Many-Body Nuclear Physics With Quantum Monte Carlo Methods And Chiral EFT

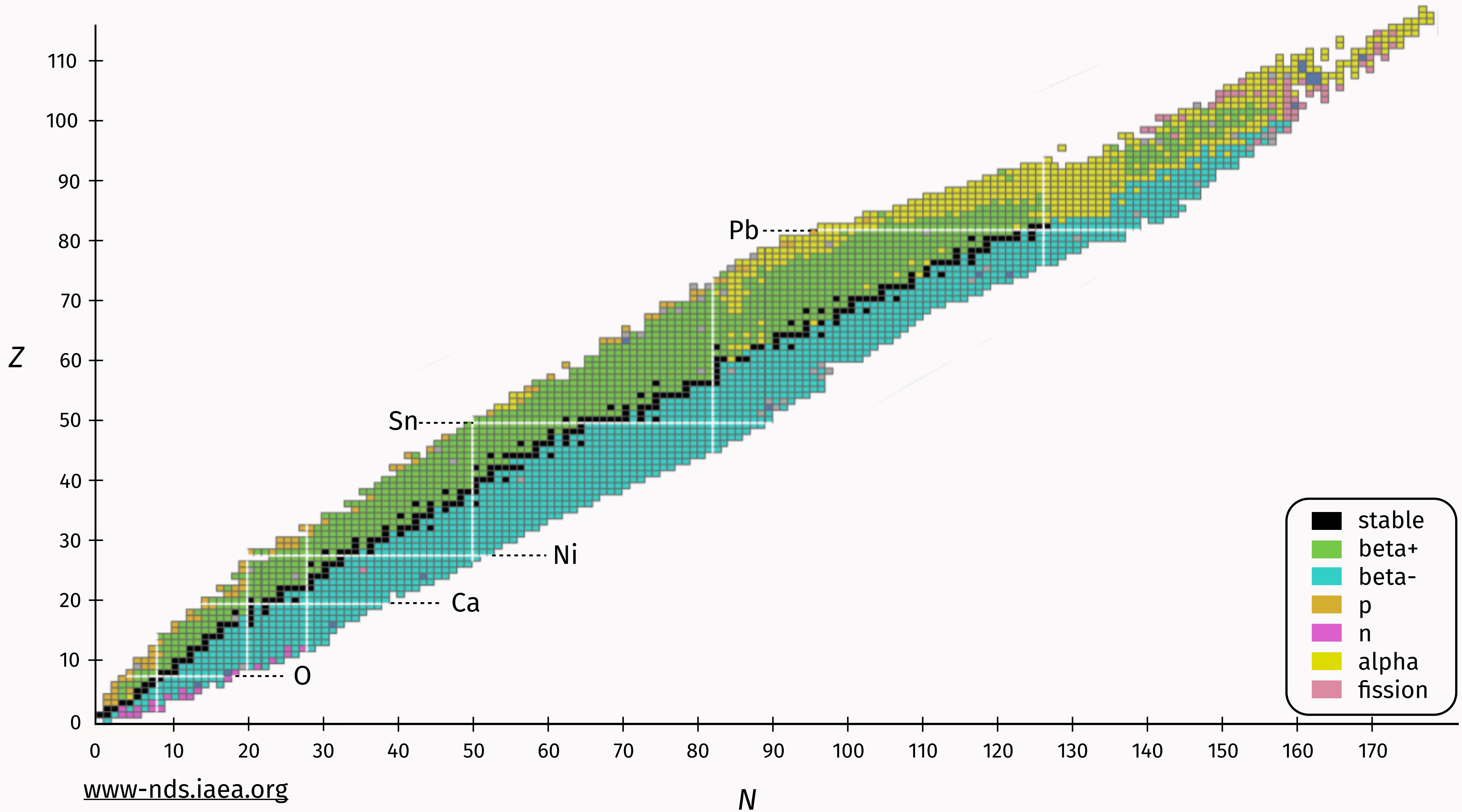
Workshop of Recent Developments in QCD and Quantum Field Theories - National Taiwan University

Joel E. Lynn

November 11, 2017

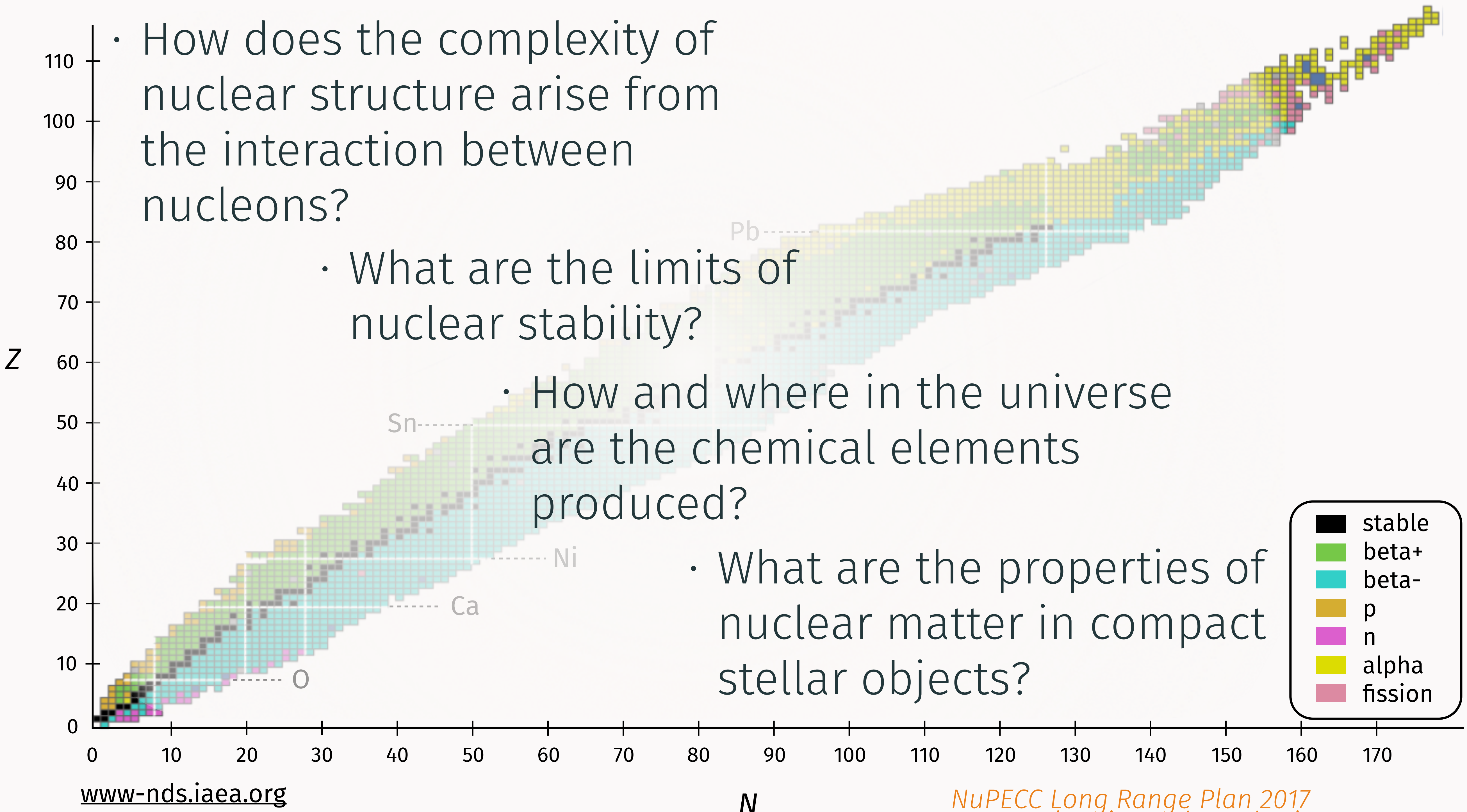
Motivation

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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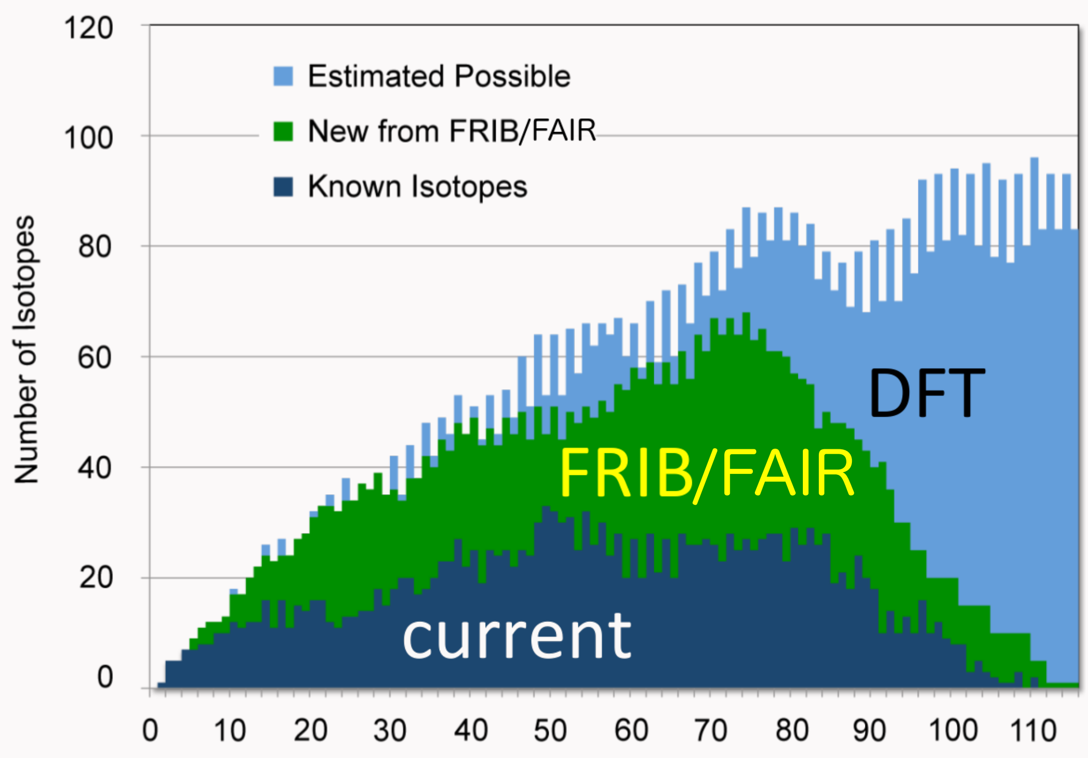
NuPECC Long Range Plan 2017
Perspectives in Nuclear Physics

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)

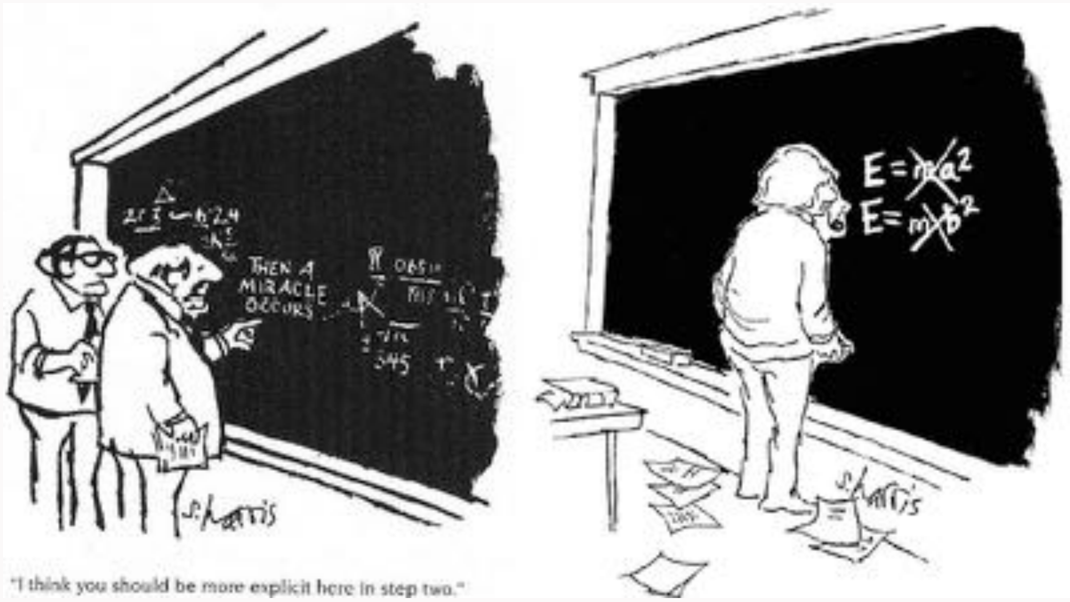
Neutron-star mergers

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.



"I think you should be more explicit here in step two."

What Can Theory Offer?

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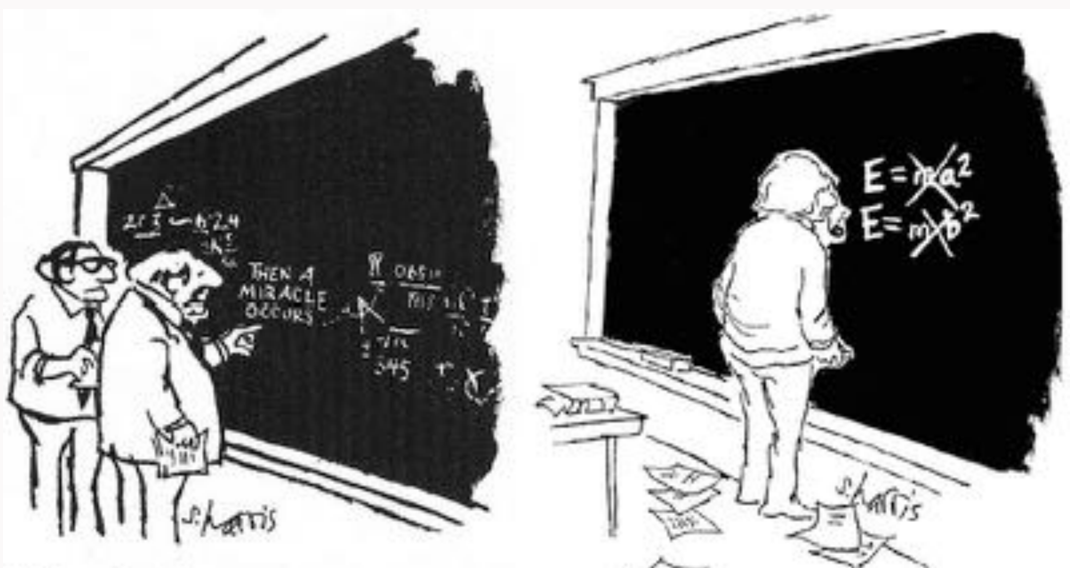
1. Advances in ***ab initio*** many-body methods.

2. Chiral effective field
   interactions.

work with protons + neutrons
&
controlled approximations

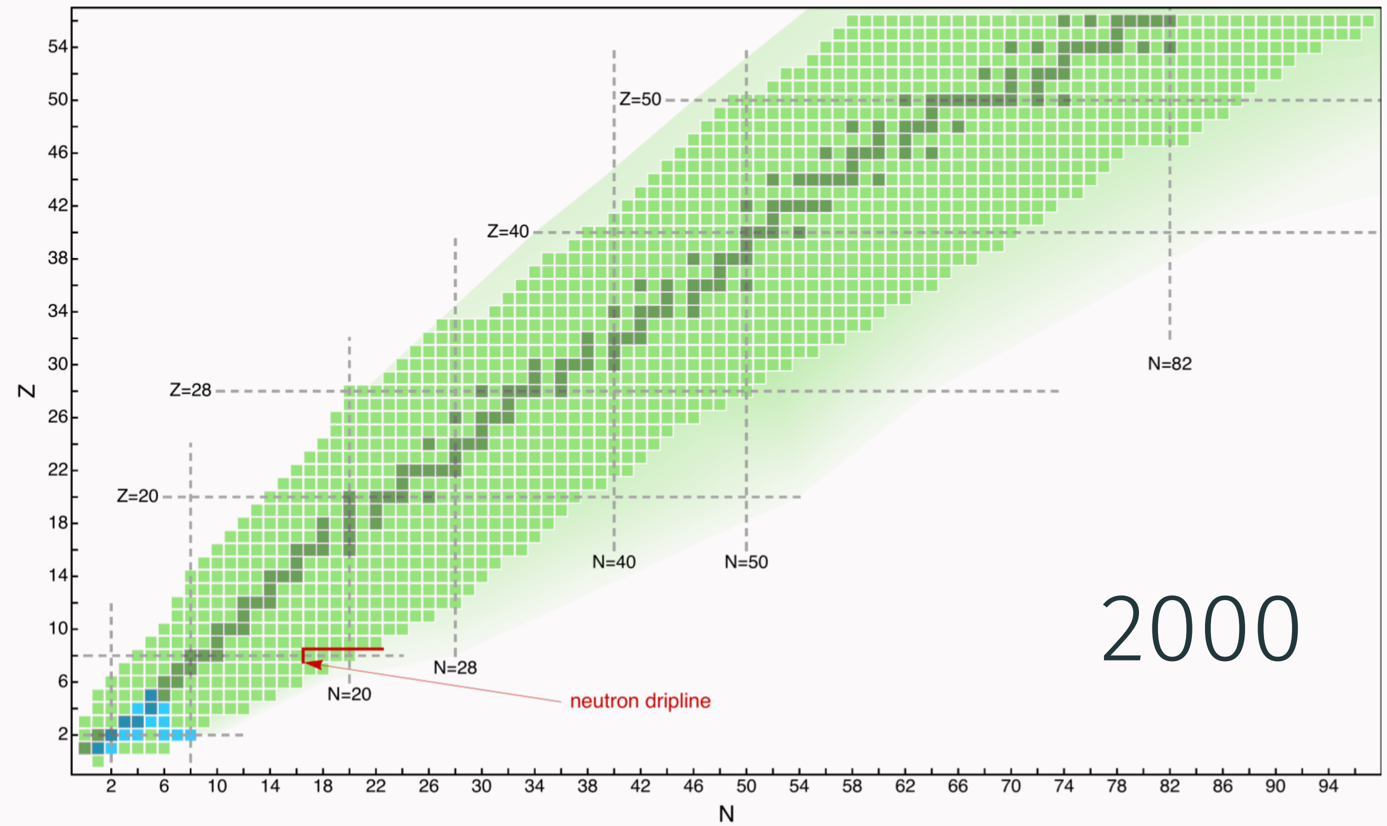


"I think you should be more explicit here in step two."

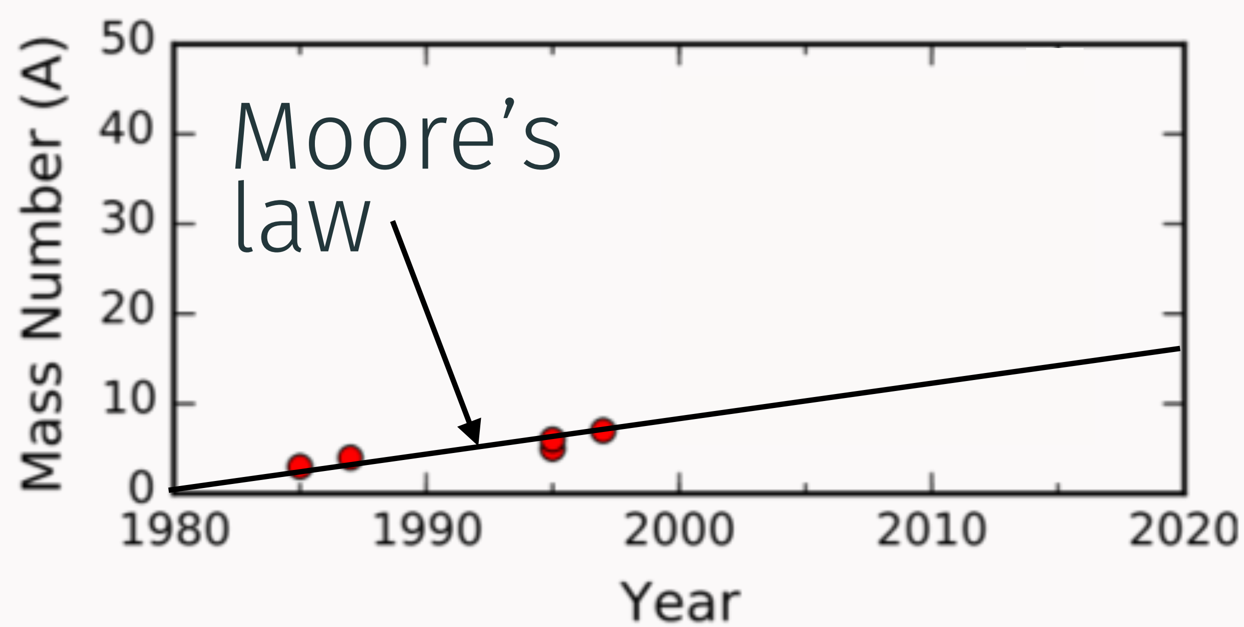
Reach Of *Ab Initio* Methods

- <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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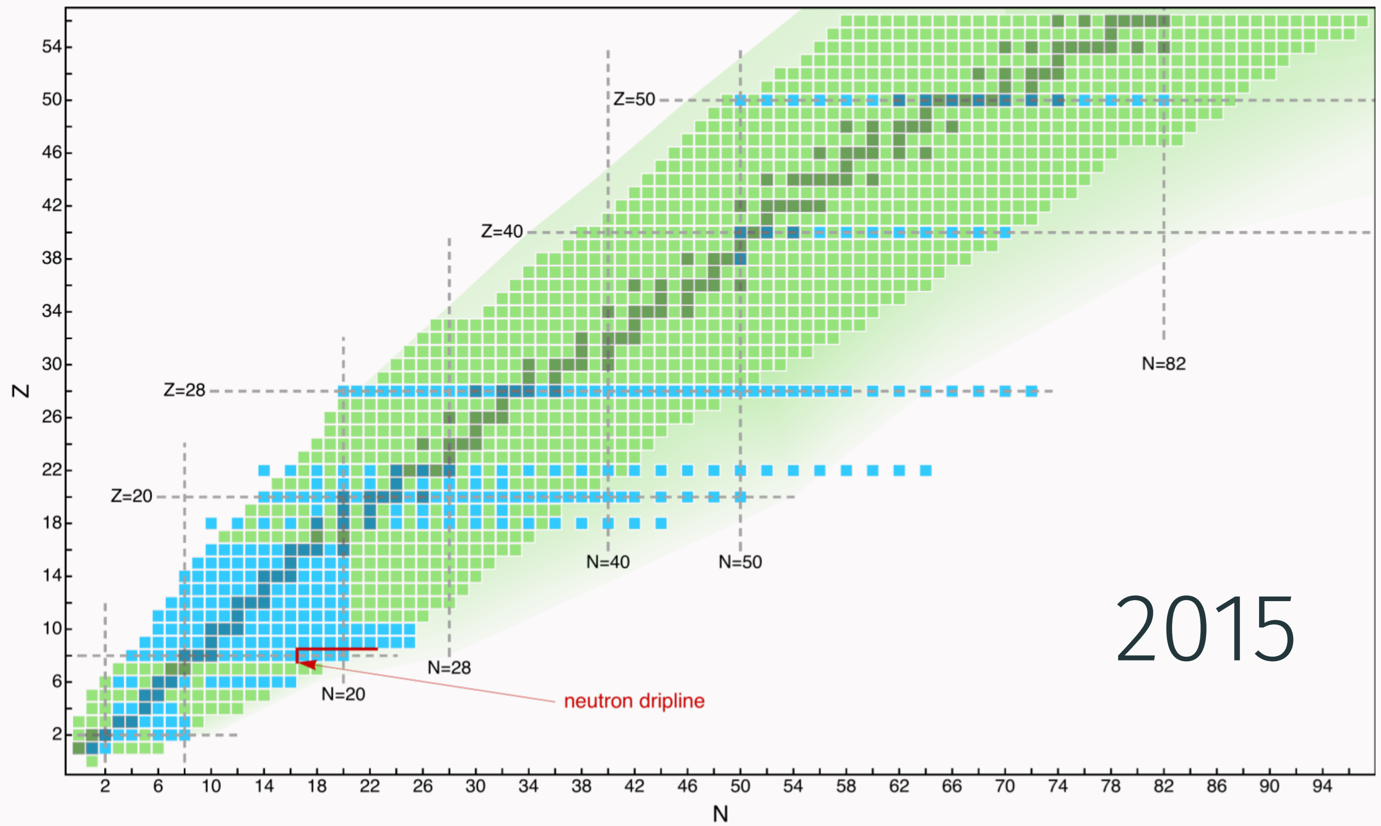

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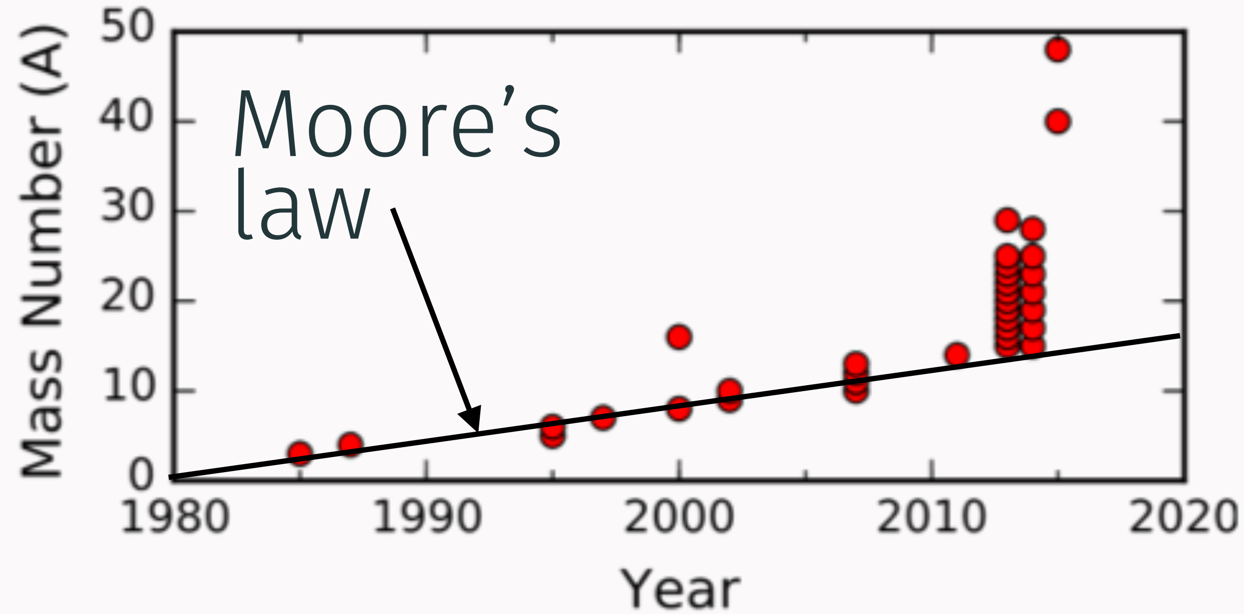

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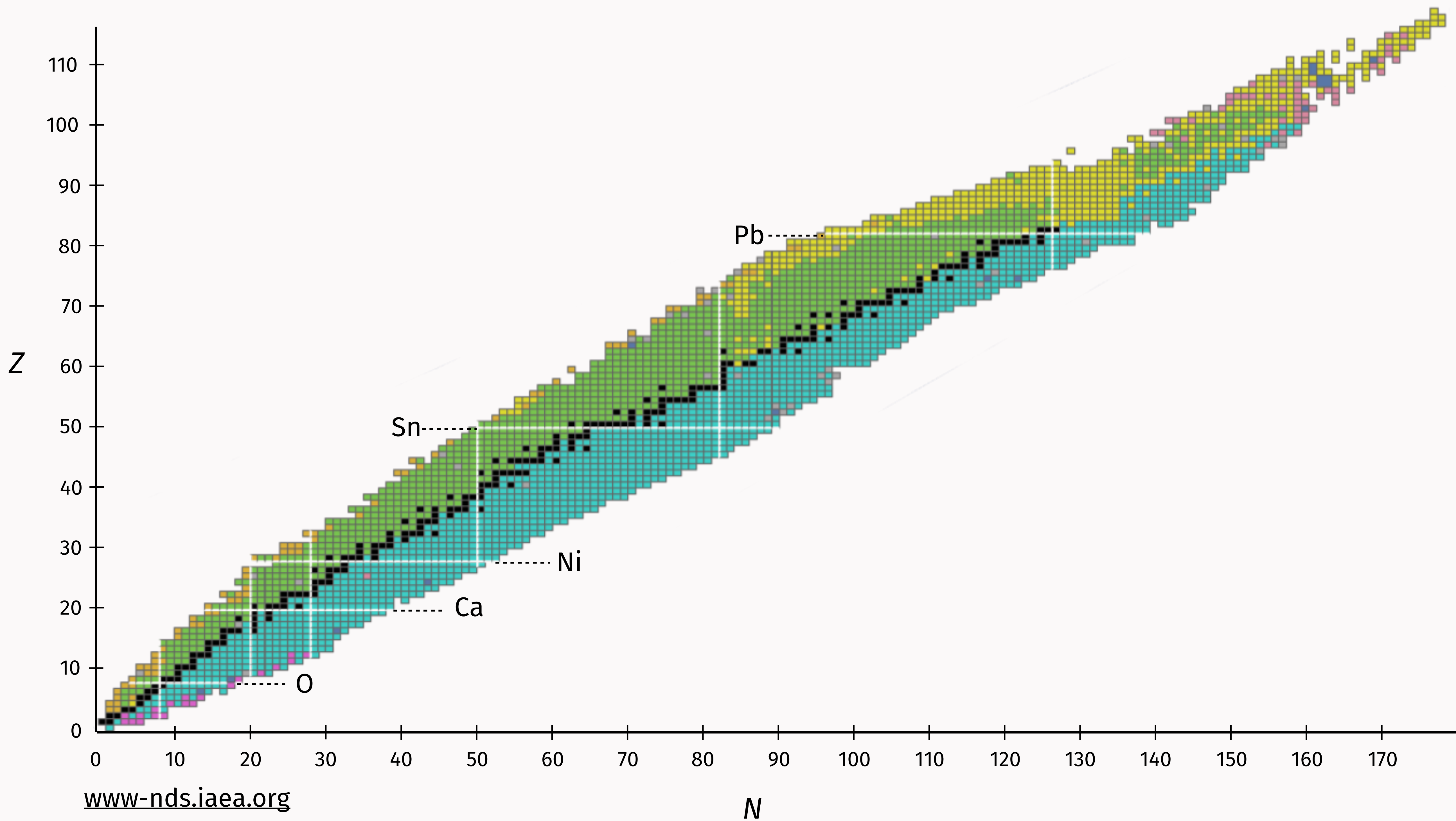
The Nuclear Landscape



