

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

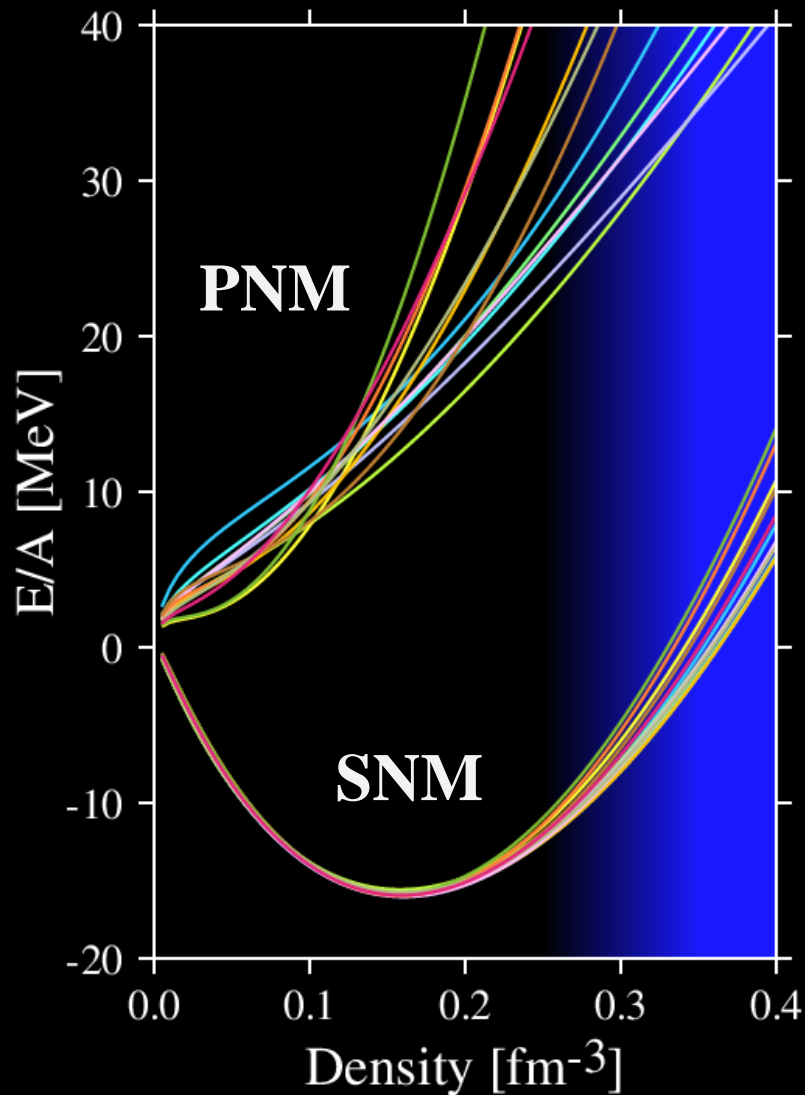
2015年3月12-14日

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Nuclear Matter Equation of State (EoS)



EoS calculated with effective interactions

- ✓ Pure Neutron Matter (PNM)
- ✓ Symmetric Nuclear Matter (SNM)

Quantities characterizing EoS

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

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

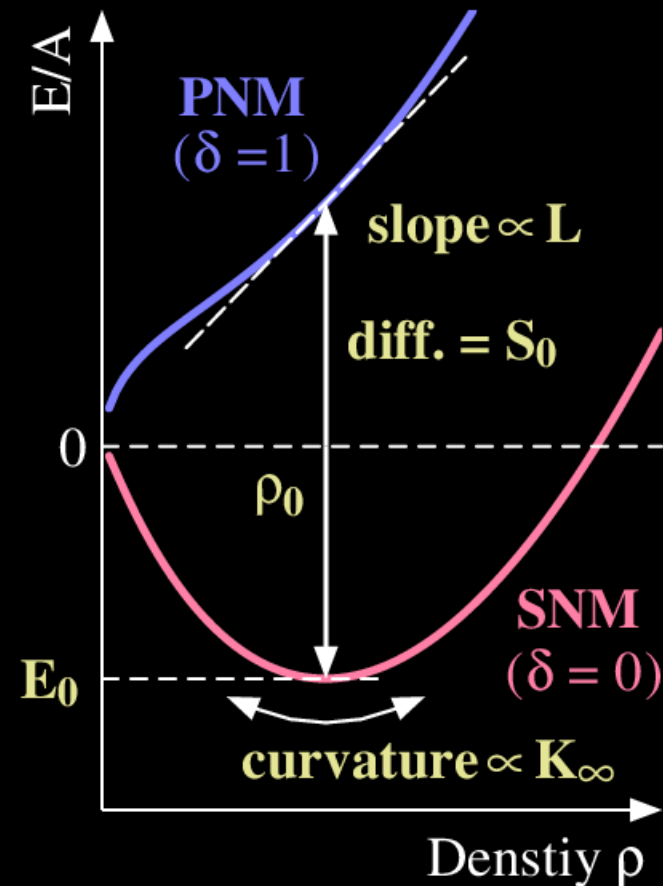
$$\text{SNM: } \frac{E}{A}(\rho, \delta=0) = E_0 + \frac{K_\infty}{2}x^2 + \dots$$

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

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

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

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



Quantities characterizing EoS

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

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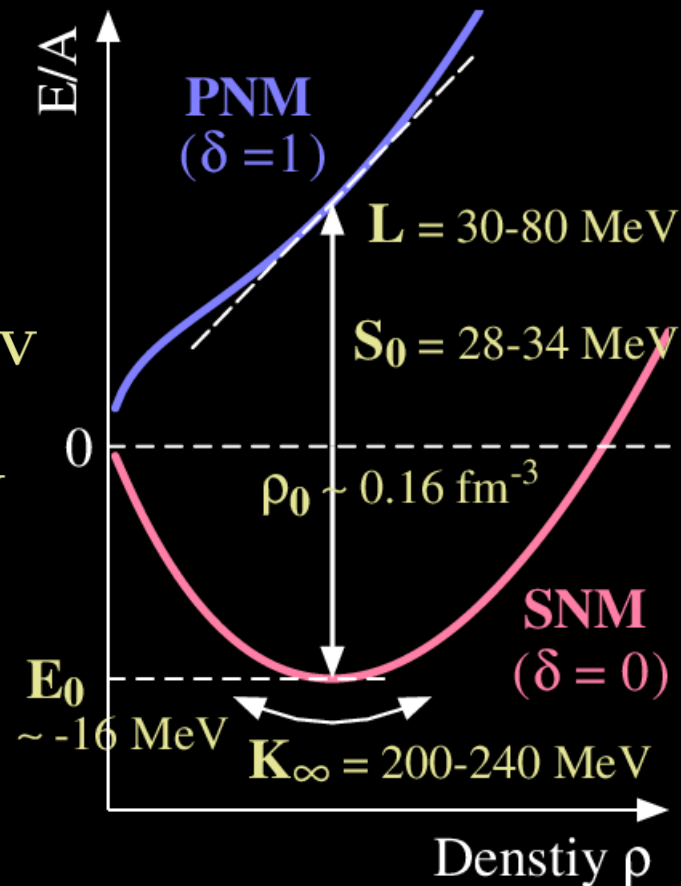
$$\text{SNM: } \frac{E}{A}(\rho, \delta=0) = E_0 + \frac{K_\infty}{2}x^2 + \dots$$

