Properties of Neutron Stars From Radio, X-Ray and Gravitational Radiation

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Office of Science

Neutron Star Mergers: From Gravitational Waves to Nucleosynthesis
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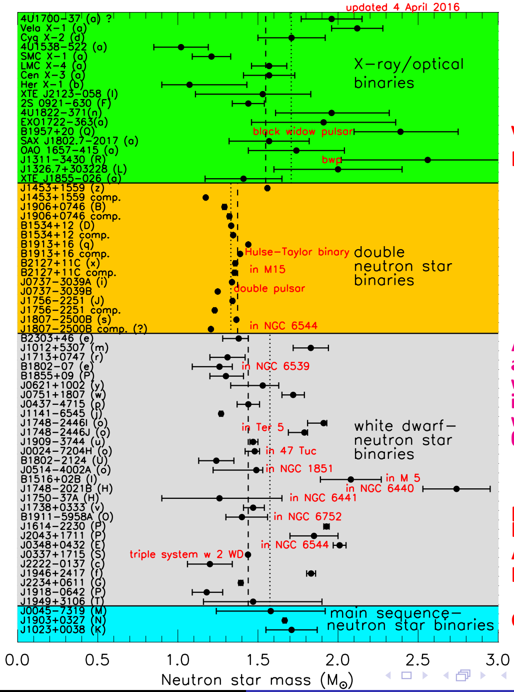
Outline

- Neutron Star Masses and Radii
- Neutron Star Crusts
- Neutron Matter Theory
- Hyperons and Quarks in Neutron Stars
- Universal Relations
- Gravitational Waves from Mergers
- Alternatives to General Relativity
- New Kinds of Observations



vanKerkwijk 2010

Romani et al. 2012

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

Causality + GR Limits and the Maximum Mass

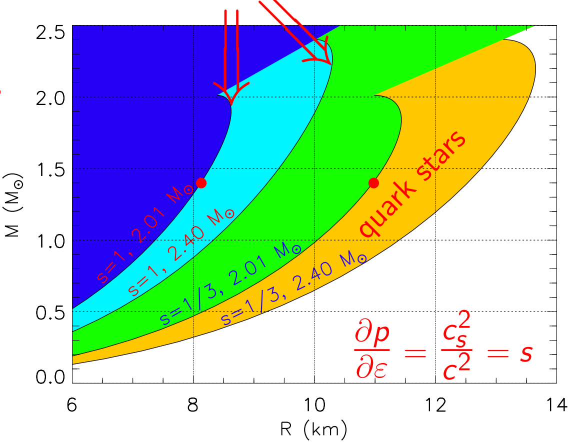
A lower limit to the maximum mass sets a lower limit to the radius for a given mass.

Similarly, a precision upper limit to R sets an upper limit to the maximum mass.

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

$M_{max} < 2.4 M_\odot$ if $R < 10.3$ km.

$M - R$ curves for minimally compact EOS



If quark matter exists in the interior, the minimum radii are substantially larger.

Radii: Observations vs. Experiment

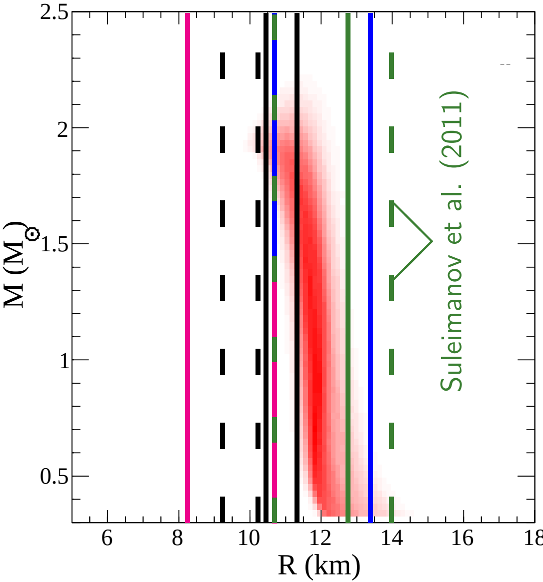
Ozel et al., PRE $z_{ph} = z$:
$R = 9.7 \pm 0.5$ km (2009-14)
PRE+QLMXB;TOV,M_{max},
crust: $R = 10.8^{+0.5}_{-0.4}$ km (2015).

Guillot & Rutledge (2014), QLMXB, common radius, N_H: $R = 9.4 \pm 1.2$ km.

Nättilä et al. (2015), PRE cooling tail $R = 11.7 \pm 1.1$ km.

Lattimer & Steiner (2013), PRE+QLMXB; TOV, causality, crust, M_{max}, $z_{\rm ph} \neq z$, alt N_H.

Lattimer & Lim (2013), nuclear experiments:
$R_{1.4} = 12.0 \pm 1.4$ km.

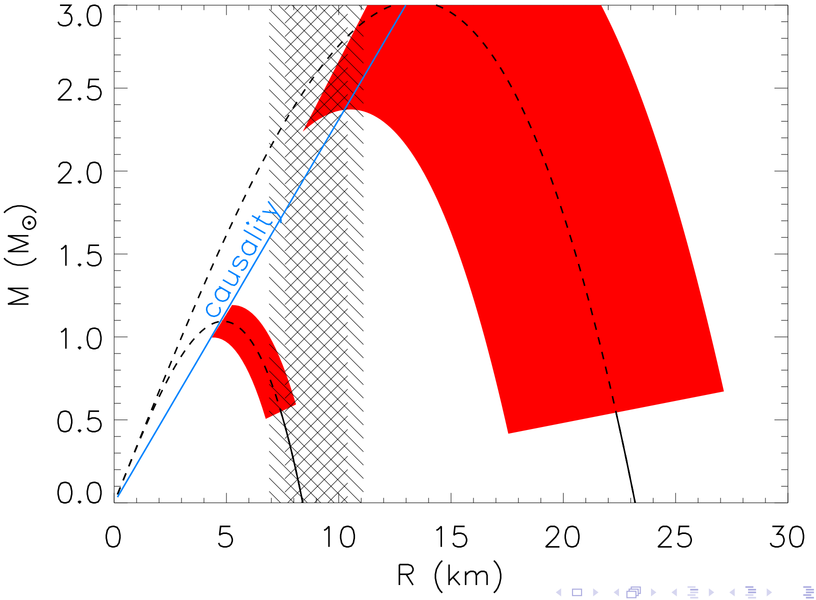


Role of Systematic Uncertainties

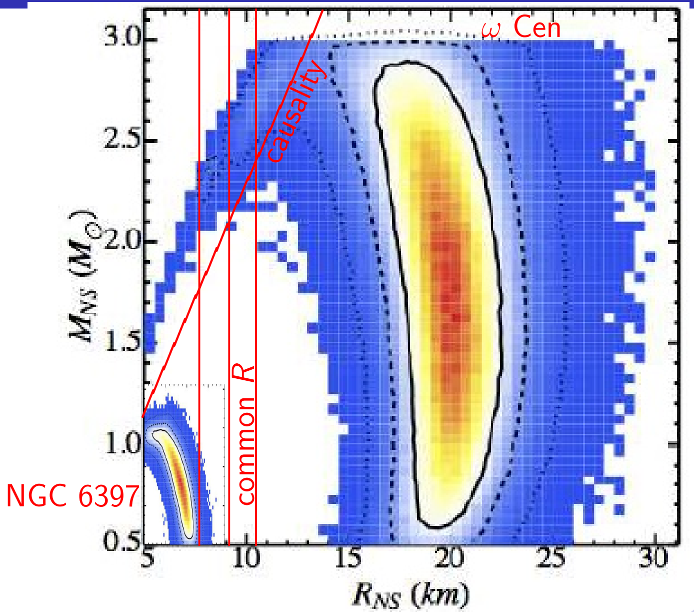
Systematic uncertainties plague radius measurements.

