LA-UR-23-20516

Applications of the GCF and the study of 3N SRCs

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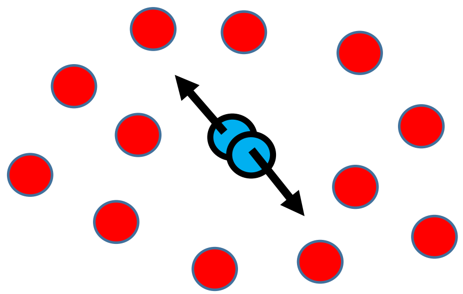
4th international workshop on quantitative challenges in short-range correlations and the EMC effect research, CEA Paris-Saclay, 2023

Generalized Contact Formalism

Generalizing the atomic contact theory of Tan

$$\Psi(r_1, r_2, \dots, r_A) \xrightarrow{r_{12}\to 0} \varphi(\boldsymbol{r}) \times A\left(\boldsymbol{R}, \{\boldsymbol{r}_k\}_{k\neq 1,2}\right)$$

universal function



For any **short-range** two-body operator $\hat{O}$

$$\langle \hat{O} \rangle = \langle \varphi | \hat{O}(r) | \varphi \rangle \, C$$

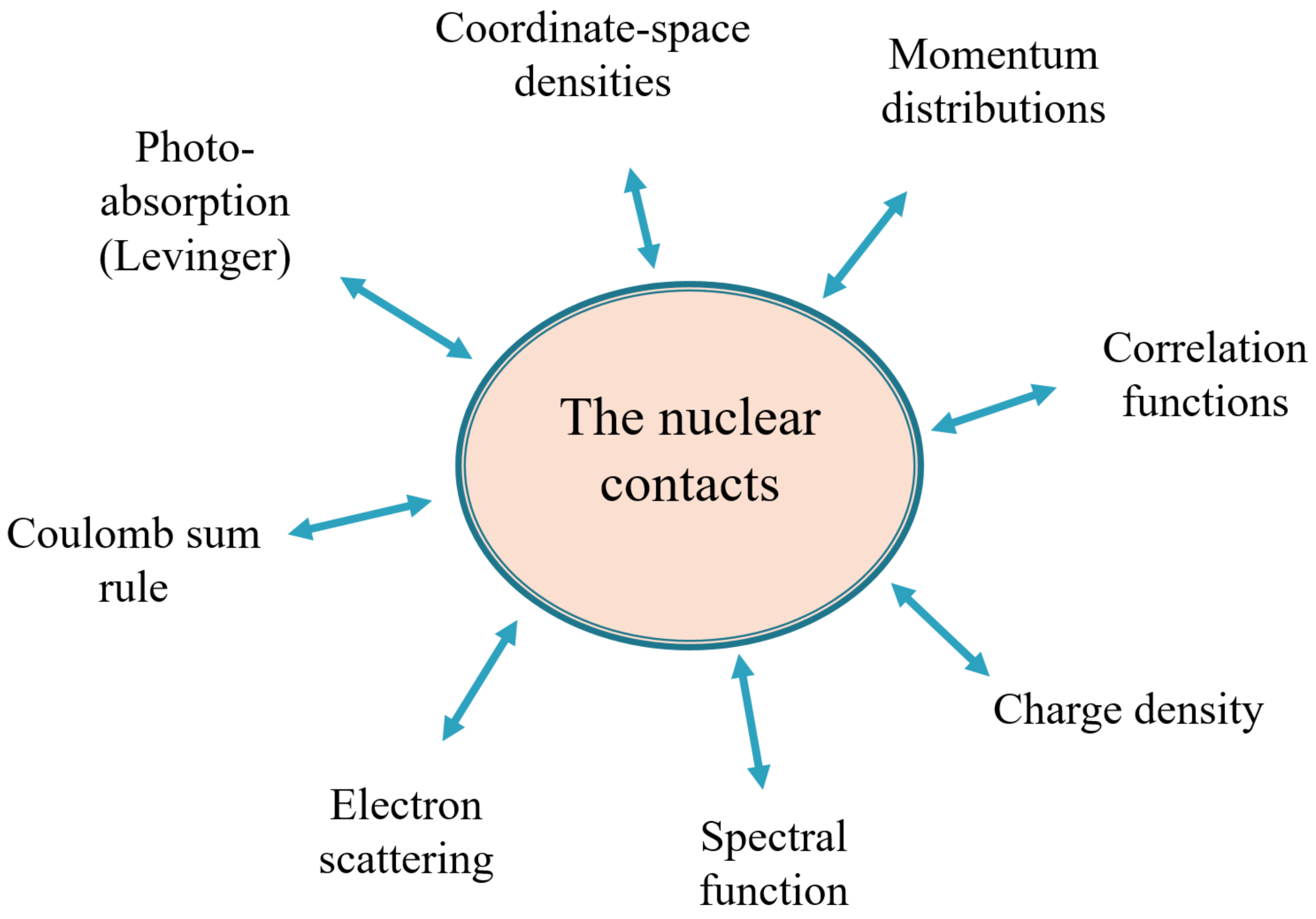
$$C \propto \langle A | A \rangle$$

- Two-body dynamics
- Universal for all nuclei
- Simply calculated

- Number of correlated pairs
- Depends on the nucleus
- Independent of the operator

RW, B. Bazak, N. Barnea, PRC 92, 054311 (2015)

The nuclear contact relations



RW, B. Bazak, N. Barnea, PRC 92, 054311 (2015)

RW, B. Bazak, N. Barnea, PRL 114, 012501 (2015)

RW, R. Cruz-Torres, N. Barnea, E. Piasetzky and O. Hen, PLB 780, 211 (2018)

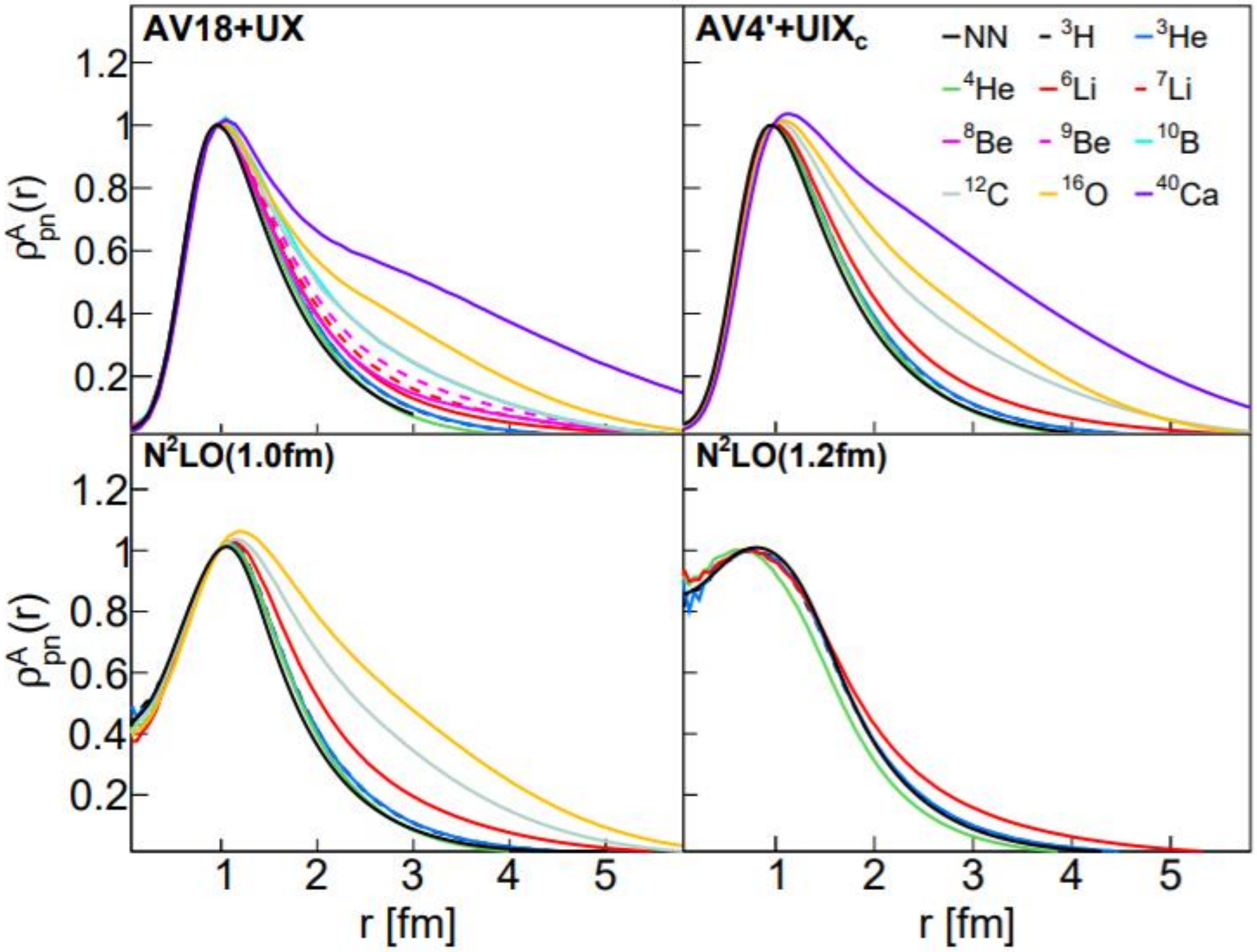
RW, I. Korover, E. Piasetzky, O. Hen and N. Barnea, PLB 791, 242 (2019)

R. Cruz-Torres, D. Lonardoni, RW, et al., Nature Physics (2020)

A. Schmidt, J.R. Pybus, RW, et al., Nature 578, 540 (2020)

Two-body density

$$\langle \hat{O} \rangle = \langle \varphi | \hat{O}(r) | \varphi \rangle \, C$$



R. Cruz-Torres, D. Lonardoni, RW, et al., Nature Physics (2020)

Three-body correlations

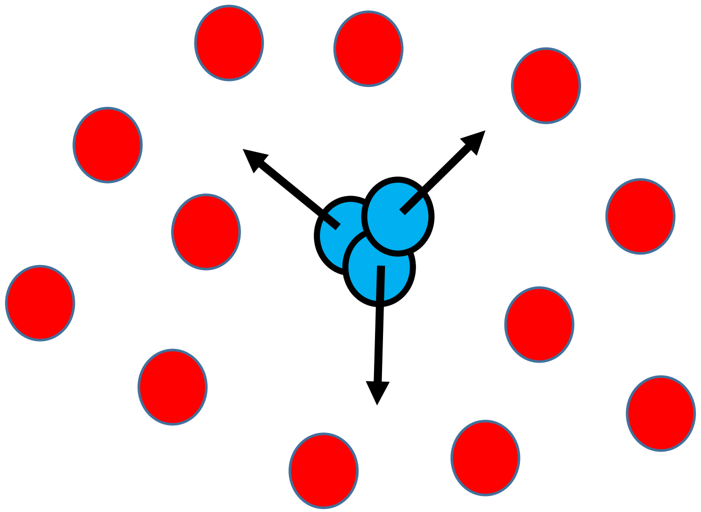
RW and S. Gandolfi, arXiv:2301.09605 [nucl-th] (2023)

