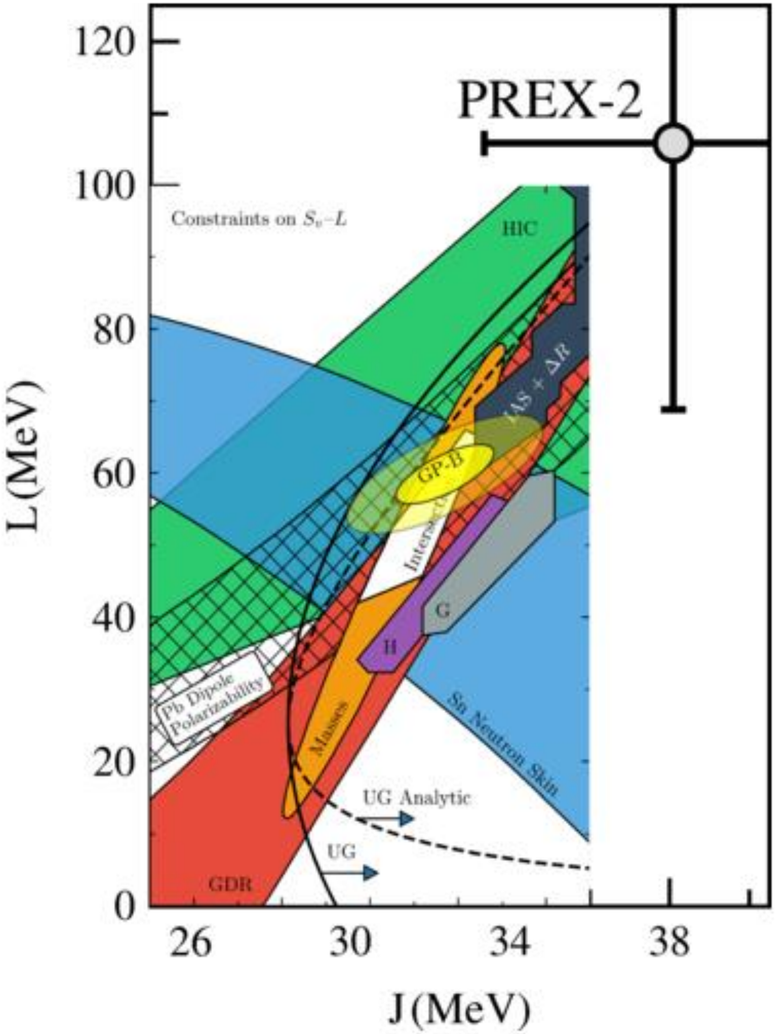
Symmetry energy constraints from nuclear structure studies



MANHATTAN COLLEGE

NuSym21
International Symposium on Nuclear Symmetry Energy
September 22, 2021, Online

Symmetry Energy: *Some Definitions*

Total energy per baryon:

$$E(\rho, \alpha) = E_{\mathrm{SNM}}(\rho) + E_{\mathrm{sym}}(\rho) \cdot \alpha^2 + \mathcal{O}\left(\alpha^4\right)$$

energy per nucleon in
symmetric nuclear matter

symmetry energy

$$E_{\mathrm{SNM}}(\rho) = B + \frac{1}{2}Kx^2 + \cdots$$

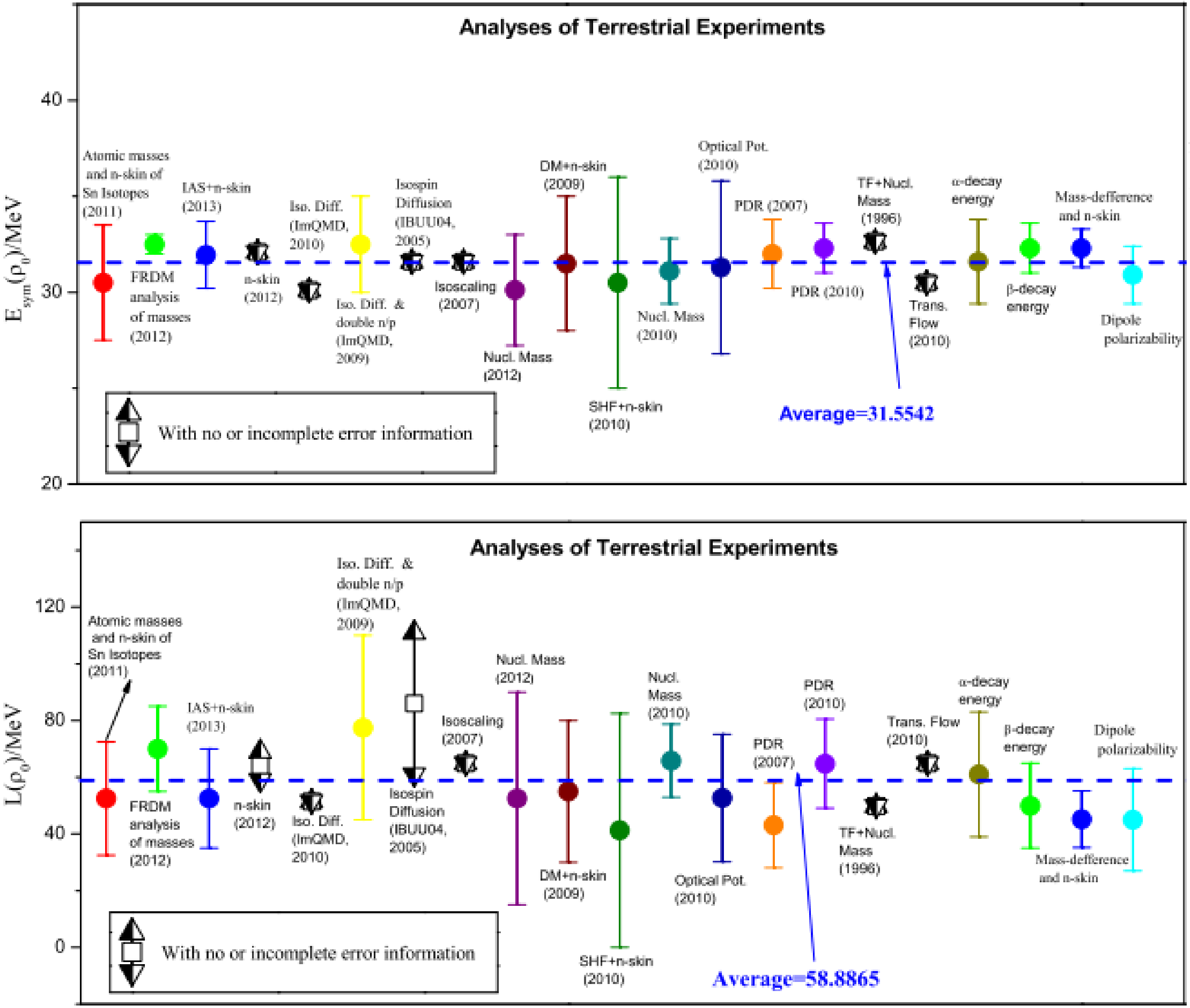
$$E_{\mathrm{sym}}(\rho) = J + Lx + \frac{1}{2}K_{\mathrm{sym}}x^2 + \cdots$$

$$\text{where } x = (\rho - \rho_{\mathrm{sat}})/3\rho_{\mathrm{sat}}$$

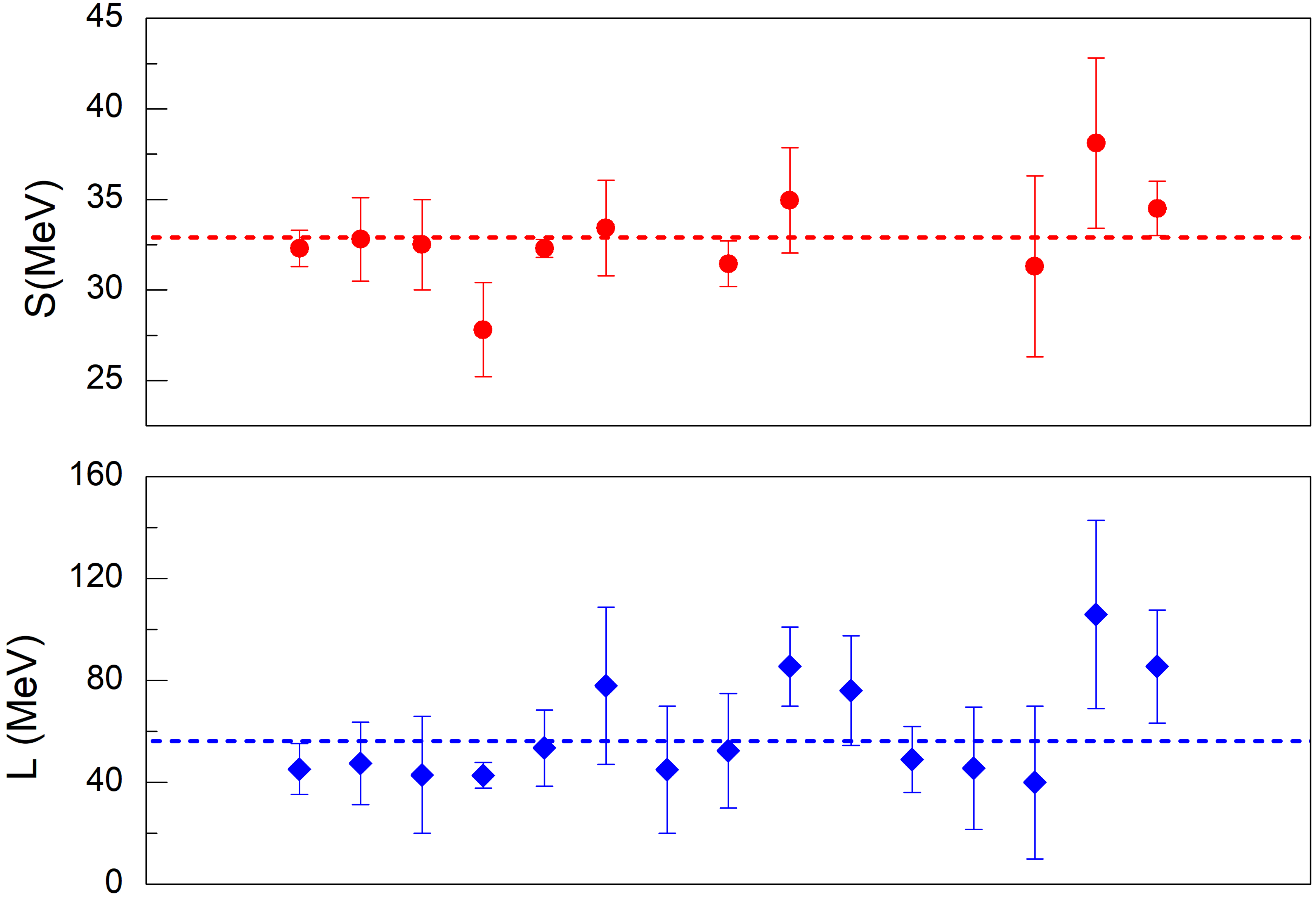
$$\text{and } \alpha = (\rho_{\mathrm{n}} - \rho_{\mathrm{p}})/\rho$$

Symmetry Energy: What do we know about these?

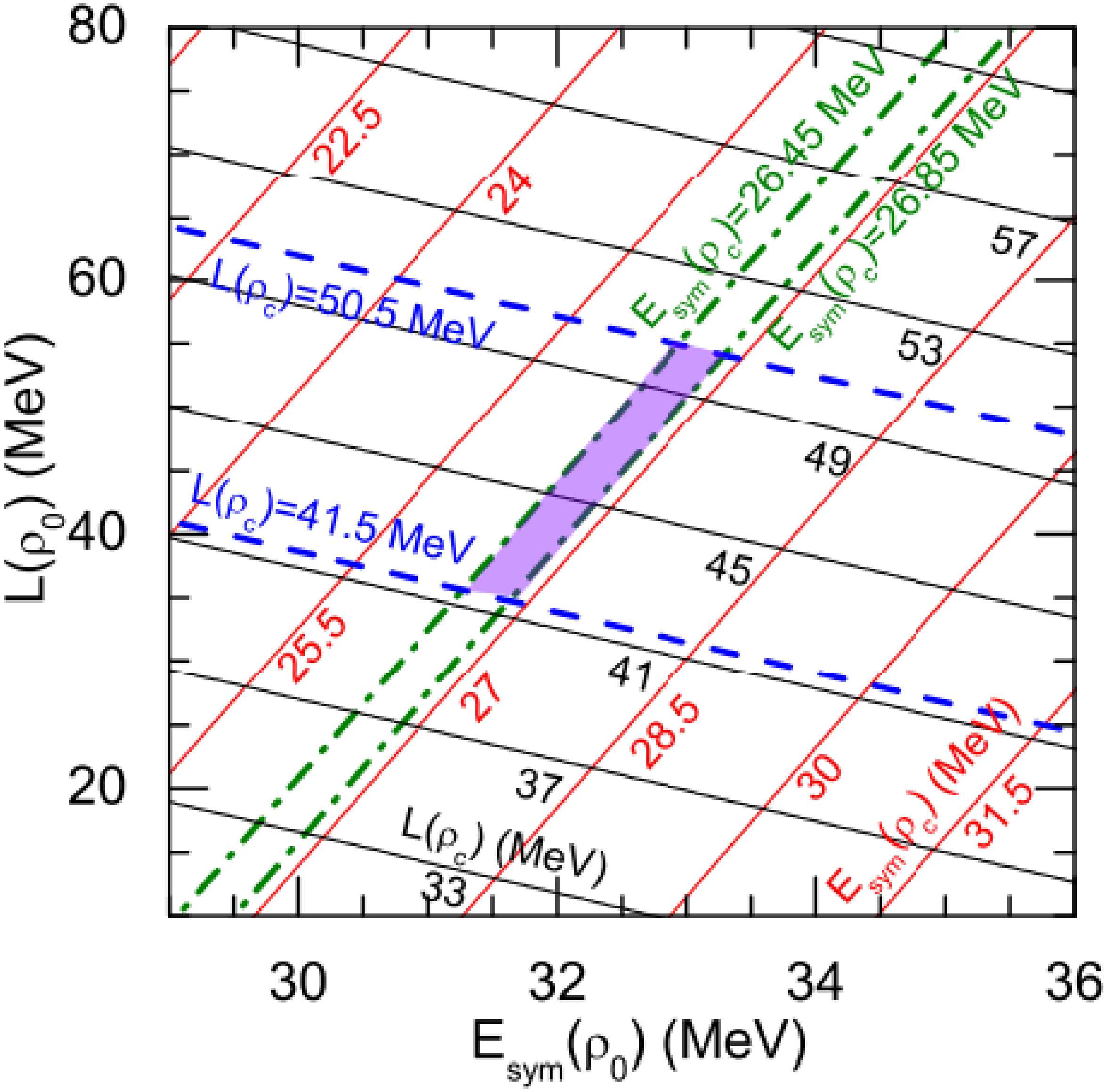
B.-A. Li, X. Han / Physics Letters B 727 (2013) 276–281



