From Neutron Skins to Neutron Stars

Phys. Rev. C 84, 064302 (2011)
Phys. Rev. C 86, 015802 (2012)

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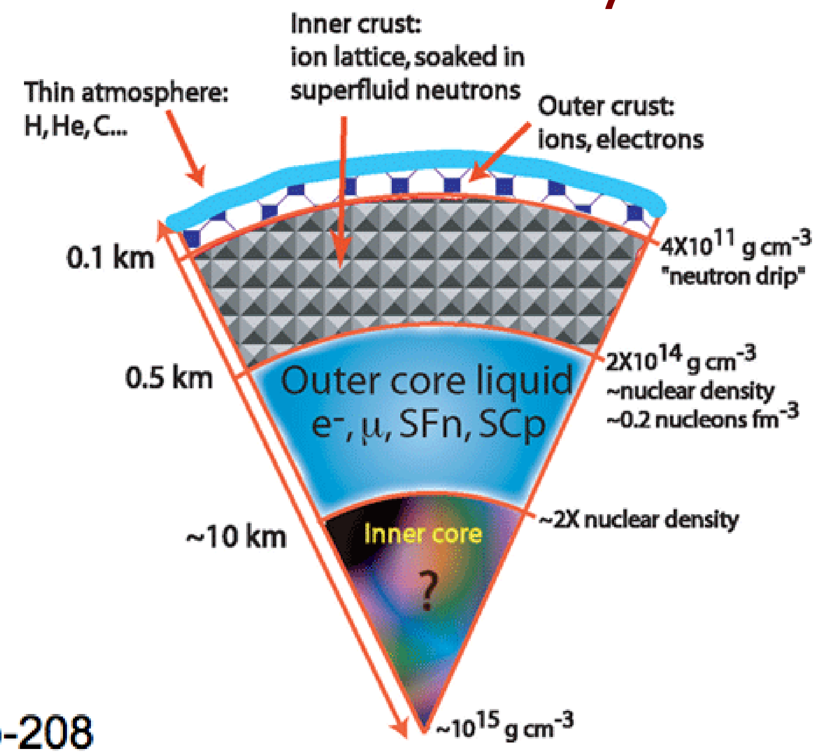
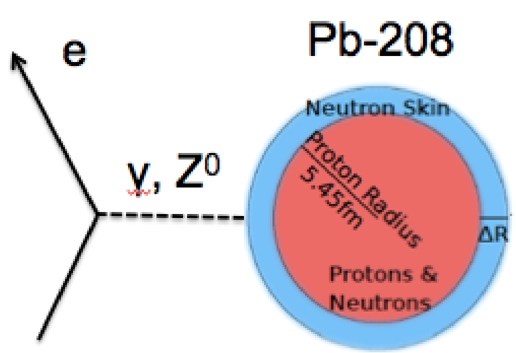
Outline

1. Motivation
2. Relativistic Density Functional and Covariance Analysis
3. Model: FSUGold (RMF)
4. Results:
   (a) Pure Neutron Matter
   (b) Neutron Star Radii
   (c) Direct Urca Process
   (d) Core-Crust Transition
   (e) Stellar Moment of Inertia
5. Conclusions





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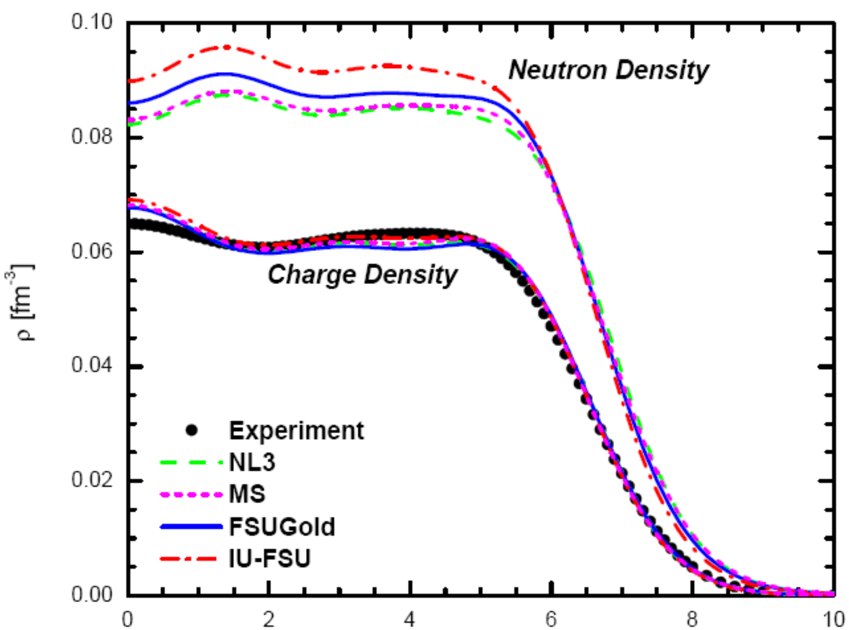
Motivation

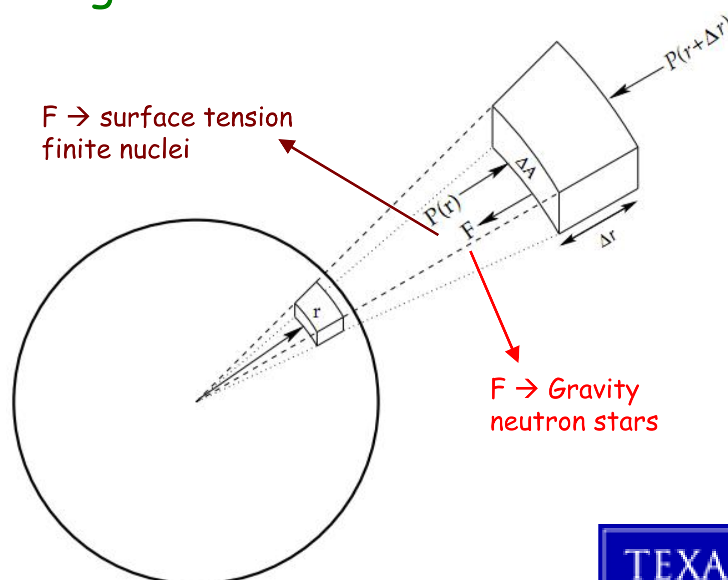
1. The **neutron skin thickness** is highly sensitive to the pressure of pure neutron matter: the greater the pressure, the thicker is the skin as neutrons are pushed out against surface tension; PRL 85, 5296 (2000); PRL 86, 5647 (2000); Nucl. Phys. A 706, 85 (2002);

