Neutron Skin and Its Ties to Nuclear Equation of State

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Exploring nuclear physics across energy scales 2024

CCAST Institute of Theoretical Physics, Beijing

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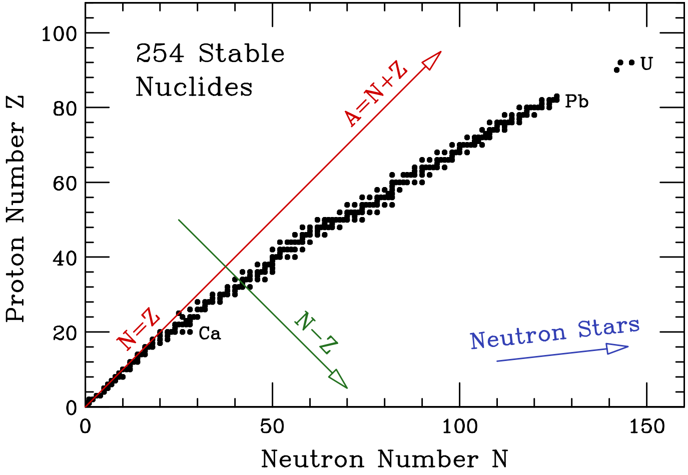
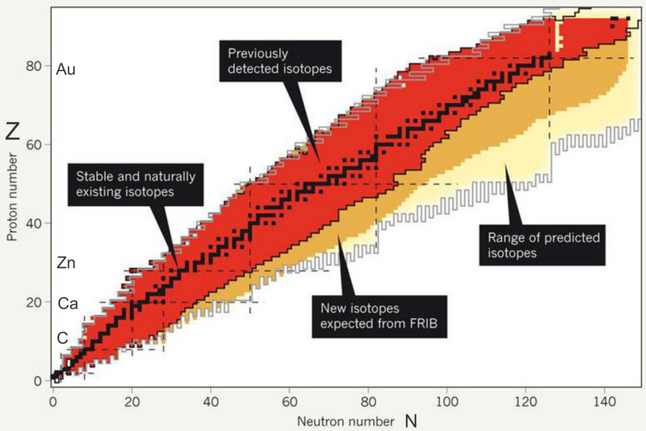
Nuclei as Binary Systems



Preference for $N \sim Z$

Extrapolation to neutron stars with $N \gg Z$?

Expanding Chart of Nuclides



Accelerator tech progress pushes chart boundaries out. . .

Thoennessen IJMP E24(15)1530002: >3000 nuclides (>10× than stable!) known

Up to 1000 new nuclides expected in next decade! FRIB: 5 new this year

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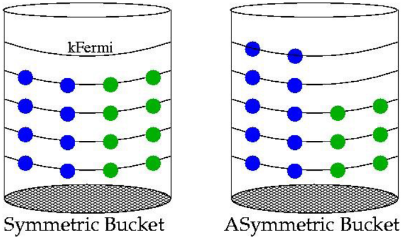
Protons & Neutrons

$N \approx Z$ favored when strong interactions dominate

Pauli principle + interactions more attractive for np pairs than pp or nn (also Pauli, but at quark level)



Mass formula:

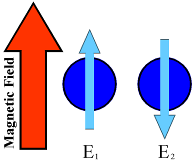
$$E = -a_V\,A + a_S\,A^{2/3} + a_C\,\frac{Z^2}{A^{1/3}} + a_a\,\frac{(N-Z)^2}{A} + E_{\text{mic}}$$

symmetry energy term $\quad a_a(A)$?

Relative spatial distribution of the species?

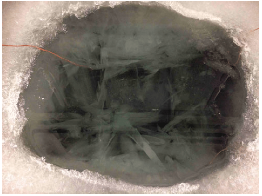
Relative Distribution of Species?

