Tidal deformability of neutron stars and gravitational waves

Chang-Hwan Lee
Pusan National University

Image credit: SXS (Simulating eXtreme Spacetimes)
Contents

• Motivation
• Neutron star physics before GW detection
• NS in new era of GW & multi-messenger astronomy
  - Direct measurement of NS mass from GW
  - Tidal Love number/deformability of NS from GW
• Prospects
Gravitational waves from neutron star binaries

- B1913+16 / Hulse & Taylor (1975)
- change in the orbital period due to GW radiation
- 1993 Nobel Prize
- LIGO is based on NS binary mergers
- GW expected in 2019
- $d = O(100 \text{ Mpc})$

NS (radio pulsar) which will coalesce within Hubble time

<table>
<thead>
<tr>
<th>PSR</th>
<th>$P$</th>
<th>$P_b$</th>
<th>$e$</th>
<th>Total Mass</th>
<th>$\tau_c$</th>
<th>$\tau_{GW}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(ms)</td>
<td>(hr)</td>
<td></td>
<td>$M_\odot$</td>
<td>(Myr)</td>
<td>(Myr)</td>
</tr>
<tr>
<td>J0737−3039A</td>
<td>22.70</td>
<td>2.45</td>
<td>0.088</td>
<td>2.58</td>
<td>210</td>
<td>87</td>
</tr>
<tr>
<td>J0737−3039B</td>
<td>2773</td>
<td>2.45</td>
<td>0.088</td>
<td>2.58</td>
<td>50</td>
<td>87</td>
</tr>
<tr>
<td>B1534+12</td>
<td>37.90</td>
<td>10.10</td>
<td>0.274</td>
<td>2.75</td>
<td>248</td>
<td>2690</td>
</tr>
<tr>
<td>J1756−2251</td>
<td>28.46</td>
<td>7.67</td>
<td>0.181</td>
<td>2.57</td>
<td>444</td>
<td>1690</td>
</tr>
<tr>
<td>B1913+16</td>
<td>59.03</td>
<td>7.75</td>
<td>0.617</td>
<td>2.83</td>
<td>108</td>
<td>310</td>
</tr>
<tr>
<td>B2127+11C</td>
<td>30.53</td>
<td>8.04</td>
<td>0.681</td>
<td>2.71</td>
<td>969</td>
<td>220</td>
</tr>
<tr>
<td>J1141−6545$^\dagger$</td>
<td>393.90</td>
<td>4.74</td>
<td>0.172</td>
<td>2.30</td>
<td>1.4</td>
<td>590</td>
</tr>
</tbody>
</table>

Nd:YAG laser 1064nm (infrared)

40kg fused Silica (SiO$_2$) (absorption < 1ppm)

Goal 200 W

Goal 750 kW

Laser Interferometer Gravitational-wave Observatory

10 ms light travel time

L$_x$ = 4 km

L$_y$ = 4 km

Power Recycling

Beam Splitter

Test Mass

Signal Recycling

Photodetector

100 kW Circulating Power

LSC

VIRGO

GSLG Scientific Collaboration
sGRB short-hard gamma-ray bursts from NS mergers

2704 BATSE Gamma-Ray Bursts

Fluence, 50-300 keV (ergs cm$^{-2}$)
GRB and Kilonova from NS binaries

r-process peak at A~195

Metzger and Berger 2012
Heavy Elements from NS mergers

Sources of Heavy Elements

• **Supernovae:**
  - neutrino-driven wind
  - r-process peak at $A \sim 130$

• **NS mergers:**
  - r-process peak at $A \sim 195$

solar pattern vs NS-merger
GW from Binary NS Mergers

GW 170817 (d=40 Mpc)
GRB 170817A by Fermi-GBM
Kilonova/X-ray/Optical Afterglows

soon after the announcement of 2017 Nobel Prize
GW170817 / GRB170817A
First event of Multi-messenger Astronomy

GW170817
GRB170817A
SSS17a/
AT2017gfo

TIMELINE

Fermi/Integral gamma-ray

Telescopes in Chile

http://horizon.kias.re.kr
Chandra X-ray

Korean Telescopes
Nature 551, 71 (2017)

VLA radio

http://horizon.kias.re.kr
NS binary merger

Gamma-ray

Earth

X-ray
Light
Radio

BH formation
GW
A gravitational-wave standard siren measurement of the Hubble constant


\[ H_0 = 70.0^{+12.0}_{-8.0} \text{ km s}^{-1} \text{Mpc}^{-1} \]
Masses in the Stellar Graveyard

in Solar Masses

LIGO-Virgo Black Holes

EM Black Holes

EM Neutron Stars

LIGO-Virgo Neutron Stars

LIGO-Virgo | Frank Elavsky | Northwestern
Gravitational-Wave & Multi-Messenger Astronomy

• First direct detection of GW in 2015
• First detection of BHs with masses 30 ~ 60 solar mass
• **GW, Gamma-ray, Optical, X-ray, Radio from NS mergers**
• New era for GW Astronomy & **Multi-Messenger Astronomy**
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Why Neutron Stars?