2. This same pressure supports **neutron stars** against gravity, therefore many neutron star properties are also very sensitive to the pressure of pure neutron matter and density dependence of the symmetry energy.
   PRL 86, 5647 (2000); PRC 64, 062802 (2001); PRC 66, 055803 (2002); ApJ 593, 463 (2003); Phys. Rep. 411, 325 (2005); Nucl. Phys. A 706, 85 (2002); PRC 82, 025810 (2010); etc

3. Correlations between neutron skins of neutron-rich nuclei and various neutron star properties are naturally expected. Our purpose is to provide meaningful theoretical error-bars and to assess the degree of correlation between them;



F. J. Fattoyev, PhD thesis



European Journal of Physics 26, 695 (2005)

Relativistic Density Functional

The effective Lagrangian density:

$$\mathcal{L}_{\rm int} = \bar{\psi}\left[g_{\rm s}\phi - \left(g_{\rm v}V_\mu\gamma^\mu + \frac{g_\rho}{2}\tau\cdot\mathbf{b}_\mu\gamma^\mu\right)\right]\psi - \frac{\kappa}{3!}(g_{\rm s}\phi)^3 - \frac{\lambda}{4!}(g_{\rm s}\phi)^4 + \frac{\zeta}{4!}\left(g_{\rm v}^2 V_\mu V^\mu\right)^2 + \Lambda_{\rm v}\left(g_{\rm v}^2 V_\mu V^\mu\right)\left(g_\rho^2 \mathbf{b}_\mu\cdot\mathbf{b}^\mu\right)$$

scalar-isoscalar

vector-isoscalar

vector-isovector ?

and higher order interactions

Covariance Analysis

PRC 81, 051303 (2010); PRC 84, 064302 (2011); PRC 85, 024304 (2012); PRC 86, 015802 (2012); PRC 87, 014324 (2013)

Model parameters are found by minimizing →

$$\chi^2(\mathbf{p}) = \sum_{n=1}^{N}\left(\frac{\mathcal{O}_n^{(\rm th)}(\mathbf{p}) - \mathcal{O}_n^{(\rm exp)}}{\Delta\mathcal{O}_n}\right)^2$$

Covariance of two observables are found from

$$\mathrm{cov}(A,B) = \sum_{i,j=1}^{F}\frac{\partial A}{\partial x_i}(\hat{\mathcal{M}}^{-1})_{ij}\frac{\partial B}{\partial x_j}$$

where

$$\mathcal{M}_{ij} = \frac{1}{2}\left(\frac{\partial\chi^2}{\partial x_i\partial x_j}\right)_{\rm x=0}$$

Correlation coefficient is

$$\rho(A,B) = \frac{\mathrm{cov}(A,B)}{\sqrt{\mathrm{var}(A)\mathrm{var}(B)}},$$

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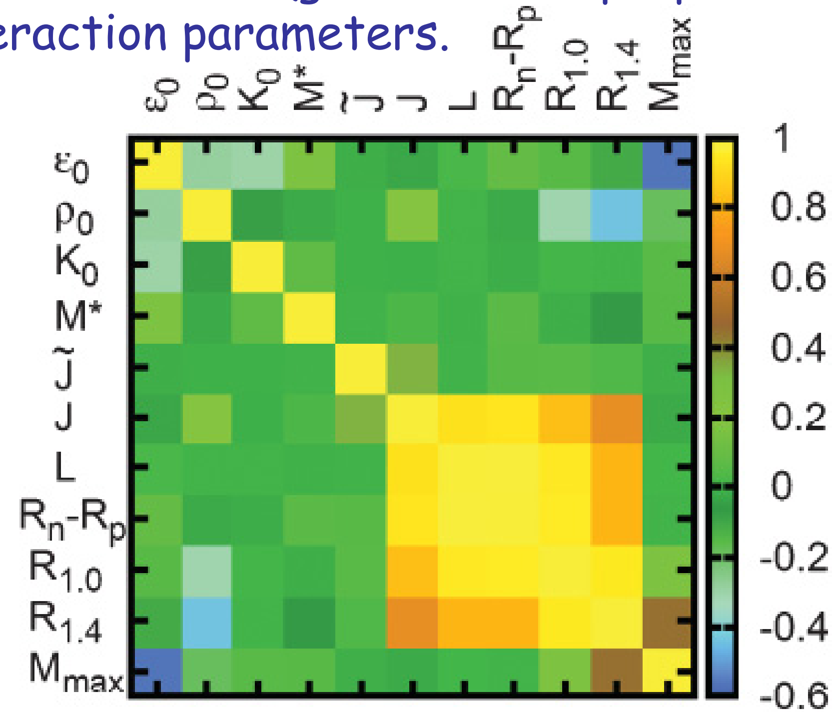
Model: FSUGold

We used an accurately-calibrated FSUGold model (ground state properties, collective excitations, etc) with 7 interaction parameters.

$$\left.\begin{aligned}
\rho_0 &= 0.1484\ \mathrm{fm}^{-3}, \\
\varepsilon_0 &= -16.30\ \mathrm{MeV}, \\
\varepsilon(2\rho_0) &= -5.887\ \mathrm{MeV}, \\
K_0 &= 230.0\ \mathrm{MeV}, \\
M_0^\star &= 0.6100 M, \\
\tilde{J} &= 26.00\ \mathrm{MeV},
\end{aligned}\right\} \text{pseudo-data } 2\%$$

$$\left. L = 60.52\ \mathrm{MeV}, \right\} 20\%$$

$$\left. M_{\max} = 1.722 M_\odot. \right\} 2\%$$



PRC 84, 064302 (2011)

Our result shows that a 20% error in the slope of symmetry energy translates to a neutron skin thickness of

$$\boxed{R_{skin} \equiv R_n - R_p = 0.207 \pm 0.037\ fm}$$

which corresponds to about a 0.7% uncertainty in the neutron radius of 208Pb.

