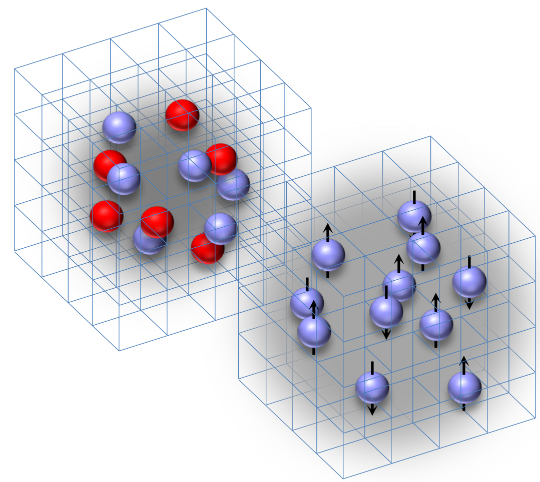
Nuclear Lattice Simulations

Dean Lee
Facility for Rare Isotope Beams
Michigan State University
Nuclear Lattice EFT Collaboration



CNRS-MSU International Research Laboratory
on Nuclear Physics and Nuclear Astrophysics
December 11-13, 2023

NUCLEI Nuclear Computational Low-Energy Initiative A SciDAC-5 Project
JÜLICH FORSCHUNGSZENTRUM
FRIB
MICHIGAN STATE UNIVERSITY
OAK RIDGE National Laboratory LEADERSHIP COMPUTING FACILITY
KISTI Korea Institute of Science and Technology Information www.kisti.re.kr

Outline

Lattice effective field theory

Pinhole algorithm

Emergent geometry and duality of ^{12}C

Wave function matching

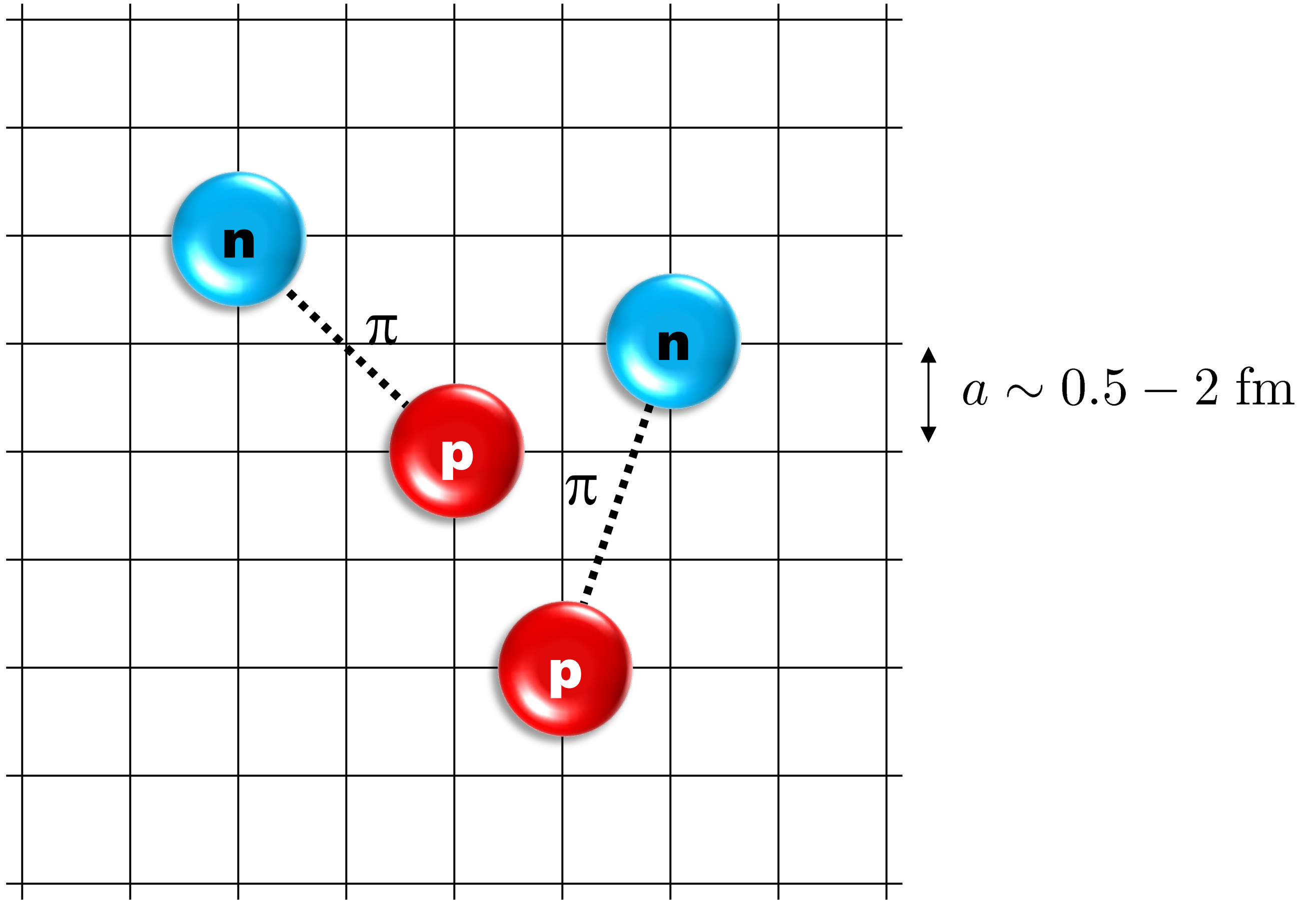
Ab initio thermodynamics

Structure factors in hot neutron matter

Superfluidity

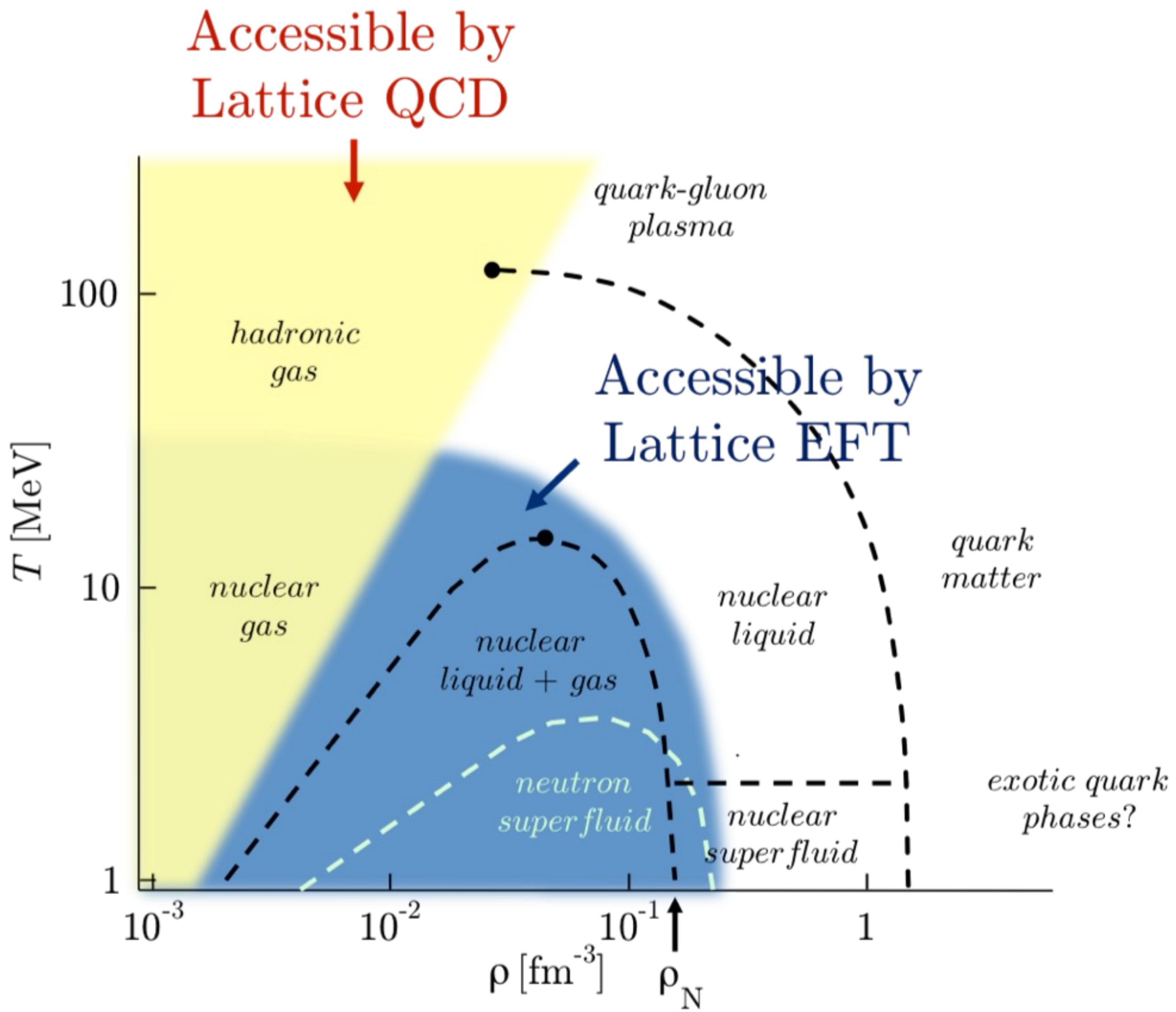
CNRS-MSU IRL Collaboration Opportunities

Lattice effective field theory



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

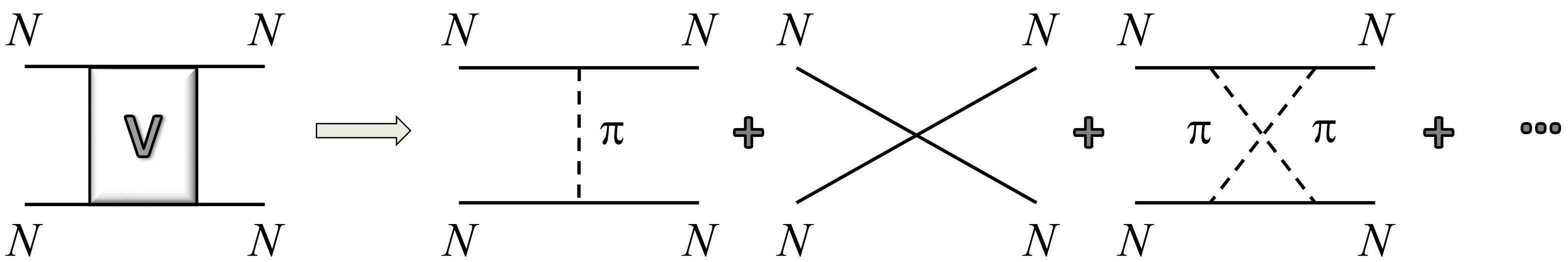
Lähde, Meißner, Nuclear Lattice Effective Field Theory (2019), Springer



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

Chiral effective field theory

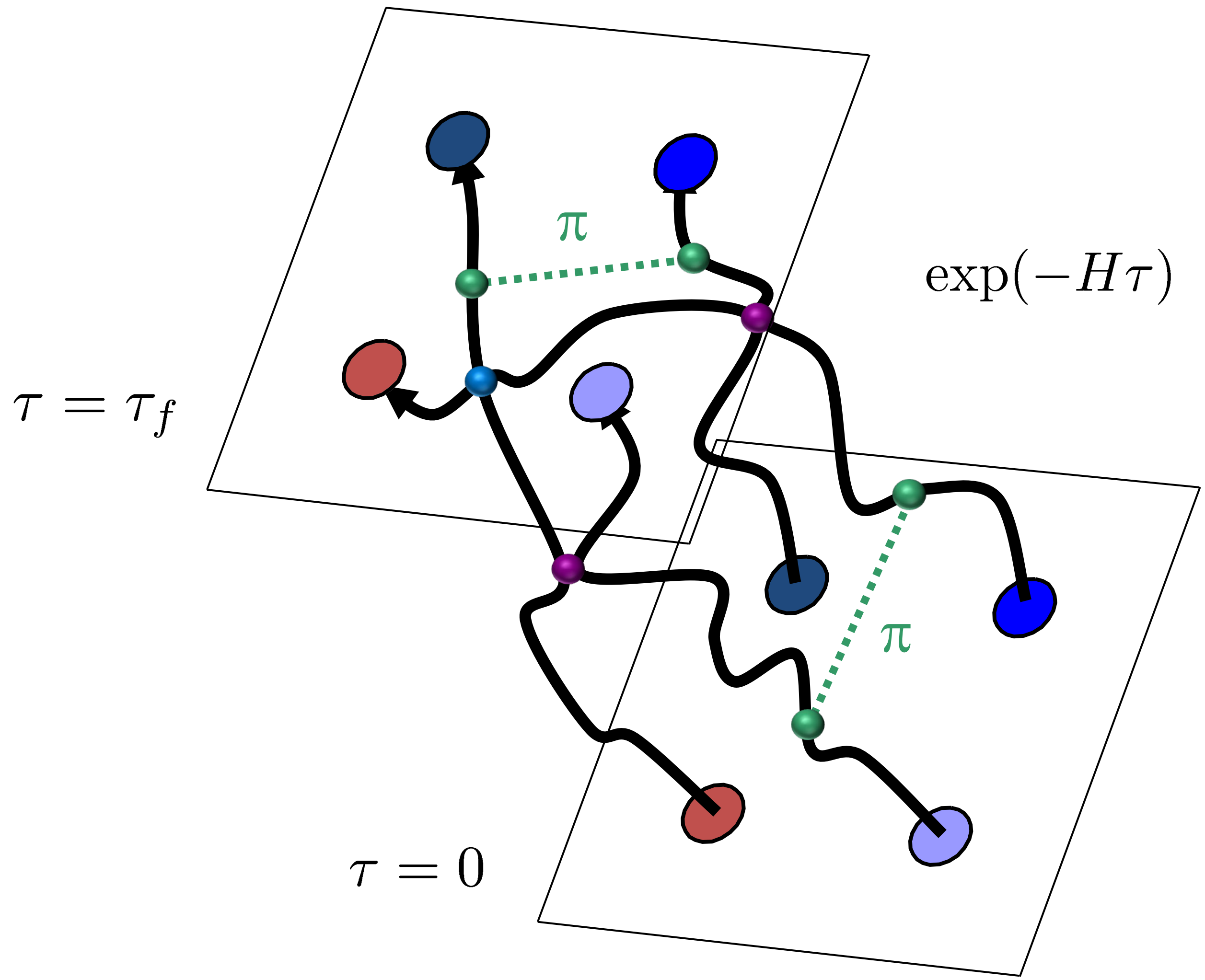
Construct the effective potential order by order



