Collective excitations as a probe of the nuclear effective interaction

NUSYM17

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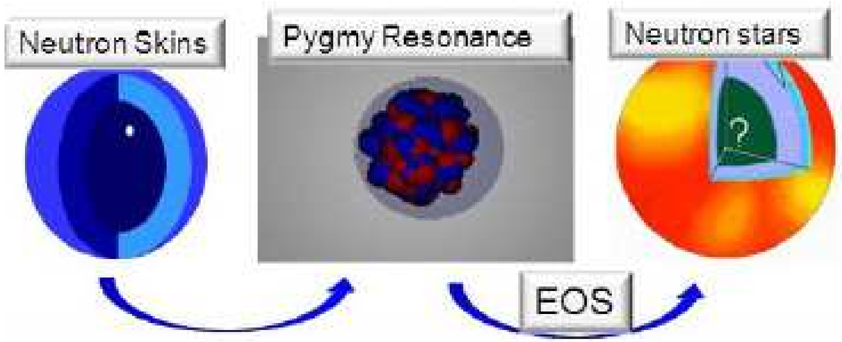
Content

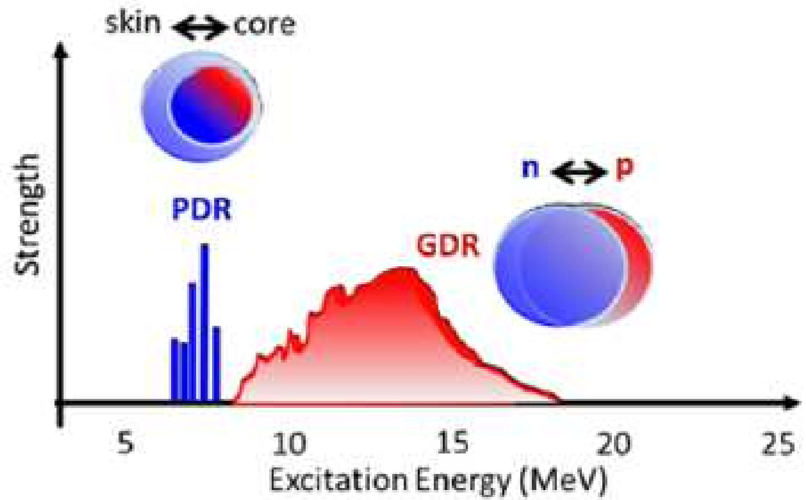
- Brief introduction to quantal dynamical approaches and transport theories: *classical vs quantal description*

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

Collective modes and effective interaction: some examples

- **Collective phenomena** in **many-body** systems ⇒ properties of **interaction**
  - **Dipole excitations** in nuclei: **Giant Dipole Resonance (GDR)**
    Pygmy Dipole Resonance (PDR)
- **Isovector** term of **effective interaction**: **symmetry energy** in EoS

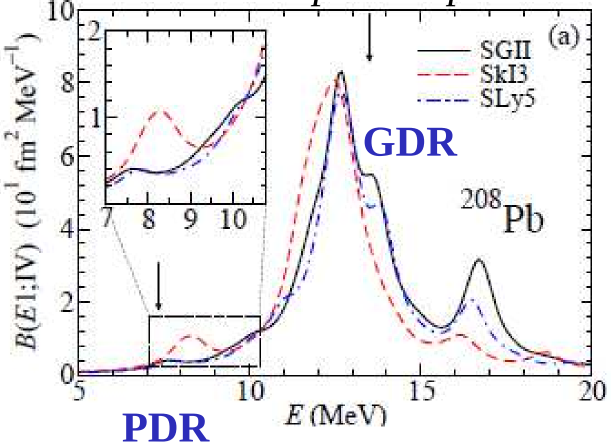




The Isovector Dipole Response (DR) in neutron-rich nuclei

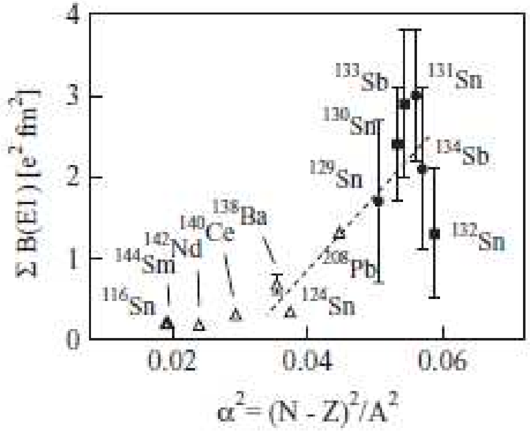
$$\vec{D} = \frac{NZ}{A}\vec{X}$$

Isovector dipole response



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

Pygmy dipole strength

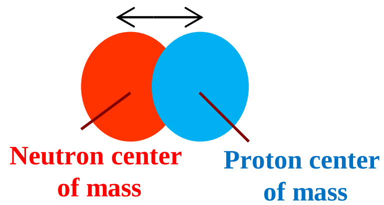


Klimkiewicz et al.

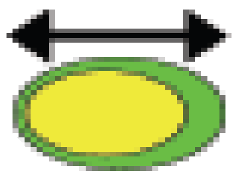
PHYSICAL REVIEW C **76**, 051603(R) (2007)

- **Giant DR**
- **Pygmy DR**

X neutrons – protons



Y excess neutrons - core



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 $\equiv$ **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:

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

- **Test-particle** method (**finite width** wave packets) $\Rightarrow$ **implicit** surface terms
- **Semi-classical** model $\Rightarrow$ **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**:

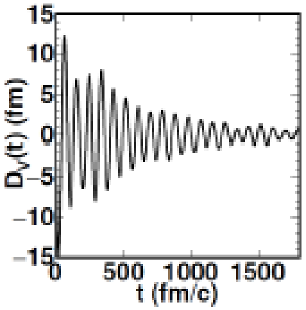
$$\hat{V}_K^{ext}(\mathbf{r},t) = \eta_K \delta(t-t_0)\hat{D}_K(\mathbf{r}) \qquad K = S, V$$

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

- **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: $S_K(E) = \sum_n |\langle n|\, \hat{D}_K \,|0\rangle|^2\, \delta\,(E-(E_n-E_0))$



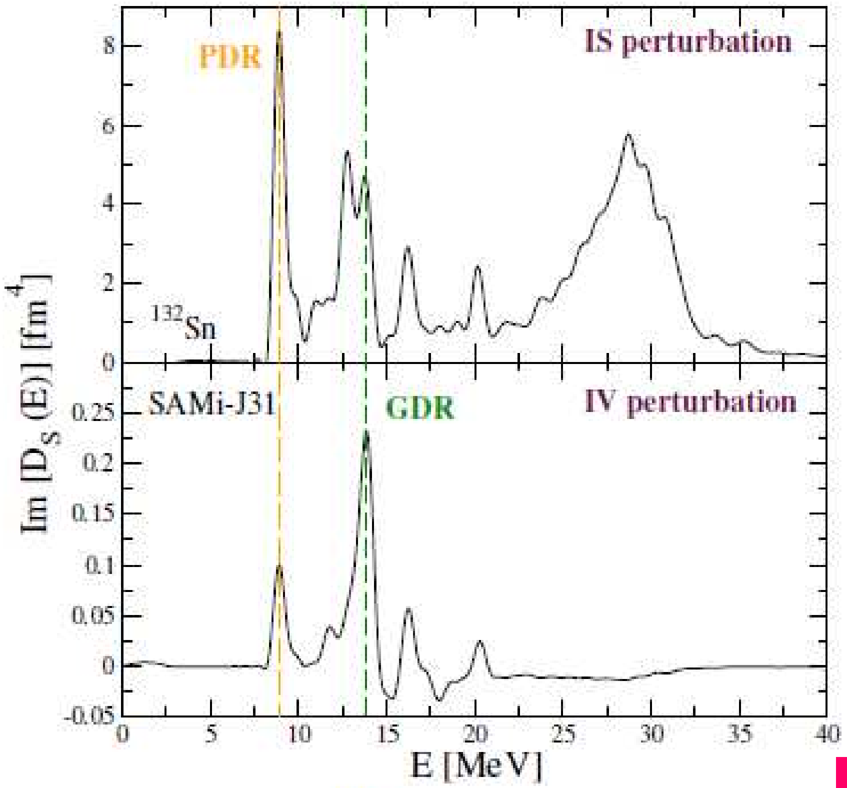
$$S_K(E) = \frac{\mathrm{Im}\, D_k(E)}{\pi \eta_k} \qquad \mathrm{D}_k\ (E)\ \text{Fourier Transform of } \mathrm{D}_k\ (\mathrm{t})$$

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

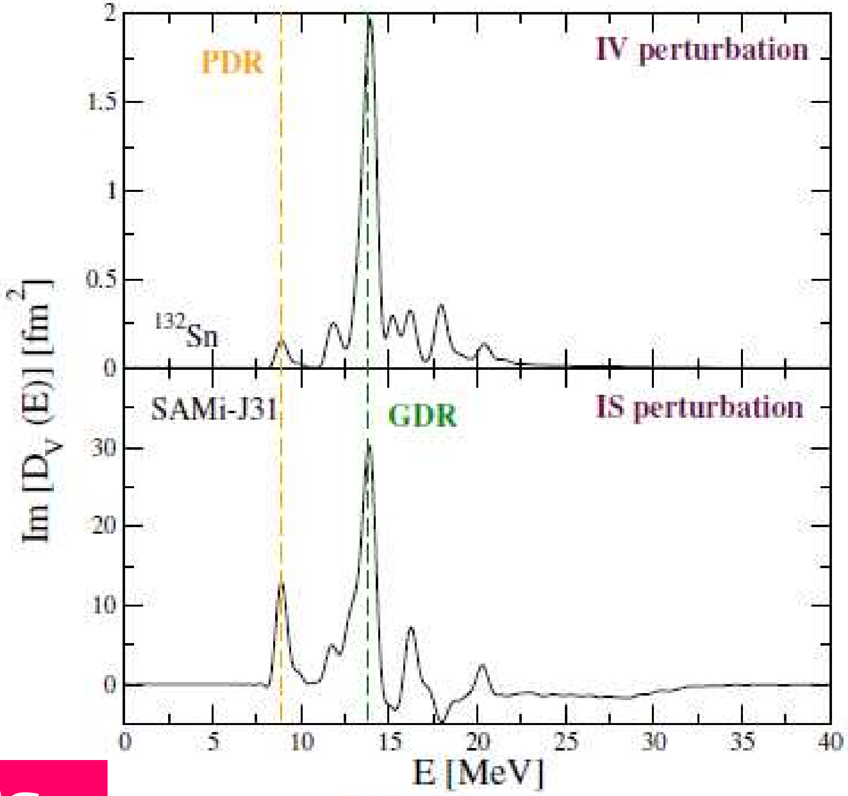
Coupling between IS and IV modes

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

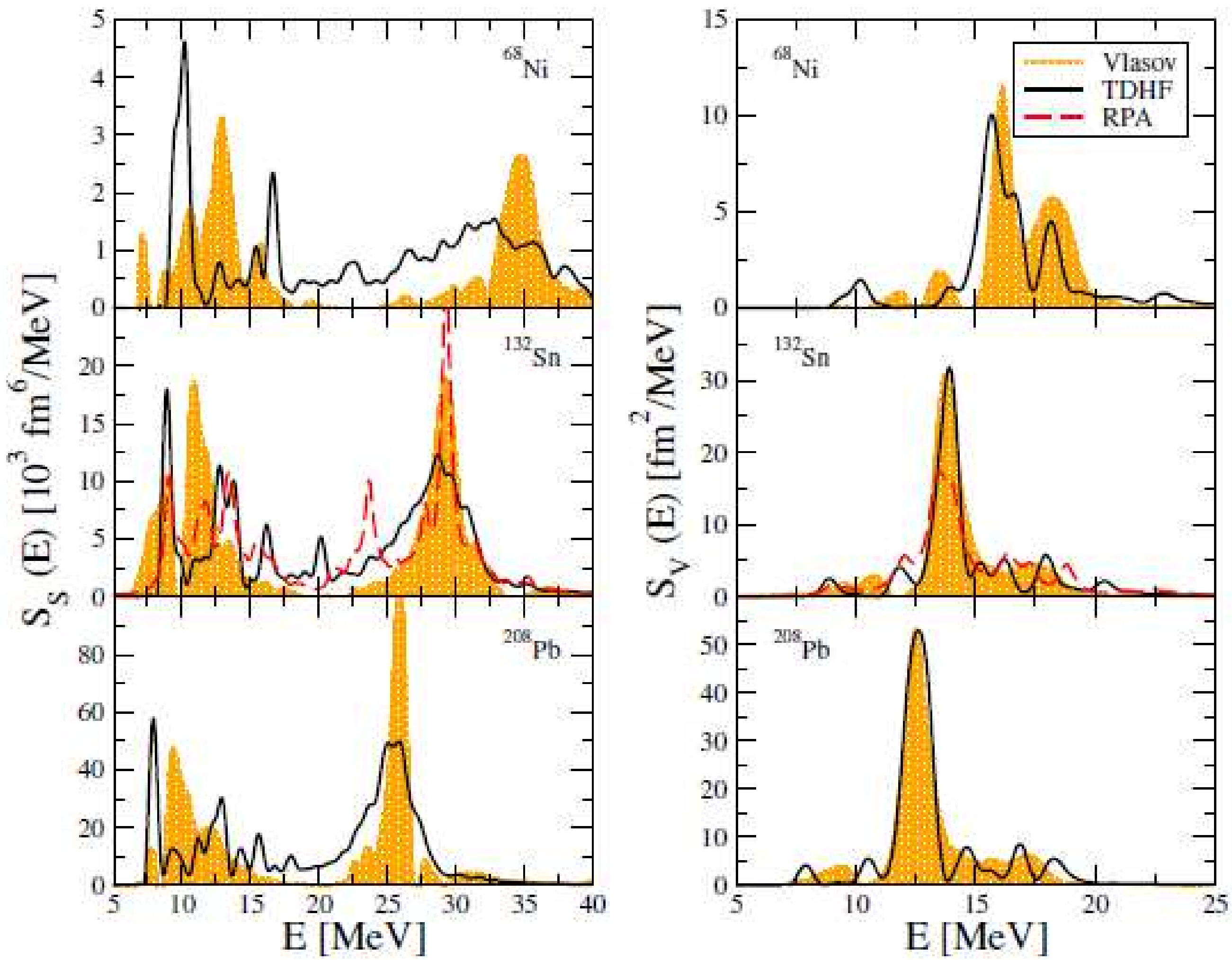


^{132}Sn

IV response

Classical vs quantal results

Skyrme interaction SAMi-J31



IS response:

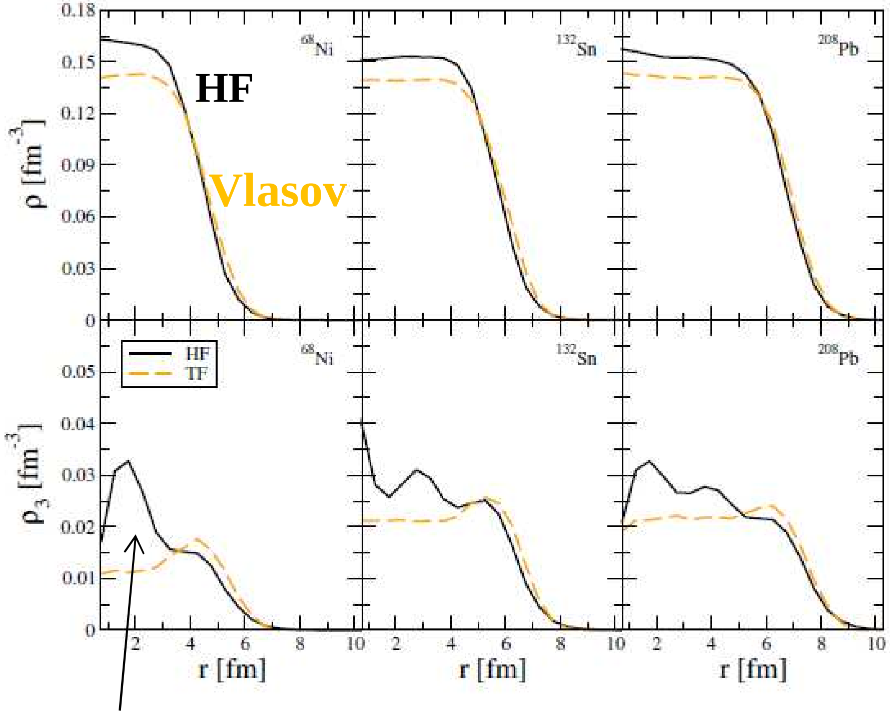
- two main low-energy regions (surface modes)
- ISGDR

IV response:

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

Classical vs quantal results

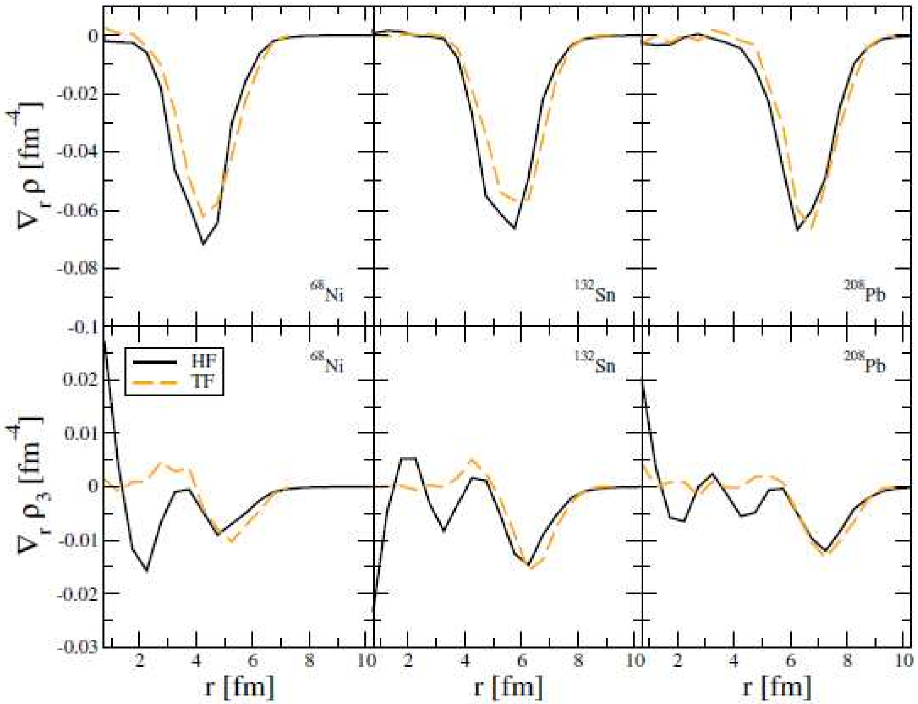
Skyrme interaction SAMi-J31



Shell effects

IS and IV density profile

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



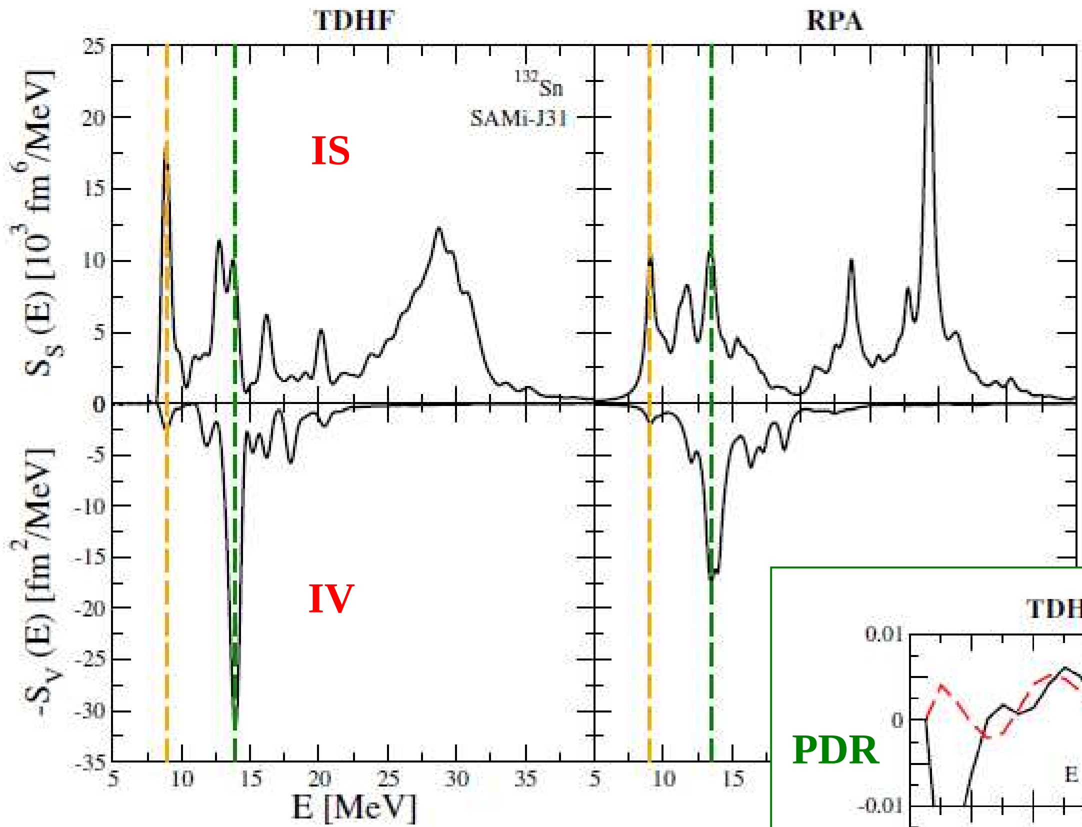
IS and IV density gradients :

- Larger gradients at the surface in the Vlasov case

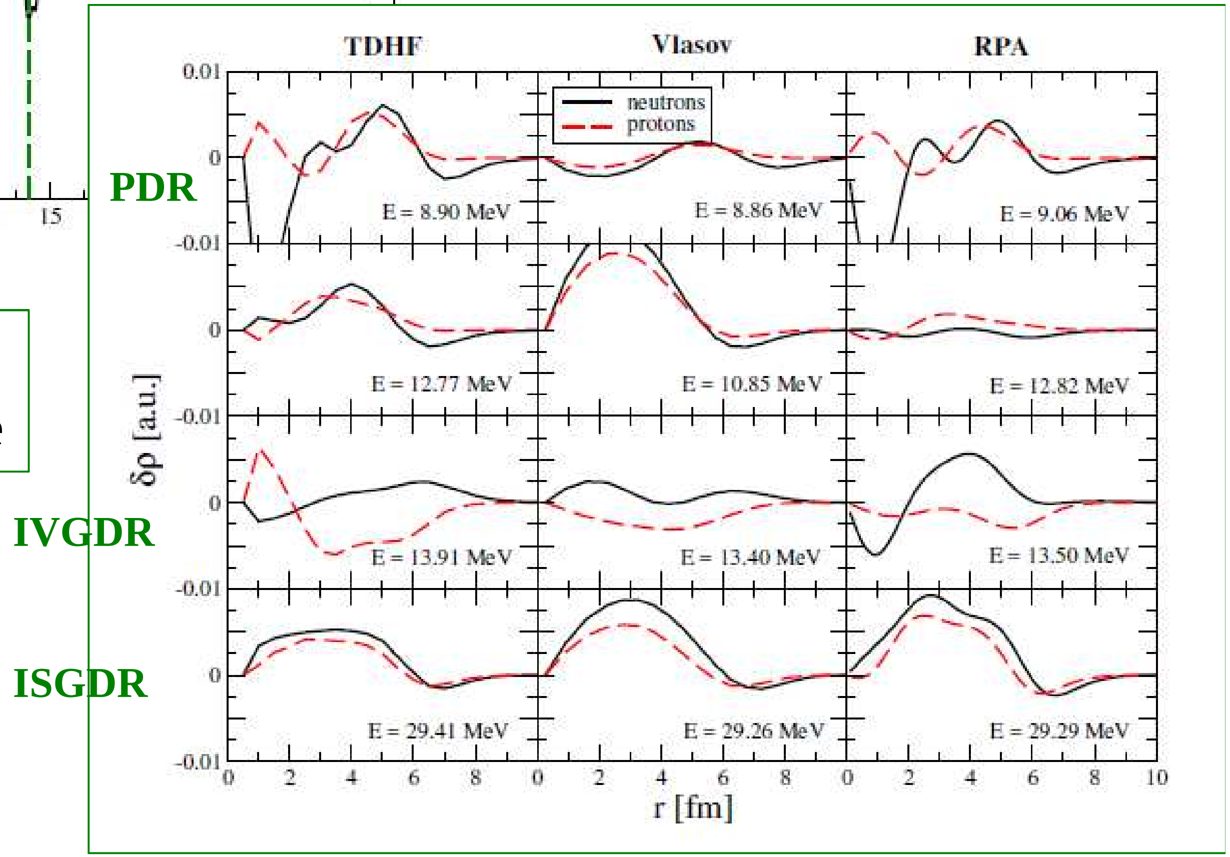
⟶ Larger (smaller) frequency of the first (second) surface mode

