Short-Range Correlations And The EMC Effect In Effective Field Theory

Exploring the role of electroweak currents in atomic nuclei

TECHNISCHE UNIVERSITÄT DARMSTADT

Bundesministerium für Bildung und Forschung

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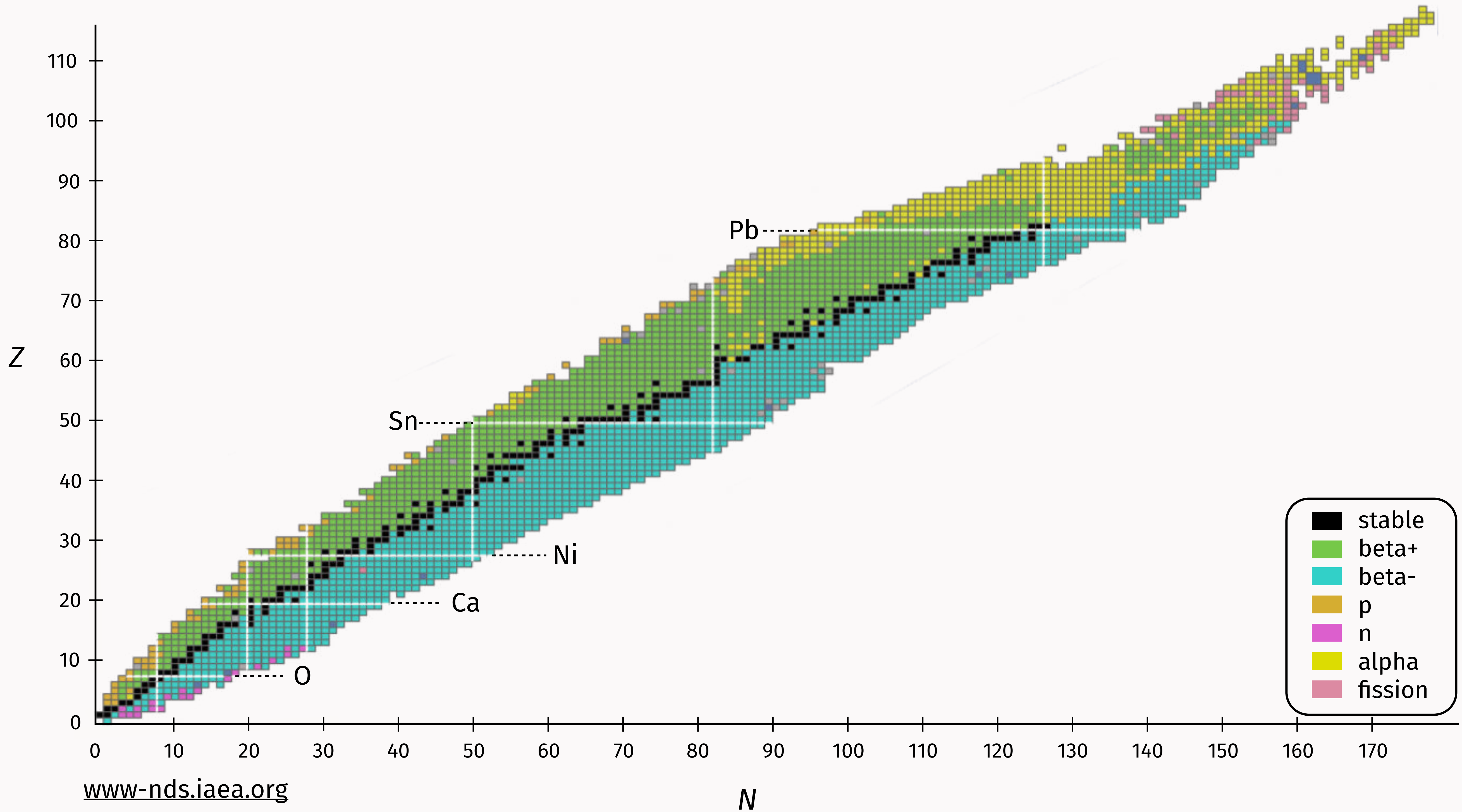
April 23, 2018

