不安定核のE1励起で探る中性子核物質の状態方程式

新学術領域研究会「中性子星核物質」
京都大学基礎物理学研究所
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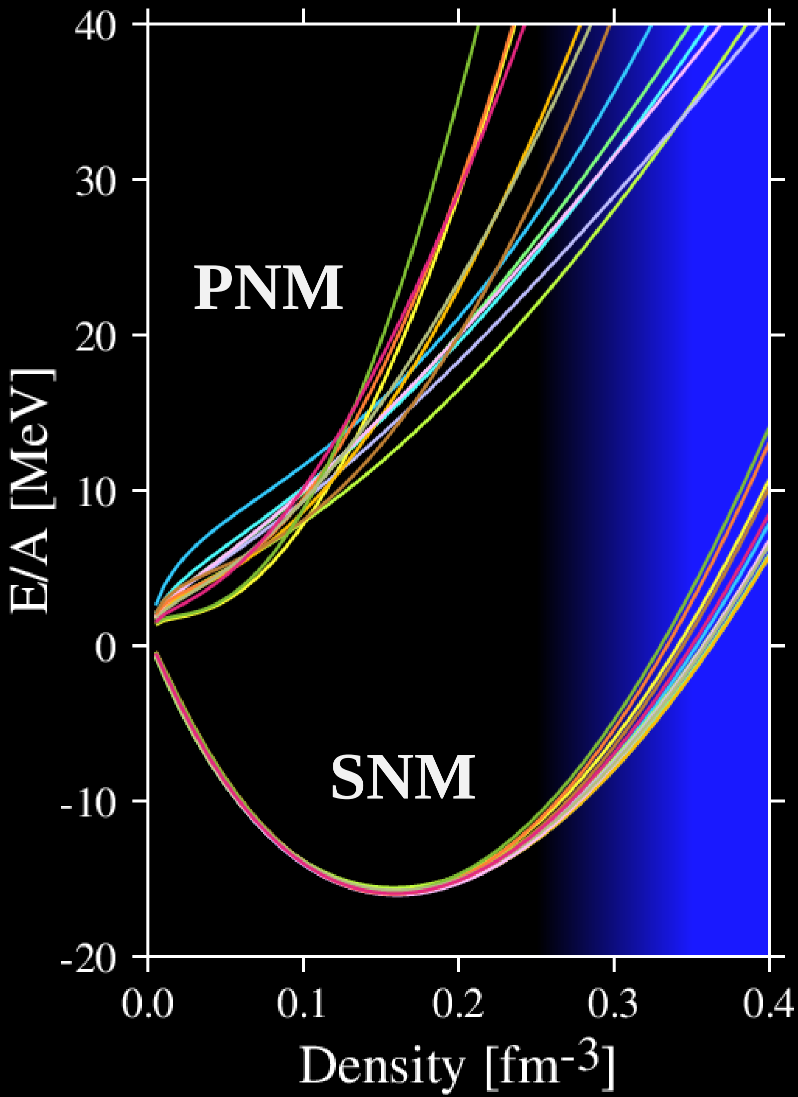
共同研究者: 中田仁 (千葉大)

Nuclear Matter Equation of State (EoS)



EoS calculated with effective interactions

✓ Pure Neutron Matter (PNM)

✓ Symmetric Nuclear Matter (SNM)

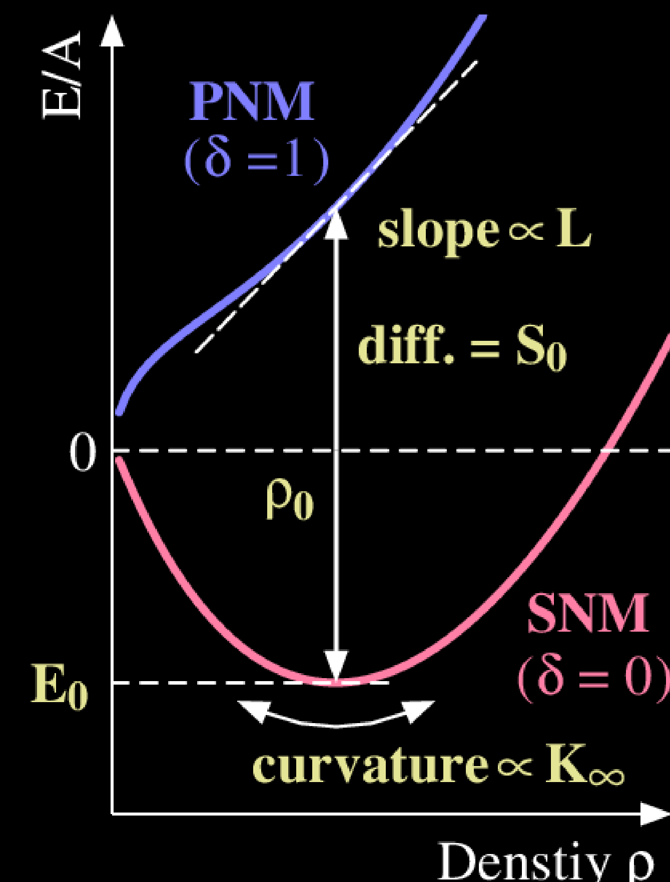
Quantities characterizing EoS

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

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

$$\mathrm{SNM}: \frac{E}{A}(\rho,\delta{=}0) = E_0 + \frac{K_\infty}{2}x^2 + \cdots$$

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



$$K_\infty = 9\rho_0^2 \frac{d^2}{d\rho^2}\frac{E(\rho,\delta{=}0)}{A}\bigg|_{\rho=\rho_0}$$

$$S_0 = \frac{E}{A}(\rho_0,\delta{=}1) - \frac{E}{A}(\rho_0,\delta{=}0)$$

$$L = 3\rho_0 \frac{d}{d\rho}E_{\mathrm{sym}}(\rho)\bigg|_{\rho=\rho_0}$$

Quantities characterizing EoS

$$\frac{E}{A}(\rho,\delta) = \frac{E}{A}(\rho,\delta{=}0) + E_{\mathrm{sym}}(\rho)\delta^2 + O(\delta^4) \qquad \delta = \frac{\rho_n-\rho_p}{\rho_n+\rho_p}\,,\ x = \frac{\rho-\rho_0}{3\rho_0}$$

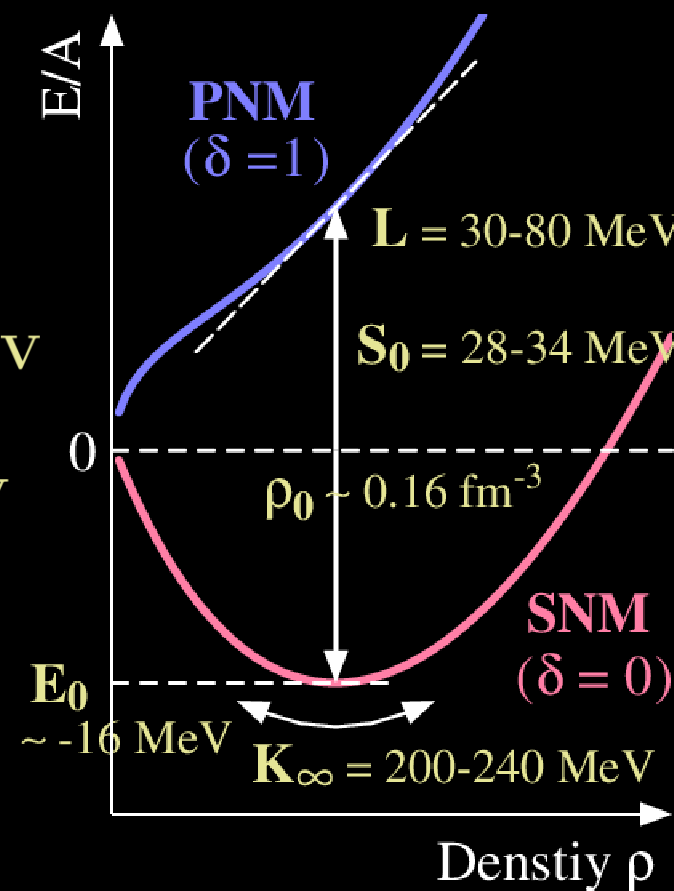
$$\mathrm{SNM}: \frac{E}{A}(\rho,\delta{=}0) = E_0 + \frac{K_\infty}{2}x^2 + \cdots$$

