Constraints on the Symmetry Energy from the Dipole Polarizability

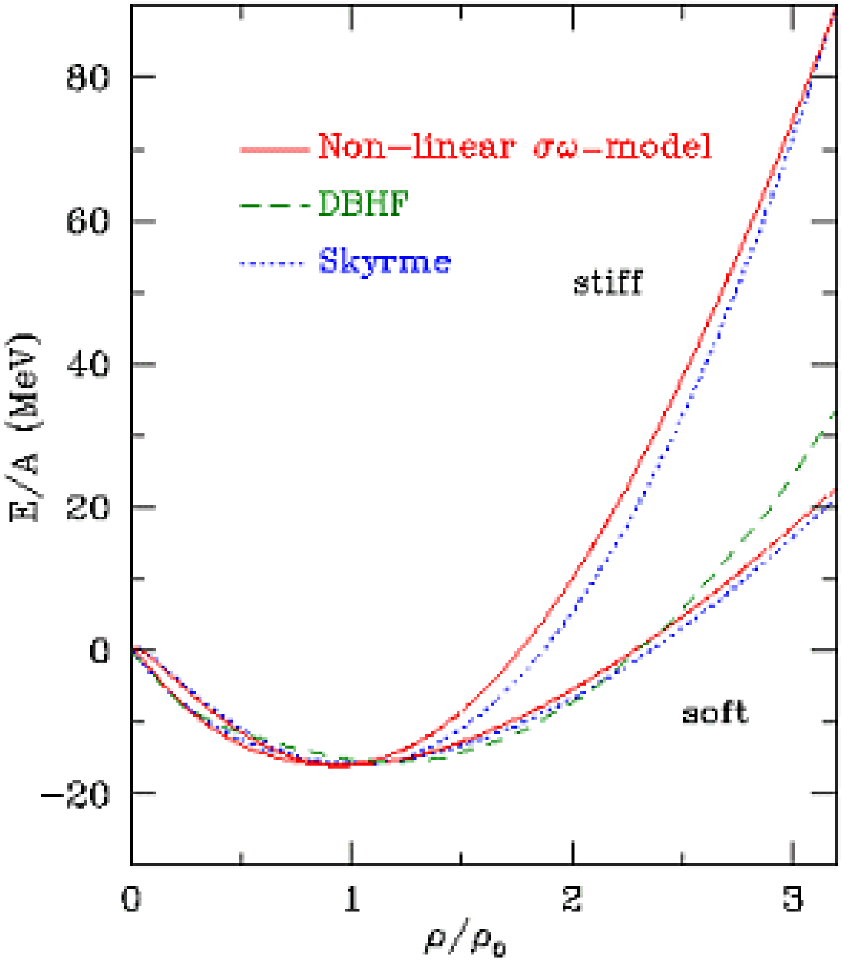
Peter von Neumann-Cosel
Institut für Kernphysik, Technische Universität Darmstadt

- Equation of State, symmetry energy, neutron skin and dipole polarizability
- Extraction of the E1 strength and dipole polarizability from small-angle (p,p‘) scattering
- Constraints from density functional theory
- Constraints from *ab initio* calculations
- Constraints from systematics

Supported by DFG under contract SFB 1245 (project id 279384907)

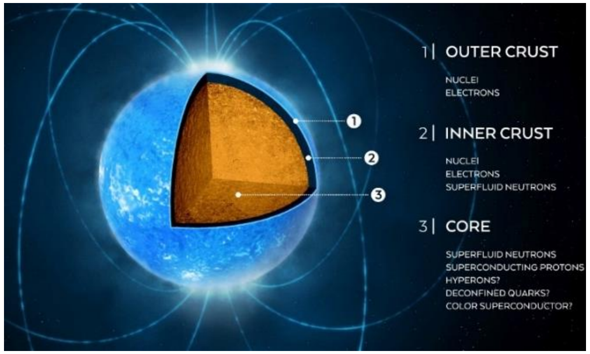
Nuclear Matter Equation of State (EOS)

- Energy as a function of density (or pressure)
- Well defined at $\rho/\rho_0 = 1$ by properties of stable nuclei
- Large differences of models at high densities: stiff or soft?



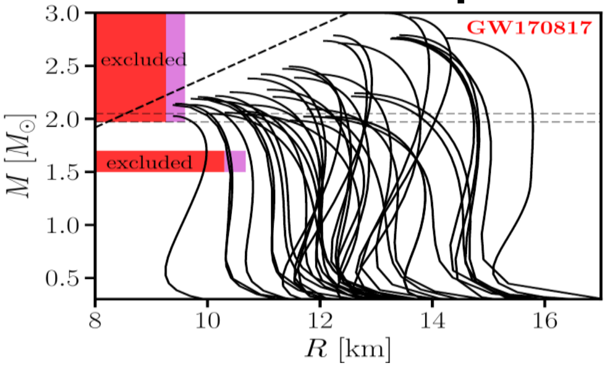
EoS of Neutron-Rich Matter

Neutron Stars



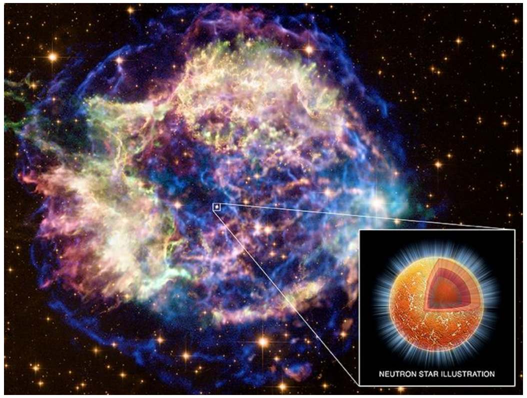
A. Watts et al., RMP 88, 021001 (2016)

Neutron Star Properties



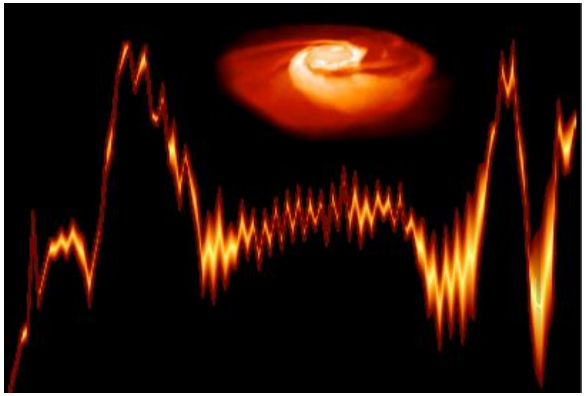
A. Bauswein et al., ApJ Lett. 885, L34 (2017)

Core-Collapse Supernovae



H. Yasin et al., PRL 124, 092701 (2020)

Neutron Star Mergers

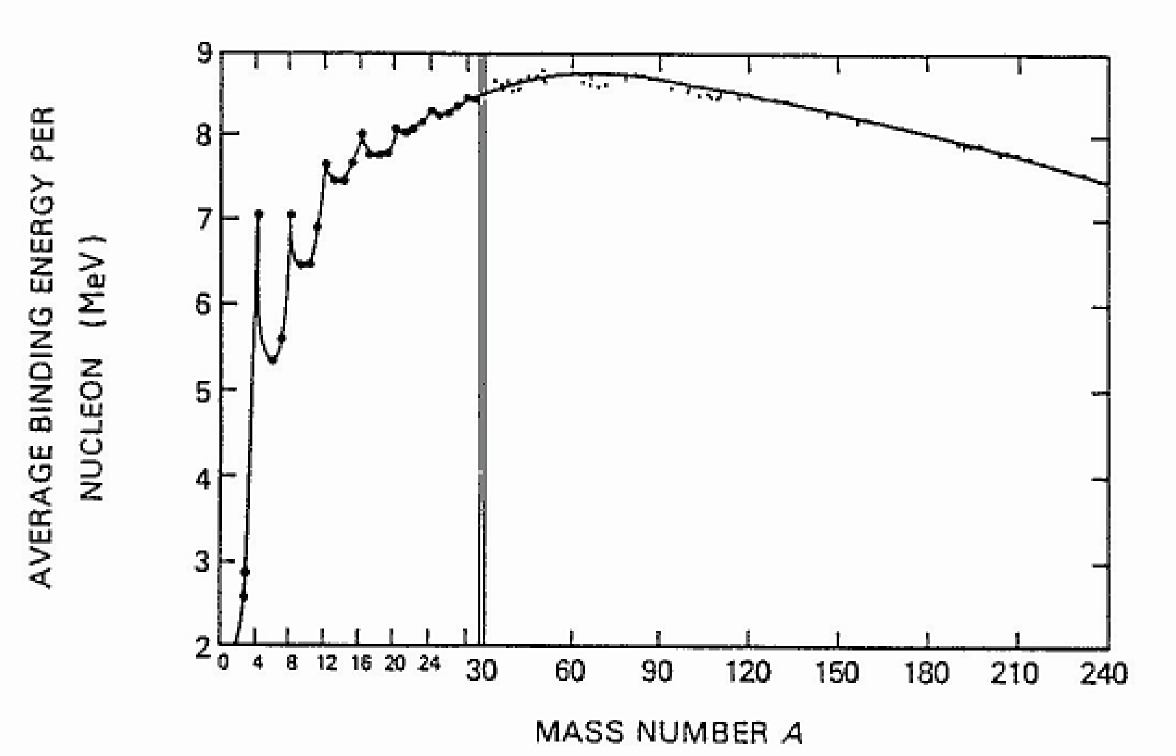


B.P. Abbott et al., PRL 119, 161101 (2017)

Binding Energy of Nuclei

$$B(A,Z) = a_v A - a_s A^{2/3} - a_c Z(Z-1)/A^{1/3} - a_{sym}(A-2Z)^2/A + \delta$$

volume surface Coulomb symmetry pairing



Binding Energy of (Infinite) Neutron-Rich Matter

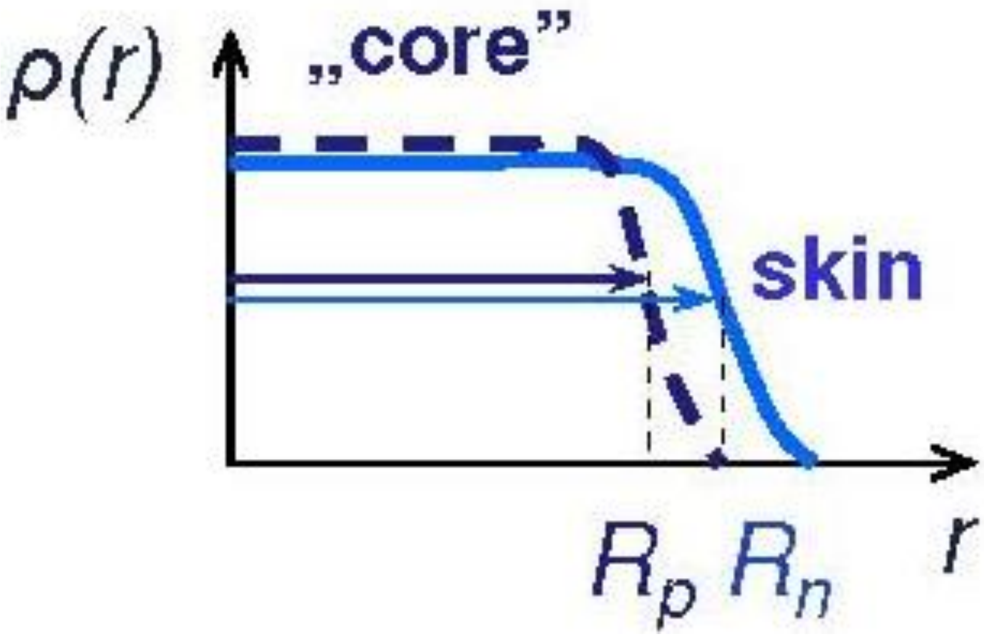
$$B(A,Z) = a_v A - a_s A^{2/3} - a_c Z(Z-1)/A^{1/3} - a_{sym}(A-2Z)^2/A + \ldots$$

volume surface Coulomb symmetry pairing

- For (infinite) neutron matter only volume and symmetry term contribute to the energy of the system.
- The volume term can be estimated from the saturation properties
- The symmetry energy represents the largest uncertainty for the EOS of neutron-rich matter.

