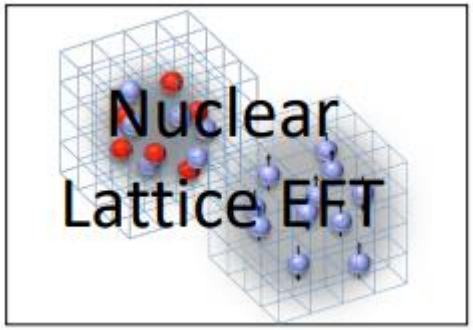

Carbon and Oxygen isotope chains (And others)

Young-Ho Song (Institute for Rare Isotope Science, IBS)
With NLEFT collaboration

Bethe Forum: Frontiers in Nuclear Physics
2023.Nov.21-23, BCTP, Bonn
https://indico.hiskp.uni-bonn.de/event/389/

ibs 기초과학연구원
Institute for Basic Science

Nuclear Lattice Effective Field Theory Collaboration

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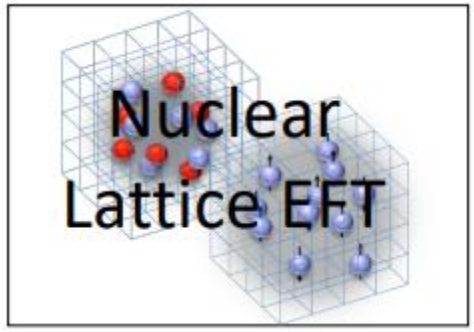
- Lukas Bovermann(Ruhr)
- Evgeny Epelbaum (Bochum)
- Dillon Frame (Juelich)
- Fabian Hildenbrand(Darmstadt)
- Hermann Krebs(Ruhr)
- Timo A. Lähde (Juelich)
- Dean Lee (MSU)
- Ning Li(Sun Yat-sen)
- Bing-Nan Lu(Graduate School of China Academy of Engineering Physic)
- Myungkuk Kim(CENS,IBS)
- Youngman Kim (CENS,IBS)
- Young-Ho Song(IRIS,IBS)
- Yuanzhuo Ma(Peking)
- Ulf-G. Meißner (Bonn/Juelich)
- Gautam Rupak(Mississippi State)
- Shihang Shen (Juelich)
- Gianluca Stellin(CEA Paris-Saclay)
- And More…



Effective field theories and energy scales

Lattice quantum chromodynamics

Chiral effective field theory

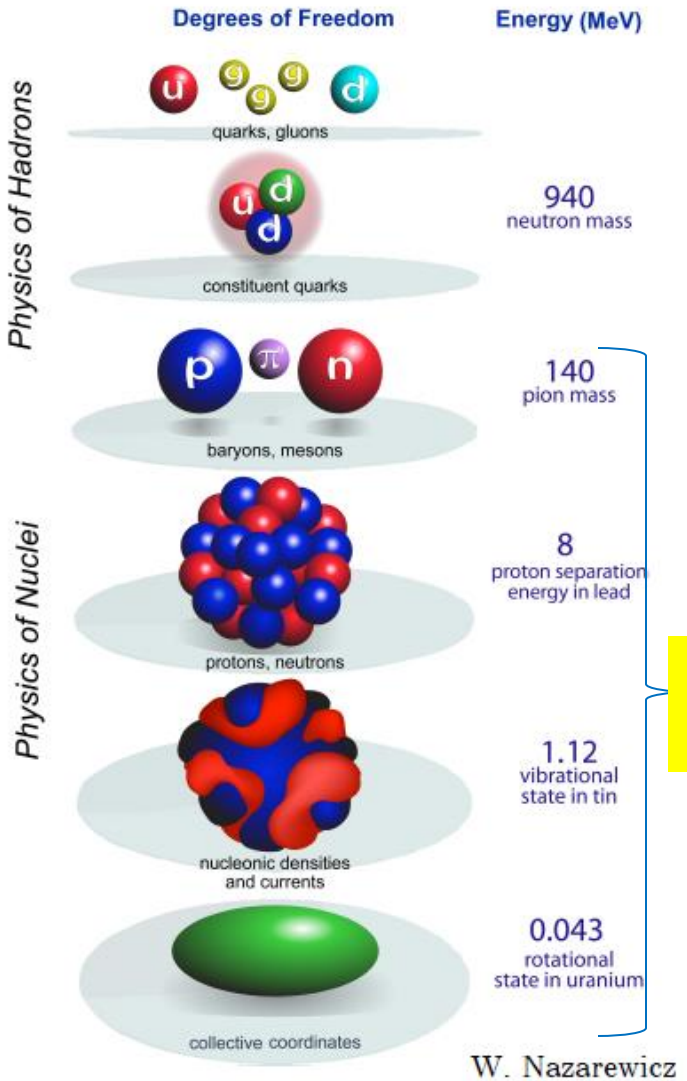
Microscopic A-body methods

Configuration interactions

Density functional methods

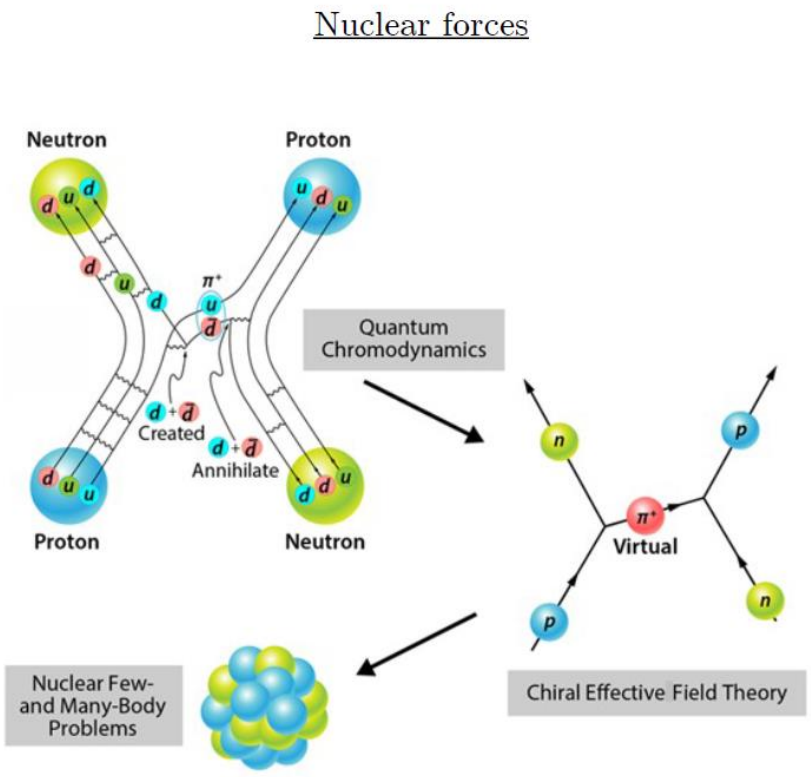
Mean field methods

Effective theory of collective modes



W. Nazarewicz

Ab-initio method



- *ab-initio* Nuclear Physics
  - (1) nucleon degrees of freedom
  - (2) nucleon-nucleon interaction

Goal: predict wide range(structure, reaction, nuclear matter) of nuclear phenomena (without parameter fitting, model assumption) from nuclear interaction (for 2-body,3-body, many-body, based on QCD)

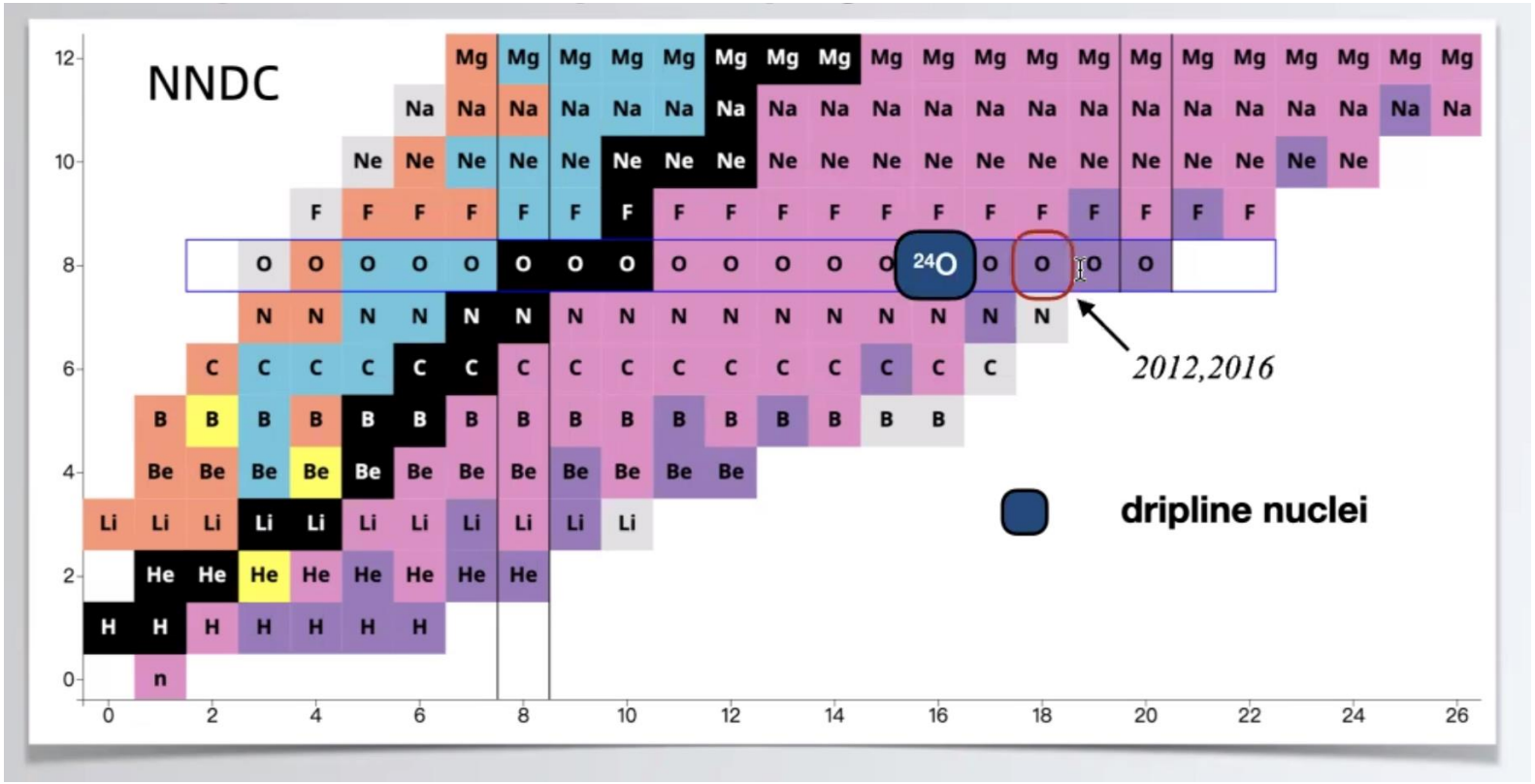
Direct connection between

Nuclear Force ↔ Nuclear Phenomena

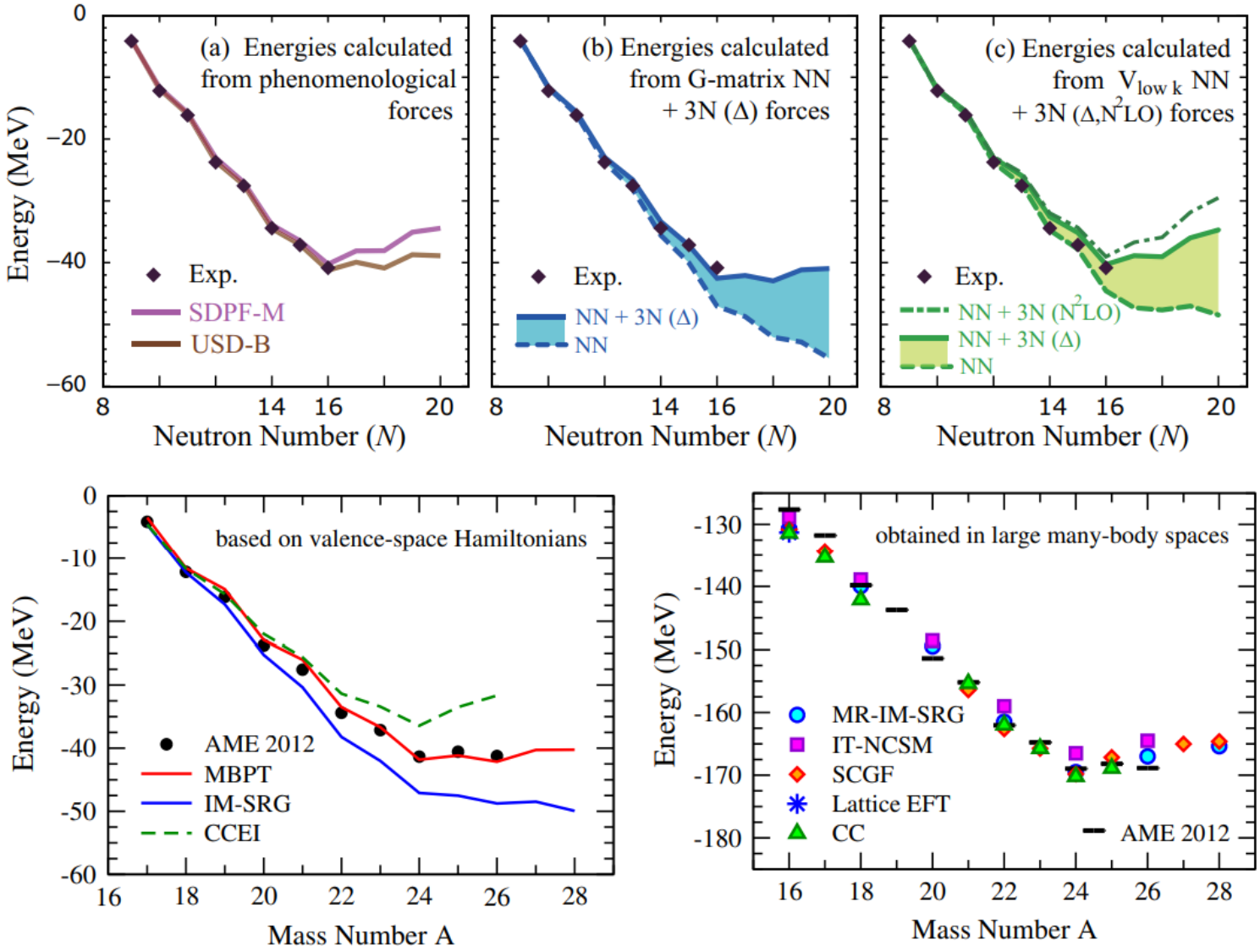
Ab initio many-body

- (ab initio) Nuclear physics is challenging.
- Non-perturbative many body problem
  - Ab-initio nuclear many body methods
    - Greens function Monte Carlo(GFMC)
    - No-core shell model(NCSM)
    - Coupled Cluster (CC)
    - IM-SRG, VS-SRG
    - Nuclear Lattice Effective Field Theory(NLEFT)
    - And more
  - With recent progress in ab-initio methods
    - Binding energies for wide range of nuclei
    - Some reaction calculation for light nuclei.

Dripline



Can we explain the dripline of Carbon, Oxygen isotopes in NLEFT?
Sensitive to nuclear force ? (Role of 3-body force?)