Compare with 48Ca: $\boxed{R_{skin} \equiv R_n - R_p = 0.197 \pm 0.019\ fm}$

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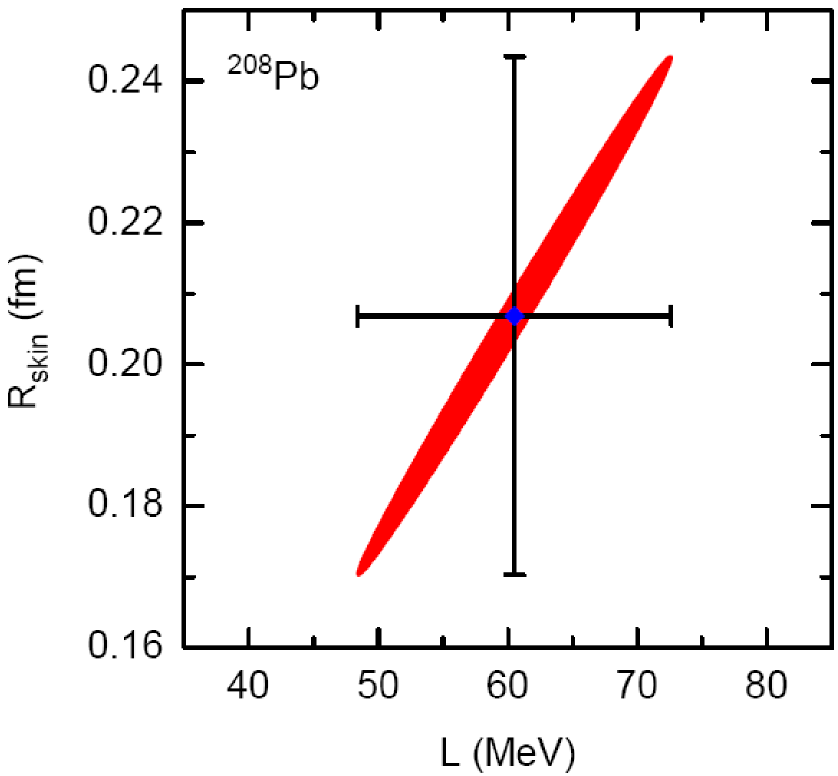

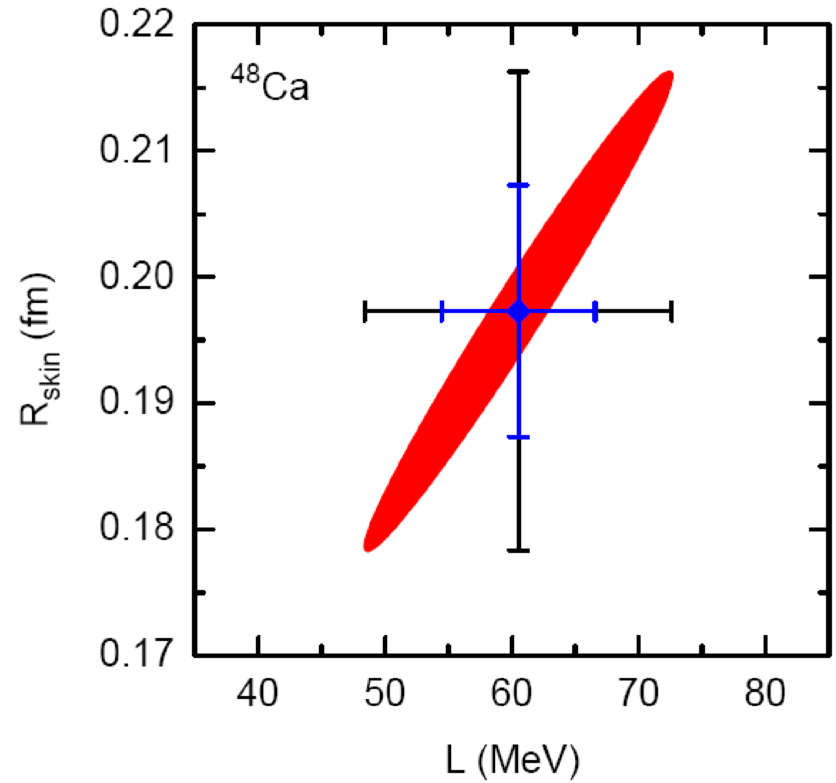

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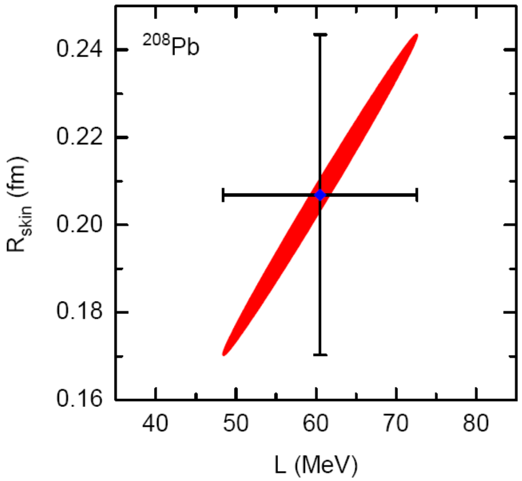