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

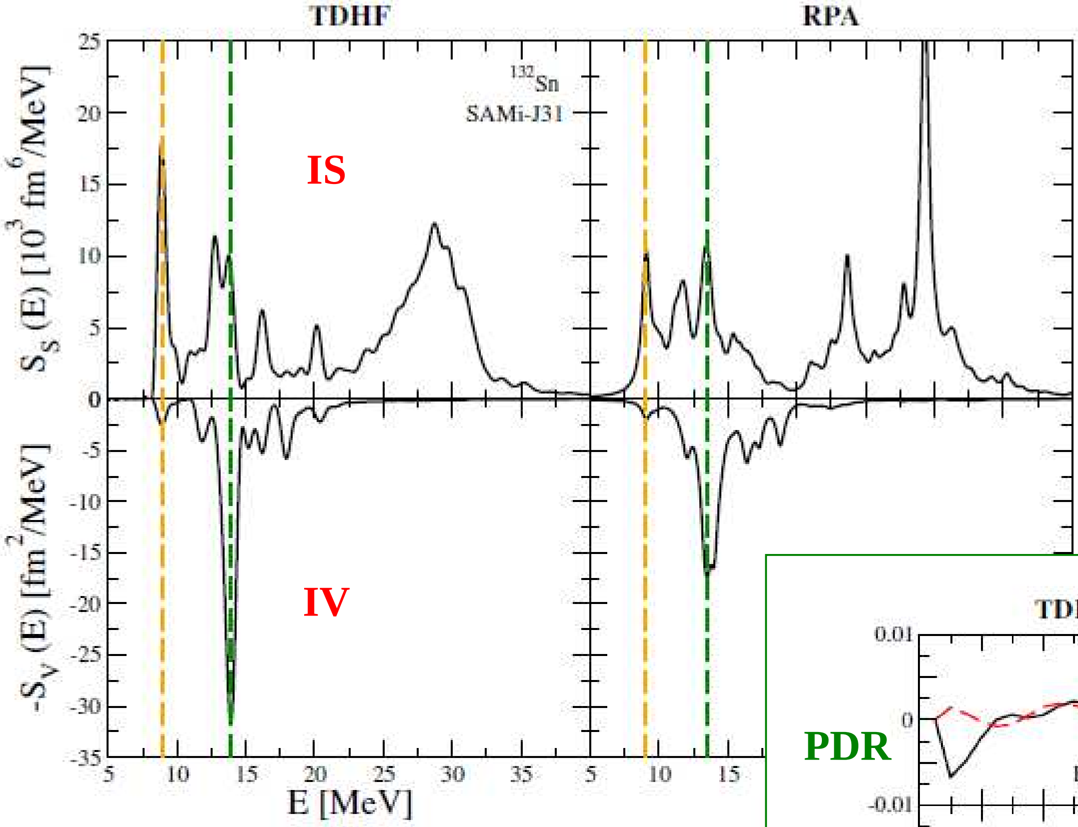


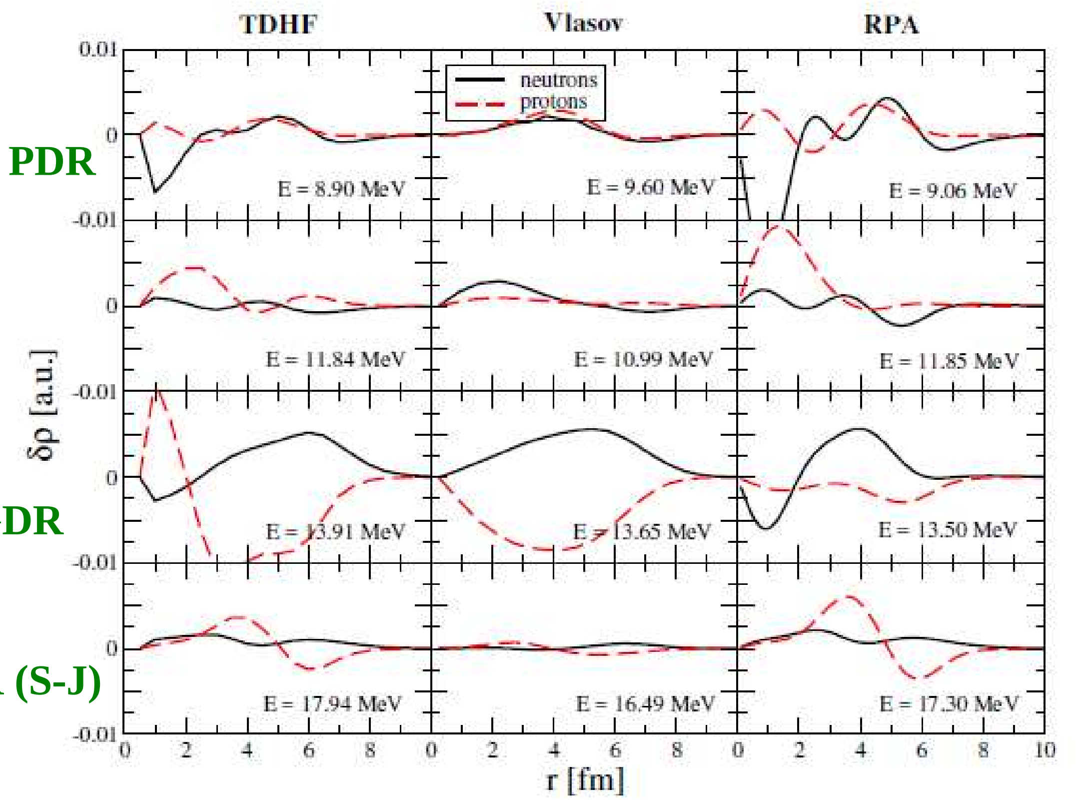
^{132}Sn

Skyrme interaction SAMi-J31

Structure of modes: transition densities

Skyrme interaction SAMi-J31





PDR

IVGDR

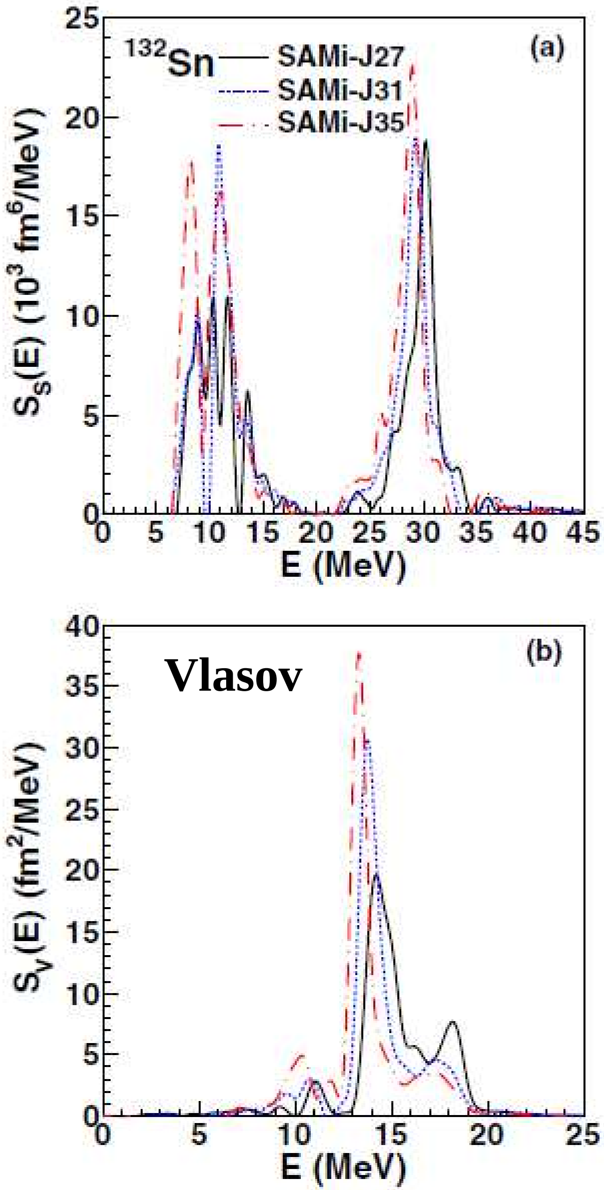
IVGDR (S-J)

Transition densities:
main peaks of the IV response

^{132}Sn

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

PDR and symmetry energy

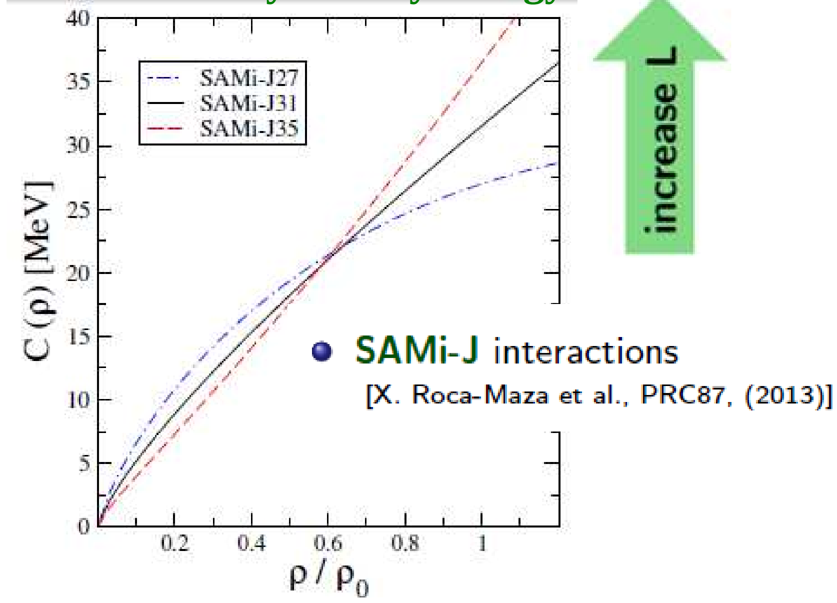


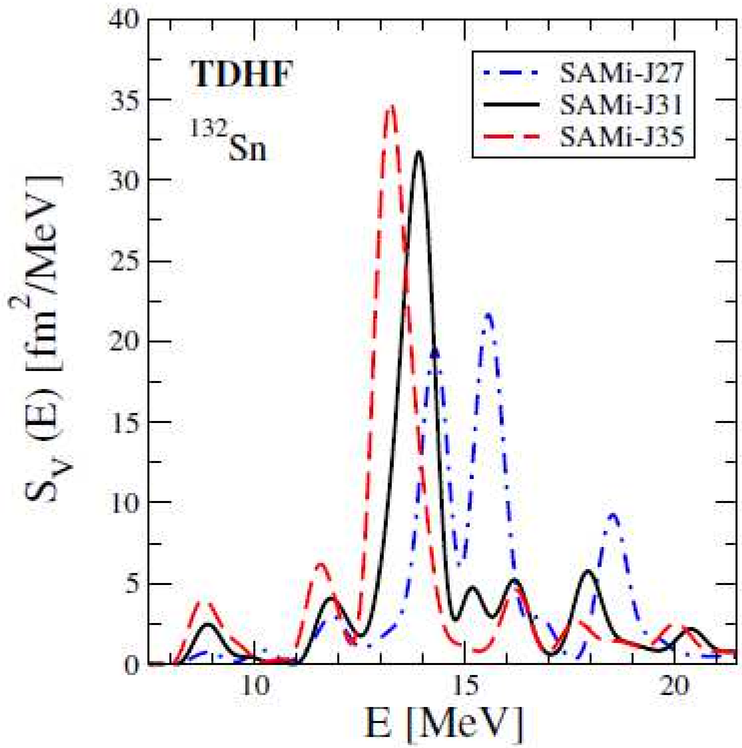
IS response

^{132}Sn

IV response

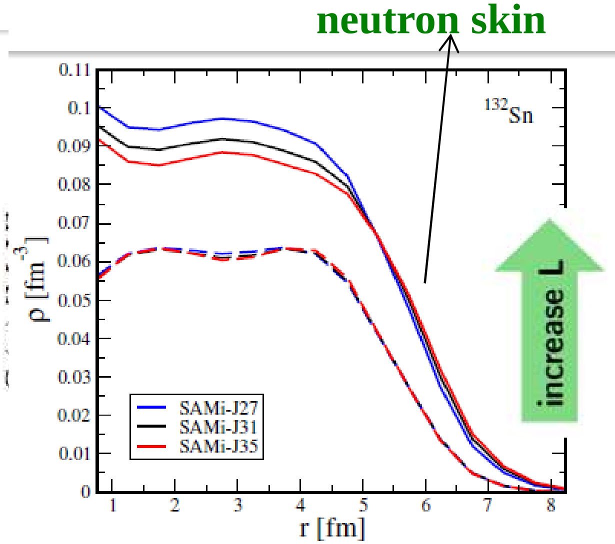
symmetry energy





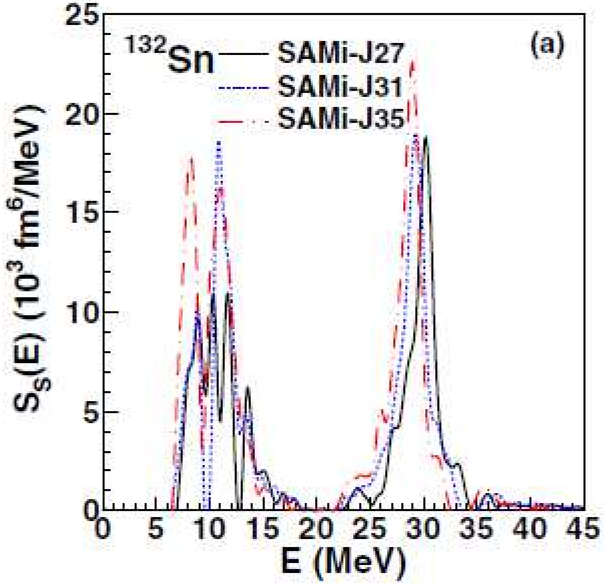
S.Burrello et al. PHYSICAL REVIEW C **94**, 014313 (2016)