- Assuming uniform surface temperatures leads to underestimates in radii.
- Uncertainties in interstellar absorption for quiesent sources; spectral determinations may disagree with pulsar dispersion estimates.
- In quiescent sources, He or C atmospheres can produce about 50% larger radii than H atmospheres.
- In PRE sources, the spherically-symmetric Eddington flux formula underestimates radii.
- Possible reduction in F_{Edd} redshift factor in PRE sources increases radii.
- Disc shadowing in PRE sources underpredicts $A = f_c^{-4}(R_\infty/D)^2$ and $R_\infty \propto \sqrt{A}$.

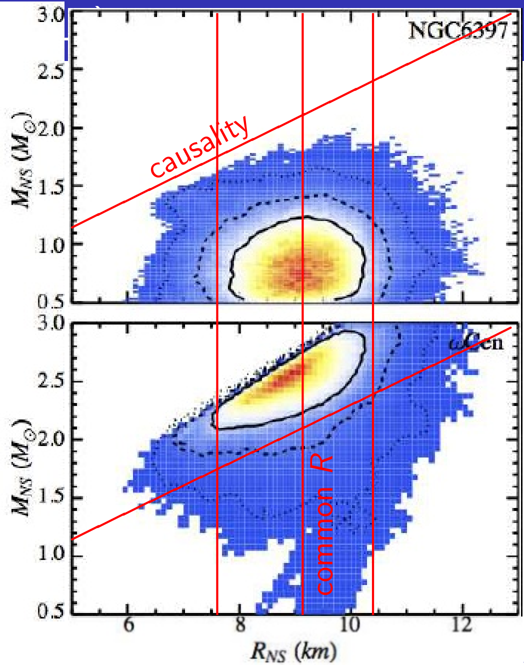
Quiescent Sources and a Common Radius



Guillot & Rutledge (2013)



Guillot & Rutledge (



PRE Burst Models

Observations measure:

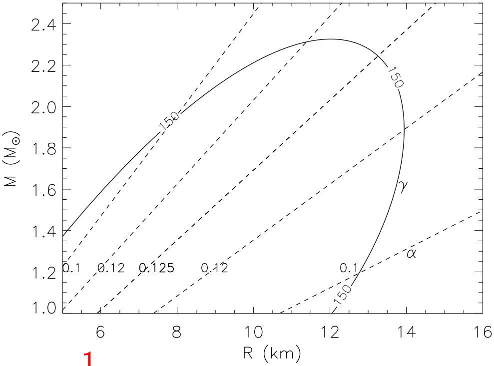
$$F_{Edd,\infty} = \frac{GMc}{\kappa D^2}\sqrt{1-2\beta}, \qquad \beta = \frac{GM}{Rc^2}$$

$$A = \frac{F_\infty}{\sigma T_\infty^4} = f_c^{-4}\left(\frac{R_\infty}{D}\right)^2$$

Determine parameters:

$$\alpha = \frac{F_{Edd,\infty}}{\sqrt{A}}\frac{\kappa D}{f_c^4 c^3} = \beta(1-2\beta)$$

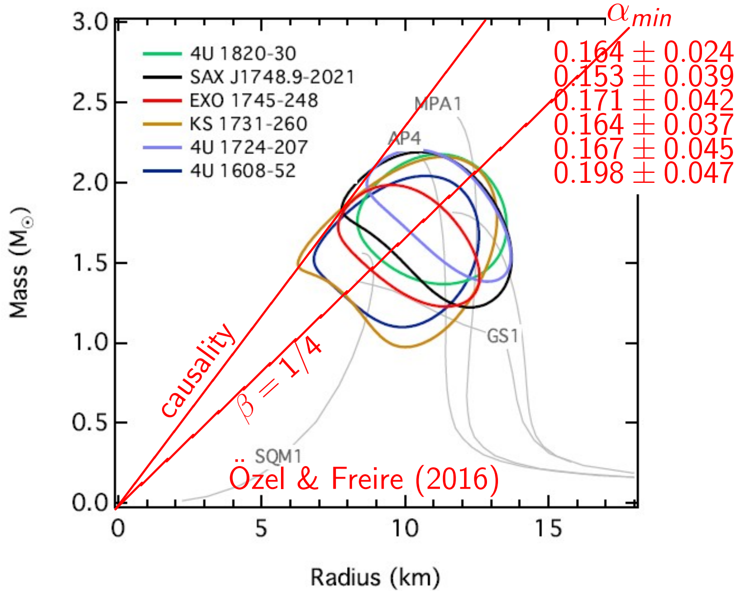
$$\gamma = \frac{Af_c^4 c^3}{\kappa F_{Edd,\infty}} = \frac{R_\infty}{\alpha}.$$



Solution:

$$\beta = \frac{1}{4} \pm \frac{\sqrt{1-8\alpha}}{4}, \qquad \alpha \le \frac{1}{8} \text{ for real solutions.}$$

PRE $M - R$ Estimates

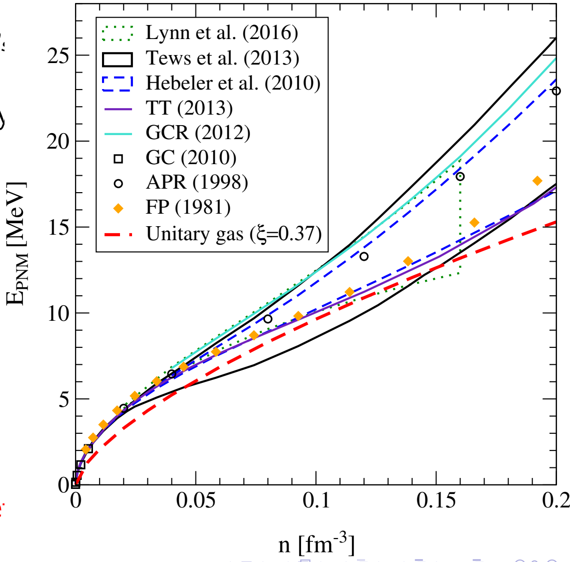


Theoretical Neutron Matter Calculations

NS crust EOS below $n_s/2$.

