第七届强相互作用量子色动力学对称性及其物质结构学术研讨会

2023.7.19 - 2023.7.22 日照，山东

From Hadronic Interactions to the Relativistic Description of Nuclear Structure

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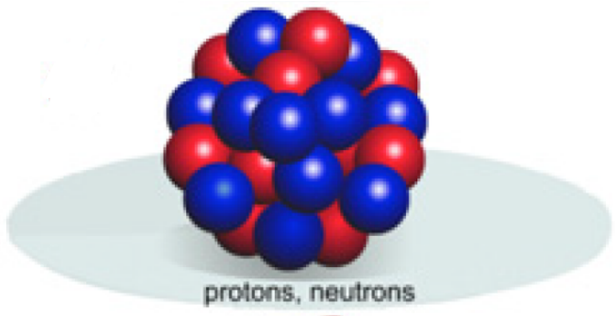
Challenge of nuclear structure theory

- Nuclear structure encompasses phenomena over **a wide range of energy scale**.

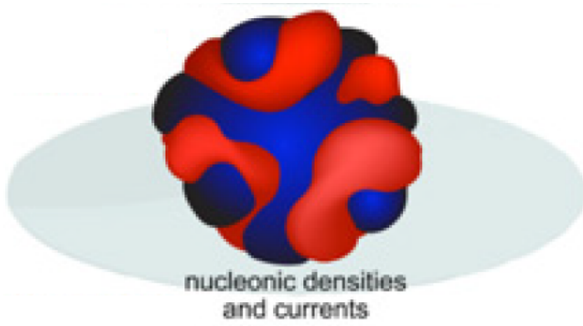
- The choice of degrees of freedom depends on the resolution of the theoretical microscope (the specific physics question).

Lattice QCD

Ab initio



DFT



High resolution

Low resolution

Why relativistic framework?

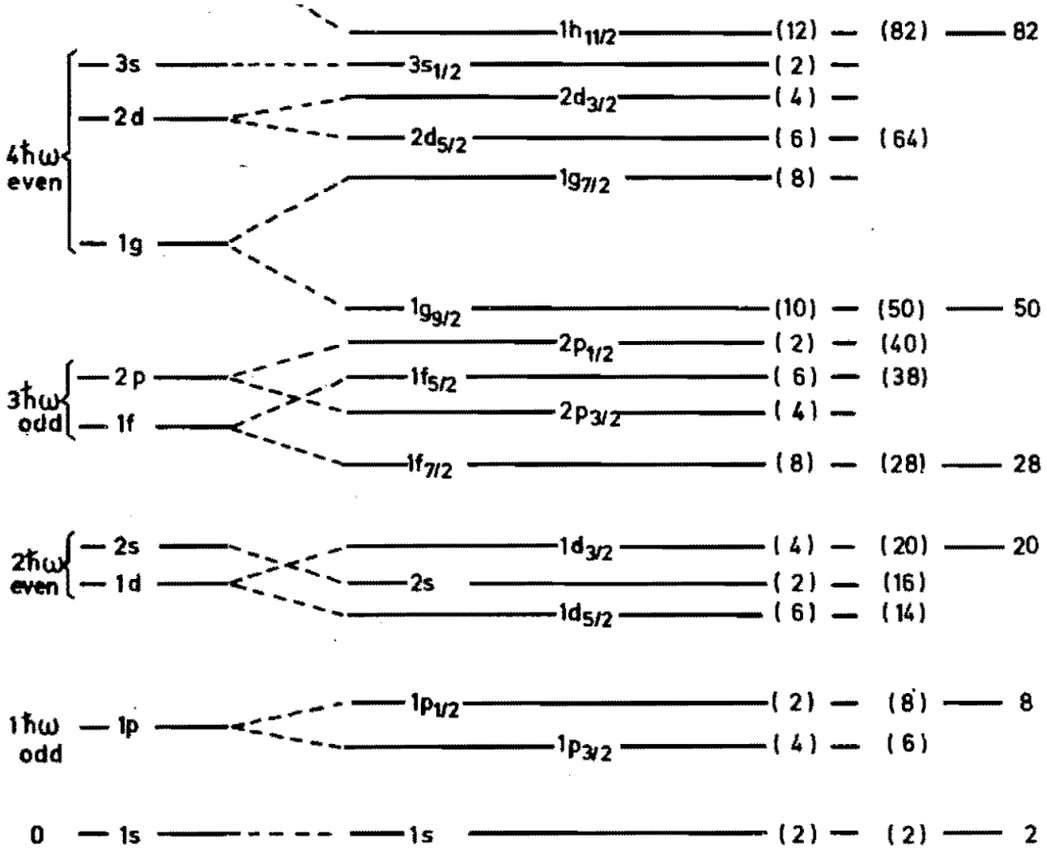
- ✓ Lorentz invariance is one of **the most fundamental symmetry in nature**
- ✓ Large spin-orbit splitting in nuclei
- ✓ Relativistic nuclear saturation
- ✓ ……

