不安定核の集団運動から探る状態体方程式のパラメーターL

新学術領域研究会
「実験と観測で解き明かす中性子星の核物質」
第3回研究会

熱川ハイツ・伊豆熱川
2014年9月23-25日

INAKURA Tsunenori (Chiba Univ.)

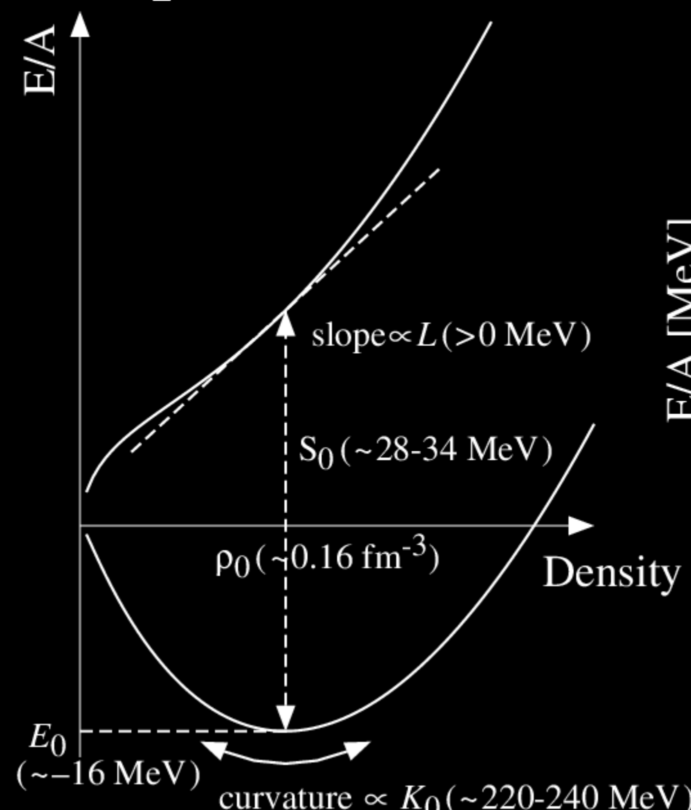
Equation of State (EoS)

$$\frac{E}{A}(\rho,\delta) = \frac{E}{A}(\rho,\delta{=}0) + E_{\mathrm{sym}}(\rho)\delta^2 + O(\delta^4)$$

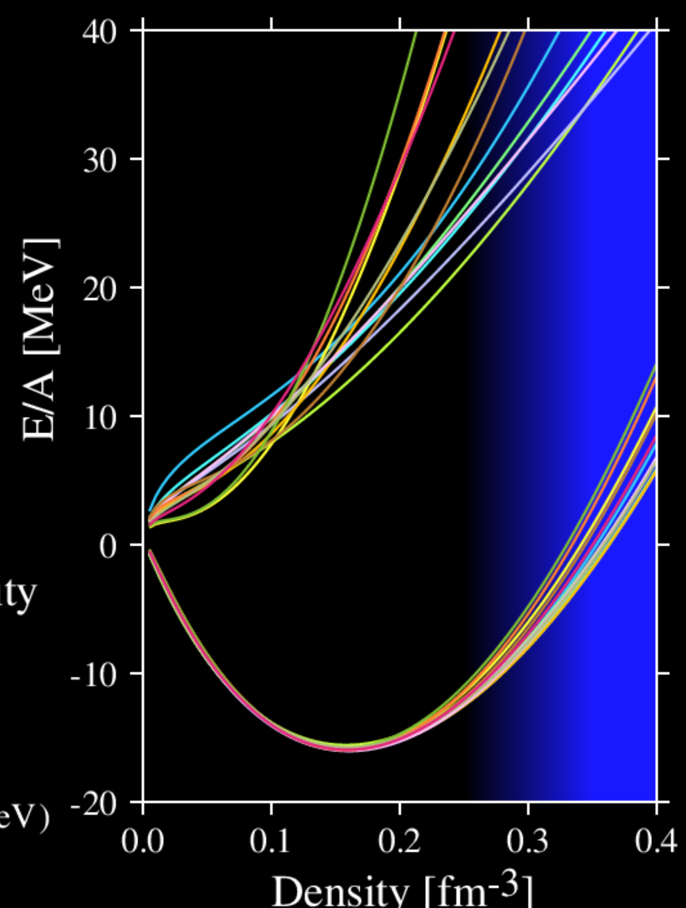
$$\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}\ ,\ x = \frac{\rho - \rho_0}{3\rho_0}$$

$$\frac{E}{A}(\rho,\delta{=}0) = \frac{E}{A}(\rho_0) + \frac{K_\infty}{2}x^2 + \cdots$$

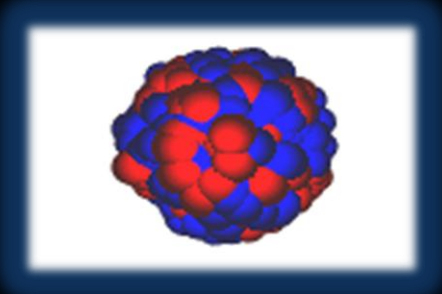
$$E_{\mathrm{sym}}(\rho) = S_0 + Lx + \frac{K_{\mathrm{sym}}}{2}x^2 + \cdots$$



EoS calculated with
Skyrme interactions



Giant Dipole Resonance (GDR)



- Symmetry energy E_{sym} is the restoring force.
- Many experimental data has been accumulated.

Unclear relation between experimental data and L, E_{sym}

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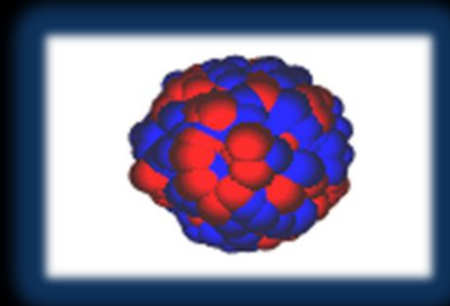

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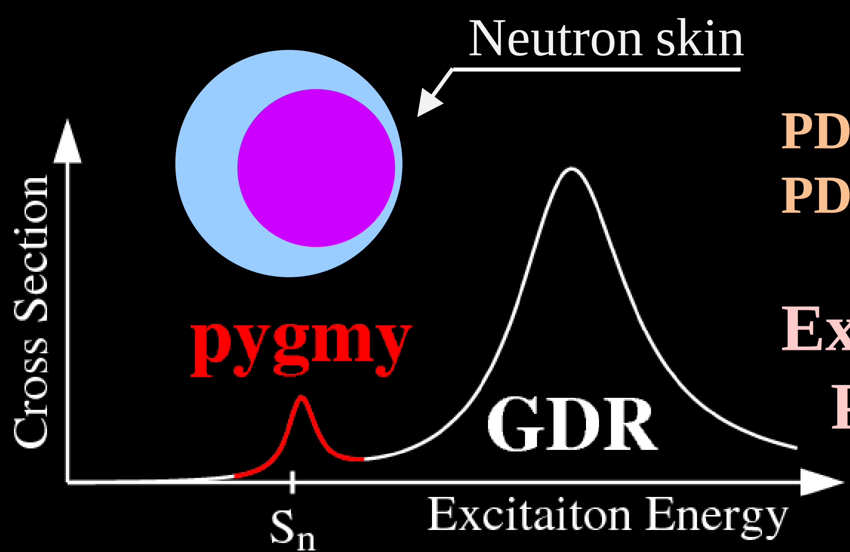
Pygmy Dipole Resonance (PDR)

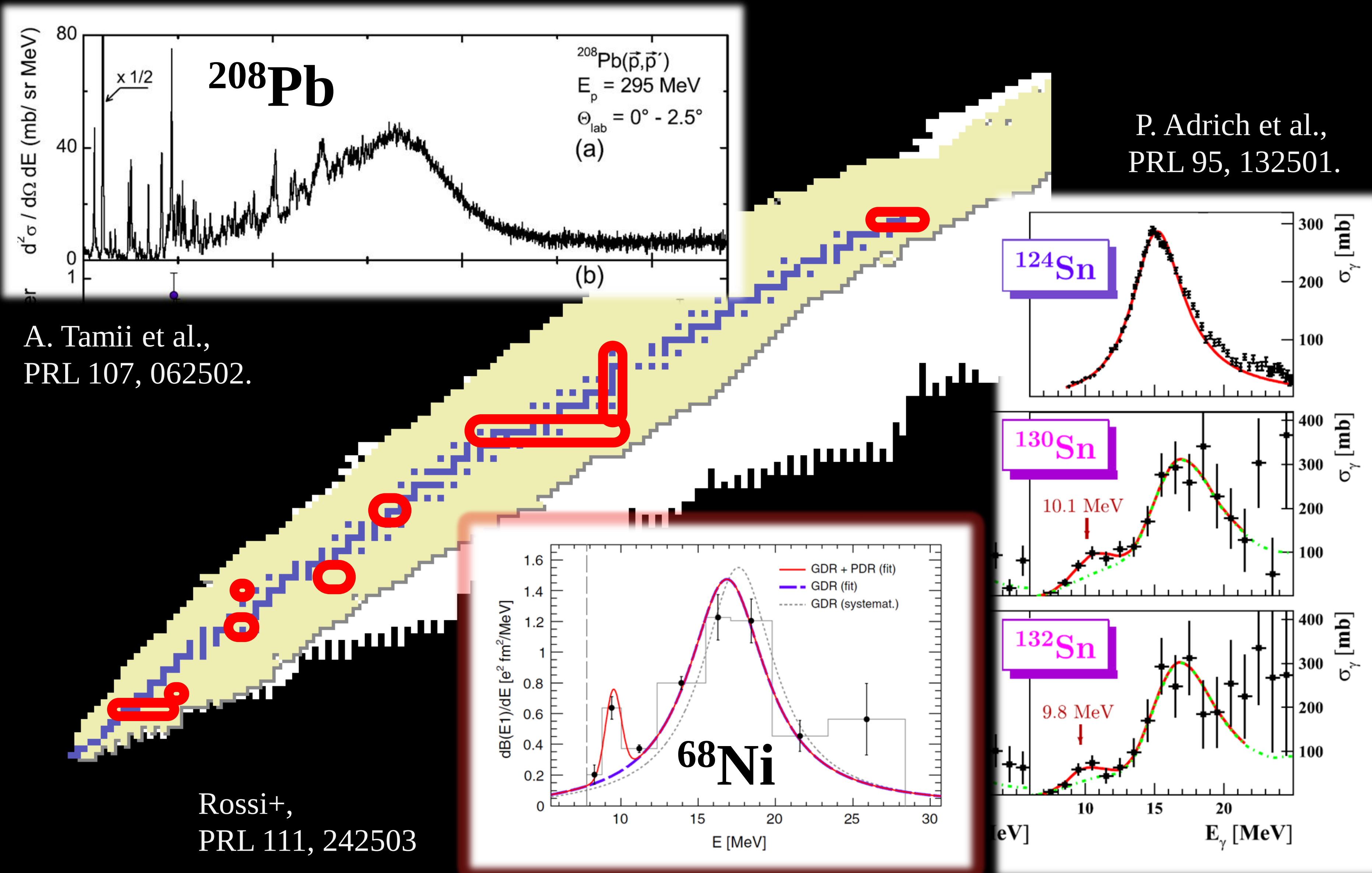
= Pygmy Dipole Strength (PDS)
= Low-lying Dipole Strength (LDS)
= Low-Energy Dipole (LED)



