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Hartree-Fock and RPA Model based on Correlated Realistic Potentials

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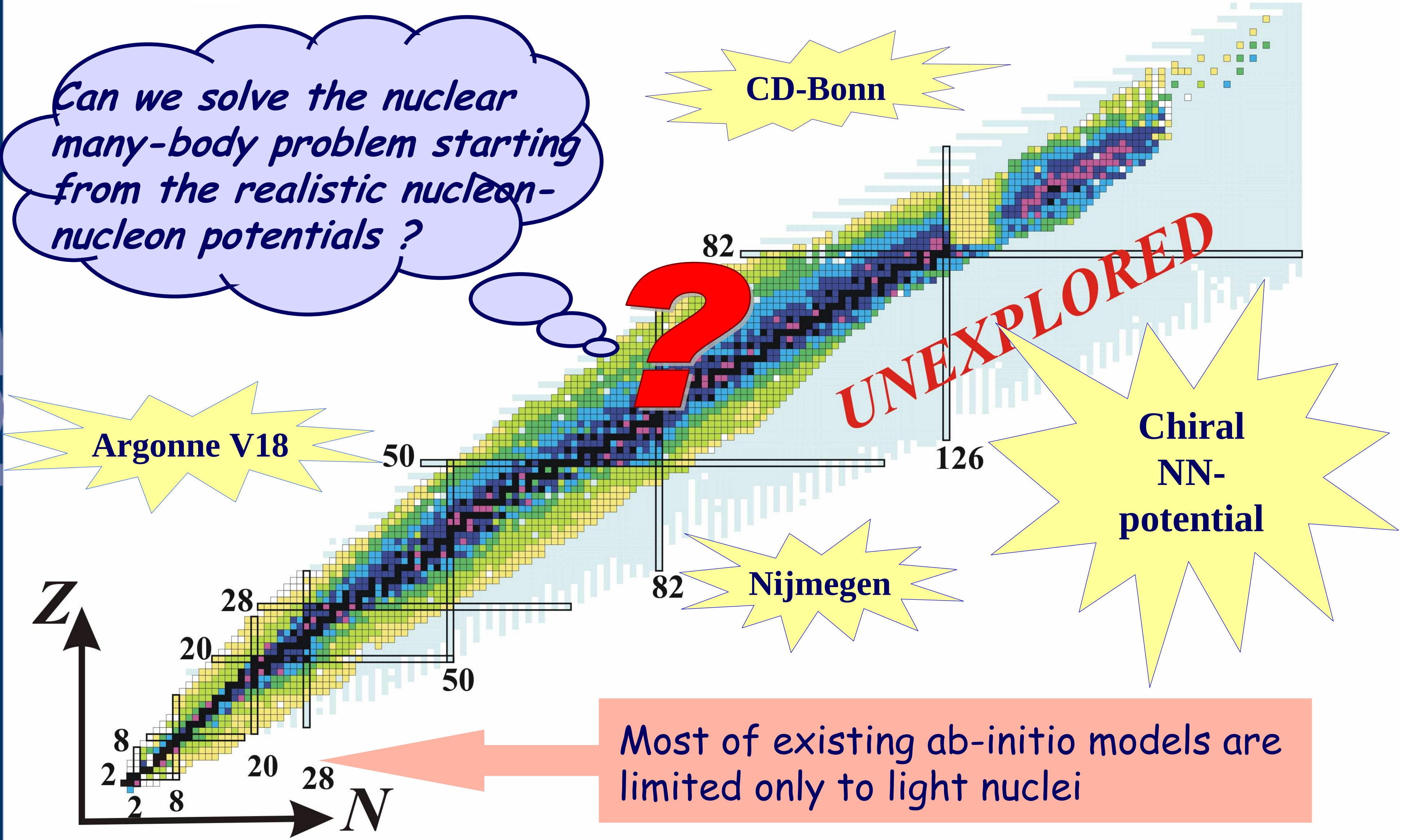
AB-INITIO DESCRIPTION OF THE NUCLEAR STRUCTURE