Recent constraints from nuclear structure (>2013)



Isotope Binding Energy Difference and the Neutron Skin Thickness



Zhang and Chen,
Phys. Lett. B 726:234-238
(2013)

$$E_{\mathrm{sym}}(\rho_c) = 26.65 \pm 0.20 \text{ MeV}$$

$$L(\rho_c) = 46.0 \pm 4.5 \text{ MeV}$$

$$\rho_c \approx 0.11 \text{ fm}^{-3}$$

Best constrained at subsaturation 95% CL

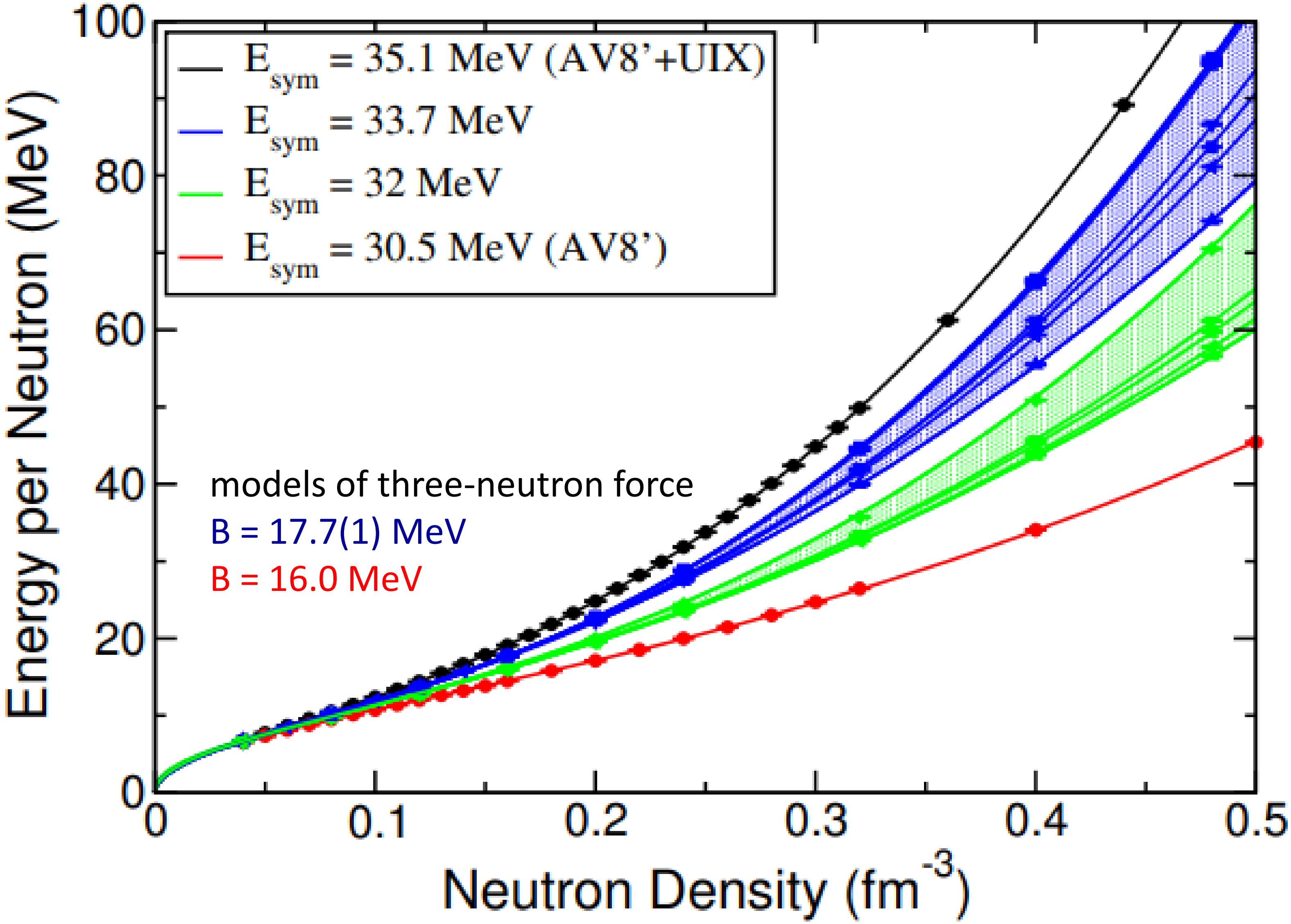
$$E_{\mathrm{sym}}(\rho_0) = 32.3 \pm 1.0 \text{ MeV}$$

$$L(\rho_0) = 45.2 \pm 10.0 \text{ MeV}$$

Extrapolated constraint at saturation (SHF)

Quantum Monte Carlo Calculations of Pure Neutron Matter

Gandolfi t al., Eur. Phys. J. A 50, 10 (2014)



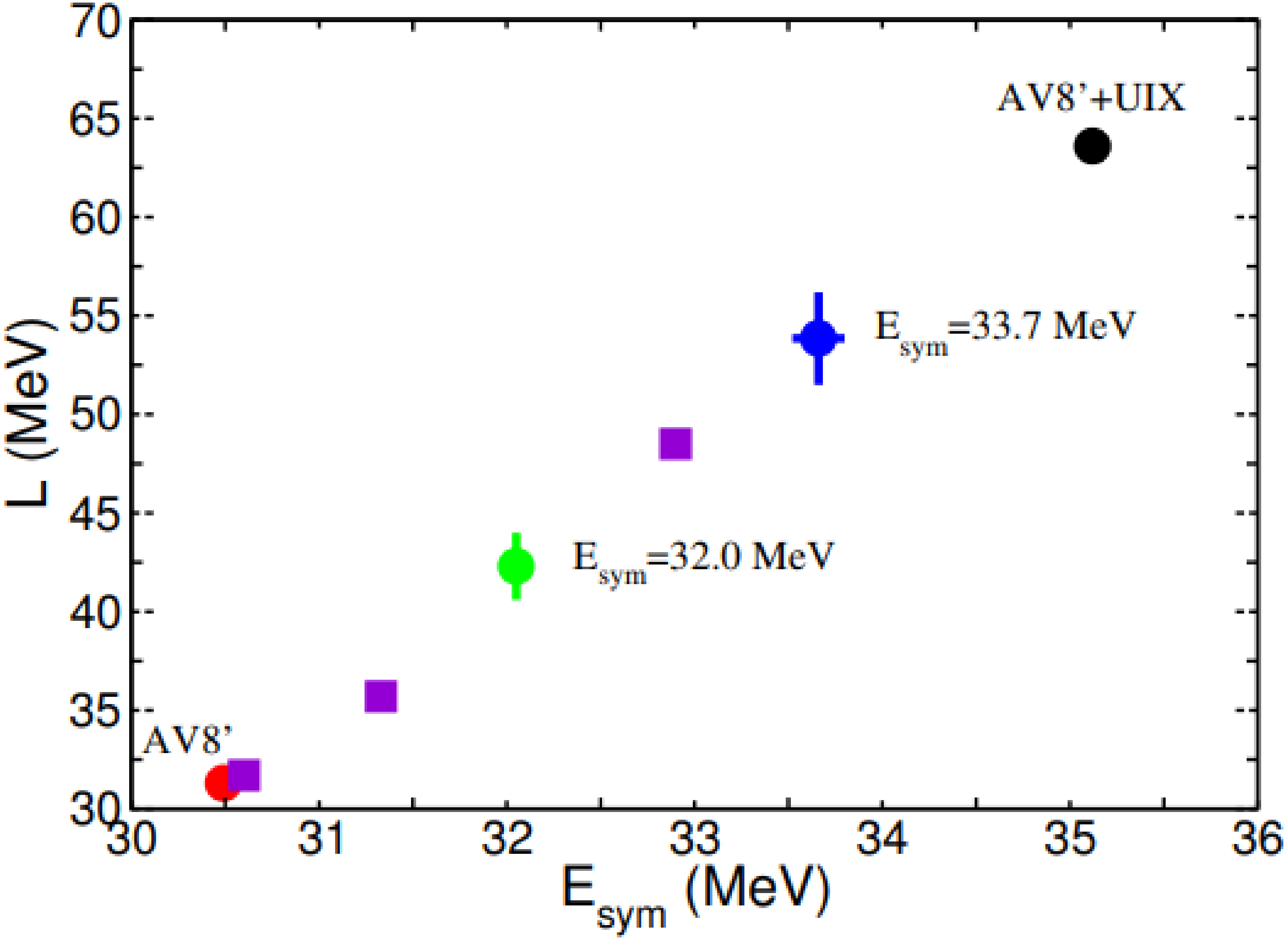
models of three-neutron force

B = 17.7(1) MeV

B = 16.0 MeV

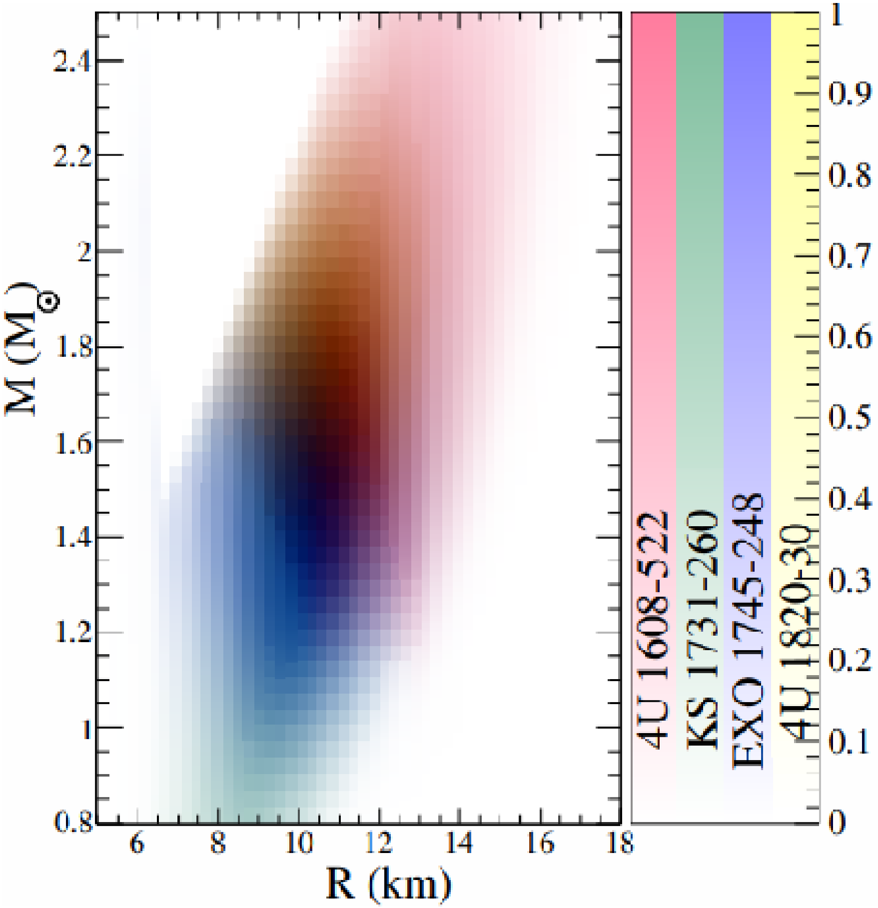
Quantum Monte Carlo Calculations of Pure Neutron Matter