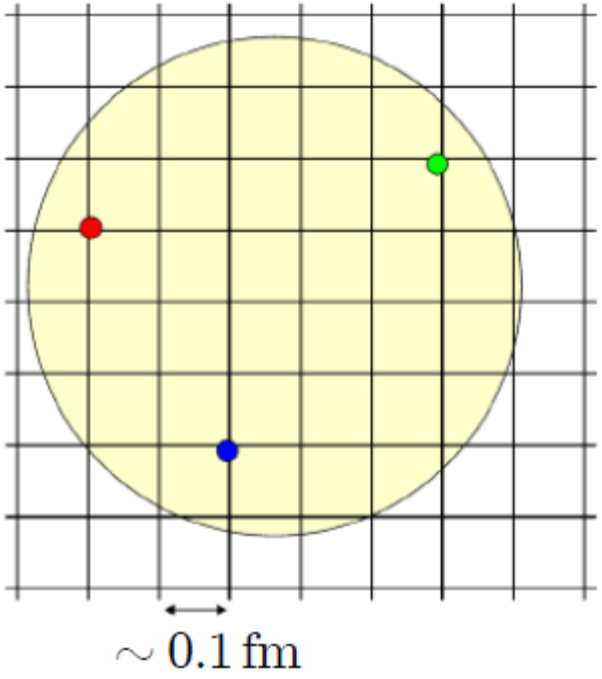
Oxygen isotopes

Ann.Rev.Nucl.Part.Sci. 65 (2015) 457-484

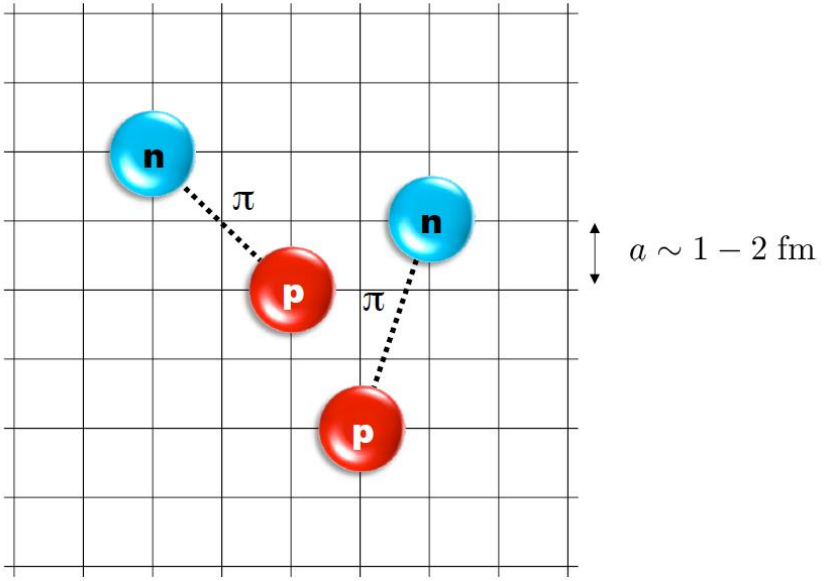
Nuclear Lattice Effective Field Theory

- One of ab initio method for many fermion system

Nucleon in LQCD



Nucleons as point particles on the lattice



(Figures from Dean's presentation)

Path integral

Correlator function for A Nucleons $\quad Z_A(t) = \langle \Psi_A | \exp(-tH) | \Psi_A \rangle$

Slater Determinants for A free Nucleons

Ground state energy by time derivative of the correlator

$$E(t) = -\frac{d}{dt} \ln Z_A(t)$$

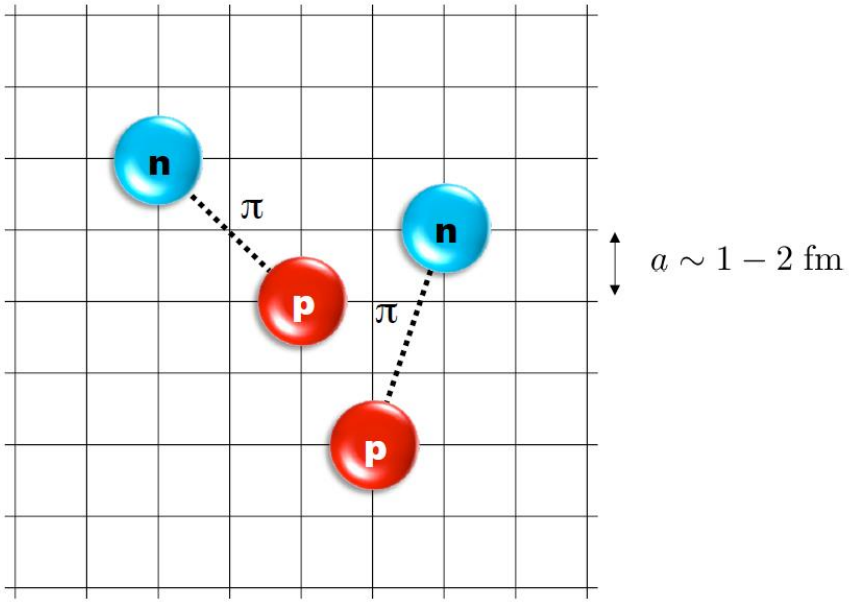
At large time only ground states survive $\Rightarrow$ $E_A^0 = \lim_{t\to\infty} E_A(t)$

$$|\Psi_A\rangle = \sum_n c_n |n\rangle_A,$$

$$Z_A(t) = \langle \Psi_A | e^{-tH} | \Psi_A \rangle = \sum_n c_n e^{-tE_n}$$

(From Dean's presentation)

Lattice Hamiltonian

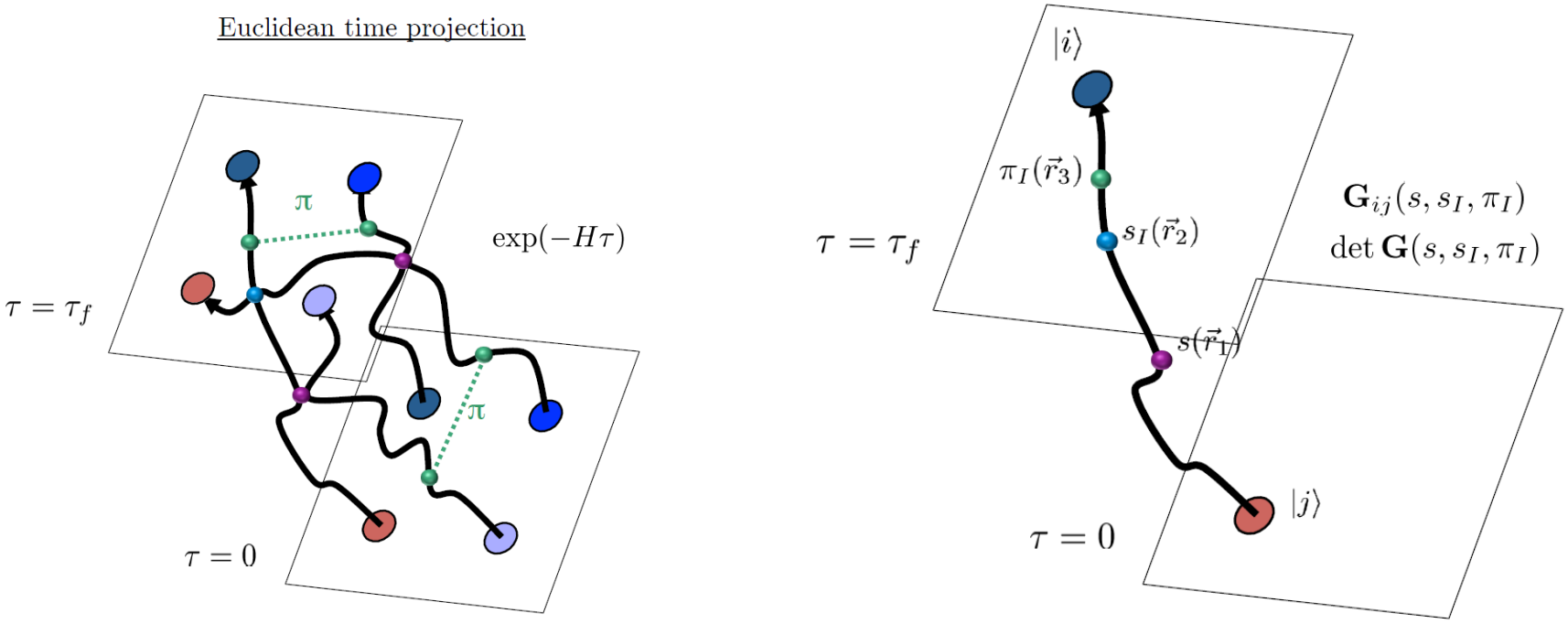


- We need to introduce a lattice scale in space and time:
- momentum space cutoff ~ 150 MeV → lattice size a= 1.316 fm
- Time cutoff ~ 1000 MeV
- We need to determine coefficients of interaction for the lattice size. (regularization scale.)
- Two-body interaction coefficients can be determined from phase shifts of np scattering.
- Three-body interaction can be fixed from binding energy of A>=3.

Auxiliary Field Monte Carlo

$$\exp\left[-\frac{C}{2}(N^\dagger N)^2\right] \quad \times \quad (N^\dagger N)^2$$

$$= \sqrt{\frac{1}{2\pi}} \int_{-\infty}^{\infty} ds \exp\left[-\frac{1}{2}s^2 + \sqrt{-C}\, s(N^\dagger N)\right] \quad \rangle \quad sN^\dagger N$$

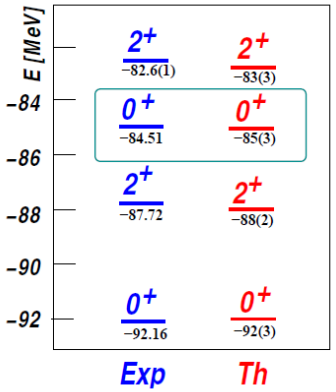


(Figure From Dean's presentation)

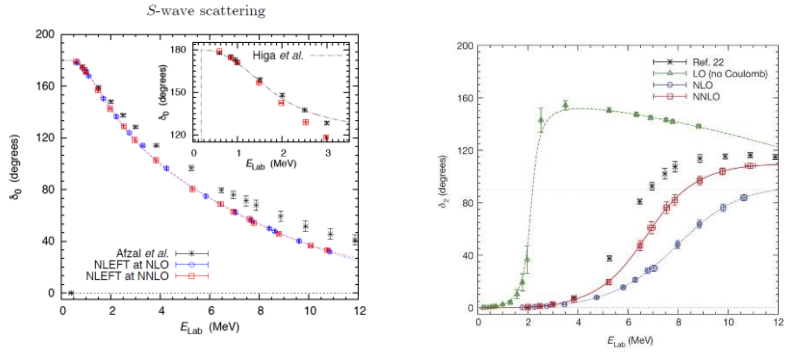
Applications of NLEFT

- Has been successfully applied to
  - Nuclear matter, Cold atom, dilute fermion system
  - Finite nuclei (A<=50)
  - First ab-initio calculation of Hoyle state
  - Cluster structure of ^{12}C and ^{16}O
  - NN scattering, N-D scattering
  - Alpha-alpha scattering
  - radiative capture, fusion
  - Etc.

The first ab-initio calculation of Hoyle state

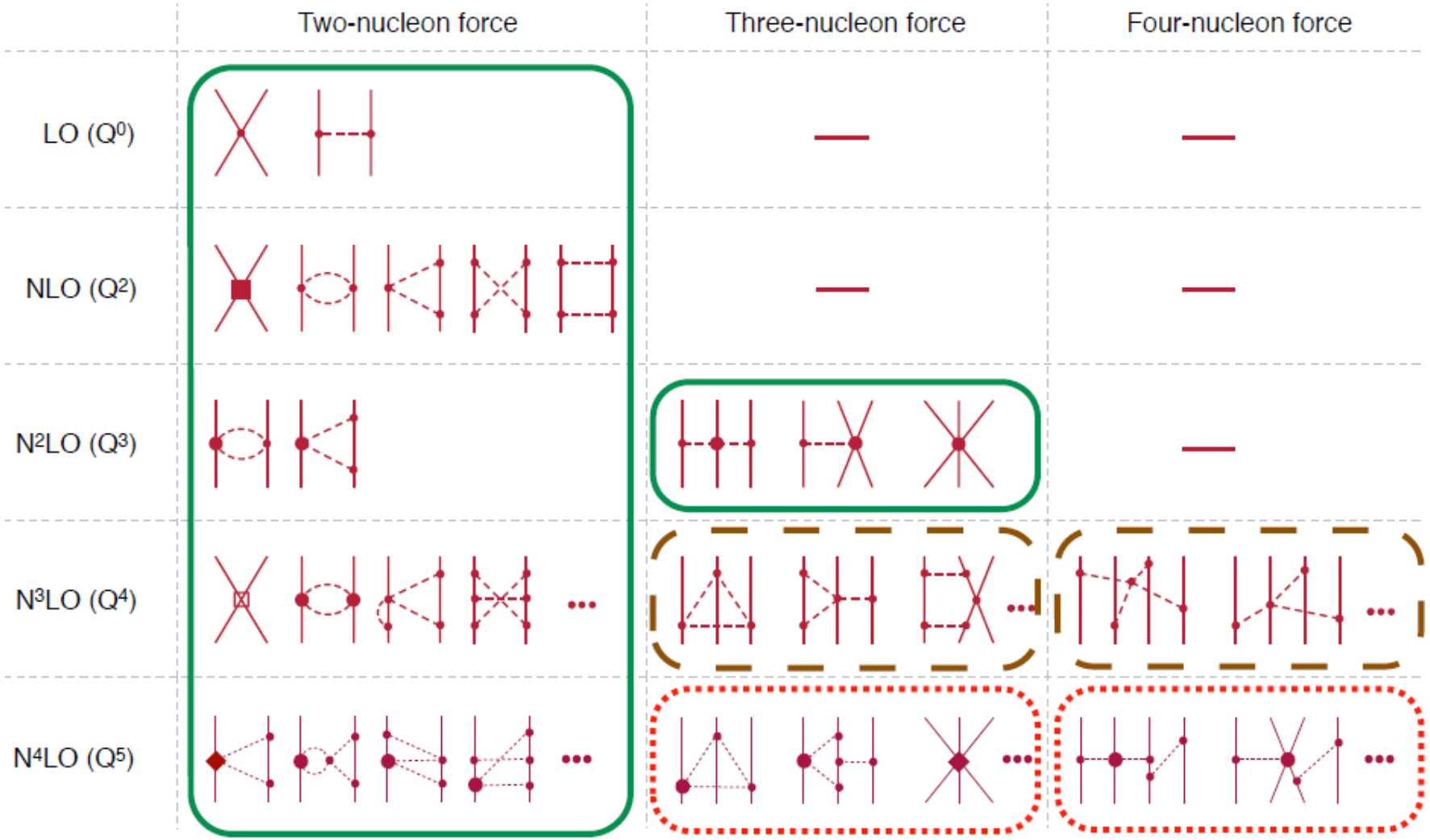


Epelbaum, Krebs, Lähde, Lee, Meißner: Phys. Rev. Lett. 109, 252501 (2012)



Ab initio alpha-alpha scattering
(Nature 528, 111-114(2015))

Chiral Effective Field Theory



Sign problem in NLEFT

- However, there is a difficulty in auxiliary MC calculation

$$Z(t) = \int \mathcal{D}s Z(s,t), \quad Z(s,t) = e^{-\frac{s^2}{2}} \det X(s,t),$$
$$= \int \mathcal{D}s e^{i\theta(s,t)} |Z(s,t)|$$

$$\langle O \rangle = \frac{\langle O e^{i\theta} \rangle_{pq}}{\langle e^{i\theta} \rangle_{pq}}, \quad \langle O \rangle_{pq} \equiv \frac{\int ds |\det X(s)| O}{\int ds |\det X(s)|}.$$

