GW170817
LIGO/VIRGO Observations of a Neutron Star Merger

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LIGO Document G1800814
• Intro to gravitational-wave astronomy

• Observation of neutron-star merger GW170817
  • Focus on “offline” gravitational-wave analysis (days-months after initial analysis & alerts)
  • Implications for neutron-star matter

• Future GW prospects
“Matter tells space-time how to curve and space-time tells matter how to move.”

- John A. Wheeler
Strong curvature

Palm Springs

Neutron star

Mass = 1.5 ☉

(small)
Black hole

Mass = 1.5 ☉

Compact objects
Gravitational waves

- Curvature of spacetime changes around moving objects
- Information propagates away from system at speed of light
- Linearized General Relativity → wave equation
- Waves stretch and squeeze the distance between freely-falling objects (Pirani 1957)

Two polarizations: + and x

www.einstein-online.info/spotlights/gravWav
Strong gravitational-wave source: compact binaries

Compact objects orbit

Wave effects from above plane of screen
Precision measurement
Fractional change from astronomical waves at Earth is $\delta L/L \sim 10^{-21}$

Class. Quantum Grav. 32 (2015) 074001
Source properties after detection
Generating millions of waveform models to compare with data.

• LEFT: example estimate of masses in BBH system

• LSC/VSC http://arxiv.org/abs/1304.1775, Veitch et al
Recovered Waveforms

GW150914
65 \text{ M} \odot

LVT151012
37 \text{ M} \odot

GW151226
22 \text{ M} \odot

GW170104
51 \text{ M} \odot

GW170608
19 \text{ M} \odot

GW170814
56 \text{ M} \odot

GW170817
2.7 \text{ M} \odot

thousands of GW cycles, 30 Hz to 1000+ Hz

time observable (seconds)

LIGO/University of Oregon/Ben Farr
Gravitational-wave localization

Image LIGO/Virgo/Leo Singer
(Milky Way image: Axel Mellinger)

LVC PRL 119, 161101 (2017)
GW170817 Masses and Spin

Minimal assumptions about source properties
(Talk Friday by Ben Lackey)

Equal mass, 1.36-1.36 $M_{\odot}$

Update to initial results, LVC Source Properties 1805.11579
GW170817 Masses and Spin

Assume low spins, as seen in galactic systems. Reduced mass/spin degeneracy, shift toward equal mass.

Equal mass, 1.36-1.36 $M_\odot$

Update to initial results, LVC Source Properties 1805.11579
Neutron-star merger: Last 30 ms

Simulation compatible with GW170817 parameters
Other scenarios are possible; post-merger GW not recovered
T. Dietrich, S. Ossokine, H. Pfeiffer, A. Buonanno (AEI)
Matter in GW170817: An astrophysical collider

Base figure from Watts et. al. “Probing the neutron star interior and the Equation of State of cold dense matter with the SKA” arxiv:1501.00042
Matter Impact on GW170817

Tidally deformed stars

- Response of a given neutron star characterized by its **tidal deformability** or **polarizability**:

\[
\lambda = \frac{Q}{E} = \frac{\text{size of quadrupole deformation}}{\text{strength of external tidal field}} = \frac{2}{3} k_2 R^5
\]

- \( R \): radius of star
- \( k_2 \): **Relativistic** love numbers (Damour 1983)
- Mass distribution inside the star
Inspiral matter dependence

- Tides accelerate inspiral - extra energy into deforming stars, extra quadrupole moment.

Flanagan & Hinderer 2008

Higher EOS pressures $\rightarrow$ larger radii $\rightarrow$ more deformation
Merger matter dependence

Compact stars: merge at higher frequency, more similar to BBH

Large-radius stars: collide earlier, merge at lower frequency

Numerical simulations: K. Hotokezaka, YITP

Simulations verify/calibrate waveform models for LSC/VSC analyses; functions of star $\Lambda$s (Bernuzzi, Dietrich, & Tichy 1706.02969)
Tidal measurements from GW170817

\[ \Lambda_{1.4} = 190^{+390}_{-120} \]

\[ \Lambda_{1.4} < 800 \]

**Discovery**
- Restricted frequencies, simplified waveform model, independent \( \Lambda \)

**Updated properties**
- Independent \( \Lambda \)
- Any spin \( \tilde{\Lambda} \leq 630 \)
- Low spin \( \tilde{\Lambda} = 300^{+420}_{-230} \)

**EOS**
- Quasi-universal relation between components
- Common spectral-parameterized eos

Without requiring support of 2 solar mass stars

**LSC-Virgo EOS 1805.11581 Source Properties 1805.11579**
Implications of first limit: \( \Lambda_{1.4} \leq 800 \)

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Annala et al  
Phys. Rev. Lett. 120, 172703  
9.9 km < \( R_{1.4} \) < 13.6 km

Fattoyev et al  
Phys. Rev. Lett. 120, 172702  
\( R_{1.4} < 13.76 \) km

- See also: Nandi and Char \( (R_{1.4} \leq 13.2–13.5 \) km), Raithel et al \( (R < 13 \) km), Most et al \( (12.00 \) km < \( R_{1.4} < 13.45 \) km) , Tews et al \( (R_{1.4} < 13.6 \) km) ...