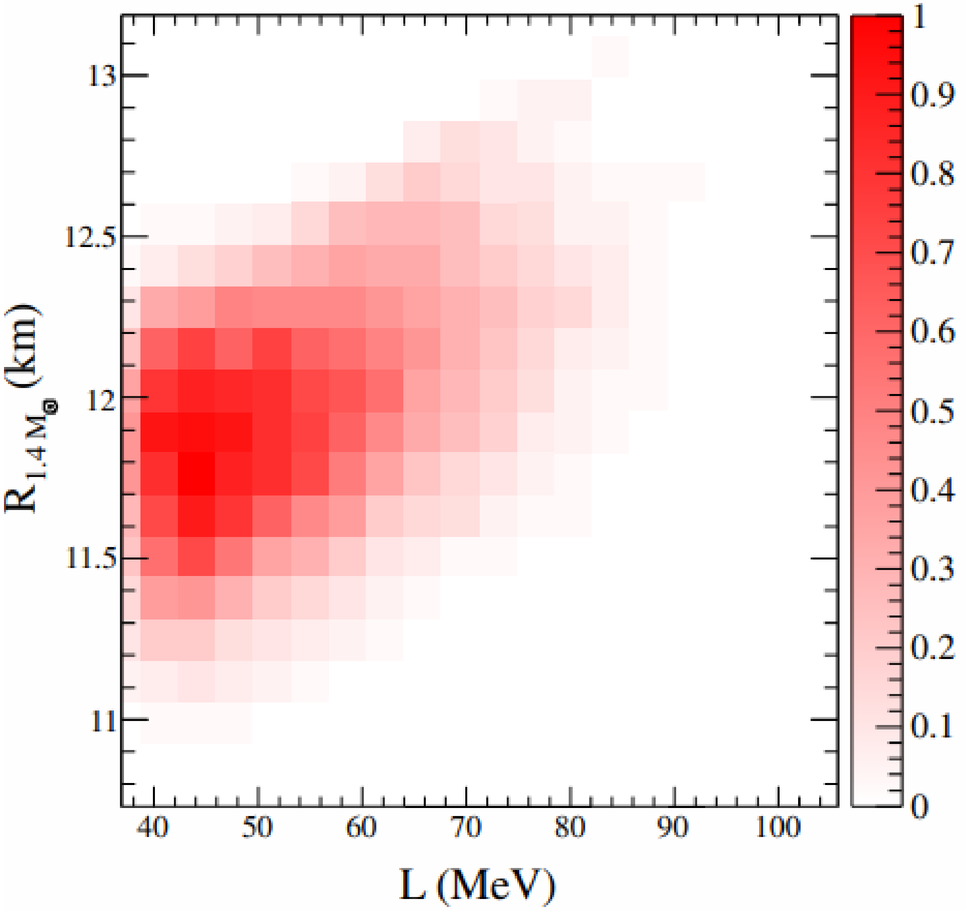
Gandolfi t al., Eur. Phys. J. A 50, 10 (2014)



Quantum Monte Carlo Calculations of Pure Neutron Matter and Neutron Stars

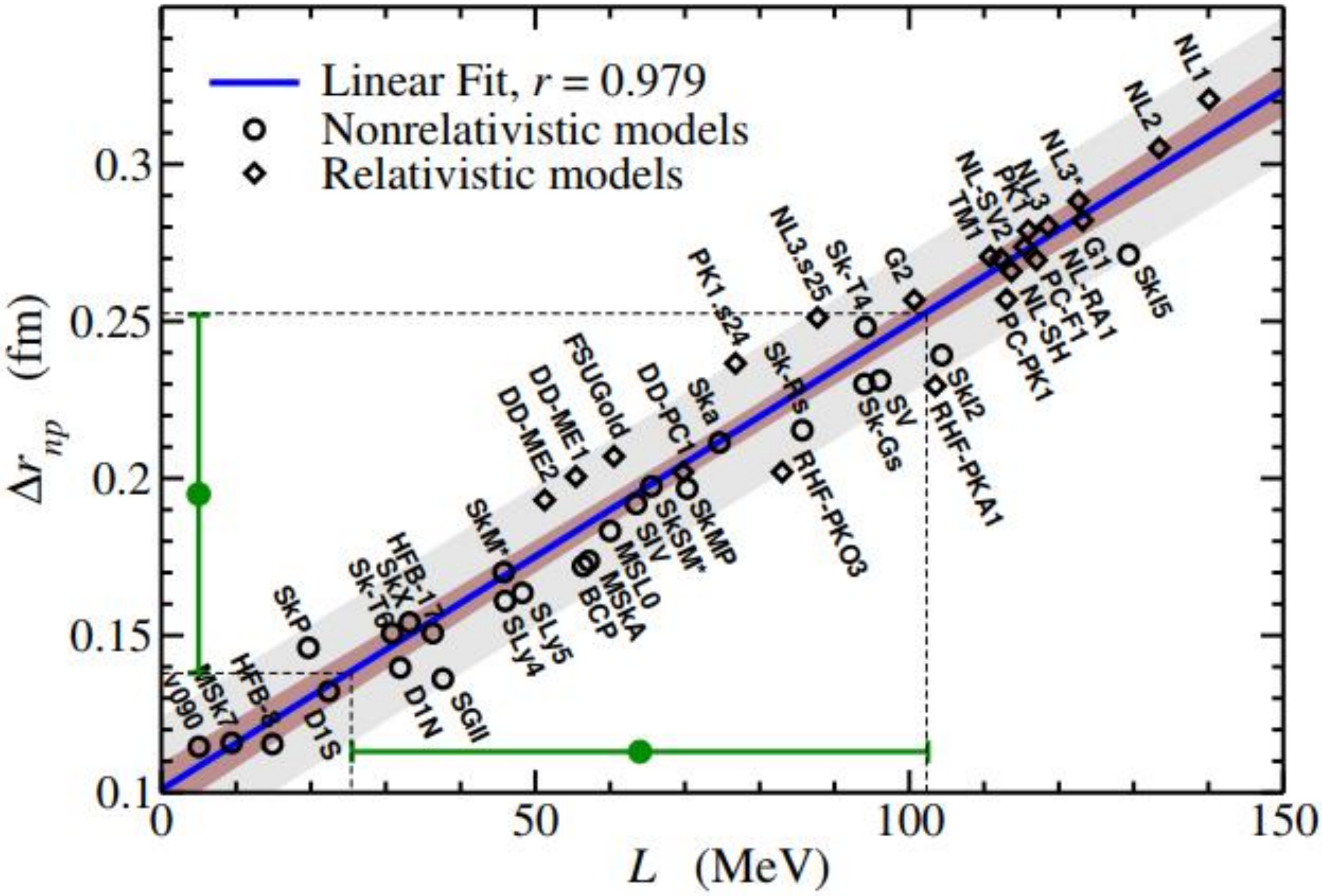
Gandolfi t al., Eur. Phys. J. A 50, 10 (2014)





Neutron skins and the density slope

Roca-Maza et al., Phys. Rev. Lett. 106, 252501(2011)



Neutron skin thickness is strongly correlated with the pressure of pure neutron matter (PNM): $P(\rho_0) \approx \rho_0 L/3$

Pressure of PNM pushes against surface tension ⇒ neutron skin!

Electric Dipole Polarizability and Neutron Radius

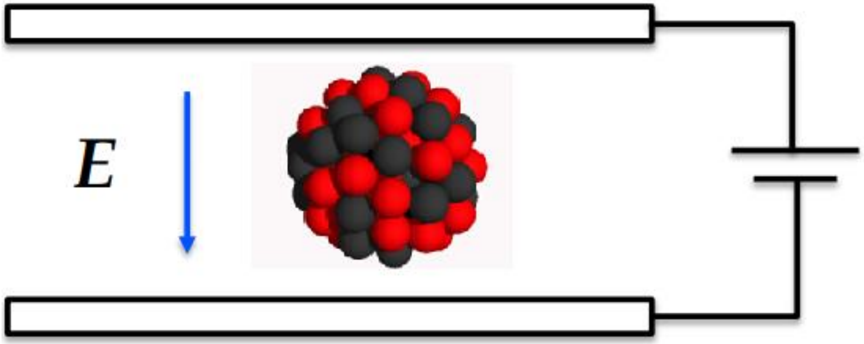
Consider the electric dipole polarizability

$$\mathbf{p} = \alpha \mathbf{E}$$

This scales as the cube of the radius:

$$\alpha = \sum_f \frac{|\langle f|rY_{10}|i\rangle|^2}{(E_i - E_f)} \propto r^3$$

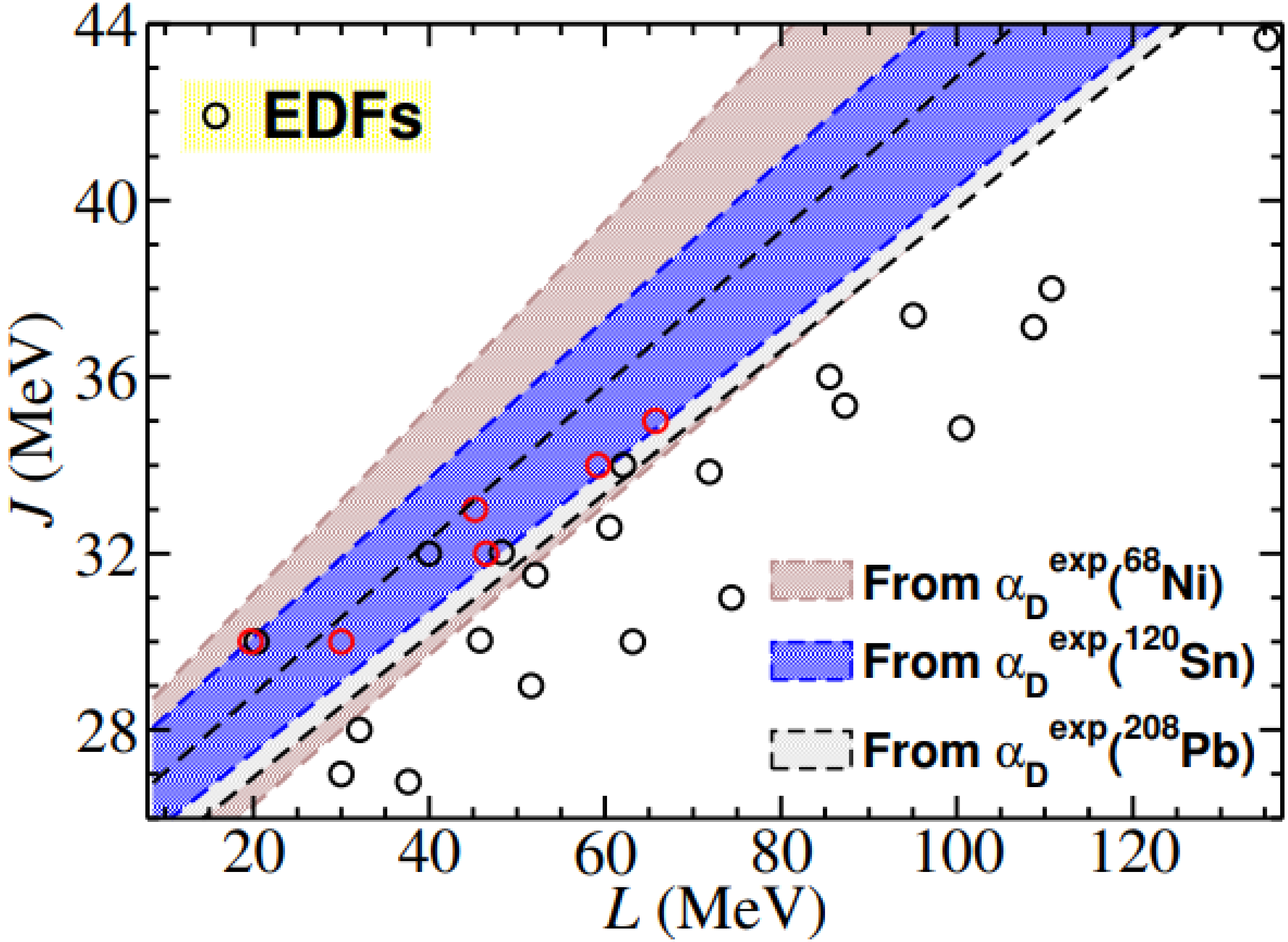
Since the energy denominator scales: 1/r.



A. Tamii *et al.* Phys. Rev. Lett. 107, 062502 (2011)

Electric Dipole Polarizability and Neutron Skin

Roca-Maza et al. Phys. Rev. C 92, 064304 (2015)

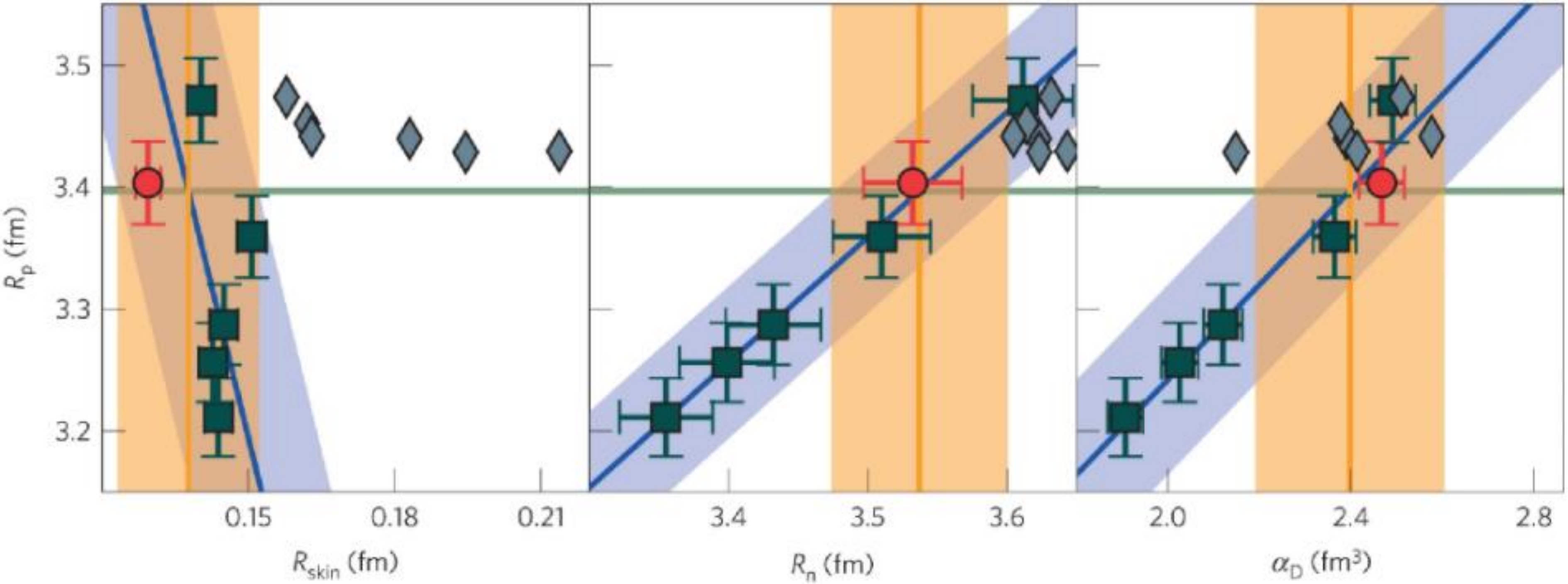


$J = 30\text{-}35\ \text{MeV},\ L = 20\text{-}66\ \text{MeV}$

Neutron and weak-charge distributions of the 48Ca nucleus *from ab-initio calculations*

Hagen et al., Nature Physics 12, 186–190 (2016)

What is the size of the atomic nucleus? Significantly smaller skins were obtained.



