# Low-energy E1 strength in select nuclei: Possible constraint on the symmetry energy and the neutron skin

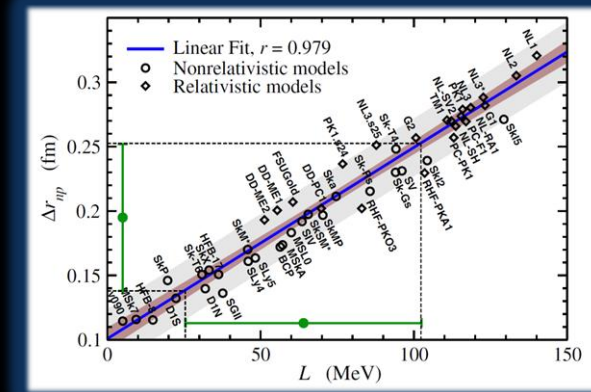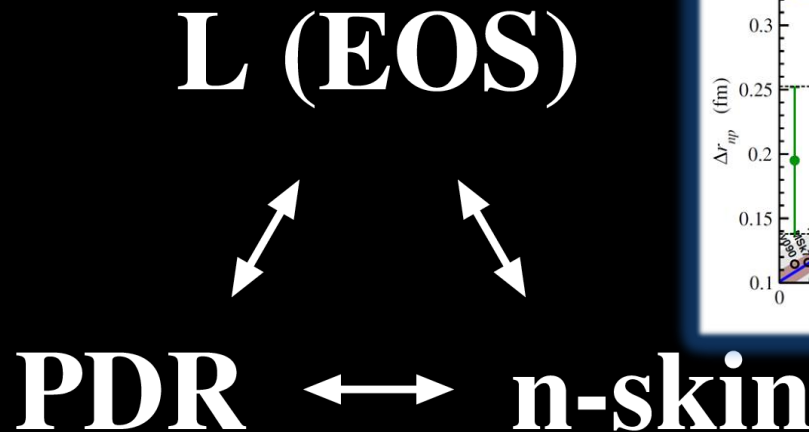**Tsunenori INAKURA (Chiba U.)**

in collaboration with
Takashi NAKATSUKASA (RIKEN)
Kazuhiro YABANA (U. of Tsukuba)
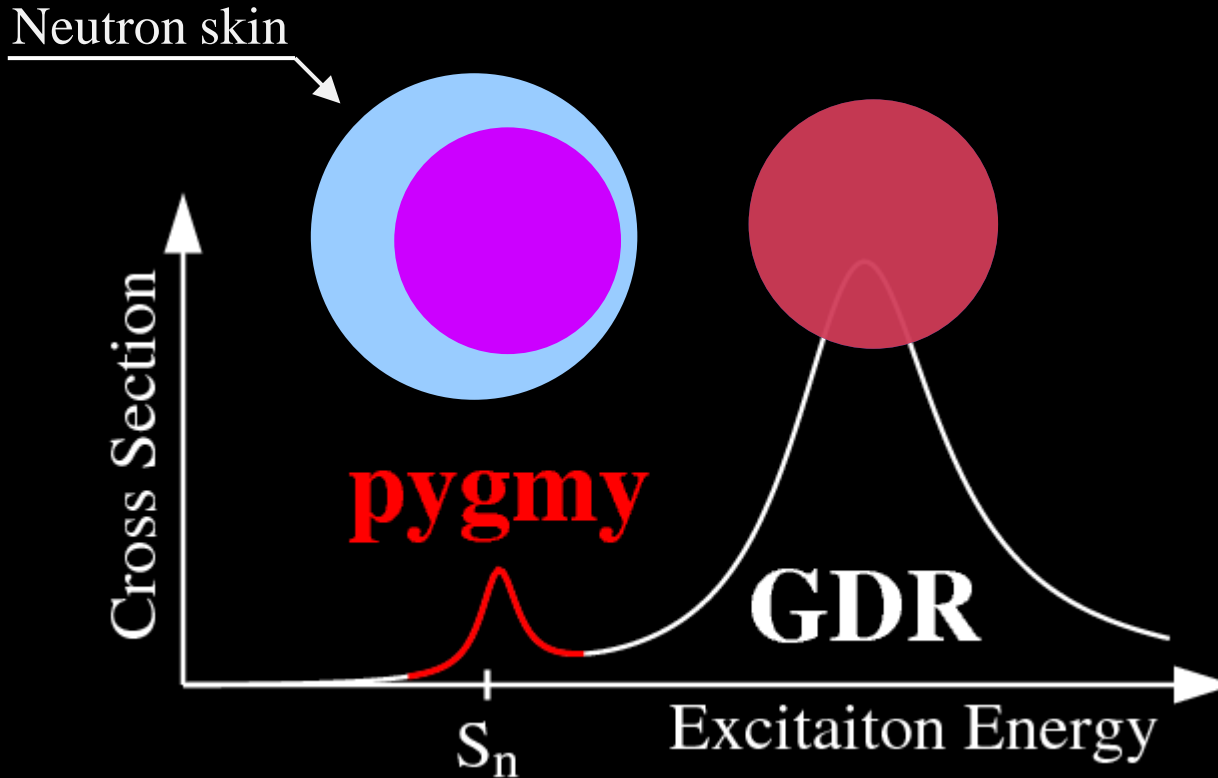Hitoshi NAKADA (Chiba U.)

# **Outline**

1.  Introduction of low-energy E1 strength
    (pygmy dipole resonance, PDR)
2.  Correlation between PDR and skin thickness
3.  Correlation between PDR and $L$
4.  Correlation suggested by X. Roca-Maza
5.  Summary

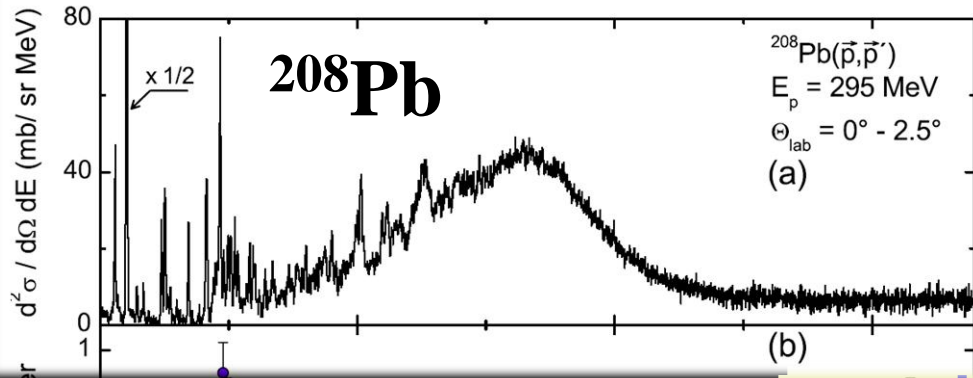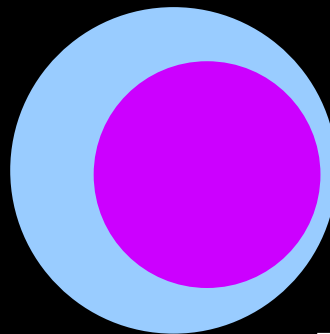**L (EOS)**

**PDR** ↔ **n-skin**



X. Roca-Maza et al.,
PRL 106, 252501

# Low-energy E1 strength: Pygmy Dipole Resonance (PDR)

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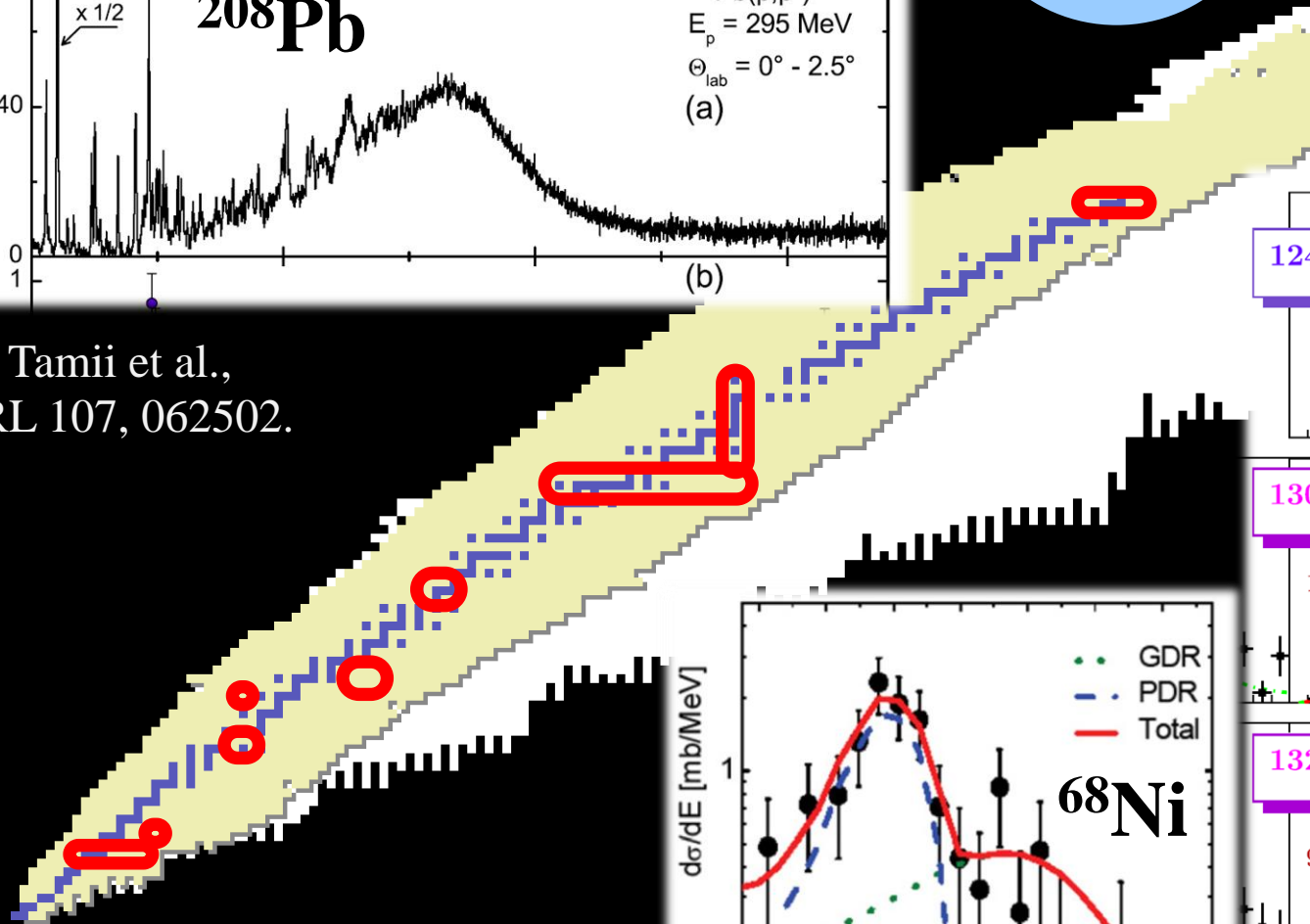PDR in ν-rich nuclei: < several % Cross Section

# **Observed PDRs**



## $^{208}$Pb

$^{208}$Pb$(\vec{p},\vec{p}')$
$E_p$ = 295 MeV
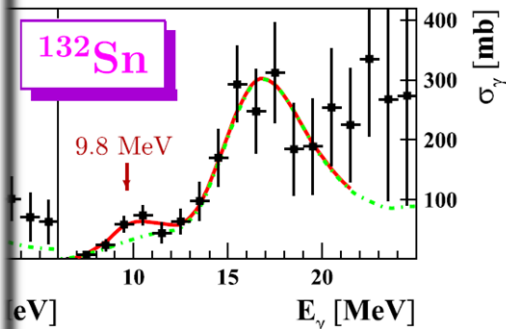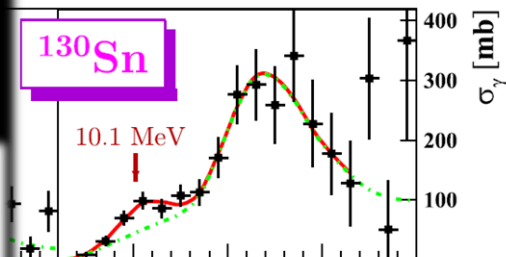$\Theta_{lab}$ = 0° - 2.5°
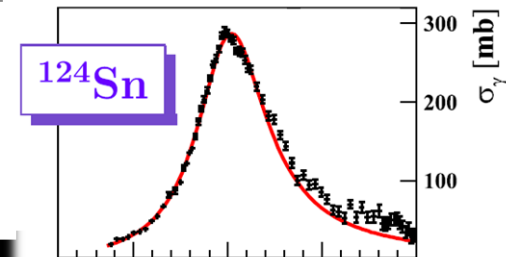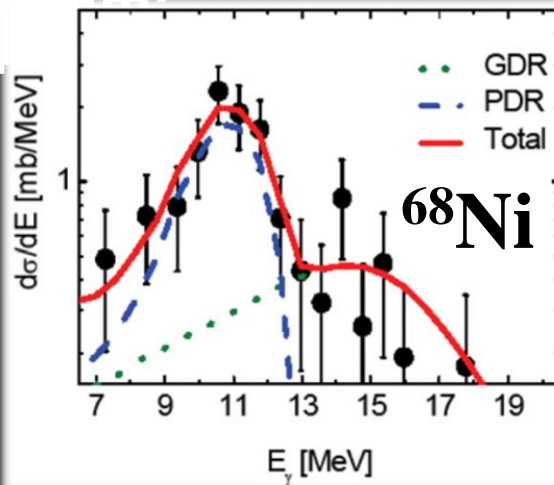(a)

