Correlating the density dependence of the symmetry energy to neutron skins and neutron-star properties

Farrukh J Fattoyev

Texas A&M University-Commerce

My TAMUC collaborators: B.-A. Li, W. G. Newton
My outside collaborators: J. Piekarewicz (FSU), C. J. Horowitz (IU), G. Shen (INT), J. Xu (SINAP)

22 July – 26 July, 2013
NuSym2013
Third International Symposium on Nuclear Symmetry Energy
NSCL/FRIB, East Lansing, Michigan

Outline

1. Motivation
2. Covariance analysis, its power and application (RMF)
3. From Heaven to Earth – connecting neutron-star properties to neutron skin:
   (a) Pure Neutron Matter
   (b) Neutron Star Radii
   (c) Neutron Star Cooling
   (d) Core-Crust Transition
   (e) Stellar Moment of Inertia
4. Part II: How well do we know density dependence of the nuclear symmetry energy (NSE)?

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Motivation

1. (a) 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);

   (b) This same pressure supports **neutron stars** against gravitational collapse;

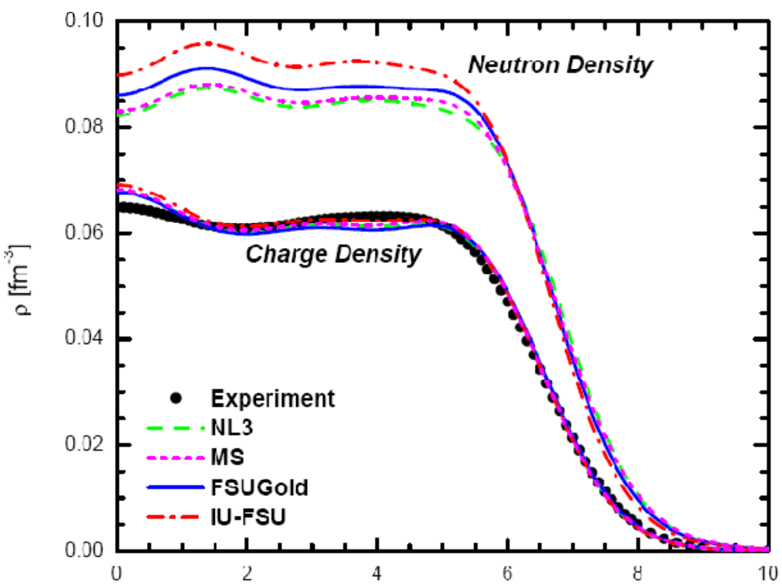
   (c) Pressure of PNM at saturation is related to the density slope of the symmetry energy:

$$P(\rho_0) \approx \rho_0 L / 3$$

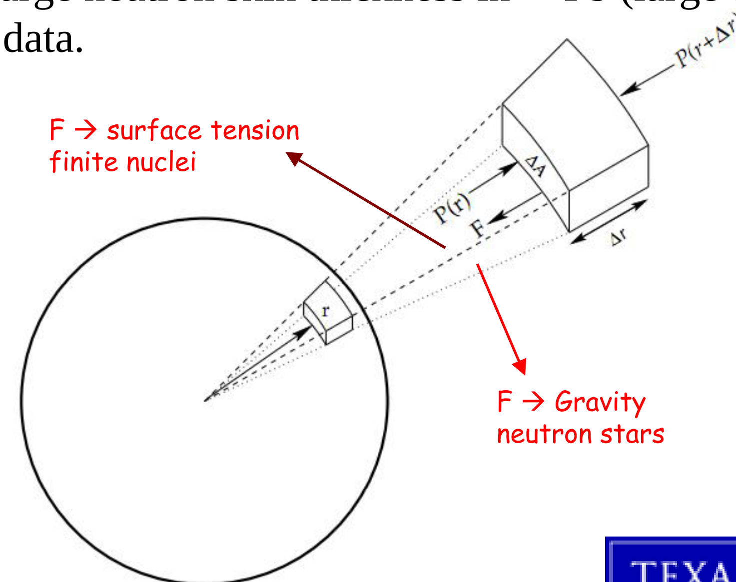
   Therefore correlations between many neutron star properties and density dependence of the symmetry energy are naturally expected.
   PRL 86, 5647 (2000); PRC 64, 062802 (2001); PRC 66, 055803 (2002); ApJ 593, 463 (2003); Phys. Rep. 411, 325 (2005); Nucl. Phys. A 706, 85 (2002); PRC 82, 025810 (2010);

2. Our goal is to provide meaningful theoretical error-bars and to assess the degree of correlation between predicted observables by using powerful covariance analysis method;

3. We would also like to test the (in)compatibility of large neutron skin thickness in ^{208}Pb (large density slope) with current experimental and observational data.



F. J. Fattoyev, PhD thesis



European Journal of Physics 26, 695 (2005)

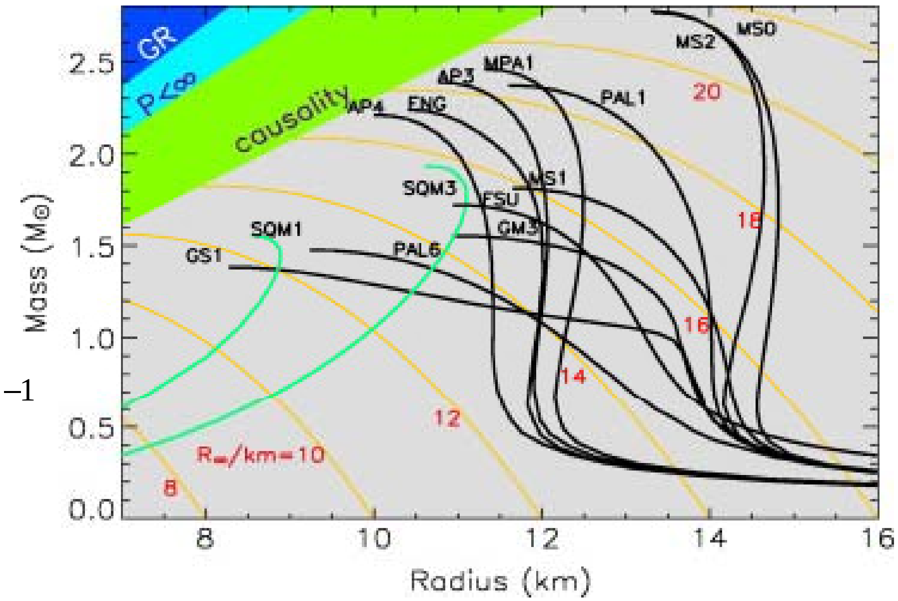
Structure of Neutron Stars: Pressure of PNM is not the whole story

1. Neutron stars satisfy the Tolman-Oppenheimer-Volkoff equation, i.e. the Einstein's GR Equations written for a spherical perfect fluid:

$$\frac{dM}{dr} = 4\pi r^2 \varepsilon(r)$$

$$\frac{dP}{dr} = -G\frac{\varepsilon(r)M(r)}{r^2}\left[1+\frac{P(r)}{\varepsilon(r)}\right] \times \left[1+\frac{4\pi r^3 P(r)}{M(r)}\right]\left[1-\frac{2GM(r)}{r}\right]^{-1}$$

J. Lattimer, New Ast. Rev. 54, 101 (2010)



2. The only unknown physics is the Nuclear Equation of State: $P(r) = P[\varepsilon(r)]$
3. Matter in neutron stars are cold, charge neutral and in beta-equilibrium. Density spans 10-11th order of magnitude.
4. Neutrons are not the only ingredients: significant amount of protons, electrons and muons exist (also speculated that hyperons and/or quark matter exist at high densities).
5. Not all properties of neutron stars are expected to be sensitive probes to the density dependence of symmetry energy!

