Neutron Dripline with Nuclear Lattice EFT

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Outline

- Motivations
- Method - Nuclear Lattice Effective Field Theory & Wavefunction matching
- Neutron dripline for Carbon & Oxygen
- Neutron dripline in Woods-Saxon potential
- Summary

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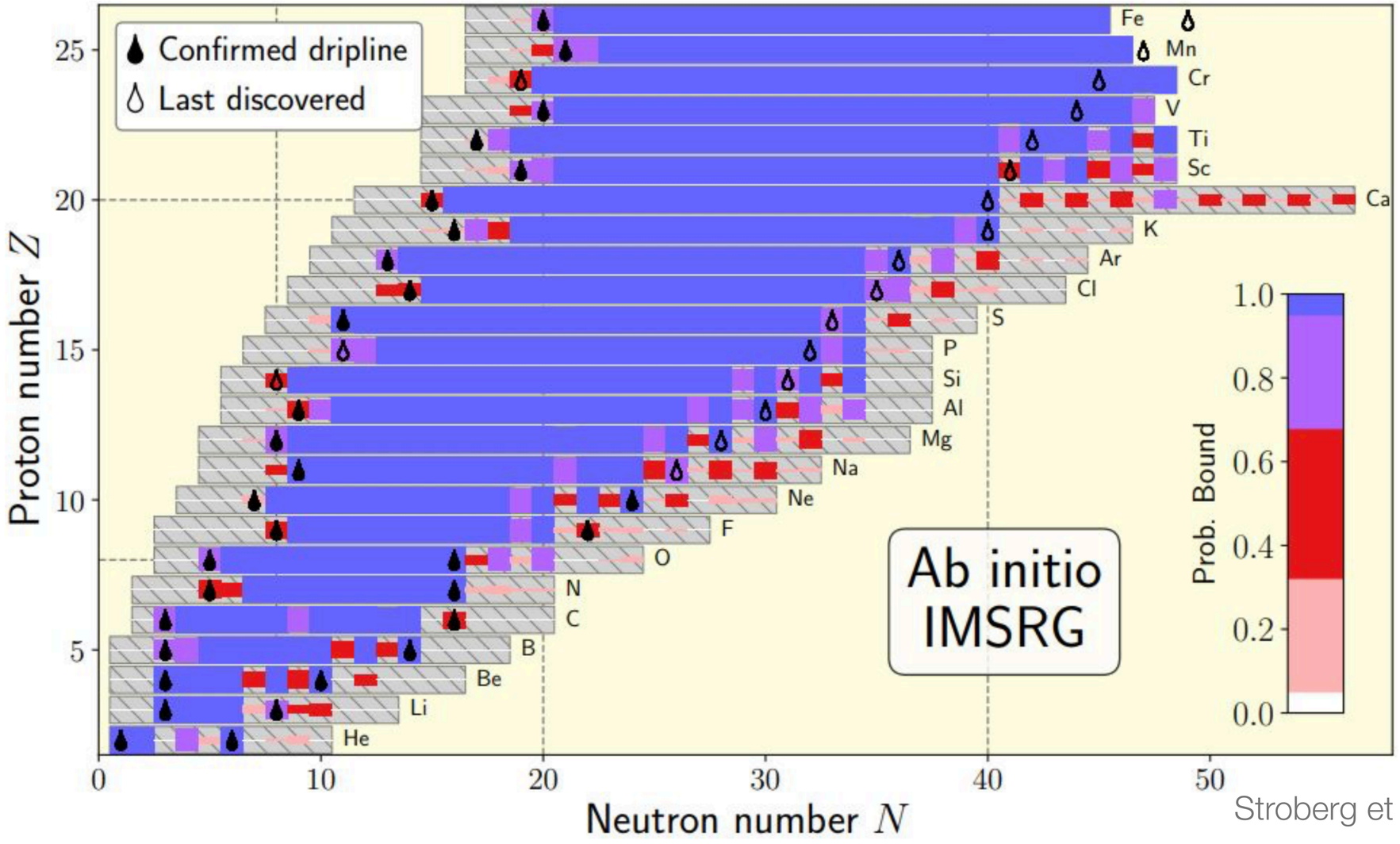
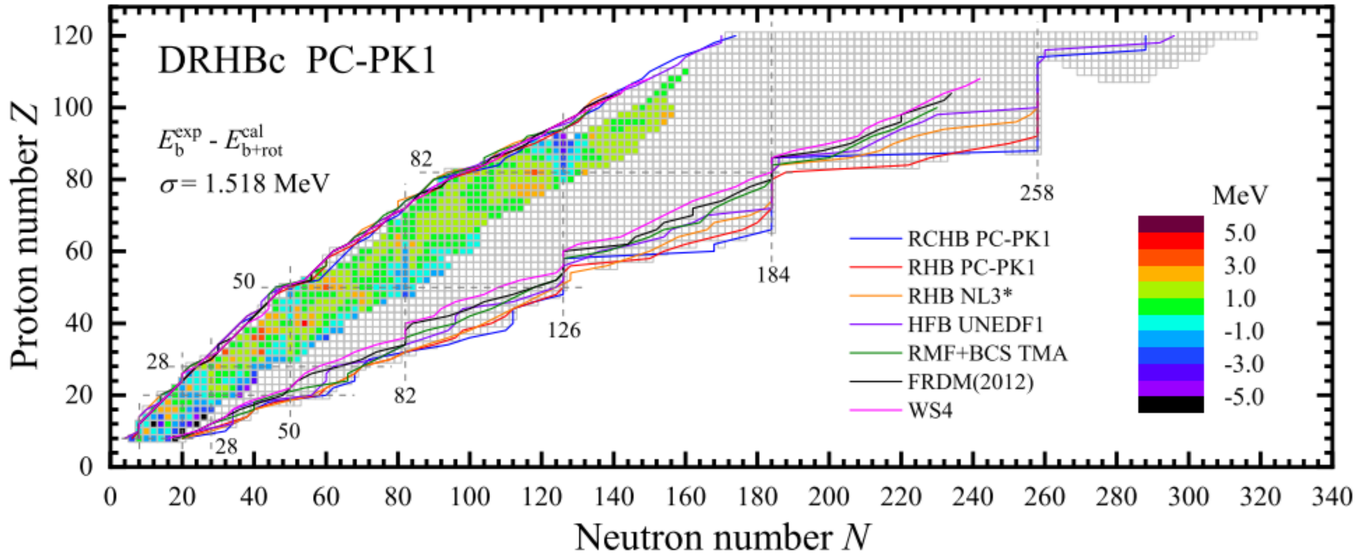
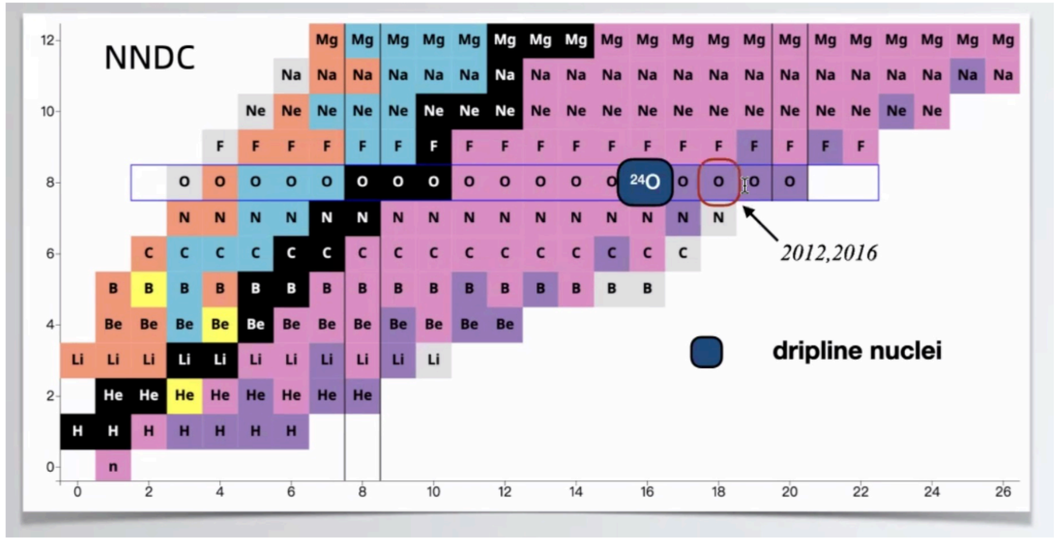
Driplines



