Neutron stars in gravitational-wave astronomy

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LIGO-Virgo-KAGRA Black Holes  LIGO-Virgo-KAGRA Neutron Stars

GW170817
GW190814
GW190917
GW191219
GW200115
GW200210

LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

2  LIGO-Virgo-Kagra GWTC-3 Catalog LIGO-P2000318-v8, arXiv:2111.03606
The population of merging compact binaries inferred using gravitational waves through GWTC-3

Lower mass gap above $\approx 2.1 M_\odot$

LIGO-Virgo-Kagra, arXiv:2111.03634 (LIGO-P2000318-v7)

Structure in the BH mass spectrum
Neutron stars observed in GW


More likely a BH?
Neutron stars observed in GW

More high-mass observations

Maximum mass close to Galactic


NS implications for stellar evolution: NS

What masses do supernovae produce?


Merger rates

LIGO/Virgo arXiv:2111.03634:

GWTC-3 NS-NS 10-1700 Gpc⁻³ yr⁻¹
GWTC-3 BH-NS 7.8-140 Gpc⁻³ yr⁻¹
GWTC-3 BH-BH 17.9-44 Gpc⁻³ yr⁻¹
Wave pattern depends on (leading order terms):

- **Chirp mass**: \( m = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \)

- **Mass ratio**: \( q = m_2/m_1 \)

- **Effective spin**: \( \chi_{\text{eff}} = \frac{S_1/m_1 + S_2/m_2}{m_1 + m_2} \cdot L \)

- **Effective tide**: \( \tilde{\Lambda} = \frac{16}{13} \frac{(m_1 + 12m_2)m_1^4 \Lambda_1 + (m_2 + 12m_1)m_2^4 \Lambda_2}{(m_1 + m_2)^5} \)
Tides in GW binaries

$\Lambda_i$ characterizes the ratio of mass quadrupole to external tidal field for an isolated star

$$\Lambda_i = \frac{2}{3} k_2 \left( \frac{R_i}{m_i} \right)^5$$

$R$ radius, $m$ mass of star

$k_2$ relativistic Love number

$k_2 = 0$ for BH

$k_2 \approx 0.05 - 0.15$ for NS

(distribution of mass within the surface)
Tides add to energy loss

- Additional orbital energy lost to the deformation of the stars
- Tidal bulges add a little extra quadrupole, GW luminosity
- Energy scale required to modify orbit is LARGE: transfer of additional $\sim 10^{46}$ erg at $\sim 100$ Hz modifies phase by $10^{-3}$ radians (Tsang et al Phys. Rev. Lett. 108, 011102 (2012))

\[
\frac{dr}{dt} = -\frac{\mathcal{L}_{GW}}{\mathcal{L}_{GW,def}}\frac{dE_{orb}(r)}{dr} + \frac{dE_{def}(r)}{dr}
\]

$\mathcal{L}_{GW} = 405$ Hz, $r = 57.1$ km

Figure: Read et al Phys. Rev. D 88, 044042 (2013)
• Stars deform in complicated, close interactions:
  
  • stars are not isolated, deformations are not linear, deformations are not pure quadrupole

• GW waveform community uses (and test) $\Lambda_1, \Lambda_2$ as effective descriptors for gravitational-wave models from numerical simulation and higher-order analytical expressions
EOS for inspiral: cold beta-equilibrium matter
Observations so far: GW170817 & GW190425

GW170817 from LIGO/Virgo GWTC-1 data release, P1800370, Phys. Rev. X 9, 031040 (2019)

GW190425 from LIGO/Virgo GWTC-2 data release, P2000223, Phys. Rev. X 11, 021053 (2021)

O1-O3:

- 90 compact binary systems
  [LVK GWTC-3 Catalog, LIGO-P2000318, arXiv:2111.03606]

O4:

- One year duration from early 2023,

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- [LVK Observing Scenarios Document, LIGO-P1200087]
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Expected impact of O4?


Simultaneous hierarchical GW constraint on EOS and mass distribution

Joint analysis required to avoid bias after ~10 events, see also Golomb+Talbot ApJ 2022
• Randomly drawn detected signals with SNR>13

• Masses from uniform distribution between 1.0 and EOS maximum mass

• 90% posterior recovery contours
Landscape of GW Astronomy

- Current generation (now)
- Next-generation (ca. 2035+)

Evans et al (incl J. Read), arXiv:2109.09882

JWST
Rubin
Roman

Tidal GW signal
GW signal of post-merger

D. Scolnic et al 2018 ApJL 852 L3
- 10 km underground triangle
- Multiple interferometers in “xylophone” configuration
• Next-generation US-based GW observatory project, under development
• 20 km and 40 km L-shaped surface observatories
• scaled up A+ technology & enhancements
Next-generation capabilities: Precision measurement

GW150914-like signal

Time before merger (s)

Strain ($10^{-21}$)

LIGO A+  Cosmic Explorer

LIGO Hanford Data (shifted)

LIGO Livingston Data
Next-generation capabilities: Cosmic Reach

CEHS: Evans et al (incl J. Read), arXiv:2109.09882
• ~1000s of neutron star mergers / year

• identify 80% of all mergers within $z=1$

• ~100 mergers with 10 minutes early warning

• ~100 NS radii with error < ~0.1 km / year

• ~10 / year SNR > 300

• ~100 post-merger GW detected / year

Evans et al (incl J. Read), arXiv:2109.09882
The only science target where smaller 20km detector may perform better than a larger 40km.
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Dan Black and Family
Nancy Goodhue-McWilliams
Thank you!

Join the Cosmic Explorer Consortium!
cosmicexplorer.org/consortium.html

Neutron-star merger: Radice et al. 2018

sky: SDSS III galaxy distribution

LIGO/VIRGO
https://www.gw-openscience.org