From Nuclei to Neutron Stars

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Objectives of this talk

- Why basic features such as M & R of a neutron star (NS) are important?
- What are some key theoretical advances made in the recent past?
- How can lab experiments, particularly at JLab, help to unravel the composition & structure of a NS?
- What key NS observations are necessary to take leaps in our understanding?
- Why care? In one object, many fields come together to make discoveries and provide understanding.

Some References

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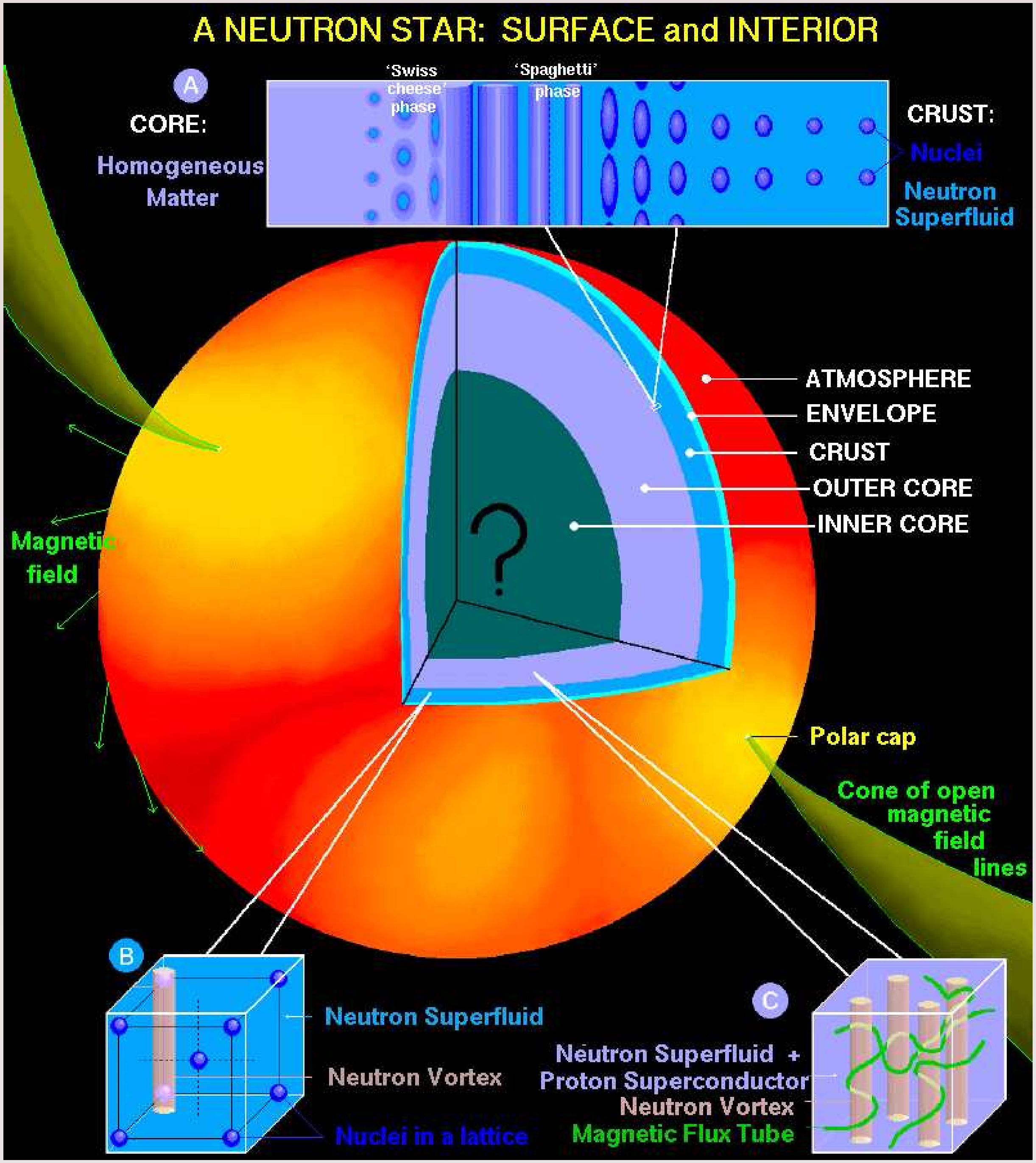
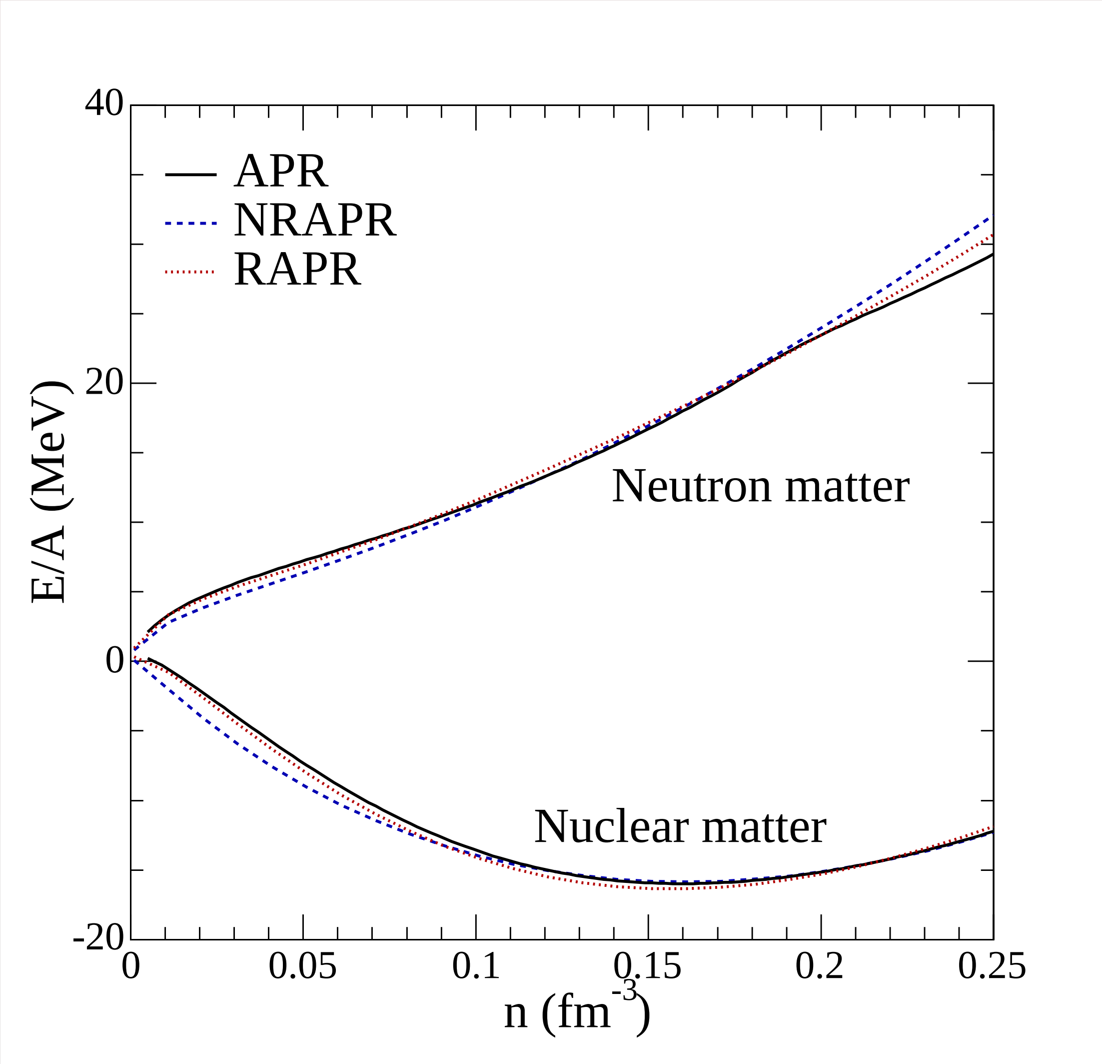


