The ultimate collision: Neutron stars rattle, shine, and sparkle.

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Neutron-star mergers and gravitational waves explore sensitivity to neutron-rich matter in neutron-star merger and gw signal.

### NS Binaries

Neutron-star mergers and gravitational waves explore sensitivity to neutron-rich matter in neutron-star merger and the gw signal.


*~10^7 yr* to *~10^8 - 10^9 yr* Orbit decays (GW radiation)

Observable @ 50 Hz to 200 Mpc

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<th>Time to Merger</th>
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Short gamma-ray burst rate is \( \sim 6 \text{ /Gpc}^3/\text{y} \)

If 2/3 are associated with BNS mergers, the rate in Ad. LIGO at design sensitivity would be about 2 per year after accounting for beaming.
GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott et al.

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)
August 17, 2017: Time-domain Multi-messenger astronomy begins
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+27 minutes: Alert notice (GCN) sent by Ad. LIGO
+11 hours: Optical transient detected in a galaxy NGC 4993 at 40 Mpc by the 1M2H team. Carnegie observatories at Los Campanas, Chile.
Multi-messenger Observations of a Binary Neutron Star Merger

Taken together the data tells an interesting story!
Where and how are the heavy-elements made?

Observed EM signal from GW170817 suggests 0.06 M☉ of heavy nuclei was produced and ejected during the merger.

Gold, platinum, plutonium and uranium is synthesized by colliding neutron stars. May even be the only source needed to explain observed abundances.

Blast Mining Neutron Stars

Phases of Dense Matter in Neutron Stars

- Inner Core: (Solid-Superfluid) neutrons, protons, electrons
- Outer Core: (Superfluid-Superconductor) neutrons, protons, electrons
- Inner Crust: (Solid-Superfluid) nuclei, electrons, neutrons
- Outer Crust: (solid) nuclei, electrons, neutrons

**Density (g/cm³)**
- Inner Core: ~3
- Outer Core: ~10
- Inner Crust: ~11.5
- Outer Crust: ~12

**Radius (km)**
- Inner Core: ~3
- Outer Core: ~10
- Inner Crust: ~11.5
- Outer Crust: ~12

**Mass (~1.4 M☉)**

**Density vs. Depth (km)**
- Neutron-rich nuclei + superfluid neutrons + e⁻
- Liquid core neutron-rich matter
- Non-spherical nuclei or pasta phase

**Matter Phases**
- Spherical nuclei + superfluid neutrons + e⁻
- Neutron-rich nuclei relativistic electrons
- 56 Fe nuclei + e⁻
- 62 Ni, 64 Ni, 84 Se, 118 Kr

**Graphical Elements**
- Neutron superfluid nuclei
- Liquid core neutron-rich matter center at 10 km
Blast Mining Neutron Stars

To extract ~0.03 M☉ from each neutron star, need to dig down >2 km in depth!

79 protons and 118 neutrons in a gold nucleus were once neutrons, swimming in a superfluid ocean inside a neutron star!
Neutron Star Merger Dynamics
(General) Relativistic (Very) Heavy-Ion Collisions at ~ 100 MeV/nucleon

Simulations: Rezzola et al (2013)

Inspiral:
Gravitational waves, Tidal Effects

Merger:
Disruption, NS oscillations, ejecta and r-process nucleosynthesis

Post Merger:
GRBs, Afterglows, and Kilonova
PRESSURE V/S ENERGY DENSITY (EOS)

\[ \log P(\varepsilon) \]

\[ \log \varepsilon \quad (\text{g/cm}^3) \]

- neutron drip
- relativistic electrons
- crust
- nuclear matter
- core
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\[ \log P(\varepsilon) \]

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Can calculate
Can speculate
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PRESSURE V/S ENERGY DENSITY (EOS)

\[ P(\varepsilon_{\text{sat}}) = 2.5 \pm 1 \text{ MeV/fm}^3 \]

- log P(\varepsilon)
- log \varepsilon (g/cm^3)

- can calculate
- can speculate

- neutron drip
- relativistic electrons
- crust
- core
- nuclear matter
PRESSURE V/S ENERGY DENSITY (EOS)

\[ \log P(\varepsilon) \]

\[ \log \varepsilon (\text{g/cm}^3) \]

- \( P(2\varepsilon_{\text{sat}}) = 13 \pm 5 \text{ MeV/fm}^3 \)
- \( P(\varepsilon_{\text{sat}}) = 2.5 \pm 1 \text{ MeV/fm}^3 \)

- Neutron drip
- Relativistic electrons
- Crust
- Nuclear matter
- Core

Can calculate
Can speculate
PRESSURE V/S ENERGY DENSITY (EOS)

\[ \log P(\varepsilon) = \log \varepsilon \]