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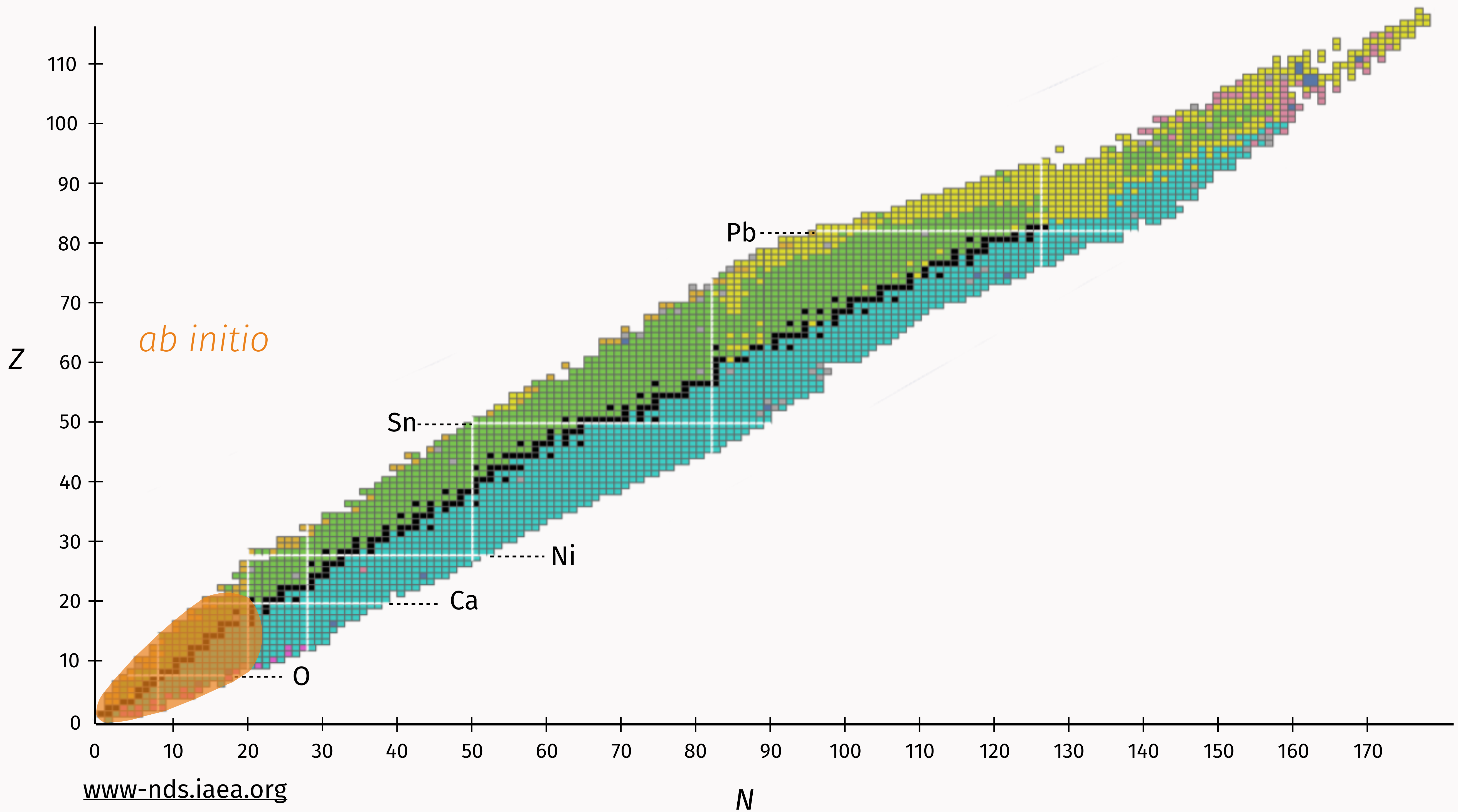
The Nuclear Landscape



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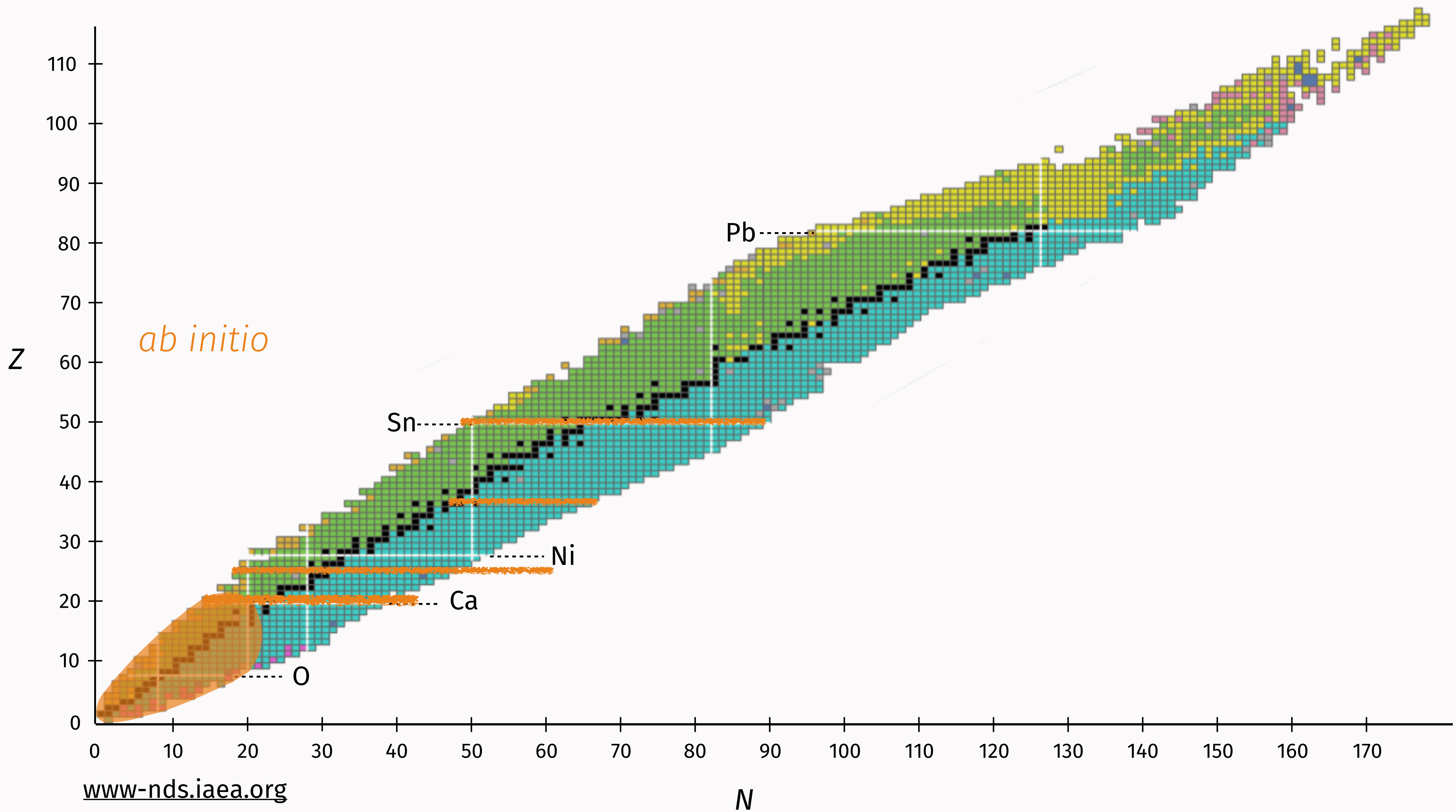

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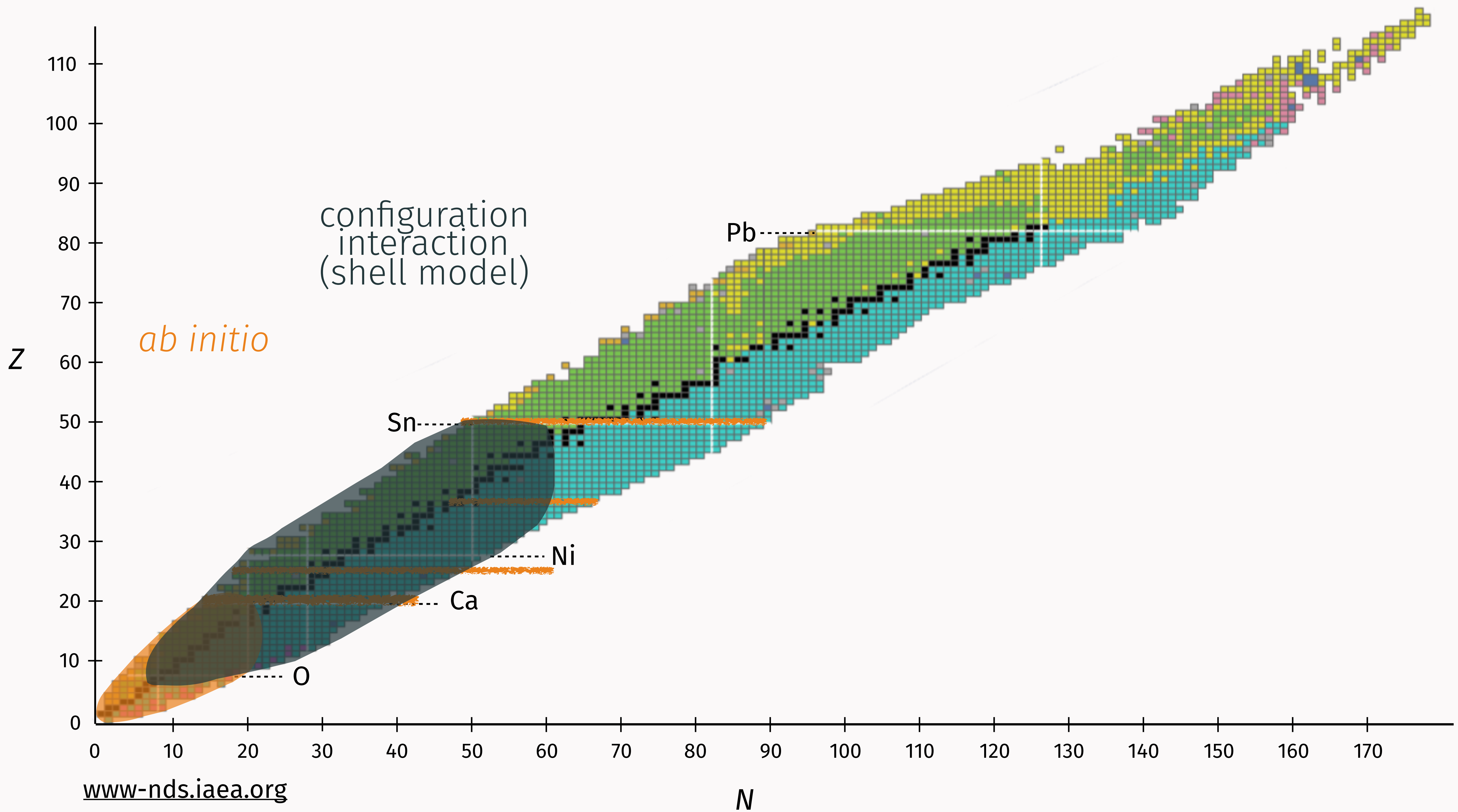

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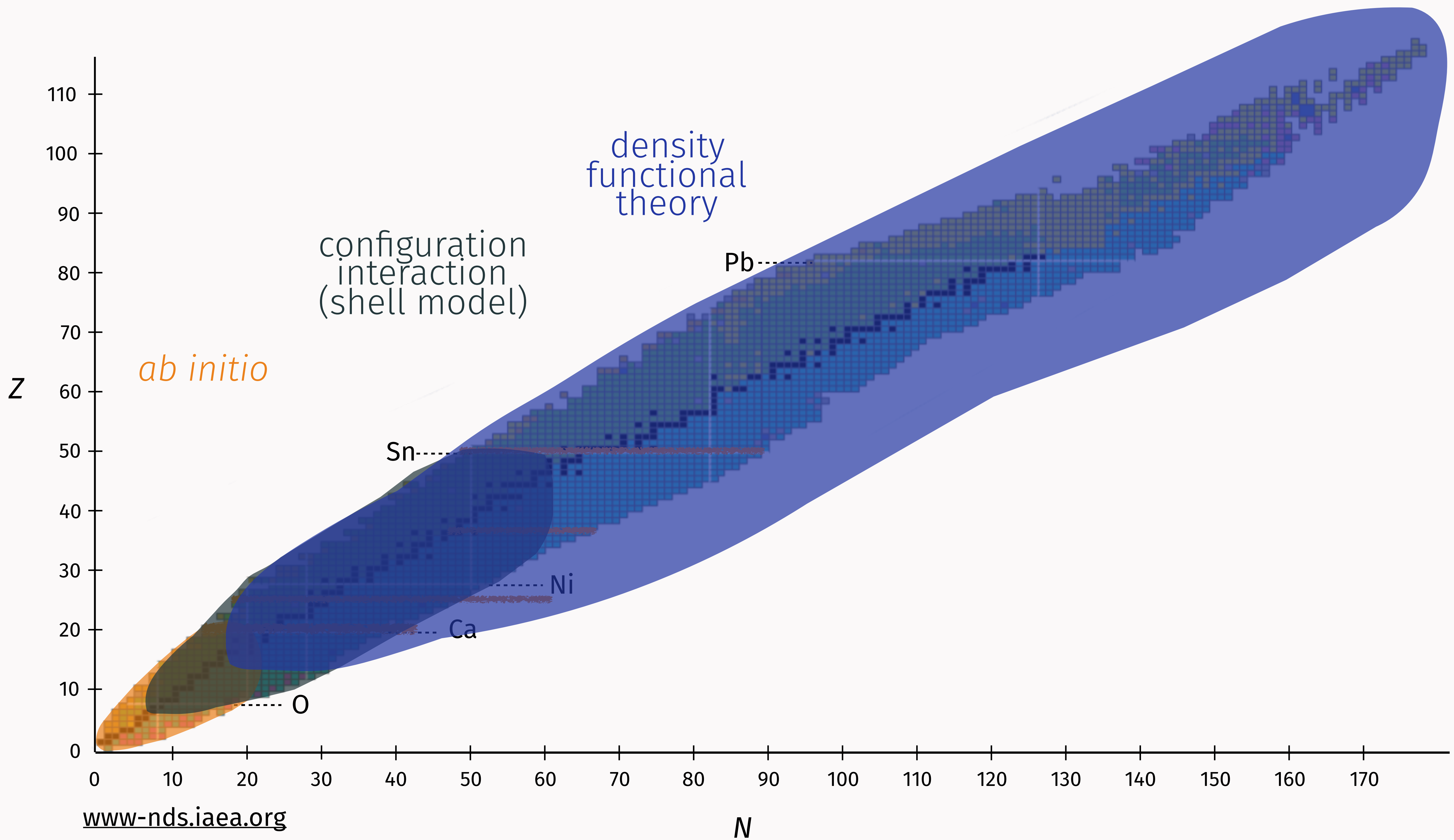

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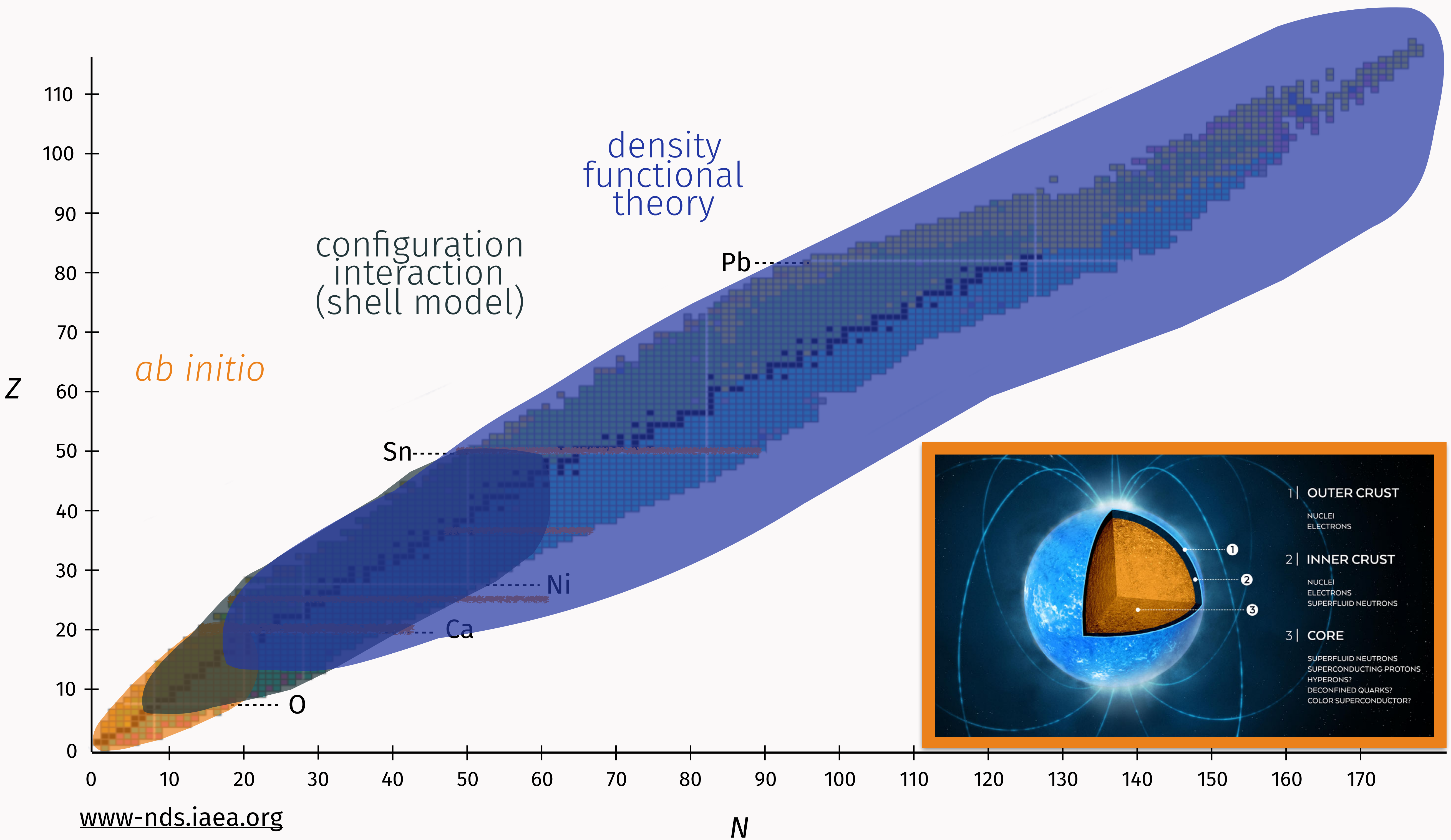

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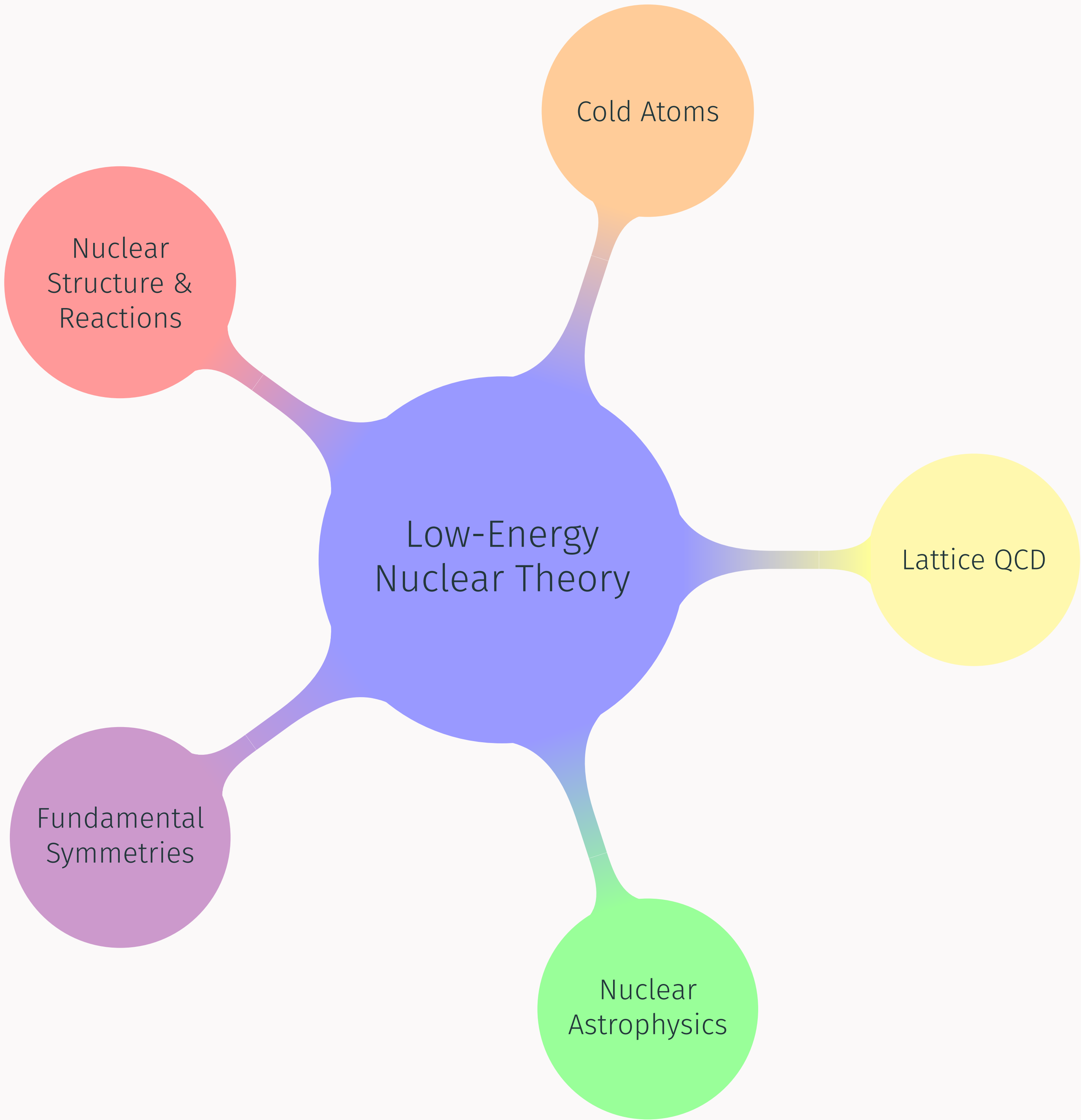
Motivation

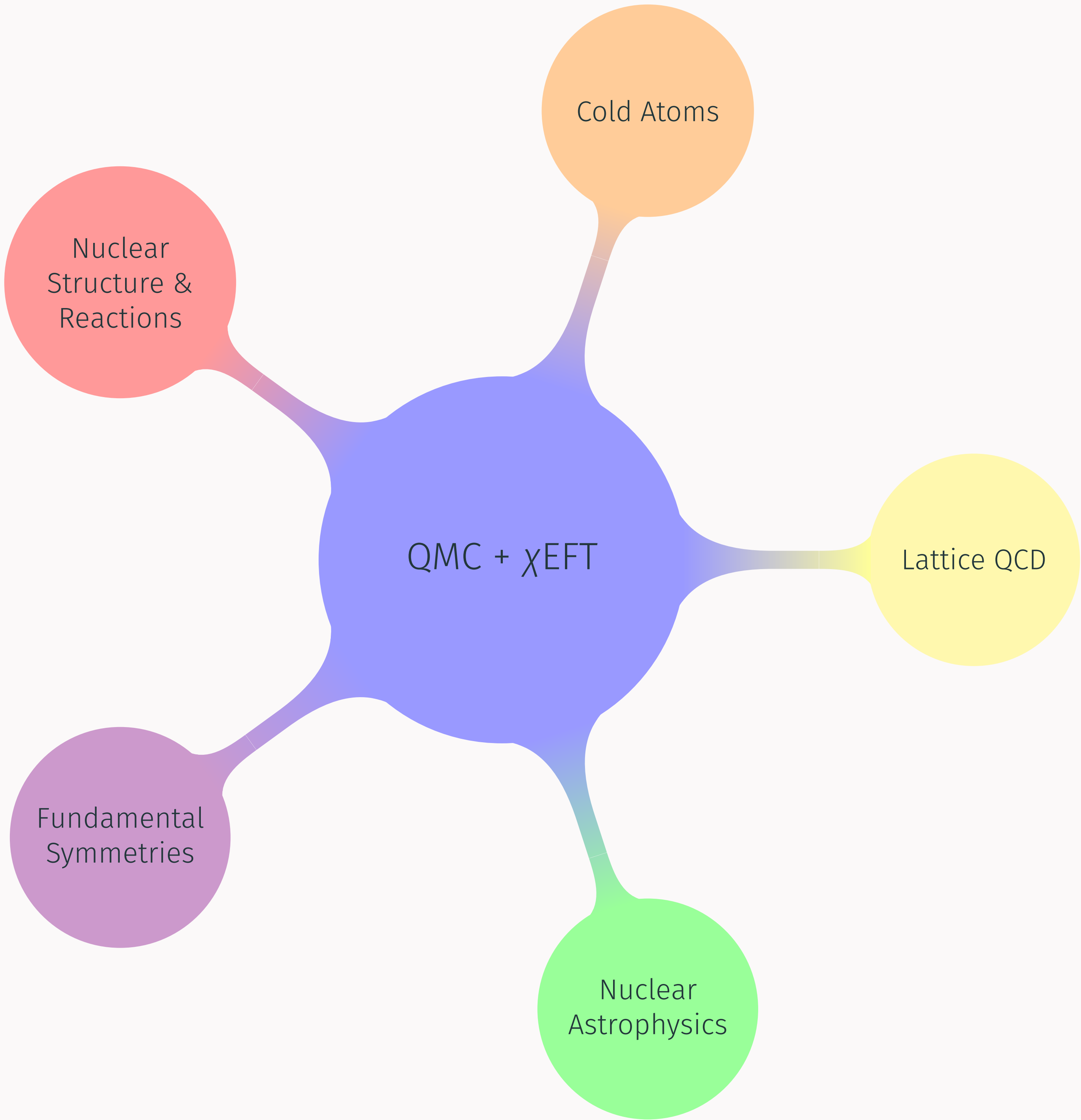
Low-energy nuclear theory sits in a privileged position, connecting many research areas.



Motivation

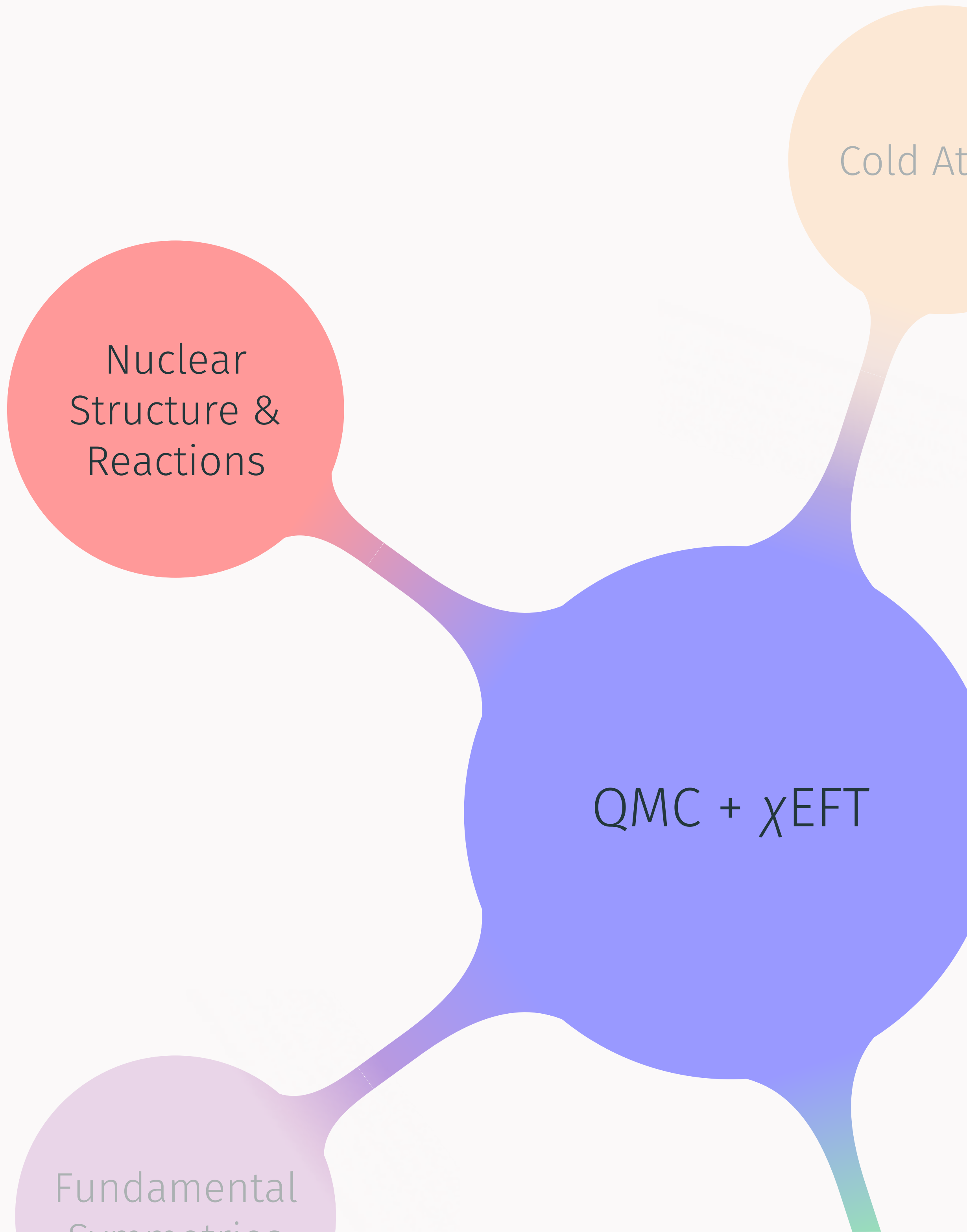
Low-energy nuclear theory sits in a privileged position, connecting many research areas.