- $M \sim (1-2)M_\odot$
  $M_\odot \simeq 2 \times 10^{33}$ g.
- $R \sim (8-16)$ km
- $\rho > 10^{15}$ g cm^{-3}
- $B_s = 10^9 - 10^{15}$ G.
- Tallest mountain:
  $\sim \frac{E_{liq}}{Am_p g_s} \sim 1$cm
- Atmospheric height:
  $\sim \frac{RT}{\mu g_s} \sim 1$cm

Lattimer & Prakash , Science **304**, 536 (2004).

The Nuclear (A)Symmetry Energy



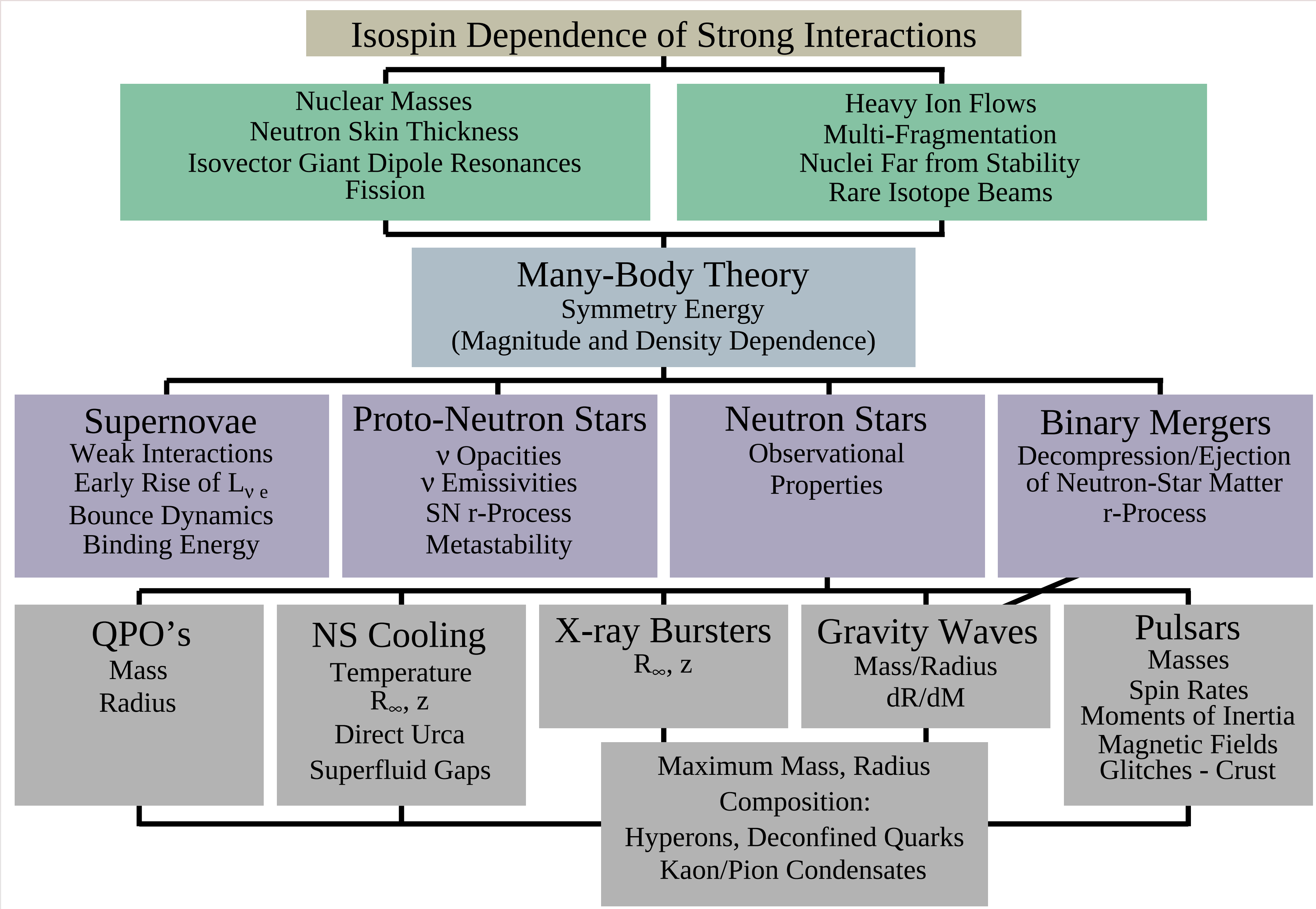
- Energy cost to create an asymmetry (δ) between neutrons and protons

$$\begin{aligned} E_{sym} &= \frac{1}{2n}\frac{d^2\epsilon}{d\delta^2} \\ \delta &= 1 - 2\frac{n_p}{n_p + n_n} \\ &= 1 - 2x \end{aligned}$$

