New Constraints on Hadronic and QCD Matter From X-Ray and Gravitational Wave Measurements

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Holographic QCD
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Neutron Star Masses and Radii

- Global constraints from GR, causality and observed pulsar masses
- Theoretical and experimental constraints from nuclear and condensed-matter physics
- X-ray observational constraints from photospheric radius expansion bursts, quiescent low-mass X-ray binaries, and NICER
- Proposed constraints from pulsar timing moment of inertia measurements
- Gravitational wave constraints and GW170817
- Implications for holographic QCD
A lower limit to the maximum mass sets a lower limit to the radius for a given mass. Similarly, a precision upper limit to $R$ sets an upper limit to the maximum mass.

$R_{1.4} > 8.15 \ (10.9) \ \text{km}$ if $M_{\text{max}} \geq 2.01M_\odot$.

$M_{\text{max}} < 3.93 \ (2.52) \ M_\odot$ if $R < 13 \ \text{km}$.

If quark matter exists in the interior, $s \sim 1/3$, minimum radii are larger, and maximum masses are smaller.
Although simple average mass of w.d. companions is 0.23 $M_\odot$ larger, weighted average is 0.04 $M_\odot$ smaller.

Demorest et al. 2010
Fonseca et al. 2016
Antoniadis et al. 2013
Barr et al. 2016
Champion et al. 2008
A 1.6ms pulsar in circular 9.17h orbit with $\sim 0.03 \, M_\odot$ companion. The pulsar is eclipsed for 50-60 minutes each orbit; eclipsing object has a volume much larger than the secondary or its Roche lobe. Pulsar is ablating the companion leading to mass loss and the eclipsing plasma. The secondary may nearly fill its Roche lobe. Ablation by the pulsar leads to secondary’s eventual disappearance. The optical light curve tracks the motion of the secondary’s irradiated hot spot rather than its center of mass motion.
PSR J2215-5135

- Redback binary MSP
- $P_{\text{orb}} = 4.14$ hr
- $T_{\text{night}} = 5660^{+260}_{-380}$ K
- $T_{\text{day}} = 8080^{+470}_{-280}$ K
- $D = 2.9 \pm 0.1$ kpc
- $e = 0.144 \pm 0.002$
- Roche lobe filling factor $f = 0.95 \pm 0.01$
- $M_{\text{pulsar}} = 2.27^{+0.17}_{-0.15} M_\odot$
- $M_{\text{comp}} = 0.33^{+0.02}_{-0.02} M_\odot$

Linares et al. (2018)

$M_1 = 2.27^{+0.17}_{-0.15}$

$M_2 = 0.33^{+0.02}_{-0.02}$

$2\sigma_{\text{pulsar}} = \pm 0.40 M_\odot$
PSR J0740+6620

- Spin frequency $\nu = 346.5$ Hz
- $\dot{\nu} = 1.464 \cdot 10^{-15}$
- Binary period 4.767 days
- Inclination $\sin i = 0.9990 \pm 0.0002$
- Orbital eccentricity $5.1 \cdot 10^{-6}$
- Mass $2.17^{+0.11}_{-0.10}$ (68.3%)
- Mass $2.17^{+0.23}_{-0.20}$ (95.4%)
Neutron Star Radii and Nuclear Symmetry Energy

- Radii are highly correlated with neutron star matter pressure at $1 - 2n_s \approx 0.16 - 0.32 \text{ fm}^{-3}$.
- Neutron star matter is nearly pure neutrons, $x \sim 0.04$.
- Nuclear symmetry energy

$$S(n) \equiv E_0(n) - E_{1/2}(n)$$

$$E_x(n) \approx E_{1/2}(n) + S_2(n)(1 - 2x)^2 + \ldots$$

$$S(n) \approx S_2(n) \approx S_v + \frac{L n - n_s}{3 n_s} + \frac{K_{sym}}{18} \left( \frac{n - n_s}{n_s} \right)^2 R_{1,4}$$

