Dipole response from semi-classical and quantal approaches

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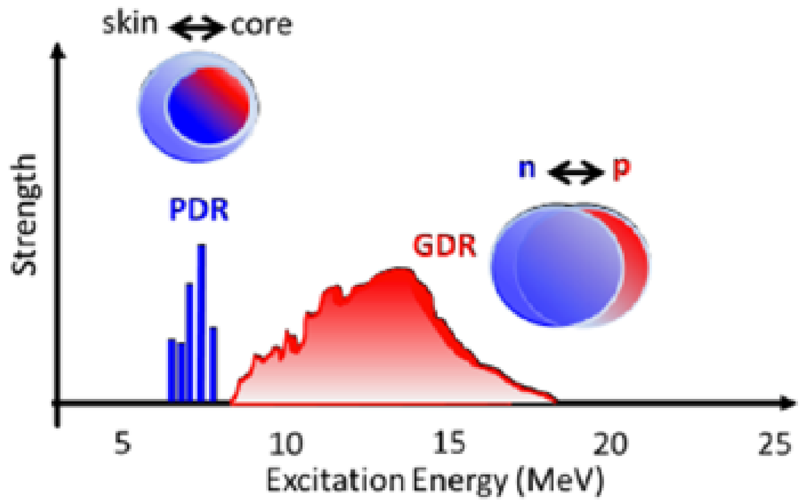
Outline

- Introduction

- Brief introduction to quantal dynamical approaches and transport theories:
  classical vs quantal description

- Small amplitude dynamics:
  - Dipole excitations: collective nature ?
  - Link to nuclear effective interaction and EOS

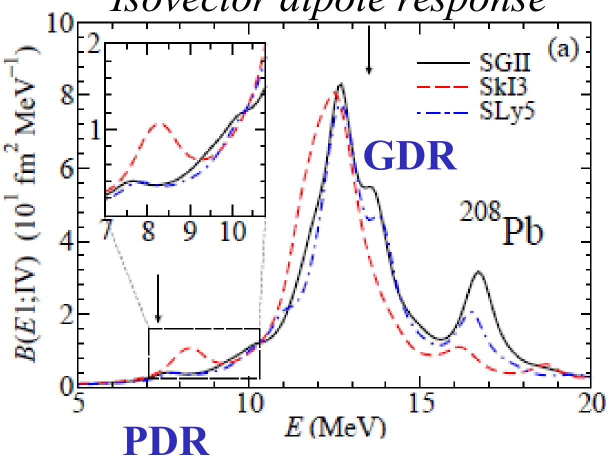
Collective modes and effective interaction: some examples



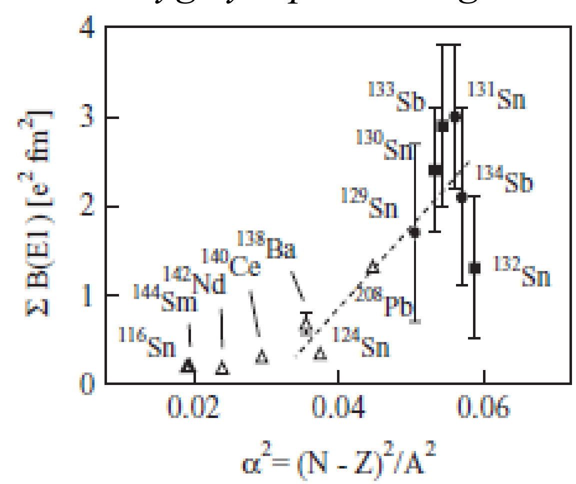
Dipole Response in neutron-rich nuclei:

- GDR: sensitive to symm. energy $\mathbf{E_{sym}}$
- Low-lying strength (PDR)

Isovector dipole response



Pygmy dipole strength



RPA calculations

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

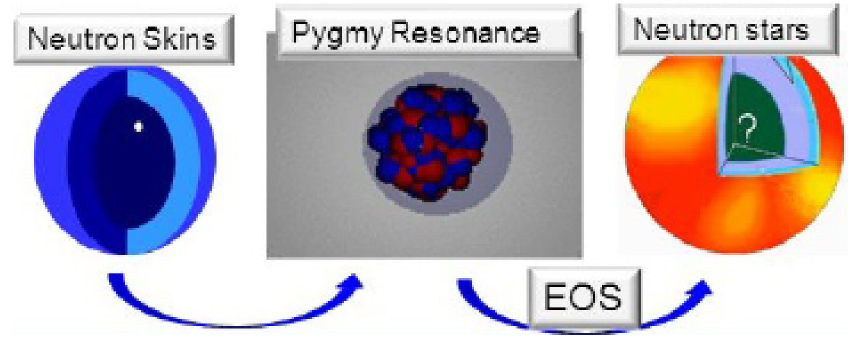
Klimkiewicz et al.

PHYSICAL REVIEW C **76**, 051603(R) (2007)

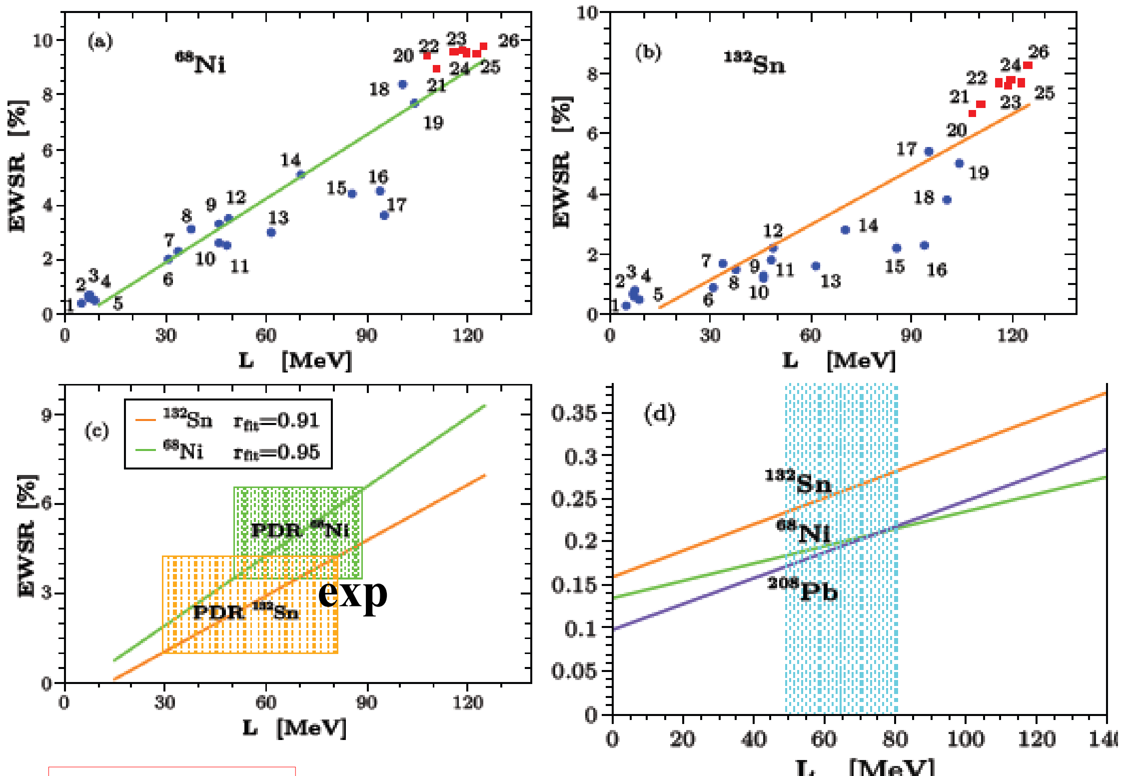
PDR EWSR and Polarizability vs L and neutron skin

$$E_{sym}(\rho) = S_0 + L\frac{\rho - \rho_0}{3\rho_0} + \ldots$$

or J



A.Carbone et al., PRC 81,041301(R) (2010)

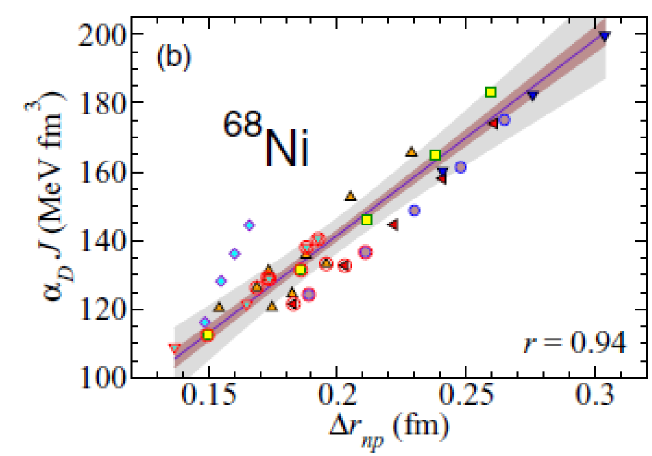


RPA calculations

Neutron skin vs L

Polarizability

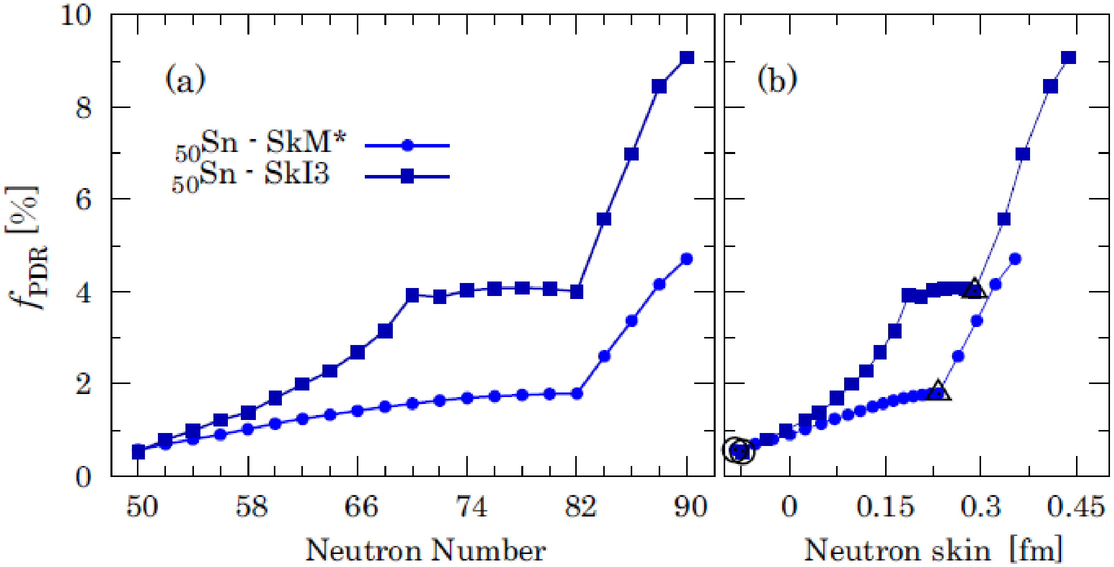
$$\alpha_D = \frac{8\pi e^2}{9}\int_0^\infty \omega^{-1} R(\omega; E1)\, d\omega$$



X.Roca-Maza, X.Vinas et al.