Ultimate testing place for physics of dense matter

e^+ e^- pair creation

\[ M = 1.5 \sim 2.0 M_\odot \]
\[ R = 10 \sim 15 \text{ km} \]
\[ A \sim 10^{57} \text{ nucleons} \]
Nuclear matter is not an ideal gas

**Condensed Matter:**
- electron degeneracy
- EM interaction

**Neutron Star:**
- hadron \((p,n)\) degeneracy
- strong interaction

- still uncertain due to the nature of strong interactions
- introduction of 3 body forces
- exotic states with strangeness
- ... ...
Why Neutron Stars?

Ultimate testing place for physics of dense matter

✓ chiral symmetry restoration
✓ color superconductivity
✓ color-flavor locking
✓ quark-gluon-plasma
✓ AdS/QCD
✓ symmetry energy
✓ tensor forces
✓ 3-body forces
✓ … …
Theomodynamics with General Relativity

Hydrostatic equilibrium

\[ \frac{dP}{dr} = -\frac{GM\rho}{r^2} \]

\[ \frac{dP}{dr} = -\frac{GM\rho}{r^2} \left( 1 + \frac{P}{\rho c^2} \right) \left( 1 + \frac{4\pi Pr^3}{Mc^2} \right) \left( 1 - \frac{2GM}{rc^2} \right)^{-1} \]

Mass continuity

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

\[ \frac{dM}{dr} = 4\pi r^2 \left( \frac{\epsilon}{c^2} \right) \]

includes all energy sources

physics of dense nuclear matter (strong interaction)

Radiative energy transport

\[ \frac{dT(r)}{dr} = -\frac{3L(r)\kappa(r)\rho(r)}{4\pi r^2 4acT(r)^3} \]

Energy conservation

\[ \frac{dL(r)}{dr} = 4\pi r^2 \rho(r)\epsilon(r) \]
Mass & radius of neutron star

Q) Which EOS?

Neutron Star-White Dwarf Binaries
1.97 solar mass NS: Nature 467 (2010) 1081
2.01 solar mass NS: Science 340 (2013) 6131
Millisecond Pulsars

Dipole Radiation

\[ \dot{E}_{\text{rot}} = I \Omega \dot{\Omega} \]

\[ \dot{E}_{\text{dipole}} = -\frac{B_\perp^2 R^6 \Omega^4}{6c^3} \]

\[ \dot{\Omega} = -\frac{B_\perp^2 R^6 \Omega^3}{6 I c^3} \]

- Parkes Multibeam
- Parkes High Latitude
- Swinburne Multibeam
- RRATs
- AXPs
- Other pulsars
Moment of Inertia / Glitches

\[ \dot{E}_{\text{rot}} = I \Omega \dot{\Omega} \]
\[ \dot{E}_{\text{dipole}} = -\frac{B_\perp^2 R^6 \Omega^4}{6c^3} \]
\[ \dot{\Omega} = -\frac{B_\perp^2 R^6 \Omega^3}{6Ic^3} \]
\[ \dot{\Omega} \propto -\Omega^n \]
\[ \tau_{\text{pulsar}} = \frac{\Omega}{(1 - n)\dot{\Omega}} \]

D. Antonopoulou (U. Amsterdam, 2015)
Superfluid Neutrons

D. Antonopoulou (U. Amsterdam, 2015)

1) OUTER CRUST
2) INNER CRUST

1. Neutron drip line
2. Ions
3. Neutron drip line
4. Superfluid neutrons

1) OUTER CRUST
2) INNER CRUST

3) OUTER CORE

- Down quark
- Up quark
- Strange quark

Nucleons
(neutrons and protons) expected to be superfluid/superconducting.
Also contains electrons and muons (not shown).

4) INNER CORE

May contain, in addition to or instead of nucleons:

- Hyperons
- Free quarks

These states of matter may also be in a superfluid or superconducting state.
Neutron Star Cooling

depends on

- particle fraction
- elements in the envelope
- nuclear superfluidity
- ...

Y. Lim, C H Hyun, CHL, IJMPE (2017)
Cooling Mechanism

- **Photon emission**: mostly on the surface
- **Neutrino emission**: entire region, major energy loss