Symmetry Energy and Neutron Skin of Nuclei

- Nuclear force leads to constant density in the interior (saturation)
- Stable heavy nuclei have *N* > *Z* because the symmetry energy is balanced by the Coulomb repulsion between protons
- Extra neutrons concentrate on the surface
  ➡ formation of a neutron skin
- Neutron skin thickness depends on the parameters of the symmetry energy



Symmetry Energy

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$$\mathcal{E}(\rho,\alpha) = \mathcal{E}_{\mathrm{SNM}}(\rho) + \alpha^2 \mathcal{S}_2(\rho) + \ldots$$

$$= \left(\varepsilon_0 + \frac{1}{2} K_0 x^2 + \ldots\right) + \alpha^2 \left(J + Lx + \frac{1}{2} K_{\mathrm{sym}} x^2 + \ldots\right) + \ldots$$

$$\boxed{P_{\mathrm{PNM}}(\rho_0) = \tfrac{1}{3}\rho_0 L} \qquad \left[\alpha = (N-Z)/A; \quad x = (\rho-\rho_0)/3\rho_0\right]$$

- Symmetry energy determined by *J* and *L*
- *L* describes density dependence (stiff or soft EoS)

Polarizability, Neutron Skin and Symmetry Energy

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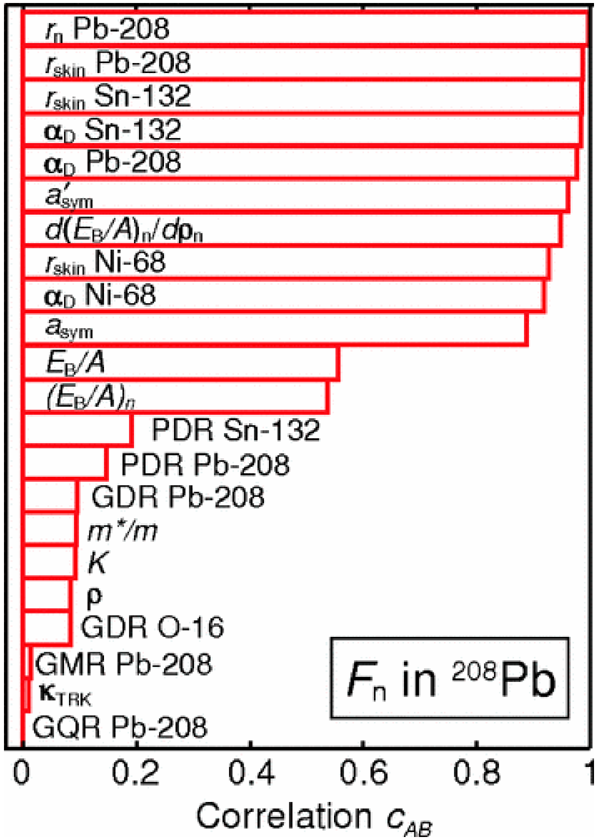
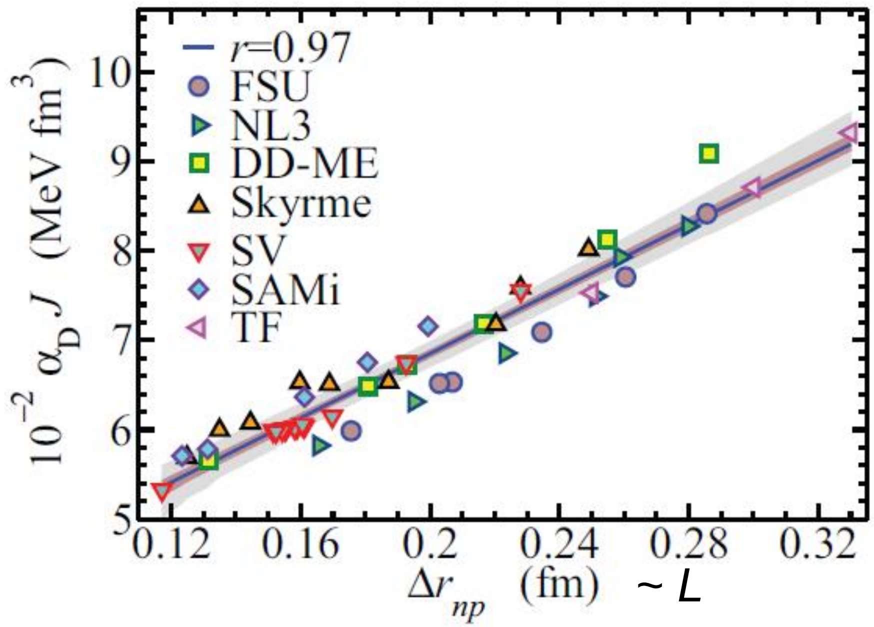
- Static nuclear dipole polarizability

$$\alpha_D = \frac{\hbar c}{2\pi^2} \int \frac{\sigma_{abs}^{E1}}{E^2} \mathrm{d}E$$

$J \rightarrow$
$L \rightarrow$



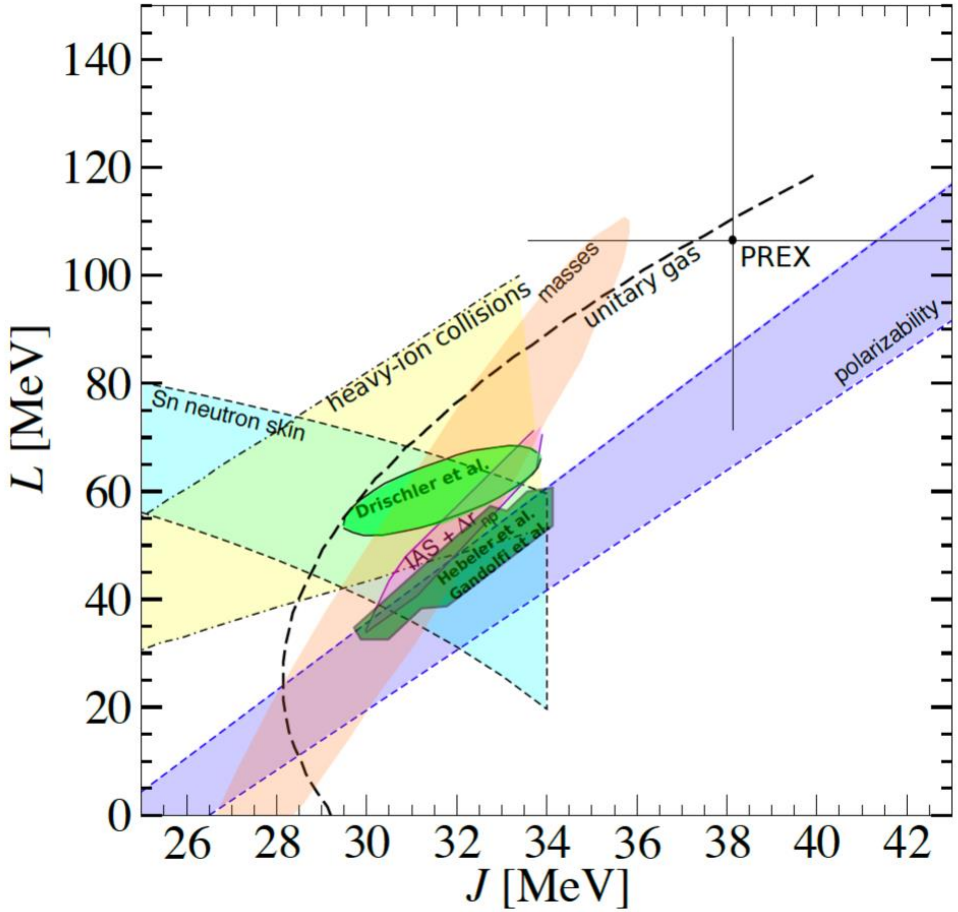
P.-G. Reinhard and W. Nazarewicz, PRC 81, 051303(R) (2010)



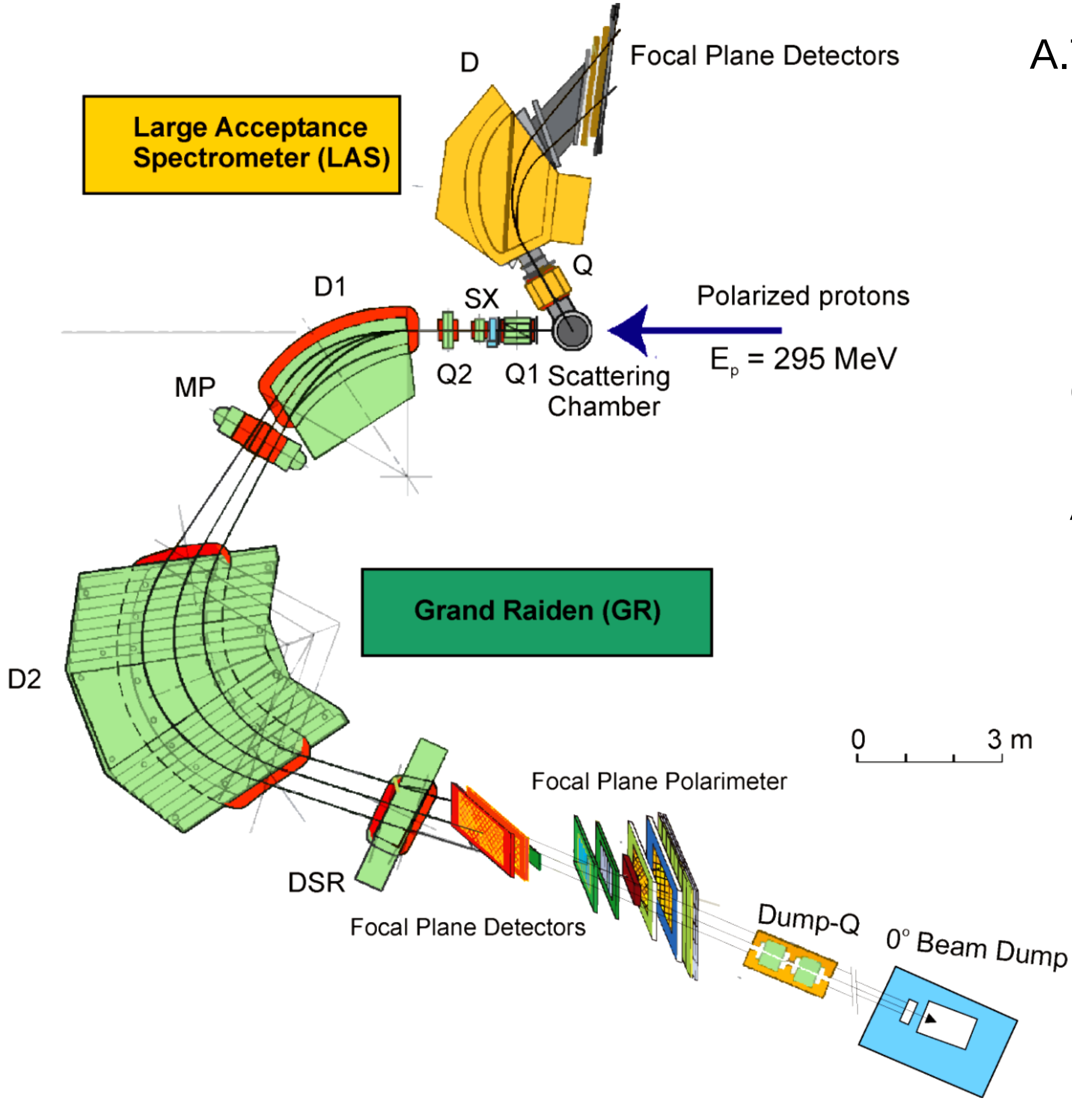
X. Roca-Maza et al., PRC 88, 024316 (2013)

