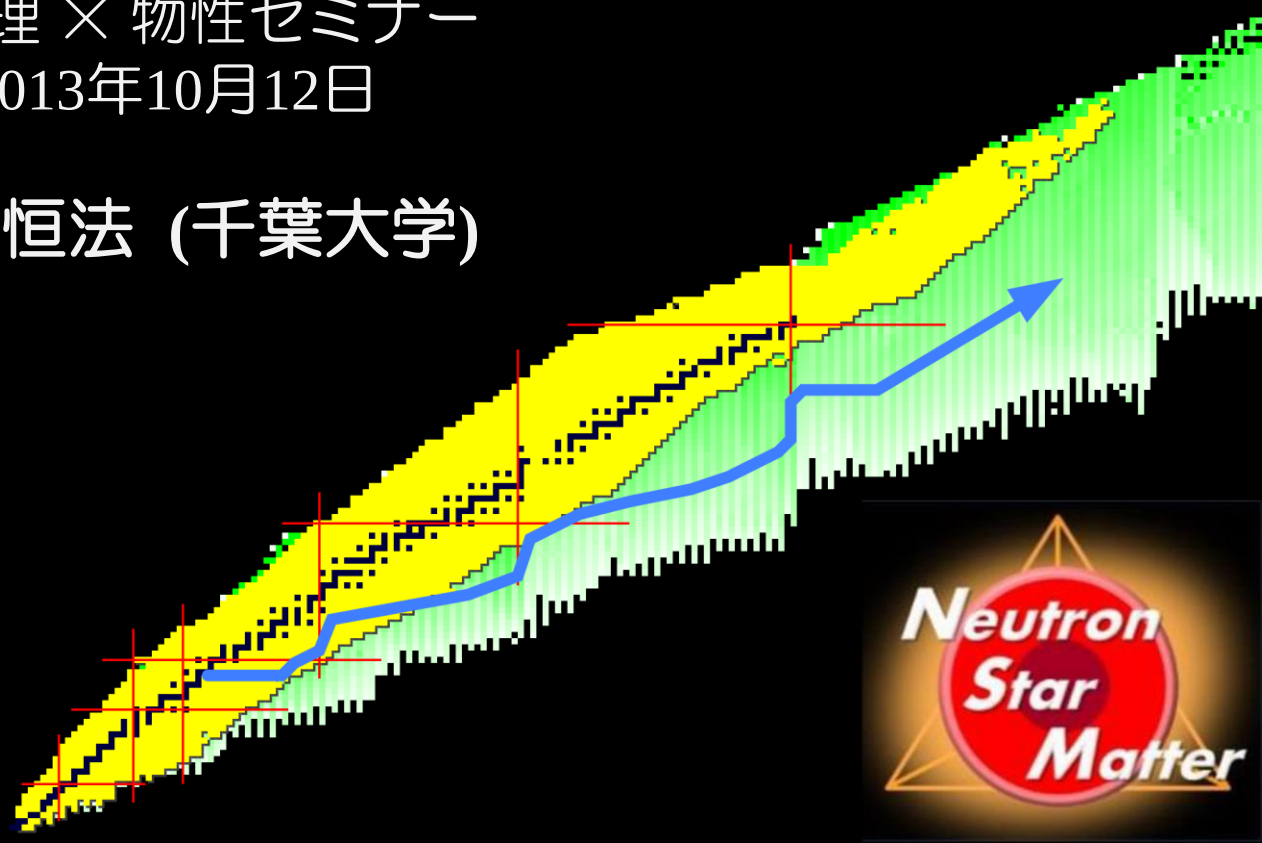
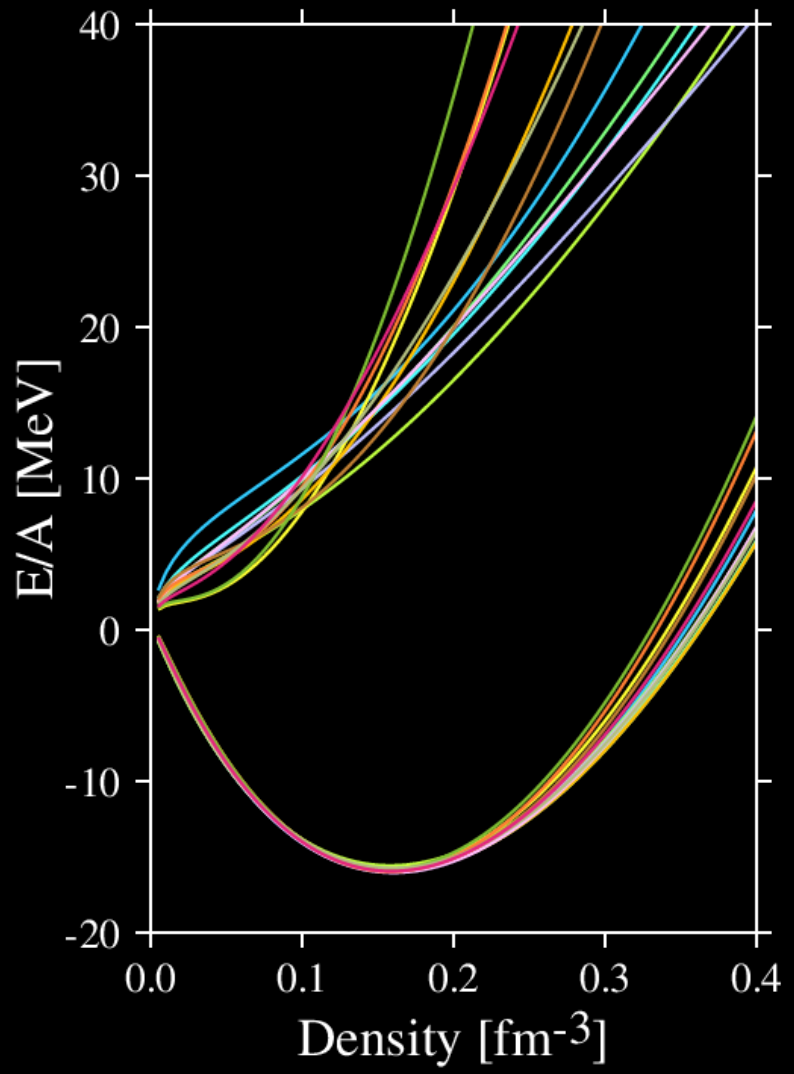
不安定核のダイポール励起と核物質の状態方程式

千葉工業大学
核物理 × 物性セミナー
2013年10月12日

稲倉恒法 (千葉大学)



核物質の状態方程式



現象論的核力を用いた
中性子物質の状態方程式
(Pure Neutron Matter, PNM)

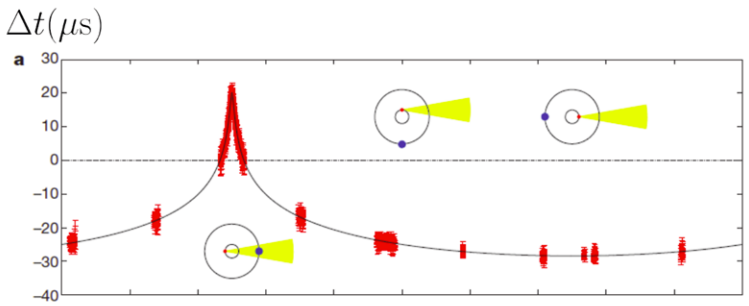
対称核物質の状態方程式
(Symmetric Nuclear Matter, SNM)

TWO SOLAR MASS PROBLEM

Demorest al. 2010 nature

A two-solar-mass neutron star measured using Shapiro delay

P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

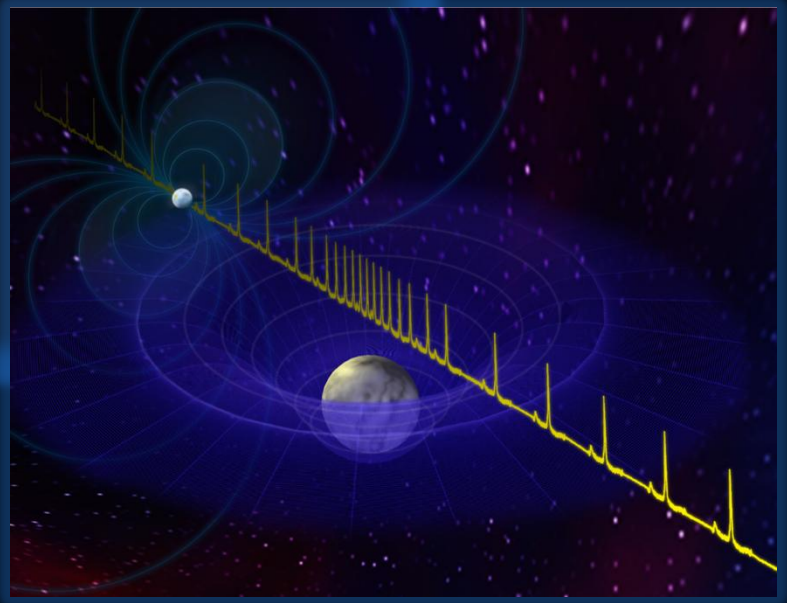


M~1.97 Ms

Credit: Bill Saxton

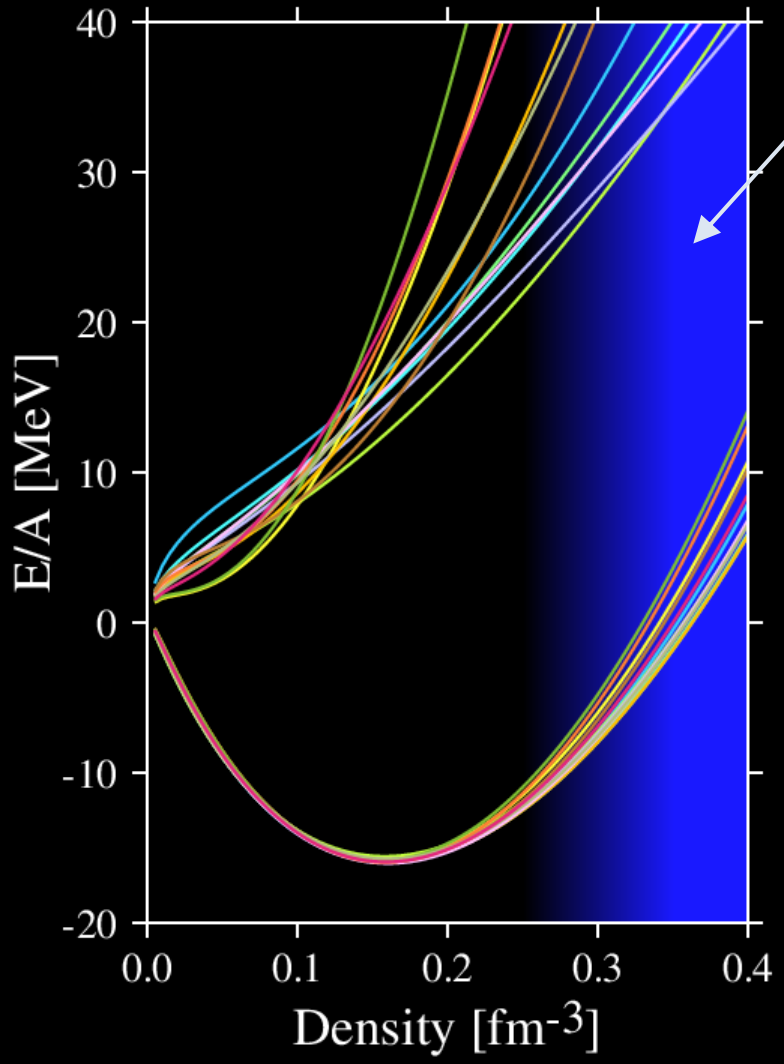
Shapiro delay

Radar signals passing near a massive object take slightly longer to travel to a target and longer to return than they would if the mass of the object were not present.

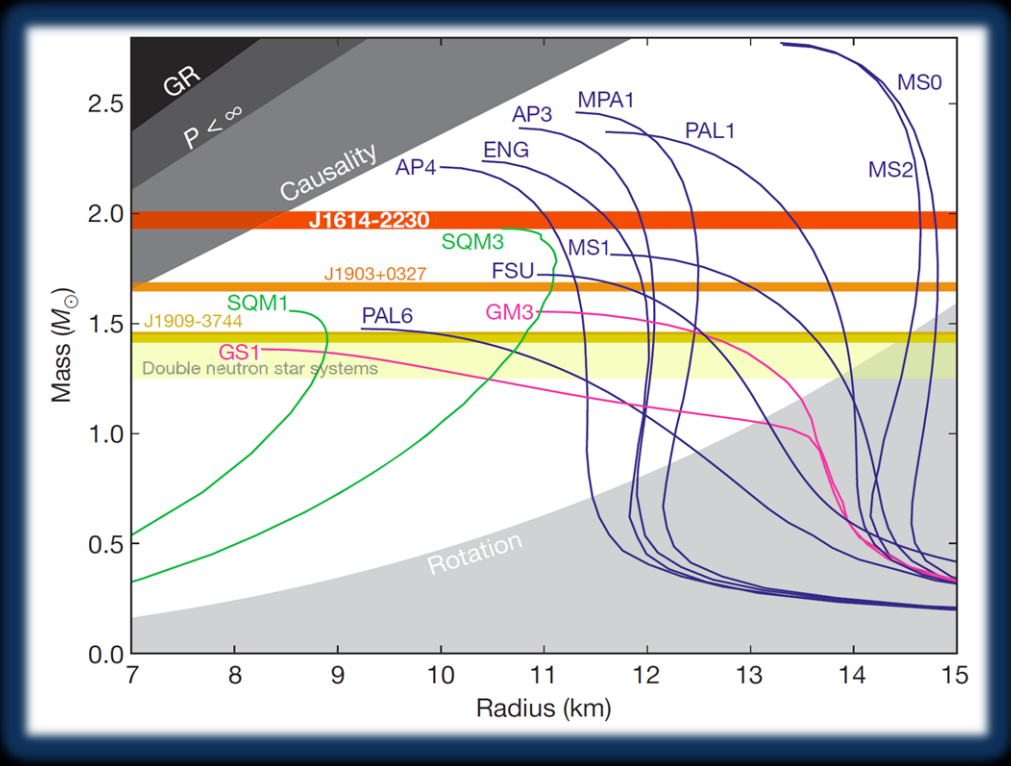


courtesy Yasutake

核物質の状態方程式と中性子星の最大質量



Hyperon の出現



Demorest et al., Nature 467, 1081 (2010)

状態方程式を特徴付ける物理量

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

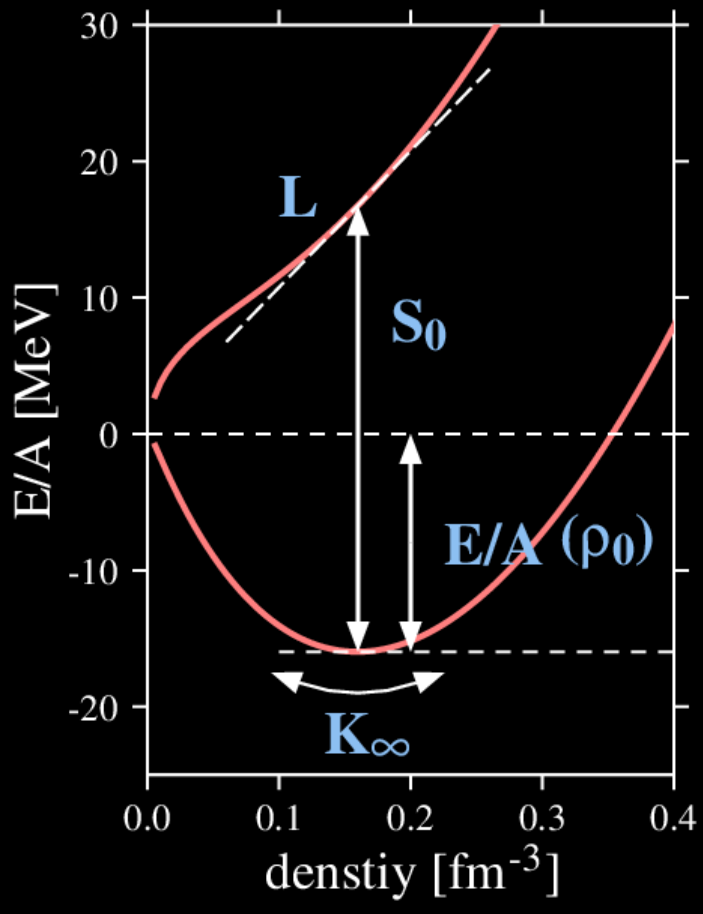
$$\delta = \frac{\rho_n-\rho_p}{\rho_n+\rho_p} \sim \frac{N-Z}{A},\ x = \frac{\rho-\rho_0}{3\rho_0}$$

