Recent developments in nuclear structure theory

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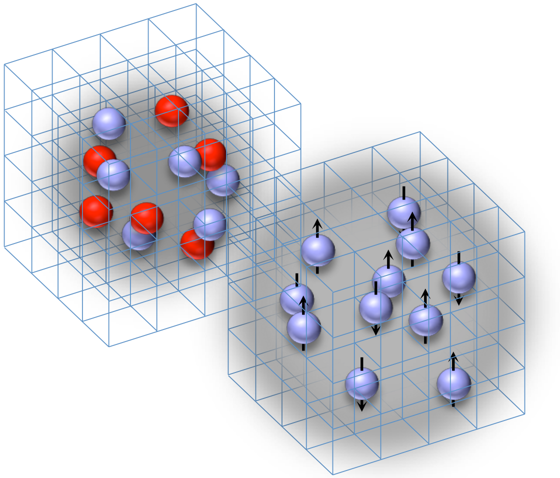
Nuclear Lattice EFT Collaboration



International Winter Meeting on Nuclear Physics
Bormio, Italy
January 22, 2019

FRIB
MICHIGAN STATE UNIVERSITY
NNSA National Nuclear Security Administration
NUCLEI Nuclear Computational Low-Energy Initiative A SciDAC-4 Project
JÜLICH FORSCHUNGSZENTRUM
OAK RIDGE National Laboratory | LEADERSHIP COMPUTING FACILITY