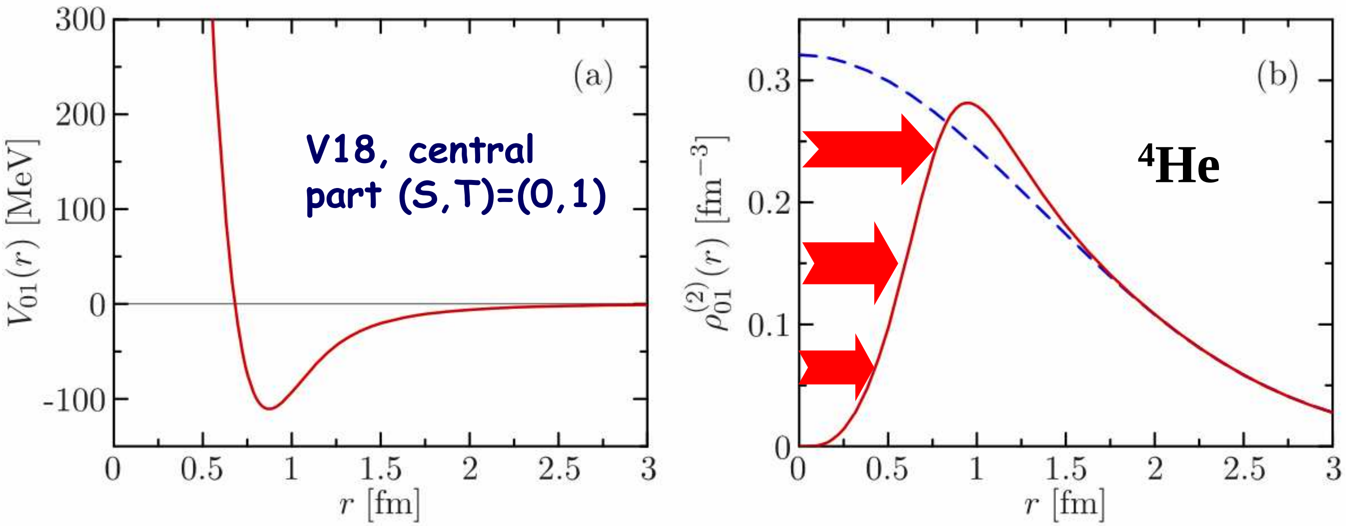
Can we solve the nuclear many-body problem starting from the realistic nucleon-nucleon potentials ?



Most of existing ab-initio models are limited only to light nuclei

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 $\xrightarrow{C}$ 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*

$$\underbrace{|\hat{\Psi}\rangle}_{\text{CORRELATED MANY-BODY STATE}} = \mathrm{C}\,\underbrace{|\Psi\rangle}_{\text{UNCORRELATED MANY-BODY STATE}}$$

$$\langle\hat{\Psi}|\,\underbrace{\mathrm{O}}_{\text{UNCORRELATED OPERATOR}}\,|\hat{\Psi}'\rangle = \underbrace{\langle\Psi|\,\mathrm{C}^{\dagger}}\,\mathrm{O}\,\underbrace{\mathrm{C}\,|\Psi'\rangle} = \langle\Psi|\,\underbrace{\hat{\mathrm{O}}}_{\text{CORRELATED OPERATOR}}\,|\Psi'\rangle$$

