Low-energy E1 mode and constraint on nuclear equation of state

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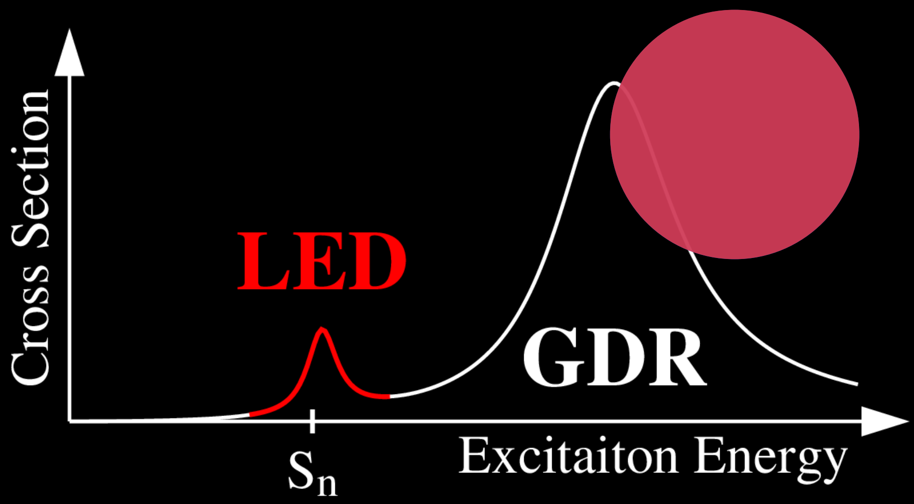
NAKADA Hitoshi (Chiba U.)
EBATA Shuichiro (Hokkaido U.)

Low-Energy E1 mode (LED)

= Low-lying dipole mode
～ Pygmy Dipole Resonance (PDR)



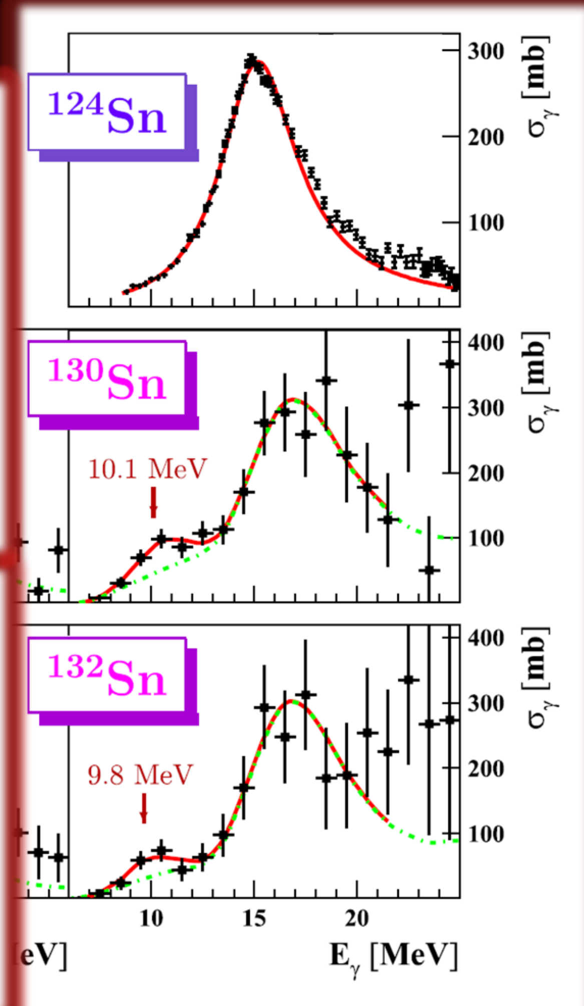
- Emerge around (neutron) threshold.
- Decoupled from GDR.
- Observed in several mass region.
- Several % of cross section in n-rich nuclei, while a few % in stable nuclei.

- Nature is still under debate.
- New collective mode such as oscillation between excess neutrons and core?
- Provide constraint on neutron matter EoS?

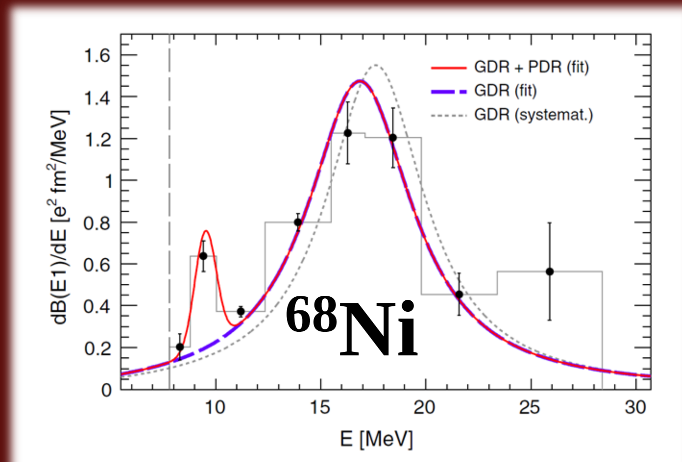
Observed LED

- 68Ni, 132Sn, 208Pb
- Ni isotope
- Sn isotope
- N=82 isotone, etc.

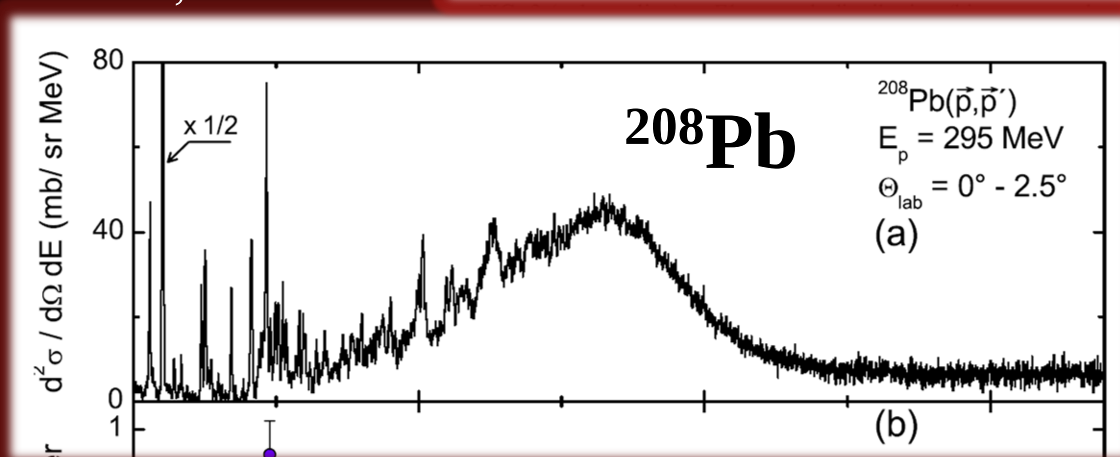
Adrich+, PRL 95, 132501.



Rossi+, PRL 111, 242503



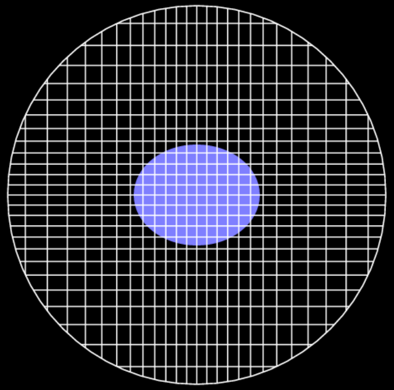
Tamii+,
PRL 107, 062502.