Stroberg et al., PRL (2021)

Neutron Dripline



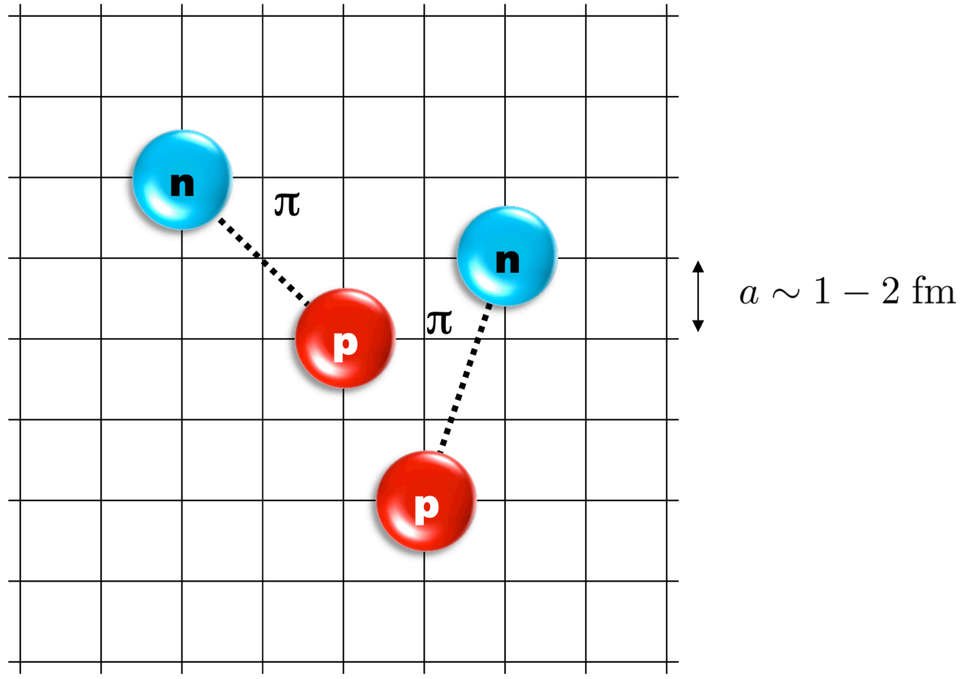


Zhang et al., At. Data Nucl. Data Tables (2022)

- Can we explain the dripline properties of Carbon and Oxygen isotopes in NLEFT?
- Is it sensitive to nuclear force? (role of 3NF)

Nuclear Lattice EFT

- one of ab initio method for few-, many-fermion system
- powerful numerical method formulated in the framework of chiral EFT
- EFT (theory) + Lattice method + Monte Carlo algorithm



Review: D.L, Prog. Part. Nucl. Phys. 63 117-154 (2009)

Nuclear Lattice EFT

$$Z^{(Lt)} = \mathrm{Tr}(\mathbf{M}^{\mathbf{L_t}}) = \int DcDc^* \exp[-S(c^*, c)]$$

- Instead of calculating Grassmann path integral of the exponential of the lattice action. we use transfer matrix operator formalism

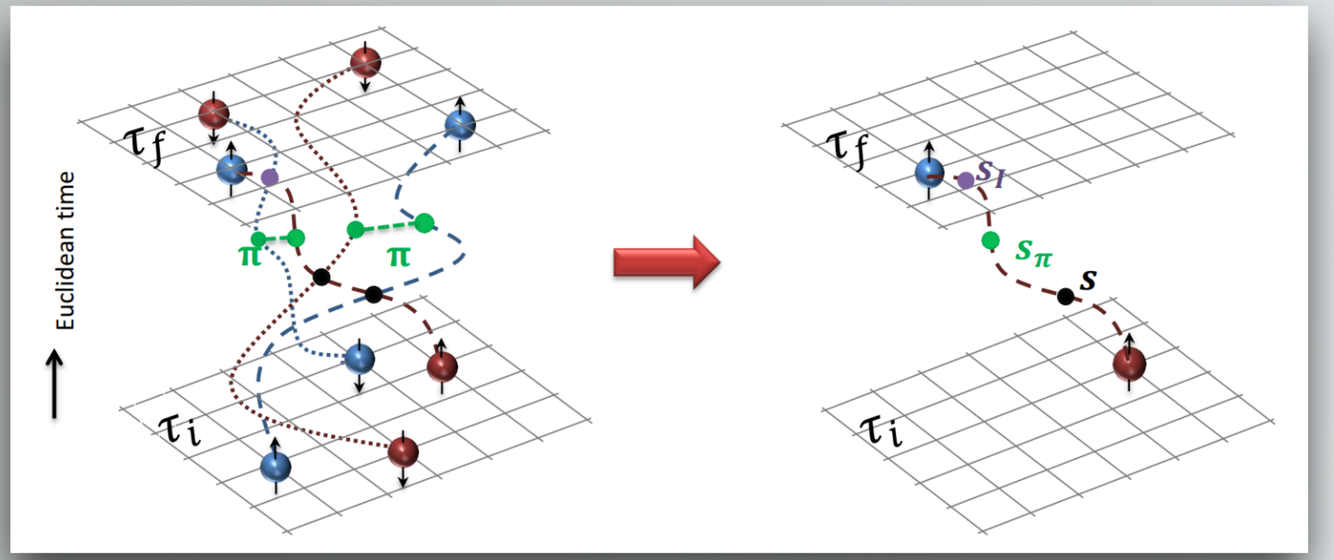
- Transfer matrix formalism $\mathbf{M} =: \exp\{-Ha_t\} :$
  with microscopic Hamiltonian $H = H_{\mathrm{free}} + V$