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

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

T. Neff
Wednesday 14:00

H. Hergert
Wednesday 14:30

Overview of the Unitary Correlation Operator Method

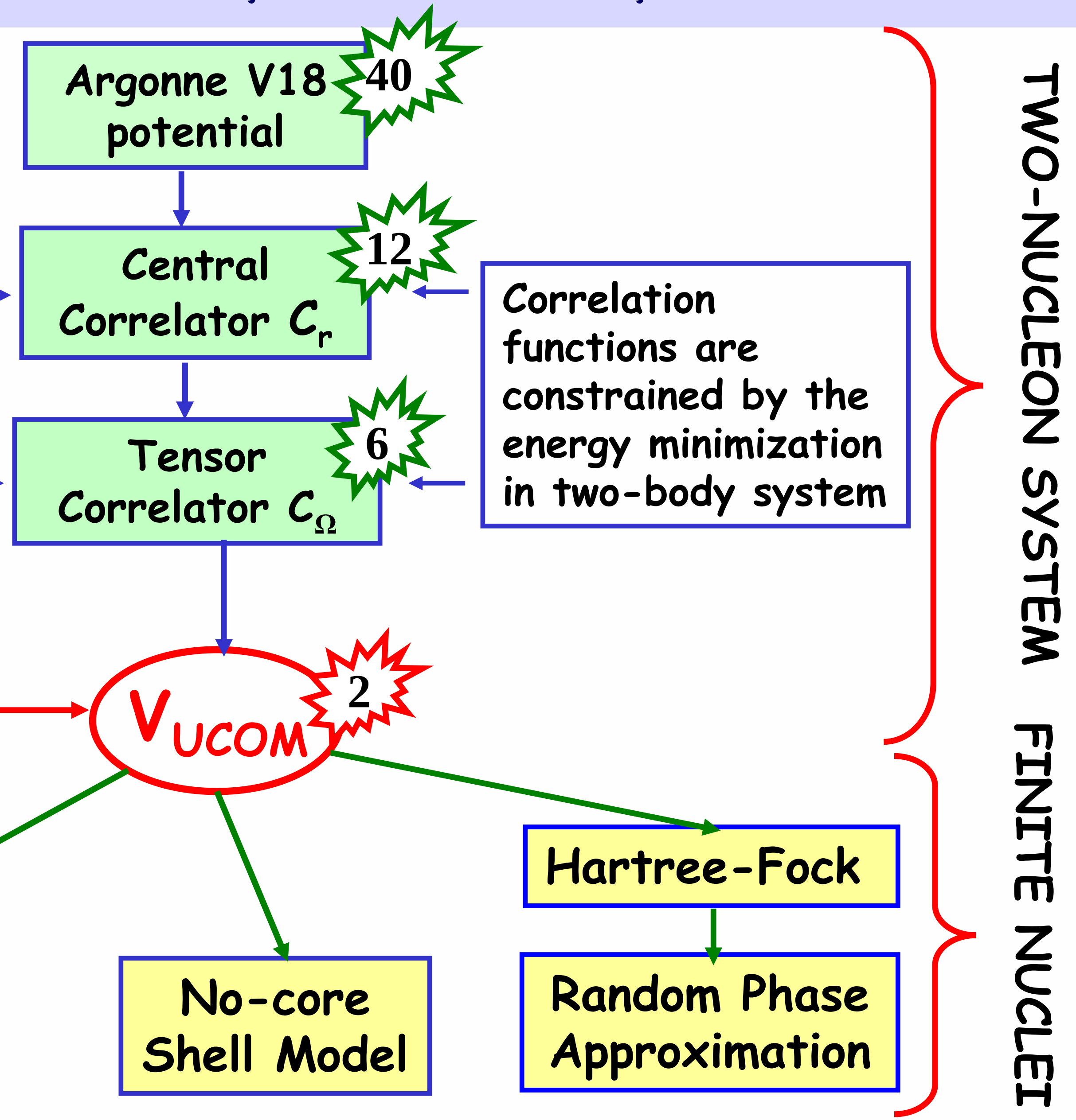
$$C = C_\Omega C_r = e^{-i\sum_{i<j} g_{\Omega,ij}} e^{-i\sum_{i<j} g_{r,ij}}$$

$$g_r = \frac{1}{2}[s(r)q_r + q_r s(r)]$$

$$g_\Omega = \vartheta(r)\, s_{12}(\mathbf{r}, \mathbf{q}_\Omega)$$

Two-body approximation

$$\hat{O} = C^\dagger O C = \hat{O}^{[1]} + \hat{O}^{[2]} + \cancel{\hat{O}^{[3]} + \dots}$$