PDR in stable nuclei: < 1% Cross Section
PDR in ν-rich nuclei: < several % Cross Section

Extract EoS information from PDR and neutron-skin properties!

Observed PDRs



P. Adrich et al.,
PRL 95, 132501.

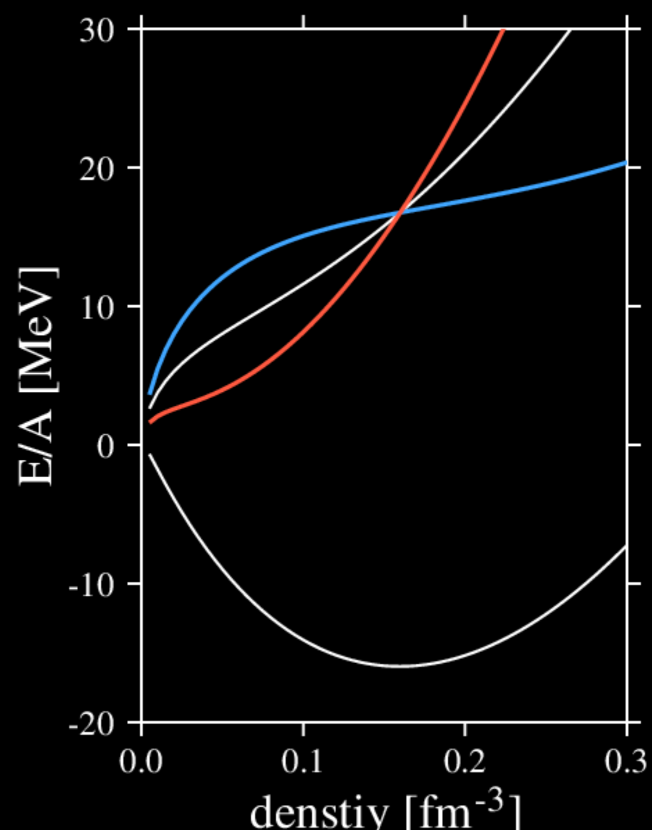
A. Tamii et al.,
PRL 107, 062502.

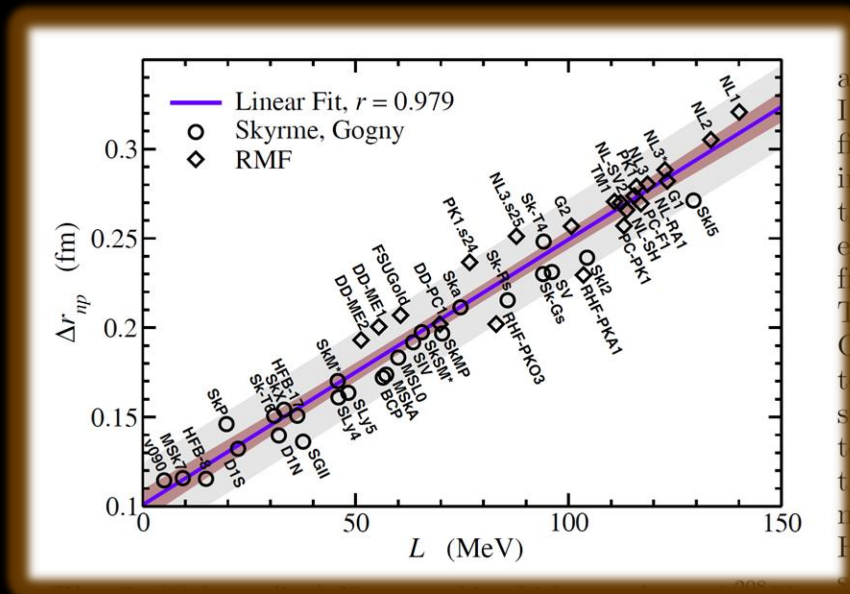
Rossi+,
PRL 111, 242503

L & skin

Large L ⇔ Small E_{sym} in low-ρ ⇔ Thick n-skin ⇔ Large PDR

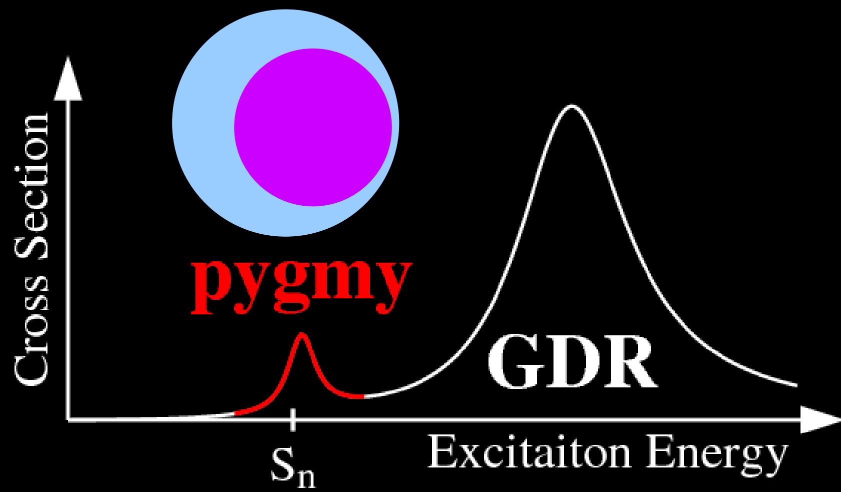
Small L ⇔ Large E_{sym} in low-ρ ⇔ Thin n-skin ⇔ Small PDR