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

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

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

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

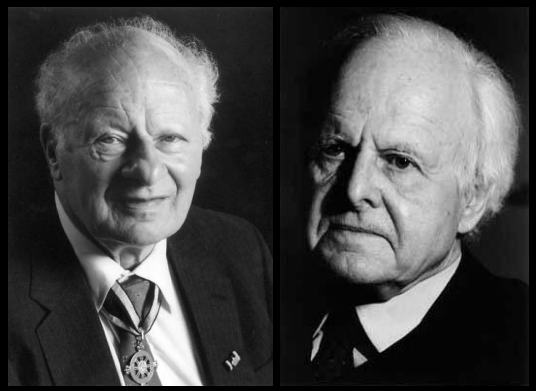


Bethe-Weizsäcker mass formula & EoS

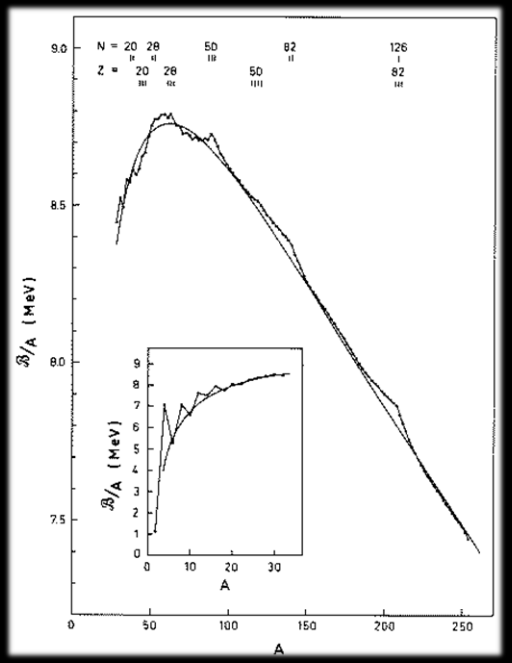
$$\frac{B(N,Z)}{A} = a_{\rm vol} - \frac{a_{\rm surf}}{A^{1/3}} - a_{\rm coul}\frac{Z^2}{A^{4/3}} - a_{\rm sym}\frac{(N-Z)^2}{A^2} + \frac{E_{\rm others}}{A}$$

$$\frac{E}{A}(\rho,\delta) = \left[\frac{E}{A}(\rho_0) + \frac{K_\infty}{2}x^2 + \cdots\right] + \left[S_0 + Lx + \frac{K_{\rm sym}}{2}x^2 + \cdots\right]\delta^2 + \mathcal{O}(\delta^4)$$

$$\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p} \sim \frac{N-Z}{A}$$



Hans Albrecht Bethe & Friedrich von Weizsäcker



A. Bohr and B.R. Mottleson,
Nuclear Structure, vol. 1, p.168

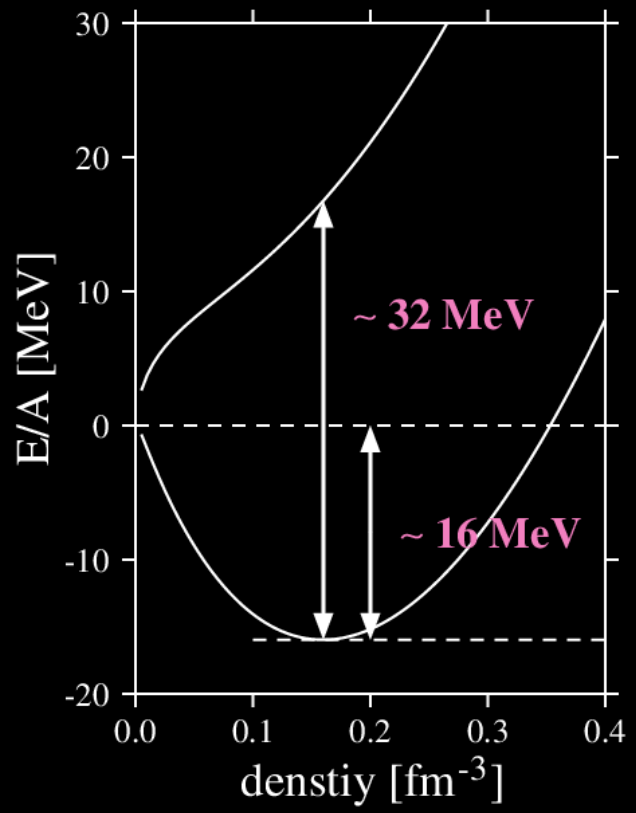
Bethe-Weizsäcker mass formula & EoS

$$\frac{B(N,Z)}{A} = a_{\rm vol} - \frac{a_{\rm surf}}{A^{1/3}} - a_{\rm coul}\frac{Z^2}{A^{4/3}} - a_{\rm sym}\frac{(N-Z)^2}{A^2} + \frac{E_{\rm others}}{A}$$

$$\frac{E}{A}(\rho,\delta) = \left[\frac{E}{A}(\rho_0) + \frac{K_\infty}{2}x^2 + \cdots\right] + \left[S_0 + Lx + \frac{K_{\rm sym}}{2}x^2 + \cdots\right]\delta^2 + \mathcal{O}(\delta^4)$$

$$\frac{E}{A}(\rho_0) \simeq a_{\rm vol} \sim -16\,{\rm MeV}$$

$$S_0 \simeq -a_{\rm sym} \sim 32\,{\rm MeV}$$



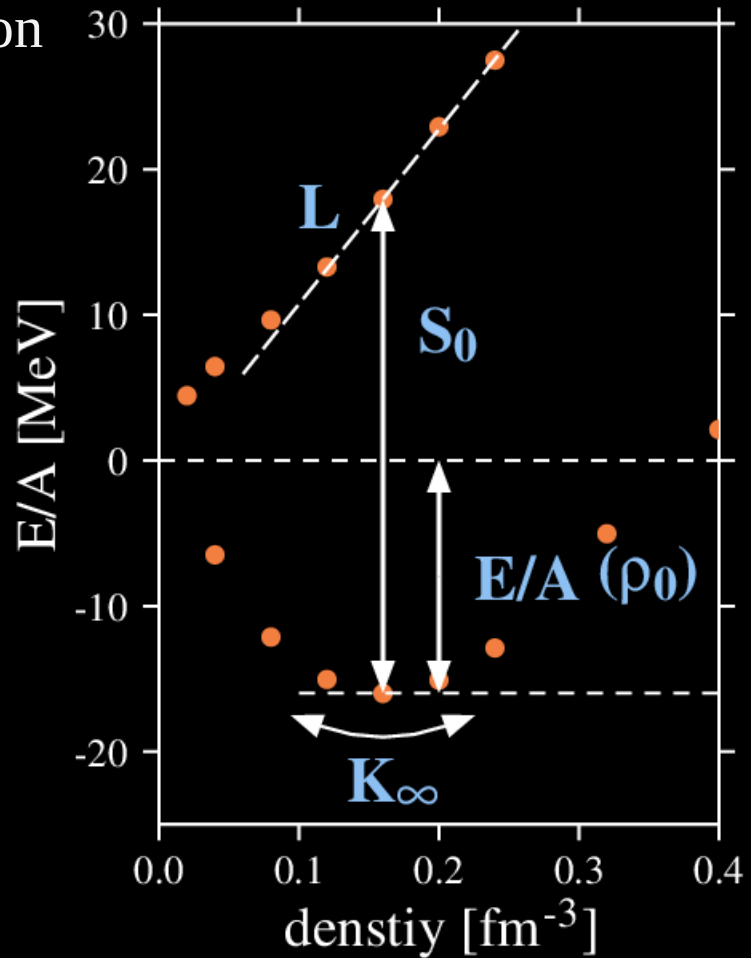
現実的核力 ➡ 状態方程式

- 現実的核力　Argonne v_{18}
- 現象論的3体力　Urbara IX
- 相対論的補正　Relativistic boost correction
- 追加補正　(for SNM)

Akamal, Pandharipande, Ravenhall, PRC58, 1804 (1998)

$$S_0 \sim 34\,\mathrm{MeV}$$
$$L \sim 70\,\mathrm{MeV}$$
$$K_\infty \sim 270\,\mathrm{MeV}$$

Vijay R. Pandharipande

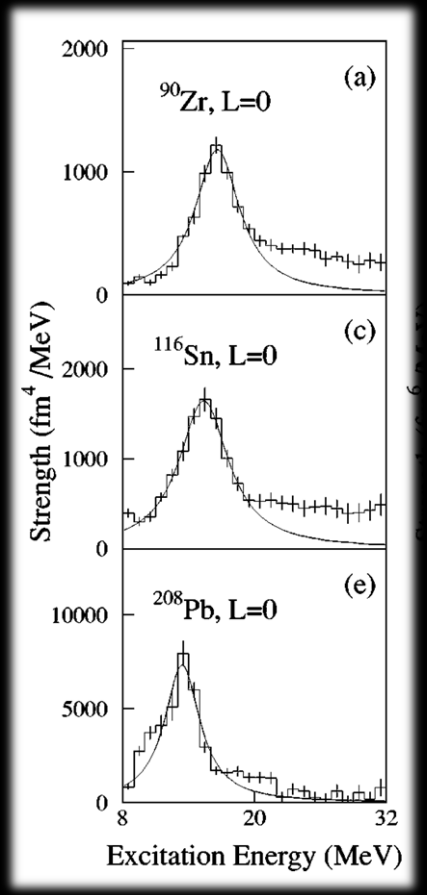


K_∞ from Isoscalar Monopole Resonance

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

$$E_{\mathrm{GMR}} = \sqrt{\frac{\hbar^2 K_A}{m\langle r^2\rangle}}, \quad K_A \sim K_\infty + K_\tau \left(\frac{N-Z}{A}\right)^2$$

Blaizot, Phys. Rep. 64, 171 (1980)

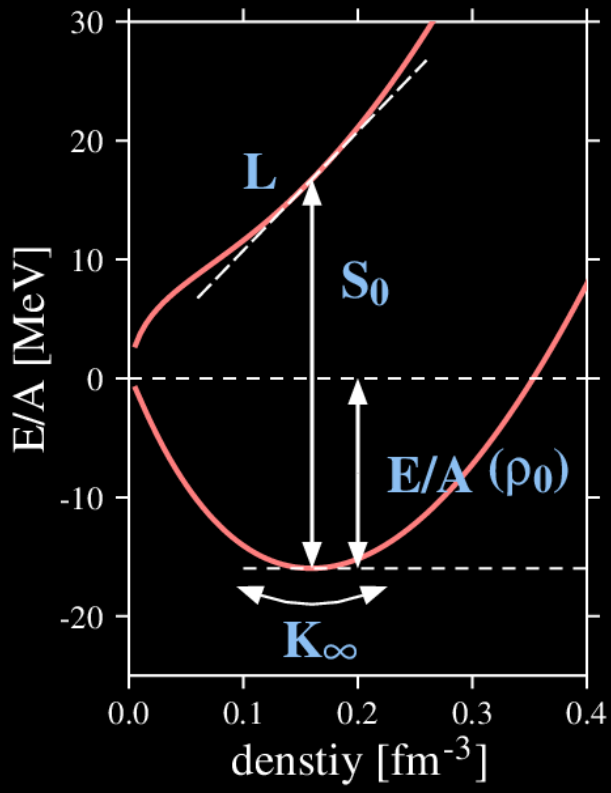


$$K_\infty \sim 230 - 240\,\mathrm{MeV}$$

$$K_\tau \sim -550 \pm 50\mathrm{MeV}$$

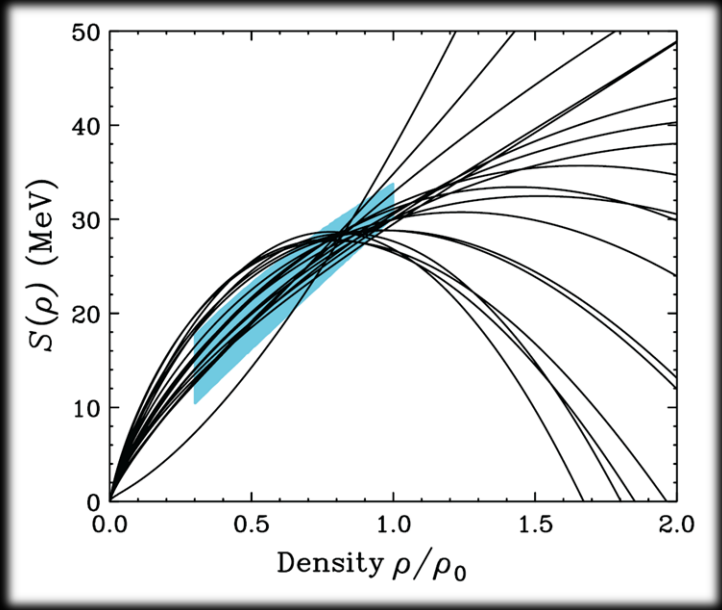
Sagawa et al., PRC 76, 034327 (2007)

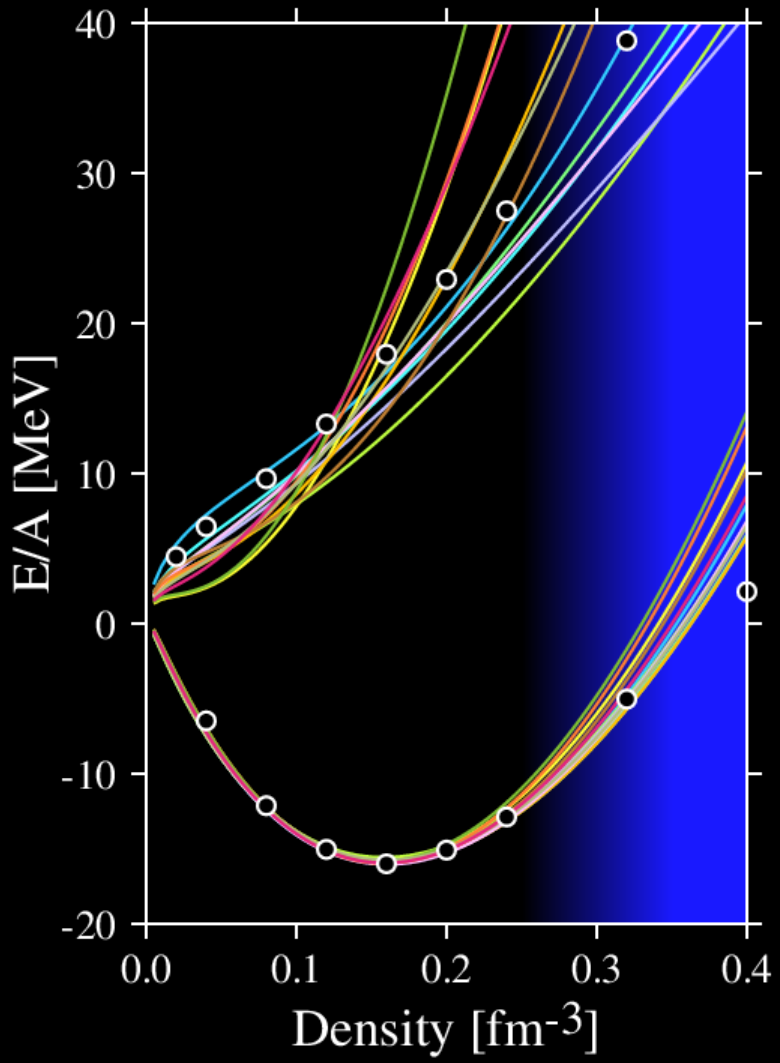
Uchida et al.,
PRC69, 051301(2004)



対称核物質：分かって来た。
中性子物質：まだまだ…

$$\frac{E}{A}(\rho_0) \sim 16\,\mathrm{MeV}$$
$$K_\infty \sim 230 - 240\,\mathrm{MeV}$$



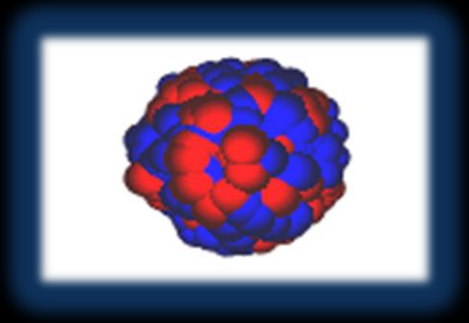


Tsang et al., PRC86, 015803 (2012)

Giant Dipole Resonance (GDR)

対称エネルギー E_{sym} が復元力
実験データが最も多い巨大共鳴

実験データと E_{sym} の関係が不明確



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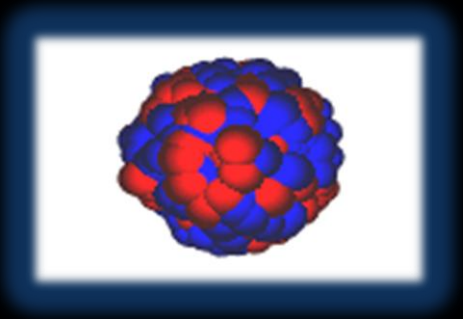
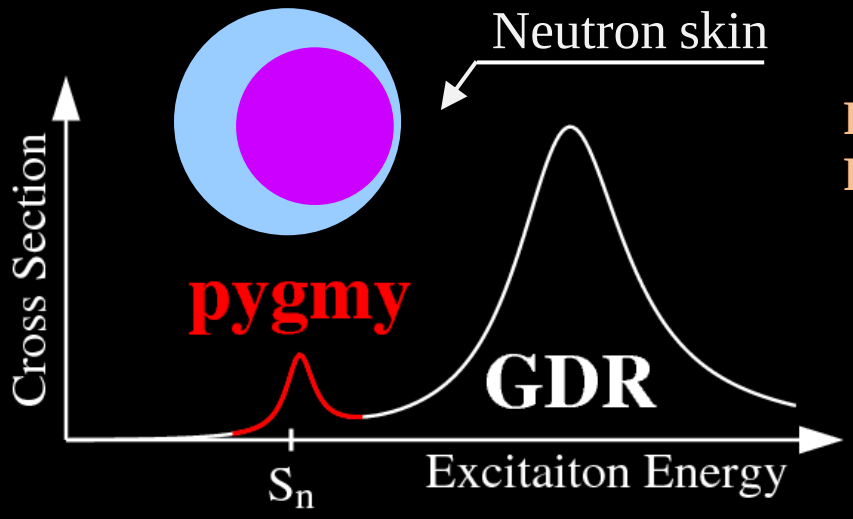


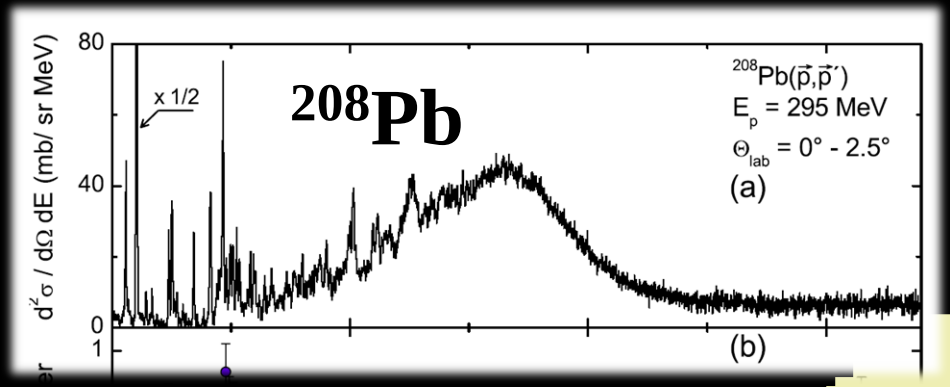
Pygmy Dipole Resonance (PDR)



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

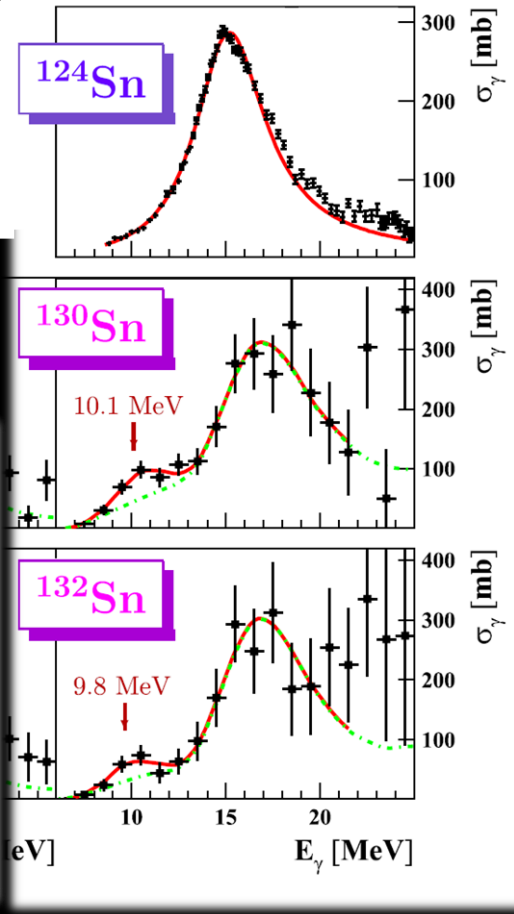
中性子スキンと **PDR**
⇔ 中性子物質(PNM)の性質

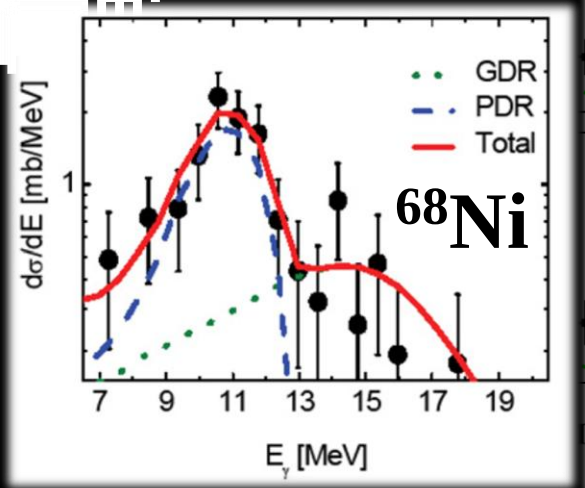
Observed PDRs



amii et al., PRL 107, 062502.