- We needs a large Euclidean time extrapolation
- If the denominator's sign oscillates rapidly
- → large uncertainty in the expectation value
- → sign problem
- SU(4) symmetric interaction in isospin symmetric system
- → No sign problem

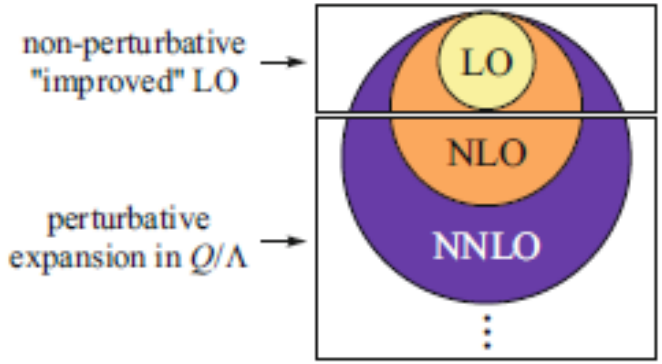
Improved action with non-locality

- In practical calculation, sign problem and convergence of perturbation have to be taken care of.
- To improve the non-perturbative calculation,
  Local and non-local smearing of contact interaction are introduced.

$$V_0 = \frac{C_0}{2} : \sum_{\mathbf{n}',\mathbf{n},\mathbf{n}''} \sum_{i',j'} a_{i',j'}^{s_{\rm NL}\dagger}(\mathbf{n}') a_{i',j'}^{s_{\rm NL}}(\mathbf{n}') f_{s_{\rm L}}(\mathbf{n}'-\mathbf{n}) f_{s_{\rm L}}(\mathbf{n}-\mathbf{n}'') \sum_{i'',j''} a_{i'',j''}^{s_{\rm NL}\dagger}(\mathbf{n}'') a_{i'',j''}^{s_{\rm NL}}(\mathbf{n}'') :, \quad V_{0,{}^1S_0}(\mathbf{n}) \text{ and } V_{0,{}^3S_1}(\mathbf{n})$$

$$a_{i,j}^{s_{\rm NL}}(\mathbf{n}) = a_{i,j}(\mathbf{n}) + s_{\rm NL} \sum_{|\mathbf{n}'|=1} a_{i,j}(\mathbf{n}+\mathbf{n}').$$

$$a_{i,j}^{s_{\rm NL}\dagger}(\mathbf{n}) = a_{i,j}^{\dagger}(\mathbf{n}) + s_{\rm NL} \sum_{|\mathbf{n}'|=1} a_{i,j}^{\dagger}(\mathbf{n}+\mathbf{n}').$$



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Essential elements for nuclear binding

Bing-Nan Lu [a], Ning Li [a], Serdar Elhatisari [b,c], Dean Lee [a,*], Evgeny Epelbaum [d], Ulf-G. Meißner [b,e,f]

$$H_{\mathrm{SU(4)}} = H_{\mathrm{free}} + \frac{1}{2!}C_2 \sum_{\boldsymbol{n}} \tilde{\rho}(\boldsymbol{n})^2 + \frac{1}{3!}C_3 \sum_{\boldsymbol{n}} \tilde{\rho}(\boldsymbol{n})^3,$$

$$\tilde{\rho}(\boldsymbol{n}) = \sum_i \tilde{a}_i^\dagger(\boldsymbol{n})\tilde{a}_i(\boldsymbol{n}) + s_L \sum_{|\boldsymbol{n}'-\boldsymbol{n}|=1} \sum_i \tilde{a}_i^\dagger(\boldsymbol{n}')\tilde{a}_i(\boldsymbol{n}'),$$

$$\tilde{a}_i(\boldsymbol{n}) = a_i(\boldsymbol{n}) + s_{NL} \sum_{|\boldsymbol{n}'-\boldsymbol{n}|=1} a_i(\boldsymbol{n}')$$

Minimal nuclear interaction

Which reproduce

(1) Light nuclei

(2) medium mass nuclei

(3) neutron matter

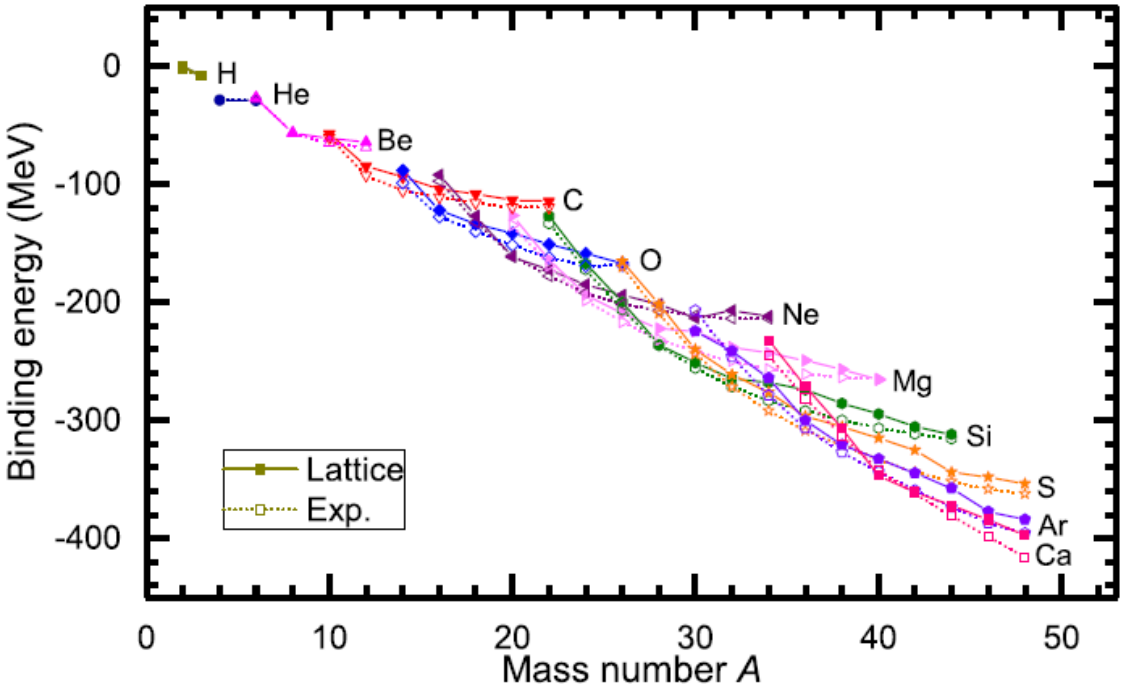
simultaneously up to few percent error in binding energy and charge radius

Only Four parameters

1. Strength of the two-nucleon S-wave interaction
2. Range of the two-nucleon S-wave interaction
3. Strength of three-nucleon contact interaction
4. Range of the local part of the two-nucleon interaction

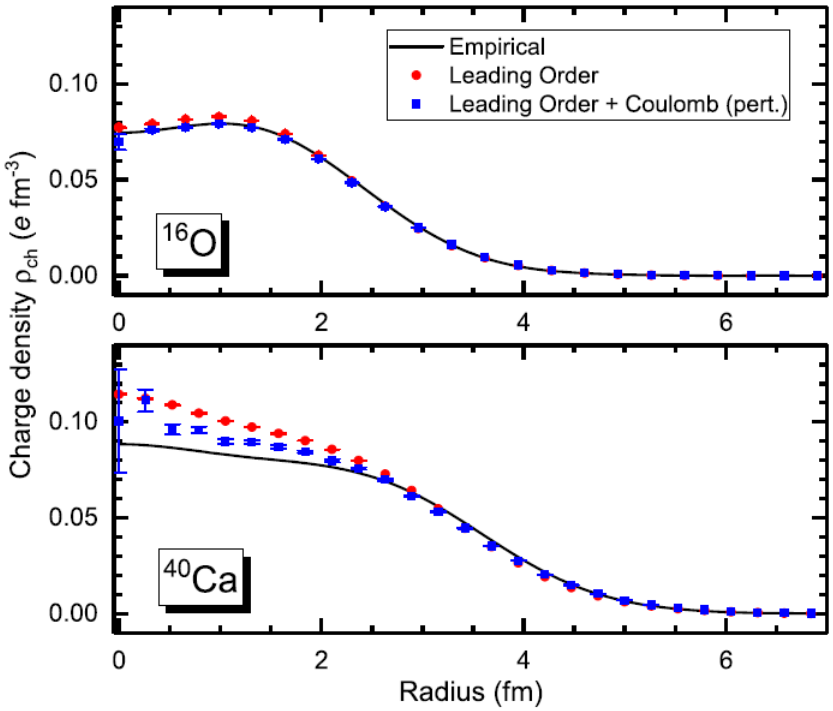
Except for the Coulomb potential, the interaction is invariant under Wigner's SU(4) symmetry.

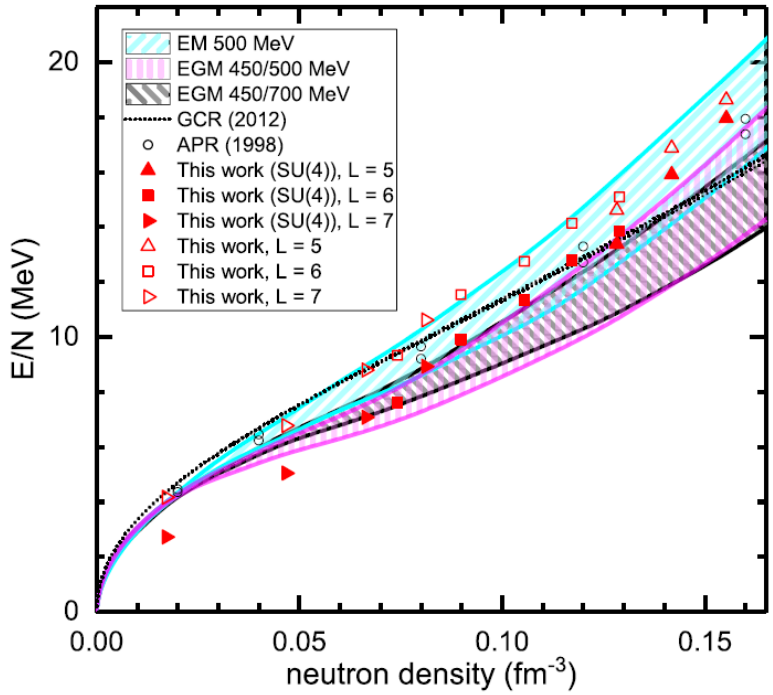
No sign problem



	B	Exp.	$R_{\rm ch}$	Exp.
^{3}H	8.48(2)(0)	8.48	1.90(1)(1)	1.76
^{3}He	7.75(2)(0)	7.72	1.99(1)(1)	1.97
^{4}He	28.89(1)(1)	28.3	1.72(1)(3)	1.68
^{16}O	121.9(1)(3)	127.6	2.74(1)(1)	2.70
^{20}Ne	161.6(1)(1)	160.6	2.95(1)(1)	3.01
^{24}Mg	193.5(02)(17)	198.3	3.13(1)(2)	3.06
^{28}Si	235.8(04)(17)	236.5	3.26(1)(1)	3.12
^{40}Ca	346.8(6)(5)	342.1	3.42(1)(3)	3.48

Can we improve the agreement by
Including higher order corrections?



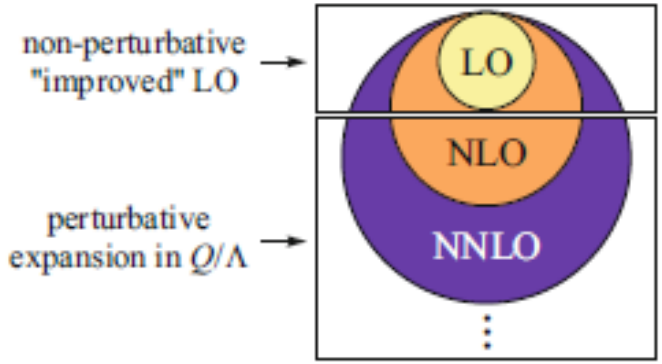


Can we improve the agreement by
Including higher order corrections?

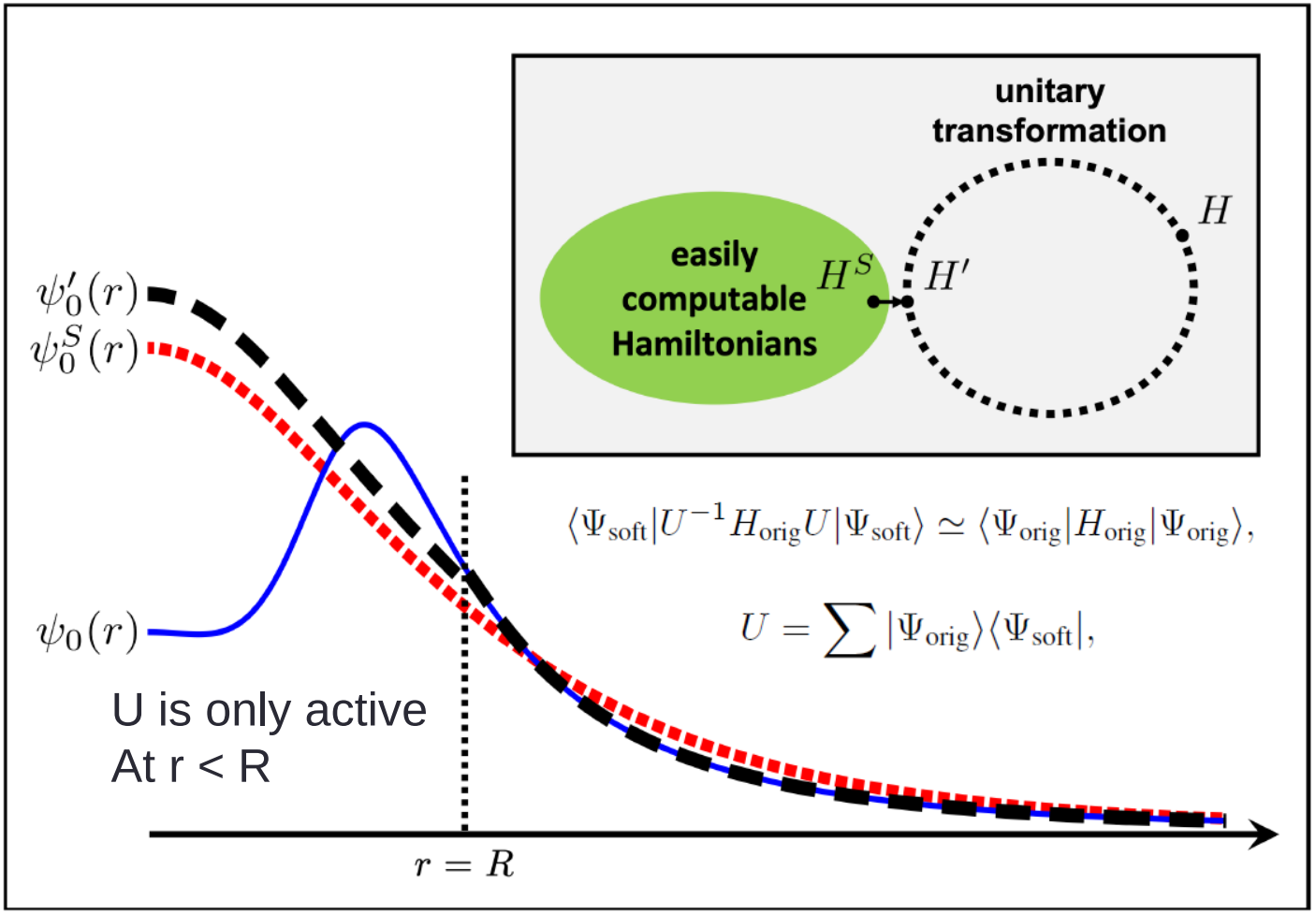
Lattice chiral Hamiltonian (N3LO)