Circle from NNLOsat chiral interaction, Ekstrom et al., *Phys. Rev. C* **91**, 051301(R) (2015).
Squares from chiral interactions, Hebeler et al., *Phys. Rev. C* **83**, 031301 (2011).
Diamonds are from various EDFs.

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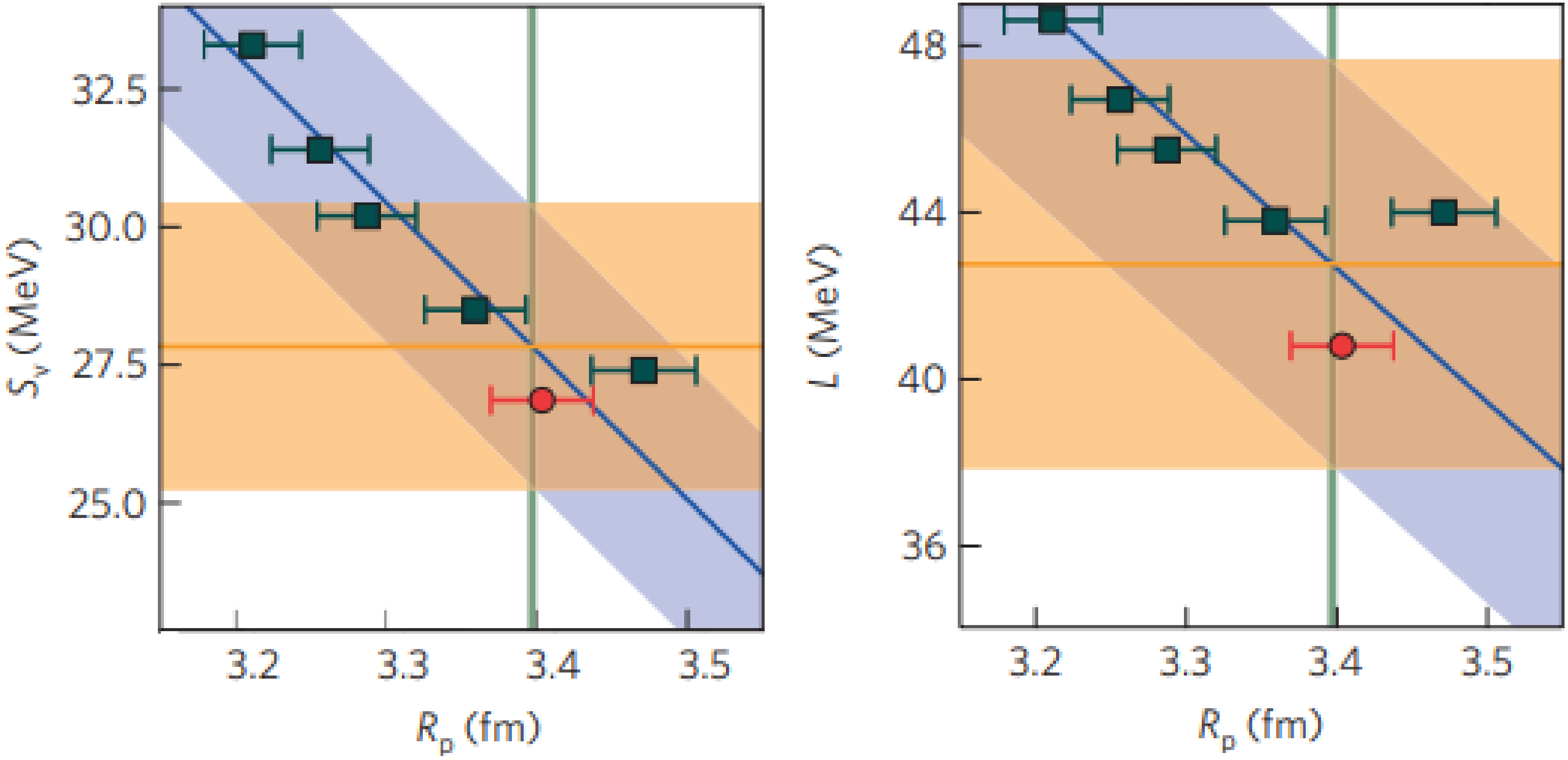
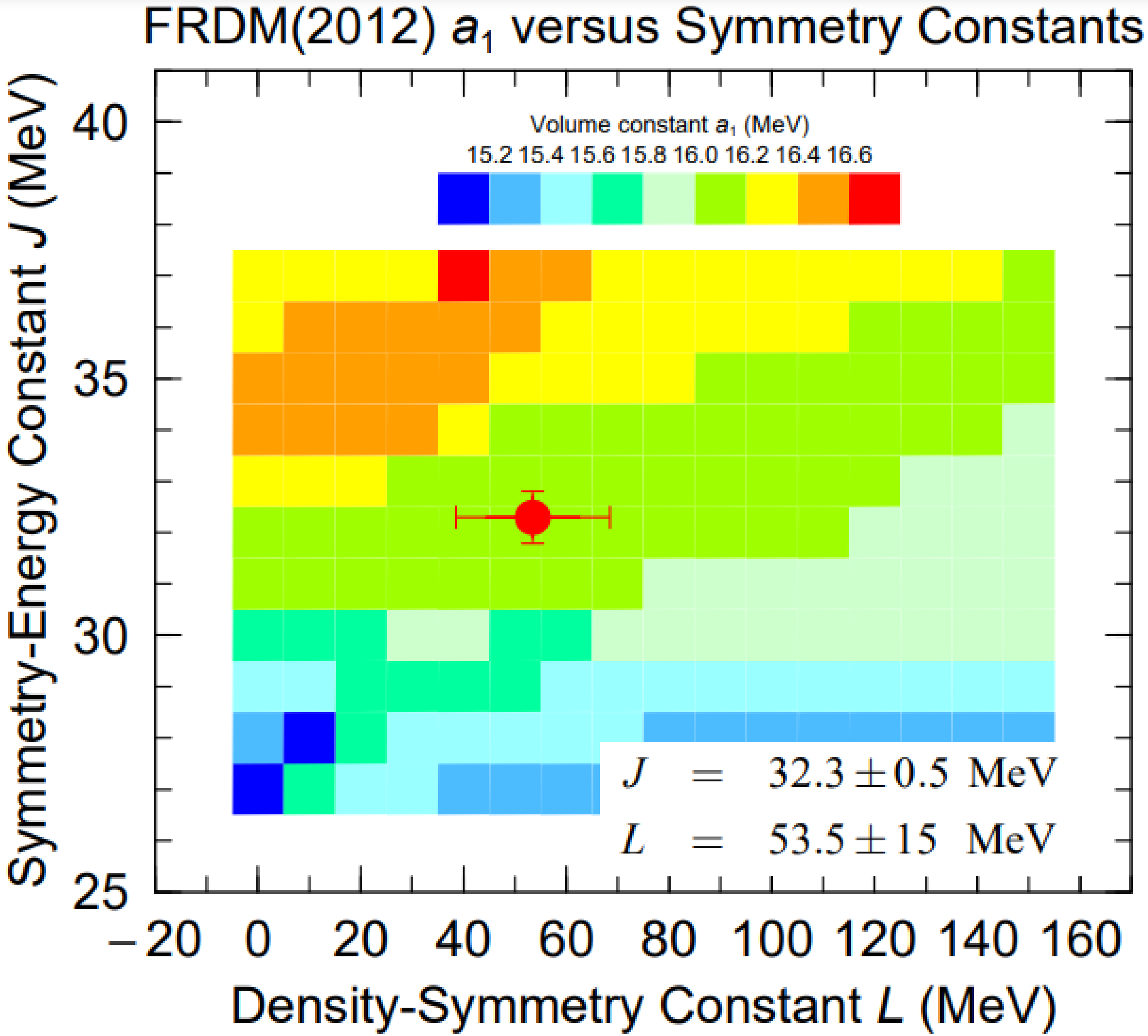


$$25.2 \lesssim S_v \lesssim 30.4 \text{ MeV} \text{ and } 37.8 \lesssim L \lesssim 47.7 \text{ MeV}.$$

Nuclear ground state masses (FRDM2012)

Moeller et al., Atomic Data and Nuclear Data Tables, 109–110, (2016)



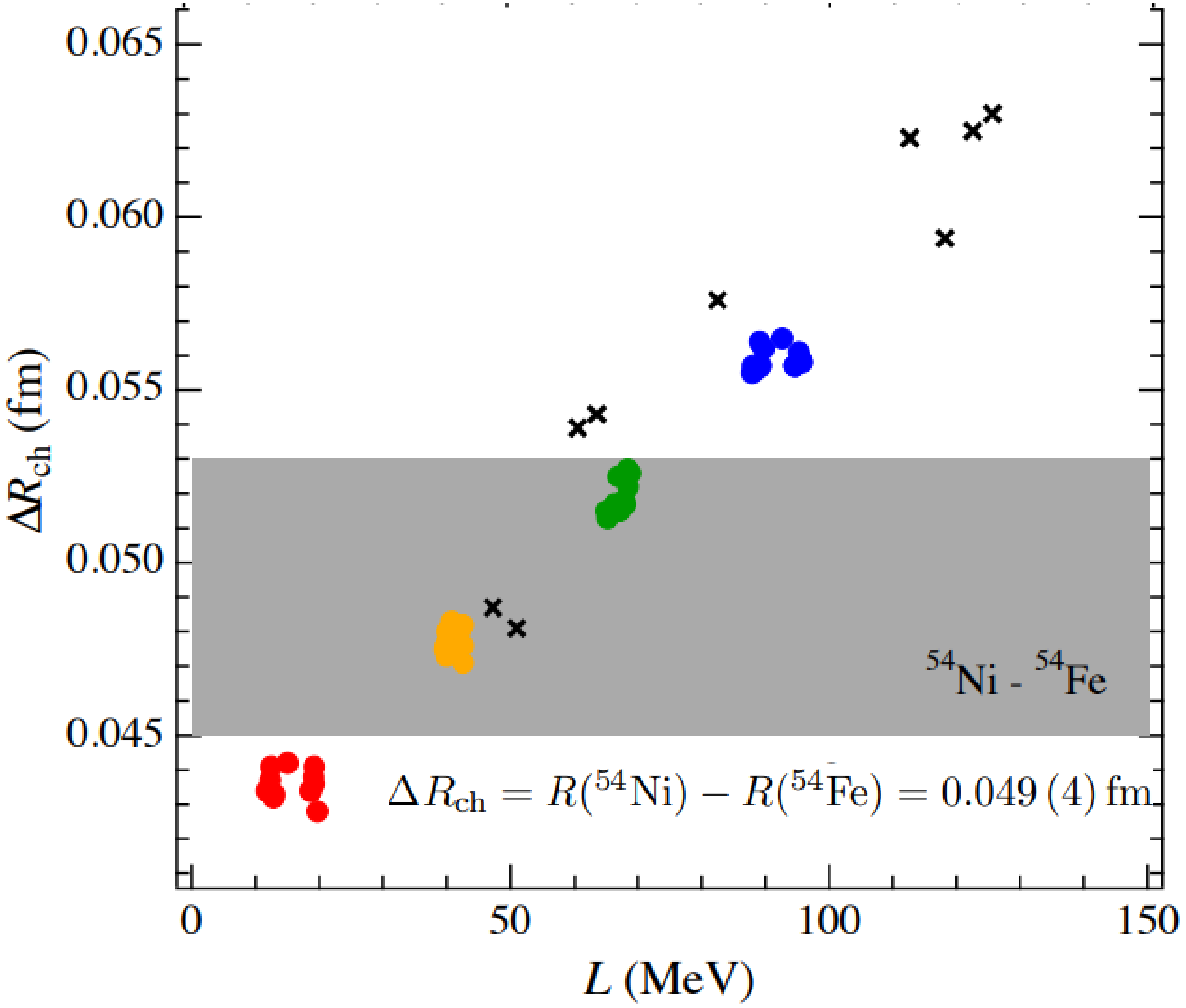
Also see, Moeller et al., Phys. Rev. Lett. 108, 052501 (2012) (FRDM1992)