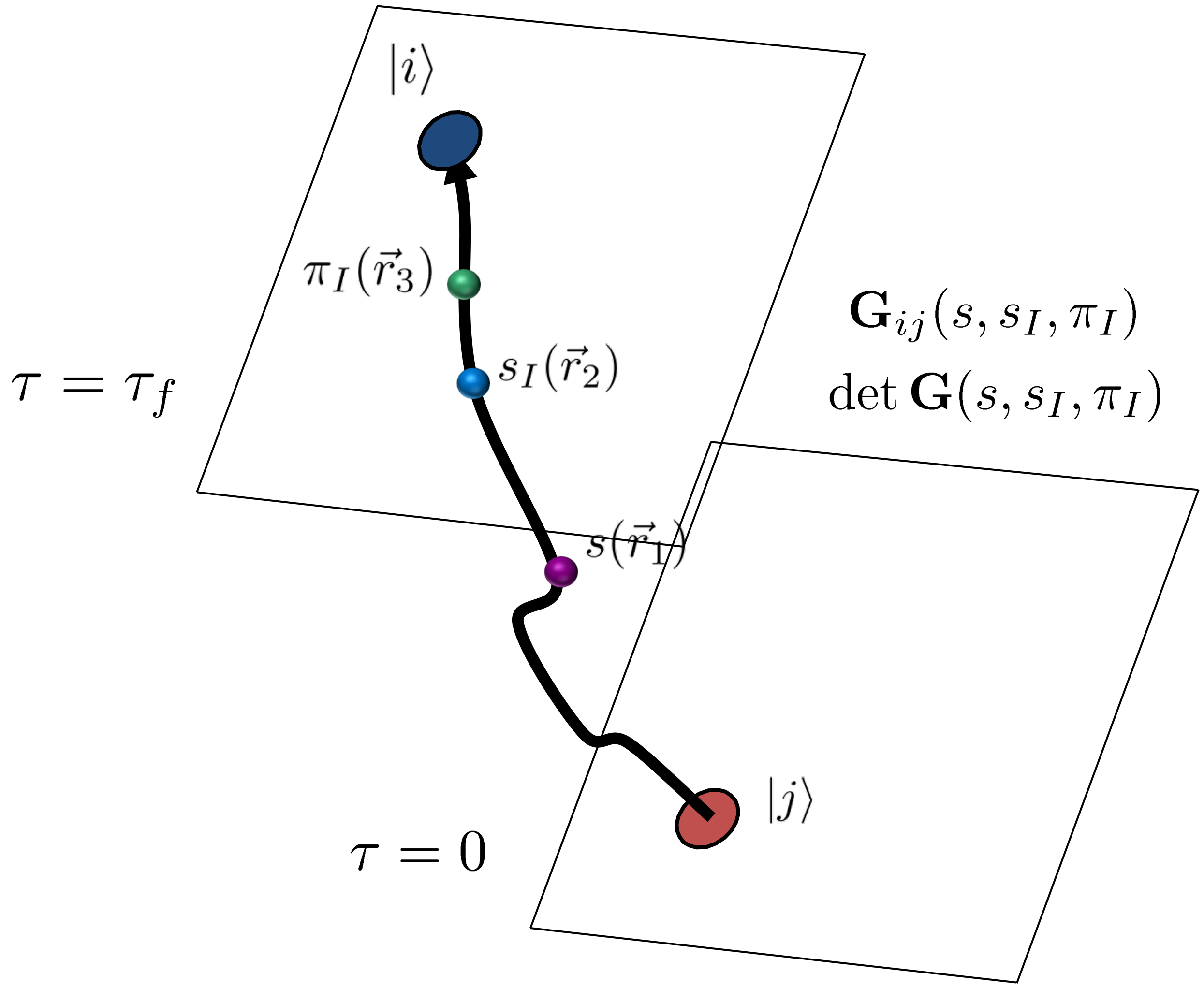
V^{OPEP} Contact interactions V^{TPEP}

Leading order (LO) Next-to-leading order (NLO)

Euclidean time projection



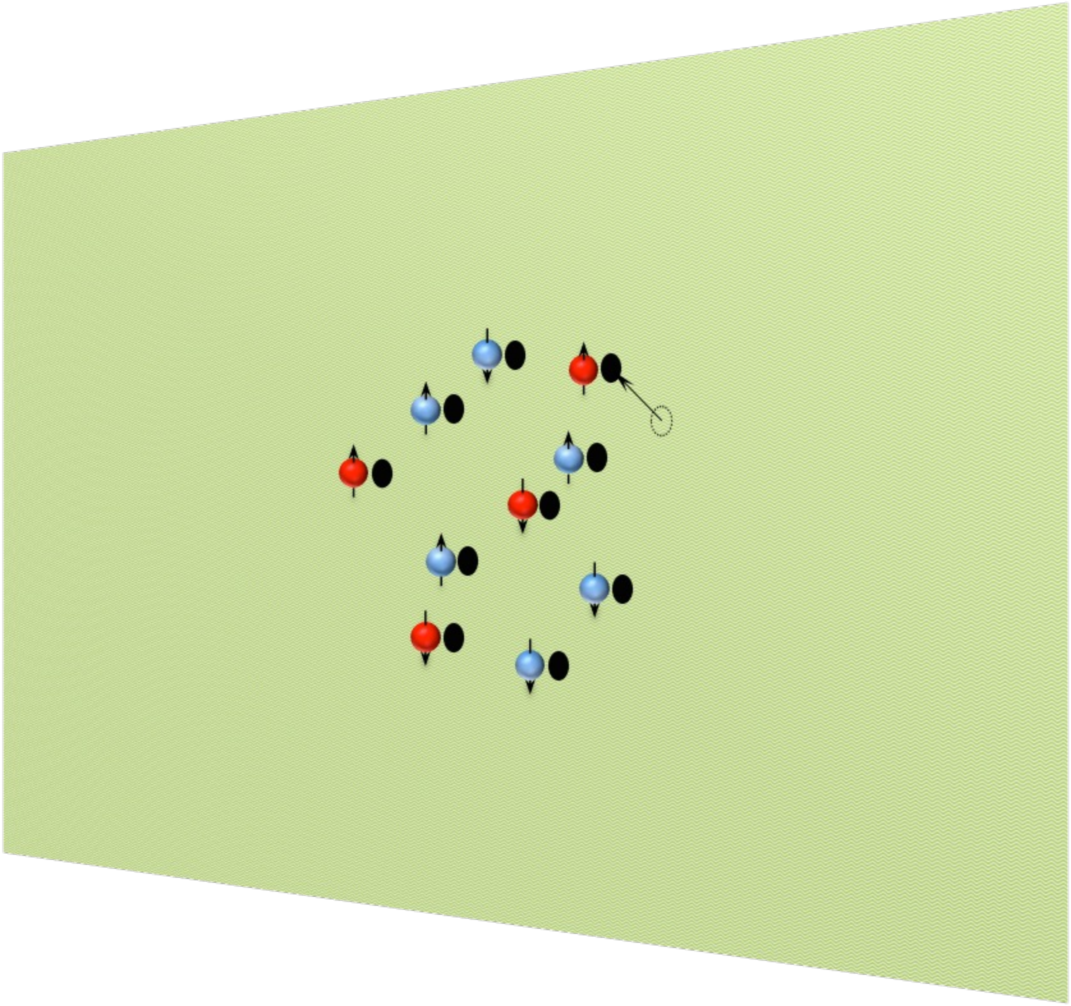
Auxiliary field method



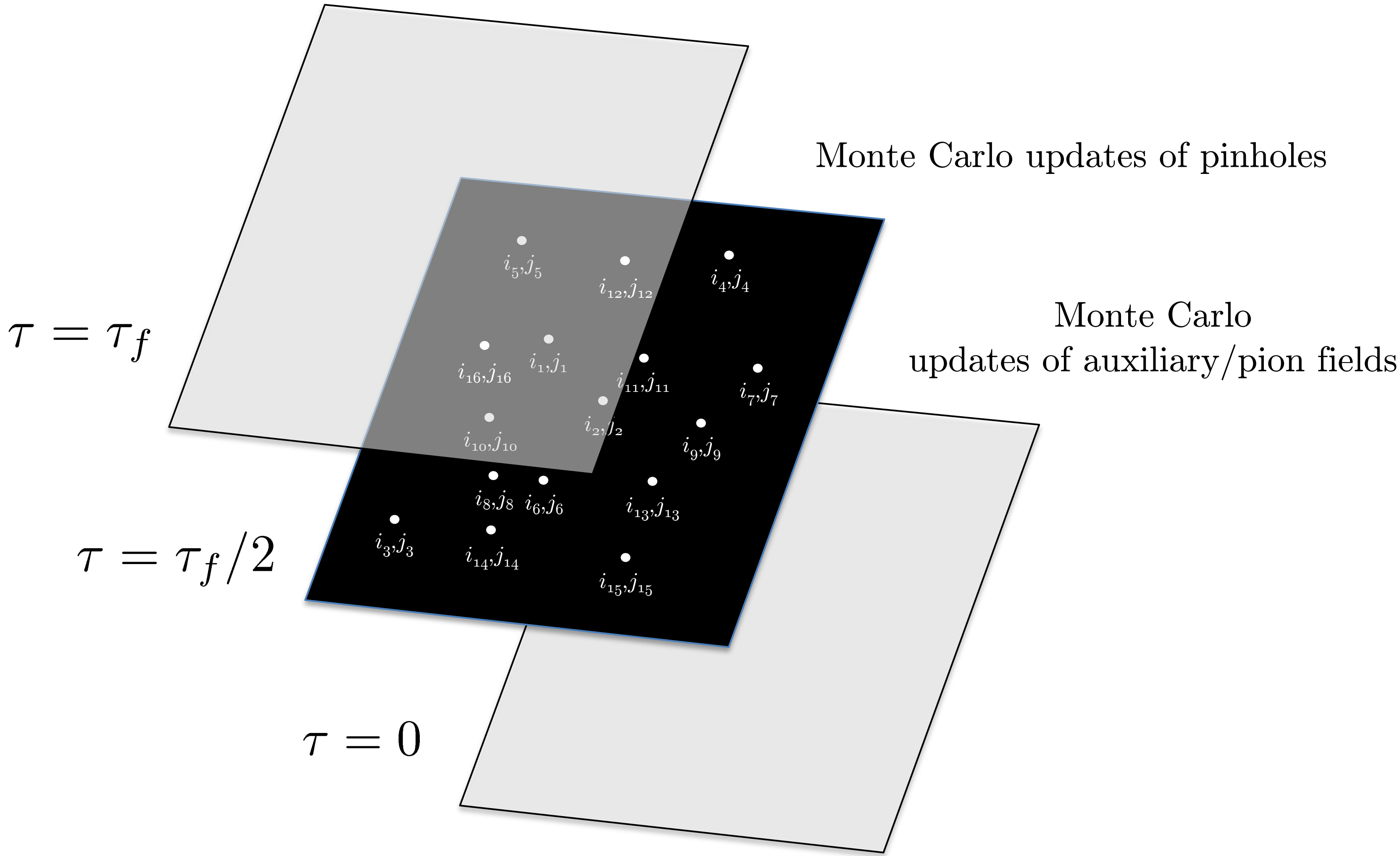
$\mathbf{G}_{ij}(s, s_I, \pi_I)$

$\det \mathbf{G}(s, s_I, \pi_I)$

Pinhole algorithm

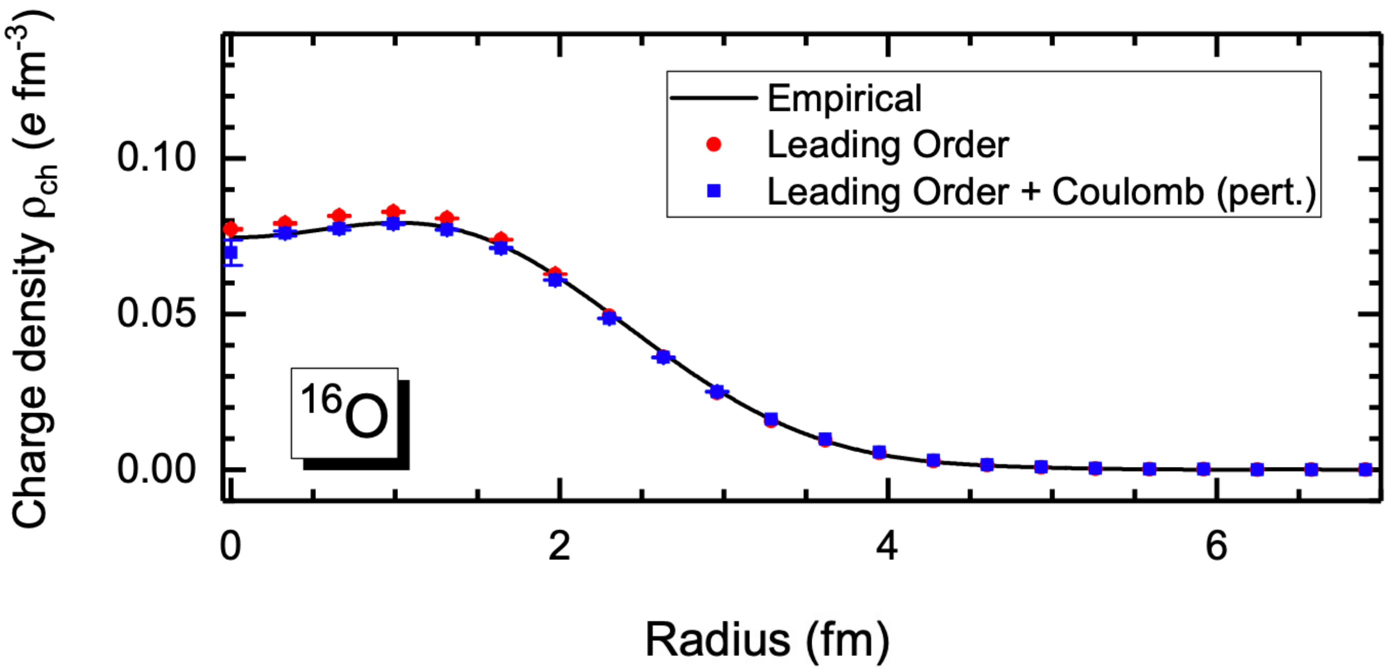


Elhatisari, Epelbaum, Krebs, Lähde, D.L., Li, Lu, Meißner, Rupak,
Phys. Rev. Lett. 119, 222505 (2017)



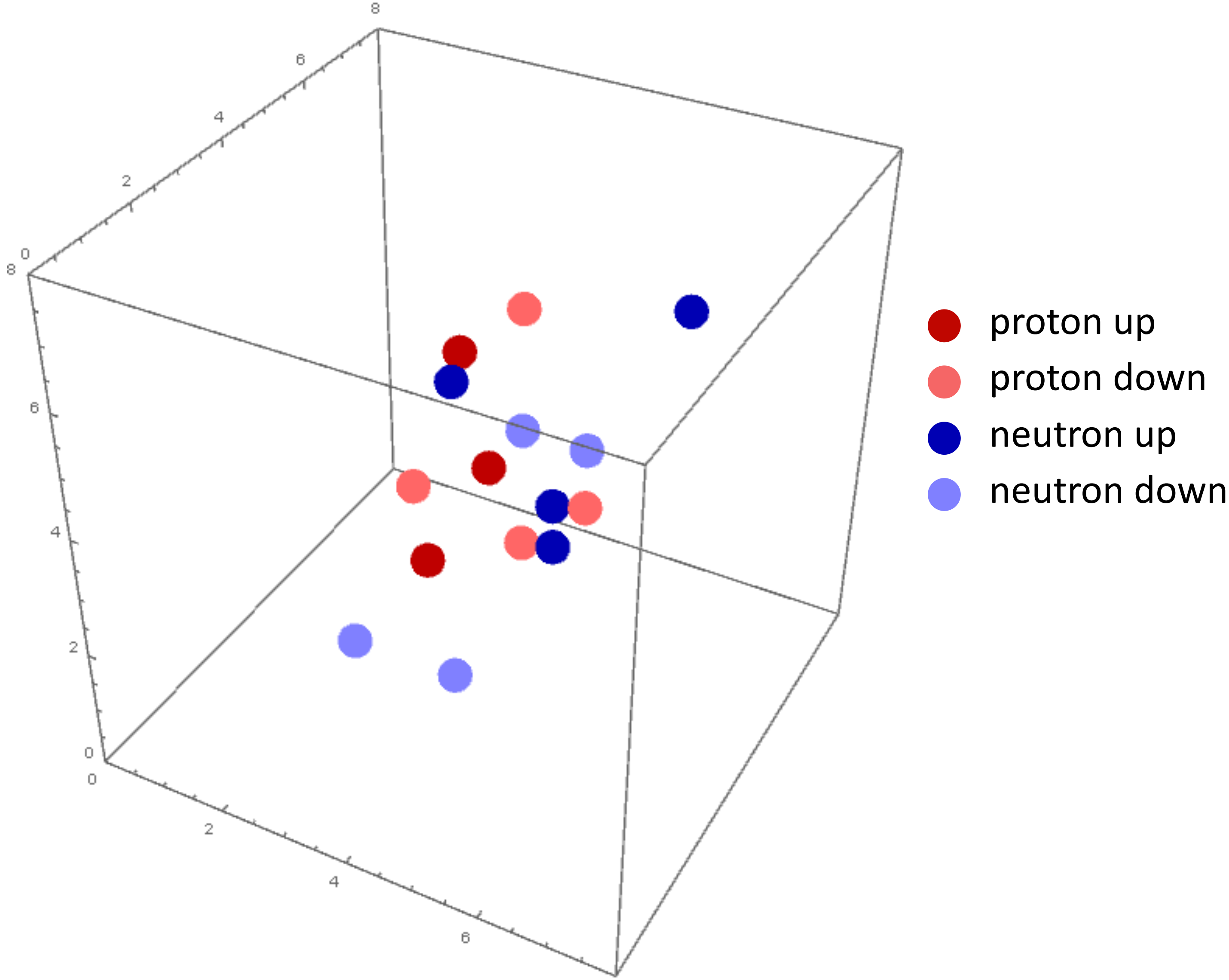
Elhatisari, Epelbaum, Krebs, Lähde, D.L., Li, Lu, Meißner, Rupak,
Phys. Rev. Lett. 119, 222505 (2017)