Symmetry Energy Constraints

F. Gulminelli and A.F. Fantina, Nucl. Phys. News 31(2), 9 (2021)



Experiments at RCNP



A.Tamii et al., NIMA 605, 326 (2009)

Measured observables

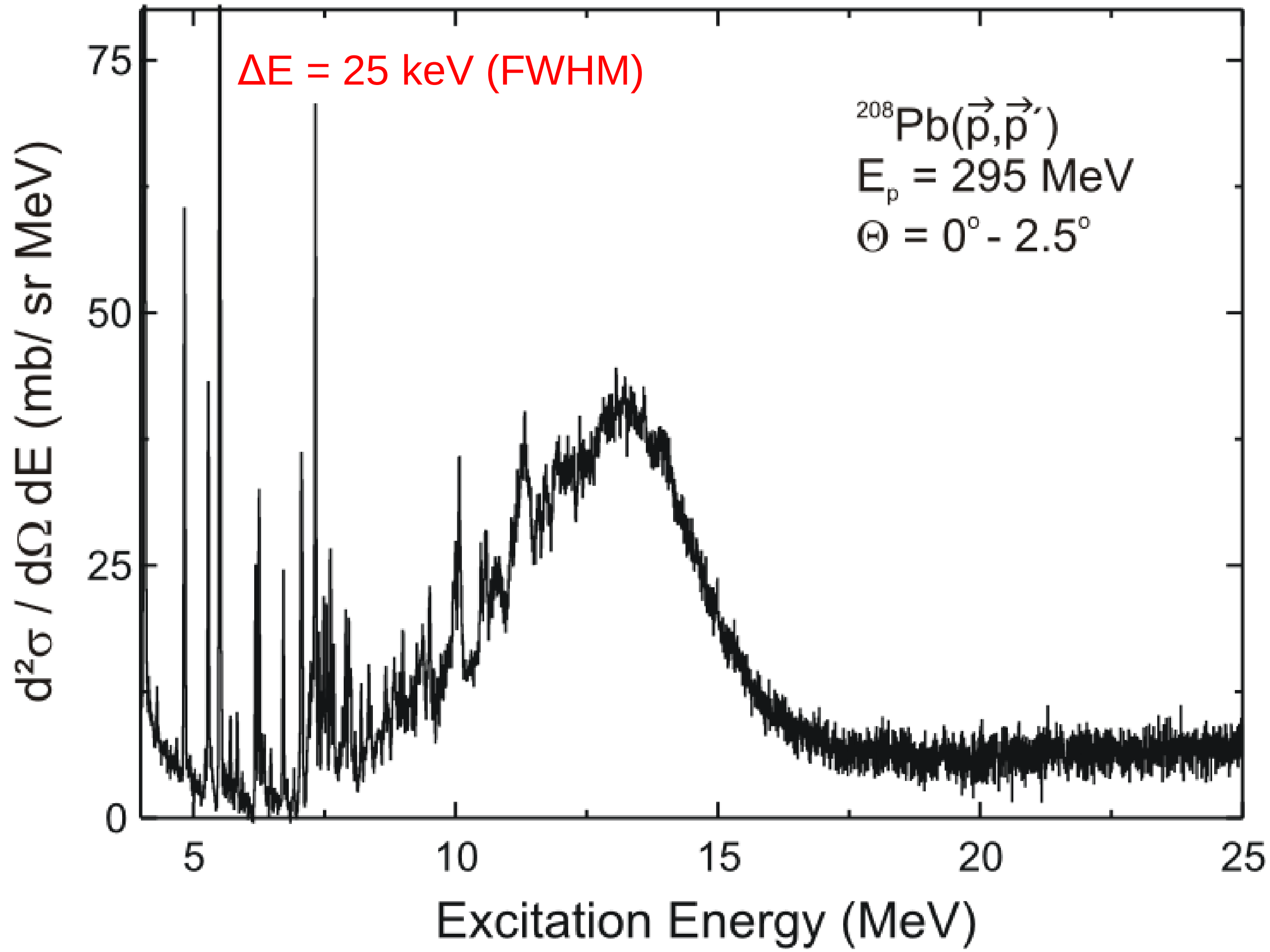
$d\sigma/d\Omega$ - angular distributions ($0° \leq \Theta \leq 10°$)

