Nuclear equation of state from nuclear collective excited state properties

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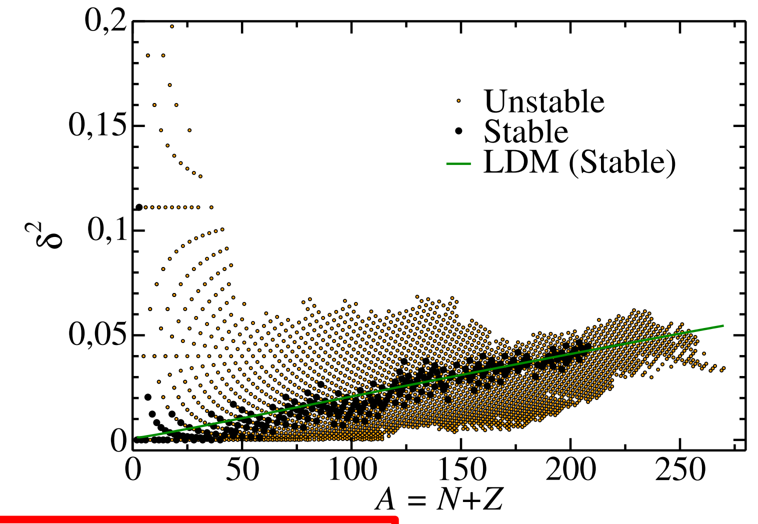
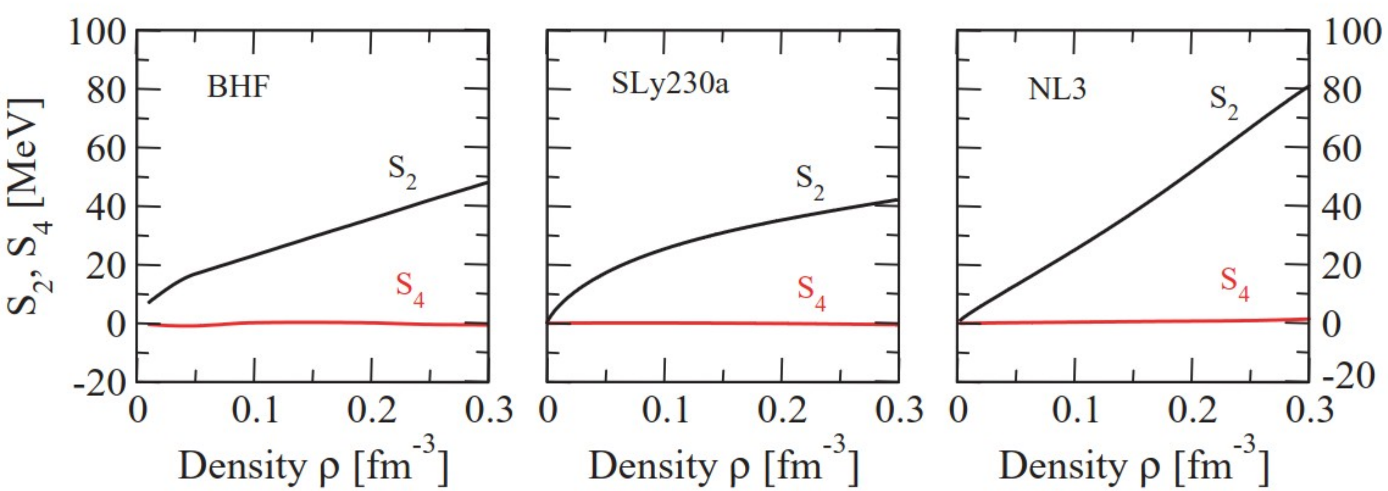
Nuclear Equation of State (EoS)

Energy per nucleon (***e***) as a **function** of the **total density** **$\rho=\rho_n+\rho_p$** and the **relative difference** **$\delta=(\rho_n-\rho_p)/\rho$** for **unpolarized uniform matter at T=0 assuming isospin symmetry** (even powers of δ). For **$\delta \to 0$**:



$$e(\rho,\delta) = e(\rho,0) + S_2(\rho)\delta^2 + S_4(\rho)\delta^4 + \mathcal{O}[\delta^6]$$

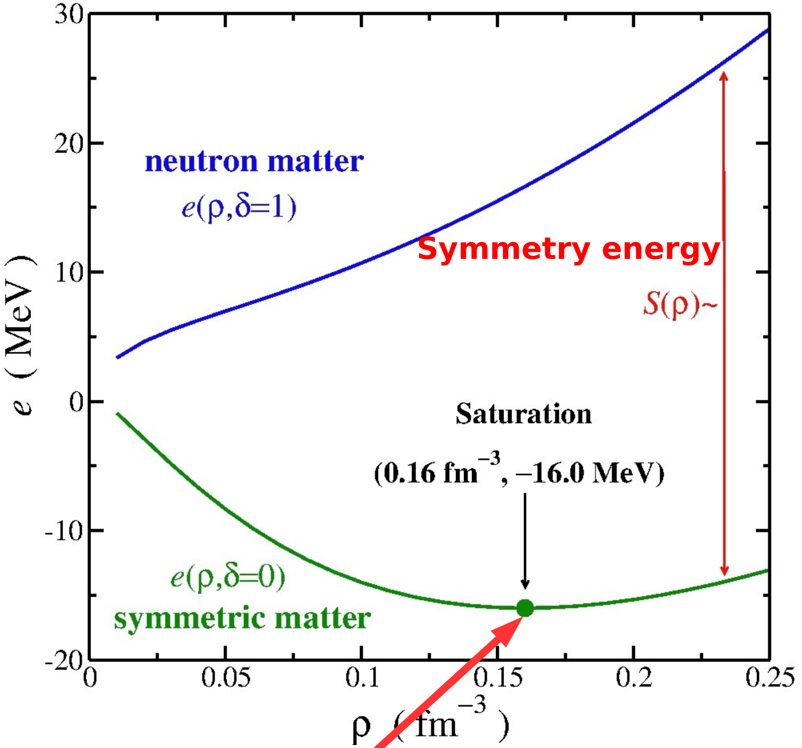


Isaac Vidaña, Constança Providência, Artur Polls, and Arnau Rios
Phys. Rev. C **80**, 045806 – Published 23 October 2009

Nuclear Equation of State (EoS)