^{16}O

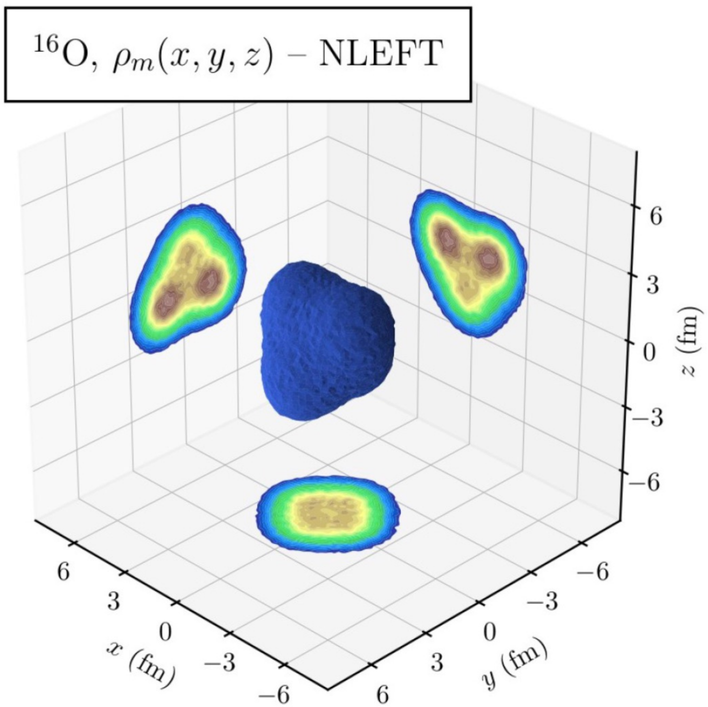


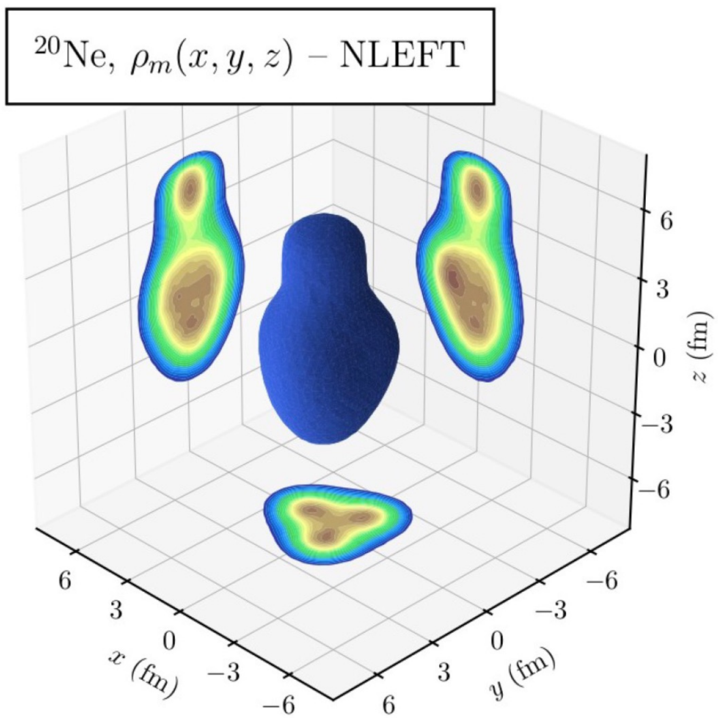
Lu, Li, Elhatisari, D.L., Epelbaum, Meißner, Phys. Lett. B 797, 134863 (2019)

^{16}O



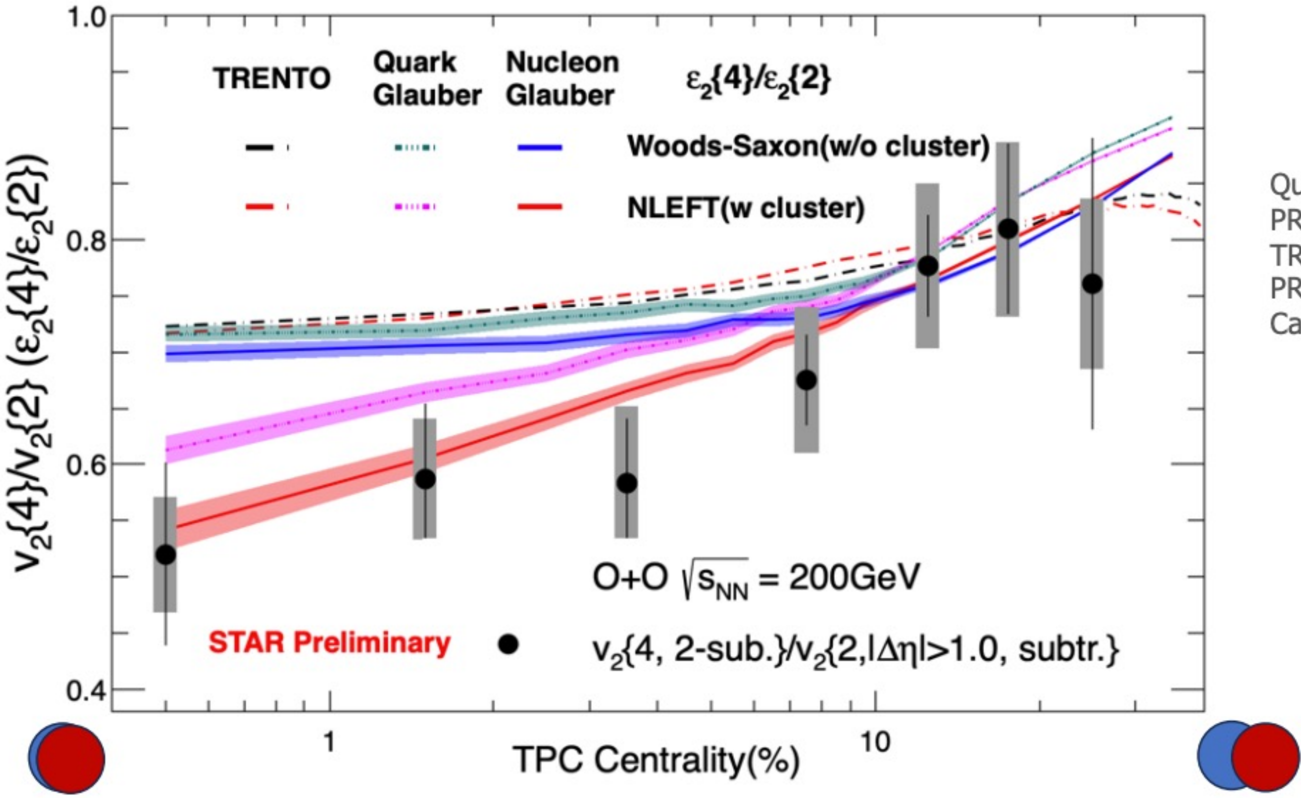
Summerfield, Lu, Plumberg, D.L., Noronha-Hostler, Timmins, Phys. Rev. C 104 L041901 (2021)





Work in progress

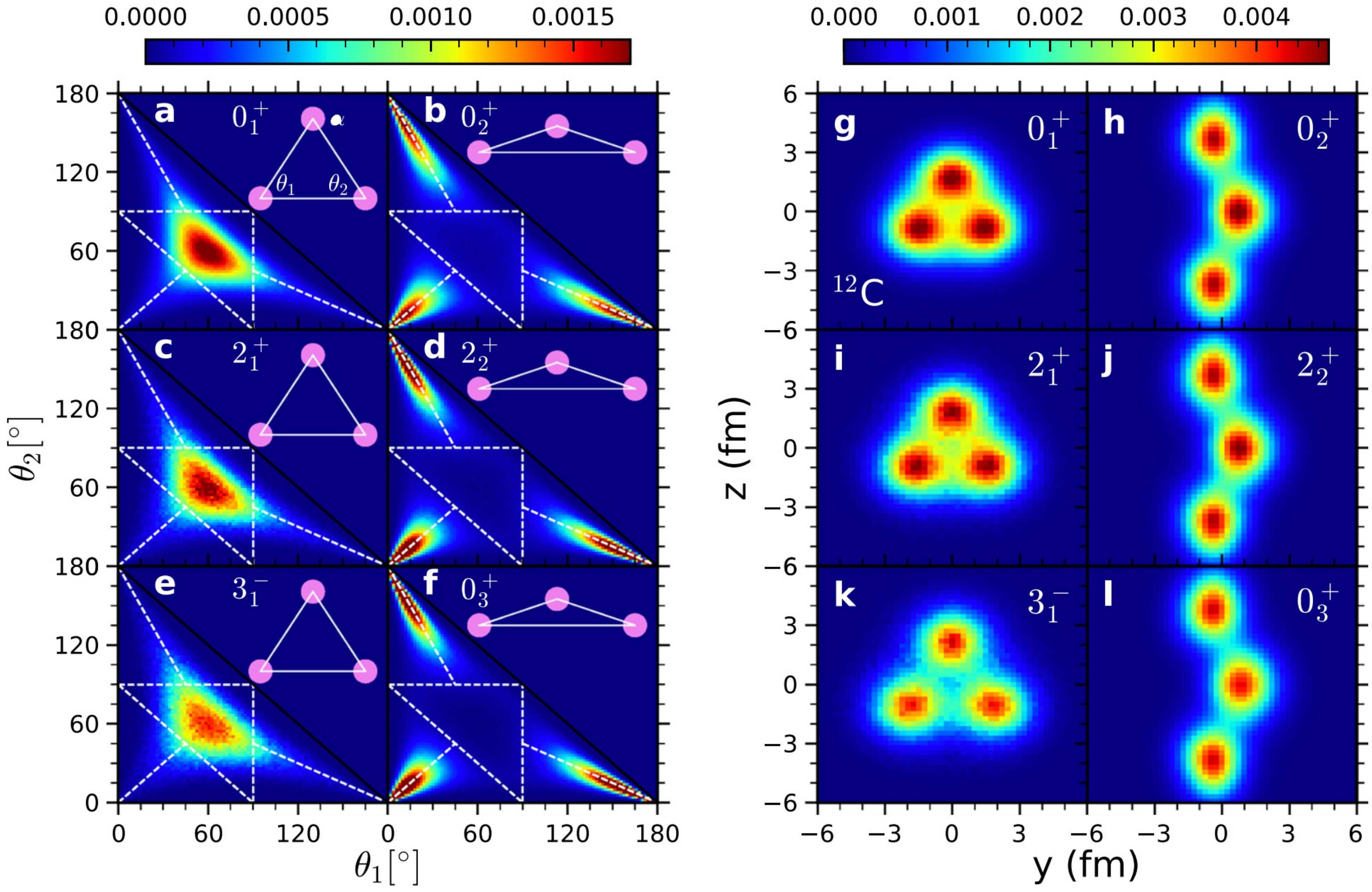
$v_2\{4\}/v_2\{2\}$: Flow fluctuation in central O+O



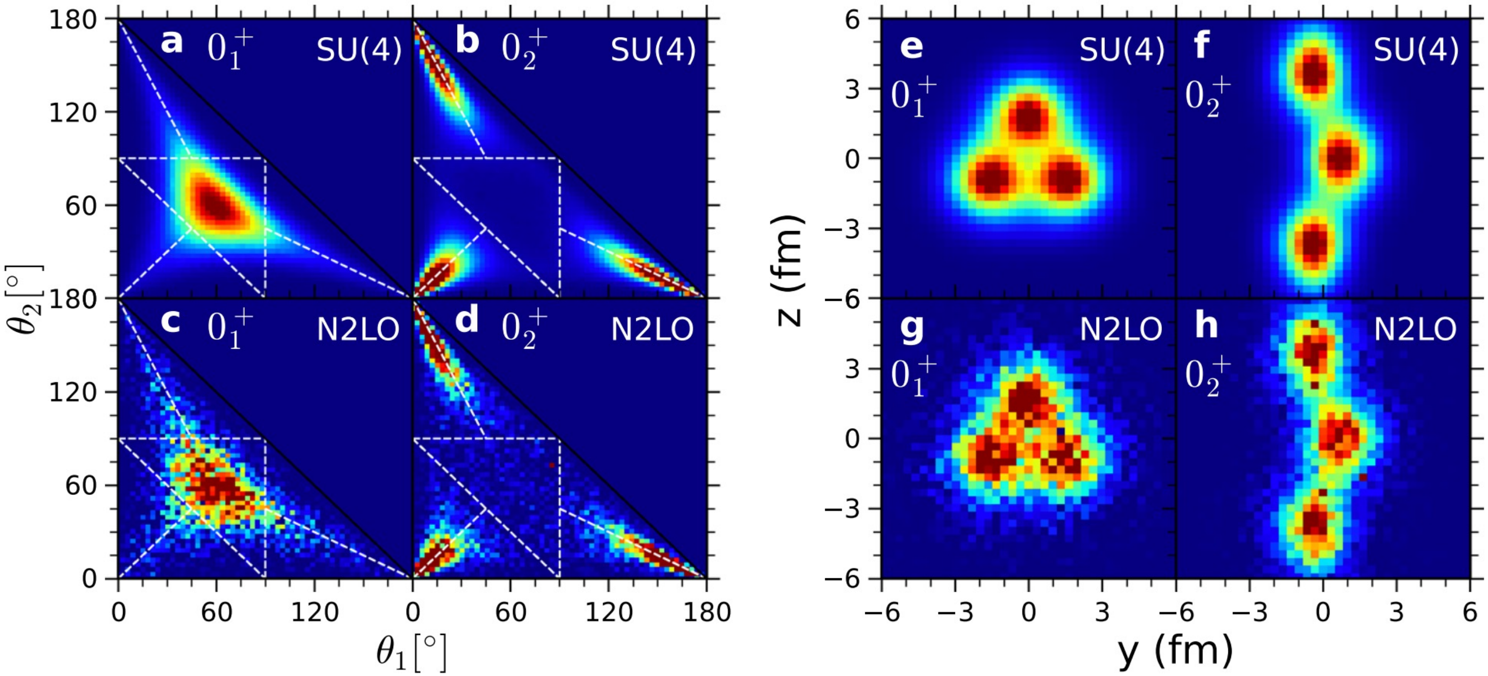
Quark Glauber:
PRC **94**, 024914 (2016)
TRENTO:
PRC.92.011901(2015)
Calculated by Giuliano

- ✓ Nucleon Glauber with NLEFT describes the $v_2\{4\}/v_2\{2\}$ better than quark Glauber
  Interplay between sub-nucleon fluctuation and many-nucleon correlation?
- ✓ Detailed hydro calculations can elucidate the role of $\boldsymbol{\alpha}$ cluster in light nuclei