A_y - asymmetry

D_{SS} at 0° - sideways polarization

D_{LL} at 0° - longitudinal polarization

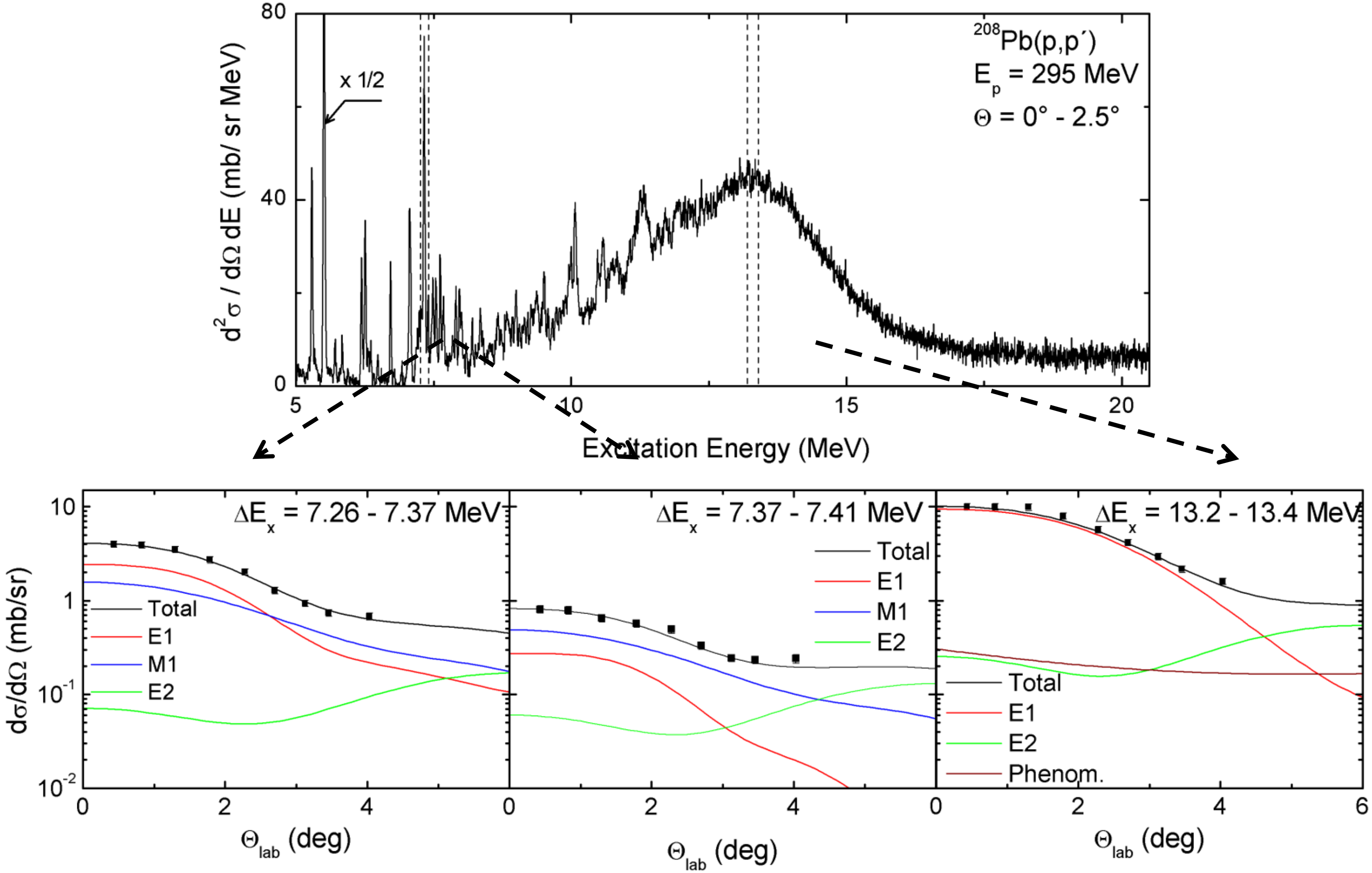
Measured Spectrum



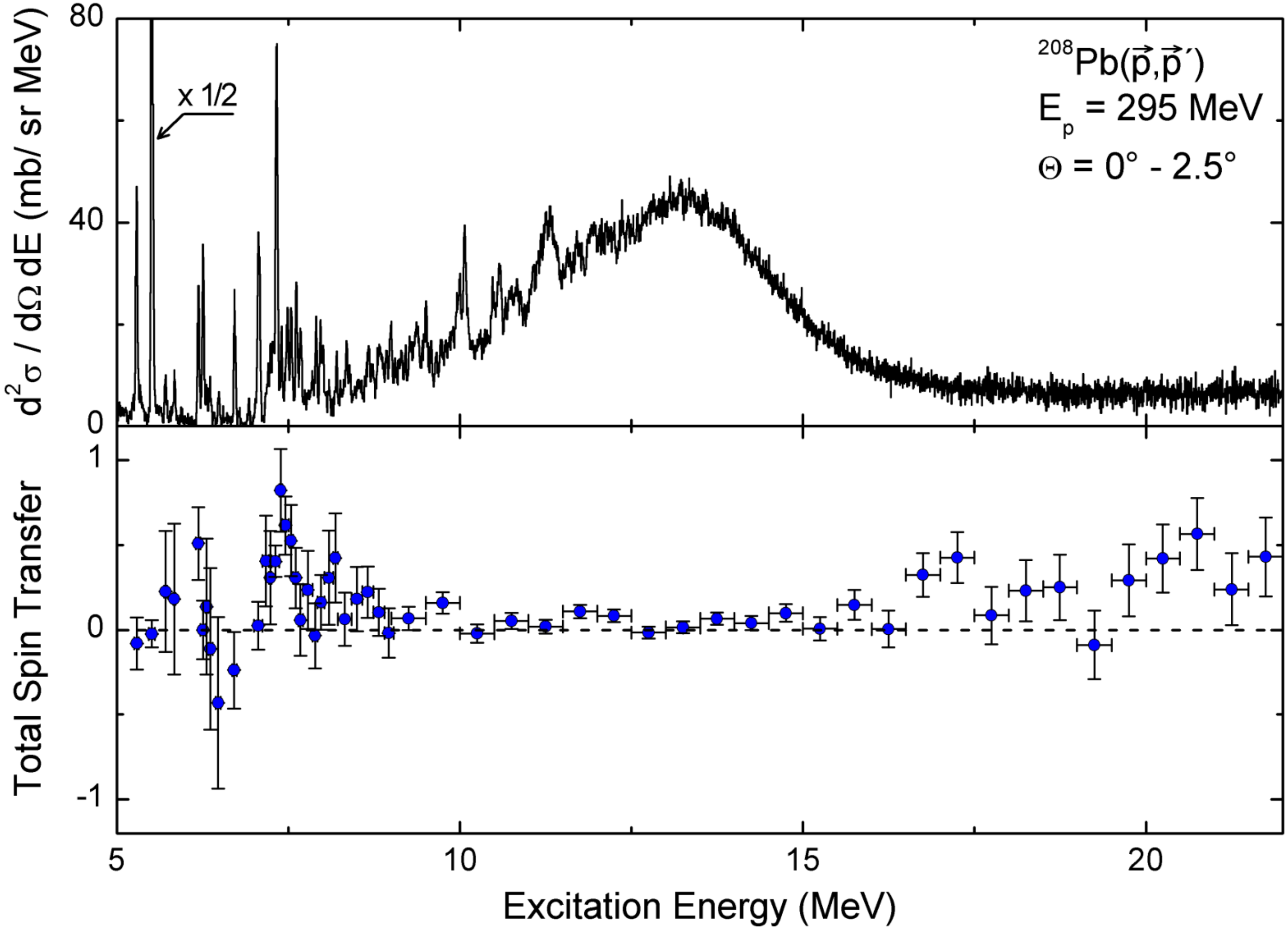
- Dominance of relativistic Coulomb excitation

Multipole Decomposition of Angular Distributions

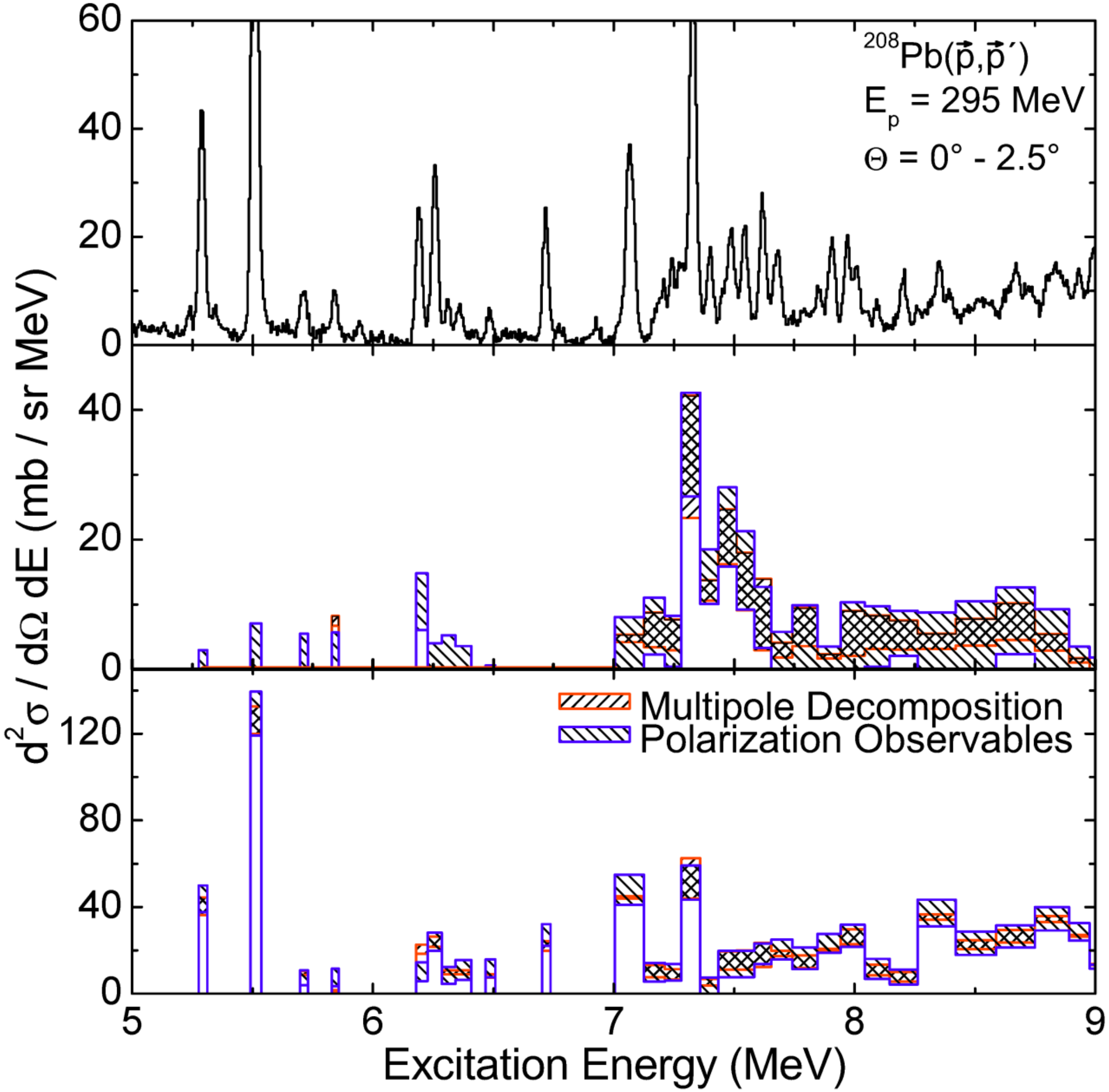
I. Poltoratska et al., PRC 85, 041304(R) (2012)



