Dipole Polarizability from Small-Angle Proton Scattering and Implications for Symmetry Energy Properties and the Formation of Neutron Skins

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- Equation of State (EoS), symmetry energy, neutron skin and dipole polarizability
- Extraction of the E1 strength from small-angle (p,p‘) scattering
- Polarizability of ^{40}Ca
- Implications for the symmetry energy

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

Nuclear Matter Equation of State (EOS)

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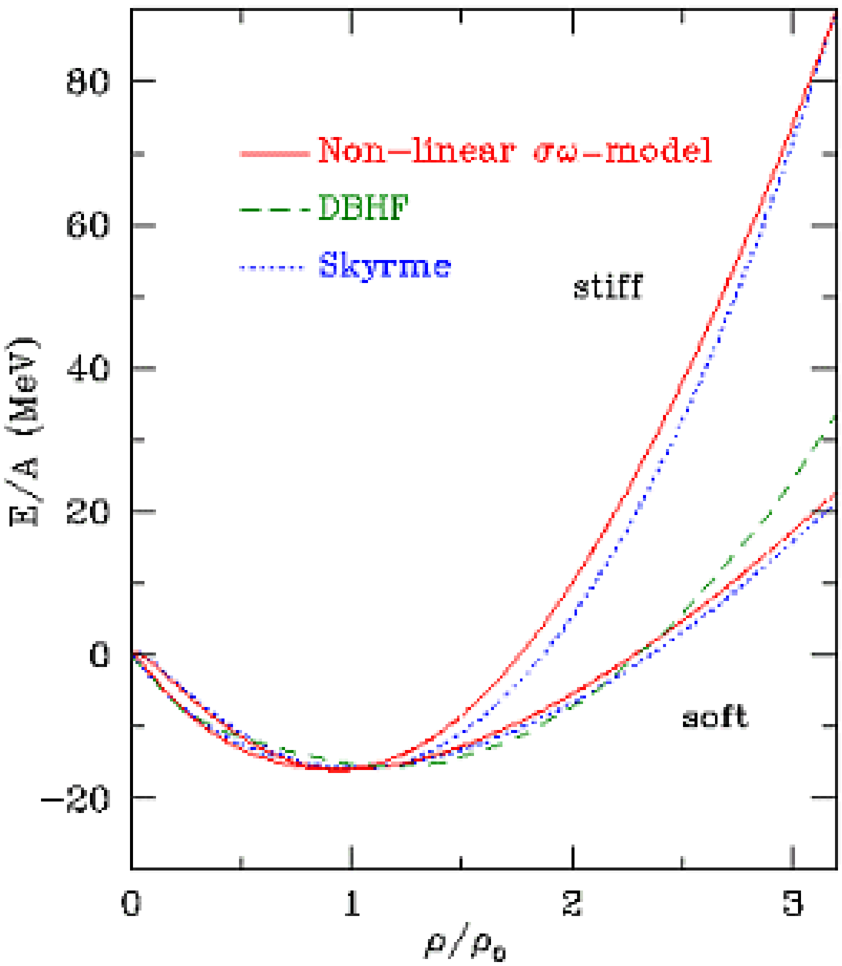
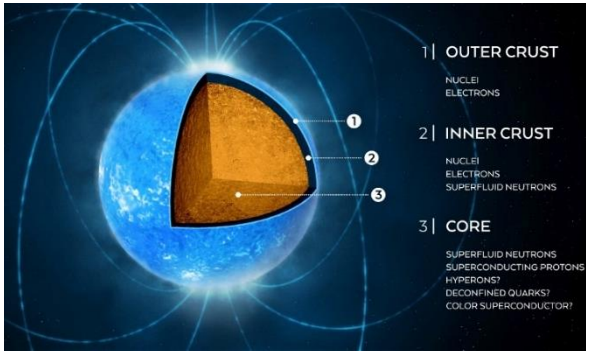
- Energy as a function of density (or pressure)
- Well defined at ρ/ρ_0 = 1 by properties of stable nuclei
- Large differences of models at high densities: stiff or soft?



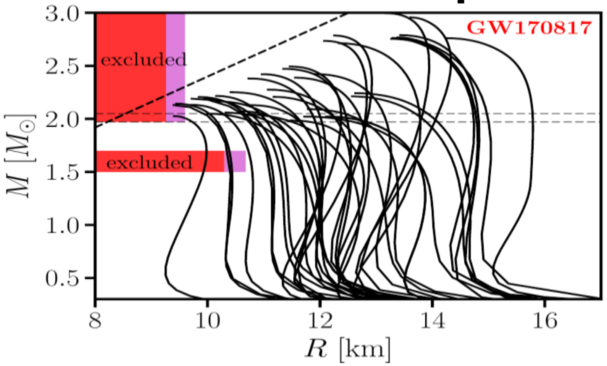
EoS of Neutron-Rich Matter

Neutron Stars



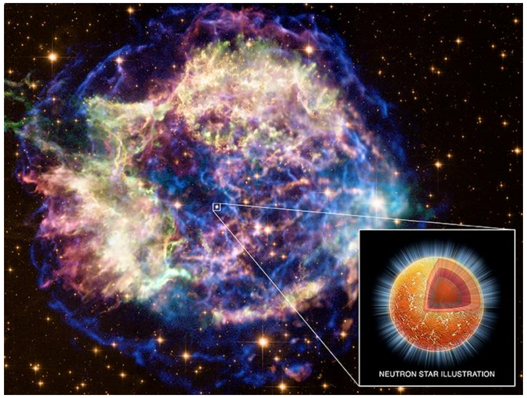
A. Watts et al., RMP 88, 021001 (2016)

Neutron Star Properties



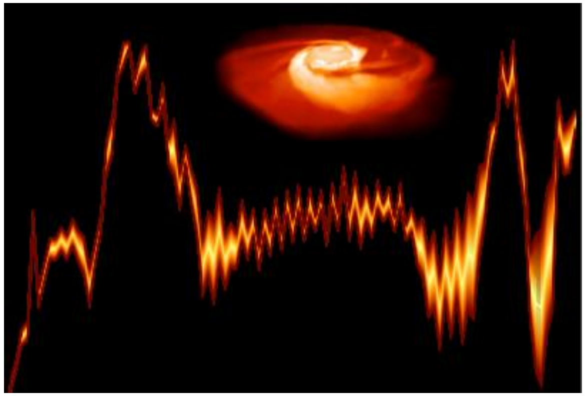
A. Bauswein et al., ApJ Lett. 885, L34 (2017)

Core-Collapse Supernovae



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

Neutron Star Mergers

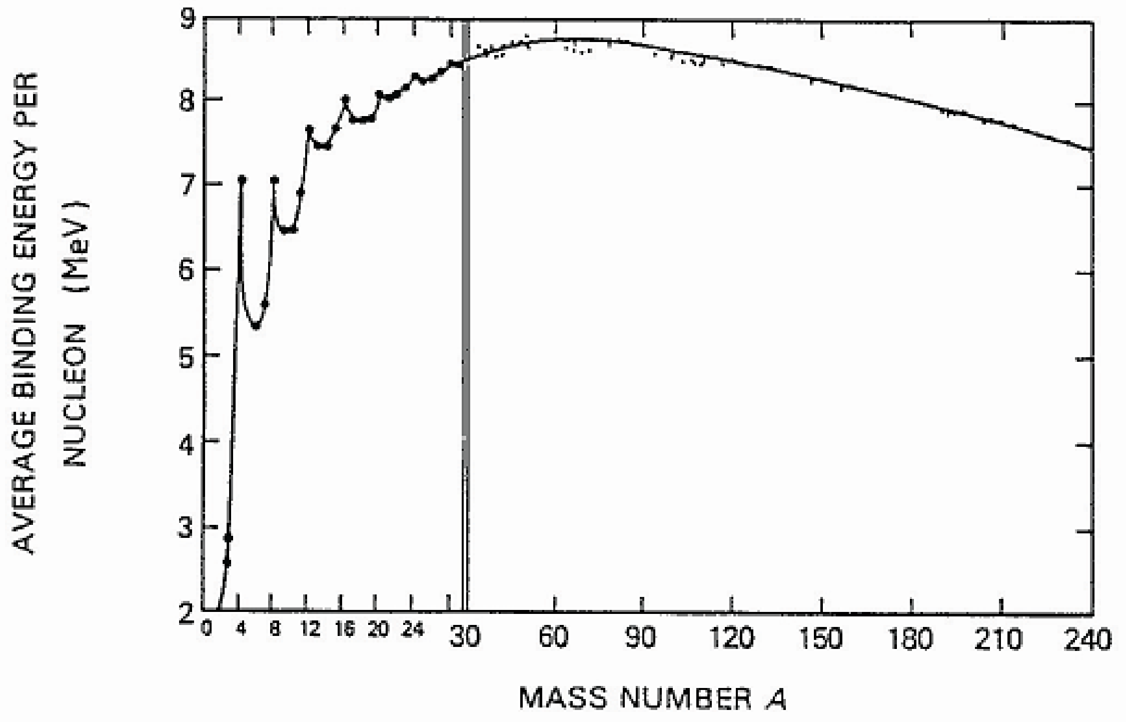


B.P. Abbott et al., PRL 119, 161101 (2017)