Adrich et al.,
PRL 95, 132501.

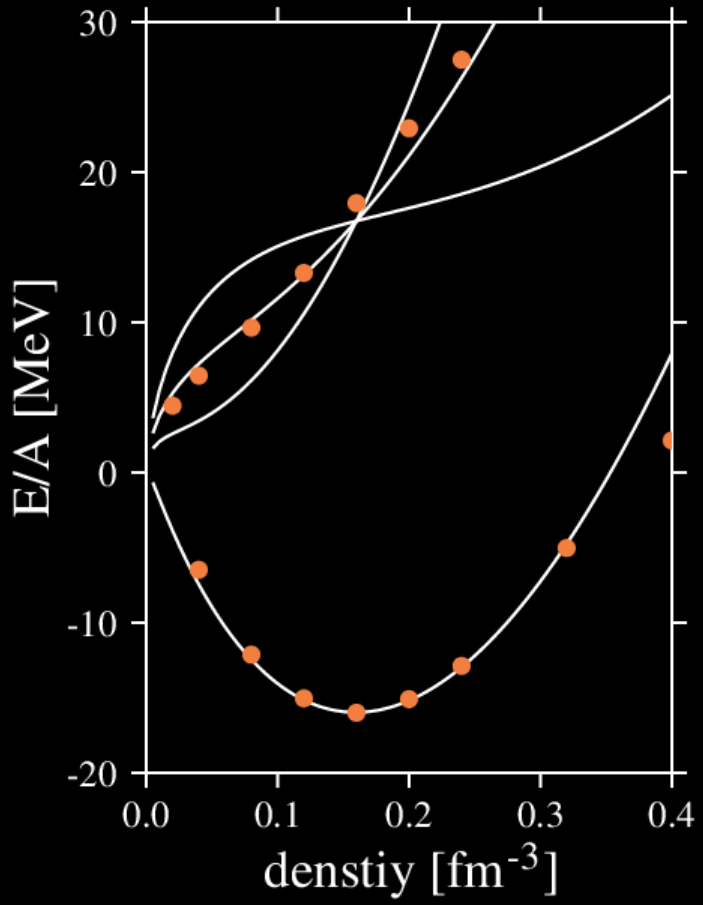


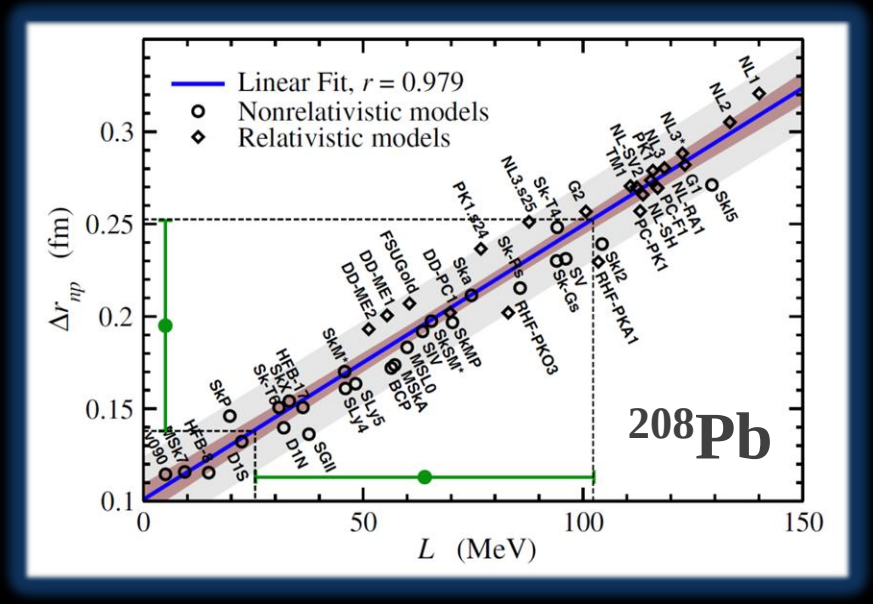


Wieland et al.,
PRL 102, 092502

L & skin

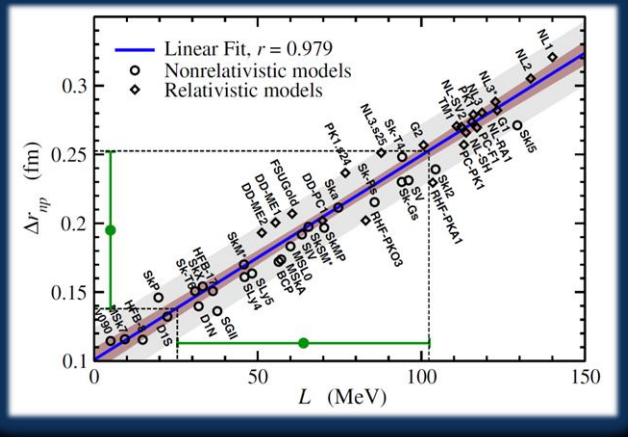
Large L ⇔ Small E_{sym} in low-ρ ⇔ Thick n-skin
Small L ⇔ Large E_{sym} in low-ρ ⇔ Thin n-skin



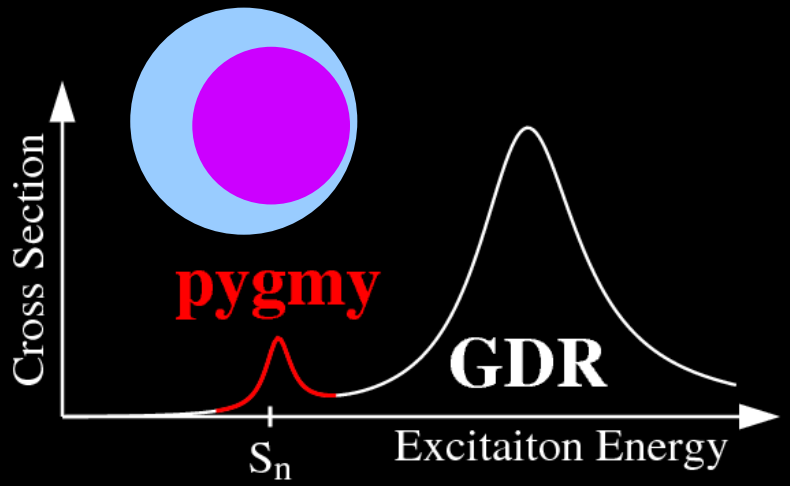


Roca-Maza et al., PRL 106, 252501 (2011)

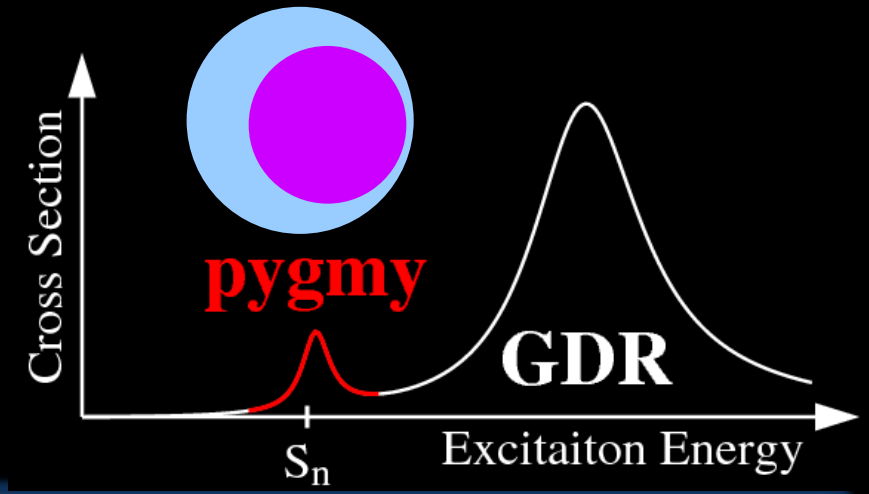
L (EOS)



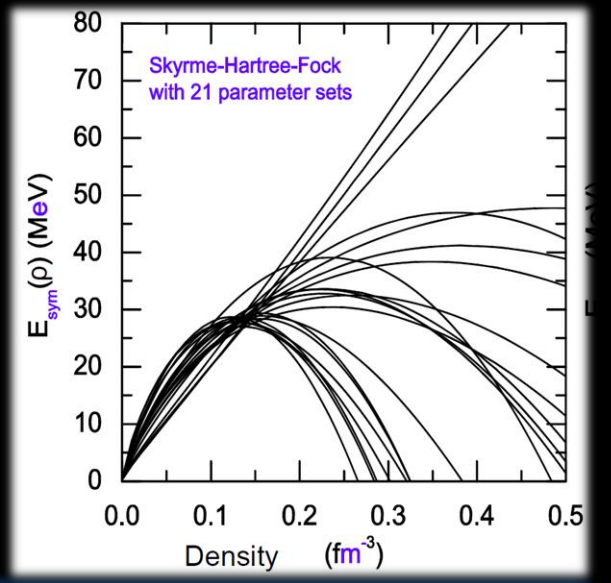
PDR ⟷ n-skin

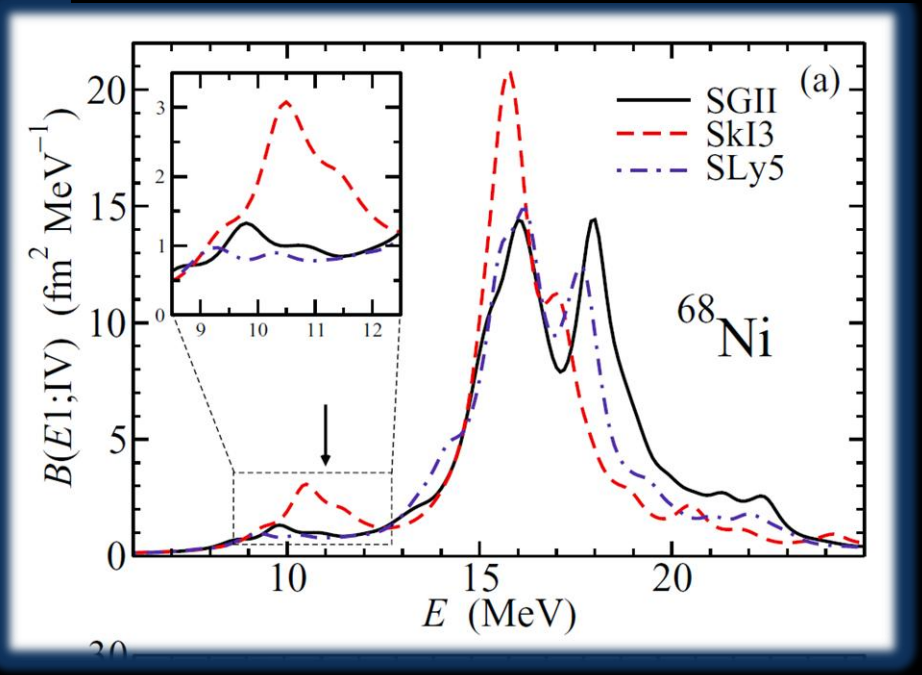


L from PDR

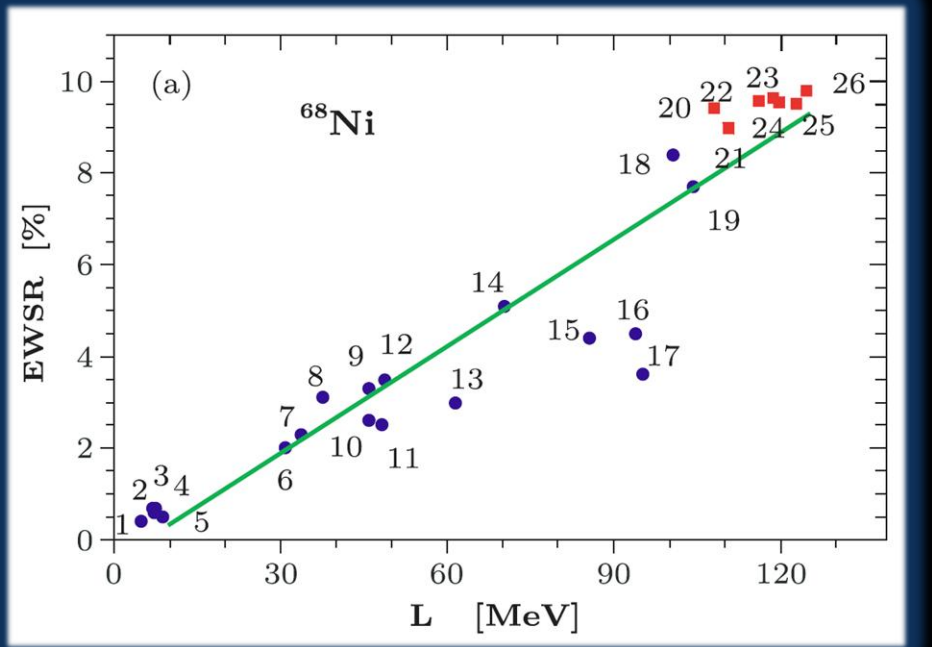


Chen et al., PRC72, 064309



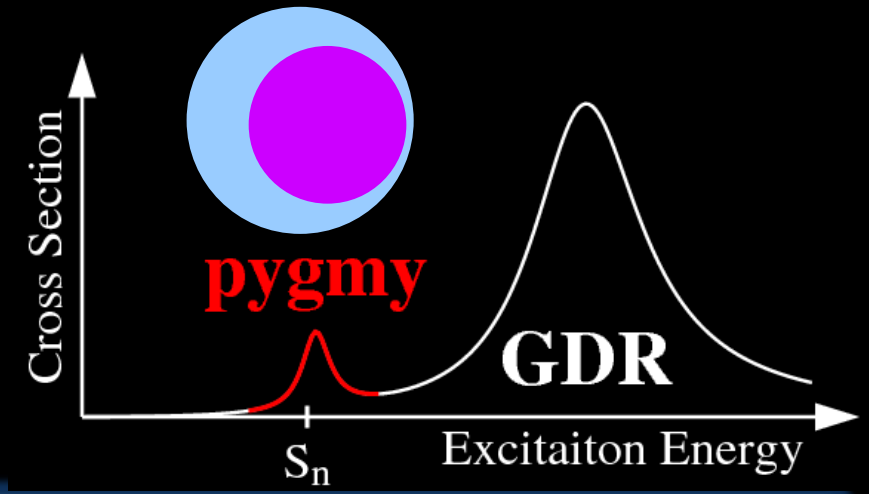


X. Roca-Maza et al.,PRC 85, 024601(2012)

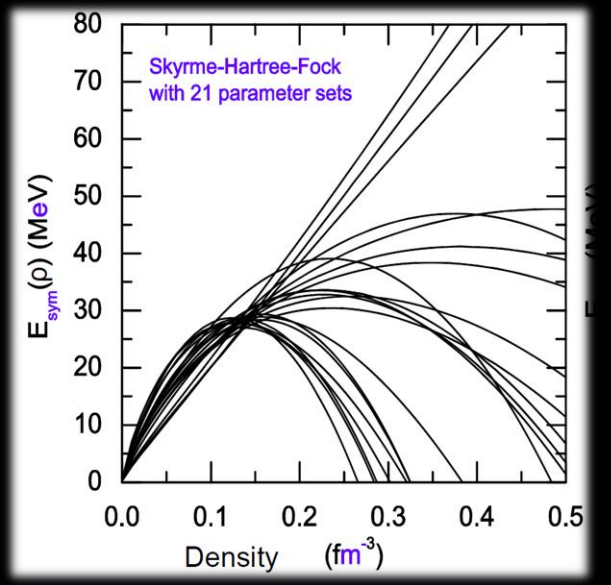


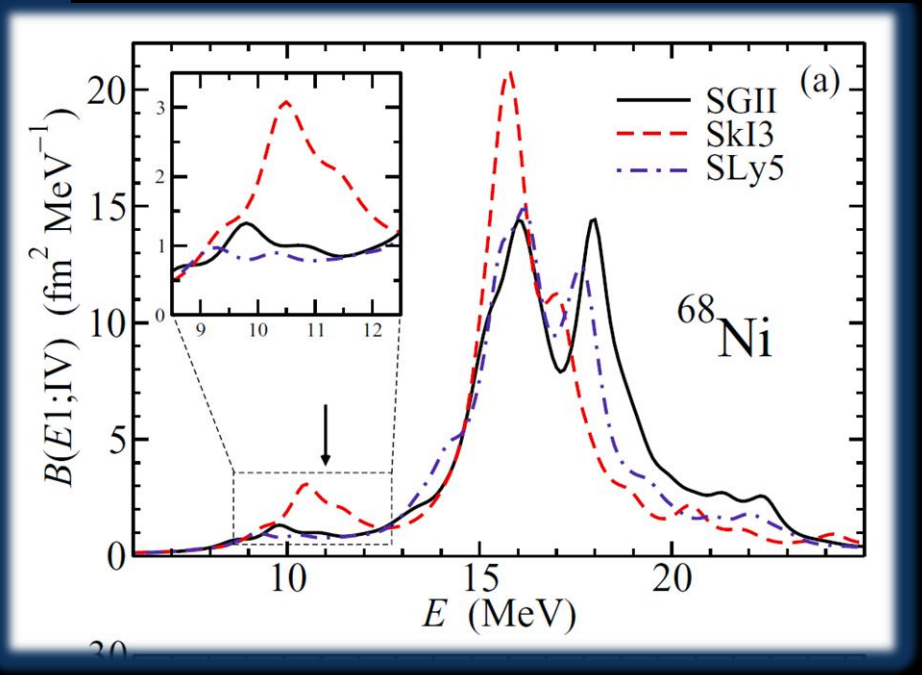
Carbone et al., PRC81, 041301® (2010)

