Density dependence of the symmetry energy close to normal density from neutron skin thickness and dipole excitations

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Ministry of Science, Education and Sports
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OUTLINE

1. Relativistic mean field theory
2. Relativistic quasiparticle random phase approximation
3. Exotic modes of excitation in nuclei
4. Nuclear symmetry energy and neutron skins derived from pygmy dipole resonance
5. Concluding remarks

1. RELATIVISTIC MEAN FIELD THEORY

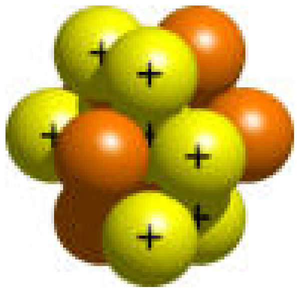
OBJECTIVES:

-quantitative description of nuclear ground state properties
-implementation of an universal effective interaction for all nuclei
-description of exotic nuclear structure away from stability
-nuclear structure for astrophysical applications

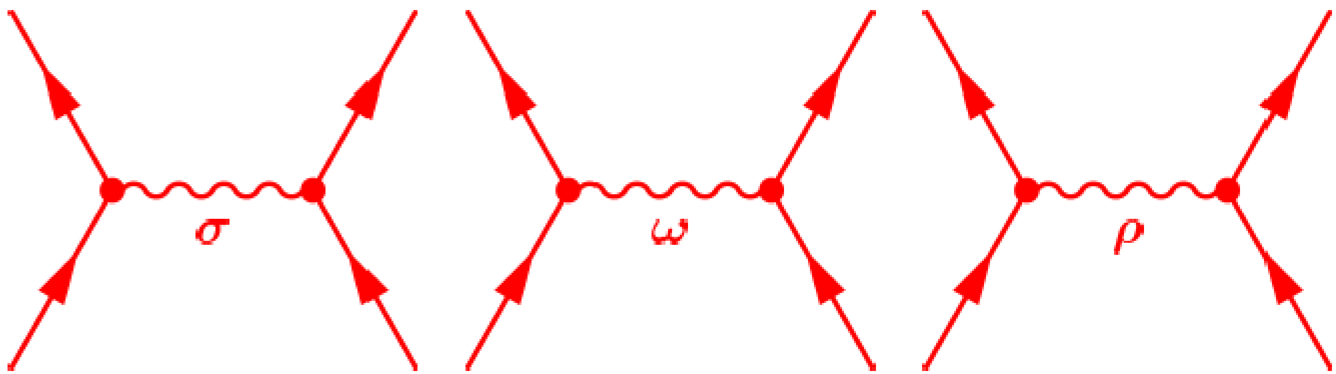
REFERENCES:

- **P. Ring, Prog. Part. Nucl. Phys. 37, 193 (1996).**
- **P.-G. Reinhard, Rep. Prog. Phys. 52, 439 (1989).**
- **D. Vretenar, A. V. Afanasjev, G. A. Lalazissis, and P. Ring, Phys. Rep. 409, 101(2005).**
- **T. Niksic, D. Vretenar, P. Finelli, P. Ring, PRC 66, 024306 (2002)**
- **G. A. Lalazissis, T. Niksic, D. Vretenar and P. Ring, PRC 71, 024312 (2005)**

RELATIVISTIC MEAN FIELD THEORY



system of Dirac nucleons coupled to the exchange mesons and the photon field through an effective Lagrangian.



$(J^{\pi},T)=(0^{+},0)$ $(J^{\pi},T)=(1^{-},0)$ $(J^{\pi},T)=(1^{-},1)$

Sigma-meson: attractive scalar field

Omega-meson: short-range repulsive field

Rho-meson: isovector field

LAGRANGIAN DENSITY

$$\mathcal{L} = \mathcal{L}_N + \mathcal{L}_m + \mathcal{L}_{int}$$

- the Lagrangian of the free nucleon: $\mathcal{L}_N = \bar{\psi}\,(i\gamma^\mu\partial_\mu - m)\,\psi$

- the Lagrangian of the free meson fields and the electromagnetic field:

$$\begin{aligned}\mathcal{L}_m \;=\; & \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu \\ & -\frac{1}{4}\vec{R}_{\mu\nu}\vec{R}^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}_\mu\vec{\rho}^\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}\end{aligned}$$

- minimal set of interaction terms:

$$\mathcal{L}_{int} = -\bar{\psi}\Gamma_\sigma\sigma\psi - \bar{\psi}\Gamma_\omega^\mu\omega_\mu\psi - \bar{\psi}\vec{\Gamma}_\rho^\mu\vec{\rho}_\mu\psi - \bar{\psi}\Gamma_e^\mu A_\mu\psi.$$

with the vertices:

$$\Gamma_\sigma = g_\sigma, \quad \Gamma_\omega^\mu = g_\omega\gamma^\mu, \quad \vec{\Gamma}_\rho^\mu = g_\rho\vec{\tau}\gamma^\mu, \quad \Gamma_e^m = e\frac{1-\tau_3}{2}\gamma^\mu$$

MODELS WITH DENSITY DEPENDENT COUPLINGS

- the meson-nucleon couplings g_σ, g_ω, g_ρ -> functions of vector density:

$$\rho_v = \sqrt{j_\mu j^\mu} \qquad j_\mu = \bar{\psi}\gamma_\mu\psi$$

- Density-dependent meson-nucleon couplings – connection to Dirac-Brueckner calculations based on realistic NN interactions

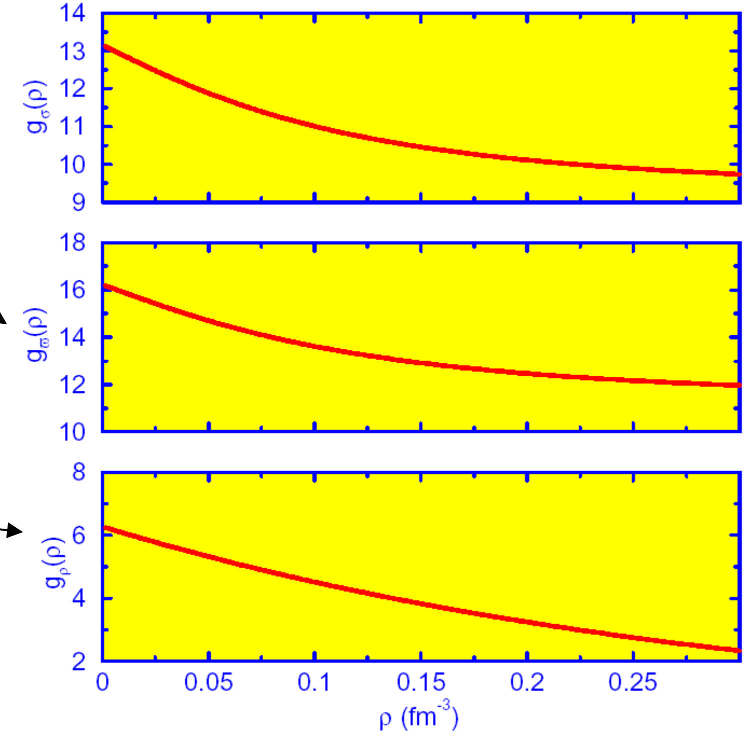
$$g_i(\rho) = g_i(\rho_{\text{sat}}) f_i(x)$$

$$f_i(x) = a_i \frac{1+b_i(x+d_i)^2}{1+c_i(x+d_i)^2}$$

$$i = \sigma, \omega$$

$$g_\rho(\rho) = g_\rho(\rho_{\text{sat}})\ \mathrm{e}^{-a_\rho(x-1)}$$

$$x = \rho/\rho_{\text{sat}}$$



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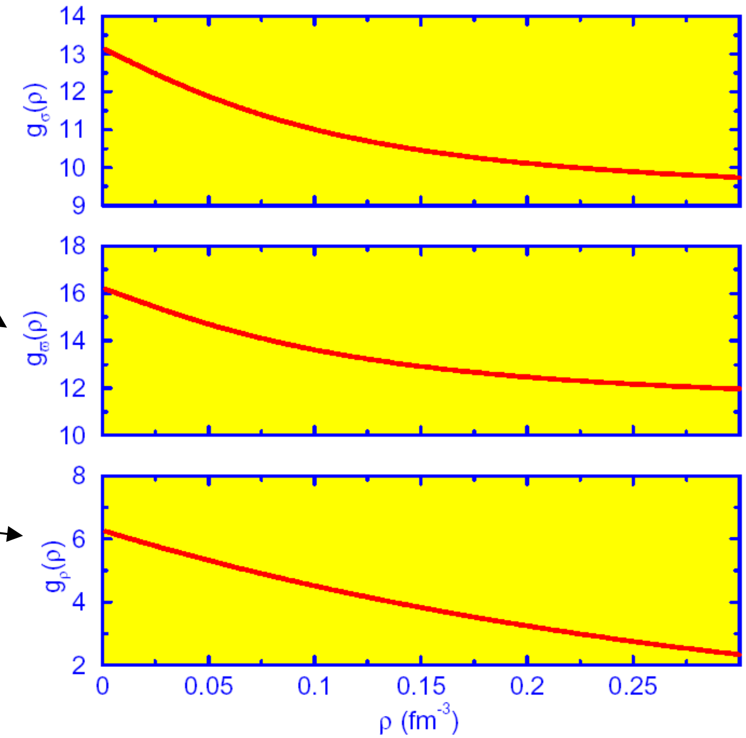


PAIRING CORRELATIONS AND RHB THEORY

Description of ground-state properties of nuclei far from stability:

Unified description of mean-field and pairing correlations

the relativistic Hartree-Bogoliubov (RHB) equations:

$$\begin{pmatrix} \hat{h}_D - m - \lambda & \hat{\Delta} \\ -\hat{\Delta}^* & -\hat{h}_D^* + m + \lambda \end{pmatrix} \begin{pmatrix} U_k(\mathbf{r}) \\ V_k(\mathbf{r}) \end{pmatrix} = E_k \begin{pmatrix} U_k(\mathbf{r}) \\ V_k(\mathbf{r}) \end{pmatrix}$$

Pairing field

Quasiparticle energy

Dirac hamiltonian

nucleon mass

chemical potential

The RHB equations are solved self-consistently, with potentials determined in the mean-field approximation from solutions of static Klein-Gordon equations:

The RMF model parameterisations

- Model parameters: meson masses + parameters of vertex functions

- a mean-field model does not contain explicit correlation effects

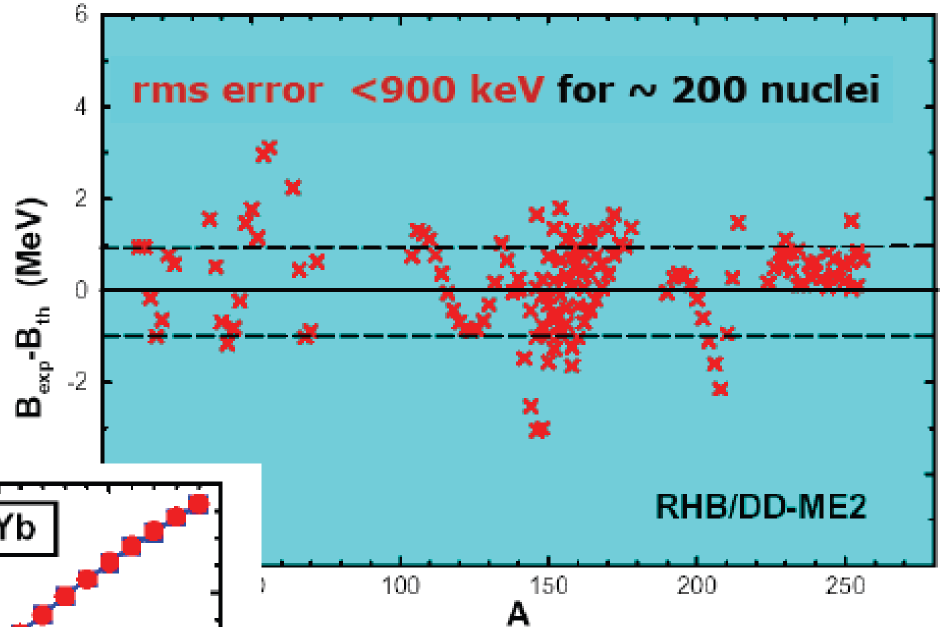
The parameters are determined from properties of nuclear matter (symmetric and asymmetric) and bulk properties of finite nuclei (binding energies, charge radii, neutron skin, surface thickness…)

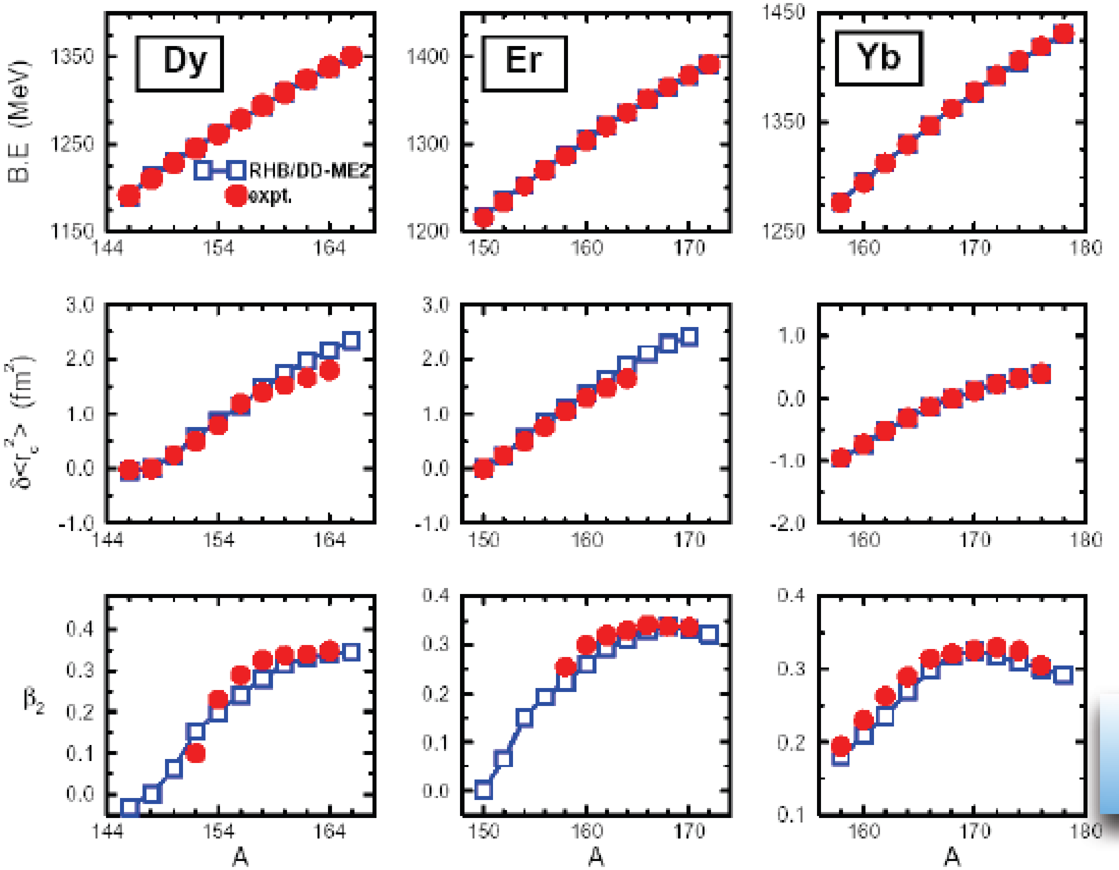
A least-squares adjustment to empirical nuclear matter properties and experimental data on ground-state properties of spherical nuclei, contains only eight (8) parameters in the general expansion of an effective Lagrangian

$$\chi^2 = \sum_i \frac{(O_i^{\mathrm{th}} - O_i^{\mathrm{expt}})^2}{(\Delta O_i)^2}$$

⇒ DD-ME1
DD-ME2

Absolute deviations of the calculated binding energies from experimental values:



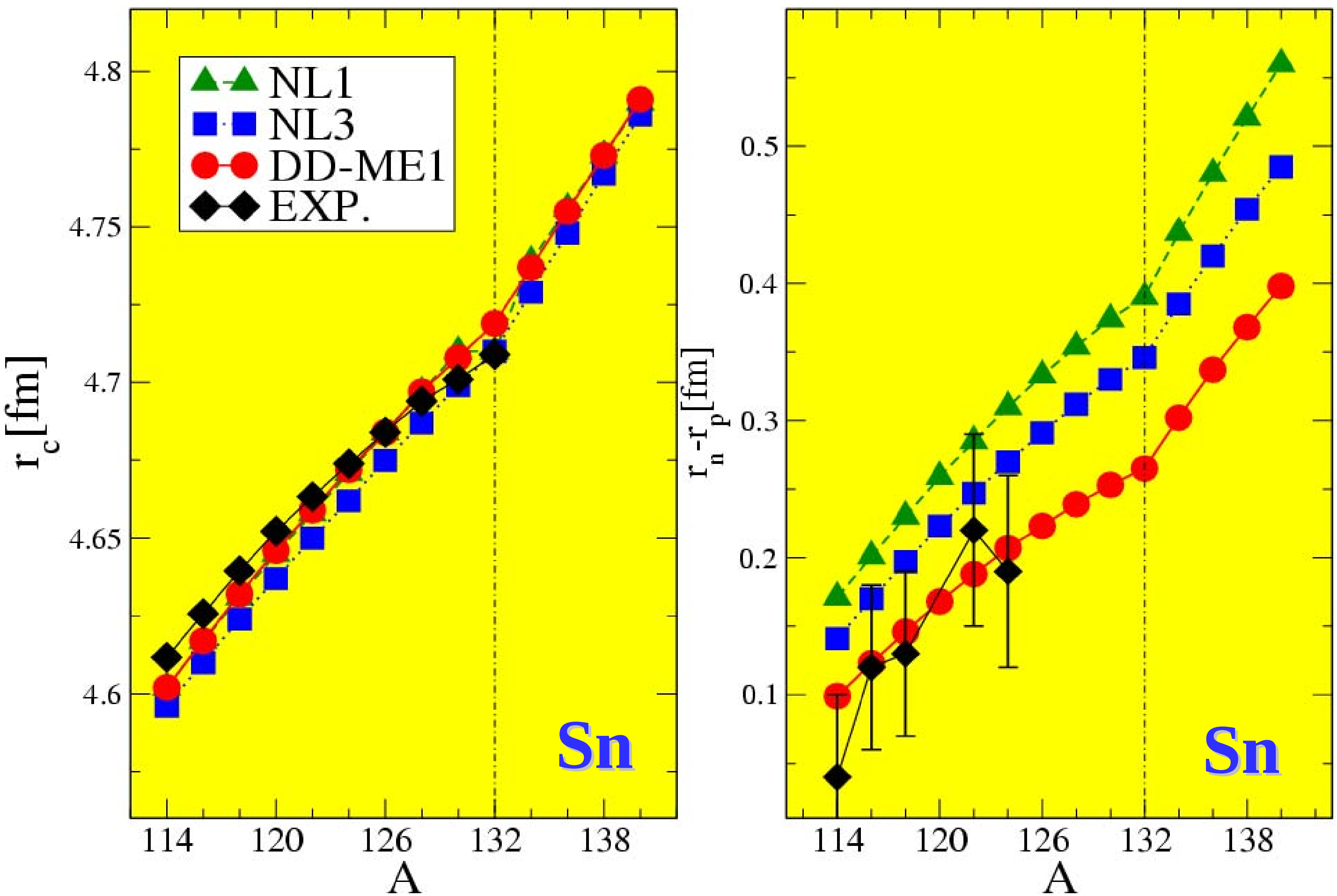


Binding energies, charge isotope shifts and quadrupole deformations of isotopic chains in the rare-earth region.

Lalazissis, Nikšić, Vretenar, Ring
Phys. Rev. C **71**, 024312 (2005)

RELATIVISTIC HARTREE-BOGOLIUBOV MODEL (RHB)

RMS CHARGE RADII | **DIFFERENCES $r_n - r_p$**



DEVELOPMENT OF THE NEUTRON SKIN

NUCLEAR MATTER PROPERTIES

Symmetric nuclear matter

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are needed to see this picture.

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decompressor
are needed to see this picture.

Neutron matter

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2. RELATIVISTIC QUASIPARTICLE RANDOM PHASE APPROXIMATION

OBJECTIVES:

-fully self-consistent description of low-amplitude collective motion in nuclei
-giant resonances, charge-exchange modes
-toward new modes of excitation in exotic nuclei
-applications in astrophysicaly relevant weak interaction rates

REFERENCES:

- **N. Paar, P. Ring, T. Nikšić, and D. Vretenar, Phys. Rev. C 67, 034312 (2003).**
- **N. Paar, T. Nikšić, D. Vretenar, and P. Ring, Phys. Rev. C 69, 054303 (2004).**
- **N. Paar, D. Vretenar, E. Khan, G. Colò, Rep. Prog. Phys. 70, 691 (2007).**

RELATIVISTIC RANDOM PHASE APPROXIMATION

small amplitude limit of the time-dependent RMF model → **The Relativistic Random Phase Approximation**

The RRPA equations are derived from the response of the density matrix to an external field:

$$\hat{f}(t) = \hat{f}e^{-i\omega t} + h.c.$$

The equation of motion for the density operator reads:

$$i\partial_t \hat{\rho} = \left[\hat{h}(\hat{\rho}) + \hat{f}(t), \hat{\rho}\right]$$

In the small amplitude limit the density matrix is expanded to linear order:

$$\hat{\rho}(t) = \hat{\rho}^{(0)} + \delta\hat{\rho}(t)$$

RELATIVISTIC RANDOM PHASE APPROXIMATION

RRPA matrix equations

$$\begin{pmatrix} A & B \\ -B^* & -A^* \end{pmatrix} \begin{pmatrix} X \\ Y \end{pmatrix} = \hbar\omega \begin{pmatrix} X \\ Y \end{pmatrix}$$