Decomposition into Spinflip / Non-Spinflip Cross Sections



Comparison of Both Methods



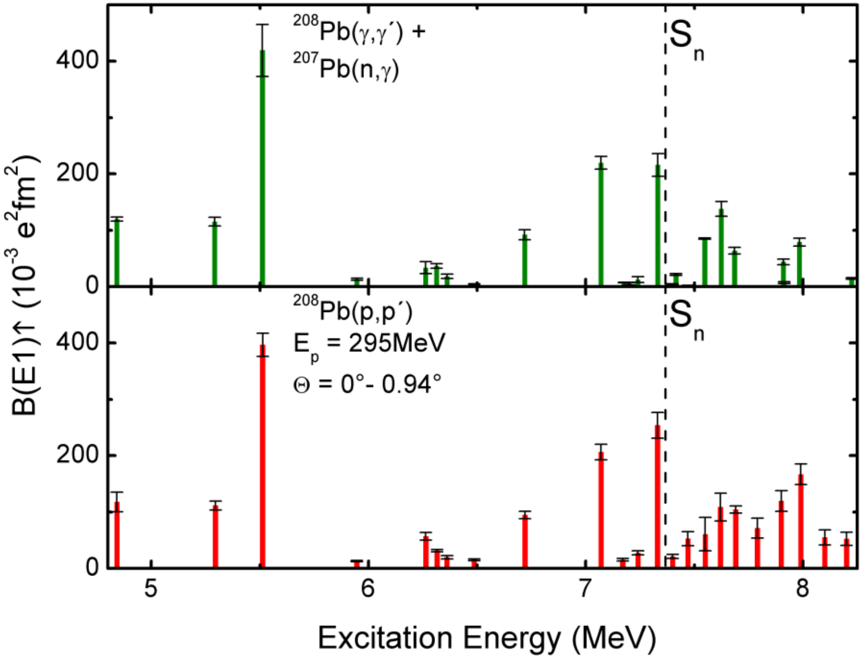
Total

ΔS = 1

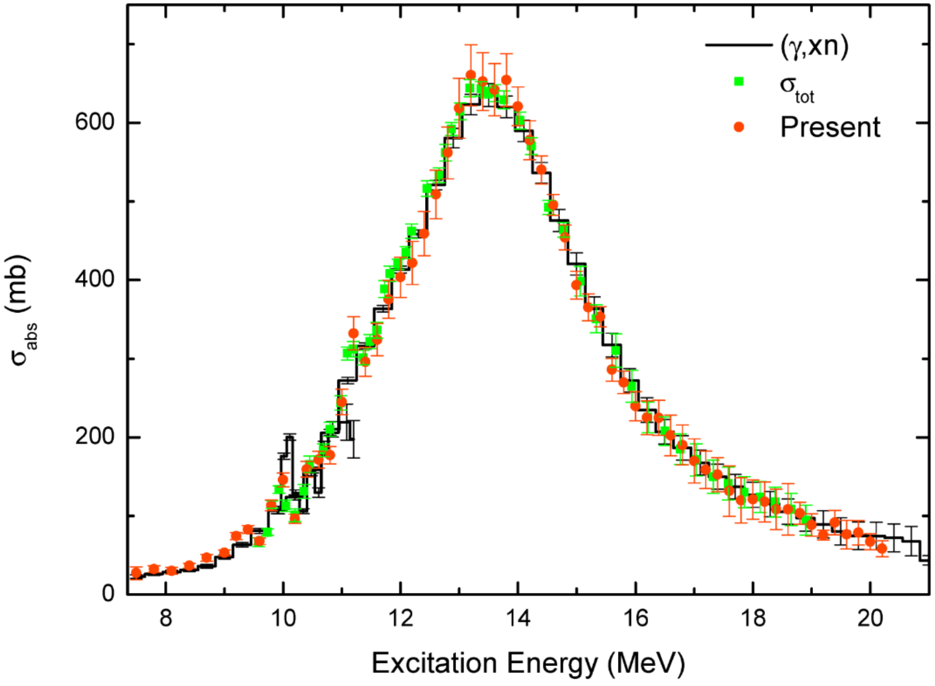
ΔS = 0

E1 Strength in ^{208}Pb

I. Poltoratska et al., PRC 85 (2012) 041304(R)

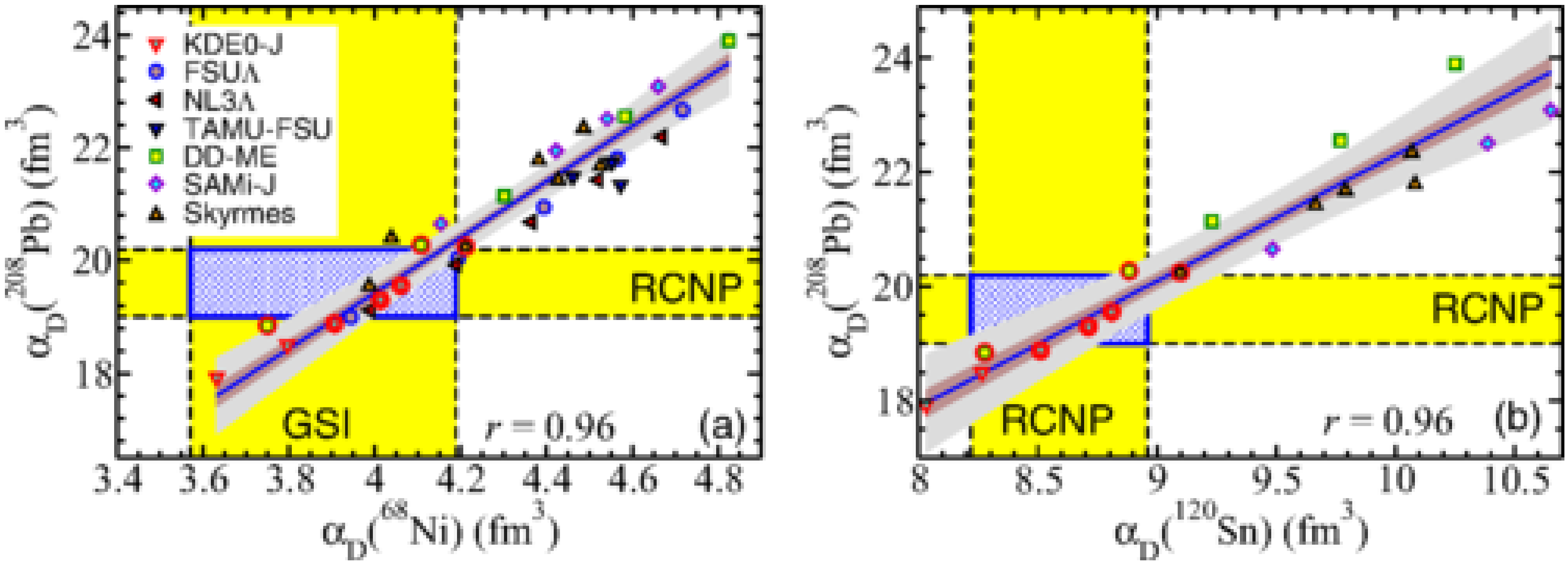


A. Tamii et al., PRL107, 062502 (2011)



Constraints on EDFs from ^{208}Pb, ^{120}Sn and ^{68}Ni

X. Roca-Maza et al., PRC 92, 064304 (2015)



- Only a handful of EDFs can describe all 3 data
- Constraints on symmetry energy: *J* = 30 - 35 MeV *L* = 20 - 66 MeV

Polarizability: Systematics in the Sn Chain

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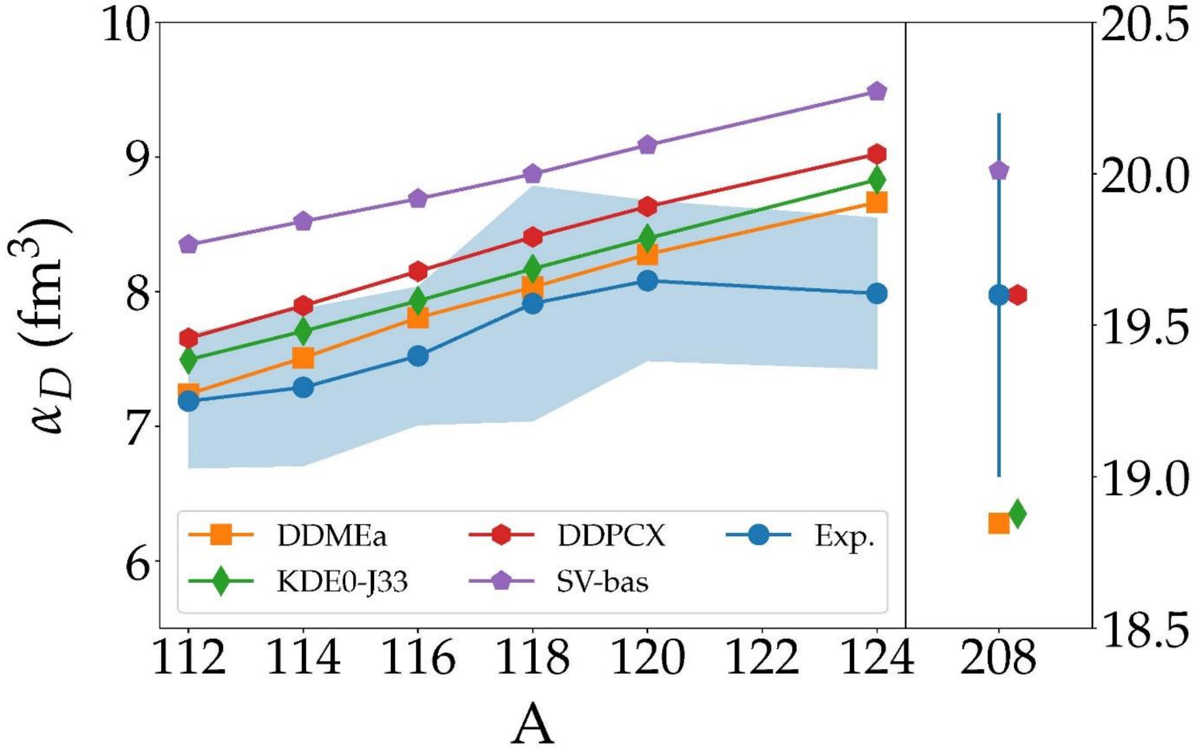
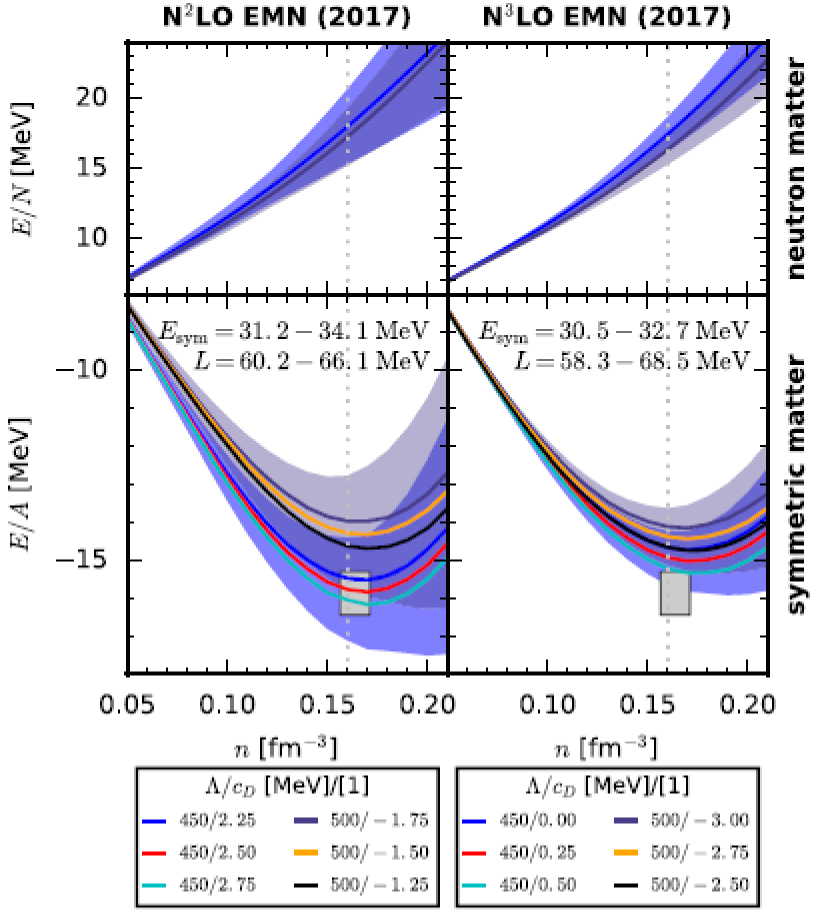
S. Bassauer et al., PLB 810, 135804 (2020)



- Simultaneous description with of $\alpha_D(^{208}Pb)$ difficult

Ab Initio Calculations

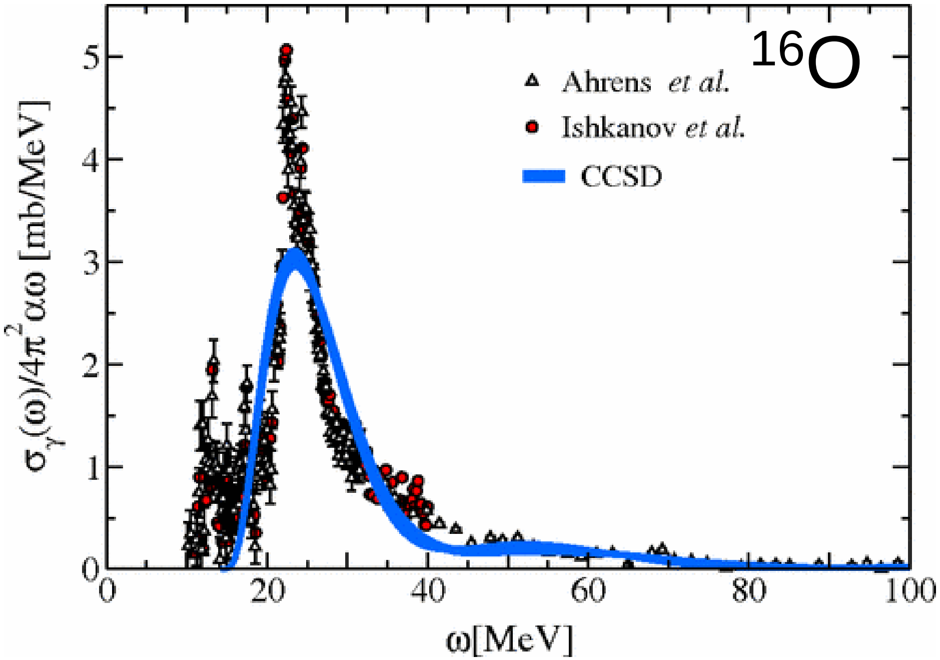


C. Drischler, K. Hebeler, and A. Schwenk, Phys. Rev. Lett. 122, 042501 (2019)

- Same interactions can be used to calculate nuclear matter
- Polarizability provides constraints for neutron matter

Ab Initio Calculations of the Polarizability

S. Bacca et al., PRL 111, 122502 (2013)



- Based on interactions derived from χEFT
- Combines Lorentz Integral Transform (LIT) with Coupled Cluster (CC) technique