L from PDR

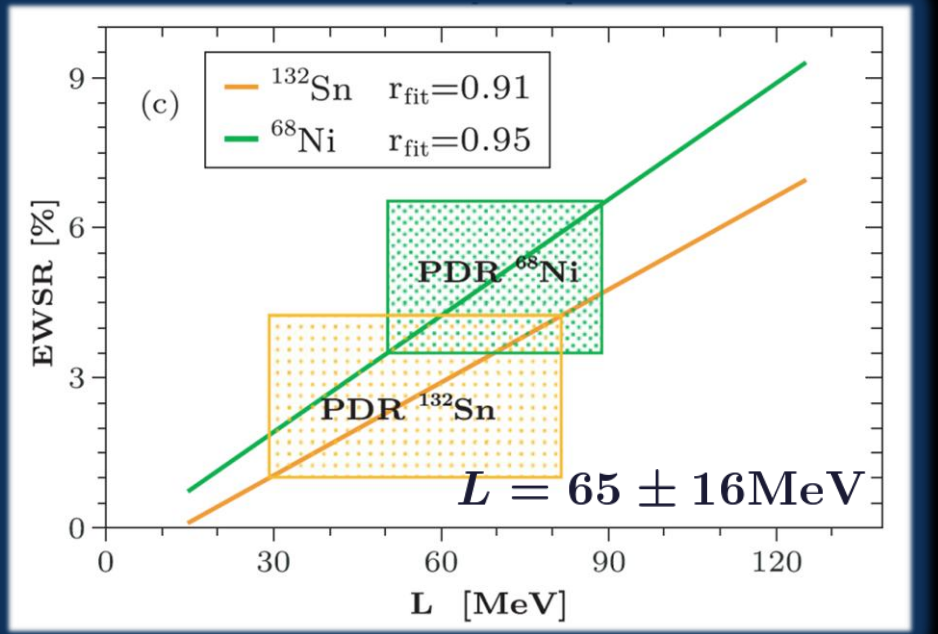


Chen et al., PRC72, 064309



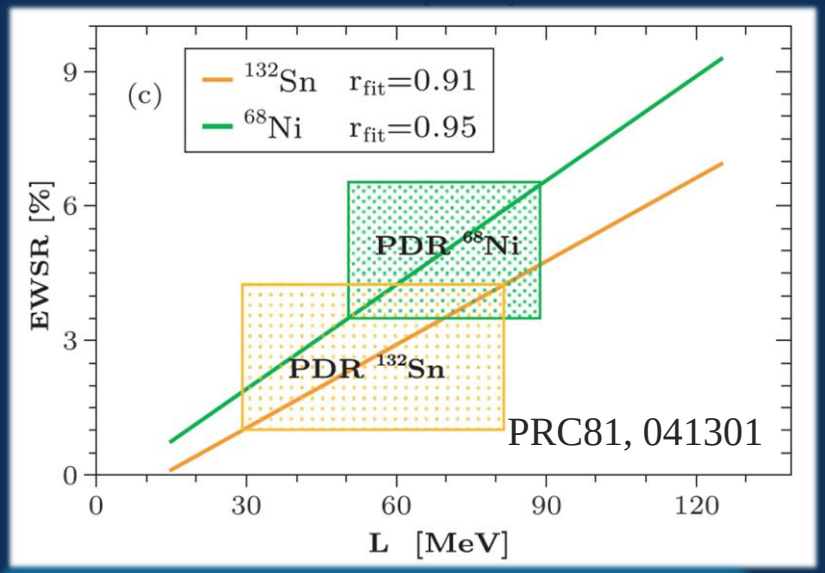


X. Roca-Maza et al.,PRC 85, 024601(2012)



Carbone et al., PRC81, 041301® (2010)

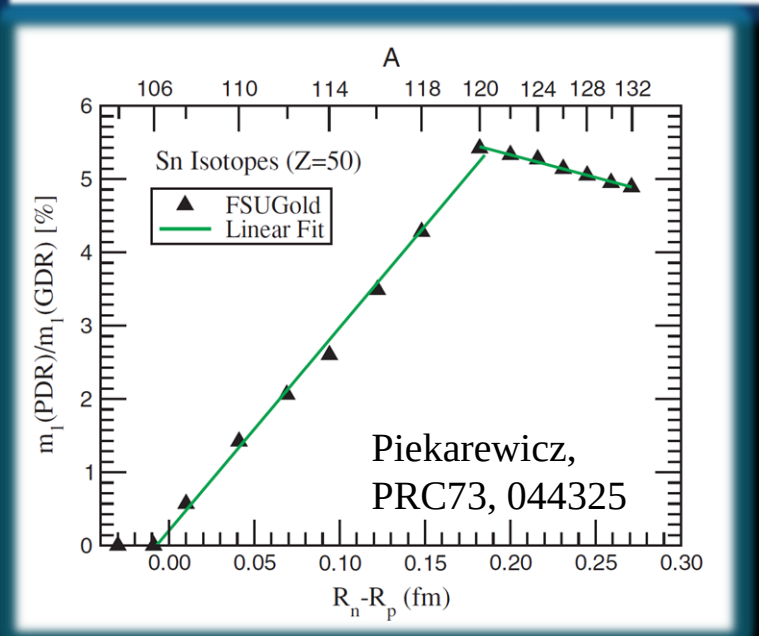
Correlation : strong or weak?



PRC81, 041301

Reinhard & Nazarewicz, PRC81, 051303(R);
Covariance analysis for 68Ni, 132Sn, and 208Pb

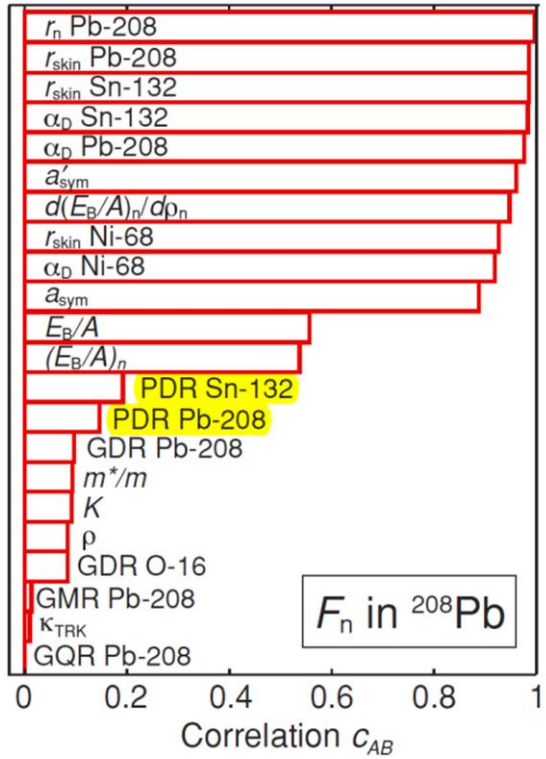
The nuclear and neutron matter binding energy seem poorly correlated with F_n, in accordance with Ref. [8]. Our covariance analysis suggests a lack of correlation between F_n (or neutron skin) and PDR strength; GMR, GDR, and GQR energies; and



Piekarewicz,
PRC73, 044325

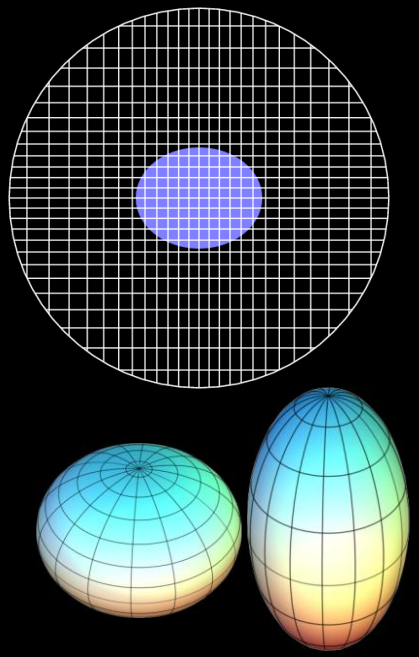
L (EOS)

PDR ⟷ n-skin



座標表示での線形応答計算 (RPA)

- 現象論的核力を用いた密度汎関数理論計算
- Skyrme 相互作用での自己無撞着な計算
- 3次元座標表示
  - スキン・ハローを持った不安定核の記述に適している。
  - 球形核も変形核も計算できる。
  - 連続状態の取り扱いがそこそこ良い。
- 応答関数の計算
  - 励起エネルギーを固定して応答関数を計算する。
  - 並列計算機との相性が良い。
- 対相関は入っていない。

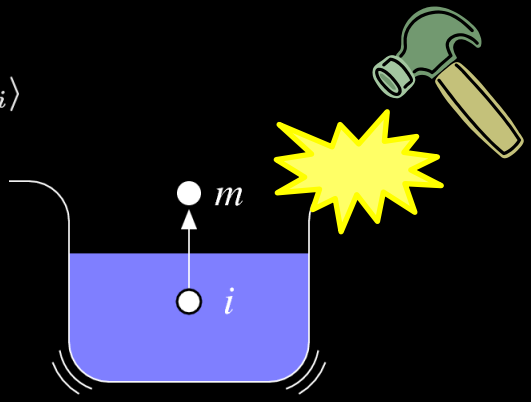


$$\left\{ \begin{bmatrix} A & B \\ B^* & A^* \end{bmatrix} - \hbar\omega \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \right\} \begin{bmatrix} X_{nj}(\omega) \\ Y_{nj}(\omega) \end{bmatrix} = - \begin{bmatrix} f(\omega) \\ g(\omega) \end{bmatrix}$$

$$A_{(mi),(nj)} = (\varepsilon_m - \varepsilon_i)\,\delta_{mn}\delta_{ij} + \langle \phi_m | \frac{\delta h}{\delta \rho_{nj}} | \phi_i \rangle\,, \quad B_{(mi),(nj)} = \langle \phi_m | \frac{\delta h}{\delta \rho_{jn}} | \phi_i \rangle$$

$$f_{mi}(\omega) = \langle \phi_m | V_{\mathrm{ext}}(\omega) | \phi_i \rangle\,, \quad g_{mi}(\omega) = \langle \phi_i | V_{\mathrm{ext}}(\omega) | \phi_m \rangle$$

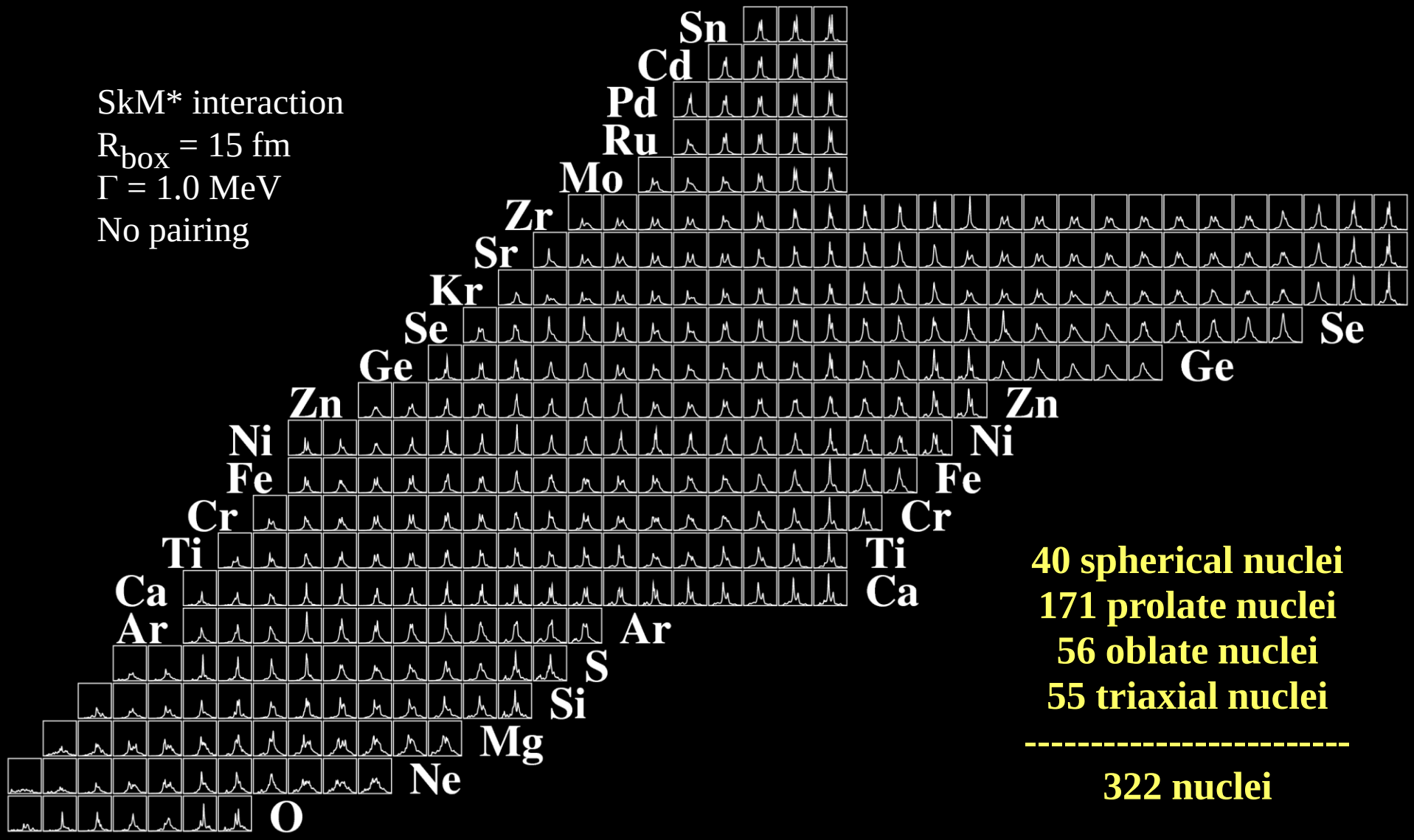
$$|\mathrm{vib.}\rangle = \sum_{\mathrm{ph}} f_{ph} |\mathrm{1p\text{-}1h}\rangle$$



