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Collective Excitations in the Unitary Correlation Operator Model and Relativistic QRPA Studies of Exotic Nuclei

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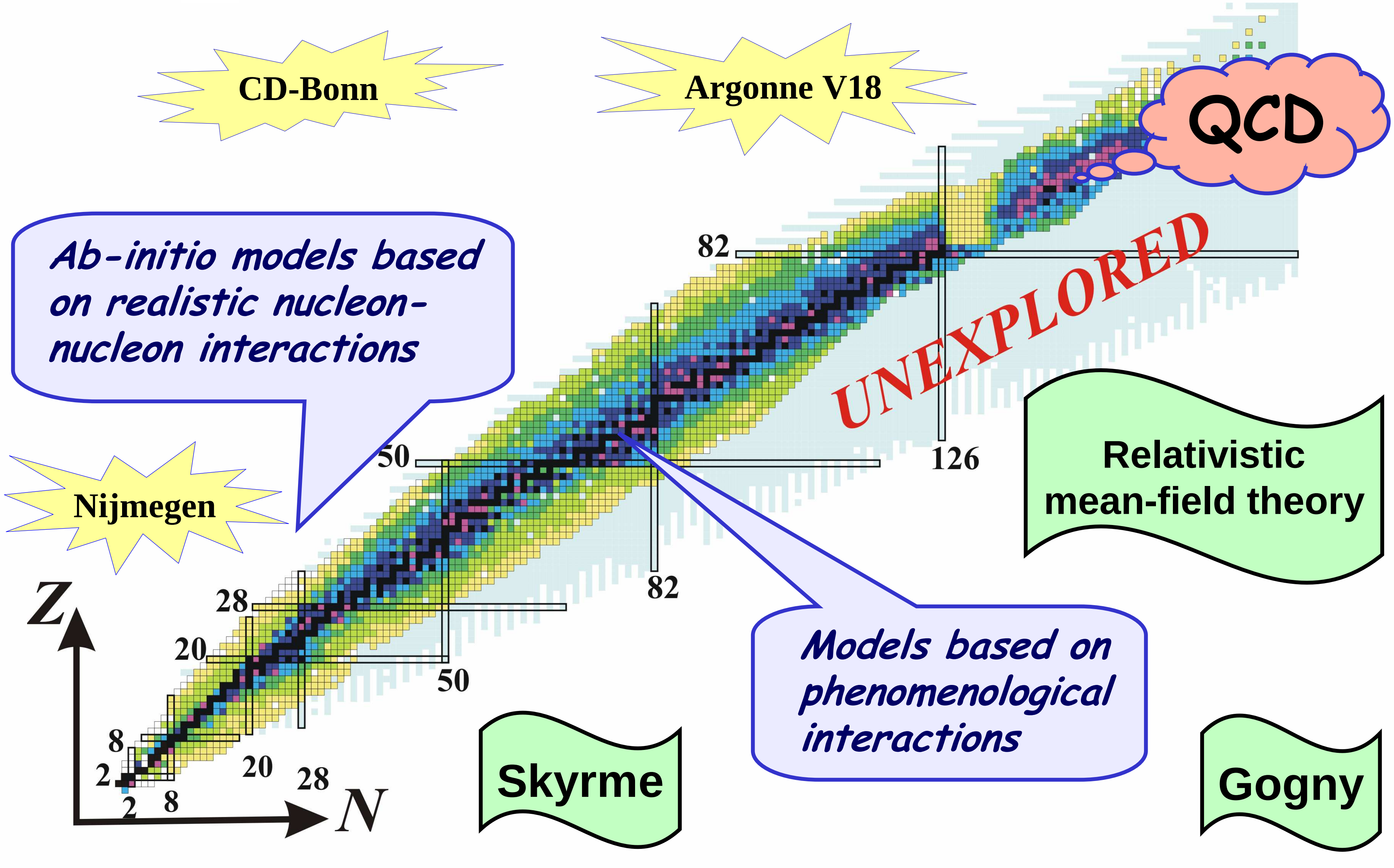
SFB 634