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

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

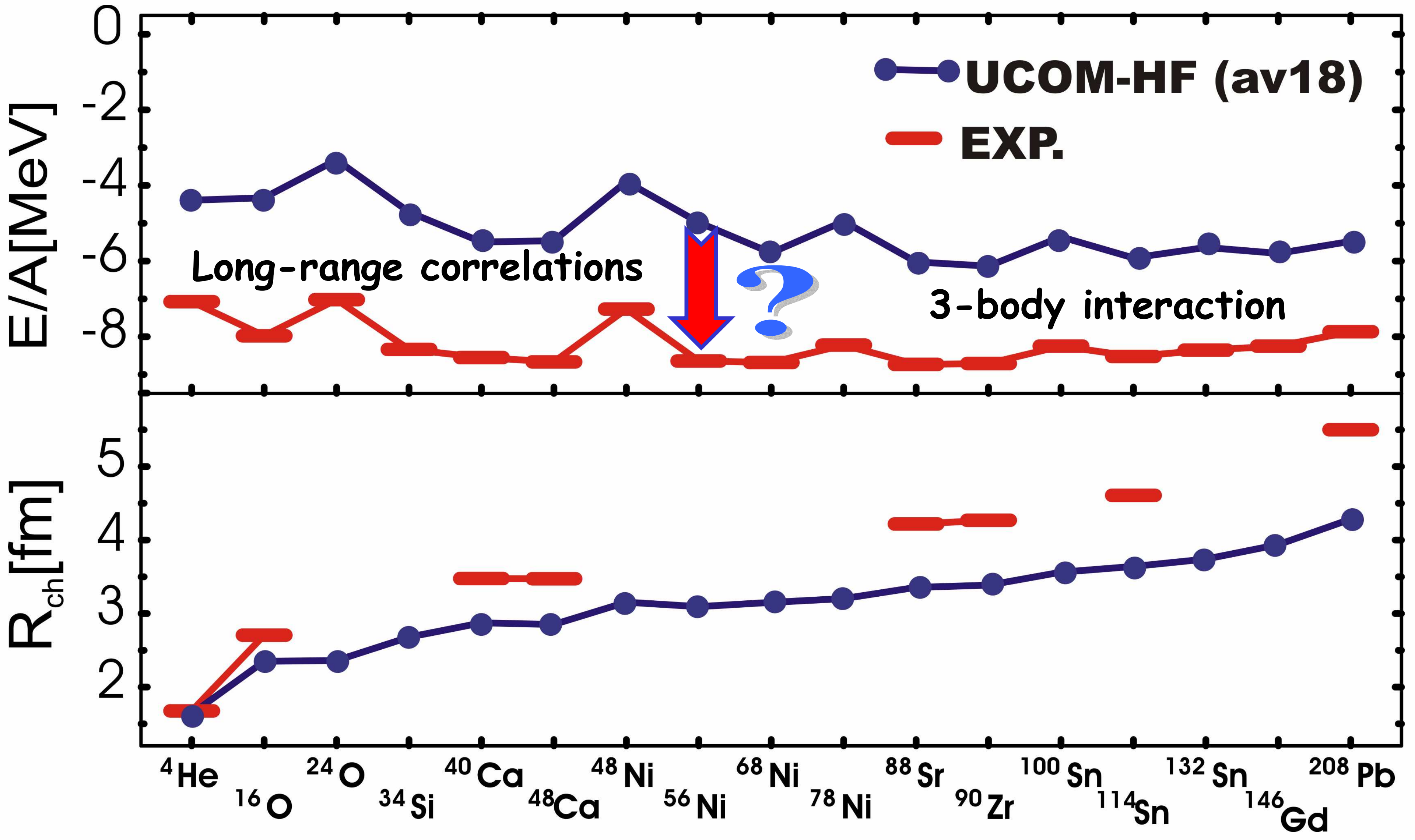
- Matrix formulation of Hartree-Fock equations as a generalized eigenvalue problem

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

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

- Included intrinsic kinetic energy to eliminate center of mass contributions

UCOM Hartree-Fock Binding Energies & Charge Radii



UCOM RANDOM-PHASE APPROXIMATION

- Description of low-amplitude collective excitation phenomena based on correlated nucleon-nucleon interaction

- Vibration creation operator (1p-1h excitations)

