Dipole resonances, neutron skins and nuclear Equation of State

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Outline

- Collective states in nuclei

  dipole excitations, pygmy modes, polarizability

- Neutron skin thickness

- Nuclear Equation of State

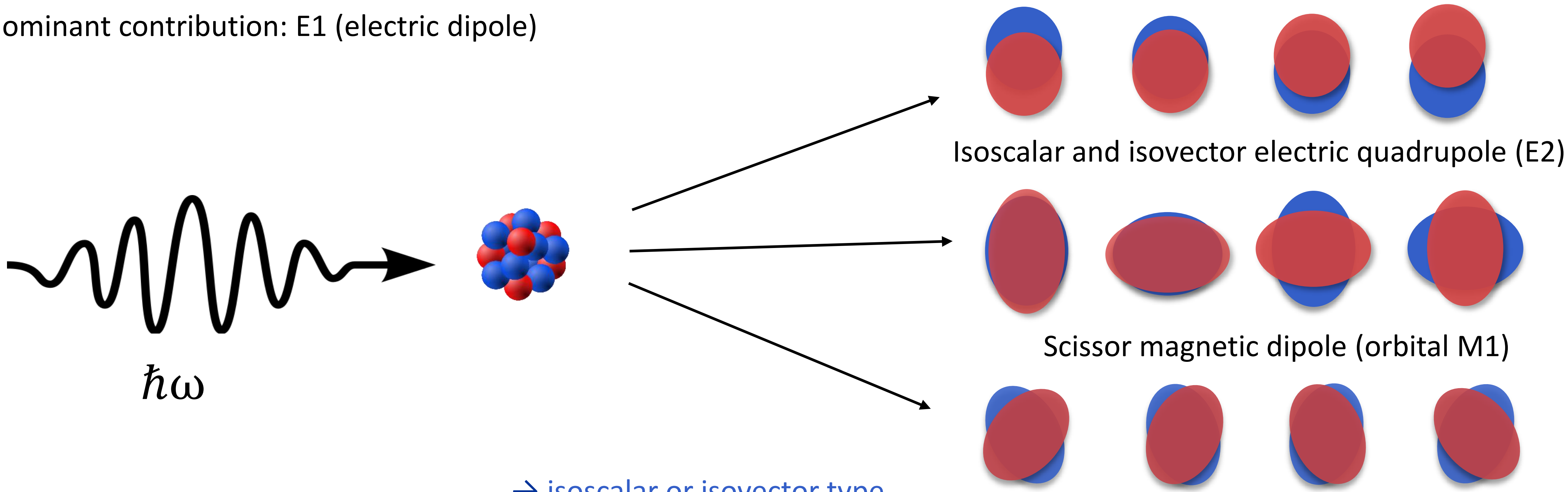
Nuclear collective vibrations

- γ -rays – an ideal external probe because interaction with nucleus is well understood
- photoabsorption cross section can be decomposed to different multipoles and electric (E) and magnetic (M) parts

$$\sigma_{\gamma}^{abs}(\hbar\omega, i \rightarrow f) \sim \sum_{\lambda, X=E,M} (\hbar\omega)^{2\lambda-1} S(X\lambda, \omega) \approx \hbar\omega\, S(E1, \omega)$$

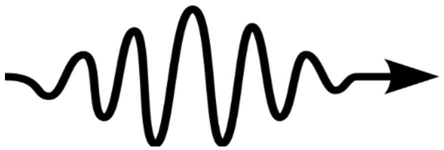
dominant contribution: E1 (electric dipole)

Isovector electric dipole (IV E1)

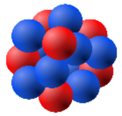


→ isoscalar or isovector type

Electric dipole excitations



$\hbar\omega$



$$\hat{H} = \hat{H}_{nuc} + \hat{H}_{int}$$

periodic perturbation with frequency ω

Reduced transition probability

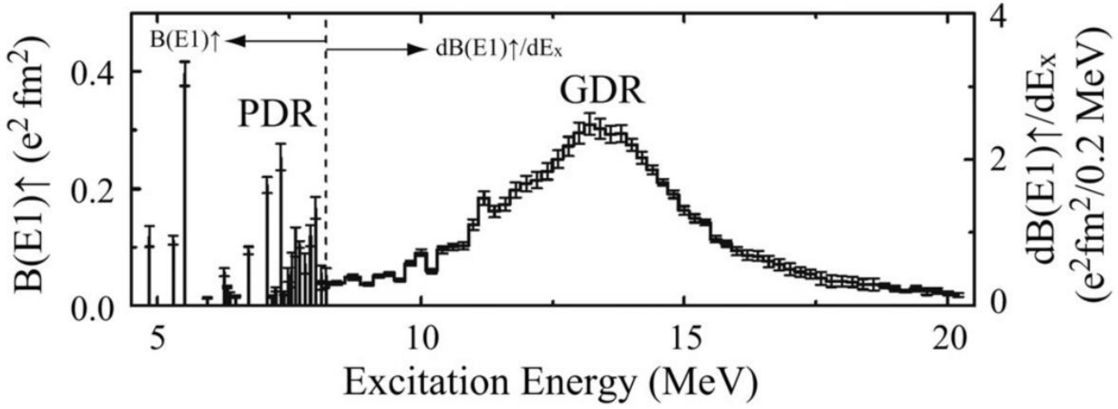
$$B(E1, i \to f) \sim \left| \left\langle f, J_f^{\pi_f} \right| \widehat{M_1^E} \left| i, J_i^{\pi_i} \right\rangle \right|^2$$

dipole operator

nuclear states calculated in some many-body approximation scheme

(γ –ray) dipole strength function

$$S(E1, \omega) = \sum_f B(E1, i \to f) \;\; \rho_\Delta(\omega - \omega_{fi}), \qquad \hbar\omega_{fi} = E_f - E_i$$

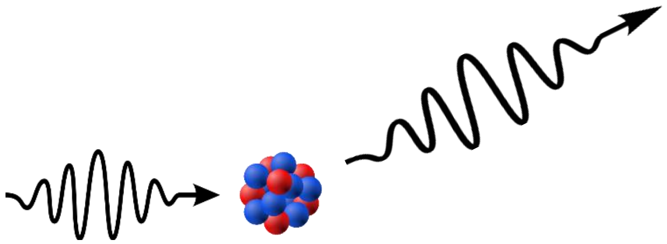


A. Tamii et al., Eur. Phys. J. A 50 (2) (2014) 28.

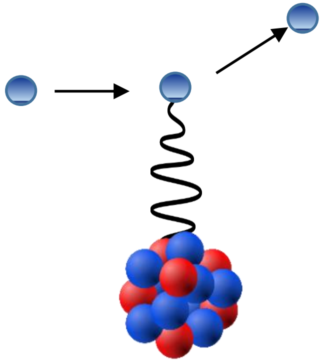
Tools for studying dipole response

- **Electromagnetic probes**

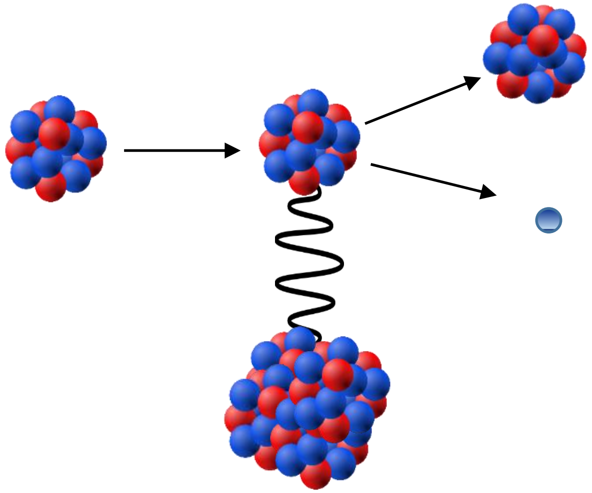
  real photons
  photonuclear (γ,γ‘) or photon scattering



  virtual photons
  Coulomb excitations: target nucleus e.g. via (p,p‘)



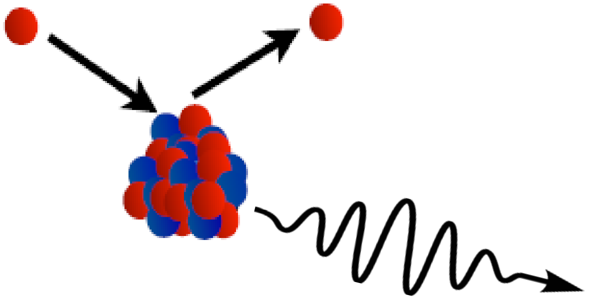
  radioactive beam (exotic nuclei)



- **Hadronic probes**

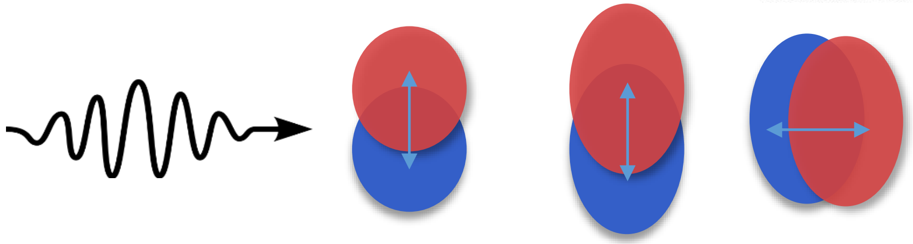
  (α,α‘γ)