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

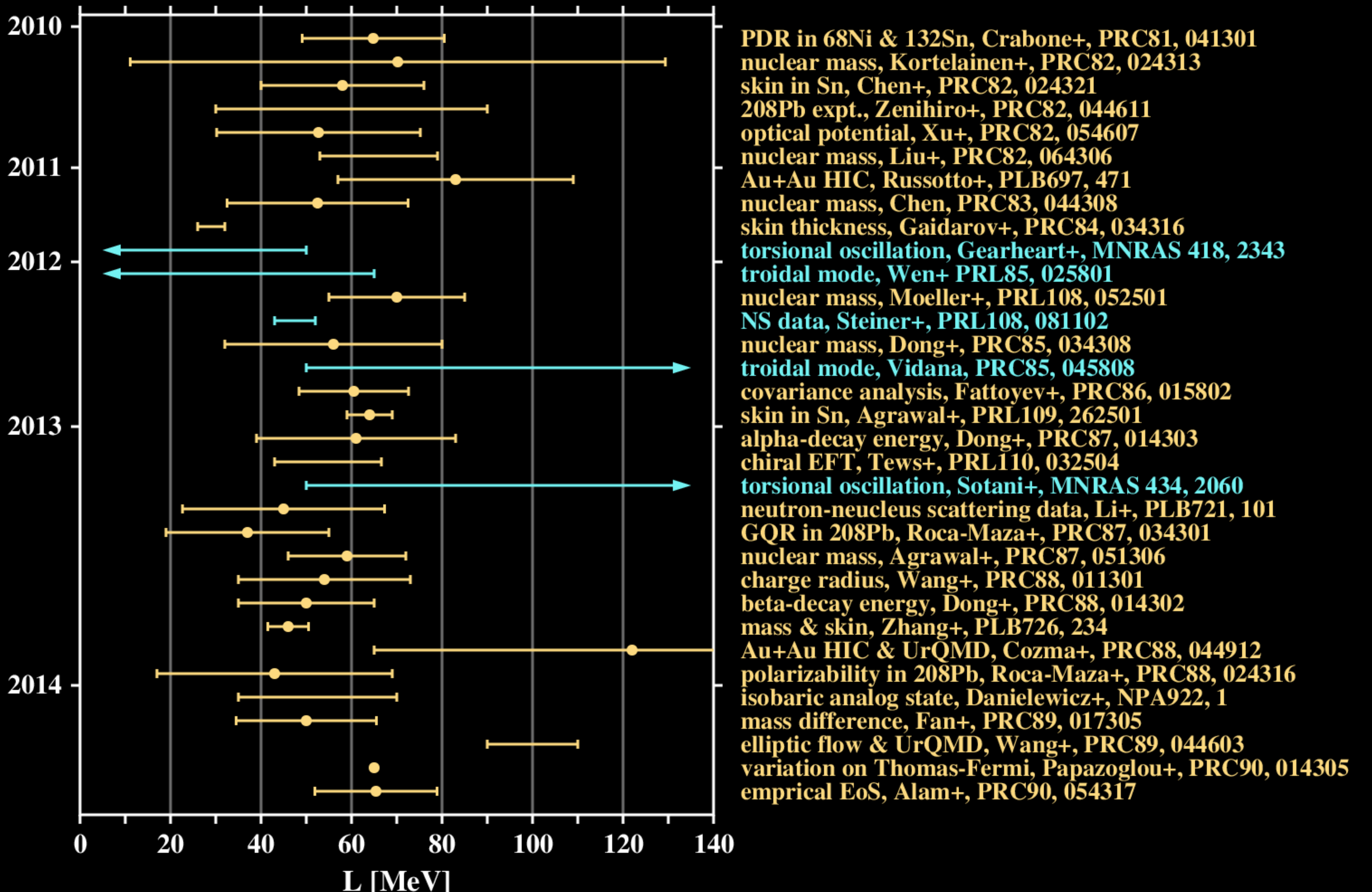
$$K_\infty = 9\rho_0^2 \frac{d^2}{d\rho^2}\frac{E(\rho,\delta{=}0)}{A}\bigg|_{\rho=\rho_0} = 200 - 240\,\mathrm{MeV}$$

$$S_0 = \frac{E}{A}(\rho_0,\delta{=}1) - \frac{E}{A}(\rho_0,\delta{=}0) = 28 - 34\,\mathrm{MeV}$$

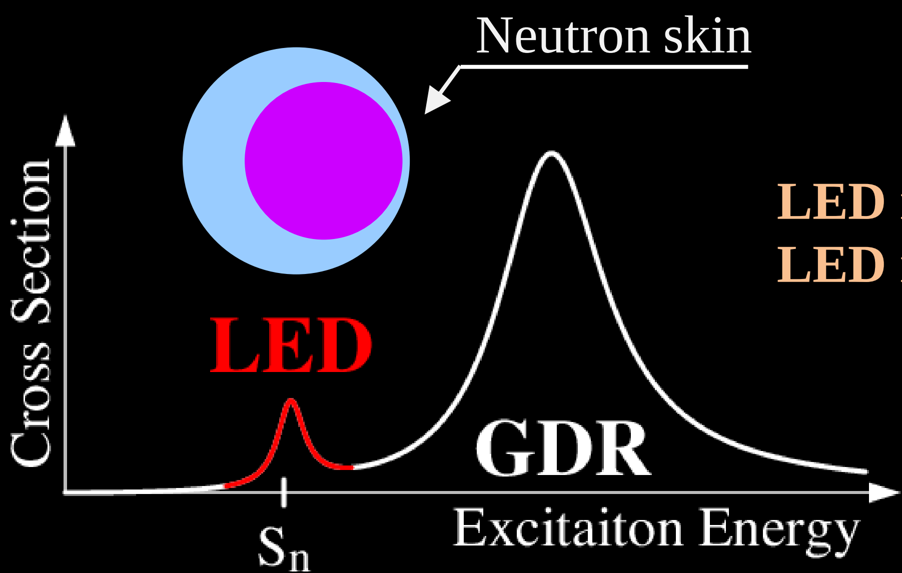
$$L = 3\rho_0 \frac{d}{d\rho}E_{\mathrm{sym}}(\rho)\bigg|_{\rho=\rho_0} = 30 - 80\,\mathrm{MeV}$$



L from observables and calculations



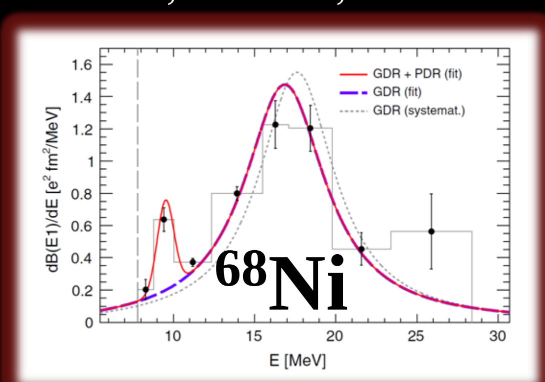
Low-Energy Dipole mode (LED) = Pygmy Dipole Resonance (PDR) = Low-lying E1 strength



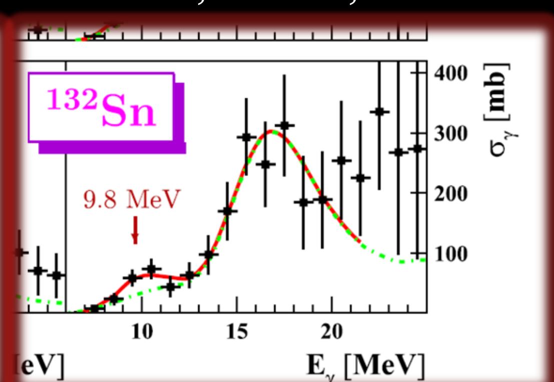
LED in stable nuclei: < 1% Cross Section
LED in ν-rich nuclei: < several % Cross Section

LED could provide some information of PNM EoS!