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

$$Q_\nu |0\rangle = 0$$

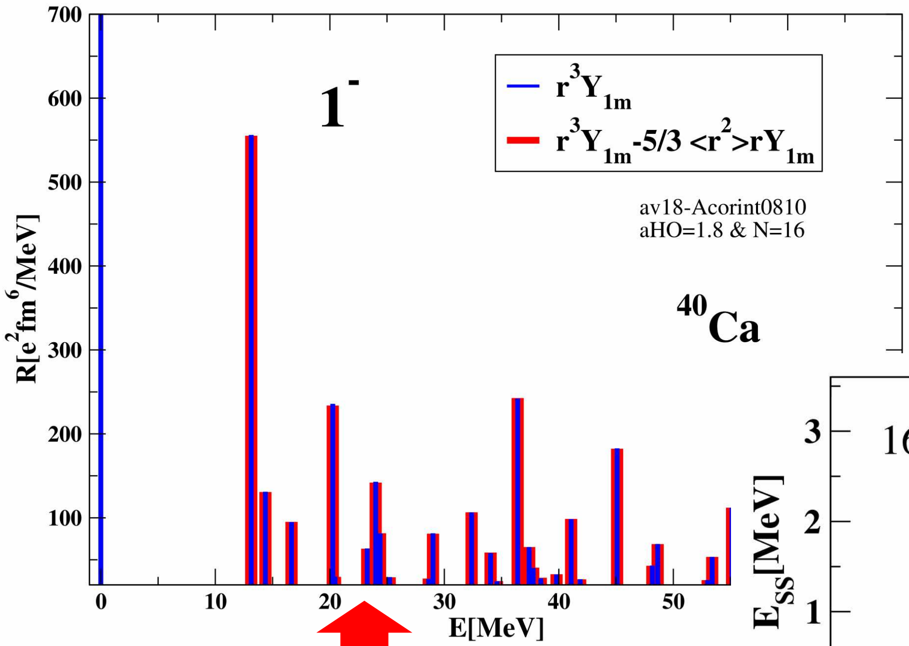
$$Q_\nu^+ |0\rangle = |\nu\rangle$$

- Schrödinger equation $\rightarrow$ Equations of motion $\rightarrow$ RPA equations

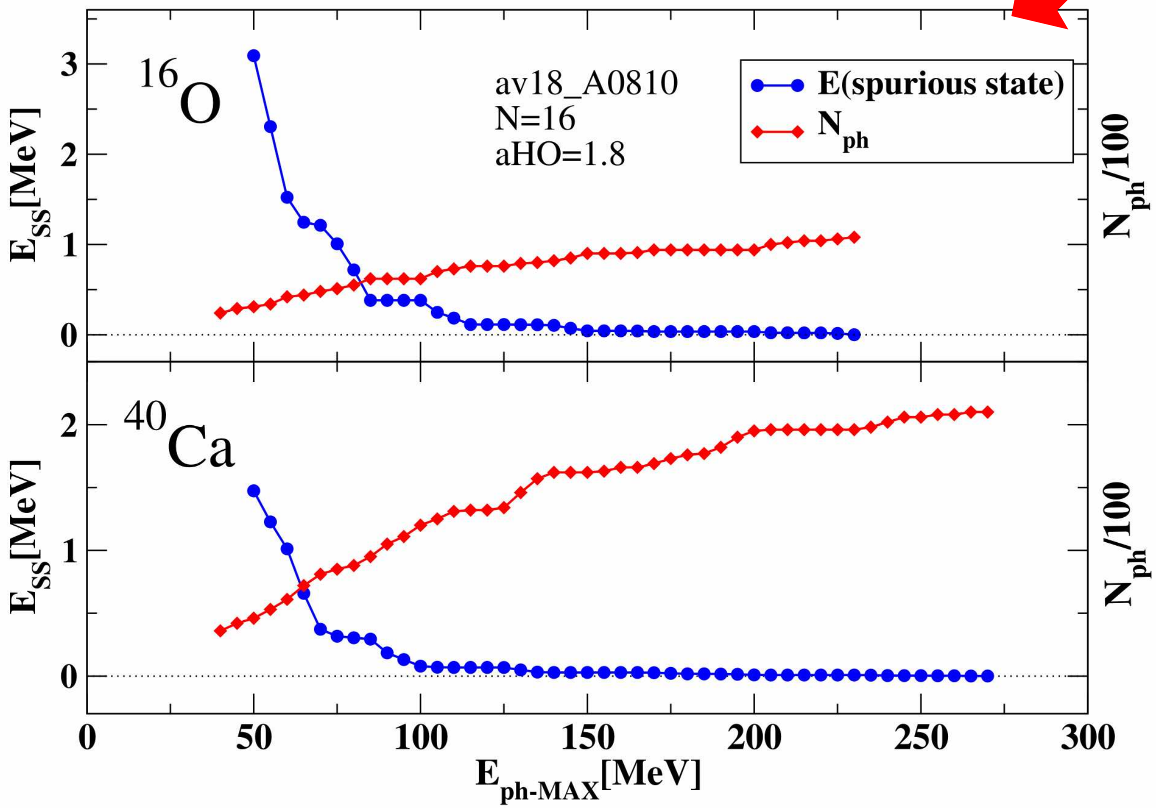
$$\begin{pmatrix} A & B \\ -B^* & -A^* \end{pmatrix} \begin{pmatrix} X^\nu \\ Y^\nu \end{pmatrix} = \omega_\nu \begin{pmatrix} X^\nu \\ Y^\nu \end{pmatrix} \Leftarrow \boxed{V_{UCOM}}$$