Unpolarized, uniform nuclear matter at T=0 assuming isospin symmetry

$$e(\rho, \delta) = e(\rho, 0) + S_2(\rho)\delta^2$$



$$P(\rho = \rho_0, \delta = 0) = 0 \;\; \text{MeV fm}^{-3}$$

It is customary to also **expand** e(ρ,0) and S(ρ) around nuclear **saturation density** $\rho_0 \sim 0.16 \text{ fm}^{-3}$

$$e(\rho, 0) = e(\rho_0, 0) + \frac{1}{2}K_0 x^2 + \mathcal{O}[\rho^3] \text{ where } x = \frac{\rho - \rho_0}{3\rho_0}$$

$$S(\rho) = J + Lx + \frac{1}{2}K_{\text{sym}} x^2 + \mathcal{O}[\rho^3, \delta^4]$$

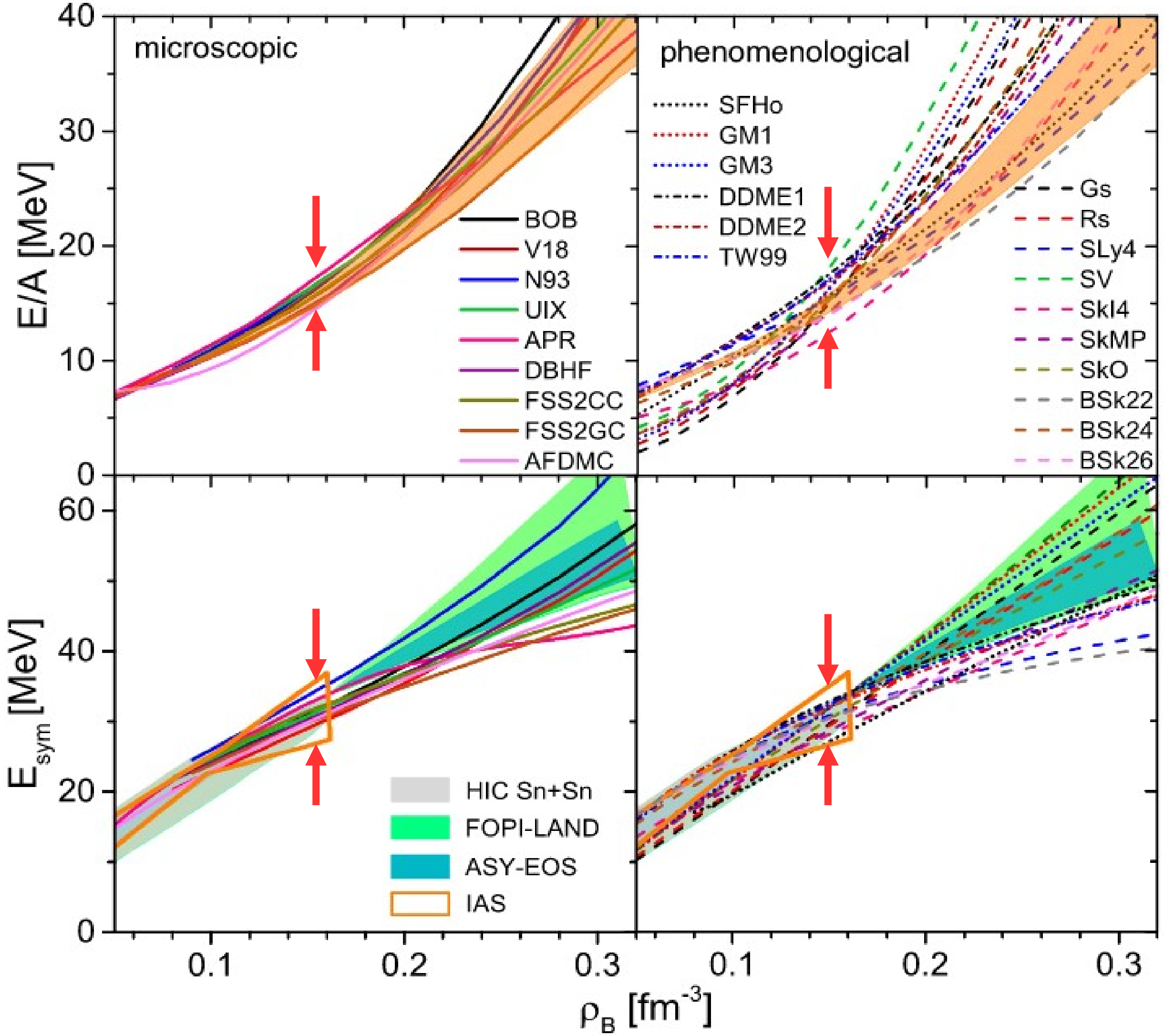
K_0 → how **compressible** is symmetric matter at ρ_0

J → **penalty energy** for converting all **protons into neutrons** in symmetric matter at ρ_0

L → **neutron pressure** in neutron matter at ρ_0

EoS from current nuclear models

Micorscopic and phenomenological models constrainted by different data display similar discrepances on the EoS



Many-body methods have been shown to agree

Main source of uncertainty in the nuclear Hamiltonian

Progress in Particle and Nuclear Physics 120 (2021) 103879

Light orange bands from χEFT from Drischler C., et al. Phys. Rev. Lett., 125 202702 (2020).

How one can connect finite nuclear properties with EoS properties:

Example: <u>Neutron skin thickness ($\Delta r_{np}=r_n-r_p$) is a good proxy to L</u>

B. Alex Brown Phys. Rev. Lett. 85, 5296 (2000)

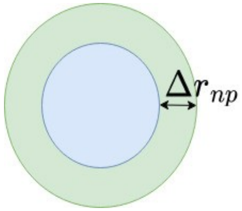
Δr_{np} in a **heavy** neutron rich **nucleus** is related to the **neutron pressure** (δ=1) around ρ_0 (***L***).

