Relativistic Hartree-Fock-Bogoliubov Model for Deformed Nuclei

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Advances in Nuclear Many-Body Theory - Primosten 2011

➊ WHY THE RELATIVISTIC HARTREE-FOCK-BOGOLIUBOV APPROACH?

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❷ THE RELATIVISTIC HARTREE-FOCK-BOGOLIUBOV MODEL

❸ DESCRIPTION OF THE Z=6,10,12 ISOTOPES

NUCLEAR ENERGY DENSITY FUNCTIONALS

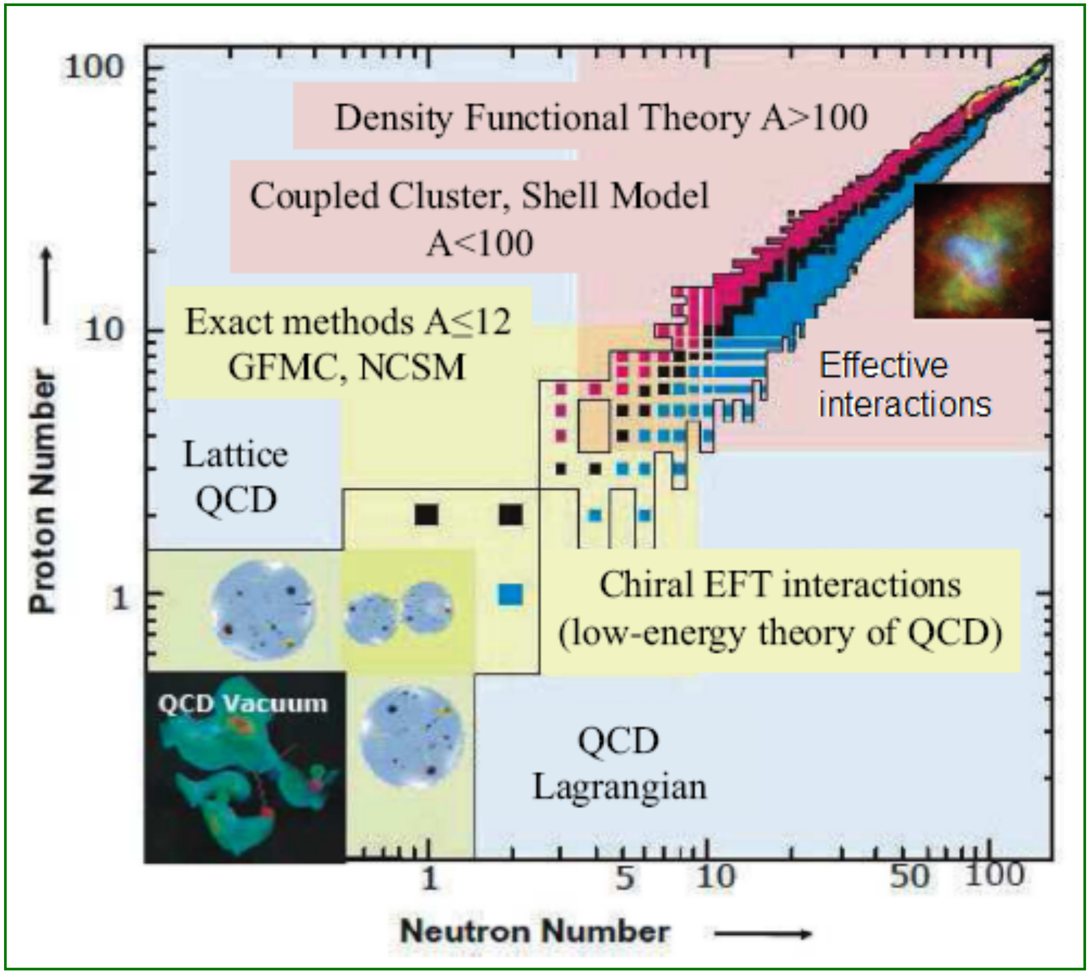

Figure from S.K. Bogner et al. (Prog.Part.Nucl.Phys.65:94-147,2010)

- Self-consistent mean field model is best suited to achieve a universal description of the whole nuclear chart

• **Relevance of covariant approach : not imposed by the need of a relativistic nuclear kinematics, but rather linked to the use of Lorentz symmetry**

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- Relativistic potentials :

S ~ -400 MeV : Scalar attractive potential

V ~ +350 MeV : 4-vector (time-like component) repulsive potential

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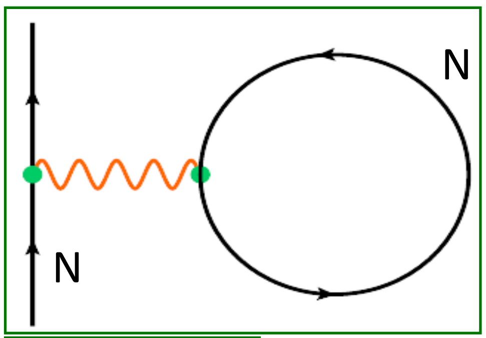
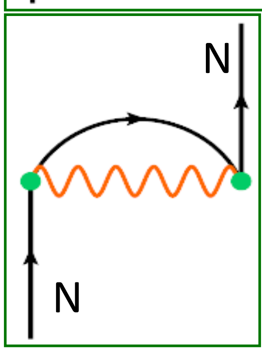
- ➲ Spin-orbit potential emerges naturally with the empirical strenght
- ➲ Time-odd fields = space-like component of 4-potential $V^\mu = (V, \mathbf{V})$
- ➲ Empirical pseudospin symmetry in nuclear spectroscopy
- ➲ Saturation mechanism of nuclear matter

FOCK TERMS

- Relativistic mean field models (RMF) treat implicitly Fock terms through fit of model parameters to data
- Relativistic Hartree-Fock models (RHF): more involved approaches which take explicitly into account the Fock contributions
  - Description of nuclear matter in better agreement with DBHF calculations
  - Tensor contribution to the NN force (pion + ρ) : better description of shell structure
  - Fully self-consistent beyond mean-field models





RHB in axial symmetry
D. Vretenar et al
(Phys.Rep. 409:101-259,2005)

RHFB in spherical symmetry
W. Long et al
(Phys. Rev. C 81:024308, 2010)

→

RHFB in axial symmetry
J.-P. Ebran et al
(accepted in Phys. Rev. C)

- Relevant degrees of freedom for nuclear structure : nucleons + mesons

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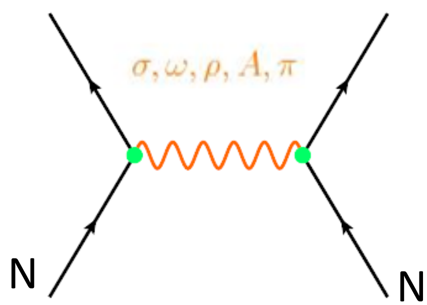
• Self-consistent mean field formalism : **in-medium** effective interaction designed to be use together with a ground-state approximated by a Slater determinent

➲ Mesons = effective degrees of freedom which generate the NN in-medium interaction : $\pi(J^{\Pi},T = 0^{-},1)$ $\sigma(0^{+},0)$ $\omega(1^{-},0)$ $\rho(1^{-},1)$



$$\mathcal{L}_{int} = -g_\sigma(\rho_v)\bar{\psi}\sigma\psi - g_\omega(\rho_v)\bar{\psi}\gamma_\mu\omega^\mu\psi - g_\rho(\rho_v)\bar{\psi}\gamma_\mu\vec{\rho}.\vec{\tau}^\mu\psi - \frac{f_\pi(\rho_v)}{m_\pi}\bar{\psi}\gamma_5\gamma_\mu\partial^\mu\vec{\pi}.\vec{\tau}\psi - e\bar{\psi}\gamma_\mu A^\mu\psi$$

