Neutron Star Radii: Large or Small?

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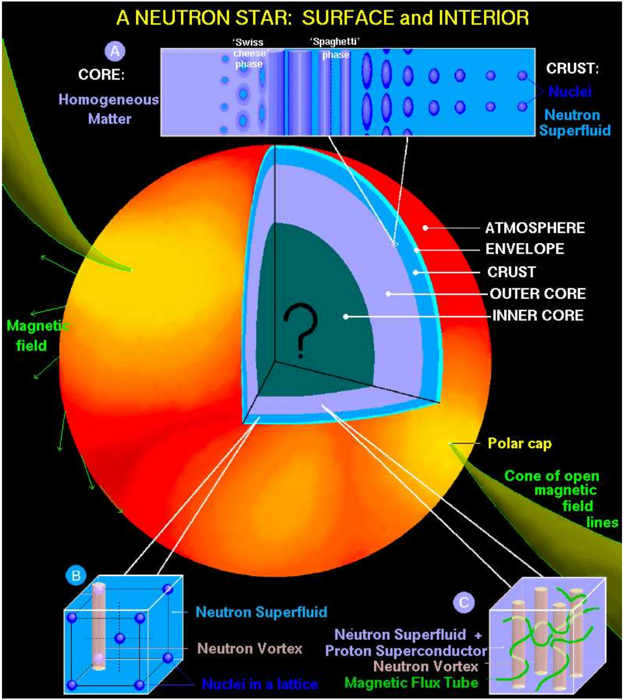
Outline

- General Relativity Constraints on Neutron Star Structure
- The Neutron Star Radius and the Nuclear Symmetry Energy
- Nuclear Experimental Constraints on the Symmetry Energy
- Constraints from Pure Neutron Matter Theory
- Astrophysical Constraints
  - Pulsar and X-ray Binary Mass Measurements
  - Photospheric Radius Expansion Bursts
  - Thermal Emission from Isolated and Quiescent Binary Sources
  - Other Proposed Mass and Radius Constraints

Dany Page, UNAM

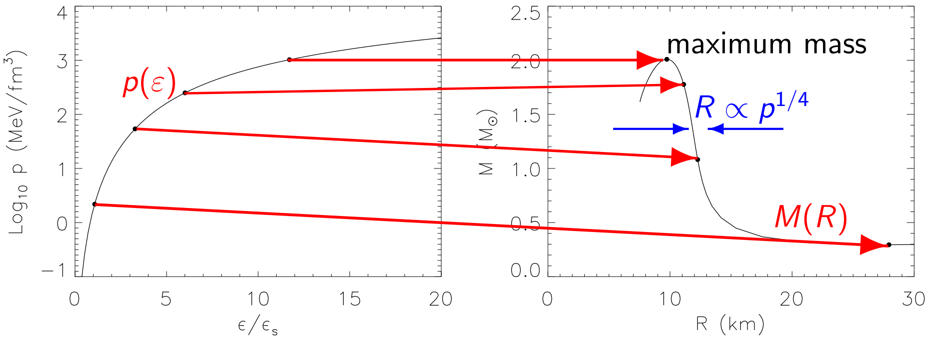


Neutron Star Structure

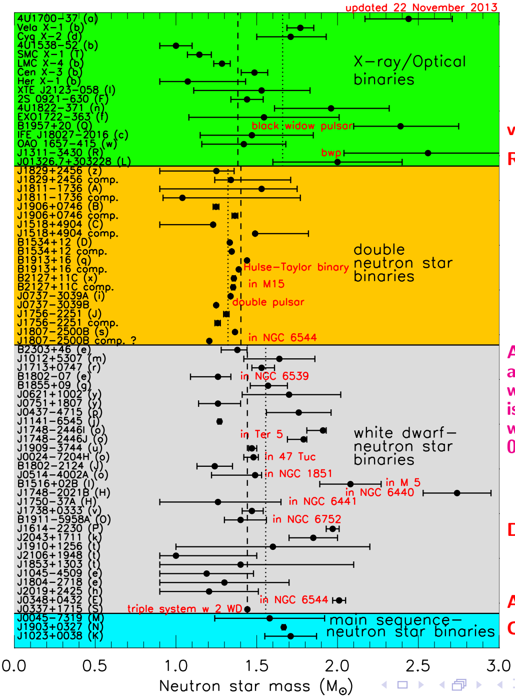
Tolman-Oppenheimer-Volkov equations

$$\frac{dp}{dr} = -\frac{G}{c^4}\frac{(mc^2 + 4\pi pr^3)(\varepsilon + p)}{r(r - 2Gm/c^2)}$$

$$\frac{dm}{dr} = 4\pi\frac{\varepsilon}{c^2}r^2$$



Equation of State ⟵ 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

Antoniadis et al. 2013

Champion et al. 2008

What is the Maximum Mass?

- PSR J1614+2230 (Demorest et al. 2010) $1.97 \pm 0.04\ M_\odot$
  A nearly edge-on system with well-measured Shapiro time delay
- PSRJ0548+0432 (Antoniadis et al. 2013) $2.01 \pm 0.04\ M_\odot$
  Measured using optical data and theoretical properties of companion white dwarf
- B1957+20 (van Kerkwijk 2010) $2.4 \pm 0.3\ M_\odot$
  Black widow pulsar with $\sim 0.03\ M_\odot$ companion; large mass errors due to uncertainties in tidally-distorted shape of the low-mass companion
- PSR J1311-3430 (Romani et al. 2012) $2.55 \pm 0.50\ M_\odot$
  Another black widow pulsar

Causality + GR Limits and the Maximum Mass

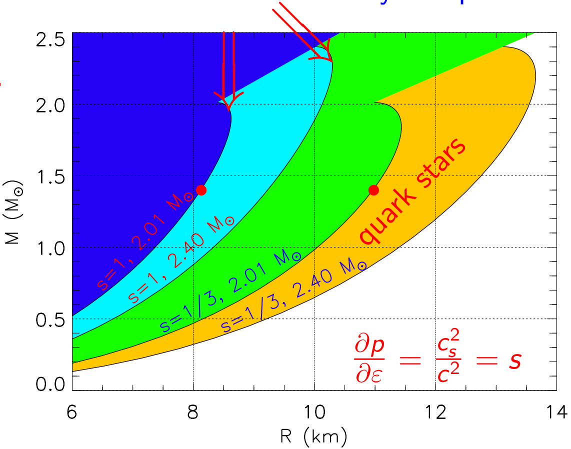
A lower limit to the maximum mass sets a lower limit to the radius for a given mass.

Similarly, a precise (M, R) measurement sets an upper limit to the maximum mass.

$1.4 M_\odot$ stars must have $R > 8.15 M_\odot$.

$1.4 M_\odot$ strange quark matter stars (and likely hybrid quark/hadron stars) must have $R > 11$ km.