X: $\delta\rho_{ph}$, $\delta\rho_{\alpha h}$

Y: $\delta\rho_{hp}$, $\delta\rho_{h\alpha}$

RRPA matrices

$$A = \begin{pmatrix} (\epsilon_p - \epsilon_h)\delta_{pp'}\delta_{hh'} & \\ & (\epsilon_\alpha - \epsilon_h)\delta_{\alpha\alpha'}\delta_{hh'} \end{pmatrix} + \begin{pmatrix} V_{ph'hp'} & V_{ph'h\alpha'} \\ V_{\alpha h'hp'} & V_{\alpha h'h\alpha'} \end{pmatrix}$$

$$B = \begin{pmatrix} V_{pp'hh'} & V_{p\alpha'hh'} \\ V_{\alpha p'hh'} & V_{\alpha\alpha'hh'} \end{pmatrix}$$

the RRPA amplitudes: $X = \begin{pmatrix} \delta\rho_{ph} \\ \delta\rho_{\alpha h} \end{pmatrix}, \quad Y = \begin{pmatrix} \delta\rho_{hp} \\ \delta\rho_{h\alpha} \end{pmatrix}$

RELATIVISTIC QUASI-PARTICLE RANDOM-PHASE APPROXIMATION

$$i\partial_t \mathcal{R} = [\mathcal{H}(\mathcal{R}), \mathcal{R}] \quad \leftarrow \quad \mathcal{R} = \mathcal{R}_0 + \delta\mathcal{R}(t)$$

Quasiparticle canonical states

$$\begin{pmatrix} A^J & B^J \\ B^{*J} & A^{*J} \end{pmatrix} \begin{pmatrix} X^{\nu,JM} \\ Y^{\nu,JM} \end{pmatrix} = E^{\nu}_{QRPA} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} X^{\nu,JM} \\ Y^{\nu,JM} \end{pmatrix}$$

both ph and αh pairs included

$$A^J_{\kappa\kappa'\lambda\lambda'} = H^{11(J)}_{\kappa\lambda}\delta_{\kappa'\lambda'} - H^{11(J)}_{\kappa'\lambda}\delta_{\kappa\lambda'} - H^{11(J)}_{\kappa\lambda'}\delta_{\kappa'\lambda} + H^{11(J)}_{\kappa'\lambda'}\delta_{\kappa\lambda} + \frac{1}{2}(\xi^+_{\kappa\kappa'}\xi^+_{\lambda\lambda'} + \xi^-_{\kappa\kappa'}\xi^-_{\lambda\lambda'})V^{ppJ}_{\kappa\kappa'\lambda\lambda'} + \zeta_{\kappa\kappa'\lambda\lambda'}V^{phJ}_{\kappa\lambda'\kappa'\lambda}$$

$$B^J_{\kappa\kappa'\lambda\lambda'} = \frac{1}{2}(\xi^+_{\kappa\kappa'}\xi^+_{\lambda\lambda'} - \xi^-_{\kappa\kappa'}\xi^-_{\lambda\lambda'})V^{ppJ}_{\kappa\kappa'\lambda\lambda'} + \zeta_{\kappa\kappa'\lambda\lambda'}(-1)^{j_\lambda - j_{\lambda'} + J}V^{phJ}_{\kappa\lambda\kappa'\lambda'}$$

PARTICLE-PARTICLE INTERACTION (Gogny)

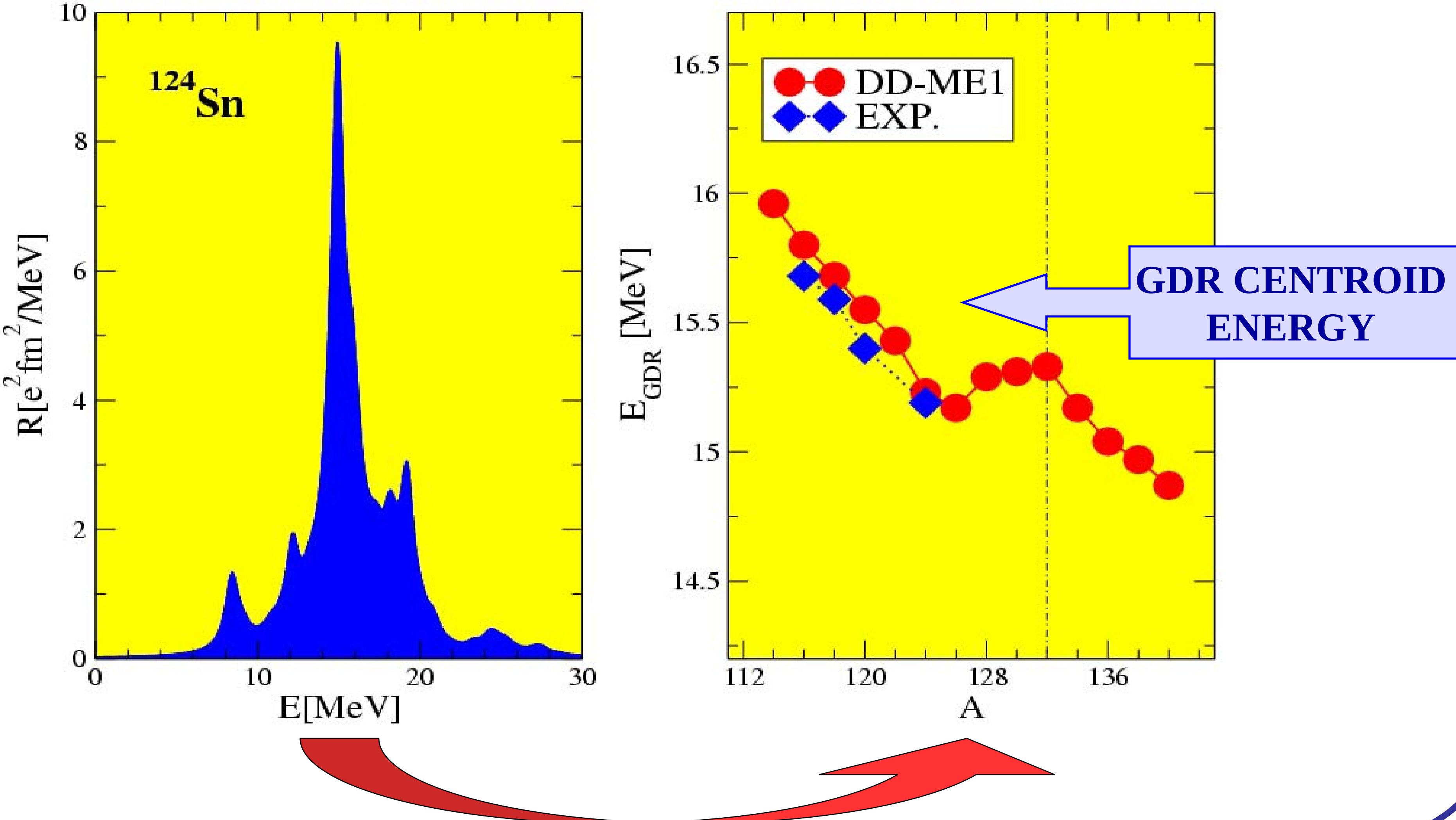
PARTICLE-HOLE INTERACTION (DD-ME1,...)

Factors including the occupation probabilities for the canonical states

<u>SELF-CONSISTENCY:</u> ***The same effective interaction determines the ground state and the QRPA residual interaction***

ISOVECTOR GIANT DIPOLE RESONANCE (GDR)

Collective mode: protons coherently oscillate against neutrons



ISOSCALAR GIANT MONOPOLE RESONANCE

The breathing mode in finite nuclei provides constrain on the asymmetry term in nuclear incompressibility (from (α, α') inelastic scattering)

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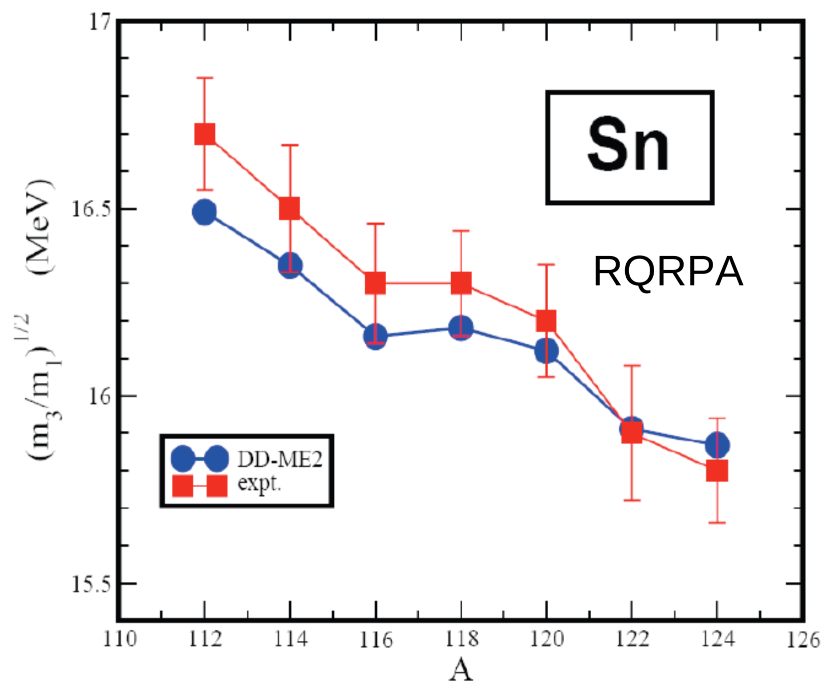


T. Li, U. Garg, Y. Liu, R. Marks, et al., Phys. Rev. Lett. 99, 162503 (2007)

3. EXOTIC MODES OF EXCITATION

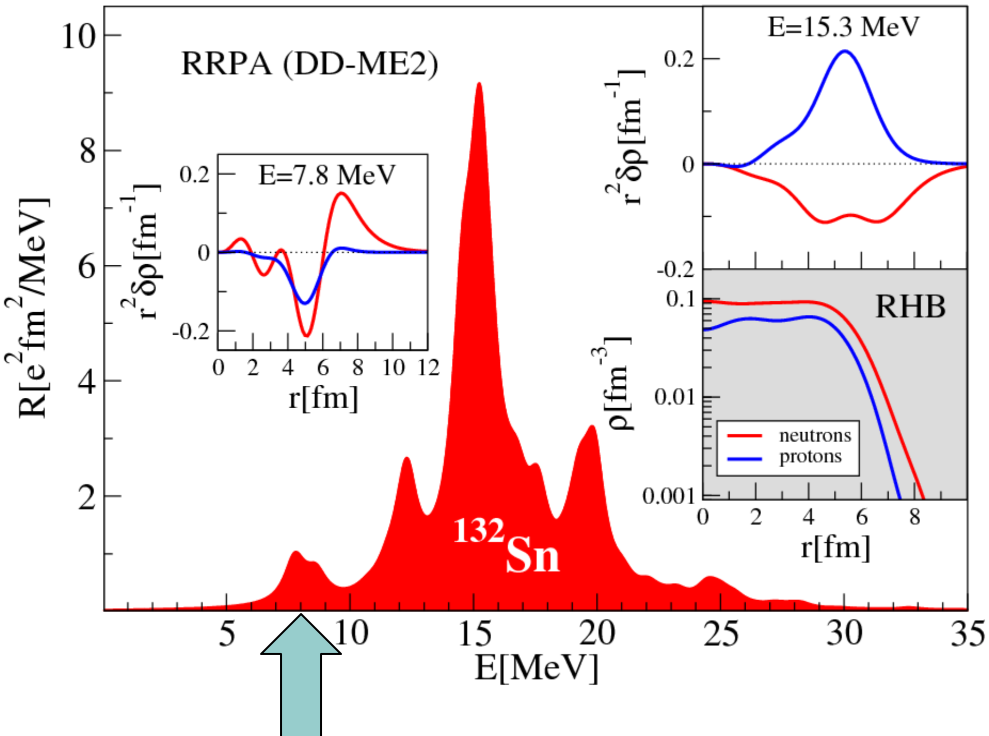
- pygmy dipole resonances (PDR)
- isovector-isoscalar structure of PDR and (α,α'γ) and (γ,γ') experiments
- excitations in proton drip-line nuclei
- exotic modes of excitation at finite temperature

