Gravitational Radiation as a probe of fundamental physics and astrophysics

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Subnuclear Physics Summer School
Erice, Italy
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Ground-based GW Sources

Modelled

- Binary Mergers
- Spinning Neutron Stars

Unmodelled

- Supernovae
- Stochastic Background

Transient

Continuous

LSC VIRGO

University of Glasgow
Compact Binaries

- Mergers of BH and NS binaries
  strong GW emitters
- Signal carries information about
  the physics of coalescence
  - binary parameters (masses, spins, position, orientation)
  - Properties of final object
  - Strong-field dynamics during merger
- Comparison to theoretical
  waveforms required to extract information

LIGO-Virgo Collaboration, PRL 116 (6) 2016
-0.19s
What is there to measure?

• Intrinsic Parameters
  • masses: \( m_1, m_2 \)
  • spins: \( \mathbf{s}_1, \mathbf{s}_2 \)

• Extrinsic Parameters
  • Inclination \( \iota \)
  • Polarisation \( \psi \)
  • Sky position \( \alpha, \delta \)
  • luminosity distance \( r \)
  • time \( t \)
  • Initial phase \( \phi_0 \)

\[
A(t) = \frac{2GM\eta}{c^2r} \left( \frac{GM\omega(t)}{c^3} \right)^{2/3}
\]

\[
\omega(t) = \omega(t; M, \eta, \vec{s}_1, \vec{s}_2)
\]

\[
h_+ (t) = \frac{A}{2} (1 + \cos^2 \iota) \cos(\omega t + \phi_0)
\]

\[
h_\times (t) = \frac{A}{4} \cos \iota \sin(\omega t + \phi_0)
\]

\[
h_{\text{det}} = F_+ (\alpha, \delta, \psi) h_+ + F_\times (\alpha, \delta, \psi) h_\times
\]

\[
M = m_1 + m_2
\]

\[
\eta = \frac{(m_1 m_2)^{1/5}}{(m_1 + m_2)^{3/5}}
\]
What is there to measure?

- Subtler effects
- NS Equation of state
  - tidal deformation
- Deviations from GR
  - eccentricity
Compact Binary Prospects

1 event

subsolarmass

10 events

smoking guns

dark matter?

GW?????

GW170817

20 events

Counterpart $H_0$

BNS+GRB+kN

100 events

Cosmology

eqn of state

host galaxy?

GW?????

Tests of GR

z-evolution

Tests of GR

GRB

physics

formation physics

% level

E.O.S.

formation

environ

time delays

formation

channels

Formation

channels

precision

cosmology

I.M.R

T.G.R

no hair

tests

area tests

GW?????

GW?????

GW?????

GW150914

mass gap?

spin misalignment?

Pair instability

mass gap?

mass gap?

mass gap?

mass gap?
Where are we now?
Masses in the Stellar Graveyard

in Solar Masses

LIGO-Virgo Black Holes

EM Black Holes

MASS GAP?

EM Neutron Stars

LIGO-Virgo Neutron Stars

LIGO-Virgo | Frank Elavsky | Northwestern
Masses

\[ L = \frac{L_\text{orbital}}{L_\text{spin}} \]

For precessing binaries the orbital angular momentum vector is not a stable direction, and it is preferable to describe the effective aligned spin 

\[ L_\text{eff} = L_\text{orbital} \]

During the inspiral the phase evolution depends at leading order on the chirp mass

\[ \frac{\dot{f}}{f} \approx \frac{C}{2} \frac{G_\text{NS}}{M_\text{eff}} \]

Left panel: We show the inferred component masses of each neutron star (NS), where the tidal deformability parameter 

\[ \tilde{\nu} \]

is the NS radius. The tidal deformabilities depend on the average tidal deformability of the system and lie within the range expected for

\[ \tilde{\nu} \approx \frac{1}{2} \]

We show the model predictions for three types of binary systems dominated by the inspiral

\[ m_1(M_\odot), m_2(M_\odot) \]

The three different panels show the posterior probability densities for the masses, spins, and SNR of the GW events.

