Compact Binary Mergers, Nuclear EOS, and LIGO

- GWs and LIGO
- Compact binary mergers
- prospects for LIGO GW detection and EM counterparts
- Neutron stars
- Nuclear EOS
- Neutron star mass & radius
- BNS mergers
- BNS r-process nucleosynthesis
- BNS merger constrains on NEOS

Alan Weinstein, Caltech
for the LIGO Scientific Collaboration

DOE/NSF NSAC Meeting,
Bethesda, March 23, 2016
The Advanced LIGO detectors

H1

10 ms light travel time

L1

iLIGO → eLIGO → aLIGO

- S5 data run
- e-LIGO installation and commissioning
- S6 data run
- Dark period
- S6 data analysis & preparations for Advanced LIGO commissioning and open data

Advanced LIGO Project

Adv LIGO Installation begins
Commissioning & initial data With Advanced LIGO

Improve amplitude sensitivity by a factor of 10x, and…
⇒ Number of sources goes up 1000x!
GWs from coalescing compact binaries (NS/NS, BH/BH, NS/BH)

- Neutron star – neutron star (Centrella et al.)

Tidal disruption of neutron star

A unique and powerful laboratory to study strong-field, highly dynamical gravity and the structure of nuclear matter in the most extreme conditions

Waveform carries lots of information about binary masses, orbit, merger
Template-based searches

Masses and (aligned) spins
Templates spaced for < 3% loss of SNR: 250K templates.

Sensitive distance in Mpc

https://dcc.ligo.org/LIGO-P1500269/public/main
GW150914

https://dcc.ligo.org/LIGO-P150914/public/main

Whitened and band-passed [40-300] Hz

Reconstructed (no whitening)

Audio:
- filtered data
- freq-shifted data
- reconstructed & shifted
GW150914 in the frequency domain

Advanced LIGO strain data near GW150914

- H1 strain
- L1 strain
- NR strain

Made with data from the LIGO Open Science Center, losc.ligo.org
Observed BBH merger rate

From GW150914 – like events (high mass BBH),
\[ \text{Rate} \sim [2-53] \text{ Gpc}^{-3} \text{ yr}^{-1} \] (comoving frame).

From both events, the observed BBH merger
\[ \text{Rate} \sim [2-400] \text{ Gpc}^{-3} \text{ yr}^{-1} \]

Same ballpark as population synthesis models, CCSN rate, etc

iLIGO+eLIGO BBH rate upper limit: $\sim< 420$ Gpc$^{-3}$ yr$^{-1}$

Expected (and measured!) compact binary merger rates

- sGRB rate

- FRB Rate
  - S6

- BNS Rate
  - O1
  - O2
  - O3

- NSBH Rate
  - O1
  - O2
  - O3

- Measured BBH Rate

Expected ranges of binary neutron star merger rates and detections

- **“It’s tough to make predictions, especially about the future”** (Yogi Berra)
- Estimated BNS rate: $[10^1 – 10^4]$ Gpc$^{-3}$yr$^{-1}$

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Estimated Run Duration</th>
<th>BNS Range (Mpc)</th>
<th>Number of BNS Detections</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>LIGO</td>
<td>Virgo</td>
</tr>
<tr>
<td>2015</td>
<td>3 months</td>
<td>40 – 80</td>
<td>–</td>
</tr>
<tr>
<td>2016–17</td>
<td>6 months</td>
<td>80 – 120</td>
<td>20 – 60</td>
</tr>
<tr>
<td>2017–18</td>
<td>9 months</td>
<td>120 – 170</td>
<td>60 – 85</td>
</tr>
<tr>
<td>2019+</td>
<td>(per year)</td>
<td>200</td>
<td>65 – 130</td>
</tr>
<tr>
<td>2022+ (India)</td>
<td>(per year)</td>
<td>200</td>
<td>130</td>
</tr>
</tbody>
</table>

Binary neutron star mergers are a unique laboratory for nuclear (astro)-physics.
Short-hard and Long-soft GRBs

(a) Merging stars
- Neutron star binary system
- Coalescence and merger
- High-temperature accretion disk

(b) Hypernova
- Collapsing star
- Supernova stalls and black hole forms
- Accretion disk restarts supernova

