Many-body factorization and position-momentum equivalence of nuclear short-range correlations

Diego Lonardoni

In collaboration with:

- ✓ R. Cruz-Torres @ MIT
- ✓ R. Weiss @ Hebrew U.
- ✓ M. Piarulli @ Washington U.
- ✓ N. Barnea @ Hebrew U.
- ✓ D. W. Higinbotham @ JLab
- ✓ E. Piasetzky @ Tel Aviv U.
- ✓ A. Schmidt @ MIT
- ✓ L. B. Weinstein @ ODU
- ✓ R. B. Wiringa @ ANL
- ✓ O. Hen @ MIT
- ✓ And more...

LA-UR-21-21660 JLab Theory Seminar - March 1, 2021

Outline

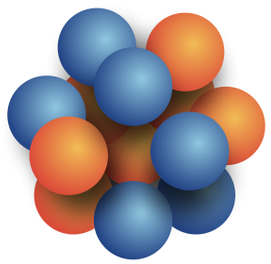
- ✓ (Biased) Introduction
  - Nuclear short range correlations (SRCs)
- ✓ Quantum Monte Carlo (QMC)
  - General idea
  - QMC wave functions
- ✓ Generalized Contact Formalism (GCF)
  - General idea
  - r- and k-space distributions
- ✓ QMC + GCF
  - Results
  - More results
  - Even more results
- ✓ Summary & Perspectives

Nuclear Short-Range Correlations

Goal: build a predictive understanding of nuclear systems, from nuclei to neutron stars

experiments

nuclei

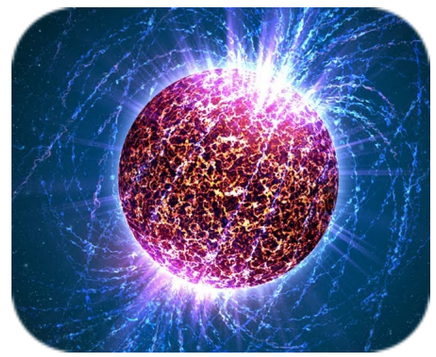


$R \sim 10^{-15}$ m

$M \sim 10^{-27}$ kg

theory ⟷

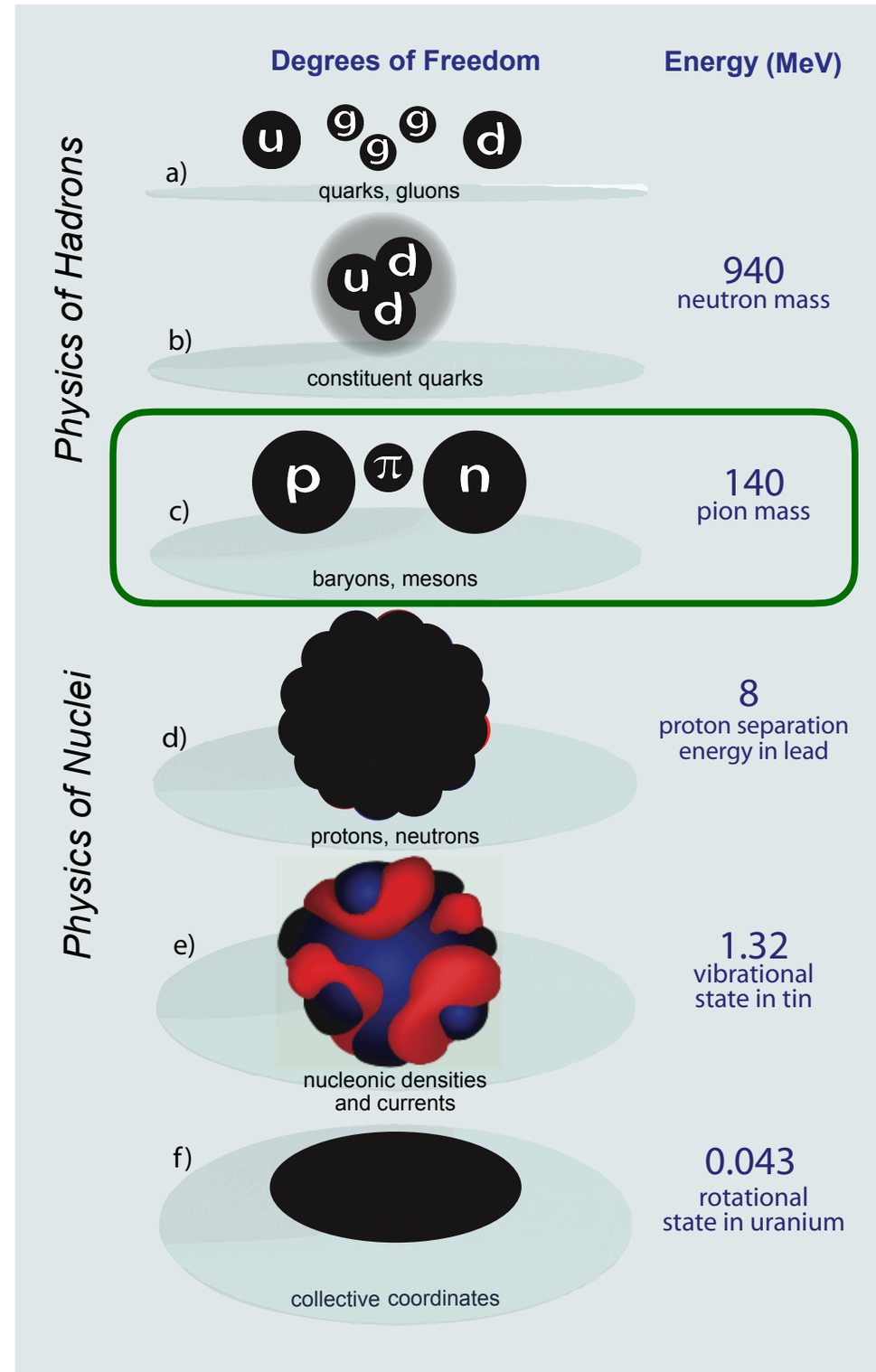
neutron stars



$R \sim 10^{4}$ m

$M \sim 10^{30}$ kg

observations



Challenge: strongly correlated many-body systems

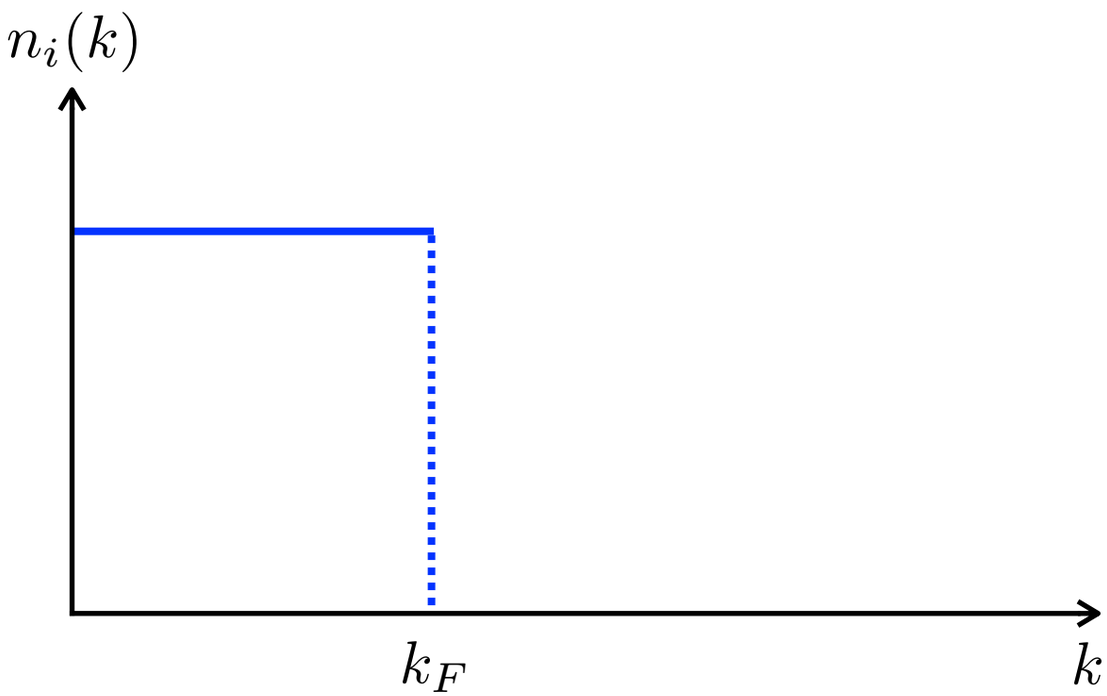
- Nuclear Hamiltonian? Scheme and scale?
- Many-body methods? Nuclear structure, nuclear dynamics, nuclear reactions, dense matter
- How to connect theory and experiments?

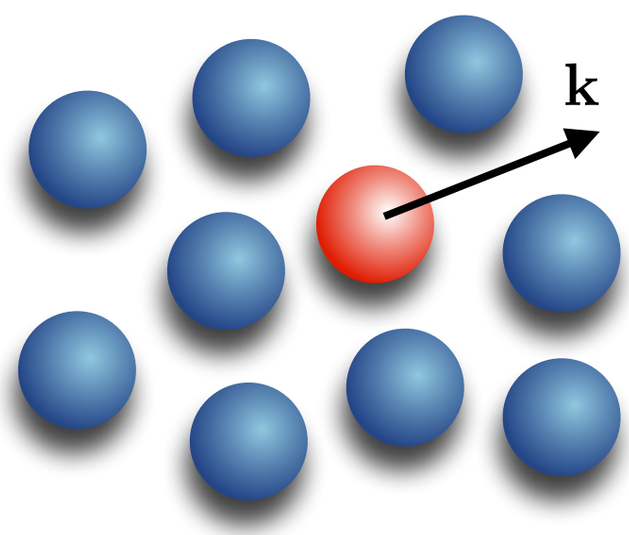
short-range correlations (SRCs):
powerful tool to investigate nuclear systems