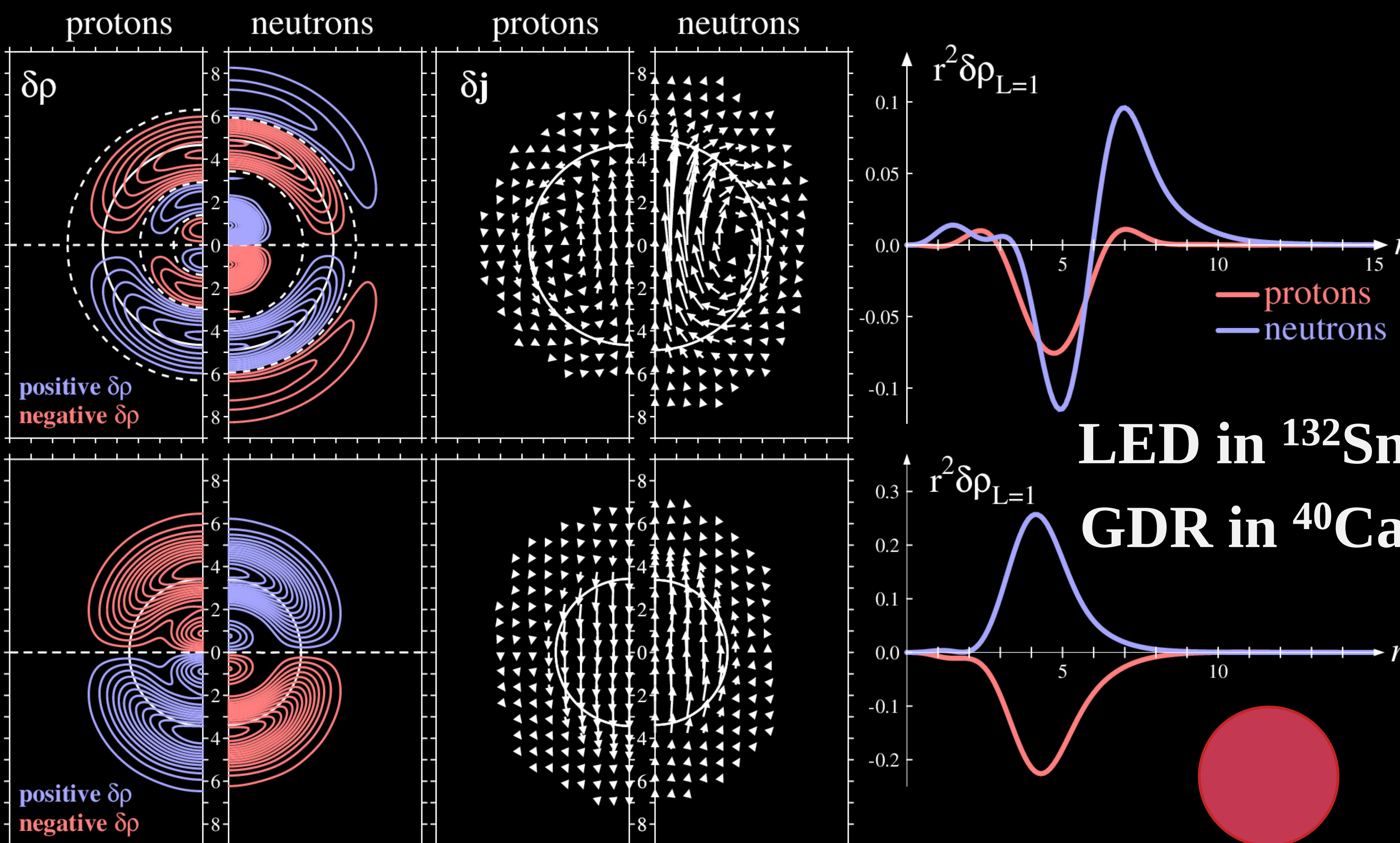
Linear response calc. (RPA) with Skyrme in 3D mesh

- **Density Functional Theory** with Skyrme energy functional.
- **Fully self-consistent** calculation. **PARAMETER FREE!**
- **3D mesh representation**
  - applicable to **deformed nuclei**.
  - 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:** small impact on E1 mode. [PRC90, 024303]

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



Transition density of LED & GDR

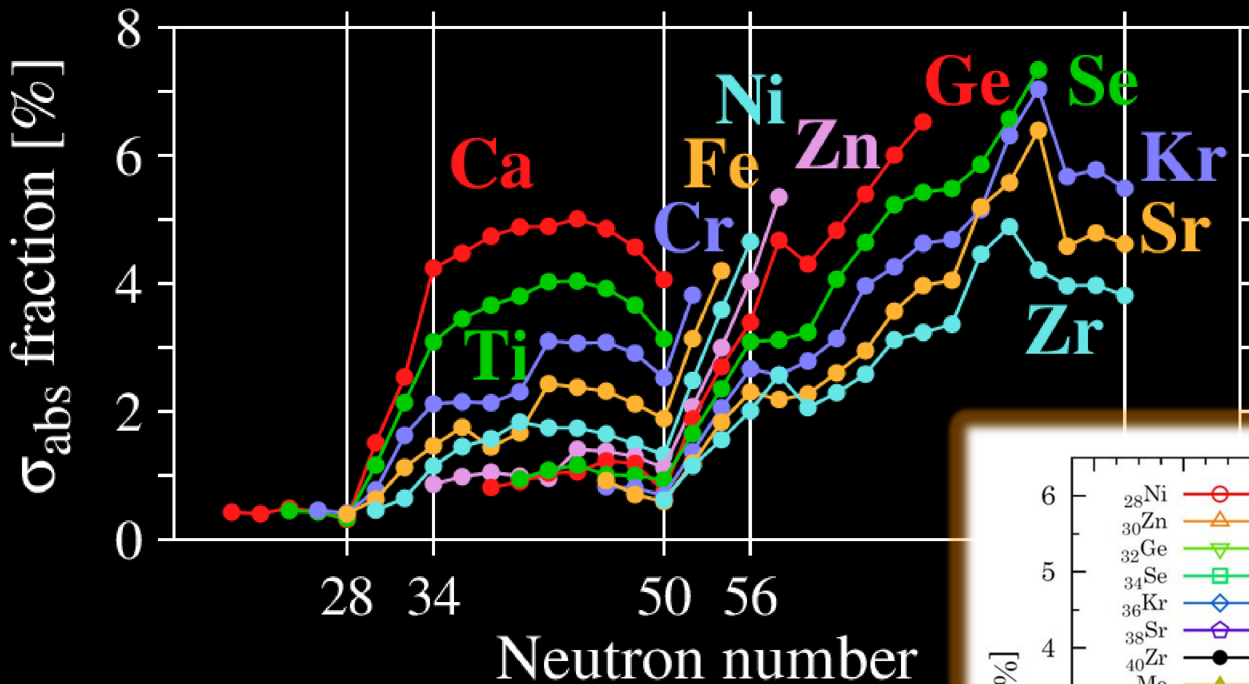


LED in ^{132}Sn

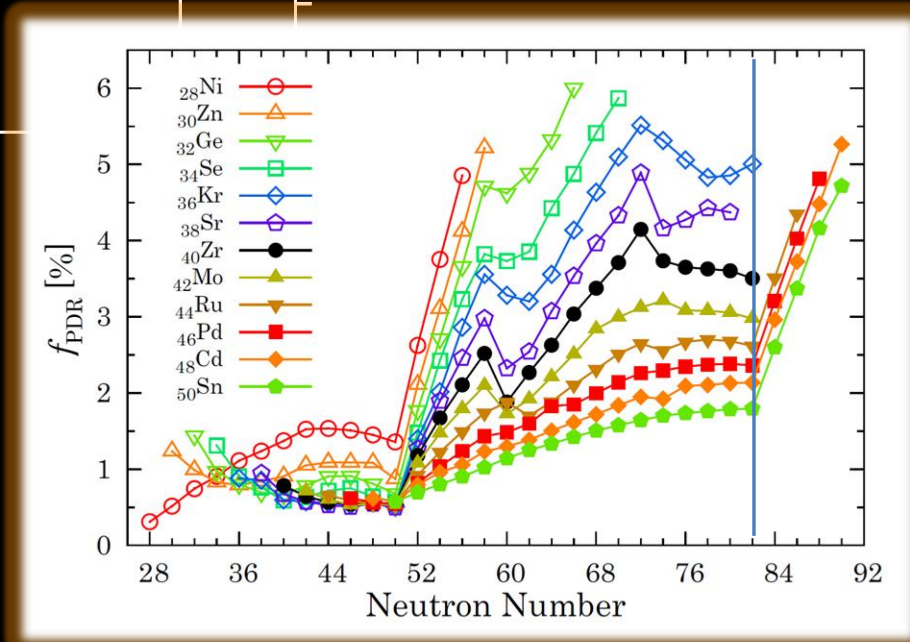
GDR in ^{40}Ca

Magic numbers for LED

$$\mathrm{LED} = \int_0^{10\mathrm{MeV}} \mathrm{d}E\, \sigma_{\mathrm{abs}}(E)$$



