Stiff Equation of State of Neutron Matter from Thick Isovector Aura

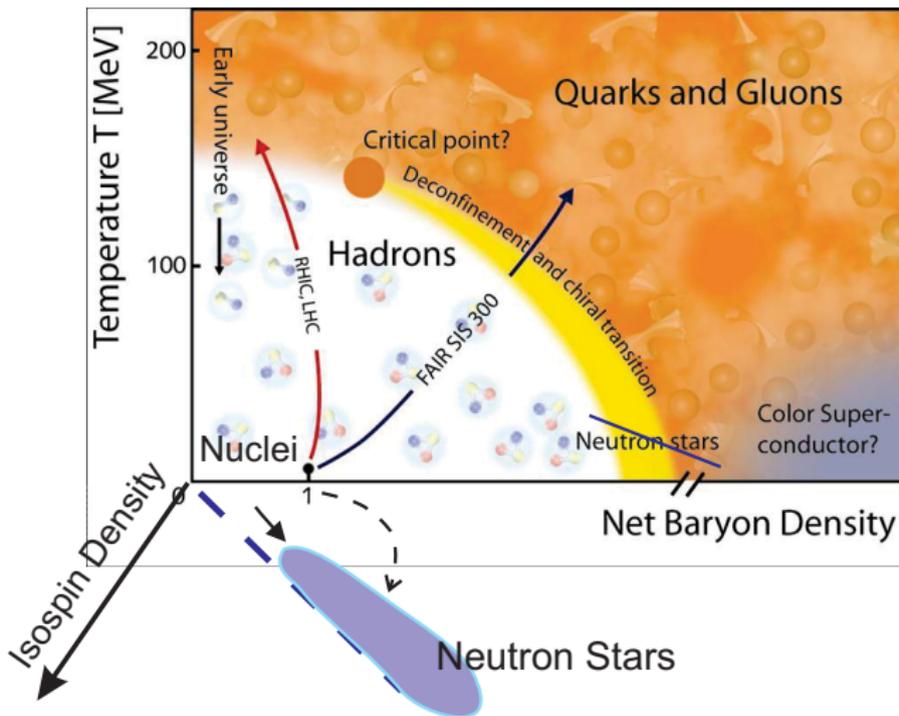Pawel Danielewicz[1] and Yannick Cianyi[2]

[1] National Superconducting Cyclotron Lab, Michigan State U

and [2] U of Kinshasa, DRC

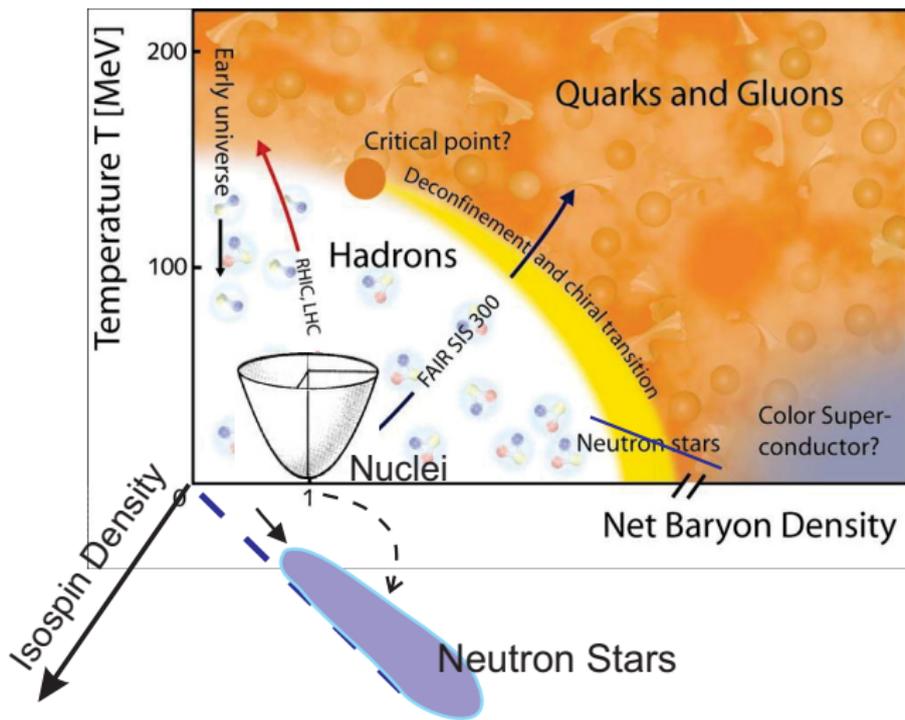XIIIth Quark Confinement and the Hadron Spectrum

