

Summary and Future The Last Word

J. M. Lattimer

Department of Physics & Astronomy

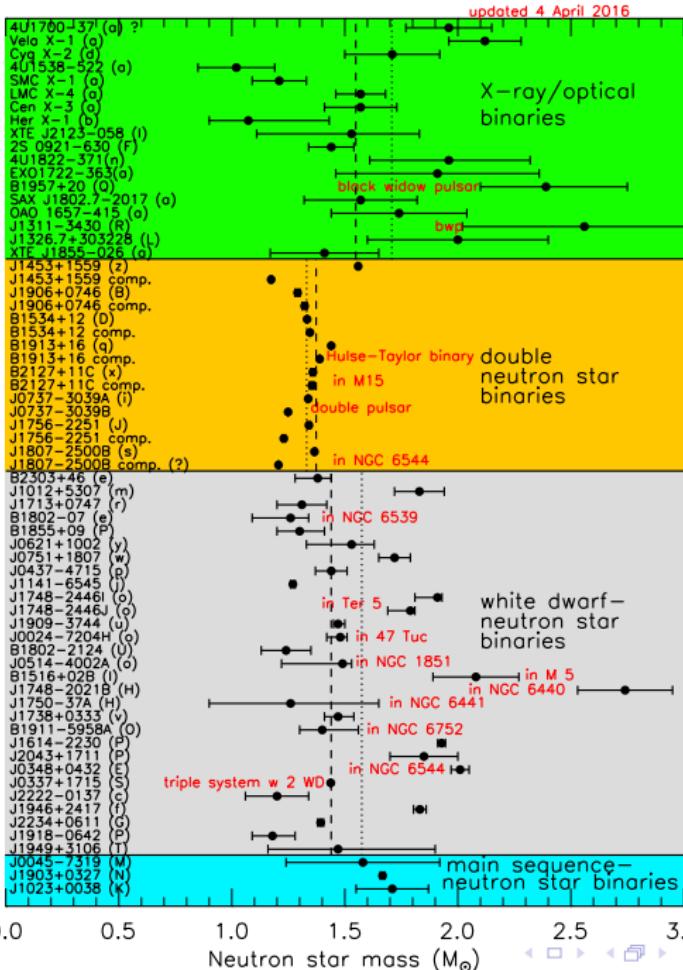


Office of Science

From Quarks to Gravitational Waves
TH-CERN
9 December, 2016

Perspectives

- ▶ 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

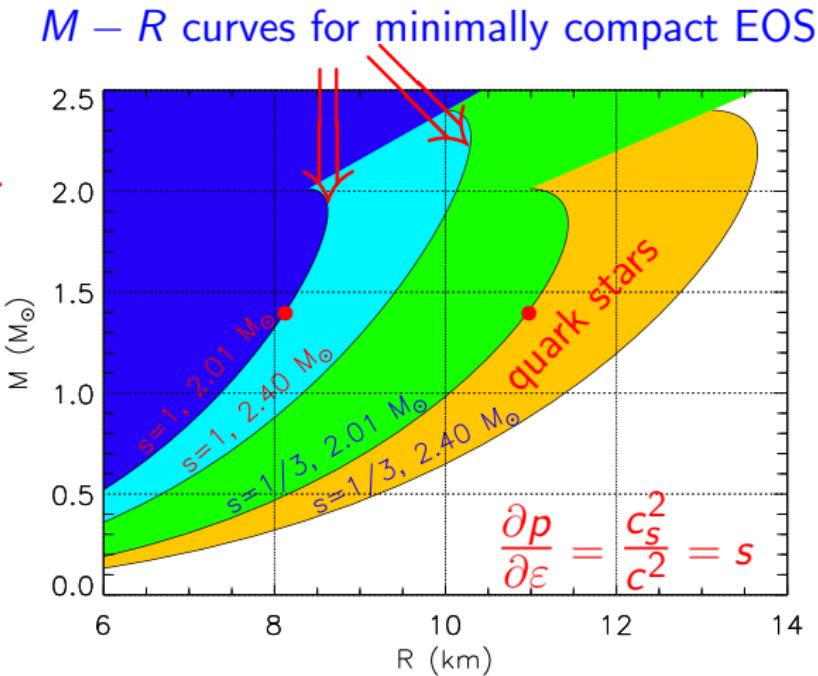
A lower limit to the maximum mass sets a lower limit to the radius for a given mass.

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

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

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

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.

Nätilä et al. (2015), PRE

cooling tail $R = 11.7 \pm 1.1$ km.

Lattimer & Steiner (2013),

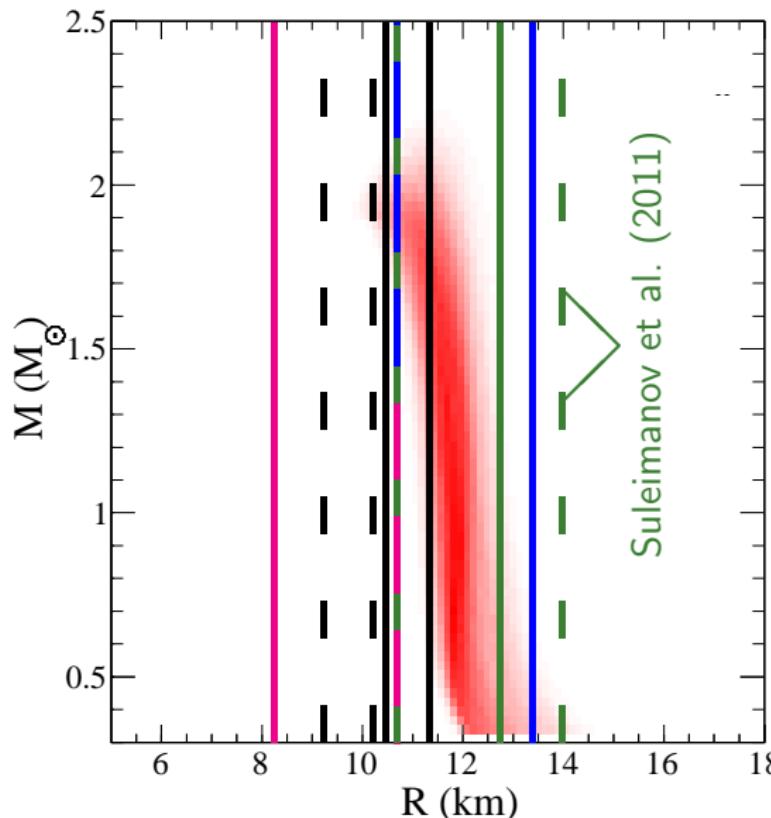
PRE+QLMXB; TOV, causality,

crust, M_{max} , $z_{ph} \neq z$, alt N_H .

Lattimer & Lim (2013), nuclear

experiments:

$R_{1.4} = 12.0 \pm 1.4$ km.

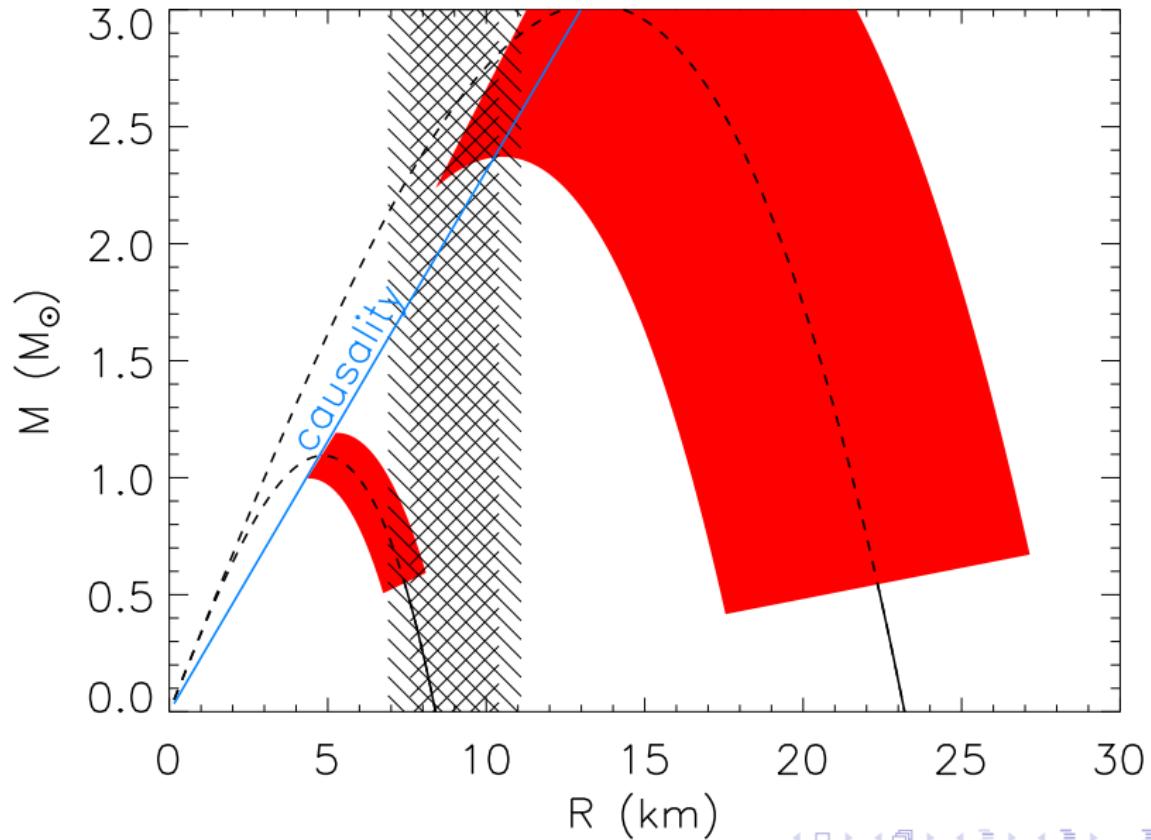


Role of Systematic Uncertainties

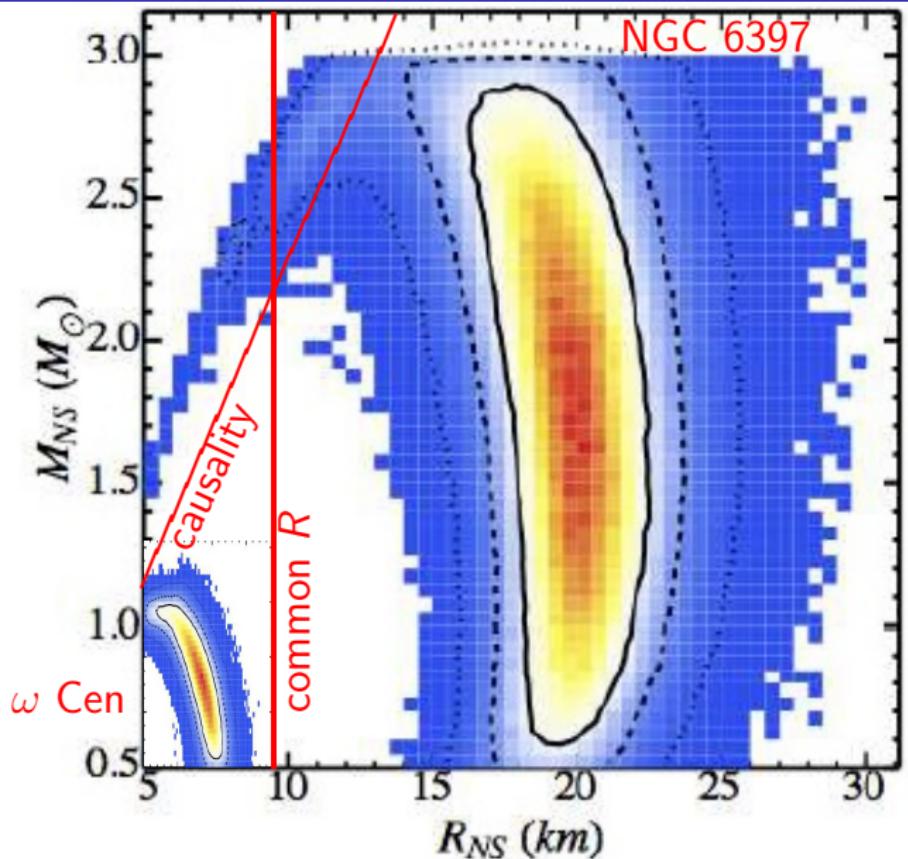
Systematic uncertainties plague radius measurements.