- Fully self-consistent model: the same interaction is used in the ground state calculations (Hartree-Fock) and in the residual RPA interaction

Fully Self-Consistent UCOM-RPA Model

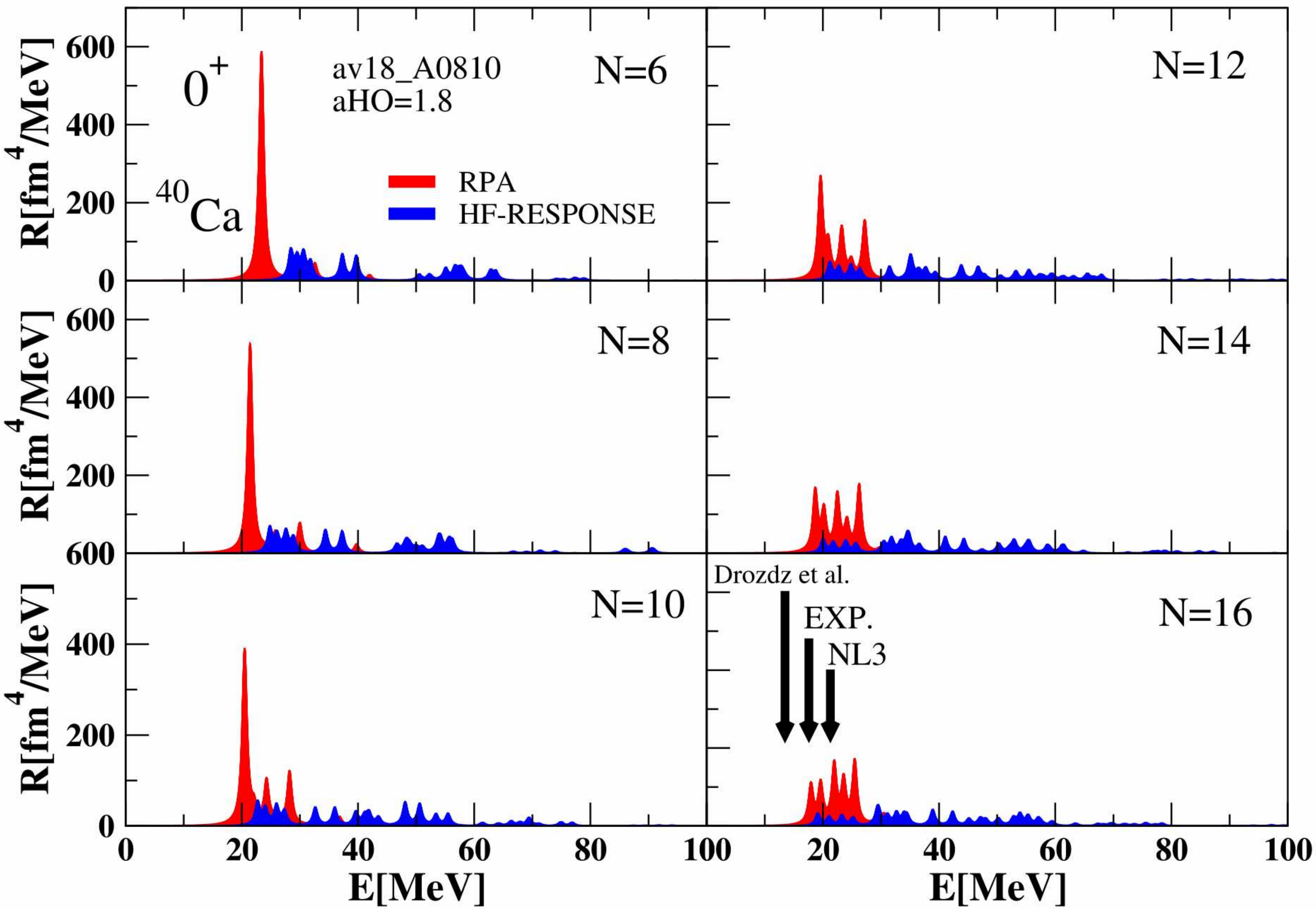


The spurious 1^- state lowers towards zero-energy for large number of ph-configurations