$M - R$ curves for maximally compact EOS



Mass-Radius Diagram and Theoretical Constraints

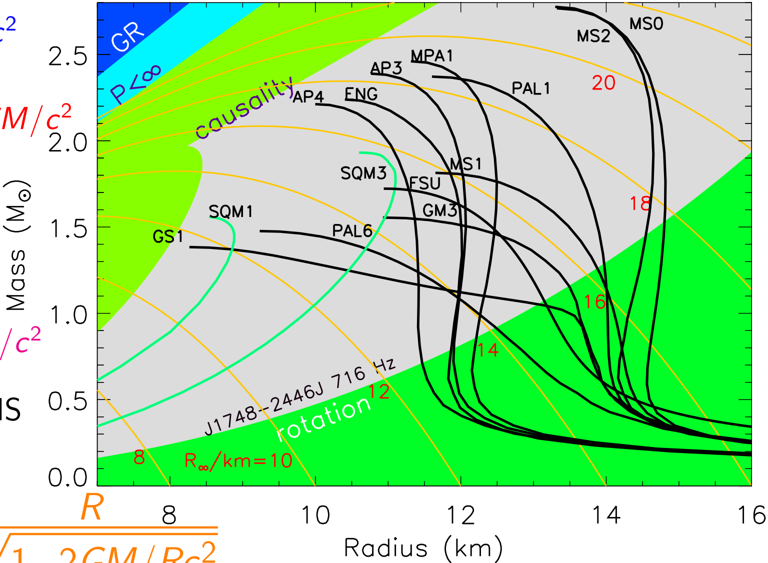
GR:
$R > 2GM/c^2$

$P < \infty$:
$R > (9/4)GM/c^2$

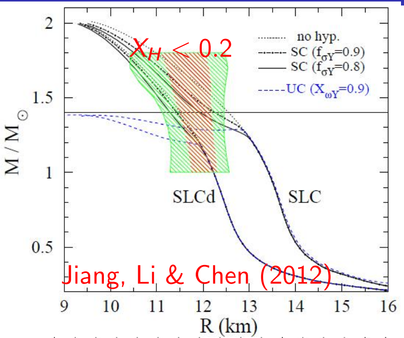
causality:
$R \gtrsim 2.9GM/c^2$

— normal NS
— SQS

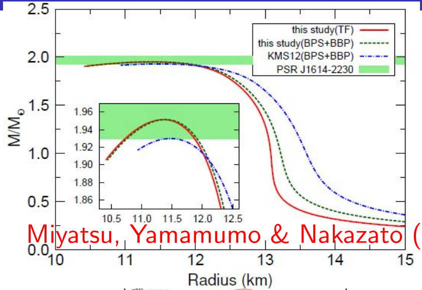
— $R_\infty = \frac{R}{\sqrt{1-2GM/Rc^2}}$



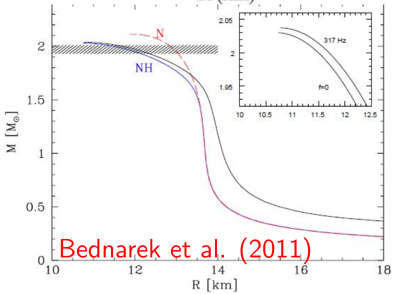
Can Hyperons Appear in Abundance in Neutron Stars?



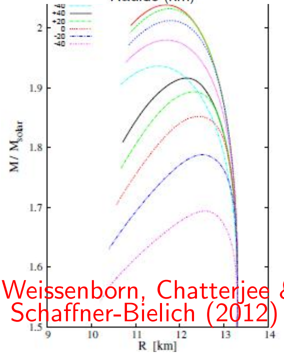
Jiang, Li & Chen (2012)



Miyatsu, Yamamumo & Nakazato (2013)

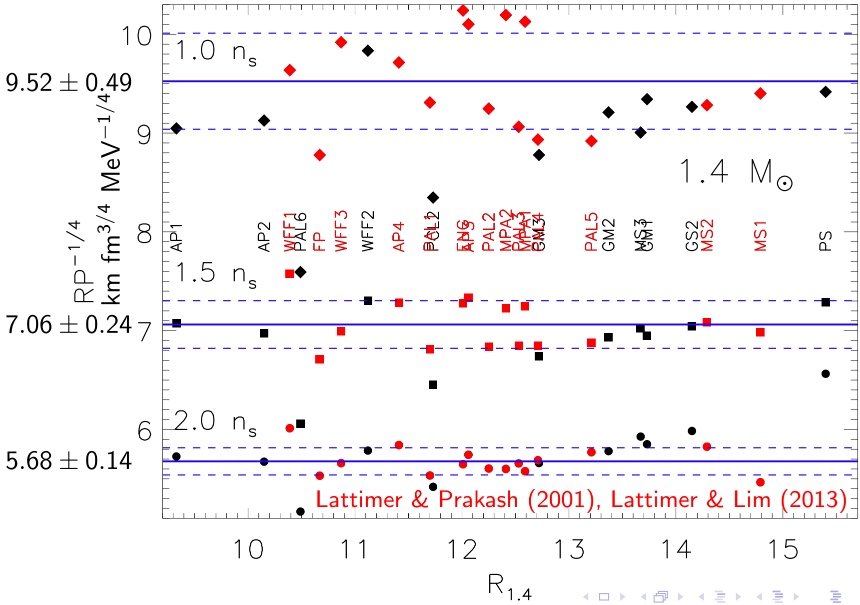


Bednarek et al. (2011)



Weissenborn, Chatterjee & Schaffner-Bielich (2012)

The Radius – Pressure Correlation



Nuclear Symmetry Energy

Defined as the difference between energies of pure neutron matter ($x = 0$) and symmetric ($x = 1/2$) nuclear matter.

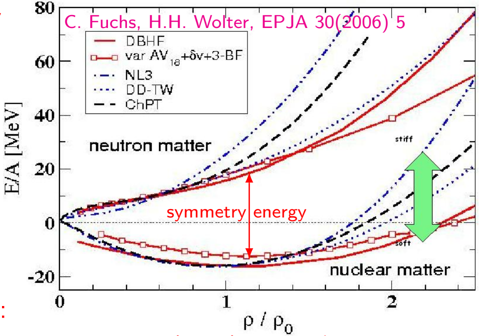
$$S(\rho) = E(\rho, x = 0) - E(\rho, x = 1/2)$$

Expanding around the saturation density (ρ_s) and symmetric matter ($x = 1/2$)

$$E(\rho, x) = E(\rho, 1/2) + (1 - 2x)^2 S_2(\rho) + \ldots$$

$$S_2(\rho) = \mathbf{S_v} + \frac{\mathbf{L}}{3}\frac{\rho - \rho_s}{\rho_s} + \ldots$$

$$\mathbf{S_v} \simeq 31 \text{ MeV}, \quad \mathbf{L} \simeq 50 \text{ MeV}$$



Connections to pure neutron matter:

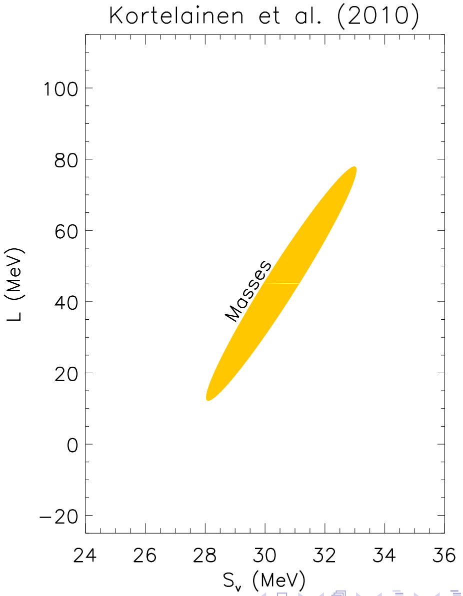
$$E(\rho_s, 0) \approx S_v + E(\rho_s, 1/2) \equiv S_v - B, \qquad p(\rho_s, 0) = L\rho_s/3$$

Neutron star matter (in beta equilibrium):

$$\frac{\partial(E + E_e)}{\partial x} = 0, \quad p(\rho_s, x_\beta) \simeq \frac{L\rho_s}{3}\left[1 - \left(\frac{4S_v}{\hbar c}\right)^3 \frac{4 - 3S_v/L}{3\pi^2\rho_s}\right]$$

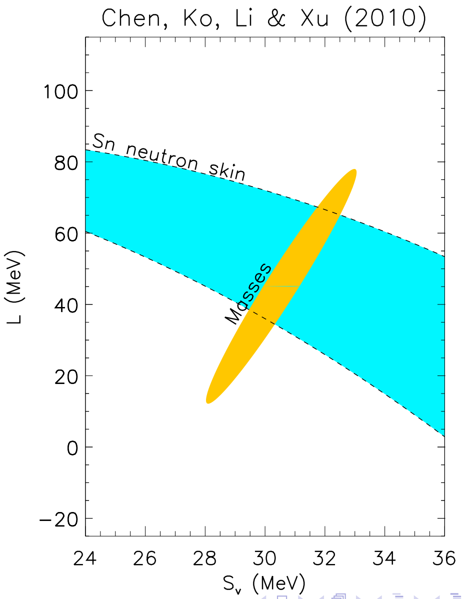
Nuclear Experimental Constraints

Binding Energies



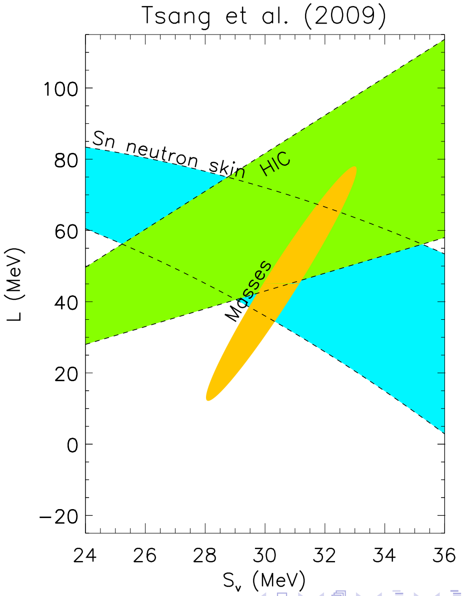
Nuclear Experimental Constraints

Neutron Skins



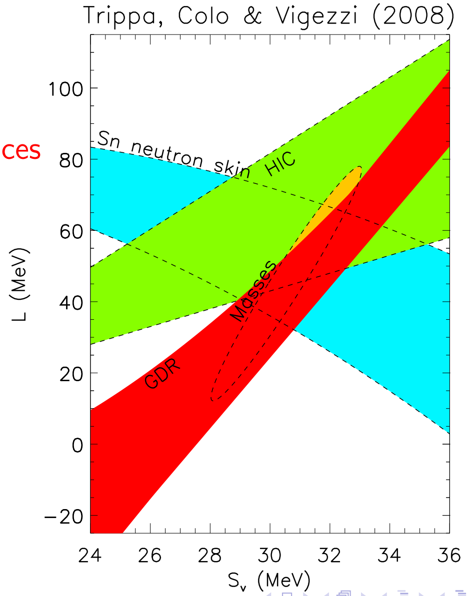
Nuclear Experimental Constraints

Flows in
Heavy Ion Collisions



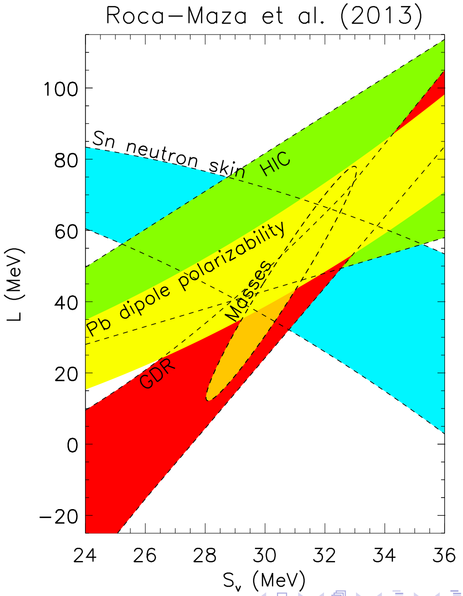
Nuclear Experimental Constraints

Giant Dipole Resonances



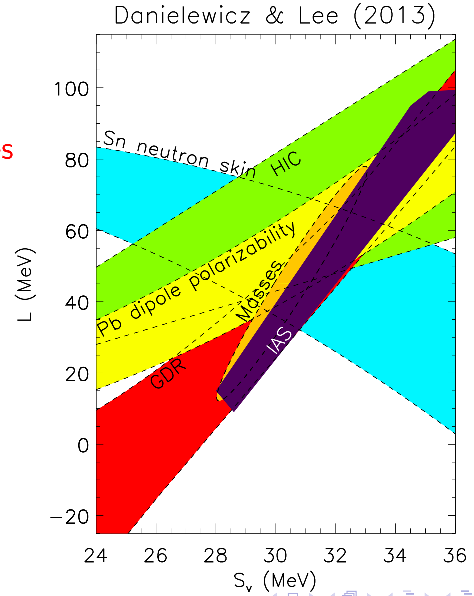
Nuclear Experimental Constraints

Dipole Polarizabilities



Nuclear Experimental Constraints

Isobaric Analog States

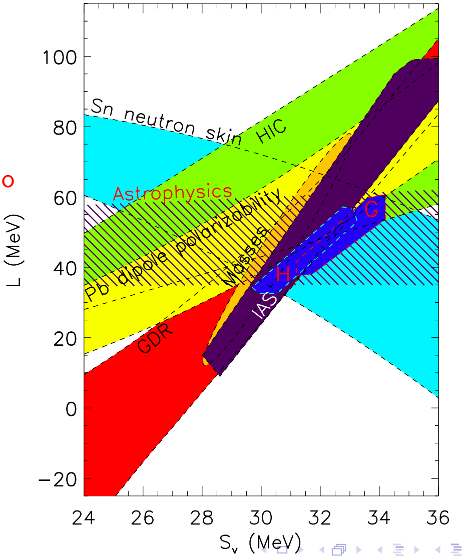


Theoretical Neutron Matter Calculations

H&S: Chiral Lagrangian

GC&R: Quantum Monte Carlo

Gandolfi, Carlson & Reddy (2011);
Hebeler & Schwenk (2011)