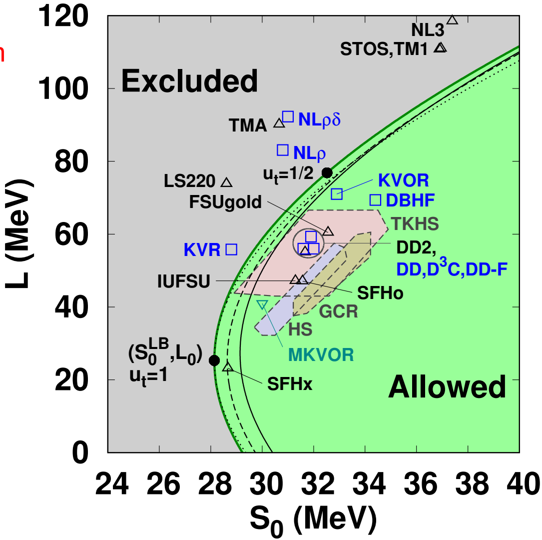
Theoretical studies below $2n_s$ using low-energy neutron scattering data and few-body calculations of light nuclei.

- Auxiliary Field Diffusion Quantum Monte Carlo (Gandolfi & Carlson)
- Chiral Lagrangian Expansion (Drischler, Hebeler, Schwenk; Sammarruca et al., Tews et al., Lynn et al., Hagen et al., Carbone et al., Corragio et al.,...)

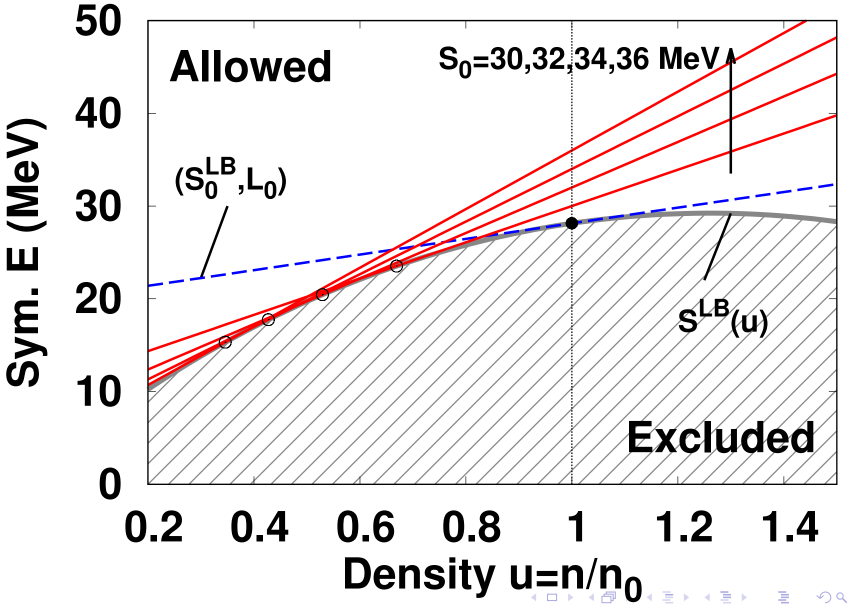


Unitary Gas Bounds

The unitary gas, *i.e.*, fermions interacting via a pairwise short-range s-wave interaction with an infinite scattering length $|ak_F|^{-1} \to 0$, shows a universal behavior. Cold atoms experiments show that $E_{\rm UG} \simeq 0.37 E_{\rm FG}$. Neutron matter has $a_0 = -18.9$ fm, $|a_0 k_{F0}|^{-1} = -0.03$. The assumption that the neutron matter energy $E_n > E_{\rm UG}$ at all densities implies strong bounds on the symmetry energy parameters S_v and L (Kolomeitsev et al. 2016).



Kolomeitsev et al. (2017)



Nuclear Experimental Constraints

The liquid droplet model is a useful frame of reference. Its symmetry parameters S_v and S_s are related to S_v and L:

$$\frac{S_s}{S_v} \simeq \frac{aL}{r_o S_v}\left[1+\frac{L}{6S_v}-\frac{K_{sym}}{12L}+\dots\right].$$

- Symmetry contribution to the binding energy:

$$E_{sym} \simeq S_v A I^2 \left[1+\frac{S_s}{S_v A^{1/3}}\right]^{-1}.$$

- Giant Dipole Resonance (dipole polarizability)

$$\alpha_D \simeq \frac{AR^2}{20S_v}\left(1+\frac{5}{3}\frac{S_s}{S_v A^{1/3}}\right).$$

- Neutron Skin Thickness

$$r_{np} \simeq \sqrt{\frac{3}{5}}\frac{2r_o I}{3}\frac{S_s}{S_v}\left(1+\frac{S_s}{S_v A^{1/3}}\right)^{-1}\left(1+\frac{10}{3}\frac{S_s}{S_v A^{1/3}}\right).$$

Theoretical and Experimental Constraints

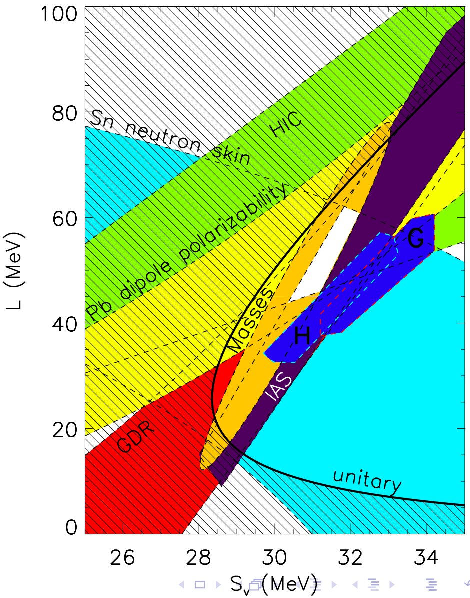
H Chiral Lagrangian

G: Quantum Monte Carlo

$S_v - L$ constraints from Hebeler et al. (2012)

Experimental constraints are compatible with unitary gas bounds.

Neutron matter constraints are compatible with experimental constraints.



Piecewise Polytropes

Crust EOS is known: $n < n_0 = 0.4n_s$.

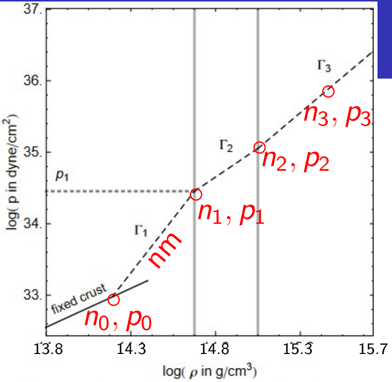
Read, Lackey, Owen & Friedman (2009) found high-density EOS can be modeled as piecewise polytropes with 3 segments.

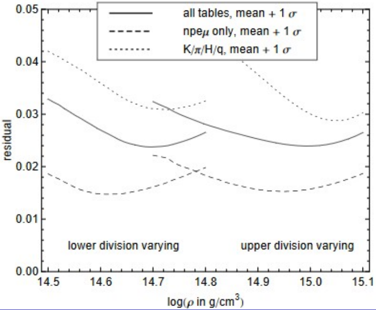
They found universal break points ($n_1 \simeq 1.85n_s, n_2 \simeq 3.7n_s$) optimized fits to a wide family of modeled EOSs.