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 Matter

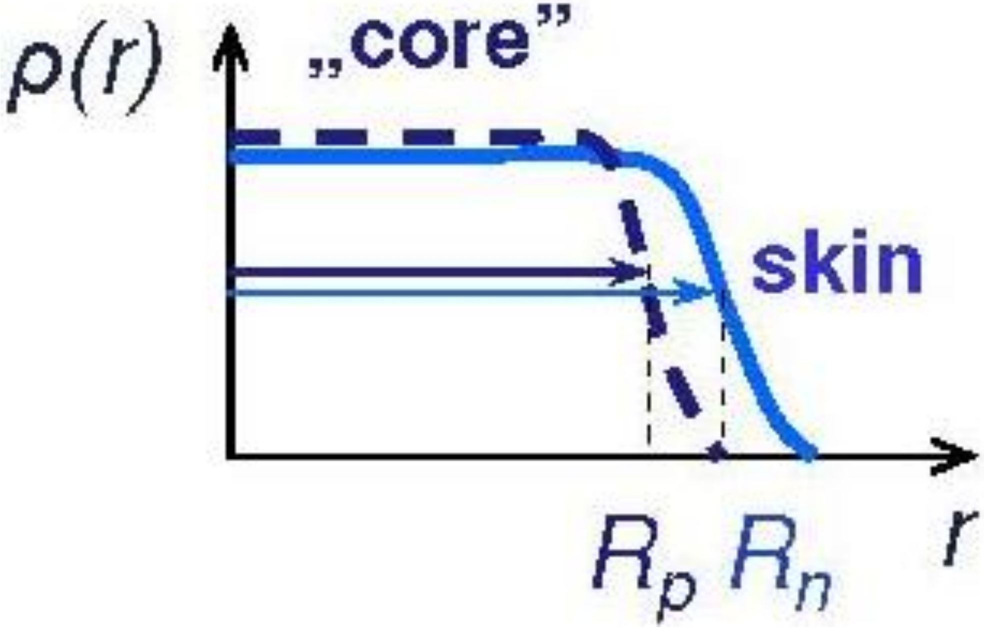
$$B(A,Z) = a_v A - a_s A^{2/3} - a_c Z(Z-1)/A^{1/3} - a_{sym}(A-2Z)^2/A + \ldots$$

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 matter.

Symmetry Energy and Neutron Skin of Nuclei

- Nuclear force leads to constant density in the interior (saturation)
- In heavy nuclei $N > Z$ 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

$$\mathcal{E}(\rho,\alpha) = \mathcal{E}_{\mathrm{SNM}}(\rho) + \alpha^2 \mathcal{S}_2(\rho) + \dots$$
$$= \left(\varepsilon_0 + \frac{1}{2}K_0 x^2 + \dots\right) + \alpha^2\left(J + Lx + \frac{1}{2}K_{\mathrm{sym}} x^2 + \dots\right) + \dots$$

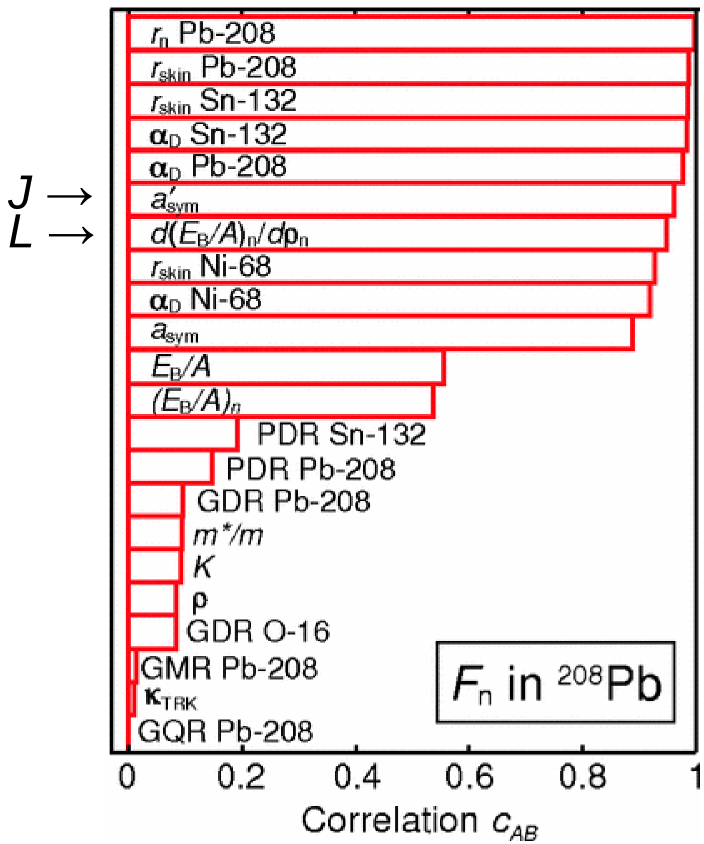
$$\boxed{P_{\mathrm{PNM}}(\rho_0) = \tfrac{1}{3}\rho_0 L} \qquad \left[\alpha = (N-Z)/A; \quad x = (\rho-\rho_0)/3\rho_0\right]$$

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

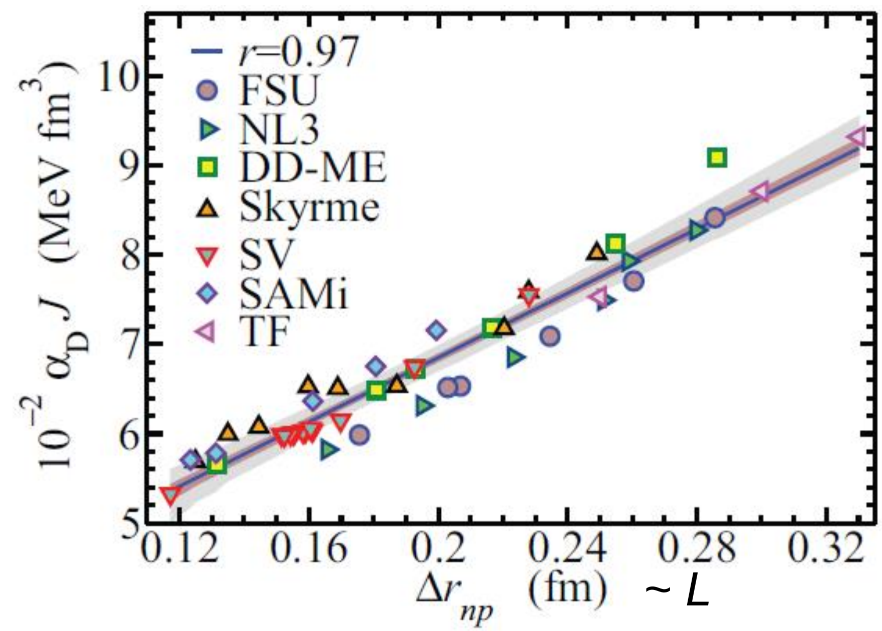
Polarizability, Neutron Skin and Symmetry Energy

