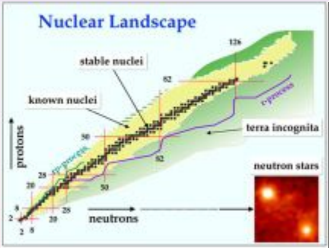
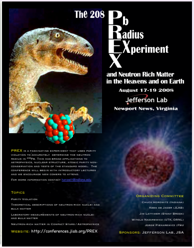
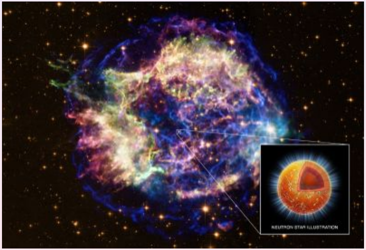
Neutron Skins and Giant Resonances: A Look Forward

International Collaborations in Nuclear Theory
Michigan State University (July-August, 2013)







Understanding the density dependence of the symmetry energy:
From finite nuclei to neutron stars

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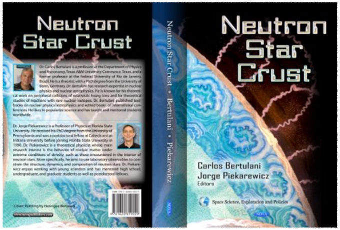
Neutron Star Crust: Preface by Jocelyn Bell



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I judge myself fortunate to be working in an exciting and fast moving area of science and at a time when the public has become fascinated by questions regarding the birth and evolution of stars, the nature of dark matter and dark energy, the formation of black holes and the origin and evolution of the universe.

The physics of neutron stars is one of these fascinating subjects. Neutron stars are formed in supernova explosions of massive stars or by accretion-induced collapse of smaller white dwarf stars. Their existence was confirmed through the discovery of radio pulsars during my thesis work in 1967. Since then this field has evolved enormously. Today we know of accretion-powered pulsars which are predominantly bright X-ray sources, rotation-powered pulsars observed throughout the electromagnetic spectrum, radio-quiet neutron stars, and highly magnetized neutron stars or magnetars. No wonder there has been an explosion in the research activity related to neutron stars!

It is now hard to collect in a single book what we already know about neutron stars along with some of the exciting new developments. In this volume experts have been asked to articulate what they believe are the critical, open questions in the field. In order for the book to be useful to a more general audience, the presentations also aim to be as pedagogical as possible.

This book is a collection of articles on the neutron stars themselves, written by well-known physicists. It is written with young researchers as the target audience, to help this new generation move the field forward. The invited authors summarize the current status of

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Nuclear Structure, Error Bars, and Correlations: Statistical

Reinhard-Nazarewicz, PRC81 (2010) 051303(R) Fattoyev-Piekarewicz, PRC86 (2012) 015802; PRC84 (2011) 064302

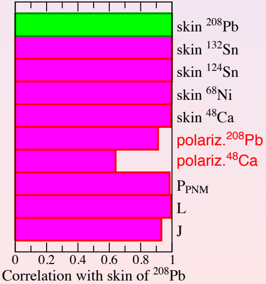
- Empirical constants determined from optimization of a quality measure

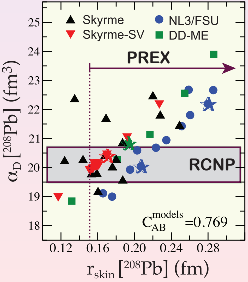
$$\chi^2(\mathbf{p}) = \sum_{n=1}^{N} \left(\frac{\mathcal{O}_n^{(\mathrm{th})}(\mathbf{p}) - \mathcal{O}_n^{(\mathrm{exp})}}{\Delta\mathcal{O}_n} \right)^2 = \chi^2(\mathbf{p}_0) + \mathbf{x}^T \hat{\Sigma}^{-1} \mathbf{x} + \ldots$$

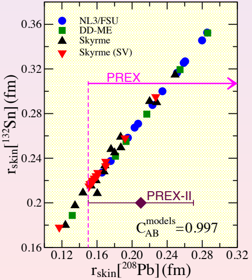
- Predictions accompanied by meaningful theoretical errors
- Covariance analysis least biased approach to uncover correlations

$$\mathrm{Cov}(A,B) = \partial_i A \, \hat{\Sigma}_{ij} \, \partial_j B \, ; \qquad \mathrm{Corr}(A,B) = \frac{\mathrm{Cov}(A,B)}{\sqrt{\mathrm{Var}(A)\mathrm{Var}(B)}}$$

- Isovector sector constrained mostly from "pseudo data"



