Time-dependent CDFT

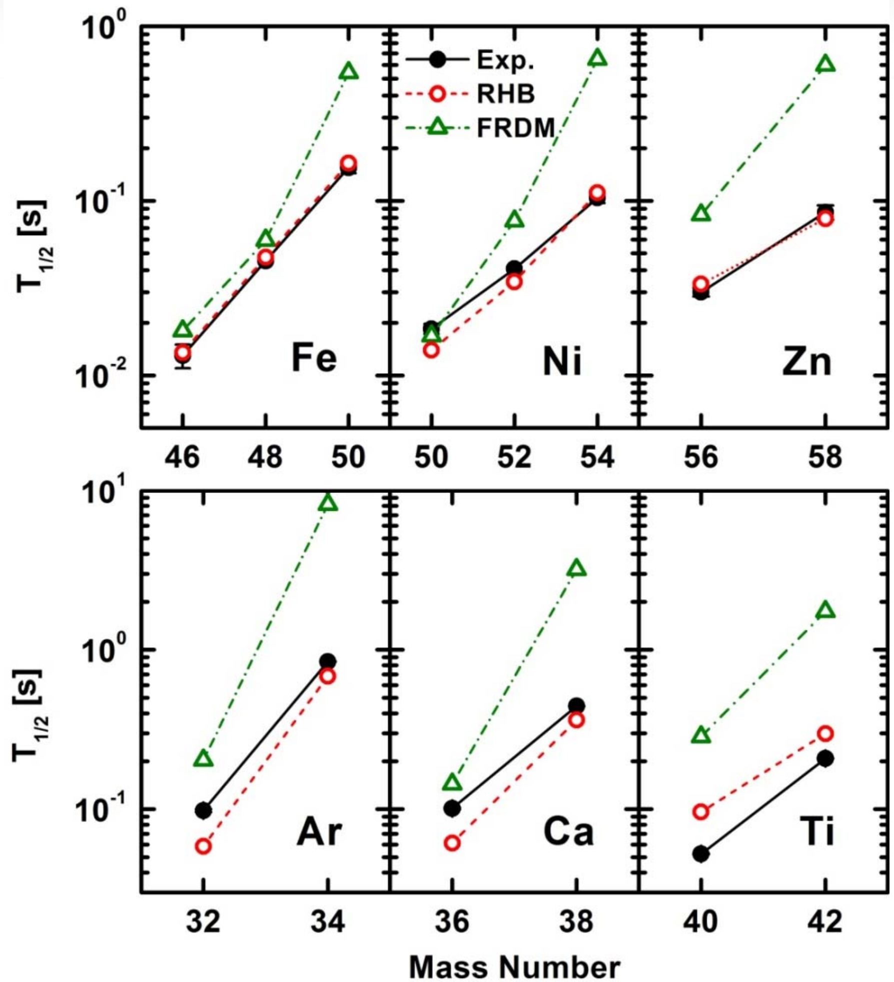
- For vibrations with small amplitude, it can be expanded in the vicinity of the ground state and a connection to the static energy density functional can be found.
- In the adiabatic approximation, i.e. by neglecting the memory effects and the energy dependence in Fourier space, one ends up with the RPA with a residual interaction derived as the second derivative of the static energy functional with the density.
- RPA provides a successful description of the mean energies of giant resonances in nuclei, but not able to reproduce the decay width of these excitations.
- For the decay width and the fragmentation of single-particle states, one has to go beyond mean field and to consider the energy dependence of the self-energy. This can be done within the particle-vibrational coupling (PVC) model.

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

RHB+QRPA: Nuclear β⁺/EC-decay half-lives

- RHB+QRPA: well reproduces the experimental half-lives for neutron-deficient Ar, Ca, Ti, Fe, Ni, and Zn isotopes by a universal T=0 pairing strength.

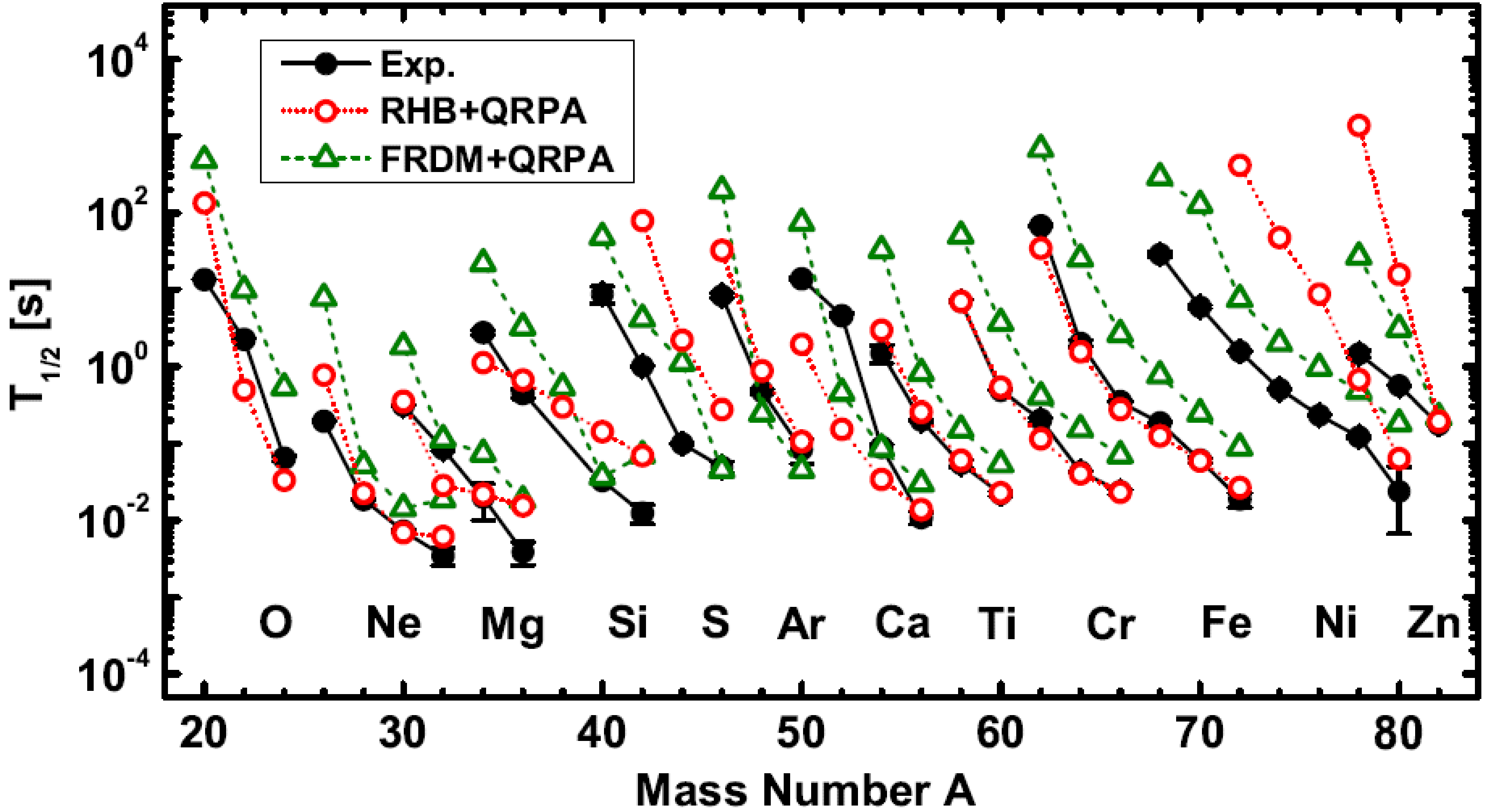
- FRDM+QRPA: systematically overestimates the nuclear half-lives ← the pp residual interactions in the T=0 channel are not considered.



Nuclear β⁺/EC-decay half-lives calculated in RHB+QRPA model with the PC-PK1 parameter set.

