Probing the Nuclear Symmetry Energy and Neutron Skin from Collective Excitations

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CONTENTS

• What are relationships between the properties of collective modes of excitation, symmetry energy and neutron skin thickness? Which dynamic observables constrain the neutron distribution and neutron skin thickness in finite nuclei?

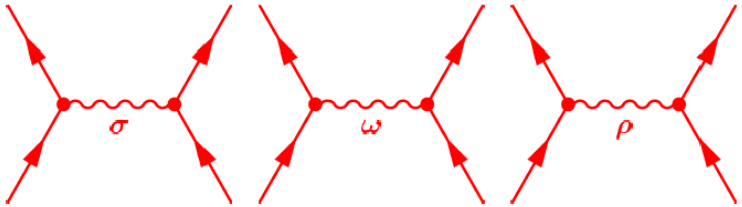
•Applications of dipole excitations and antianalog giant dipole resonance, based on recent experimental data and relativistic nuclear energy density functional, in constraining the neutron-skin thickness in nuclei, nuclear matter symmetry energy at saturation density and slope of the symmetry energy

• Assessing statistical correlations by means of covariance analysis involving response properties of nuclei, nuclear matter properties, and ground state properties. Theoretical uncertainties in modeling various observables.

P.-G. Reinhard, W. Nazarewicz, X. Roca-Maza, G. Colò, J. Piekarewicz, D. Vretenar

RELATIVISTIC NUCLEAR ENERGY DENSITY FUNCTIONAL

System of Dirac nucleons coupled by the exchange mesons and the photon field



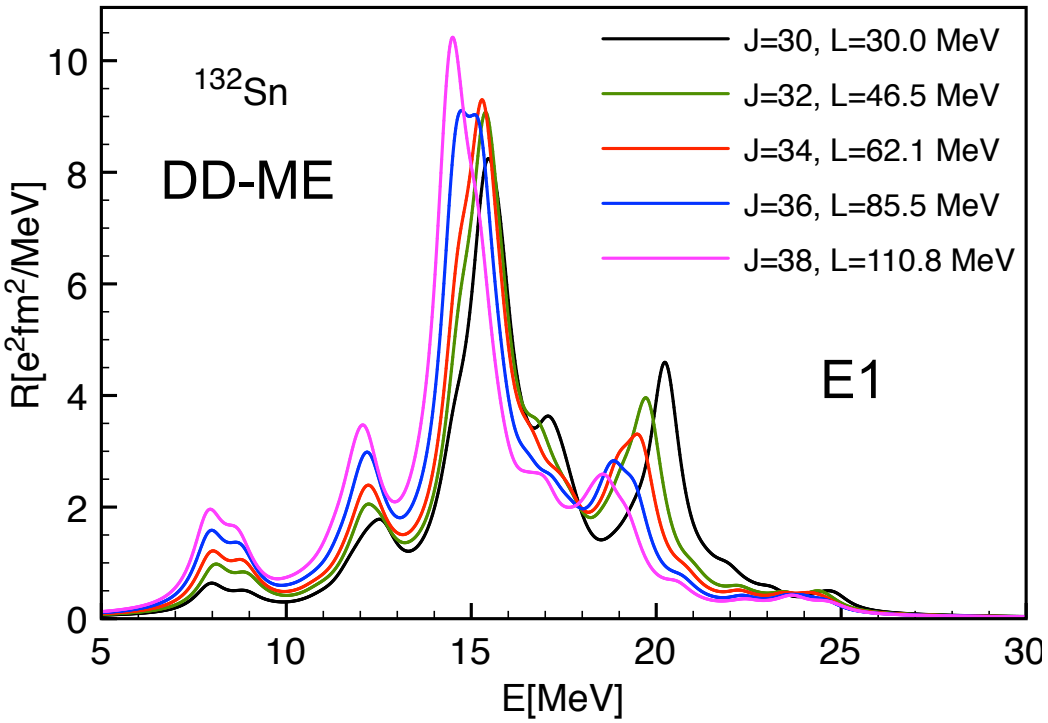
- unified microscopic description of the structure of finite nuclei

-in the limit of small amplitude vibrations, fully self-consistent relativistic quasiparticle RPA (RQRPA) allows analysis of giant resonances, low-energy multipole response in weakly-bound nuclei, dynamics of exotic modes of excitation, weak interaction rates, neutrino-nucleus reactions, etc.

- **D. Vretenar, A. V. Afanasjev, G. A. Lalazissis, and P. Ring, Phys. Rep. 409, 101(2005).**
- **N.P., D. Vretenar, E. Khan, G. Colò, Rep. Prog. Phys. 70, 1 (2007).**

CONSTRAINTS ON THE SYMMETRY ENERGY AND NEUTRON SKINS

In order to explore the evolution of the excitation spectra as a function of the density dependence of the symmetry energy, a set of interactions is used, that span a broad range of values for the symmetry energy at saturation density (J) and the slope parameter (L).



Nuclear matter energy per part.:

$$E(\rho,\alpha) = E(\rho,0) + S_2(\rho)\alpha^2 + \dots$$

$$\alpha = (N-Z)/A$$

Symmetry energy term:

$$S_2(\rho) = J + L\epsilon + \dots$$

$$\epsilon = (\rho_0 - \rho)/(3\rho_0)$$

$$L = 3\rho_0 \frac{dS_2(\rho)}{dr}|_{\rho_0}$$

Constraining the symmetry energy from dipole polarizability

- Theoretical constraints on the symmetry energy at saturation density (J) and slope of the symmetry energy (L) from dipole polarizability (α_D) using relativistic nuclear energy density functionals

$$\alpha_D = \frac{8\pi}{9} e^2 m_{-1}$$

+

- Exp. data from polarized proton inelastic scattering, α_D=18.9(13)fm^3/e^2
  A. Tamii et al., PRL. 107, 062502 (2011)

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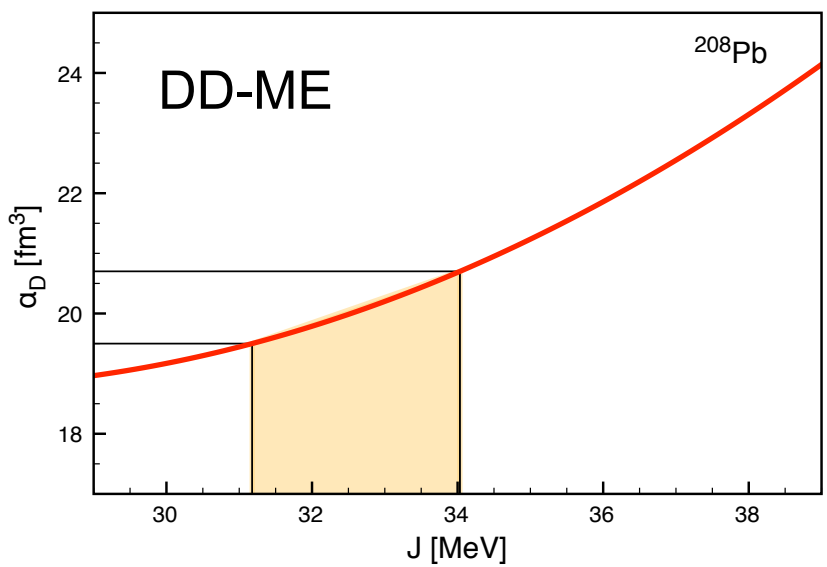
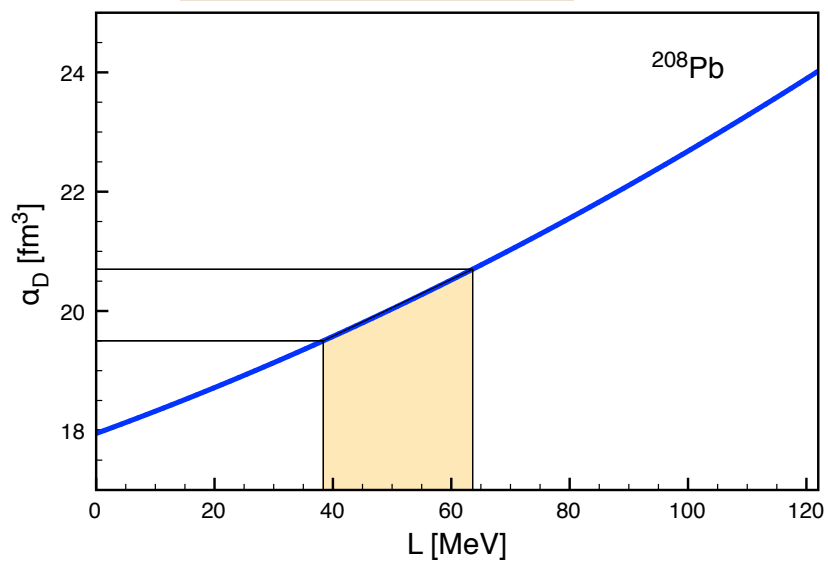


