From Nuclear Forces To Nuclei

EMMI Physics Day

TECHNISCHE UNIVERSITÄT DARMSTADT

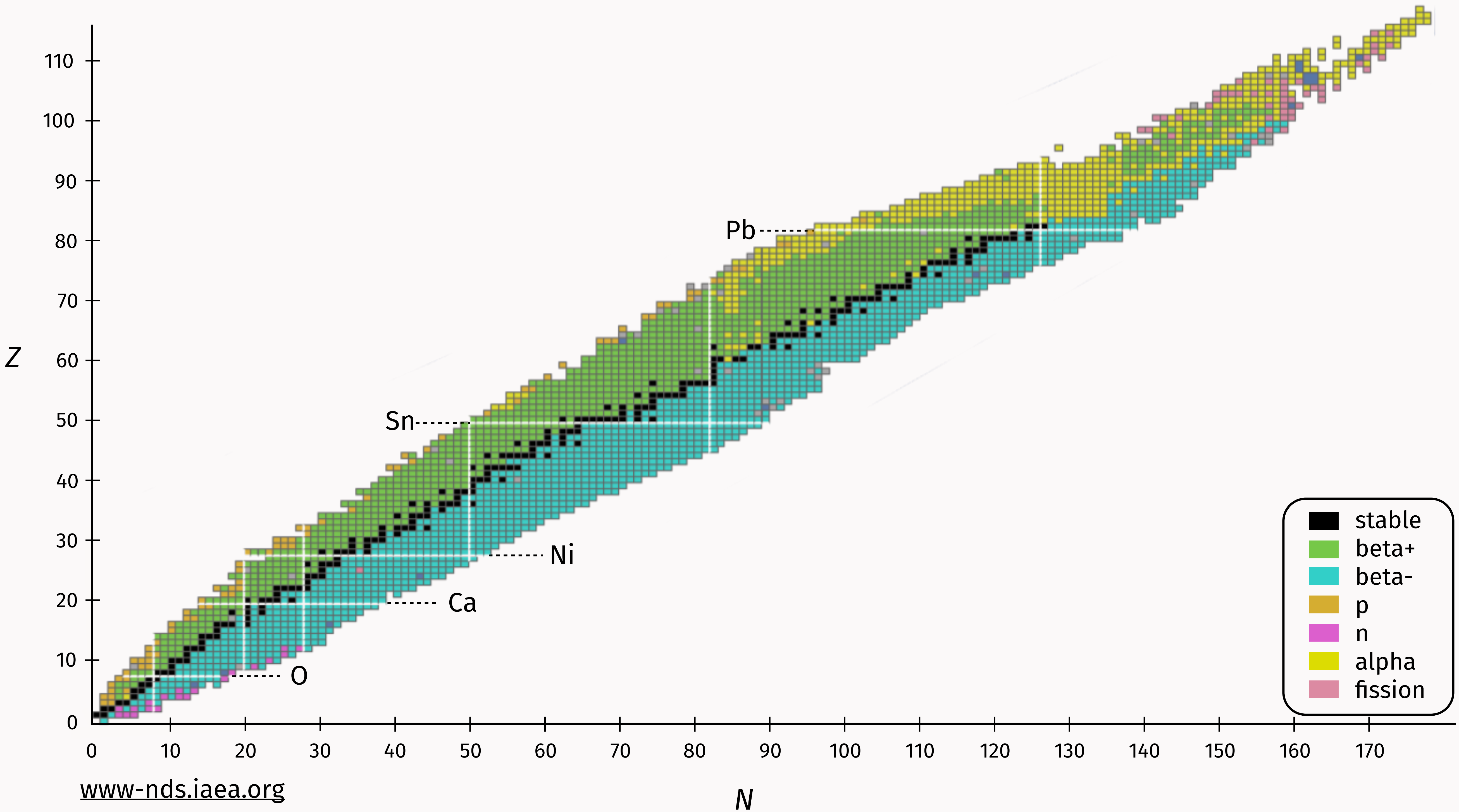
European Research Council

Joel E. Lynn

November 28, 2017

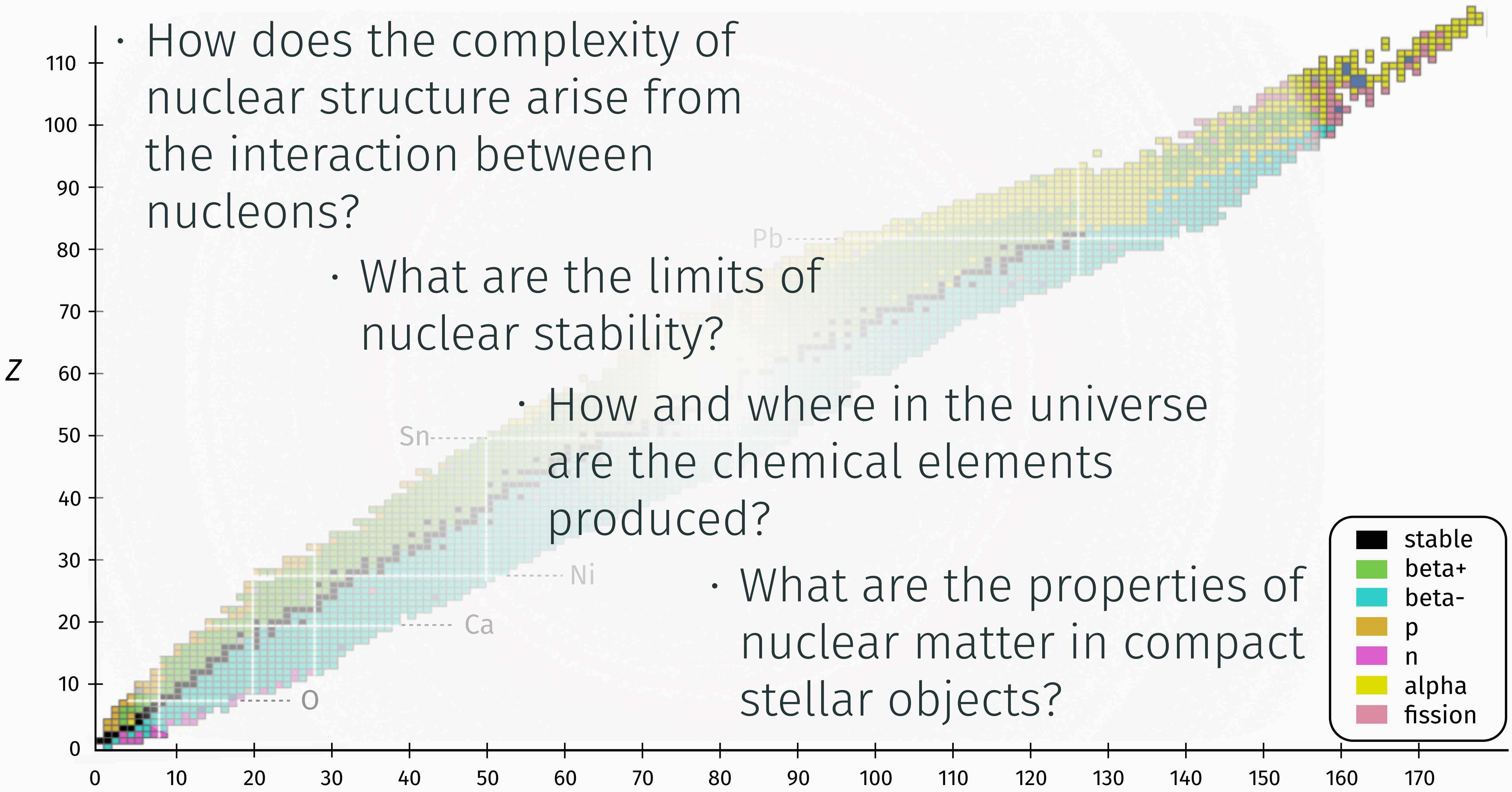
Motivation

The Nuclear Landscape



The Nuclear Landscape

- How does the complexity of nuclear structure arise from the interaction between nucleons?
- What are the limits of nuclear stability?
- How and where in the universe are the chemical elements produced?
- What are the properties of nuclear matter in compact stellar objects?



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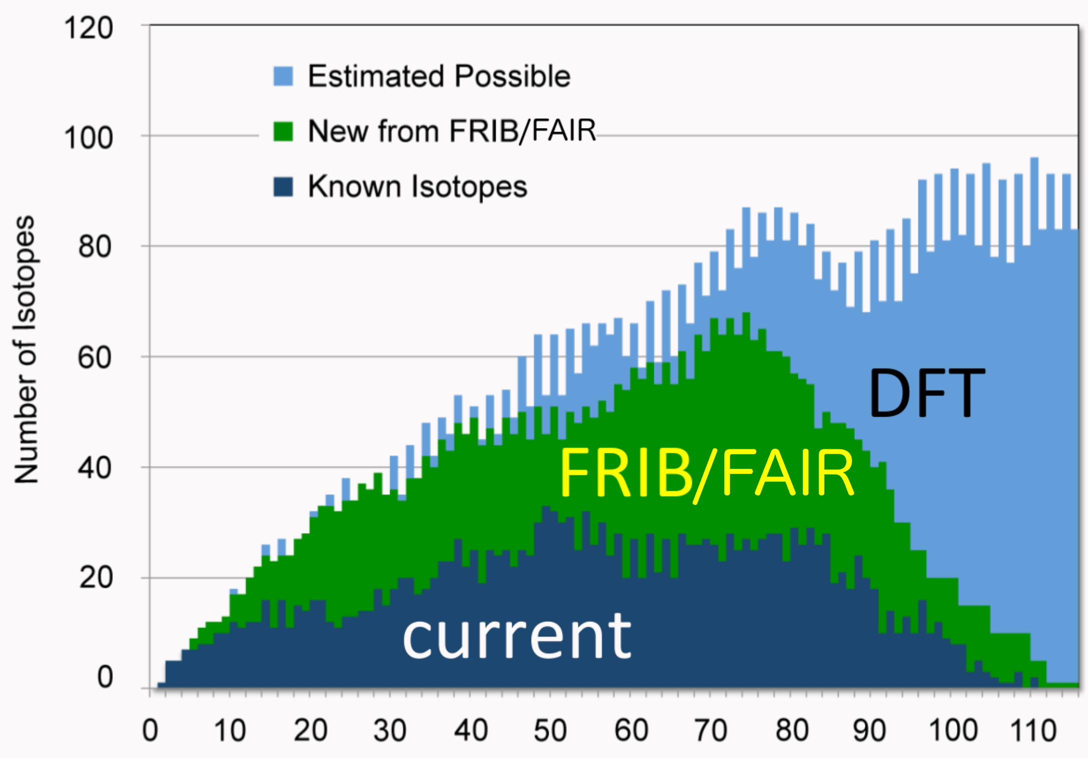
NuPECC Long Range Plan 2017
Perspectives in Nuclear Physics

Extending The Nuclear Landscape

Cutting-edge experimental results

Rare-isotope facilities



adapted from A. B. Balentekin et al., Mod. Phys. Lett. A **29**, 1430010 (2014)

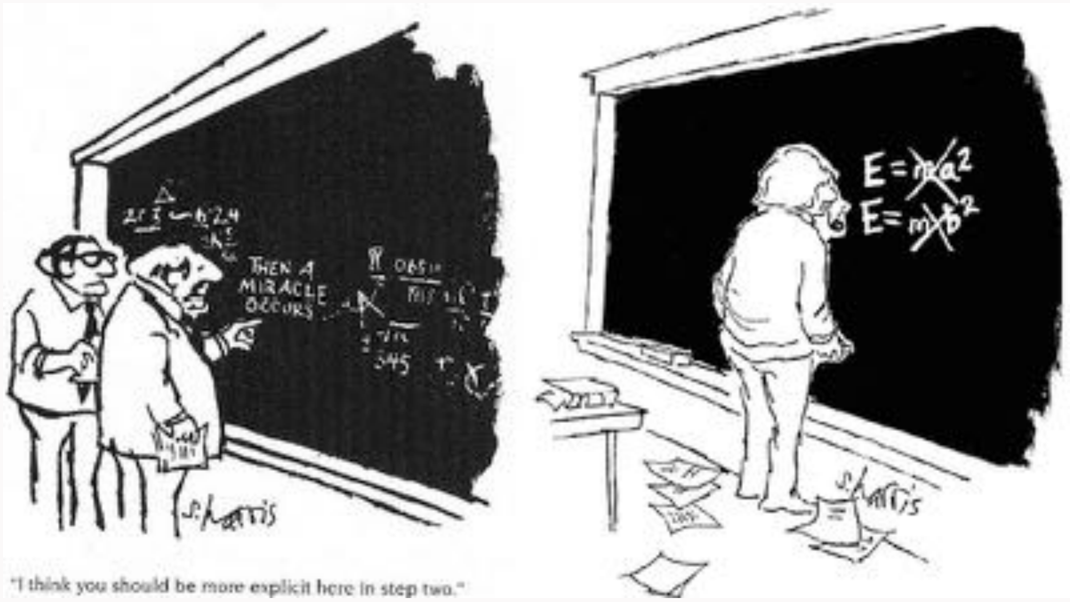
Neutron-star mergers

adapted from M. McLaughlin, APS Physics Viewpoint, October 16, (2017)

What Can Theory Offer?

Nuclear theory has experienced a renaissance in the past few decades thanks (in part) to two developments.

1. Advances in *ab initio* many-body methods.
2. Chiral effective field theory (EFT) for nuclear interactions.



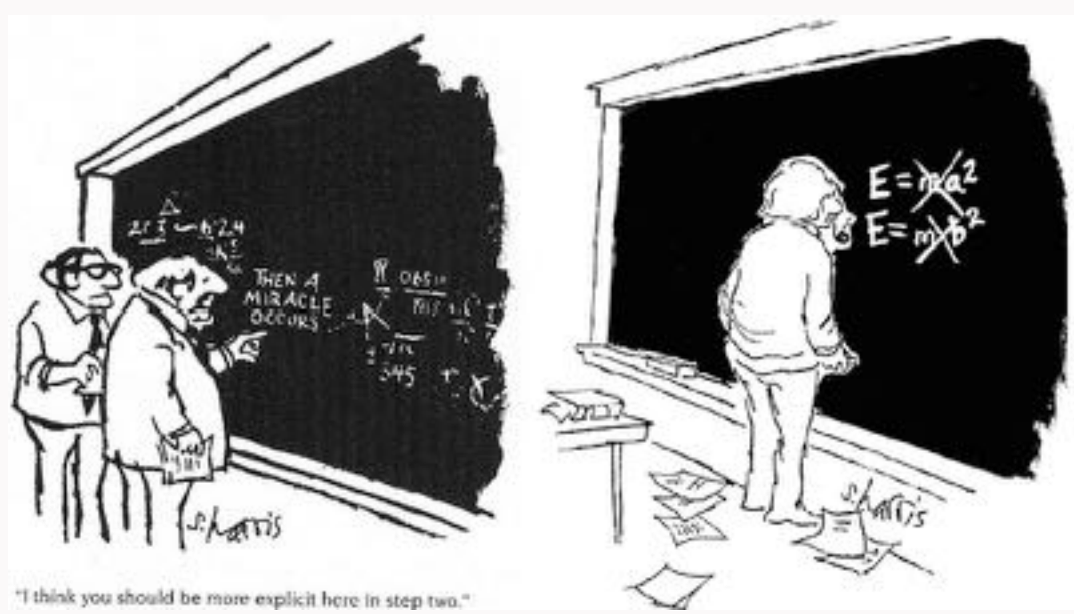
What Can Theory Offer?

Nuclear theory has experienced a renaissance in the past few decades thanks (in part) to two developments.

1. Advances in ***ab initio*** many-body methods.

   work with protons + neutrons
   &
   controlled approximations

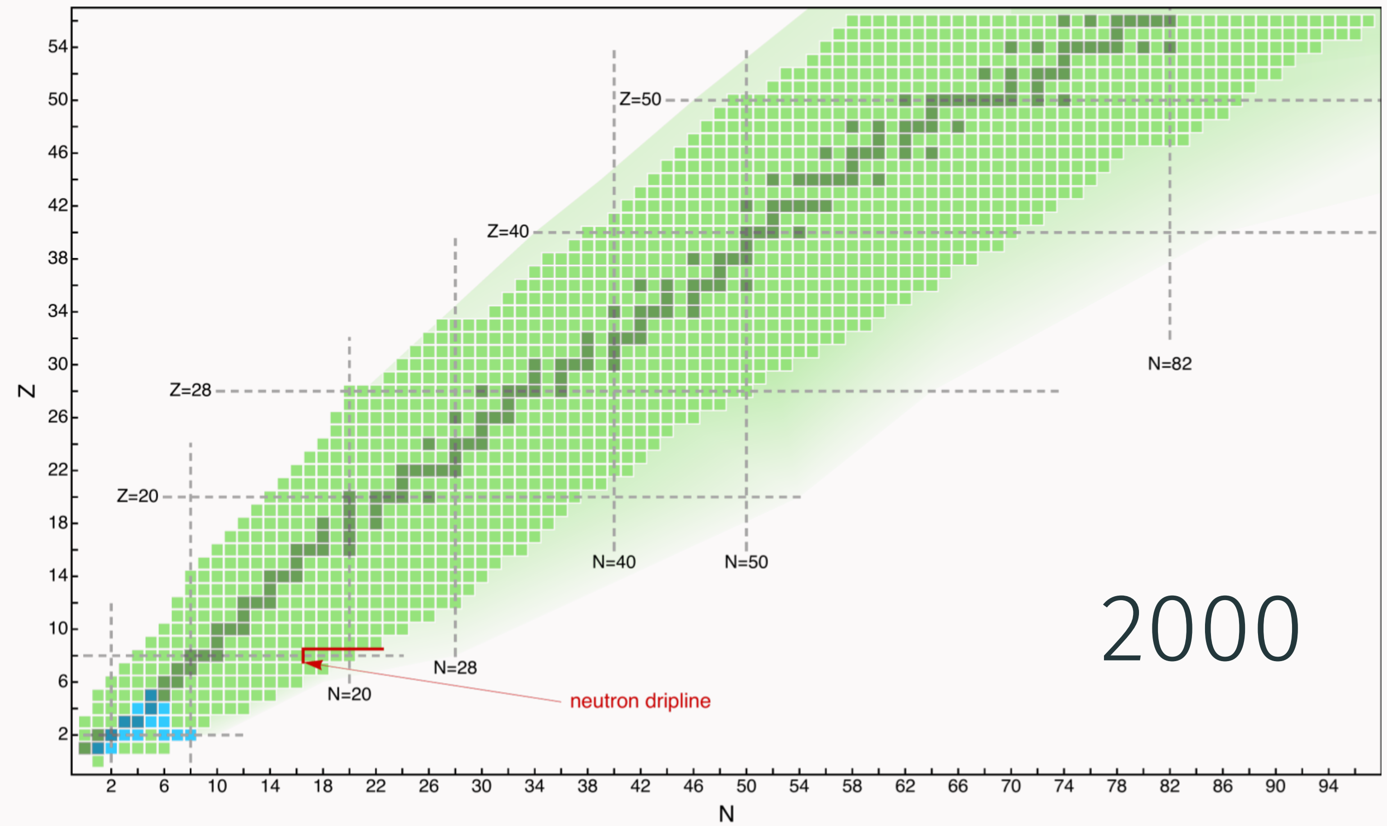
2. Chiral effective field
   interactions.



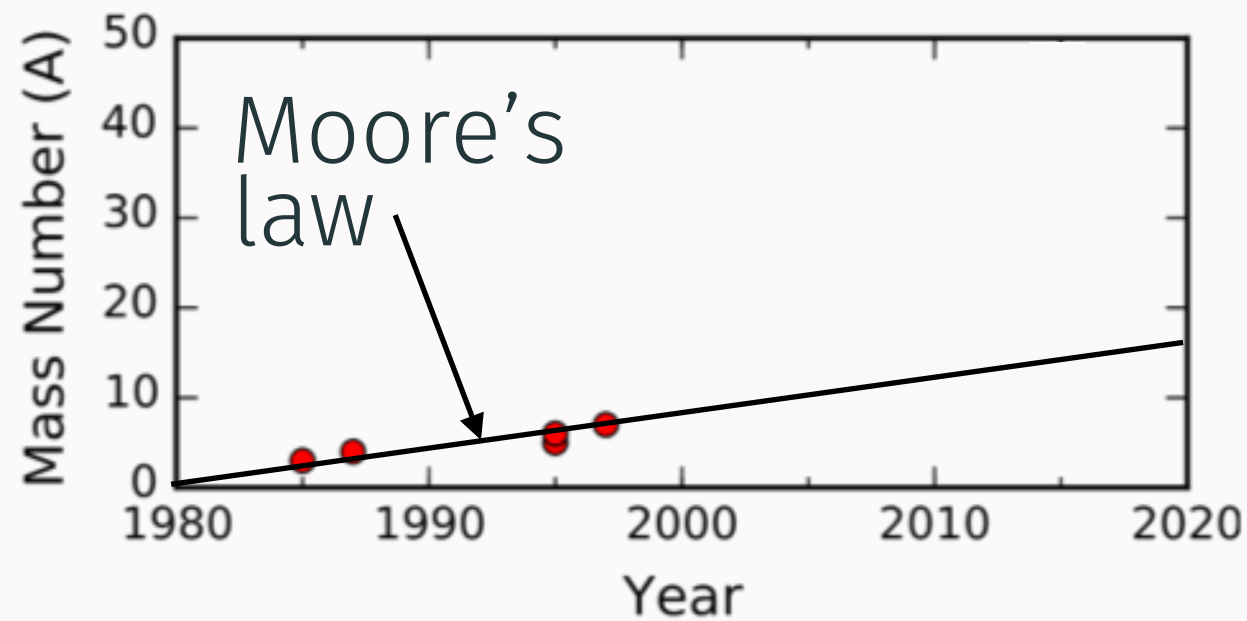
Reach Of *Ab Initio* Methods

- <u>1980s & 1990s:</u>
  Exact methods (exponential scaling) e.g. *Green's Function Monte Carlo Method* (***GFMC***), No-Core Shell Model. Limited by Moore's law - $A < 10, 12$

- <u>2000s and beyond</u>:
  New methods (polynomial scaling) e.g. Coupled cluster, *auxiliary-field diffusion Monte Carlo* (***AFDMC***). Closed-shell nuclei around up to $A = 40$.



from H. Hergert et al., Phys. Rep. **621**, 165 (2016)



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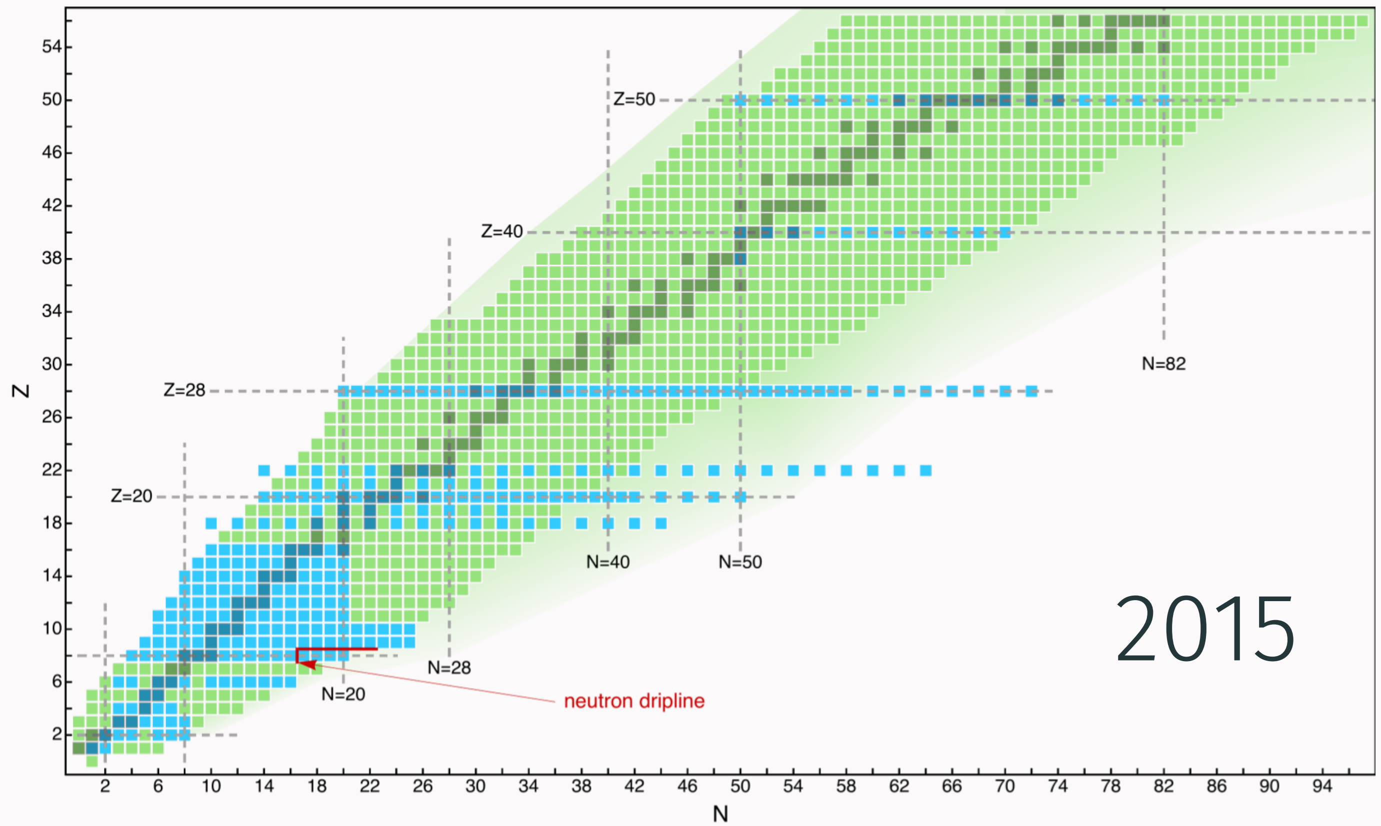

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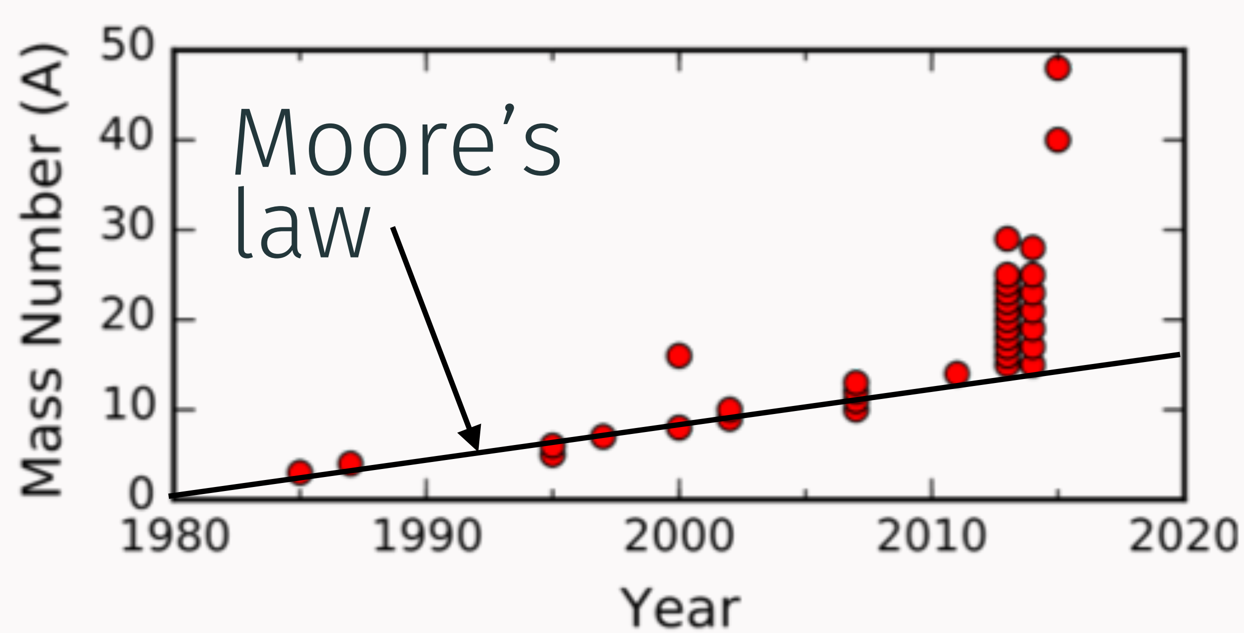

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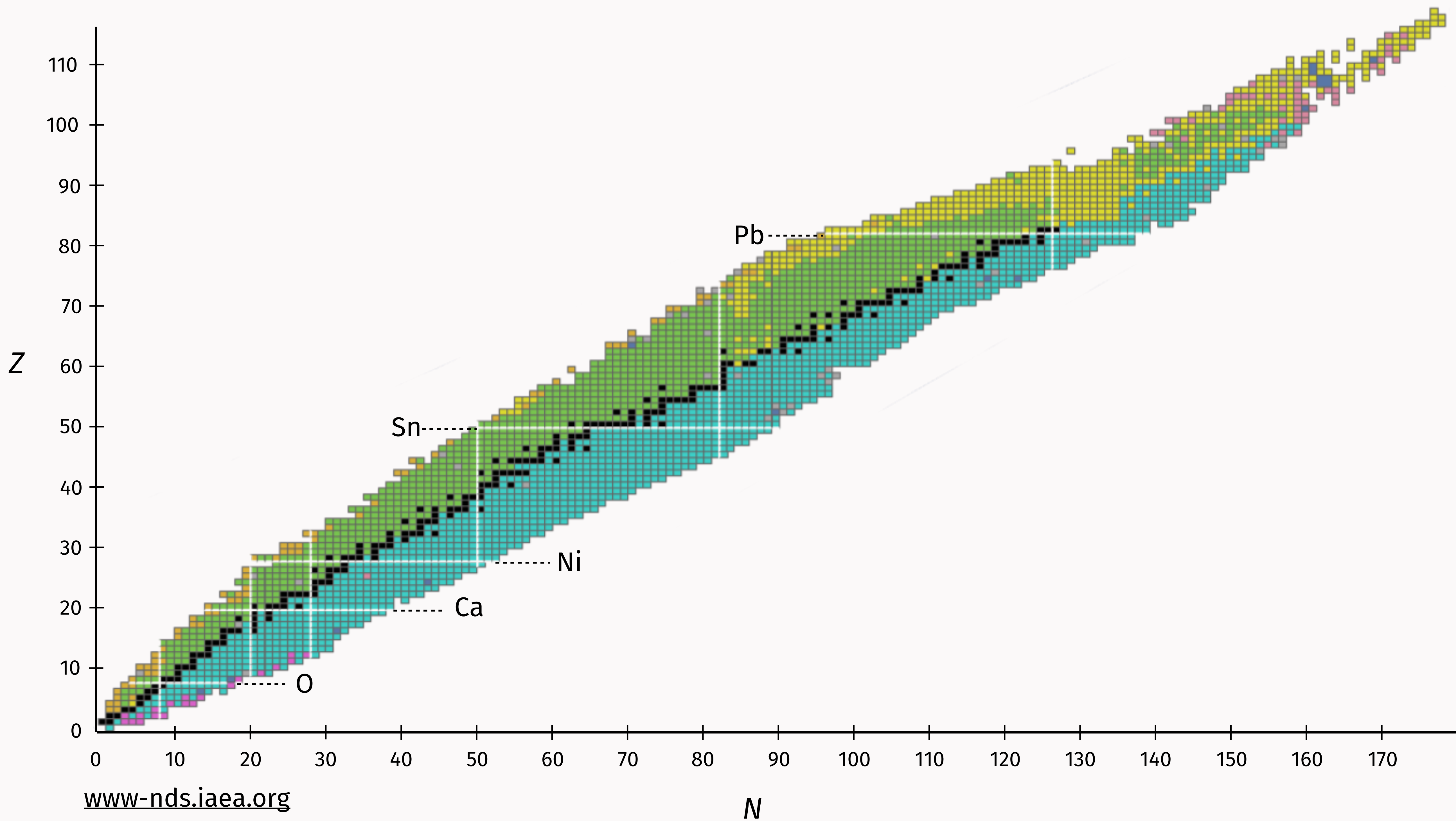
The Nuclear Landscape



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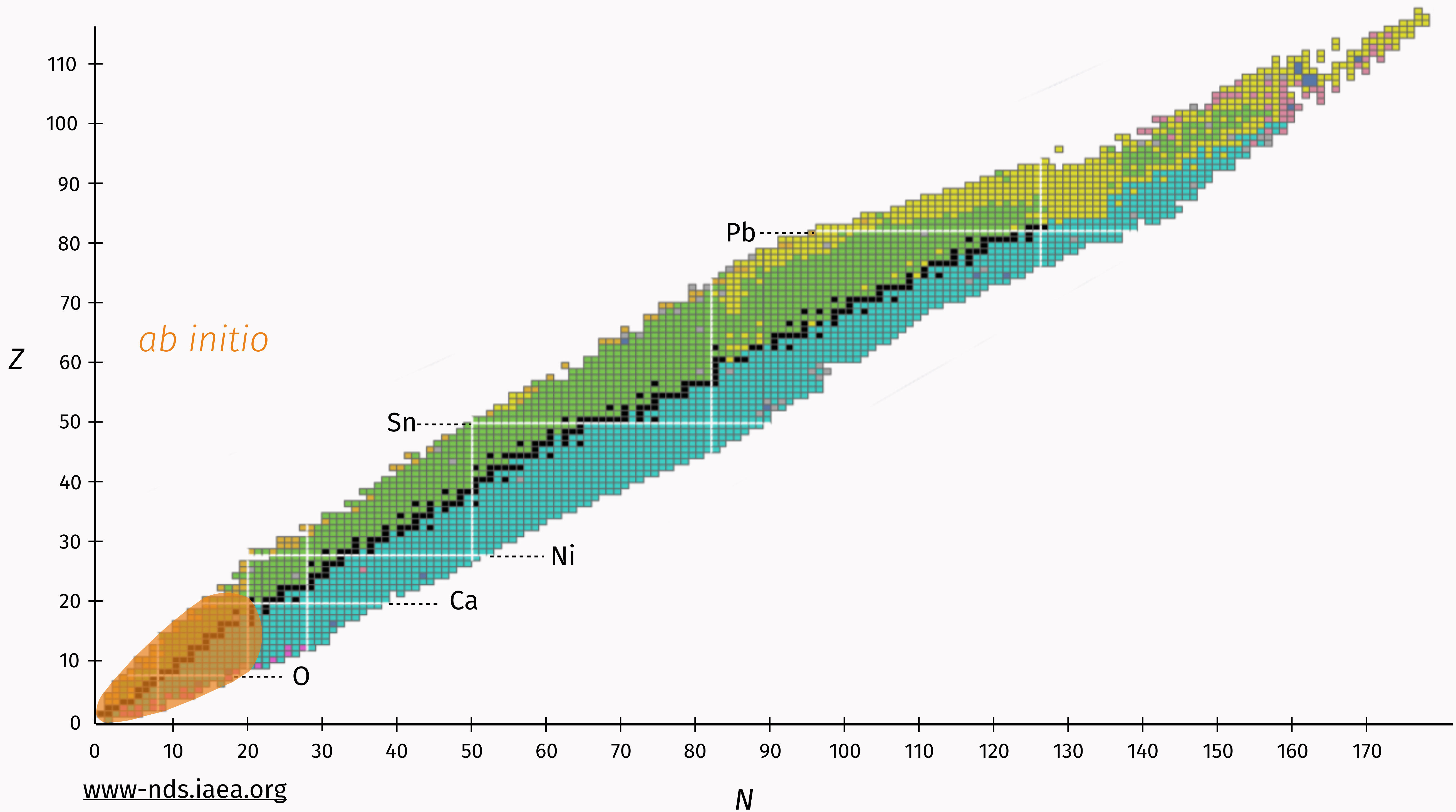

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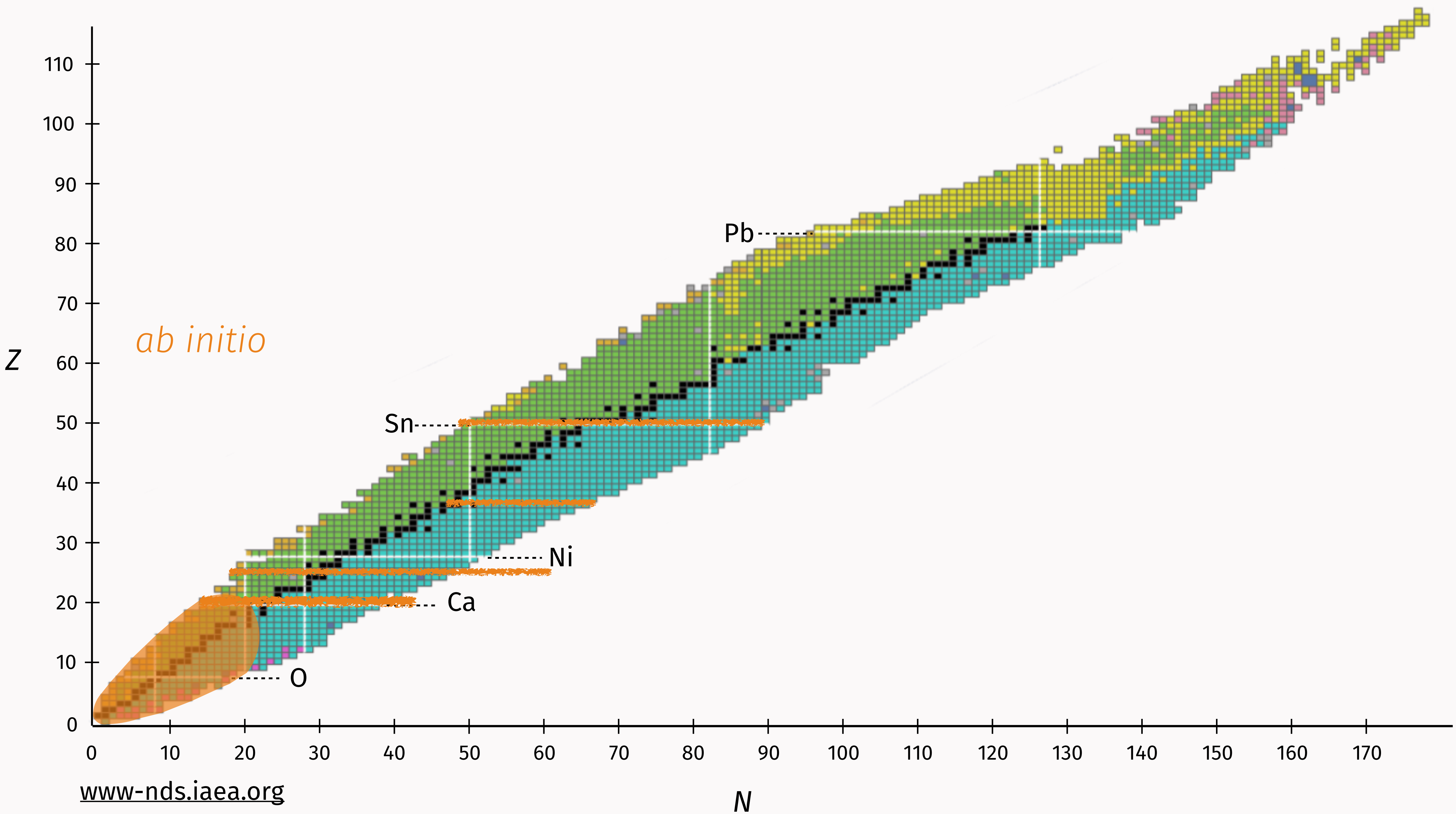

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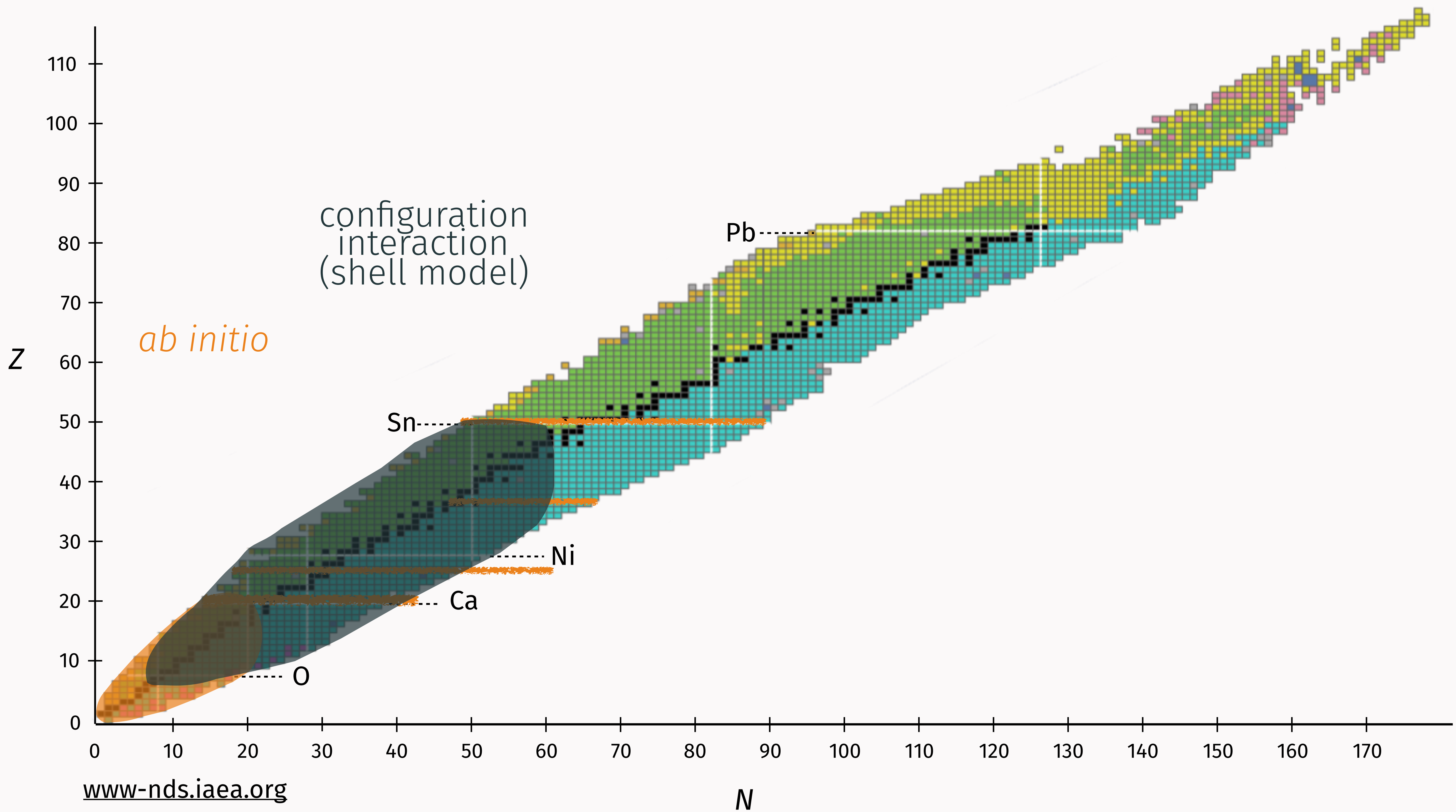

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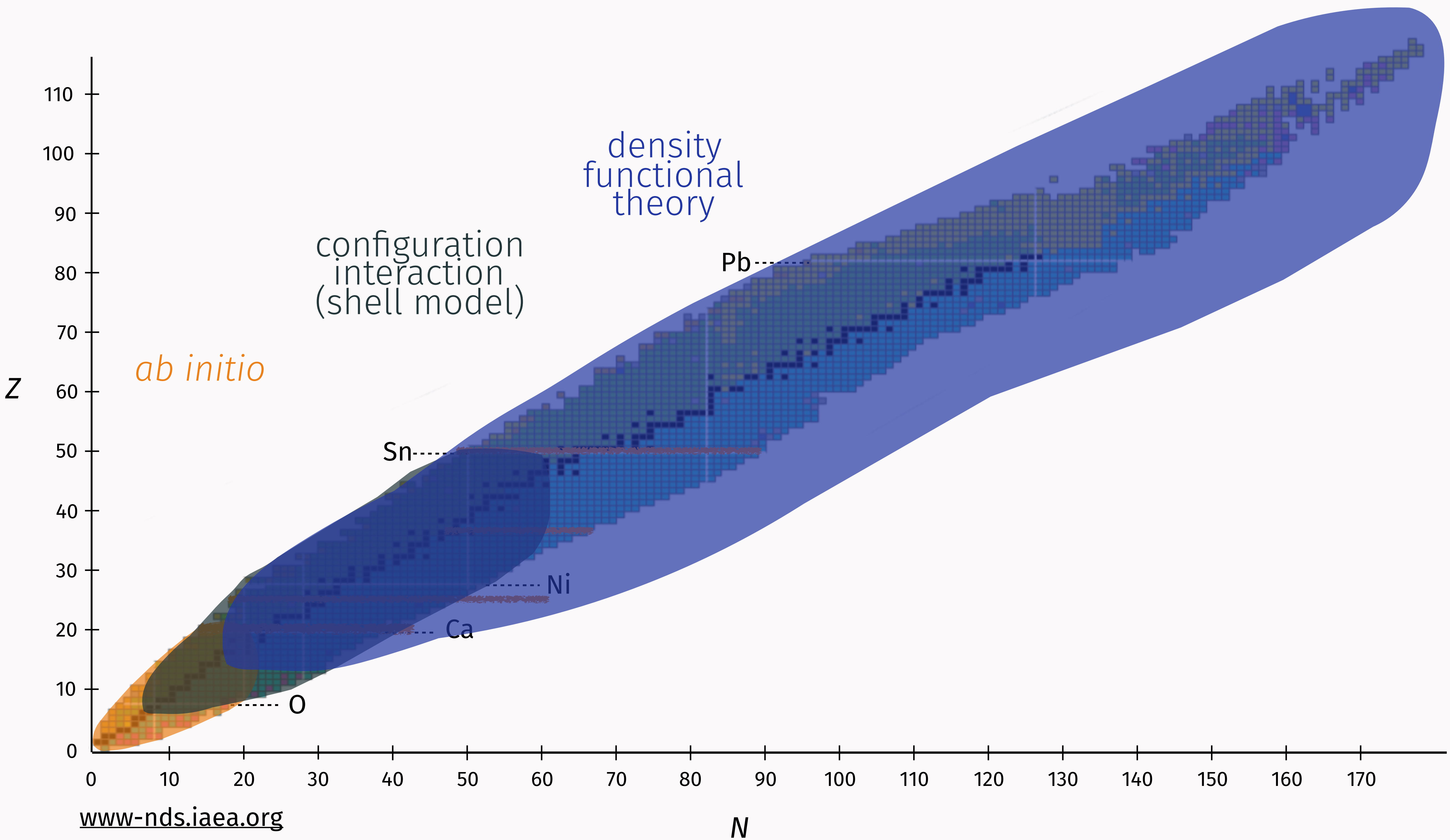

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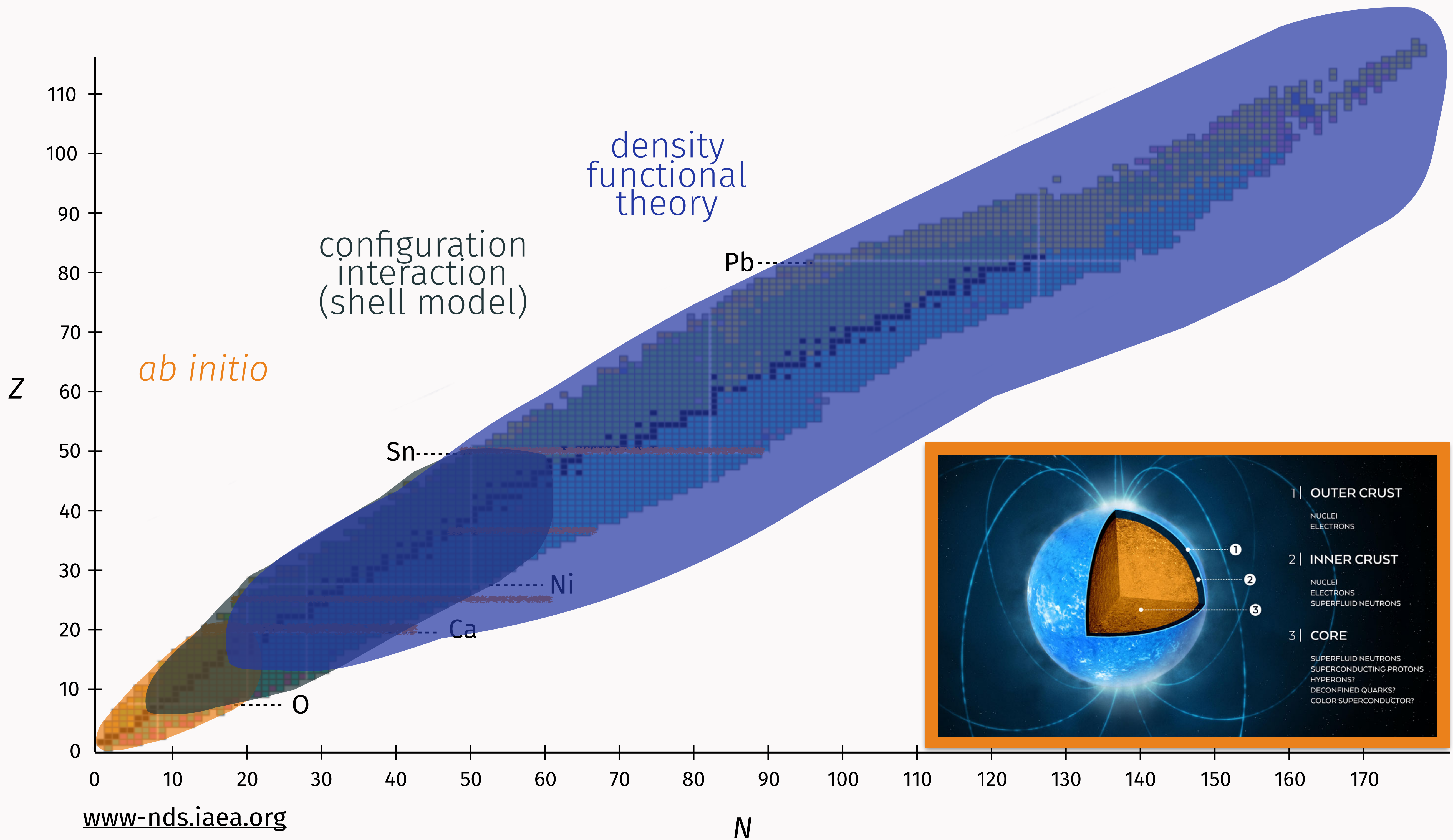

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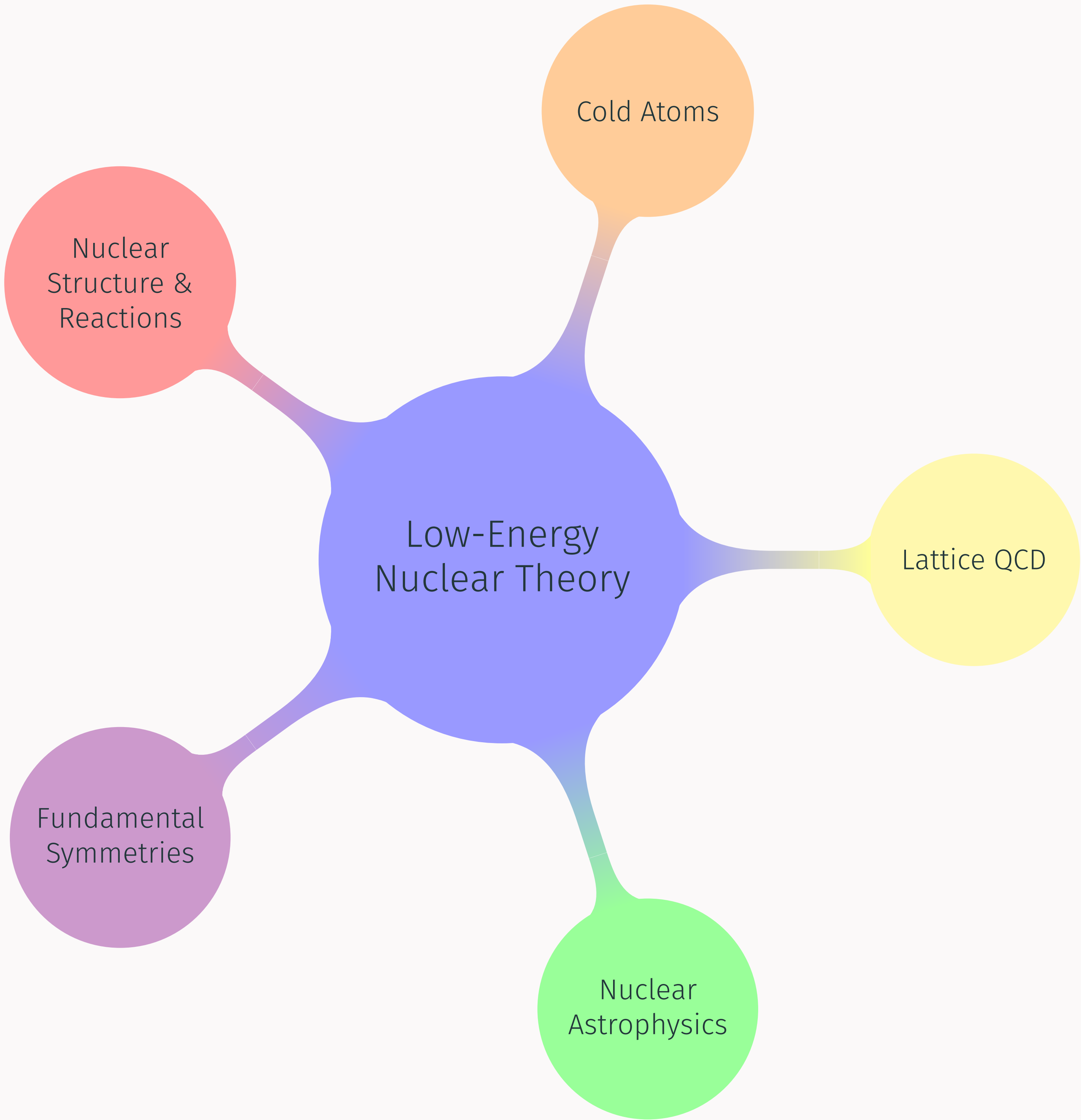
Motivation

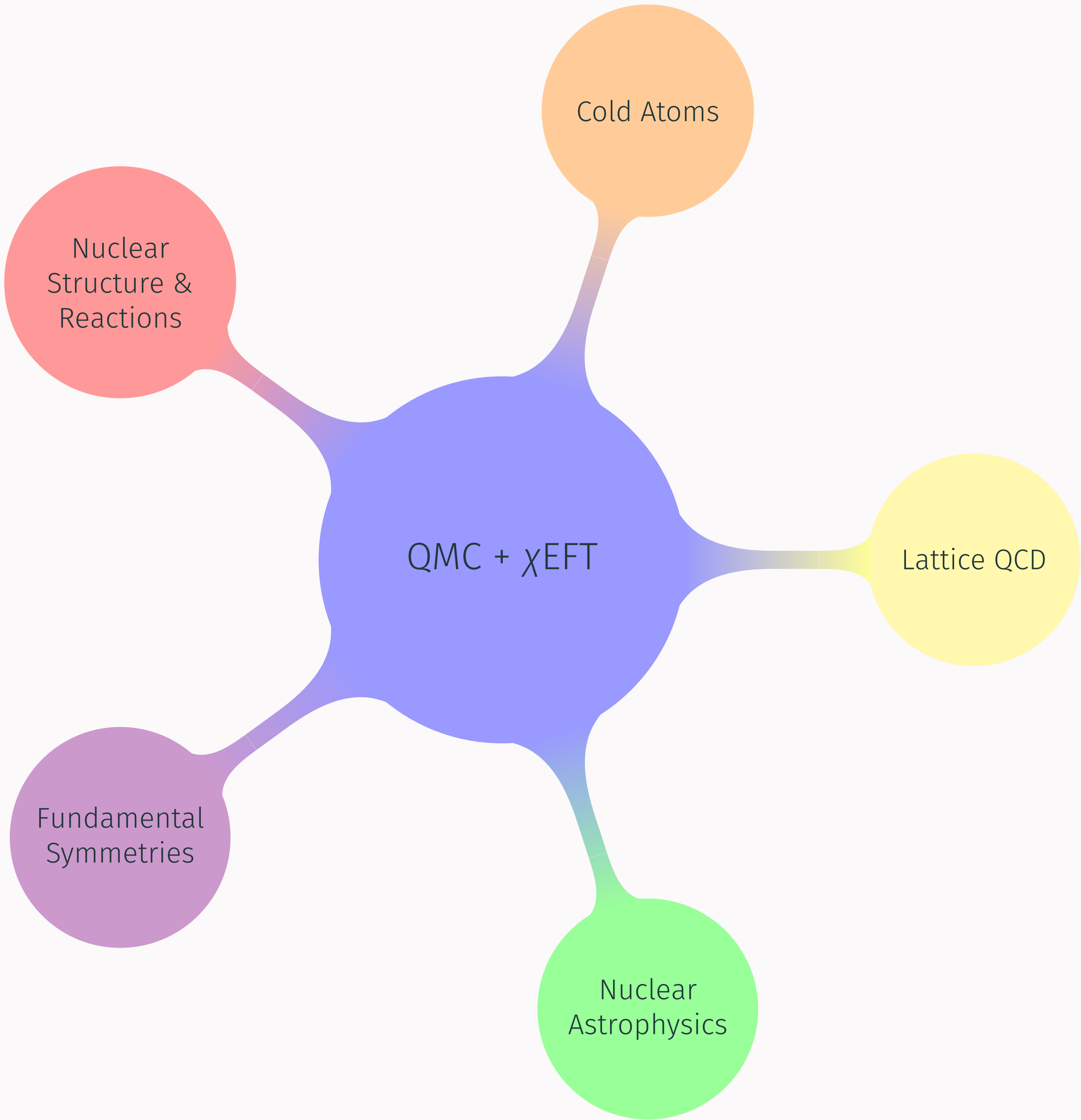
Low-energy nuclear theory sits in a privileged position, connecting many research areas.