Niu et al., PRC 87, 051303(R) (2013)

RHB+QRPA/PC-PK1: Nuclear β-decay half-lives



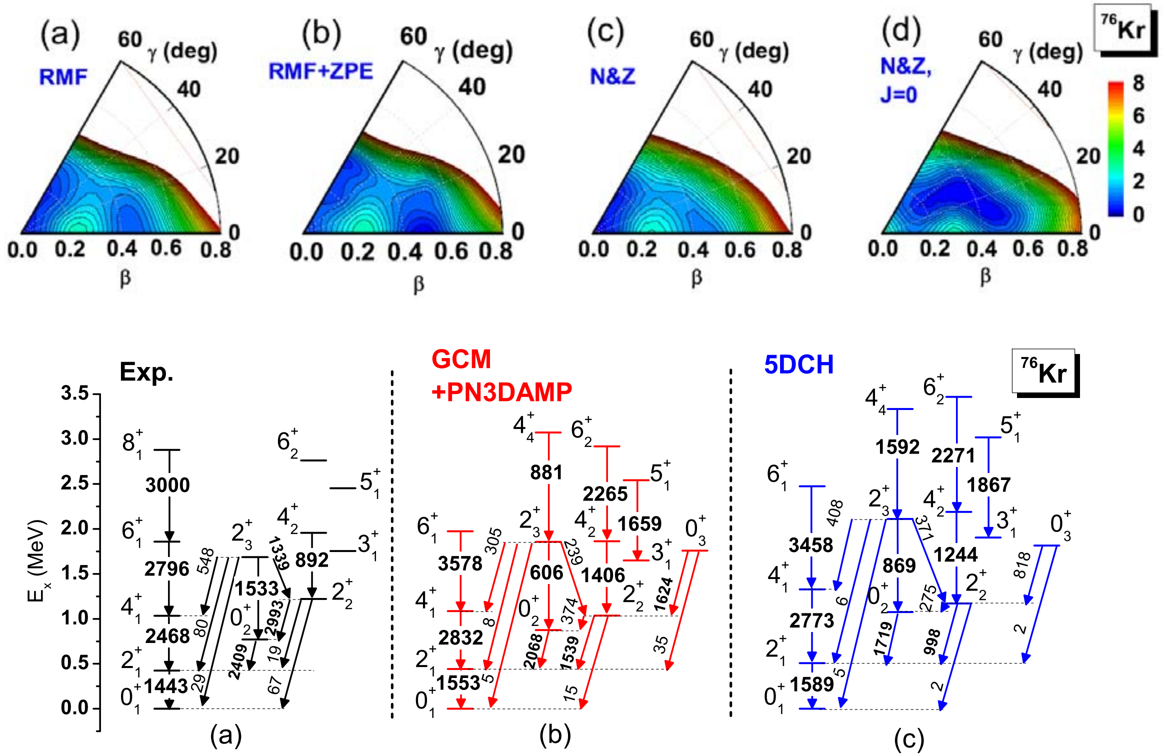
Z. Y. Wang, Z. M. Niu, Y. F. Niu, J. Y. Guo arXiv:1503.01222
Nuclear \$β\$-decay half-lives in the relativistic point-coupling model

Symmetry restoration and fluctuations

- Many-body energy takes the form of a functional of all transition density matrices between the various Slater determinants of different deformation and orientation. Mixing of these different configurations allows the restoration of symmetries and to take into account fluctuations around the mean-field equilibrium solution.
- In full space and with deformation degrees of freedom, such calculations require considerable numerical efforts, at the limit of present computer capabilities.
- A considerable simplification is by using the constraint calculations for the derivation of a **collective Hamiltonian** in these degrees of freedom.

Nuclear low-lying states: CDFT+GCM+PN3DAMP

7D GCM: two deformation parameters + projection 3DAM and 2PN



◆ The low-energy spectrum in ^{76}Kr are well reproduced after including triaxiality in the full microscopic GCM+ PN3DAMP calculation based on the CDFT using PC-PK1.

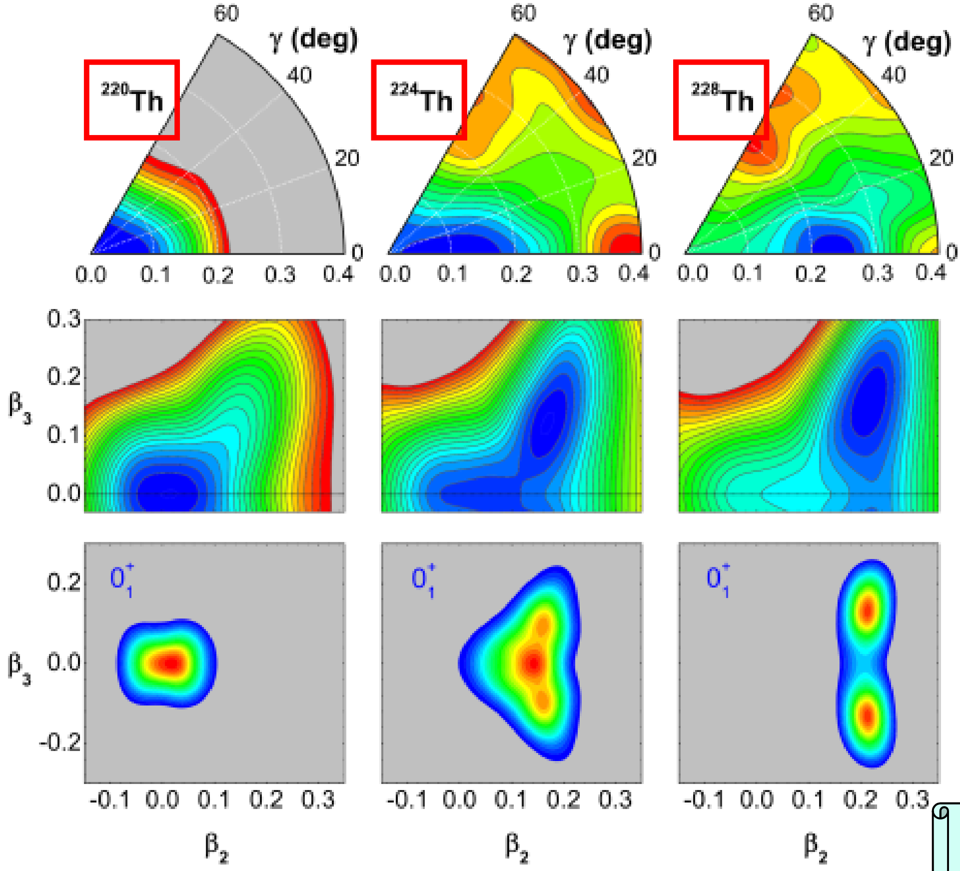
◆ This study answers the important question of dynamic correlations and triaxiality in shape-coexistence nucleus ^{76}Kr and provides the first benchmark for the EDF based collective Hamiltonian method.

Yao, Hagino, Li, Meng, Ring, Phys. Rev. C 89, 054306 (2014)

Benchmark for the collective Hamiltonian in five dimensions

Simultaneous shape phase transition

5DCH Calculations based on CDFT PC-PK1 indicate a simultaneous quantum shape phase transition from spherical to prolate shapes, and from reflection symmetric to octupole shapes.