**O1:** 3 BBHs

**O2:** 7 BBHs, 1 BNS

**O3:** ~1 BBH / week so far!
Mass distribution

<table>
<thead>
<tr>
<th>Model</th>
<th>$\alpha$</th>
<th>$m_{\text{max}}$</th>
<th>$m_{\text{min}}$</th>
<th>$\beta_q$</th>
<th>$\lambda_m$</th>
<th>$\mu_m$</th>
<th>$\sigma_m$</th>
<th>$\delta_m$</th>
<th>$\mathbb{E}[\alpha]$</th>
<th>$\text{Var}[\alpha]$</th>
<th>$\zeta$</th>
<th>$\sigma_e$</th>
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<tr>
<td>A</td>
<td>[-4, 12]</td>
<td>[30, 100]</td>
<td>5</td>
<td>0</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>[0, 1]</td>
<td>[0, 0.25]</td>
<td>1</td>
<td>[0, 10]</td>
</tr>
<tr>
<td>B</td>
<td>[-4, 12]</td>
<td>[30, 100]</td>
<td>[5, 10]</td>
<td>[-4, 12]</td>
<td>0</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>[0, 1]</td>
<td>[0, 0.25]</td>
<td>1</td>
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</tr>
<tr>
<td>C</td>
<td>[-4, 12]</td>
<td>[30, 100]</td>
<td>[5, 10]</td>
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<td>(0, 10)</td>
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<td>[0, 1]</td>
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<td>[0, 1]</td>
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</table>

LVC, arXiv:1811.12940
Compact Binary Prospects

1 event
- subsolar mass
- GW?????

10 events
- BNS
- GW170817
- Counterpart H₀
- BNS+GRB+kN
- dark matter?
- eqn of state
- host galaxy?
- Tests of GR
- z-evolution
- mass gap?
- spin distribution
- spin misalignment?
- Pair instability mass gap?
- 15

100 events
- NSBH
- GW?????
- Cosmology
- Precision Cosmology
- %-level E.O.S.
- time delays
- formation channel physics
- GRB physics
- no hair tests area tests

- BBH
- GW150914
- Formation channels
- I.M.R
- T.G.R
Spins I - Orbital alignment

- Co-evolved BH binaries are expected to have aligned spins
- We see effective spins mostly ~0: are BBHs non-spinning or just not aligned?
- c.f. BHs in X-ray binaries which seem to be highly spinning!

FIG. 5. Parameter estimation summary plots II. Posterior probability densities of the mass ratio and spin parameters of the GW events. The shaded probability distributions have equal maximum widths, and horizontal lines indicate the medians and 90% credible intervals of the distributions. For the two-dimensional distributions, the contours show 90% credible regions. Events are ordered by source frame chirp mass. The colors correspond to the colors used in summary plots. For GW170817 we show results for the high-spin prior $a_i < 0.89$. Top left panel: The mass ratio $q = m_2/m_1$. Top right panel: The effective aligned spin magnitude $e^{\text{eff}}$. Bottom left panel: Contours of 90% credible regions for the effective aligned spin and mass ratio of the binary components for low (high) mass binaries are shown in the upper (lower) panel. Bottom right panel: The effective precession spin posterior (colored) and its effective prior distribution (white) for BBH (BNS) events. The priors have been conditioned on the effective posterior distributions.

The component masses of the BBHs show a strong degeneracy with each other. Lower mass systems are dominated by the inspiral of the binary, and the component mass contours trace out a line of constant chirp mass Eq. (5) which is the best measured parameter in the inspiral [34, 121, 127]. Since higher-mass systems merge at a lower GW frequency, their GW signal is dominated by the merger of the binary. For high mass binaries the total mass can be measured with accuracy comparable to that of the chirp mass [142–145].

We show posteriors for the ratio of the component masses Eq. (6) in the top left panel of Fig. 5. This parameter is much harder to constrain than the chirp mass. The width of the posteriors depends mostly on SNR and so the mass ratio is best measured for the loudest events, GW170817, GW150914 and GW170814. Even though GW170817 has the highest SNR of all events, its mass ratio is less well constrained, because the signal power comes predominantly from the inspiral, while the merger contributes little compared to BBH [146]. GW151226 and GW151012 have posterior support for more unequal mass ratios than the other events, with lower bounds of 0.28 and 0.30 at 90% credible level.