Lagrangian

- Characterized by 8 free parameters fitted on the mass of 12 spherical nuclei + nuclear matter saturation point
- Legendre transformation

Lagrangian

Hamiltonian

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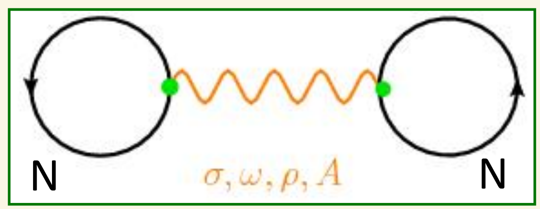
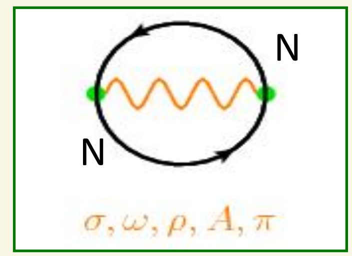
- Legendre transformation

- Quantization
- Mean-field approximation : expectation value in the HFB ground state





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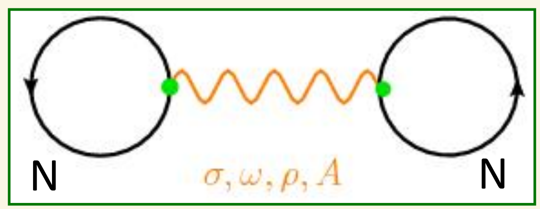

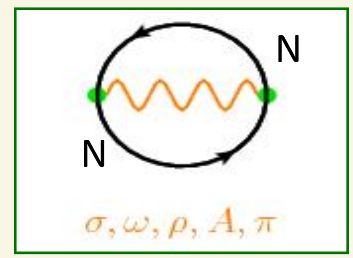

EDF

Lagrangian

Hamiltonian

EDF

RHFB equations

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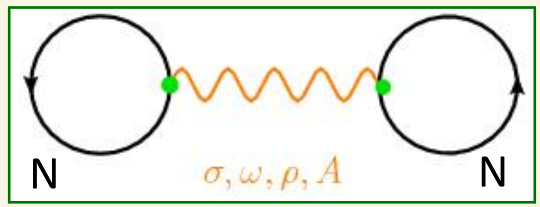
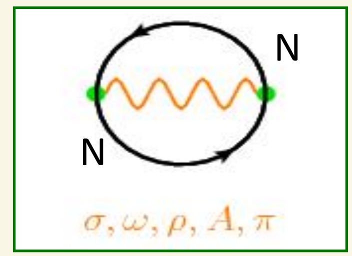
- Legendre transformation

- Quantization
- Mean-field approximation : expectation value in the HFB ground state





- Minimization

$$-i\alpha.\nabla + \beta M^*(r) + \left[V(r) + \Sigma^R(r)\right]\Big\} f_i(r,q_i) + \mathcal{F}_i(r,q_i) = \epsilon_i f_i(r,q_i)$$

Lagrangian → Hamiltonian → EDF → RHFB equations → Observables

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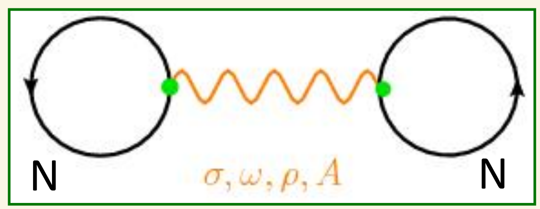
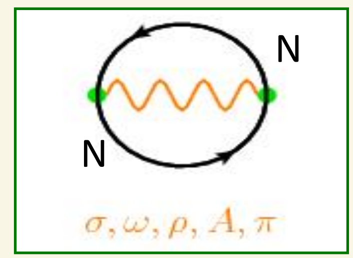
- Legendre transformation

- Quantization
- Mean-field approximation : expectation value in the HFB ground state





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- Resolution in a deformed harmonic oscillator basis

❸ Description of the Z=6,10,12 isotopes

A) Ground state observables

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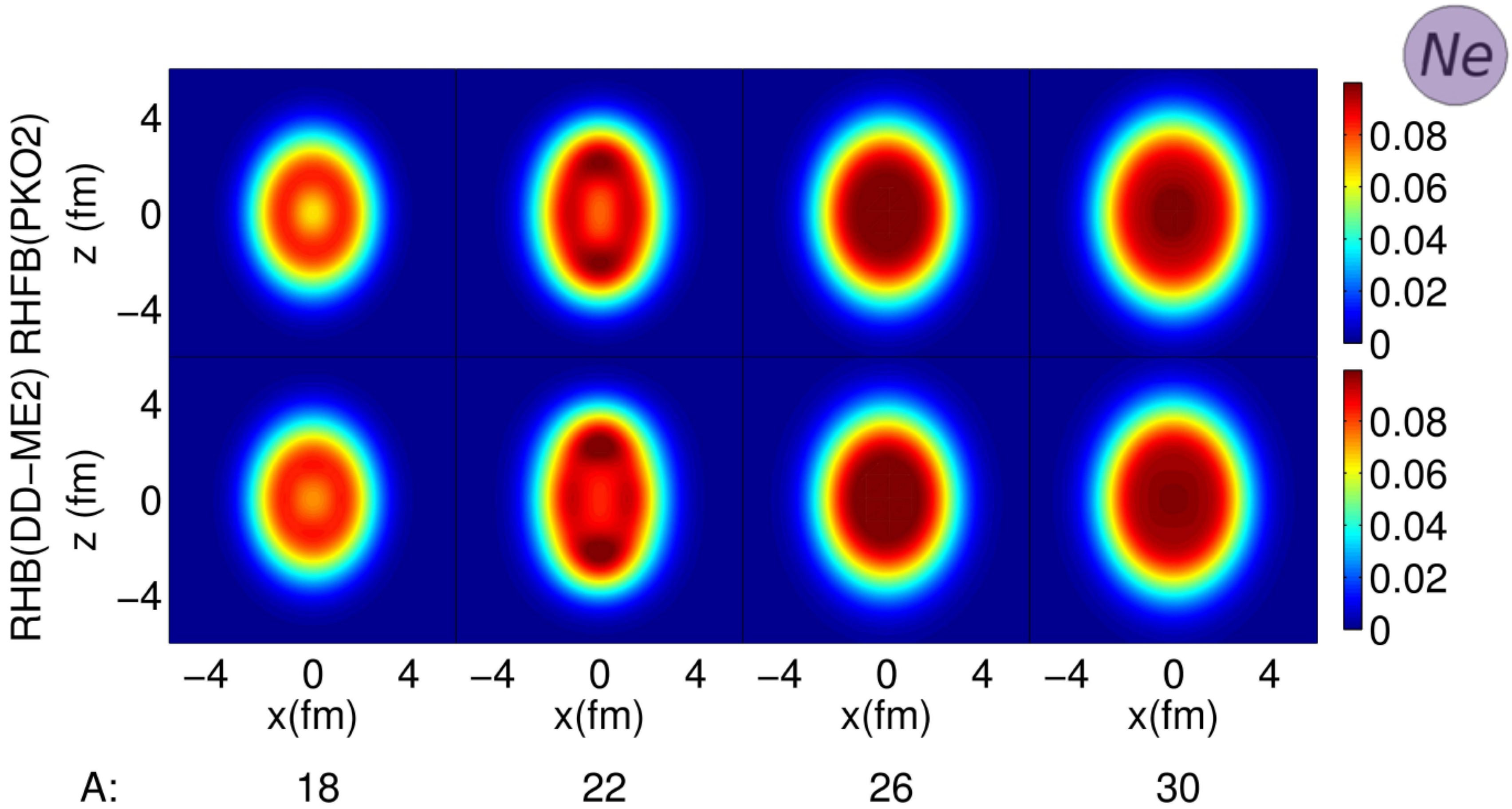
Neutron density in the Neon isotopic chain