PHYSICAL REVIEW C **92**, 064304 (2015)

Strength of PDR vs N/Z and neutron skin: Sn isotopic chain



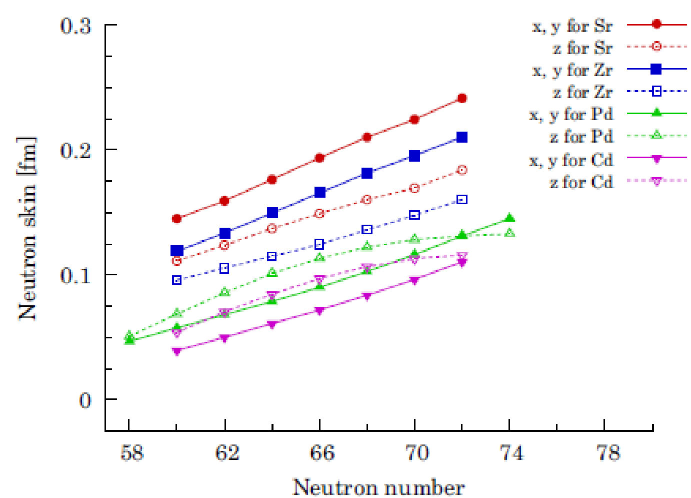
S.Ebata et al. TDHFB calculations

PHYSICAL REVIEW C **90**, 024303 (2014)

- The neutron skin thickness increases monotonically with N/Z

The EWSR exhausted by PDR does not !

Shell effects ?



Dynamics of many-body systems

- **Small amplitude dynamics** of nuclei
  - **Quantal** approaches: **TDHF** [in coll. with D. Lacroix and G. Scamps]
    HF+RPA [in coll. with X. Roca Maza]
  - **Semi-classical** approaches: **Vlasov** model [see V. Baran et al., PRC88, (2013)]
- **Transport equation** for the 1-body distributions f_q (**r**, **p**, t)

$$\frac{\partial f_q}{\partial t} + \frac{\partial \epsilon_q}{\partial \mathbf{p}}\frac{\partial f_q}{\partial \mathbf{r}} - \frac{\partial \epsilon_q}{\partial \mathbf{r}}\frac{\partial f_q}{\partial \mathbf{p}} = 0 \quad \Rightarrow \quad \rho_q(\mathbf{r},t) = \frac{2}{(2\pi\hbar)^3}\int d\mathbf{p}\, f_q(\mathbf{r},\mathbf{p},t) \qquad q = p, n$$

- **Vlasov** equation ≡ **semi-classical** limit of **TDHF** equation

$$\frac{\partial f}{\partial t} + \{f, H_{eff}\} = 0 \qquad \Longleftarrow \qquad i\hbar\dot{\hat{\rho}}(t) = \left[\hat{H}_{eff}[\rho], \hat{\rho}\right]$$

- **Mean-field** with **Skyrme** interactions: →
  - **SAMi-J** interactions [X. Roca-Maza et al., PRC87, (2013)]

$$\mathcal{E} = \frac{\hbar^2}{2m}\tau + C_0\rho^2 + D_0\rho_3^2 + C_3\rho^{\sigma+2} + D_3\rho^{\sigma}\rho_3^2 + C_{eff}\rho\tau + D_{eff}\rho_3\tau_3 + C_{\nabla}(\nabla\rho)^2 + D_{\nabla}(\nabla\rho_3)^2$$

- **Semi-classical** model ⇒ **no shell effects** but reproduction of **experimental** values ($\sqrt{\langle r_p^2\rangle}$, B/A) and **ground state** properties

Dipole oscillations and response functions

- Instantaneous **ground-state perturbation**:

$$\hat{V}_K^{ext}(\mathbf{r},t) = \eta_K \delta(t-t_0)\hat{D}_K(\mathbf{r}) \qquad K = S, V$$

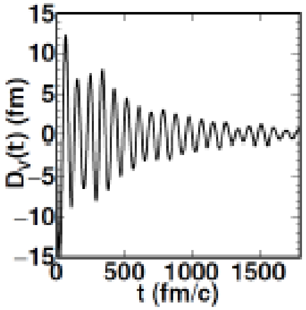
$$\Rightarrow |\Phi_0\rangle \rightarrow |\Phi_K(t_0)\rangle = e^{i\eta_K \hat{D}_K}\,|\Phi_0\rangle$$

- **Isoscalar (IS)** or **isovector (IV) dipole** operator:

$$\hat{D}_S = \sum_i \left(r_i^2 - \frac{5}{3} < r^2 >\right) z_i, \qquad \hat{D}_V = \sum_i \tau_i \frac{N}{A} z_i - (1-\tau_i)\frac{Z}{A} z_i, \quad \tau_i = 0\,(1) \quad \text{for n (p)}$$

- **Dynamical evolution** of the excitation: $\mathrm{D}_K(t) = \langle \Phi_K(t)|\,\hat{D}_K\,|\Phi_K(t)\rangle$
- **Strength** function: $S_K(E) = \sum_n |\langle n|\,\hat{D}_K\,|0\rangle|^2\,\delta(E-(E_n-E_0))$

$$S_K(E) = \frac{\mathrm{Im}\,D_k(E)}{\pi\eta_k} \qquad \mathrm{D}_k\,(E)\ \text{Fourier Transform of}\ \mathrm{D}_k\,(\mathrm{t})$$

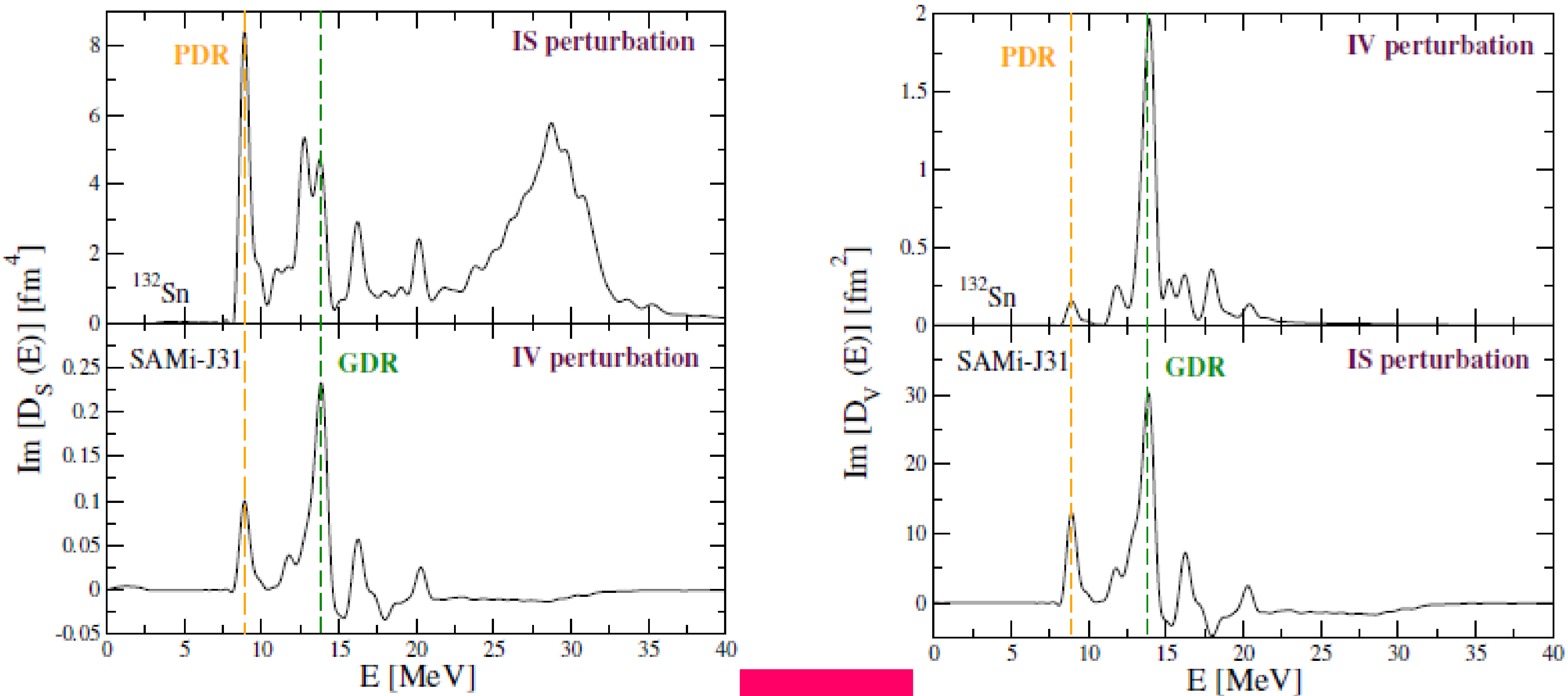


- **Three regions of A**: ^{68}**Ni** (N/Z = 1.43), ^{132}**Sn** (N/Z = 1.64), ^{208}**Pb** (N/Z = 1.54)

Coupling between IS and IV modes

TDHF results
Skyrme interaction SAMi-J31

- **Symmetric** nuclear matter: **IS** and **IV** modes are **decoupled**
- **Neutron-rich** systems: n and p oscillate with **different amplitudes** ⇒ **coupling**