For $n_0 < n < n_1$, assume neutron matter EOS. Arbitrarily choose $n_3 = 7.4n_s$.

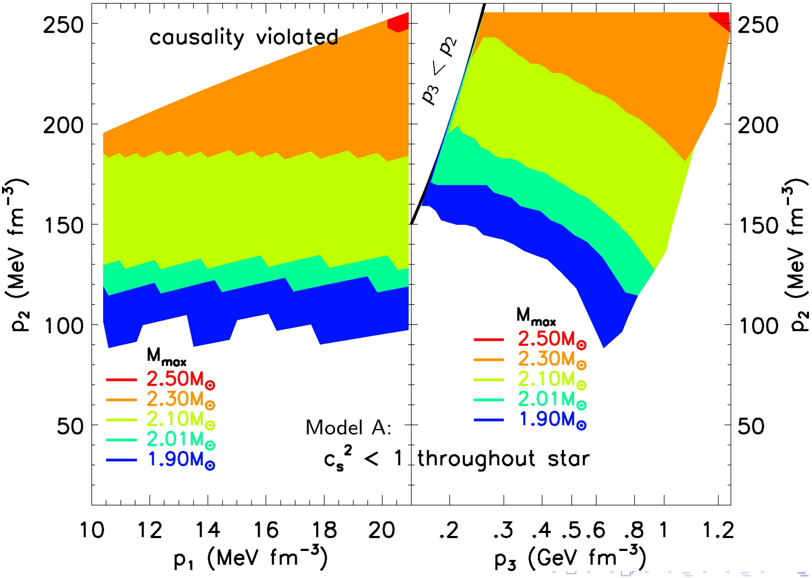
For a given p_1 (or Γ_1):
$0 < \Gamma_2 < \Gamma_{2c}$ or $p_1 < p_2 < p_{2c}$.
$0 < \Gamma_3 < \Gamma_{3c}$ or $p_2 < p_3 < p_{3c}$.

Minimum values of p_2, p_3 set by M_{max}; maximum values set by causality.

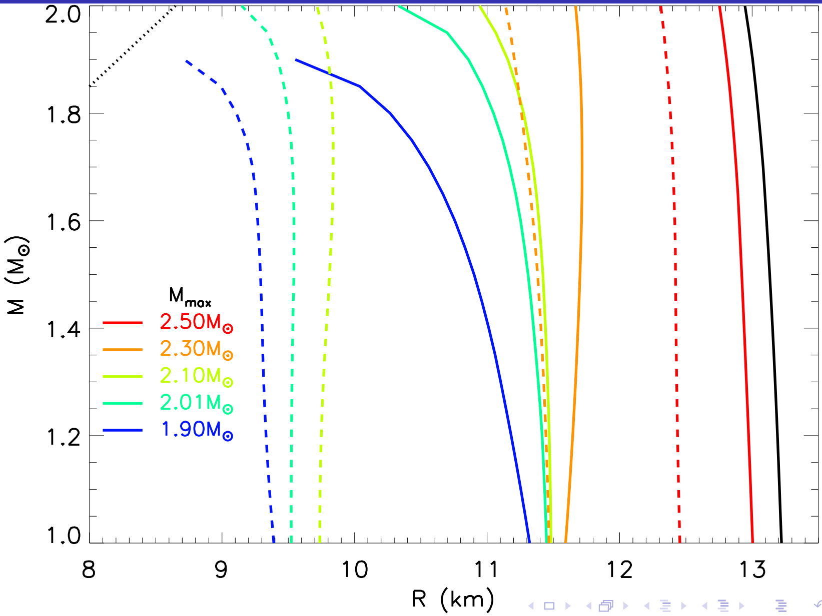




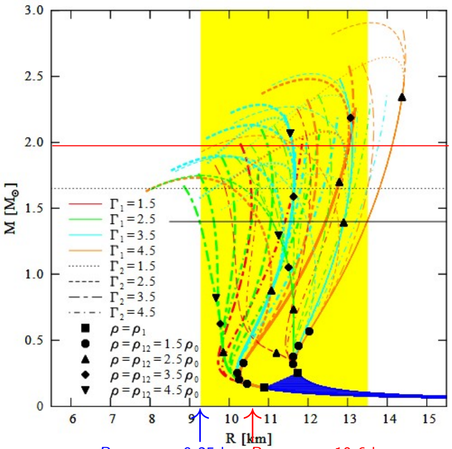
Maximum Mass and Causality Constraints



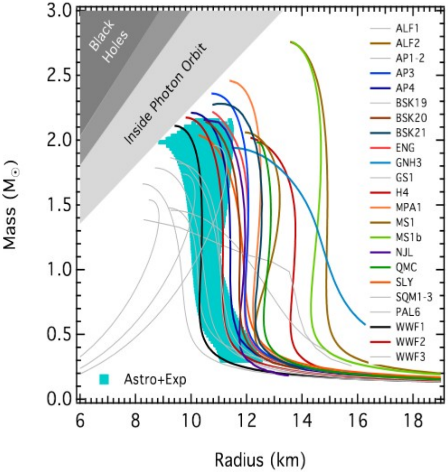
Mass-Radius Constraints from Causality



Other Studies

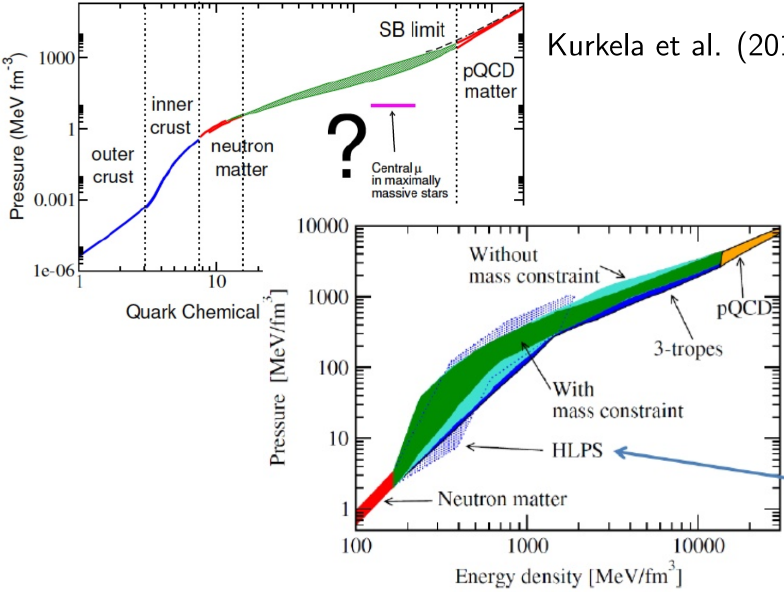


$R_{1.4,min} = 9.25$ km $R_{1.4,min} = 10.6$ km
$M_{max} = 1.66 M_\odot$ $M_{max} = 1.97 M_\odot$