Auxiliary field Quantum Monte Carlo

Hubbard–Stratonovich transformation

Example: $$H = \sum_{nn'} -\psi_n^\dagger \frac{\nabla^2_{nn'}}{2M} \psi_{n'} + C \sum_n : \left(\psi_n^\dagger \psi_n\right)^2 :$$

$$: \exp\left(-a_t H\right) := \int \prod_n ds_n \, : \exp\left[\sum_n \left(-\frac{s_n^2}{2} + a_t \psi_n^\dagger \sum_{n'} \frac{\nabla^2_{nn'}}{2M} \psi_{n'} + \sqrt{-a_t C} s_n \psi_n^\dagger \psi_n\right)\right] :$$



two-body interaction —> single particle in background fields

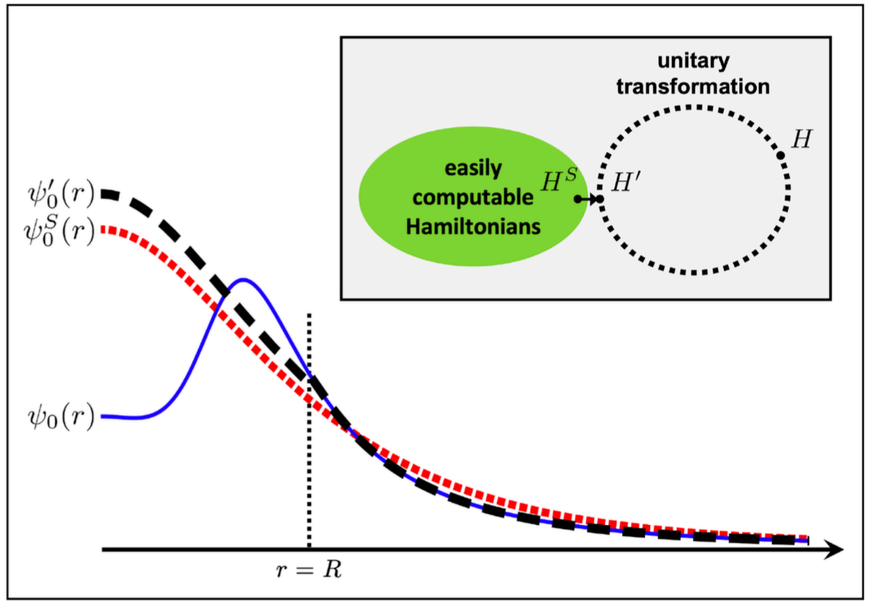
slide from Y. Ma

Wavefunction Matching method

3N potential 2N GIR at N3LO

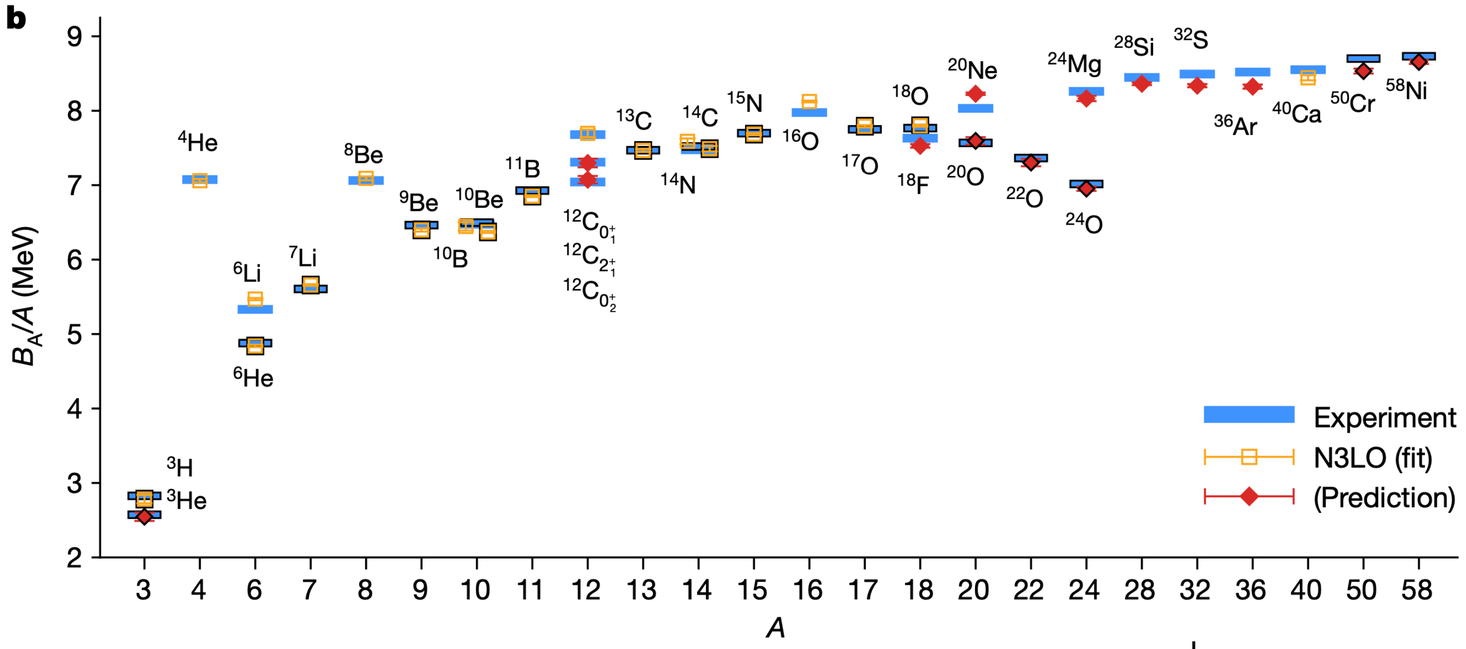
$$H = K + V_{\mathrm{OPE}}^{\Lambda_\pi} + V_{\mathrm{C}_\pi}^{\Lambda_\pi} + V_{\mathrm{Coulomb}} + V_{\mathrm{3N}}^{Q^3} + V_{\mathrm{2N}}^{Q^4} + W_{\mathrm{2N}}^{Q^4} + V_{\mathrm{2N,WFM}}^{Q^4} + W_{\mathrm{2N,WFM}}^{Q^4}$$