Nuclear Short-Range Correlations

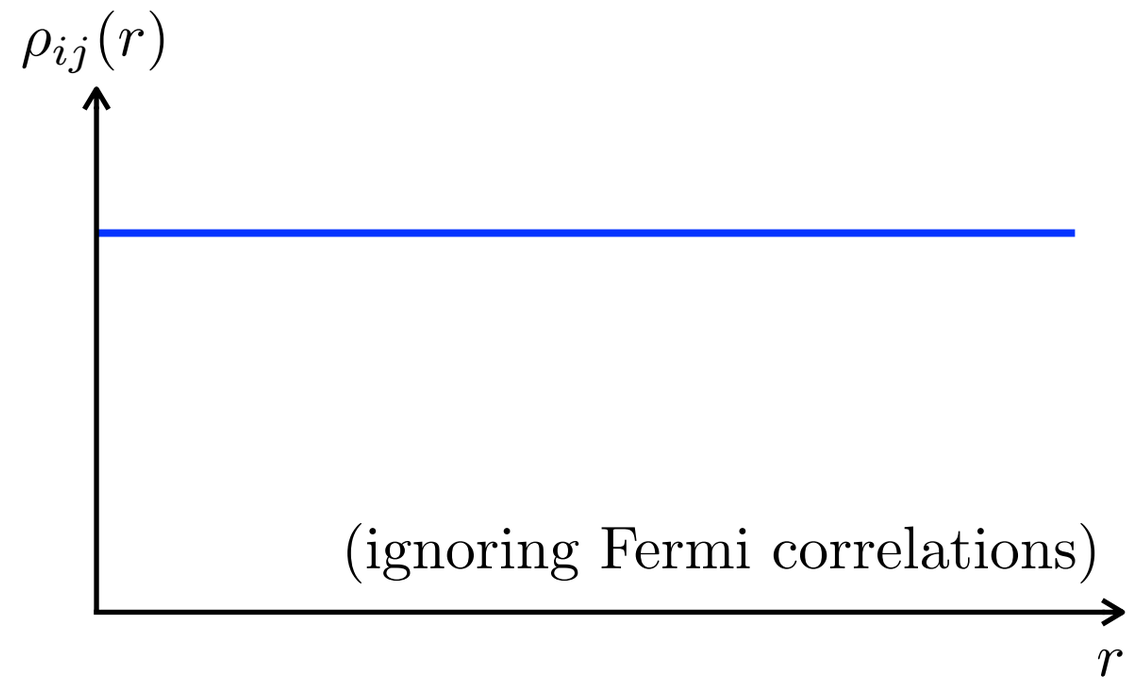
Fermi gas

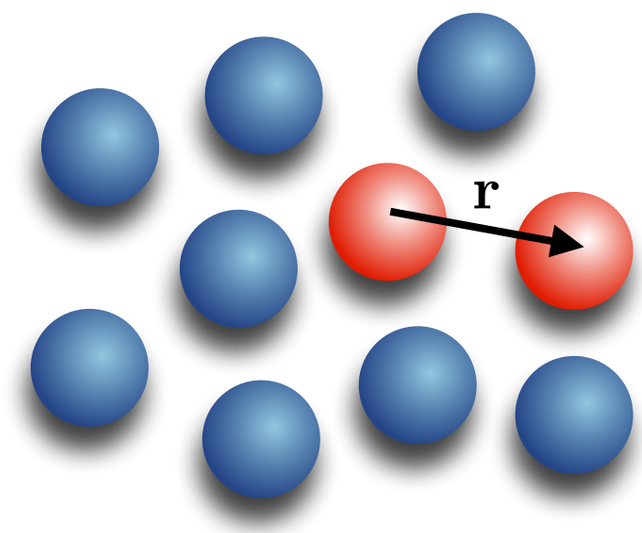
one-body k-space distribution





two-body r-space distribution



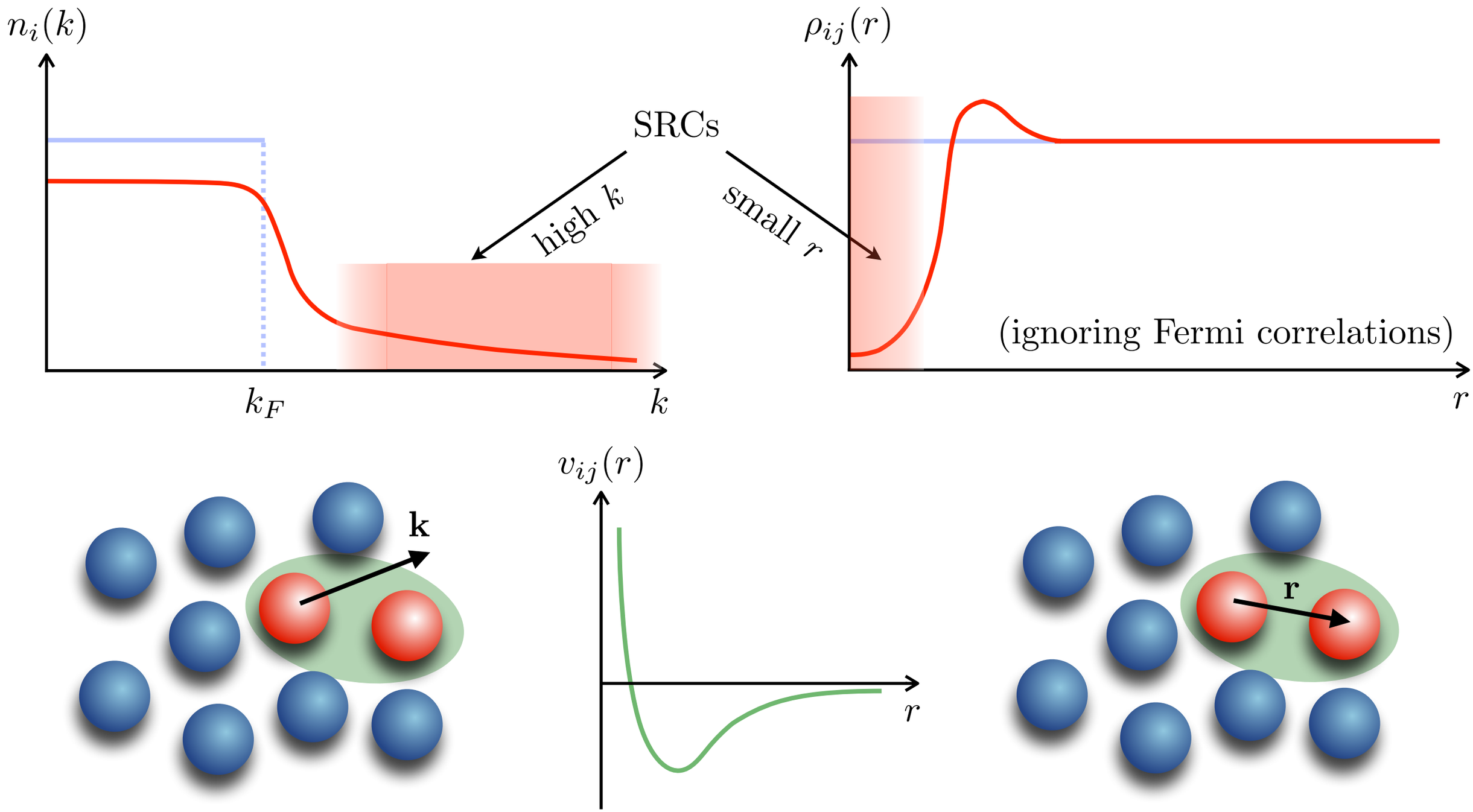


Nuclear Short-Range Correlations

Fermi gas + two-body potential

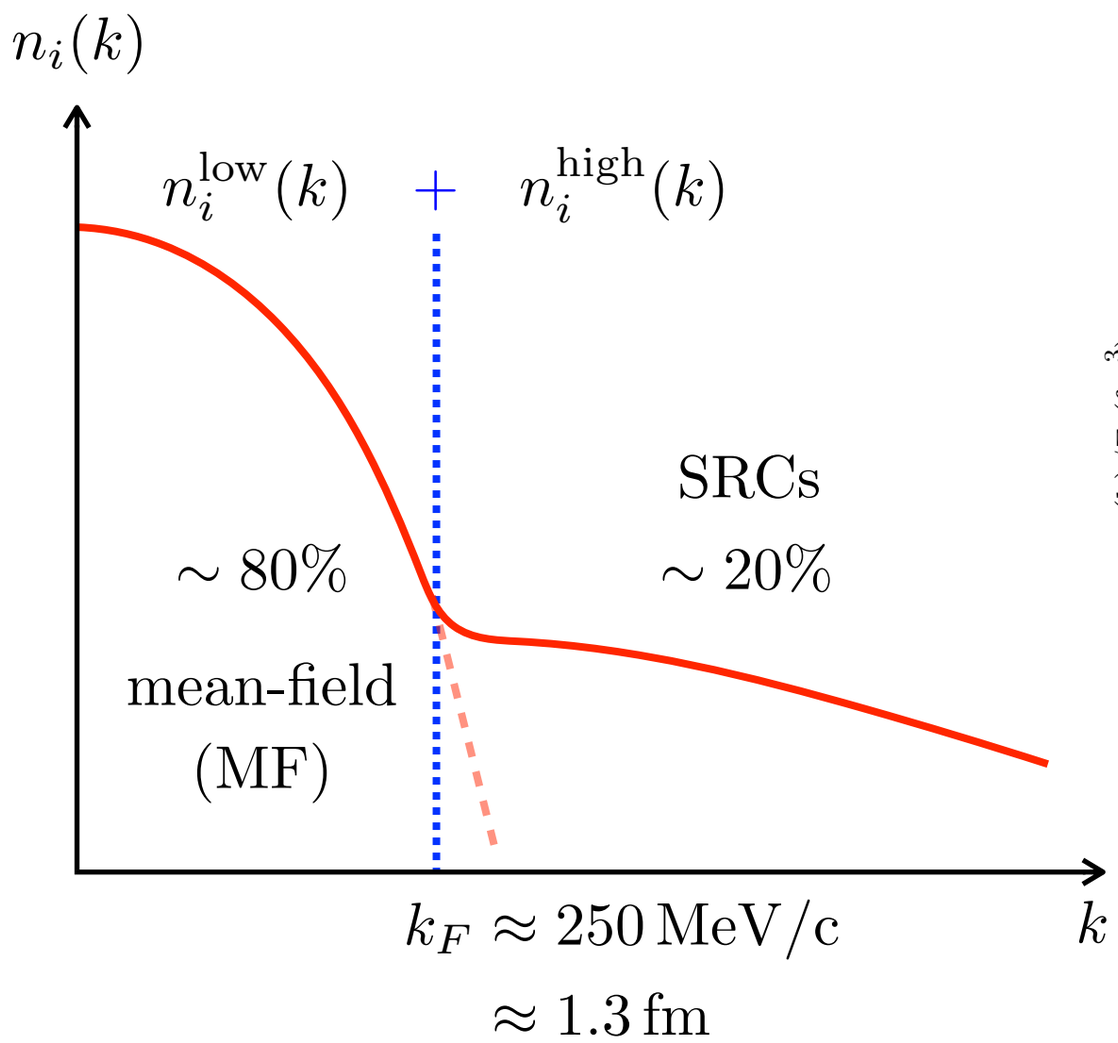
one-body k-space distribution

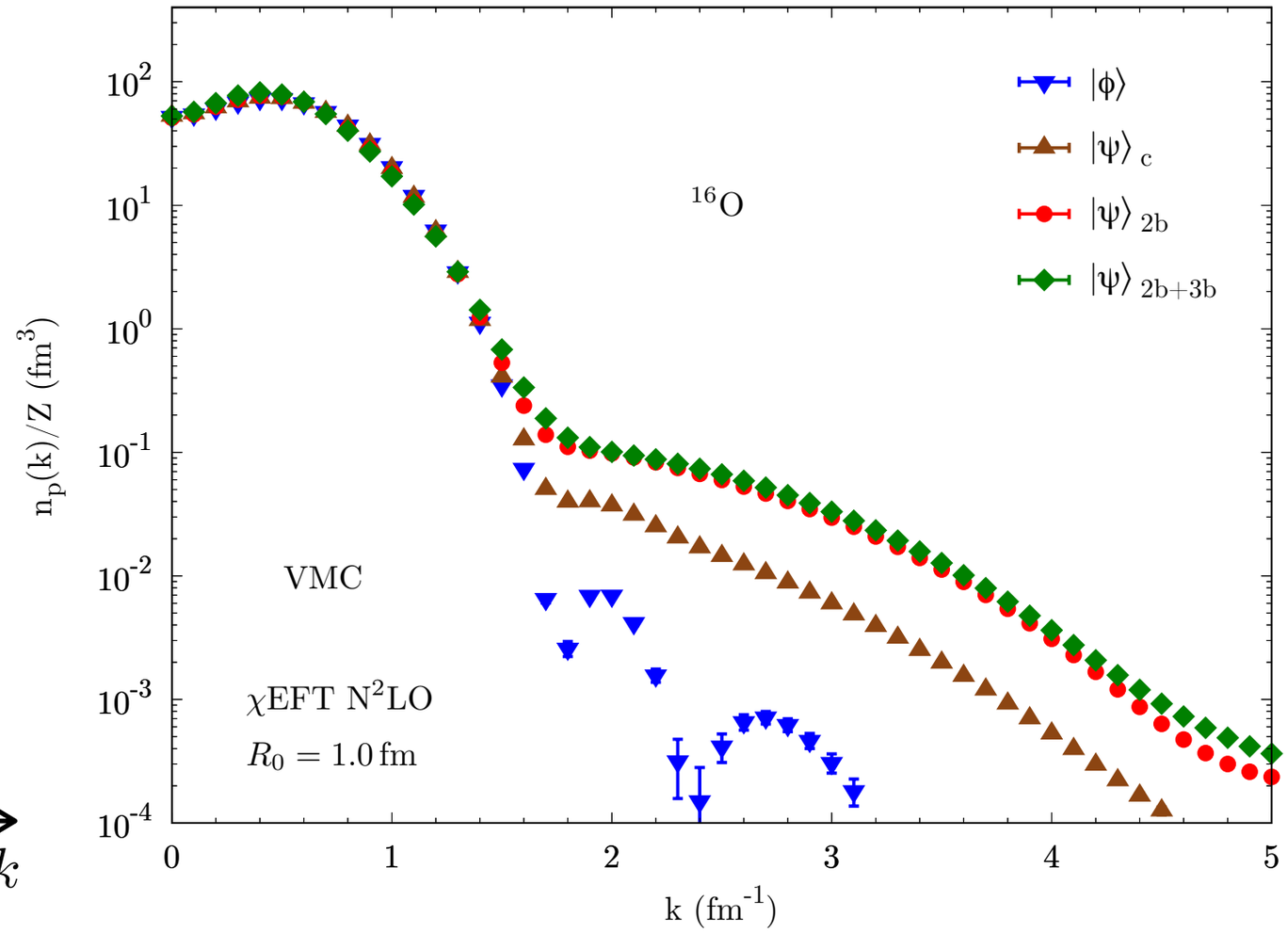
two-body r-space distribution



Nuclear Short-Range Correlations

Nuclei: realistic nuclear Hamiltonian (two- and three-body interactions)





D.L. *et al.*, Phys. Rev. C **98**, 014322 (2018)

Question 1: why do we care about SRCs?

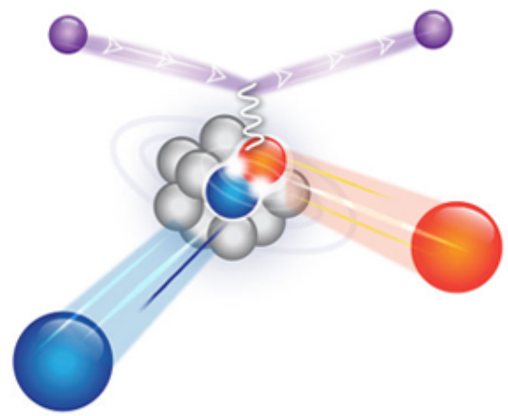
Question 2: can mean-field still be relevant in the study of SRCs?

Def: SRC pairs: pairs of nucleons having large relative momentum compared to their center-of-mass momentum and to the typical nuclear Fermi momentum

Nuclear Short-Range Correlations

O. Hen *et al.*, Rev. Mod. Phys. **89**, 045002 (2017)

lepton scattering from nuclei

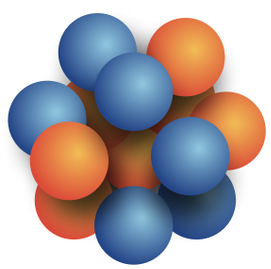


internal structure of nucleons bound in nuclei

interpretation of neutrino oscillation measurements

H. Gallagher *et al.*, Annu. Rev. Nucl. Part. Sci. **61**, 355-378 (2011)

nuclear charge radii



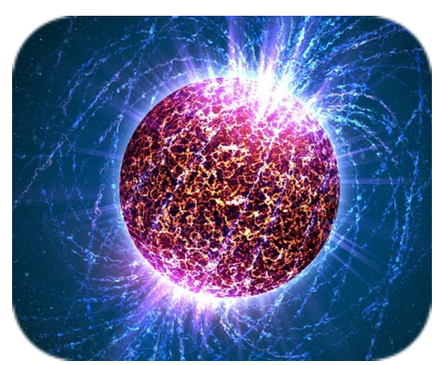
G. A. Miller, *et al.*, Phys. Lett. B **793**, 360-364 (2019)

SRCs

neutrinoless double beta decay matrix elements

F. Simkovic *et al.*, Phys. Rev. C **79**, 055501 (2009)
V. Cirigliano *et al.*, Phys. Rev. Lett. **120**, 202001 (2018)

nuclear symmetry energy

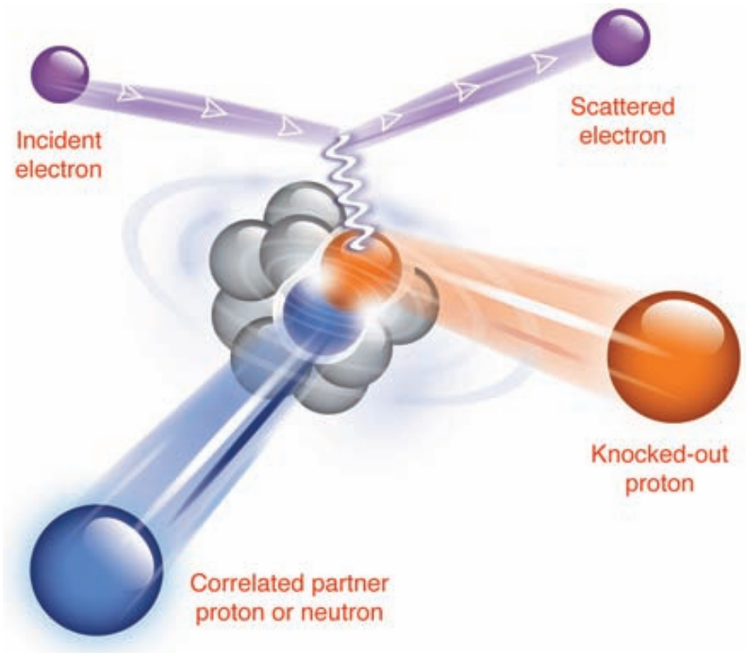


neutron star properties

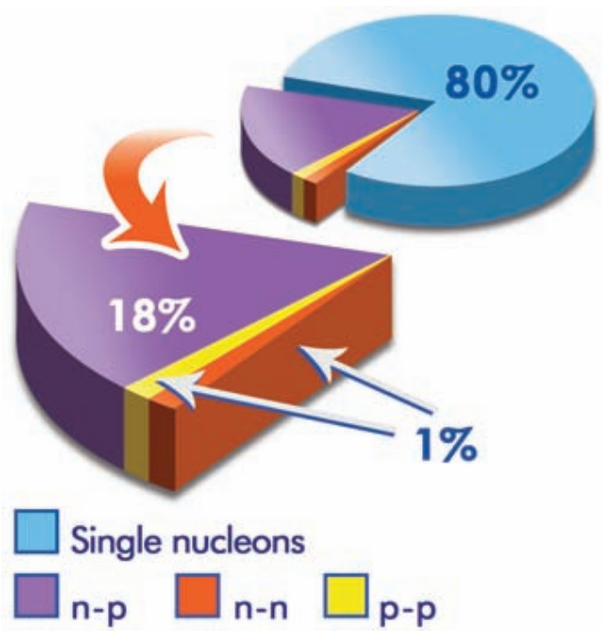
B. A. Li *et al.*, Prog. Part. Nucl. Phys. **99**, 29-119 (2018)