- \( P(2\varepsilon_{\text{sat}}) = 13 \pm 5 \text{ MeV/fm}^3 \)
- \( P(\varepsilon_{\text{sat}}) = 2.5 \pm 1 \text{ MeV/fm}^3 \)

\[ P = P_{\text{max}} + \varepsilon \]

- Can calculate
- Can speculate

nuclear matter
neutron drip
relativistic electrons
crust
core

\( n\varepsilon \) 
\( \log n \varepsilon \)
\[ P(\varepsilon_{\text{sat}}) = 2.5 \pm 1 \text{ MeV/fm}^3 \]

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\[ P = P_{\text{max}} + \varepsilon \]

RELATIVISTIC ELECTRONS

NEUTRON DRIP

CRUST

NUCLEAR MATTER

CORE

can calculate

can speculate
PRESSURE V/S ENERGY DENSITY (EOS)

\[ P = P_{\text{max}} + \varepsilon \]

- \( P(2\varepsilon_{\text{sat}}) = 13 \pm 5 \text{ MeV/fm}^3 \)
- \( P(\varepsilon_{\text{sat}}) = 2.5 \pm 1 \text{ MeV/fm}^3 \)

can calculate

Relativistic electrons

Neutron drip

Can speculate

Maximum mass

Nuclear matter

Core

Crust

Can calculate

\( \log P(\varepsilon) \)

\( \log \varepsilon (\text{g/cm}^3) \)
Can calculate $P = P_{\text{max}} + \varepsilon$

$P(2\varepsilon_{\text{sat}}) = 13 \pm 5 \text{ MeV/fm}^3$

$P(\varepsilon_{\text{sat}}) = 2.5 \pm 1 \text{ MeV/fm}^3$

Maximum Mass Radii

Can speculate $\log P(\varepsilon) \text{ vs } \log \varepsilon (\text{g/cm}^3)$

Neutron drip

Relativistic electrons

Crust

Core

Nuclear matter

Can calculate)

Can speculate
PRESSURE V/S ENERGY DENSITY (EOS)

\[ \log P(\varepsilon) \]

\[ \log \varepsilon \ (g/cm^3) \]

- \( P(2\varepsilon_{\text{sat}}) = 13 \pm 5 \text{ MeV/fm}^3 \)
- \( P(\varepsilon_{\text{sat}}) = 2.5 \pm 1 \text{ MeV/fm}^3 \)

First Order Phase Transition

Maximum Mass

2 M⊙ NS

can calculate

can speculate

core

nuclear matter

radius

neutron drip

relativistic electrons
PRESSURE V/S ENERGY DENSITY (EOS)

\[ \log P(\varepsilon) \]

\[ \log \varepsilon \ (g/cm^3) \]

- Neutron drip
- Relativistic electrons
- Crust
- Core

- Maximum Mass
- 2 \( M_\odot \) NS

First Order Phase Transition

\[ P(2\varepsilon_{\text{sat}}) = 13 \pm 5 \text{ MeV/fm}^3 \]

\[ P(\varepsilon_{\text{sat}}) = 2.5 \pm 1 \text{ MeV/fm}^3 \]

Can calculate
Can speculate
• Modern EOS based on EFT inspired nuclear forces and Quantum Monte Carlo calculations provide useful predictions despite uncertainties at high density.

• Nuclear description viable up to $5 \times 10^{14} \, \text{g/cm}^3$:
  - Radius = 10 - 12 kms
  - Maximum mass = 2 - 2.5 solar masses

• Nuclear description viable up to $2.5 \times 10^{14} \, \text{g/cm}^3$:
  - Radius = 9.5 - 14 kms
  - Maximum mass = 2 - 3 solar masses

Tews, Carlson, Gandolfi and Reddy (2018)
Gravitational waves during inspiral

GWs are produced by fluctuating quadrupoles.

\[ g_{\mu\nu}(r, t) = \eta_{\mu\nu} + h_{\mu\nu}(r, t) \]

\[ h_{\mu\nu}(r, t) = \frac{2G}{r} \ddot{I}_{ij}(t_R) \quad I_{ij}(t) = \int d^3x \rho(t, \vec{x}) x_i x_j \]

For \( R_{\text{orbit}} \gg R_{\text{NS}} \):

\[ \ddot{I}_{ij}(t) \approx M \frac{R_{\text{orbit}}^2}{f^2} \approx M^{5/3} f^{2/3} \]

\[ h \approx 10^{-23} \left( \frac{M_{\text{NS}}}{M_\odot} \right)^{5/3} \left( \frac{f}{200 \text{ Hz}} \right)^{2/3} \left( \frac{100 \text{ Mpc}}{r} \right) \]

\[ h(t) = h \cos (2\pi f(t) t) \]
Late Inspiral:  $R_{\text{orbit}} \lesssim 10 R_{\text{NS}}$