$d^2\sigma / d\Omega\, dE$ (mb/ sr MeV)

x 1/2

(b)

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

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

$^{124}$Sn

$^{130}$Sn
10.1 MeV

$^{132}$Sn
9.8 MeV

$\sigma_\gamma$ [mb]

$^{68}$Ni

$d\sigma/dE$ [mb/MeV]

- GDR
- PDR
- Total

$E_\gamma$ [MeV]

O. Wieland et al.,
PRL 102, 092502

# Correlations between E1 and n-skin

L (EOS)

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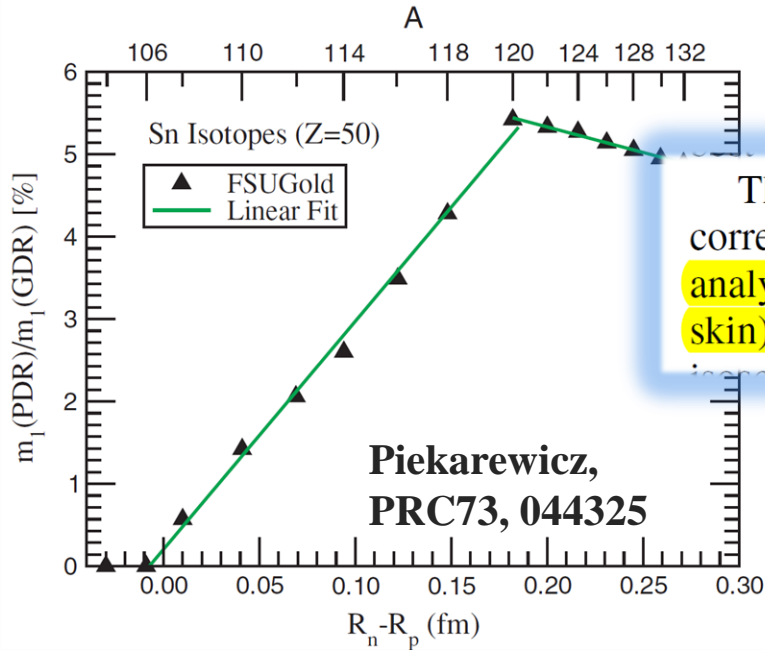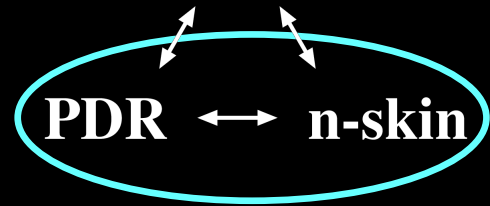
Reinhard & Nazarewicz, PRC81, 051303(R);
Covariance analysis for 68Ni, 132Sn, and 208Pb

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**

**Volz et al., NPA 779, 1.**
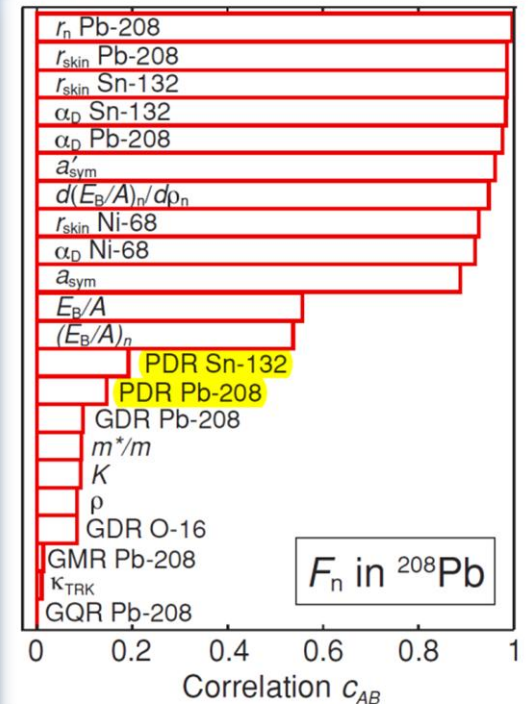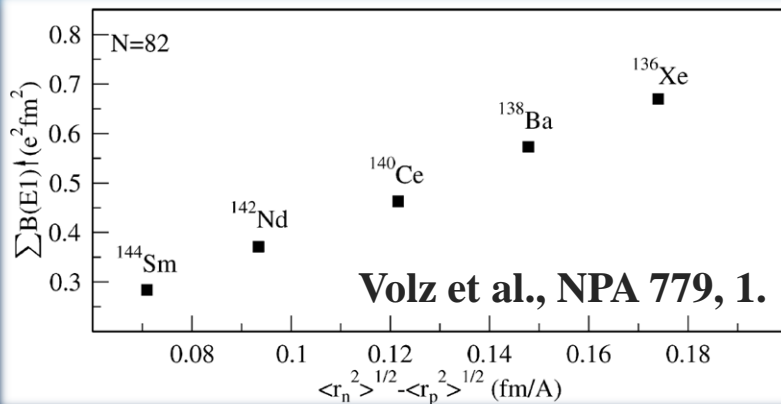
# RPA calculation

- Fully self-consistent calc. with Skyrme interaction
- 3D mesh representation
    - suitable for unstable nuclei having skin (or halo)
    - applicable to deformed nuclei
    - good approximation for continuum state
- No paring correlation
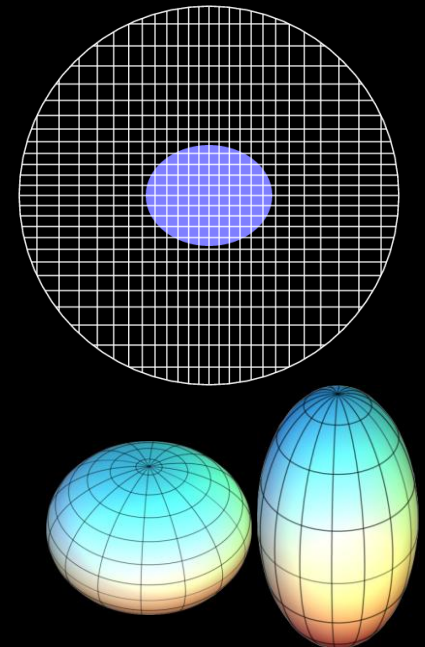
$$\left\{ \begin{bmatrix} A & B \\ B^* & A^* \end{bmatrix} - \hbar\omega \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \right\} \begin{bmatrix} X_{nj}(\omega) \\ Y_{nj}(\omega) \end{bmatrix} = - \begin{bmatrix} f(\omega) \\ g(\omega) \end{bmatrix}$$

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

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

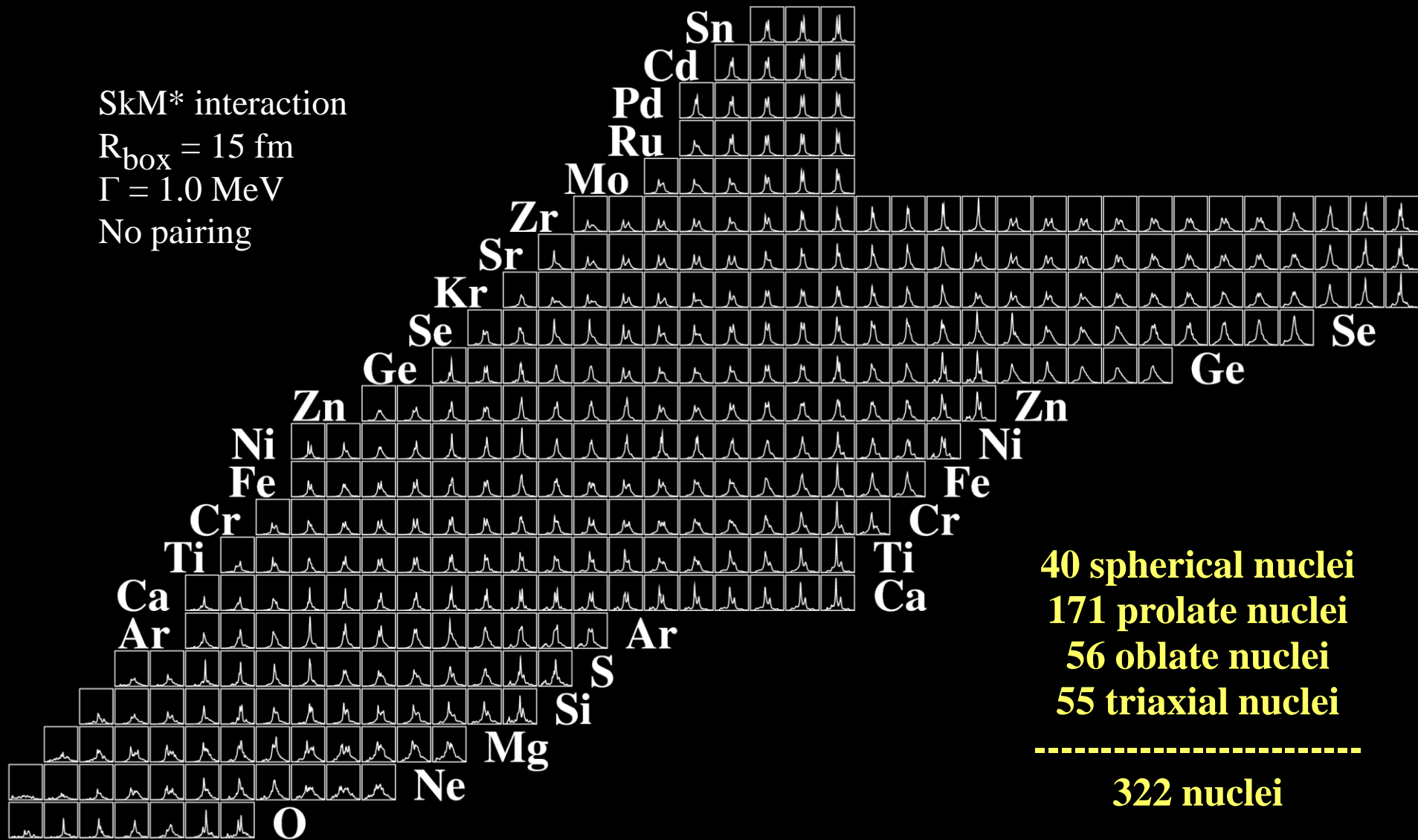$$|\text{vib.}\rangle = \sum_{ph} f_{ph}|1p-1h\rangle$$