- Static nuclear dipole polarizability

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



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



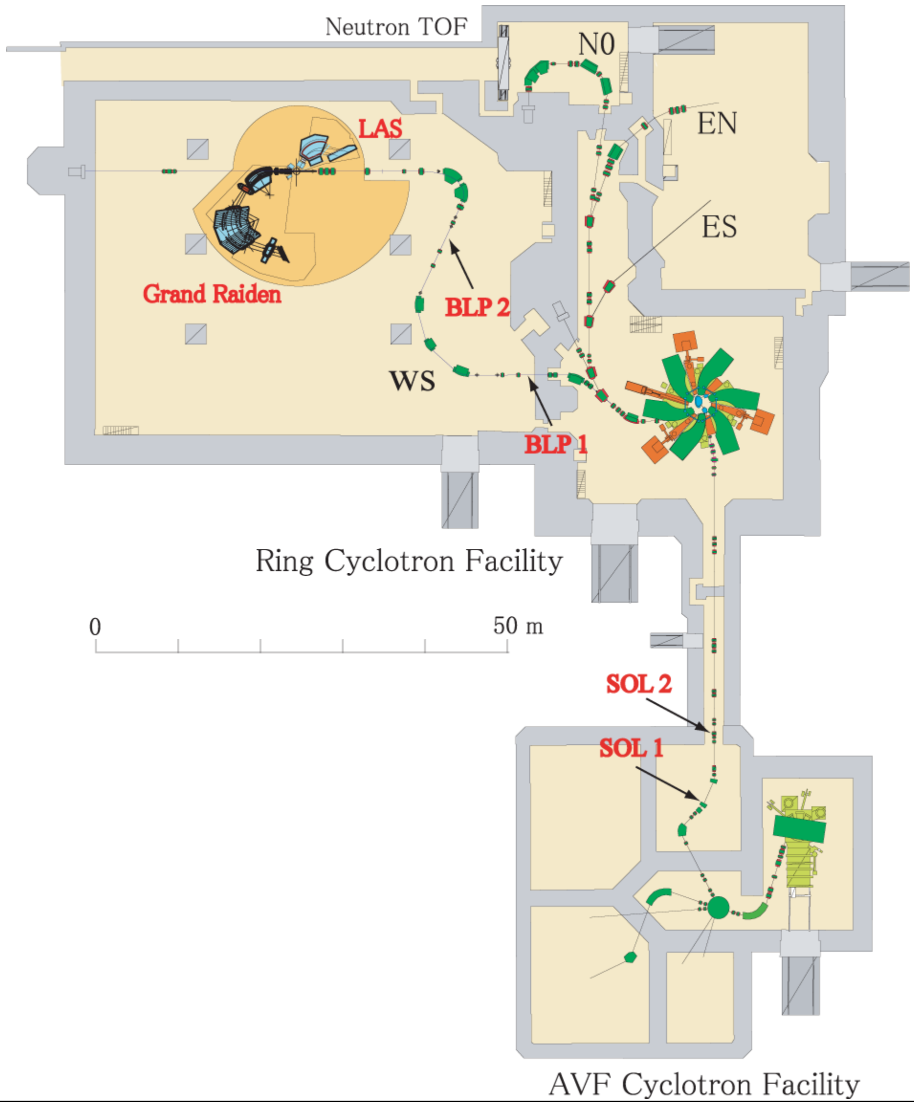
X. Roca-Maza et al., PRC 88, 024316 (2013)

Experimental Approach

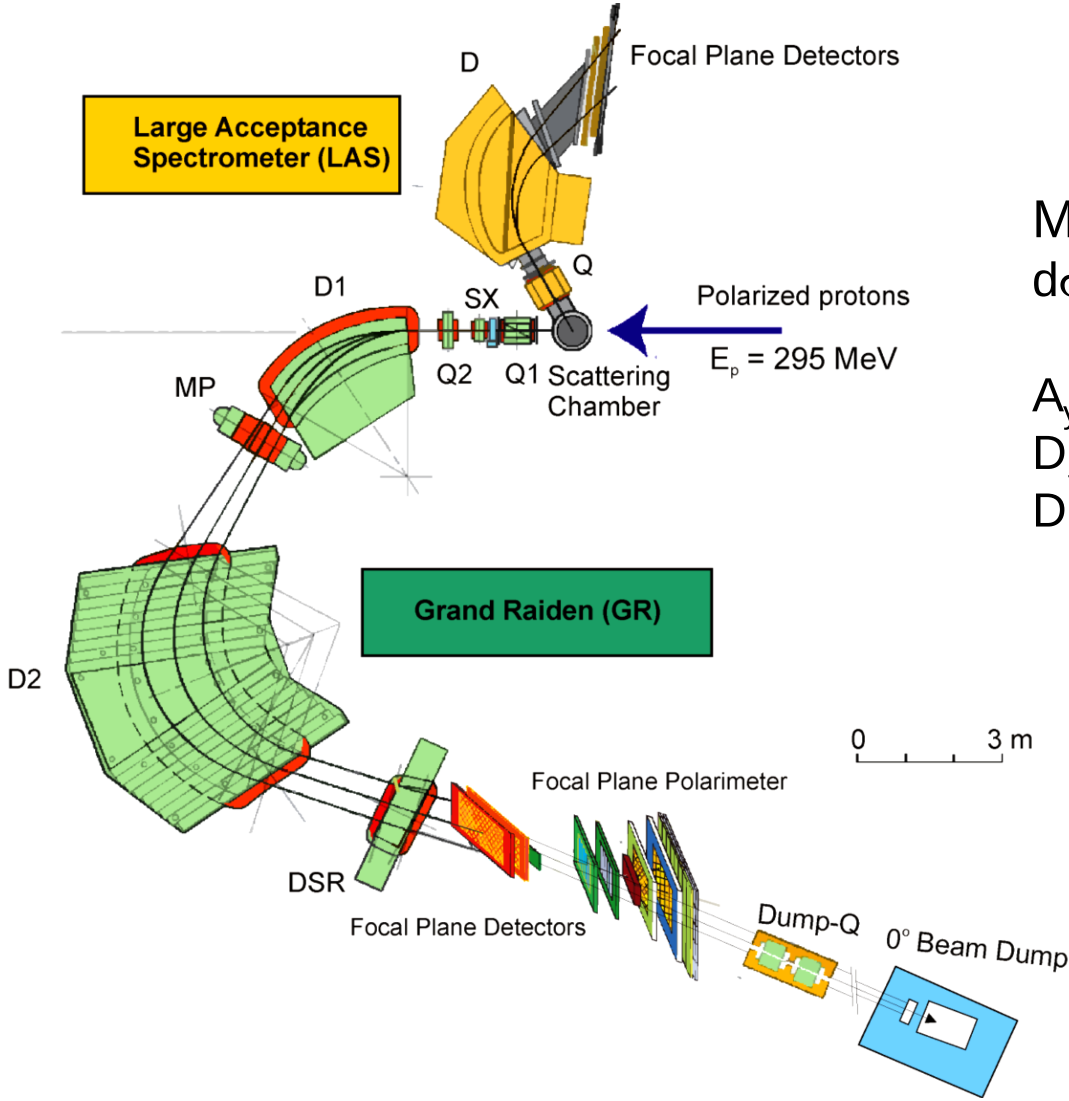
- Proton scattering at a few hundred MeV and angles close to 0º
  - Experiments possible at RCNP and iThemba LABS
  - Review: PvNC and A. Tamii, EPJA 55, 110 (2019)

- Polarizabilty studies
  - ^{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)
  - ^{48}Ca: J. Birkhan et al., PRL 118, 252501 (2017)