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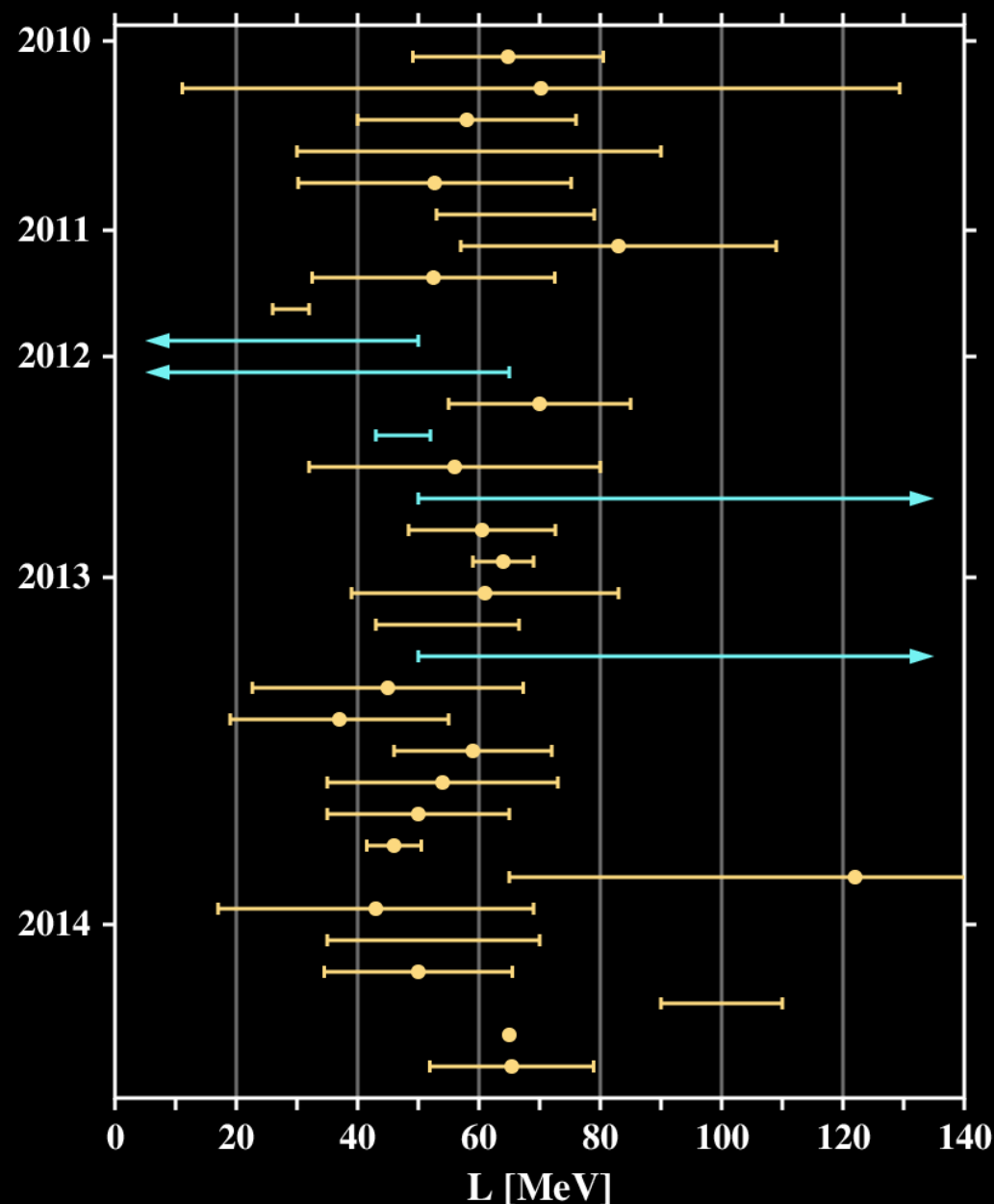
$$K_\infty = 9\rho_0^2 \frac{d^2}{d\rho^2} \frac{E(\rho, \delta=0)}{A} \Big|_{\rho=\rho_0} = 200 - 240 \text{ MeV}$$

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

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

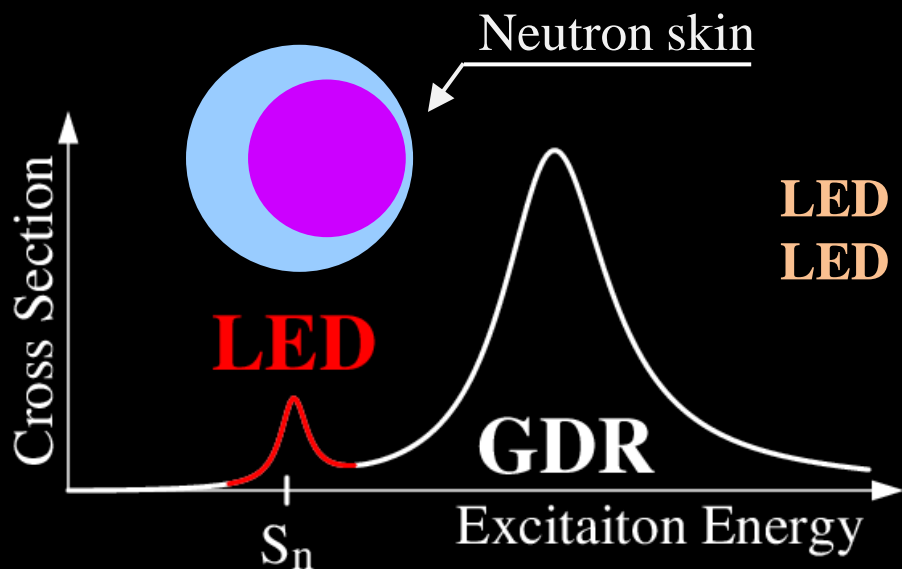


L from observables and calculations



PDR in ^{68}Ni & ^{132}Sn , Crabone+, PRC81, 041301
nuclear mass, Kortelainen+, PRC82, 024313
skin in Sn, Chen+, PRC82, 024321
 ^{208}Pb expt., Zenihiro+, PRC82, 044611
optical potential, Xu+, PRC82, 054607
nuclear mass, Liu+, PRC82, 064306
Au+Au HIC, Russotto+, PLB697, 471
nuclear mass, Chen, PRC83, 044308
skin thickness, Gaidarov+, PRC84, 034316
torsional oscillation, Gearheart+, MNRAS 418, 2343
troidal mode, Wen+ PRL85, 025801
nuclear mass, Moeller+, PRL108, 052501
NS data, Steiner+, PRL108, 081102
nuclear mass, Dong+, PRC85, 034308
troidal mode, Vidana, PRC85, 045808
covariance analysis, Fattoyev+, PRC86, 015802
skin in Sn, Agrawal+, PRL109, 262501
alpha-decay energy, Dong+, PRC87, 014303
chiral EFT, Tews+, PRL110, 032504
torsional oscillation, Sotani+, MNRAS 434, 2060
neutron-nucleus scattering data, Li+, PLB721, 101
GQR in ^{208}Pb , Roca-Maza+, PRC87, 034301
nuclear mass, Agrawal+, PRC87, 051306
charge radius, Wang+, PRC88, 011301
beta-decay energy, Dong+, PRC88, 014302
mass & skin, Zhang+, PLB726, 234
Au+Au HIC & UrQMD, Cozma+, PRC88, 044912
polarizability in ^{208}Pb , Roca-Maza+, PRC88, 024316
isobaric analog state, Danielewicz+, NPA922, 1
mass difference, Fan+, PRC89, 017305
elliptic flow & UrQMD, Wang+, PRC89, 044603
variation on Thomas-Fermi, Papazoglou+, PRC90, 014305
emprical EoS, Alam+, PRC90, 054317

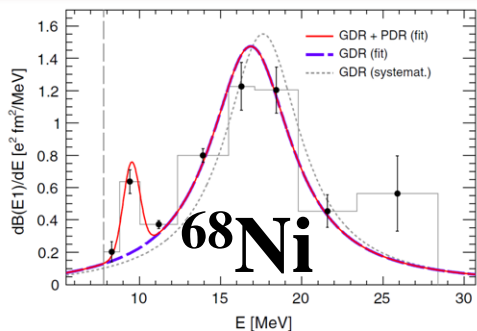
Low-Energy Dipole mode (LED) = Pygmy Dipole Resonance (PDR)
= Low-lying E1 strength



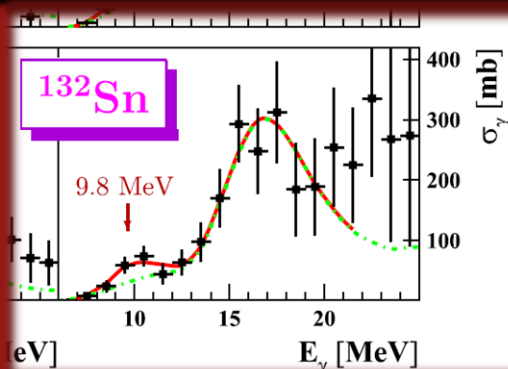
LED in stable nuclei: < 1% Cross Section
LED in ν -rich nuclei: < several % Cross Section

LED could provide some information of PNM EoS!