PDR and symmetry energy

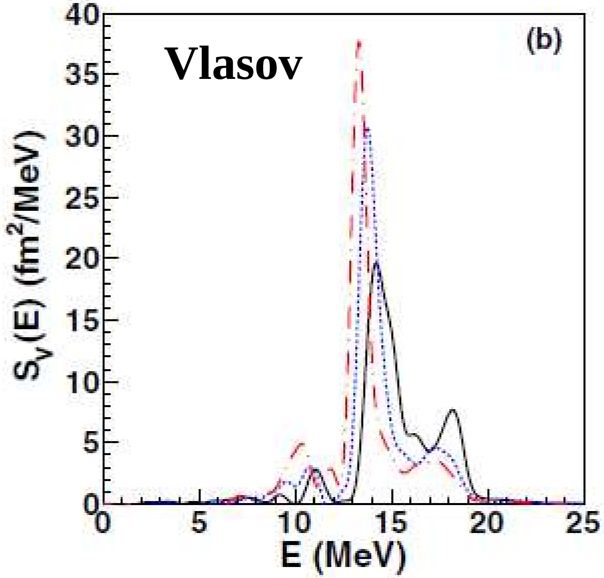


(2013)]

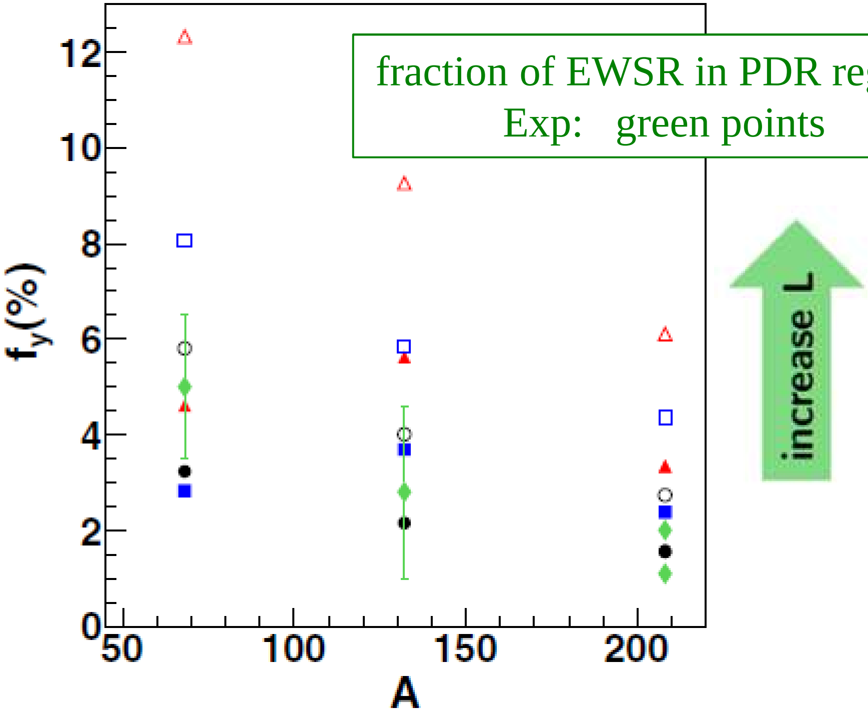
132Sn



IS response

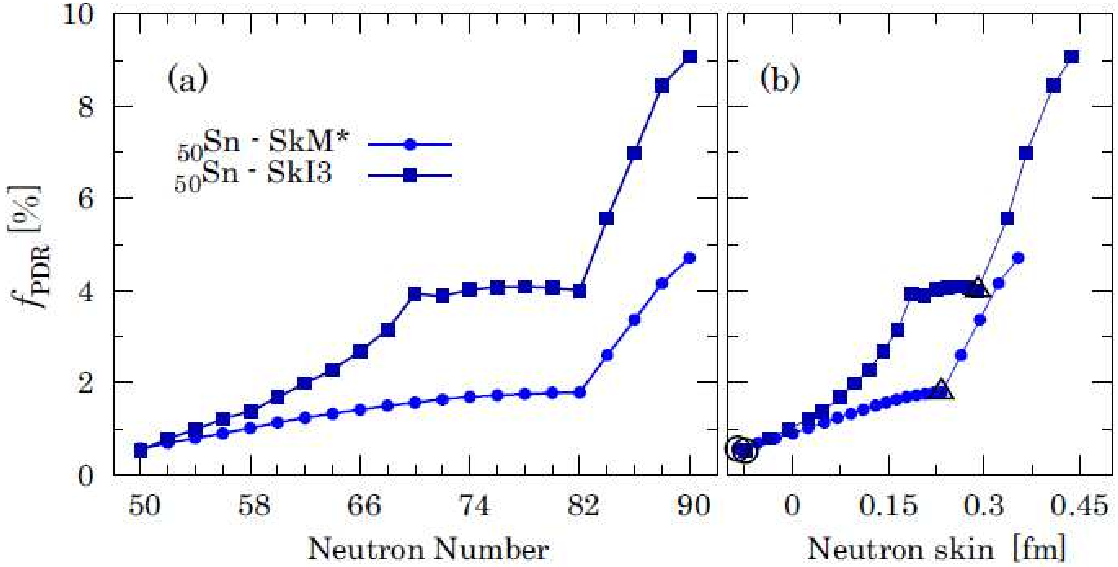


IV resp



fraction of EWSR in PDR region:
Exp: green points

Strength of PDR vs N/Z and neutron skin



S.Ebata et al. TDHFB calculations

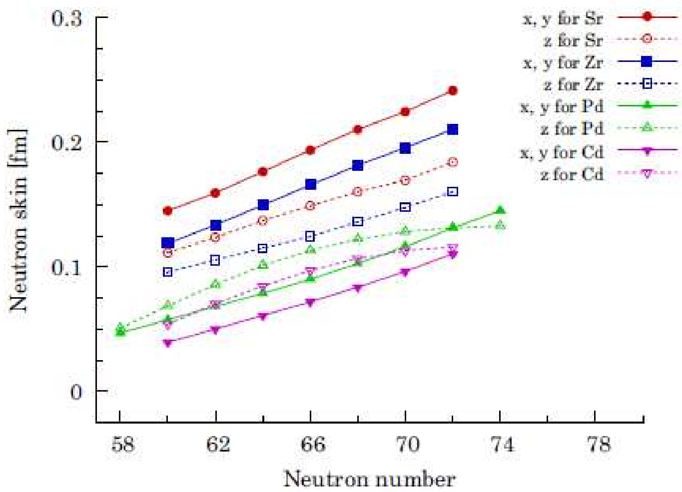
PHYSICAL REVIEW C 90, 024303 (2014)

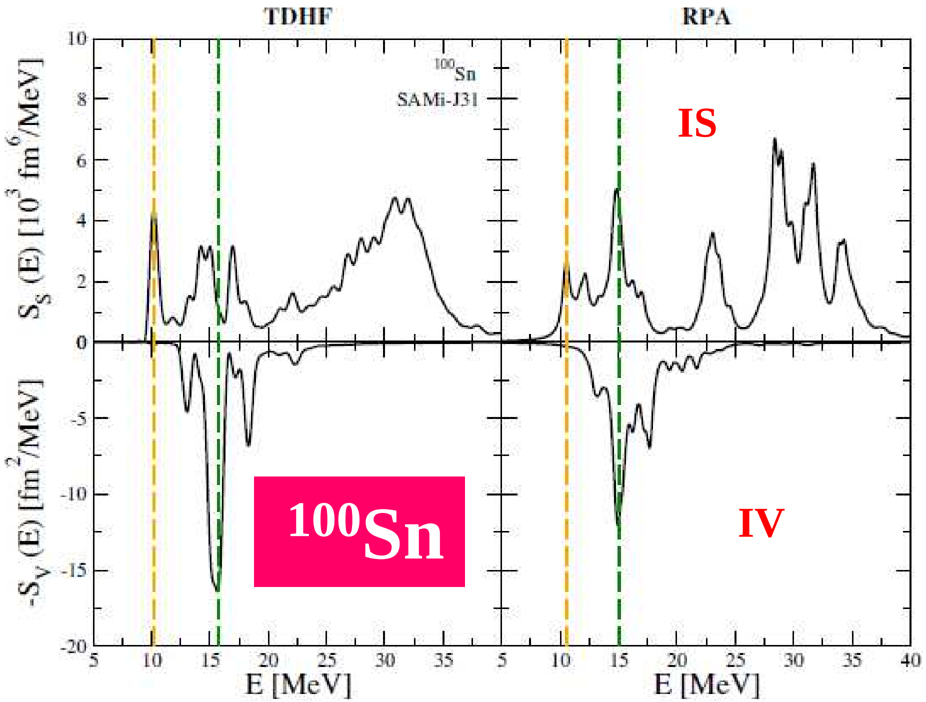
- The neutron skin thickness increases with N/Z

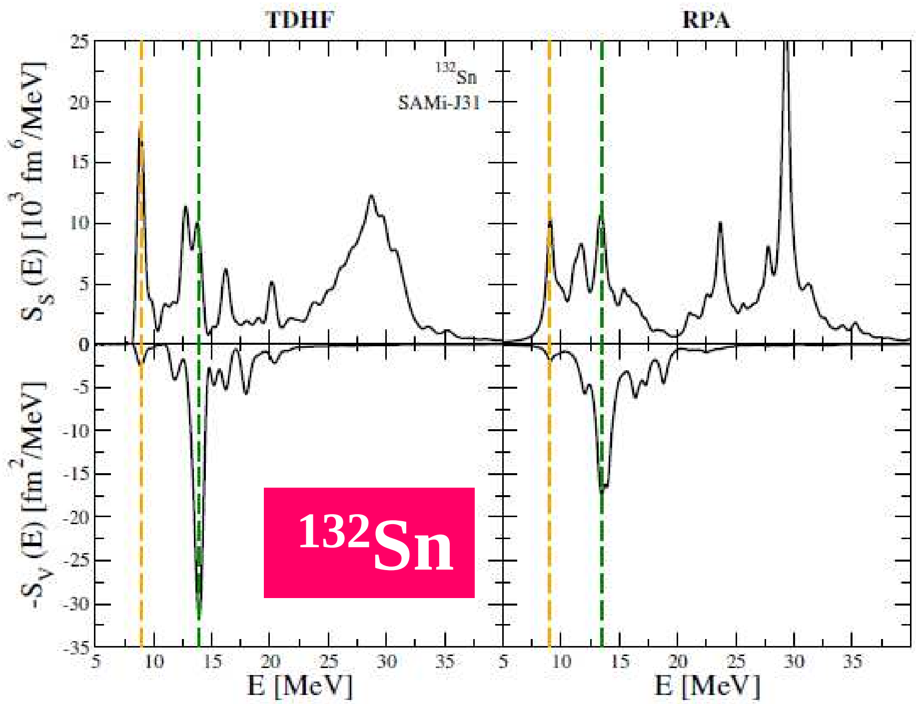
The EWSR exhausted by PDR does not !

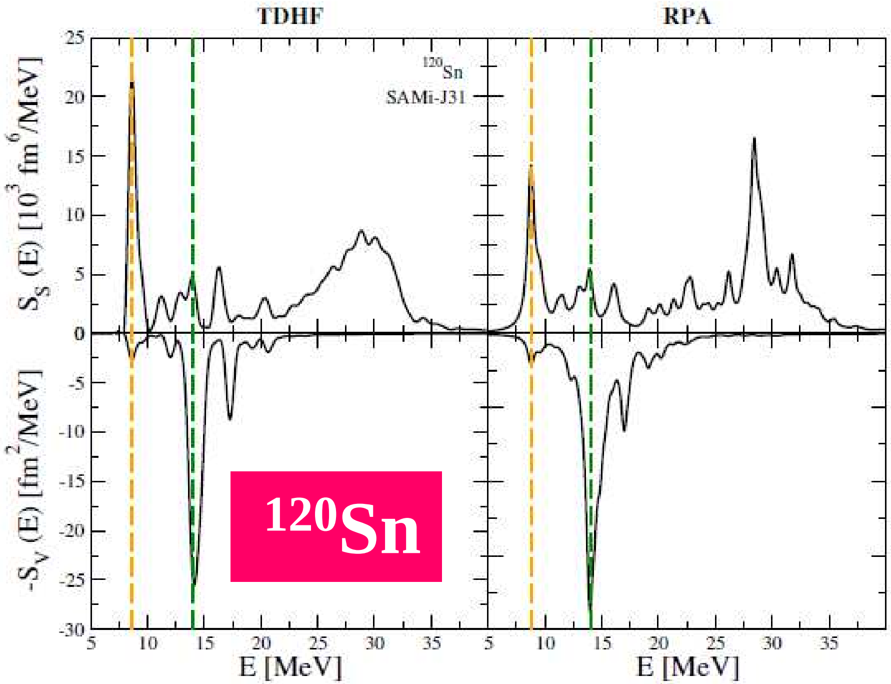
Shell effects ?