The final mass, radiated energy, final spin, and peak luminosity of the BH remnant from a BBH coalescence are LVC, arXiv:1811.12907.
Spins II - In-plane component

- In-plane spins are fingerprint of dynamical capture formation
- Better sensitivity required to measure in-plane spins for objects like these we are seeing

LVC, arXiv:1811.12907
Spins III

GW170809
GW170818
GW151226
GW170809
GW170823
GW170829
GW170104
GW170608
GW151012

LVC, arXiv:1811.12907
Gravitational regimes

- Field strength
  \[ \epsilon = \frac{GM}{c^2 R} \]

- Curvature
  \[ \xi = \left( R_{\alpha\beta\gamma\delta} R^{\alpha\beta\gamma\delta} \right)^{1/2} \]

- Compact binaries probe in high curvature, high potential regime
Gravitational regimes

\[ R^{1/2} = \left( \frac{M}{L} \right)^{3.1/2} \text{[km}^{-1}] \]

\[ \Phi = \frac{M}{L} \]

GW151226
Double Binary Pulsar (Shapiro Delay)
Double Binary Pulsar (Orbital Decay)
LAGEOS
Lunar Laser Ranging
Perihelion Precession of Mercury
Cassini
Pulsar Timing Arrays

Yunes+ 1603.08955
Waveforms in GR

- Full solution requires **numerical relativity** solution of field equations
- Use approximate waveform families for comparison to data
  - Only capture a subset of the physics: spin dynamics, higher harmonics, treatment of merger
  - Applicable in certain regimes: near-equal-mass ratio, non-extremal spins
- Can describe amplitude and phase evolution in freq domain:

\[
h(f; \theta) = A(f; \theta) e^{i\Phi(f; \theta)}
\]
\[
\Phi(f; \theta) \equiv \Phi(f; m_1, m_2, \vec{s}_1, \vec{s}_2)
\]
non-GR signatures

• Theoretical modifications to GR predictions in different regimes:
  
  • non-GR action (extra fields, higher order curvature): practically no numerical simulations - rely on post-newtonian theory
  
  • propagation (massive graviton, Lorentz invariance violations): GR-like source dynamics, modified dispersion relation in propagation
  
  • non-GR BHs (hairy BHs, exotic compact objects):
    • different tidal deformation in inspiral
    • different quasi-normal mode spectrum in ringdown
    • exotic solutions: firewalls, echoes, …
  
• Large phase space to explore

• source modelling in non-GR gravity mostly unexplored!
What are the alternatives?

- Extra degrees of freedom
  - additional fields
  - additional curvature terms in action
- Test GR fundamental assumptions
  - Lorentz invariance
  - Equivalence principle
- Strong field behaviour

Lovelock theorem: In 4D, the only divergence free symmetric rank-2 tensor constructed only by the metric and its derivatives up to 2nd order and preserving diffeomorphism invariance is the Einstein tensor plus a constant.

Extra fields
- Nondynamical fields
  - Palatini f(R)
  - Eddington-Born-Infeld
- Dynamical fields (SEP violations)
  - Scalar-tensor, Metric f(R)
  - Horndeski, galileons
  - Quadratic gravity, n-DBI
- Vectors
  - Scalar-tensor, Metric f(R)
  - Horndeski, galileons
  - Quadratic gravity, n-DBI
- Tensors
  - Einstein-Aether
  - Horava-Lifshitz
  - TeVeS

WEP violations
- Massive gravity
  - dRGT theory
  - Massive bimetric gravity
- Lorentz-violations
  - Einstein-Aether
  - Horava-Lifshitz
  - n-DBI

Berti+ 1501.07274
Parametrised tests of GR

- GW phase modelled as effective series (IMRPhenom waveforms)
  \[ h(f; \theta) = A(f; \theta) e^{i\Phi(f;\theta)} \]
  \[ \Phi(f; \theta) = \sum_{k=0}^{7} (\varphi_k + \varphi_k^{(l)}) f^{(k-5)/3} + \sum_{i \neq k} \varphi_i g(f) \]
  \[ \varphi_j \equiv \varphi_j(m_1, m_2, s_1, s_2) \]