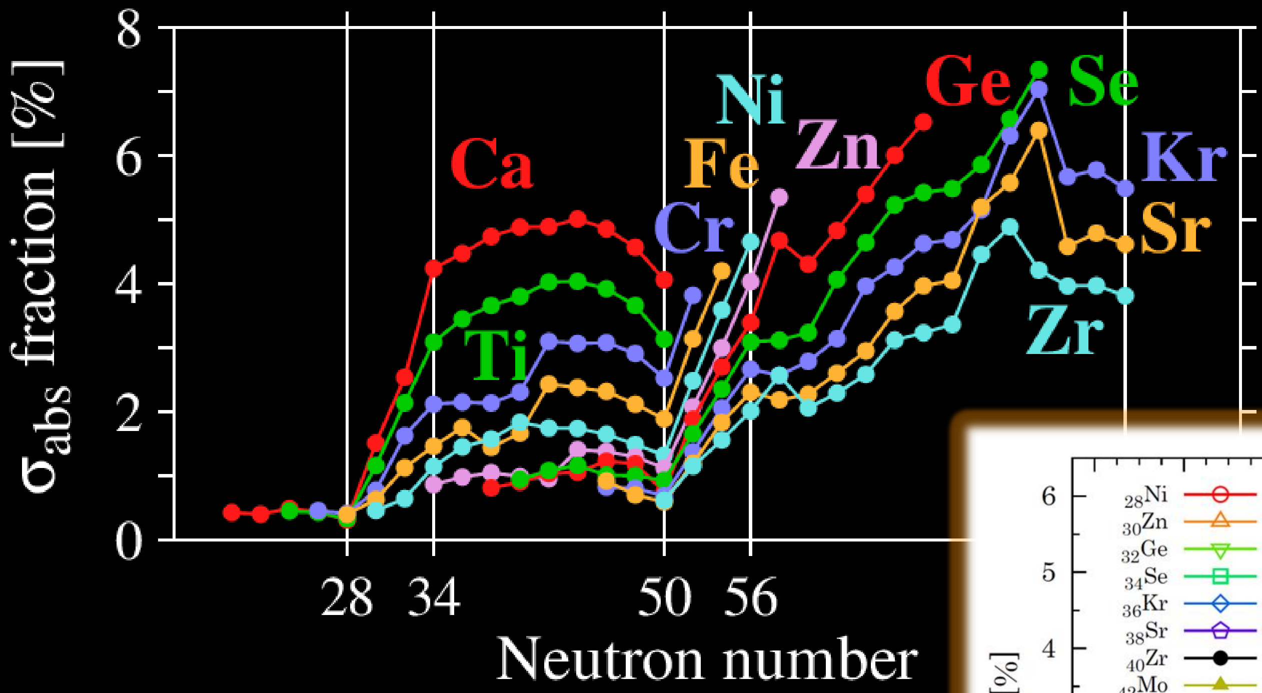
Inakura+,
PRC84, 021302



LED emerges & develops
in **all calculated isotopes**
beyond **N = 28, 50, 82.**

Canonical-basis TDHFB (with pairing corr.)
Ebata, Nakatsukasa, Inakura, PRC90, 024303

Magic numbers for LED



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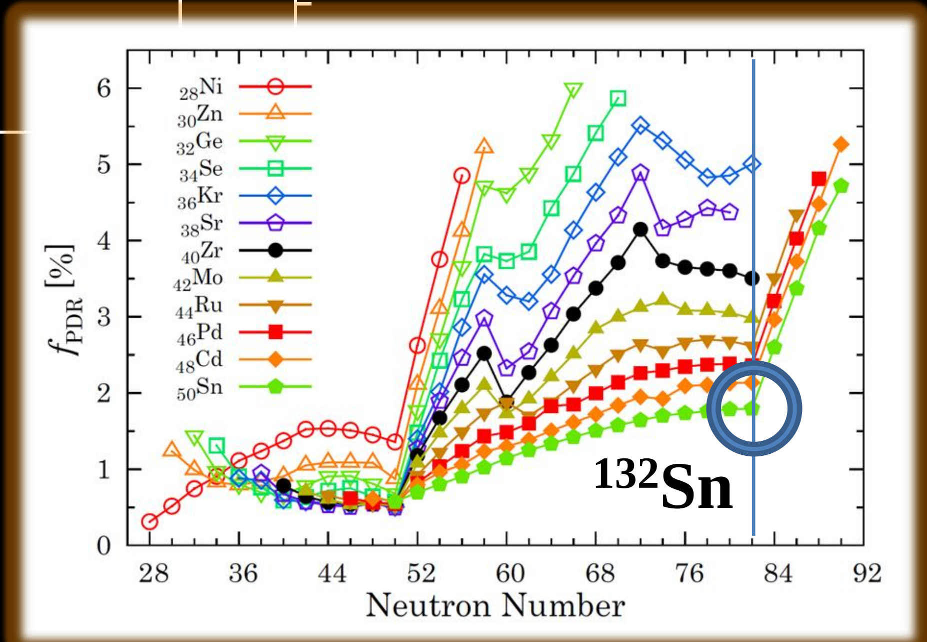
PRC84, 021302



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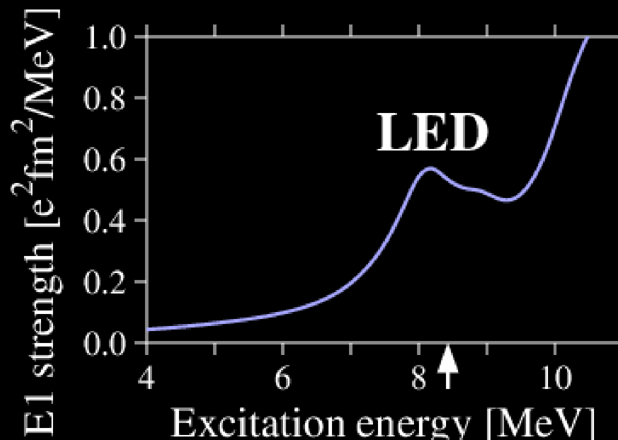
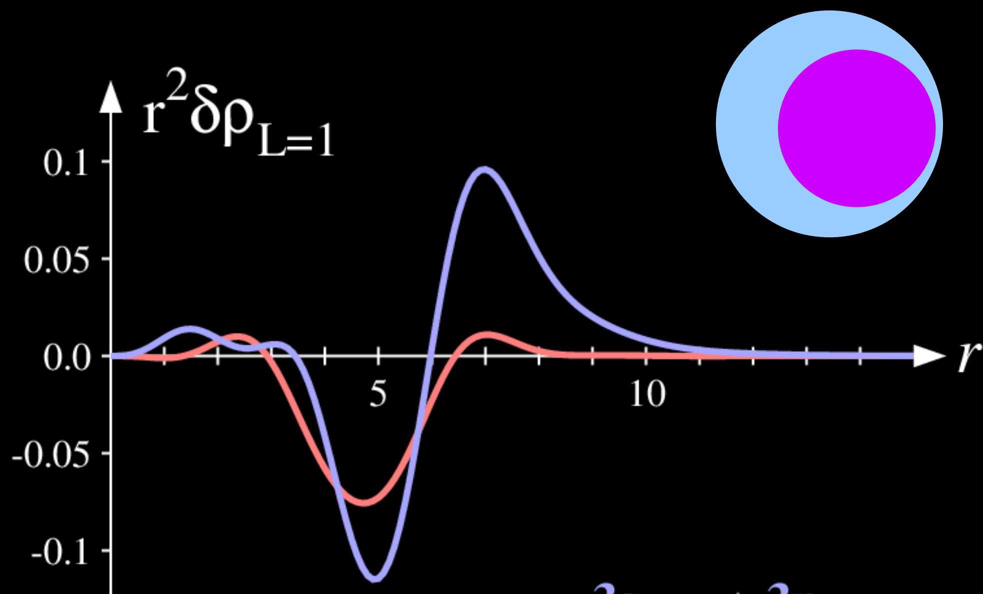
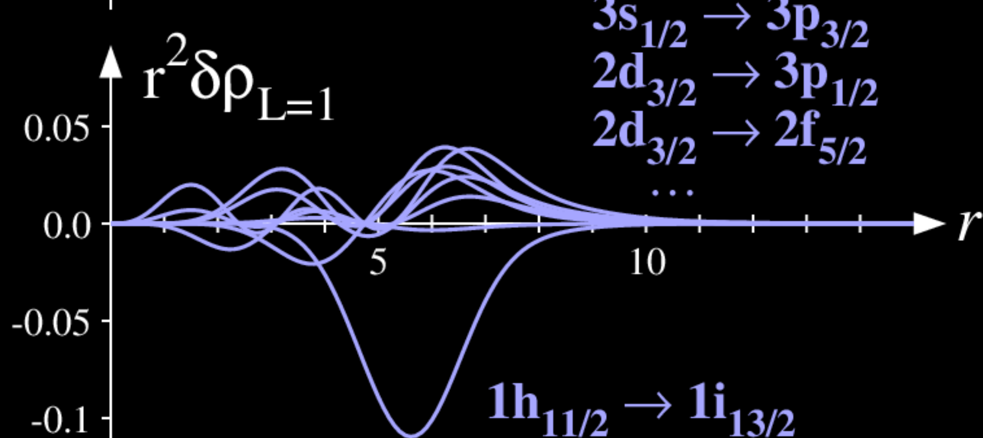
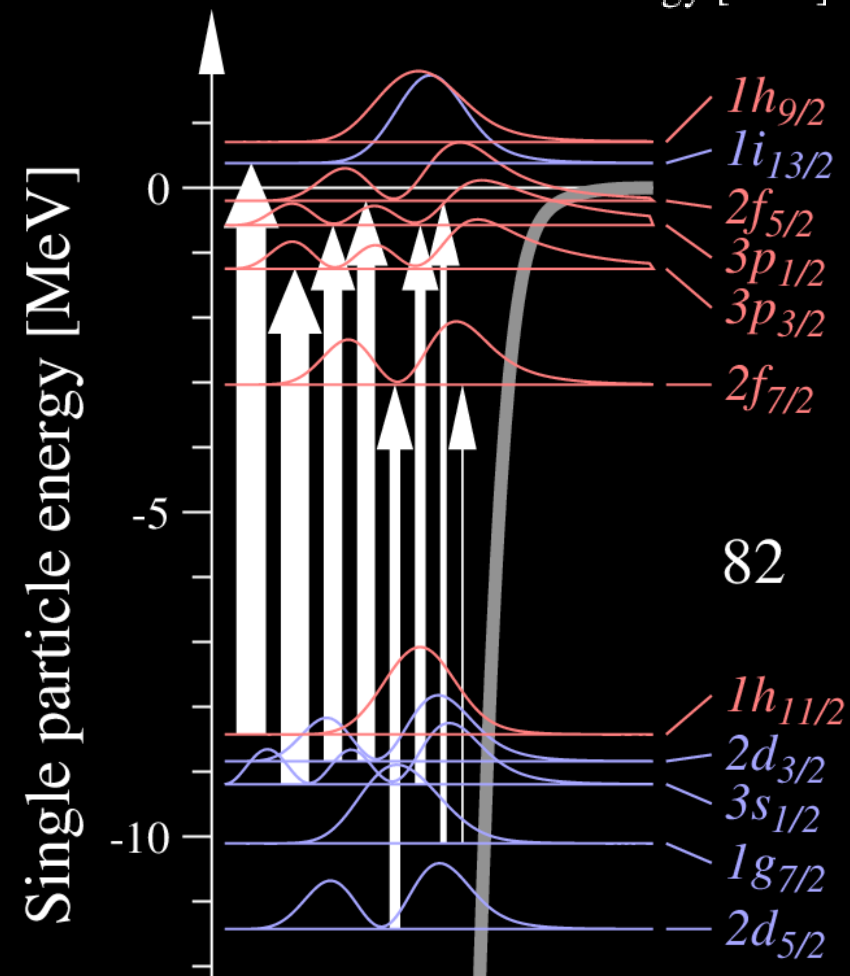
Collective LED (in ^{132}Sn)