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Relativistic Mean-Field Model

PRL 95, 122501 (2005)

The effective interaction Lagrangian density:

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

scalar-isoscalar

vector-isoscalar

vector-isovector ?

and higher order interactions

For a full discussion on RMF model please refer to a talk given by Ohnishi on July 22.

Model parameters are fitted to a large body of ground state properties: binding energies, charge radii, collective excitations.

Complicated dynamics encoded in few empirical constants

g_s, g_v	Ground state properties of finite nuclei; Nuclear matter saturation
g_ρ	Ground state properties of heavy nuclei; Nuclear symmetry energy (NSE)
κ, λ	Isoscalar giant monopole resonance; Incompressibility of symmetric nuclear matter, K_0
Λ_v	Neutron radius of heavy nuclei – Neutron star radii; Density dependence of NSE
ζ	Neutron star structure; maximum mass

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 a quality measure:

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

Traditionally, once the model is found, its success is gauged by predicting observables that are not included in the fit. An important physics is left behind: assessing uncertainty in the model predictions!

Covariance of two observables, A and B, are found from:

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

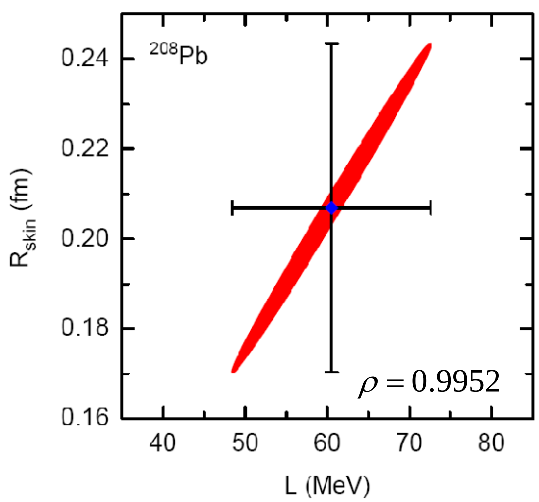
where

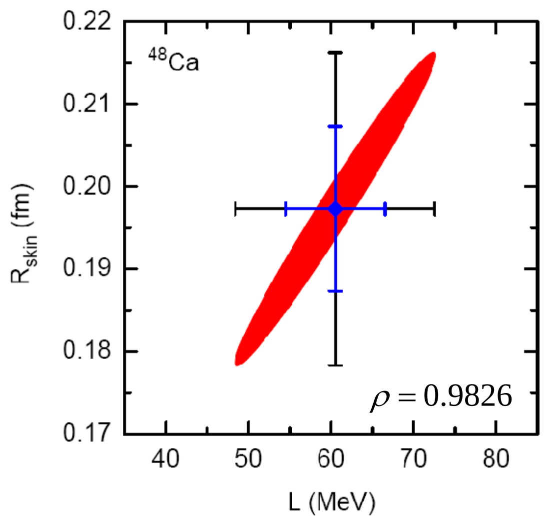
$$\mathcal{M}_{ij} = \frac{1}{2} \left(\frac{\partial \chi^2}{\partial x_i \partial x_j} \right)_{\mathbf{x}=0}$$

Correlation coefficient

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

<u>An example: FSUGold – accurately calibrated model to ground state properties</u>





$$L \equiv 60.52 \pm 12.10 MeV [20\%]$$

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

$$R_{skin} \equiv R_n - R_p = 0.197 \pm 0.019\ fm$$

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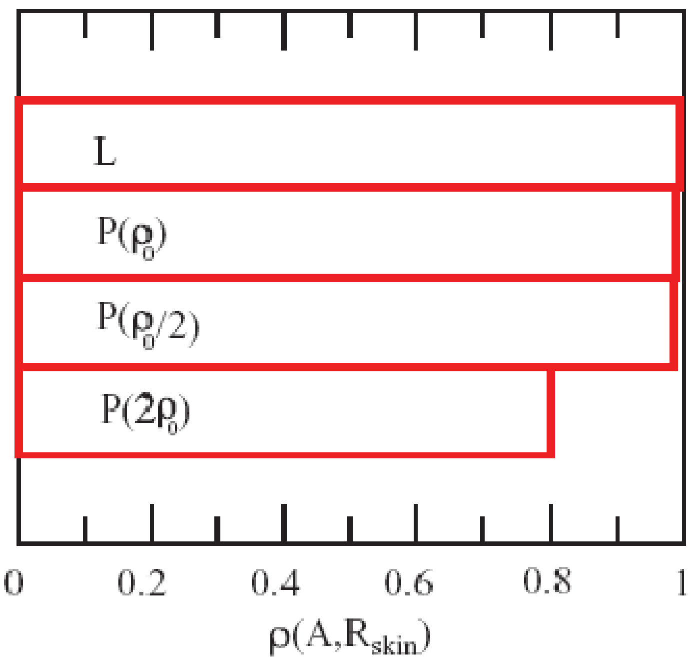
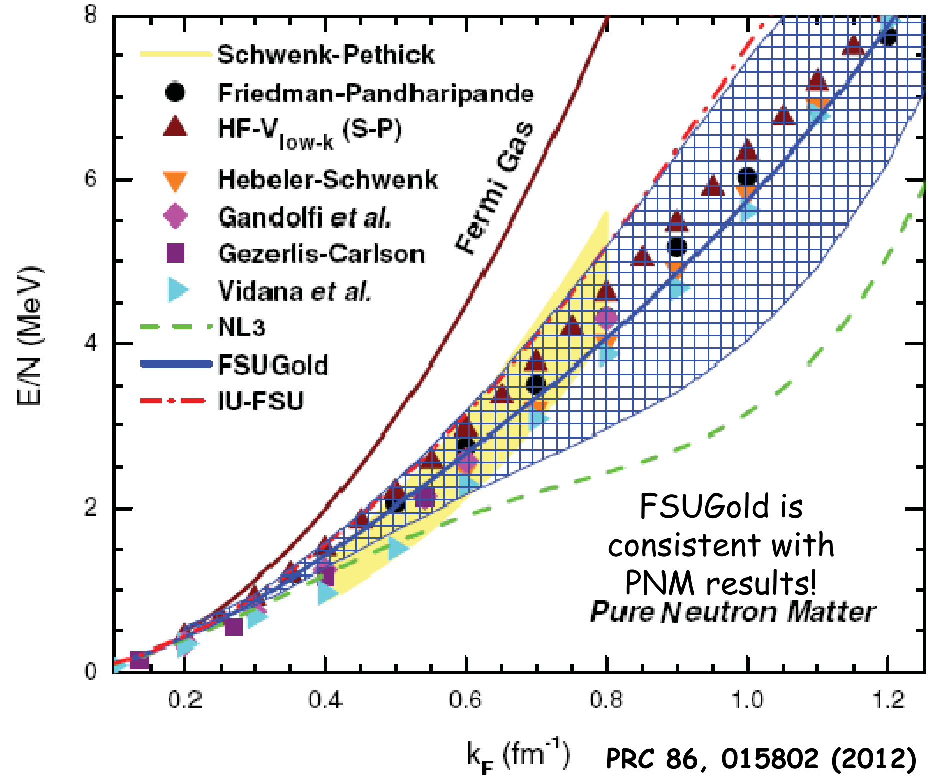
Results