- Independent common-radius result of De et al \( (8.7 \) km < \( R < 14.1 \) km)
New Common-EOS Radius constraints

\[ R_1 = 10.8^{+2.0}_{-1.7}, \quad R_2 = 10.7^{+2.1}_{-1.5} \]

\[ R_1 = 11.9^{+1.4}_{-1.4}, \quad R_2 = 11.9^{+1.4}_{-1.4} \]

Quasi-universal \( \Lambda_1 - \Lambda_2 \) & \( \Lambda - R \) (similar w/ spectral eos)

Spectral parameterized eos, **AND** support of 1.97 \( M_{\odot} \) star

*LSC-Virgo EOS 1805.11581*
GW170817 + $M_{\text{max}} > 1.97 M_{\odot}$

Twice saturation: $22^{+11}_{-17}$ MeV fm$^{-3}$ (GW only: $18^{+7}_{-15}$ MeV fm$^{-3}$)

Prior
90% range

Posterior
90% (50%) range

For comparison:
H4 (top)
APR4
WFF1 (bottom)

Overlap x-ray constraints (e.g. Steiner, Lattimer, Brown 2010)

$LSC$-$Virgo$ EOS $1805.11581$
And there was light!

Upcoming talks: additional implications for dense matter

Observing Plan (under development)

- Goal for next few years: improve BNS range by factor \(\sim 2\), high-frequency sensitivity by factor \(\sim 5\)
- Combine information from multiple detections?

GW170817-based rate
\[320–4740 \text{ Gpc}^{-3} \text{ yr}^{-1}\]
LSC/Virgo PRL 119, 161101 (2017)

1000 \text{ Gpc}^{-3} \text{ yr}^{-1}

\(\sim 40 \text{ yr}^{-1}\) detected w/ Advanced LIGO Design
LSC/Virgo Class. Quant. Grav. 27:173001 (2010)
Thank you!
International network of gravitational-wave observatories

Gravitational Wave Observatories

Operation at Designed Sensitivity

LIGO / Caltech

Inspired by TJ Massinger
BBH detections

GW150914

GW151226

GW170814

< 2 s of data shown for each

GW170104

GW170608
Simulations of BBH sources

Time to merger: 0.454 s

GW150914
M=36.29Msun
D=440Mpc

GW151226
M=14.7Msun
D=440Mpc

GW170104
M=31.19Msun
D=880Mpc

GW170608
M=12.7Msun
D=340Mpc

GW170814
M=31.25Msun
D=540Mpc
Known host galaxy

- Hubble constant / inclination angle constraint
  LVC et al Nature 551 85–88 2017

LVC Source Properties 1805.11579
Sky location: Detector dependent strain

Hanford
SNR ~16

Livingston
SNR ~25

Virgo
SNR ~2

HL amplitudes recovered by matched-filter GW search, Virgo reconstruction

LIGO/Virgo/ Brown, Lovelace, Nitz, and Read
Inspiral and chirp

- Energy loss $\rightarrow$ decreasing radius $\rightarrow$ increasing freq.

\[
E = -\frac{1}{2} \left( \frac{Gm\mu}{r} \right) (1 + [\text{PN}])
\]

\[
\dot{E}_{GW} = -\frac{32}{5} \frac{c^5}{G} \left( \frac{\mu}{m} \right)^2 \left( \frac{Gm}{c^2 r} \right)^5 (1 + [\text{PN}])
\]

\[\delta L/L\]
Matched-filter search for compact binary mergers

- Integrate known signal predictions against data over many cycles, for coincident time and parameters
  - $\chi^2$-weighted SNR, time slide background estimate
  - Relative likelihood of noise model and signal, single detector background estimate

Properties of dense matter

Equation of state in beta equilibrium

Mass-radius relation, max mass, deformability

Nuclear density

Neutron star properties

Ozel and Friere 2016
Counterpart identified!

Host galaxy NGC 4993, only 40 Mpc away