→ EoS:

$$P(\rho_0,\delta) = \rho_0^2 \frac{\partial e(\rho,\delta)}{\partial \rho}\bigg|_{\rho=\rho_0} = \frac{1}{3}\rho_0\delta^2 L$$

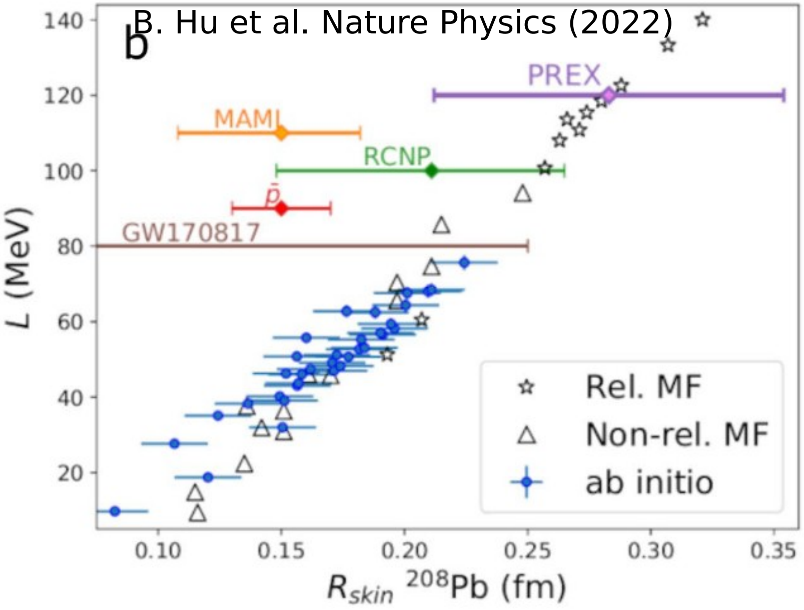
→ Macro Model:

$$\Delta r_{np} \approx \frac{1}{12}\frac{N-Z}{A}\frac{R}{J}L$$



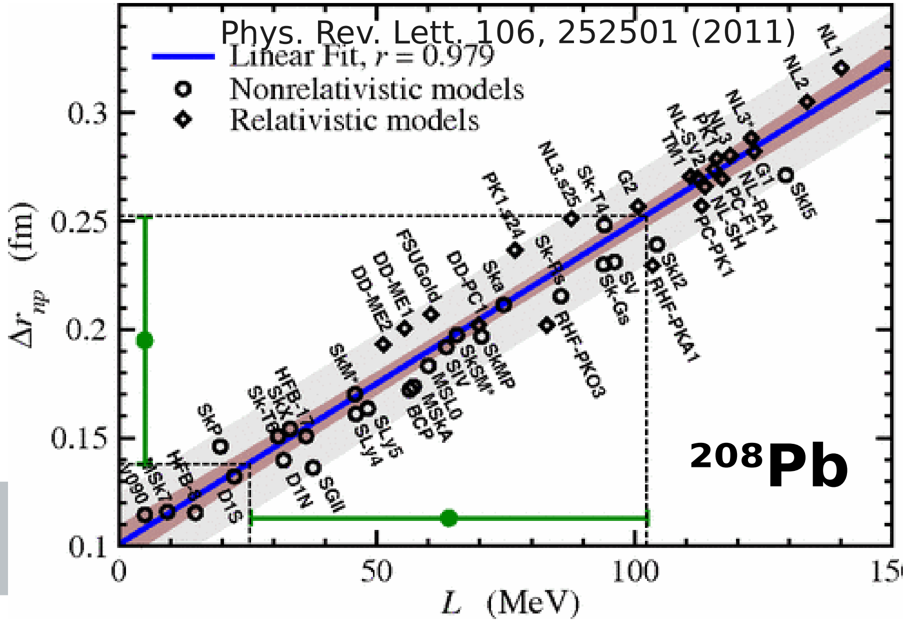
→ Micro & Pheno models:

B. Hu et al. Nature Physics (2022)



→ More Pheno models:

Phys. Rev. Lett. 106, 252501 (2011)



Which information can be obtained on the EoS from nuclear collective excitations?

(personal overview)

Giant Monopole Resonance
do we understand it?

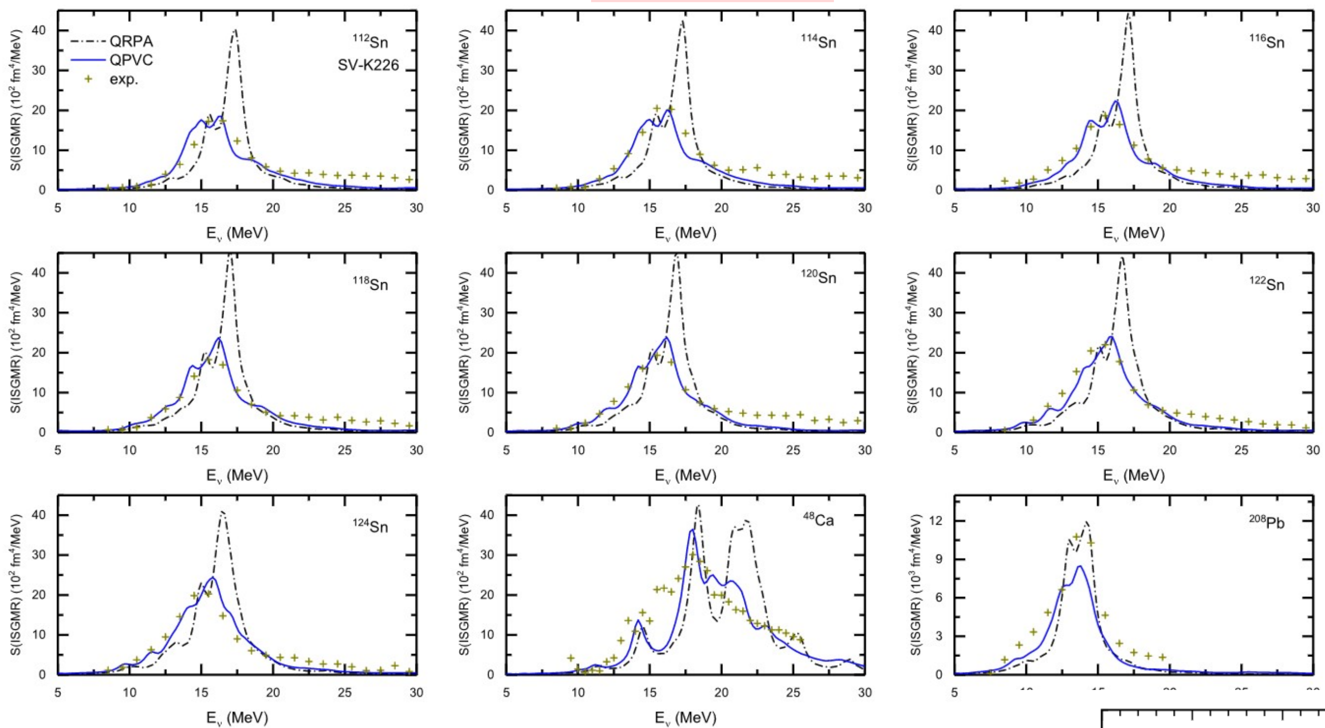
The compression-mode giant resonances and nuclear incompressibility
Umesh Garg [a], Gianluca Colò [b c]
Progress in Particle and Nuclear Physics
Volume 101, July 2018, Pages 55-95