J=32.5±0.5 MeV, L=70±15 MeV

Charge Radius of Neutron-deficient 54Ni

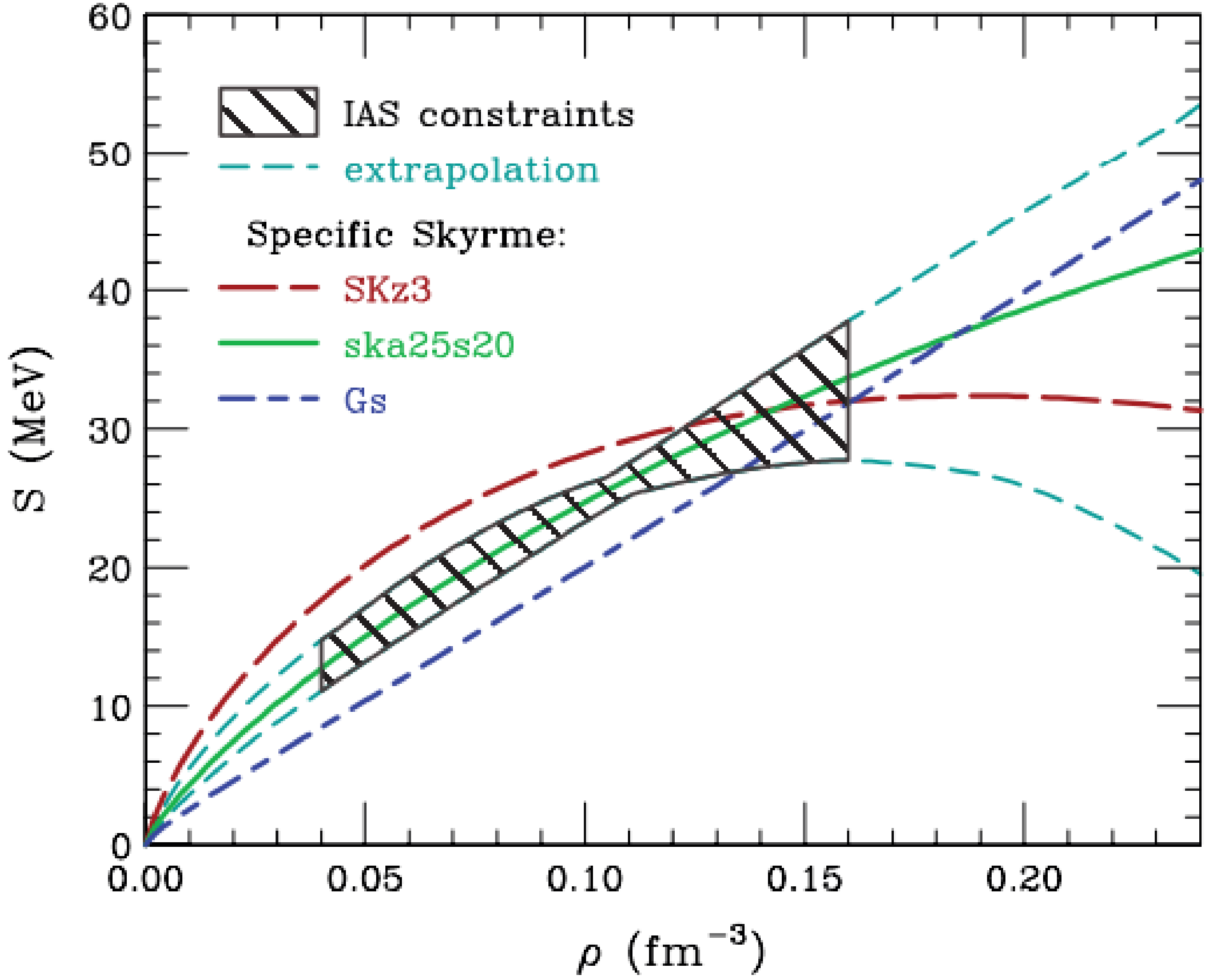
Pineda et al., arXiv:2106.10378 (2021)

Colinear laser spectroscopy: R(54Ni) = 3.737(3) fm
Combine with the known charge radius of 54Fe mirror nucleus.
(Also see, A. Brown, Phys. Rev. Lett. **119**, 122502)



Excitation Energies of Isobaric Analog States, Charge Invariance and Masses

Danielewicz and Lee, Nucl. Phys. A 922, 1 (2014)



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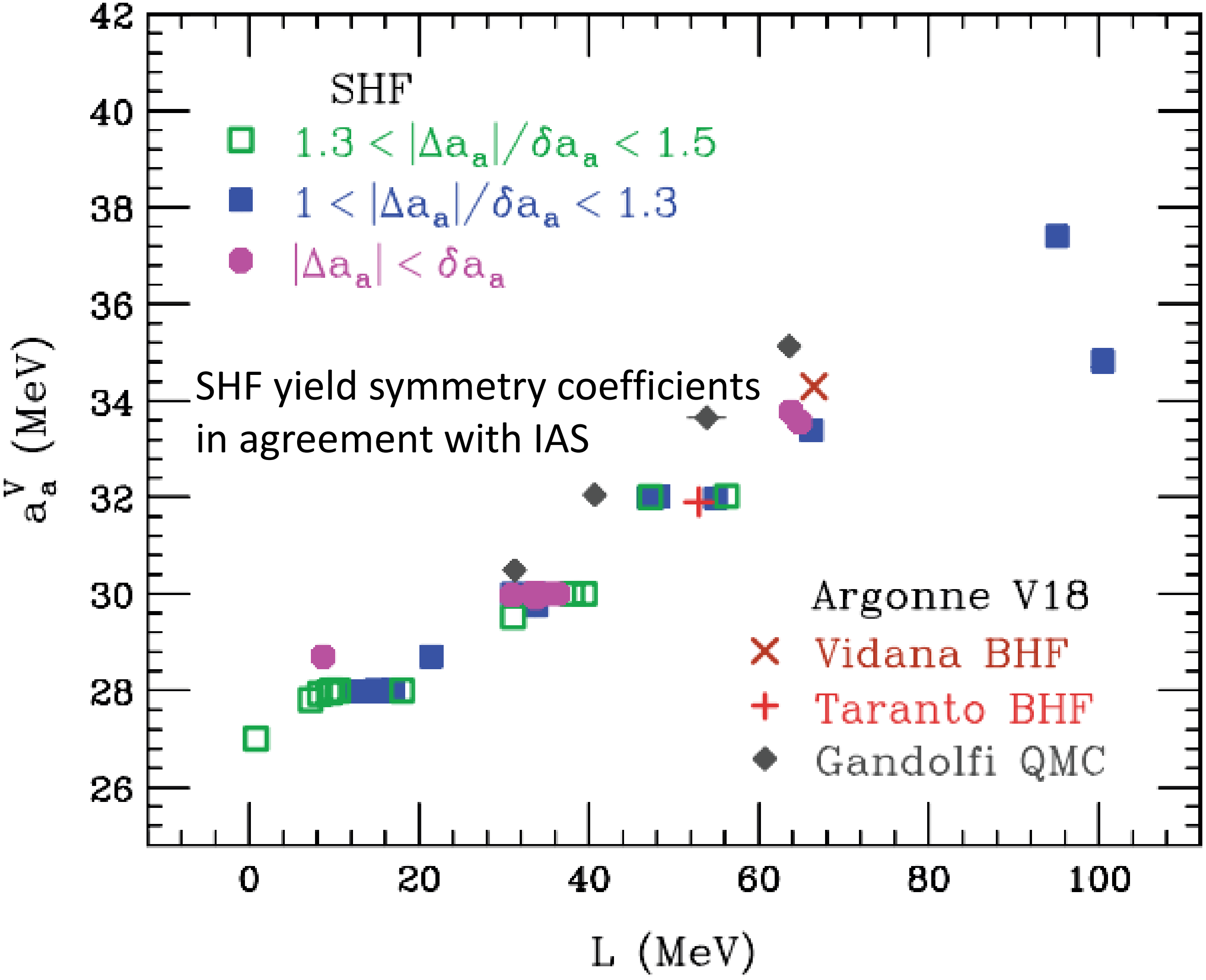
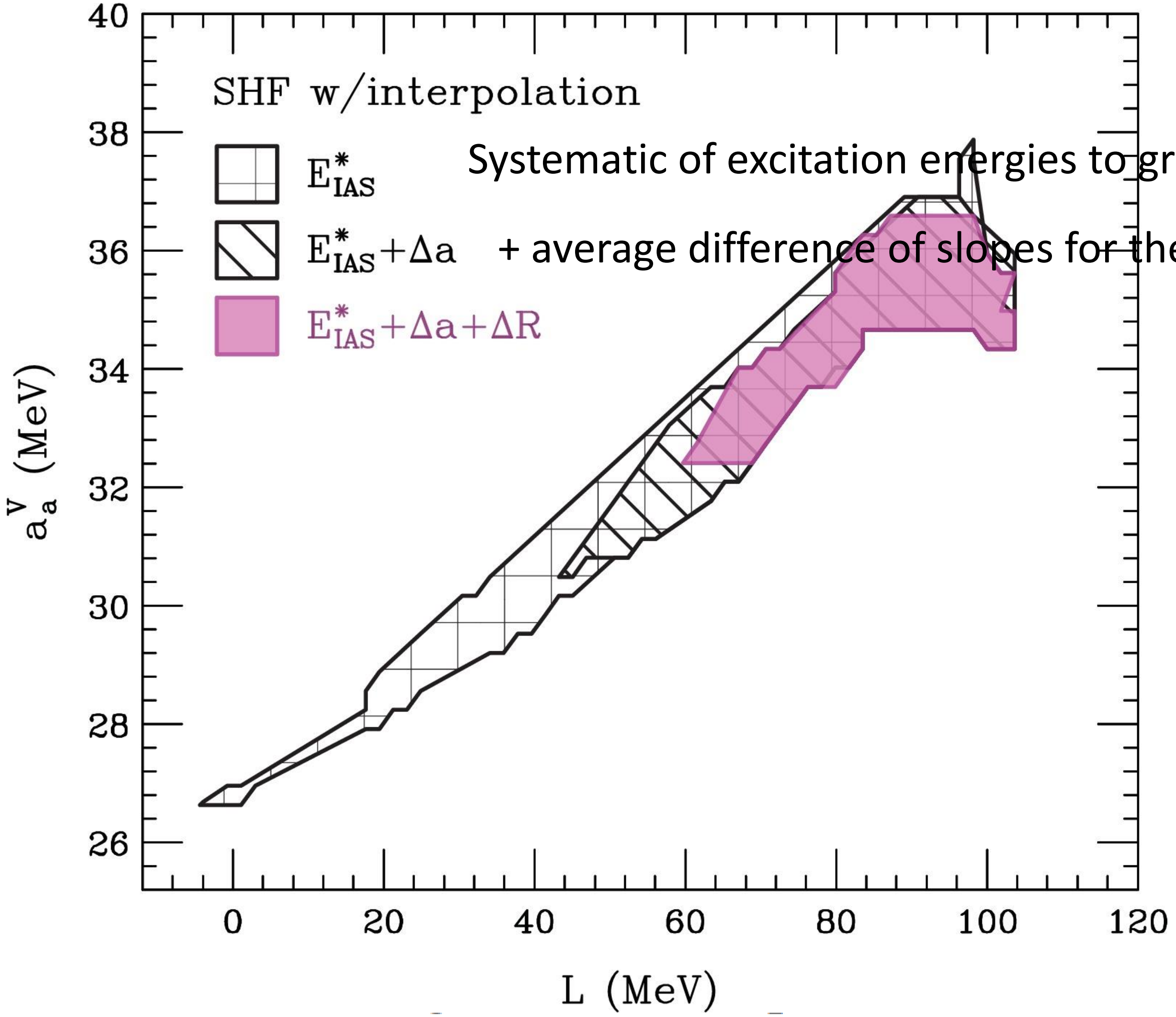


SHF yield symmetry coefficients in agreement with IAS

$$a_a^V = (30.2 - 33.7)\,\text{MeV} \;\text{ and }\; L = (35 - 70)\,\text{MeV}$$

Isovector Skins: Difference in the radii of isovector and isoscalar potentials

Danielewicz et al, Nucl. Phys. A 958, 147 (2017)



Systematic of excitation energies to ground-state

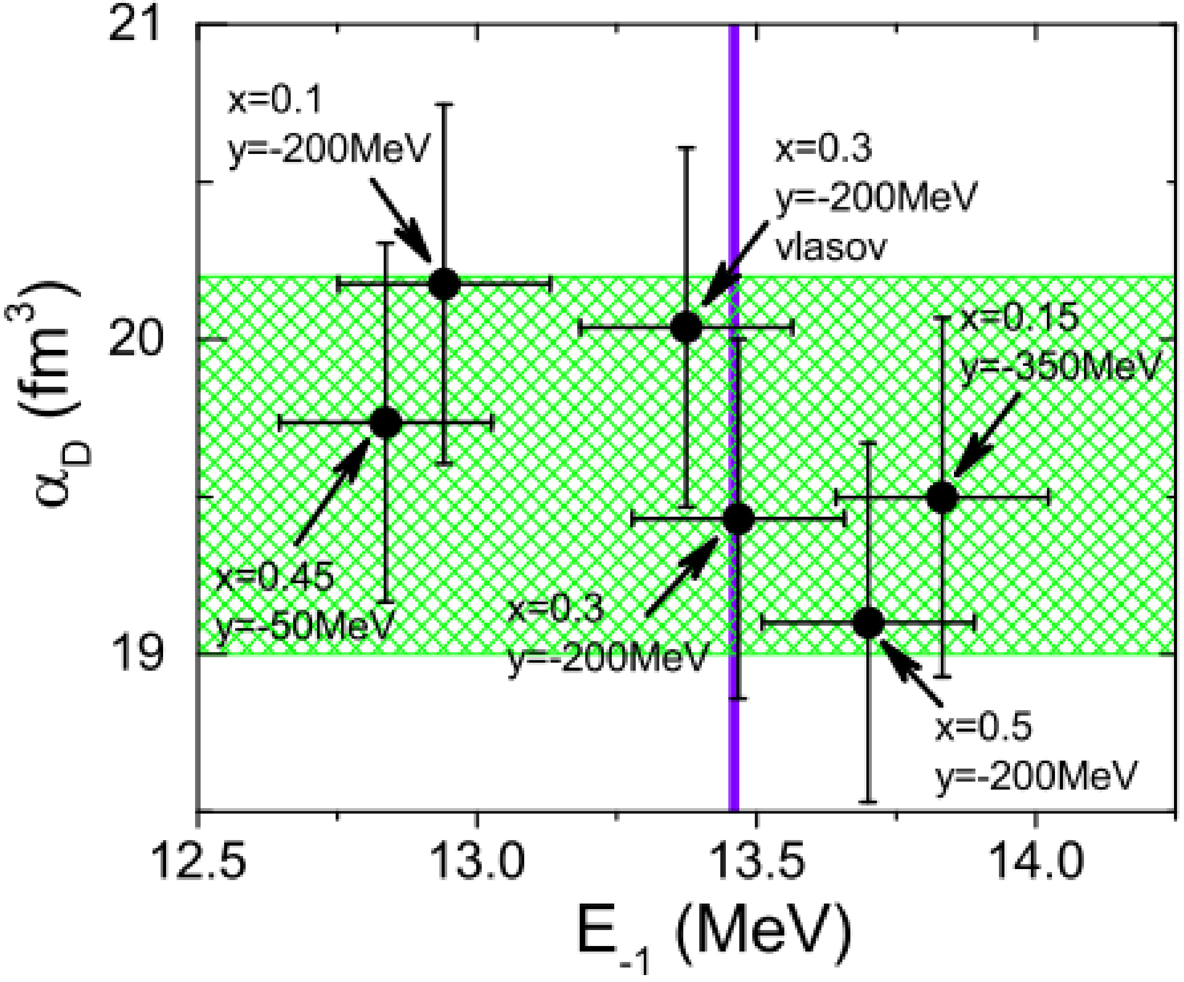
+ average difference of slopes for the isovector and isoscalar potential surfaces