- non-GR theories modify coefficients in series (e.g. PPE Yunes+ 0909.3328, 1603.08955)

- Look for generic modifications of coefficients (Li+ 1110.0530, Agathos+ 1311.0420)
  \[ \hat{\varphi}_j \equiv \varphi_j^{GR} (1 + \delta \hat{\varphi}_j) \quad \delta \hat{\varphi}_j = 0 \iff \text{GR} \]

- Calculate posterior on deviations \( \delta \hat{\varphi}_j \) along with GR physical parameters
Results for parameterised tests

GW150914 1602.03841

5 events 1903.04467
Black Hole Ringdowns

- “No-hair theorem” states that stationary BHs are described by mass, spin (and charge) only.

- When final BH forms it is highly excited, rapidly settles down to Kerr state by emitting GW “ringdown”.

- BH perturbation theory [Chandrasekhar] gives a series of quasi-normal modes but very rapidly decaying! 
  
  \[ h_+ - i h_\times = \frac{M_f}{D_L} \sum_{lmn} A_{lmn} S_{lmn}(t, \varphi) e^{i(t-t_{lmn})\omega_{lmn} + \phi_{lmn}} \]

- Mode frequencies should only depend on mass and spin - in GR! Leaver 1985, Berti+ CQG 26 163001 (2009), Berti+ gr-qc/0605118

- BH spectroscopy will test GR in this regime by observing multiple mode frequencies (need louder signals first!)
So far events are consistent with dynamics during the merger phase.

Discrepancies would reveal non-GR inspiral-merger-ringdown consistency.

With one ringdown mode ($l=m=2$ dominates) we can still measure the mass and spin of the final BH.

Compare between mass and spin inferred from the inspiral portion of the signal.

- Account for energy loss to radiation via numerical relativity fits.
- Discrepancies would reveal non-GR dynamics during the merger phase.
- So far events are consistent with GR predictions.

LIGO-Virgo Collaboration,
Tests of General Relativity with GWTC-1

1903.04467
Beyond Black Holes
LIGO Hanford

GW170817

LIGO Livingston

Virgo

BINARY NEUTRON STAR
Neutron star masses

GW170817

Double neutron stars

Recycled pulsars

Slow pulsars

Bursters

Neutron star masses

0.0 1.0 2.0 3.0

Mass (M_{\odot})

1.0 1.1 1.2 1.3

m_1 [M_{\odot}]

1.4

GW170817

|\chi_z| < 0.05

|\chi_z| < 0.89

Likelihood

0.8 1.0 1.2 1.4 1.6 1.8 2.0

Mass (M_{\odot})

0.6 0.7 0.8 0.9

m_2 [M_{\odot}]

1.5 1.6 1.7 1.8

1.9 2.0

0.0 1.0 2.0 3.0

Mass (M_{\odot})

0.0 1.0 2.0 3.0

1.0 1.1 1.2 1.3

m_1 [M_{\odot}]

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GW170817

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Among these inferred distributions, the narrowness of the DNS distribution stands out. There are also some studies of a particular class of MSPs called black widows (and their cousins redbacks) that have suggested higher NS masses (e.g., van Kerkwijk et al. 2011). These MSPs have maximum masses and fall below this value. The current record holder on this front is J0348+0432 with a mass of 2.6. Maximum Mass of Neutron Stars

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Mass, mass ratio, spin

The four waveform models used are TaylorF2, PhenomDNRT, PhenomPNRT, and SEOBNRT. Using the high-spin prior (top) and low-spin prior (bottom).

**FIG. 6.** Posterior PDF for the mass, mass ratio, and spin. The marginal posterior is shaped by the prior distributions for our spin inferences, which in turn influences the inferred component spins, a prior which allows for high spins. For the low-spin prior (bottom), the 90% credible intervals are reduced by nearly a factor of 2.

While all of the models provide constraints on the effective spin, most of the SNR for GW170817 entries the phase evolution at different PN orders. Generally speaking, the impact on the phase evolution, and are thus easier to measure due to two main factors: 1) the small values observed for GW150914 or GW170814, but the constraints are diﬀerent from the BBH systems detected so far, and 2) the expansion at different PN orders.