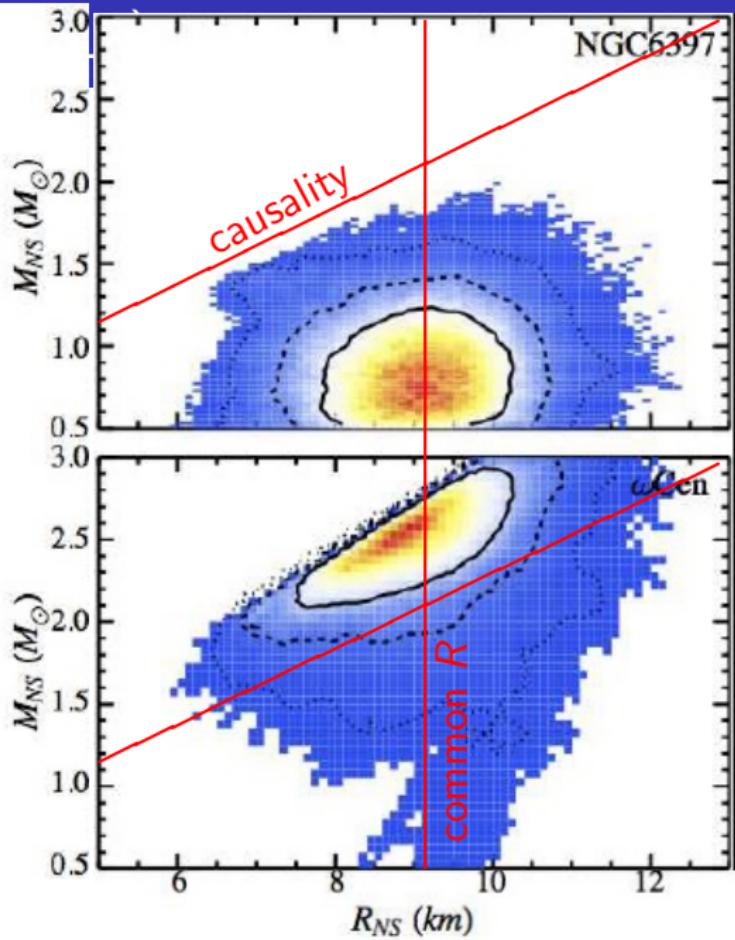
- ▶ Assuming uniform surface temperatures leads to underestimates in radii.
- ▶ Uncertainties in interstellar absorption for quiescent sources; spectral determinations may disagree with pulsar dispersion estimates.
- ▶ In quiescent sources, He or C atmospheres can produce about 50% larger radii than 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)





PRE Burst Models

Observations measure:

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

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

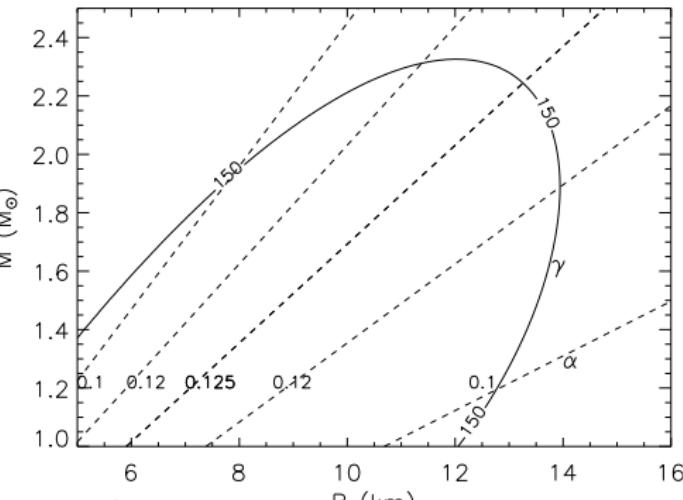
Determine parameters:

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

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

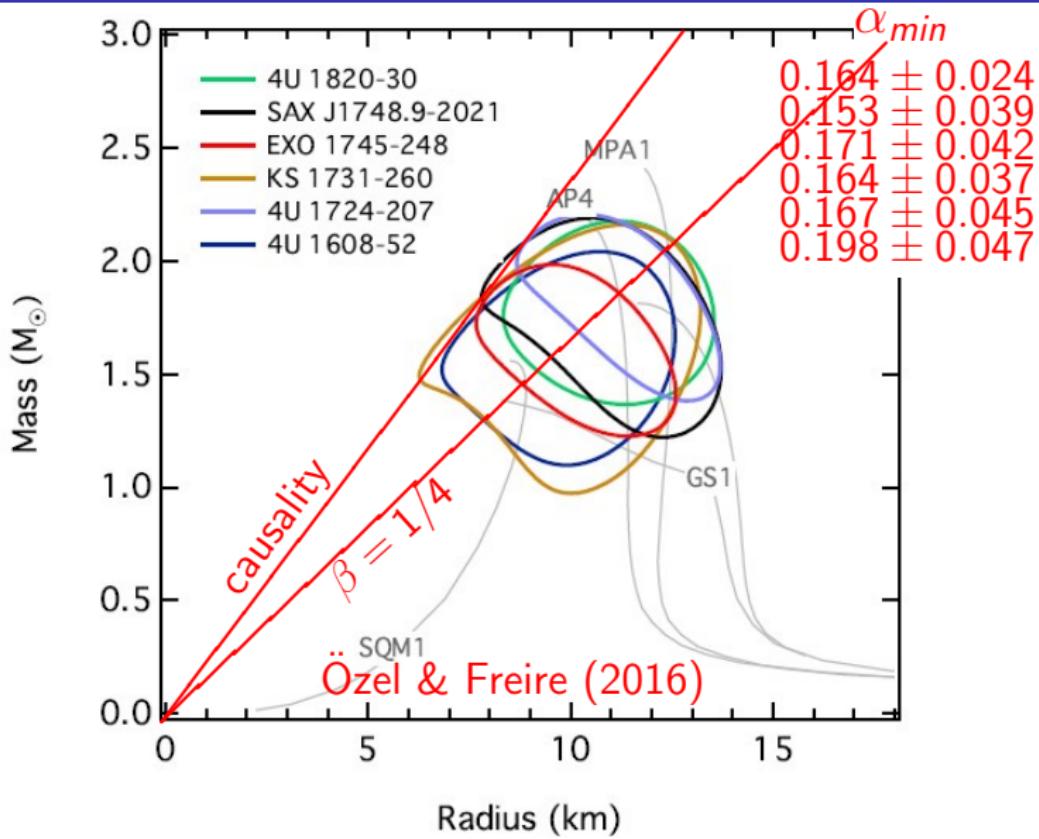
Solution:

$$\beta = \frac{1}{4} \pm \frac{\sqrt{1 - 8\alpha}}{4},$$



$$\alpha \leq \frac{1}{8} \text{ for real solutions.}$$

PRE M – R Estimates

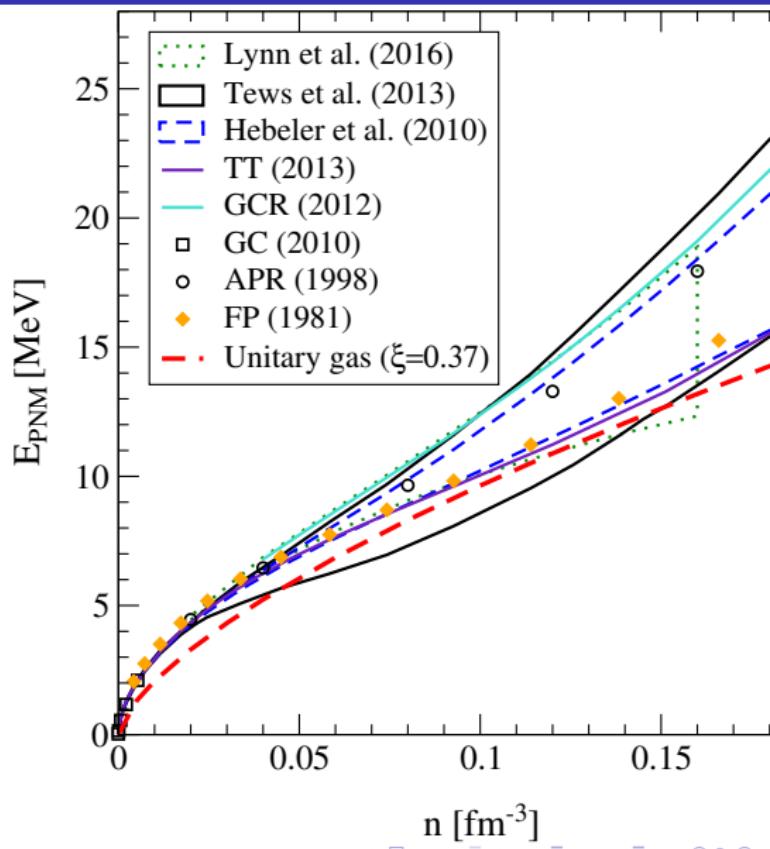


Theoretical Neutron Matter Calculations

NS crust EOS below $n_s/2$.

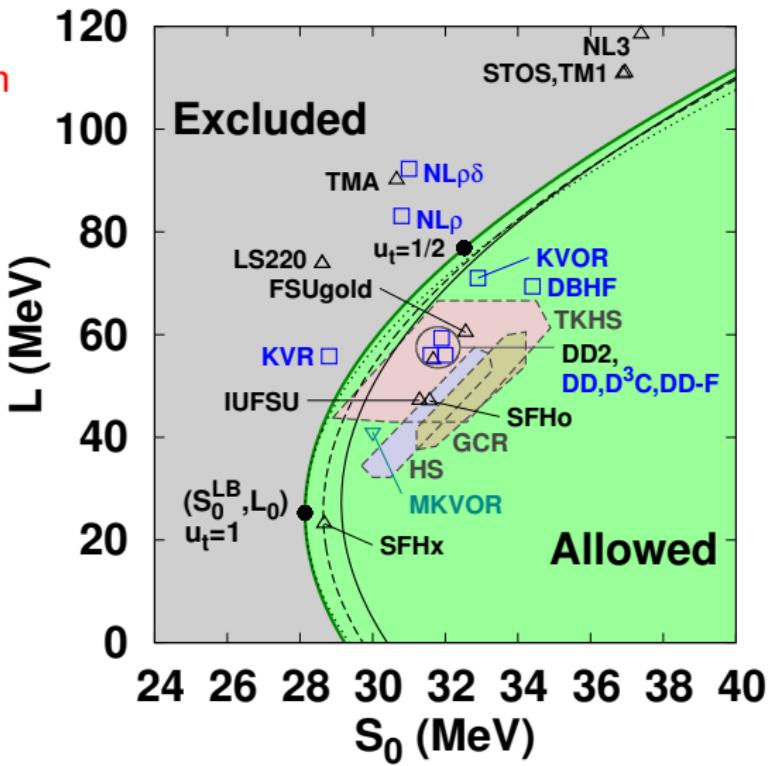
Theoretical studies below $2n_s$ using low-energy neutron scattering data and few-body calculations of light nuclei.