The Nuclear Landscape



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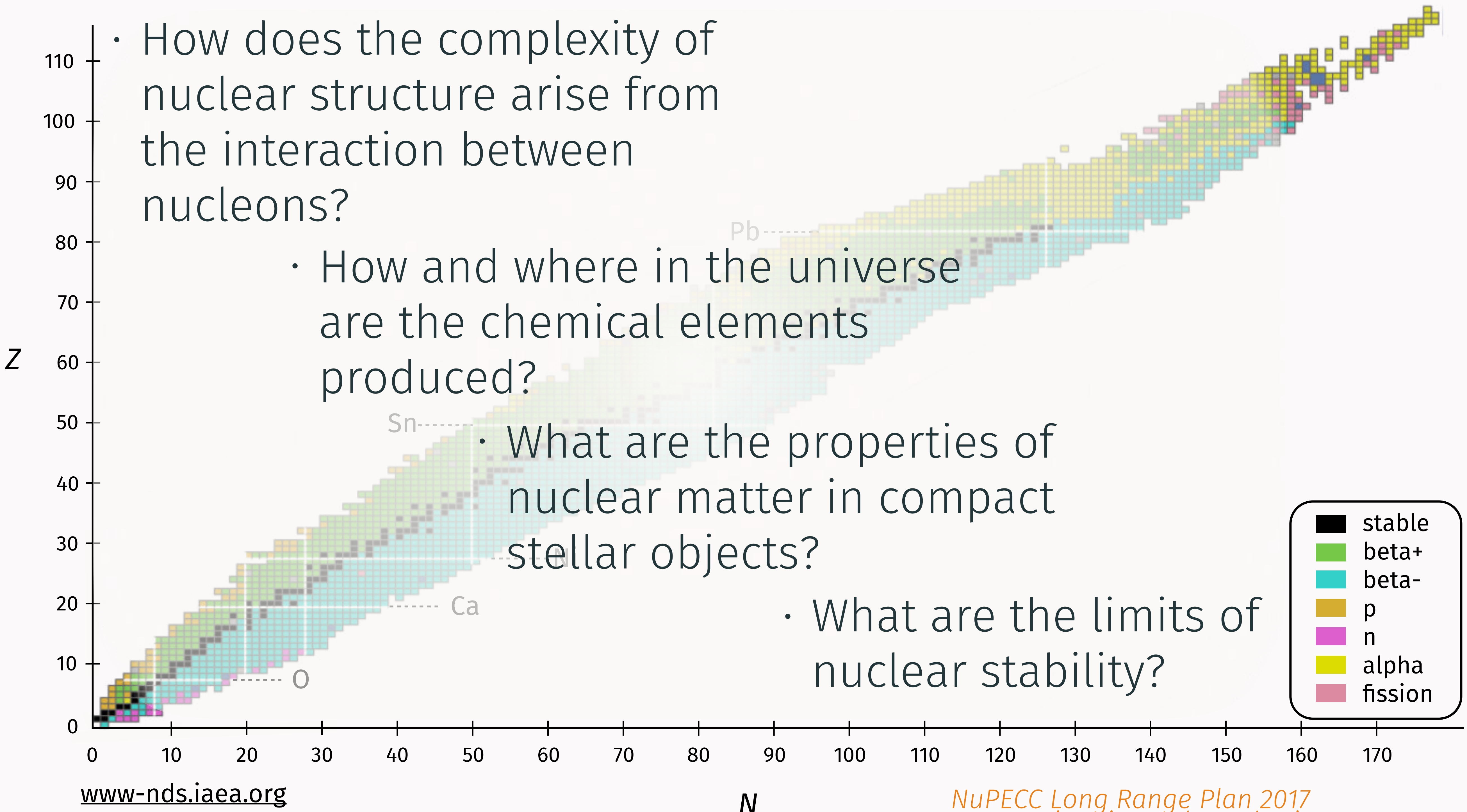
The Nuclear Landscape

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



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NuPECC Long Range Plan 2017
Perspectives in Nuclear Physics