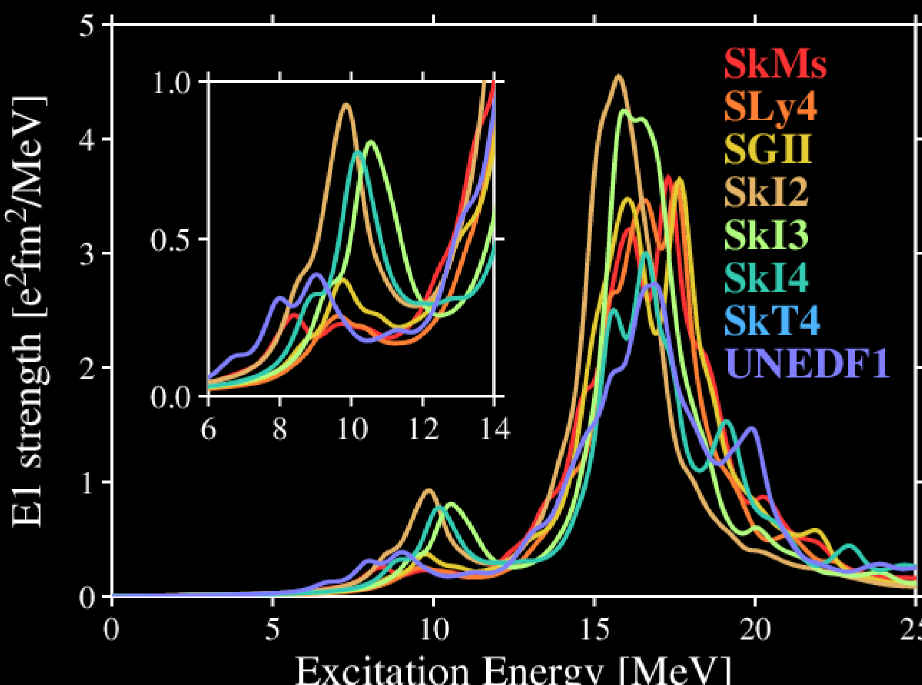




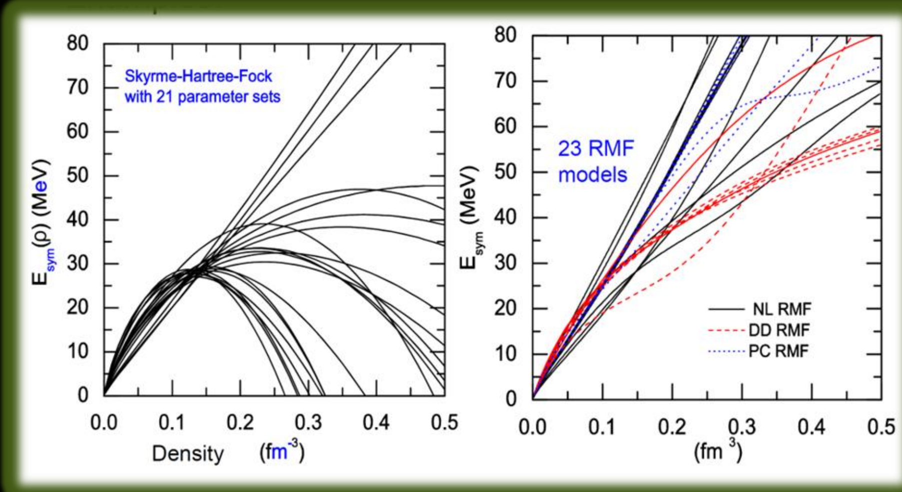
Roca-Maza+, PRL 106, 252501

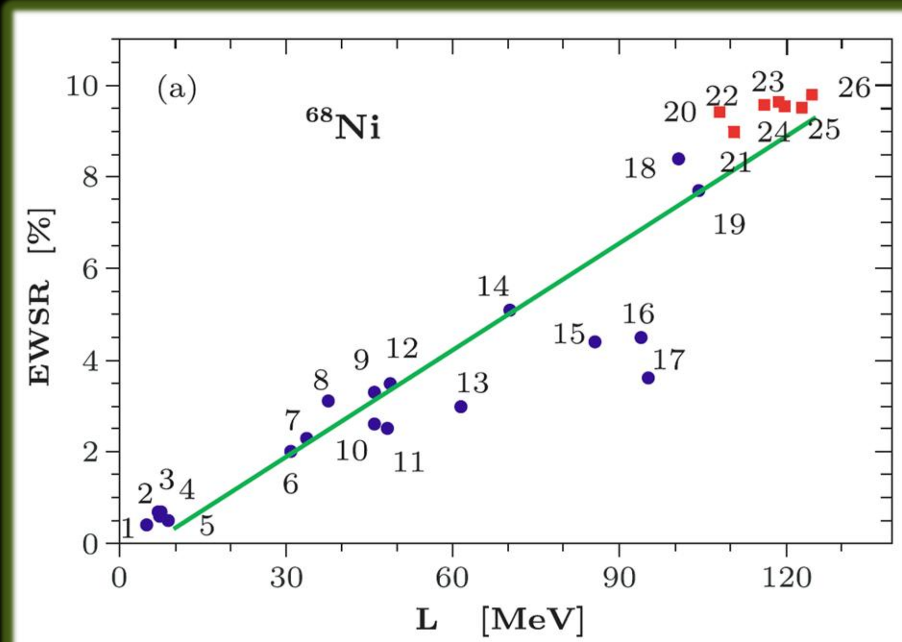
L from PDR





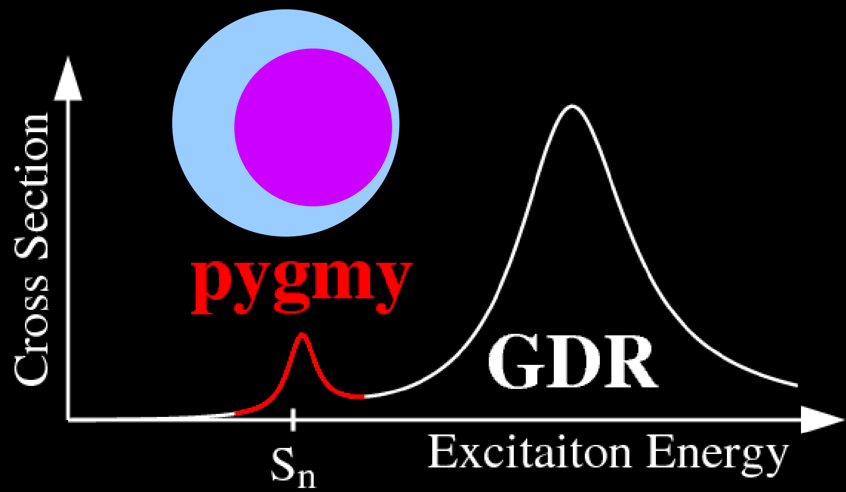
Chen+, PRC72, 064309; PRC76, 054316

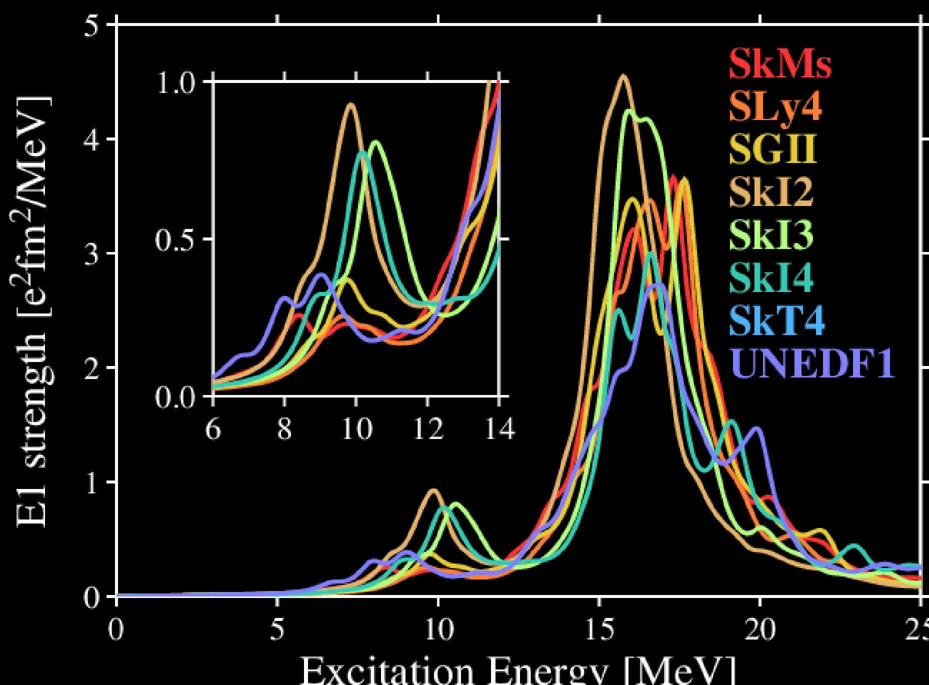




Carbone+, PRC81, 041301® (2010)

L from PDR





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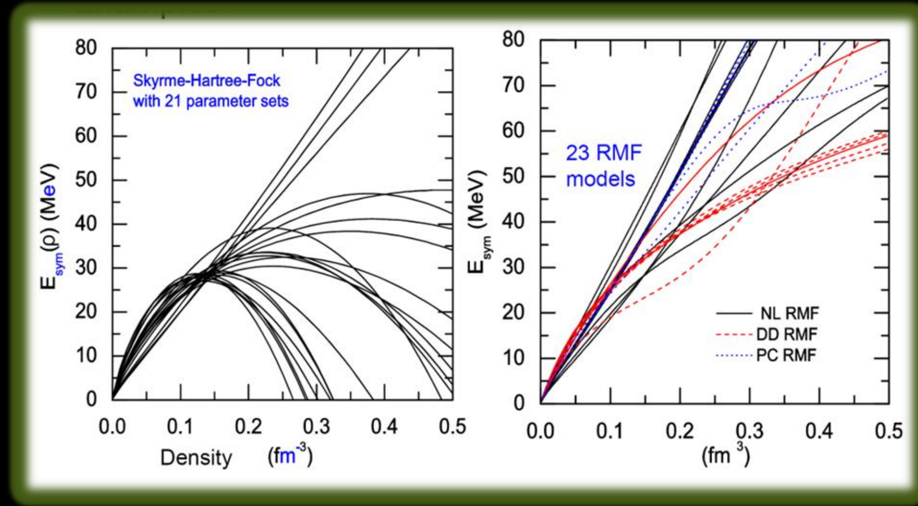
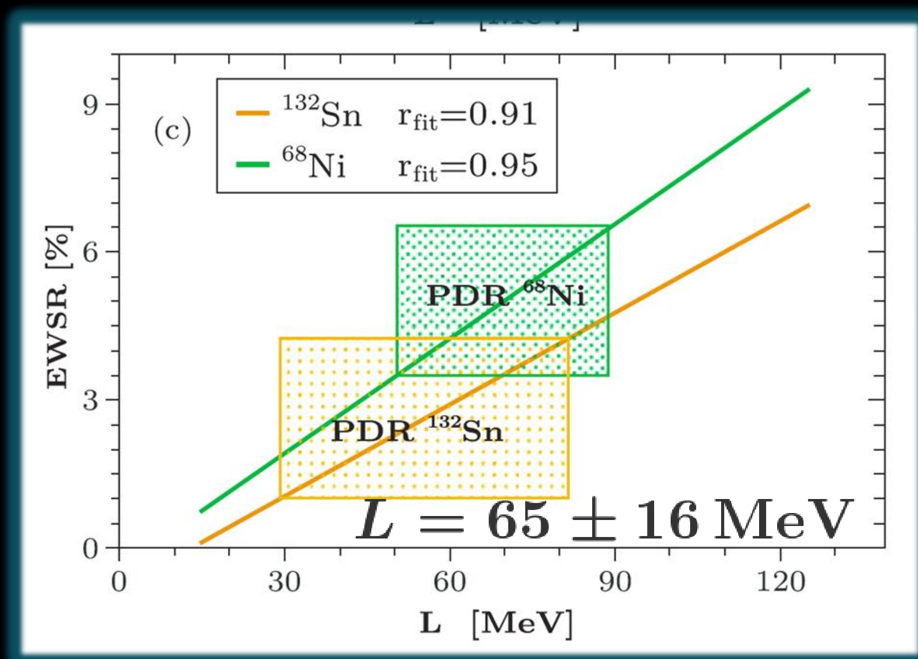