Statistical considerations: entropy vs energy

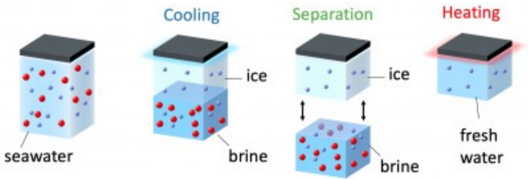


Example: $H_2O + NaCl$

Above freezing & below saturation, salinity (relative *NaCl* concentration) uniform, entropy & energy go along but, when water freezes, *NaCl* gets expelled from ice, as energy wins



Industrial desalination:



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Charge Symmetry & Charge Invariance

Charge symmetry: invariance of nuclear interactions under $n \leftrightarrow p$ interchange

An isoscalar quantity F does not change under $n \leftrightarrow p$ interchange.
E.g. nuclear energy. Expansion in asymmetry $\eta = (N - Z)/A$, for smooth F, yields even terms only:

$$F(\eta) = F_0 + F_2\,\eta^2 + F_4\,\eta^4 + \ldots$$

An isovector quantity G changes sign. Example: $\rho_{np}(r) = \rho_n(r) - \rho_p(r)$.
Expansion with odd terms only:

$$G(\eta) = G_1\,\eta + G_3\,\eta^3 + \ldots$$

Note: $G/\eta = G_1 + G_3\,\eta^2 + \ldots$.

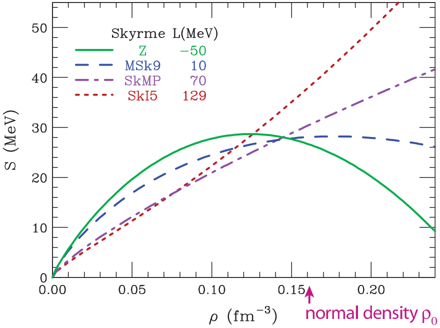
In nuclear practice, analyticity requires shell-effect averaging!

Charge invariance: invariance of nuclear interactions under rotations in n-p space.

Energy in Uniform Matter

$$\frac{E}{A}(\rho_n, \rho_p) = \frac{E_0}{A}(\rho) + S(\rho)\left(\frac{\rho_n - \rho_p}{\rho}\right)^2 + \mathcal{O}(\ldots^4)$$

symmetric matter (a)symmetry energy $\rho = \rho_n + \rho_p$



Net $\rho = \rho_n + \rho_p$ isoscalar

Difference $\rho_n - \rho_p$ isovector

$\rho_a = \frac{A}{N-Z}(\rho_n - \rho_p)$ isoscalar

$$\rho_{n,p}(r) = \frac{1}{2}\left[\rho(r) \pm \frac{N-Z}{A}\rho_a(r)\right]$$

ρ & ρ_a universal in isobaric chain!

Energy min in Thomas-Fermi:

$$\rho_a(r) \propto \frac{\rho(r)}{S(\rho(r))}$$

low $S \Leftrightarrow$ high ρ_a

$$S(\rho) = S(\rho_0) + \frac{L}{3}\frac{\rho - \rho_0}{\rho_0} + \ldots$$

Unknown: $S(\rho_0)$? L ?

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Symmetry-Energy Stiffness: *M* & *R* of *n*-Star

$$\frac{E}{A} = \frac{E_0}{A}(\rho) + S(\rho)\left(\frac{\rho_n - \rho_p}{\rho}\right)^2$$

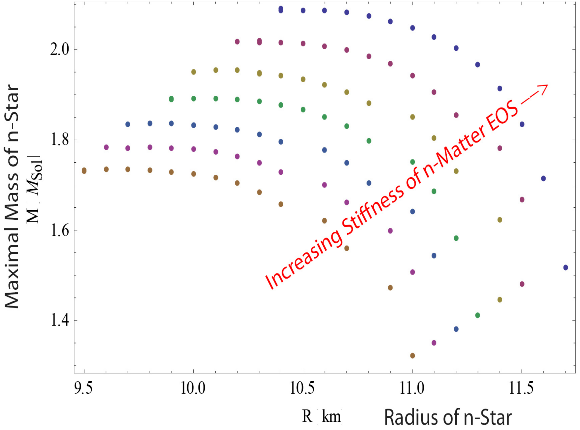
$$S \simeq a_a^V + \frac{L}{3}\frac{\rho - \rho_0}{\rho_0}$$

In neutron matter:
$\rho_p \approx 0$ & $\rho_n \approx \rho$.