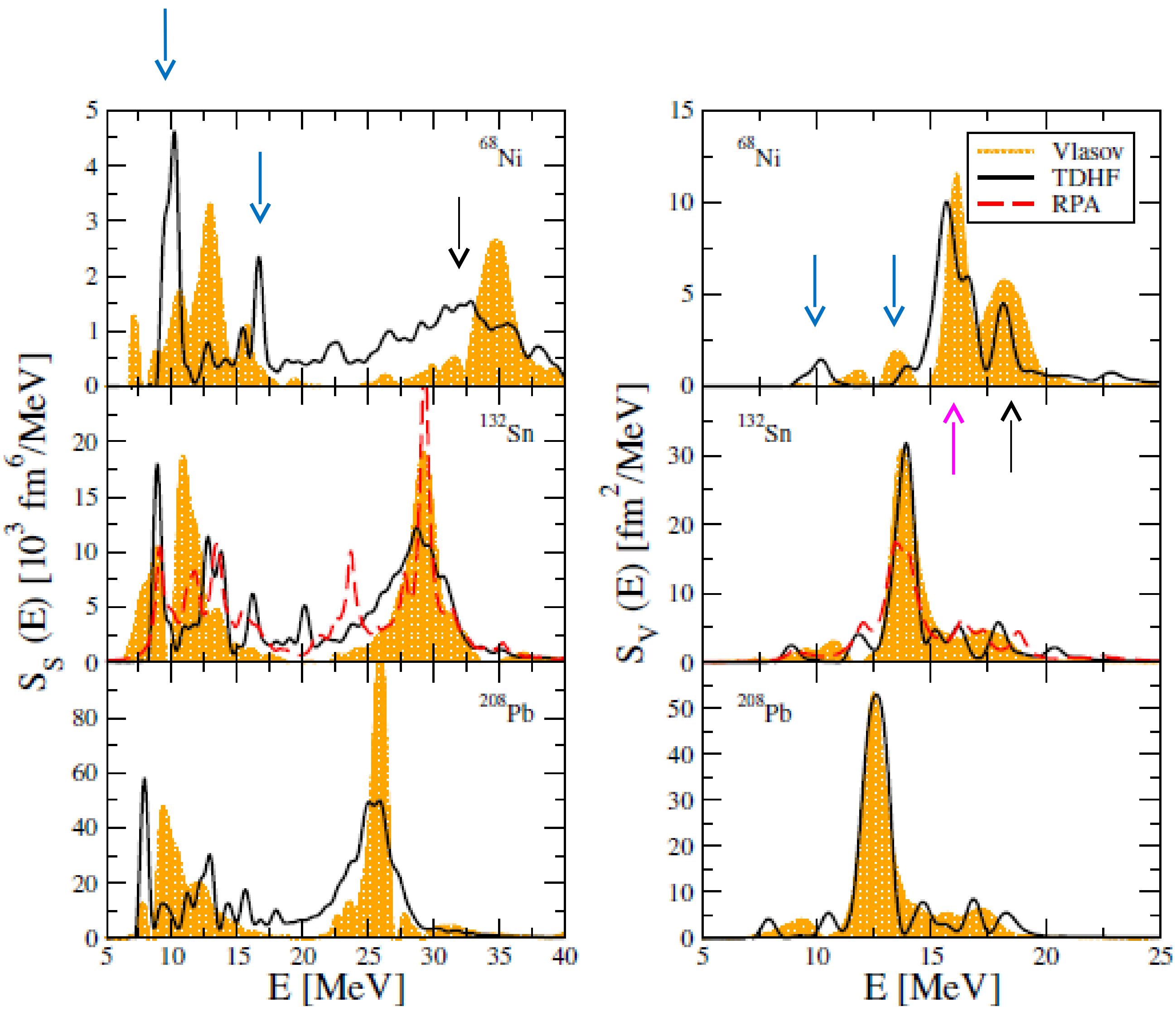
IS response

^{132}Sn

IV response

Classical vs quantal results: IS and IV response

Skyrme interaction SAMi-J31



IS response

IV response

IS response:

- two main low-energy regions (surface modes)
- ISGDR

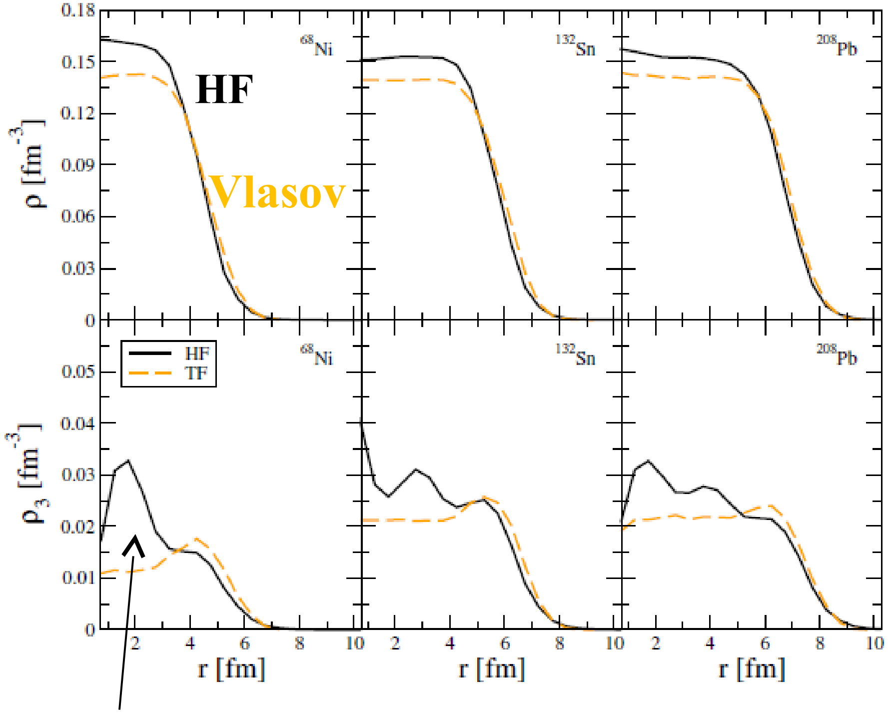
IV response:

- two main low-energy modes
- IVGDR (Goldhaber-Teller)
- IV Steinwedel-Jensen

Classical vs quantal results:

IS and IV density profile

Skyrme interaction SAMi-J31

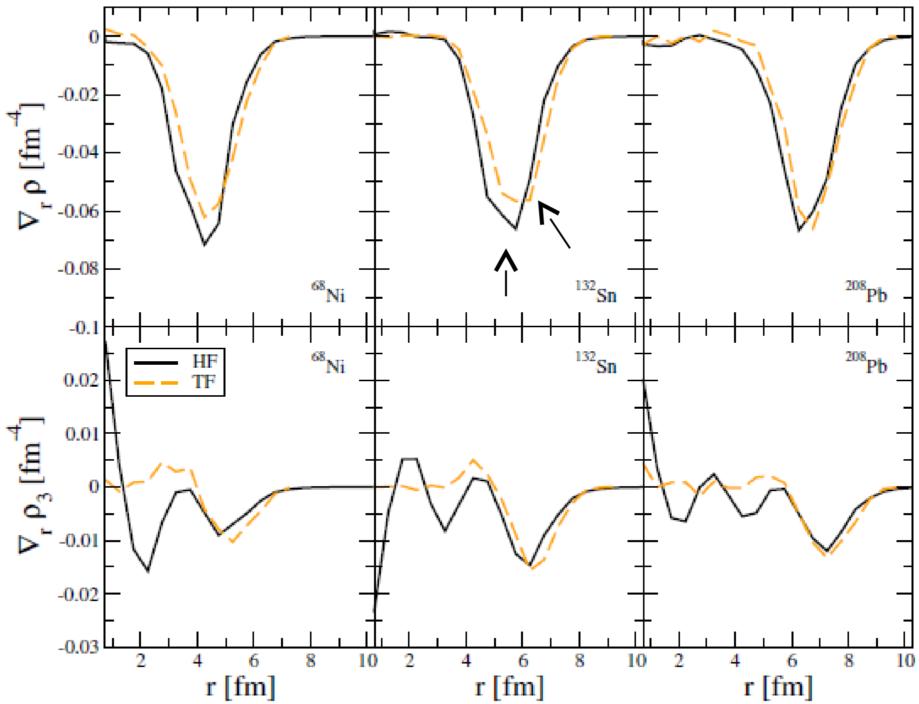


Shell effects

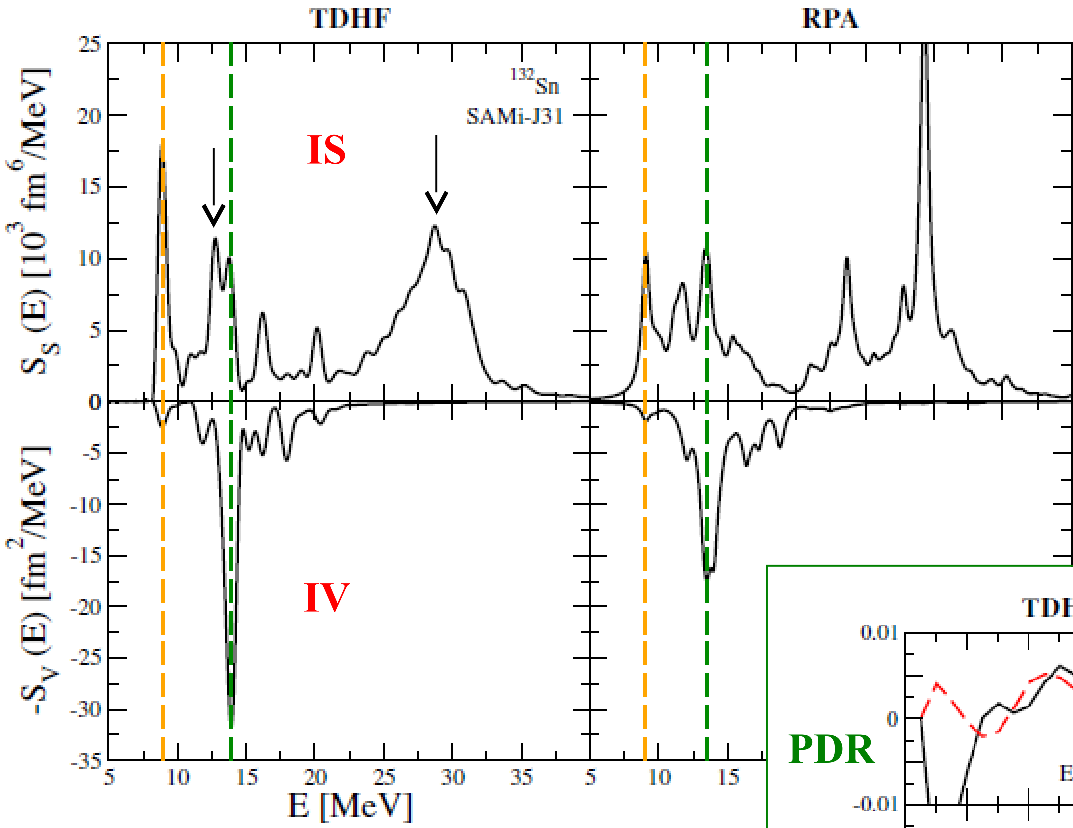
- Differences in energy of the surface modes (TDHF vs Vlavov) could be associated with the different density profile