THEORY OF THE NUCLEAR STRUCTURE

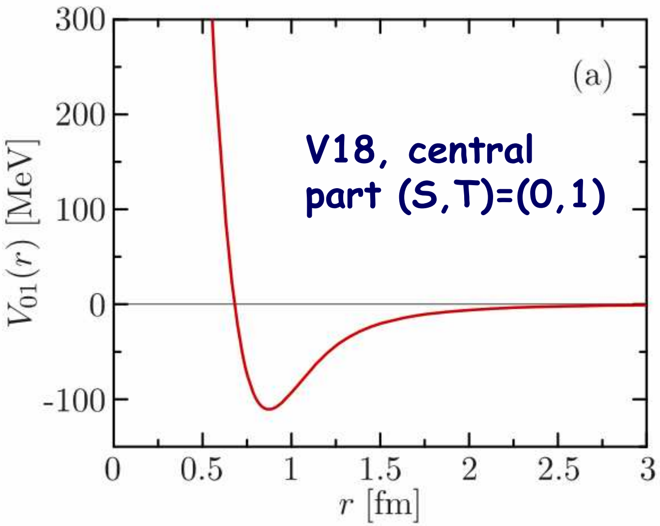


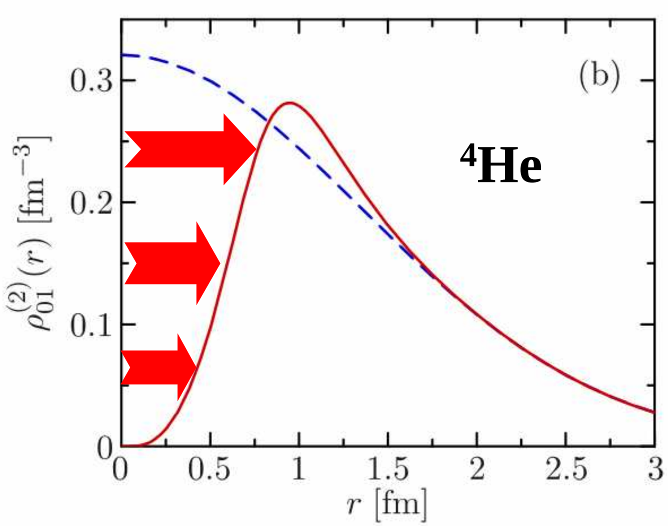
1. Hartree-Fock and Random-Phase Approximation (RPA) in the Unitary Correlation Operator Model (UCOM)

Realistic and Effective Nucleon-Nucleon Interactions

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

- Realistic nucleon-nucleon interaction has strong repulsive core at small distances ~ 0.5 fm





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

Realistic nucleon-nucleon interactions → C → Effective nucleon-nucleon interaction

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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

$$|\hat{\Psi}\rangle = C\,|\Psi\rangle$$

UNCORRELATED MANY-BODY STATE

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

UNCORRELATED OPERATOR

CORRELATED OPERATOR

- Instead of correlated many-body states, we use the correlated operators in nuclear structure models for finite nuclei

R. Roth et al., Nucl. Phys. A 745, 3 (2004)
H. Feldmeier et al., Nucl. Phys. A 632, 61 (1998)
T. Neff et al., Nucl. Phys. A 713, 311 (2003)

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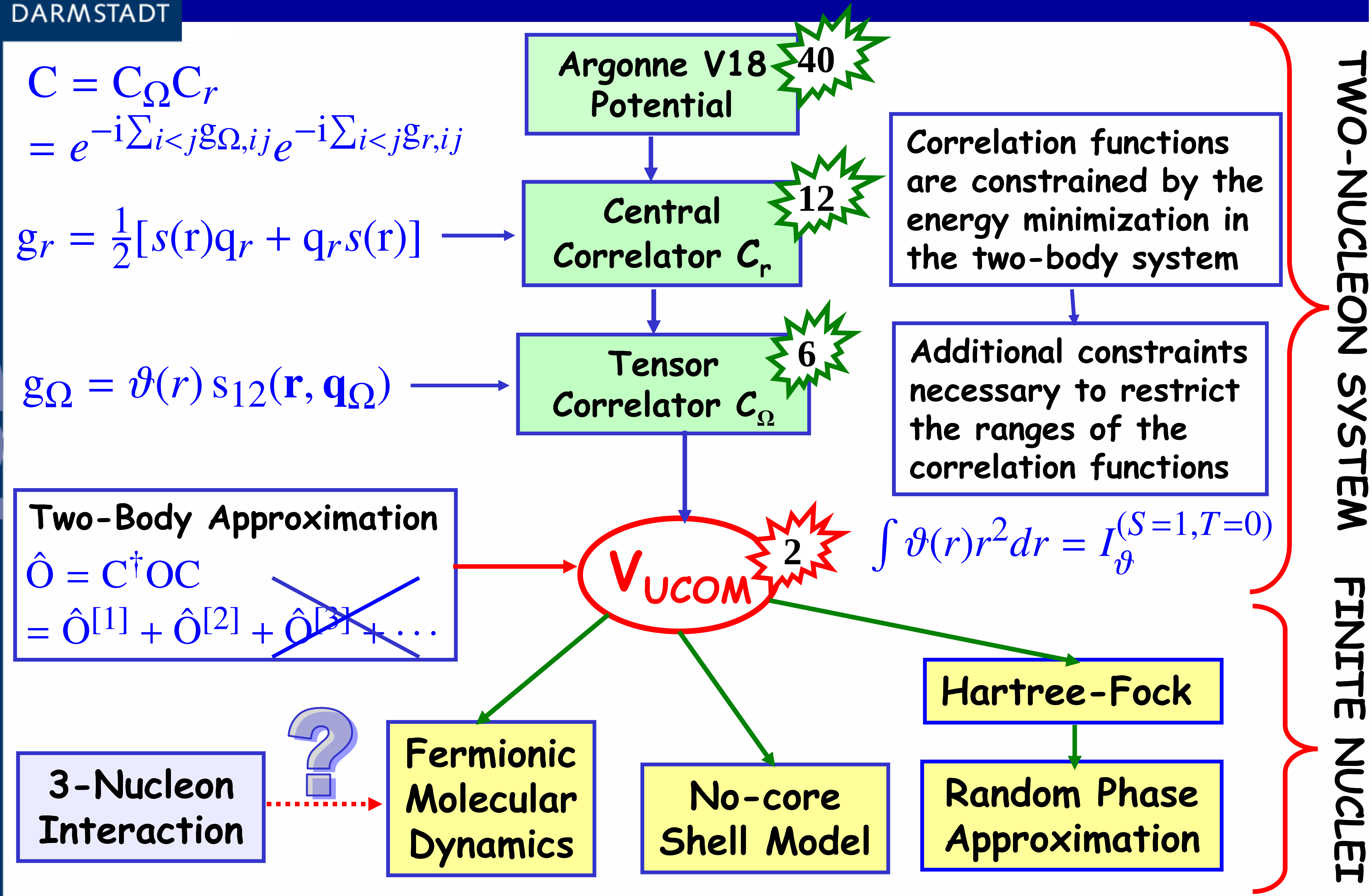
THE UNITARY CORRELATION OPERATOR METHOD