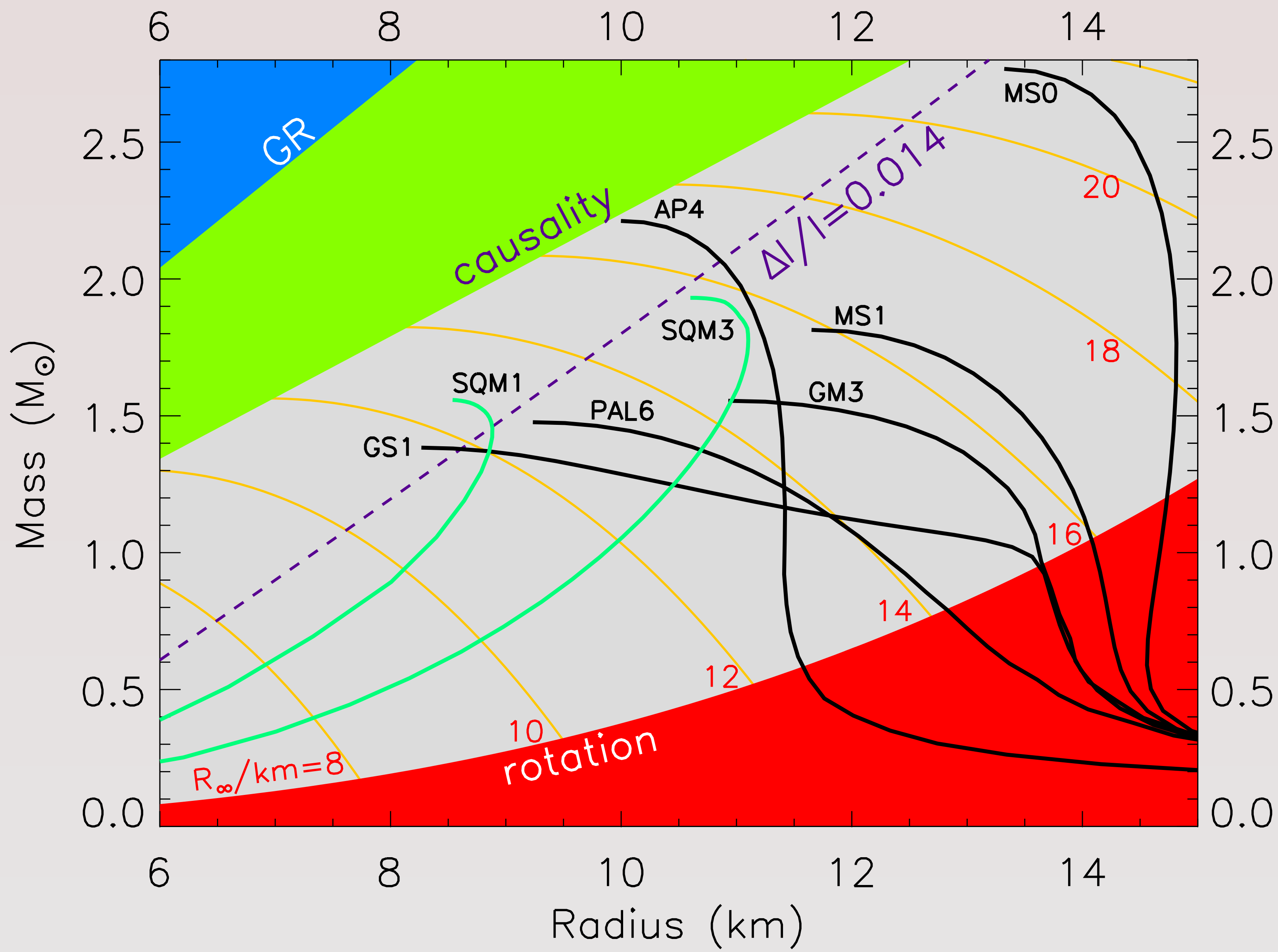
- Structure of nuclei & neutron stars determined by the energy & pressure of beta-stable nucleonic matter

$$\begin{aligned} E(n,x) &\simeq E(n,0.5) + E_{sym}(n)(1-2x)^2 \\ P(n,x) &\simeq n^2[E'(n,0.5) + E'_{sym}(n)(1-2x)^2] \end{aligned}$$

Some Connections



Mass Radius Relationship



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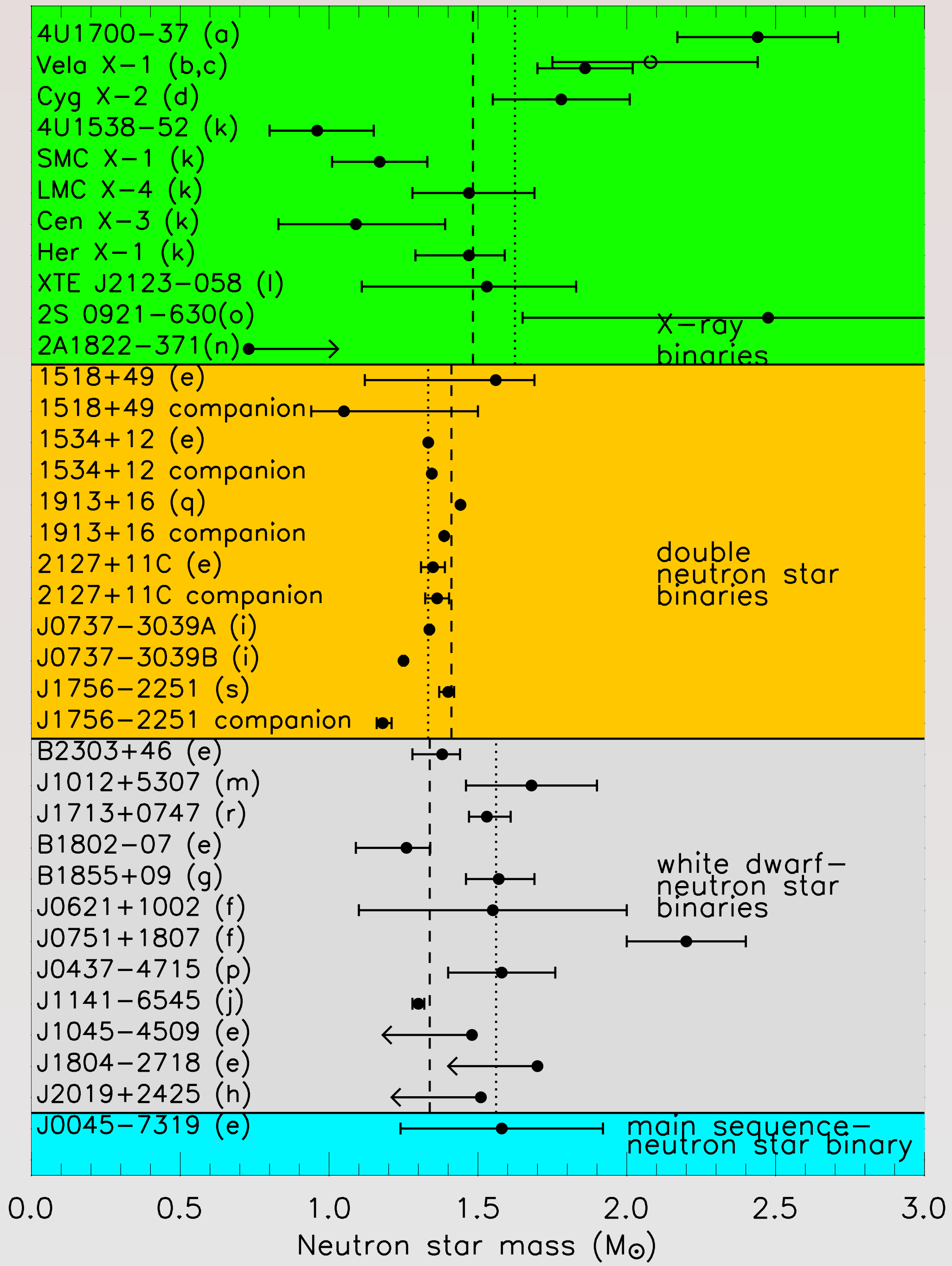
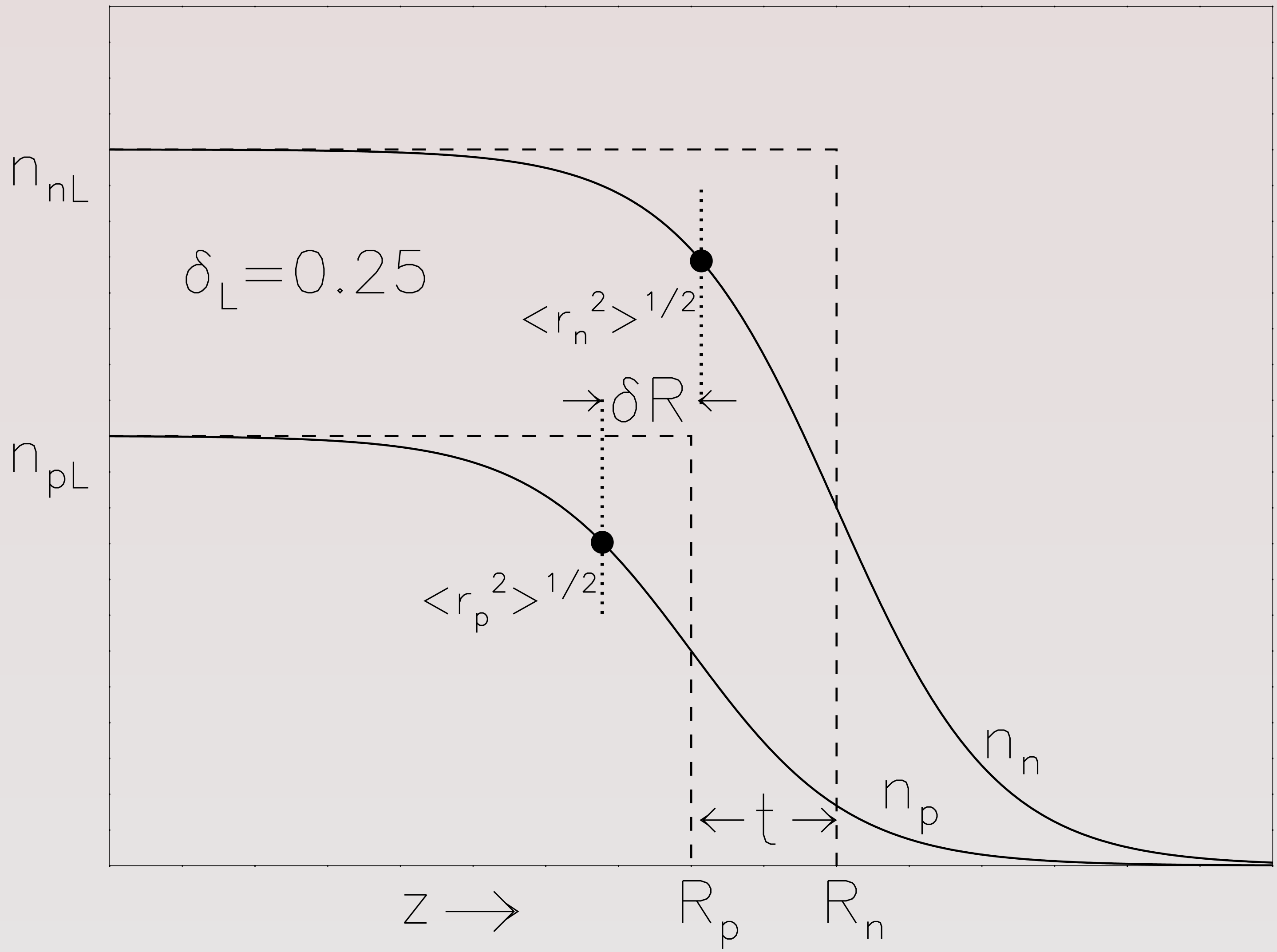
Measured Neutron Star Masses