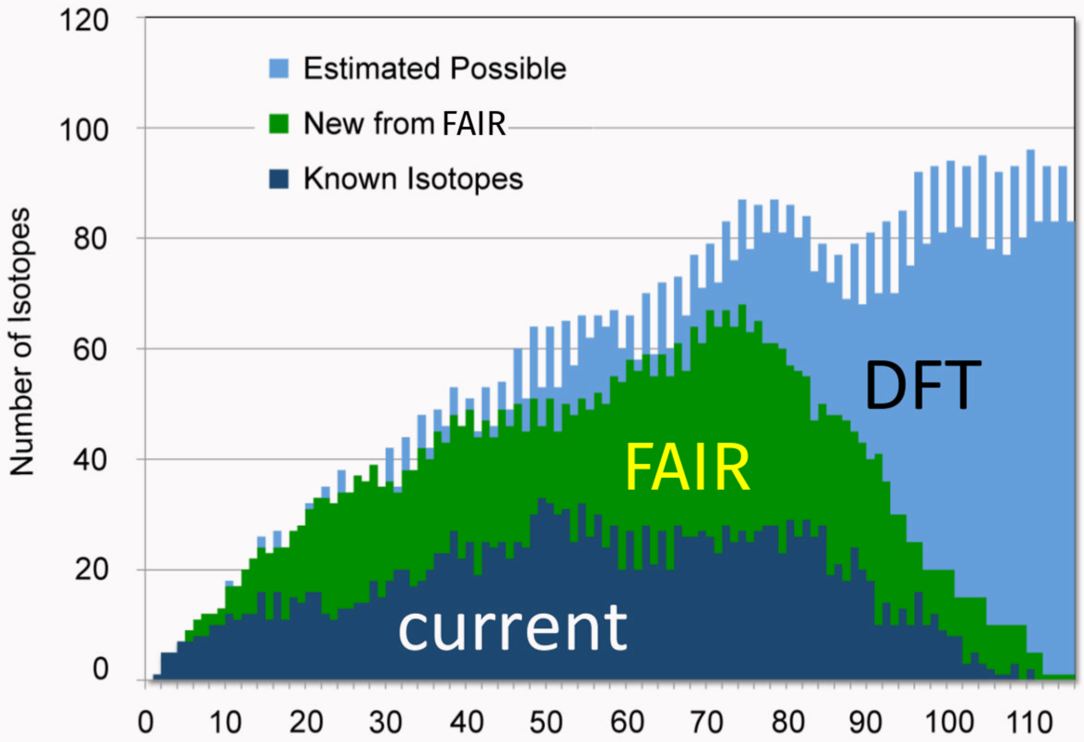
Extending The Nuclear Landscape

Cutting-edge experimental results

Neutron-star mergers

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

Rare-isotope facilities



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

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.

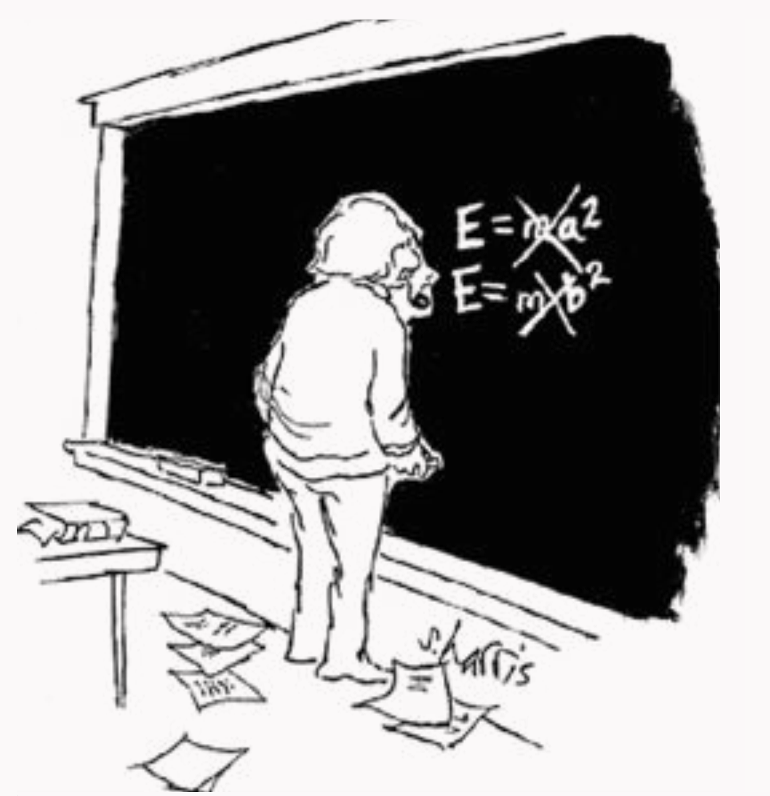
What Can Theory Offer?

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.

2. Chiral effective field interactions.

work with protons + neutrons
&
controlled approximations



Outline

- Quantum Monte Carlo Methods
- Local Chiral EFT
- The EMC effect and SRCs in EFT
- Outlook and Conclusion

Quantum Monte Carlo (QMC) Methods

QMC Methods

QMC methods in two lines:

$$H |\Psi\rangle = E |\Psi\rangle$$

$$\lim_{\tau \to \infty} e^{-H\tau} |\Psi_T\rangle \to |\Psi_0\rangle$$

QMC methods in more than two lines:

J. Carlson et al, RMP **87**, 1067 (2015).

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}
$$

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

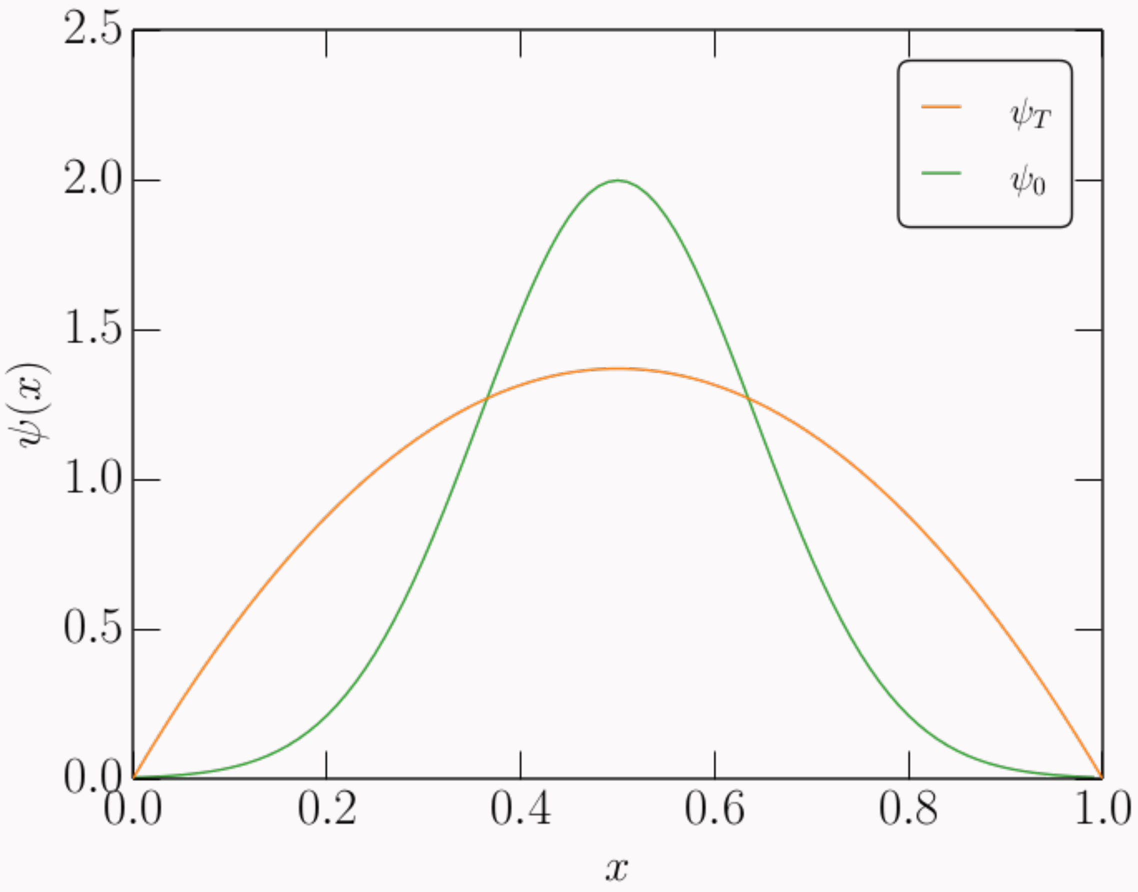
QMC Methods - An Example

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

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

Trial wave function; e.g.