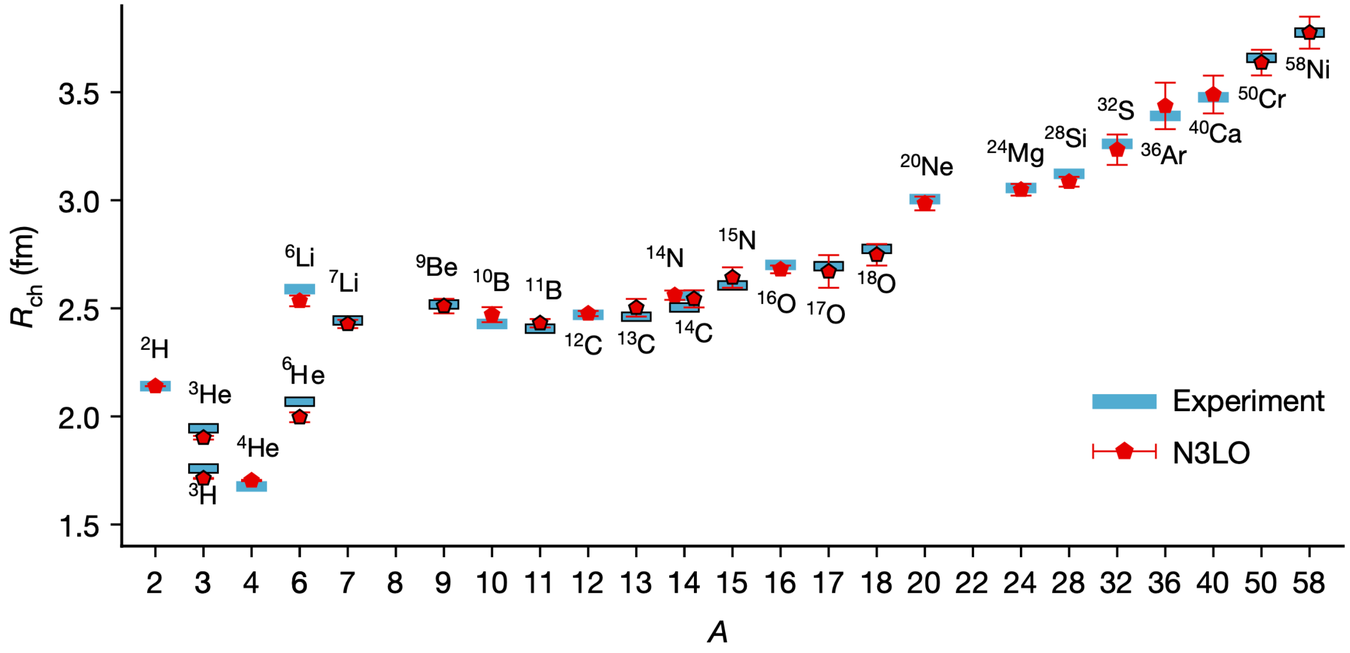
Kinetic E. | OPEP at leading order | Coulomb | 2N short-range at N3LO | WFM interaction & GIR correction



Elhatisari, Bovermann, Ma, Epelbaum, Frame, Hildenbrand, Krebs, Lähde, D.L., Li, Lu, M. Kim, Y. Kim, Meißner, Rupak, Shen, Song, Stellin, Nature 630, 59 (2024)

- realistic high-fidelity H (chiral EFT interaction at N3LO)
- avoid severe sign problem - creating a new H' (WFM method)





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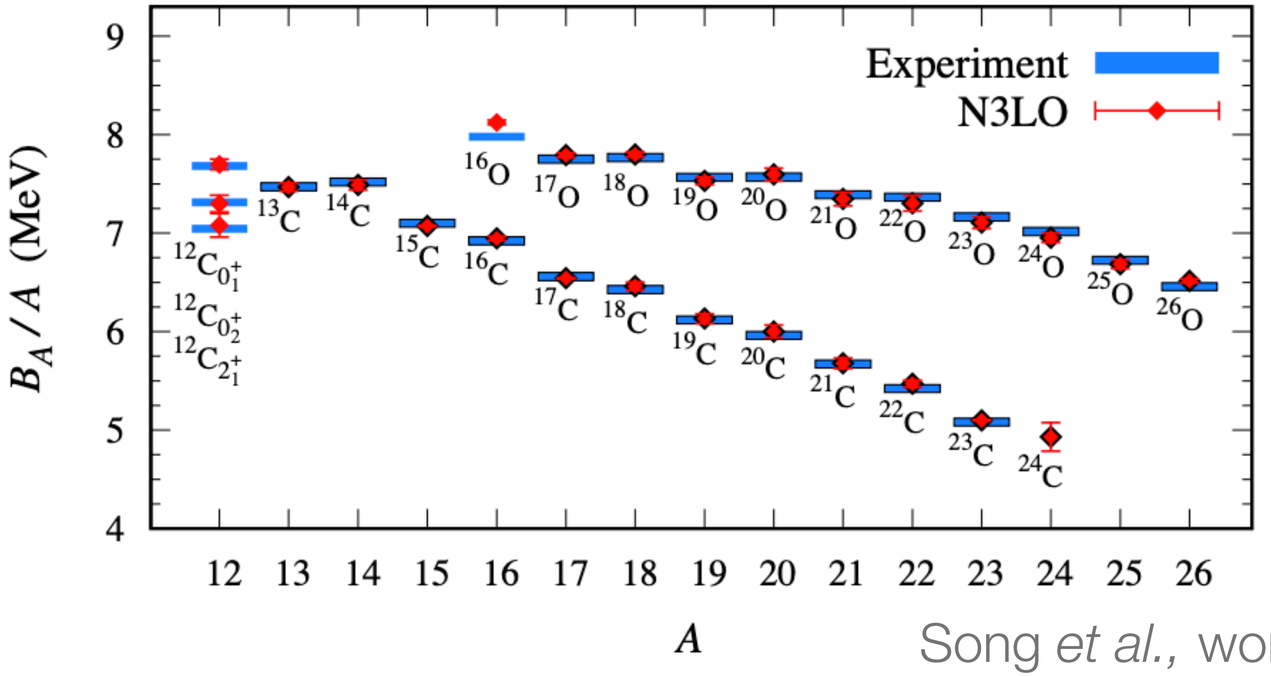
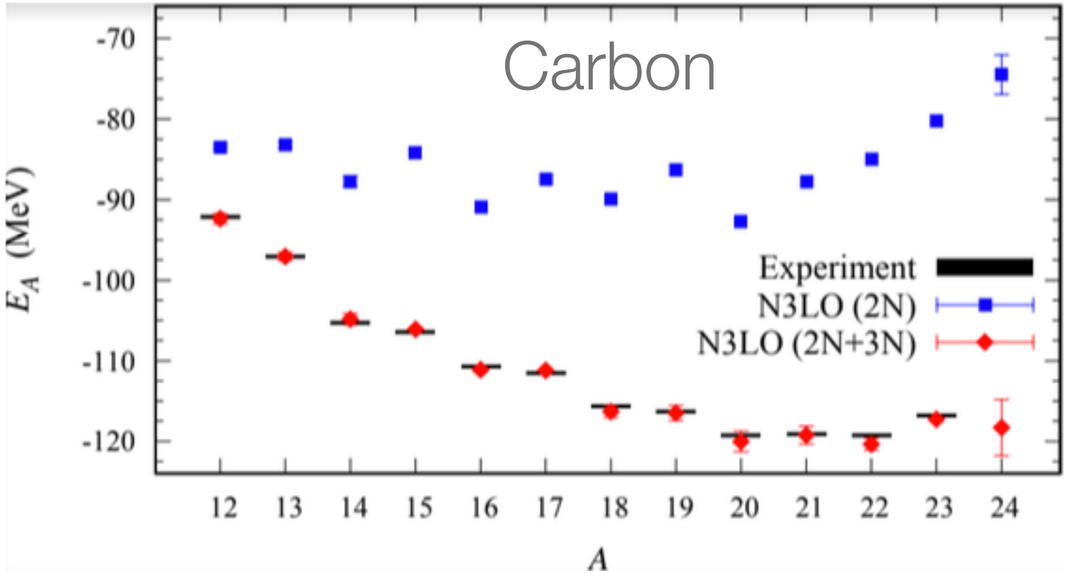
Carbon and Oxygen isotopes (preliminary)