Then, $\frac{E}{A}(\rho) \approx \frac{E_0}{A}(\rho) + S(\rho)$

Pressure:

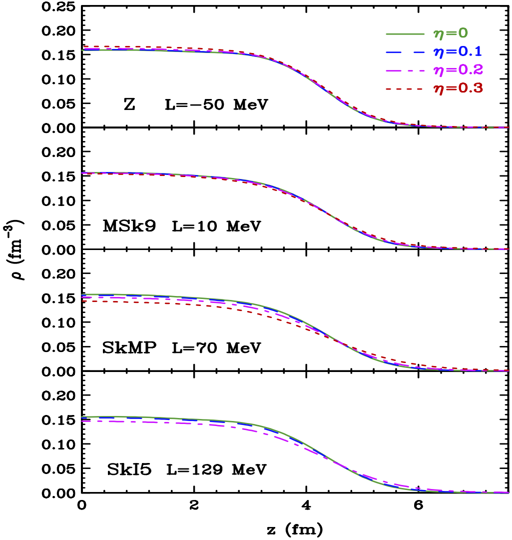
$$P = \rho^2 \frac{\mathrm{d}}{\mathrm{d}\rho}\frac{E}{A} \simeq \rho^2 \frac{\mathrm{d}S}{\mathrm{d}\rho} \simeq \frac{L}{3\rho_0}\rho^2$$



Schematic Calculation by Stephen Portillo (Harvard U)