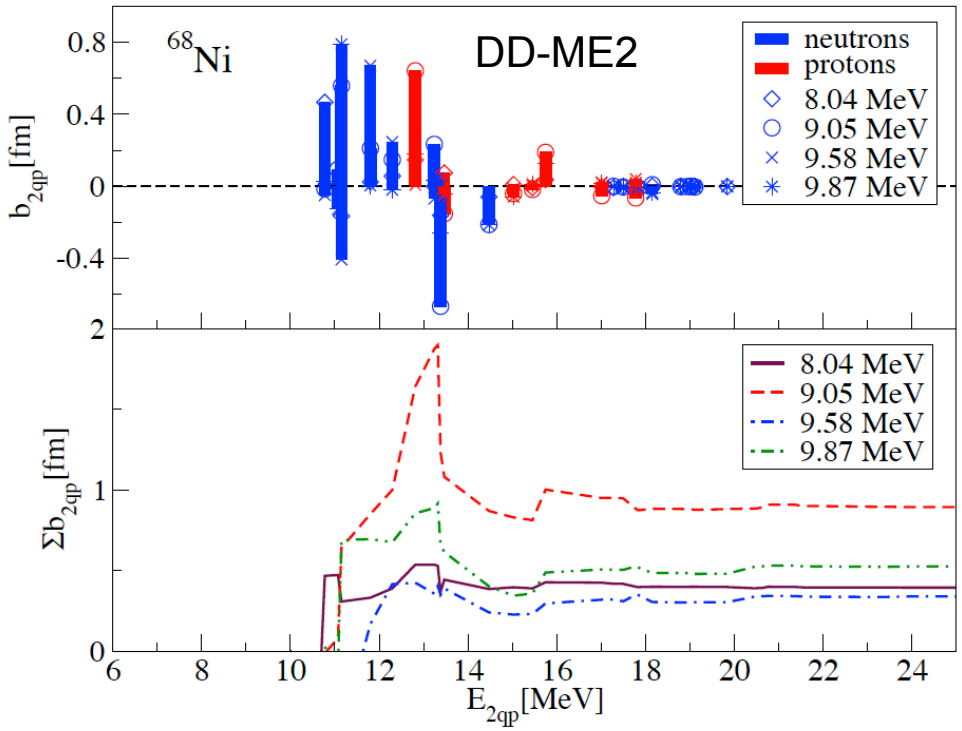
J=(32.6±1.4) MeV



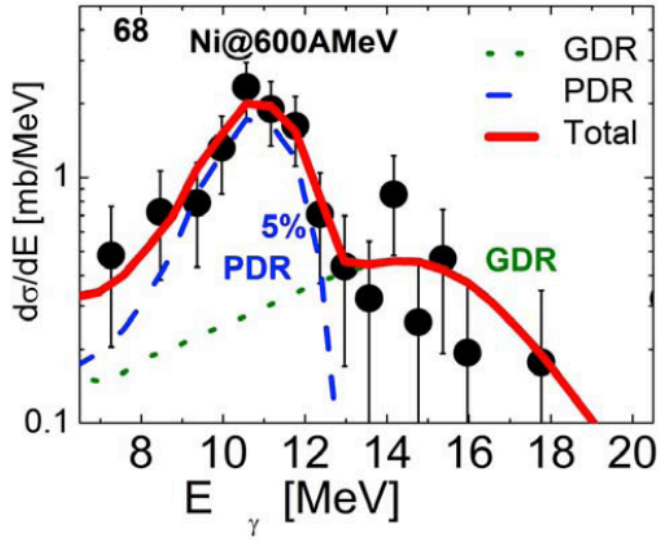
L=(50.9±12.6) MeV

PYGMY DIPOLE STRENGTH IN ^{68}Ni

The pygmy dipole strength for ^{68}Ni and comparison to experimental data
➔ γ decay from Coulomb excitation of ^{68}Ni at 600 MeV/nucleon (INFN,GSI,…)



	$S_{EW}(E1)$ [e^2fm^2MeV]	% EWSR (TRK)	B(E1) [e^2fm^2]
RNEDF	14.4	5.9 %	1.57
Exp.	12.2 ± 3.7	(5±1.5) %	1.2



O. Wieland et al., PRL 102, 092502 (2009)

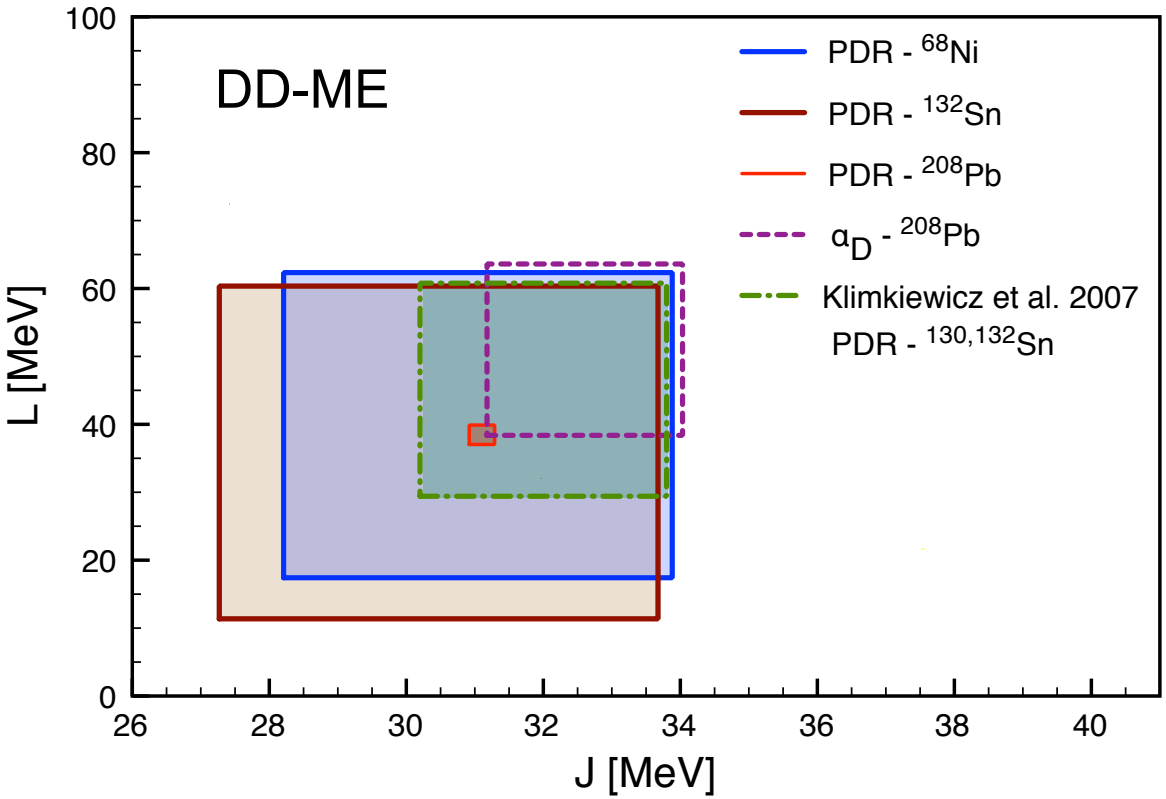
9.05 MeV: coherent neutron transitions:
2p3/2➔ 3s1/2
2p1/2➔ 2d3/2
1f5/2➔2d3/2
1f5/2➔2d5/2

2p3/2, 2p1/2,1f5/2:
12 excess neutrons
above N=Z core

EXCESS NEUTRONS OSCILLATION MODE

Constraining the symmetry energy

Various constraints from dipole excitations on the slope of the symmetry energy (L) and symmetry energy at saturation density (J)