Hartree-Fock Model Based on Correlated NN-potential

- 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

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

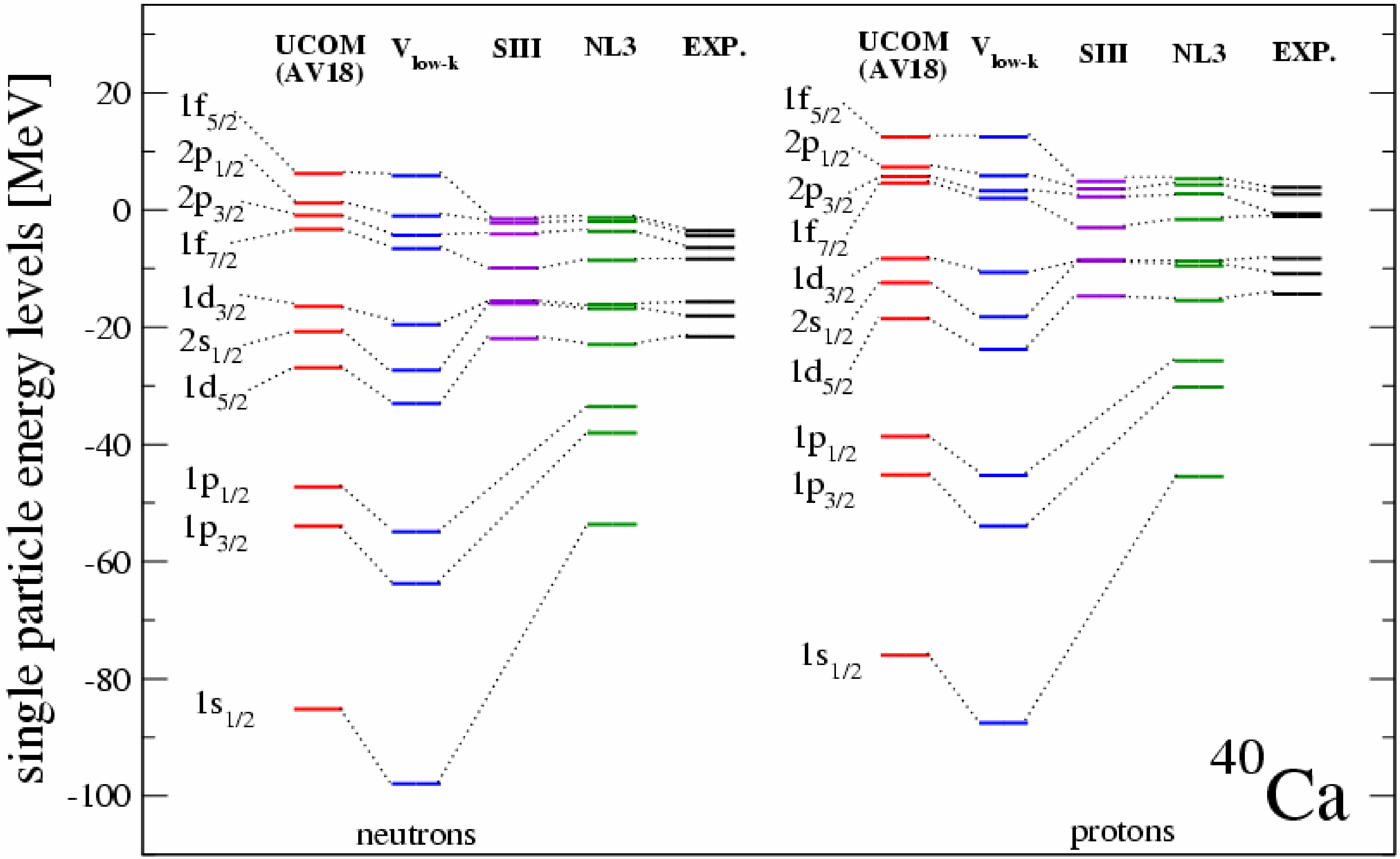
- Matrix formulation of Hartree-Fock equations as a generalized eigenvalue problem