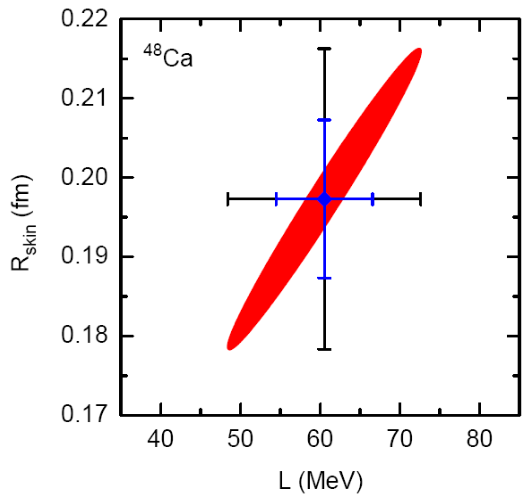

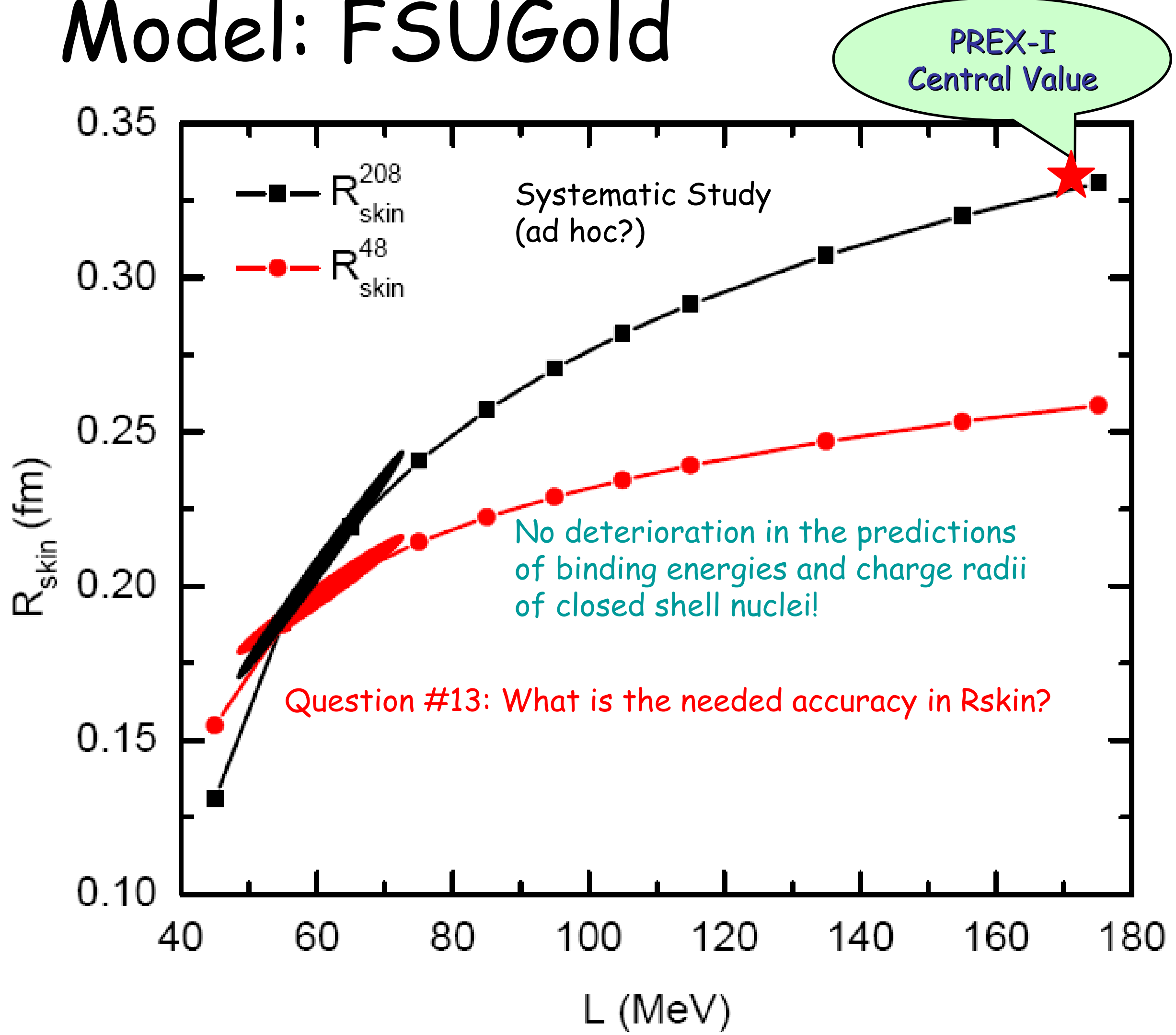

$$R_{skin} \equiv R_n - R_p = 0.207 \pm 0.037\ fm$$

Not necessarily the same error-bars if used different models!

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Compare with 48Ca: $$R_{skin} \equiv R_n - R_p = 0.197 \pm 0.019\ fm$$

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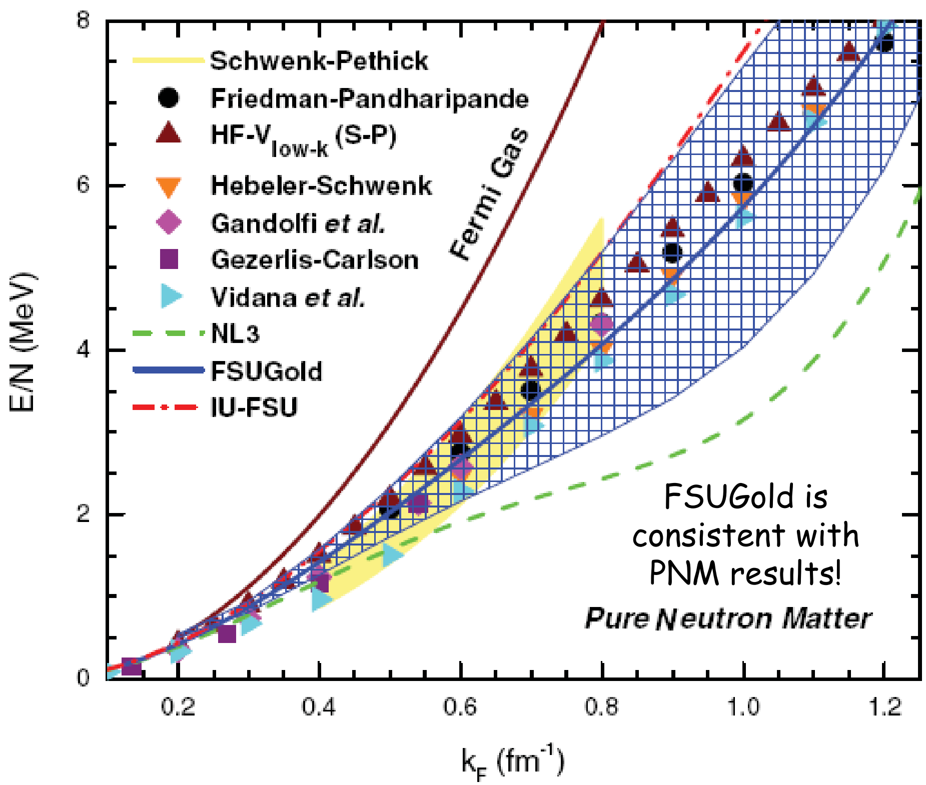
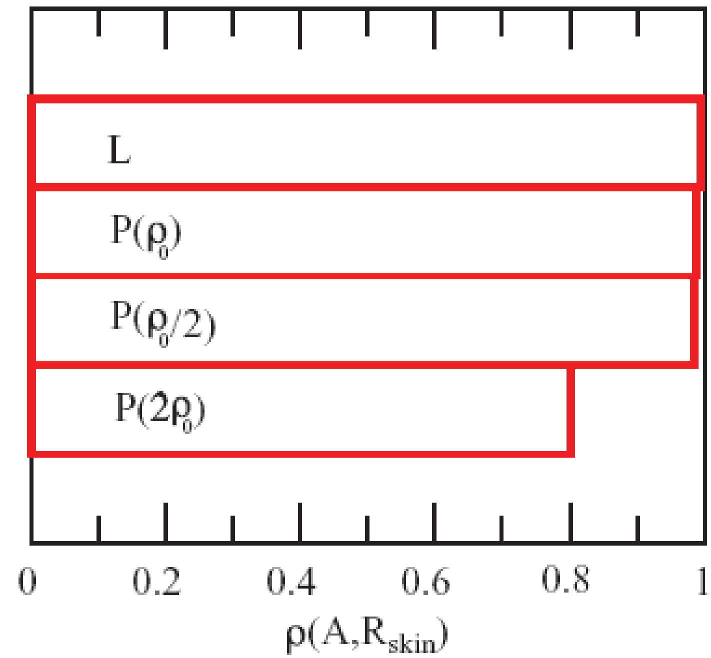
Results