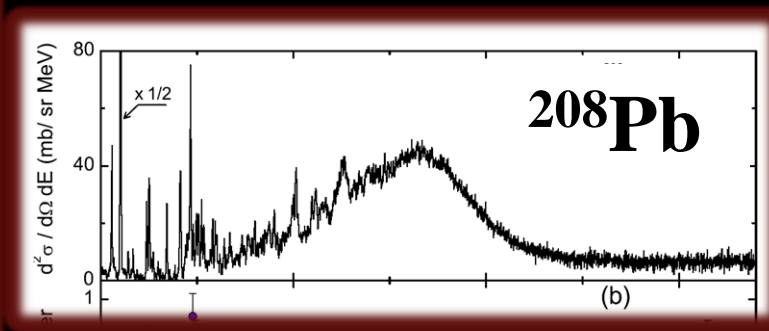
Rossi+, PRL 111, 242503



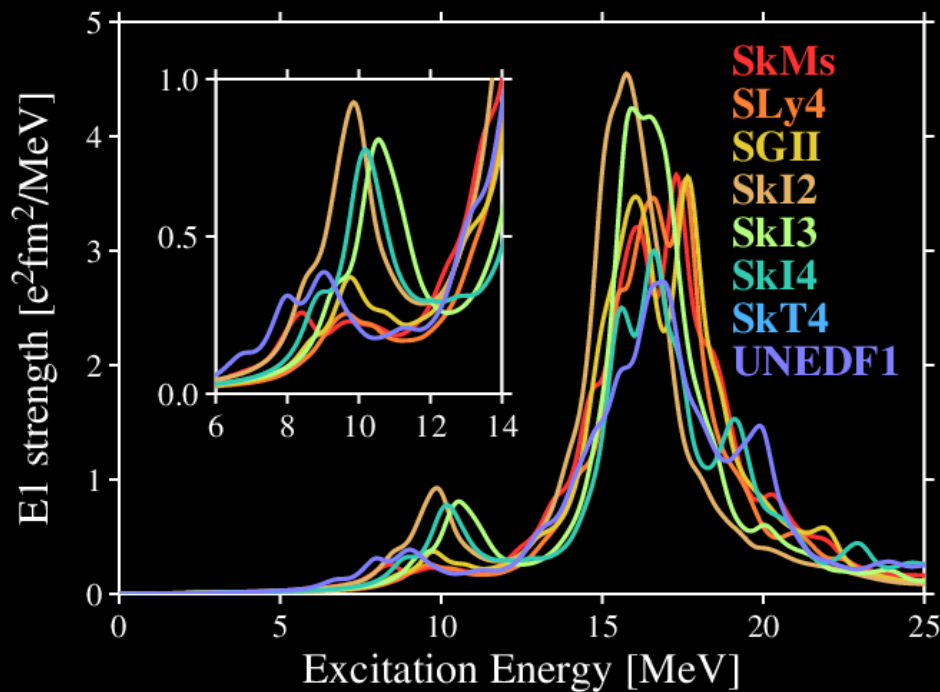
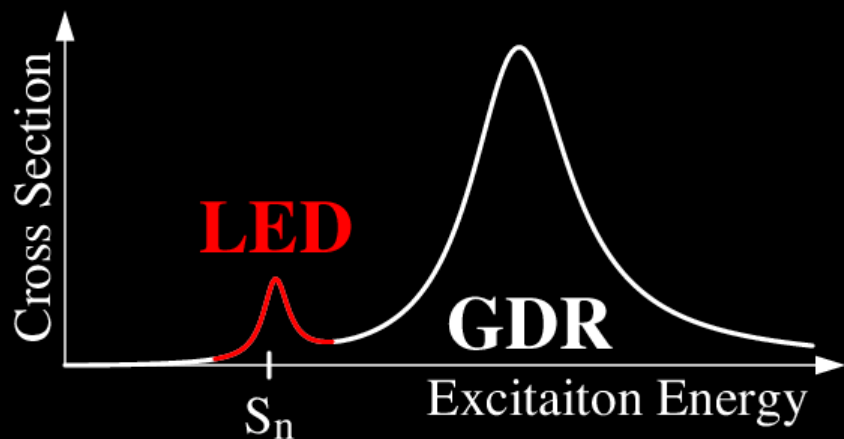
Adrich+, PRL 95, 132501



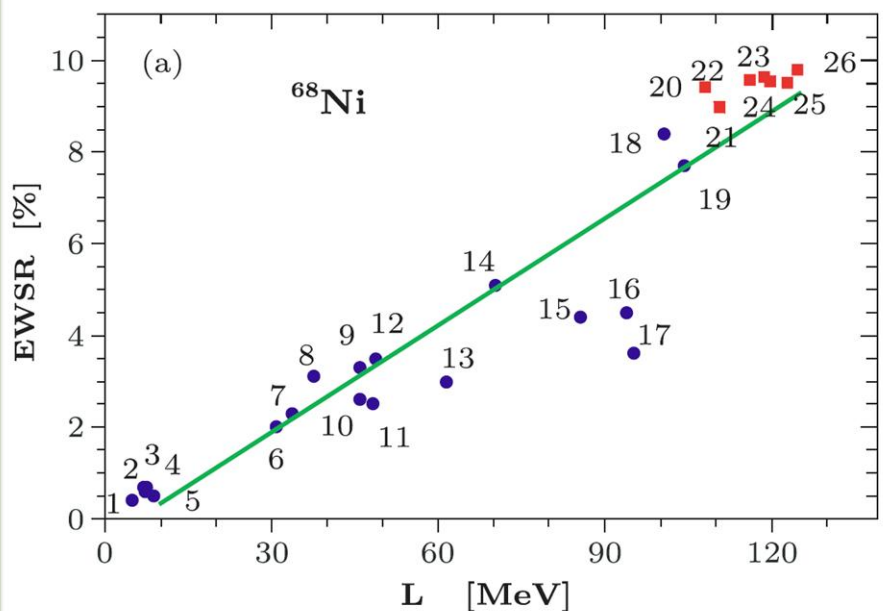
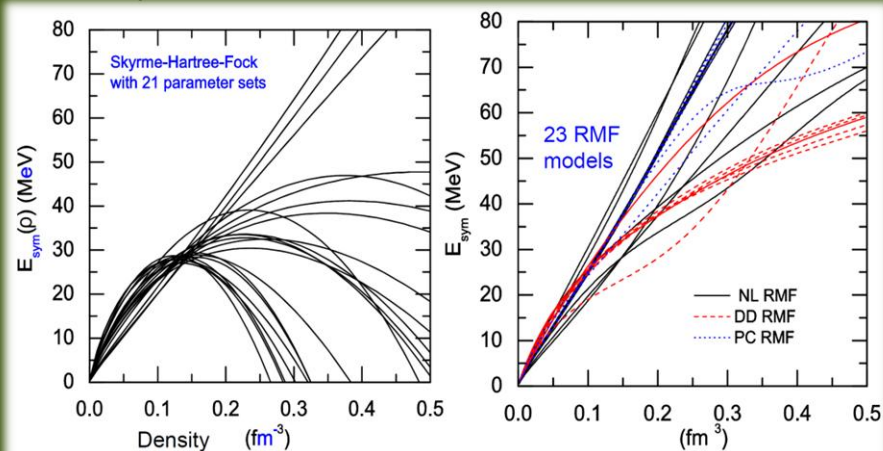
Tamii+, PRL 107, 062502



L from LED cross section

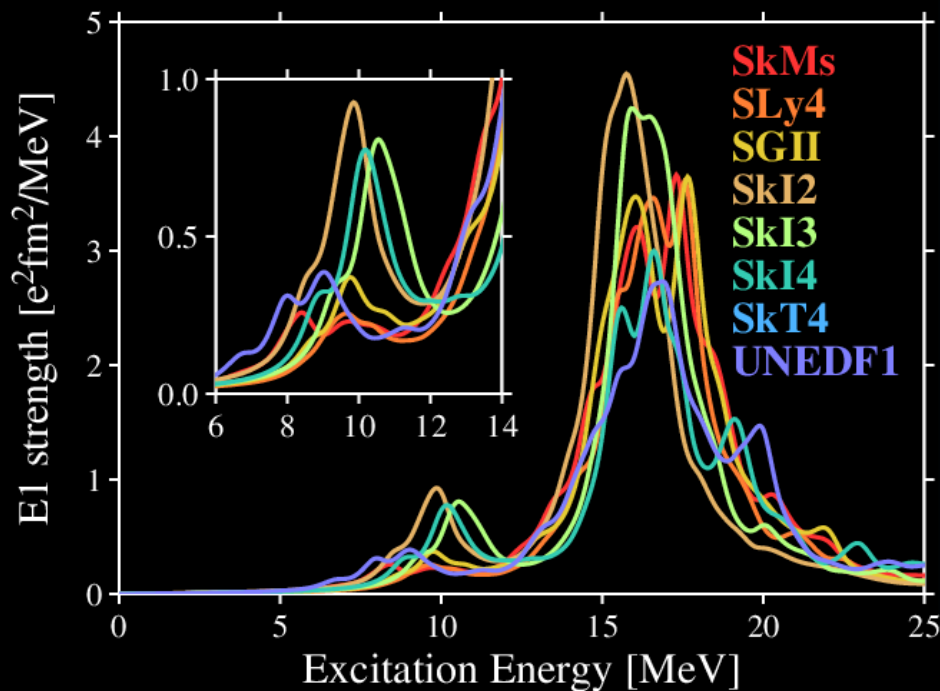
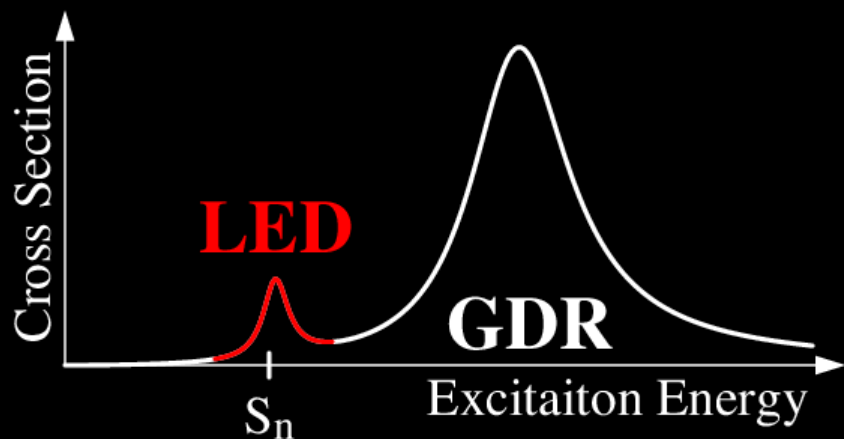