➡ Look also at the IS response which is sensitive to surface details





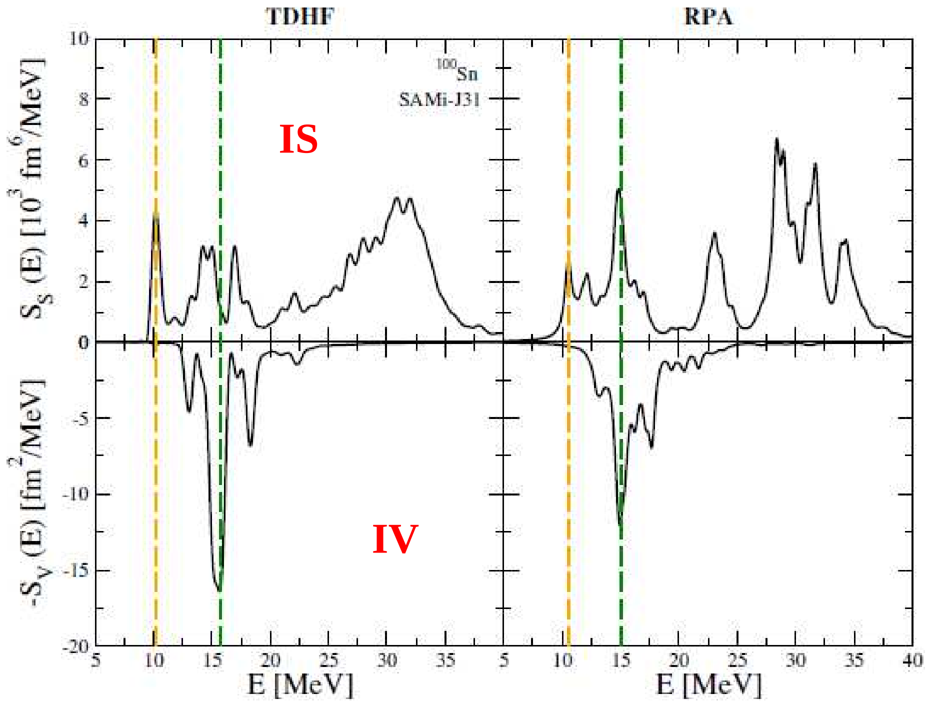


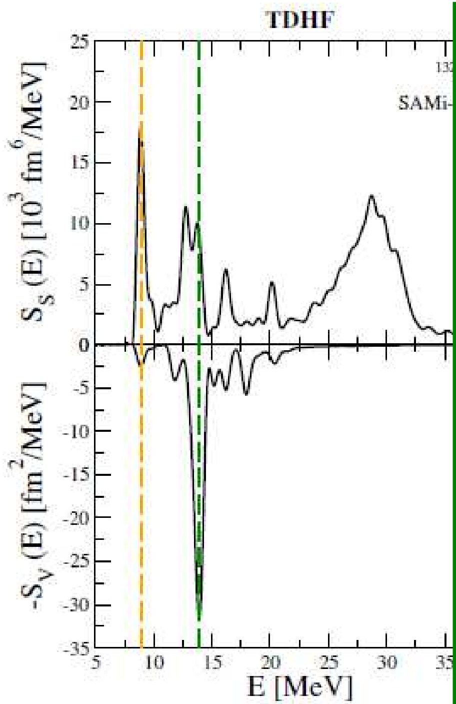


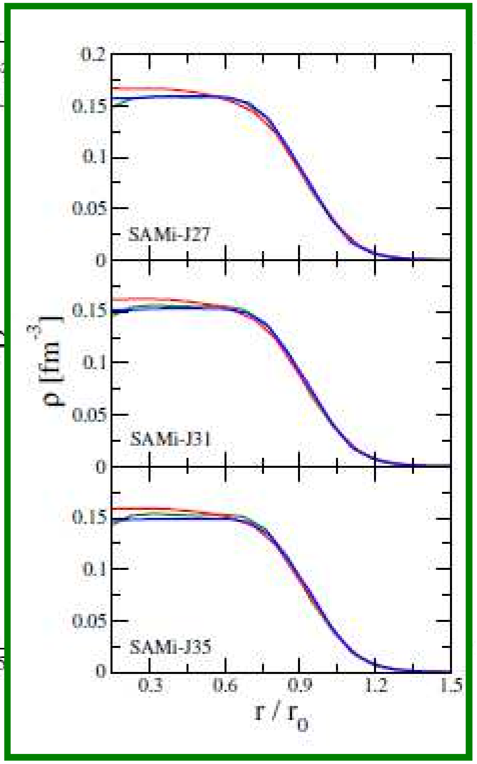
Sn isotopic chain: ^{100}Sn ^{120}Sn ^{132}Sn

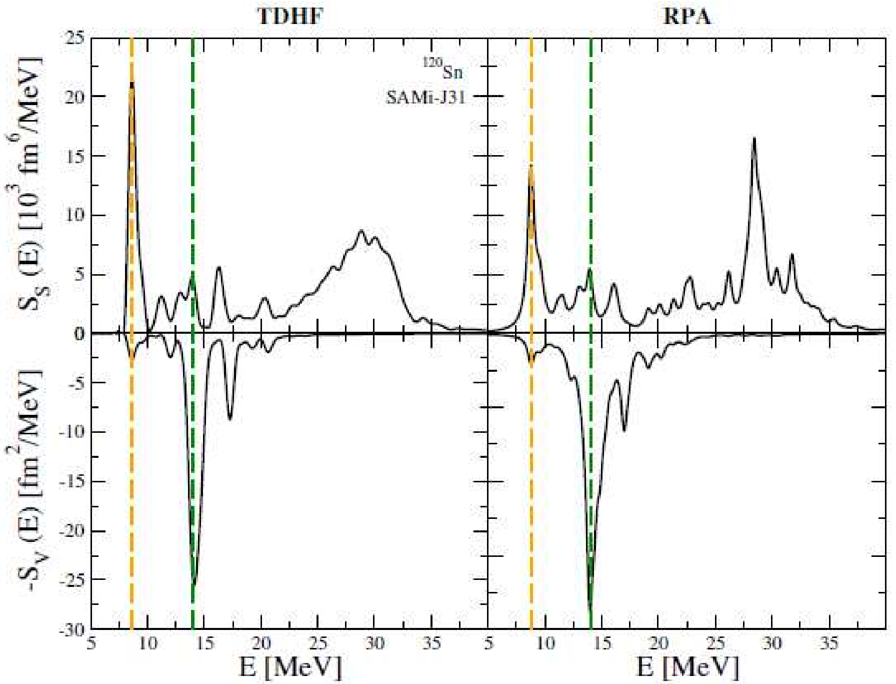
- No PDR in ^{100}Sn
- The low energy IS surface mode is more robust in ^{120}Sn

Skyrme interaction SAMi-J31





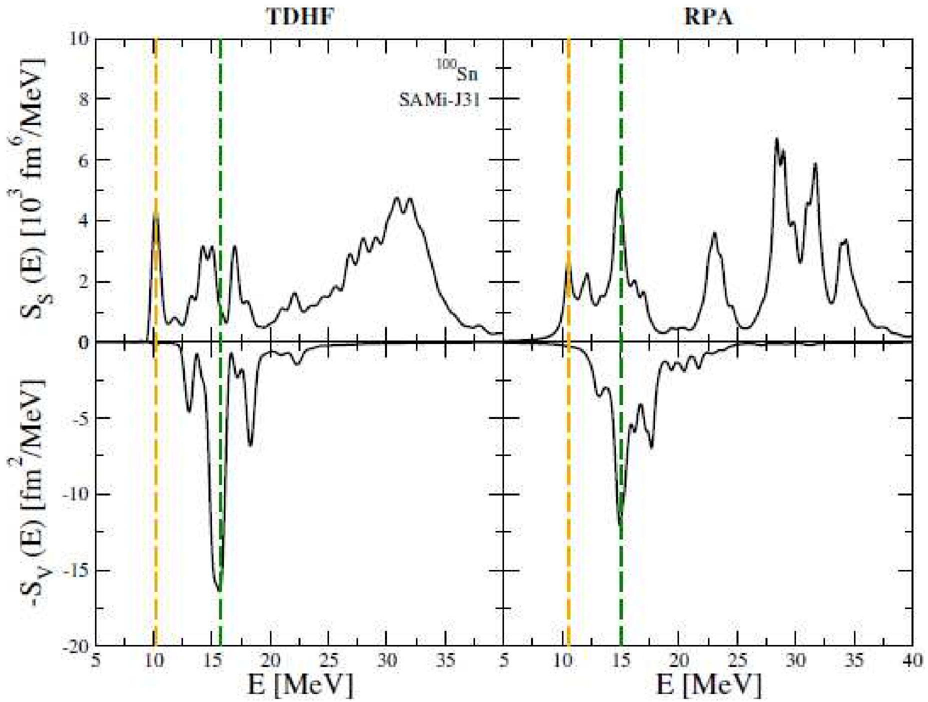


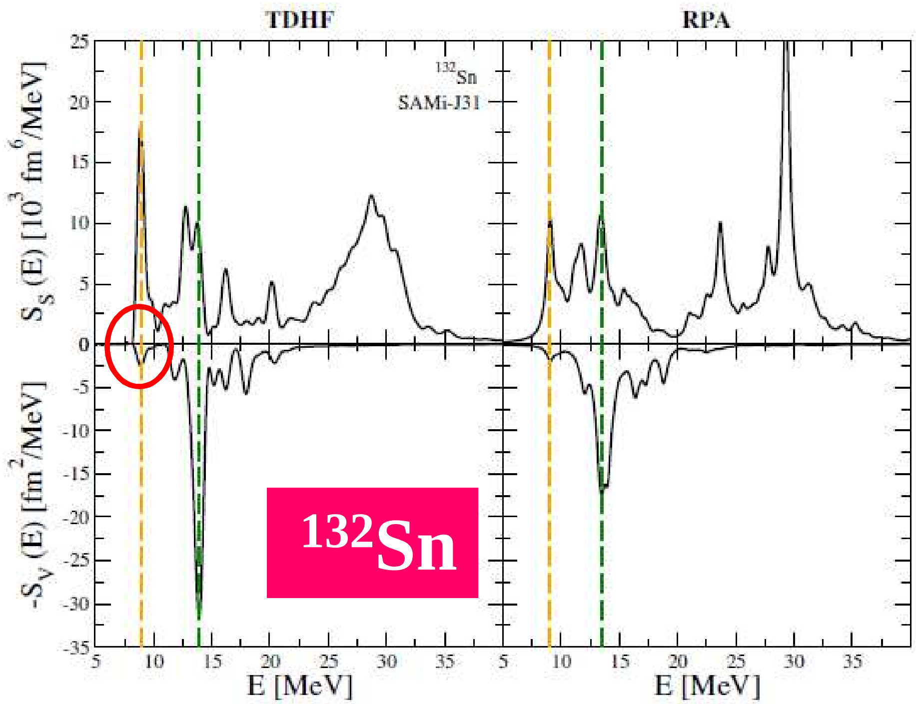


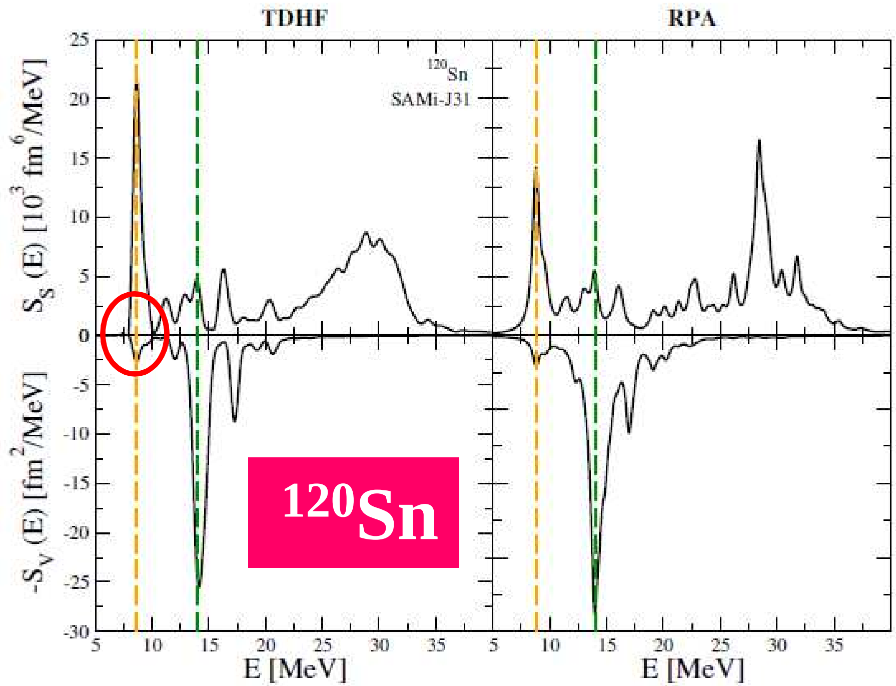
Sn isotopic chain: ^{100}Sn ^{120}Sn ^{132}Sn

- No PDR in ^{100}Sn
- The low energy IS surface mode is more robust in ^{120}Sn (look at density profile)