→ next talk by Francesca Bonaiti

The Case of ^{48}Ca: χEFT versus EDFs

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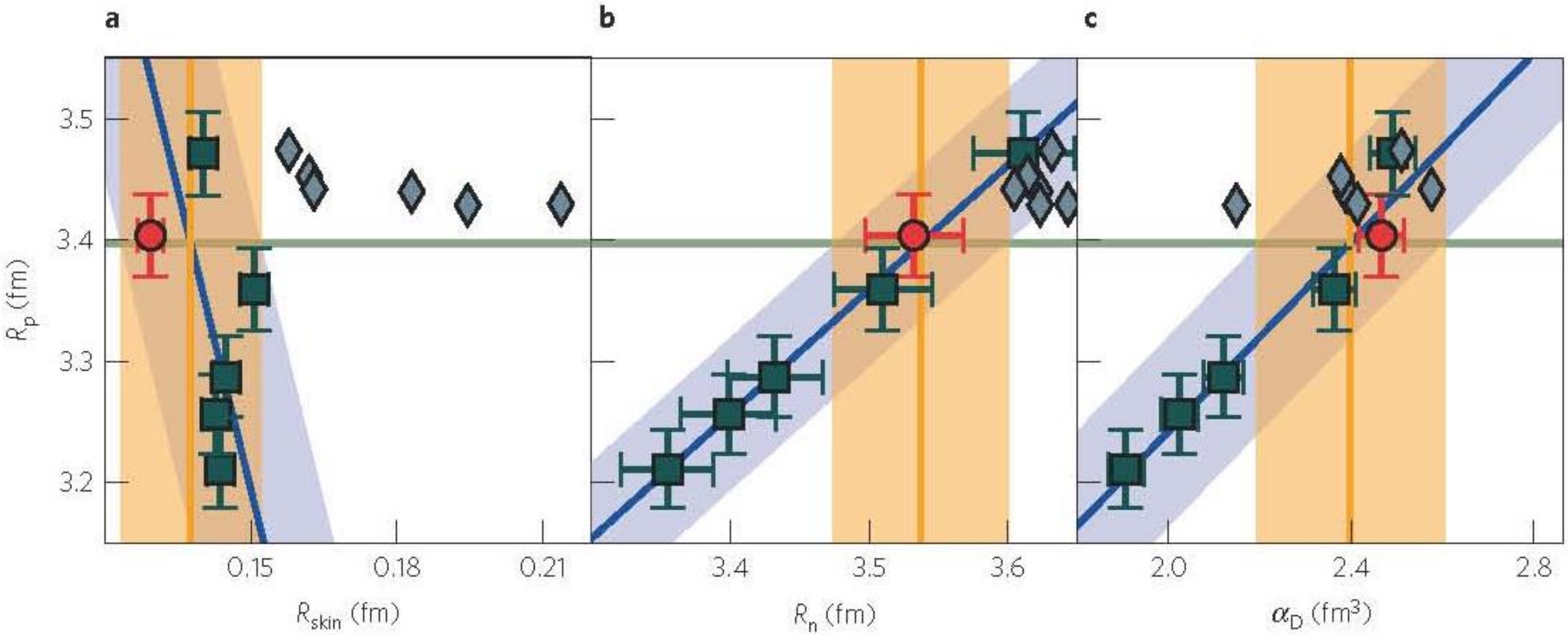
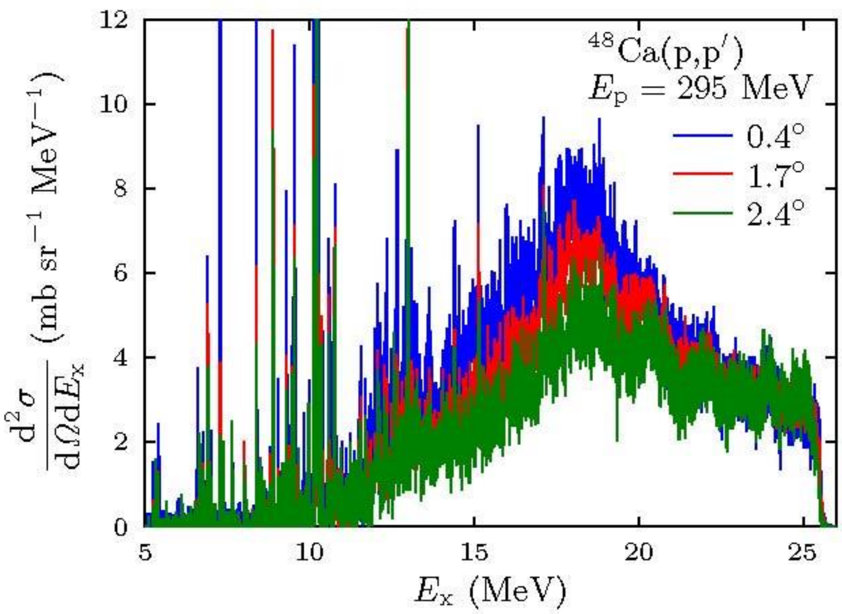
G. Hagen et al., Nat. Phys. 12, 186 (2016)

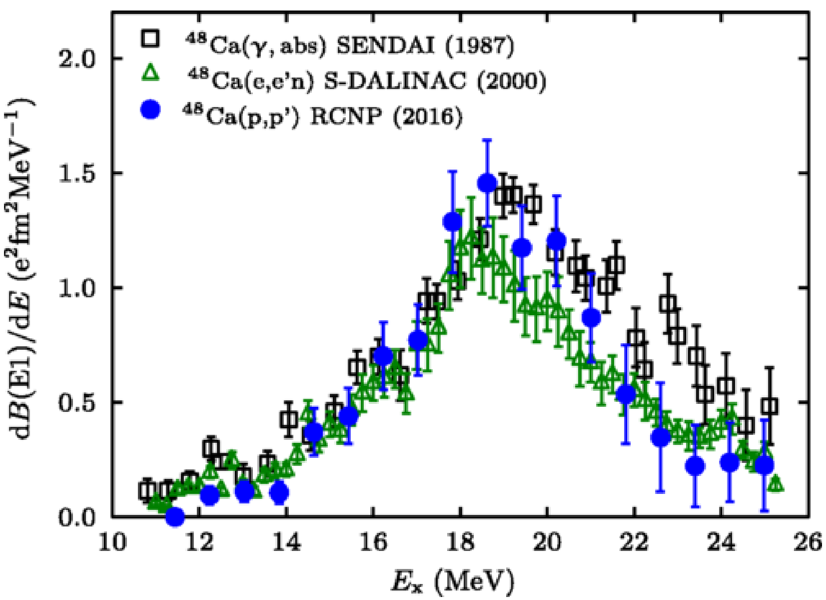


- Small neutron skin predicted by EFT
- Different correlation between R_p and R_n

Polarizability of ^{48}Ca

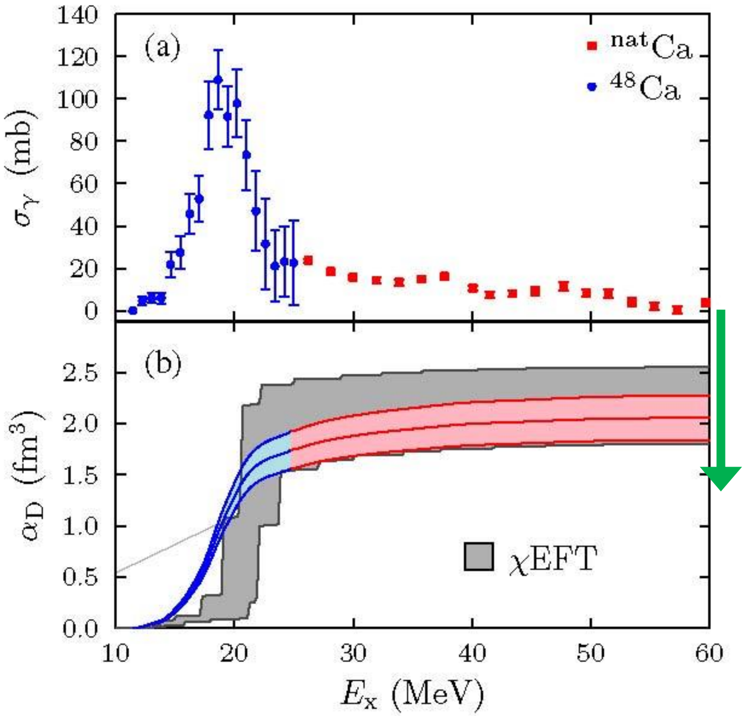
J. Birkhan et al., PRL 118, 252501 (2017)



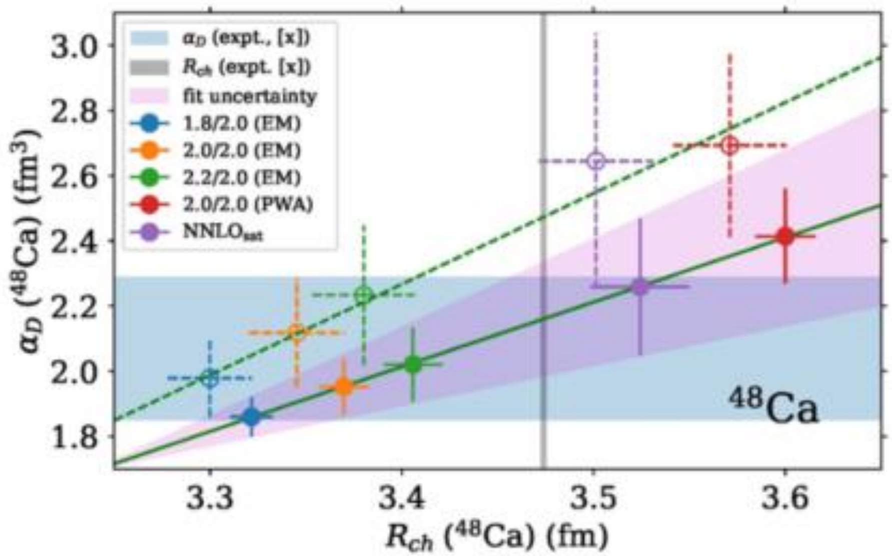


Polarizability of ^{48}Ca

J. Birkhan et al., PRL 118, 252501 (2017)



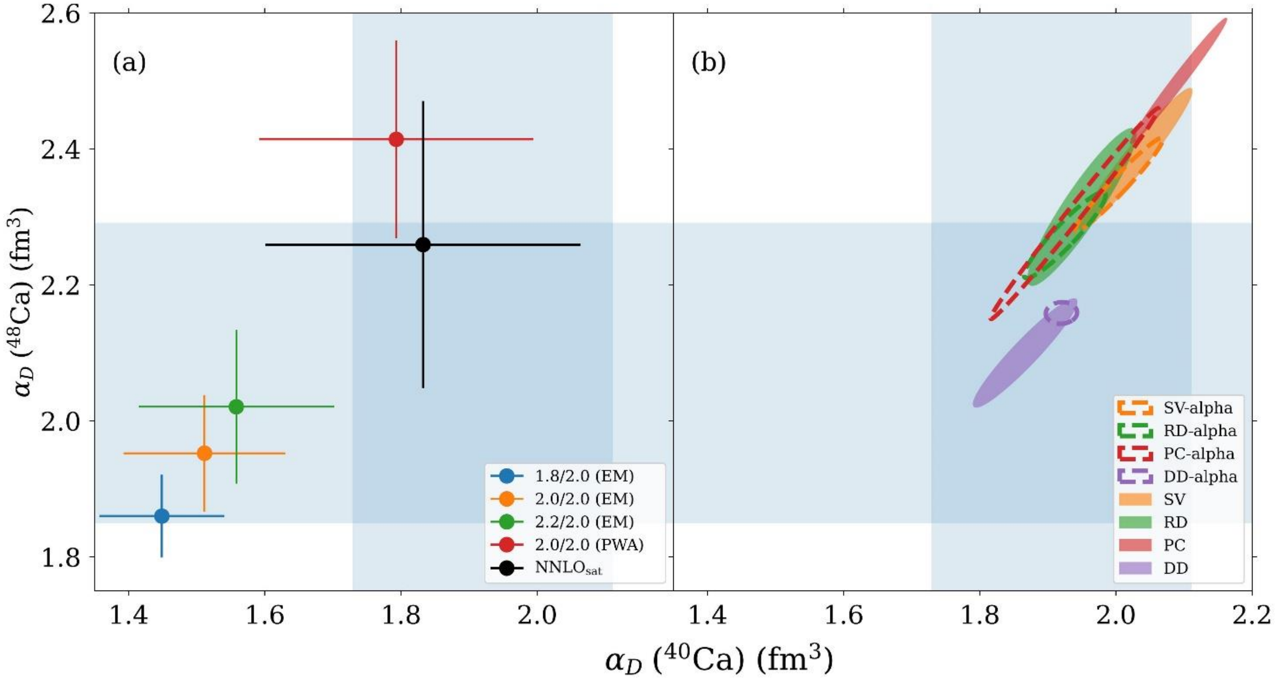
M. Miorelli et al., PRC 98, 014324 (2018)