National University of Ireland, Maynooth, Ireland
1-6 August 2018

Bulk Properties of Strongly-Interacting Matter

Introduction
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Data Analysis
○○○○

Bayesian Inference
○○○

Conclusions
○○

Equation of State

Structure/Direct Reactions - $\rho \leq \rho_0$. HI Collisions - coarse, but all ρ

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:

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

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

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

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

In nuclear practice, analyticity requires shell-effect averaging!

Charge invariance: invariance of nuclear interactions under rotations in *n-p* space. Isospin $\vec{T} = \sum_{i=1}^{A} \vec{\tau}_i$ SU(2)

Introduction
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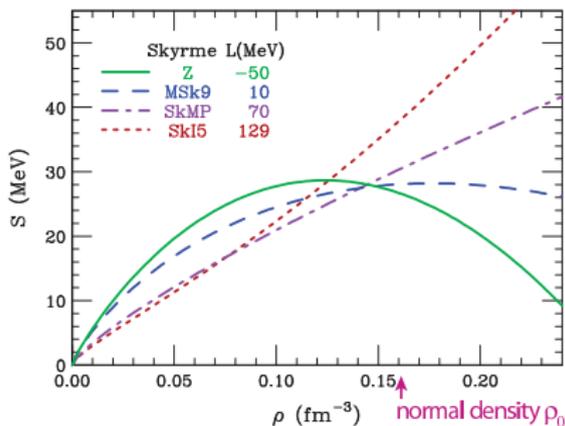Data Analysis
○○○○

Bayesian Inference
○○○

Conclusions
○○

Examples: Nuclear Energy, Densities

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

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

Skyrme L(MeV)
Z   −50
MSk9   10
SkMP   70
SkI5   129

S (MeV) vs ρ (fm^{-3})

normal density ρ_0

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

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

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

Difference $\rho_n - \rho_p$ isovector

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

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

Energy min in Thomas-Fermi:

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

low $S \Leftrightarrow$ high ρ_a

Stiffness of EOS & Mass & Radius of n-Star

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

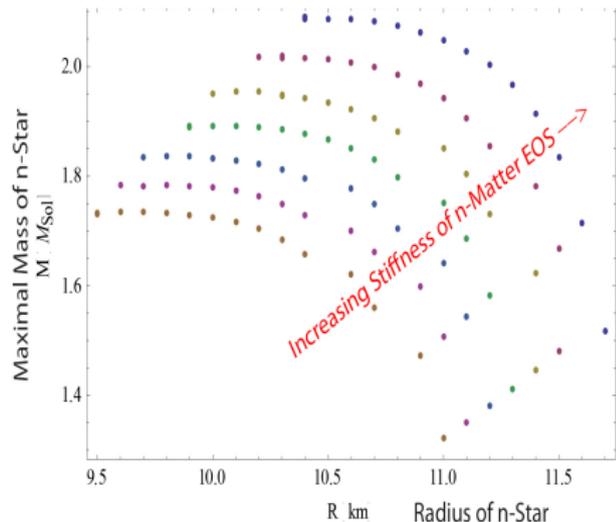$$S \simeq a_a^V + \frac{L}{3}\frac{\rho - \rho_0}{\rho_0}$$

