Collective Excitations in Atomic Nuclei based on Density Functionals and Correlated Nucleon-Nucleon Interactions

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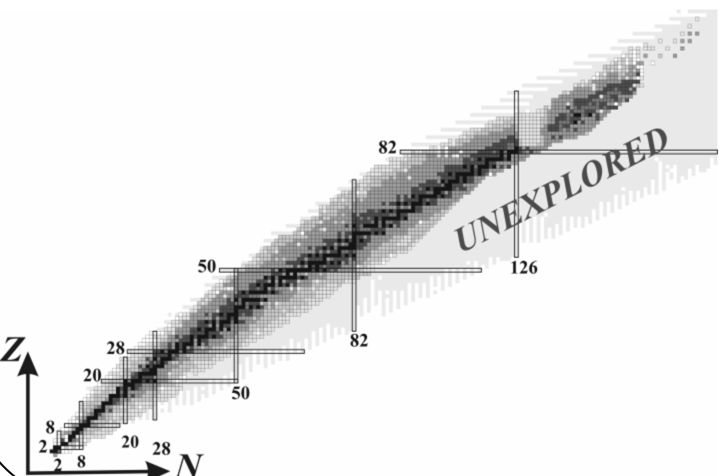
COLLECTIVE EXCITATIONS IN ATOMIC NUCLEI

ENERGY DENSITY FUNCTIONAL

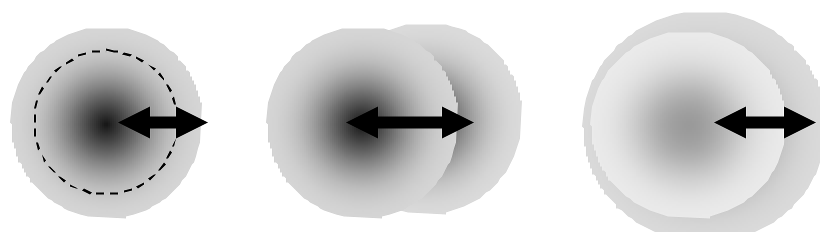
REALISTIC NN INTERACTION

EFFECTIVE INTERACTION

MICROSCOPIC DESCRIPTION OF THE GROUND STATE

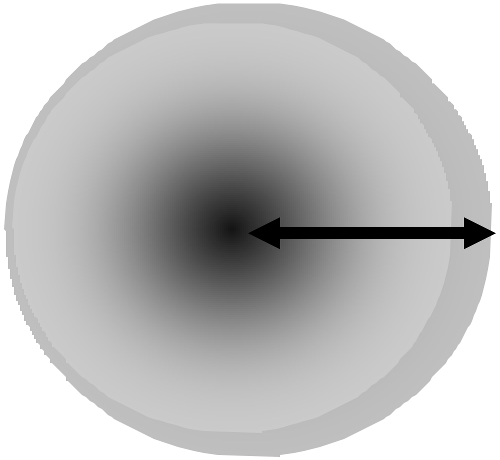


DESCRIPTION OF COLLECTIVE NUCLEAR VIBRATIONS

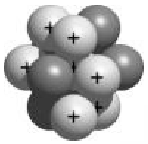


Fully self-consistent theory provides
a direct connection between
effective interactions
and excitation phenomena

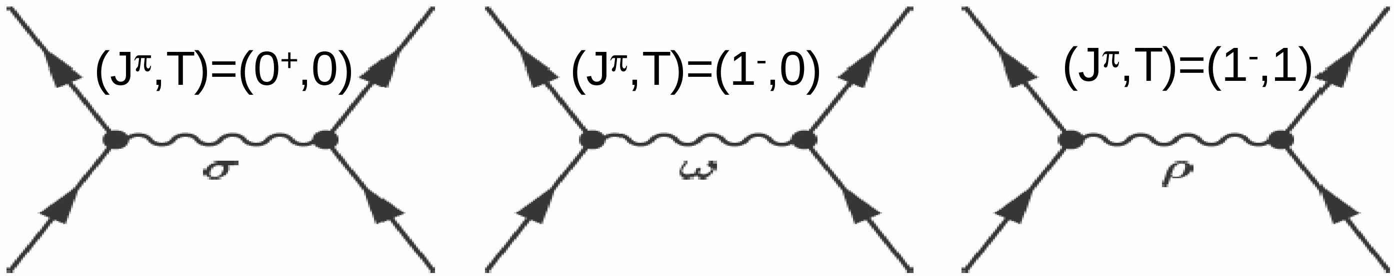
1. Collective Excitation Phenomena in the Relativistic Framework based on Density-dependent Interactions



RELATIVISTIC MEAN FIELD THEORY



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



Sigma-meson: attractive scalar field

Omega-meson: short-range repulsive field

Rho-meson: isovector field

THE LAGRANGIAN DENSITY: $L_{RMF}[\psi, \sigma, \omega^\mu, \vec{\rho}^\mu, A^\mu]$

An effective density dependence introduced via a non-linear potential:

$$U(\sigma) = \tfrac{1}{2}m_\sigma^2\sigma^2 + \tfrac{g_2}{3}\sigma^3 + \tfrac{g_3}{4}\sigma^4$$

NL1 **NL-Z2** **NL3**

Density dependent meson-nucleon couplings (phenomenological):

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

$$f_i(x) = a_i \frac{1+b_i(x+d_i)^2}{1+c_i(x+d_i)^2} \qquad i = \sigma, \omega$$

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

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

TW-99 **DD-ME1**

THE RELATIVISTIC HARTREE-BOGOLIUBOV MODEL

Unified description of mean-field and pairing correlations

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

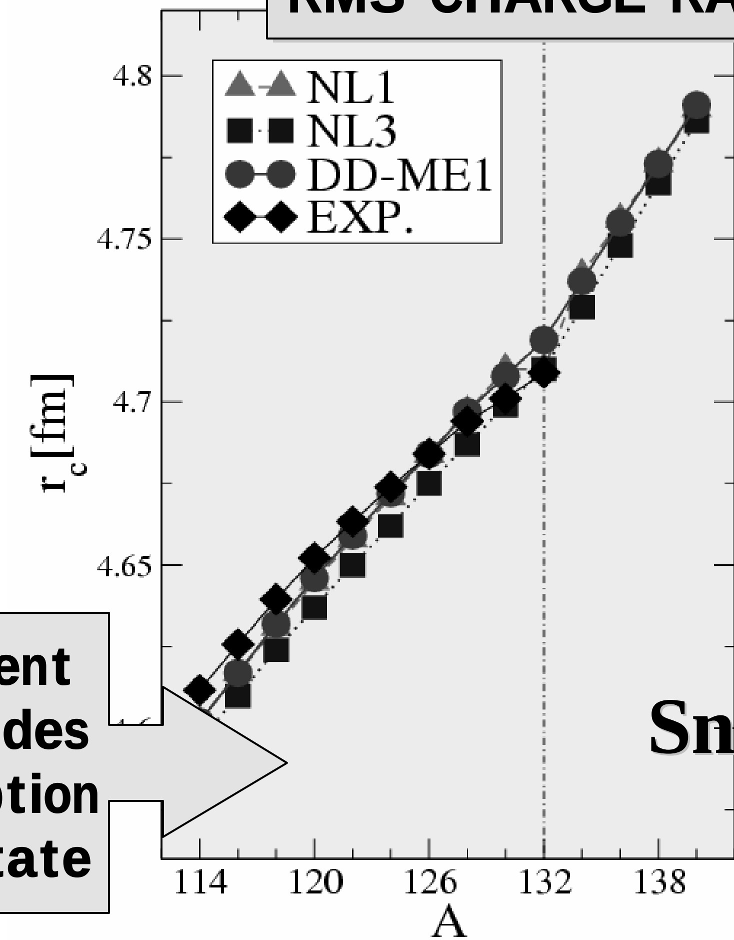
Dirac hamiltonian

Pairing field

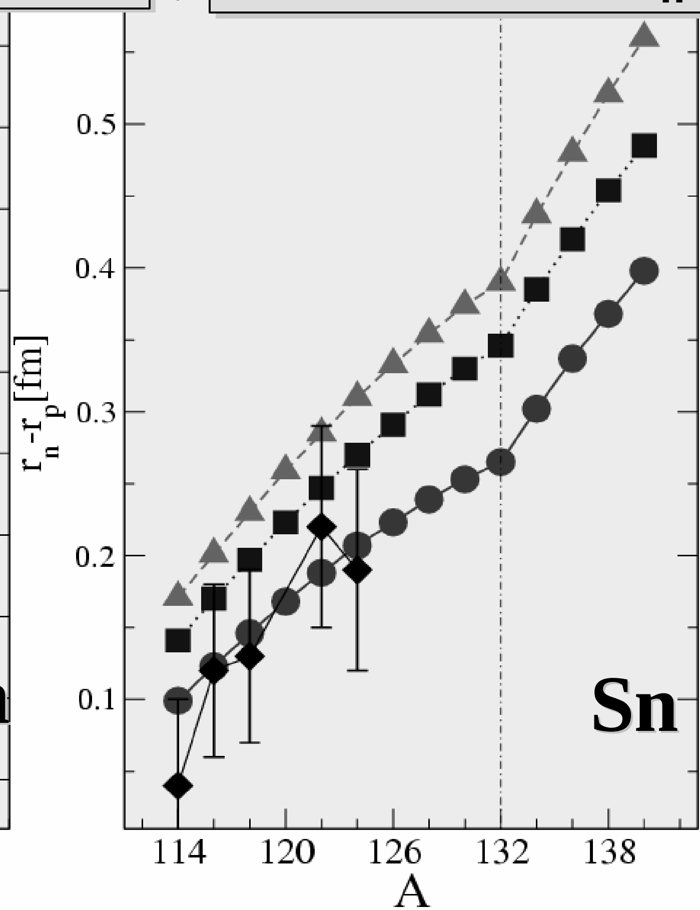
Gogny pairing interaction: finite range spin-isospin dependent force

Density dependent interaction provides improved description of the ground state

RMS CHARGE RADII



DIFFERENCES r_n-r_p



RELATIVISTIC QUASI-PARTICLE RANDOM-PHASE APPROXIMATION

Paar, Ring, Niksic, Vretenar, Phys. Rev. C67, 034312 (200

- Derived from the time-dependent RHB equation in the limit of small oscillations around the RHB ground state generalized density

Quasiparticle canonical states

both ph and αh pairs included

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

$$A^J = H^{11(J)}_{\kappa\lambda}\delta_{\kappa'\lambda'} - H^{11(J)}_{\kappa'\lambda}\delta_{\kappa\lambda'} - H^{11(J)}_{\kappa\lambda'}\delta_{\kappa'\lambda} + H^{11(J)}_{\kappa'\lambda'}\delta$$

$$+\frac{1}{2}$$

$$+$$

$$B^J = \frac{1}{2}$$

$$(-1)^{j_\lambda - j_{\lambda'} + J}$$

ELF-CONSISTENCY:
he same effective
teraction determines
he ground state and
he QRPA residual
teraction

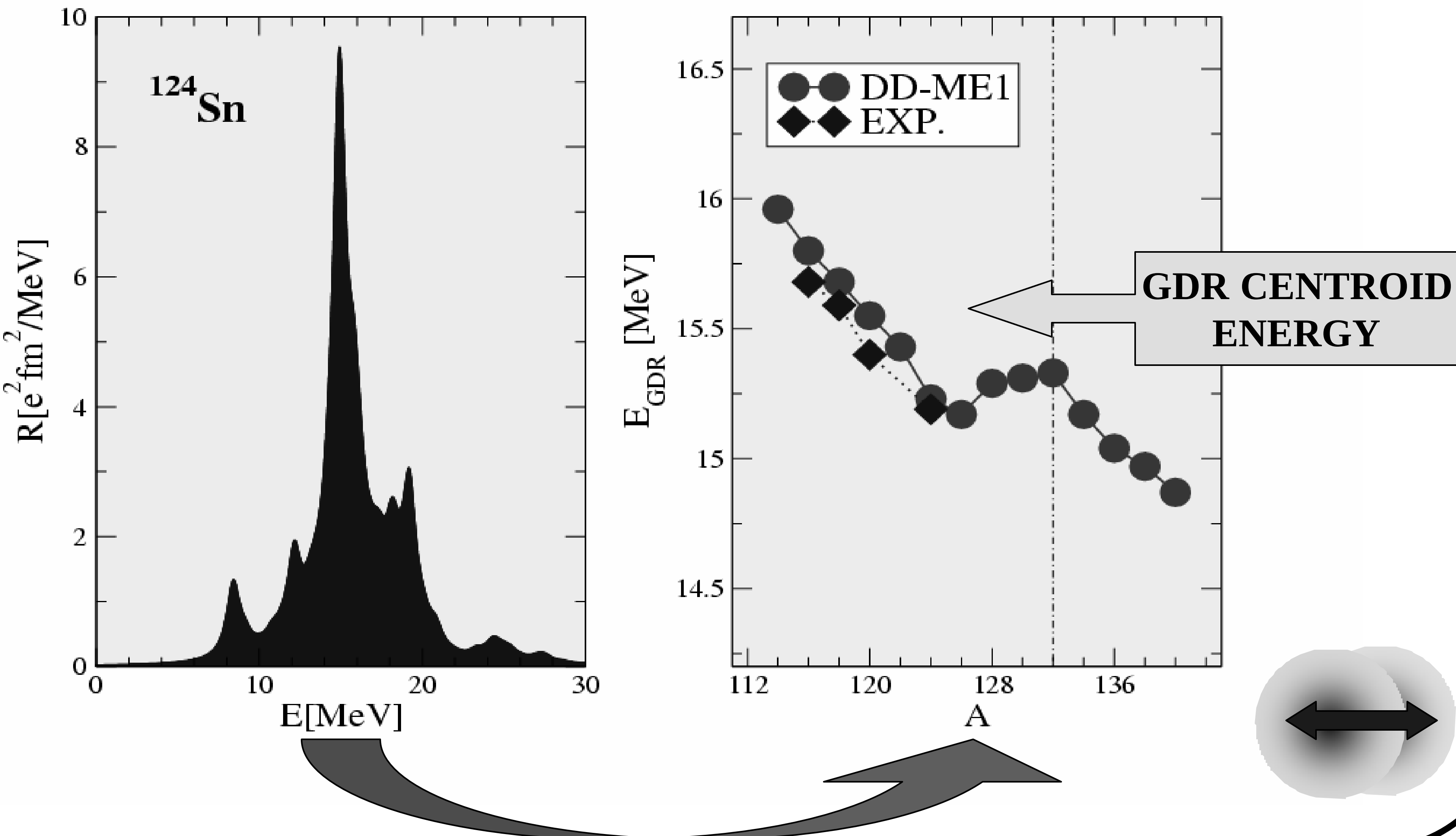
PARTICLE-PARTICLE INTERACTION (Gogny)

PARTICLE-HOLE INTERACTION (NL3,DD-ME1,...)