Masses

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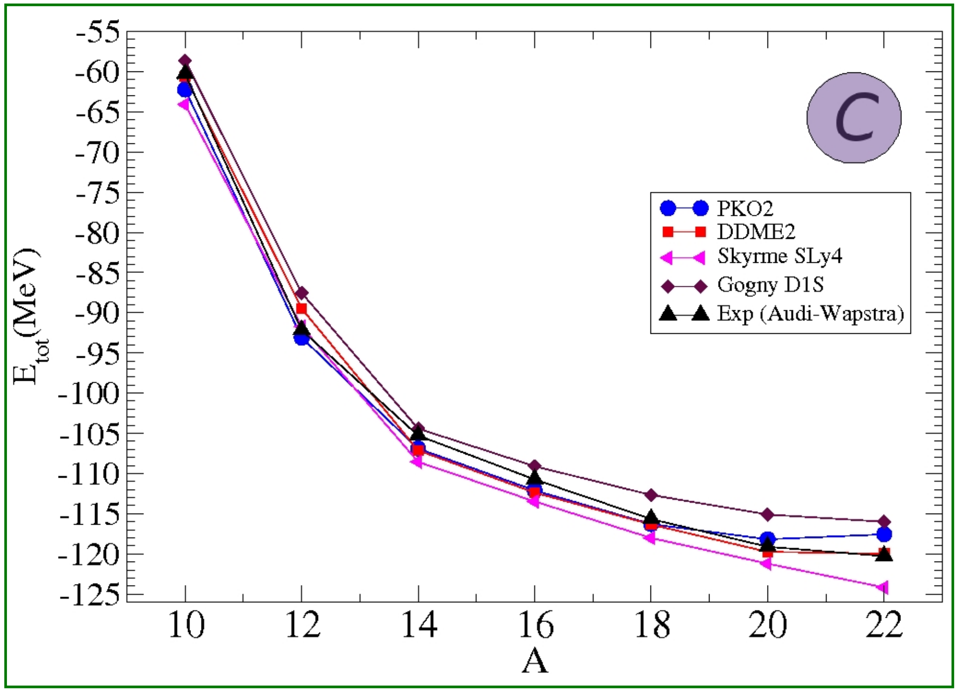
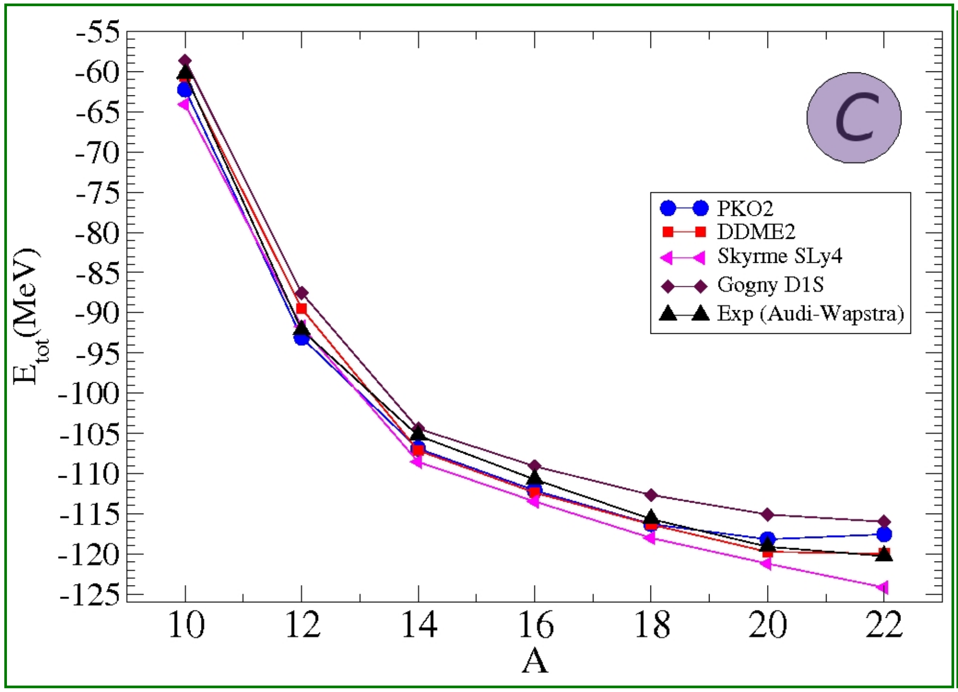
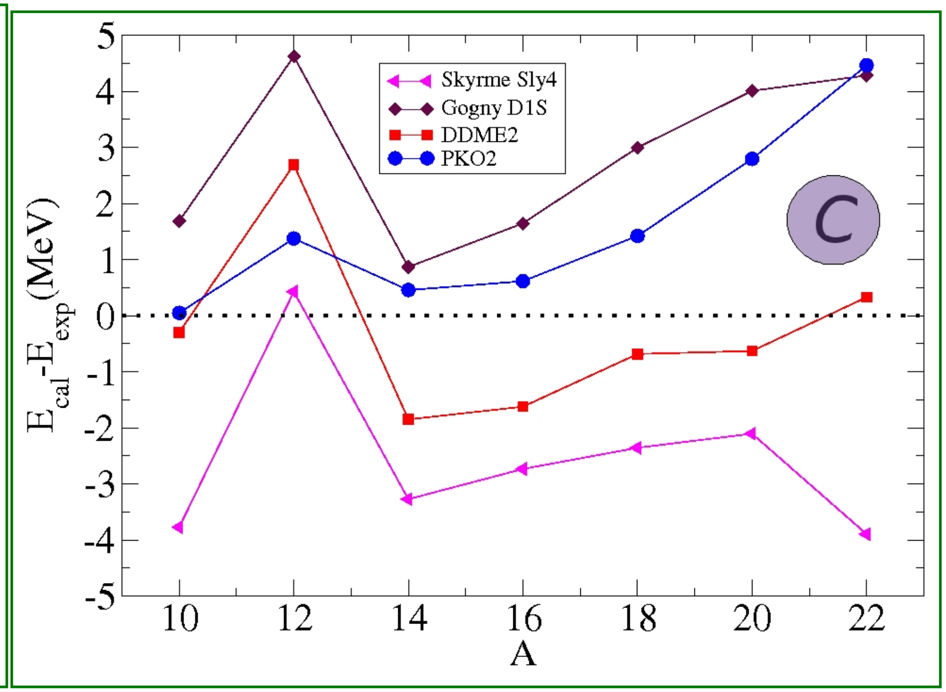

C
PKO2
DDME2
Skyrme SLy4
Gogny D1S
Exp (Audi-Wapstra)
E_{tot}(MeV)
A
-55
-60
-65
-70
-75
-80
-85
-90
-95
-100
-105
-110
-115
-120
-125
10
12
14
16
18
20
22