<table>
<thead>
<tr>
<th>Name</th>
<th>Process</th>
<th>Emissivity(^b) (erg cm(^{-3}) s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modified Urca</td>
<td>(n + n \rightarrow n + p + e^- + \bar{\nu}_e) (n + p + e^- \rightarrow n + n + \nu_e)</td>
<td>(\sim 2 \times 10^{21} \ \mathcal{R} T_9^8)  Slow</td>
</tr>
<tr>
<td>(neutron branch)</td>
<td>(p + n \rightarrow p + p + e^- + \bar{\nu}_e) (p + p + e^- \rightarrow p + n + \nu_e)</td>
<td>(\sim 10^{21} \ \mathcal{R} T_9^8)  Slow</td>
</tr>
<tr>
<td>Modified Urca</td>
<td>(n + n \rightarrow n + n + \nu\bar{\nu})</td>
<td>(\sim 10^{19} \ \mathcal{R} T_9^8)  Slow</td>
</tr>
<tr>
<td>(proton branch)</td>
<td>(n + p \rightarrow n + p + \nu\bar{\nu})</td>
<td>(\sim 10^{19} \ \mathcal{R} T_9^8)  Slow</td>
</tr>
<tr>
<td>Bremsstrahlung</td>
<td>(p + p \rightarrow p + p + \nu\bar{\nu})</td>
<td></td>
</tr>
<tr>
<td>Cooper pair formations</td>
<td>(n + n \rightarrow [nn] + \nu\bar{\nu})</td>
<td>(\sim 5 \times 10^{21} \ \mathcal{R} T_9^7)</td>
</tr>
<tr>
<td>Direct Urca</td>
<td>(n \rightarrow p + e^- + \bar{\nu}_e) (p + e^- \rightarrow n + \nu_e)</td>
<td>(\sim 10^{27} \ \mathcal{R} T_9^6)  Fast</td>
</tr>
<tr>
<td>(\pi^-) condensate</td>
<td>(n + &lt; \pi^- &gt; \rightarrow n + e^- + \bar{\nu}_e)</td>
<td>(\sim 10^{26} \ \mathcal{R} T_9^6)  Fast</td>
</tr>
<tr>
<td>(K^-) condensate</td>
<td>(n + &lt; K^- &gt; \rightarrow n + e^- + \bar{\nu}_e)</td>
<td>(\sim 10^{25} \ \mathcal{R} T_9^6)  Fast</td>
</tr>
</tbody>
</table>
Fine-tuning Problem

- abrupt drop: ignition of direct URCA
- stiffer EoS allows early direct Urca
- no calculated-curve can explain middle-age data
- require real fine-tuning

NS mass: $1.0 - 2.0 \, M_{\odot}$

with Yeunhwan Lim, Chang Ho Hyun, Kyujin Kwak
Low-Mass X-ray Binaries (LMXB)

Accreting Object: NS or BH
Companion: Low-Mass Main Sequence
Age: Old (> $10^9$ year)
Accretion timescale: $10^7$ - $10^9$ year
X-ray energy: Soft (< 10 keV)
M & R from LMXB

with Myungkuk Kim, Young-Min Kim, Kyujin Kwak

Ozel et al. 2009
Mass & radius from LMXB

- in collaboration with MK Kim, YM Kim, K Kwak
# Low-Mass X-ray Binaries (LMXB)


<table>
<thead>
<tr>
<th>Object</th>
<th>$M (M_\odot)$</th>
<th>$R$ (km)</th>
<th>$M (M_\odot)$</th>
<th>$R$ (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$r_{ph} = R$</td>
<td></td>
<td>$r_{ph} \gg R$</td>
<td></td>
</tr>
<tr>
<td>4U 1608–522</td>
<td>$1.52^{+0.22}_{-0.18}$</td>
<td>$11.04^{+0.53}_{-1.50}$</td>
<td>$1.64^{+0.34}_{-0.41}$</td>
<td>$11.82^{+0.42}_{-0.89}$</td>
</tr>
<tr>
<td>EXO 1745–248</td>
<td>$1.55^{+0.12}_{-0.36}$</td>
<td>$10.91^{+0.86}_{-0.65}$</td>
<td>$1.34^{+0.450}_{-0.28}$</td>
<td>$11.82^{+0.47}_{-0.72}$</td>
</tr>
<tr>
<td>4U 1820–30</td>
<td>$1.57^{+0.13}_{-0.15}$</td>
<td>$10.91^{+0.39}_{-0.92}$</td>
<td>$1.57^{+0.37}_{-0.31}$</td>
<td>$11.82^{+0.42}_{-0.82}$</td>
</tr>
<tr>
<td>M13</td>
<td>$1.48^{+0.21}_{-0.64}$</td>
<td>$11.04^{+1.00}_{-1.28}$</td>
<td>$0.901^{+0.28}_{-0.12}$</td>
<td>$12.21^{+0.18}_{-0.62}$</td>
</tr>
<tr>
<td>ω Cen</td>
<td>$1.43^{+0.26}_{-0.61}$</td>
<td>$11.18^{+1.14}_{-1.27}$</td>
<td>$0.994^{+0.51}_{-0.21}$</td>
<td>$12.09^{+0.27}_{-0.66}$</td>
</tr>
<tr>
<td>X7</td>
<td>$0.832^{+1.19}_{-0.051}$</td>
<td>$13.25^{+1.37}_{-3.50}$</td>
<td>$1.98^{+0.10}_{-0.36}$</td>
<td>$11.3^{+0.95}_{-1.03}$</td>
</tr>
</tbody>
</table>
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• Prospects
Response of NS to GW during Inspiral

perturbative approaches
Tidal deformability & Love number

Selected references

- A.E.H. Love (1909) - The Yielding of the Earth to Disturbing Forces
- K.S. Thorne & A. Campolattaro (1967) - non-radial pulsation of NS
- J.B. Hartle & K.S. Thorne (1969) - stability of rotating NS
- … …
- K.S. Thorne (1998) - Tidal stabilization of rigid rotating, fully relativistic neutron star
- … …
Tidal deformability & Love number

\[- \frac{(1 + g_{tt})}{2} = - \frac{m}{r} - \frac{3Q_{ij}}{2r^3} \left( n^i n^j - \frac{1}{3} \delta^{ij} \right) + \mathcal{O} \left( \frac{1}{r^3} \right) + \frac{\mathcal{E}_{ij}}{2} r^2 n^i n^j + \mathcal{O}(r^3) \]