- Mean & weighted means in $M_\odot$
- X-ray binaries: 1.62 & 1.48
- Double NS binaries: 1.33 & 1.41
- WD & NS binaries: 1.56 & 1.34
- Lattimer & Prakash, PRL, 94 (2005) 111101

The Skin Thickness

Schematic neutron and proton distributions in a neutron-rich nucleus

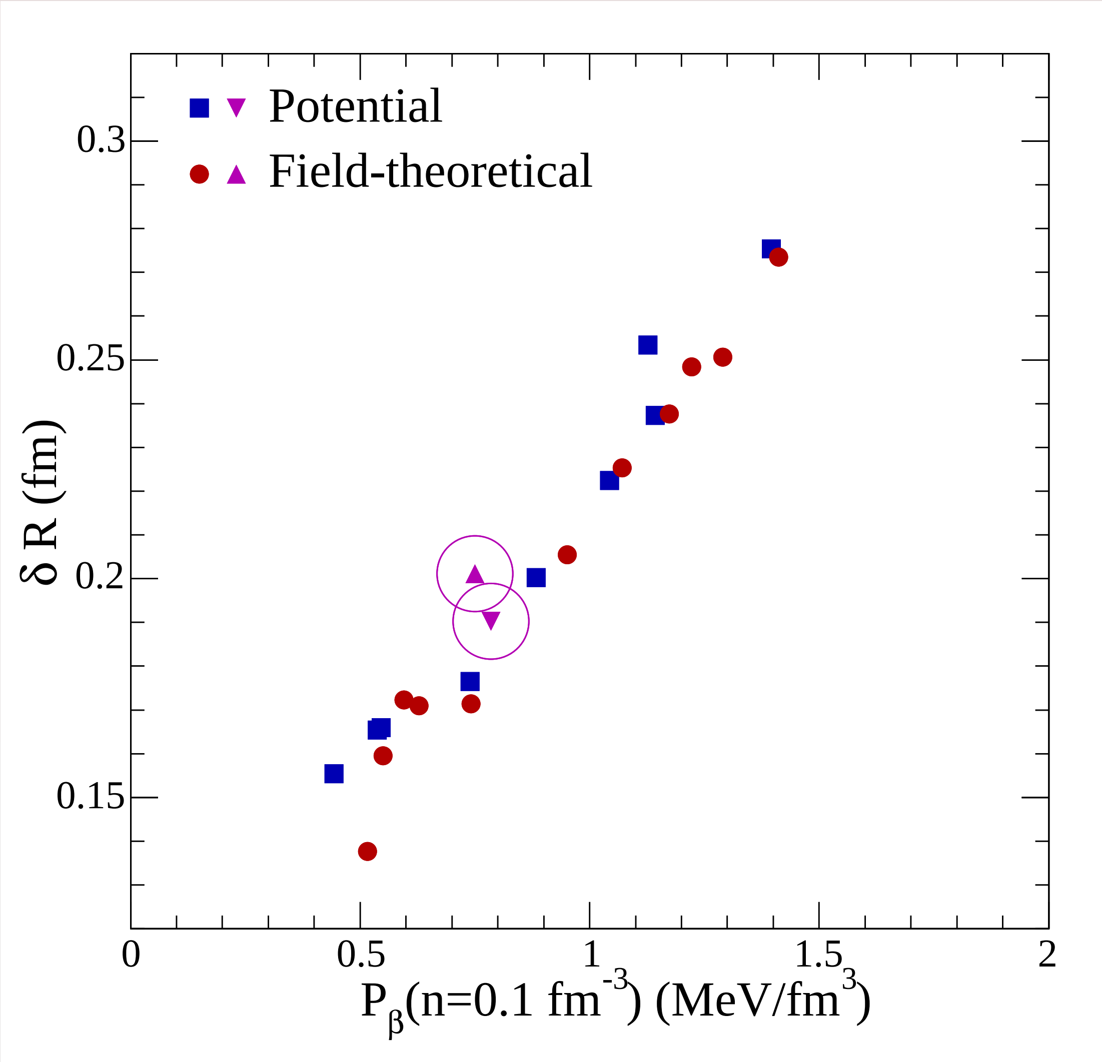


Nuclear charge radii known to better than 0.1%

Neutron-matter radii known poorly! JLab can fix this!!