IS and IV density gradients :

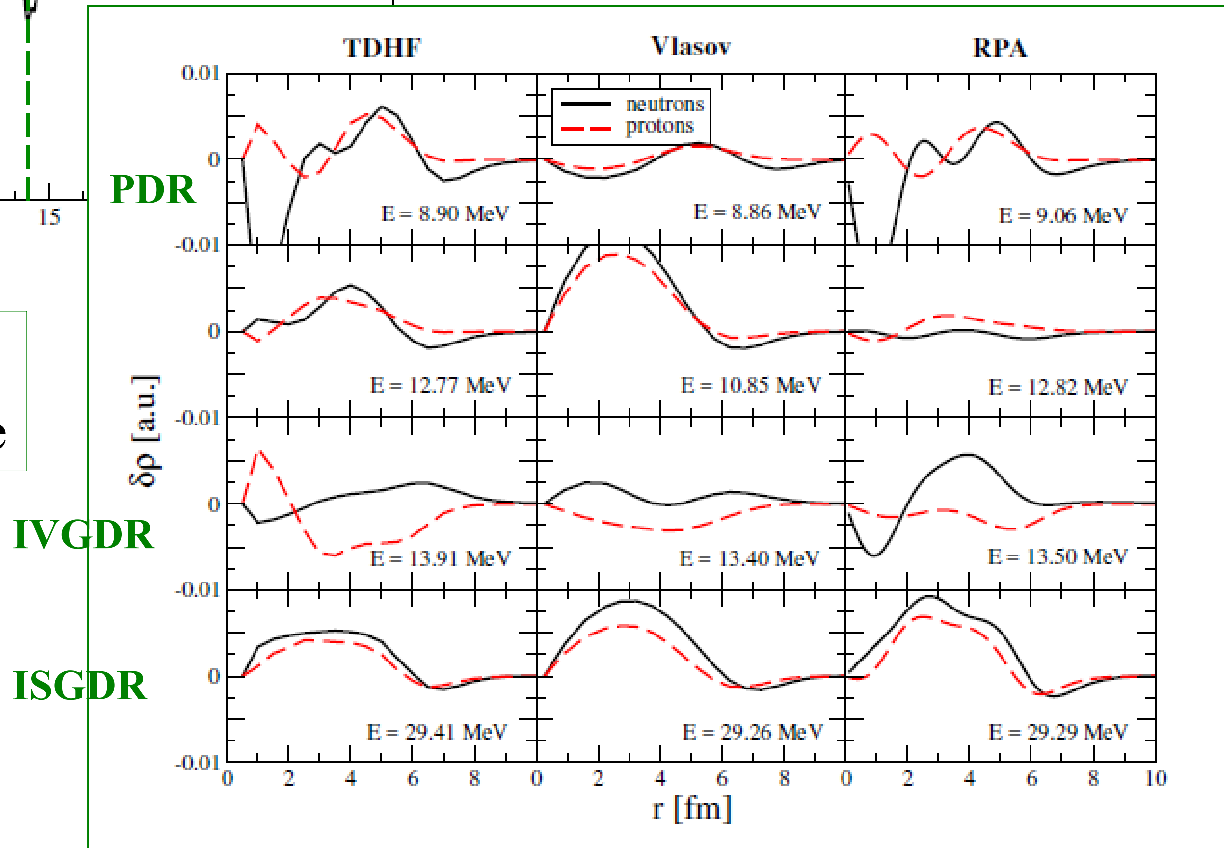
- Larger gradients at the surface in the Vlasov case
  ⟶ Larger frequency of the PDR mode



Structure of modes: transition densities



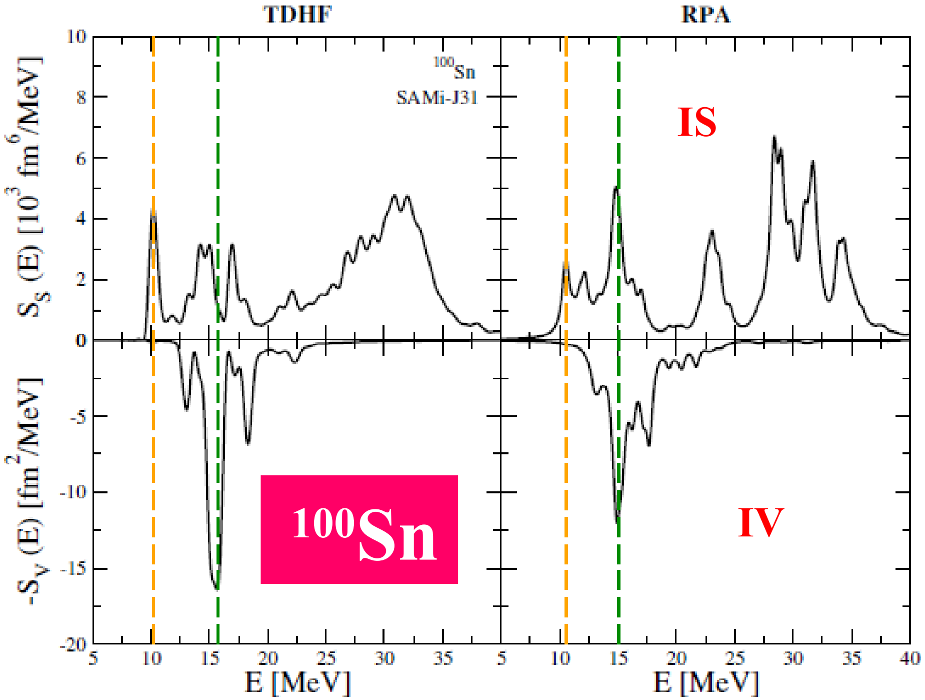
$$\delta\rho_q(r,E) \propto \int_{t_0}^{\infty} dt\, \delta\rho_q(r,t)\, \sin\frac{Et}{\hbar}$$

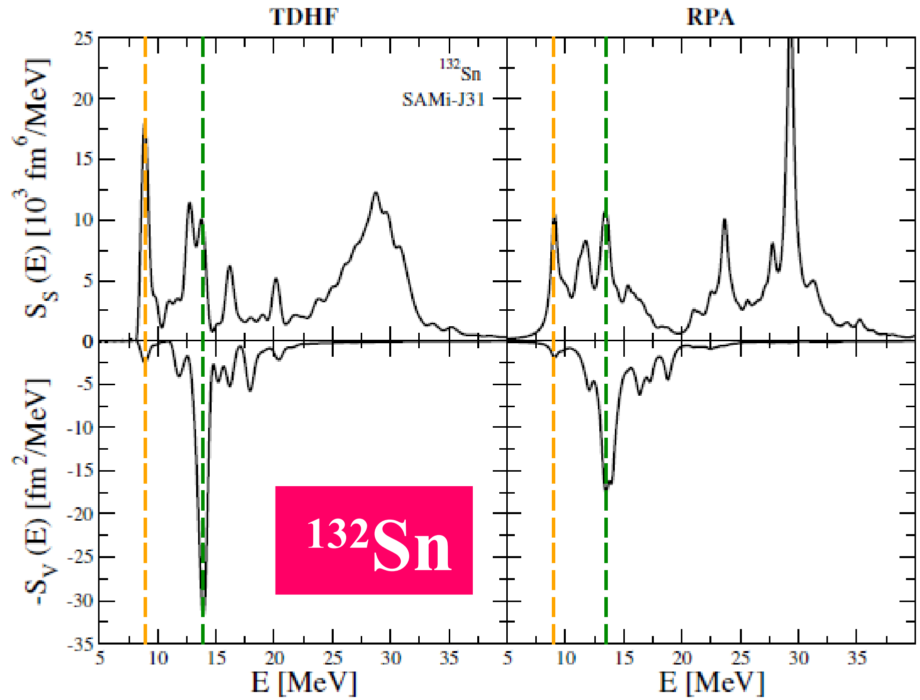


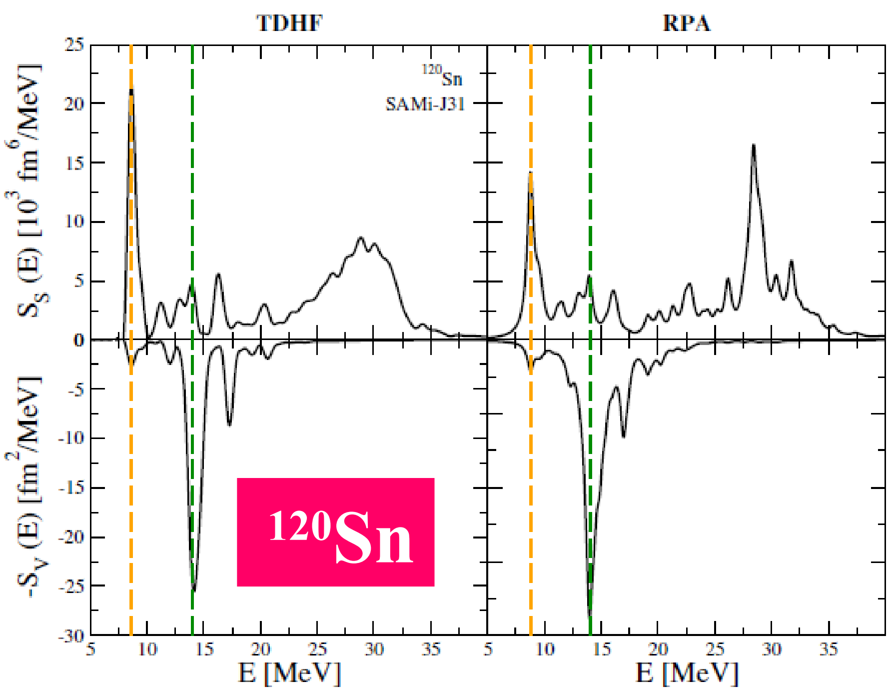
Transition densities:
main peaks of the IS response