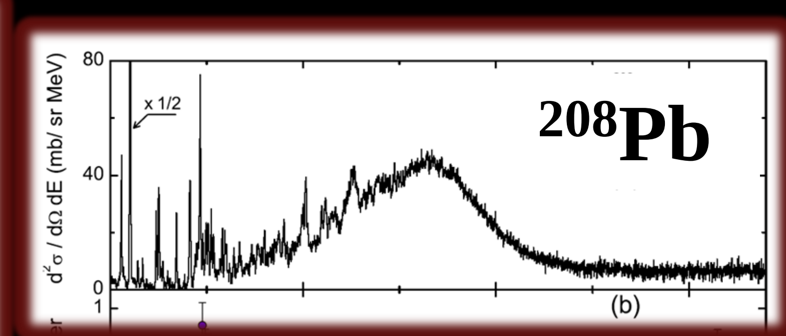
Rossi+, PRL 111, 242503



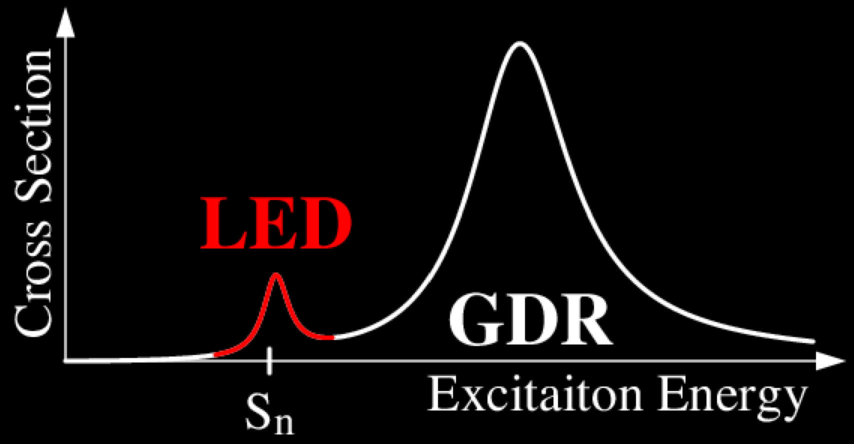
Adrich+, PRL 95, 132501

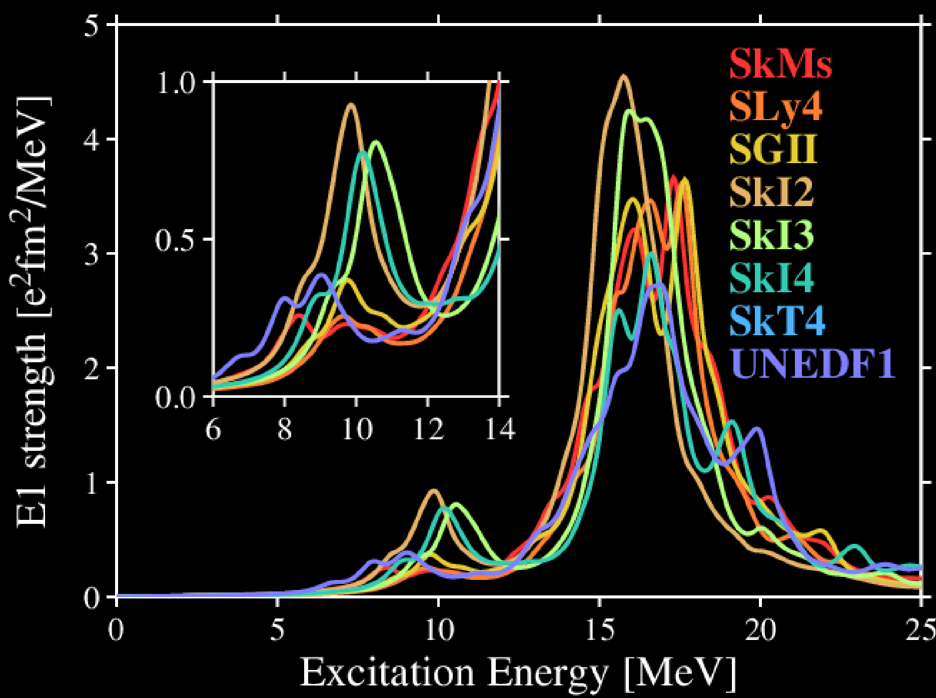


Tamii+, PRL 107, 062502

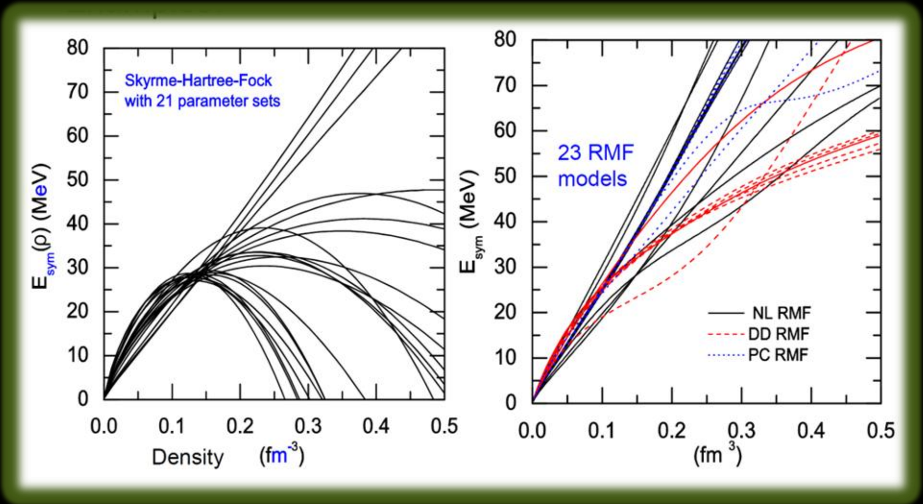


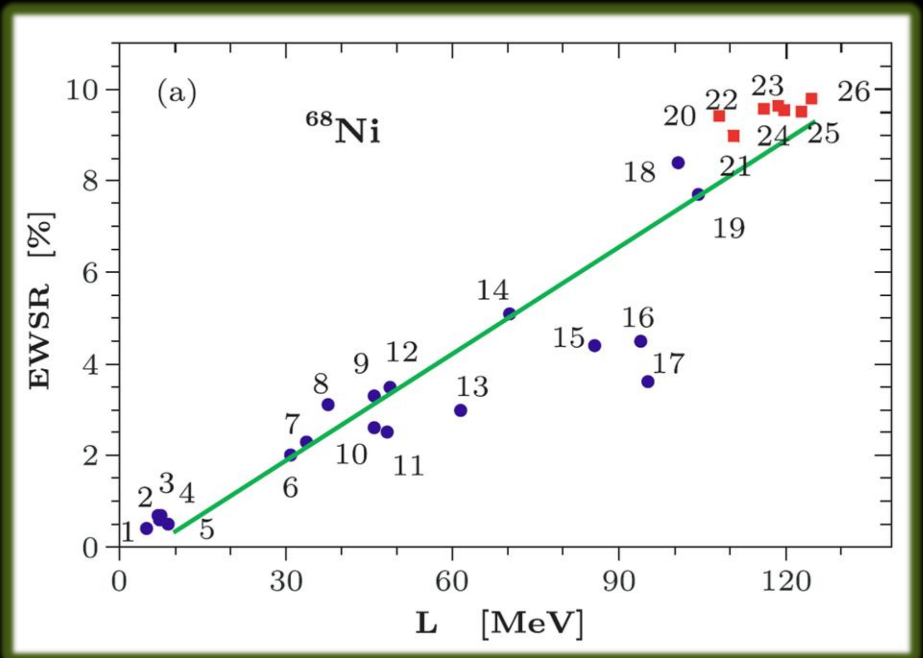
L from LED cross section





Chen+, PRC72, 064309; PRC76, 054316

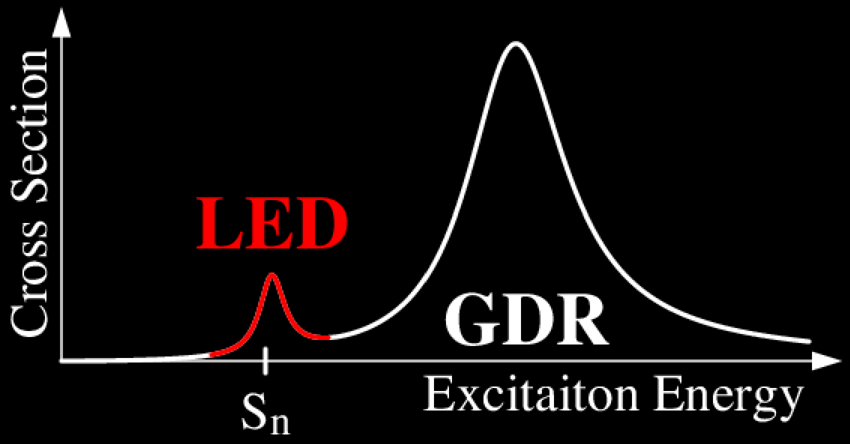


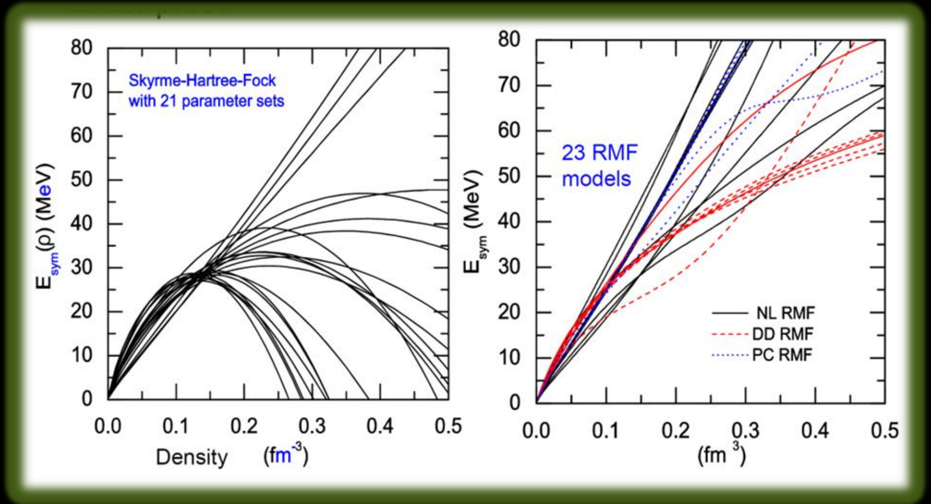


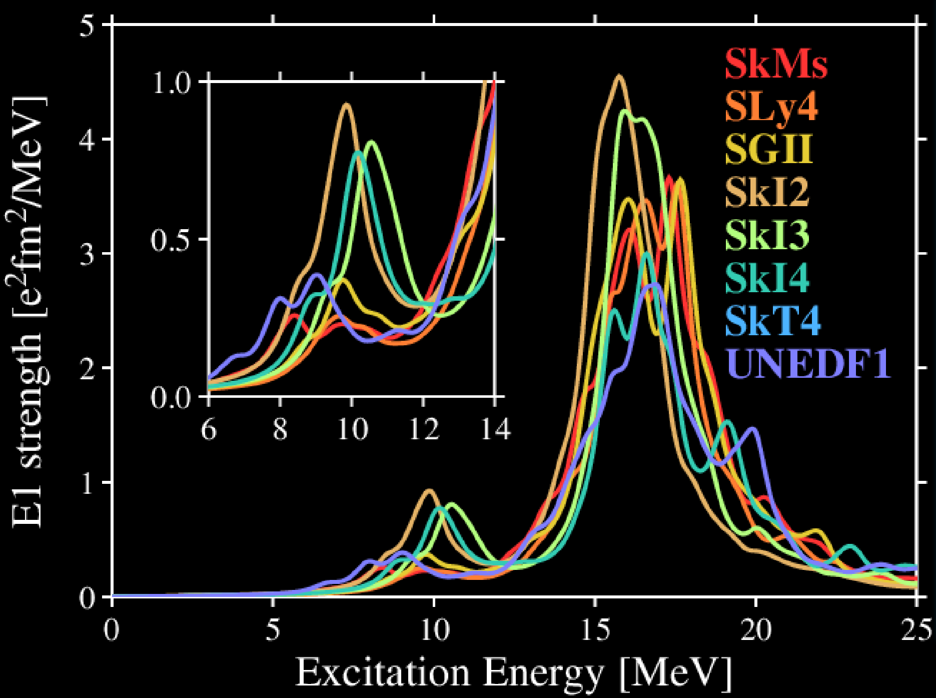
Carbone+, PRC81, 041301® (2010)