Hebeler, Lattimer, Pethick & Schwenk 2010 Özel & Freire 2016

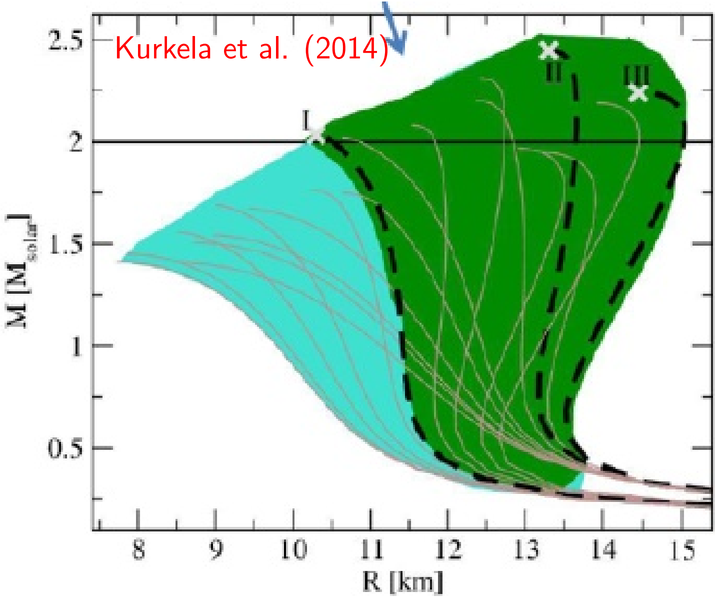
Constraints From Above



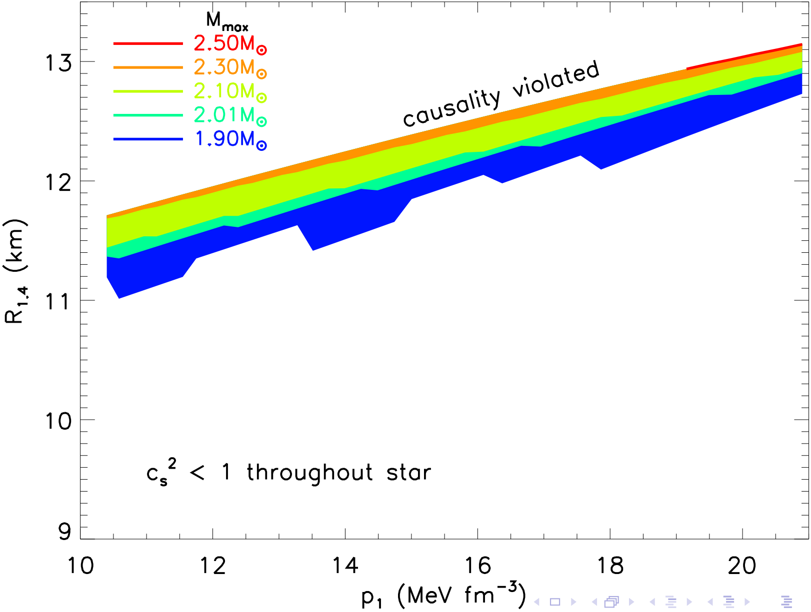
Kurkela et al. (2014)

HLPS [Hebeler, Lattimer, Pethick, Schwenk, ApJ 773 (2013)] without high-density constraint