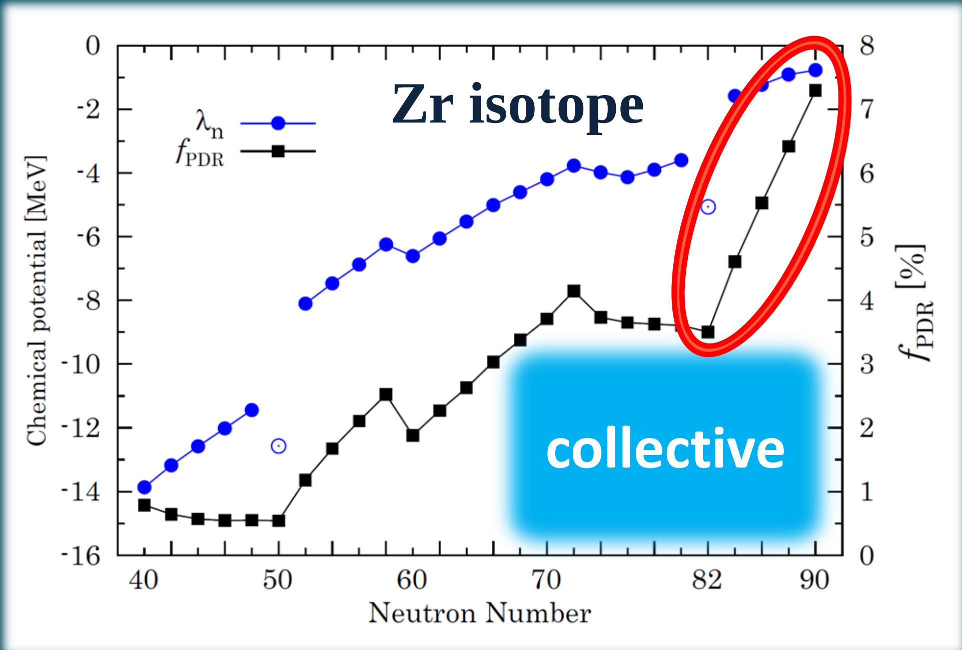






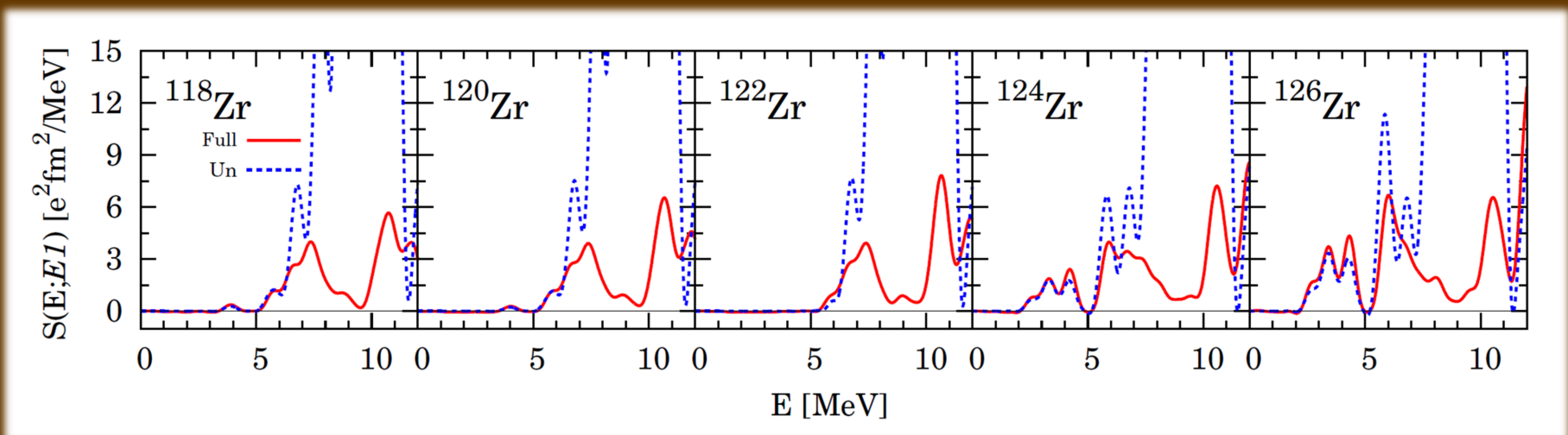


Non-collective LED



N <= 82
collective LED
N > 82
collective + <u>non-collective</u> LED.

Ebata, Nakatsukasa, Inakura,
PRC90, 024303



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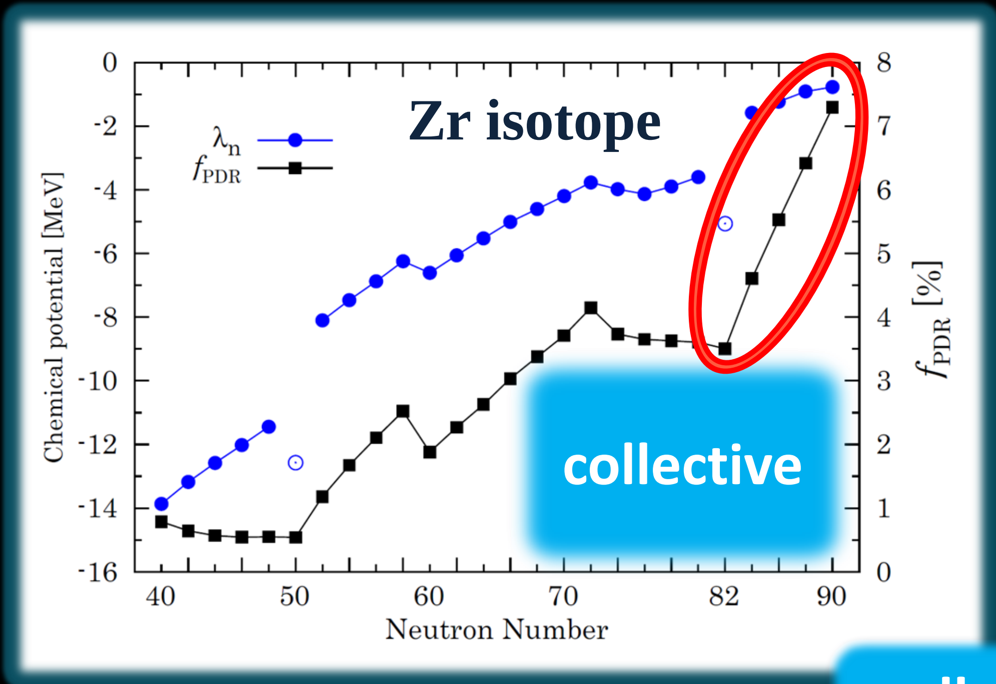