Stiffer symmetry energy correlates with larger neutron-star mass & radii

Asymmetry Dependence of **Net Density**

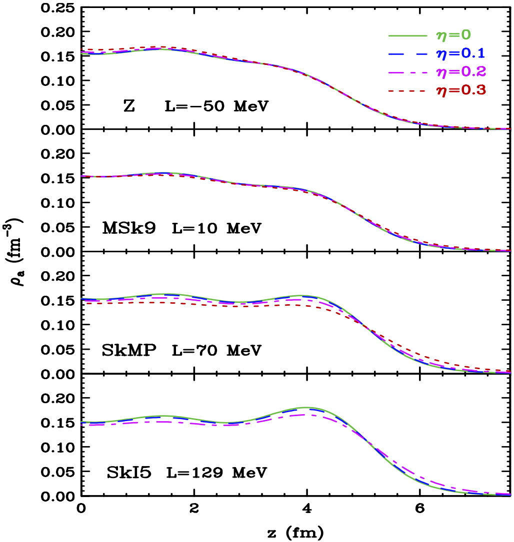


Half-∞ matter results for different Skyrme interactions and asymmetries

$$\eta = \frac{N-Z}{A}$$

PD&Lee NP818(09)36

Asymmetry Dependence of **Isovector Density**

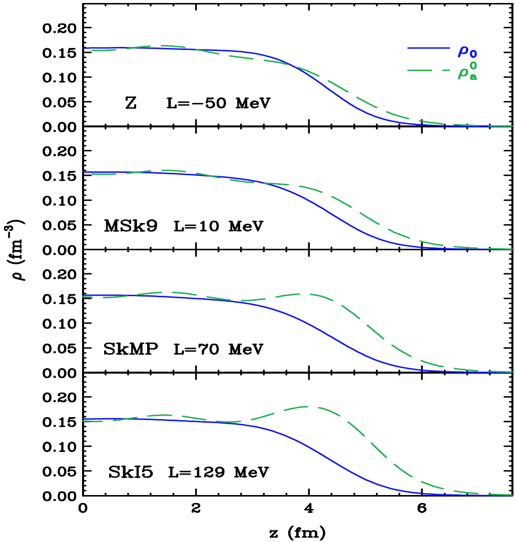


$$\rho_a = \frac{2a_a^V}{\mu_a}(\rho_n - \rho_p)$$

Half-∞ matter results for different Skyrme interactions and asymmetries

PD&Lee NP818(09)36

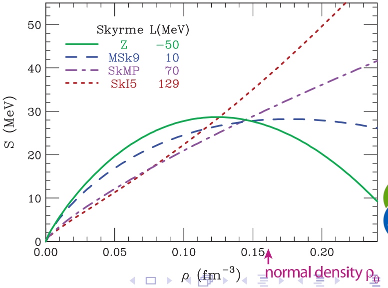
Sensitivity to $S(\rho)$



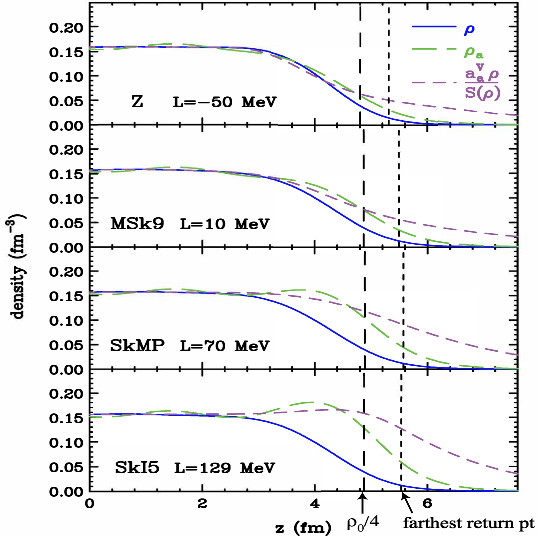
Results f/different Skyrme ints in half-∞ matter

Isoscalar (ρ=ρ_n+ρ_p; blue) & isovector (ρ_n-ρ_p; green) densities displaced relative to each other

As $S(\rho)$ changes, so does displacement of ρ_a vs ρ



Sensitivity to $S(\rho)$



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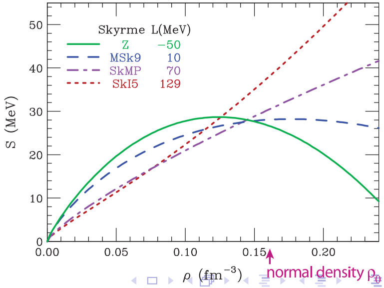
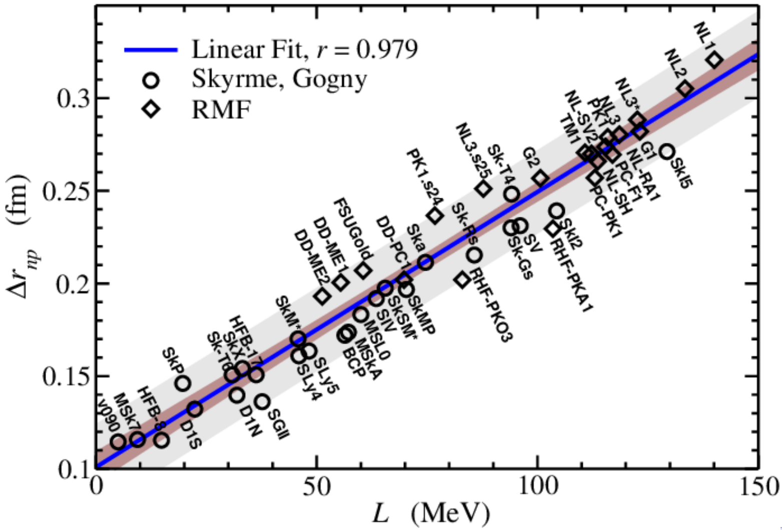


Correlation Between Stiffness & ^{208}Pb *n*-Skin

Viñas *et al* EPJA50(14)1

also Xavier Roca-Maza



From skin to *n*-star...