Outline

Effective Theories

Lattice Quantum Chromodynamics

Chiral Effective Field Theory

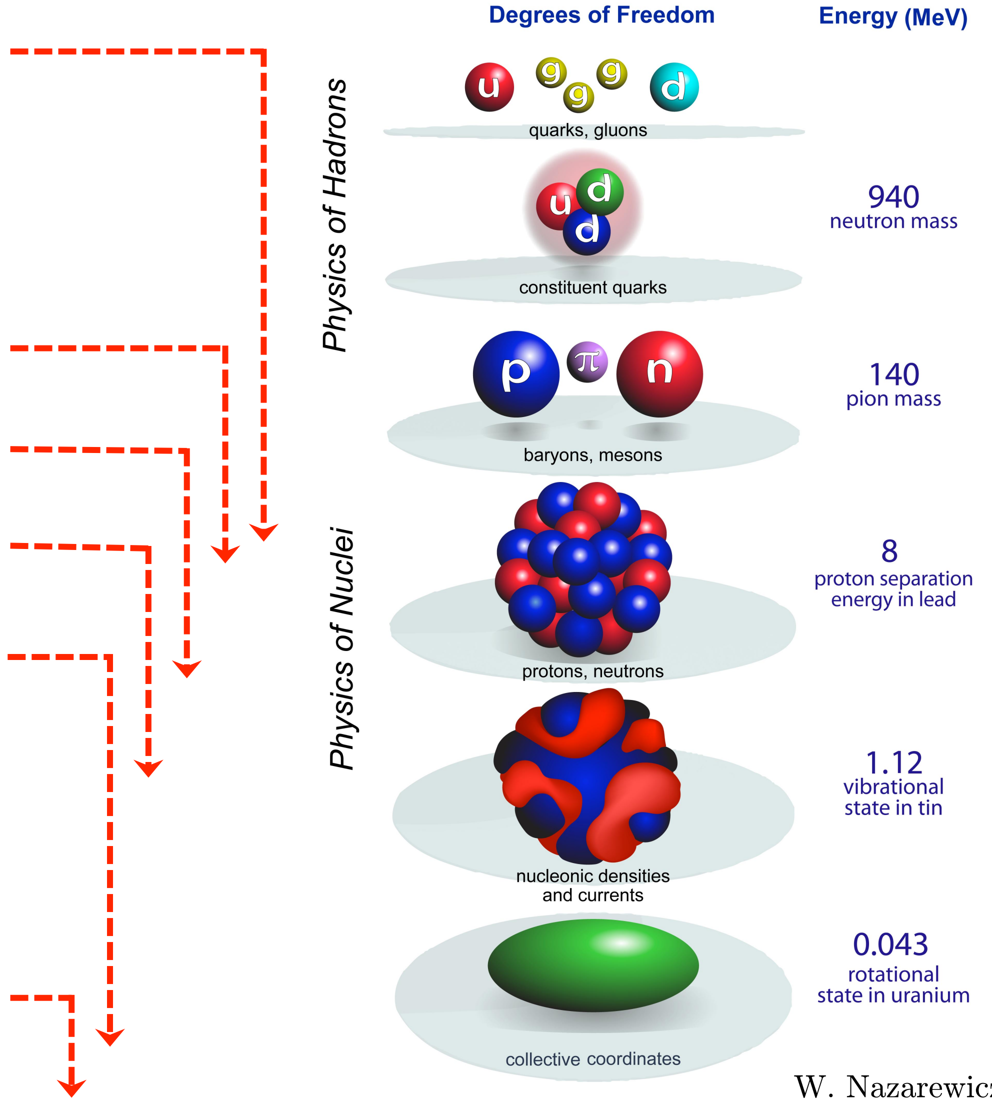
Microscopic A-body Methods

Configuration Interactions

Density Functional Methods

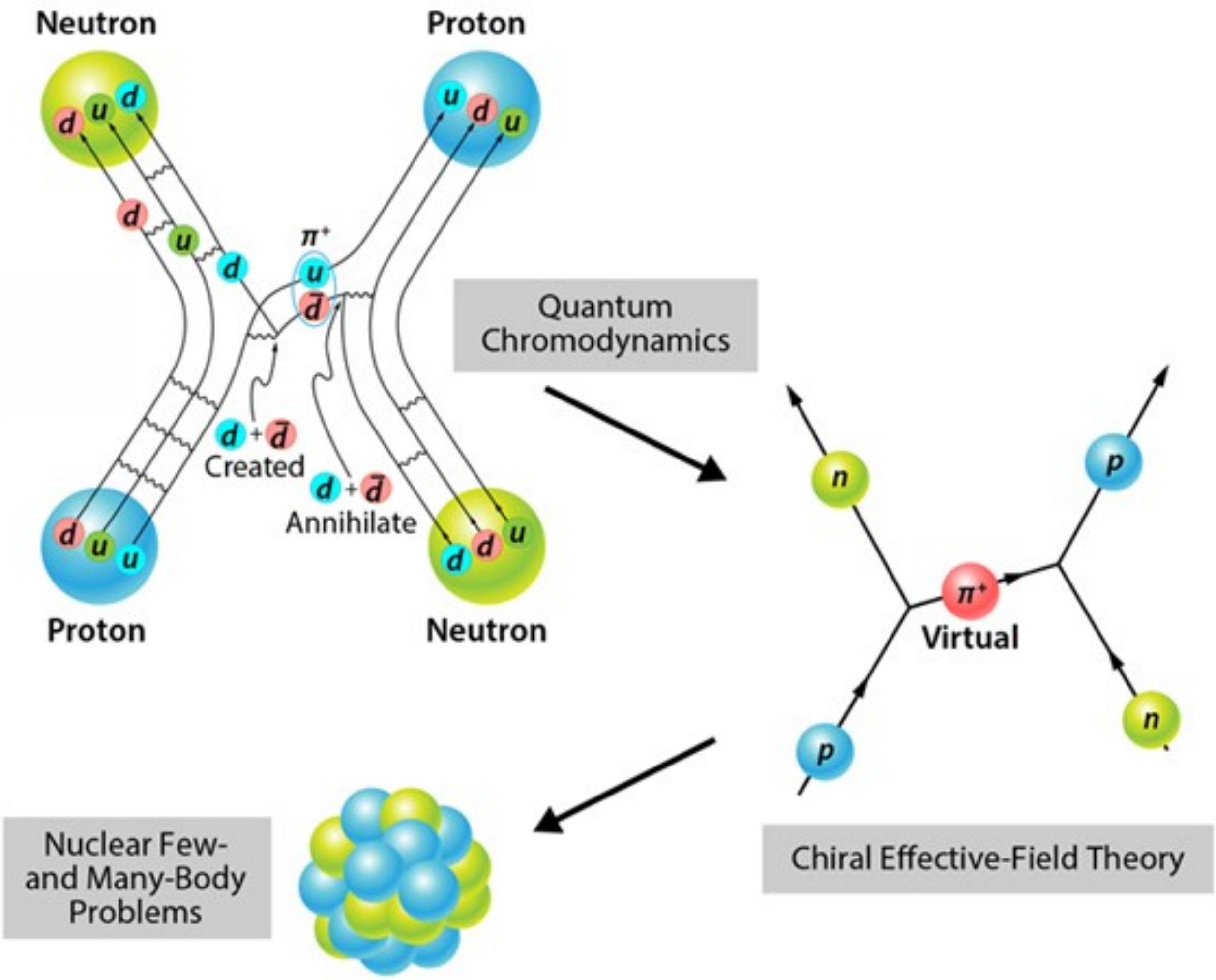
Mean Field Methods

Effective Theory of Collective Modes

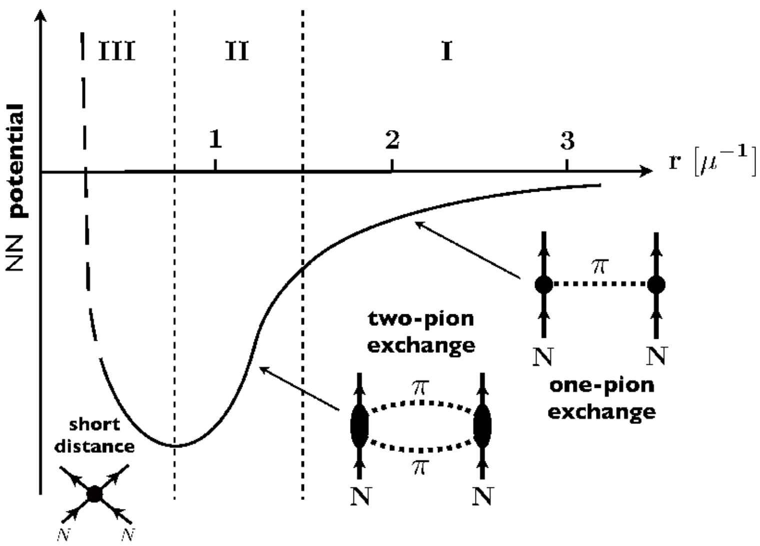


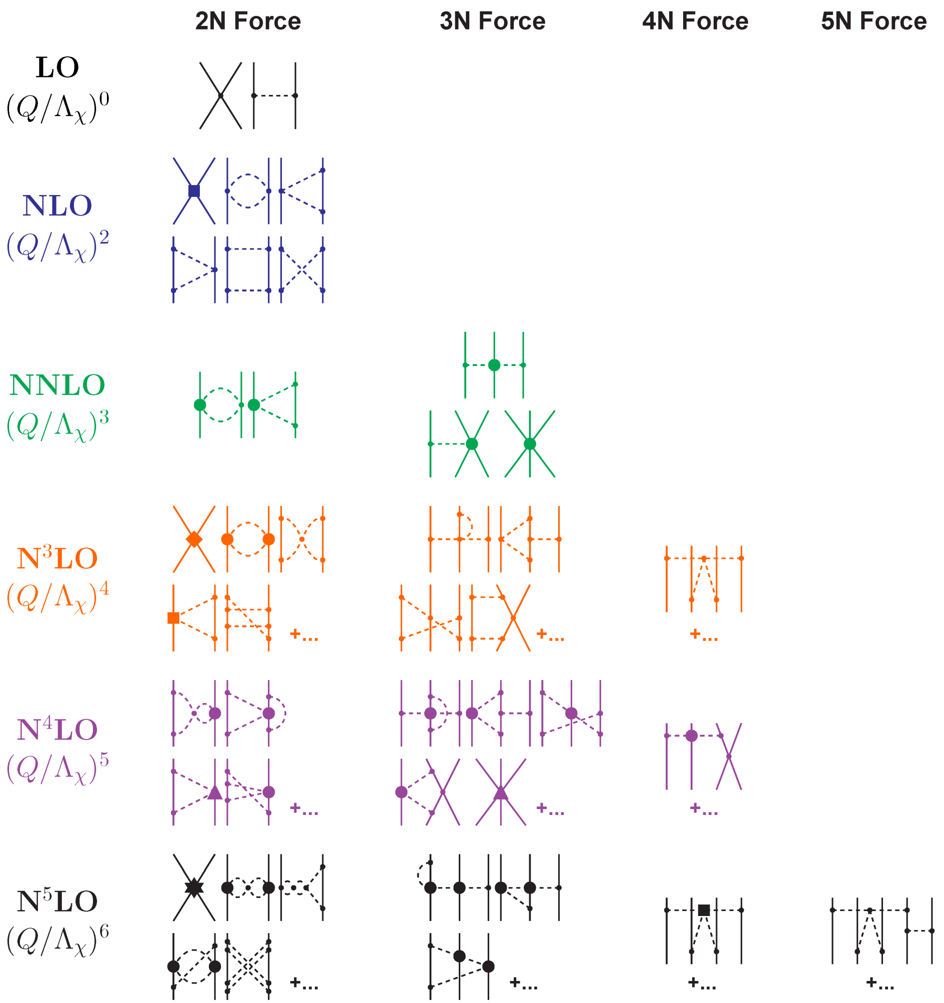
W. Nazarewicz

Nuclear Forces



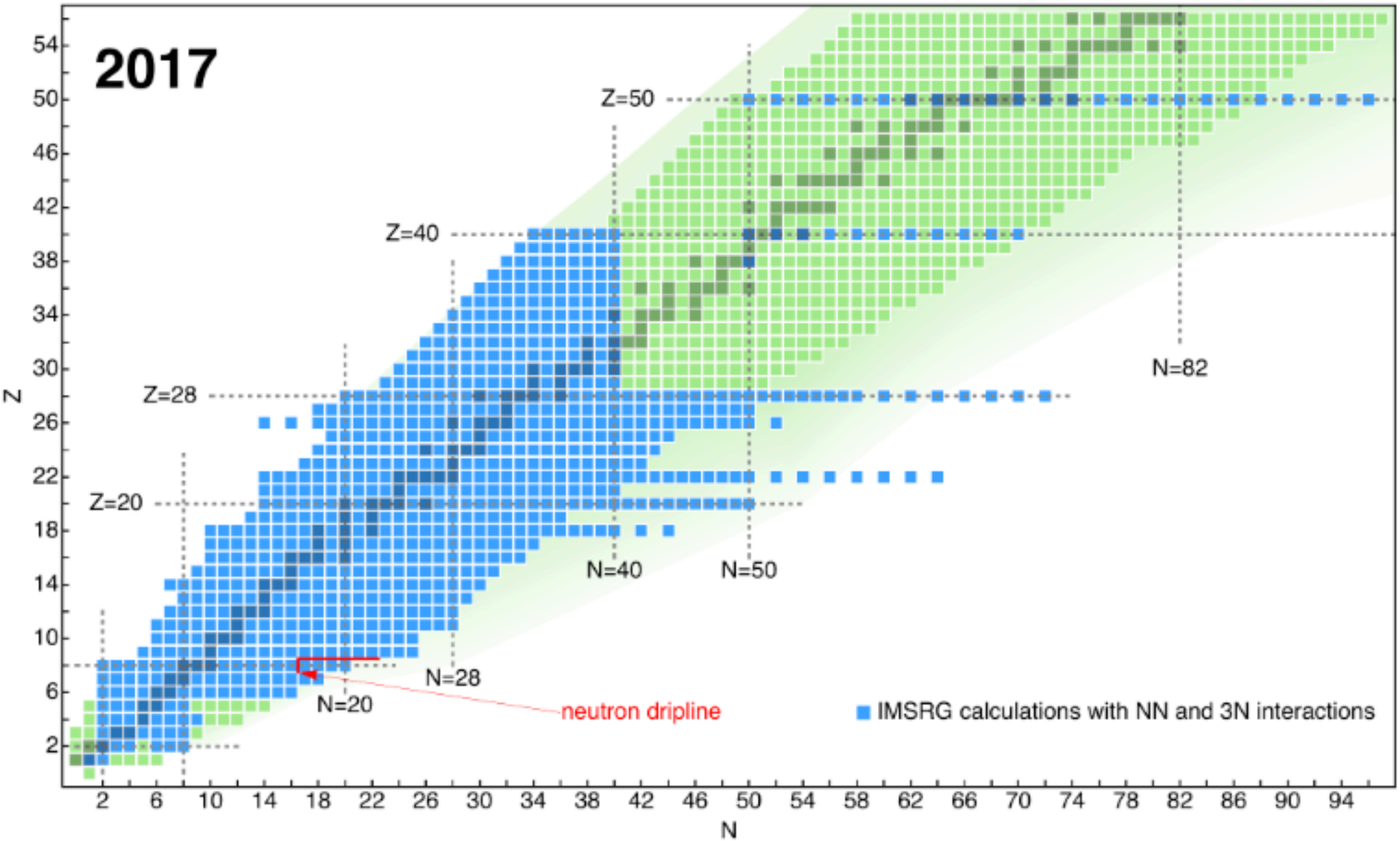
Chiral Effective Field Theory





Weinberg, van Kolck, Epelbaum, Glöckle, Meißner, Krebs, Entem, Machleidt, ...

Nuclear Structure with Microscopic A-body Methods

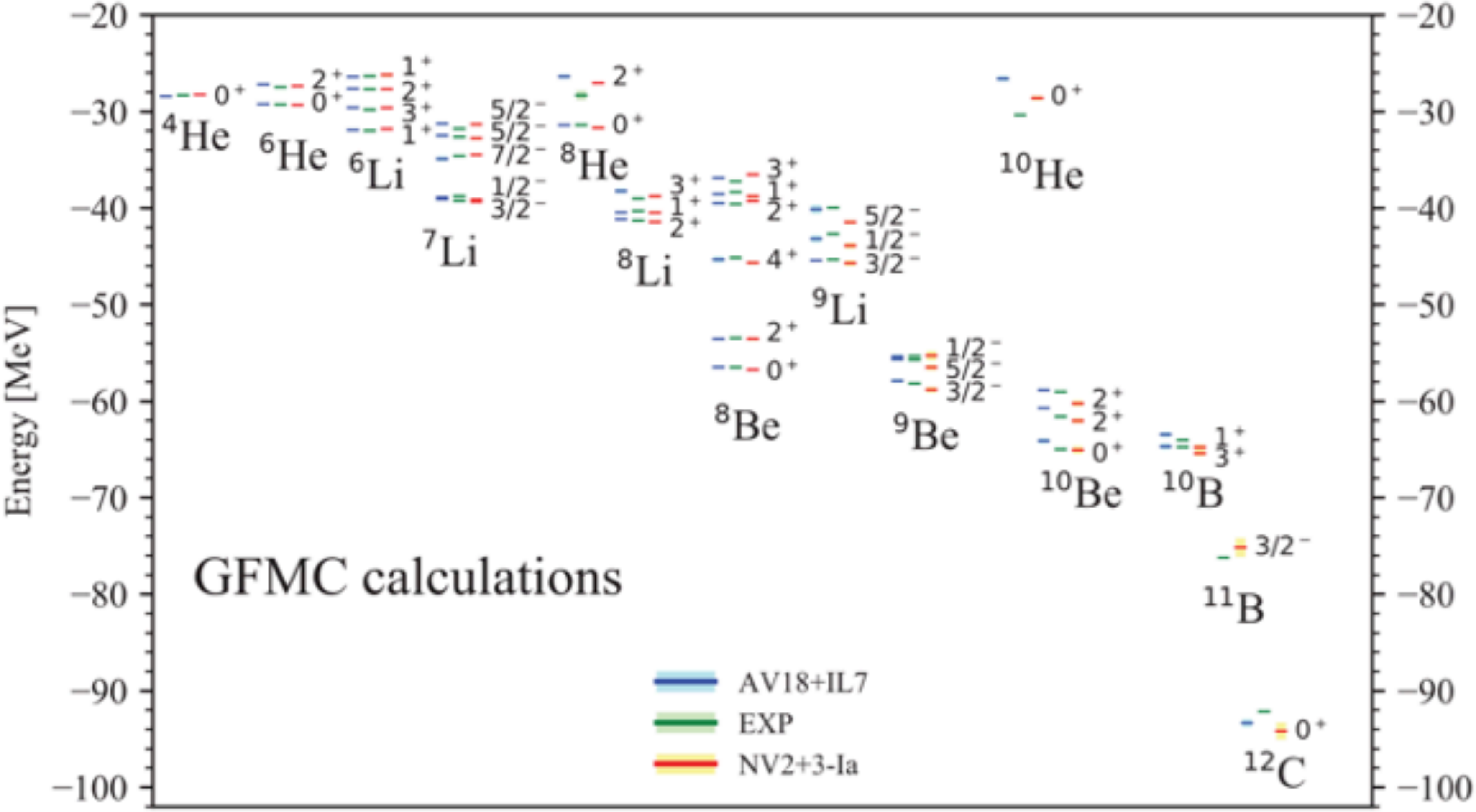


Hergert, Yao, Morris, Parzuchowski, Bogner, Engel,
Recent Progress in Many-Body Theories, June 25-30, 2017, APCTP, Pohang, Korea

Light-Nuclei Spectra from Chiral Dynamics

M. Piarulli, A. Baroni, L. Girlanda, A. Kievsky, A. Lovato, Ewing Lusk, L. E. Marcucci, Steven C. Pieper, R. Schiavilla, M. Viviani, and R. B. Wiringa