\( \mathcal{E}_{ij} \): external quadrupole tidal field

\( Q_{ij} \): quadrupole moment of NS

\[ \lambda \quad \text{Tidal deformability} \]

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

\[ n^i = \frac{x^i}{r} \]

\[ k_2 : \quad l = 2 \quad \text{Tidal Love number} \]

\[ k_2 = \frac{3}{2} G \lambda R^{-5} \]

Hinderer et al. PRD 81 (2010)
Regge-Wheeler gauge

linear $l = 2$ perturbation onto spherically symmetric star

$$
\begin{align*}
\frac{dH}{dr} &= \beta \\
\frac{d\beta}{dr} &= 2 \left(1 - 2 \frac{m_r}{r}\right)^{-1} H \left\{-2\pi \left[5\epsilon + 9p + f(\epsilon + p)\right] + \frac{3}{r^2} + 2 \left(1 - 2 \frac{m_r}{r}\right)^{-1} \left(\frac{m_r}{r^2} + 4\pi rp\right)^2\right\} \\
&\quad + \frac{2\beta}{r} \left(1 - 2 \frac{m_r}{r}\right)^{-1} \left\{-1 + \frac{m_r}{r} + 2\pi r^2(\epsilon - p)\right\}
\end{align*}
$$

$$
\begin{align*}
 ds^2 &= -e^{2\Phi(r)} \left[1 + H(r)Y_{20}(\theta, \varphi)\right] dt^2 \\
&\quad + e^{2\Lambda(r)} \left[1 - H(r)Y_{20}(\theta, \varphi)\right] dr^2 \\
&\quad + r^2 \left[1 - K(r)Y_{20}(\theta, \varphi)\right] \left(d\theta^2 + \sin^2(\theta) d\varphi^2\right)
\end{align*}

\begin{align*}
K'(r) &= H'(r) + 2H(r)\Phi'(r) \\
f &= \frac{d\epsilon}{dp}
\end{align*}

Tidal love number

\[ k_2 = \frac{3}{2} G \lambda R^{-5} \]

\[ k_2 : \ l = 2 \text{ Tidal Love number} \]

\[
k_2 = \frac{8C^5}{5} (1 - 2C)^2 \left[ 2 + 2C(y - 1) - y \right] \\
\times \left\{ 2C \left[ 6 - 3y + 3C(5y - 8) \right] \\
+ 4C^3 \left[ 13 - 11y + C(3y - 2) + 2C^2(1 + y) \right] \\
+ 3(1 - 2C)^2 \left[ 2 - y + 2C(y - 1) \right] \ln(1 - 2C) \right\}^{-1}
\]

\[
y = \frac{R \beta(R)}{H(R)} \quad C = \frac{M}{R}
\]
Theomodynamics with General Relativity

\[ P = P(\rho, T, \text{composition}) \]
\[ \kappa = \kappa(\rho, T, \text{composition}) \]
\[ \epsilon = \epsilon(\rho, T, \text{composition}) \]

**Hydrostatic equilibrium**

\[ \frac{dP}{dr} = -\frac{GM\rho}{r^2} \]
\[ \frac{dP}{dr} = -\frac{GM\rho}{r^2} \left( 1 + \frac{P}{\rho c^2} \right) \left( 1 + \frac{4\pi Pr^3}{Mc^2} \right) \left( 1 - \frac{2GM}{rc^2} \right)^{-1} \]

**Mass continuity**

\[ \frac{dM}{dr} = 4\pi r^2 \rho \]
\[ \frac{dM}{dr} = 4\pi r^2 \left( \frac{\epsilon}{c^2} \right) \]
- includes all energy sources
- physics of dense nuclear matter
  (strong interaction)

**Radiative energy transport**

\[ \frac{dT(r)}{dr} = -\frac{3L(r)\kappa(r)\rho(r)}{4\pi r^2 4acT(r)^3} \]

**Energy conservation**

\[ \frac{dL(r)}{dr} = 4\pi r^2 \rho(r)\epsilon(r) \]
Systematic Parameter Errors in Inspiring Neutron Star Binaries