Experimental Efforts & Observations

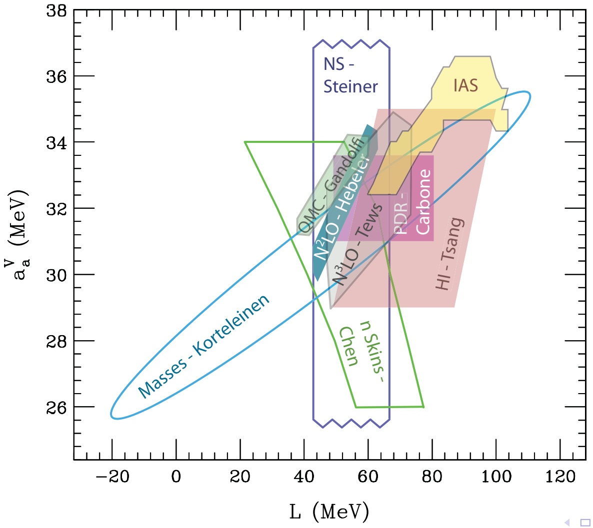
Experiments directly probing ground-state geometry:

- Elastic scattering
- Parity-violation in electron scattering
- Quasielastic charge exchange reactions
- Charge radii of mirror nuclei
- Charge-changing reactions

Other data testing symmetry energy:

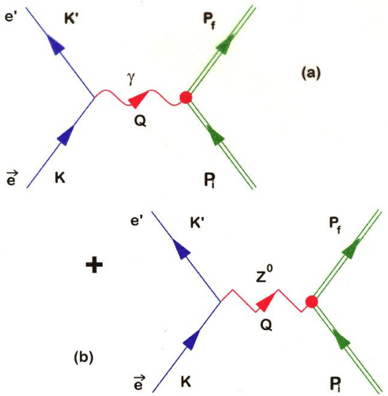
- Dipole polarizability
- Masses
- Heavy ions: diffusion, π^-/π^+ ratio, ...
- Neutron star: maximal *M*, *M*-*R* relation, deformability
- ...

Sample Symmetry-Energy Constraints

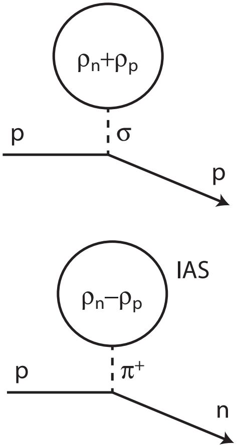


Differently Probing 2 Densities??

Jefferson Lab
Direct: $\sim p$
Interference: $\sim n$



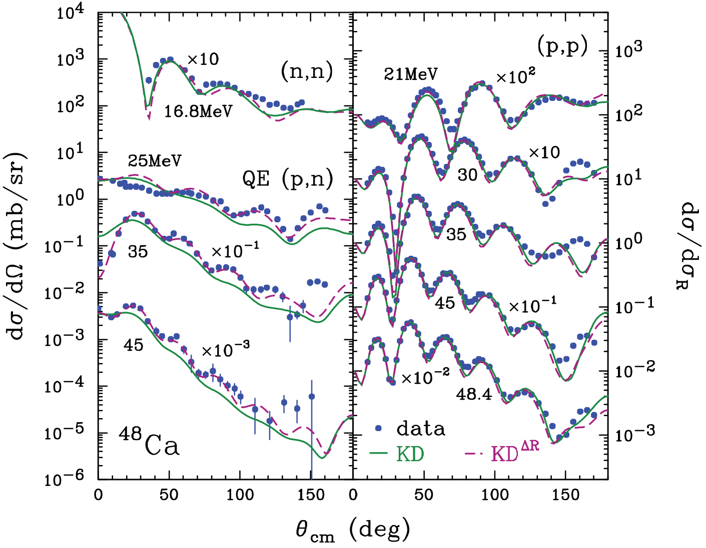
PD, Singh, Lee NPA958(17)147
[after Dao Tien Khoa]



elastic: $\sim p + n$

charge exchange:
$\sim n - p$

Simultaneous Fits to Elastic & Charge-Exchange: ^{48}Ca



Koning-Delaroche (KD) optical potential w/isoscalar & isovector terms & no skin NPA713(03)231 applied simultaneously to elastic scattering & quasielastic charge exchange

Different radii for isovector & isoscalar densities/potentials: $R_a = R + \Delta R$