  (^{17}O, ^{17}O‘γ)



Isovector giant dipole resonance (IVGDR)

- dominant component of the photoabsorption cross section
- first measurement of IVGDR: Bothe and Gentner (1937) in ^{63}Cu*(γ,n)* reaction
- Goldhaber, Teller (1948): **isovector** dipole collective oscillation of protons against neutrons



PHYSICAL REVIEW VOLUME 74, NUMBER 9 NOVI

On Nuclear Dipole Vibrations

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AND

E. TELLER
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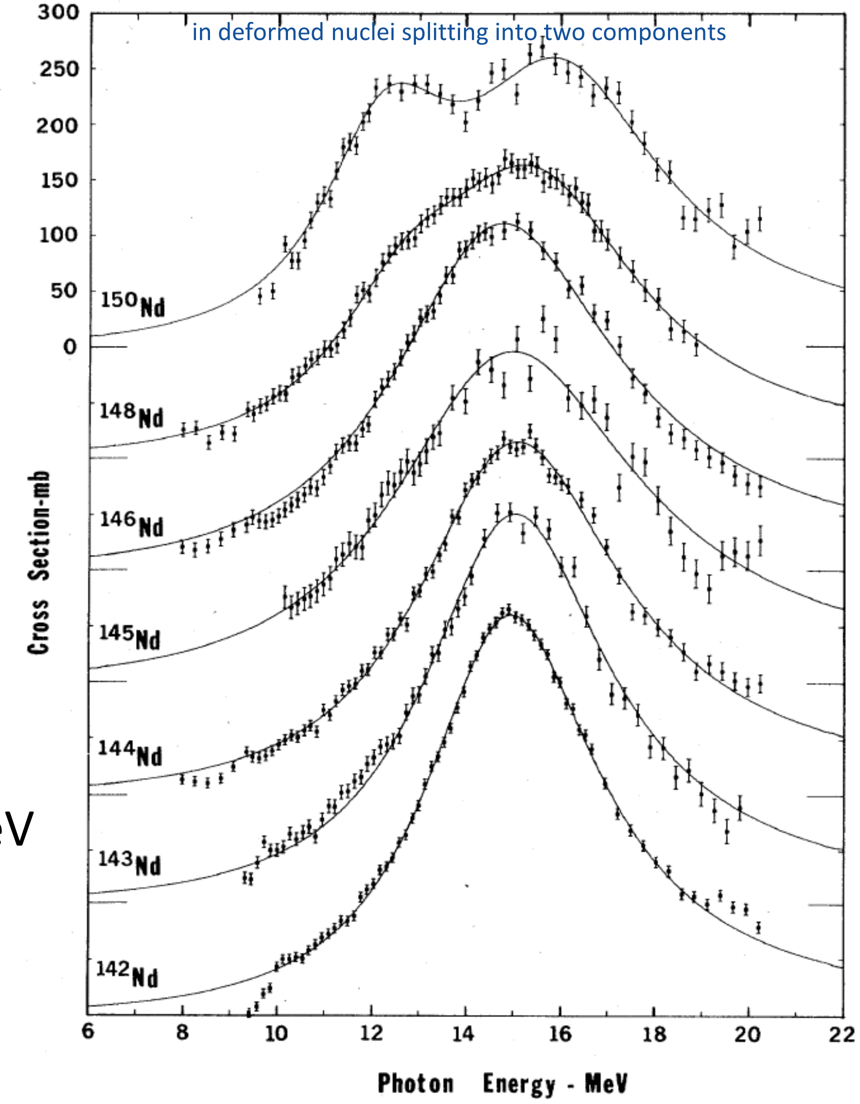
(Received July 22, 1948)

- **a general phenomenon observed in all nuclei**

- energy centroid $E_x = 31.2\ A^{-1/3} + 20.6\ A^{-1/6}$ MeV, width 2.5 – 5 MeV
- **Thomas-Reiche-Kunh (TRK) sum rule**

$$\int_{S_n \approx 8MeV}^{E_{max} \approx 25MeV} \sigma_\gamma^{abs}\, dE \approx \frac{60NZ}{A} MeV.mb$$



B.L. Berman and S.C. Fultz, Rev. Mod. Phys. 47, 713 (1975).

Nuclear dipole response

Giant resonances → coherent motion of many nucleons → large transition probabilities (B(E1))
collectivity → TRK sum rule

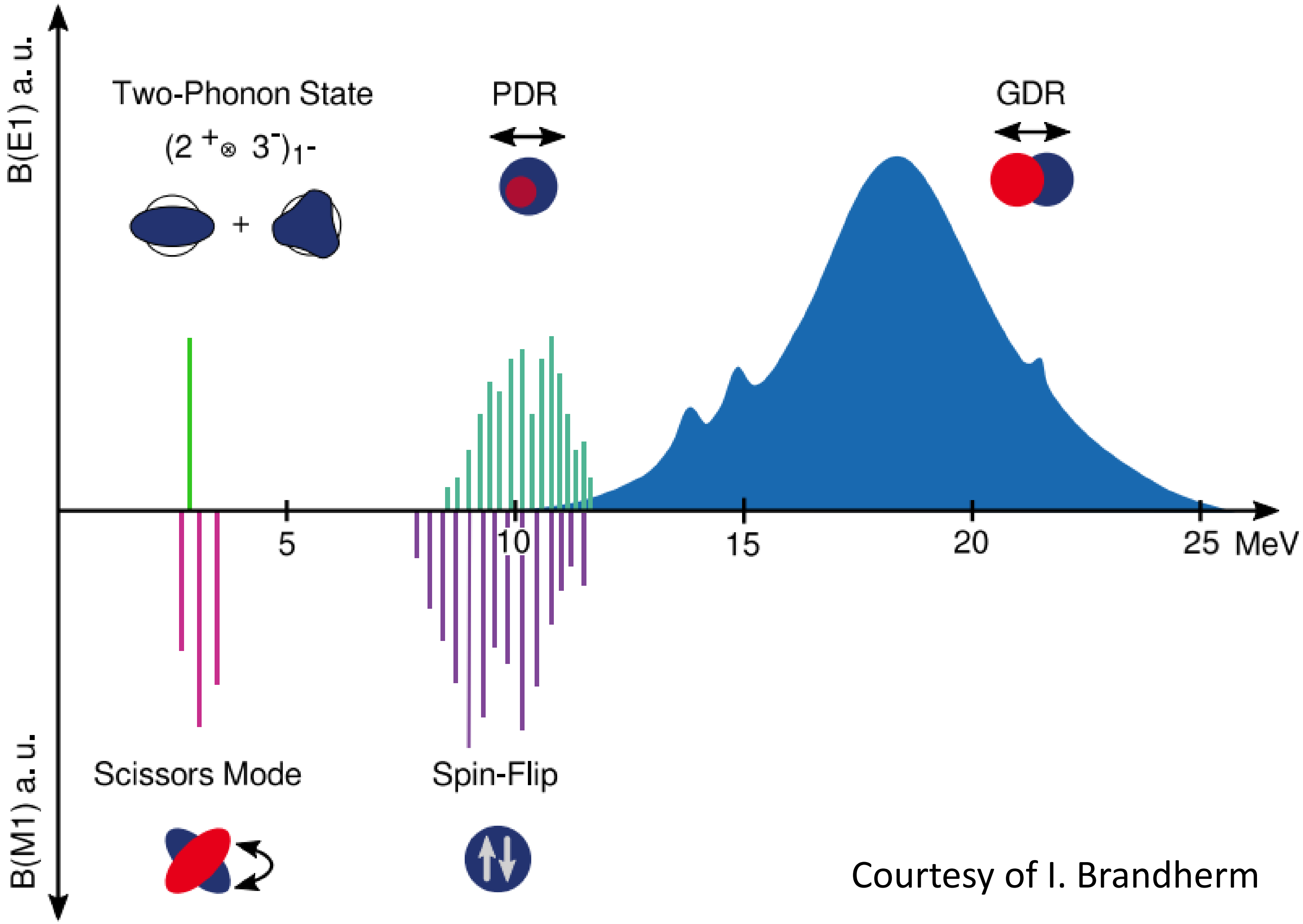
(quasi) harmonic vibrations

- low-lying 2-phonon vibrations
  oscillations of shape (density)

- Pygmy dipole resonance (PDR)
  soft mode around S_n
  observed in neutron-rich nuclei
  exhausts small fraction of TRK (less then %)

  oscillation of **neutron skin** against
  symmetric *pn* core?