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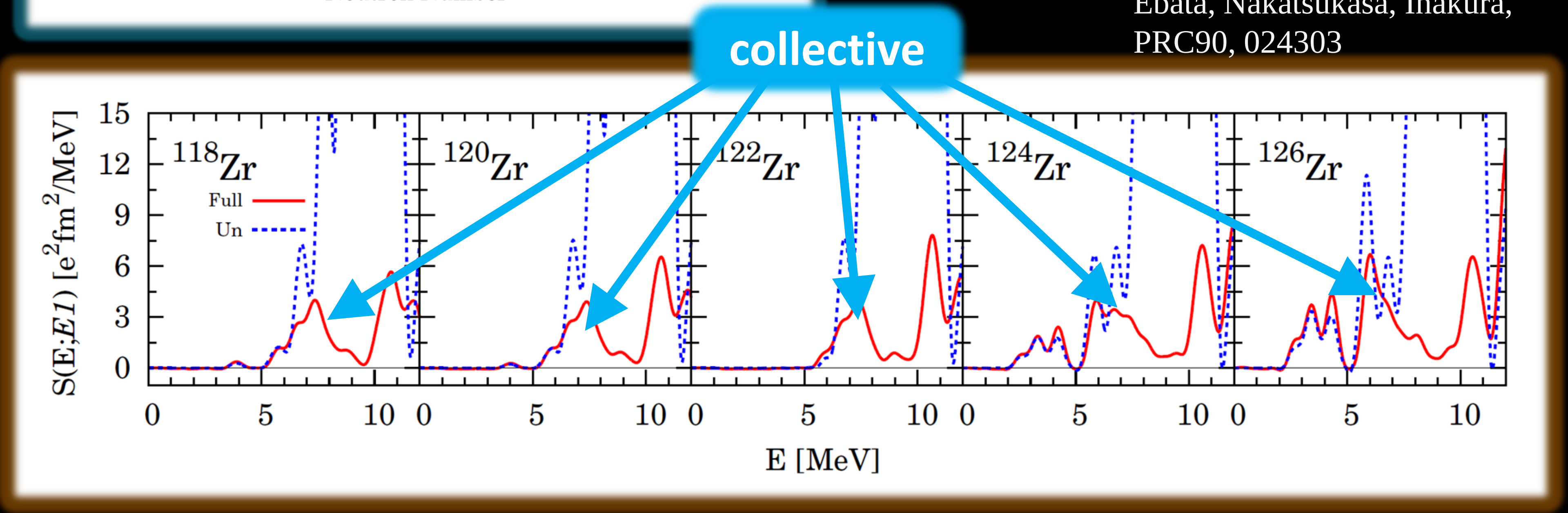
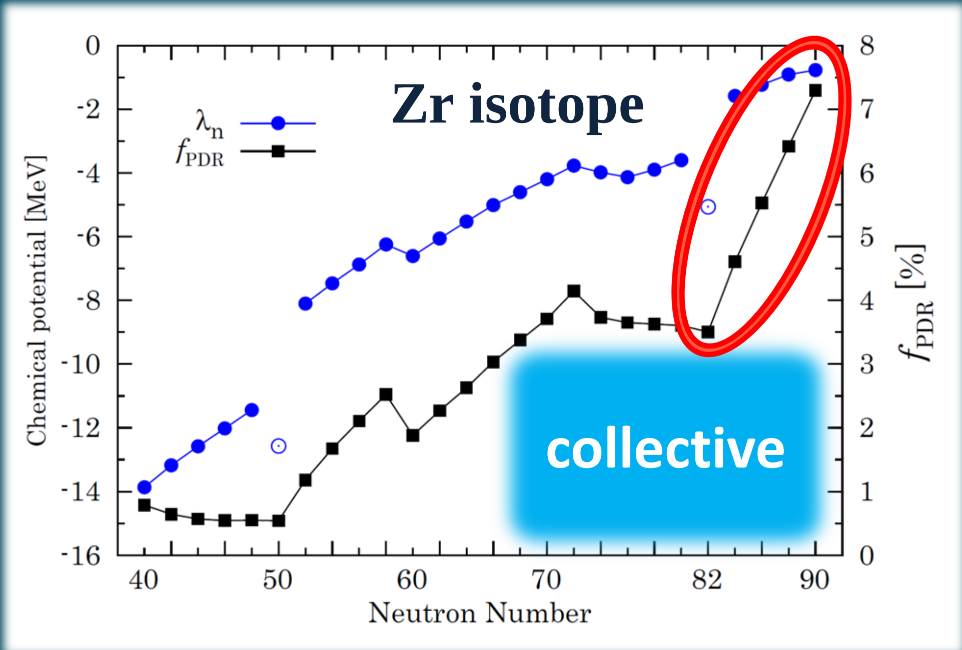
Ebata, Nakatsukasa, Inakura, PRC90, 024303



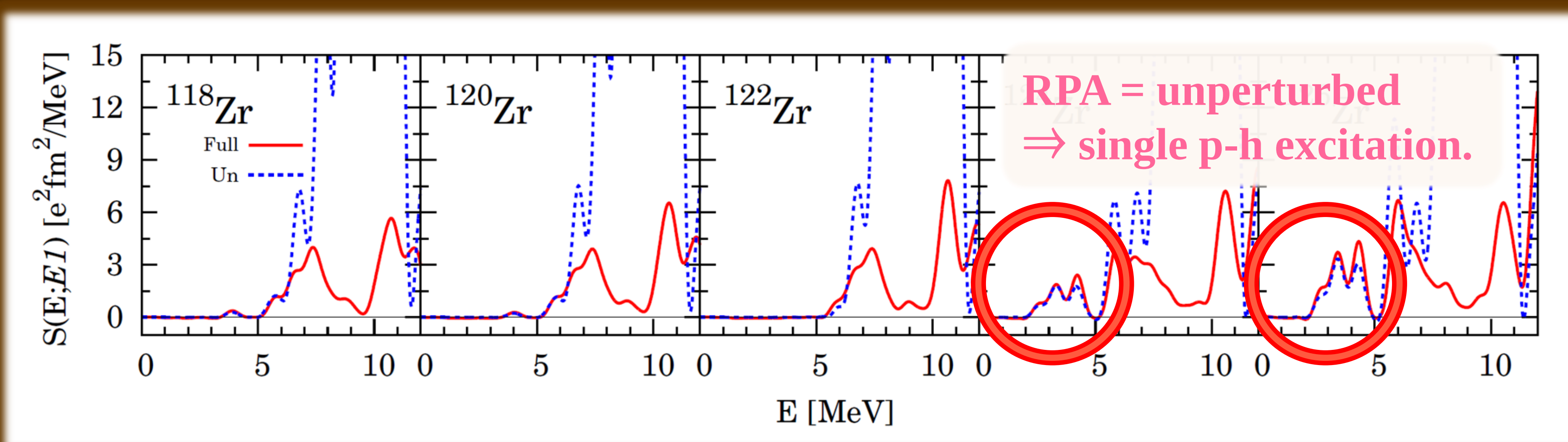
Non-collective LED



Single particle-hole excitation to continuum state (= neutron emission mode)

- appear above threshold S_n.
- δρ similar to collective LED.