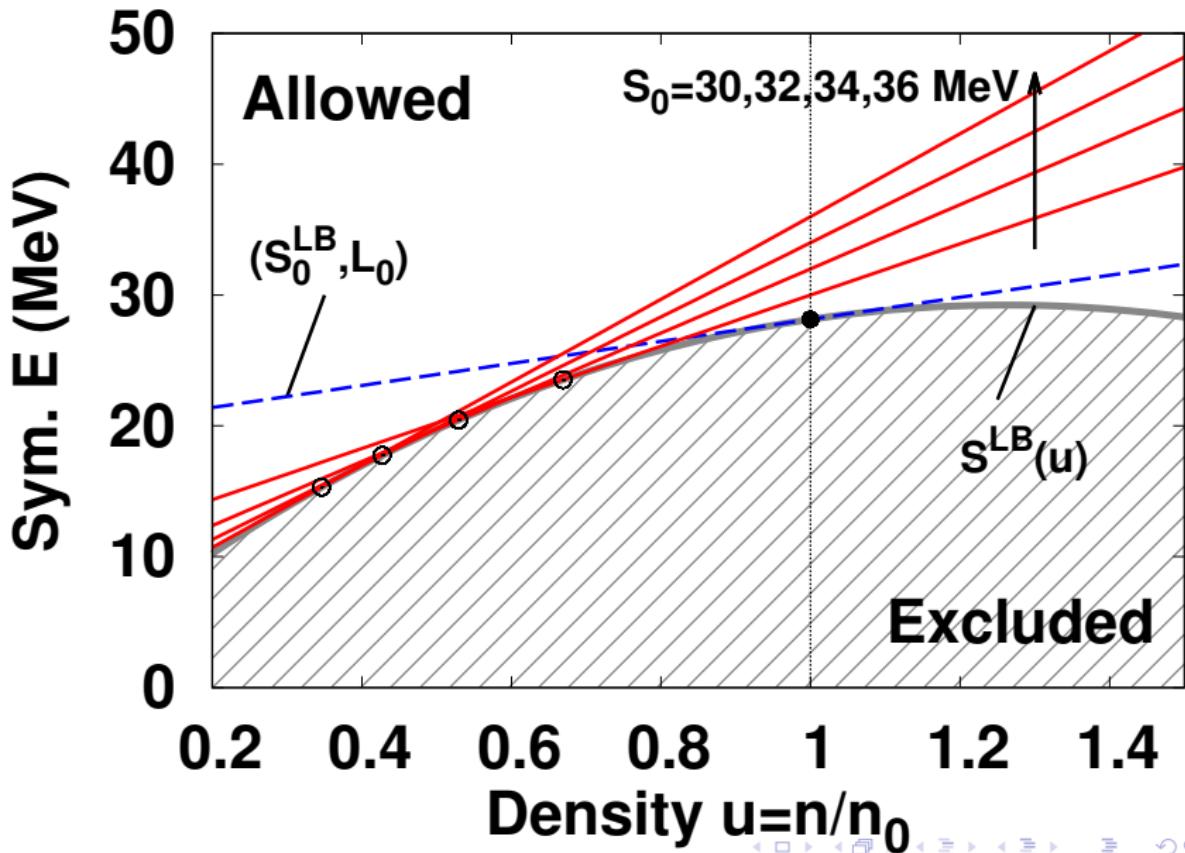
- ▶ Auxiliary Field Diffusion Quantum Monte Carlo (Gandolfi & Carlson)
- ▶ Chiral Lagrangian Expansion (Drischler, Hebeler, Schwenk; Sammarruca et al., Tews et al., Lynn et al., Hagen et al., Carbone et al., Coraggio et al.,...)



Unitary Gas Bounds

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





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:

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

- ▶ 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

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

Theoretical and Experimental Constraints

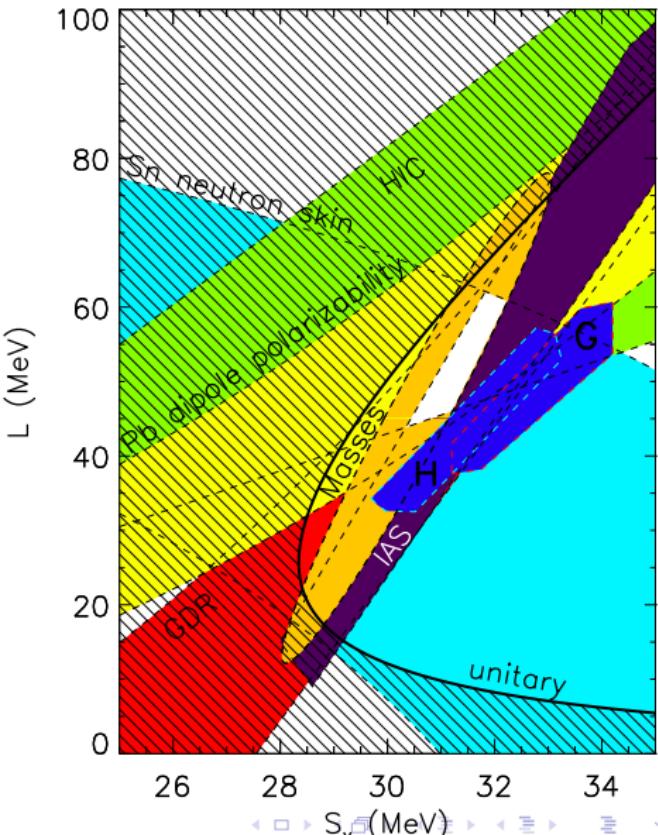
H Chiral Lagrangian

G: Quantum Monte Carlo

$S_\nu - L$ 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.

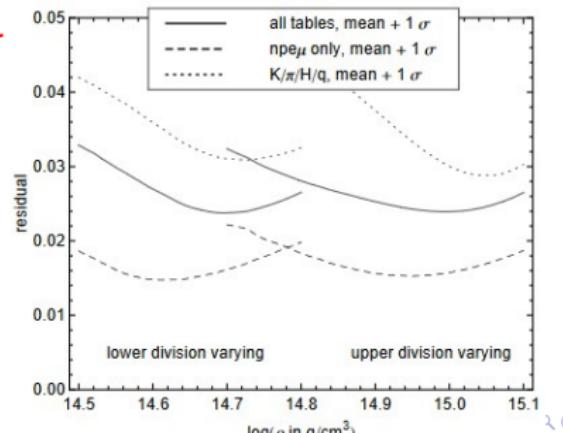
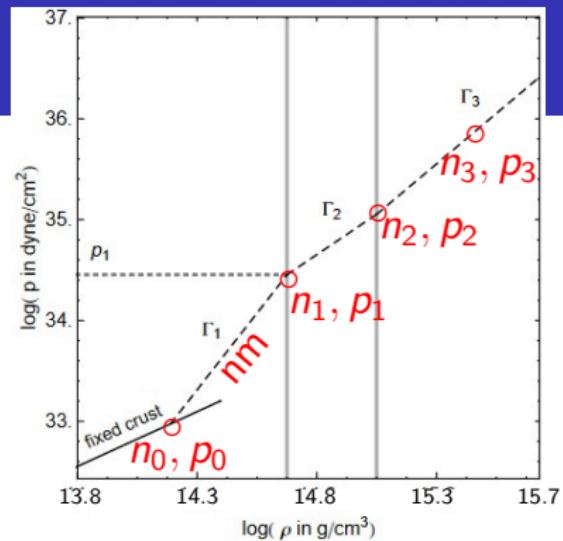
For $n_0 < n < n_1$, assume neutron matter EOS. Arbitrarily choose $n_3 = 7.4n_s$.

For a given p_1 (or Γ_1):

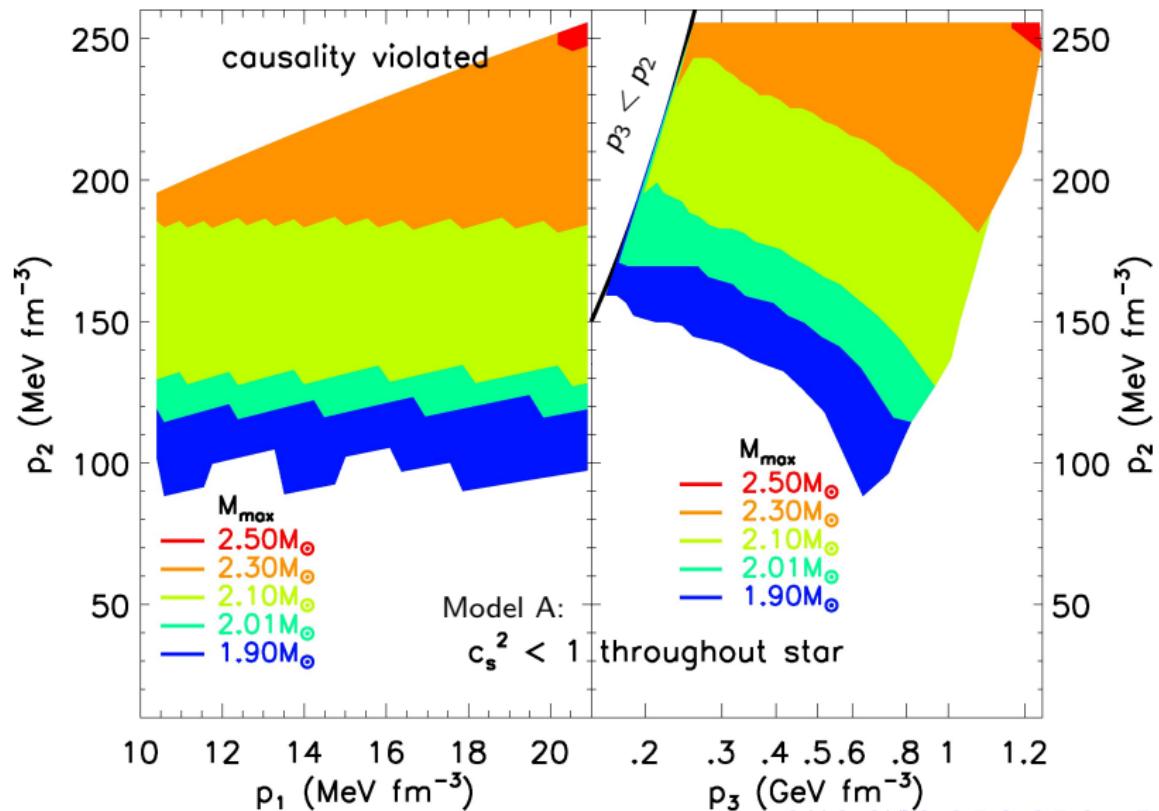
$0 < \Gamma_2 < \Gamma_{2c}$ or $p_1 < p_2 < p_{2c}$.

$0 < \Gamma_3 < \Gamma_{3c}$ or $p_2 < p_3 < p_{3c}$.

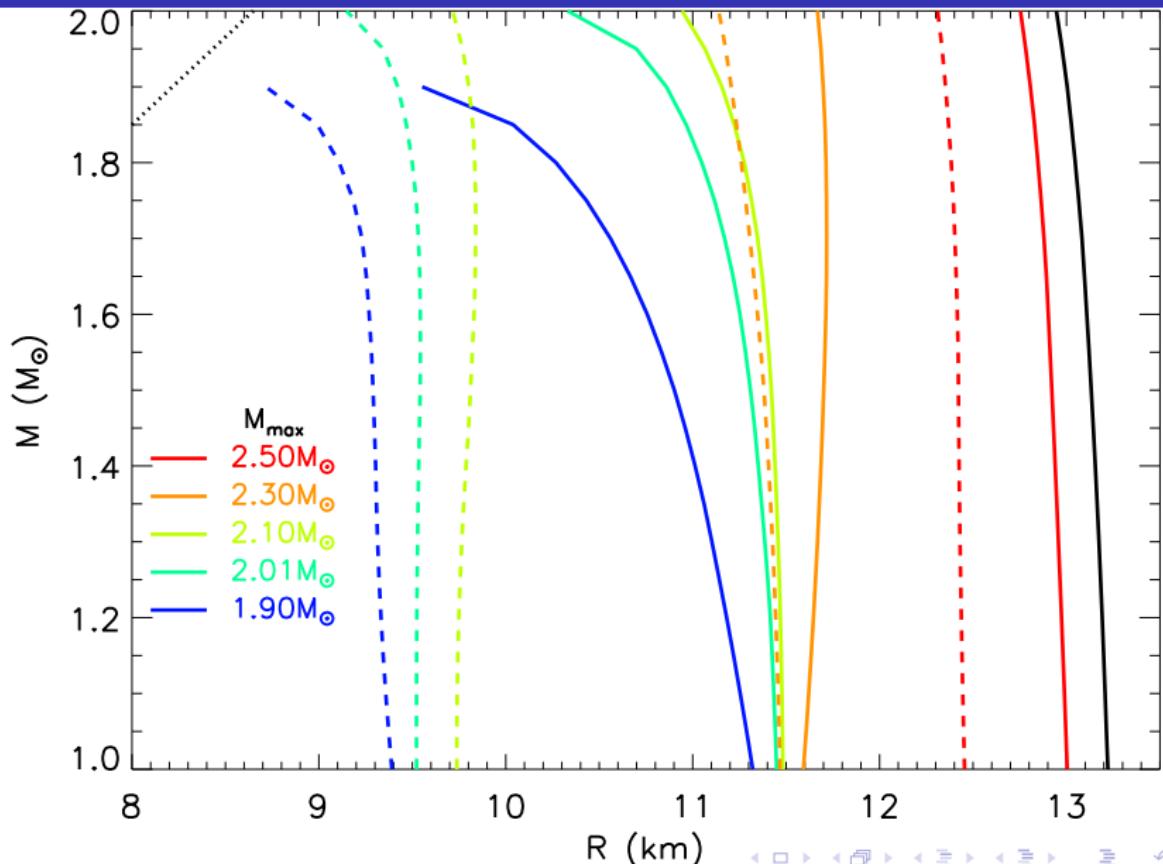
Minimum values of p_2, p_3 set by M_{max} ; maximum values set by causality.