Nuclear Short-Range Correlations

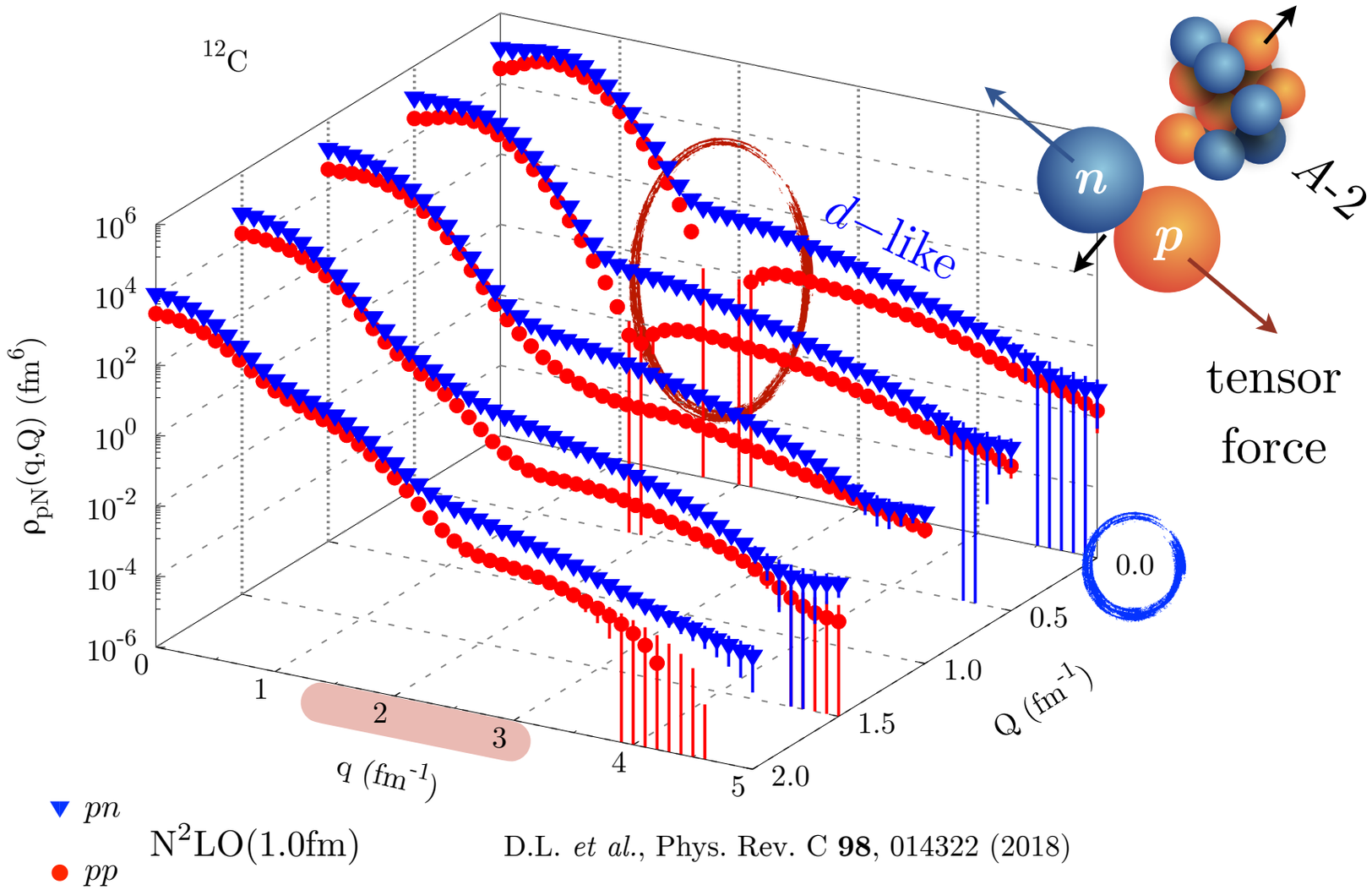
Nucleon knockout experiments



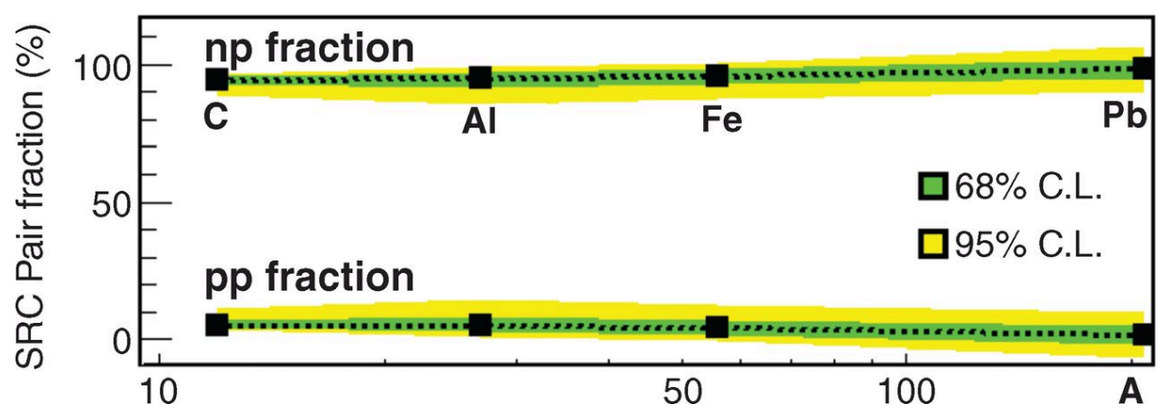
$^{12}C(e, e'pN) \quad p_{miss} \approx 300 - 600\,\text{MeV}$



R. Subedi *et al.*, Science **320**, 1476 (2008)



D.L. *et al.*, Phys. Rev. C **98**, 014322 (2018)



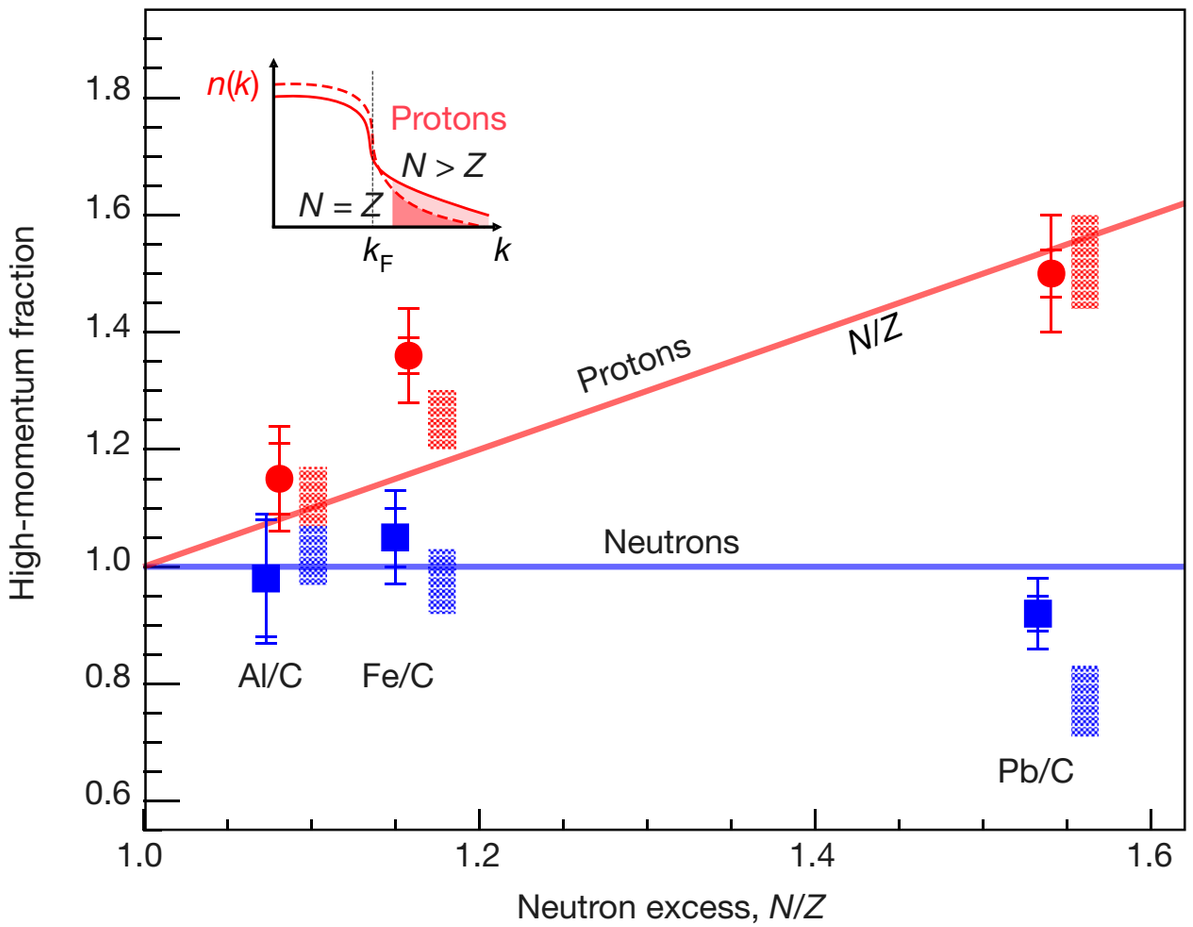
np dominance

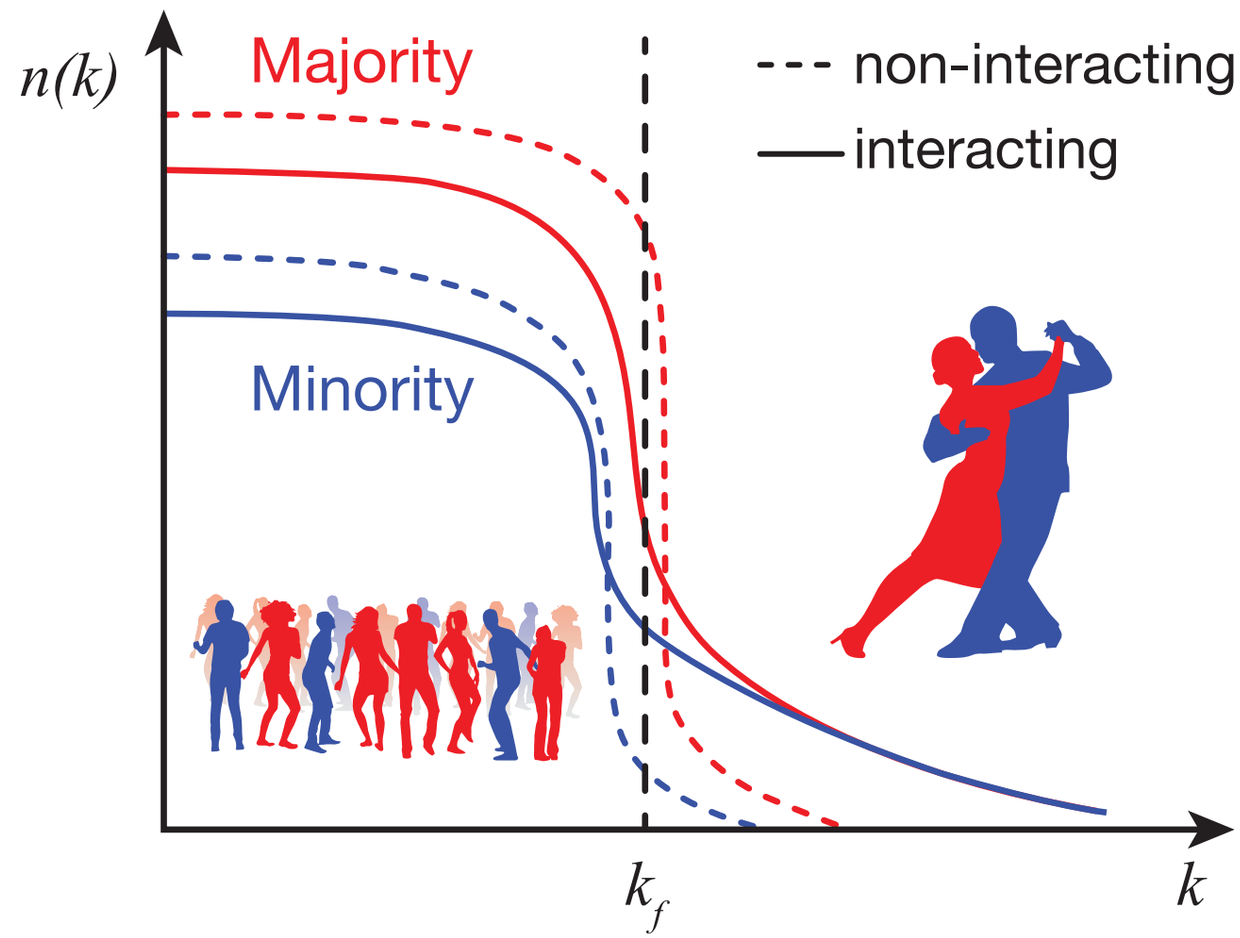
O. Hen *et al.*, Science **346**, 614 (2014)

Nuclear Short-Range Correlations

Nucleon knockout experiments

n & p high-momentum fractions





the fraction of correlated
protons / neutrons
grow / saturate
with neutron excess

analogous to a dance party with a majority of girls: boy-girl interactions will make the average boy dance more than the average girl

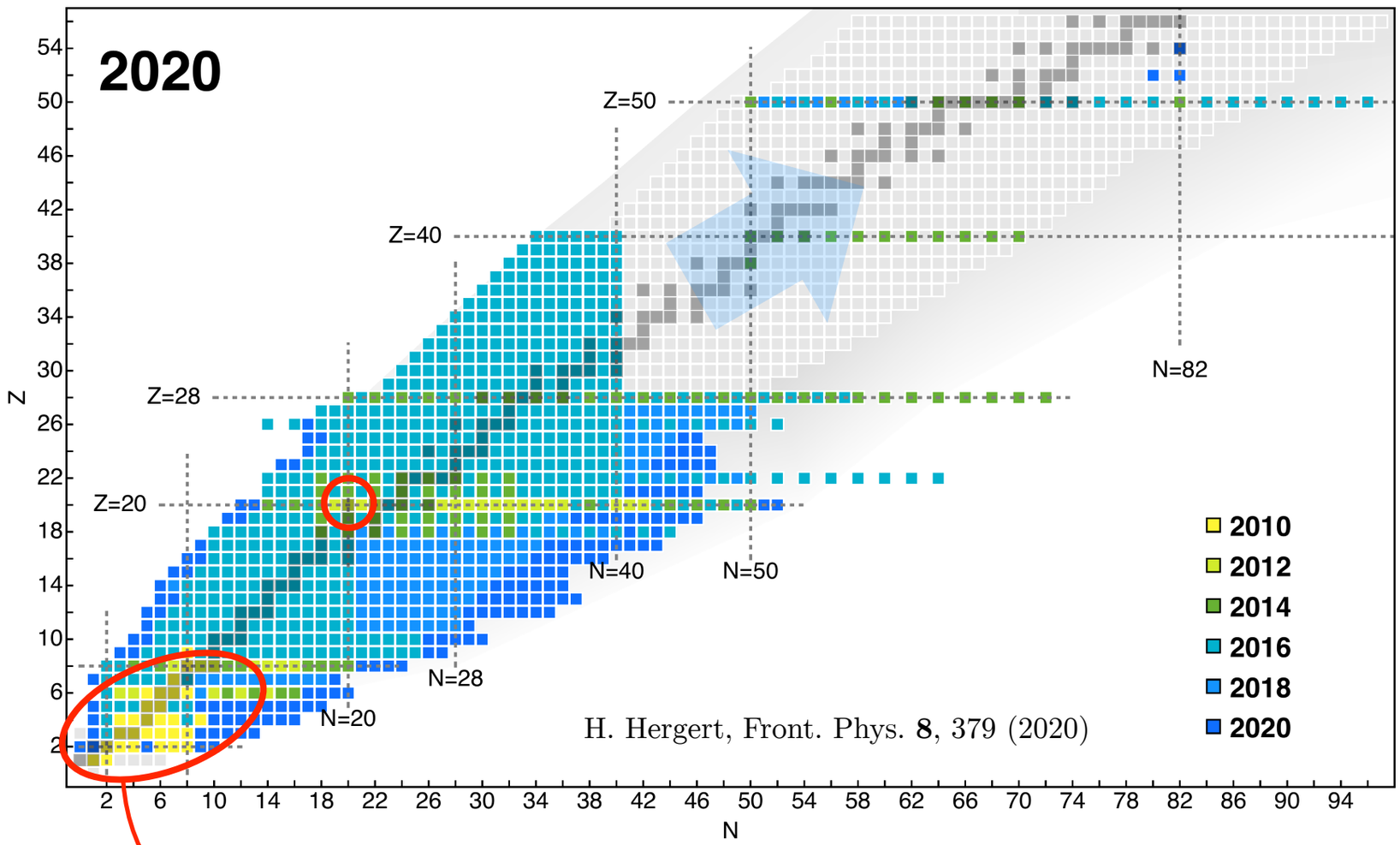
M. Duer *et al.*, Nature **560**, 617-621 (2018)

O. Hen *et al.*, Science **346**, 614 (2014)

Nuclear Short-Range Correlations

Question: how can we *quantitatively* study SRCs and compare to observations?

Need: reliable ab-initio many-body method capable of handling SRCs



several options:

- IMSRG
- CC
- SCGF
- MBPT
- ...

but:

- "soft" Hamiltonians
- weaker SRC
- induced many-body terms

Quantum Monte Carlo $\longrightarrow$ $A \lesssim 24$ (& 40-ish)

Nuclear Short-Range Correlations

Question: how can we *quantitatively* study SRCs and compare to observations?