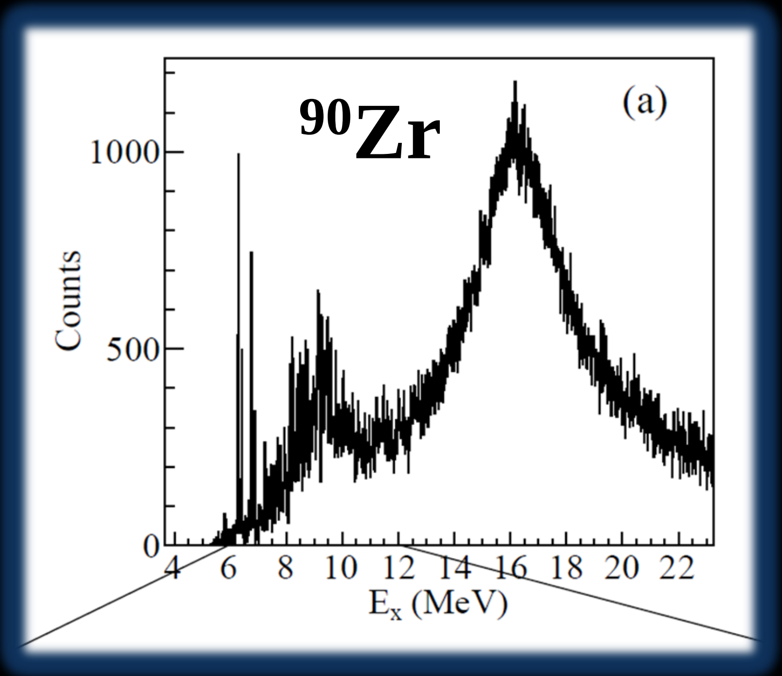
Ebata, Nakatsukasa, Inakura, PRC90, 024303



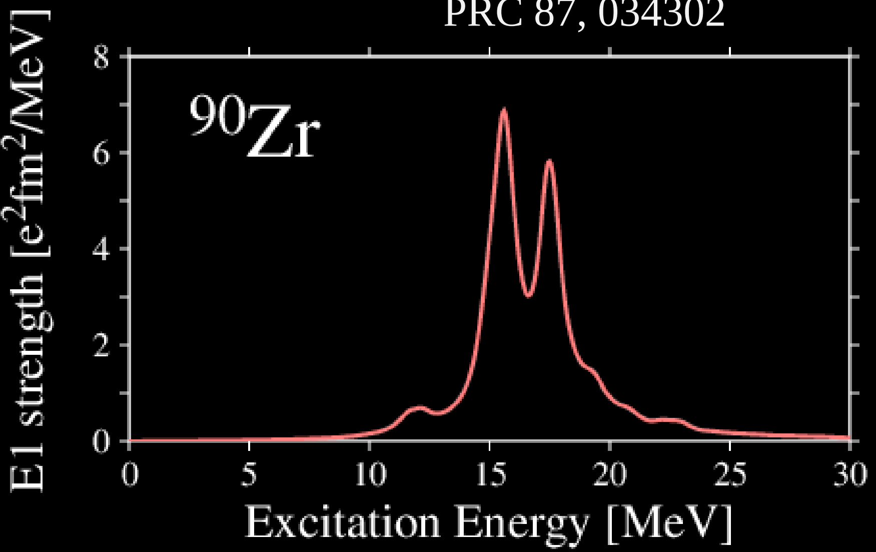
RPA = unperturbed
⇒ single p-h excitation.

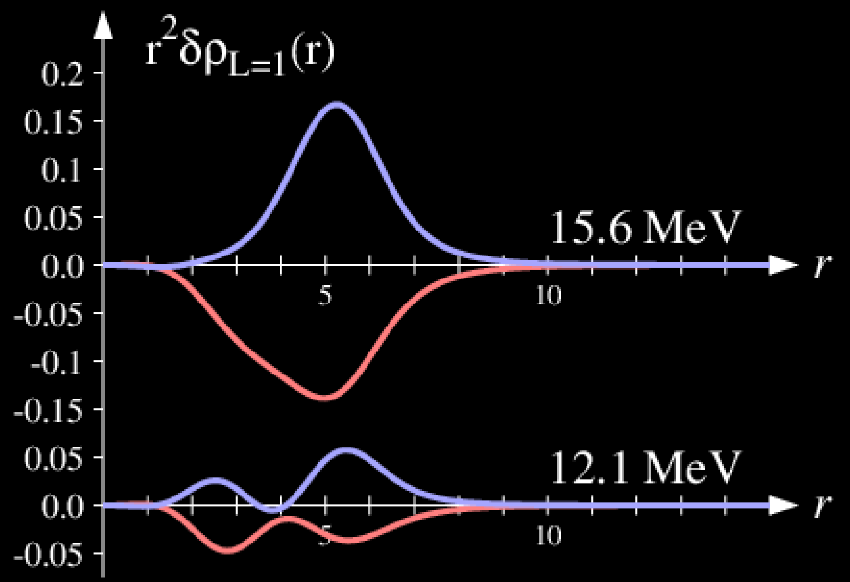
Fragmentation of GDR?

Nakada, Inakura, Sawai,
PRC 87, 034302



Iwamoto+, PRL 108, 262501





Constraint on EoS from LED

Inakura and Nakada,
accepted in PRC.
arXiv: 1509.02982

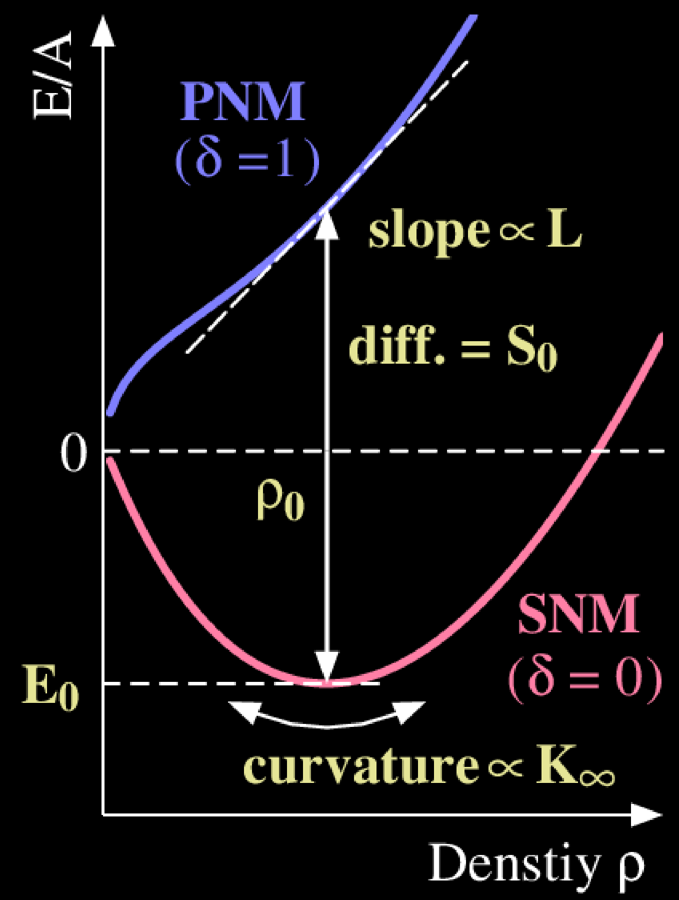
Quantities characterizing EoS

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

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

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

$$\text{PNM}: E_{\rm sym}(\rho) = S_0 + Lx + \cdots$$



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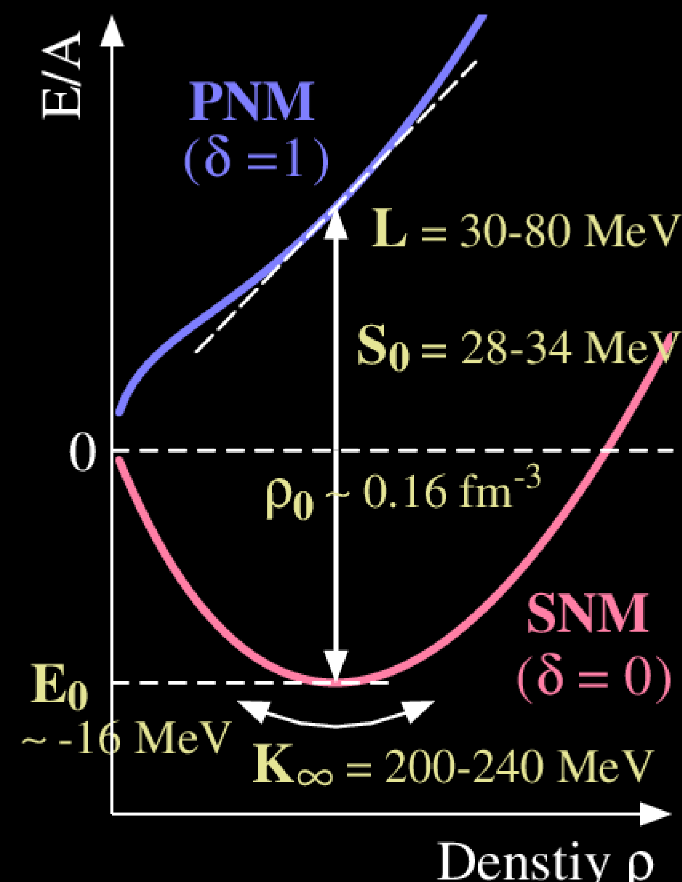
$$\rho_0 \sim 0.16\ \text{fm}^{-3}$$