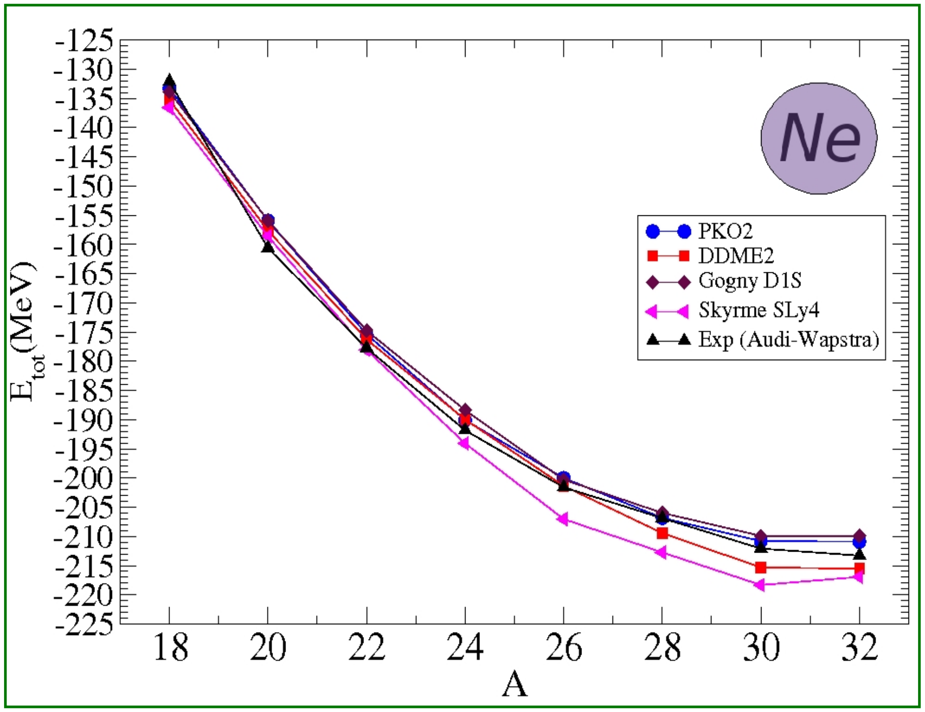
Masses

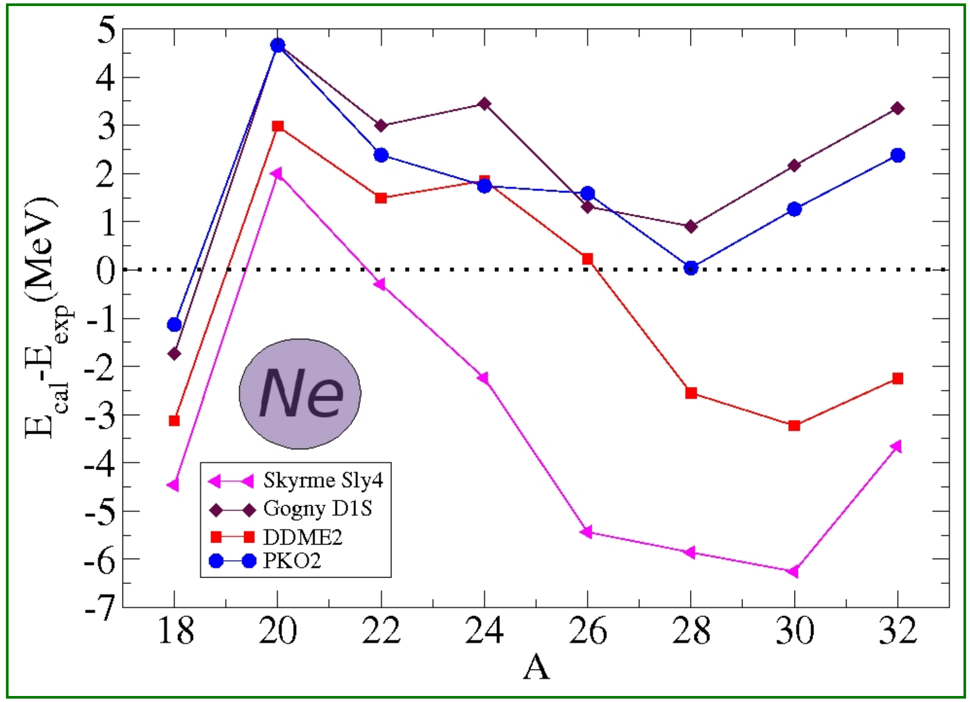




- Calculation obtained with the PKO2 interaction: ^{10}C, ^{14}C and ^{16}C are better reproduced with the RHFB model