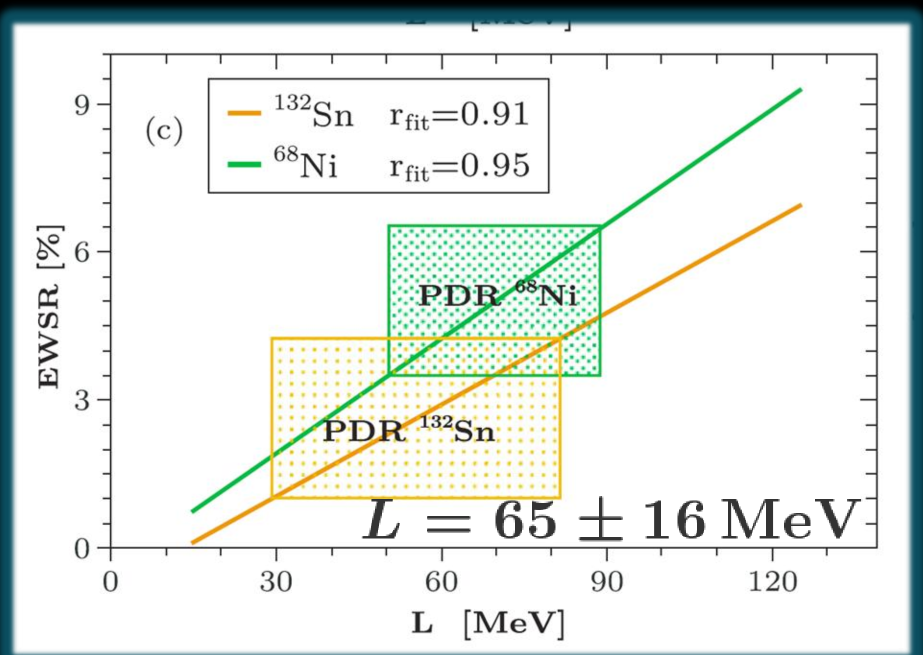
L from LED cross section

Chen+, PRC72, 064309; PRC76, 054316







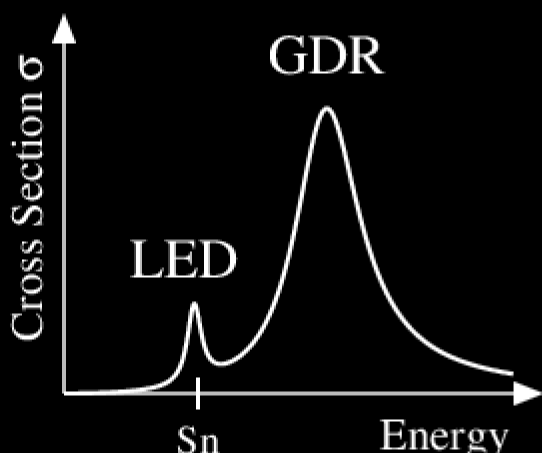


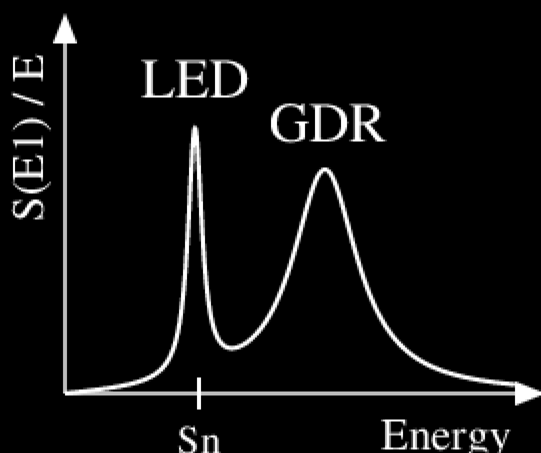
Carbone+, PRC81, 041301® (2010)

Cross section(σ) & Polarizability(α_D)

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

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

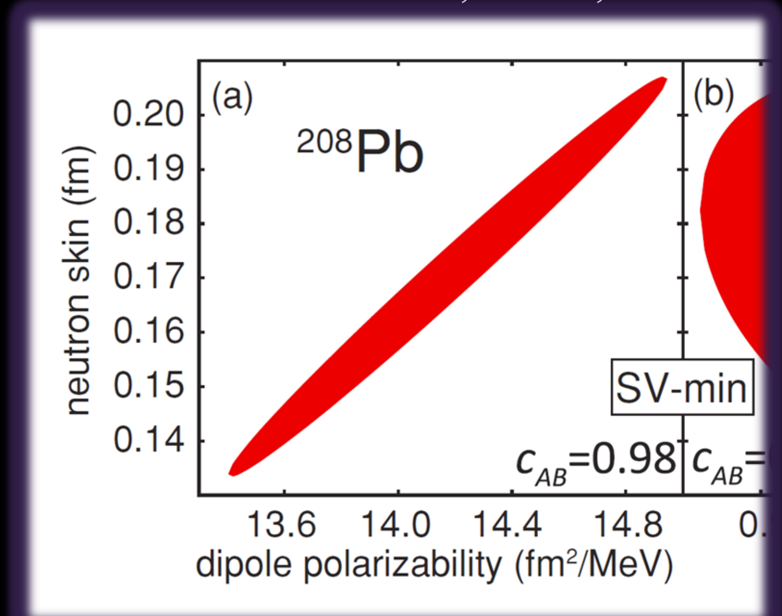


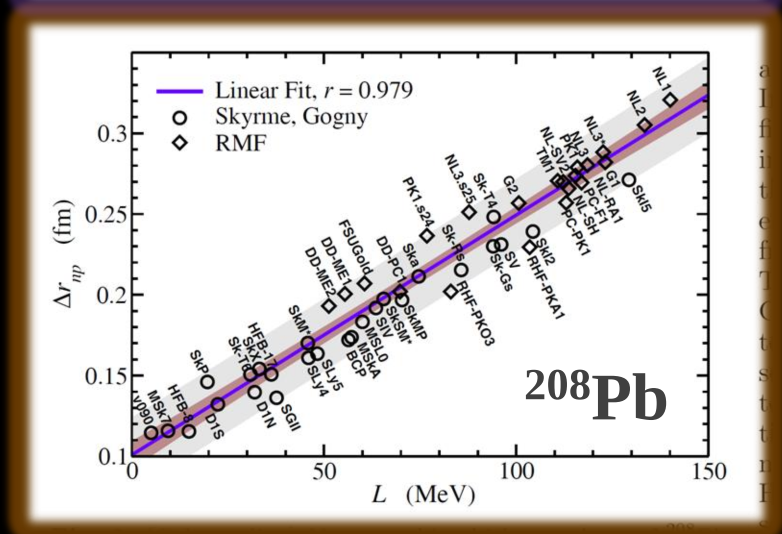


Roca-Maza+, PRL 106, 252501

Covariance Analysis

Reinhard+, PRC81, 051303

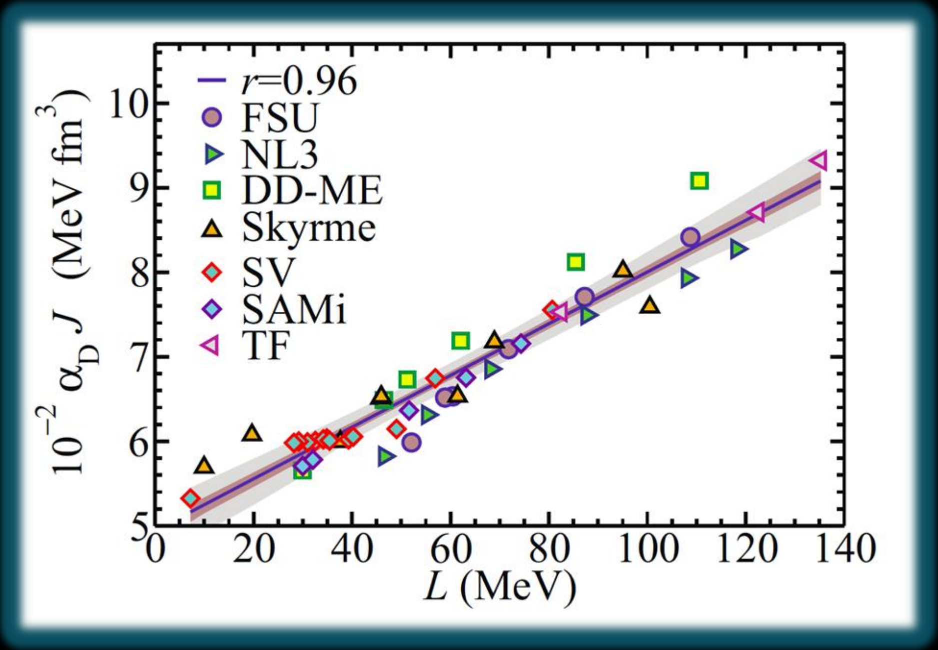




New correlation

Droplet Model **(with some approximations & assumptions) yields**

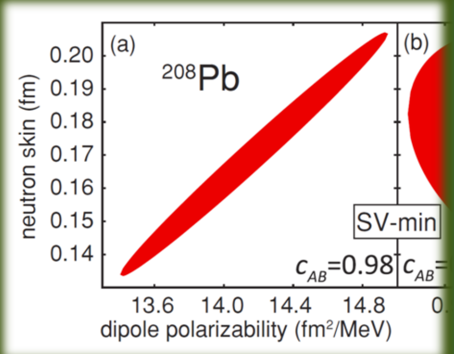
$$\alpha_D S_0 \sim \frac{\pi e^2}{54} A \langle r^2 \rangle \left(1 + \frac{5}{3} \frac{L}{S_0} \varepsilon_A \right), \ \varepsilon_{208} \sim \frac{1}{8}$$