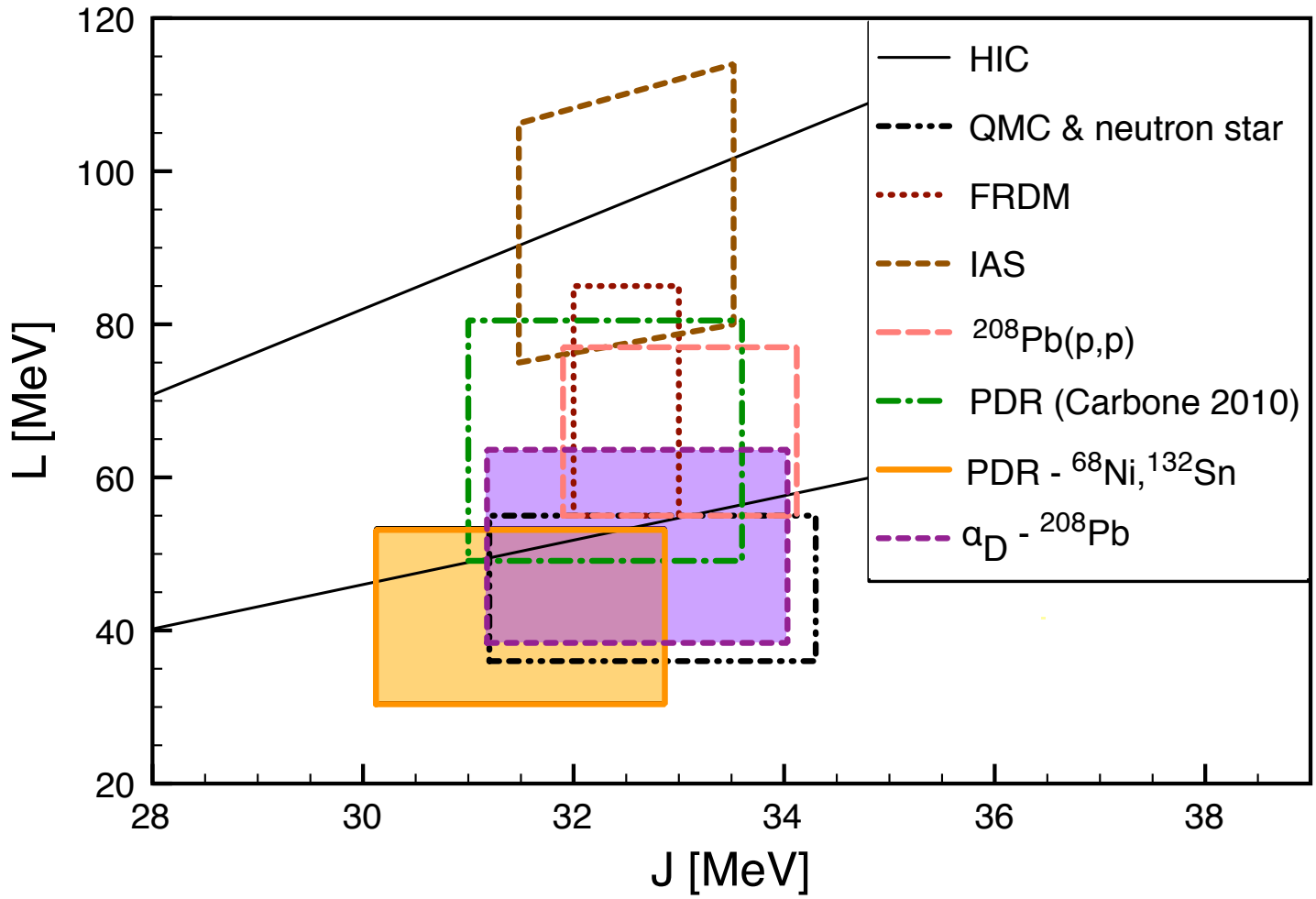
- Energy weighted pygmy dipole strength in ^{68}Ni, ^{132}Sn, ^{208}Pb
- Dipole polarizability in ^{208}Pb
- PDR/GDR B(E1) strength in ^{132}Sn, ^{130}Sn (Klimkiewicz et al. 2007)

Based on exp. data on PDR & α_D

^{68}Ni : O. Wieland et al, PRL. 102, 092502 (2009)
^{132,130}Sn: A. Klimkiewicz et al., PRC 76, 051603 (R) (2007)
^{208}Pb: I. Poltoratska et al., PRC 85, 041304 (R) (2012)
^{208}Pb (α_D): A. Tamii et al., PRL 107, 062502 (2011)

Constraining the symmetry energy

• Constraining the symmetry energy at saturation density and slope of the symmetry energy from various approaches:



Also see M. B. Tsang et al., PRC 86, 015803 (2012)

Covariance analysis – Model dependence

Pierson product-moment correlation $c_{AB} = \frac{|\overline{\Delta A\, \Delta B}|}{\sqrt{\overline{\Delta A^2}\ \overline{\Delta B^2}}}$

Talks W. Nazarewicz
J. Piekarewicz

Relativistic functionals:

- Relativistic point coupling model (PC-min1)
- Relativistic model with density dependent meson-nucleon couplings (DDME-min1)

- The model parameters (9) of both interactions are constrained by the same set of (17) nuclei and their properties: binding energies, charge radii, diffraction radii, surface thickness (N.P.)

- (for relativistic EDFs – FSUGold also see talk by J. Piekarewicz)

Non-relativistic functionals (Skyrme):

- SLy5 (X. Roca-Maza, G. Colò)

- SV-min
  - (Skyrme type parameterization embraces nuclear bulk properties for selected semimagic nuclei)
  - (P.-G. Reinhard, W. Nazarewicz)

COVARIANCE ANALYSIS IN CONNECTION TO EDFs

- Covariance analysis allows calculation of theoretical uncertainty of any physical quantity of interest

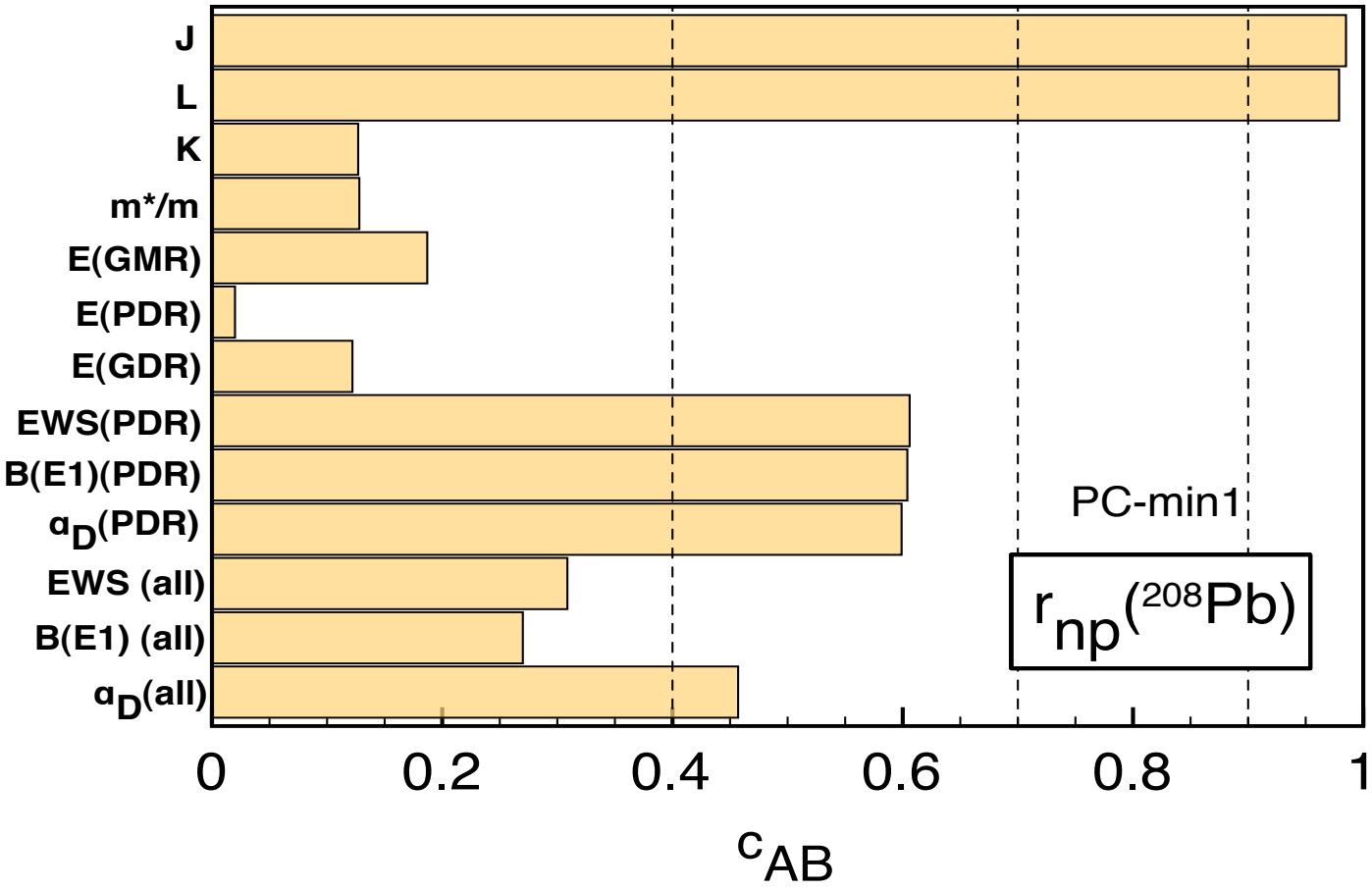
E.g., proton and neutron distribution radii (r_p,r_n), neutron skin thickness (r_{np})

	r_p(fm)	r_n(fm)	r_{np} (fm)	
SV-min	5.444 ± 0.005	5.614 ± 0.039	0.170 ± 0.036	(P.G.Reinhard)
FSUGold	5.469 ± 0.035	5.676 ± 0.041	0.207 ± 0.037	(J. Piekarewicz)
DDME-min1	5.523 ± 0.003	5.658 ± 0.041	0.194 ± 0.040	(N.P.)