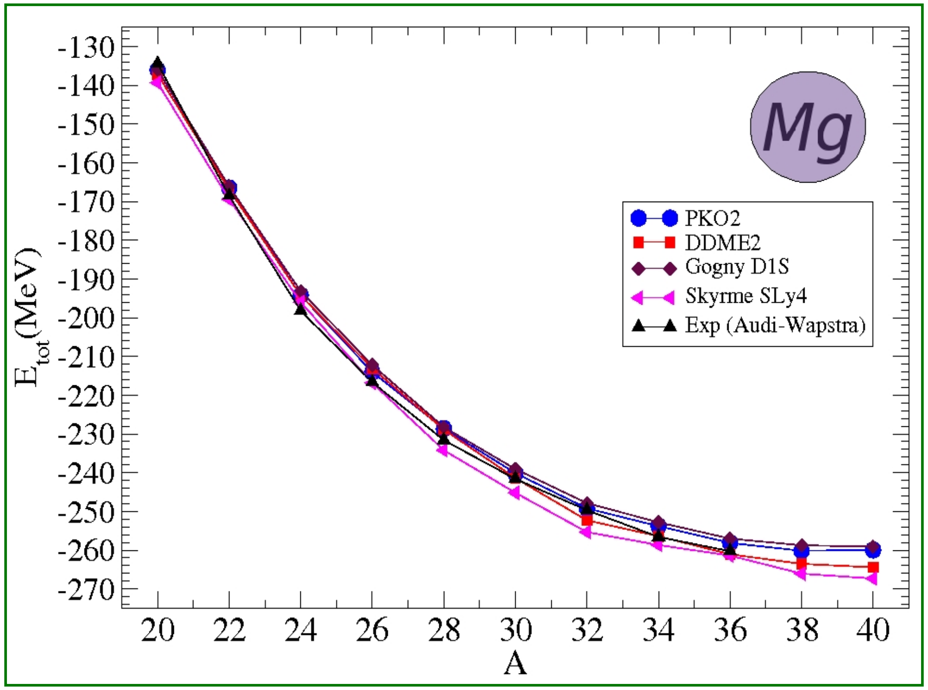
Masses

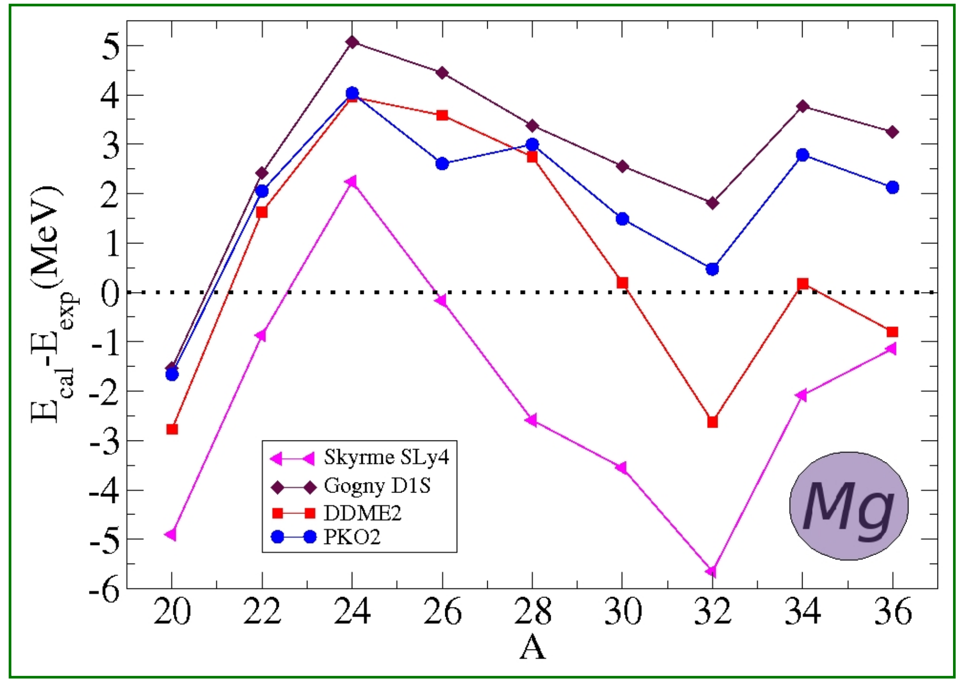




- Good agreement between RHFB calculations and experiment

Masses





➲ RHFB model successfully describes the Z=6,10,12 isotopes masses

Two-neutron drip-line

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- Two-neutron separation energy E : $S_{2n} = E_{tot}(Z,N) - E_{tot}(Z,N-2)$. Gives global information on the Q-value of an hypothetical simultaneous transfer of 2 neutrons in the ground state of (Z,N-2)

- $S_{2n} < 0 \Rightarrow$ (Z,N) Nucleus can spontaneously and simultaneously emit two neutrons $\Rightarrow$ it is beyond the two neutrons drip-line

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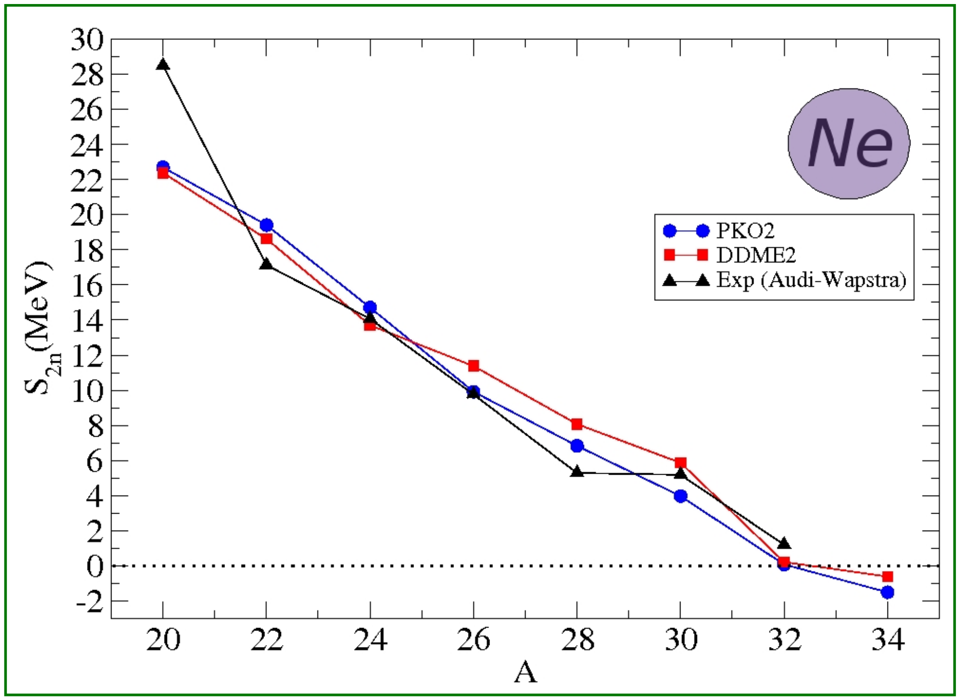
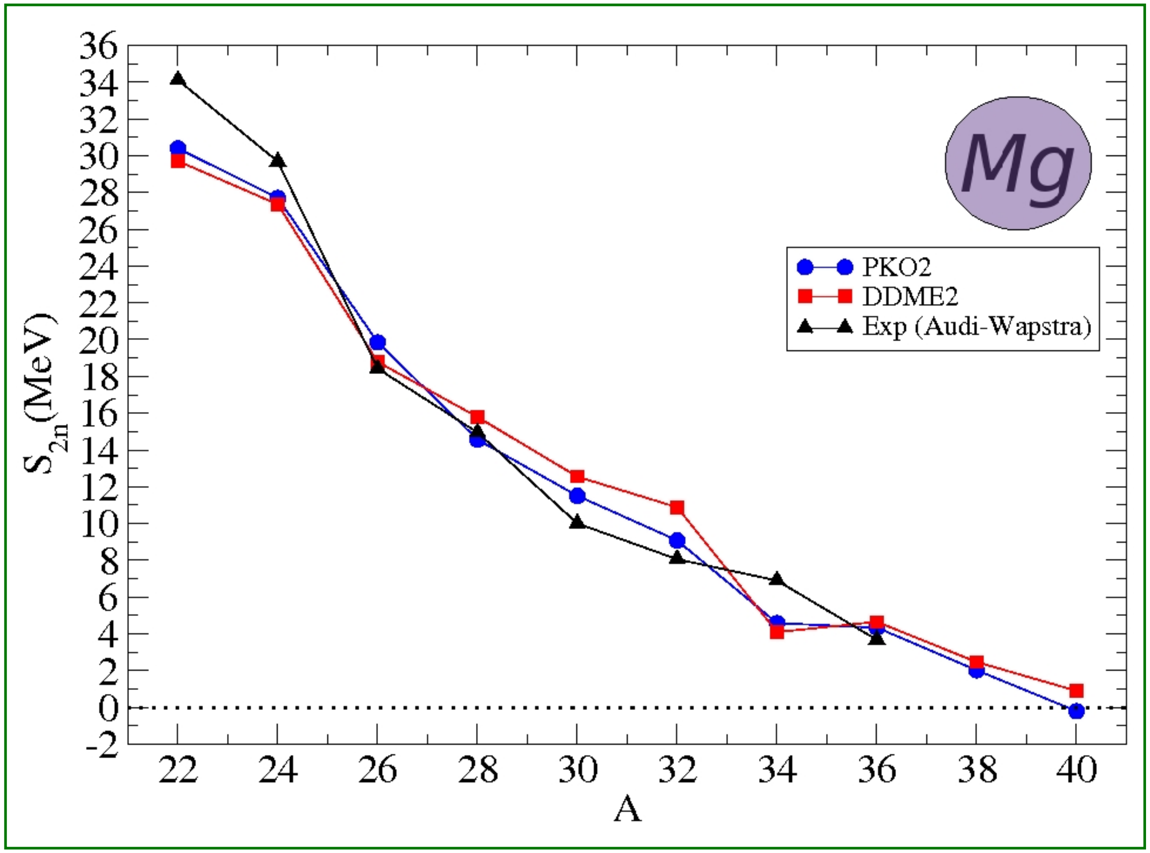