Song *et al.*, work in progress

Woods-Saxon potential for protons

- Mean field picture is very useful to understand the general behavior
- Half ab initio / phenomenological approach
- Replacing proton contributions into WS potential -> Neutrons are bounded by effective proton mean field

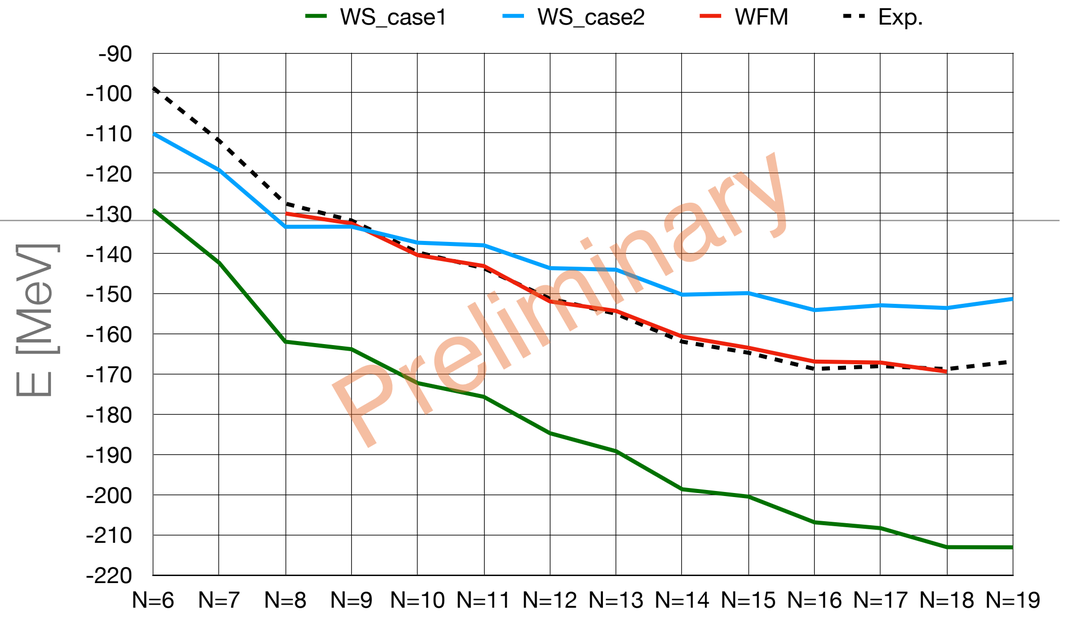
$$V_p(r) = -\frac{V_0}{1+\exp\left(\frac{r-R}{a}\right)}$$

set 1 - $V_0 = -45\,\mathrm{MeV}, a_0 = 0.5\,\mathrm{fm}, R = 1.386 \times 8^{1/3}$

set 2 - $V_0 = -45\,\mathrm{MeV}, a_0 = 0.5\,\mathrm{fm}, R = 1.259 \times 8^{1/3}$