Skyrme interaction SAMi-J31





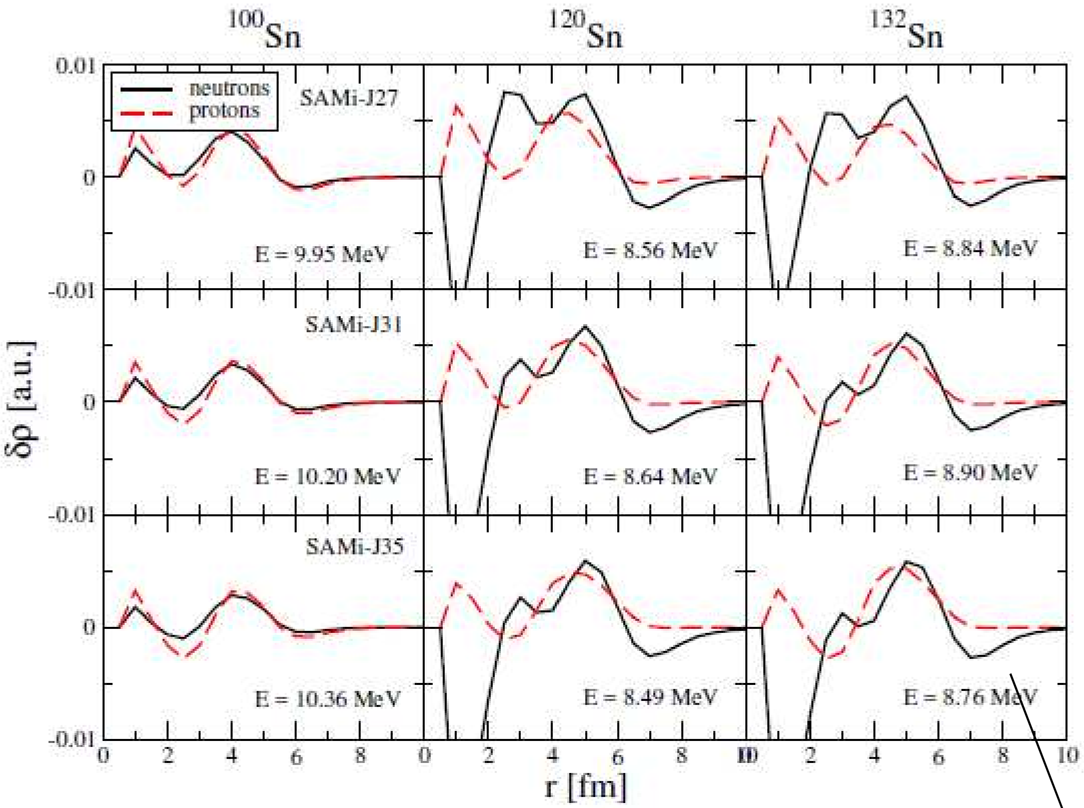


Sn isotopic chain: ^{100}Sn ^{120}Sn ^{132}Sn

- No PDR in ^{100}Sn
- The low energy IS surface mode is more robust in ^{120}Sn

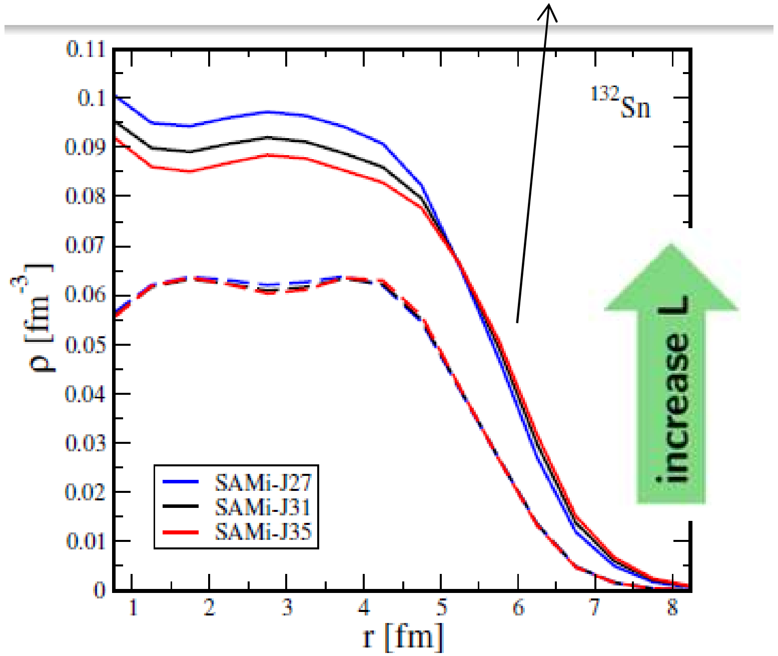
→ The ratio IV/IS strength could be a better indicator

Structure of modes: PDR transition densities



THDF results (from IS excitation)

neutron skin



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

^{132}Sn

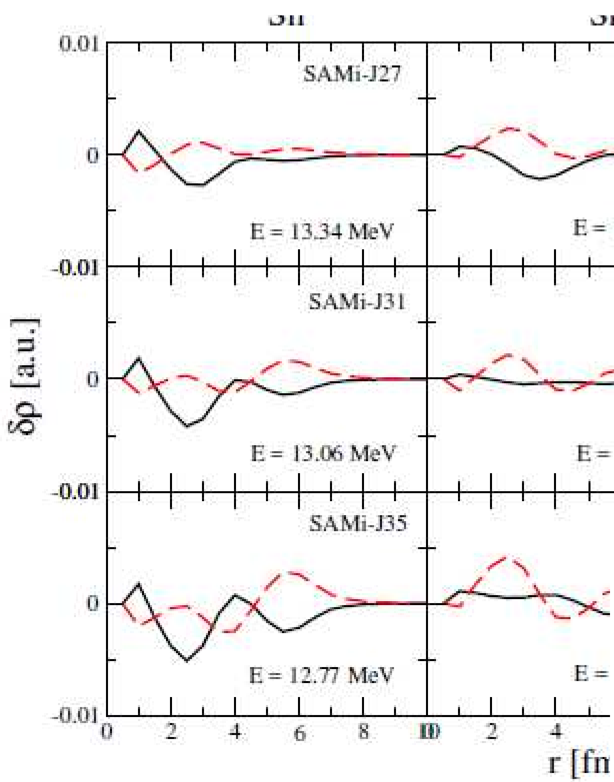
❑ Conclusions

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

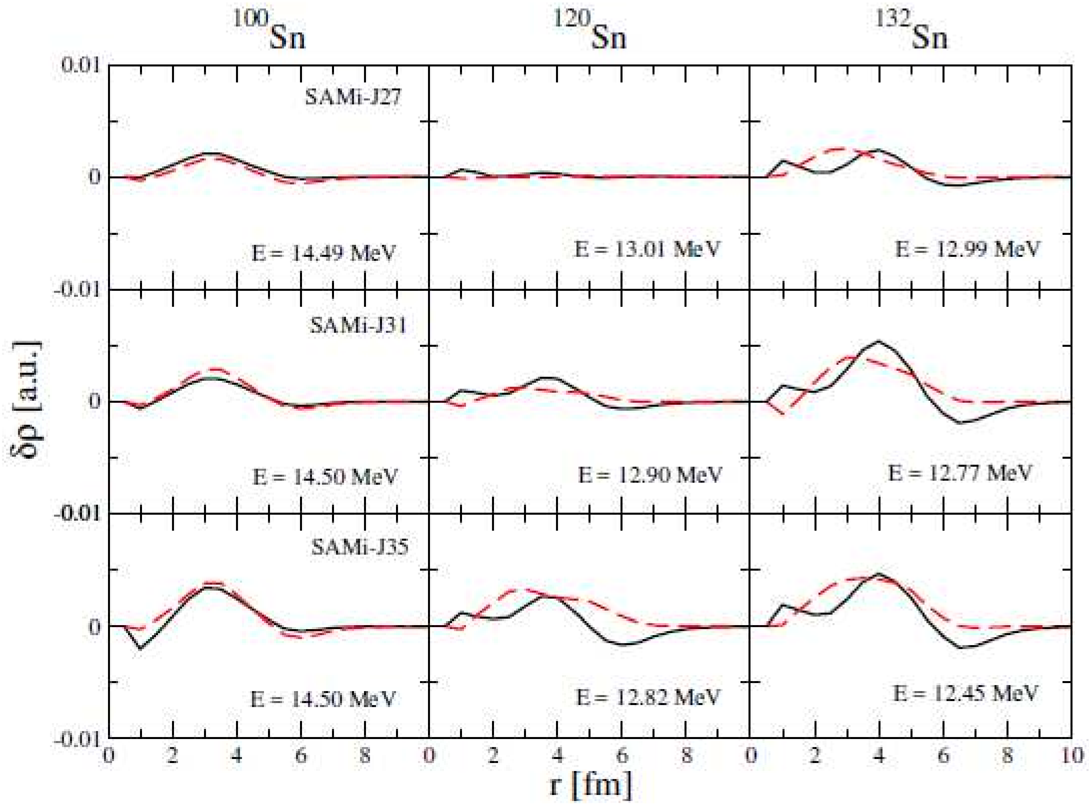
- the dipole response can be understood at a semi-classical level but shell effects may influence the initial density profile (surface modes sensitive to it)

- in neutron-rich systems the IV response cannot be understood without considering also the IS response: isoscalar-isovector coupling --- the PDR is an isoscalar-like mode

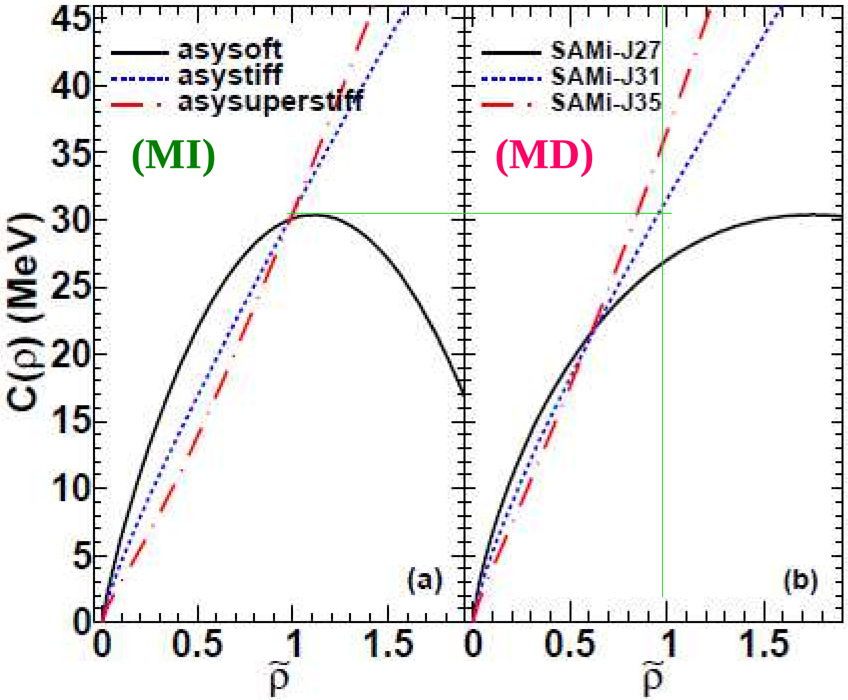
- the PDR strength is related to the neutron skin and to the symmetry energy slope L



TDHF
Second IV and IS peak

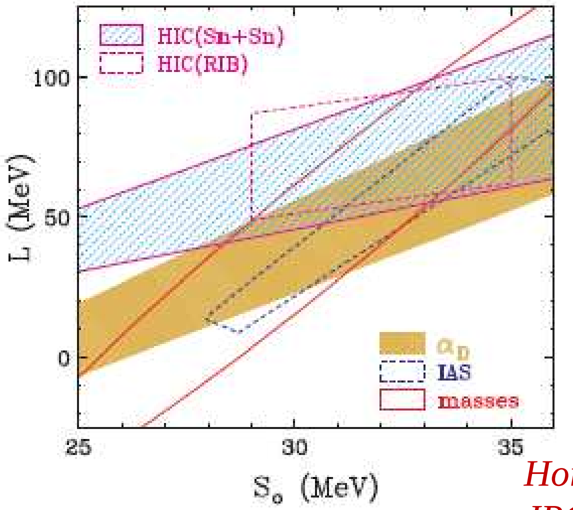


More refined calculations: a bidimensional E_{sym} analysis



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

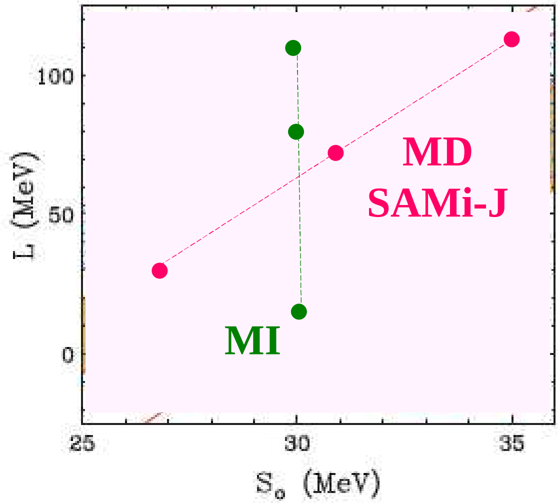
or J *around normal density*



Horowitz et al, JPG 41,093001 (2014)