- Uncertainty larger than in ^{208}Pb due to unknown parametrization of the nuclear background
- Triple correlations important

^{40}Ca vs. ^{48}Ca

R.W. Fearick et al., PRR 5, L022044 (2023)



- Constraints from χEFT: J = 27–33 MeV, L = 41–49 MeV
- Constraints from EDFs: J = 30–35 MeV, L = 32-82 MeV
  J = 30–32 MeV, L = 35-52 MeV [α_D(^{208}Pb) included]

New Ab Initio Calculation of ^{208}Pb and ^{48}Ca

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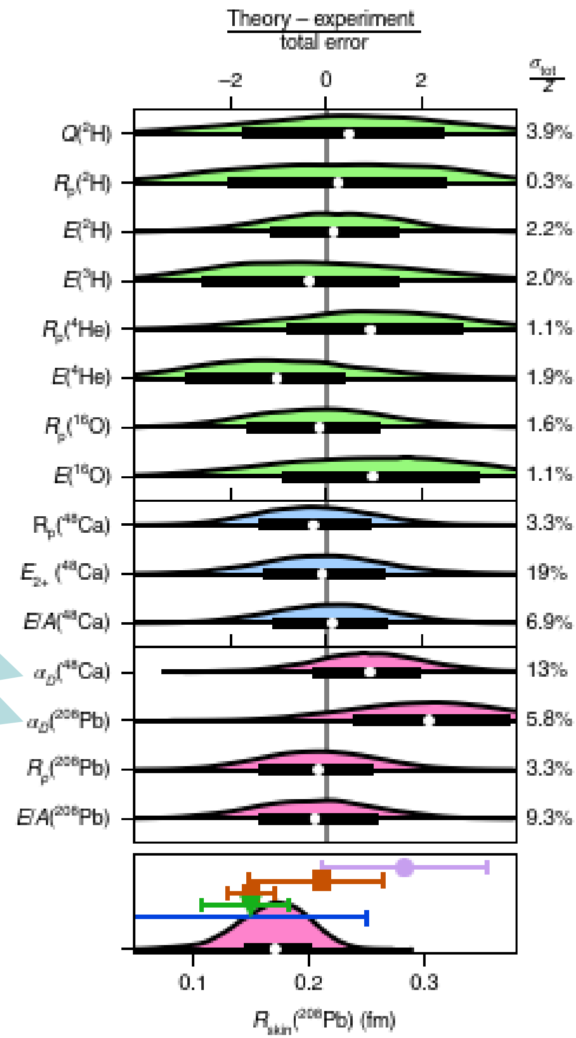
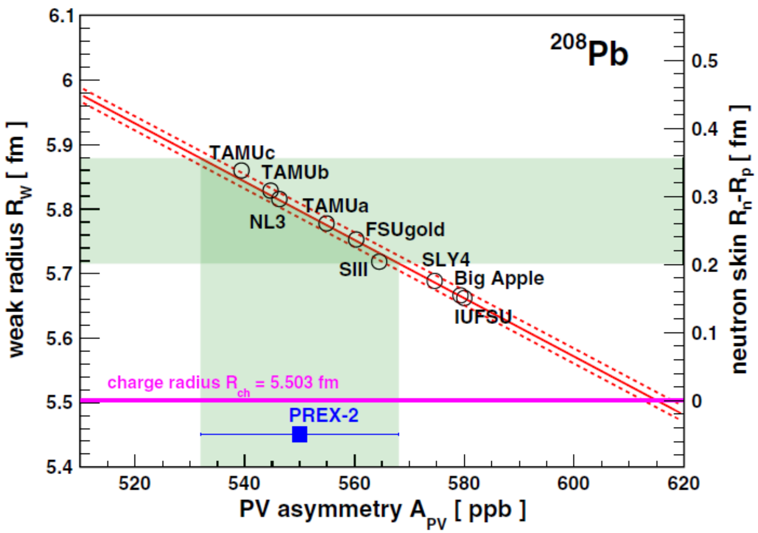
B. Hu et al, Nat. Phys. 18, 1196 (2022)

- Unknown LECs constrained by nucleon scattering data and selected observables in light nuclei
- Reasonable agreement for α_D results (slightly too high)
- Constraints on symmetry energy: J = 27 - 31 MeV L = 37 - 66 MeV

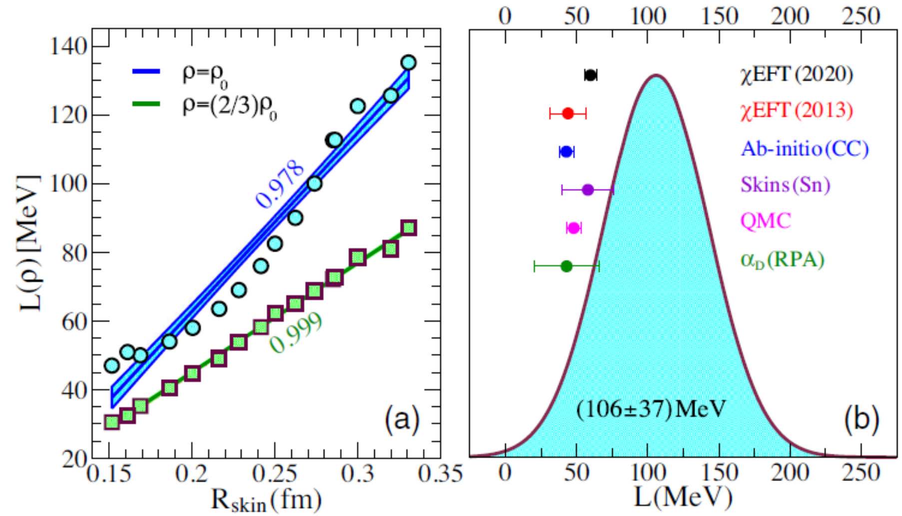


PREX Constraints on Neutron Skin and Density Dependence of the Symmetry Energy

D. Adhikari et al., PRL 126, 172502 (2021)



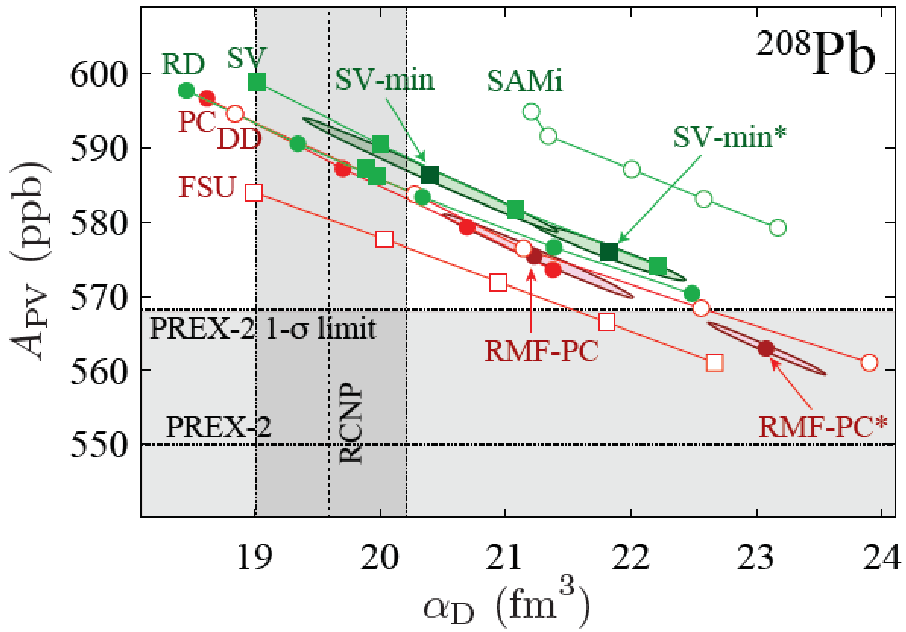
B.T. Reed et al., PRL 126, 172503 (2021)

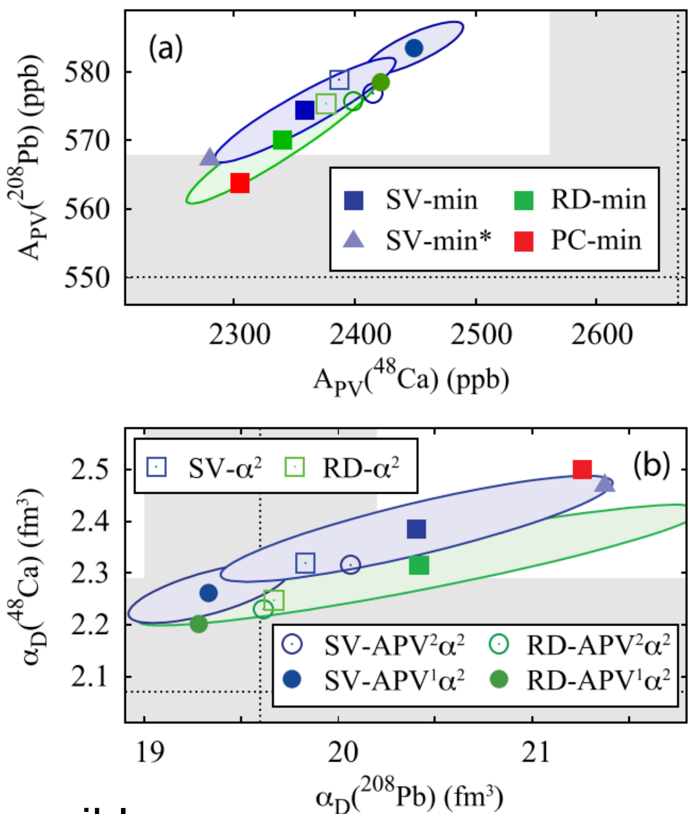


- Derived density dependence of the symmetry energy $L = 106(37)$ MeV

PREX and CREX versus Dipole Polarizability

P.-G. Reinhard, X. Roca-Maza and W. Nazarewicz, PRL 127, 232501 (2021); PRL 129, 232501 (2022)