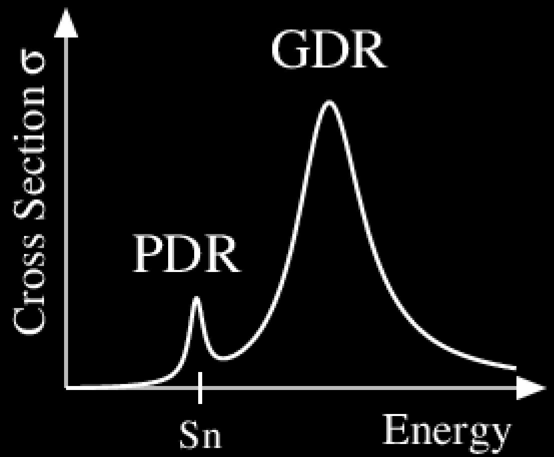
Carbone+, PRC81, 041301® (2010)

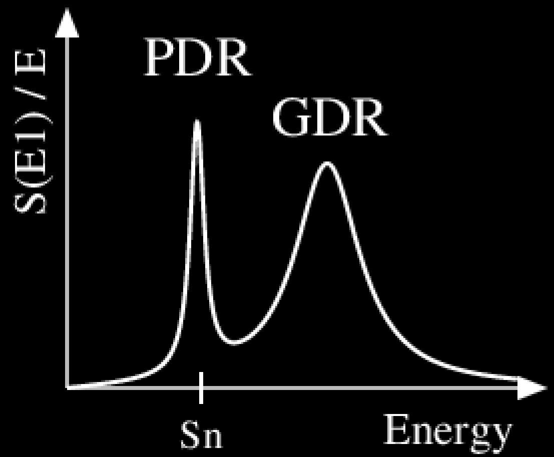
Cross section(σ_{abs}) & Polarizability(α_D)

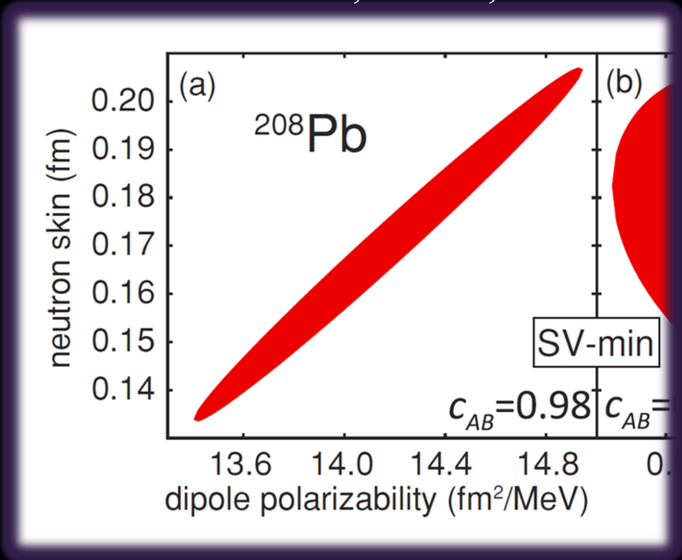
$$\sigma_{\mathrm{abs}} = \frac{16\pi^3 e^2}{9\hbar c} m_1 \propto m_1 = \int \mathrm{d}E\, S(E1) E$$

$$\alpha_D = \frac{8\pi e^2}{9} m_{-1} \propto m_{-1} = \int \mathrm{d}E\, \frac{S(E1)}{E}$$

Covariance Analysis
Reinhard+, PRC81, 051303





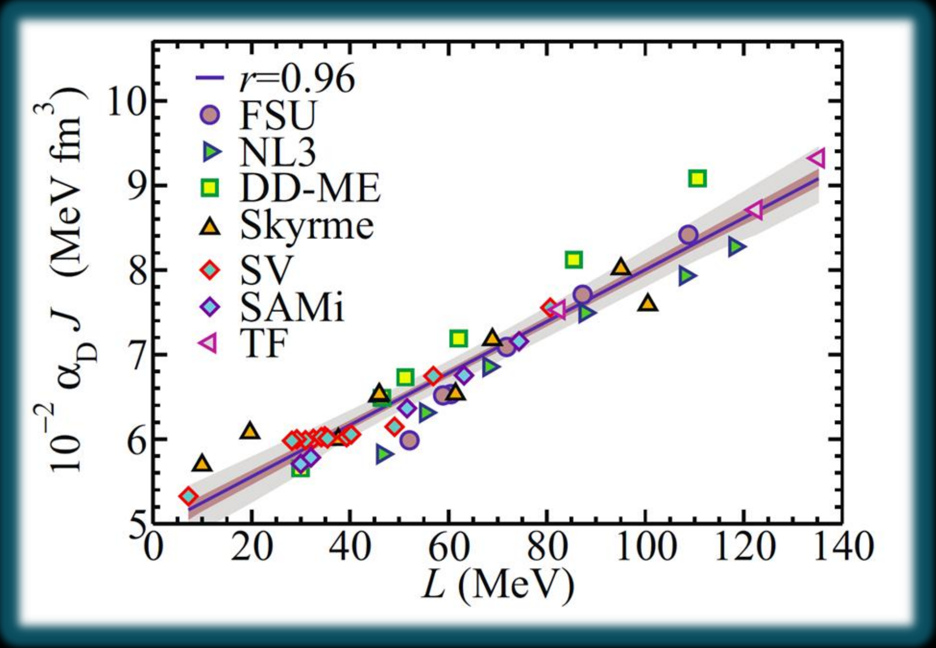


Thick n-skin ⇔ Large restoring force ⇔ Large eccentricity ⇔ Large α_D
Thin n-skin ⇔ Small restoring force ⇔ Small eccentricity ⇔ Small α_D

New correlation

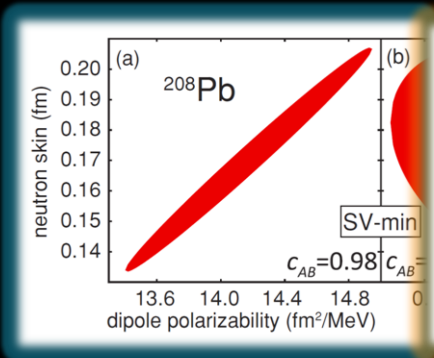
Based on Droplet Model (with some approximations & assumptions),

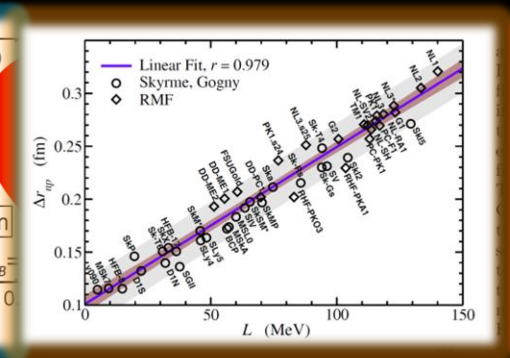
$$\alpha_D S_0 \sim \frac{\pi e^2}{54} A \langle r^2 \rangle \left(1 + \frac{5}{3} \frac{L}{S_0} \varepsilon_A \right), \ \varepsilon_{208} \sim \frac{1}{8}$$

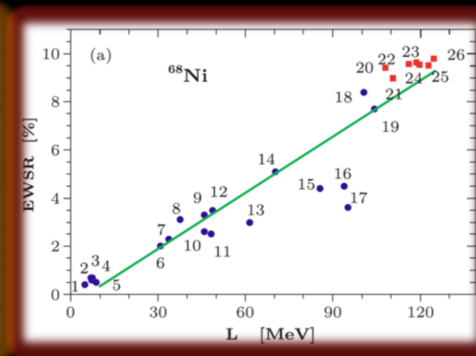


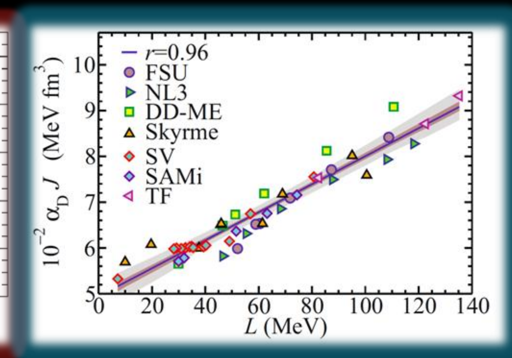
Roca-Maza+, PRC88, 024316 (2013)

L is a key ingredient of EoS









Which is best?
Interaction-dependence?

L (EOS)

↙↗ ↖↘

PDR ⟷ n-skin

Established?

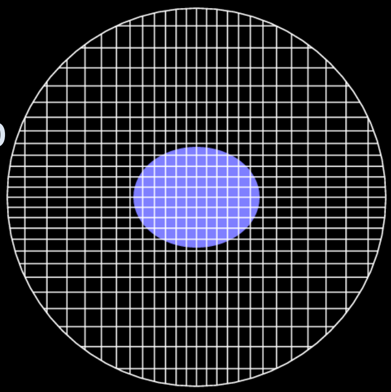
Analysis has been performed **ONLY** in **flagship nuclei: ^{68}Ni, ^{132}Sn, ^{208}Pb.**

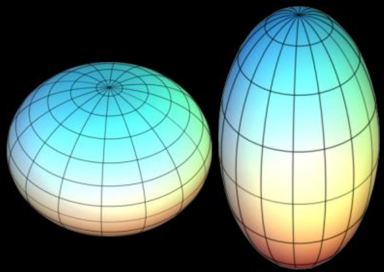
How about other nuclei?