Pure Neutron Matter:



PRC 86, 015802 (2012)



Finite-nuclei observables are not sensitive to the high-density component of the EOS!

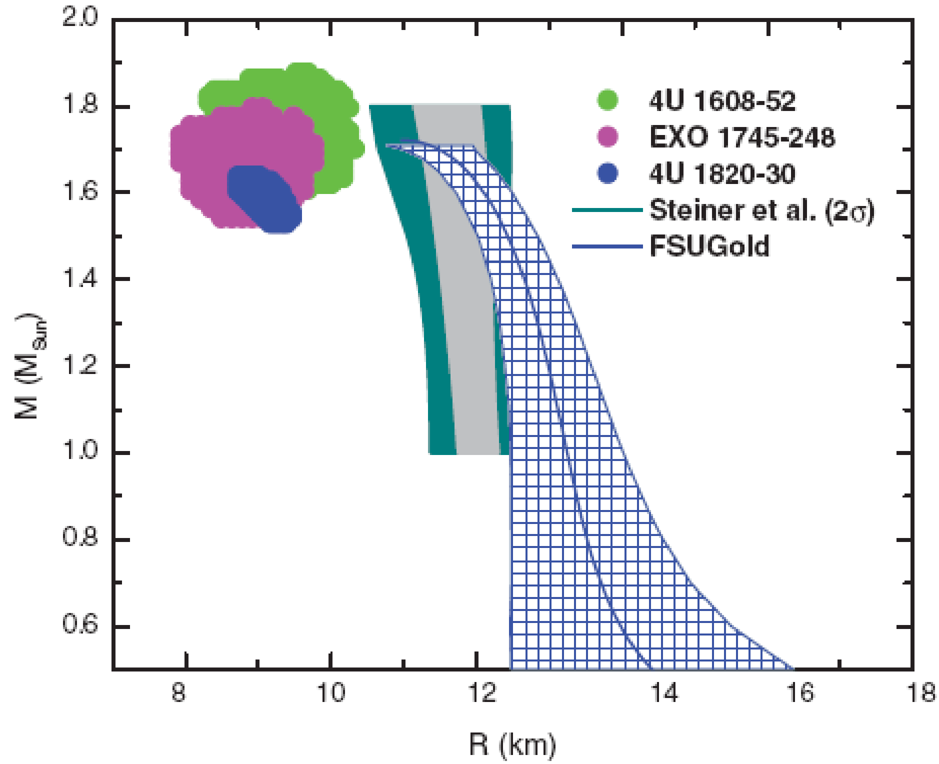
A	$\langle A\rangle \pm \Delta A$	$\rho(A, R_{\rm skin})$
L (MeV)	$(60.5152 \pm 12.1011)[19.997\%]$	0.9952
$P(\rho_0)$	$(3.1842 \pm 0.6349)[19.940\%]$	0.9882
$P(\rho_0/2)$	$(0.4874 \pm 0.1721)[35.304\%]$	0.9861
$P(2\rho_0)$	$(21.8569 \pm 1.2735)[5.827\%]$	0.8016

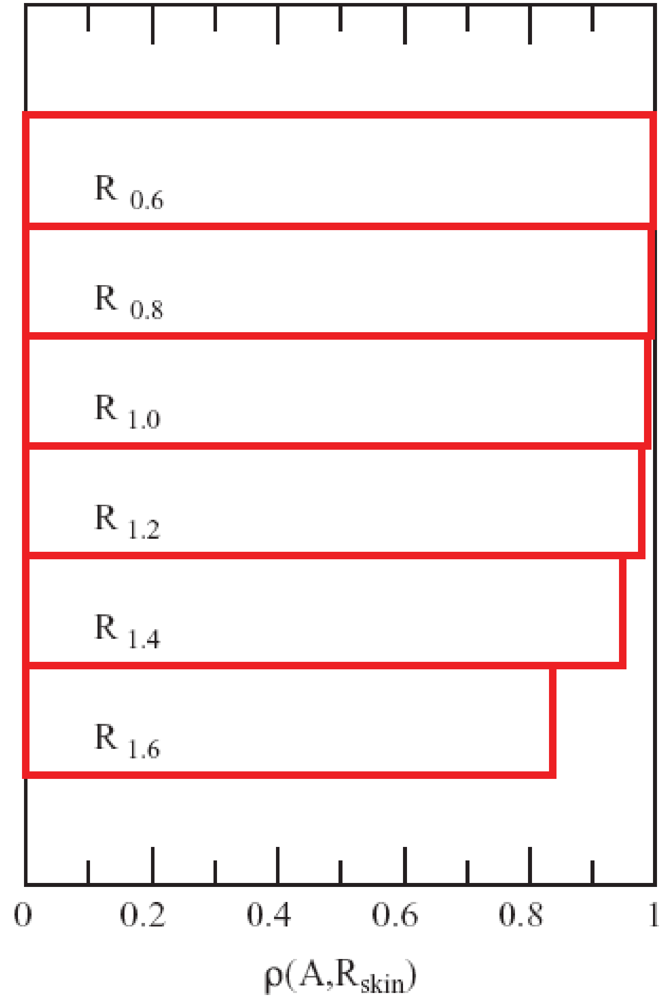
For comparison correlation coefficient between the neutron skin of 48Ca and L is 0.9826