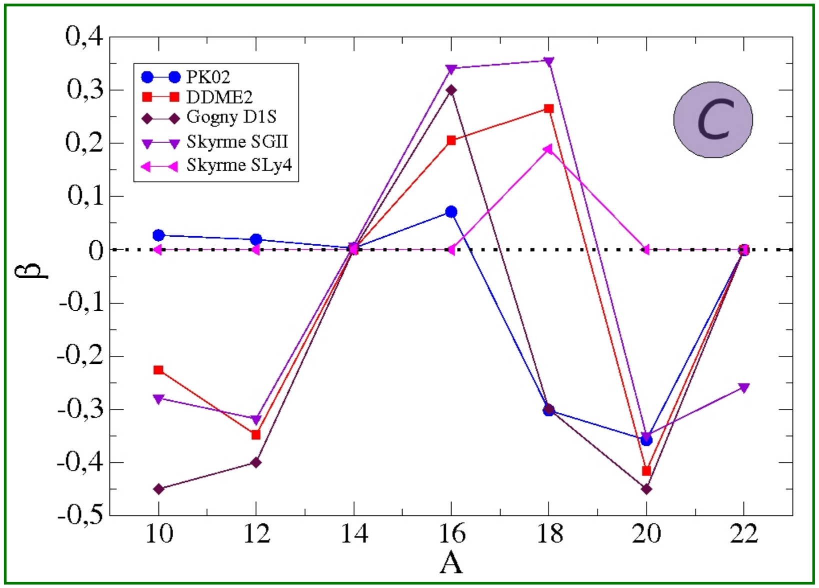
PKO2 : Drip-line between ^{32}Ne and ^{34}Ne

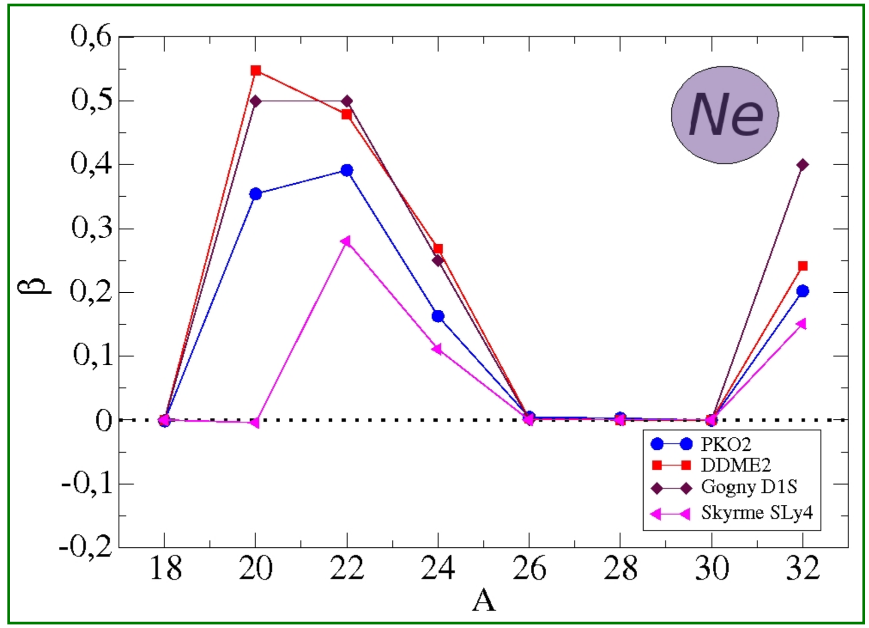
Two-neutron drip-line

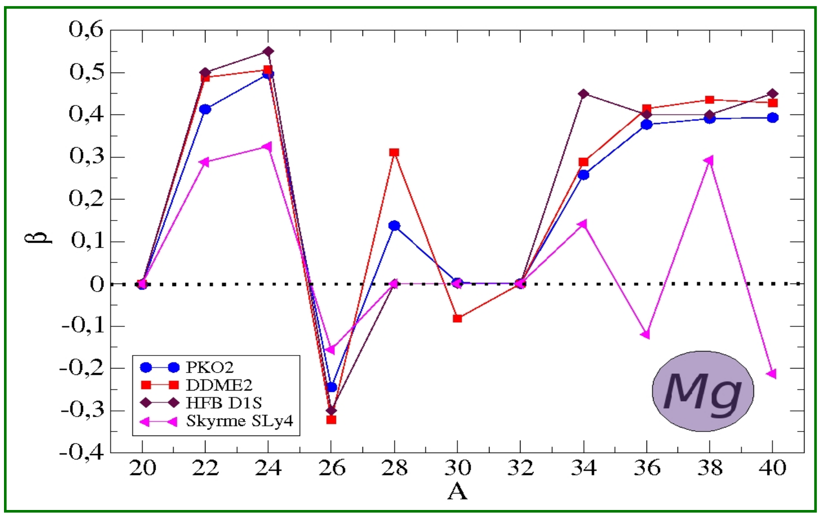


- In the Z=12 isotopic chain, drip-line between ^{38}Mg and ^{40}Mg
- S_{2n} from PKO2 generally in better agreement with data than DDME2.