Need: reliable ab-initio many-body method capable of handling SRCs + effective theory to connect ab-initio results to observables

↓ Quantum Monte Carlo (QMC)

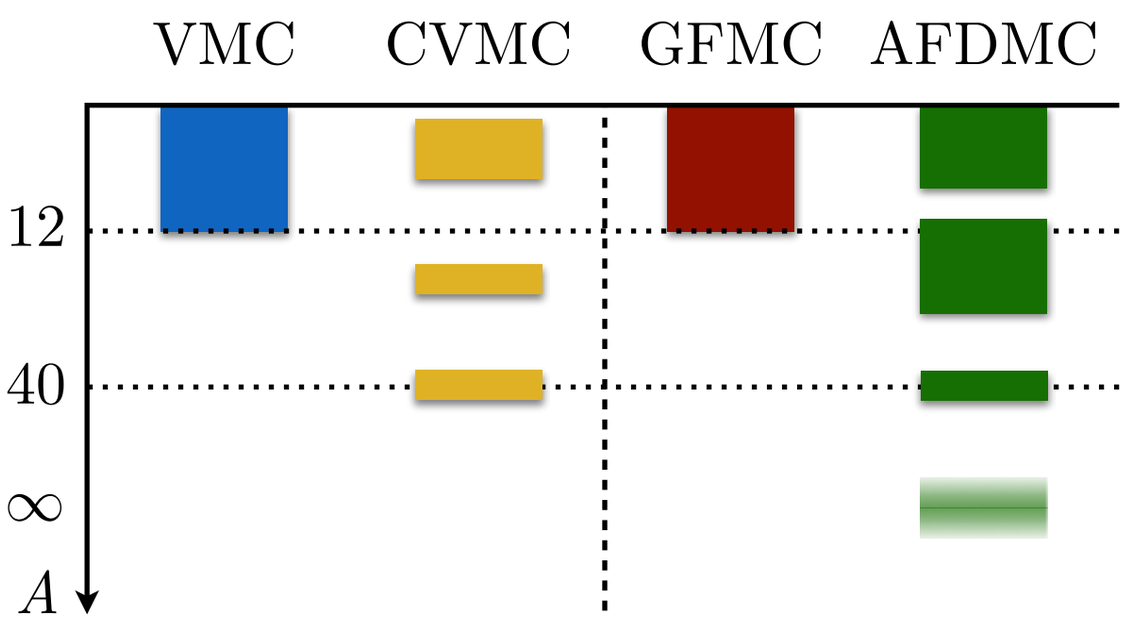
- limited to relatively light nuclei
- difficult to describe relevant reactions

↓ short-range expansion, high-momentum expansion

Generalized Contact Formalism (GCF)

QMC + GCF ⟶ quantitative study of SRCs

Quantum Monte Carlo



$$H = \sum_i T_i + \sum_{i<j} V_{ij} + \sum_{i<j<k} V_{ijk}$$

V_{ij} : fit to NN scattering & d

V_{ijk} : fit to nuclei observables

$\downarrow$

phenomenological & χEFT

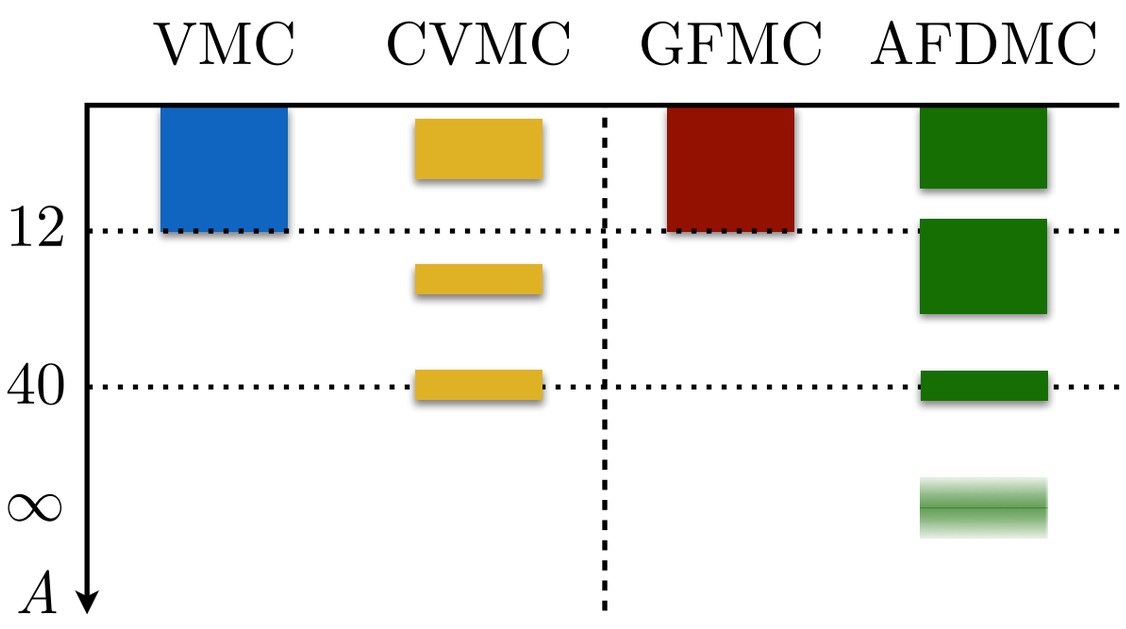
$$|\Psi_T\rangle = \mathcal{F}\,|\Phi\rangle \quad \begin{cases} |\Phi\rangle : \text{ mean-field component, quantum numbers, symmetry} \\ \mathcal{F} : \text{ correlations (2b \& 3b)} \longrightarrow \text{ induced by } H \end{cases}$$

VMC: $\dfrac{\langle\Psi_T|H|\Psi_T\rangle}{\langle\Psi_T|\Psi_T\rangle} = E_T \geq E_0 \longrightarrow |\Psi_T\rangle$ optimization

DMC: $|\Psi_0\rangle \propto \lim_{\tau\to\infty} e^{-(H-E_T)\tau}|\Psi_T\rangle \longrightarrow$ imaginary time propagation

Pros:
- non-perturbative
- controlled approx.
- correlated systems
- bare nuclear interactions
- uncertainty quantification
- scalability

Quantum Monte Carlo



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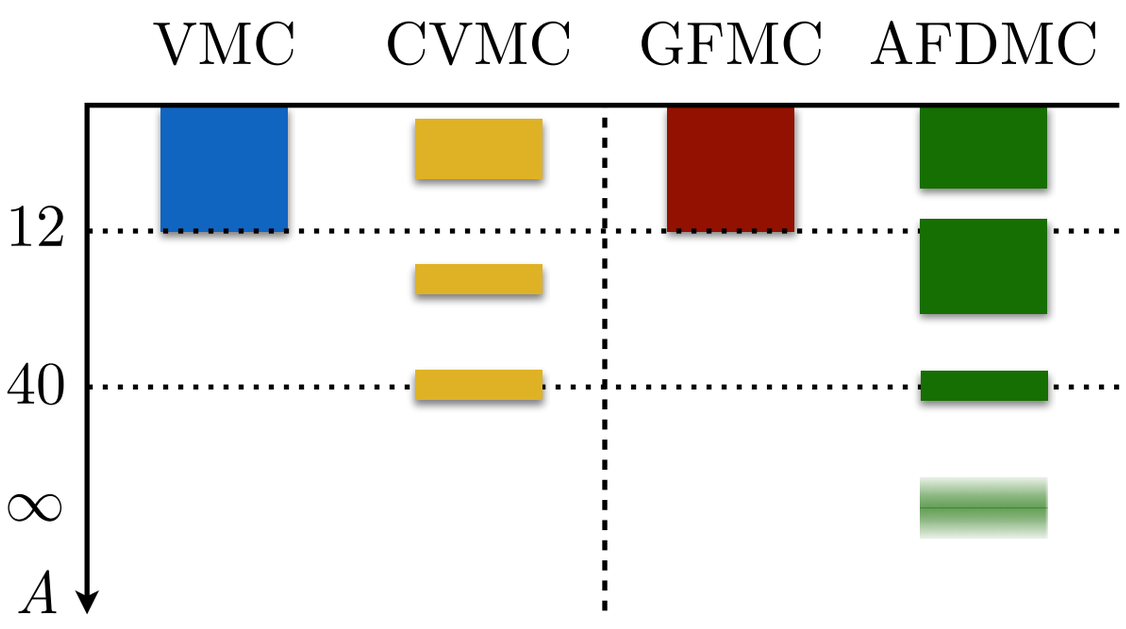
$\downarrow$

- written in r-space: direct access to nucleon coordinates $(r_i,\, r,\, R)$
- spinor structure: direct access to nucleon spin/isospin projections
- transform to k-space: possible access to nucleon momenta $(k,\, q,\, Q)$
- access to the short-range and high-momentum components of the wave function

QMC review: J. A. Carlson *et al.*, Rev. Mod. Phys. **87**, 1067 (2015)

Quantum Monte Carlo



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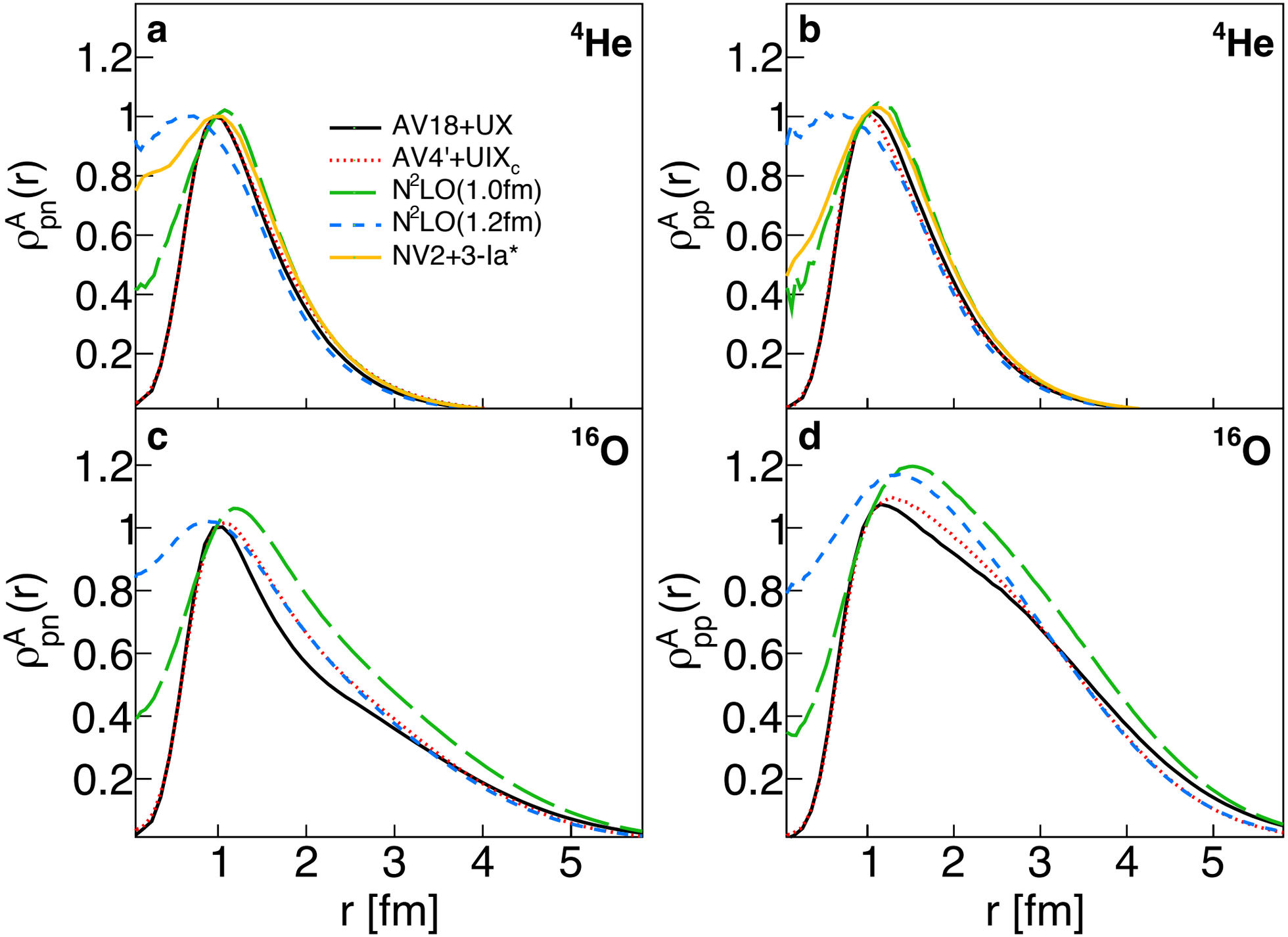
$\downarrow$

$|\Psi_T\rangle$

- single- and two-nucleon coordinate-space distributions: $\rho_N(r_i)$, $\rho_{NN}(r, R)$
- single- and two-nucleon momentum-space distributions: $n_N(k)$, $n_{NN}(q, Q)$

QMC review: J. A. Carlson *et al.*, Rev. Mod. Phys. **87**, 1067 (2015)

Two-nucleon coordinate-space distributions



interactions

phenomen.:
AV18+UIX
AV4'+UIX$_c$

↓

harder

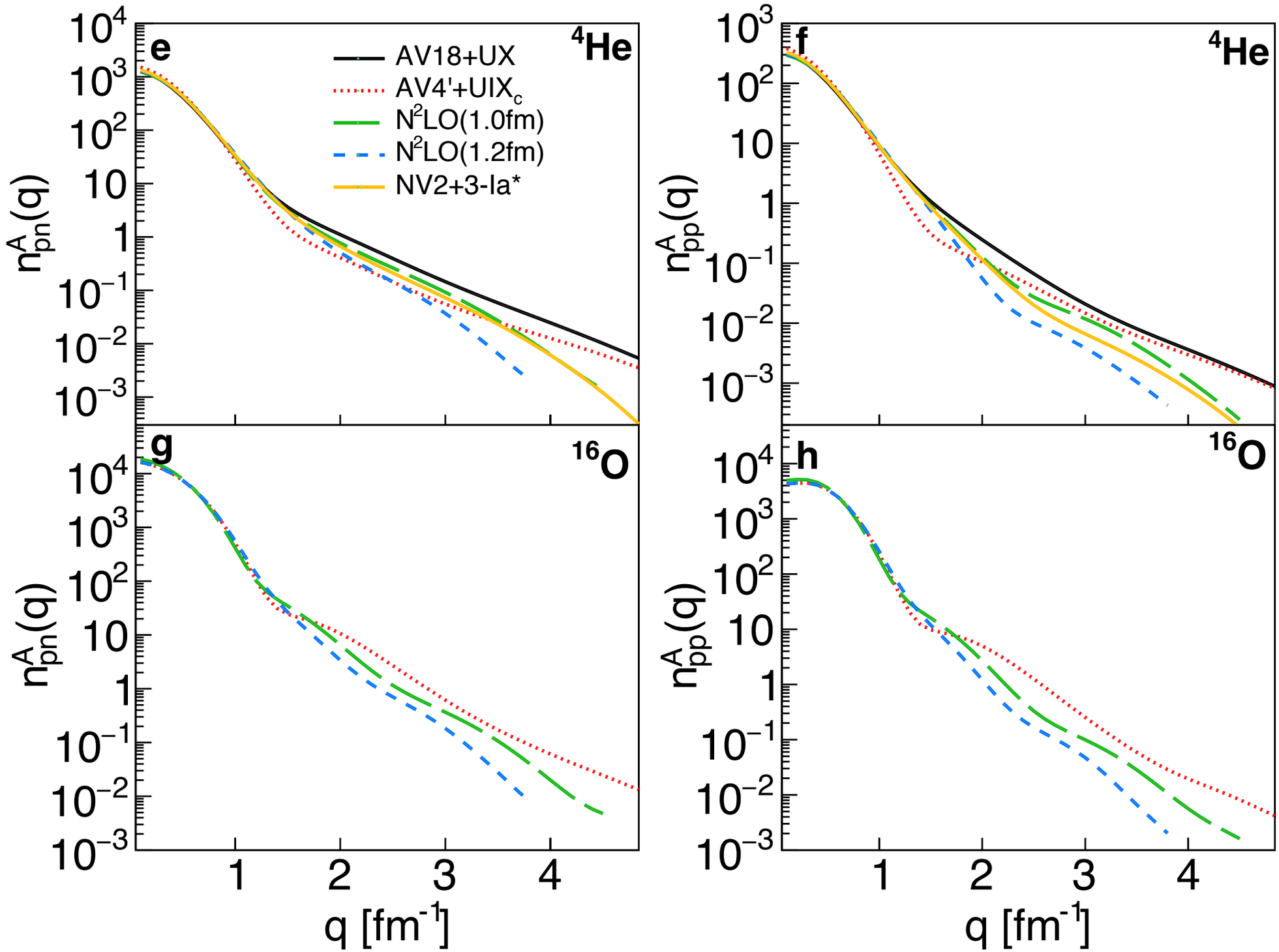
chiral EFT:
N^{2}LO(1.0fm)
N^{2}LO(1.2fm)
NV2+3-Ia*