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:

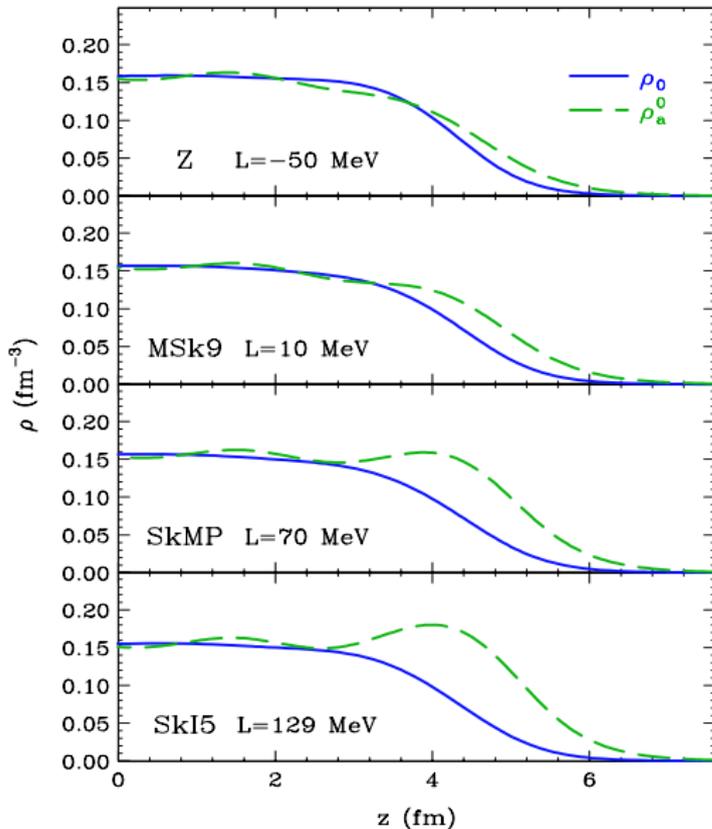$$P = \rho^2 \frac{d}{d\rho}\frac{E}{A} \simeq \rho^2 \frac{dS}{d\rho} \simeq \frac{L}{3\rho_0}\rho^2$$

Schematic Calculation by Stephen Portillo (Harvard U)

Stiffer symmetry energy correlates with
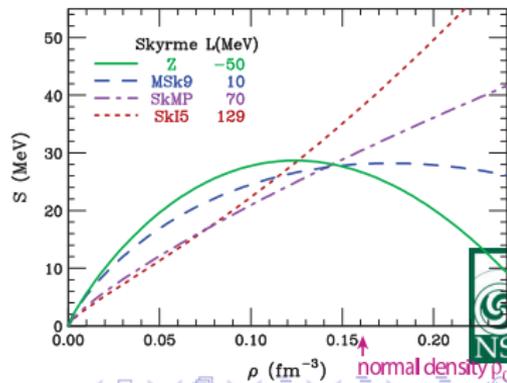   larger max mass of neutron star & larger radii

Relation between ρ, ρ_a & $S(\rho)$
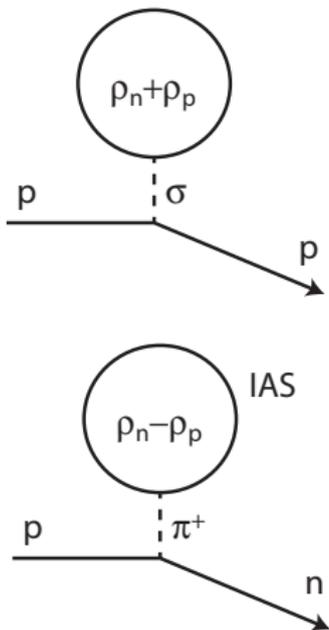

Results f/different Skyrme ints in half-∞ matter.