# Systematic calc. of E1 mode

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

SkM* interaction
$R_{box}$ = 15 fm
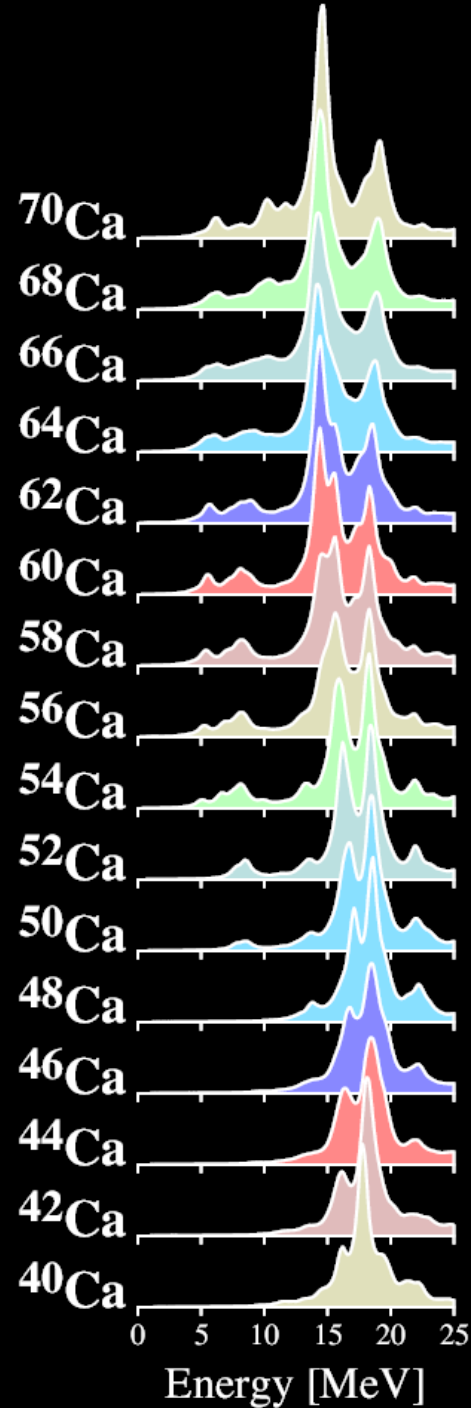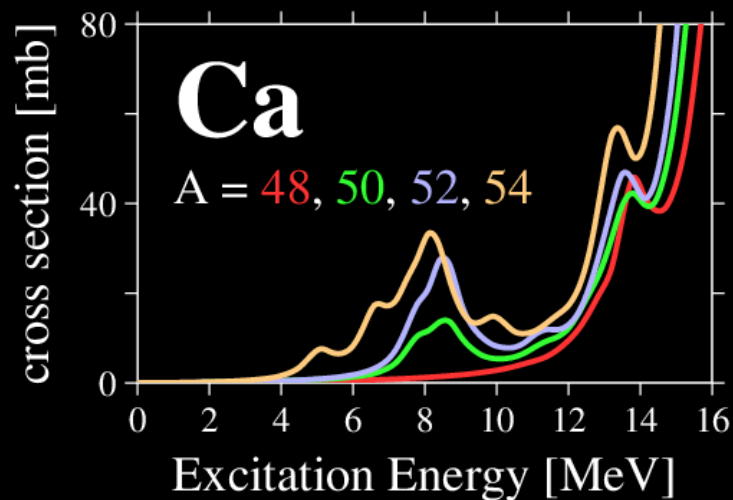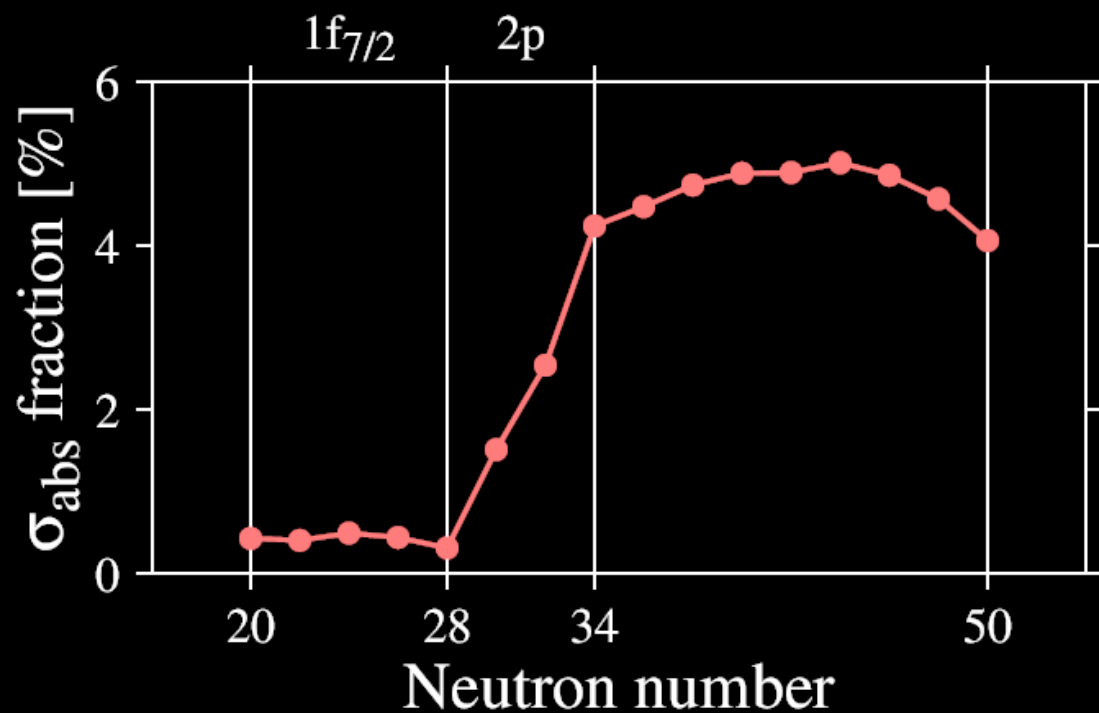$\Gamma$ = 1.0 MeV
No pairing



**40 spherical nuclei**
**171 prolate nuclei**
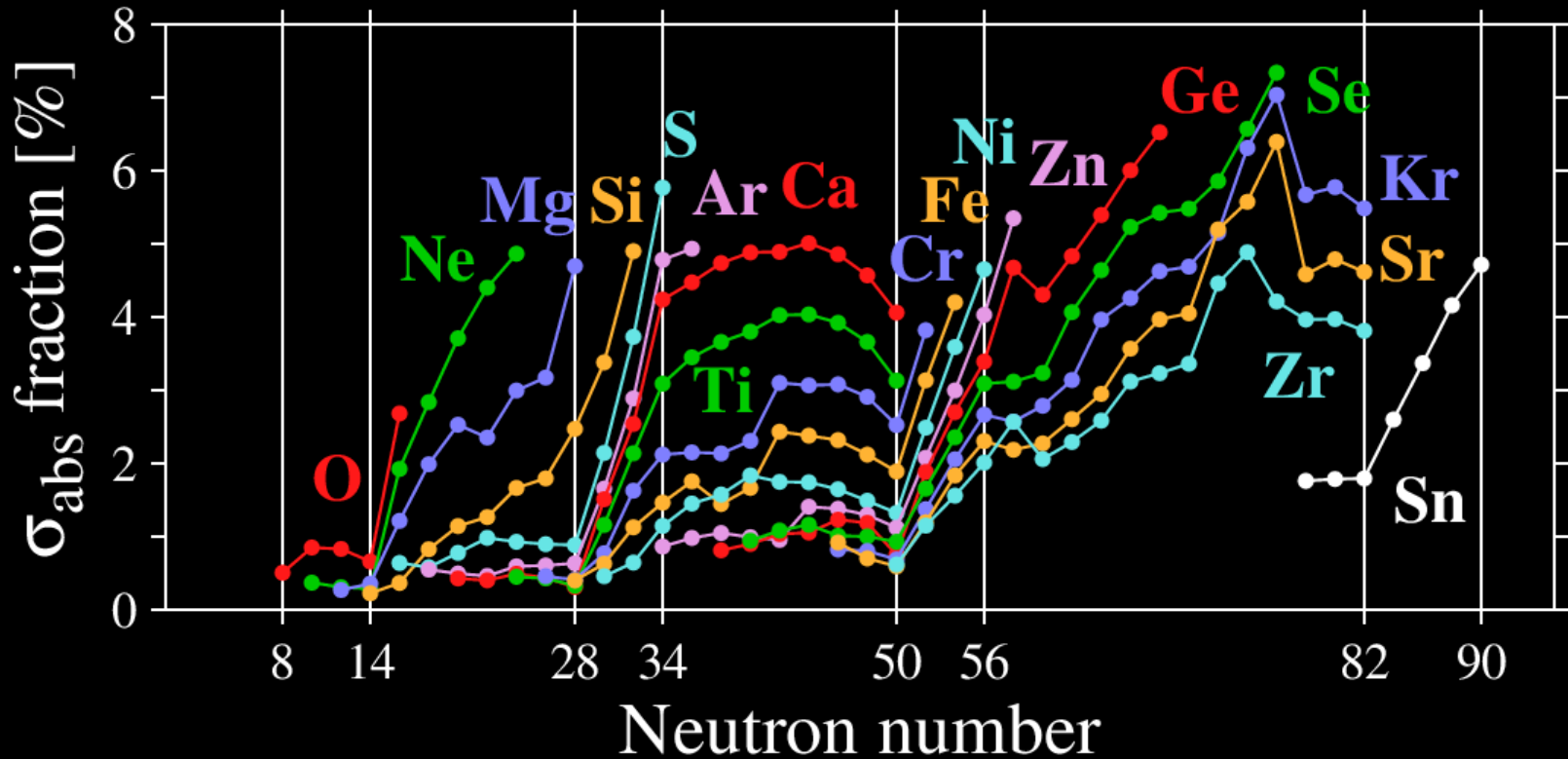**56 oblate nuclei**
**55 triaxial nuclei**
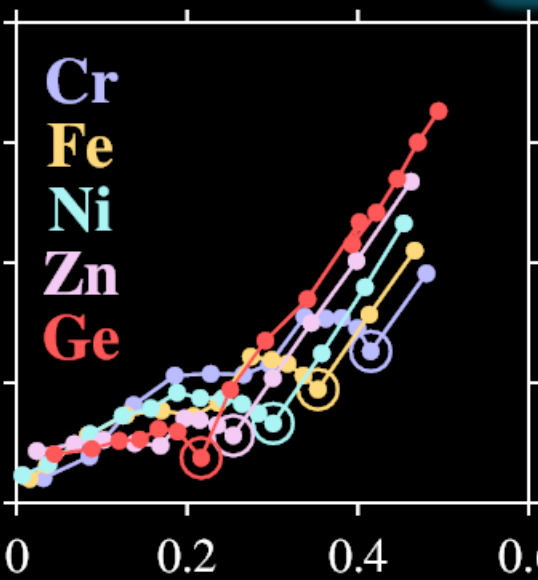-------------------------
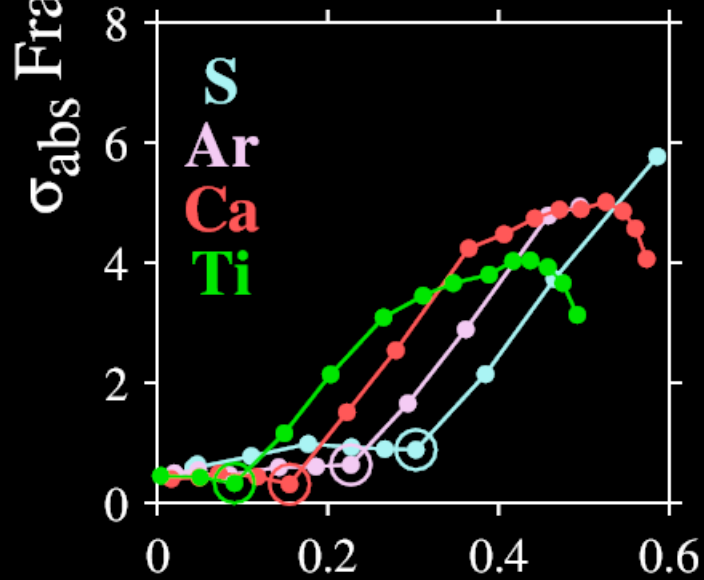**322 nuclei**

# PDR in Ca isotopes

# PDR in n-rich nuclei
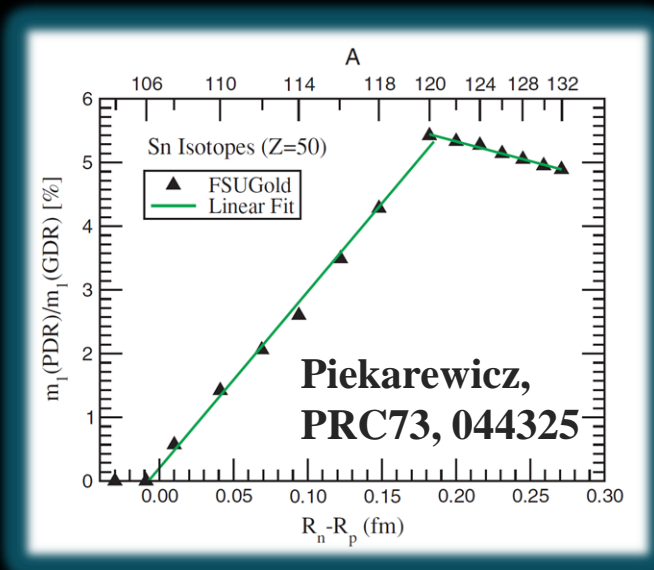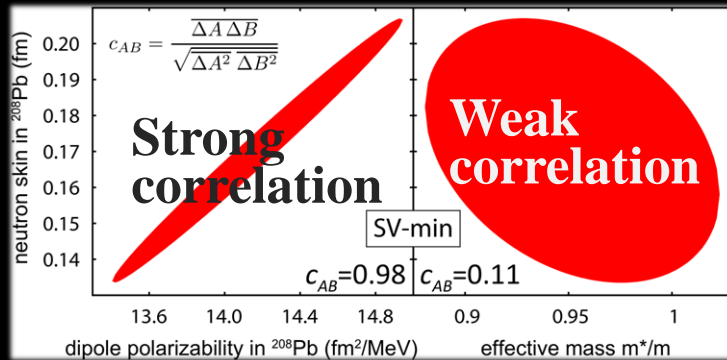
Inakura et al., PRC84, 021302

# PDR & Skin



L (EOS)

PDR ⟷ n-skin

Piekarewicz,
PRC73, 044325

$\sigma_{abs}$ Fraction [%]

diff. of Rrms [fm]