Binding energies

$$H_{\text{full}} = H_{\text{N3LO}}$$

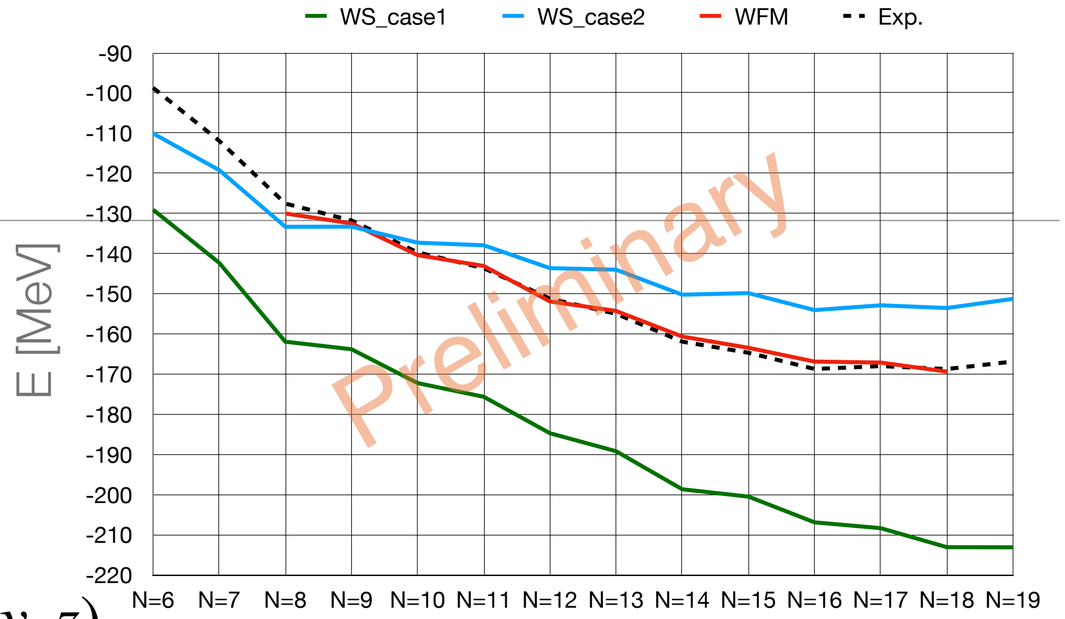


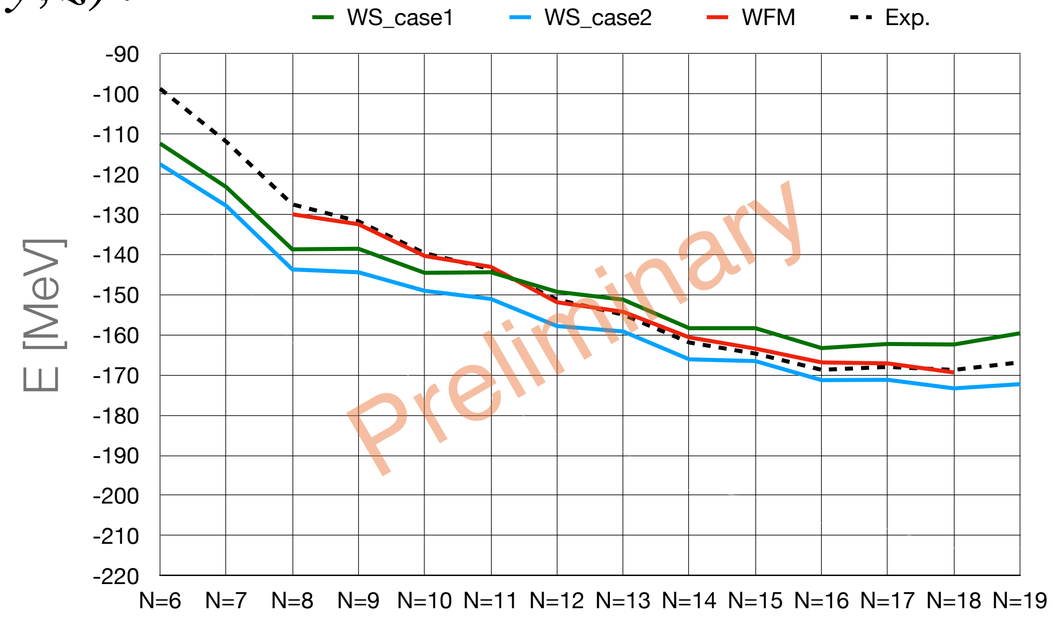
Binding energies

$$H_{\text{full}} = H_{\text{N3LO}} + H_{\text{pert}}$$

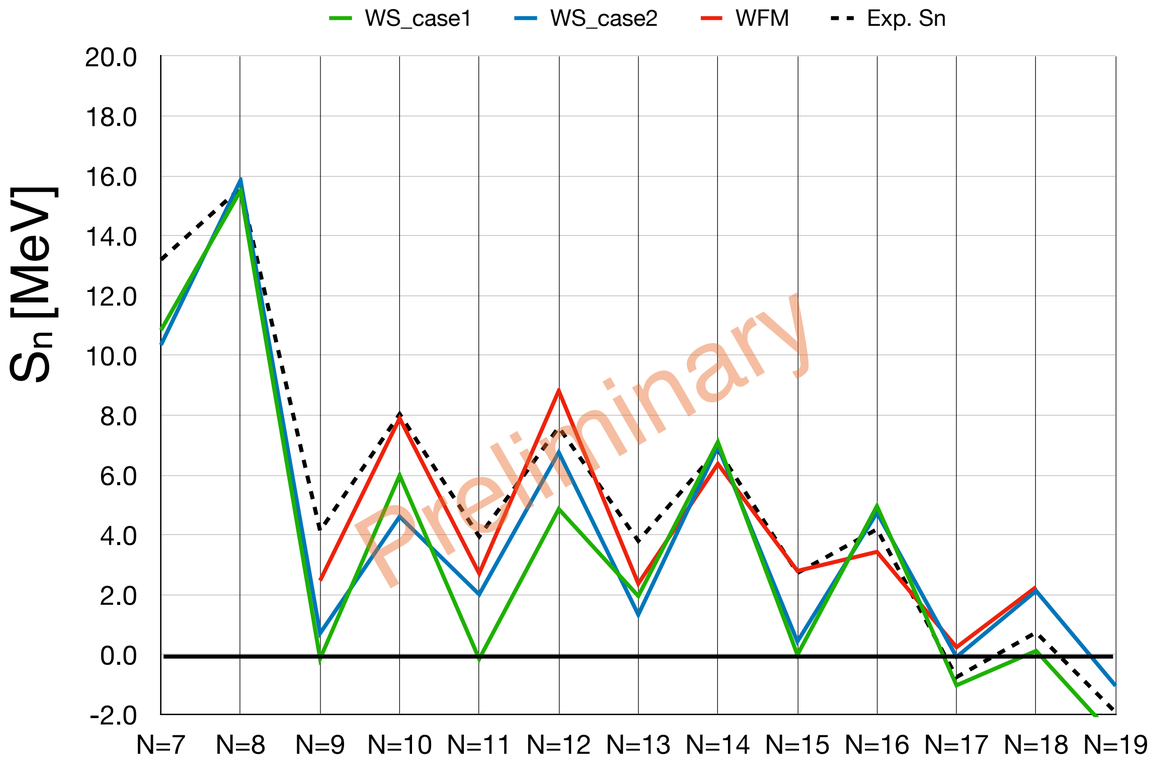
$$H_{p*n} = C_{p*n} \times \sum_{x,y,z} WS(x,y,z) * \rho_n(x,y,z)\,.$$