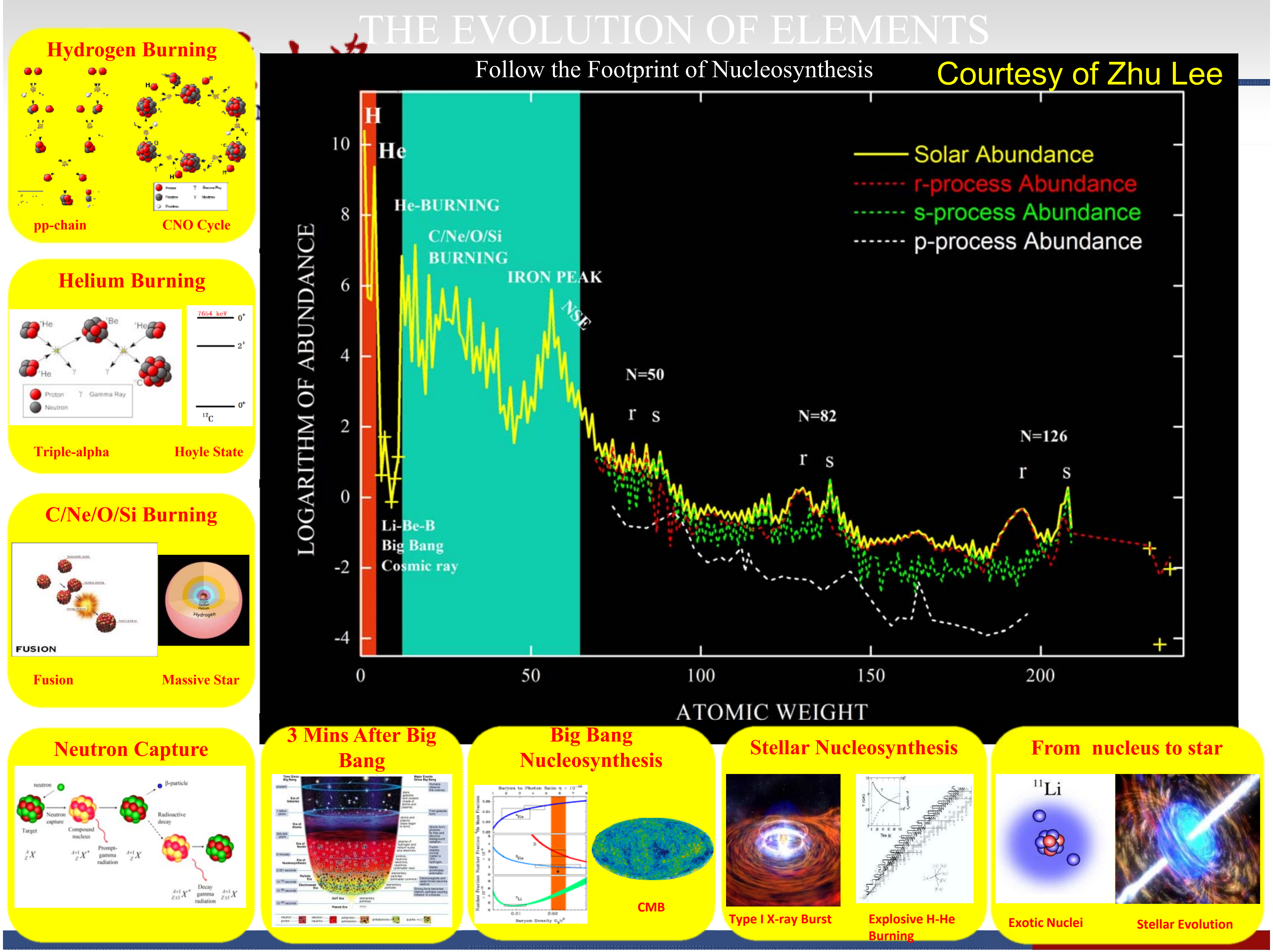
triaxial quadrupole energy surfaces

axially-symmetric quadrupole–octupole energy surfaces

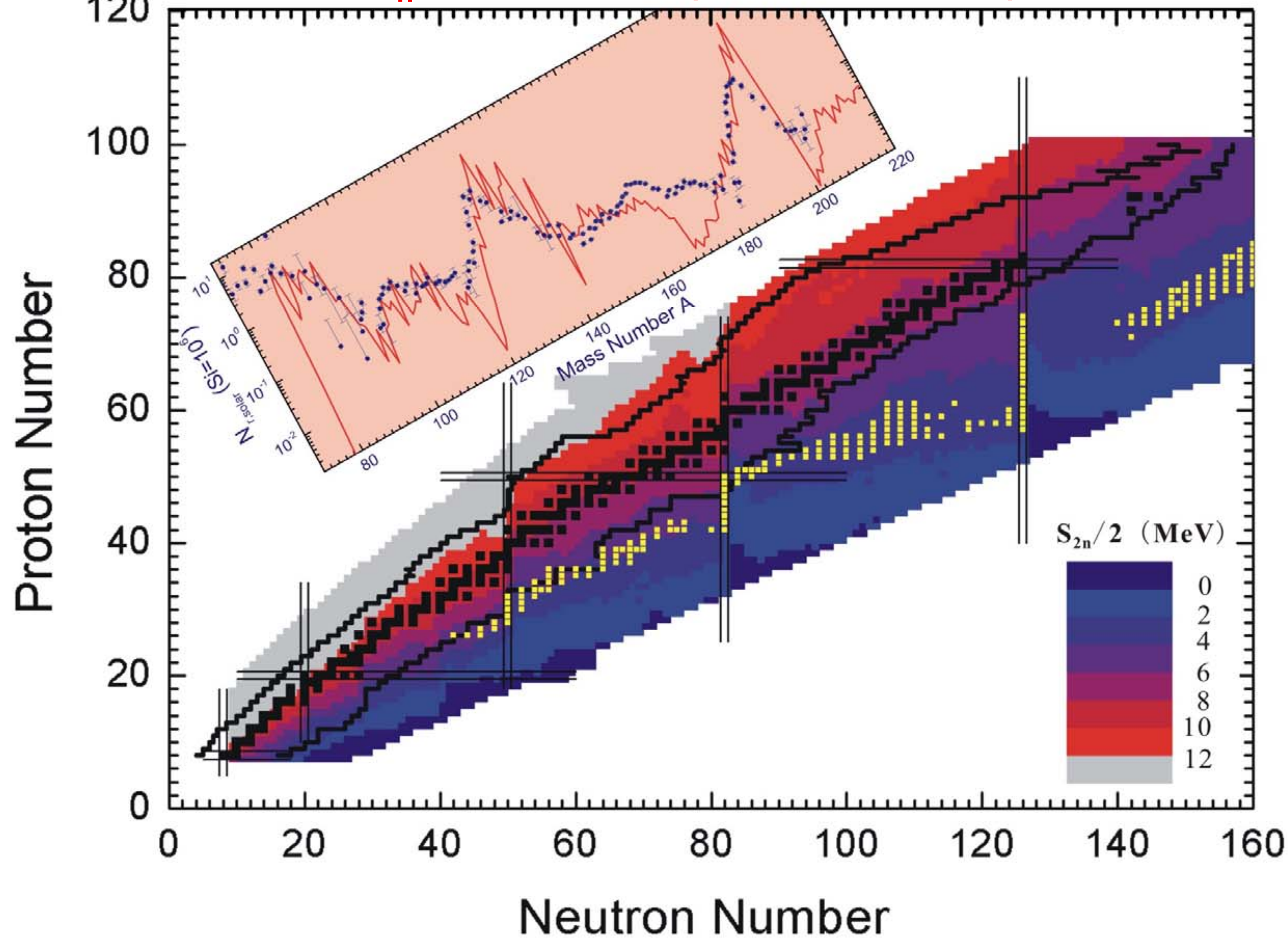
probability density distributions for the ground states

Li, Song, Yao, Vretenar, and Meng, Phys. Lett. B 726 (2013) 866

Application of CDFT in Nuclear astrophysics


THE EVOLUTION OF ELEMENTS
Follow the Footprint of Nucleosynthesis
Courtesy of Zhu Lee
Hydrogen Burning
pp-chain
CNO Cycle
Helium Burning
Triple-alpha
Hoyle State
C/Ne/O/Si Burning
FUSION
Fusion
Massive Star
Neutron Capture
H
He
He-BURNING
C/Ne/O/Si
BURNING
IRON PEAK
NSE
N=50
N=82
N=126
r s
Li-Be-B
Big Bang
Cosmic ray
Solar Abundance
r-process Abundance
s-process Abundance
p-process Abundance
LOGARITHM OF ABUNDANCE
ATOMIC WEIGHT
10
8
6
4
2
0
-2
-4
0
50
100
150
200
3 Mins After Big Bang
Big Bang Nucleosynthesis
CMB
Stellar Nucleosynthesis
Type I X-ray Burst
Explosive H-He Burning
From nucleus to star
^{11}Li
Exotic Nuclei
Stellar Evolution

nuclear inputs: S_n(RMF), $T_{1/2}$(β-decay), P_{1n}, P_{2n}, P_{3n} (FRDM), astrophysical parameters: T_9=1.5, $n_n=10^{20-28}$, ω, τ (least-square fit),



Application of CDFT in Fundamental physics

Element $|V_{ud}|$ of the CKM matrix

- **Cabibbo-Kobayashi-Maskawa matrix**
  - quark eigenstates of weak interaction ⟺ quark mass eigenstates
  - Unitarity of CKM matrix ⟹ test of Standard Model
- **To determine $|V_{ud}|$ in nuclear superallowed β decays**
  - Experimental measurements ft survey:2009 by Hardy & Towner
  - Theoretical corrections
    a. radiative corrections Marciano:2006, Towner:2008
    b. isospin symmetry-breaking corrections δ_c
- **Definition of δ_c** $|M_F|^2 = |\langle f|\, T_{\pm}\,|i\rangle|^2 = |M_0|^2(1-\delta_c),$

  where $|M_F|^2$ is the superallowed transition strength

  and $|M_0|^2$ is the strength with exact isospin symmetry
- **Microscopic approaches for δ_c**
  - shell model Towner:2008
  - self-consistent charge-exchange RPA calculations e.g. Sagawa:1996
- **Self-consistent relativistic RPA approaches：the isospin symmetry-breaking corrections δ_c.**

$|V_{ud}|$ and unitarity of the CKM matrix

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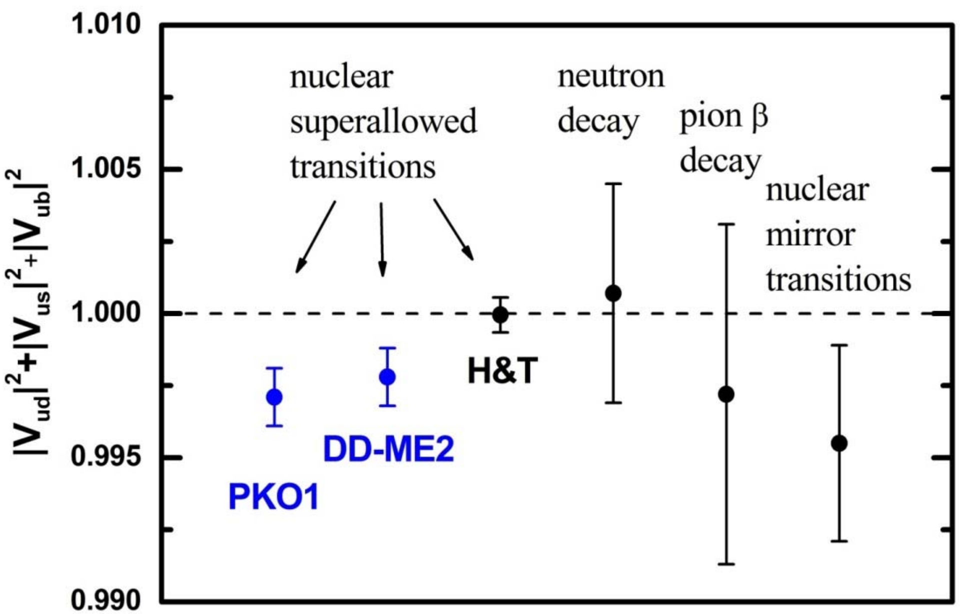
Up-down element and unitarity of the CKM matrix.