arXiv:2211.01264 [pdf, ps, other] nucl-th

Towards a Unified Description of Isoscalar Giant Monopole Resonances in a Self-Consistent Quasiparticle-Vibration Coupling Approach

Authors: Z. Z. Li, Y. F. Niu, G. Colò

SV-K226



$K_\infty = 226$ MeV

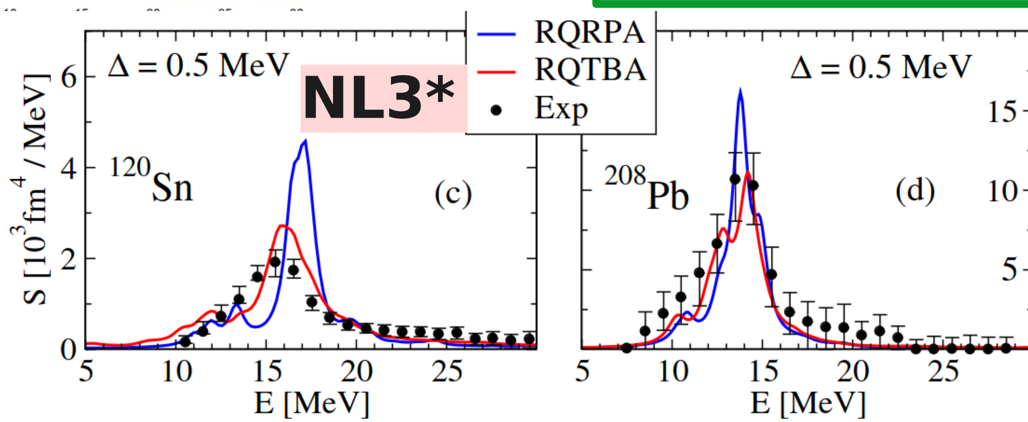
These calculations points towards a **plausible estimate** on K = 220-260 MeV. **Is that the final word?** Further experiments are planned.

Very **recently** two works explain **ISGMR** in different nuclei within the **PVC** approach

$$(E_x^{ISGMR})^2 \equiv K_A \frac{\hbar^2}{m\langle r^2\rangle}$$

$K_\infty = 258$ MeV

NL3*



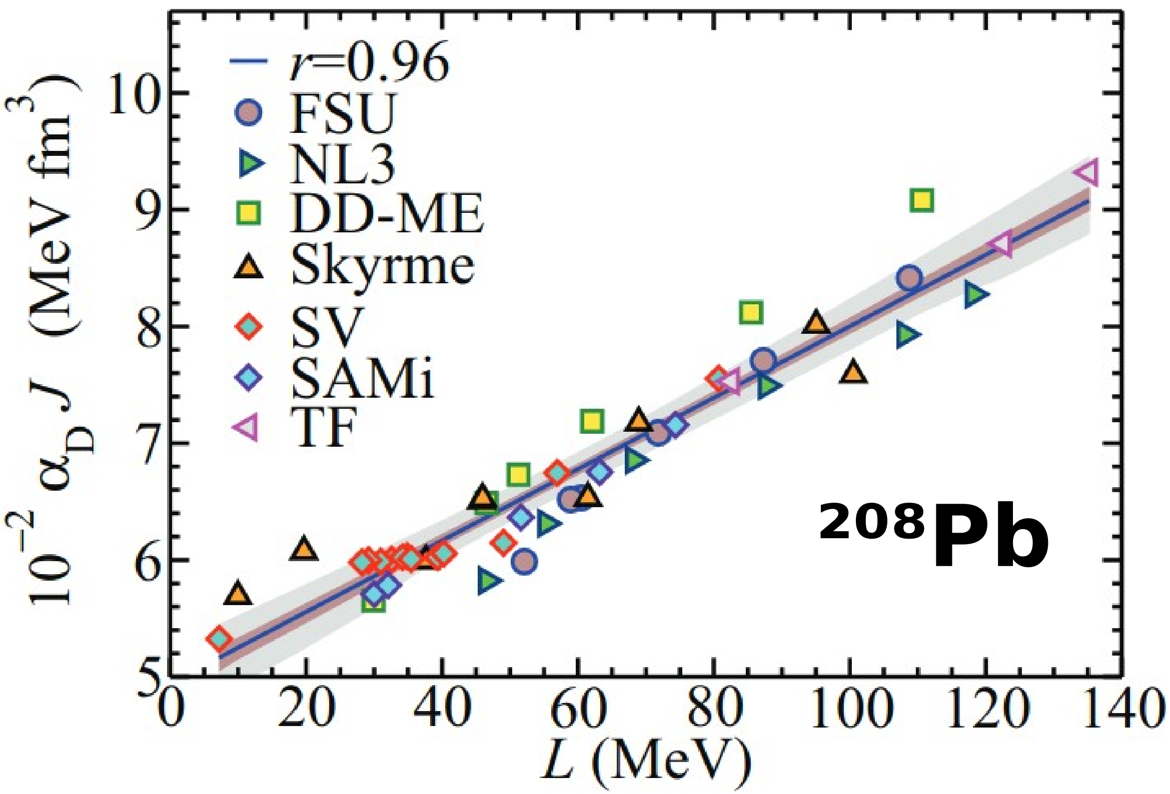
Relativistic approach to the nuclear breathing mode