Einstein

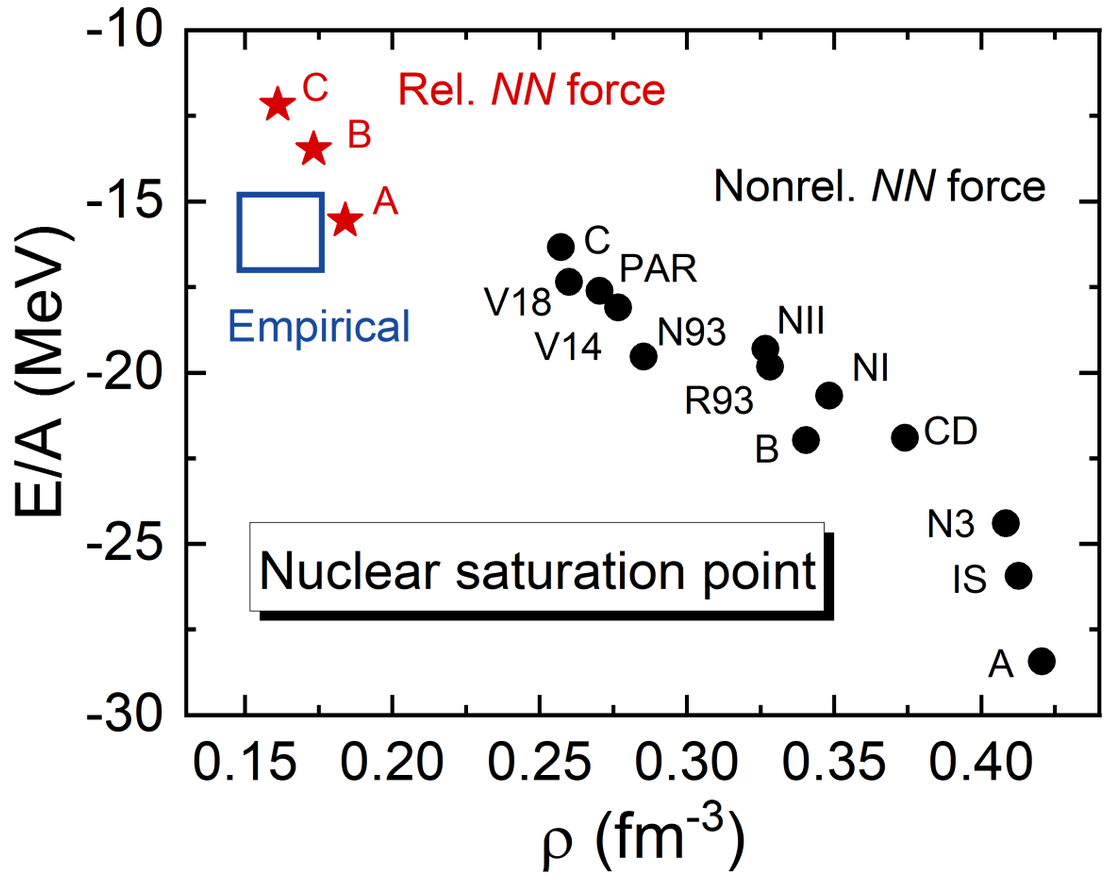
Dirac

Mayer

Jensen



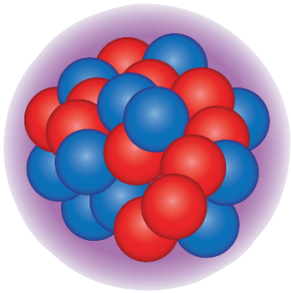
P. Ring and P. Schuck, *The Nuclear Many-Body Problem* (1980)

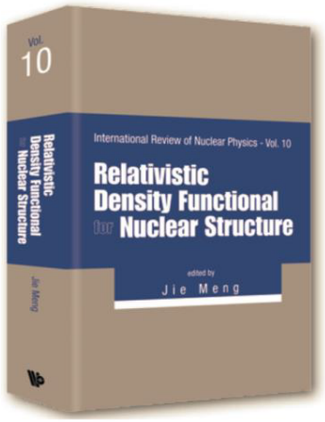


Data from Z. H. Li et. al., PRC 74, 047304 (2006)

Major research interests

- ✓ ***Hadronic interactions from Lattice QCD***
- ✓ ***Relativistic ab initio calculations of nuclei***
- ✓ Deep-learning Quantum Monte Carlo methods
- ✓ Nuclear relativistic density functional theory
- ✓ ***DRHBc nuclear mass table***
- ✓ Exotic rotations and deformations of nuclei
- ✓ Nuclear fission and fusion dynamics
- ✓ Nucleosynthesis processes in astrophysics
- ✓ Test of fundamental symmetries in nuclear systems
- ✓ …….





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Authors from China, Croatia, France, Germany, Italy, Japan, and USA.


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Review

Towards an *ab initio* covariant density functional theory for nuclear structure

Shihang Shen [a,b,c], Haozhao Liang [d,e], Wen Hui Long [f,g], Jie Meng [a,h,i,*], Peter Ring [a,j]


Contents lists available at ScienceDirect
Progress in Particle and Nuclear Physics
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Review

Beyond-mean-field approaches for nuclear neutrinoless double beta decay in the standard mechanism

J.M. Yao [a,b,*], J. Meng [c,d], Y.F. Niu [e], P. Ring [f]

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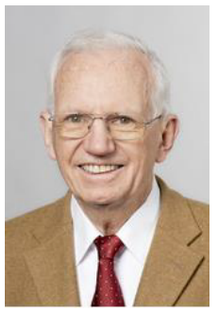

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Cong Pan

Yanyu Chen

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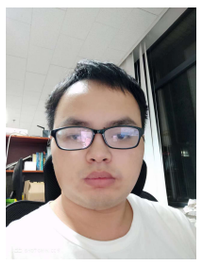
Fangfang Xu



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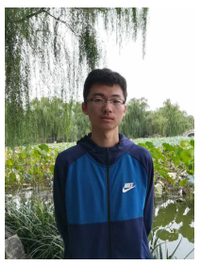

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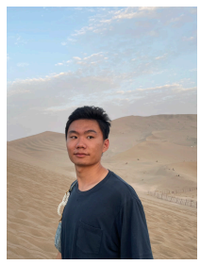
Bo Li



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Teng Qu

Chang Zhou

Tianxing Huang

Peng Guo

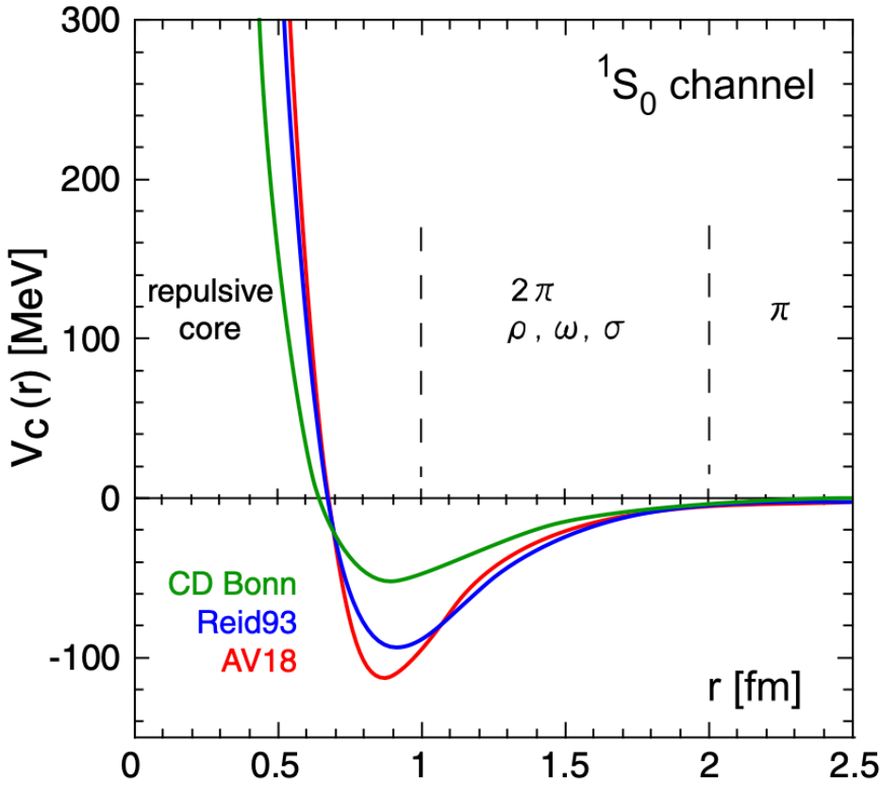
Hadronic interactions from Lattice QCD

Nucleon-nucleon interactions

- The nucleon-nucleon (NN) interaction is one of the most fundamental inputs for the theoretical description of nuclear systems.