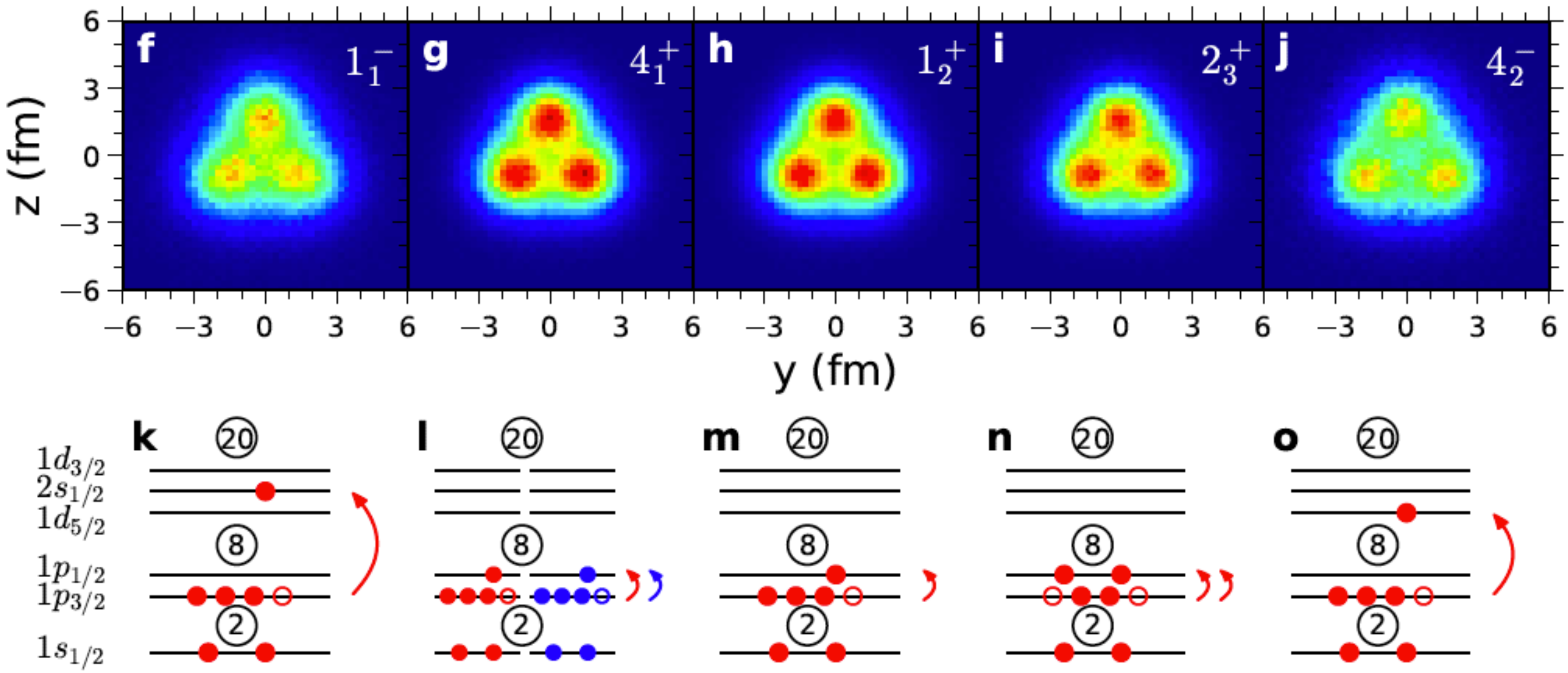
Emergent geometry and duality of ^{12}C



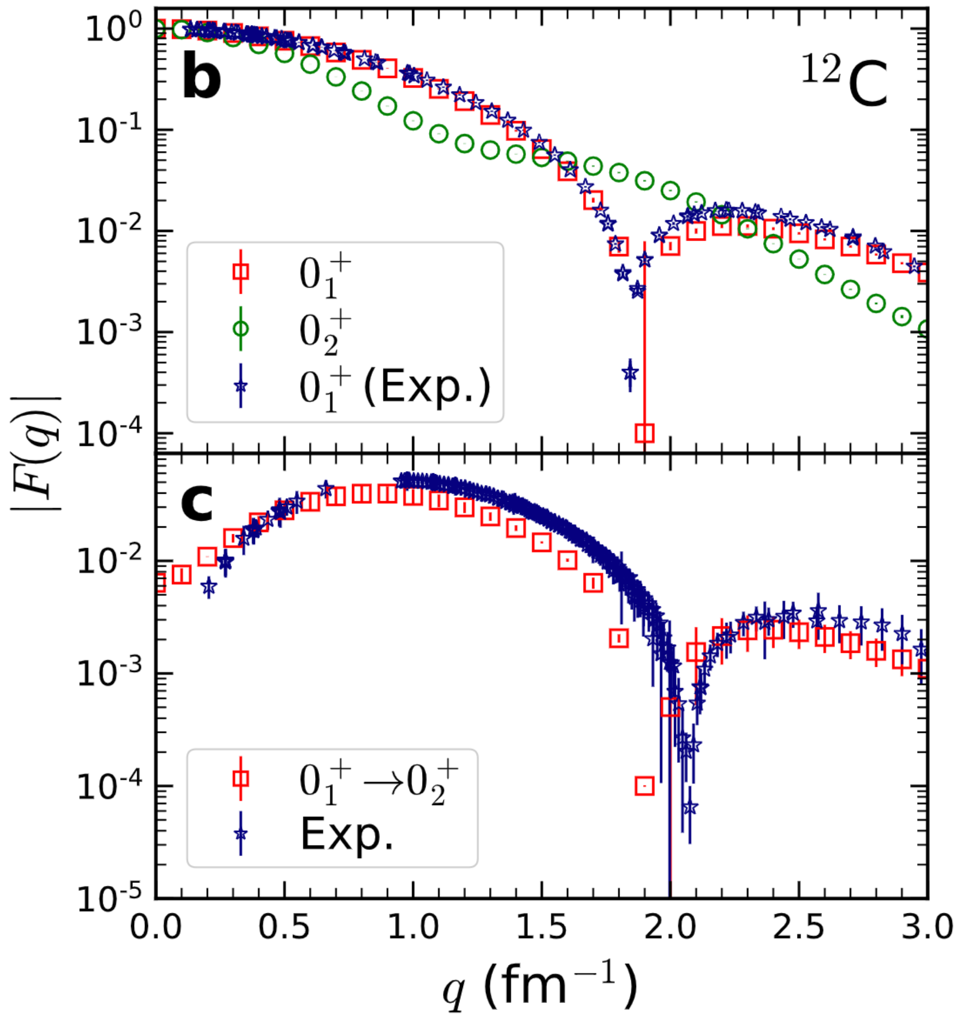
Shen, Elhatisari, Lähde, D.L., Lu, Meißner, Nature Commun. 14, 2777 (2023)



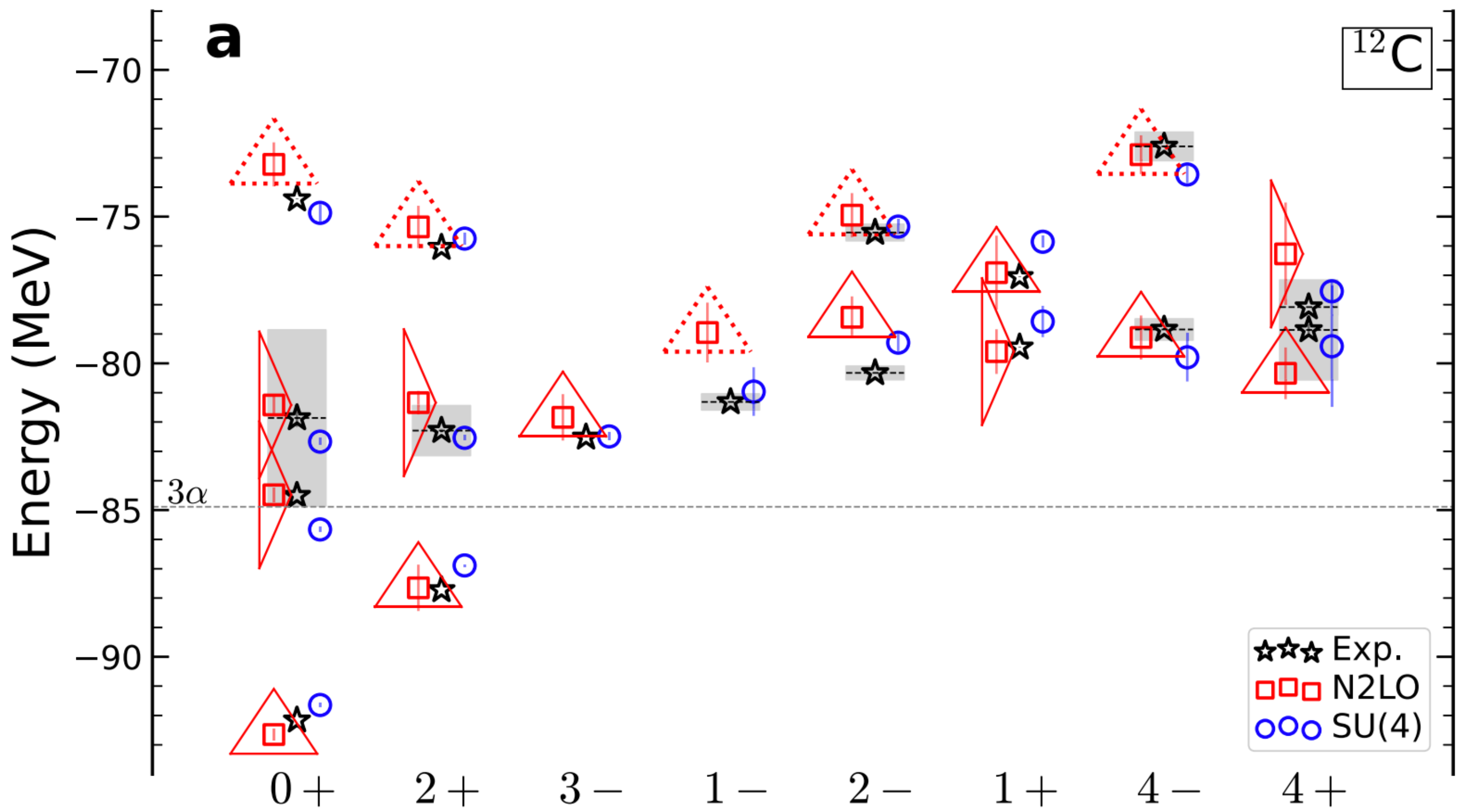
Shen, Elhatisari, Lähde, D.L., Lu, Meißner, Nature Commun. 14, 2777 (2023)



f
1_1^-
g
4_1^+
h
1_2^+
i
2_3^+
j
4_2^-
z (fm)
y (fm)
k
l
m
n
o
$1d_{3/2}$
$2s_{1/2}$
$1d_{5/2}$
$1p_{1/2}$
$1p_{3/2}$
$1s_{1/2}$
20
8
2

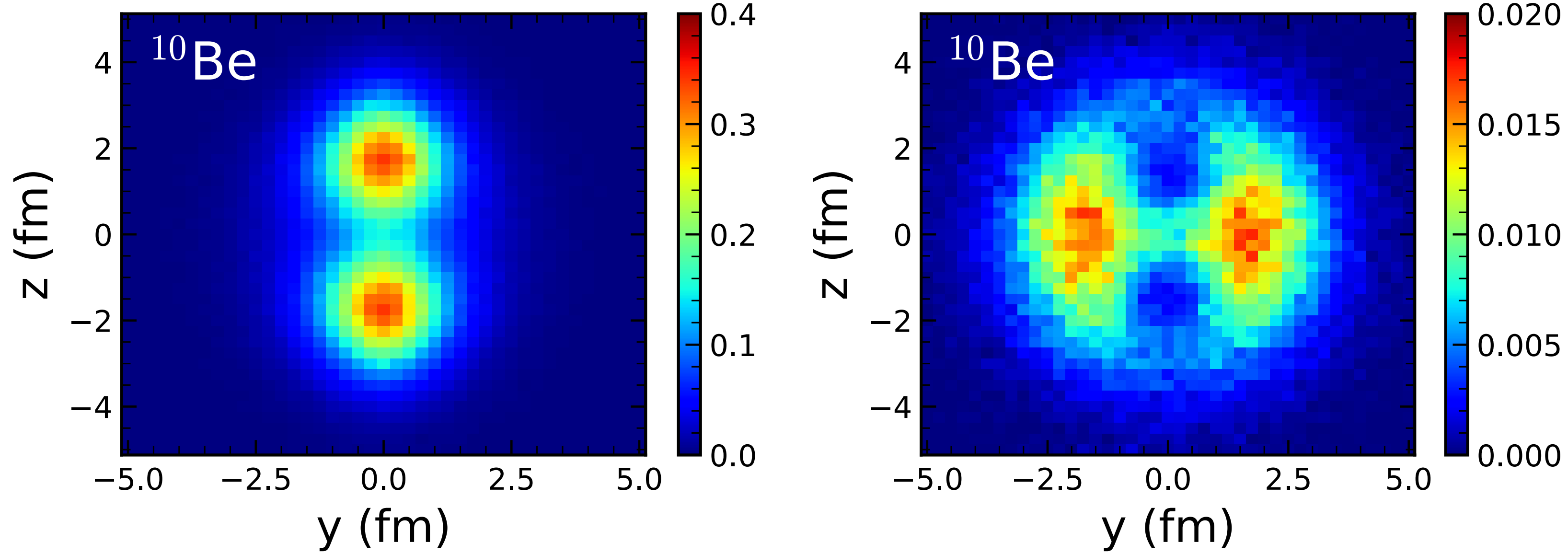


Shen, Elhatisari, Lähde, D.L., Lu, Meißner, Nature Commun. 14, 2777 (2023)



Shen, Elhatisari, Lähde, D.L., Lu, Meißner, Nature Commun. 14, 2777 (2023)

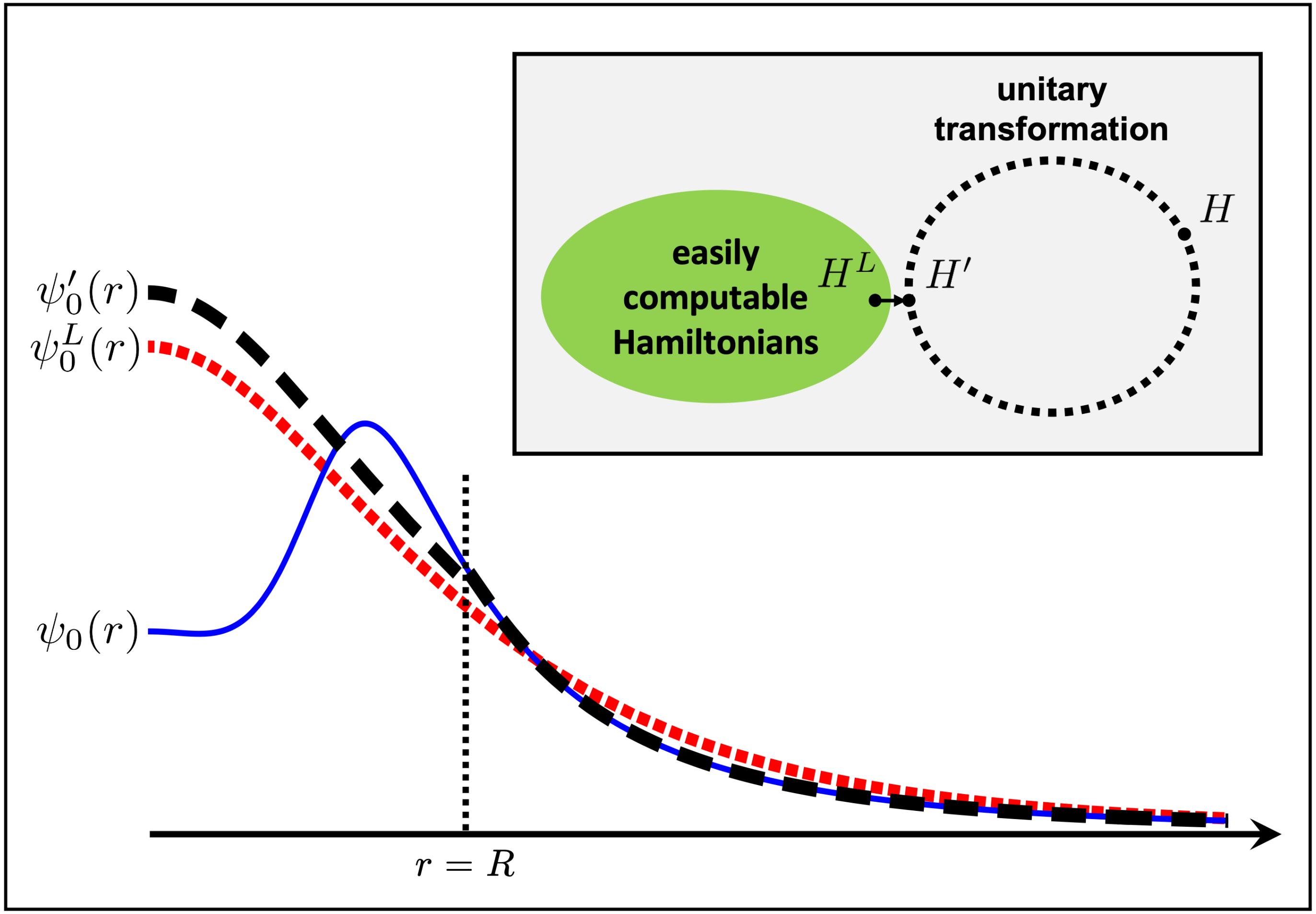
Seeing the structure of ^{10}Be



The left panel shows the intrinsic shape of the total nucleon density for ^{10}Be. The right panel shows the density distribution of the two neutrons furthest away from the protons in ^{10}Be