Axial deformation



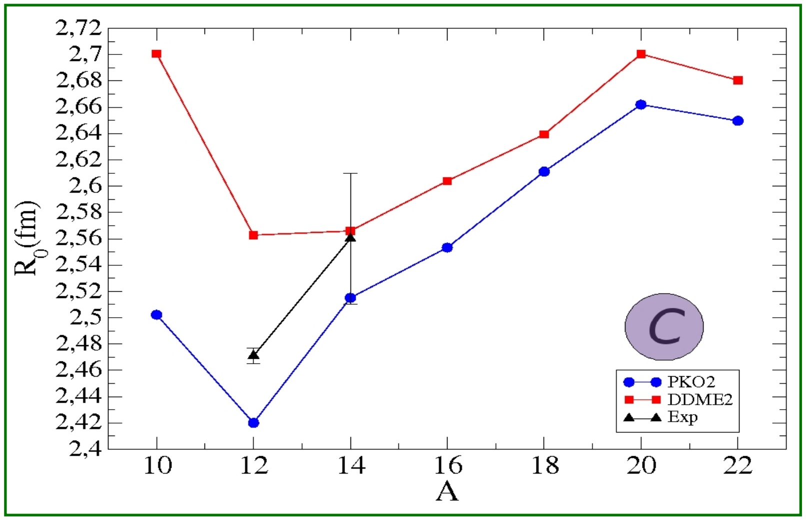


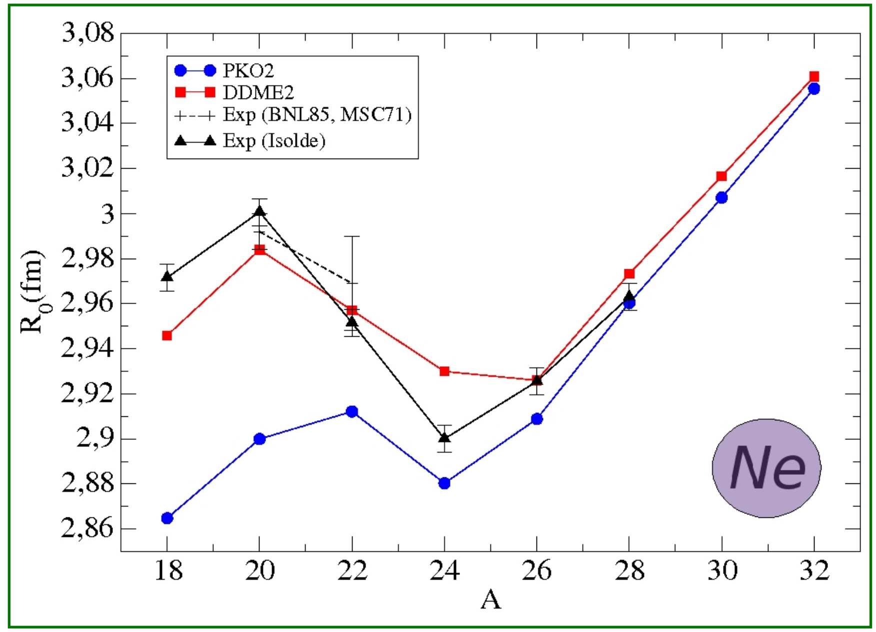


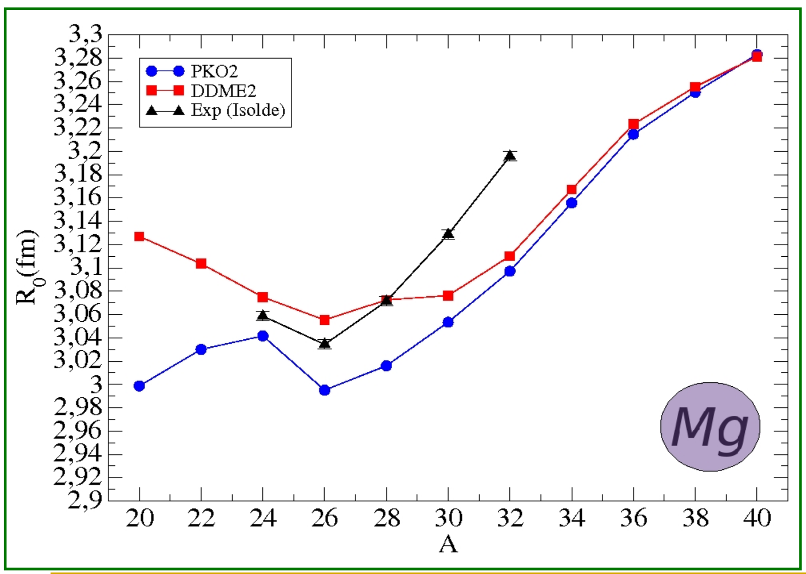
➲For Ne et Mg, PKO2 deformation's behaviour qualitatively the same than the other interactions