Marc Favata

\[ \tilde{h}_T(f) = A f^{-7/6} e^{i \Psi_T(f)} \]

\[ \Psi_T(f) = \varphi_c + 2\pi f t_c + \frac{3}{128\eta v^5} (\Delta \Psi_{3.5\text{PN}}^{pp} + \Delta \Psi_{3\text{PN}}^{\text{spin}} + \Delta \Psi_{2\text{PN}}^{\text{ecc.}} + \Delta \Psi_{6\text{PN}}^{\text{tidal}} - \Delta \Psi_{6\text{PN}}^{\text{tm}}) \]

\[ v = (\pi f M)^{1/3} \]

\[ \frac{v}{c} = (GM\pi f / c^3)^{1/3} \]

\[ \Delta \Psi_{6\text{PN}}^{\text{tidal}} = -\frac{39}{2} \tilde{\Lambda} v^{10} + v^{12} \left( \frac{6595}{364} \delta \tilde{\Lambda} - \frac{3115}{64} \tilde{\Lambda} \right) \]

\[ \tilde{\Lambda} \equiv \frac{32}{M^5} = \frac{8}{13} [(1 + 7\eta - 31\eta^2)(\hat{\lambda}_1 + \hat{\lambda}_2) \]

\[ -\sqrt{1 - 4\eta(1 + 9\eta - 11\eta^2)(\hat{\lambda}_1 - \hat{\lambda}_2)}. \]
**phase shift vs deformability**

\[
\frac{d\Psi_T}{dx}\bigg|_{\text{tidal,5PN}} = -\frac{195}{8} \frac{x^{3/2}}{\eta} \frac{\tilde{\lambda}}{M^5} \propto \frac{\tilde{\lambda}}{M^5}
\]

\[
x = (\omega M)^{2/3} \Rightarrow \left(\omega \frac{GM}{c^3}\right)^{2/3}
\]

\[
\eta = m_1 m_2 / M^2
\]

\[
\Lambda = \frac{\lambda}{m^5} \Rightarrow G\lambda \left( \frac{c^2}{Gm} \right)^5 \approx 950.5 \left( \frac{m_\odot}{m} \right)^5 \left( \frac{\lambda}{10^{36} \text{ g cm}^2 \text{ s}^2} \right)
\]

\[
\Lambda = G \left( \frac{c^2}{Gm} \right)^5 \times \frac{2}{3} \frac{R^5}{G} k_2 = \frac{2}{3} \left( \frac{Rc^2}{Gm} \right)^5 k_2 \approx 9495 \left( \frac{R_{10 \text{km}}}{m_{M_\odot}} \right)^5 k_2
\]
accumulated GW phase

$$|\Delta \phi_{GW}(f)| = |\Psi(f)_{pp(3.5PN)} - \Psi(f)_{pp(3.5PN)} + \text{tidal(5PN)}|$$
Accumulated GW phase

the number of wave cycles in frequency domain

\[ \Delta N_{\text{cyc, } \Psi} = \frac{1}{2\pi} \left[ \Psi(f_2) - \Psi(f_1) + (f_1 - f_2) \frac{d\Psi}{df_1} \right] \]

\( f_1 = 10 \text{ Hz,} \)
the low frequency cutoff for
Advanced LIGO
due to seismic noises

Waveform models:
TaylorT2 for \( \Delta N_{\text{cyc}} \)
TaylorF2(SPA) \( \Delta N_{\text{cyc, } \Psi} \)

Moore et al., PRD.93.124061(2016)
accumulated GW phase

waveform model: TaylorF2(SPA)

$M_{\text{ch}} = 1.188M_\odot$

$M_1 = M_2 = 1.365M_\odot$

$\sim 600$ Hz
Measurement error vs. source distance

Fig. 1: Tidal deformability measurement error vs. distance to the source. Distances to galaxy clusters and GW20170817 distance are marked.

Y.B. Choi, H. S. Cho, C.-H. Lee
GW 170817 \((d=40 \text{ Mpc})\)
GRB 170817A by Fermi-GBM
Kilonova/X-ray/Optical Afterglows

soon after the announcement of
2017 Nobel Prize
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)
GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

TABLE I. Source properties for GW170817: we give ranges encompassing the 90% credible intervals for different assumptions of the waveform model to bound systematic uncertainty. The mass values are quoted in the frame of the source, accounting for uncertainty in the source redshift.

|                           | Low-spin priors ($|\chi| \leq 0.05$)                  | High-spin priors ($|\chi| \leq 0.89$)                  |
|---------------------------|---------------------------------------------------|---------------------------------------------------|
| Primary mass $m_1$        | $1.36_{-1.0}^{+1.60} M_\odot$                     | $1.36_{-0.50}^{+2.26} M_\odot$                     |
| Secondary mass $m_2$      | $1.17_{-0.88}^{+1.36} M_\odot$                     | $0.86_{-0.36}^{+1.36} M_\odot$                     |
| Chirp mass $\mathcal{M}$  | $1.188_{-0.002}^{+0.004} M_\odot$                 | $1.188_{-0.002}^{+0.004} M_\odot$                 |
| Mass ratio $m_2/m_1$      | $0.7_{-1.0}^{+1.0}$                                | $0.4_{-1.0}^{+1.0}$                                |
| Total mass $m_{\text{tot}}$ | $2.74_{-0.01}^{+0.04} M_\odot$                     | $2.85_{-0.09}^{+0.47} M_\odot$                     |
| Radiated energy $E_{\text{rad}}$ | $> 0.025 M_\odot c^2$                               | $> 0.025 M_\odot c^2$                               |
| Luminosity distance $D_L$ | $40_{-14}^{+8} \text{ Mpc}$                       | $40_{-14}^{+8} \text{ Mpc}$                       |
| Viewing angle $\Theta$    | $\leq 55^\circ$                                    | $\leq 56^\circ$                                    |
| Using NGC 4993 location   | $\leq 28^\circ$                                    | $\leq 28^\circ$                                    |
| Combined dimensionless tidal deformability $\tilde{\Lambda}$ | $\leq 800$                                      | $\leq 700$                                      |
| Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$ | $\leq 800$                                      | $\leq 1400$                                      |
prefer lower $\Lambda$ (soft EOS)
## Revised Properties of GW170817