- Giant dipole resonance (GDR)
  high frequency collective oscillation of
  protons against neutrons
  exhausts TRK sum rule

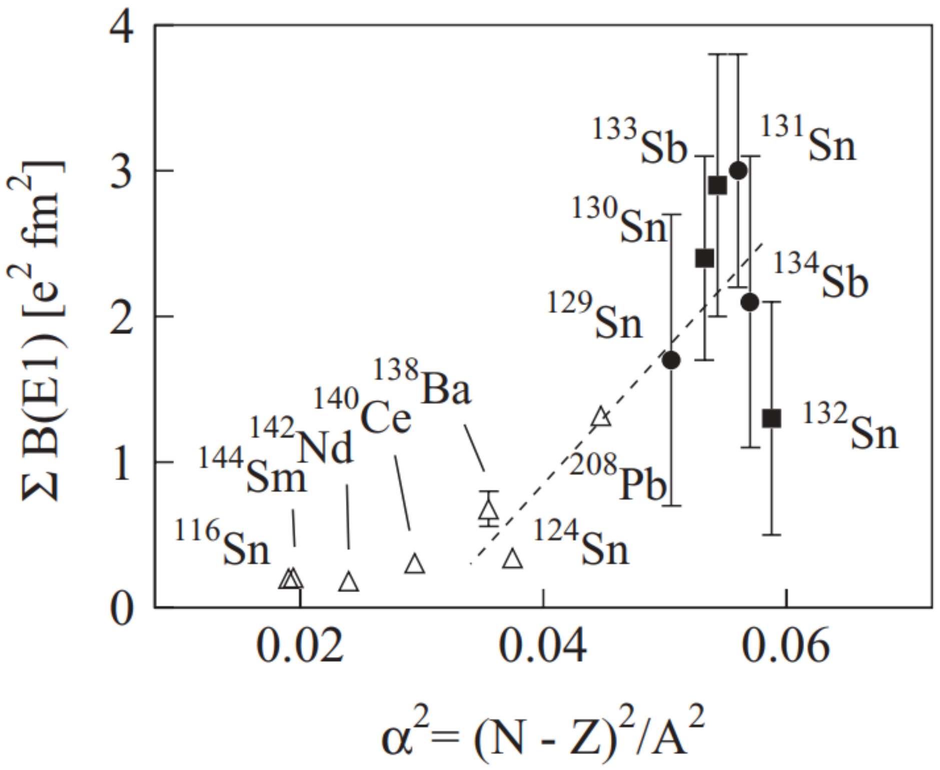


Courtesy of I. Brandherm

Pygmy dipole resonance

- enhancement on the low-energy tail of the GDR observed in neutron-rich nuclei
- concentrated around the neutron separation energy
- **related to nuclear dipole polarizability and neutron skin thickness**

- „traditional“ macroscopic picture → oscillation of *pn* symmetric core against neutron skin questioned by *Repko et al.* → compressional and toroidal collective motion



A. Klimkiewicz et al., Phys. Rev. C 76, 051603(R), (2007).

PHYSICAL REVIEW C **87**, 024305 (2013)

Toroidal nature of the low-energy *E*1 mode

A. Repko,[1] P.-G. Reinhard,[2] V. O. Nesterenko,[3,*] and J. Kvasil[1]
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[2]*Institut für Theoretische Physik II, Universität Erlangen, D-91058 Erlangen, Germany*
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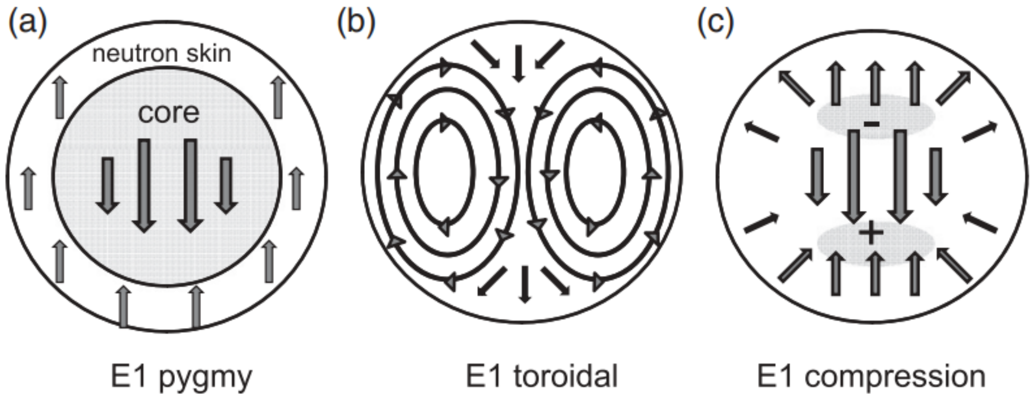
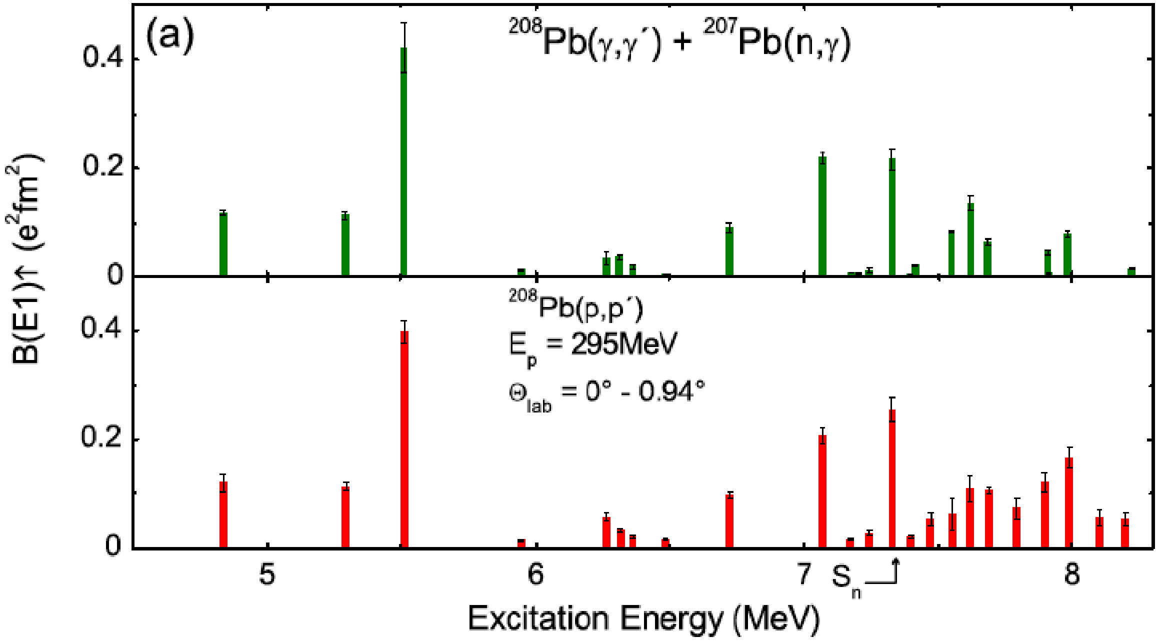
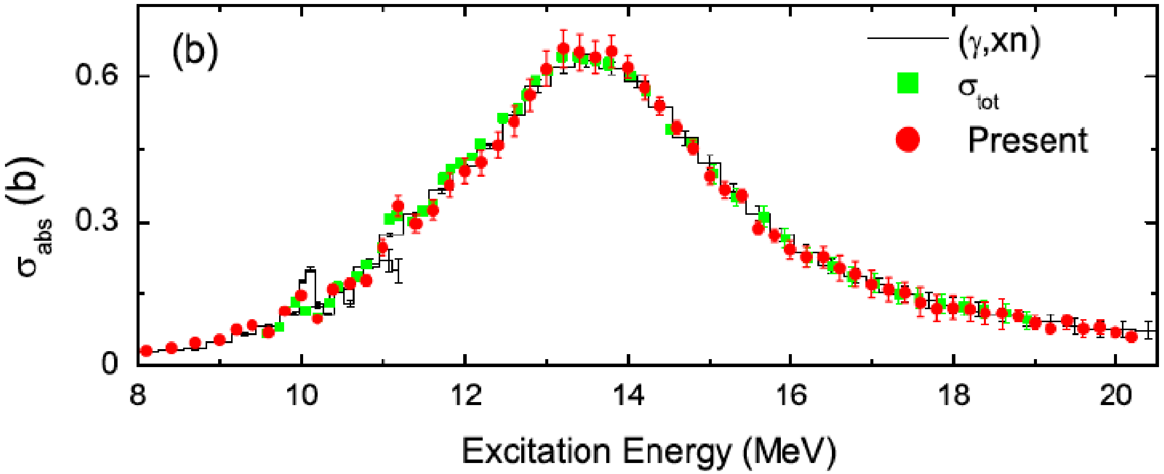