Mass, mass ratio, and spin values. They are also consistent with the limits reported on the 90% upper and lower limits on the mass, mass ratio, and spin. They are also consistent with the limits reported on the mass, mass ratio, and spin.

**FIG. 4.** Marginalized posteriors for the binary inclination. The 90% credible regions for component masses using a uniform-in-volume prior (blue) and EM-constrained luminosity distance prior (brown).

**FIG. 5.** 90% credible regions for component masses using a uniform-in-volume prior (blue) and EM-constrained luminosity distance prior (brown). 1-D marginal distributions have been renormalized to have equal maxima, and the vertical and horizontal lines give the 90% upper and lower limits on the masses.

For the small spin case, the true thickness of the contour is determined by the uncertainty in the chirp mass, is too small to show. The points mark the edge of the 90% credible regions. 1-D marginal distributions have been renormalized to show. The points mark the edge of the 90% credible regions.

**Small spin**

**Large spin**

Owing to its low mass, most of the SNR for GW170817 comes from the inspiral phase, while the merger and combined GW and EM constraints to constrain the source of GW170817 to higher luminosity. The characteristic velocity within the system enters the phase evolution at the characteristic velocity within the system, where $L_{\text{ISCO}}$ is the characteristic velocity within the system. The inspiral is written as a PN expansion, a power series in $v/c$, where $L_{\text{ISCO}}$ is the characteristic velocity within the system. The inspiral measurement using the inspiral portion of the signal is diﬀerent than the BBH systems detected so far, and consequently the component masses, are influenced by the uncertainty in the chirp mass.
BNS Spins

While all of the models provide constraints on the effective precession angle of 0°, low-density polytrope. Here, we use the 4-piece low-density polytrope. The upper 90th percentile at 0° comes from the PhenomDNRT model, whereas the other two models provide 90% upper limits that are 0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.89

\[ p \]

\[ \text{PDF} \]

\[ \text{Prior} \]

\[ \text{Posterior} \]

\[ \text{PhenomPNRT} \]

\[ \text{PhenomDNRT} \]

\[ \text{SEOBNRT} \]

\[ \text{TaylorF2} \]

\[ \text{Prior} \]

\[ \text{Posterior} \]

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Beyond Black Holes

• Black Holes are vacuum solutions of field equations, \( T_{\mu \nu} = 0 \)

\[
R_{\mu \nu} - \frac{1}{2} R g_{\mu \nu} = \frac{8 \pi G}{c^4} T_{\mu \nu}
\]

• Schwarzschild or Kerr metrics

• Material bodies (e.g. stars) have internal stress-energy

• Need to solve coupled matter and gravity in hydrostatic equilibrium: Tolman-Oppenheimer-Volkoff Equation

• Requires solving for \( P(r), \rho(r), m(r) \), but have only two equations

\[
\frac{dP}{dr} = -\frac{(\rho + P)(4 \pi Pr^3 + m)}{r(r - 2m)}
\]

\[
\frac{dm}{dr} = 4 \pi r^2 \rho
\]

• Need **equation of state** \( P(\rho(r), T) \) to know relation between pressure and density and find internal structure of star
Movie credit: BAM Collaboration
Tidal Deformability

• A material body mass $m$ is deformed by an external tidal field $\varepsilon_{ij}$

• Acquires a quadrupole

$$Q_{ij} = -\lambda(EOS, m)\varepsilon_{ij}$$

• tidal deformability (polarizability) parameter

$$\lambda = \frac{2k_2 R^5}{3G}$$

• $k_2$ and $R$ are L=2 Love Number and NS radius, both functions of mass and EOS
What’s inside a neutron star?