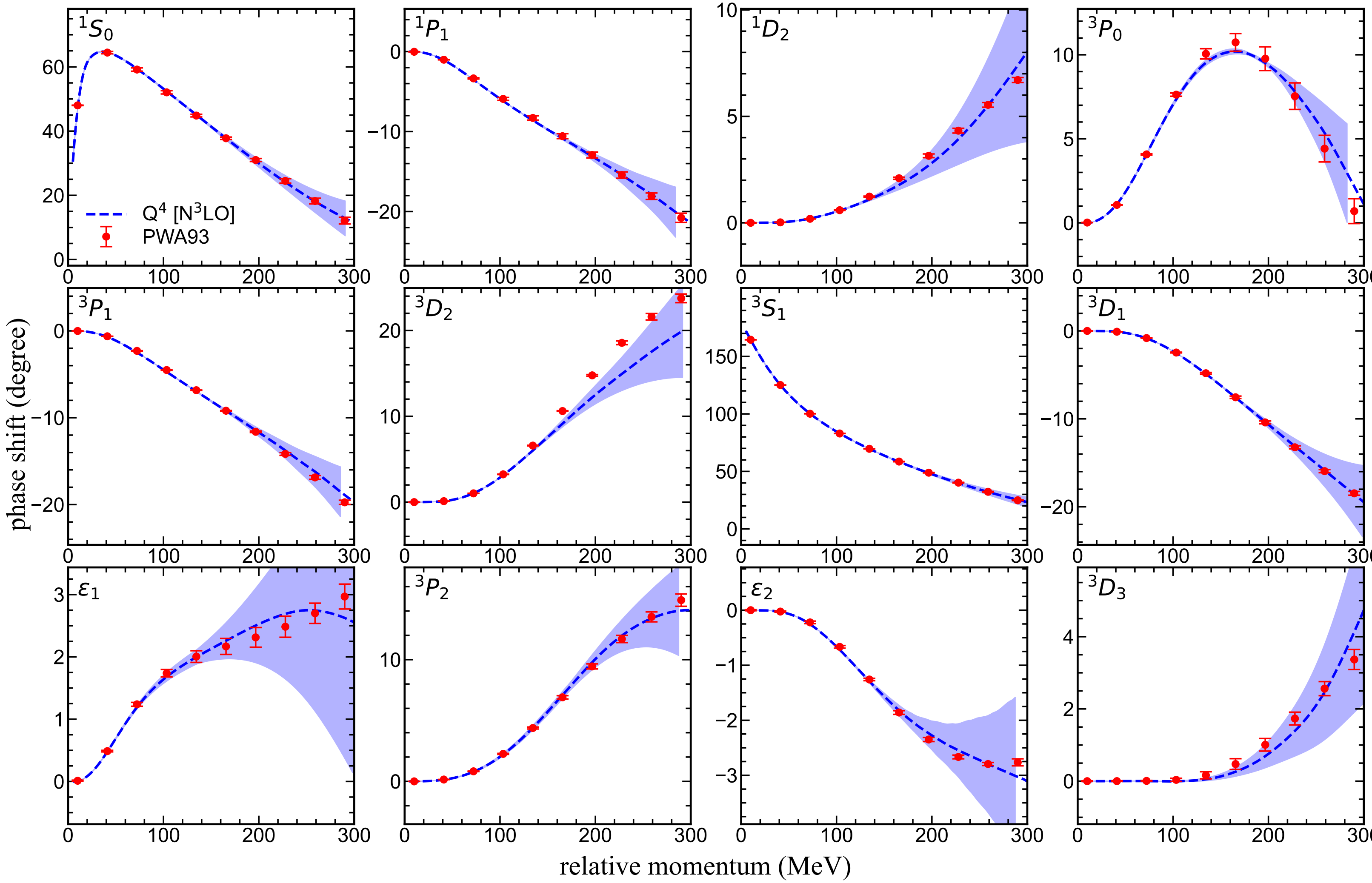
Shen, et al., work in progress

Wave function matching

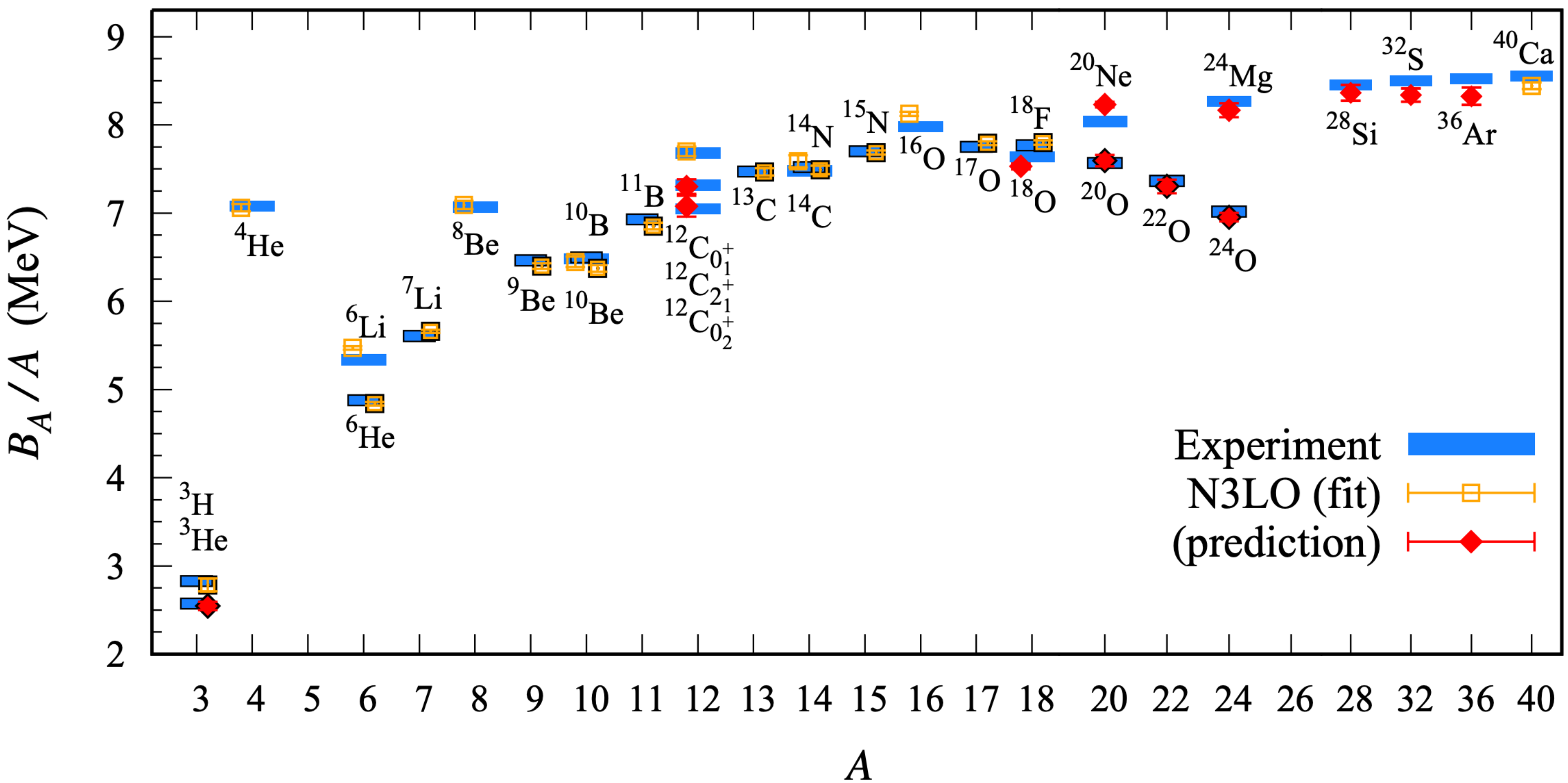


Elhatisari, Bovermann, Epelbaum, Frame, Hildenbrand, Krebs, Lähde, D.L., Li, Lu, M. Kim, Y. Kim, Ma, Meißner, Rupak, Shen, Song, Stellin, arXiv: 2210.17488

N3LO chiral effective field theory interaction

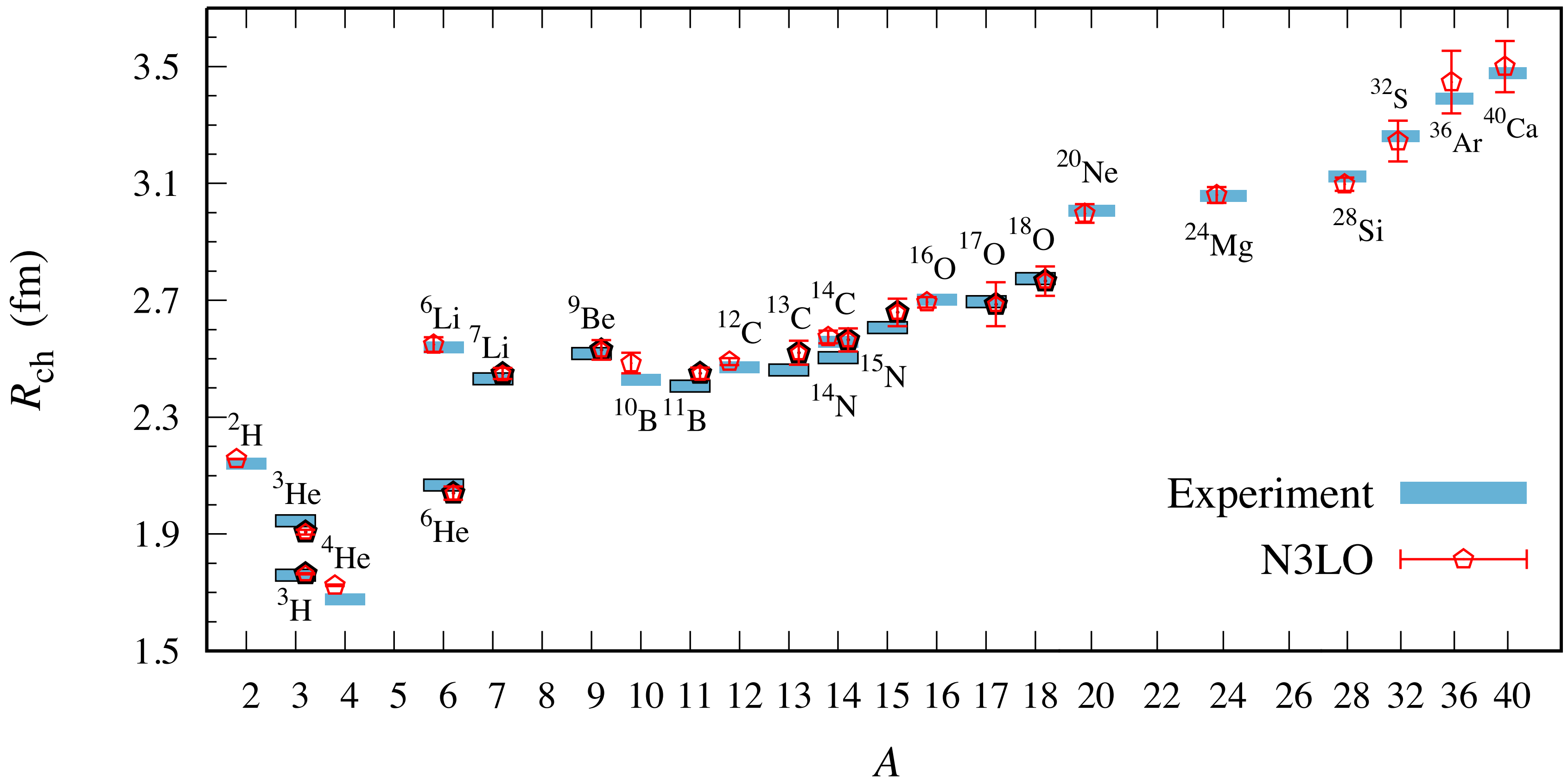


Binding energy per nucleon



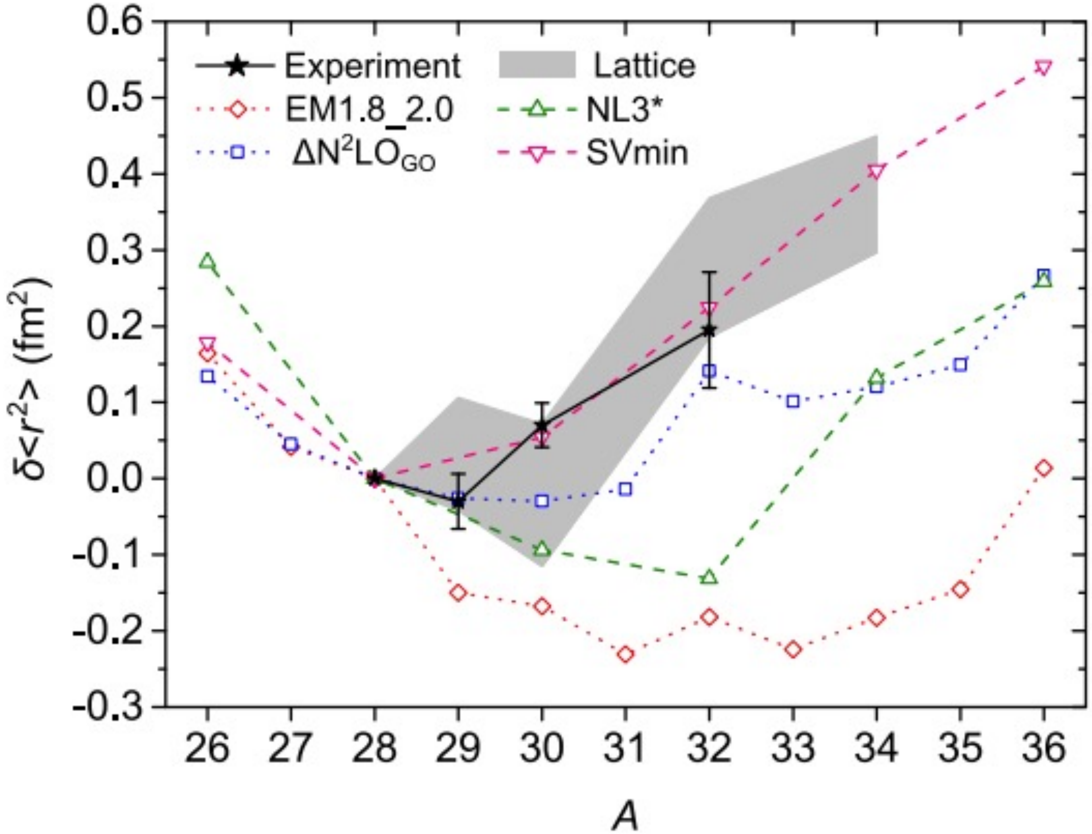
Elhatisari, Bovermann, Epelbaum, Frame, Hildenbrand, Krebs, Lähde, D.L., Li, Lu, M. Kim, Y. Kim, Ma, Meißner, Rupak, Shen, Song, Stellin, arXiv: 2210.17488

Charge radius



Elhatisari, Bovermann, Epelbaum, Frame, Hildenbrand, Krebs, Lähde, D.L., Li, Lu, M. Kim, Y. Kim, Ma, Meißner, Rupak, Shen, Song, Stellin, arXiv: 2210.17488