S
Ar
Ca
Ti

Cr
Fe
Ni
Zn
Ge

Se
Kr
Sr
Zr
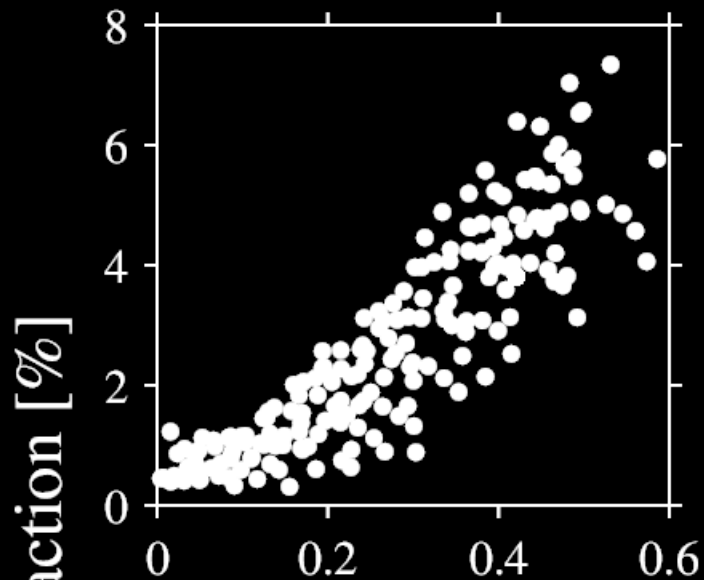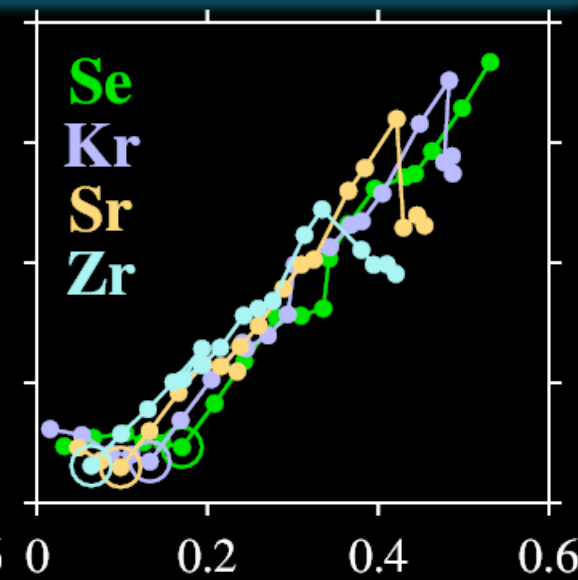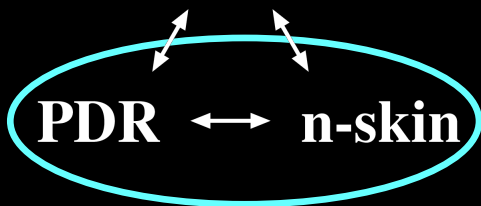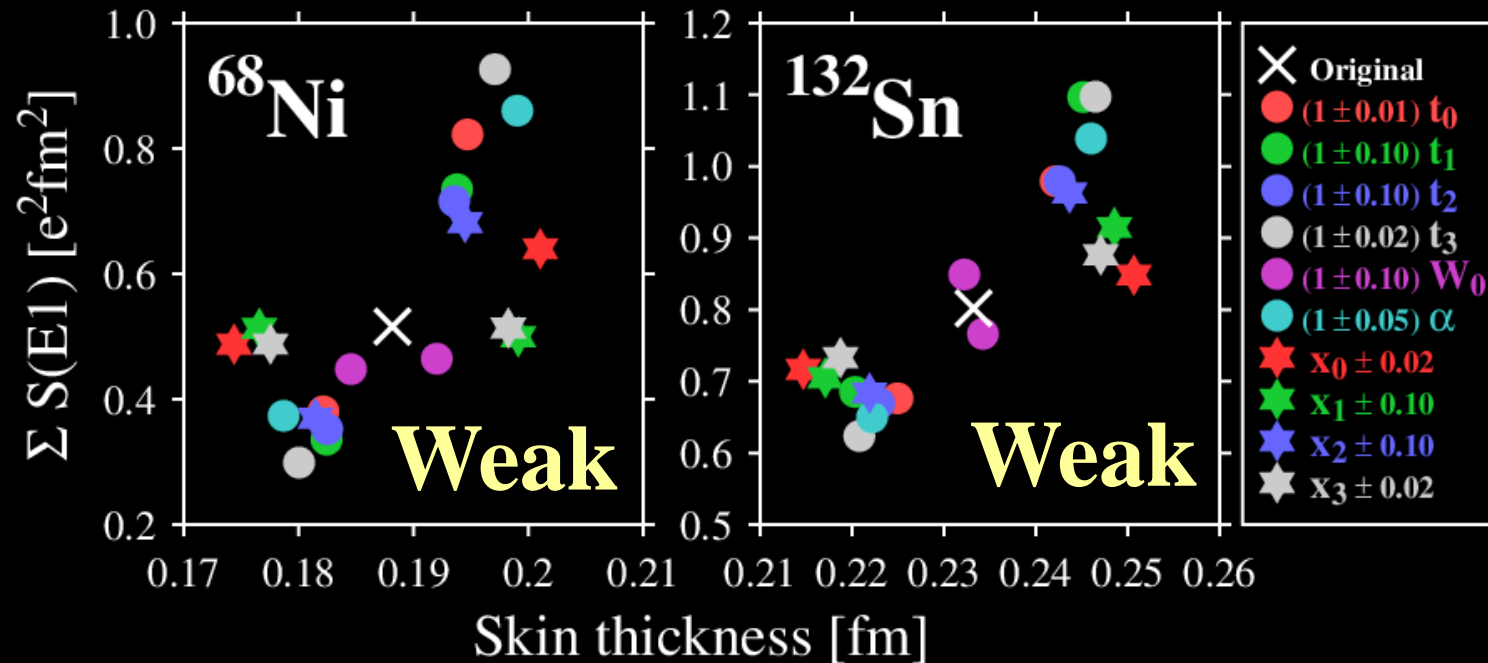
# Confirmation of weak correlations



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 ⁶⁸Ni &¹³²Sn



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
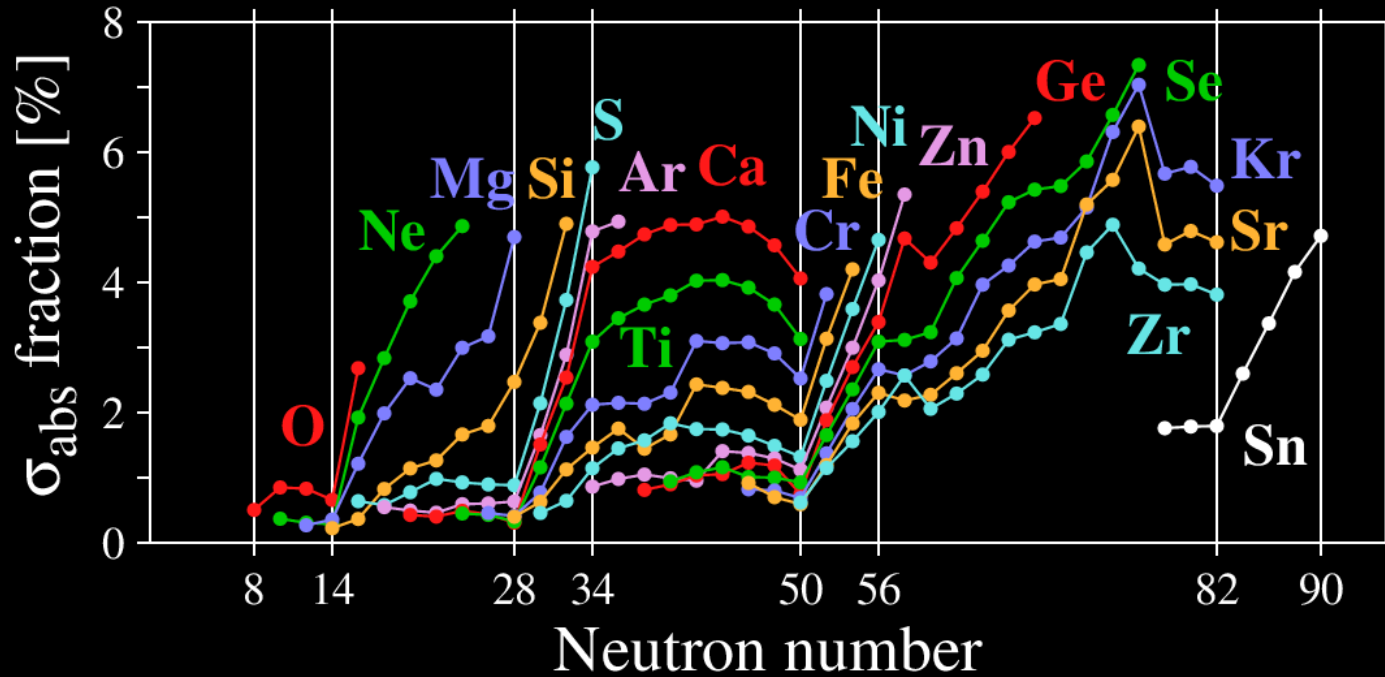
# Correlation in $^{68,78,84}$Ni
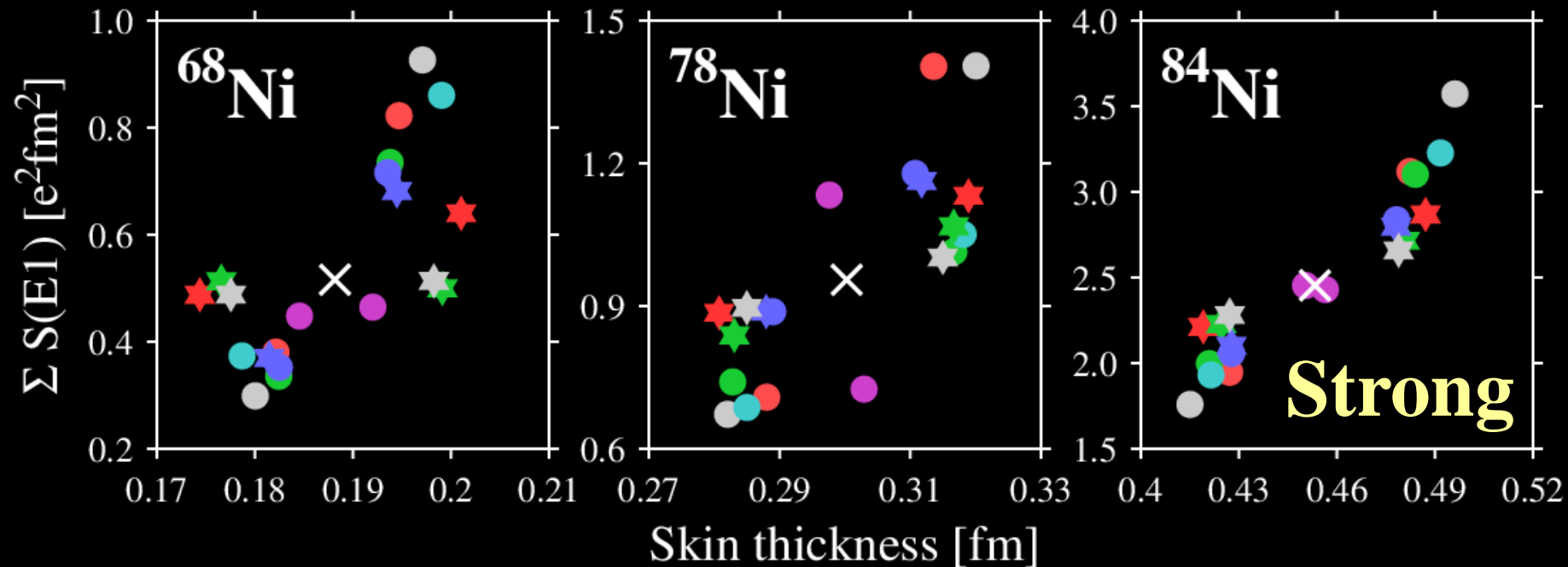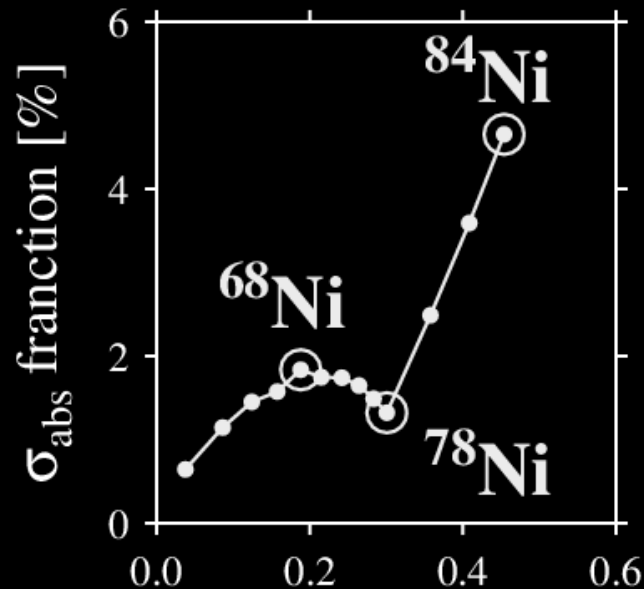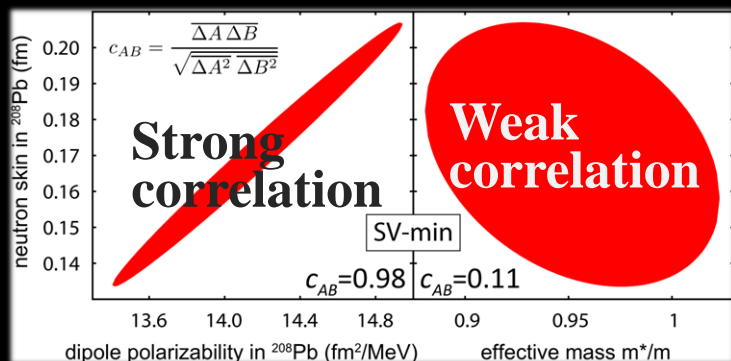
# Interaction dependence of PDR correlation
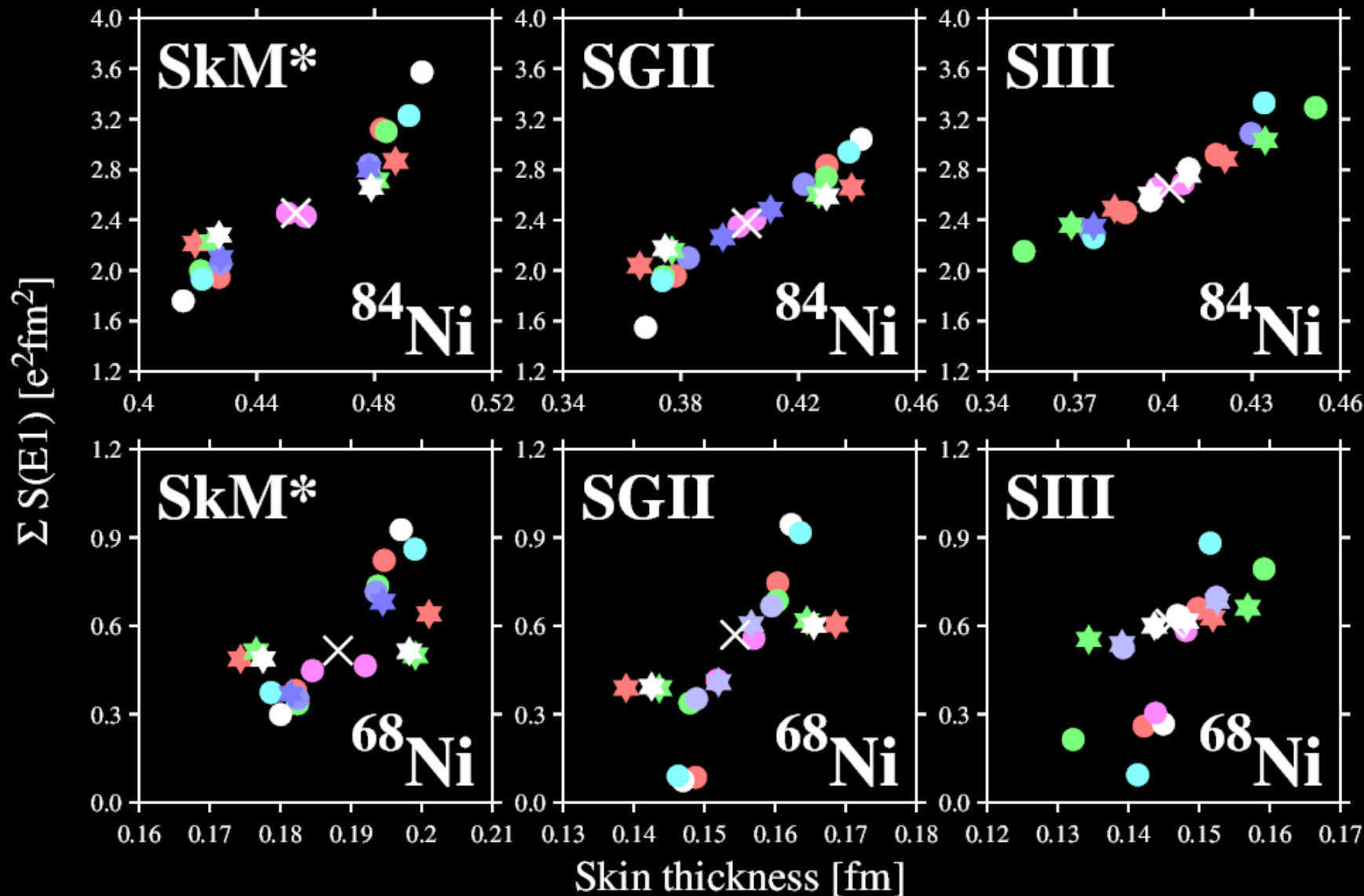
# Difficult to observe the PDR in 84Ni…