Factors including the occupation probabilities for the canonical states

ISOVECTOR GIANT DIPOLE RESONANCE (GDR)

- Collective mode: protons coherently oscillate against neutrons

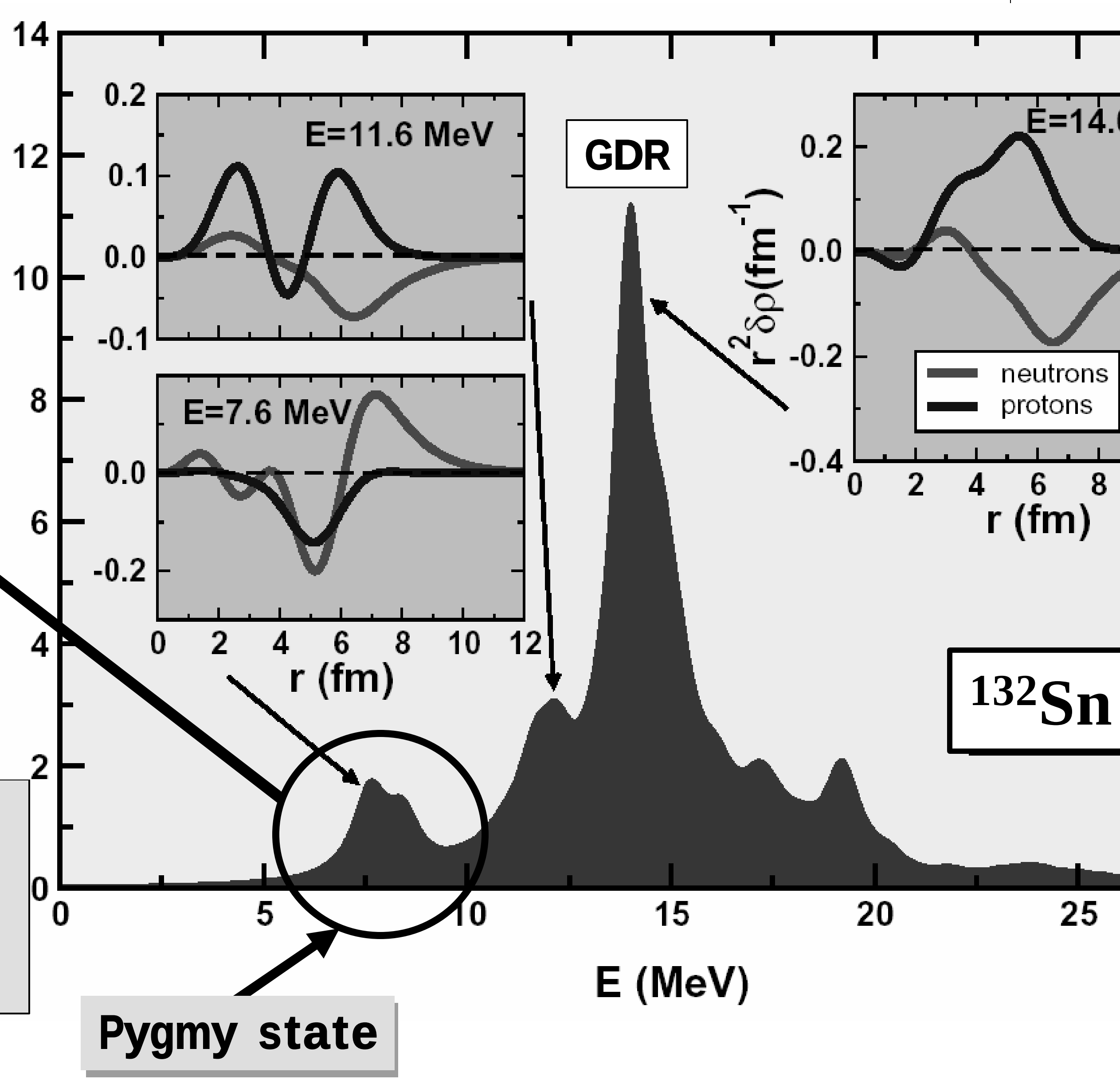


THE PYGMY DIPOLE RESONANCE (PDR) IN ^{132}Sn

Vretenar, Paar, Ring, Lalazissis, Nucl. Phys. A692, 496 (20

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

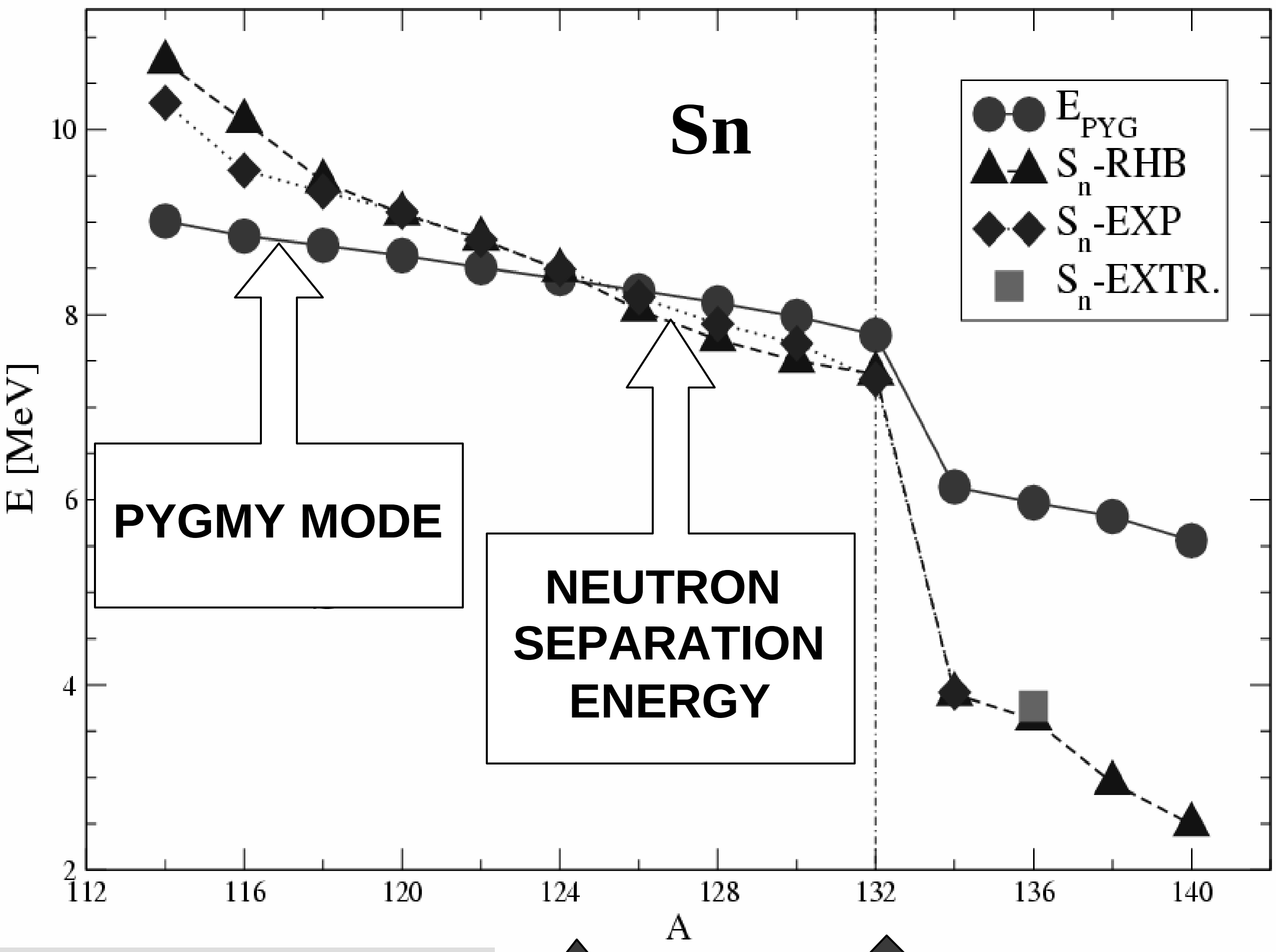
^{132}Sn at 7.6 MeV
28.2% $2d_{3/2} \rightarrow 2f_{5/2}$
21.9% $2d_{5/2} \rightarrow 2f_{7/2}$
19.7% $2d_{3/2} \rightarrow 3p_{1/2}$
10.5% $1h_{11/2} \rightarrow 1i_{13/2}$
3.5% $2d_{5/2} \rightarrow 3p_{3/2}$
1.9% $1g_{7/2} \rightarrow 2f_{5/2}$
1.5% $1g_{7/2} \rightarrow 1h_{9/2}$
0.6% $1g_{7/2} \rightarrow 2f_{7/2}$
0.6% $2d_{3/2} \rightarrow 3p_{3/2}$



DR? EXCESS NEUTRONS SCILLATE AGAINST HE PROTON-NEUTRON ORE

ISOTOPIC DEPENDENCE OF THE PYGMY DIPOLE RESONANCE (PD

Paar, Niksic, Vretenar, Ring, Phys. Lett. B 606, 288 (200



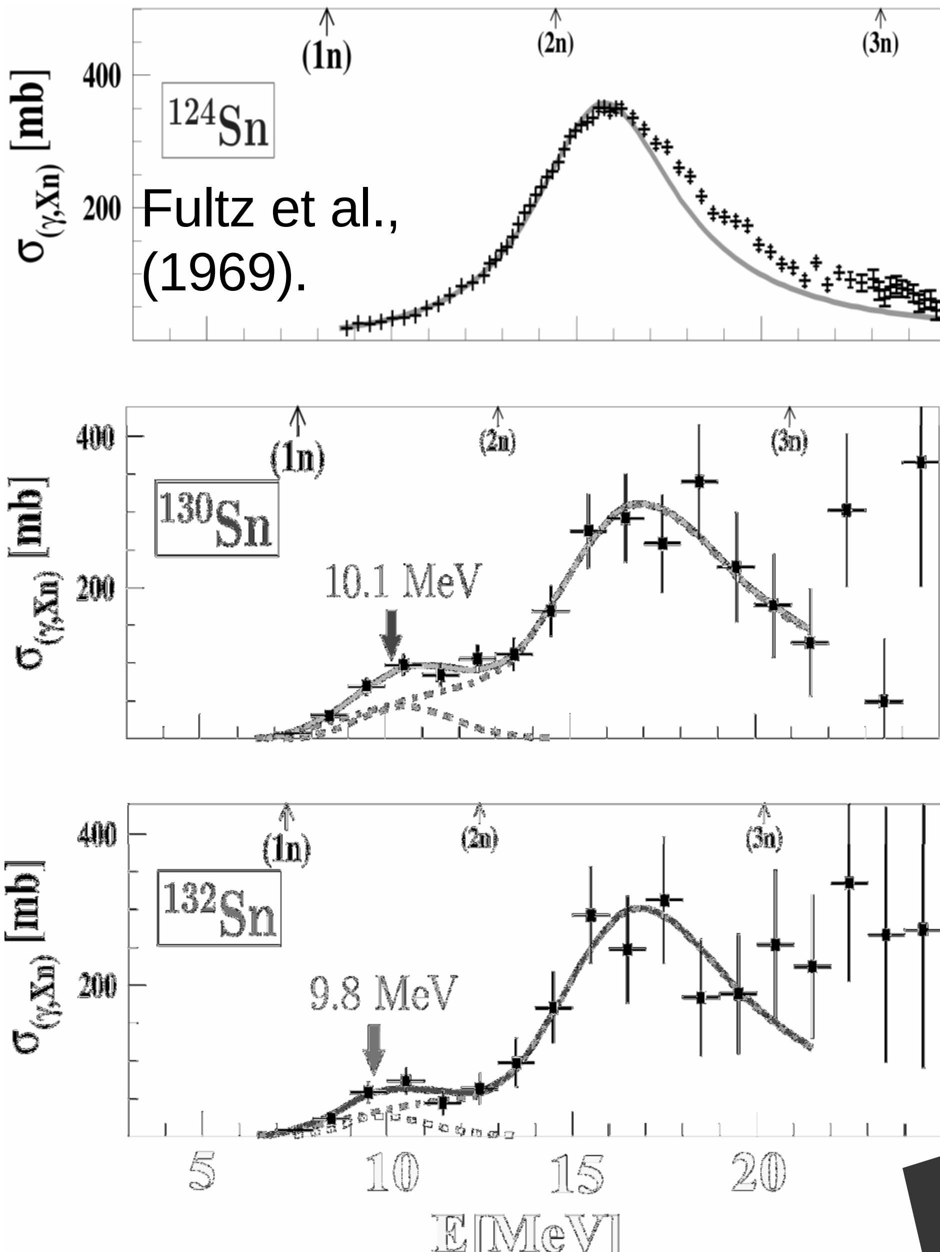
Already at moderate proton-neutron asymmetry, PDR peak is obtained above the neutron emission threshold

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

CROSSING BETWEEN THE PYGMY ENERGY AND NEUTRON SEP. EN.