Motivation

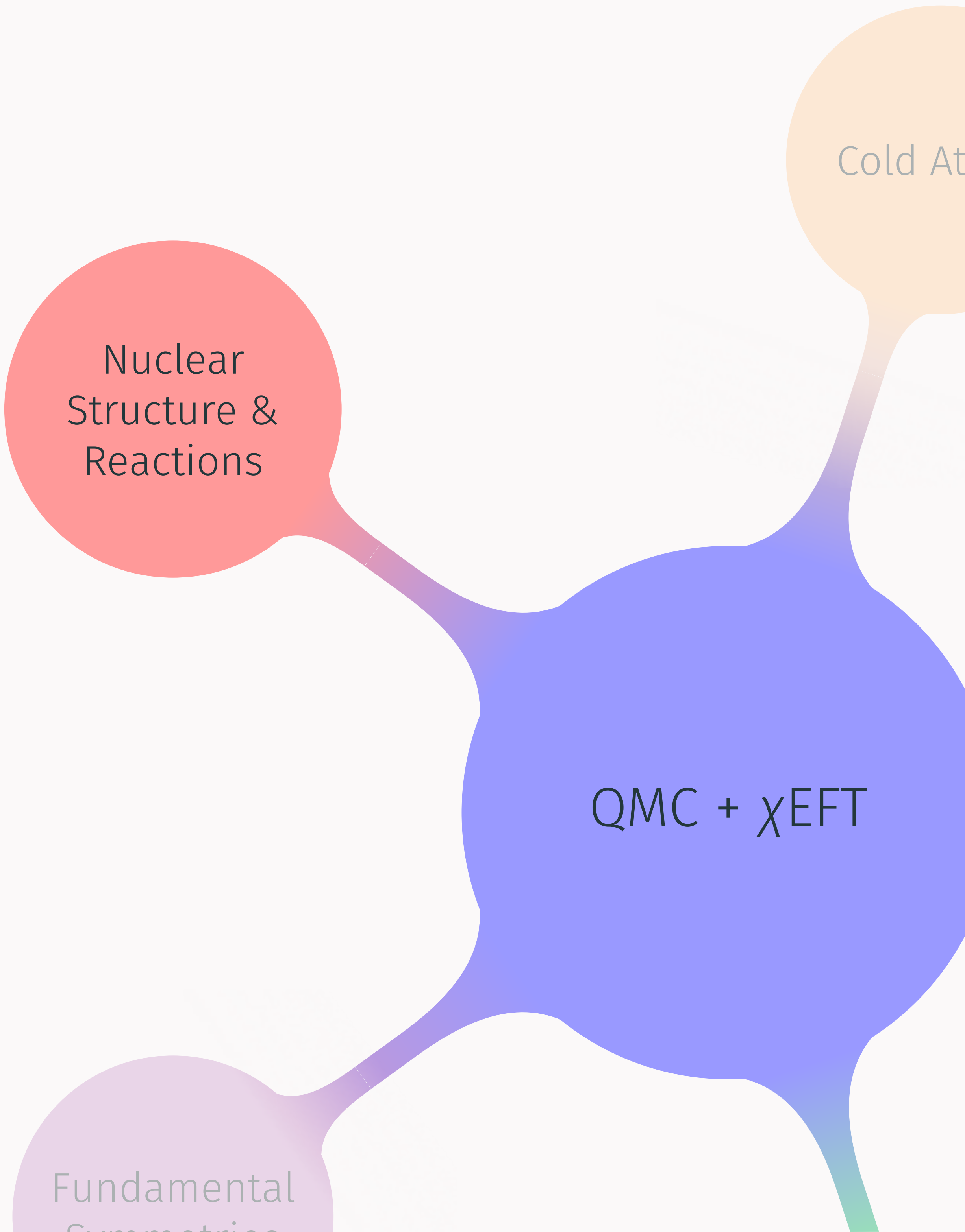
Low-energy nuclear theory sits in a privileged position, connecting many research areas.

Quantum Monte Carlo (QMC) methods with chiral effective field theory (χEFT) interactions is a compelling piece of the puzzle!



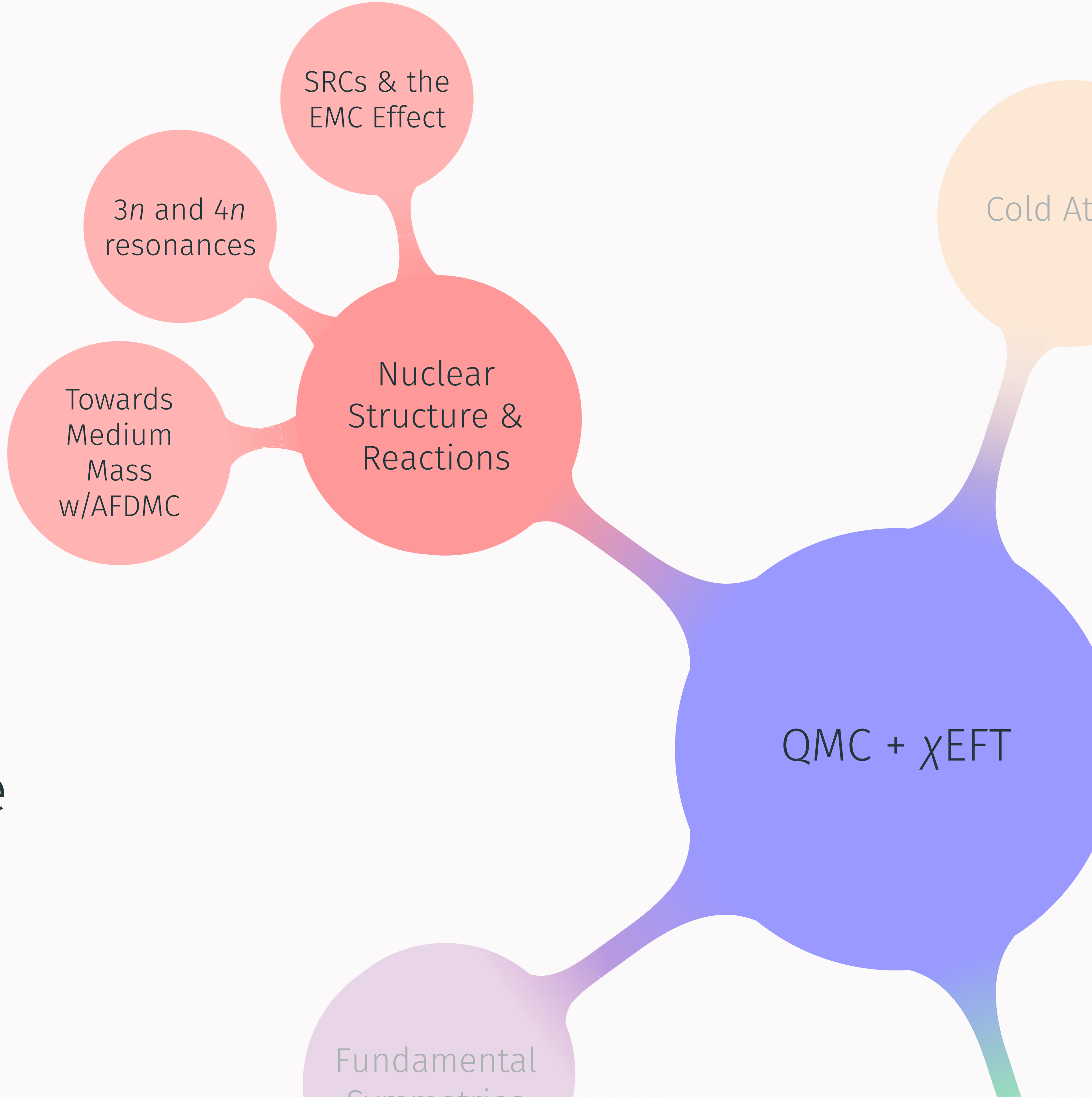
Outline

- Quantum Monte Carlo Methods
- Chiral EFT



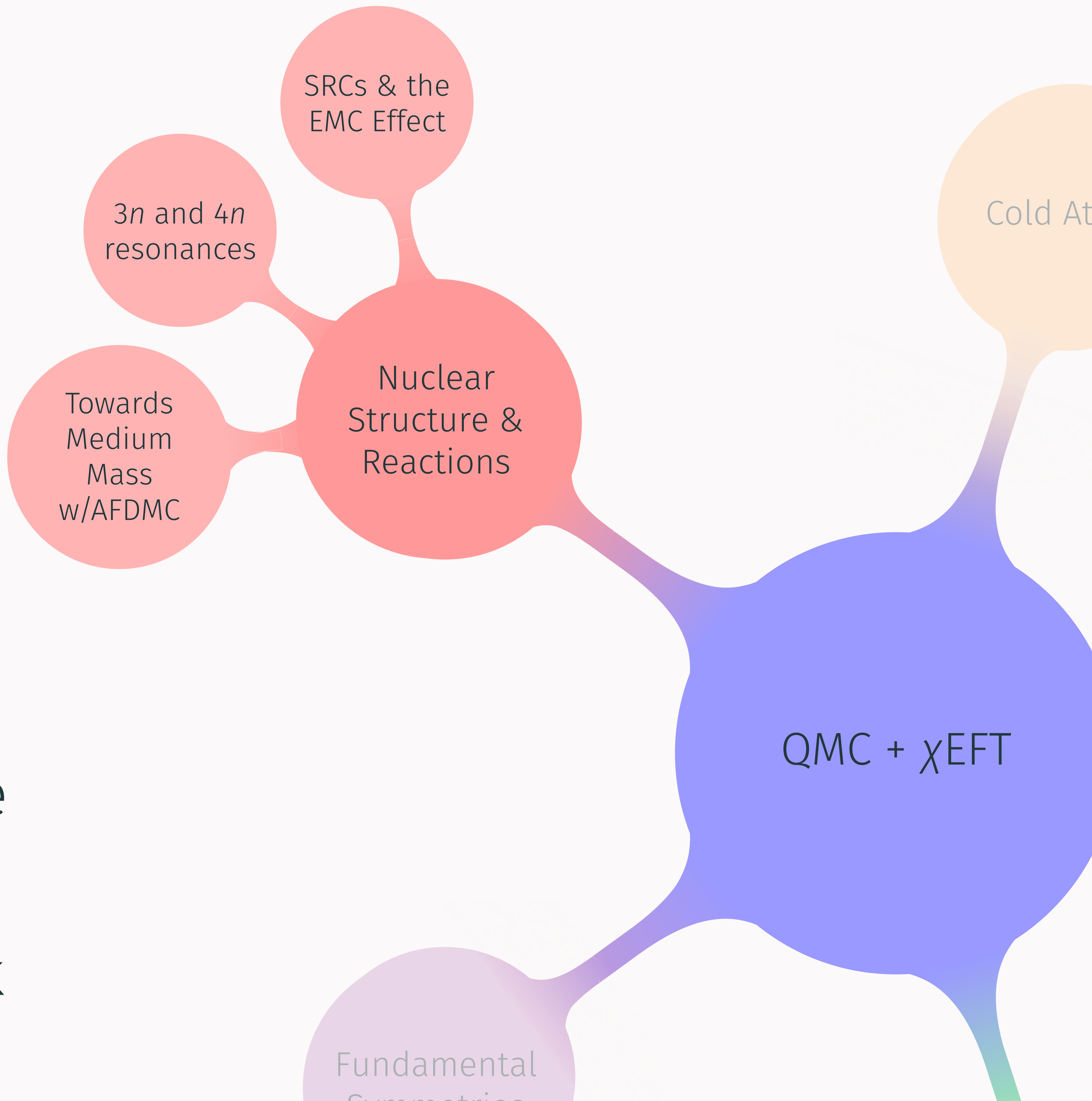
Outline

- Quantum Monte Carlo Methods
- Chiral EFT
- Towards medium-mass nuclei with the AFDMC method
- $3n$ & $4n$ resonances
- Short-range correlations and the EMC effect



Outline

- Quantum Monte Carlo Methods
- Chiral EFT
- Towards medium-mass nuclei with the AFDMC method
- $3n$ & $4n$ resonances
- Short-range correlations and the EMC effect
- Summary & Outlook



Quantum Monte Carlo (QMC) Methods

QMC Methods - Variational Monte Carlo (VMC) Method

1. Start with a trial wave function Ψ_T and generate a random position: $\mathbf{R} = \mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_A$.

2. Metropolis algorithm: Generate new positions $\mathbf{R}'$ based on the probability $P = \frac{|\Psi_T(\mathbf{R}')|^2}{|\Psi_T(\mathbf{R})|^2}$. $\longrightarrow$ $\{$  $\}$

3. Invoke the variational principle: $E_T = \frac{\langle \Psi_T | H | \Psi_T \rangle}{\langle \Psi_T | \Psi_T \rangle} > E_0$.

QMC Methods - Diffusion Monte Carlo Method

- The wave function is imperfect: $|\Psi_T\rangle = \sum_{i=0}^{\infty} \alpha_i |\Psi_i\rangle$.
- Propagate in imaginary time to project out the ground state $|\Psi_0\rangle$.

$$
\begin{aligned}
|\Psi(\tau)\rangle &= e^{-(H-E_T)\tau} |\Psi_T\rangle \\
&= e^{-(E_0-E_T)\tau}[\alpha_0 |\Psi_0\rangle + \sum_{i\neq 0} \alpha_i e^{-(E_i-E_0)\tau} |\Psi_i\rangle].
\end{aligned}
$$

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\end{aligned}
$$

$$
|\Psi(\tau)\rangle \xrightarrow{\tau\to\infty} |\Psi_0\rangle .
$$

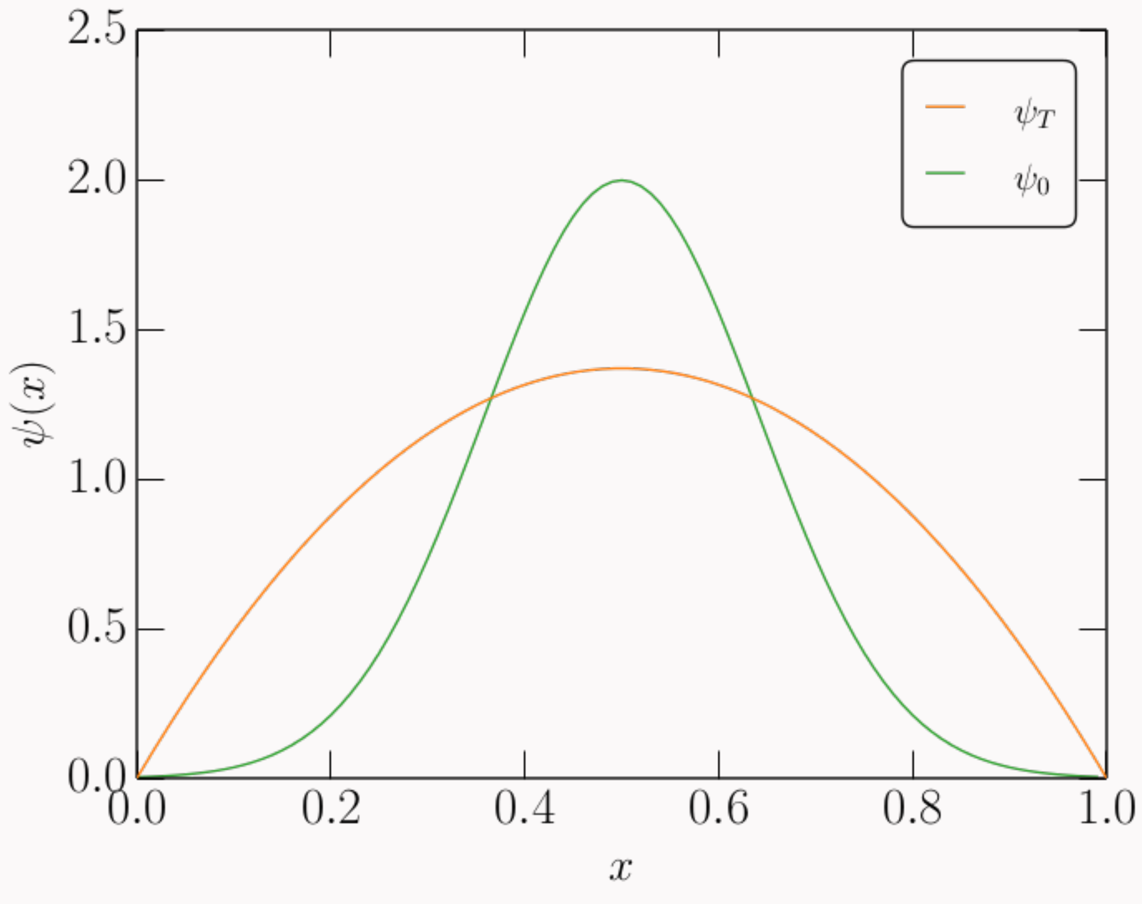
QMC Methods - An Example

$$H = \frac{p^2}{2} + \frac{1}{2}\omega^2 x^2$$

$$\psi_0(x) = \left(\frac{\omega}{\pi}\right)^{1/4} e^{-\omega x^2/2}$$

Trial wave function; e.g.

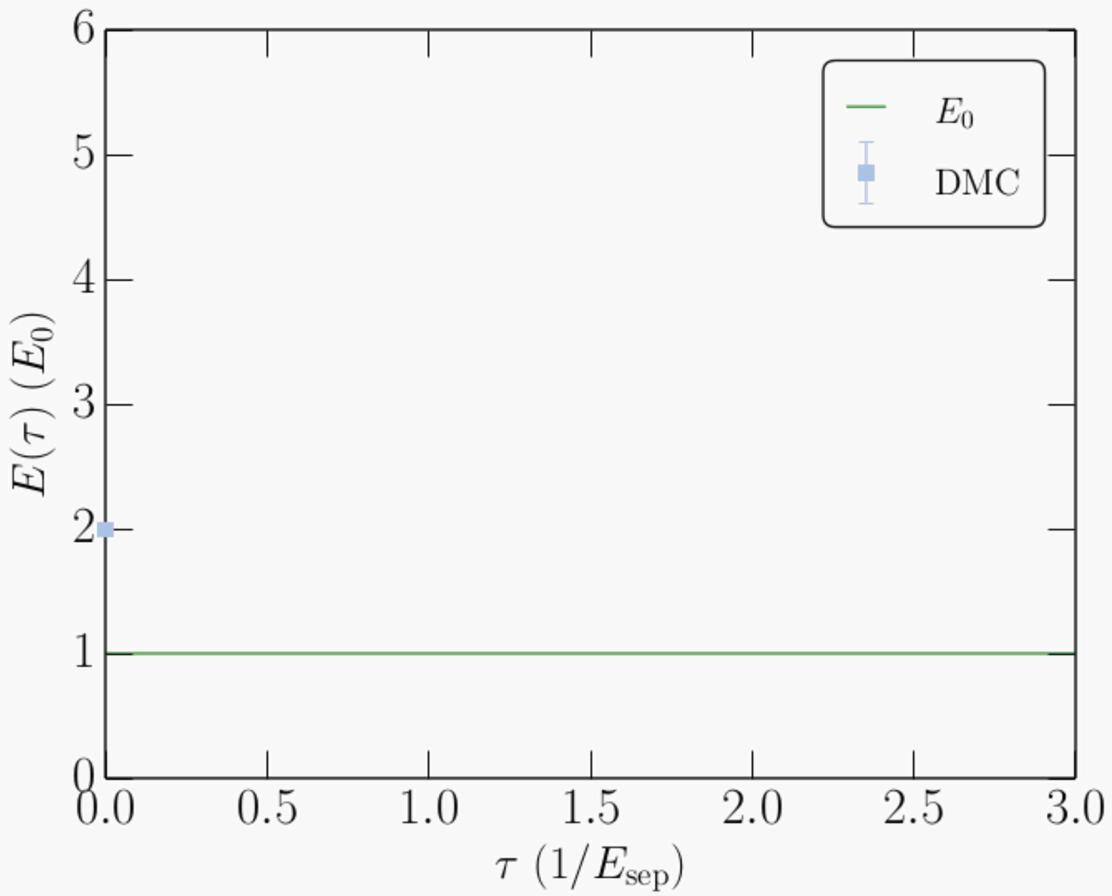
$$\Psi_T(x) = \sqrt{30}x(1-x).$$

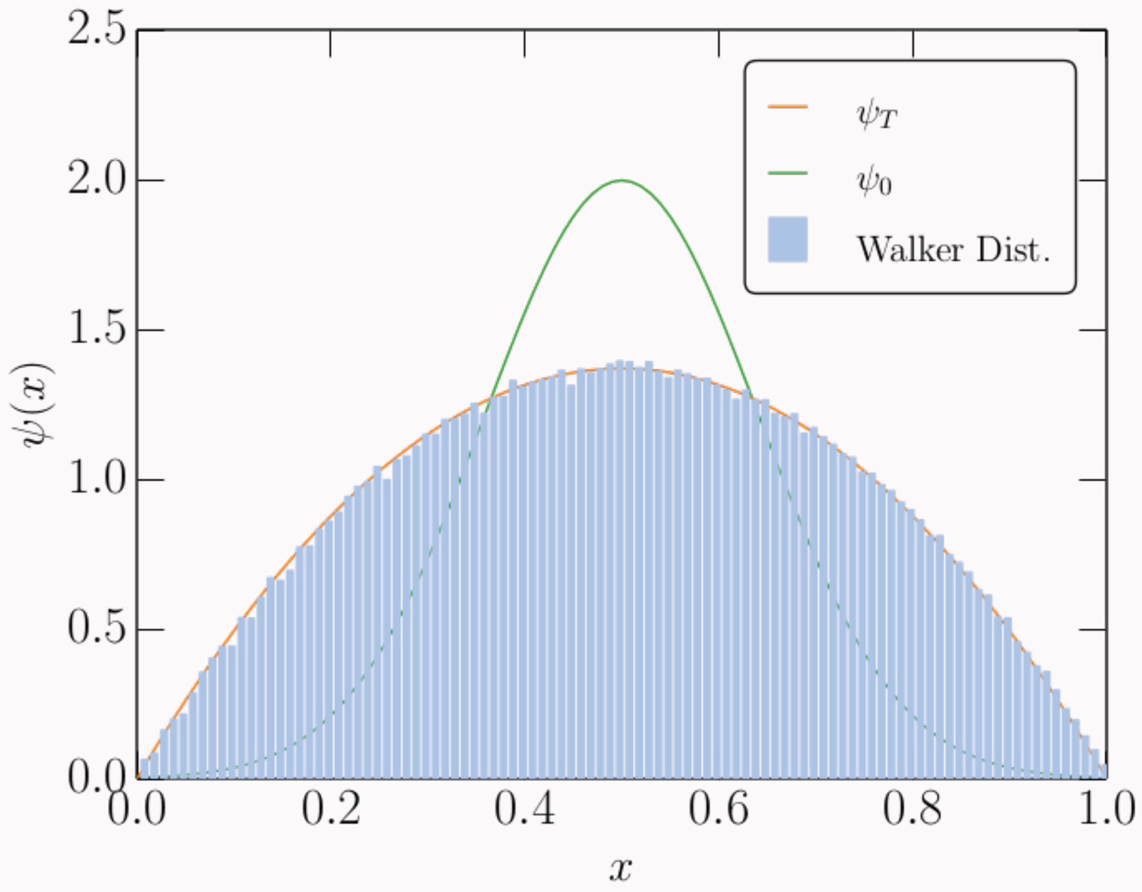


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 0.00$

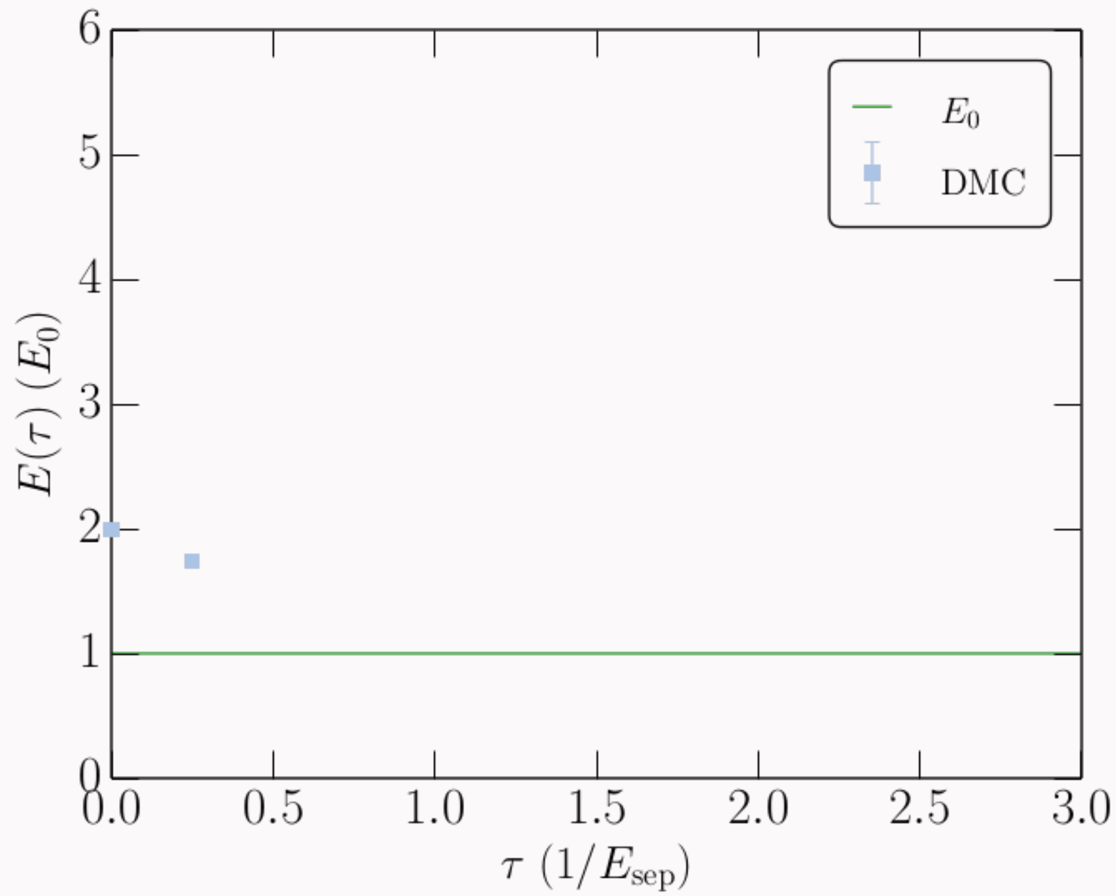


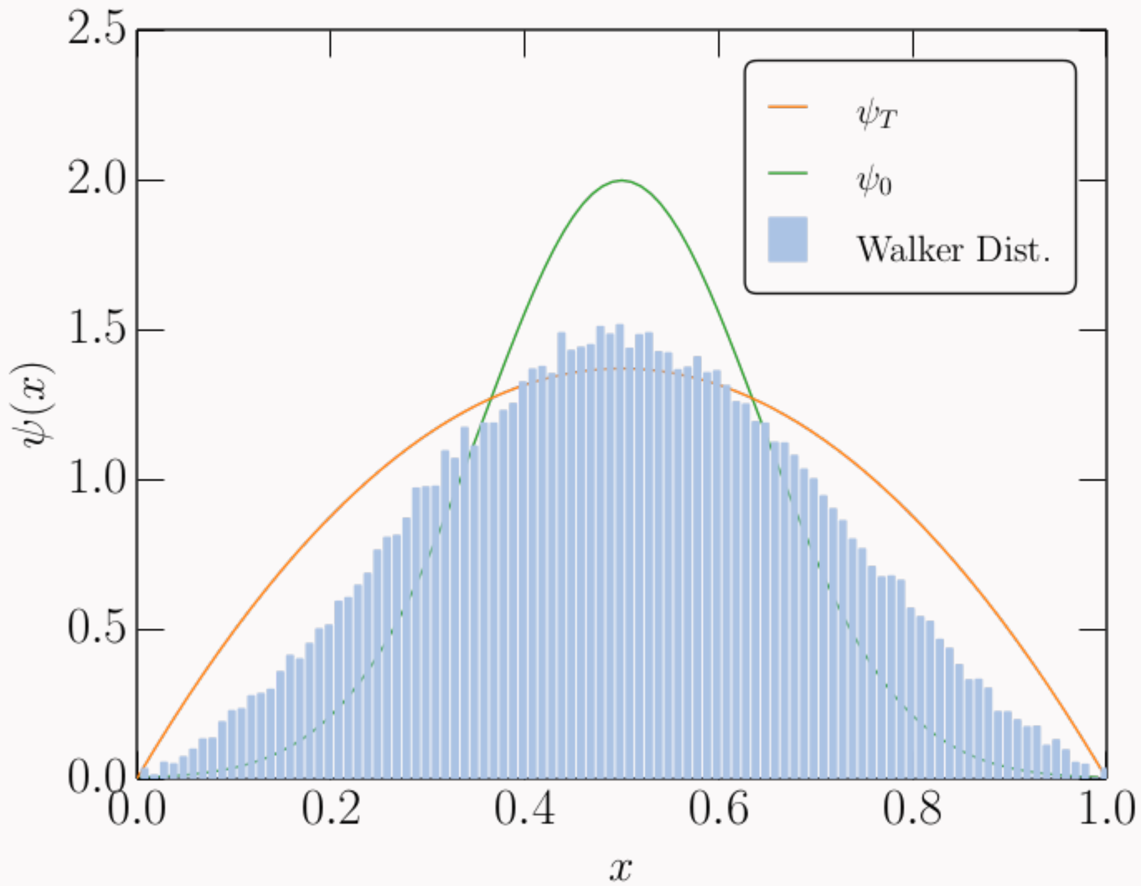


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 0.25$

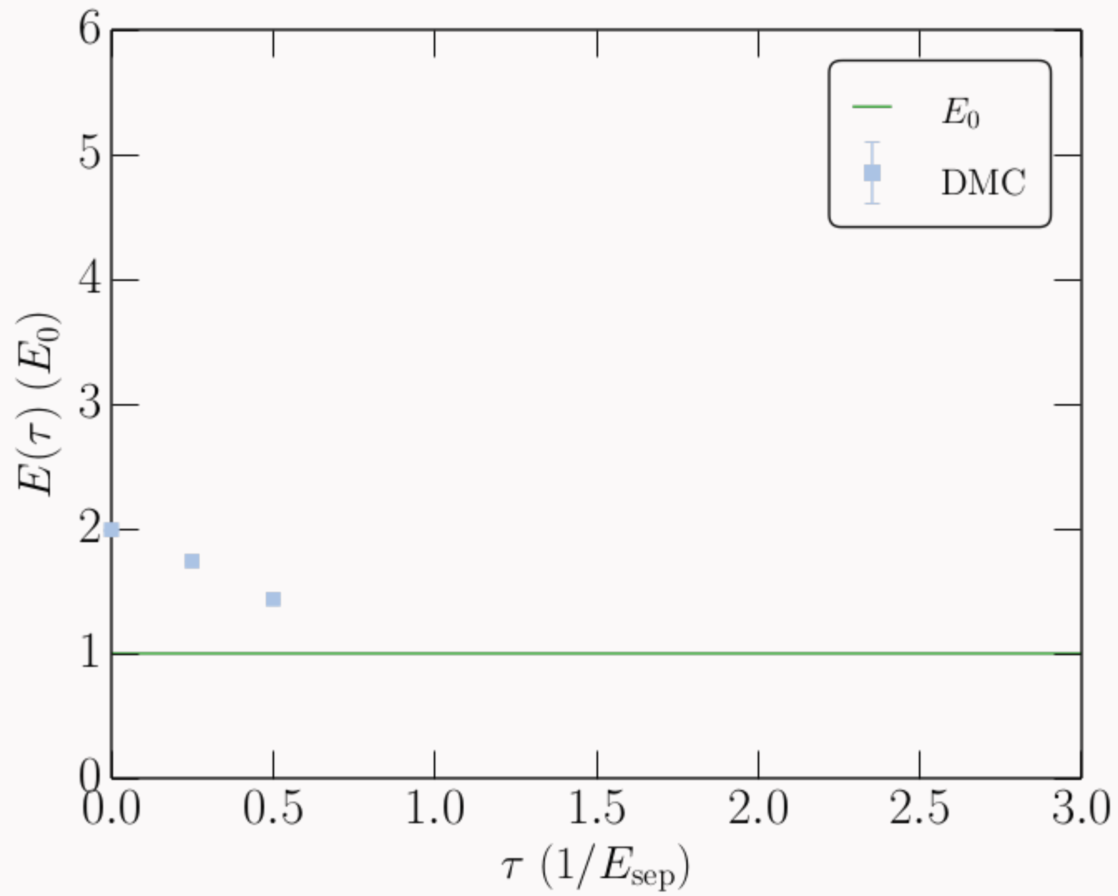


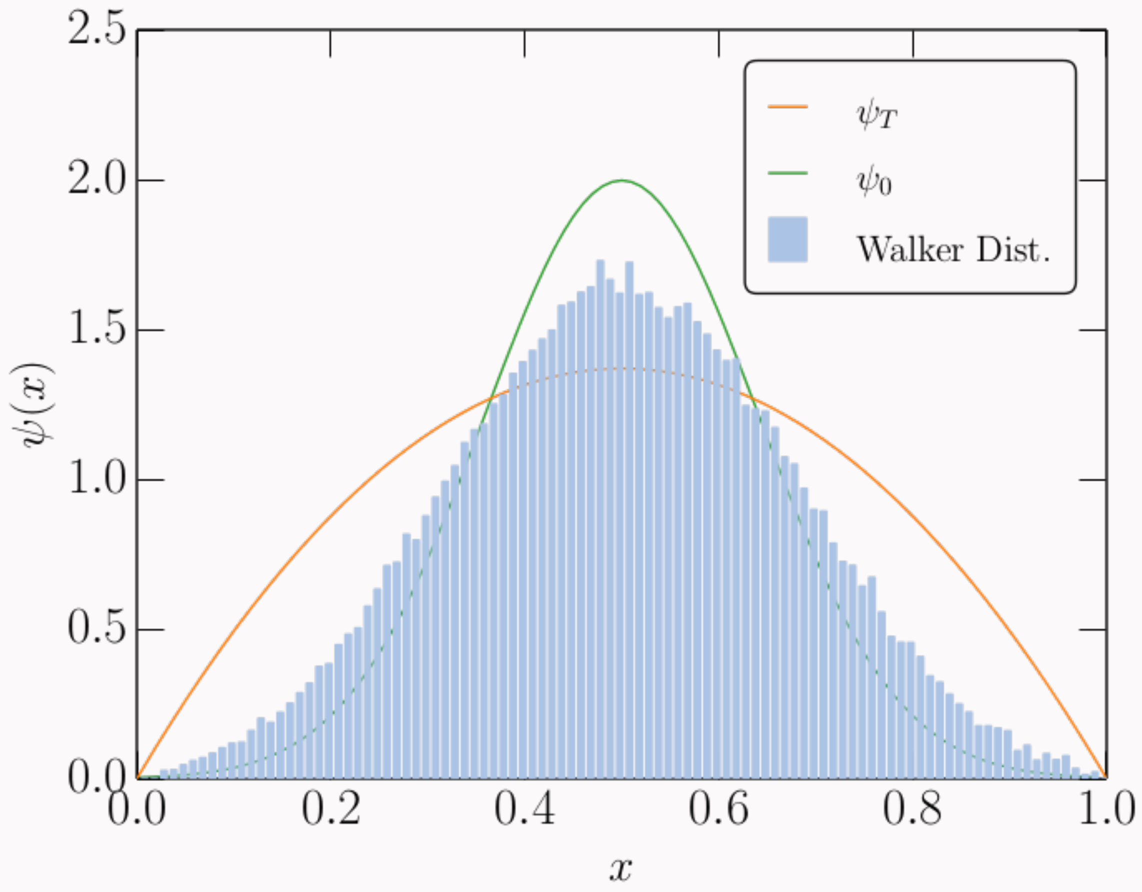


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 0.50$

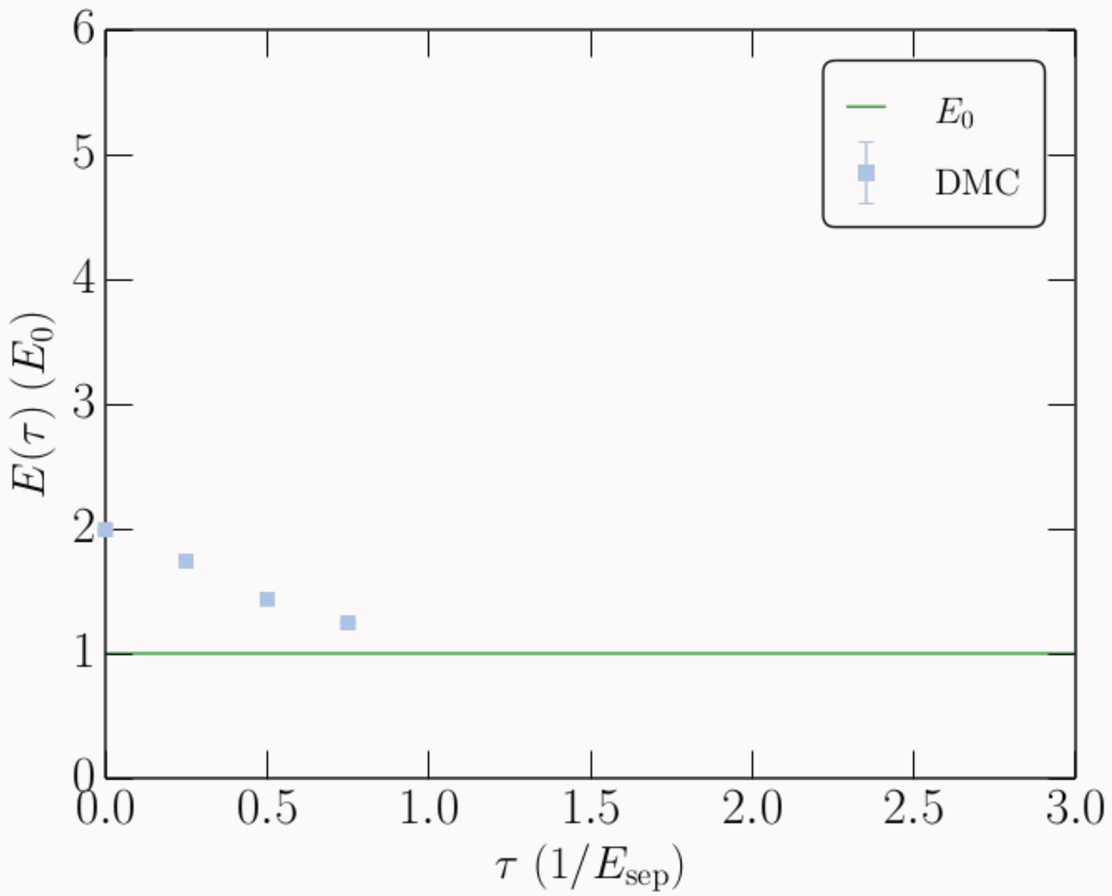


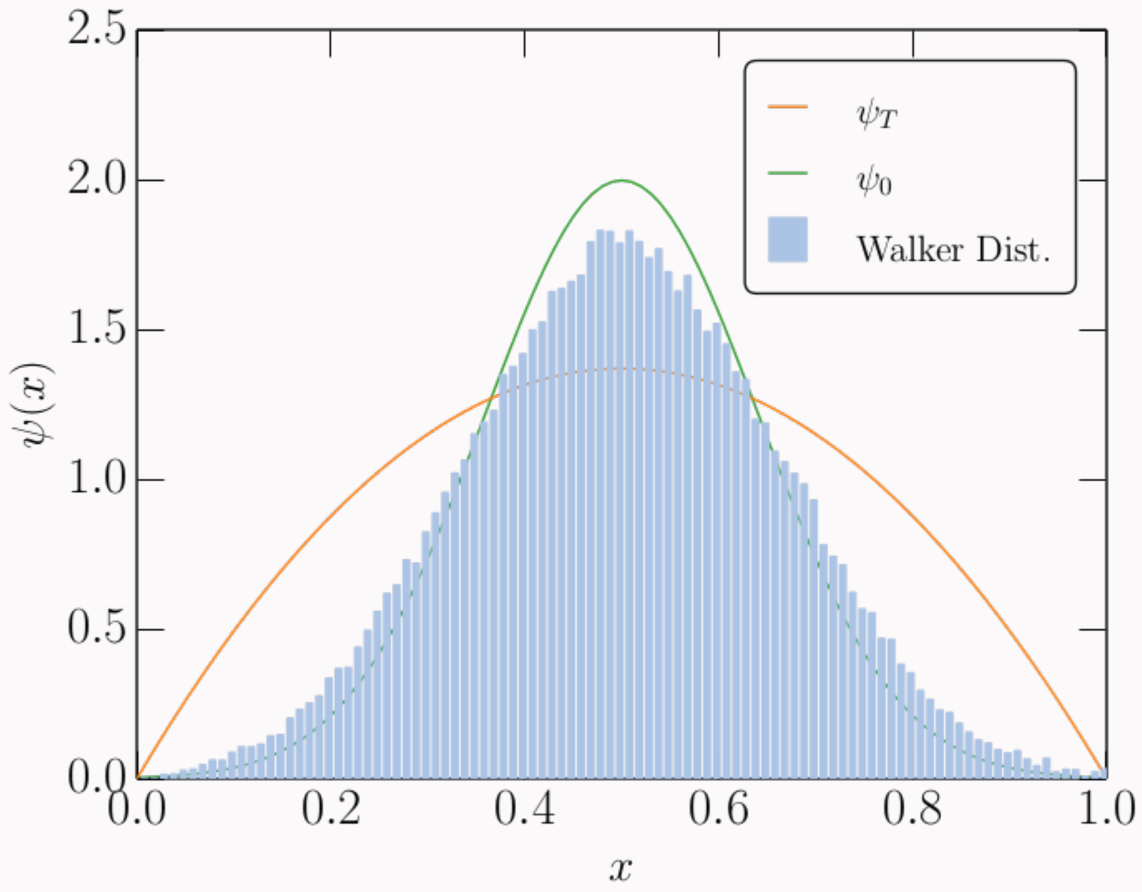


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 0.75$

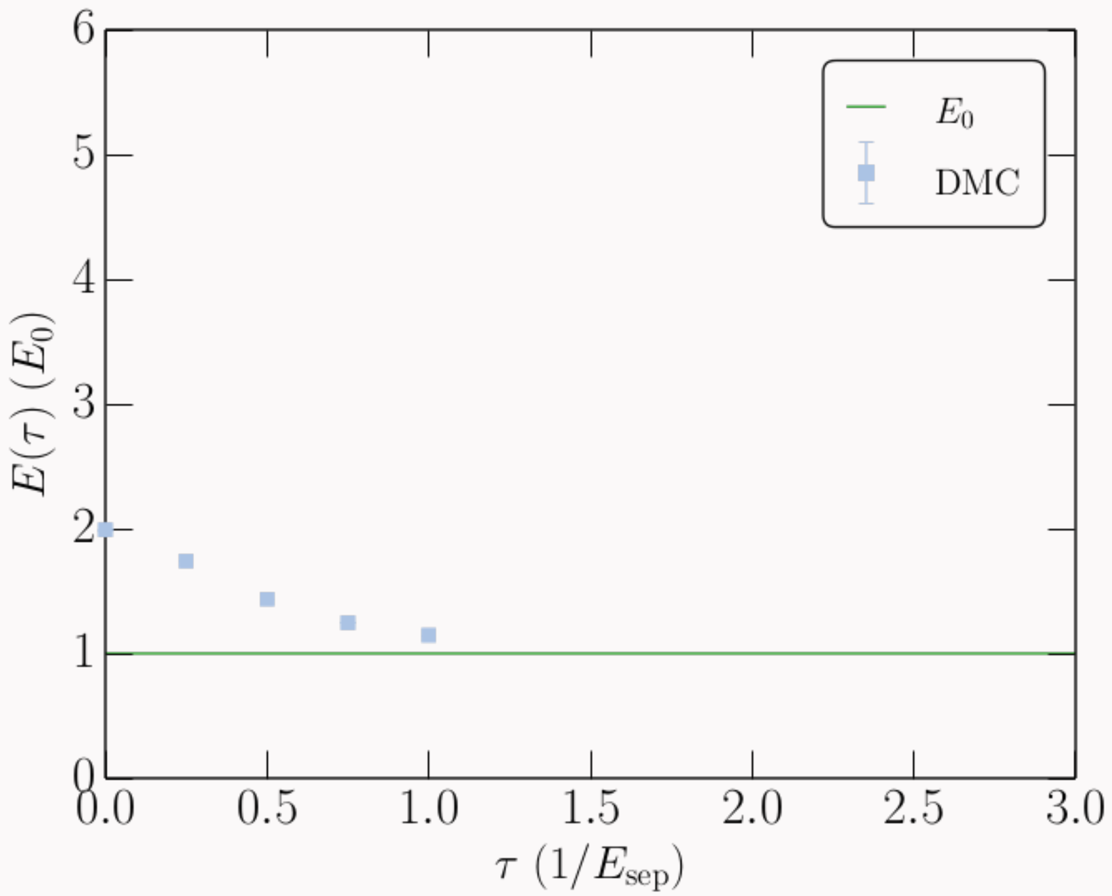


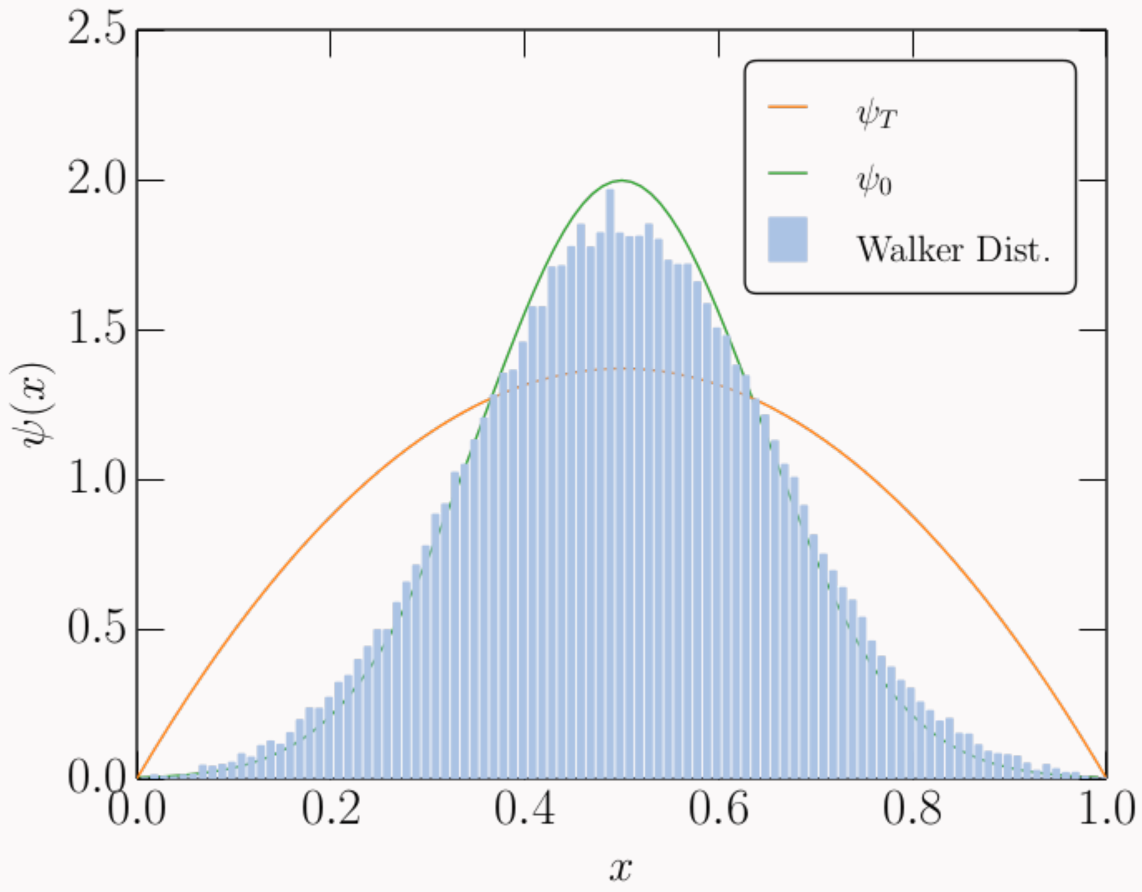


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 1.00$





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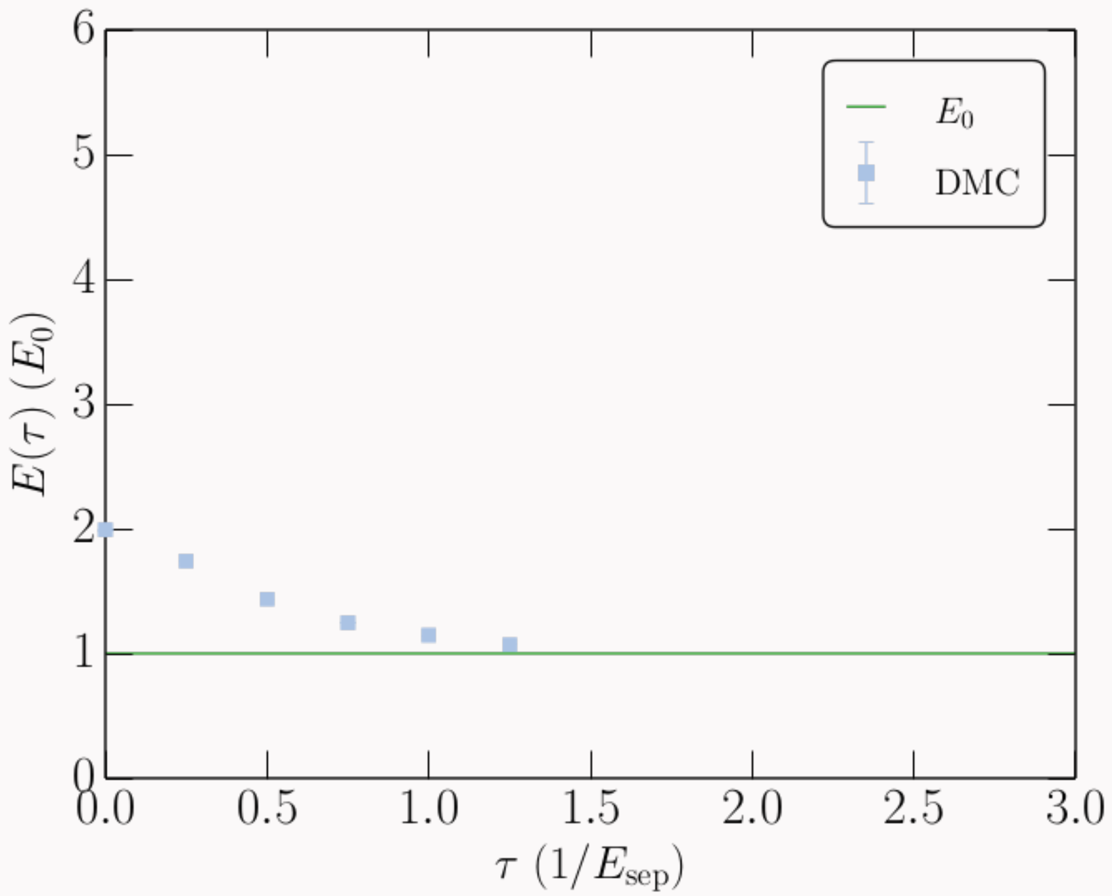
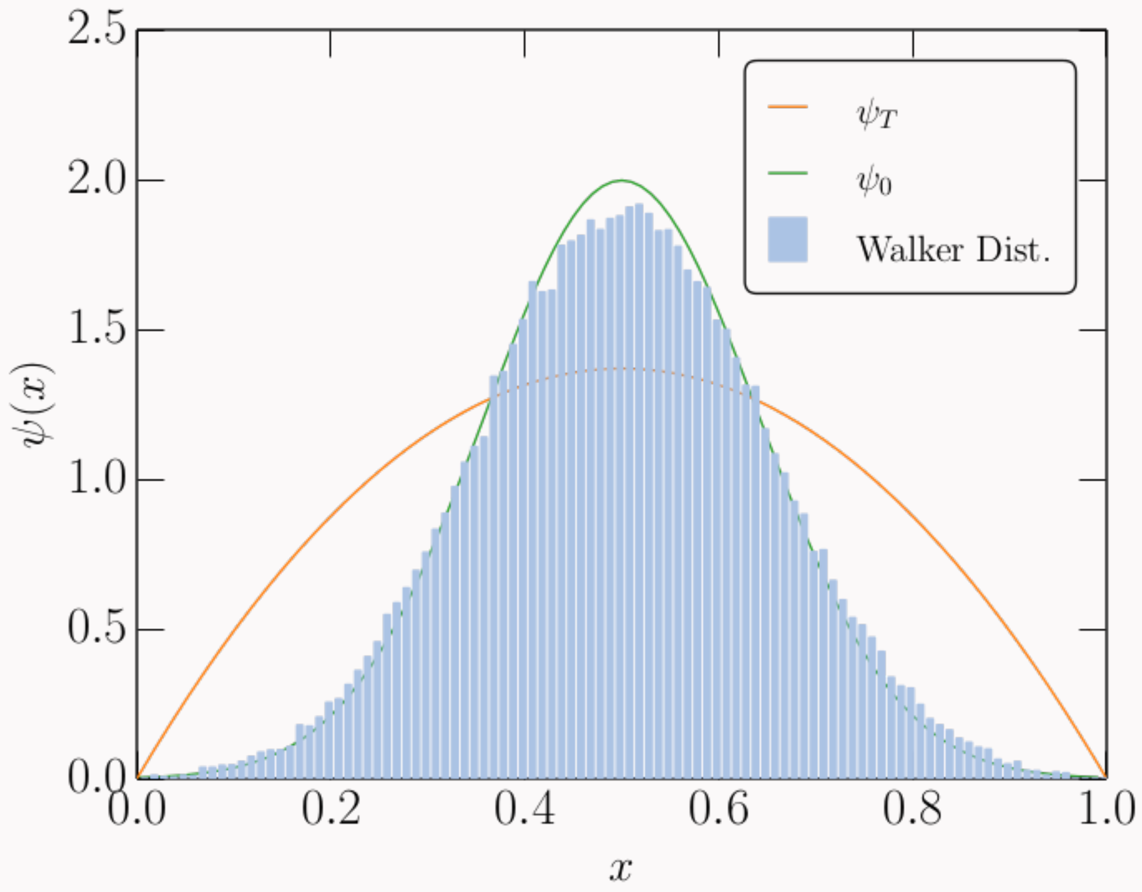
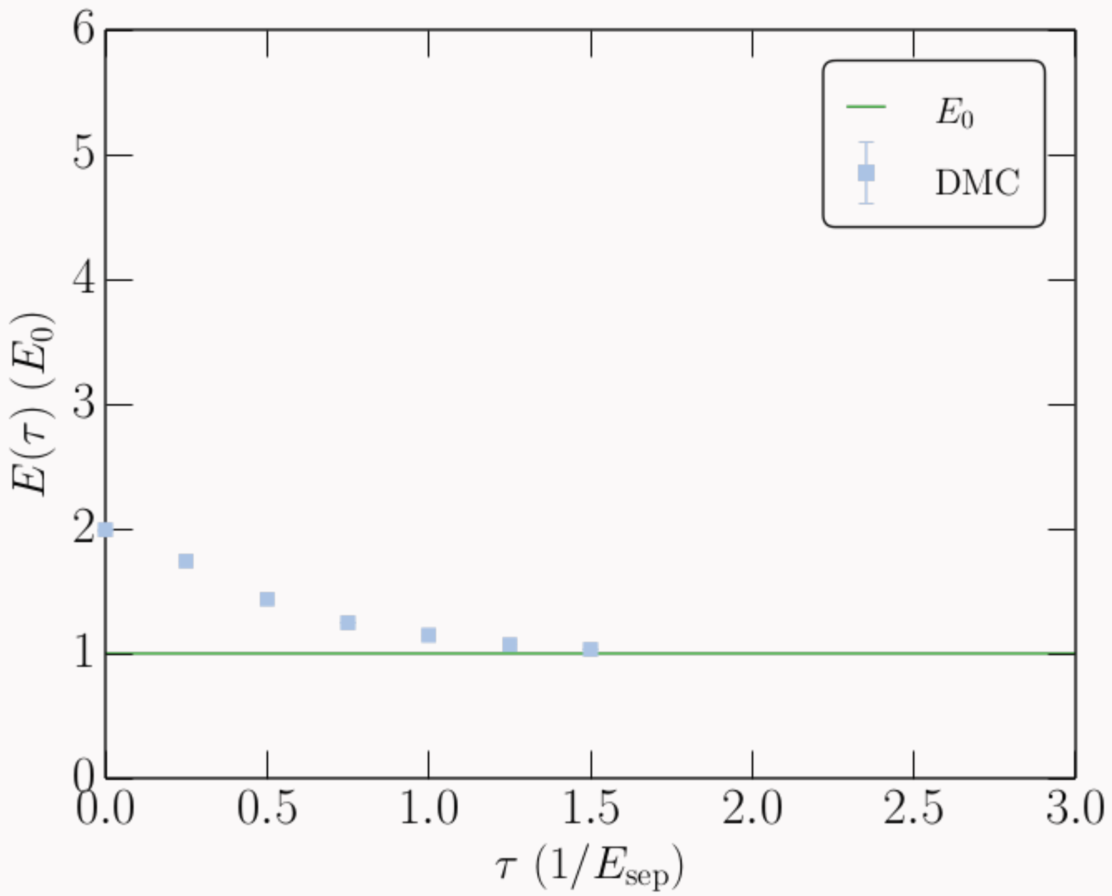