(Dilute) Pure Neutron Matter:





PRC 86, 015802 (2012)

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

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

Notice that correlations remains as large: $\rho\left(L, R_{skin}^{48Ca}\right) = 0.9826$

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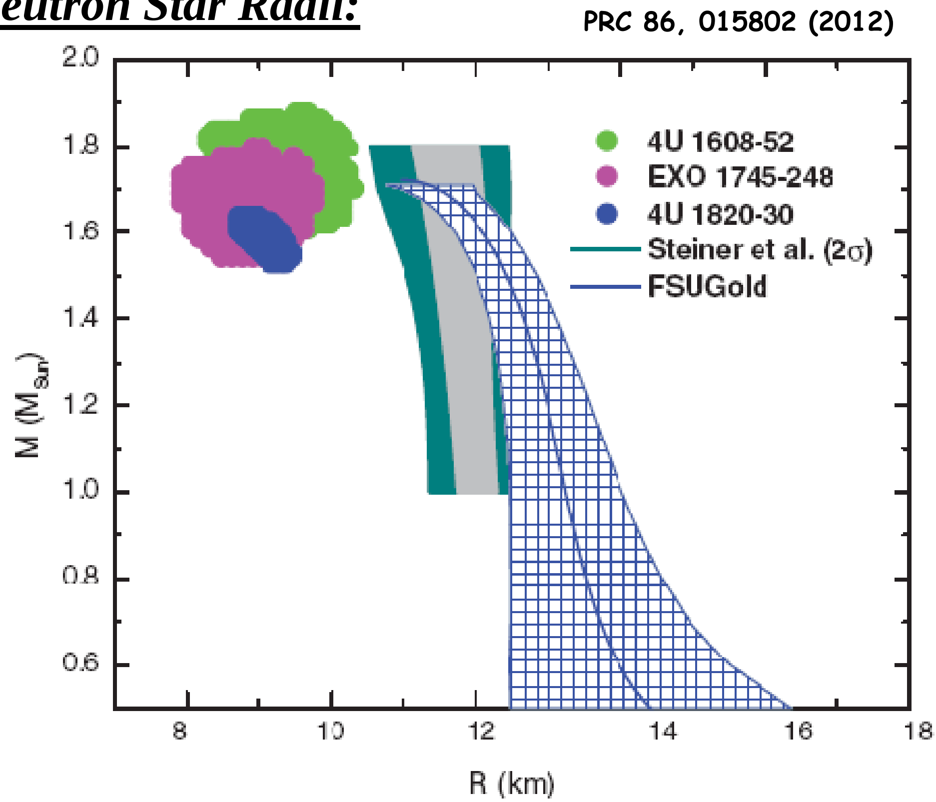
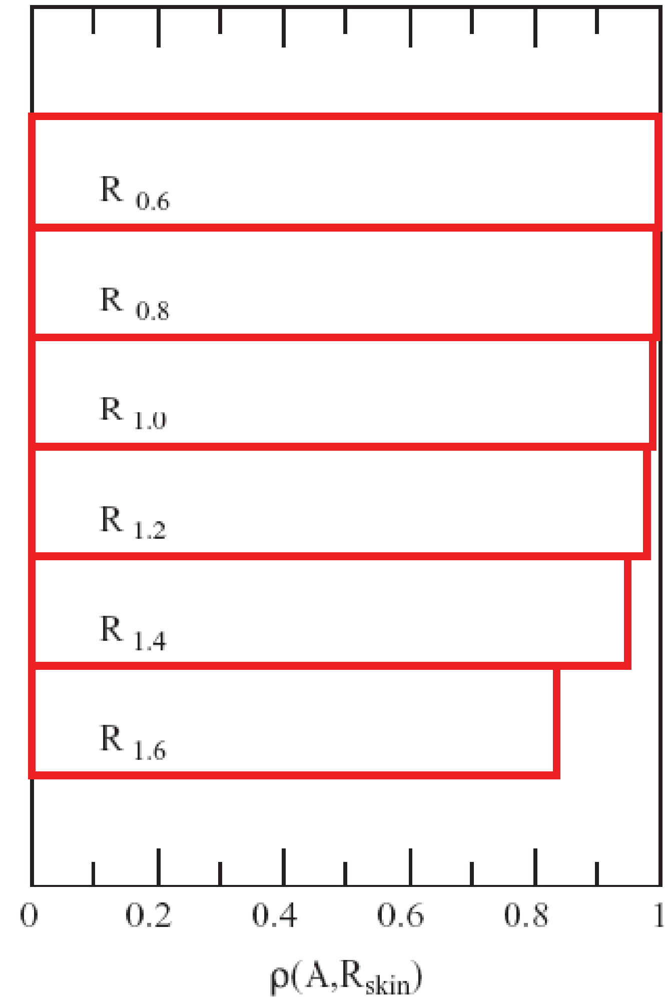
Results

Neutron Star Radii:





Conclusion:
Low-mass neutron stars are very sensitive probes. But they are rarely found in nature → Neutron radii remain the sole alternative (PREX and CREX).