Generalized Contact Formalism

Three-body correlations

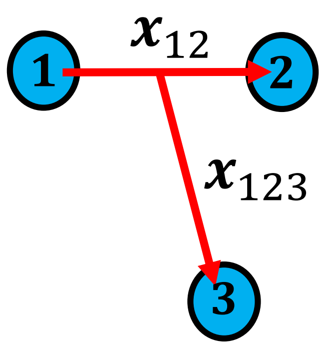
$$\Psi(r_1, r_2, \dots, r_A) \xrightarrow{r_{12}, r_{13}, r_{23} \to 0} \varphi(\boldsymbol{r}_{12}, \boldsymbol{r}_{13}) \times B\left(\boldsymbol{R}_{123}, \{\boldsymbol{r}_k\}_{k \neq 1,2,3}\right) \quad ?$$

universal function



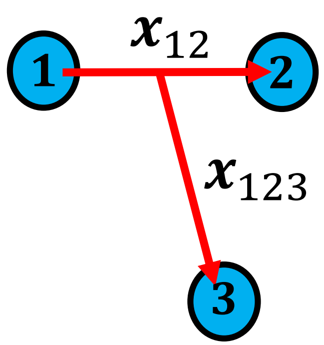
Three-body correlations

$$\Psi(r_1, r_2, \dots, r_A) \xrightarrow{r_{12}, r_{13}, r_{23} \to 0} \varphi(\boldsymbol{x}_{\mathbf{12}}, \boldsymbol{x}_{\mathbf{123}}) \times B\left(\boldsymbol{R}_{\mathbf{123}}, \{\boldsymbol{r}_k\}_{k \neq 1,2,3}\right)$$



Three-body wave functions – Quantum numbers: π, j, m, t, t_z

Three-body correlations



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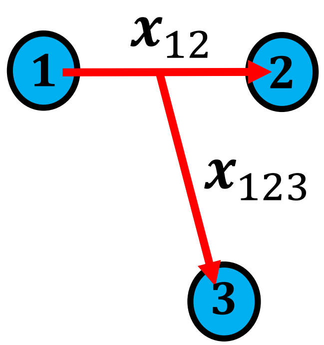
Three-body wave functions – Quantum numbers: π, j, m, t, t_z

- S-wave dominance at short distances $\ell = 0 \Longrightarrow \boxed{\pi = +}$
- Spin $S = \frac{1}{2}, \frac{3}{2} \; + \; \ell = 0 \Longrightarrow j = \frac{1}{2}, \frac{3}{2}$

Three-body correlations



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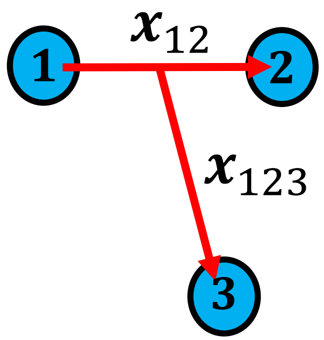
Three-body correlations



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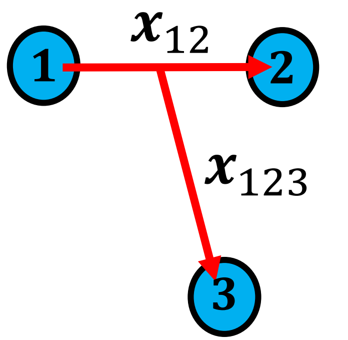
Three-body correlations



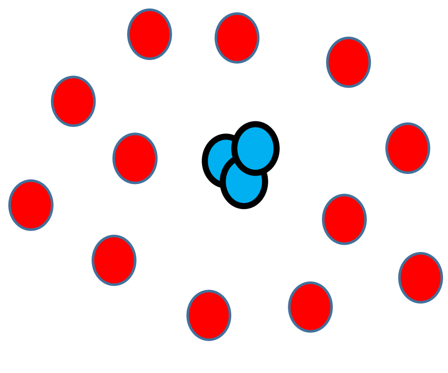
$$\Psi(r_1, r_2, \dots, r_A) \xrightarrow{r_{12}, r_{13}, r_{23} \to 0} \varphi(\boldsymbol{x}_{12}, \boldsymbol{x}_{123}) \times B\left(\boldsymbol{R}_{123}, \{\boldsymbol{r}_k\}_{k \neq 1,2,3}\right)$$

- A **single** leading channel:

$$\boxed{j^\pi = \frac{1}{2}^+, t = \frac{1}{2}}$$

- The same quantum numbers as ^{3}He

- Therefore, **at short-distances** we expect:
  - $\boldsymbol{T = 1/2}$ **dominance** (over $T = 3/2$)
  - **Universality** - All nuclei should behave like ^{3}He

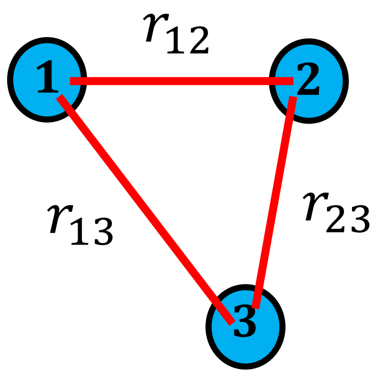


Three-body density

Ab-initio calculations – AFDMC (with Stefano Gandolfi):

$$\rho_3(r_{12}, r_{13}, r_{23}) \equiv \binom{A}{3} \langle \Psi | \delta(|\boldsymbol{r}_1 - \boldsymbol{r}_2| - r_{12}) \delta(|\boldsymbol{r}_1 - \boldsymbol{r}_3| - r_{13}) \delta(|\boldsymbol{r}_2 - \boldsymbol{r}_3| - r_{23}) | \Psi \rangle$$

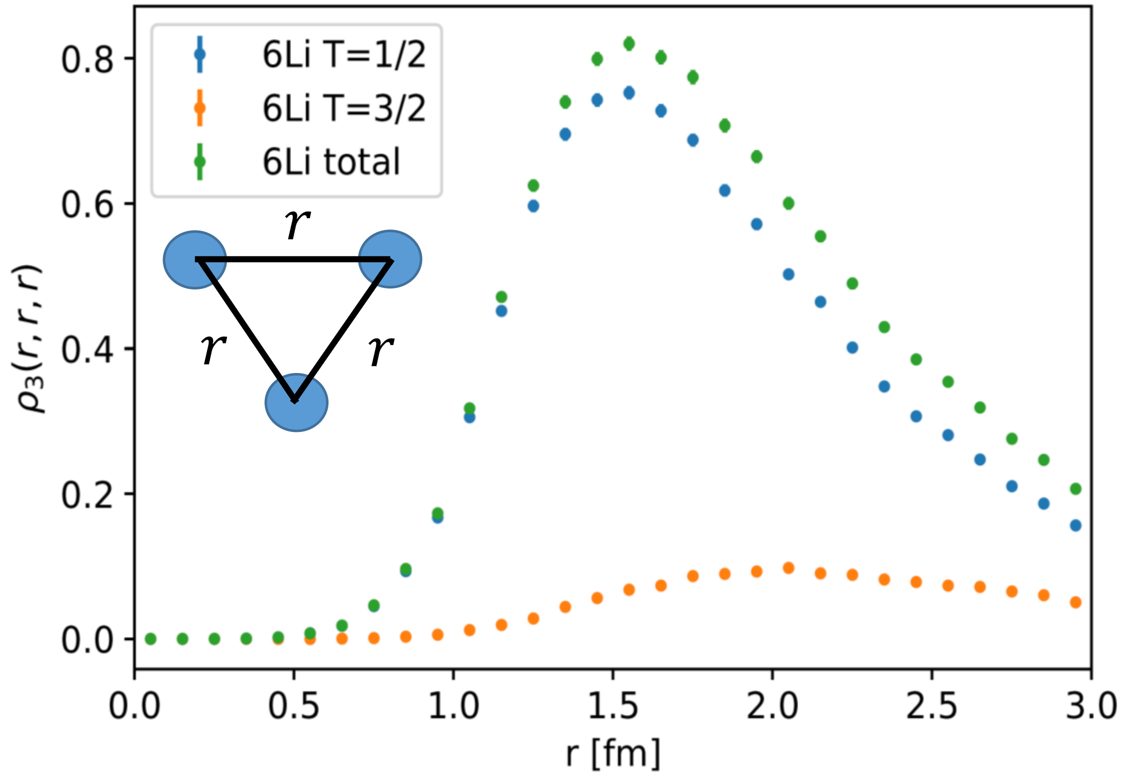
- Projections to $T = \frac{1}{2}$ and $T = \frac{3}{2}$
- N2LO($R = 1.0$ fm)E1 local chiral interaction
- Nuclei: ^{3}He, ^{4}He, ^{6}Li, , ^{16}O



Three-body density

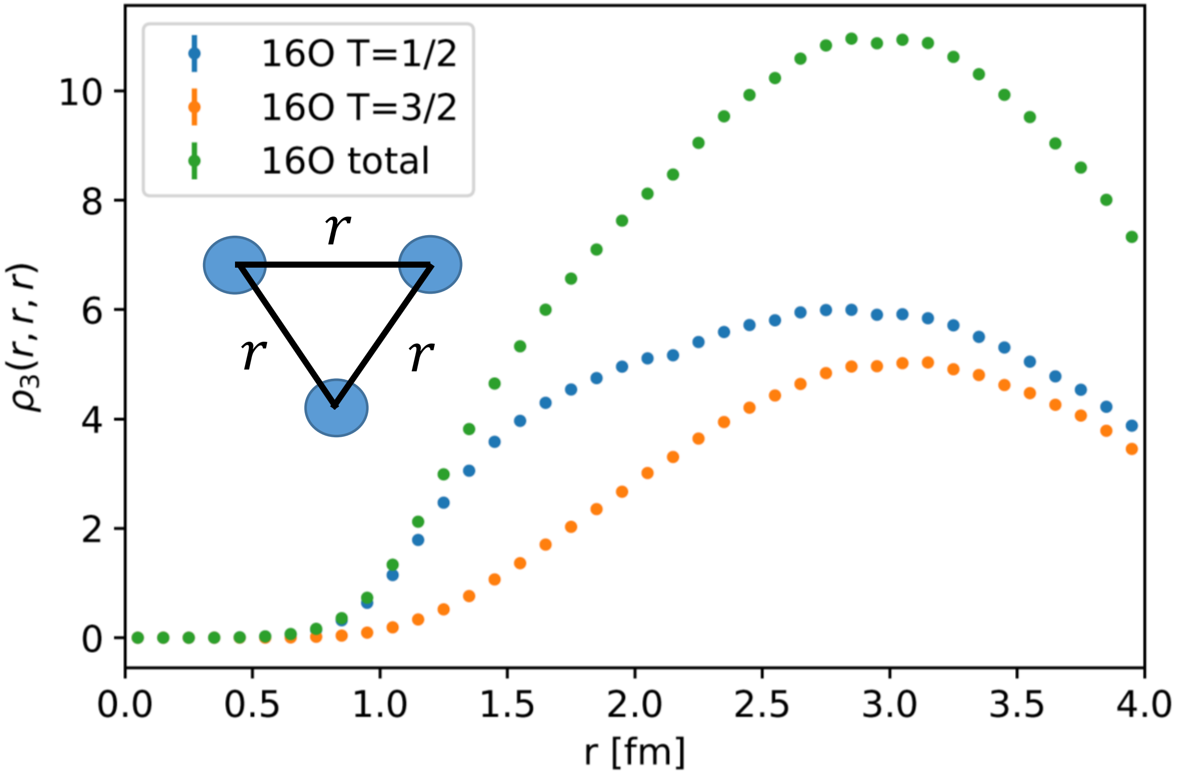
$T = 1/2 \quad \text{vs} \quad T = 3/2$

$^{6}\mathrm{Li}$



Total number of triplets: $T = \frac{1}{2}: 16 \quad ; \quad T = \frac{3}{2}: 4$

$^{16}\mathrm{O}$



Total number of triplets: $T = \frac{1}{2}: 336 \quad ; \quad T = \frac{3}{2}: 224$