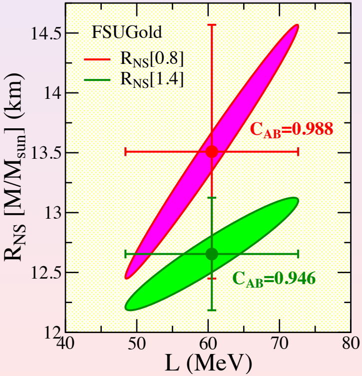


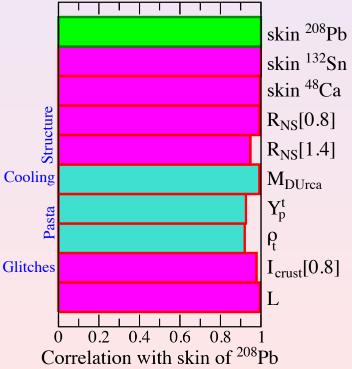


The Enormous Reach of the Neutron Skin

Reinhard-Nazarewicz, PRC 81 (2010) 051303; Fattoyev-Piekarewicz, PRC 86 (2012) 015802; PRC 84 (2011) 064302

- Neutron skin as proxy for neutron-star radii . . . and more!
- Calibration of nuclear functional from optimization of a quality measure
- Predictions accompanied by meaningful theoretical errors
- Covariance analysis least biased approach to uncover correlations
- Neutron skin strongly correlated to a myriad of neutron star properties:
  Radii, Enhanced Cooling, Moment of Inertia, . . .

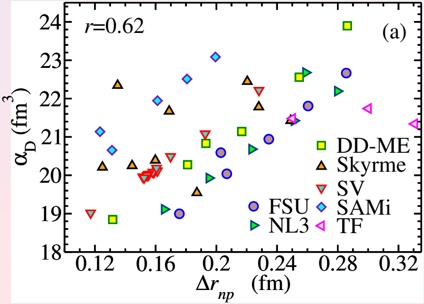


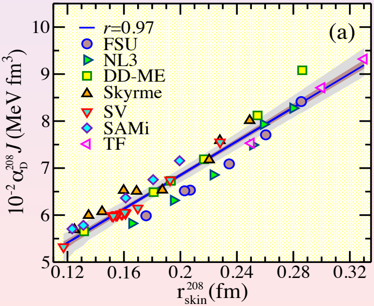


The Electric Dipole Polarizability in ^{208}Pb

RCNP: A. Tamii *et al.*, PRL 107, 062502 (2011)

- IVGDR: *Coherent oscillations of protons against neutrons*
  Nuclear symmetry energy as the restoring force
- RCNP: polarized proton inelastic scattering at very forward angles
  Cross sections at very small angles arise purely from CoulEx
- High-resolution exp. in excellent agreement with photo-absorption data
- Accurate measurement of E1 polarizability: $\alpha_{\rm D} = (20.1 \pm 0.6)\,{\rm fm}^3$
- E1 polarizability as a complement to $R_{\rm skin}^{208}$





Neutron Skin and Dipole Polarizability in ^{208}Pb

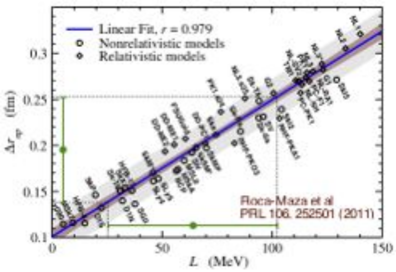
Roca-Maza *et al.*, **PRL 106, 252501 (2011); PRC (in press)**

- Neither J nor L are measurable observables; requires theoretical input
- Statistical and systematic correlation analyses essential
  Seek laboratory/astrophysical observables strongly correlated to J, L, ...
- Use strong $r_{\rm skin}^{208}$ *vs* L correlation to constrain L

$$r_{\rm skin}^{208} = \frac{r_{\rm s}}{2}\left(\frac{L + L_{\rm s} \pm \delta L_{\rm s}}{L_{\rm s}}\right) \quad \left[r_{\rm s} = 0.2\,{\rm fm},\, L_{\rm s} = 68.7\,{\rm MeV},\, \delta L_{\rm s} = 6.8\,{\rm MeV}\right]$$

$$\Delta L_{\rm PREXII}(0.06\,{\rm fm}) = 40.8\,{\rm MeV};\;\; \Delta L_{\rm SPREX}(0.02\,{\rm fm}) = 13.6\,{\rm MeV}$$

$$\Delta L = \sqrt{(\Delta L_{\rm exp})^2 + (\Delta L_{\rm th})^2} = 15.2\,{\rm MeV}$$



Neutron Skin and Dipole Polarizability in ^{208}Pb . . . continuation

Roca-Maza *et al.*, PRL 106, 252501 (2011); PRC (in press); Zhang and Chen, arXiv:1302.5327

- Use strong $J\alpha_{\rm D}^{208}$ *vs* L correlation to constrain J

$$\alpha_{\rm D}^{208} = \frac{\alpha_{RCNP}^{208}}{\left(J/J_{\alpha}\right)}\frac{1}{2}\left(1+\frac{L}{L_{\alpha}}\right)$$