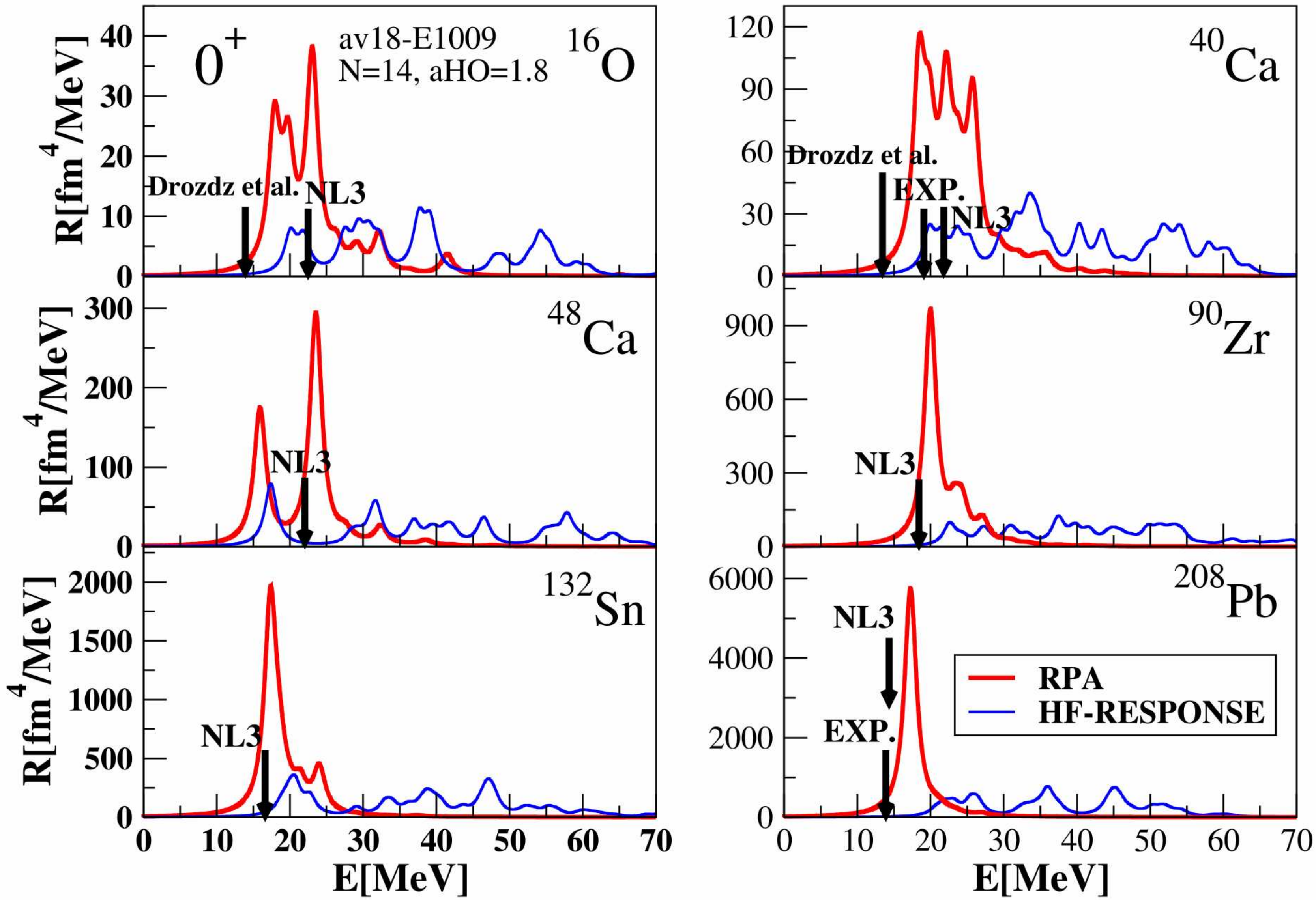


<u>Fully-self consistent RPA model:</u> there is no mixing between the spurious 1^- state and low-lying excitation spectra