Three-body density

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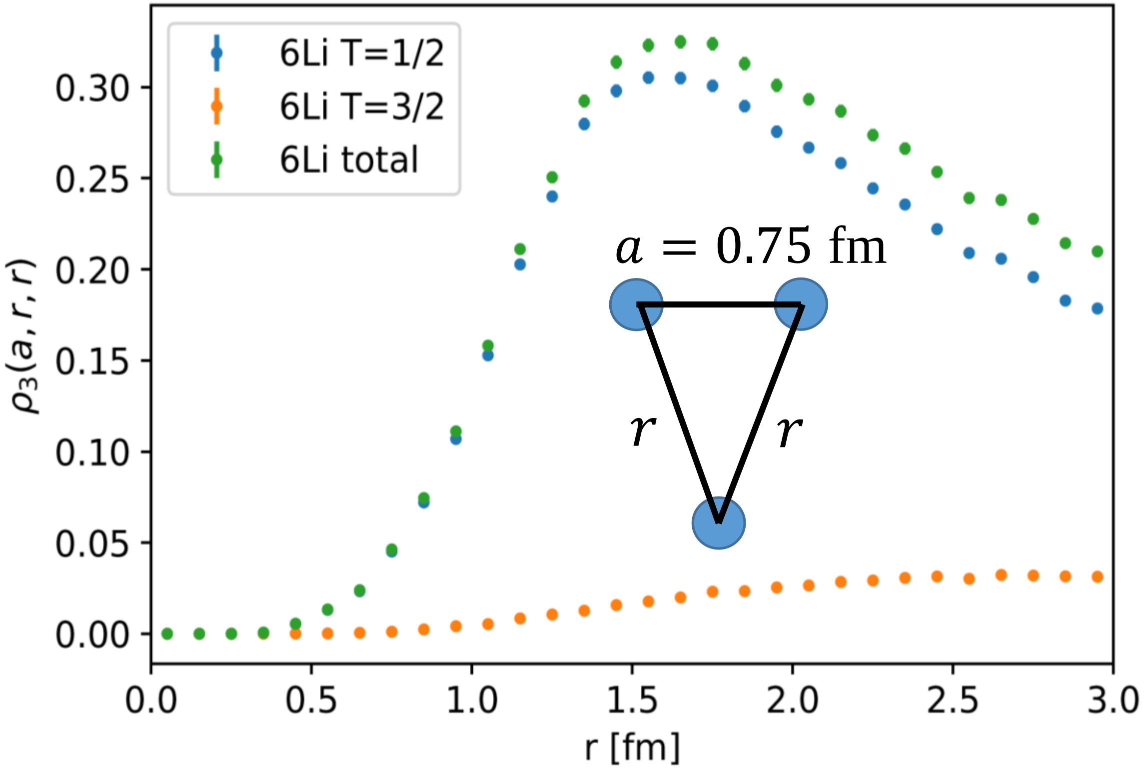

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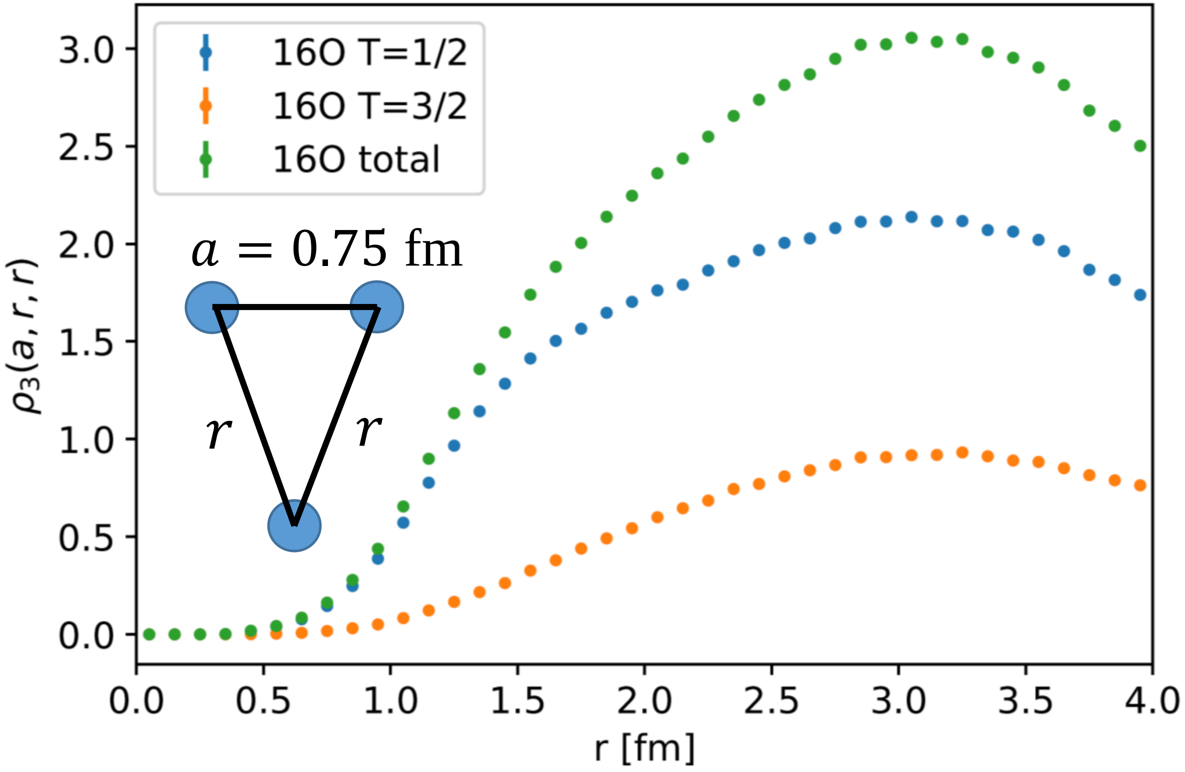


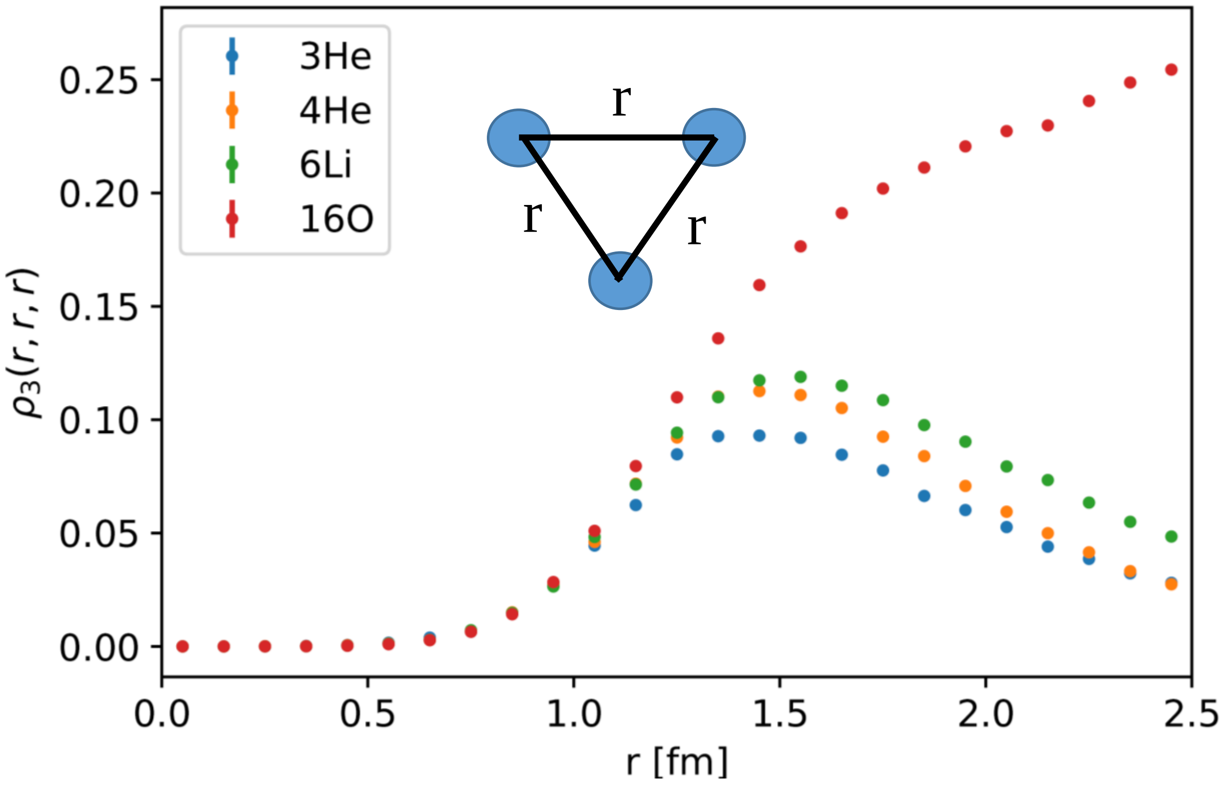
Total number of triplets: $T = \frac{1}{2}: 336 \quad ; \quad T = \frac{3}{2}: 224$