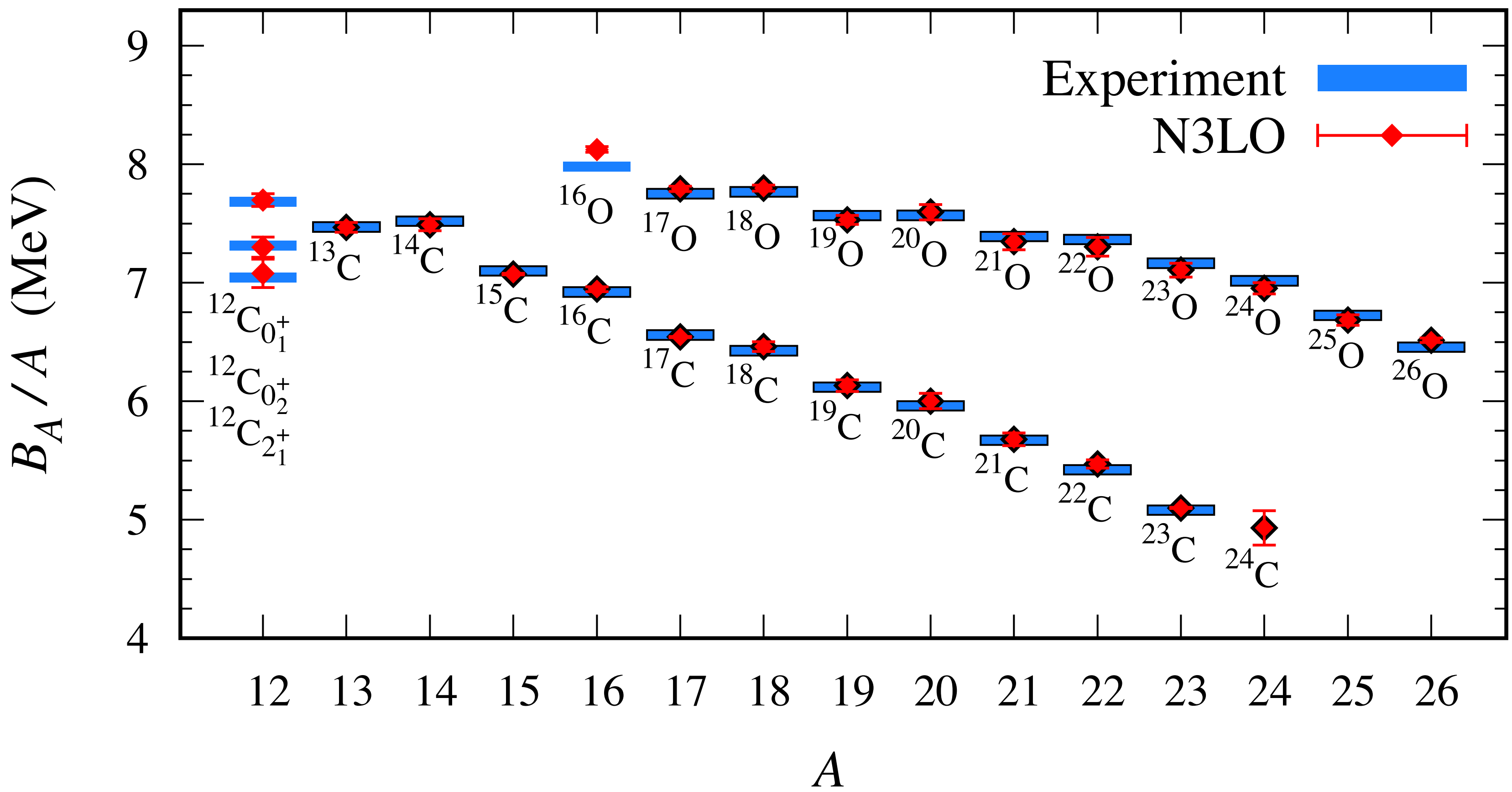
Silicon isotopes



König et al., arXiv: 2309.02037

Lattice calculations led by Y. Ma

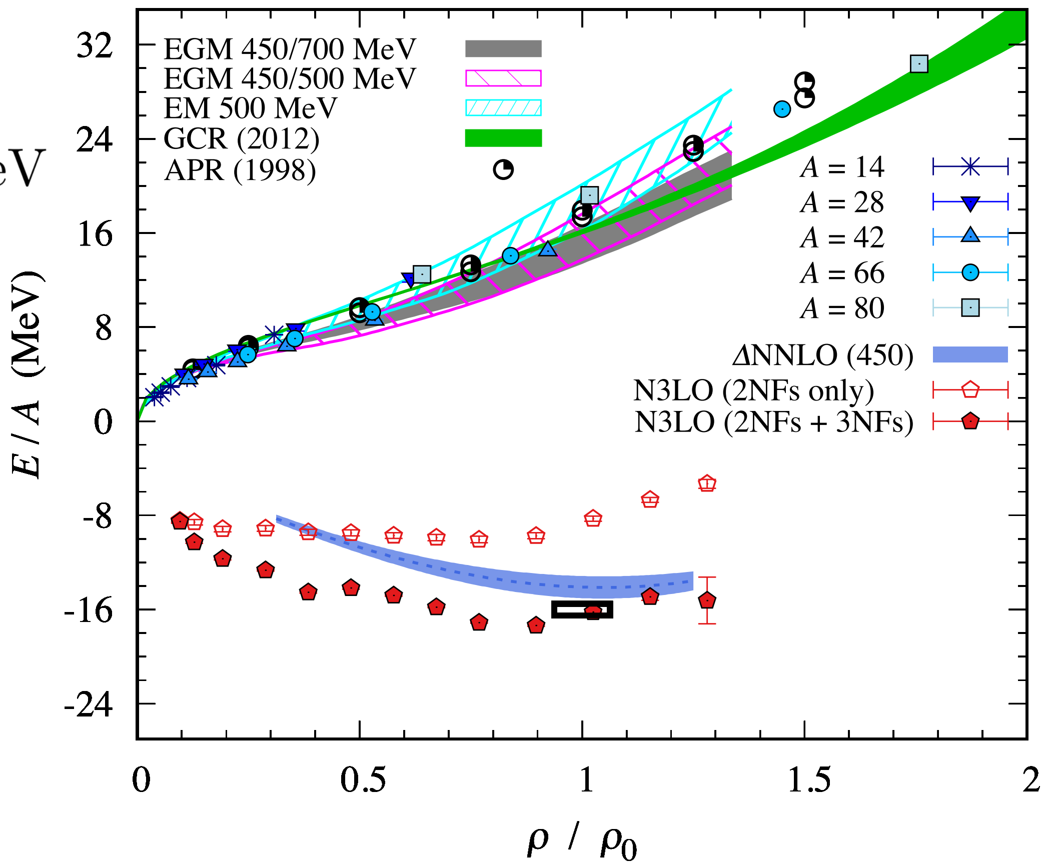
Carbon and oxygen isotopes



M. Kim, Song, Y. Kim, Ma, et al., work in progress

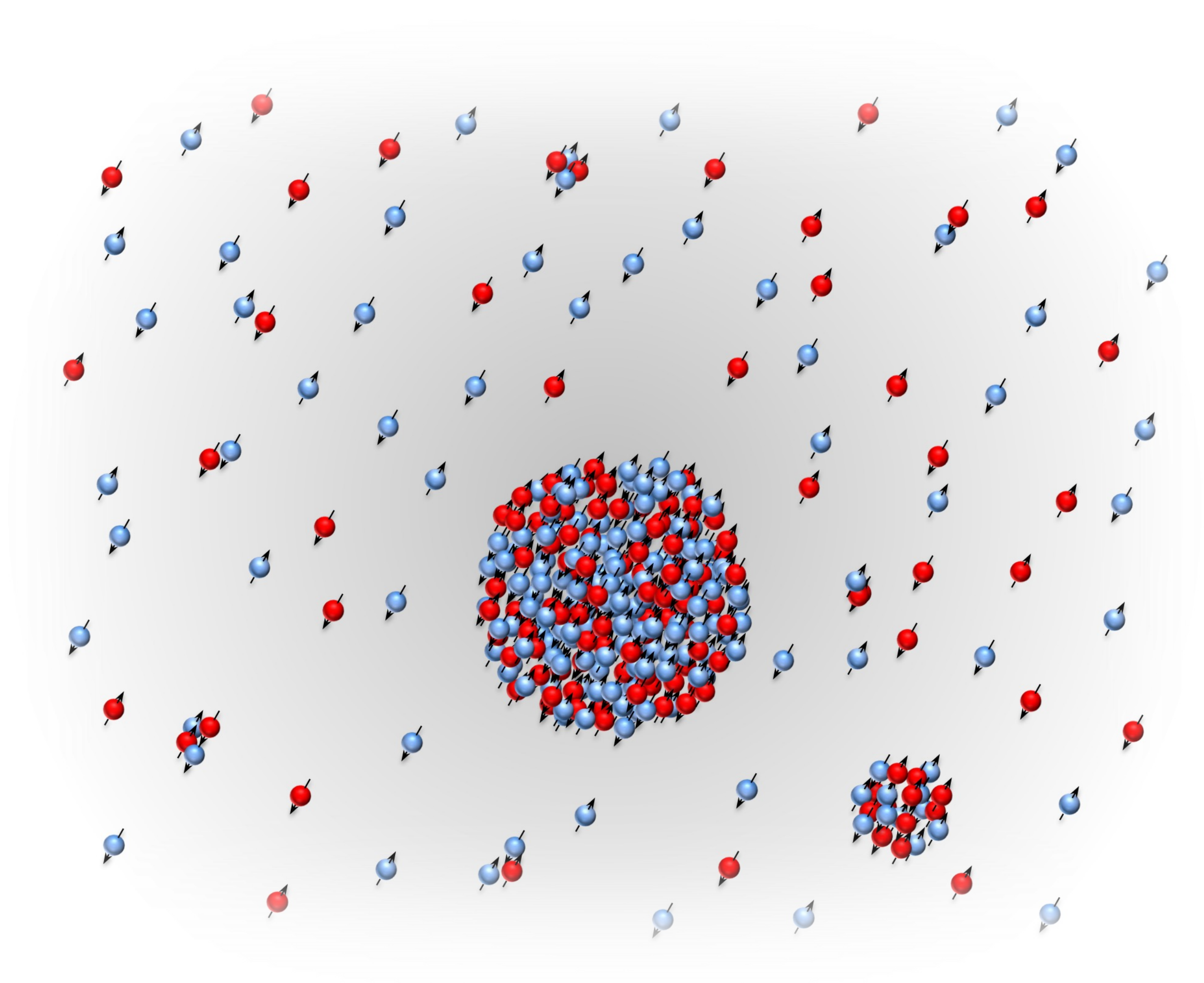
Neutron and nuclear matter

$L = 56.4(5.8)$ MeV



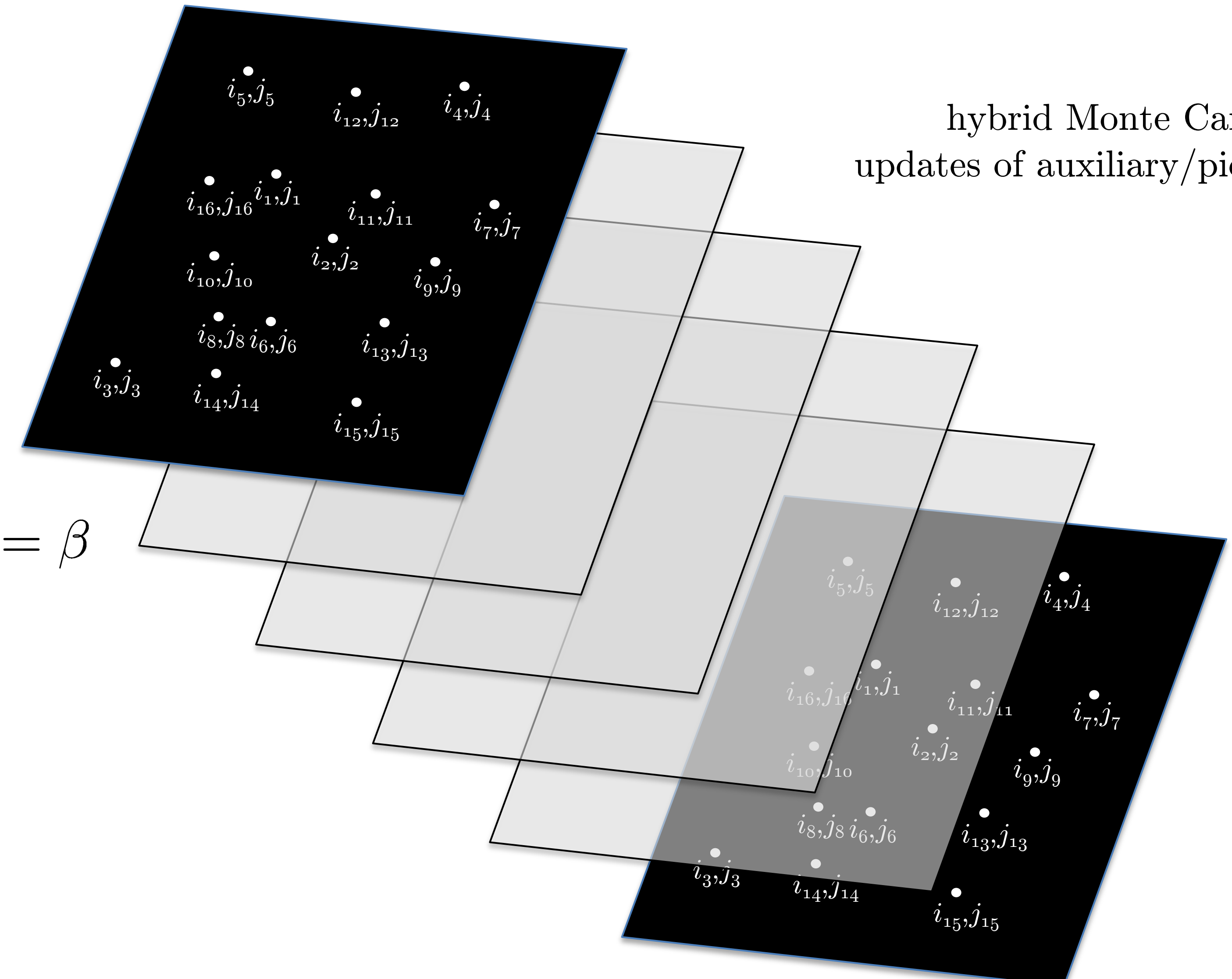
Elhatisari, Bovermann, Epelbaum, Frame, Hildenbrand, Krebs, Lähde, D.L., Li, Lu, M. Kim, Y. Kim, Ma, Meißner, Rupak, Shen, Song, Stellin, arXiv: 2210.17488

Ab initio nuclear thermodynamics



Lu, Li, Elhatisari, D.L., Drut, Lähde, Epelbaum, Meißner, Phys. Rev. Lett. 125, 192502 (2020)