Nuclear dipole response

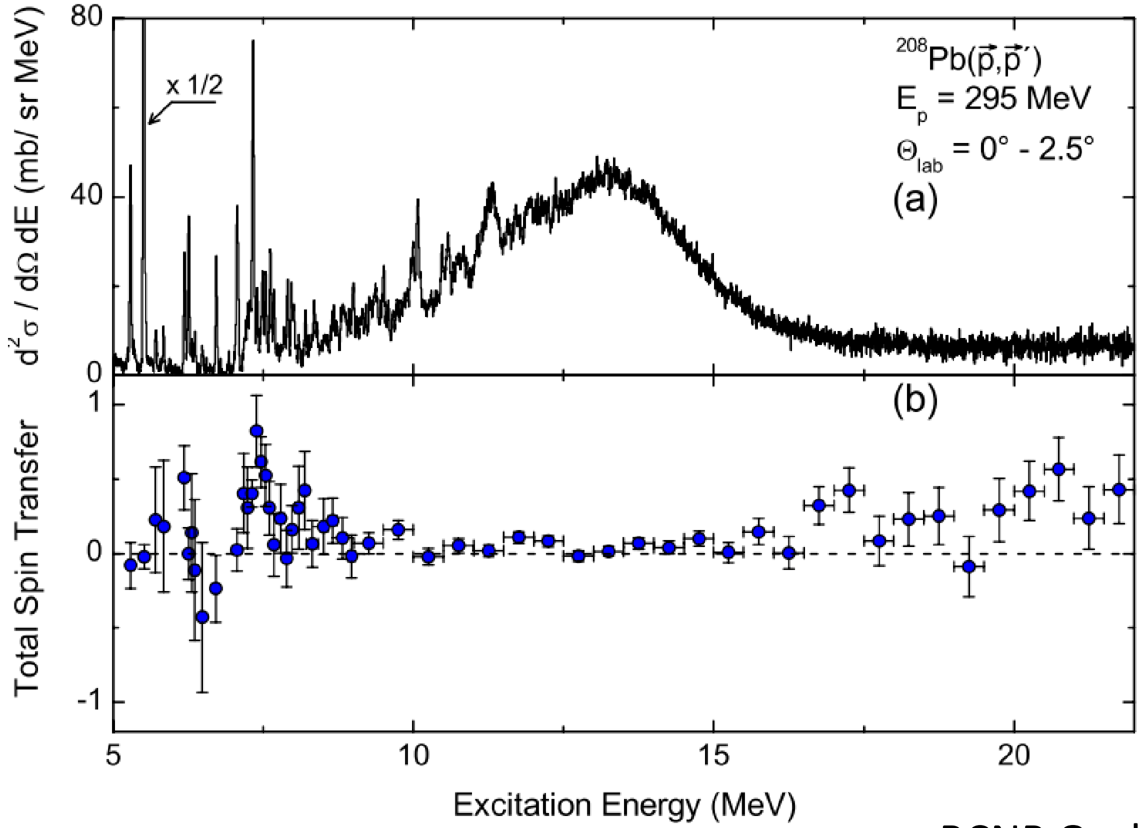
For some nuclei complementary measurements exist, good example is ^{208}Pb





Low-lying discrete states (bellow S_n)

Fine structure of GDRs



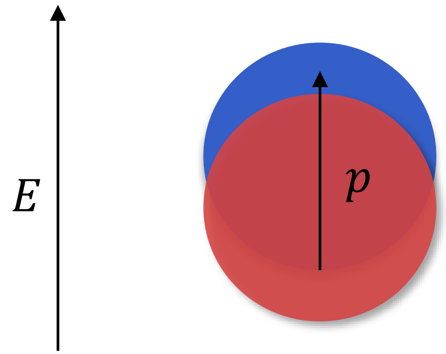
RCNP Osaka

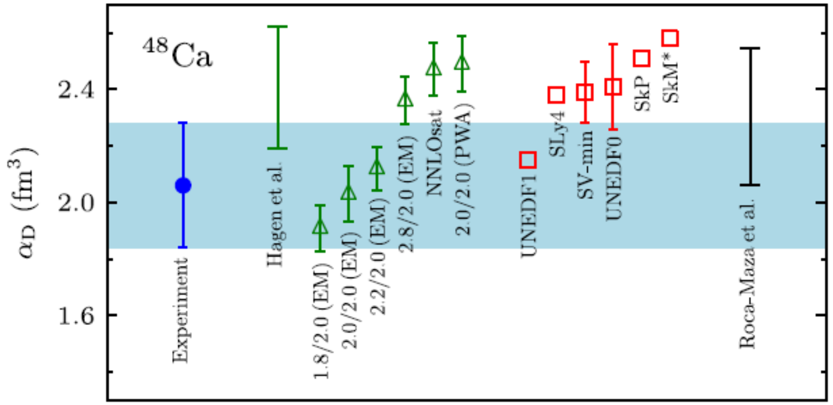
Tamii et al. Phys. Rev. Lett. 107, 062502 (2011)

Dipole polarizability

- response to an external static electric field E
  → electric dipole moment p

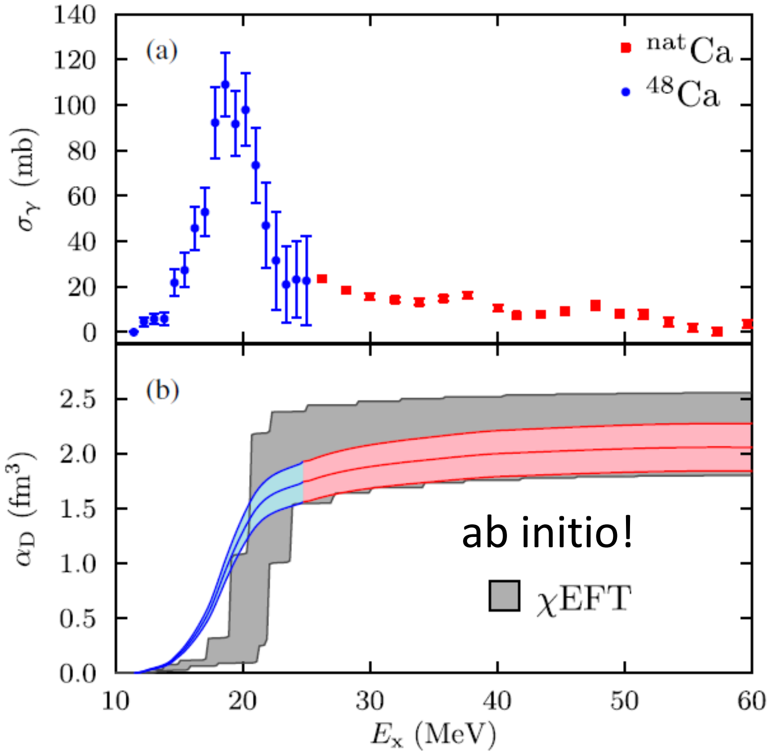
  electric dipole polarizability α_D





$$\alpha_D = \frac{p}{E} \sim \int \frac{S(E1,\omega)}{\omega} d\omega \sim \int \frac{\sigma_\gamma^{abs,E1}(\omega)}{\omega^2} d\omega$$

strength function (or photoabsorption cross section) → dipole polarizability
important contribution from PDR (neutron-rich systems)



Birkhan et al., Phys. Rev. Lett 118, 252501 (2017)

Why is α_D useful?

correlation with **neutron skin** thickness → nuclear structure
neutron skin thickness sensitive to symmetry energy
important for understanding of neutron matter → neutron stars

Neutron skin thickness

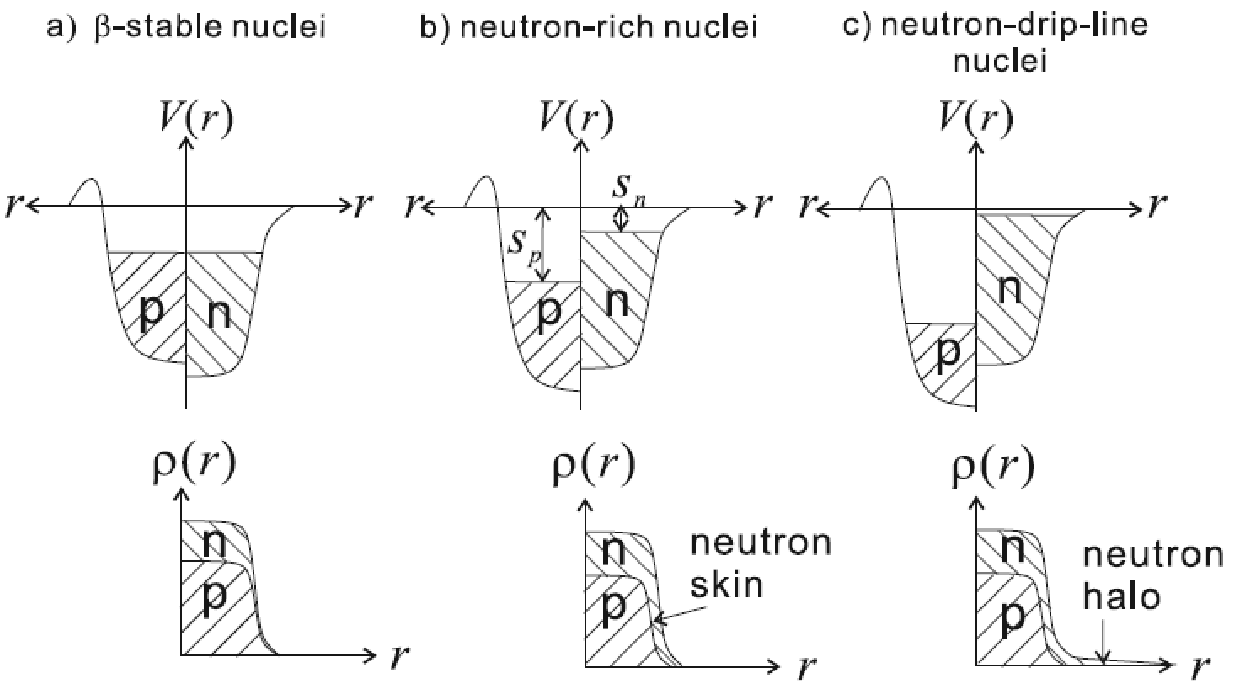
- **charged radii and densities well measured**

electron scattering → information about size, surface thickness, saturation density, (e.g. rms charged radius of ^{208}Pb is known with error 0.02%).