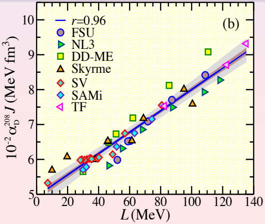
$$\alpha_{RCNP}^{208} = 20.1\,{\rm fm}^3,\, J_{\alpha} = 49.2\,{\rm MeV},\, L_{\alpha} = 159.4\,{\rm MeV}$$

- Assuming error dominated by $\Delta L_{\rm PREXII/SPREX}$

$$\Delta J_{\rm PREXII}(0.06\,{\rm fm}) = 6.3\,{\rm MeV};\;\; \Delta J_{\rm SPREX}(0.02\,{\rm fm}) = 2.1\,{\rm MeV}$$

- Alternatively: Nuclear masses constrain symmetry energy at $\rho \approx 0.11\,{\rm fm}^3$

$$J \approx \widetilde{J} + L/9\;(\widetilde{J} \approx 26\,{\rm MeV}) \quad \left[\widetilde{J} = 26.65 \pm 0.20\,{\rm MeV},\; J = 32.3 \pm 1.0\,{\rm MeV}\right]$$



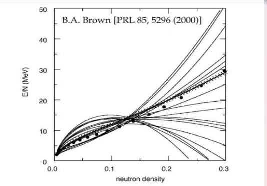
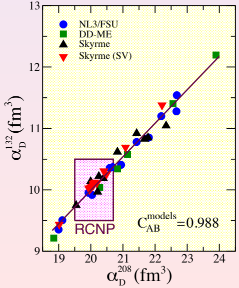
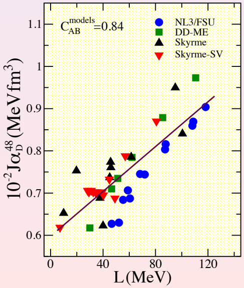


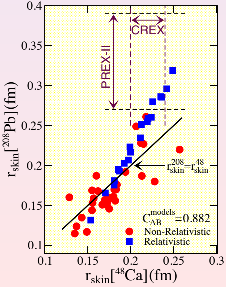
FIG. 2. The neutron EOS for 18 Skyrme parameter sets. The filled circles are the Friedman-Pandharipande (FP) variational calculations and the crosses are SkX. The neutron density is in units of neutron/fm^3.

Neutron Skin and Dipole Polarizability: A look forward

- $r_{\rm skin}^{208}$ and $\alpha_{\rm D}^{208}$ strong isovector indicators used to constrain J and L
- Neither $r_{\rm skin}^{48}$ nor $\alpha_{\rm D}^{48}$ correlate strongly with L
  Too large surface to volume ratio - far from bulk limit
- ^{48}Ca a doubly magic, neutron-rich nucleus within ab-initio reach
  Critical insights for DFT, role of three-body force, . . .
- PREX-II and CREX as powerful calibrating anchors for skins at FRIB
- CREX fully approved by JLAB PAC; $\alpha_{\rm D}^{48}$ being analyzed at RCNP
- $r_{\rm skin}$ and $\alpha_{\rm D}$ in both ^{48}Ca and ^{208}Pb:
  Powerful four-legged stool of isovector observables!!



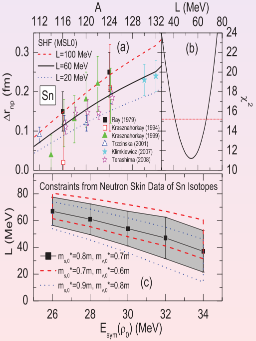


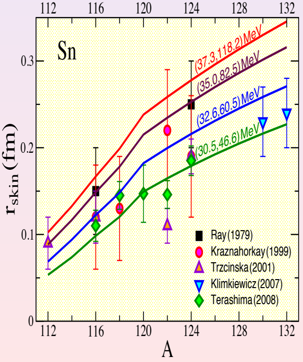


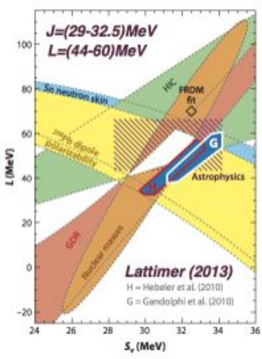
Tin Skins: A look backwards

Chen *et al.*, PRC 82, 024321 (2010); Lattimer and Lim ApJ. 771, 51 (2013)

- Hadronic experiments with large and uncontrolled uncertainties: proton scattering, anti-protonic atoms, pygmy and spin-dipole modes
- $J \approx \widetilde{J} + L/9 \; \left(\widetilde{J} = 26.65 \pm 0.20\,\mathrm{MeV},\; J = 32.3 \pm 1.0\,\mathrm{MeV};\; \mathrm{Zhang\ and\ Chen}\right)$
- Not all observables—and theoretical models—are created equal
- Enormous disservice to both the nuclear- and astro-physics communities