↓

softer

R. Cruz-Torres, D.L. *et al.*, Nat. Phys. (2020)

Two-nucleon momentum-space distributions



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Generalized Contact Formalism

Idea: factorization of the many-body wave function

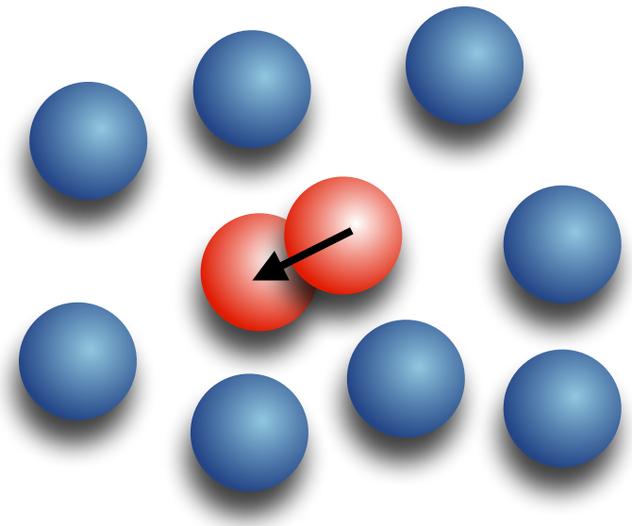
$$\Psi\left(\mathbf{r}_1,\ldots,\mathbf{r}_i,\mathbf{r}_j,\ldots,\mathbf{r}_A\right) \xrightarrow{r_{ij}\to 0} \varphi\left(\mathbf{r}_{ij}\right) A\left(\mathbf{R}_{ij},\{\mathbf{r}_k\}_{k\neq i,j}\right)$$

$$\mathbf{r}_{ij} = \mathbf{r}_i - \mathbf{r}_j$$

$$\mathbf{R}_{ij} = \frac{\mathbf{r}_i + \mathbf{r}_j}{2}$$

$\downarrow$ two-body system

$\downarrow$ (A-2)-body system



$$\left[-\frac{\hbar^2}{m}\nabla^2 + V(r)\right]\varphi(r) = E\varphi(r)$$

for $r_{ij}\to 0$ the energy becomes negligible: $E \ll \dfrac{\hbar^2}{mr^2}$

$\varphi(r)$ $\equiv$ zero-energy solution of the two-body Schrödinger eq.

Note:

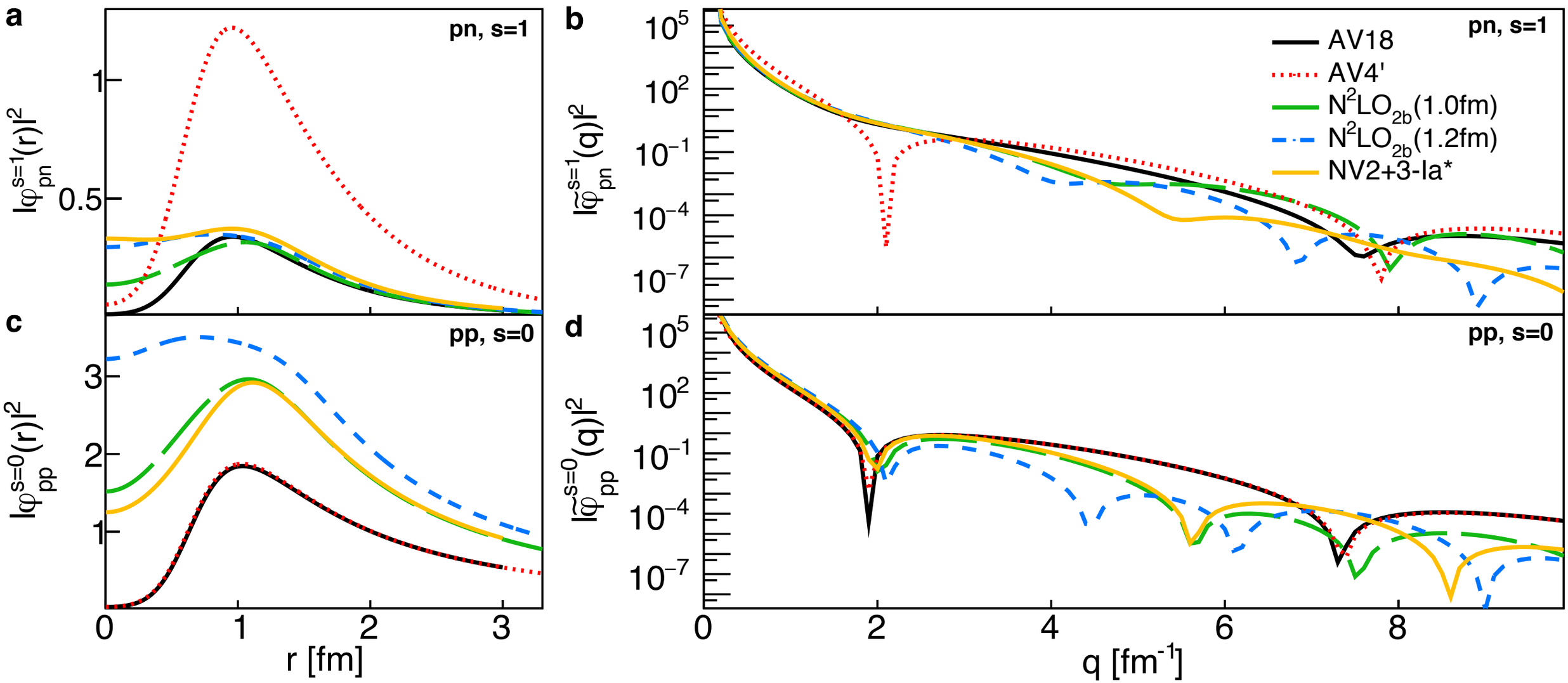
$\varphi(r)$: universal function, nucleus-independent (only depends on $V(r)$)

$A\left(\mathbf{R}_{ij},\{\mathbf{r}_k\}_{k\neq i,j}\right)$: nucleus-dependent function

R. Weiss *et al.*, Phys. Rev. C **92**, 054311 (2015)

Universal functions

$\tilde{\varphi}(q)$: Fourier transform of $\varphi(r)$



interactions

phenomen.:
AV18+UIX ⟶ harder
AV4'+UIX$_c$

chiral EFT:
N²LO(1.0fm)
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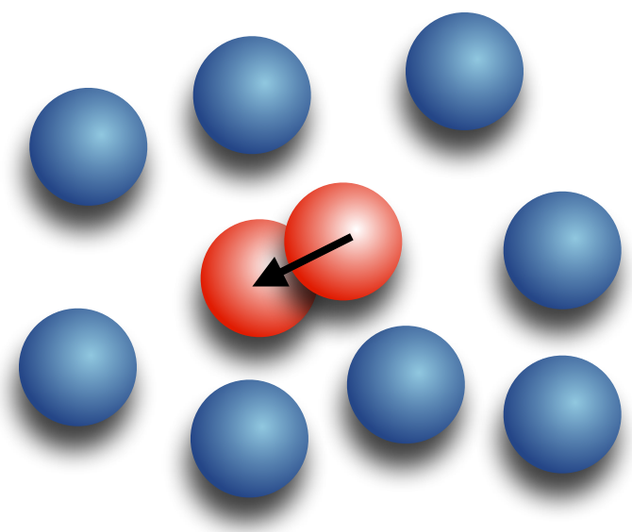
$$\mathbf{r}_{ij} = \mathbf{r}_i - \mathbf{r}_j$$

$$\mathbf{R}_{ij} = \frac{\mathbf{r}_i + \mathbf{r}_j}{2}$$

$\varphi\left(\mathbf{r}_{ij}\right)$ ↓ two-body system

$A\left(\mathbf{R}_{ij},\{\mathbf{r}_k\}_{k\neq i,j}\right)$ ↓ (A-2)-body system



two-body operator $\mathcal{O}(\mathbf{r}_{ij})$:

$$\langle\mathcal{O}\rangle = \sum_{i<j}\langle\Psi\left|\mathcal{O}\left(\mathbf{r}_{ij}\right)\right|\Psi\rangle \xrightarrow{r_{ij}\to 0} \langle\varphi\left|\mathcal{O}\left(\mathbf{r}_{ij}\right)\right|\varphi\rangle\, N\,\langle A|A\rangle = \langle\varphi\left|\mathcal{O}\left(\mathbf{r}_{ij}\right)\right|\varphi\rangle\, C$$

N : number of pairs

$\langle\varphi\left|\mathcal{O}\left(\mathbf{r}_{ij}\right)\right|\varphi\rangle$ ↙ describes the behavior of the pair

$N\,\langle A|A\rangle$ ↘ indicates the probability to find a correlated pair

Def: contact $\quad C = N\,\langle A|A\rangle$

R. Weiss *et al.*, Phys. Rev. C **92**, 054311 (2015)

Generalized Contact Formalism

Note: atomic contact

two component Fermi gas + short-range force (nonzero s-wave scattering length a)

zero-range condition: $r_0 \ll a, d$

interaction range	scattering length	interparticle distance

$$\Psi \xrightarrow{r_{ij}\to 0} \left(\frac{1}{r_{ij}} - \frac{1}{a}\right) A\left(\mathbf{R}_{ij}, \{\mathbf{r}_k\}_{k\neq i,j}\right) \qquad C = 16\pi^2 N_{\uparrow\downarrow} \langle A|A\rangle$$

$N_{\uparrow\downarrow}$: number of spin up/down pairs

several quantities are connected to the contact C

$$k \to \infty \quad \begin{cases} n(k) = \dfrac{C}{k^4} \\ T + U = \dfrac{\hbar^2}{4\pi m a} C + \displaystyle\sum_\sigma \frac{d^3k}{(2\pi)^3} \frac{\hbar^2 k^2}{2m} \left(n_\sigma(k) - \frac{C}{k^4}\right) \end{cases} \longrightarrow$$

experimentally verified in ultra cold atomic systems consisting of ^{40}K and ^{6}Li atoms

and many more...

S. Tan, Ann. Phys. **323**, 2952 (2008); Ann. Phys. **323**, 2971 (2008); Ann. Phys. **323**, 2987 (2008)

Generalized Contact Formalism

Problem: from atomic contact to nuclear contact?

atomic systems

$$\Psi \xrightarrow{r_{ij}\to 0} \left(\frac{1}{r_{ij}} - \frac{1}{a}\right) A\left(\mathbf{R}_{ij}, \{\mathbf{r}_k\}_{k\neq i,j}\right) \qquad r_0 \ll a, d$$

nuclear systems

$$r_0 \approx 1.4\,\text{fm} \qquad a_{s\text{-wave}}^{\text{singlet}} \approx -20\,\text{fm}$$

$$d \approx 1.8\,\text{fm} \qquad a_{s\text{-wave}}^{\text{triplet}} \approx 5.38\,\text{fm}$$

$$\cancel{r_0 \ll a, d}$$

R. Weiss *et al.*, Phys. Rev. C **92**, 054311 (2015)

Generalized Contact Formalism

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atomic systems

$$\Psi \xrightarrow{r_{ij}\to 0} \left(\frac{1}{r_{ij}} - \frac{1}{a}\right) A\left(\mathbf{R}_{ij}, \{\mathbf{r}_k\}_{k\neq i,j}\right) \qquad r_0 \ll a, d$$

$$\downarrow$$

nuclear systems

$$\Psi \xrightarrow{r_{ij}\to 0} \varphi\left(\mathbf{r}_{ij}\right) A\left(\mathbf{R}_{ij}, \{\mathbf{r}_k\}_{k\neq i,j}\right) \qquad \cancel{r_0 \ll a, d}$$

$$\downarrow$$

nucleons: ~~two-component Fermions~~

$$\Psi \xrightarrow{r_{ij}\to 0} \sum_{\alpha} \varphi_{ij}^{\alpha}\left(\mathbf{r}_{ij}\right) A_{ij}^{\alpha}\left(\mathbf{R}_{ij}, \{\mathbf{r}_k\}_{k\neq i,j}\right)$$

channels $\alpha = (l_2 s_2)\, j_2 m_2$

nucleon pair $ij \in \{pp, nn, pn\}$

$\longrightarrow$ nuclear contacts: $C_{ij}^{\alpha\beta} \propto \left\langle A_{ij}^{\alpha} \middle| A_{ij}^{\beta} \right\rangle$