Systematic calc. of E1 mode

T. Inakura *et al.*, PRC84, 021302

SkM* interaction
R_{box} = 15 fm
Γ = 1.0 MeV
No pairing



40 spherical nuclei
171 prolate nuclei
56 oblate nuclei
55 triaxial nuclei

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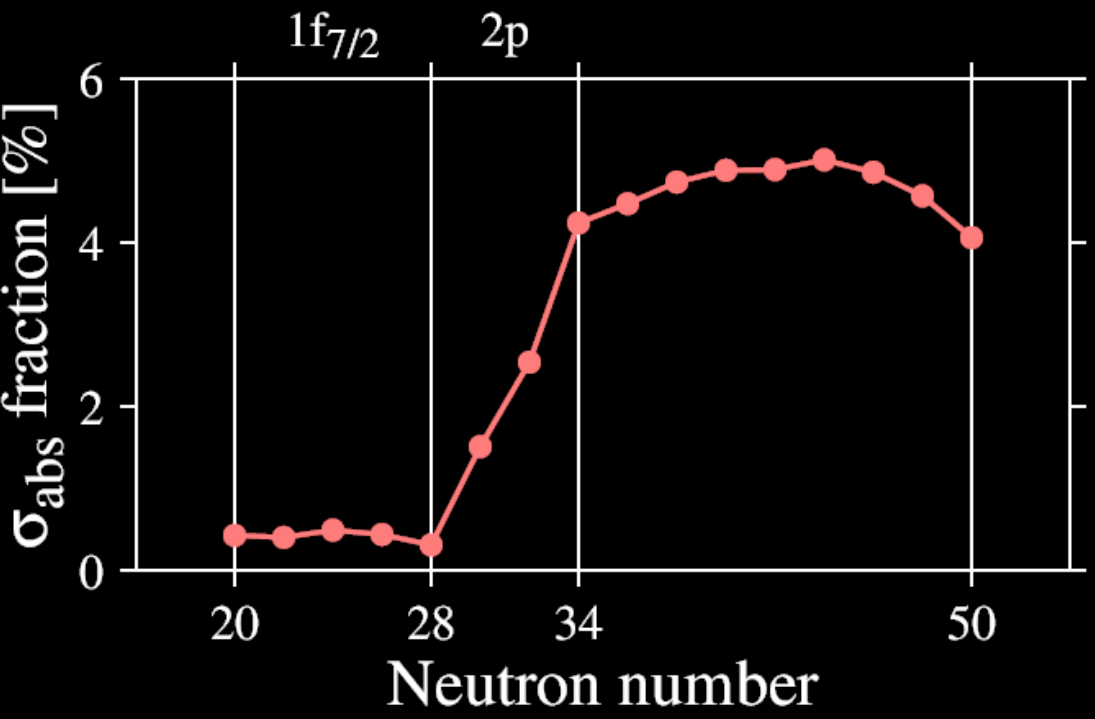
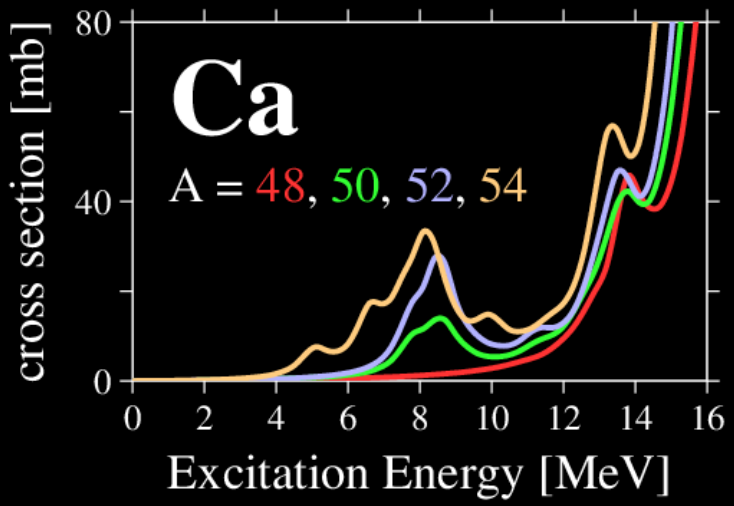
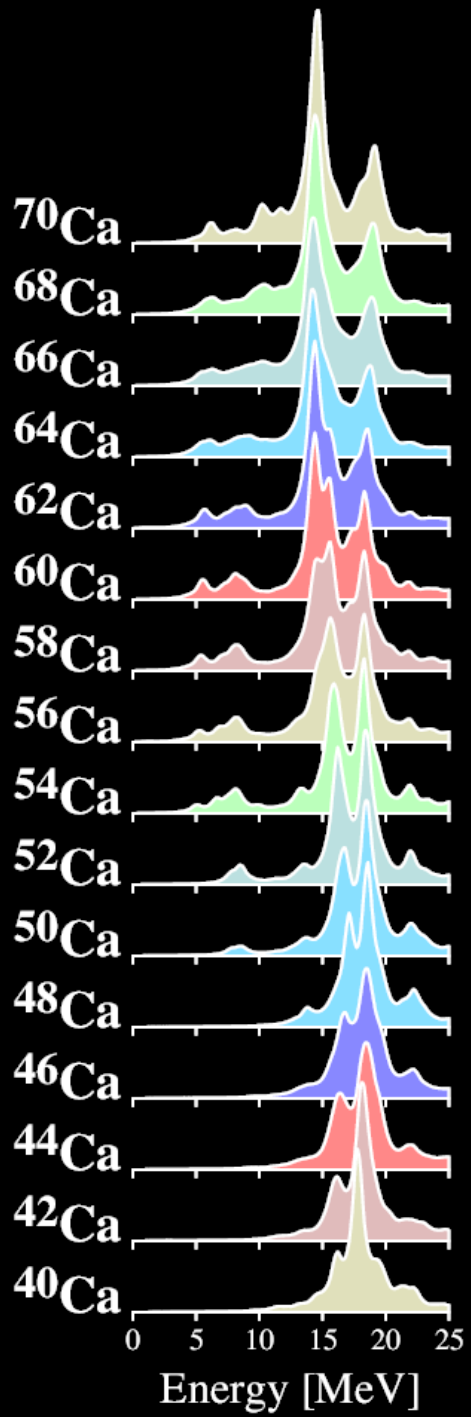
322 nuclei

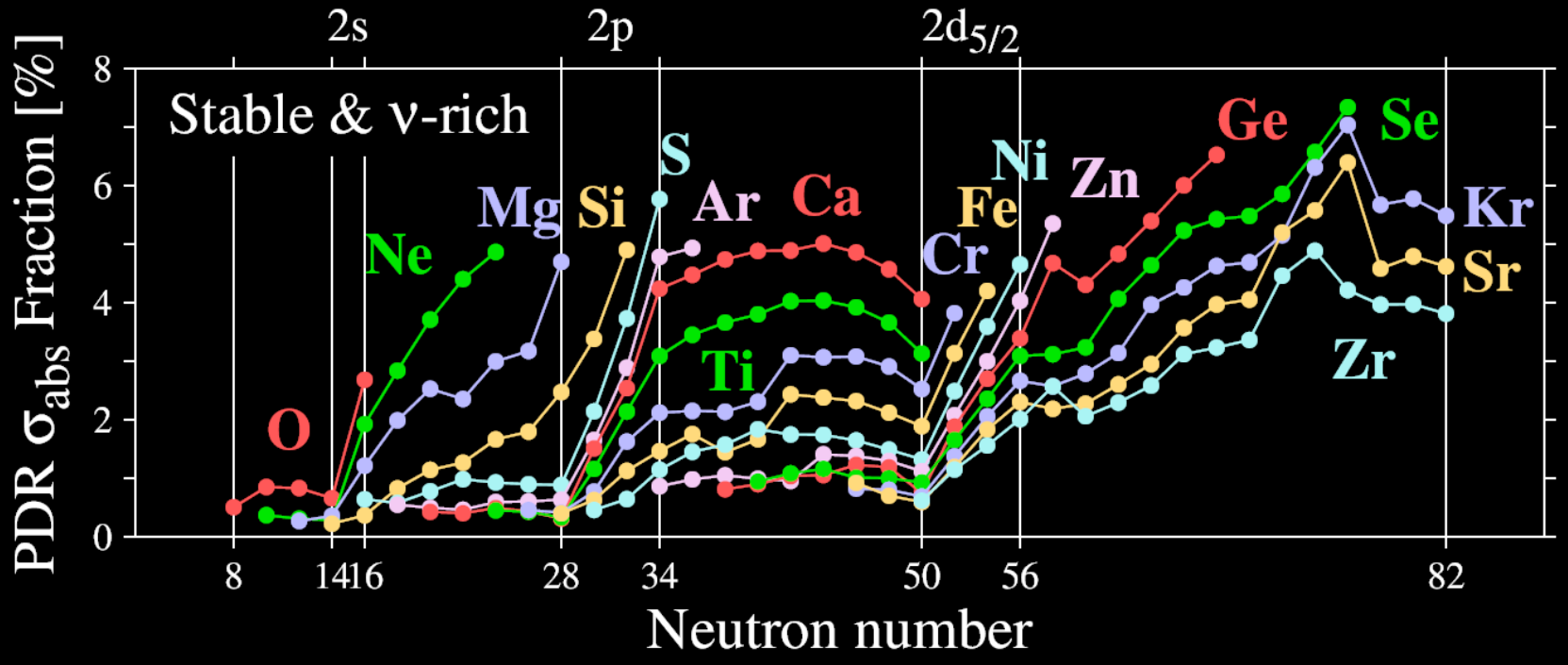
PDR in Ca isotopes







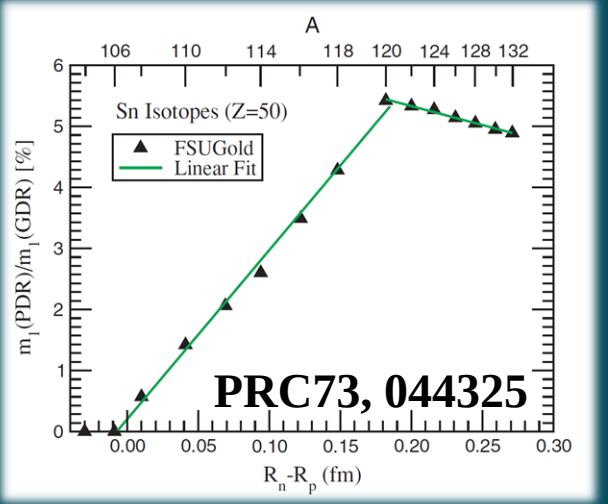
PDR in n-rich nuclei



N=30 N=34

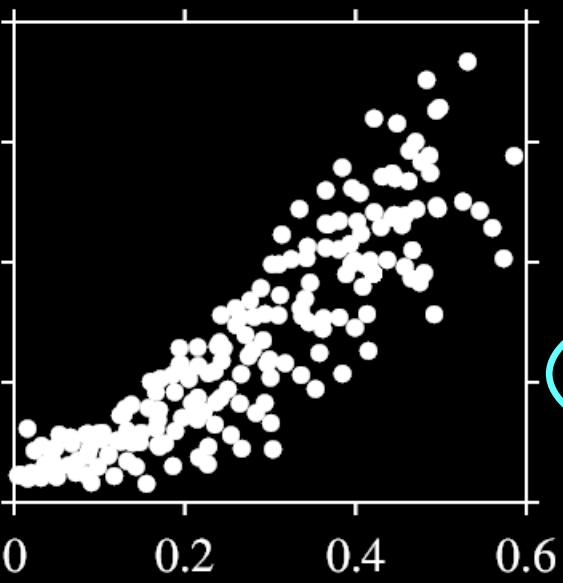
		^{48}Ni	^{50}Ni	^{52}Ni	^{54}Ni	^{56}Ni	^{58}Ni	^{60}Ni	^{62}Ni	^{64}Ni	^{66}Ni	^{68}Ni	^{70}Ni	^{72}Ni	^{74}Ni	^{76}Ni	^{78}Ni	^{80}Ni	^{82}Ni	^{84}Ni
		^{46}Fe	^{48}Fe	^{50}Fe	^{52}Fe	^{54}Fe	^{56}Fe	^{58}Fe	^{60}Fe	^{62}Fe	^{64}Fe	^{66}Fe	^{68}Fe	^{70}Fe	^{72}Fe	^{74}Fe	^{76}Fe	^{78}Fe	^{80}Fe	
	^{42}Cr	^{44}Cr	^{46}Cr	^{48}Cr	^{50}Cr	^{52}Cr	^{54}Cr	^{56}Cr	^{58}Cr	^{60}Cr	^{62}Cr	^{64}Cr	^{66}Cr	^{68}Cr	^{70}Cr	^{72}Cr	^{74}Cr	^{76}Cr		
	^{38}Ti	^{40}Ti	^{42}Ti	^{44}Ti	^{46}Ti	^{48}Ti	^{50}Ti	^{52}Ti	^{54}Ti	^{56}Ti	^{58}Ti	^{60}Ti	^{62}Ti	^{64}Ti	^{66}Ti	^{68}Ti	^{70}Ti	^{72}Ti		
^{34}Ca	^{36}Ca	^{38}Ca	^{40}Ca	^{42}Ca	^{44}Ca	^{46}Ca	^{48}Ca	^{50}Ca	^{52}Ca	^{54}Ca	^{56}Ca	^{58}Ca	^{60}Ca	^{62}Ca	^{64}Ca	^{66}Ca	^{68}Ca	^{70}Ca		
^{30}Ar	^{32}Ar	^{34}Ar	^{36}Ar	^{38}Ar	^{40}Ar	^{42}Ar	^{44}Ar	^{46}Ar	^{48}Ar	^{50}Ar	^{52}Ar	^{54}Ar								
^{28}S	^{30}S	^{32}S	^{34}S	^{36}S	^{38}S	^{40}S	^{42}S	^{44}S	^{46}S	^{48}S	^{50}S									
^{26}Si	^{28}Si	^{30}Si	^{32}Si	^{34}Si	^{36}Si	^{38}Si	^{40}Si	^{42}Si	^{44}Si	^{46}Si										

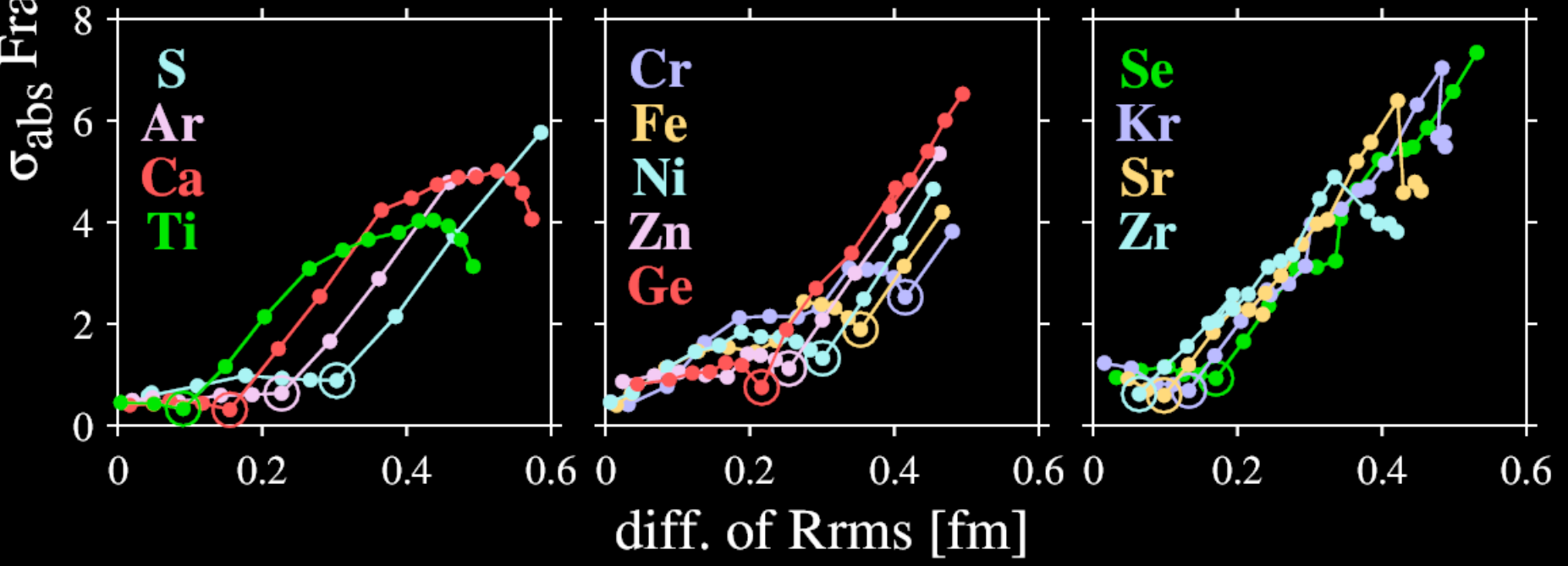
PDR & Skin



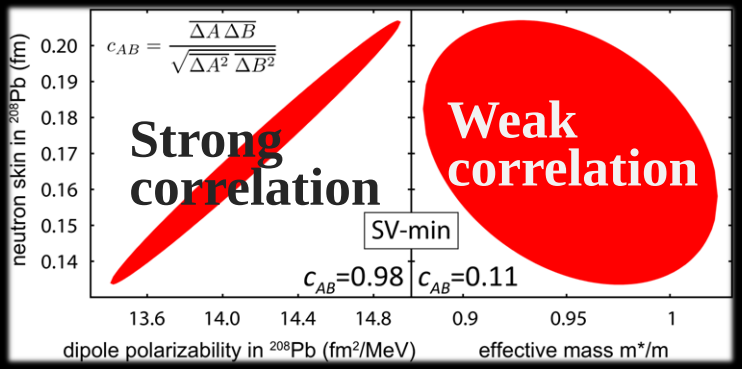
L (EOS)

PDR ↔ n-skin



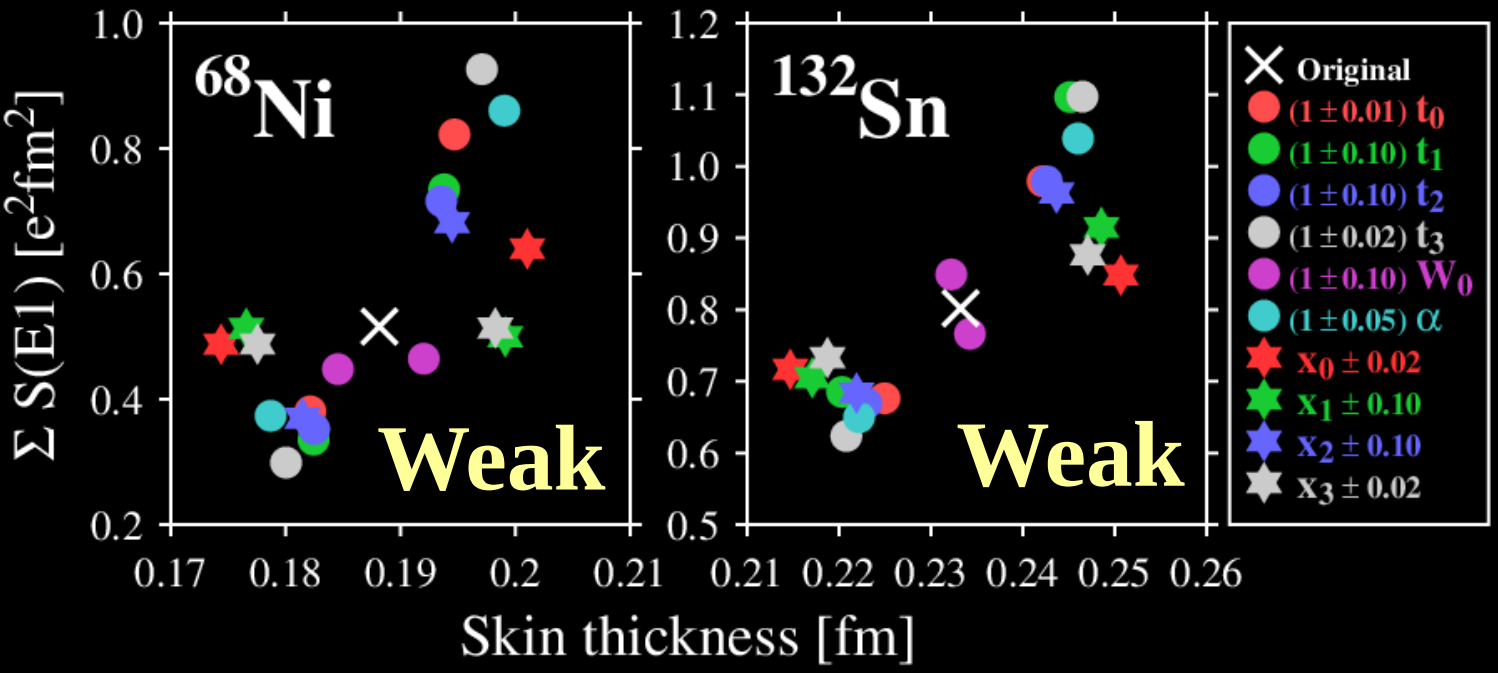


Correlation between neutron skin & PDR in ^{68}Ni & ^{132}Sn

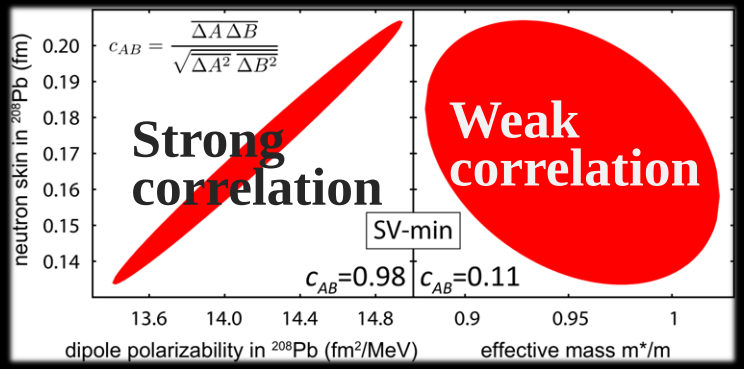


Reinhard & Nazarewicz, PRC81, 051303(R);
Covariance analysis for 68Ni, 132Sn, and 208Pb

correlated with F_n, in accordance with Ref. [8]. Our covariance analysis suggests a lack of correlation between F_n (or neutron skin) and PDR strength; GMR, GDR, and GQR energies; and