- Neutron stars are supported by neutron degeneracy press
- $T << T_{\text{Fermi}}$ (for old NSs). Use zero-temperature limit
- Phase transition at high density to strange quark matter?
Realistic EOSs

- Large nuclei have densities \( \sim 2.7 \times 10^{14} \text{ g/cm}^3 \), or \( n_0 = 0.16 \text{ nucleons/fm}^3 \)
- For Neutron Stars, relevant densities are \( \sim 0.5-2 n_0 \)
- Existing constraints from symmetric nuclear matter, chiral EFT, causality (sound speed < c)
- n.b. other astrophysical observations will contribute (e.g. NICER) in coming years
Effect on gravitational waveform

- Tidal-induced quadrupole changes energy and luminosity functions for GW inspiral [Wade+ 1402.5156]

\[
\delta E_{\text{tidal}} = -\frac{1}{2} c^2 M \eta x \left[ -\left( \frac{9}{\chi_1} - 9 \right) \frac{c^{10}}{G^4 M^5} x^5 - \left( \frac{33}{2\chi_1} - \frac{11}{2} + \frac{11}{2} \chi_1 - \frac{33}{2} \chi_1^2 \right) \frac{c^{10}}{G^4 M^5} x^6 + (1 \leftrightarrow 2) \right]
\]

\[
\delta L_{\text{tidal}} = \frac{32}{5} c^5 G \eta^2 x^5 \left[ \left( \frac{18}{\chi_1} - 12 \right) \frac{c^{10}}{G^4 M^5} x^5 - \left( \frac{176}{7\chi_1} + \frac{1803}{28} - \frac{643}{4} \chi_1 + \frac{155}{2} \chi_1^2 \right) \frac{c^{10}}{G^4 M^5} x^6 + (1 \leftrightarrow 2) \right]
\]

- Effect is a frequency-dependent phase-lag in the overall inspiral Post-Newtonian waveform

\[
\delta \psi_{\text{tidal}} = \frac{3}{128 \eta x^{5/2}} \left[ \left( -\frac{39}{2} \tilde{\Lambda} \right) x^5 + \left( -\frac{3115}{64} \tilde{\Lambda} + \frac{6595}{364} \sqrt{1 - 4\eta} \delta \tilde{\Lambda} \right) x^6 \right]
\]

\[
\tilde{\Lambda} = \frac{8}{13} \left[ \left( 1 + 7\eta - 31\eta^2 \right) (\Lambda_1 + \Lambda_2) + \sqrt{1 - 4\eta} (1 + 9\eta - 11\eta^2) (\Lambda_1 - \Lambda_2) \right]
\]

\[
\frac{\lambda}{m^5} = \Lambda = \frac{2}{3} k_2 \left( \frac{Rc^2}{Gm} \right)^5
\]

- \(\tilde{\Lambda}\) “chirp-lambda” easiest parameter to constrain from inspiral

- EOS also affects tidal disruption, quadrupole-monopole coupling, quantity of ejecta and stability of remnant (hypermassive neutron star?)
Approximating Equations of State

- Actual equations of state are complicated functions of microphysical parameters.
- Capture them as a parameterised family of approximations:
  - Piecewise Polytrope [e.g. Read+ PRD 79 (2008)]: connect parts between phase transitions with polytropic EOS fits
  - Spectral decomposition [e.g. Lindblom PRD 82 (2010)]: expand pressure or enthalpy in Chebyshev polynomial basis
- Both these methods can approximate realistic range of EOS
Figure 7
(a) A large sample of proposed EoSs calculated under different physical assumptions and using a range of computational approaches. See the text for the descriptions of the EoSs, the acronyms, and the references. (b) The mass-radius curves corresponding to the EoSs shown in panel a.

4.2. Constraints on the Equation of State from Low-Energy Experiments

For symmetric matter (i.e., nuclei containing roughly equal numbers of neutrons and protons) near the nuclear saturation density, there are a range of experimental constraints. Most robustly, two-body potentials can be inferred from nucleon–nucleon scattering data below 350 MeV and the properties of light nuclei (Akmal et al. 1998, Morales et al. 2002).

The other significant constraints that arise from these experiments and are relevant for the NS EoSs are often expressed in terms of the symmetry energy parameters: $S_v$ and $L$ (see Equations 18 and 19 in the previous section as well as the discussion in Lattimer 2012). The experiments that yield the most accurate data and the least model-dependent results involve fitting nuclear masses and charge radii (Kl"upfel et al. 2009, Kortelainen et al. 2010). Nevertheless, the symmetry parameters that can be extracted from such data are highly correlated, as shown in Figure 8.

