What have we learned about binary neutron stars since the discovery of GW170817?

Duncan Brown
As massive objects move around, the curvature of space changes.

The strength of the gravitational waves radiated is given by their strain:

\[ h(t) = \frac{\text{change in length}}{\text{length}} \]
Typical strains from astrophysical sources when the waves arrive at the Earth are

\[ h \sim \frac{G}{c^4} \frac{E_{\text{NS}}}{r} \sim 10^{-21} \]

However, the energy radiated is enormous

\[ L_{\text{GW}} \sim \left( \frac{c^5}{G} \right) \left( \frac{v}{c} \right)^6 \left( \frac{R_S}{r} \right)^2 \sim 10^{59} \text{erg/s} \]

Solar luminosity \( L \sim 10^{33} \text{ erg/s} \)
Gamma Ray Bursts \( L \sim 10^{49-52} \text{ erg/s} \)
Imagine measuring this distance to a precision of ten microns.
GW170817
DECam observation
(0.5–1.5 days post merger)

GW170817
DECam observation
(>14 days post merger)

The equation of state (EOS) of cold, ultra-dense matter remains poorly constrained at high densities.

At $T = 0$, the EOS relates pressure to density $P = P(\rho)$.

Nuclear experiments are only able to constrain EOS models up to the nuclear saturation density ($2.7 \times 10^{14}$ g / cm$^3$).

Densities of the cores of neutron stars reach 8 - 10 times nuclear saturation density and so neutron stars allow us to explore the EOS at much higher densities.
"Soft" EOS, low radius

"Stiff" EOS, large radius

Not detectable for GW170817
The information about the EOS is encoded in the gravitational-wave phase evolution

$$\Phi_{GW}(t) = 0pN(t; M) \left[ 1 + 1pN(t; \eta) + \cdots + 3.5pN(t; \eta) + 5pN(t; \text{EOS}) \right]$$

$$M = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

$$\eta = \frac{(m_1 m_2)}{(m_1 + m_2)^2}$$
Tidal effects enter the post-Newtonian gravitational-wave phase as

\[ \lambda \equiv -\frac{Q_{ij}}{\mathcal{E}_{ij}} \quad \Lambda \equiv \frac{\lambda}{m^5} = \frac{2}{3} k_2 \left( \frac{Gm}{Rc^2} \right)^{-5} \]

\[ \tilde{\Lambda} = \frac{16}{13} \frac{(12q + 1)\Lambda_1 + (12 + q)q^4\Lambda_2}{(1 + q)^5} \]

\[ q = \frac{m_2}{m_1} \leq 1 \]
Information about chirp mass and mass ratio come from lower frequencies.

Tidal information comes from late inspiral signal.

Tidal information not strongly degenerate with other parameters.
• Does the gravitational-wave signal show evidence for finite size effects?

• Use Bayesian inference to decide

• Model the waveform with and without the tidal deformability

• Compute the Bayes factor comparing GW170817 against two models (BBH and BNS)
Calculate Bayes factor for specific EOS vs BBH

Only the stiffest EOS are ruled out at high confidence

Soft EOSes and black holes are all consistent with GW170817

c.f. Abbott et al. CQG 37 045006 (2020)
But black holes are... black!
Analyses of Gravitational-Wave Observations

• Agnostic to neutron star's equation of state:
  • Abbott et al. PRL 119, 161101 (2017)
  • Abbott et al. PRX 9, 011001 (2019)
  • Dai, Venumadhav, Zackay arXiv:1806.08793

• Analyses with a constraint on the equation of state:
  • De, Finstad, Lattimer, DAB, Berger, Biwer. PRL 121, 091102 (2018)
  • Abbott et al. PRL 121, 161101 (2018)
• For nearly every specific EOS in the mass range relevant to GW170817 [1.1,1.6] solar masses, change in radius is very small

$$\langle \Delta R \rangle \equiv \langle R_{1.6} - R_{1.1} \rangle = -0.070 \text{ km}$$

• Common EOS constraint

$$\hat{R} \equiv R_1 \approx R_2 \quad \Lambda_1 = q^6 \Lambda_2$$

\[ \langle \hat{R} \rangle = 10.8 \text{ km} \]

\[ 8.9 \leq \hat{R} \leq 13.2 \text{ km} \]
GW loss timescale
inspiral

merger
dynamical time
differential rotation

viscous time
rigid rotation

spin-down time
final remnant

$\Omega$ (r)

$\Omega$

$\Omega_0$

$\sim (1.3 - 1.6) M_{\text{TOV}}$

$\sim 1.2 M_{\text{TOV}}$

$M_{\text{TOV}}$

prompt collapse
HMNS
SMNS
NS

Ben Margalit
Kilonova light curves suggest the existence of a hyper massive neutron star remnant cannot be massive enough to directly collapse to black hole
The merger remnant also places a constraint on the maximum neutron star mass

The remnant NS cannot be long lived, or there would be **too much** energy in the EM observation

\[ M_{\text{max}} \leq 2.17M_\odot \text{ (90\%)} \]
• Construct physically plausible EOS using Chiral Effective Field Theory calibrated against nuclear experiments

• Directly marginalize over EOS using GW observations

• Apply constraint that the merger remnant did not immediately collapse to black hole from Bauswin et al. PRL 111,131101 (2013)


$R_1 = 11.03^{+0.86}_{-0.60}$  $R_2 = 10.94^{+1.00}_{-0.56}$

$m_1 = 1.49^{+0.31}_{-0.11}$  $m_2 = 1.25^{+0.19}_{-0.15}$

• Use the constraints on the neutron star radius to determine tidal disruption in a neutron-star black-hole merger

• Electromagnetic counterpart is only expected if the neutron star disrupts before merger
NSBH mergers are unlikely to produce EM counterparts.
Generalize rapid parameter measurement method of Zackay et al. (2018) (originally proposed by Cornish) to coherent network statistic.