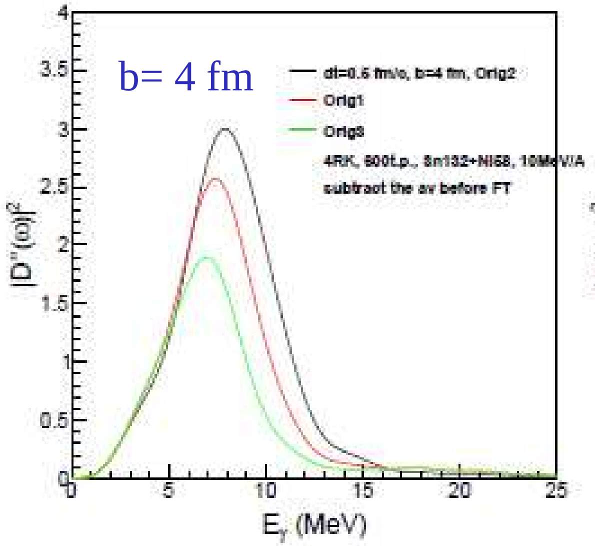
SAMi-J interactions:
Skyrme interactions
especially devised to improve the spin-isospin properties of nuclei

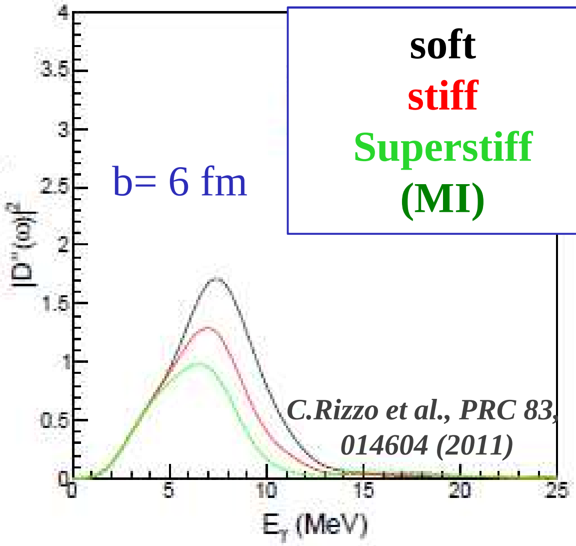
X. Roca-Maza, G. Colò, H. Sagawa, Phys. Rev. C **86**, 031306(R) (2012); X. Roca-Maza *et al.*, Phys. Rev. C **87**, 034301 (2013).



S_0 – L correlation

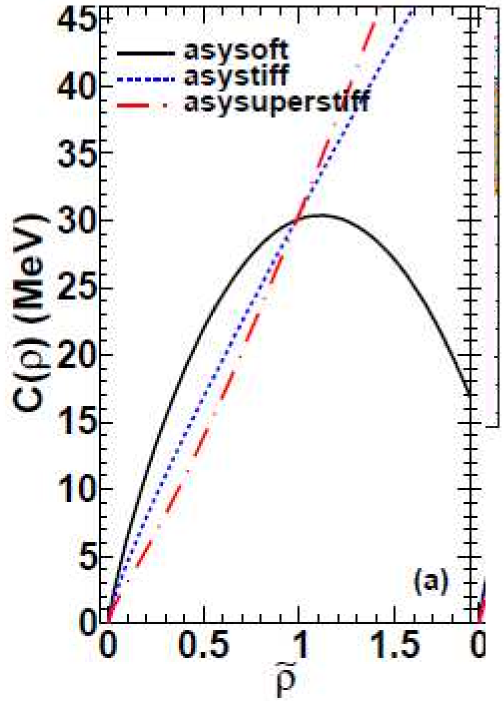
The pre-equilibrium dipole strength ^{132}Sn + ^{58}Ni, 10 MeV/A



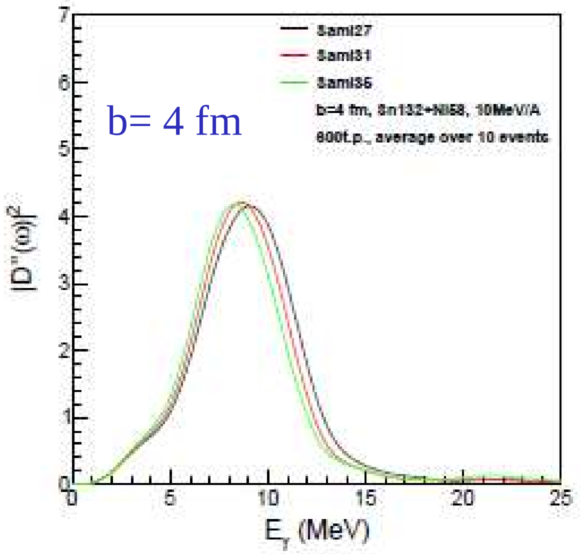


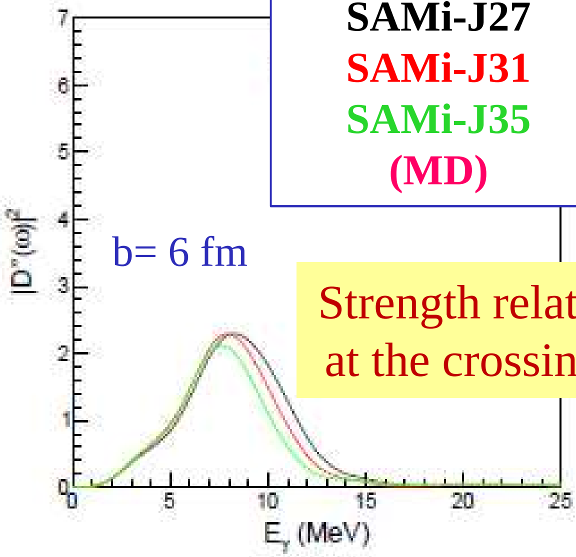
soft
stiff
Superstiff
(MI)

C.Rizzo et al., PRC 83, 014604 (2011)

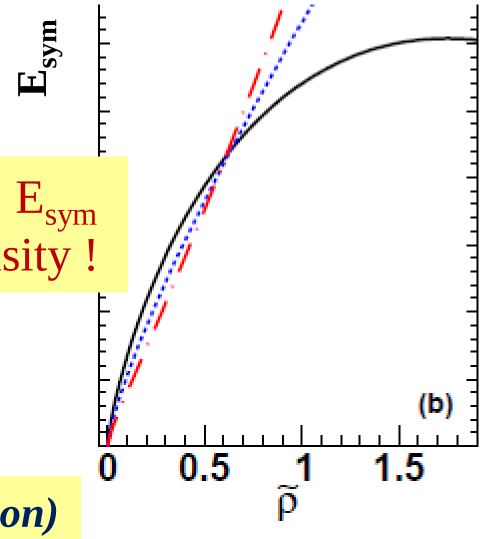


➢ *DD sensitive to E_{sym} below normal density*





SAMi-J27
SAMi-J31
SAMi-J35
(MD)



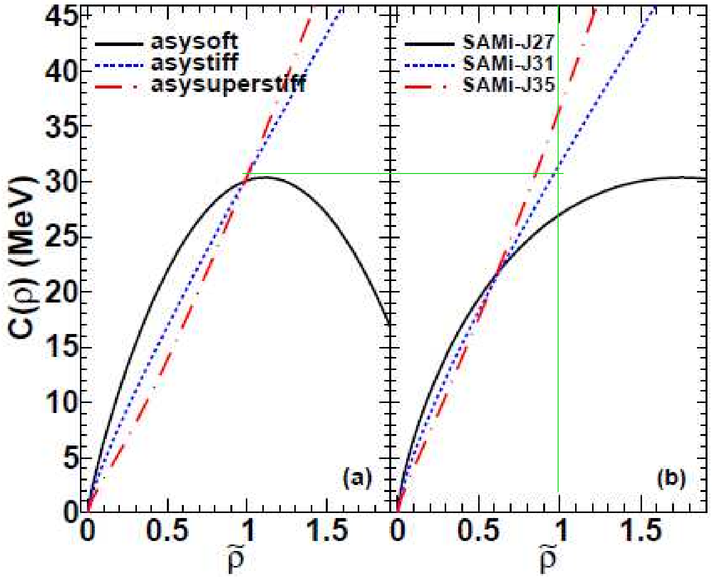
Strength related to E_{sym} at the crossing density !

^{132}Sn + ^{58}Ni , E/A = 10 MeV/u

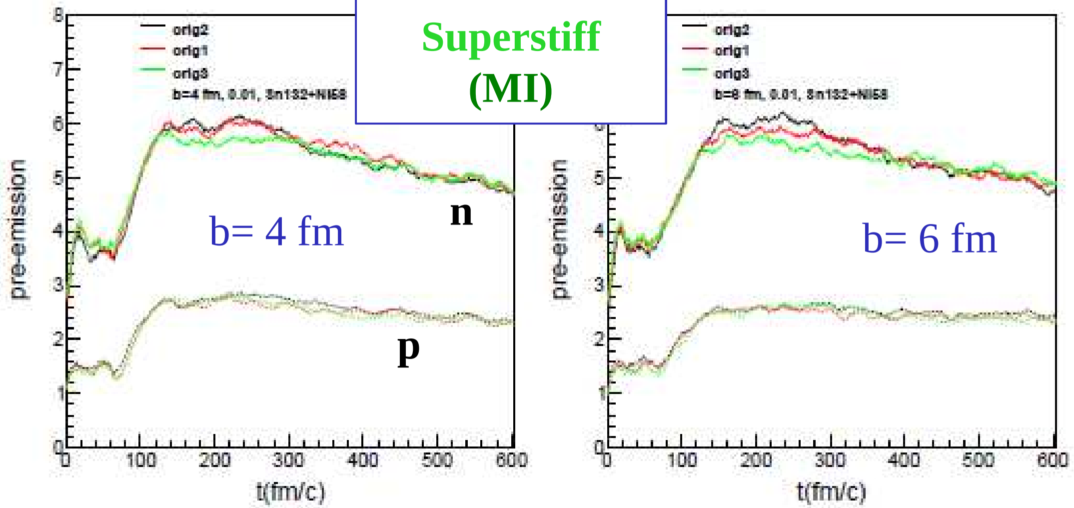
(free n-n cross section)

E_{sym} effects on pre-equilibrium particle emission

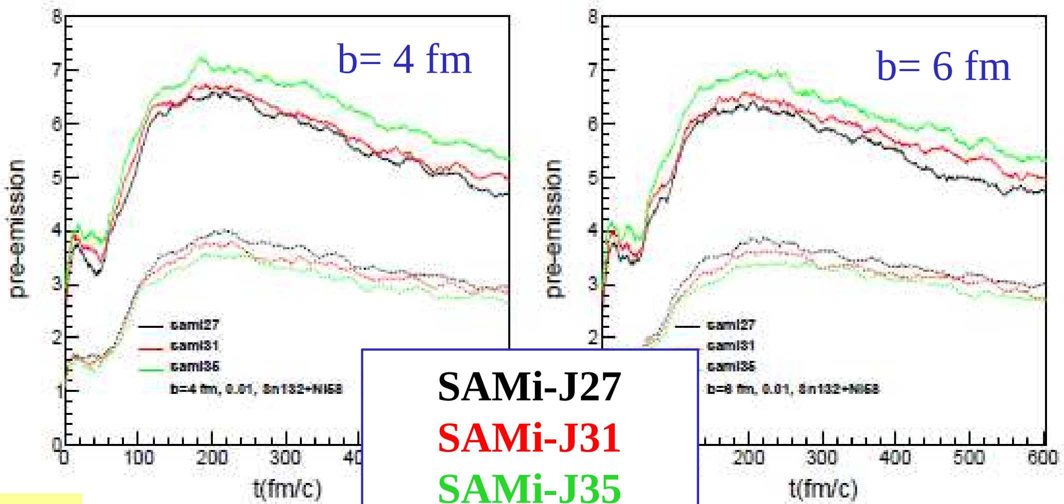
$^{132}Sn + ^{58}Ni$, E/A = 10 MeV/u



soft
stiff
Superstiff
(MI)



Number of nucleons in regions with density $\rho < 0.01\ fm^{-3}$



SAMi-J27
SAMi-J31
SAMi-J35
(MD)

➢ Particle emission looks sensitive to E_{sym} close to normal density:

N/Z = 2.1 SAMi-J35

N/Z = 1.6 SAMi-J27

(at t = 200 fm/c)

600 test particles (t.p.) , free n-n cross section

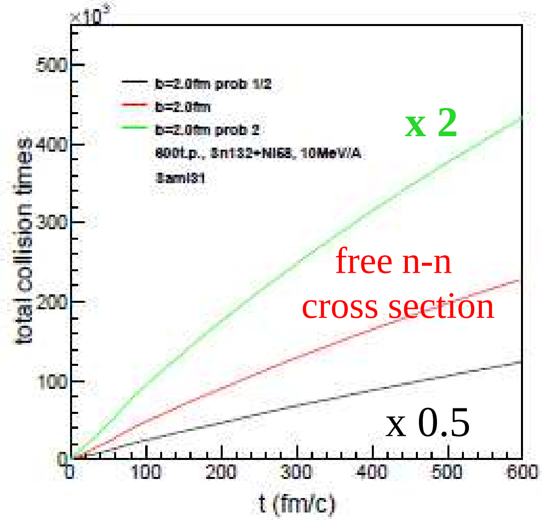
Sensitivity of pre-equilibrium effects to n-n cross sections