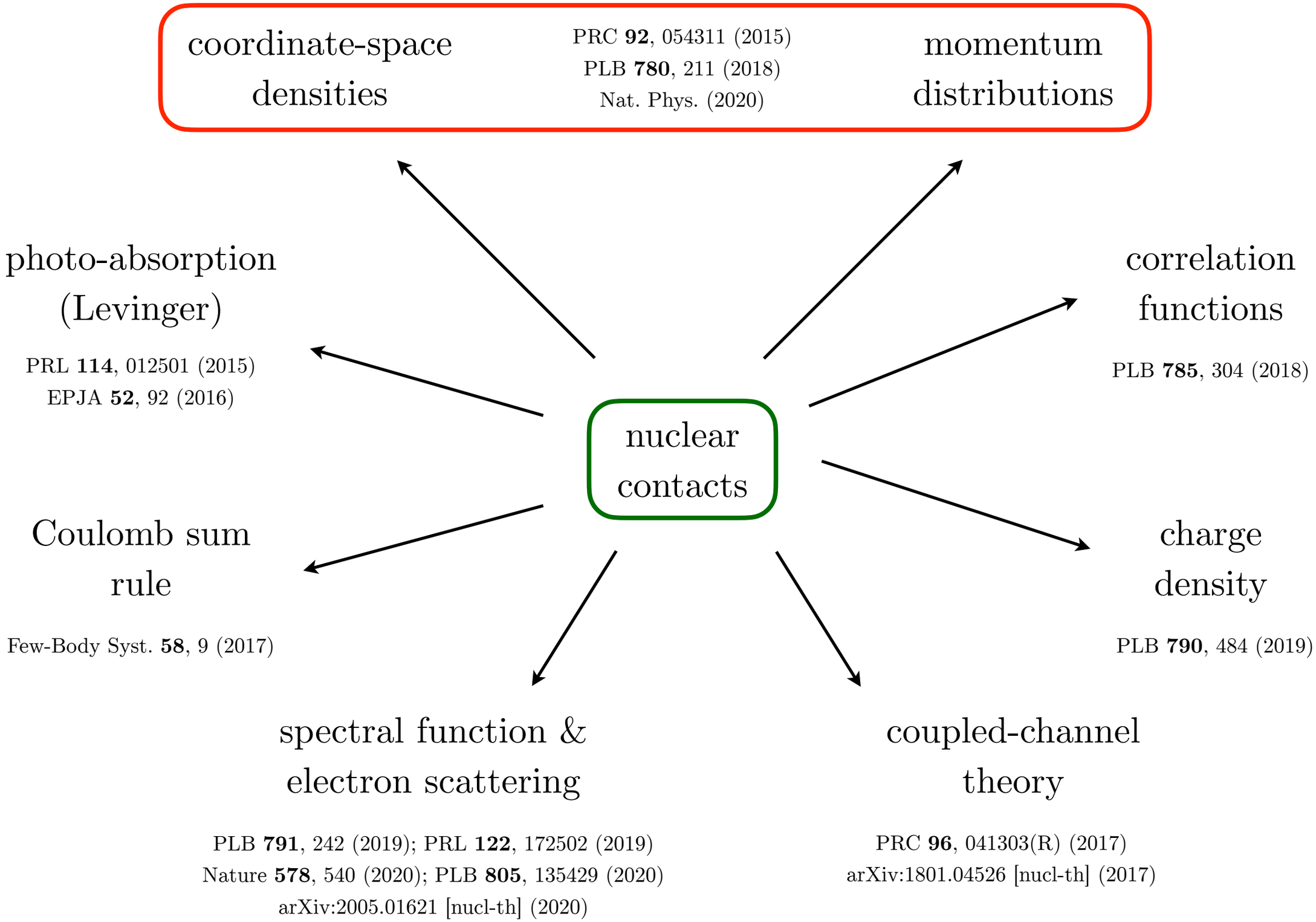
3 matrices of contacts

(deuteron) spin-one: $l_2 = 0, 2;\ s_2 = 1;\ j_2 = 1;\ t_2 = 0$

spin-zero: $l_2 = 0;\ s_2 = 0;\ j_2 = 0;\ t_2 = 1$

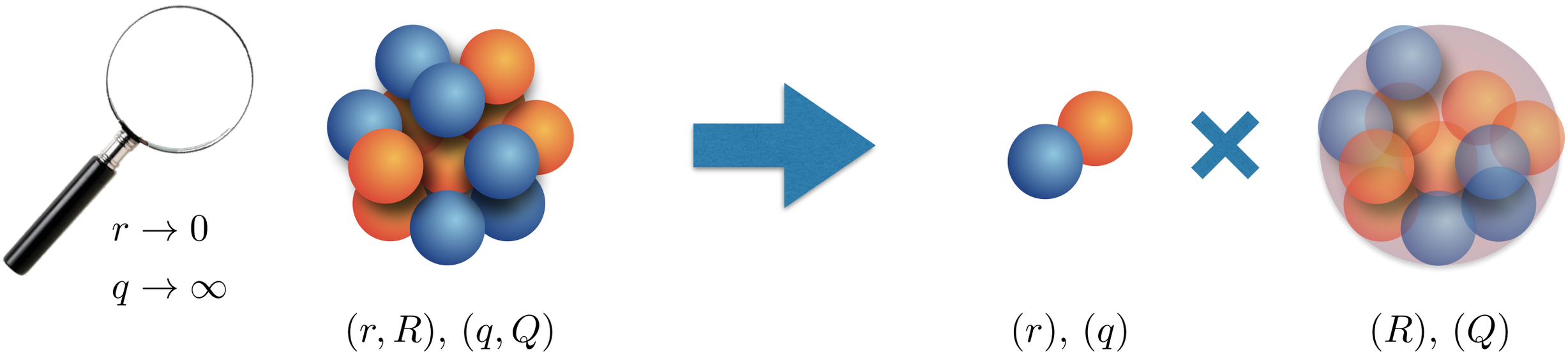
R. Weiss *et al.*, Phys. Rev. C **92**, 054311 (2015)

Generalized Contact Formalism



Generalized Contact Formalism

strong interaction among the nucleons in an SRC pair ⟵ scale separation ⟶ pair's weaker interaction with its surroundings



$$\rho^A_{\alpha,NN}(r,R) = |\varphi^\alpha_{NN}(r)|^2 \times C^A_{\alpha,NN}(R)$$

$$n^A_{\alpha,NN}(q,Q) = |\tilde{\varphi}^\alpha_{NN}(q)|^2 \times \tilde{C}^A_{\alpha,NN}(Q)$$

$$C^A_{\alpha,NN} \equiv \int d\mathbf{R}\, C^A_{\alpha,NN}(R),$$

$$\tilde{C}^A_{\alpha,NN} \equiv \frac{1}{(2\pi)^3} \int d\mathbf{Q}\, \tilde{C}^A_{\alpha,NN}(Q),$$

$\varphi^\alpha_{NN}(r)$, $\varphi^\alpha_{NN}(q)$ ⟶ universal two-body functions

$C^A_{\alpha,NN}(R)$, $\tilde{C}^A_{\alpha,NN}(Q)$ ⟶ density distributions of NN SRC pairs in a nucleus A

$C^A_{\alpha,NN}$, $\tilde{C}^A_{\alpha,NN}$ ⟶ nuclear contacts: number of NN SRC pairs in a nucleus A

Generalized Contact Formalism

$\varphi^{\alpha}_{NN}(r)$
$\varphi^{\alpha}_{NN}(q)$ $\longrightarrow$ model dependent
nucleus independent

$C^{A}_{\alpha,NN}$
$\tilde{C}^{A}_{\alpha,NN}$ $\longrightarrow$ nucleus dependent
model independent?

$\downarrow$

encapsulate the many-body dynamics
driving the formation of SRC pairs

$\downarrow$

they should be:

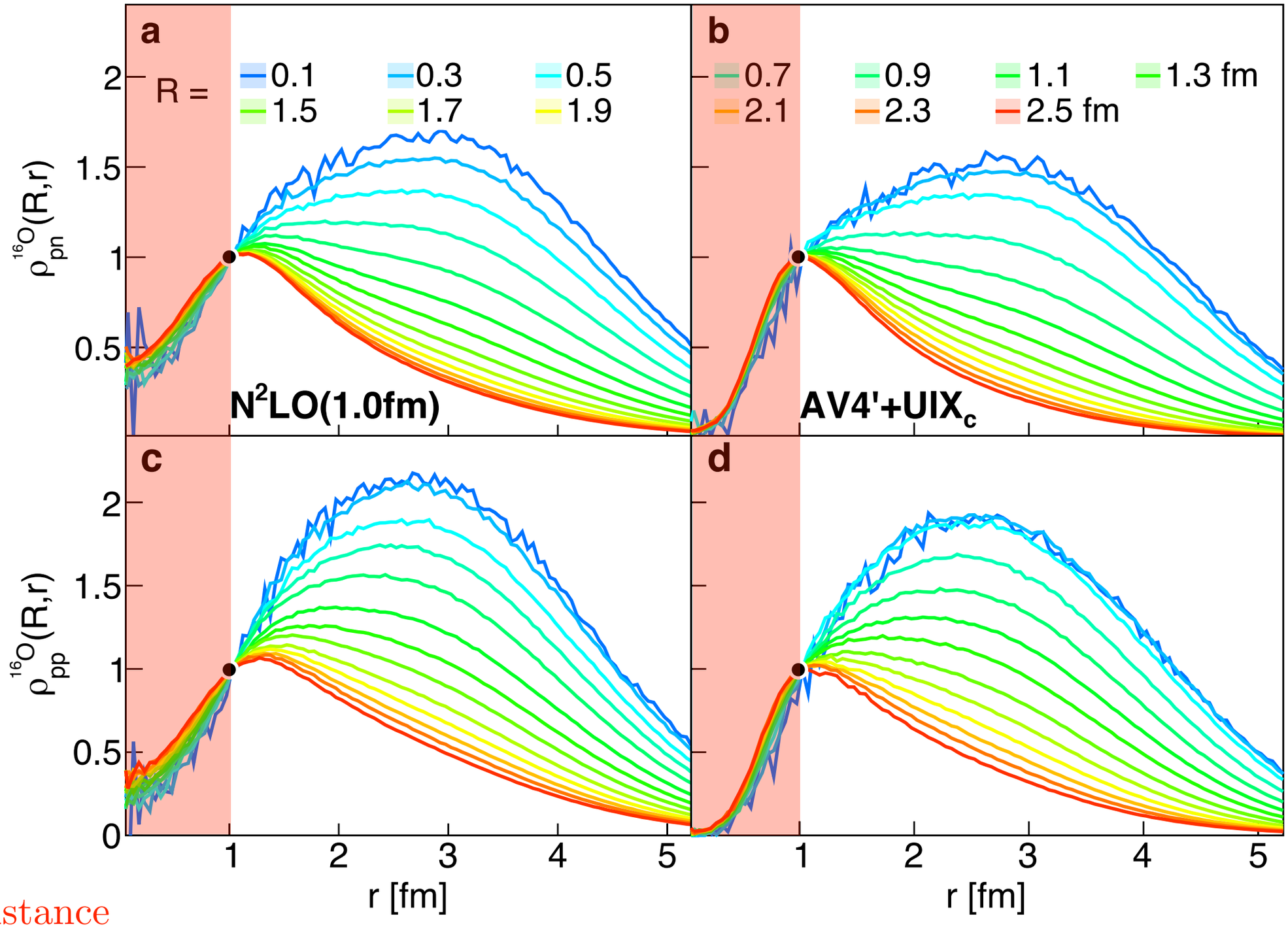
- scale separated from the correlated two-body part
- less sensitive to the short-distance NN interaction

Questions:

- validity of the factorization?
- contacts: short-range vs mean-field?
- r-space vs k-space?
- what can we learn?

QMC + GCF: results

QMC two-nucleon coordinate-space distributions (scaled)



short-distance factorization!

R. Cruz-Torres, D.L. *et al.*, Nat. Phys. (2020)

QMC + GCF: results

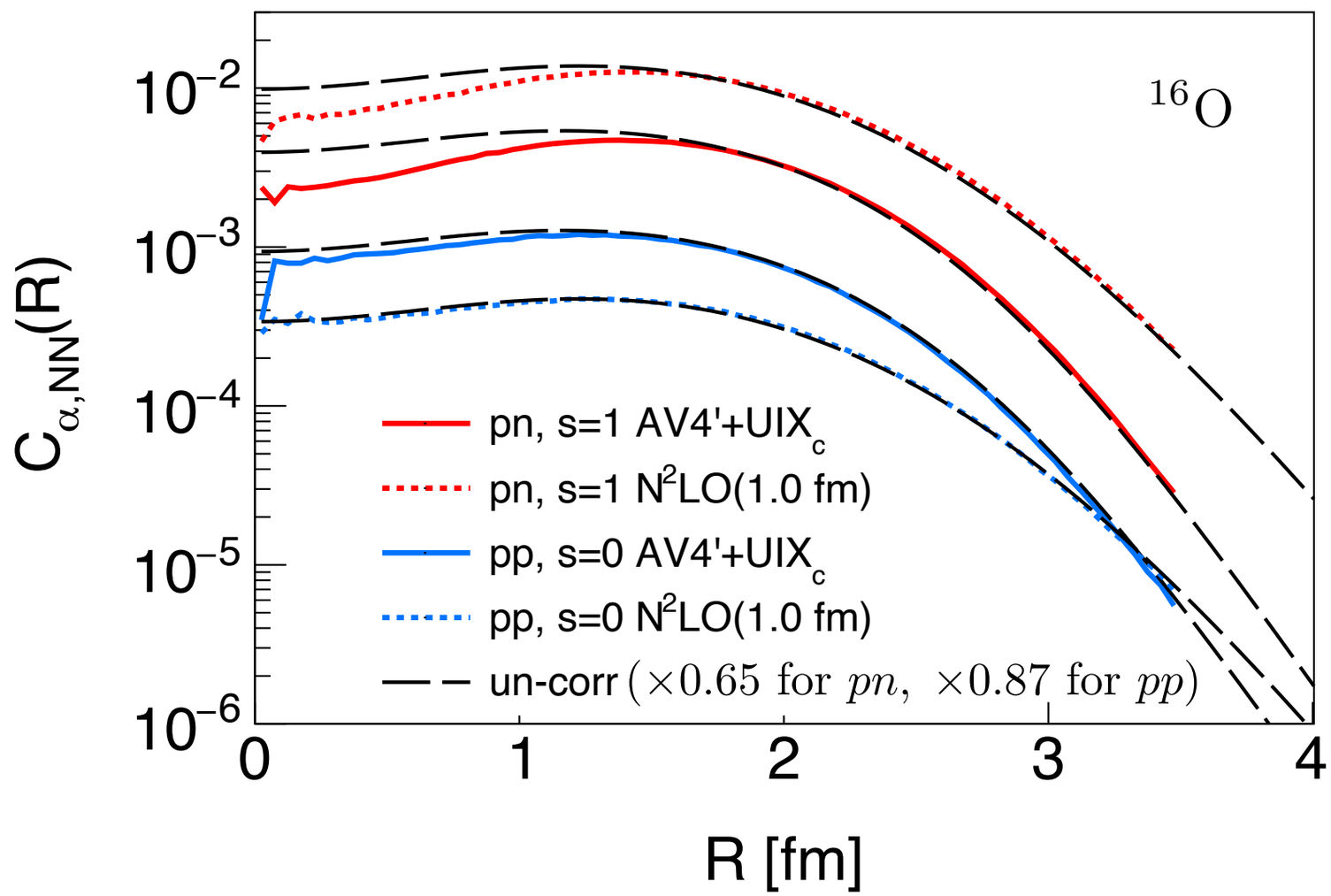
QMC two-nucleon coordinate-space distributions $\longrightarrow$ absolute contact distributions

$\rho^A_{\alpha,NN}(r,R) = |\varphi^\alpha_{NN}(r)|^2 \times C^A_{\alpha,NN}(R)$ $\longrightarrow$ integrate over r in [0-1] fm $\longrightarrow$ $C^A_{\alpha,NN}(R)$

$$C^{^{16}\mathrm{O}}_{NN,\mathrm{uncorr}}(R) = \int d\Omega_R \int_0^{1\,\mathrm{fm}} d\mathbf{r}\, \rho_N^{^{16}\mathrm{O}}\left(\mathbf{R}+\frac{\mathbf{r}}{2}\right) \rho_N^{^{16}\mathrm{O}}\left(\mathbf{R}-\frac{\mathbf{r}}{2}\right)$$

+ Pauli exclusion principle for pp pairs

R. Cruz-Torres *et al.*, Phys. Lett. B **785**, 304-308 (2018)



R. Cruz-Torres, D.L. *et al.*, Nat. Phys. (2020)

agreement is insensitive to the integration range in [0-1] fm

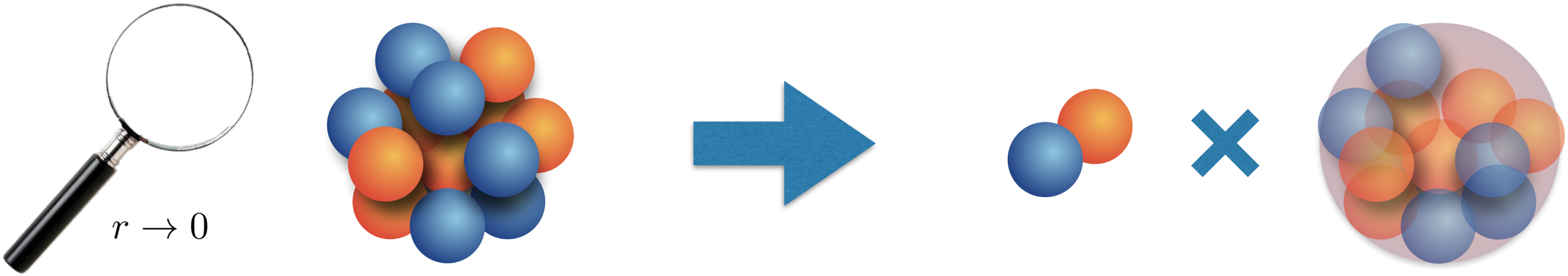
density distribution of SRC pairs (shape of $C(R)$)

$\downarrow$

mean-field property, minimal sensitivity to the short-distance NN interaction!