$70 < L < 101$ MeV and $33.5 < a_a^V < 36.4$ MeV

Nuclear Giant Resonances (ISGQR and IVGDR)

Xu and Qin, Phys. Rev. C 102, 024306 (2020)

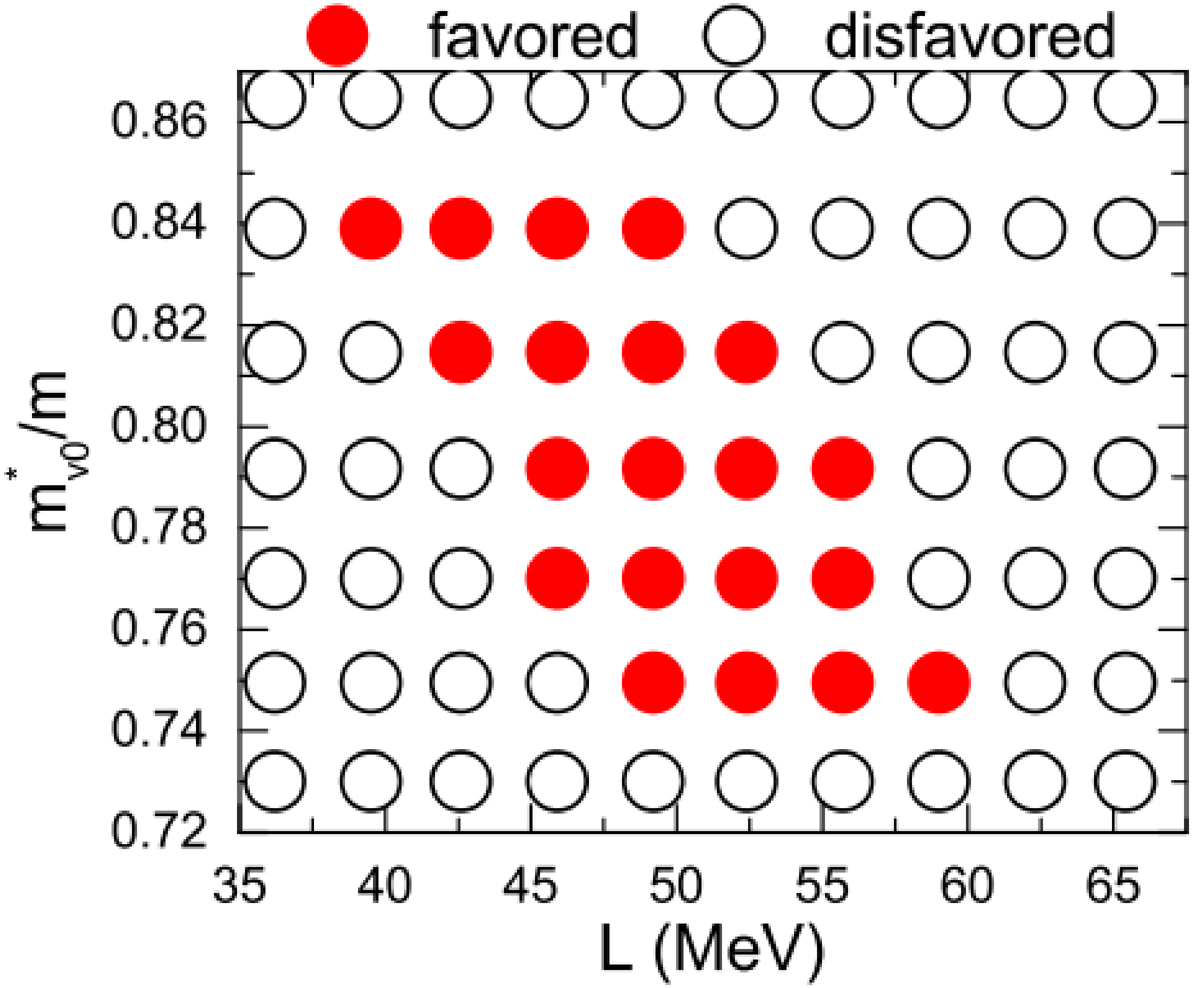
Isospin-dependent Boltzmann-Uehling-Uhlenbeck transport approach



IVGDR and electric dipole polarizability

Nuclear Giant Resonances (ISGQR and IVGDR)

Xu and Qin, Phys. Rev. C 102, 024306 (2020)

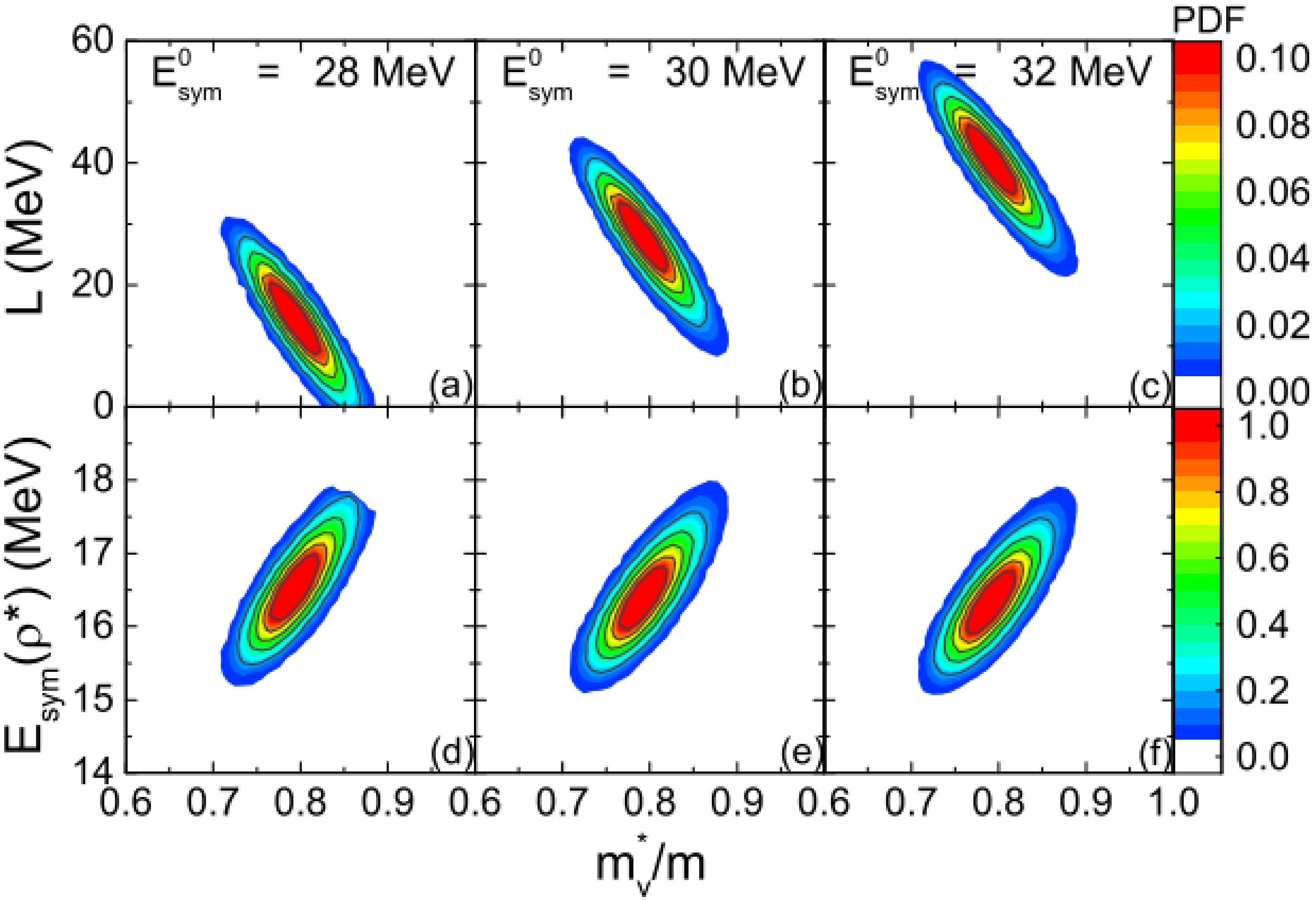


$36 < L < 62$ MeV

IVGDR and electric dipole polarizability

IVGDR in 208Pb and Electric Dipole Polarizability

Xu et al. Phys. Lett. B 810, 135820 (2020)



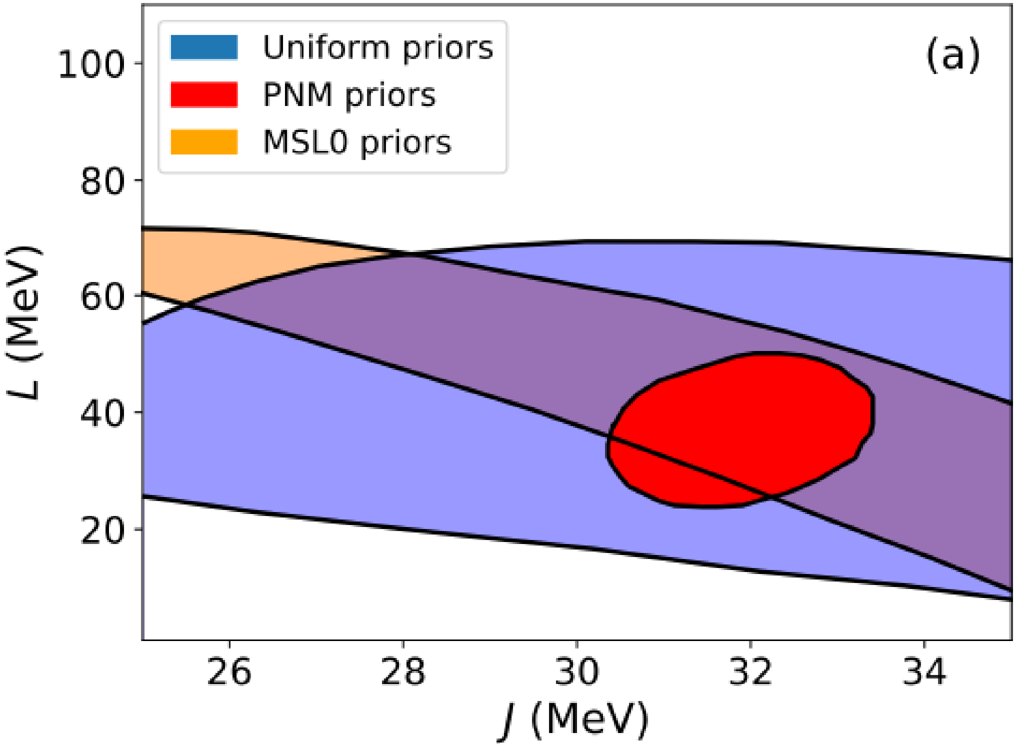
Neutron skins in Sn isotopes and Bayesian approach

Xu et al., Phys. Rev. C 102, 044316 (2020)

$L = 45.5^{+26.5}_{-21.6}$ MeV surrounding its mean value

$L = 53.4^{+18.6}_{-29.5}$ MeV surrounding its maximum *a posteriori* value

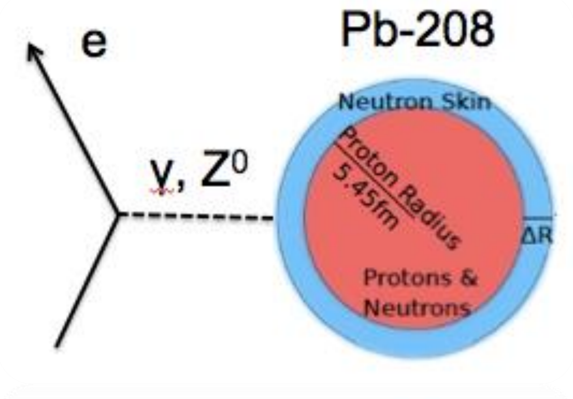
Newton and Crocombe, Phys. Rev. C 103, 064323 (2021)



$J = 31.3^{+4.2}_{-5.9}$ MeV, $L = 40^{+34}_{-26}$ MeV uninformative priors

$J = 31.9^{+1.3}_{-1.3}$ MeV, $L = 37^{+9}_{-8}$ MeV pure neutron matter priors.