- Phenomenological NN interactions
  - AV18, Bonn, …

- EFT-based NN interactions
  - Chiral EFT, Pionless EFT, …



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

- Theoretical descriptions of nuclear systems suffer from uncertainties from various models of NN interactions。

Goal: Deriving (relativistic) NN interactions from Lattice QCD simulations

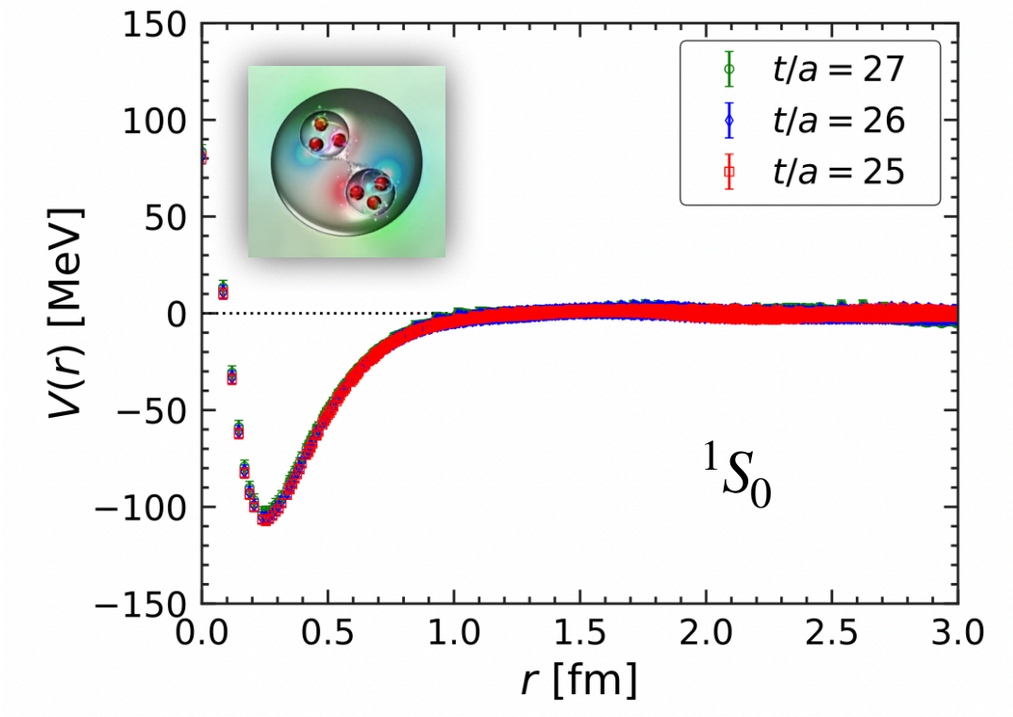
Hadronic interactions from Lattice QCD

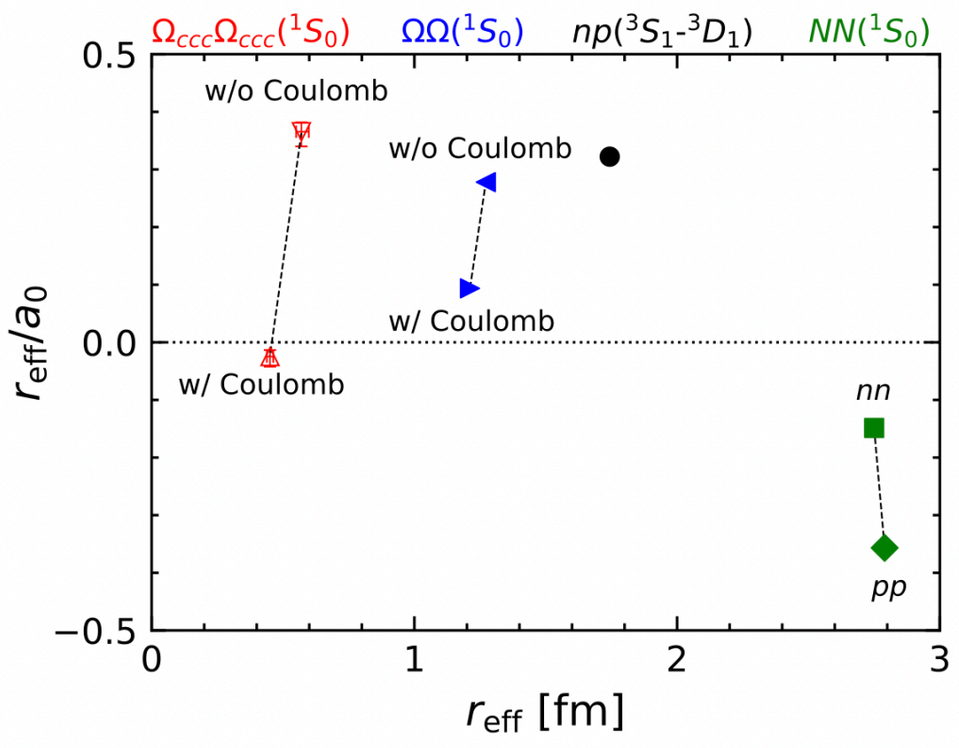
- A systematic study of hadron-hadron interactions by (2+1)-flavor lattice QCD with nearly physical light-quark masses
  - Meson-meson: D^*-D

    Y. Lyu, S. Aoki, T. Doi, T. Hatsuda, Y. Ikeda, and J. Meng, arXiv: 2302.04505 (2023)
  - Baryon-meson: N-ϕ

    Y. Lyu, T. Doi, T. Hatsuda, Y. Ikeda, J. Meng, K. Sasaki, and T. Sugiura, PRD 106, 074507 (2022)
  - Baryon-baryon: Ω_{ccc}-Ω_{ccc}, Ω_{sss}-Ω_{sss}

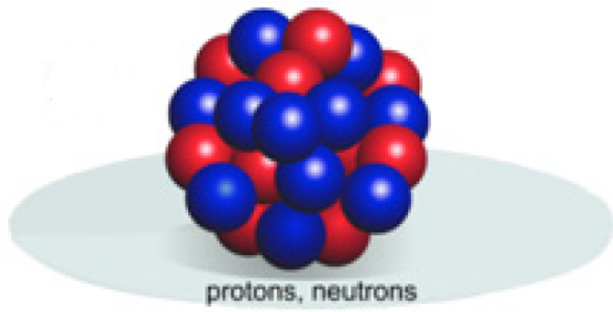
    Y. Lyu, H. Tong, T. Sugiura, S. Aoki, T. Doi, T. Hatsuda, J. Meng, and T. Miyamoto, PRL 127, 072003 (2021); PRD 106, 074507 (2022)





Y. Lyu and H. Tong et. al., PRL 127, 072003 (2021)

Relativistic ab initio calculations of nuclei



Relativistic nucleon-nucleon interactions

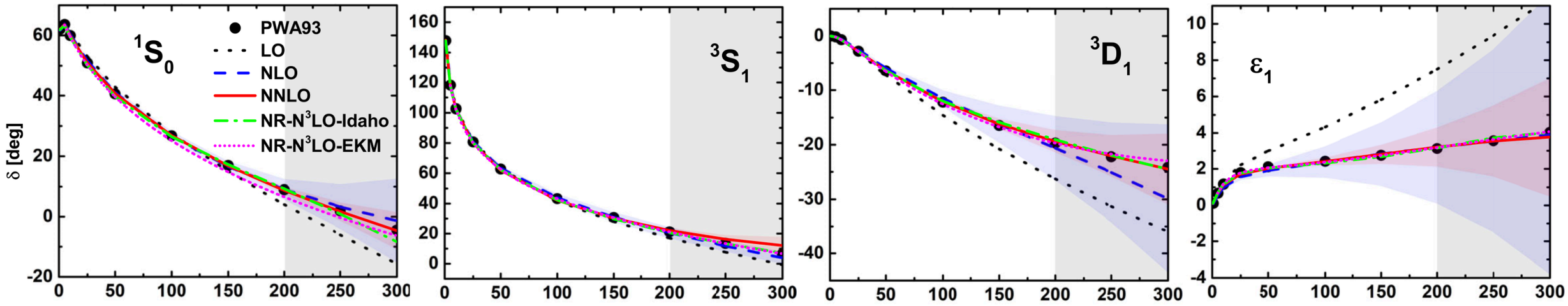
- Starting point: the relativistic NN interaction that reproduces NN scattering data (Bonn, pionless EFT, chiral EFT, …)