Correlation between neutron skin & PDR in ^{68}Ni & ^{132}Sn



Reinhard & Nazarewicz, PRC81, 051303(R);
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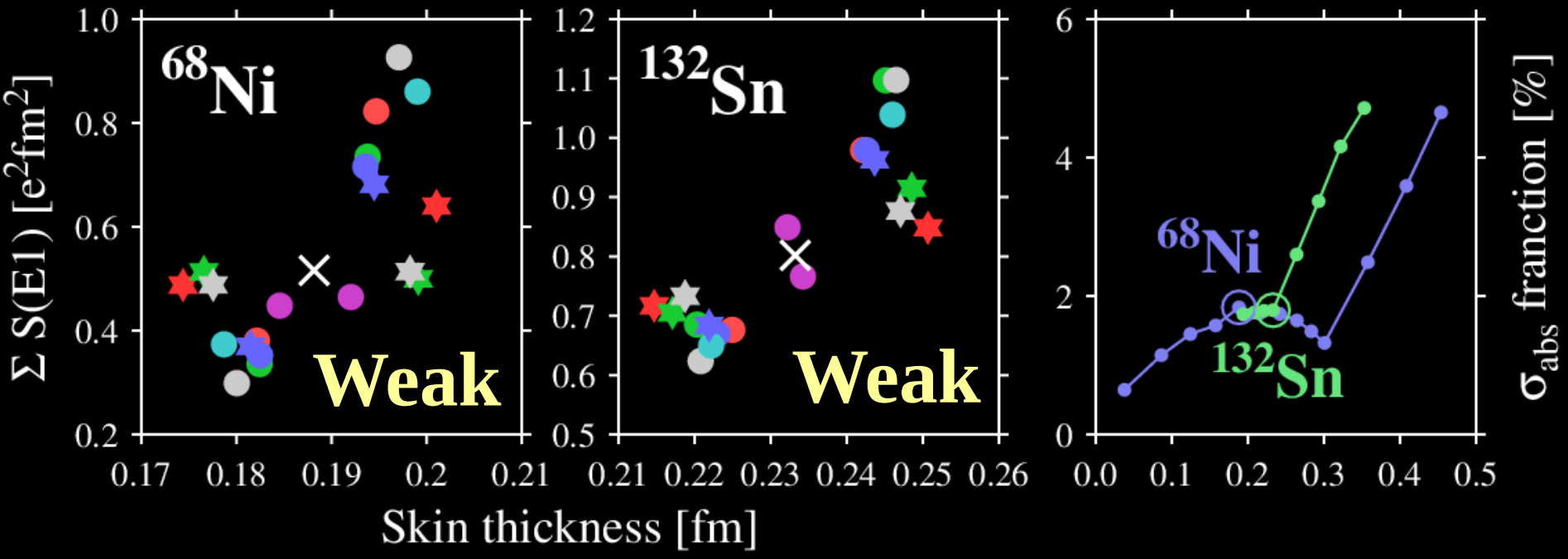
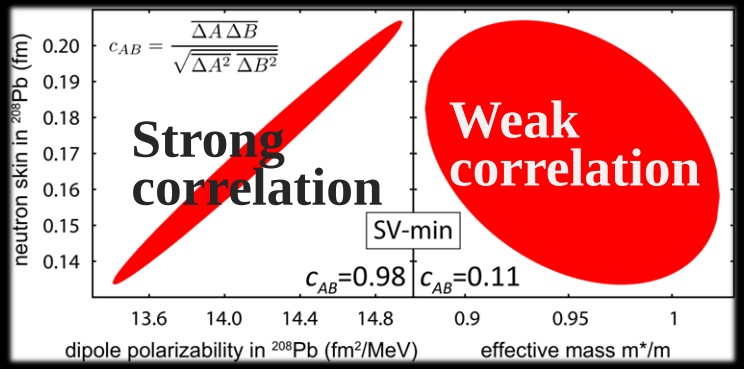
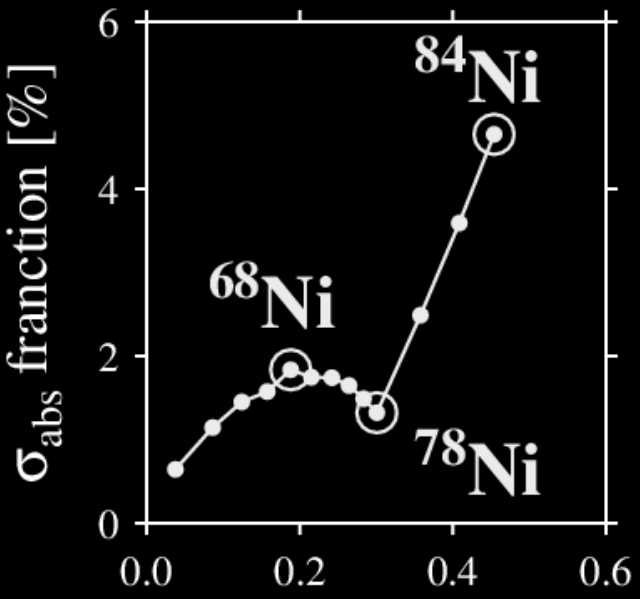
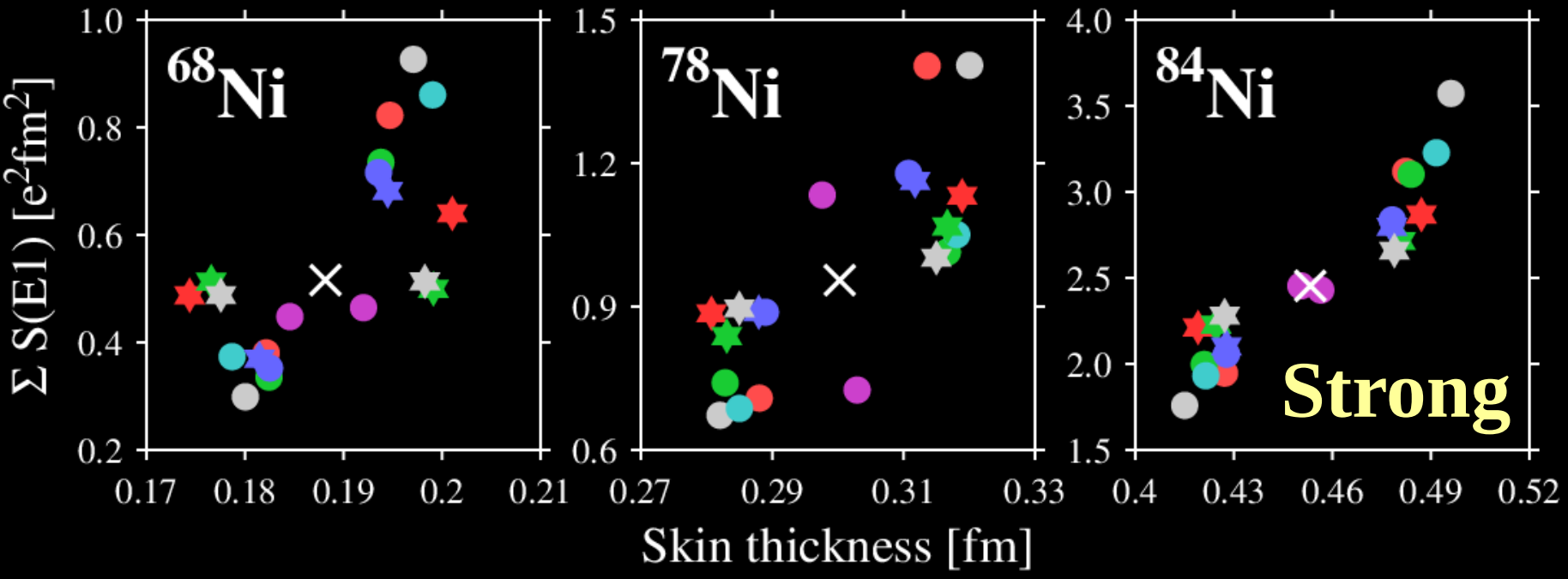


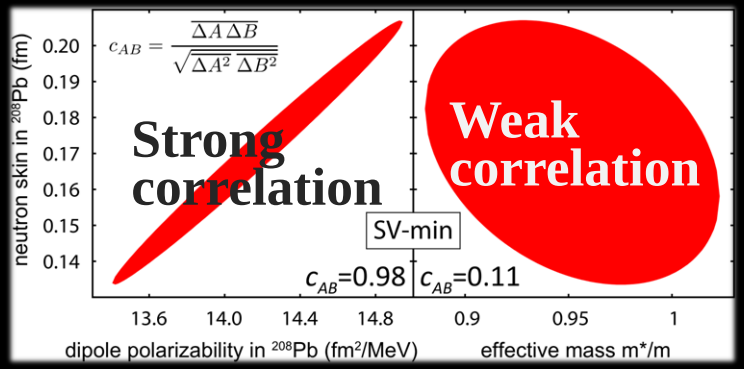
Correlation in ^{68,78,84}Ni

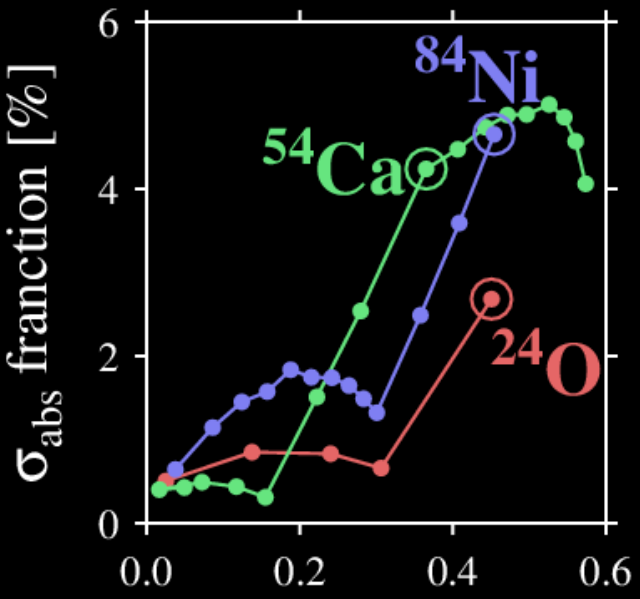


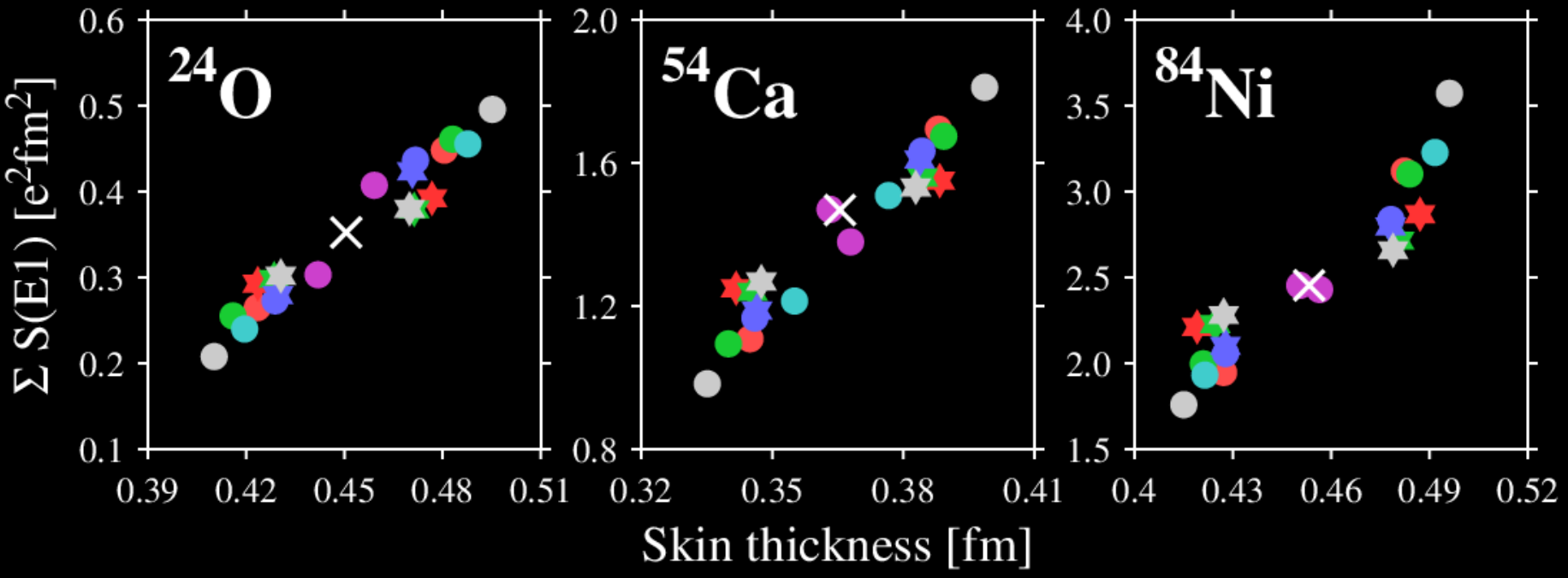


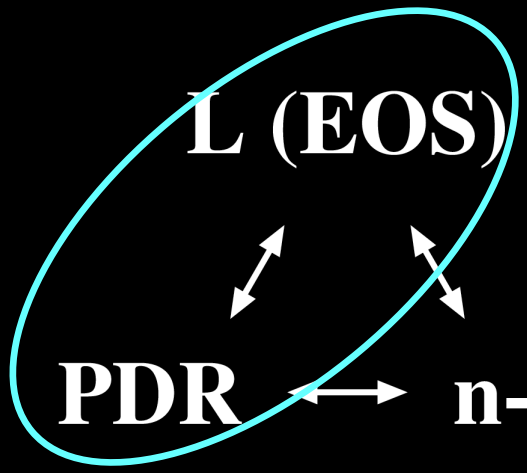


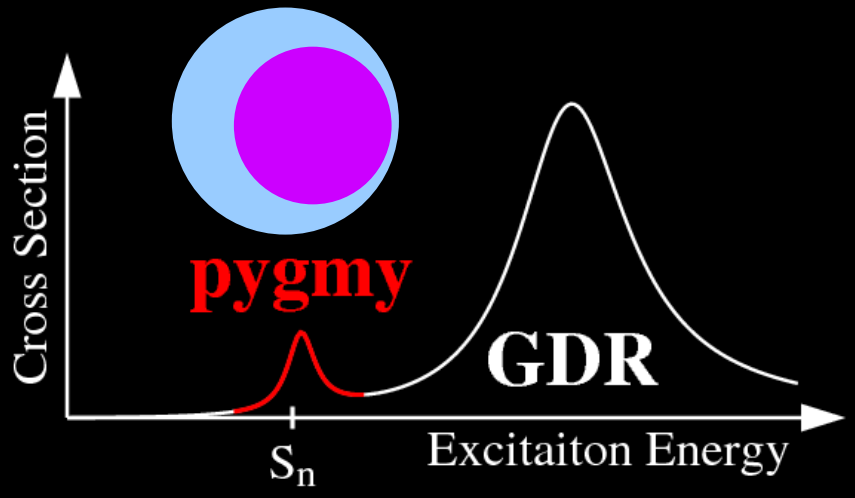
Linear Correlations

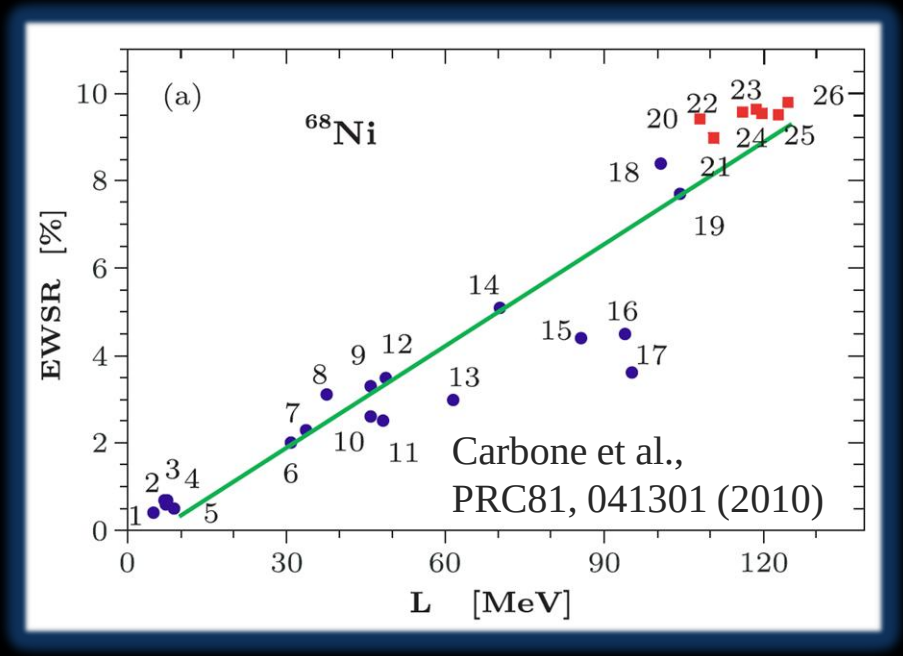










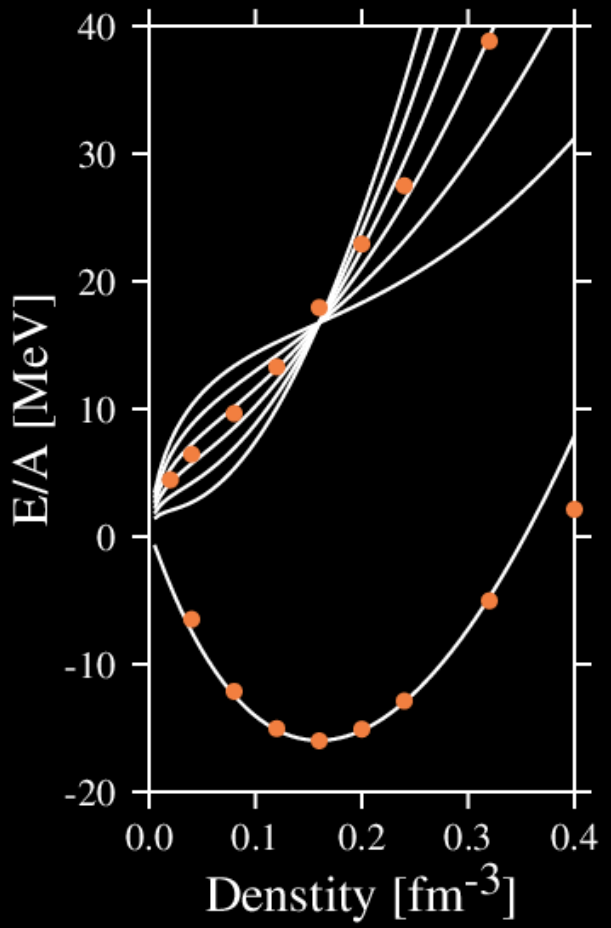


Linear correlation?