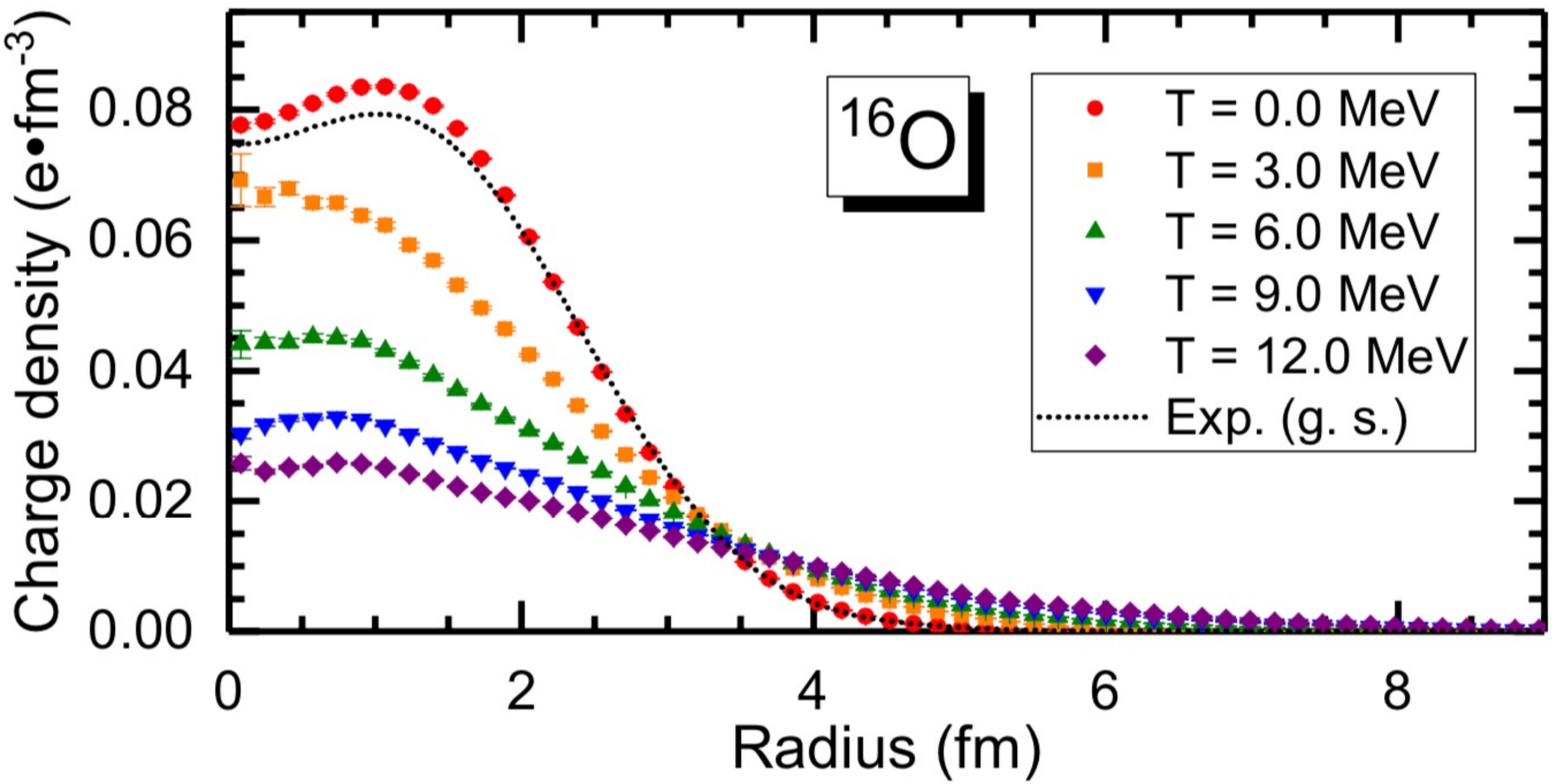
Metropolis updates of pinholes



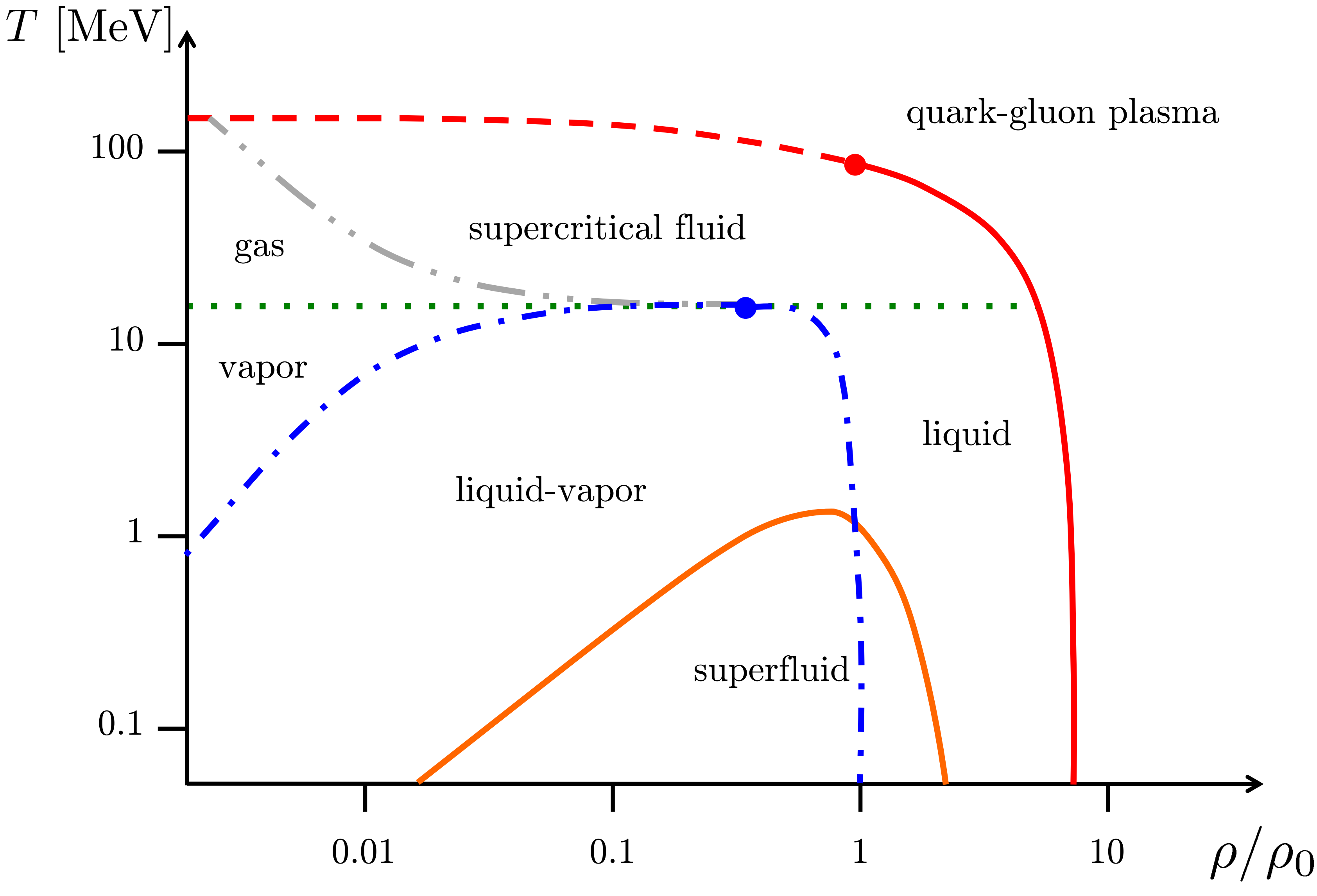
hybrid Monte Carlo
updates of auxiliary/pion fields

$\tau = \beta$

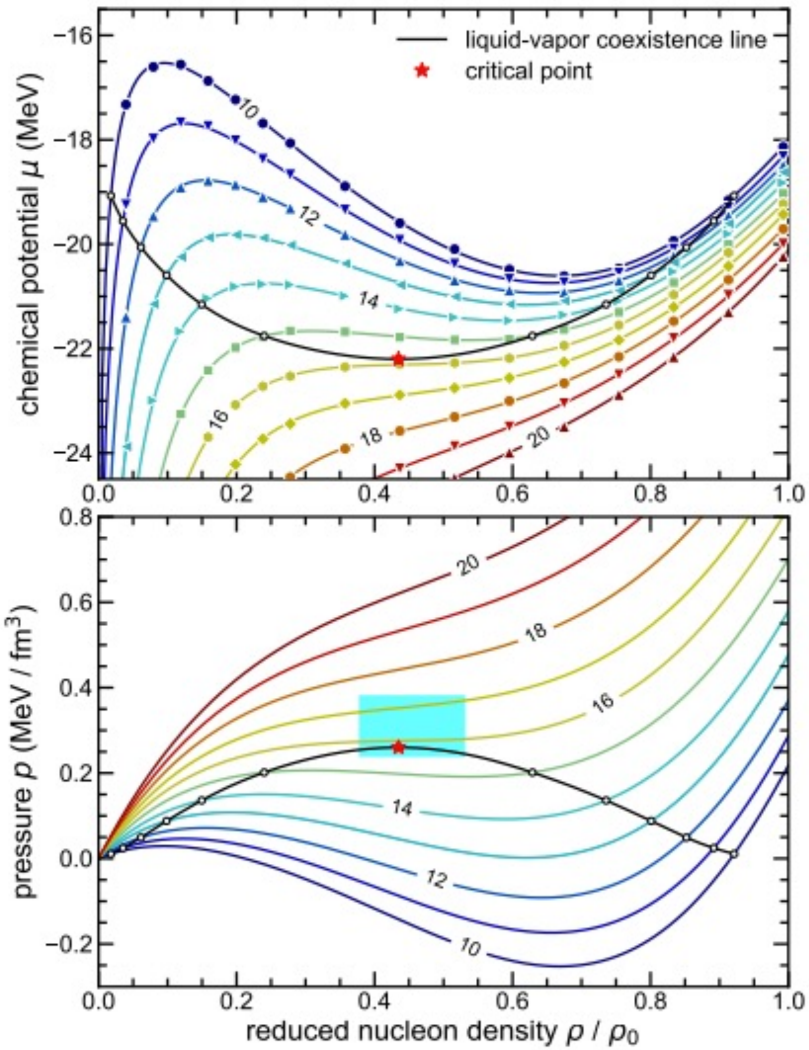
$\tau = 0$



Charge density (e•fm^{-3})
0.08
0.06
0.04
0.02
0.00
0
2
4
6
8
Radius (fm)
^{16}O
T = 0.0 MeV
T = 3.0 MeV
T = 6.0 MeV
T = 9.0 MeV
T = 12.0 MeV
Exp. (g. s.)



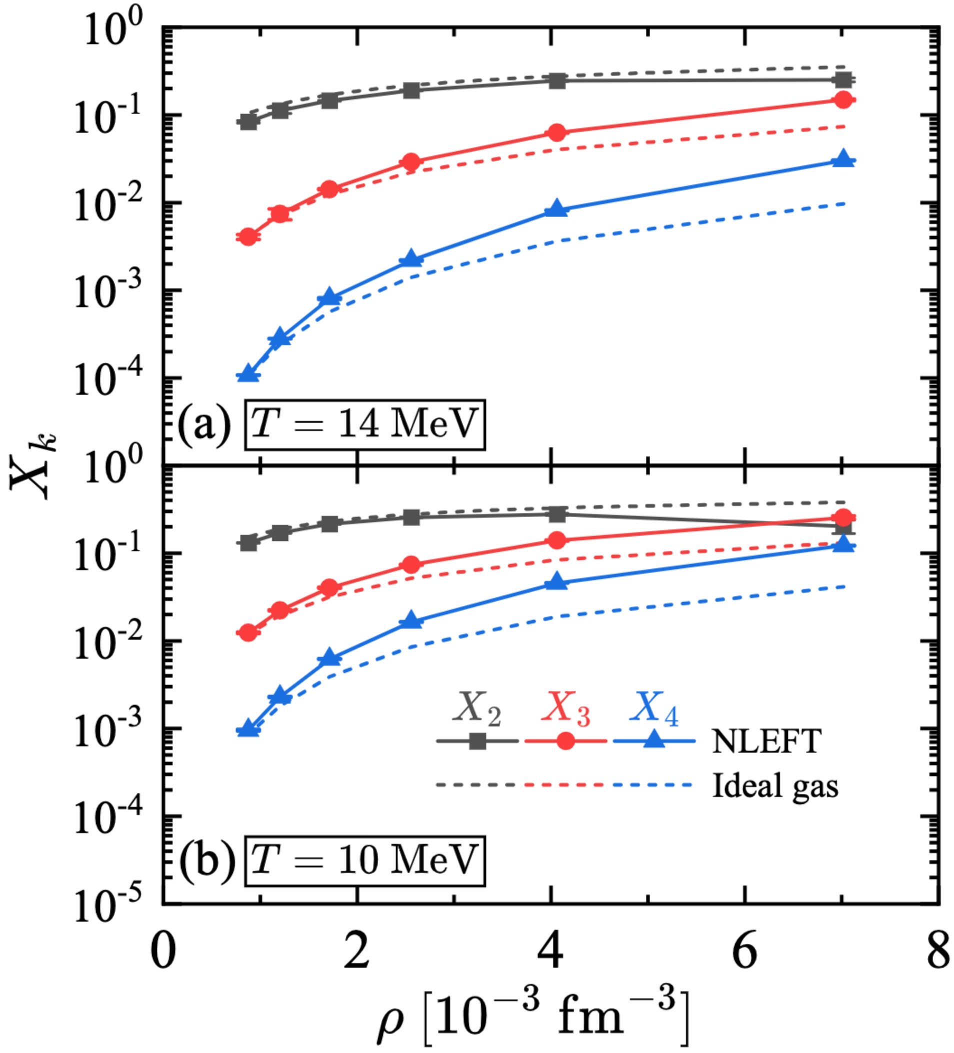
T [MeV]
100
10
1
0.1
quark-gluon plasma
supercritical fluid
gas
vapor
liquid
liquid-vapor
superfluid
0.01
0.1
1
10
ρ/ρ_0



$$T_c = 15.80(0.32)(1.60)\,\mathrm{MeV}$$
$$\rho_c = 0.089(04)(18)\,\mathrm{fm}^{-3}$$
$$\mu_c = -22.20(0.44)(2.20)\,\mathrm{MeV}$$
$$P_c = 0.260(05)(30)\,\mathrm{MeV\ fm}^{-3}$$

Lu, Li, Elhatisari, D.L., Drut, Lähde, Epelbaum, Meißner, Phys. Rev. Lett. 125, 192502 (2020)

Cluster abundances versus density and temperature



Ren, Elhatisari, Lähde, D.L., Meißner, arXiv:2305.15037

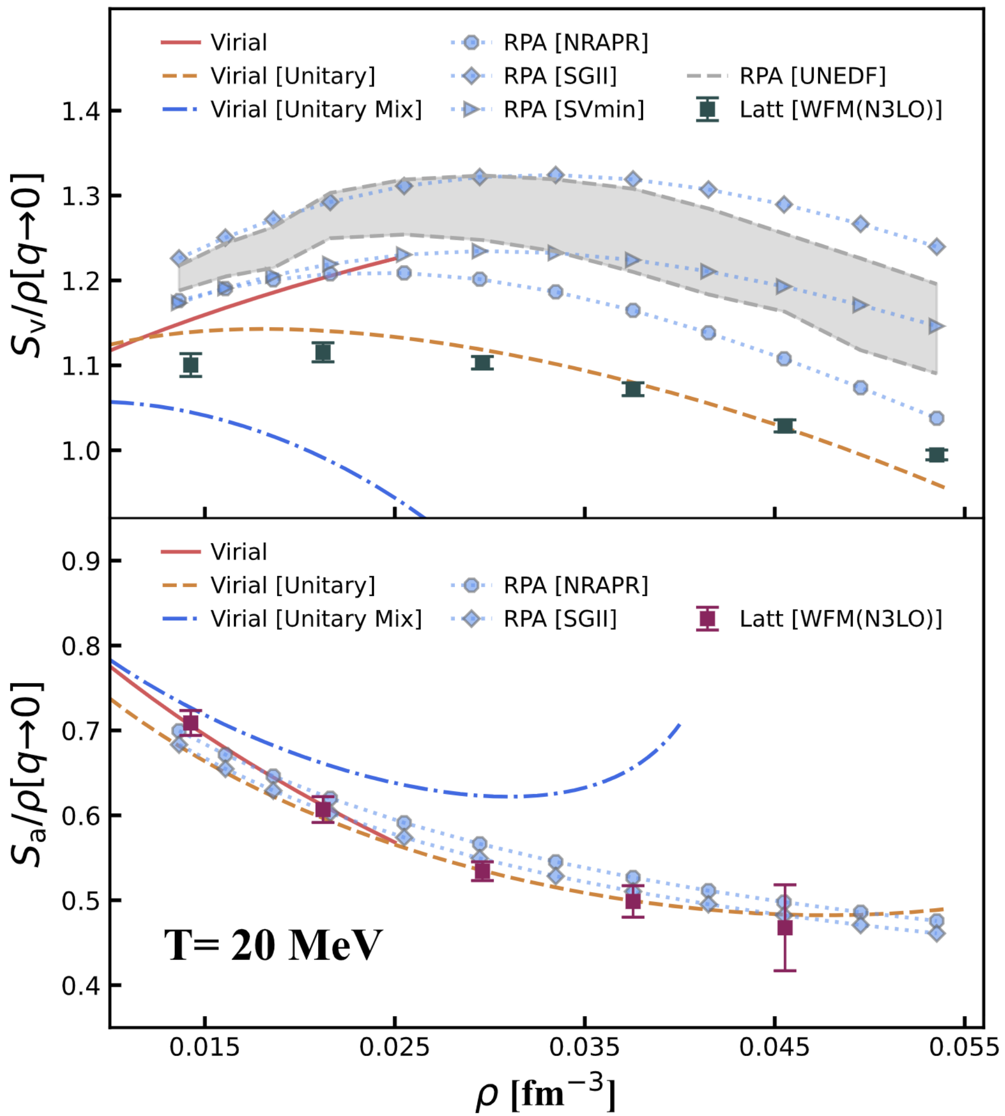
Structure factors for hot neutron matter

$$S_{\mathrm{v}}(\boldsymbol{q}) = \frac{1}{L^3} \sum_{\boldsymbol{n}\boldsymbol{n}'} \mathrm{e}^{-i\boldsymbol{q}\cdot\boldsymbol{n}} \left[\langle \hat{\rho}(\boldsymbol{n}+\boldsymbol{n}')\hat{\rho}(\boldsymbol{n}')\rangle - (\rho^0)^2\right]$$

$$S_{\mathrm{a}}(\boldsymbol{q}) = \frac{1}{L^3} \sum_{\boldsymbol{n}\boldsymbol{n}'} \mathrm{e}^{-i\boldsymbol{q}\cdot\boldsymbol{n}} \left[\langle \hat{\rho}_z(\boldsymbol{n}+\boldsymbol{n}')\hat{\rho}_z(\boldsymbol{n}')\rangle - (\rho_z^0)^2\right]$$