	PKO1	PKO2	PKO3	PKO1*	DD-ME1	DD-ME2	NL3	TM1
$\|V_{\rm ud}\|$	0.9727(3)	0.9728(3)	0.9727(3)	0.9730(3)	0.9731(3)	0.9731(3)	0.9730(3)	0.9731(3)
$\|V_{\rm ud}\|^2+\|V_{\rm us}\|^2+\|V_{\rm ub}\|^2$	0.9971(10)	0.9971(10)	0.9971(10)	0.9977(10)	0.9978(10)	0.9978(10)	0.9975(10)	0.9978(10)



- ✓ Well agree with those obtained in neutron decay, pion β decay and nuclear mirror transitions.
- ✓ Somewhat deviate from the unitarity condition.

Liang, Van Giai, Meng, PRC (2009)

Particle Data Group:

"We note, however, that the possibility of additional nuclear Coulombic corrections has been raised recently [Miller:2008, Auerbach:2009, Liang:2009]."

Neutrinoless Double-beta decay

A second-order weak process： two protons are simultaneously transformed into two neutrons, or vice versa, inside an atomic nucleus.

❖ Two-neutrino double-beta ($2\nu\beta\beta$) decay

Goeppert-Mayer 1935, Phys. Rev. 48, 512

$$(A, Z) \rightarrow (A, Z+2) + e^- + e^- + \bar{\nu}_e + \bar{\nu}_e$$

❖ Neutrinoless double-beta ($0\nu\beta\beta$) decay

Majorana 1937, Nuovo Cim. 14, 171 Furry 1939, Phys. Rev. 56, 1184

$$(A, Z) \rightarrow (A, Z+2) + e^- + e^-$$

Lepton number violating process

Majorana's theory of neutrinos $\bar{\nu}_M = \nu_M$

The 2vββ mode is allowed in SM while 0vββ decay would go beyond SM. The $0\nu\beta\beta$ decay occurs only if <u>neutrinos are Majorana particles</u> and <u>lepton numbers can be violated</u>.

The calculation of the NME requires two main ingredients : One is **the decay operator**, which reflects the mechanism governing the decay process. The other is **the wave functions of the initial and final states**.

Nuclear matrix elements

❖ The $0\nu\beta\beta$-decay rate

$$\Gamma^{0\nu} = G^{0\nu}(Q_{\beta\beta}, Z) \times |M^{0\nu}|^2 \times |\langle m_\nu \rangle|^2$$

Unknown

- Kinematic phase space factor $G^{0\nu}(Q_{\beta\beta}, Z)$ can be accurately determined.

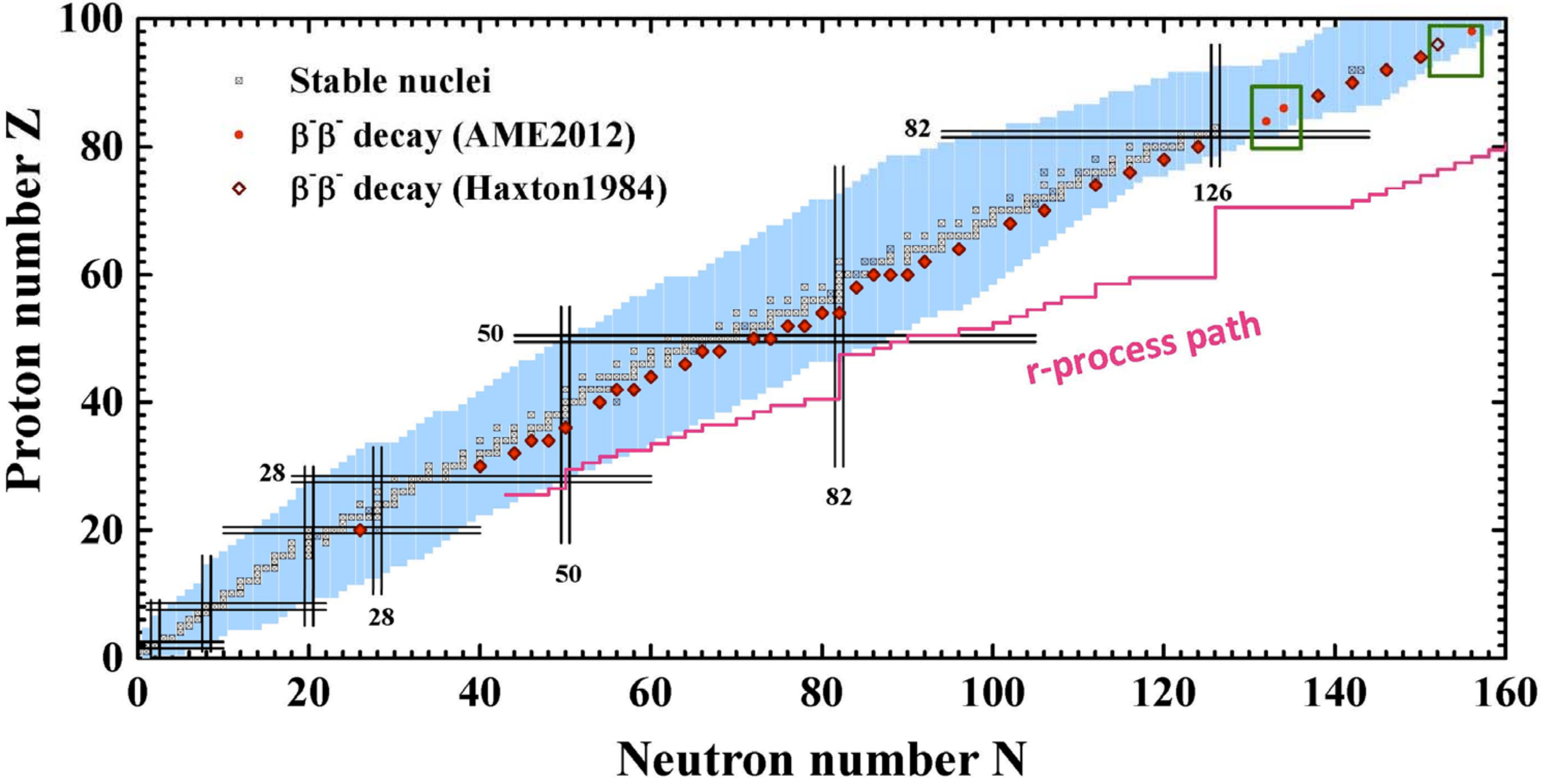
Kotila & Iachello 2012, PRC 85, 034316

- Nuclear matrix element $M^{0\nu}$ depend on nuclear structure models.

$$M^{0\nu} = \langle \Psi_F | \hat{O}^{0\nu} | \Psi_I \rangle$$

Accurate nuclear matrix elements are crucial for extracting the effective neutrino mass.