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

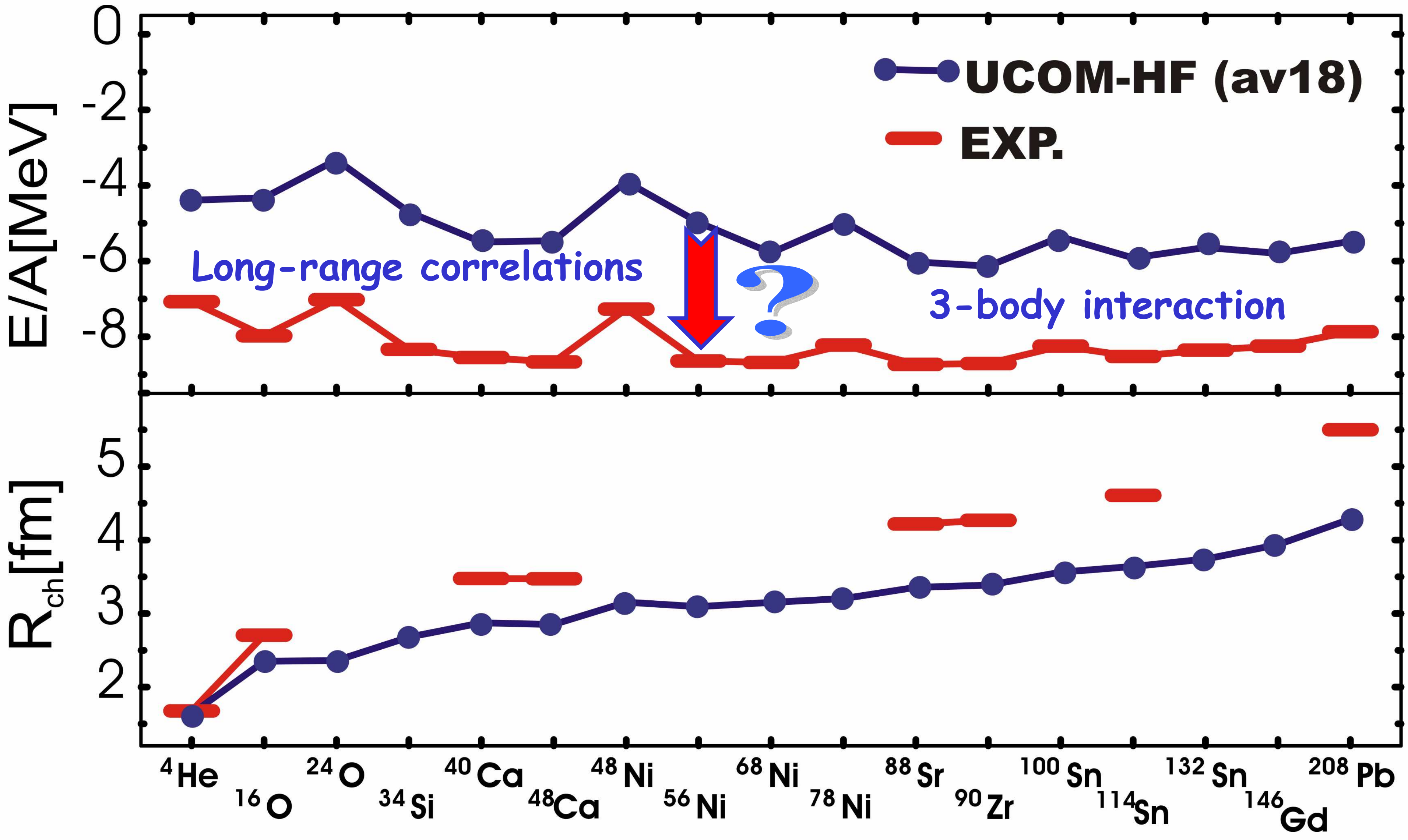
$$v^{(lj)}_{\alpha\beta} = \sum_{n'l'j'J\alpha'\beta'} \langle N_{n'l'j'}\rangle D^{(l'j')}_{n'\alpha'} D^{(l'j')}_{n'\beta'} \langle(\alpha l j, \alpha' l' j')J|\,V_{UCOM}\,|(\beta l j, \beta' l' j')J\rangle_A$$

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

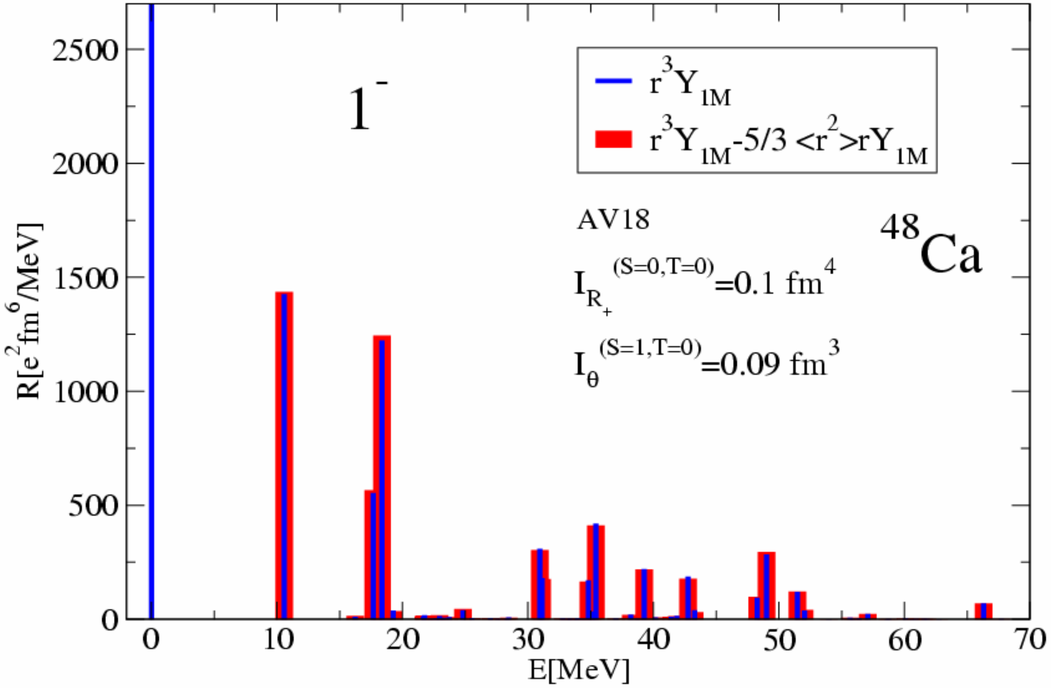
UCOM Hartree-Fock Single-Particle Spectra