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
  - Locality
  - 3N Interaction



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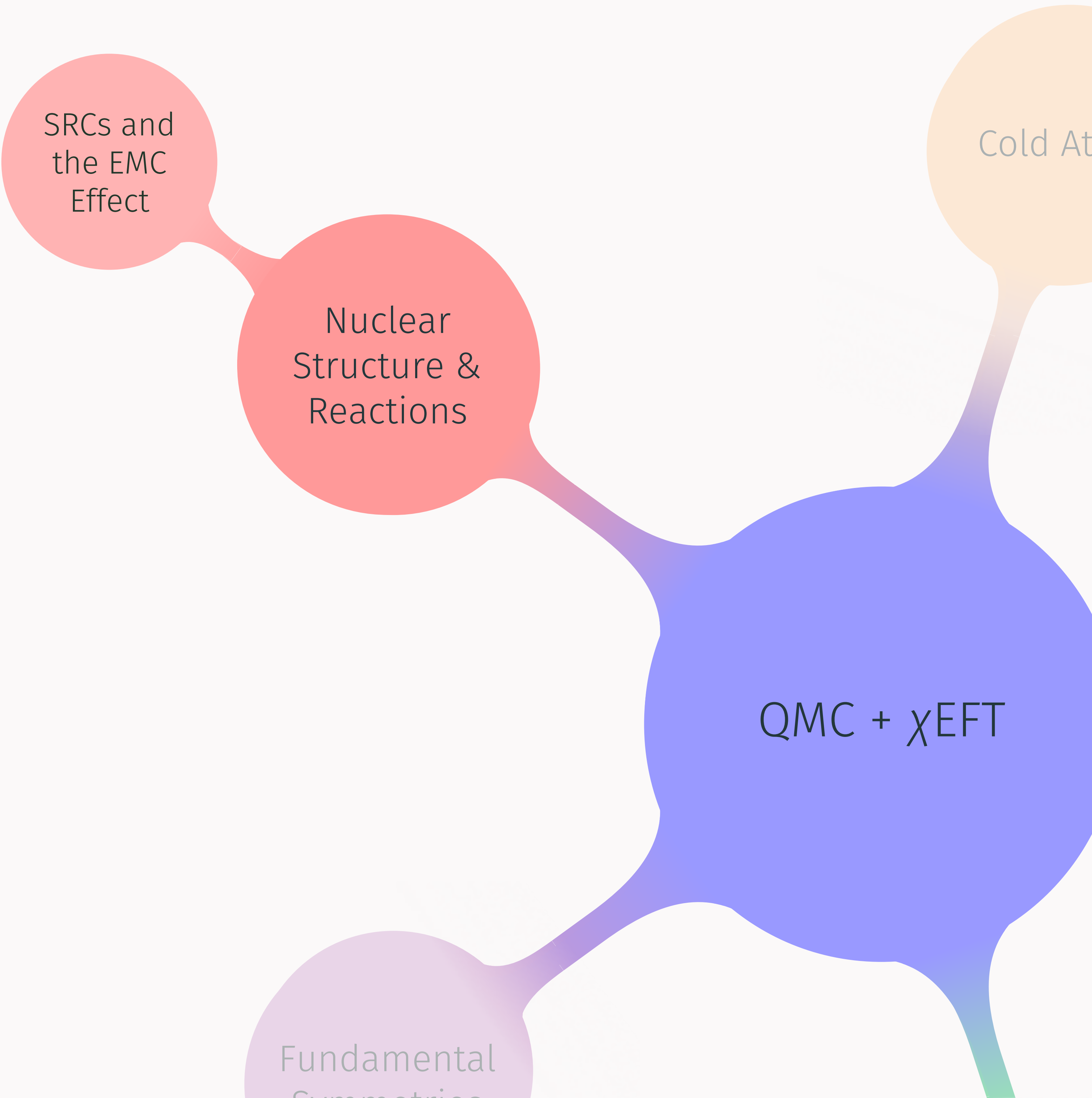
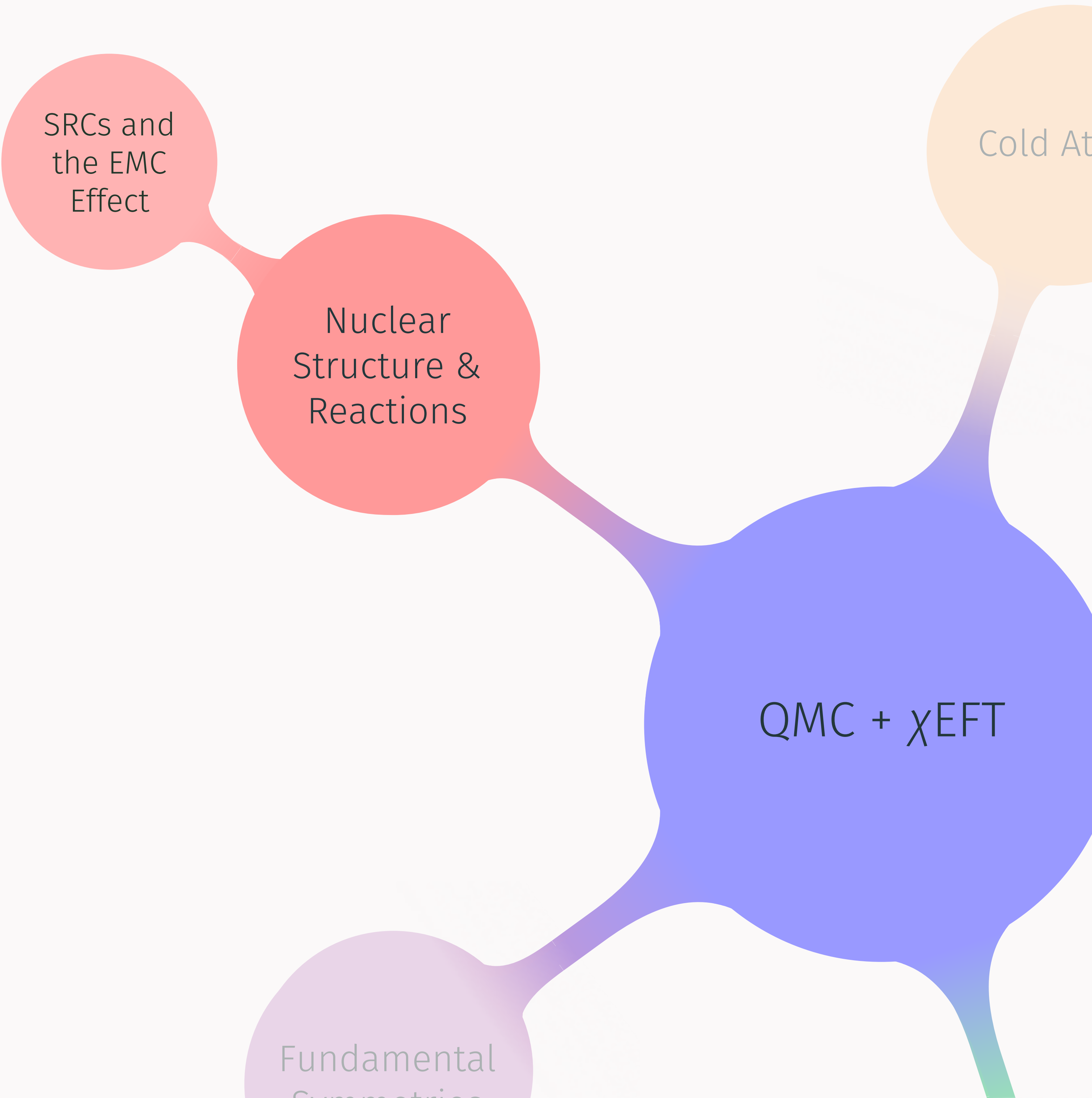
    - $3N$ Interaction
- Short-range correlations and the EMC effect



Outline

- Quantum Monte Carlo Methods
- Chiral EFT
  - Locality
  - 3N Interaction
- 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: $\mathsf{R} = \mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_A$.

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

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}
$$

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

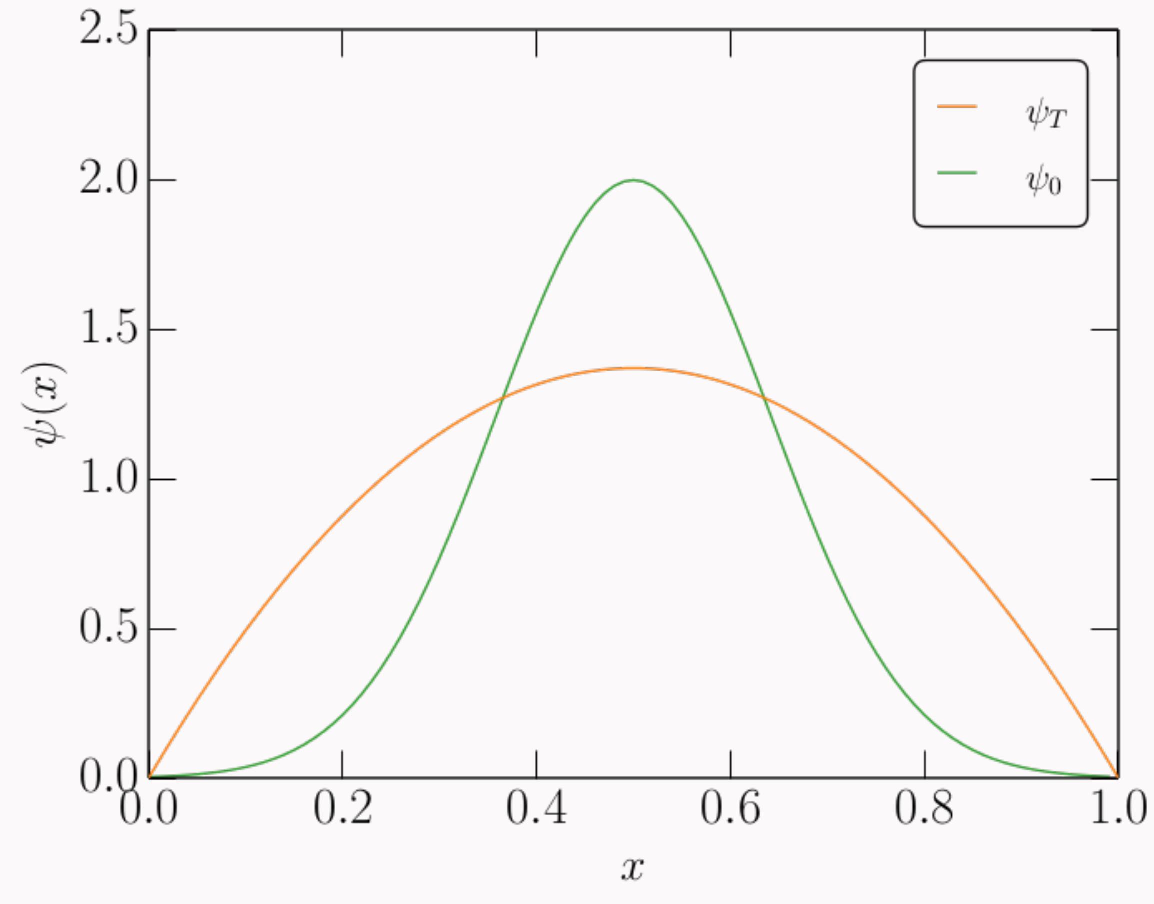
QMC Methods - An Example

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

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

Trial wave function; e.g.

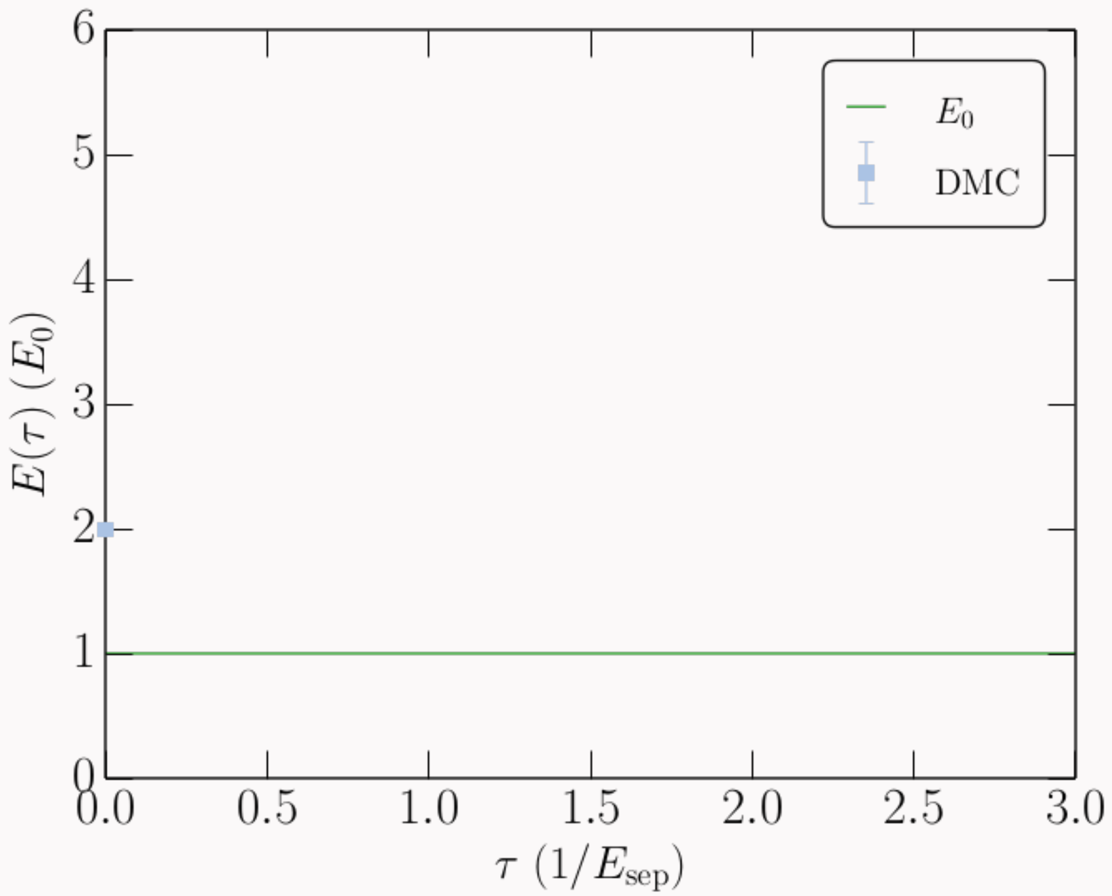
$$\Psi_T(x) = \sqrt{30}x(1-x).$$

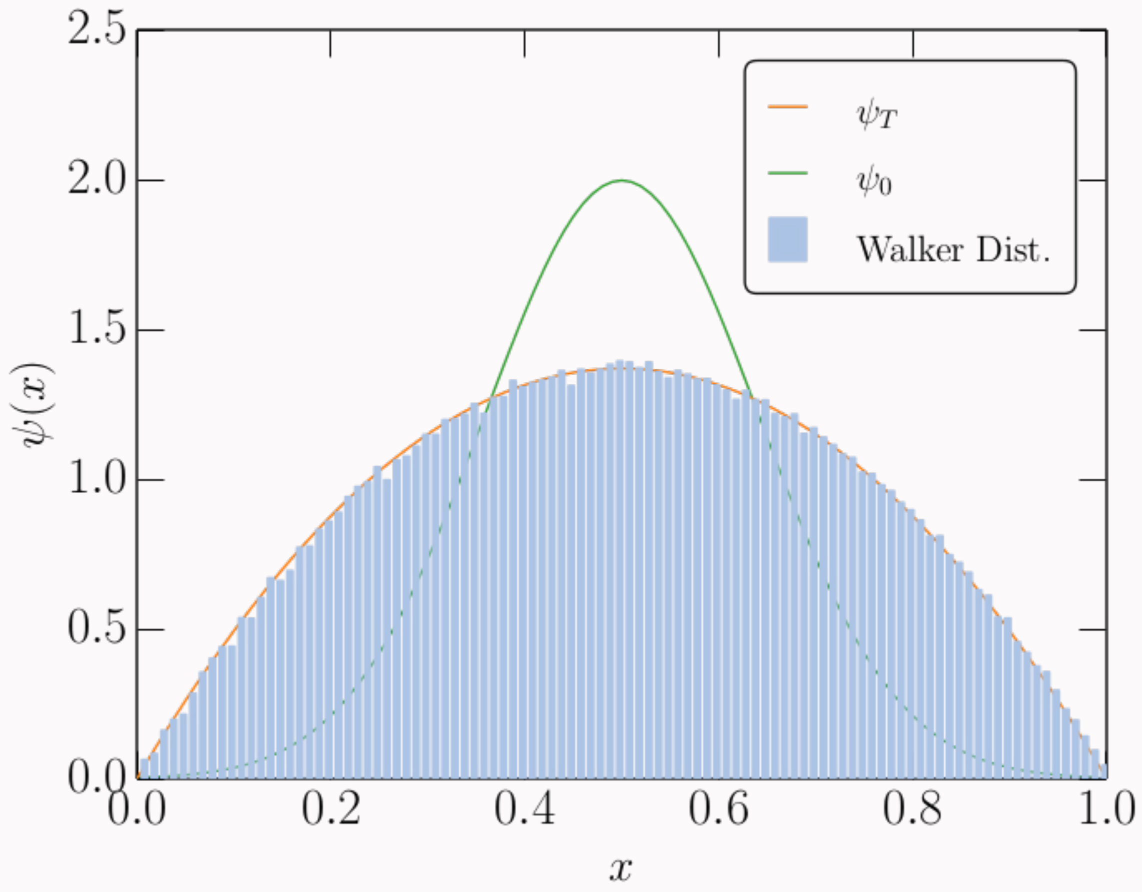


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 0.00$





QMC Methods - An Example

Imaginary-time evolution:

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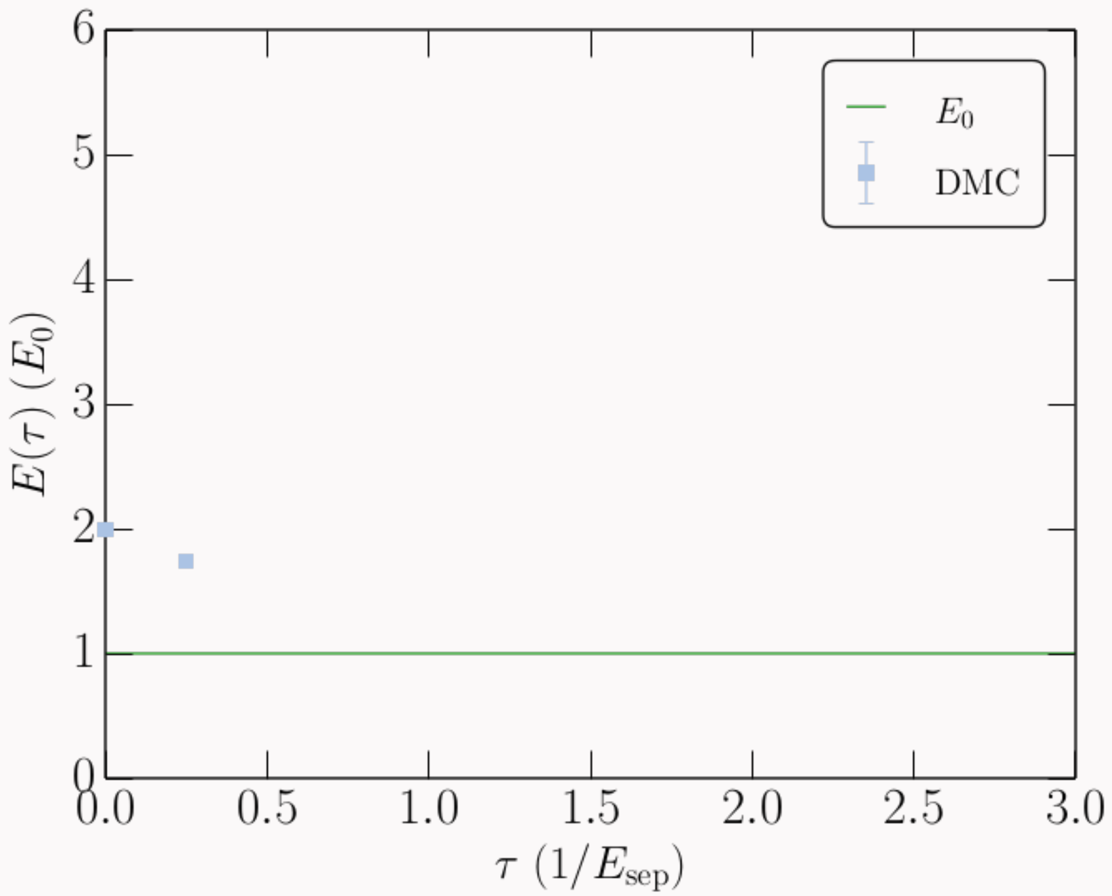
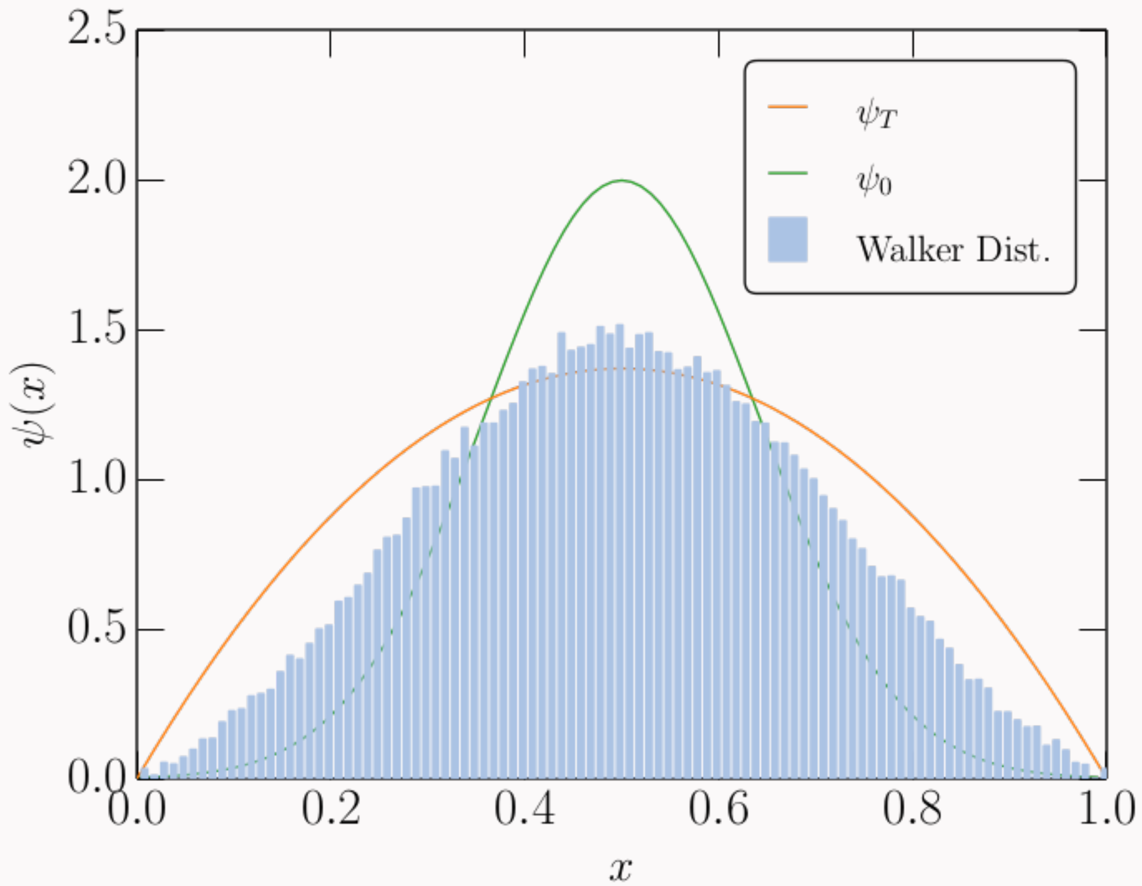
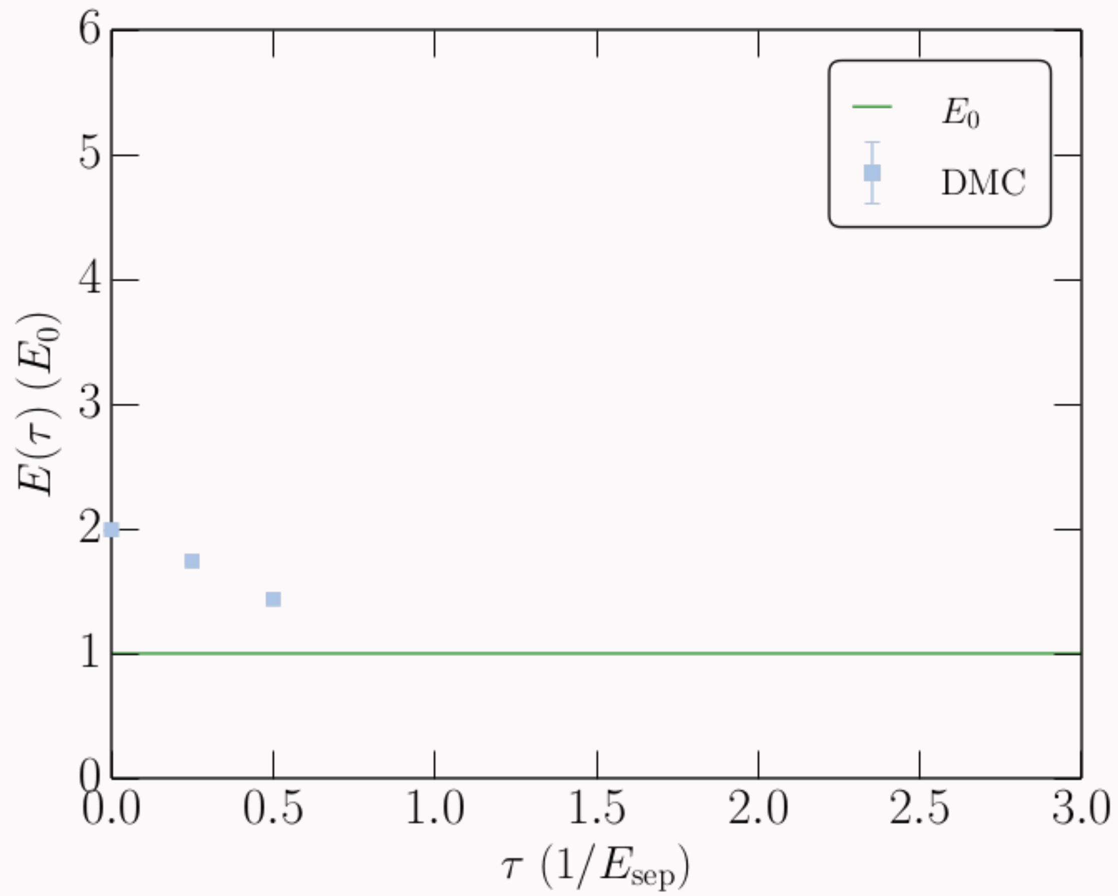