Nuclear neutrinoless double β-decay



Relativistic description of nuclear matrix elements in neutrinoless double-β decay

Phys. Rev. C 90, 054309 – Published 10 November 2014
Song, Yao, Ring, and Meng

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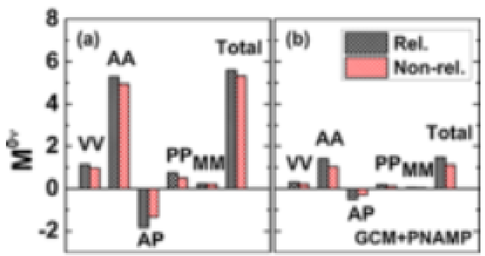
Editors' Suggestion

Relativistic description of nuclear matrix elements in neutrinoless double-β decay

L. S. Song, J. M. Yao, P. Ring, and J. Meng
Phys. Rev. C **90**, 054309 (2014) – Published 10 November 2014



Phys. Rev. C 91, 024316 (2015)
Yao, Song, Hagino, Ring, and Meng

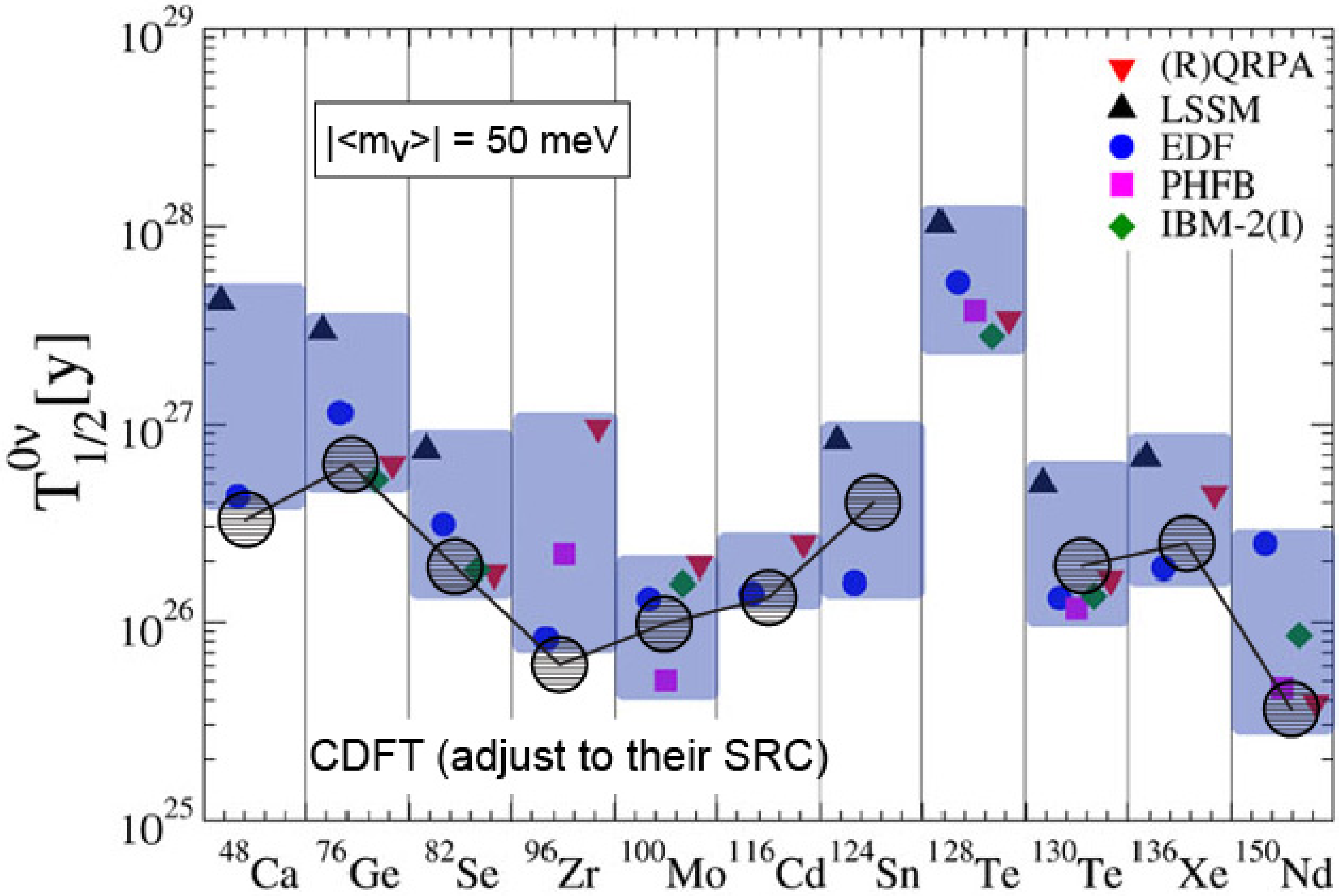
The authors report a fully relativistic des
based on a state-of-the-art nuclear struc
and electric quadrupole transitions in bo
double-β decay experiments.

TABLE II. The calculated NME $M^{0\nu}$ of the $0\nu\beta\beta$ decay with the REDF (PC-PK1), in comparison with those by the NREDF (D1S), RQRPA, PHFB, ISM, and IBM2. Only the results considering the short-range correlation (SRC) effect by UCOM, except for the IBM2 where CCM is used and using the parameter $R = 1.2A^{1/3}$ fm are adopted for comparison. The values in the parentheses are the results with additional pairing fluctuations.

Models $g_A(0)$	REDF(PC-PK1) 1.254	NREDF(D1S) 1.25	RQRPA (Tübingen) 1.254	PHFB 1.254	ISM 1.25	IBM2 1.269
^{48}Ca → ^{48}Ti	2.94	2.37 (2.23)			0.85	2.38
^{76}Ge → ^{76}Se	6.13	4.60 (5.55)	5.17		2.81	6.16
^{82}Se → ^{82}Kr	5.40	4.22 (4.67)	5.32		2.64	4.99
^{96}Zr → ^{96}Mo	6.47	5.65 (6.50)	1.77	3.32		3.00
^{100}Mo → ^{100}Ru	6.58	5.08 (6.59)	3.88	7.22		4.50
^{116}Cd → ^{116}Sn	5.52	4.72 (5.35)	3.21			3.29
^{124}Sn → ^{124}Te	4.33	4.81 (5.79)			2.62	4.02
^{130}Te → ^{130}Xe	4.98	5.13 (6.40)	4.07	4.66	2.65	4.61
^{136}Xe → ^{136}Ba	4.32	4.20 (4.77)	2.54		2.19	3.79
^{150}Nd → ^{150}Sm	5.60	1.71 (2.19)		3.24		2.88

Life-time for 0νν decay： Relativity & SRC

DOUBLE-BETA DECAY HALF-LIFE OF SEVERAL NUCLEI FROM DIFFERENT NUCLEAR MANY-BODY CALCULATIONS IN THE LIGHT NEUTRINO EXCHANGE SCENARIO



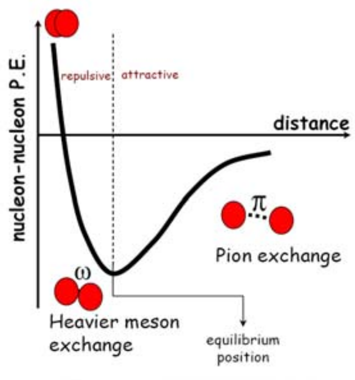
Vergados, Ejiri and Simkovic, Rep. Prog. Phys. 75 106301 (2012)

Song, Yao, Ring, Meng, Phys. Rev. C 95, 024305 (2017)

Nuclear covariant density functional theory tomorrow

The effective interaction in current CDFT is not derived from the basic theory of the strong interaction --- QCD. As indicated by the successes achieved by the covariant density functional, the feasibility of a unified self-consistent description of nuclear ground state and excitation properties starting from an effective nucleon-nucleon interaction is anticipated.

In future, one needs to obtain properly the nucleon-nucleon interaction in nuclear medium starting from the quantum chromo-dynamics, eventually to build the standard model of nuclear structure that can implement the ab initio exploration for all nuclei in the nuclear chart.



Thank you for your attention!

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Validity of CDFT

ab initio calculation in nuclear physics

ab initio----- "from the beginning"

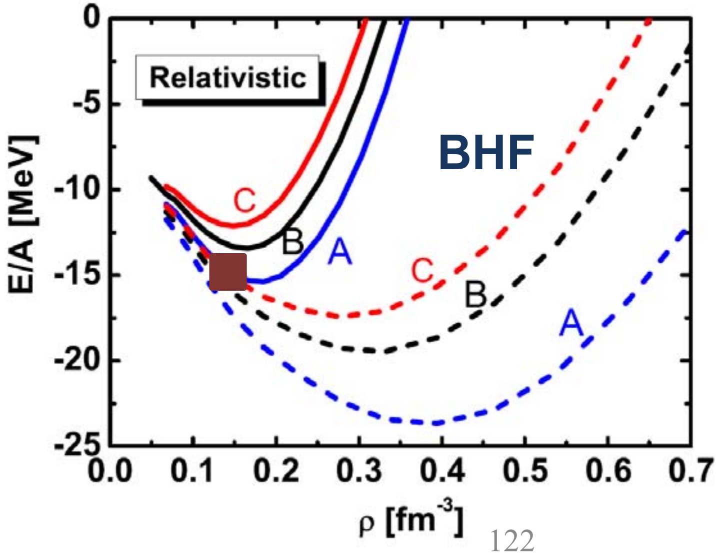
- without additional assumptions
- without additional parameters

ab initio in nuclear physics

- with realistic nucleon-nucleon interaction
- with some few-body methods and many-body methods, such as Monte Carlo method, shell model and energy density functional theory