- **(not?)surprisingly neutron densities are not known very precisely**

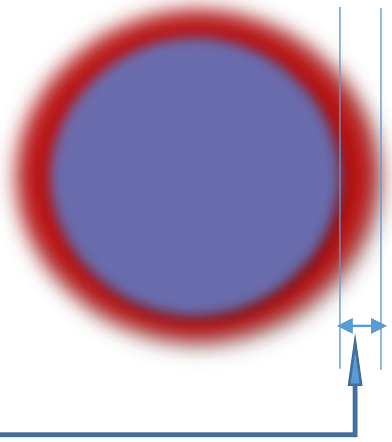
hadronic probes suffer from large uncertainties (reaction mechanisms, „unknown“ interaction)

neutron-rich nuclei → development of neutron skin



Auman T. , Nakamura T., Phys. Scr. T152, 014012(2013).

How large is the neutron skin?



$$\Delta r_{np} = \sqrt{\langle r_N^2 \rangle} - \sqrt{\langle r_P^2 \rangle}$$

Neutron skin thickness

Simplified droplet model (DM) → approximately linear increase of neutron skin thickness with *pn* asymmetry

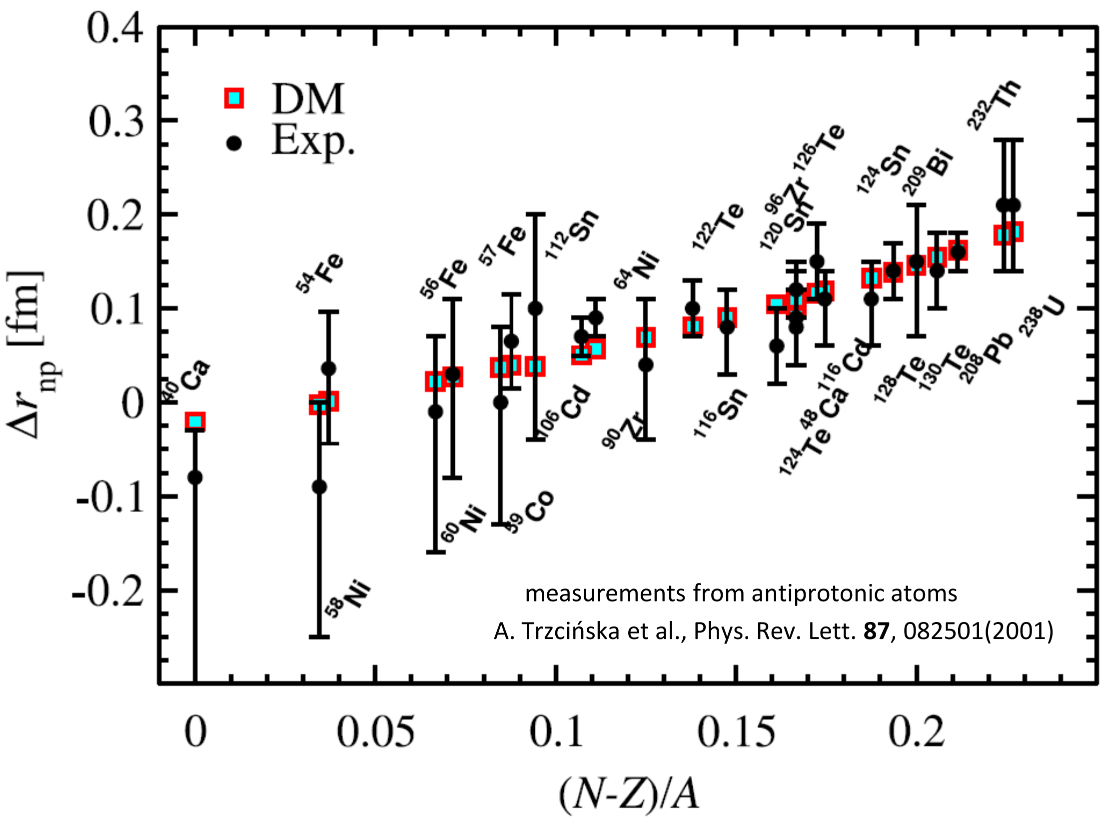
X. Roca-Maza, N. Paar / Progress in Particle and Nuclear Physics 101 (2018) 96–176

importance of symmetry energy (at the surface and in the core)
In real world, it is more complicated (e.g. shell effects …)

$$\Delta r_{\rm np}^{\rm DM} = \frac{2\langle r^2\rangle^{1/2}}{3}\frac{a_{AS}}{a_A}(I - I_C) + \Delta r_{np}^{C}$$

$$I \equiv (N-Z)/A$$

$$\langle r^2\rangle^{1/2} \approx 0.9A^{1/3}$$

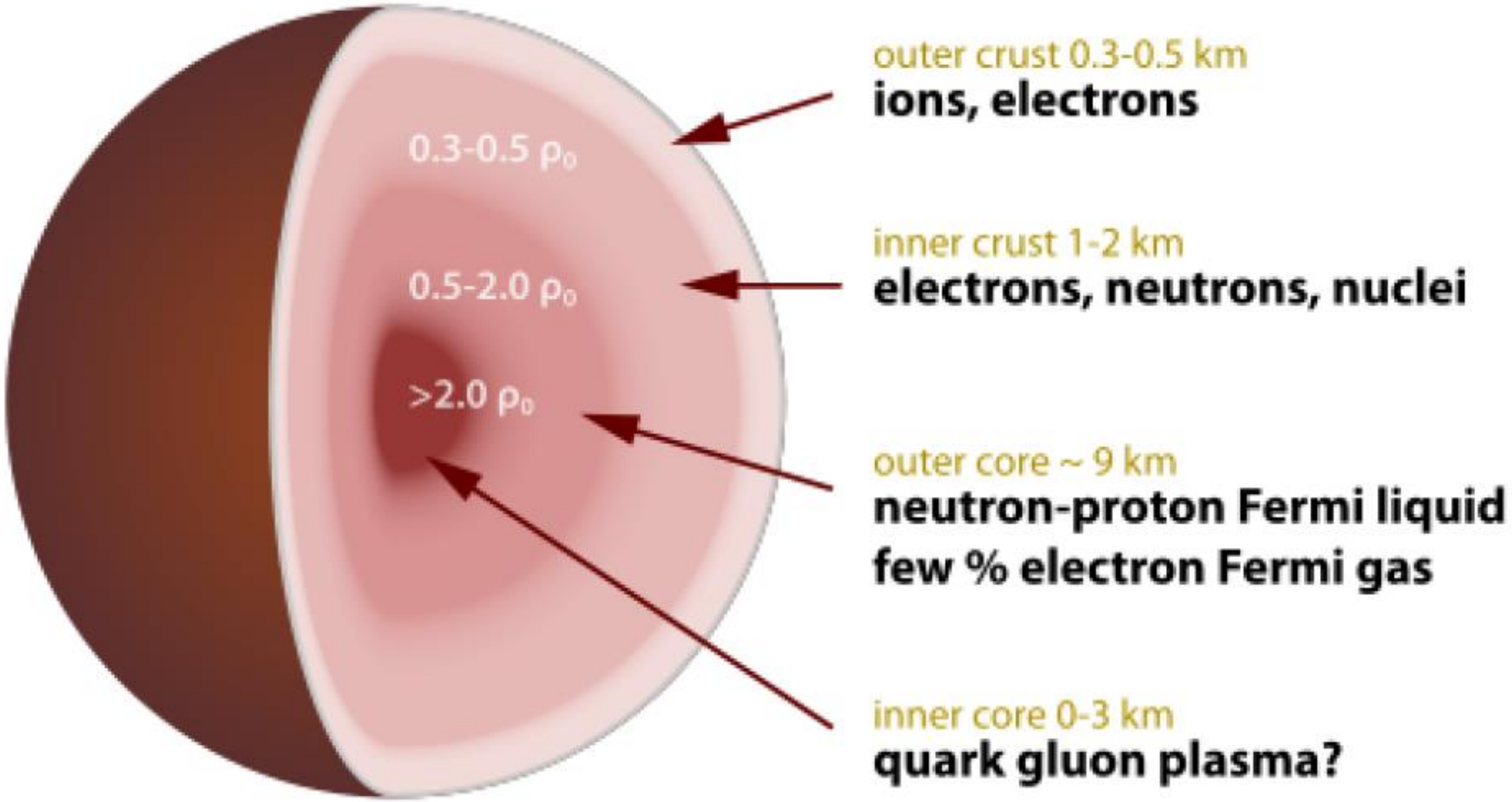


$$B(A,Z) = (a_V - a_S A^{-1/3})A - a_C\frac{Z(Z-1)}{A^{1/3}} - (a_A - a_{AS}A^{-1/3})\frac{(A-2Z)^2}{A}$$

competition between surface tension and symmetry energy difference at core (high density) and surface (low density)

Nuclear Equation of state (EoS)

- EoS describes relationships between the energy, pressure, temperature, density and proton-neutron asymmetry.