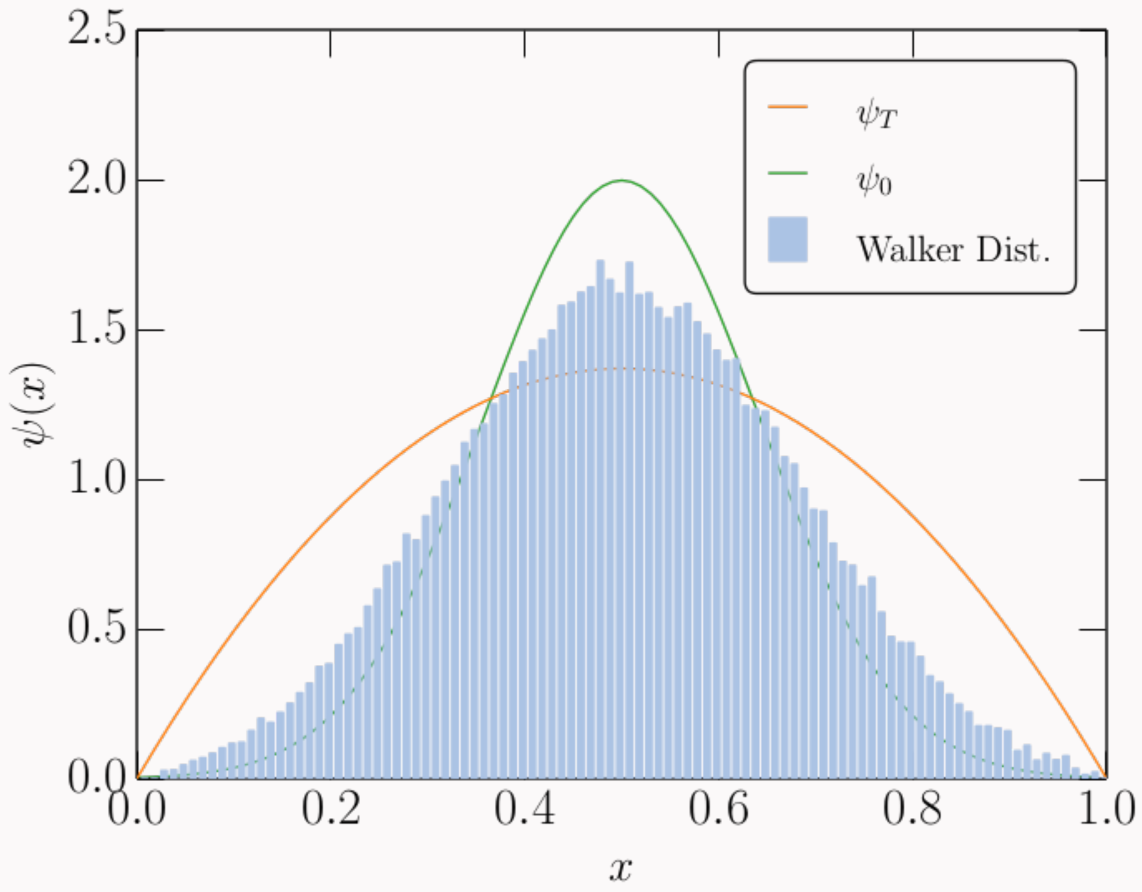


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 0.50$

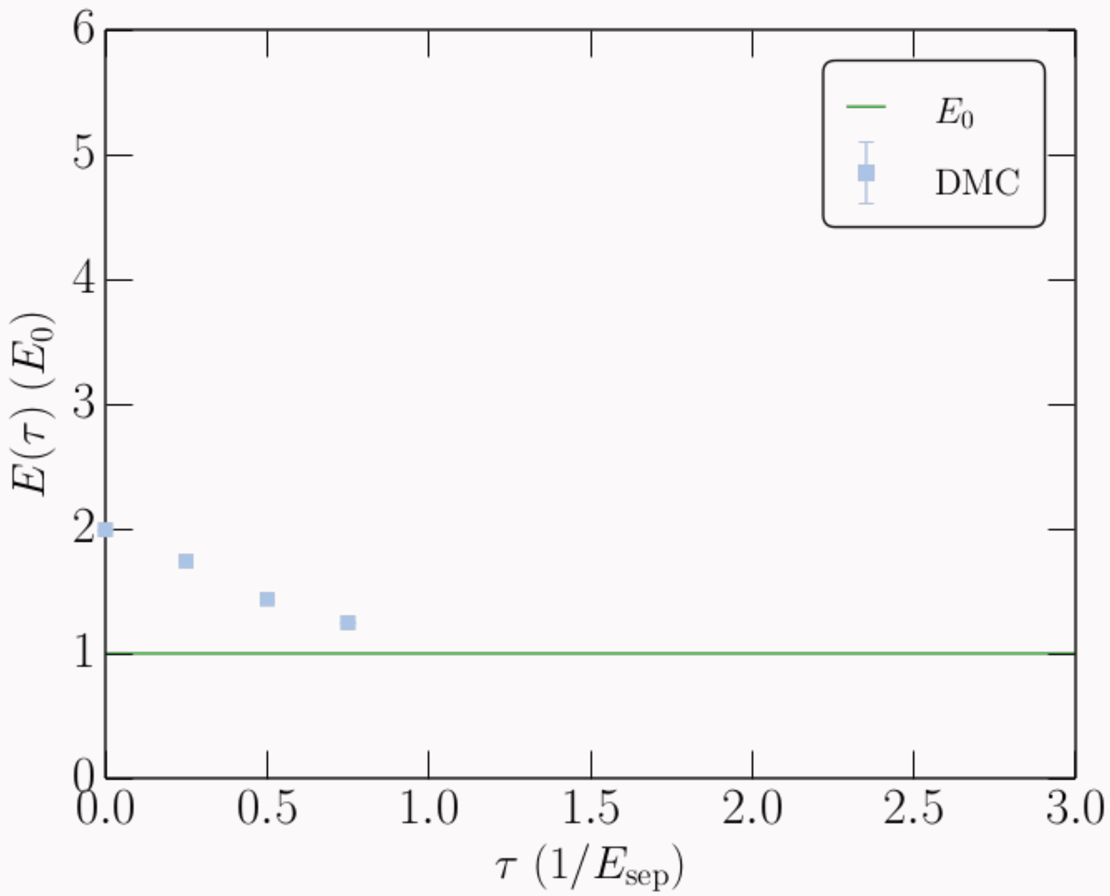


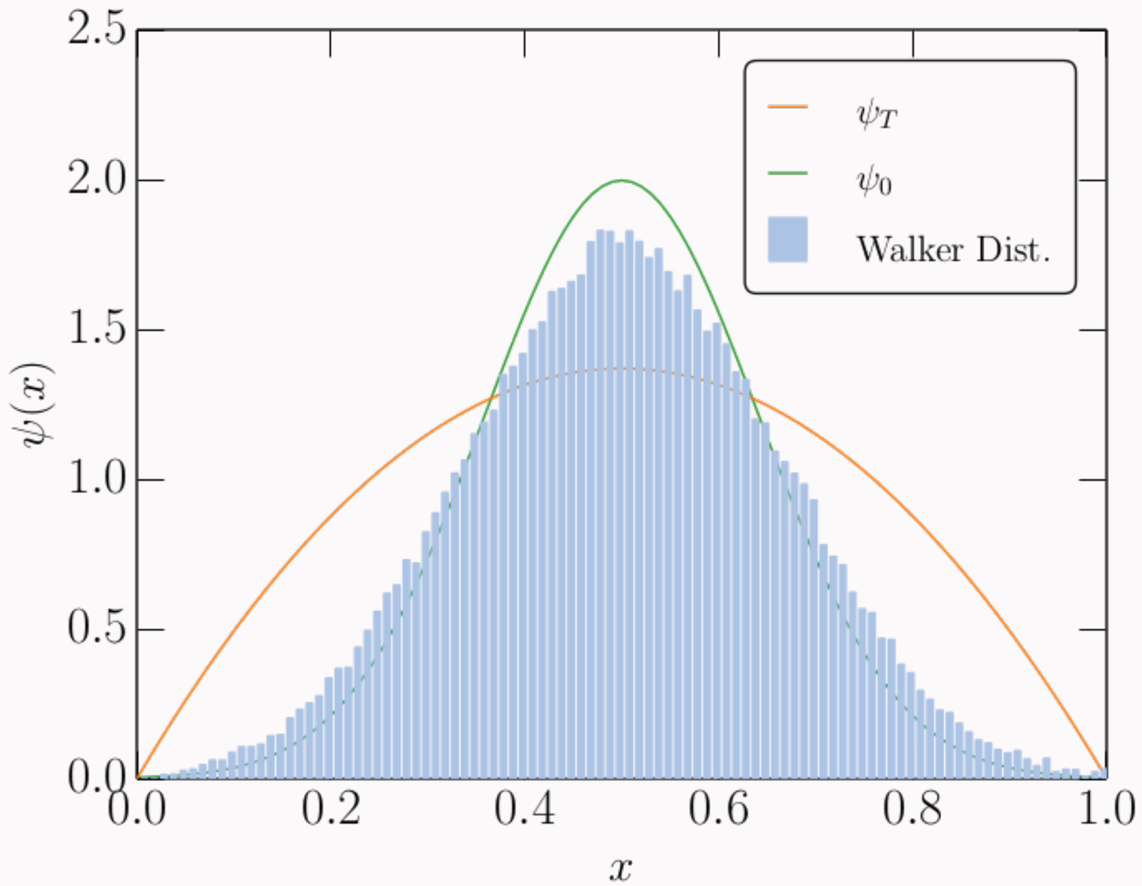


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 0.75$

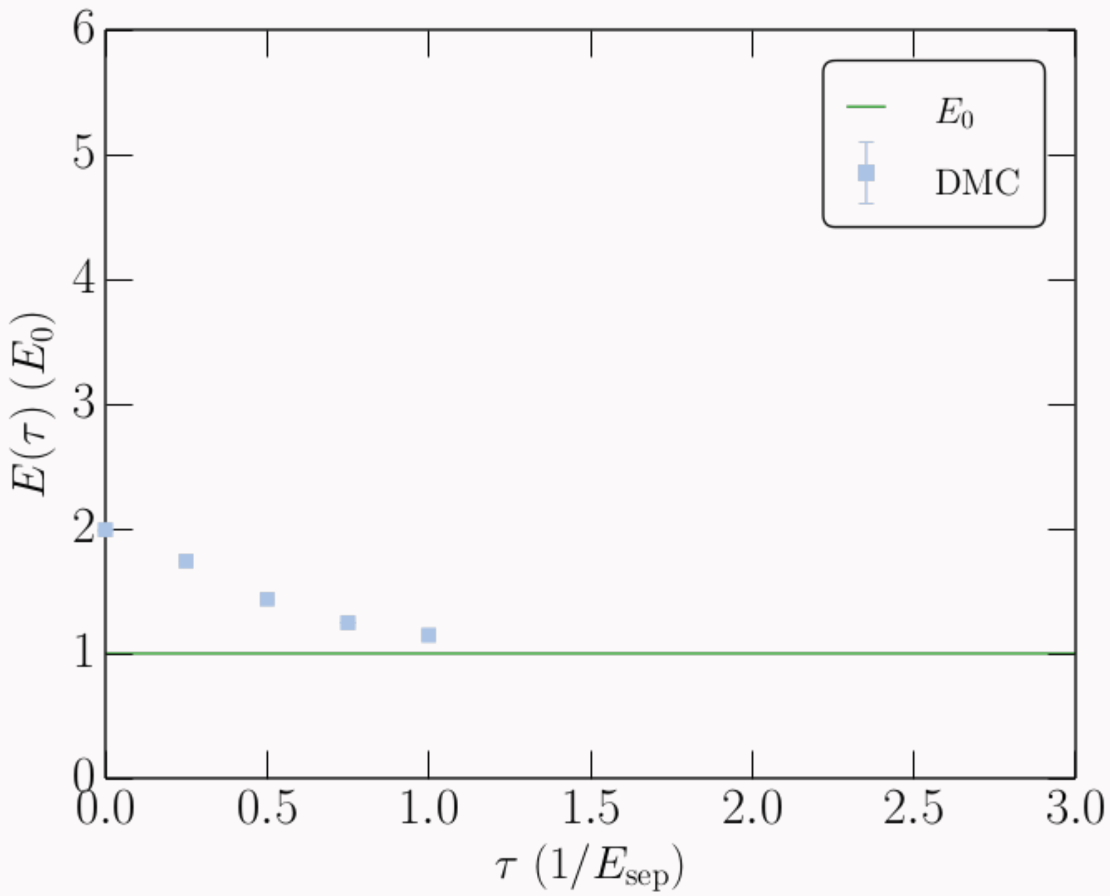


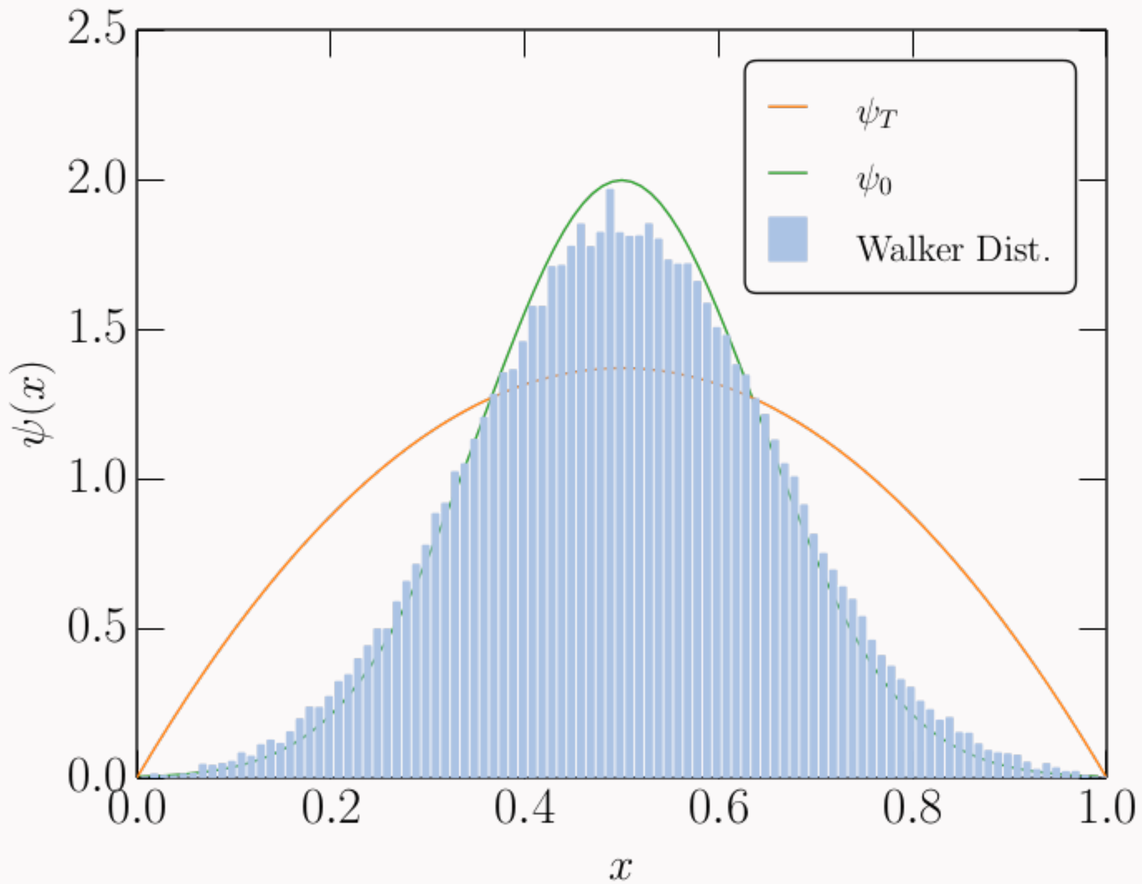


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 1.00$





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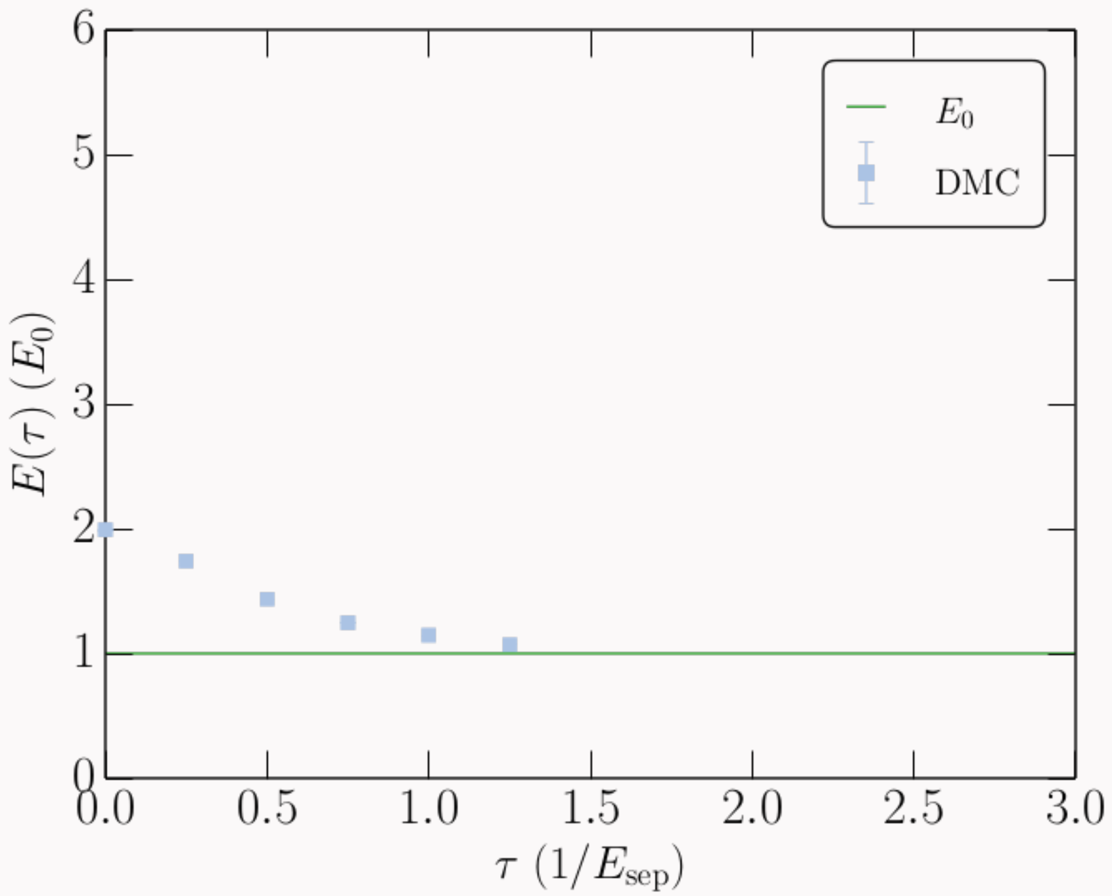

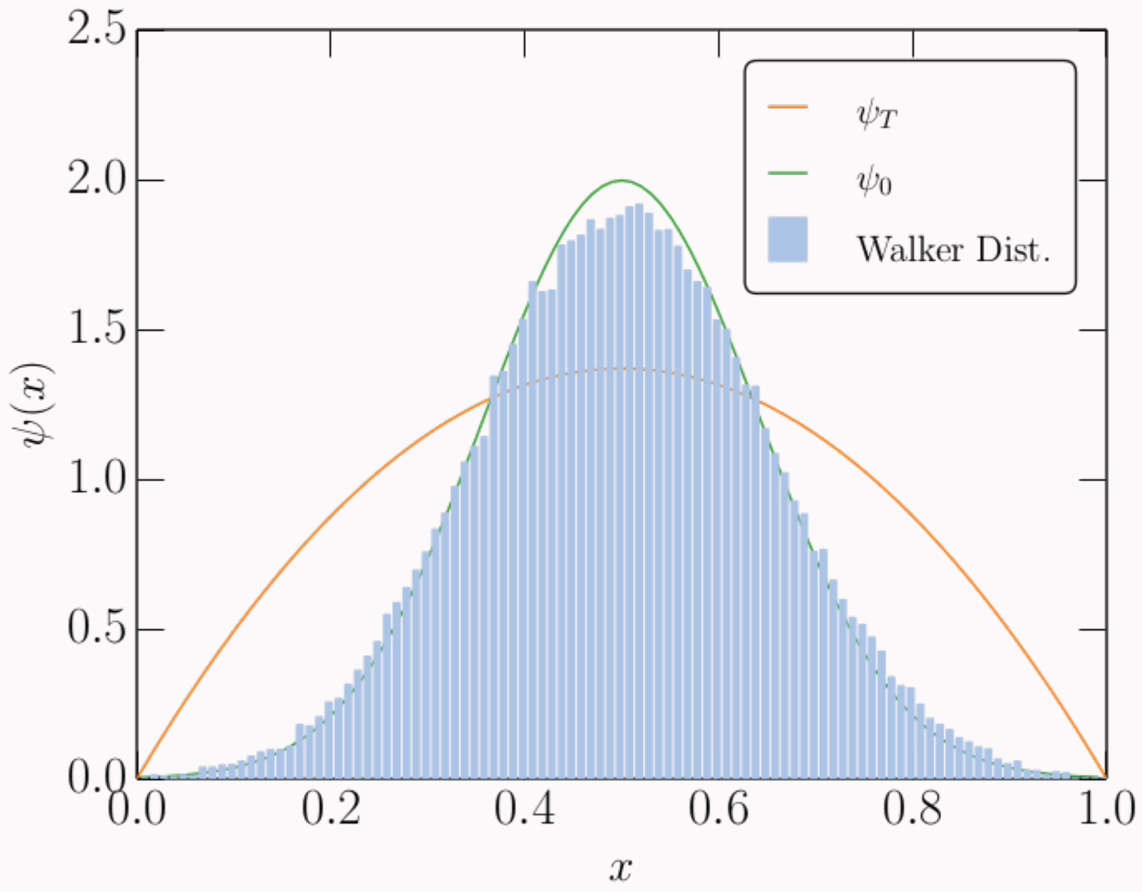

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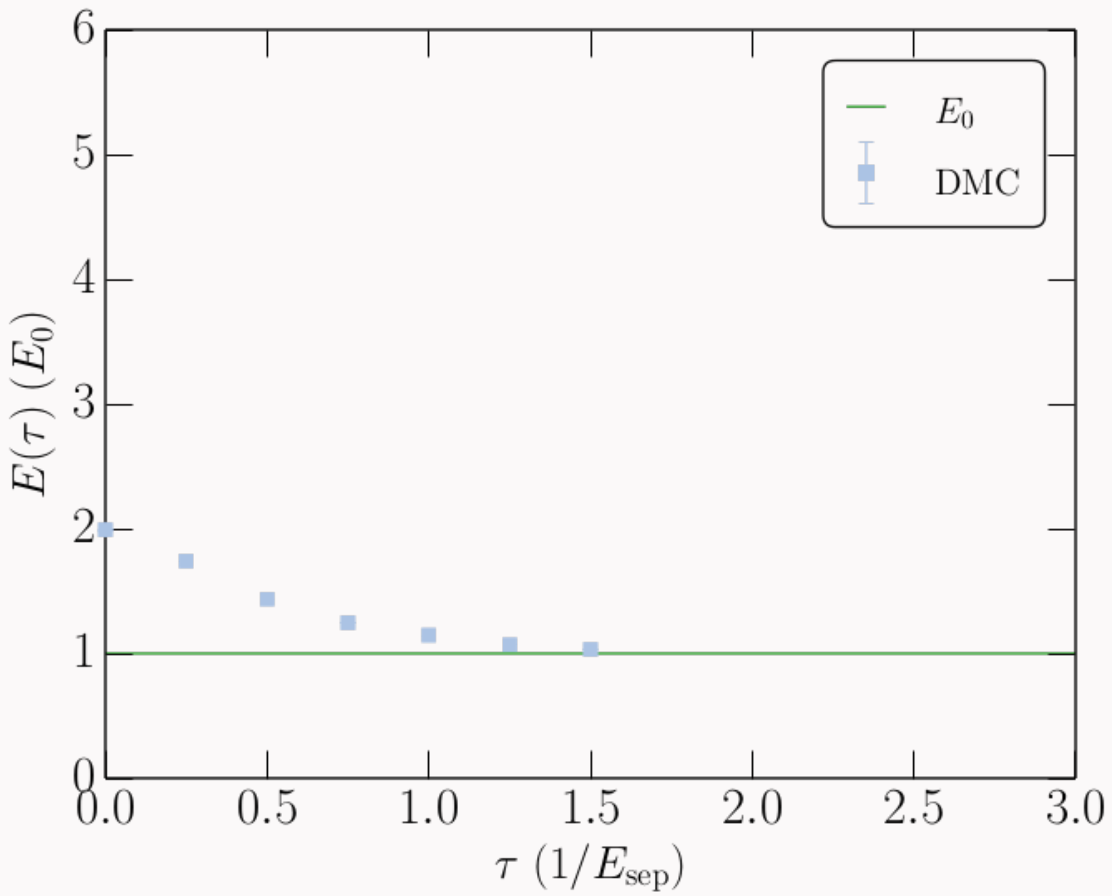
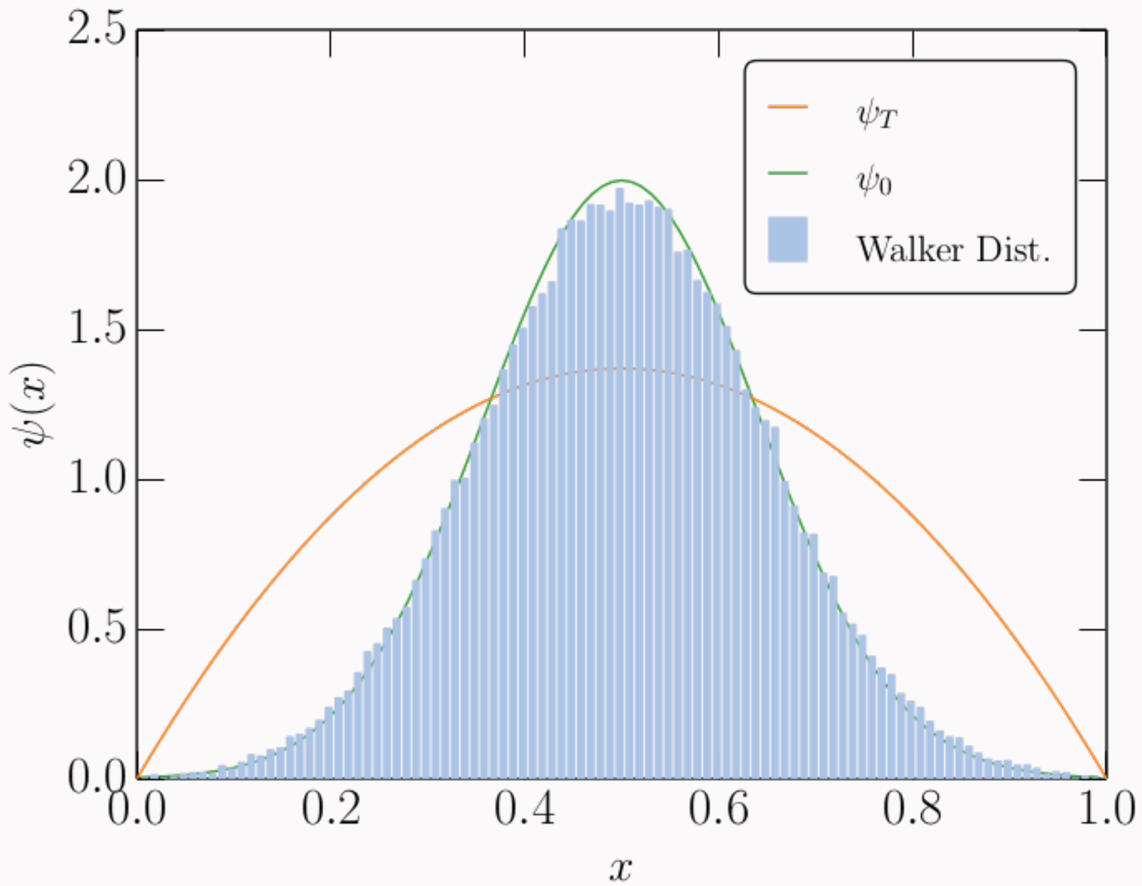
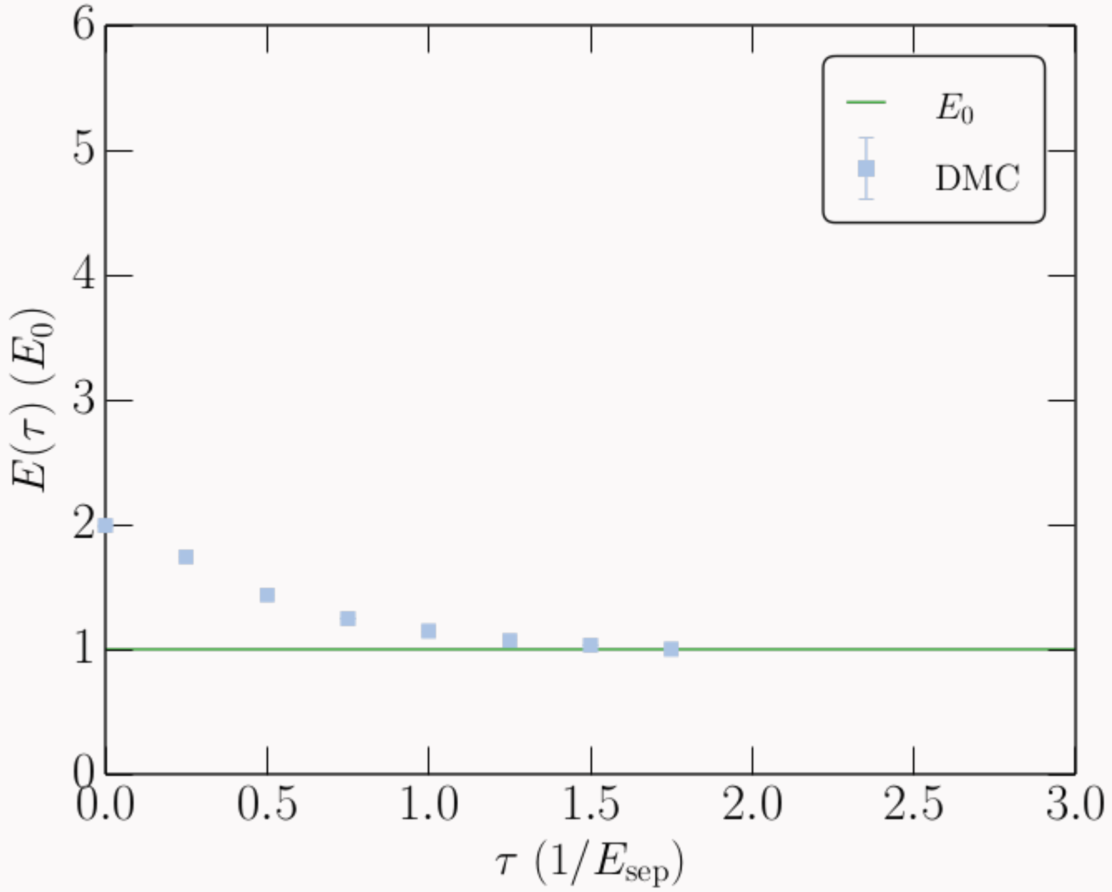


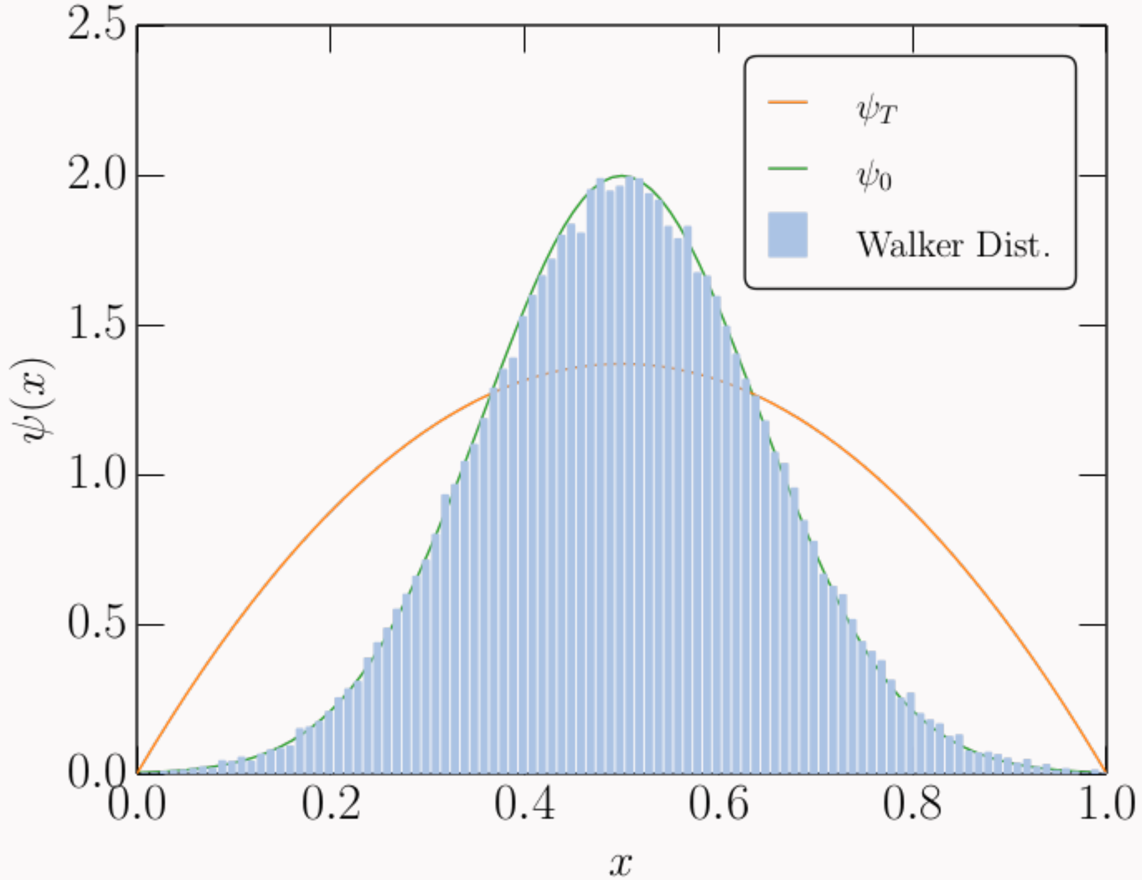


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 1.75$

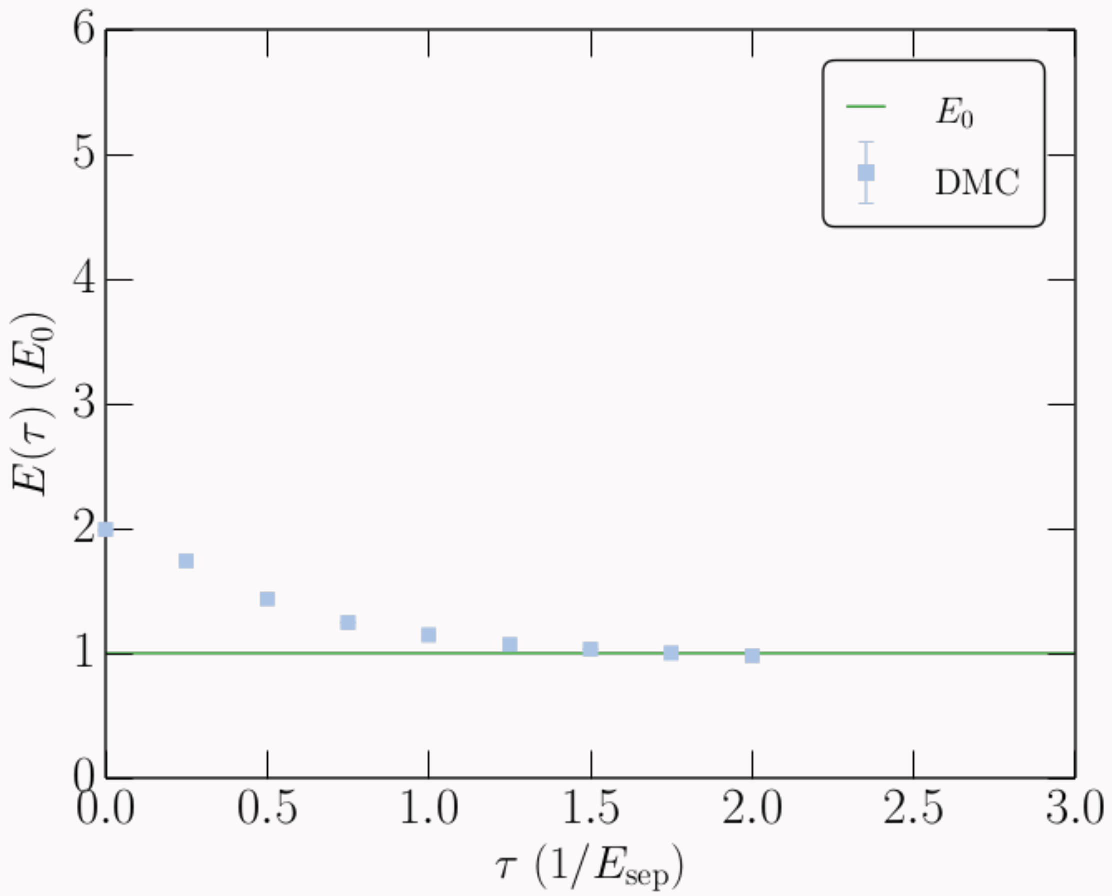


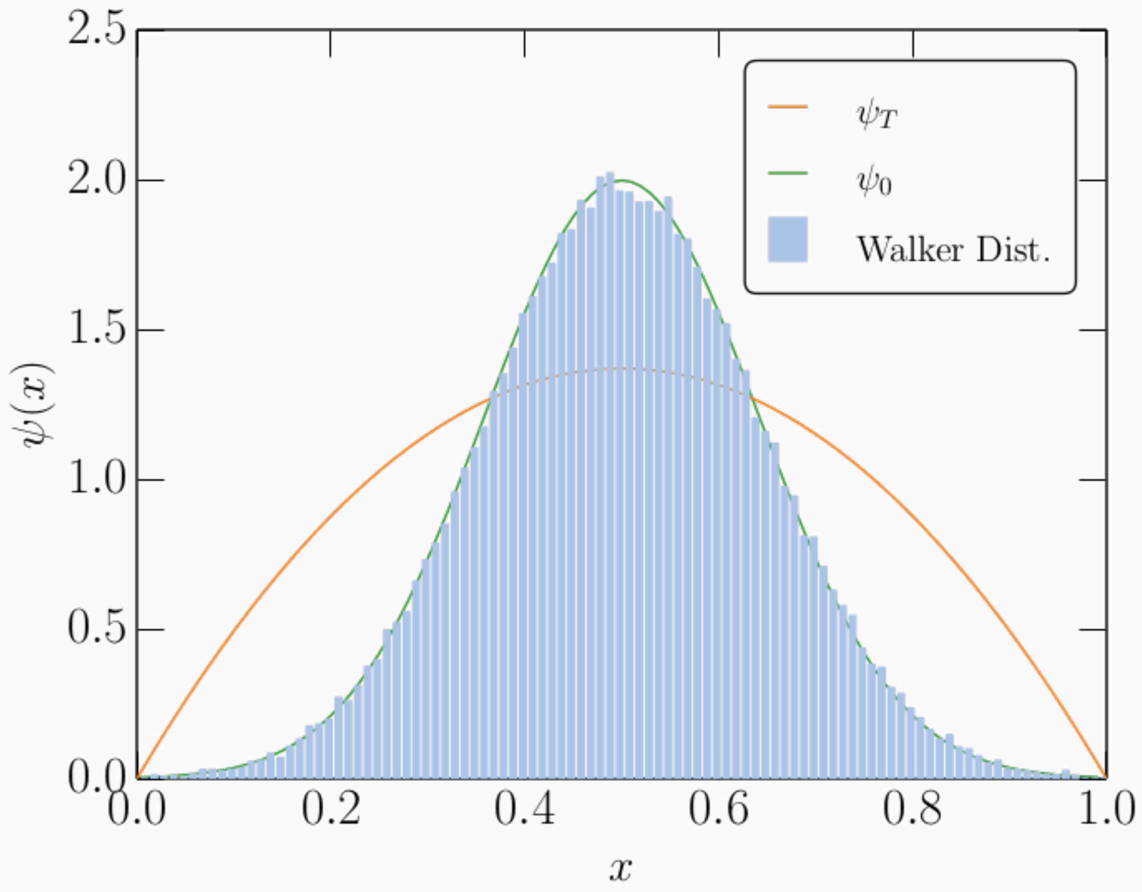


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 2.00$





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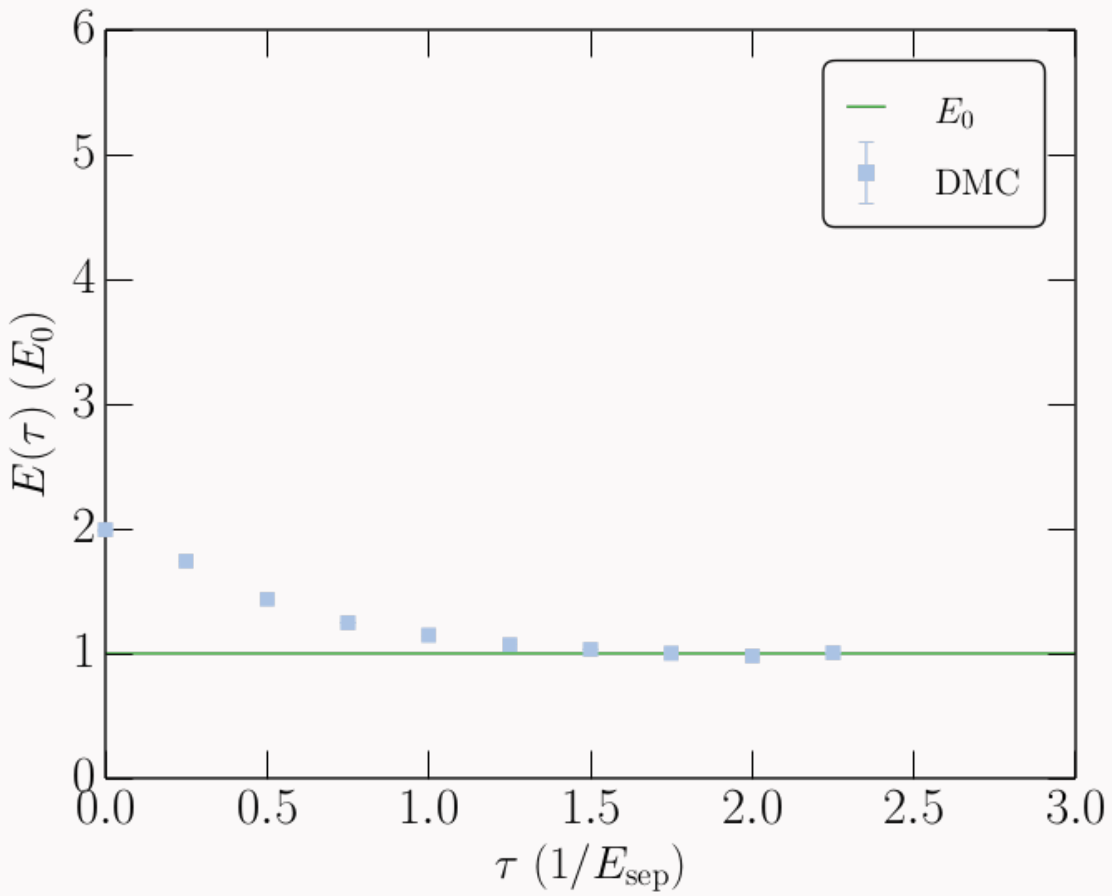