The Typel-Brown Correlation

Neutron skin thickness vs pressure of subnuclear neutron-star matter



- Nucleus: $^{208}\mathrm{Pb}$
- Neutron skin thickness:

$$\delta R = \langle r_n^2 \rangle^{1/2} - \langle r_p^2 \rangle^{1/2}$$

- Matter Pressure:

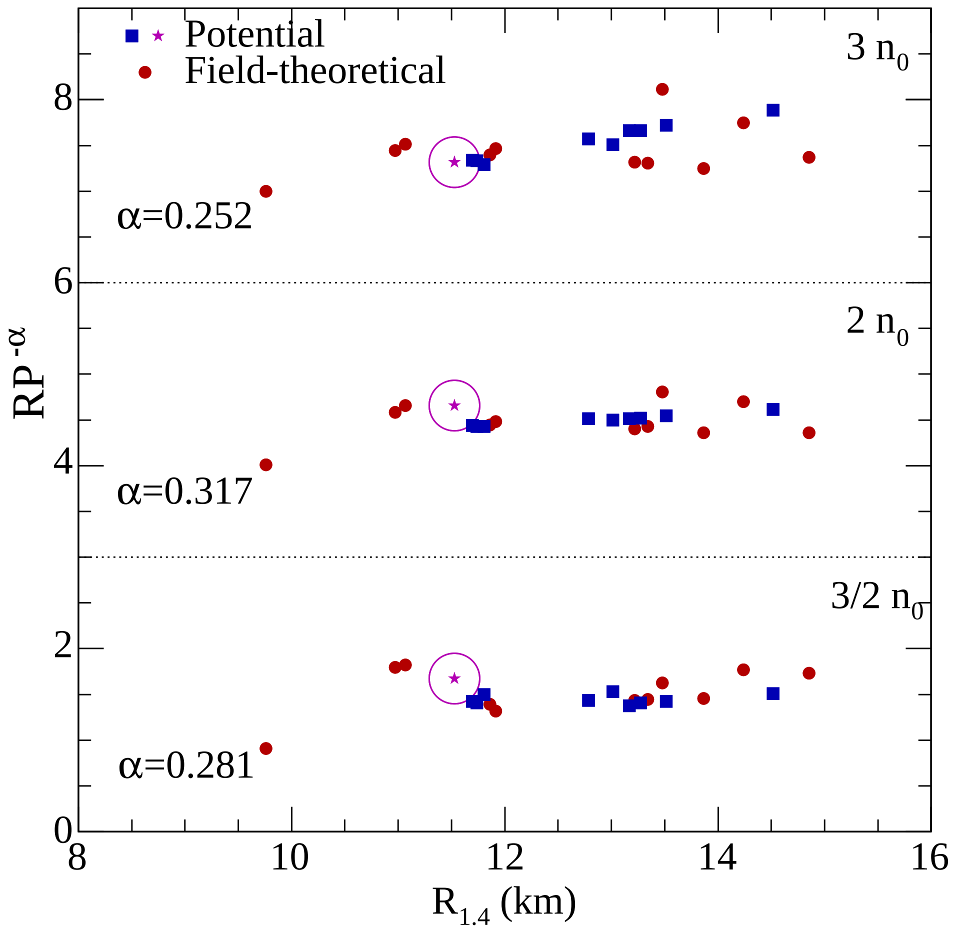
$$P_\beta(n,x) = P_{nuc}(n,x) + P_e + P_\mu$$

- For $\delta R = 0.2 \pm 0.025$ fm, $P_\beta = 0.9 \pm 0.3\ \mathrm{MeV/fm^3}$

Nuclear charge radii known to better than 1%
Neutron-matter radii known poorly! JLab can fix this!!