Elena Litvinova
Phys. Rev. C **107**, L041302 – Published 5 April 2023

Dipole polarizability, J and L

$$\alpha_D = \frac{8\pi e^2}{9} m_{-1}(E1)$$

Dipole polarizability (α *J*) probes the **neutron skin thickness**



$$\alpha_D \approx \frac{\pi e^2}{54}\frac{\langle r^2\rangle}{J} A \left(1 + \frac{5}{2}\frac{\Delta r_{np} - \Delta r_{np}^{\rm surf} - \Delta r_{np}^{\rm Coul}}{\langle r^2\rangle^{1/2}(I - I_{\rm Coul})}\right)$$

$$J = 25.0(2) + 0.19(2)L \quad \text{for } ^{68}\text{Ni},$$
$$J = 25.4(1.1) + 0.17(1)L \quad \text{for } ^{120}\text{Sn},$$
$$J = 24.5(8) + 0.17(1)L \quad \text{for } ^{208}\text{Pb}.$$

$$S(\langle\rho\rangle \approx 0.08 \text{ fm}^{-3}) \approx 25 \text{ MeV}$$

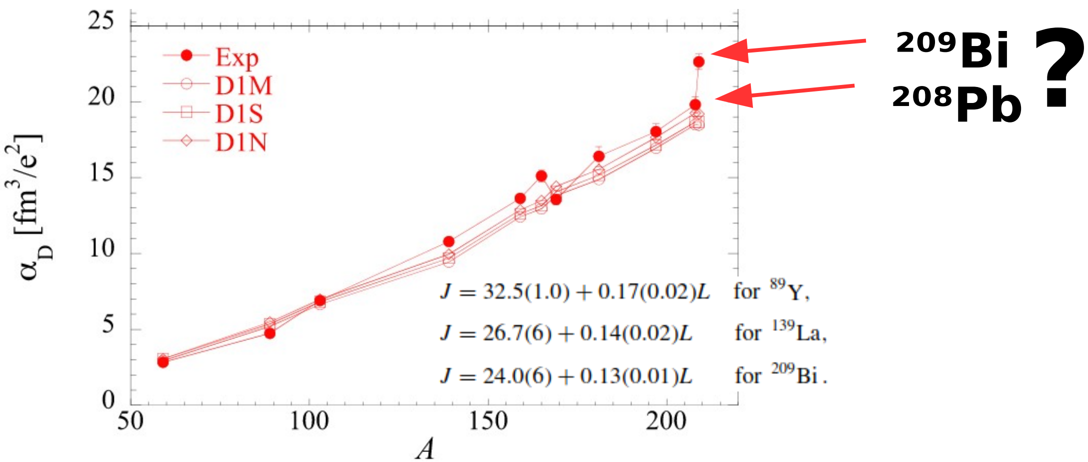
Determination of the J vs L relation from experimental data according to Energy Density Functionals (EDFs)

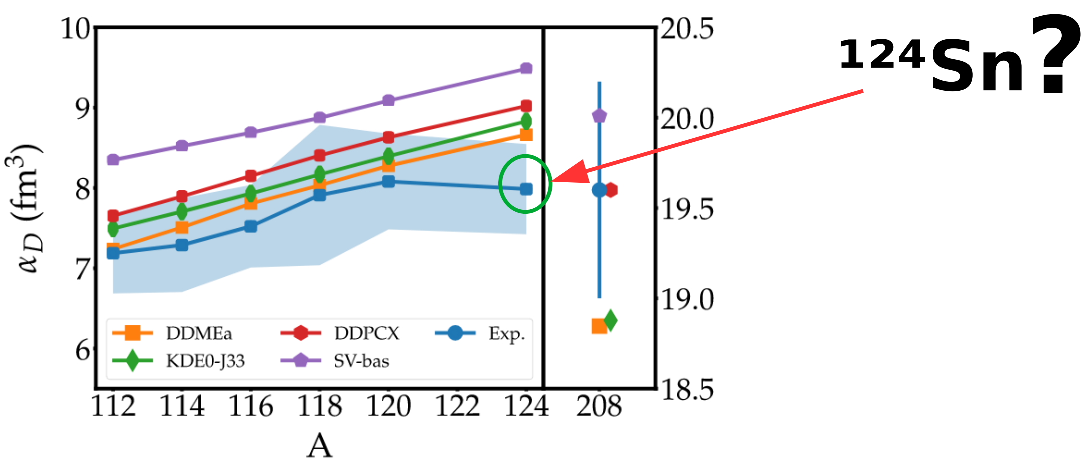
X. Roca-Maza, M. Brenna, G. Colò, M. Centelles, X. Viñas, B. K. Agrawal, N. Paar, D. Vretenar, and J. Piekarewicz
Phys. Rev. C **88**, 024316 – Published 20 August 2013

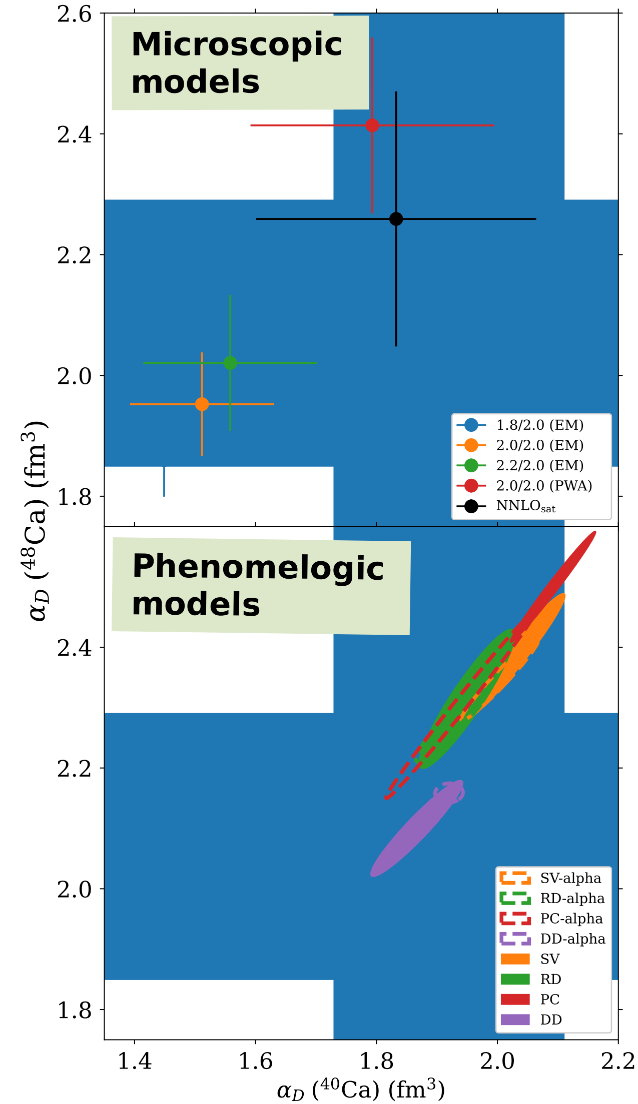
X. Roca-Maza, X. Viñas, M. Centelles, B. K. Agrawal, G. Colò, N. Paar, J. Piekarewicz, and D. Vretenar
Phys. Rev. C **92**, 064304 – Published 8 December 2015

Dipole polarizability:
do we understand it?