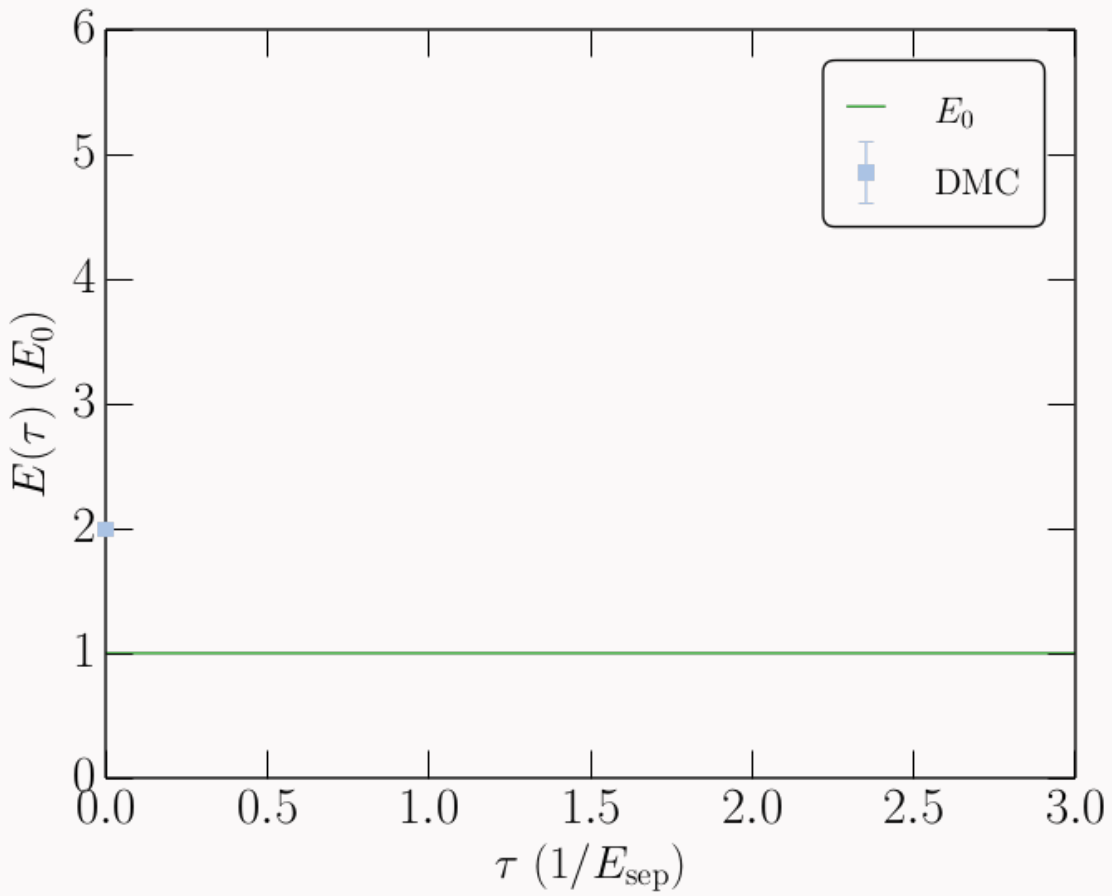
$$\Psi_T(x) = \sqrt{30}x(1-x).$$

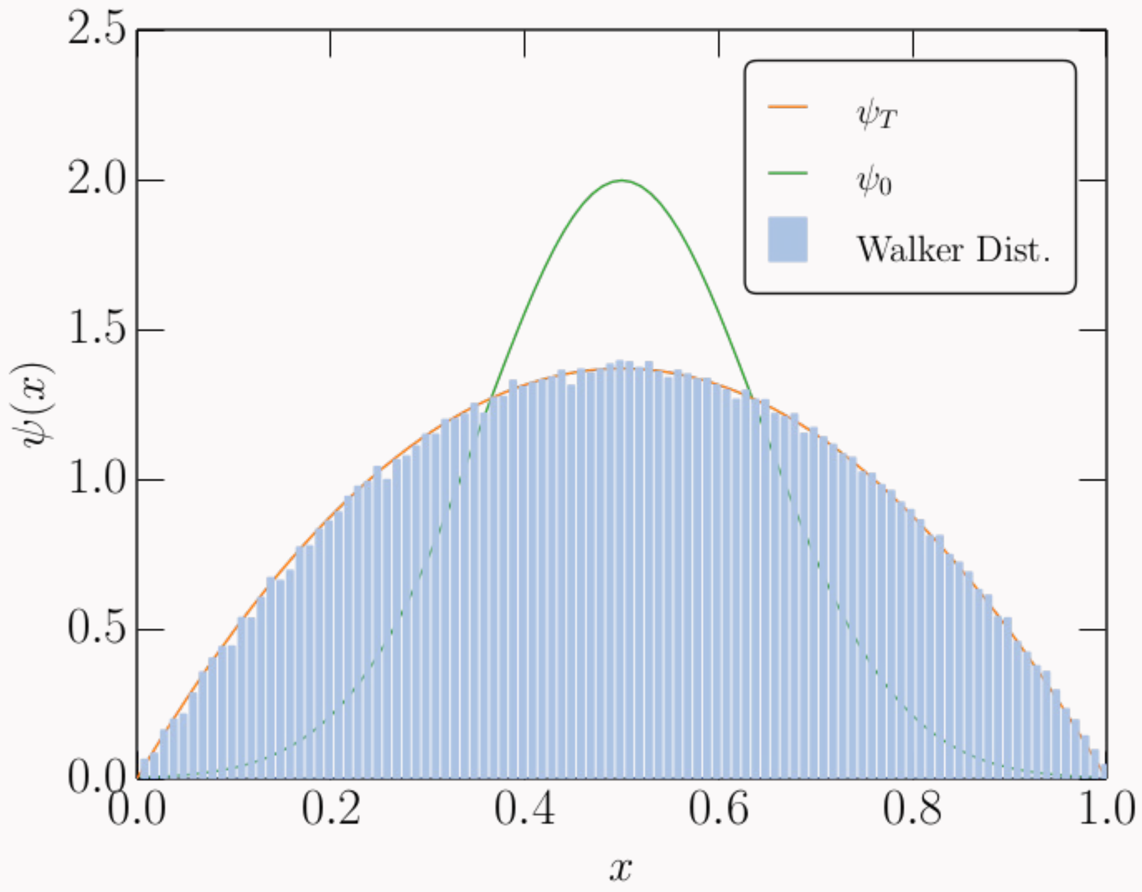