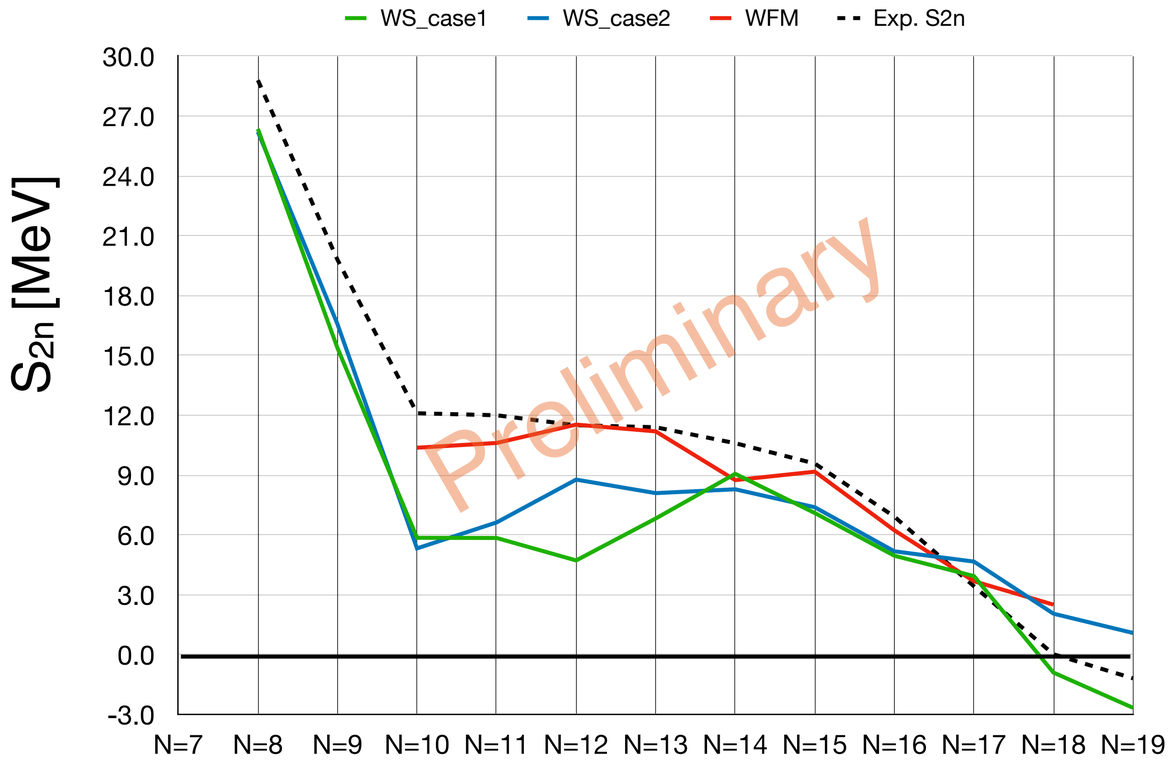
$$H_{p*nn} = C_{p*nn} \times \sum_{x,y,z} WS(x,y,z) * \rho_{n,\uparrow}(x,y,z) * \rho_{n,\downarrow}(x,y,z)\,.$$