QMC + GCF: results

strong interaction among the nucleons in an SRC pair ⟵ scale separation ⟶ pair's weaker interaction with its surroundings



$r \to 0$

$q \to \infty$

$(r, R),\ (q, Q)$ $\qquad$ $(r),\ (q)$ $\qquad$ $(R),\ (Q)$

$$\rho^A_{\alpha,NN}(r,R) = |\varphi^\alpha_{NN}(r)|^2 \times C^A_{\alpha,NN}(R)$$

$$n^A_{\alpha,NN}(q,Q) = |\tilde{\varphi}^\alpha_{NN}(q)|^2 \times \tilde{C}^A_{\alpha,NN}(Q)$$

integrate over R or Q:

$$\rho^A_{\alpha,NN}(r) = |\varphi^\alpha_{NN}(r)|^2 \times C^A_{\alpha,NN}$$

$$n^A_{\alpha,NN}(q) = |\tilde{\varphi}^\alpha_{NN}(q)|^2 \times \tilde{C}^A_{\alpha,NN}$$

$$C^A_{\alpha,NN} \equiv \int d\mathbf{R}\, C^A_{\alpha,NN}(R),$$

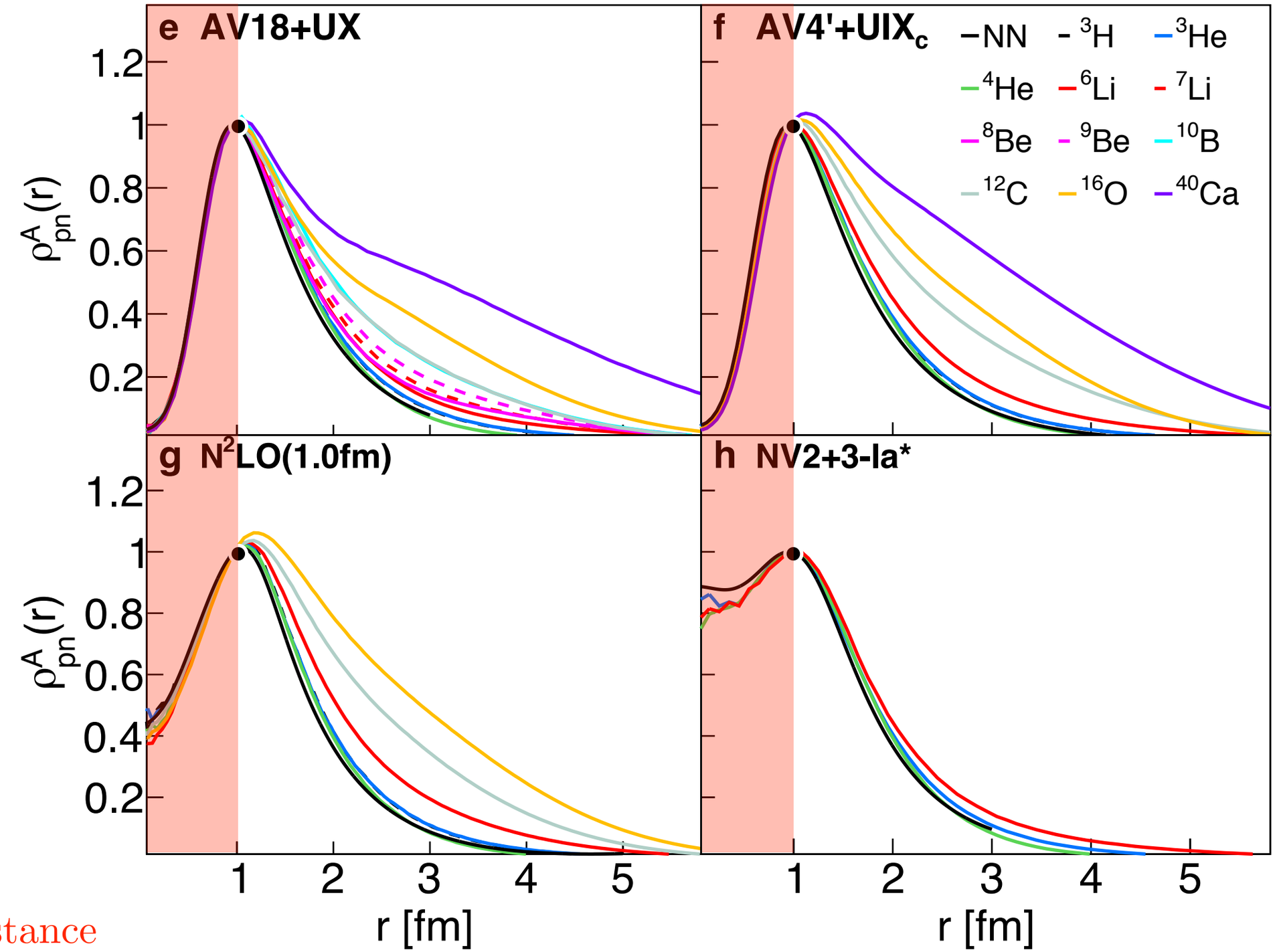
$$\tilde{C}^A_{\alpha,NN} \equiv \frac{1}{(2\pi)^3} \int d\mathbf{Q}\, \tilde{C}^A_{\alpha,NN}(Q),$$

Note: ρ/n norm.: number of pairs

φ norm.: choice

QMC + GCF: results

QMC two-nucleon coordinate-space distributions (scaled)

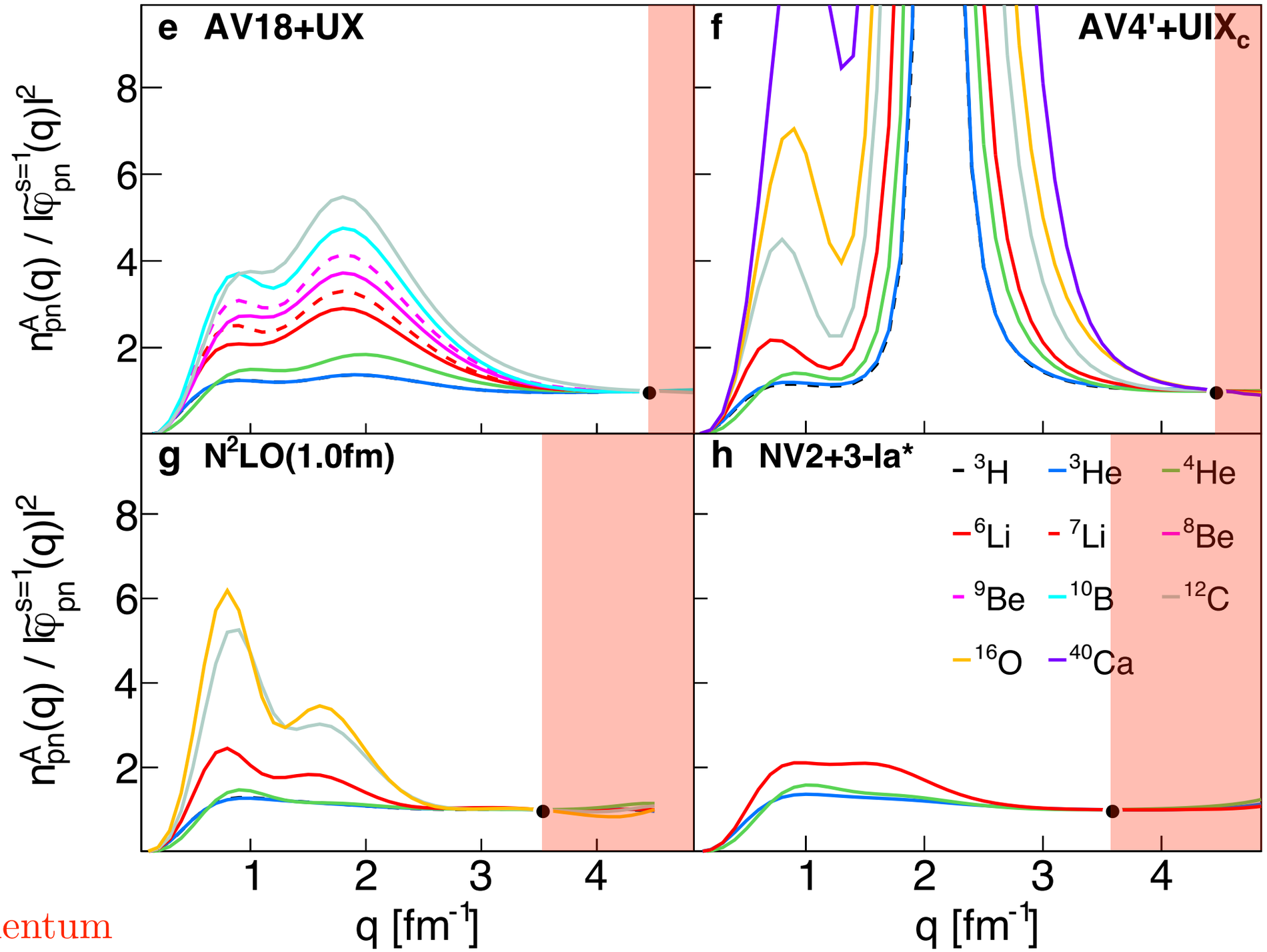


short-distance factorization!

R. Cruz-Torres, D.L. *et al.*, Nat. Phys. (2020)

QMC + GCF: results

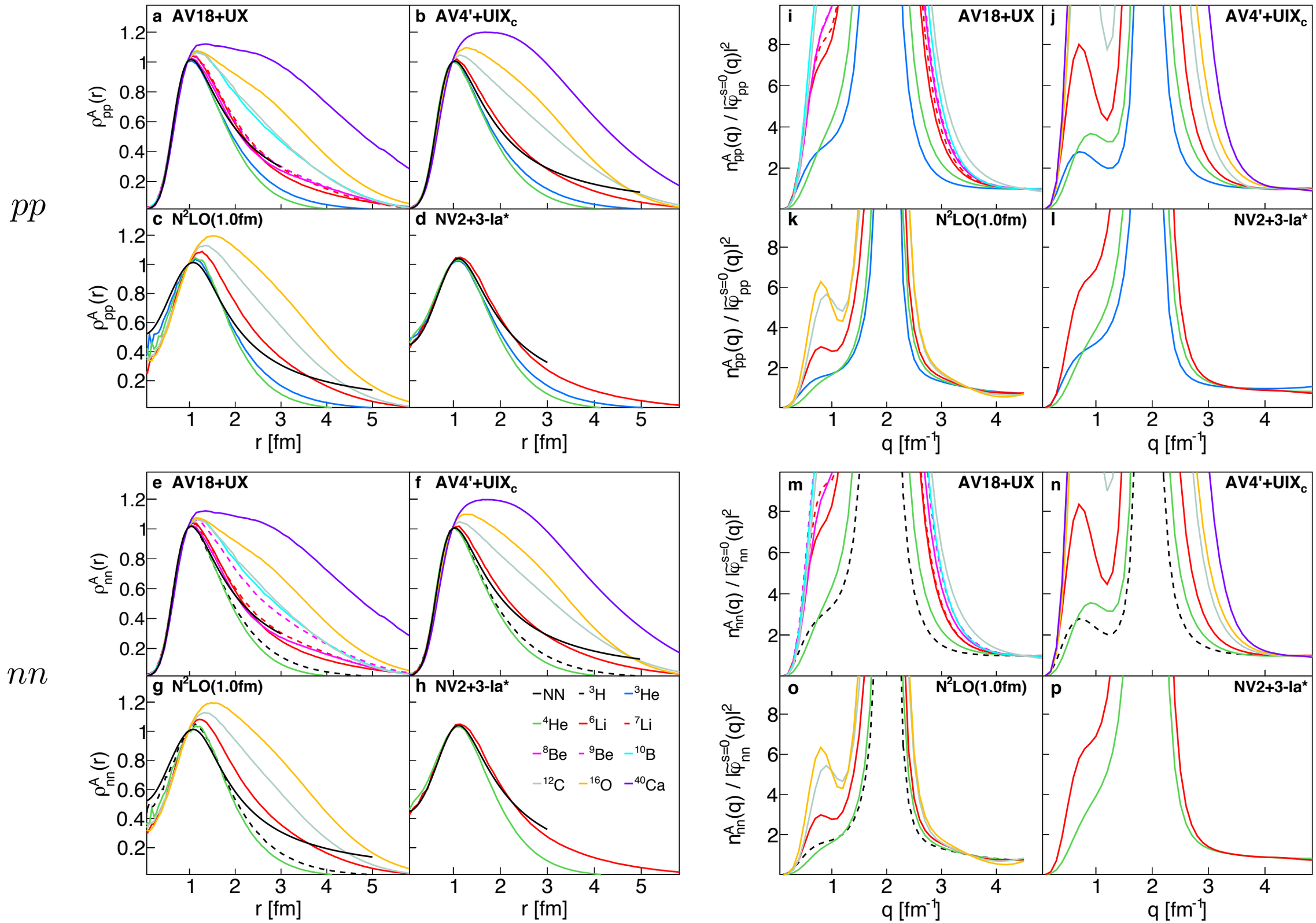
QMC two-nucleon momentum-space distributions (scaled)



high-momentum factorization!

R. Cruz-Torres, D.L. *et al.*, Nat. Phys. (2020)

QMC + GCF: results



R. Cruz-Torres, D.L. *et al.*, Nat. Phys. (2020)

QMC + GCF: results

Nuclear contact ratios

$$\rho^A_{\alpha,NN}(r) = |\varphi^\alpha_{NN}(r)|^2 \times C^A_{\alpha,NN}$$

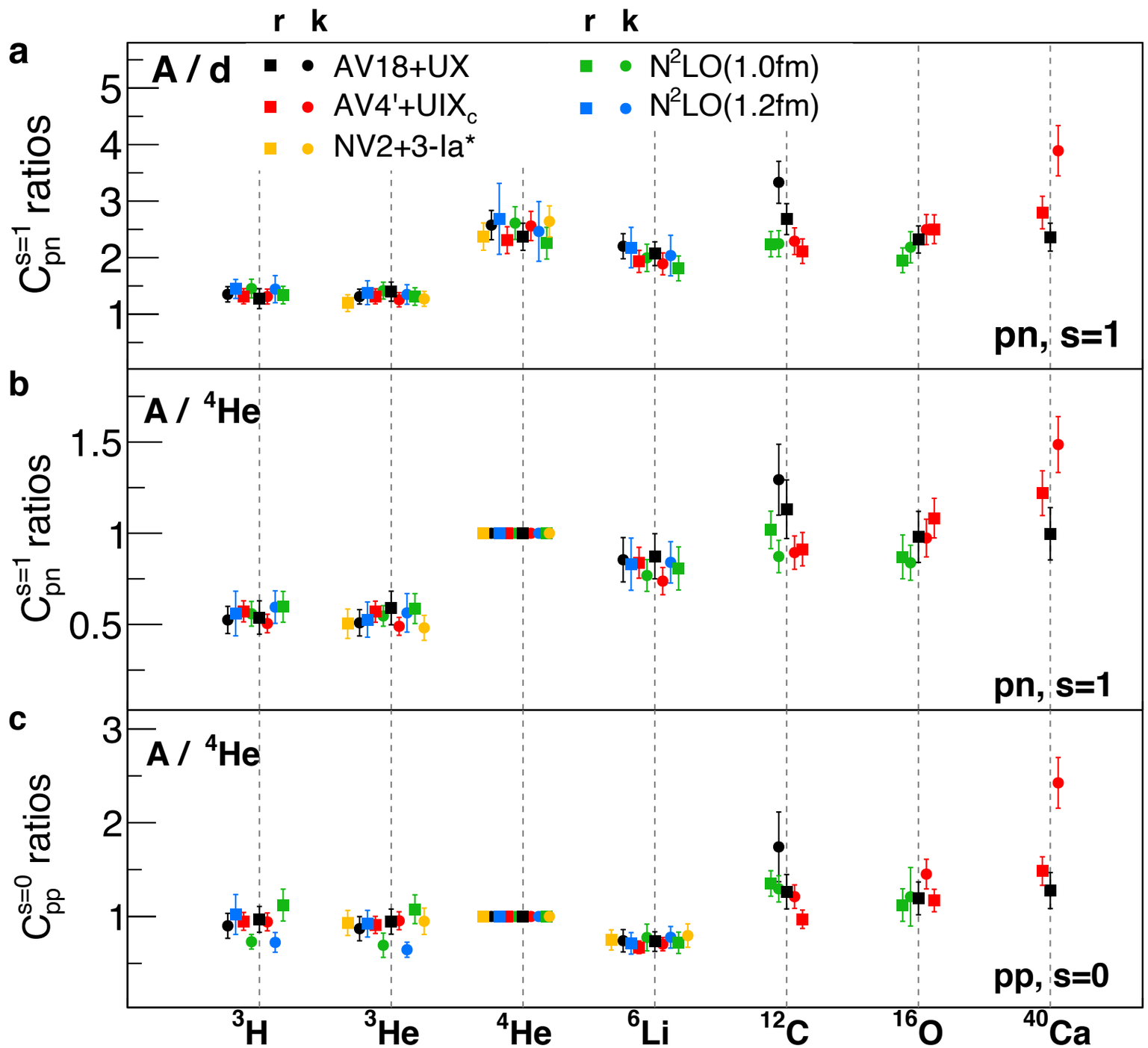
$$n^A_{\alpha,NN}(q) = |\tilde{\varphi}^\alpha_{NN}(q)|^2 \times \tilde{C}^A_{\alpha,NN}$$

$$\downarrow \; A \text{ to } A_0$$

r-space: $$\frac{\rho^A_{\alpha,NN}(r)}{\rho^{A_0}_{\alpha,NN}(r)} = \frac{C^A_{\alpha,NN}}{C^{A_0}_{\alpha,NN}}$$

k-space: $$\frac{n^A_{\alpha,NN}(q)}{n^{A_0}_{\alpha,NN}(q)} = \frac{\tilde{C}^A_{\alpha,NN}}{\tilde{C}^{A_0}_{\alpha,NN}}$$

1. scale- & scheme-independent!
2. same for short-distance & high-momentum pairs!