$$E_0 \sim -16\ \text{MeV}$$

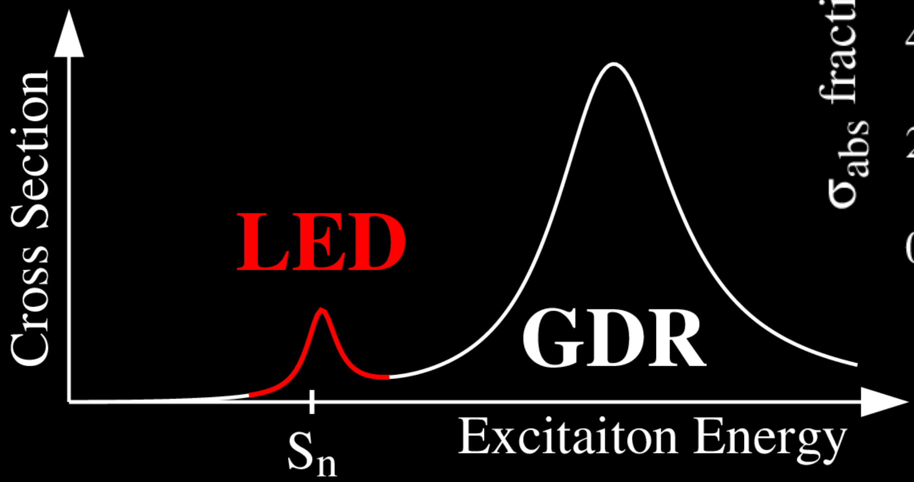
$$K_\infty = 200 - 240\ \text{MeV}$$

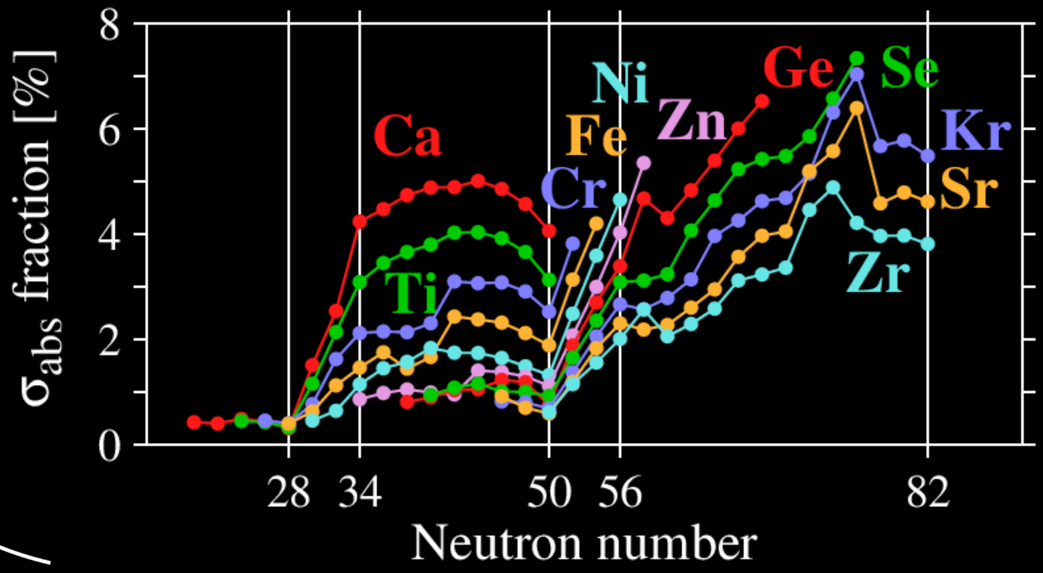
$$S_0 = 28 - 34\ \text{MeV}$$

$$L = 30 - 80\ \text{MeV}$$



Constraint on EoS from LED

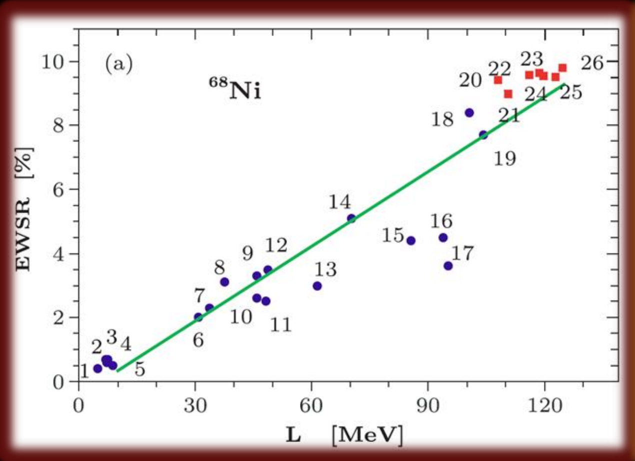




- LED emerges and develops in neutron-rich nuclei with neutron skin which is approximately neutron matter.
- Does LED provide some information on EoS !?

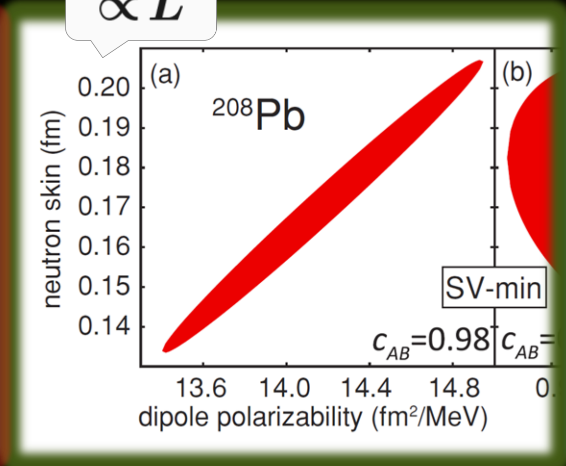
L from LED

Carbone+, PRC81, 041301

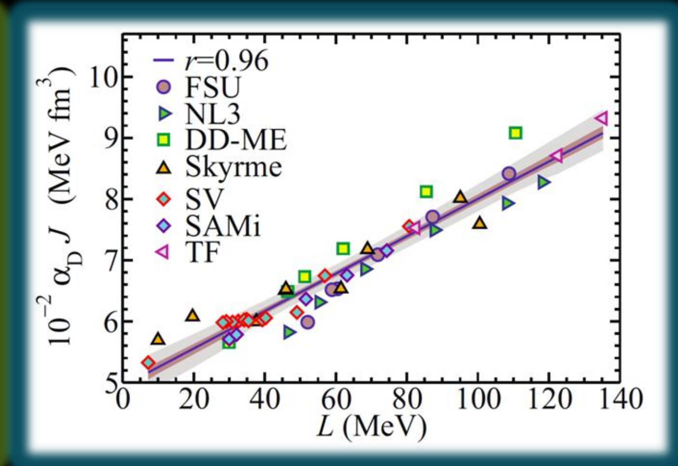


Reinhard+,
PRC81, 051303

$\propto L$



Roca-Maza+, PRC88, 024316



LED cross section

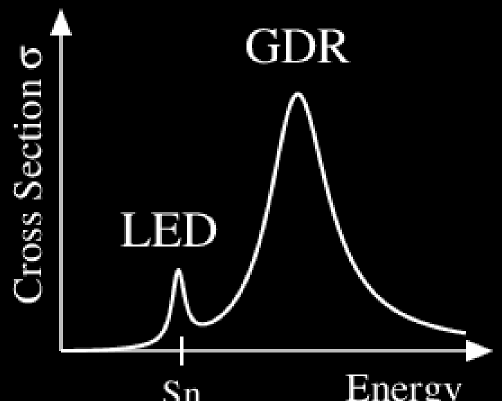
$$\sigma_{\mathrm{LED}} \propto \int \mathrm{d}E\, S(E1)\, E$$