Full N3LO Hamiltonian includes

- Free Hamiltonian(Kinetic term)
- Short range (nonlocal smeared) contact interactions up to Q^4 order
- Isospin-breaking short range interactions
- One pion exchange potential
- Two pion exchange potential up to Q^4 order
- Coulomb interaction
- Long range isospin breaking interaction(isospin dependence in OPE)
- Galilean Invariance Restoration (GIR) term (because of non-local interaction.)
- Three nucleon interaction



Wave function matching



H and H' are fully equivalent to two-body observables

The goal is to make the perturbation expansion from "simple" wave function gives a good convergence

$$H_{\rm wfm} = H_{\rm soft} + (U^{-1}H_{\rm orig}U - H_{\rm soft})$$
$$= H_{\rm soft} + H_{\rm diff},$$

Wave function matching Hamiltonian

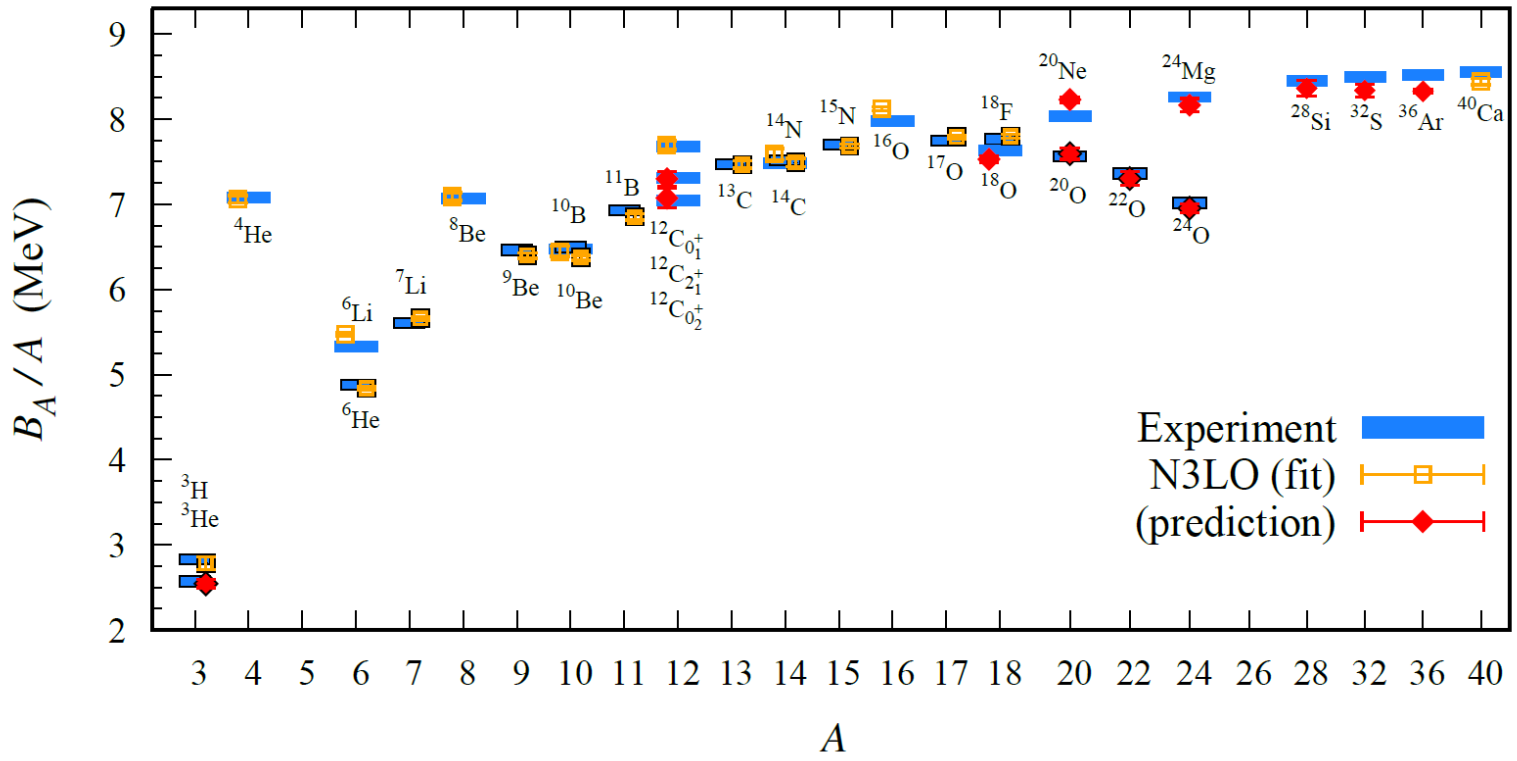
- N3LO Hamiltonian

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

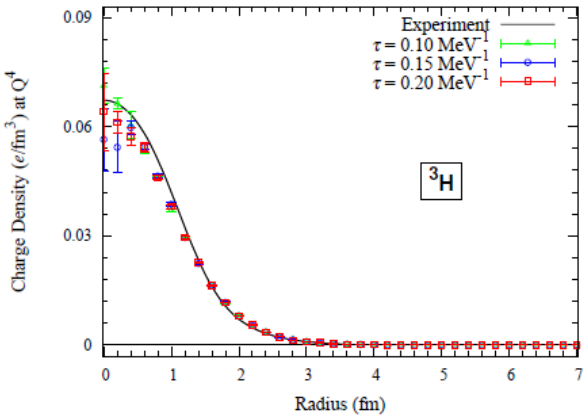
$$V_{\mathrm{3N}}^{\mathrm{Q}^3} = V_{c_E}^{(l)} + V_{c_E}^{(t)} + V_{c_E}^{(d)} + V_{c_D}^{(d)} + V_{\mathrm{3N}}^{(\mathrm{TPE})},$$

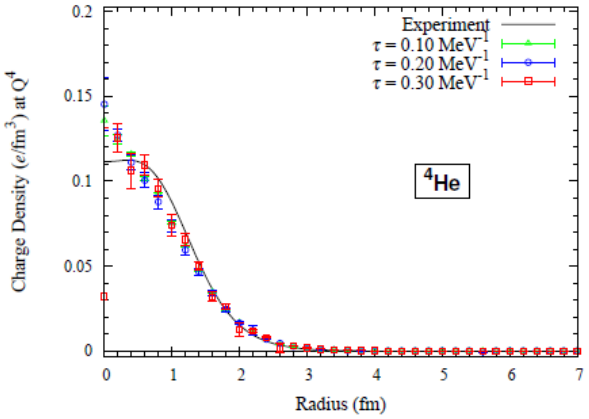
V_2N : short range NN interactions
W_2N: GIR restoration term for V_2N
V_2N,WFM : difference from H_s
W_2N,WFM: GIR restoration correction to V_2N,WFM
V_3N : contains short range 3N interaction parameters(to be fitted)
and two pion exchange correction to 3N

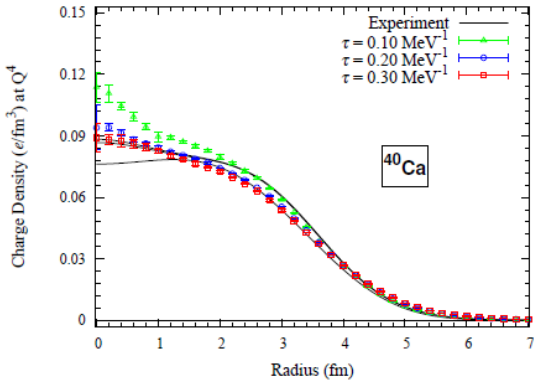
BE/A from WFM

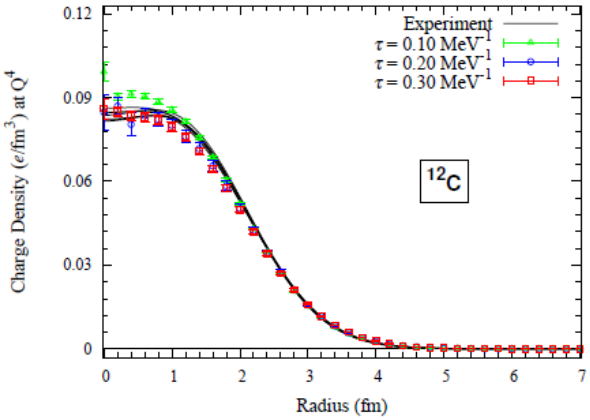

B_A / A (MeV)
9
8
7
6
5
4
3
2
3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 20 22 24 26 28 32 36 40
A
^{3}H
^{3}He
^{4}He
^{6}Li
^{6}He
^{7}Li
^{8}Be
^{9}Be
^{10}B
^{10}Be
^{11}B
$^{12}C_{0_1^+}$
$^{12}C_{2_1^+}$
$^{12}C_{0_2^+}$
^{13}C
^{14}N
^{14}C
^{15}N
^{16}O
^{17}O
^{18}F
^{18}O
^{20}Ne
^{20}O
^{22}O
^{24}Mg
^{24}O
^{28}Si
^{32}S
^{36}Ar
^{40}Ca
Experiment
N3LO (fit)
(prediction)