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 0.00$

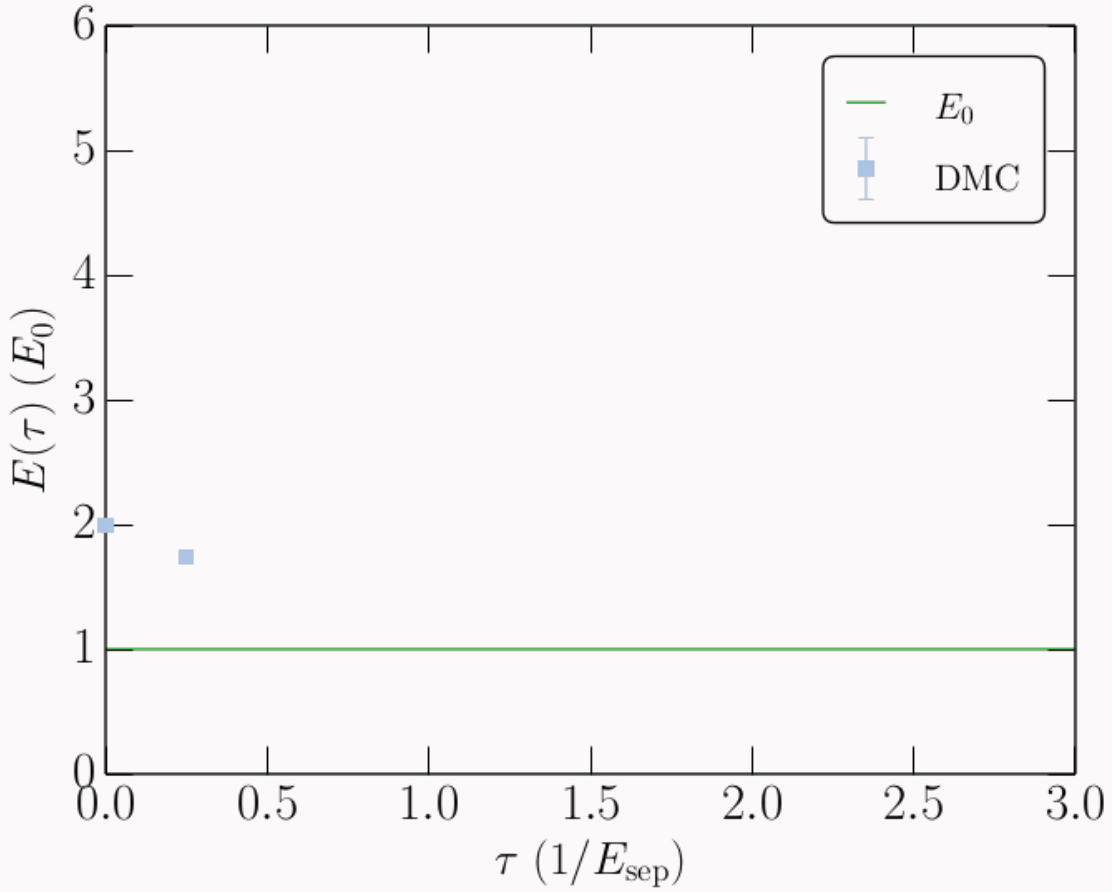