ANOMALOUS KINK AT THE SHELL CLOSURE

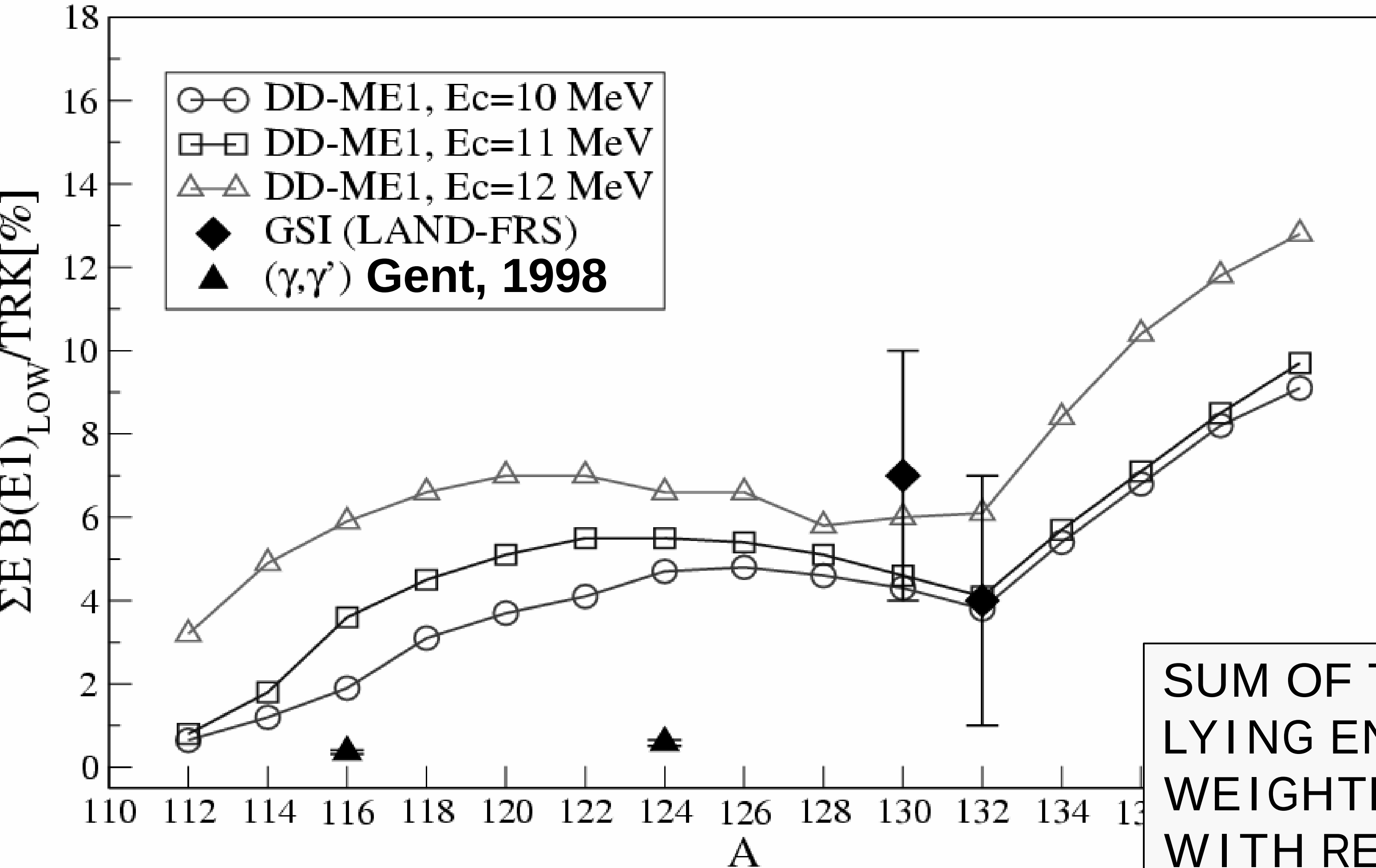
NEW EXPERIMENTAL EVIDENCE OF THE LOW-LYING E1 STRENGT
(First reaction experiment with fission fragment beams)



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

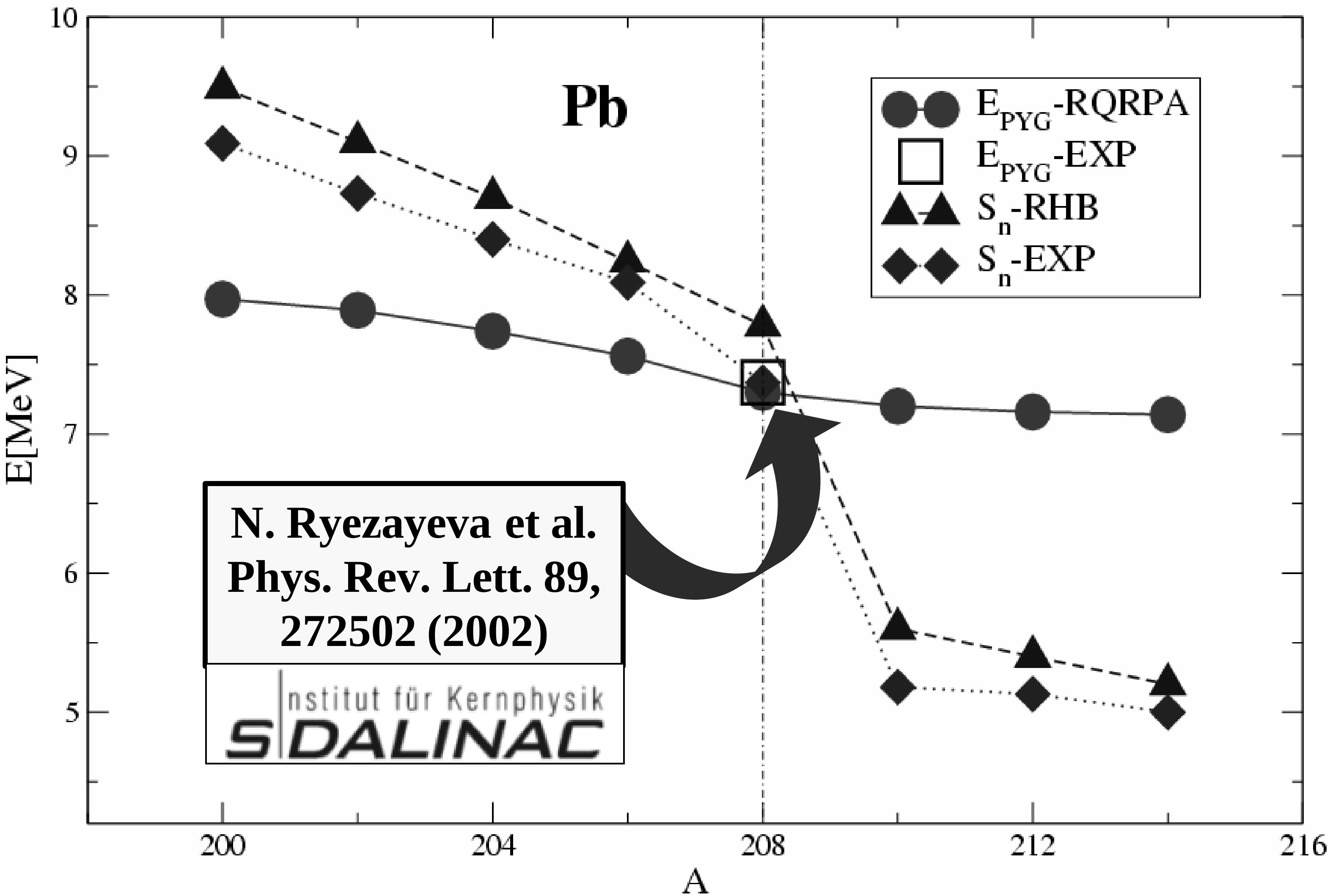
APPEARANCE OF THE PRONOUNCED LOW-LYING RESONANCE-LIKE STRUCTURE ABOVE THE NEUTRON THRESHOLD