RCNP Osaka Facility



0º Setup at RCNP

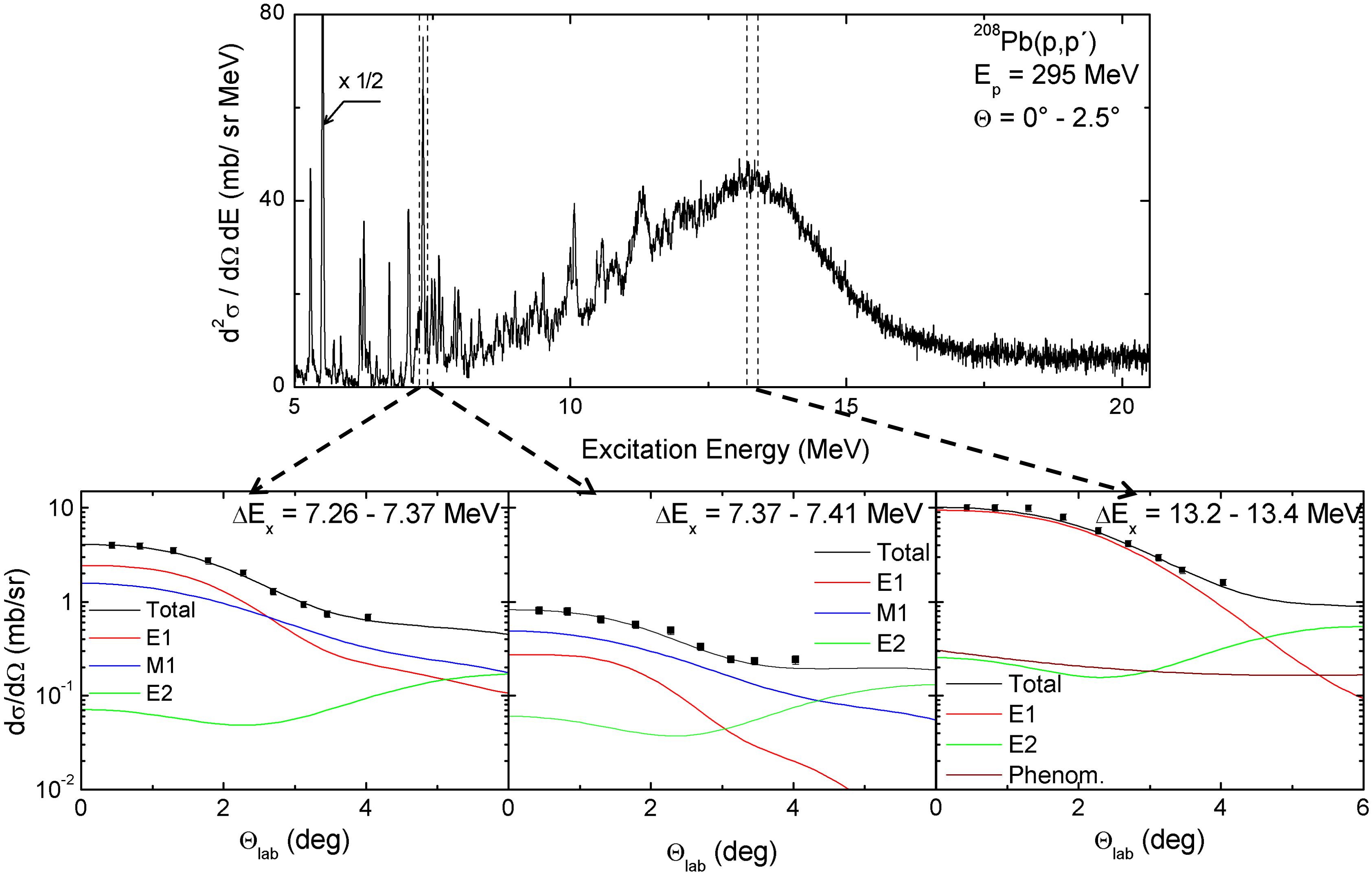


Measured observables

$d\sigma/d\Omega$	- angular distributions ($0° \leq \Theta \leq 10°$)
A_y	- asymmetry
D_{SS} at 0°	- sideways polarization
D_{LL} at 0°	- longitudinal polarization

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

Multipole Decomposition of Angular Distributions



E1/M1 Decomposition by Spin-Transfer Observables

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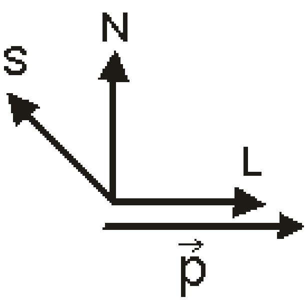
T. Suzuki, PTP 103, 859 (2000)

Polarization observables at 0° ➡ spinflip / non-spinflip separation

(model-independent)

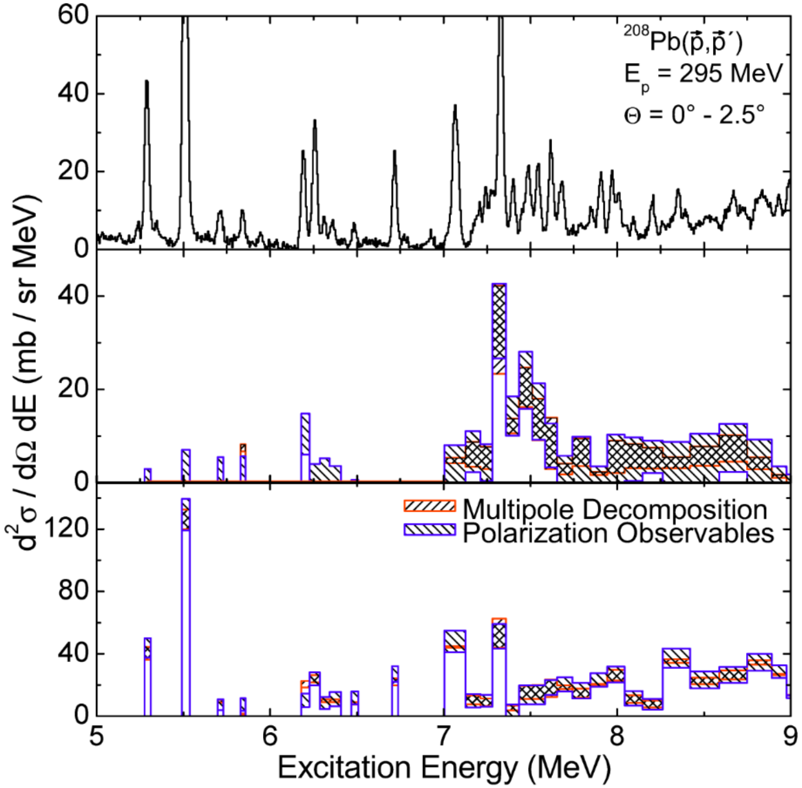


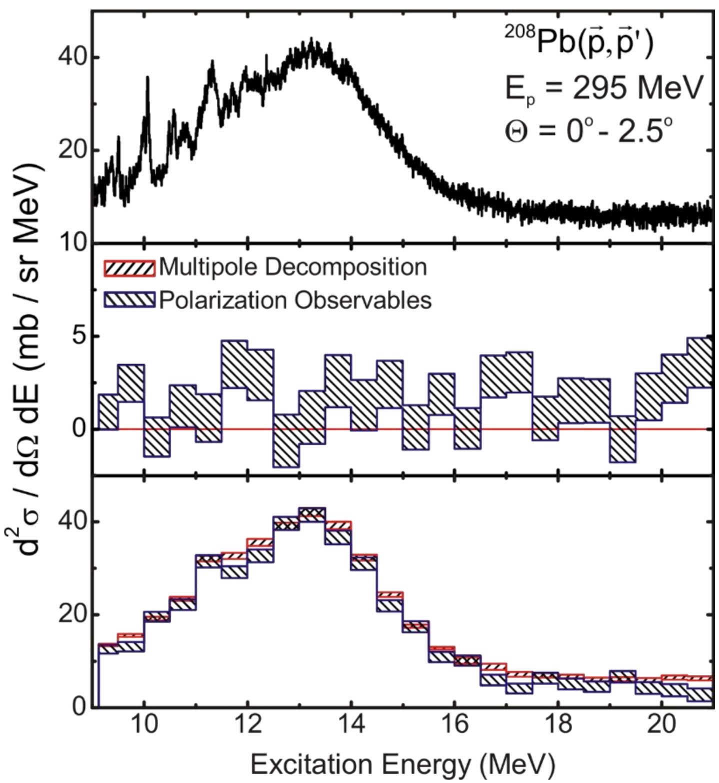
$$D_{SS} + D_{NN} + D_{LL} = \begin{cases} -1 \text{ for } \Delta S=1 \rightarrow 1^{+} \\ 3 \text{ for } \Delta S=0 \rightarrow 1^{-} \end{cases}$$

sideway | normal | longitudinal

At 0° $D_{SS} = D_{NN}$ ➡ Total Spin Transfer $\Sigma \equiv \frac{3-(2D_{SS}+D_{LL})}{4} = \begin{cases} 1 \text{ for } \Delta S = 1 \\ 0 \text{ for } \Delta S = 0 \end{cases}$

Comparison of Both Methods





Total

ΔS = 1

ΔS = 0

^{40}Ca: Data

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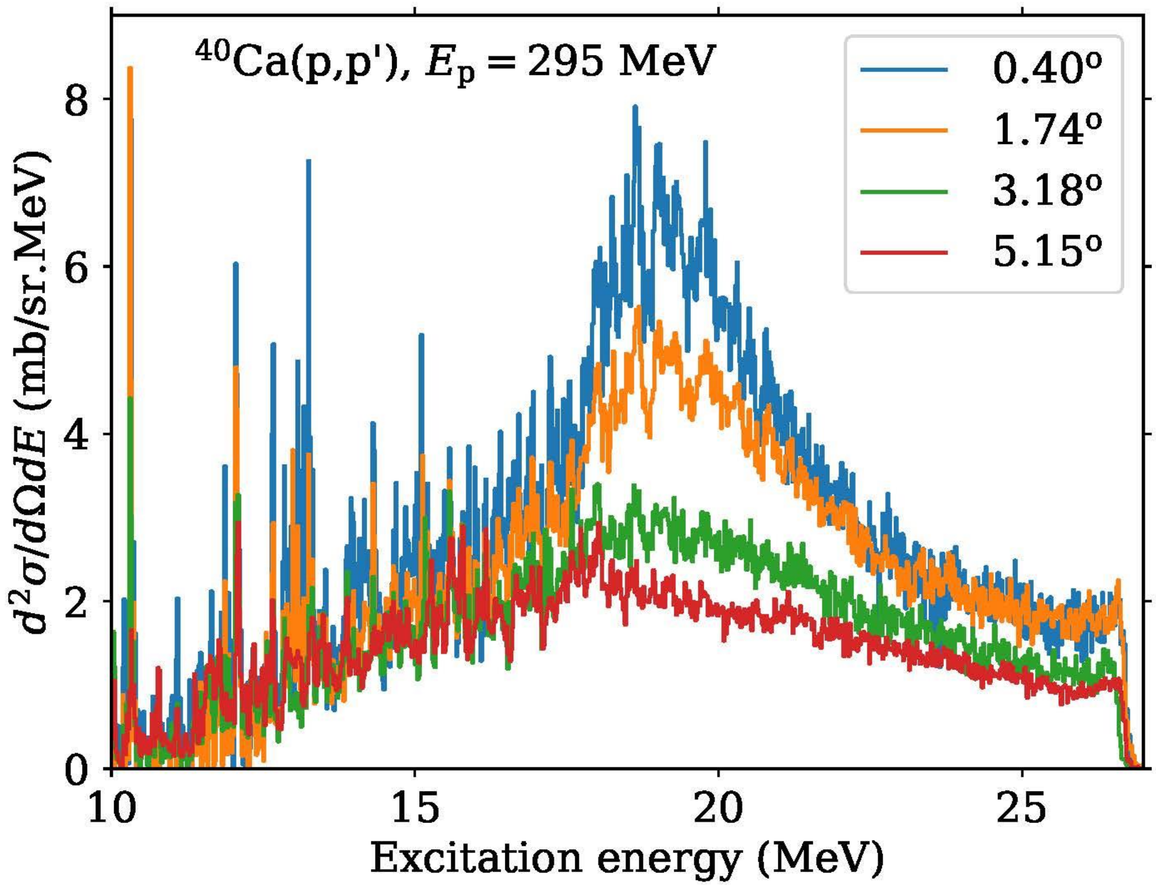