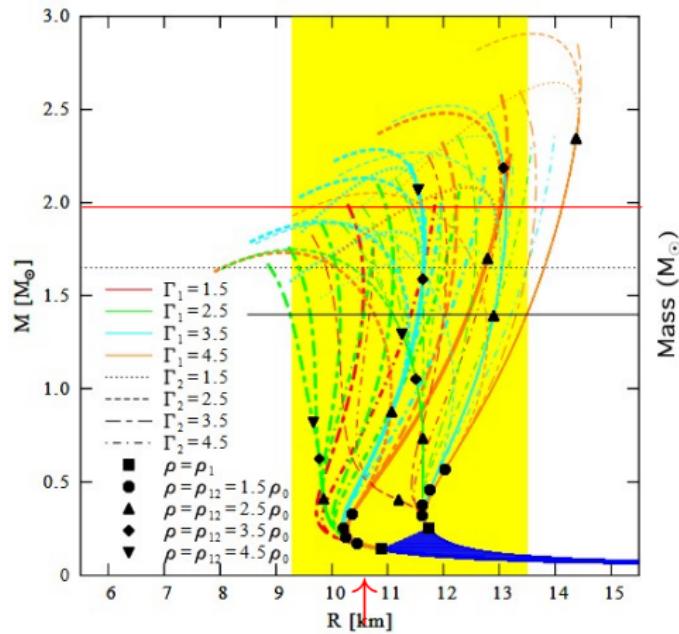
Maximum Mass and Causality Constraints



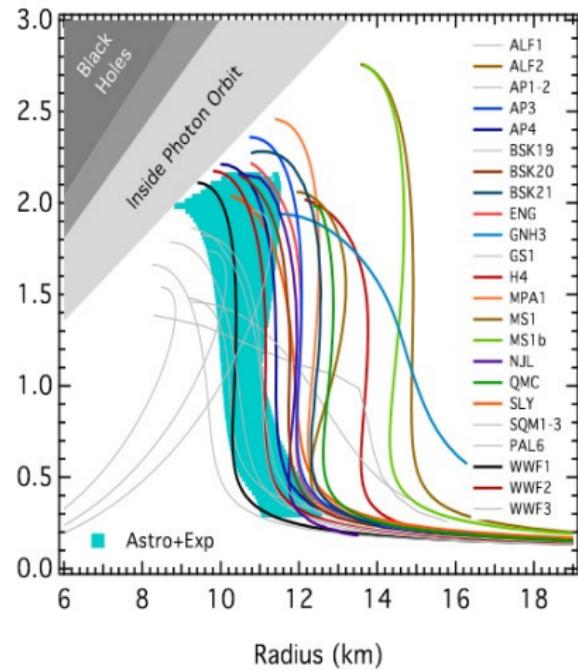
Mass-Radius Constraints from Causality



Other Studies

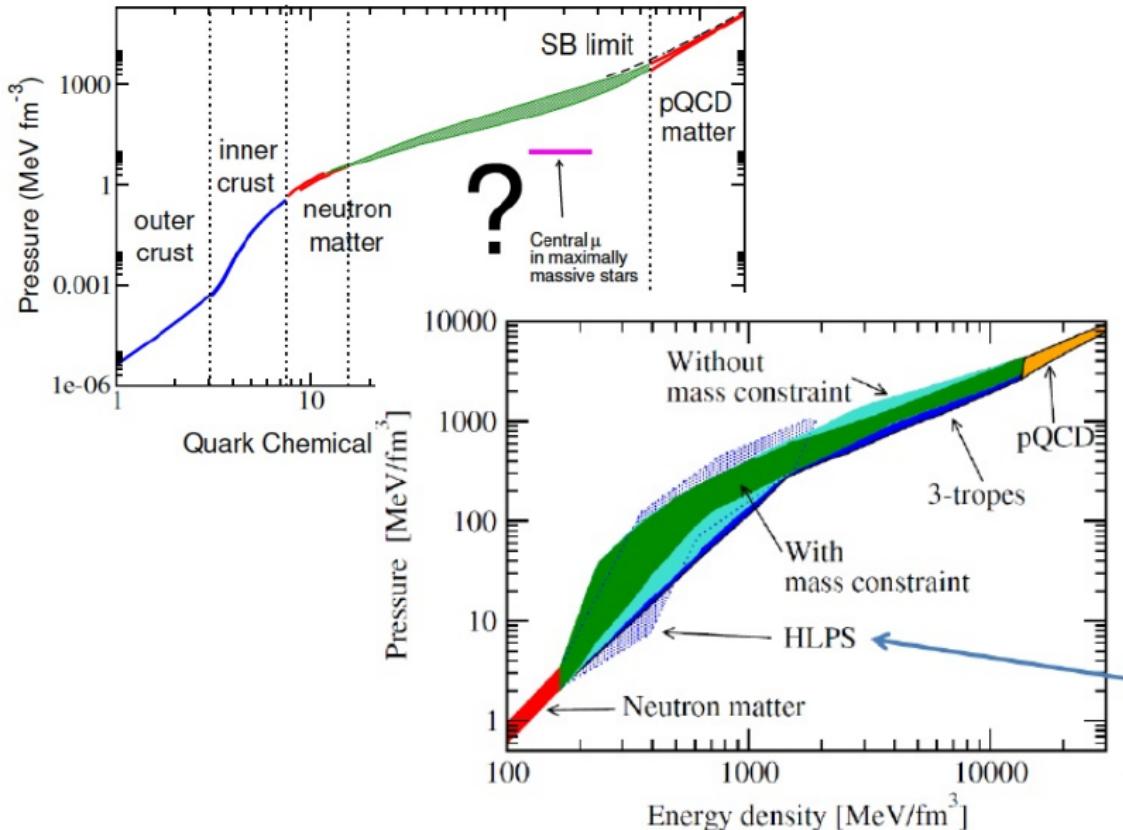


Hebeler, Lattimer, Pethick & Schwenk 2010

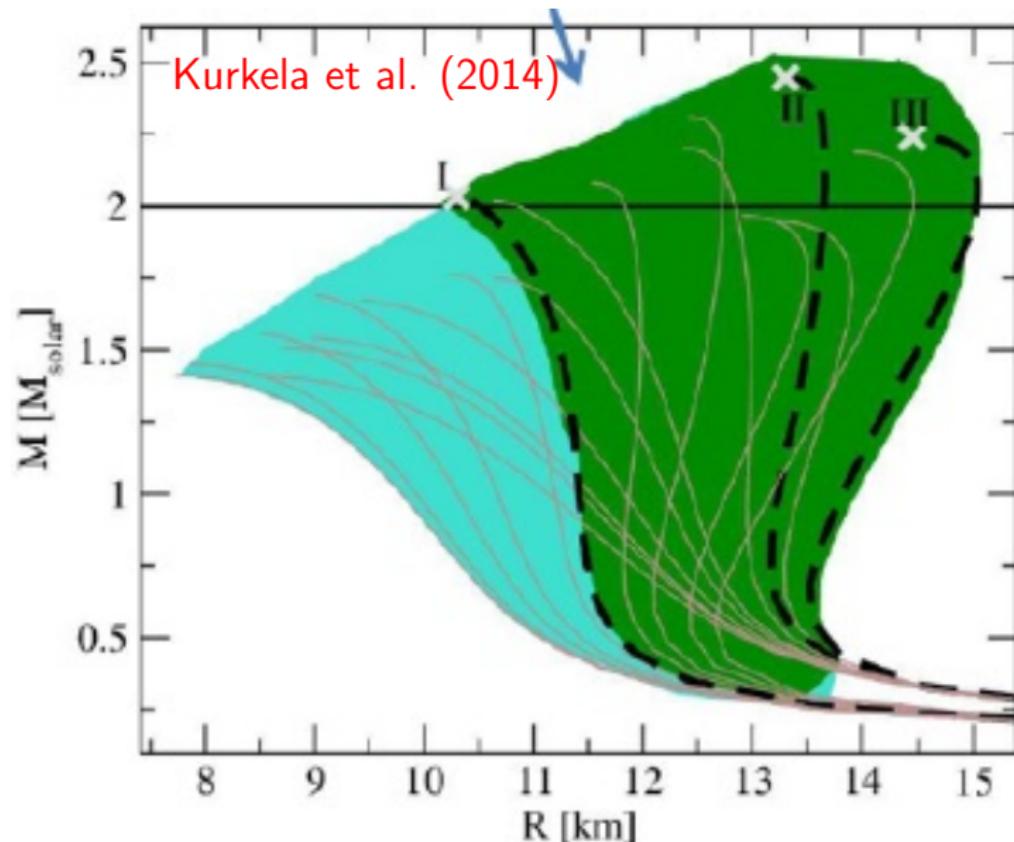


Özel & Freire 2016

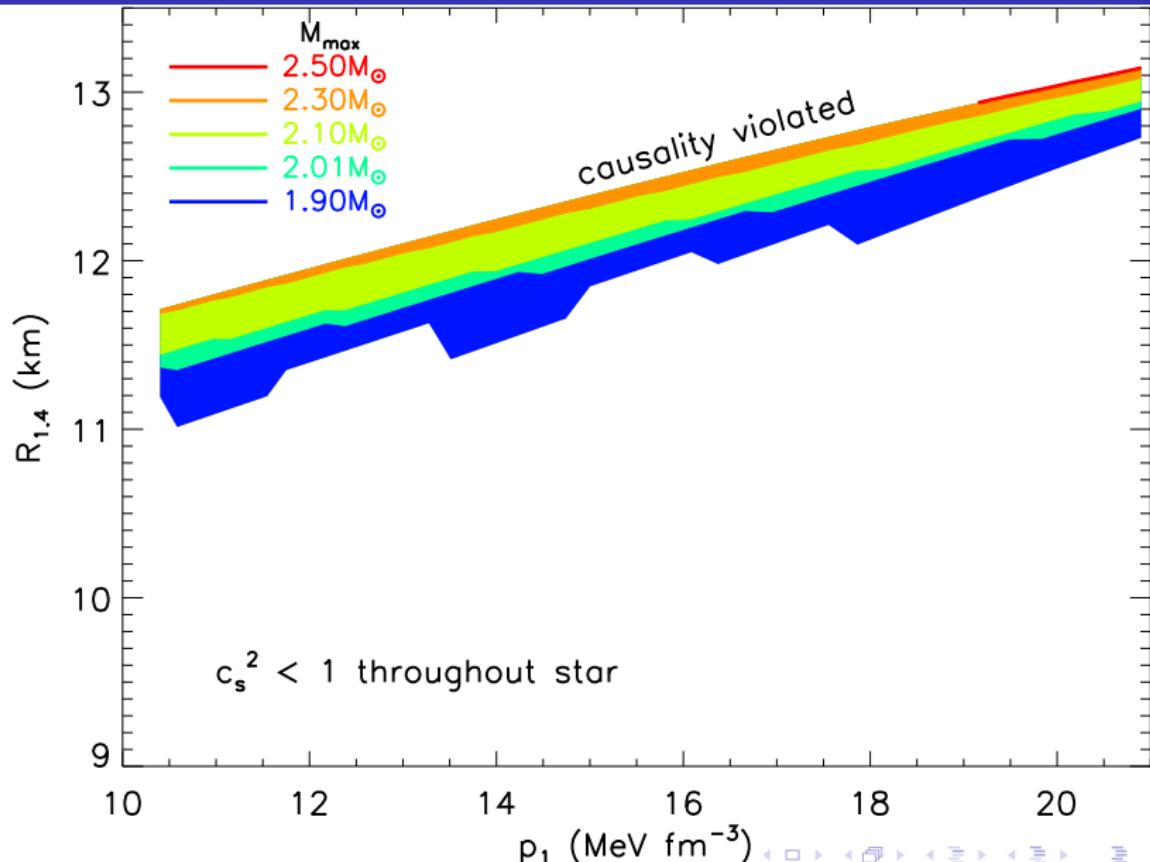
Constraints From Above



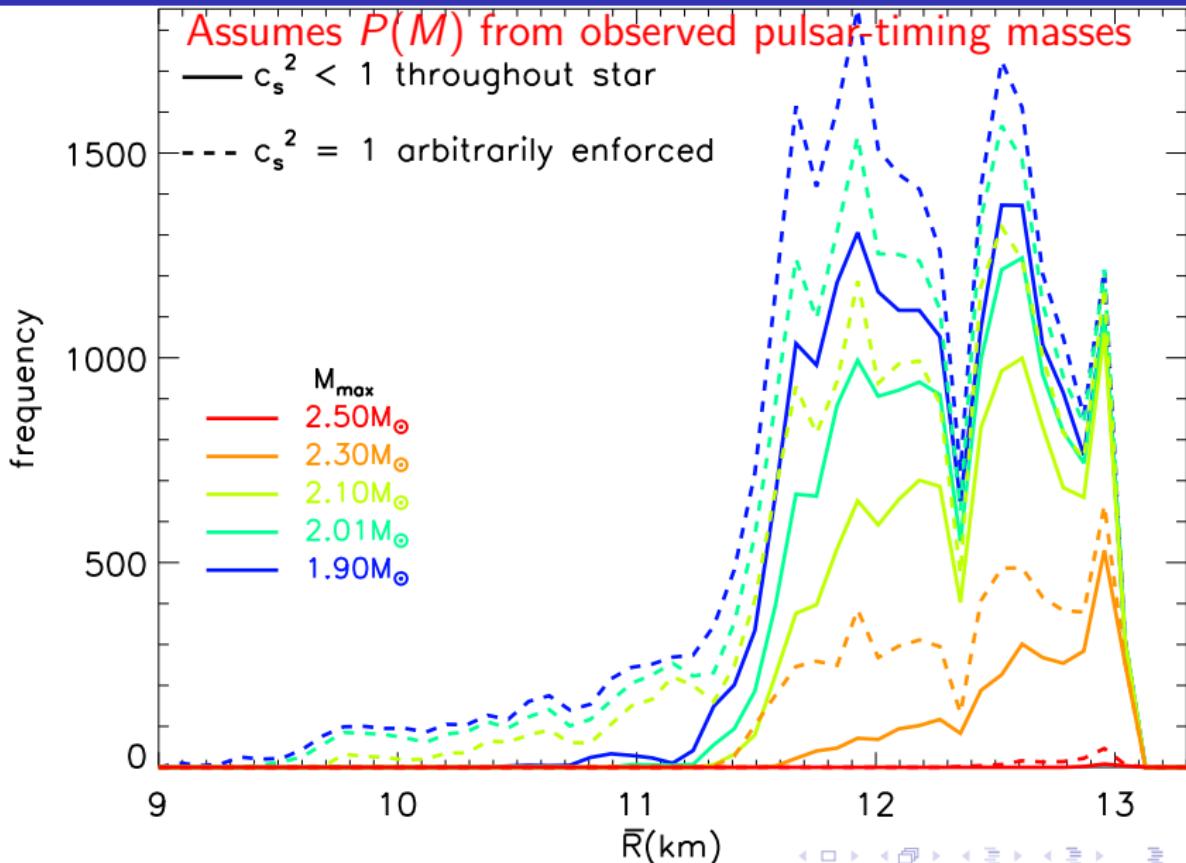