Time

Relativistic outflow
Supernova (case b only)
BNS and NSBH mergers

Figure 1 from I Baros et al 2013 Class. Quantum Grav. 30 123001
Binary neutron star merger

http://www.nasa.gov/mission_pages/swift/bursts/short_burst_nsu_multimedia.html

Dana Berry/NASA
Electromagnetic radiation from sGRB progenitors

Short GRB

Ejecta-ISM shock radio emission from days to years

“kilonova” Prompt optical emission from seconds to days

Metzger & Berger 2011
Low-latency identification of transients for rapid (< ~100s) followup

EM counterparts to GW sources (if any) are short-lived and faint
sky localization with the GW detector network
Global Relay of Observatories
Watching Transients Happen
Kasliwal (2016)
Neutron stars

- Remnants of core collapse supernovae
- A unique laboratory for fundamental physics
- Strong, Weak, EM, gravity – all under the most extreme conditions
- Structure can be revealed through binary mergers

http://www.astro.umd.edu/~miller/nstar.html
All four fundamental forces under the most extreme conditions

- **Gravity**: Compact stars have gravitational fields $GM/c^2R \sim O(1)$, strong tidal effects, strong curvature, highly relativistic
- **Strong interaction at > 2x nuclear density in core**
  - Hard repulsive core of nucleon-nucleon interaction plays crucial role
  - Potential transition to hyperonic matter, strange quark matter, QGP
  - Complex ionic crystal lattice structure in crust: “nuclear pasta”
- **Weak interaction under extreme conditions with neutrino trapping -> beta equilibrium**
- **EM**: Superfluid core supporting extreme magnetic fields (perhaps $> 10^{15}$ Gauss at surface), flux tube pinning in core
Neutron Star Equation of State

- Simplification: $T=0$, pure neutron & proton gas. Appropriate (?) for interior of cold neutron stars.
Phase diagram of ground state

Cold equation of state: pressure vs density

- Neutron drip
- Nuclei + neutron pressure
- Nuclei + electron pressure
- Above nuclear density

J. Read, CGWAS 2015
Neutron Star Equation of State

- T=0, pure neutron & proton gas. \( f = \epsilon \)

\[
\epsilon(n_n, n_p) = \frac{3}{5} \frac{p_{F,n}^2}{2m_n} \frac{n_n}{n} + \frac{3}{5} \frac{p_{F,p}^2}{2m_p} \frac{n_p}{n} \quad p_F = (3\pi^2 h^3)^{1/3} n^{1/3}
\]

\[
P = n^2 \frac{\partial \epsilon}{\partial n} \propto n^{5/3}
\]

\[
\Gamma = \left. \frac{d \ln P}{d \ln \rho} \right|_s = \frac{5}{3}
\]

\[
P = K \rho^{\Gamma}
\]

"polytrope"

\( \Gamma = 5/3 \) corresponds to a non-relativistic gas.
A relativistic gas has \( \Gamma = 4/3 \), which is unstable to collapse.
Note that (unlike ideal gas law \( P = n k T \))
the result is independent of temperature.
In general, \( p v^n = \text{const} \) is polytropic, with \( \Gamma = 1+1/n \); here,
\( n = \) polytropic index (NOT \( n = \rho/m_N \))
Neutron Star Equation of State

Nuclear Statistical Equilibrium \((\rho > 10^7 \text{ g/cm}^3, T > 0.5 \text{ MeV})\)

\[ P = P(\rho, T, Y_e) \]

Composition determined by Saha-type equation.

\[ s = 1.2 \text{ k_B/baryon} \]
\[ Y_e = 0.3 \]

Something happens near \(10^{14} \text{ g/cm}^3\)!

\[ P \approx K \rho^\Gamma \]
\[ \Gamma = \left| \frac{d \ln P}{d \ln \rho} \right|_s \approx \frac{4}{3} \]
Neutron Star Equation of State

Nuclear Physics:
\[ R_{\text{nuc}} = A^{1/3} r_0 \]
\[ r_0 = 1.25 \text{ fm} \]