^{132}Sn

Skyrme interaction SAMi-J31





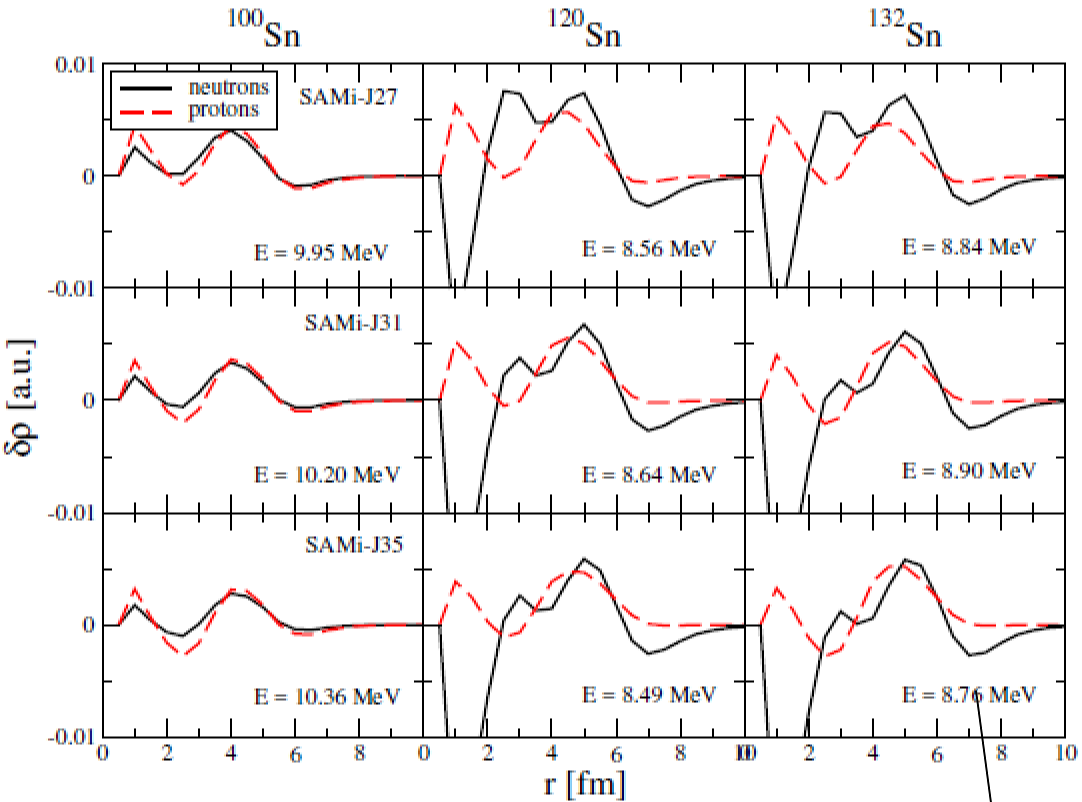


Sn isotopic chain: ^{100}Sn ^{120}Sn ^{132}Sn

- No PDR in ^{100}Sn
- Similar IV PDR strength in ^{120}Sn and ^{132}Sn

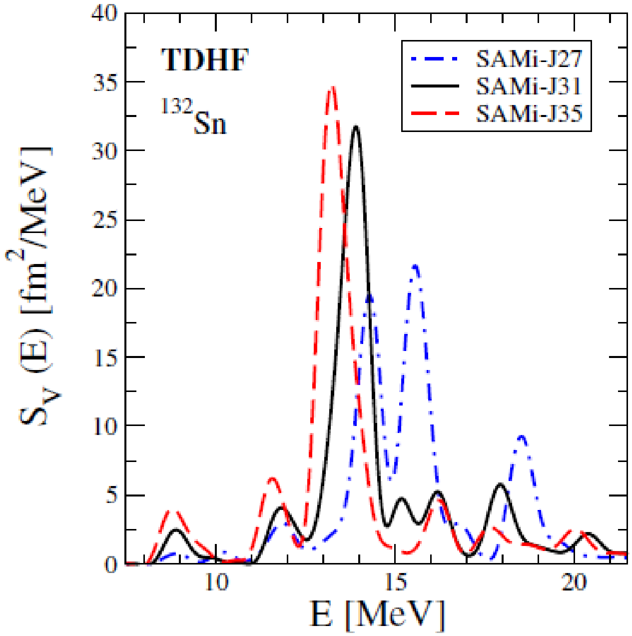
Skyrme interaction SAMi-J31

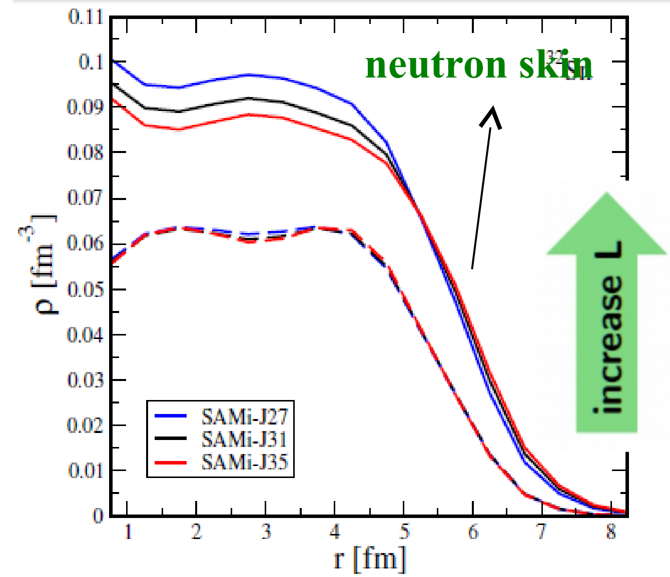
Structure of modes: "PDR" transition densities



TDHF results (from IS excitation)

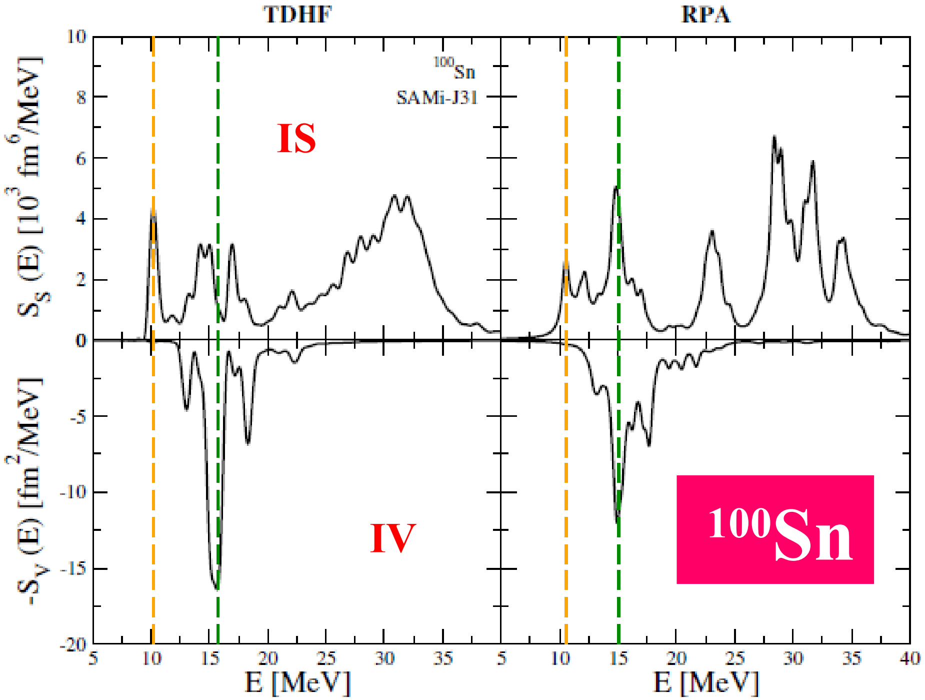
IV response

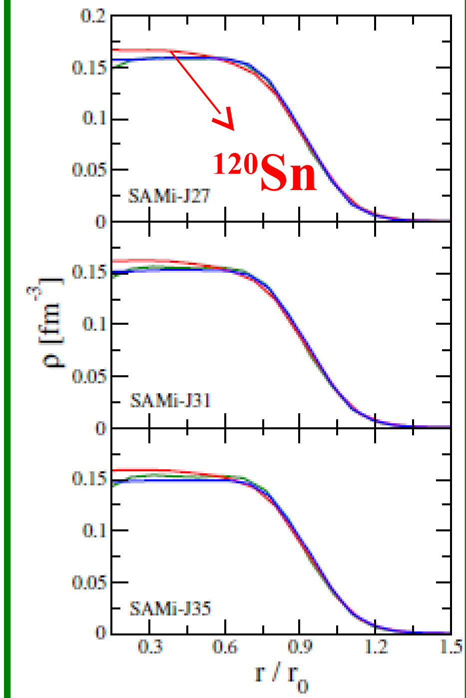




Wider neutron osscillation
at the surface with SAMi-J35
(thicker neutron skin)