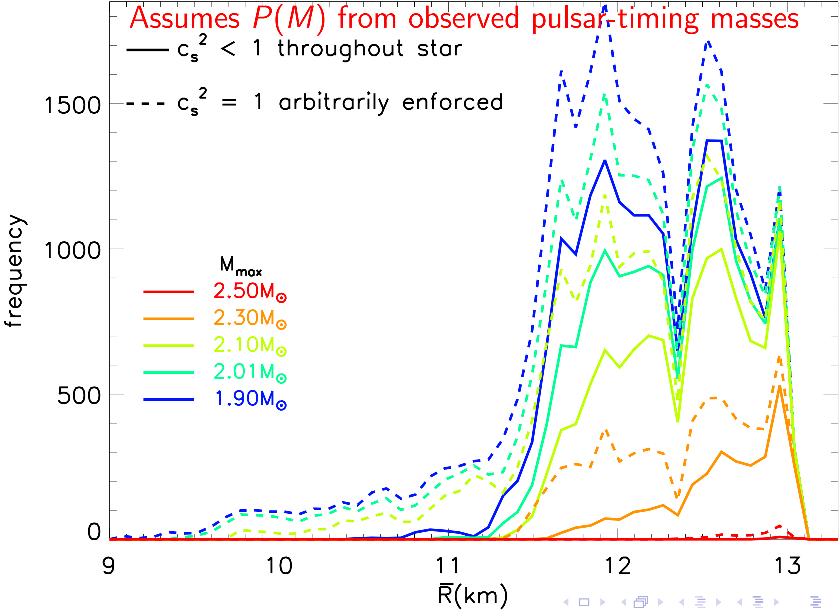
pQCD + Neutron Matter Constraints



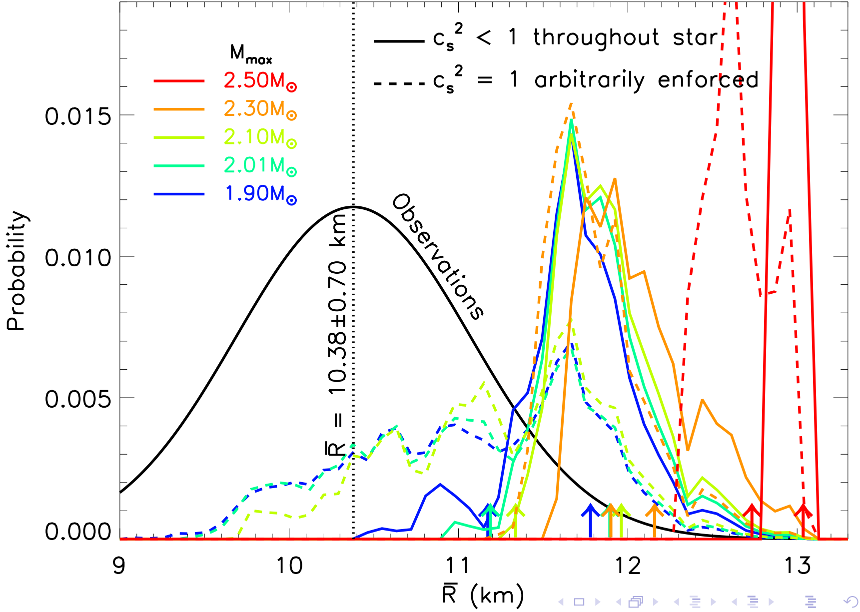
Radius - p_1 Correlation



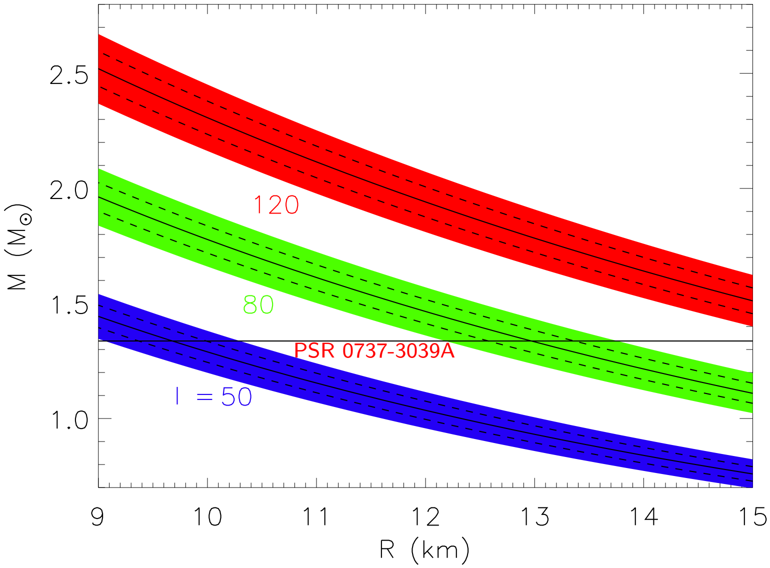
Piecewise-Polytrope Average Radius Distributions



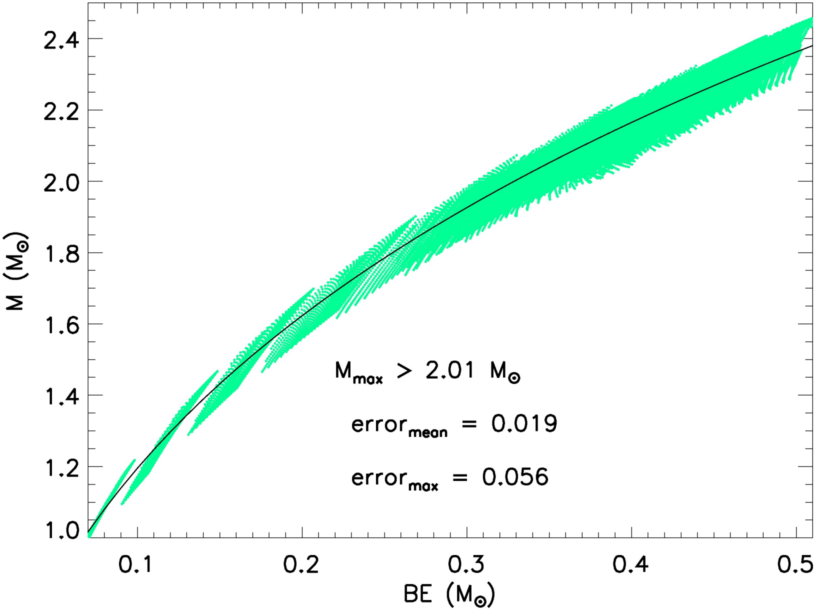
Folding Observations with Piecewise Polytropes