Phys. Rev. Lett. **120**, 052503 – Published 1 February 2018

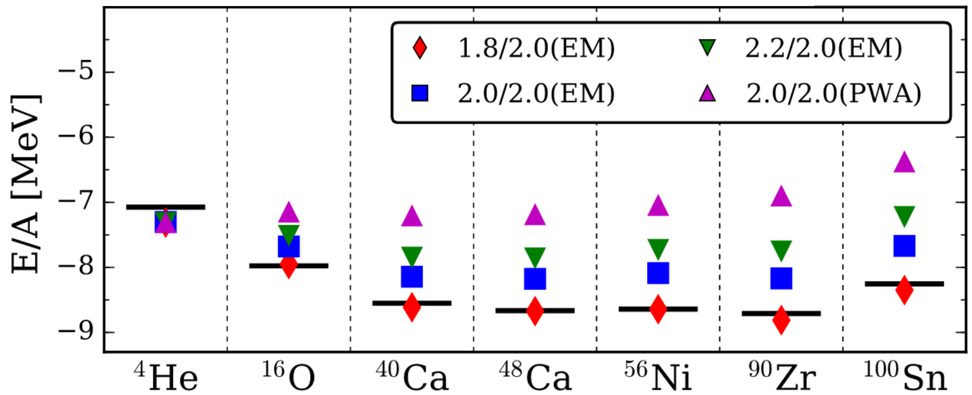


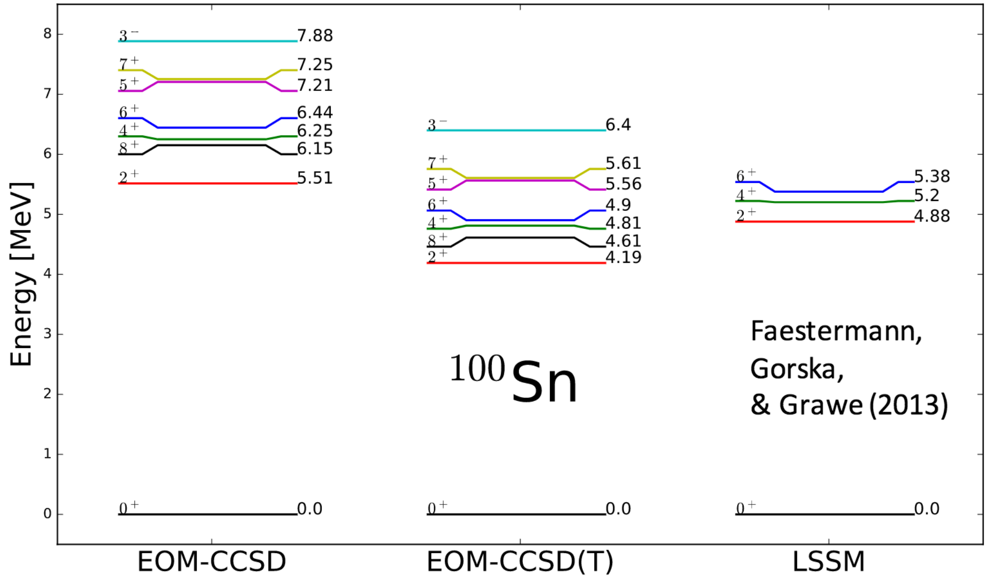
Editors' Suggestion

Structure of the Lightest Tin Isotopes

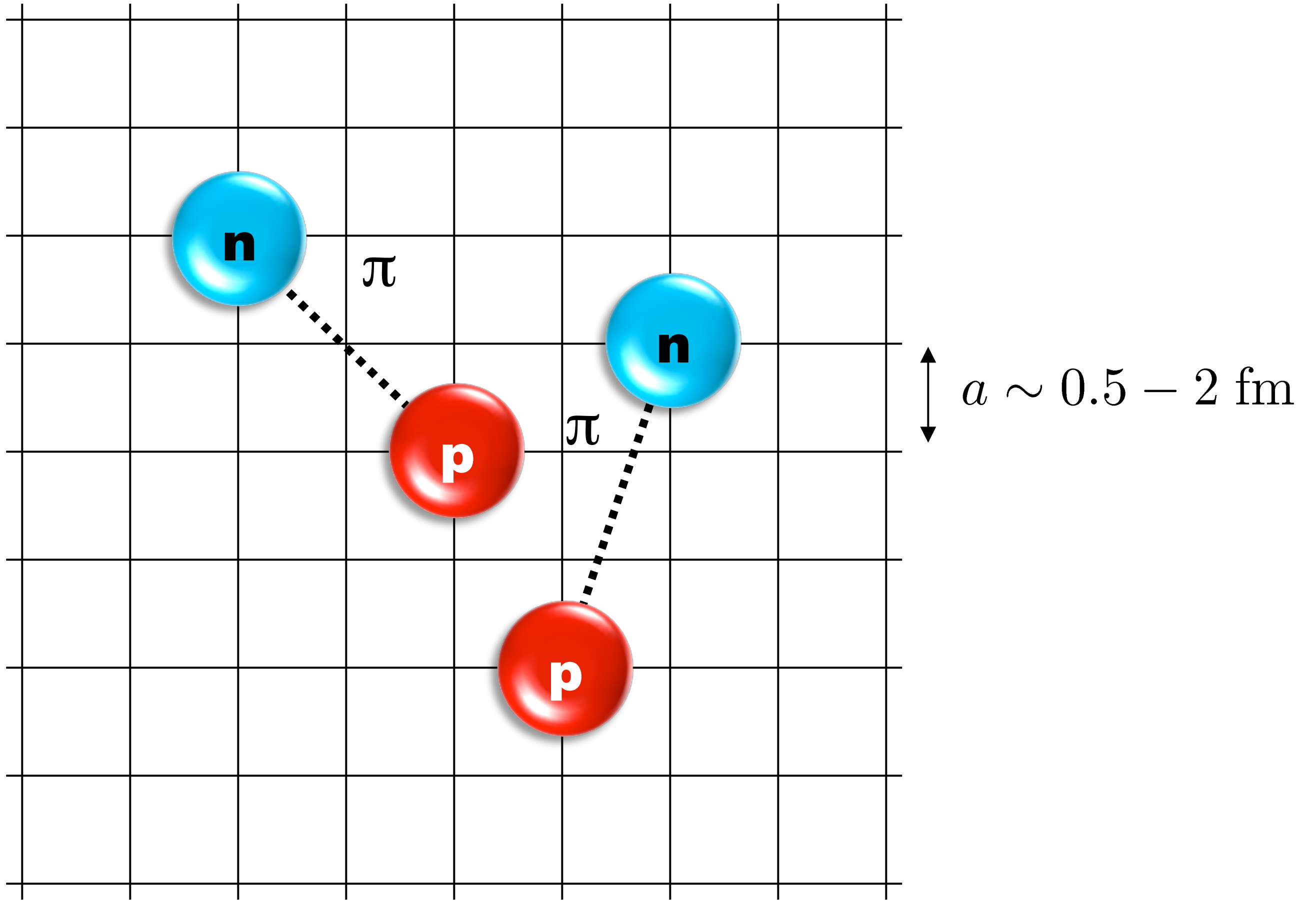
T. D. Morris, J. Simonis, S. R. Stroberg, C. Stumpf, G. Hagen, J. D. Holt, G. R. Jansen, T. Papenbrock, R. Roth, and A. Schwenk