UCOM Hartree-Fock Binding Energies & Charge Radii



UCOM Random-Phase Approximation



Low-amplitude collective oscillations

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

($|0\rangle \approx |HF\rangle$ & Quasiboson approximation)

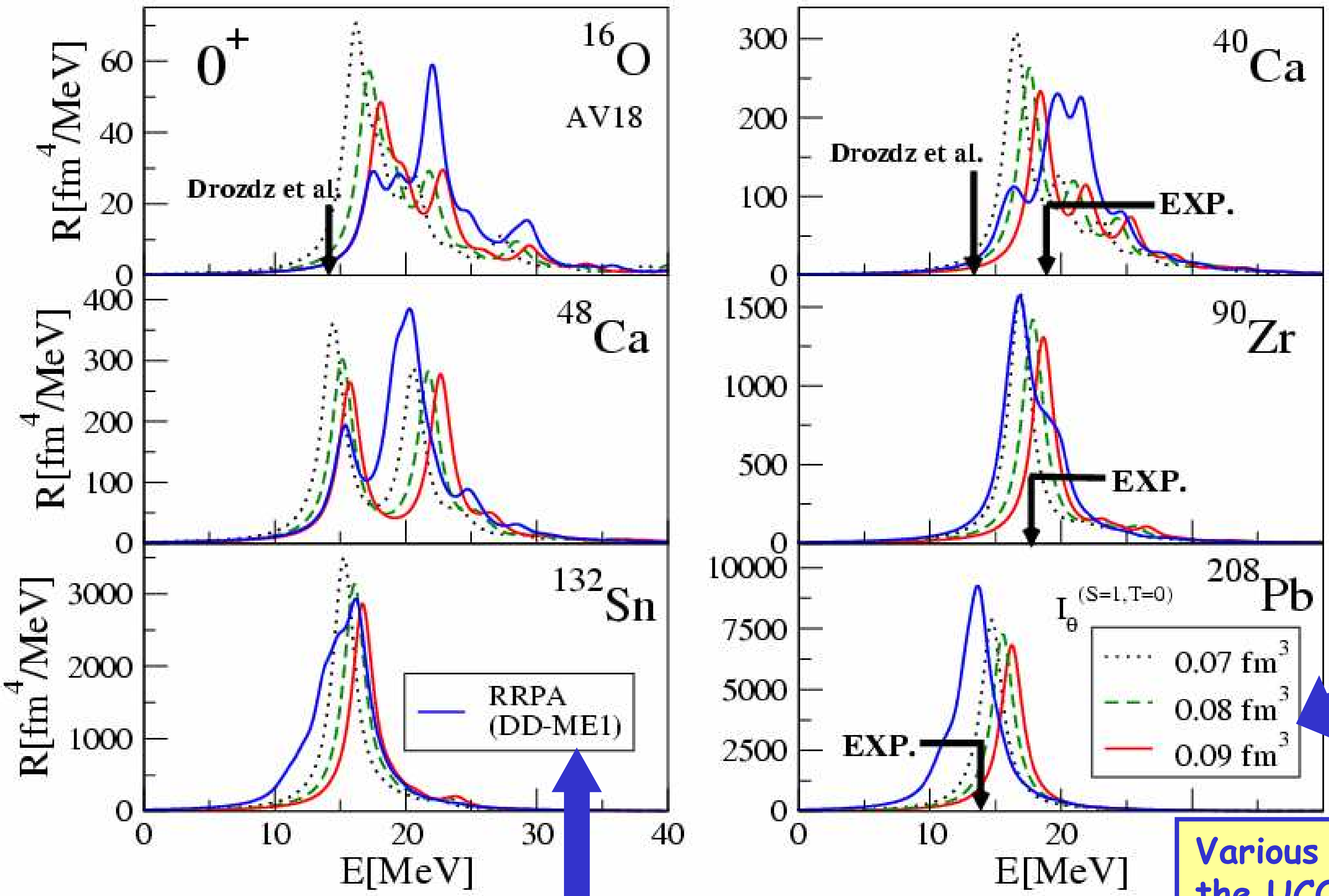
$$\begin{pmatrix} A & B \\ -B^* & -A^* \end{pmatrix} \begin{pmatrix} X^\nu \\ Y^\nu \end{pmatrix} = \omega_\nu \begin{pmatrix} X^\nu \\ Y^\nu \end{pmatrix}$$

V_{UCOM}

EXCITATION ENERGIES

Fully-self consistent RPA model: there is no mixing between the spurious 1⁻ state and excitation spectra