The Lattimer-Prakash Correlation

Neutron star radius vs pressure of supranuclear neutron-star matter

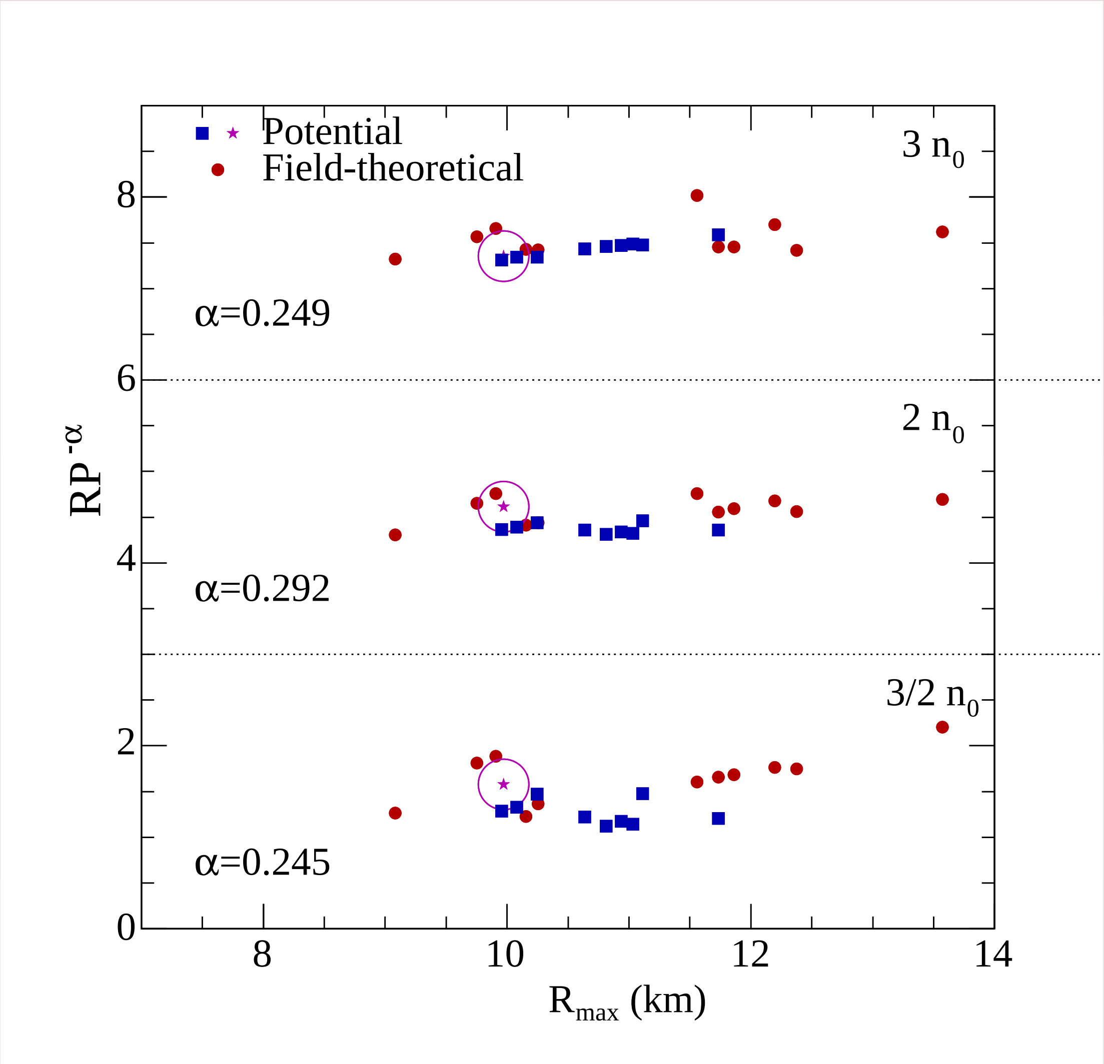


- Radii of 1.4 $M_\odot$ neutron stars from GR structure (TOV) equations
- Pressure from models of neutron-star matter
- Correlation stems from GR & matter properties as analytical studies show

Pressure of neutron-star matter poorly known!
Measurement of neutron-star radii being vigorously pursued!

The Lattimer-Prakash Correlation

Neutron star radius vs pressure of supranuclear neutron-star matter

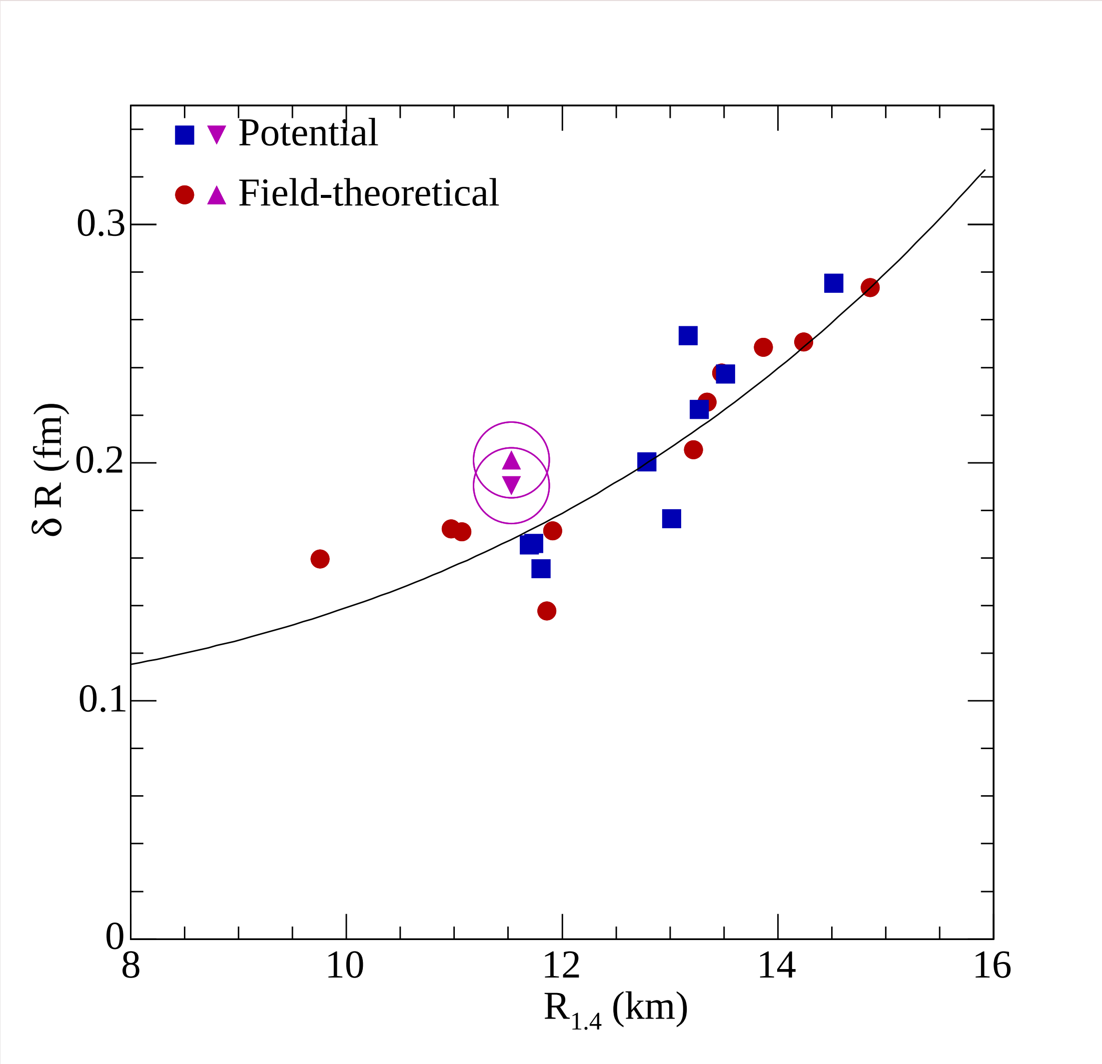


- Radii of maximum mass neutron stars from GR structure (TOV) equations
- Pressure from models of neutron-star matter
- Correlation stems from GR & matter properties as analytical studies show

Pressure of neutron-star matter poorly known!
Measurement of neutron-star radii being vigorously pursued!