R. Cruz-Torres, D.L. *et al.*, Nat. Phys. (2020)

QMC + GCF: results

Nuclear contact ratios

Implications:

- contact ratios: determined by mean-field physics, *i.e.*, by the average field of the other A-2 nucleons
- contact ratios: insensitive to the details of the NN interaction at short distance
- contact ratios: simplify calculations for heavier nuclei!

Example:

hard interactions (such as AV18) $\longrightarrow$ difficult to use in many-body calculations of medium-mass nuclei

1. calculate $C^{A_0}_{\alpha,NN}$ for a light nucleus A_0 using the hard interaction
2. calculate the ratio $C^{A}_{\alpha,NN}/C^{A_0}_{\alpha,NN}$ using a soft interaction
3. multiply the two to get $C^{A}_{\alpha,NN}$ for the hard interaction

bonus 1: works in both r- and k-space

bonus 2: many observables have been already derived with the GCF

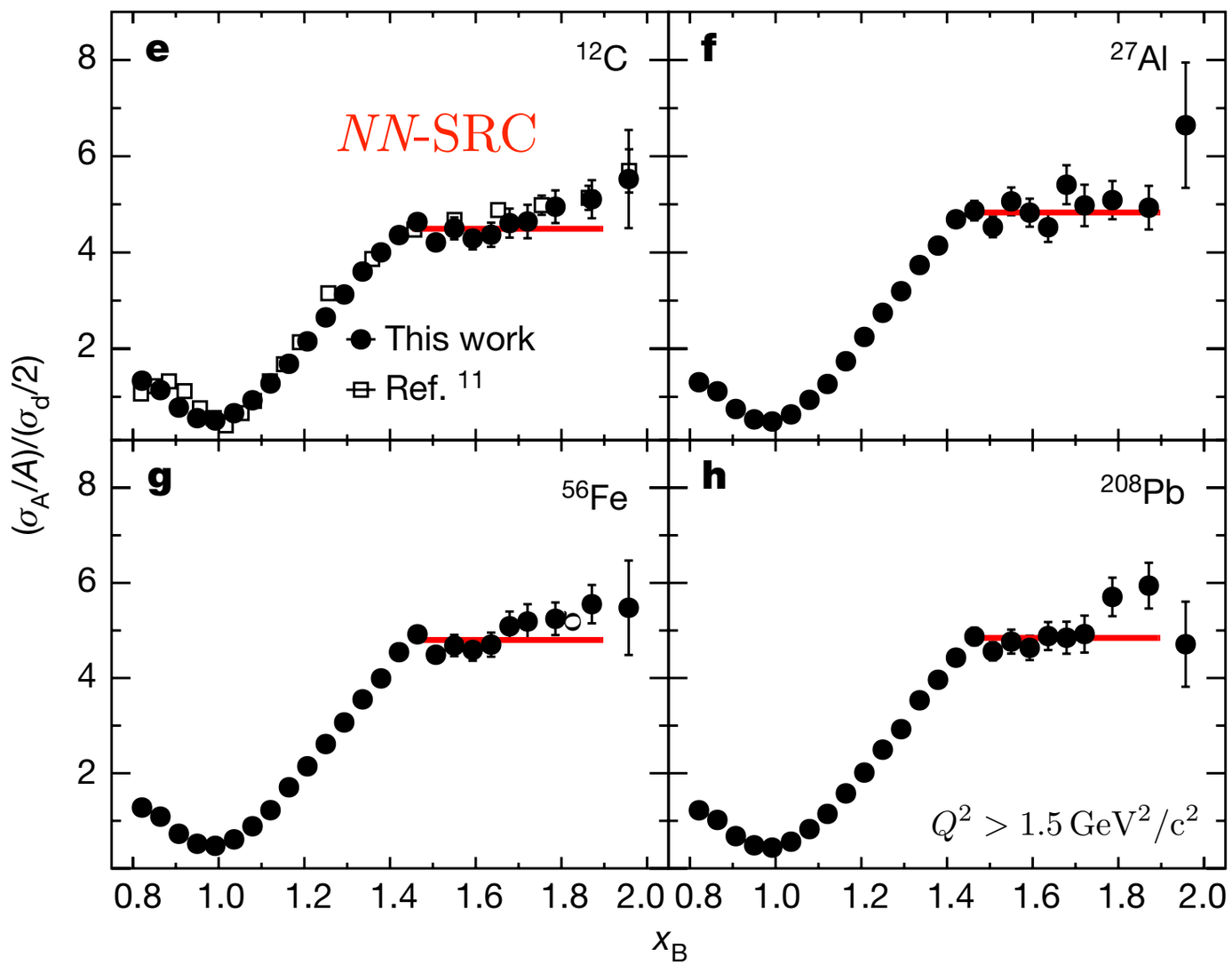
R. Cruz-Torres, D.L. *et al.*, Nat. Phys. (2020)

QMC + GCF: results

Nuclear contact ratios

Implications:

- A/d (e,e') inclusive cross section ratios: observed scaling for x_B>1.5



B. Schmookler *et al.*, Nature **566**, 354-358 (2019)

extraction of SRC scaling coefficient $a_2(A/d)$

traditionally:

- interpreted as relative abundance of SRC pairs
- thought to be sensitive to the nature of the NN interaction
- can be computed as k- or r-space distribution ratios

contact ratios: doubts about the sensitivity of $a_2(A/d)$ to the nuclear interaction!

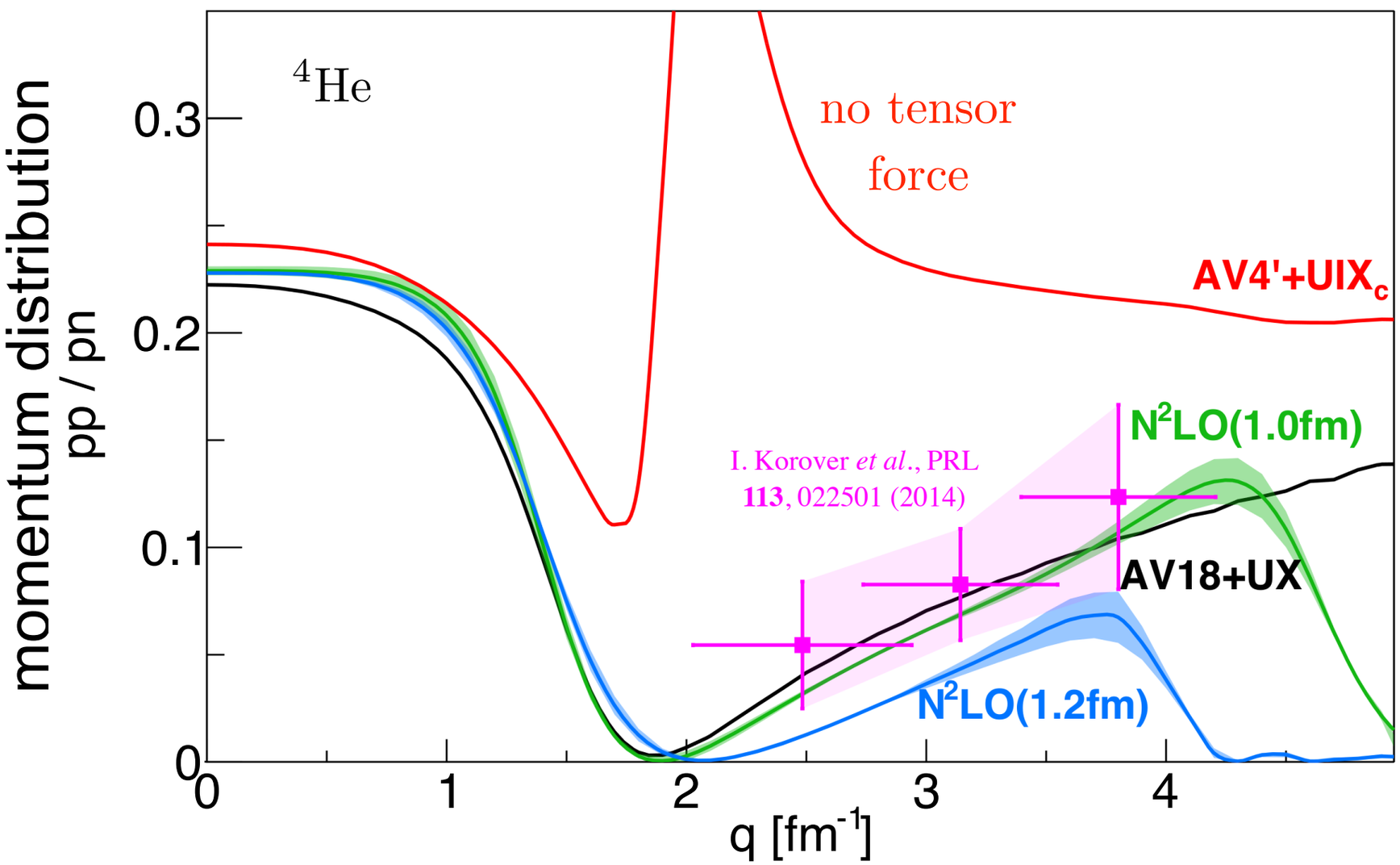
R. Cruz-Torres, D.L. *et al.*, Nat. Phys. (2020)

QMC + GCF: results

Nuclear contacts

Implications:

- exclusive measurements of two-nucleon knockout $A(e,e'NN)$: sensitive to NN interaction

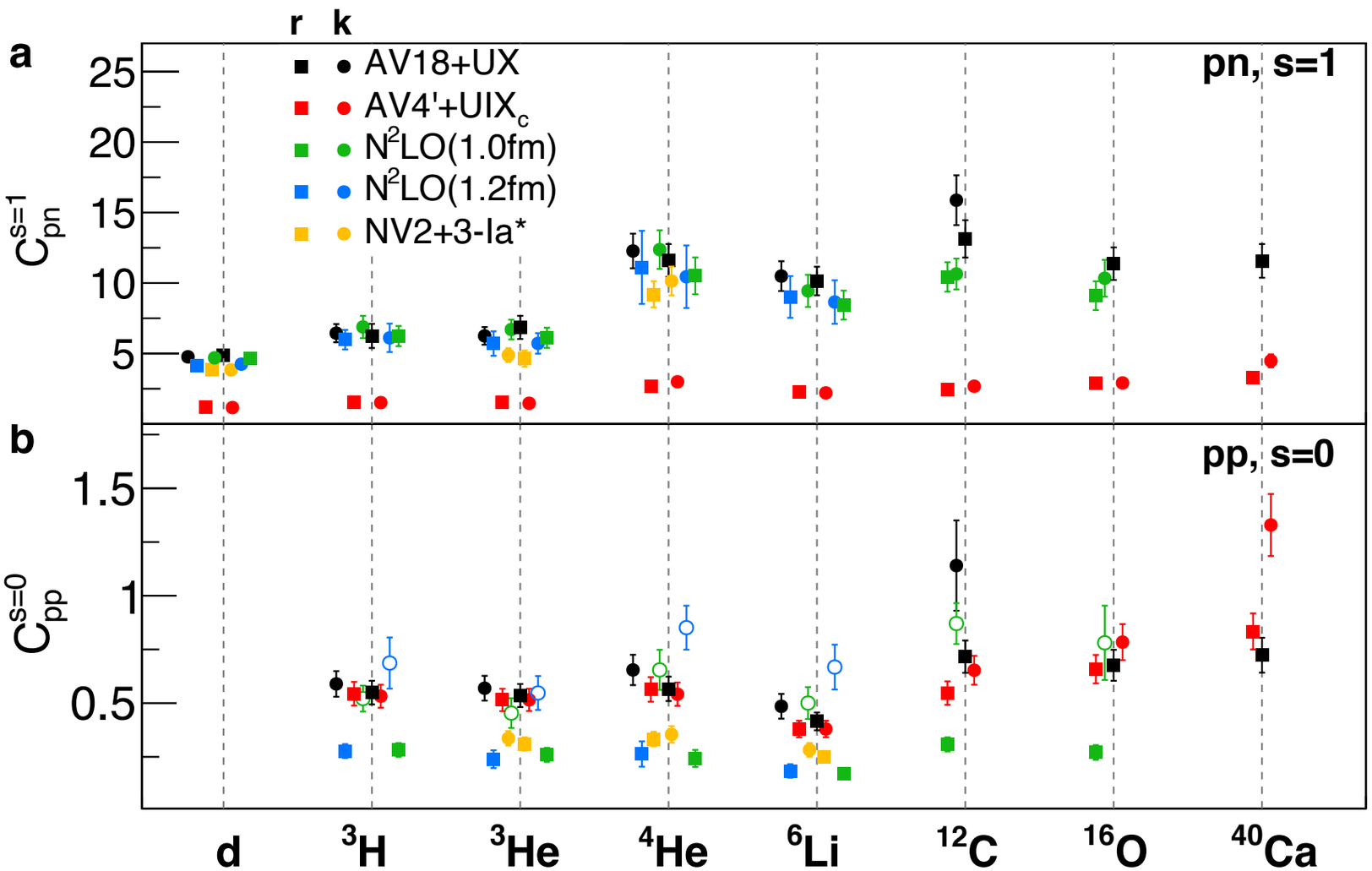


contacts: key for relating $A(e,e'NN)$ measurements to NN interaction models and ab-initio many-body calculations!

R. Cruz-Torres, D.L. *et al.*, Nat. Phys. (2020)

QMC + GCF: results

Nuclear contacts



pn, $s = 1$ channel

- r- to k-space equivalence
- scale & scheme independ.

↓

exception: AV4'+UIX$_c$

expected: no tensor force!

pp, $s = 0$ channel

- more complex
- similar conclusions

pp discrepancy:

- regulator artifacts and three-body effects: difficult to identify a clear high-momentum scaling plateau in the spin-0 pp channel
- A to ^{4}He contact ratios: r- to k-space equivalence ⟶ pp discrepancy not beyond three-body level

R. Cruz-Torres, D.L. *et al.*, Nat. Phys. (2020)

Summary & Perspectives

- QMC calculations have been performed for nuclei from ^{2}H to ^{40}Ca with different nuclear interaction models: phenomenological and chiral EFT
- QMC r- and k-space distributions have been analyzed using the GCF and spin/isospin-dependent nuclear contacts and contact ratios have been extracted
- Result: universal factorization of the many-body nuclear wave function at short-distance into a strongly-interacting pair and a weakly-interacting residual system
- Result: position-momentum equivalence of SRC
- Result: the relative abundance of SRC pairs in the nucleus is a long-range (mean-field) quantity that is insensitive to the short-distance nature of the nuclear force

Future work

- Many-body methods benchmark
- Applications of the nuclear contacts and contact ratios
- Derive next order corrections to the current formulation of the GCF
- Study three-nucleon correlations
- Combining GCF with long-range/low-momentum expansions

Thank you!!