-nuclear symmetry energy and neutron skins derived from PDR

REFERENCES:

- N. Paar, D. Vretenar, E. Khan, and G. Colo, Rep. Prog. Phys. 70, 691 (2007)
- N. Paar, D. Vretenar, and P. Ring, Phys. Rev. Lett. 94, 182501 (2005)
- N. Paar, Y. F. Niu, D. Vretenar, and J. Meng, Phys. Rev. Lett. 103, 032502 (2009)
- Y. F. Niu, N. Paar, D. Vretenar, and J. Meng, Phys. Lett. B, in press (2009)

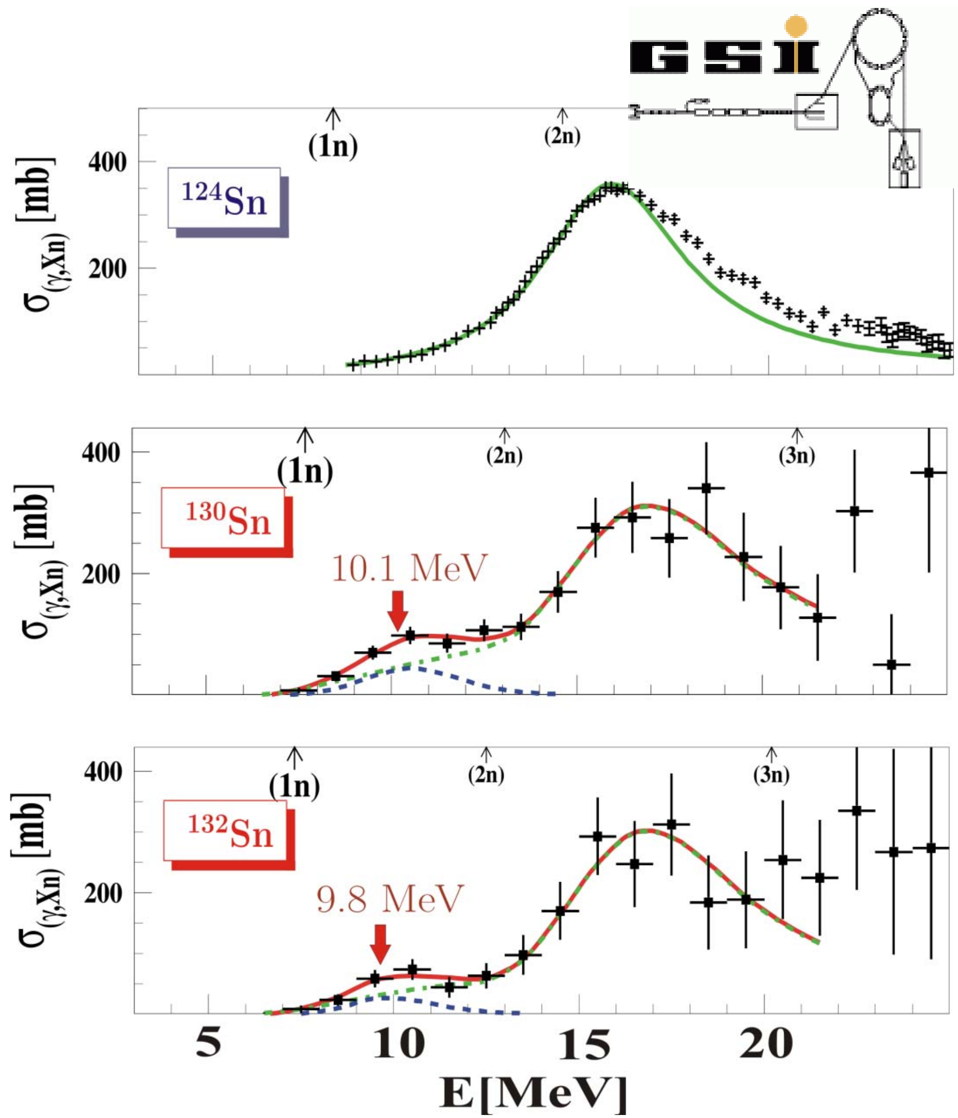
PYGMY DIPOLE RESONANCES (PDR)



^{132}Sn at 7.6 MeV

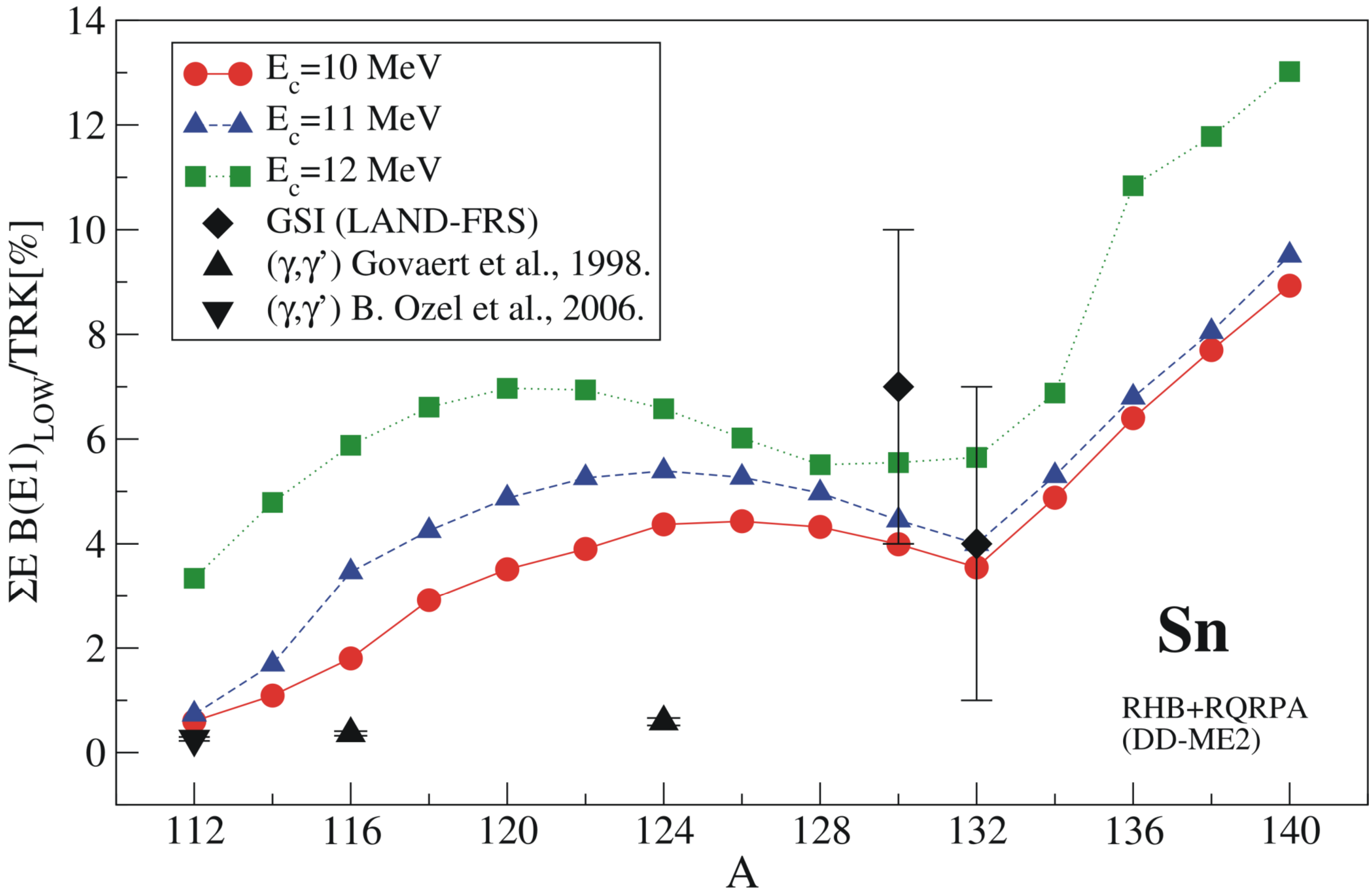
- 28.2% $2d_{3/2} \rightarrow 2f_{5/2}$
- 21.9% $2d_{5/2} \rightarrow 2f_{7/2}$
- 19.7% $2d_{3/2} \rightarrow 3p_{1/2}$
- 10.5% $1h_{11/2} \rightarrow 1i_{13/2}$
- 3.5% $2d_{5/2} \rightarrow 3p_{3/2}$
- 1.9% $1g_{7/2} \rightarrow 2f_{5/2}$
- 1.5% $1g_{7/2} \rightarrow 1h_{9/2}$
- 0.6% $1g_{7/2} \rightarrow 2f_{7/2}$
- 0.6% $2d_{3/2} \rightarrow 3p_{3/2}$

Distribution of the neutron particle-hole configurations for the peak at 7.6 MeV



P.Adrich et al., Phys. Rev. Lett. 95, 132501(2005)

ISOTOPIC DEPENDENCE OF THE PYGMY DIPOLE RESONANCE (PDR)



Paar, Vretenar, Khan, Colò, Rep. Prog. Phys. 70, 691 (2007).