Abbott et al. (LSC and Virgo), arxiv:1805.11579

<table>
<thead>
<tr>
<th>Property</th>
<th>Low-spin prior ($\chi \leq 0.05$)</th>
<th>High-spin prior ($\chi \leq 0.89$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binary inclination $\theta_{JN}$</td>
<td>$146^{+25}_{-27}$ deg</td>
<td>$152^{+21}_{-27}$ deg</td>
</tr>
<tr>
<td>Binary inclination $\theta_{JN}$ using EM distance constraint [104]</td>
<td>$151^{+15}_{-11}$ deg</td>
<td>$153^{+15}_{-11}$ deg</td>
</tr>
<tr>
<td>Detector frame chirp mass $M_{\text{det}}$</td>
<td>$1.1975^{+0.0001}<em>{-0.0001} M</em>\odot$</td>
<td>$1.1976^{+0.0004}<em>{-0.0002} M</em>\odot$</td>
</tr>
<tr>
<td>Chirp mass $M$</td>
<td>$1.186^{+0.001}<em>{-0.001} M</em>\odot$</td>
<td>$1.186^{+0.001}<em>{-0.001} M</em>\odot$</td>
</tr>
<tr>
<td>Primary mass $m_1$</td>
<td>$(1.36, 1.60) M_\odot$</td>
<td>$(1.36, 1.89) M_\odot$</td>
</tr>
<tr>
<td>Secondary mass $m_2$</td>
<td>$(1.16, 1.36) M_\odot$</td>
<td>$(1.00, 1.36) M_\odot$</td>
</tr>
<tr>
<td>Total mass $m$</td>
<td>$2.73^{+0.04}<em>{-0.01} M</em>\odot$</td>
<td>$2.77^{+0.02}<em>{-0.05} M</em>\odot$</td>
</tr>
<tr>
<td>Mass ratio $q$</td>
<td>$(0.73, 1.00)$</td>
<td>$(0.53, 1.00)$</td>
</tr>
<tr>
<td>Effective spin $\chi_{\text{eff}}$</td>
<td>$0.00^{+0.02}_{-0.01}$</td>
<td>$0.02^{+0.08}_{-0.02}$</td>
</tr>
<tr>
<td>Primary dimensionless spin $\chi_1$</td>
<td>$(0.00, 0.04)$</td>
<td>$(0.00, 0.50)$</td>
</tr>
<tr>
<td>Secondary dimensionless spin $\chi_2$</td>
<td>$(0.00, 0.04)$</td>
<td>$(0.00, 0.61)$</td>
</tr>
<tr>
<td>Tidal deformability $\tilde{A}$ with flat prior</td>
<td>$300^{500}<em>{-190} (\text{symmetric})/ 300^{420}</em>{-230} (\text{HPD})$</td>
<td>$(0, 630)$</td>
</tr>
</tbody>
</table>

\[
300^{500}_{-190} (\text{symmetric})/ 300^{420}_{-230} (\text{HPD}) \quad (0, 630)
\]
A new constraint by GW Observation

Low-spin prior: $\chi \leq 0.05$
Neutron Star of Known Mass

GW170817: BNS
M1: 1.36~1.60 M⊙ (1.36~2.26)
M2: 1.17~1.36 M⊙ (0.86~1.36)

Spectral expansion of adiabatic index [Lindblom et al.]

\[ \epsilon(p) = \sum_k \epsilon_k \Phi_k(p). \]

\[ \Gamma(p) = \exp \left[ \sum_k \gamma_k \Phi_k(p) \right] \]

\[ \Gamma(x) = \exp \left( \sum_k \gamma_k x^k \right) \]

\[ \frac{d\epsilon(p)}{dp} = \frac{\epsilon(p) + p}{p \Gamma(p)} \]

\[ \epsilon(p) = \frac{\epsilon_0}{\mu(p)} + \frac{1}{\mu(p)} \int_{p_0}^{p} \frac{\mu(p')}{\Gamma(p')} dp' \]

\[ \mu(p) = \exp \left[ - \int_{p_0}^{p} \frac{dp'}{p' \Gamma(p')} \right] \]

piecewise polytropic EoS

\[ p(\rho) = K_i \rho^{\Gamma_i} \]
A new constraint by GW Obs. (1)

\[ \Lambda(1.4M_\odot) = 190^{+390}_{-120} \]

\[ P(2\,\rho_{\text{nuc}}) = 3.5^{+2.7}_{-1.7} \times 10^{34} \text{ dyne/cm}^2 \]
\[ P(6\,\rho_{\text{nuc}}) = 9.0^{+7.9}_{-2.6} \times 10^{35} \text{ dyne/cm}^2 \]

\[ \rho_{\text{nuc}} = 2.8 \times 10^{14} \text{ g/cm}^3 \]

Abbott et al. (LSC and Virgo), arxiv:1805.11581 (PRL accepted)
Universal (Eos-insensitive) relations

I-Love-Q relation, ...