Consensus Experimental Constraints

H&S: Chiral Lagrangian

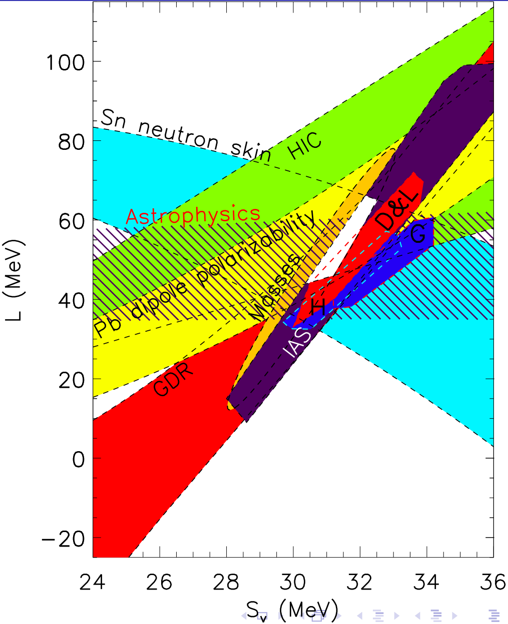
GC&R: Quantum Monte Carlo

D&L: IAS + neutron skin

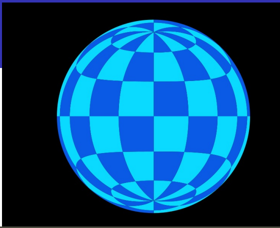
$r_{np} = 0.179 \pm 0.023$ fm

white: all experimental

$r_{np} = 0.175 \pm 0.020$ fm



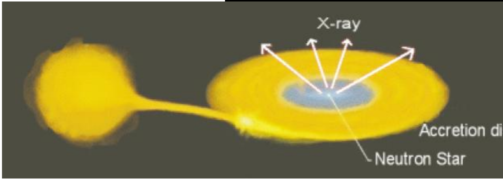
Simultaneous Mass/Radius Measurements



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

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

- Observational uncertainties include distance D, interstellar absorption N_H, atmospheric composition

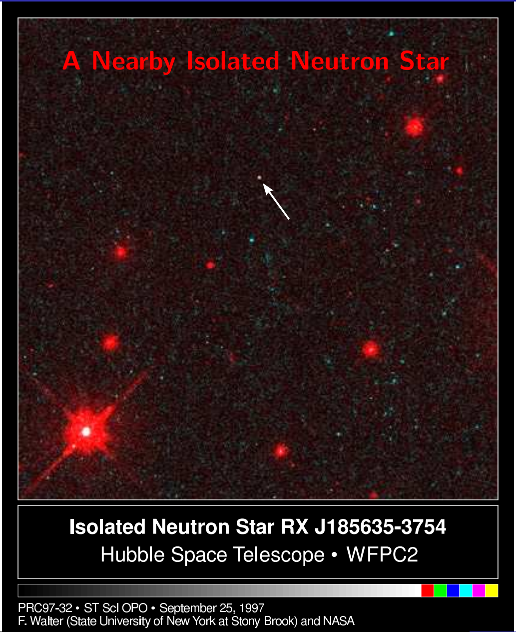


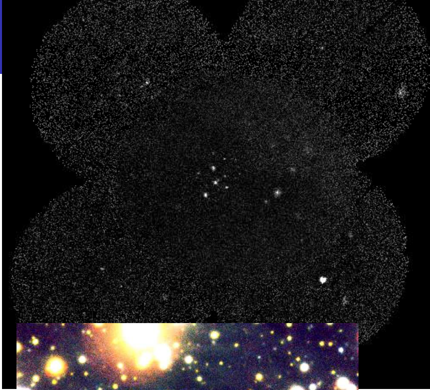
Best chances for accurate radius measurement:

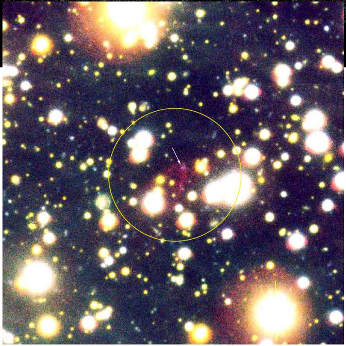
- Nearby isolated neutron stars with parallax (uncertain atmosphere)
- Quiescent low-mass X-ray binaries (QLMXBs) in globular clusters (reliable distances, low B H-atmosperes)
- Bursting sources (XRBs) with peak fluxes close to Eddington limit (where gravity balances radiation pressure)

$$F_{\rm Edd} = \frac{cGM}{\kappa D^2}\sqrt{1-2GM/Rc^2}$$

RX J1856-3754



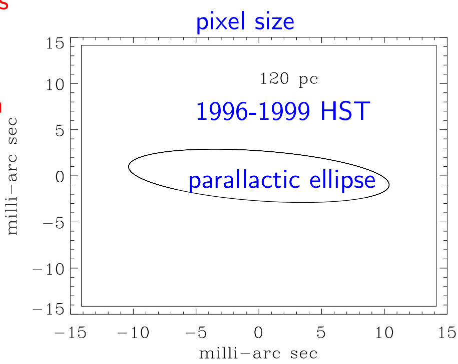




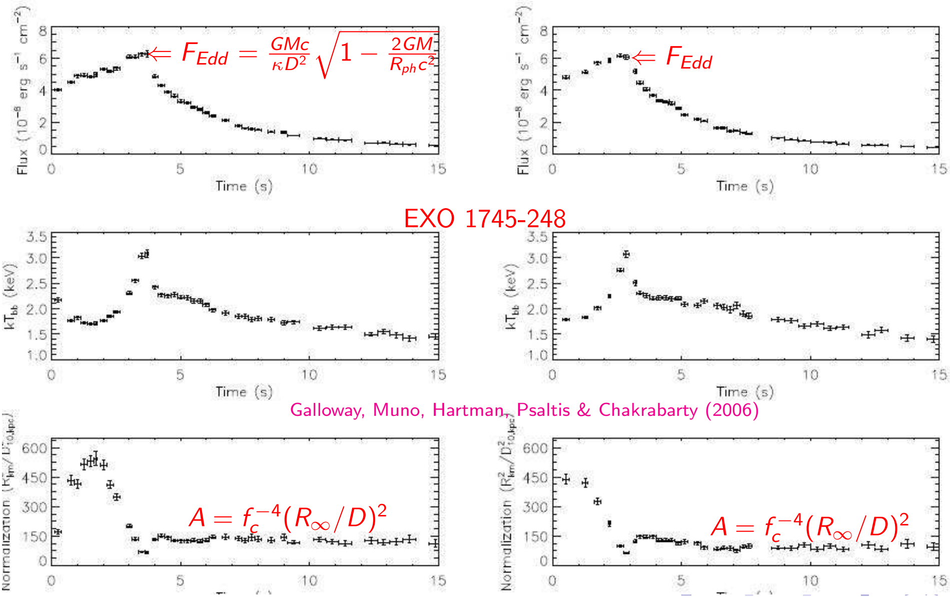
A Bowshock Nebula Near the Neutron Star RX J1856.5-3754 (Detail)
(VLT KUEYEN + FORS2)