PREX is Wrong! $r_{\rm skin}^{208} = 0.33^{+0.16}_{-0.18}$ fm

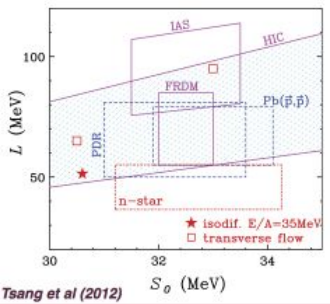
- Statistical error large: Models with $r_{\rm skin}^{208} \gtrsim 0.15$ fm within 1σ
- Statements from the Literature:

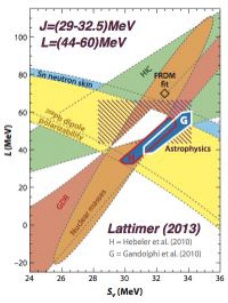
  "$L_{\rm PREX} = (148.5 \pm 113.5)$ mean value discrepant but errors very large" (Lattimer 2013)

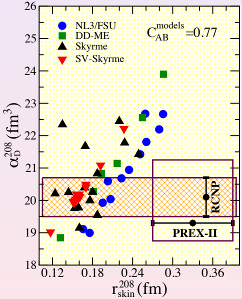
  "... if $L = (64.8 \pm 15.7)$ MeV one obtains $r_{\rm skin}^{208} \gtrsim (0.194 \pm 0.024)$ fm" (Carbone 2010)

  "... QMC combined with NStars give $L = (36 - 55)$ MeV to 95% C.L." (Tsang 2012)

  "... permissible ranges reasonably restricted: $L = (44 - 60)$ MeV" (Lattimer 2013)





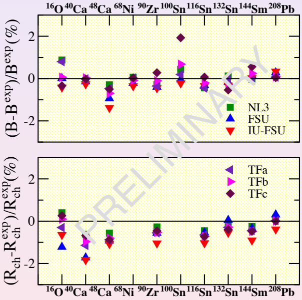


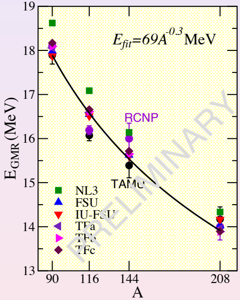
So, is PREX central value already ruled out?

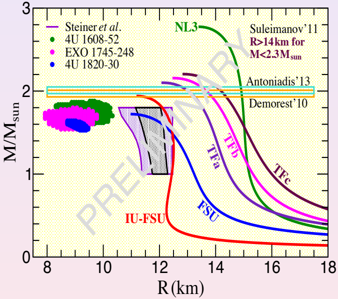
Is PREX Wrong? Is PREX central value already ruled out?

F. Fattoyev and JP (submitted to PRL)

- Is it possible to construct models that reproduce **real data** and have thick skins?
- Three models: TFa, TFb, TFc with:
  $r_{\rm skin}^{208} = (0.25, 0.30, 0.33)$ fm and $L = (83, 123, 135)$ MeV
- To compute nuclear masses, charge radii, monopole excitations, and MvsR
- So far, no evidence that these models are significantly worse or better than FSUGold, . . .







"The reports of my death have been greatly exaggerated" Mark Twain

Future Directions in Nuclear Structure . . . some thoughts

- Theoretical Pillar:
  Search for an accurately-calibrated microscopic theory that both predicts and provides well-quantified theoretical uncertainties from finite nuclei to neutron stars
- (Some) Experimental Pillars: Neutron Skins and Giant Resonances
  Neutron Skins: Very compelling case; thickness of neutron skins emerges from a competition between surface tension and DDSE (where do the extra neutrons go?)
  PREX-II and PREX-III and/or ^{124}Sn and/or ^{112}Sn? Physics case must be compelling

  IsGMR: Strong sensitivity to the DDSE: $K_0(\alpha) = K_0 + (K_{\rm sym} - 6L + \ldots)\alpha^2$
  Softness of Sn? Measurement of GMRs for exotic (large α) nuclei at FRIB, . . .

  IvGDR: Electric Dipole Polarizability as a strong isovector indicator: $J\alpha_D \propto \left(1 + \frac{5}{3}\frac{L}{J}\epsilon_A\right)$
  Systematics of α_D *vs* L (RCNP); Measurement of α_D for exotic (large α) nuclei at GSI, FRIB, . . .; Correlating emergence of low-energy dipole strength with development of neutron-rich skin (Pygmy), . . .
- All part of a coherent plan that involves critical laboratory and astrophysical data

All observables (and theories) are created equal but some are more equal than others!