	r_{np} (fm) (EXP.)	
PREX	0.33 ± 0.17	S. Abrahamyan et al., PRL. 108, 112502 (2012).
(p,p)	0.156 ± 0.025	A. Tamii et al., PRL 107, 062502 (2011).
(α,α')	0.12 ± 0.07	A. Krasznahorkay et al., NPA 731, 224 (2004).
Antiproton abs.	0.18 ± 0.03	A. Trzinska et al., PRL 87, 082501 (1991).

Which quantity correlates with the neutron skin thickness?

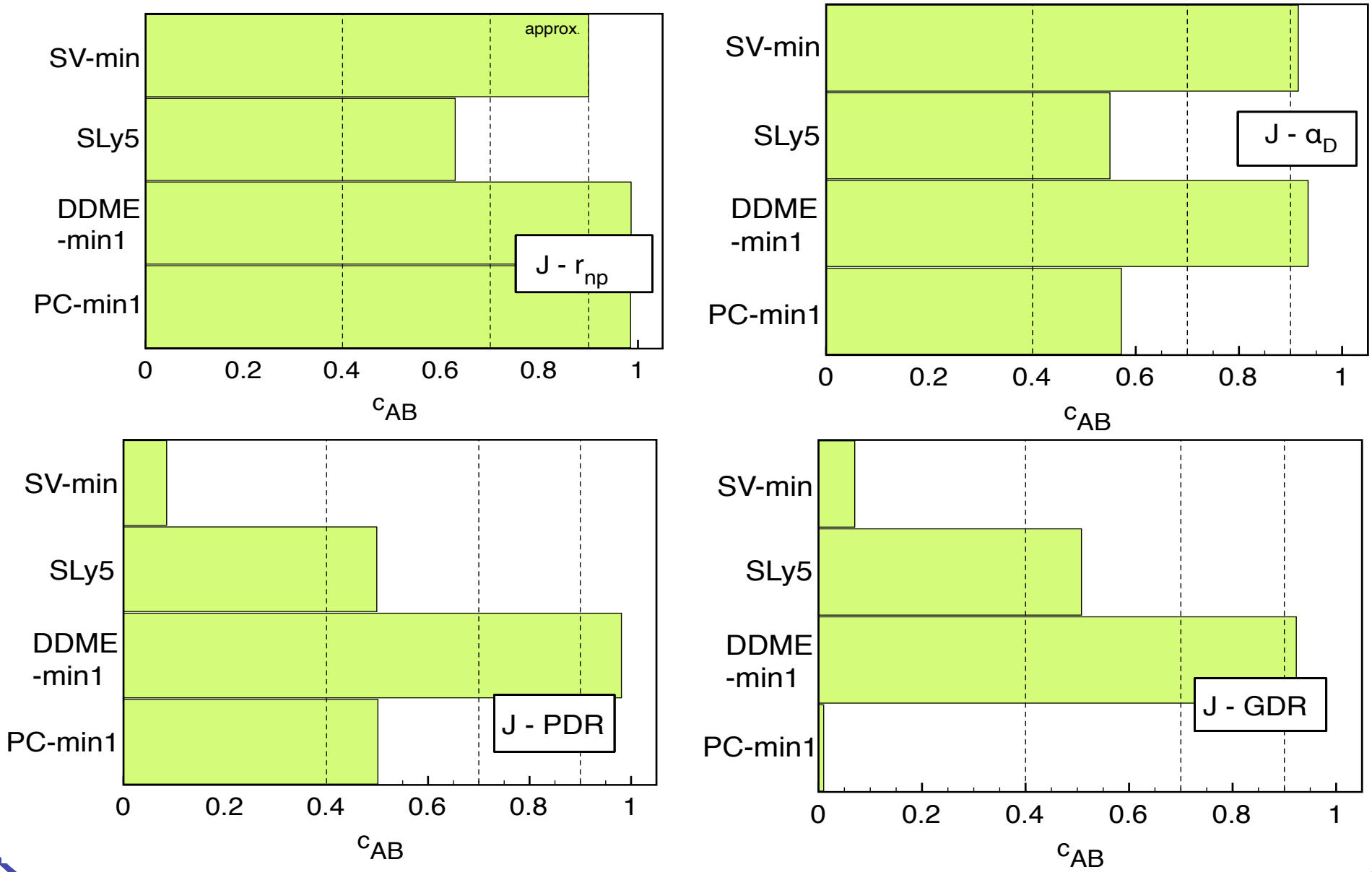
Pierson product-moment correlation coefficient for various dynamic quantities of dipole excitations versus neutron skin thickness (r_{np}):



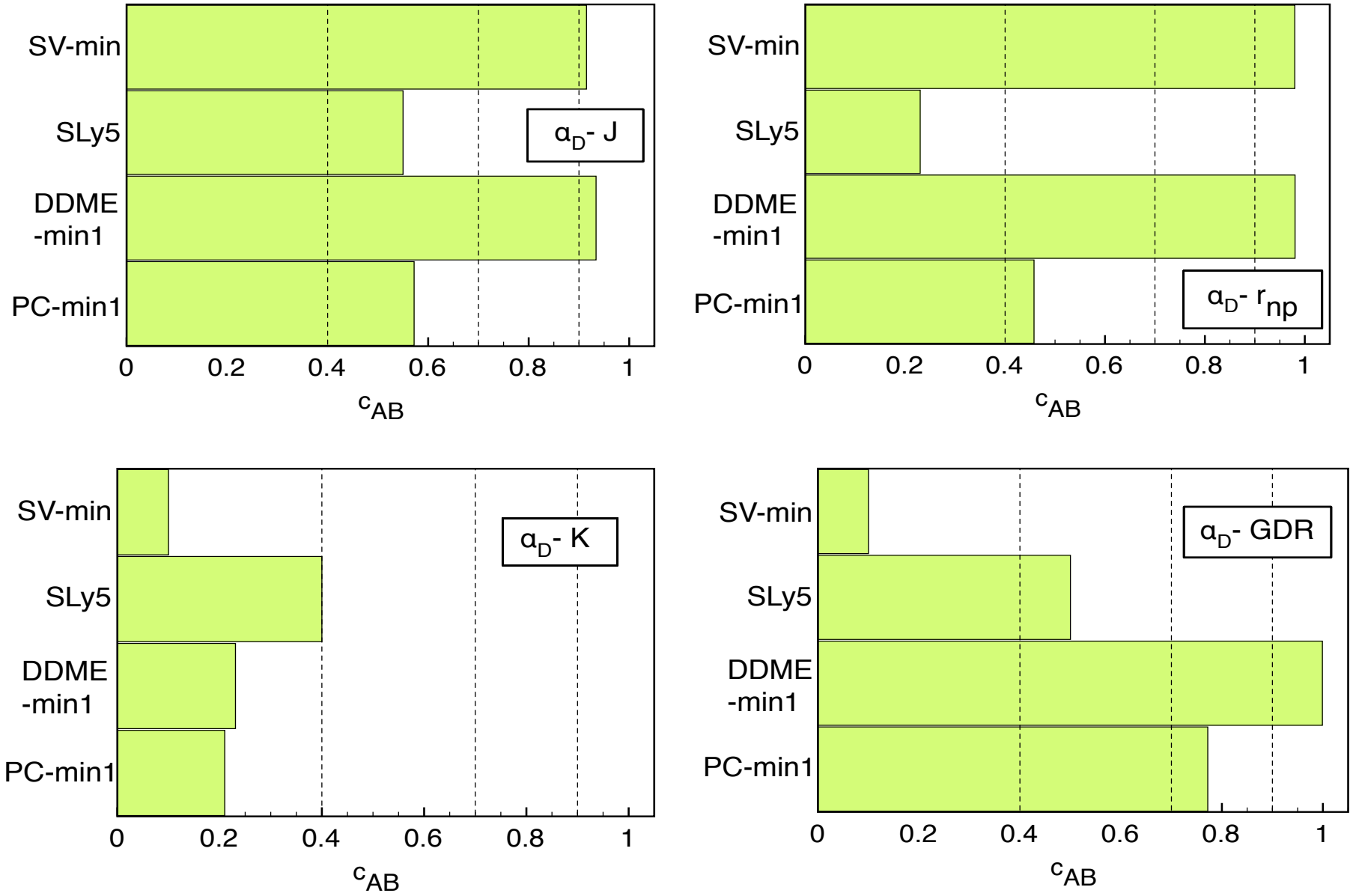
Strength-related quantities (B(E1),energy weighted strength (EWS), α_D) are better correlated with r_{np} than excitation energies.