Nuclear Density:
\[ \bar{\rho}_{\text{nuc}} = \frac{A m_b}{4 \pi R_{\text{nuc}}^3} \]
\[ \rho_{\text{nuc}} \sim 2.7 \times 10^{14} \text{ g cm}^{-3} \]
\[ n_{\text{nuc}} \sim 0.16 \text{ fm}^{-3} \]

\[ s = 1.2 \text{ k}_B/\text{baryon} \]
\[ Y_e = 0.3 \]

\[ \Gamma = \left. \frac{d \ln P}{d \ln \rho} \right|_s \]

"Stiffening" of the EOS

C. Ott, 2012
Neutron Star Equation of State

Nuclear Physics:

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\[ Y_e = 0.3 \]

\[ \Gamma = \left. \frac{d \ln P}{d \ln \rho} \right|_s \]

What is causing the stiffening of the nuclear EOS?
C. Ott, 2012
Nuclear Equation of State

• T=0, interacting pure neutron & proton gas.

\[ \epsilon(n_n, n_p) = \frac{3}{5} \frac{p_{F,n}^2}{2m_n} n_n + \frac{3}{5} \frac{p_{F,p}^2}{2m_p} n_p + \frac{V_{np}(n_n, n_p)}{n} \]

nucleon-nucleon (NN) potential energy density

• Nuclear force is NN many-body interaction = “effective” strong force interaction.

• Mediated by mesons: 
  \( \pi (s=0), \sigma (s=0), \omega (s=1), \rho (s=1) \)

• Dependent on separation and spin orientation. **Scalar**, **vector**, and **tensor** components. **Vector component is repulsive.**
Nucleon-Nucleon Interaction

Example: Bethe & Johnson 74
2-pion exchange attractive; omega-exchange repulsive

\[ V_{NN} = -g_\pi^2 \frac{e^{-2\mu_\pi r}}{r} + g_\omega^2 \frac{e^{-\mu_\omega r}}{r} \]

\[ \mu_\pi = \frac{m_\pi}{(\hbar c)} \]
\[ \mu_\omega = \frac{m_\omega}{(\hbar c)} \]
\[ g_\omega^2/(\hbar c) = 29.6 \]
\[ g_\pi^2/(\hbar c) = 10 \]

"Repulsive Core"

short-ranged attractive force

nuclei live here!

C. Ott, 2012
What happens above nuclear density?
Inside neutrons: quarks

$\rho/c^2$ in g/cm$^3$

$nuclear\ density$

$\rho$ in g/cm$^3$

$1 \times 10^{14}$ $2 \times 10^{14}$ $5 \times 10^{14}$ $1 \times 10^{15}$ $2 \times 10^{15}$

$10^{16}$ $10^{15}$ $10^{14}$ $10^{13}$ $10^{12}$

neutrons, protons
+mesons?
+hyperons?

quark matter?

J. Read, CGWAS 2015
images: S. Socherer
Neutron Star Structure

Newtonian:
\[
\frac{dP}{dr} = -\frac{GM\rho}{r^2} \quad \frac{dM}{dr} = 4\pi r^2 \rho \quad \text{(no maximum mass!)}
\]

GR: Tolman-Oppenheimer-Volkov (TOV) eqns
\[
\frac{dP}{dr} = -G\left(\rho \left(1 + \frac{\epsilon}{c^2}\right) + \frac{P}{c^2}\right)\frac{M + 4\pi r^3 p/c^2}{r \left(r - 2GM/c^2\right)}
\]
\[
\frac{dM_g}{dr} = 4\pi r^2 \rho \left(1 + \frac{\epsilon}{c^2}\right) \quad \text{gravitational mass}
\]
\[
\frac{dM_b}{dr} = \frac{4\pi r^2}{\sqrt{1 - \frac{2GM}{rc^2}}} \rho \quad \text{baryonic mass}
\]

*Radius is circumferential radius!*

- Solve by ODE integration from \(r=0\), invert \(P(\rho)\) at each step to obtain \(\rho\).

C. Ott, 2012
Building neutron star mass-radius relation with TOV and NEOS

Knowing masses and radii would really help!

arXiv:1305.3510v1
Neutron star masses

Mass and radius constraints

Strange quark models appear to be ruled out...
Astrophysical constraints on masses and radii of NSs

Binary neutron star mergers

Daniel Price and Stephan Rosswog
Matter distribution during the disruption of the neutron star

About half of the remnant material is unbound, while a relatively low mass hot disk forms.