LOW-LYING E1 STRENGTH IN TIN ISOTOPES – RQRPA(DD-ME1



SUM OF THE LOW-LYING ENERGY WEIGHTED STRENGTH WITH RESPECT TO THE CLASSICAL (TRK) SUM RULE

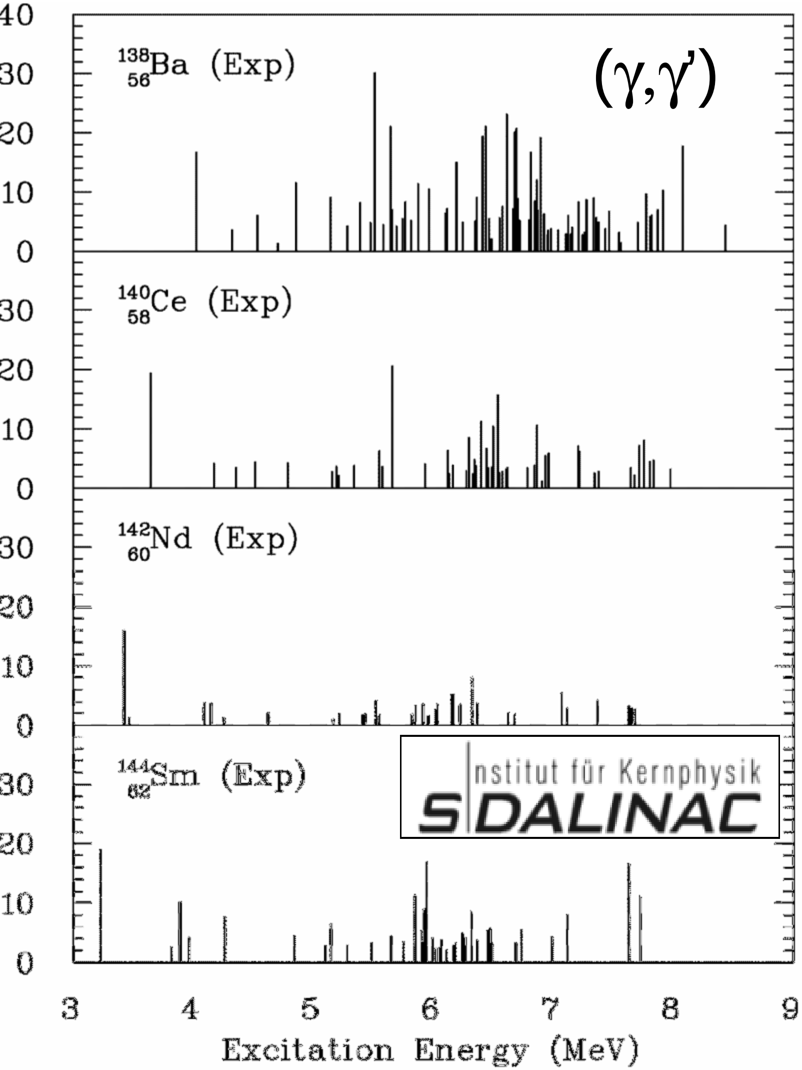
PDR IN HEAVY NUCLEAR SYSTEMS WITH NEUTRON EXCESS



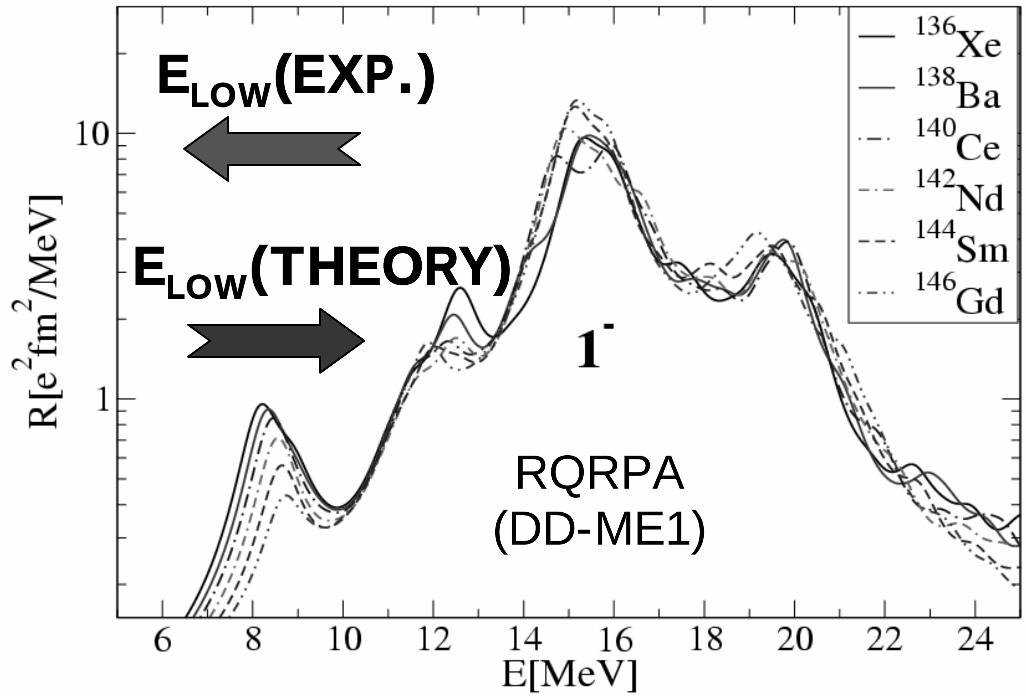
N. Ryezayeva et al. Phys. Rev. Lett. 89, 272502 (2002)

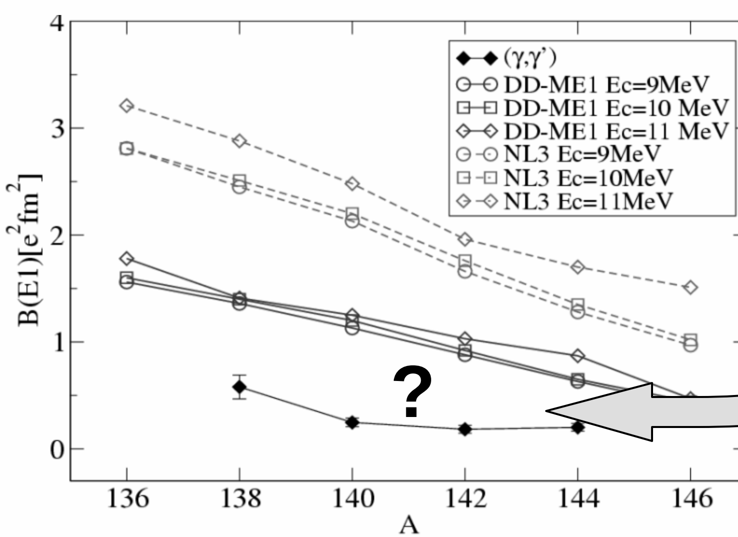
Institut für Kernphysik S-DALINAC

THE PUZZLE OF LOW-LYING E1 STRENGTH IN N=82 ISOTONES



Zilges et al.





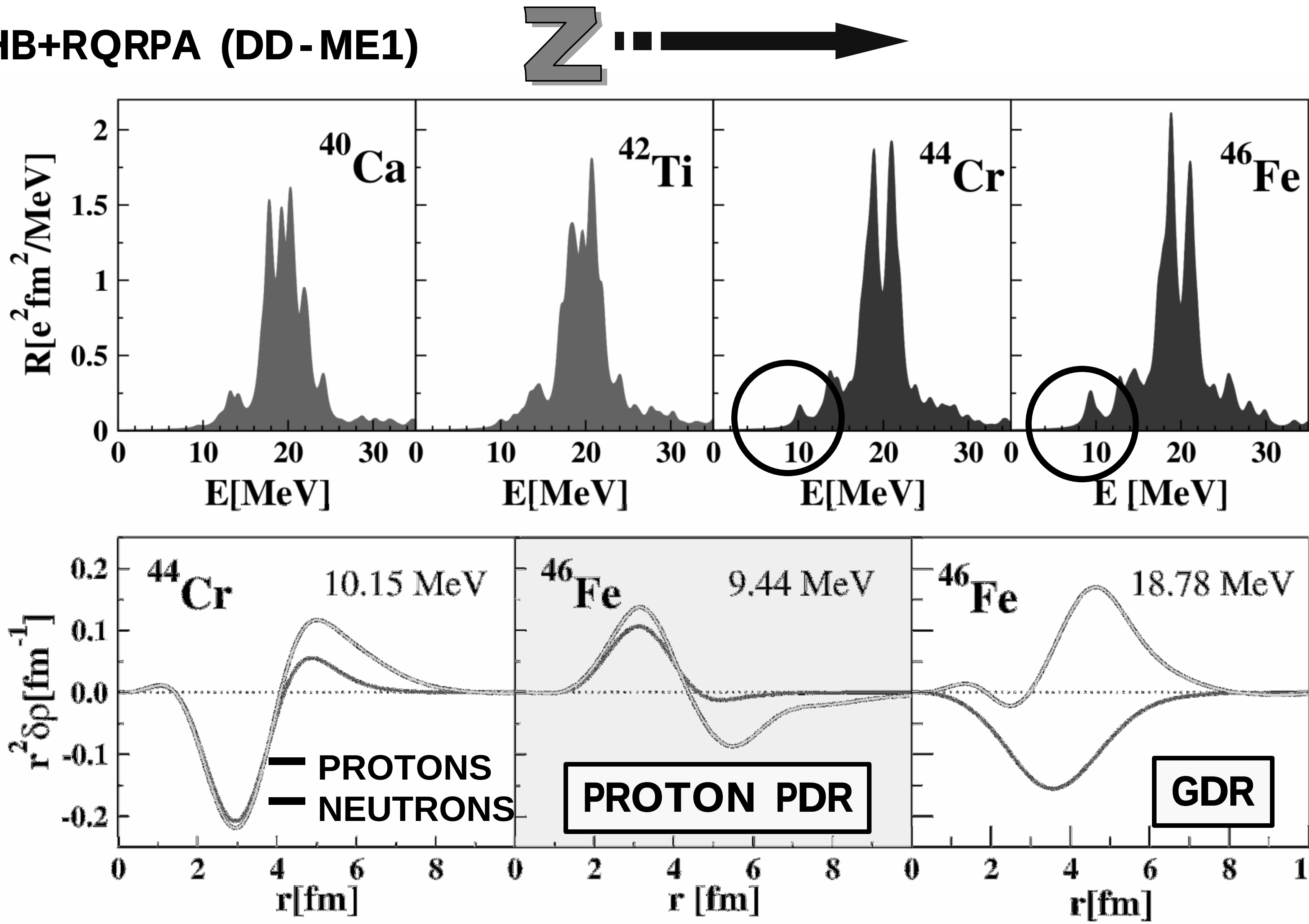
THE MISSIN
LOW-LYING
STRENGTH ?

Z

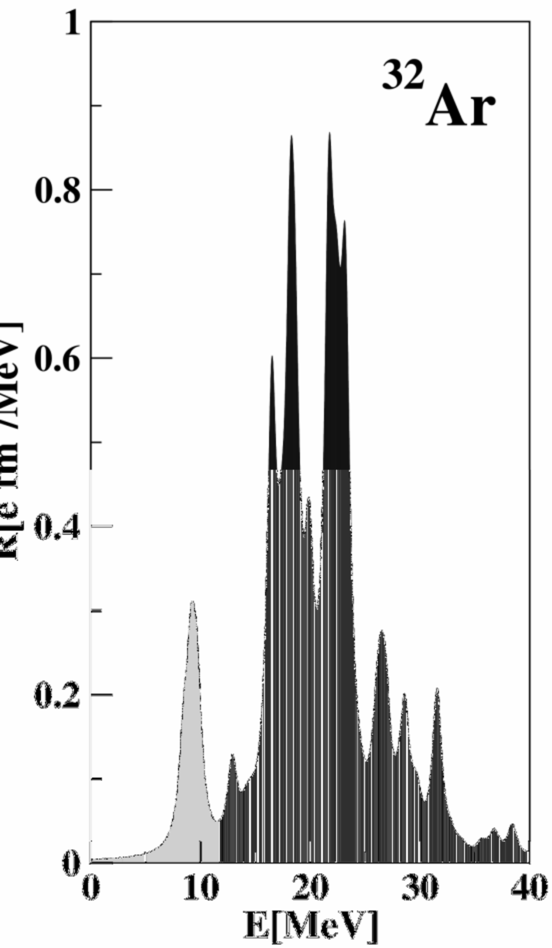
THE PROTON ELECTRIC PYGMY DIPOLE RESONANCE

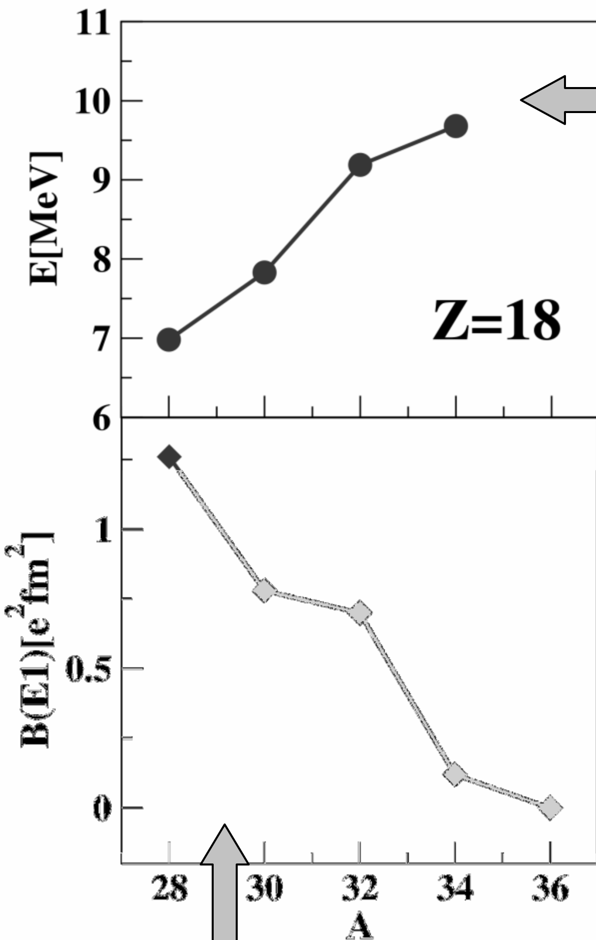
Paar, Vretenar, Ring, Phys. Rev. Lett. 94, 182501 (200

RHB+RQRPA (DD-ME1)



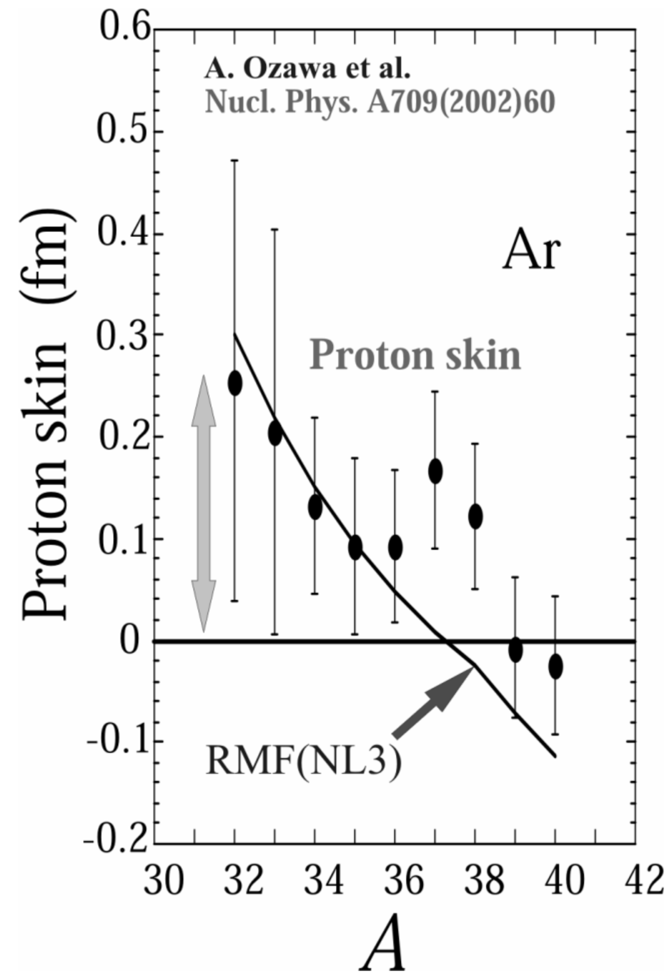
Proton PDR provides an evidence about the proton skin