ΔR: isovector skin

PD/Singh/Lee NPA958(17)147

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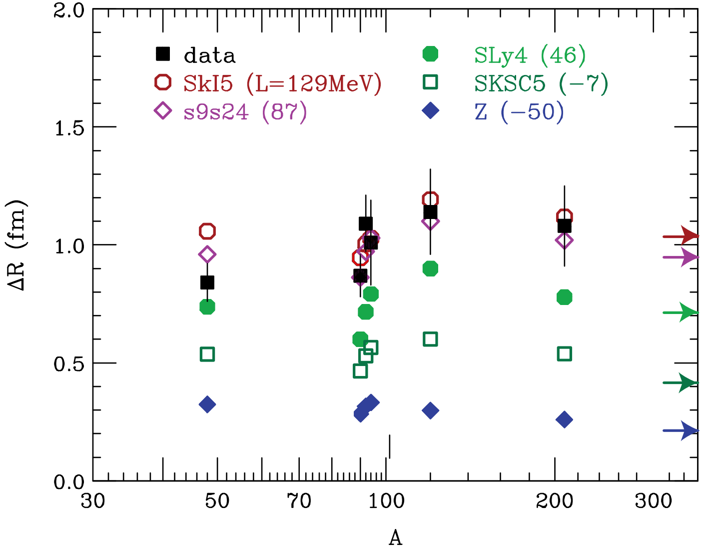
Thickness of Isovector Skin



6 targets analyzed
differential cross section
+ analyzing power

Colored: Skyrme predictions
Arrows: half-infinite matter

Thick isovector skin
∼ 0.9 fm!
∼ *A*-independent. . .

^{48}Ca & ^{208}Pb consistent!

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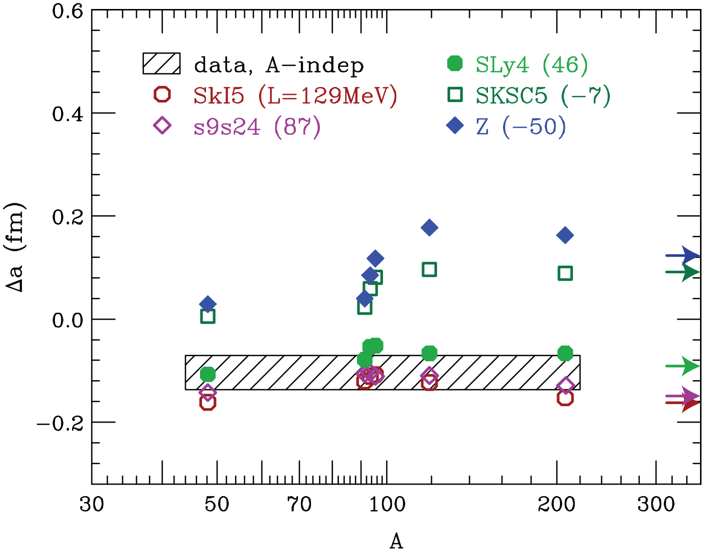
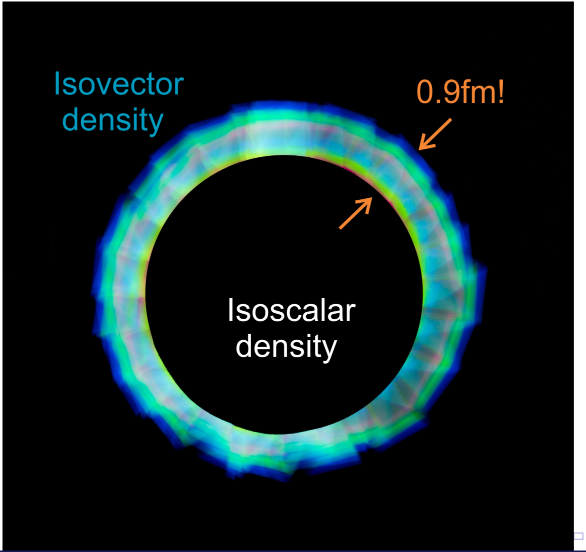
Diffuseness: Isovector-Isoscalar Difference