Astrometry of RXJ 1856-3754

- Walter & Lattimer (2002) determined $D = 117 \pm 12$ pc and $v \simeq 190$ km/s from 1996-1999 HST Planetary Camera observations
- Star's age is probably 0.5 million years
- Walter et al. (2010) determined $D \simeq 115 \pm 8$ pc based on 2002-2004 HST Advanced Camera for Surveys observations (double the resolution)
- A two-temperature black body fit gives $R_\infty \simeq 13 - 15$ km.
- A magnetic hydrogen atmosphere model (Ho et al. 2007) gives $R \approx 14$ km and $M \approx 1.3 M_\odot$.
- Redshift or gravity measurements, which would allow more precise M and R determinations, are not yet possible.



Photospheric Radius Expansion X-Ray Bursts



PRE Burst Models

Ozel et al. $z_{\rm ph} = z$ $\beta = GM/Rc^2$ Steiner et al. $z_{\rm ph} << z$

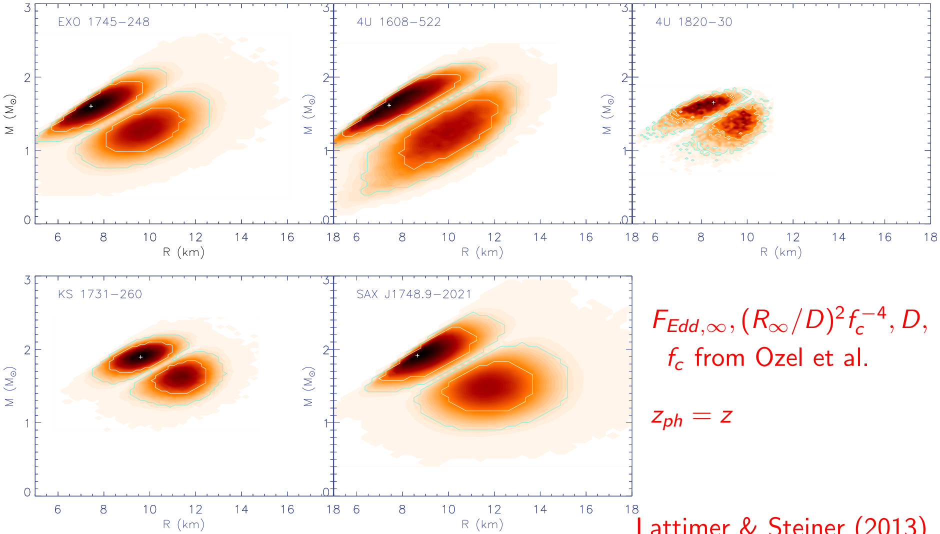
$$\begin{aligned}
F_{\rm Edd} &= \frac{GMc}{\kappa D}\sqrt{1-2\beta} \\
A &= \frac{F_\infty}{\sigma T_\infty^4} = f_c^{-4}\left(\frac{R_\infty}{D}\right)^2 \\
\alpha &= \frac{F_{\rm Edd}}{\sqrt{A}}\frac{\kappa D}{F_c^2 c^3} = \beta(1-2\beta) \\
\gamma &= \frac{Af_c^4 c^3}{\kappa F_{\rm Edd}} = \frac{R_\infty}{\alpha} \\
\beta &= \frac{1}{4} \pm \frac{1}{4}\sqrt{1-8\alpha} \\
\alpha &\le \frac{1}{8} \text{ required.}
\end{aligned}$$

$$\begin{aligned}
F_{\rm Edd} &= \frac{GMc}{\kappa D} \\
\alpha &= \beta\sqrt{1-2\beta} \\
\theta &= \cos^{-1}\left(1-54\alpha^2\right) \\
\beta &= \frac{1}{6}\left[1+\sqrt{3}\sin\left(\frac{\theta}{3}\right)\right. \\
&\quad \left.-\cos\left(\frac{\theta}{3}\right)\right] \\
\alpha &\le \sqrt{\frac{1}{27}} \simeq 0.192 \text{ required.}
\end{aligned}$$

α

EXO 1745-248	4U 1608-522	4U 1820-30	KS 1731-260	SAX J1748.9-2021
0.188 ± 0.035	0.247 ± 0.058	0.235 ± 0.04	0.199 ± 0.032	0.177 ± 0.036

$M - R$ PRE Burst Estimates

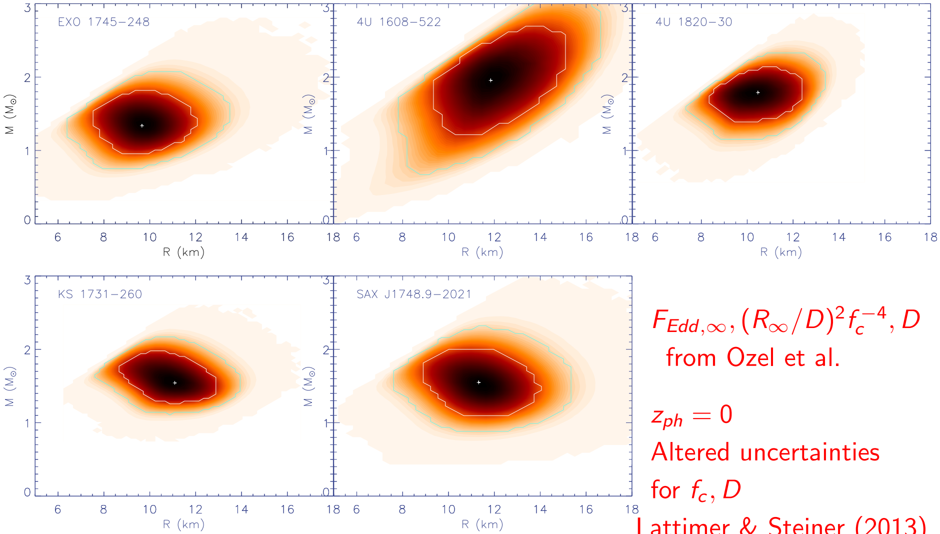


$F_{Edd,\infty}, (R_\infty/D)^2 f_c^{-4}, D,$
f_c from Ozel et al.