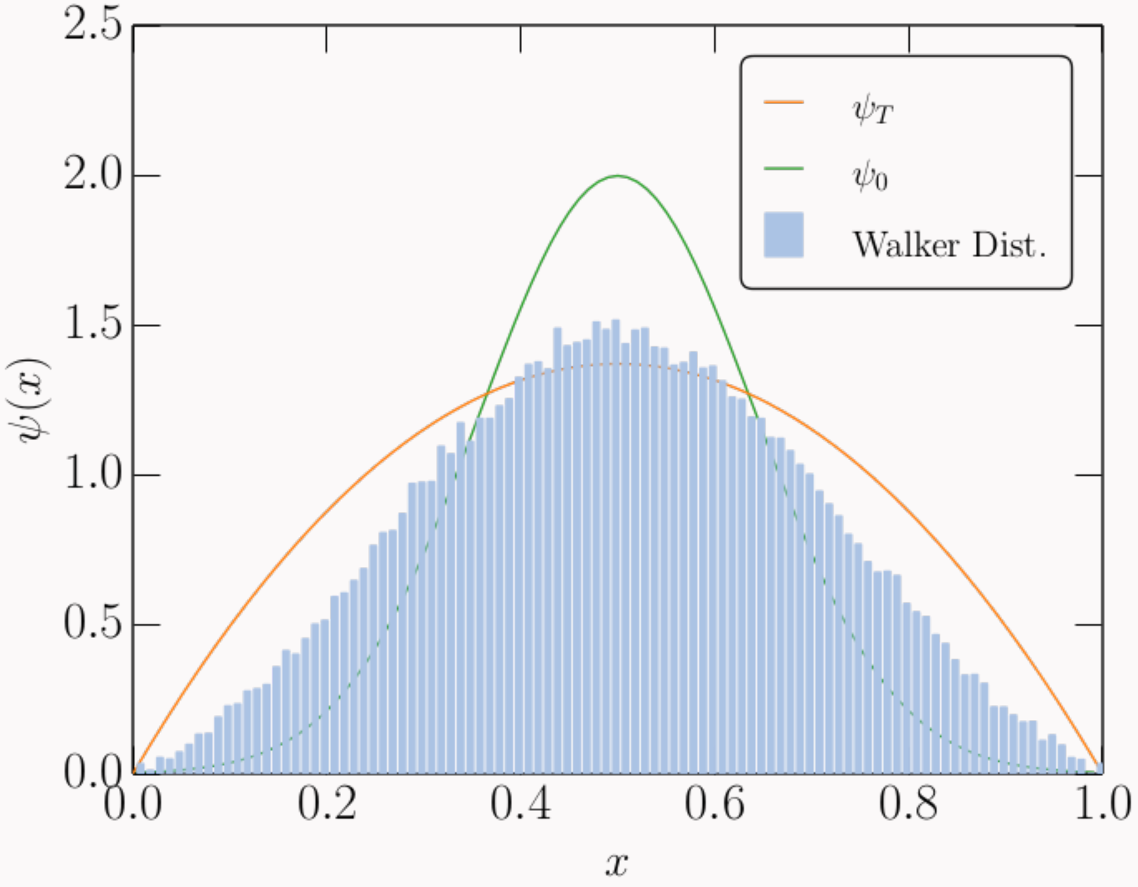


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 0.25$

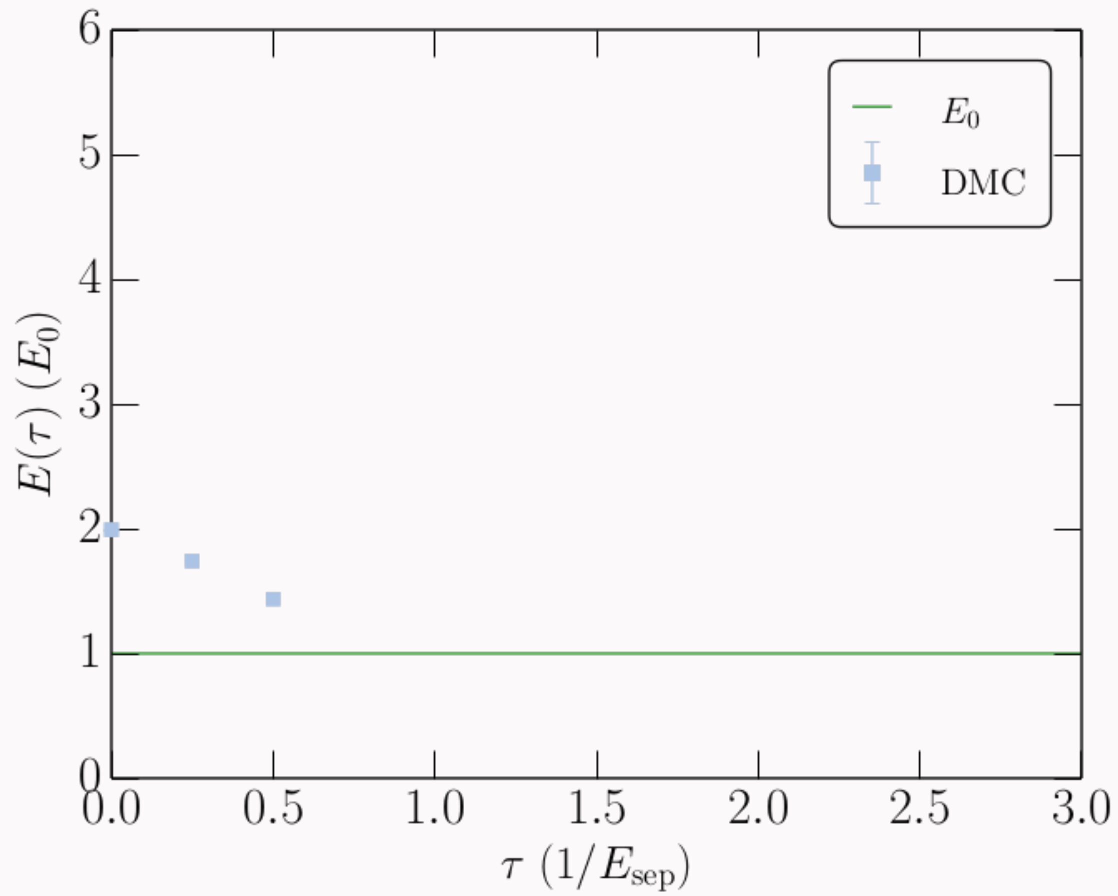