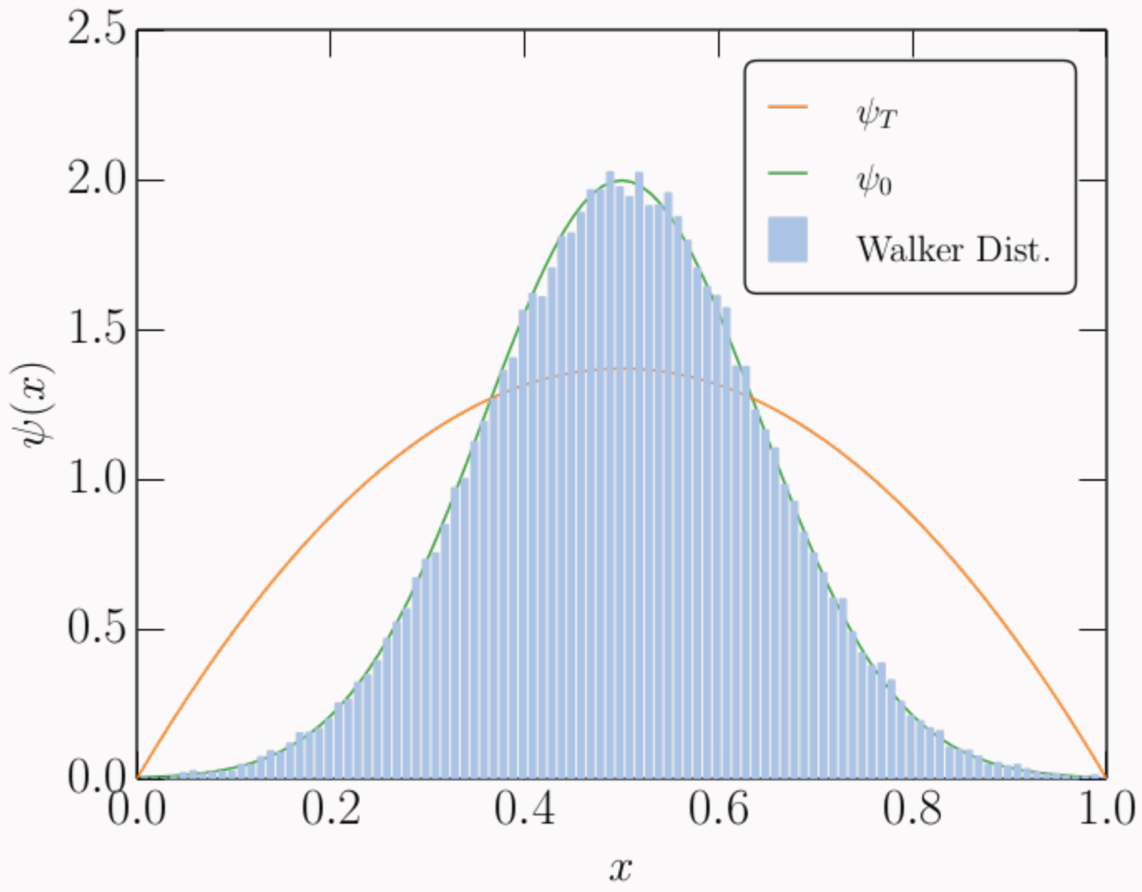

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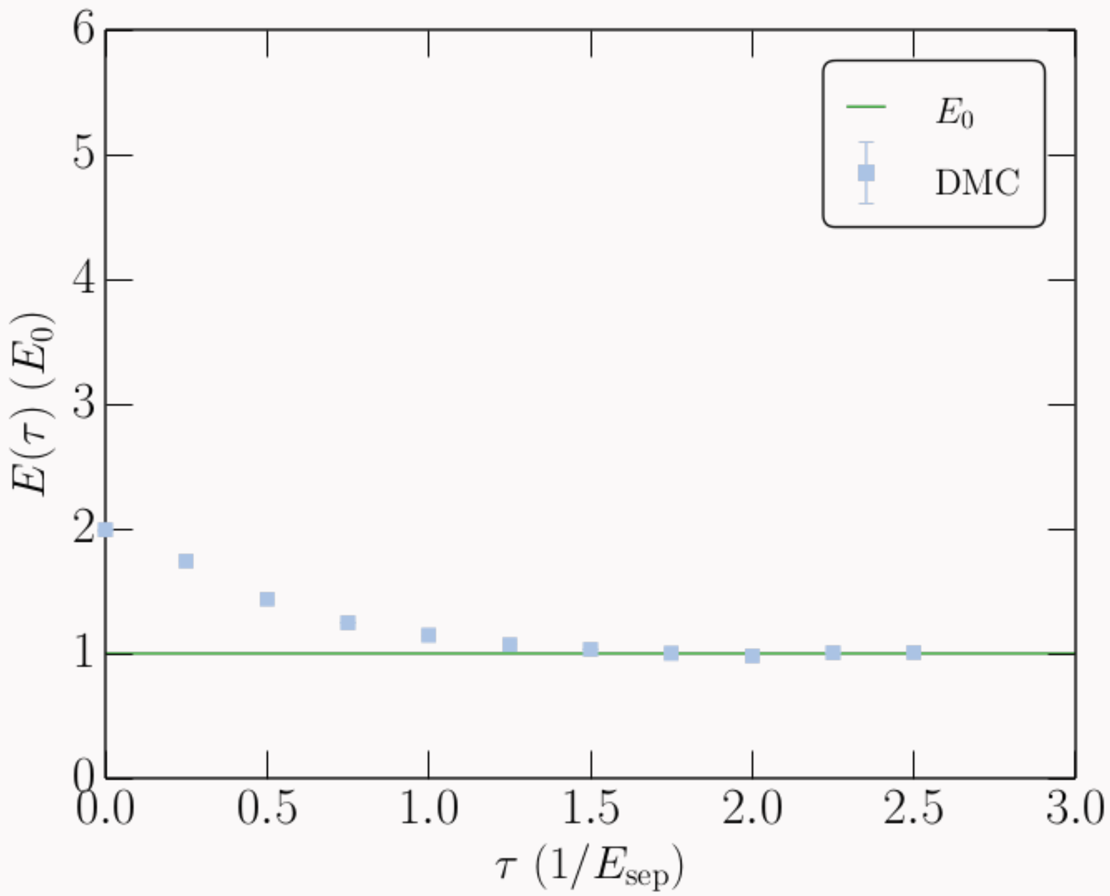

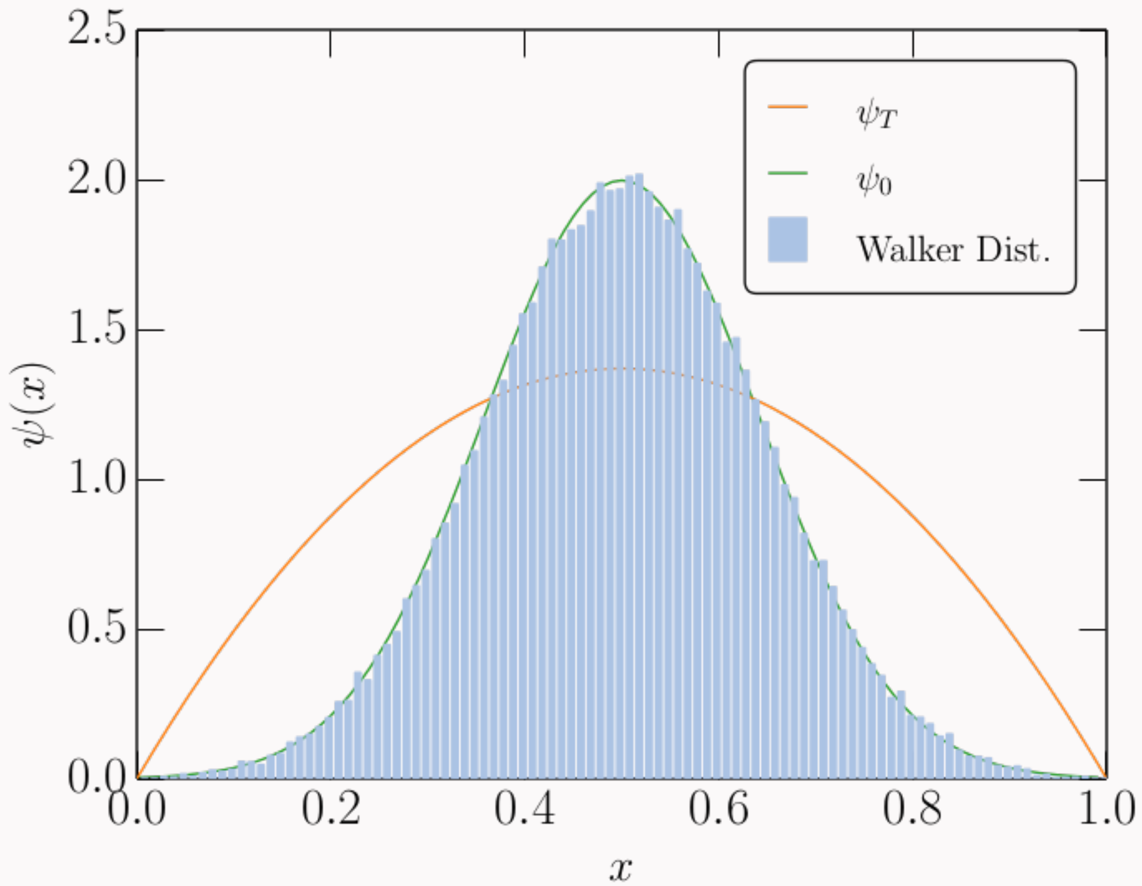

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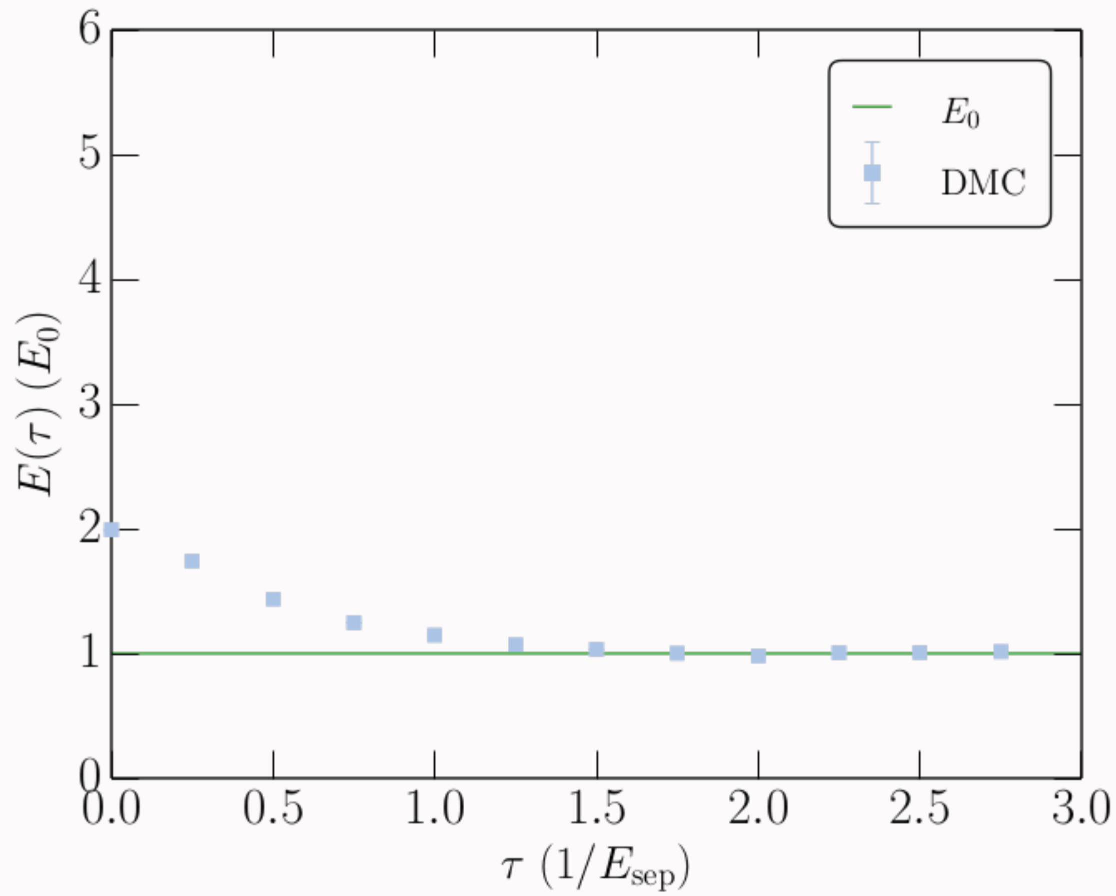
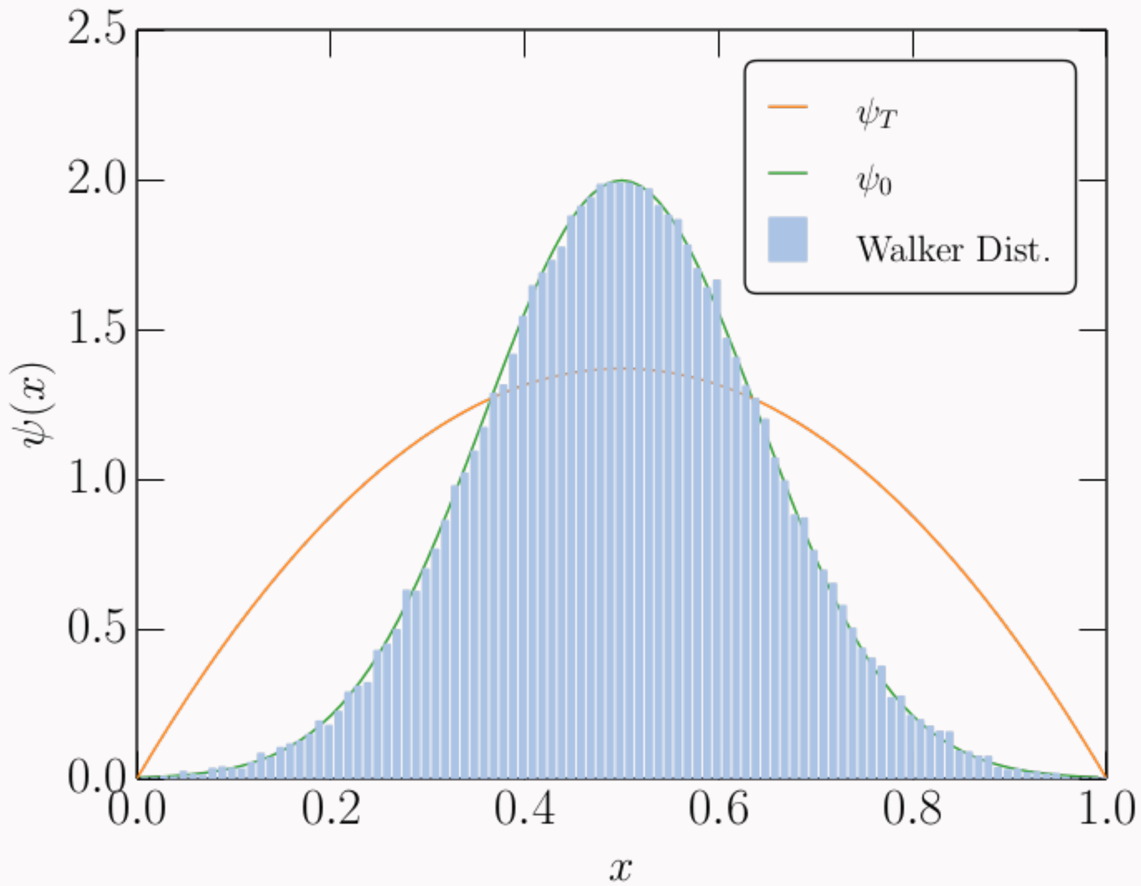
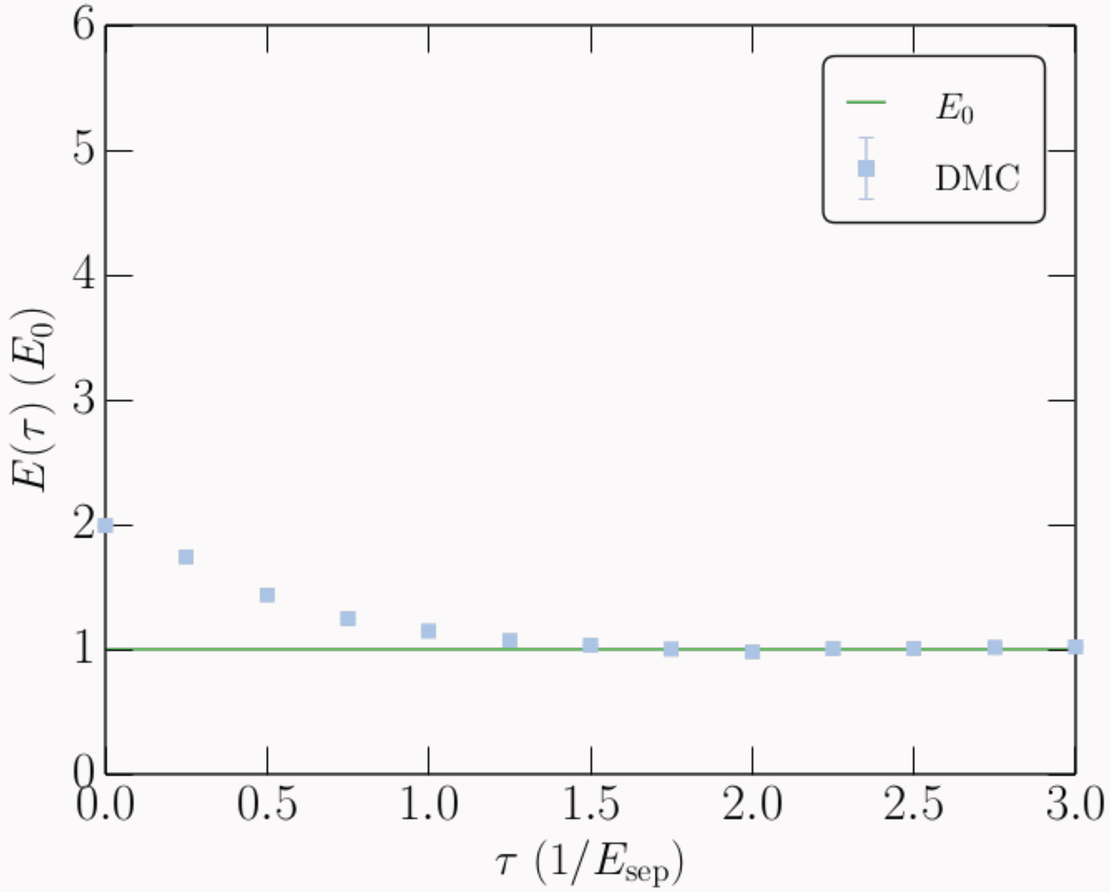


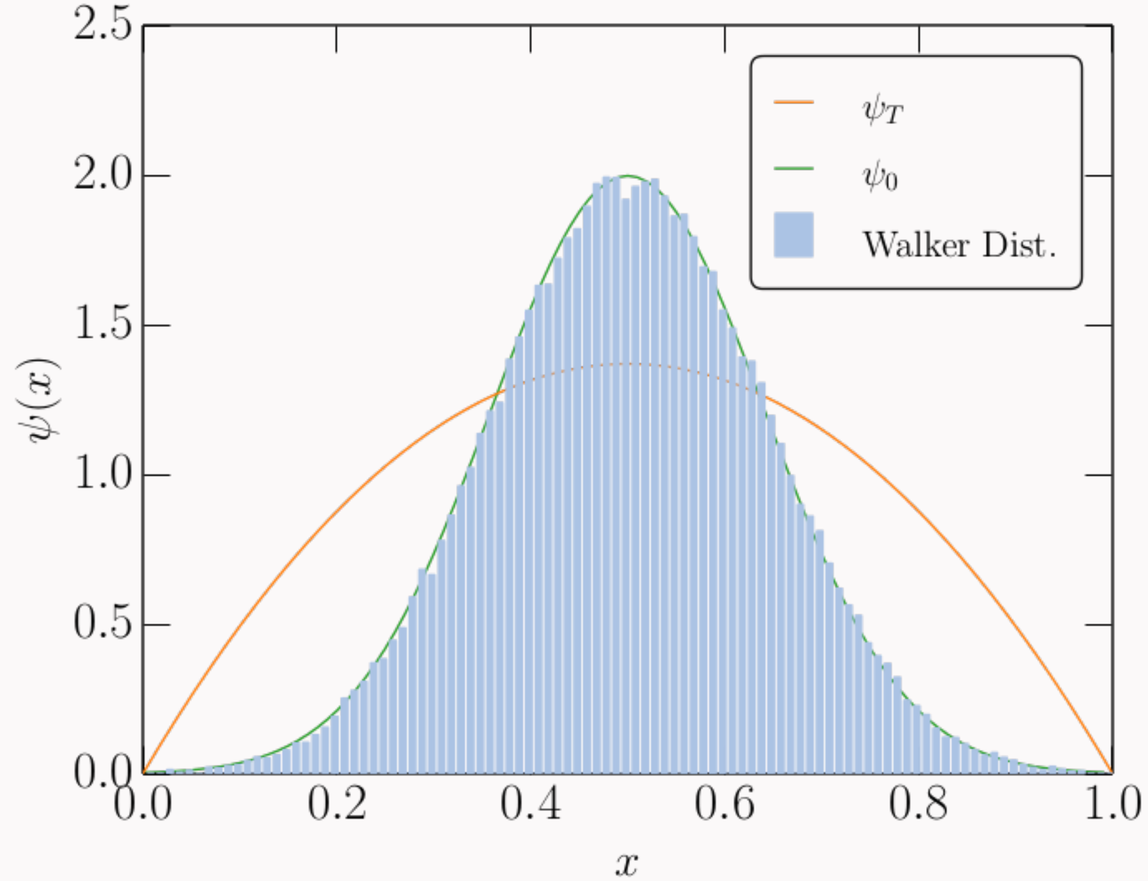


QMC Methods - An Example

Imaginary-time evolution:

τ = 3.00





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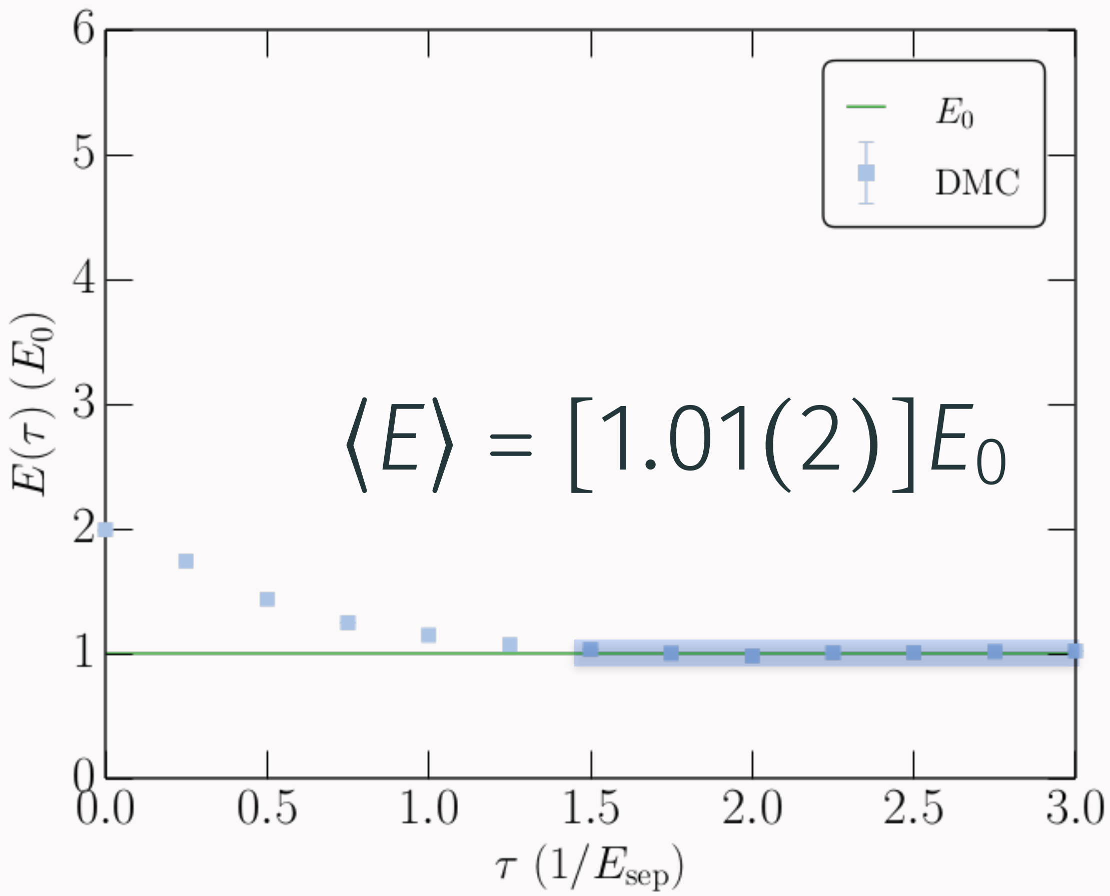
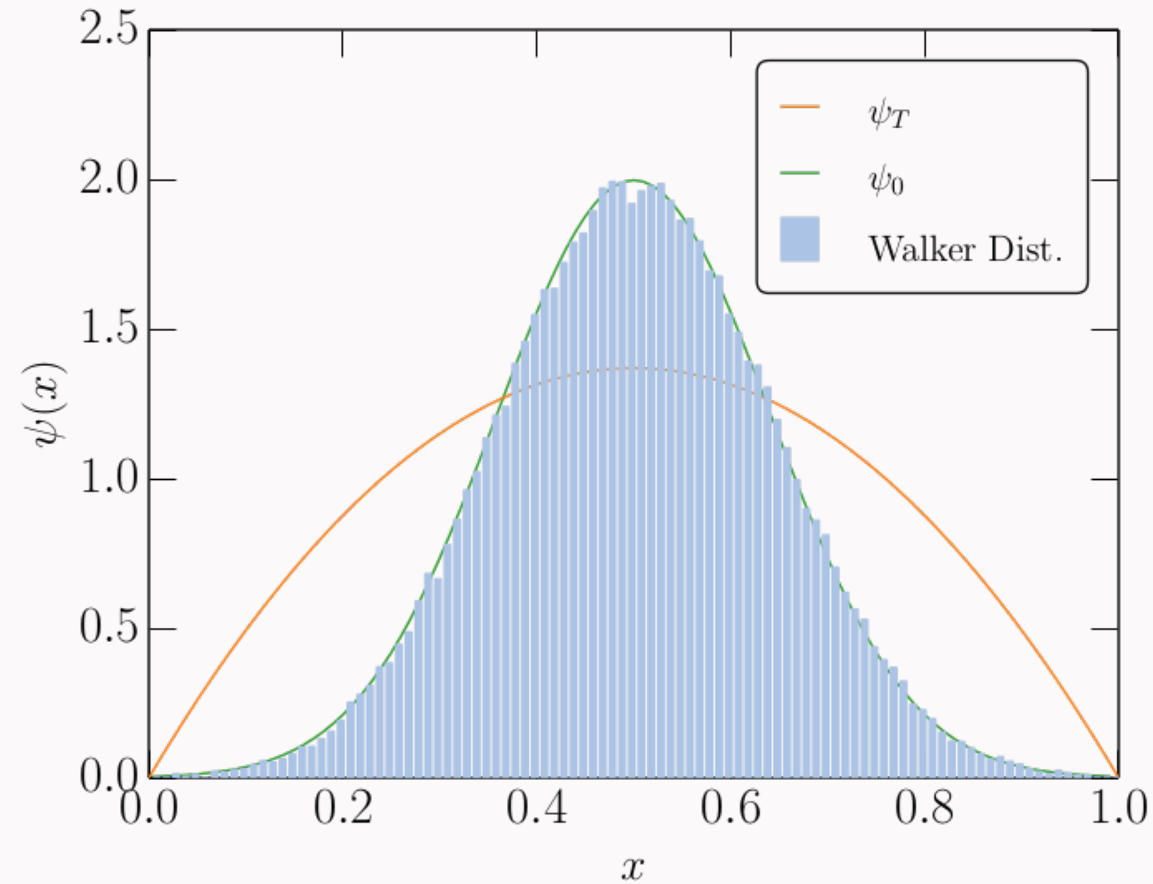


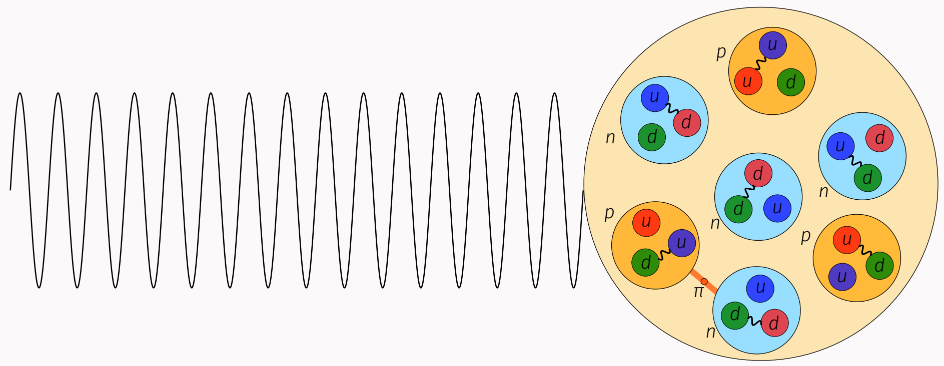


QMC Methods - Compare/Contrast GFMC & AFDMC

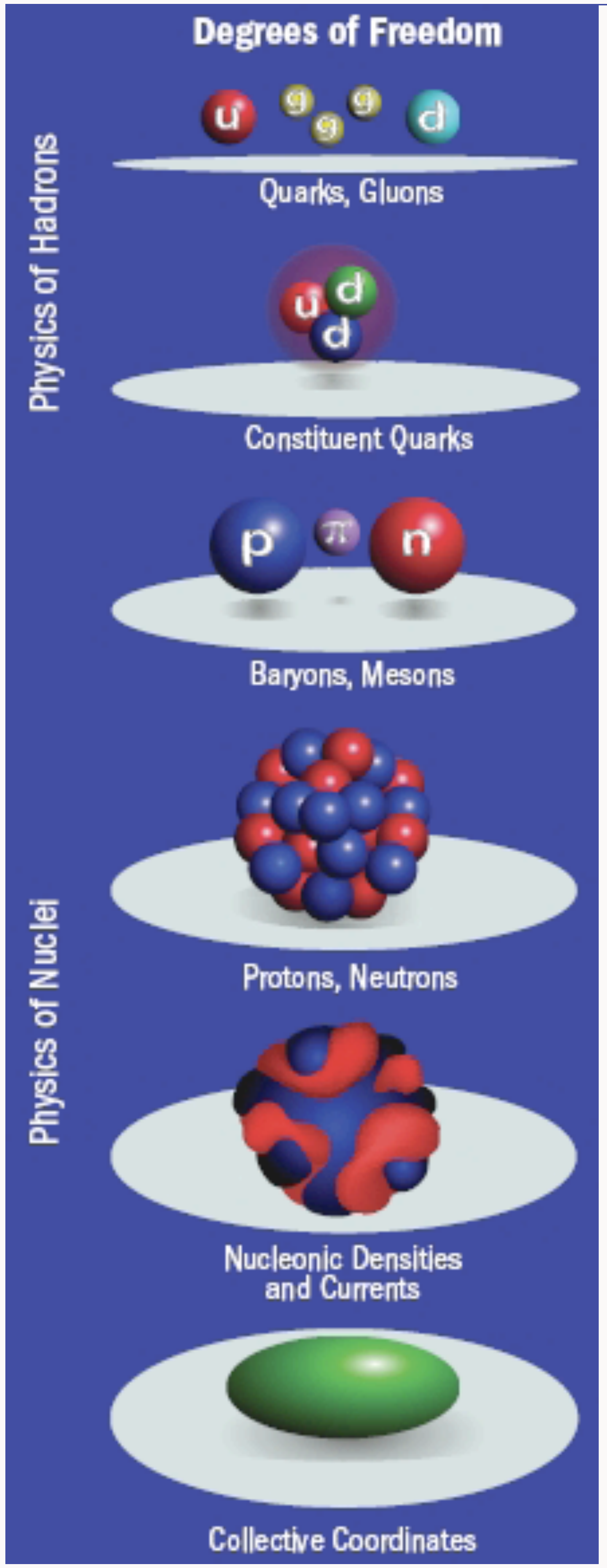
Green's function Monte Carlo (GFMC)	Auxiliary-field diffusion Monte Carlo (AFDMC)
• $\lvert\Psi_T\rangle \sim 3A$ coordinates & $2^A\binom{A}{Z}$ complex amplitudes: *Exponential scaling.*	• $\lvert\Psi_T\rangle \sim 3A$ coordinates & $4A$ complex amplitudes $(\lvert n\uparrow\rangle, \lvert n\downarrow\rangle,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

Chiral Effective Field Theory (EFT)

Chiral EFT

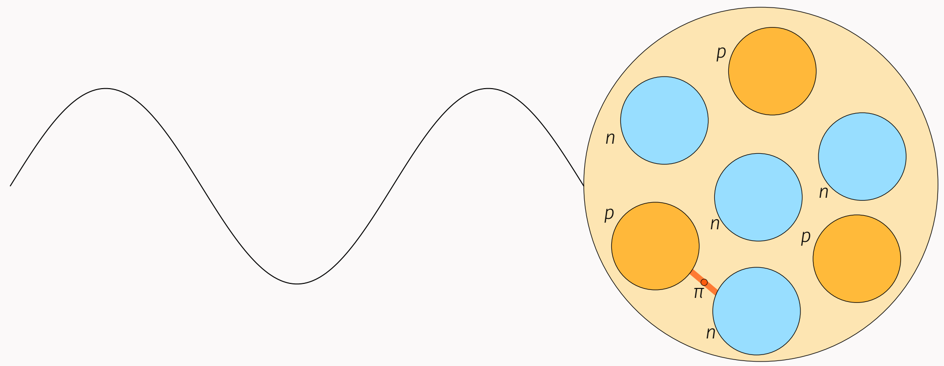


- If probed at high energies, substructure is resolved.
- At low energies, details are not resolved.
- Can replace fine structure by something simpler (think of multipole expansion): low-energy observables unchanged.