Possible to run full parameter estimation for BNS and NSBH in less than 20 mins from detection.


Daniel Finstad
• Single detector event, so no EM counterpart
• Total mass $\sim 3.4 \, M_{\text{sun}}$ is much larger than GW170817
• $D \sim 160$ Mpc
• However, GW signal is weaker than GW170817...consistent with BNS, NSBH, and BBH models

Non-linear tides
• Energy from the inspiral can couple into interior stellar oscillation modes in neutron stars.

• This can excite a nonlinear, non-resonant instability of p and g modes Weinberg et al. (2013).

• Essick et al. (2016) developed a parametric model for examining p-g mode instabilities in gravitational wave data.

• Abbott et al. [Phys. Rev. Lett. 122, 061104 (2019)] show that the GW170817 is consistent with a signal that neglects p-g mode tides.
Consistency of GW170817 with non-linear tide model is due entirely to degeneracy of model with standard waveforms. Any measurable effects are ruled out.

Steven Reyes

Eccentric Binaries
If the binary’s orbit is eccentric rather than circular then this will change the gravitational waves radiated. See e.g. Moore and Yunes GQG 36 185003 (2019)

Use GW170817 and GW190425 to constrain eccentricity

\[ e \leq 0.024 \text{ (GW170817)} \]
\[ e \leq 0.048 \text{ (GW190425)} \]

90% confidence

Amber Lenon

Lenon, Nitz, DAB MNRAS 497, 1966 (2020)
Cosmic Explorer
Binary mergers throughout cosmic time

Cosmic Explorer

• Facility: 40km L-shaped detector on Earth's surface
• 14cm wide laser beams, 2 MW laser
• R&D progress needed in optical coatings, quantum noise, thermal compensation
• Year ~ 2030 and ~ 1B USD

CE1 and CE2: two-stage approach

<table>
<thead>
<tr>
<th></th>
<th>CE1</th>
<th>CE2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2030s, à la aLIGO</td>
<td>2040s, à la Voyager</td>
</tr>
<tr>
<td>Wavelength</td>
<td>1.0 µm</td>
<td>1.5 to 2.0 µm</td>
</tr>
<tr>
<td>Temp.</td>
<td>293 K</td>
<td>123 K</td>
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<tr>
<td>Material</td>
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<td>silicon</td>
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<tr>
<td>Mass</td>
<td>320 kg</td>
<td></td>
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<tr>
<td>Coating</td>
<td>silica/tantala</td>
<td>silica/aSi</td>
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<tr>
<td>Spot size</td>
<td>12 cm</td>
<td>14 to 16 cm</td>
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<tr>
<td>Suspension</td>
<td>1.2 m fibers</td>
<td>1.2 m ribbons</td>
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<tr>
<td>Arm power</td>
<td>1.4 MW</td>
<td>2.0 to 2.3 MW</td>
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<tr>
<td>Squeezing</td>
<td>6 dB</td>
<td>10 dB</td>
</tr>
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</table>

Interested in Cosmic Explorer?

https://cosmicexplorer.org/consortium.html
Can we optimize Cosmic Explorer to detect gravitational waves from core collapse supernovae?
Supernovae in Cosmic Explorer

70 kpc at SNR 8
95 kpc at SNR 8
c.f. DUNE

Srivastava, Ballmer, DAB, Afle, Burrows, Radice, Vartanyan PRD 100, 043026 (2019)
• Can we measure the parameters of the progenitor star?

• Try to extract ratio of core's rotational kinetic energy to gravitational potential energy $\beta$ (primarily from the bounce)

• Try to extract the equation of state (primarily from the post merger ringing of the protoneutron star)

• Use Richers et al. catalog of supernovae waveforms to constrict a principal component basis to extract physical parameters

Build a Bayesian measurement algorithm using PCA and test with simulations

Generate posteriors on $\beta$ and $f_{\text{peak}}$

<table>
<thead>
<tr>
<th>Equation of State</th>
<th>$f_{\text{peak}}$ Mean value [Hz]</th>
<th>$f_{\text{peak}}$ Standard deviation [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFHo</td>
<td>772.1</td>
<td>5.6</td>
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<tr>
<td>SFHx</td>
<td>768.9</td>
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<tr>
<td>LS180</td>
<td>728.4</td>
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<td>HSIUF</td>
<td>724.2</td>
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<td>LS220</td>
<td>723.7</td>
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<td>GShefFSU2.1</td>
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<td>GShefFSU1.7</td>
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<tr>
<td>BHBLP</td>
<td>699.7</td>
<td>8.6</td>
</tr>
<tr>
<td>BHBL</td>
<td>699.7</td>
<td>8.2</td>
</tr>
</tbody>
</table>

For a galactic progenitor with $\beta = 0.02$, 90% credible interval is 0.02 (aLIGO), 0.002 (CE)

A galactic supernova observed by Cosmic Explorer could constrain $f_{\text{peak}}$ to within 10 Hz

Chaitanya Afle
• GW170817 has opened up a new era of EOS constraints

• Upcoming detections will provide yet more information (both from GW and EM)

• Improvements to aLIGO and future detectors (Cosmic Explorer) will give precision measurements of neutron stars, post-merger signatures, and possibly supernovae!