Careful assessment needed!

Linear response calculation with Skyrme in 3D mesh

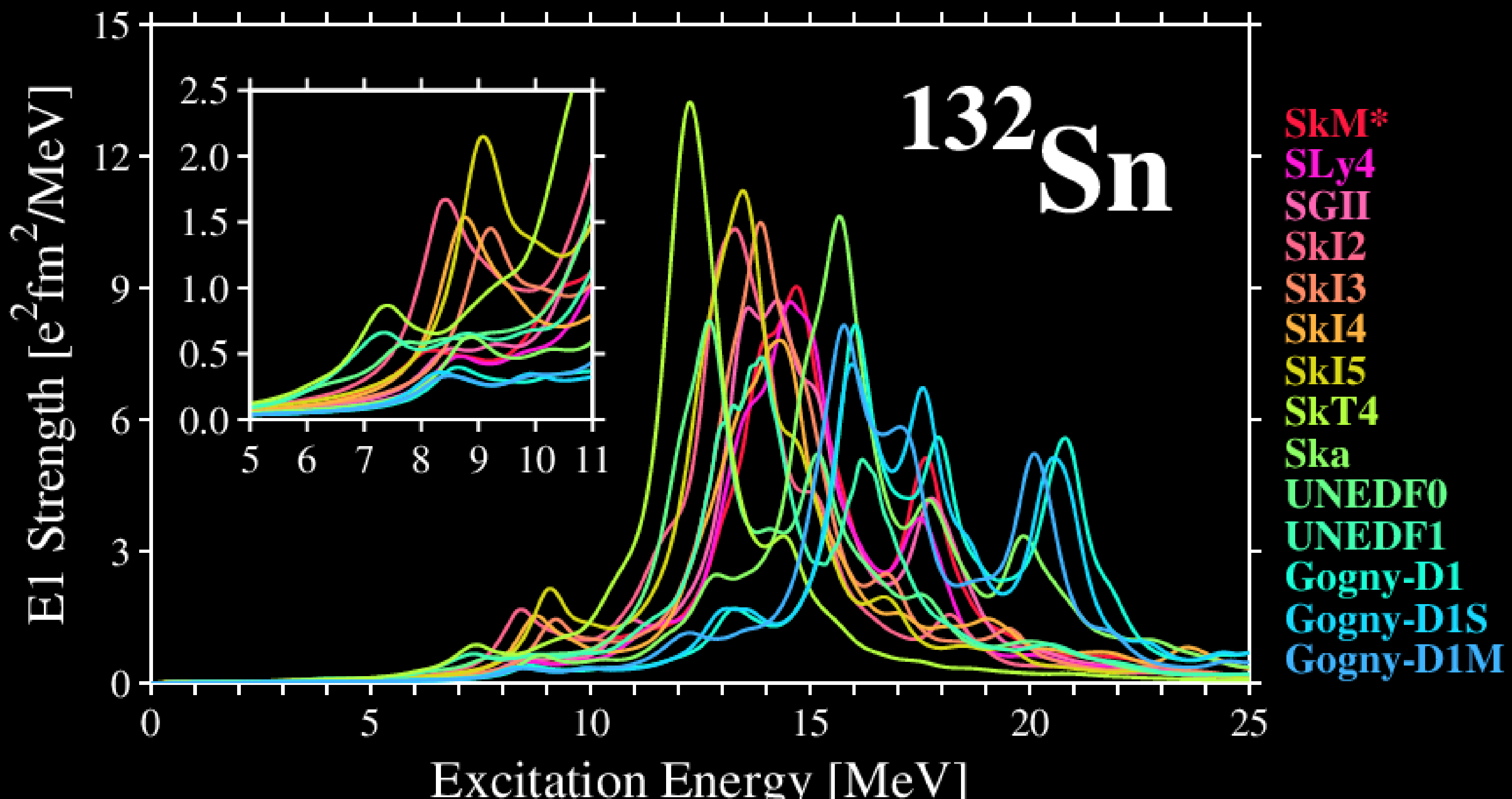
- Density Functional Theory with Skyrme energy functional
- Fully self-consistent calculation. **PARAMETER FREE!**
- 3D mesh representation
  - suitable for describing unstable nuclei having skin or halo
  - applicable for deformed nuclei
  - deal with continuum states in good approximation
- Linear response calculation
  - compute linear response at fixed complex energy
  - good compatibility with paralleled computer
- **No pairing correlation** which has small impact on E1 mode.





14 interactions

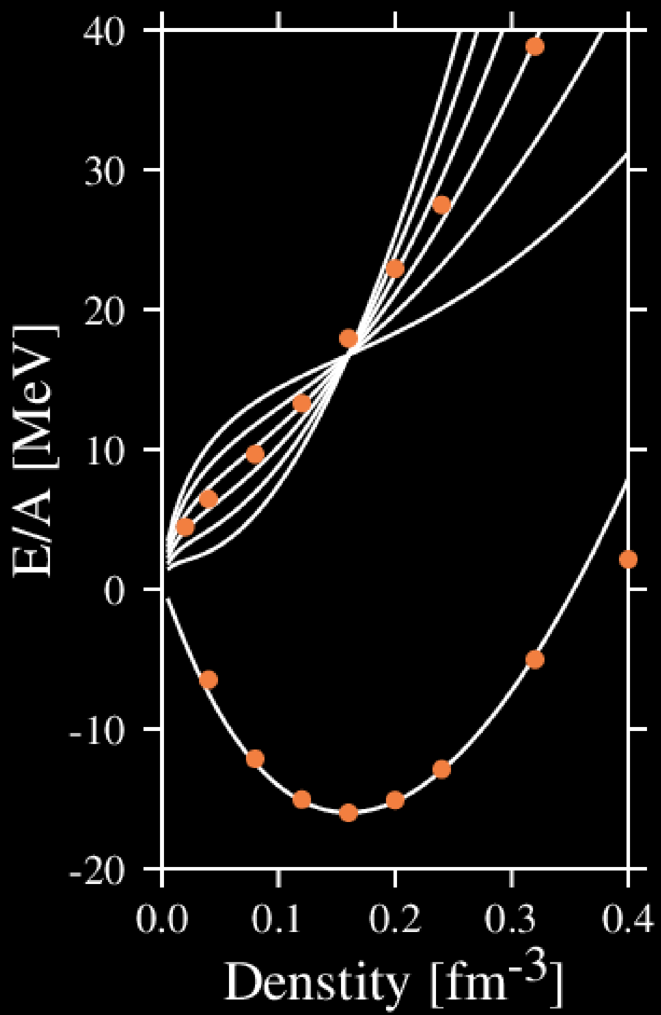
- 3 Skyrme which are widely used: SkM*, SLy4, SGII
- 2 Skyrme which are less used: SkT4, Ska
- 2 Skyrme which are recently made: UNEDF0, UNEDF1
- 4 Skyrme to cover wide region of L: SkI2, SkI3, SkI4, SkI5
- 3 Gogny to check model dependence D1, D1S, D1M



Introduction of L-dependence

$$V_{\mathbf{Skyrme}} \Rightarrow V_{\mathbf{Skyrme}} - V_L \left[\rho^{\alpha}(r) - \rho_0^{\alpha}\right] P_{\sigma}\delta(r)$$