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

Results

Direct Urca Process (fast cooling):

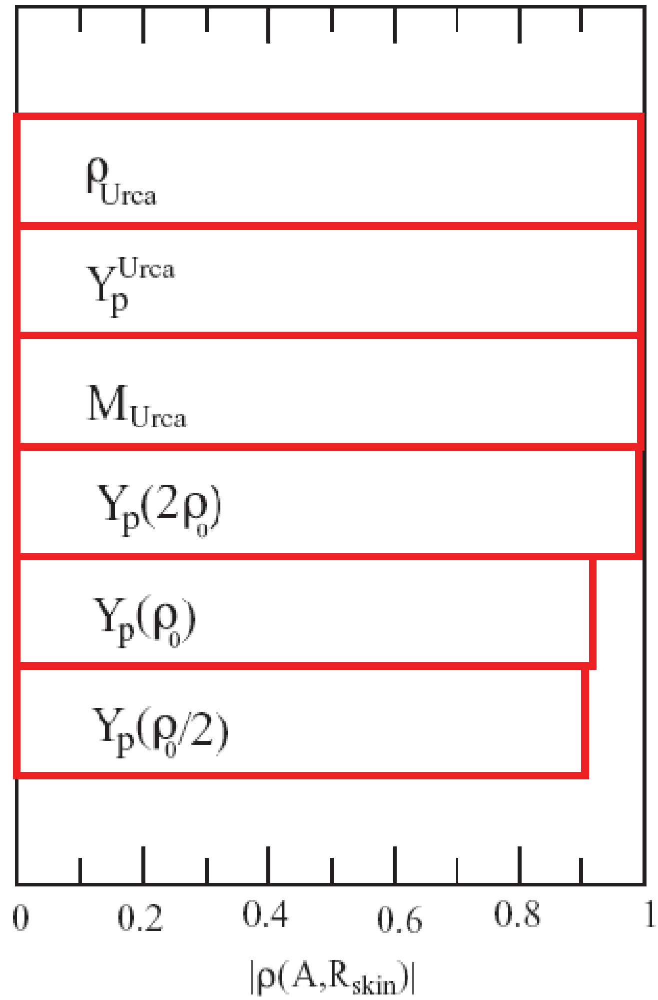
$$n \rightarrow p + e^- + \bar{\nu}_e,$$
$$e^- + p \rightarrow n + \nu_e.$$

Simplest case: $Y_p \equiv 1/9$

In a realistic case when muons exist, threshold proton fraction is a an EOS dependent:

$$Y_p^{\text{Urca}} \lesssim 0.15$$

Models with stiff symmetry energy (large slope) favor large proton fractions at high density → correlation;
These same models (large slope) favor small proton fractions at low densities → anticorrelation;



A	$\langle A\rangle \pm \Delta A$	$\rho(A, R_{\text{skin}})$
ρ_{Urca}	$(0.4668 \pm 0.1324)[28.359\%]$	-0.9928
$M_{\text{Urca}}/M_\odot$	$(1.3012 \pm 0.2658)[20.427\%]$ ★	-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

Conclusion:
Large Urca mass threshold → thin skin (small L) and vice versa.
Observation of thin 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:

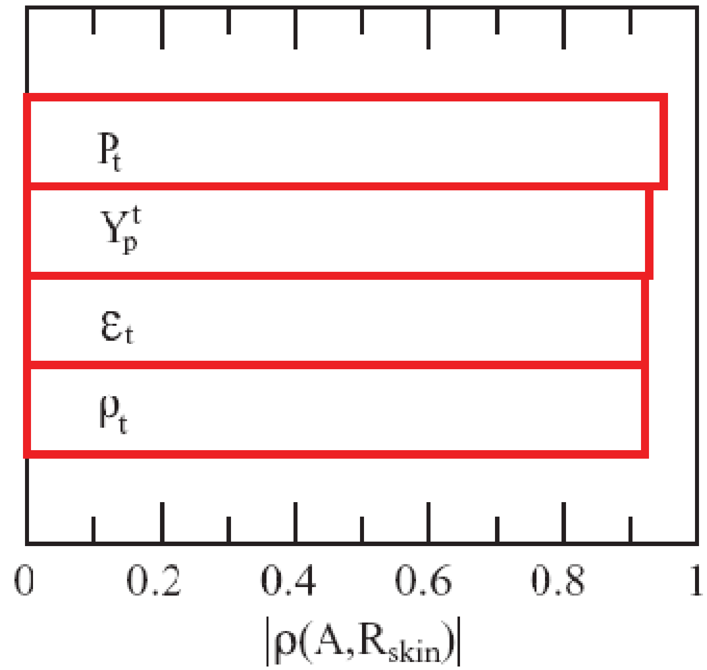
- Pulsar Glitches;
- Giant Flares (through QPO) – Talk by H. Sotani
- Gravitational Waves – Talk by W. G. Newton

Core-crust transition density depends on the proton fraction, i.e. density dependence of NSE:

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. We strongly suggest to perform such analyses using other models.

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

A	$\langle A\rangle \pm \Delta A$	$\rho(A, R_{\text{skin}})$
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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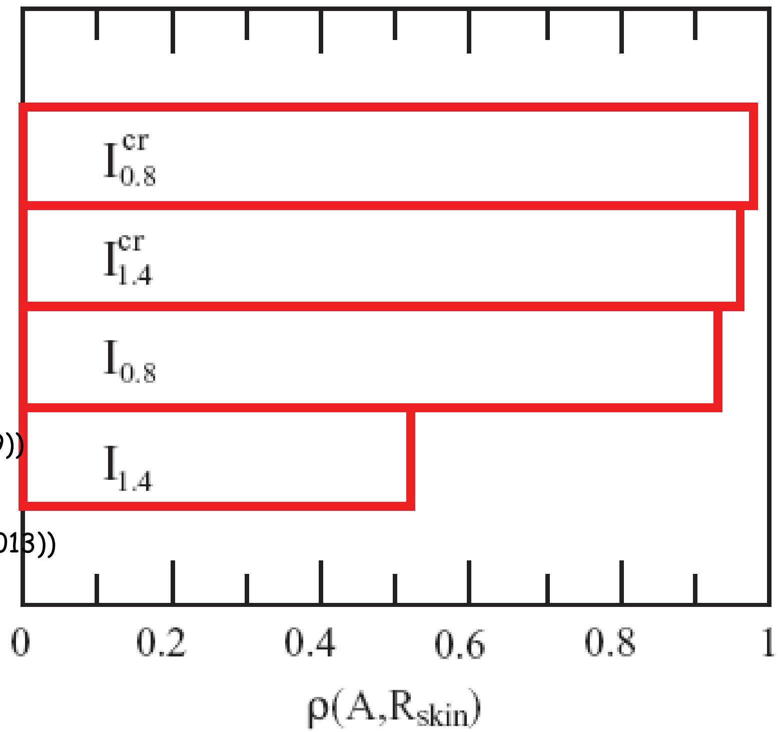
Results



Stellar Moment of Inertia:

Moment of inertia of PSR J0737-3039A can be measured with a10% accuracy – Talk by J. Lattimer

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 (recently it was shown that this value could be much larger (PRL 83, 3362 (1999)) (PRL 110, 011101 (2013))