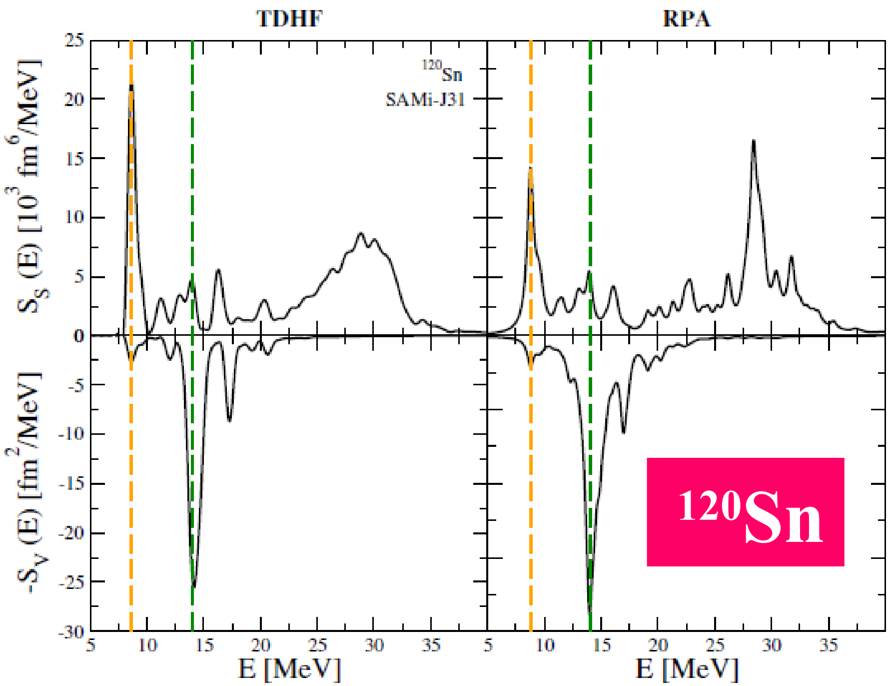
^{132}Sn





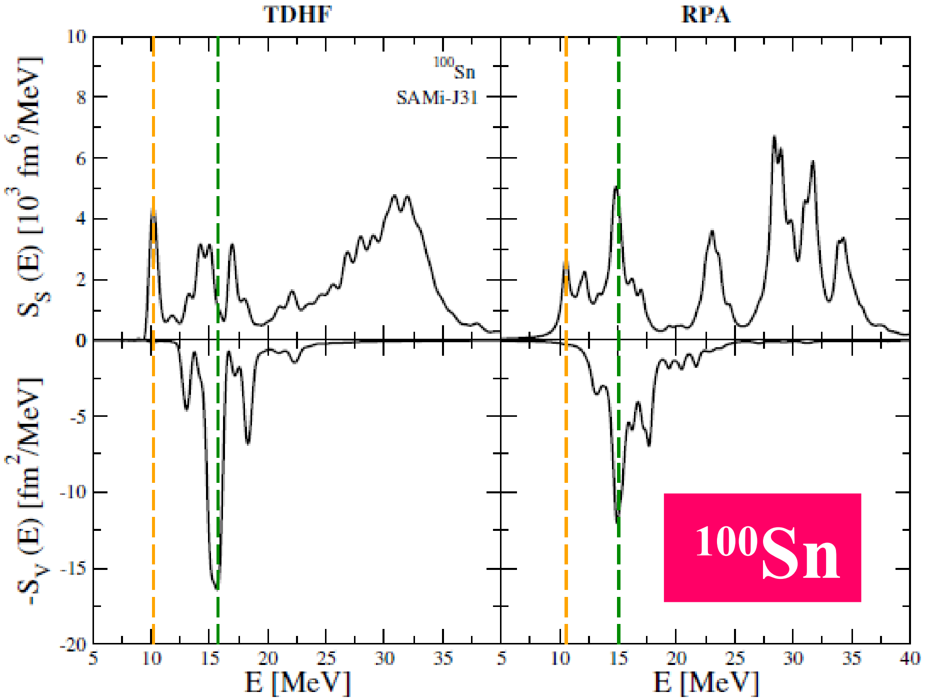
Sn isotopic chain:

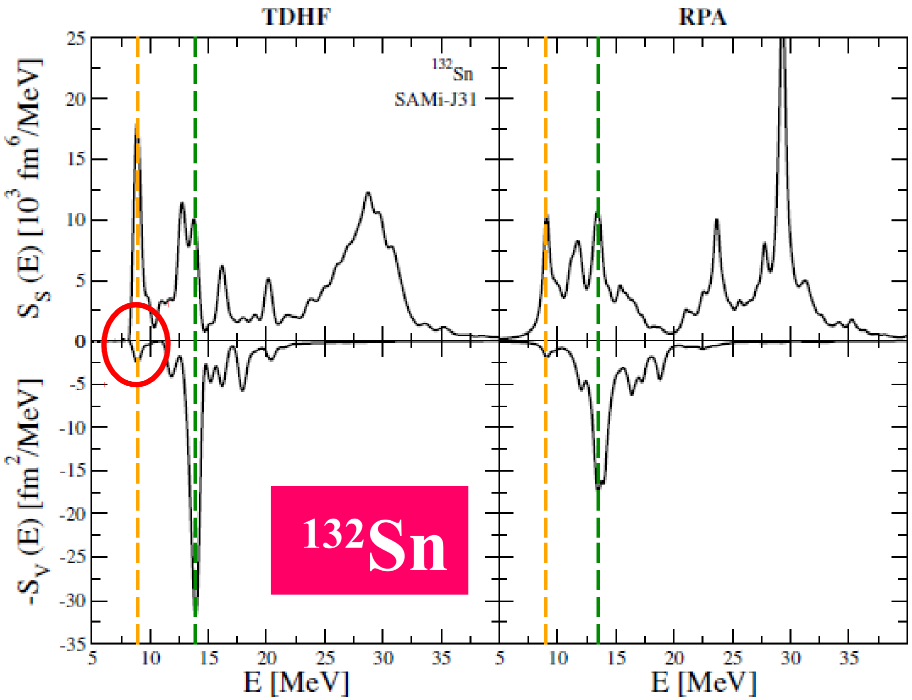
^{100}Sn ^{120}Sn ^{132}Sn

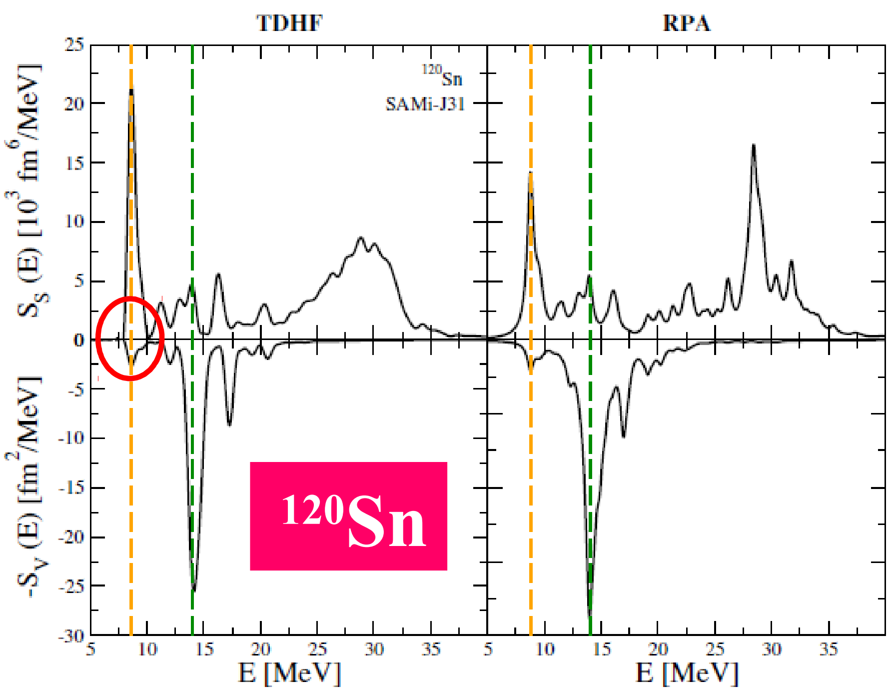


- The low energy IS surface mode is more robust in ^{120}Sn
  → different density profile

Skyrme interaction SAMi-J31







Sn isotopic chain: ^{100}Sn ^{120}Sn ^{132}Sn

- Similar EWSR for PDR in ^{120}Sn and ^{132}Sn
- The low energy IS surface mode is more robust in ^{120}Sn

→ The ratio IV/IS strength could be a better indicator of the slope L

❑ Conclusions

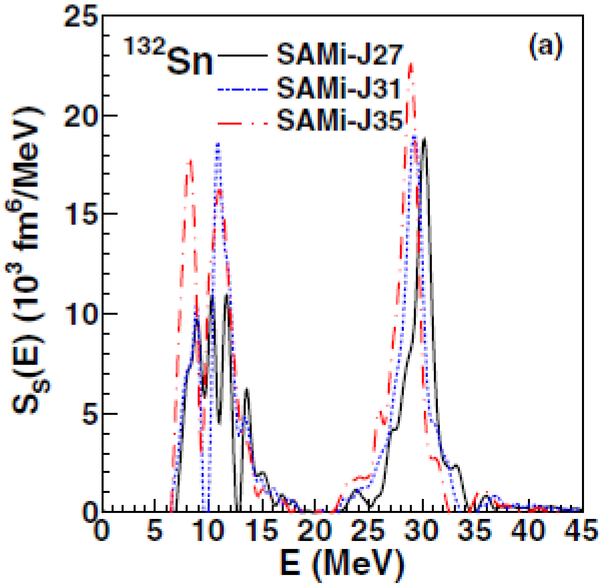
➢ Nuclear excitations in n-rich systems:
A way to constrain the nuclear effective interaction.
⟶ IV response sensitive to symmetry energy details

- the dipole response can be understood at a semi-classical level but shell effects may influence the initial density profile (low-lying surface modes sensitive to it)

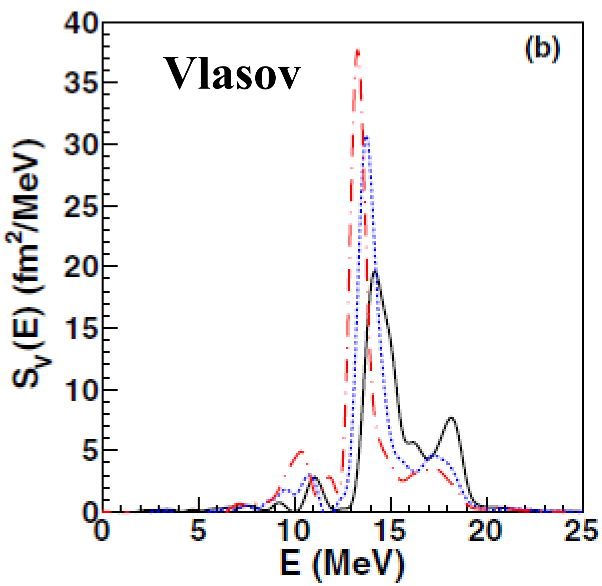
- in neutron-rich systems, IS and IV responses are connected : isoscalar-isovector coupling --- the PDR is an isoscalar-like mode

- the PDR strength is related to the neutron skin (i.e. to the symmetry energy slope L), but also to the leading IS strength