$z_{ph} = z$

Lattimer & Steiner (2013)

$M - R$ PRE Burst Estimates



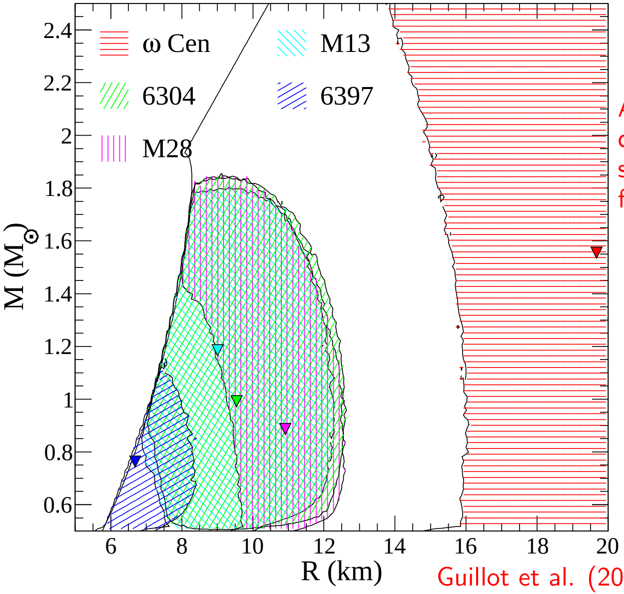
$F_{Edd,\infty}, (R_\infty/D)^2 f_c^{-4}, D$ from Ozel et al.

$z_{ph} = 0$

Altered uncertainties for f_c, D

Lattimer & Steiner (2013)

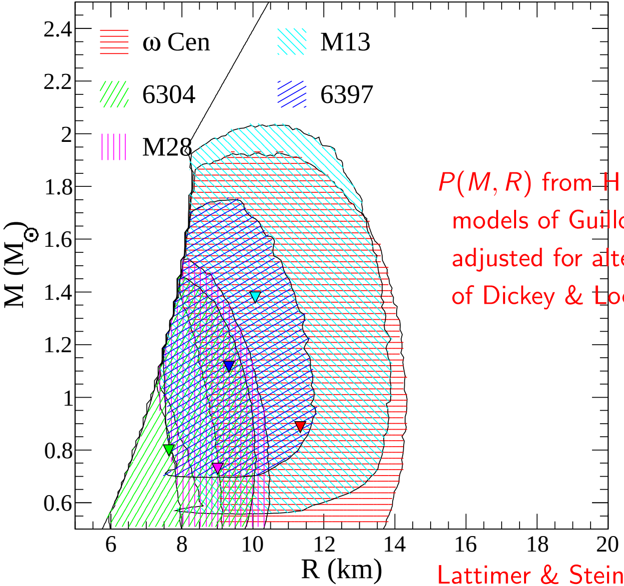
$M - R$ QLMXB Estimates



Absorption (N_H) determined self-consistently from spectra

Guillot et al. (2013)

$M - R$ QLMXB Estimates

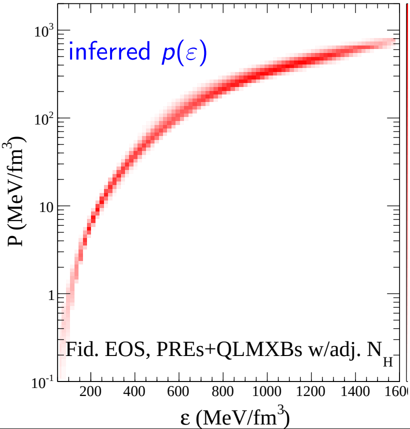


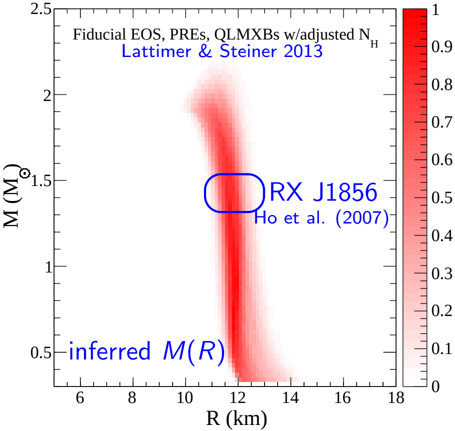
$P(M, R)$ from H atmosphere models of Guillot et al. (2013), adjusted for alternate N_H values of Dickey & Lockman (1990)

Lattimer & Steiner (2013)

Bayesian TOV Inversion

- $\varepsilon < 0.5\varepsilon_0$: Known crustal EOS
- $0.5\varepsilon_0 < \varepsilon < \varepsilon_1$: EOS parametrized by K, K', S_v, γ
- Polytropic EOS: $\varepsilon_1 < \varepsilon < \varepsilon_2$: n_1; $\varepsilon > \varepsilon_2$: n_2
- EOS parameters $K, K', S_v, \gamma, \varepsilon_1, n_1, \varepsilon_2, n_2$ uniformly distributed
- $M_{\max} \geq 1.97$ $M_\odot$, causality enforced
- All 10 stars equally weighted





Astronomy vs. Astronomy vs. Physics

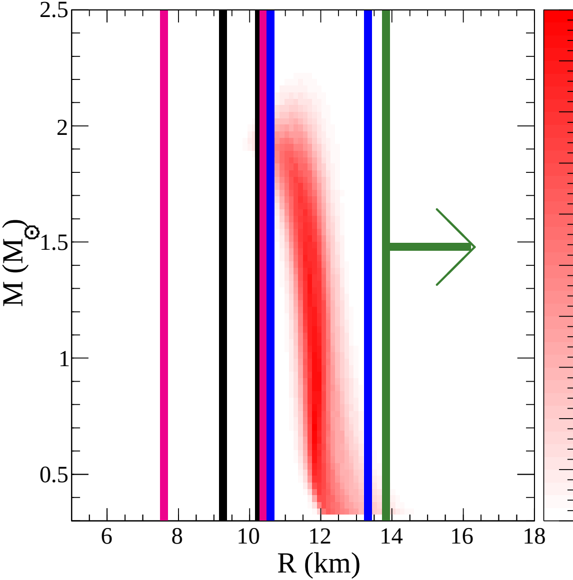
Ozel et al., PRE bursts $z_{\rm ph}$
z: $R = 9.74 \pm 0.50$ km.

Suleimanov et al., long PRE bursts: $R_{1.4} \gtrsim 13.9$ km

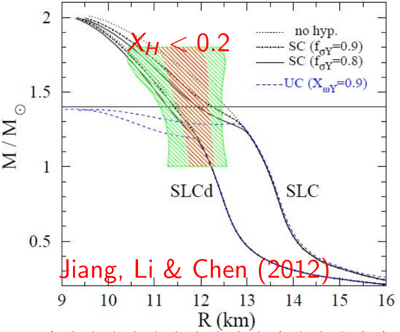
Guillot et al. (2013), all stars have the same radius, self N_H: $R = 9.1^{+1.3}_{-1.5}$ km.