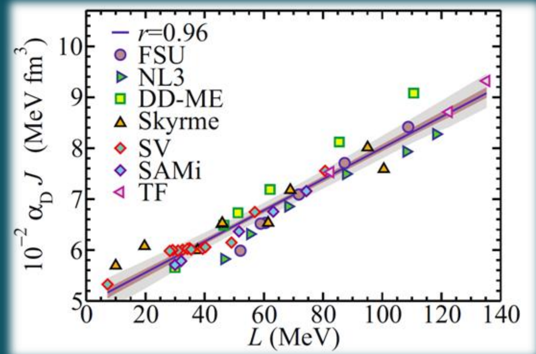


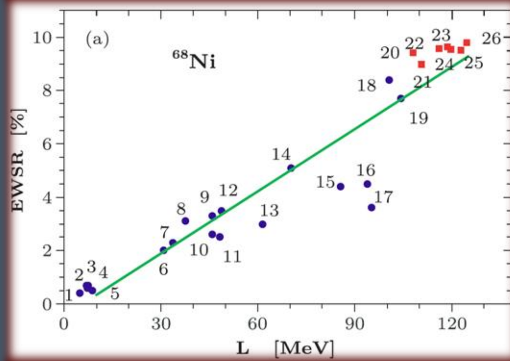
Roca-Maza+, PRC88, 024316 (2013)

L from E1 mode

Which is best? Interaction-dependence?

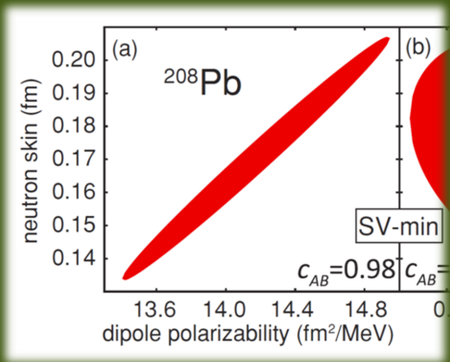


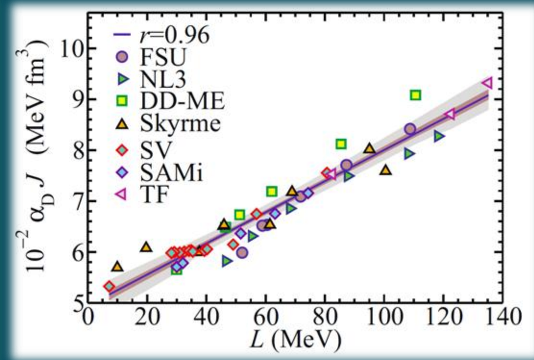


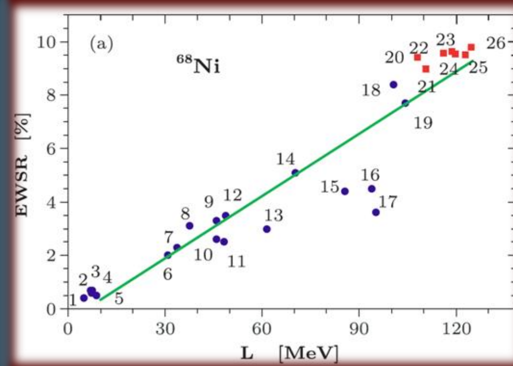


L from E1 mode

Which is best? Interaction-dependence?







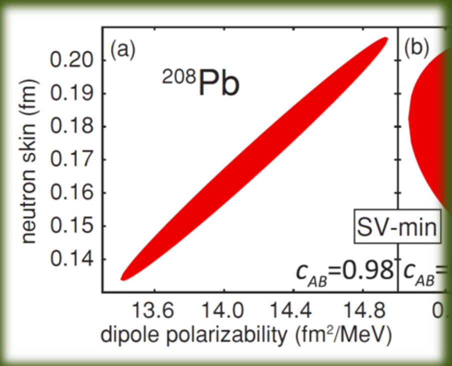
Correlation is analyzed within **single** interaction

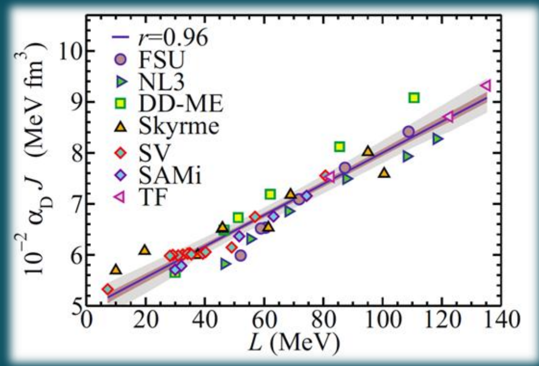
Correlation is calculated using **many** interactions.

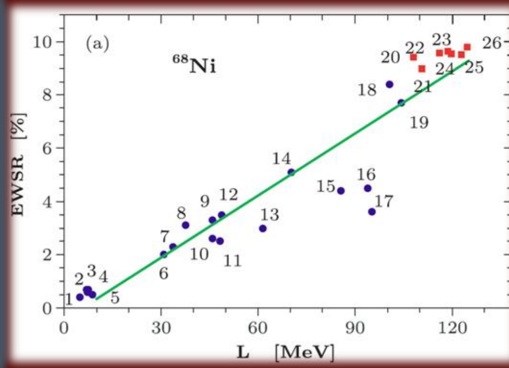
Same correlation?

L from E1 mode

Which is best? **Interaction-dependence?**







Correlation is analyzed within **single** interaction

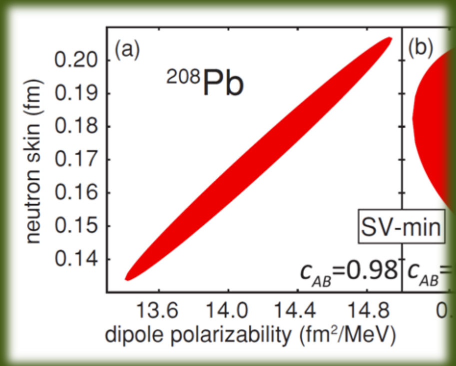
Correlation is calculated using **many** interactions.

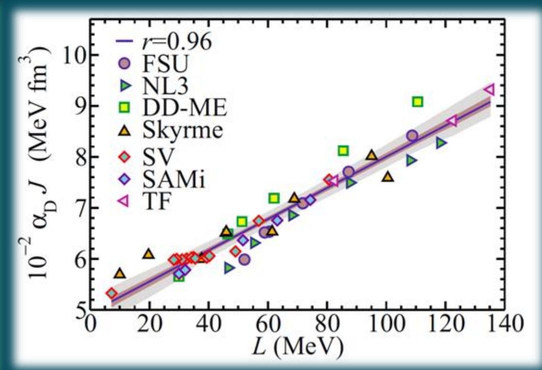
Same correlation?

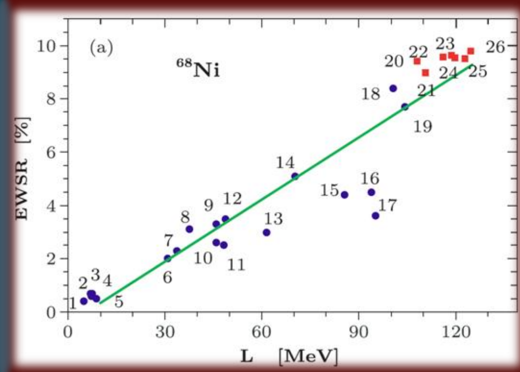
“Ideal” quantity…

- **strongly correlates with *L*.**
- **independent of interaction and model.**
- **shows similar correlations.**

L from E1 mode







Which is best?

Interaction-dependence?

Same correlation?

Analysis has been performed **ONLY** in **^{48}Ca, ^{68}Ni, ^{132}Sn, ^{208}Pb**.