- $S_v \equiv S_2(n_s) \approx 32 \text{ MeV}$, $L \sim 50 \text{ MeV}$; nuclear systematics.
- Neutron matter energy and pressure at $n_s$:

$$E_0(n_s) \approx S_v + E_{1/2}(n_s) = S_v - B \sim 13 - 17 \text{ MeV}$$

$$p_0(n_s) = \left( n^2 \frac{\partial E_0(n)}{\partial n} \right)_{n_s} \approx \frac{L n_s}{3} \sim 2.1 - 3.7 \text{ MeV fm}^{-3}$$
Bounds From The Unitary Gas Conjecture

Neutron matter energy should be larger than the unitary gas energy $E_{UG} = \xi_0 (3/5) E_F$

$$E_{UG} = 12.6 \left( \frac{n}{n_s} \right)^{2/3} \text{MeV}$$

The unitary gas refers to fermions interacting via a pairwise short-range s-wave interaction with an infinite scattering length and zero range. Cold atom experiments show a universal behavior with the Bertsch parameter $\xi_0 \approx 0.37$.

$$S_v \geq 28.6 \text{ MeV}; \quad L \geq 25.3 \text{ MeV}; \quad p_0(n_s) \geq 1.35 \text{ MeV fm}^{-3}; \quad R_{1.4} \geq 9.7 \text{ km}$$
Theoretical and Experimental Constraints

H Chiral Lagrangian

G: Quantum Monte Carlo

neutron matter calculations from Hebeler et al. (2012)

unitary gas constraints from Tews et al. (2017)

Combined experimental constraints are compatible with unitary gas bounds.

Neutron matter calculations are compatible with both.

$10.9 \text{ km} \leq R_{1.4} \leq 13.1 \text{ km}$
Both the assumed minimum value of the neutron star maximum mass and the assumed matter pressure at $n_1 = 1.85n_s$ are important in restricting allowed $M - R$ and $p - \varepsilon$ values. Chiral interactions ($N^3\text{LO}$) for neutron matter predict $p_1 \approx 14.2 \pm 5.8 \text{ MeV fm}^{-3}$.

$\varepsilon_s$
Simultaneous Mass and Radius Measurements

- Measurements of flux $F_\infty = (R_\infty/D)^2 \sigma T_{\text{eff}}^4$ and color temperature $T_c \propto \lambda_{\text{max}}^{-1}$ yield an apparent angular size (pseudo-BB):

$$R_\infty/D = (R/D)/\sqrt{1 - 2GM/Rc^2}$$

- Observational uncertainties include distance $D$, nonuniform $T$, interstellar absorption $N_H$, and atmospheric composition.

  Best chances are:

  - Isolated neutron stars with parallax (atmosphere ??).
    RX J1856-3754: $D = 115 \pm 8$ pc (Walter et al. 2010), $R_\infty = 14.3 \pm 1.0$ km for H atmosphere (Ho et al. 2007).
  - Quiescent low-mass X-ray binaries (QLMXBs) in globular clusters (reliable distances, low $B$ H-atmosperes).
  - Bursting sources with peak fluxes close to Eddington limit (PREs) where gravity balances radiation pressure.
PRE $M - R$ Estimates

$\alpha_{min}$

0.164 ± 0.024
0.153 ± 0.039
0.171 ± 0.042
0.164 ± 0.037
0.167 ± 0.045
0.198 ± 0.047

Özel & Freire (2016)
QLMXB $M - R$ Estimates

Özel & Freire (2016)
Lightcurve modeling constrains the compactness \((M/R)\) and viewing geometry of a non-accreting millisecond pulsar through the depth of modulation and harmonic content of emission from rotating hot-spots, thanks to gravitational light-bending...
… while phase-resolved spectroscopy promises a direct constraint of radius $R$. 
GW170817