UCOM-RPA Isoscalar Giant Monopole Resonance

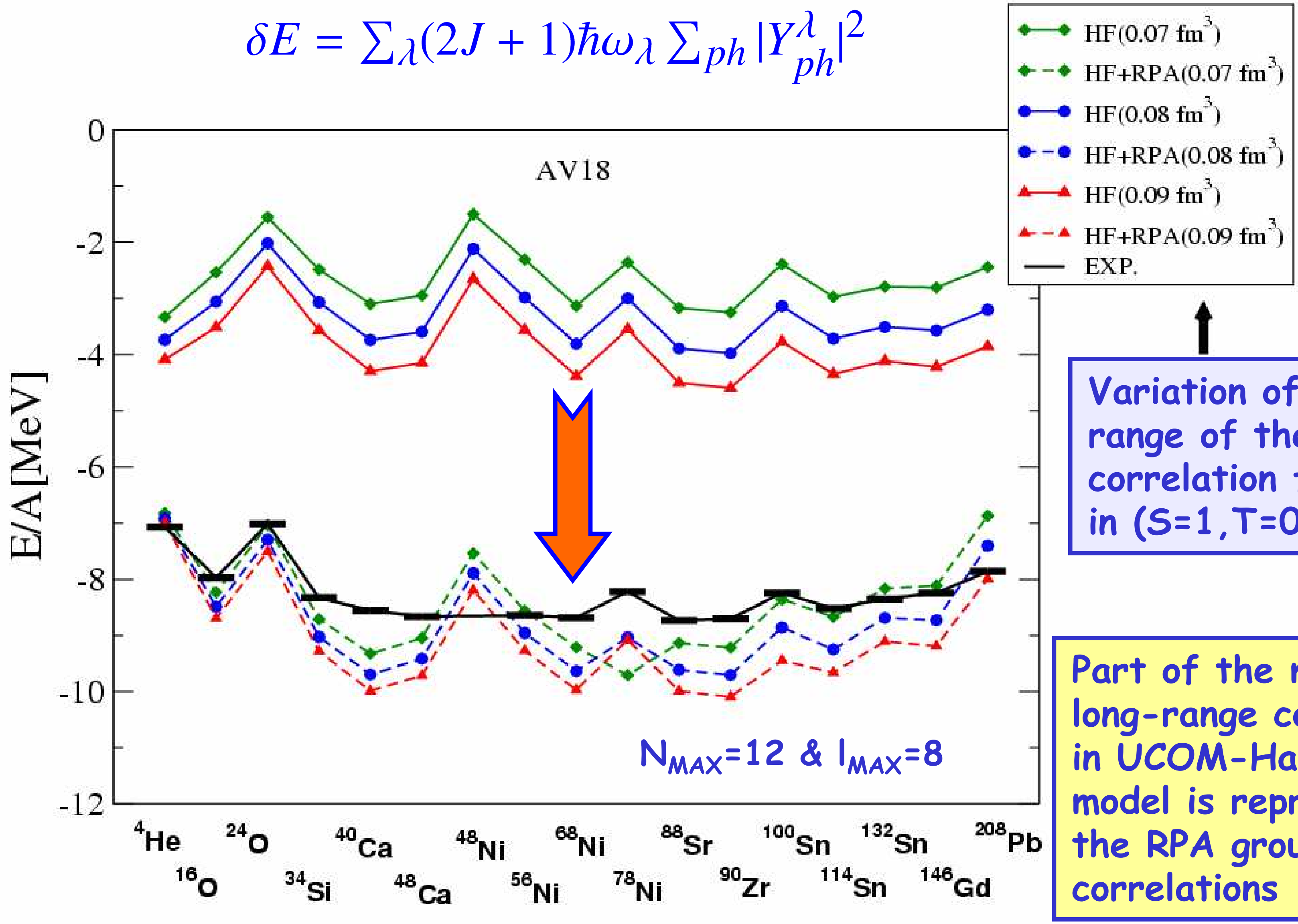


Relativistic RPA (DD-ME1 interaction)

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 ground state correlations

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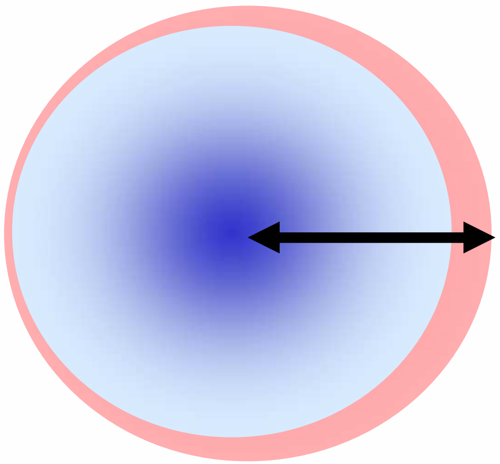
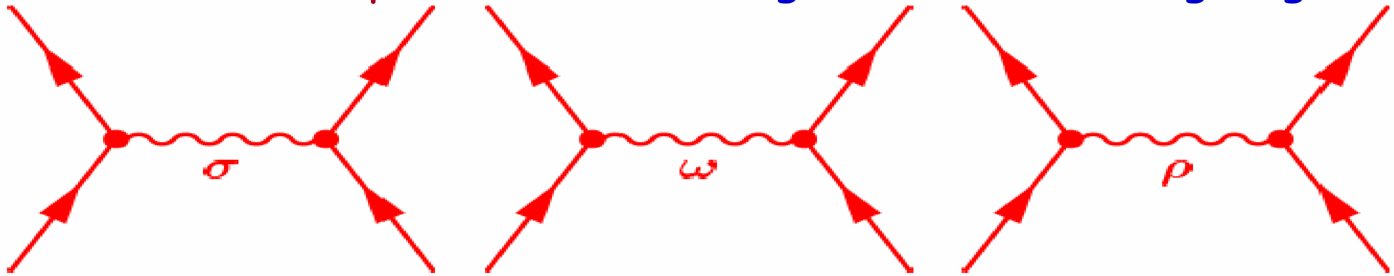
2. Collective Excitations in Exotic Nuclei within the Relativistic Quasiparticle RPA



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 ENERGY FUNCTIONAL: $E_{RMF}[\psi, \sigma, \omega^{\mu}, \vec{\rho}^{\mu}, A^{\mu}]$

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

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

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**

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RELATIVISTIC QUASI-PARTICLE RANDOM-PHASE APPROXIMATION

Paar, Ring, Niksic, Vretenar, Phys. Rev. C67, 034312 (2003)