Both the PDR and overall strength properties are correlated with the neutron skin thickness.

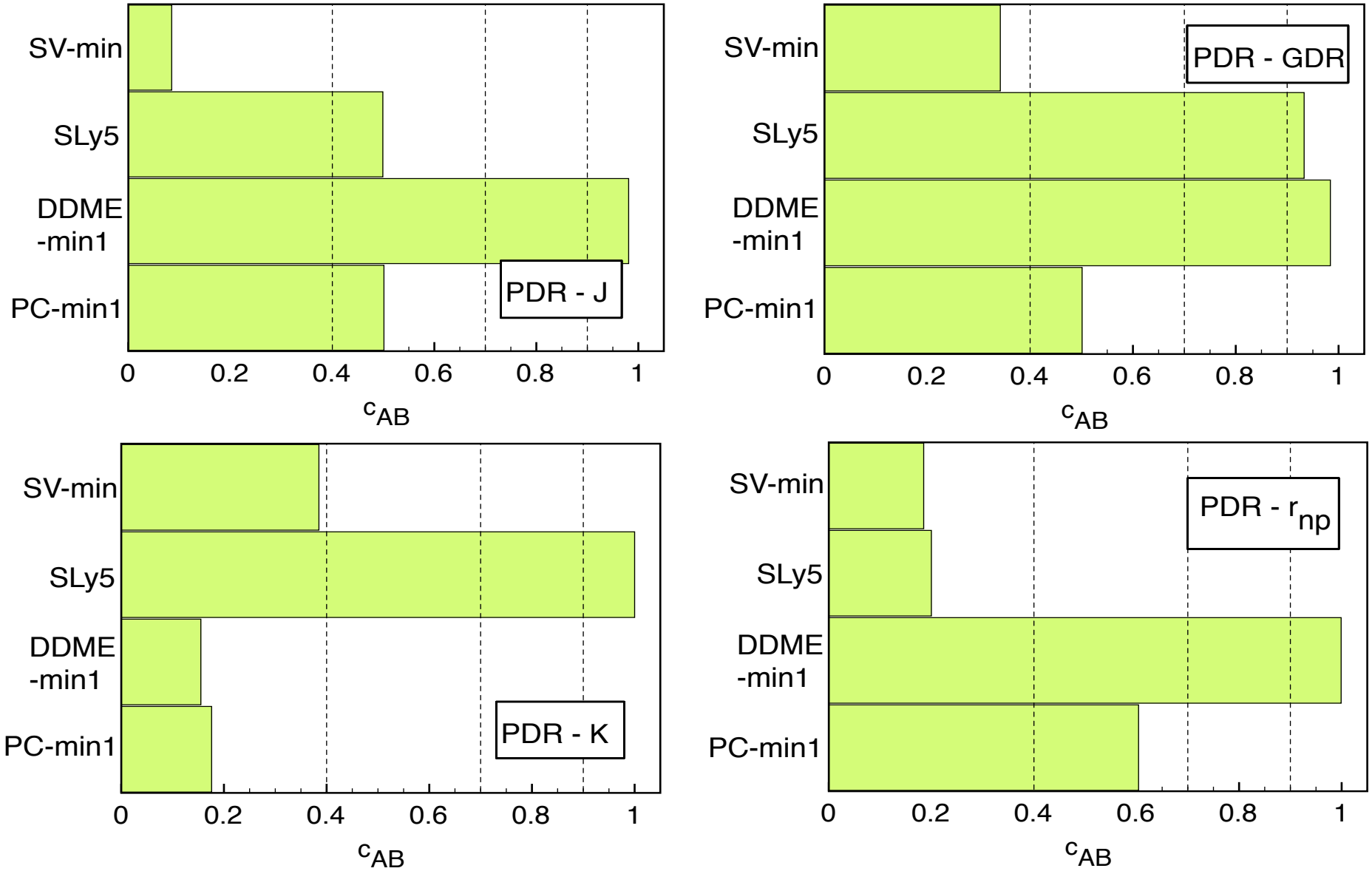
CORRELATIONS WITH THE SYMMETRY ENERGY AT SATURATION DENSITY (J)