Phys. Rev. Lett. **120**, 152503 – Published 12 April 2018

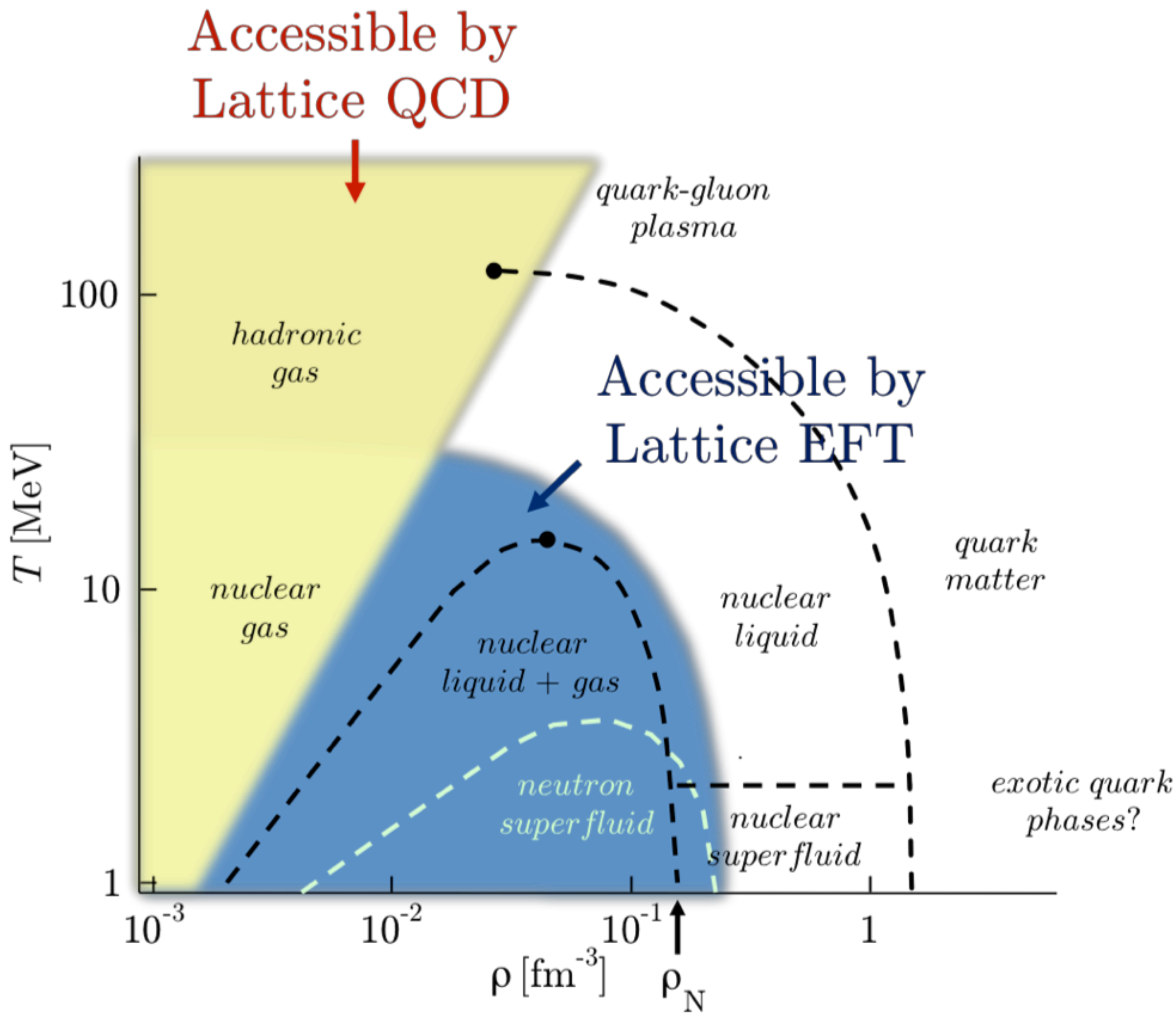




Lattice Effective Field Theory

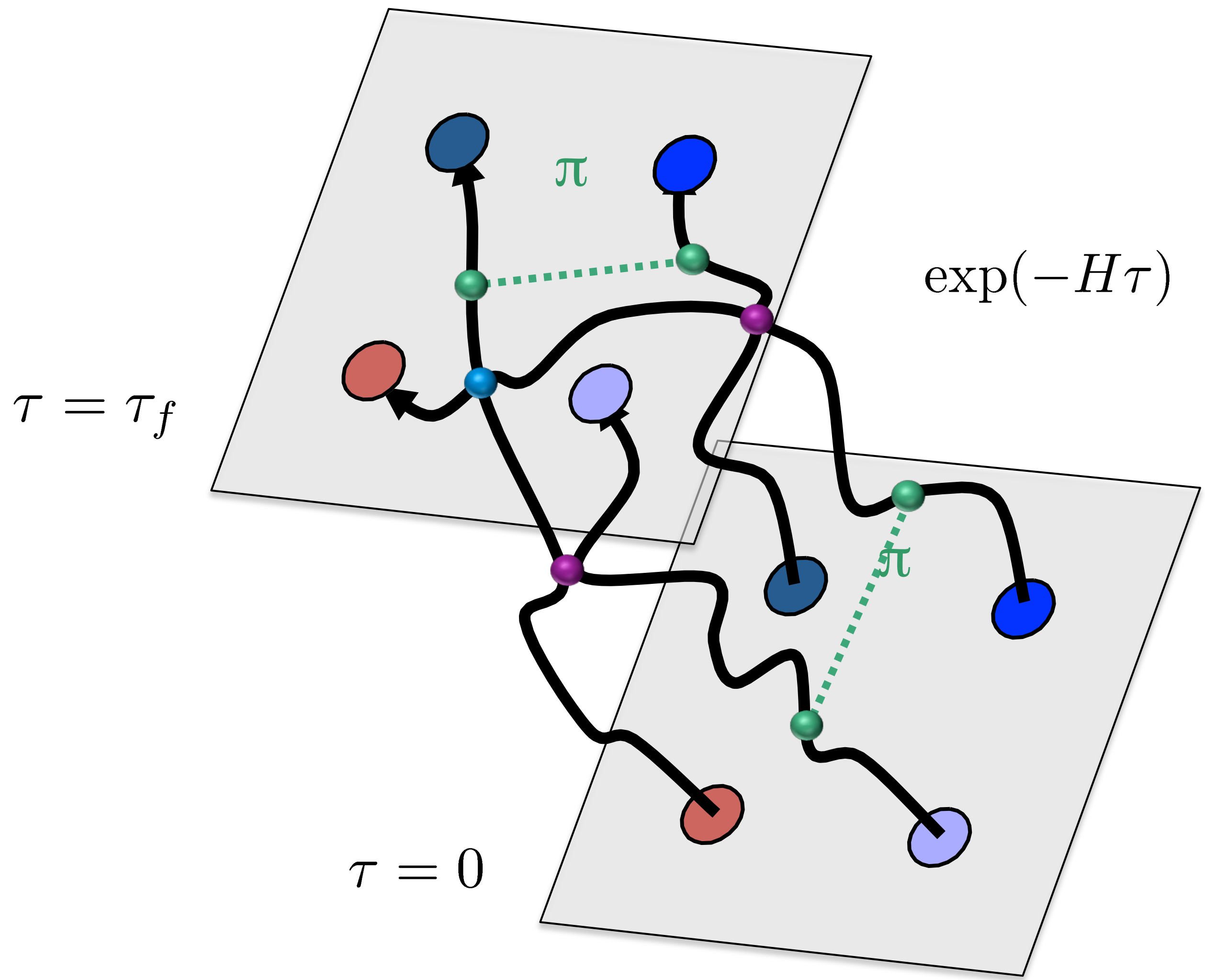


Review: D.L, Prog. Part. Nucl. Phys. 63 117-154 (2009)
TALENT summer school lectures: qmc2016.wordpress.ncsu.edu



Accessible by
Lattice QCD
quark-gluon
plasma
100
hadronic
gas
Accessible by
Lattice EFT
T [MeV]
10
nuclear
gas
nuclear
liquid + gas
nuclear
liquid
quark
matter
neutron
superfluid
nuclear
superfluid
exotic quark
phases?
1
10^{-3}
10^{-2}
10^{-1}
1
ρ [fm^{-3}]
ρ_N

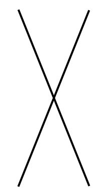
Euclidean time projection



Auxiliary field method

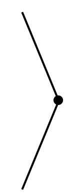
We can write exponentials of the interaction using a Gaussian integral identity

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



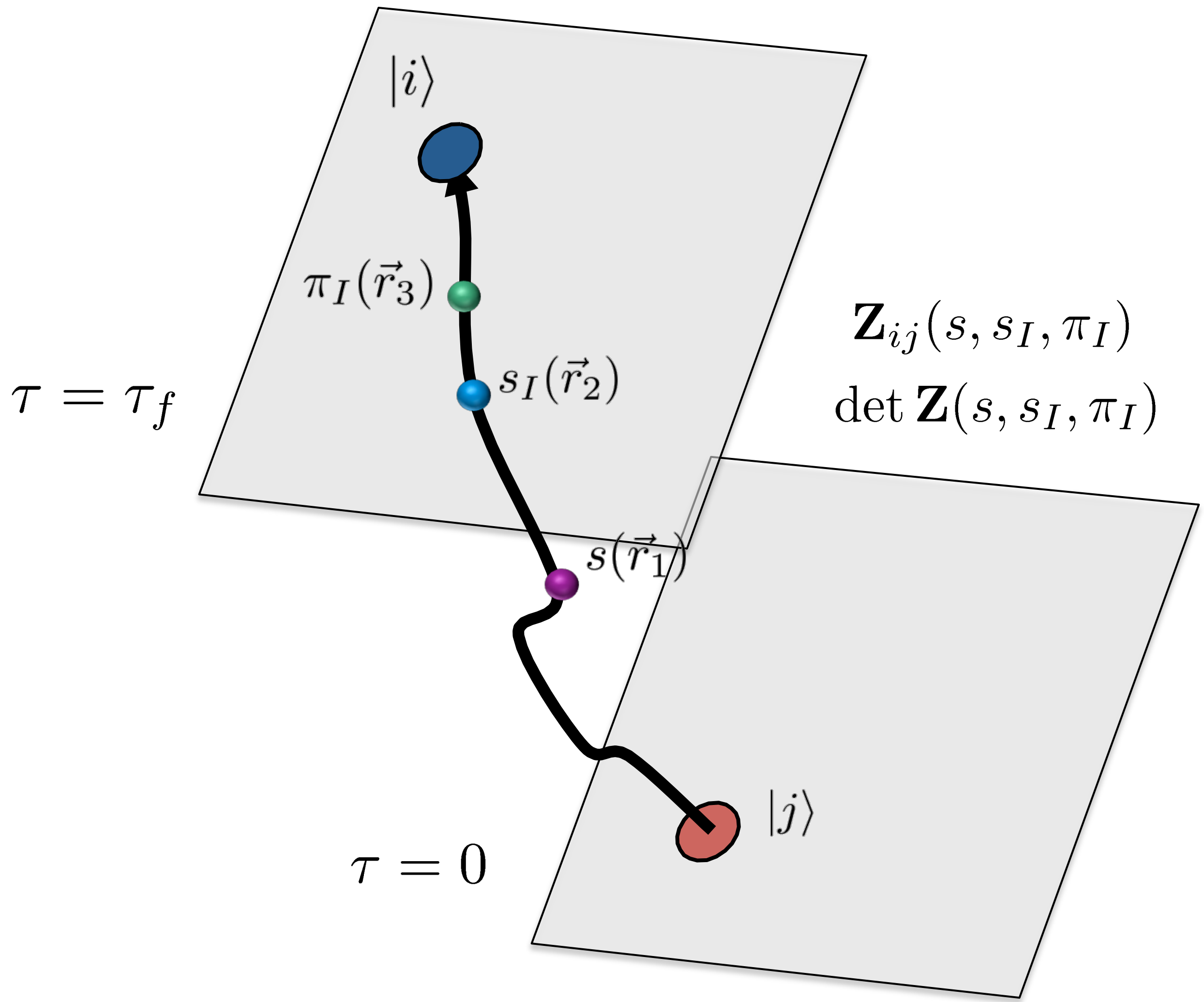
$(N^\dagger N)^2$

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



$sN^\dagger N$

We remove the interaction between nucleons and replace it with the interactions of each nucleon with a background field.



$|i\rangle$
$\pi_I(\vec{r}_3)$
$\mathbf{Z}_{ij}(s, s_I, \pi_I)$
$s_I(\vec{r}_2)$
$\tau = \tau_f$
$\det \mathbf{Z}(s, s_I, \pi_I)$
$s(\vec{r}_1)$
$|j\rangle$
$\tau = 0$

Seeing Structure with Pinholes

Consider the density operator for nucleon with spin i and isospin j

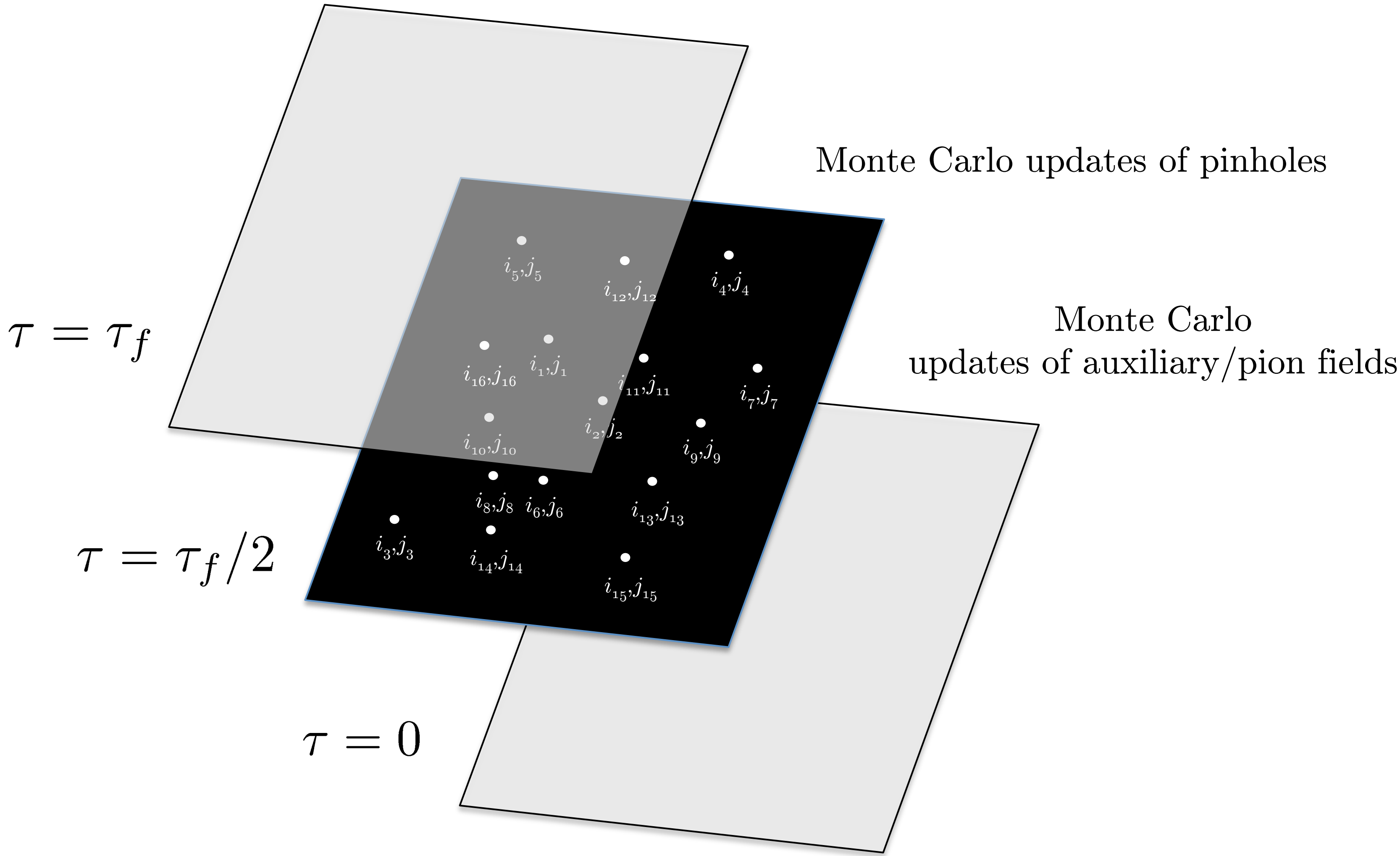
$$\rho_{i,j}(\mathbf{n}) = a^{\dagger}_{i,j}(\mathbf{n})a_{i,j}(\mathbf{n})$$