S. Goriely, S. Péru, G. Colò, X. Roca-Maza, I. Gheorghe, D. Filipescu, and H. Utsunomiya
Phys. Rev. C **102**, 064309 – Published 9 December 2020



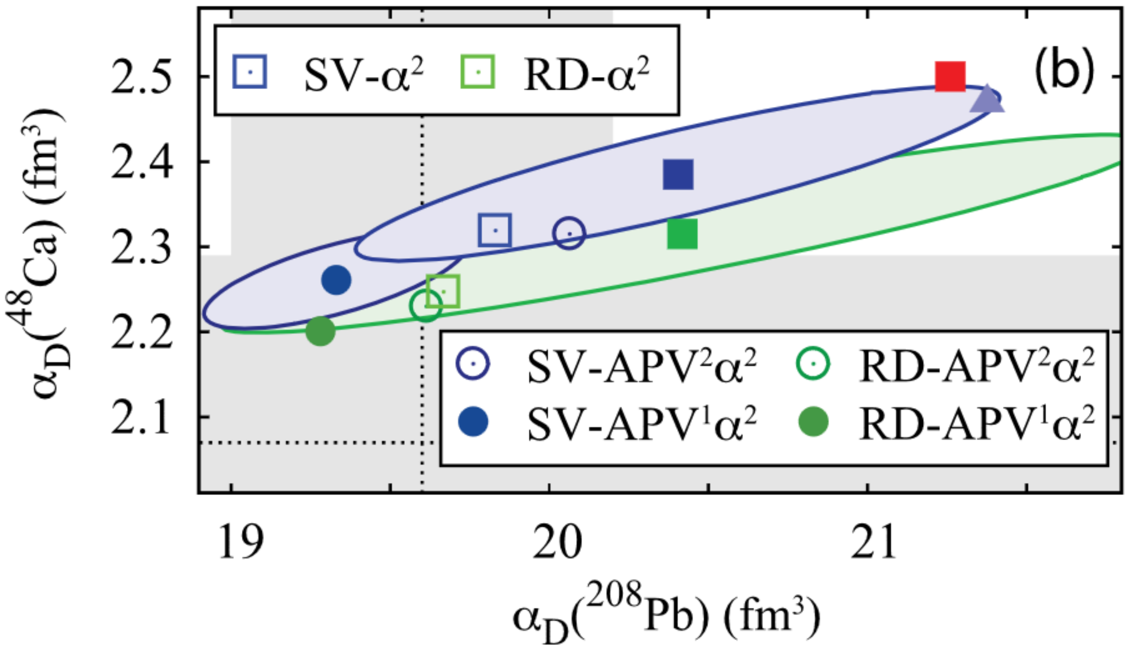




S. Bassauer, P. von Neumann-Cosel, P.-G. Reinhard et al.
Physics Letters B 810 (2020) 135804

Electric dipole polarizability of ^{40}Ca
R. W. Fearick, P. von Neumann-Cosel, S. Bacca, J. Birkhan, F. Bonaiti, I. Brandherm, G. Hagen, H. Matsubara, W. Nazarewicz, N. Pietralla, V. Yu. Ponomarev, P. -G. Reinhard, X. Roca-Maza, A. Richter, A. Schwenk, J. Simonis, and A. Tamii
Phys. Rev. Research **5**, L022044 – Published 31 May 2023

A_{PV} (sensitive to Δr_{np}) vs α_D (sensitive to J and Δr_{np}) in ^{48}Ca and ^{208}Pb

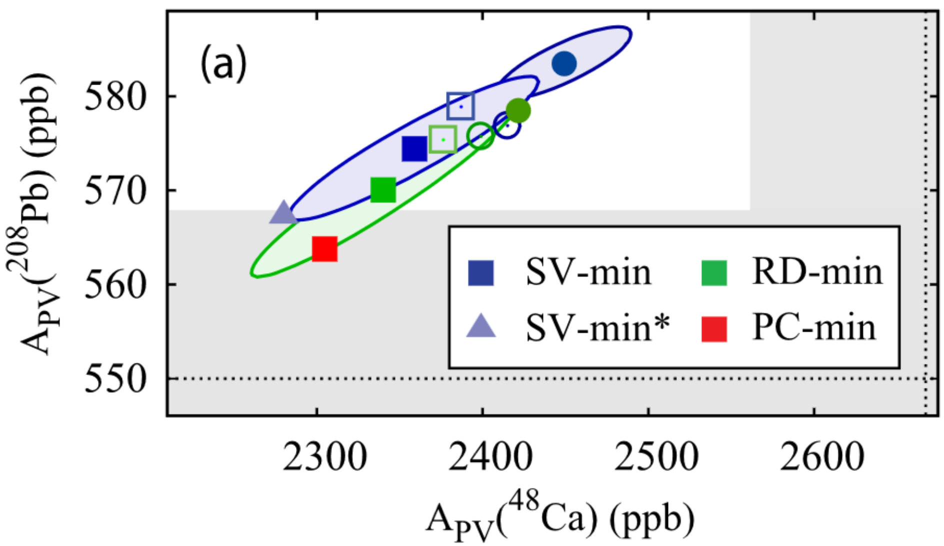


Simultaneous description of **dipole polarizabilities** → point to a **good understanding** of **symmetry energy** and **neutron skins**

Ab-initio (B. Hu) Nature Physics (2022)