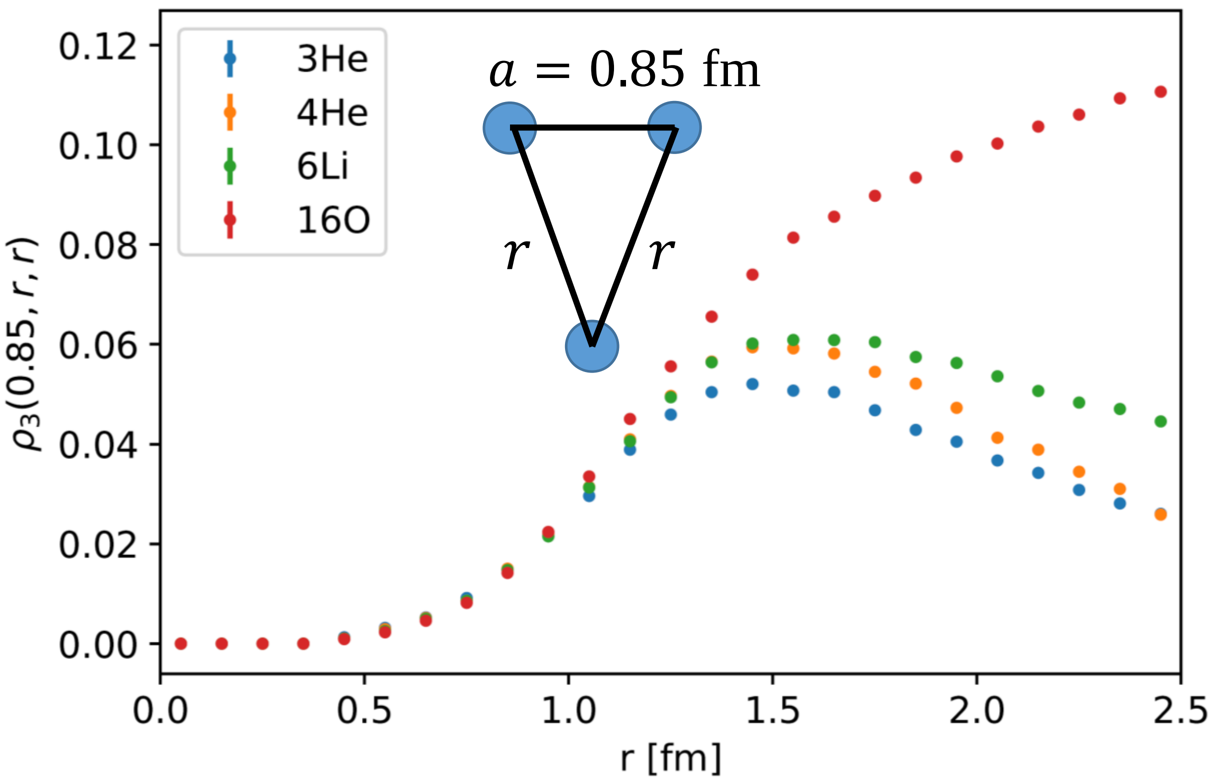
Three-body density

Same scaling factor for all geometries!

$$\boldsymbol{T = \frac{1}{2}}\ \textbf{universality:}$$

rescaled densities



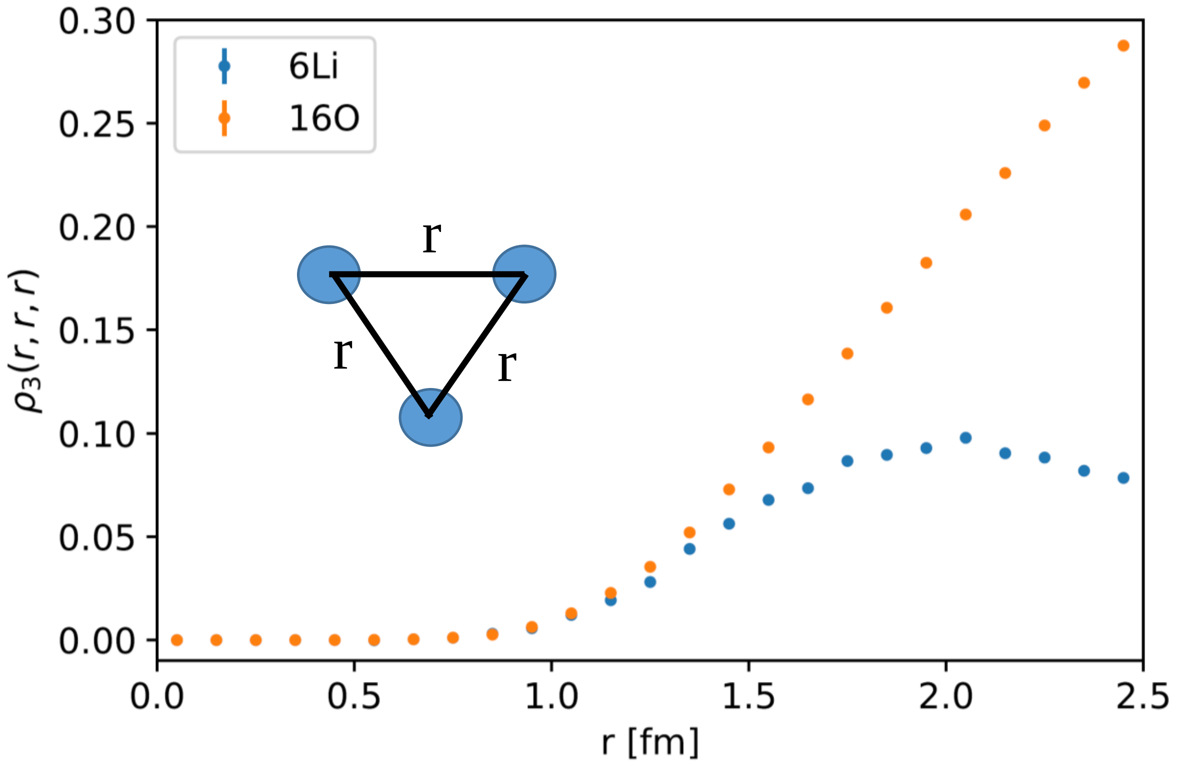


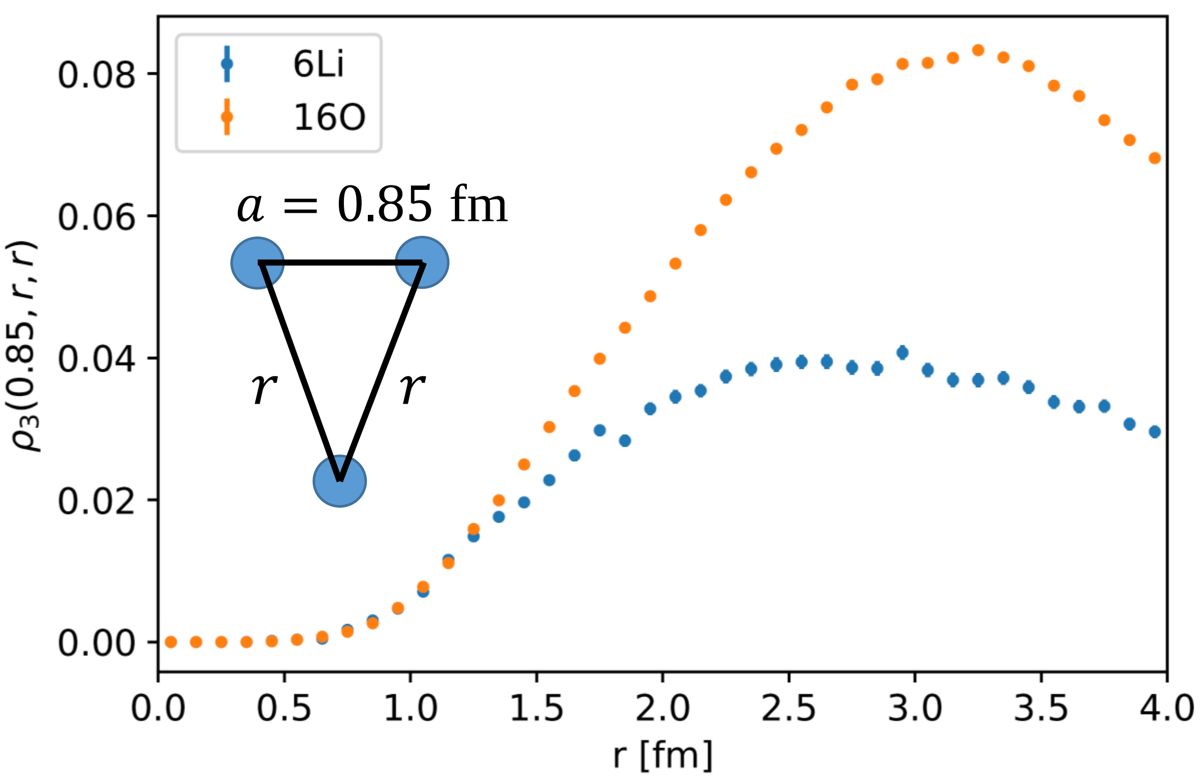
Three-body density

Same scaling factor for all geometries!

$$\boldsymbol{T = \frac{3}{2}}\ \textbf{universality:}$$

rescaled densities





Three-body density

$T = \frac{3}{2}$ **universality:**

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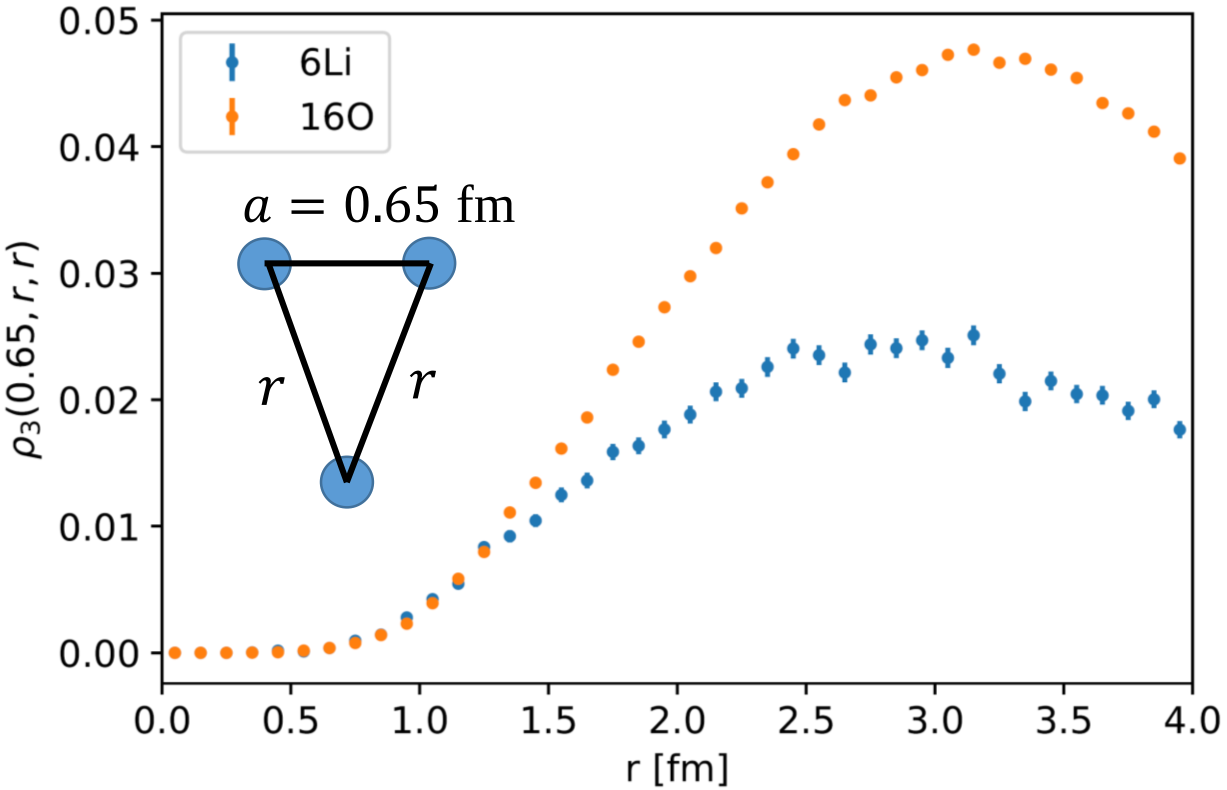