Isoscalar ($\rho=\rho_n+\rho_p$; blue) & isovector ($\rho_a \propto \rho_n-\rho_p$; green) densities displaced relative to each other.

As $S(\rho)$ changes, $\rho_a(r) \propto \frac{\rho(r)}{S(\rho(r))}$, so does displacement.
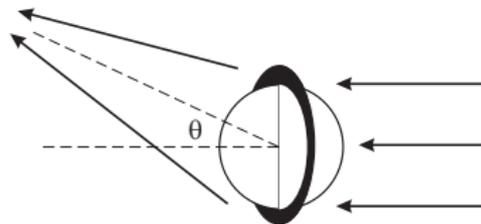
Introduction
oooooo

Data Analysis
●ooo

Bayesian Inference
ooo

Conclusions
oo

Probing Independently 2 Densities

elastic scattering: $\sim \rho_p + \rho_n$

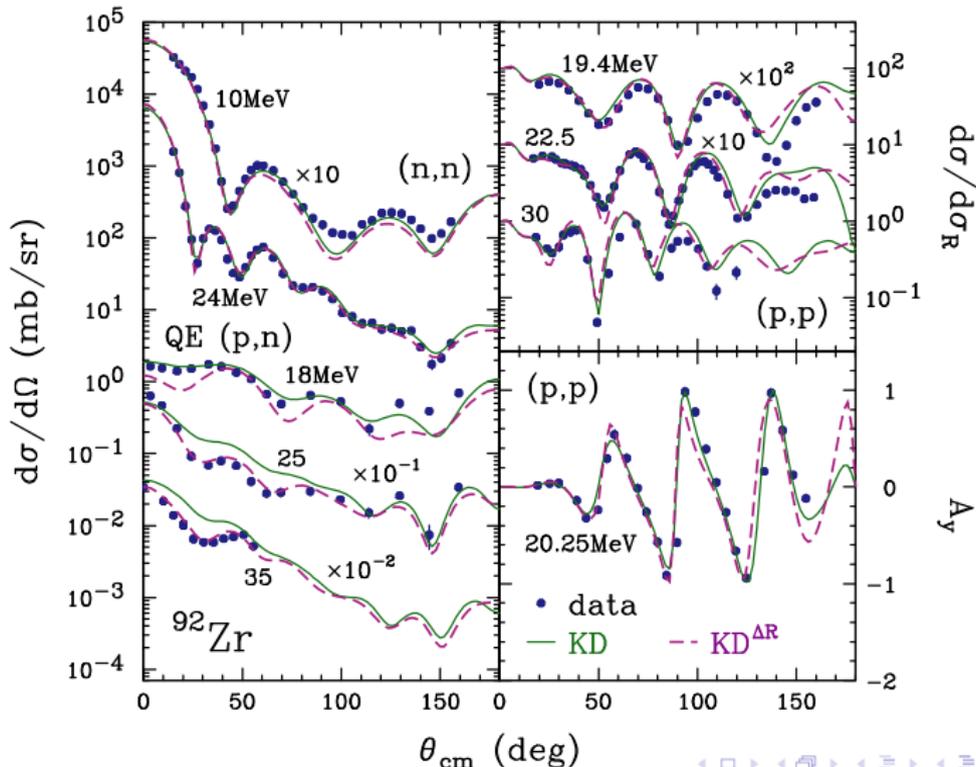charge exchange $p \to n$: $\sim \rho_n - \rho_p$