$\alpha_D(^{48}\text{Ca})$ $2.30^{+0.31}_{-0.26}$

$\alpha_D(^{208}\text{Pb})$ $22.6^{+2.1}_{-1.8}$



No simultaneous description of **parity violating asymmetries** (ground state observable) → point to a **deficient understanding** of **neutron skins**

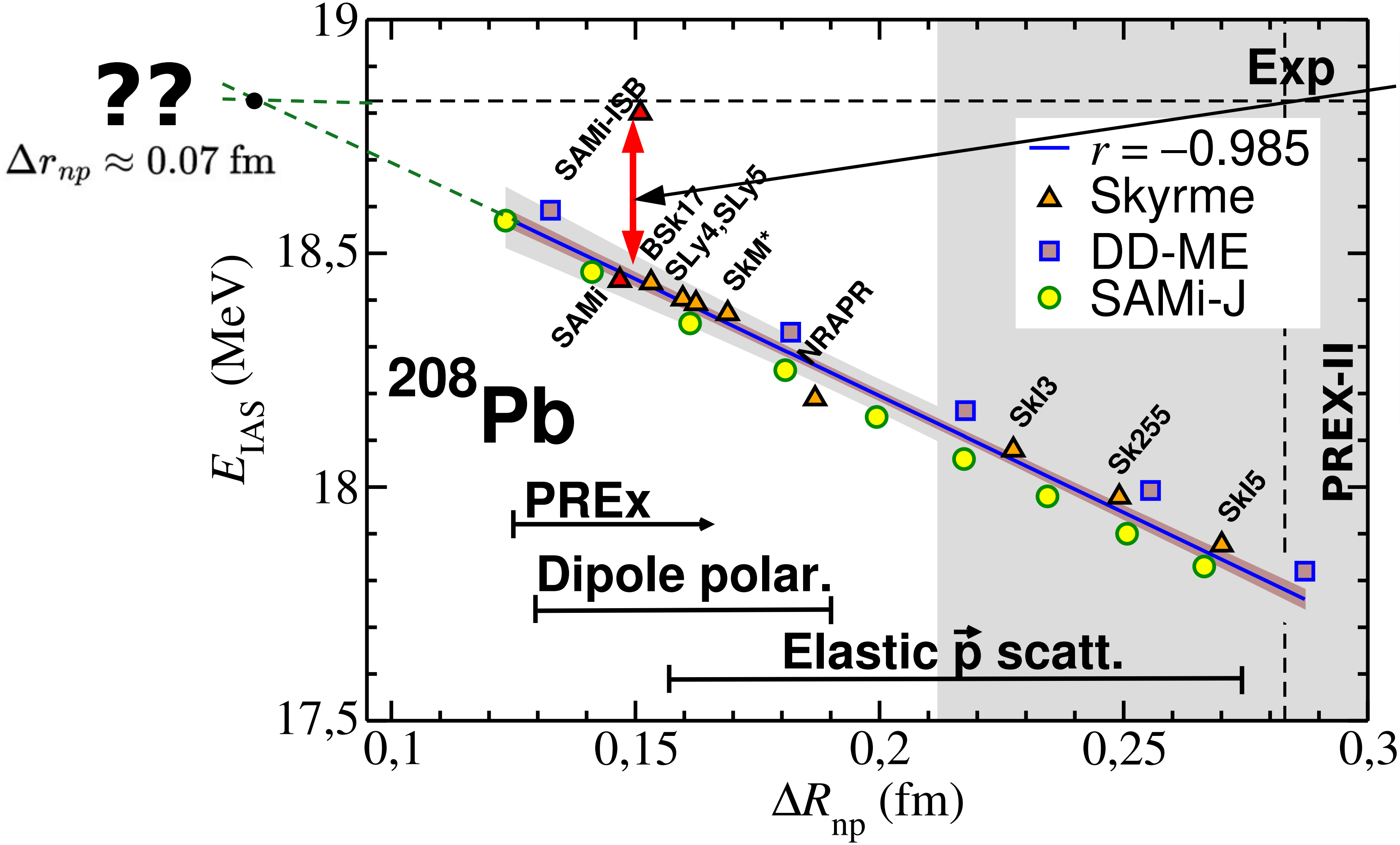
Paul-Gerhard Reinhard, Xavier Roca-Maza, and Witold Nazarewicz, PRL 127 232501 (2021) and PRL 129 232501 (2022)

Magenta dashed lines from Δr_{np} in G. Hagen et al. Nature Physics 12, 186–190 (2016) and H. Bu et al. Nature Physics (2022)

Isobaric Analog State, ISB and Δr_{np}

$$E_{\mathrm{IAS}} = \frac{\langle 0|T_+[\mathcal{H},T_-]|0\rangle}{\langle 0|T_+T_-|0\rangle} \approx \frac{6}{5}\frac{Ze^2}{r_0A^{1/3}}\left(1-\sqrt{\frac{5}{12}}\frac{N}{N-Z}\frac{\Delta R_{\mathrm{np}}}{r_0A^{1/3}}\right)$$

$$F = T_\pm = \sum_i^A t_\pm(i)$$



Isospin symmetry breaking (ISB) missing effects:

1) **Nuclear strong int.**
2) **Coulomb corrections**

The larger the Δr_{np}, the larger the ISB contributions to IAS in ^{208}Pb

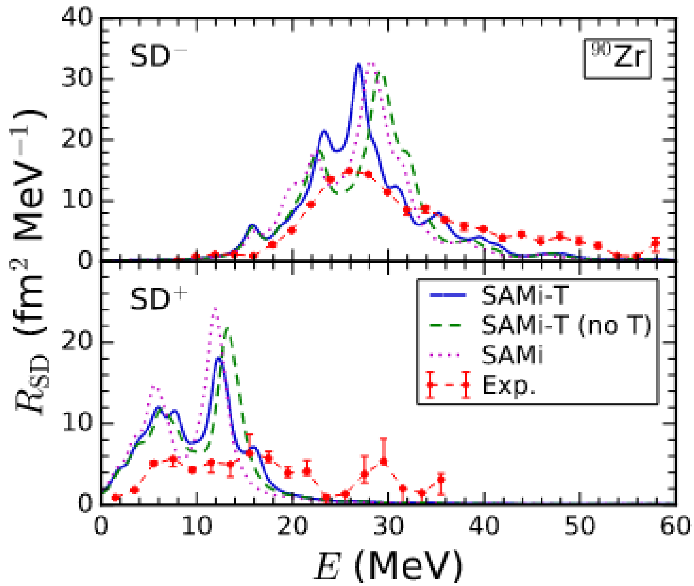
X. Roca-Maza, G. Colò, and H. Sagawa
Phys. Rev. Lett. **120**, 202501 – Published 18 May 2018