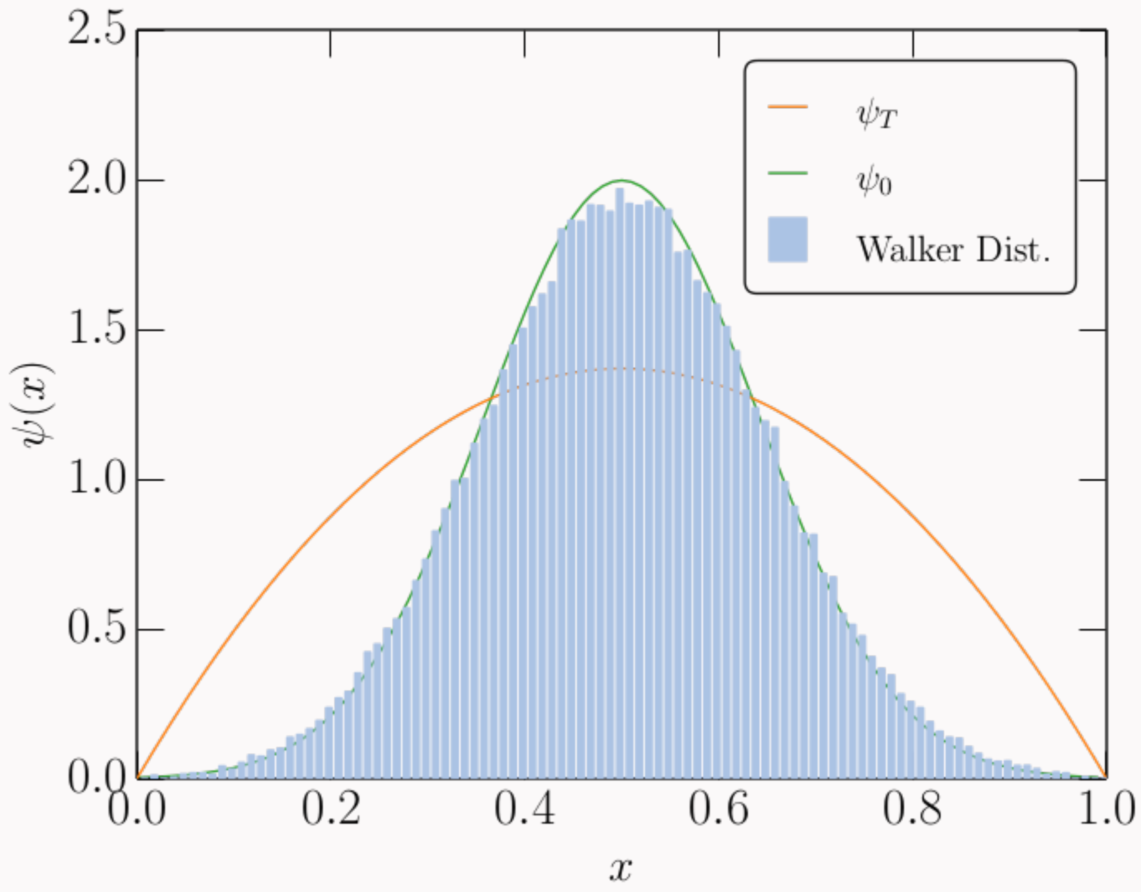


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 1.50$





QMC Methods - An Example

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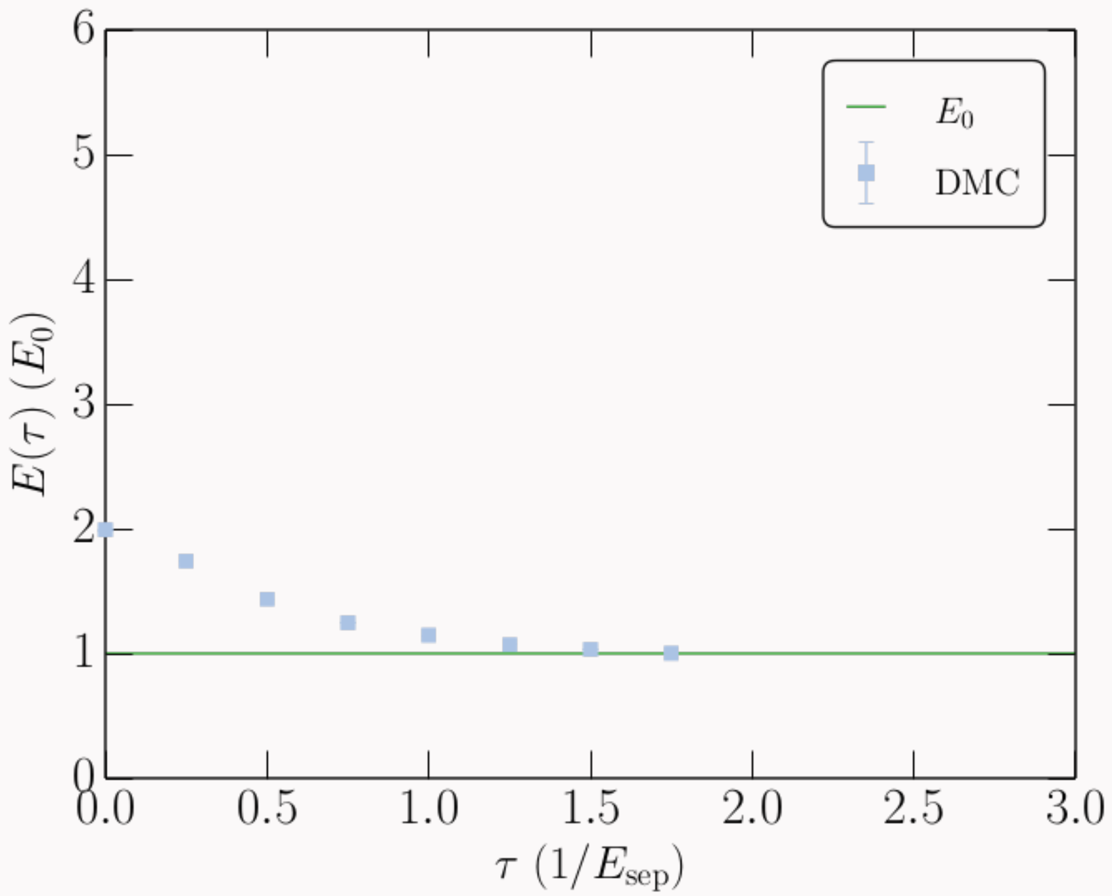
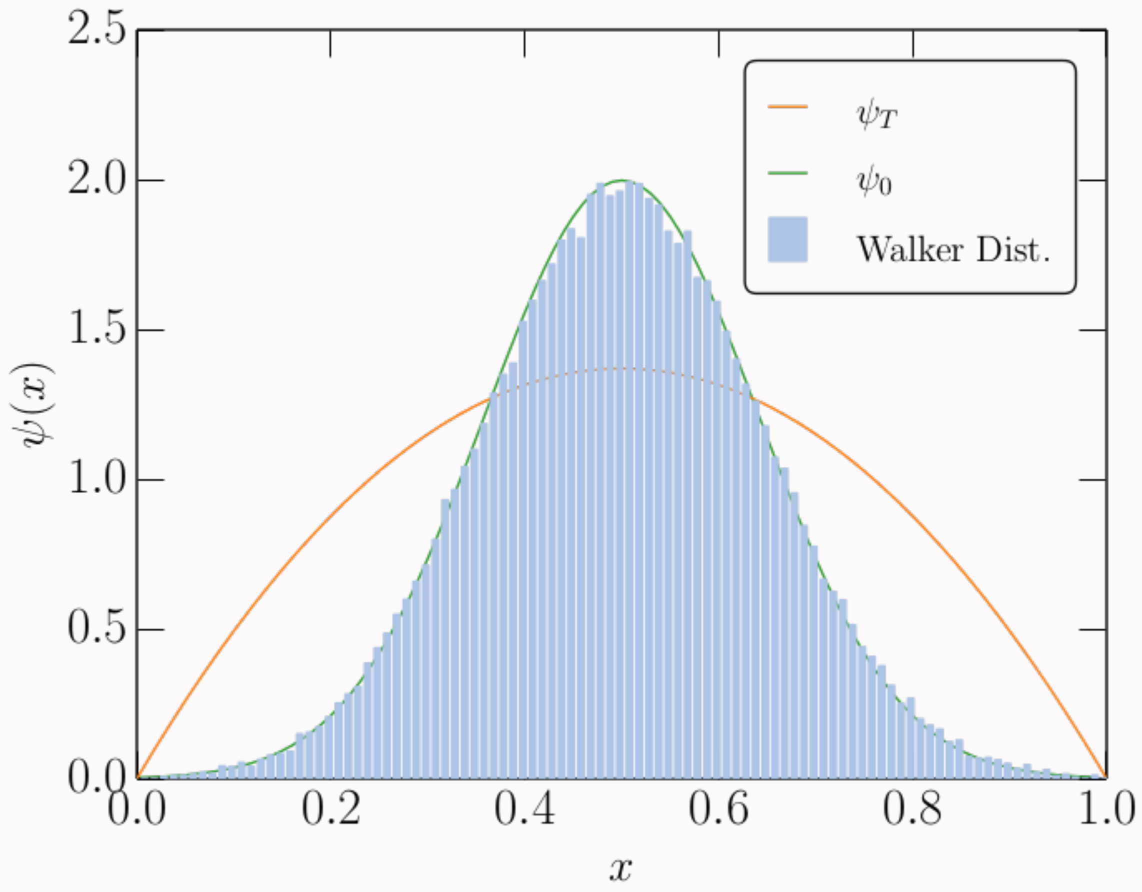
$\tau = 1.75$

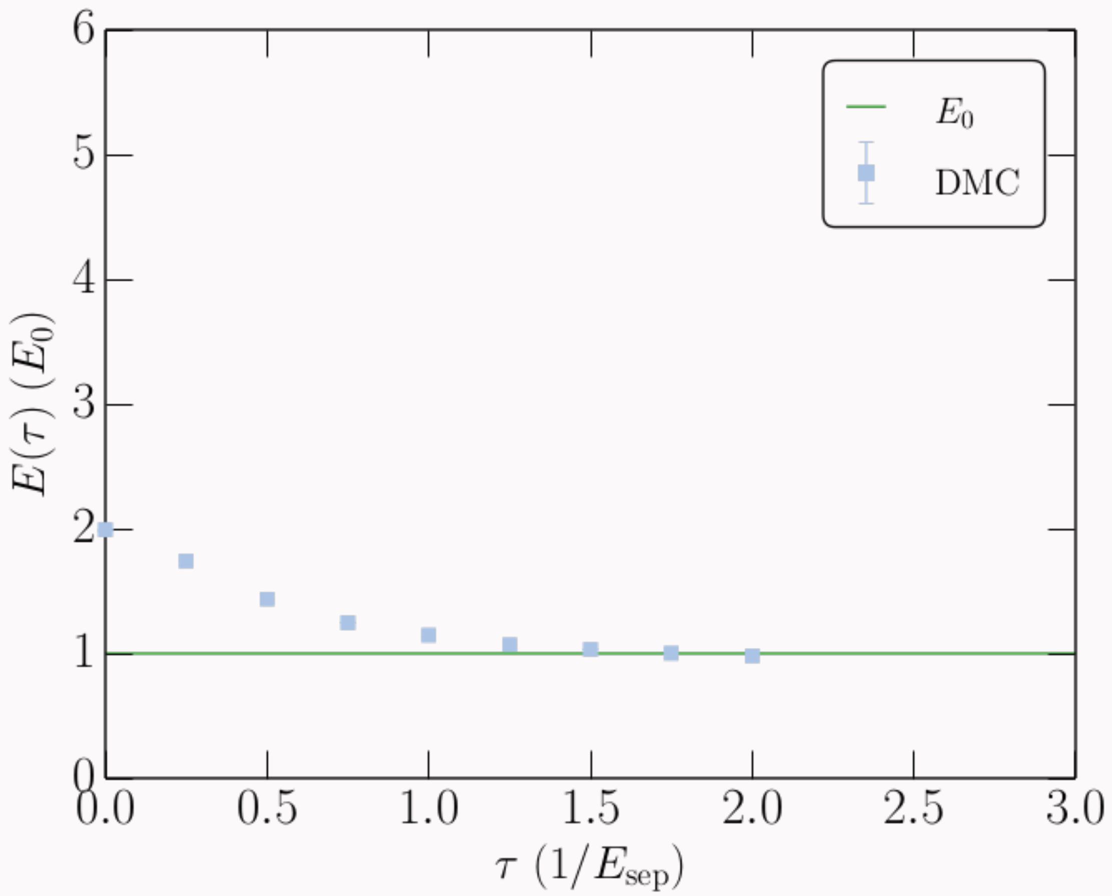


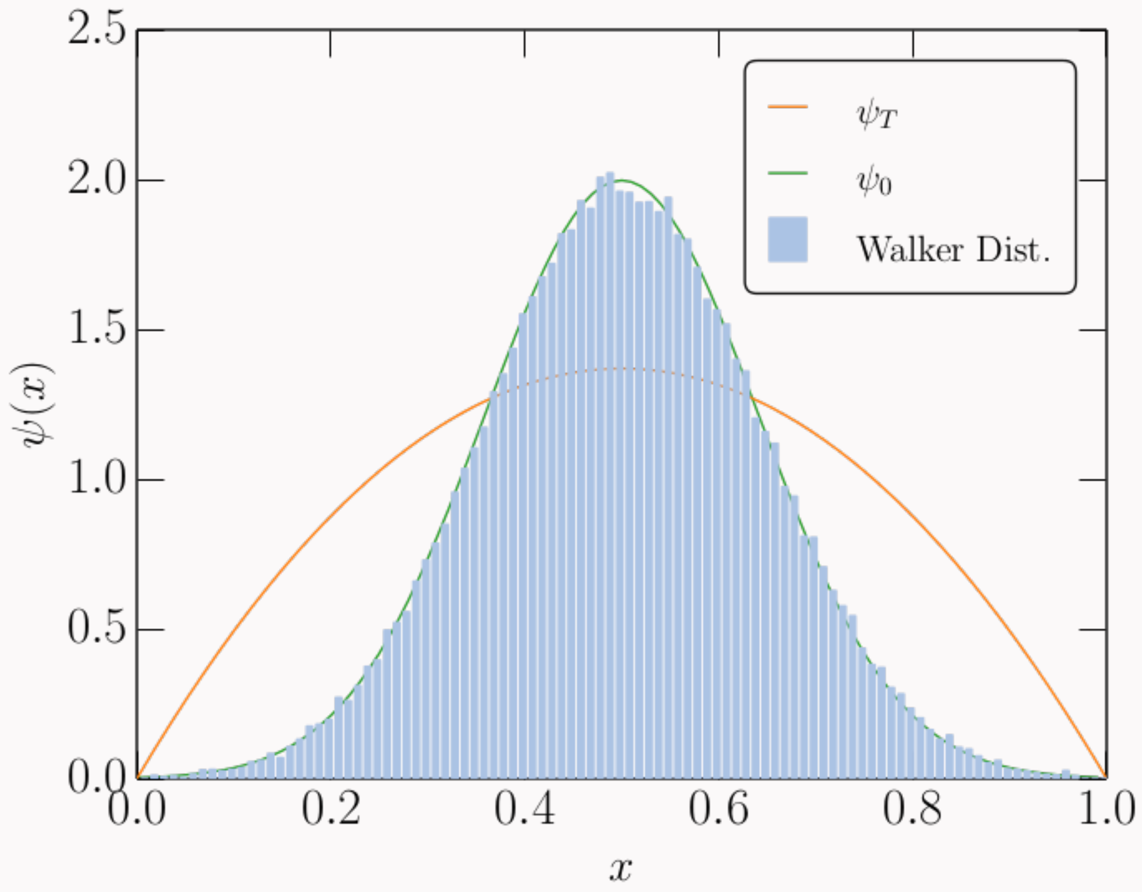


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 2.00$





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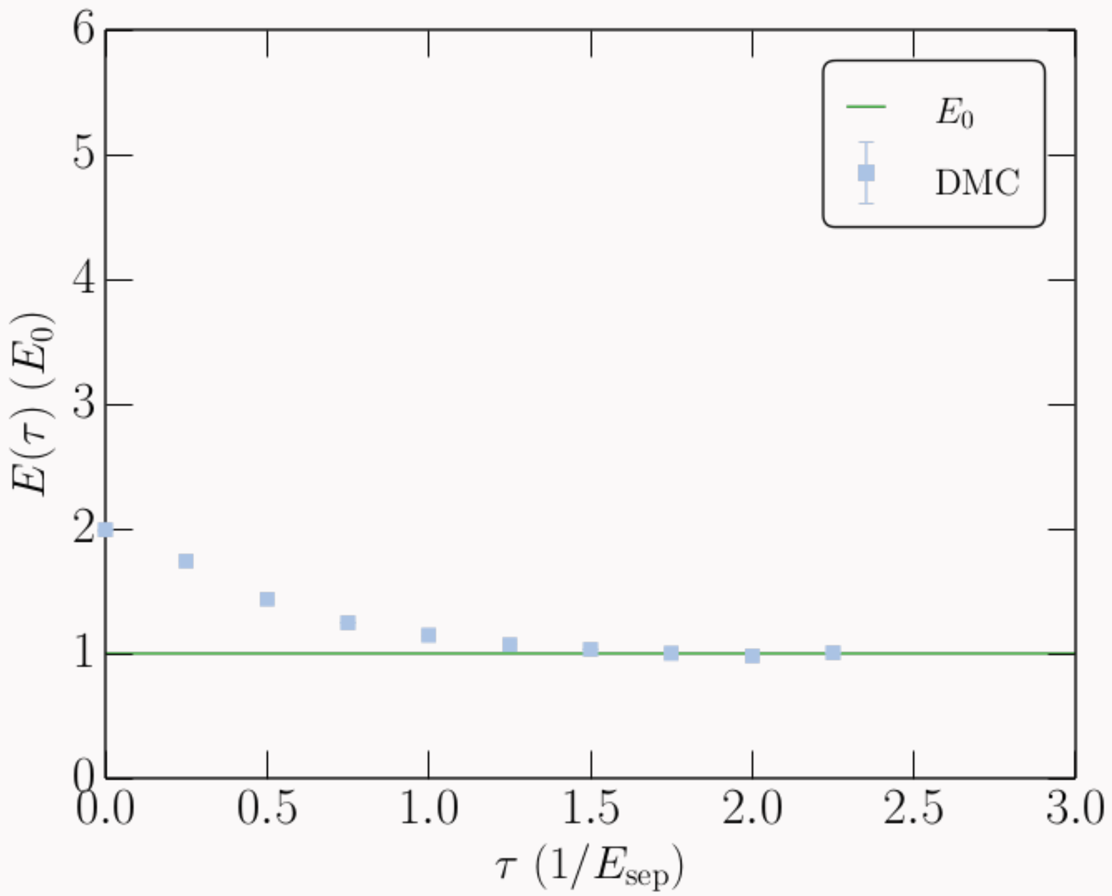

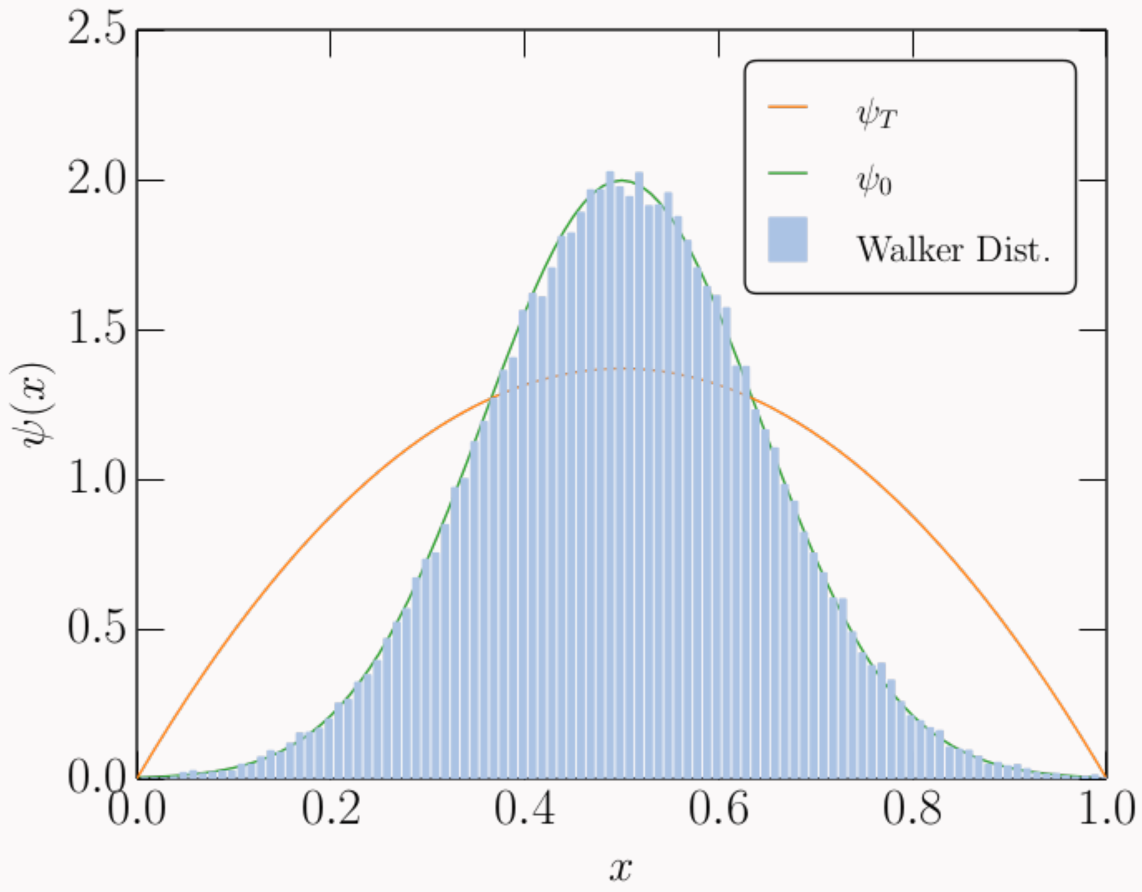

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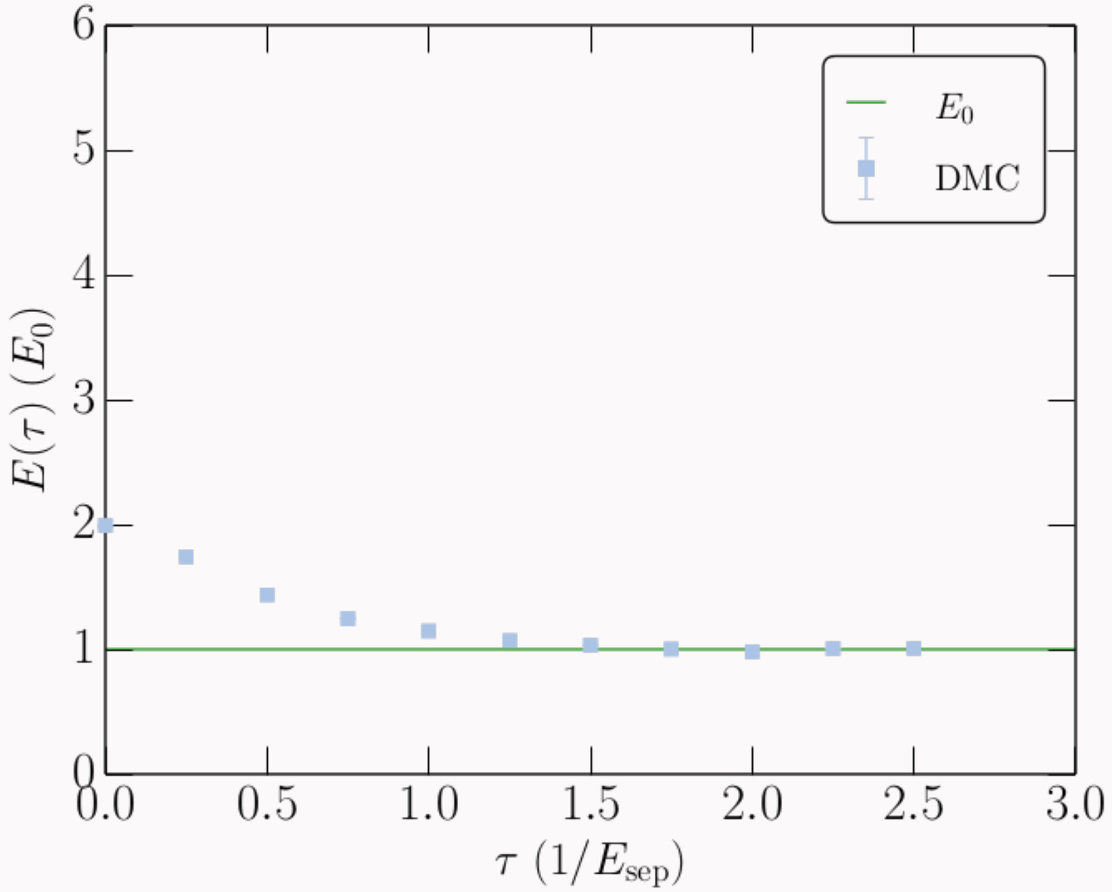

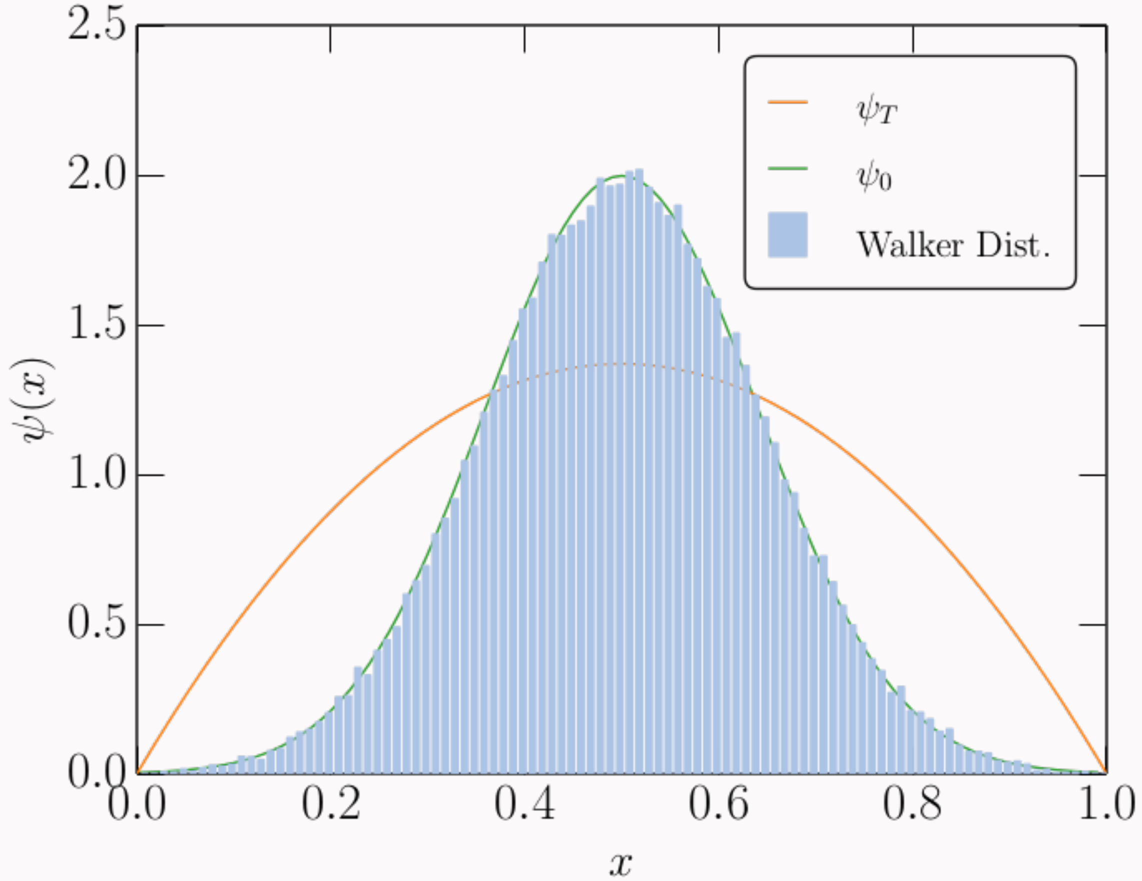

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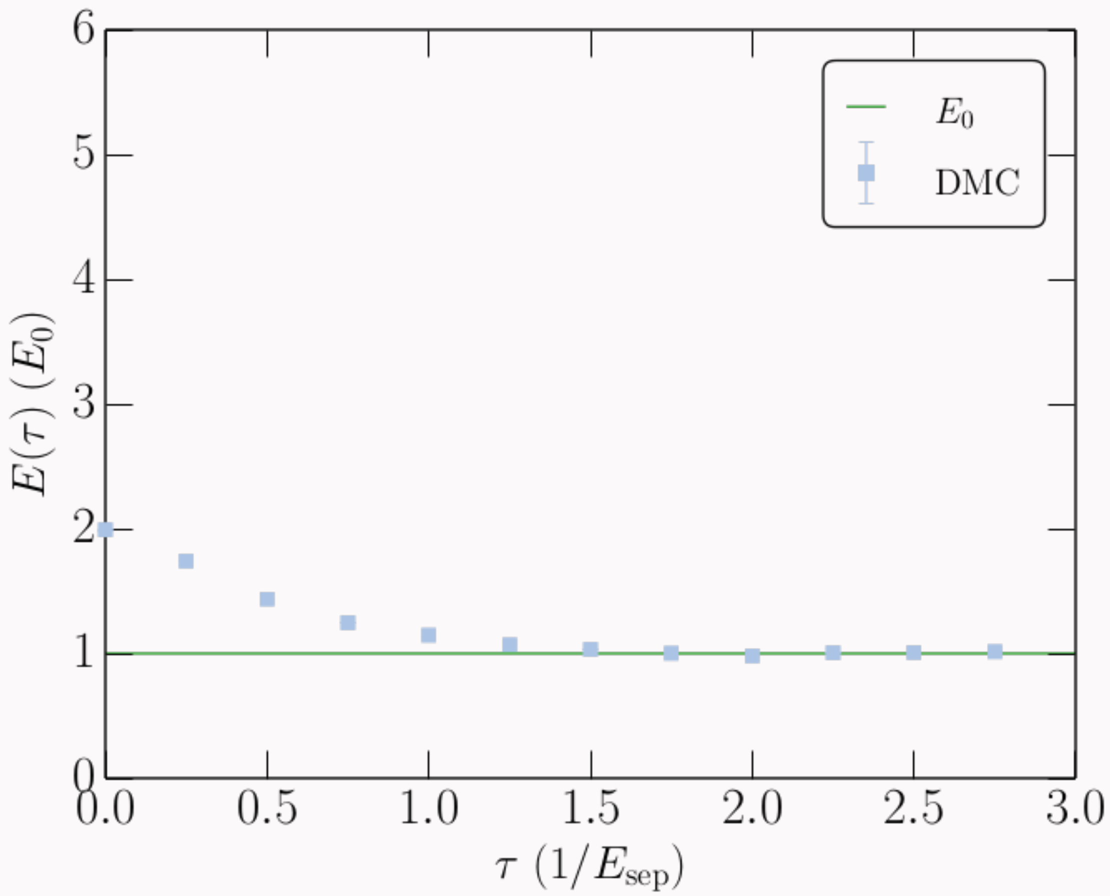
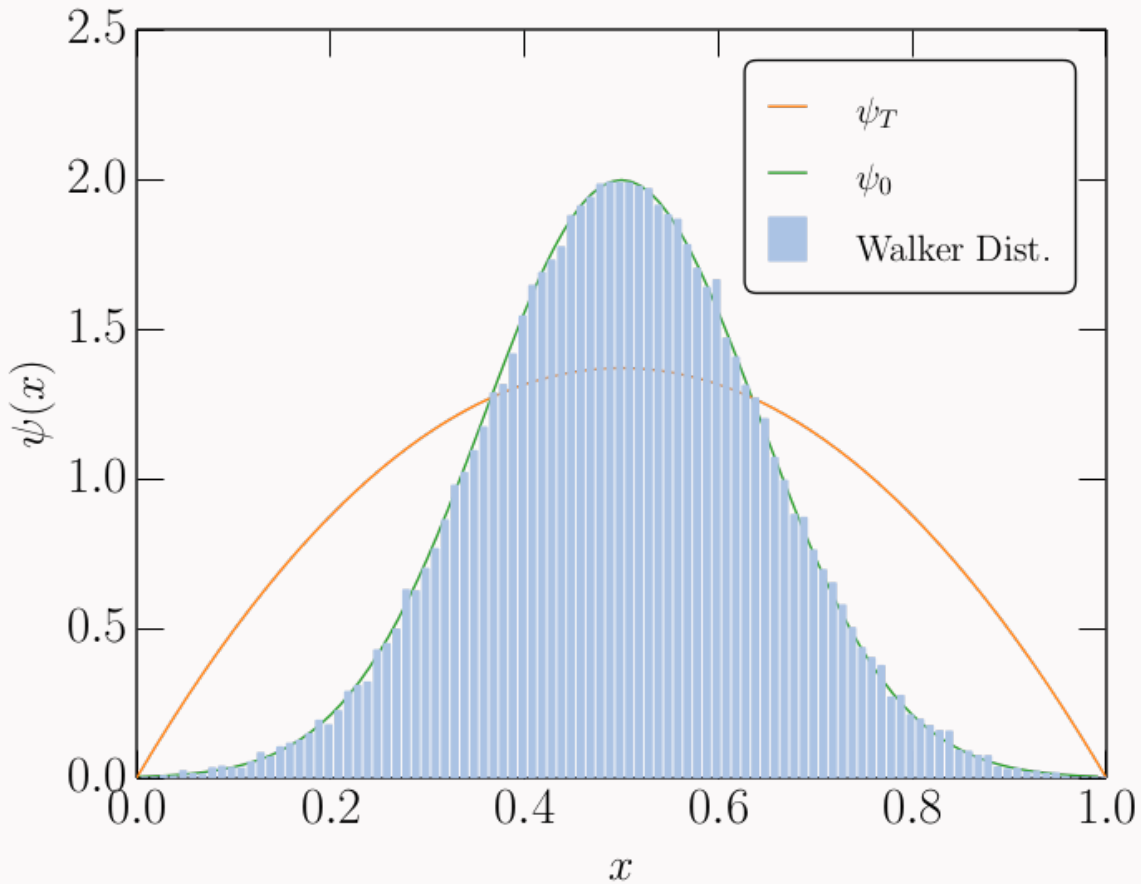
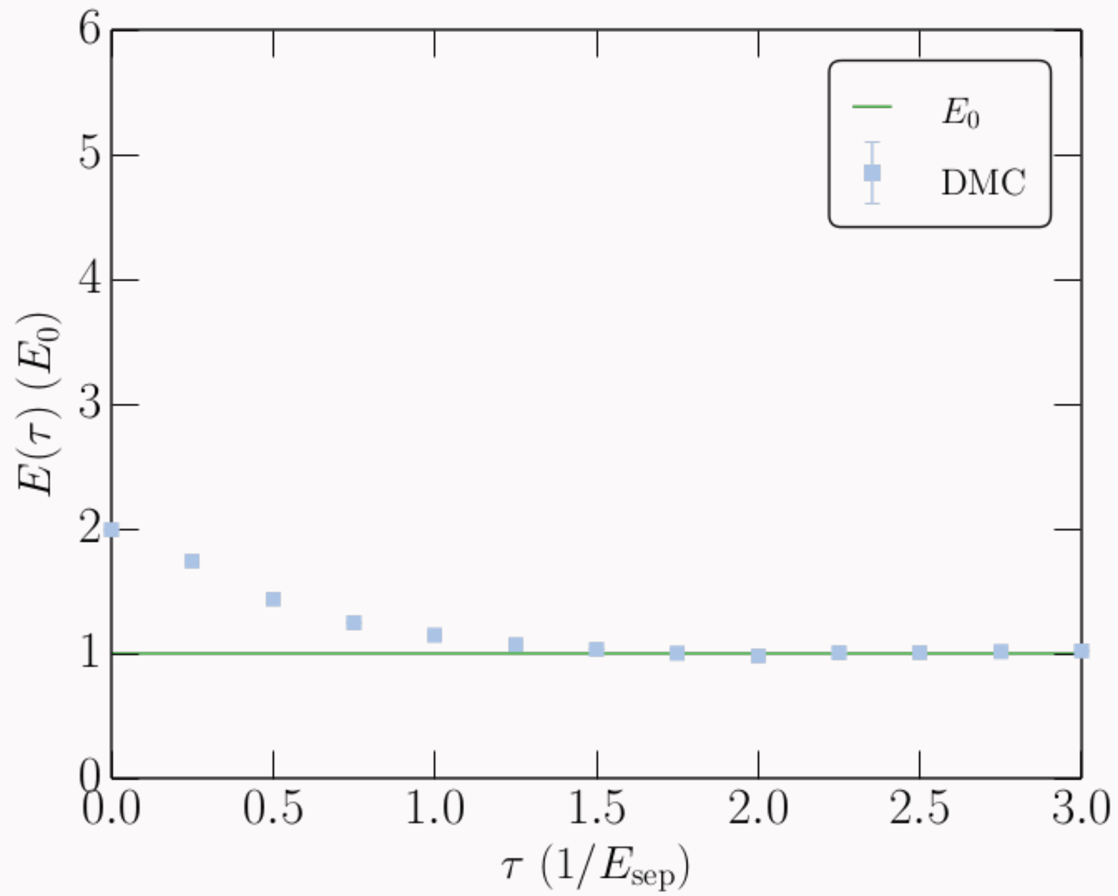


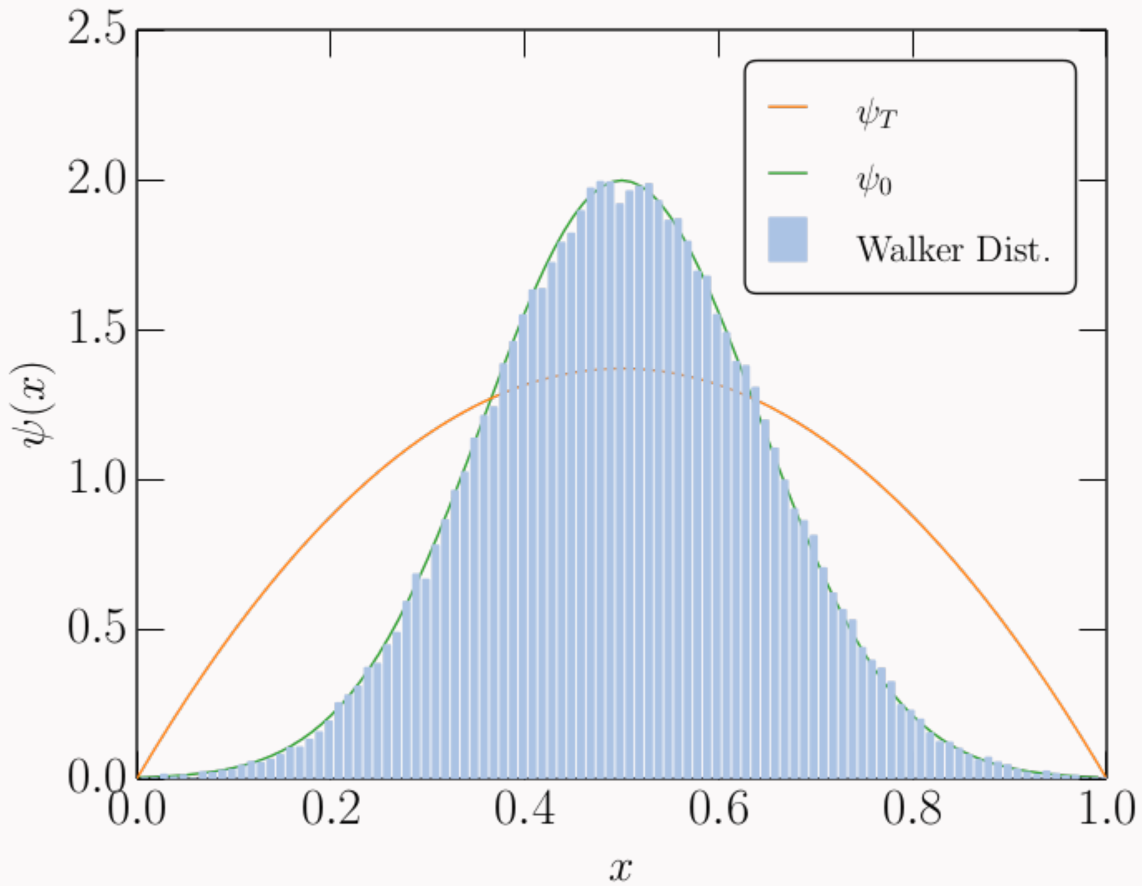


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 3.00$





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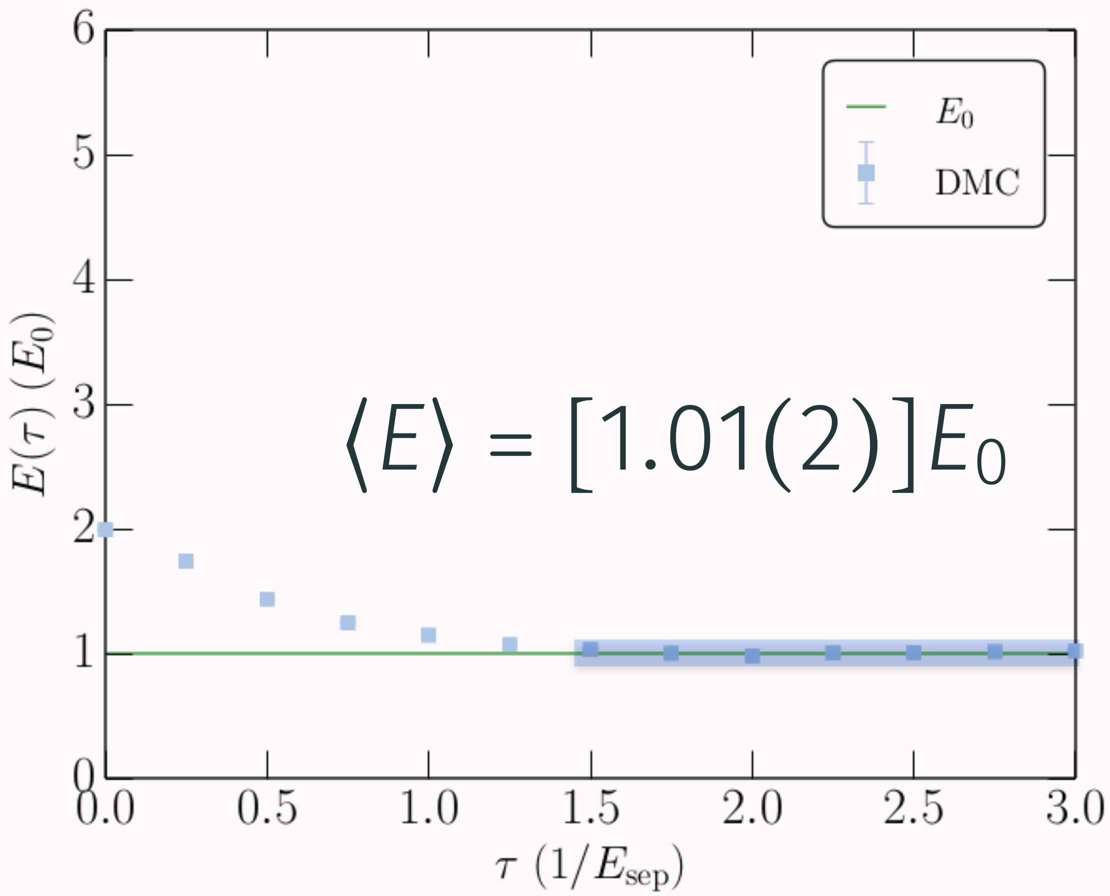
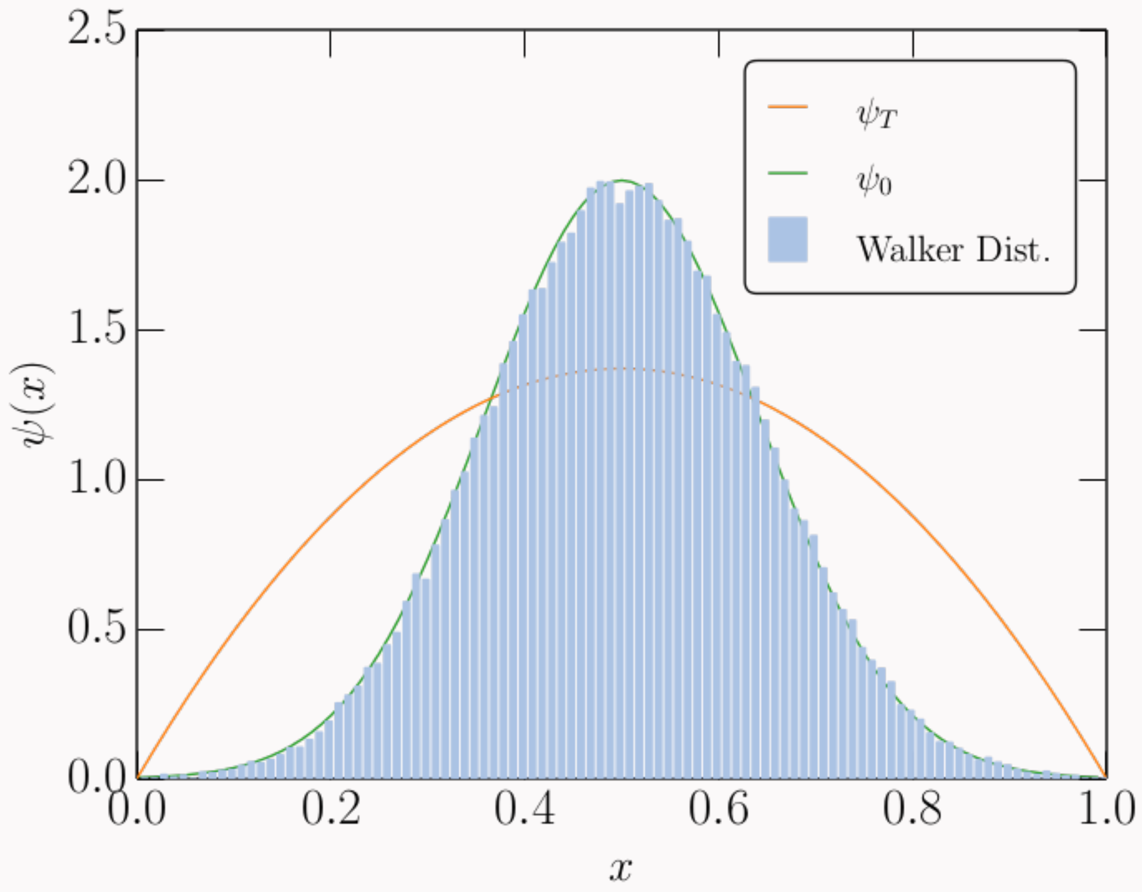


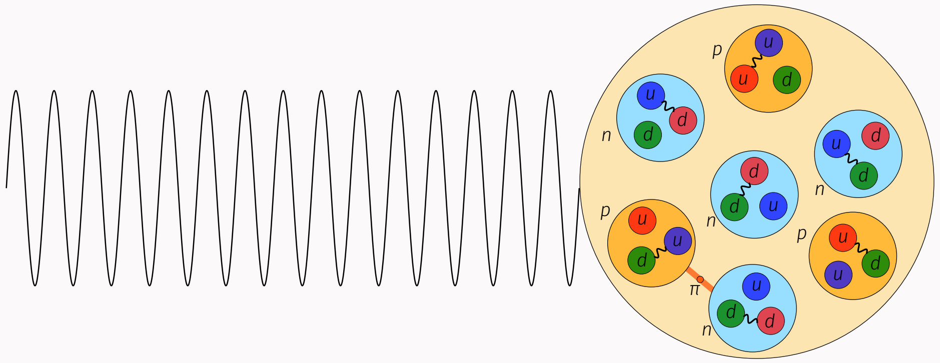


QMC Methods - Compare/Contrast GFMC & AFDMC

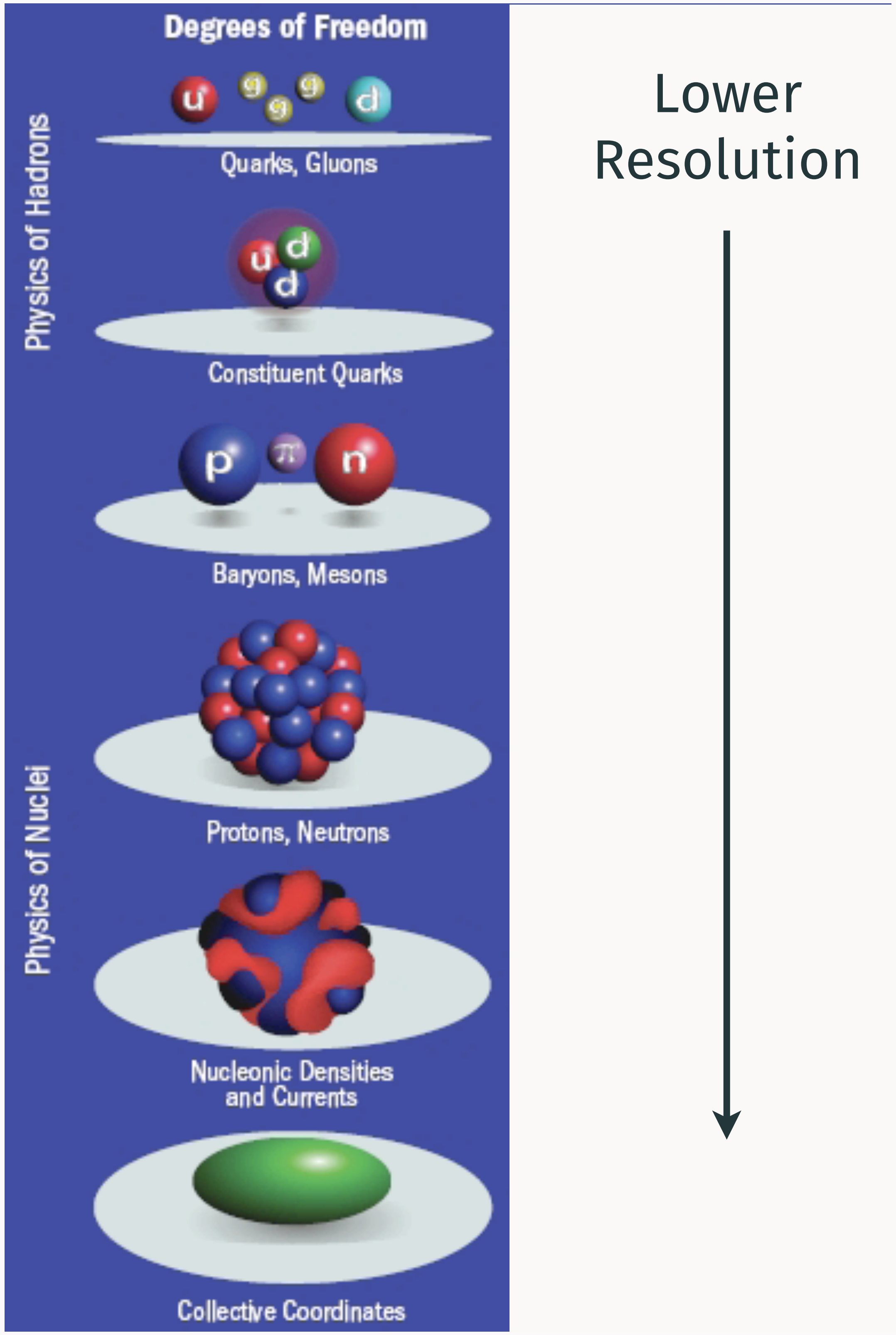
Green's function Monte Carlo (GFMC)	Auxiliary-field diffusion Monte Carlo (AFDMC)
• $\vert\Psi_T\rangle \sim 3A$ coordinates & $2^A\binom{A}{Z}$ complex amplitudes: *Exponential scaling.*	• $\vert\Psi_T\rangle \sim 3A$ coordinates & $4A$ complex amplitudes $(\vert n\uparrow\rangle, \vert n\downarrow\rangle, \vert p\uparrow\rangle, \vert p\downarrow\rangle)$: *Polynomial scaling.*

Chiral Effective Field Theory (EFT)

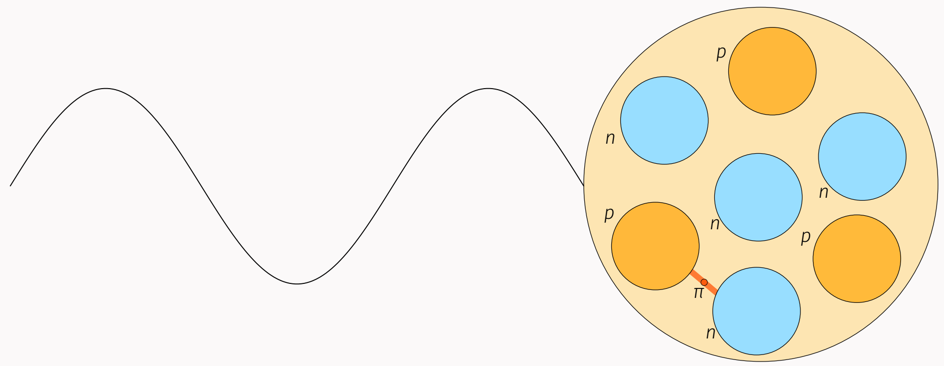
Chiral EFT



- If probed at high energies, substructure is resolved.
- At low energies, details are not resolved.
- Can replace fine structure by something simpler (think of multipole expansion): low-energy observables unchanged.