ESA/Hubble/L Calcada

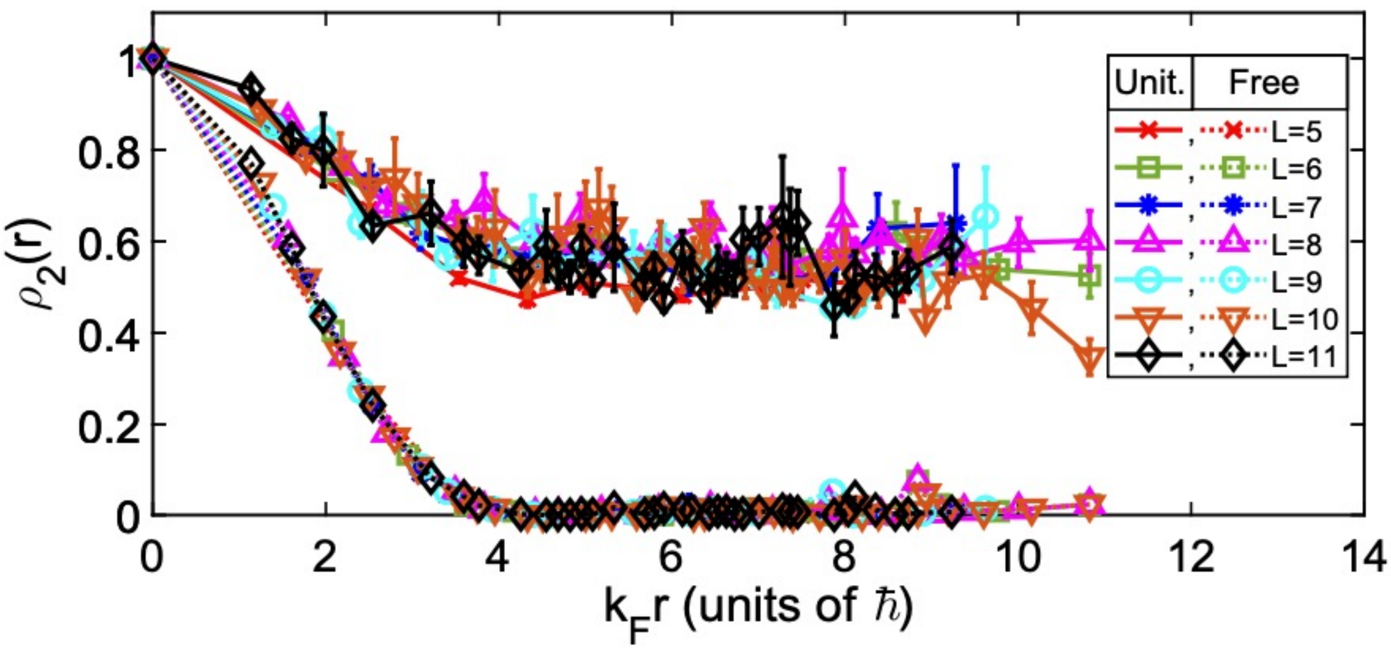
Ma, Lin, Lu, Elhatisari, D.L., Meißner, Steiner, Wang, arXiv:2306.04500



Ma, Lin, Lu, Elhatisari, D.L., Meißner, Steiner, Wang, arXiv:2306.04500

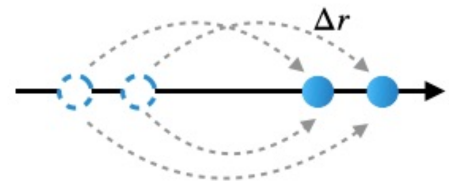
Superfluidity

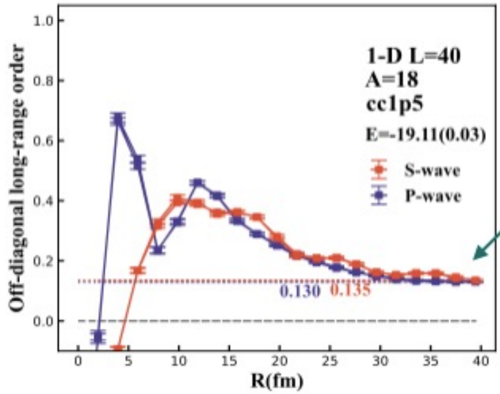
Ground state S-wave superfluid long-range order in the unitary limit



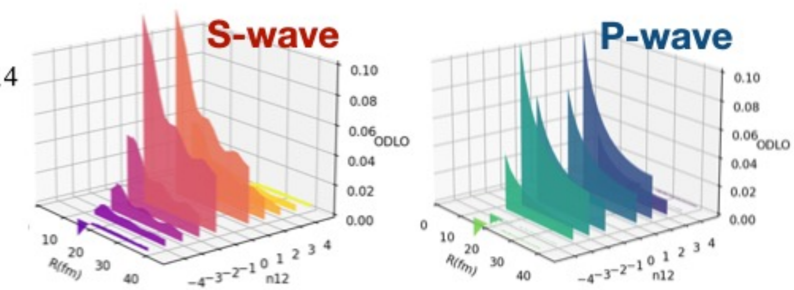
He, Li, Lu, D.L., Phys. Rev. A 101, 063615 (2020)

Off-diagonal long-range order



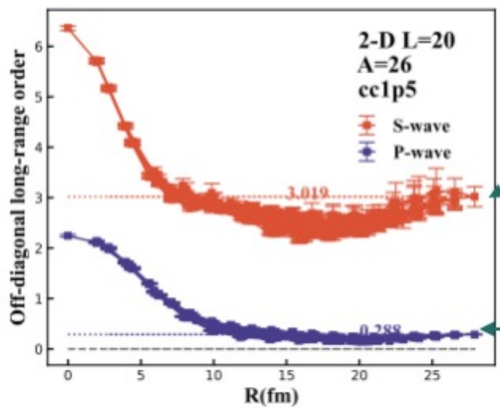


$$\alpha \approx \frac{0.13}{18/2} = 0.014$$



max @ |r_12|=1

max @ |r_12|=2



$$\alpha \approx \frac{3}{26/2} = 0.23$$

$$\alpha \approx \frac{0.29}{26/2} = 0.022$$

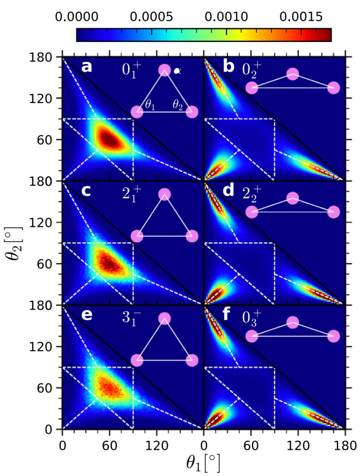
condensate fraction

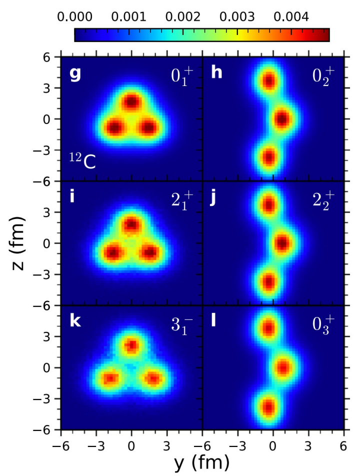
$$\rho_2(\mathbf{r}_1', \mathbf{r}_2', \mathbf{r}_1, \mathbf{r}_2) = \alpha N/2 \cdot \phi^*(|\mathbf{r}_1' - \mathbf{r}_2'|)\phi(|\mathbf{r}_1 - \mathbf{r}_2|)$$

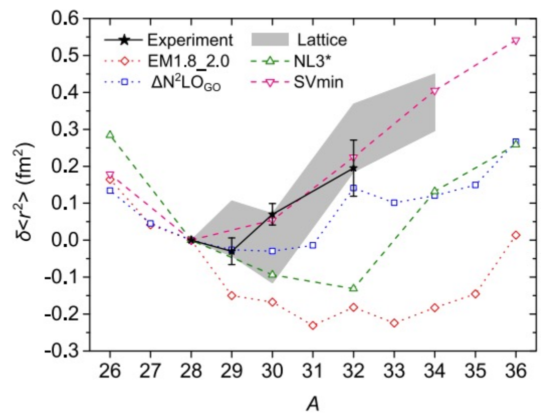
Ma, Given, Hicks, et al., work in progress

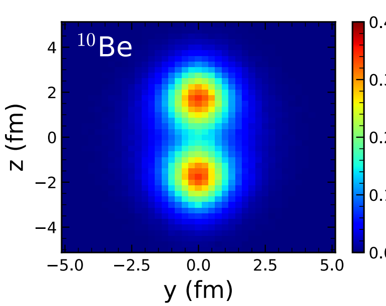
CNRS-MSU IRL Collaboration Opportunities

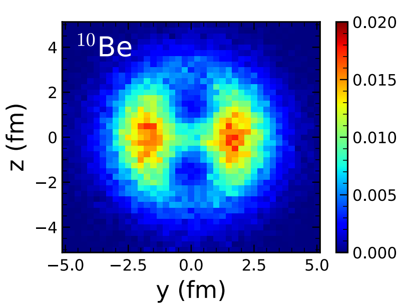
Clustering, intrinsic shapes, charge radii, neutron skins, ANCs, spectroscopy, electromagnetic transitions

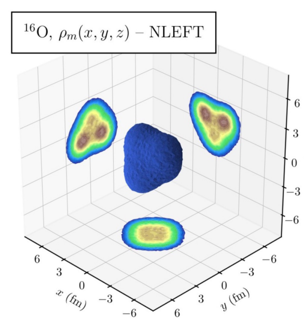


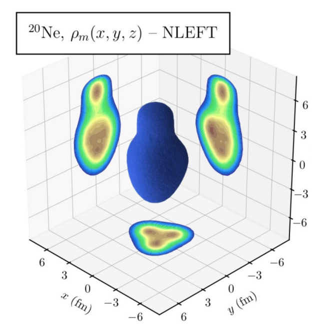






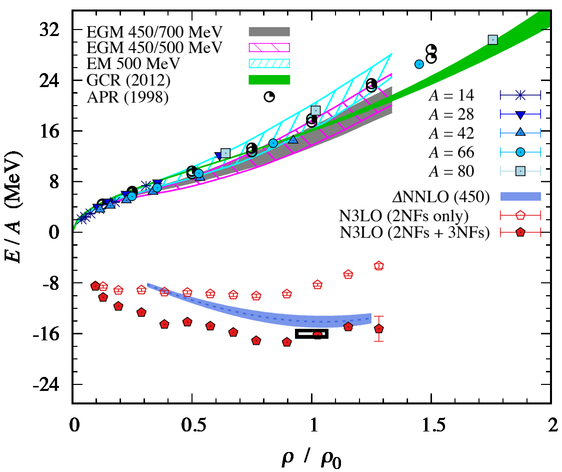


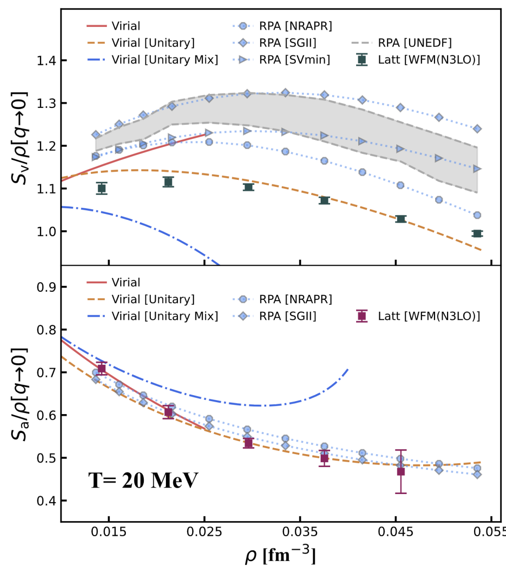


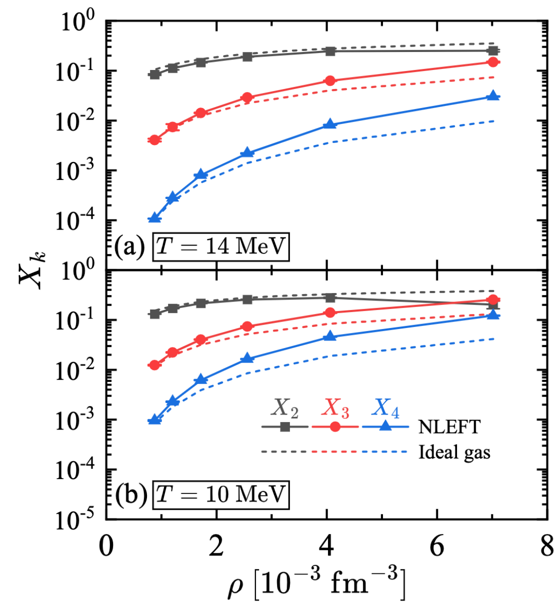


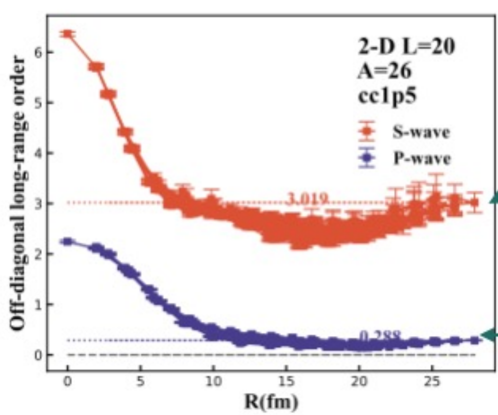
CNRS-MSU IRL Collaboration Opportunities

Equation of state, superfluidity, thermodynamics, cluster abundances



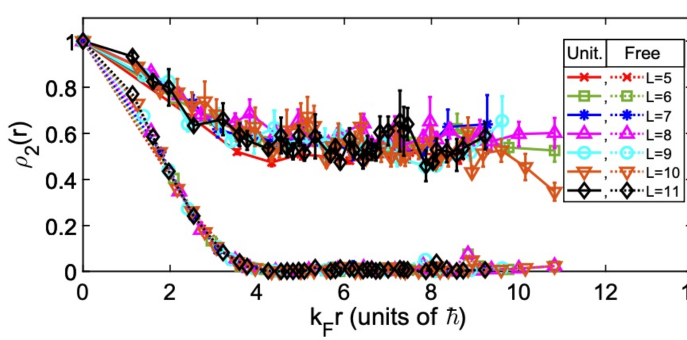






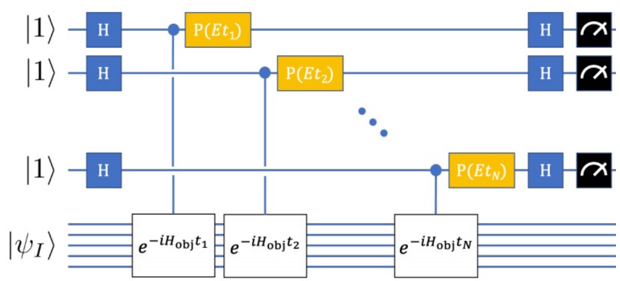
$$\alpha \approx \frac{3}{26/2} = 0.23$$

$$\alpha \approx \frac{0.29}{26/2} = 0.022$$



CNRS-MSU IRL Collaboration Opportunities

Quantum computing, emulators, machine learning



STREAMLINE

SmarT Reduction and Emulation Applying Machine Learning In Nuclear Environments