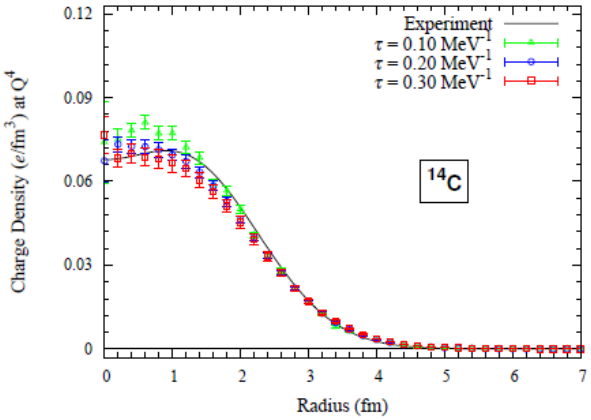
Charge density from WFM



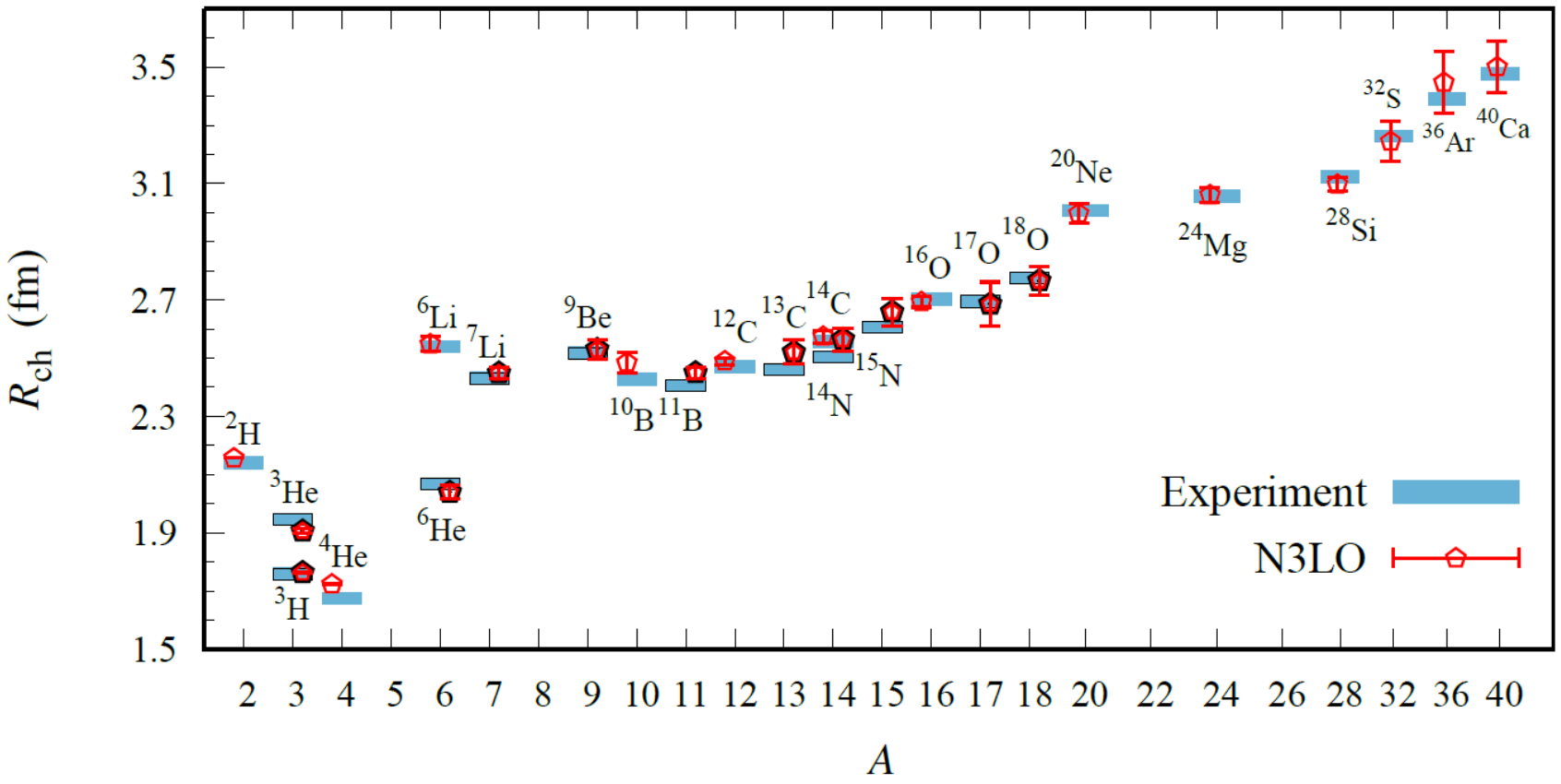




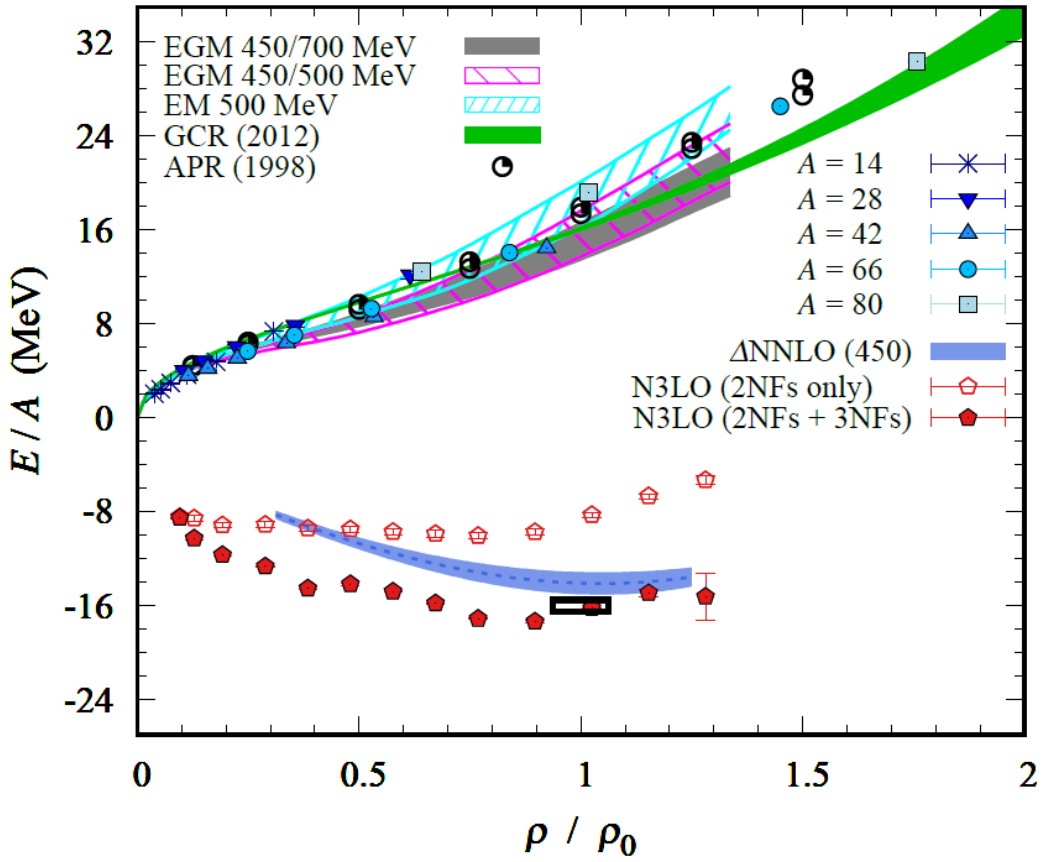




Charge Radius



Nuclear/Neutron Matter

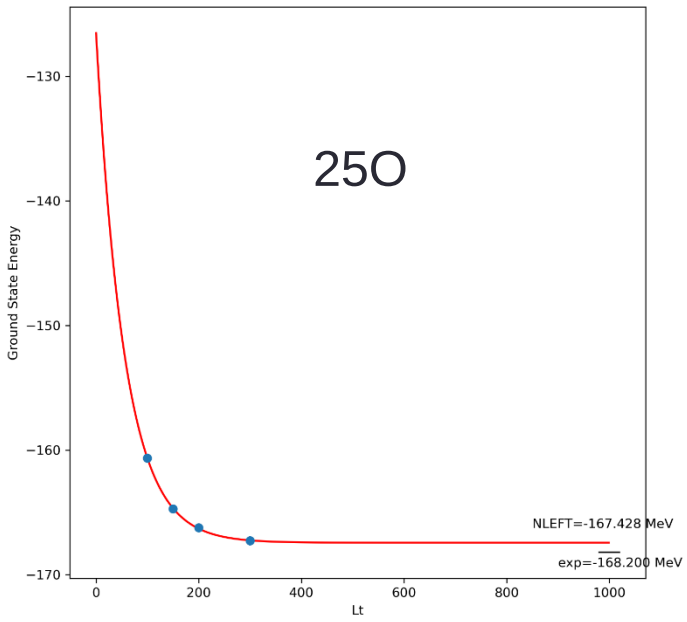


Neutron matter:
A=4~80
box size 6.6 ~ 13.2 fm.

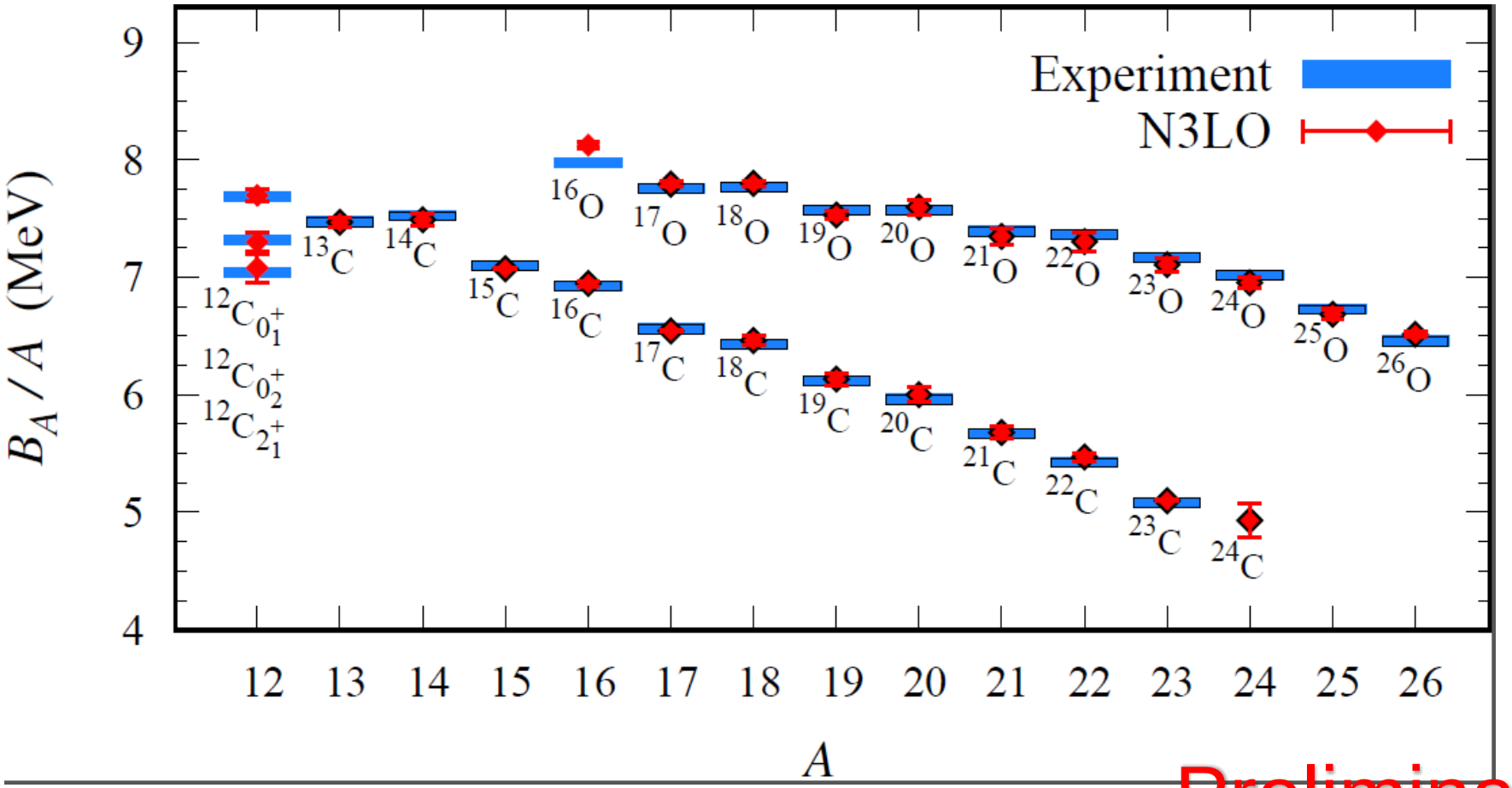
Nuclear matter:
A=4 ~ 160
Box size 7.92~9.24 fm.

Carbon/Oxygen Isotope calculations

- WFM Hamiltonian
- Initial wave functions are prepared with HO wave functions
- No projection operator used but prepared with correct M_z