- LIGO-Virgo detected a signal consistent with a BNS merger, followed 1.7 s later by a weak sGRB.
- 16600 orbits observed over 165 s.
- $M = 1.1867 \pm 0.0001 \, M_\odot$
- $M_{\text{tot}, \text{max}} = 2^{6/5} \, M = 2.726 \, M_\odot$
- $E_{\text{GW}} > 0.025 \, M_\odot \, c^2$
- $D_L = 40 \pm 10 \, \text{Mpc}$
- $75 < \tilde{\Lambda} < 560 \ (90\%)$
- $M_{\text{ejecta}} \sim 0.06 \pm 0.02 \, M_\odot$
- Blue ejecta: $\sim 0.01 \, M_\odot$
- Red ejecta: $\sim 0.05 \, M_\odot$
- Likely r-process production
- Ejecta + GRB: $M_{\text{max}} \lesssim 2.2 \, M_\odot$

Abbott et al. (2017)

Drout et al. (2017)

New Constraints on Hadronic and QCD Matter From X-Ray and Gravitational Wave Measurements
Properties of Known Double Neutron Star Binaries

- Both component masses are accurately measured (9)
  — Only the total binary mass is accurately measured (7)

Binaries with $\tau_{GW} > t_{\text{universe}}$ (7)

$q = M_2/M_1$ is the binary mass ratio for a system

$\mathcal{M} = (M_1 M_2)^{3/5} (M_1 + M_2)^{-1/5}$ is the chirp mass

$\chi = cJ/(GM^2)$ is the dimensionless spin parameter for individual pulsars
Waveform Model Parameter Determinations

There are 13 free wave-form parameters including finite-size effects at third PN order \((v/c)^6\). LV17 used a 13-parameter model; De et al. (2018) used a 9-parameter model.

- Sky location (2) EM data
- Distance (1) EM data
- Inclination (1)
- Coalescence time (1)
- Coalescence phase (1)
- Polarization (1)
- Component masses (2)
- Spin parameters (2)
- Tidal deformabilities (2) correlated with masses

Extrinsic

Intrinsic
Tidal Deformability

The tidal deformability $\lambda$ is the ratio of the induced dipole moment $Q_{ij}$ to the external tidal field $E_{ij}$, $Q_{ij} \equiv -\lambda E_{ij}$.

Work with the dimensionless quantity

$$\Lambda = \frac{\lambda c^{10}}{G^{4}M^{5}} \equiv \frac{2}{3}k_{2} \left(\frac{Rc^{2}}{GM}\right)^{5}$$

$k_{2}$ is the dimensionless Love number.

For a neutron star binary, $\tilde{\Lambda}$ is the relevant quantity

$$\tilde{\Lambda} = \frac{16}{13} \frac{(1 + 12q)\Lambda_{1} + (12 + q)q^{4}\Lambda_{2}}{(1 + q)^{5}}, \quad q = M_{2}/M_{1} \leq 1$$

Postnikov, Prakash & Lattimer (2010)
The Effect of Tides

Tides accelerate the inspiral and produce a phase shift compared to the case of two point masses.

\[
\delta \Phi_t = -\frac{117}{256} \frac{(1 + q)^4}{q^2} \left( \frac{\pi f_{GW} GM}{c^3} \right)^{5/3} \tilde{\Lambda} + \cdots
\]

credit: Jocelyn Read
\[ \Lambda = a \beta^{-6} \]
\[ \beta = \frac{GM}{Rc^2} \]
\[ a = 0.0086 \pm 0.0011 \]
for
\[ M = 1.35 \pm 0.25 \, M_\odot \]

If \( R_1 \approx R_2 \approx R_{1.4} \)

it follows that
\[ \Lambda_2 \approx q^{-6} \Lambda_1. \]
Binary Deformability and the Radius

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

\[ \approx \frac{16a}{13} \left( \frac{R_{1.4} c^2}{G M} \right)^6 q^{8/5} (12 - 11q + 12q^2) (1 + q)^{26/5} \]

- \( \tilde{\Lambda} = a' \left( \frac{R_{1.4} c^2}{G M} \right)^6 \)
  - \( a' = 0.0035 \pm 0.0006 \) for \( M = 1.2 \pm 0.2 \, M_\odot \)

- GW10817:
  - \( a' = 0.00375 \pm 0.00025 \)

- \( R_{1.4} = 11.5 \pm 0.3 \)
  - \( \frac{M}{M_\odot} \left( \frac{\tilde{\Lambda}}{800} \right)^{1/6} \) km

- GW10817:
  - \( R_{1.4} = 13.4 \pm 0.1 \left( \frac{\tilde{\Lambda}}{800} \right)^{1/6} \) km

- Zhao & Lattimer (2018)
Measurability of Tidal Deformability

De et al. (2018)
De18 takes advantage of the precisely-known electromagnetic source position (Soares-Santos et al. 2017).