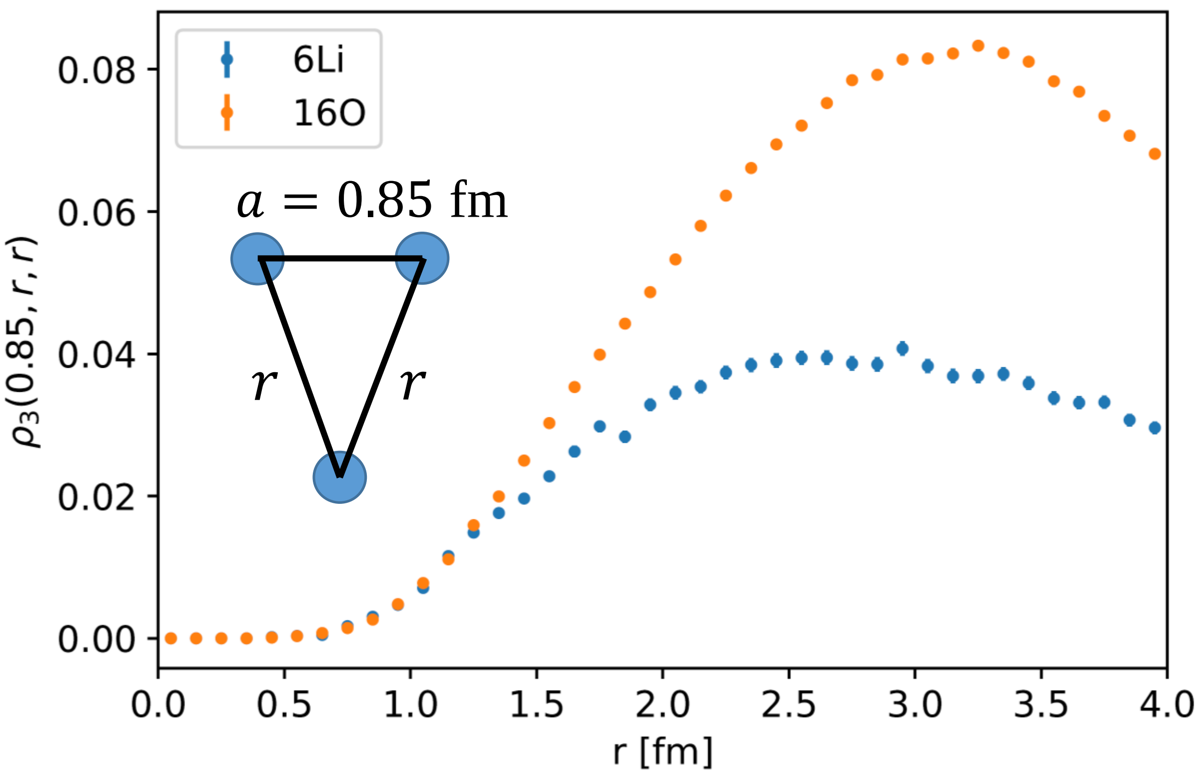

Three-body contact values ($T = 1/2$)

$$\frac{C(^{4}\mathrm{He})}{C(^{3}\mathrm{He})} \times \frac{3}{4} = 3.8 \pm 0.3$$

$$\frac{C(^{6}\mathrm{Li})}{C(^{3}\mathrm{He})} \times \frac{3}{6} = 3.1 \pm 0.3$$

$$\frac{C(^{16}\mathrm{O})}{C(^{3}\mathrm{He})} \times \frac{3}{16} = 4.2 \pm 0.5$$

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Can be compared to inclusive cross section ratios (in the appropriate kinematics)

$$a_3(A) = \frac{3}{A} \frac{\sigma_{eA}}{(\sigma_{e\,^3\mathrm{He}} + \sigma_{e\,^3\mathrm{H}})/2}$$

For a **symmetric** nucleus A

$$a_3(A) = \frac{3}{A} \frac{C(A)}{C(\,^3\mathrm{He})}$$

Three-body contact values ($T = 1/2$)

$$\frac{C(^{4}\mathrm{He})}{C(^{3}\mathrm{He})} \times \frac{3}{4} = 3.8 \pm 0.3 \qquad \frac{C(^{6}\mathrm{Li})}{C(^{3}\mathrm{He})} \times \frac{3}{6} = 3.1 \pm 0.3 \qquad \frac{C(^{16}\mathrm{O})}{C(^{3}\mathrm{He})} \times \frac{3}{16} = 4.2 \pm 0.5$$

Sargsian et al predicted [PRC 100, 044320 (2019)]:

$$a_3(A) = 1.12 \frac{a_2(A)^2}{a_2(^{3}\mathrm{He})^2} \quad \Longrightarrow \quad a_3(^{4}\mathrm{He}) \approx 3.15$$

Inclusive electron scattering

$$a_3(A) = \frac{3}{A}\frac{\sigma_{eA}}{(\sigma_{e\,^3\mathrm{He}}+\sigma_{e\,^3\mathrm{H}})/2}$$

symmetric nucleus A

$$a_3(A) = \frac{3}{A}\frac{C(A)}{C(\,^3\mathrm{He})}$$

- Symmetric nucleus A – equal abundance of ppn and pnn triplets
- $\sigma_{e\,^3\mathrm{He}} + \sigma_{e\,^3\mathrm{H}}$ – also equal abundance of ppn and pnn triplets
- Also possible to look at $\frac{4}{A}\frac{\sigma_{eA}}{\sigma_{e\,^4\mathrm{He}}}$ for symmetric nucleus A

Inclusive electron scattering

$$a_3(A) = \frac{3}{A}\frac{\sigma_{eA}}{(\sigma_{e\,^3\mathrm{He}}+\sigma_{e\,^3\mathrm{H}})/2}$$

symmetric nucleus A

$$a_3(A) = \frac{3}{A}\frac{C(A)}{C(\,^3\mathrm{He})}$$

It is **not** clear that we should see a plateau (x_B- independence) for:

$$\frac{3}{A}\frac{\sigma_{eA}}{\sigma_{e\,^3\mathrm{He}}}$$

or for a_3 if $N \neq Z$

Considered in experiments

There can still be a plateau in some cases, if a specific reaction/configuration is dominant

Inclusive electron scattering

$$a_3(A) = \frac{3}{A}\frac{\sigma_{eA}}{(\sigma_{e\,^3\mathrm{He}}+\sigma_{e\,^3\mathrm{H}})/2}$$

symmetric nucleus A

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Other effects that might break the plateau:

- CM motion of the triplet in nucleus A
- Energy of the $A - 3$ system
- Contribution of $t = 3/2$ triplets (*e.g.*: ppp, nnn)

Detailed reaction calculations are needed

Neutrinoless double beta decay

RW, P. Soriano, A. Lovato, J. Menendez, R. B. Wiringa, PRC 106, 065501 (2022)

Neutrinoless double beta decay

$$nn \to pp + 2e$$

Measurement of the decay will provide information about:

- Majorana nature of neutrinos
- Matter dominance of the universe
- Neutrino mass
- …

Nuclear matrix elements (NMEs) are needed

$^{76}\mathrm{Ge}$, $^{100}\mathrm{Mo}$, $^{130}\mathrm{Te}$, $^{136}\mathrm{Xe}$

NMEs - Methods

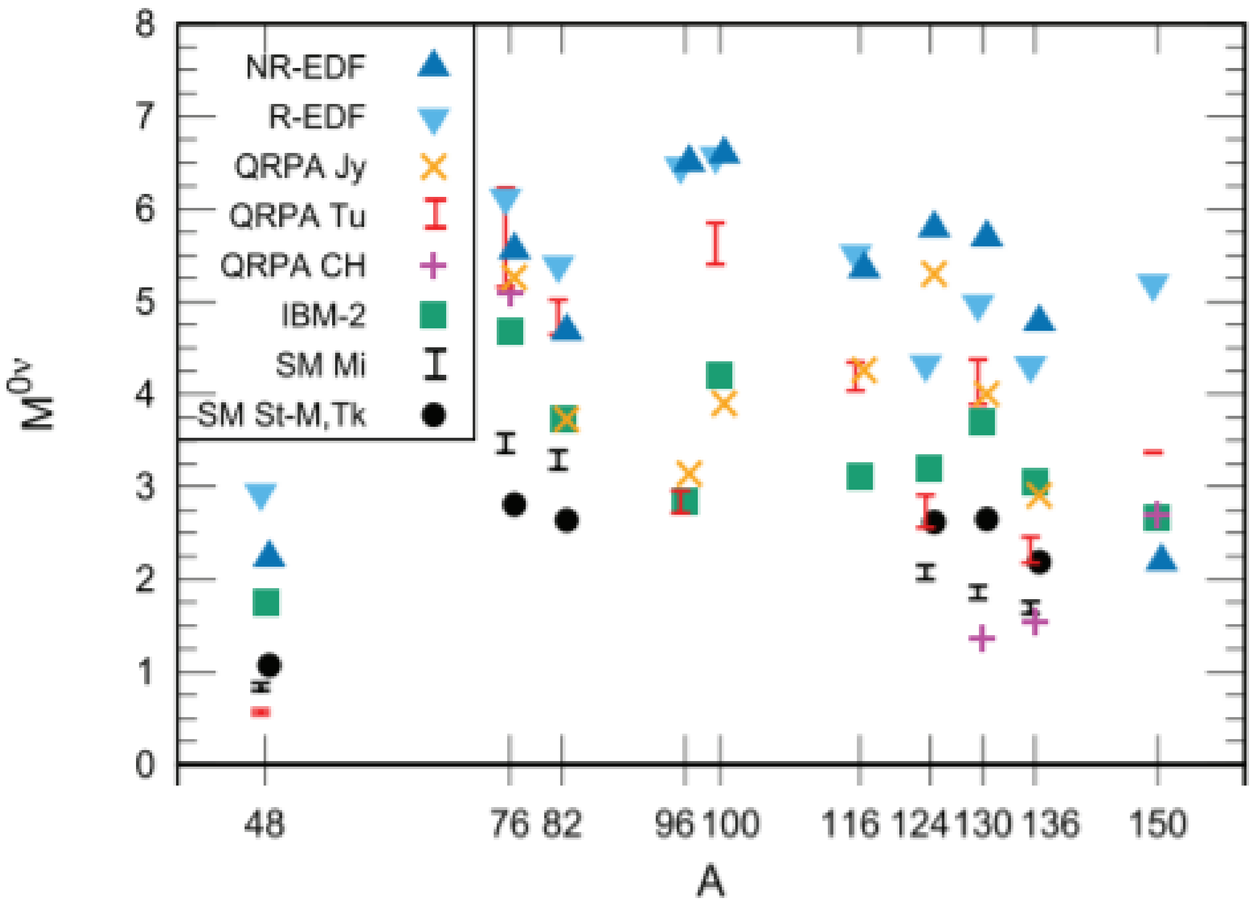
Phenomenological

- Shell model, QRPA, EDF, IBM
- Describe well **long-range** properties
- Missing **short-range** physics
- SRCs introduced using correlation functions