- No consistent description of A_{PV} and α_D for ^{208}Pb possible

  → new MREX experiment important

Systematics of the Dipole Polarizability

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- Data
  - ^{208}Pb: A. Tamii et al., PRL 107, 062502 (2011)
  - ^{120}Sn: T. Hashimoto et al., PRC 92, 031305(R) (2015)
  - ^{112,114,116,118,120,124}Sn: S. Basssauer et al., PLB 810, 135804 (2020)
  - ^{90}Zr: T. Klaus, PhD thesis, TU Darmstadt (2020)
  - ^{68}Ni: D.M. Rossi et al., PRL 111, 242503 (2013)
  - ^{58}Ni: I. Brandherm et al., in preparation (2024)
  - ^{48}Ca: J. Birkhan et al., PRL 118, 252501 (2017)
  - ^{40}Ca: R.W. Fearick et al., PRR 5, L022044 (2023)
  - ^{27}Al,^{16}O: J. Ahrens et al., NPA 251, 479 (1975)

Systematics: Migdal Model

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- Hydrodynamic model with interpenetraiting proton and neutron fluids

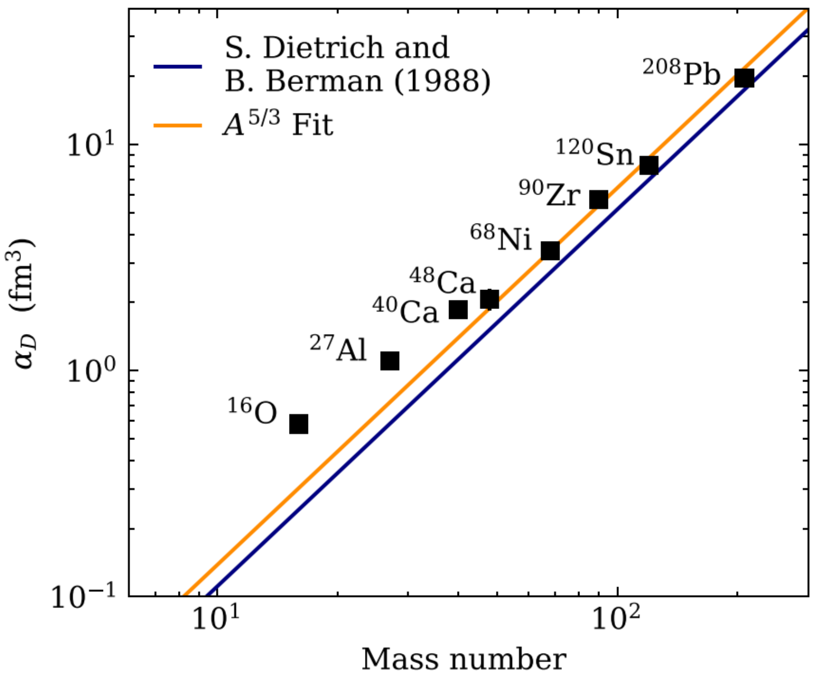
$$\alpha_D = \frac{e^2 R^2 A}{40 \cdot a_{\text{sym}}} \propto A^{5/3}\,\text{fm}^3$$

- a_{sym}: Symmetry energy parameter in the Bethe-Weizsäcker mass formula

- S.Dietrich and B.Bermann,
  At. Data Nucl. Data Tables 38, 199 (1988)

$$\alpha_D = 2.4 \times 10^{-3} \cdot A^{5/3}\,\text{fm}^3$$

- Fit: $\alpha_D = 3.0(3) \times 10^{-3} \cdot A^{5/3}\,\text{fm}^3$

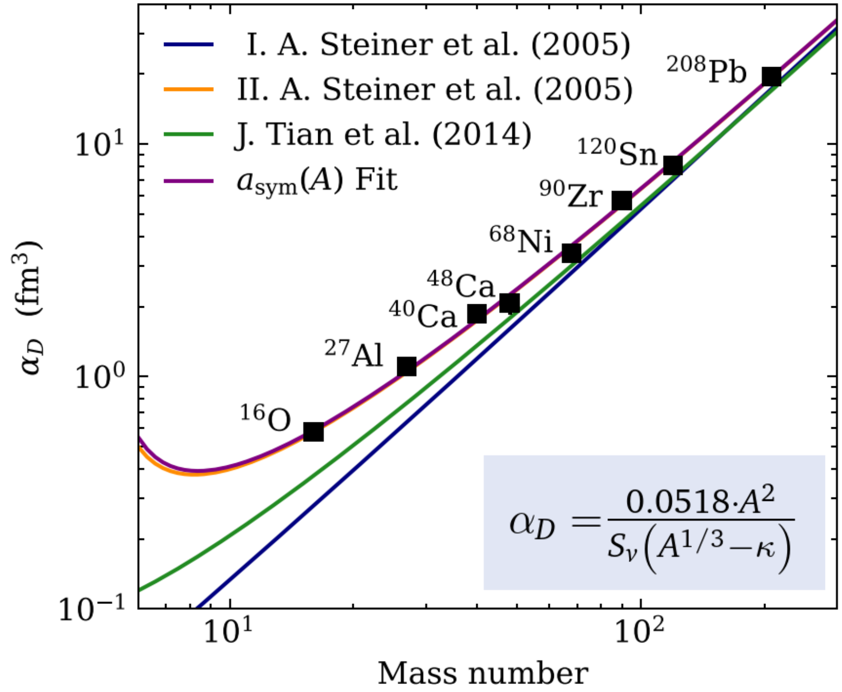


Systematics: Volume and Surface Contributions

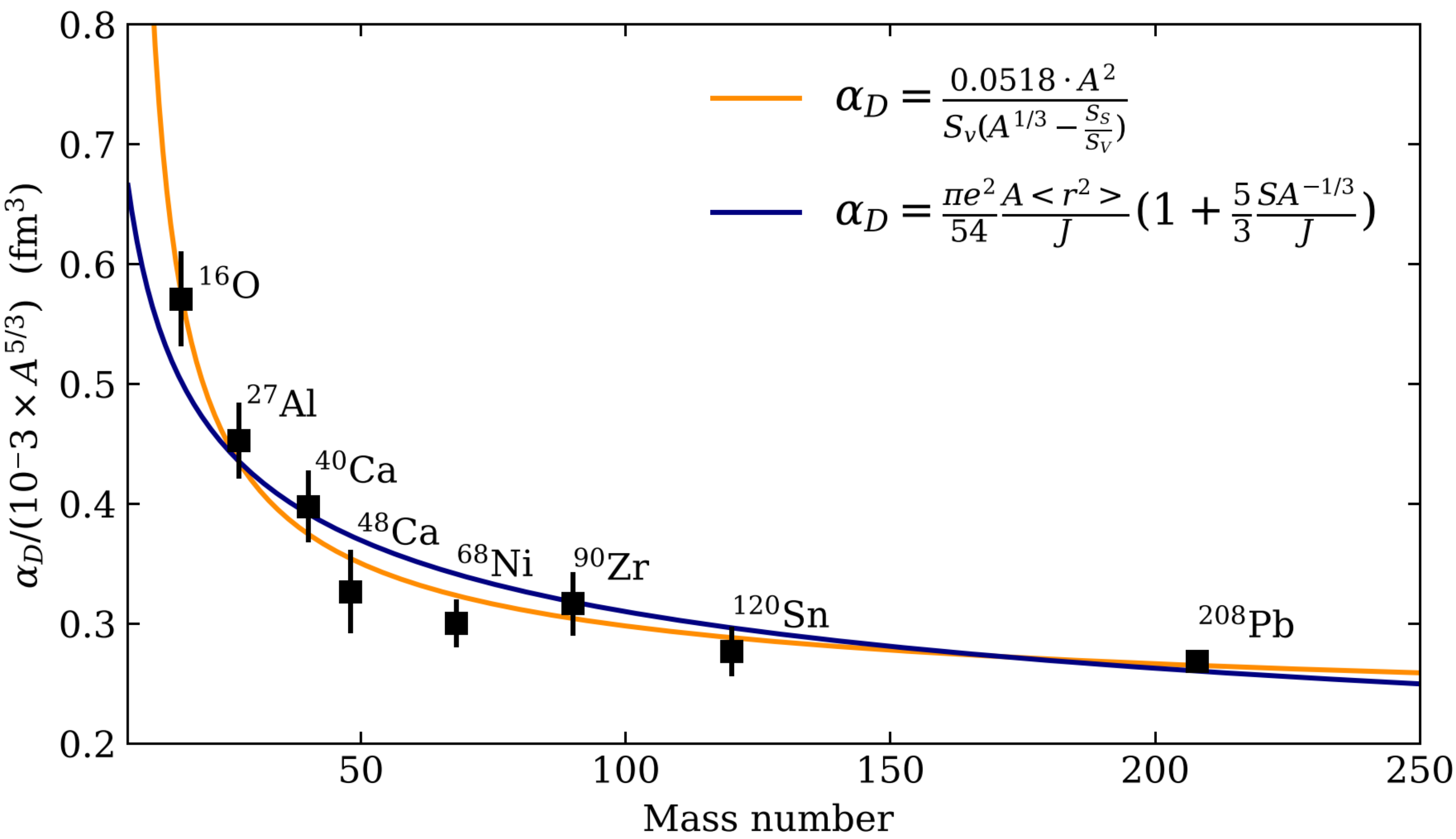
- Refined model: a_{sym} mass dependent

$$a_{\mathrm{sym}}(A) = S_v\left(1 - \frac{\kappa}{A^{1/3}}\right), \quad \kappa = \frac{S_s}{S_v}$$

J.Tian et al., Phys. Rev. C 90, 024313 (2014)	$S_v = 28.3\,\mathrm{MeV}$ $\kappa = 1.27$
(I.) A.W. Steiner et al., Phys. Rep. 411, 325 (2005)	$S_v = 24.1\,\mathrm{MeV}$ $\kappa = 0.545$
(II.) A.W. Steiner et al., Phys. Rep. 411, 325 (2005)	$S_v = 27.3\,\mathrm{MeV}$ $\kappa = 1.68$
Fit	$S_v = 27.3(8)\,\mathrm{MeV}$ $\kappa = 1.69(6)$



Constraints on *J* and *L* from Droplet Model



- Work in progress …….

Summary

- Proton scattering at and close to 0° - a versatile experimental tool to extract the polarizabilty

- Constraints on the symmetry energy from EDFs
  - correlation $\alpha_D \cdot J \sim L$
  - Systematics dramatically reduce number of suitable interactions

- Constraints on the symmetry energy from χEFT
  - good description for ^{40,48}Ca and ^{208}Pb
  - *L* values derived significantly smaller than those derived from PREX

- Constraints on the symmetry energy from systematics
  - volume and surface contributions can be separated
  - relation to *J* and *L* within the droplet model?

Questions

- How important would be results with improved accuracy (in particular in lighter nuclei)?
- Extension of EFT calculations to open-shell nuclei?
- Importance of experiments in very neutron-rich nuclei?

Acknowledgement

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