The Horowitz-Piekarewicz Correlation

Neutron skin thickness vs neutron star radius

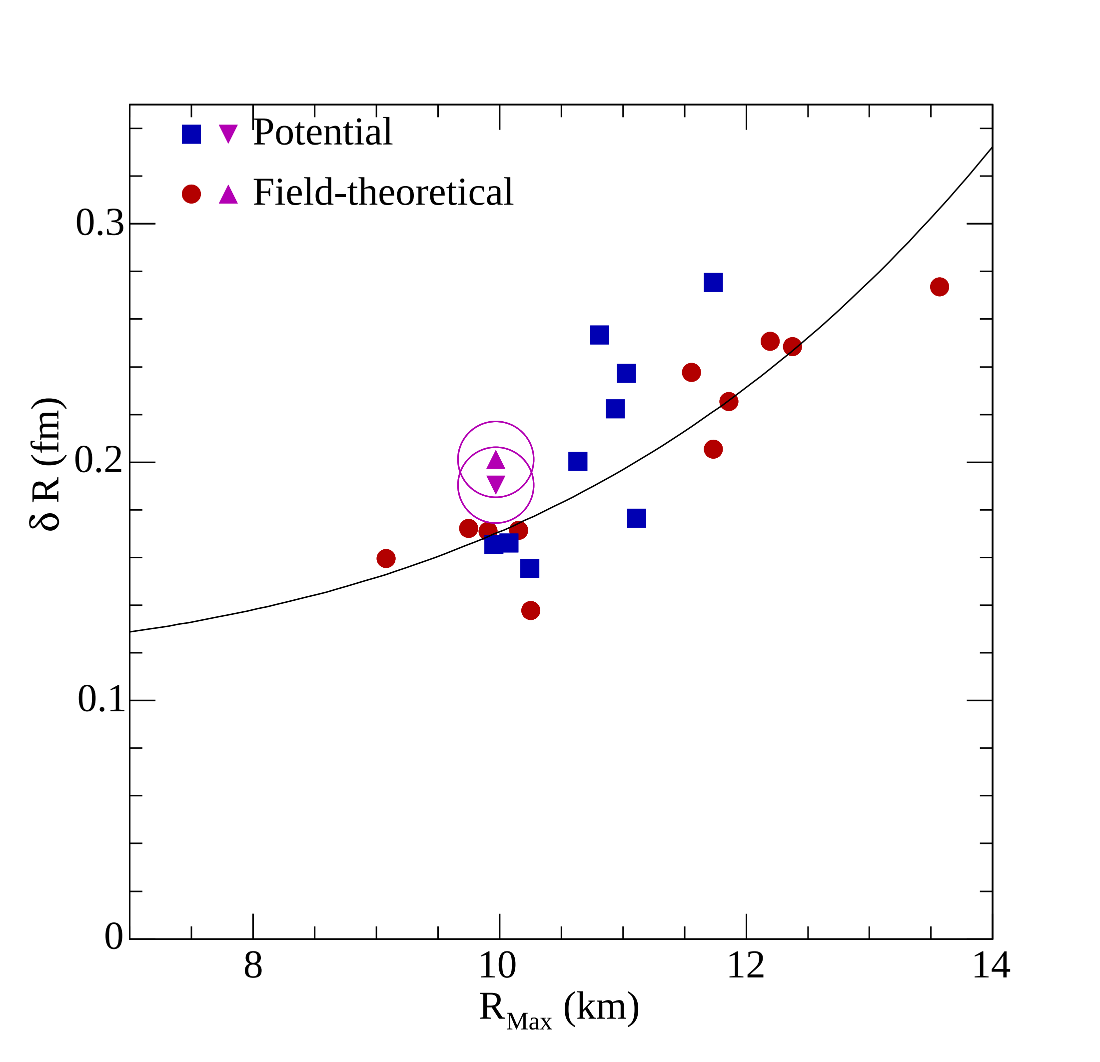


- Radii of 1.4 $M_\odot$ neutron stars from GR structure (TOV) equations
- Skin thicknesses from models of nuclei

For $\delta R = 0.2 \pm 0.025$ fm, $\quad R_{1.4} = 13 \pm 0.5$ km

The Horowitz-Piekarewicz Correlation

Neutron skin thickness vs neutron star radius



- Radii of maximum mass neutron stars from GR structure (TOV) equations
- Skin thicknesses from models of nuclei

For $\delta R = 0.2 \pm 0.025$ fm, $R_{max} = 11 \pm 0.5$ km
Here M_{max} can vary up to 2.2 $M_\odot$

Neutron star radius measurements

Object	R (km)	D (kpc)	Ref
Omega Cen Chandra	13.5 ± 2.1	$5.36 \pm 6\%$	Rutledge et al. ('02)
Omega Cen (XMM)	13.6 ± 0.3	$5.36 \pm 6\%$	Gendre et al. ('02)
M13 (XMM)	12.6 ± 0.4	$7.80 \pm 2\%$	Gendre et al. ('02)
47 Tuc X7 (Chandra)	$14.5^{+1.6}_{-1.4}$ $(1.4\ M_\odot)$	$5.13 \pm 4\%$	Rybicki et al. ('05)
M28 (Chandra)	$14.5^{+6.9}_{-3.8}$	$5.5 \pm 10\%$	Becker et al. ('03)
EXO 0748-676 (Chandra)	13.8 ± 1.8 $(2.10 \pm 0.28\ M_\odot)$	9.2 ± 1.0	Ozel ('06)

Moment of inertia (I) measurements

Spin precession periods:

$$P_{p,i} = \frac{2c^2 a P M (1-e^2)}{G M_{-i}(4M_i + 3M_{-i})} \, .$$

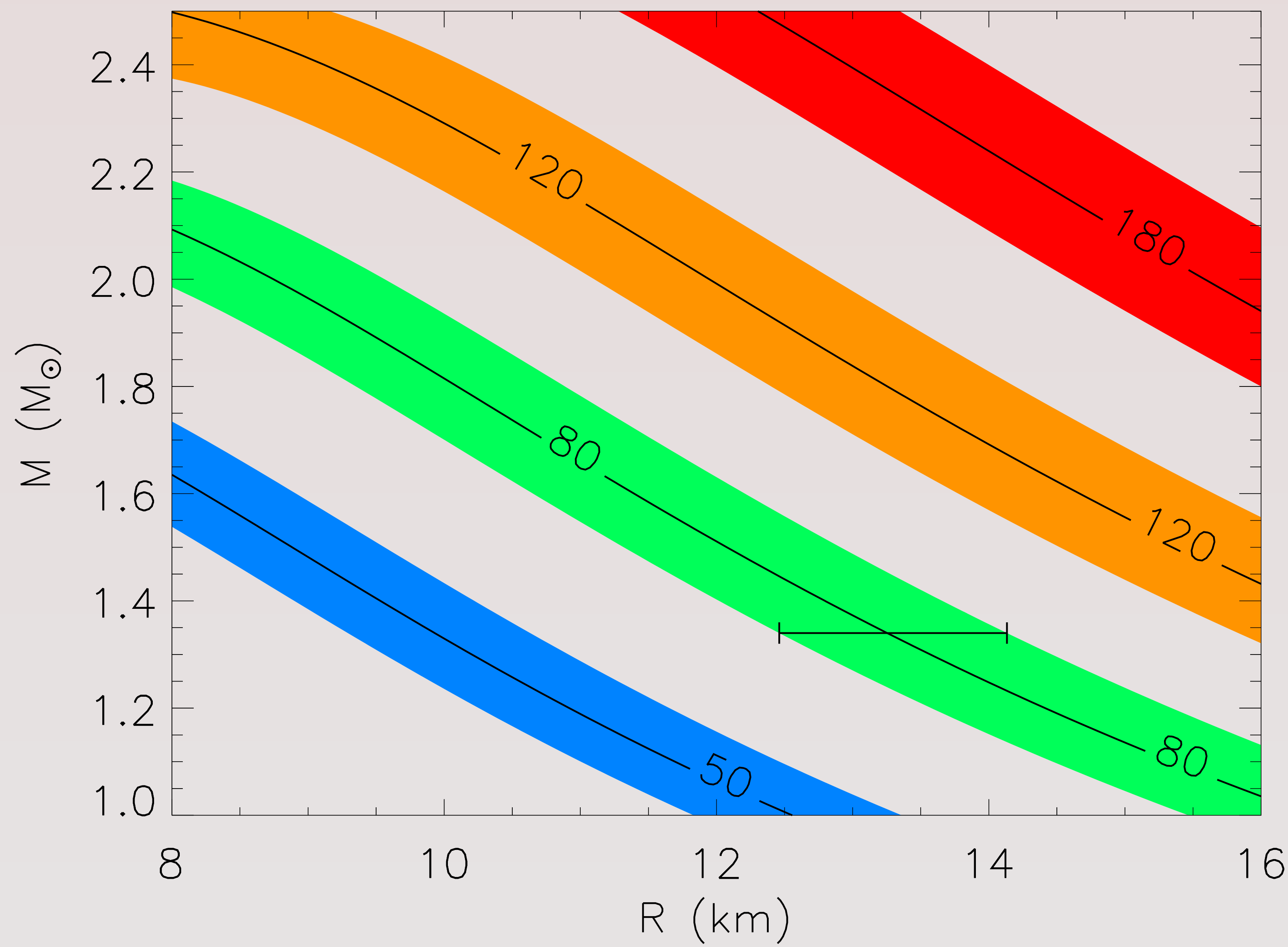
Spin-orbit coupling causes a periodic departure from the expected time-of-arrival of pulses from pulsar A of amplitude