$$M = \langle SM | f(r)\ \hat{O}\ f(r) | SM \rangle$$

NMEs - Methods

Nuclear matrix elements



J. Engel and J. Menendez, Rep. Prog. Phys. 80 046301 (2017)

Very different values of matrix elements

NMEs - Methods

ab-initio

Based on single-particle basis expansion:

Quantum Monte Carlo:

NMEs - Methods

ab-initio

Based on single-particle basis expansion:

- Coupled Cluster, VS-IMSRG, IMSRG + GCM
- Applied for ^{48}Ca, ^{76}Ge, ^{82}Se
- "soft" interactions → possibly larger contribution of two-body nuclear currents

Quantum Monte Carlo:

NMEs - Methods

ab-initio

Based on single-particle basis expansion:

- Coupled Cluster, VS-IMSRG, IMSRG + GCM
- Applied for ^{48}Ca, ^{76}Ge, ^{82}Se
- “soft” interactions $\rightarrow$ possibly larger contribution of two-body nuclear currents

Quantum Monte Carlo:

- Can be applied to both “soft” and “hard” (local) interactions
- Captures well short-range dynamics
- Available only for $A \leq 12$ nuclei for $0\nu 2\beta$

Our approach: GCF-SM method

Quantum Monte Carlo	+	Shell Model	+	Generalized Contact Formalism
Accurate solution for light nuclei		Long-range physics		Short-range physics

NMEs and transition densities

Light Majorana neutrino exchange mechanism

$$M^{0\nu} = \langle \Psi_f | O^{0\nu} | \Psi_i \rangle$$

$$O^{0\nu} = O_F^{0\nu} + O_{GT}^{0\nu} + O_T^{0\nu} + O_S^{0\nu}$$

V. Cirigliano, et. al., PRL 120, 202001 (2018)

$$M_\alpha^{0\nu} = \int_0^\infty dr\, \rho_\alpha^{0\nu}(r)$$

NMEs and transition densities

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V. Cirigliano, et. al.,
PRL 120, 202001 (2018)

$$M_\alpha^{0\nu} = \int_0^\infty dr\, \rho_\alpha^{0\nu}(r)$$

$r < 1$ fm

GCF

$r > 1$ fm

Shell model

GCF-SM: Short distances ($r < 1$ fm)

- New contacts

$$C(f,i) = \frac{A(A-1)}{2}\langle A(f)|A(i)\rangle$$

$$\rho_{\alpha}^{0\nu}(r) \propto |\phi(r)|^2 C(f,i)$$

GCF-SM: Short distances ($r < 1$ fm)

- New contacts

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$$\rho_\alpha^{0\nu}(r) \propto |\phi(r)|^2 C(f,i)$$

Contact values are extracted based on model independence of ratios

$$\boxed{\frac{C^{V_1}(X)}{C^{V_1}(Y)} = \frac{C^{V_2}(X)}{C^{V_2}(Y)}}$$

Model independence of contact ratios

- For $0\nu 2\beta$:

$$\frac{C^{AV18}(f_1, i_1)}{C^{AV18}(f_2, i_2)} = \frac{C^{SM}(f_1, i_1)}{C^{SM}(f_2, i_2)}$$

$$C^{AV18}(f_1, i_1) = \frac{C^{SM}(f_1, i_1)}{C^{SM}(f_2, i_2)} C^{AV18}(f_2, i_2)$$

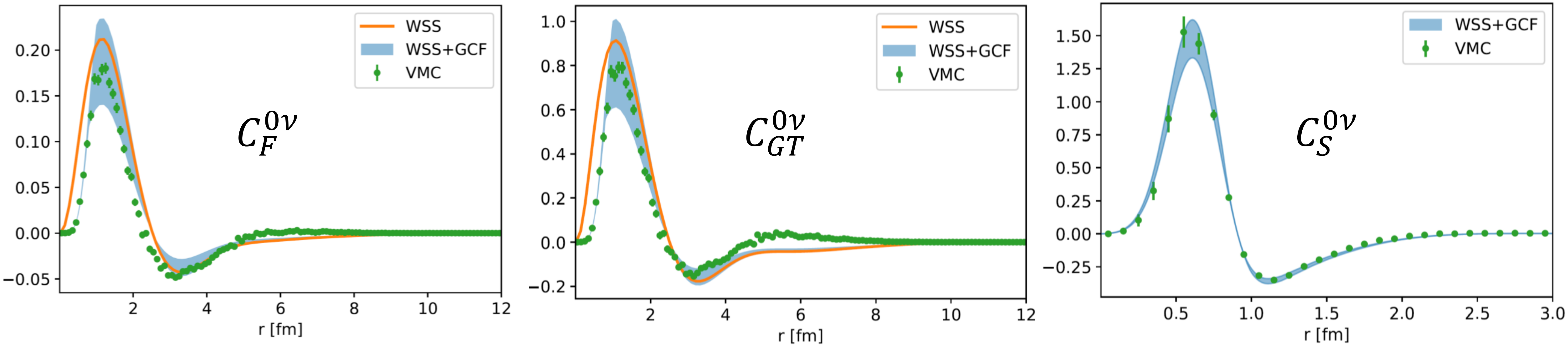
- For example

Exact QMC calculations

$$C^{AV18}\left({}^{76}\mathrm{Ge} \rightarrow {}^{76}\mathrm{Se}\right) = \frac{C^{SM}\left({}^{76}\mathrm{Ge} \rightarrow {}^{76}\mathrm{Se}\right)}{C^{SM}\left({}^{12}\mathrm{Be} \rightarrow {}^{12}\mathrm{C}\right)} C^{AV18}\left({}^{12}\mathrm{Be} \rightarrow {}^{12}\mathrm{C}\right)$$

Validation using light nuclei (AV18)

Using $^{6}He \rightarrow {}^{6}Be$ and $^{10}Be \rightarrow {}^{10}C$ to "predict" $^{12}Be \rightarrow {}^{12}C$

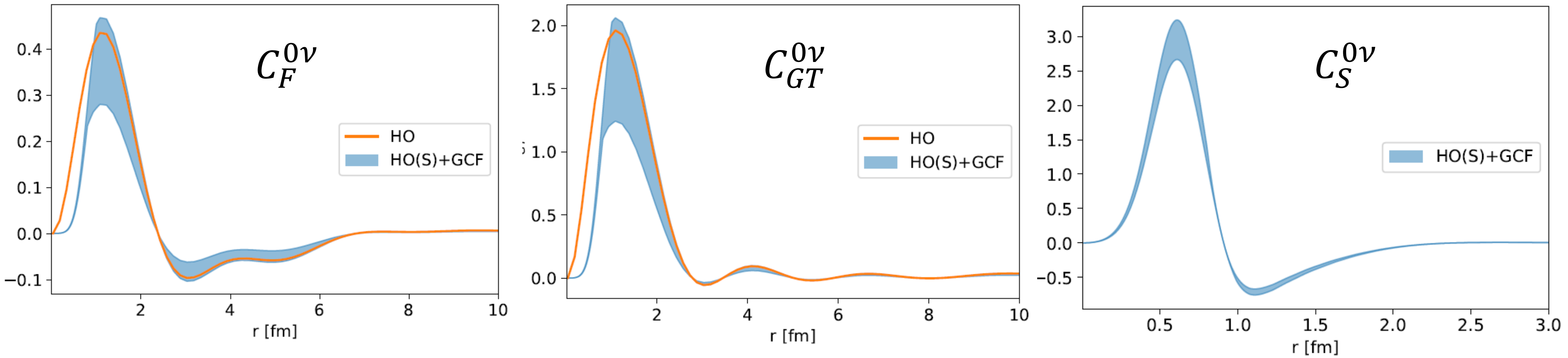


Short distances - GCF

Long distances – Shell model

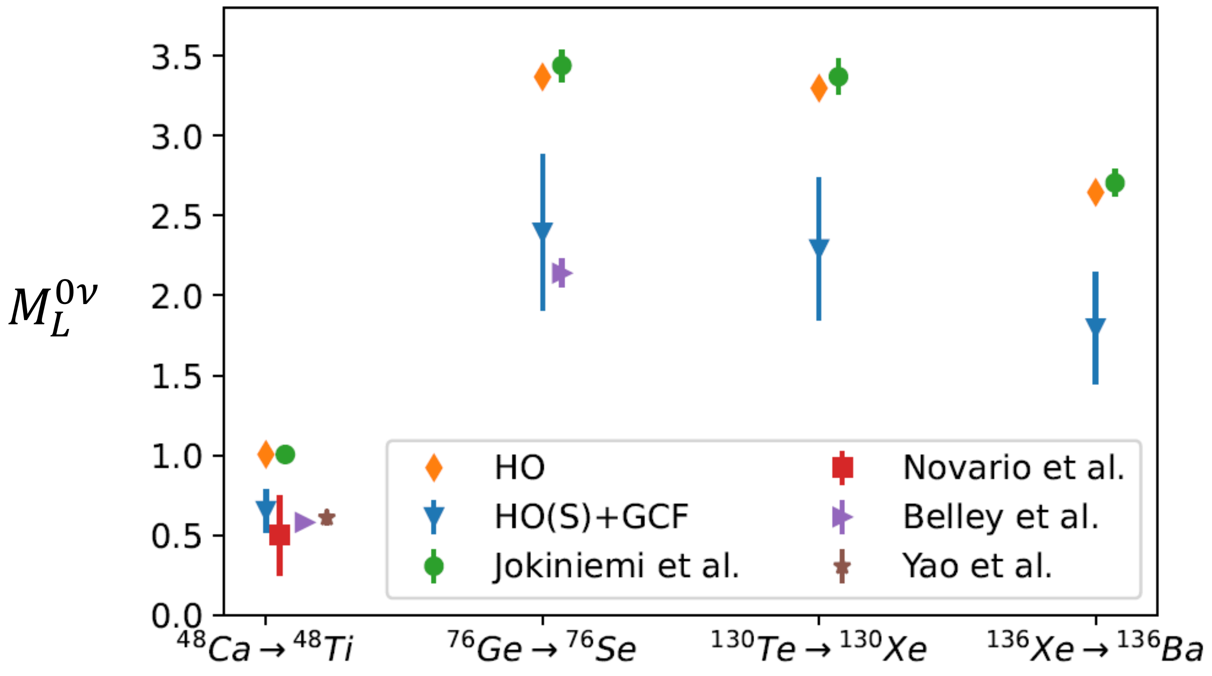
Results – heavy nuclei (AV18)