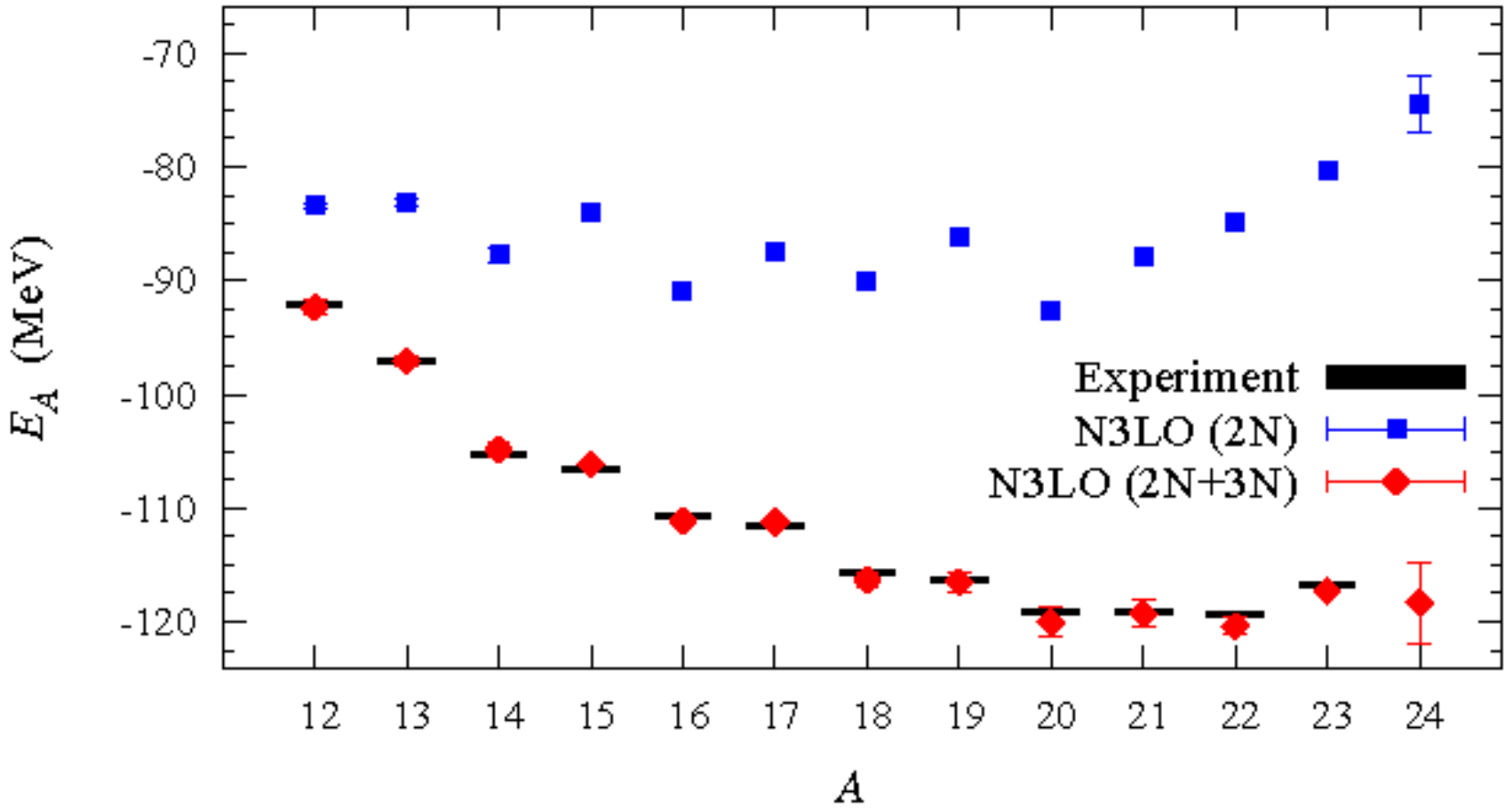


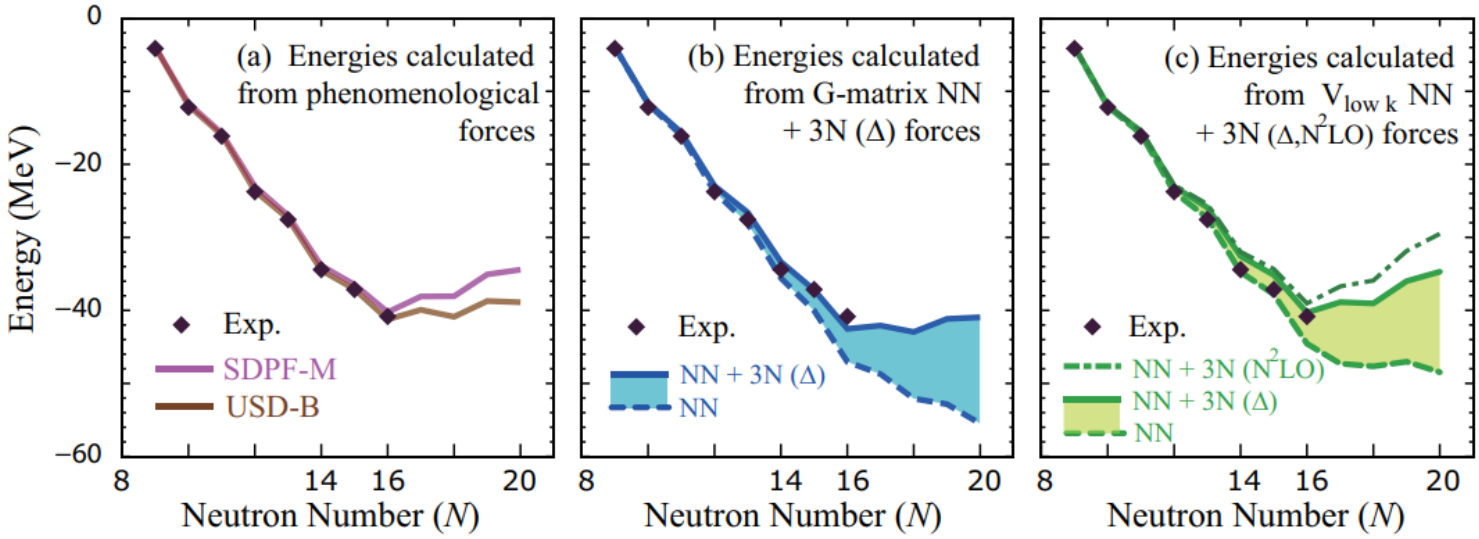
Carbon and Oxygen



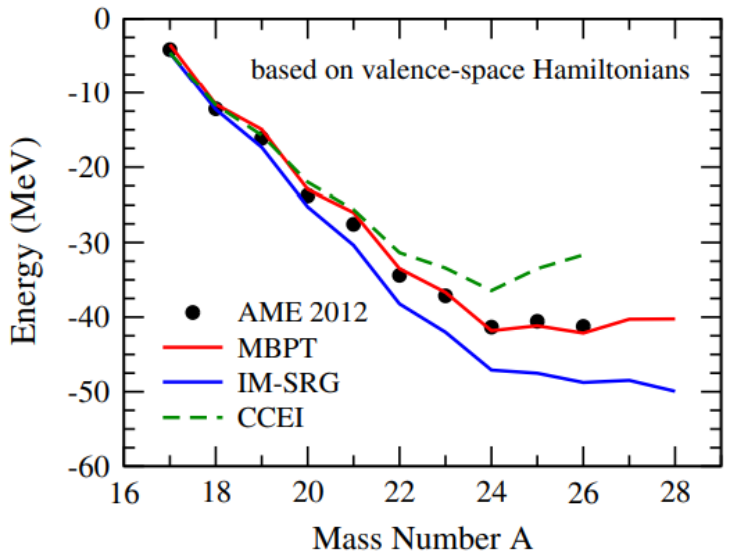
Preliminary

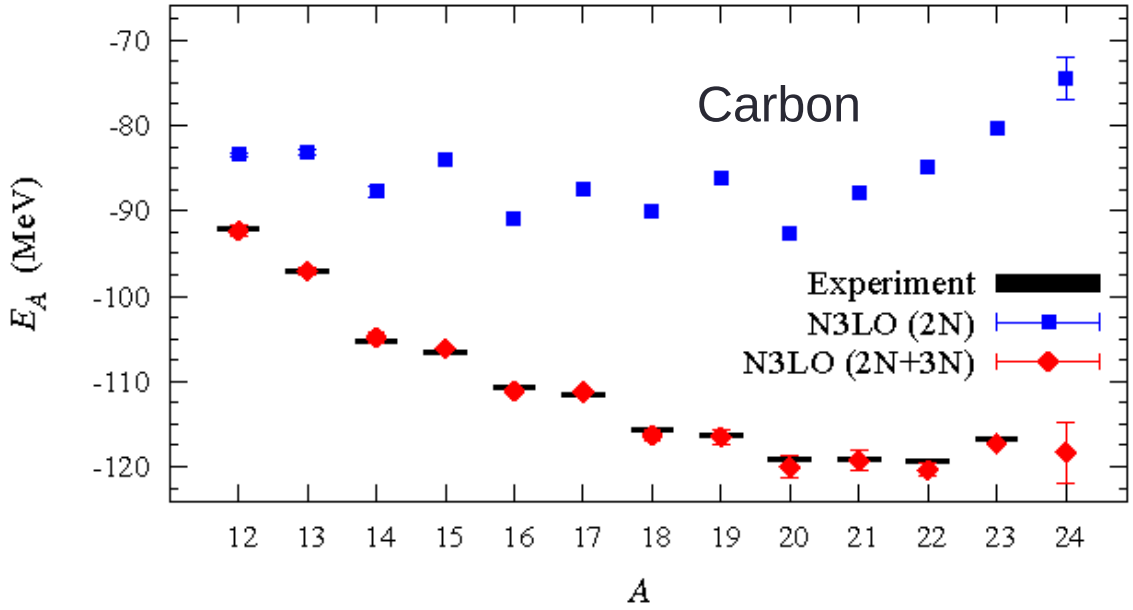
Carbon isotopes



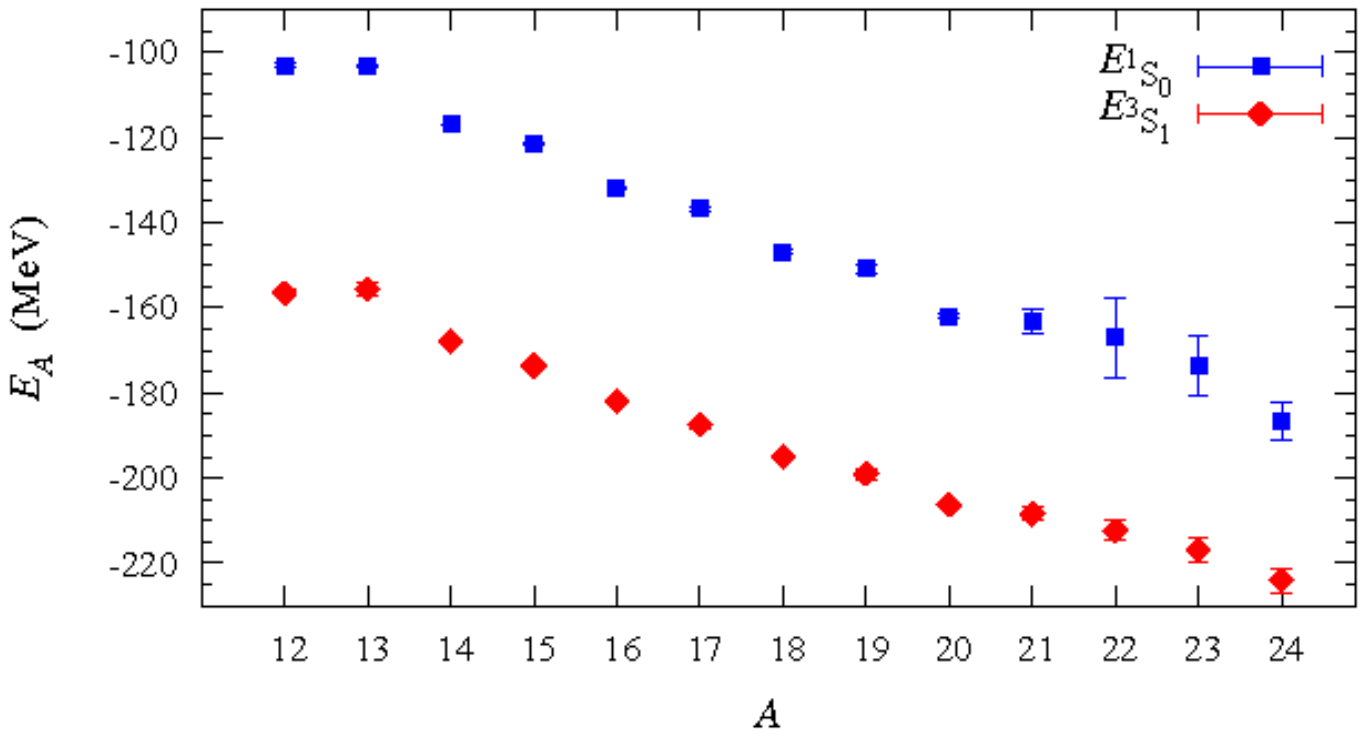

(a) Energies calculated from phenomenological forces
Exp.
SDPF-M
USD-B
(b) Energies calculated from G-matrix NN + 3N (Δ) forces
Exp.
NN + 3N (Δ)
NN
(c) Energies calculated from V low k NN + 3N (Δ,N2LO) forces
Exp.
NN + 3N (N2LO)
NN + 3N (Δ)
NN
Energy (MeV)
Neutron Number (N)

Oxygen

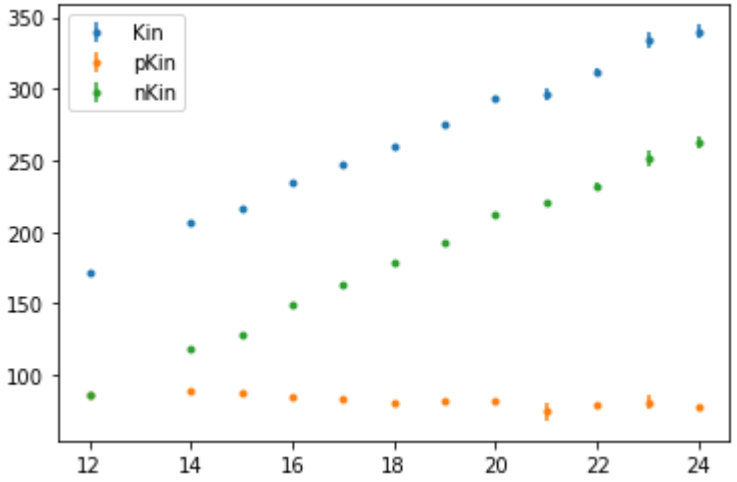

based on valence-space Hamiltonians
AME 2012
MBPT
IM-SRG
CCEI
Energy (MeV)
Mass Number A

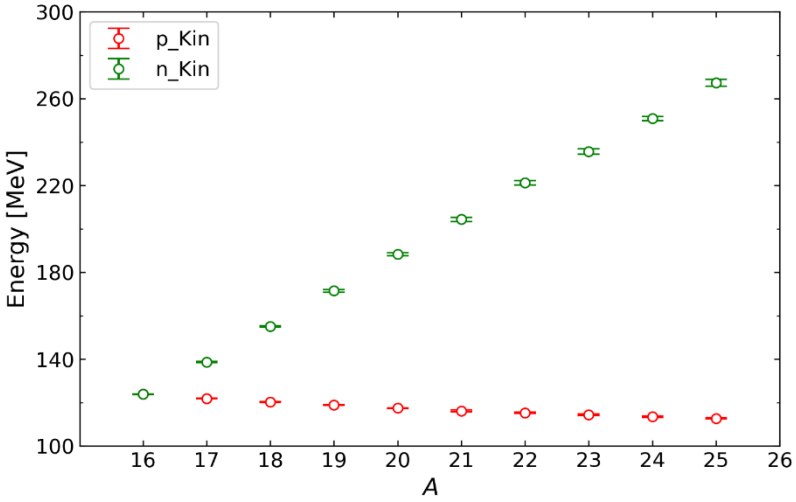

Carbon
Experiment
N3LO (2N)
N3LO (2N+3N)
E_A (MeV)
A

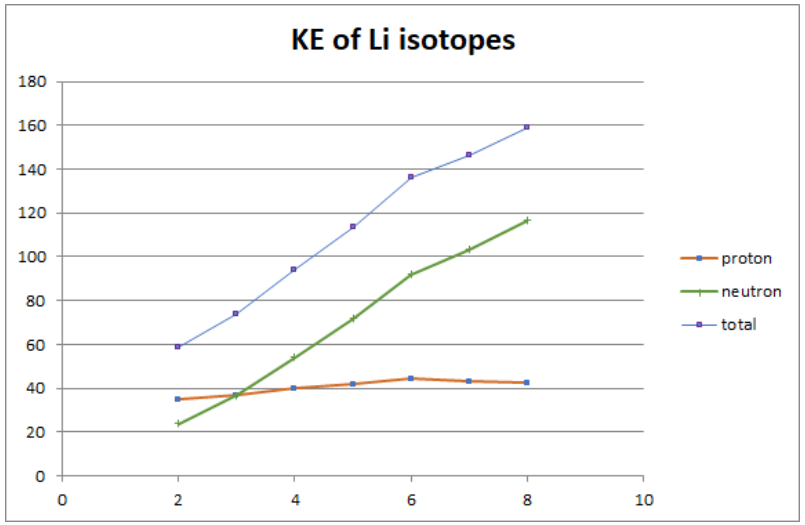
Carbon isotopes



Kinetic energy







- Some pattern observed for
  - 2N, 3N contribution
  - 1S0, 3S1 contact terms
  - p/n kinetic energies
- However, each contributions are n ot physical observable and can be model dependent

NCSM results from I.-J. Shin(IRIS,IBS)

Charge Radius

Exp				Lattice Calculation			
Carbon	Exp E/A	Exp E	charge R	E(MeV)		R_pp	R_ch
12	7680.145	92.16174	2.4702	97.72(45)		2.4141(204)	2.5426(204)
13	7469.850	97.10805	2.4614	97.46(25)		2.5252(441)	2.6450(441)
14	7520.320	105.28448	2.5025	106.21(32)		2.4622(314)	2.5815(314)
15	7100.17	106.50255		107.77(46)		2.5788(400)	2.6897(400)
16	6922.05	110.7528		112.34(65)		2.5974(508)	2.7043(508)
17	6558.0	111.486		113.15(27)		2.6854(416)	2.7858(416)
18	6426.1	115.6698		118.82(92)		2.6622(410)	2.7603(410)
19	6118	116.242		118.05(78)		2.7087(157)	2.8020(157)
20	5961	119.22		124.17(104)		2.7704(752)	2.8587(752)
21	5674#	119.154		119.27(65)		2.7736(845)	2.8587(845)
22	5421	119.262		124.88(34)		2.7682(1679)	2.8504(1679)
23	5080#	116.840		119.58(53)		-	

$$\langle r_{\rm ch}^2 \rangle = \langle r_{\rm pp}^2 \rangle + R_{\rm p}^2 + \frac{N}{Z} R_{\rm n}^2 + \frac{3\hbar^2}{4m_{\rm p}^2 c^2},$$

Rn^2 = -0.105

0.7056 0.033172

Exp				Lattice Calculation			
Oxygen	Exp E/A	Exp E	charge R	E(MeV)		R_pp	R_ch
16	7976.207	127.619312	2.6991	130.12(39)		2.7134(702)	2.8283(702)
17	7750.729	131.762393	2.6932	132.31(15)		2.6955(171)	2.8088(171)
18	7767.098	139.807764	2.7726	140.84(32)		2.8329(469)	2.9387(469)
19	7566.50	143.7635		143.27(20)		2.7702(88)	2.8760(88)
20	7568.57	151.3714		151.68(42)		2.7236(383)	2.8288(383)
21	7389.4	155.1774		154.28(29)		2.7768(796)	2.8778(796)
22	7364.9	162.0278		162.04(60)		2.9162(761)	3.0104(761)
23	7163	164.749		162.80(70)		2.7575(471)	2.8546(471)
24	7040	168.96		168.72(27)		2.9159(748)	3.0057(748)
25	6728	168.2		166.61(49)		2.9115(565)	2.9993(565)
26	6497	168.922		168.77(44)		2.9674(543)	3.0514(543)
27	6185#	166.995		166.45(15)		2.9737(408)	3.0554(408)
28	5988#	167.664					

From Yuanzhuo Ma

Summary

- Wave function matching method seems to be promising
  - New method to improve the N3LO calculation of NLEFT
  - Preliminary study shows promising results for wide range of observables in one scheme (same interaction and many-body method)
    - NN scattering
    - Binding energy (from 3H to 40Ca)
    - Symmetric Nuclear matter
    - Neutron matter
    - Dripline of Oxygen isotope.
    - Carbon excited states
- Also, Carbon isotopes, odd Oxygen isotopes, Cluster structure, excited states will be studied.

Others 1

(Only preliminary results)

G.T. transition amplitude

nature physics

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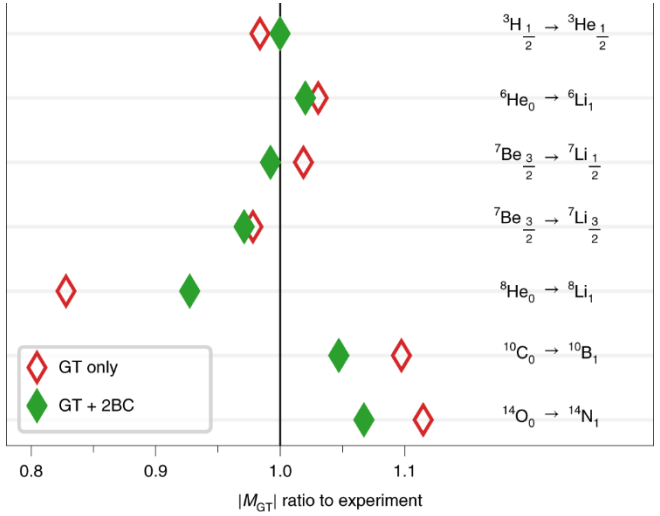
nature › nature physics › letters › article

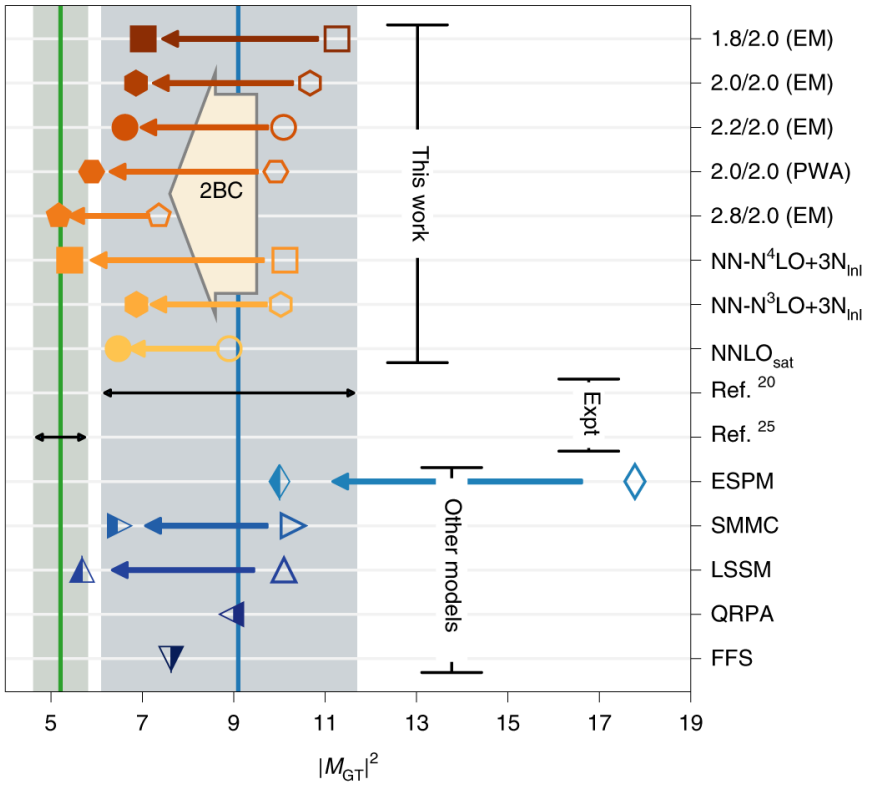
Letter | Published: 11 March 2019

Discrepancy between experimental and theoretical β-decay rates resolved from first principles

P. Gysbers, G. Hagen ✉, J. D. Holt, G. R. Jansen, T. D. Morris, P. Navrátil, T. Papenbrock, S. Quaglioni, A. Schwenk, S. R. Stroberg & K. A. Wendt

Nature Physics **15**, 428–431 (2019) | Cite this article





G.T. transition amplitude

$$Z_{ij} = \langle i|M^{L_t}|j\rangle = \int dse^{-V(s)} \det \boldsymbol{X}_{ij}(s)$$

$$[\boldsymbol{X}_{ij}(s, L_t)]_{lm} = \langle \phi_l^{(i)}|M(s)^{L_t}|\phi_m^{(j)}\rangle$$

1. Needs to compute two nuclei at the same time
2. For orthogonal states, Z_{12} = 0.
   (Sampling channels one at a time is not suitable.)
3. How should we sample auxiliary fields for Z_{12} ?