PD, Sigh, Lee NPA958(17)147

Introduction
oooooo

Data Analysis
o●oo

Bayesian Inference
ooo

Conclusions
oo

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

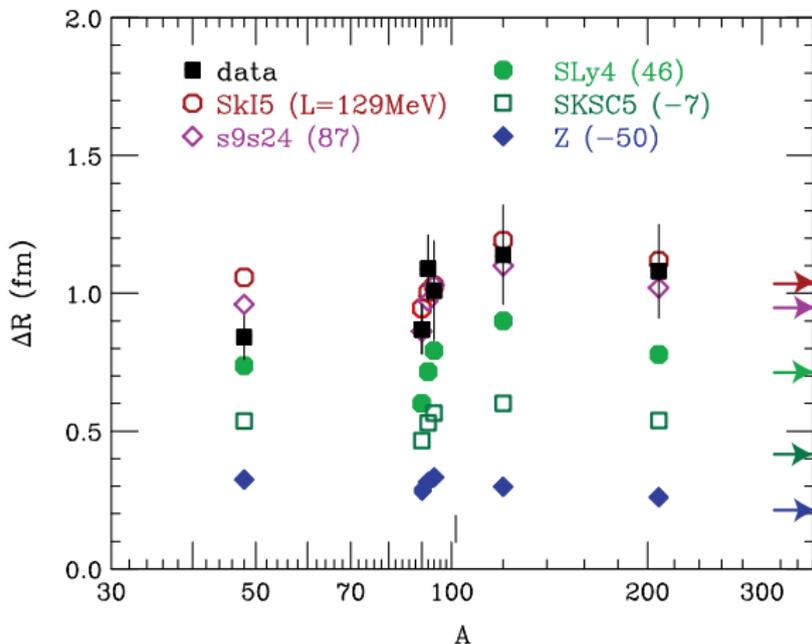## Different radii for densities: $R_a = R + \Delta R$
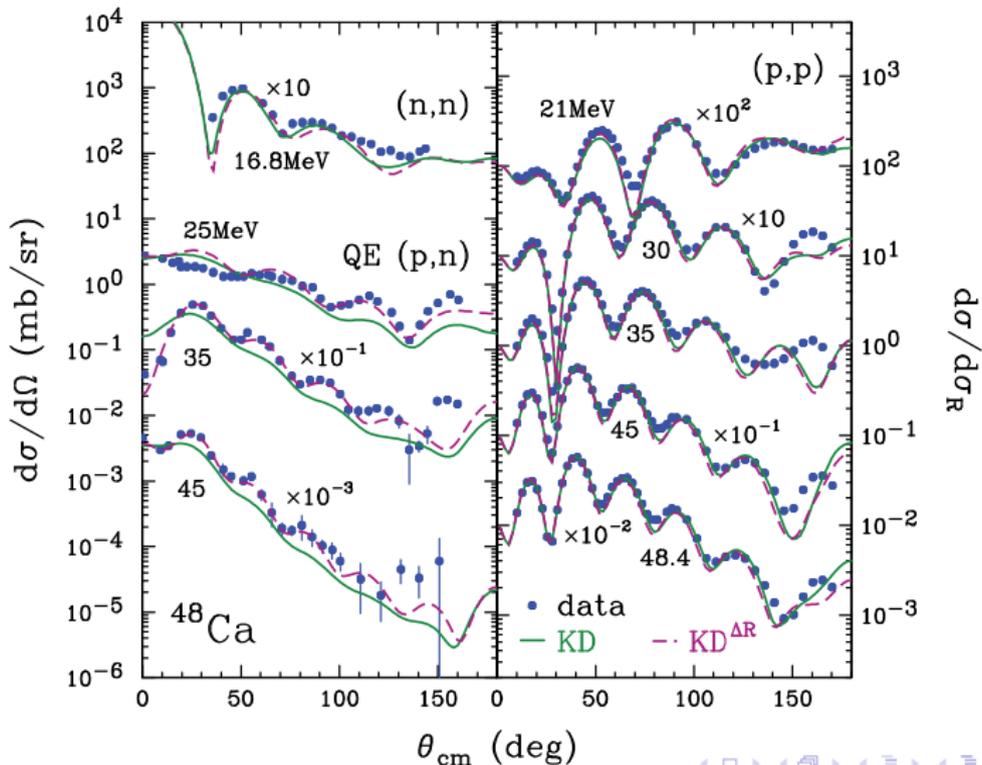
Simultaneous Fits to Elastic & Charge-Change: ^{92}Zr

Different radii for densities: $R_a = R + \Delta R$

Thickness of Isovector Aura

6 targets analyzed, differential cross section + analyzing power

Colored: Skyrme predictions. Arrows: half-infinite matter

Thick ~ 0.9 fm isovector aura! $\sim$Independent of A.