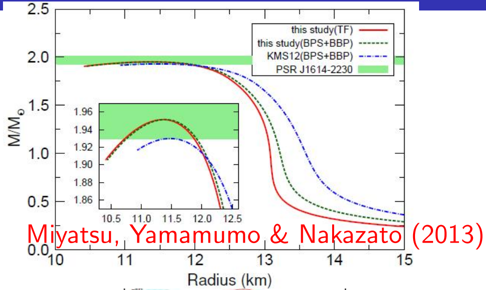
Lattimer & Steiner (2013), TOV, crust EOS, causality, maximum mass $> 2M_\odot$, $z_{\rm ph} = z$, alt N_H.

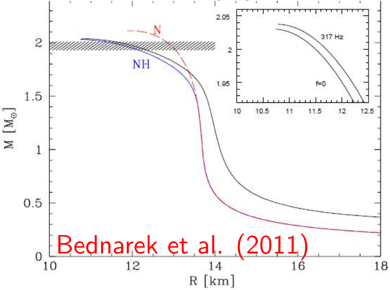
Lattimer & Lim (2013), nuclear experiments:
29 MeV $< S_v <$ 33 MeV,
40 MeV $< L <$ 65 MeV,
$R_{1.4} = 12.0 \pm 1.4$ km.

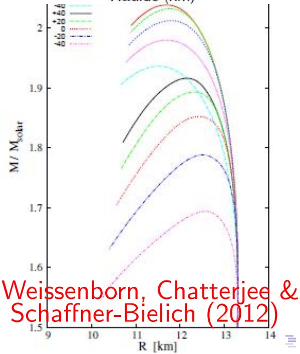


Can Hyperons Appear in Abundance in Neutron Stars?

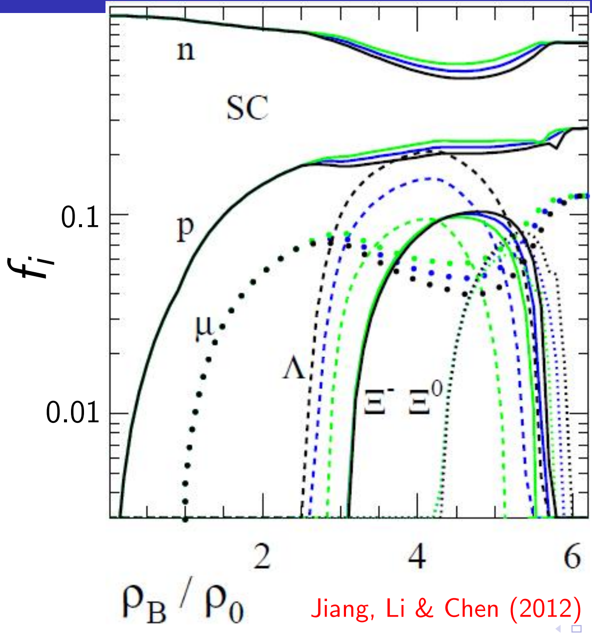






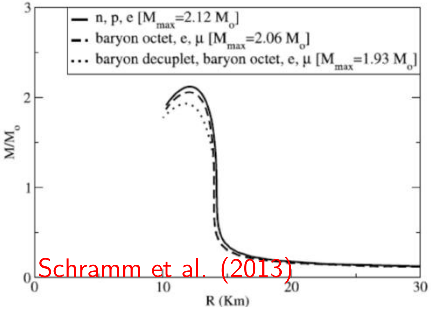


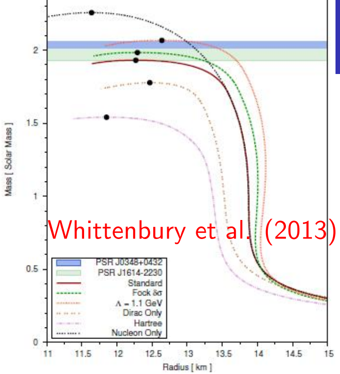
Hyperon Stars with Small Radii

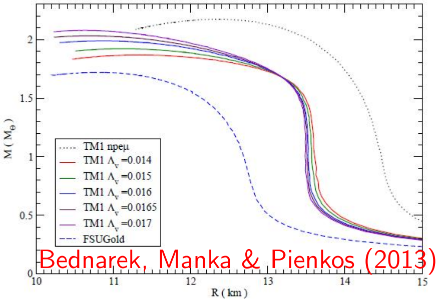


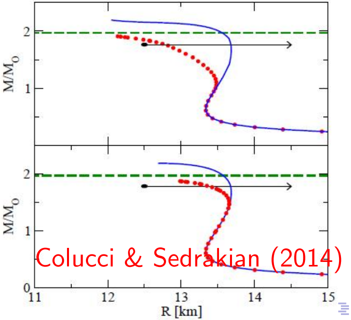
Jiang, Li & Chen (2012)

More Hyperon Stars

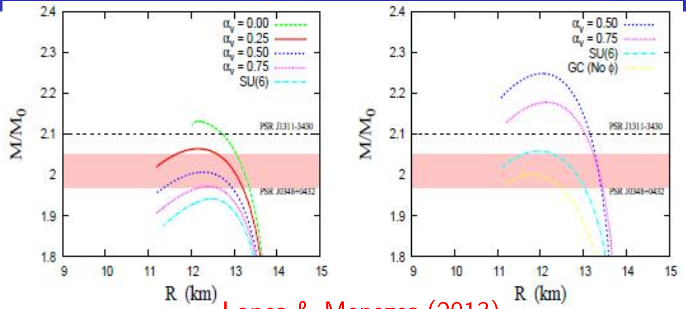




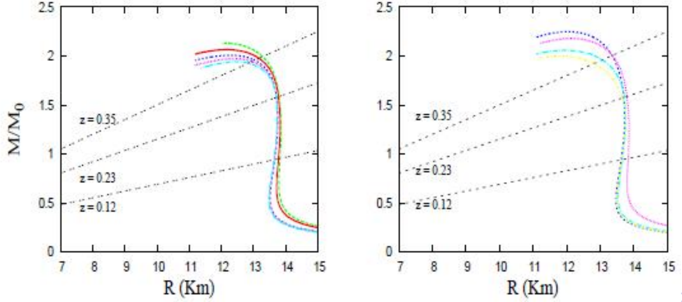




Still More Hyperon Stars



Lopes & Menezes (2013)

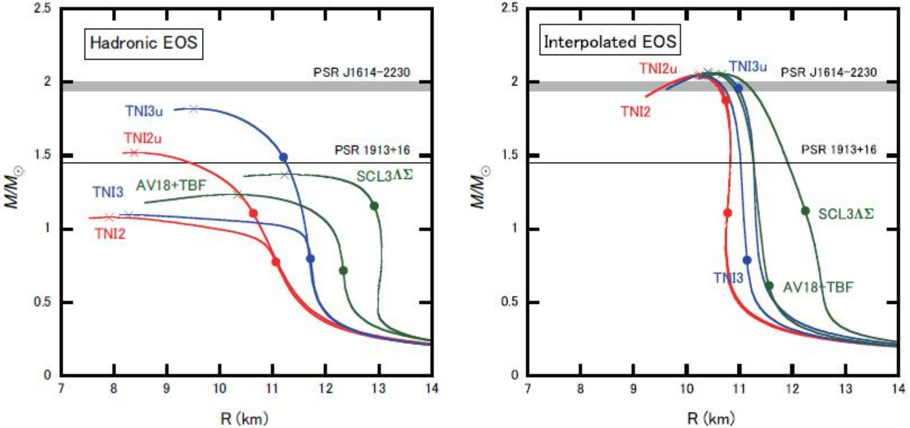


Another Approach – Hadron-Quark Crossover

Replace phase transition with ad-hoc crossover (physical justification?)