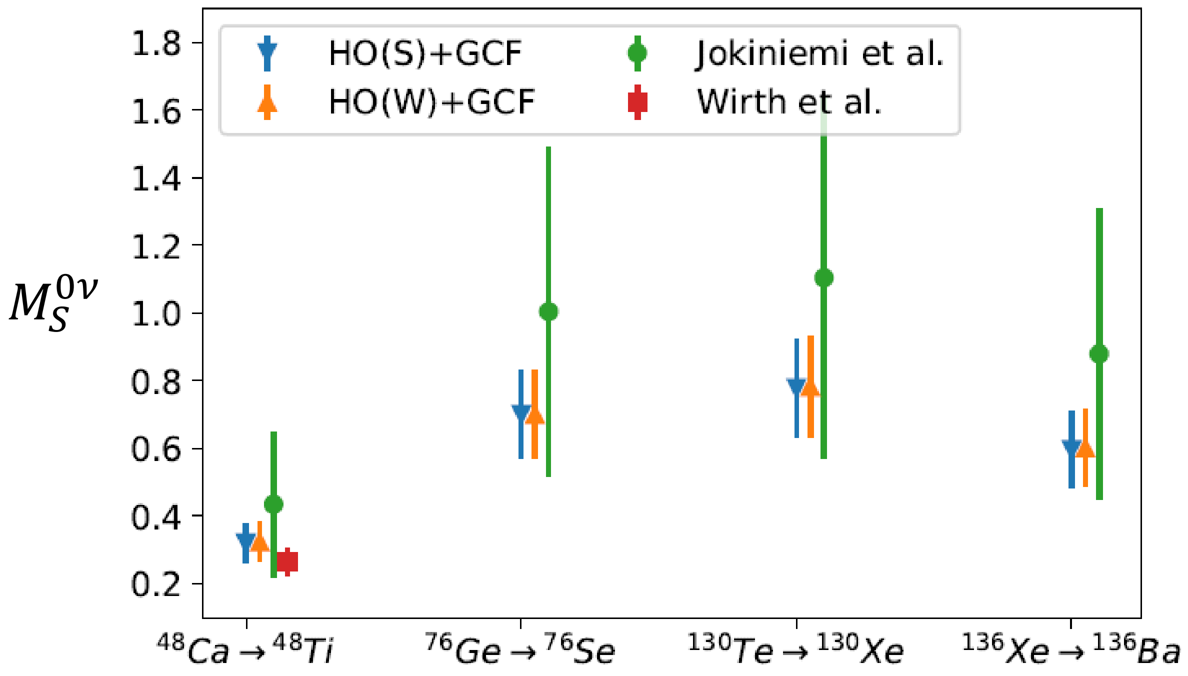
- Transition densities (using $A = 6, 10, 12$ to predict heavy nuclei):



$$^{76}\mathrm{Ge} \rightarrow {}^{76}\mathrm{Se}$$

Results – heavy nuclei (AV18)

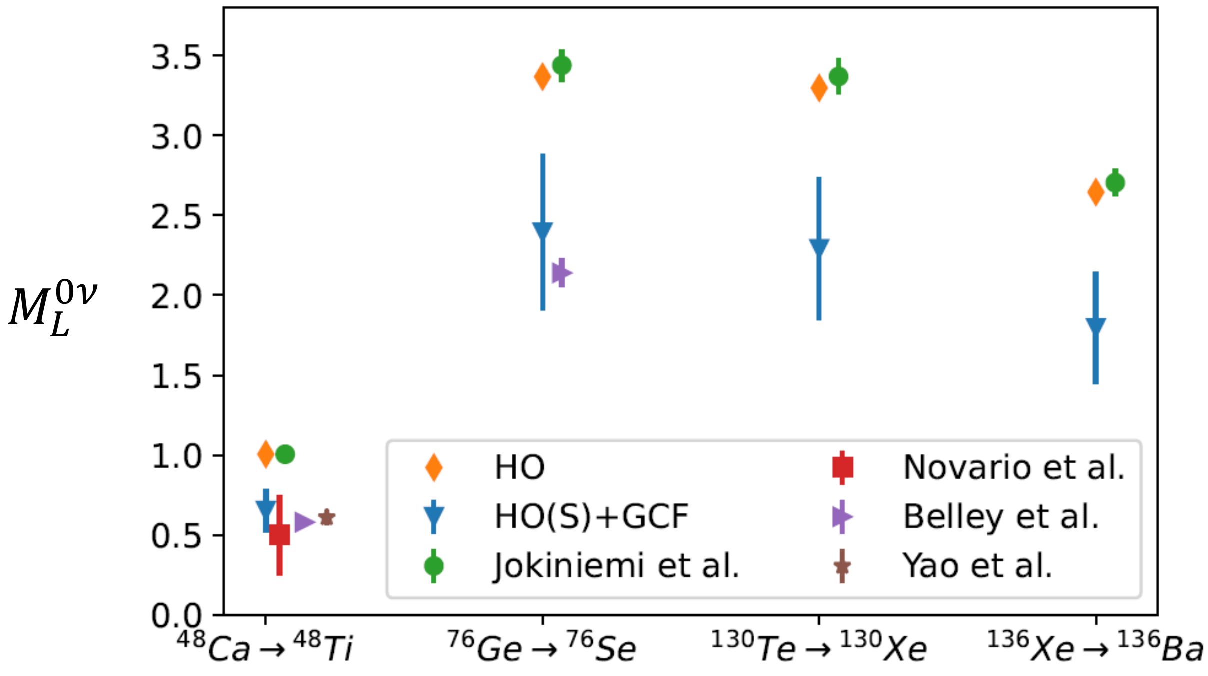




$$M_F + M_{GT} + M_T$$

Significant reduction due to SRCs

Results – heavy nuclei (AV18)



$$M_F + M_{GT} + M_T$$

Significant reduction due to SRCs

Next:

- Model and cutoff dependence - chiral interactions
- Include 3N-SRCs and other corrections
- Detailed comparison with other methods (using the same interaction)
- Tensor matrix elements

Summary and Outlook

Three-body correlations - Conclusions

- 3N SRC factorization

$$\Psi(r_1, r_2, \ldots, r_A) \xrightarrow{r_{12}, r_{13}, r_{23} \to 0} \varphi(\boldsymbol{x}_{\mathbf{12}}, \boldsymbol{x}_{\mathbf{123}}) \times B\left(\boldsymbol{R}_{\mathbf{123}}, \{\boldsymbol{r}_k\}_{k \neq 1,2,3}\right)$$

- Single leading channel - $j^{\pi} = \frac{1}{2}^{+}, t = \frac{1}{2}$
- $\boldsymbol{T = 1/2}$ **dominance** – small number of ppp SRC triplets
- **Universal behavior** of SRC triplets
- **Scaling factors – 3N contact ratios**
  - Relevant for inclusive scattering (a_3)

Three-body correlations - Future work

- Identifying 3N SRC domain, leading configurations…
- Model-dependence study – Additional interactions
- Effects of three-body forces, Tensor force
- Momentum space distributions
- Spectral function, electron scattering…

Future work

- Next order corrections to the GCF
  - Systematic expansion

- Electron scattering:
  - Beyond the spectral function PWIA description (coherent contributions + FSI)
  - Relativistic effects

- GCF + SM: $0\nu\beta\beta$, single-beta decay, spectral function…

BACKUP

Generalized Contact Formalism

$$\Psi(r_1, r_2, \dots, r_A) \xrightarrow{r_{12} \to 0} \varphi(\boldsymbol{r}) \times A\left(\boldsymbol{R}, \{\boldsymbol{r}_k\}_{k \neq 1,2}\right)$$

universal function

For any short-range two-body operator $\hat{O}$ (assuming that acts on protons):

$$\langle \hat{O} \rangle = \sum_{i<j} \langle \Psi | \hat{O}(\boldsymbol{r}_{ij}) | \Psi \rangle = \langle \varphi | \hat{O}(r) | \varphi \rangle \frac{Z(Z-1)}{2} \langle A | A \rangle$$

The pp contact $\quad C_{pp} \equiv \frac{Z(Z-1)}{2} \langle A | A \rangle$

The number of correlated pairs

RW, B. Bazak, N. Barnea, PRC 92, 054311 (2015)

Generalized Contact Formalism

$$\Psi \xrightarrow{r_{ij}\to 0} \sum_{\alpha} \varphi_{ij}^{\alpha}(\boldsymbol{r}_{ij}) A_{ij}^{\alpha}(\boldsymbol{R}_{ij},\{\boldsymbol{r}_k\}_{k\neq i,j}) \quad ; \quad \boldsymbol{C}_{\boldsymbol{ij}}^{\boldsymbol{\alpha\beta}} \propto \langle A_{ij}^{\alpha} | A_{ij}^{\beta} \rangle$$

Channels α
$= \pi_2\, S_2\, j_2 m_2$

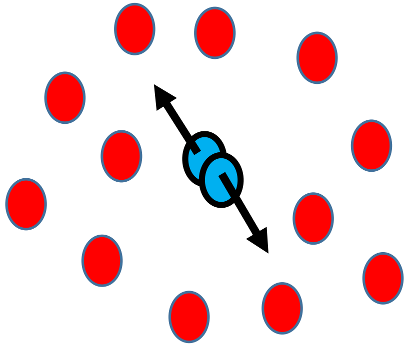
“universal“
function

The pair kind
$ij \in \{pp, nn, pn\}$

Main channels:

The **deuteron** channel: $\ell_2 = 0{,}2\,;\, s_2 = 1\,;\, j_2 = 1\,;\, t_2 = 0$

The **spin-zero** channel: $\ell_2 = 0\,;\, s_2 = 0\,;\, j_2 = 0\,;\, t_2 = 1$



RW, B. Bazak, N. Barnea,
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The pair kind
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This factorized form can be derived using:

- RG arguments — S. K. Bogner and D. Roscher, Phys. Rev. C 86, 064304 (2012).
A. J. Tropiano, S. K. Bogner, and R. J. Furnstahl, Phys. Rev. C 104, 034311 (2021)
- Coupled Cluster expansion — S. Beck, RW, N. Barnea