Lower Resolution

Chiral EFT



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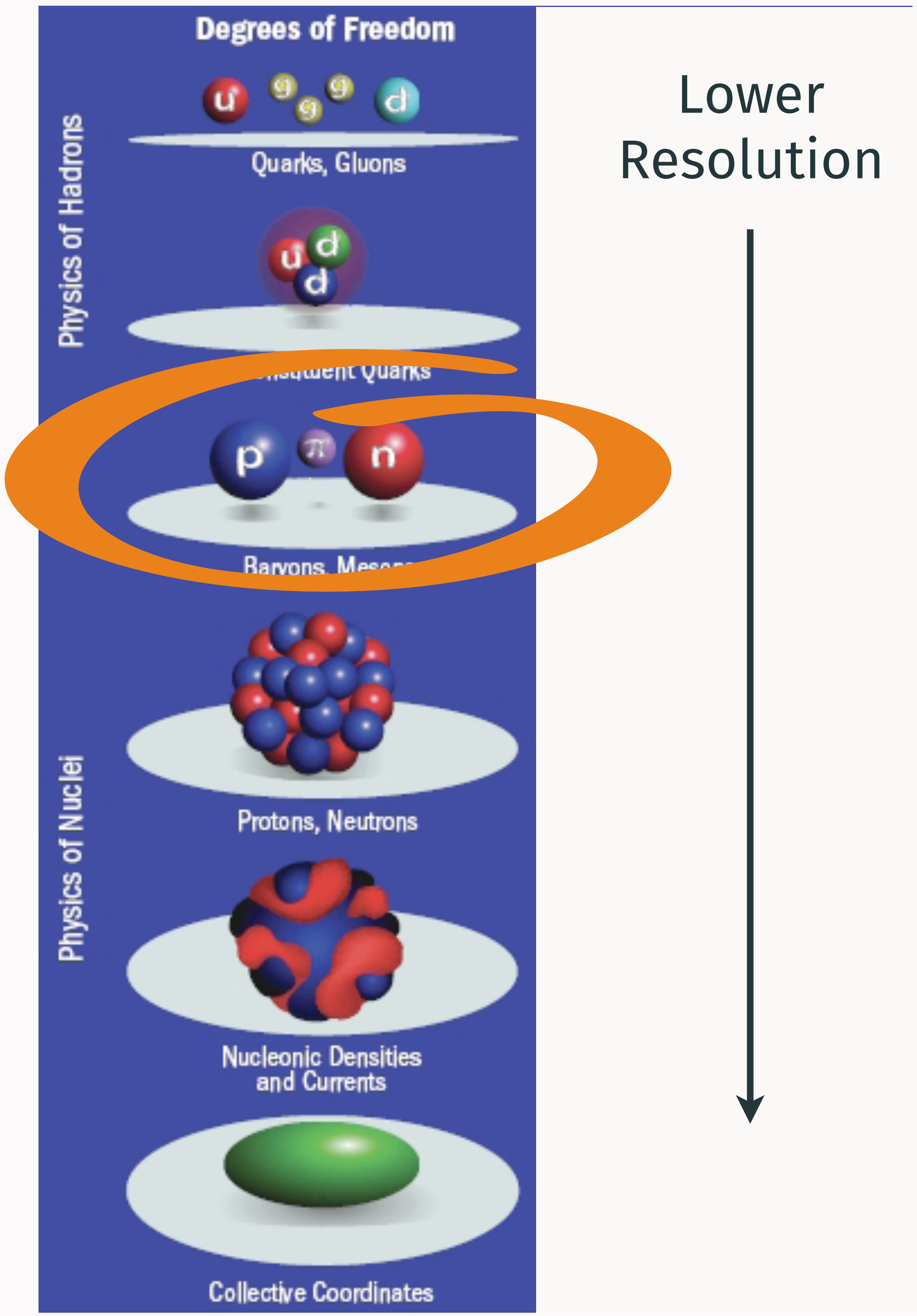
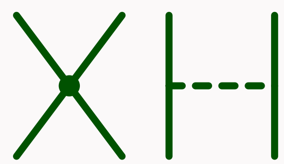
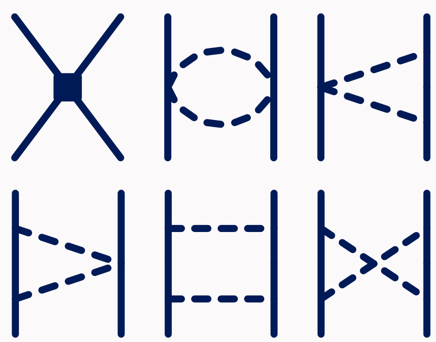
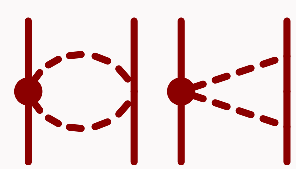
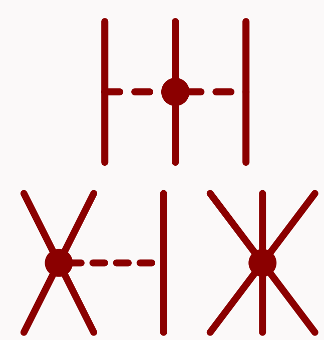
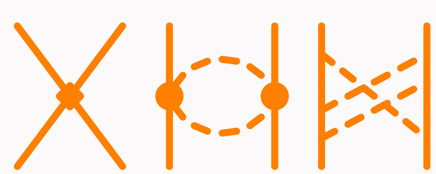


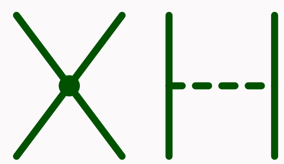
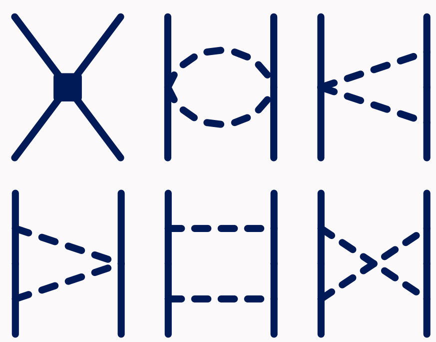
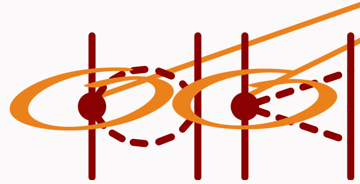
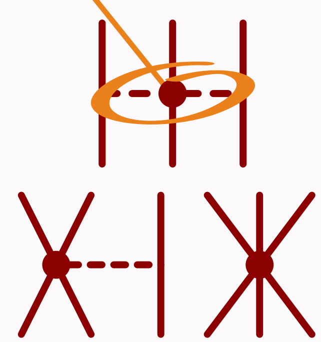
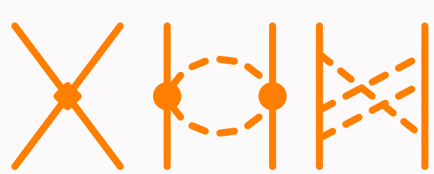
Chiral EFT

		NN	NNN
LO	$\mathcal{O}\left(\frac{Q}{\Lambda_b}\right)^0$		–
NLO	$\mathcal{O}\left(\frac{Q}{\Lambda_b}\right)^2$		–
N²LO	$\mathcal{O}\left(\frac{Q}{\Lambda_b}\right)^3$	 $+\cdots$	
N³LO	$\mathcal{O}\left(\frac{Q}{\Lambda_b}\right)^4$	 $+\cdots$	 $+\cdots$

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

		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	$\mathcal{O}\left(\frac{Q}{\Lambda_b}\right)^4$	 $+\cdots$	 $+\cdots$

Same LECs in NN & $3N$ sectors!

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

- Chiral EFT: Expand in powers of Q/Λ_b.
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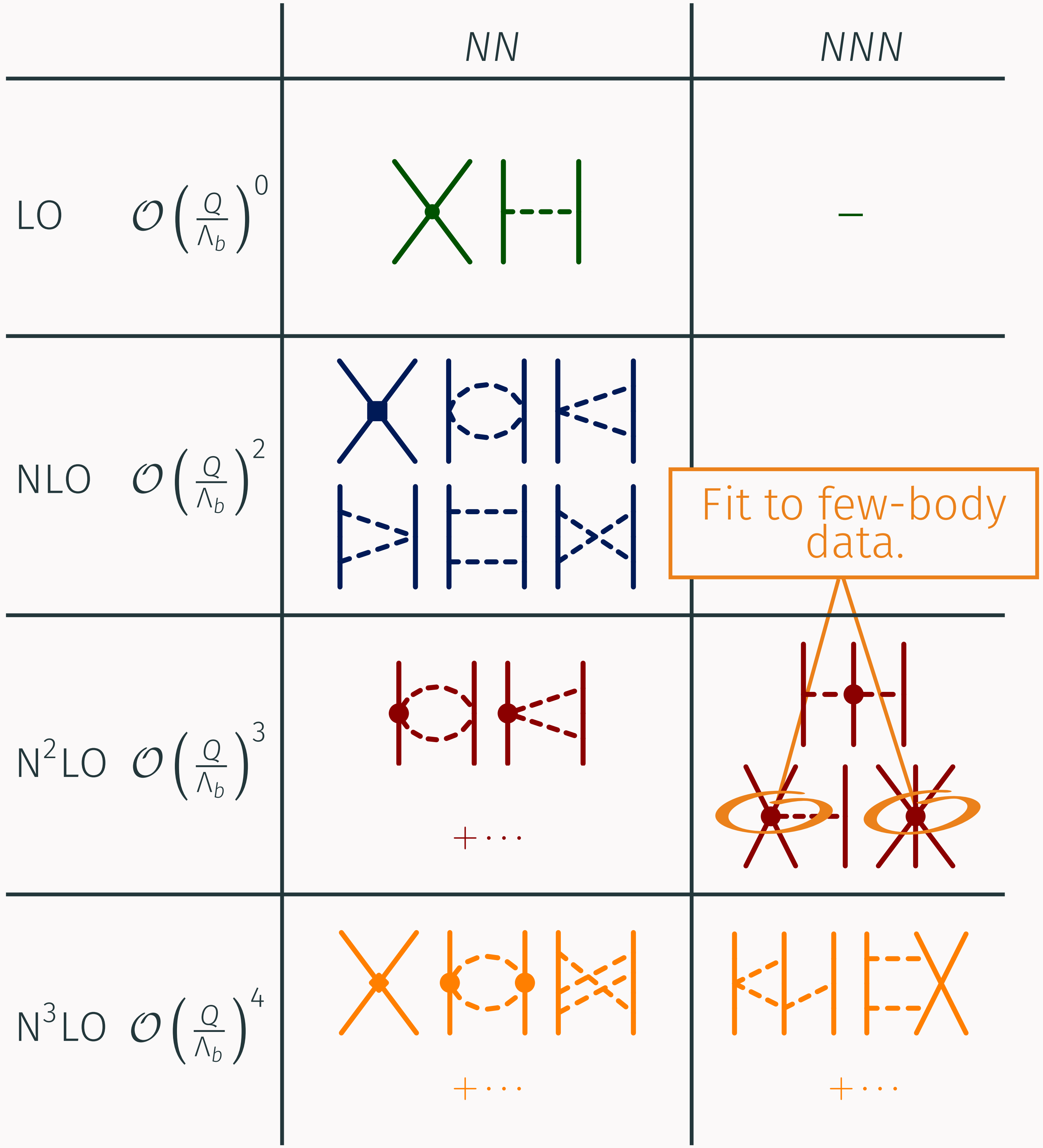
Chiral EFT



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

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- Long-range physics: π exchanges.
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- Many-body forces & currents enter systematically.

Chiral EFT

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

Definitions.

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

Regulator:

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

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^2LO.

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Regulator:

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

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

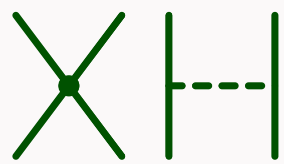
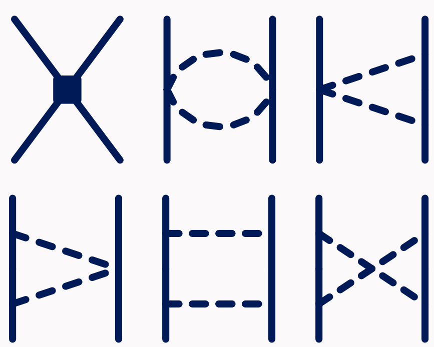
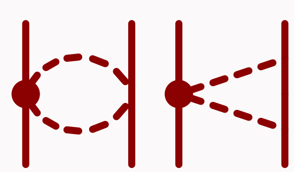
Contacts:

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

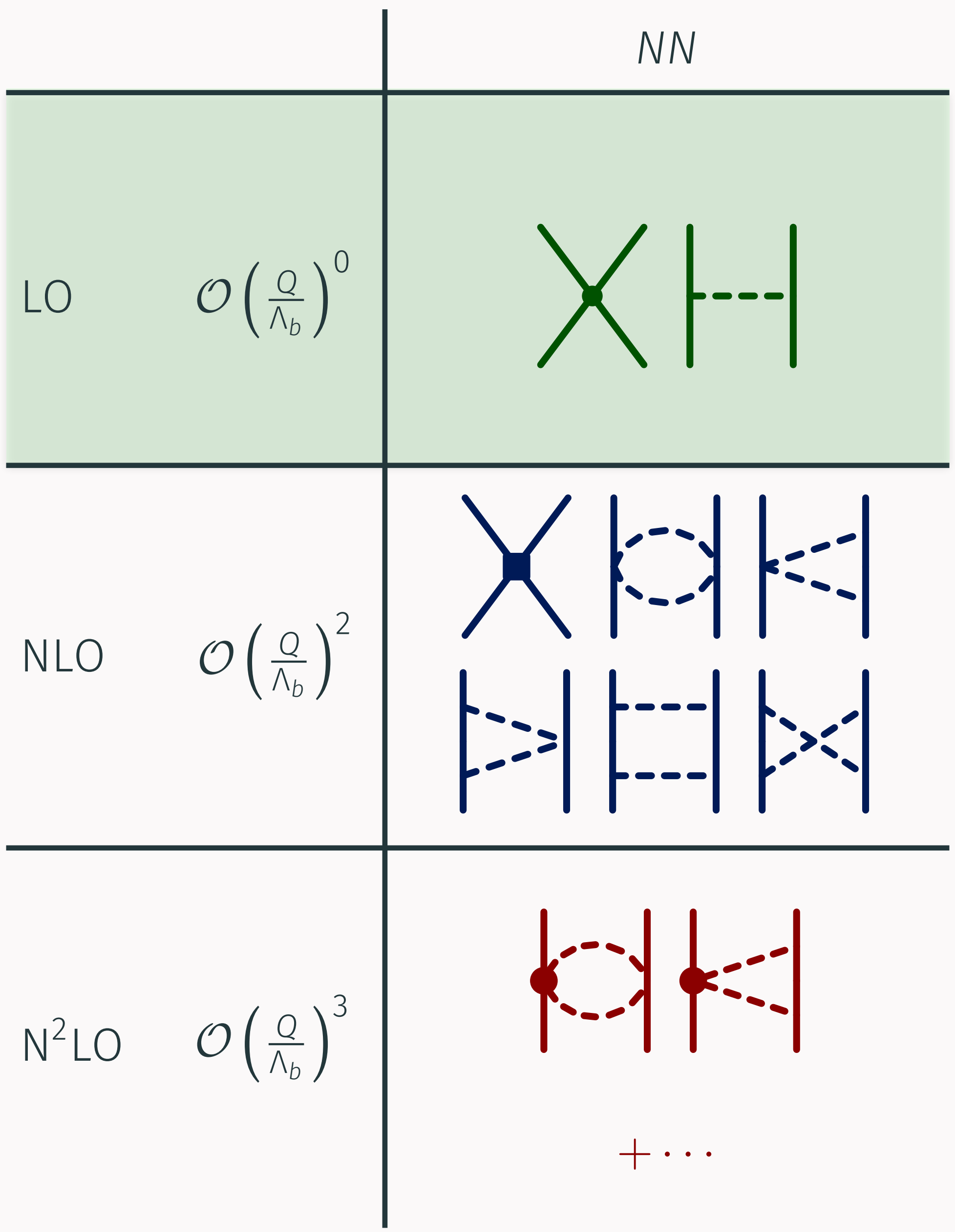
$\rightarrow$ Choose contacts $\propto \mathbf{q}$ (As much as possible!)

[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^2LO	$\mathcal{O}\left(\frac{Q}{\Lambda_b}\right)^3$	 $+\cdots$

Chiral EFT



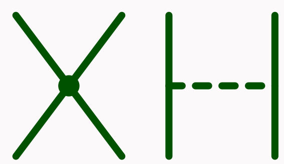
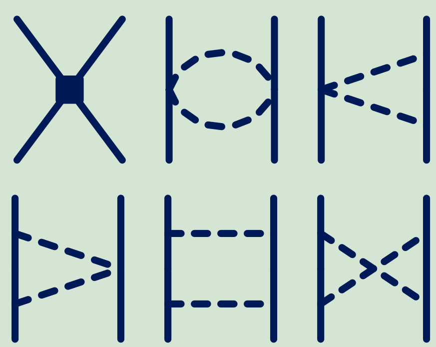
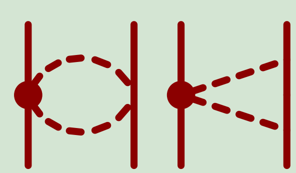
$$V_{\text{cont}}^{(0)} = \alpha_1 + \alpha_2(\sigma_1 \cdot \sigma_2) + \alpha_3(\tau_1 \cdot \tau_2) + \alpha_4(\sigma_1 \cdot \sigma_2)(\tau_1 \cdot \tau_2)$$

Pauli Exclusion Principle

$\rightarrow$ Only two independent contacts!

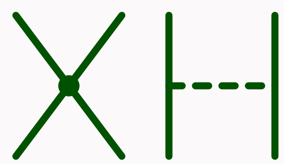
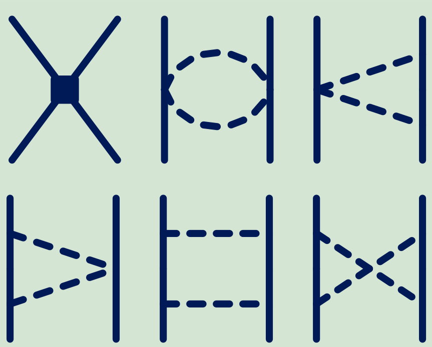
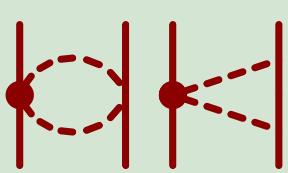
$$V_{\text{cont}}^{(0)} = C_S + C_T(\sigma_1 \cdot \sigma_2)$$

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	$\mathcal{O}\left(\frac{Q}{\Lambda_b}\right)^3$	 $+\cdots$

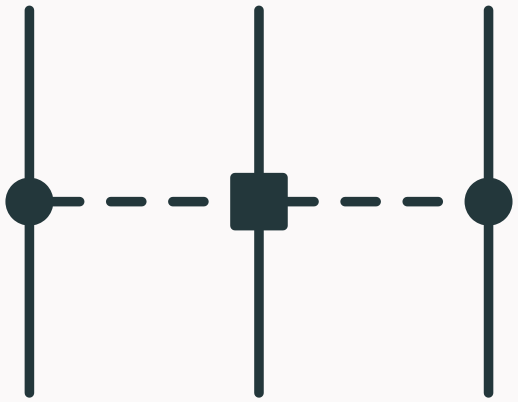
$$
\begin{aligned}
V^{(2)}_{\text{cont}} &= \gamma_1 q^2 + \gamma_2 q^2 (\sigma_1 \cdot \sigma_2) \\
&+ \gamma_3 q^2 (\tau_1 \cdot \tau_2) + \gamma_4 q^2 (\sigma_1 \cdot \sigma_2)(\tau_1 \cdot \tau_2) \\
&+ \gamma_5 k^2 + \gamma_6 k^2 (\sigma_1 \cdot \sigma_2) + \gamma_7 k^2 (\tau_1 \cdot \tau_2) \\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

Chiral EFT

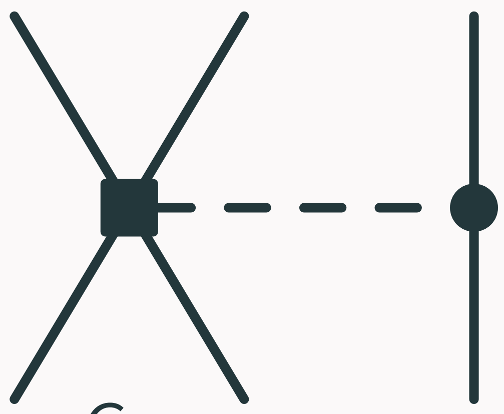
		NN
LO	$\mathcal{O}\left(\frac{Q}{\Lambda_b}\right)^0$	
NLO	$\mathcal{O}\left(\frac{Q}{\Lambda_b}\right)^2$	
$\mathrm{N}^2\mathrm{LO}$	$\mathcal{O}\left(\frac{Q}{\Lambda_b}\right)^3$	 $+\cdots$

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

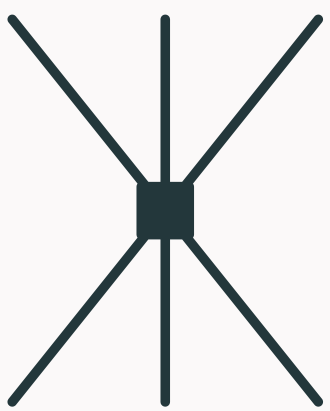
Three-Nucleon Interaction



$c_1,\ c_3,\ c_4$

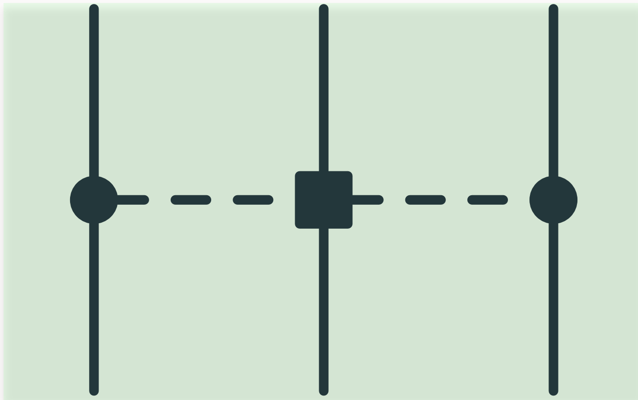


c_D

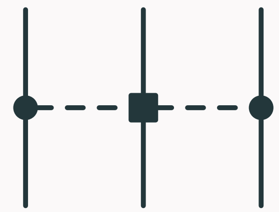


c_E

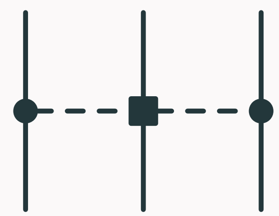
Three-Nucleon Interaction



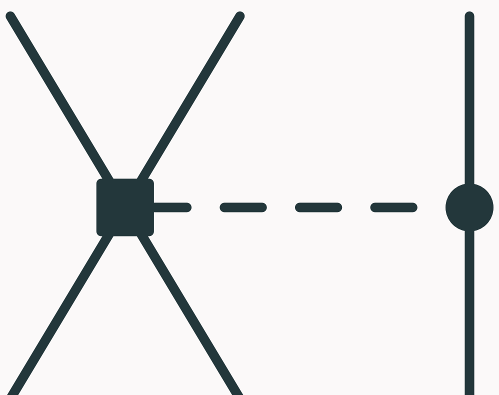
c_1, c_3, c_4

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

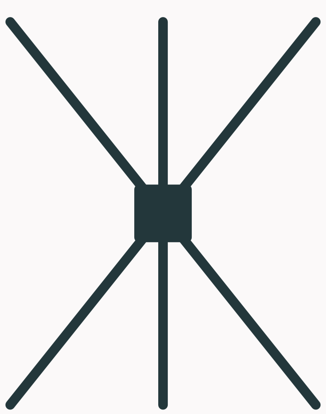
c_1

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

c_3, c_4

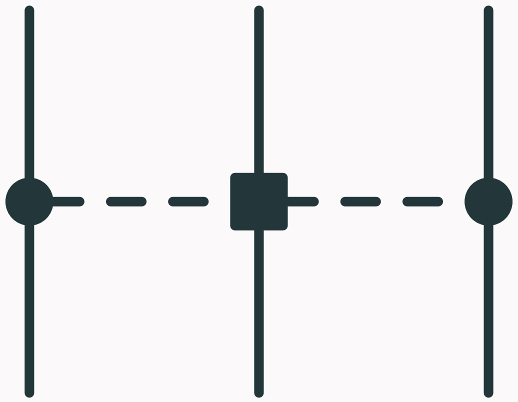


c_D

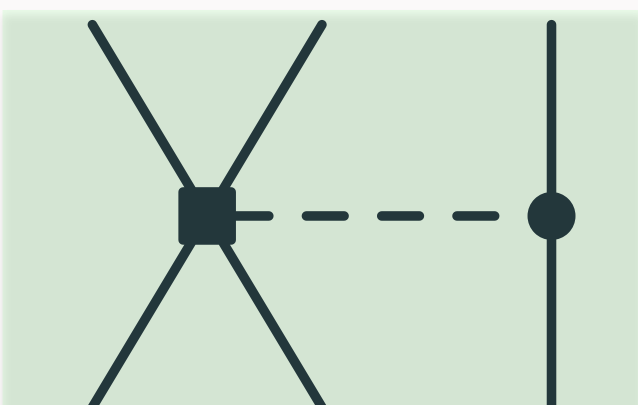


c_E

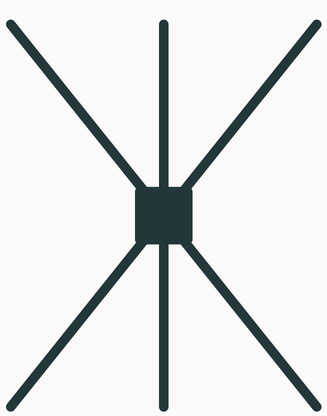
Three-Nucleon Interaction



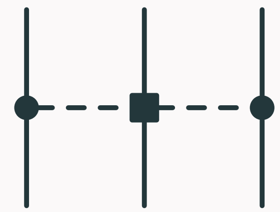
$c_1,\ c_3,\ c_4$



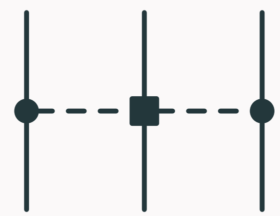
c_D



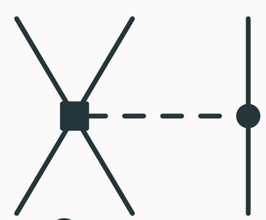
c_E

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

c_1

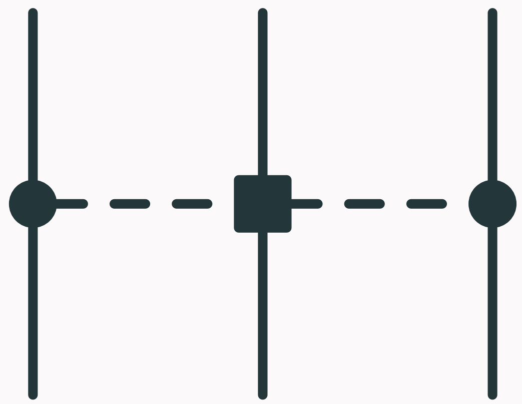
$\mathcal{F}\Big\{$  $\Big\}$ $\rightarrow\sim$ Fujita-Miyazawa