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	$\langle A\rangle \pm \Delta A$	$\rho(A, R_{\rm skin})$
$I^{\rm cr}_{0.8}$	$(8.7777 \pm 2.5612)[29.178\%]$	0.9781
$I^{\rm cr}_{1.4}$	$(5.8988 \pm 1.4055)[23.827\%]$	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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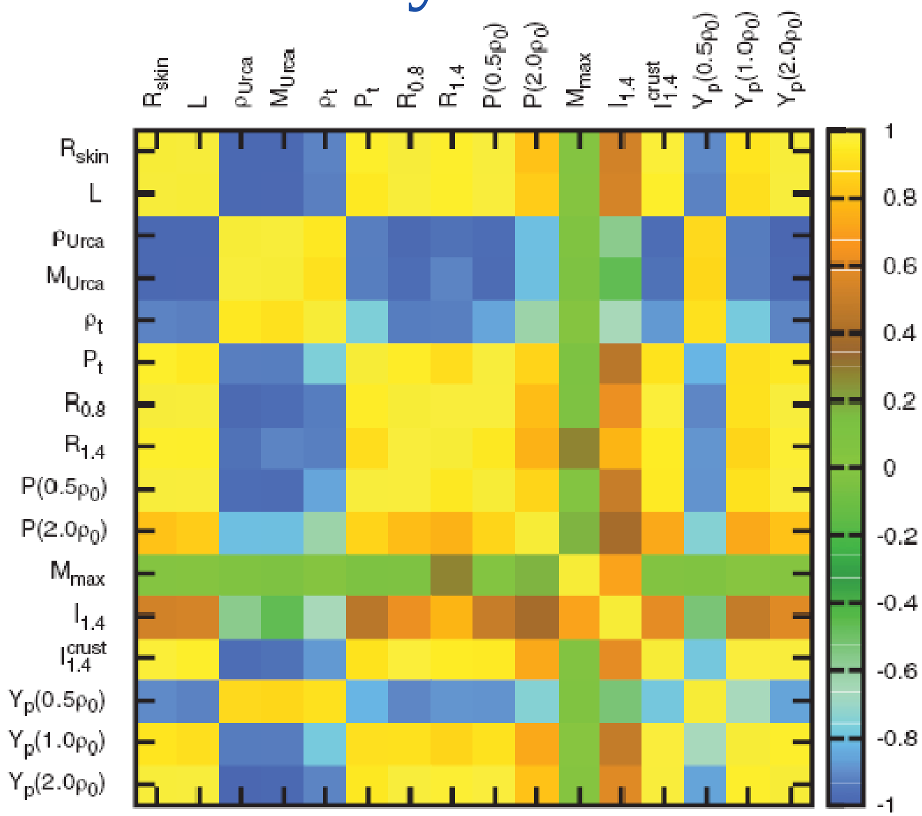
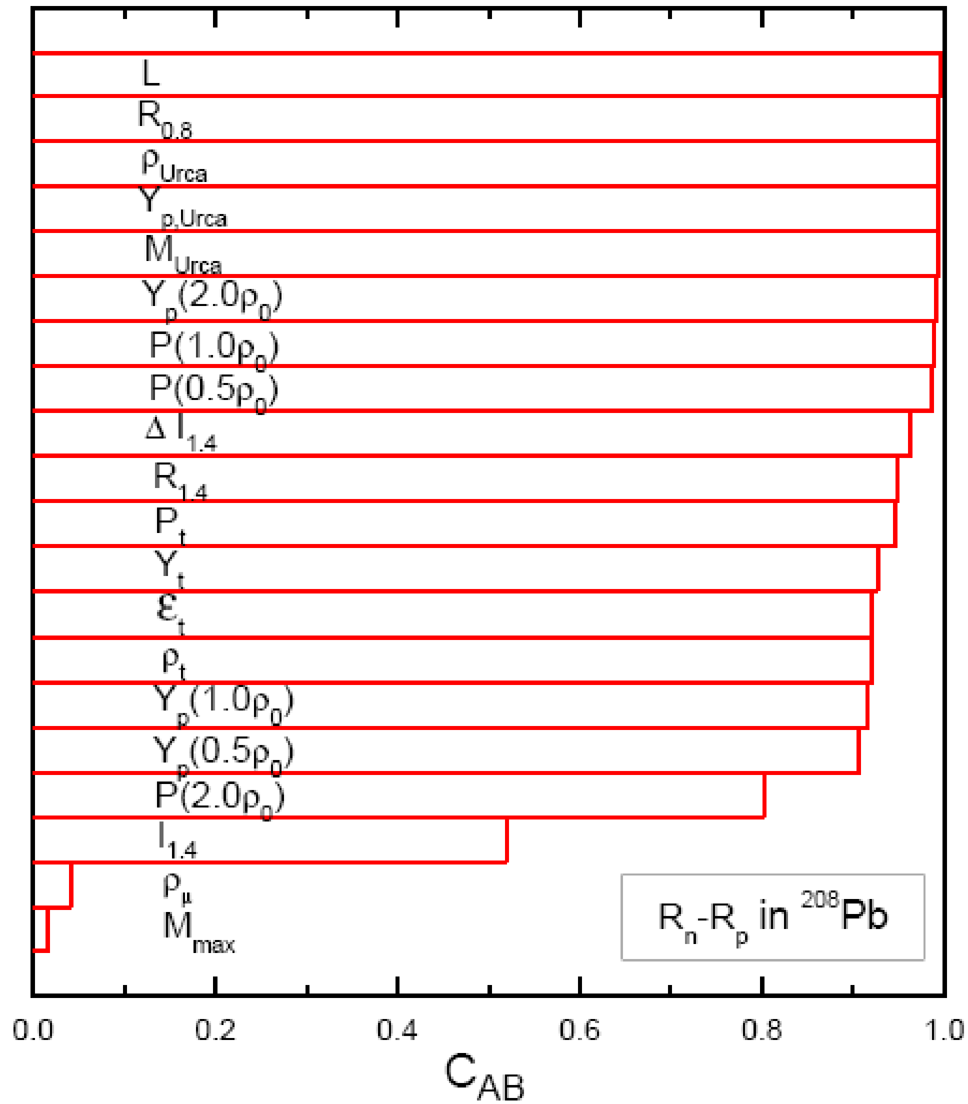
Summary of Results