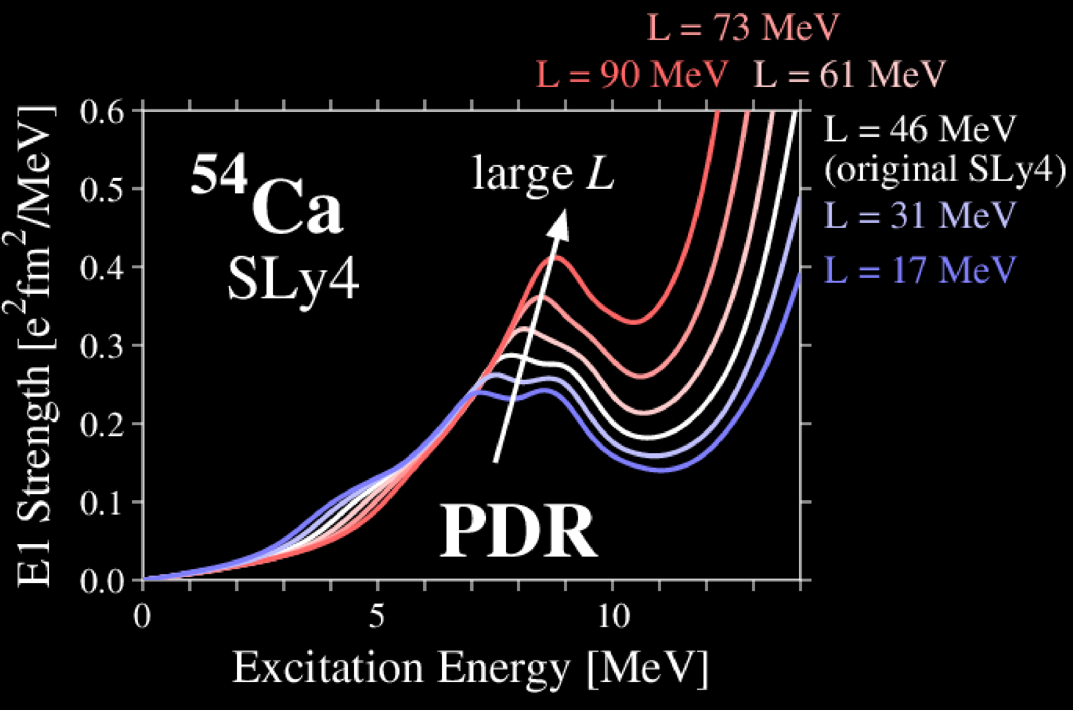
Ono+, PRC68, 051601



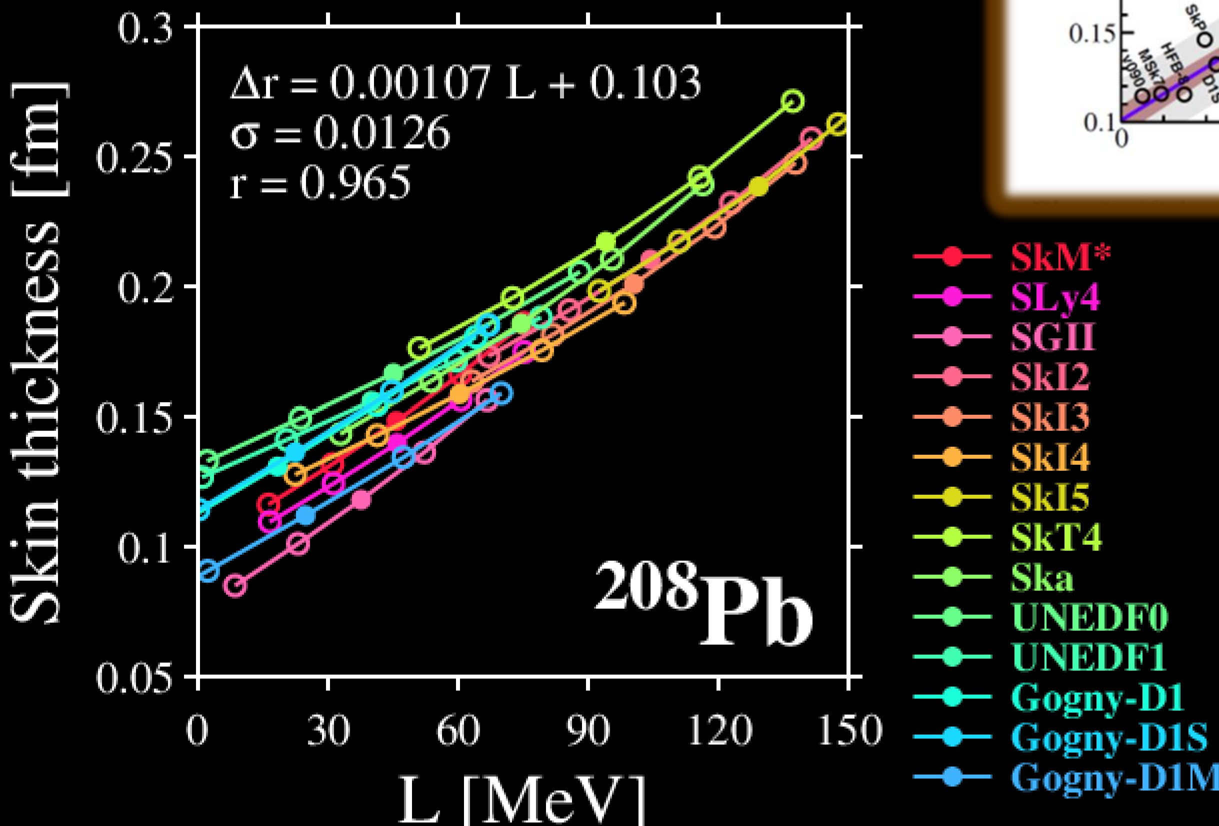
This additional term

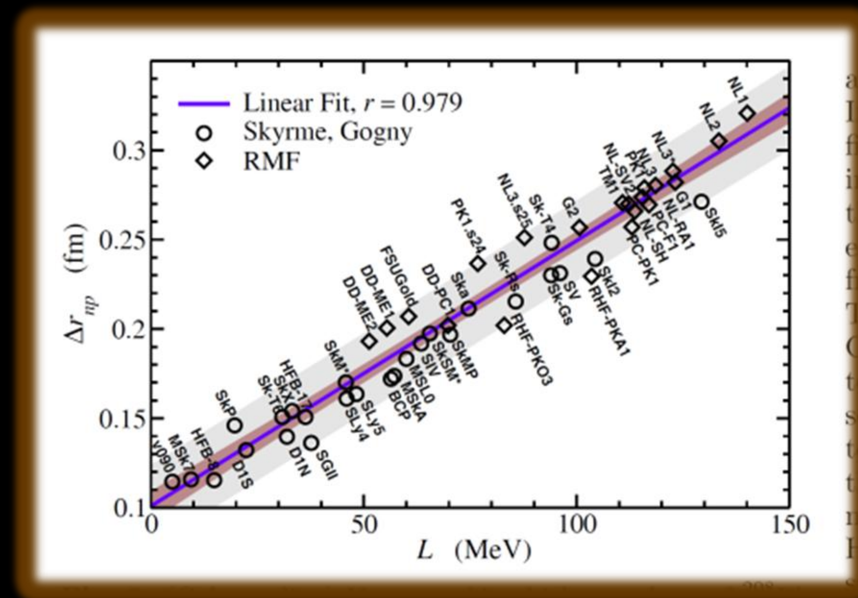
- does not affect SNM EoS nor $E_{sym}(\rho_0)$.
- changes L.

V_L is a parameter to control L.