Uses existing knowledge of $H_0$ and the redshift of NGC 4993 to fix the distance (Cantiello et al. 2017).

Assumes both neutron stars have the same equation of state, which implies $\Lambda_1 \approx q^6 \Lambda_2$.

Baseline model effectively has 9 instead of 13 parameters.

Explores variations of mass, spin and deformability priors.

Low-frequency cutoff taken to be 20 Hz, not 30 Hz (LV17), doubling the number of analyzed orbits.

De18 find that including $\Lambda - M$ correlations produces

- a 90% lower $\tilde{\Lambda}$ confidence bound (which is above its causal minimum value), and
- the 90% upper $\tilde{\Lambda}$ confidence bound is reduced by 30%.
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Zhao and Lattimer (2018)
GW170817

Zhao and Lattimer (2018)
GW170817

Zhao and Lattimer (2018)

New Constraints on Hadronic and QCD Matter From X-Ray and Gravitational Wave Measurements
LV18 Determined $R_1 \approx R_2$ for GW170817

$\Lambda_2 - \Lambda_1$ correlations from parameterized EOSs with $M_{\text{max}} > 1.97M_\odot$

$R_1(\text{km}) = 11.9^{+1.4}_{-1.4}$

$R_2(\text{km}) = 11.9^{+1.4}_{-1.4}$
GW170817 Summary

▶ It’s important to include correlations among $\Lambda_1, \Lambda_2, M_1$ and $M_2$ in a model-independent fashion.
▶ It’s important to include as many orbits as possible; the effective low frequency cutoff is about 20 Hz.
▶ Better waveform models appear to reduce the uncertainties in $\tilde{\Lambda}$ (by about 15%).
▶ The observation of a sGRB, mass ejection, and apparent nucleosynthesis of extremely heavy nuclei (r-process most likely) from electromagnetic observations strongly suggest the rapidly-rotating remnant survived only a fraction of a second before collapsing to a black hole.
▶ This implies the remnant could not be supported by uniform rotation even if spinning at its mass-shedding (Keplerian) frequency.
▶ Since uniform rotation can support at least 17% more baryons than the non-rotating maximum mass, the measured inspiralling mass from gravitational waves sets an upper limit $M_{\text{max}} \lesssim 2.2 M_\odot$. 
Buchdahl exact GR solution

\[ \varepsilon = \sqrt{\rho p^*_0 - 3p} \]

\[ R_0 = \sqrt{\frac{\pi}{2p^*_0}} \]

\[ \frac{M}{R} = \frac{R}{R_0} \sqrt{\frac{R^2}{R_0^2} - 1} + 1 - \frac{R^2}{R_0^2} \]

\[ R \approx R_0 + \frac{M^2}{2R_0} + \cdots \]

Low mass stars are quark stars unless \( m_0 > 313.1 \) MeV. For 313.1 MeV \( > m_0 > 300 \) MeV, 1.4\( M_\odot \) stars have quark crusts, and have too large tidal deformabilities to satisfy GW170817.
The Future

- A few more neutron star mergers per year should allow significant improvements to radii and maximum mass constraints. The systems are expected to be quite similar to GW170817, except they will be further away and may not have observed optical transients or sGRBs.
- It should be possible within a few years to establish pulsar-timing bounds to the moment of inertia of PSR 0737-3037A, which, with its known mass, will set tight independent radius constraints.
- NICER expects to release radius estimates with 1 km-accuracy by years’ end.
- Ongoing and planned nuclear experiments, including neutron skin measurements at J-Lab and Mainz, will offer complementary information.
- Further *ab-initio* nuclear matter studies will be important.
- Further measurements of black widow pulsar systems should give some surprises.