Chen+, PRC72, 064309; PRC76, 054316

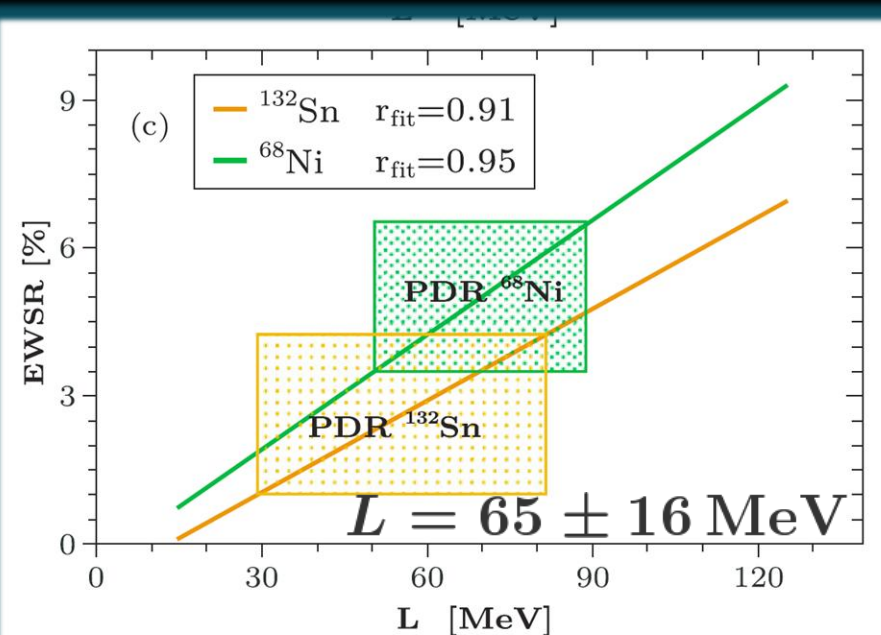
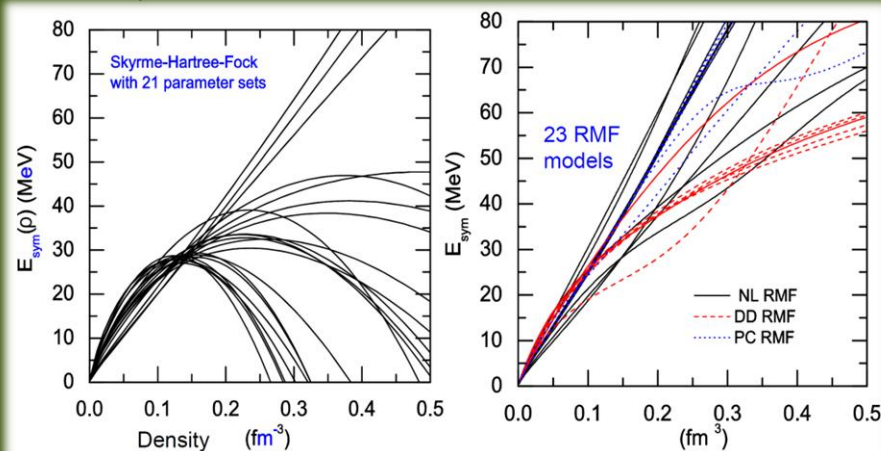


Carbone+, PRC81, 041301® (2010)

L from LED cross section



Chen+, PRC72, 064309; PRC76, 054316



Carbone+, PRC81, 041301® (2010)

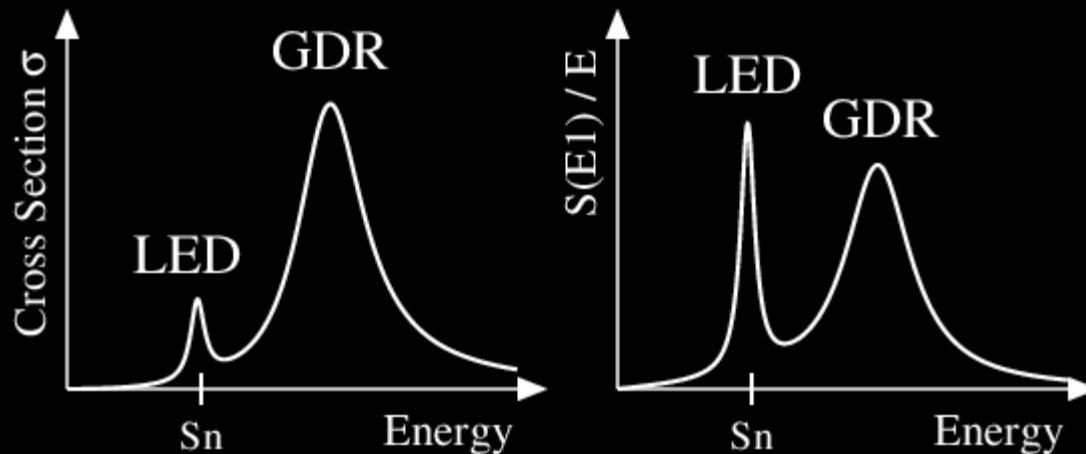
Cross section(σ) & Polarizability(α_D)

Covariance Analysis

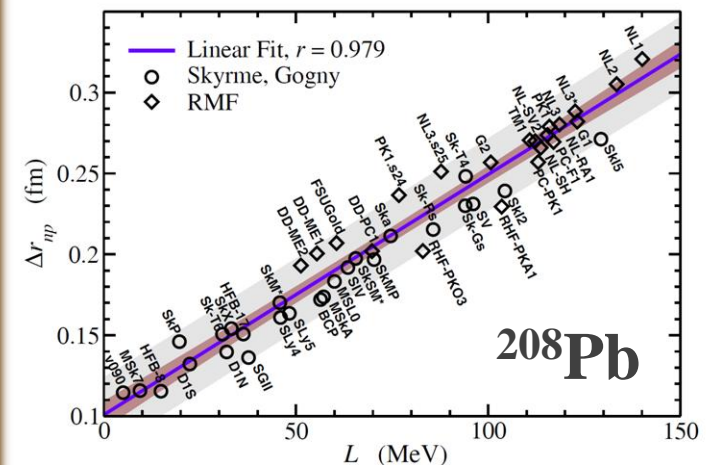
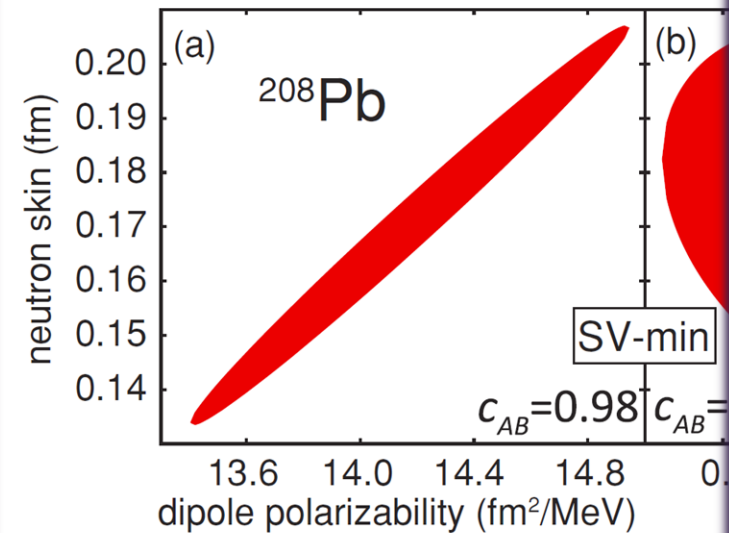
Reinhard+, PRC81, 051303