R. Machleidt, Adv. Nucl. Phys. 19, 189 (1989)

E. Epelbaum and J. Gegelia, PLB 716, 338 (2012)

J. X. Lu, C. X. Wang, Y. Xiao, L. S. Geng, J. Meng, and P. Ring, PRL 128, 142002 (2022)

……



NN Scattering phase shift from relativistic chiral NN interactions

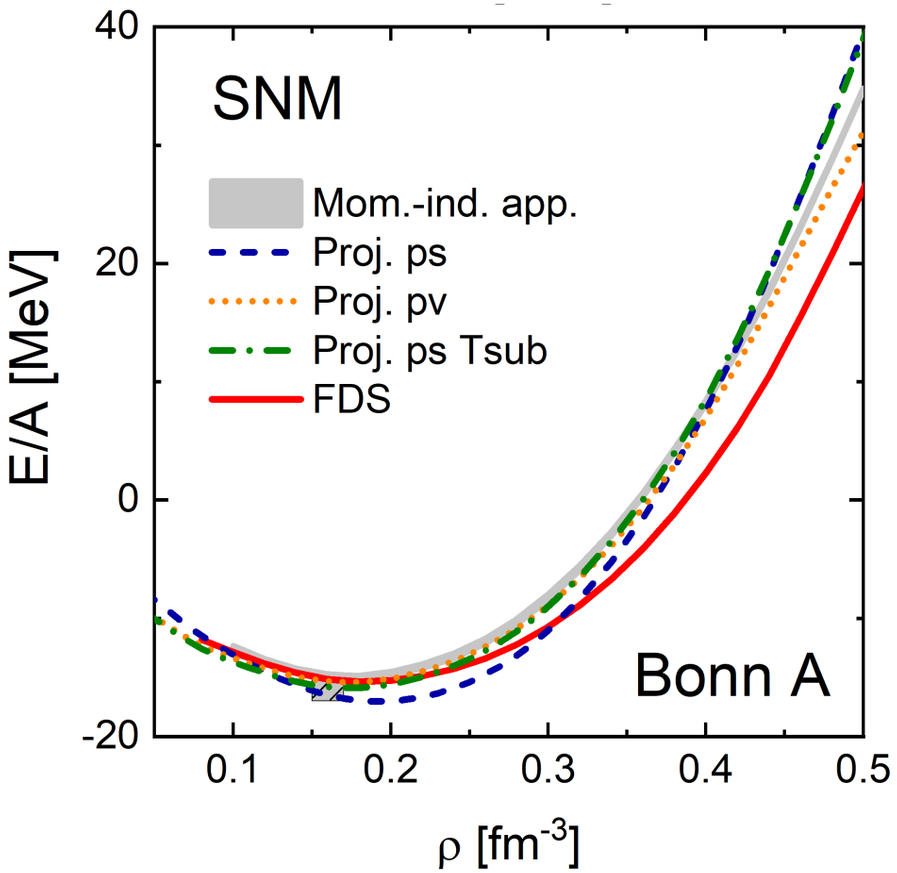
Taken from Lu2022PRL

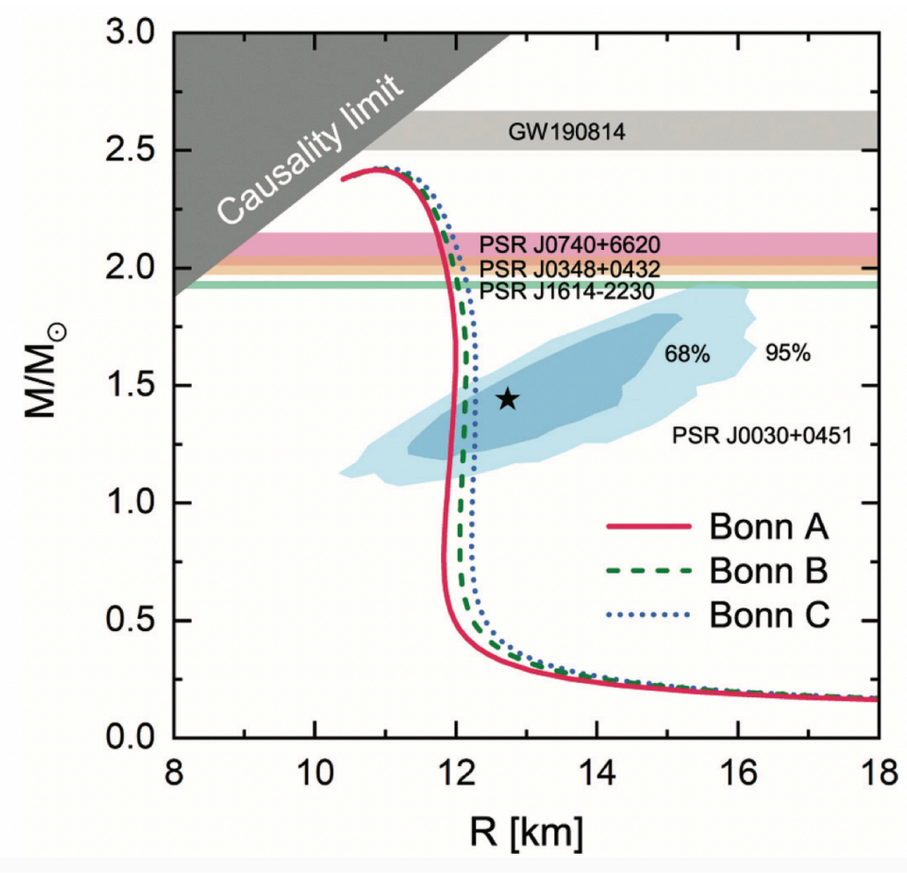
Goal: providing accurate descriptions of light nuclei and nuclear matter

Relativistic Brueckner theory in full Dirac space

- The first fully self-consistent relativistic Brueckner Hartree-Fock calculations in the full Dirac space.
  - Nuclear equation of state and symmetry energy
  - Neutron star physics
  - ……

S. B. Wang, Q. Zhao, P. Ring, and J. Meng, PRC 103, 054319 (2021)
S. B. Wang, H. Tong, Q. Zhao, C. C. Wang, P. Ring, and J. Meng, PRC 106, L021305 (2022)
S. B. Wang, H. Tong, Q. Zhao, C. C. Wang, P. Ring, and J. Meng, arXiv:2304.13333 (2023)