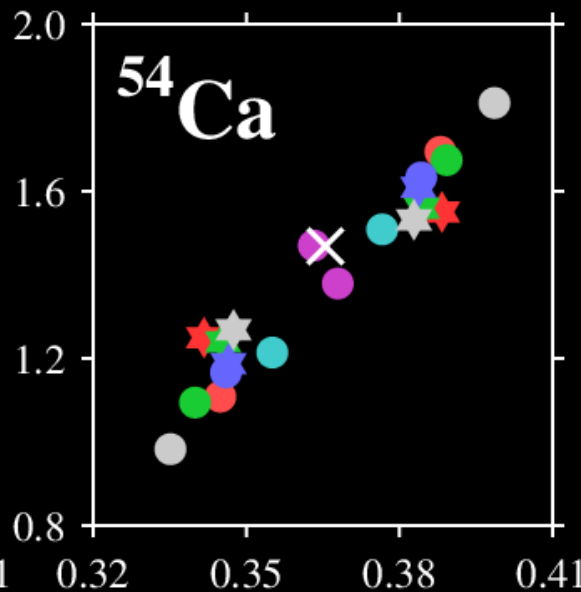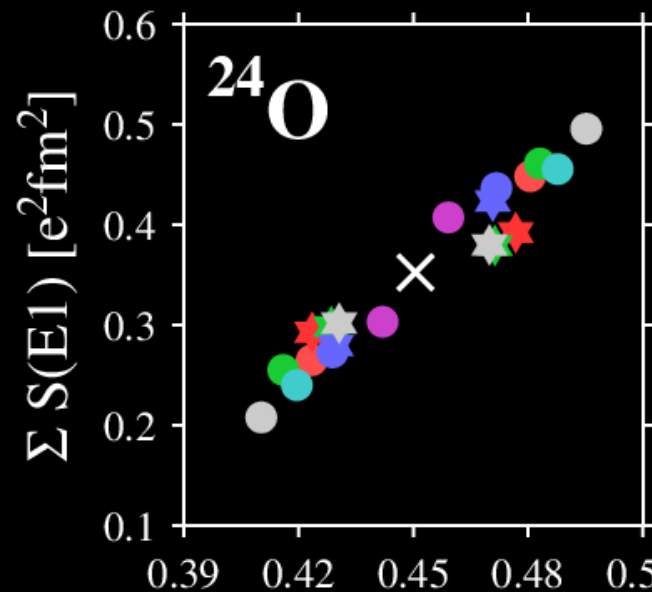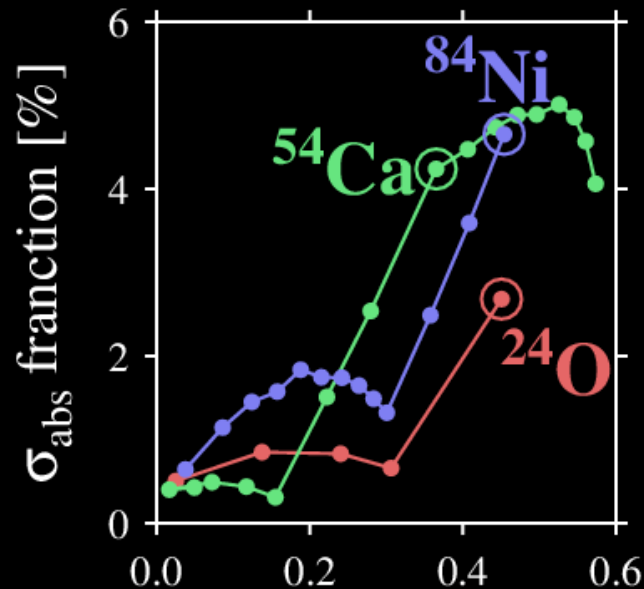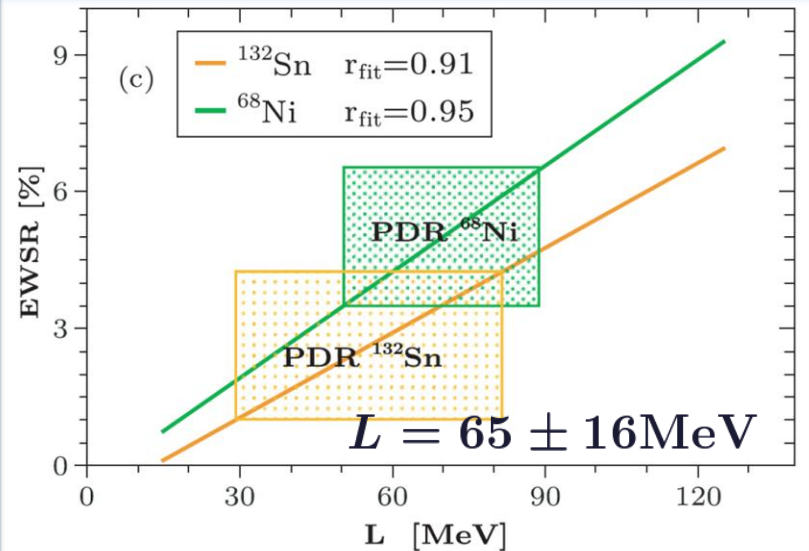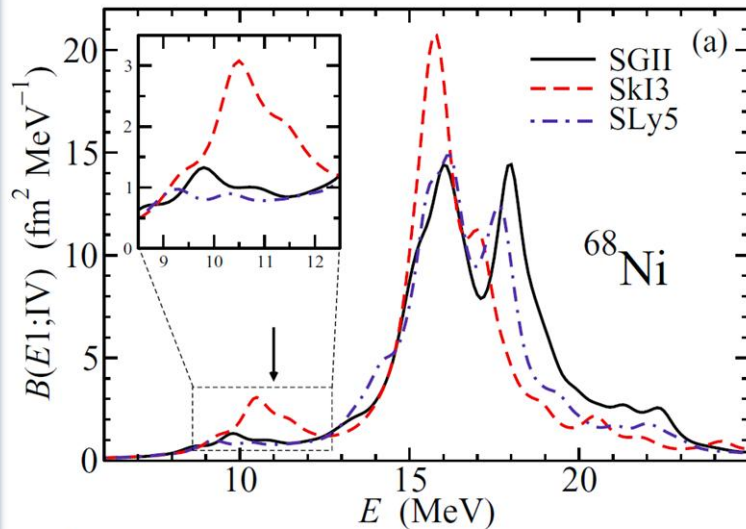$$\Rightarrow \text{54Ca, 24O}$$
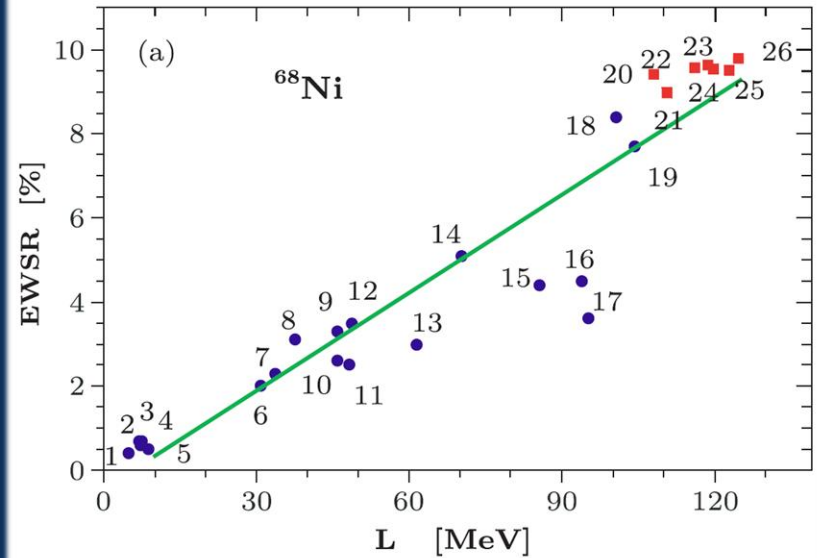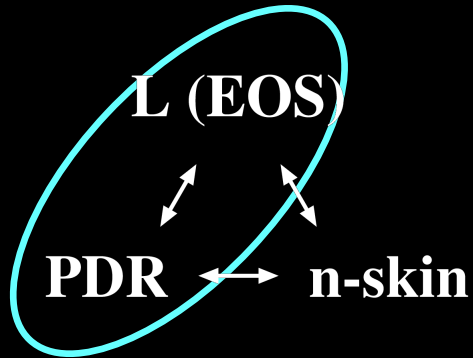
# Skin & PDR
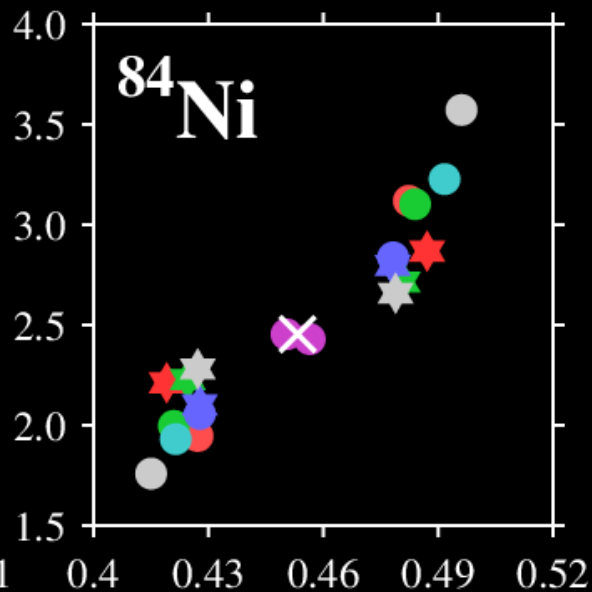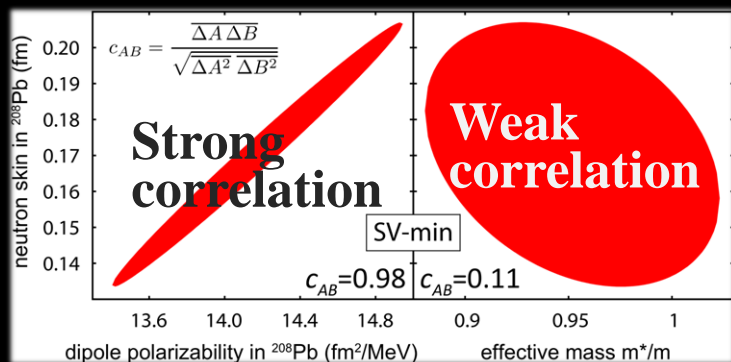
# **Short summary**

➢ The strong correlation between PDR and skin thickness
   is present in properly select nuclei.
➢ $^{24}$O & $^{54}$Ca are candidates to probe the neutron skin thickness.
➢ However, slope of the correlation depends on interaction.