Neutron separation energies





Kim *et al.*, work in progress

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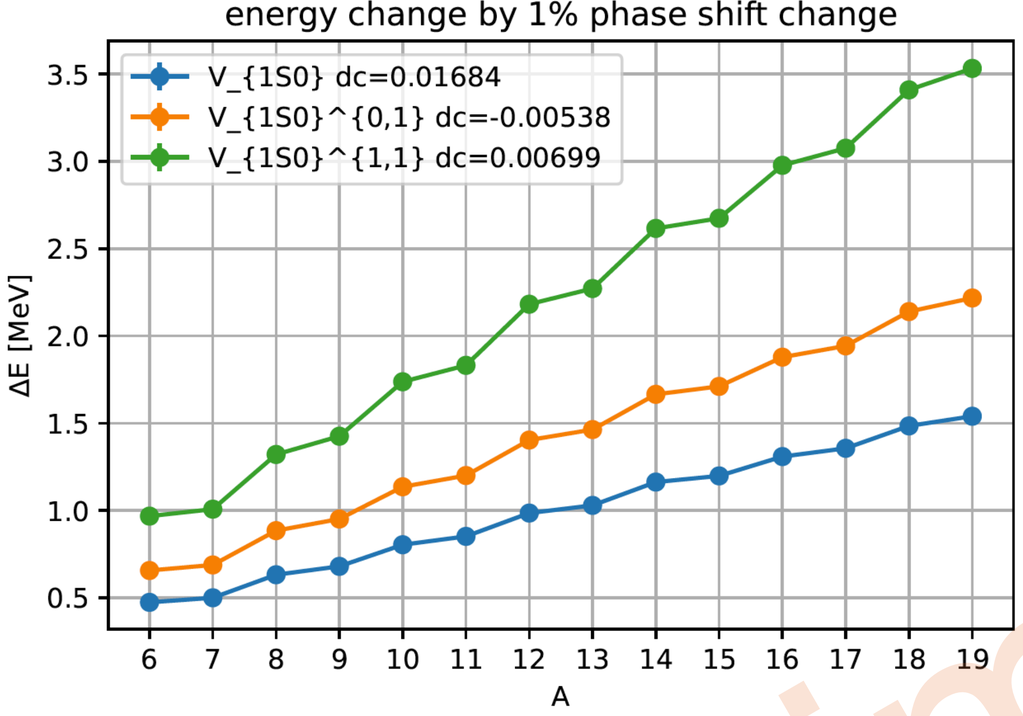
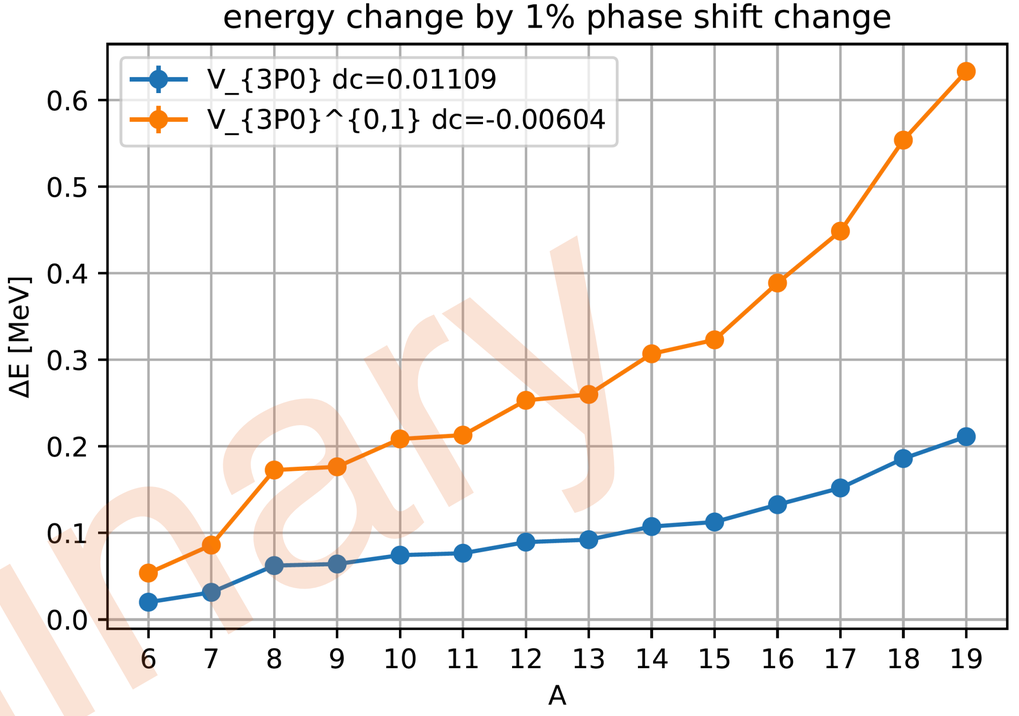
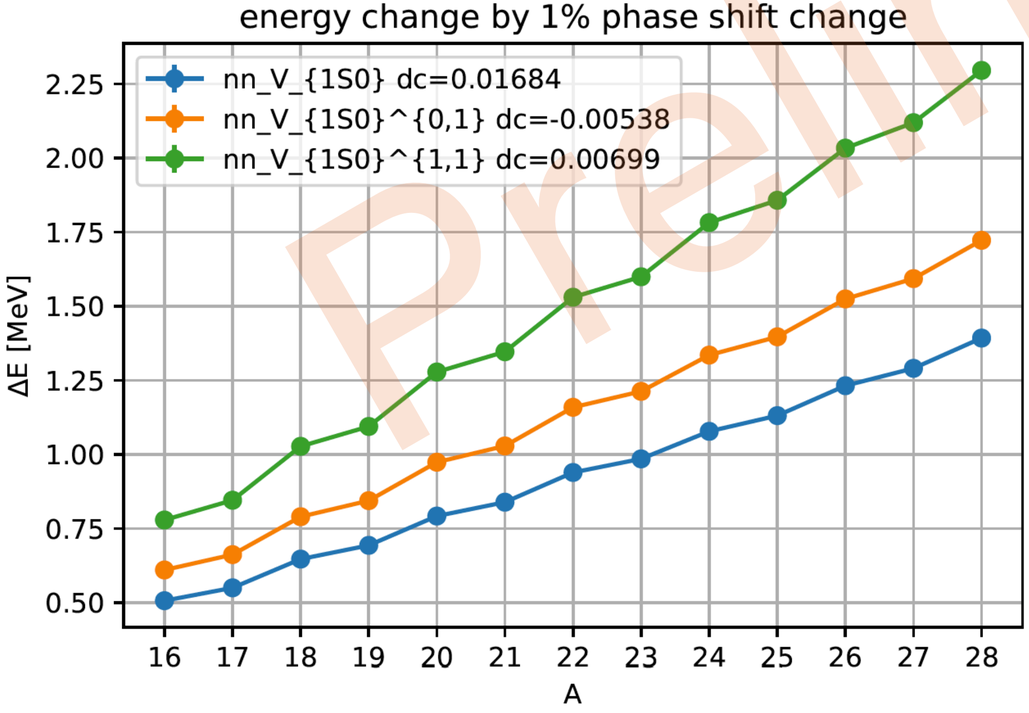
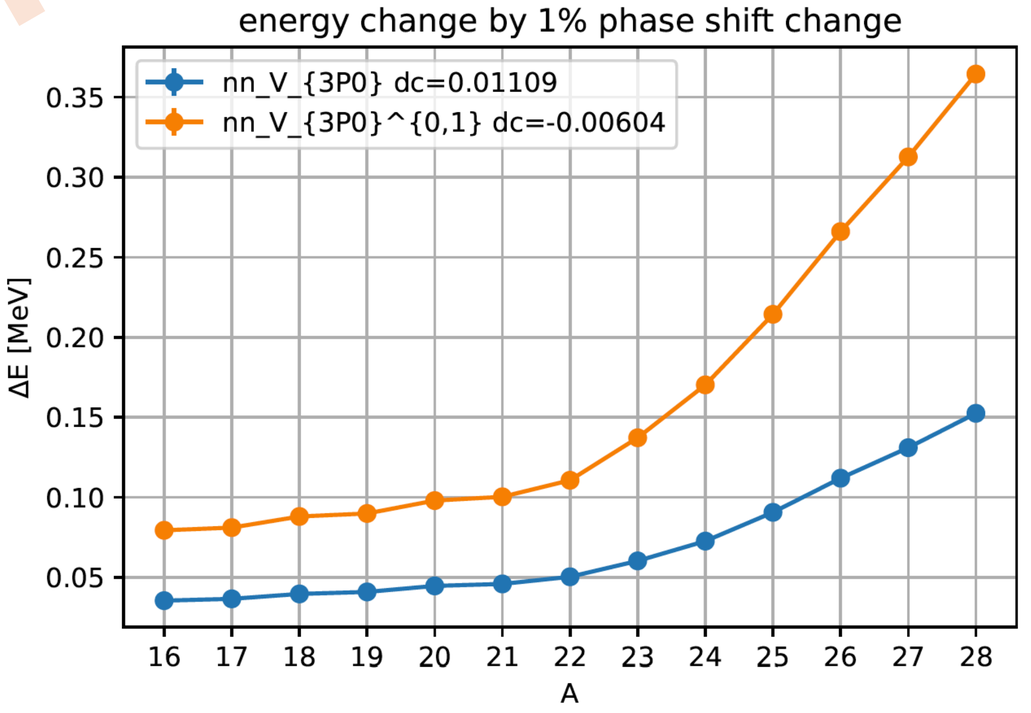
WS





WFM





Summary & outlook

- NLEFT is powerful to understand nuclear properties and successfully reproduce and estimate binding energies and charge radii with chiral EFT interaction at N3LO using wavefunction matching method.

- Toward neutron rich isotope for carbon and oxygen, the results are in good agreement with experimental measurement. We do further analysis for understanding the structure of carbon and oxygen.

- Woods-Saxon potential for proton mean field reproduce not only separation energies but also similar patter in terms of shell-model orbitals in oxygen isotopes. Also it has potential to extend neutron rich side at large N (such as Au, Pb, etc.)