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

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



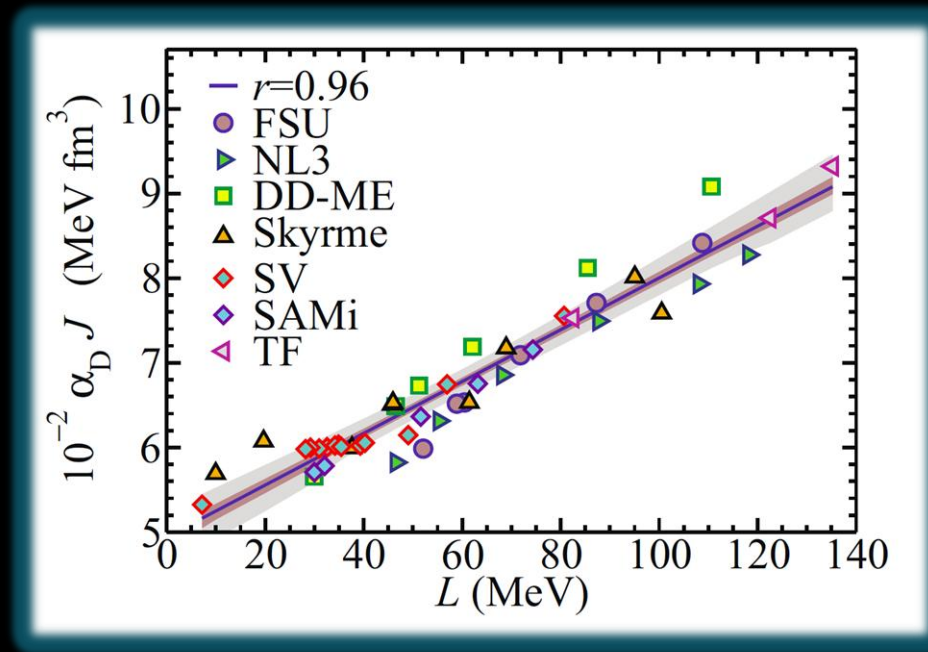
Roca-Maza+,
PRL 106, 252501



New correlation

Droplet Model (with some approximations & assumptions) yields

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

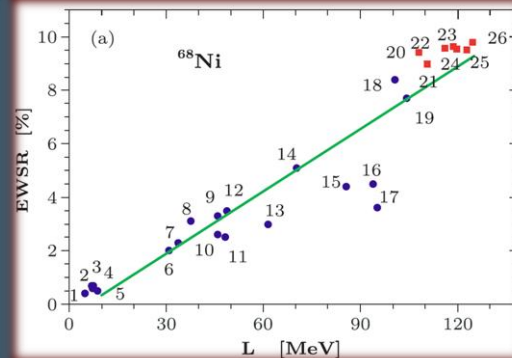
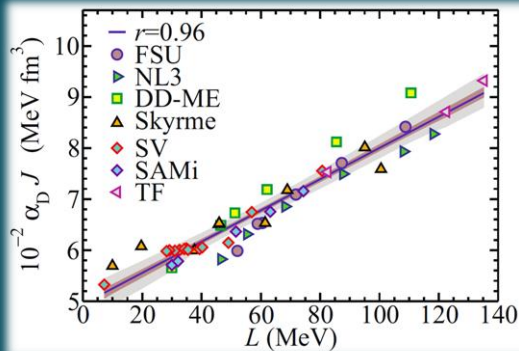
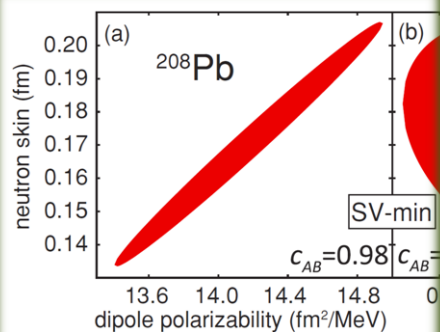


Roca-Maza+, PRC88, 024316 (2013)

L from E1 mode

Which is best?

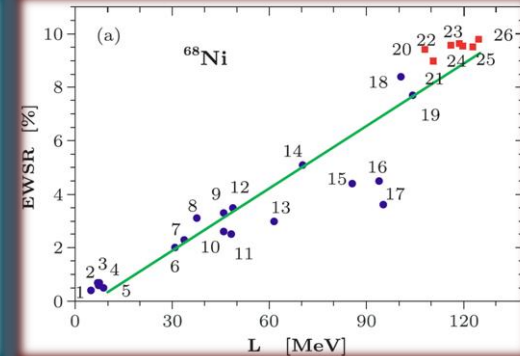
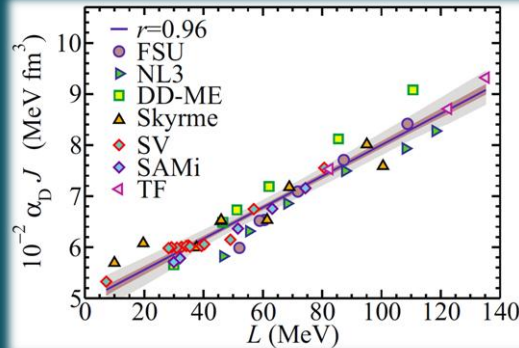
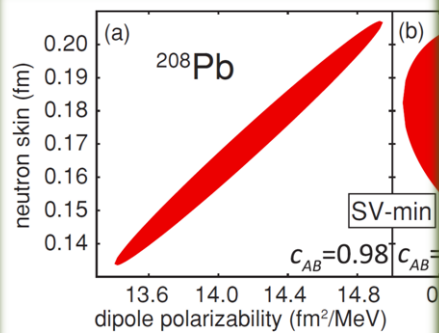
Interaction-dependence?



L from E1 mode

Which is best?

Interaction-dependence?



Correlation is analyzed within **single** interaction

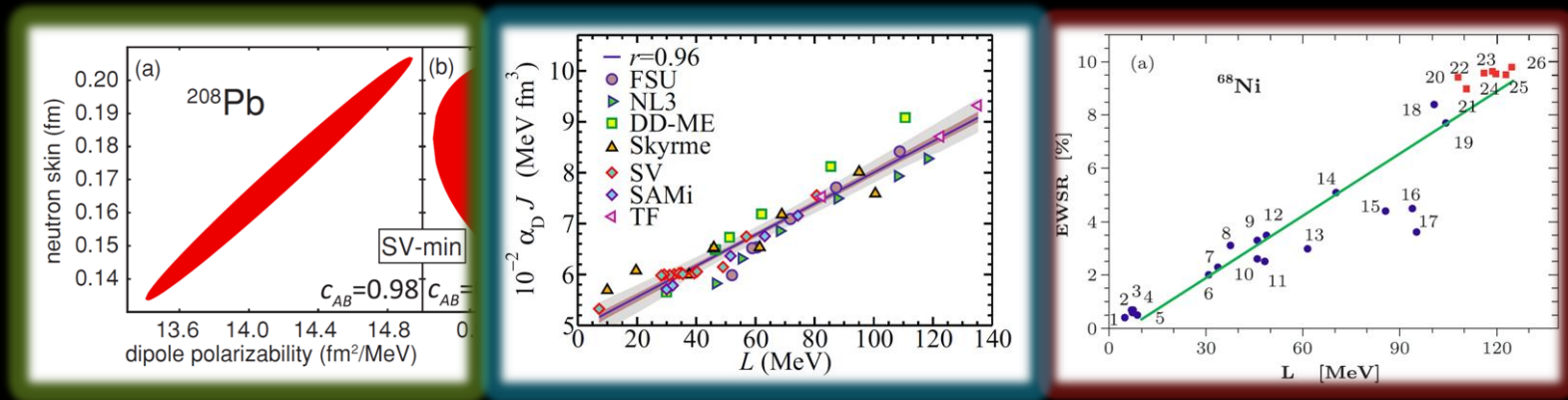
Correlation is calculated using **many** interactions.

Same correlation?

L from E1 mode

Which is best?

Interaction-dependence?



Correlation is analyzed within **single** interaction

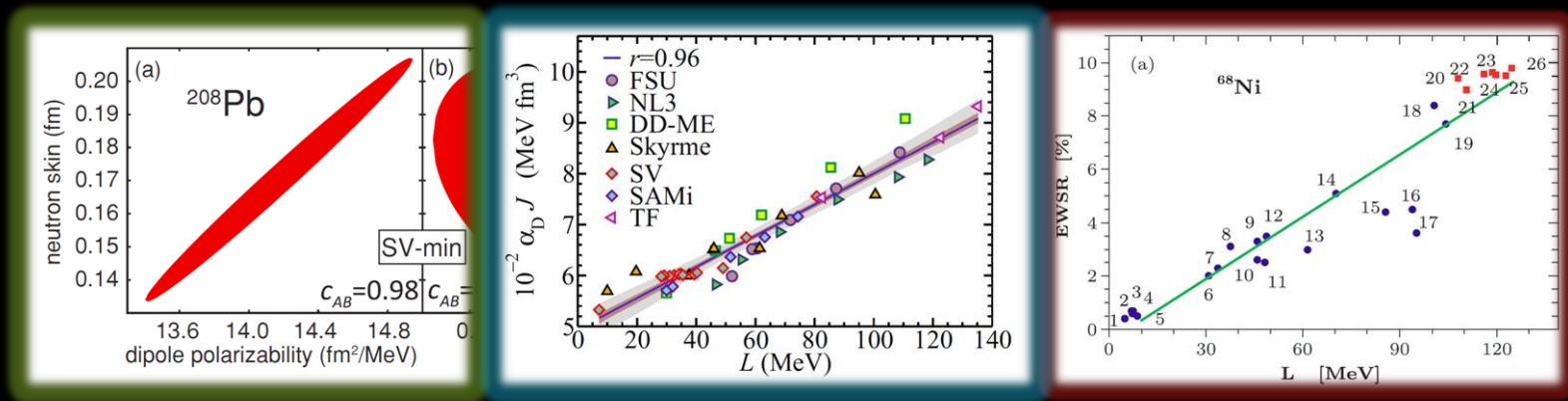
Correlation is calculated using **many** interactions.