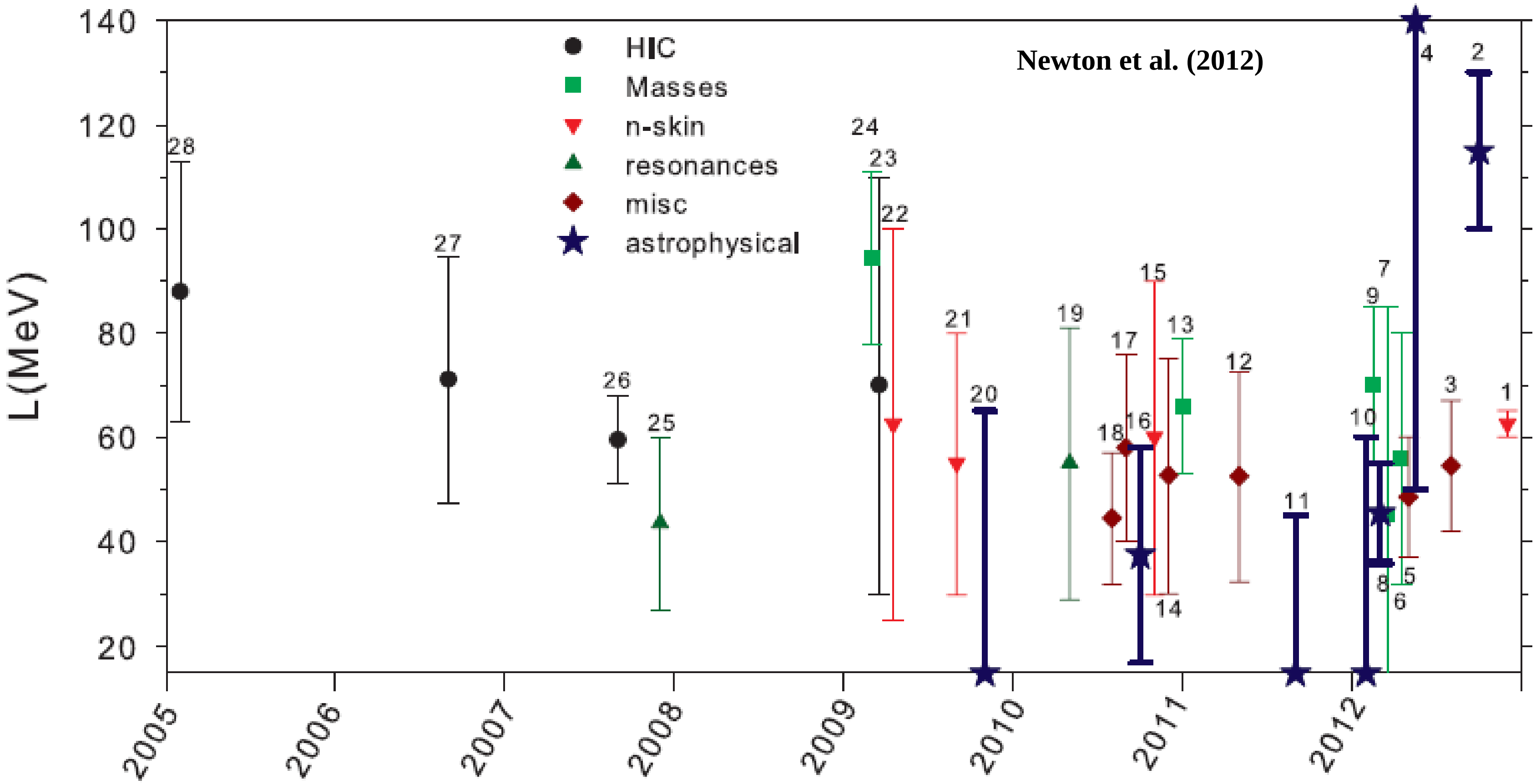
1. Covariance analysis is a powerful tool to quantify correlations and uncertainties for predicted observables.

2. Many neutron star observables are sensitive probe to the NSE.

3. Example: A **20%** uncertainty in determination of the slope of NSE requires a very stringent measurement on the neutron radius of lead (at a **0.7%** level), or parity violating asymmetry of the order of **~2%.**

   → ***PREX-II (2014-15) and CREX (2016)***

Part II
How thick is the neutron skin in ^{208}Pb? How well do we know L?

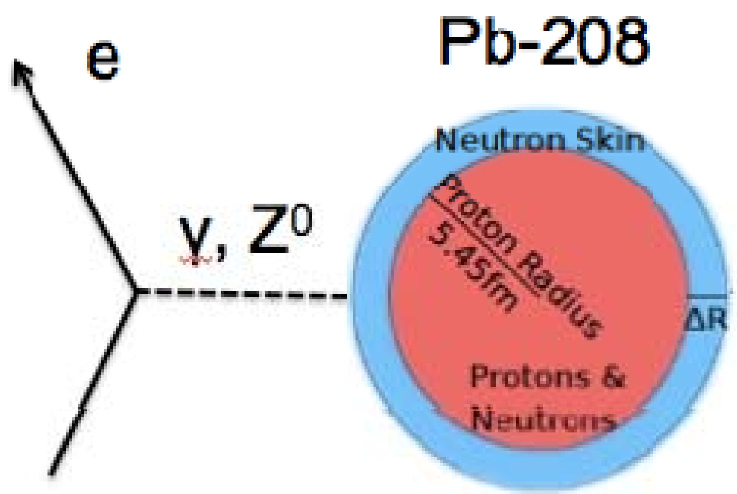


Parity Violating Electron Scattering Experiments

- PREX-I ran for two months in 2012 – Talk by K. Kumar
- Purely electroweak measurement:
  photons are coupled to protons, Z^0-bosons are coupled mainly to neutrons
- First electroweak results:

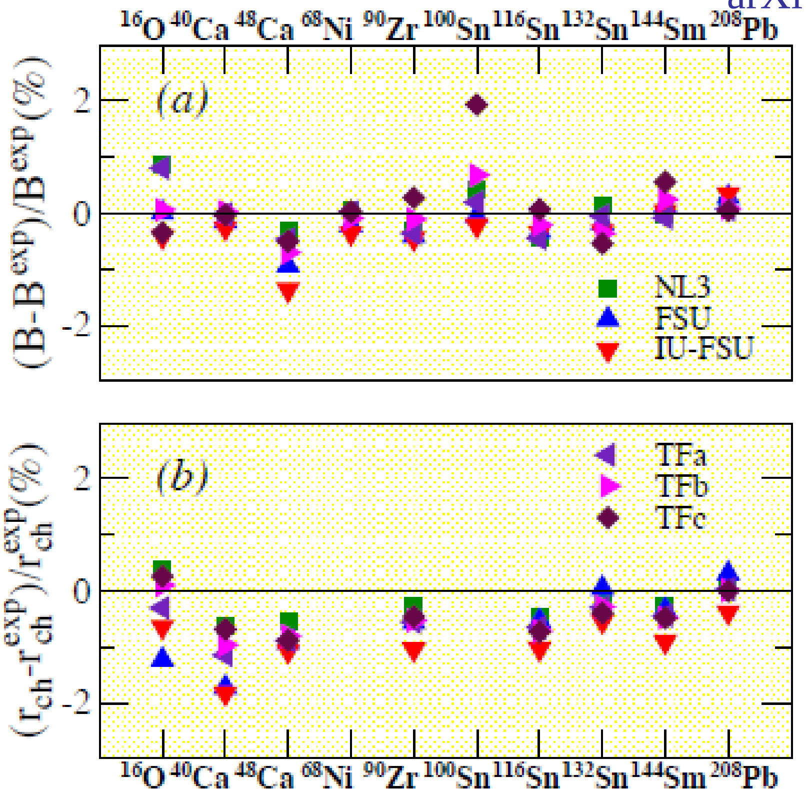
$$R_{skin} \equiv R_n - R_p = 0.33^{+0.16}_{-0.18}\ fm$$