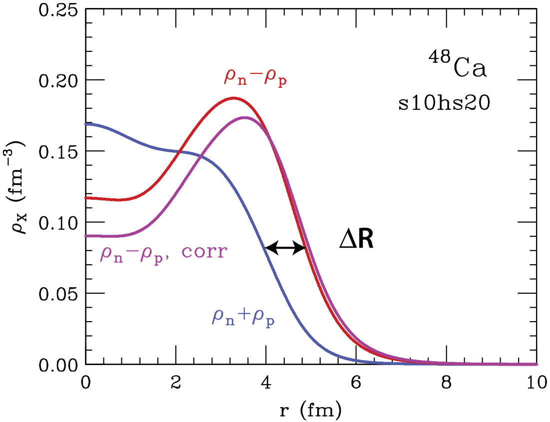
Colored: Skyrme predictions. Arrows: half-infinite matter

Sharper isovector surface than isoscalar!

Isovector Skin



Isovector vs Neutron Skin?



Much Larger Than Neutron!

Surface radius $R \simeq \sqrt{\frac{5}{3}}\, \langle r^2 \rangle^{1/2}$

rms neutron skin

$$\langle r^2 \rangle^{1/2}_{\rho_n} - \langle r^2 \rangle^{1/2}_{\rho_p}$$

$$\simeq 2\, \frac{N-Z}{A} \left[\langle r^2 \rangle^{1/2}_{\rho_n - \rho_p} - \langle r^2 \rangle^{1/2}_{\rho_n + \rho_p} \right]$$

rms isovector skin

Estimated $\Delta R \sim 3 \left(\langle r^2 \rangle^{1/2}_{\rho_n} - \langle r^2 \rangle^{1/2}_{\rho_p} \right)$ for ^{48}Ca/^{208}Pb!

Even before consideration of Coulomb effects that further enhances difference!

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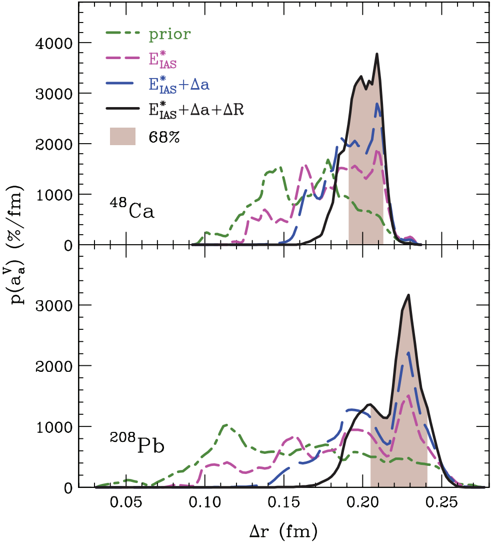
Likelihood f/Neutron-Skin Values



Sizeable *n*-Skins

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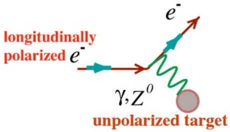
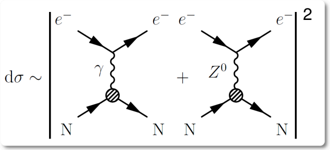
Parity Violating Scattering Experiments





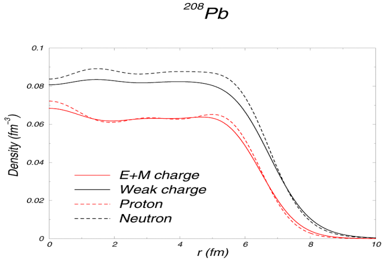
A_{PV} from interference

$$A_{PV} = \frac{\sigma^R - \sigma^L}{\sigma^R + \sigma^L}$$

after Michaels, Horowitz & Thiel

$$A_{PV} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \left[\underbrace{1 - 4\sin^2(\theta_W)}_{\approx 0} - \frac{F_W(Q^2)}{F_{ch}(Q^2)} \right] \sim 10^{-4} \times Q^2$$