L-dependence

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

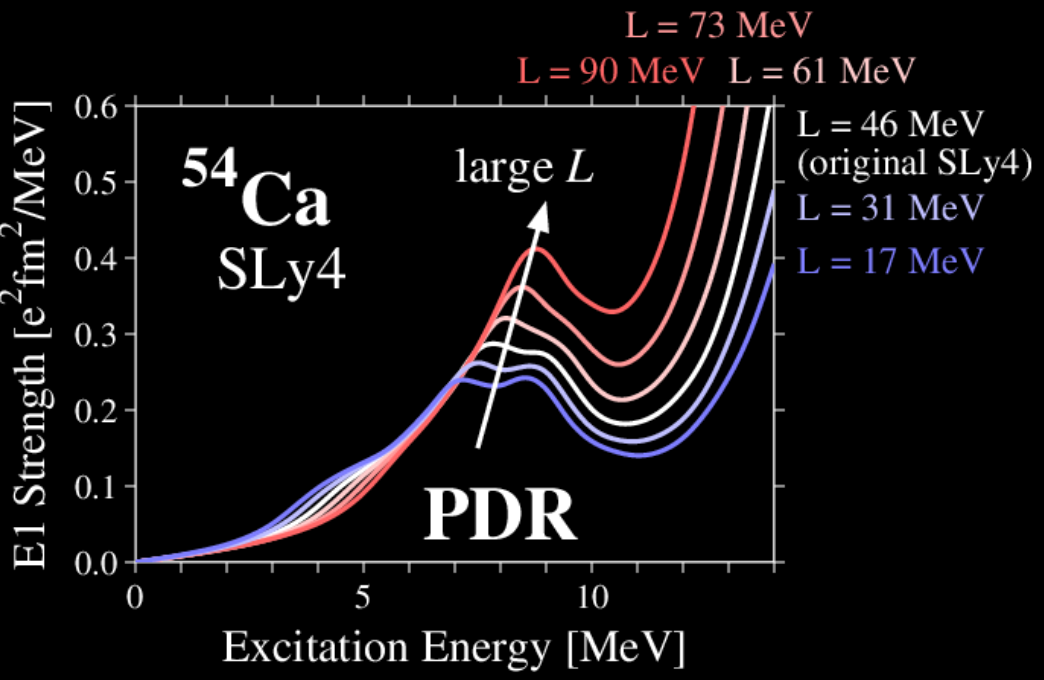
Cf. Ono et al., PRC68, 051601(R) (2003)



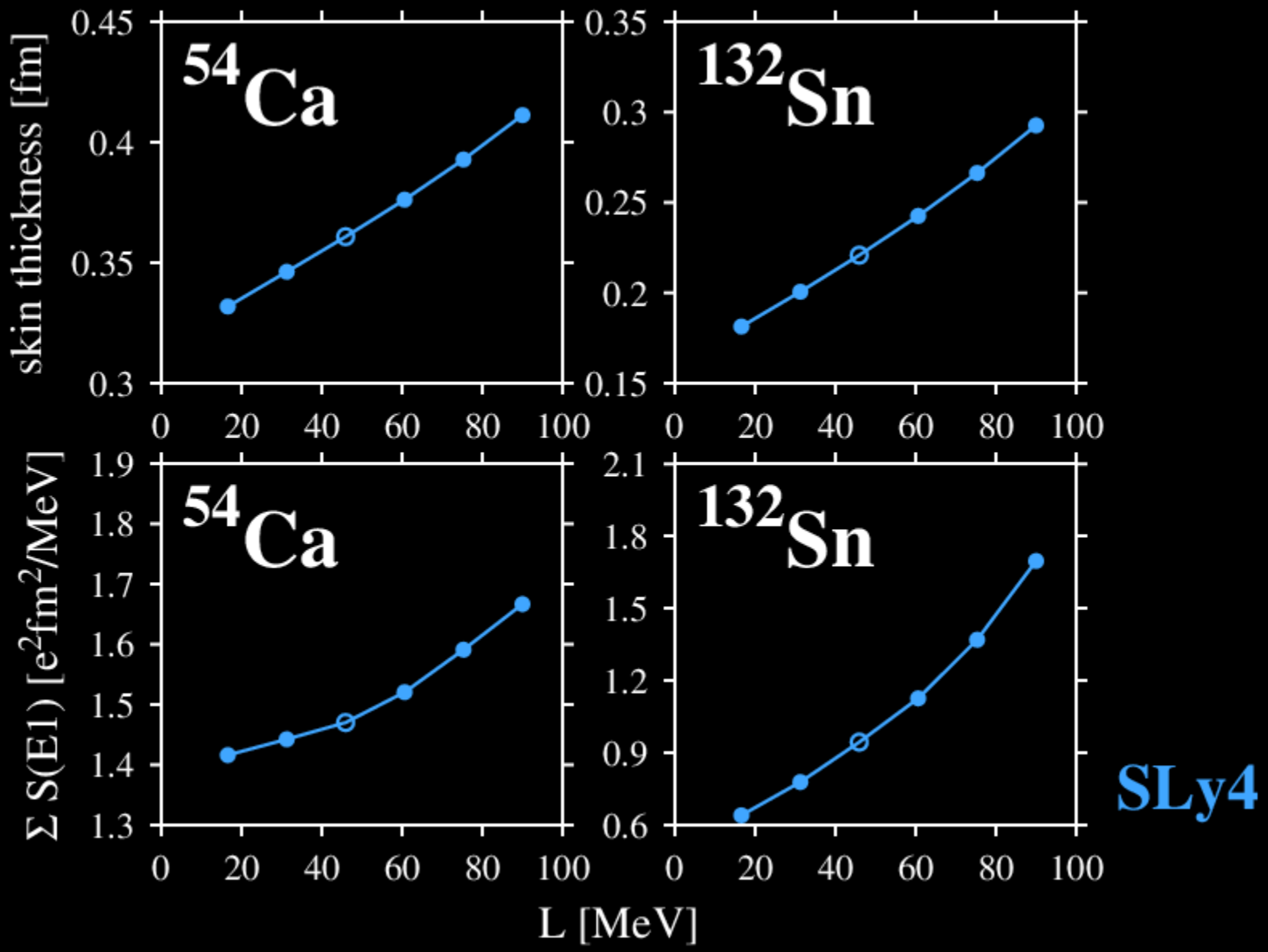
This additional term

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

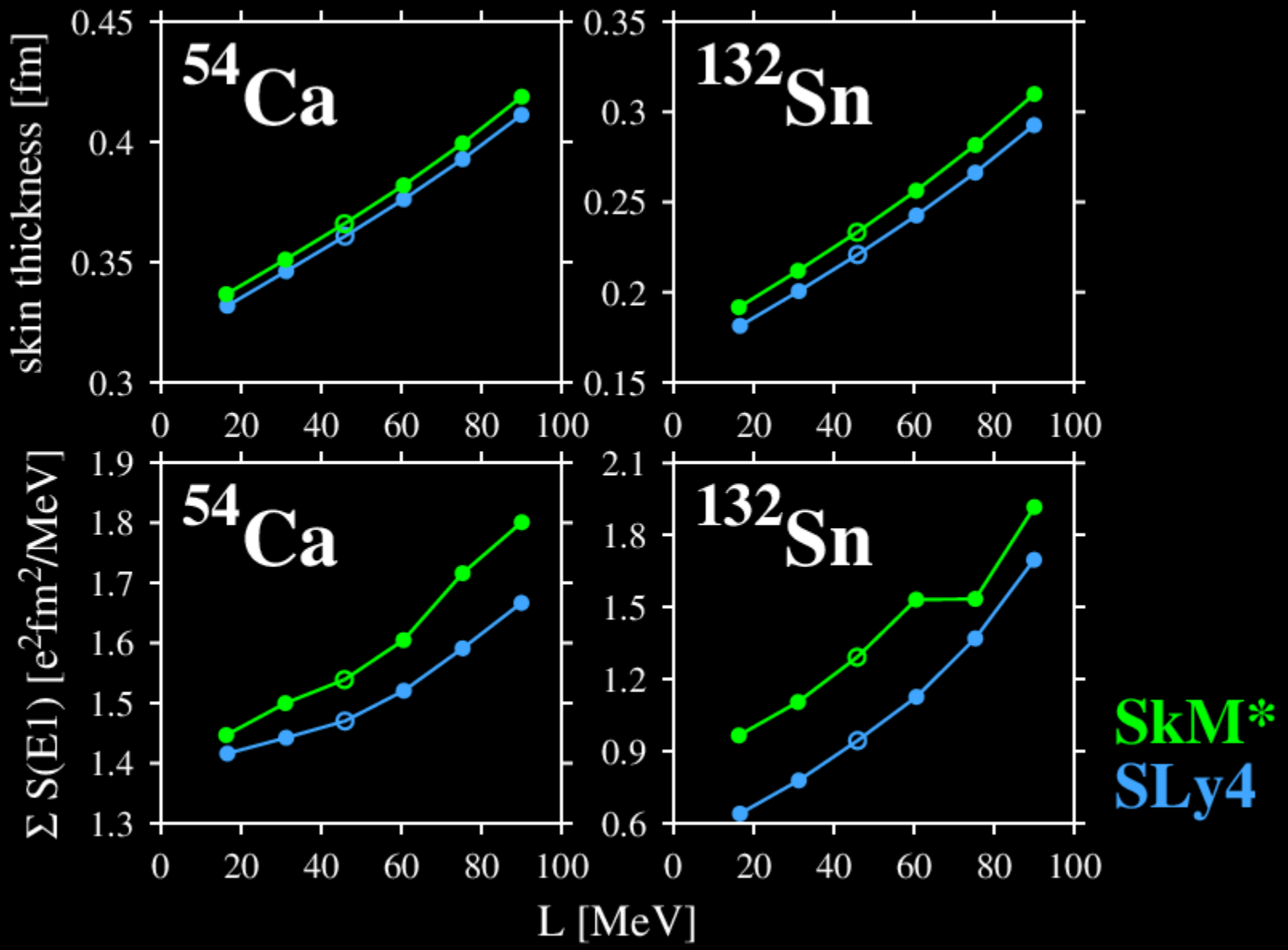
V_L is a parameter to control *L*.