CENTROID ENERGY OF THE LOW-LYING STRENGTH

LOW-LYING TRANSITION STRENGTH B(E1)

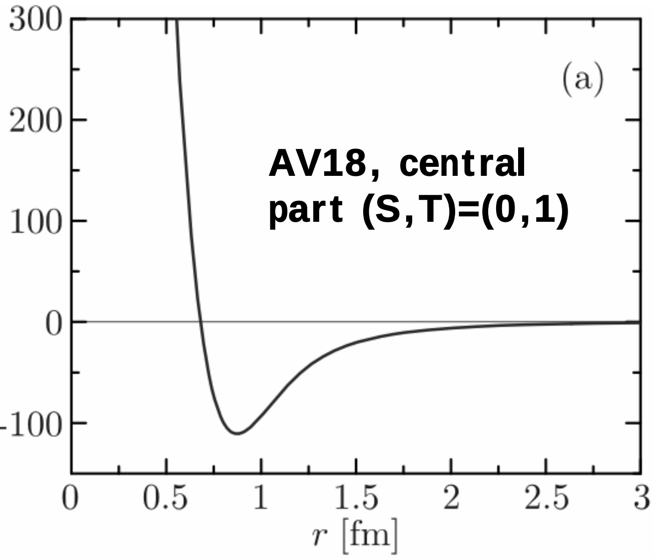


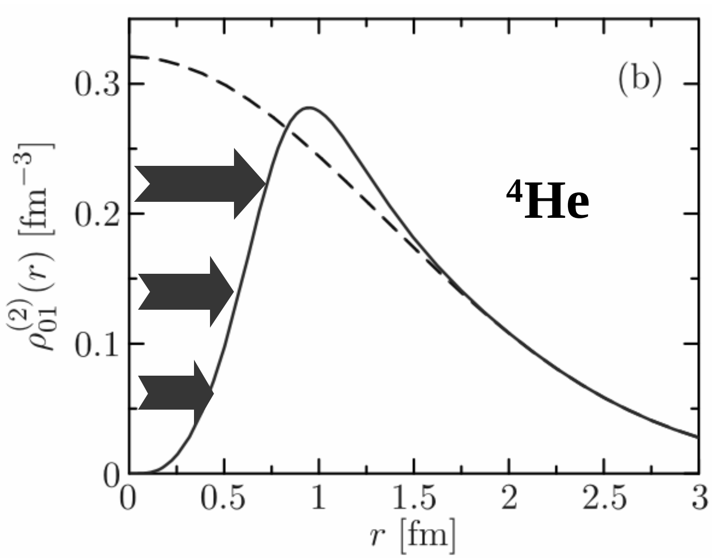
2. Collective Excitation Phenomena based on Realistic Nucleon-Nucleon Interactions within the Unitary Correlation Operator Method (UCOM)

Realistic and Effective Nucleon-Nucleon Interactions

- Realistic nucleon-nucleon interactions are determined from the phase-shift analysis of nucleon-nucleon scattering

- strong repulsive core at small distances ~ 0.5 fm





Very large or infinite matrix elements of interaction (relative wave functions penetrate the core)

$$\text{Realistic nucleon-nucleon interaction} \xrightarrow{C} \text{Effective nucleon-nucleon interaction}$$

THE UNITARY CORRELATION OPERATOR METHOD

- ***Short-range*** **central and** ***tensor*** **correlations are included in the simple many body states via** ***unitary transformation***

CORRELATED MANY-BODY STATE

$$|\hat{\Psi}\rangle = \quad |\Psi\rangle$$

UNCORRELATED MANY-BODY STATE

$$\langle\hat{\Psi}|\,\mathrm{O}\,|\hat{\Psi}'\rangle = \underbrace{\langle\Psi|\,\mathrm{C}^{\dagger}}\,\mathrm{O}\,\underbrace{\mathrm{C}\,|\Psi'\rangle} = \langle\Psi|\,\hat{\mathrm{O}}\,|\Psi'\rangle$$

UNCORRELATED OPERATOR

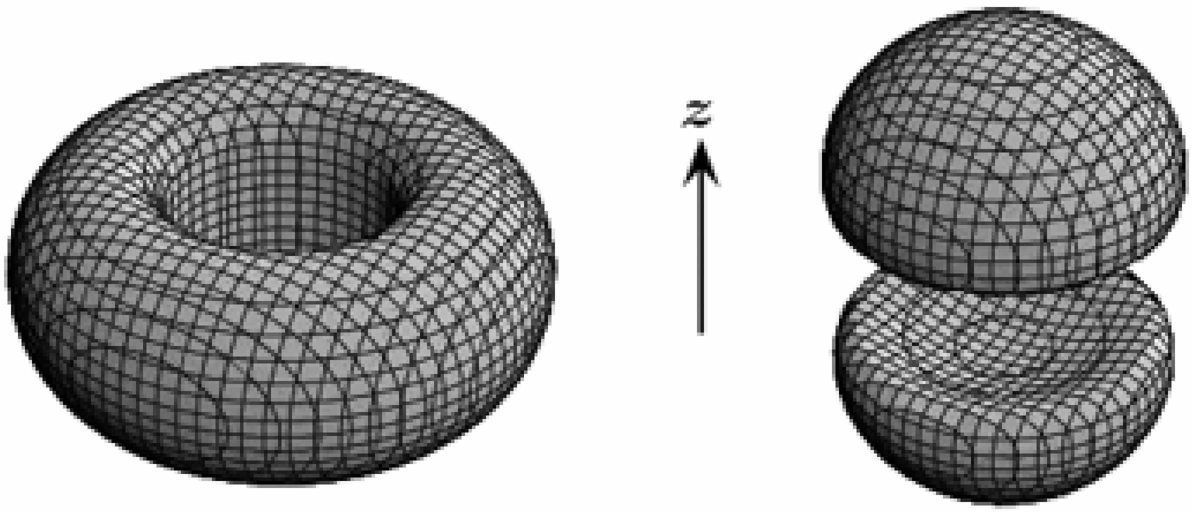
CORRELATED OPERATOR

- **Instead of correlated many-body states, the correlated operators are employed in nuclear structure models of finite nuclei**

R. Roth et al., Nucl. Phys. A 745, 3 (2004)
T. Neff et al., Nucl. Phys. A 713, 311 (2003)
R. Roth et al., Phys. Rev. C 72, 034002 (2005)

DEUTERON: MANIFESTATION OF CORRELATIONS

$M_S = 0$ | $M_S = \pm 1$
$\frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$ | $|\uparrow\uparrow\rangle, |\downarrow\downarrow\rangle$