Neutron-rich matter can also be probed by measuring the neutron skin thickness of heavy nuclei. Studies within both the mean-field theory and the liquid droplet model frameworks have shown that the neutron skin thickness, defined as the difference of their neutron and proton root-mean-squared radii $\Delta r_{np} = \langle r^2_n \rangle^{1/2} - \langle r^2_p \rangle^{1/2}$, is a sensitive function of $S_v$ and $L$ and, thus, serves as a good probe of the symmetry energy (Centelles et al. 2009, Chen et al. 2010, Roca-Maza et al. 2011). The neutron skin thickness was measured by a variety of experiments for $\approx 20$ neutron-rich Sn isotopes with $\sim 30–50\%$ uncertainties. Chen et al. (2010) used these measurements to place additional constraints on the symmetry energy parameters (see Figure 8). In addition, the neutron skin thickness has been determined by...
Bayesian analysis. We could assume accurate knowledge of the astrophysical parameters, although this is often not the case.

We use two Bayesian data analysis methods: hypothesis testing and parameter estimation. These methods are particularly useful for obtaining best-case scenarios depending on the detector noise realizations. For instance, we can use these techniques to study the early waveform termination due to the finite neutron star quadrupole-monopole interaction [49, 50], the impact of hyperons, and other effects.

**Figure 2. Tidal deformability**

The parameter that is directly measurable by gravitational waves is the tidal deformability, which is a measure of the compactness of the gravitational wave source. The tidal deformability is defined as the ratio of the change in the tidal field to the change in the tidal wave. It is given by the following equation:

\[
Q_{ij} = -\lambda(m) \mathcal{E}_{ij}
\]

where \(Q_{ij}\) is the tidal deformability, \(\lambda(m)\) is the tidal stiffness, and \(\mathcal{E}_{ij}\) is the tidal wave.

The tidal stiffness is given by the following equation:

\[
\lambda(m) = (2/3) k_2(m) R^5(m)
\]

where \(k_2(m)\) is the tidal Love number, \(R(m)\) is the radius of the gravitational wave source, and \(m\) is the mass.

In our simulations, we consider both equal and unequal mass configurations. We perform 29 merger simulations using the GR hydrodynamics code to study the impact of hyperons and other effects. We compute the mass of the dynamic ejecta and of the remnant from GW observations. We consider both equal and unequal mass configurations.

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Chain of inference

1. Microphysics of nuclear matter: quarks, hadrons
   Symmetry energy, EFTs

2. Equation of state, numerical solutions

3. Approximate EOS: Spectral / polytropic

4. Stellar structure, tidal deformability

5. Tidal ejecta & post-merger remnant

6. Gravitational Waveform
Results: GW170817

Small spin

Large spin

LIGO-Virgo Collaboration:1805.11579
Kilonova

- **on-axis GRB (unobserved)**
- **off-axis GRB**
- **GRB jet**
- **Blue KN**
- **light r-nuclei**
- **Xe**
- **v ~ 0.25 c**
- **disk winds**
- **v ~ 0.1 c**
- **NS NS**
- **HMNS**
- **BH**
- **Red KN**
- **heavy r-nuclei**
- **t ~ week**
- **t ~ day**
- **Θ_{obs} ~ 11-33°**
- **orphan X-ray, radio afterglow**
- **observer**

**Table 1: Key Properties of GW170817**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>M_A</td>
<td>10^36</td>
<td>Fong et al. 2017</td>
</tr>
<tr>
<td>M_1</td>
<td>1.46</td>
<td>Kasen et al. 2017</td>
</tr>
<tr>
<td>M_2</td>
<td>1.36</td>
<td>Kasen et al. 2017</td>
</tr>
<tr>
<td>M_{tot}</td>
<td>10^49</td>
<td>Kasen et al. 2017</td>
</tr>
<tr>
<td>f_{max}</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
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<td></td>
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<td></td>
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</tr>
</tbody>
</table>
After collision, what happens to remnant?

- Low stiffness: prompt collapse to BH - less disk wind
- Higher stiffness: Hypermassive Neutron star exists for unknown time period (probably ~milliseconds)
Joint constraints

Combine inspiral-driven upper limits with EM-driven lower limits
- Require ejecta+disk to form GRB
- Implies lower limit on NS radius -> stiffness
Combining Events

- Combine multiple events to improve precision
Future observations?