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 ⁴⁸Ca, ⁶⁸Ni, ¹³²Sn, ²⁰⁸Pb.

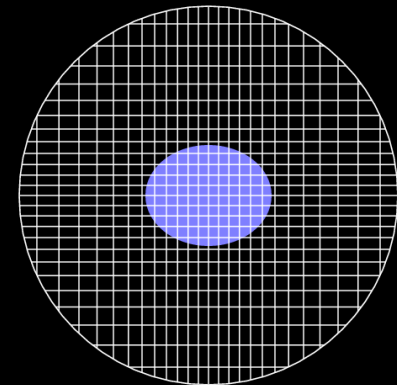
How about other nuclei?

Careful assessment needed!

Linear response calc. with Skyrme in 3D mesh

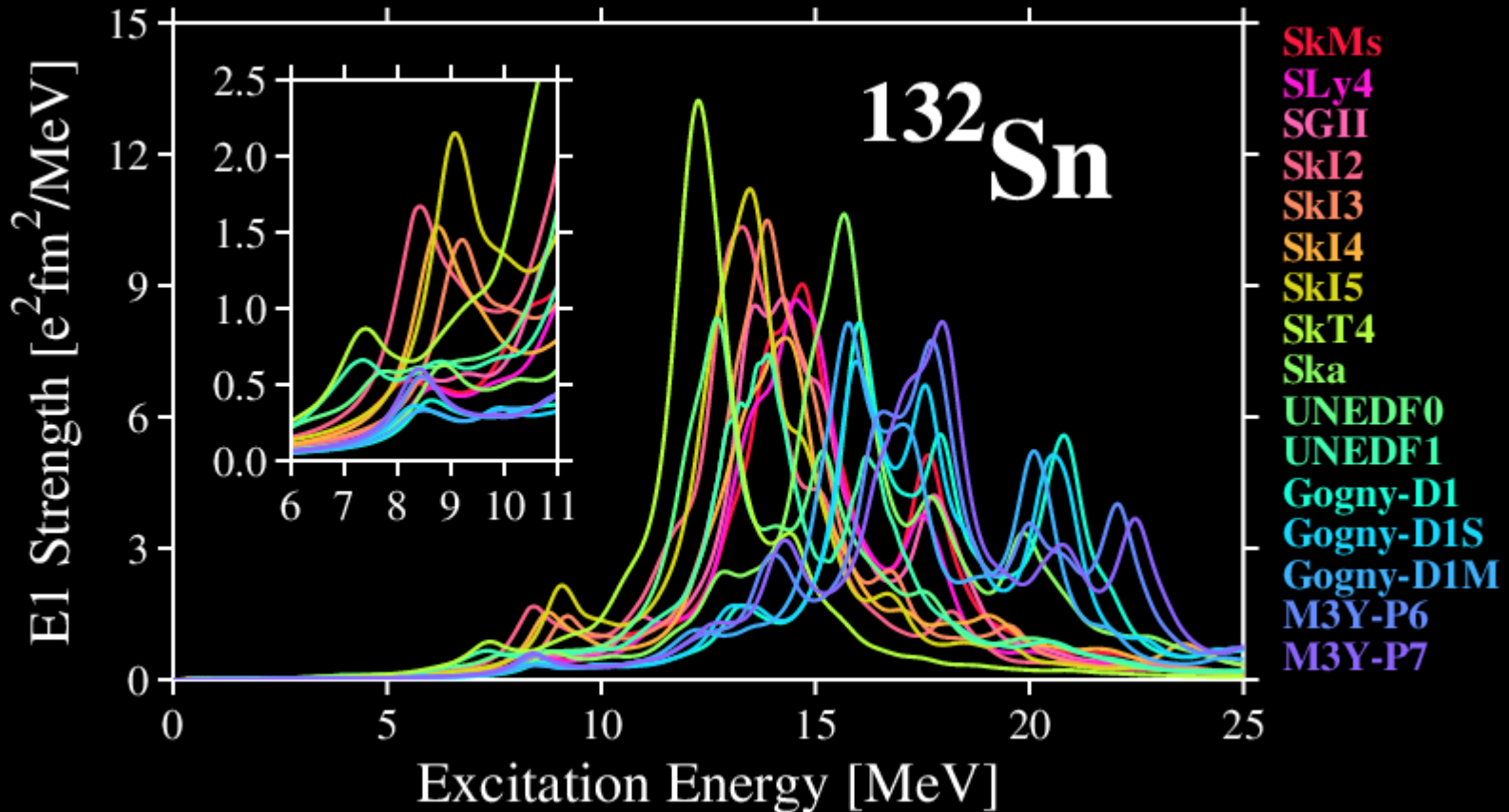
- Density Functional Theory with Skyrme energy functional.
- **Fully self-consistent calculation. PARAMETER FREE!**
- **3D mesh representation**
 - suitable for describing unstable nuclei having skin or halo.
 - deal with continuum states in good approximation.
- **Linear response calculation**
 - compute 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

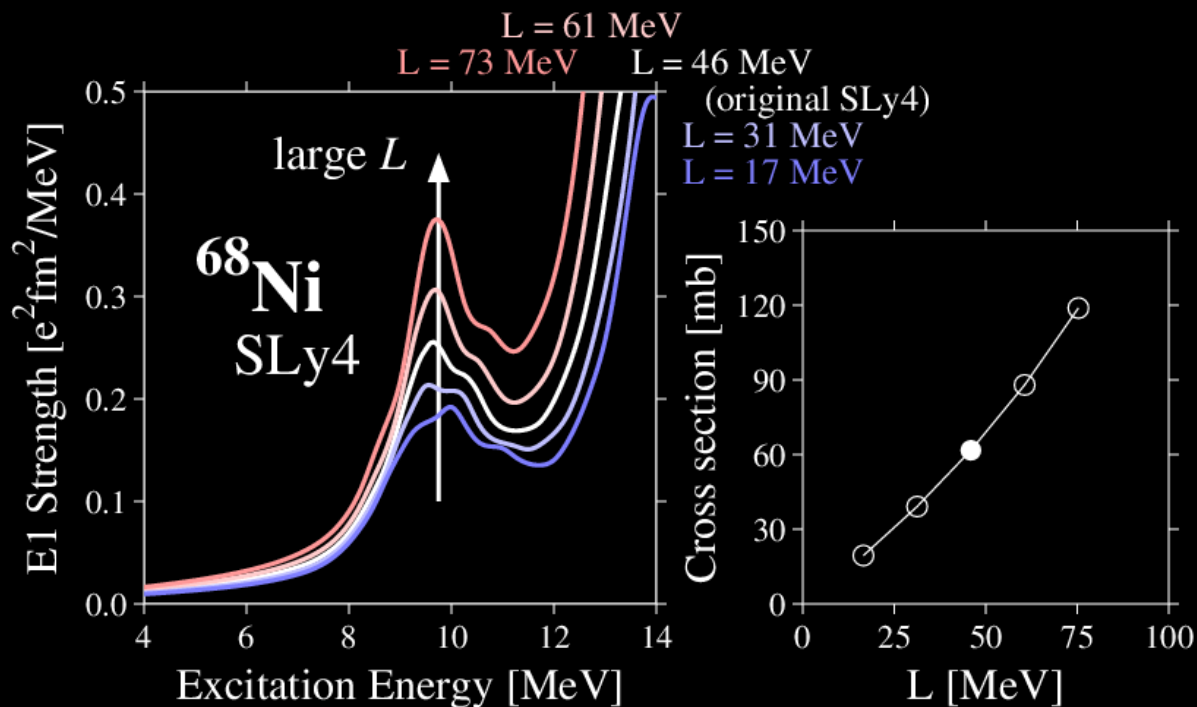
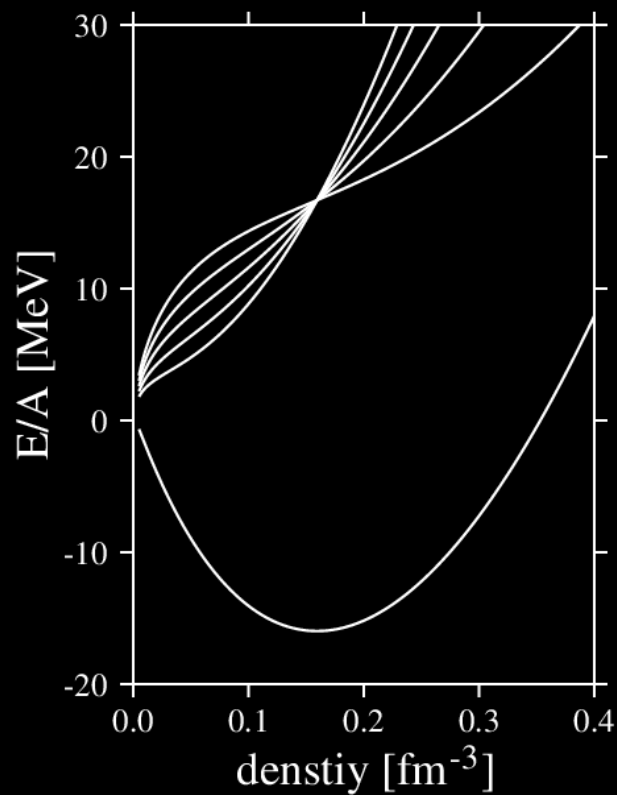
$$V \Rightarrow V - V_L [\rho^\alpha(r) - \rho_0^\alpha] P_\sigma \delta(r)$$