CORRELATIONS WITH DIPOLE POLARIZABILITY

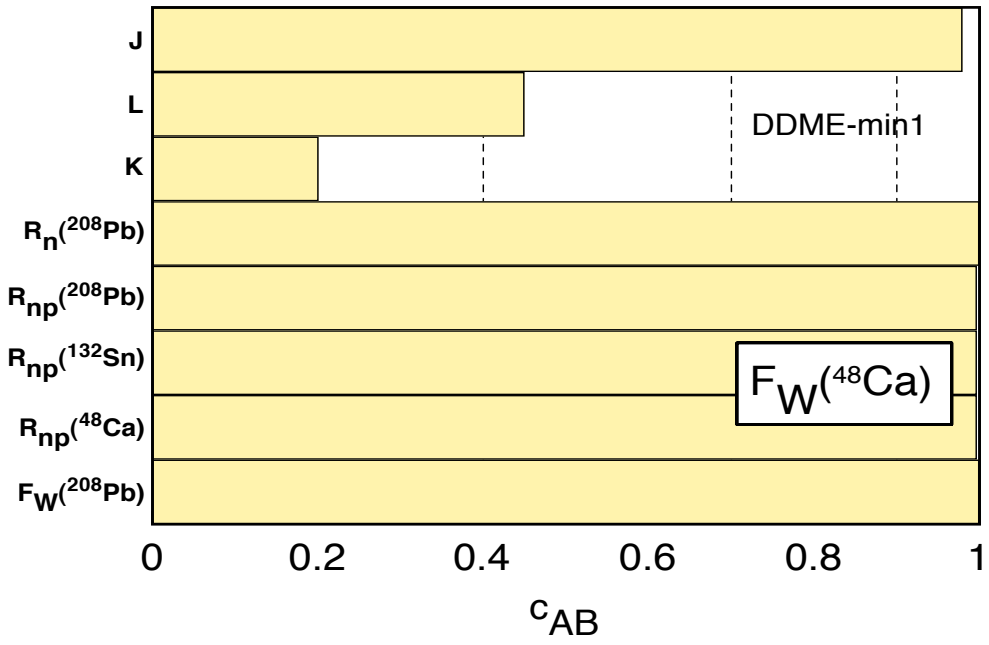


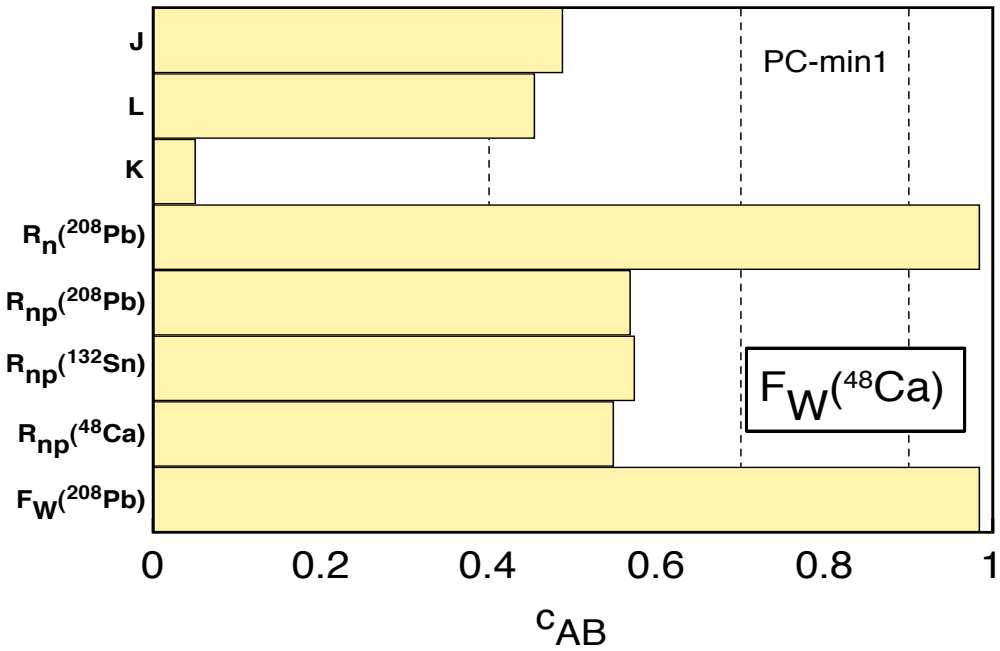
CORRELATIONS WITH THE PYGMY DIPOLE STRENGTH



CORRELATIONS WITH THE WEAK CHARGE FORM FACTORS

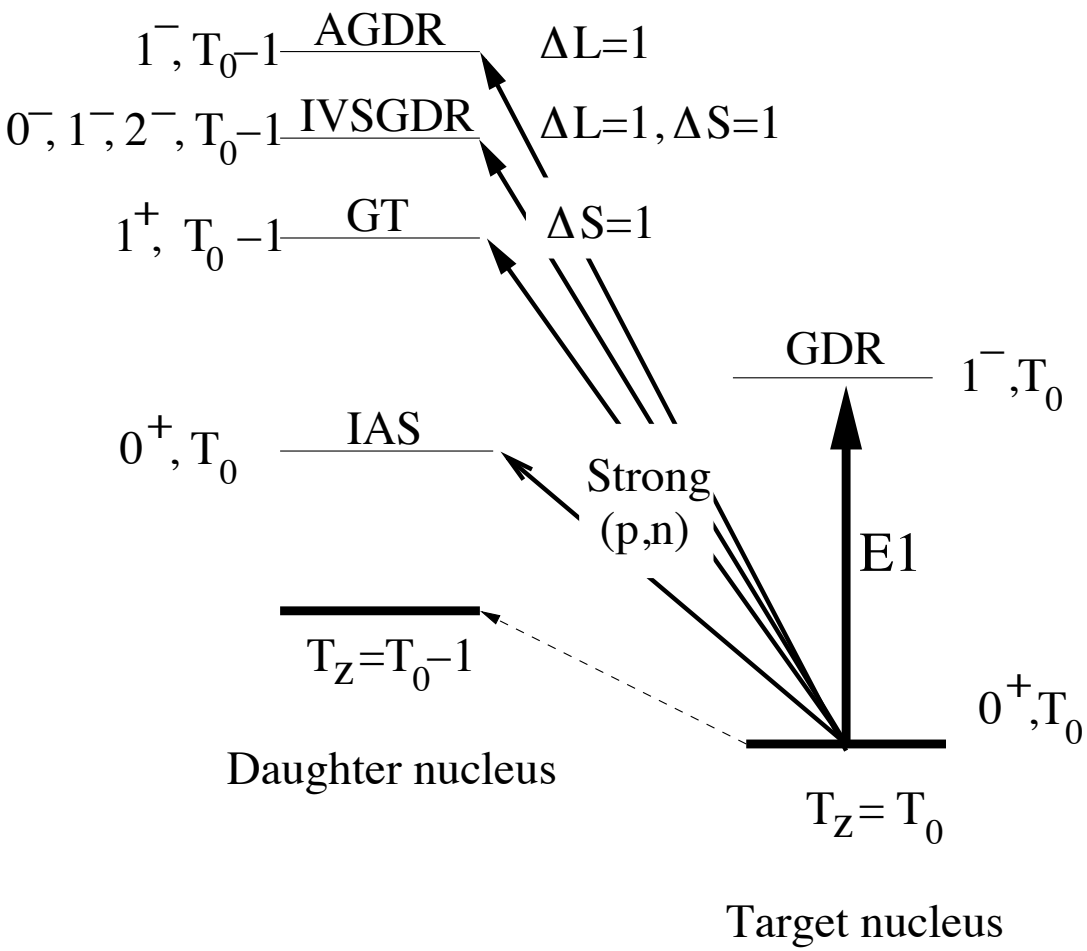
q=0.778 fm^{-1} corresponding to the CREX experiment

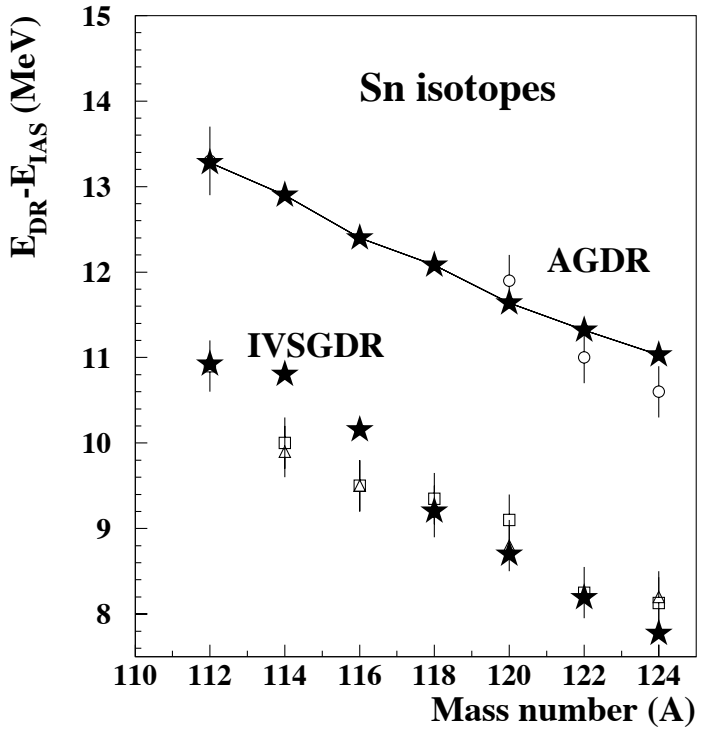


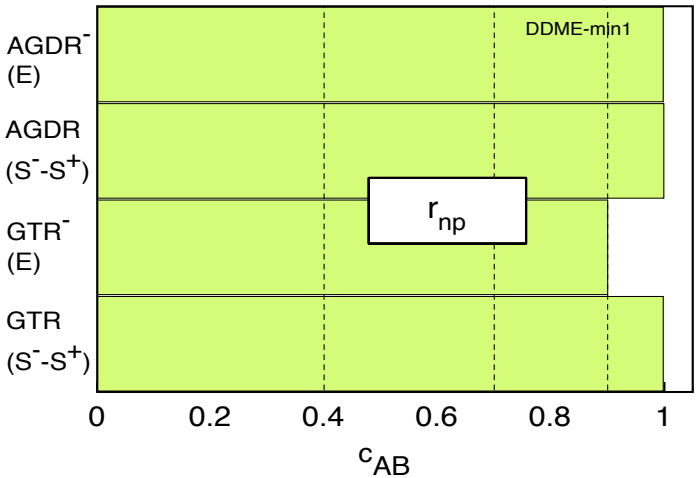


Weak charge form factors (^{48}Ca) reasonably correlate with the neutron radii (^{208}Pb), and neutron skin thicknesses (^{48}Ca,^{132}Sn,^{208}Pb).