PDR and symmetry energy



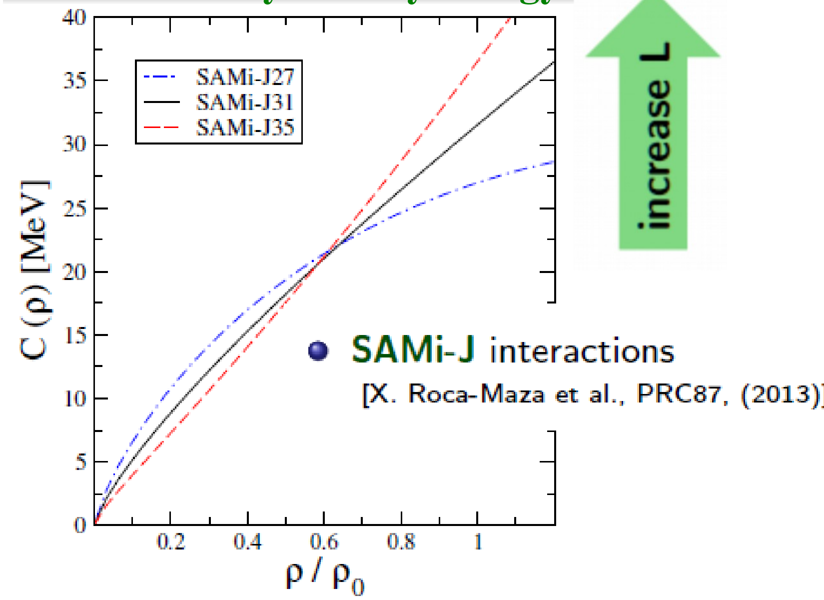
IS response

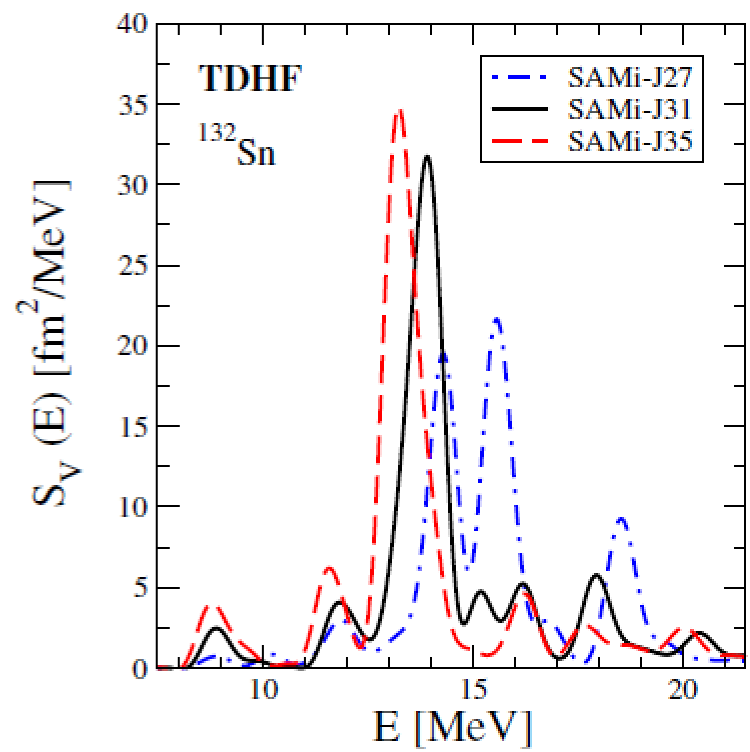


^{132}Sn

IV response

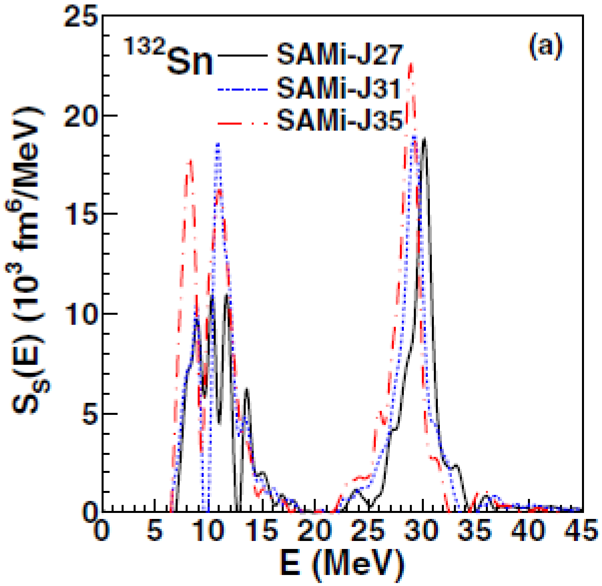
symmetry energy



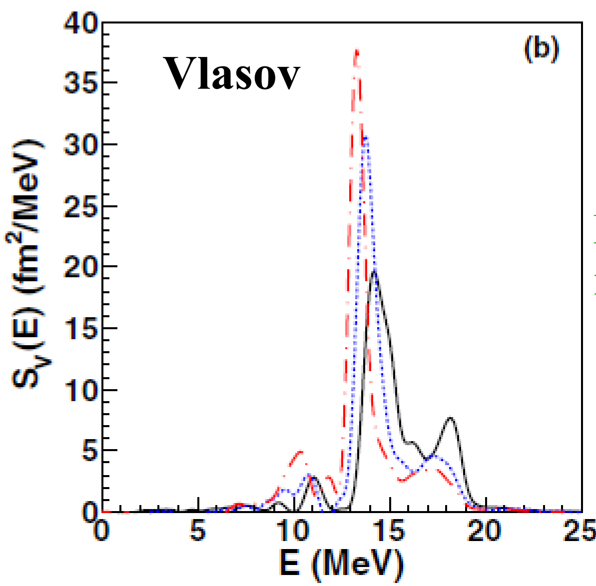


S.Burrello et al. PHYSICAL REVIEW C **94**, 014313 (2016)