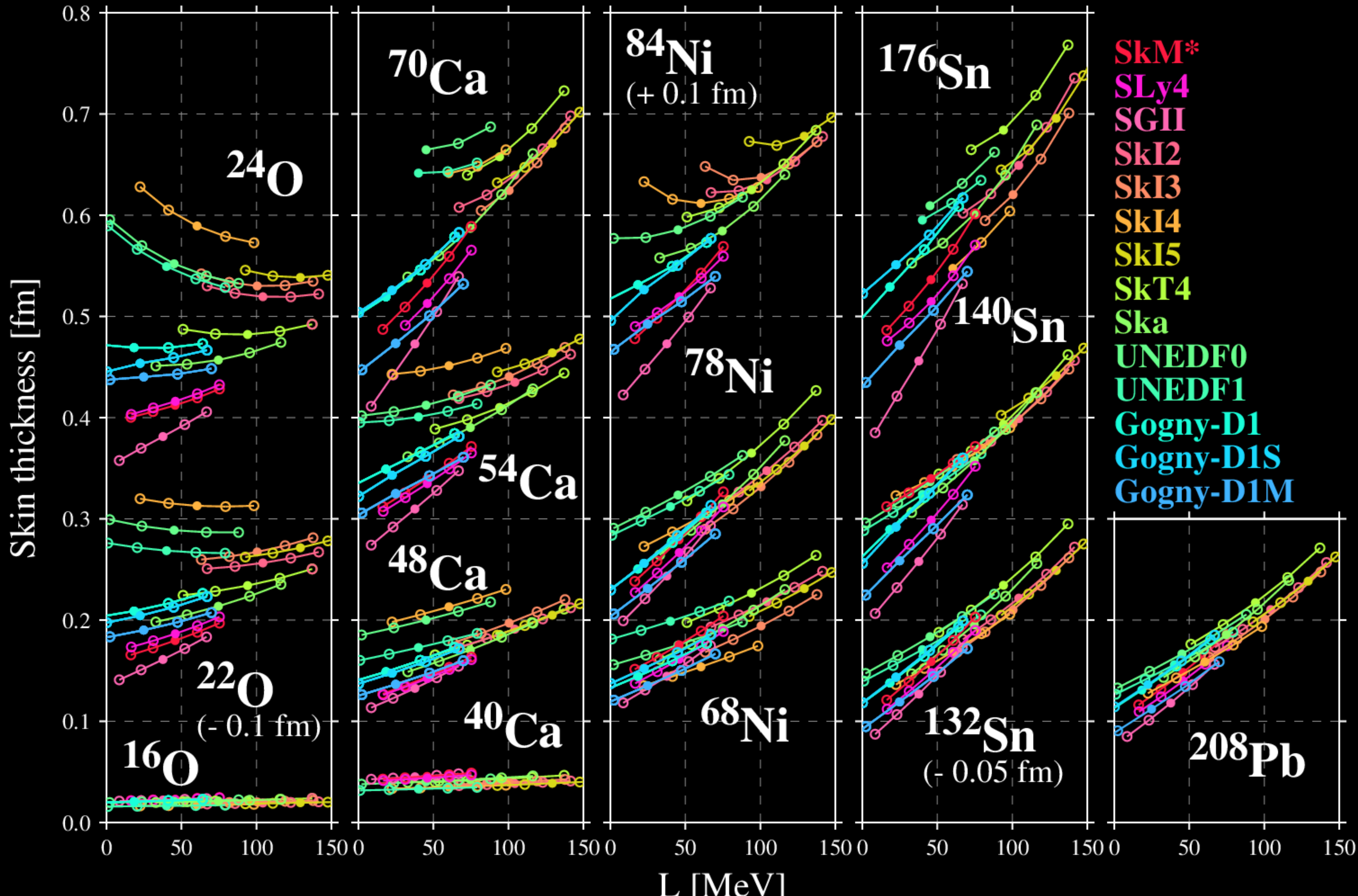
L & skin





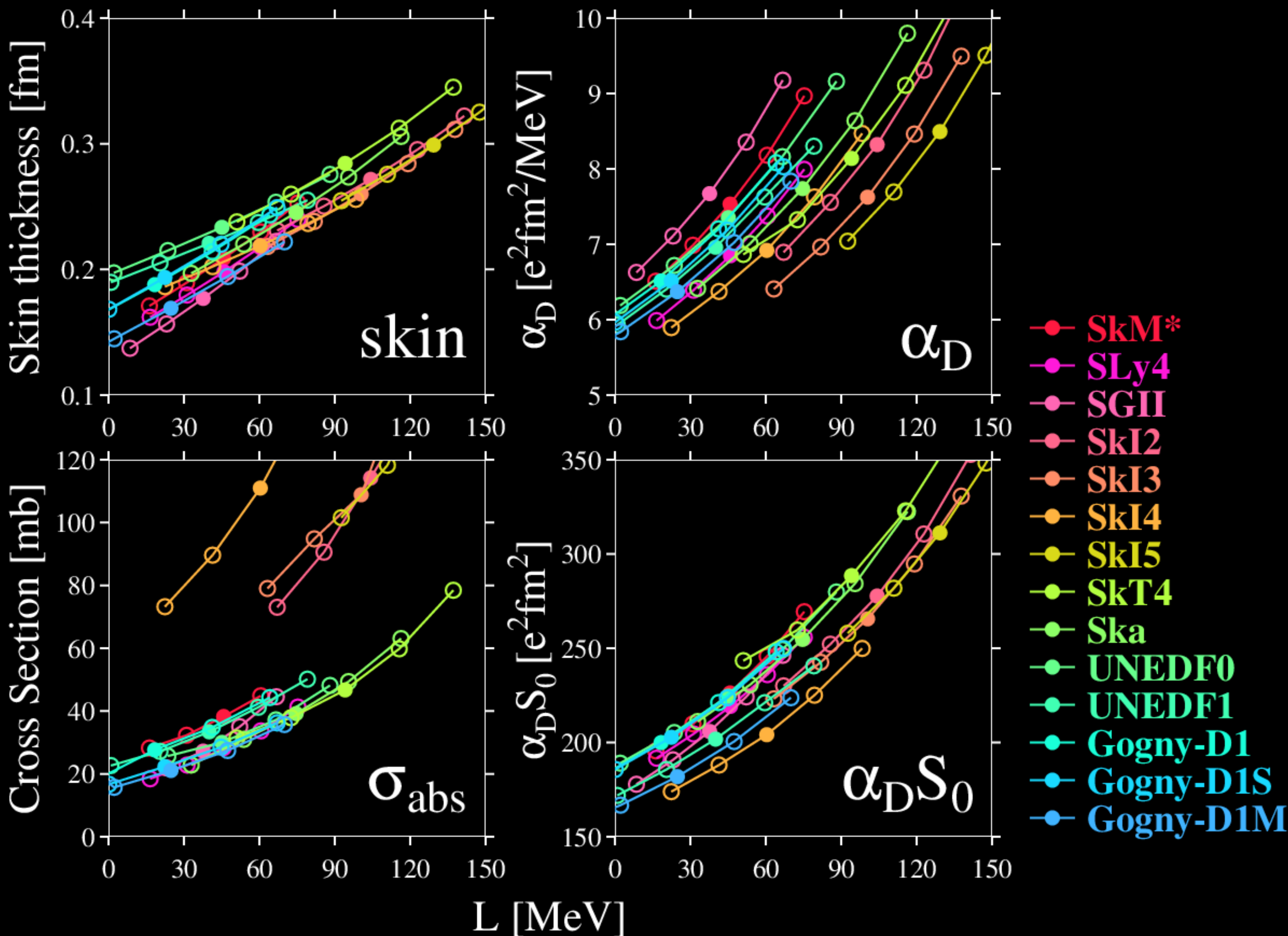
Roca-Maza+,
PRL 106, 252501

Skin & *L*

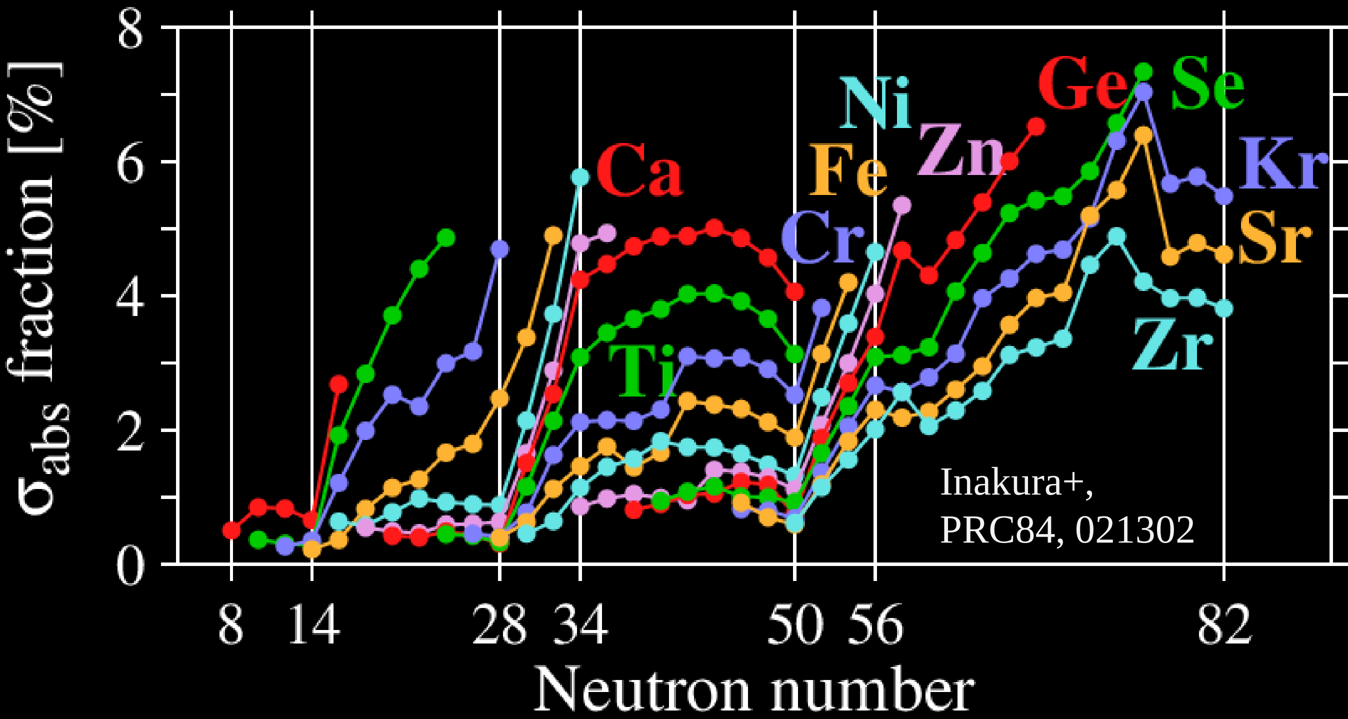


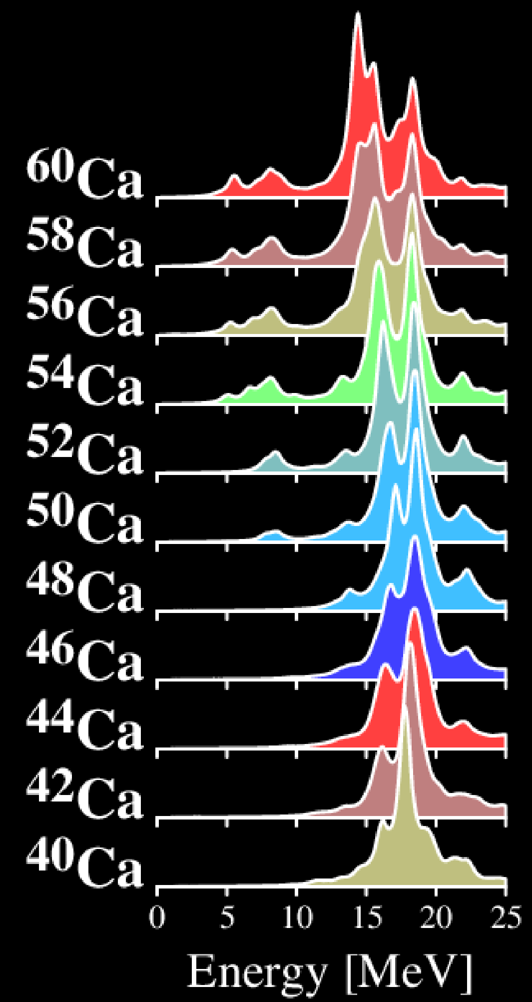
Skin thickness [fm]
L [MeV]
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
50
100
150
24O
22O
(- 0.1 fm)
16O
70Ca
54Ca
48Ca
40Ca
84Ni
(+ 0.1 fm)
78Ni
68Ni
176Sn
140Sn
132Sn
(- 0.05 fm)
208Pb
SkM*
SLy4
SGII
SkI2
SkI3
SkI4
SkI5
SkT4
Ska
UNEDF0
UNEDF1
Gogny-D1
Gogny-D1S
Gogny-D1M