Pb-208: Where do extra 44 neutrons go?
Parity Violating Experiment



	proton	neutron
Electric charge	1	0
Weak charge	0.07	-0.99

Proton form factor

$$F_P(Q^2) = \frac{1}{4\pi}\int d^3r\ j_0(qr)\ \rho_P(r)$$

Neutron form factor

$$F_N(Q^2) = \frac{1}{4\pi}\int d^3r\ j_0(qr)\ \rho_N(r)$$

Parity Violating Asymmetry

$$A = \frac{\left(\frac{d\sigma}{d\Omega}\right)_R - \left(\frac{d\sigma}{d\Omega}\right)_L}{\left(\frac{d\sigma}{d\Omega}\right)_R + \left(\frac{d\sigma}{d\Omega}\right)_L} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}}\left[\underbrace{1 - 4\sin^2\theta_W}_{\approx 0} - \frac{F_N(Q^2)}{F_P(Q^2)}\right]$$

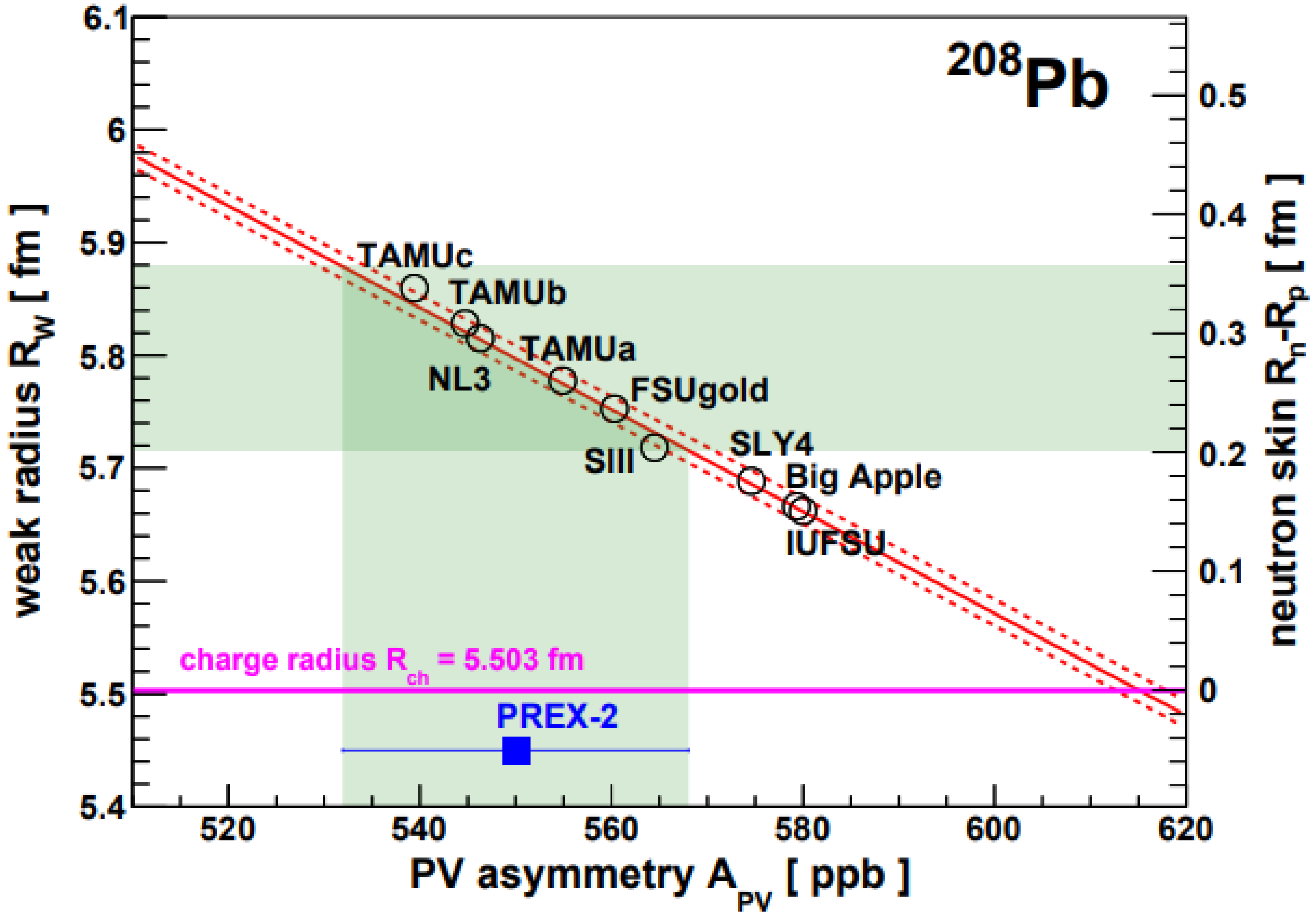
Formula Credit: Roberts Michaels

- ○ Proton form factors are known with enormous precision (Hofstadter 1950's – to date).
- ○ Neutron form factors are as fundamental as proton form factors (still elusive after more than 80 years of nuclear physics).
- ○ PREX at JLAB measured the neutron skin thickness of 0.28±0.07 fm (2021).
- ○ CREX (2021) and MESA at Mainz (planned 2023) will also measure neutron skin.

Recent Developments: PREX-II

PREX-II measured that the neutron skin thickness is large: 0.283±0.071 fm.

D. Adhikari et al. (PREX Collaboration), Phys. Rev. Lett. 126, 172502 (2021)



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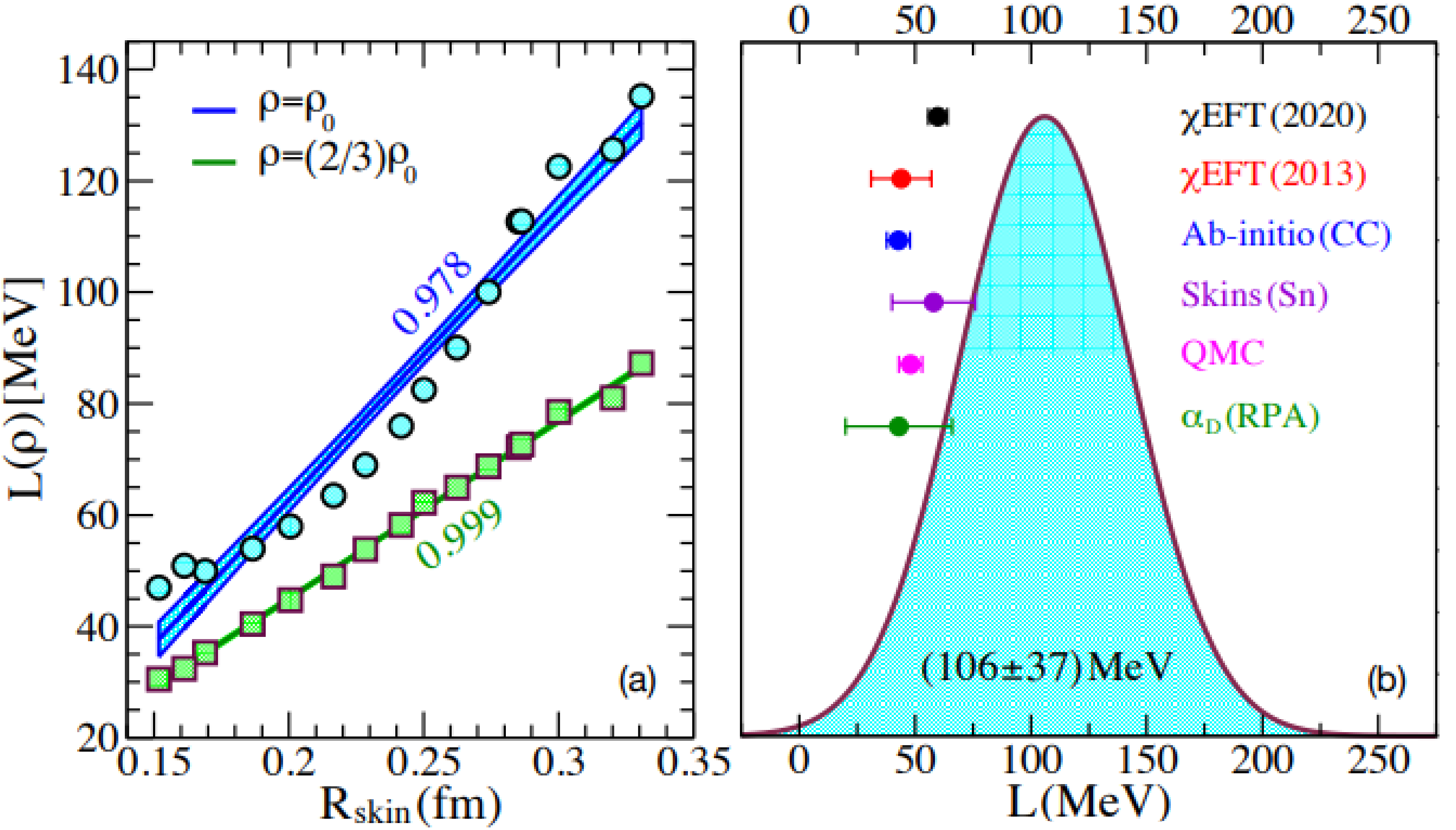
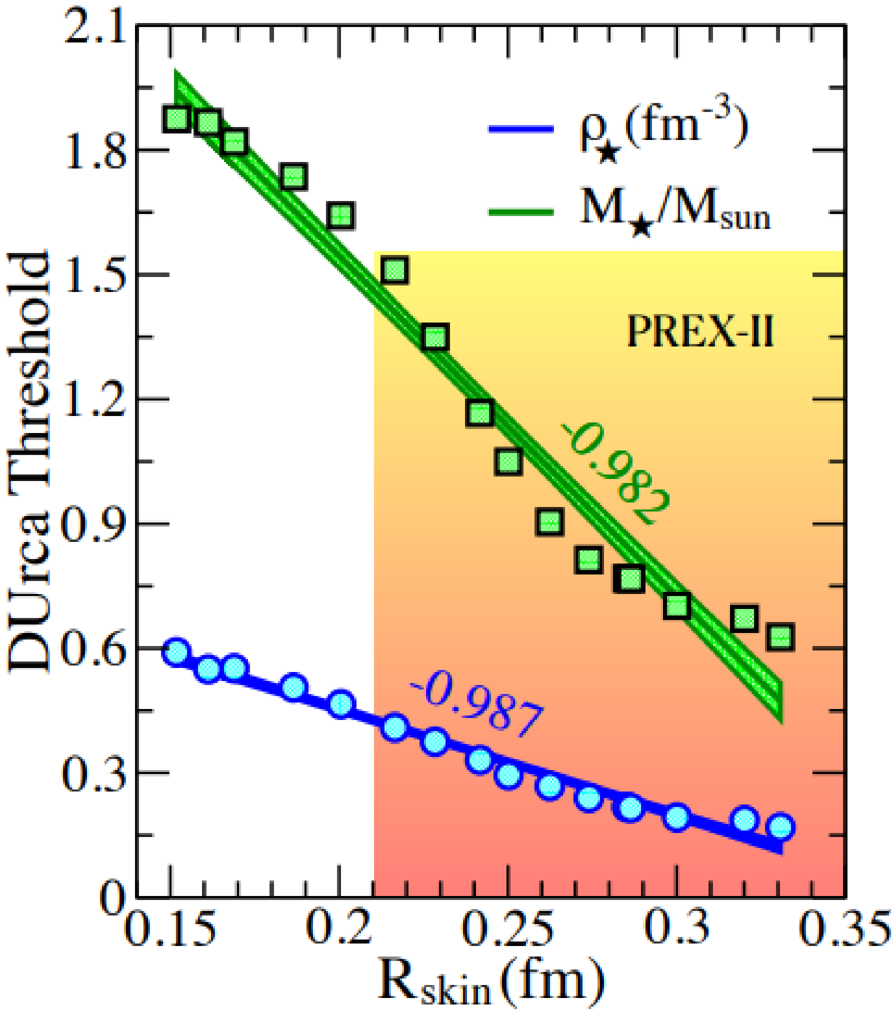


$$J = (38.1 \pm 4.7)\mathrm{MeV}$$
$$L = (106 \pm 37)\mathrm{MeV}$$

Reed et al., Phys. Rev. Lett. 126, 172503 (2021)