$c_3,\ c_4$

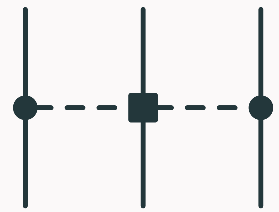
$\mathcal{F}\Big\{$  $\Big\}$ $\rightarrow$ 1π-Exchange + Contact

c_D

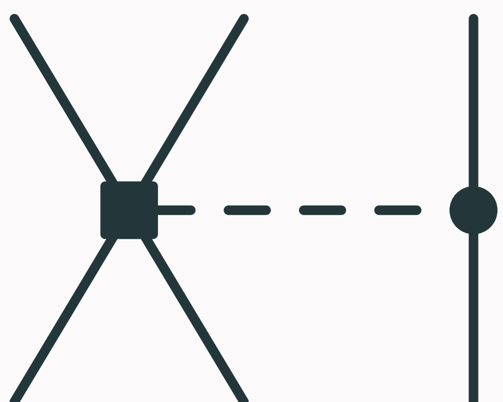
Three-Nucleon Interaction



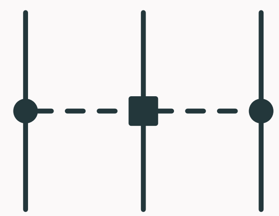
$c_1,\ c_3,\ c_4$

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

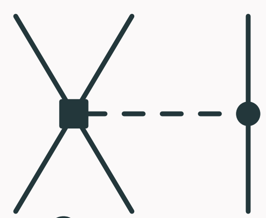
c_1



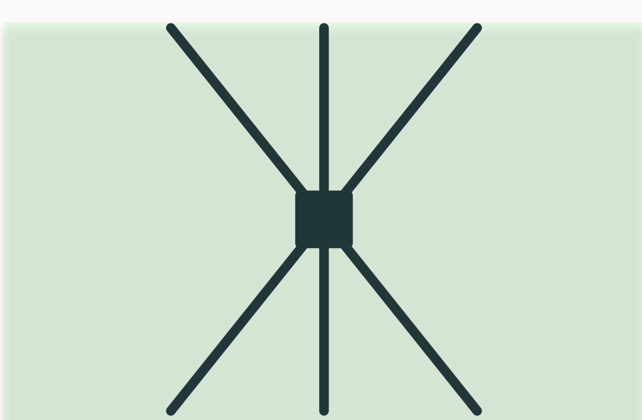
c_D

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

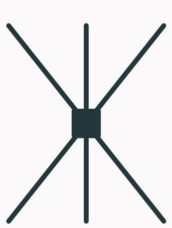
$c_3,\ c_4$

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

c_D



c_E

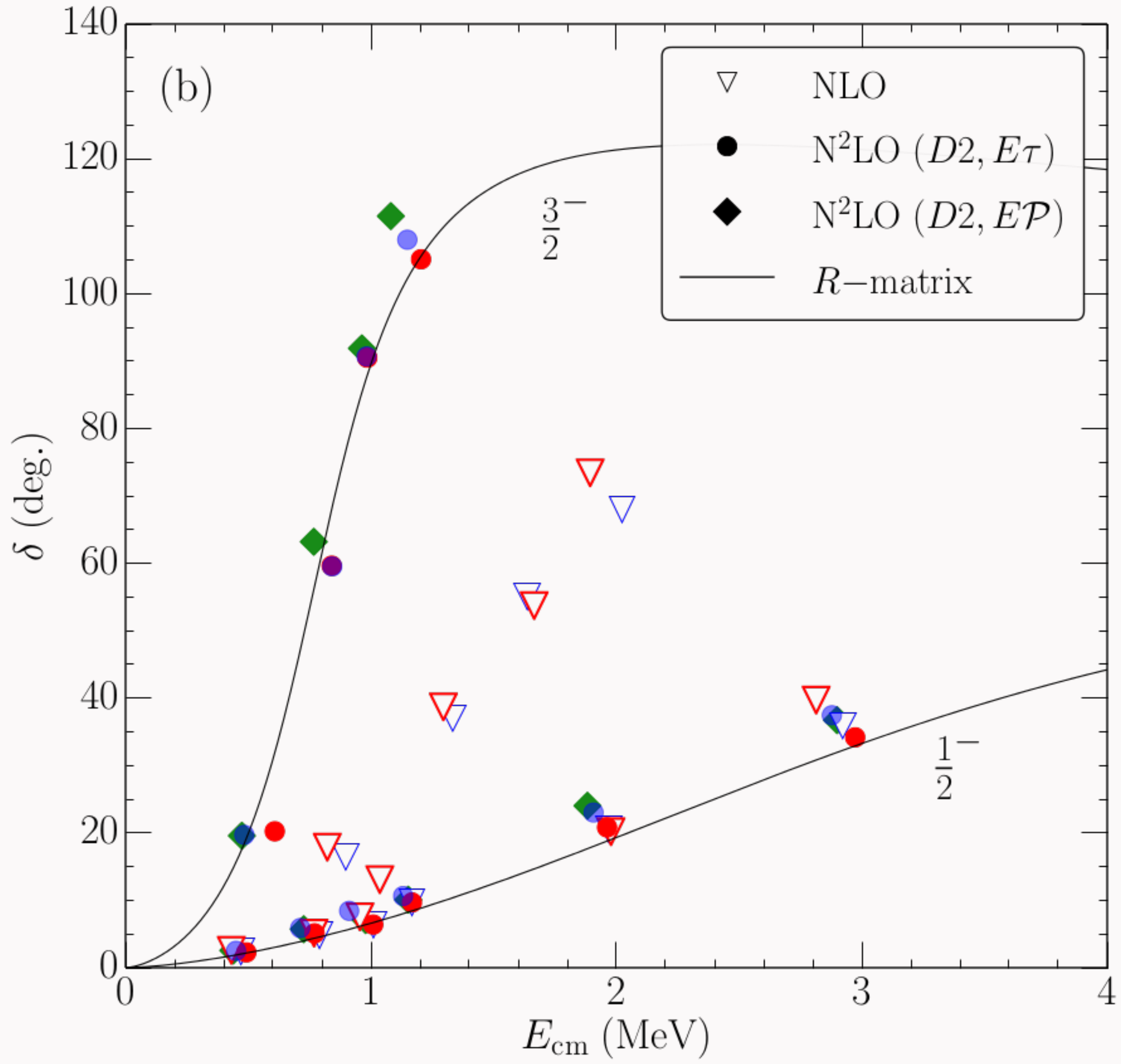
$\mathcal{F}\Big\{$  $\Big\}$ $\rightarrow$ Contact

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.



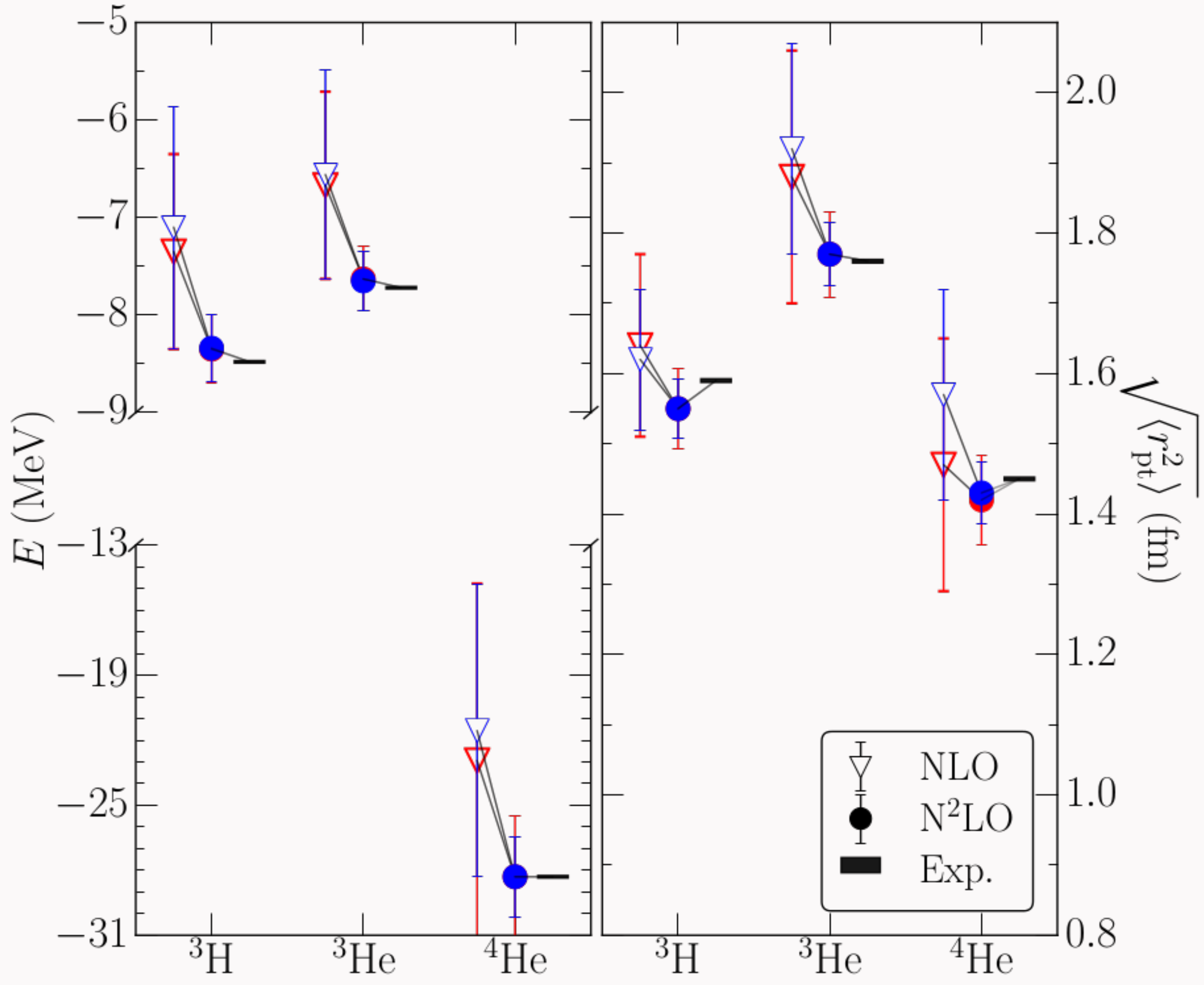
JEL et al, PRL **116**, 062501 (2016)

QMC Methods + Chiral EFT Interactions - The Rug

First Results

One consistent approach:

Light Nuclei

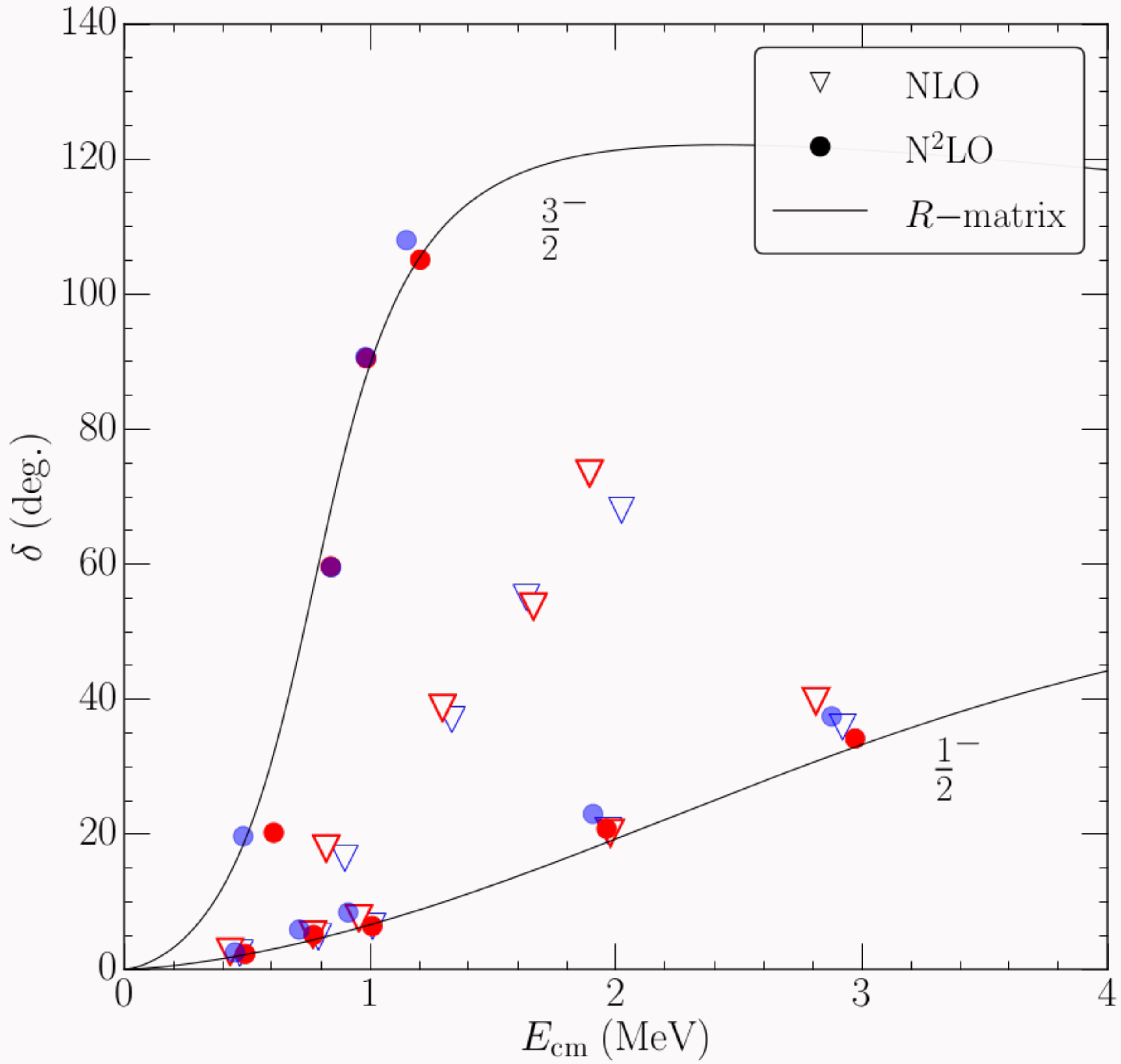


JEL et al, PRL **116**, 062501 (2016)

First Results

One consistent approach:

n-*α* Elastic Scattering

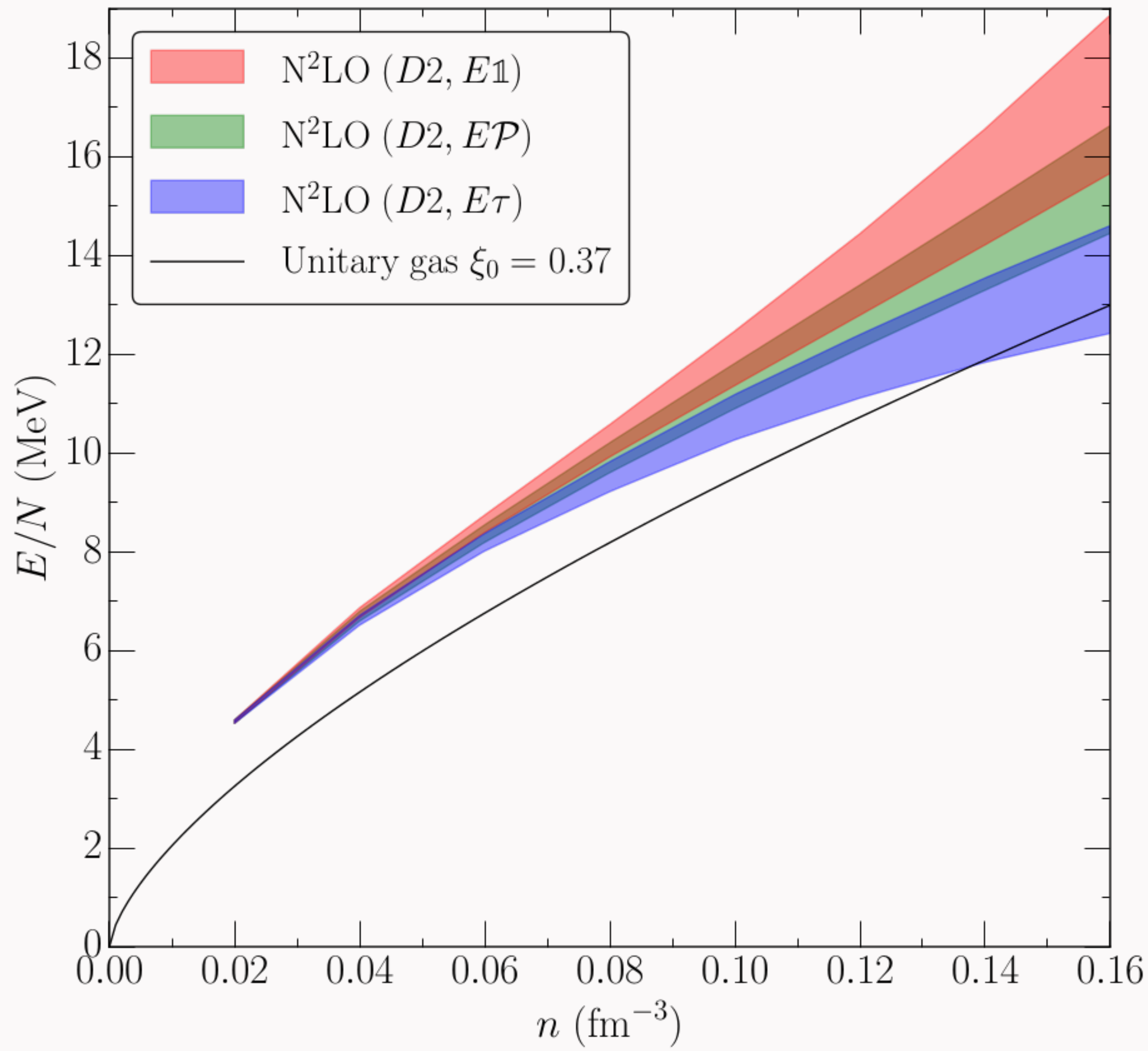


JEL et al, PRL **116**, 062501 (2016)

First Results

One consistent approach:

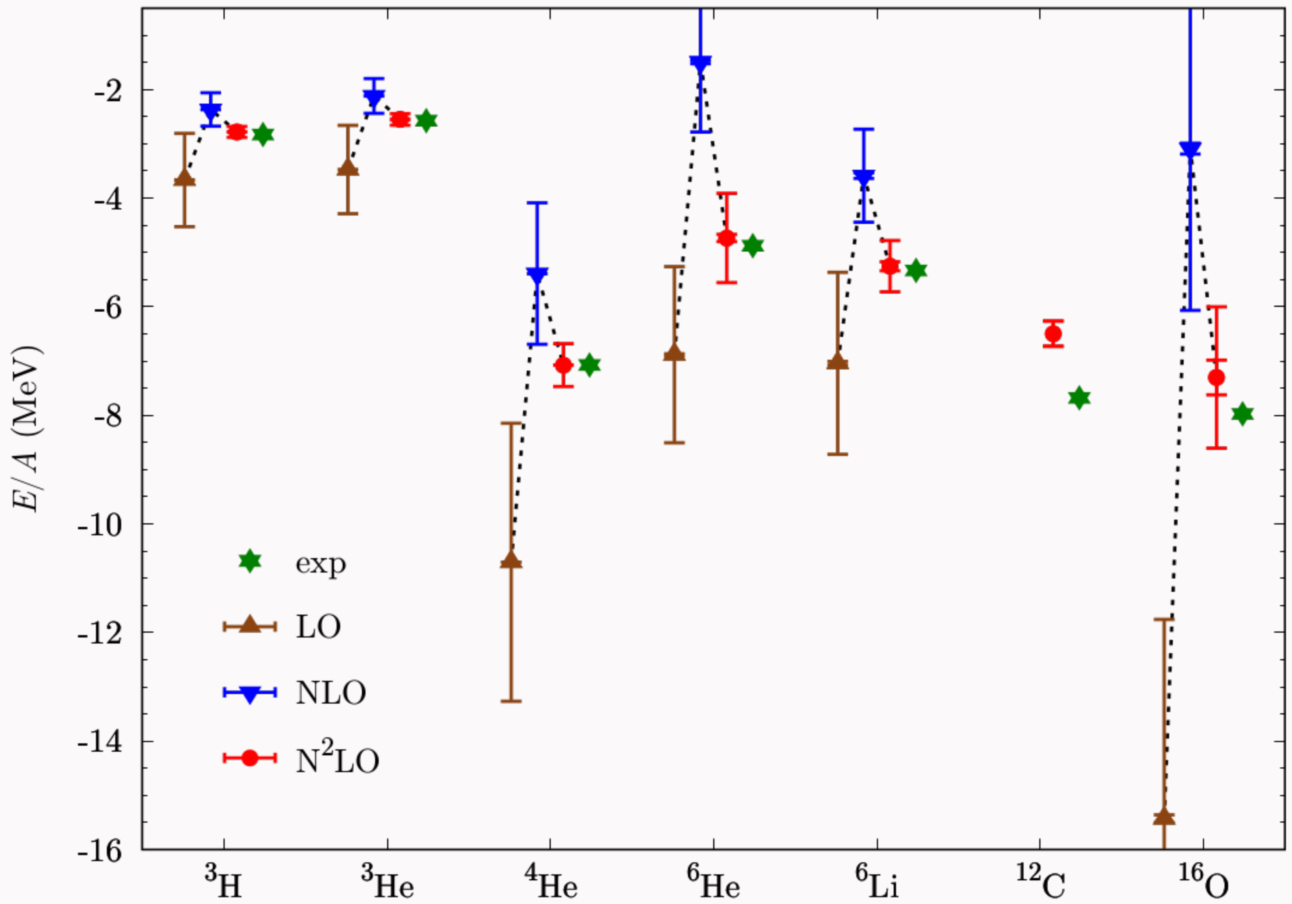
Neutron Matter

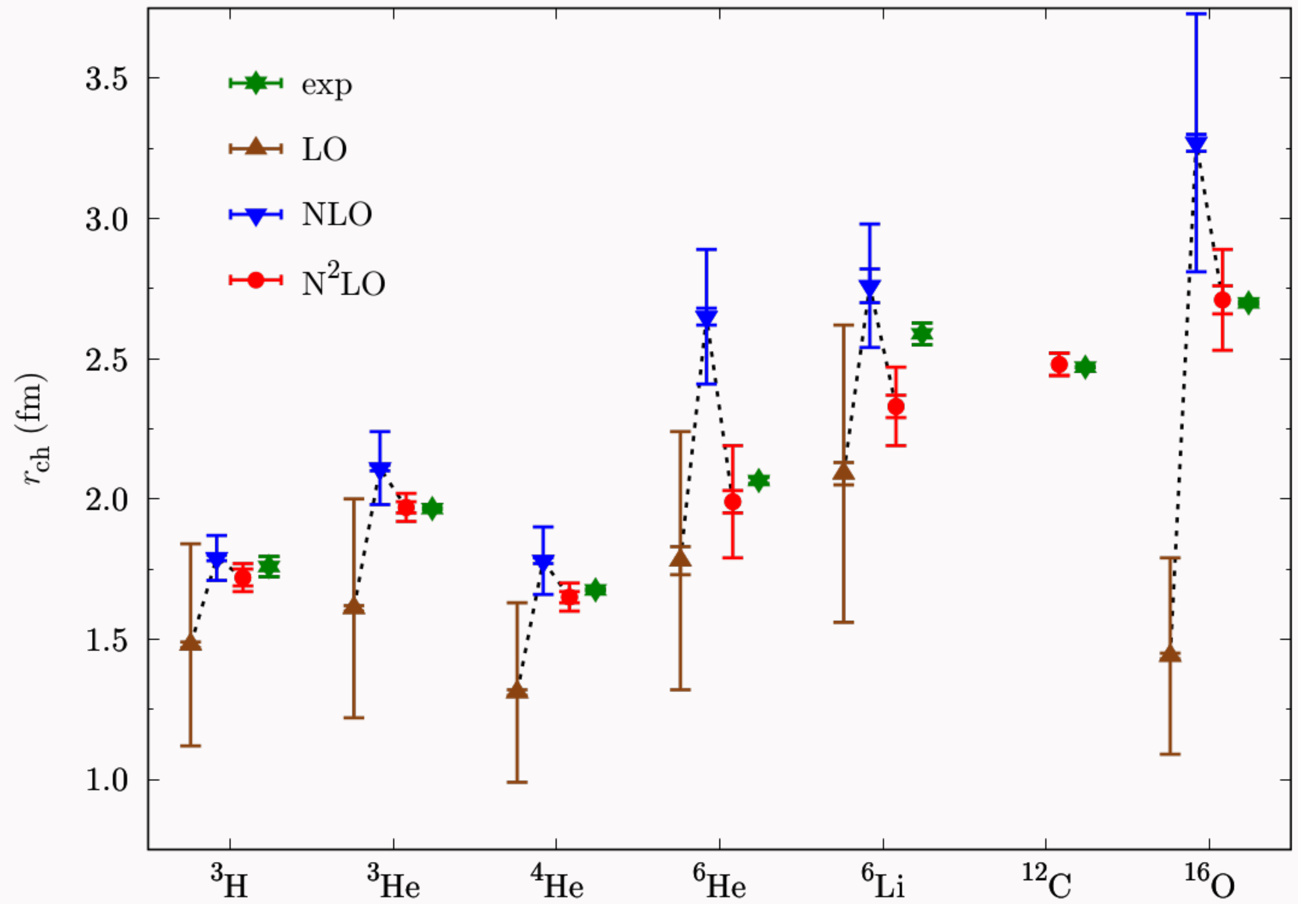


JEL et al, PRL **116**, 062501 (2016)

Recent 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)

Short-Range Correlations (SRCs) & EMC Effect

Some History And Definitions

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

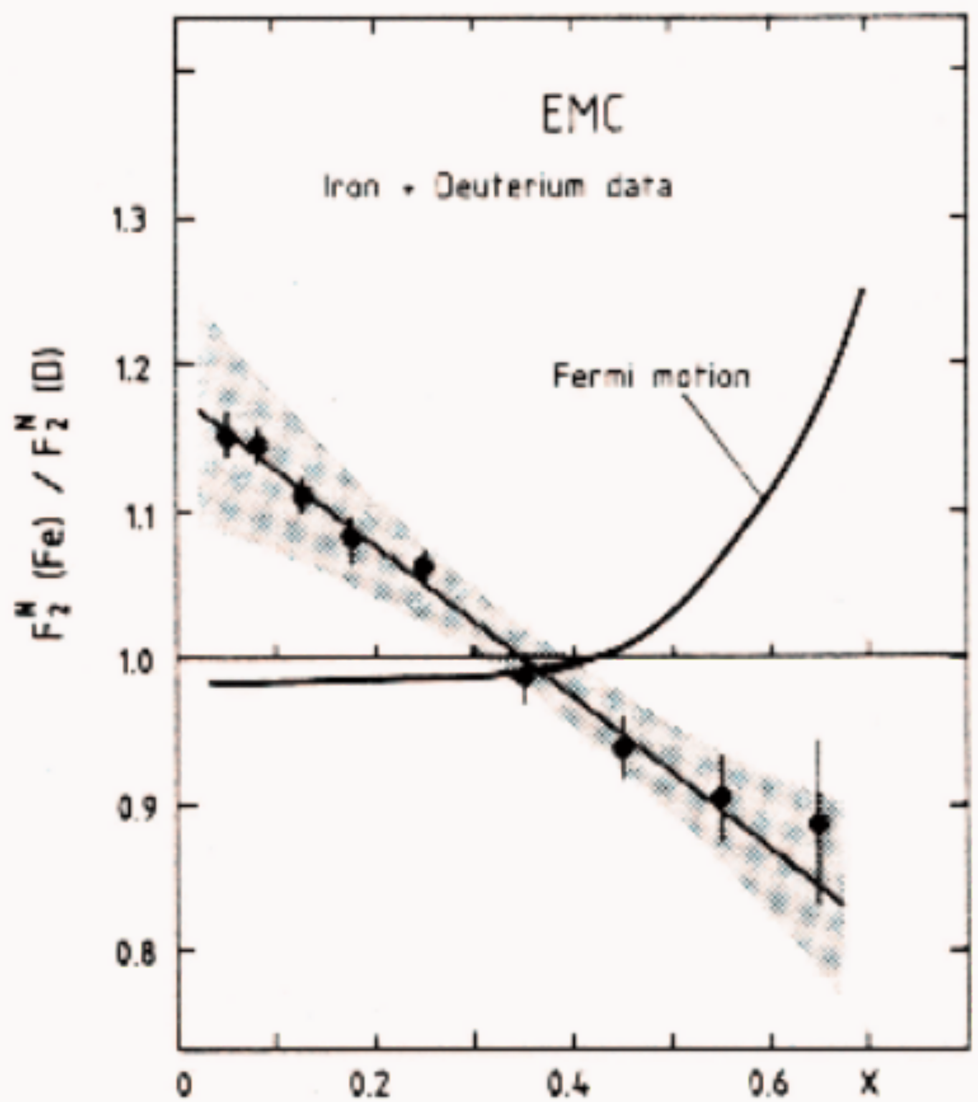
$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}Q^2\mathrm{d}x} \propto \frac{4\pi\alpha^2}{Q^4}\frac{F_2^A(x,Q^2)}{x}$$

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)

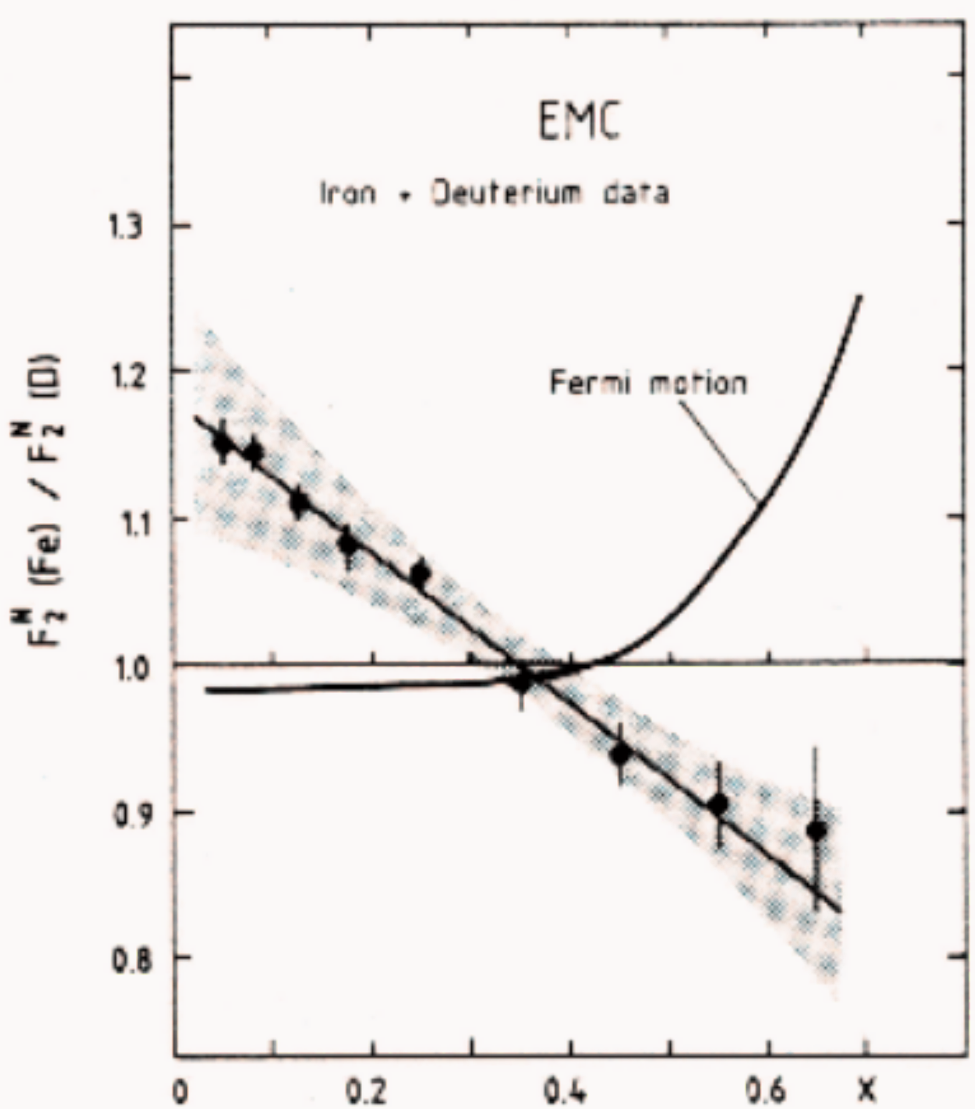
J. J. Aubert et al. (EMC), Phys. Lett. B. **123**, 275