Results

Neutron Star Radii:

PRC 86, 015802 (2012)





1. Constraining EOS at low densities from radii of low-mass NSs are difficult as they may be very rare.
2. However this is possible from neutron radii as they contain the same information.

A	$\langle A\rangle \pm \Delta A$	$\rho(A, R_{\rm skin})$
$R_{0.6}$	$(13.9785 \pm 1.5183)[10.862\%]$	0.9953
$R_{0.8}$	$(13.5204 \pm 1.0446)[7.726\%]$	0.9931
$R_{1.0}$	$(13.2439 \pm 0.7776)[5.872\%]$	0.9866
$R_{1.2}$	$(12.9864 \pm 0.5964)[4.593\%]$	0.9770
$R_{1.4}$	$(12.6568 \pm 0.4603)[3.637\%]$	0.9486
$R_{1.6}$	$(12.1038 \pm 0.3881)[3.206\%]$	0.8361

Results

Direct Urca Process (fast cooling):

$$n \to p + e^- + \bar{\nu}_e,$$

$$e^- + p \to n + \nu_e.$$

Model independent threshold proton fraction of 1/9!

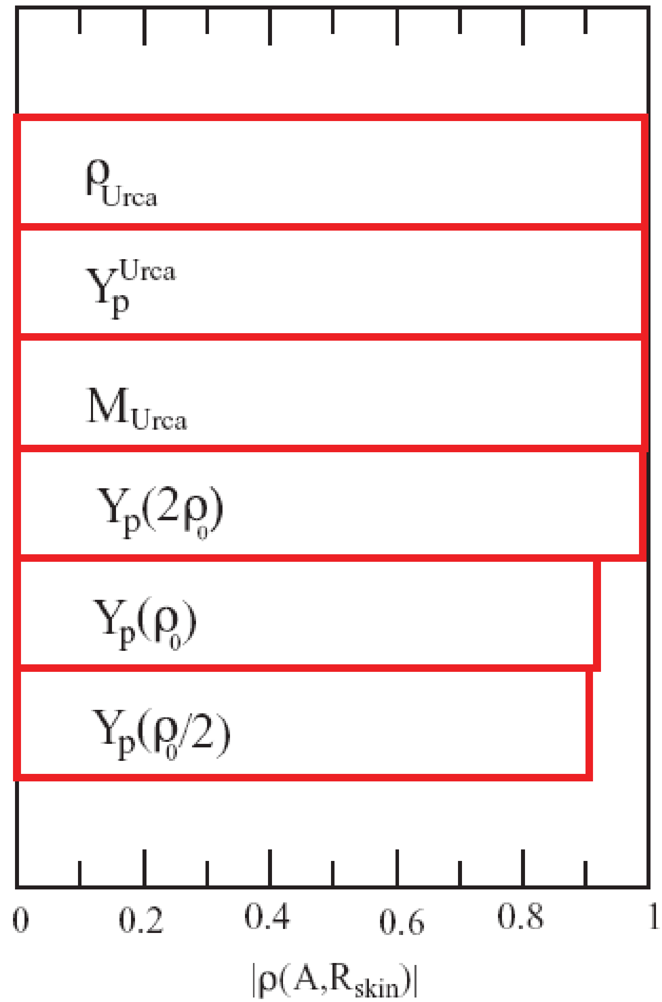
Modified Urca Process requires a bystander neutron to conserve momentum at the Fermi surface (slow cooling)

In a realistic case of a non-zero muon fraction, threshold proton fraction is about:

$$\boxed{Y_p^{\mathrm{Urca}} \lesssim 0.15}$$

Models with stiff symmetry energy (large slope) favor large proton fractions at high density → correlation;

These same models (large slope) also drop faster (compared to models with the soft symmetry energy) at low densities → anticorrelation;



A	$\langle A \rangle \pm \Delta A$	$\rho(A, R_{\mathrm{skin}})$
ρ_{Urca}	$(0.4668 \pm 0.1324)[28.359\%]$	-0.9928
$M_{\mathrm{Urca}}/M_\odot$	$(1.3012 \pm 0.2658)[20.427\%]$	-0.9927
Y_p^{Urca}	$(0.1367 \pm 0.0019)[1.421\%]$	-0.9927
$Y_p(2\rho_0)$	$(0.1064 \pm 0.0138)[13.000\%]$	$+0.9906$
$Y_p(\rho_0)$	$(0.0609 \pm 0.0055)[9.055\%]$	$+0.9166$
$Y_p(\rho_0/2)$	$(0.0346 \pm 0.0051)[14.651\%]$	-0.9063

Thin skin → large Urca mass threshold;

Observation of large skin AND enhanced cooling of stars → indicator for exotic core

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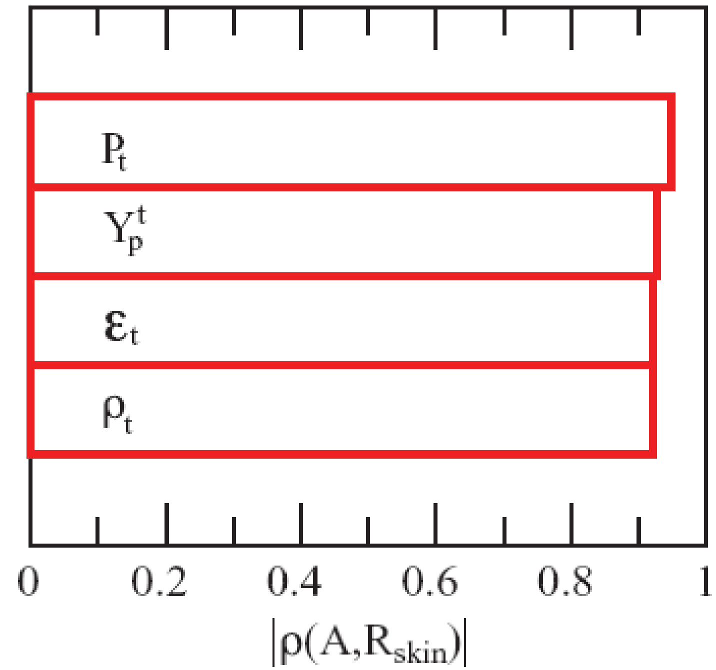
Results



Core-Crust Transition:

Crust is believed to play important role for:

- Pulsar Glitches;
- Giant Flares (through QPO);
- Gravitational Waves.