Chiral EFT



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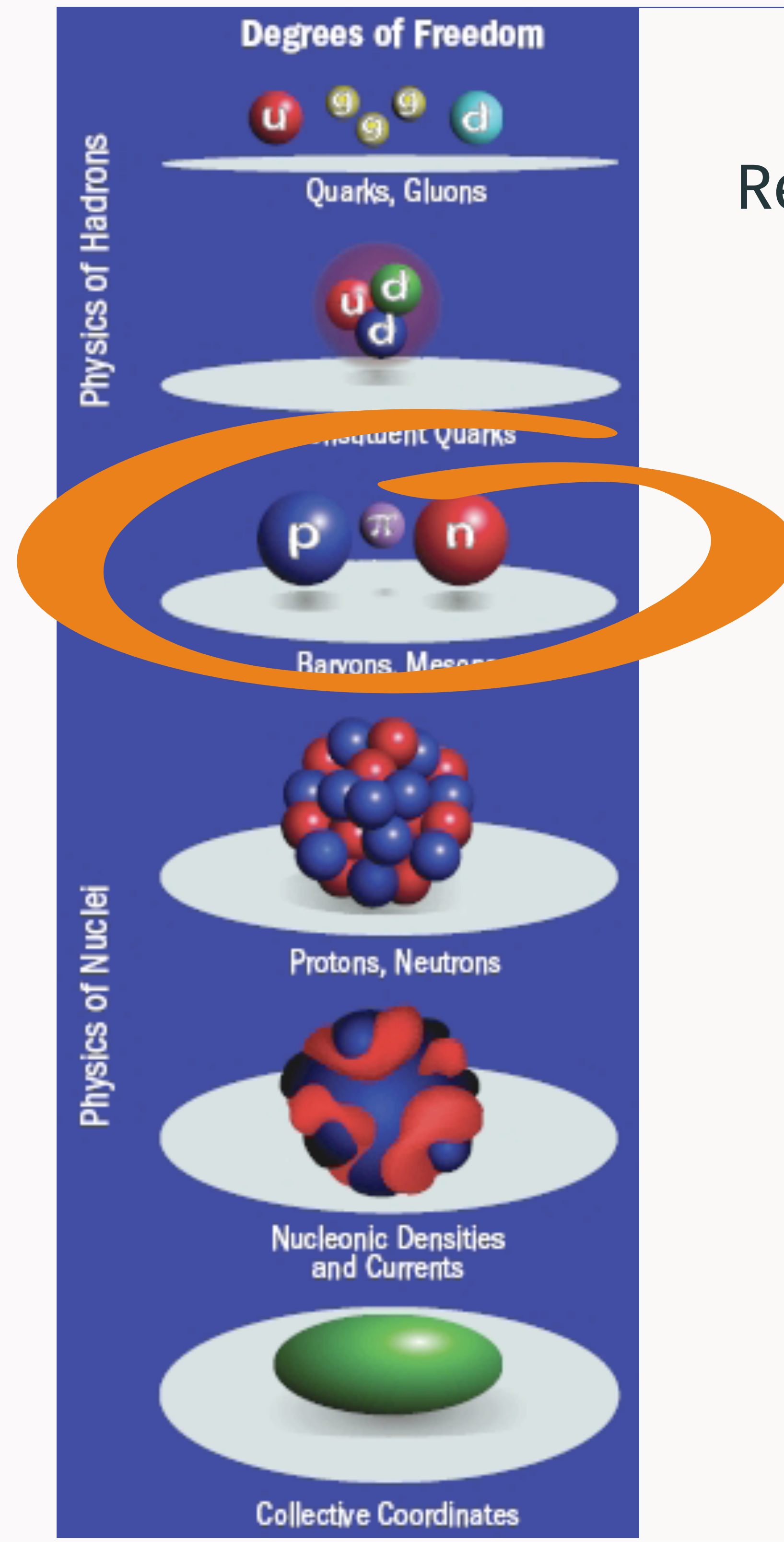
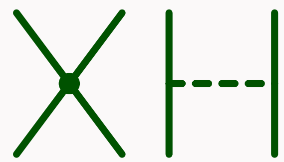
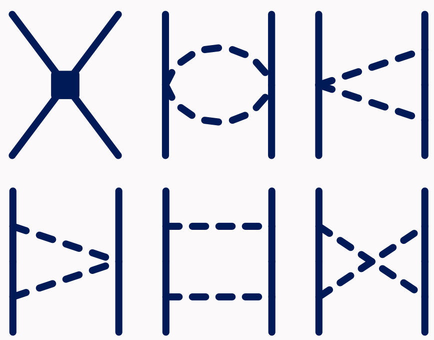
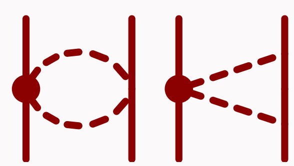
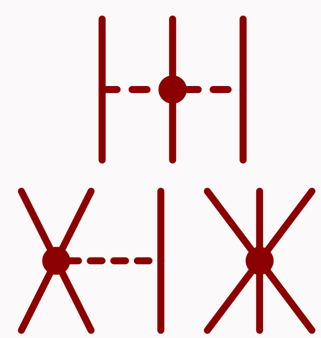
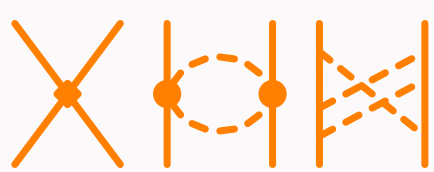


Lower Resolution

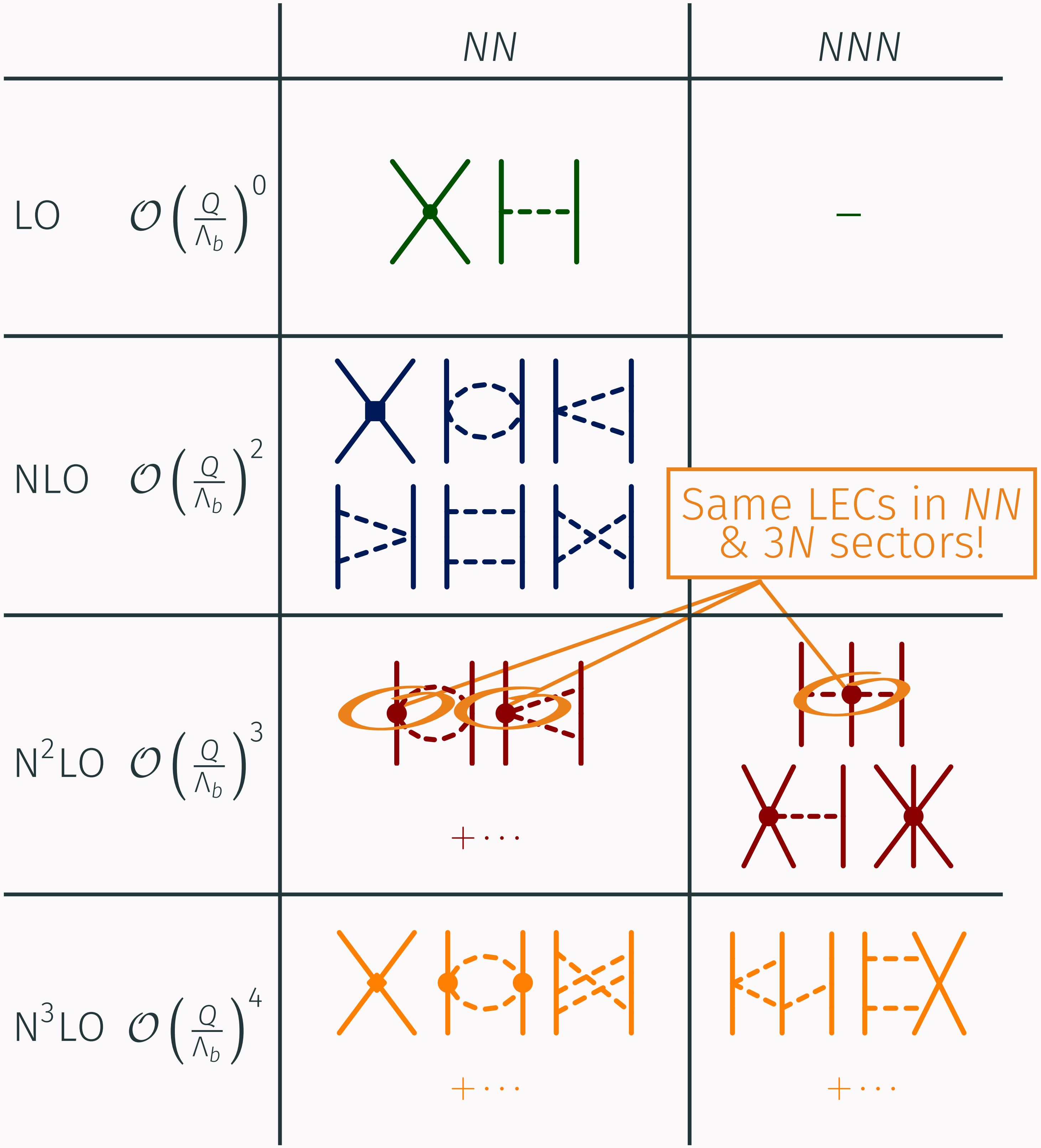
Chiral EFT

		NN	NNN
LO	$\mathcal{O}\left(\frac{Q}{\Lambda_b}\right)^0$		–
NLO	$\mathcal{O}\left(\frac{Q}{\Lambda_b}\right)^2$		–
N^{2}LO	$\mathcal{O}\left(\frac{Q}{\Lambda_b}\right)^3$	 $+\cdots$	
N^{3}LO	$\mathcal{O}\left(\frac{Q}{\Lambda_b}\right)^4$	 $+\cdots$	 $+\cdots$

Weinberg, van Kolck, Kaplan, Savage, Wise, Bernard, Epelbaum, Kaiser, Machleidt, Meißner,...

- Chiral EFT: Expand in powers of Q/Λ_b.
  $Q \sim m_\pi \sim 100$ MeV
  $\Lambda_b \sim 500$ MeV
- Long-range physics: π exchanges.
- Short-range physics: Contacts $\times$ LECs.
- Many-body forces & currents enter systematically.

Chiral EFT



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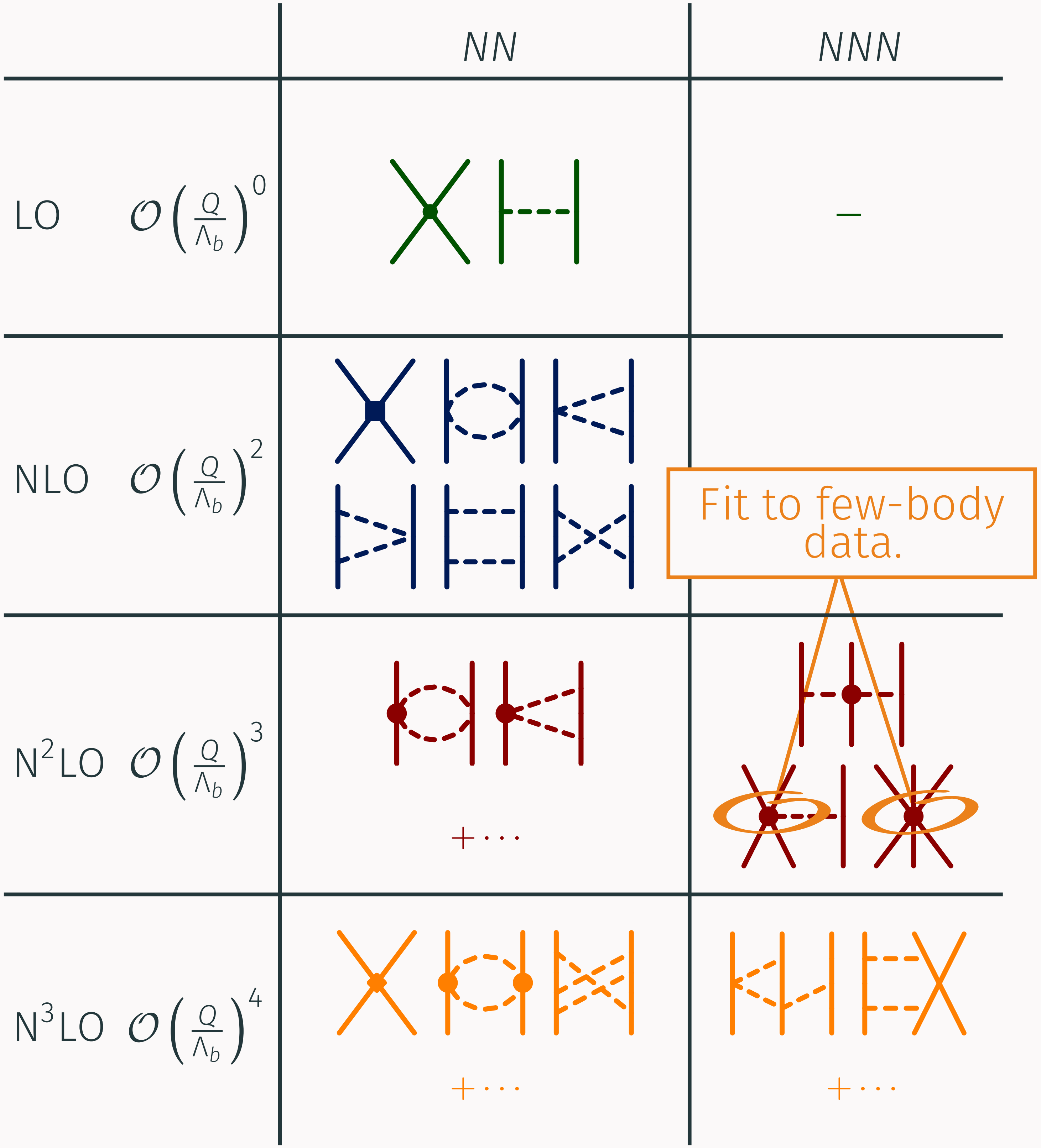

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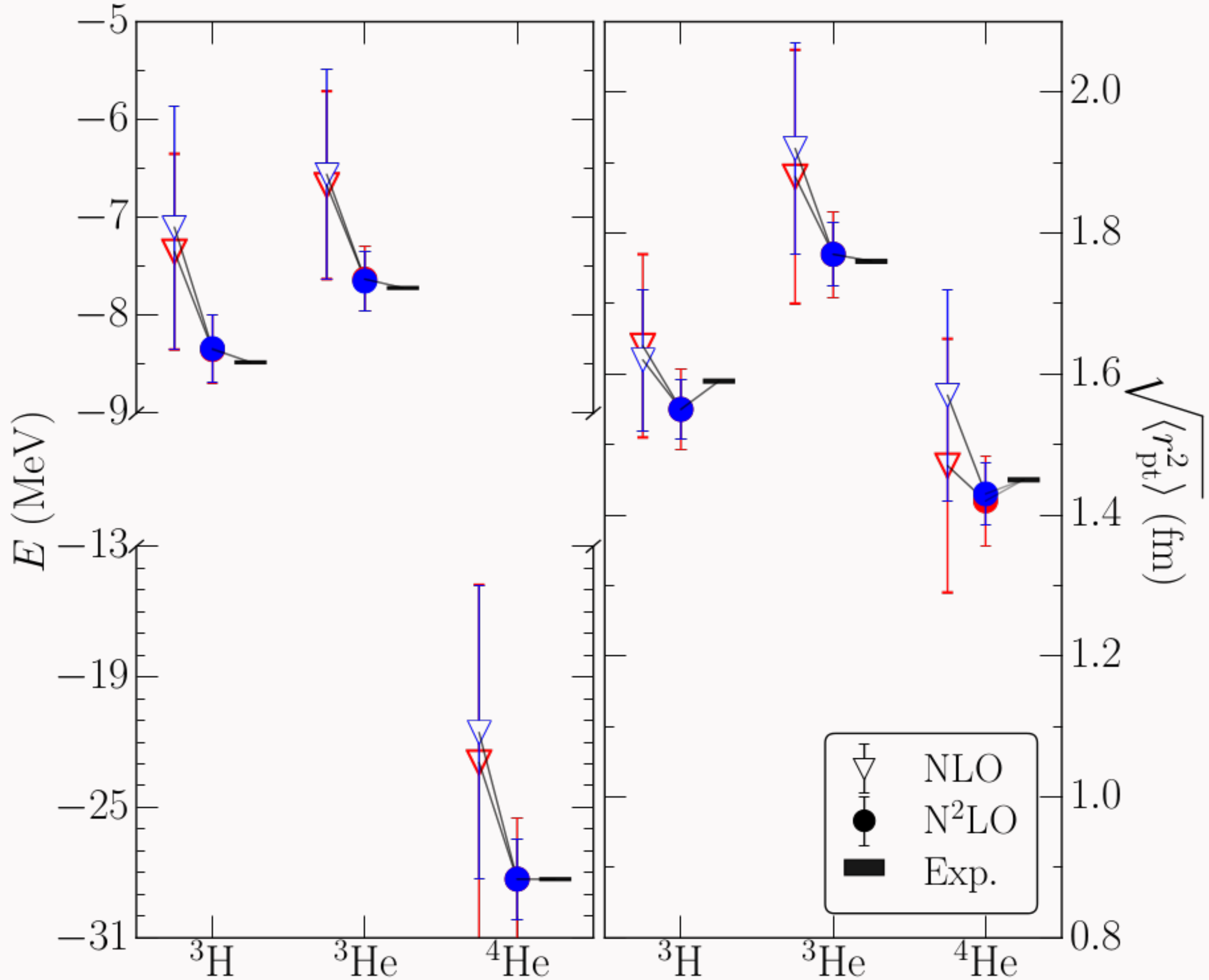
First Results

One consistent approach:

Light Nuclei

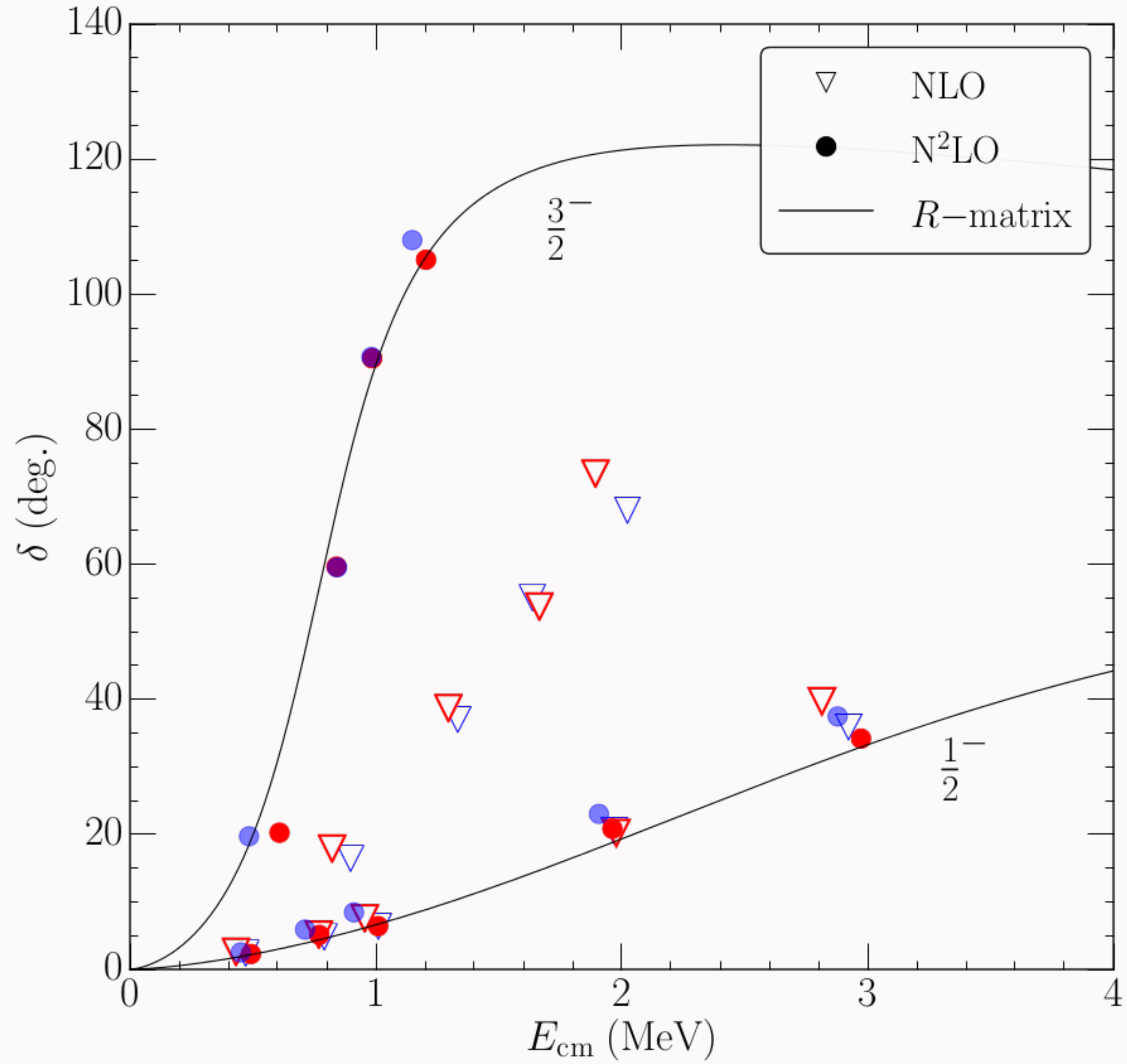


JEL et al, PRL **116**, 062501 (2016)

First Results

One consistent approach:

n-α Elastic Scattering

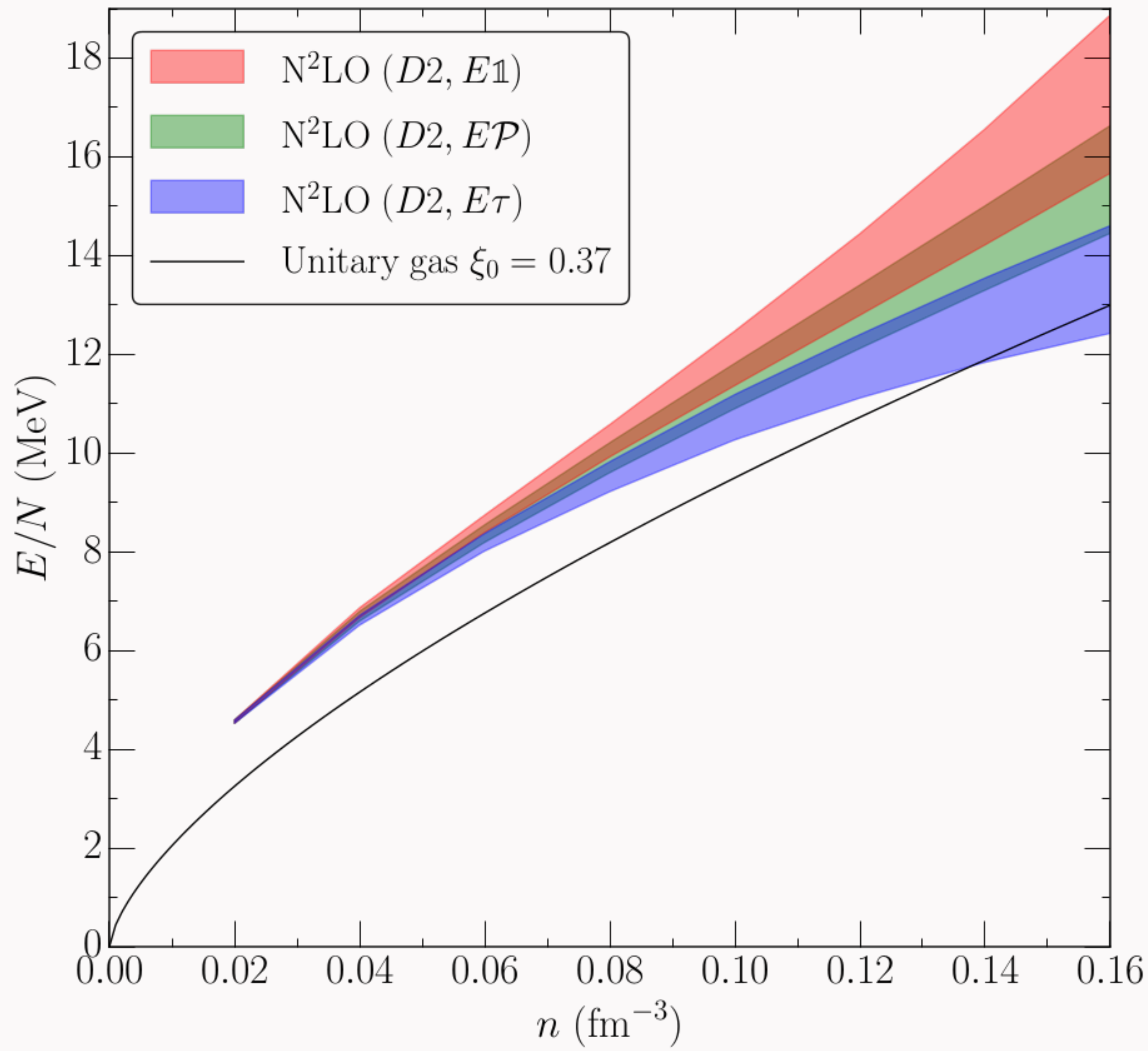


JEL et al, PRL **116**, 062501 (2016)

First Results

One consistent approach:

Neutron Matter

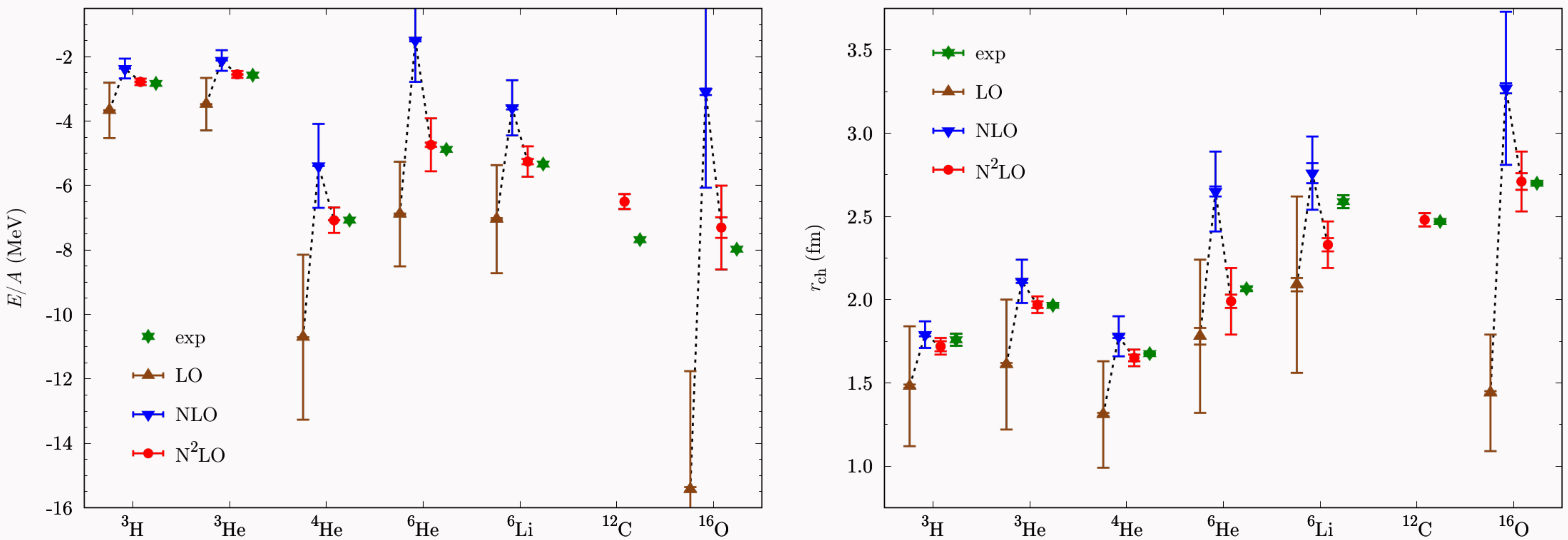


JEL et al, PRL **116**, 062501 (2016)

Recent Advances In AFDMC Calculations

AFDMC Results

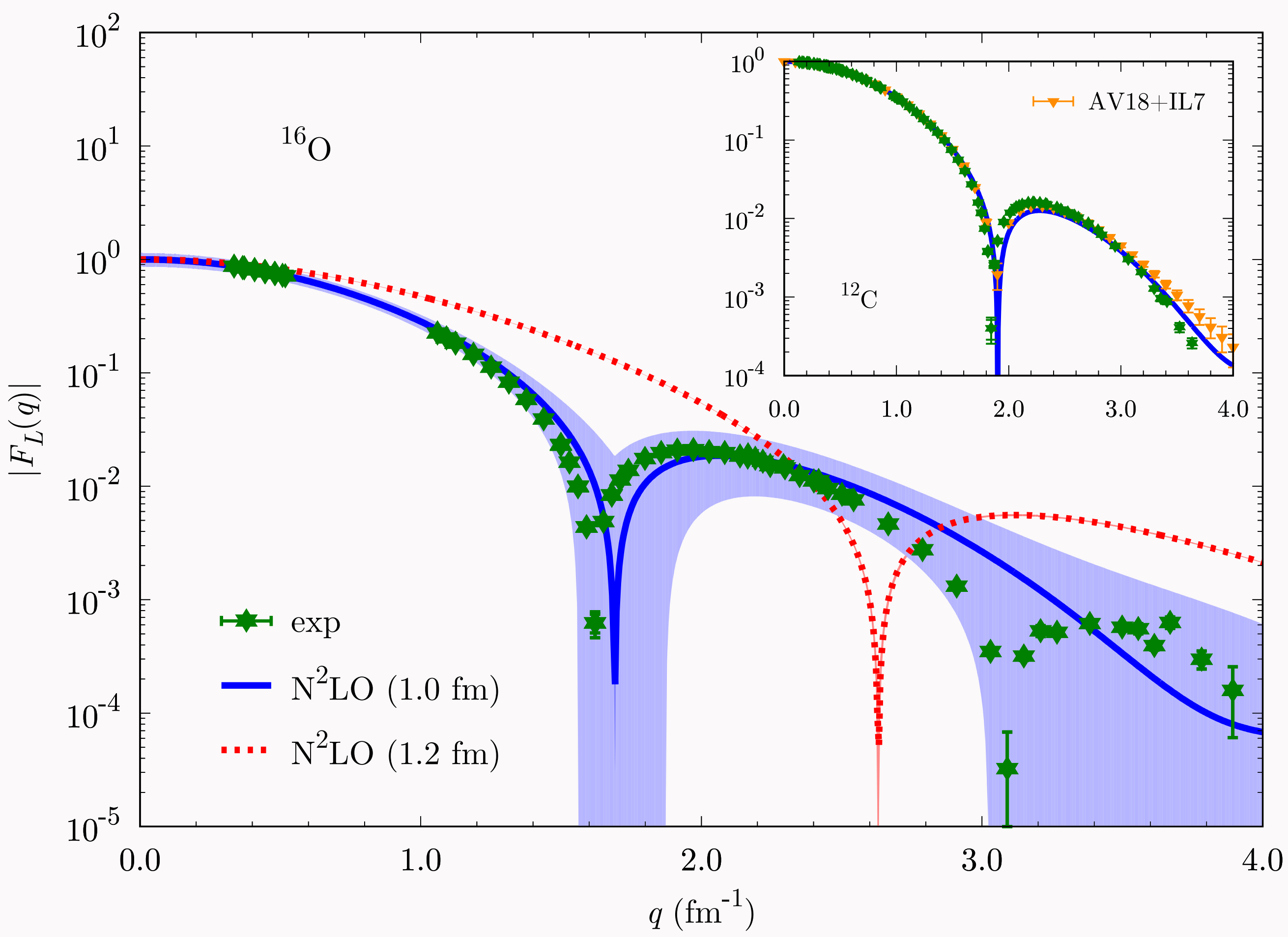
Energies and charge radii of selected nuclei up to ^{16}O well reproduced.

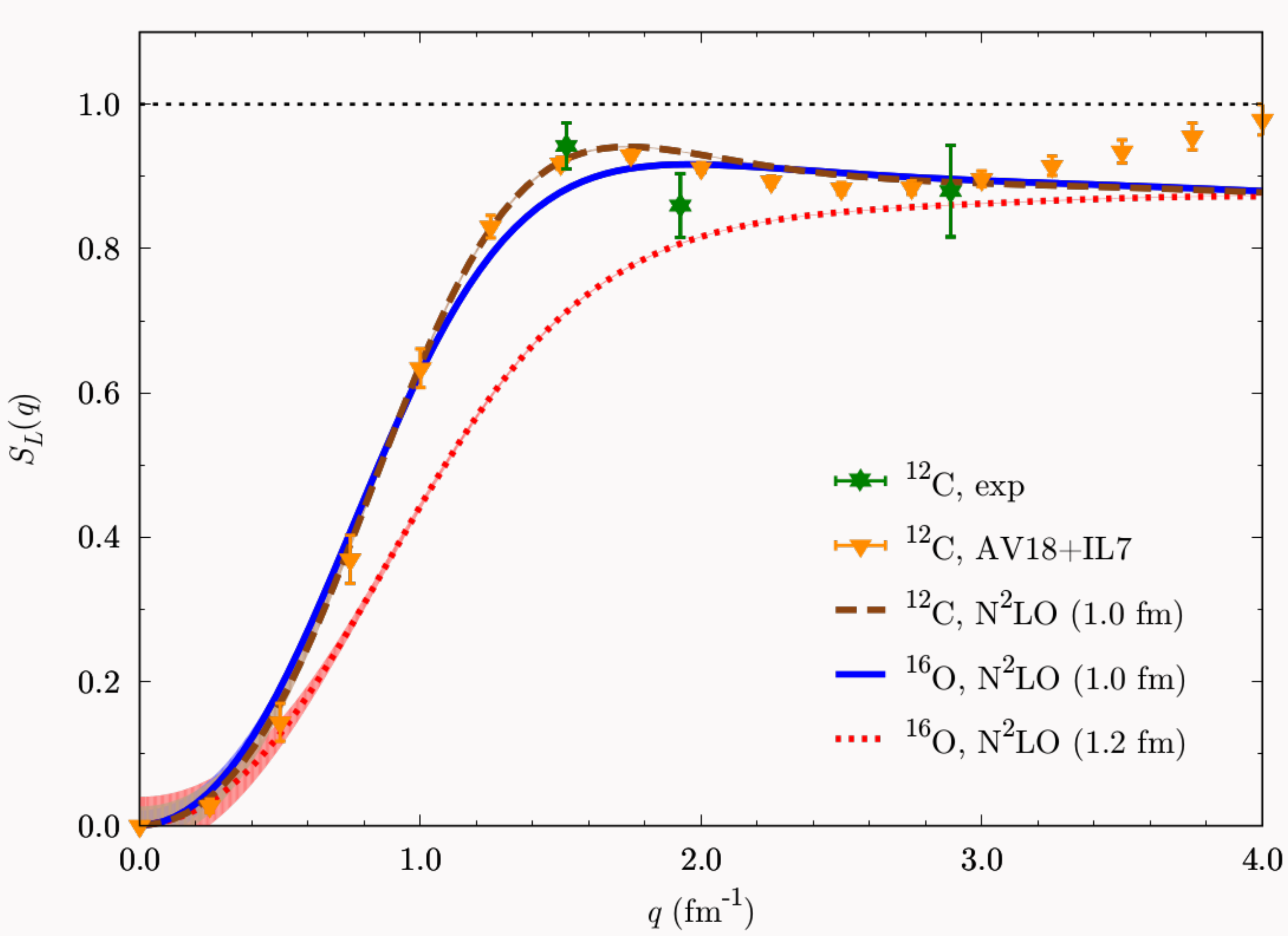


D. Lonardoni, J. Carlson, S. Gandolfi, JEL, K. E. Schmidt, A. Schwenk, X. Wang, arXiv:1709.09143 [nucl-th] (2017)

AFDMC Results

Charge form factors and Coulomb sum rules also well reproduced.





D. Lonardoni, J. Carlson, S. Gandolfi, JEL, K. E. Schmidt, A. Schwenk, X. Wang, arXiv:1709.09143 [nucl-th] (2017)

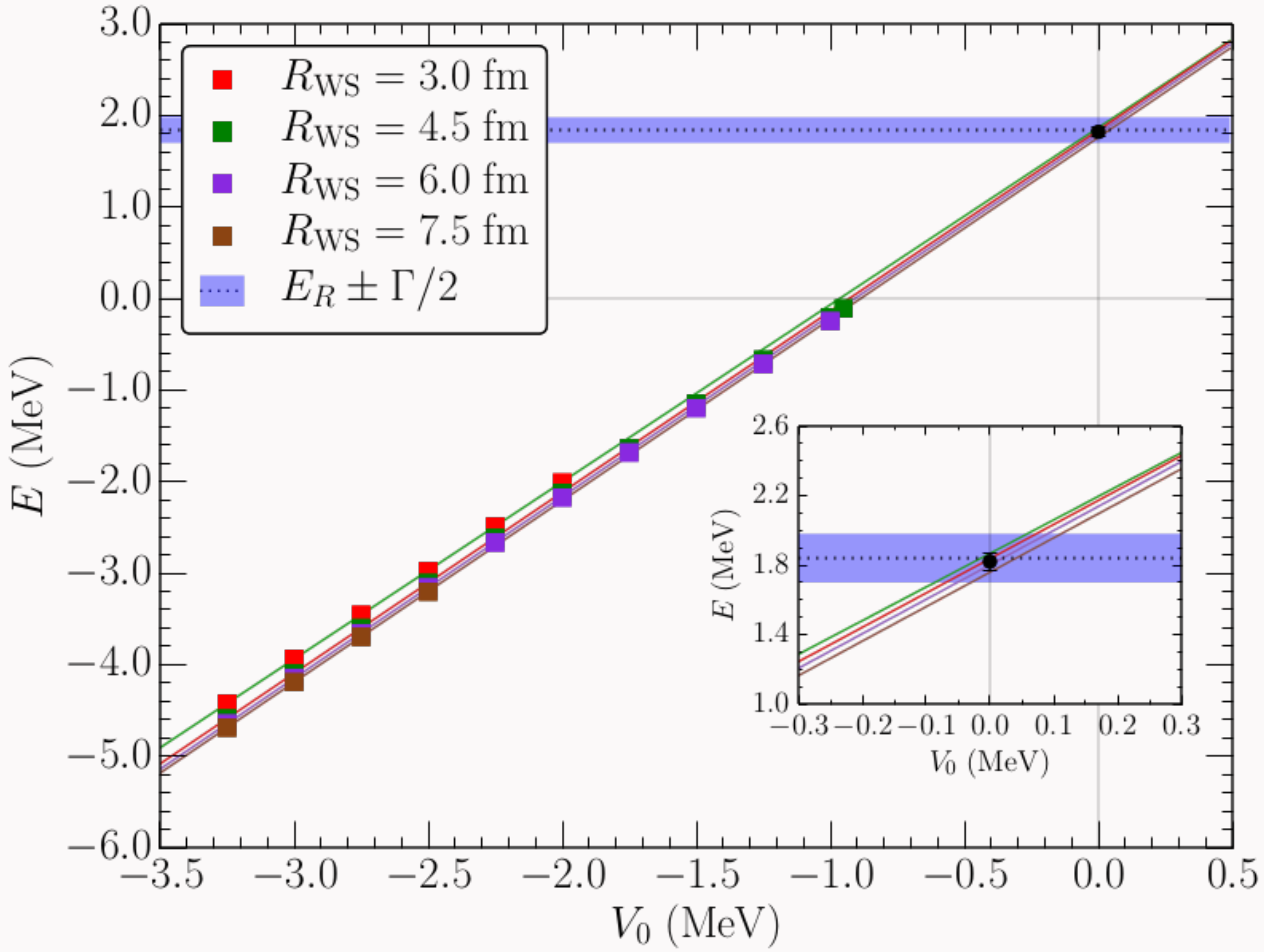
$3n$, $4n$ Resonances

A Two-Body Test

A simple S-wave potential + Woods-Saxon:

$$V(r) = V_1 e^{-\left(\frac{r}{R_1}\right)^2} + V_2 e^{-\left(\frac{r-r_2}{R_2}\right)^2}$$

$$V_{\mathrm{WS}}(r) = V_0/[1 + e^{(r-R_{\mathrm{WS}})/a}]$$



S. Gandolfi, H.-W. Hammer, P. Klos, JEL, A. Schwenk, PRL **118**, 232501 (2017)

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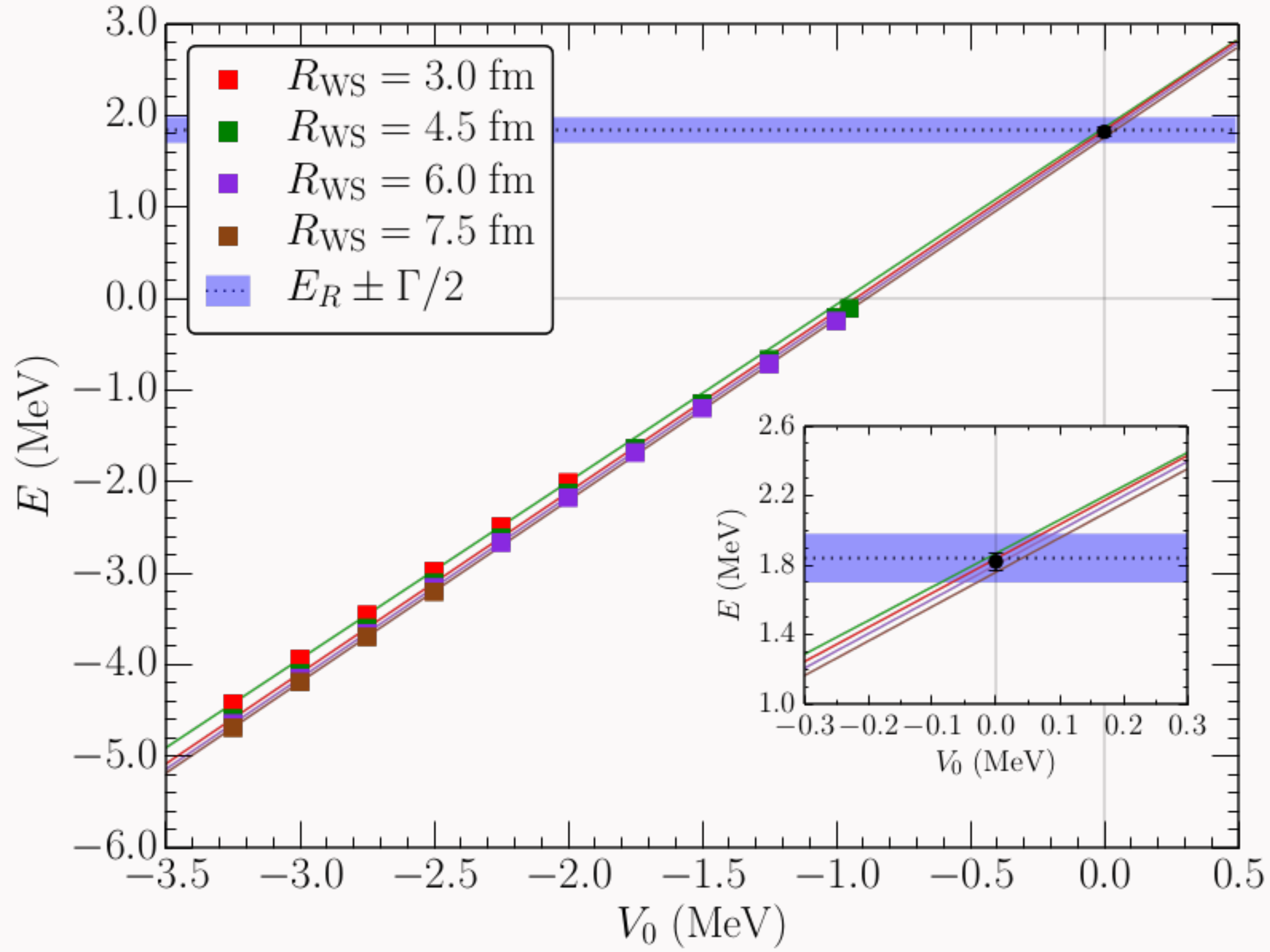
- Different Woods-Saxon radii: Independence of trap geometry.
- Extrapolations give 1.83(5) MeV. (Compare to 1.84 MeV).