Spin-projected two-bod
density of the deuteron
for AV18 potential

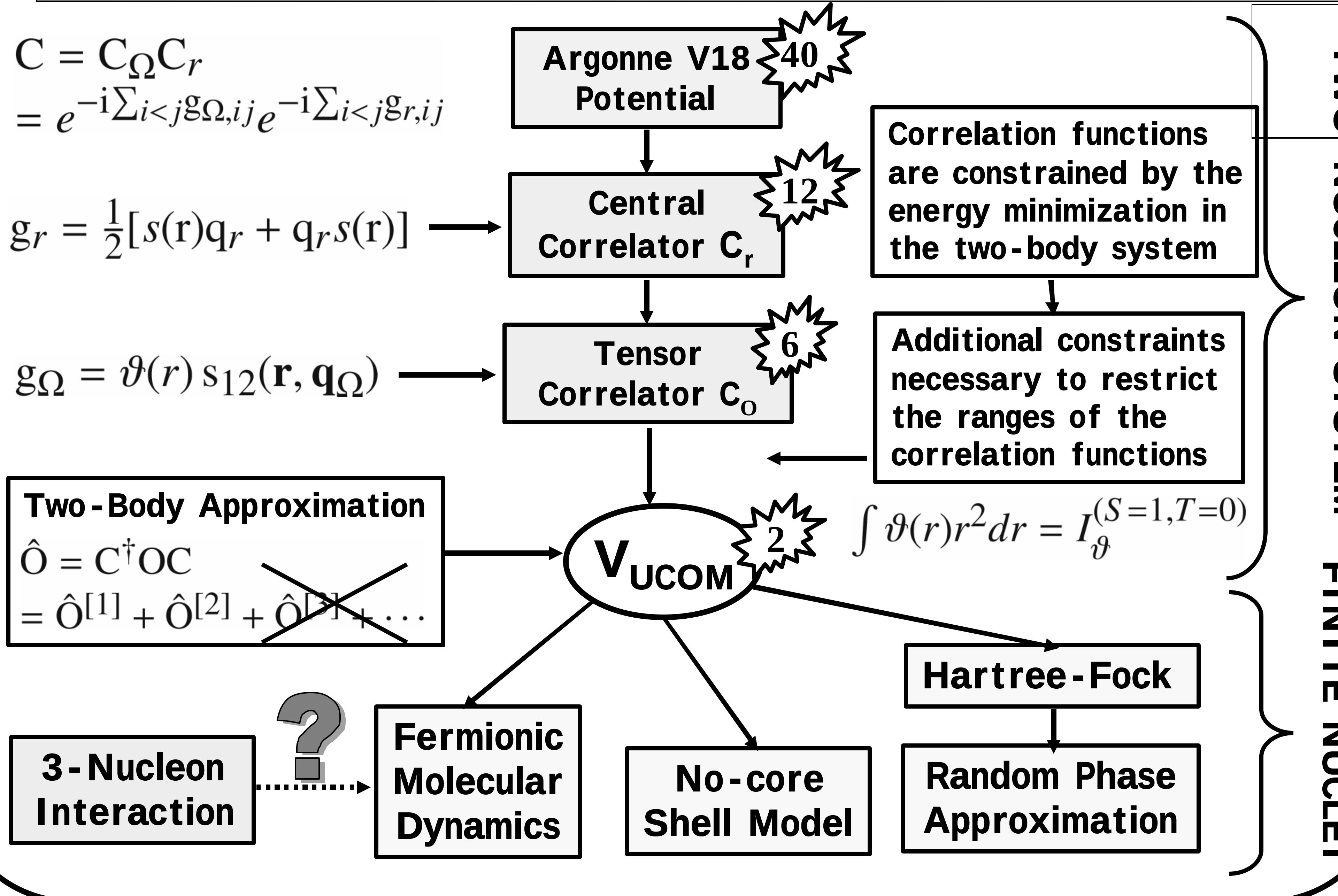
TWO-BODY DENSITY FULLY SUPPRESSED AT SMALL PARTICLE DISTANCES

ANGULAR DISTRIBUTION DEPENDS STRONGLY ON RELATIVE SPIN ORIENTATION

CENTRAL CORRELATIONS

TENSOR CORRELATIONS

THE UNITARY CORRELATION OPERATOR METHOD

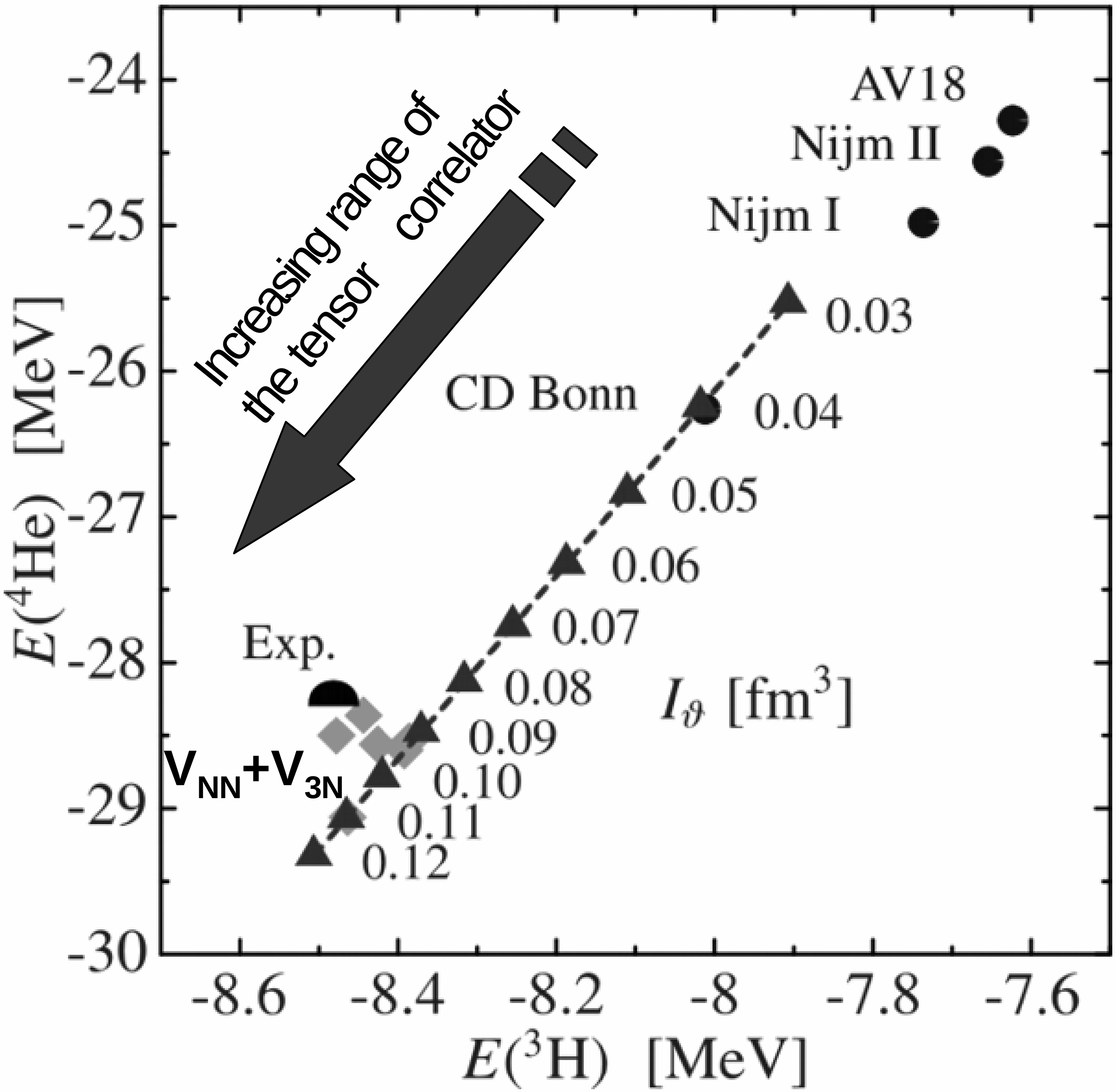


CORRELATED REALISTIC NN INTERACTION - V_{UCOM}

$$\hat{\mathrm{H}}^{C2} = \hat{\mathrm{T}}^{[1]} + \hat{\mathrm{T}}^{[2]} + \hat{V}^{[2]} = T + V_{UCOM}$$

- Closed operator expression for the correlated interaction V_{UCOM} in two-body approximation
- Correlated interaction and original NN-potential are phase shift equivalent by construction
- Central and tensor correlations are essential to obtain bound nuclear system
- Momentum-space matrix elements of the correlated interaction V_{UCOM} are similar to low-momentum interaction $V_{low\text{-}k}$

WHAT IS OPTIMAL RANGE FOR THE TENSOR CORRELATOR



NO-CORE SHELL MODE
CALCULATIONS USING
V_{UCOM} POTENTIAL

R. Roth et al, nucl-th/05050

SELECT A CORRELATOR WITH ENERGY CLOSE TO EXPERIMENTAL VALUE

CANCELLATION OF OMMITED 3-BODY CONTRIBUTIONS OF THE CLUSTER EXPANSION AND GENUINE 3-BODY FORCE

Hartree-Fock Model Based on Correlated Realistic NN-potentia

- **Nucleons are moving in an average single-particle potential**

$$\hat{h}\,|\phi_{nljm}\rangle = E_{nlj}\,|\phi_{nljm}\rangle$$

- **Expansion of the single-particle state in harmonic-oscillator basis**

$$|\phi_{nljm}\rangle = \sum_{\alpha} D^{(lj)}_{n\alpha}\,|u_{\alpha ljm}\rangle$$

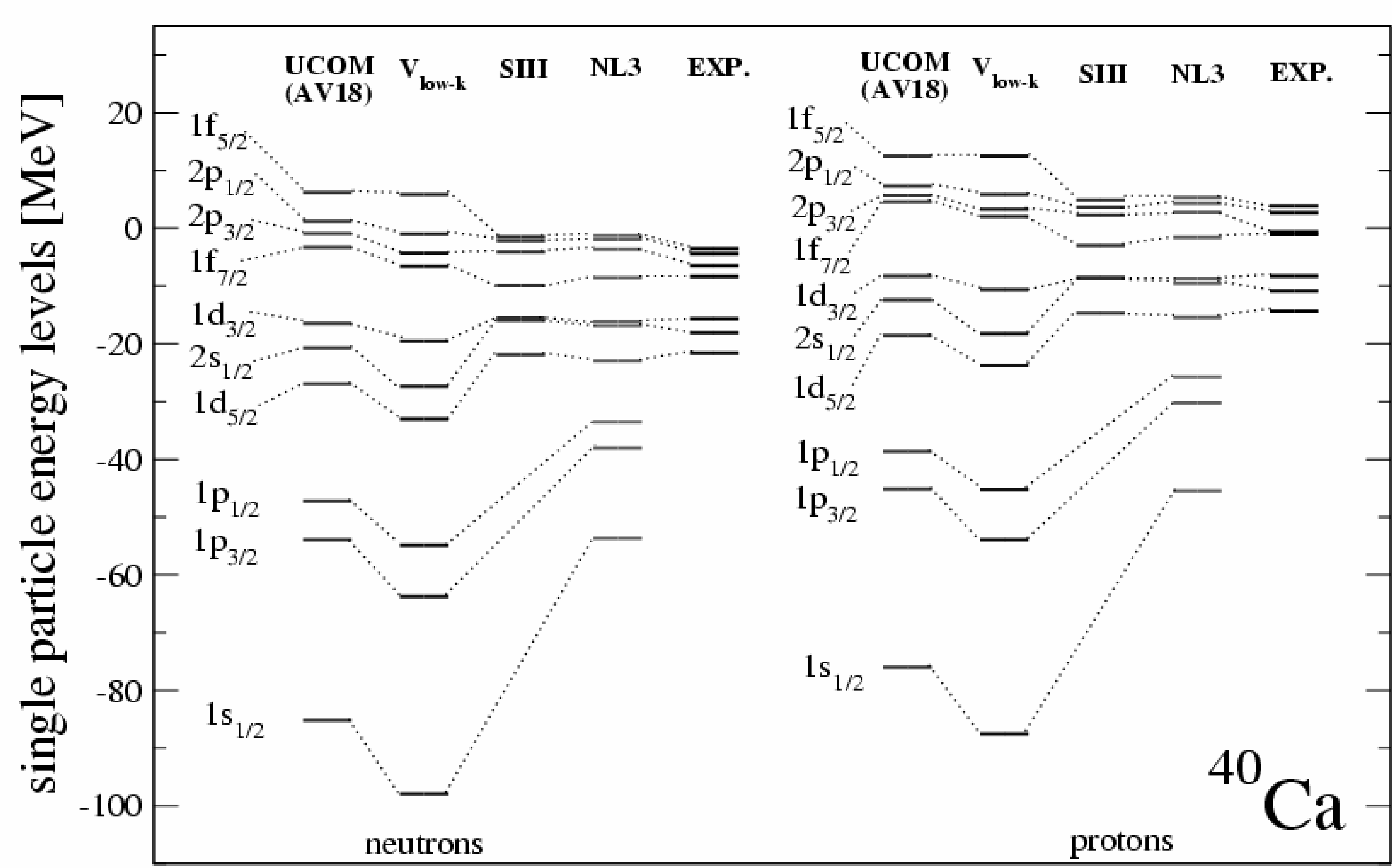
- **Matrix formulation of Hartree-Fock equations as a generalized eigenvalue problem**

$$\boxed{\sum_{\beta} h^{(lj)}_{\alpha\beta} D^{(lj)}_{n\beta} = E_{nlj} \sum_{\beta} N^{(lj)}_{\alpha\beta} D^{(lj)}_{n\beta}}$$

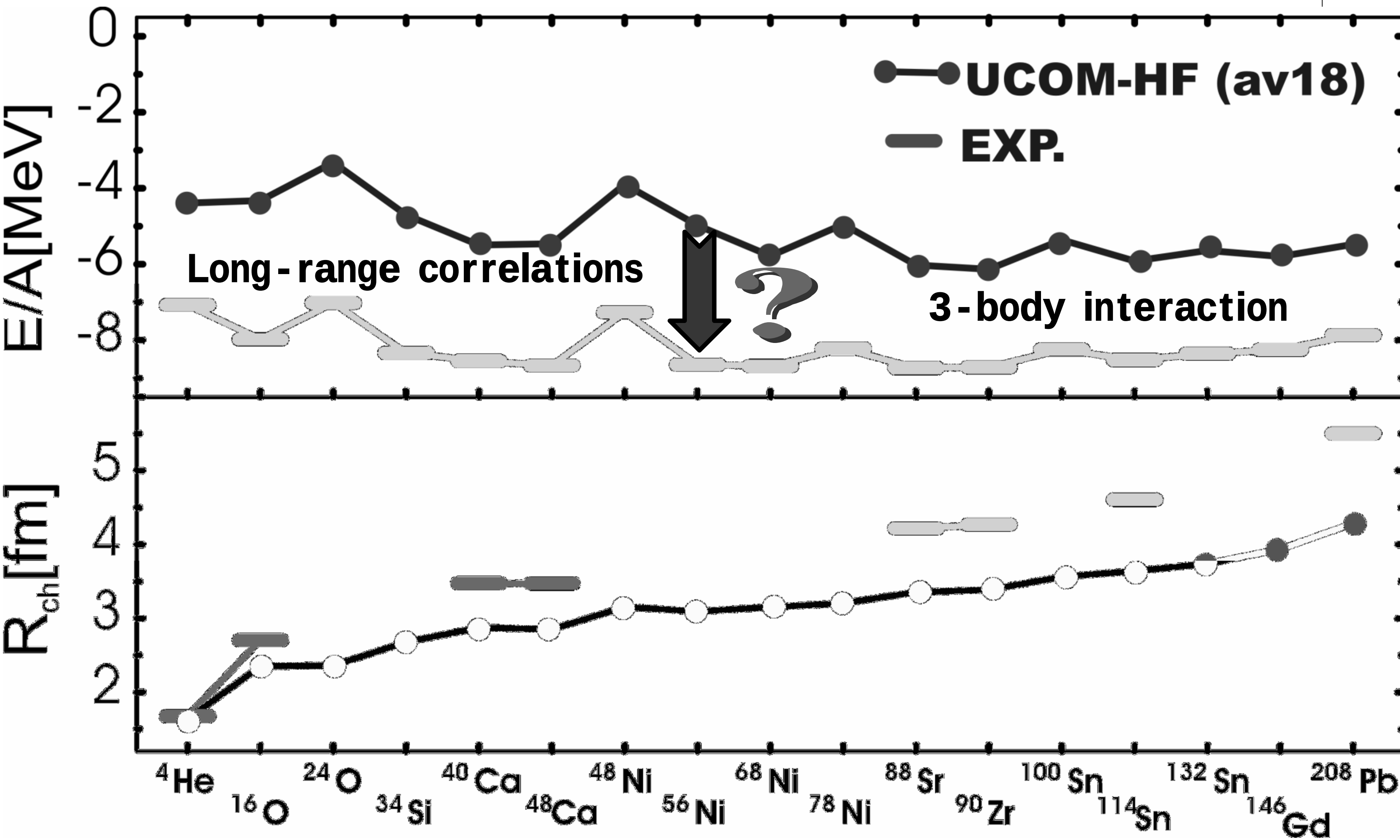
$$v^{(lj)}_{\alpha\beta} = \sum_{n'l'j'J\alpha'\beta'} \langle N_{n'l'j'}\rangle D^{(l'j')}_{n'\alpha'} D^{(l'j')}_{n'\beta'} \langle(\alpha lj, \alpha' l' j')J| \quad |(\beta lj, \beta' l' j')J\rangle_A$$

- **Restrictions on the maximal value of the major shell quantum number N_{MAX}=12 and orbital angular momentum l_{MAX}=8**