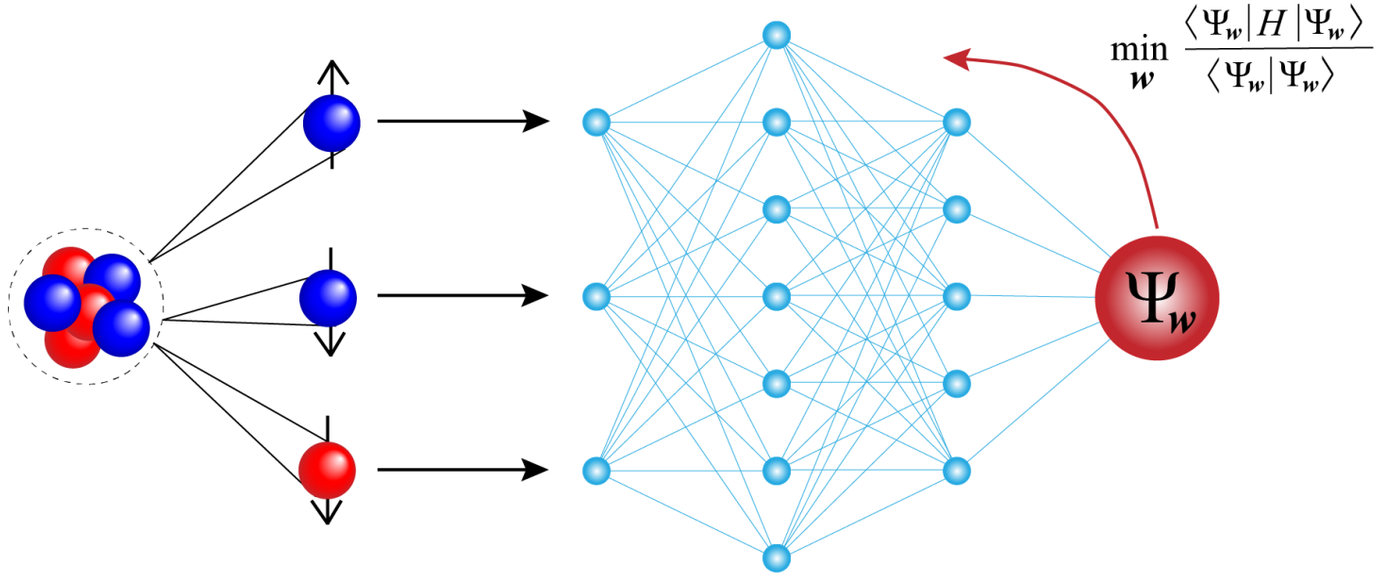




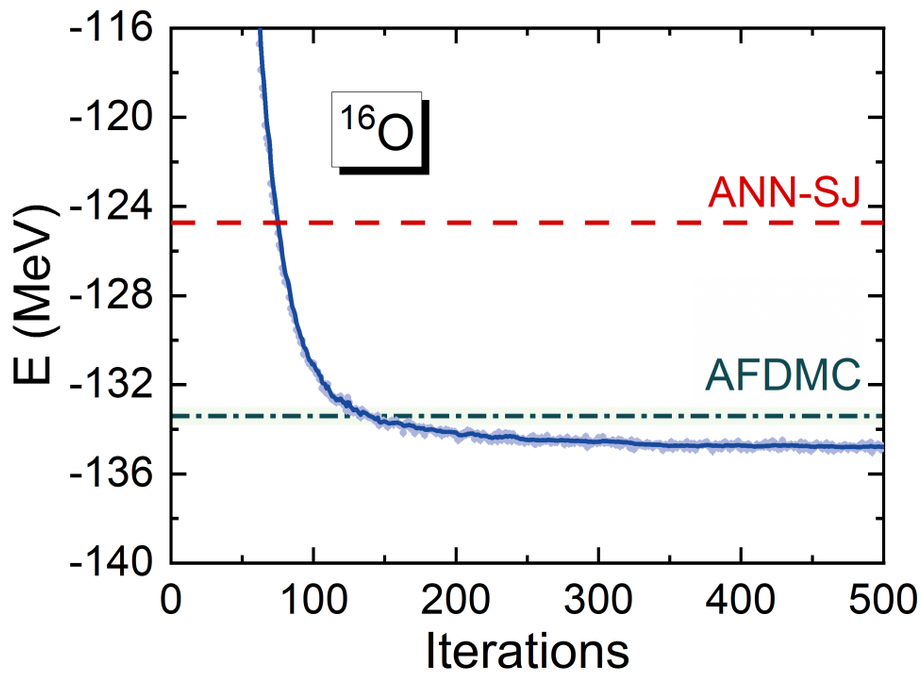
Relativistic Quantum Monte Carlo

- A new relativistic ab initio many-body method is developed by combining Quantum Monte Carlo and artificial neural-networks.

▸ Neural-network wave function



▸ Benchmark in light nuclei

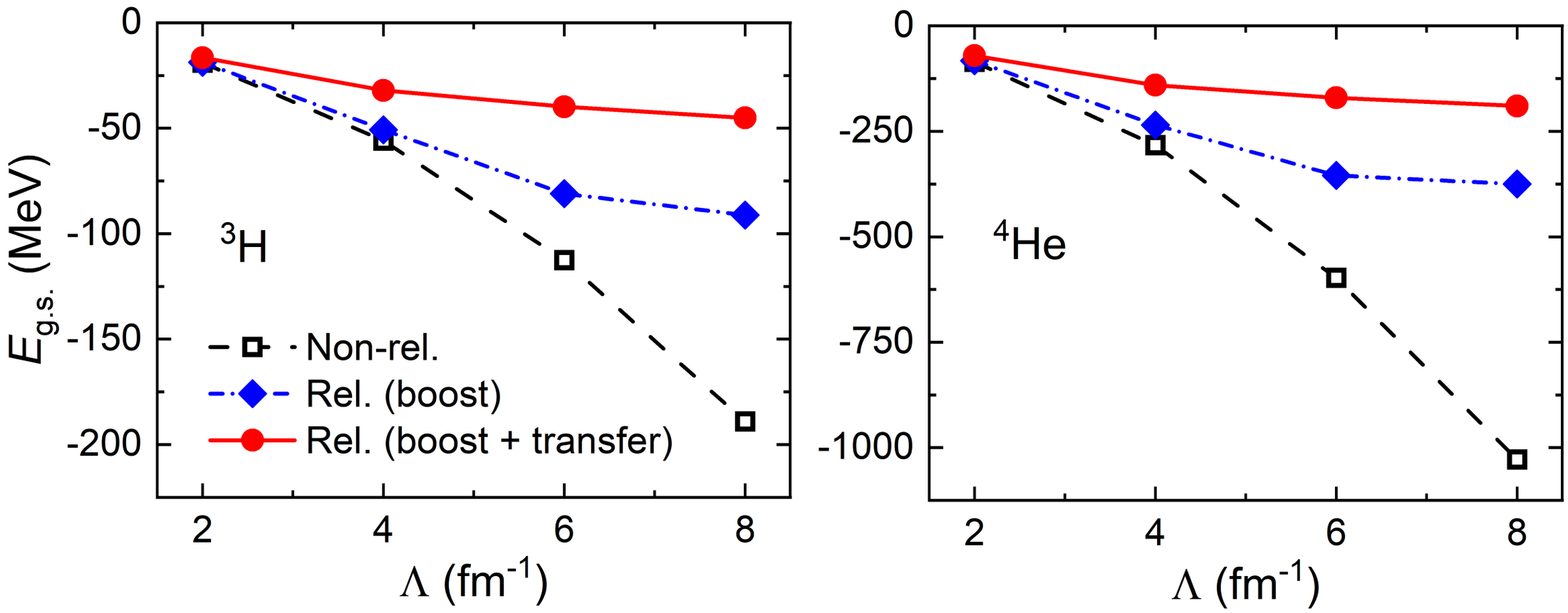


LO χEFT Hamiltonian: Schiavilla et. al., PRC 103, 054003 (2021)

YLY and P. W. Zhao, Phys. Rev. C 107, 034320 (2023)

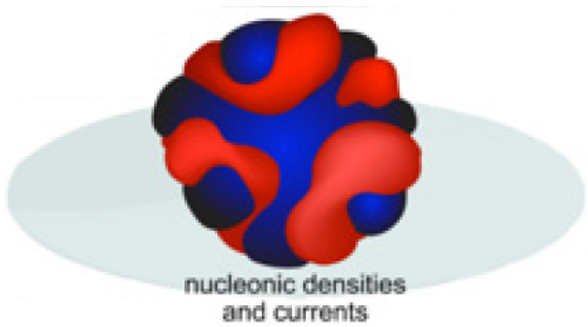
Relativistic effects in light nuclei

- As a first step, the light nuclei are studied starting from nuclear interactions derived from pionless EFT.
- Relativistic effects have a crucial impact on the renormalizability of few-nucleon systems in pionless EFT.