The origin of the elements – astrophysical nucleosynthesis

- Lightest elements (H, He, Li) forged in Big Bang
- Heavier elements (C, O, N, ... Fe) forged in the core of massive stars, distributed to ISM by core-collapse supernovae (star-death)
- Elements beyond Fe (like Cu, Au, Pb, Pt, U...) are forged during the SN ("r-process")
- but many/most of them might come from binary neutron star mergers (second-death)

By Cmglee - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=31761437
Nucleosynthesis in binary neutron star collisions

C. Ott;  http://www.lippuner.ca/files/nucleosynthesis_000_med.mp4
Nuclear abundances from detailed simulations on BNS mergers
GWs from BNS mergers

Spectrum of BBH inspiral, scale to 1.35-1.35, 45 Mpc
Spectrum of NS-NS inspiral, 1.35-1.35, 45 Mpc

True EOS unknown!

$S_n(f)$ and $2(f |\tilde{h}(f)|)^{1/2}$

AdvancedLIGO

Einstein Telescope

Initial LIGO
effectively point-particle
tidal effects

NS-NS EOS HB

NS-NS merger

AFTER NSNS merger

J. Read, CGWAS 2015
Spectrum of NS-NS inspiral, 1.35-1.35, 45 Mpc

\( \sqrt{S_n(f)} \) and \( 2(f |\tilde{h}(f)|)^{1/2} \)

- Effectively point-particle
- Tidal effects
- Initial LIGO
- Advanced LIGO
- Einstein Telescope
- NS-NS EOS 2H
- NS-NS merger
- AFTER NSNS merger

J. Read, CGWAS 2015
Consider two extended bodies in orbit or free-fall:

Residual gravitational effect is **tide**.

Amount of deformation depends on size and matter properties.

Deformation induces change in gravitational potential.

J. Read, CGWAS 2015
Tides and the Quadrupole moment $Q$

$$Q = \frac{2}{3} k R^5 \left( \frac{m}{d^3} \right)$$

gives the gravitational potential around a deformed body

$$U = -\frac{M}{r} - \frac{3}{2} \frac{Q(\cos^2\theta - 1)}{r^3}$$

This tells us about things like satellite movement, tidal locking ("back-reaction" on bulges), and orbital dynamics in binary systems

J. Read, CGWAS 2015
Calculate in GR:

Perturb a spherically symmetric neutron star, impose quadrupole angular dependence, look at scaling with distance from star $r$

$$
\lambda = \frac{Q}{E} = \frac{\text{size of quadrupole deformation}}{\text{strength of external tidal field}} \\
(\sim r^{-3}) \quad (\sim r^2)
$$

Love number $k_2$

Radius $R$

$$
\lambda = \frac{2}{3} k_2 R^5 \quad (G = c = 1)
$$

J. Read, CGWAS 2015
Equation of state determines $\lambda$ for each $M$
Effect of tides on orbit:

some energy into tides as stars come closer together
a bit of extra GW luminosity from rotating quadrupoles

stars merge earlier
Tidal effect on PN waveforms
Large stars, Hypermassive Remnant

Compact stars, Prompt Collapse

Simulations & animations by K Hotokezaka
Sekiguchi+ 11: First full GR NS-NS simulation with realistic microphysics, finite-temperature nuclear EOS of H. Shen+ ‘98,’11
Effects of tidal disruption of neutron stars near merger.
J. Read, CGWAS 2015

- arxiv.org/abs/1306.4065
Frequency of peak of final hyper-massive NS resonance
Universality of peak frequency

\[ \kappa_2^T = 2 \left( \frac{q^4}{(1+q)^5} \frac{k_2^A}{C_A^5} + \frac{q}{(1+q)^5} \frac{k_2^B}{C_B^5} \right) \]

Many observations required to constrain NEOS

\[ Q_{ij} = -\lambda(EOS; m) \epsilon_{ij} \]

\[ \lambda(m) = \frac{2}{3} k_2(m) R^5(m) \]

Constraining the NEOS using GWs from BNS
THANK YOU!

Questions?