UCOM Hartree-Fock Single-Particle Spectra

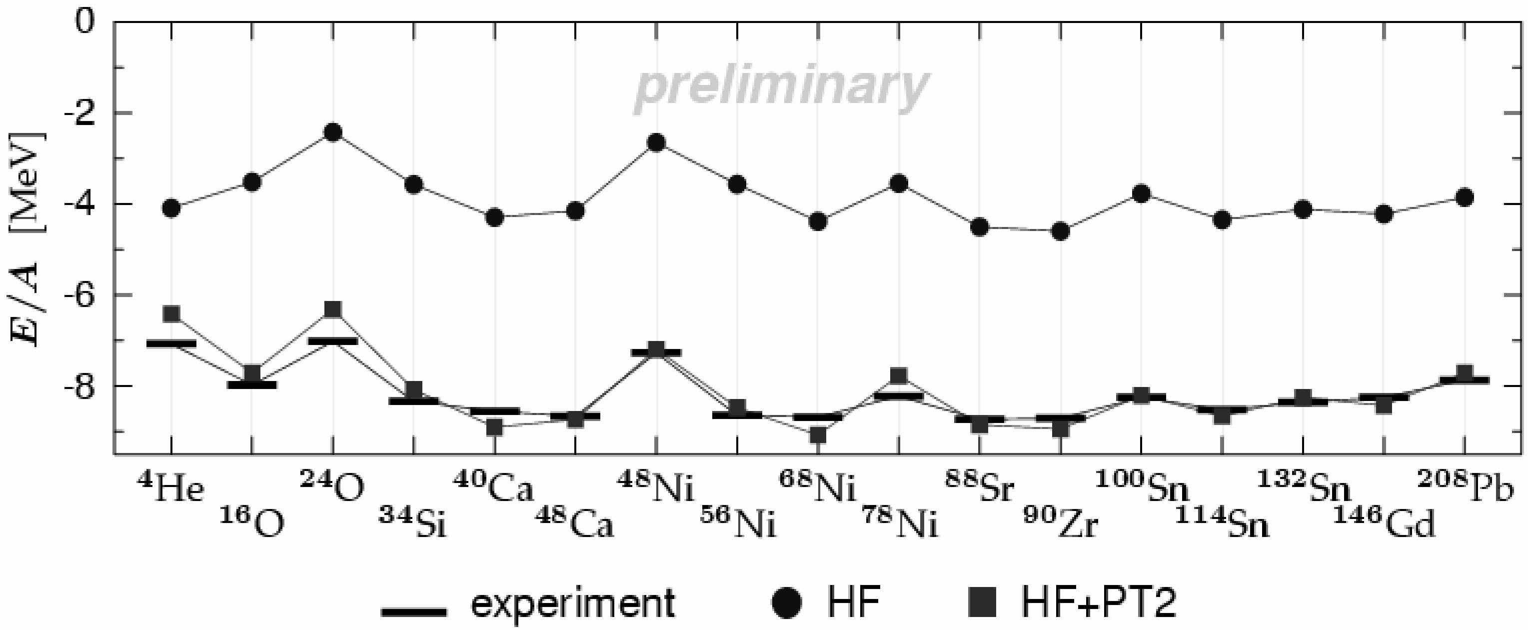


UCOM Hartree-Fock Binding Energies & Charge Radii



- **many-body perturbation theory**: second-order energy shift gives estimate for influence of long-range correlations

$$\Delta E^{(2)} = -\frac{1}{4} \sum_{i,j}^{\text{occu.}} \sum_{a,b}^{\text{unoccu.}} \frac{\left|\left\langle \phi_a \phi_b \right| \mathrm{T}_{\text{int}} + \mathrm{V}_{\text{UCOM}} \left| \phi_i \phi_j \right\rangle\right|^2}{\epsilon_a + \epsilon_b - \epsilon_i - \epsilon_j}$$



UCOM Random-Phase Approximation

<u>Low-amplitude collective oscillations</u>

Vibration creation operator (1p-1h):

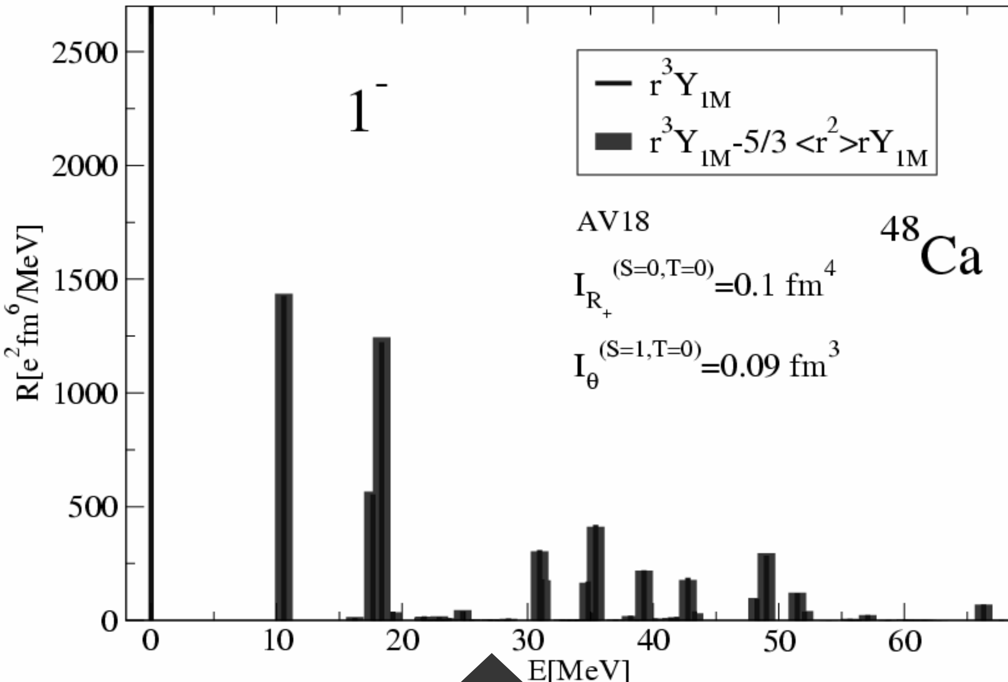
$$Q_\nu^+ = \sum_{mi} X_{mi}^\nu a_m^+ a_i - \sum_{mi} Y_{mi}^\nu a_i^+ a_m$$
$$Q_\nu |0\rangle = 0$$
$$Q_\nu^+ |0\rangle = |\nu\rangle$$

Equations of motion ® RPA

$(|0\rangle \approx |HF\rangle$ **&** $[Q_\nu(m,i), Q_\mu^+(n,j)] = \delta_{\nu\mu}\delta_{mn}\delta_{ij})$

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

V

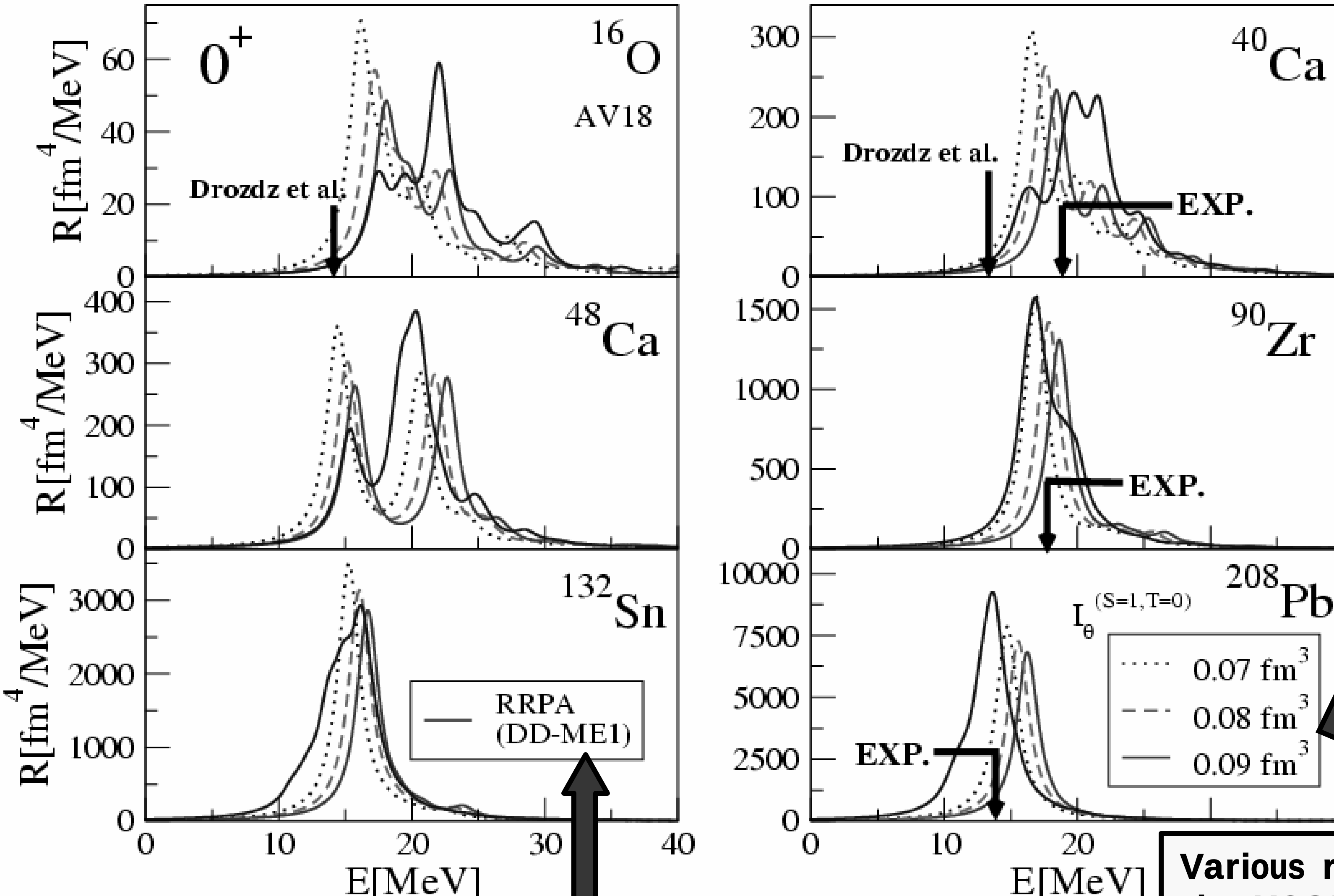


EXCITATION ENERGIES

<u>Fully-self consistent RPA model:</u> there is no mixing between the spurious 1- state and excitation spectra

Sum rules: ?=±3%

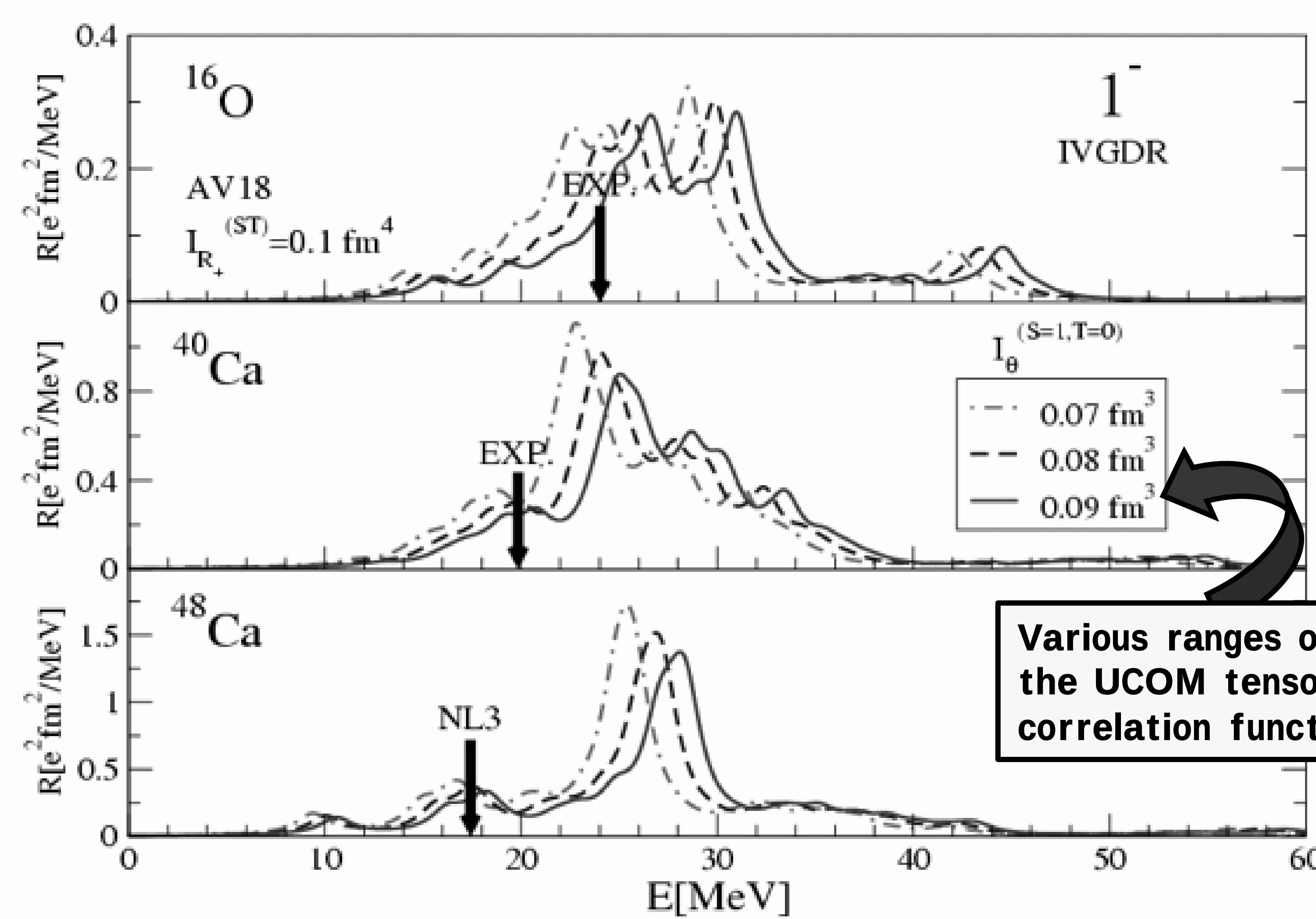
UCOM-RPA Isoscalar Giant Monopole Resonance