Transition depends on the proton fraction (density dependence of symmetry energy at low densities)!

Stiff symmetry energy falls rapidly at low densities;
Tolerates a large isospin asymmetry;
Small proton fraction → low transition density!

The thicker is the neutron skin the smaller is the proton fraction – inverse correlation!

PRL 88, 5647 (2001)

Note: Covariance analysis cannot assess systematic errors associated with the limitation of a given model. Example: A strong correlation found between the transition pressure and neutron skin. Therefore, we suggest to perform such analyses using other models.

PRC 82, 025810 (2010)
EPL 91, 32001 (2010)
PRC 83, 045810 (2011)

A	$\langle A \rangle \pm \Delta A$	$\rho(A, R_{skin})$
P_t	$(0.4020 \pm 0.1071)[26.640\%]$	$+0.9474$
Y_p^t	$(0.0351 \pm 0.0069)[19.711\%]$	-0.9260
$\mathcal{E}_t$	$(71.5337 \pm 5.3747)[7.514\%]$	-0.9207
ρ_t	$(0.0755 \pm 0.0056)[7.369\%]$	-0.9203

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Results

Stellar Moment of Inertia:

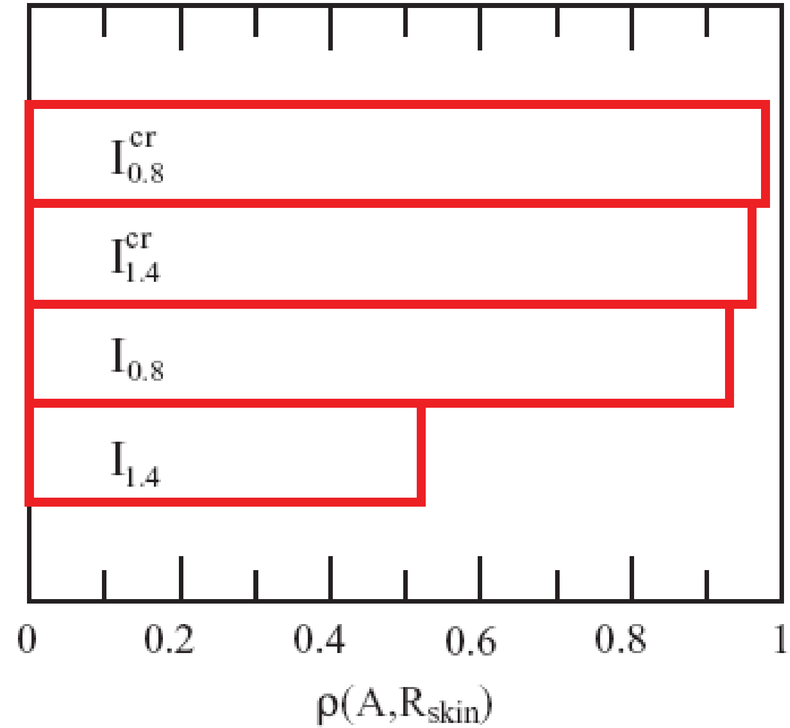
Prospects of measuring the moment of inertia of PSR J0737-3039A (10% accuracy).
We found a mild correlation only!

APJ 629, 979 (2005)
MNRAS 364, 635 (2005)

Vela pulsar glitches suggest that at least 1.6% of the total moment of inertia should reside in the crust.

PRL 83, 3362 (1999)

The strong correlation is due to transition properties.



$$I_{\rm cr} \approx \frac{16\pi}{3}\frac{R_t^6 P_t}{R_s}\left[1-\left(\frac{R_s}{R}\right)\left(\frac{I}{MR^2}\right)\right] \times\left[1+\frac{48}{5}(R_t/R_s-1)(P_t/\mathcal{E}_t)+\cdots\right]$$

A	$\langle A\rangle \pm \Delta A$	$\rho(A, R_{\rm skin})$
$I_{0.8}^{\rm cr}$	$(8.7777 \pm 2.5612)[29.178\%]$	0.9781
$I_{1.4}^{\rm cr}$	$(5.8988 \pm 1.4055)[23.827\%]$	0.9619
$I_{0.8}$	$(7.4067 \pm 0.3204)[4.326\%]$	0.9299
$I_{1.4}$	$(14.7660 \pm 0.3437)[2.327\%]$	0.5192