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

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

$$\begin{aligned} A^{J}_{\kappa\kappa'\lambda\lambda'} = {} & H^{11(J)}_{\kappa\lambda}\delta_{\kappa'\lambda'} - H^{11(J)}_{\kappa'\lambda}\delta_{\kappa\lambda'} - H^{11(J)}_{\kappa\lambda'}\delta_{\kappa'\lambda} + H^{11(J)}_{\kappa'\lambda'}\delta_{\kappa\lambda} \\ & + \frac{1}{2}\left(\xi^{+}_{\kappa\kappa'}\xi^{+}_{\lambda\lambda'} + \xi^{-}_{\kappa\kappa'}\xi^{-}_{\lambda\lambda'}\right)V^{ppJ}_{\kappa\kappa'\lambda\lambda'} \\ & + \zeta_{\kappa\kappa'\lambda\lambda'}V^{phJ}_{\kappa\lambda'\kappa'\lambda} \end{aligned}$$

$$\begin{aligned} B^{J}_{\kappa\kappa'\lambda\lambda'} = {} & \frac{1}{2}\left(\xi^{+}_{\kappa\kappa'}\xi^{+}_{\lambda\lambda'} - \xi^{-}_{\kappa\kappa'}\xi^{-}_{\lambda\lambda'}\right)V^{ppJ}_{\kappa\kappa'\lambda\lambda'} \\ & + \zeta_{\kappa\kappa'\lambda\lambda'}(-1)^{j_\lambda - j_{\lambda'} + J}V^{phJ}_{\kappa\lambda\kappa'\lambda'} \end{aligned}$$

Quasiparticle canonical states

↑

both nucleons in the continuum

↑

both nucleons in discrete bound levels

↑

nucleon in a bound level and nucleon in the continuum

↑

Transitions to the Dirac sea

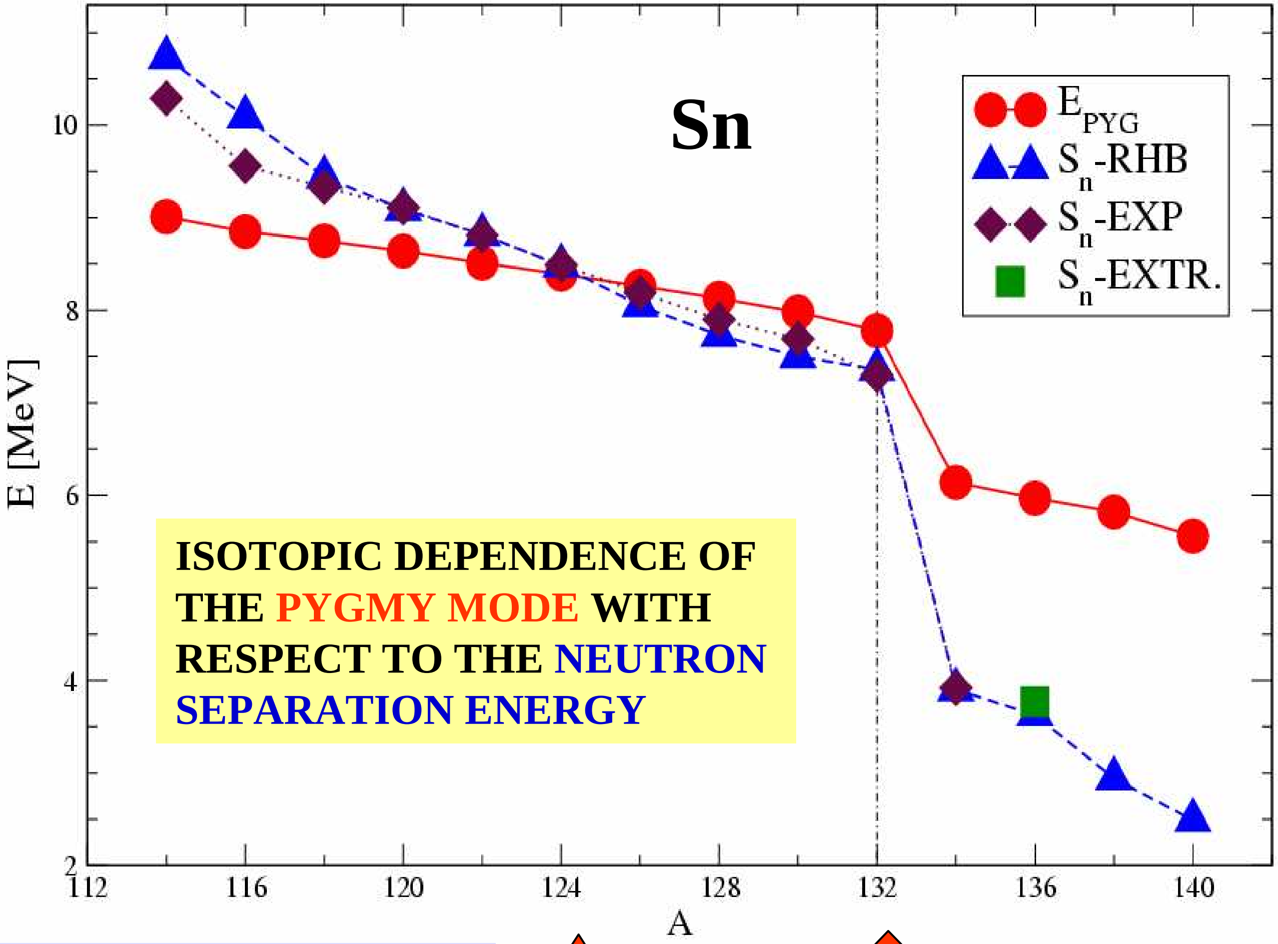
PARTICLE-PARTICLE INTERACTION (Gogny)