Bayesian Inference

Probability density in parameter space $p(x)$ updated as experimental data on observables E, value $\overline{E}$ with error σ_E, get incorporated

Probability p is updated iteratively, starting with prior p_{prior}

$p(a|b)$ - conditional probability

$$p(x|\overline{E}) \propto p_{\text{prior}}(x) \int dE \, e^{-\frac{(E-\overline{E})^2}{2\sigma_E^2}} \, p(E|x)$$

For large number of incorporated data, p becomes independent of p_{prior}

In here, p_{prior} and $p(E|x)$ are constructed from all Skyrme ints in literature, and their linear interpolations. p_{prior} is made uniform in plane of symmetry-energy parameters (L, S_0)

Introduction
○○○○○○
Data Analysis
○○○○
Bayesian Inference
○●○
Conclusions
○○

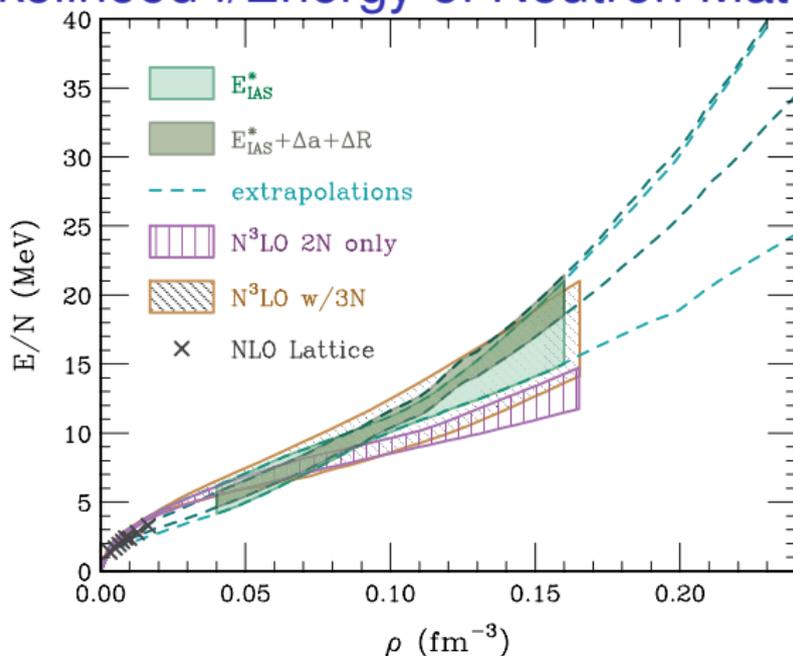# Likelihood f/Symmetry-Energy Slope
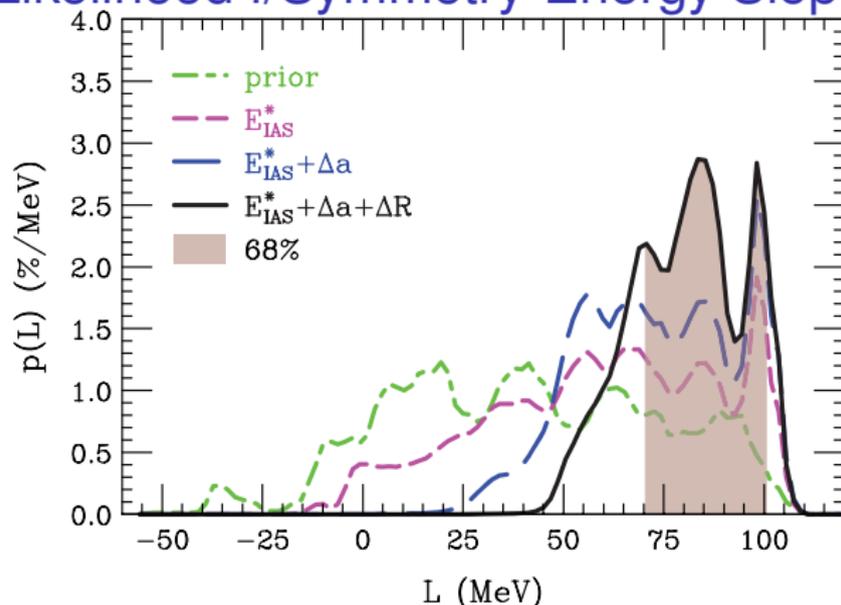
E_{IAS}^* - from excitations to isobaric analog states
in PD&Lee NPA922(14)1