pQCD + Neutron Matter Constraints



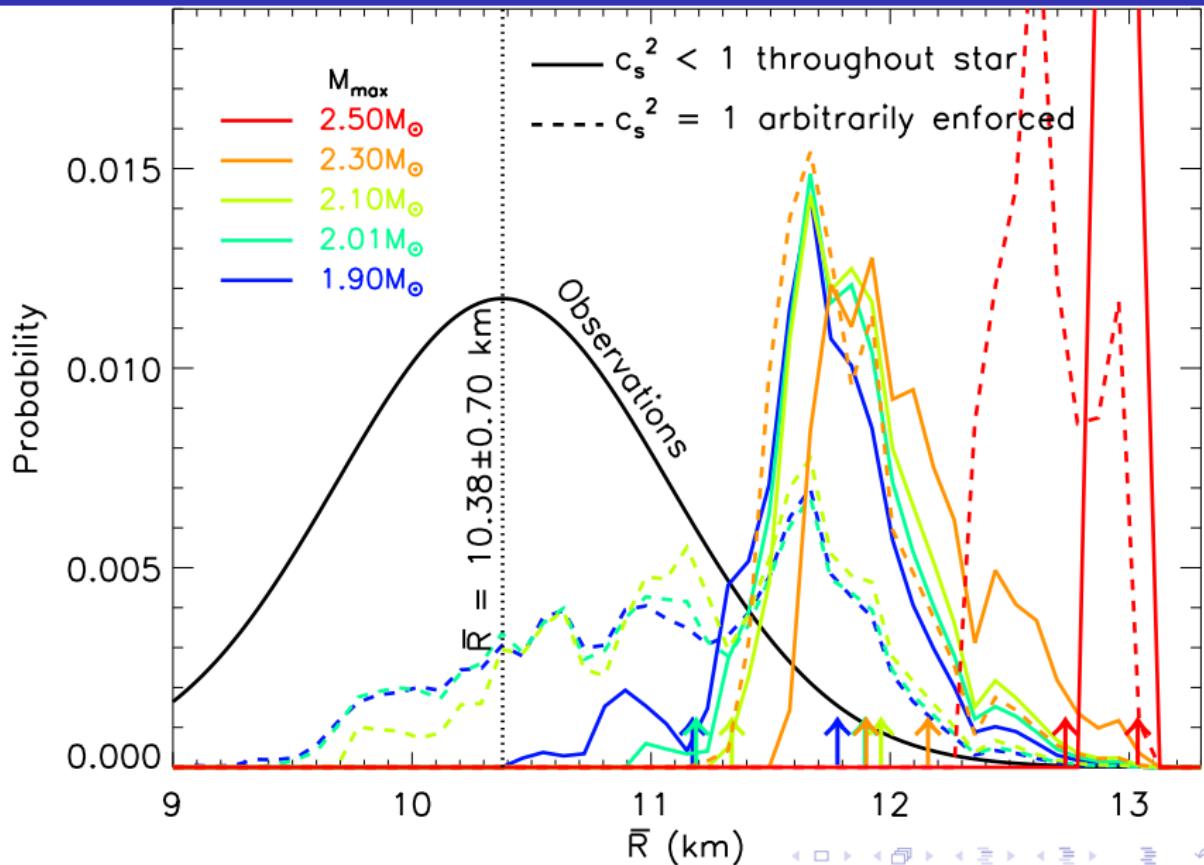
Radius - p_1 Correlation



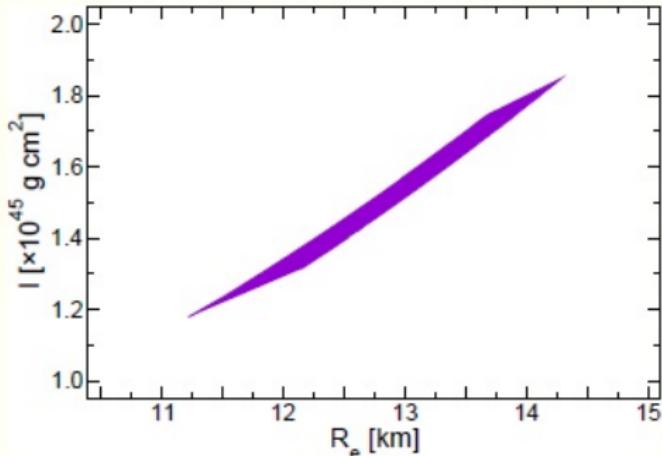
Piecewise-Polytrope Average Radius Distributions



Folding Observations with Piecewise Polytropes

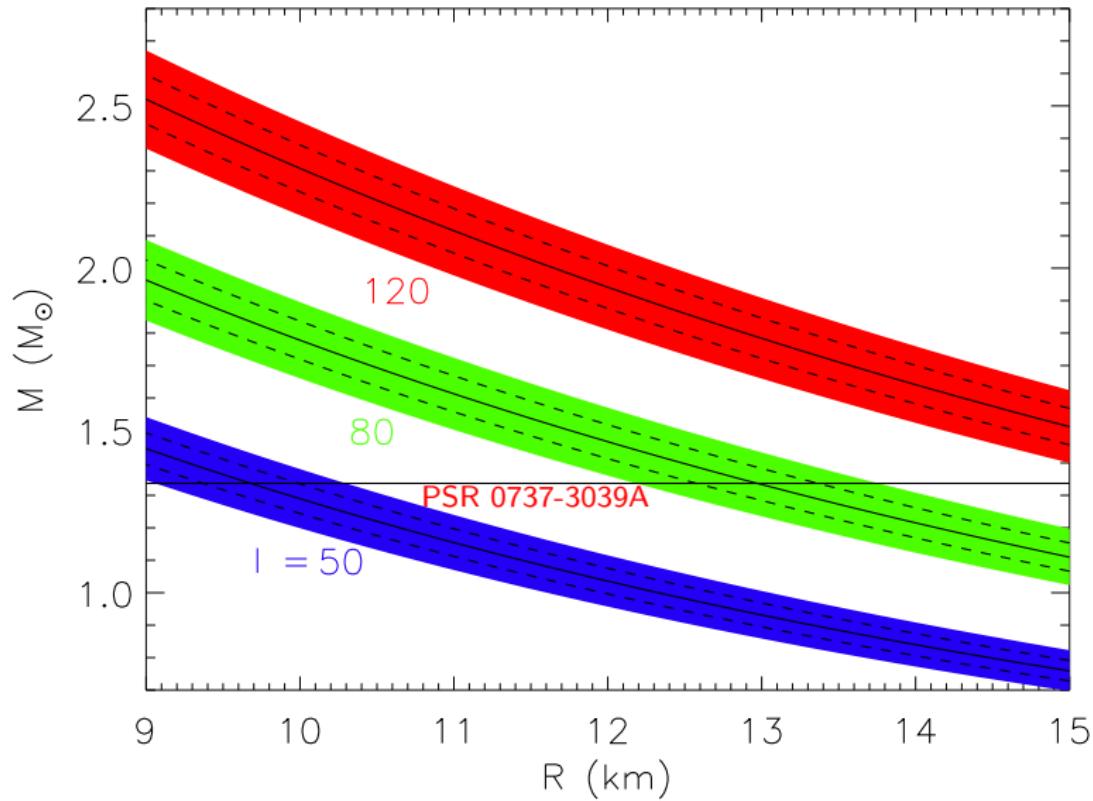


$I - R_e$ FOR THE DOUBLE PULSAR PSR J0737-3039A

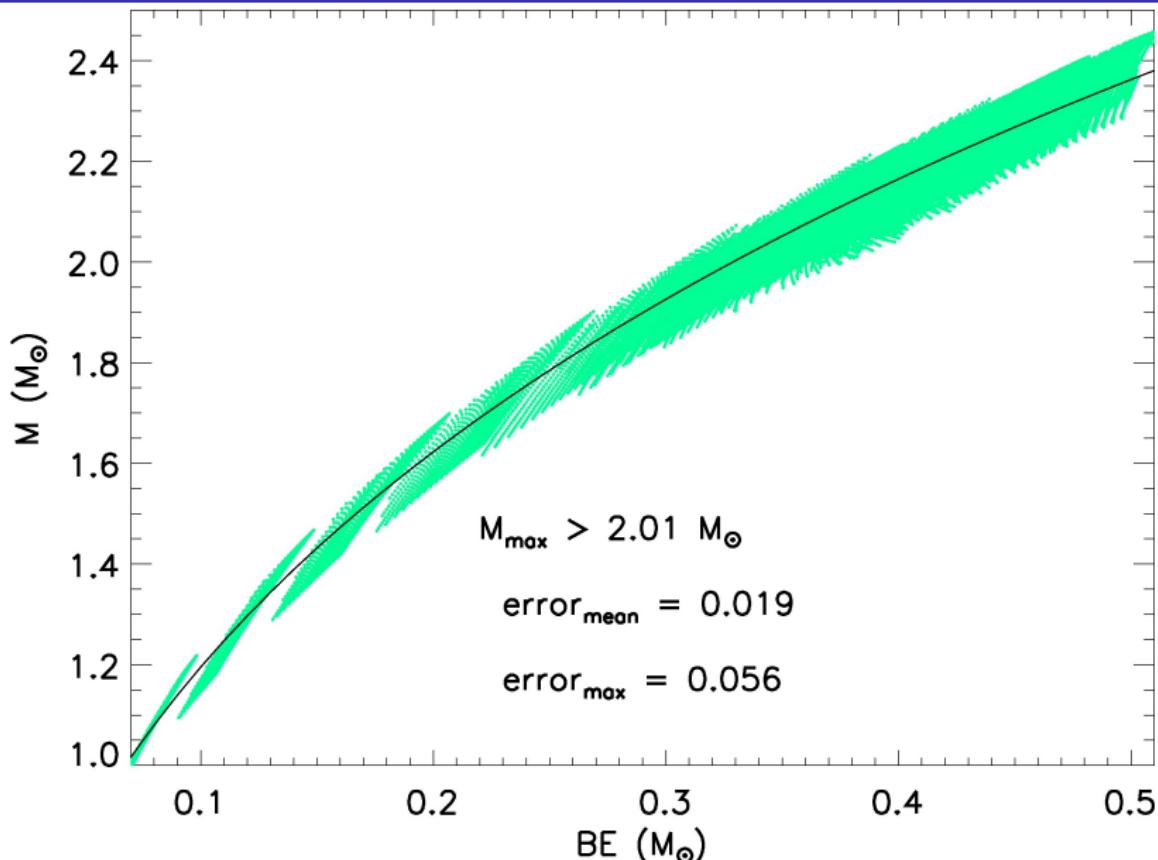


Allowed region of (I, R_e) points for PSR J0737-3039A.