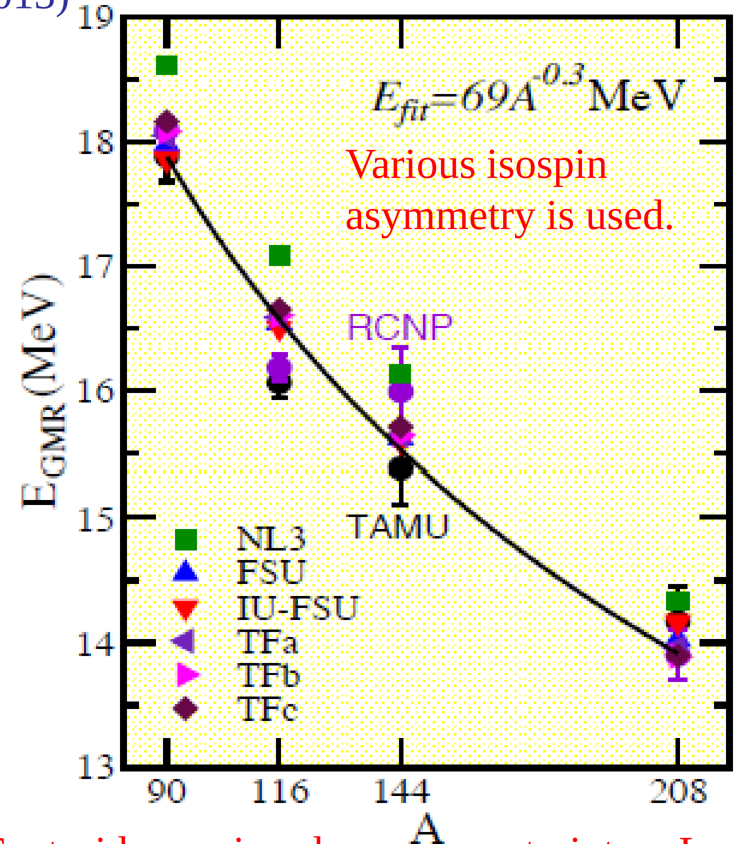
- Large error-bars: accommodate all models
- Central value is intriguing – none of the nuclear EDFs predict such a large value.
- PREX-II and CREX are coming…
- Question: Is such a large value already incompatible with laboratory and astrophysical data?



Ground state properties and giant resonances

arXiv:1306.6034 (2013)



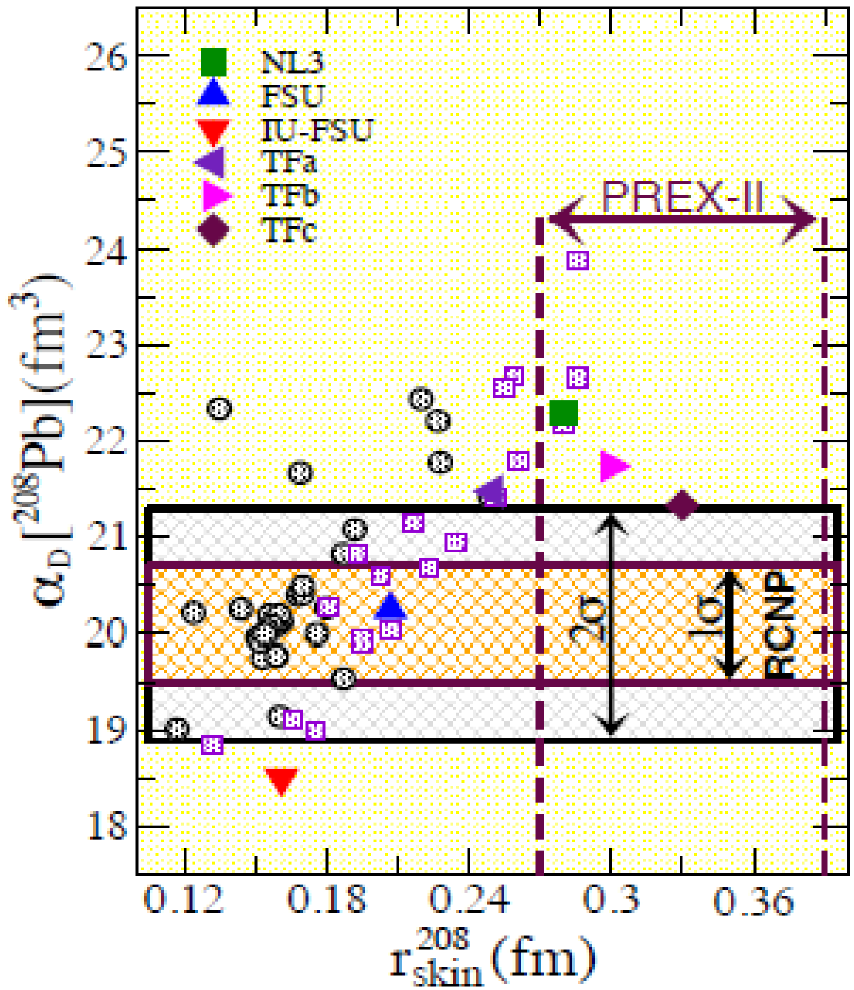


#1. Ground State properties are poor isovector indicators. #2. Centroid energies place no constraint on L.