Tidal forces deform neutron stars. Induces a quadrupole moment.

\[ Q_{ij} = \lambda E_{ij} \]
\[ E_{ij} = -\frac{\partial^2 V(r)}{\partial x_i \partial x_j} \]

Quadrupole polarizability

External field

Tidal deformations are large for a large NS:  $\lambda = k_2 R_{\text{NS}}^5$

Tidal interactions advance the orbit and change the rotational phase.
Tidal Effects at Late Times

- Both NSs contribute to tidal effect
- Leads to phase shift of 5–15 radians

Matter effects
- Both NSs contribute to tidal effect
- Leads to phase shift of 5–15 radians

\[ h_+ \text{ at } 100 \text{Mpc} \]

\[ t \text{ (s)} \]

Measuring the EOS directly
- The tidal deformability is calculated from the EOS
- This can be inverted to find EOS parameters from observations of the tidal parameters and masses

\[ \Gamma_1, \Gamma_2, \Gamma_3 \]

\[ \rho_1 \text{ fixed}, \rho_2 \text{ fixed} \]

\[ p(\rho, m_1, m_2) = \begin{cases} \rho_1, & 0 < \rho < 1 \\ \rho_2, & 1 < \rho < 2 \\ \rho_3, & \rho > 2 \end{cases} \]

\[ \rho = 1 \]

\[ \rho = 2 \]

\[ \rho_1, \rho_2, \rho_3 \]

\[ p(\Gamma, m_1, m_2) \]

\[ \begin{array}{c}
\text{BBH} \\
\text{BNS, } \Lambda_1 = \Lambda_2 = 591
\end{array} \]

400Hz up to merger

\[ \text{\textcopyright B. Lackey, L. Wade. PRD 91, 043002 (2015)} \]
Parameters from GW data analysis

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Primary mass $m_1$</td>
<td>$1.36 - 1.60 , M_\odot$</td>
</tr>
<tr>
<td>Secondary mass $m_2$</td>
<td>$1.17 - 1.36 , M_\odot$</td>
</tr>
<tr>
<td>Chirp mass $\mathcal{M}$</td>
<td>$1.188^{+0.004}<em>{-0.002} , M</em>\odot$</td>
</tr>
<tr>
<td>Mass ratio $m_2/m_1$</td>
<td>$0.7 - 1.0$</td>
</tr>
<tr>
<td>Total mass $m_{\text{tot}}$</td>
<td>$2.74^{+0.04}<em>{-0.01} , M</em>\odot$</td>
</tr>
<tr>
<td>Radiated energy $E_{\text{rad}}$</td>
<td>$&gt; 0.025 M_\odot c^2$</td>
</tr>
<tr>
<td>Luminosity distance $D_L$</td>
<td>$40^{+8}_{-14} , \text{Mpc}$</td>
</tr>
<tr>
<td>Viewing angle $\Theta$</td>
<td>$\leq 55^\circ$</td>
</tr>
<tr>
<td>Using NGC 4993 location</td>
<td>$\leq 28^\circ$</td>
</tr>
<tr>
<td>Combined dimensionless tidal deformability $\tilde{\Lambda}$</td>
<td>$\leq 800$</td>
</tr>
<tr>
<td>Dimensionless tidal deformability $\Lambda(1.4M_\odot)$</td>
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• Tidal deformations were small suggesting that $R < 14$ km. Compatible with current dense matter theories.

• Data favors a finite tidal polarizability but cannot distinguish between radii in the range 9-13 kms.
Many detections and next generation detectors

10% measurement of neutron star radius may be possible.
Many detections and next generation detectors

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Many detections and next generation detectors

Frequency of quasi-normal modes, post merger are also sensitive to the EOS. Will be accessible with next generation GW detectors.

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Many detections and next generation detectors

Frequency of quasi-normal modes, post merger are also sensitive to the EOS. Will be accessible with next generation GW detectors.

$$f_{\text{peak}} [\text{kHz}] = 199(M/R)^2 - 28.1(M/R) + 2.33$$

$$f_{\text{spiral}} [\text{kHz}] = 358(M/R)^2 - 82.1(M/R) + 6.16$$

$$f_{2-0} [\text{kHz}] = 392(M/R)^2 - 88.3(M/R) + 5.95$$

Bauswein & Stergioulas (2015)

10% measurement of neutron star radius may be possible.
Electromagnetic Signatures: Ejecta and Kilonova

- Mergers produce and eject heavy elements.
  Lattimer & Schramm 1974
- Radioactive heavy elements power an EM signal.
- Magnitude and color of the optical emission is sensitive to the composition of the ejecta.
  Kasen 2013