Moment of Inertia - Radius Constraints



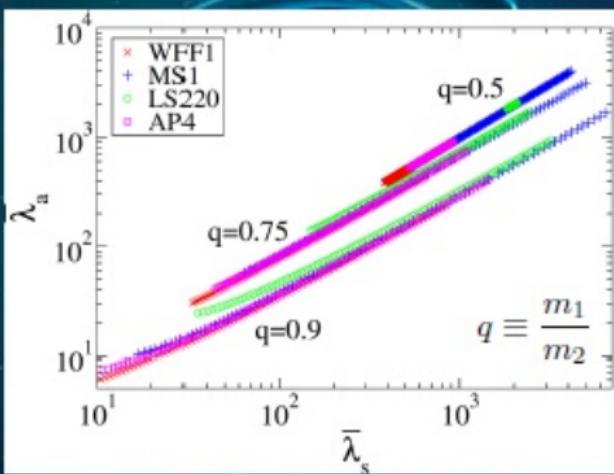
Binding Energy - Mass Correlations



Binary Love Relations NS – NS Mergers

(I) symmetric/anti-symmetric

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

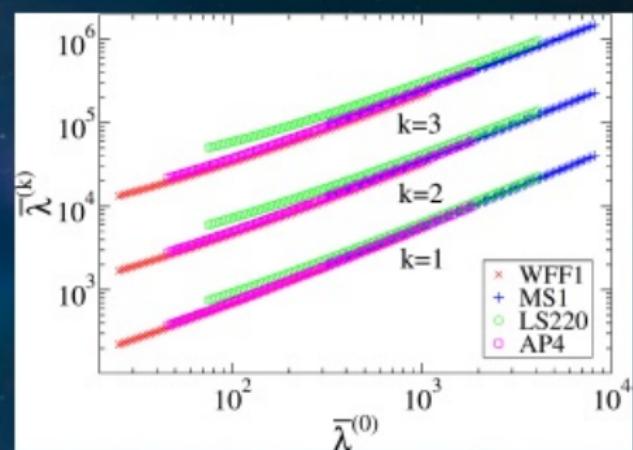


(II) Taylor expansion

[Messenger & Read (2012)]

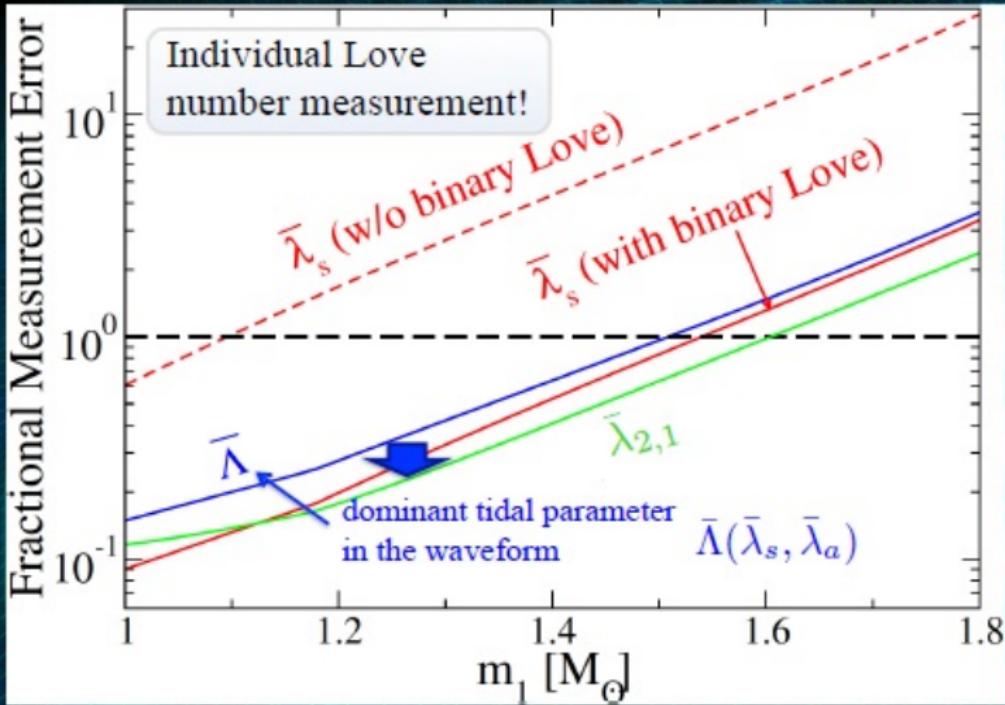
$$\bar{\lambda}_{2,A}(m_A) = \sum_{k=0} \frac{\bar{\lambda}^{(k)}}{k!} \left(1 - \frac{m_A}{m_0}\right)^k$$