$$\delta t_A = \frac{M_B}{M}\frac{a}{c}\delta_i \cos i = \frac{a}{c}\frac{I_A}{M_A a^2}\frac{P}{P_A}\sin\theta_A \cos i$$

P: Orbital period a: Orbital separation e: Eccentricity
$M = M_1 + M_2$: Total mass
i: Orbital inclination angle θ_A: Angle between $\mathbf{S}_A$ and $\mathbf{L}$.
I_A: Moment of Inertia of A

For PSR 0707-3039, $\delta t_A \simeq (0.17 \pm 0.16) I_{A,80}\ \mu\mathrm{s}$;
Needs improved technology & is being pursued.

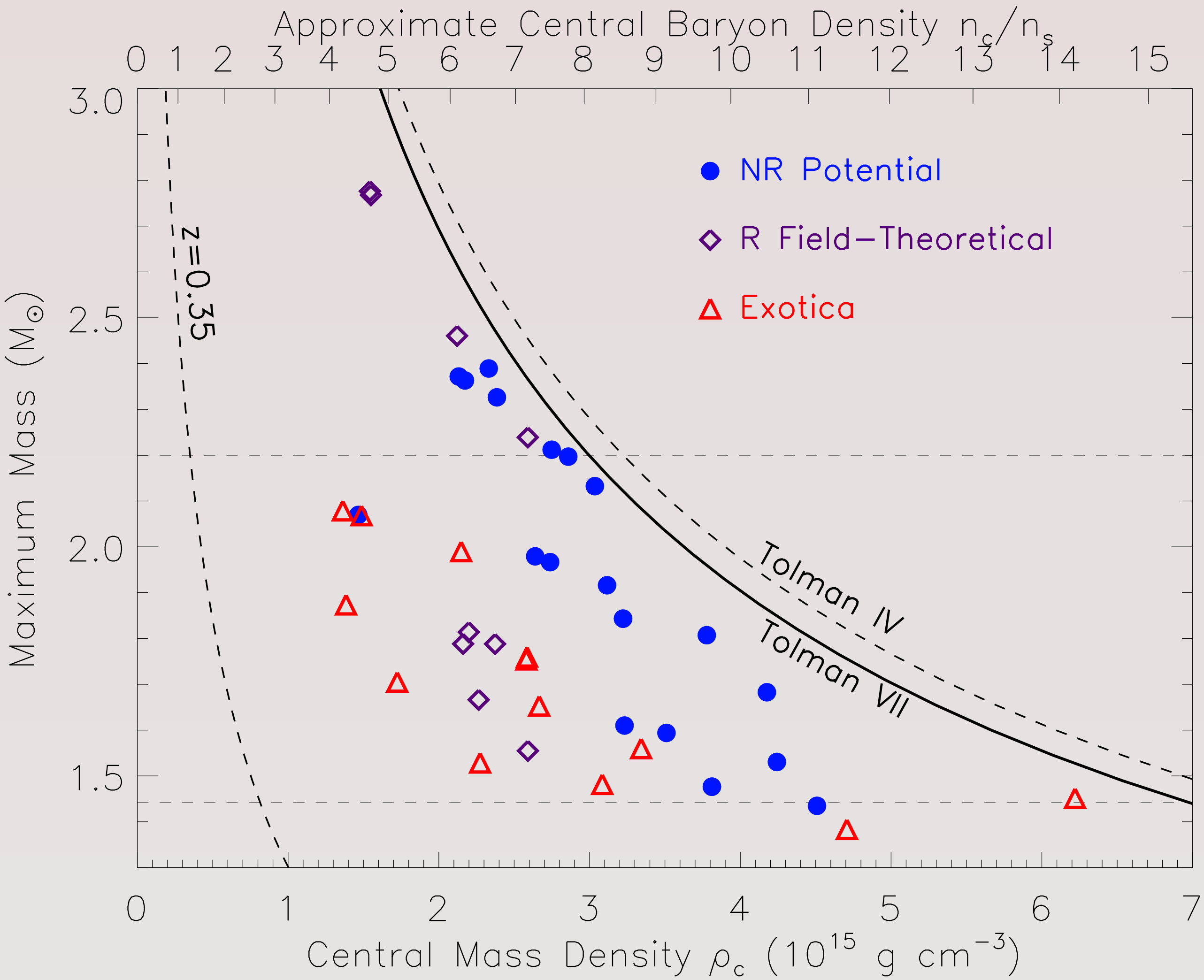
Limits on R from M & I measurements



- 10% error bands on I in M$_\odot$ km^2
- Horizontal error bar for $M = 1.34$ M$_\odot$ & $I = 80 \pm 8$ M$_\odot$ km^2

J. M. Lattimer & B. F. Schutz, Astrophys. Jl. **629** (2005)

Ultimate Energy Density of Cold Matter



- Tolman VII: $\epsilon = \epsilon_c(1-(r/R)^2)$
- $\epsilon_c \propto (M_\odot/M)^2$
- A measured red-shift provides a lower limit.
- **Crucial to establish an upper limit to M_{max}.**

Lattimer & Prakash, PRL, 94 (2005) 111101.

Outlook

- Growing observations of neutron stars can delineate the equation of state (EOS) of neutron-star matter and shed light on the density dependence of the symmetry energy (strong interactions in a many-body context).
- Precise laboratory experiments, particularly those involving neutron-rich nuclei, are sorely needed to pin down the subnuclear aspects of the symmetry energy.
- All power to parity violating electron scattering experiments at JLab to measure the neutron distributions precisely. Besides being the first, it can also be the best!!