf)^{-2/3} + ...$$

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**Upper Bound on the Graviton Mass**

$$E^2 = p^2 c^2 + m_g^2 c^4$$

$$\lambda_g = \frac{h}{m_g c}$$

$$\frac{v_s^2}{c^2} \approx 1 - \frac{h^2 c^2}{\lambda_g^2 E^2}$$

**Compton Wavelength of the Graviton**

$m_g \leq 1.2 \times 10^{-22} \text{ eV/c}^2$

with O2 events:

$m_g < 5 \times 10^{-23} \text{ eV/c}^2$

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https://arxiv.org/abs/1903.04467
GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs, PRX in press.
https://arxiv.org/abs/1811.12907
Sources localization

GW170818-HLV
GW170104
GW151012
GW151226
GW170608
GW170809
GW170729
GW170823
GW170817-HLV
GW170814-HLV
GW150914

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Masses in the Stellar Graveyard
in Solar Masses

LIGO-Virgo Black Holes

EM Black Holes

EM Neutron Stars

LIGO-Virgo Neutron Stars

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LIGO-Virgo | Frank Elavsky | Northwestern
3rd observation run (O3)

• The O3 run started 1st of April 2019

• LIGO/Virgo low-latency public alerts for transient event candidates
  o Notices and circulars available through the Gamma-ray Coordinates Network (GCN)
    https://gcn.gsfc.nasa.gov/gcn3_archive.html
  o Event candidates will be publicly available
    https://gracedb.ligo.org

• Observations so far (14/6/2019)
  o BBH - 12 events  BNS - 2 events  BHNS - 1 event?
  o No associated EM event detected
Inference: classification

Five numbers, summing to unity, giving probability that the sources belongs to the following five categories:

<table>
<thead>
<tr>
<th></th>
<th>Terrestrial</th>
<th>BNS</th>
<th>Mass Gap</th>
<th>NSBH</th>
<th>BBH</th>
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<tbody>
<tr>
<td>GW150914</td>
<td>$5 \times 10^{-40}$</td>
<td>0.00</td>
<td>0.06</td>
<td>0.01</td>
<td>0.93</td>
</tr>
<tr>
<td>GW170817</td>
<td>$1 \times 10^{-48}$</td>
<td>1.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Contents of an alert

Sky localization

For the skymap, the 90% credible region is 387 deg^2. The luminosity distance estimate is 1473 +/- 358 Mpc.

Type of event

- BBH: 100%
- Terrestrial: <1%
- NSBH: 0%
- MassGap: 0%
- BNS: 0%

Distance

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Bright future for gravitational wave research

Gravitational wave research
- LIGO and Virgo operational
- KAGRA to join next year
- LIGO-India under construction (2025)
- ESA selects LISA, NASA rejoins
- Pulsar Timing Arrays, such as EPTA and SKA
- Cosmic Microwave Background radiation

Einstein Telescope
- Design financed by EU in FP7
- APPEC gives GW a prominent place in the new Roadmap and especially the realization of ET

Next steps for 3G
- Organize the community and prepare a credible plan for EU funding agencies
- ESFRI Roadmap (2019)