fiducial mass

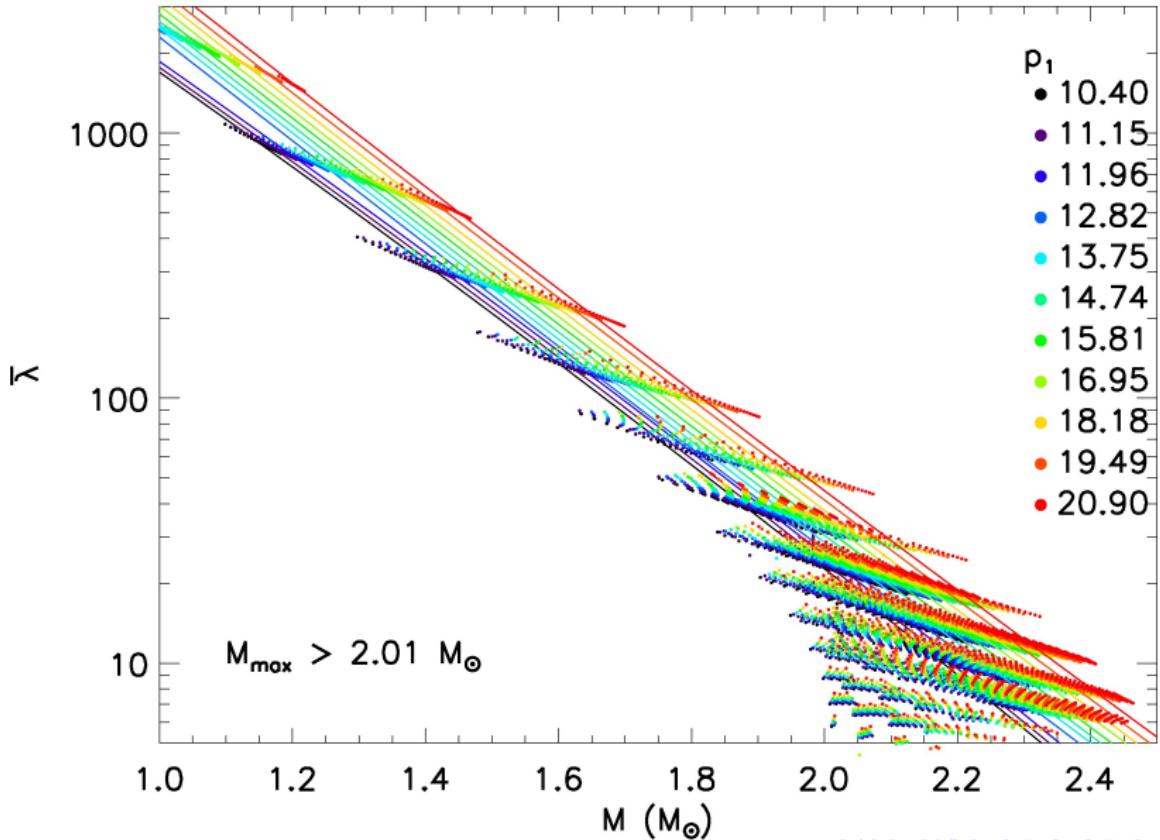


Universal to $\mathcal{O}(10\%)$

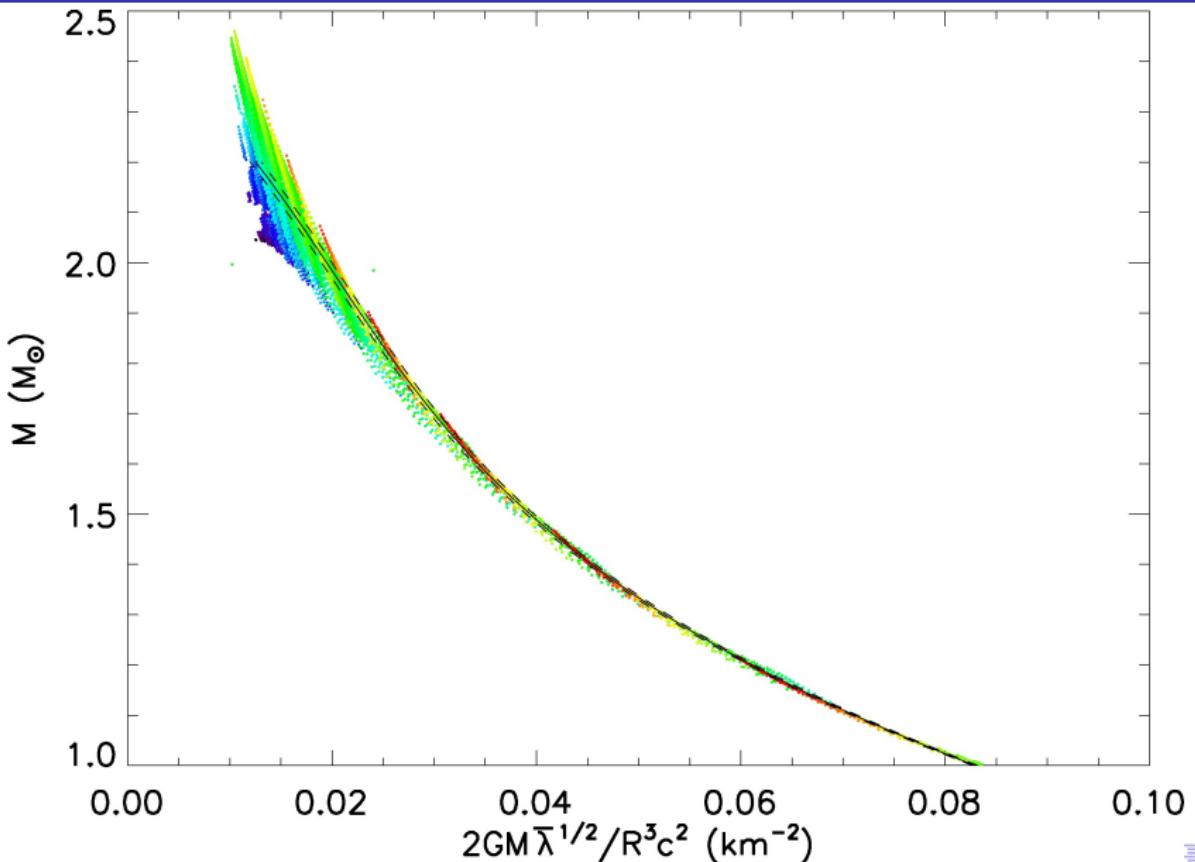
(I) Nuclear Physics



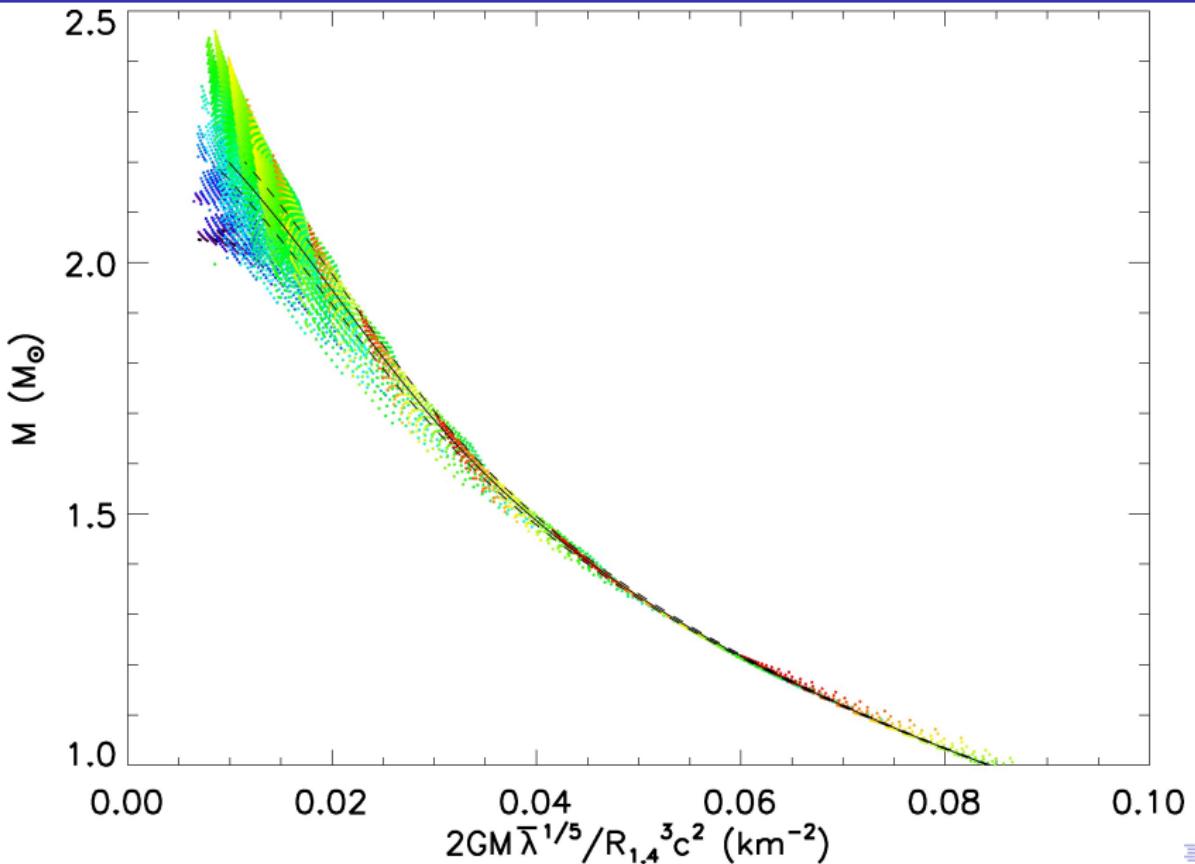
Tidal Deformability - Mass



Tidal Deformability



Tidal Deformability



Binary Tidal Deformability

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

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

where

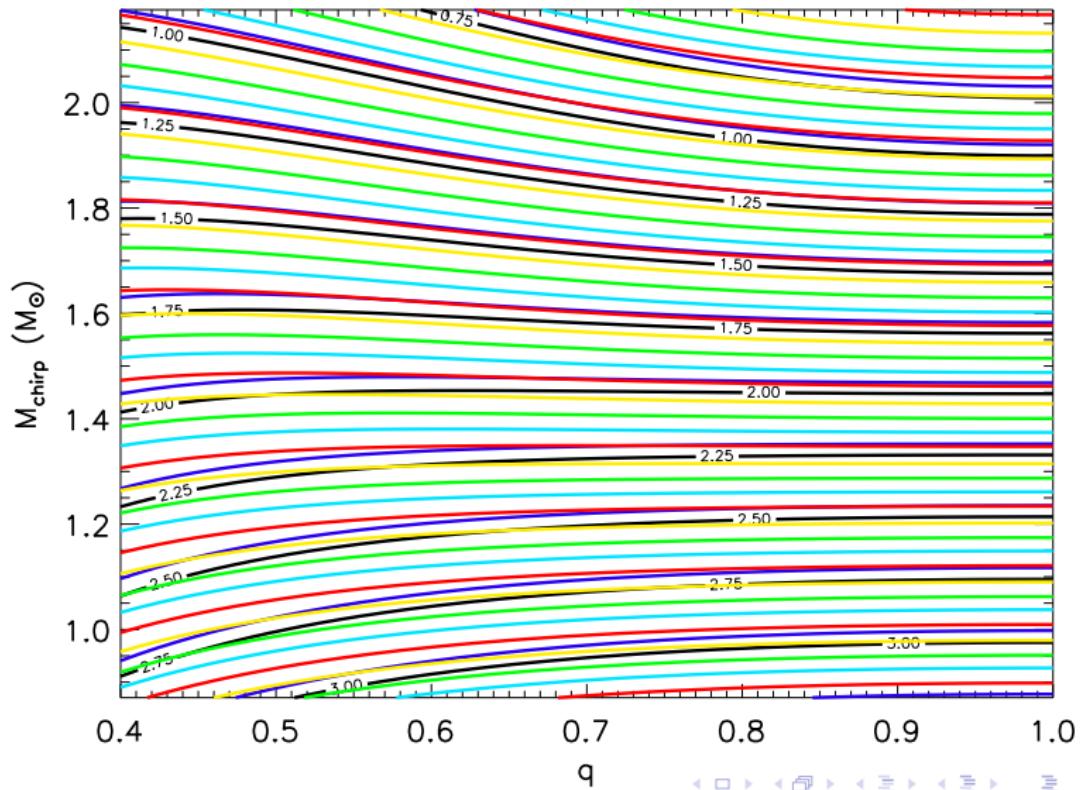
$$q = \frac{M_1}{M_2} < 1$$

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

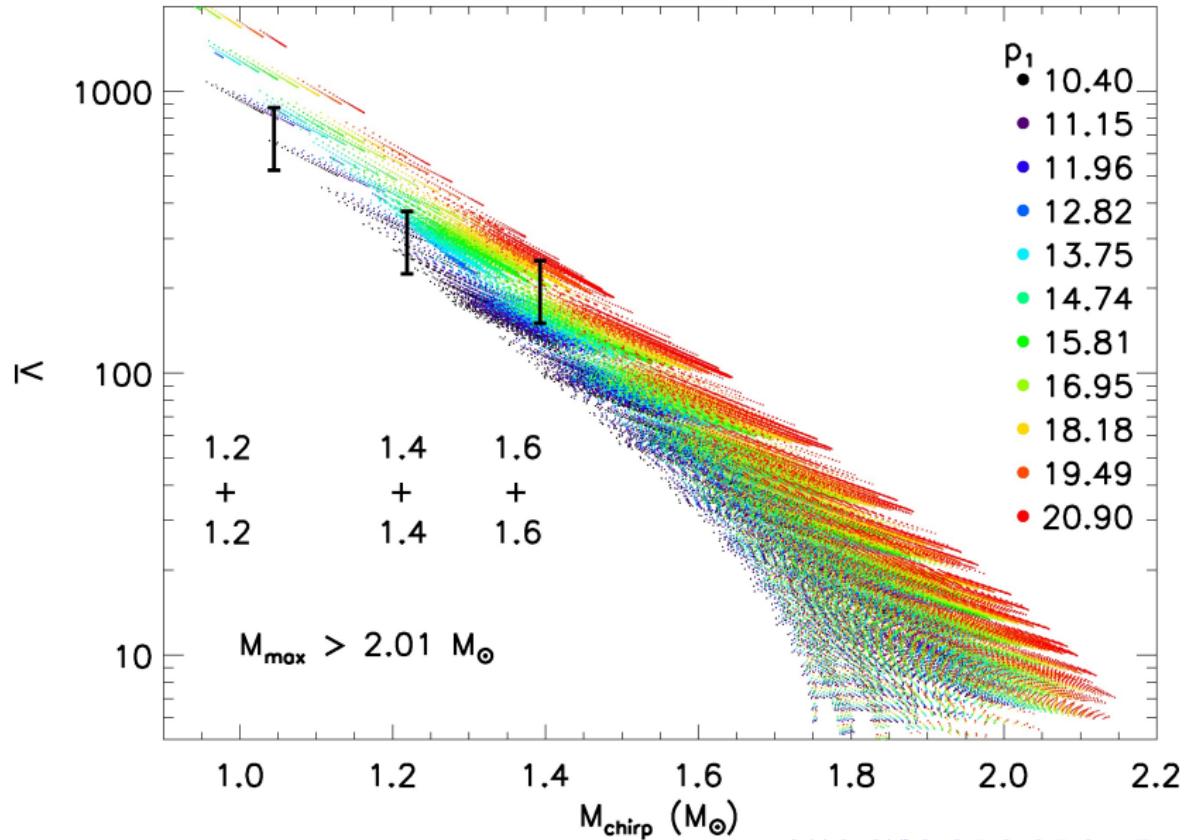
$$\Delta M_{chirp} \sim 0.01 - 0.02\%, \quad \Delta \bar{\Lambda} \sim 20 - 25\%$$