Relativistic RPA (DD-ME1 interaction)

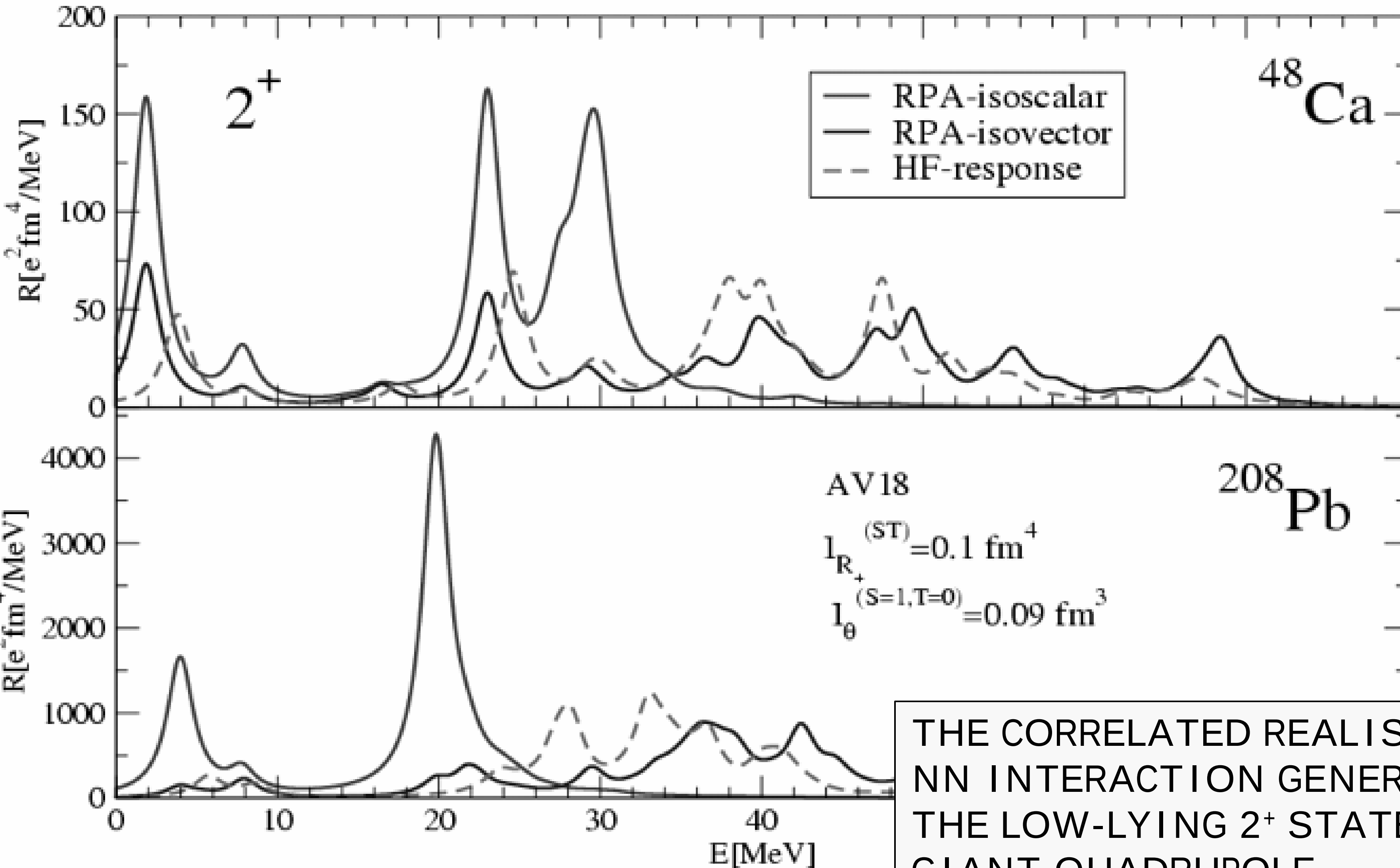
Various ranges of the UCOM tensor correlation functions

UCOM-RPA Isovector Giant Dipole Resonance



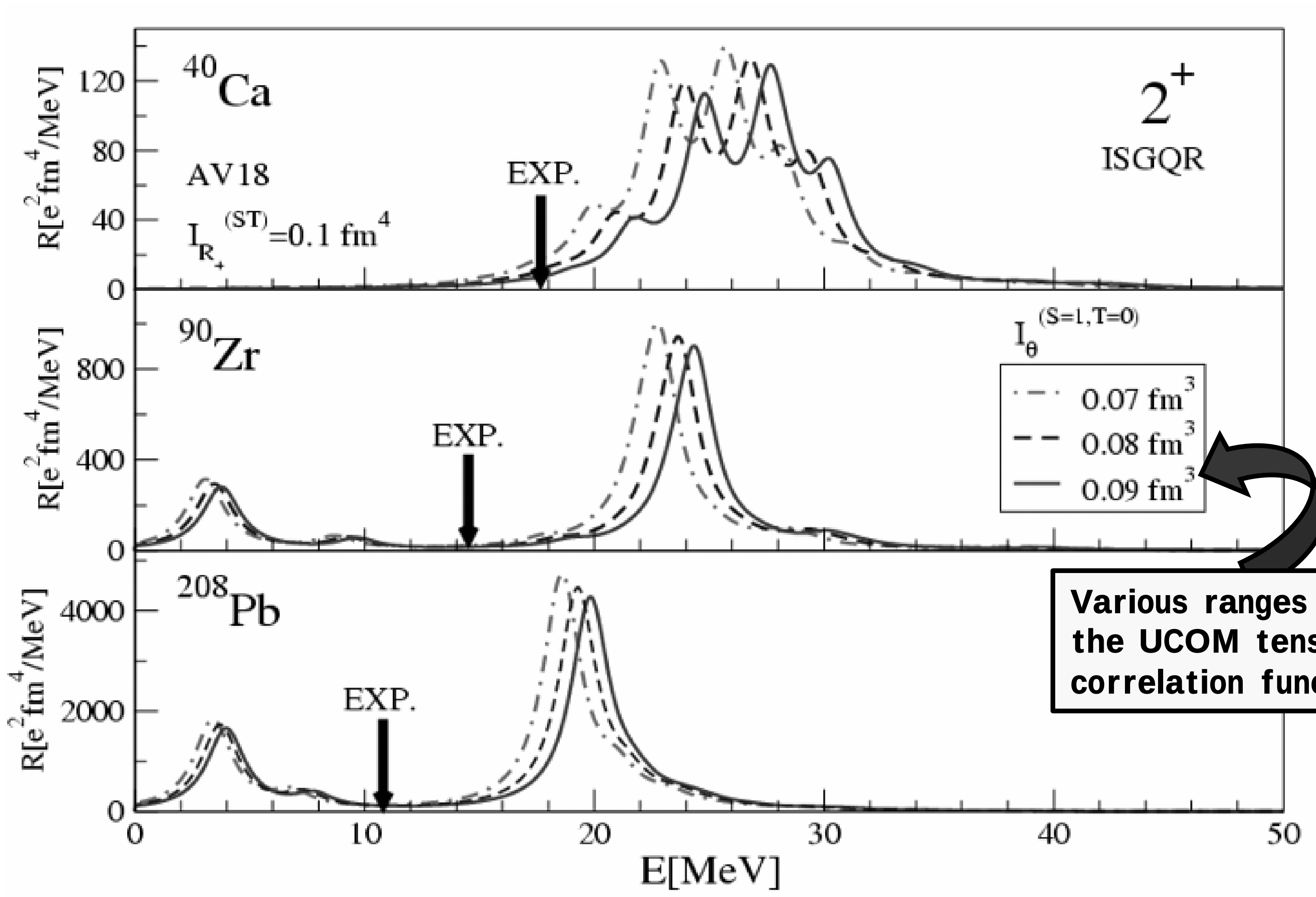
Various ranges of the UCOM tensor correlation functions

UCOM - RPA Giant Quadrupole Resonance



THE CORRELATED REALISTIC NN INTERACTION GENERATES THE LOW-LYING 2^+ STATE AND GIANT QUADRUPOLE RESONANCE

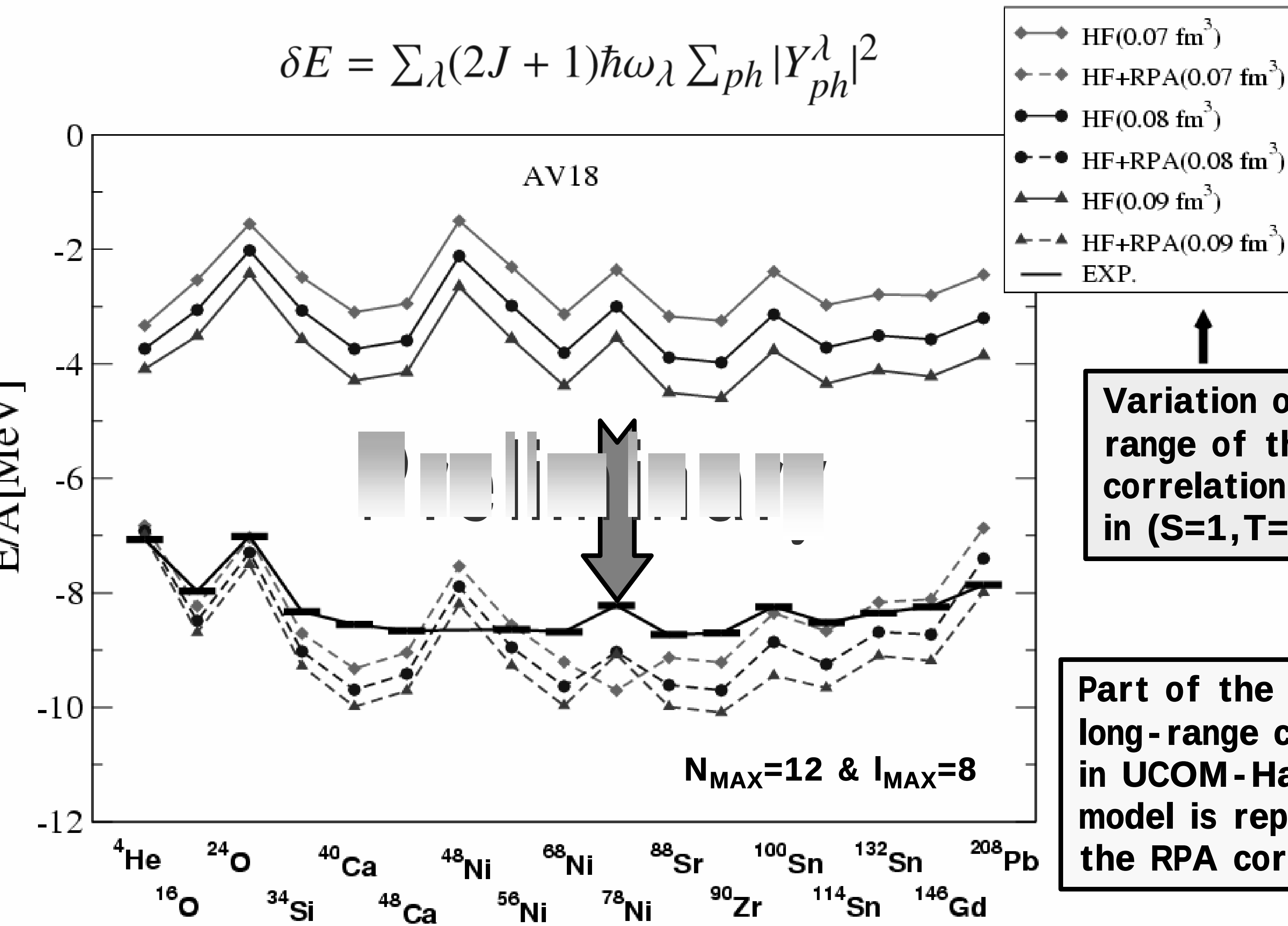
UCOM-RPA Isoscalar Giant Quadrupole Resonance



Various ranges of the UCOM tensor correlation functions

UCOM-RPA GROUND-STATE CORRELATIONS

$$\delta E = \sum_\lambda (2J+1)\hbar\omega_\lambda \sum_{ph} |Y^\lambda_{ph}|^2$$



Variation of the range of the tensor correlation function in (S=1,T=0) channel

Part of the missing long-range correlations in UCOM-Hartree-Fock model is reproduced by the RPA correlations

COLLABORATORS

RMF-RQRPA	UCOM
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D. Vretenar	*R. Roth*

SFB 634