We construct the normal-ordered A-body density operator

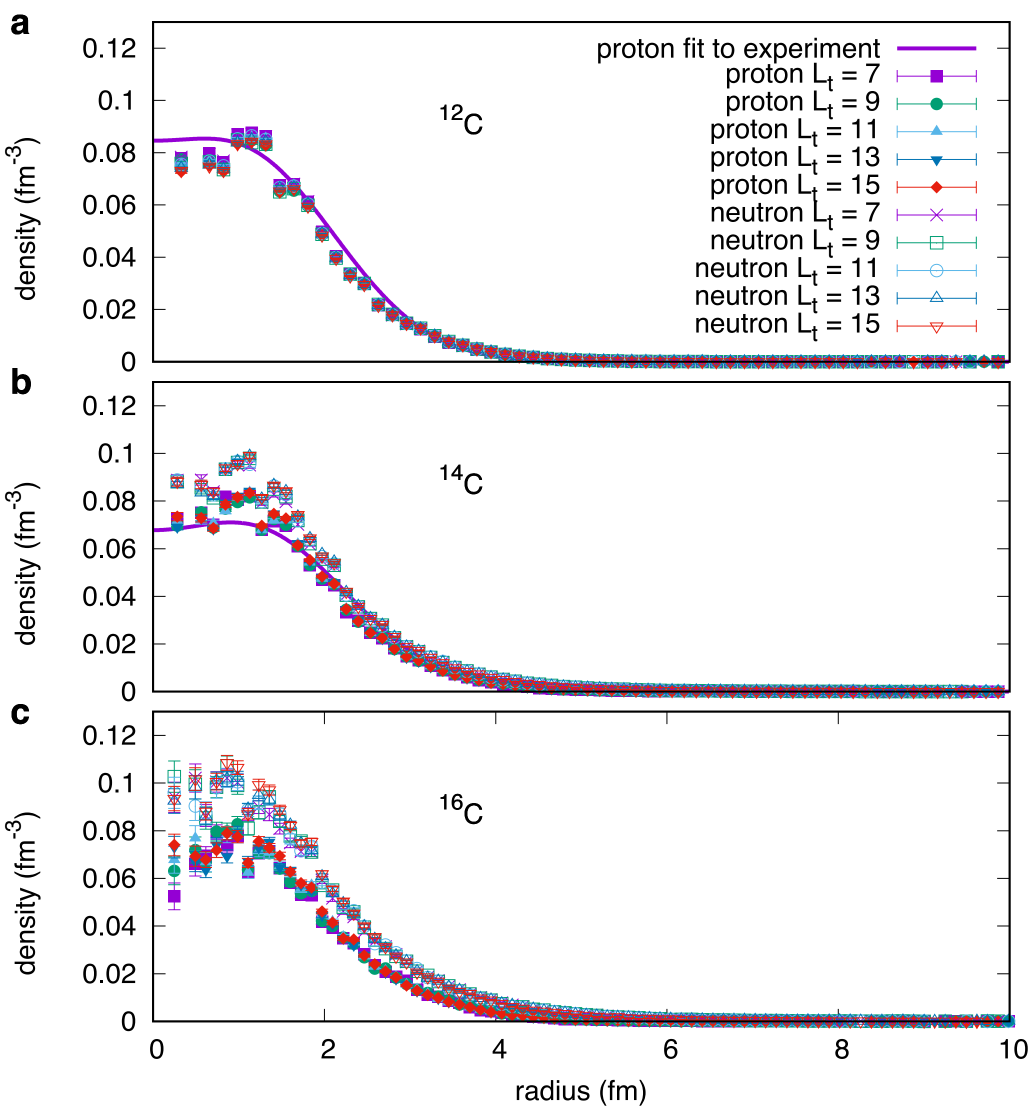
$$\rho_{i_1,j_1,\cdots i_A,j_A}(\mathbf{n}_1,\cdots\mathbf{n}_A) = :\rho_{i_1,j_1}(\mathbf{n}_1)\cdots\rho_{i_A,j_A}(\mathbf{n}_A):$$

In the simulations we do Monte Carlo sampling of the amplitude

$$A_{i_1,j_1,\cdots i_A,j_A}(\mathbf{n}_1,\cdots\mathbf{n}_A,t) = \langle\Psi_I|e^{-Ht/2}\rho_{i_1,j_1,\cdots i_A,j_A}(\mathbf{n}_1,\cdots\mathbf{n}_A)e^{-Ht/2}|\Psi_I\rangle$$



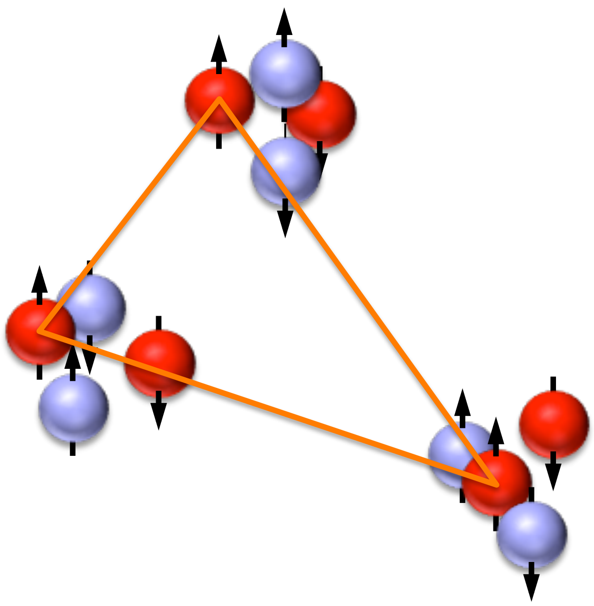
Elhatisari, Epelbaum, Krebs, Lähde, D.L., Li, Lu, Meißner, Rupak, PRL 119, 222505 (2017)



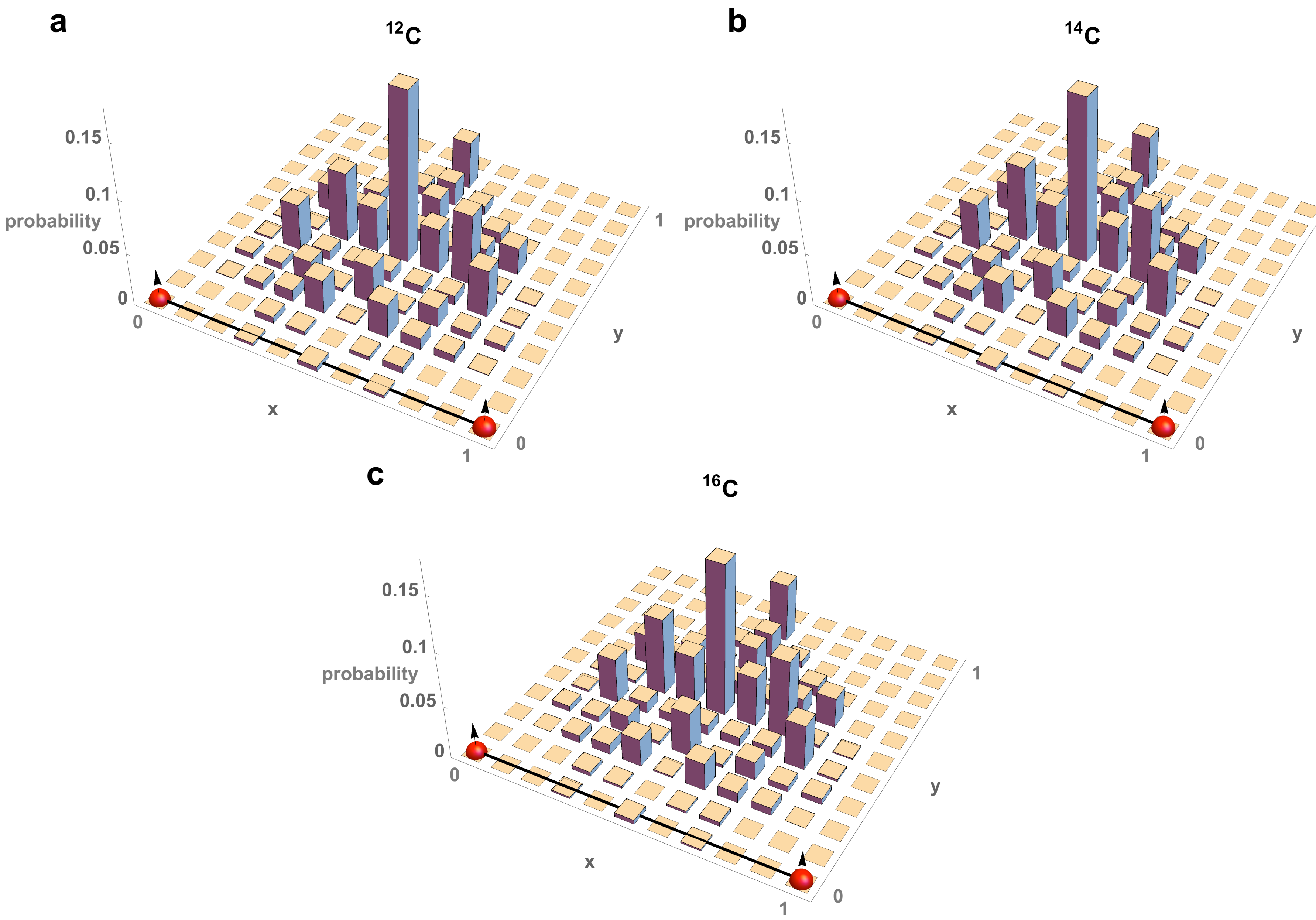
Elhatisari, Epelbaum, Krebs, Lähde, D.L., Li, Lu, Meißner, Rupak, PRL 119, 222505 (2017)

Model-independent measure of alpha cluster geometry

For the carbon isotopes, we can map out the alpha cluster geometry by computing the density correlations of the three spin-up protons. We compute these density correlations using the pinhole algorithm.