ANTI-ANALOG GDR AND NEUTRON-SKIN THICKNESS

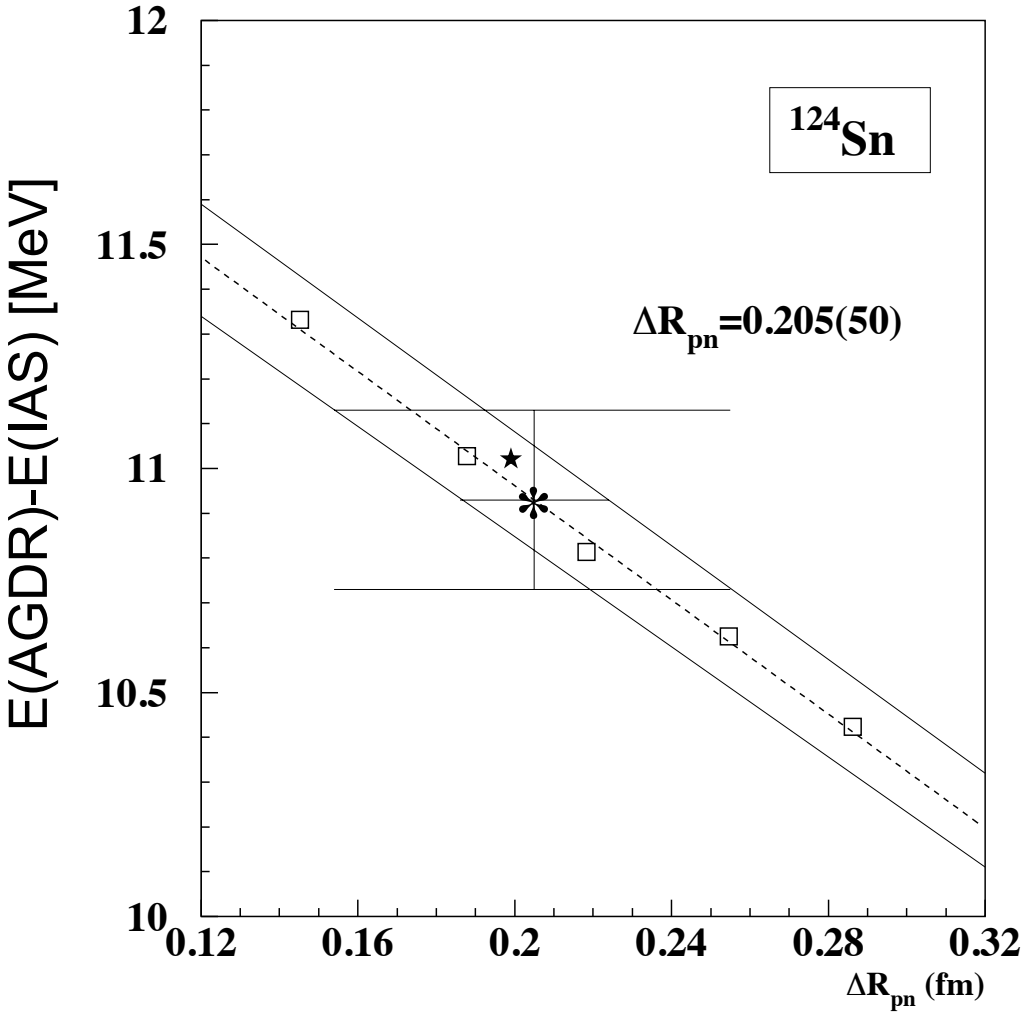






ANTI-ANALOG GDR AND NEUTRON-SKIN THICKNESS

TEST CASE: ^{124}Sn



METHOD	ΔR_{pn} (fm)
(p,p) 0.8 GeV	0.25 ± 0.05
(α,α') IVGDR 120 MeV	0.21 ± 0.11
Antiproton absorption	0.19 ± 0.09
(^{3}He,t) IVSGDR	0.27 ± 0.07
Pygmy dipole resonance	0.19 ± 0.05
(p,p) 295 MeV	0.185 ± 0.05
AGDR - present result	0.21 ± 0.05

neutron skin thickness

A. Krasznahorkay, N. P., D. Vretenar, M.N. Harakeh, Phys. Lett. B 720, 428 (2013).

FINAL REMARKS

- Dipole excitations, charge exchange excitations, parity violating electron scattering (PREX II, CREX) provide valuable constraints on the neutron skin thickness and nuclear matter symmetry energy.

- Statistical covariance analysis based on various effective interactions (SV-min, SLy5,PC-min1,DDME-min1) indicates important correlations between various quantities and observables and provides the insight into the features of model dependence.

- Possible extensions and improvements of the isovector part of the EDFs? E.g. point coupling interactions with four isovector terms (isovector-vector + isovector-scalar, 4 parameters), revised exp. data sets ?

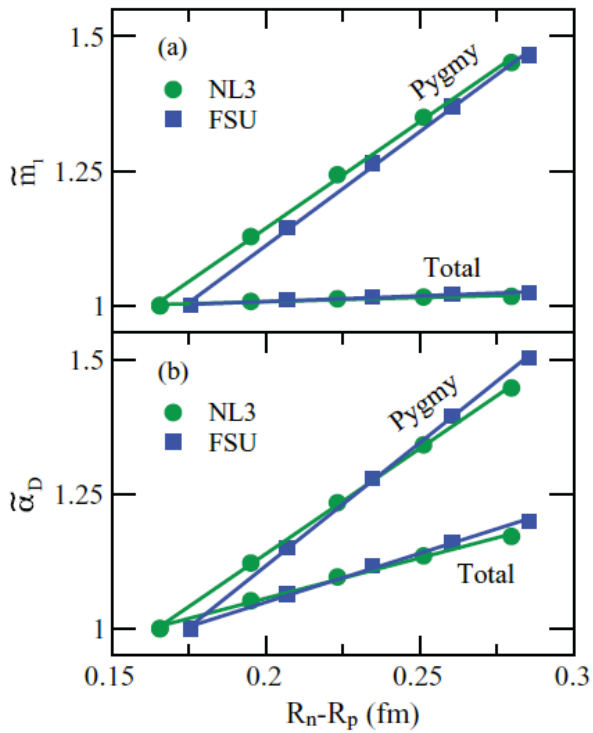
- Constraining theoretical models using PREX, CREX, (p,p), (p,n) data?

Application of the PDR : constraints on the symmetry energy

• The pygmy dipole mode provides possible way to constrain the nuclear matter properties and neutron skin thickness in finite nuclei. **Why?**

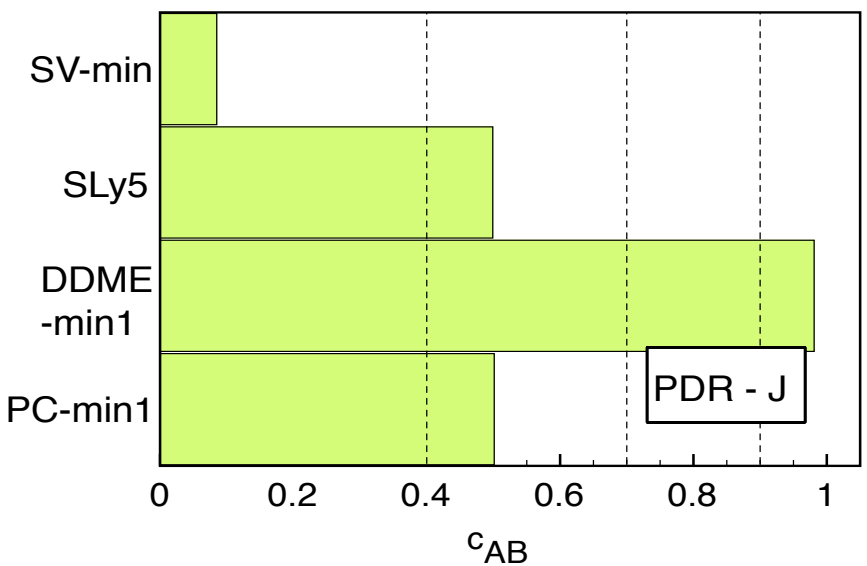
1) PDR is dominated by neutron transitions, its transition densities at the surface are dominated by neutrons.

2) PDR strength is strongly sensitive on the neutron excess (more than GDR)



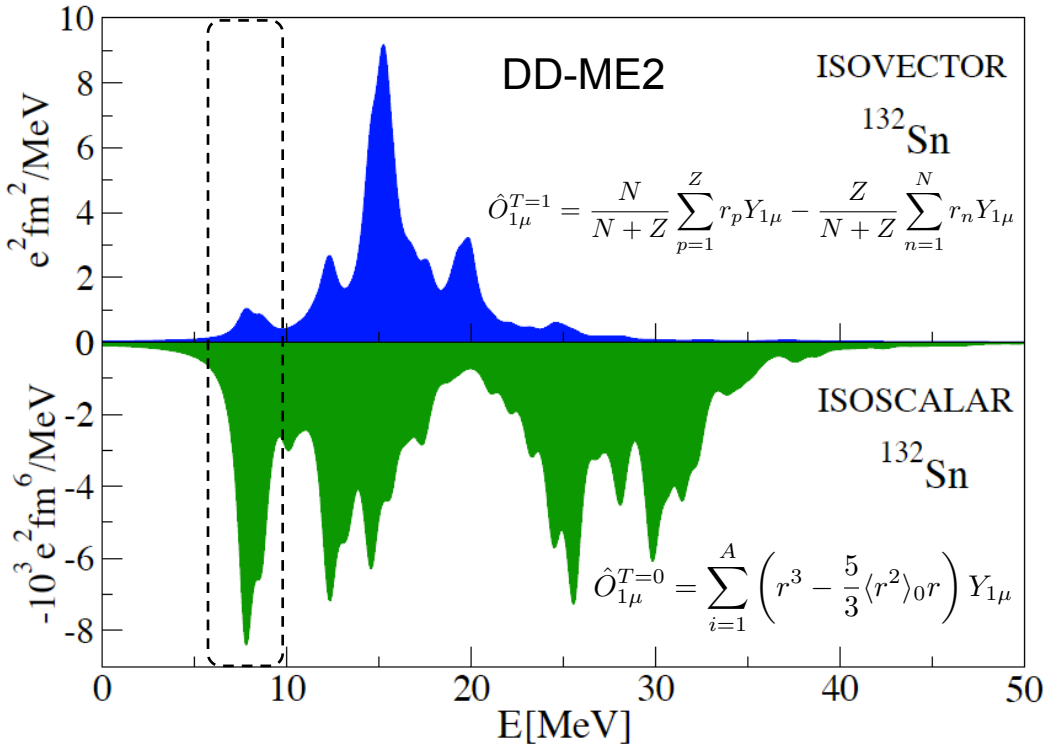
J. Piekarewicz, PRC 83, 034319 (2011)