- Moment of inertia (I)
- Tital Love number (Love)
- Quadrupole moment (Q)

Applications

- X-ray observations
- Gravitational-wave measurements
- Gravitational & astrophysical test of GR
A new constraint by GW Obs. (2)

EoS insensitive relations (Yagi&Yunes,PR2017)

\[ R_1 = 10.8^{+2.0}_{-1.7} \text{ km} \]
\[ R_2 = 10.7^{+2.1}_{-1.5} \text{ km} \]

Parametrized EoS: \( M_{\text{max}} \geq 1.97 \, M_\odot \)

\[ R_1 = 11.9^{+1.4}_{-1.4} \text{ km} \]
\[ R_2 = 11.9^{+1.4}_{-1.4} \text{ km} \]
Contents

• Motivation
• Neutron star physics before GW detection
• NS in new era of GW & multi-messenger astronomy
  - Direct measurement of NS mass from GW
  - Tidal Love number/deformability of NS from GW
• Prospects
What we have done in Korea

Tidal deformability of neutron stars with realistic nuclear energy density functionals

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2Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA
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4Department of Physics, Pusan National University, Busan 46241, Korea

(Received 1 May 2018; revised manuscript received 14 August 2018; published 26 December 2018)
Constraints on Nuclear EoS

- Nuclear data: hundreds of models (Skyrme force, RMF, …)
- Neutron star maximum mass
  
  \[1.97 \pm 0.04 \text{ M}_\odot \text{ [Nature 467, 1081 (2010)]}\]
  
  \[2.01 \pm 0.04 \text{ M}_\odot \text{ [Science 340, 448 (2013)]}\]

Mass-Radius relations

**GW170817**
- $M_{\text{chirp}} = 1.188 \, M_{\odot}$
- low spin prior: $M_1 = 1.36 \sim 1.60 \, M_{\odot}$, $M_2 = 1.17 \sim 1.36 \, M_{\odot}$
- high spin prior: $M_1 = 1.36 \sim 2.26 \, M_{\odot}$, $M_2 = 0.86 \sim 1.36 \, M_{\odot}$

$M_{\odot}$
Tidal deformability of a NS

GW170817, $M_{\text{chirp}} = 1.188 M_{\odot}$
- low spin prior : $\Lambda(1.4 M_{\odot}) < 800$
- high spin prior : $\Lambda(1.4 M_{\odot}) < 1400$

Kim et al., arxiv:1805.00219
**Prospects of the Observing Runs**


<table>
<thead>
<tr>
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<tbody>
<tr>
<td></td>
<td>4 months</td>
<td>9 months</td>
<td>12 months</td>
<td>(per year)</td>
<td>(per year)</td>
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<tr>
<td>Planned run duration</td>
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<td>LIGO</td>
<td>40–60</td>
<td>60–75</td>
<td>75–90</td>
<td>105</td>
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<td>Virgo</td>
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<td>20–40</td>
<td>40–50</td>
<td>40–70</td>
<td>80</td>
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<td>KAGRA</td>
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<td>Expected burst range/Mpc</td>
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<tr>
<td>LIGO</td>
<td>40–80</td>
<td>80–120</td>
<td>120–170</td>
<td>190</td>
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<tr>
<td>Virgo</td>
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<td>20–65</td>
<td>65–85</td>
<td>65–115</td>
<td>125</td>
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<td>KAGRA</td>
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<td>140</td>
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<tr>
<td>Expected BNS range/Mpc</td>
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<tr>
<td>LIGO</td>
<td>60–80</td>
<td>60–100</td>
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<tr>
<td>Virgo</td>
<td></td>
<td>25–30</td>
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<td>KAGRA</td>
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<tr>
<td>Achieved BNS range/Mpc</td>
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<tr>
<td>LIGO</td>
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<tr>
<td>Virgo</td>
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</tr>
<tr>
<td>KAGRA</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Estimated BNS detections</td>
<td>0.05–1</td>
<td>0.2–4.5</td>
<td>1–50</td>
<td>4–80</td>
<td>11–180</td>
</tr>
<tr>
<td>Actual BNS detections</td>
<td>0</td>
<td>1</td>
<td></td>
<td></td>
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<tr>
<td>90% CR % within 5 deg²</td>
<td>&lt; 1</td>
<td>1–5</td>
<td>1–4</td>
<td>3–7</td>
<td>23–30</td>
</tr>
<tr>
<td>20 deg²</td>
<td>&lt; 1</td>
<td>7–14</td>
<td>12–21</td>
<td>14–22</td>
<td>65–73</td>
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<tr>
<td>median/deg²</td>
<td>460–530</td>
<td>230–320</td>
<td>120–180</td>
<td>110–180</td>
<td>9–12</td>
</tr>
<tr>
<td>Searched area % within 5 deg²</td>
<td>4–6</td>
<td>15–21</td>
<td>20–26</td>
<td>23–29</td>
<td>62–67</td>
</tr>
<tr>
<td>20 deg²</td>
<td>14–17</td>
<td>33–41</td>
<td>42–50</td>
<td>44–52</td>
<td>87–90</td>
</tr>
</tbody>
</table>