^{40}Ca: Multipole Decomposition Analysis

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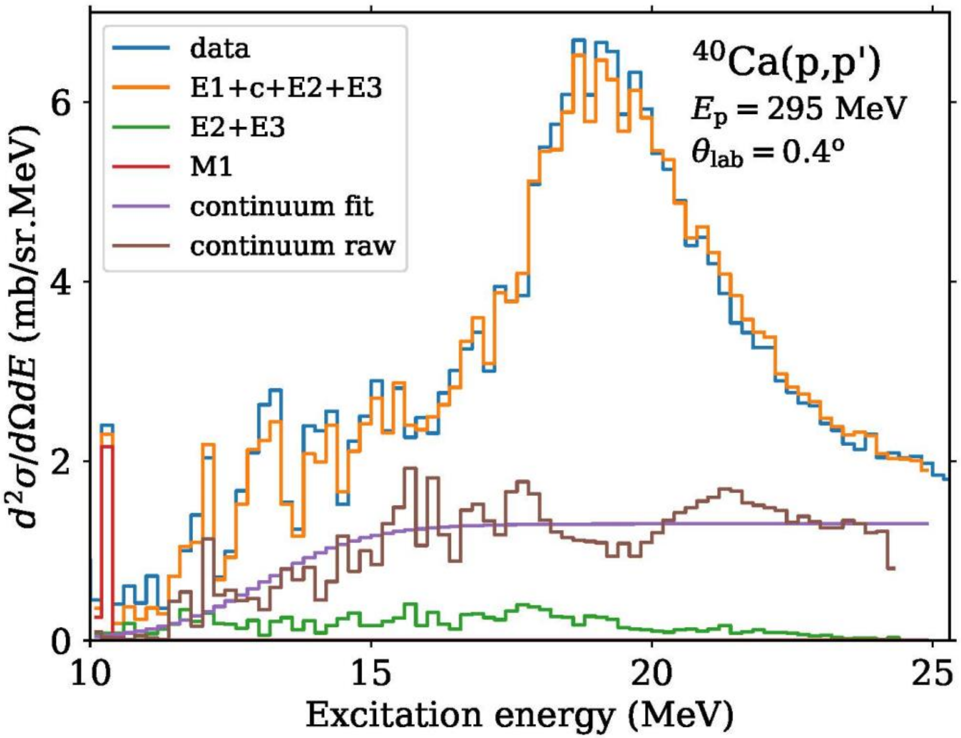
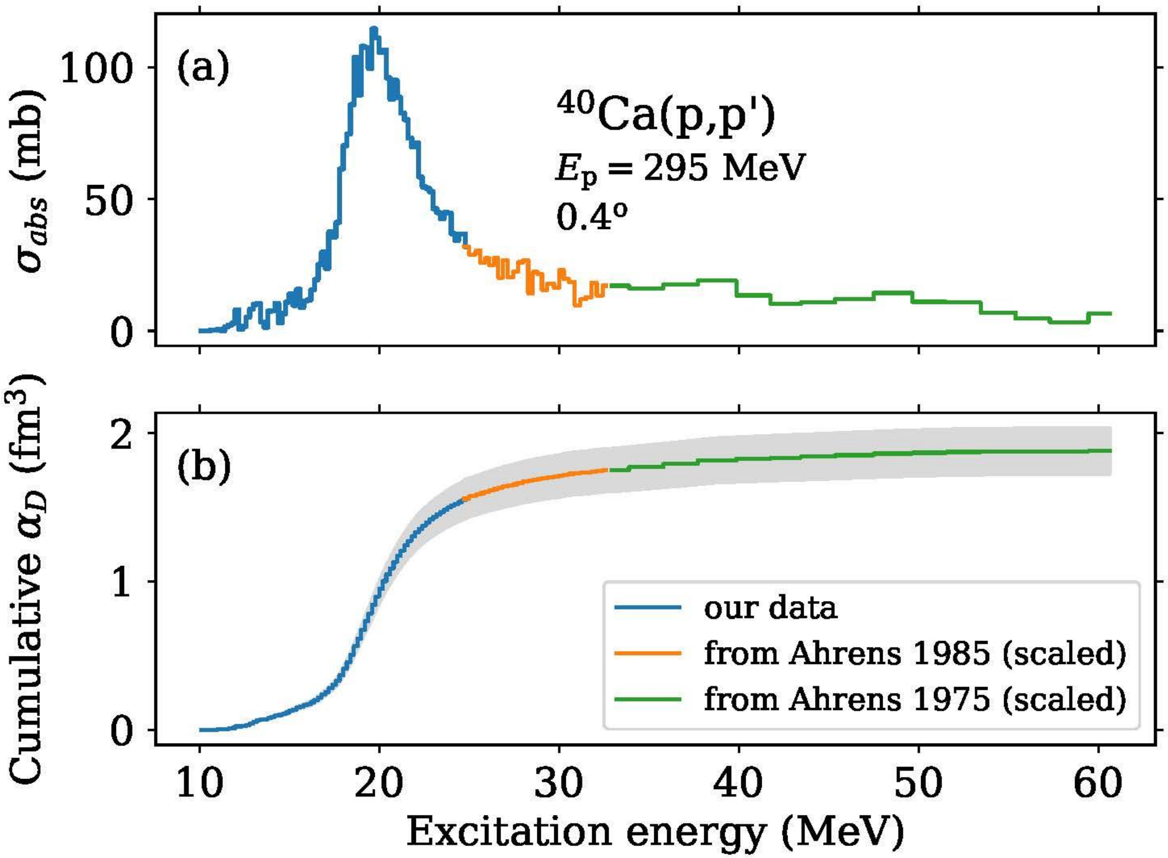
R.W. Fearick et al, in preparation



- Constraints on continuum cross sections from phenomenological parameterization of QFS (C. Kalbach) and assuming a Fermi function