- Light curves expected to vary with NS mass, radius, and presence of BH
- Also with viewing angle - how well can GWs disentangle effects?
Cosmology

• Compact binaries are **standard sirens**
  
  • Luminosity distance can be inferred directly from signal
  
  • If we know the *redshift*, can calculate Hubble constant
  
  \[ H_0 = \frac{cz}{d_L} \]

• Electromagnetic counterpart required to uniquely find host galaxy - binary neutron star / NS-BH binary

• If no Em counterpart can statistically associate with galaxy catalogue
The measurement of the GW polarization is crucial for inferring the binary inclination. This inclination, $\theta$, is defined as the angle between the line of sight vector from the source to the detector and the orbital angular momentum vector of the binary system. For electromagnetic (EM) phenomena it is typically not possible to tell whether a system is orbiting clockwise or counter-clockwise (or, equivalently, face-on or face-off), and sources are therefore usually characterized by a viewing angle: $\min(\theta, 180 - \theta)$. By contrast, GW measurements can identify the sense of the rotation, and thus $\theta$ ranges from 0 (counter-clockwise) to 180 deg (clockwise). Previous GW detections by LIGO had large uncertainties in luminosity distance and inclination (Abbott et al. 2016a) because the two LIGO detectors that were involved are nearly co-aligned, preventing a precise polarization measurement. In the present case, thanks to Virgo as an additional detector, the cosine of the inclination can be constrained at $0.683\% (1\sigma)$ confidence to the range $[1.00, 0.81]$ corresponding to inclination angles between $[144, 180]$ deg. This implies that the plane of the binary orbit is almost, but not quite, perpendicular to our line of sight to the source ($\theta \approx 180 \text{ deg}$), which is consistent with the observation of a coincident GRB (LVC, GBM, & INTEGRAL 2017 in prep.; Goldstein et al. 2017, ApJL, submitted; Savchenko et al. 2017, ApJL, submitted). We report inferences on $\cos \theta$ because our prior for it is flat, so the posterior is proportional to the marginal likelihood for it from the GW observations. EM follow-up of the GW sky localization region (Abbott et al. 2017c) discovered an optical transient (Coulter et al. 2017; Soares-Santos et al. 2017; Valenti et al. 2017; Arcavi et al. 2017; Tanvir et al. 2017; Lipunov et al. 2017) in close proximity to the galaxy NGC 4993. The location of the transient was previously observed by the Distance Less Than 40 Mpc (DLT40) survey on 2017 July 27.99 UT and no sources were found (Valenti et al. 2017). We estimate the probability of a random chance association between the optical counterpart and NGC 4993 to be $0.004\%$ (see the Methods section for details). In what follows we assume that the optical counterpart is associated with GW170817, and that this source resides in NGC 4993. To compute $H_0$ we need to estimate the background Hubble flow velocity at the position of NGC 4993. In the traditional electromagnetic calibration of the cosmic “distance ladder” (Freedman et al. 2001), this step is commonly carried out using secondary distance indicator information, such as the Tully-Fisher relation (Sakai et al. 2000), which allows one to infer the background Hubble flow velocity in the local Universe scaled back from more distant secondary indicators calibrated in quiet Hubble flow. We do not adopt this approach here, however, in order to preserve more fully the independence of our results from the electromagnetic distance ladder. Instead we estimate the Hubble flow velocity at the position $LIGO$-Virgo + others, Nature 551 (2017)
Outlook

• Gravitational Wave detections give us new insights into fundamental physics and astrophysics

• Only just beginning! Detector improvements (and 3rd generation) will dramatically increase the power of GW observations as number of events increases.

• More types of binaries yet to be seen - what will they bring?

• Multimessenger astronomy can help to pin down nuclear astrophysics processes even further.

• Expect the unexpected! What novelties will nature show us in the gravitational-wave astronomy?

• Find out more! download data, software:
  Gravitational Wave Open Science Centre: gw-openscience.org
  LIGO-Virgo publications: papers.ligo.org
Who knows what else is waiting to be discovered…?