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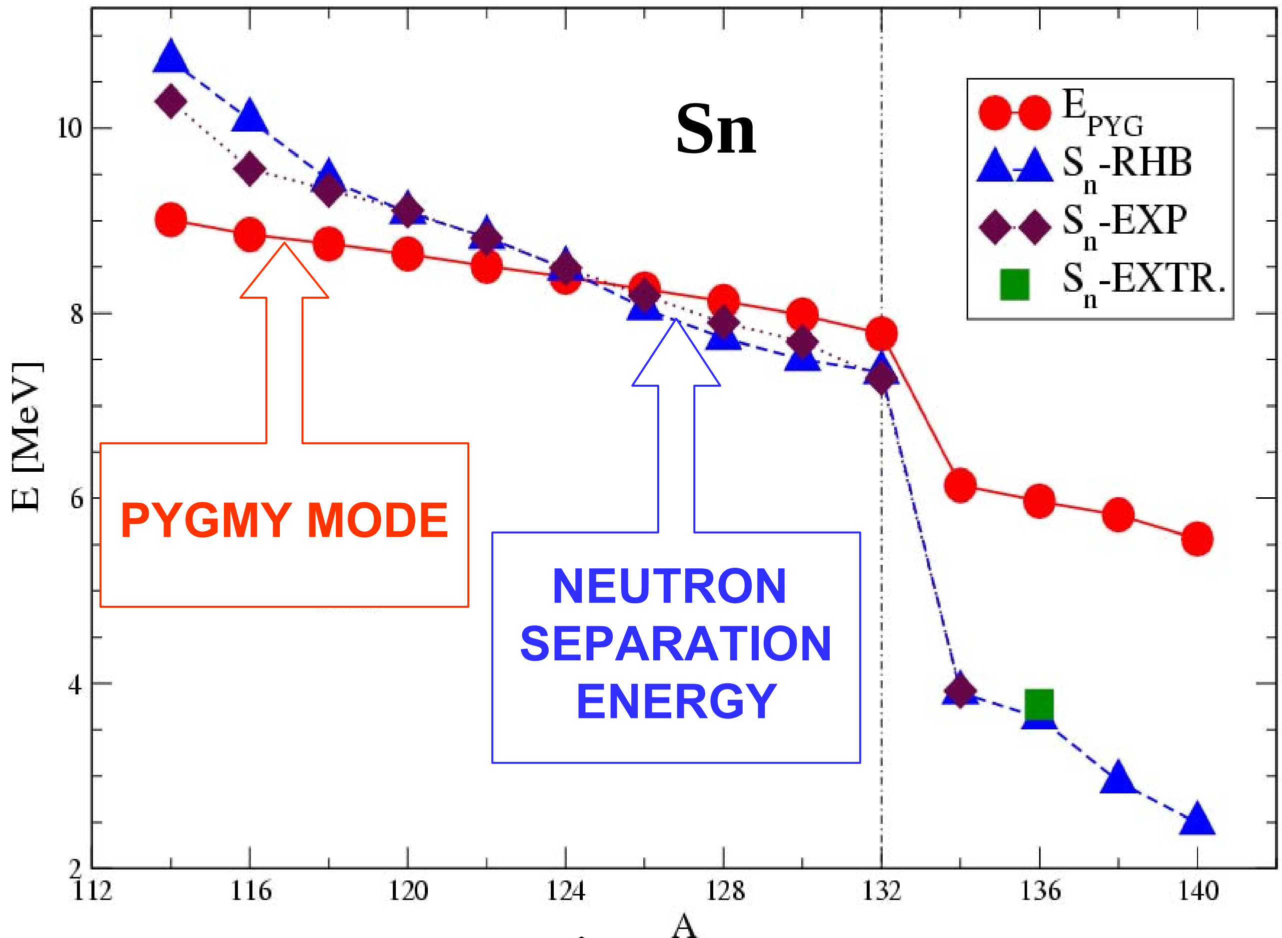
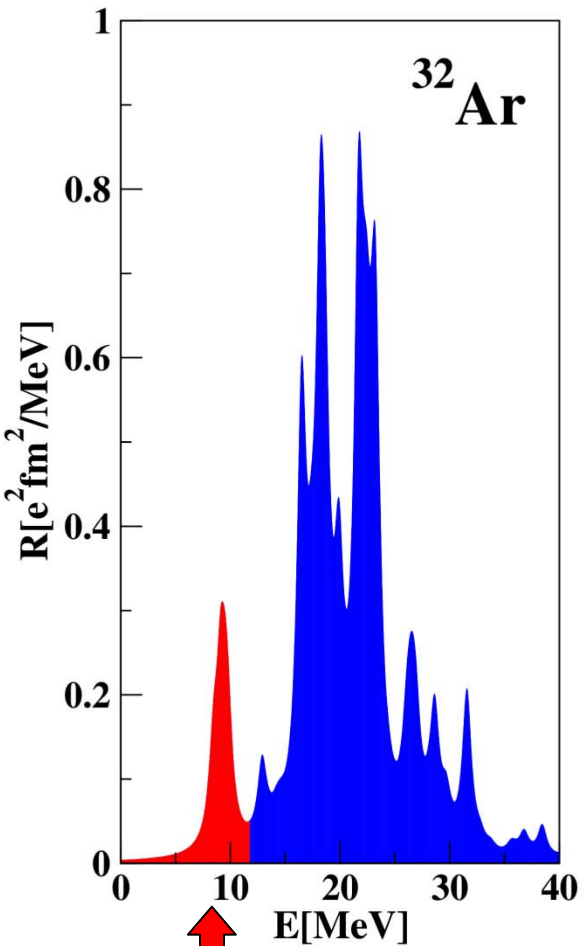


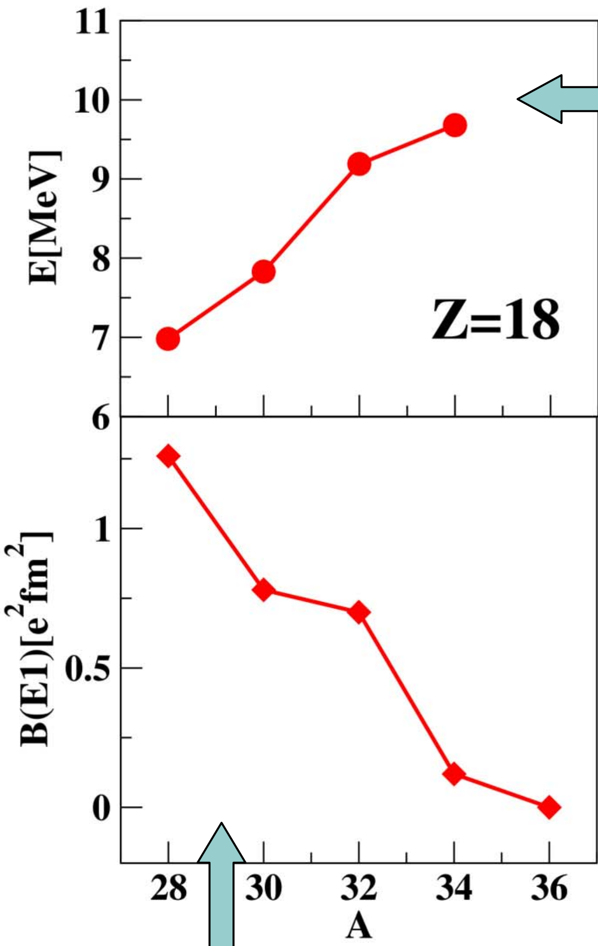
Already at moderate proton-neutron asymmetry, PDR peak is obtained above the neutron emission threshold

Implications for the observation of the PDR in (γ,γ') experiments

CROSSING BETWEEN THE PYGMY ENERGY AND NEUTRON SEP. EN.

Dipole Excitations towards the Proton Drip-Line





CENTROID ENERGY OF THE LOW-LYING STRENGTH

PROTON PYGMY DIPOLE RESONANCE

LOW-LYING TRANSITION STRENGTH B(E1)

The analysis of exp. data for ^{30,32}Ar is in progress at GSI (2009).

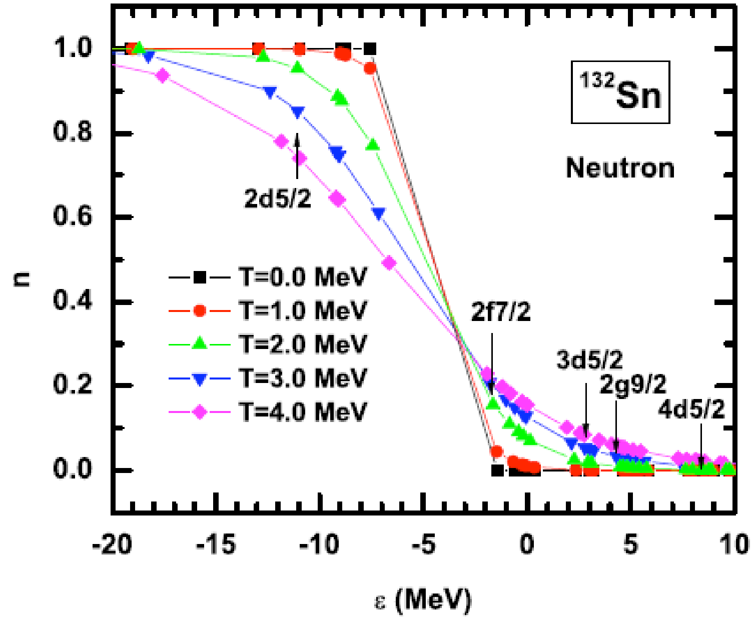
Paar, Vretenar, Ring, Phys. Rev. Lett. 94, 182501 (2005)