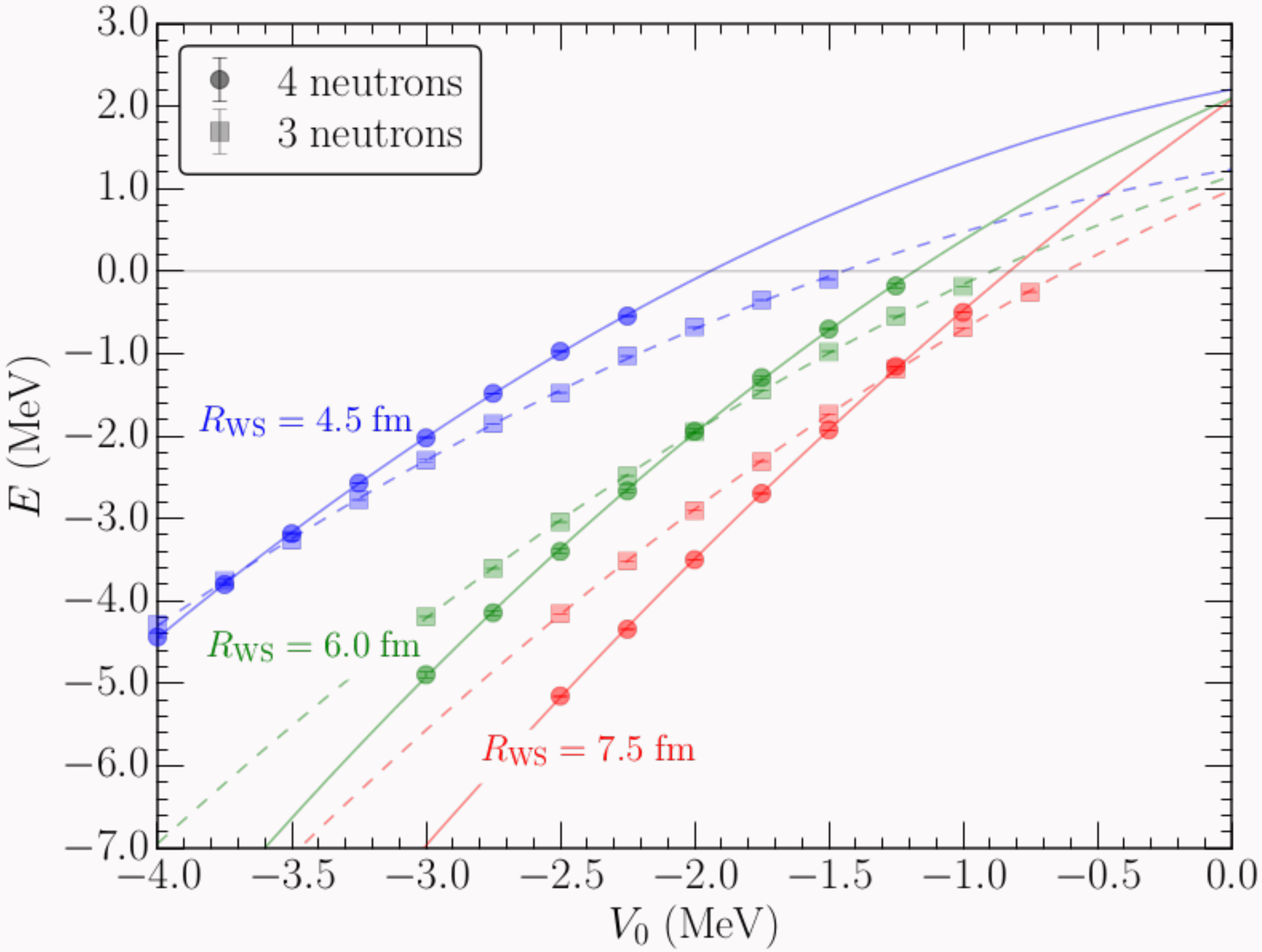


S. Gandolfi, H.-W. Hammer, P. Klos, JEL, A. Schwenk, PRL **118**, 232501 (2017)

Neutrons In A Trap

Now confine 3 & 4 neutrons in the external potential.

$$H = -\sum_i \frac{\hbar^2}{2m}\nabla_i^2 + \sum_i V_{\rm WS}(r_i) + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk},$$



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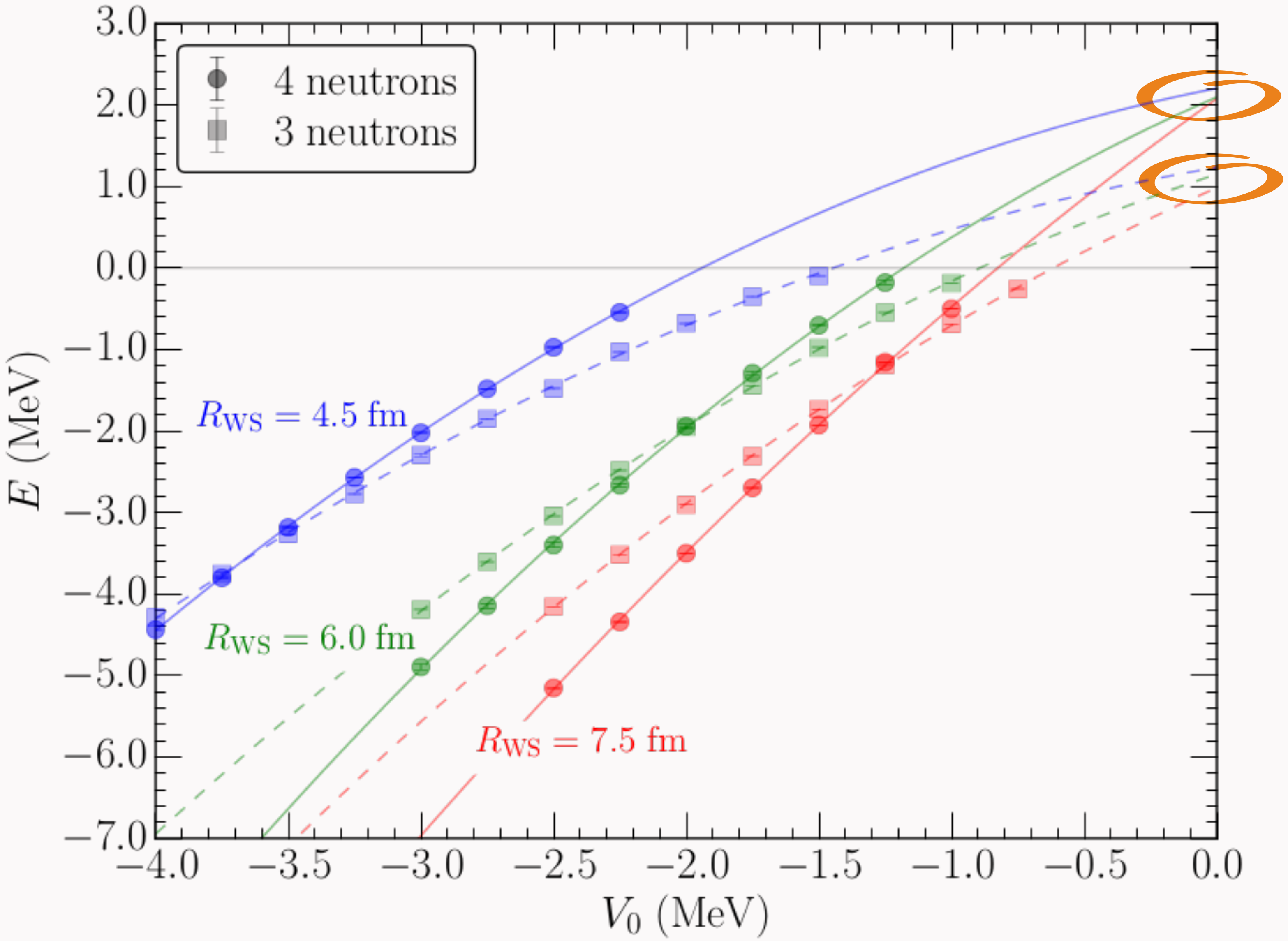
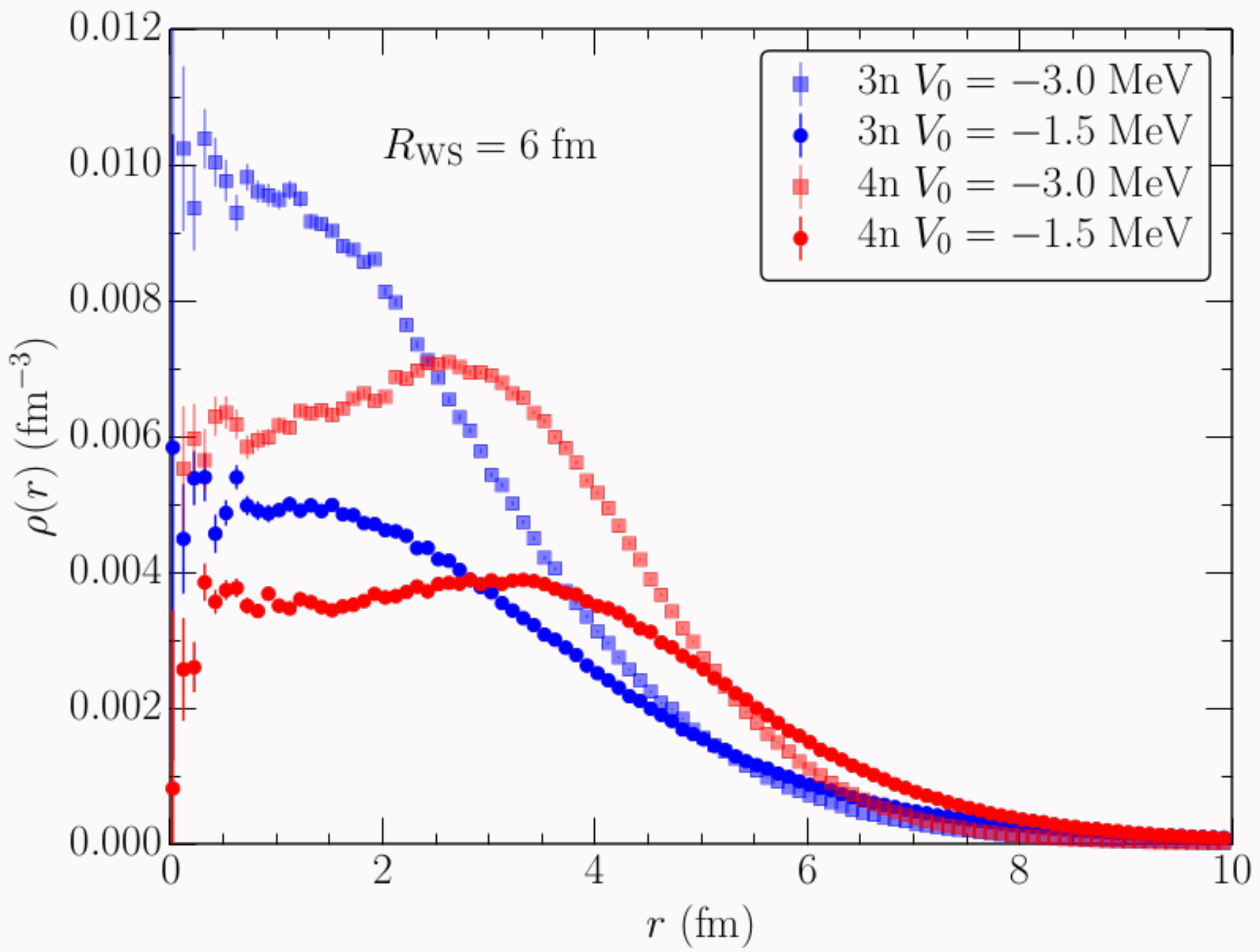


- E_{4n} = 2.1(2) MeV,
  E_{3n} = 1.1(2) MeV.
- ^3n resonance lower than ^4n resonance!

S. Gandolfi, H.-W. Hammer, P. Klos, JEL, A. Schwenk, PRL **118**, 232501 (2017)

One-Body Densities

- The ^3n and ^4n systems are very dilute.
- ^3n and ^4n systems show different short-distance structure.



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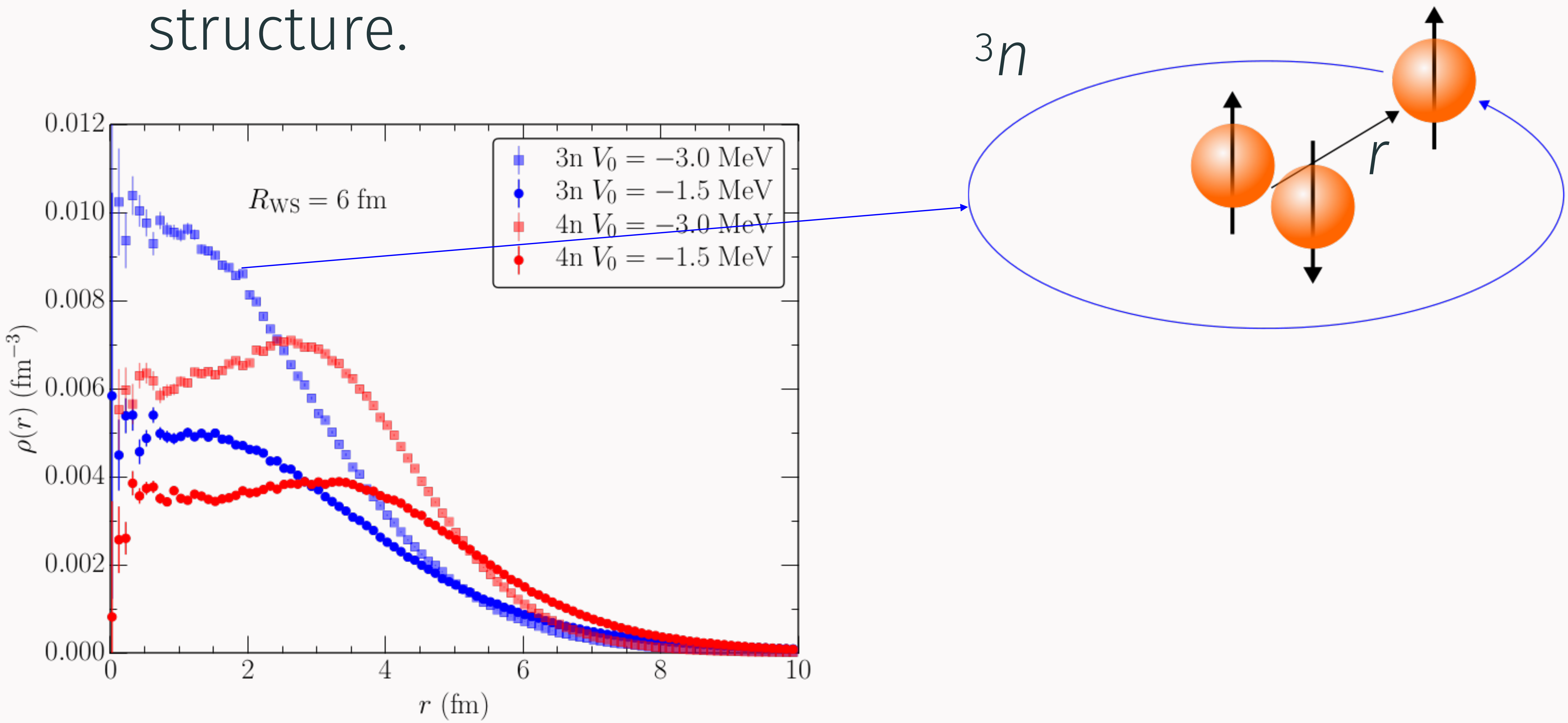

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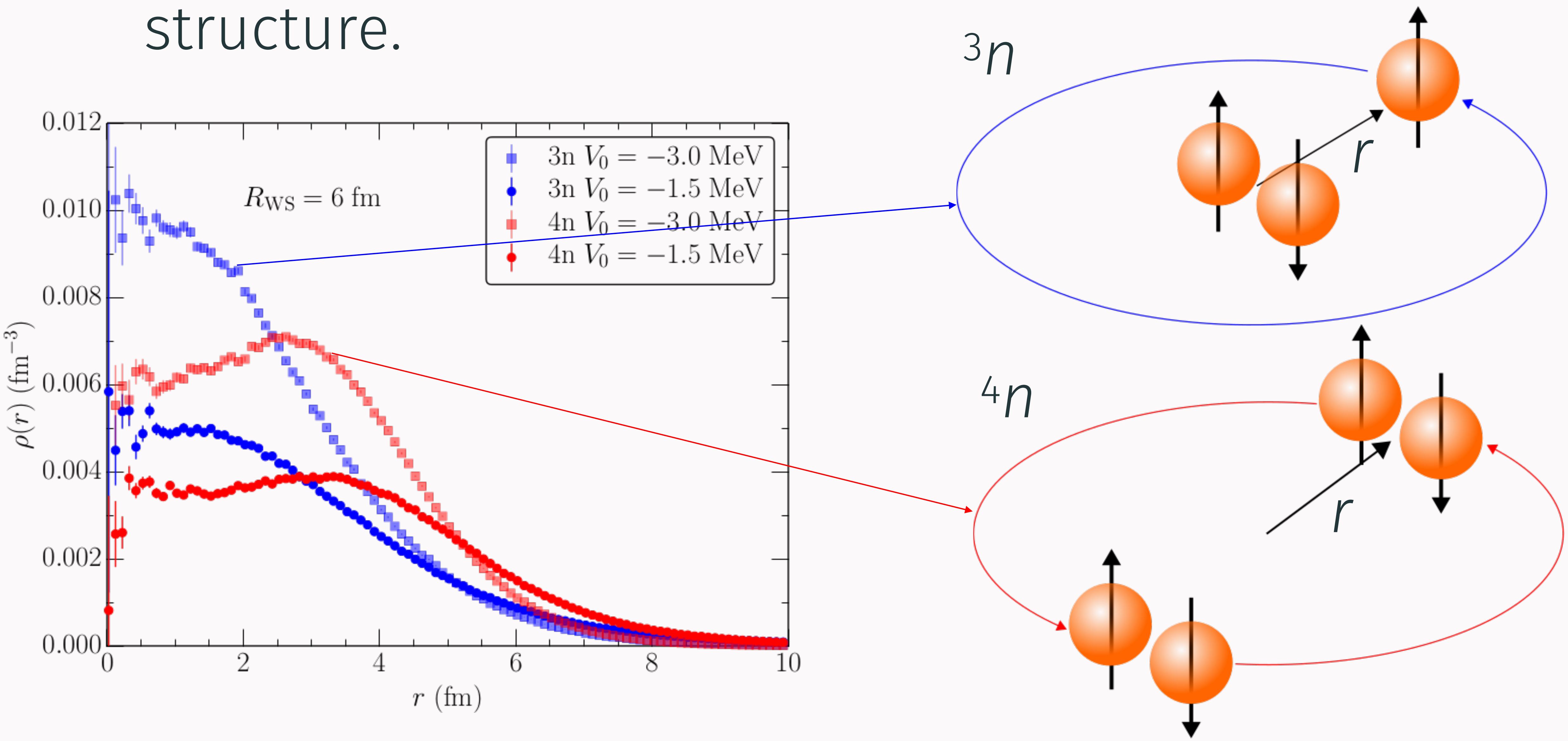


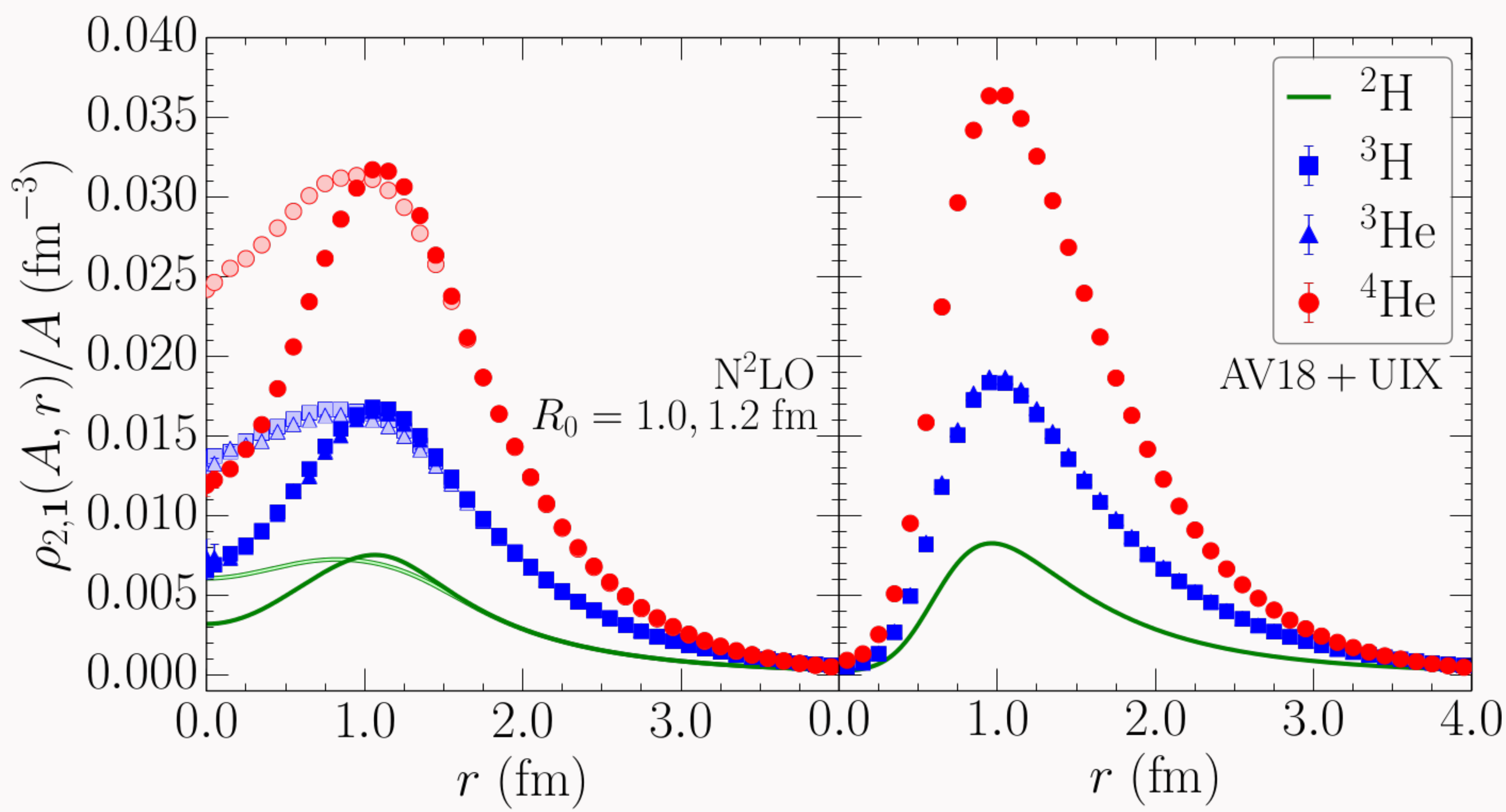
S. Gandolfi, H.-W. Hammer, P. Klos, JEL, A. Schwenk, PRL **118**, 232501 (2017)

Short-Range Correlations (SRCs) & EMC Effect

Two-Body Densities

$$\rho_{2,1}(A,r) \equiv \frac{1}{4\pi r^2}\left\langle \Psi_0 \middle| \sum_{i<j} \delta(r - r_{ij}) \middle| \Psi_0 \right\rangle$$

Scale and scheme dependent

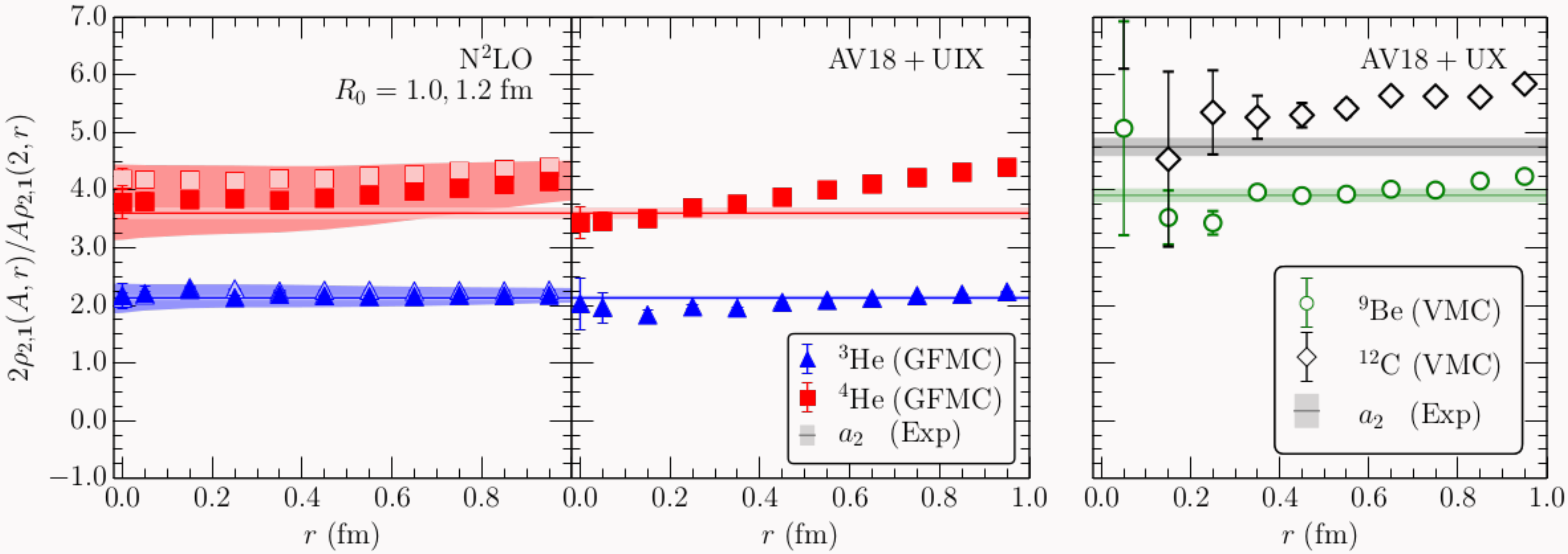


J.-W Chen, W. Detmold, JEL, A. Schwenk, arXiv:1607.03065 [hep-ph] (2016) [Accepted to PRL]

SRC Correlation Factors

$$a_2 \equiv \lim_{r \to 0} \frac{2\rho_{2,1}(A,r)}{A\rho_{2,1}(2,r)}$$

Scale and scheme *independent*!

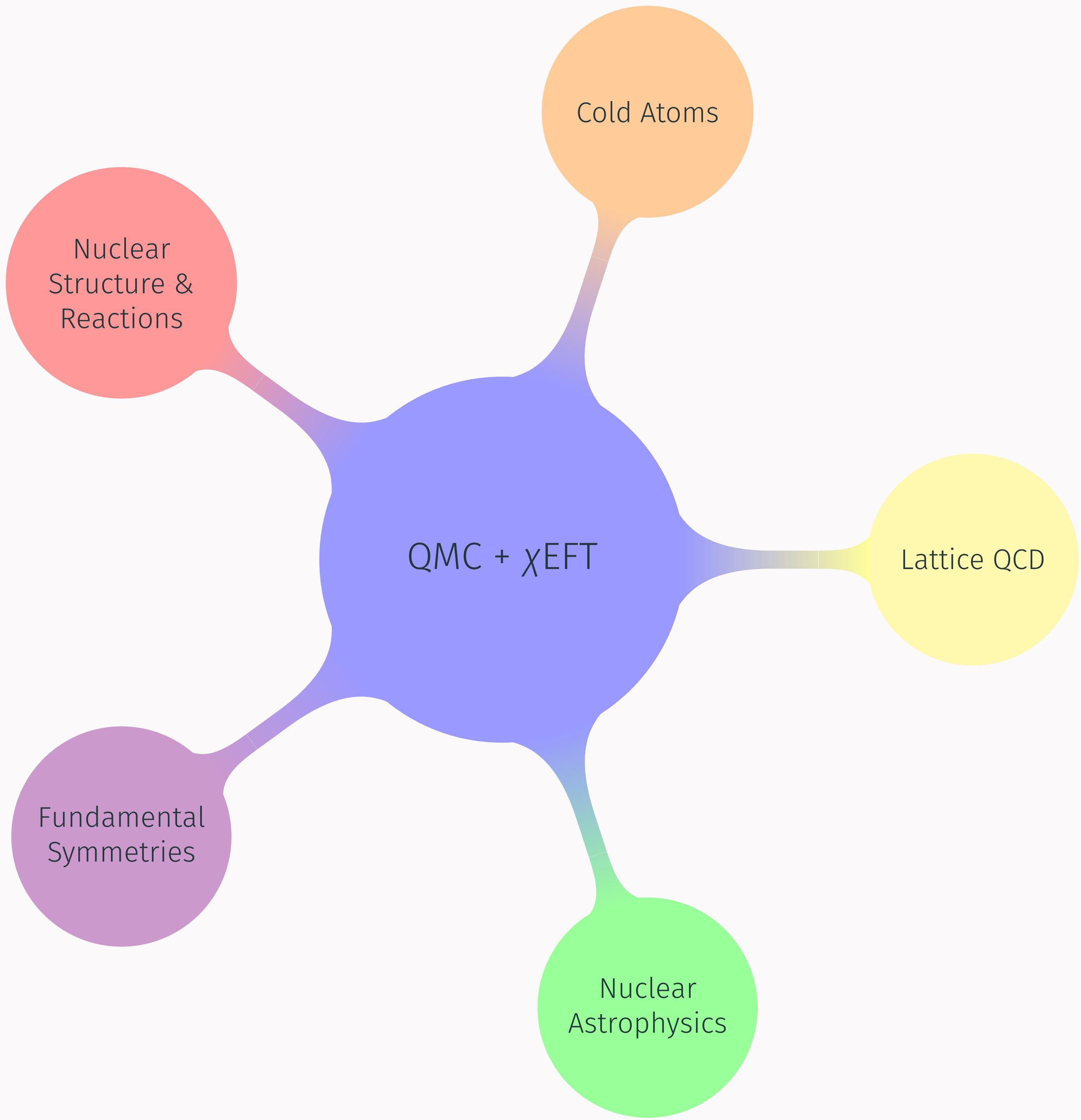


J.-W Chen, W. Detmold, JEL, A. Schwenk, arXiv:1607.03065 [hep-ph] (2016) [Accepted to PRL]

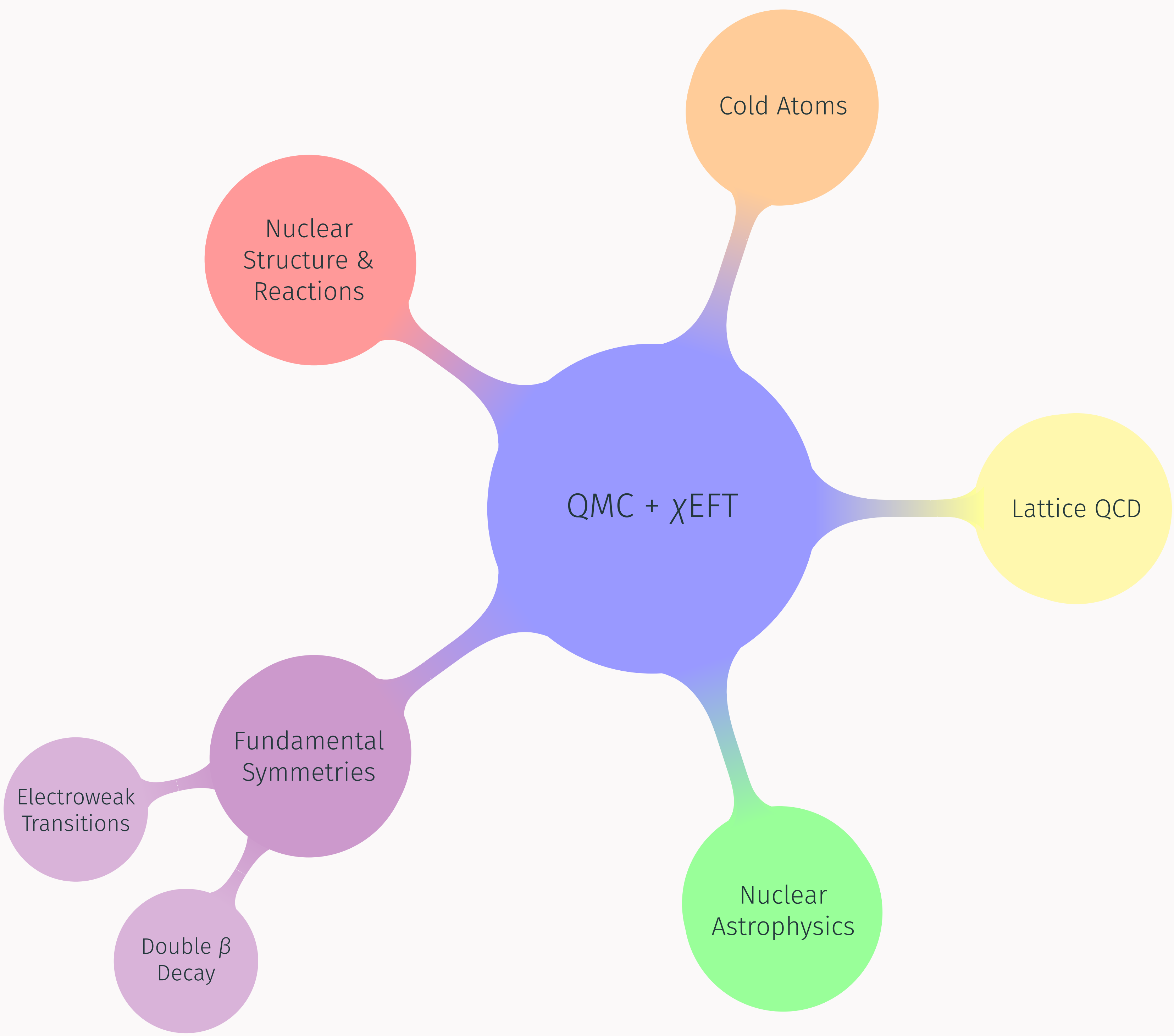
Summary

- An exciting time in nuclear physics thanks to new experiments, many-body methods, and chiral EFT.
- QMC methods with chiral EFT interactions: A powerful set of tools to advance nuclear physics.
- AFDMC is beginning to reach towards *ab initio* medium-mass nuclei.
- A $3n$ resonance might be lower in energy than a $4n$ resonance and might be observable as well.
- We can make scheme- and scale-independent predictions for SRC scaling factors.

Outlook


Cold Atoms
Nuclear Structure & Reactions
QMC + χEFT
Lattice QCD
Fundamental Symmetries
Nuclear Astrophysics

Outlook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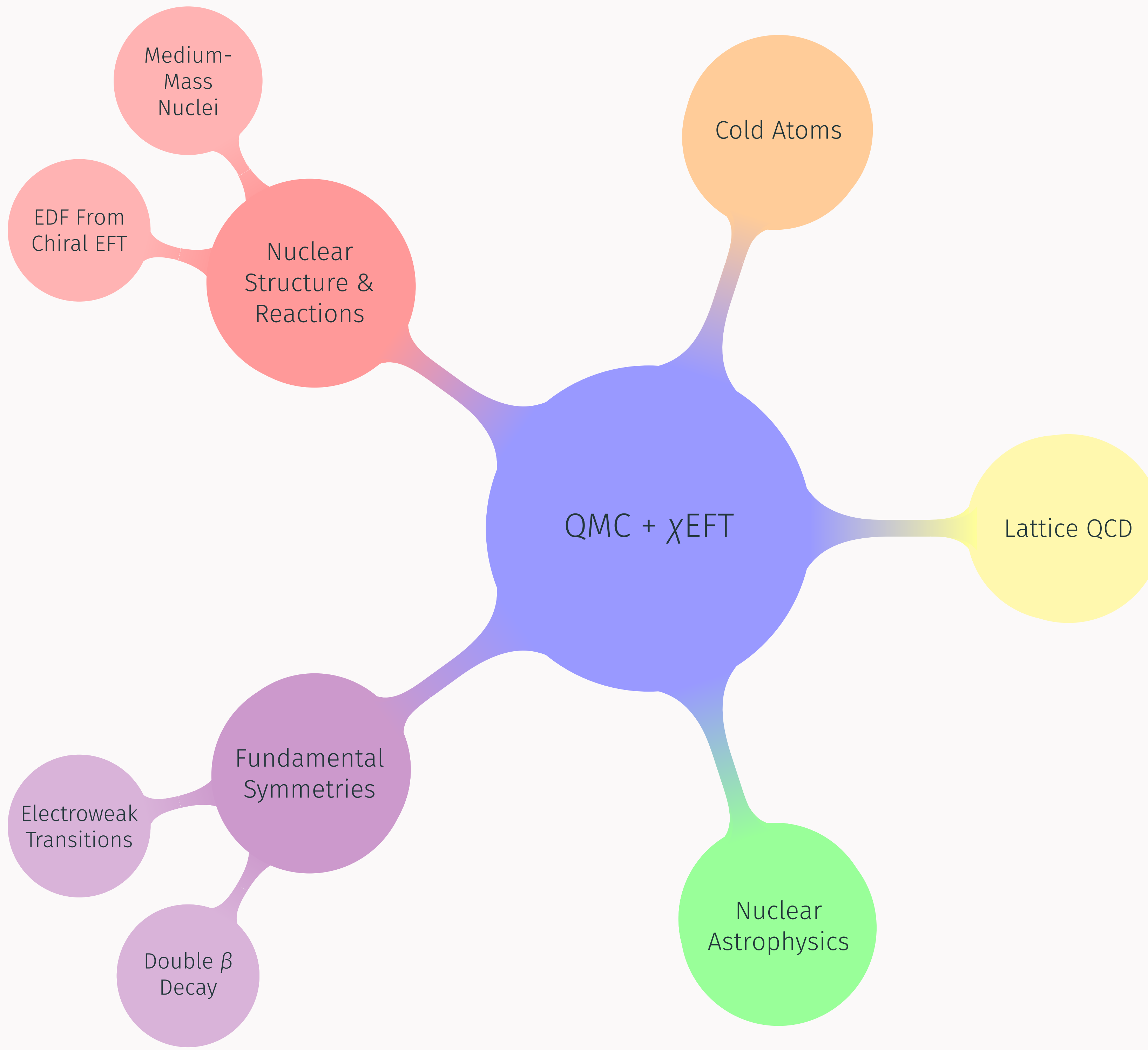
Electroweak Transitions
Double β Decay
Nuclear Astrophysics

Outlook



Medium-
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Nuclei
EDF From
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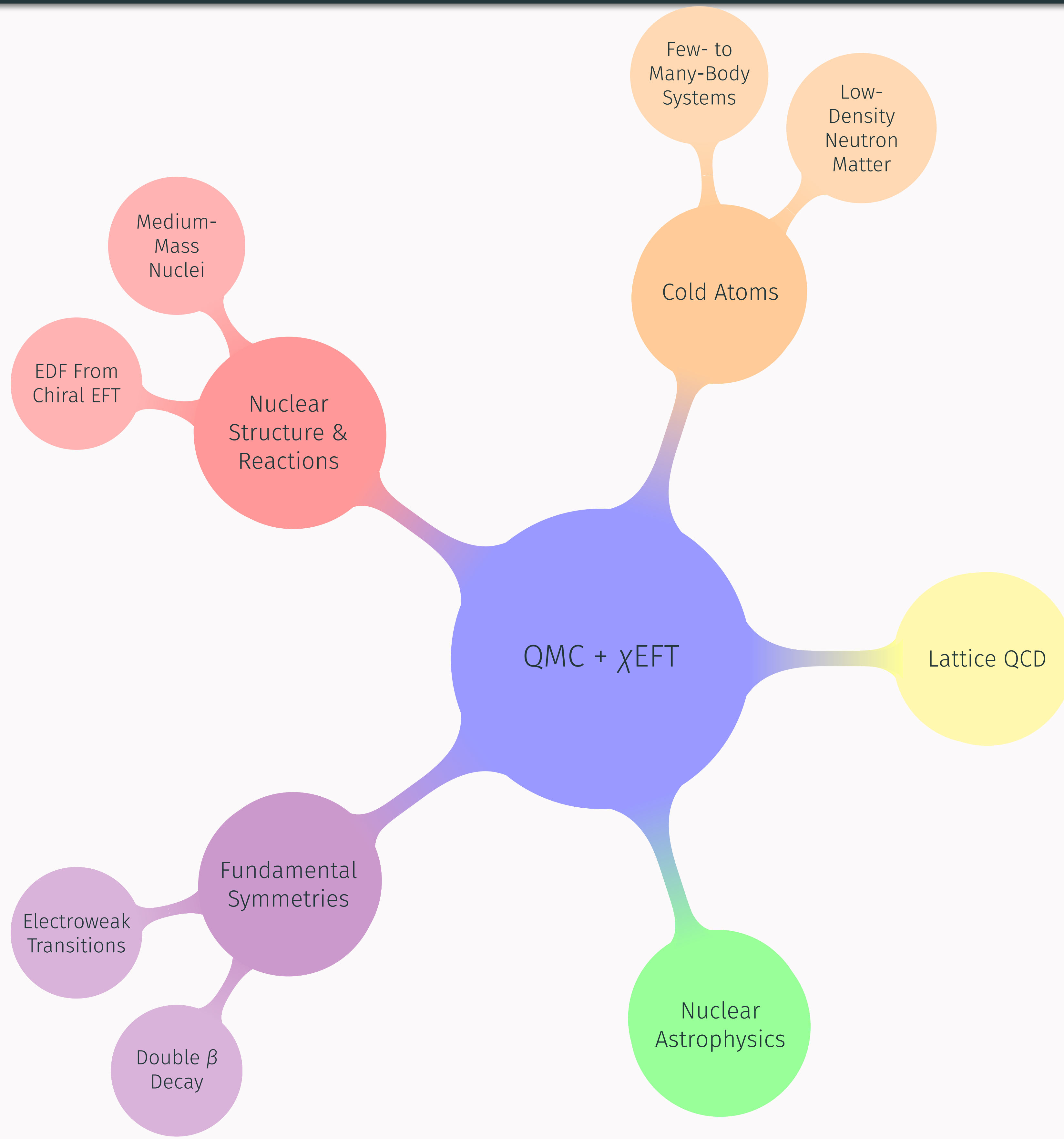

QMC + χEFT
Nuclear Structure & Reactions
Medium-Mass Nuclei
EDF From Chiral EFT
Cold Atoms
Few- to Many-Body Systems
Low-Density Neutron Matter
Lattice QCD
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Fundamental Symmetries
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Acknowledgments

Collaborators

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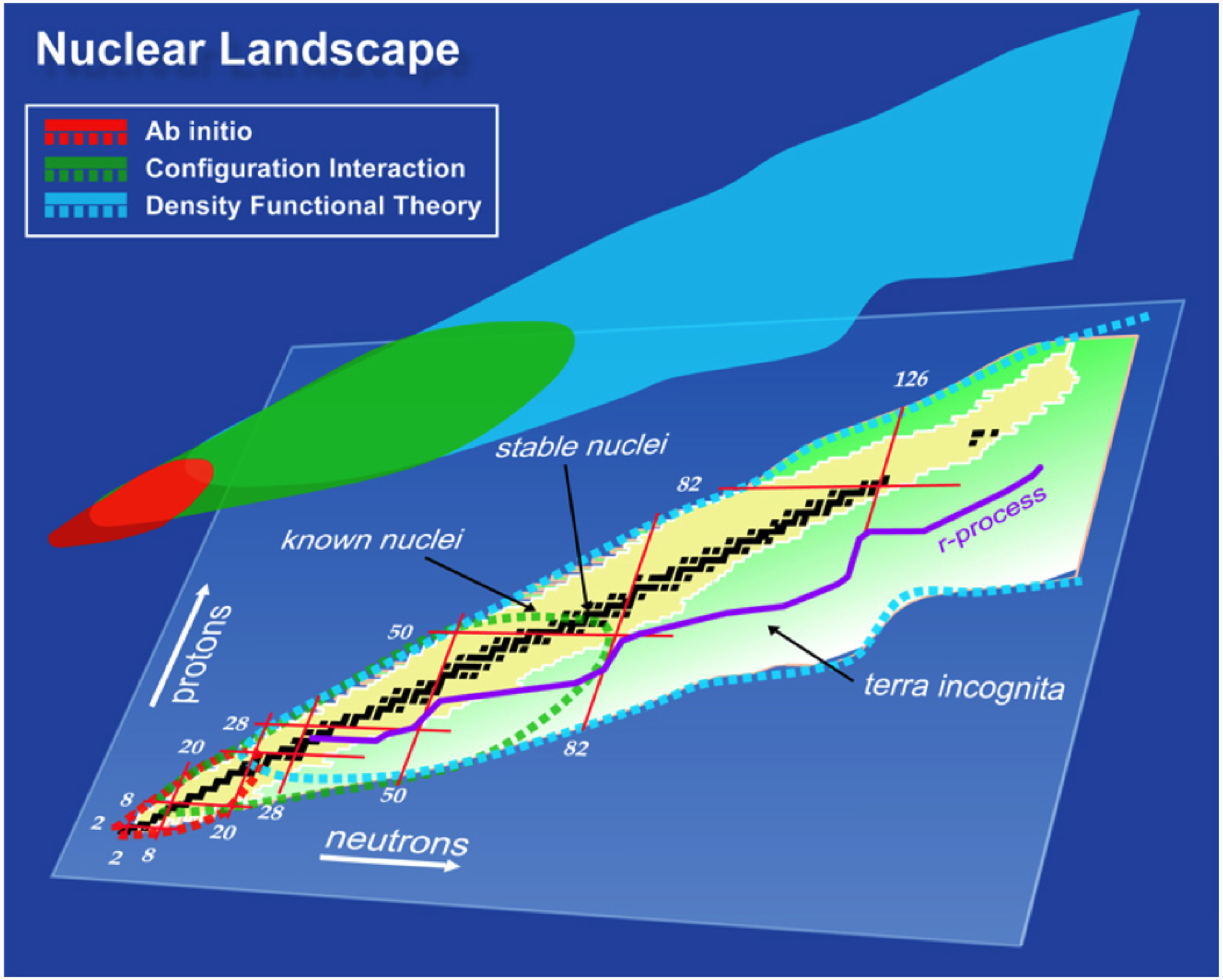
Thank you for your attention!

Reach Of *Ab Initio* Methods



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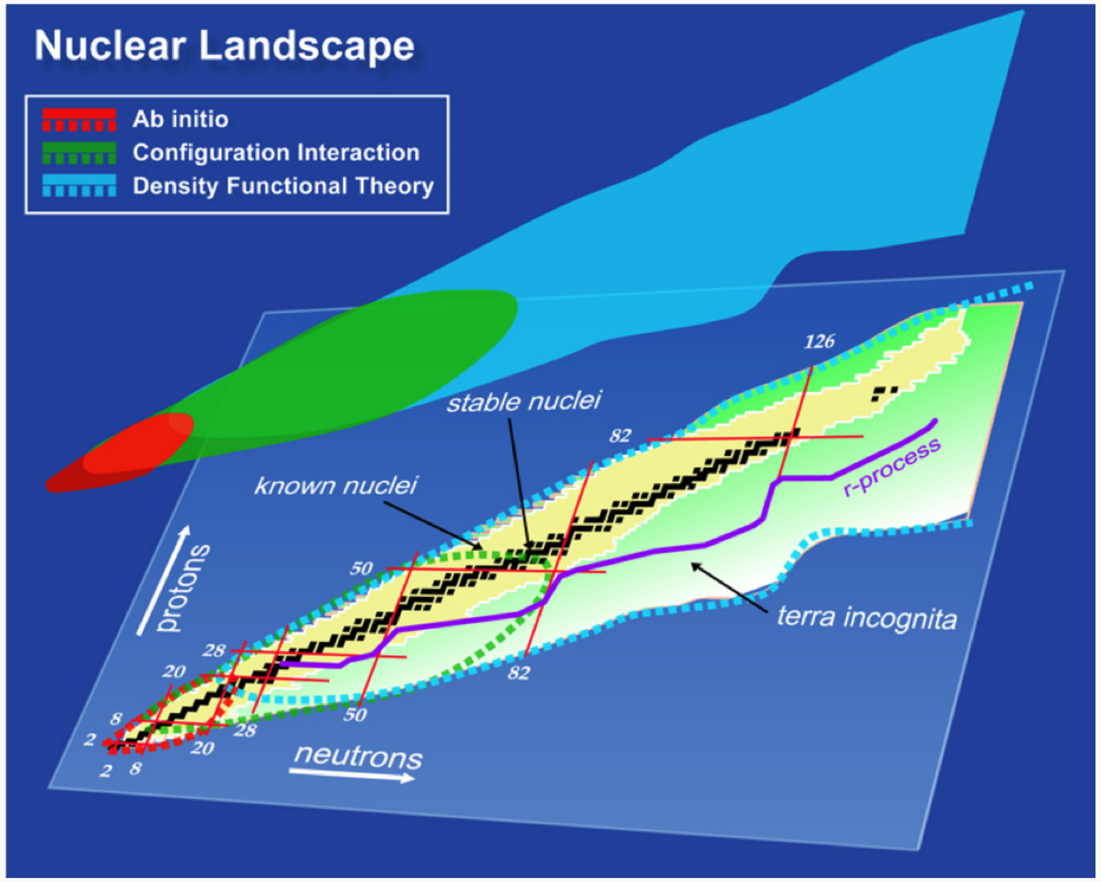

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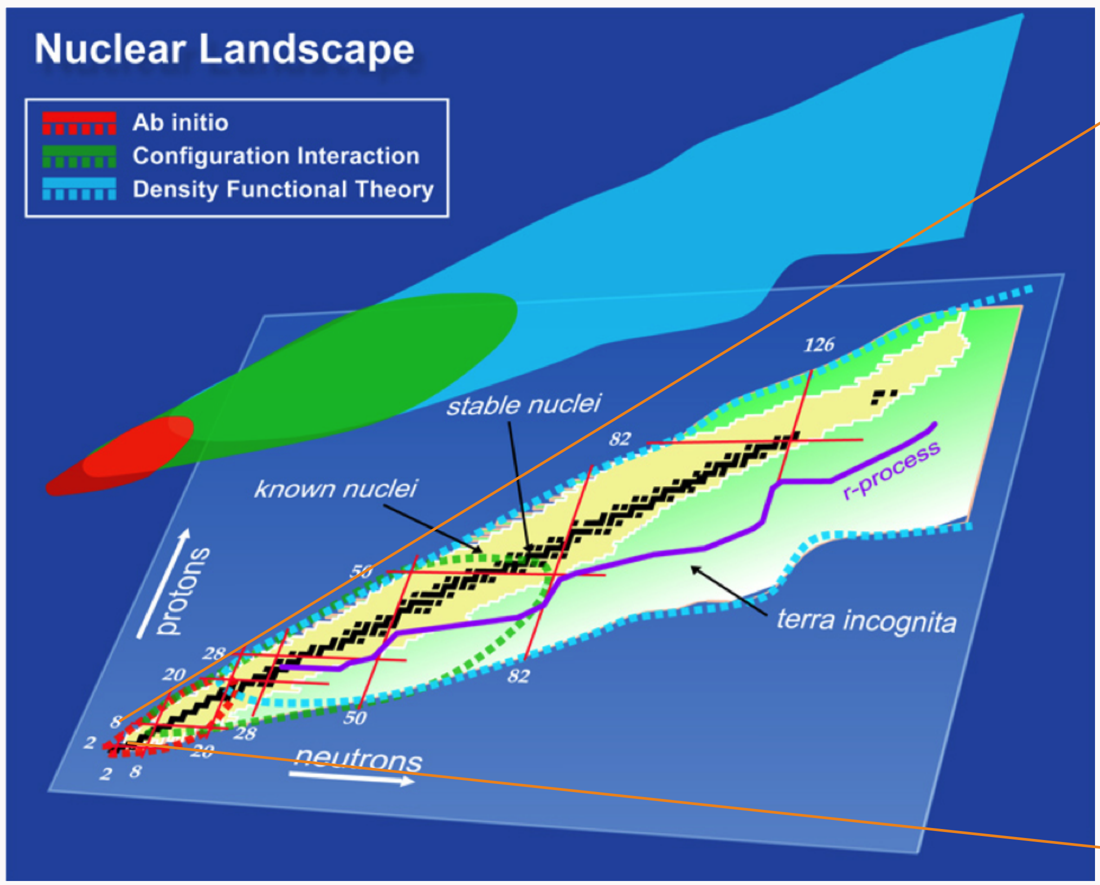
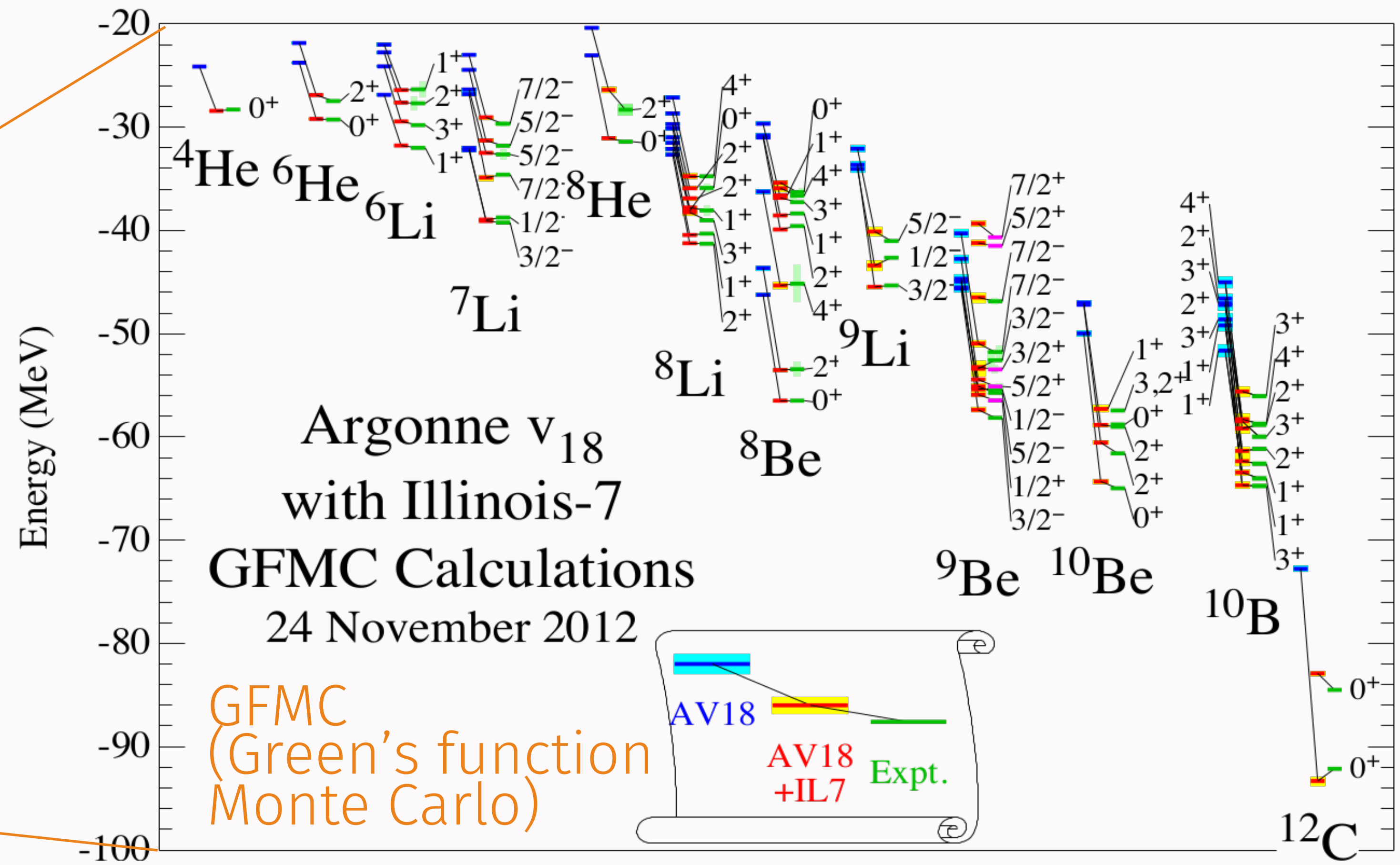


from H. Nam et al., J. Phys. Conf. Ser. **402**, 012033 (2012)