Elhatisari, Epelbaum, Krebs, Lähde, D.L., Li, Lu, Meißner, Rupak, PRL 119, 222505 (2017)



a
^{12}C
b
^{14}C
c
^{16}C
probability
0.15
0.1
0.05
0
x
y
0
1

A Tale of Two Interactions

Two LO interactions, A and B, have nearly identical nucleon-nucleon phase shifts and well as three- and four-nucleon bound states

Nucleus	A (LO)	B (LO)	A (LO + Coulomb)	B (LO + Coulomb)	Experiment
^{8}Be	$-58.61(14)$	$-59.73(6)$	$-56.51(14)$	$-57.29(7)$	-56.591
^{12}C	$-88.2(3)$	$-95.0(5)$	$-84.0(3)$	$-89.9(5)$	-92.162
^{16}O	$-117.5(6)$	$-135.4(7)$	$-110.5(6)$	$-126.0(7)$	-127.619
^{20}Ne	$-148(1)$	$-178(1)$	$-137(1)$	$-164(1)$	-160.645

Elhatisari, Li, Rokash, Alarcon, Du, Klein, Lu, Meißner, Epelbaum, Krebs, Lähde, D.L., Rupak, PRL 117, 132501 (2016)

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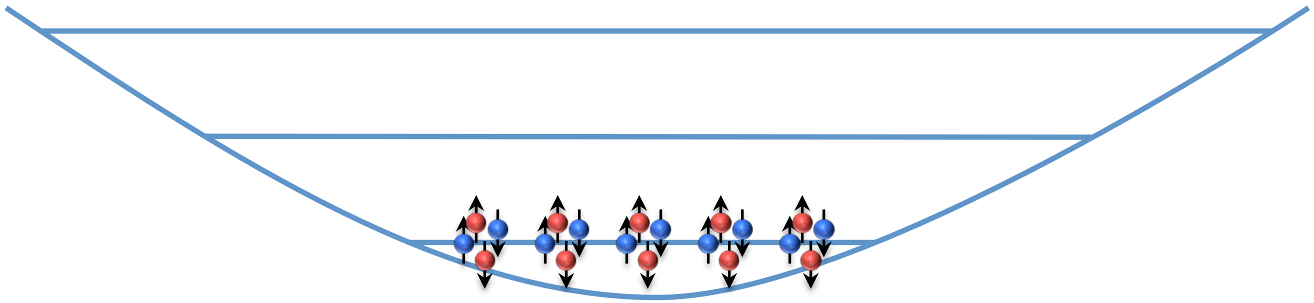
$$\frac{E_{^8\mathrm{Be}}}{E_{^4\mathrm{He}}} = 1.997(6)$$

$$\frac{E_{^{12}\mathrm{C}}}{E_{^4\mathrm{He}}} = 3.00(1)$$

$$\frac{E_{^{16}\mathrm{O}}}{E_{^4\mathrm{He}}} = 4.00(2)$$

$$\frac{E_{^{20}\mathrm{Ne}}}{E_{^4\mathrm{He}}} = 5.03(3)$$

Bose condensate of alpha particles!



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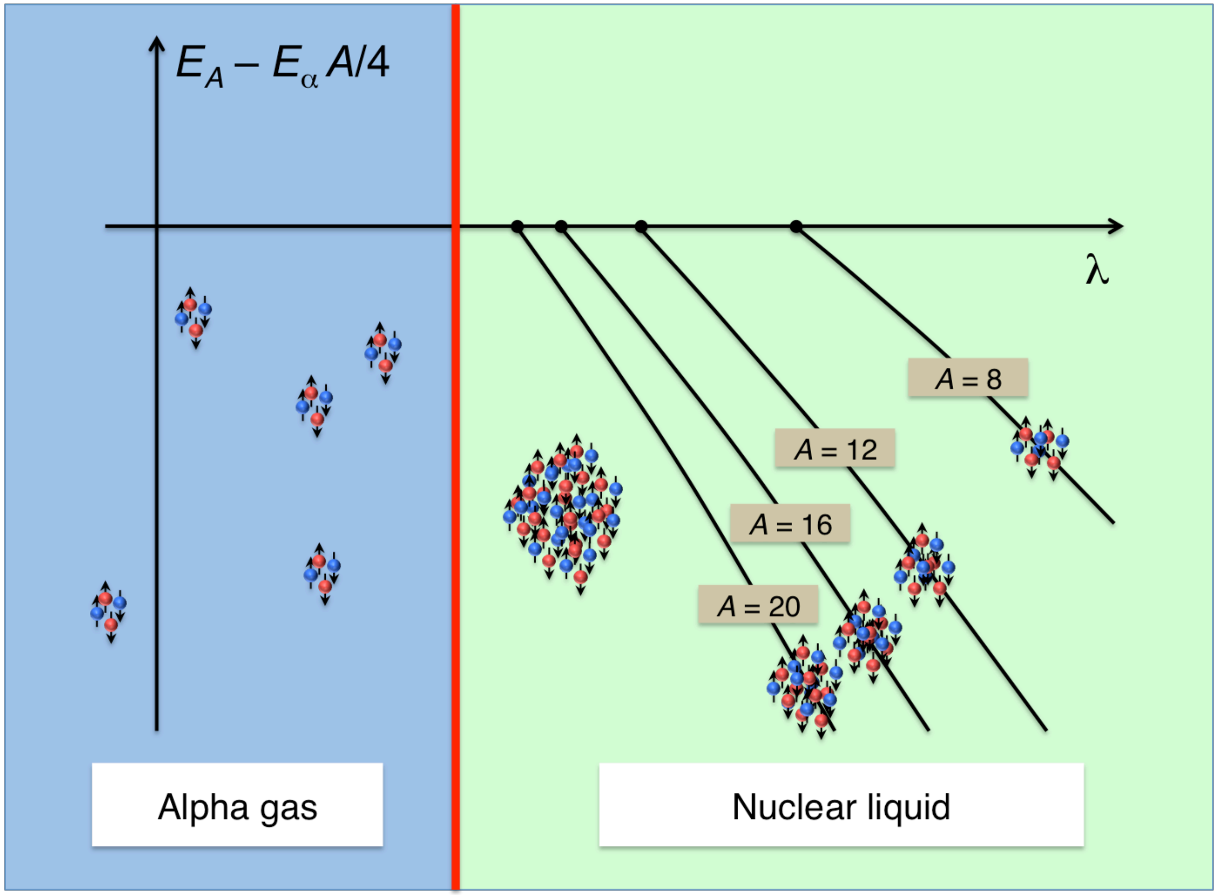
$$\frac{E_{^{16}\mathrm{O}}}{E_{^{4}\mathrm{He}}} = 4.00(2)$$

$$\frac{E_{^{20}\mathrm{Ne}}}{E_{^{4}\mathrm{He}}} = 5.03(3)$$

Control parameters: Sensitivity to interaction range and locality



Elhatisari, Li, Rokash, Alarcon, Du, Klein, Lu, Meißner, Epelbaum, Krebs, Lähde, D.L., Rupak, PRL 117, 132501 (2016)

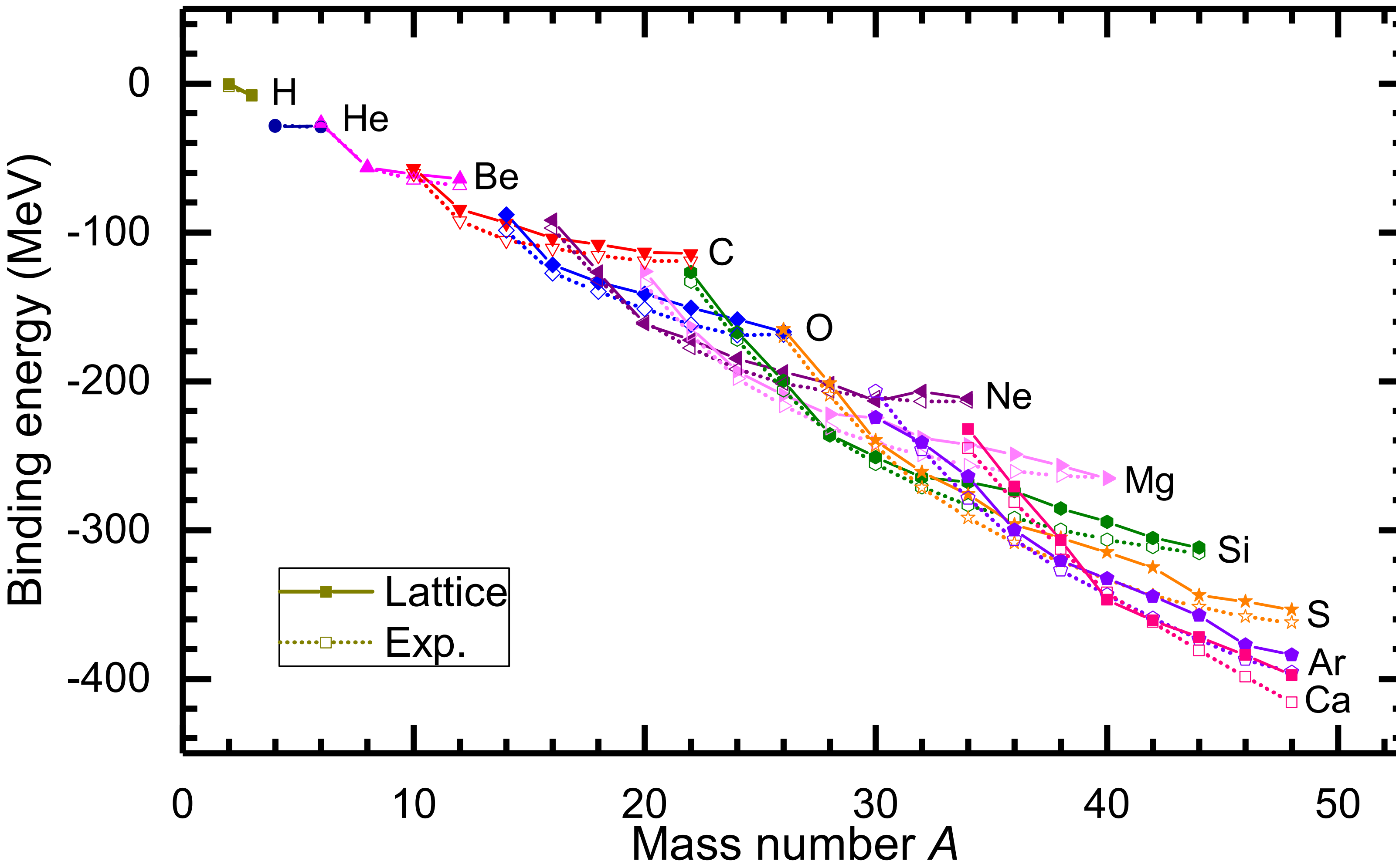
Essential Elements for Nuclear Binding

What is the minimal nuclear interaction that can reproduce the ground state properties of light nuclei, medium-mass nuclei, and neutron matter simultaneously with no more than a few percent error in the energies and charge radii?