- stellar mass depends on EoS at the highest densities
- radius is sensitive to properties of the EoS in the vicinity of nuclear matter saturation density

Nuclear Equation of state (EoS)

- parametrization of energy per nucleon dependence of uniform infinite system ($A \to \infty,\ V \to \infty, \frac{A}{V} \to$ const.)
- unknown parameters → data from finite nuclei

polarizability, neutron skin thickness → symmetry energy part of EoS

→ EoS for neutron matter

$$e(\rho,\delta) = e(\rho,0) + S(\rho)\delta^2 + \mathcal{O}[\delta^4]$$

$$\rho \equiv \rho_n + \rho_p \qquad \delta \equiv \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

parametrization of **symmetry energy**

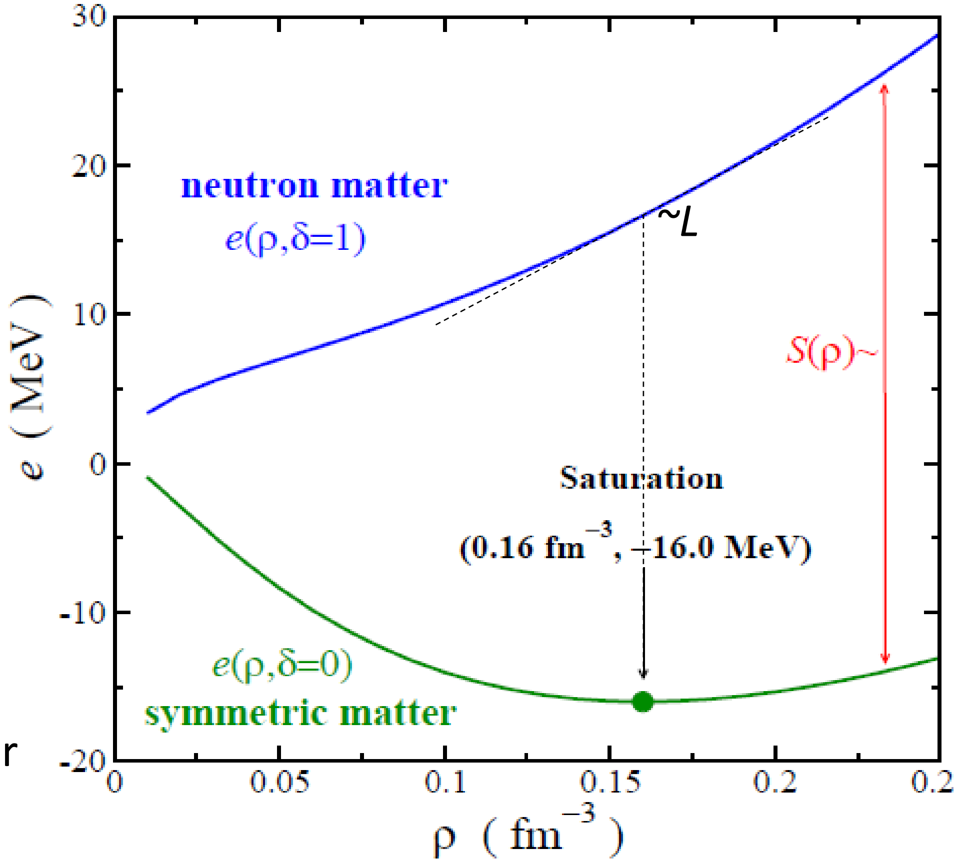
$$S(\rho) = J + L\frac{\rho-\rho_0}{3\rho_0} +$$

Saturation density

$$\rho_0 = \frac{3A}{4\pi R^3}$$

Pressure of neutron matter

$$P_0 \approx \frac{1}{3}\rho_0 L$$

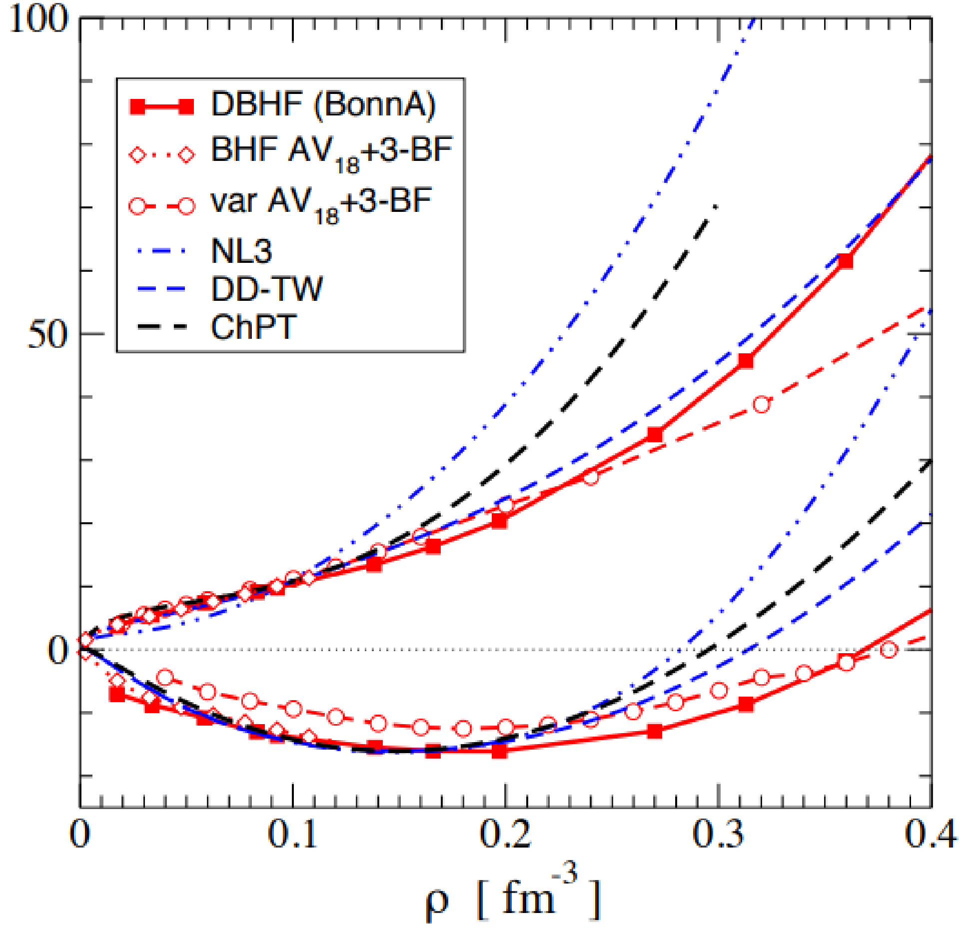


X. Roca-Maza, N. Paar, Progress in Particle and Nuclear Physics 101 (2018) 96–176

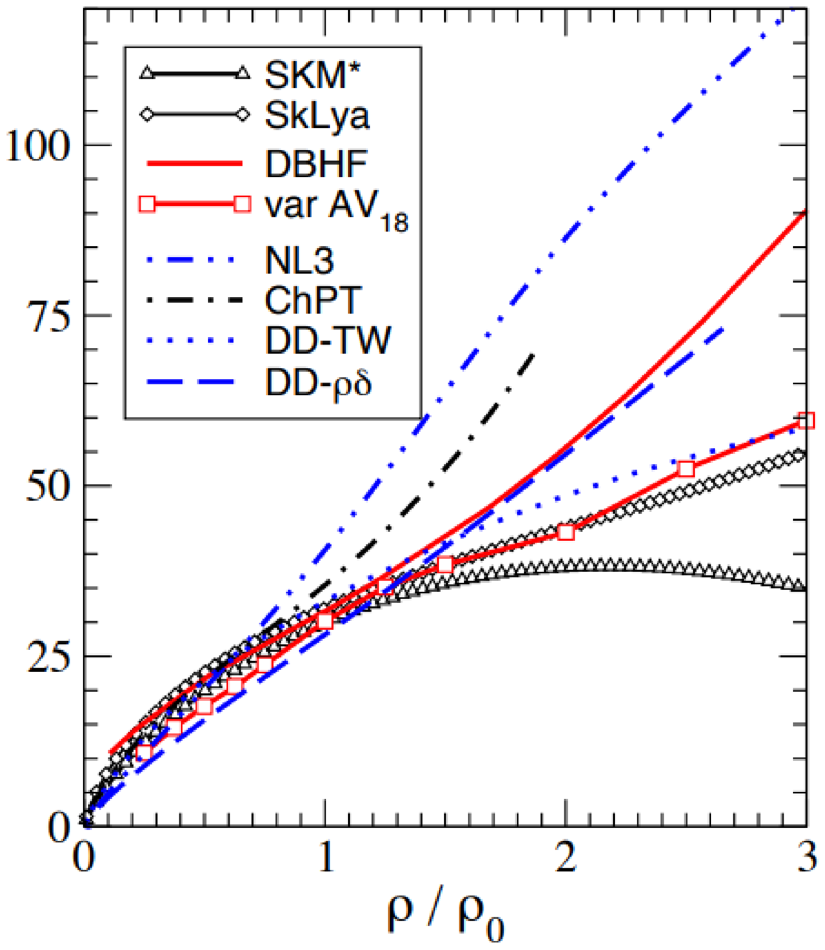
Nuclear Equation of state (EoS)