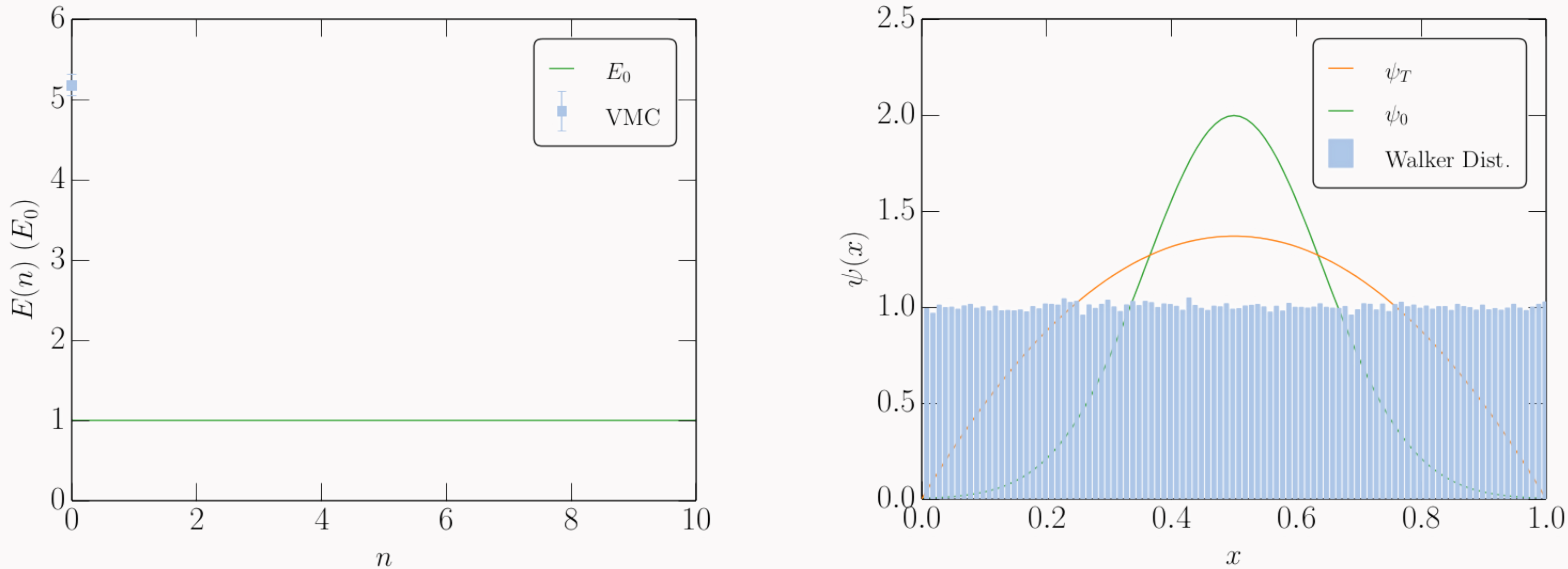
from the Argonne National Lab Group

QMC Methods - An Example

First, VMC equilibration:

$$\frac{\langle \psi_T | H | \psi_T \rangle}{\langle \psi_T | \psi_T \rangle}$$

Metropolis step $n = 0$



QMC Methods - An Example

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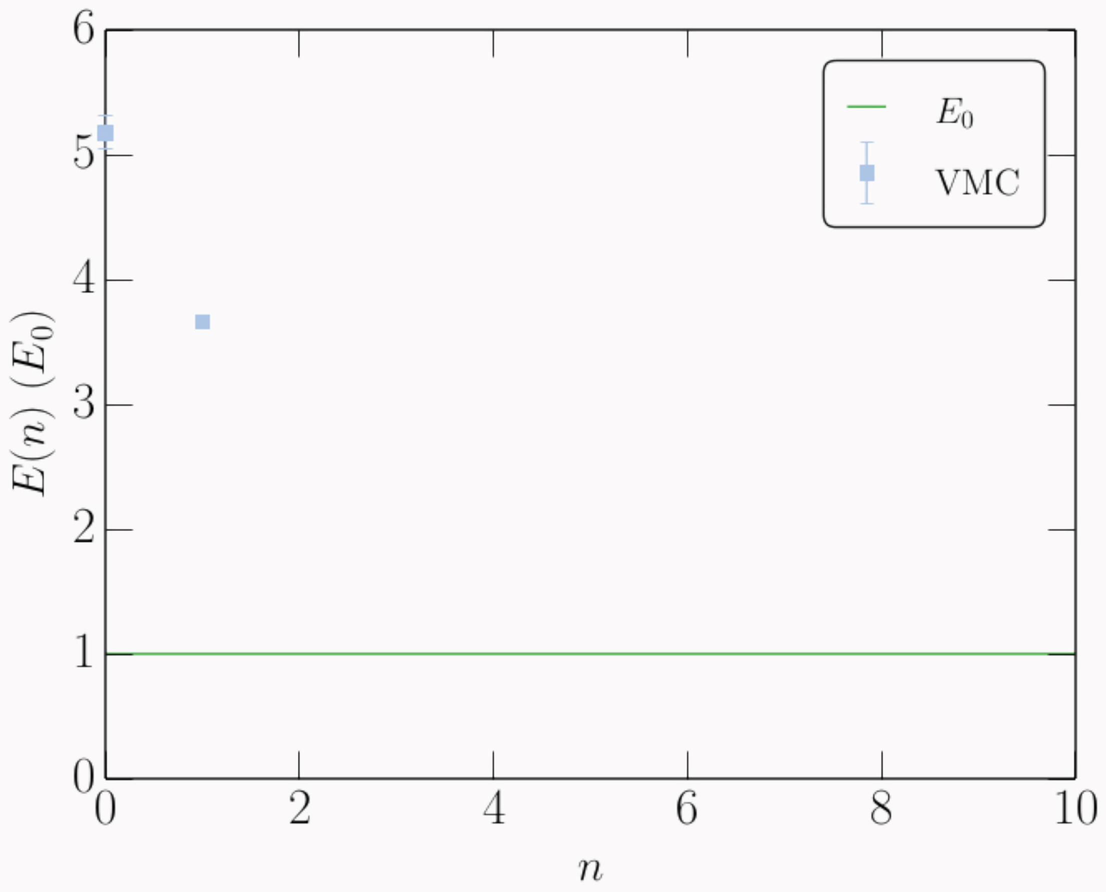
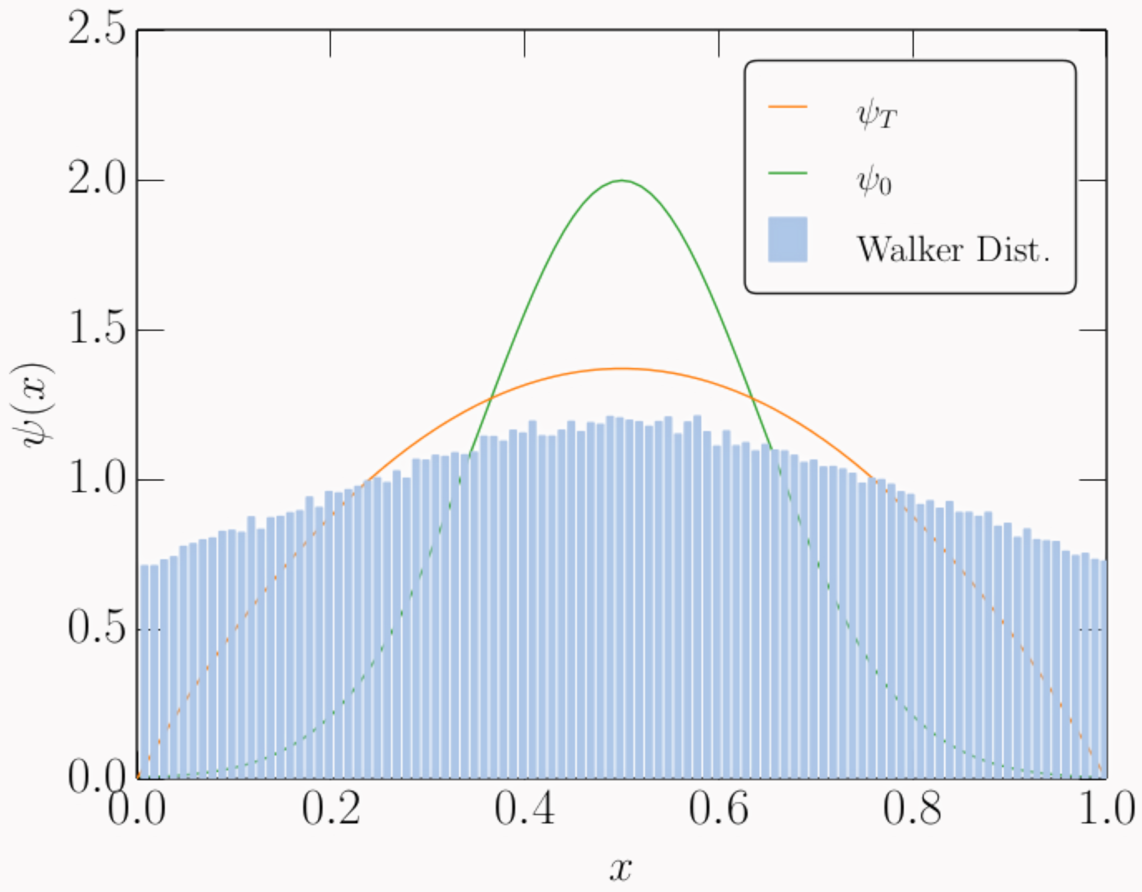
$$\frac{\langle \psi_T | H | \psi_T \rangle}{\langle \psi_T | \psi_T \rangle}$$

Metropolis step $n = 1$





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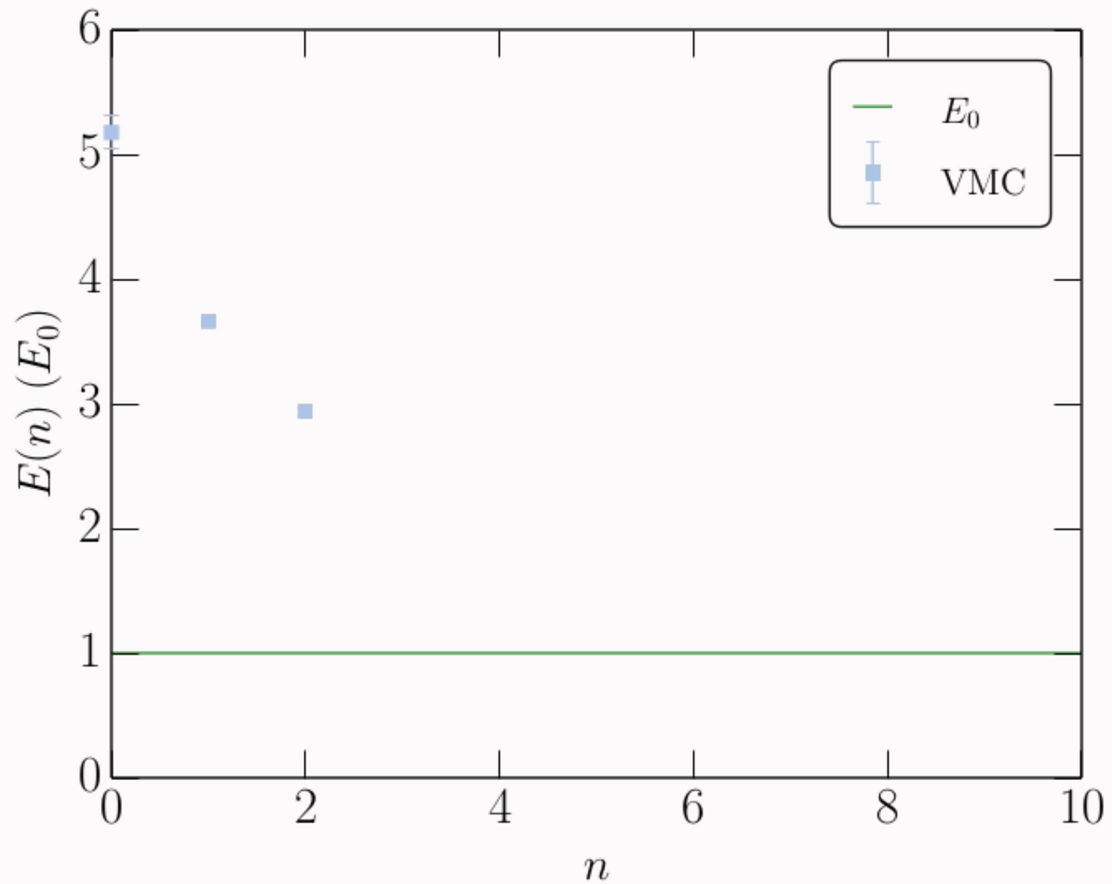
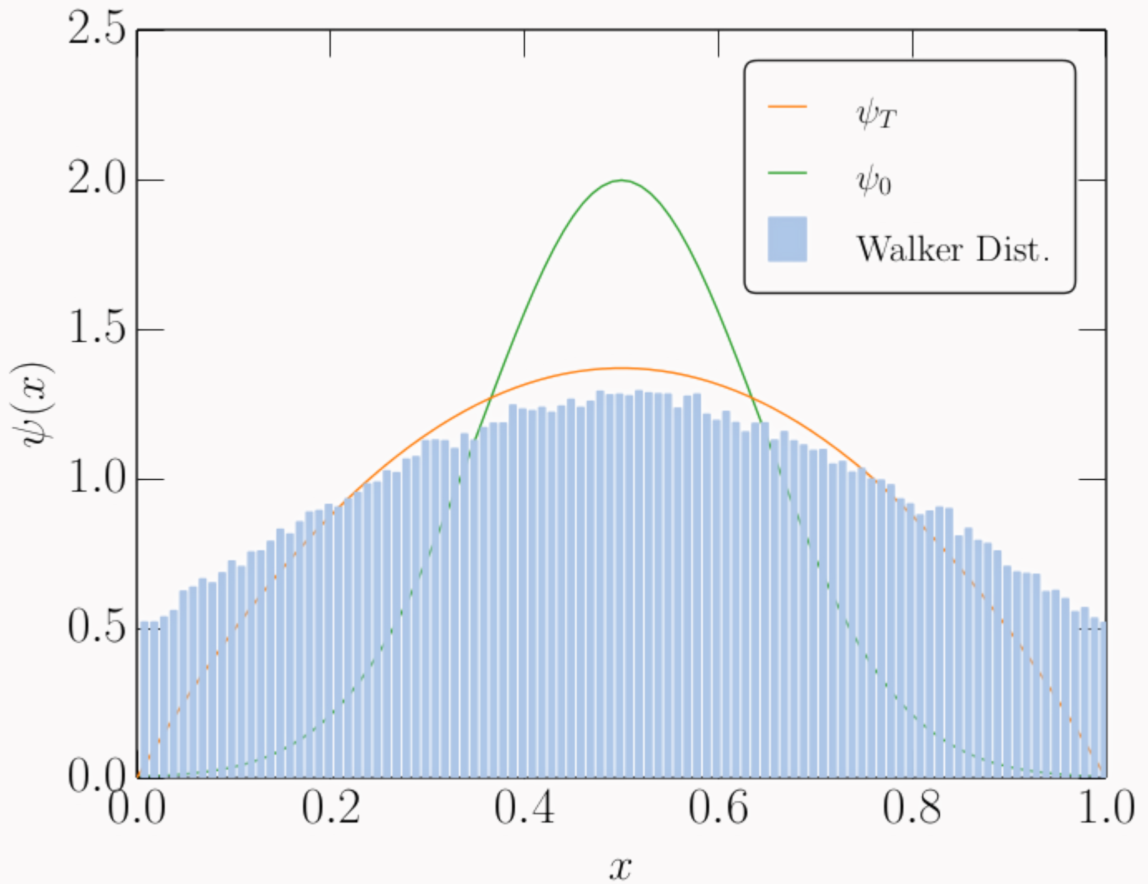
Metropolis step $n = 2$





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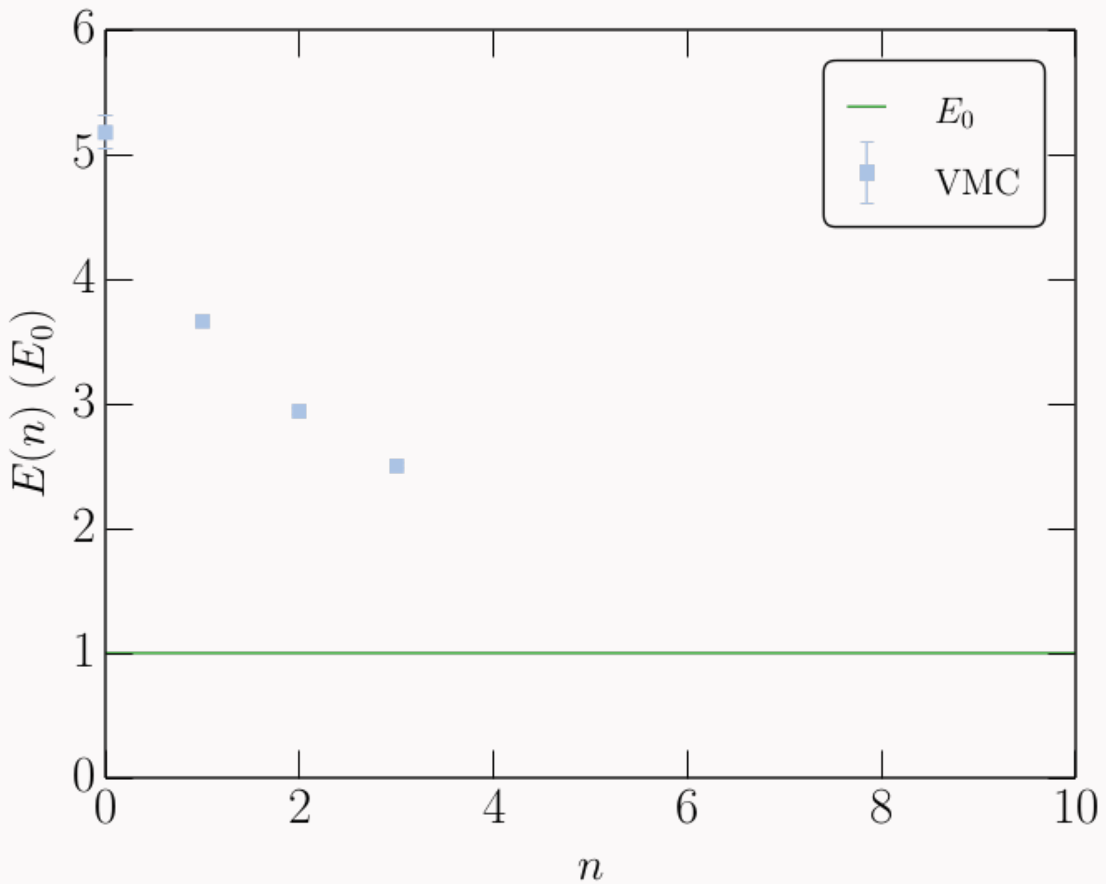
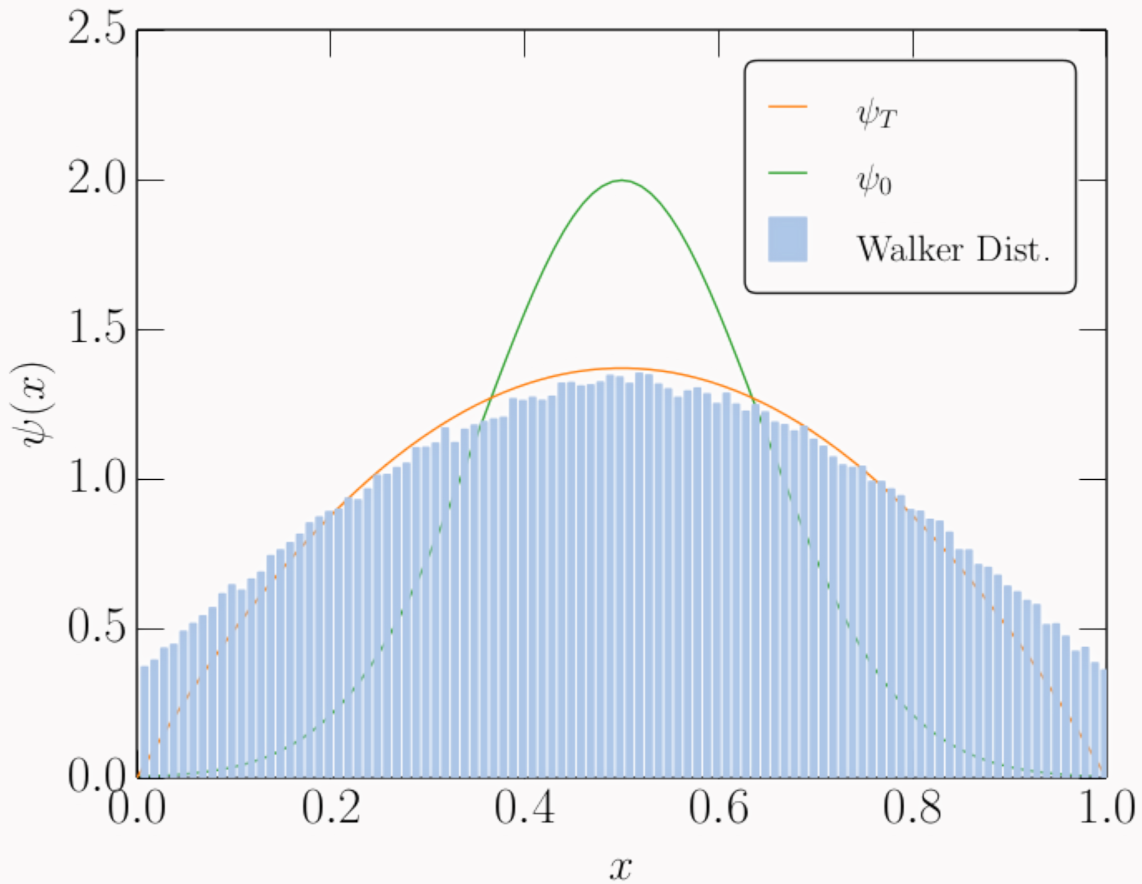
$$\frac{\langle \psi_T | H | \psi_T \rangle}{\langle \psi_T | \psi_T \rangle}$$

Metropolis step $n = 3$





QMC Methods - An Example

First, VMC equilibration:

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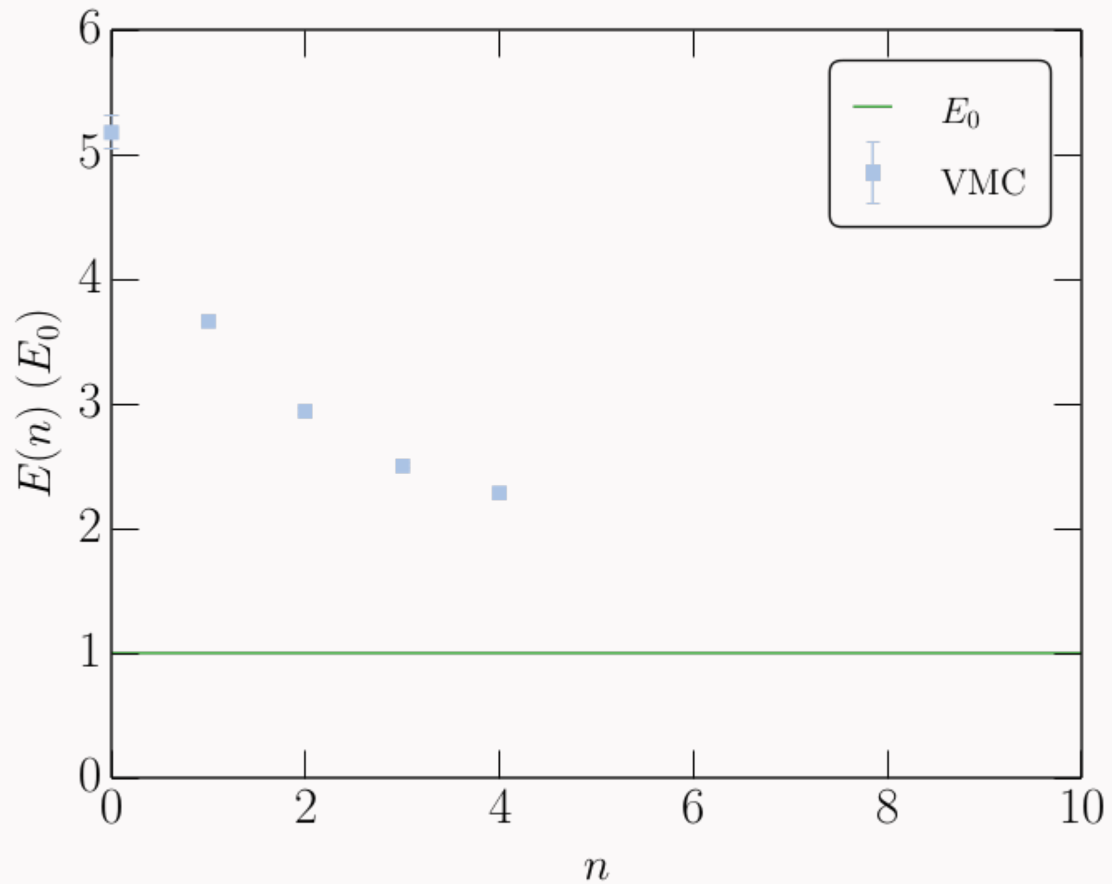
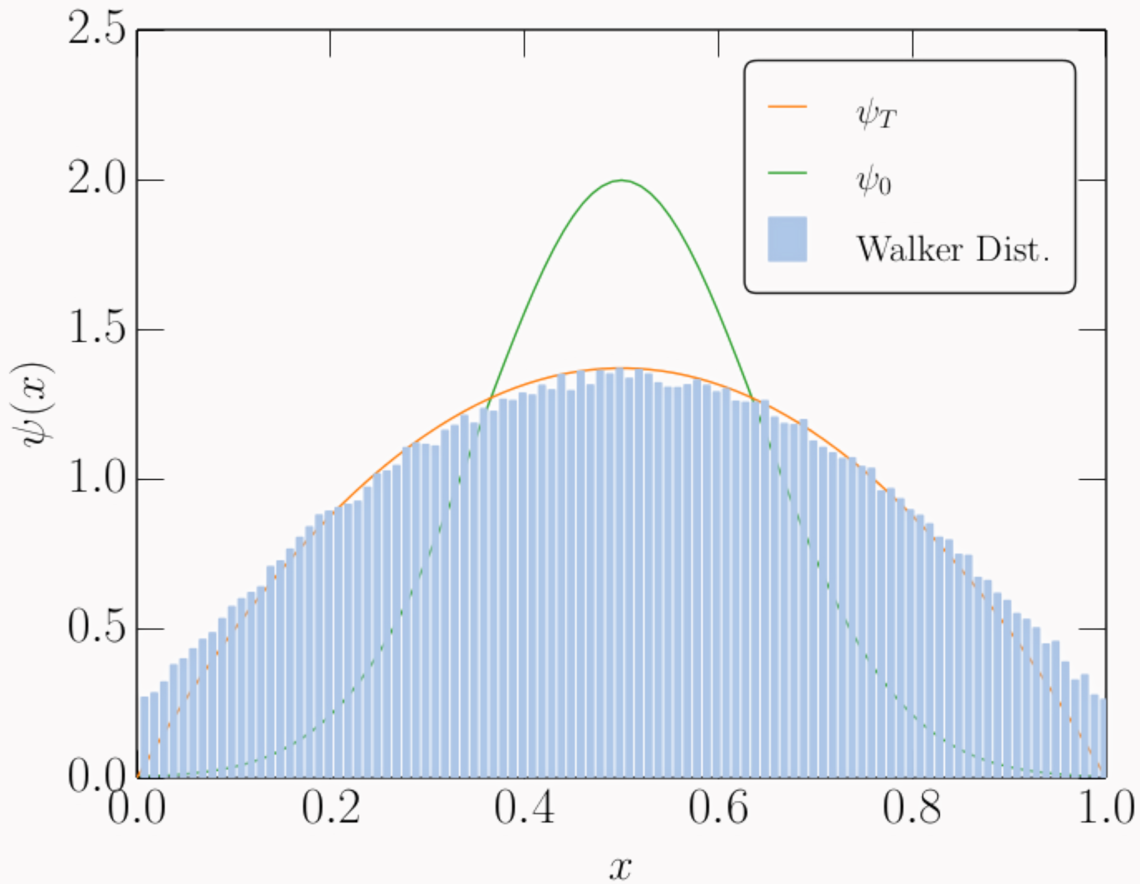
Metropolis step $n = 4$





QMC Methods - An Example

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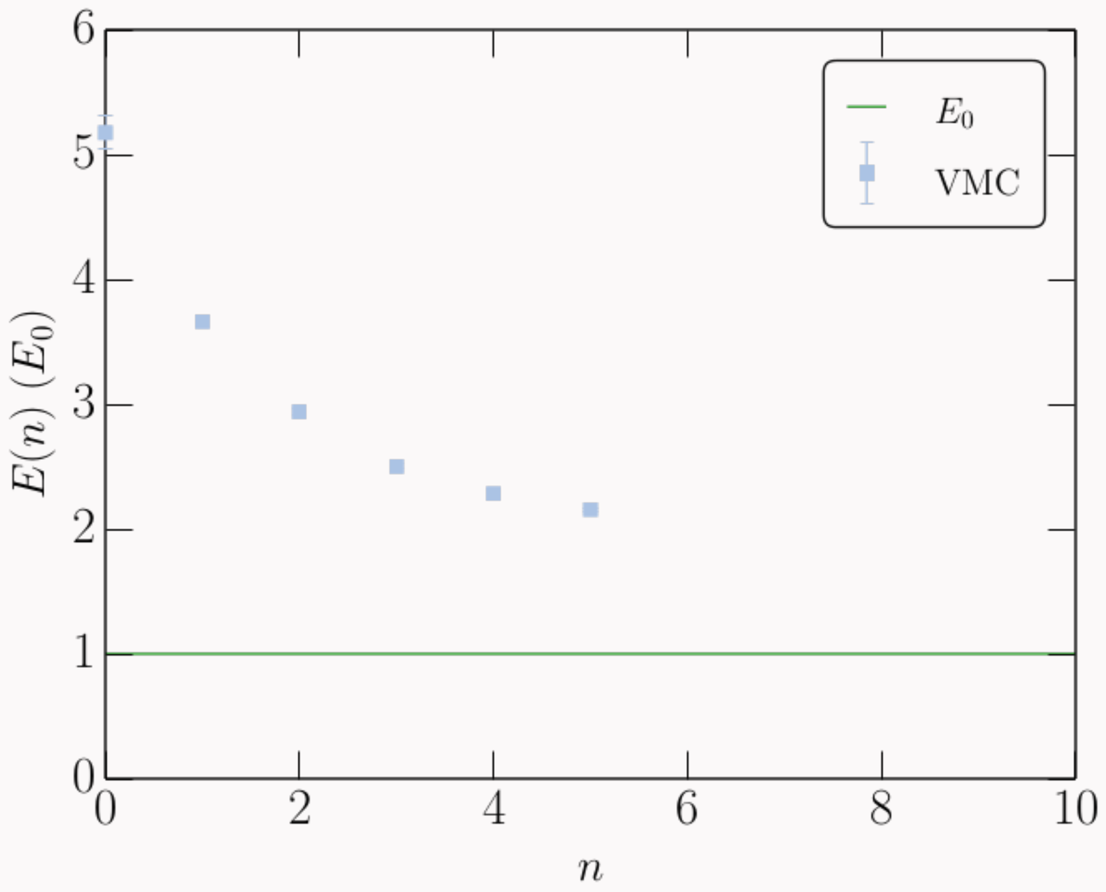
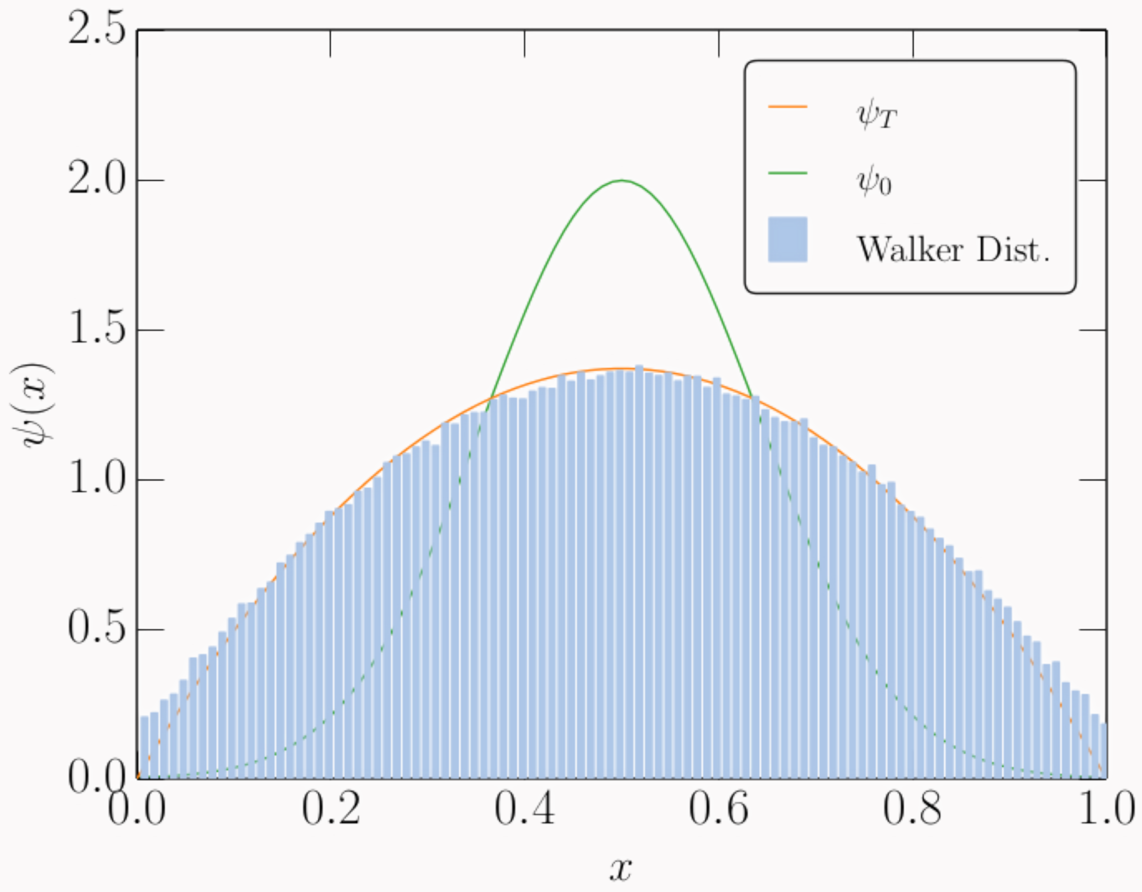
$$\frac{\langle \psi_T | H | \psi_T \rangle}{\langle \psi_T | \psi_T \rangle}$$

Metropolis step $n = 5$





QMC Methods - An Example

First, VMC equilibration:

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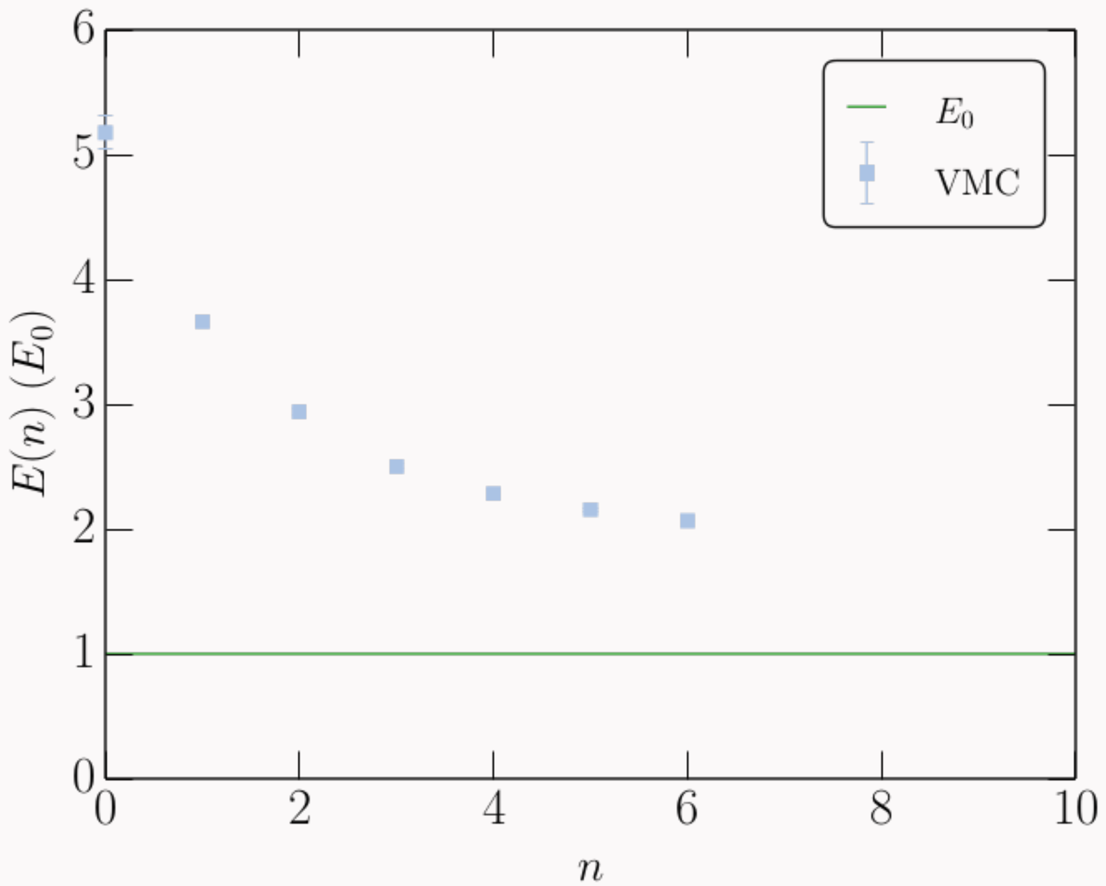
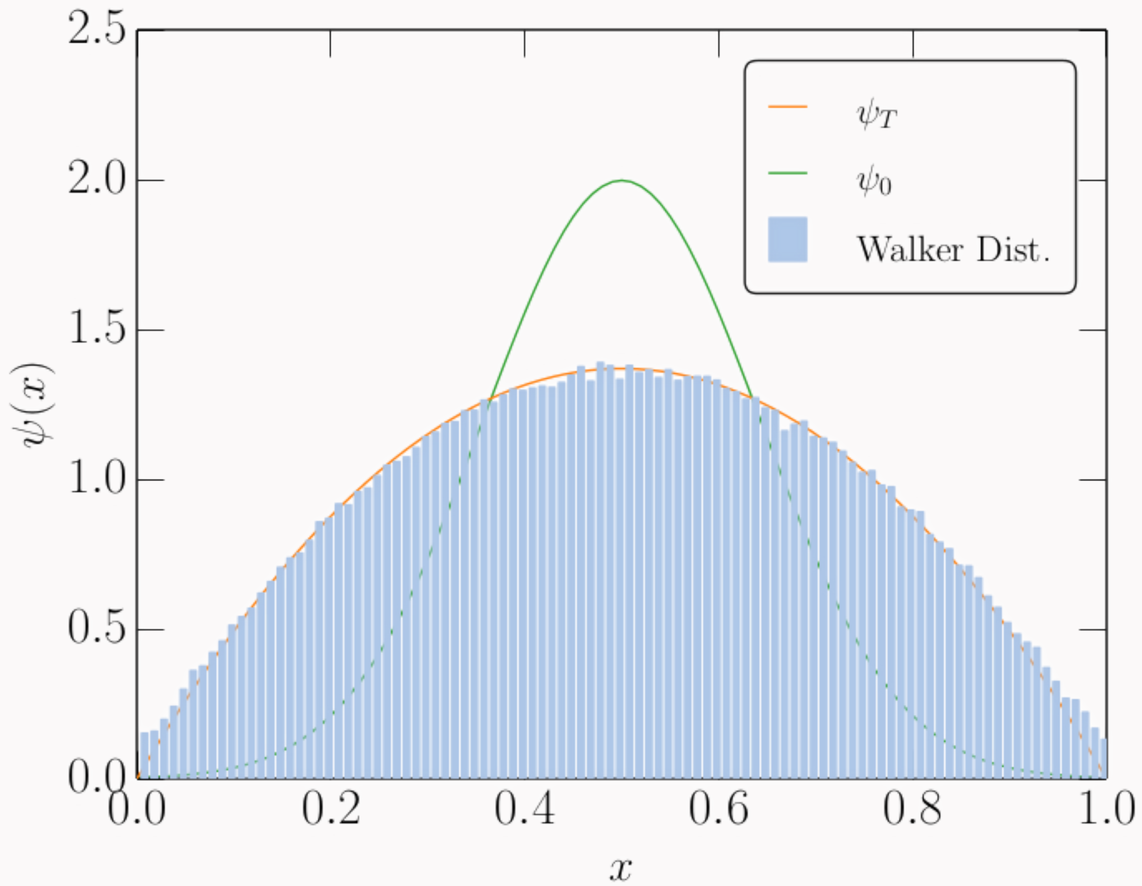
Metropolis step $n = 6$





QMC Methods - An Example

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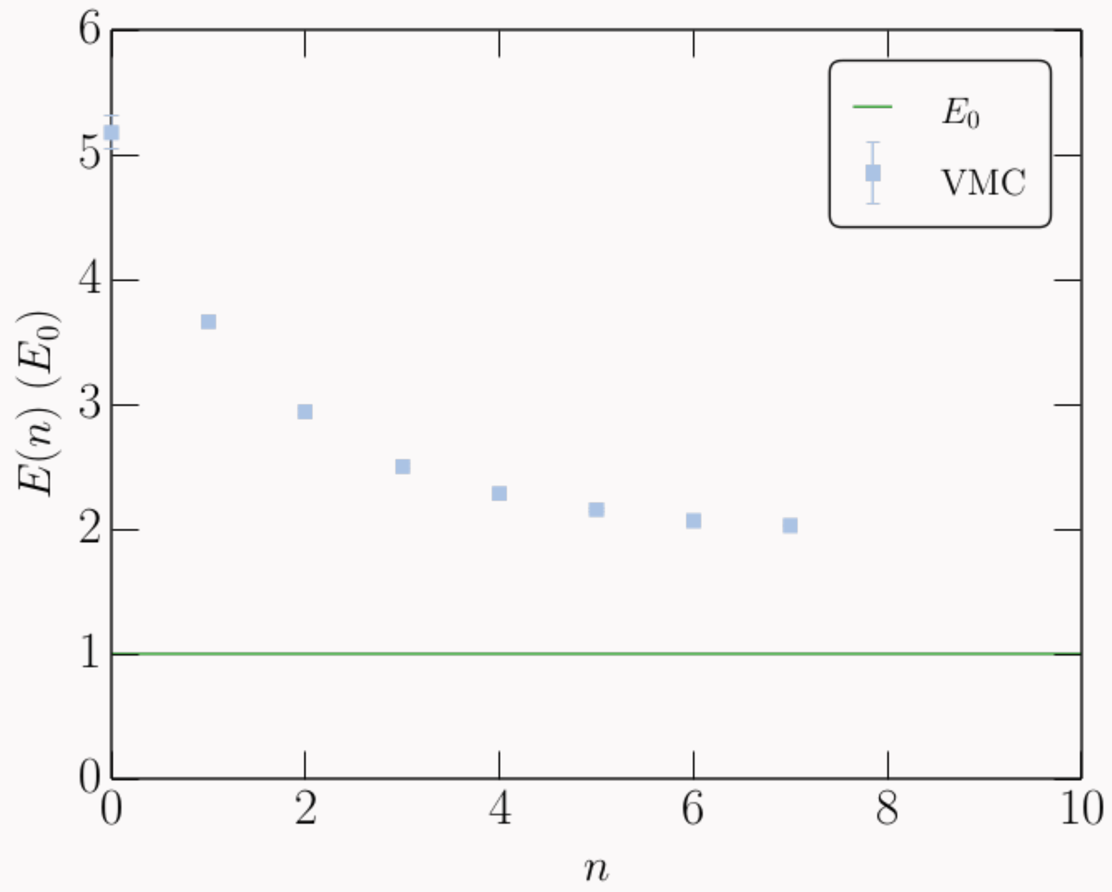
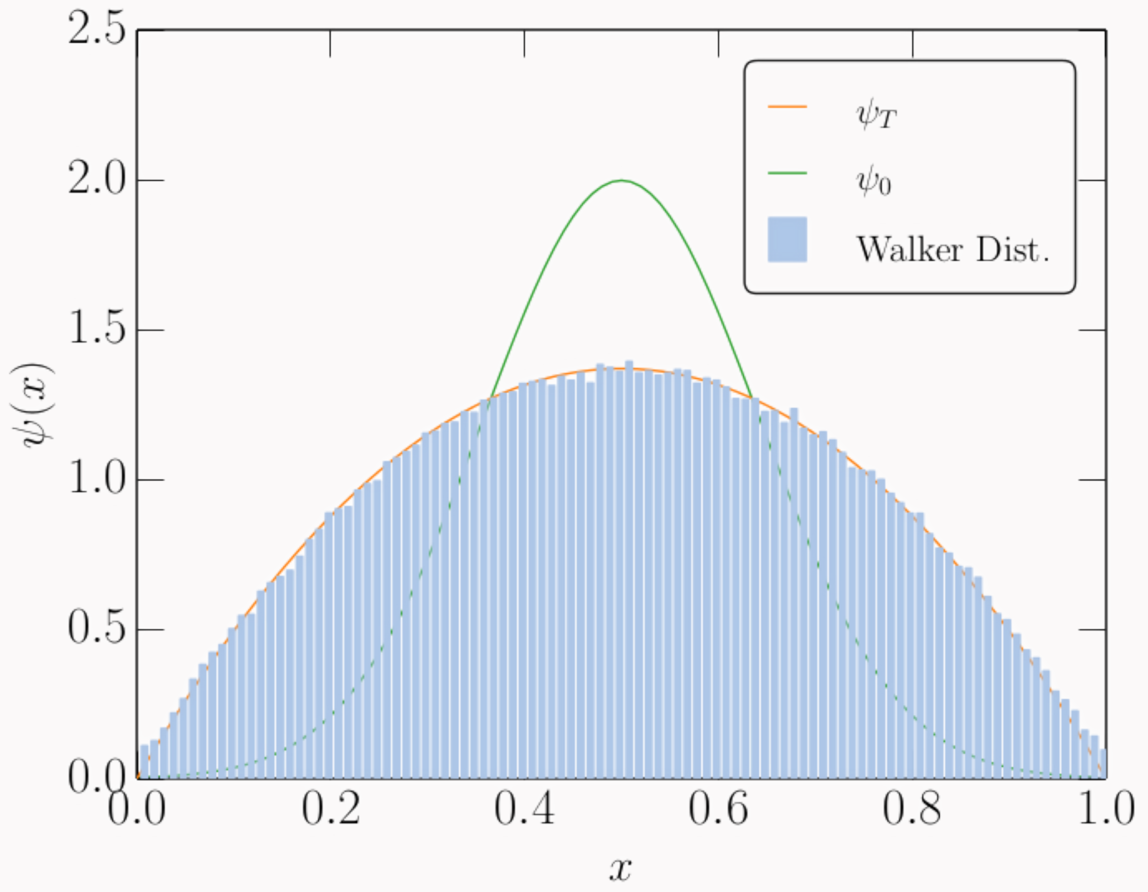
Metropolis step $n = 7$





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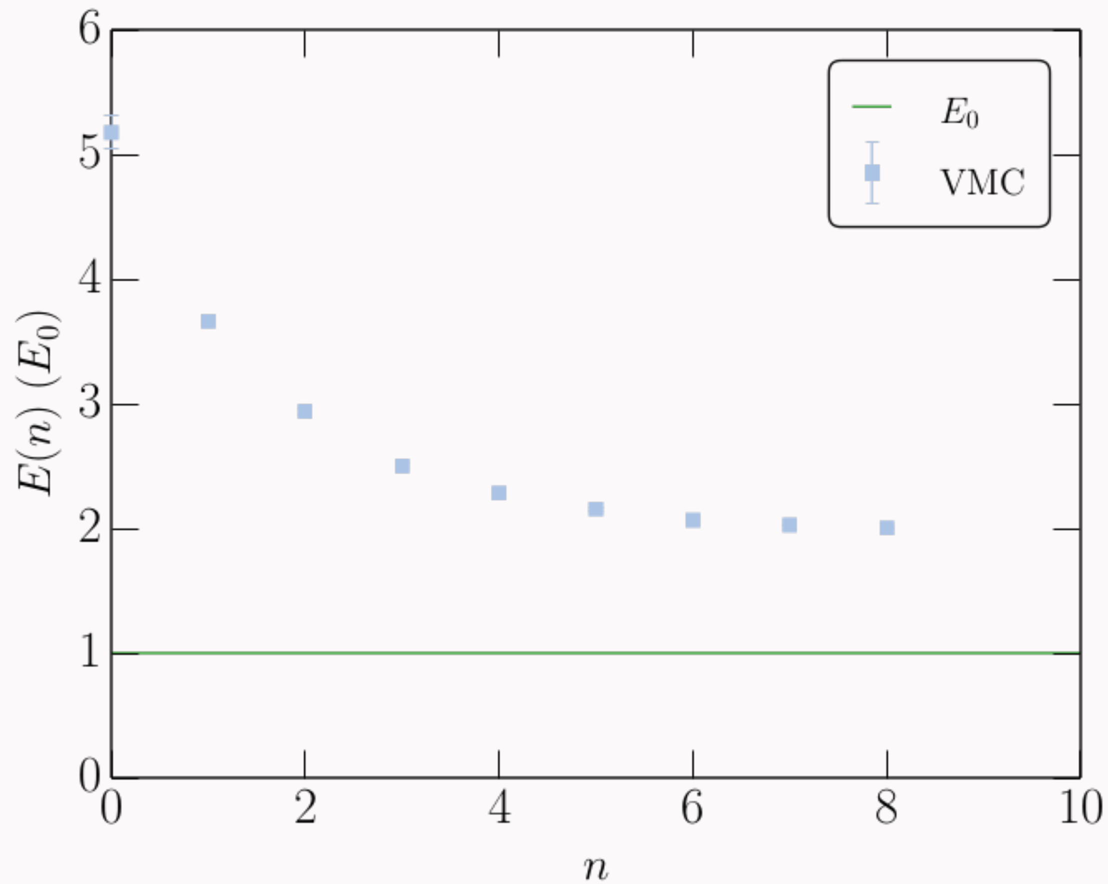
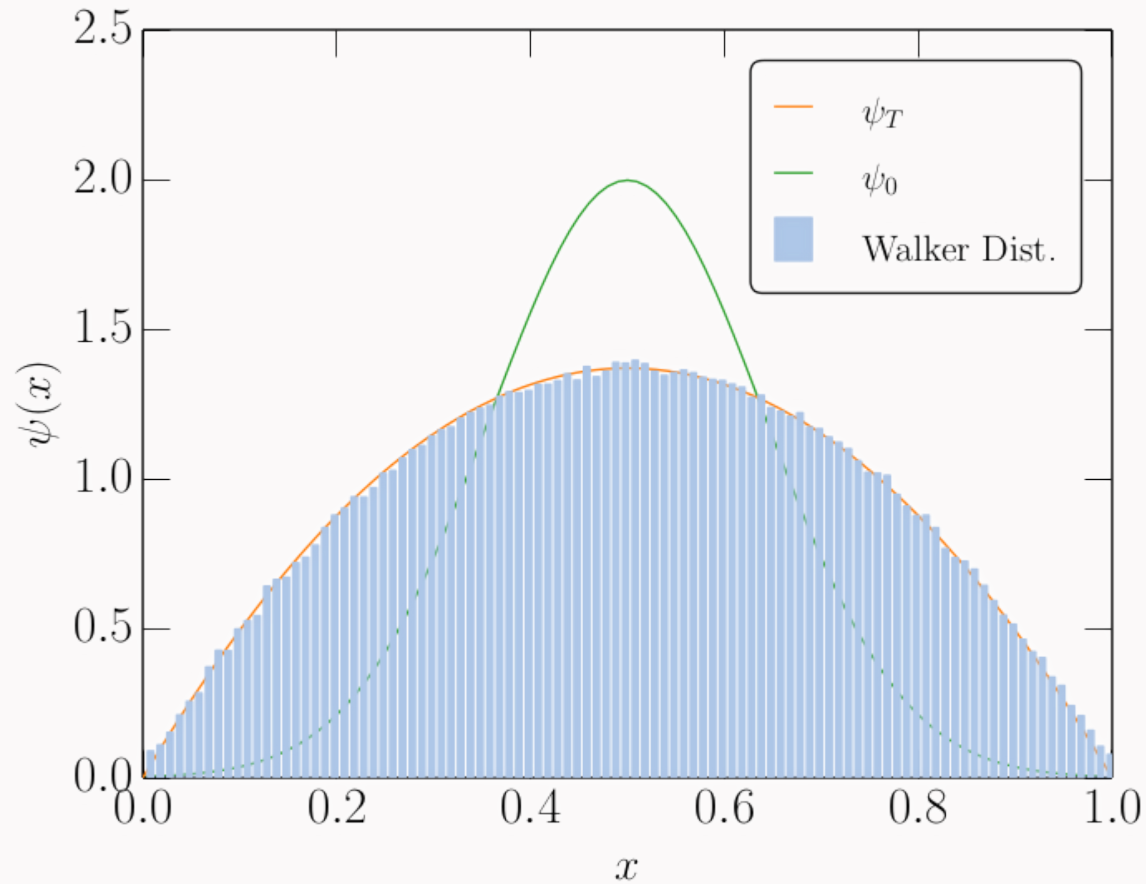
Metropolis step $n = 8$