$^{132}Sn + {}^{58}Ni$, E/A = 10 MeV/u

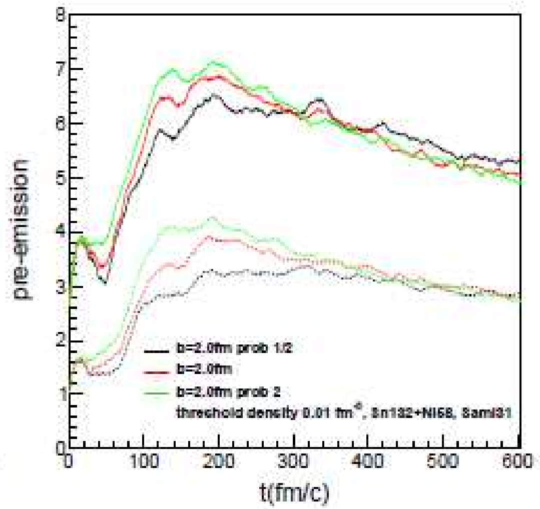
b= 2 fm

SAMi-J31 interaction

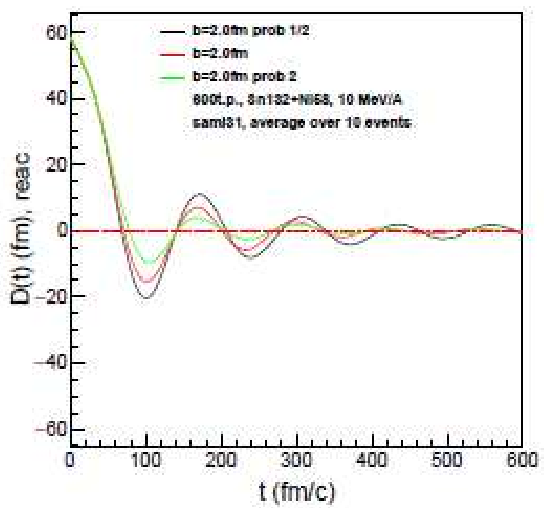
total t.p. collision number



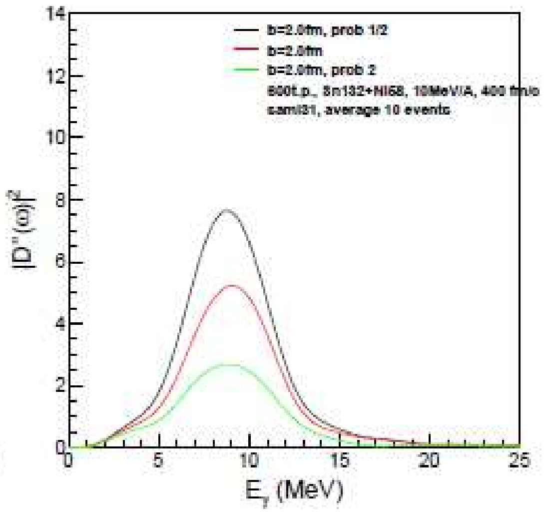
nucleons emitted



- enhanced nucleon emission for larger cross section, but the N/Z is not so sensitive !



dipole oscillations



DD strength

- small n-n cross section
  - ⟶ larger damping time τ
  - ⟶ larger DD strength

see energy-integrated yield

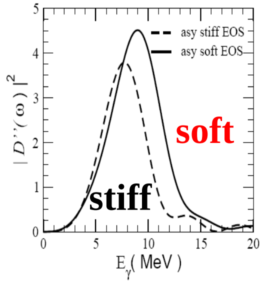
$$P_\gamma \sim \omega_0^3 \tau D(t_0)^2$$

Dynamical dipole (DD) emission and symmetry energy

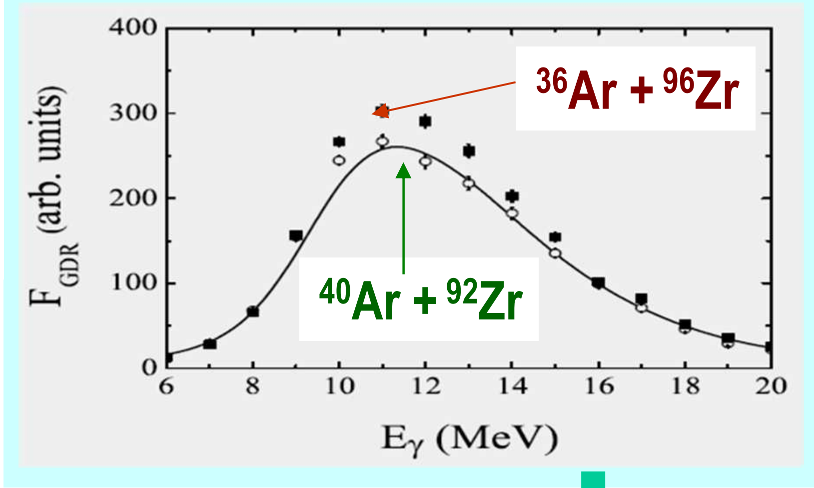
Bremsstrahlung:
Quantitative estimation

V.Baran, D.M.Brink, M.Colonna, M.Di Toro, PRL.87 (2001)

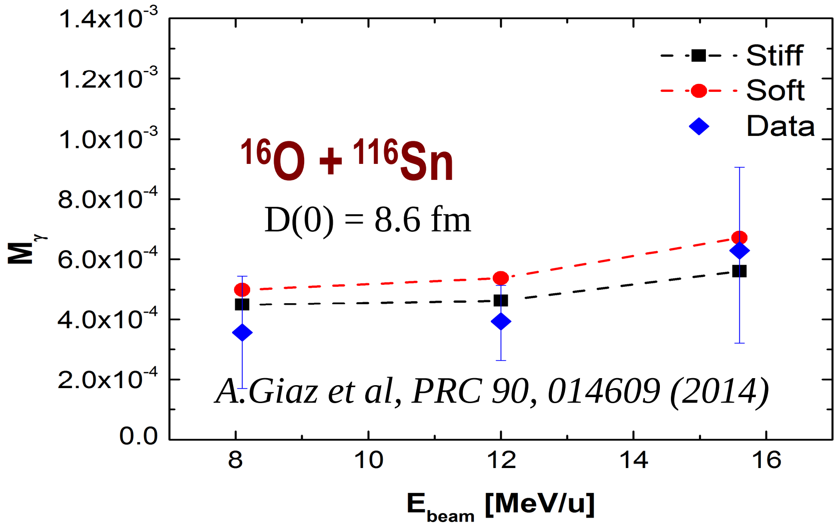
$$\frac{dP}{dE_\gamma} = \frac{2e^2}{3\pi\hbar c^3 E_\gamma}\left(\frac{NZ}{A}\right)^2 \left|X''(\omega)\right|^2$$



B.Martin et al., PLB 664 (2008) 47

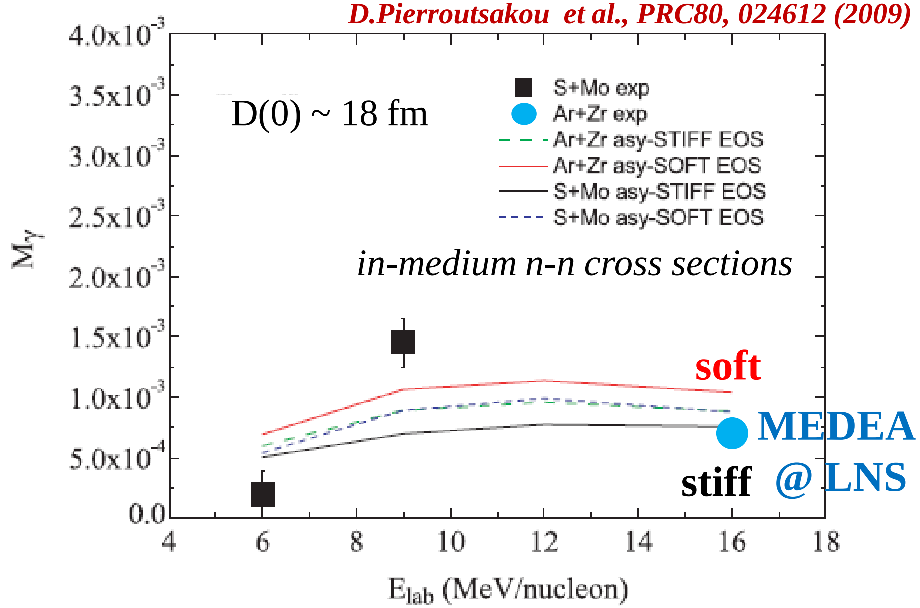


Experimental evidence of the extra-yield (LNL & LNS data)



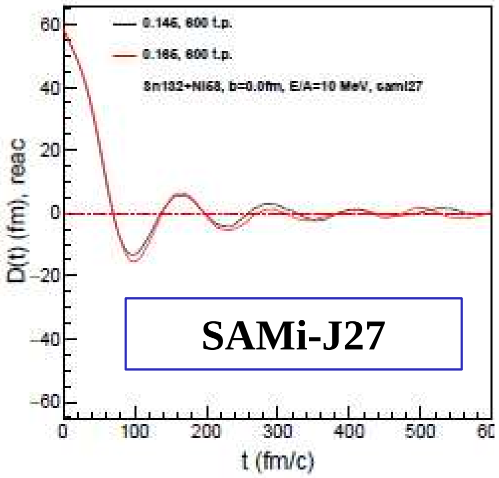
A.Corsi et al., PLB 679, 197 (2009), LNL experiments

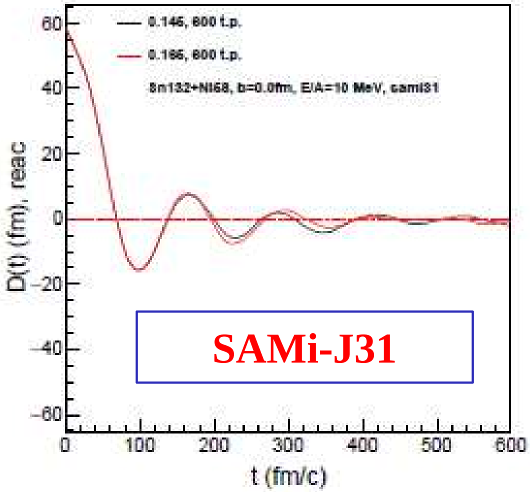
D.Pierroutsakou et al., PRC80, 024612 (2009)

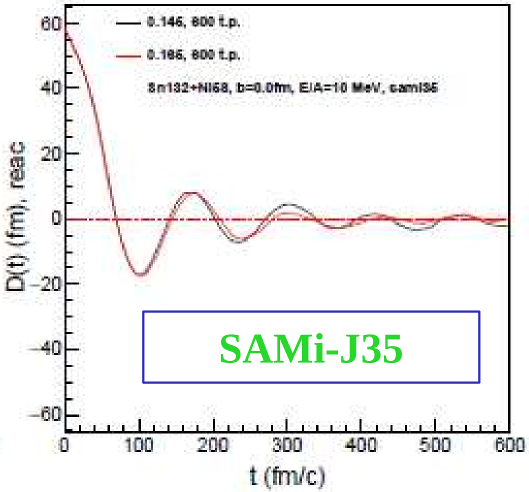


→ DD in the fusion-evaporation of the **40Ca + 152Sm** heavy system, PRC 93, 044619(2016)

Looking at dipole oscillations



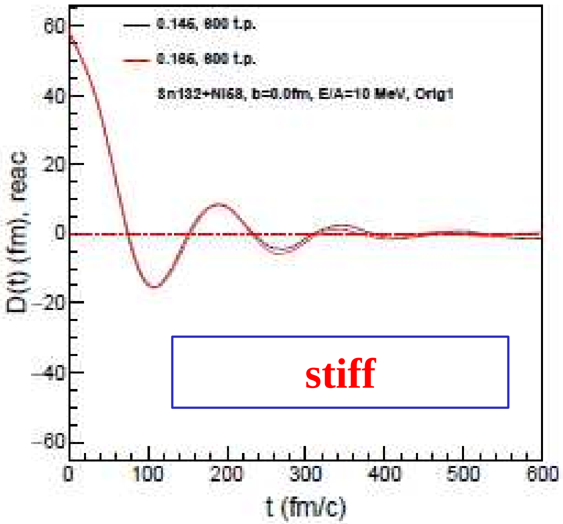




Energy-integrated yield

$$P_\gamma \sim \omega_0^3 \tau D(t_0)^2$$

Is ω_0 just sensitive to E_{sym} ?



➤ Stiff and SAMi-J31: same symmetry energy, but different oscillation frequency: momentum dependence (MD) effects ! (also seen in the GDR case)