Photoabsorption Cross Sections ^{40}Ca

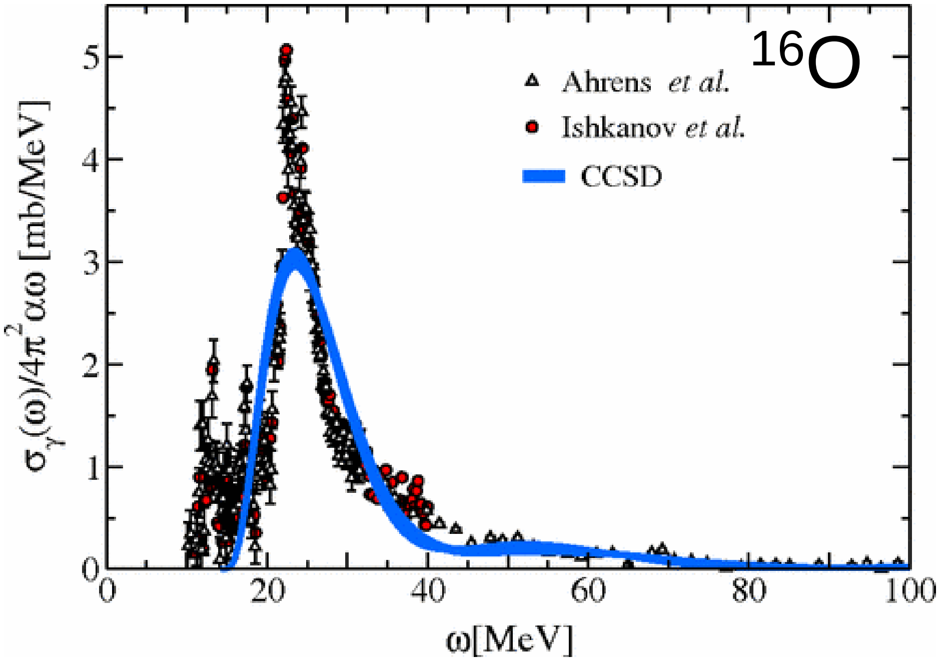
R.W. Fearick et al, in preparation



$\alpha_D = 1.86(14)$ fm^3

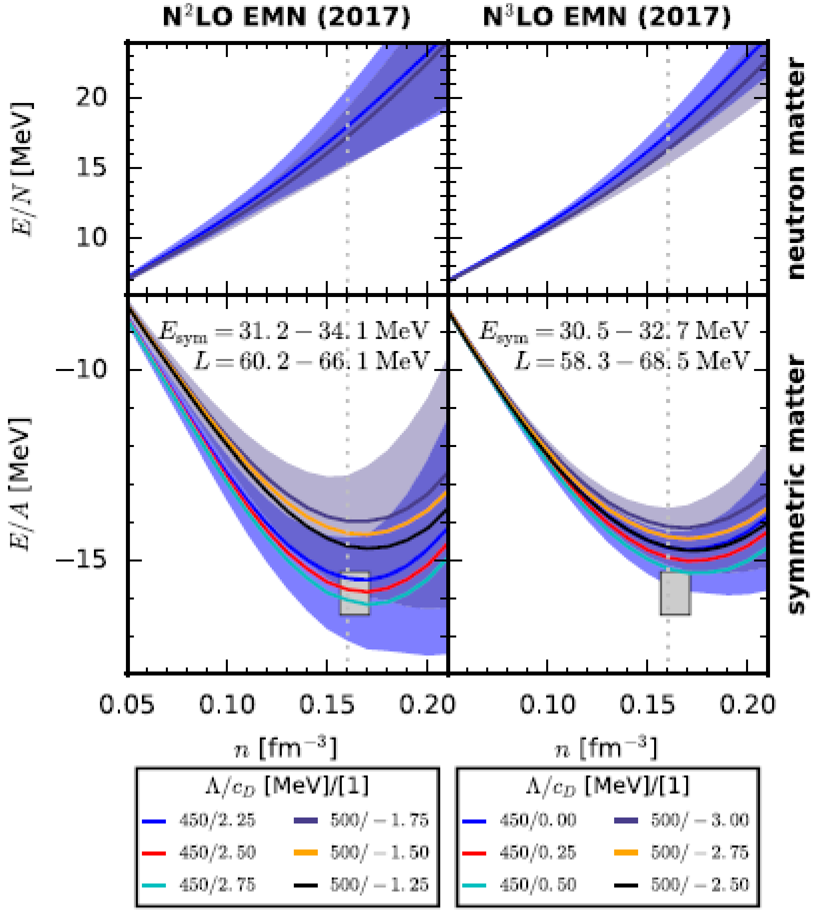
Theoretical Approach: *ab initio*

S. Bacca et al., Phys. Rev. Lett. 111, 122502 (2013)



- Based on interactions derived from χEFT
- Combines Lorentz Integral Transform (LIT) with Coupled Cluster (CC) technique
- Method applicable to magic nuclei only

Theoretical Approach: *ab initio*

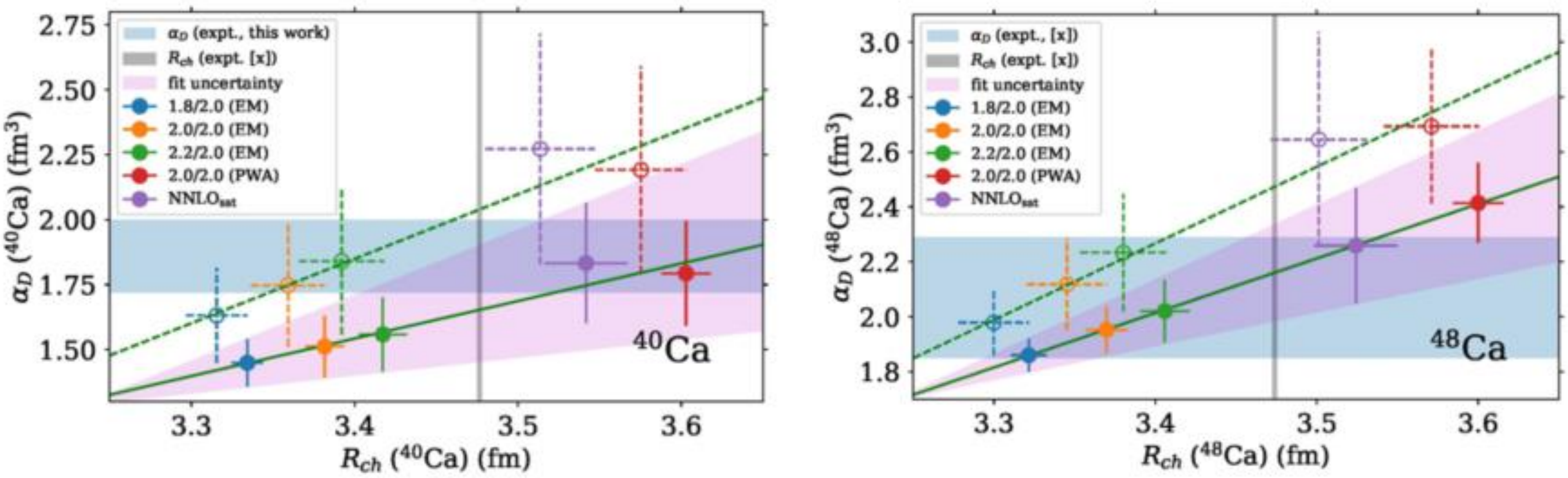


C. Drischler, K. Hebeler, and A. Schwenk, Phys. Rev. Lett. 122, 042501 (2019)

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

Polarizability ^{40}Ca: *Ab Initio* Calculations

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



- Improved calculations with triple correlations in the ground state
  M. Miorelli et al., PRC 98, 014324 (2018)
- Consistent description of ^{40}Ca and ^{48}Ca
- Constraints on symmetry energy: J = 28 - 32 MeV L = 41 - 49 MeV

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

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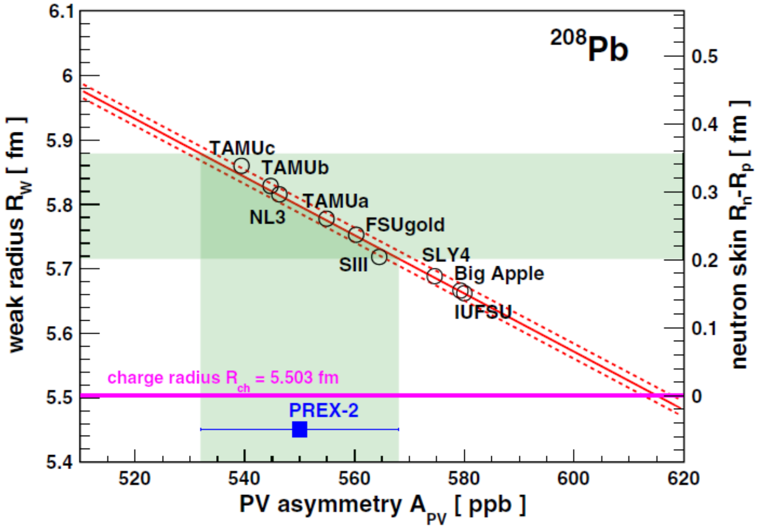
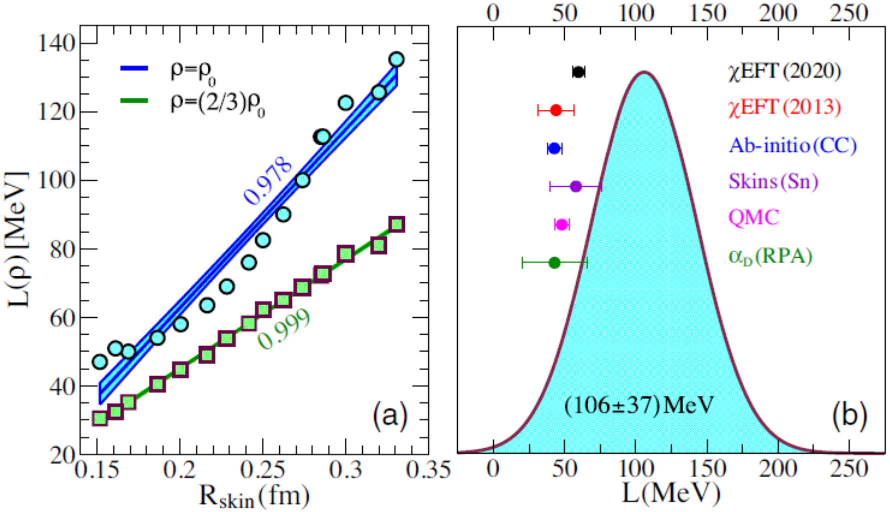
D. Adhikari et al., PRL 126, 172502 (2021)