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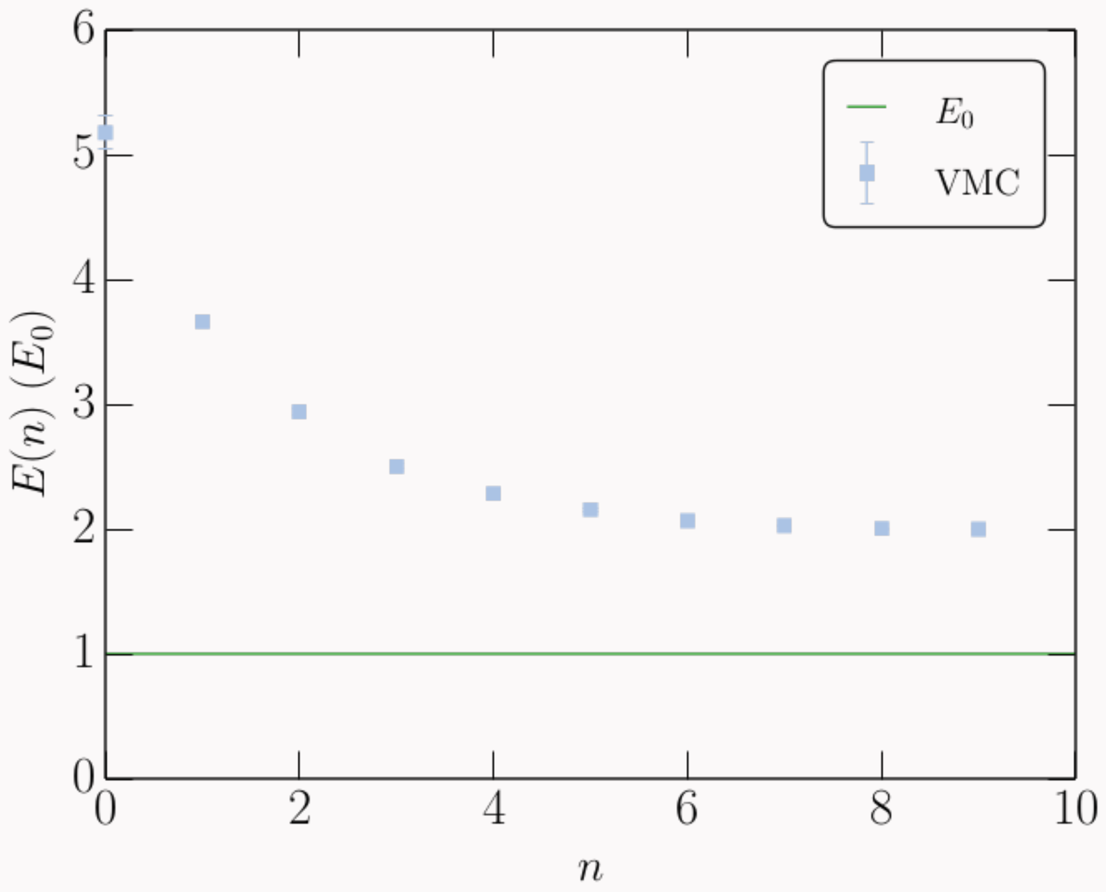
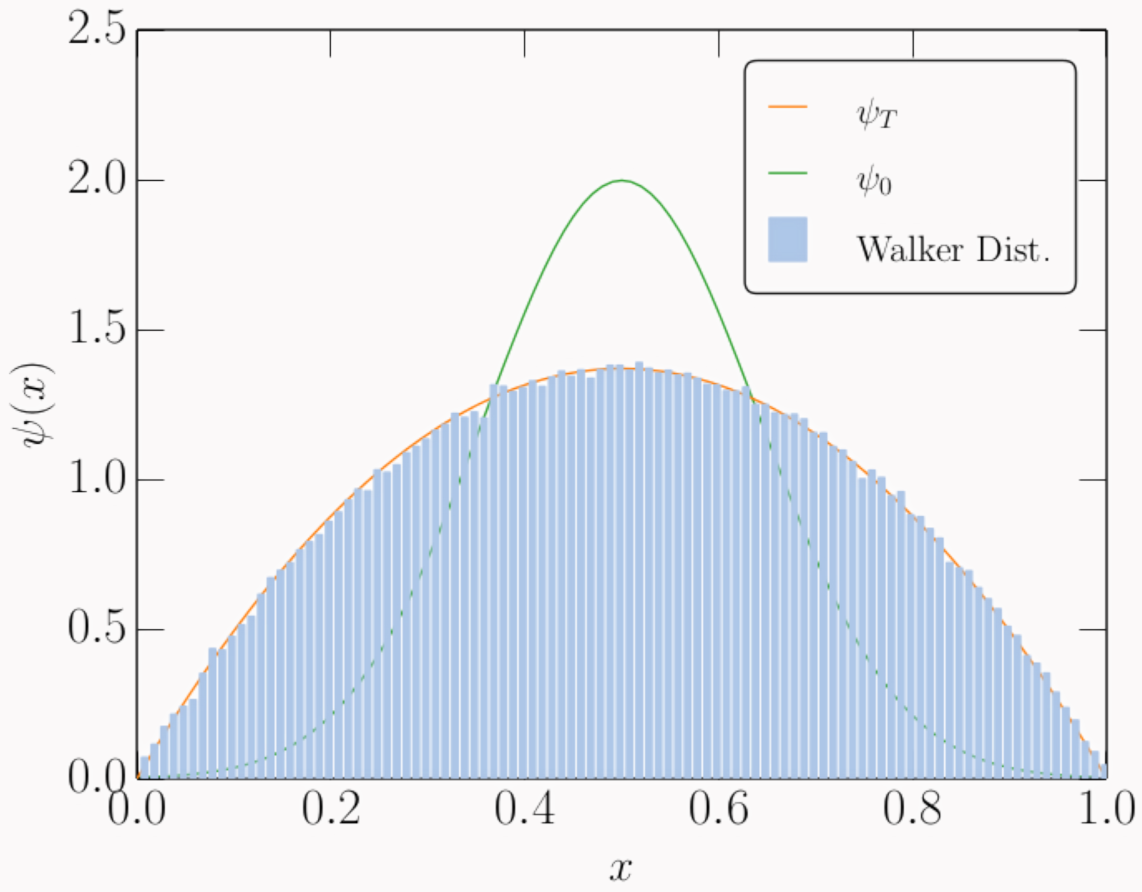
Metropolis step $n = 9$



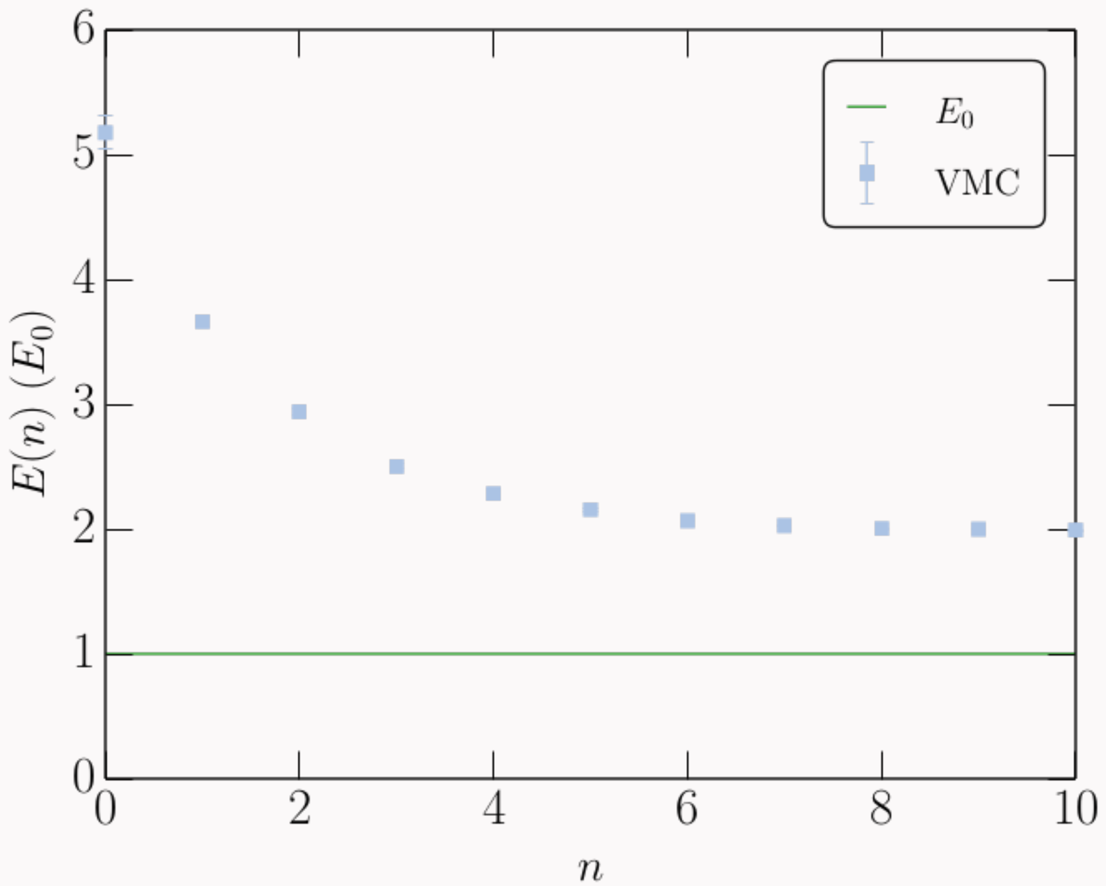


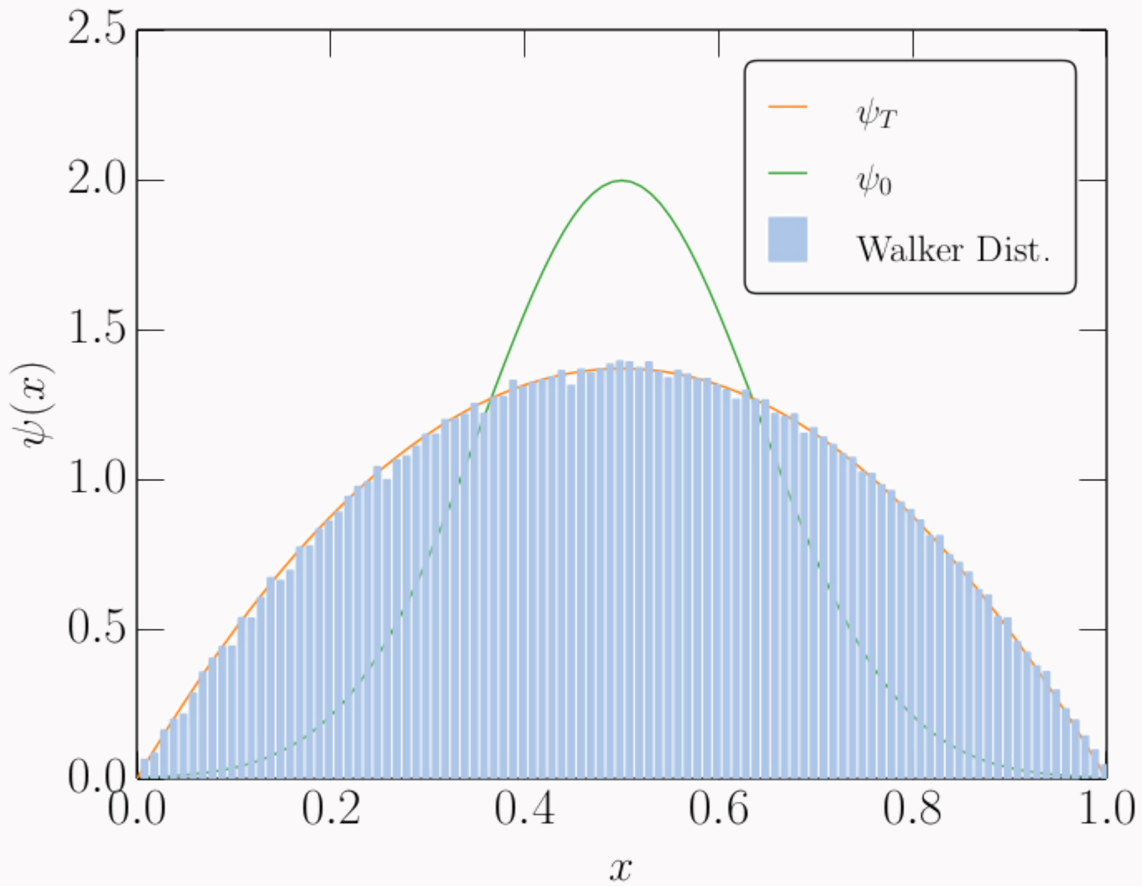
QMC Methods - An Example

First, VMC equilibration:

$$\frac{\langle \psi_T | H | \psi_T \rangle}{\langle \psi_T | \psi_T \rangle}$$

Metropolis step n =10





Chiral EFT

Local construction possible[1] up to N^2LO.

Definitions.

$$\mathbf{q} = \mathbf{p} - \mathbf{p}', \quad \mathbf{k} = \mathbf{p} + \mathbf{p}'$$

Regulator:

$$f(p, p') = e^{-(p/\Lambda)^n} e^{-(p'/\Lambda)^n}$$

Contacts:

$\propto$ $\mathbf{q}$ and $\mathbf{k}$

[1]A. Gezerlis et al, PRL **111** 032501 (2013); JEL et al, PRL **113** 192501 (2014); A. Gezerlis et al, PRC **90** 054323 (2014)

Chiral EFT

Local construction possible[1] up to N^{2}LO.

Definitions.

$$\mathbf{q} = \mathbf{p} - \mathbf{p}', \; \mathbf{k} = \mathbf{p} + \mathbf{p}'$$

Regulator:

~~$f(p, p') = e^{-(p/\Lambda)^n} e^{-(p'/\Lambda)^n}$~~

$$\rightarrow f_{\text{long}}(r) = 1 - e^{-(r/R_0)^4} \; : \; R_0 = 1.0, 1.1, 1.2 \text{ fm}.$$

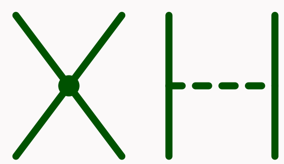
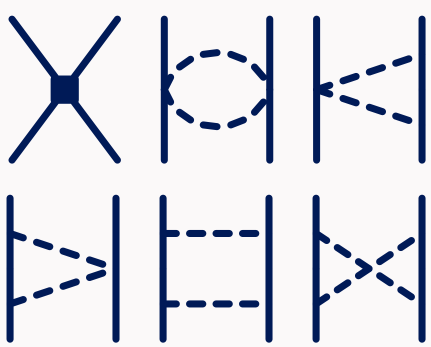
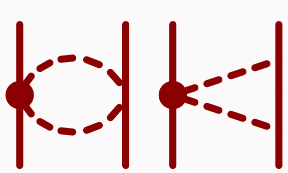
Contacts:

~~$\propto \mathbf{q}$ and $\mathbf{k}$~~

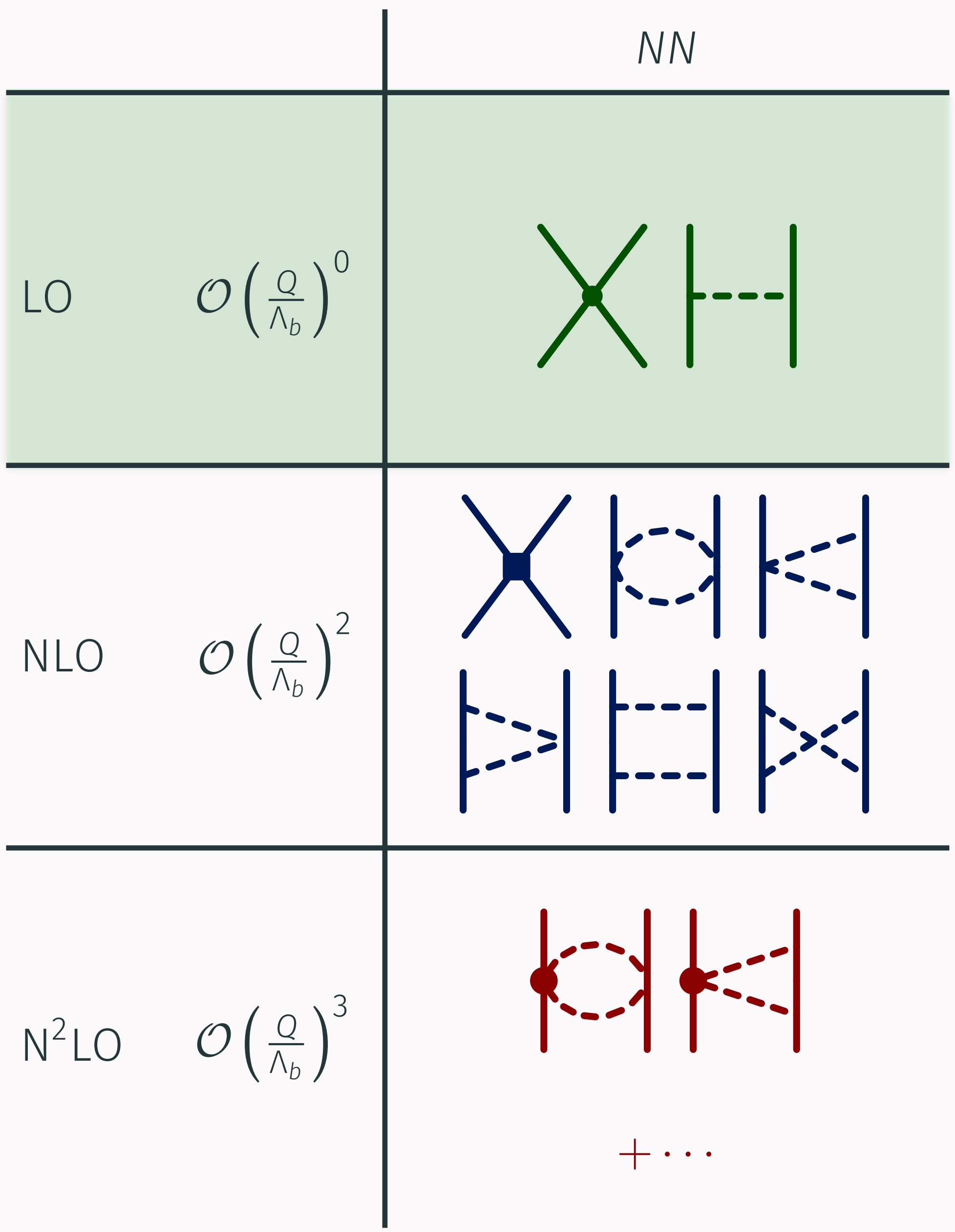
$\rightarrow$ Choose contacts $\propto \mathbf{q}$ (As much as possible!)

[1] A. Gezerlis et al, PRL **111** 032501 (2013); JEL et al, PRL **113** 192501 (2014); A. Gezerlis et al, PRC **90** 054323 (2014)

Chiral EFT

		NN
LO	$\mathcal{O}\left(\frac{Q}{\Lambda_b}\right)^0$	
NLO	$\mathcal{O}\left(\frac{Q}{\Lambda_b}\right)^2$	
N^{2}LO	$\mathcal{O}\left(\frac{Q}{\Lambda_b}\right)^3$	 $+\cdots$

Chiral EFT



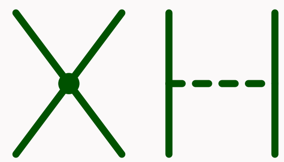
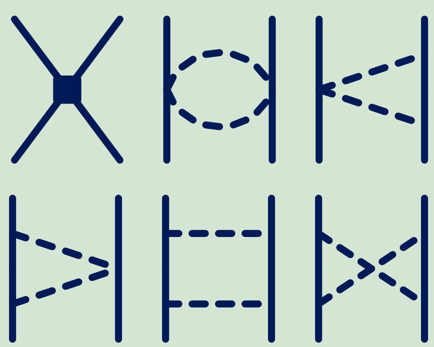
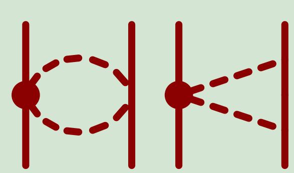
$$V^{(0)}_{\text{cont}} = \alpha_1 + \alpha_2(\sigma_1 \cdot \sigma_2) + \alpha_3(\tau_1 \cdot \tau_2) + \alpha_4(\sigma_1 \cdot \sigma_2)(\tau_1 \cdot \tau_2)$$

Pauli Exclusion Principle

$\rightarrow$ Only two independent contacts!

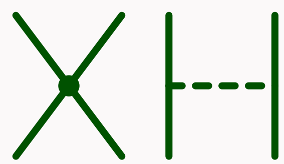
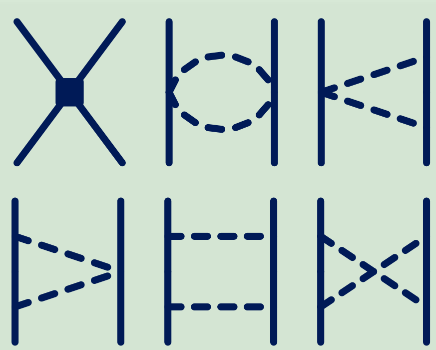
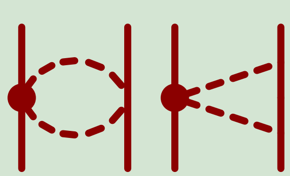
$$V^{(0)}_{\text{cont}} = C_S + C_T(\sigma_1 \cdot \sigma_2)$$

Chiral EFT

		NN
LO	$\mathcal{O}\left(\frac{Q}{\Lambda_b}\right)^0$	
NLO	$\mathcal{O}\left(\frac{Q}{\Lambda_b}\right)^2$	
N^{2}LO	$\mathcal{O}\left(\frac{Q}{\Lambda_b}\right)^3$	 $+\cdots$

$$
\begin{aligned}
V^{(2)}_{\text{cont}} &= \gamma_1 q^2 + \gamma_2 q^2(\sigma_1\cdot\sigma_2) \\
&+ \gamma_3 q^2(\tau_1\cdot\tau_2) + \gamma_4 q^2(\sigma_1\cdot\sigma_2)(\tau_1\cdot\tau_2) \\
&+ \gamma_5 k^2 + \gamma_6 k^2(\sigma_1\cdot\sigma_2) + \gamma_7 k^2(\tau_1\cdot\tau_2) \\
&+ \gamma_8 k^2(\sigma_1\cdot\sigma_2)(\tau_1\cdot\tau_2) \\
&+ (\sigma_1+\sigma_2)(\mathbf{q}\times\mathbf{k})(\gamma_9 + \gamma_{10}(\tau_1\cdot\tau_2)) \\
&+ (\sigma_1\cdot\mathbf{q})(\sigma_2\cdot\mathbf{q})(\gamma_{11} + \gamma_{12}(\tau_1\cdot\tau_2)) \\
&+ (\sigma_1\cdot\mathbf{k})(\sigma_2\cdot\mathbf{k})(\gamma_{13} + \gamma_{14}(\tau_1\cdot\tau_2))
\end{aligned}
$$

Chiral EFT

		NN
LO	$\mathcal{O}\left(\frac{Q}{\Lambda_b}\right)^0$	
NLO	$\mathcal{O}\left(\frac{Q}{\Lambda_b}\right)^2$	
N^{2}LO	$\mathcal{O}\left(\frac{Q}{\Lambda_b}\right)^3$	 $+\cdots$

$$
\begin{aligned}
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&+ \gamma_5 k^2 + \gamma_6 k^2(\sigma_1\cdot\sigma_2) + \gamma_7 k^2(\tau_1\cdot\tau_2) \\
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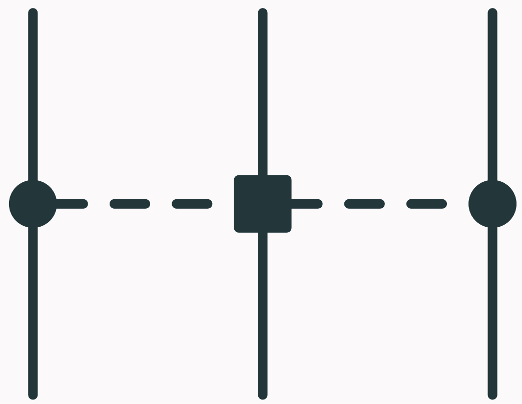
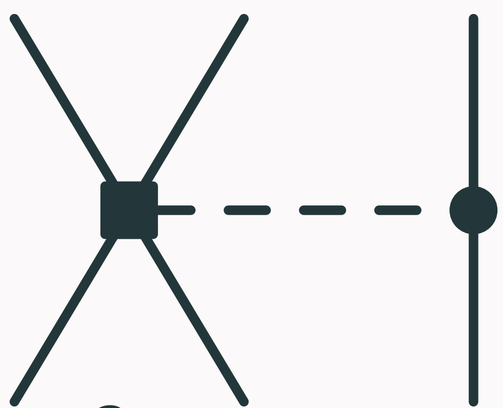
&+ (\sigma_1+\sigma_2)(\mathbf{q}\times\mathbf{k})(\gamma_9 + \gamma_{10}(\tau_1\cdot\tau_2)) \\
&+ (\sigma_1\cdot\mathbf{q})(\sigma_2\cdot\mathbf{q})(\gamma_{11} + \gamma_{12}(\tau_1\cdot\tau_2)) \\
&+ (\sigma_1\cdot\mathbf{k})(\sigma_2\cdot\mathbf{k})(\gamma_{13} + \gamma_{14}(\tau_1\cdot\tau_2))
\end{aligned}
$$

Three-Nucleon Interactions

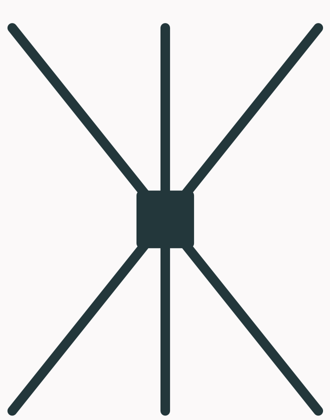
Three-Nucleon Interaction



$c_1,\ c_3,\ c_4$

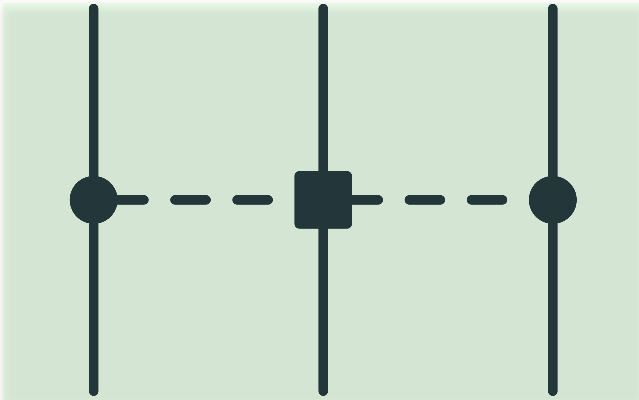


c_D

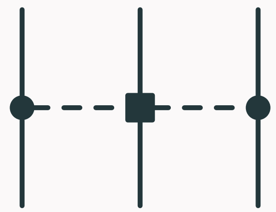


c_E

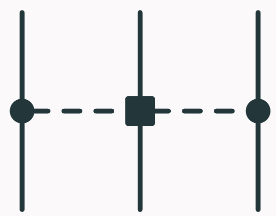
Three-Nucleon Interaction



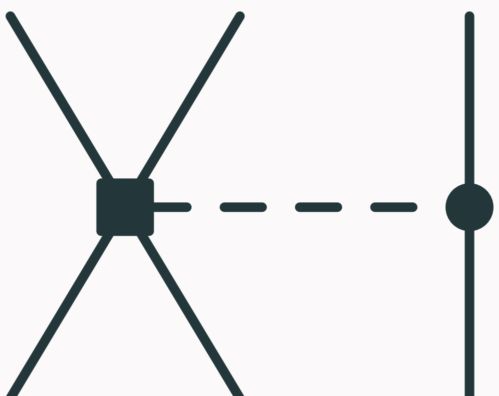
$c_1,\ c_3,\ c_4$

$\mathcal{F}\Big\{$  $\Big\}$ $\rightarrow\sim$ Tucson-Melbourne a' Term

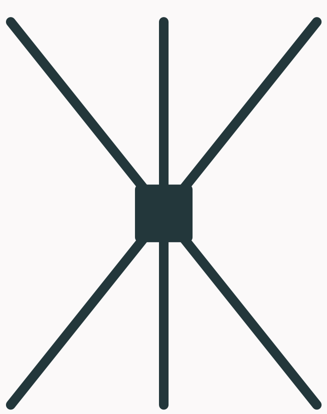
c_1

$\mathcal{F}\Big\{$  $\Big\}$ $\rightarrow\sim$ Fujita-Miyazawa

$c_3,\ c_4$

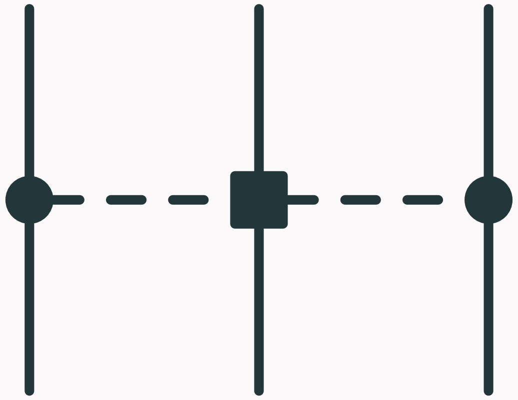


c_D

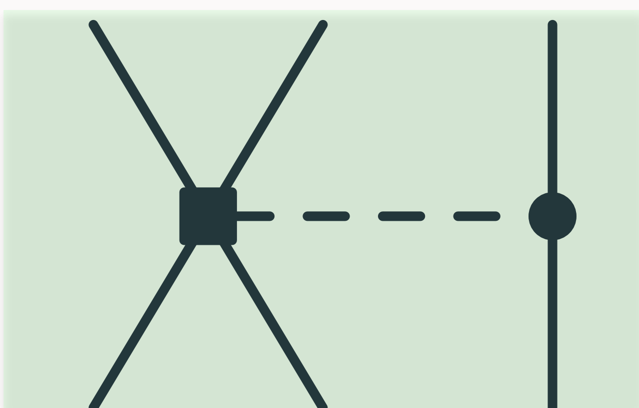


c_E

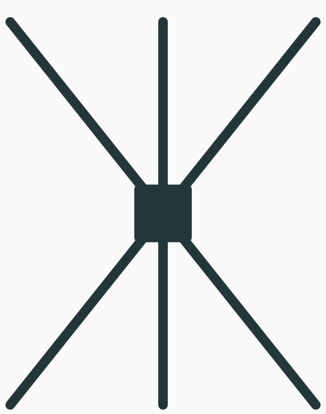
Three-Nucleon Interaction



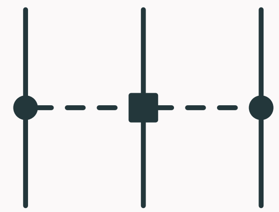
c_1, c_3, c_4



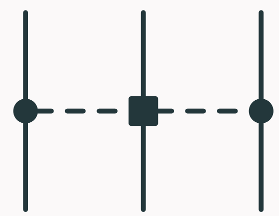
c_D



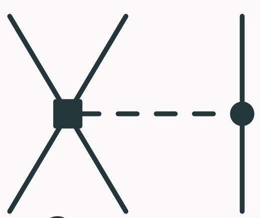
c_E

$\mathcal{F}\Big\{$  $\Big\}$ $\rightarrow\sim$ Tucson-Melbourne a' Term

c_1

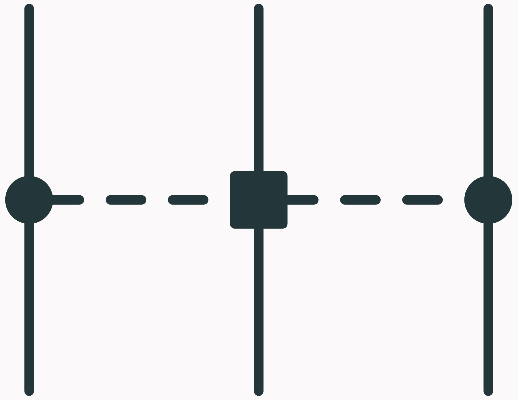
$\mathcal{F}\Big\{$  $\Big\}$ $\rightarrow\sim$ Fujita-Miyazawa

c_3, c_4

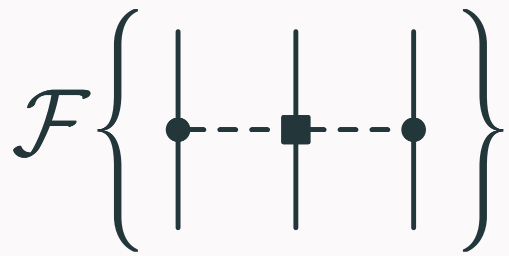
$\mathcal{F}\Big\{$  $\Big\}$ $\rightarrow$ 1π-Exchange + Contact

c_D

Three-Nucleon Interaction

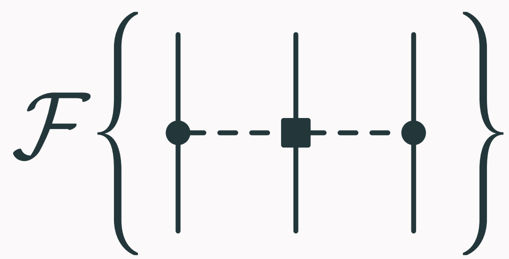


$c_1,\ c_3,\ c_4$



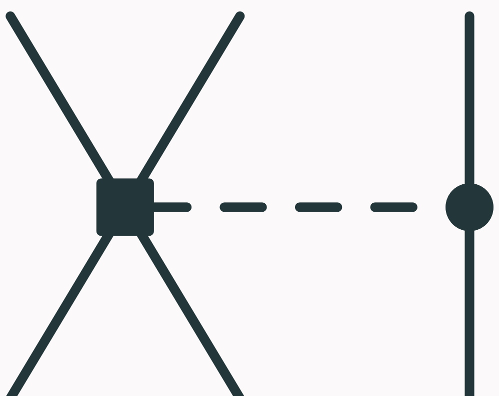
c_1

$\rightarrow\sim$ Tucson-Melbourne a' Term

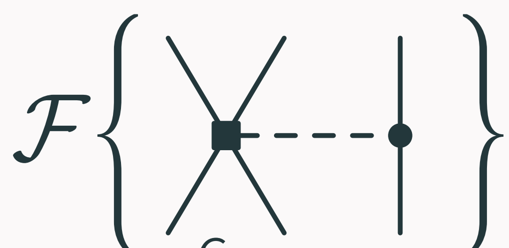


$c_3,\ c_4$

$\rightarrow\sim$ Fujita-Miyazawa

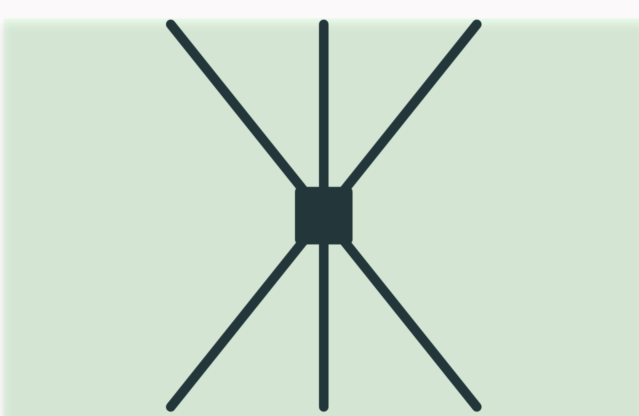


c_D

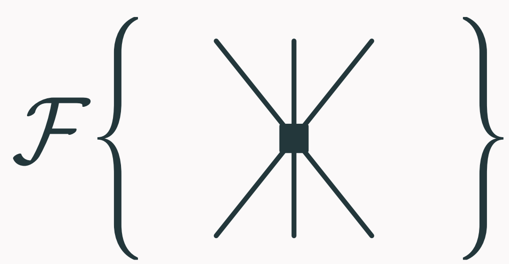


c_D

$\rightarrow$ 1π-Exchange + Contact



c_E



c_E

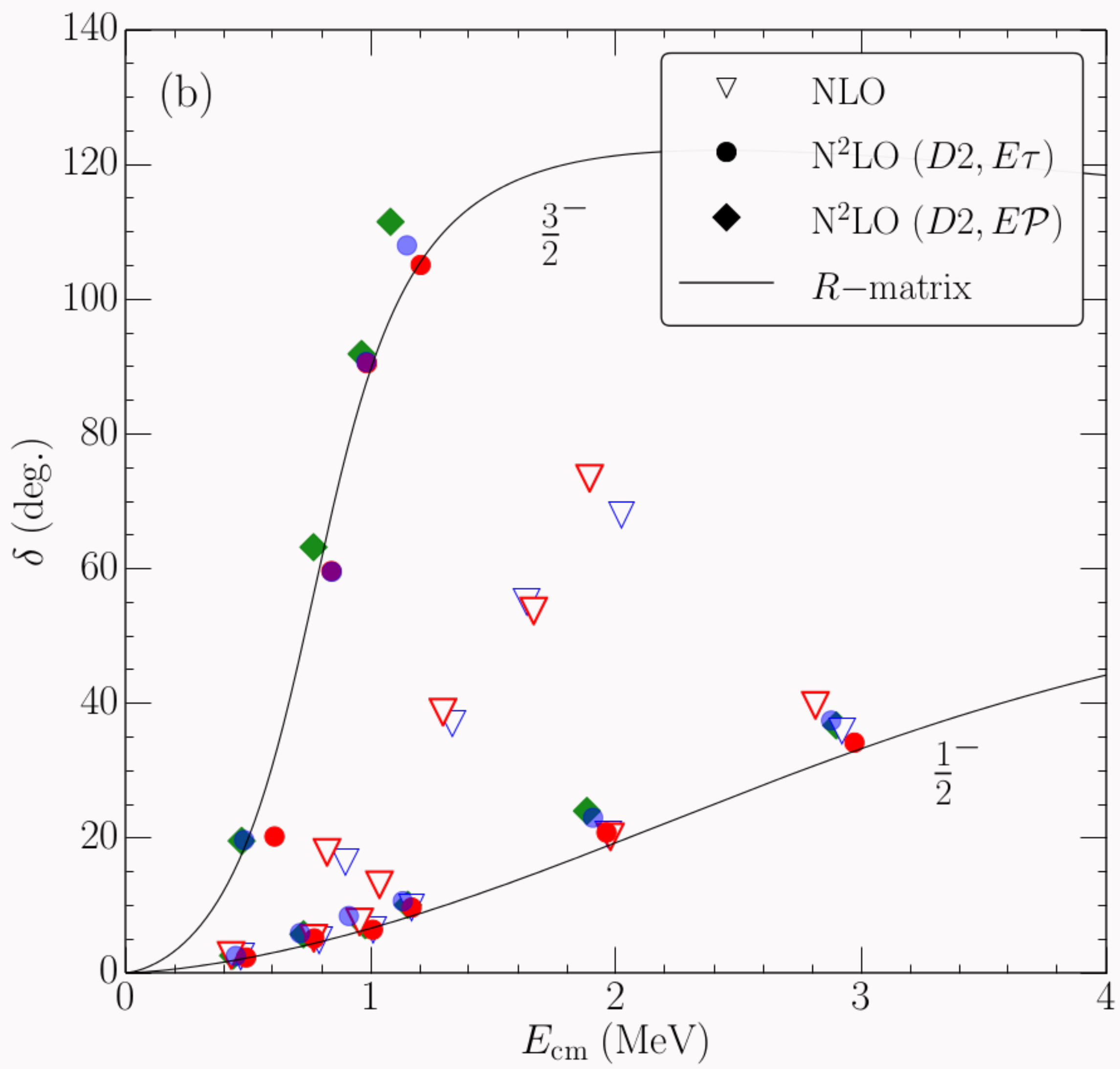
$\rightarrow$ Contact

Fitting c_D And c_E

Choosing Observables

What to fit c_D and c_E to?

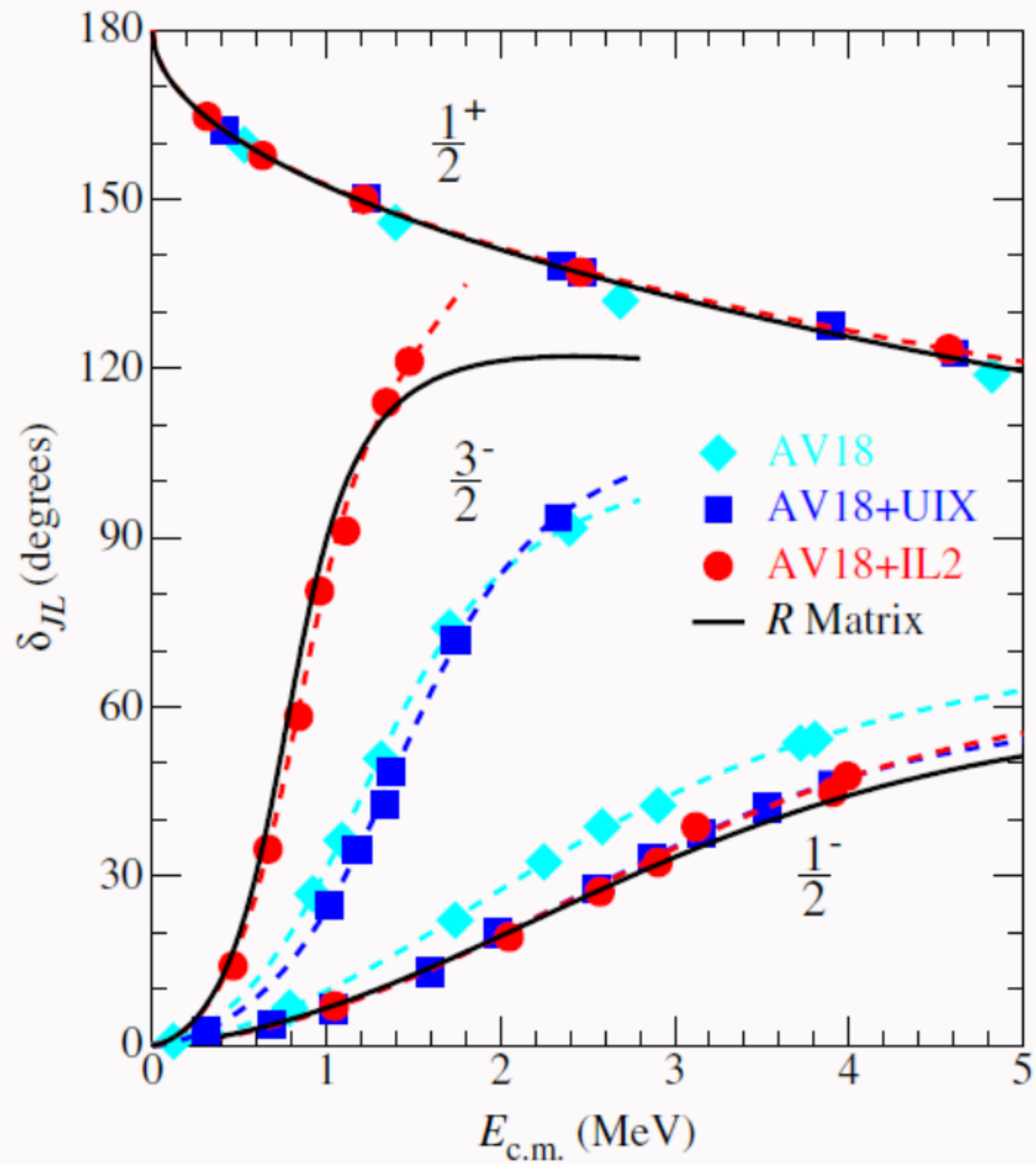
- Uncorrelated observables.
- Probe properties of light nuclei: ^{4}He E_B.
- Probe $T = 3/2$ physics: n-α scattering phase shifts.



JEL et al, PRL **116**, 062501 (2016)

n-α Scattering - Details

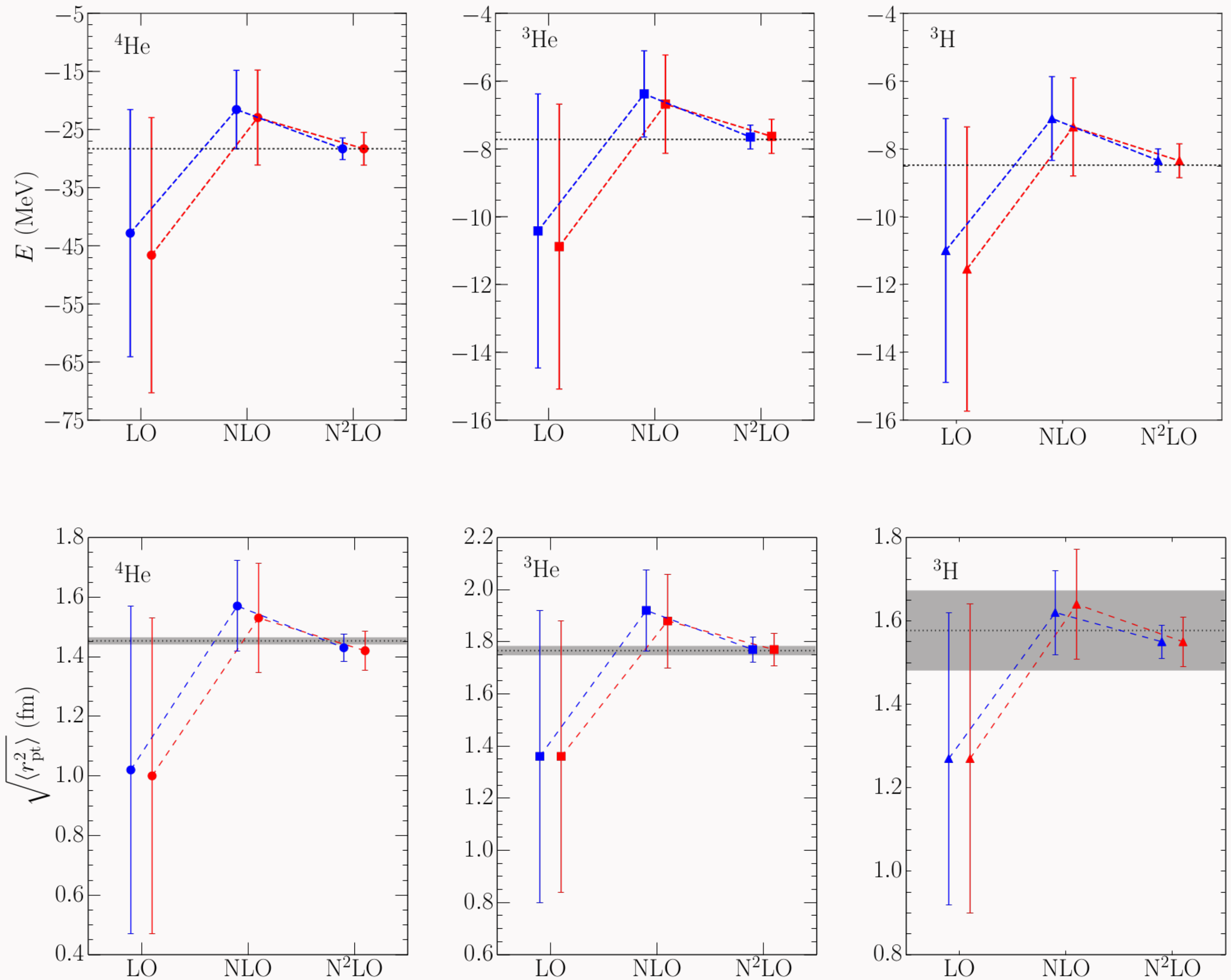
- Results[2] showed need for greater spin-orbit splitting than was provided for by the Urbana IX (UIX) 3*N* interaction.
- Interpretation was *T*=3/2 component in Illinois 3*N* interaction was necessary. (?)

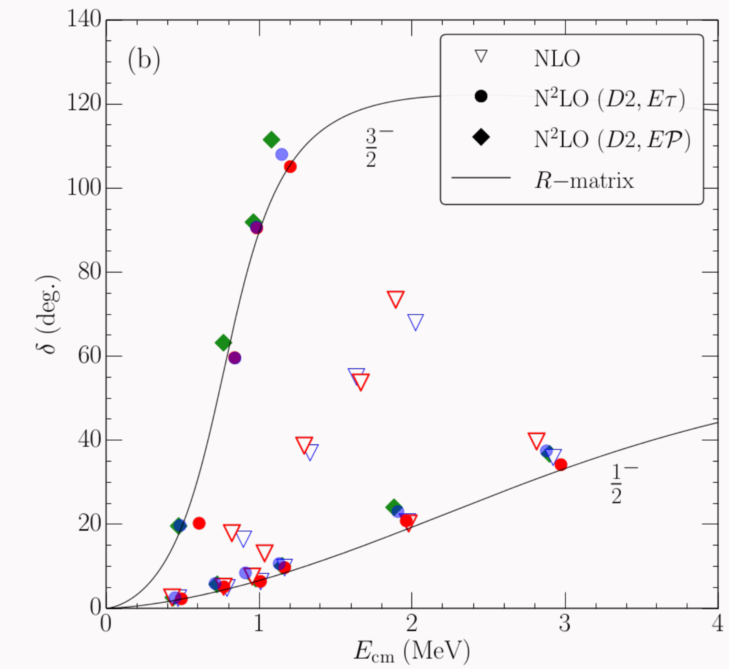


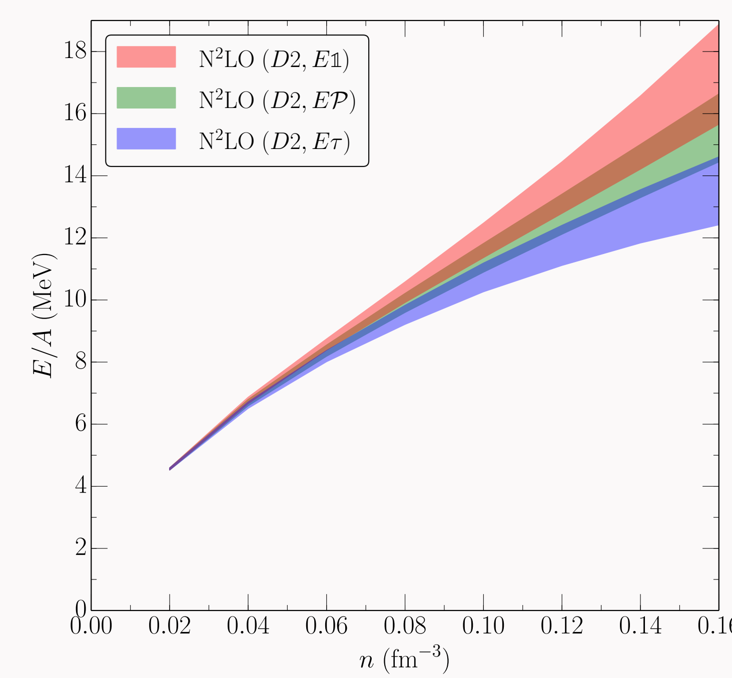
[2] K. M. Nollet et al, PRL **99** 022502 (2007)

Results

A simultaneous description of properties of light nuclei, n-α scattering and neutron matter is possible.







JEL et al, PRL **116**, 062501 (2016)

Uncertainty Analysis

Sources of uncertainty include

- Systematic uncertainty due to truncation of the chiral expansion
- Uncertainty in knowledge of πN LECs (long range)
- Uncertainty in knowledge of LECs for contacts (short range)
- Uncertainties in experimental data or partial-wave analysis.

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- Uncertainty in knowledge of πN LECs (long range)
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Uncertainty Analysis

Define

$$X^{(i)} = X^{(0)} + \Delta X^{(2)} + \cdots + \Delta X^{(i)},$$

$$\Delta X^{(2)} = X^{(2)} - X^{(0)}, \ \Delta X^{(i)} - X^{(i-1)}, \ i > 2.$$

Expected size

$$\Delta X^{(i)} = \mathcal{O}(Q^i X^{(0)}).$$

Then,

$$\delta X^{(0)} = Q^2 |X^{(0)}|, \ \delta X^{(i)} = \max(Q^{i+1}|X^{(0)}|, Q^{i+1-j}|\Delta X^{(j)}|), \ 2 \leq j \leq i.$$

$$Q = \max(p/\Lambda_b, m_\pi/\Lambda_b).$$

Four Neutrons: A Recent History


2003
2005
Experiment
Theory
2002

F. M. Marqués et al. Phys. Rev. C **65**, 052501.

Experimental claim of a bound tetraneutron from detection of neutron clusters from ^{14}Be fragmentation.

~6 events!

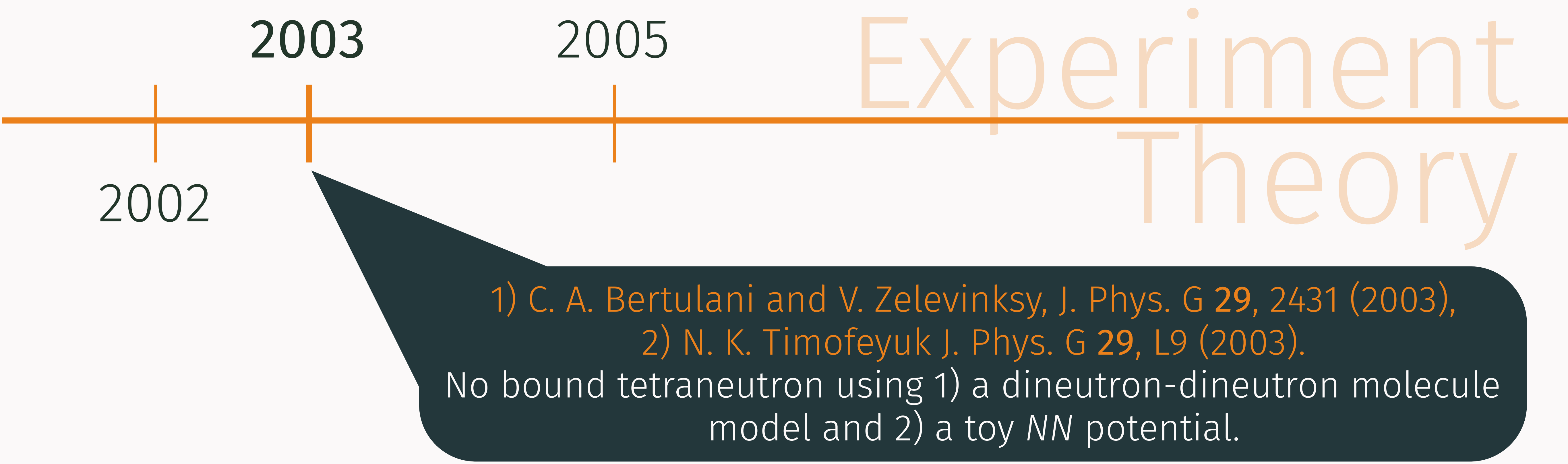
2003

2005

Experiment

Theory

2002


2002
2003
2005
Experiment
Theory
1) C. A. Bertulani and V. Zelevinksy, J. Phys. G **29**, 2431 (2003),
2) N. K. Timofeyuk J. Phys. G **29**, L9 (2003).
No bound tetraneutron using 1) a dineutron-dineutron molecule model and 2) a toy *NN* potential.

2002

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Experiment

Theory

1) C. A. Bertulani and V. Zelevinksy, J. Phys. G **29**, 2431 (2003),
2) N. K. Timofeyuk J. Phys. G **29**, L9 (2003).
No bound tetraneutron using 1) a dineutron-dineutron molecule model and 2) a toy *NN* potential.

S. C. Pieper Phys. Rev. Lett. **90**, 252501.
Modern nuclear Hamiltonians cannot tolerate a bound tetraneutron.
But...
“This suggests that there might be a ^4n resonance near 2 MeV"

2003

2005

Experiment

Theory

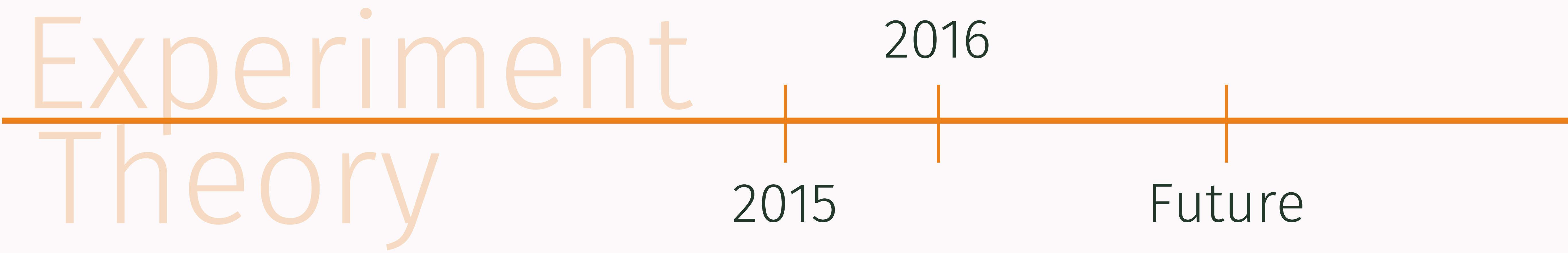
2002

R. Lazauskas and J. Carbonell, Phys. Rev. C **72**, 034003.

Complex scaling w/ Reid 93 potential (*NN* only!)