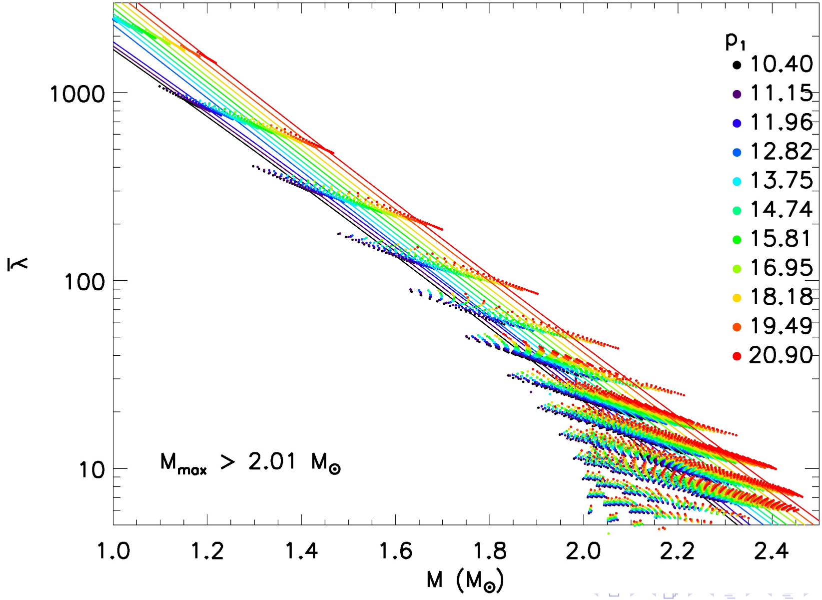
Moment of Inertia - Radius Constraints



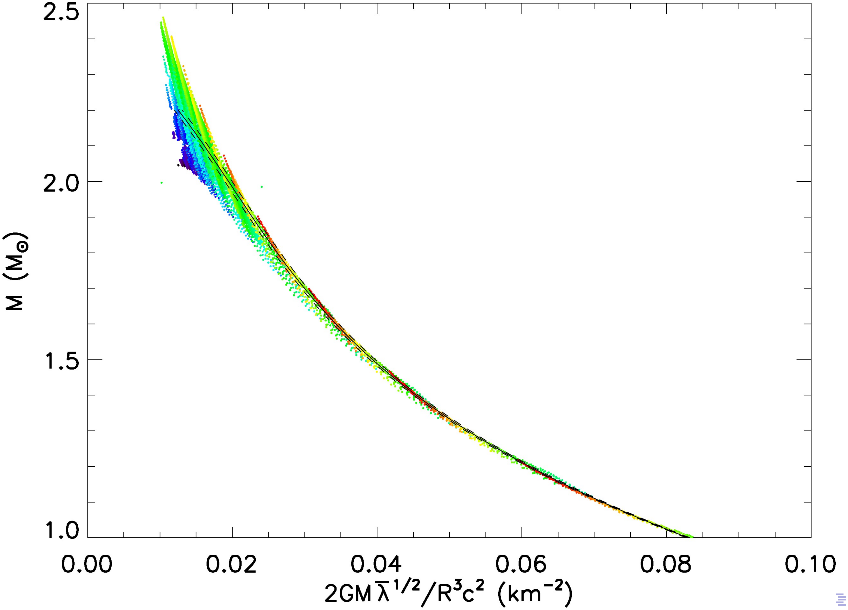
Binding Energy - Mass Correlations



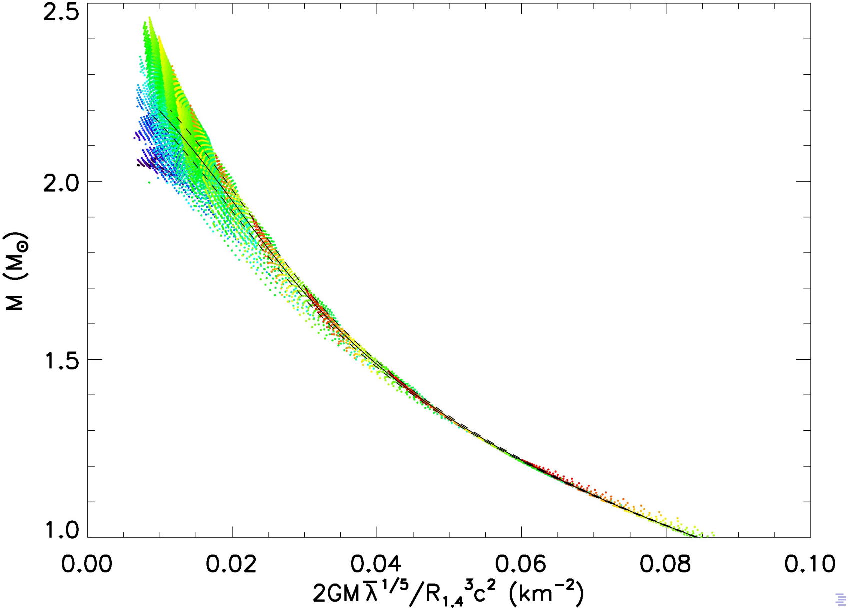
Tidal Deformatibility - Mass



Tidal Deformatibility



Tidal Deformatibility



Binary Tidal Deformability

In a neutron star merger, both stars are tidally deformed. The most accurately measured deformability parameter is

$$\bar{\Lambda} = \frac{16}{13}\left[\bar{\lambda}_1 q^4(12q+1) + \bar{\lambda}_2(1+12q)\right]$$

where

$$q = \frac{M_1}{M_2} < 1$$

For $S/N \approx 20-30$, typical measurement accuracies are expected to be (Rodriguez et al. 2014; Wade et al. 2014):

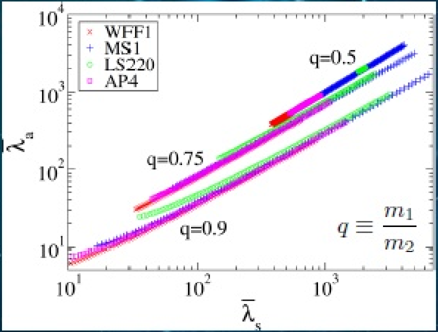
$$\Delta M_{chirp} \sim 0.01-0.02\%, \qquad \Delta\bar{\Lambda} \sim 20-25\%$$

$$\Delta(M_1+M_2) \sim 1-2\%, \qquad \Delta q \sim 10-15\%$$

Binary Love Relations NS – NS Mergers

(I) symmetric/anti-symmetric

$$\bar{\lambda}_s \equiv \frac{\bar{\lambda}_{2,1} + \bar{\lambda}_{2,2}}{2}, \quad \bar{\lambda}_a \equiv \frac{\bar{\lambda}_{2,1} - \bar{\lambda}_{2,2}}{2}$$

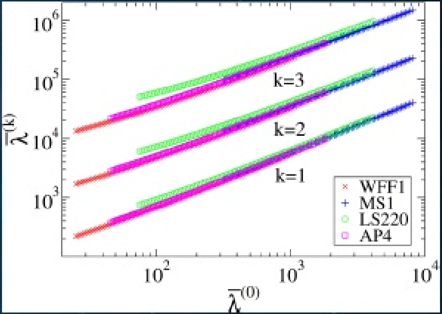


(II) Taylor expansion

[Messenger & Read (2012)]

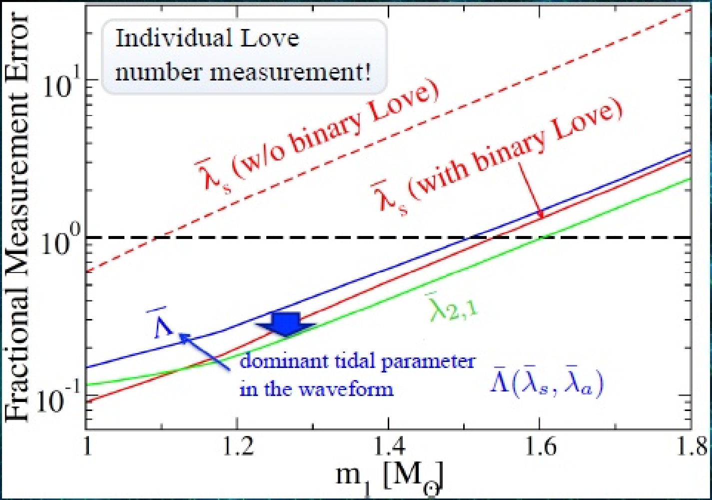
fiducial mass

$$\bar{\lambda}_{2,A}(m_A) = \sum_{k=0} \frac{\bar{\lambda}^{(k)}}{k!}\left(1 - \frac{m_A}{m_0}\right)^k$$