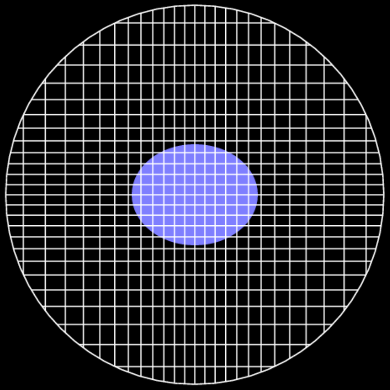
How about other nuclei?

Careful assessment needed!

Linear response calc. with Skyrme in 3D mesh

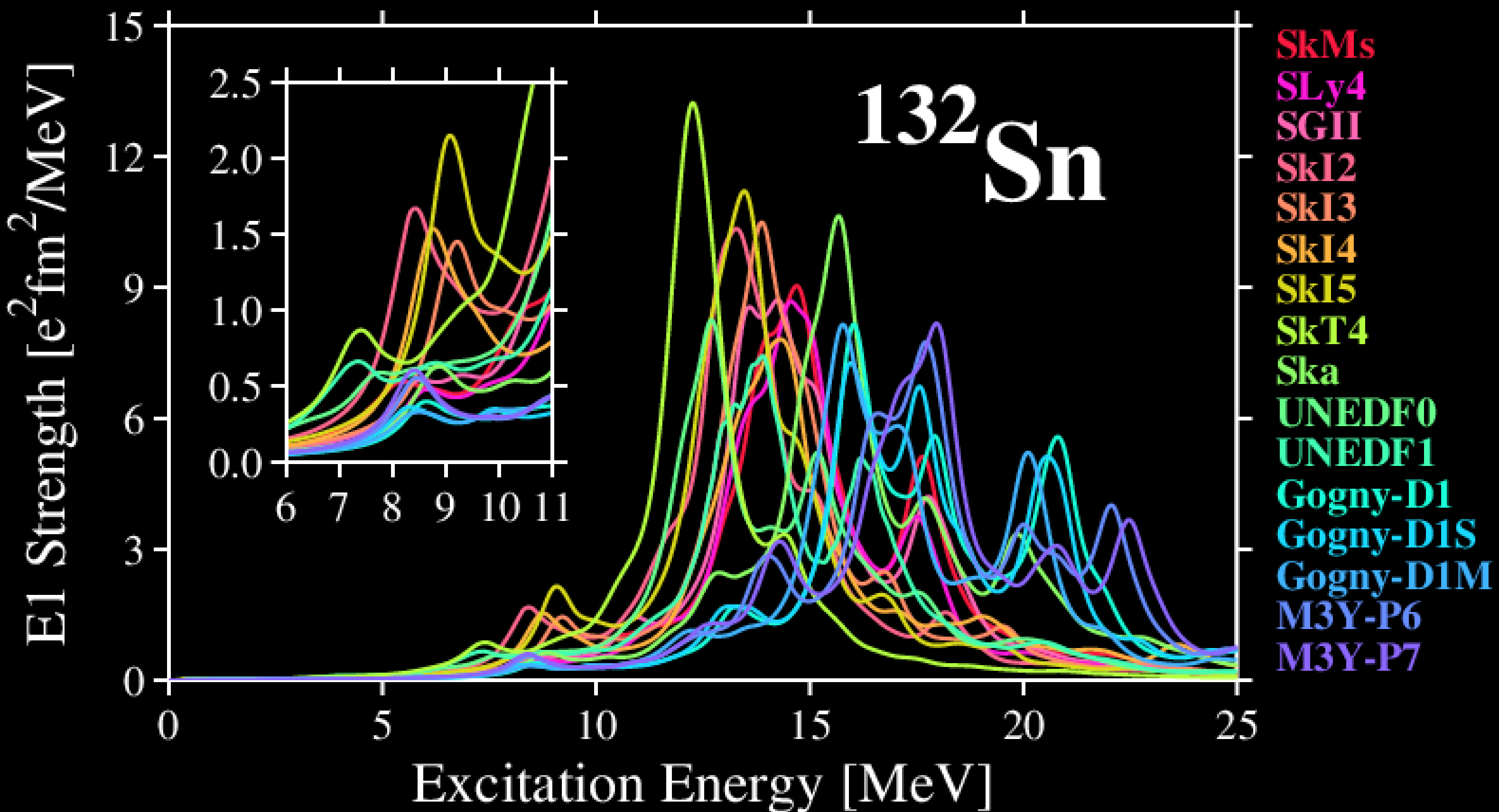
- Density Functional Theory with Skyrme energy functional.
- **Fully self-consistent** calculation. **PARAMETER FREE!**
- **3D mesh representation**
  - suitable for describing unstable nuclei having skin or halo.
  - deal with continuum states in good approximation.
- **Linear response calculation**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

$$\left\{\begin{bmatrix} A & B \\ B^* & A^* \end{bmatrix} - \hbar\omega \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}\right\}\begin{bmatrix} X_{nj}(\omega) \\ Y_{nj}(\omega) \end{bmatrix} = -\begin{bmatrix} f(\omega) \\ g(\omega) \end{bmatrix}$$



16 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 range of *L*: SkI2, SkI3, SkI4, SkI5
- 3 Gogny to check model dependence: D1, D1S, D1M
- 2 M3Y to check model dependence: M3Y-P6, M3Y-P7



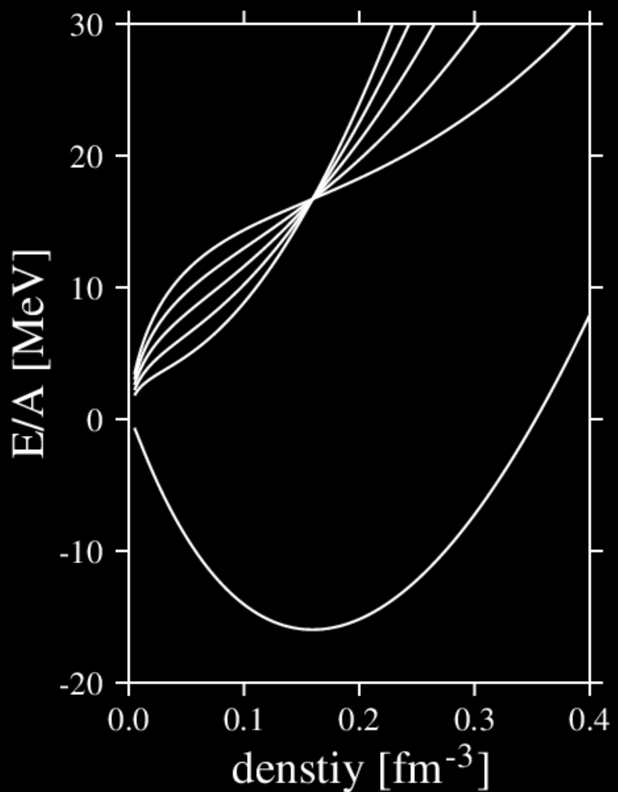
Introduction of L-dependence

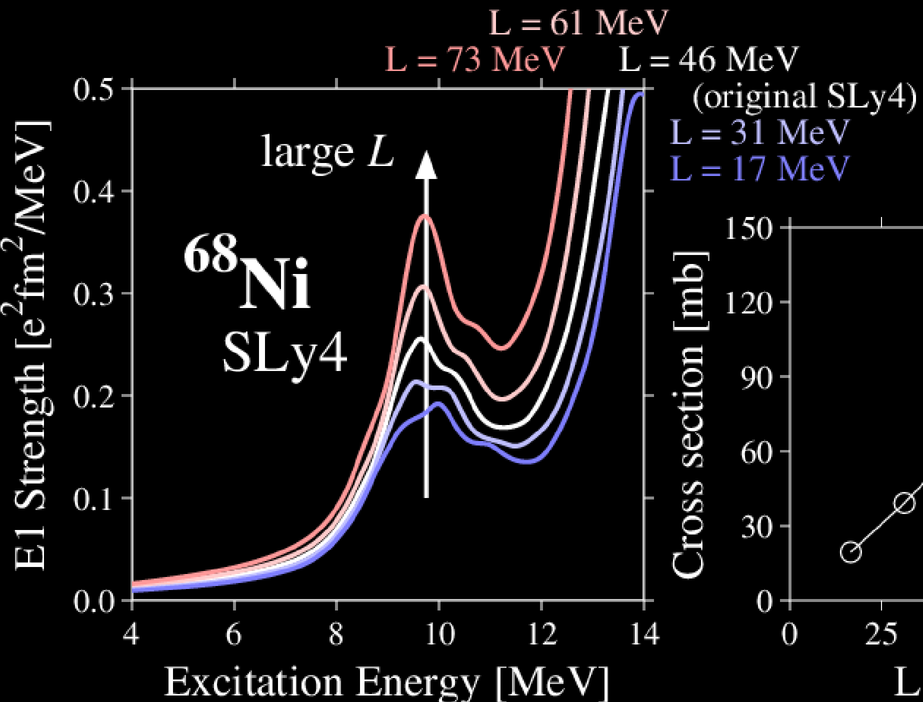
$$V \Rightarrow V - V_L \left[\rho^{\alpha}(r) - \rho_0^{\alpha}\right] P_{\sigma}\delta(r)$$

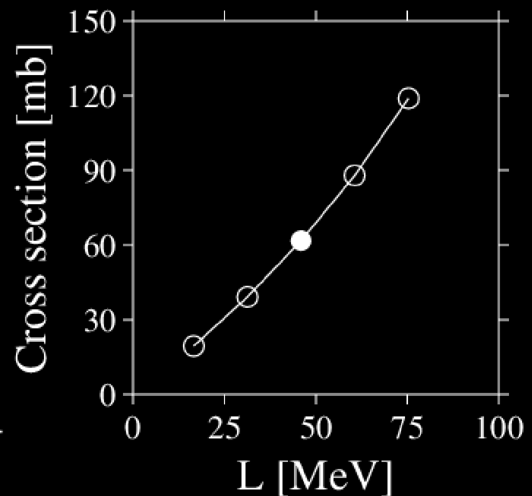
Ref. Ono+, PRC68, 051601

The additional term
- ➢ does not affect SNM EoS nor S_0.
- ➢ changes L.