different models → different predictions

nuclear EoS



symmetry energy

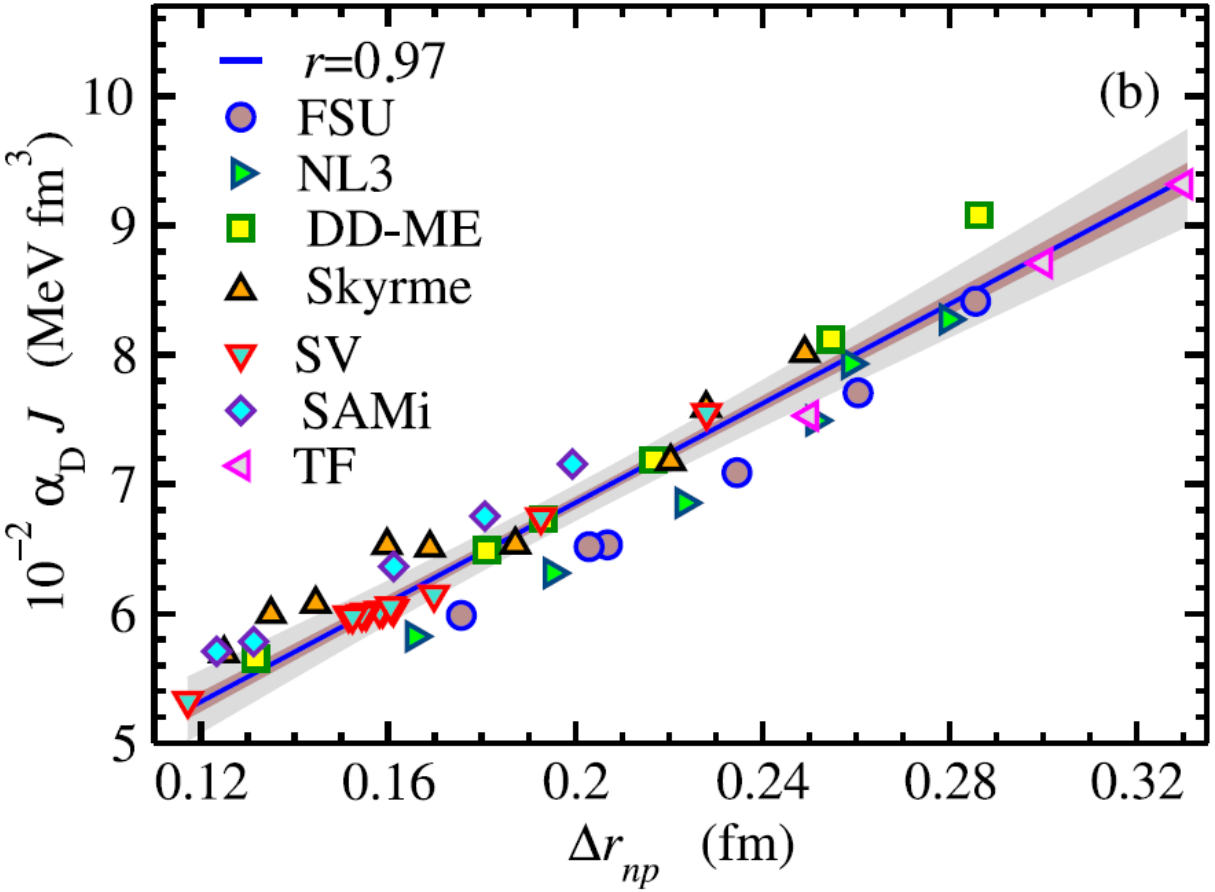


J. Wambach INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS, Erice 2014

Symmetry energy parameters in EoS

How to determine symmetry energy parameter ***L*** *?* (nuclear masses are insensitive to *L*)

Energy density functional (EDF) nuclear models (mean-field calculations) „predictions“
→ strong correlation between **dipole polarizability** α_D **and symmetry energy slope parameter** ***L***



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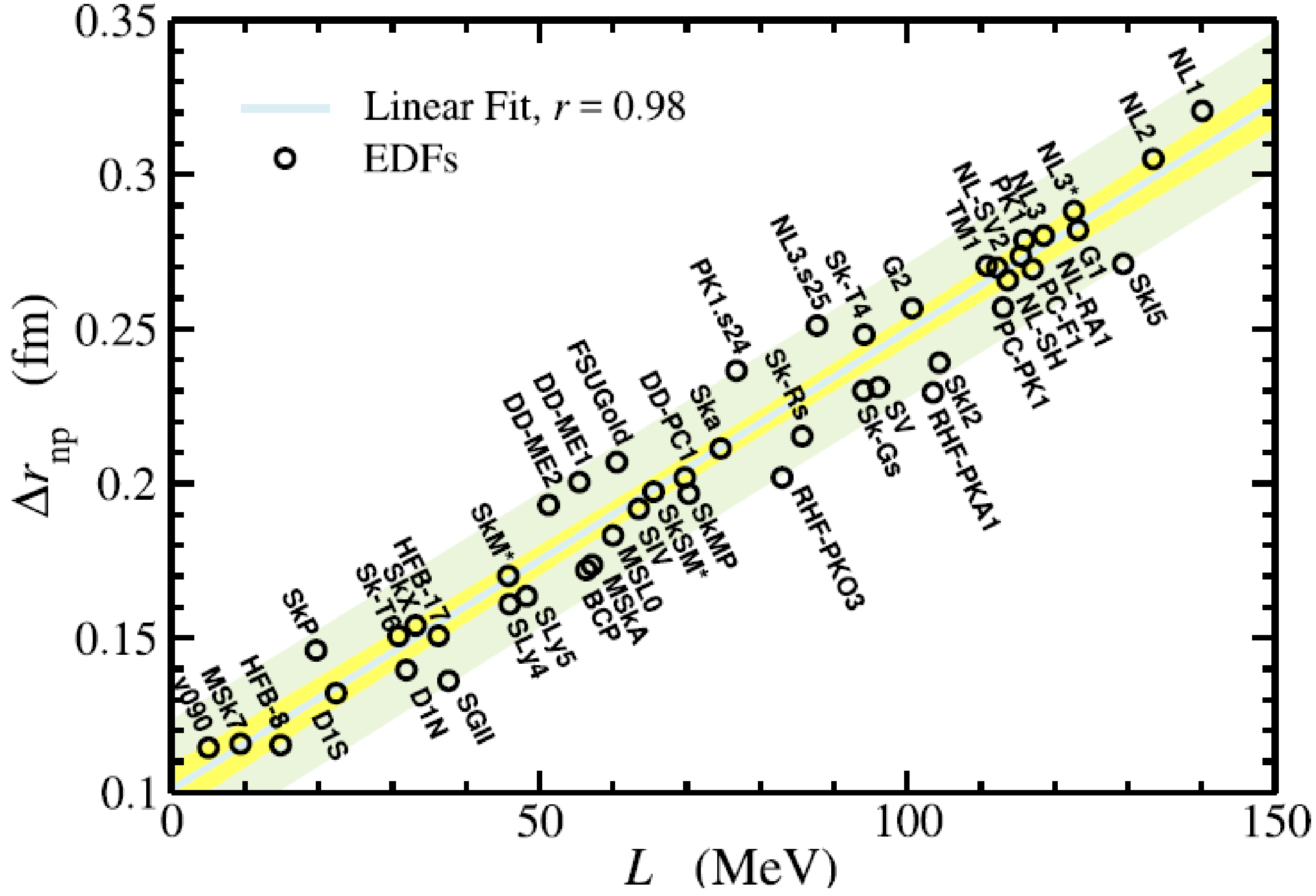
^{208}Pb

EDFs : set of microscopic models developed
for precise description of bulk properties
across the chart

$$\alpha_D \sim \int \frac{\sigma_\gamma^{abs,E1}(\omega)}{\omega^2} d\omega$$

Symmetry energy parameters in EoS

… and strong correlation between **neutron skin thickness Δr_{np}, and symmetry energy slope parameter L**



^{208}Pb

How to determine (measure) **neutron skin thickness?**

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Pb Radius EXperiment and Ca Radius EXperiment @JLAB

- goal: determination of neutron skin thickness with minimal model-dependence

electroweak parity violating measurements of elastic scattering of longitudinally polarized electrons from ^{208}Pb (PREX) and ^{48}Ca(CREX)

weak coupling of proton to Z^0 → sensitive to neutron distribution
→ neutral weak formfactor extraction from parity violation asymmetry
→ „neutron“ radius