Low-lying ^4n resonance not seen.


2003
2005
Experiment
Theory
2002


Experiment
Theory
2016
2015
Future

K. Kisamori et al., Phys. Rev. Lett. **116**, 044006.

A recent double-charge-exchange reaction $^{8}_{2}\text{He}+^{4}_{2}\text{He} \rightarrow ^{8}_{4}\text{Be} + ^{4}n$ measurement at the RIKEN radioactive ion beam factory (RIBF) suggests a tetraneutron resonance at **0.83±0.65(stat)±1.25(syst) MeV.**

Experiment

Theory

2016

2015

Future

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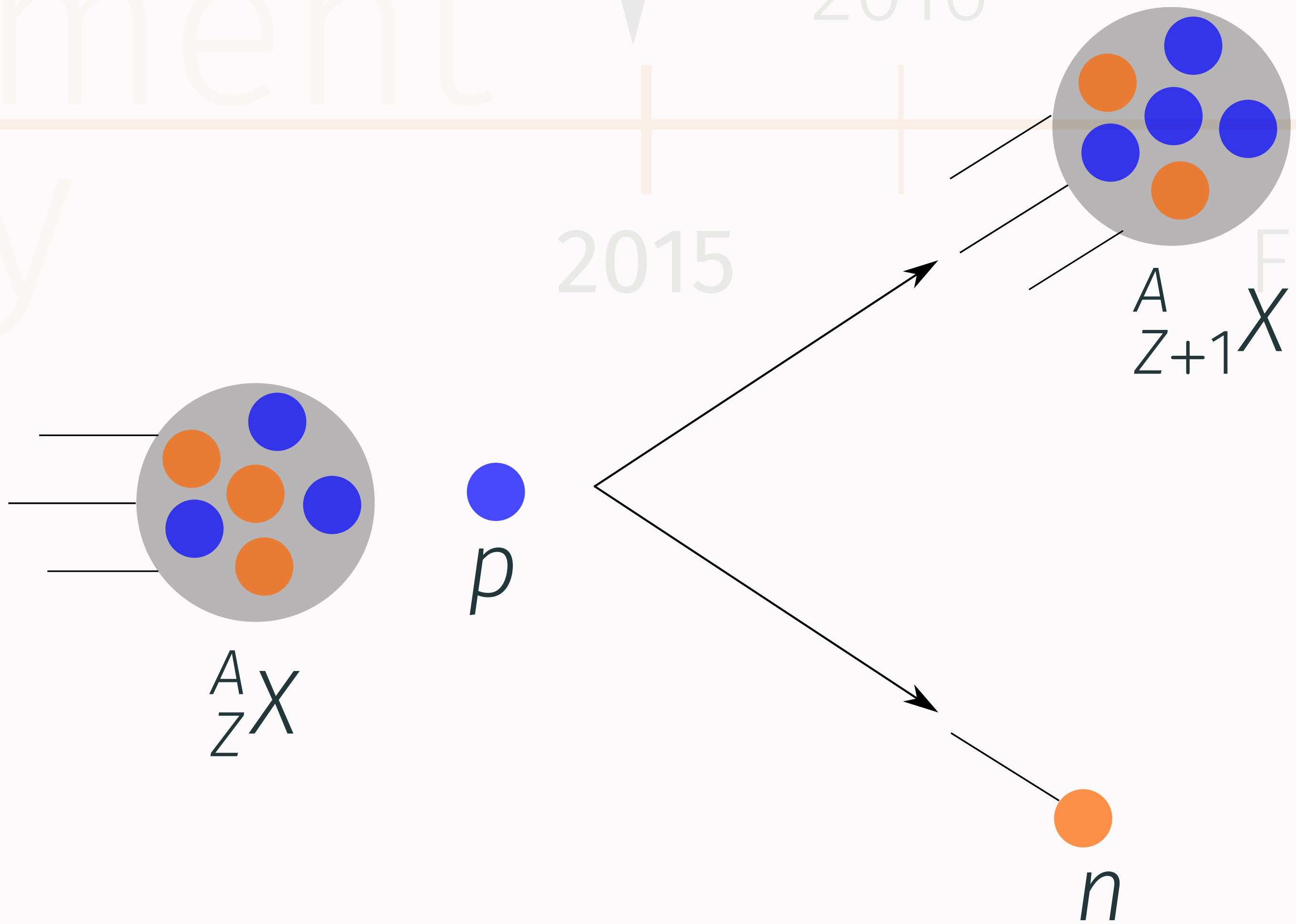
Single-charge-exchange reaction

$$^A_ZX(p,n)^A_{Z+1}X$$



K. Kisamori et al., Phys. Rev. Lett. **116**, 044006.
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Double-charge-exchange reaction

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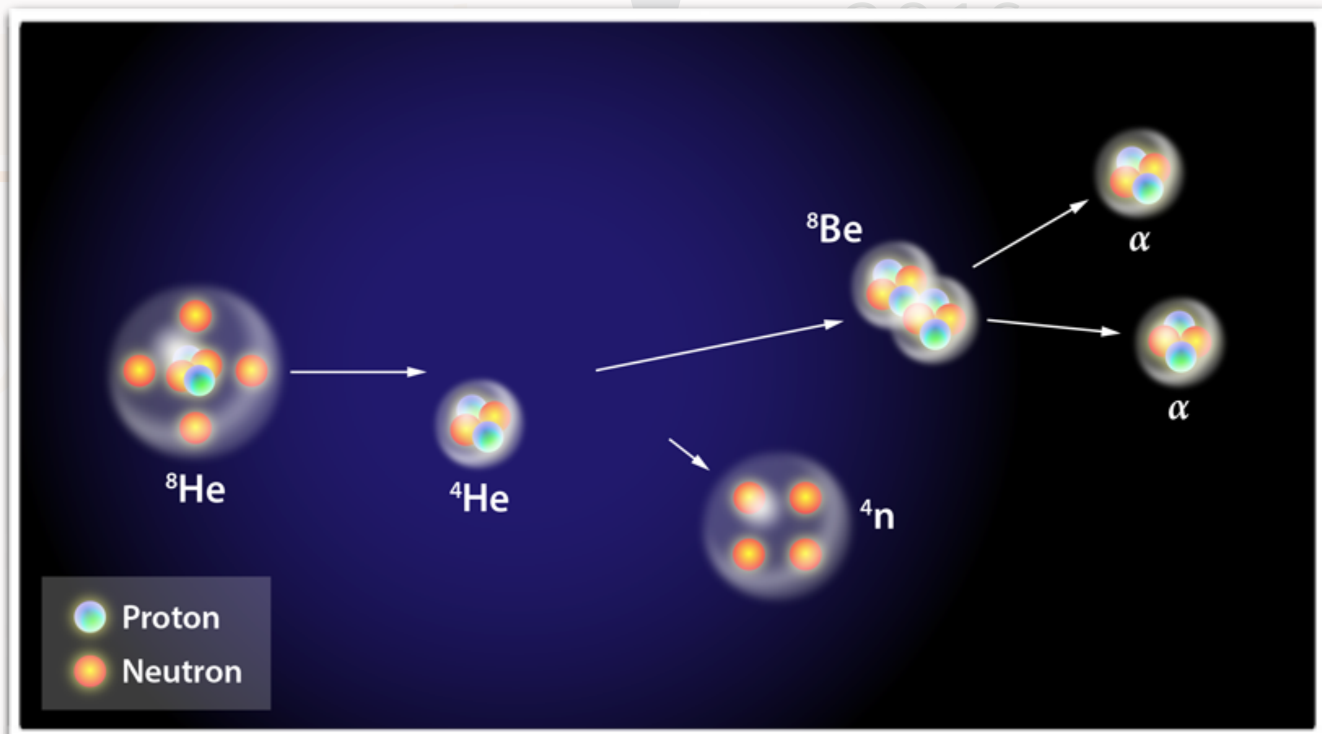

APS/Alan Stonebraker

Experiment
Theory
Future

K. Kisamori et al., Phys. Rev. Lett. **116**, 044006.

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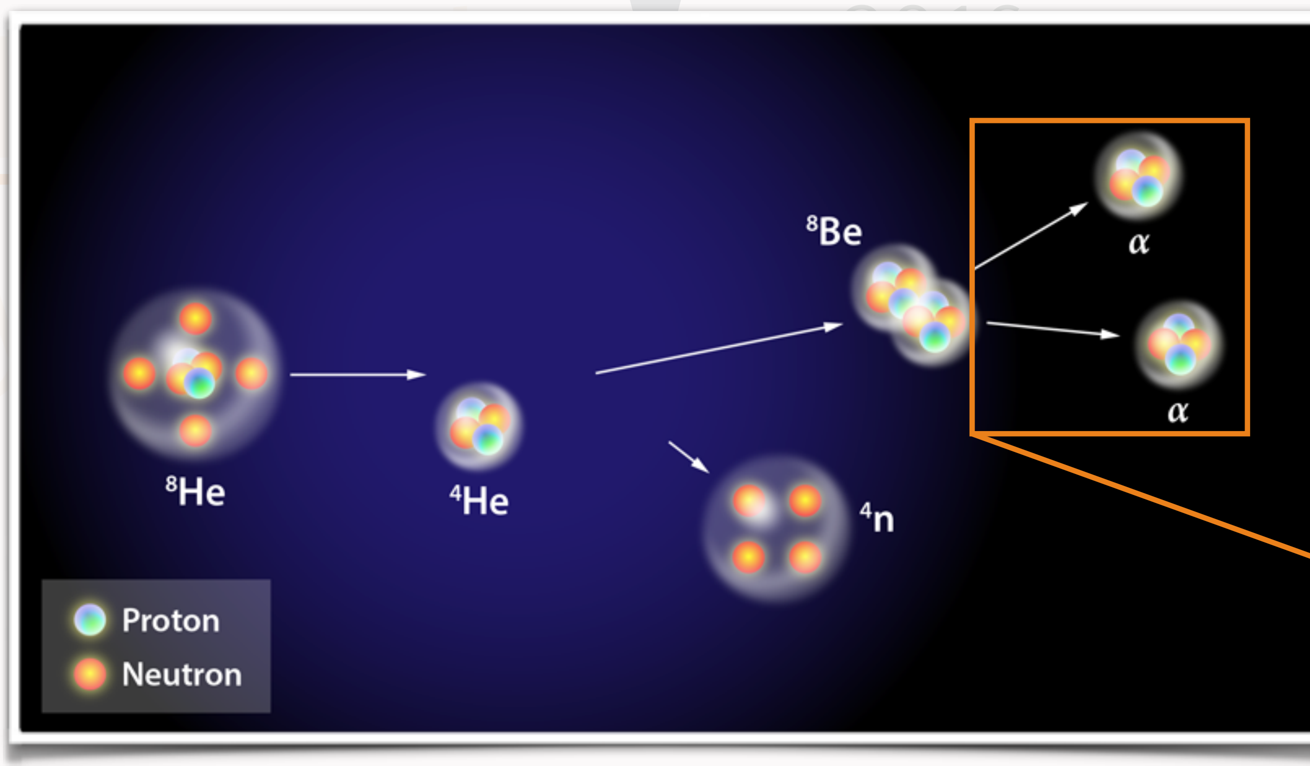
Double-charge-exchange reaction

$${}^{8}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{8}_{4}\mathrm{Be} + {}^{4}n$$



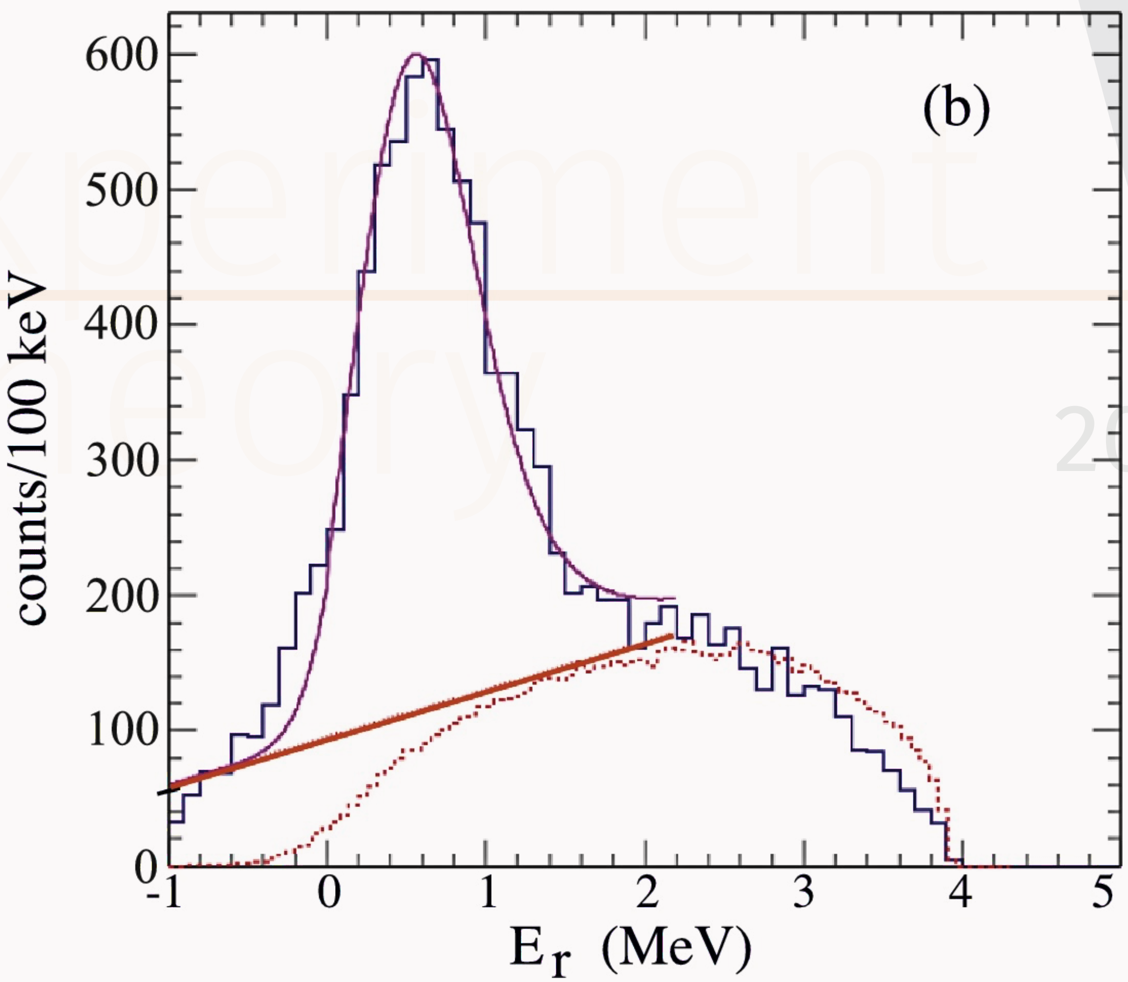
Measured

APS/Alan Stonebraker

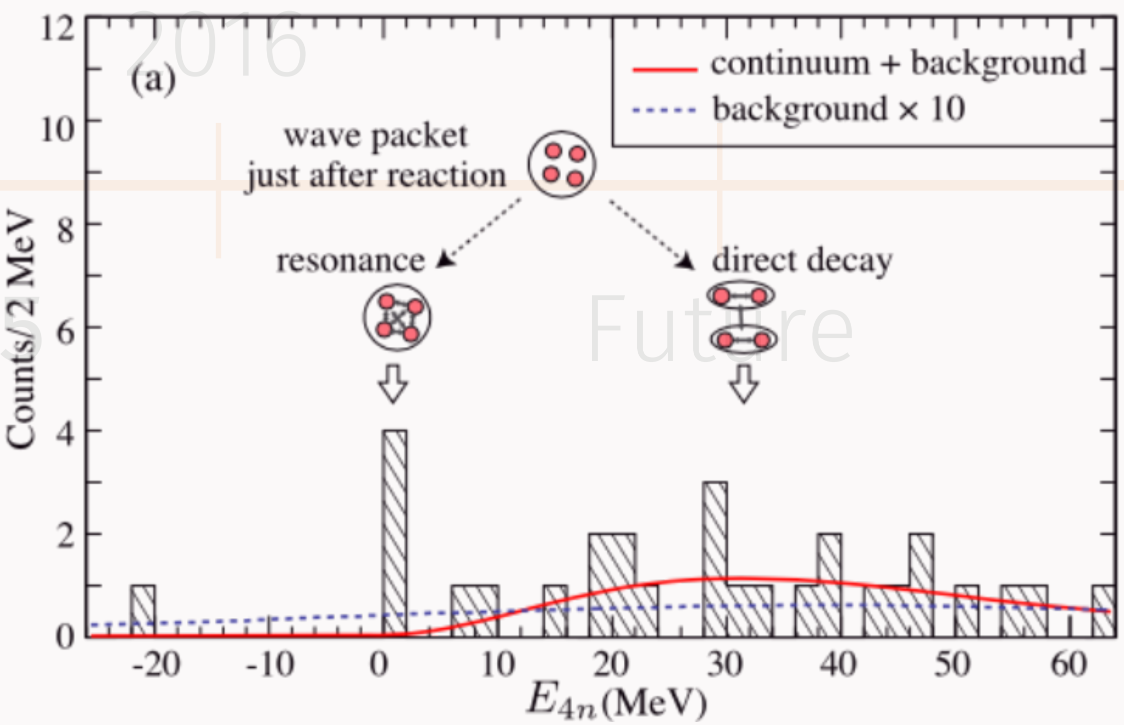
Know $P_{^8\mathrm{He}}$, P_α, $P_{\alpha'}$, and $P_\alpha \cdot P_{\alpha'}$:
Calculate “missing mass” spectrum of ${}^{4}n$.

K. Kisamori et al., Phys. Rev. Lett. **116**, 044006.

A recent double-charge-exchange reaction $^{8}_{2}\text{He}+^{4}_{2}\text{He} \rightarrow ^{8}_{4}\text{Be} + ^{4}n$ measurement at the RIKEN radioactive ion beam factory (RIBF) suggests a tetraneutron resonance at **0.83±0.65(stat)±1.25(syst) MeV.**



from A. Sanetullaev et al., Phys. Lett. B **755**, 481 (2016)



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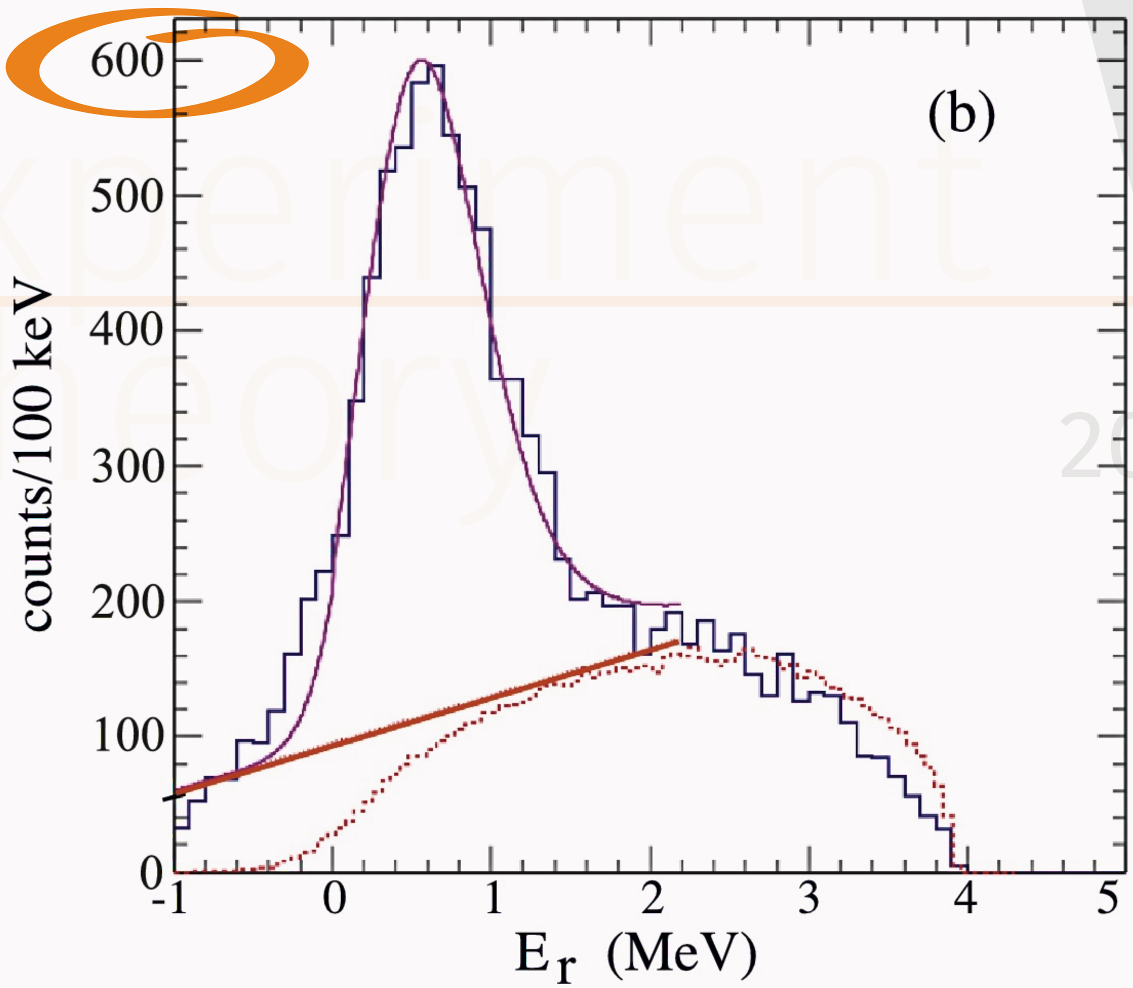
Relatively low statistics: More data needed!



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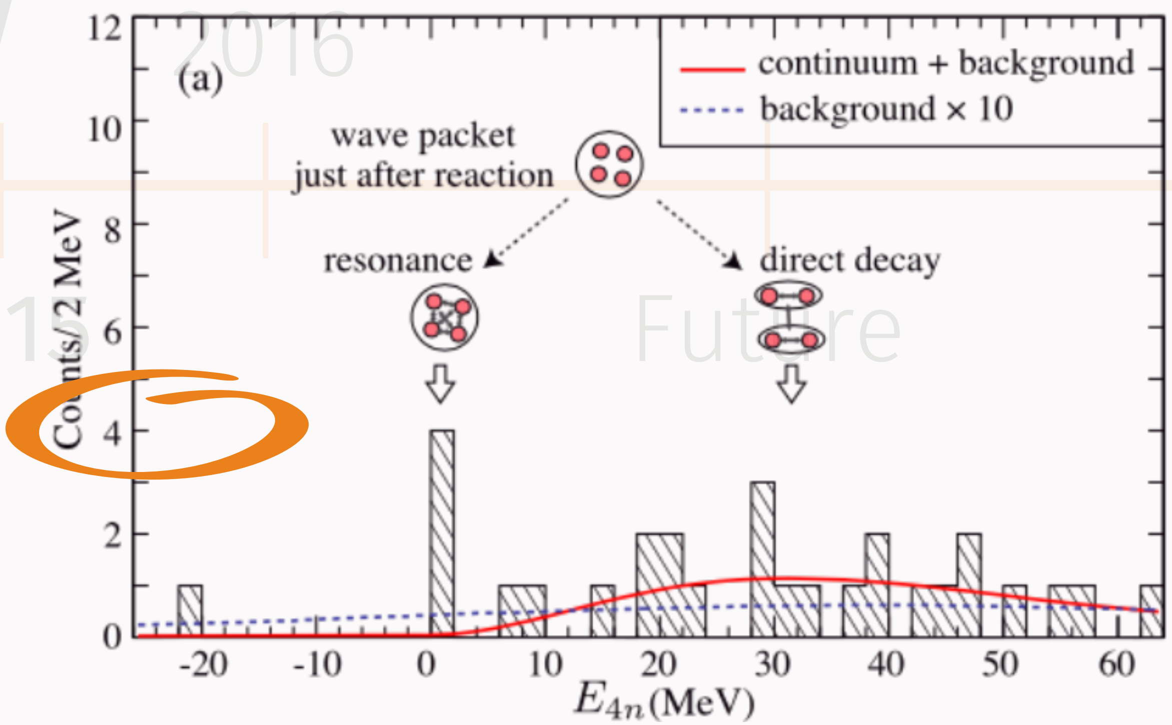

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Experiment

Theory

2016

2015

Future

Experiment

Theory

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E. Hiyama, R. Lazauskas, J. Carbonell, and M. Kamimura, Phys. Rev. C **93**, 044004.

Complex scaling w/AV8’ potential + toy $T = 3/2$ $3N$ interaction. Low-lying ^4n resonance only possible if other well-known resonance structures in light nuclei are strongly perturbed.

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A. M. Shirokov, G. Papadimitriou, A. I. Mazur, R. Roth, J. P. Vary, Phys. Rev. Lett. **117**, 1825022.
No-Core Shell Model + Single-State Harmonic Oscillator Representation of Scattering equations. Compelling confirmation of a ^4n resonance at 0.8 MeV with **JISP** NN interaction.

T. Aumann, D. Rossi, S. Shimoura, S. Paschalis et al., RIBF Experimental Proposal NP1406-SAMURAI19. ${}^{8}_{2}\mathrm{He}(p, p\alpha)^{4}n$

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T. Aumann, D. Rossi, S. Shimoura, S. Paschalis et al., RIBF Experimental Proposal
NP1406-SAMURAI19. ${}^{8}_{2}\mathrm{He}(p, p\alpha)^{4}n$

F. M. Marqués et al., RIKEN-RIBF proposal
“Many-neutron systems: search for superheavy ^{7}H and its tetraneutron decay,” NP-1512-SAMURAI34.

Experiment

Theory

2015 | 2016 | Future

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F. M. Marqués et al., RIKEN-RIBF proposal "Many-neutron systems: search for superheavy ^{7}H and its tetraneutron decay," NP-1512-SAMURAI34.

S. Shimoura et al., RIKEN-RIBF proposal "Tetraneutron resonance produced by exothermic double-charge exchange reaction," NP1512-SHARAQ10.

Experiment

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Experiment

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What's still missing?

An *ab initio* calculation with chiral *NN* and 3*N* interactions.

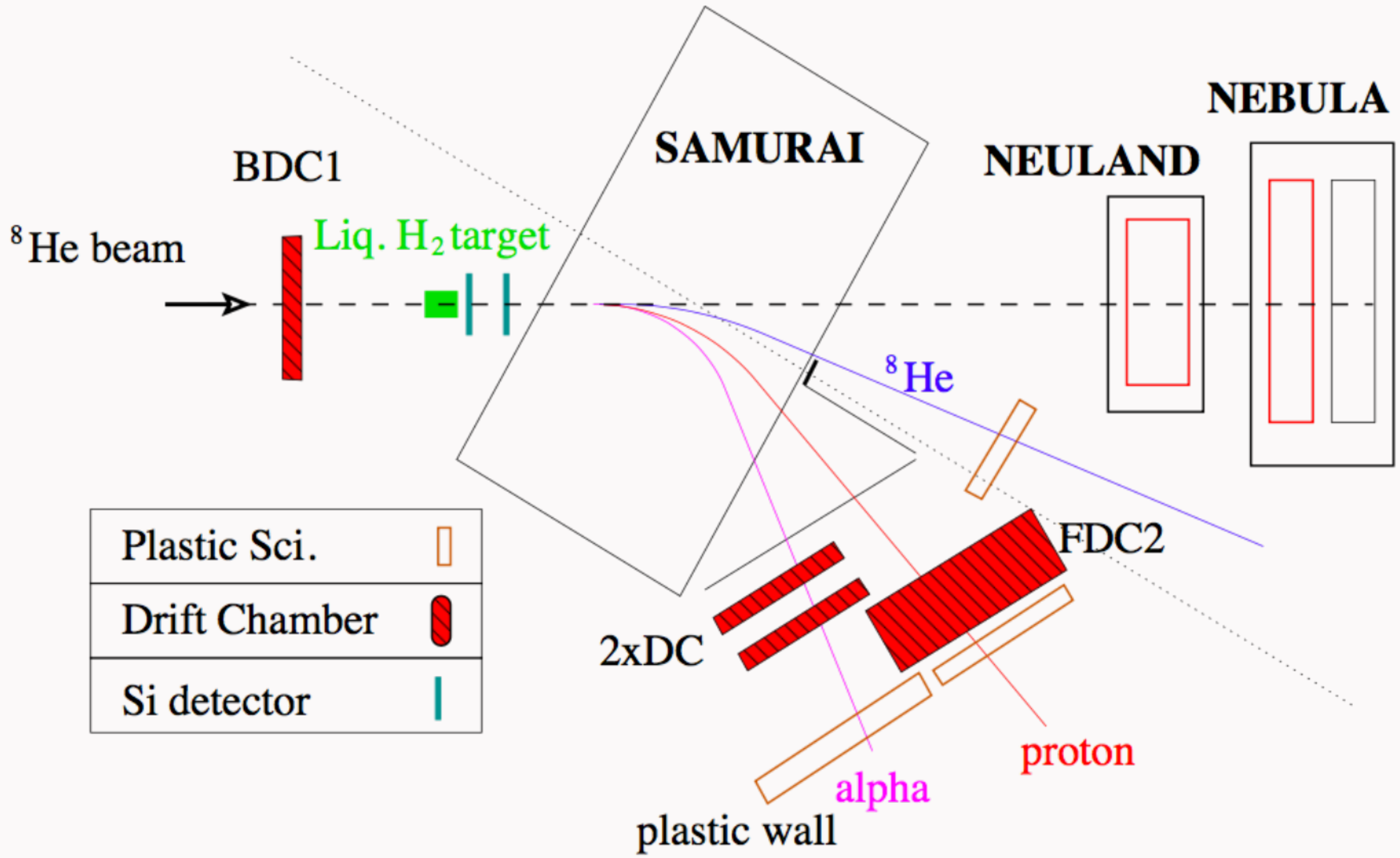
Initial efforts using Quantum Monte Carlo calculations with chiral interactions.

(This talk!)

Motivation - Exp. Proposal Of SFB 1245 A06.4

Quasi-free alpha knockout reaction RIBF at RIKEN utilizing the so-called SAMURAI configuration

$$^{8}_{2}\mathrm{He}(p, p\alpha)^{4}n$$

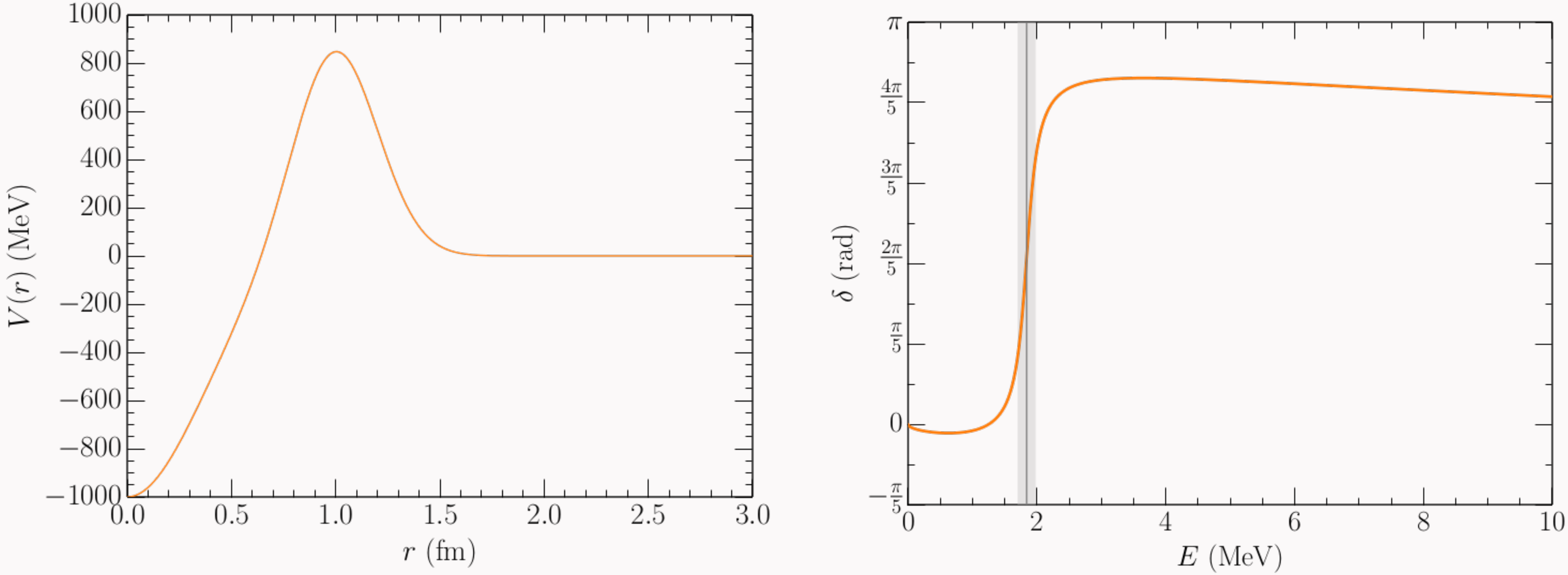


A Two-Body Test

A simple S-wave potential:

$$V(r) = V_1 e^{-\left(\frac{r}{R_1}\right)^2} + V_2 e^{-\left(\frac{r-r_2}{R_2}\right)^2}$$

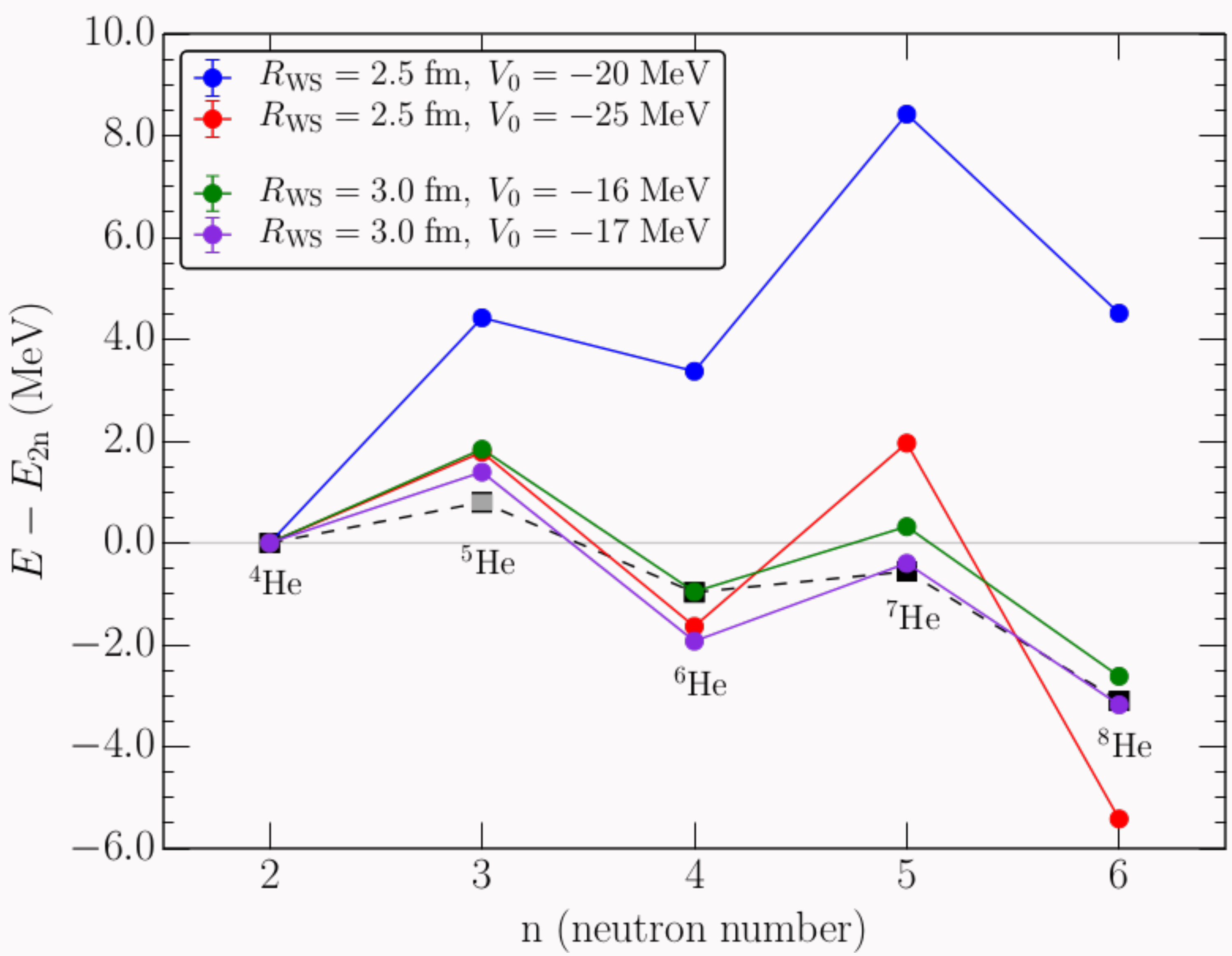
$$E_R = 1.84 \text{ MeV}, \;\; \Gamma = 0.282 \text{ MeV}$$



D. Lonardoni, J. Carlson, S. Gandolfi, JEL, K. E. Schmidt, A. Schwenk, X. Wang, arXiv:1709.09143 [nucl-th] (2017)

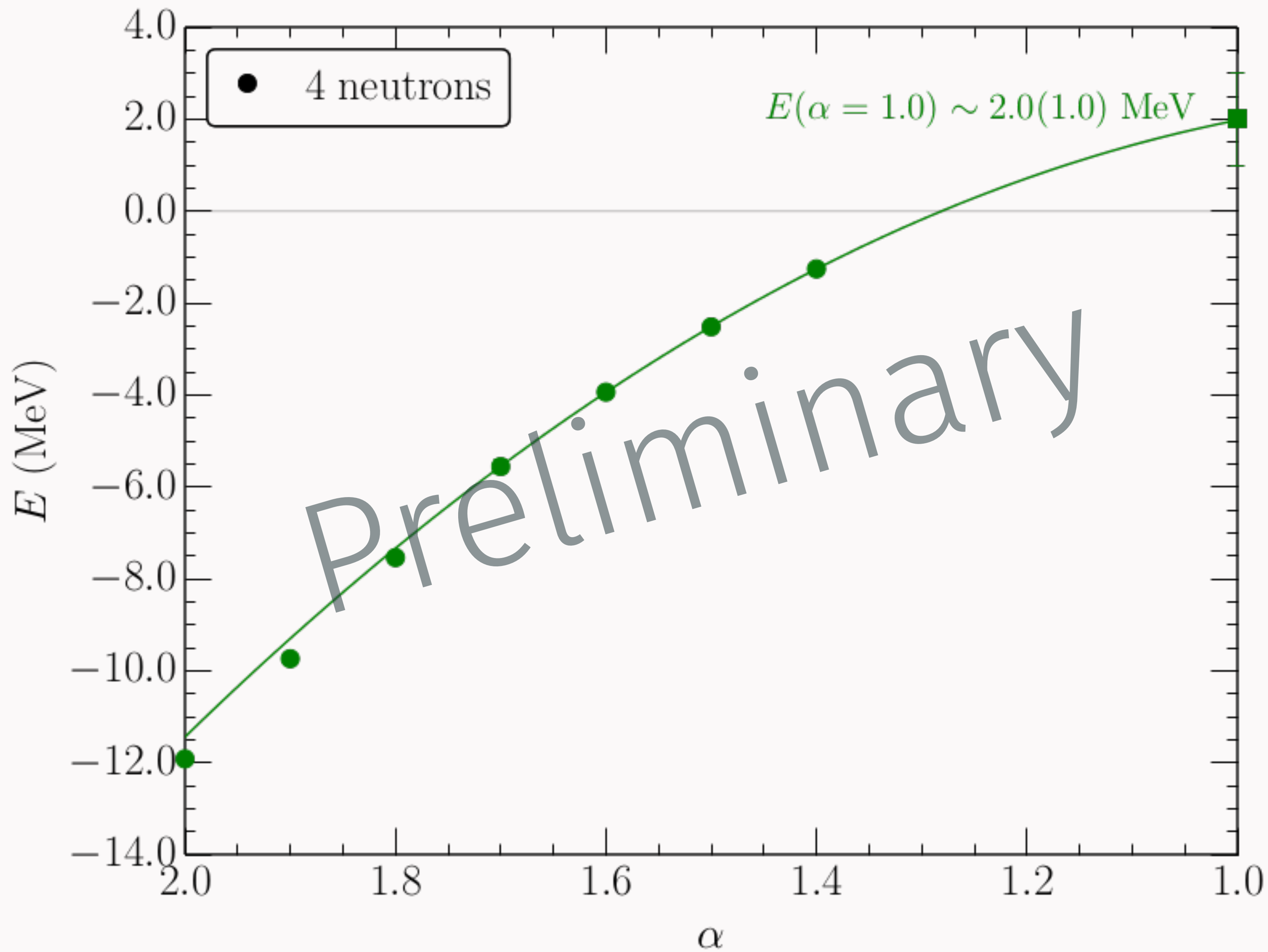
Helium Chain

- That ^3n is lower than ^4n is not an artifact of the Woods-Saxon potential.
- In helium chain, ^3n is always higher than ^4n.



Another Extrapolation*

$$V \to \alpha V, \;\; E_R = \lim_{\alpha \to 1} E(\alpha)$$



* à la K. Fossez, J. Rotureau, N. Michel, and M. Płoszajczak arXiv:1612.01483

Cold Atoms Connections

- Extrapolated energies for ${}^3n$ and ${}^4n$ are consistent with scaling like the number of pairs. $E_{A_n} \sim \frac{A(A-1)}{2}$
- Mean-field interaction of dilute gas of spin-1/2 fermions: $E_{\mathrm{MF}}/A = \frac{k_F^2}{2m}\frac{2}{3\pi}(k_F a) \sim A \Rightarrow E_{\mathrm{MF}} \sim A^2$
- Cold atomic gas experiments could determine if one-body density behavior is governed by large-scattering-length physics or details of nuclear interactions.

Some History And Definitions

Deep inelastic scattering (DIS) cross section for EM interactions of charged leptons with nuclear targets:

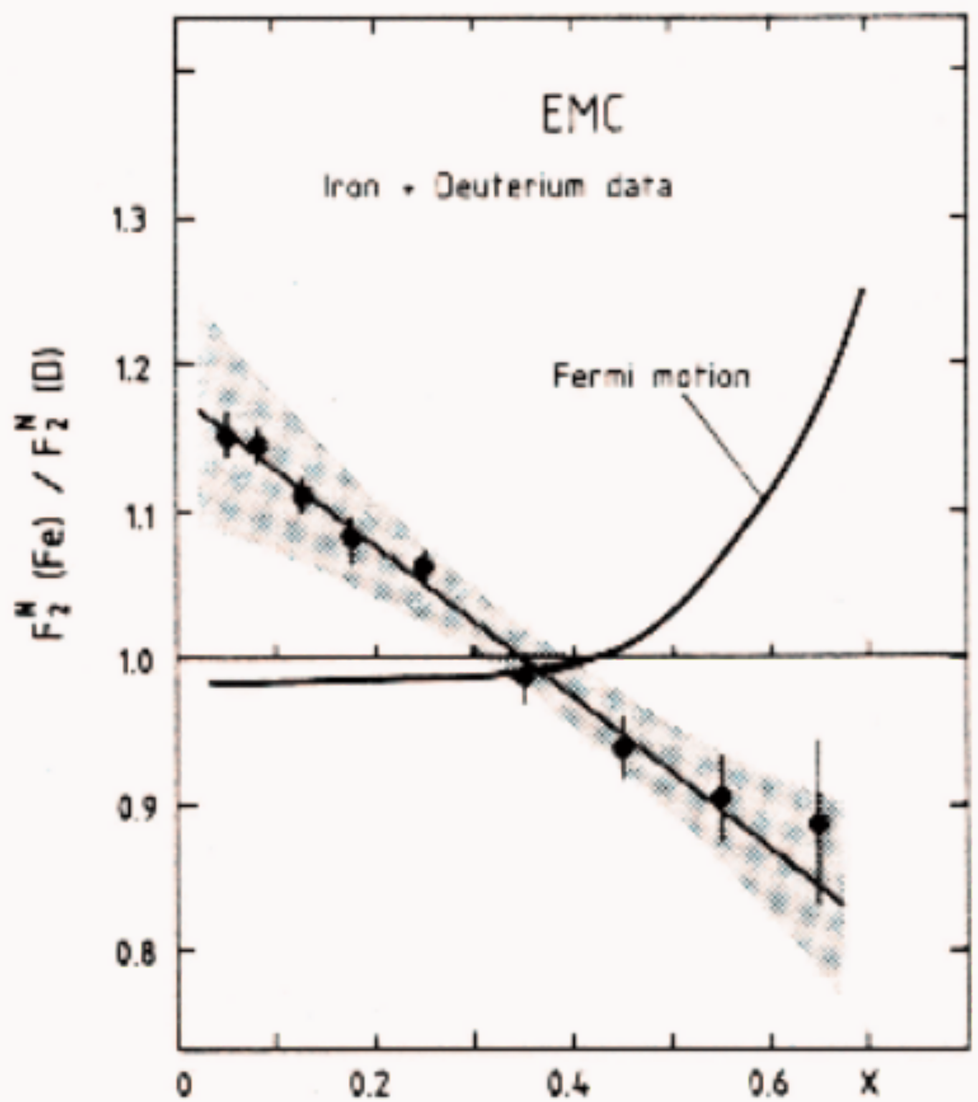
$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}Q^2\mathrm{d}x} \propto \frac{4\pi\alpha^2}{Q^4}\frac{F_2^A(x,Q^2)}{x}$$

Bjorken $x = Q^2/(2p \cdot q)$, and $Q^2 = -q^2$ are defined in terms of the target four-momentum p and the momentum transfer from the lepton to the target, q.

The ratio $R_{\mathrm{EMC}}(A,x) = \frac{2F_2^A(x,Q^2)}{AF_2^d(x,Q^2)} \sim \frac{2\sigma^A}{A\sigma^d}$ plays an important role.

1983 EMC Paper

One-picture/One-sentence summary



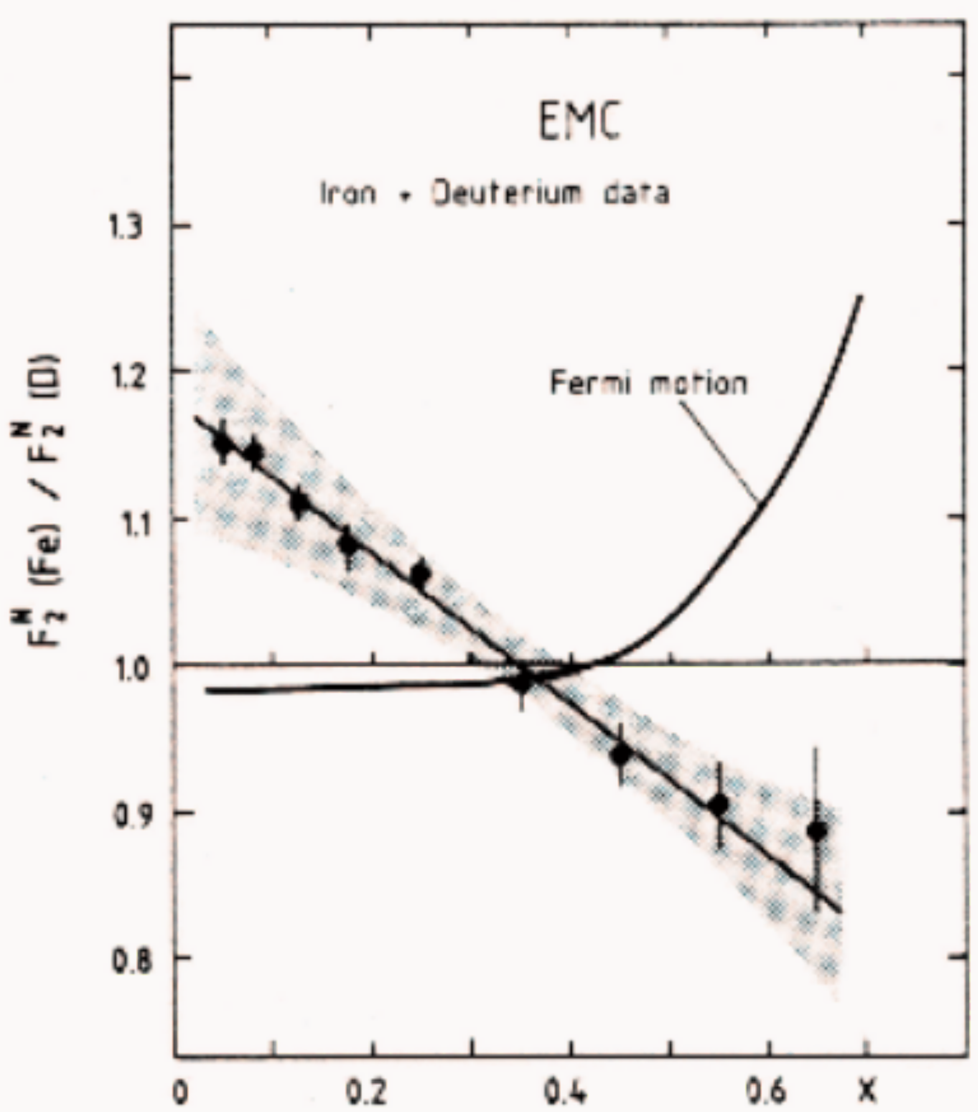
K. Rith, arXiv:1402.5000 [hep-ex] (2014)

J. J. Aubert et al. (EMC), Phys. Lett. B. **123**, 275
"We are not aware of any published detailed prediction presently available which can explain the behaviour of these data."

1983 EMC Paper

The strength of the EMC effect is given in terms of the slope:

$$\mathrm{d}R_{\mathrm{EMC}}(A,x)/\mathrm{d}x|_{0.35<x<0.7} \sim \mathrm{d}\left(\sigma^A/\sigma^d\right)/\mathrm{d}x|_{0.35<x<0.7}$$

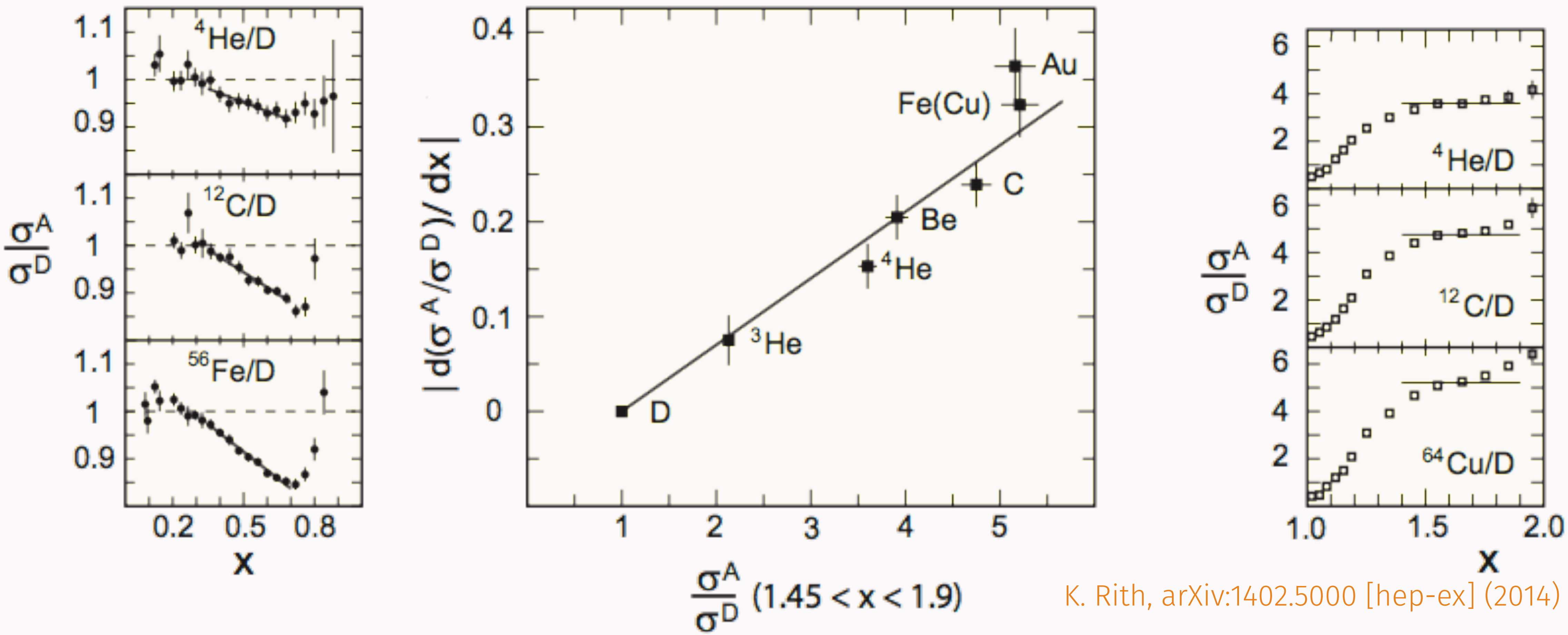


K. Rith, arXiv:1402.5000 [hep-ex] (2014)

Short-Range Correlations And The EMC Effect

$$\text{SRC scaling factor } a_2(A,x) \equiv \frac{2\sigma^A}{A\sigma^d}\Big|_{1.5<x<2}.$$

$$dR_{EMC}/dx \propto a_2$$



K. Rith, arXiv:1402.5000 [hep-ex] (2014)

Implications Of EFT

J.-W. Chen & W. Detmold, Phys. Lett. B **625**, 165 (2005):

Structure functions factorize: $F_2^A(x)/A = F_2^N(x) + g_2(A,\Lambda) f_2(x,\Lambda)$

$$g_2(A,\Lambda) = \frac{1}{A}\langle A|(N^\dagger N)^2|A\rangle_\Lambda$$

J.-W. Chen, W. Detmold, JEL, A. Schwenk,
arXiv:1607.03065 [hep-ph] (2016):

$$a_2(A, x>1) = \frac{g_2(A,\Lambda)}{g_2(2,\Lambda)} \Rightarrow \frac{\mathrm{d}R_{\mathrm{EMC}}}{\mathrm{d}x} \propto a_2.$$