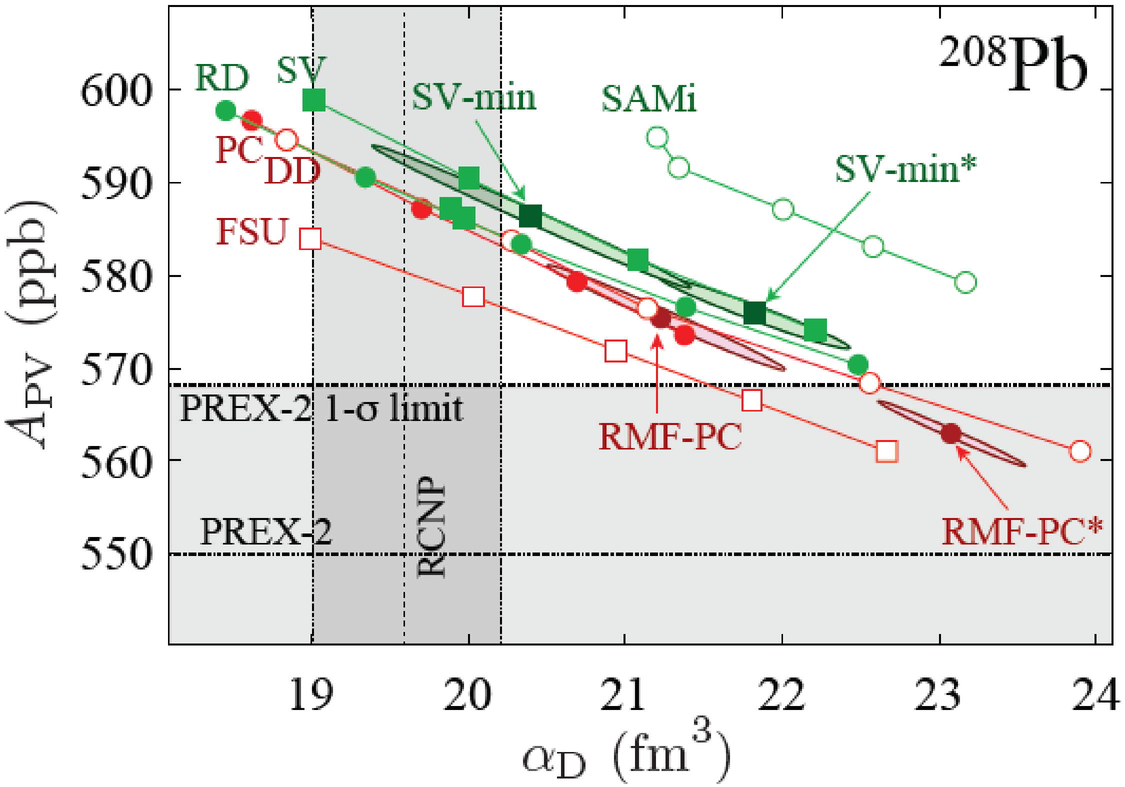
B.T. Reed et al., PRL 126, 172503 (2021)



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

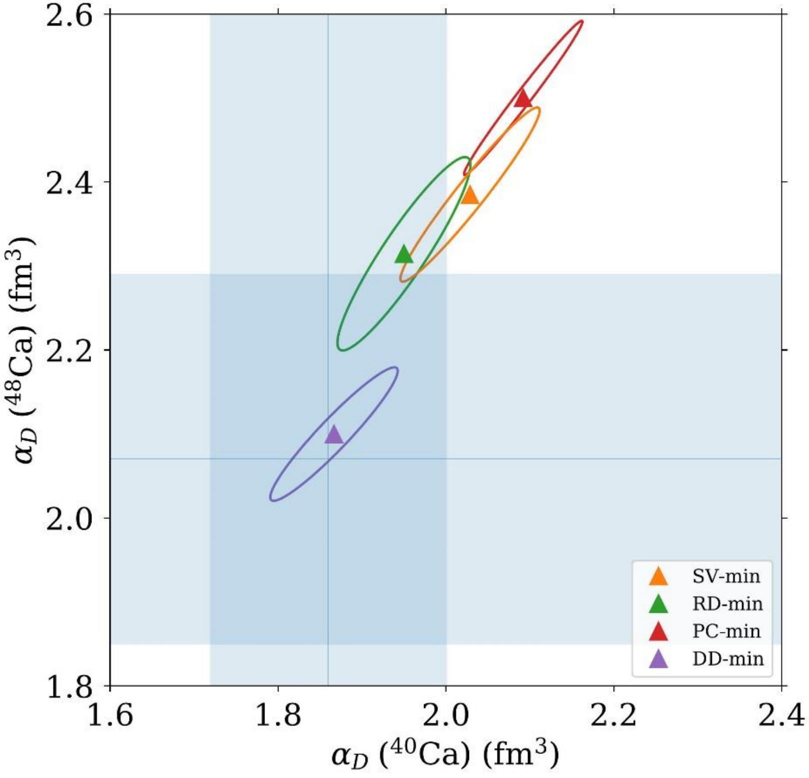
PREX-II versus Polarizability Constraints

P.-G. Reinhard, X. Roca-Maza and W. Nazarewicz, arXiv: 2105.15050

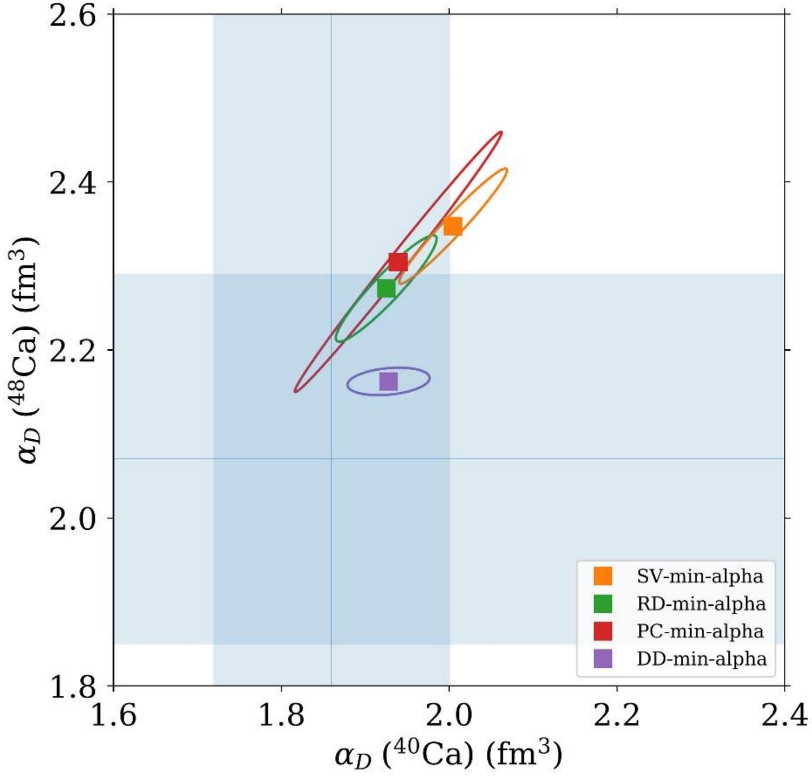


- No consistent description of A_{PV} and α_D(^{208}Pb) possible
- Similar analysis by J. Piekarewicz, PRC 104, 024329 (2021)

Extension to $^{40,48}Ca$



include $\alpha_D(^{208}Pb)$ in the fit



- $\alpha_D(^{40,48}Ca)$ can be reproduced when $\alpha_D(^{208}Pb)$ is included in the fit
- Corresponding symmetry energy parameter range $L \approx 30 - 70$ MeV

Summary and Outlook

- Proton scattering at 0° - a versatile experimental tool to extract the complete electric dipole response in nuclei and thus the polarizabilty

- ^{40}Ca and correlation with ^{48}Ca
  - consistent description with *ab initio* theory
  - consistent description with EDFs which reproduce the polarizabilty in ^{208}Pb

- PREX-II and polarizability results in ^{208}Pb cannot be described simultaneously by EDF theory