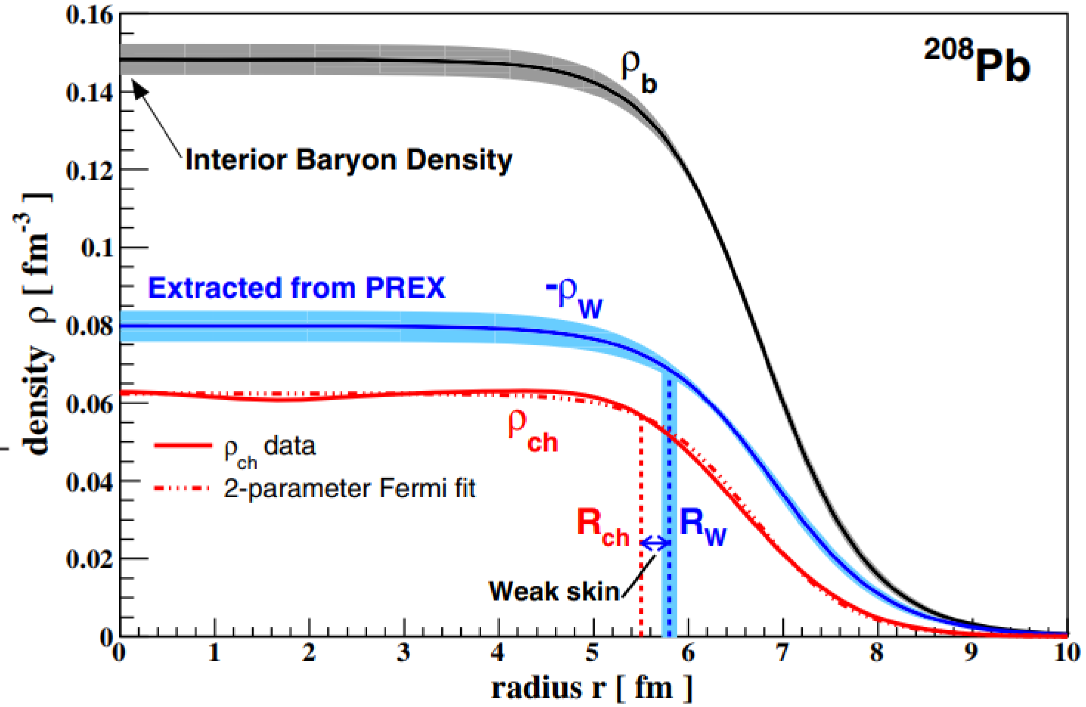
$$A_{\mathrm{PV}} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx \frac{G_F Q^2 |Q_W|}{4\sqrt{2}\pi\alpha Z} \frac{F_W(Q^2)}{F_{\mathrm{ch}}(Q^2)} \approx 10^{-7}$$

$$R_{\mathrm{skin}} = (0.283 \pm 0.071)\ \mathrm{fm}$$

PHYSICAL REVIEW LETTERS **126**, 172502 (2021)

Editors' Suggestion | Featured in Physics

Accurate Determination of the Neutron Skin Thickness of ^{208}Pb through Parity-Violation in Electron Scattering



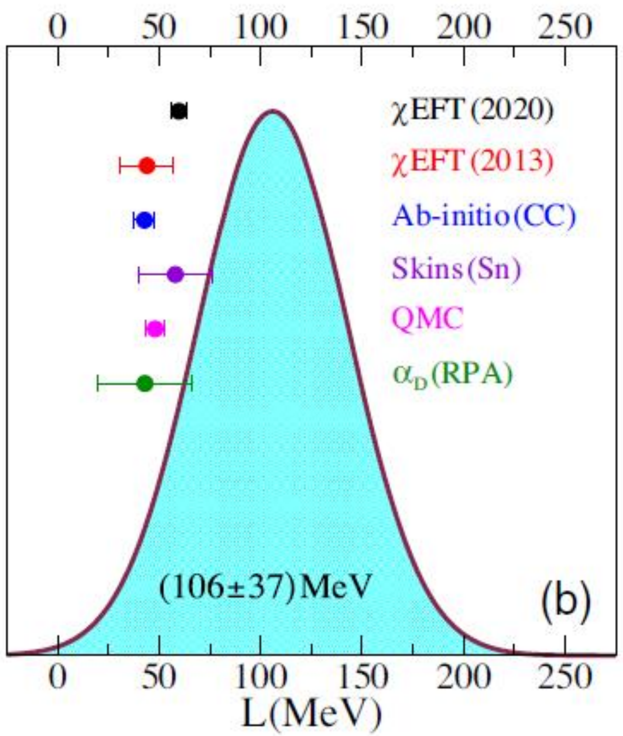
Pb Radius EXperiment and Ca Radius EXperiment @JLAB

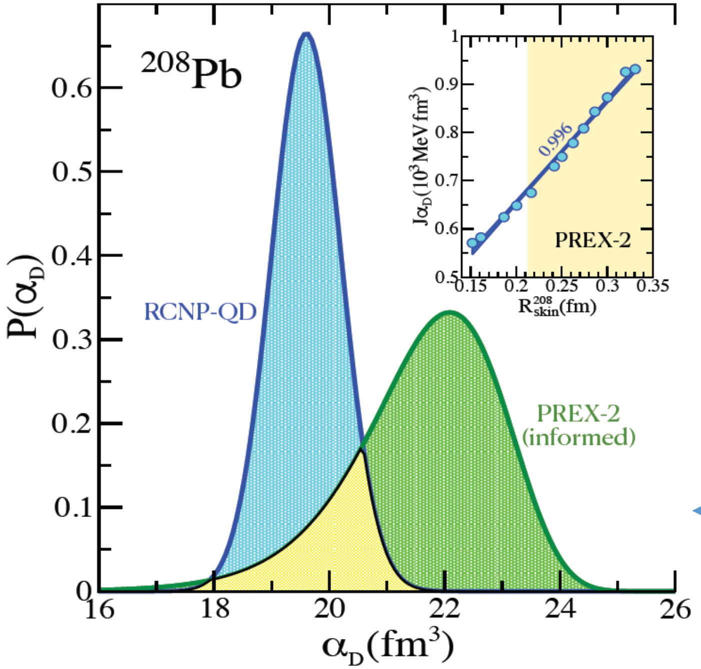
"some tension" between nuclear models and PREX-II data…
CREX → smaller value of neutron skin in ^{48}Ca.

PREX-II data → stiff symmetry energy

$$J = (38.1 \pm 4.7)\ \text{MeV},$$
$$L = (106 \pm 37)\ \text{MeV}.$$

dipole polarizability, ab-initio, EFT
→ more soft





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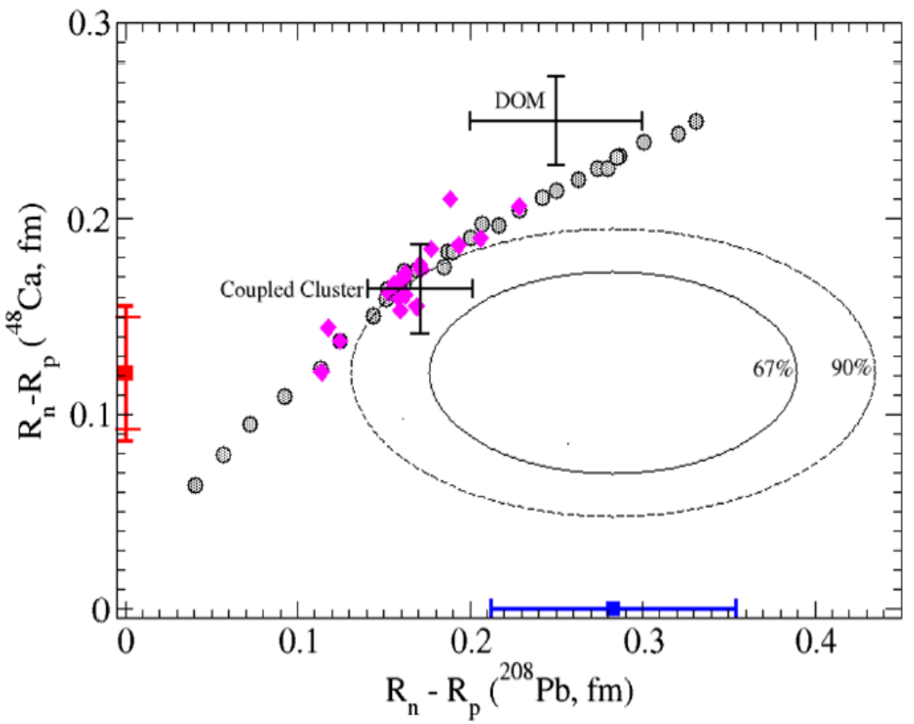
Editors' Suggestion

Precision Determination of the Neutral Weak Form Factor of ^{48}Ca



PHYSICAL REVIEW C 104, 024329 (2021)

Editors' Suggestion

Implications of PREX-2 on the electric dipole polarizability of neutron-rich nuclei

J. Piekarewicz

Summary

- laboratory experiments + theory useful for a determination of some fundamental nuclear properties

  dipole polarizability, neutron skin thickness

  → constraints on parameters of EoS → neutron matter properties

- nuclear dipole excitations unique determination of dipole polarizability

- measuring of neutron skin → parity-violating electron scattering

- linking neutron stars with properties of nuclei