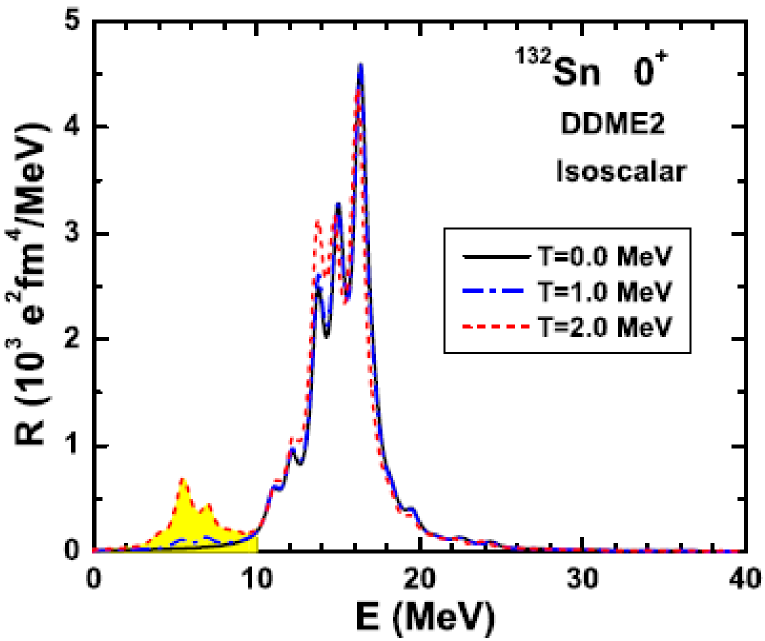
MONOPOLE AND DIPOLE RESPONSE AT FINITE TEMPERATURE

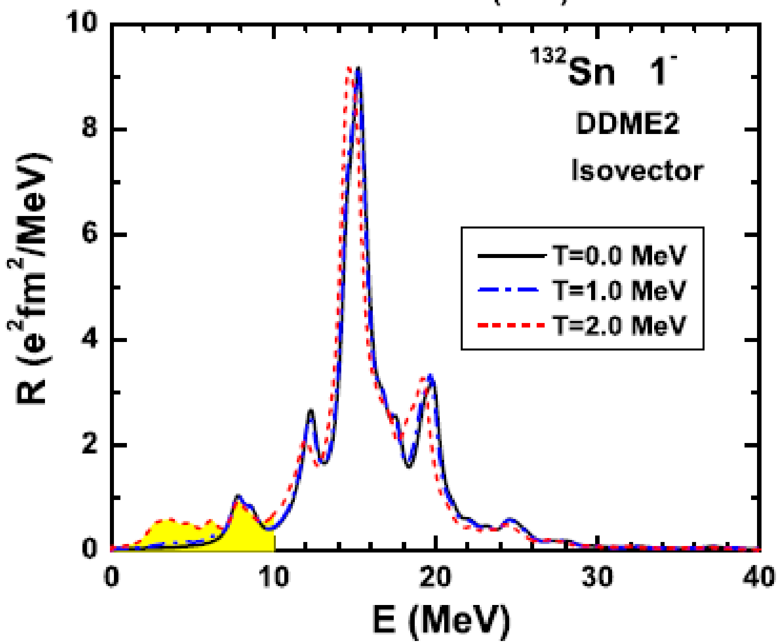
Finite temperature RMF+RPA

Y. F. Niu, N. Paar, D. Vretenar, and J. Meng, Phys. Lett. B, in press (2009)

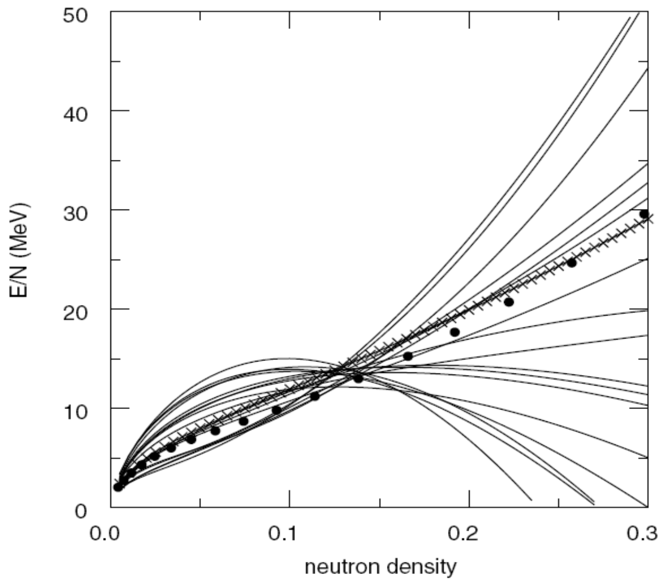
With increased temperature new low-lying transitions appear both in monopole and dipole response







Symmetry energy $S_2(\rho)$ and neutron skin in ^{208}Pb

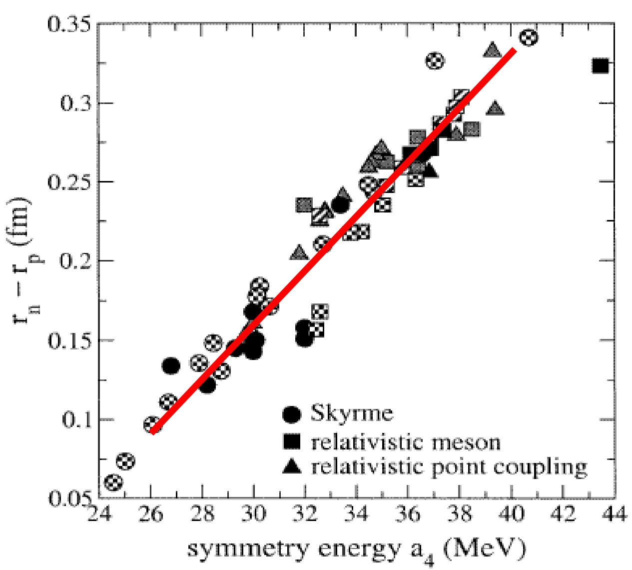


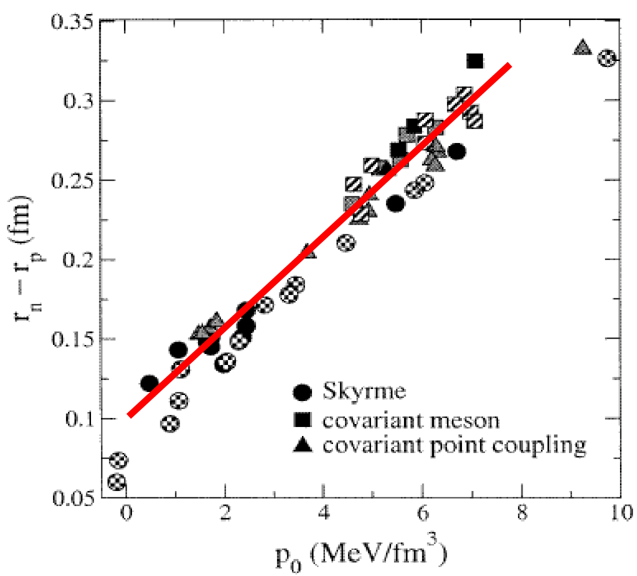
$$E(\rho,\alpha) = E(\rho,0) + S_2(\rho)\alpha^2 + O(\alpha^4)\,,\ \alpha = \frac{N-Z}{A}$$

$$S_2(\rho) = \frac{1}{2}\frac{\partial^2 E(\rho,\alpha)}{\partial \alpha^2}\bigg|_{\alpha=0} =$$

$$= a_4 + \frac{p_0}{\rho_0^2}(\rho-\rho_0) + \frac{\Delta K_0}{18\rho_0^2}(\rho-\rho_0)^2 + \ldots$$

Alex Brown,
PRL 85 (2000) 5296





R.J.Furnstahl
NPA 706(2002)85-110

- strong linear correlation between neutron skin thickness and parameters **a_4, p_0**

4. NUCLEAR SYMMETRY ENERGY AND NEUTRON SKINS DERIVED FROM PYGMY DIPOLE RESONANCE

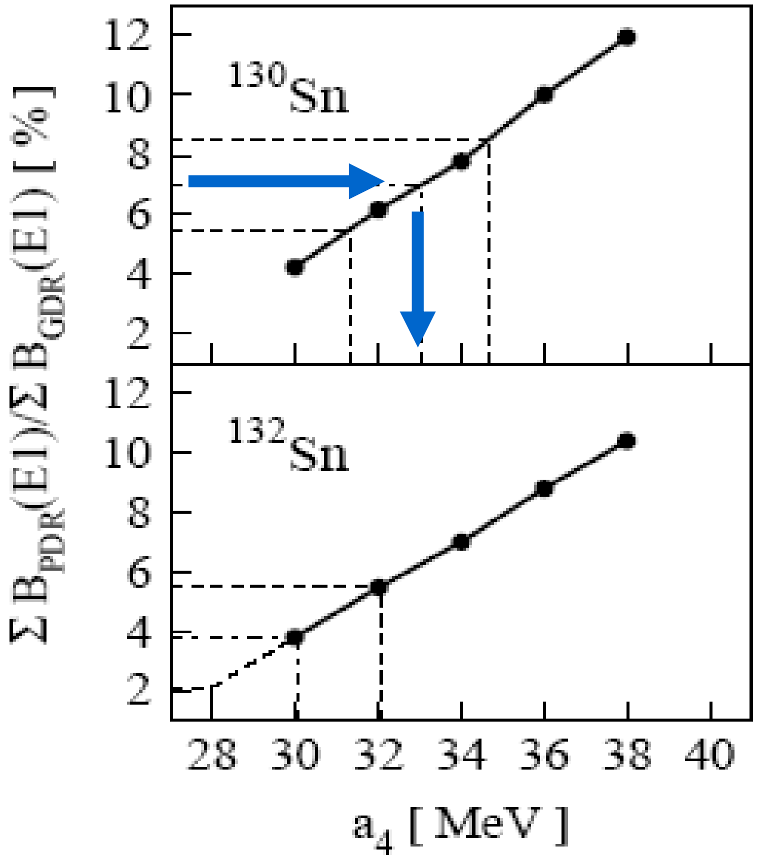
Theory: Precise knowledge of neutron-skin thickness could constrain the density dependence of $S(\rho)$

Work Hypothesis: **Pygmy-Strength (since related to skin)**
should do the same job,
but, experimentally, is accessed much easier !

➡ Quantitative attempt to determine the neutron skin thickness by means of RHB + RQRPA, using various density-dependent effective interactions and recent experimental data on PDR