We construct an interaction with 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. Relative strength of the local part of the interaction

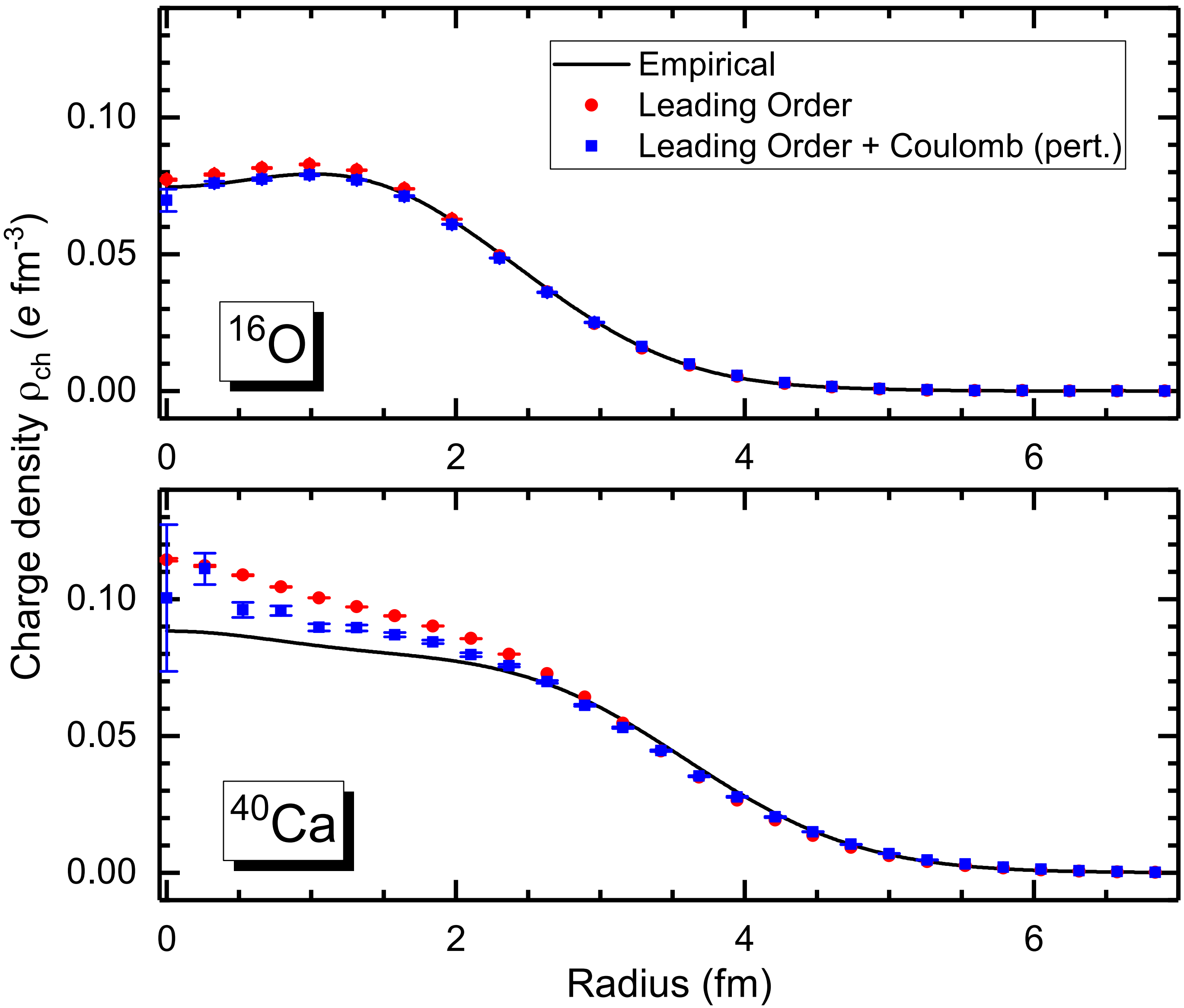
Lu, Li, Elhatisari, D.L., Epelbaum, Meißner, arXiv:1812.10928



Lu, Li, Elhatisari, D.L., Epelbaum, Meißner, arXiv:1812.10928

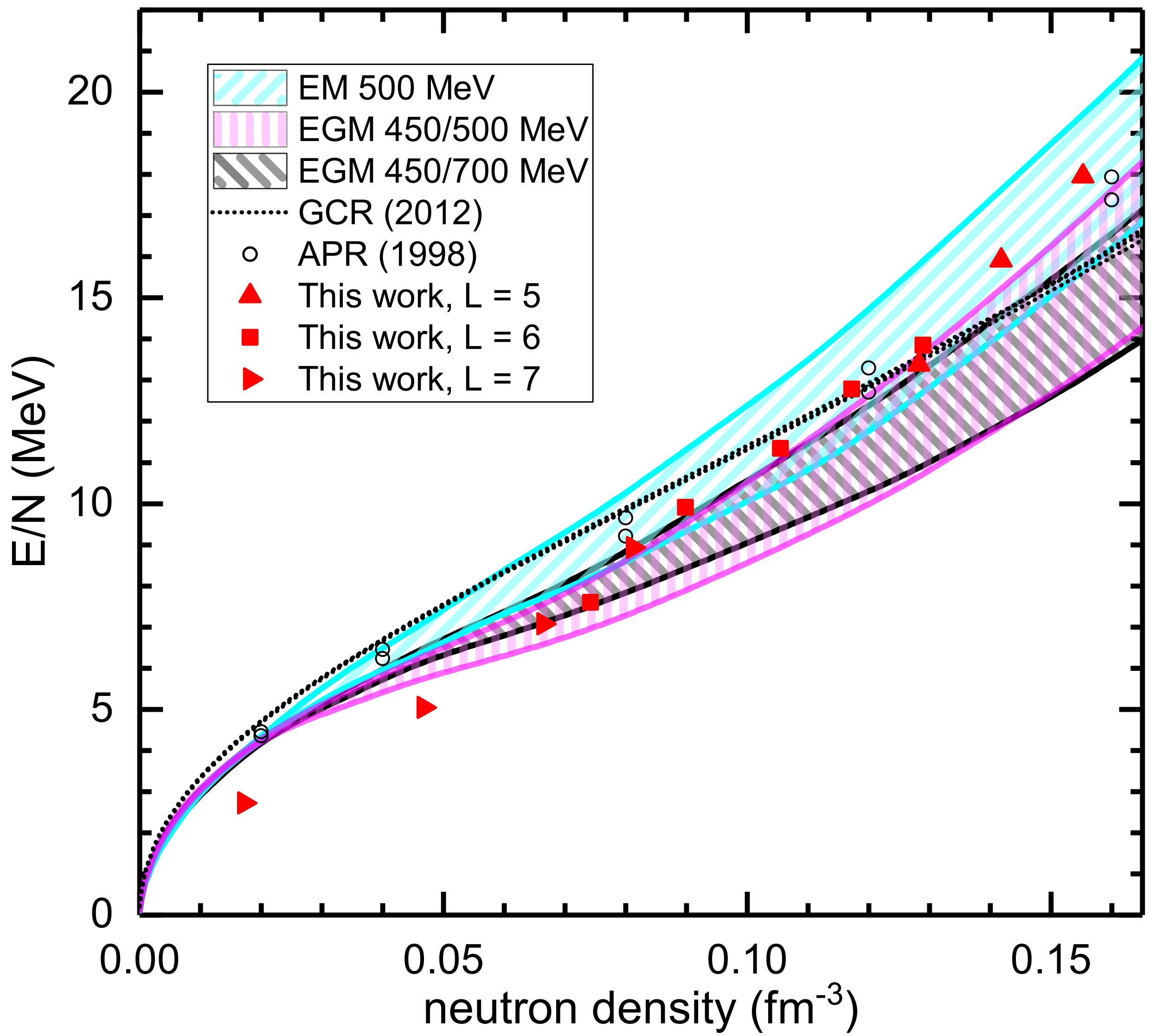
	B	Exp.	R_{ch}	Exp.
^{3}H	8.48(2)(0)	8.48	1.90(1)(1)	1.76
^{3}He	7.75(2)(0)	7.72	1.99(1)(1)	1.97
^{4}He	28.89(1)(1)	28.3	1.72(1)(3)	1.68
^{16}O	121.9(1)(3)	127.6	2.74(1)(1)	2.70
^{20}Ne	161.6(1)(1)	160.6	2.95(1)(1)	3.01
^{24}Mg	193.5(02)(17)	198.3	3.13(1)(2)	3.06
^{28}Si	235.8(04)(17)	236.5	3.26(1)(1)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

Lu, Li, Elhatisari, D.L., Epelbaum, Meißner, arXiv:1812.10928



Lu, Li, Elhatisari, D.L., Epelbaum, Meißner, arXiv:1812.10928

Pure neutron matter



Lu, Li, Elhatisari, D.L., Epelbaum, Meißner, arXiv:1812.10928

Nuclear thermodynamics using pinholes

In order to compute thermodynamic properties of finite nuclei, nuclear matter, and neutron matter, we need to compute the partition function

$$\mathrm{Tr}\exp(-\beta H)$$

We compute the quantum mechanical trace over A-nucleon states by summing over pinholes (position eigenstates) for the initial and final states