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

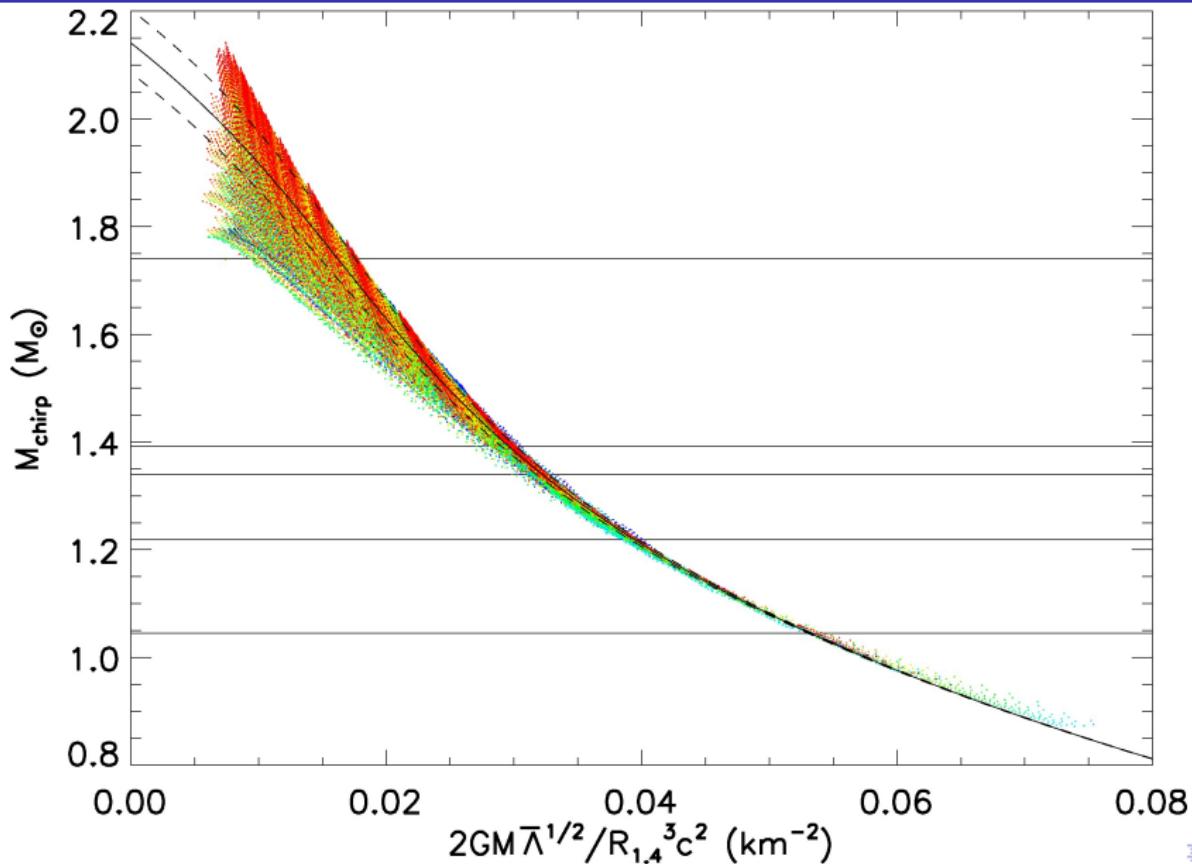
Tidal Deformability - $\bar{\Lambda}$



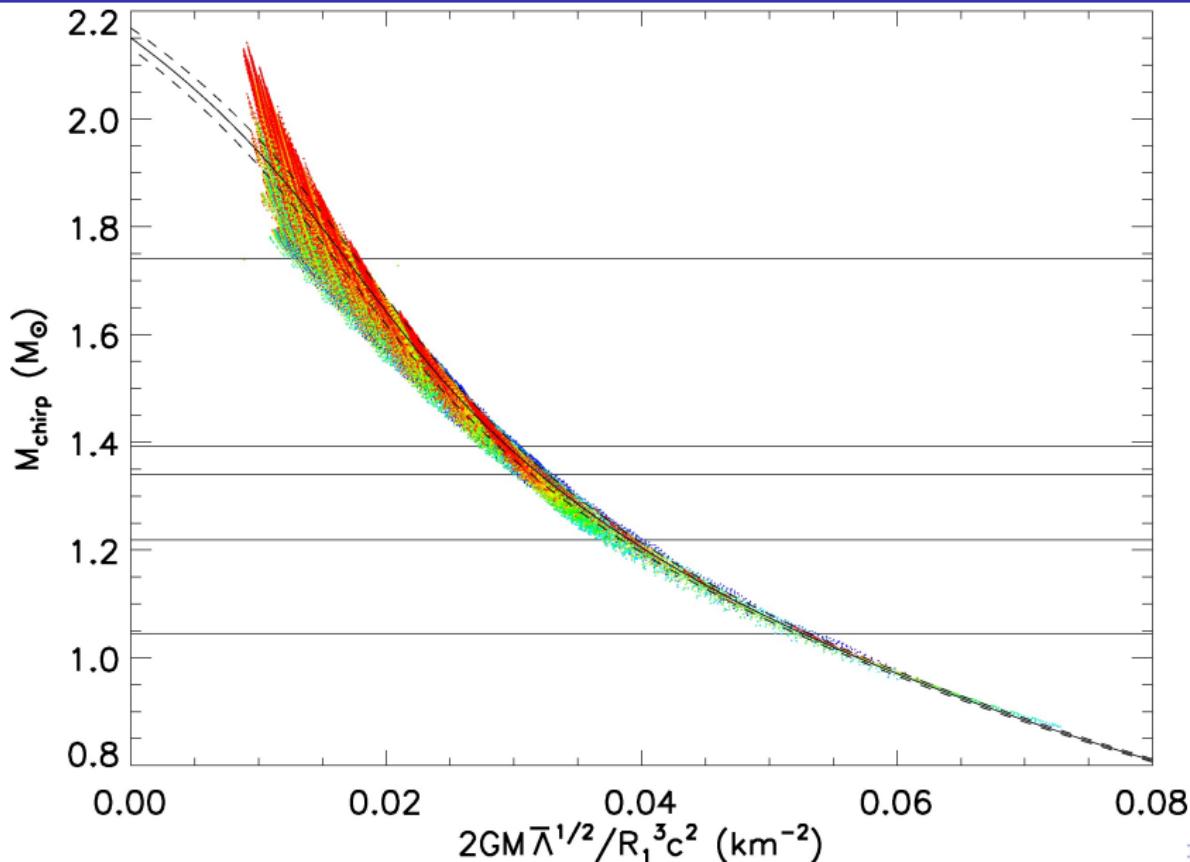
Binary Tidal Deformability



Binary Tidal Deformability



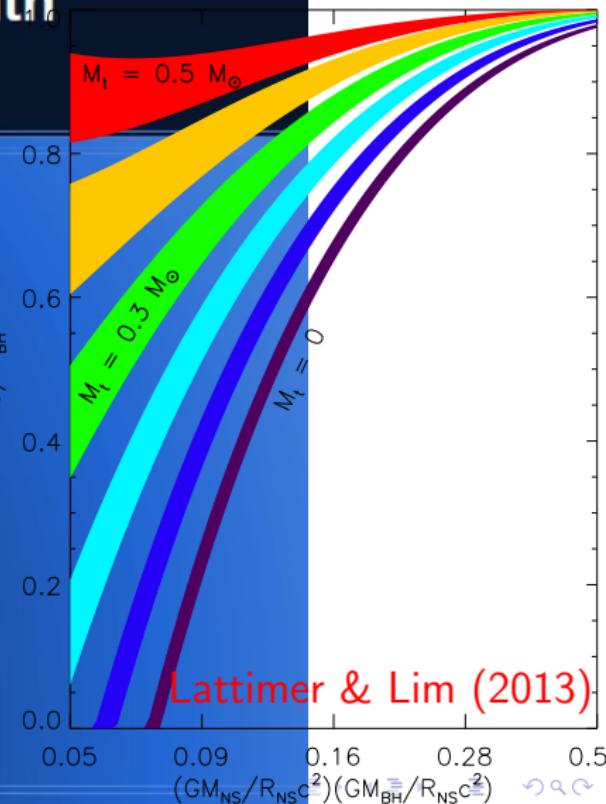
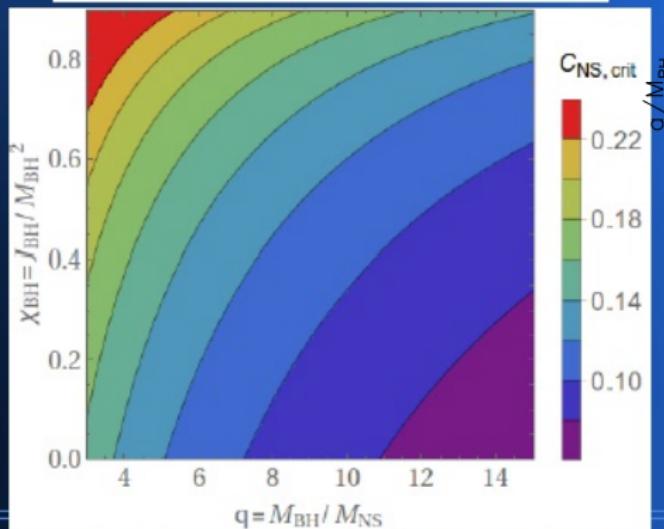
Binary Tidal Deformability



Black Hole–Neutron Star Mergers

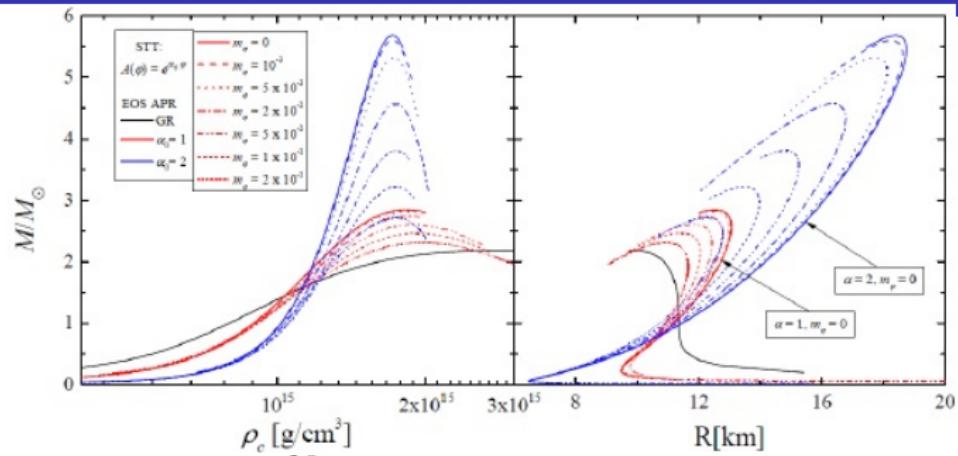
Probing the nuclear EOS with GW+sGRB observations

$$C_{NS,crit} = \left(2 + 2.14 q^{2/3} \frac{R_{ISCO}}{M_{BH}} \right)^{-1}$$

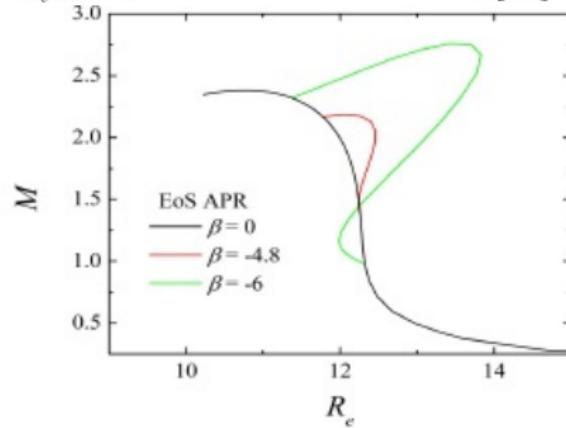
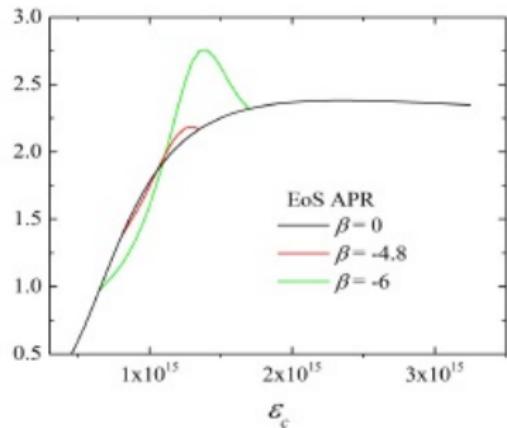


Alternatives to GR

Kokkotas

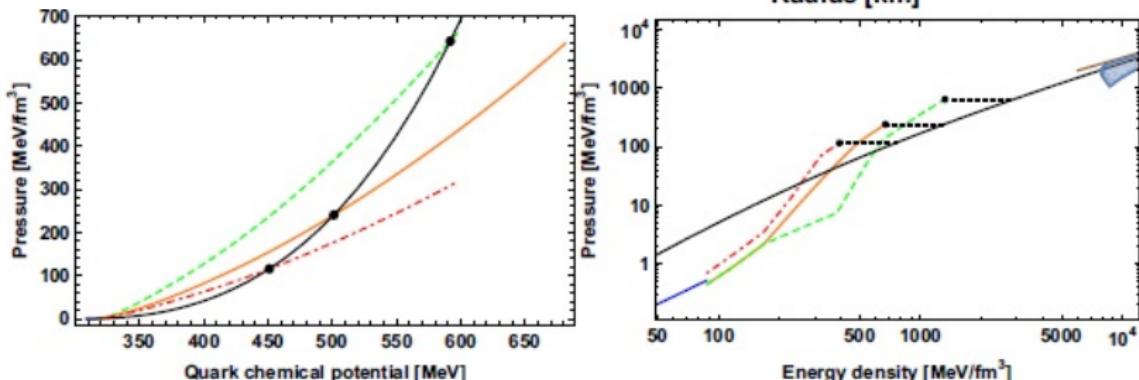
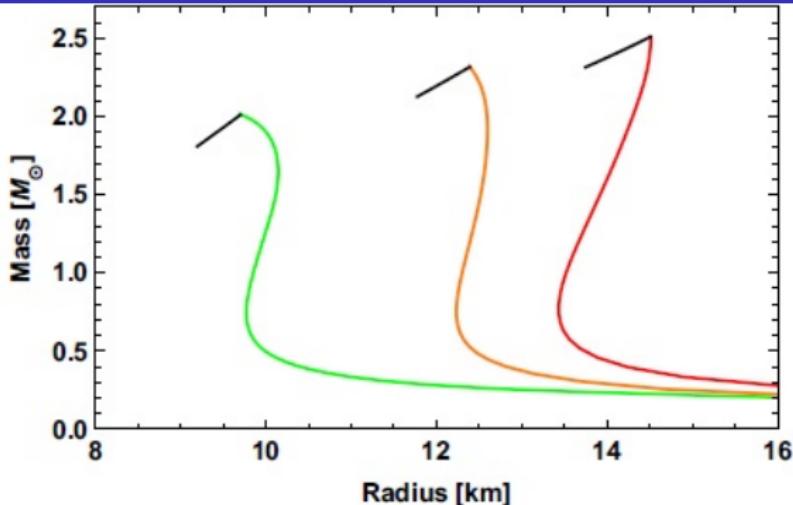


M



Holographic Stars Don't Exist

Jokela



Future Observations

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

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

- ▶ Compactness from $\nu_{\text{r-mode}}$.
- ▶ 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?