# Correlation between *L* and PDR (and $\alpha_D$)

Ongoing calculation, tentative result.

# *L* from PDR

L (EOS)

PDR ⟷ n-skin







X. Roca-Maza et al.,PRC 85, 024601(2012)        Carbone et al.,  PRC81, 041301® (2010)
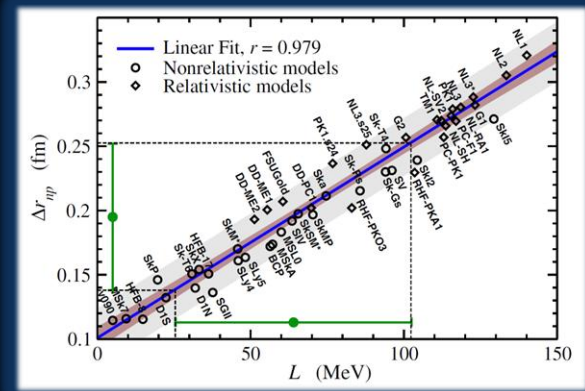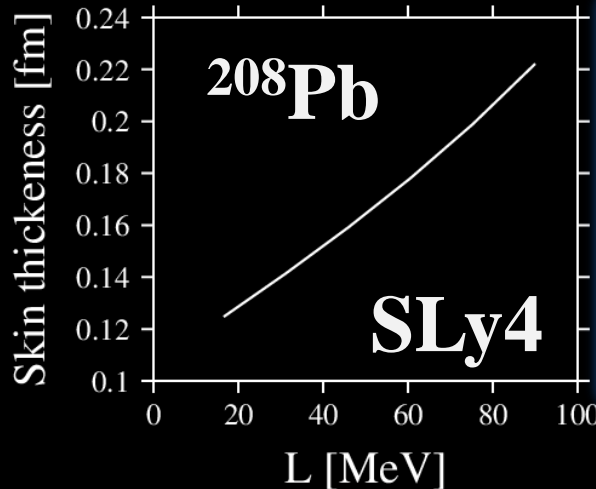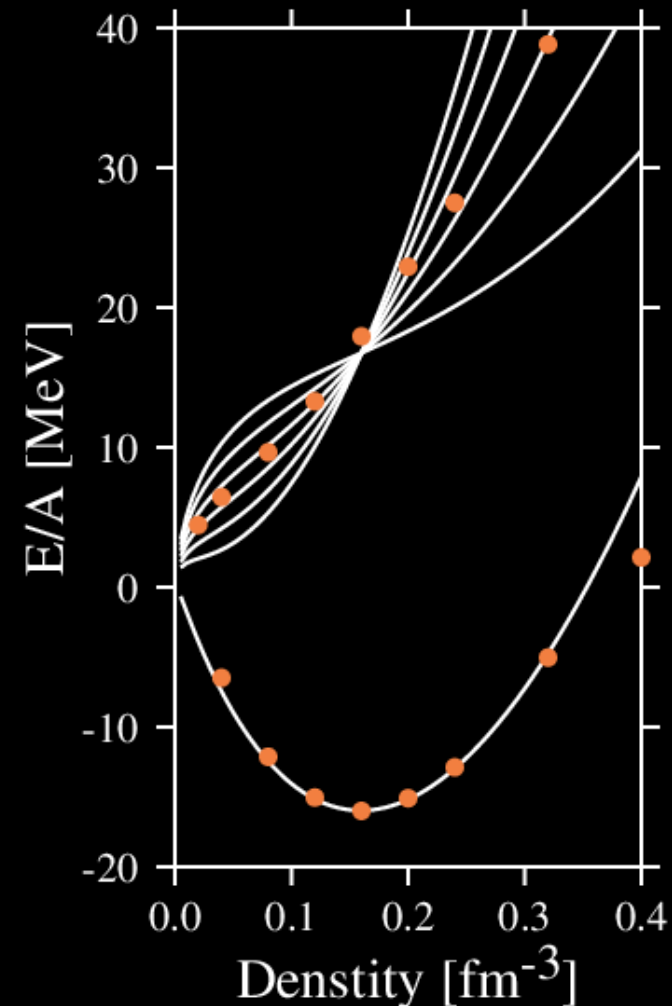
# *L*-dependence

$$V_{\text{Skyrme}} \Rightarrow V_{\text{Skyrme}} - V_L \left[ \rho^\alpha(r) - \rho_0^\alpha \right] P_\sigma \delta(r)$$
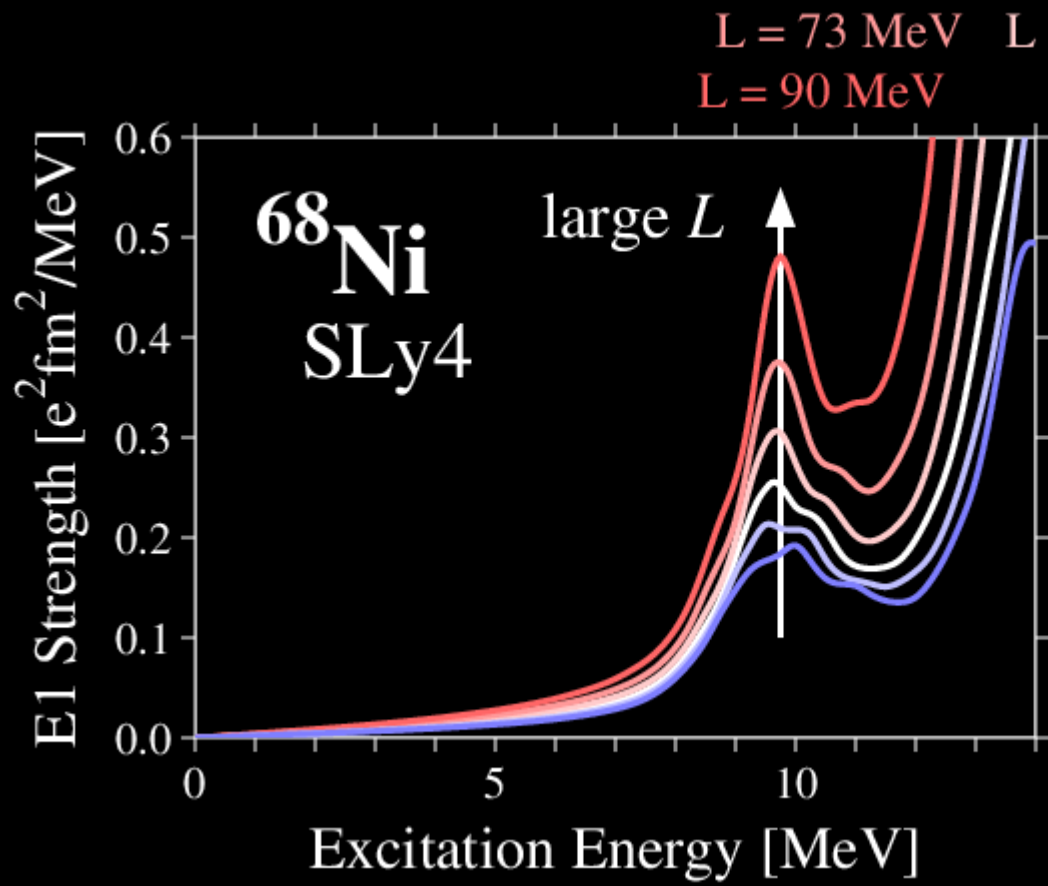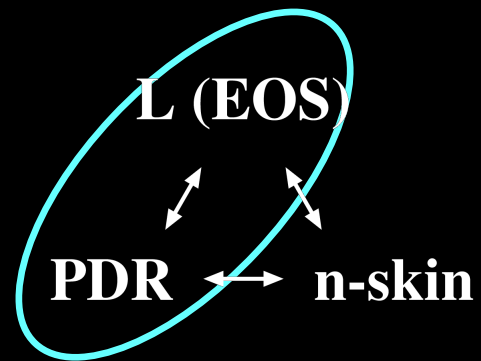
Cf. Ono et al., PRC68, 051601(R) (2003)

This additional term
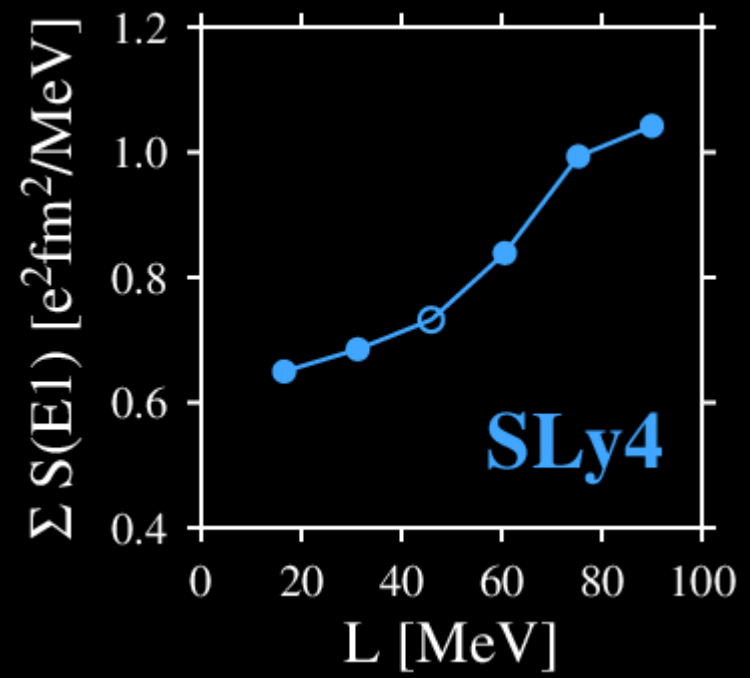- does not affect SNM EoS nor Esym($\rho_0$).
- changes *L*.

$V_L$ is a parameter to control *L*.



208Pb
SLy4

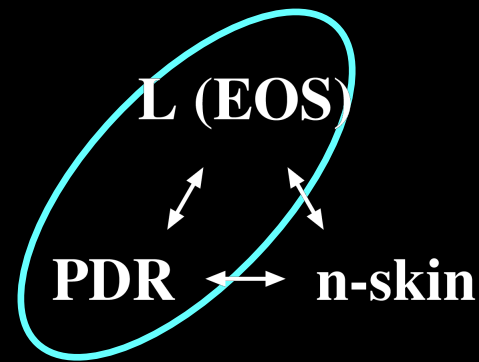# *L*-dependence of PDR

L (EOS)

PDR ↔ n-skin

L = 73 MeV   L = 61 MeV
L = 90 MeV   L = 46 MeV
(original SLy4)
L = 31 MeV
L = 17 MeV

$^{68}$Ni
SLy4

large *L*

E1 Strength [$e^2 fm^2/MeV$]