Collaborators ^{40}Ca Project

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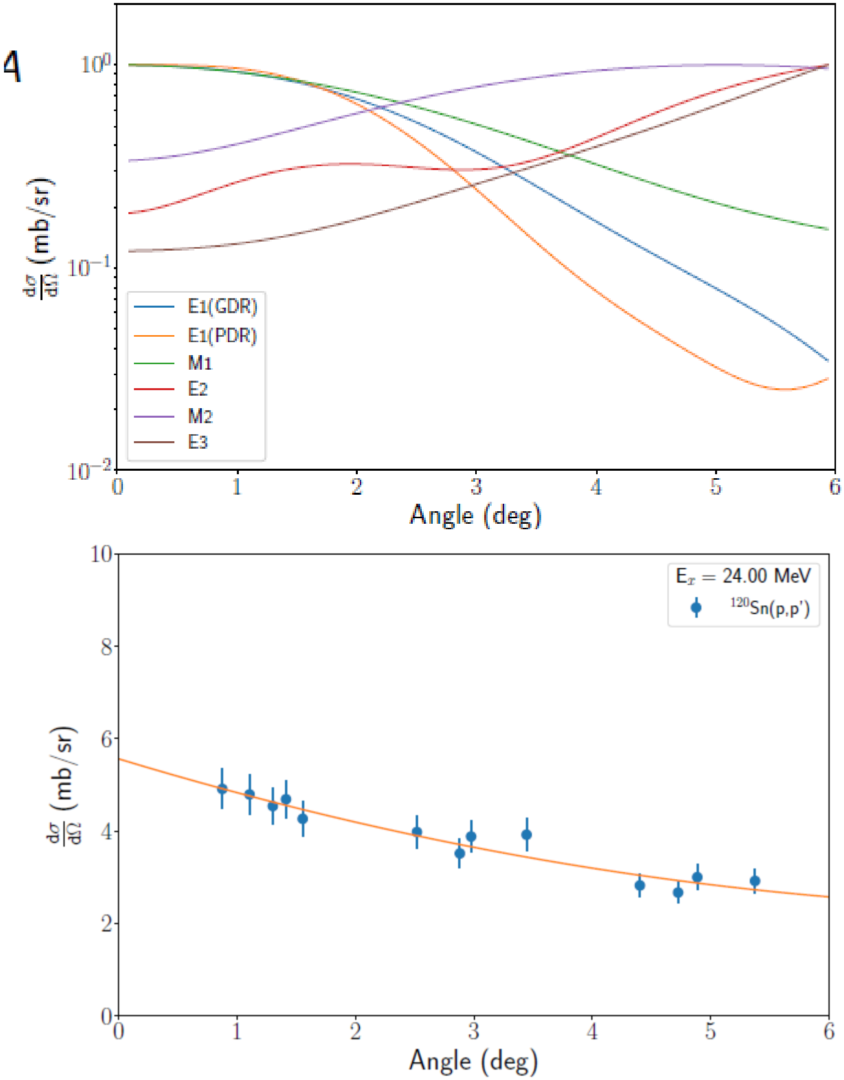
Multipole Decomposition Analysis

$$\frac{d\sigma}{d\Omega}(\theta, E_x)_{exp} = \sum_{J^\pi} a^{J^\pi} \frac{d\sigma}{d\Omega}(\theta, E_x, J^\pi)_{DWBA}$$



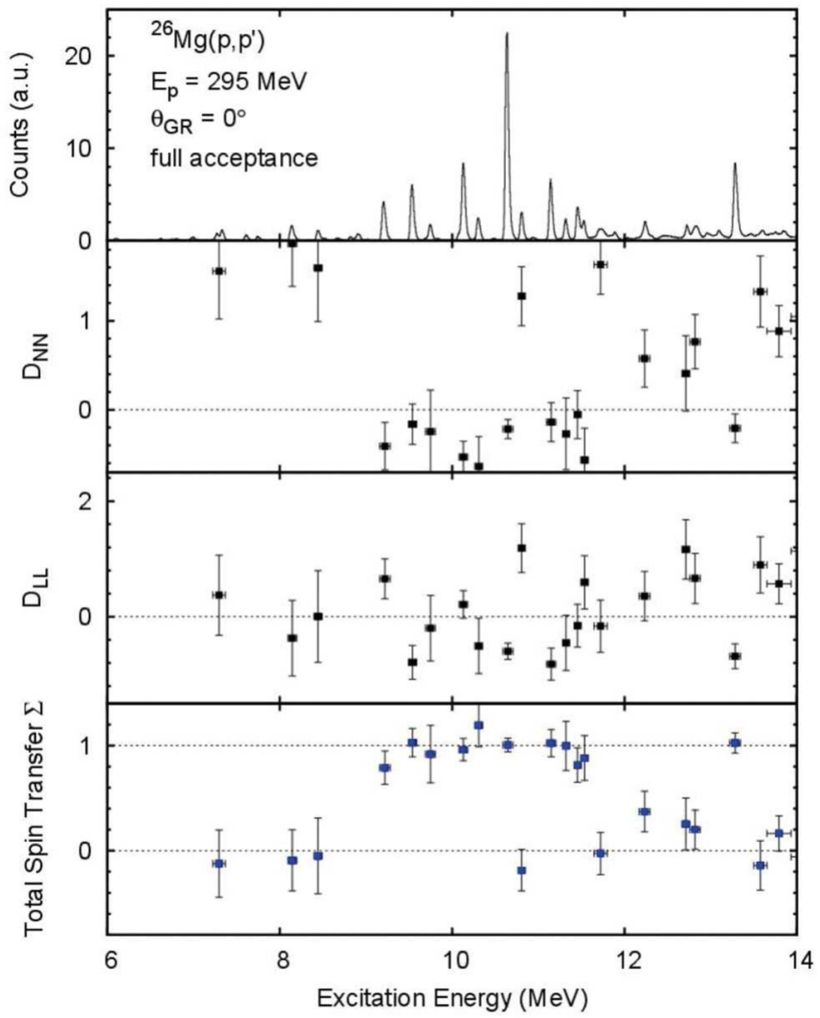
Transition amplitudes and single-particle wave functions from QPM

E3 transition as a substitute for possible higher multipole contributions

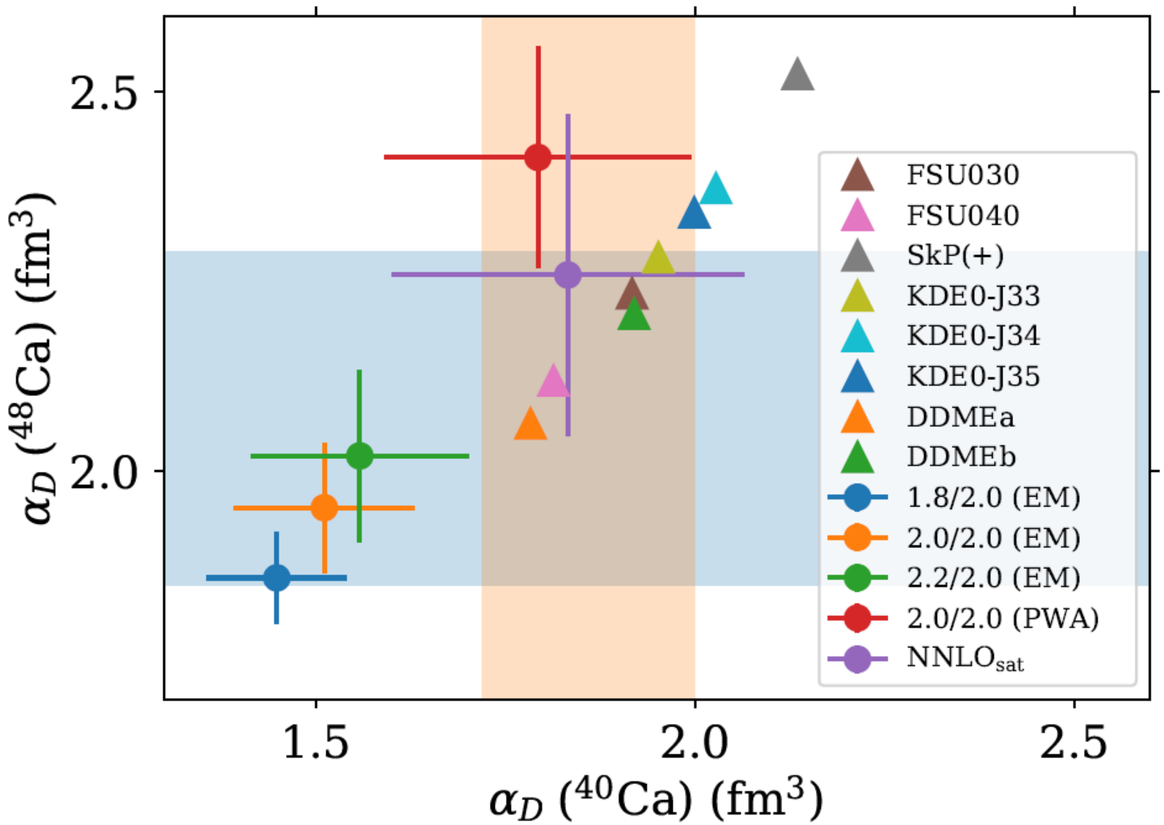
Phenomenological background (quasifree scattering)

ISGQR and ISGMR contributions subtracted prior to MDA

Total Spin Transfer



Polarizability ^{40}Ca: *ab initio* vs. EDFs



- EDFs selected to decribe polarizability of ^{68}Ni, ^{120}Sn and ^{208}Pb
  X. Roca-Maza et al., PRC 92, 064304 (2015)

Symmetry Energy Constraints

F. Gulminelli and A.F. Fantina, arXiv:2110.02616