Astrophysical Implications of the Large Skin

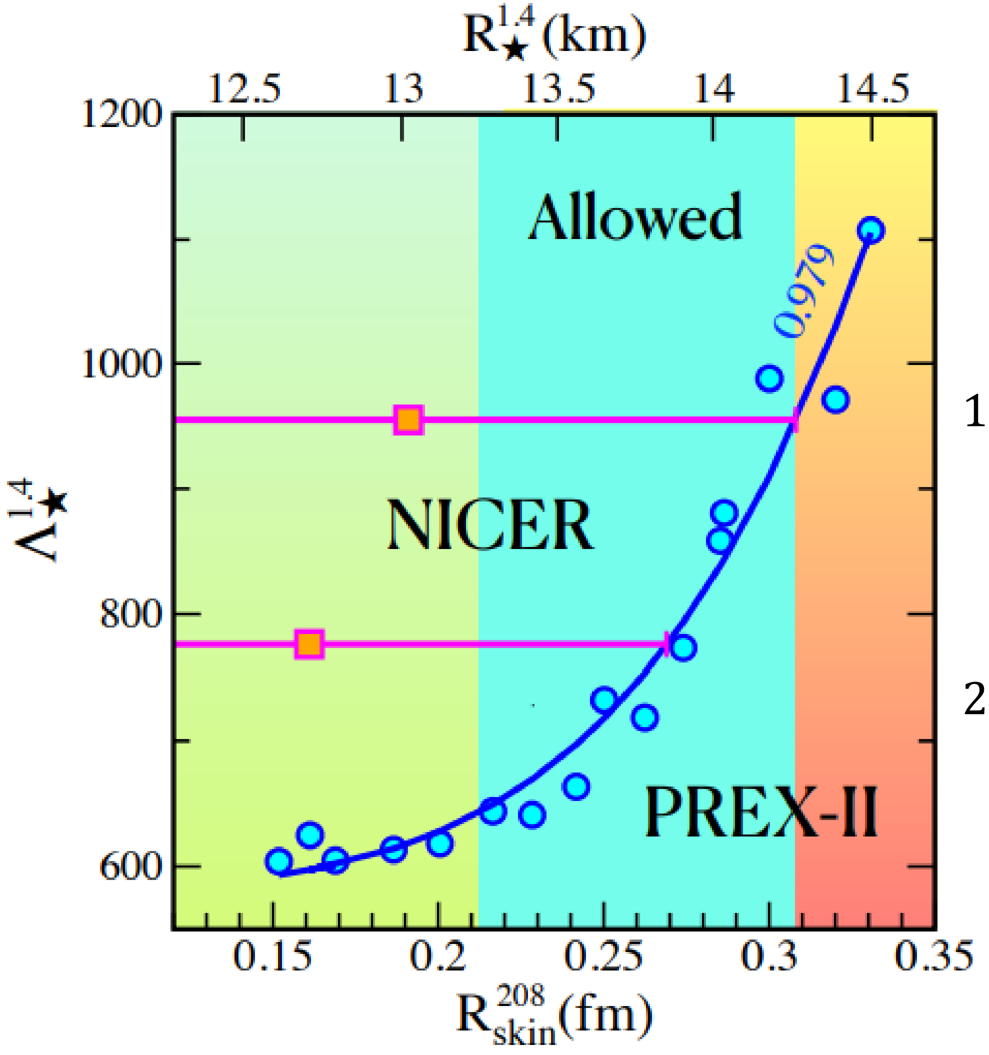
Reed et al., Phys. Rev. Lett. 126, 172503 (2021)



The lack of observation of cold stars (only a few observed so far) suggests that the neutrino emissivity might be suppressed by nucleon pairing or there is a phase transition at the inner regions of the star (Mendes et al. in preparation, 2021) .

Astrophysical Implications of Large Skin

Reed et al., Phys. Rev. Lett. 126, 172503 (2021)



$$0.21 \lesssim R_{\rm skin}({\rm fm}) \lesssim 0.31$$
$$13.25 \lesssim R_\star^{1.4}({\rm km}) \lesssim 14.26$$
$$642 \lesssim \Lambda_\star^{1.4} \lesssim 955.$$

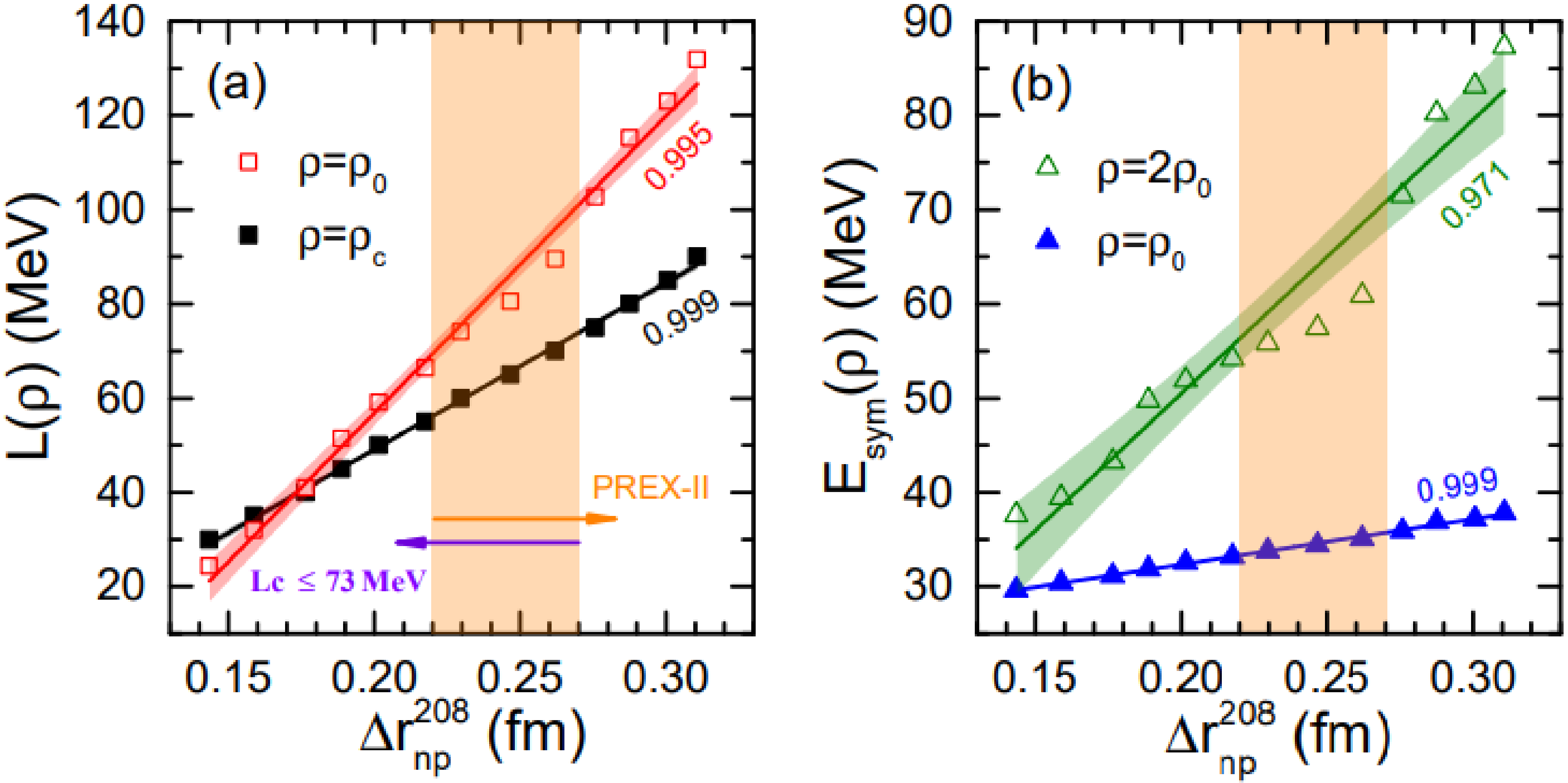
Some thoughts:

1. If tidal polarizability remains small (<600), then the symmetry energy should be soft at high density to get a consistent prediction with the observational data.
2. It becomes even harder to reconcile this data with the GW190814 mass if it turns out to be a neutron star. In such cases, one can speculate that gravity in the strong field regime may not be fully described by General Relativity and alternative models of gravity should be tested. (see, e.g., Fattoyev, Arabian J. of Mathematics, July (2019))

PREX II: Re-Analyses with Experimental and Observational Data

Yue et al., arXiv:2102.05267 (2021)

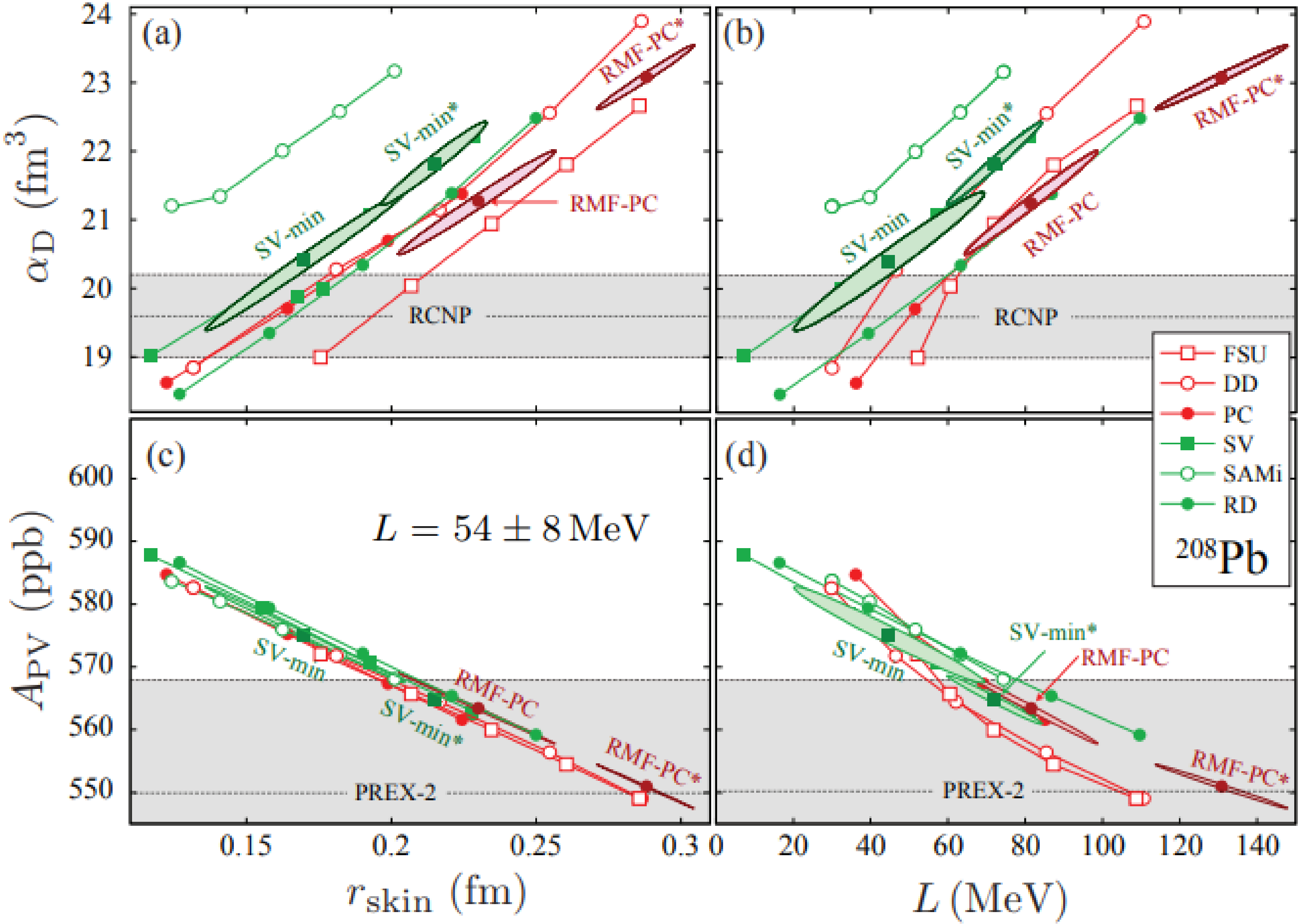
Exp: GS properties and GMR of finite nuclei and EOS of SNM from HIC (flow data)
Obs: Maximum mass of a NS (PSR J0740+6620), GW170817, and NICER Mass-vs-Radius PSR J0030+045



Neutron skins and dipole polarizability

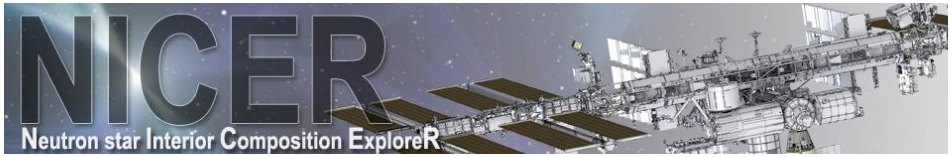
Reinhard et al., arXiv:2105.15050 (2021)

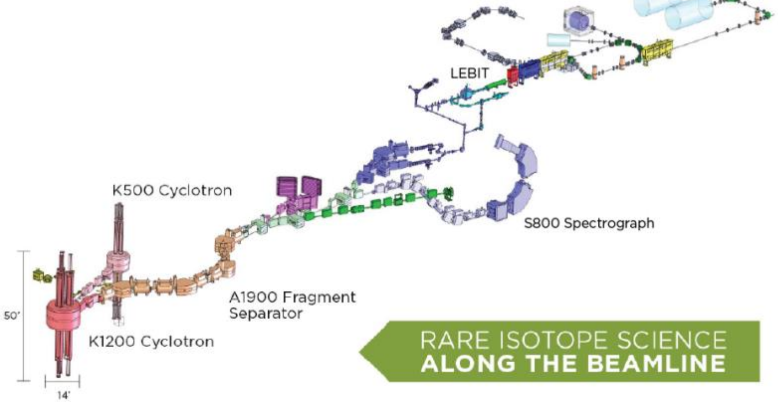
EDFs are used that allow PV asymmetric parameter, dipole polarizability and neutron skin.



Some Concluding Remarks

- Current *experimental* data from nuclear structure is putting tighter constraints on the density dependence of the symmetry energy *at and below saturation*.
- When combined with observational data this constraint gets better and sometimes creates a tension.
- Future experiments on dipole polarizabilities, neutron skins, and mirror charge radii are essential to have a better understanding of the symmetry energy at and below saturation.
- The higher coefficients of the Taylor expansion is still uncertain (For example, Ksym is expected to strongly affect the crust-core properties of neutron star).
- Nuclear structure does not constrain the symmetry energy at supra-saturation: nuclear reactions are needed.
- Current and future GW observations from BNS mergers and NS radii observations (NICER) should provide a better understanding of the symmetry energy at high densities.





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My Collaborators:

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S. Reddy (UW)
D. Page (UNAM)
J. Xu (SINAP)
X.-H. Li (U. South China)
C. Xu (Nanjing U)
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W.-Z. Jiang (Southeast U.)
X.-T. He (Nanjing U. Aeronautics and Astronautics)
B.-J. Cai (Shanghai U.)

Thank You!

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