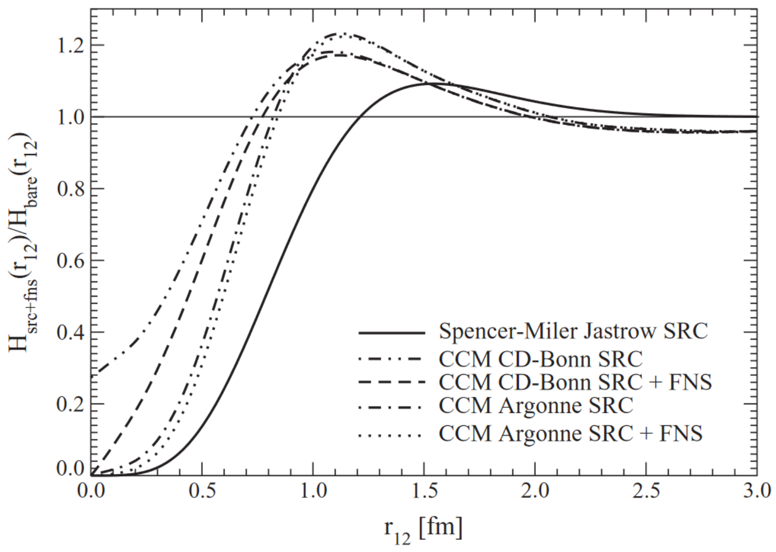
$$\Psi = e^{\hat{T}} |\Phi_0\rangle = \sum_{n=1}^{A} \frac{1}{n!} \hat{T}^{\mathrm{n}} \, |\Phi_0\rangle$$

Shell model + correlation functions

$$M = \langle SM | f(r)\, \hat{O}\, f(r) | SM \rangle$$

- Correlation function - Main features:
  - reduction at short distances
  - peak around 1 fm
  - $f(r) \to 1$ for r $\to \infty$

$$f(r) = 1 - c e^{-ar^2}(1 - br^2)$$



F. Simkovic et al., PRC 79, 055501 (2009)

- Extracted for example from coupled-cluster calculations:

$$|\Psi\rangle = e^{\hat{T}} |\Phi\rangle$$

- Possible inconsistencies:

$$|\mathrm{SM}\rangle \neq |\Phi\rangle$$

More consistent approaches – evolved effective operator (Coraggio, Engel,…)

NMEs and transition densities

Light Majorana neutrino exchange mechanism

$$M^{0\nu} = \langle \Psi_f | O^{0\nu} | \Psi_i \rangle$$

$$O^{0\nu} = O_F^{0\nu} + O_{GT}^{0\nu} + O_T^{0\nu} + O_S^{0\nu}$$

$$4\pi r^2 \rho_F(r) = \langle \Psi_f | \sum_{a<b} \delta(r - r_{ab}) \tau_a^+ \tau_b^+ | \Psi_i \rangle$$

$$C_\alpha^{0\nu}(r) \equiv (8\pi R_A) 4\pi r^2 \rho_\alpha(r) V_\alpha^{0\nu}(r)$$

$$M_\alpha^{0\nu} = \int_0^\infty dr\, C_\alpha^{0\nu}(r)$$

GCF-SM: Short distances ($r < 1$ fm)

- Fermi density for example:

$$\rho_F(r) = \frac{1}{4\pi r^2} \langle \Psi_f | \sum_{a<b} \delta(r - r_{ab}) \tau_a^+ \tau_b^+ | \Psi_i \rangle$$

- New contacts

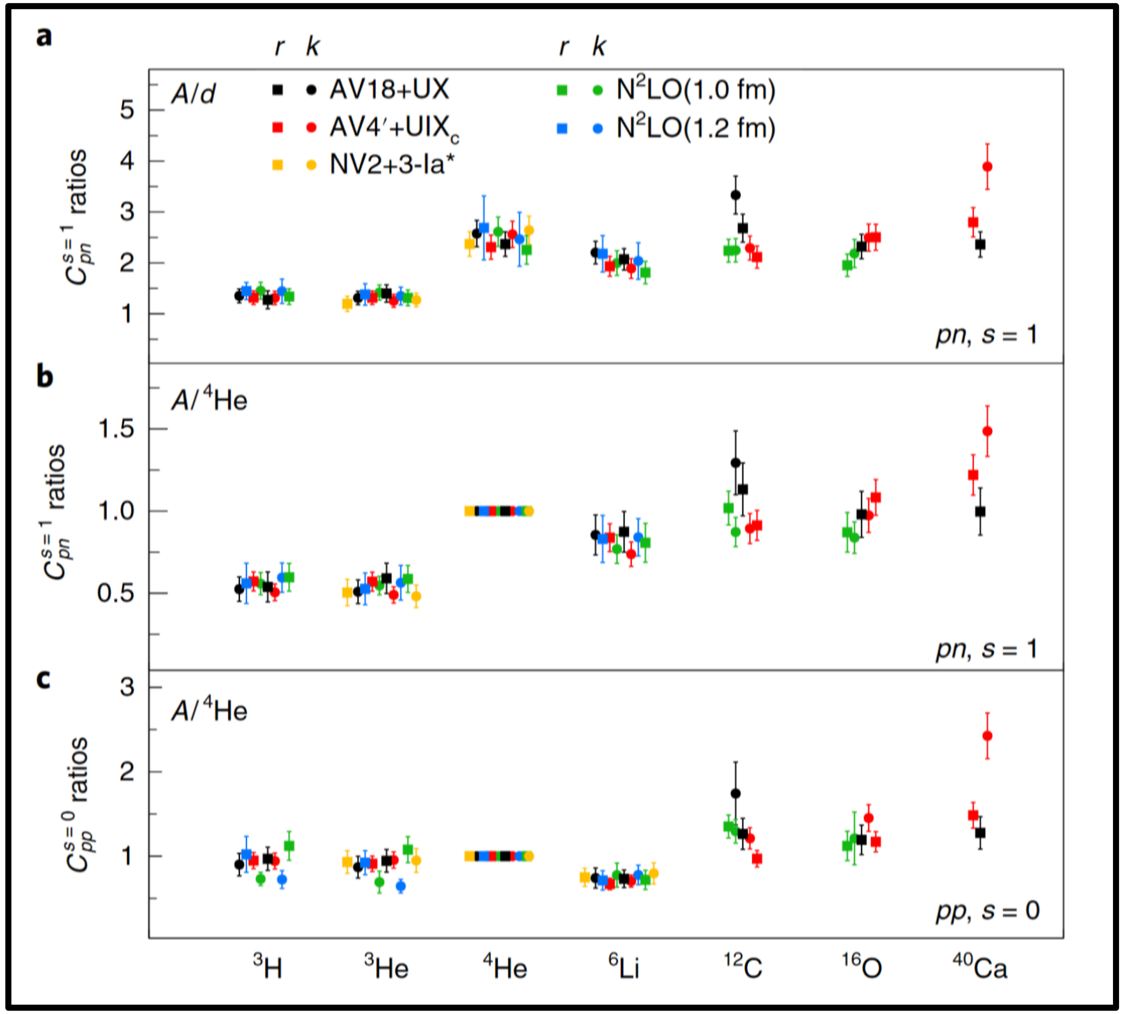
$$C(f,i) = \frac{A(A-1)}{2} \langle A(f) | A(i) \rangle$$

$$\boxed{\rho_F(r) \rightarrow \frac{1}{4\pi} |\phi(r)|^2 C(f,i)}$$

$$\boxed{\rho_{GT}(r) \rightarrow -\frac{3}{4\pi} |\phi(r)|^2 C(f,i)}$$

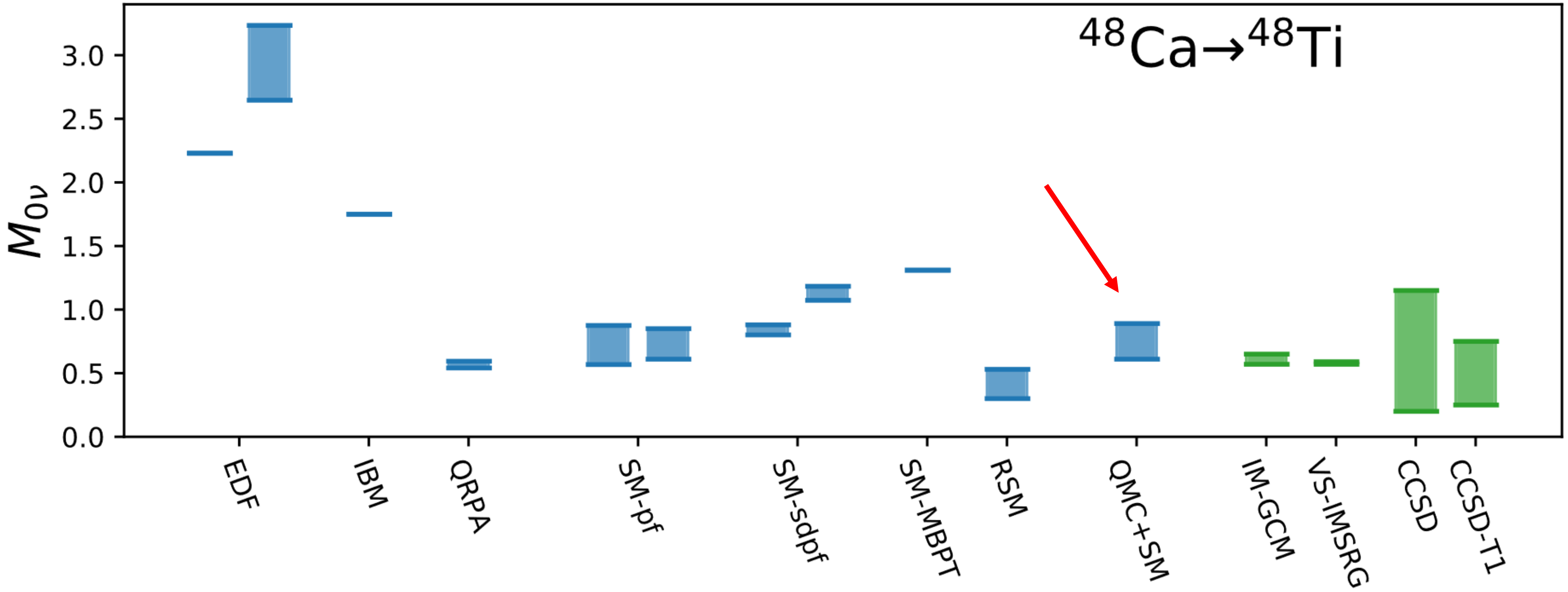
The values of the contacts are needed

Model independence of contact ratios



$$\boxed{\frac{C^{V_1}(X)}{C^{V_1}(Y)} = \frac{C^{V_2}(X)}{C^{V_2}(Y)}}$$

Results – heavy nuclei (AV18)



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