Figure 3: Evolution of the ultraviolet to near-infrared spectral energy distribution (SED) of SSS17a. (A) The vertical axis, log \( F_{\nu,0} \), is the logarithm of the observed flux. Fluxes have been corrected for foreground Milky Way extinction (33). Detections are plotted as filled symbols and upper limits for the third epoch (1.0 days post-merger) as downward pointing arrows. Less-constraining upper limits at other epochs are not plotted for clarity. Between 0.5 and 8.5 days after the merger, the peak of the SED shifts from the near-UV (<4500 Å) to the near-IR (>1 µm), and fades by a factor >70. The SED is broadly consistent with a thermal distribution and the colored curves represent best-fitting blackbody models at each epoch. In 24 hours after the discovery of SSS17a, the observed color temperature falls from &10,000 K to ⇠5,000 K. The epoch and best-fitting blackbody temperature (rounded to 100 K) are listed. SEDs for each epoch are also plotted individually in Figure S2 and described in (33). (B) Filter transmission functions for the observed photometric bands.
Remarkably, models that fit these light curves suggests:

1. Merger ejected ~ 0.06 M\(_\odot\) of radioactive nuclei
2. Radioactive ejecta had two components
3. One component with A>130 (heavy r-process)
4. Second component with A<130 (light r-process)
5. Mass of the A>130 component ~ 0.04 M\(_\odot\)
6. Mass of the A<130 component ~ 0.025 M\(_\odot\)

Tremendous detail in the observed light curves!
Merger Ejecta & Nucleosynthesis

Shock and neutrino wind driven ejecta:
Processed by neutrinos, much like in a supernova.
Not as neutron rich. Broad range of $Y_n \sim 0.6-0.8$.
Makes the light r-process $A < 130$.

Tidal ejecta:
Early, and very neutron-rich. $Y_n > 0.8$
Robust heavy r-process.
Makes $A=130$ and $A=190$ peaks.

Simulations find that the amount and composition of the material ejected depends:

- Neutron star radius
- Lifetime and neutrino emission of the merged hot and rapidly rotating neutron star
- Magnetic fields generated during the merger.

Typical mass ejected is $0.01-0.05 \, M_\odot$. 
Heavy nuclei dominate opacity

Metzger et al. 2010  Kasen 2013

• Iron group elements made when ejecta has \( Y_n < 0.75 \) have an opacity

\[ K_{\text{Fe-like}} \sim 1 \text{ cm}^2/\text{g} \]

(d-shell electrons contribute to transitions)

• Heavy r-process elements (with lanthanides) made when ejecta has \( Y_n > 0.8 \) have an opacity

\[ K_{\text{Lanthanides}} \sim 10 \text{ cm}^2/\text{g} \]

(f-shell electrons, dense level spacing and order or magnitude more allowed transitions)

To fit observed light curves requires:

\[ \sim 0.04 \text{ } M_\odot \text{ of heavy nuclei with } A>140 \]
\[ \sim 0.025 \text{ } M_\odot \text{ of moderately heavy nuclei with } A<140 \]
Neutron excess in the ejecta is moderated by weak interactions. Large neutrino fluxes from the hot hyper-massive neutron star drives matter towards smaller neutron excess.

\[
\begin{align*}
\nu_e + n &\rightarrow e^- + p \\
\bar{\nu}_e + p &\rightarrow e^+ + n \\
\end{align*}
\]

High temperatures created in dense shocked matter produces positrons. They would also deplete neutrons.

\[
e^+ + n \rightarrow p + \bar{\nu}_e
\]

Neutrino fluxes and spectra are sensitive properties of hot and dense matter and neutrino oscillations.

The lifetime and dynamics of the hyper-massive merged neutron star plays a central role.
QCD Phase Diagram & Neutron Star Mergers

QCD Phase transition
Cross-over

nucleons
+pions+ resonances

First-order

quark gluon plasma

neutron-rich liquid

nuclei + neutrons

color superconductor

$T$ (MeV)

$\rho$ (g/cm$^3$)
QCD Phase Diagram & Neutron Star Mergers

- Quark gluon plasma
- Nuclei + neutrons
- Neutron-rich liquid
- Color superconductor

QCD Phase transition
Cross-over

First-order

Co
QCD Phase Diagram & Neutron Star Mergers

- QCD Phase transition
- Cross-over
- First-order
- Quark gluon plasma
- Neutron-rich liquid
- Color superconductor
- Nucleons + pions + resonances
- Neutron + neutrons
Conclusions and Outlook

• NSs merge and emit GWs. The detection rate is likely to be greater than a few per year.

• Connection between EM signals (especially the Kilonova) and GWs will rely on our understanding of dense matter, neutrino physics, nuclear structure and reactions.

• EOS, weak interactions and transport at extreme density are critical to model mergers and interpret observations. May help probe the QCD phase diagram.

• Details worth pursuing with multi-physics merger simulations. Multi-messenger astronomy is here and has much to reveal.