As a starter,

- WFM wave function(at LO)
- only 1-body operator are used. (no 2BC contributions)

$$\sigma\tau$$

Trial : Re-weighting method

$$
\begin{aligned}
\langle O \rangle_{ij} &= \frac{\langle i | M^{L_t/2} O M^{L_t/2} | j \rangle}{\langle i | M^{L_t} | j \rangle} \\
&= \frac{\int ds e^{-V(s)} \det \boldsymbol{X}^{O}{}_{ij}(s)}{\int ds e^{-V(s)} \det \boldsymbol{X}_{ij}(s)} \\
&= \frac{\frac{1}{N} \sum_s e^{-V(s)} \det \boldsymbol{X}^{O}{}_{ij}(s)/P_1(s)}{\frac{1}{N} \sum_s e^{-V(s)} \det \boldsymbol{X}_{ij}(s)/P_2(s)}
\end{aligned}
$$

Compute A nuclei (A wave vectors)

→ Select A-1 or A-2 s.p. waves to construct trial wave functions

→ Use the same auxiliary fields sampling for A nuclei

→ Reweight probability for A-1 or A-2 nuclei

Trial : Re-weighting method

- 4He within 5He

	5He		4He	
Lt=100	-0.25592E+02	0.12145E+00	-0.28048E+02	0.22358E+00
Lt=200	-0.26400E+02	0.21669E+00	-0.28407E+02	0.25195E+00
Lt=300	-0.26458E+02	0.18151E+00	-0.28794E+02	0.28754E+00
Lt=400	-0.26647E+02	0.15672E+00	-0.27967E+02	0.33789E+00
Fit	26.62 +/- 0.12		28.43 +/- 0.42	
Exp.	27.5605		28.2956	

- It may be used for the Separation energy calculation

→ Correlated error estimation of separation energy

Trial : Re-weighting method

- Preliminary calculation of 3H → 3He by using 4He sampling
  - |<3He| tau_{+}|3H >|~1 and |<3He|sigma_z tau_{+}|3H>|~1
  - Significant increase of BE error compared to independent calculations

- Preliminary calculation of 6He(0+) → 6Li(1+) by using 7Li(3/2-) sampling
  - To fix the angular momentum, two projection operators are used.
  - However,
    - Bad convergence in binding energy of 6He, 6Li
    - Two Projection operators raises sign problem.

$$\begin{aligned} & \langle A|P_B M^{L_t/2} O M^{L_t/2} P_A|B\rangle \\ = & \sum_{\theta_1,\theta_2} f_A(\theta_1) f_B(\theta_2) \langle A|R_A(\theta_1) M^{L_t/2} O M^{L_t/2} R_B(\theta_2)|B\rangle \end{aligned}$$

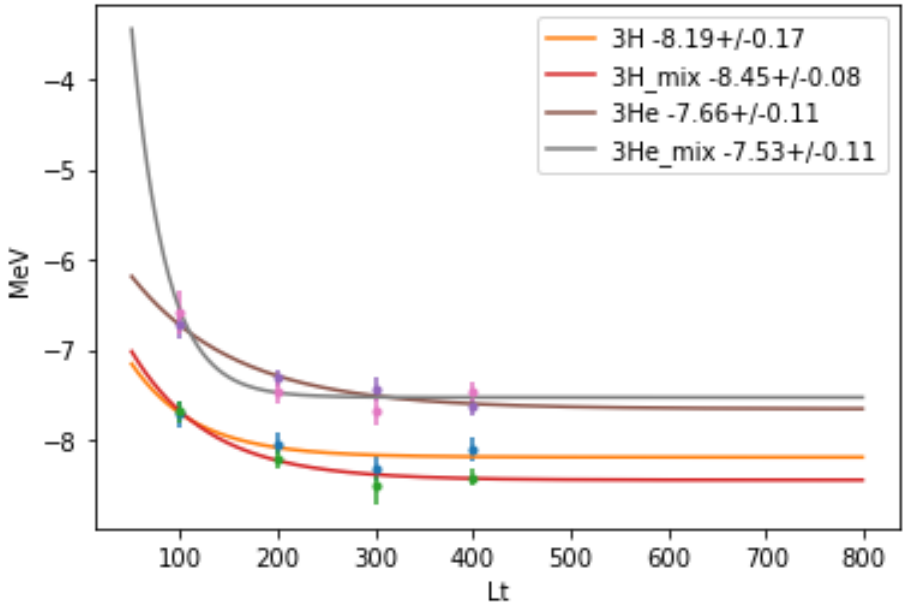
Trial : Mixed Sampling

Working on mixed sampling approach

Preliminary

$$P(x) \simeq a|\det X_{11}(x)| + b|\det X_{22}(x)|$$

- Instead of projection operator, fix the Jz of initial wave functions

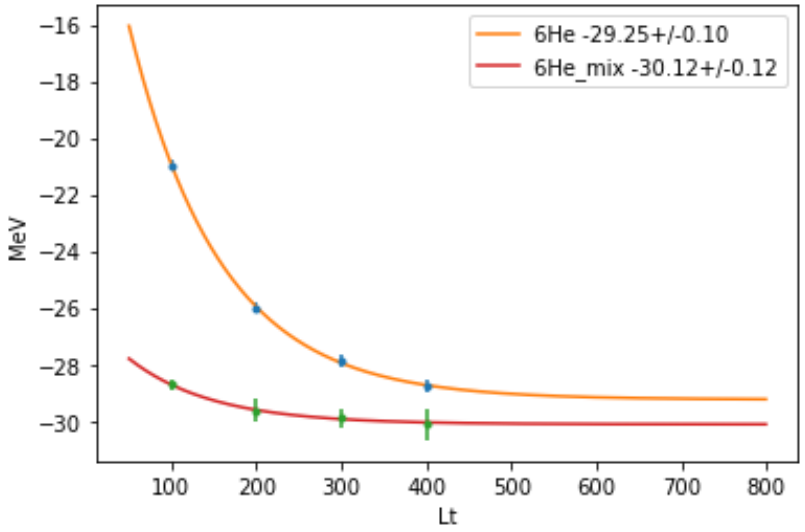


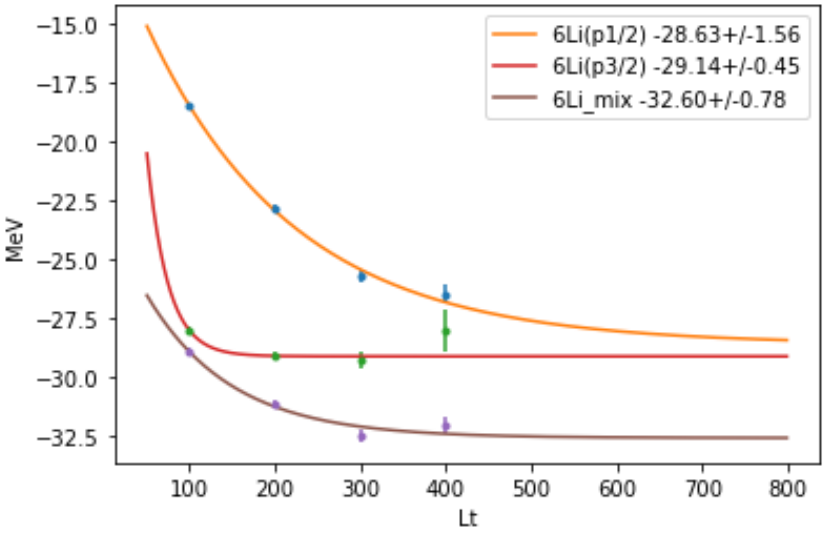
- Preliminary calculation 3H->3He
  - Better convergence than re-weight method
  - <3He| GT| 3H> ~ 1.0 for all Lt
  - (Only LO wave function)

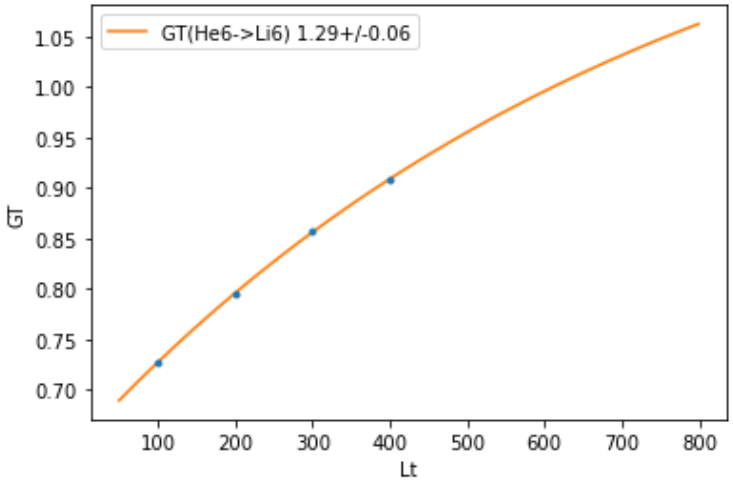
BE(3He)= 7.718 (exp.)
BE(3H) = 8.482 (exp.)
<3He| GT| 3H> ~ 0.958 (exp.)

Trial : Mixed Sampling

Preliminary







- Mixed Sampling
- 6He(0+)→6Li(1+)
- B.E. Lt dependence changed
- <6Li| (GT) |6He> have Lt dependence

BE(6He) =29.27(exp.)
BE(6Li) =31.99(exp.)
<6Li| (GT) |6He> ~ 1.25 (exp)

Summary

- G.T. Transition amplitudes
  - Two nuclei with different Z at the same time
  - → re-weighting method was not successful
  - → mixed sampling seems to work

- To do :
  - 2BC correction
  - higher order wave function correction

Others 2

(Only preliminary results)

Dripline for unitary Fermions

- Unitary Fermion Gas :
  - A strongly coupled conformal system
  - Physically interesting multi-fermion system with simple interaction

$$\mathcal{A} = \frac{4\pi}{M}\frac{1}{p\cot\delta - ip} \qquad p\cot\delta = -\frac{1}{a} + \frac{1}{2}r_0 p^2 + O(p^4)$$

  - $p\cot\delta = 0$: Unitary limit

→largest possible scattering amplitude. Infinite scattering length.
(Realistic nuclear force is close to unitary limit.)

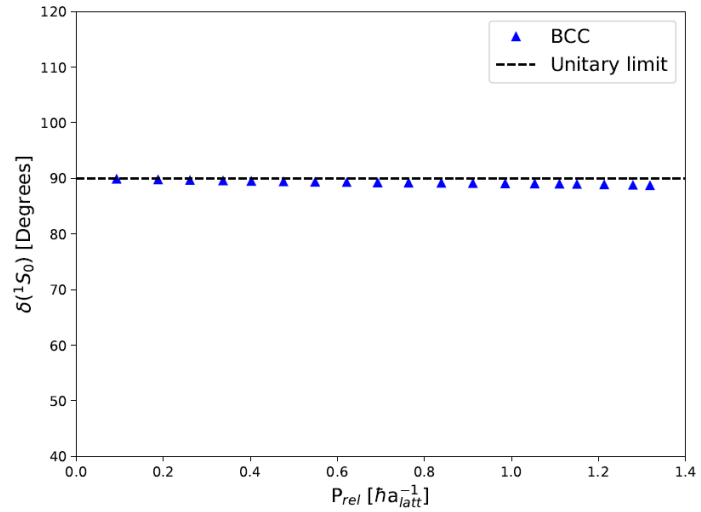
Universality of unitary limit of many fermion system
→ Bertsch Parameter

$$r_e \ll n^{-\frac{1}{3}} \ll a_s$$

$$E_0 = \xi E_{FG},$$

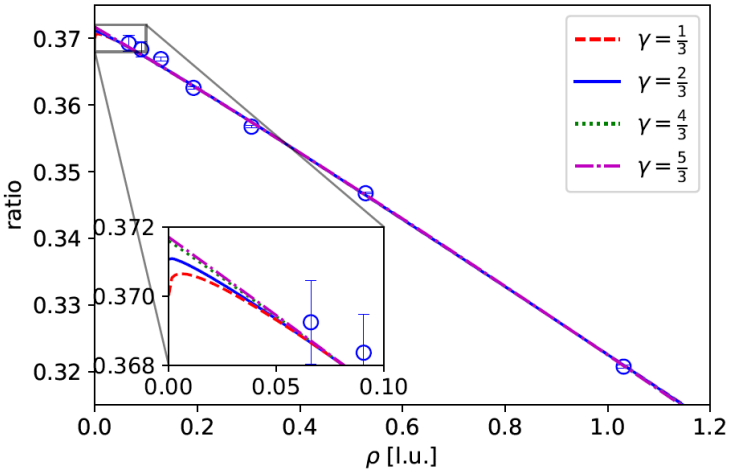
Bertsch parameter

Unitary limit Hamiltonian



1S0 NN scattering phase shift is fitted for unitary limit .
→ Very large scattering length.
In cubic and BCC lattice

N=66 neutrons (33 spin up, 33 spin down)
L = 4,…, 10



$$\xi = E_0 / E_{\mathrm{FG}}$$

$\xi^{\mathrm{thermo}}_{33,33} = 0.369(2)$ and $\xi^{\mathrm{finite}}_{33,33} = 0.372(2)$ Cubic lattice

$\xi^{\mathrm{therm}} = 0.369(2)$ $\xi^{\mathrm{few}} = 0.371(2)$ BCC lattice

Unitary Fermions under trap

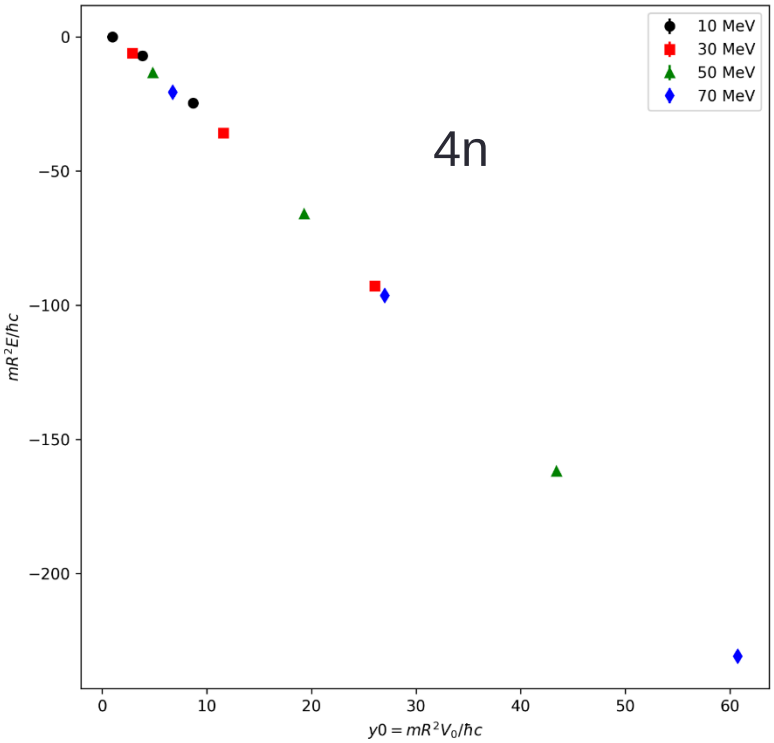
- Unitary Fermion itself does not form a bound nuclei
  → Introduce an external spherical well potential
  Can we find a relation between trap shape and dripline?