YLY and P. W. Zhao, Phys. Lett. B 835, 137587 (2022)

DRHBc nuclear mass table



Nuclear density functional theory

- The many-body problem is mapped onto a one-body problem.

Hohenberg-Kohn Theorem

The exact ground-state energy of a quantum many-body system is a universal functional of the density.

$$E[\rho] = E_{\text{kin}}[\rho] + E_{\text{int}}[\rho]$$

Kohn-Sham DFT

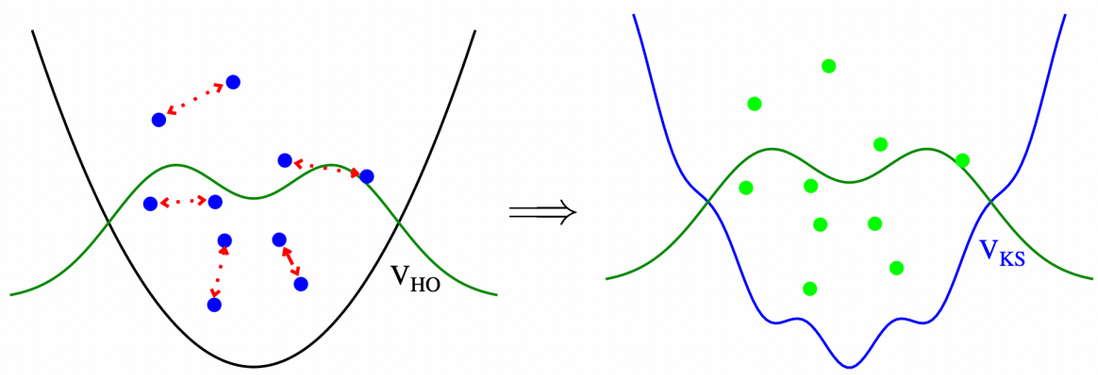


Fig from Drut2010PPNP

$$E[\rho] \Rightarrow \boxed{\hat{h} = \frac{\delta E}{\delta \rho}} \Rightarrow \boxed{\hat{h}\varphi_i = \varepsilon_i \varphi_i} \Rightarrow \boxed{\rho = \sum_{i=1}^{A} |\varphi_i|^2}$$

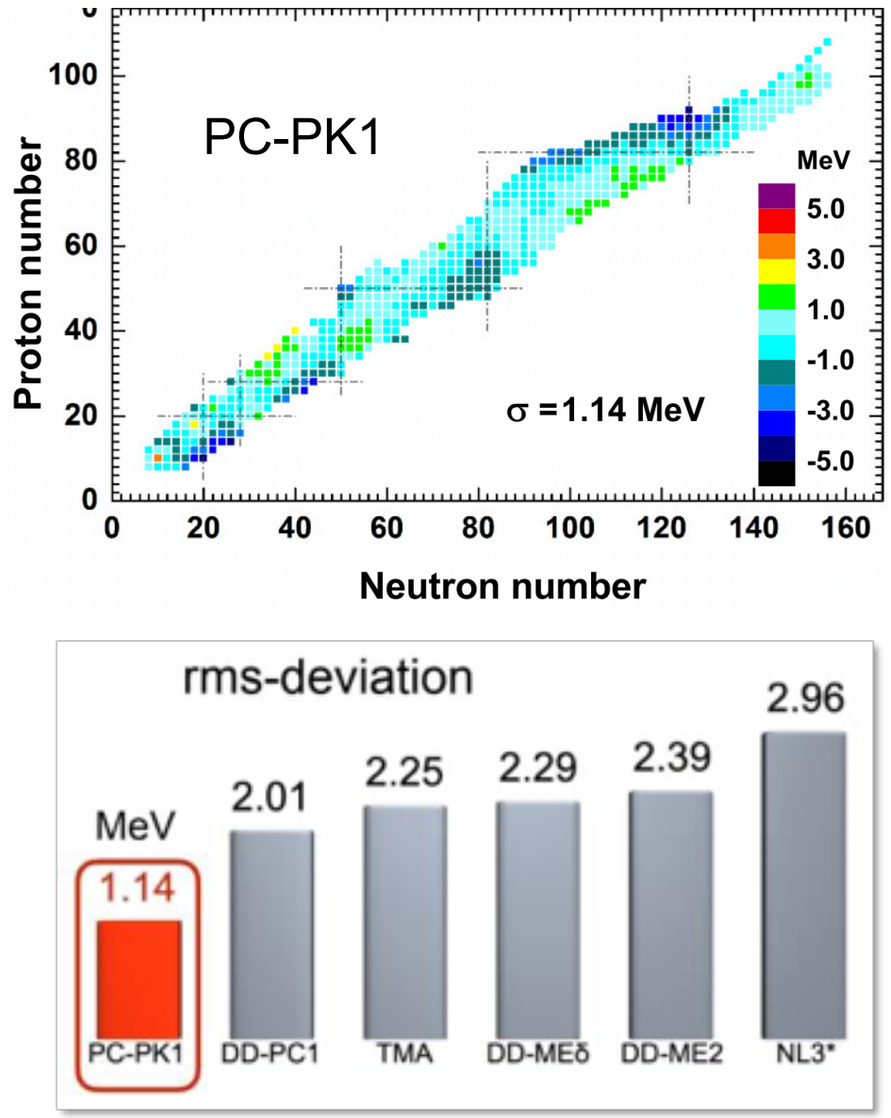
Goal: Predicting nuclear properties on the nuclear landscape based on an accurate and unified energy density functional