UCOM-RPA Isoscalar Giant Monopole Resonance

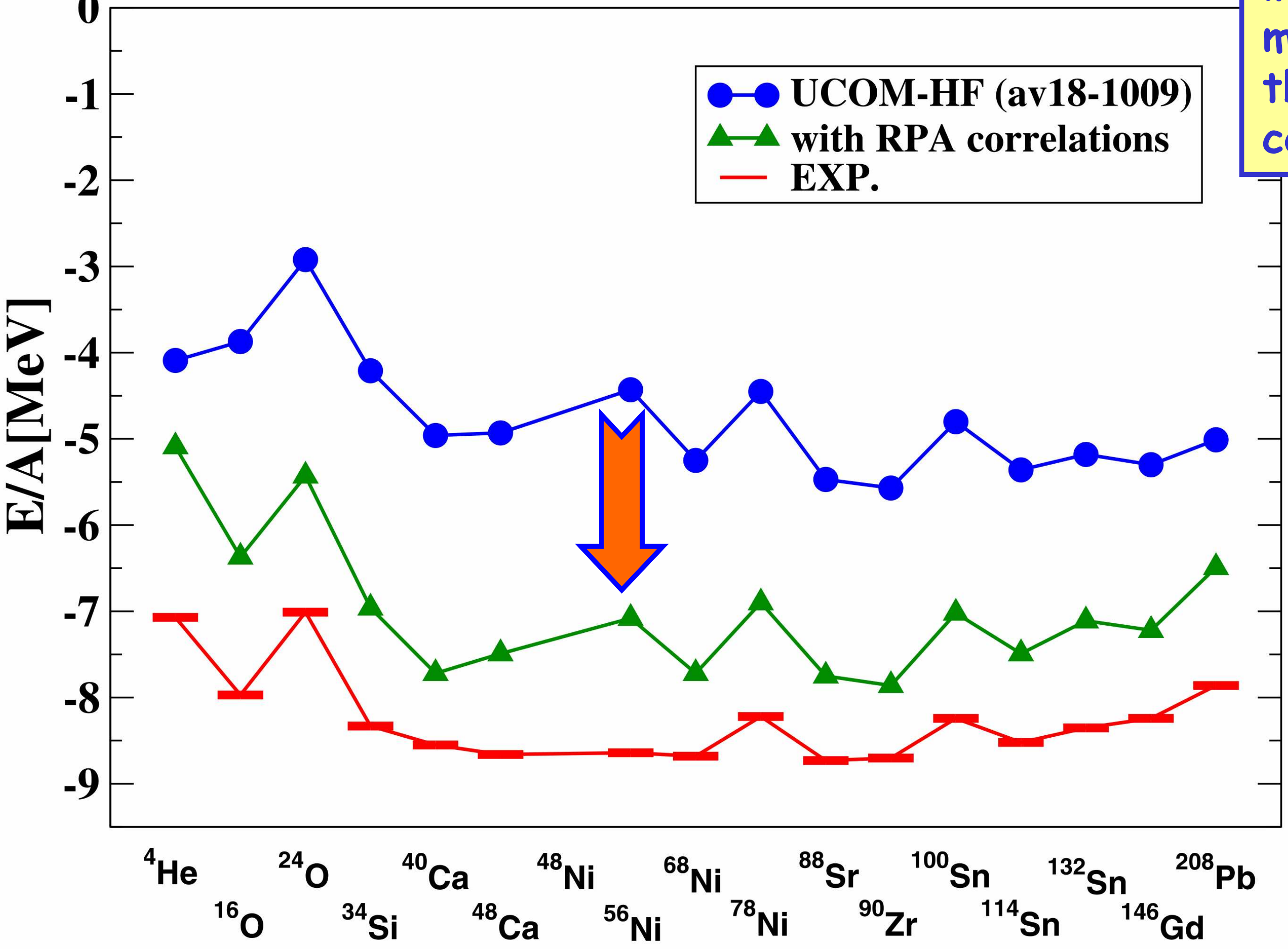


UCOM-RPA Isoscalar Giant Monopole Resonance



UCOM-RPA GROUND-STATE CORRELATIONS

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



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

$N_{MAX}=12$

$l_{MAX}=8$

Not converged yet…

SUMMARY

The correlated realistic nucleon-nucleon (NN) potentials provide a good starting point for the nuclear structure models:

The unitary correlation operator model (UCOM) is used to treat the *short-range and tensor correlations in NN potentials* →Hartree-Fock calculations

> UCOM Hartree-Fock model results with underbinding and small radii → need for the *long-range correlations* and *three-body interaction*

Fully self-consistent UCOM Random-Phase Approximation (RPA) is formulated for the studies of collective excitations in finite nuclei

> UCOM-RPA model based only on the correlated nucleon-nucleon interaction results with a collective Isoscalar Giant Monopole Resonance

RPA ground-state correlations recover part of the missing long-range correlations in the UCOM-Hartree-Fock model