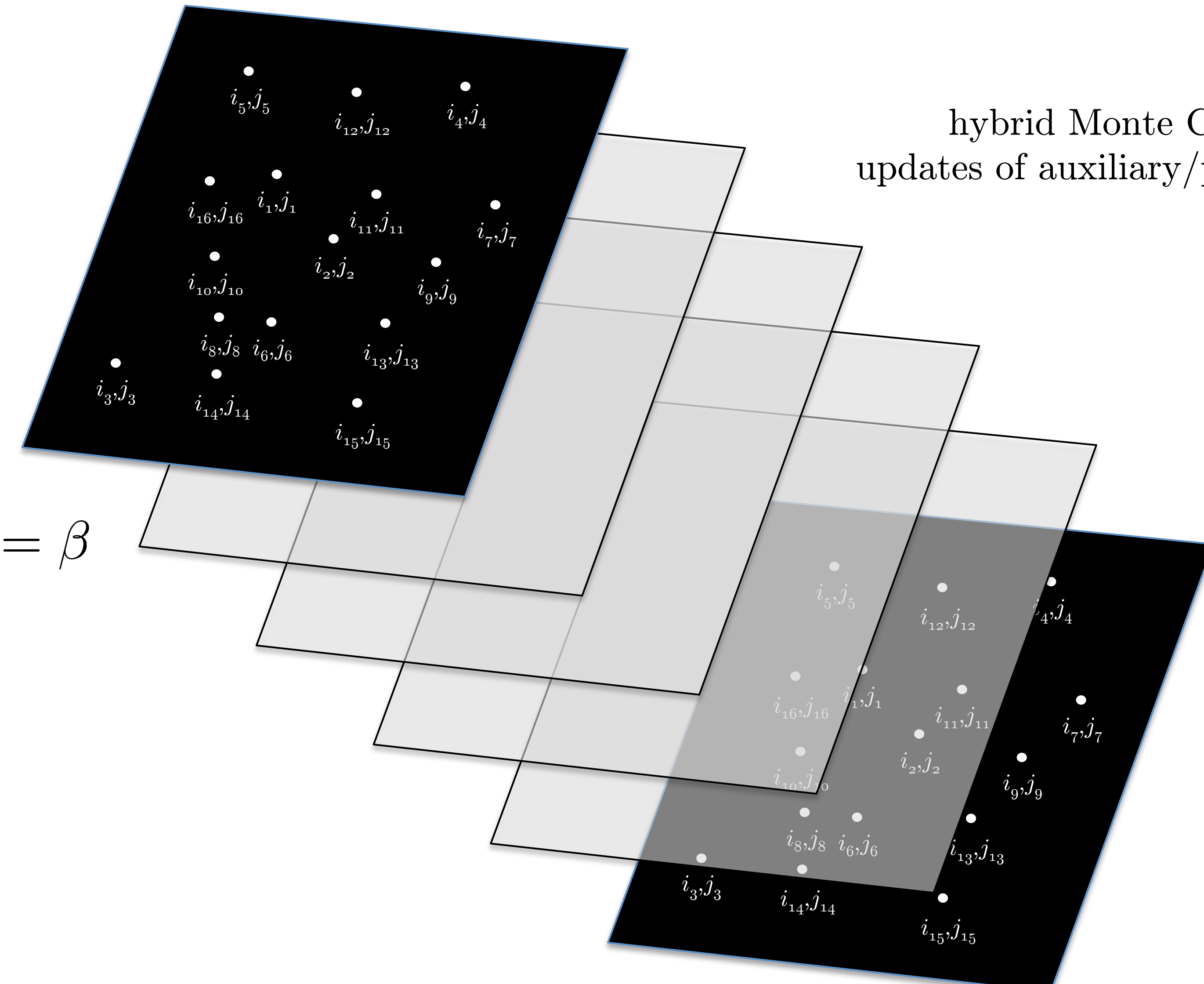
$$\mathrm{Tr}\, O = \frac{1}{A!} \sum_{i_1 \cdots i_A, j_1 \cdots j_A, \mathbf{n}_1 \cdots \mathbf{n}_A} \langle 0 | a_{i_A,j_A}(\mathbf{n}_A) \cdots a_{i_1,j_1}(\mathbf{n}_1)\, O\, a^{\dagger}_{i_1,j_1}(\mathbf{n}_1) \cdots a^{\dagger}_{i_A,j_A}(\mathbf{n}_A) | 0 \rangle$$

This can be used to calculate the partition function in the canonical ensemble.

Lu, *et al.*, work in progress

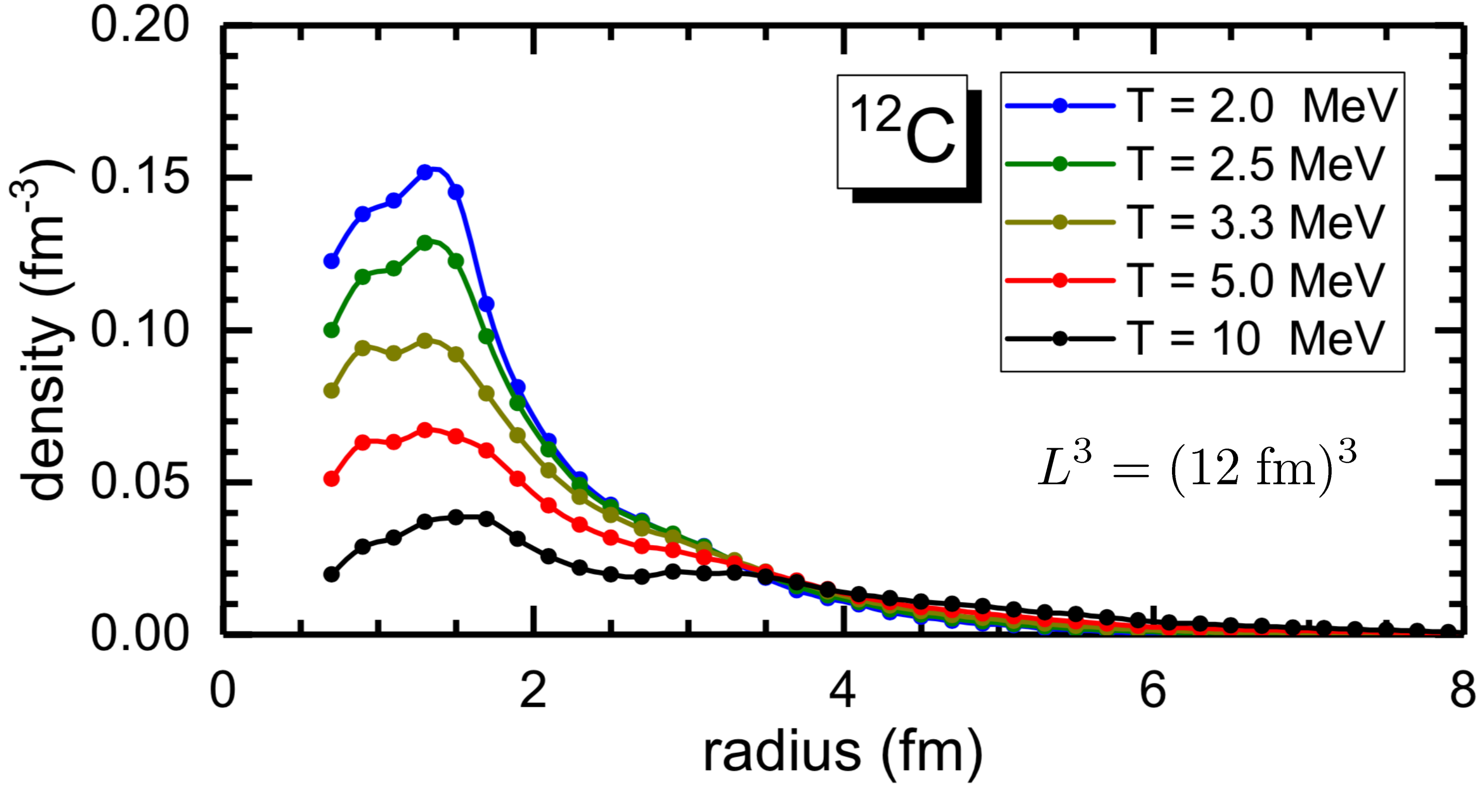
Metropolis updates of pinholes

hybrid Monte Carlo
updates of auxiliary/pion fields

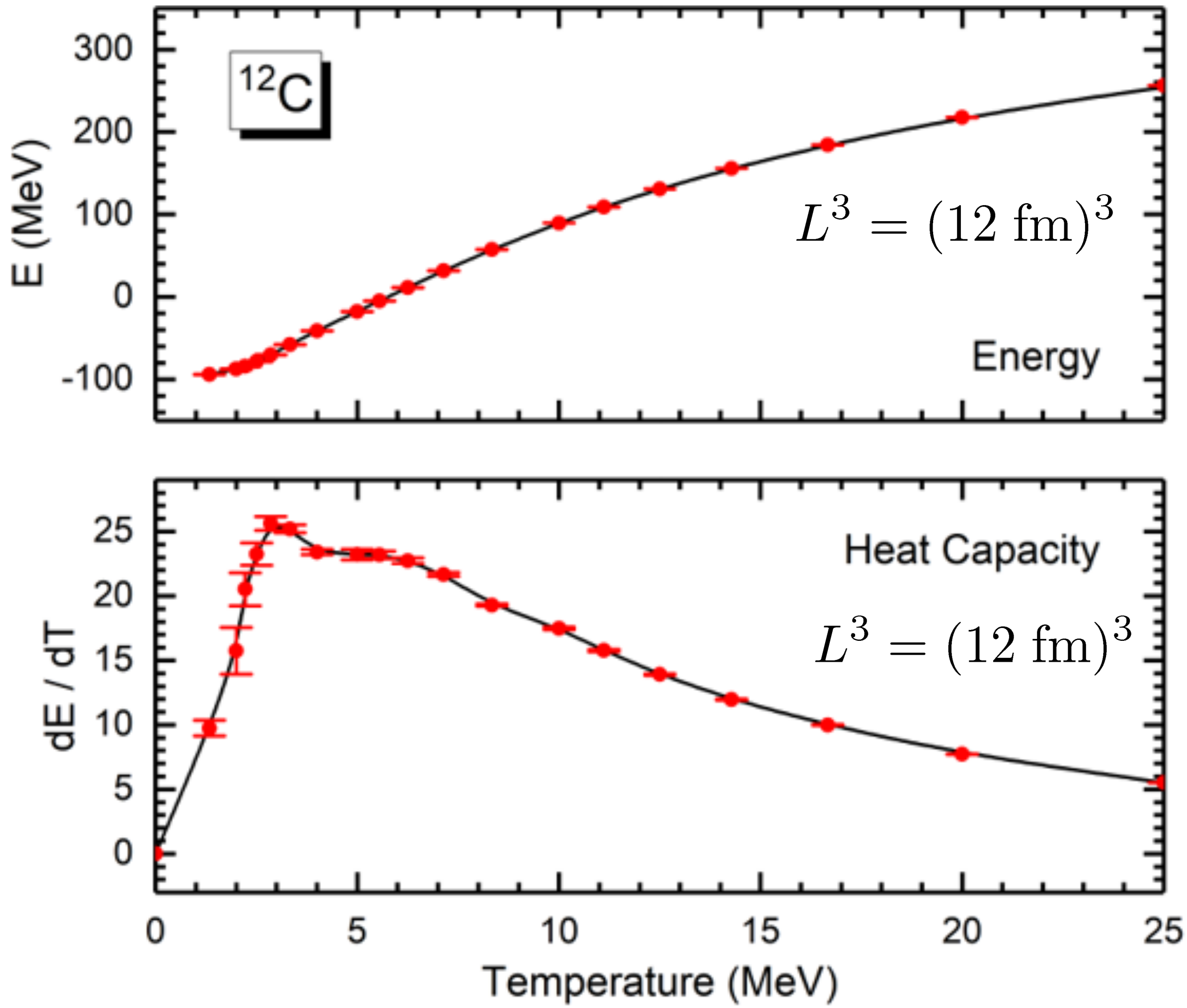


$\tau = \beta$

$\tau = 0$



Courtesy: Bing-Nan Lu



Courtesy: Bing-Nan Lu

Summary and Outlook

Significant progress being made by several different groups on calcualtions of light and medium-mass nuclei, and the connection between nuclear forces and nuclear structure.

In nuclear lattice EFT, we have new projects which are pushing the current frontiers in several different areas. In this talk, I have covered recent work on the essential elements for nuclear binding and the pinhole algorithm for structure and thermodynamics.