PKO2 β systematically weaker than DDME2 and Gogny D1S one

Charge radii



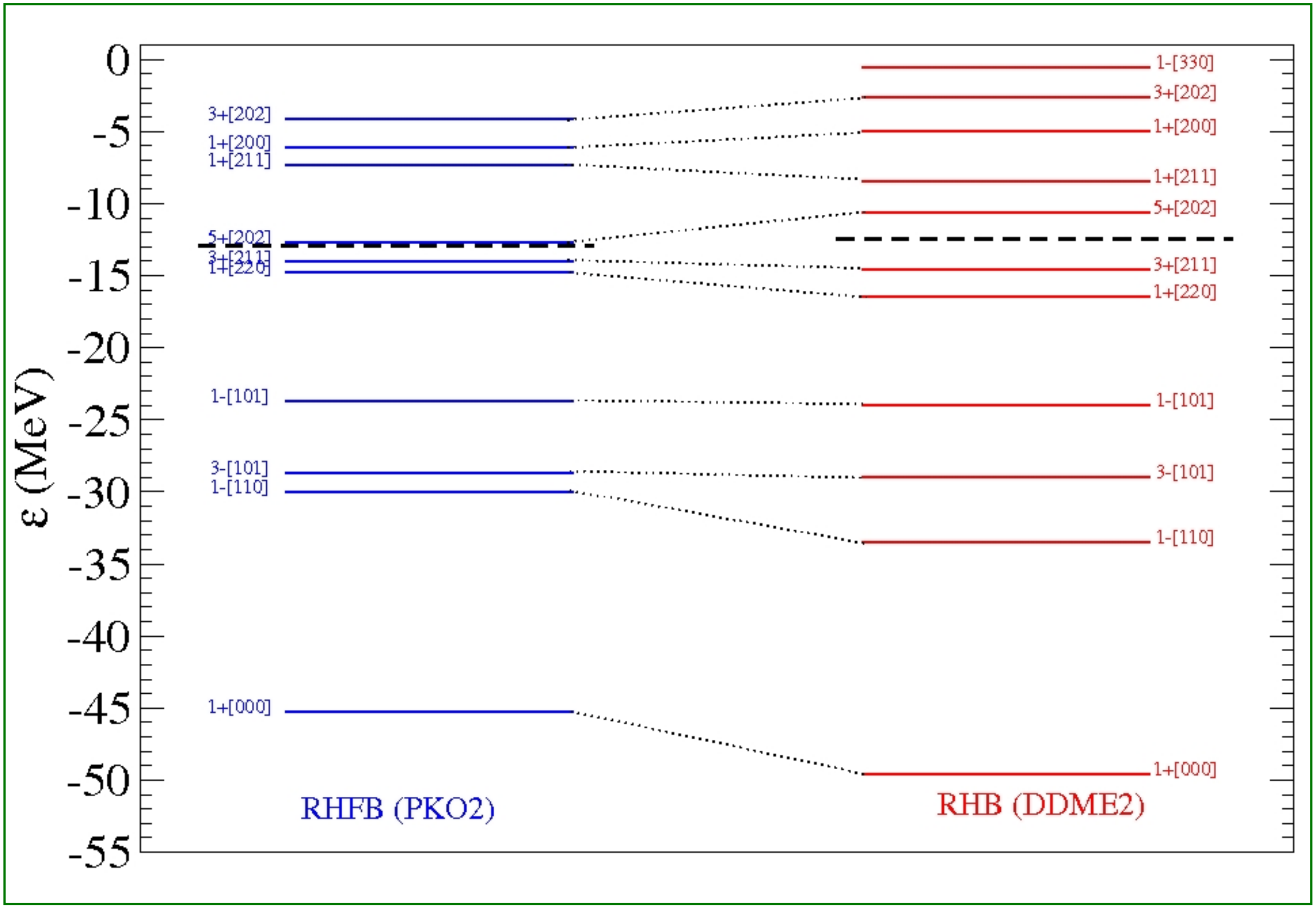




➲DDME2 closer to experimental data

Better agreement between PKO2 and DDME2 for heavier isotopes

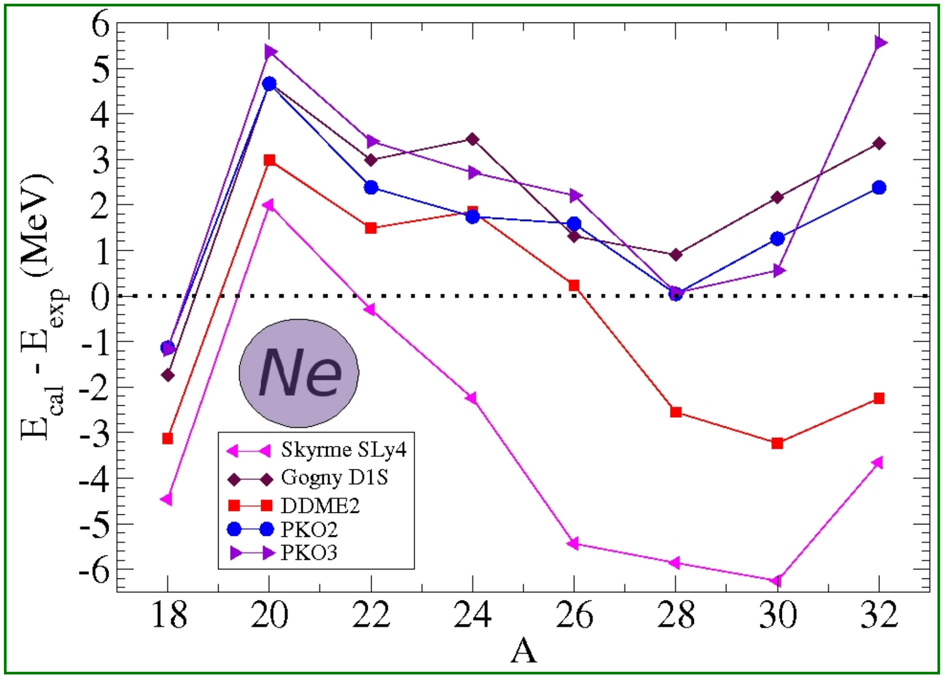
B) Shell structure

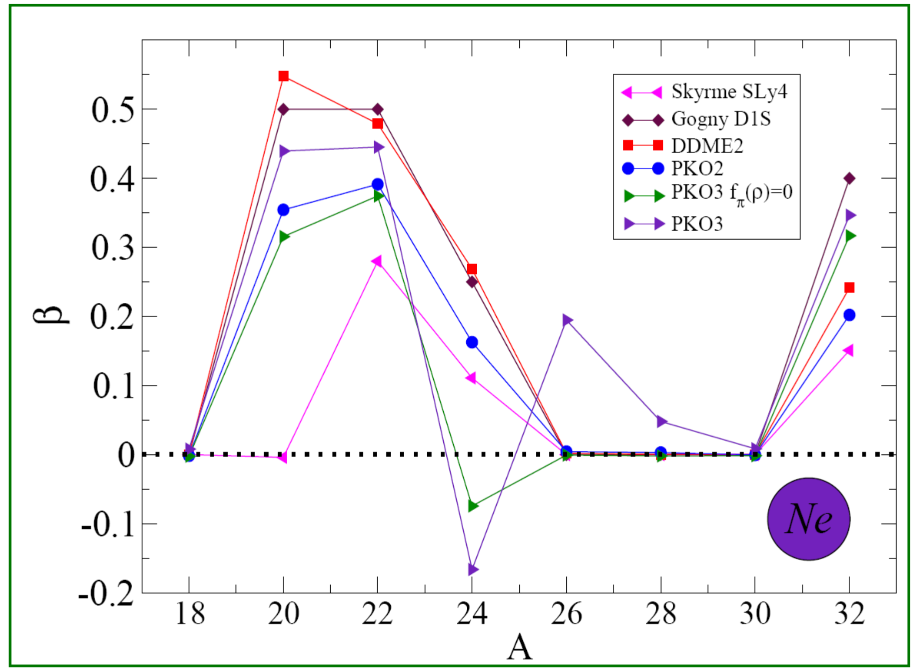


Protons levels in ^{28}Mg

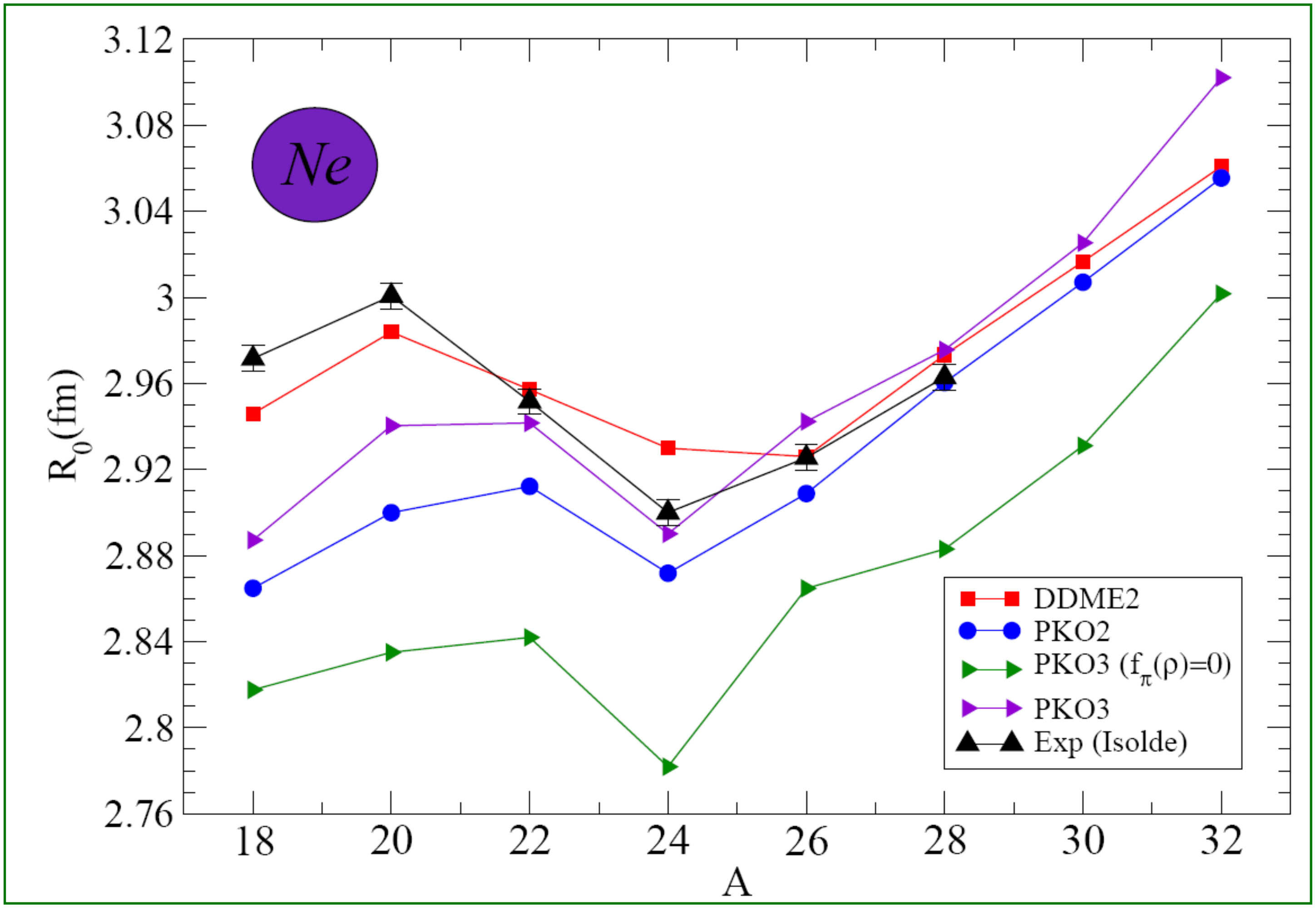
Higher density of state around the Fermi level in the case of the RHFB model

C) Role of the pion in the relativistic mean field models





- PKO3 masses not as good as PKO2 ones
- PKO3 deformations in better agreement with DDME2 and Gogny D1S. Qualitative isotopic variation of β changes around the N=20 magic number.



➲ PKO3 charge radii in the Z=12 isotopic chain systematically greater than PKO2 ones

Conclusion and perspectives

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- Development of a RHFB model in axial symmetry :
  - Takes advantage of a covariant formalism leading to a more efficient description of nuclear systems
  - Contains explicitly the Fock term
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- Development of a point coupling + pion relativistic model