Ref. Ono+, PRC68, 051601

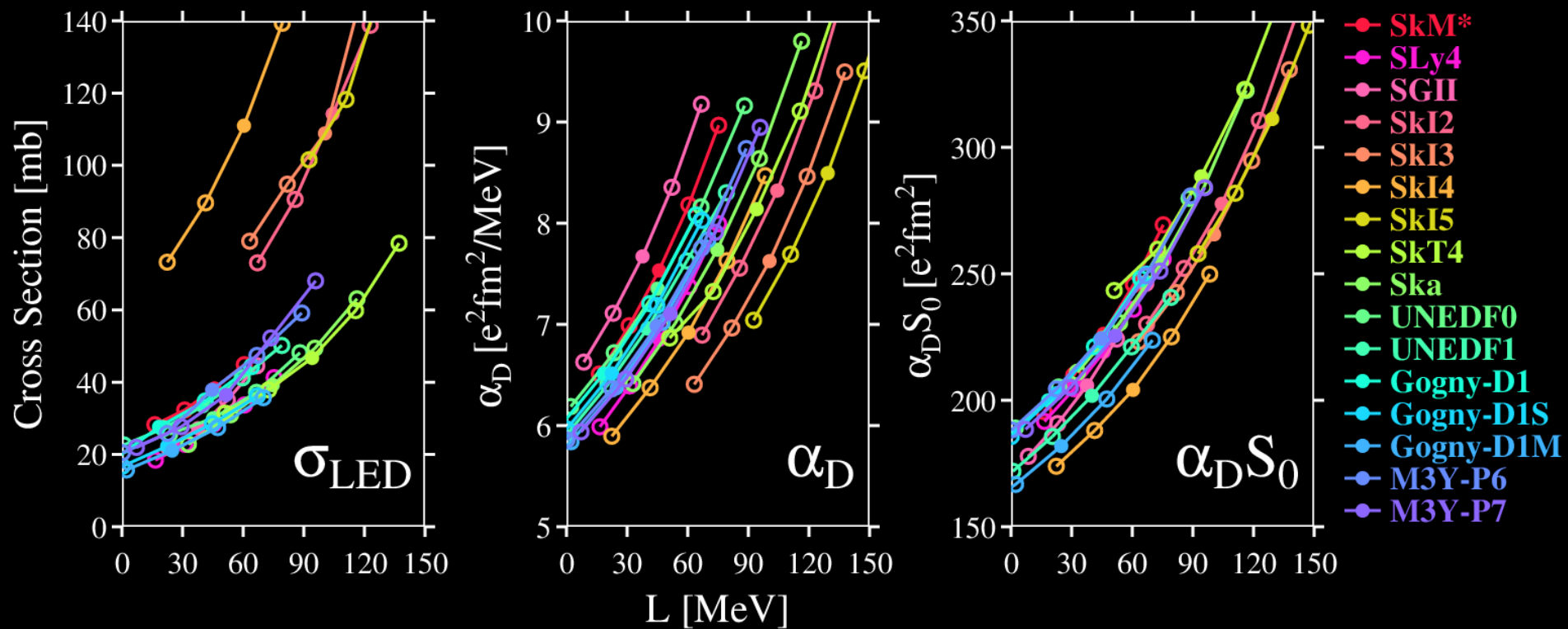
The additional term

- does not affect SNM EoS nor S_0 .
- changes L .

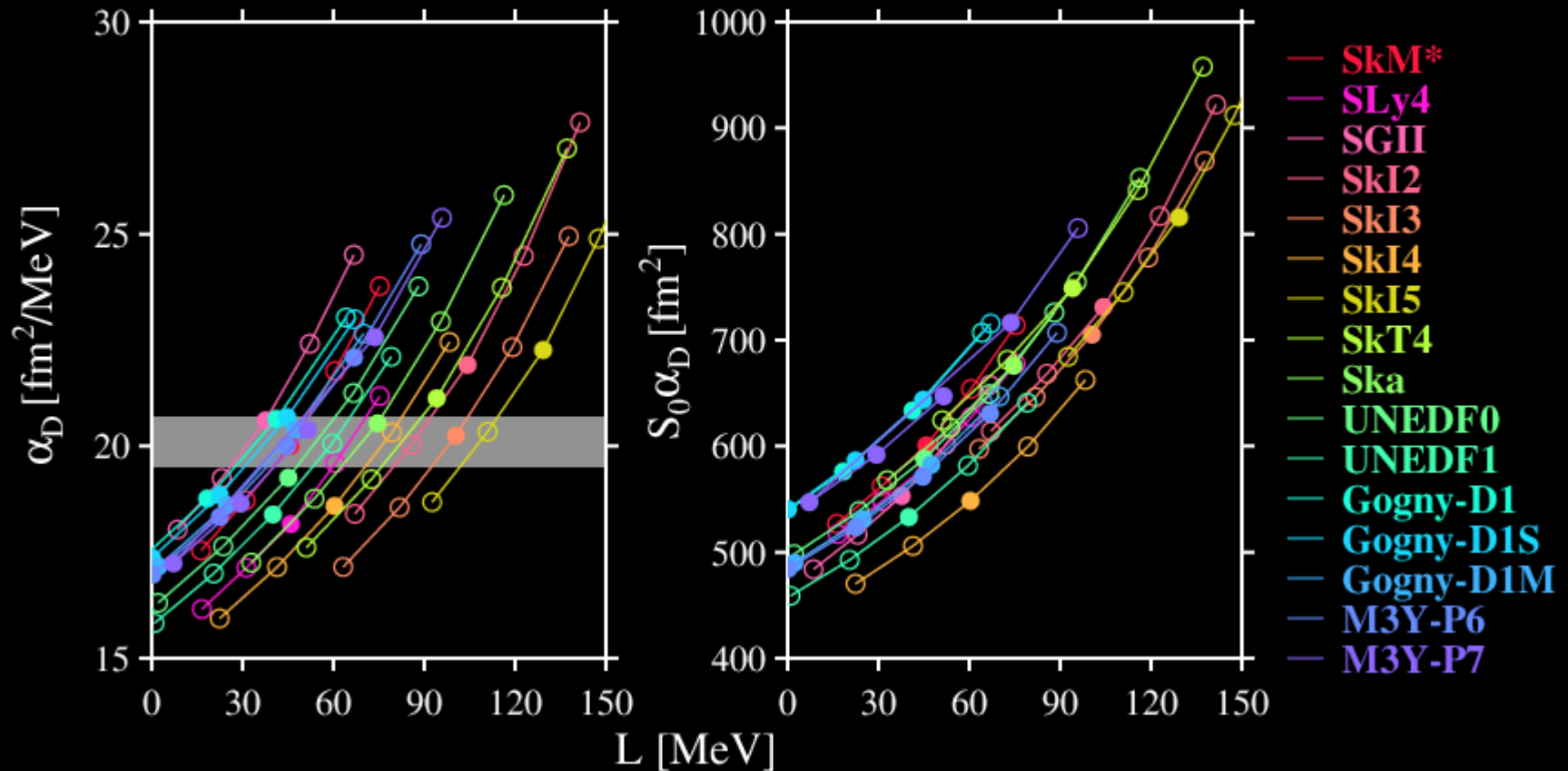
V_L is a parameter to control L .