Relativistic density functional: PC-PK1

- One of the most accurate relativistic density functional PC-PK1

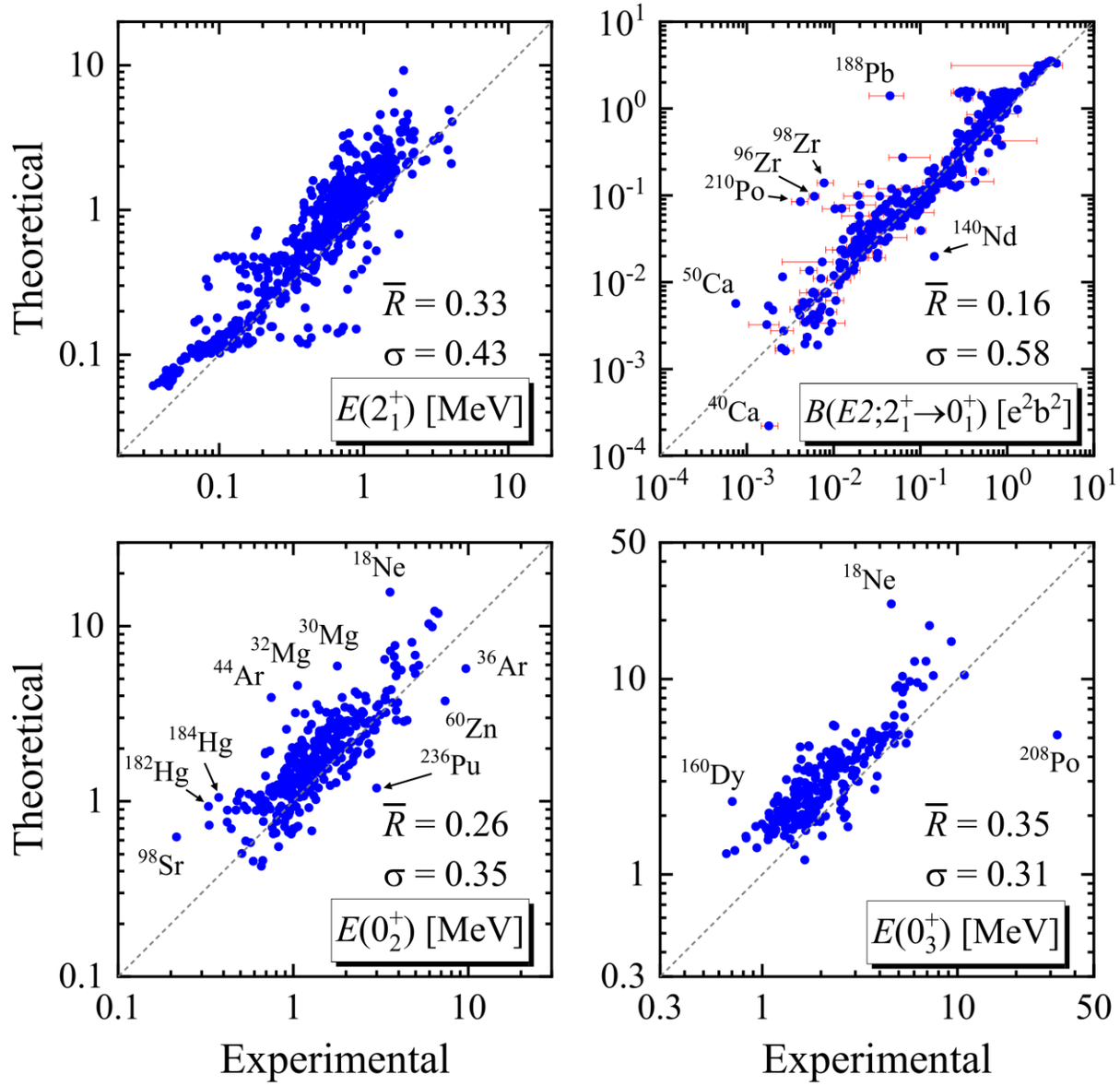
P. W. Zhao, Z. P. Li, J. M. Yao, and J. Meng, PRC 82, 054319 (2010)

✓ Nuclear mass



K. Q. Lu, Z. X. Li, Z. P. Li, J. M. Yao, J. Meng, PRC 91, 027304 (2015)

✓ Low-lying excited states



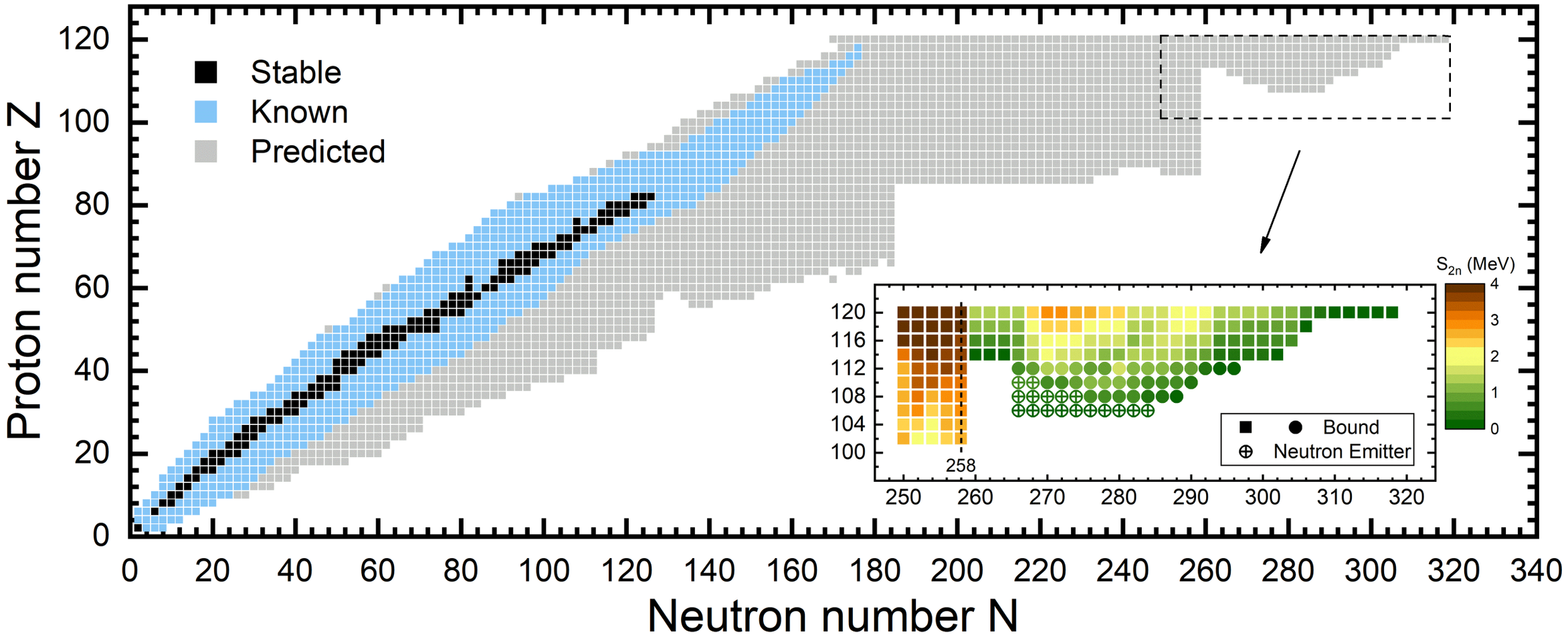
YLY, P. W. Zhao, and Z. P. Li, PRC 107, 024308 (2023)

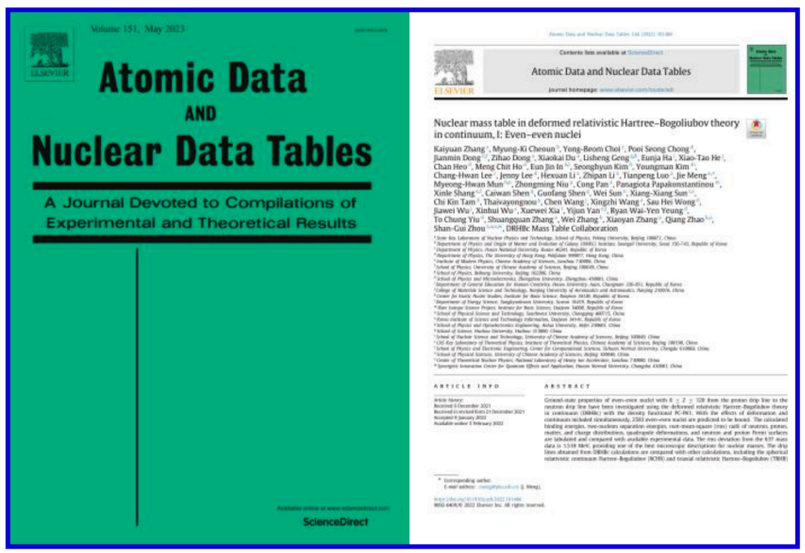
DRHBc collaboration

- The deformed relativistic Hartree-Bogoliubov theory in continuum (DRHBc) was developed to simultaneously include deformation, pairing correlations, and continuum effects, providing a proper description for exotic nuclei.