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

Factors including the occupation probabilities for the canonical states

THE PYGMY DIPOLE RESONANCE (PDR)

Paar, Niksic, Vretenar, Ring, Phys. Lett. B 606, 288 (2005)



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

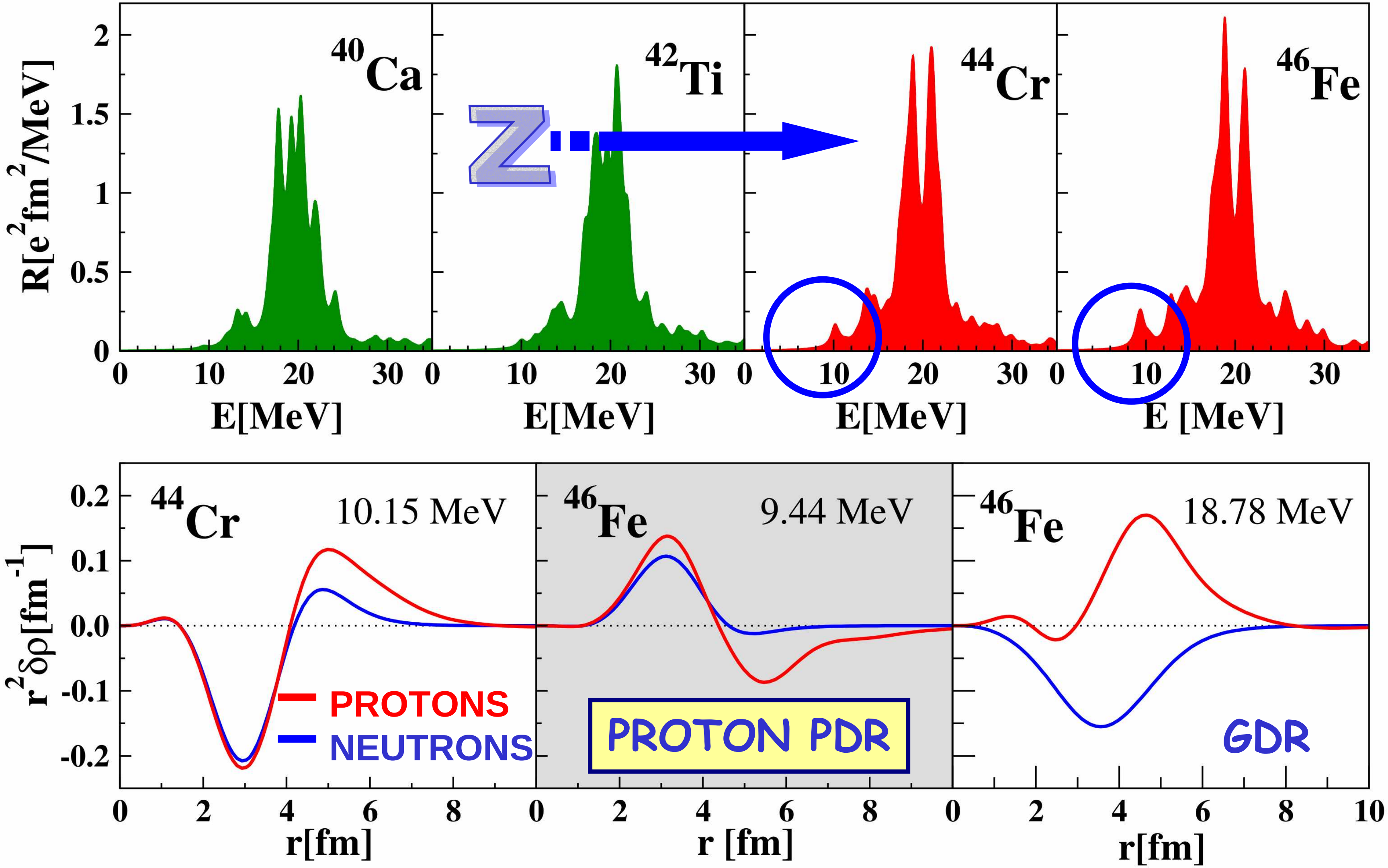
Implications for the observation of the PDR in (γ,γ') experiments

CROSSING BETWEEN THE PYGMY ENERGY AND NEUTRON SEP. EN.

ANOMALOUS KINK AT THE SHELL CLOSURE

THE PROTON ELECTRIC PYGMY DIPOLE RESONANCE

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



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SUMMARY

- The unitary correlation operator model (UCOM) is used to treat the *short-range and tensor correlations* in realistic NN interactions to provide a low-momentum effective interaction for the models of nuclear structure

  - UCOM Hartree-Fock model results with underbinding and small radii → need for the *long-range correlations* (recovered by RPA & perturbation theory) and the *three-body interaction*

- Fully self-consistent UCOM Random-Phase Approximation (RPA) is constructed in the UCOM Hartree-Fock single-nucleon basis, and employed in the studies of giant resonances in finite nuclei

  - Relativistic QRPA studies of exotic nuclei → Pygmy dipole resonance, i.e. collective low-lying excitations *that* correspond to the *vibration of loosely bound excess nucleons* against the proton-neutron core (both on the neutron and proton rich side of the nuclide chart)

- In more neutron-rich nuclei PDR is located above the neutron separation energy → implications for the measurements of the Pygmy mode

COLLABORATORS

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