$P(\rho) = P_H f_-(\rho) + P_Q f_+(\rho)$

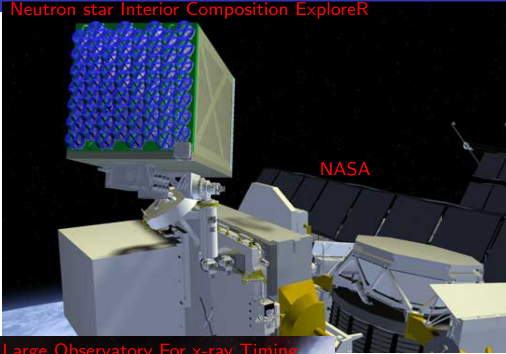
$f_\pm(\rho) = [1 \pm \tanh\{(\rho - \bar{\rho})/\Gamma)\}]/2$



Masuda, Hatsuda & Takatsuka (2012)

Additional Proposed Radius and Mass Constraints

- Pulse profiles
  Hot or cold regions on rotating neutron stars alter pulse shapes: NICER and LOFT will enable timing and spectroscopy of thermal and non-thermal emissions. Light curve modeling $\rightarrow M/R$; phase-resolved spectroscopy $\rightarrow R$.
- Moment of inertia
  Spin-orbit coupling of ultra-relativistic binary pulsars (e.g., PSR 0737+3039) vary i and contribute to $\dot{\omega}$: $I \propto MR^2$.
- Supernova neutrinos
  Millions of neutrinos detected from a Galactic supernova will measure BE$= m_B N - M$, $< E_\nu >$, τ_ν.
- QPOs from accreting sources
  ISCO and crustal oscillations



Constraints from Observations of Gravitational Radiation

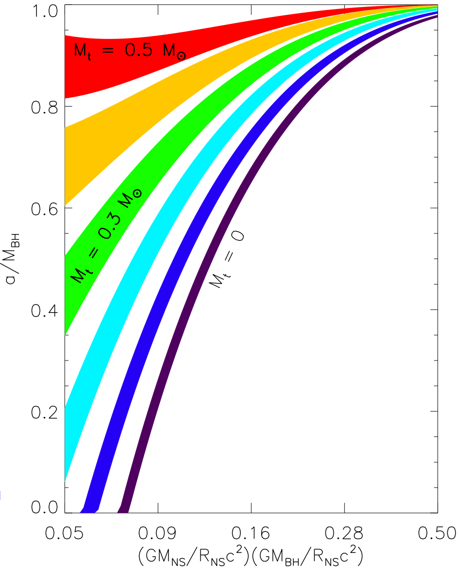
Mergers:

Chirp mass $\mathcal{M} = (M_1 M_2)^{3/5} M^{-1/5}$ and tidal deformability $\lambda \propto R^5$ (Love number) are potentially measurable during inspiral.

$\bar{\lambda} \equiv \lambda M^{-5}$ is related to $\bar{I} \equiv I M^{-3}$ by an EOS-independent relation (Yagi & Yunes 2013). Both $\bar{\lambda}$ and $\bar{I}$ are also related to M/R in a relatively EOS-independent way (Lattimer & Lim 2013).

- Neutron star - neutron star: $M_{\rm crit}$ for prompt black hole formation, $f_{\rm peak}$ depends on R.
- Black hole - neutron star: $f_{\rm tidal\ disruption}$ depends on $R, a, M_{\rm BH}$. Disc mass depends on $a/M_{\rm BH}$ and on $M_{\rm NS} M_{\rm BH} R^{-2}$.

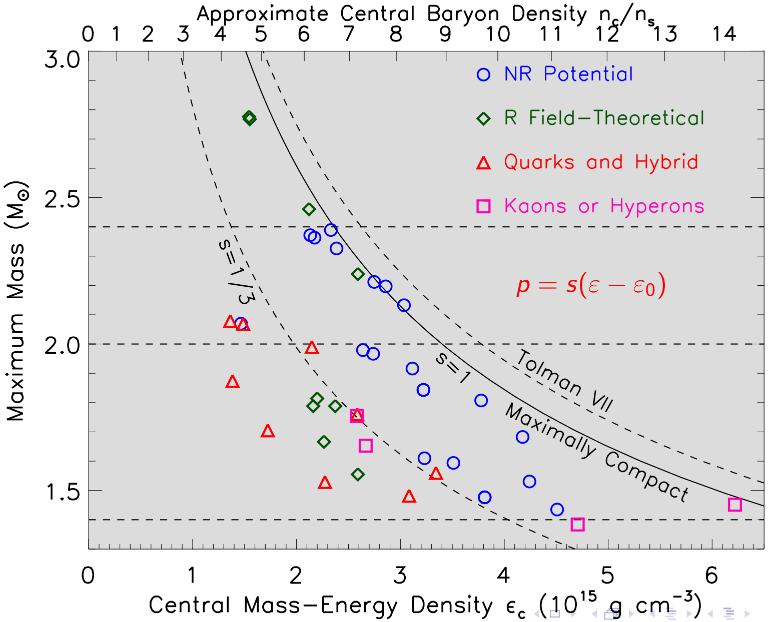
Rotating neutron stars: r-modes



Conclusions

- Nuclear experiments set reasonably tight constraints on symmetry energy parameters and the symmetry energy behavior near the nuclear saturation density.
- Theoretical calculations of pure neutron matter predict very similar symmetry constraints.
- These constraints predict neutron star radii $R_{1.4}$ in the range 12.0 ± 1.4 km.
- Combined astronomical observations of photospheric radius expansion X-ray bursts and quiescent sources in globular clusters suggest $R_{1.4} \sim 12.1 \pm 0.6$ km.
- The nearby isolated neutron star RX J1856-3754 appears to have a radius near 12 km, assuming a solid surface with thin H atmosphere (Ho et al. 2007).
- The observation of a 1.97 $M_{\odot}$ neutron star, together with the radius constraints, implies the EOS above the saturation density is relatively stiff; abundance of hyperons or any phase transition must be small.

Maximum Energy Density in Neutron Stars



Consistency with Neutron Matter and Heavy-Ion Collisions