Oscillations in prior of no significance
- represent availability of Skyrme parametrizations

Introduction
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Data Analysis
oooo

Bayesian Inference
ooo●

Conclusions
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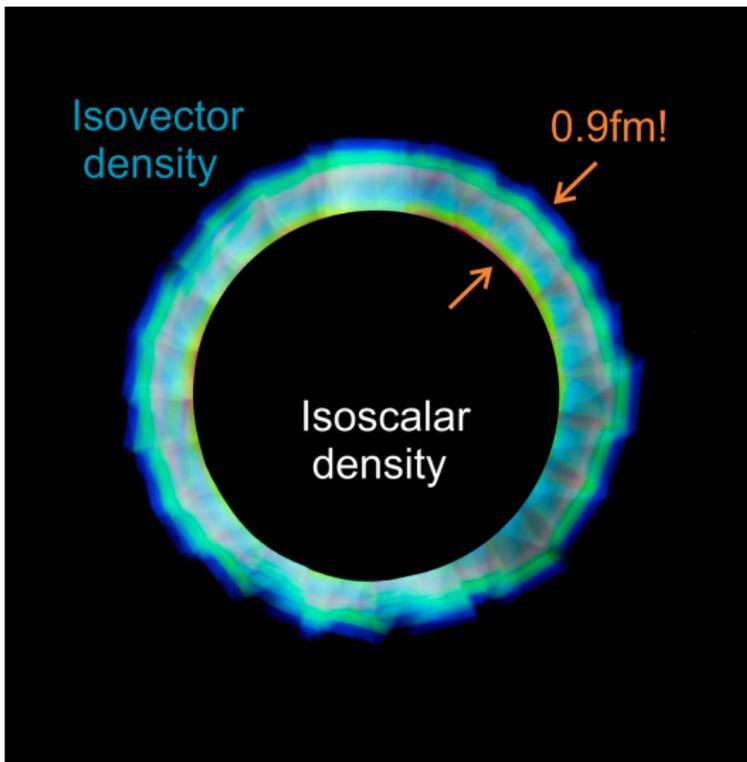
Likelihood f/Energy of Neutron Matter

E^*_{IAS} - from excitations to isobaric analog states
in PD&Lee NPA922(14)1

Some oscillations due to prior

Isovector Aura

Conclusions

- Symmetry-energy polarizes nuclear densities, pushing isovector density out to region of low isoscalar density

- For large A, displacement of isovector relative to isoscalar surface is expected to be roughly independent of nucleus and depend on slope of symmetry energy

- Surface displacement can be studied in comparative analysis of data on elastic scattering and quasielastic charge-exchange reactions

- Such an analysis produces thick isovector aura
  $\Delta R \sim 0.9$ fm!

- Symmetry & neutron energies are stiff!
  $L = (70 - 100)$ MeV, $S(\rho_0) = (33.5 - 36.5)$ MeV at 68% level