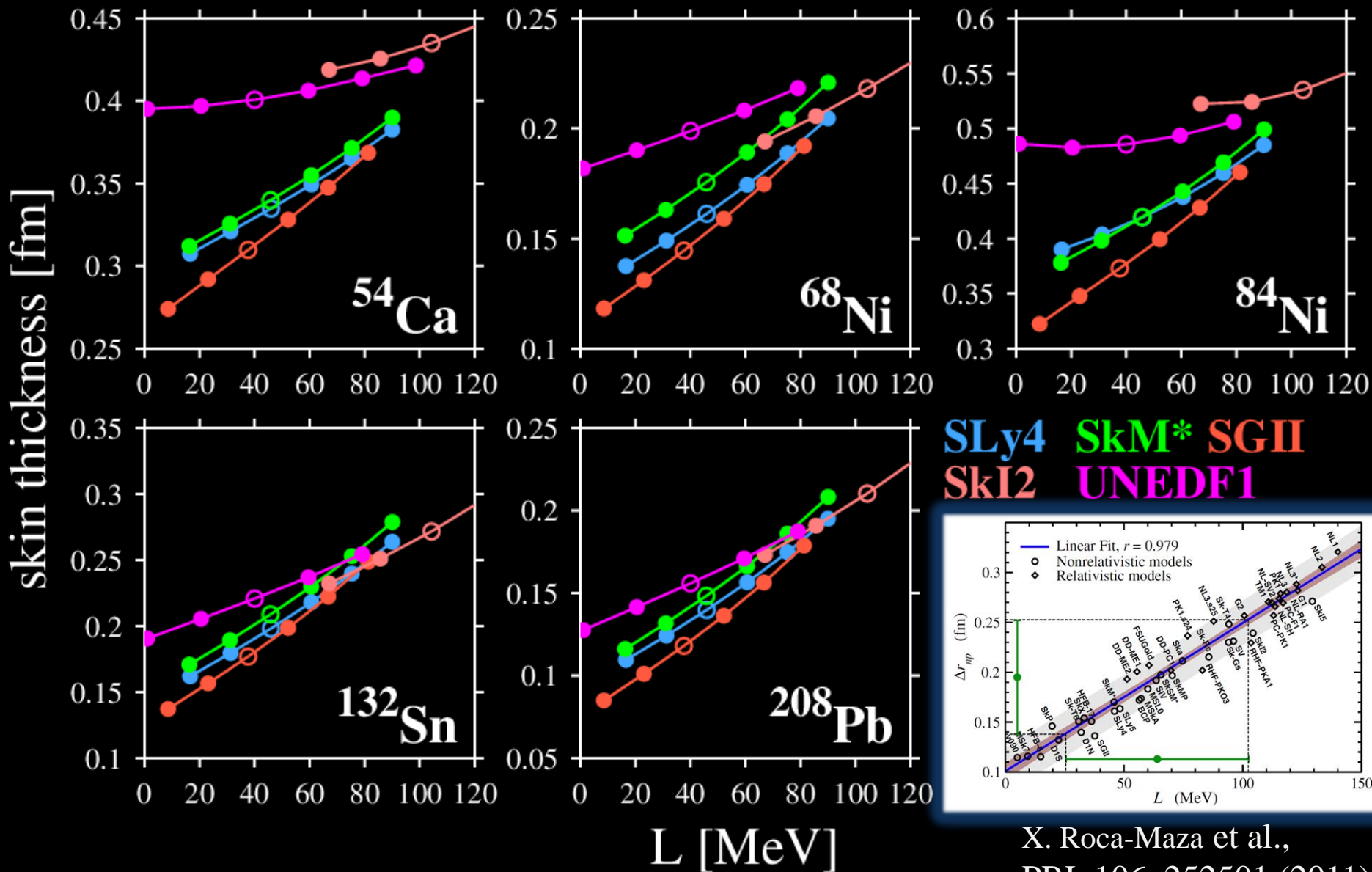Excitation Energy [MeV]

$\Sigma S(E1)$ [$e^2 fm^2/MeV$]

L [MeV]

SLy4
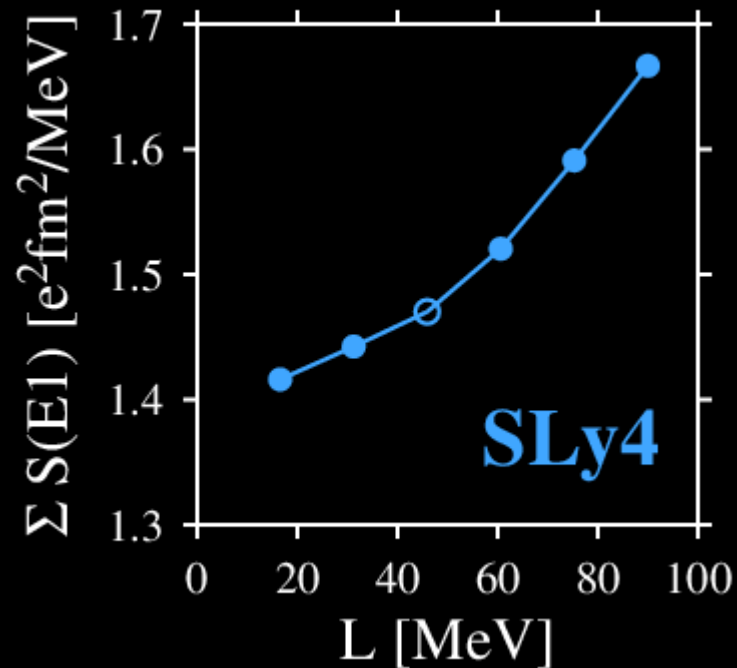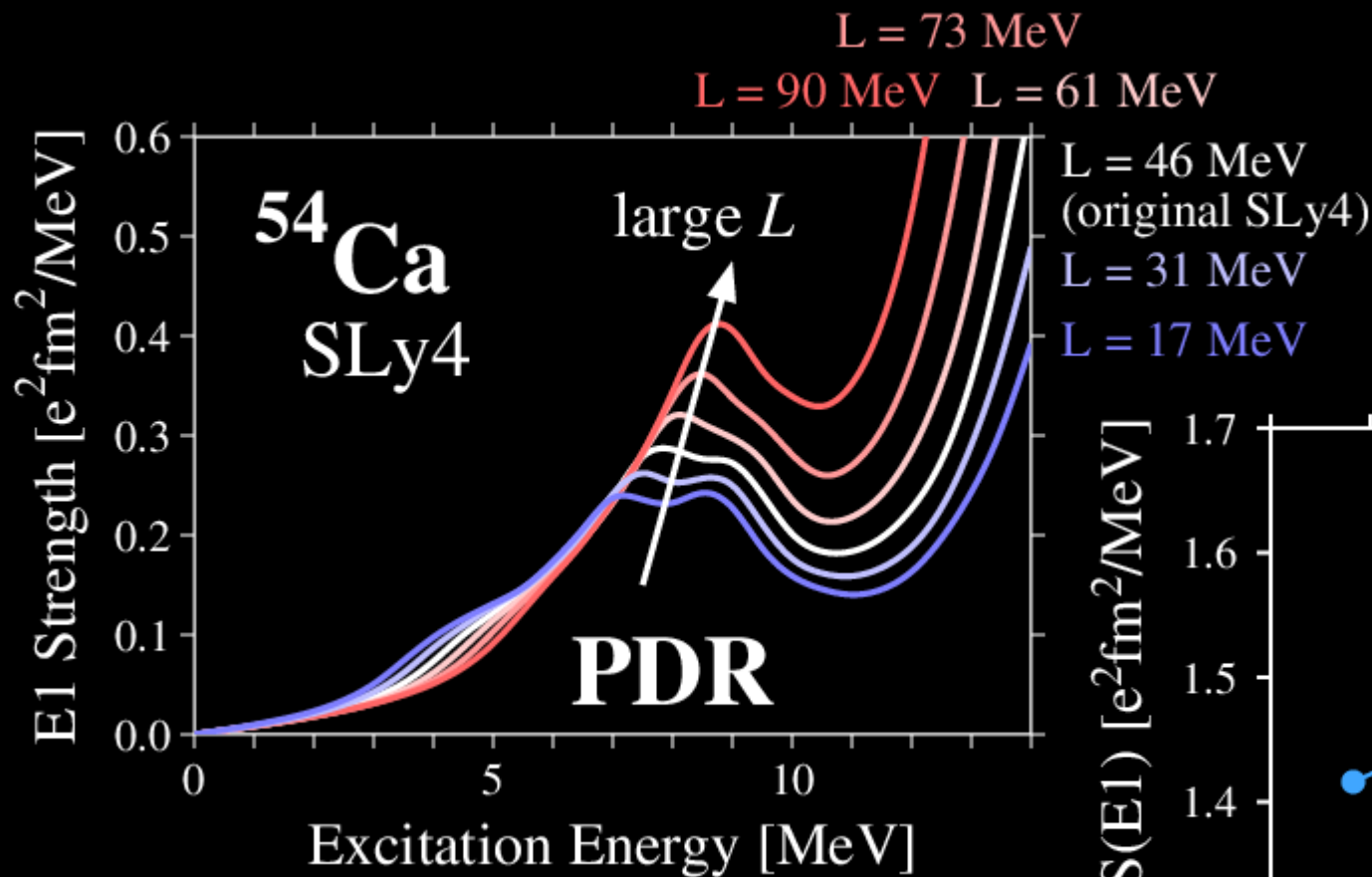
# *L*-dependence of PDR