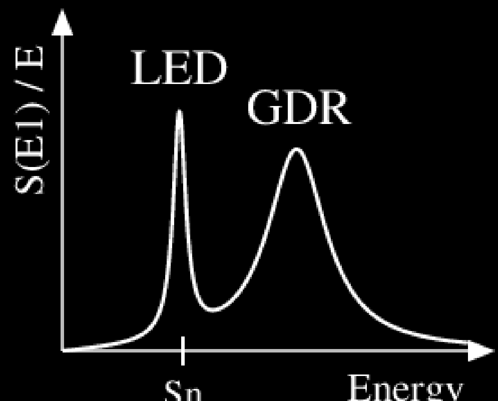
Dipole polarizability

$$\alpha_D \propto \int \mathrm{d}E\, \frac{S(E1)}{E}$$

$\alpha_D S_0$

$S_0(\text{or } J)$: Symm. energy





Introduction of L-dependence

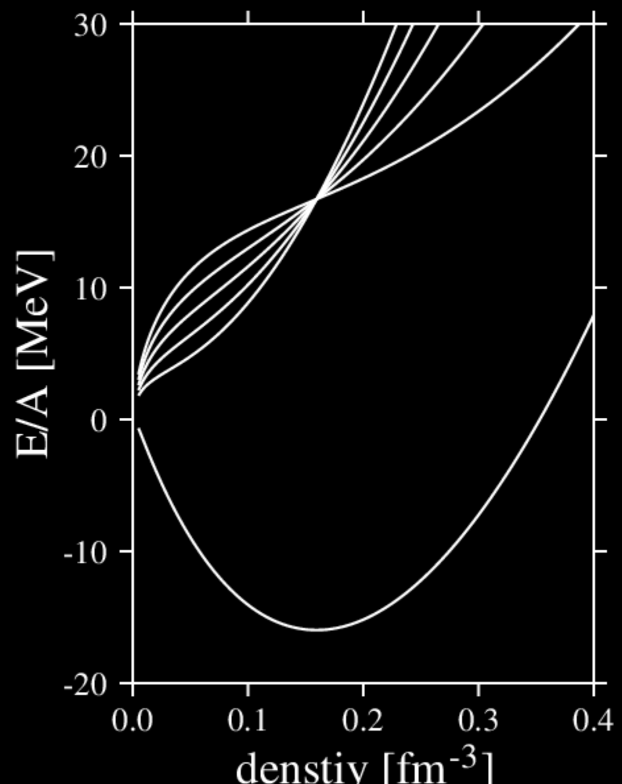
$$v_{ij} \Rightarrow v_{ij} - V_L \left[\rho^\alpha(r) - \rho_0^\alpha\right] P_\sigma \delta(r)$$

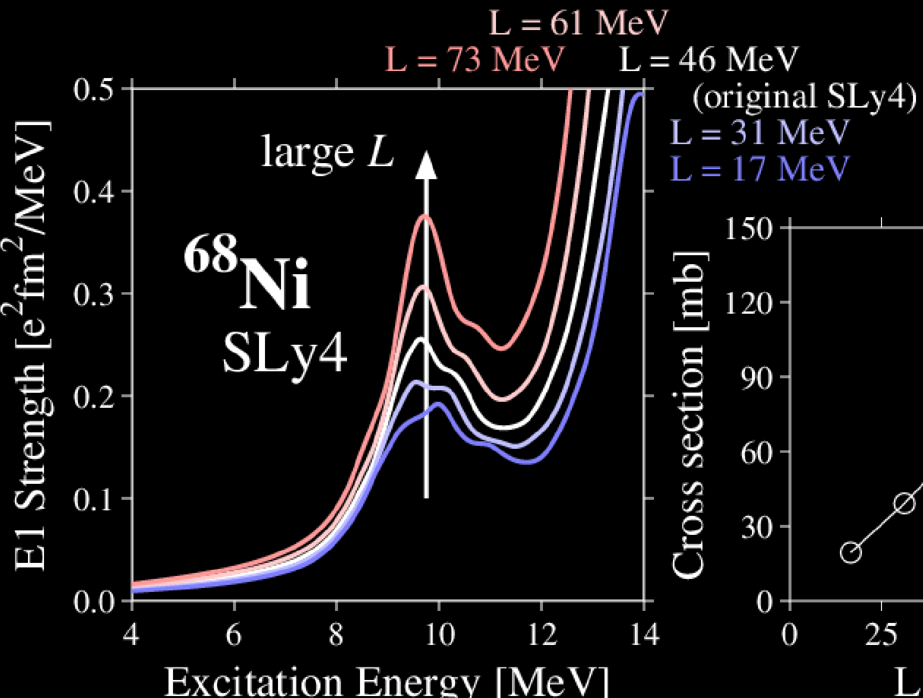
Ono+, PRC68, 051601

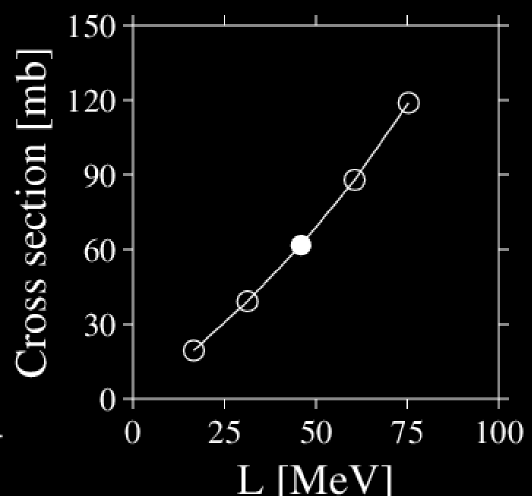
The additional term

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

V_L is a parameter to control *L*.







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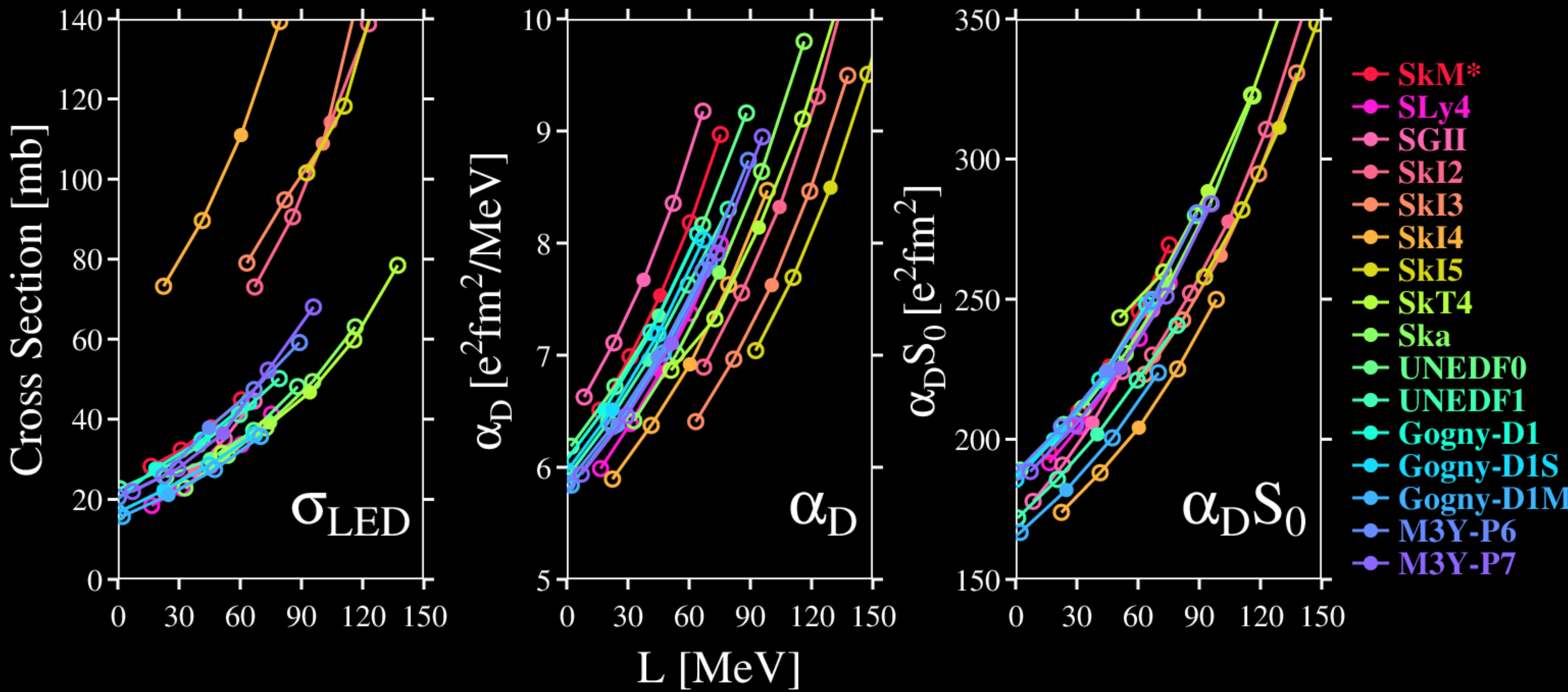
Correlations in ^{132}Sn



Uncertainty for L : 12 MeV.

Summary

- LED emerges & develops in all isotopes beyond N = 28, 50, 82.
  - collective motion: oscillation between skin and core.
  - single p-h excitation to continuum: neutron emission.
  - fragmentation of GDR.
- LED provide constraint on neutron matter EoS.
  - $\alpha_D S_0$ correlates well with slope parameter L.