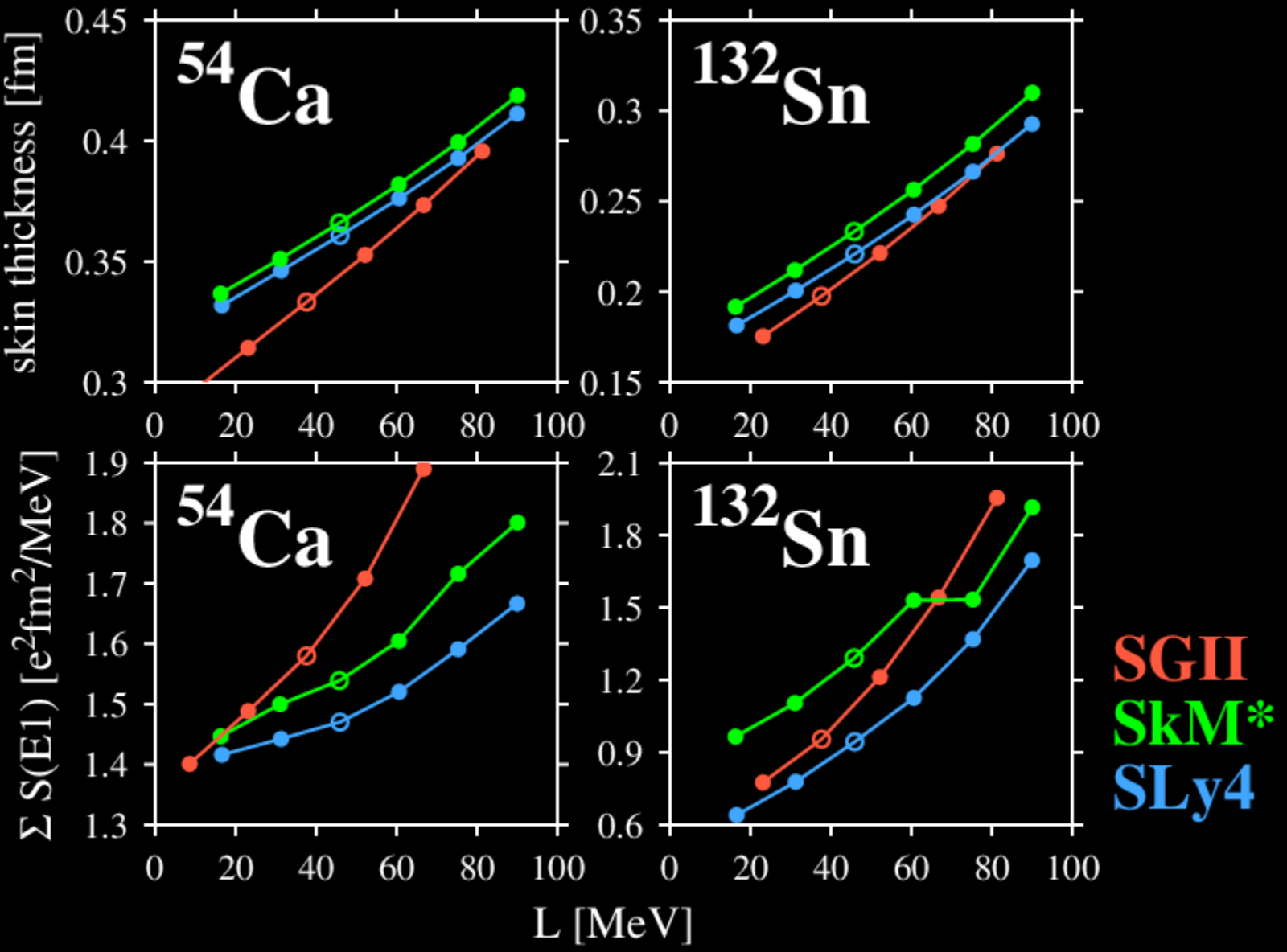
L-dependence of PDR strength



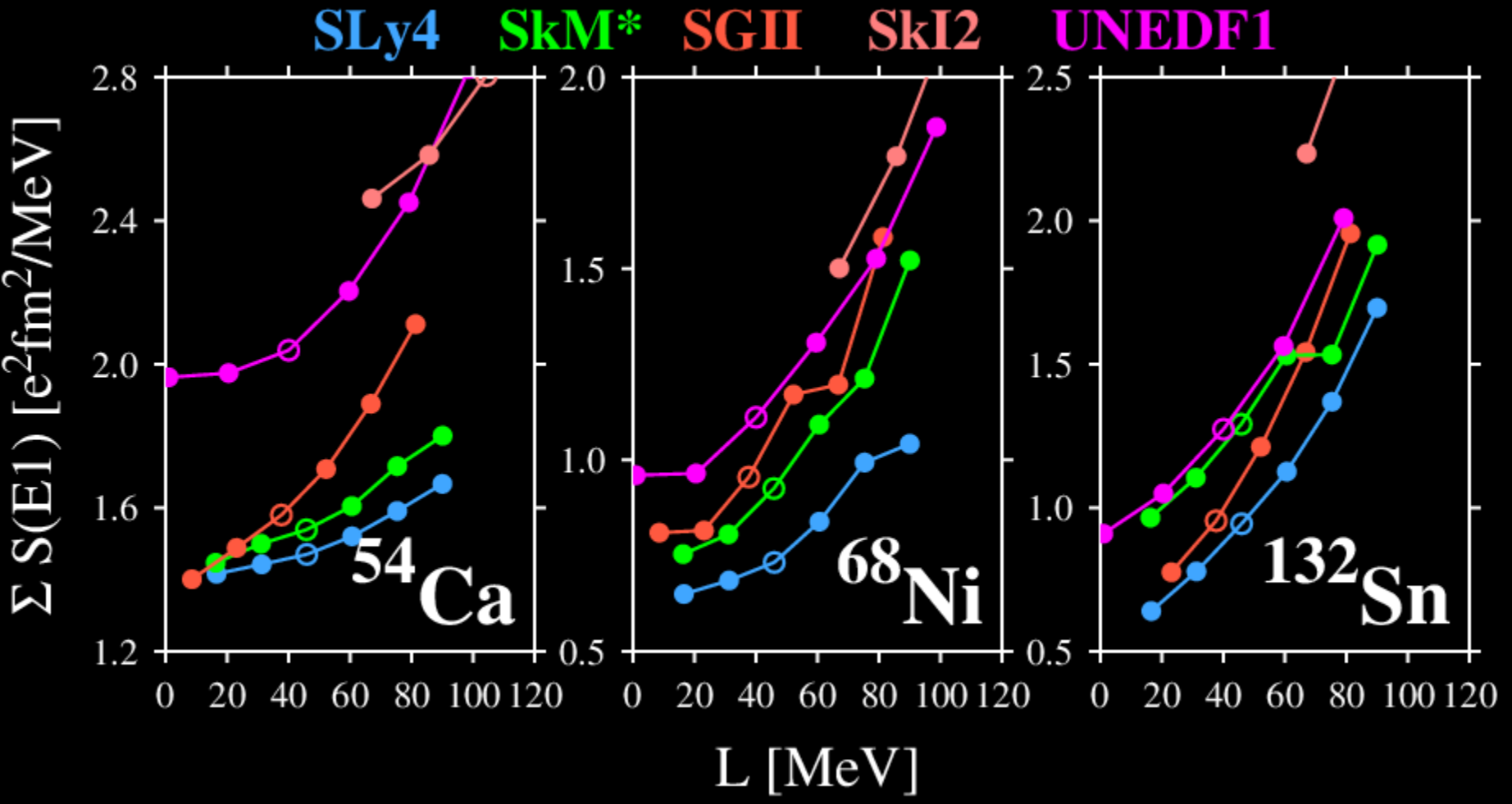
L-dependence of PDR strength



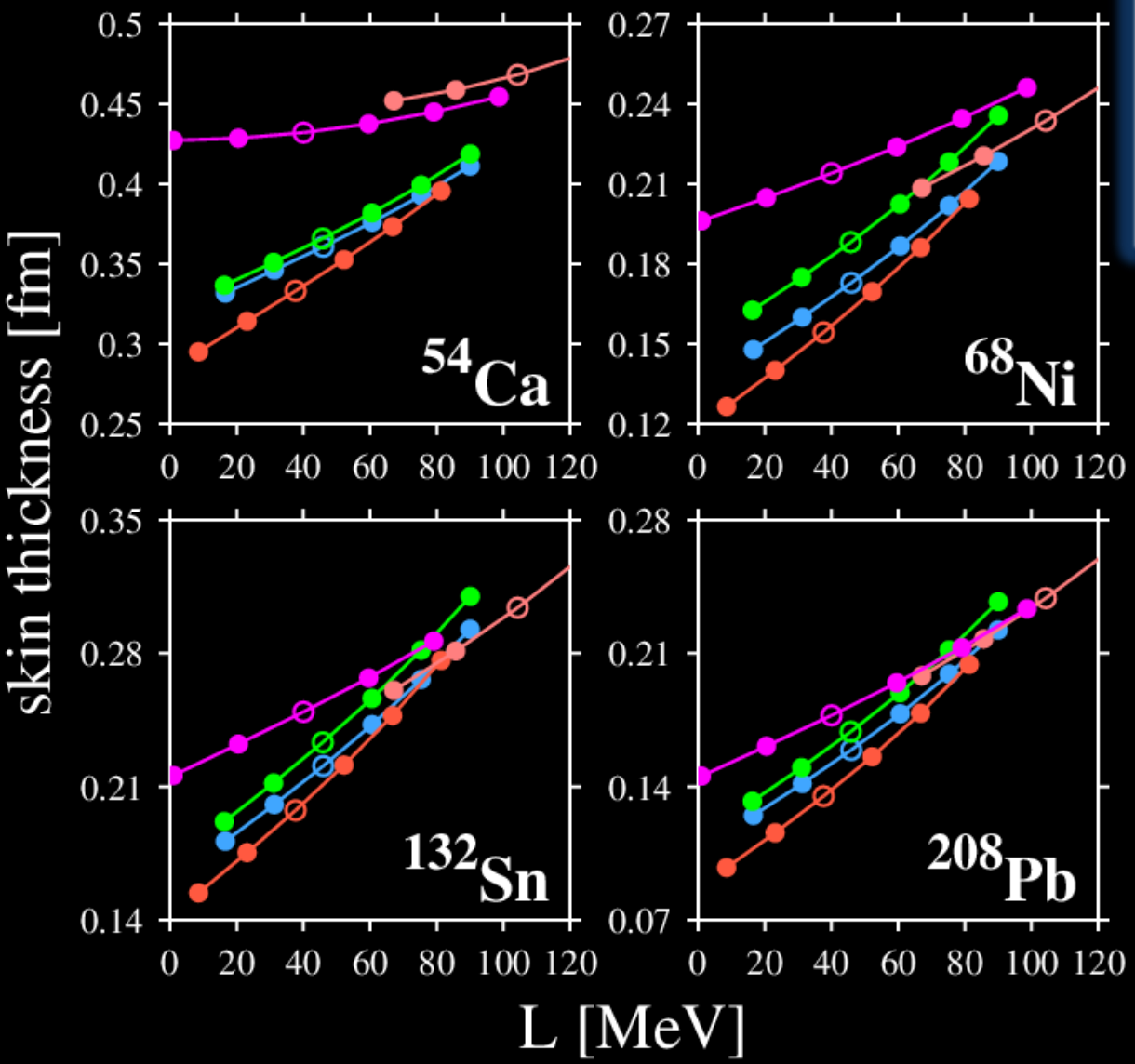
L-dependence of PDR strength



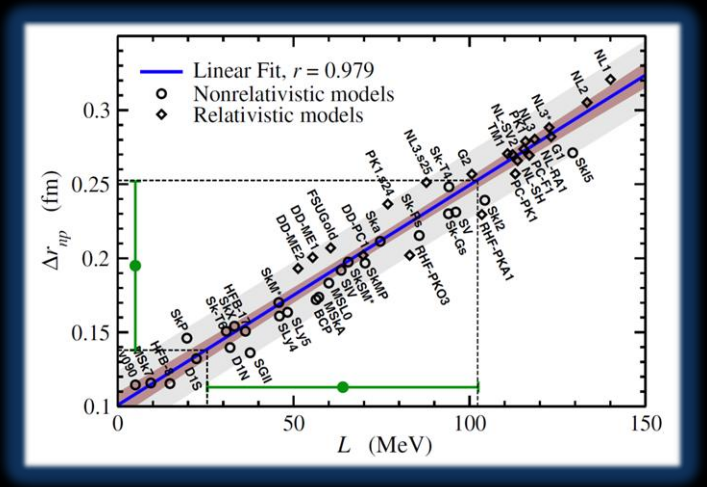
L- & interaction-dep. of PDR strength



Skin & *L*



SLy4
SkM*
SGII
SkI2
UNEDF1

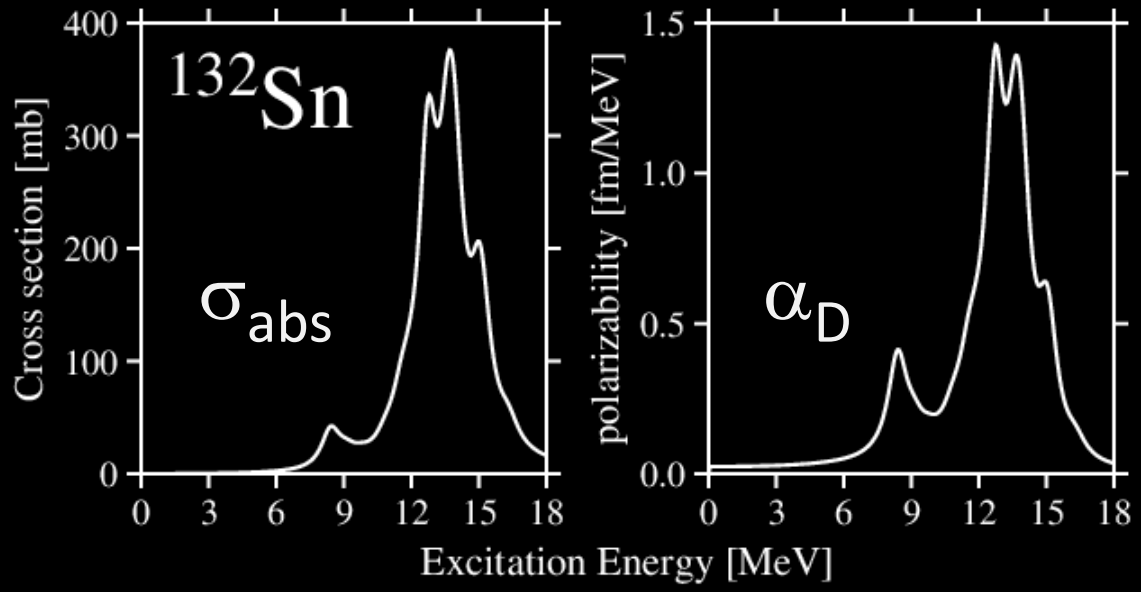


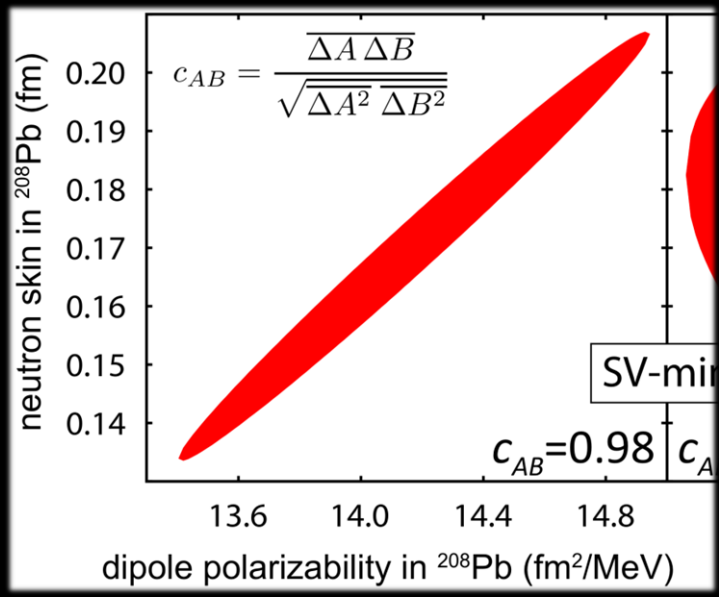
X. Roca-Maza et al.,
PRL 106, 252501 (2011)

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

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

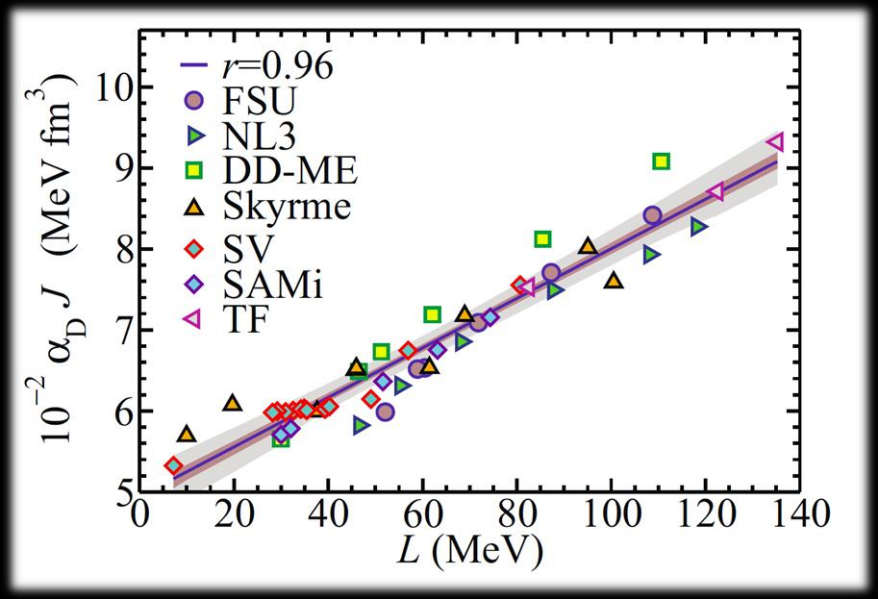
$$\alpha_D = \frac{8\pi e^2}{9} m_{-1} \propto m_{-1} = \int {\rm d}E\, \frac{S(E1)}{E}$$





Reinhard & Nazarewicz,
PRC81, 051303 (2010)

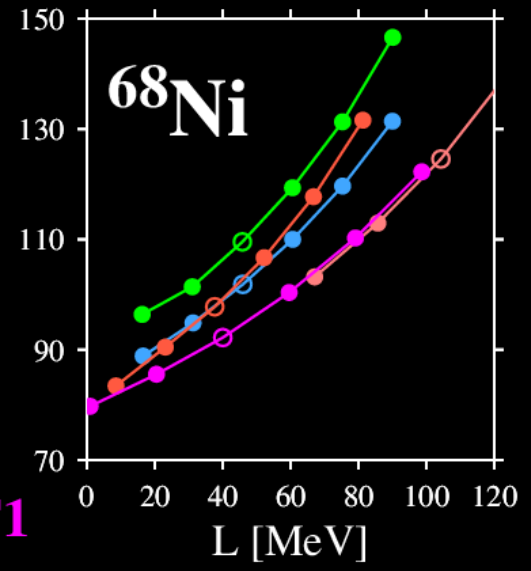
New correlation constraining on *L*

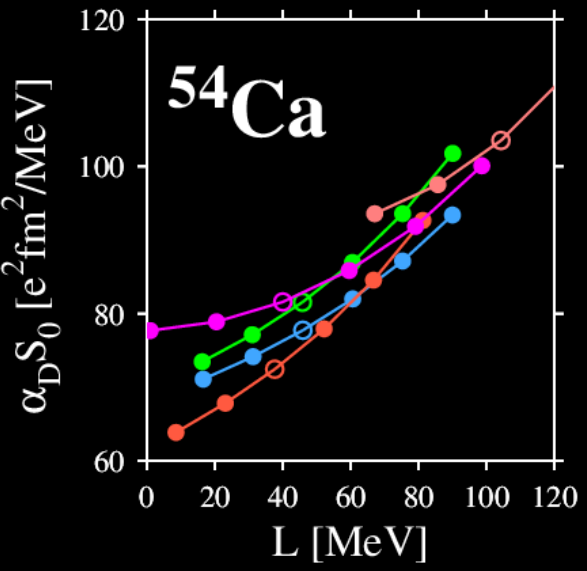


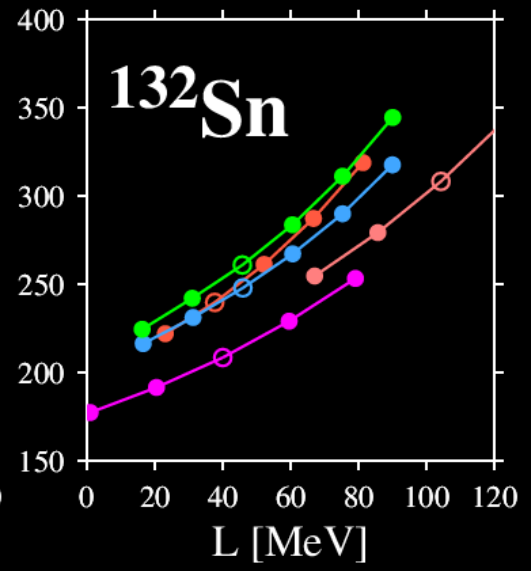
Roca-Maza et al., PRC88, 024316 (2013)

$$\alpha_D^{\mathrm{DM}} S_0 \sim \frac{\pi e^2}{54} A\langle r^2\rangle \left(1+\frac{5}{24}\frac{L}{S_0}\right)$$

SLy4
SkM*
SGII
SkI2
UNEDF1

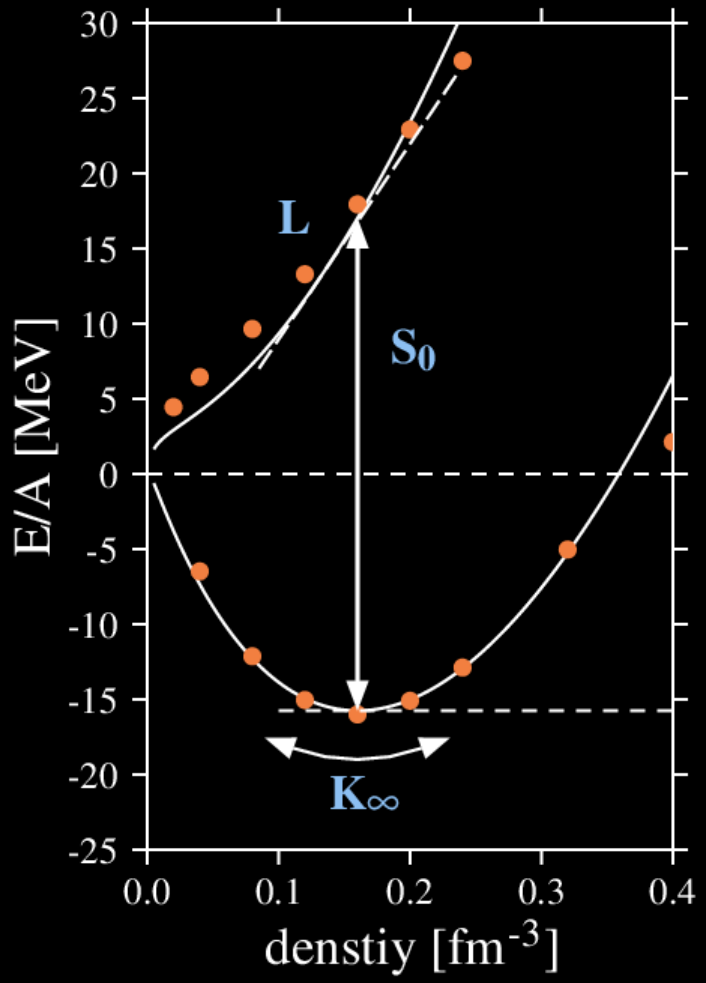






Summary

不安定核のダイポール励起から
L に拘束を掛けれそうである。
但し、相互作用依存性があるので
合理的な取捨選択が求められる。



Cf. Stone et al., PRC 68, 034324 (2003)