Correlations in ^{132}Sn



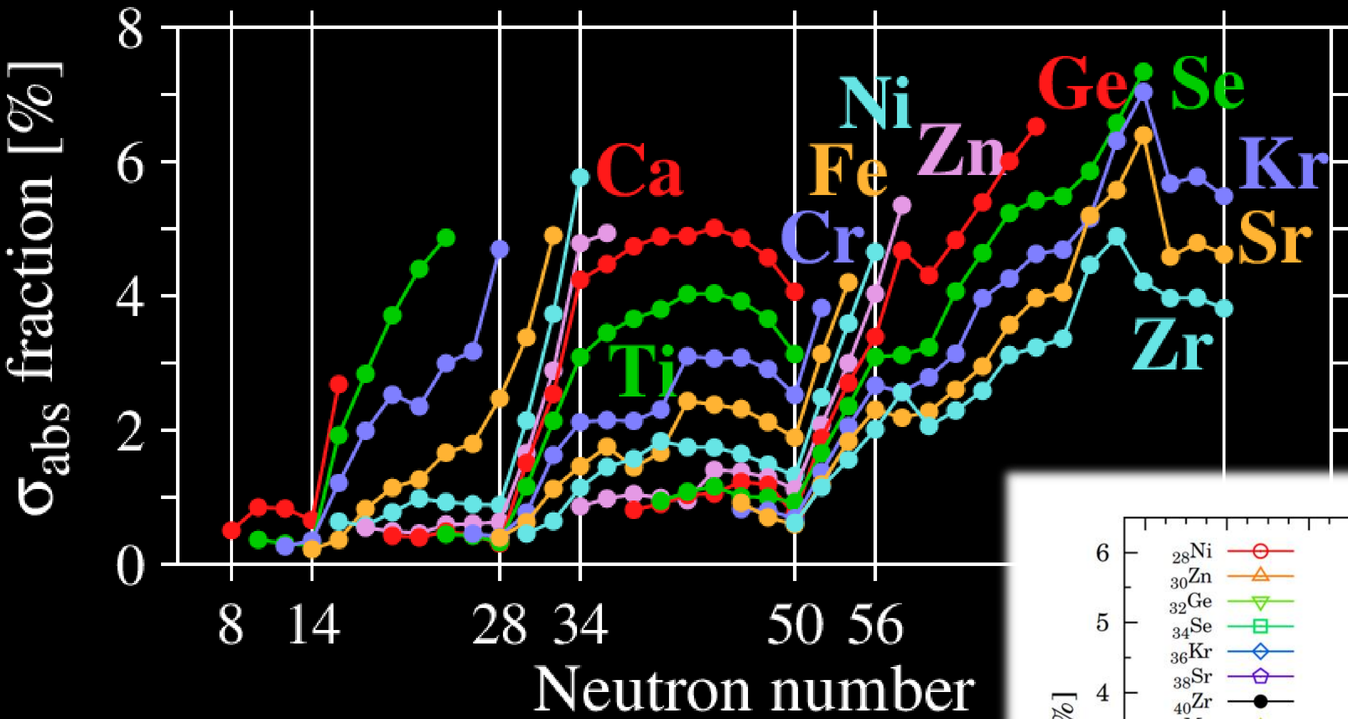
PDR in n-rich nuclei



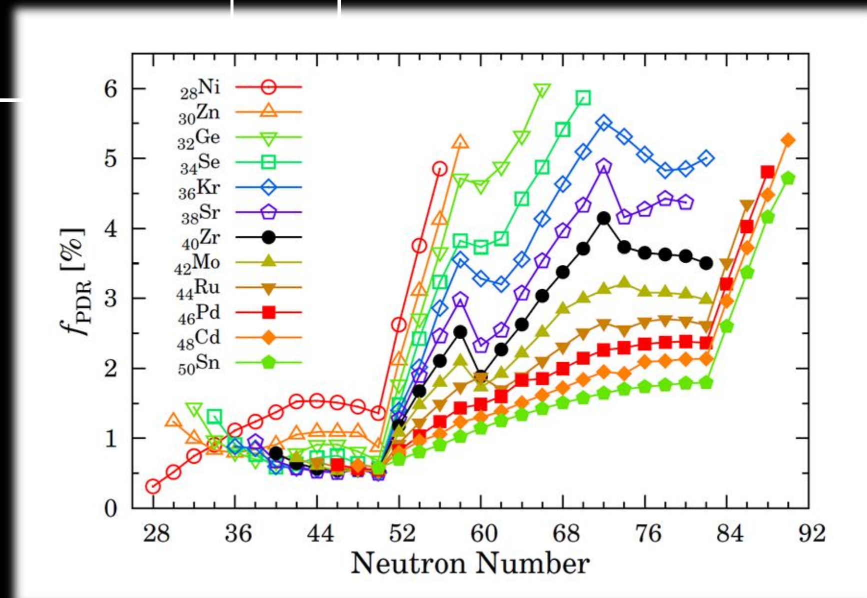


PDR appears in all calculated isotopes and grows up in ν-rich region beyond
N = 14, 28, 50, 82,
although only ^{68}Ni, ^{132}Sn, ^{208}Pb are calculated as **flagship nuclei.**

PDR in n-rich nuclei



Inakura+, PRC84, 021302



Ebata+, PRC90, 024303

PDR appears in all calculated isotopes and grows up in ν-rich region beyond
N = 14, 28, 50, 82,
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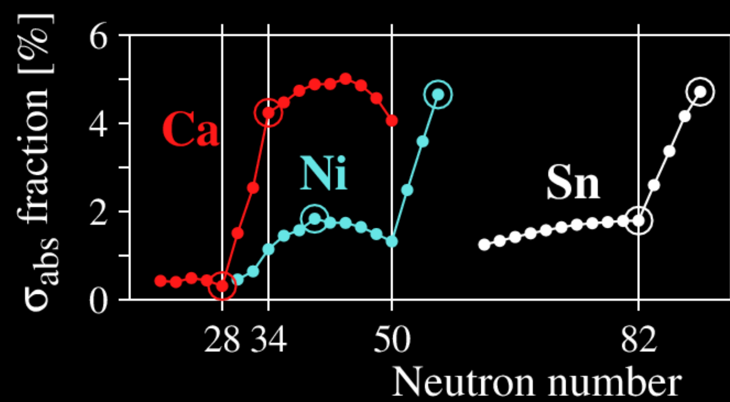
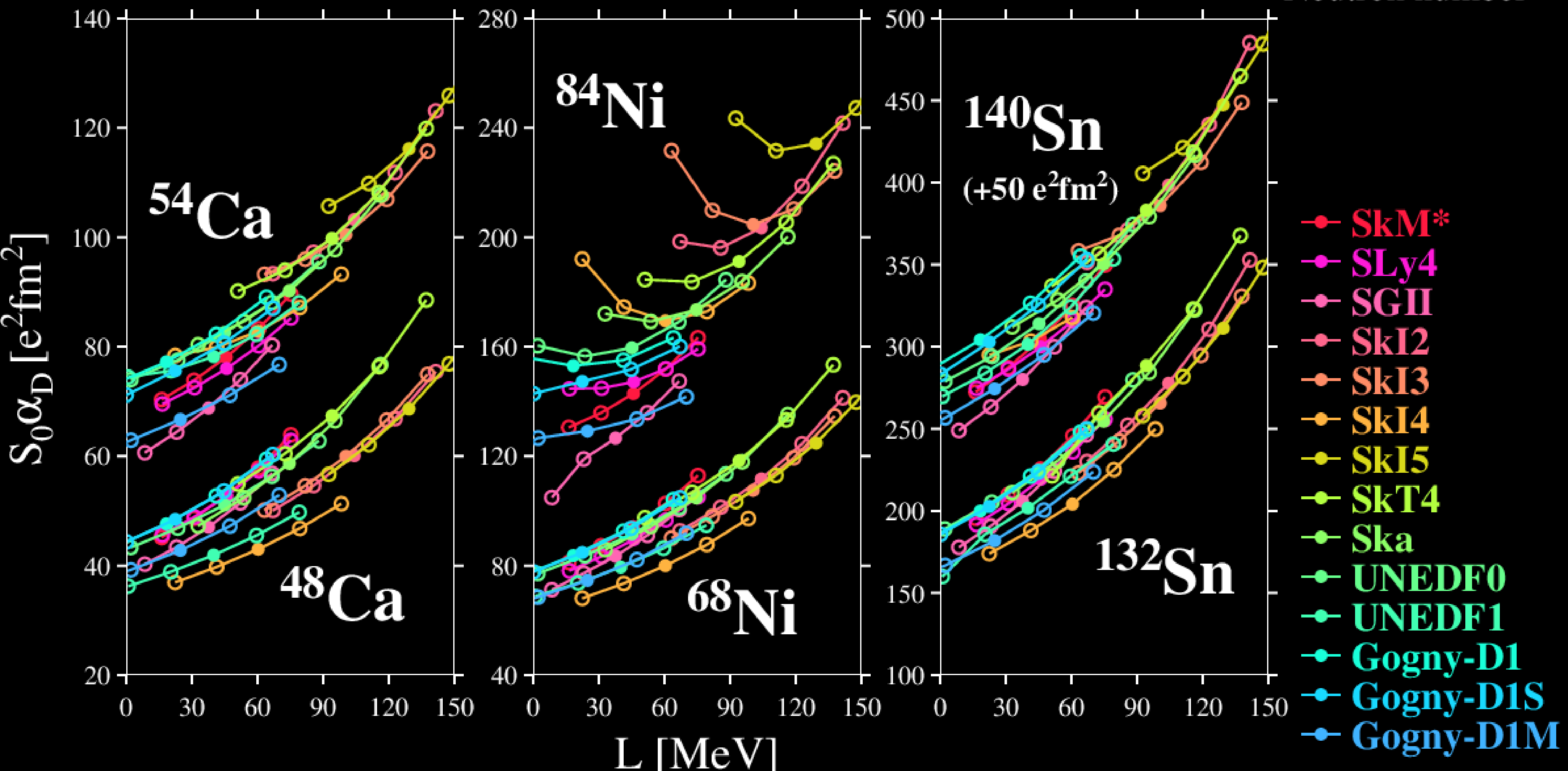
Well-developed PDR makes correlation conspicuous.





Summary

- $\alpha_D S_0$ and skin thickness correlates to L with less interaction dependence than cross section σ and α_D, though not always good enough.
- Well-developed PDR makes their correlation more conspicuous, and therefore better in constraining L from skin or $\alpha_D S_0$.
- Halo nuclei (e.g. 84Ni) are not welcome because their correlations are strongly influenced by loosely bound orbits.