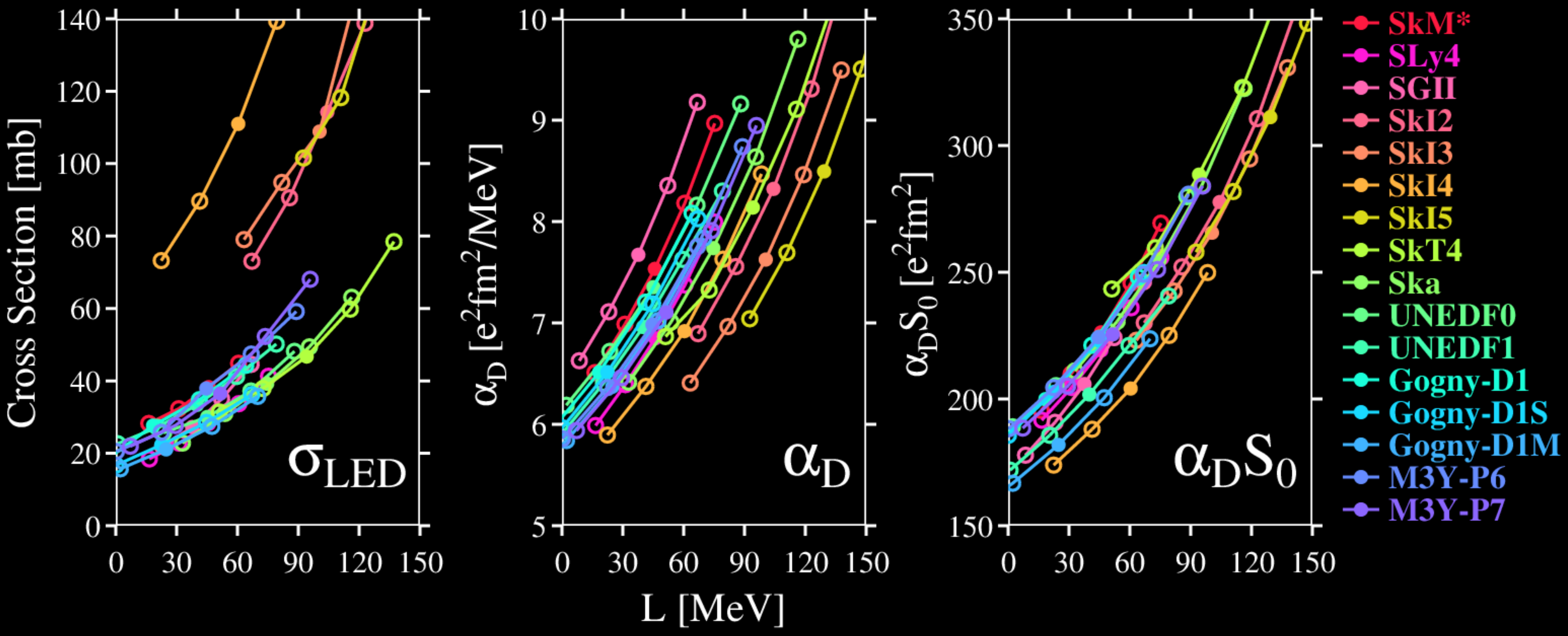
V_L is a parameter to control L.