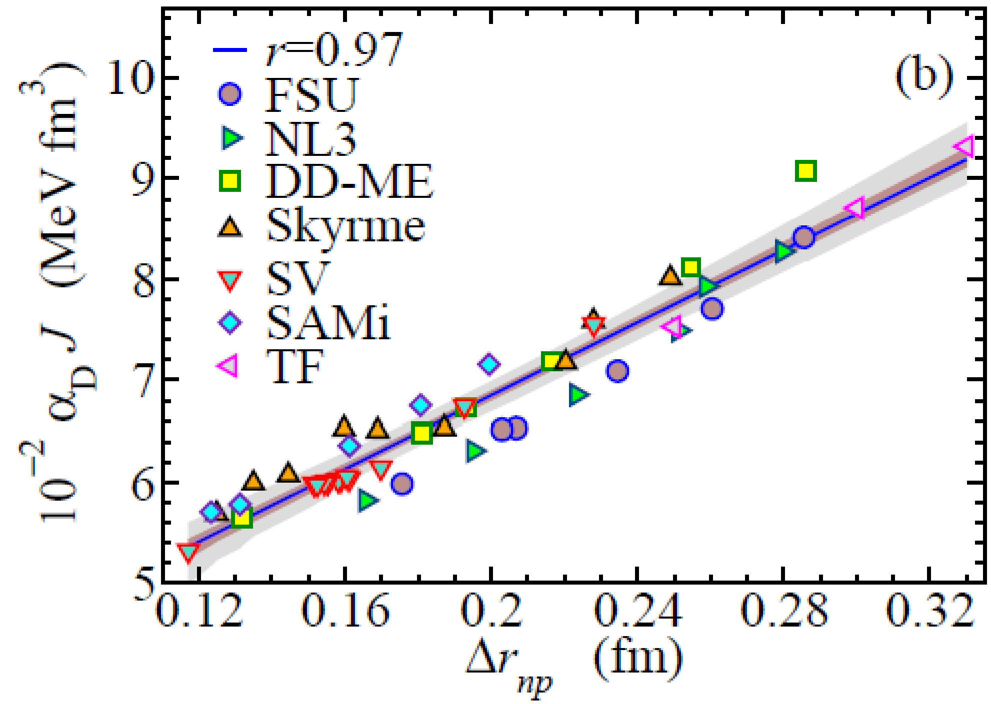
Model	ρ_0 (fm^{-3})	ε_0	K_0	$\tilde{J}$	J	L	K_{sym}	r_{skin}^{208} (fm)
NL3	0.148	−16.24	271.5	25.68	37.29	118.2	100.9	0.28
FSU	0.148	−16.30	230.0	26.00	32.59	60.5	−51.3	0.21
IU-FSU	0.155	−16.40	231.2	26.00	31.30	47.2	28.7	0.16
TFa	0.149	−16.23	245.1	26.00	35.05	82.5	−68.4	0.25
TFb	0.149	−16.40	250.1	27.59	40.07	122.5	45.8	0.30
TFc	0.148	−16.46	260.5	30.20	43.67	135.2	51.6	0.33

Electric dipole polarizability

arXiv:1306.6034 (2013)



Large skin predicted by TFc is consistent with the RNCP data *at 2-sigma level.*
Systematic uncertainties need to be addressed
(Also see talk by A. Tamii)

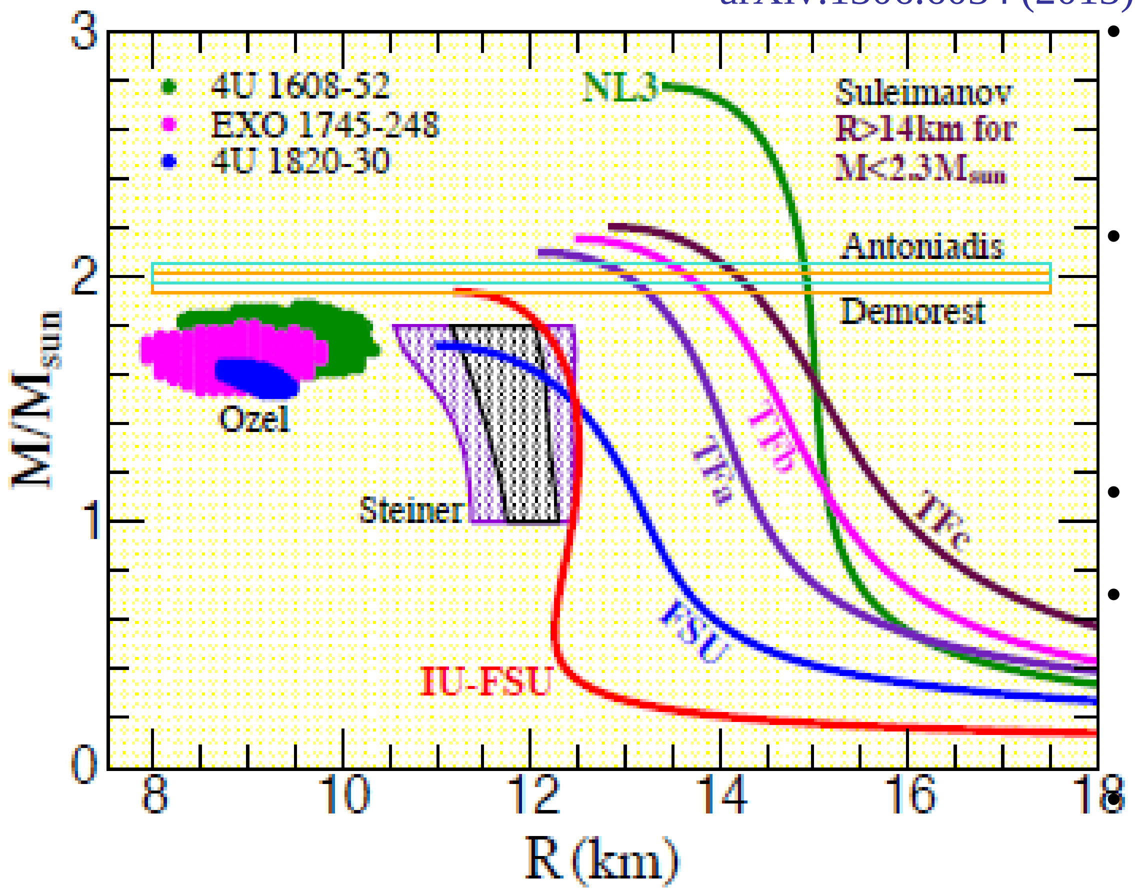


arXiv:1307.4806 (2013)
Also talk by X. Roca-Maza

Combining experimental results at 1-sigma level with the projected PREX-II uncertainty (assuming that central value remains in tact) rules out all current EDF models.

Neutron Stars

arXiv:1306.6034 (2013)



- Results by Ozel *et al.* (2010) suggest small radii of 8-10 km (also see Guillot *et al.*) – very difficult to reconcile with model predictions;
- Additional 3 neutron stars were supplemented by Steiner *et al.* (2010) – suggest larger neutron star radii of 11-12 km (or more recently up to 13.2 km);
- Results by Suleimanov *et al.* (2011) suggest radii of >14 km;
- A recent study by Lattimer and Steiner (2013) suggests that knowledge of atmosphere composition is quite important ;
- QPO results by Sotani *et al.* suggest large L, although their EOS model is very simple.

Conclusions: (More discussion in the last week by J. Piekarewicz)

- *Much work needs to be done in both theoretical and observational front to determine the density dependence of NSE;*
- *Improvements in both statistical and systematic uncertainties of future experiments and observations will and should place vital constraints on the NSE.*
- *For now however ruling out large neutron skin – hence large L – seems premature.*
- *What if: large L (from experiment) and low R_{NS} (from observation)? → strong signal for exotic core. And more…*

THANK YOU!