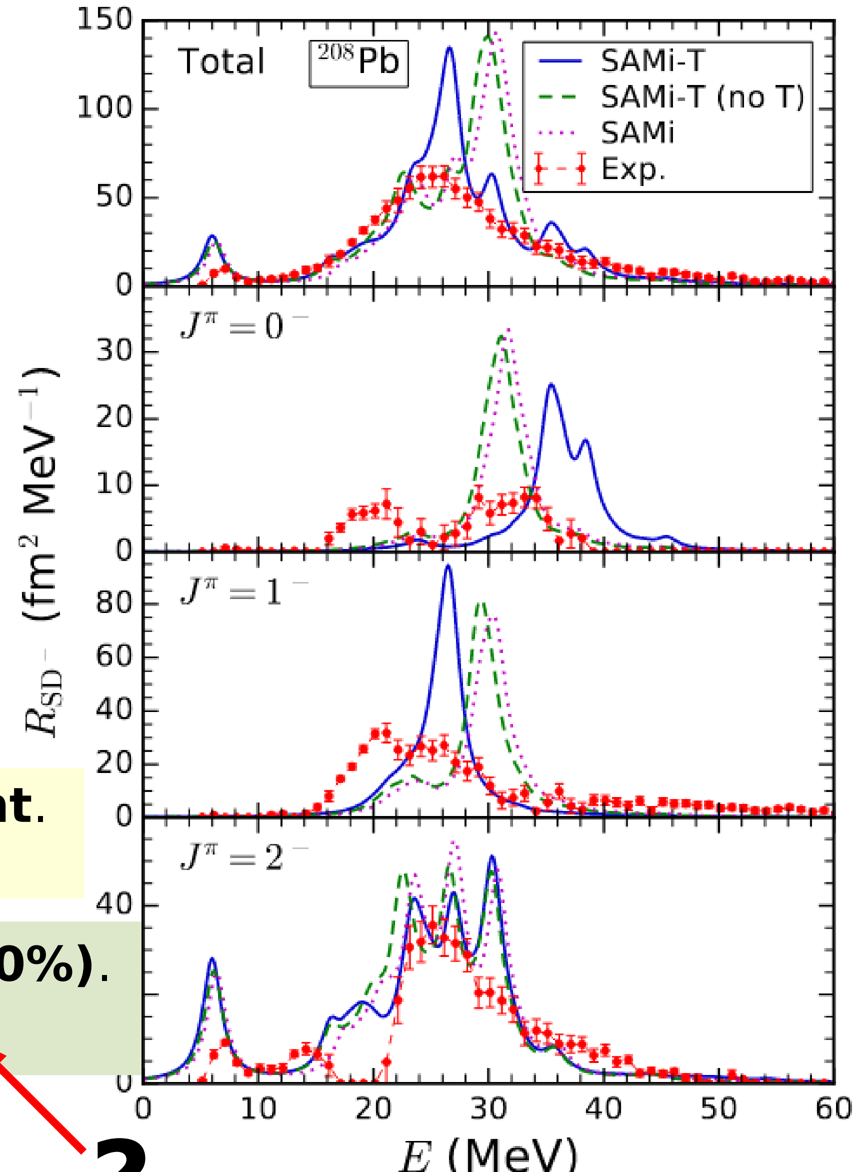
Spin Dipole Resonance and Δr_{np}

Difficult to measure and analyze?

$$\sum_{i=1}^{A} \sum_{M} \tau_{\pm}(i) r_i^L \left[Y_L(\hat{r}_i) \otimes \boldsymbol{\sigma}(i) \right]_{JM}$$

$$m_0(t_-) - m_0(t_+) = \frac{9}{4\pi}\left(N\langle r_n^2\rangle - Z\langle r_p^2\rangle\right)$$





→ ⁹⁰Zr **exp and theo sum rules in agreement**.
From exp. sum rule: $\Delta r_{np} = 0.07 \pm 0.04$ fm

→ ²⁰⁸Pb **exp sum rule < theo sum rule (~20%)**.
From exp. sum rule: $\Delta r_{np} = 0.07 \pm 0.03$ fm

?

Shihang Shen (申时行), Gianluca Colò, and Xavier Roca-Maza
Phys. Rev. C **99**, 034322 – Published 20 March 2019

Conclusions

Different ways to investigate properties of the symmetry energy and/or the Δr_{np} provide different answers:

→ current nuclear models likely miss relevant physics

→ interest in repeating and/or improving the analysis of some key experiments (or propose new ones)

Summary

with qualitative indication of accuracy needed to describe experiment (<u>note that absolute values might be subject to systematics</u>)

- → $\rho_0 \in$ **[0.154,0.159]** fm^{-3} → variation range **2%**
  - → needed to describe experiment (R_{ch}) **≤0.1%**
- → $e_0 \in$ **[15.6,16.2]** MeV→ variation range **4%**
  - → needed to describe experiment (B) **≤0.0001%**
- → $K_0 \in$ **[220,260]** MeV→ variation range **15%**
  - → needed to describe experiment (E_x^{GMR}) **≤7%**
- → $J \in$ **[30,35]** MeV → variation range **15%**
  - → needed to describe experiment (α) **≤15%**
- → $L \in$ **[20,120]** MeV → variation range **150%**
  - → needed to describe experiment (α) **≤50%**
- → ...

Nuclear equation of state from ground and collective excited state properties of nuclei

X. Roca-Maza [a], N. Paar [b]

Progress in Particle and Nuclear Physics

Volume 101, July 2018, Pages 96-176

Collaborators

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→ Nils **Paar** & Dario **Vretenar** (University of Zagreb)

→ Bijay K. **Agrawal** (Saha Institute of Nuclear Physics)

→ P.-G. **Reinhard** (University of Erlangen-Nürnberg)

→ Yifei **Niu** (Lanzhou University)

→ Witold **Nazarewicz** (FRIB and Michigan State University)

→ Stephane **Goriely** (Université Libre de Bruxelles)

→ Sophie **Péru** (Université Paris-Saclay, CEA)