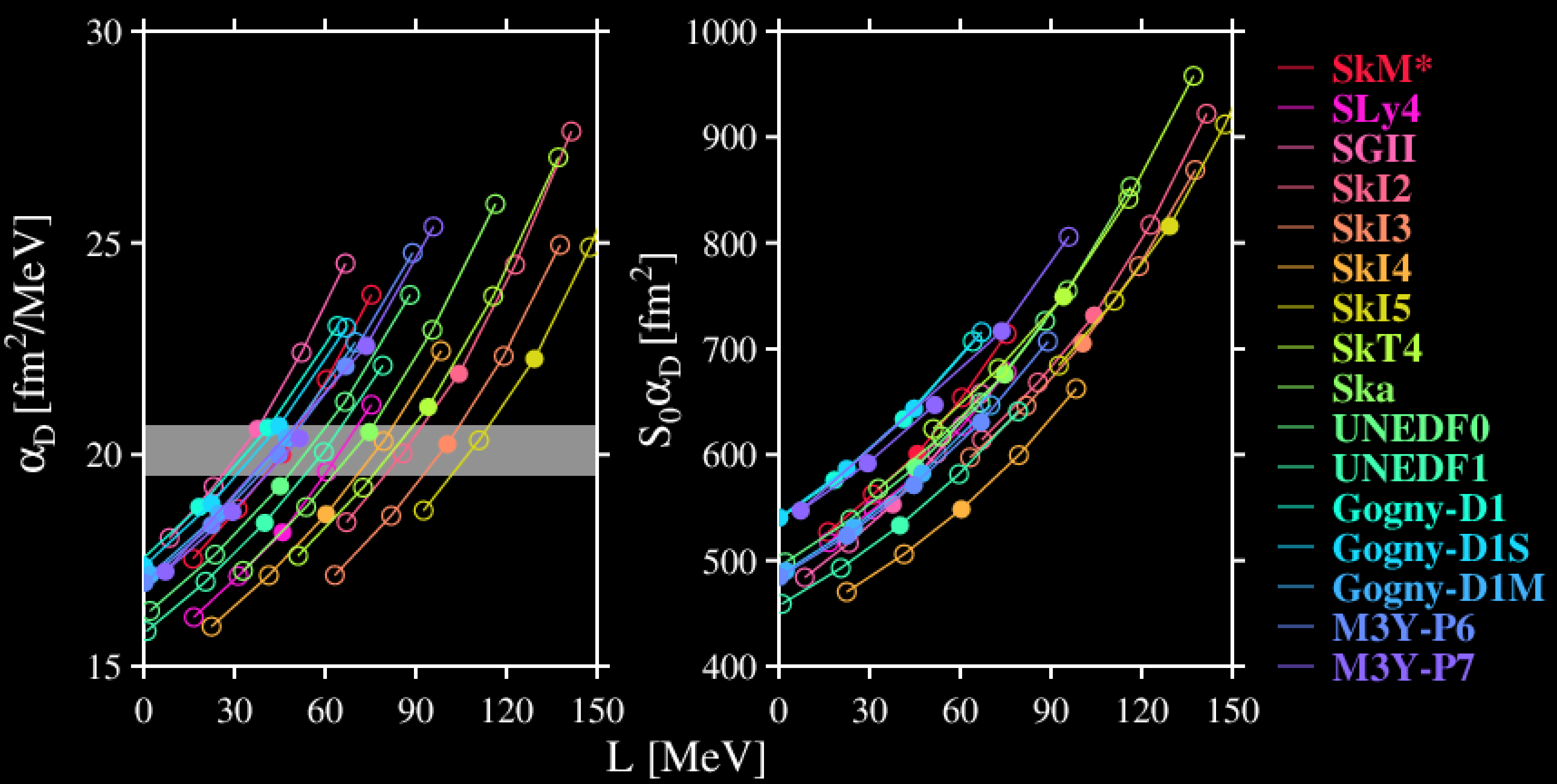




Correlations in ^{132}Sn

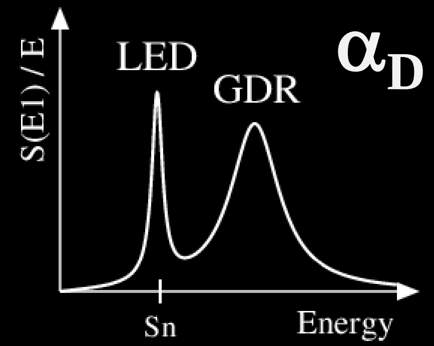


Comparison with experimental data in ^{208}Pb

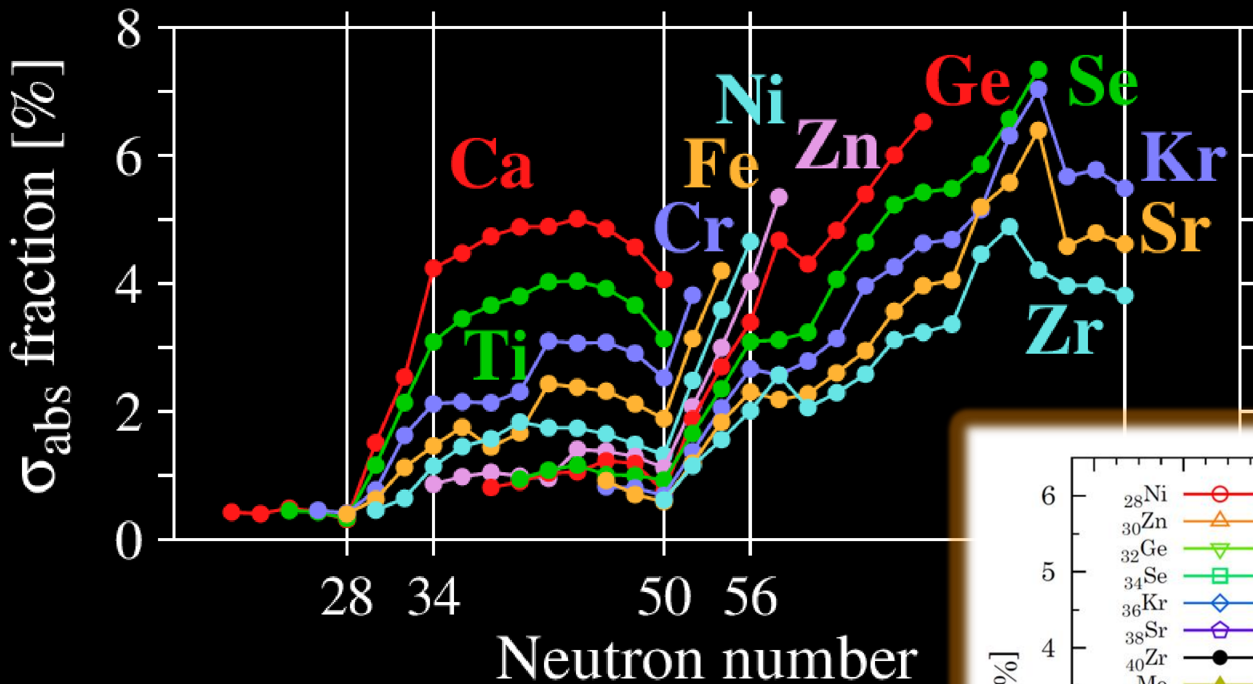


Experimental data: Tamii+, PRL107, 062502

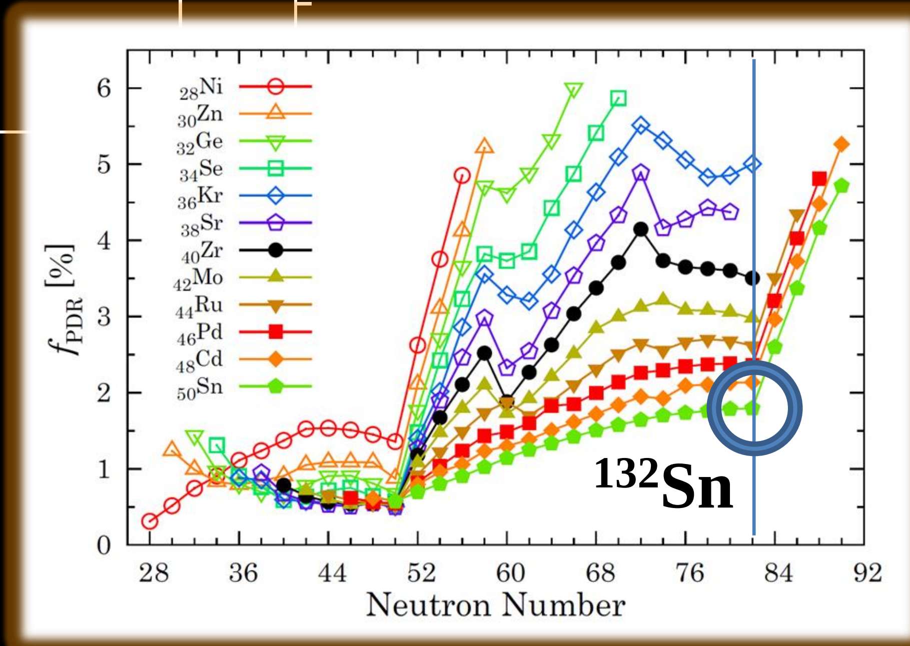
Which LED is better?



α_D



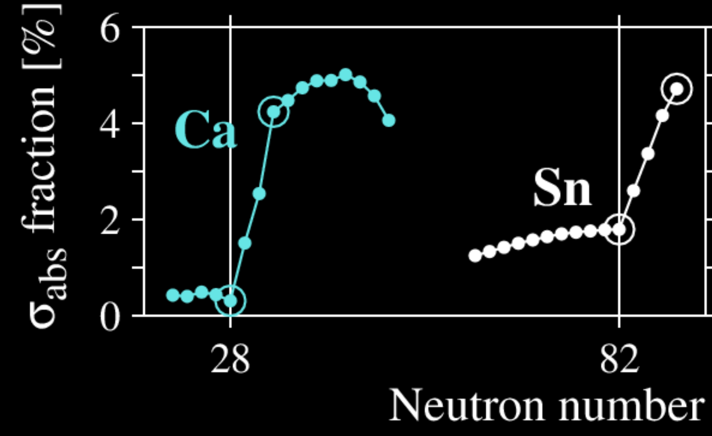
Inakura+, PRC84, 021302

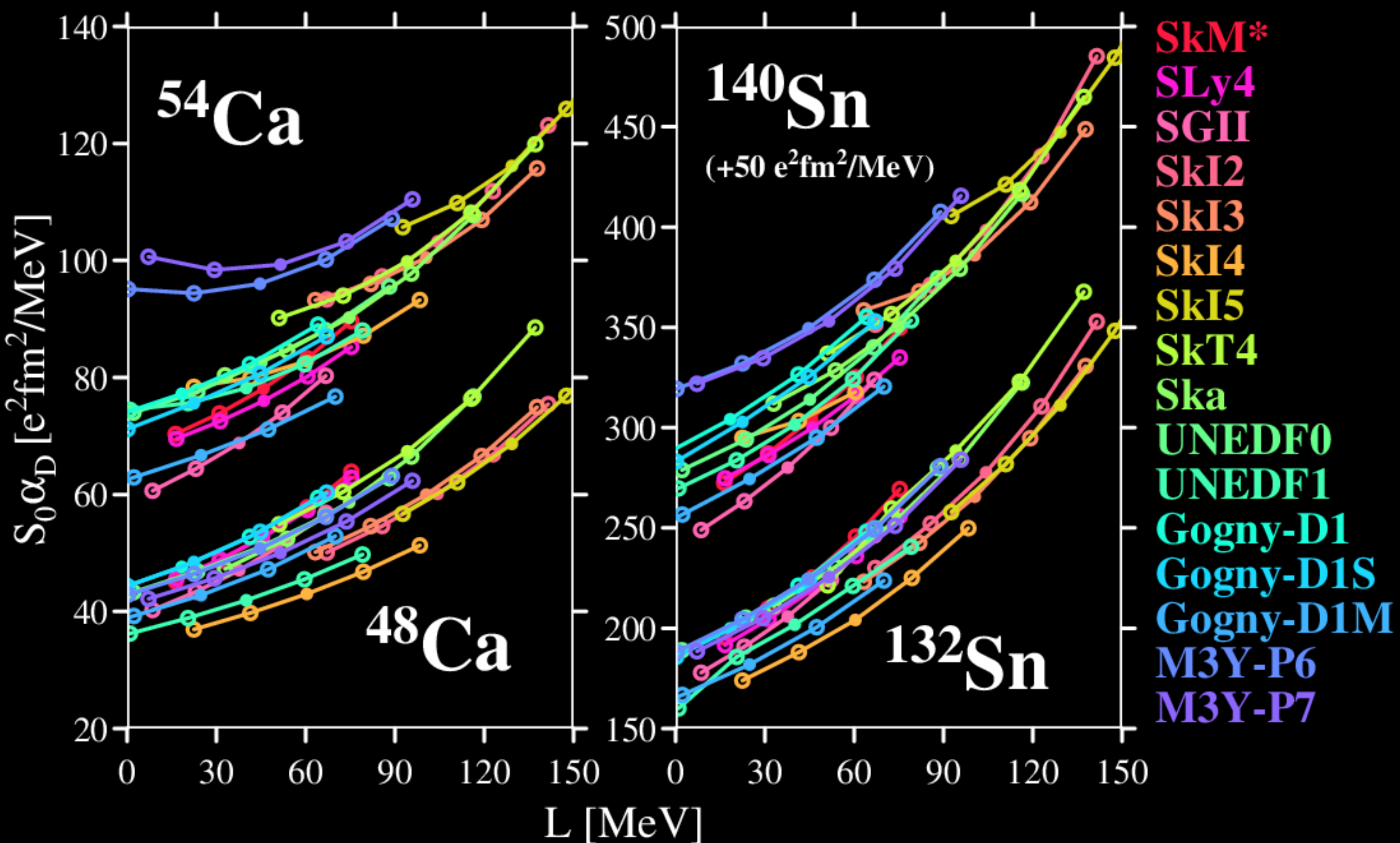


Canonical-basis TDHFB
Ebata, Nakatsukasa, Inakura, PRC90, 024303

LED appears in all calculated isotopes and develops in ν-rich region **beyond** ***N* = 28, 50, 82**, although only **^{48}Ca, ^{68}Ni, ^{132}Sn, ^{208}Pb** have been analyzed.

Well-developed LED makes correlation conspicuous.





Summary

E1 mode is useful to constrain slope parameter L.

- $\alpha_D S_0$ correlates to L.
- Heavy mass & well-developed LED make their correlation more conspicuous, and therefore better for constraining L.
- However, model dependence remains somewhat.