PDR and symmetry energy

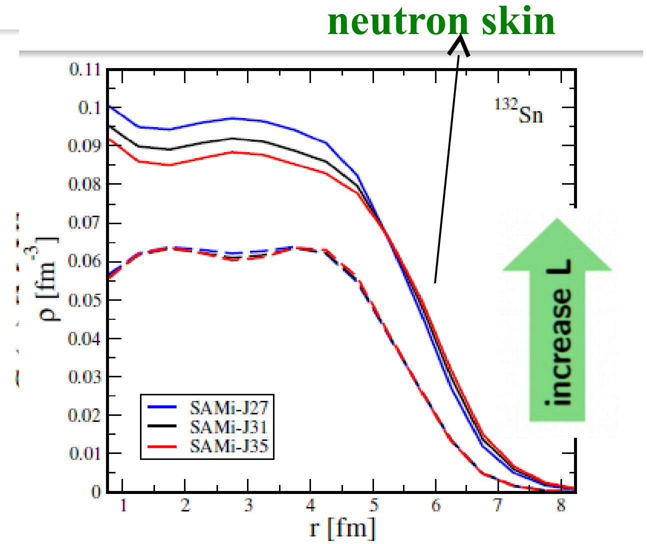


IS response

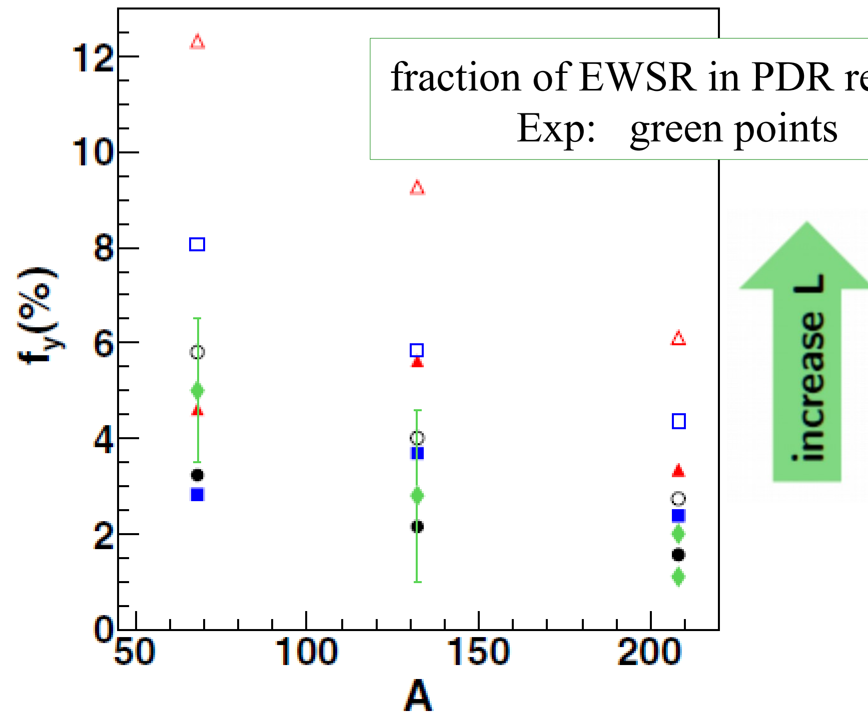


IV response

^{132}Sn

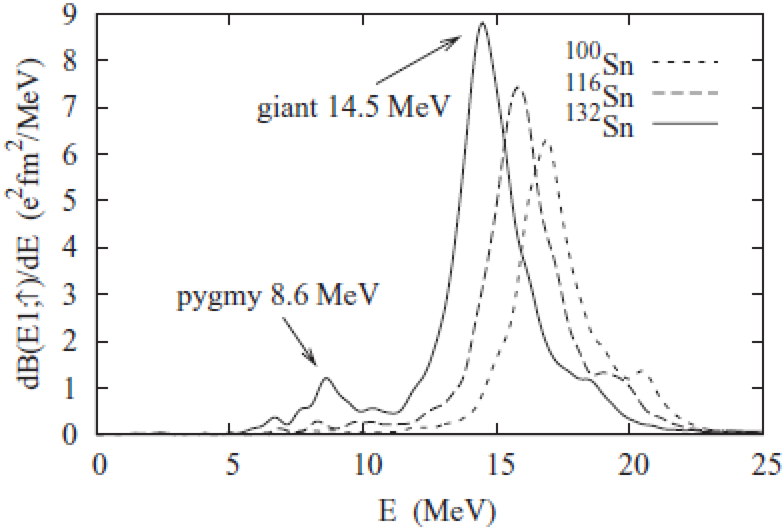


fraction of EWSR in PDR region:
Exp: green points

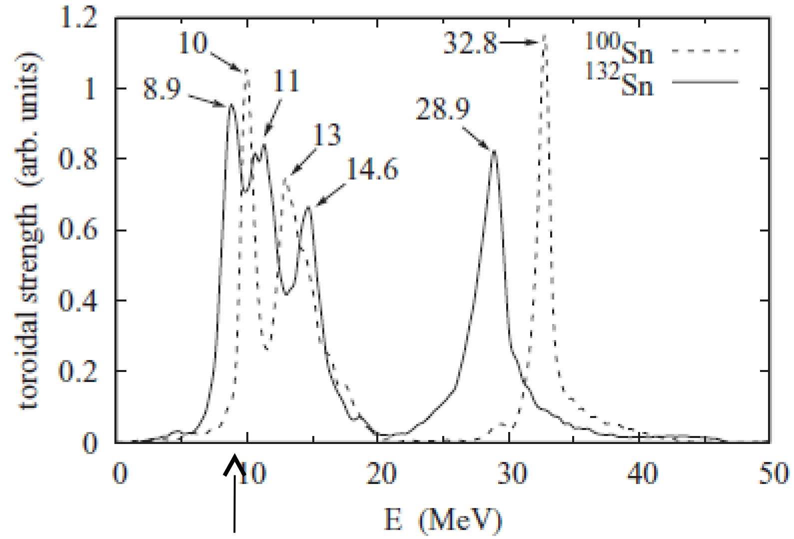


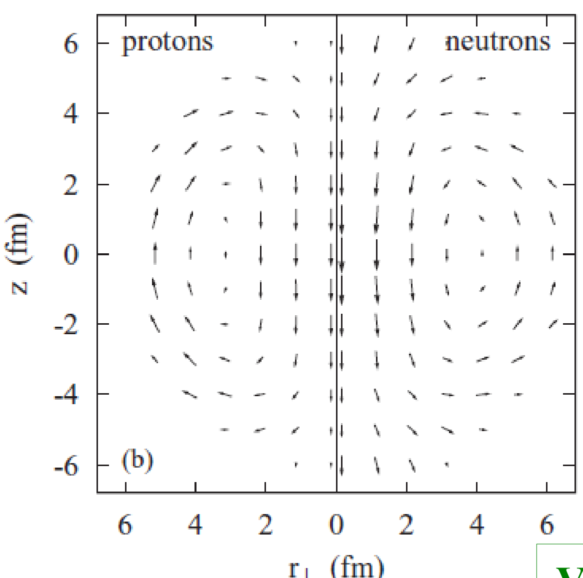
Semi-classical calculations with simpler eff. interactions

IV response



IS (toroidal) response





E = 8.9 MeV

Velocity fields

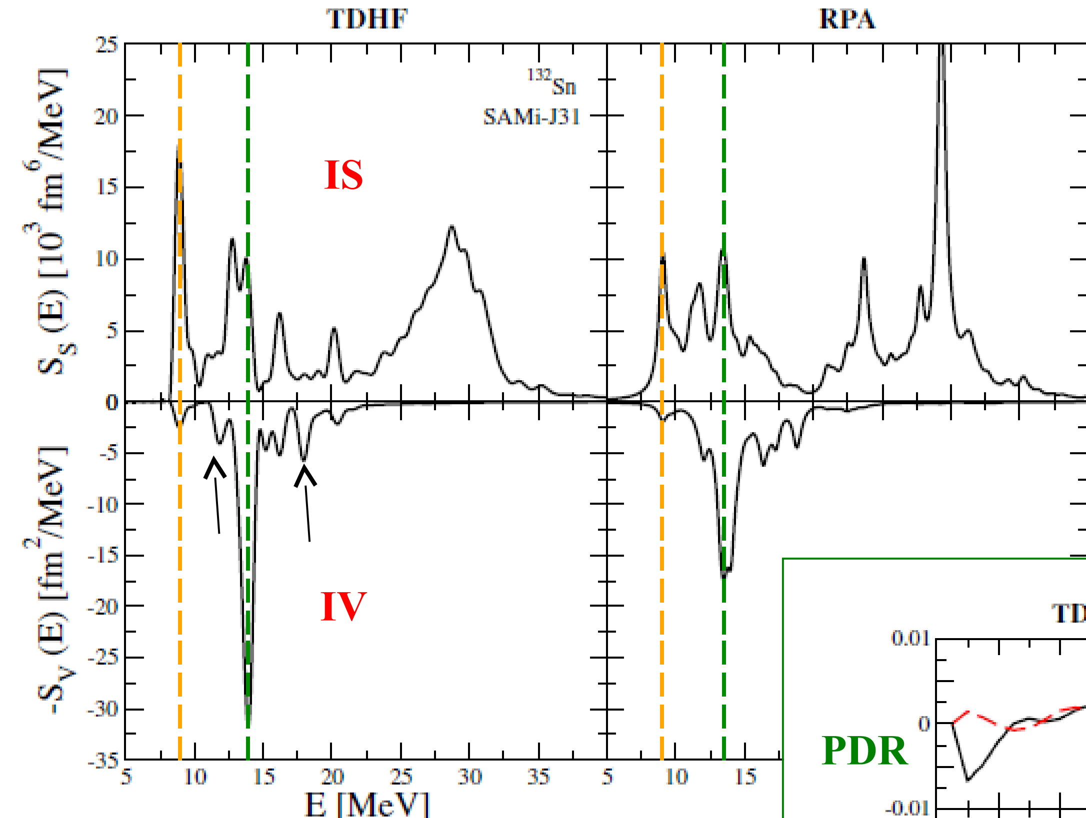
❑ The **low-lying** modes are interpreted as **surface** modes of toroidal shape (the surface moves against the core)

M. Urban
PHYSICAL REVIEW C **85**, 034322 (2012)

We observe that the mode at 10 MeV in ^{100}Sn (Fig. 13) has qualitatively the same velocity field and transition density as the mode corresponding to the PDR in ^{132}Sn (Fig. 9). From this one may conclude that the existence of this mode does not require the presence of a neutron skin. The neutron excess is only needed to be able to probe this mode with the electric dipole operator. Looking closely at the velocity field of this mode (Figs. 9 and 13), one realizes that the velocity field is almost constant in the center of the nucleus, contrary to the velocity field of the toroidal mode, which lies at slightly higher energy [11 MeV in ^{132}Sn (Fig. 10) and 13 MeV in ^{100}Sn (Fig. 14)]. This can be interpreted in the sense hat the lower one of the two modes is an oscillation of the surface (not necessarily the neutron skin, because ^{100}Sn does not have one) against the core, whereas the higher one is the original torus mode which, in the framework of nuclear fluid dynamics, exists already in a uniform sphere. This interpretation is corroborated by the transition densities, which in the case of the higher mode (Figs. 10 and 14) are much more concentrated in the inner part of the nucleus, while those of the lower mode (Figs. 9 and 13) are much stronger in the surface region. Another support for this interpretation is the energy of this mode: According

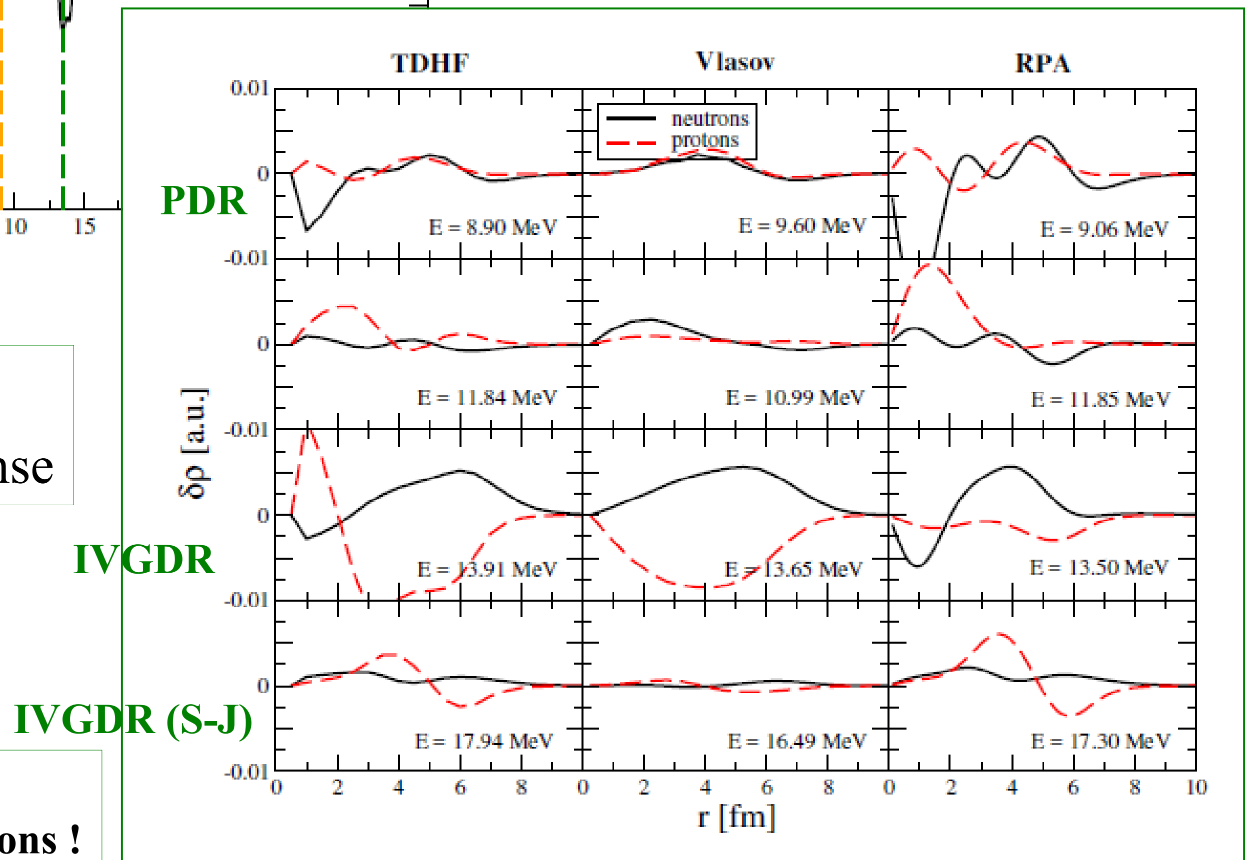
Structure of modes: transition densities

Skyrme interaction SAMi-J31



Transition densities:
main peaks of the IV response

^{132}Sn



PDR and IVGDR TD
are the same for IS and IV excitations !

PHYSICAL REVIEW C **87**, 024305 (2013)

Toroidal nature of the low-energy $E1$ mode

A. Repko,[1] P.-G. Reinhard,[2] V. O. Nesterenko,[3,*] and J. Kvasil[1]