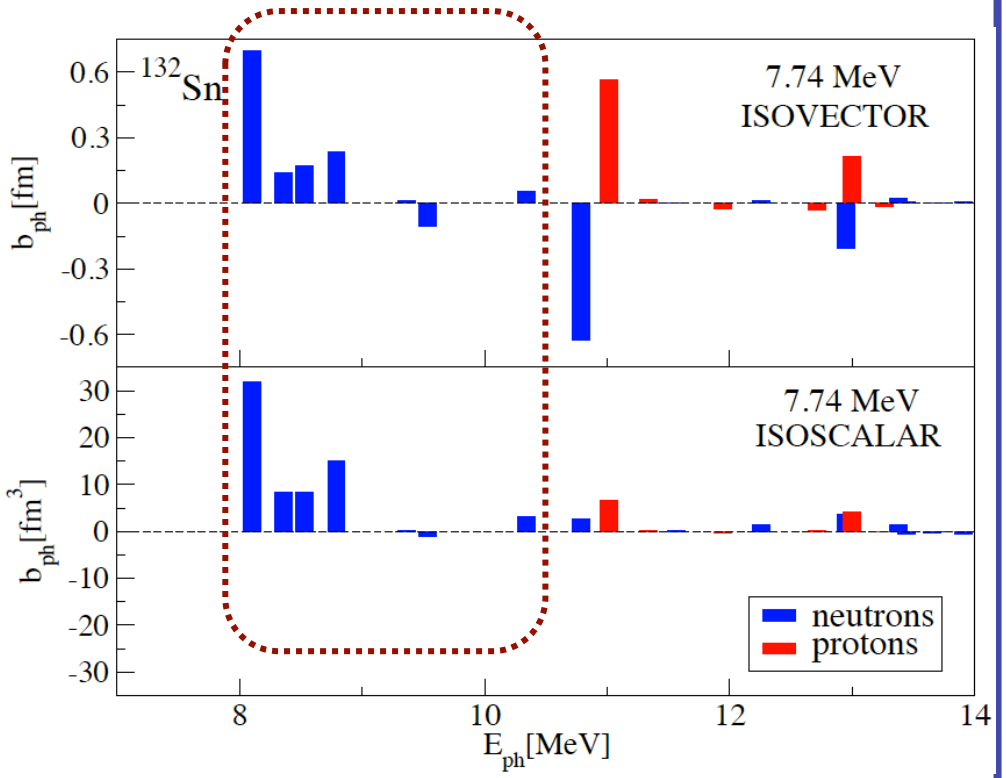
3) Covariance analysis with PC-min1, DDME-min1, SLy5 effective interactions indicates correlation between the PDR transition strength and symmetry energy at saturation density:



ISOVECTOR AND ISOSCALAR DIPOLE EXCITATIONS

What can we learn from comparison between the isovector and isoscalar dipole transition strength in neutron rich nuclei ?





Both in the isoscalar and isovector channel, pronounced low-energy dipole transition strengths are peaked at exactly the same energy. Their structure is dominated by identical neutron transitions with similar relative contributions in the transition strength (apart from the decoherence in the isovector channel).

THEORY FRAMEWORK

1. Relativistic point coupling model

$$
\begin{aligned}
\mathcal{L} &= \mathcal{L}^{\mathrm{free}} + \mathcal{L}^{\mathrm{4f}} + \mathcal{L}^{\mathrm{hot}} + \mathcal{L}^{\mathrm{der}} + \mathcal{L}^{\mathrm{em}}, \\
\mathcal{L}^{\mathrm{free}} &= \bar{\psi}(\mathrm{i}\gamma_\mu \partial^\mu - m)\psi, \\
\mathcal{L}^{\mathrm{4f}} &= -\tfrac{1}{2}\,\alpha_{\mathrm{S}}(\bar{\psi}\psi)(\bar{\psi}\psi) - \tfrac{1}{2}\,\alpha_{\mathrm{V}}(\bar{\psi}\gamma_\mu\psi)(\bar{\psi}\gamma^\mu\psi) \\
&\quad -\tfrac{1}{2}\,\alpha_{\mathrm{TS}}(\bar{\psi}\vec{\tau}\psi)\cdot(\bar{\psi}\vec{\tau}\psi) - \tfrac{1}{2}\,\alpha_{\mathrm{TV}}(\bar{\psi}\vec{\tau}\gamma_\mu\psi)\cdot(\bar{\psi}\vec{\tau}\gamma^\mu\psi), \\
\mathcal{L}^{\mathrm{hot}} &= -\tfrac{1}{3}\,\beta_{\mathrm{S}}(\bar{\psi}\psi)^3 - \tfrac{1}{4}\,\gamma_{\mathrm{S}}(\bar{\psi}\psi)^4 - \tfrac{1}{4}\,\gamma_{\mathrm{V}}[(\bar{\psi}\gamma_\mu\psi)(\bar{\psi}\gamma^\mu\psi)]^2, \\
\mathcal{L}^{\mathrm{der}} &= -\tfrac{1}{2}\,\delta_{\mathrm{S}}(\partial_\nu\bar{\psi}\psi)(\partial^\nu\bar{\psi}\psi) - \tfrac{1}{2}\,\delta_{\mathrm{V}}(\partial_\nu\bar{\psi}\gamma_\mu\psi)(\partial^\nu\bar{\psi}\gamma^\mu\psi) \\
&\quad -\tfrac{1}{2}\,\delta_{\mathrm{TS}}(\partial_\nu\bar{\psi}\vec{\tau}\psi)\cdot(\partial^\nu\bar{\psi}\vec{\tau}\psi) - \tfrac{1}{2}\,\delta_{\mathrm{TV}}(\partial_\nu\bar{\psi}\vec{\tau}\gamma_\mu\psi)\cdot(\partial^\nu\bar{\psi}\vec{\tau}\gamma^\mu\psi), \\
\mathcal{L}^{\mathrm{em}} &= -eA_\mu\bar{\psi}[(1-\tau_3)/2]\gamma^\mu\psi - \tfrac{1}{4}\,F_{\mu\nu}F^{\mu\nu}.
\end{aligned}
$$

T. Buervenich et al., PRC 65, 044308 (2002)

THEORY FRAMEWORK

2. Relativistic model with density-dependent meson-nucleon couplings

$$\mathcal{L} = \bar{\psi}\left(i\boldsymbol{\gamma}\cdot\boldsymbol{\partial} - m\right)\psi \;+\; \frac{1}{2}(\partial\sigma)^2 - \frac{1}{2}m_\sigma\sigma^2$$
$$-\;\frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega^2 \;-\; \frac{1}{4}\vec{\mathrm{R}}_{\mu\nu}\vec{\mathrm{R}}^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}^{\,2} \;-\; \frac{1}{4}\mathrm{F}_{\mu\nu}\mathrm{F}^{\mu\nu}$$
$$-\;g_\sigma\bar{\psi}\sigma\psi \;-\; g_\omega\bar{\psi}\gamma\cdot\omega\psi \;-\; g_\rho\bar{\psi}\gamma\cdot\vec{\rho}\vec{\tau}\psi \;-\; e\bar{\psi}\gamma\cdot A\frac{(1-\tau_3)}{2}\psi$$

The density dependence of the vertex functions

$$g_i(\rho) = g_i(\rho_{\mathrm{sat}})f_i(x) \quad \text{for} \quad i = \sigma,\omega$$

$$f_i(x) = a_i\frac{1 + b_i(x+d_i)^2}{1 + c_i(x+d_i)^2}$$

$$g_\rho(\rho) = g_\rho(\rho_{\mathrm{sat}})\,\exp\left[-a_\rho(x-1)\right]$$