**We expect to observe more BNS and/or NS-BH**
NICER Neutron star Interior Composition ExploreR

- **launch**: June 2017, SpaceX
- **platform**: ISS ELC (ExPRESS Logistics Carrier)
- **instrument**: X-ray (0.2-12 keV)
- **objective**
  - **structure**: neutron star radii to 5%, cooling timescales
  - **dynamics**: stability of pulsars as clocks, properties of outbursts, oscillations, and precession
  - **energetics**: intrinsic radiation patterns, spectra, and luminosities
RAON Site: Sindong in Daejeon

Courtesy of Youngman Kim (IBS)
○ **Goal**: To build a heavy ion accelerator complex RAON for rare isotope science researches in Korea
○ **Project period**: 2011.12 - 2021.12
○ **Total Budget**: ~$1.43 billion

(Facilities ~ $0.46 bill., Bldgs & Utilities ~ $0.97 bill.)
- include initial experimental apparatus

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**Rare Isotope Science Project (RISP)**

**Origin of Matter**
- Nuclear Astrophysics
- Nuclear Matter
- Super Heavy Element Search
- High-precision Mass Measurement

**Properties of Exotic Nuclei**
- Nuclear Structure
- Electric Dipole Moment and Symmetry
- Nuclear Theory
- Hyperfine Structure Study

**Applied Science**
- Bio-Medical Science
- Material Science
- Neutron Science

**Future Extension**
- Charged Lepton Flavor Violation
1. Overview

Project Milestone

**System Installation**
- 2014: ECR-IS beam & ISOL beam (SI beam) (Dec 2015)
- 2015: RFQ beam (Dec 2016)
- 2016: SCL demo beam (Dec 2017)
- 2017: SCL installation (April 2019)
- 2018: ISOL Commissioning (July 2020)
- 2019: 18.5MeV/u SI beam (Dec 2020)
- 2020: D-1 Experiment (Jan 2021)
- 2021: 18.5MeV/u RI beam (Sep 2021)

**Facility Construction**
- 2014: Completion of basic design (Dec 2015)
- 2015: Beginning of priority construction (Feb 2017)
- 2016: Completion of detail design (June 2017)
- 2017: Beginning of construction (Sep 2017)
- 2018: Supply of utilities (Dec 2018)
- 2019: Completion of construction (Aug 2020)
- 2020: Building Permit (April 2021)
- 2021: Completion of inspection of the radiation facility (Dec 2021)

(2018) SCL3 manufacturing
SCL2 Prototype

(2019) SCL3 Installation
SCL2 manufacturing

(2020) SCL3 Beam Commissioning/
Const Completion

(2021) SCL3 Beam Commissioning/
Project Completion
Major achievements

QWR cryomodule test complete (2017.05)

HWR cryomodule test complete (2018.03)

1st Oxygen Ion beam acceleration with RFQ (2016.12)

Achievement of low temperature test for LTS and HTS quadrupole prototype magnet (LTS 2016.1, HTS 2017.1)

Superconducting RF Test facility (2016.06)

1st Oxygen Ion beam acceleration with QWR module, SCL Demo (2017.10)

High purity Sn beam extraction using RILIS (2015.12)
Nuclear Equation of States

\[ E(\rho, x) = -B + \frac{K_0}{18} \left( \frac{\rho}{\rho_0} - 1 \right)^2 + \frac{K'_0}{162} \left( \frac{\rho}{\rho_0} - 1 \right)^3 + E_{\text{sym}}(\rho)(1 - 2x)^2 + \cdots \]

Incompressibility
\[ K_0 \approx 230 \text{ MeV} \]

Skewness
\[ K'_0 \approx -2000 \text{ MeV} \]

Symmetry Energy
\[ S_0 \equiv E_{\text{sym}}(\rho_0) \]
\[ L \equiv 3\rho \frac{\partial E_{\text{sym}}}{\partial \rho} \bigg|_{\rho_0} \]

J.M. Latter, Y. Lim (2016)
Symmetry energy / Theoretical uncertainties

Courtesy of Lie-Wen Chen

waiting for RAON@IBS

E_{sym} (MeV)

\rho/\rho_0

NL-RMF(18)
PC-RMF(3)
RHF(2)
DD-RMF(2)
Gogny-HF(2)
SHF(33)
Prospects

• **Expecting more GWs from NS binary mergers!**
  - Mass & tidal deformability of NS can be measured simultaneously by GWs.
  - GWs can give constrains on the radius of NS and high-density EOS.

• **Expecting new results from RAON!**
  - RAON can give constraints on high-density EOS
Binary interactions are always interesting

Thanks