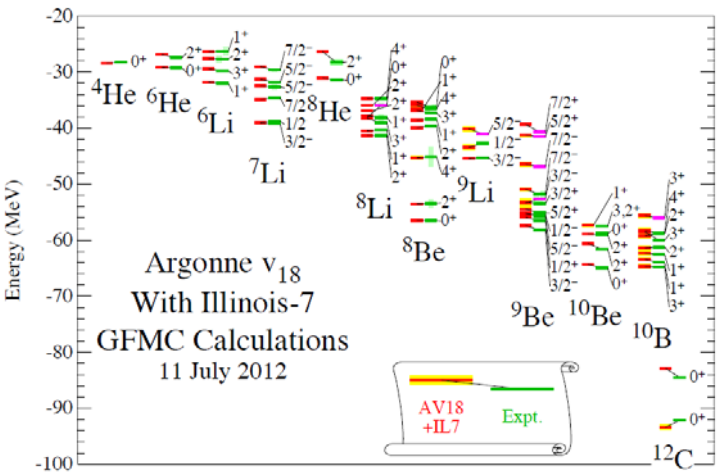
ab initio in nuclear matter

- Variational method — Akmal PRC1998
- Green's function method — Dickhoff PPNP2004
- Chiral Perturbation theory — Kaiser NPA2002
- Brueckner-Hartree-Fock (BHF) theory — Baldo RPP2012
- Relativistic BHF (RBHF) theory — Brockmann PRC1990
- ....



ab initio calculation for light nuclei

- Gaussian Expansion Method — Hiyama PPNP2003
- Green Function Monte Carlo Method — Pieper PRC2004
- Lattice Chiral Effective Field Theory — Lee PPNP2009
- No-Core Shell Model — Barrett PPNP2012
- ……



Pieper, Wiringa, et al.

ab initio calculation for heavier nuclei

- Coupled Channel method — Hagen PRL2009
- BHF theory — Hjorth-Jensen Phys.Rep.1995
  - With HJ potential — Dawson Ann.Phys.1962
  - With Reid potential — Machleidt NPA1975
  - With Bonn potentials — Muether PRC1990

	Bonn C	Bonn B	Bonn A	Exp.
$\varepsilon_{1s_{1/2}}$	−39.73	−44.37	−50.46	-40 ± 8
$\varepsilon_{1p_{3/2}}$	−16.98	−19.49	−22.89	−18.4
$\varepsilon_{1p_{1/2}}$	−11.64	−13.24	−15.44	−12.1
E	−71.84	−85.60	−104.96	−127.68
r_c	2.465	2.380	2.291	2.737

^{16}O in BHF method in Bonn potential

Relativistic Brueckner Hartree-Fock: Dirac BHF (RBHF)

➢Nuclear matter Anastasio PRep 1978 Brockmann PLB 1984 ter Haar PRep. 1987

➢Defining an effective medium dependent meson-exchange interaction based upon the nuclear matter G matrix Brockmann PRC1990 Brockmann PRL 1992 Fritz PRL 1993

ab initio calculation attempt with CDFT: extracted interaction from the *ab initio* calculation in nuclear matter

➢ Density-dependent relativistic mean field theory Brockmann PRL1992

➢ Density-dependent relativistic Hartree-Fock theory Fritz PRL1993

First Full Relativistic Brueckner Hartree-Fock calculation for finite nucleus

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CHIN. PHYS. LETT. Vol. 33, No. 10 (2016) 102103 Express Letter

Relativistic Brueckner–Hartree–Fock Theory for Finite Nuclei *

Shi-Hang Shen(申时行)[1,2], Jin-Niu Hu(胡金牛)[3], Hao-Zhao Liang(梁豪兆)[2,4], Jie Meng(孟杰)[1,5,6**],
Peter Ring[1,7], Shuang-Quan Zhang(张双全)[1]

[1]*State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871*
[2]*RIKEN Nishina Center, Wako 351-0198, Japan*
[4]*Departme*
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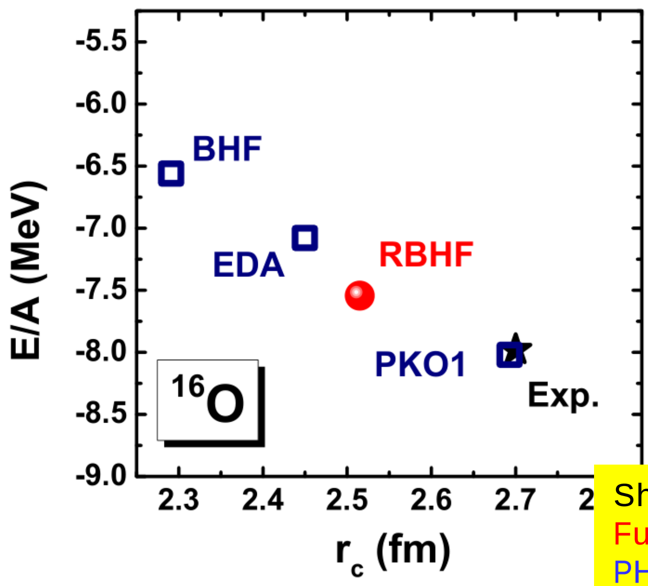
Technischen Universität München, D-85748 Garching, Germany

Shi-Hang Shen, Jin-Niu Hu,Hao-Zhao Liang, Jie Meng, Peter Ring, Shuang-Quan Zhang,
Relativistic Brueckner–Hartree–Fock Theory for Finite Nuclei .
Chin. Phys. Lett. 33 (2016) 102103



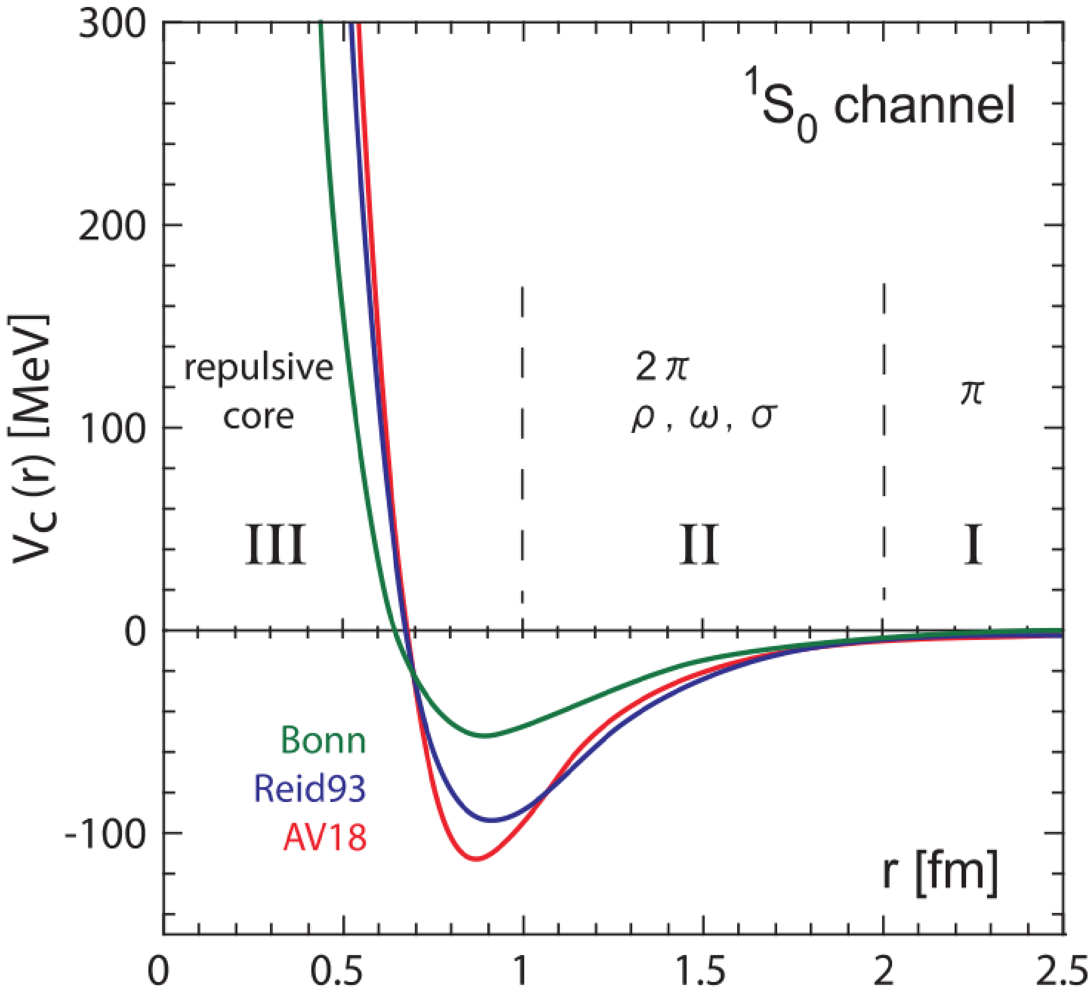
"This is the best paper on the topic and the only one with fully self-consistent solutions. To my opinion this paper is important to theoretical nuclear physics."