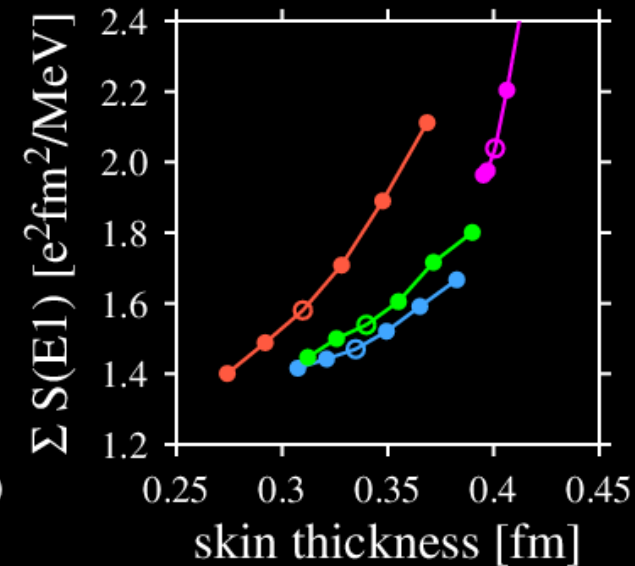# *L*- and interaction-dep. of PDR

# Skin & *L*
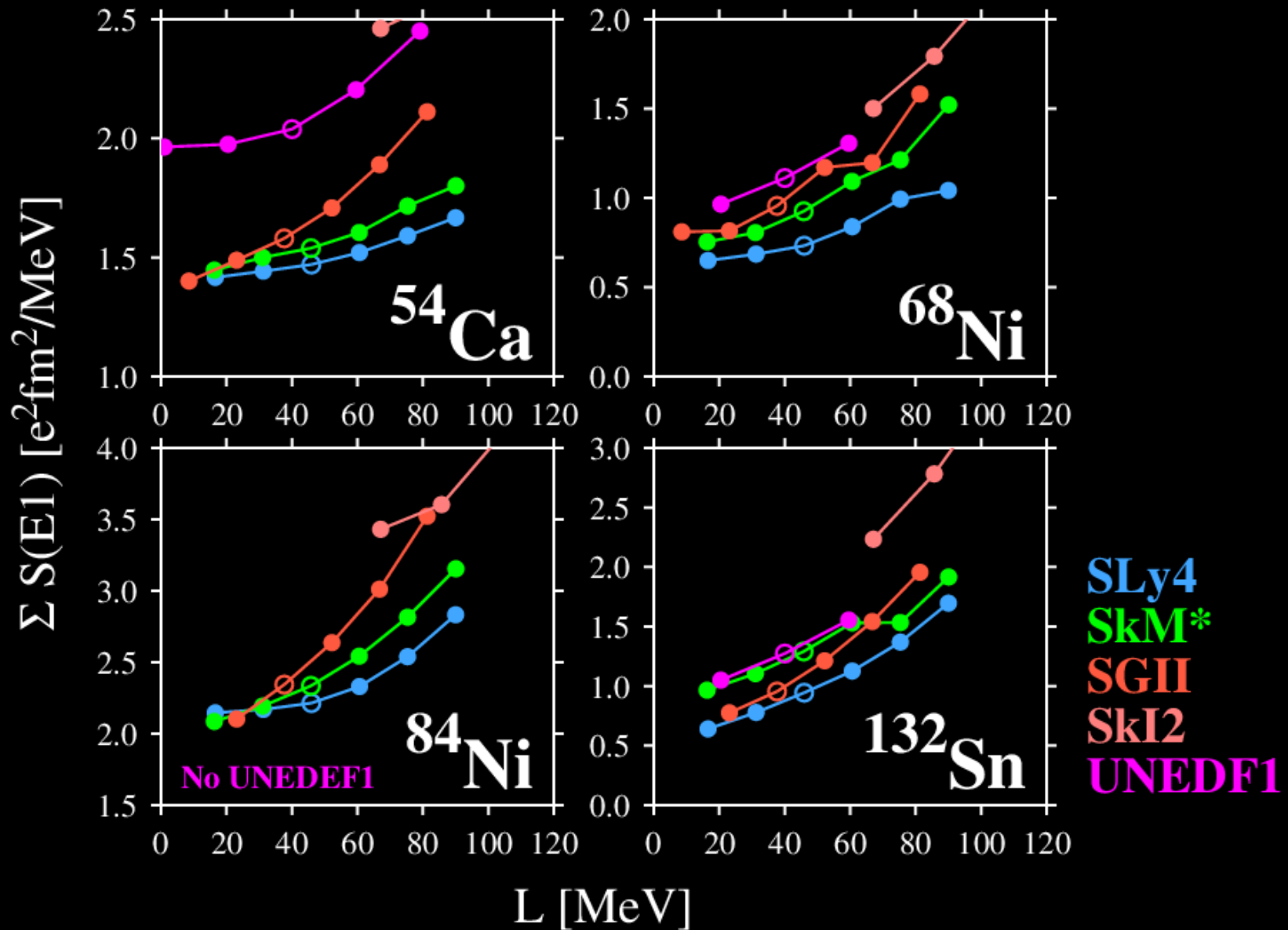


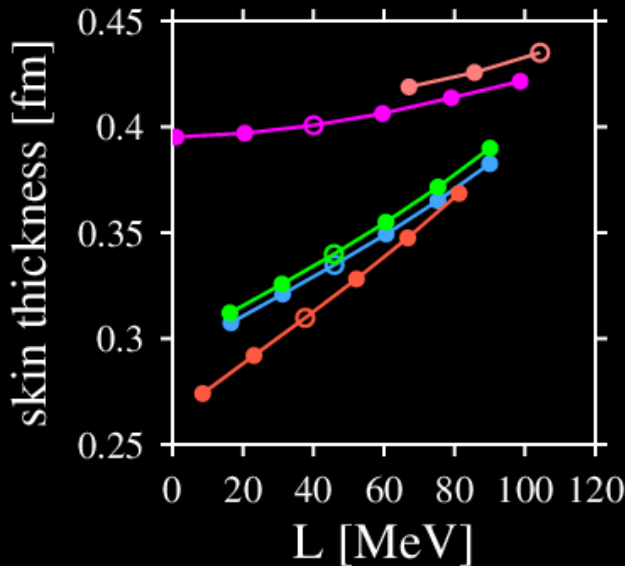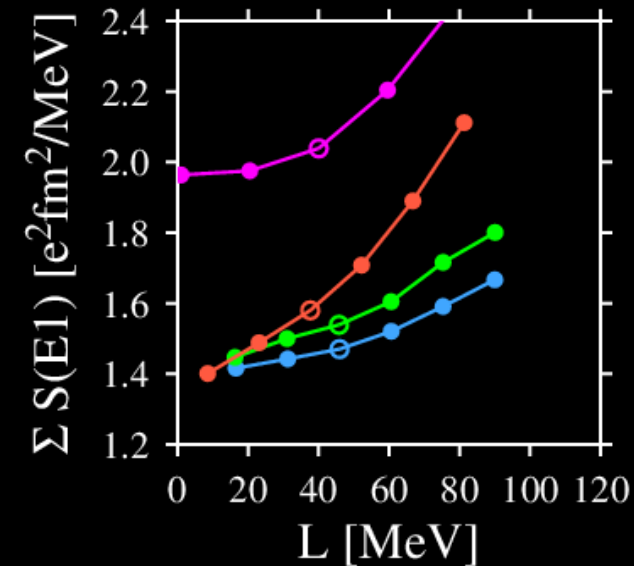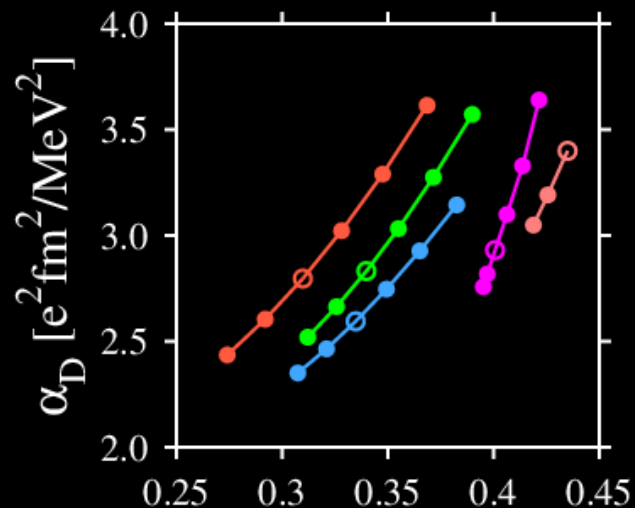SLy4  SkM*  SGII
SkI2  UNEDF1

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

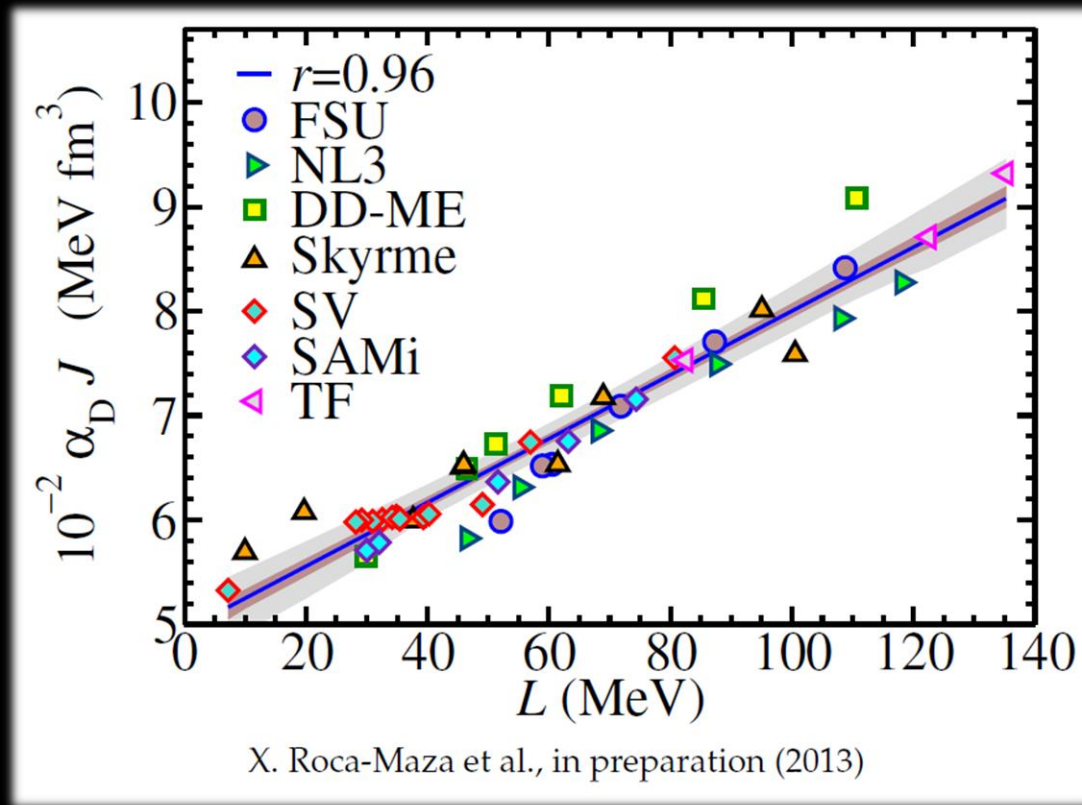# Correlations between *L*, skin and PDR(& α_D)
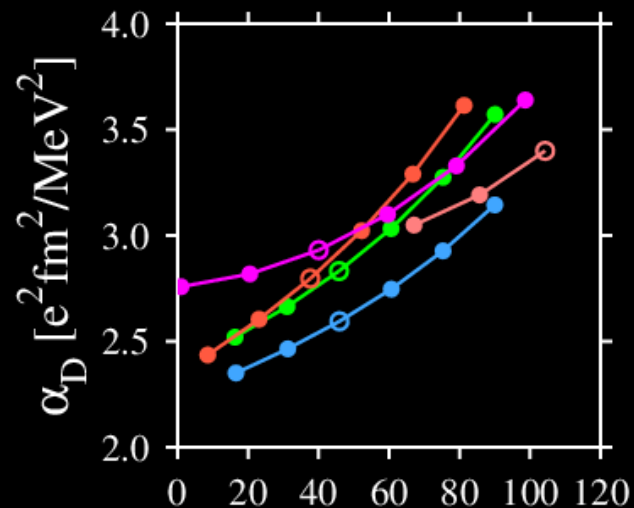


$^{54}$Ca

(Preliminary)
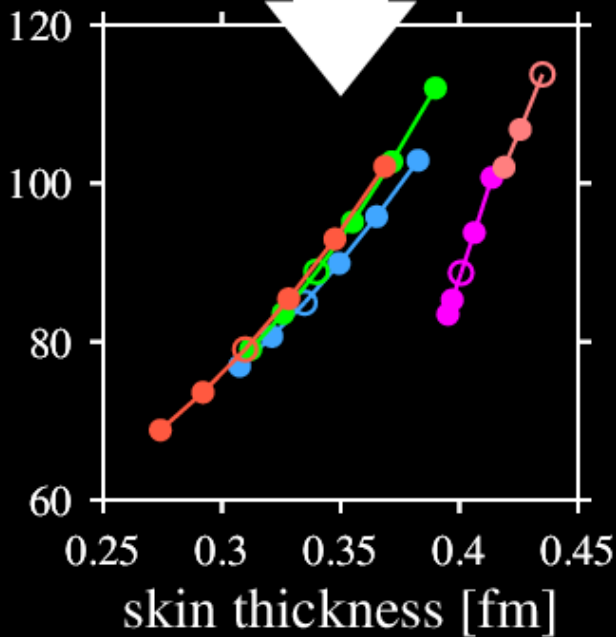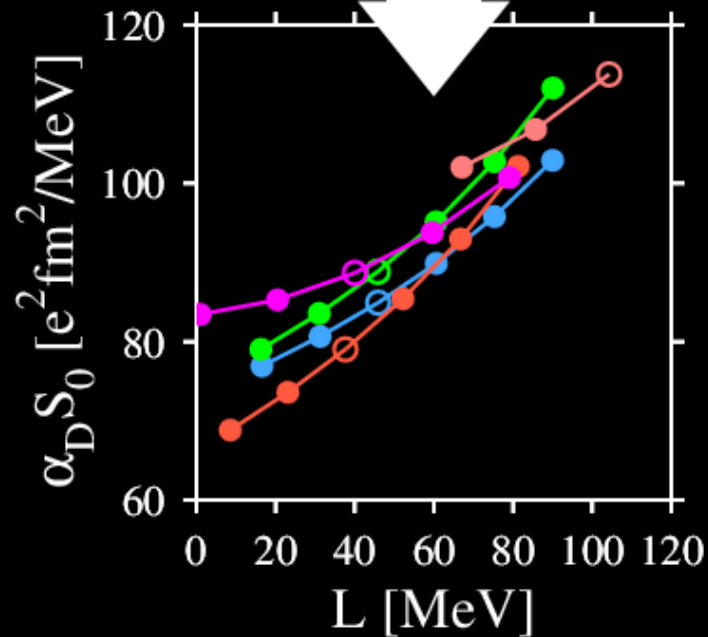
SLy4  SkM*  SGII
SkI2  UNEDF1

# Short summary

- ➢ PDR- *L* correlation has interaction dependence, especially in light nuclei.
- ➢ It may have some connection with *L*-skin correlation.
- ➢ $\alpha_D$ - *L* correlation is insensitive to interaction, compared with PDR- *L* correlation.

# New correlation:



taken from X. Roca-Maza's talk on Wed.
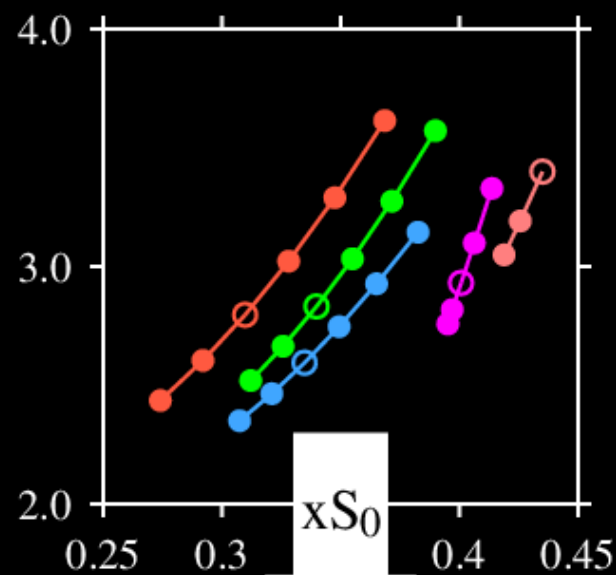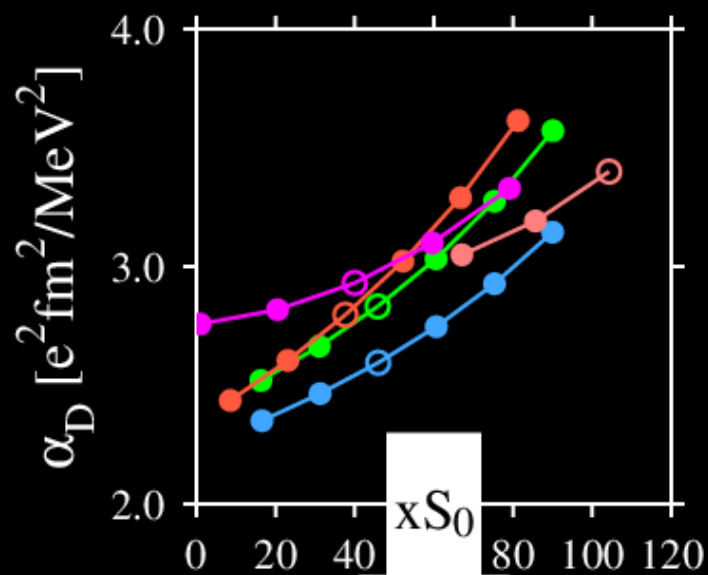
$^{54}$Ca

(Preliminary)

SLy4
SkM*
SGII
SkI2
UNEDF1

# **Summary**

➤ PDR and $\alpha_D$ have approximately linear correlation with *L* and skin thickness in select nuclei.

➤ However, the slope depends on interaction.

➤ Detail analysis of interaction is required.