	p	n
electric charge	1	0
weak charge	0.07	-1



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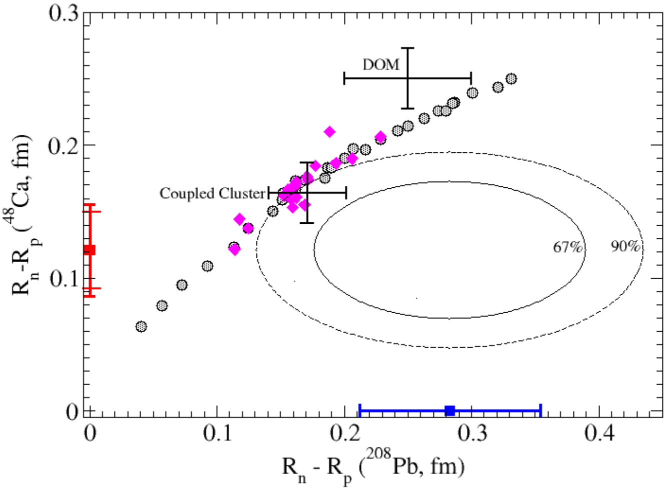
PREX-2 vs CREX

Months of running at Jefferson Lab, just for single mom transfer per target, PREX-2 for ^{208}Pb & CREX for ^{48}Ca!

^{208}Pb has higher n-p asymmetry than ^{48}Ca, but stronger Coulomb, so n-skins expected similar

The experiments yield results at tension with each other



Adhikari *et al* PRL129(22)042501

Tension on Earth & vs Heaven

CREX vs PREX: 2 Camps

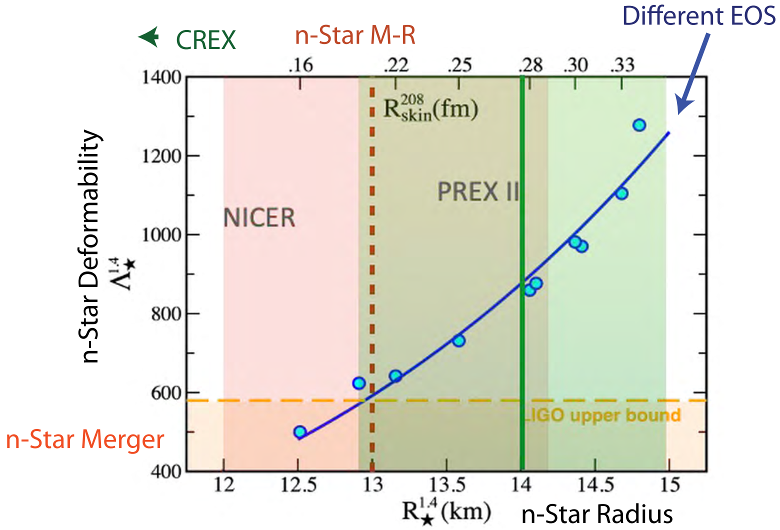
- Bayesian combination of two,
  e.g., Zhang&Chen PRC108(23)024317, $L \sim 15\,\text{MeV}$?!
- The expts cannot be simultaneously right,
  e.g. Yuksel&Paar PLB836(23)137622

Follow-up MREX for ^{208}Pb at Mainz

Observations of heavenly objects

- Maximal n-star masses
- LIGO: gravitational waves $\rightarrow$ n-star deformability
- NICER: X-rays from n-stars $\rightarrow$ M/R for n-stars

Heaven vs Earth



after Chuck Horowitz

selected constraints

larger deformability ↔ larger radius

Conclusions

- In nuclear surface, isovector density leaks out of isoscalar density. In effect of isovector skin, rms radius for majority nucleons is greater than for minority, or majority-nucleon skin appears
- Size of isovector or majority skin is a direct consequence of dependence of symmetry energy on ρ, at $\rho \lesssim \rho_0$, and diffuseness for isoscalar density
- Constraints on skins can emerge from data that directly reflect nuclear geometry and from data that in other ways probe ρ-dependence of symmetry energy
- As uncertainties in skin constraints or in ρ-dependence of symmetry energy become more seriously determined, lack of consensus emerges

DOE DE-SC0019209

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