Long paper： arXiv:1705.01691

Shi-Hang Shen, Hao-Zhao Liang, Jie Meng, Peter Ring, Shuang-Quan Zhang,
Fully self-consistent relativistic Brueckner-Hartree-Fock theory for finite nuclei.
PHYSICAL REVIEW C 96, 014316 (2017)

Nuclear Force from Lattice QCD

Two nucleon interaction：**Nuclear Force from Lattice QCD**



N. Ishii, S. Aoki, and T. Hatsuda, *PRL* **99**, 022001 (2007)

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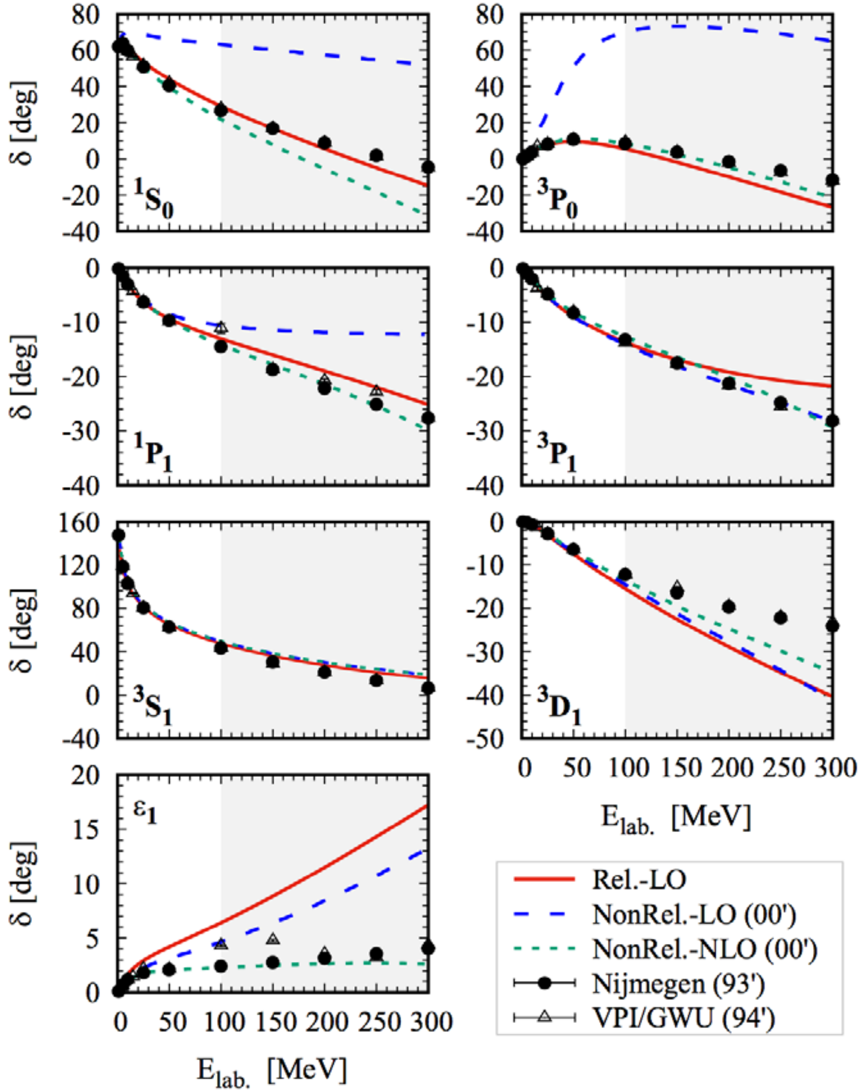
Covariant chiral nuclear force.

Toward microscopic nucleon interaction



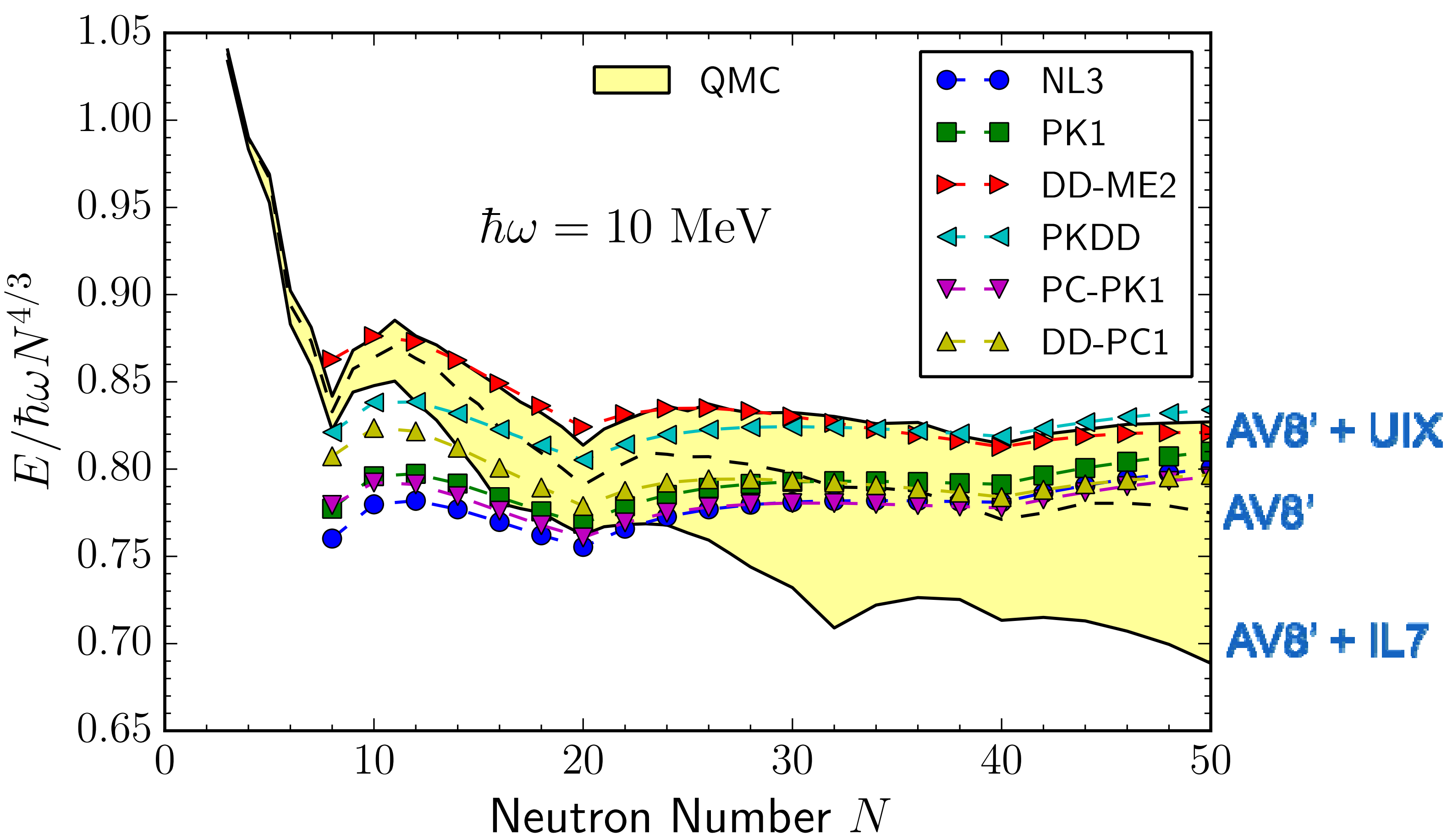
Leading order covariant chiral nucleon-nucleon interaction

The relativistic framework presents a more efficient formulation of the chiral nuclear force.