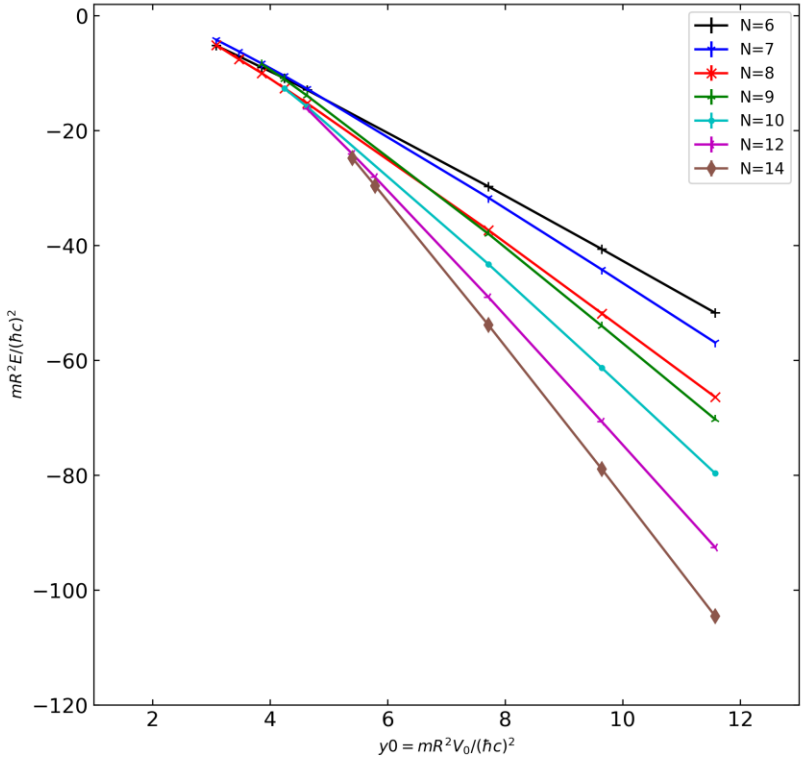
- Separation energy have to be calculated accurately
  → Use an re-weighting method to reduce error in separation energy.
  (correlated error estimation in energy difference.)

- Unfortunately, realistic mean-field potential is rather expensive.
  (reaching dripline in Unitary limits is difficult.)
  → limited to shallow external potential.
  Try to see the dependence on parameter : $y_0 = m R^2 V$

(Work in progress. Only preliminary results)

Neutrons in trap

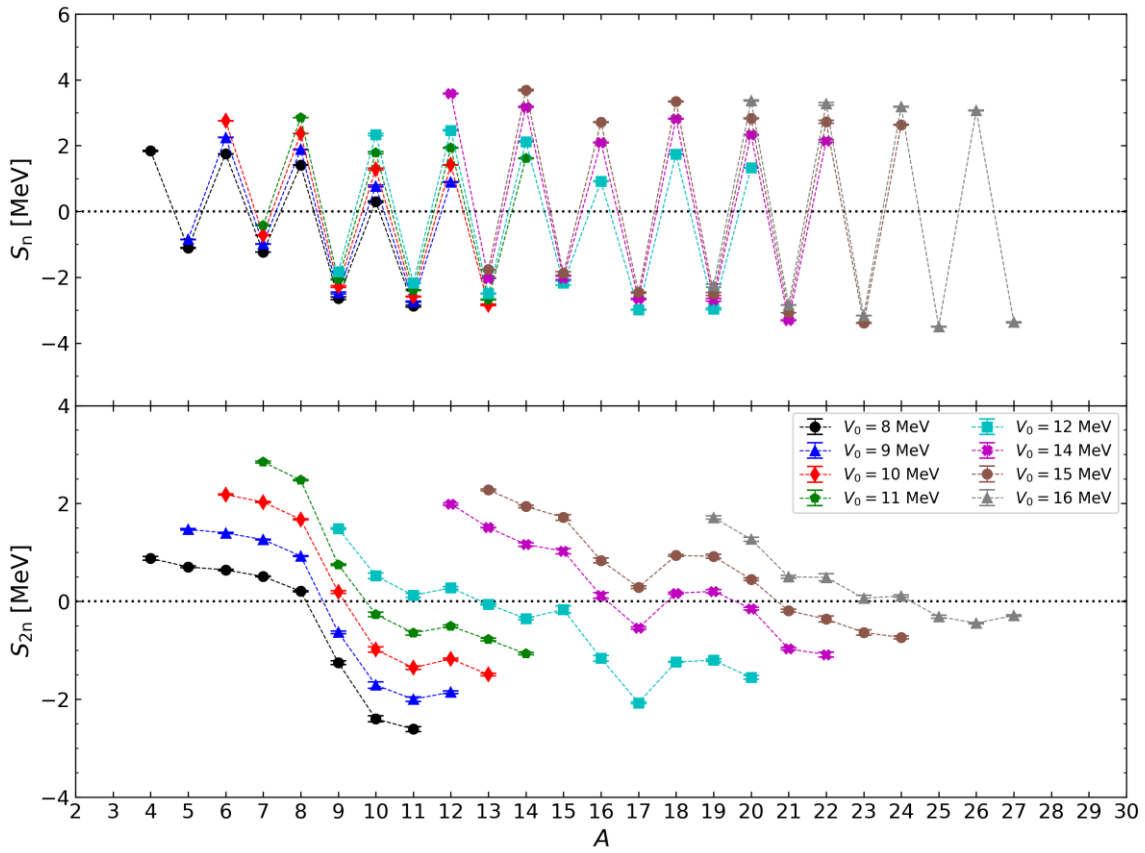




Separation energies

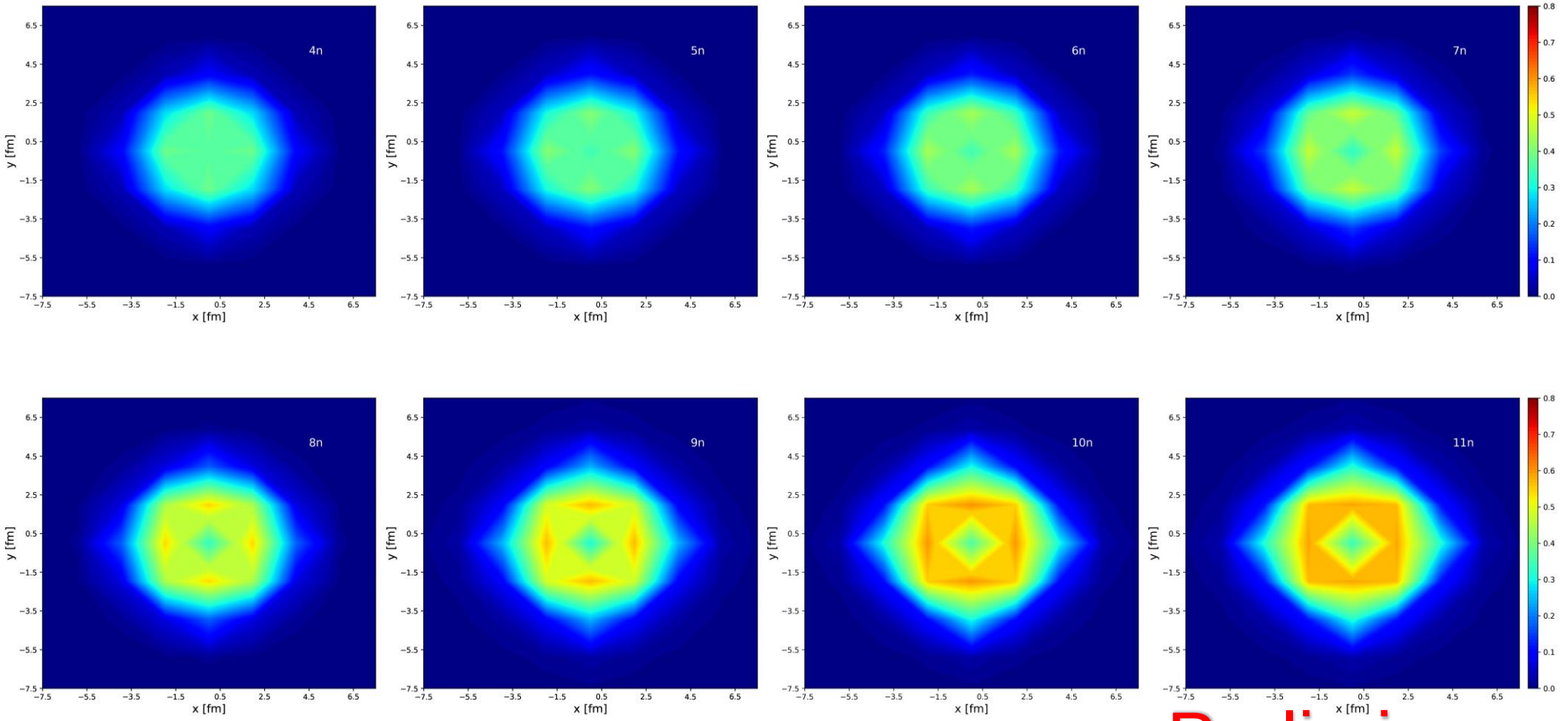
Lattice spacing
100 MeV

Spherical well
radius~ 4fm



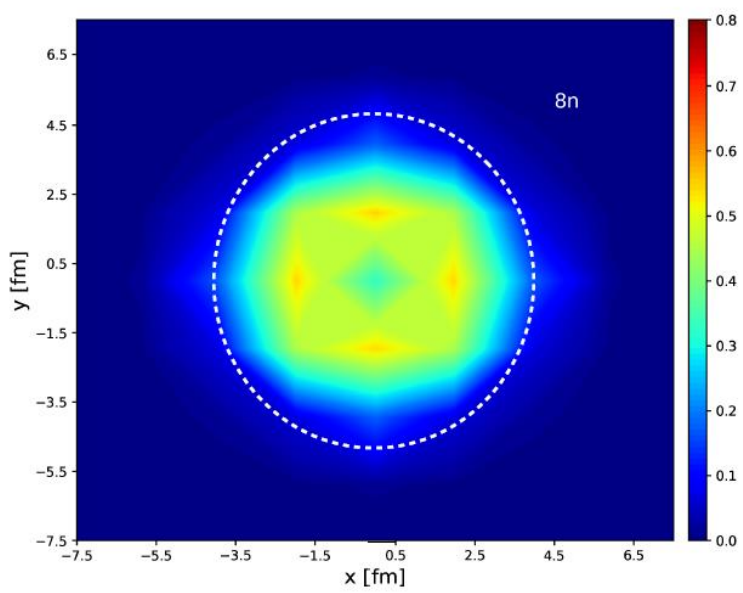
Preliminary

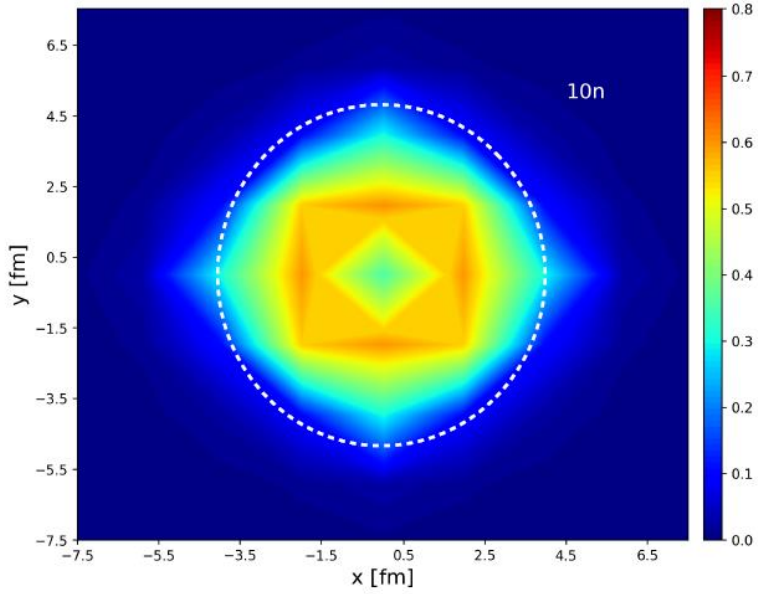
V0=8MeV density contour



Preliminary

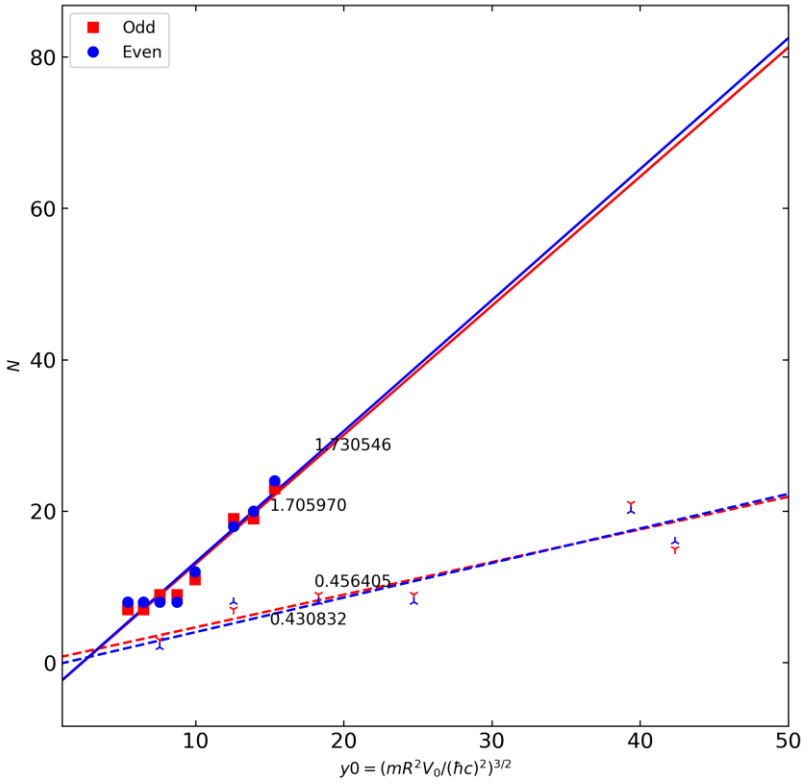
V0=8MeV density contour





Preliminary

Extrapolation?



- Linear Fit
- Needs More data

Preliminary

Summary

- Unitary Fermions in trap
  - One could find driplines from two neutron separation energies
  - Density distribution shows leakage of neutrons
  - y0 dependence
  - However, not enough data yet for any conclusion.
  - → To reduce computational cost, looking at 1d case.