"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:

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

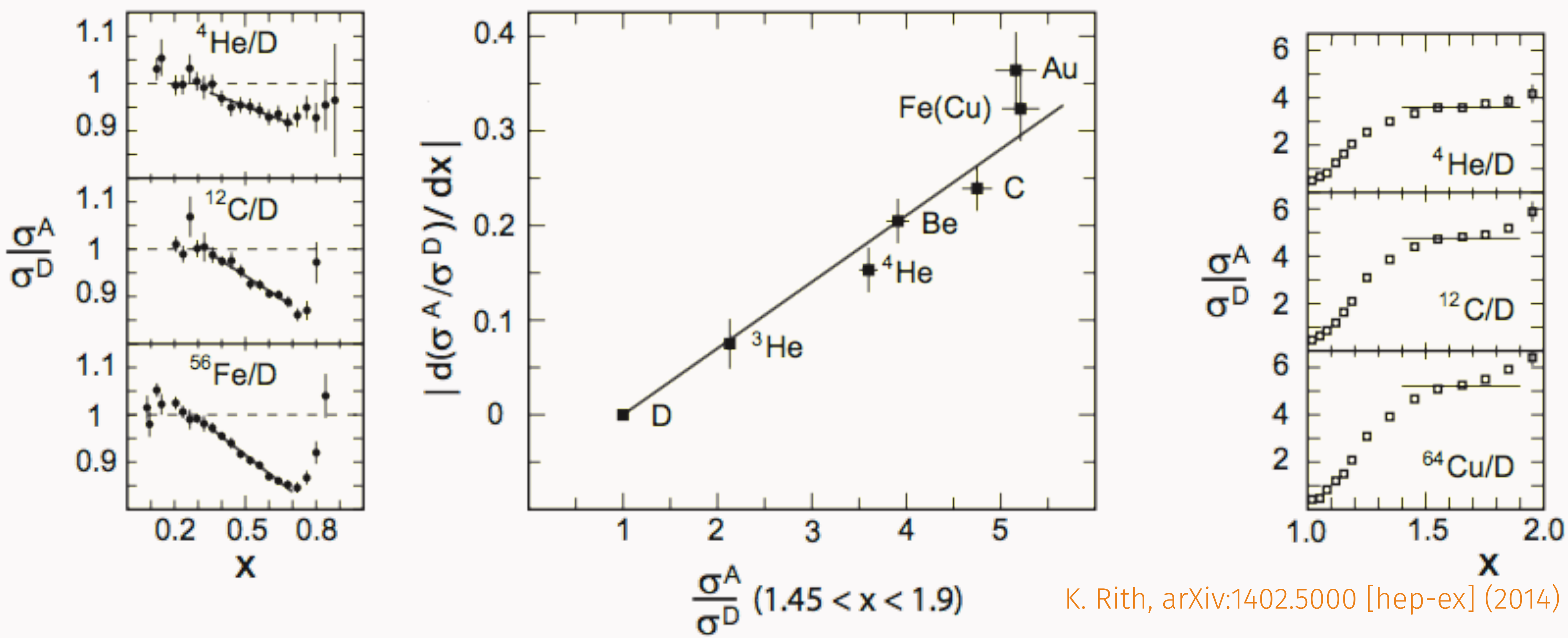


K. Rith, arXiv:1402.5000 [hep-ex] (2014)

Short-Range Correlations And The EMC Effect

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

$$\mathrm{d}R_{\mathrm{EMC}}/\mathrm{d}x \propto a_2$$



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) (PRL in press):

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

EFT Arguments In Detail

$$F_2^A(x, Q^2) = \sum_i Q_i^2 x q_i^A(x, Q)$$

$q_i^A(x, Q)$ nuclear PDFs

Leading twist (twist-2) expansion of PDFs
+ Operator product expansion:

$$\langle A; p | \mathcal{O}^{\mu_0 \cdots \mu_n} | A; p \rangle = \langle x^n \rangle_A (Q) p^{(\mu_0} \ldots p^{\mu_n)}$$

$$\langle x^n \rangle_A (Q) = \int_{-A}^{A} \mathrm{d}x x^n q_A(x, Q)$$ Mellin transform

$$\mathcal{O}^{\mu_0 \cdots \mu_n} = \bar{q} \gamma^{(\mu_0} \mathrm{i}D^{\mu_1} \ldots \mathrm{i}D^{\mu_n)} q$$

EFT Arguments In Detail

Matching QCD operators to hadronic operators.

$$\mathcal{O}^{\mu_0\cdots\mu_n} \to : \langle x^n \rangle_N M^n v^{(\mu_0}\cdots v^{\mu_n)} N^\dagger N [1 + \alpha_n N^\dagger N]$$
$$+ \langle x^n \rangle_\pi \pi^\alpha \mathrm{i}\partial^{(\mu_0}\cdots \mathrm{i}\partial^{\mu_n)} + \cdots :$$

$$Q \gg \Lambda \gg P$$

$$\langle x^n \rangle_A (Q) = \langle x^n \rangle_N (Q) \left[A + \alpha_n(\Lambda, Q) \langle A | : (N^\dagger N)^2 : | A \rangle_\Lambda \right]$$

Inverse Mellin transform

$$q_A(x, Q)/A \simeq q_N(x, Q) + g_2(A, \Lambda) \tilde{q}_2(x, Q, \Lambda)$$

$$F_2^A(x, Q^2) \simeq F_2^N(x, Q^2) + g_2(A, \Lambda) f_2(x, Q^2, \Lambda)$$

EFT Arguments In Detail

For quasielastic kinematics

$$\sigma_A/A \simeq \sigma_N + g_2(A,\Lambda)\sigma_2(\Lambda)$$

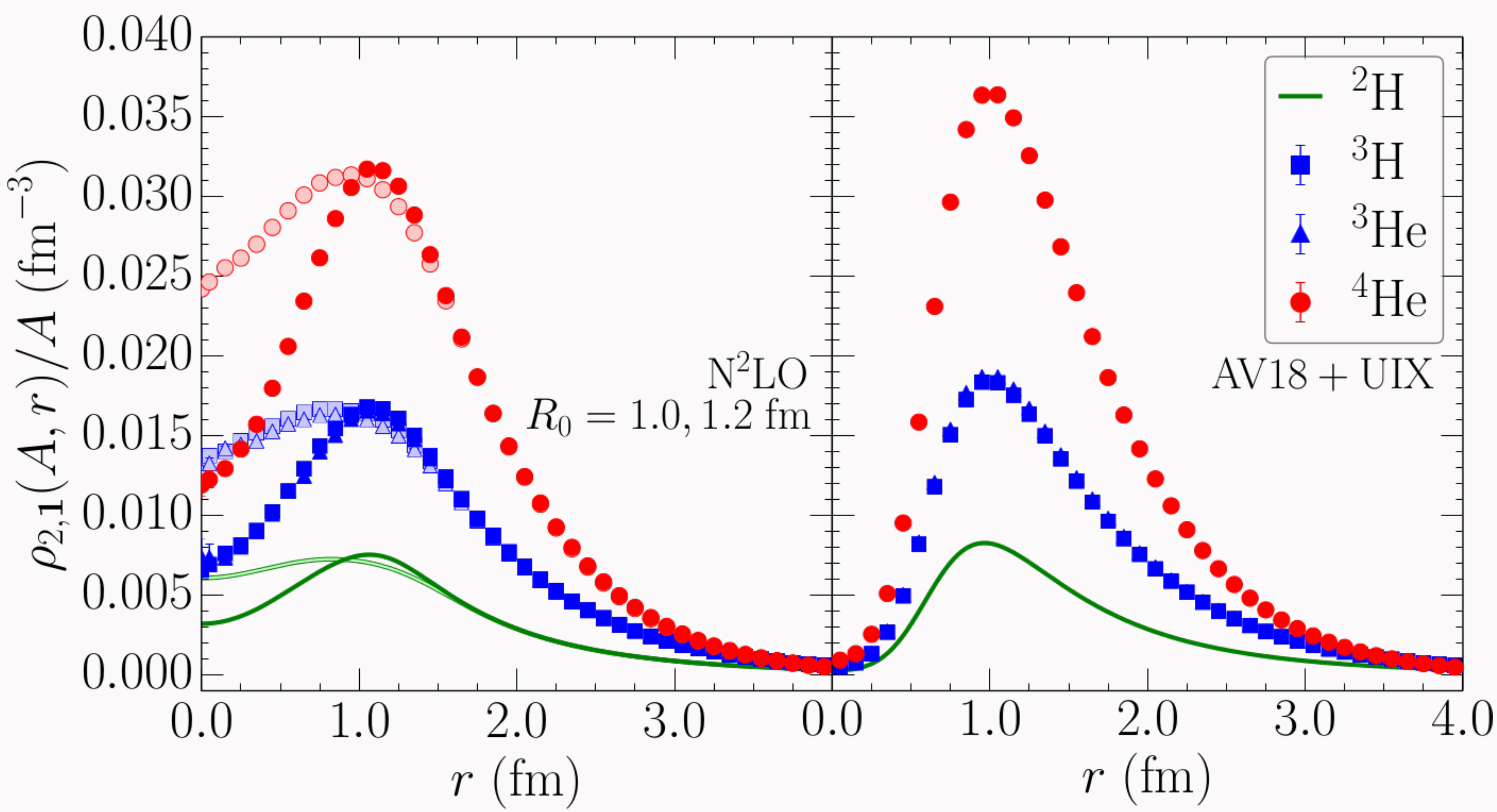
$$a_2(A, x > 1) \simeq \frac{g_2(A,\Lambda)}{g_2(2,\Lambda)}$$

$$\frac{\mathrm{d}R_{\mathrm{EMC}}(A,x)}{\mathrm{d}x} \simeq C(x)[a_2(A) - 1]$$

Two-Body Distribution Functions (g_2)

$$g_2(A,\Lambda) = \rho_{2,1}(A, r=0)/A, \;\; \rho_{2,1}(A,r) \equiv \frac{1}{4\pi r^2}\left\langle \Psi_0 \middle| \sum_{i<j} \delta(r - r_{ij}) \middle| \Psi_0 \right\rangle$$

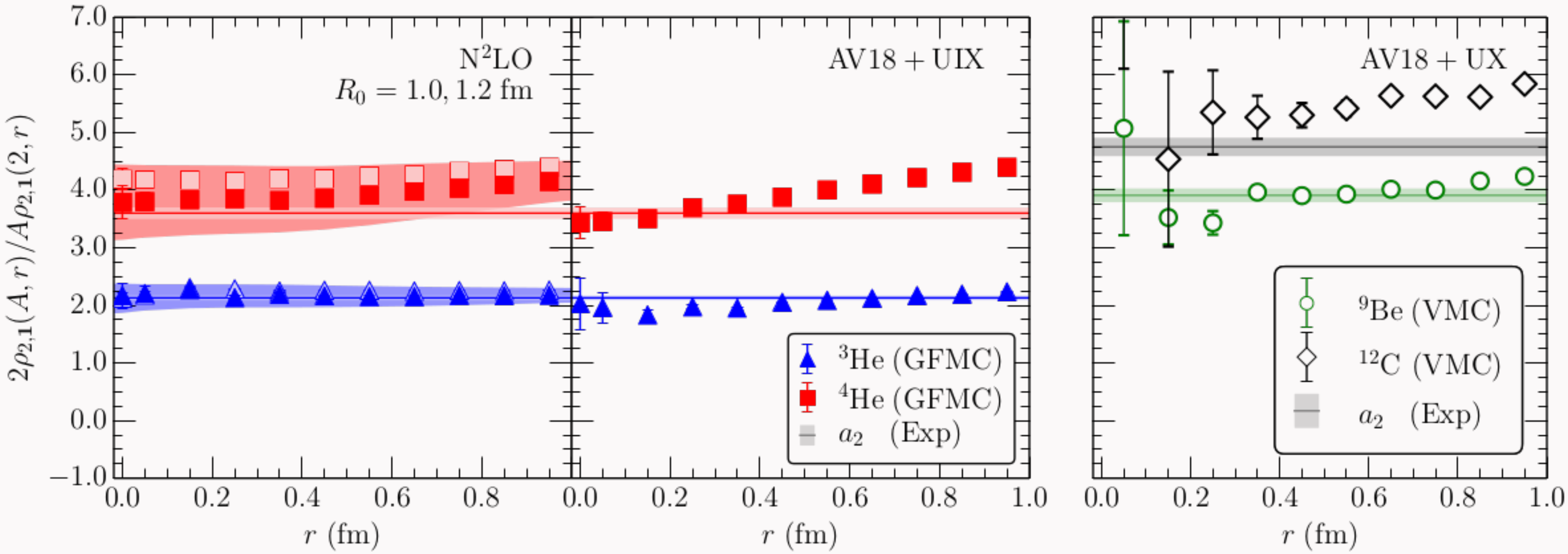
Scale and scheme dependent



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*!

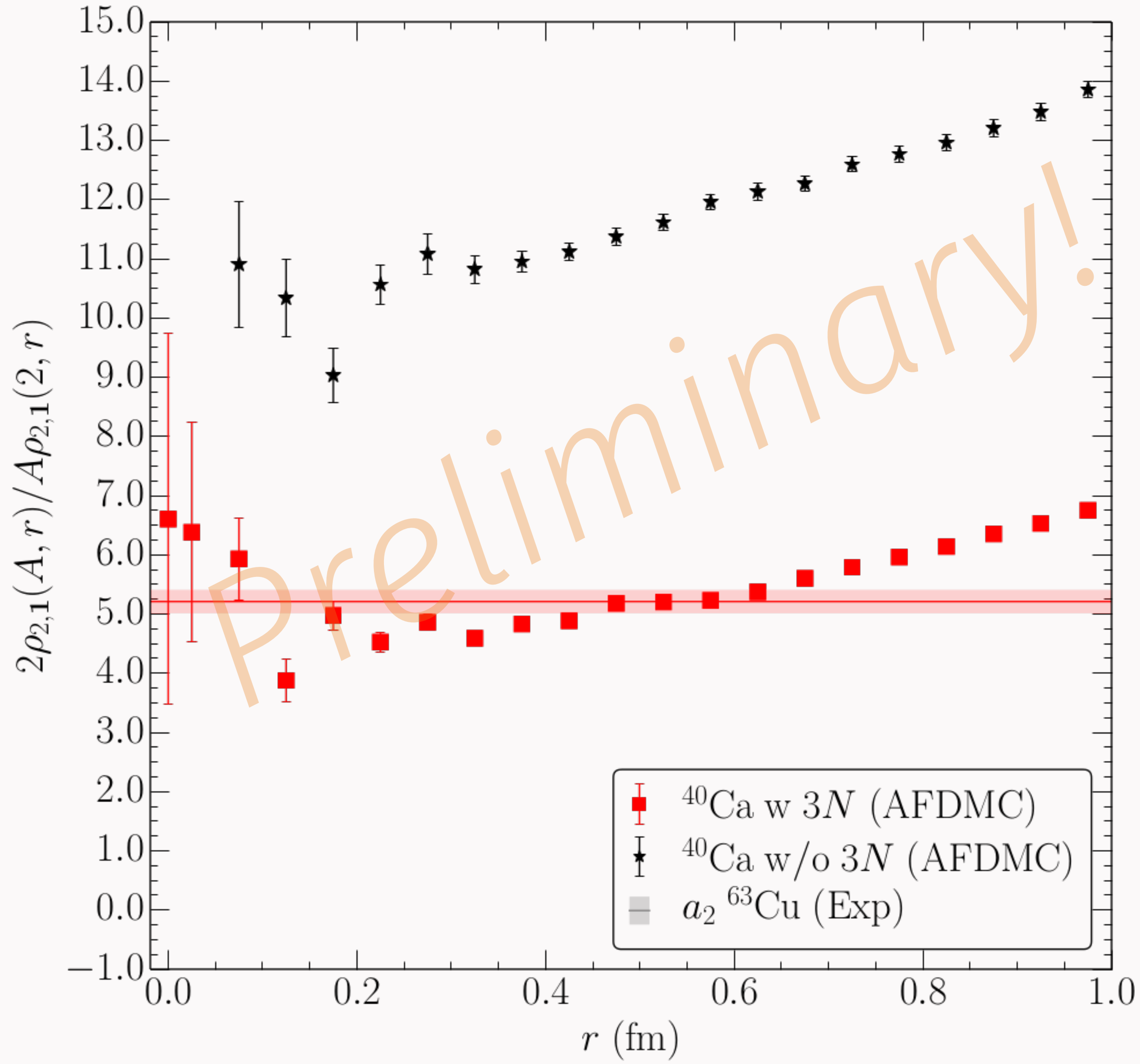


J.-W Chen, W. Detmold, JEL, A. Schwenk, arXiv:1607.03065 [hep-ph] (2016)

SRC Correlation Factors

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

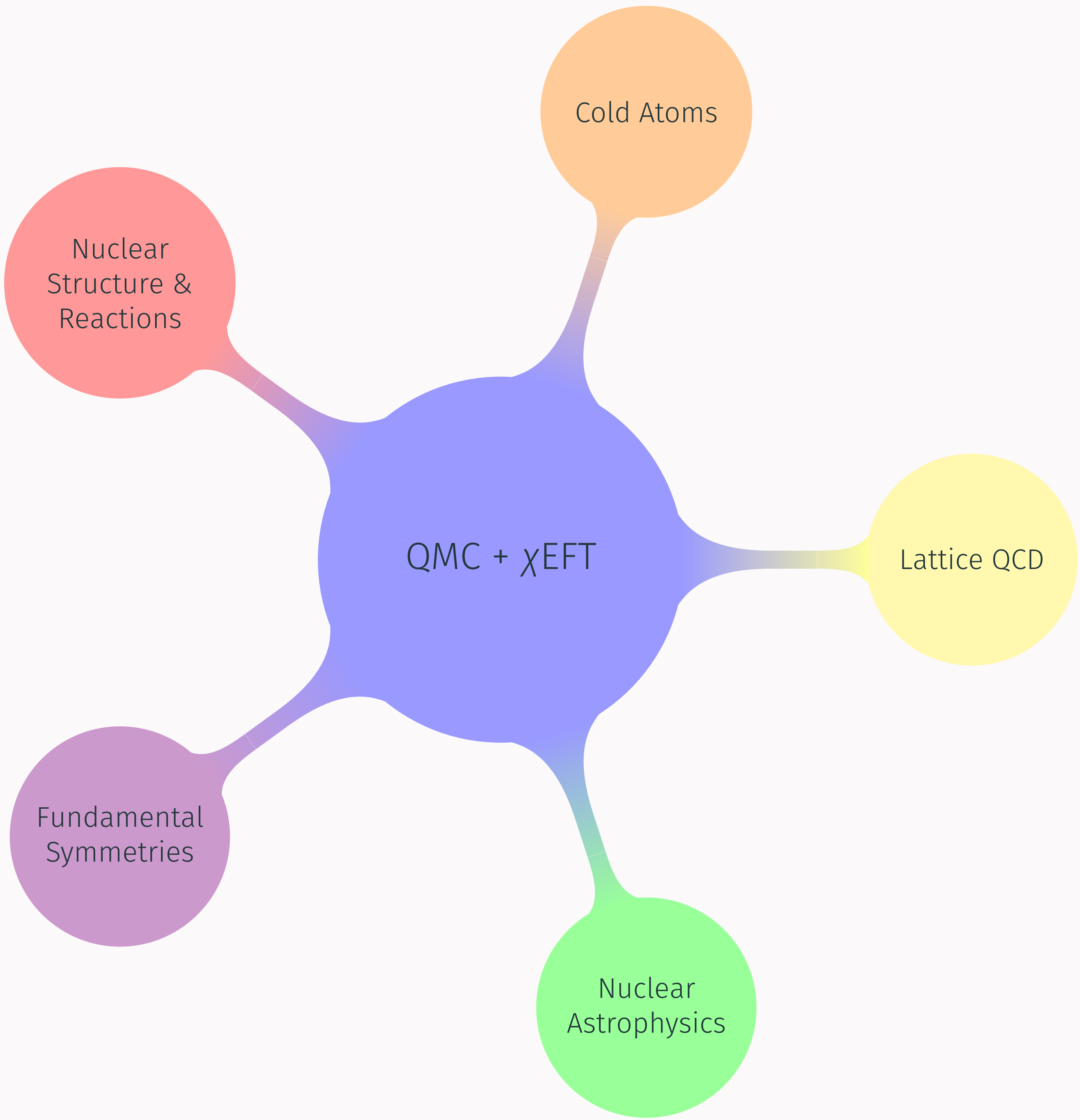
A prediction for a_2 in ^{40}Ca:
Saturates as expected.



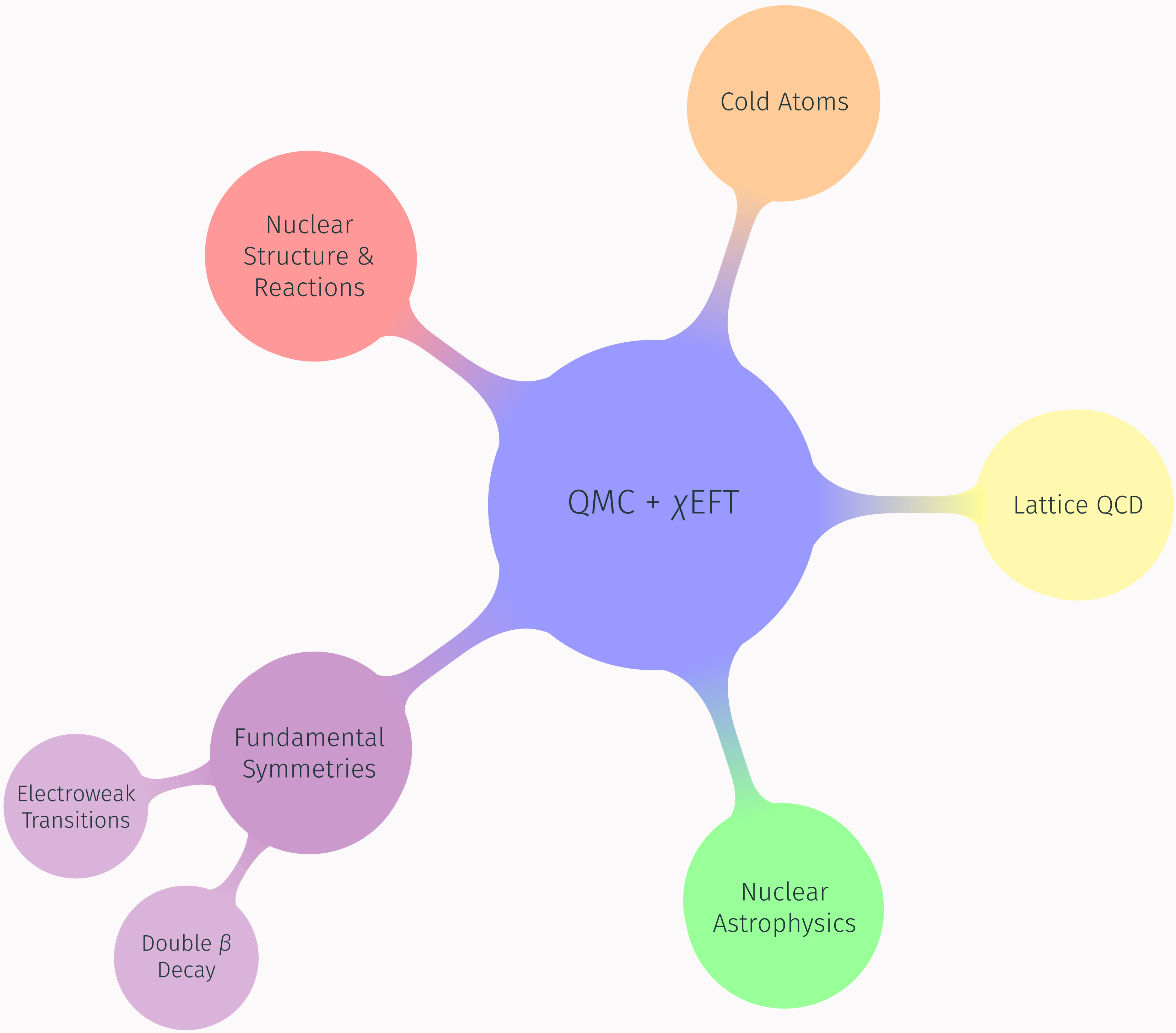
Summary

- 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.
- EFT predicts (postdicts) the linear relationship between
- We can make scheme- and scale-independent predictions for SRC scaling factors.
- Our results suggest that EFT can shed light on the existence of a_3.

Outlook


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

Outlook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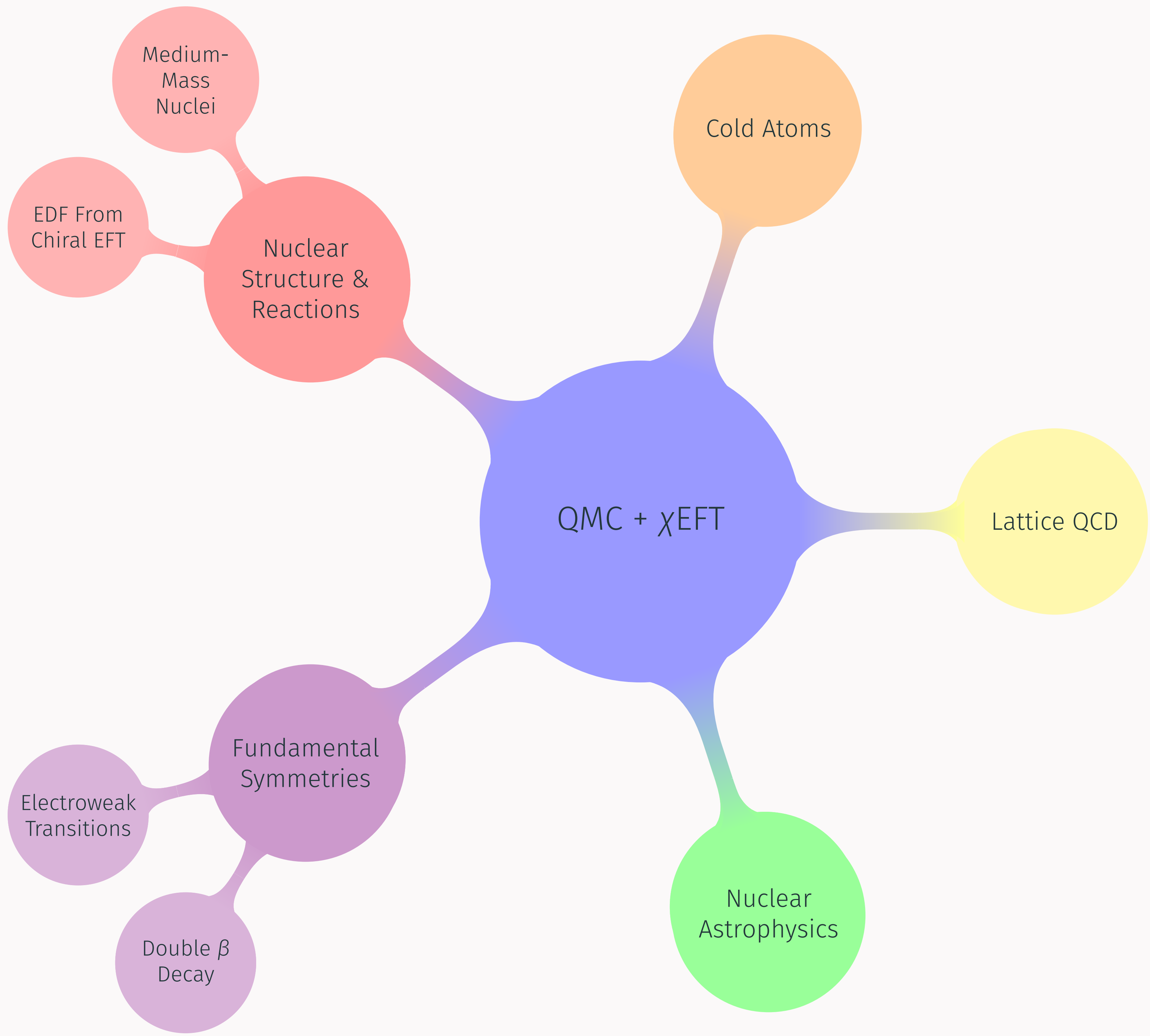
Outlook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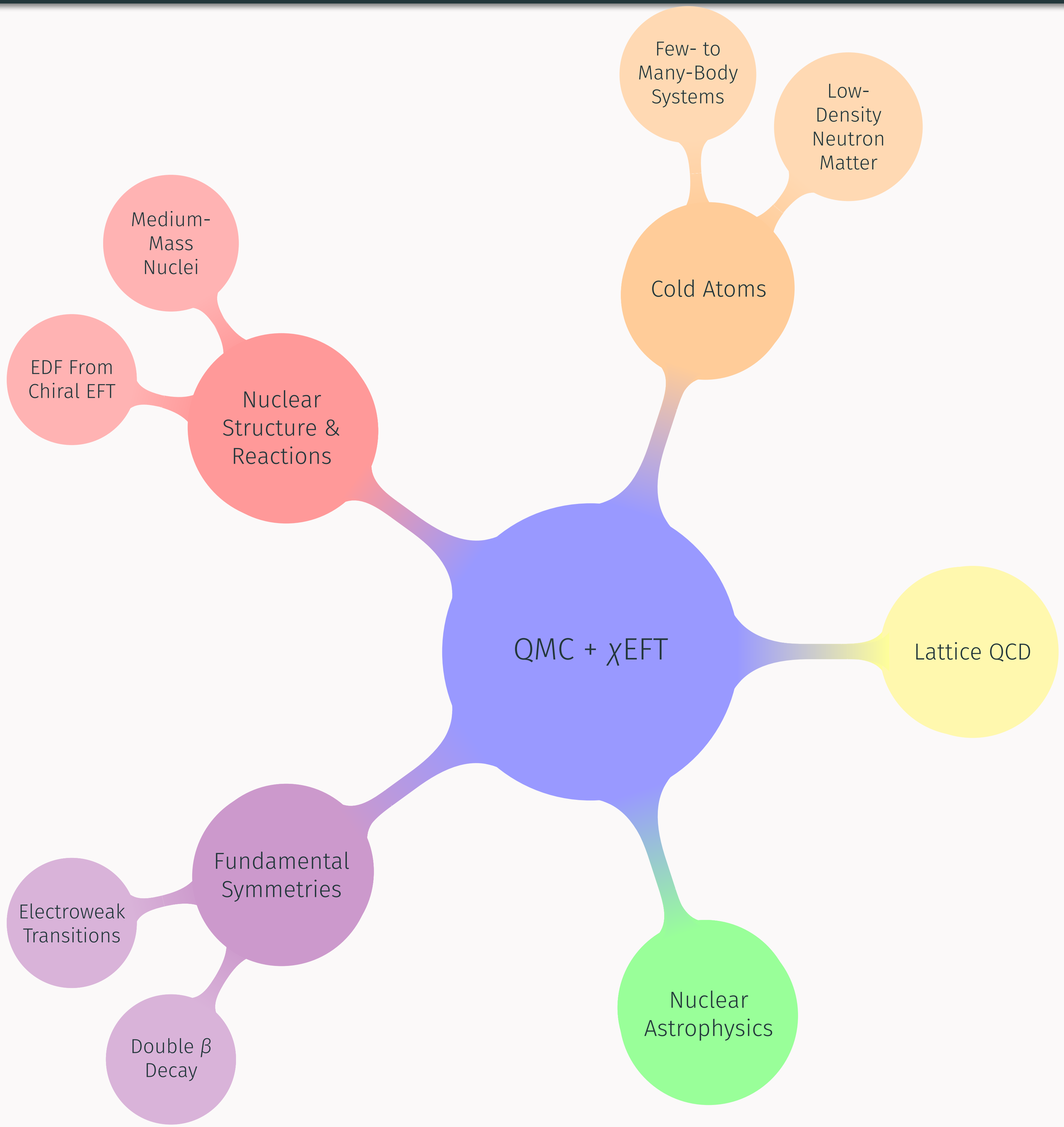
QMC + χEFT
Nuclear Structure & Reactions
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Acknowledgments

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Thank you for your attention!