Ren, Li, Geng, Long, Ring, and Meng, **Chinese Physics C** 42 (2018) 014103

arXiv:1611.08475

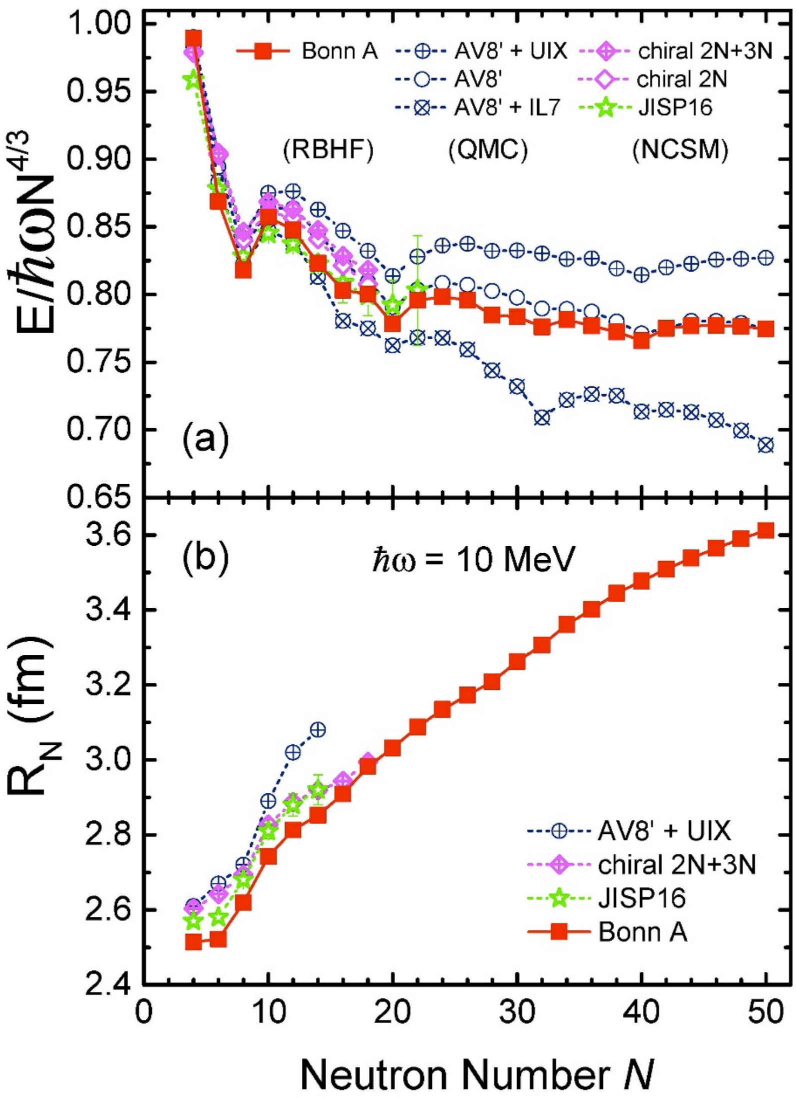
Energy variation in Neutron drop

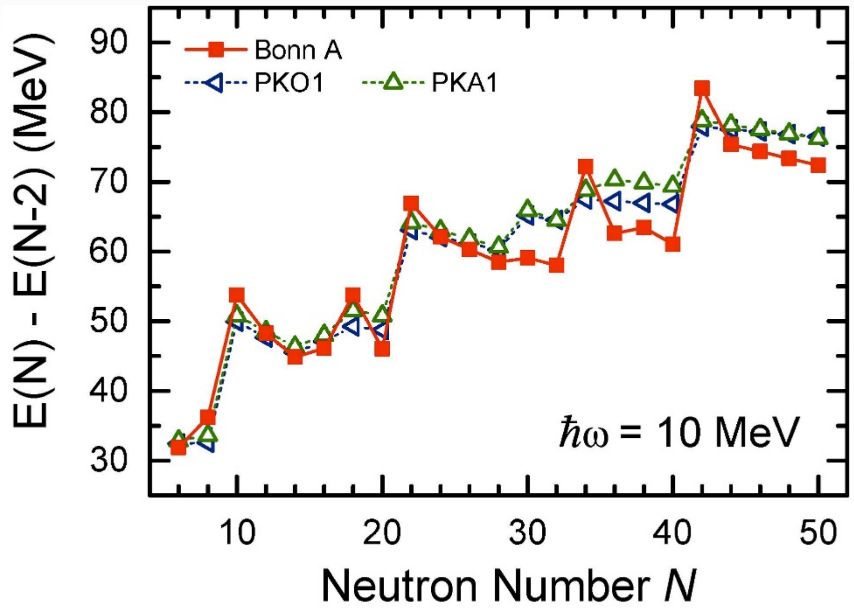


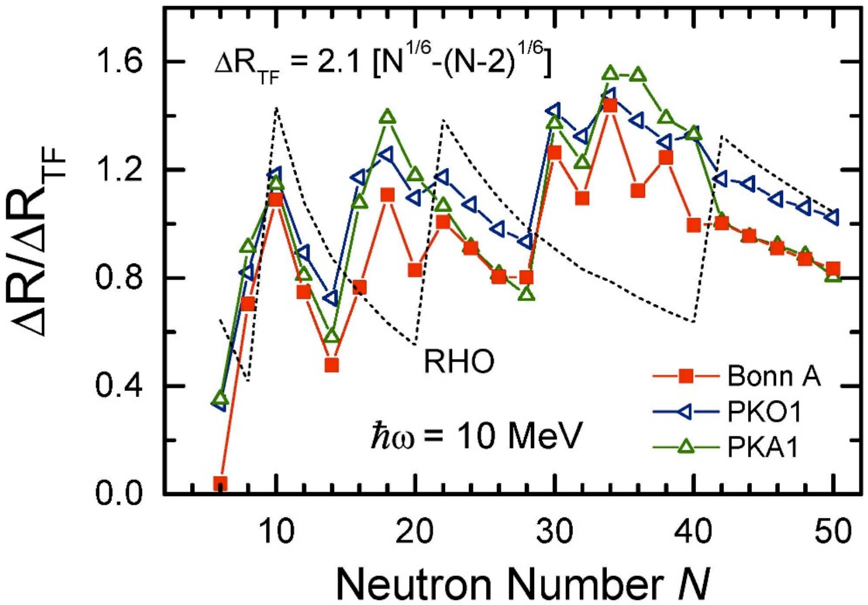
Zhao and Gandolfi PRC 94 (2016)041302(R)

The three-body forces and isovector density functionals are still very unclear !

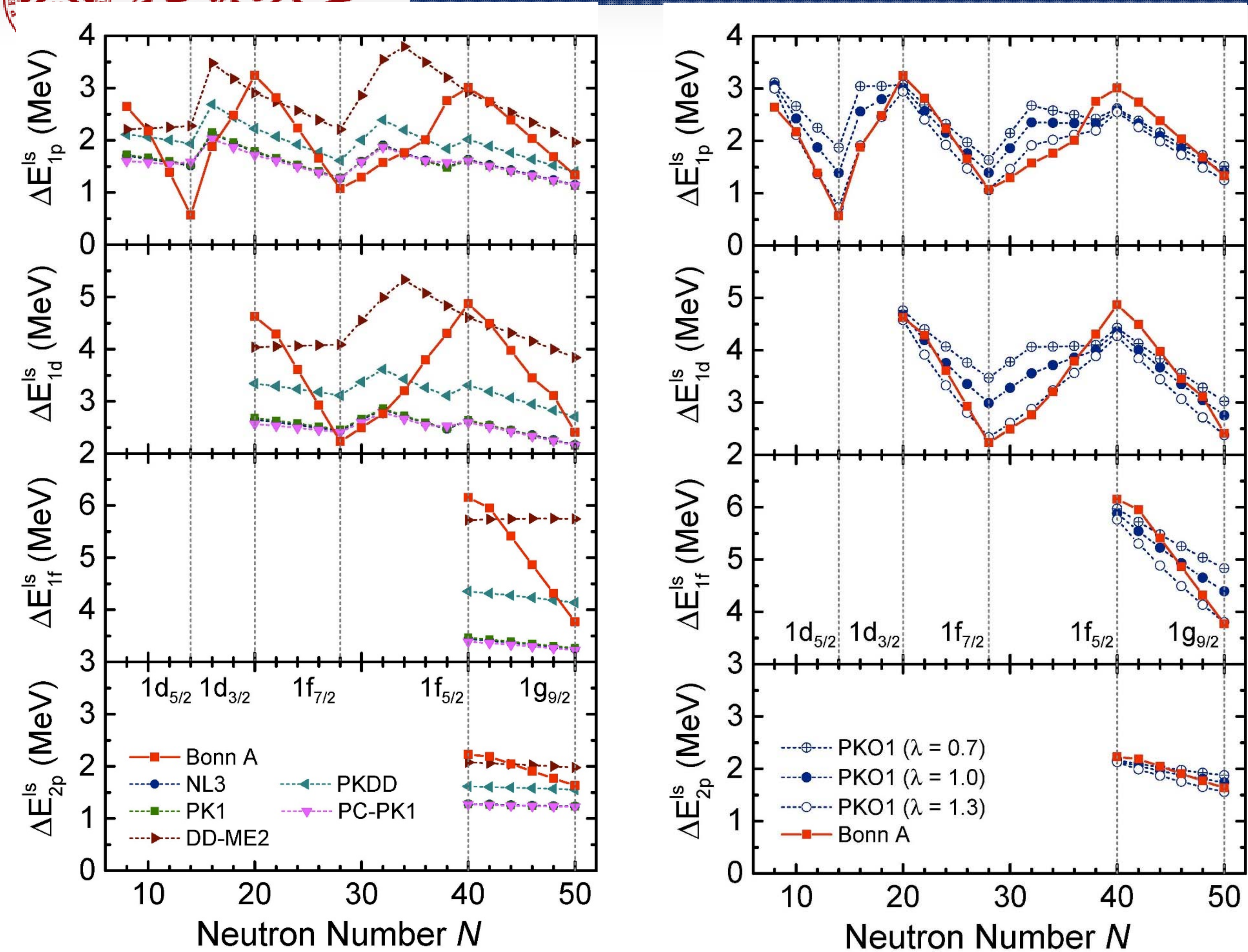
Energy and drop size in Neutron drop







Tensor force and so splitting in Neutron drop



Thank you for your attention!