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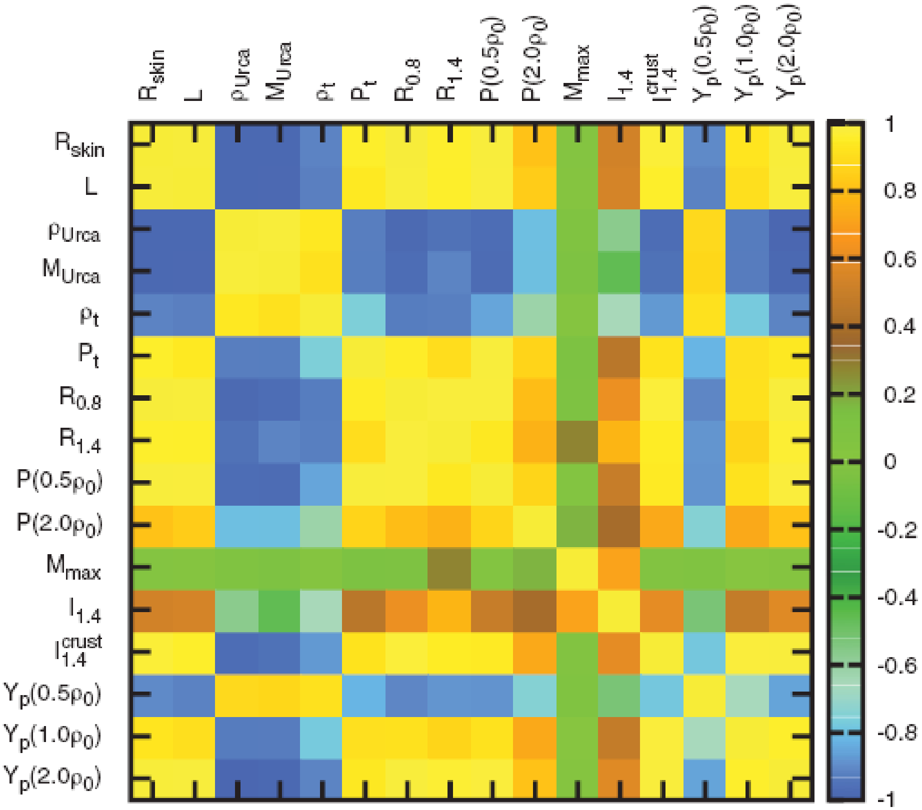
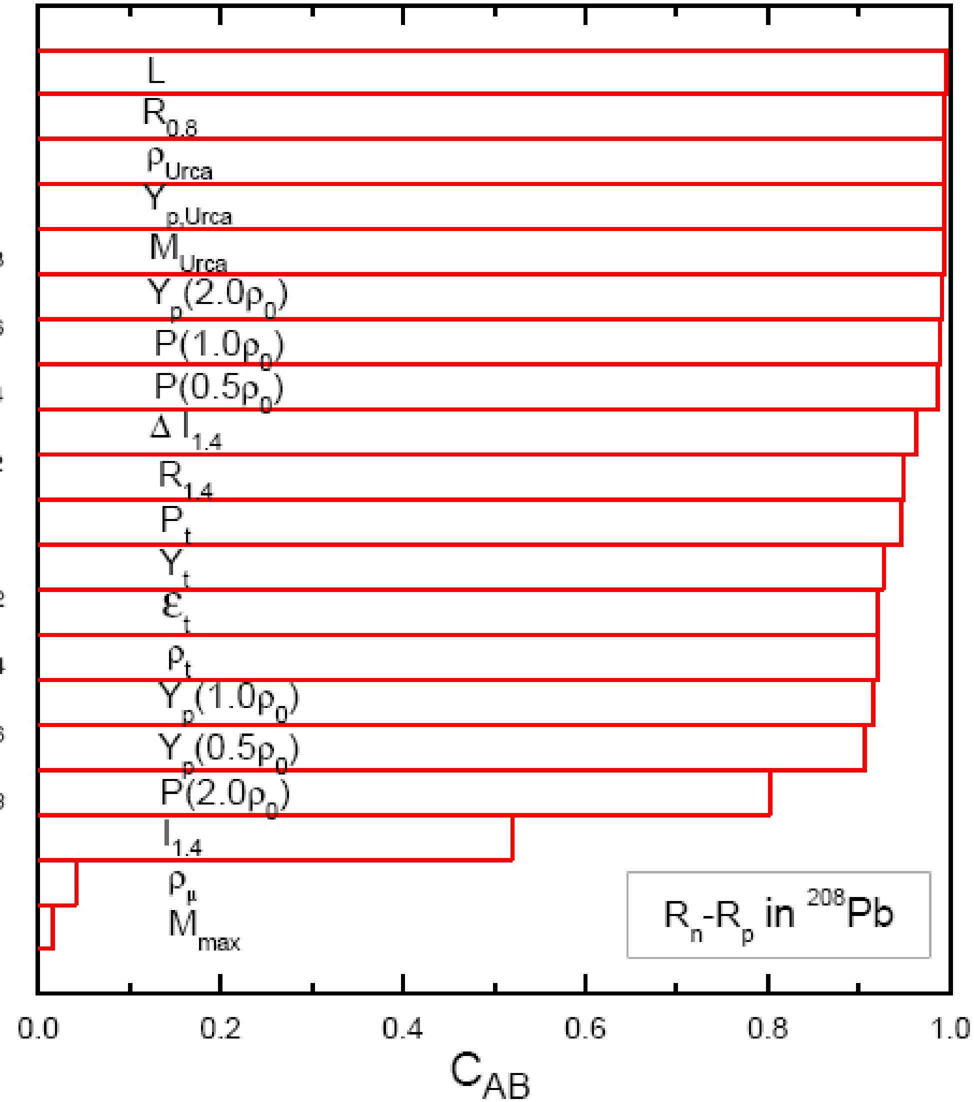
Conclusions





1. Covariance analysis is used to quantify correlations and theoretical uncertainties between neutron skin of 208Pb and various neutron star observables.
2. A **10%** uncertainty in determination of the slope of the symmetry energy requires a very stringent measurement on the neutron radius of lead (at a **0.35%** level), or parity violating asymmetry of the order of **~1%.**
3. Measuring a ~0.8 solar-mass NS radii to about 10% would be ideal (~0.8% in neutron radius of lead), but they are rare, and even if found, achieving such an accuracy has not been easy so far.

   Therefore precise(!) measurements of neutron radii of both 48Ca and 208Pb will remain the sole alternative.

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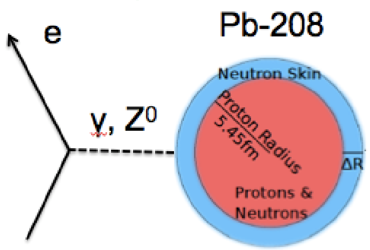
The main part of this work was done in collaboration with

Prof. Jorge Piekarewicz — Florida State University

Other Collaborators

Prof. Horowitz, C. J.	Indiana University
Prof. Li, B.-A.	Texas A&M University-Commerce
Prof. Newton, W. G.	Texas A&M University-Commerce
Dr. Shen, G.	University of Washington
Dr. Xu, J.	Shanghai Institute of Applied Physics



THANK YOU!

PREX

Welcome, CREX!