A. Klimkiewicz, N. Paar, et al., (LAND collaboration), Phys. Rev. C 76, 051603(R) (2007)

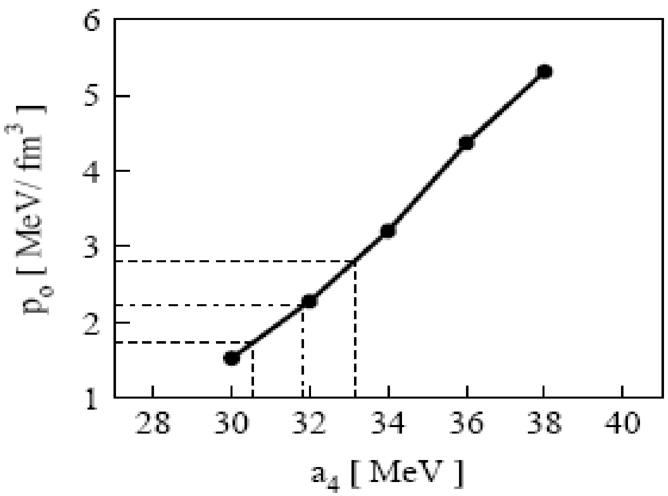
PDR strength versus a_4, p_o



RHB+RQRPA calculations and exp. data (GSI) for PDR strength

Result (*averaged ^{130,132}Sn) :*

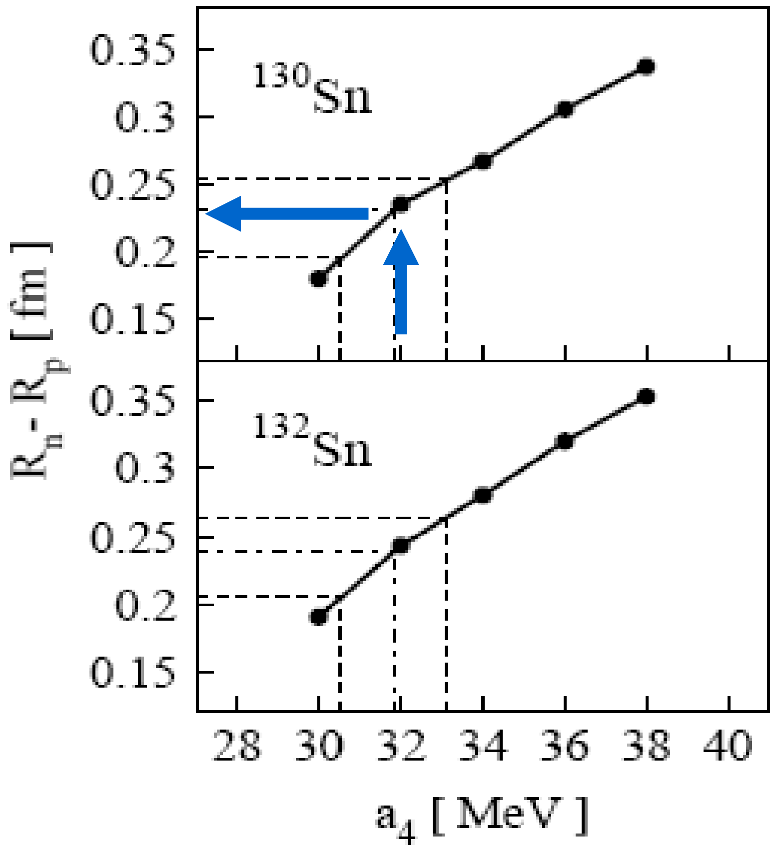
a_4 = 32.0 ± 1.8 MeV



p_o = 2.3 ± 0.8 MeV/fm^3

S(ρ) : moderate stiffness

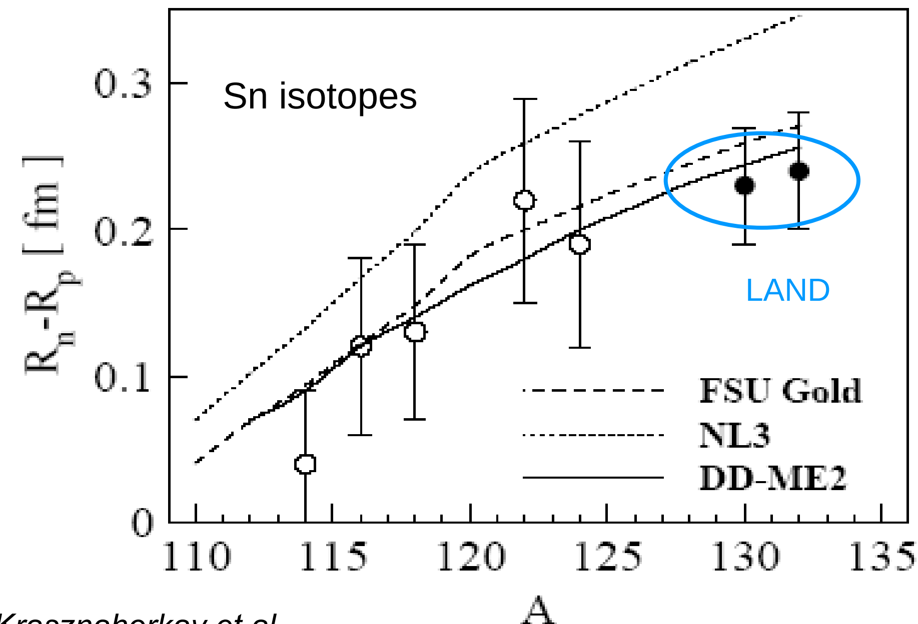
Neutron skin thickness



$R_n - R_p$:

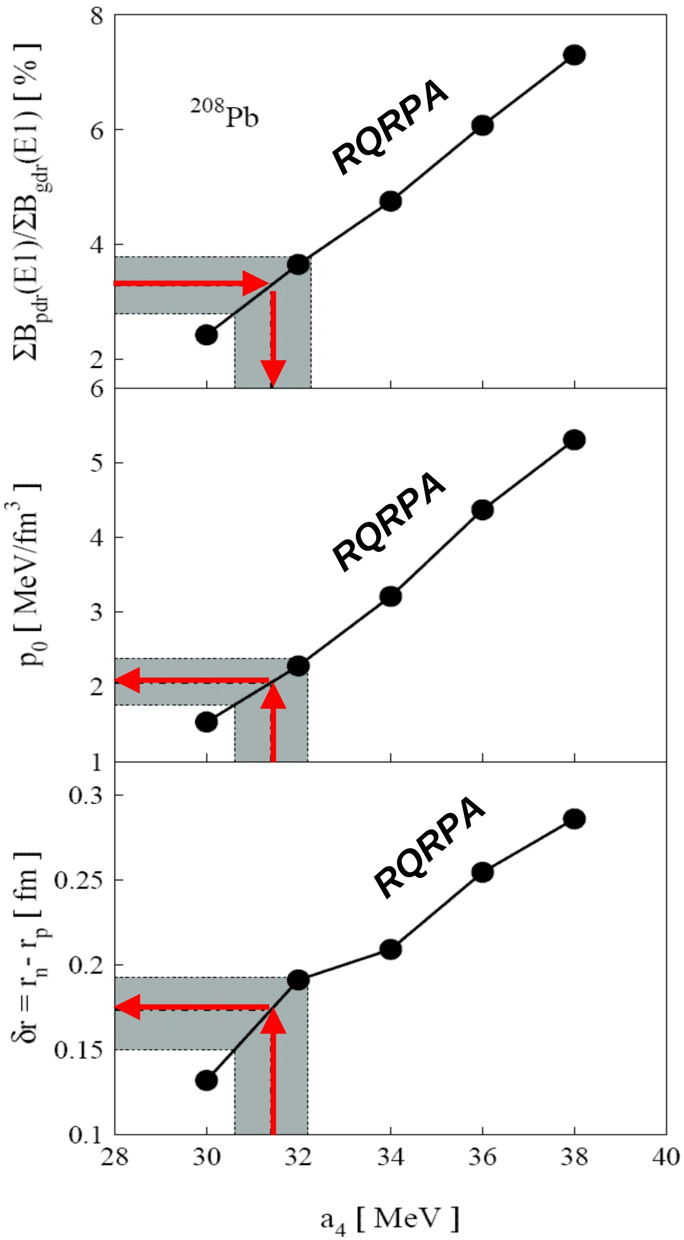
^{130}Sn: 0.23 ± 0.04 fm

^{132}Sn: 0.24 ± 0.04 fm



A.Krasznahorkay et al.
PRL 82(1999)3216

^{208}Pb analysis



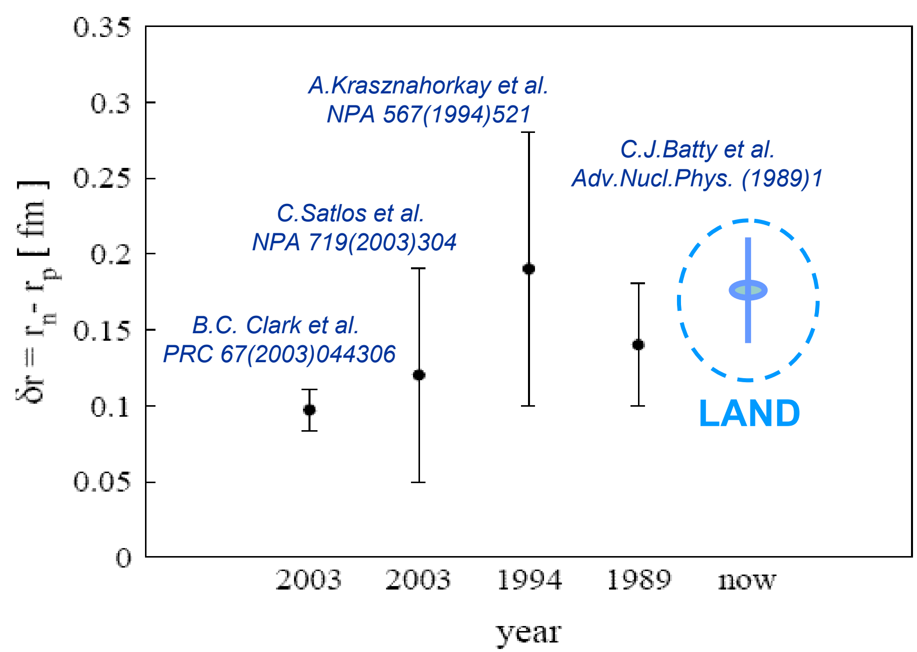
$\sum B_{pdr}(E1)=1.98\ e^2\ fm^2$

from N.Ryezayeva et al., PRL 89(2002)272501

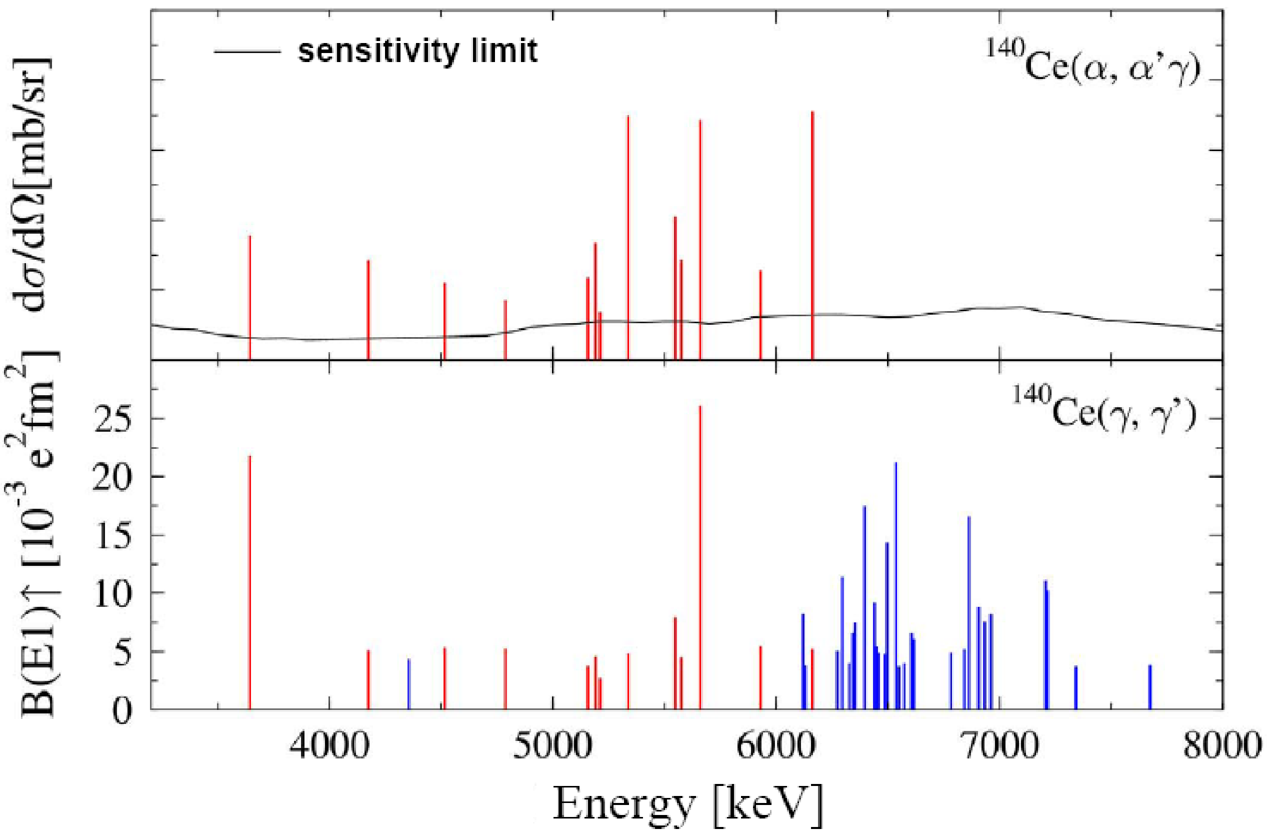
$\sum B_{gdr}(E1)=60.8\ e^2\ fm^2$

from A.Veyssiere et al.,NPA 159(1970)561

$$R_n - R_p = 0.18 \pm 0.035\ \text{fm}$$



Splitting of the E1 strength in ^{140}Ce : (γ,γ') vs. $(\alpha,\alpha'\gamma)$

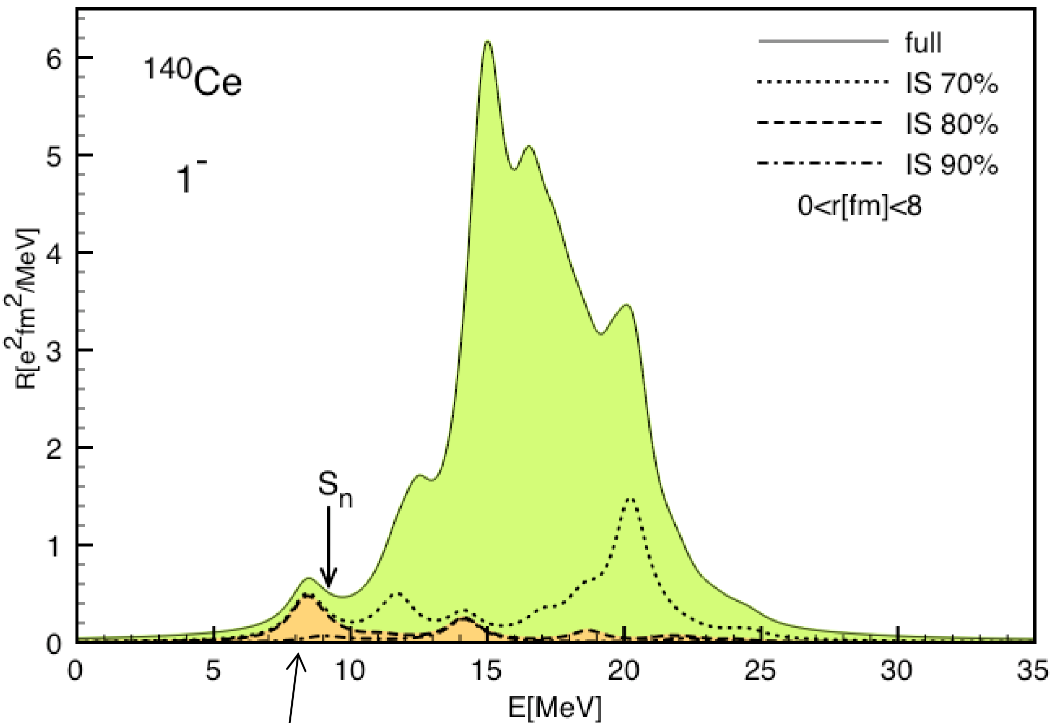


D. Savran et al.,
Phys. Rev. Lett. 97, 172502 (2006)

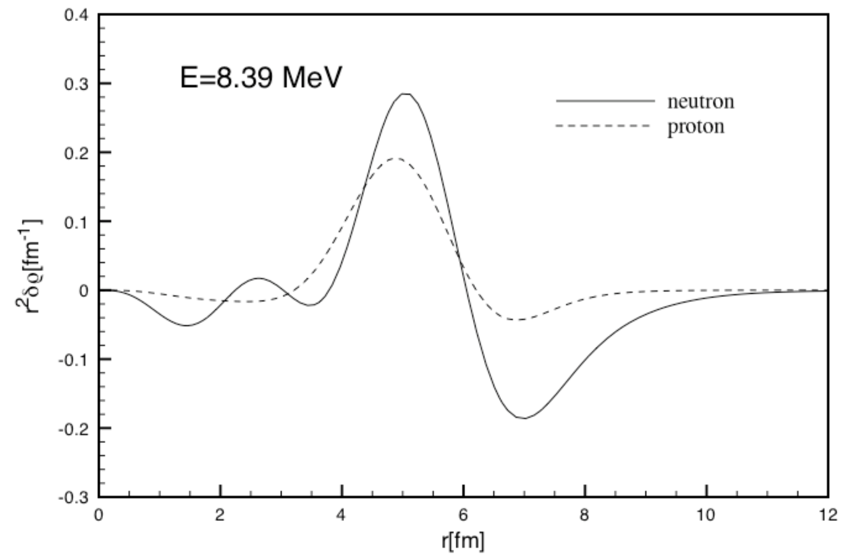
SPLITTING OF THE LOW-LYING DIPOLE TRANSTION STRENGTH

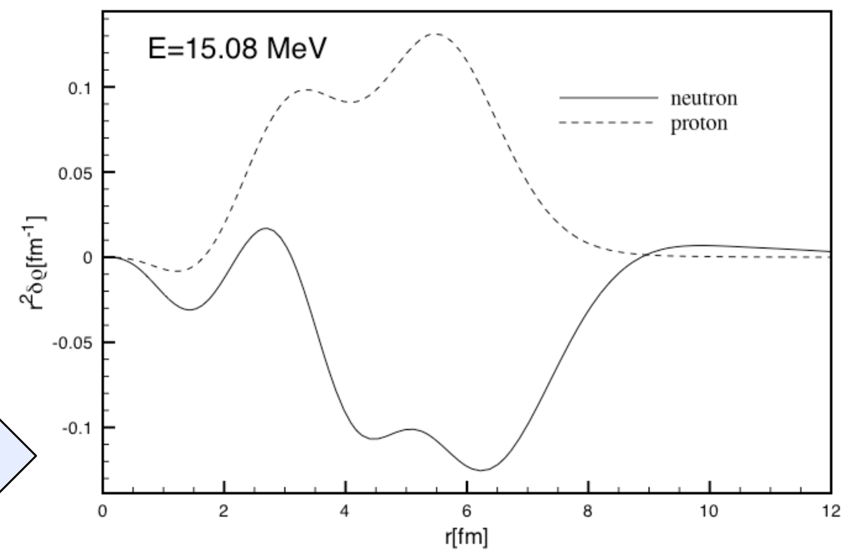
- Photons interact with nucleus as a whole, induce primarily isovector transitions
- α-particles interact with the nuclear surface, inducing isoscalar transitions with surface-peaked transition densities

ISOVECTOR-ISOSCALAR SPLITTING OF DIPOLE RESPONSE



Transitions of dominant isoscalar nature

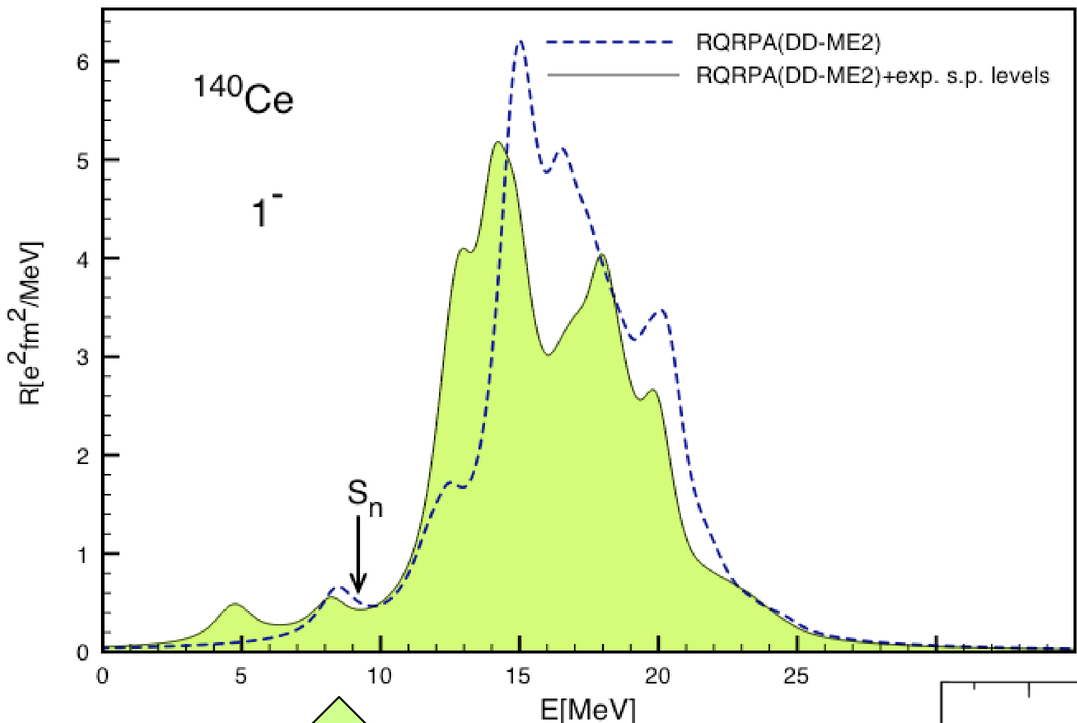




Transition densities for the PDR and GDR states

N. Paar, Y. F. Niu, D. Vretenar, and J. Meng, Phys. Rev. Lett. 103, 032502 (2009)

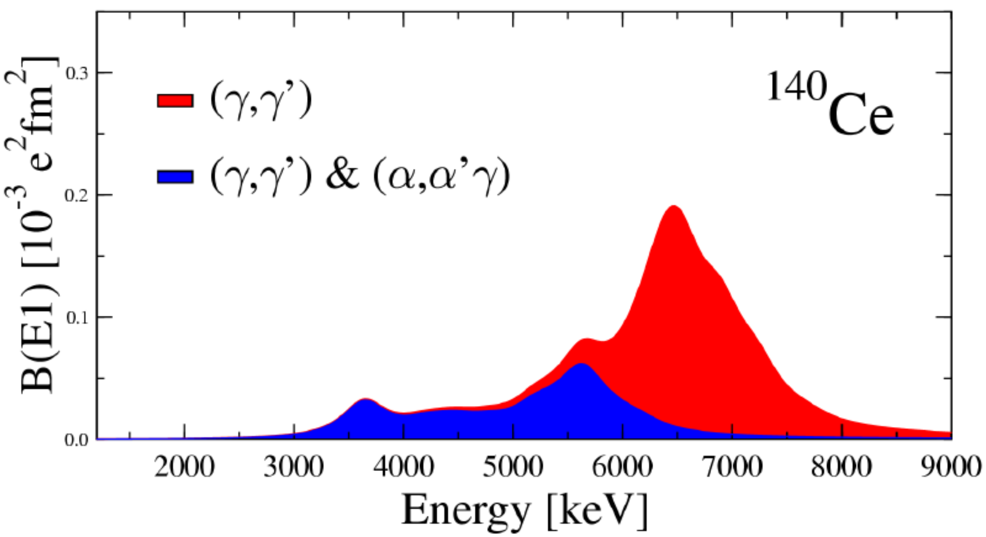
ISOVECTOR-ISOSCALAR SPLITTING OF DIPOLE RESPONSE



Splitting of the pygmy dipole resonance

D. Savran et al., Phys. Rev. Lett. 97, 172502 (2006).

EXP. STRENGTH DISTRIBUTION FOLDED WITH LORENTZIAN Γ=300 keV



COLLECTIVE PROPERTIES OF THE PDR

$$B_J^T(E_\lambda) = \frac{1}{2J_i+1}\left|\sum_{\mu\mu'}\left\{X^{\lambda,J0}_{\mu\mu'}\langle\mu||\hat{Q}_J^T||\mu'\rangle + (-1)^{j_\mu - j_{\mu'}+J}\,Y^{\lambda,J0}_{\mu\mu'}\,\langle\mu'||\hat{Q}_J^T||\mu\rangle\right\}(u_\mu v_{\mu'} + (-1)^J v_\mu u_{\mu'})\right|^2 ,$$

Coherent contributions to the transition strength B(E1) from several neutron configurations