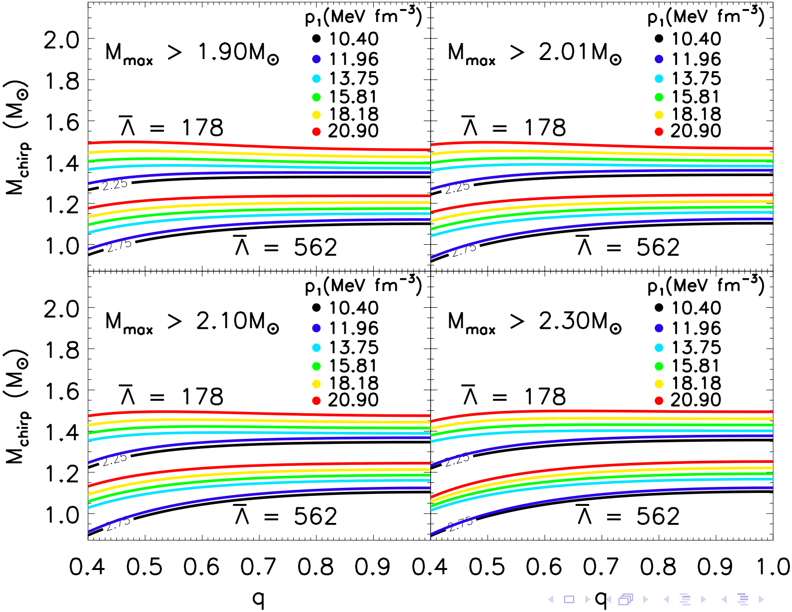


Universal to $\mathcal{O}(10\%)$

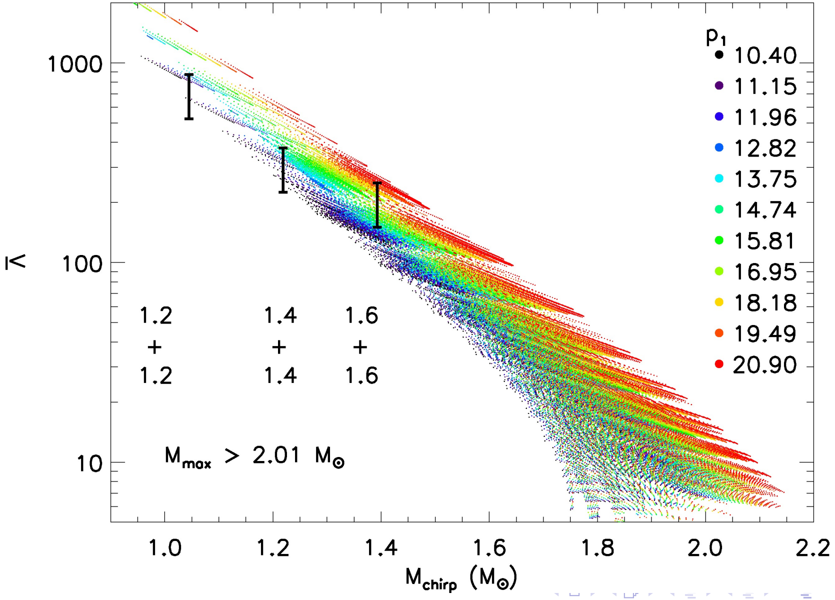
(I) Nuclear Physics



Binary Tidal Deformatibility - $\bar{\Lambda}$



Binary Tidal Deformatibility



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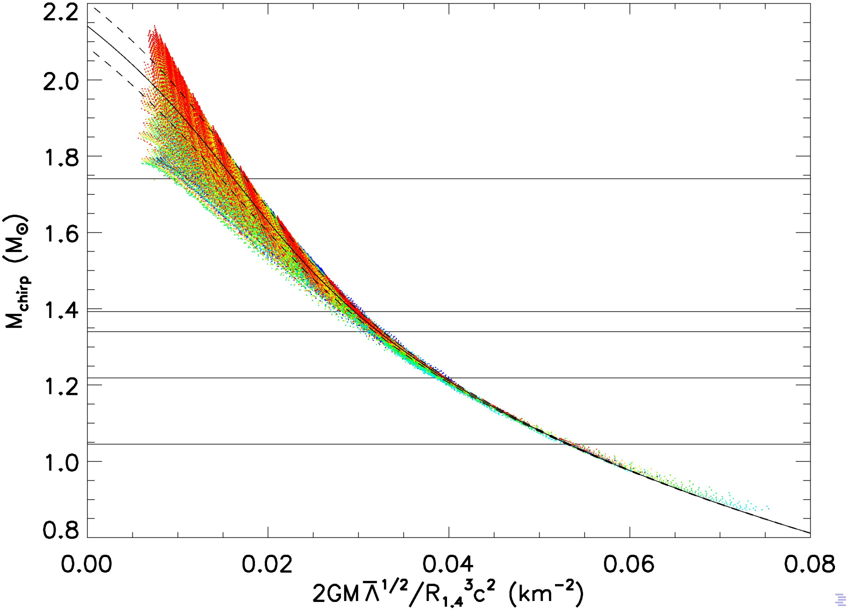
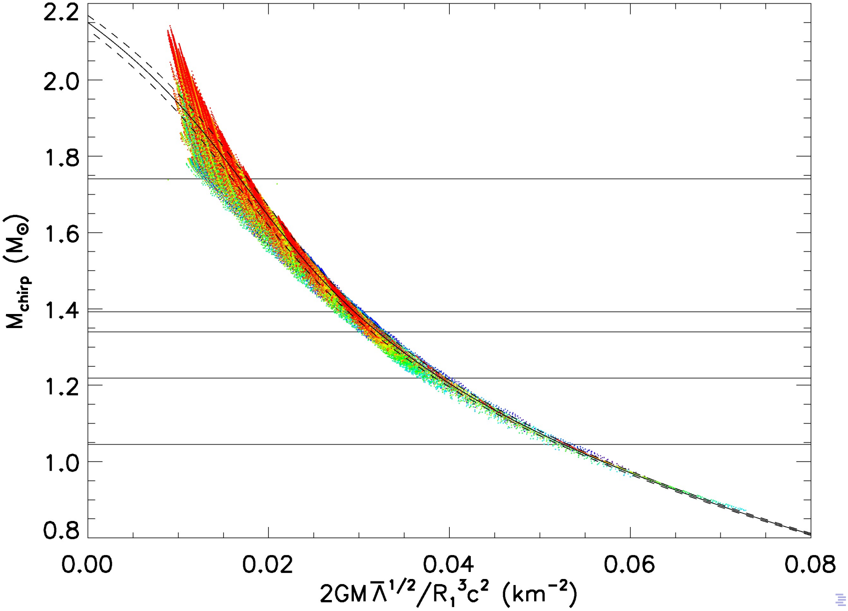
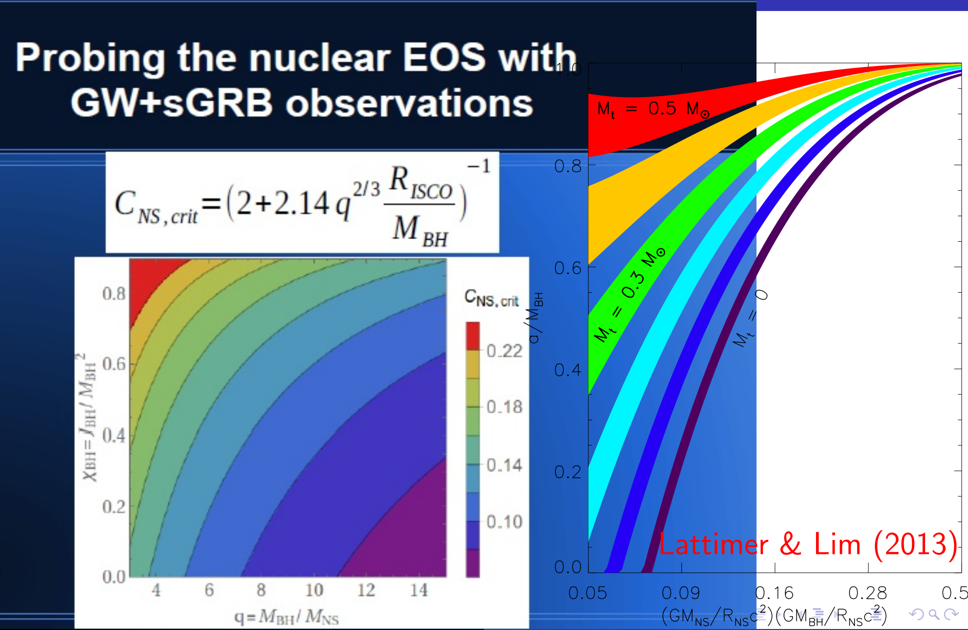


Binary Tidal Deformatibility



Black Hole–Neutron Star Mergers



Future Observations

- Twin stars with different radii:
  Evidence for phase transitions
- Neutron star seismology and r-modes from GW observations:

$$\nu_{ellipticity} = 2f, \qquad \nu_{r-mode} \approx (4/3)f$$

  - Compactness from ν_{r-mode}.
  - Temperature if r-modes dominate heating.
  - Moment of inertia if r-modes dominate spindown.
  - Require factor of 3–10 improvement in sensitivity over aLIGO.
  - Potential sources would be very young.
- What else?