Correlations in ^{132}Sn

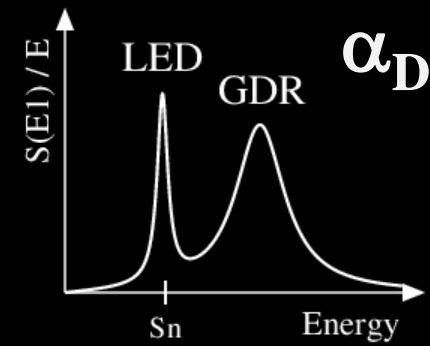
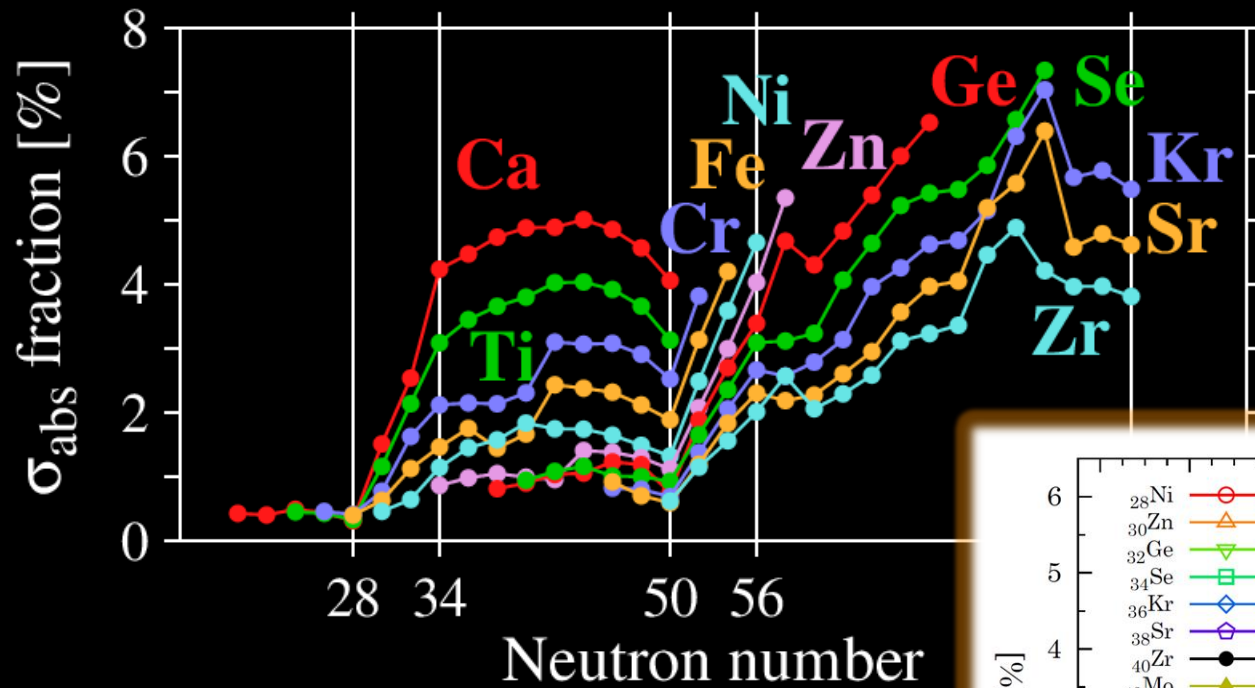


Comparison with experimental data in ^{208}Pb



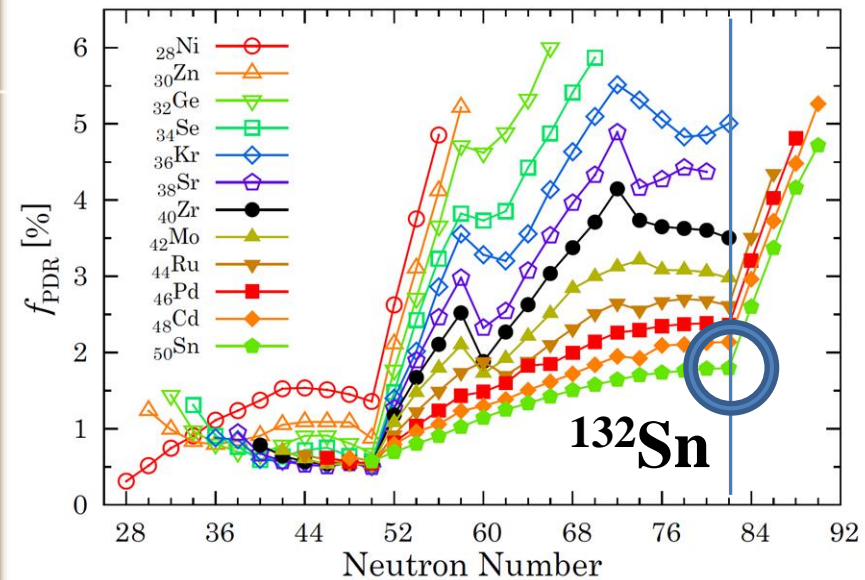
Experimental data: Tamii+, PRL107, 062502

Which LED is better?



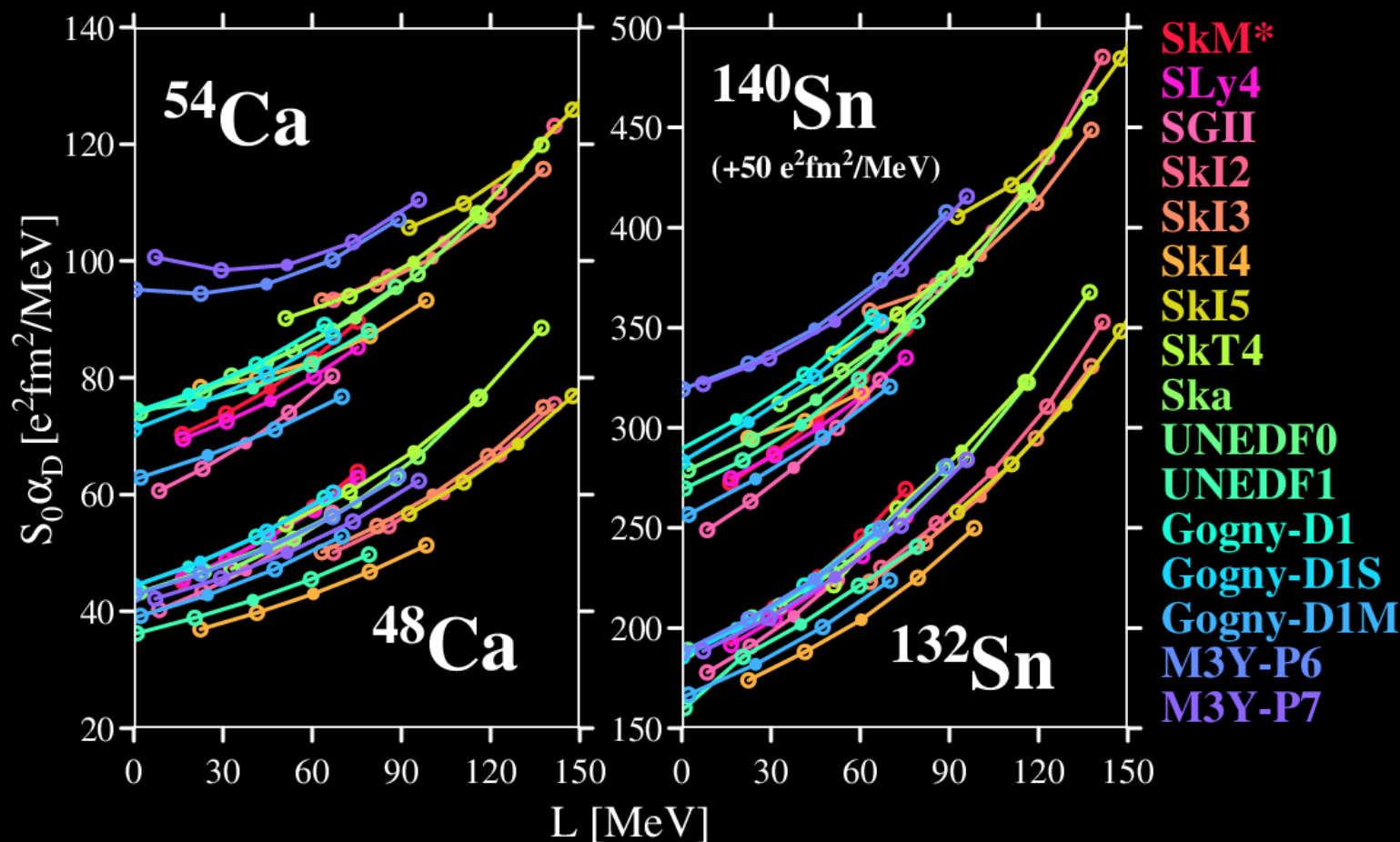
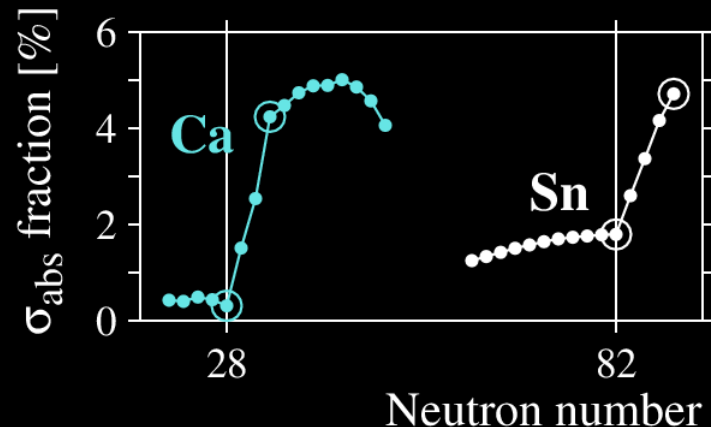
Inakura+,
PRC84, 021302

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.



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

**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.