- The DRHBc Mass Table Collaboration:

DRHBc mass table for even-even nuclei



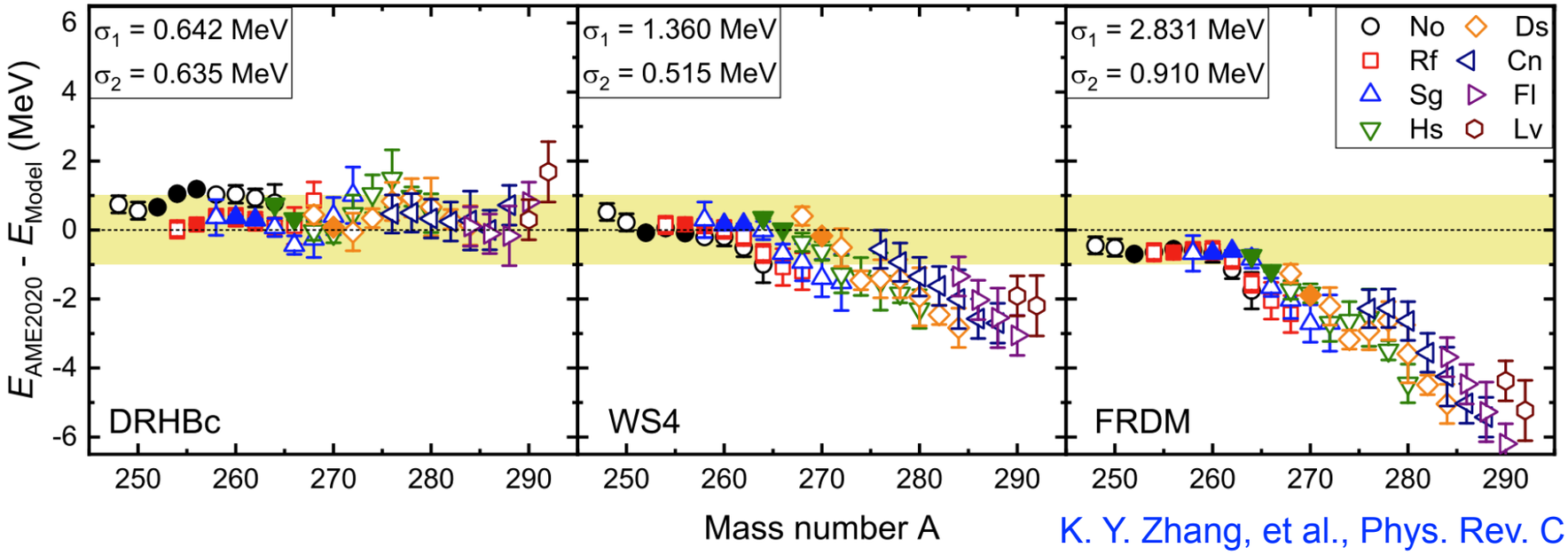


- ✓ Including deformation, pairing, and continuum effects simultaneously
- ✓ Among the most accurate mass table

K. Y. Zhang et. al., (DRHBc Mass Table Collaboration), ADNDT 144, 101488 (2022)

Further applications

- Accurate predictions for superheavy nuclei ($Z \geq 102$).



K. Y. Zhang, et al., Phys. Rev. C 104, L021301 (2021)

- DRHBc theory for odd nuclei.

  The DRHBc mass table for odd nuclei is under construction.

PHYSICAL REVIEW C **106**, 014316 (2022)

Deformed relativistic Hartree-Bogoliubov theory in continuum with a point-coupling functional. II. Examples of odd Nd isotopes

Cong Pan (潘琮),[1] Myung-Ki Cheoun,[2] Yong-Beom Choi,[3] Jianmin Dong (董建敏),[4,5] Xiaokai Du (杜晓凯),[1] Xiao-Hua Fan (范小华),[6] Wei Gao (高威),[7] Lisheng Geng (耿立升),[8,7] Eunja Ha,[9] Xiao-Tao He (贺晓涛),[10] Jinke Huang (黄靳苛),[7] Kun Huang (黄坤),[10] Seonghyun Kim,[2] Youngman Kim,[11] Chang-Hwan Lee,[3] Jenny Lee,[12] Zhipan Li (李志攀),[6] Zhi-Rui Liu (刘治瑞),[10] Yiming Ma (马艺铭),[13] Jie Meng (孟杰),[1,*] Myeong-Hwan Mun,[2,14] Zhongming Niu (牛中明),[15] Panagiota Papakonstantinou,[11] Xinle Shang (尚新乐),[4,5] Caiwan Shen (沈彩万),[16] Guofang Shen (申国防),[8] Wei Sun (孙玮),[6] Xiang-Xiang Sun (孙向向),[17,18] Jiawei Wu (吴佳威),[10] Xinhui Wu (吴鑫辉),[1] Xuewei Xia (夏学伟),[19] Yijun Yan (晏一珺),[4,5] To Chung Yiu,[12] Kaiyuan Zhang (张开元),[1,20] Shuangquan Zhang (张双全),[1] Wei Zhang (张炜),[7] Xiaoyan Zhang (张晓燕),[15] Qiang Zhao (赵强),[21,1] Ruyou Zheng (郑茹尤),[8] and Shan-Gui Zhou (周善贵)[18,22,23,24]
(DRHBc Mass Table Collaboration)

- Providing accurate nuclear mass inputs for nuclear physics and astrophysics applications.

Summary

- **The goal is to describe nuclear structure in the relativistic framework starting from different degrees of freedom.**
  - Deriving (relativistic) NN interactions from Lattice QCD simulations
  - Providing accurate ab initio descriptions of light nuclei and nuclear mater
  - Predicting nuclear properties on the nuclear landscape based on an accurate and unified energy density functional

- **Some representative progress:**
  - ✓ Deriving D^*-D, N-ϕ, Ω_{ccc}-Ω_{ccc}, and Ω_{sss}-Ω_{sss} interactions from lattice QCD
  - ✓ Developing the relativistic Brueckner Hartree-Fock method in full Dirac space and the relativistic Quantum Monte Carlo method
  - ✓ Constructing the DRHBc mass table for even-even nuclei

Acknowledgments

Professors: Jie Meng, Shuangquan Zhang, and Pengwei Zhao

Group members: Yakun Wang, Yiping Wang , Dandan Zhang, Yanyu Chen, Xiaokai Du, Fangfang Xu, Weijiang Zou, Xiaofei Jiang, Bo Li, Lingyi Dai, Teng Qu, Chang Zhou, Tianxing Huang, Peng Guo

Thank you!

Appendix