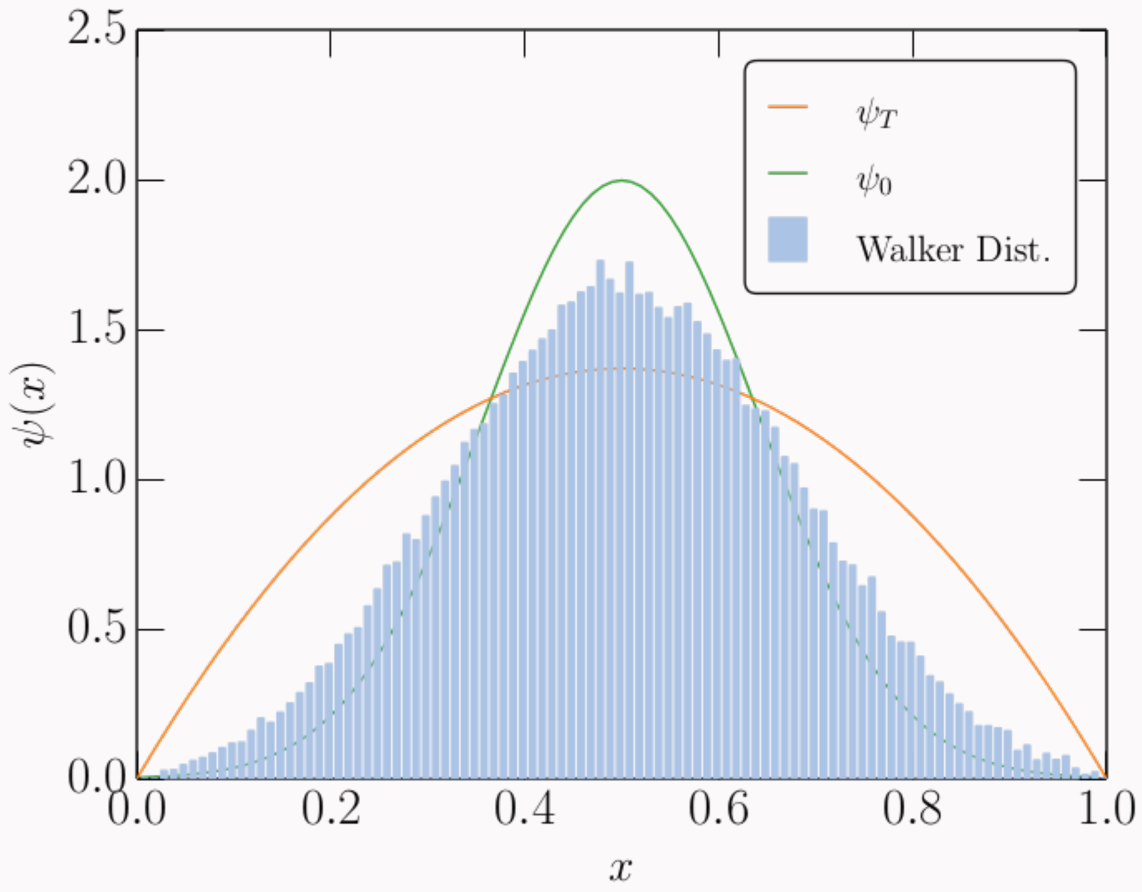


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 0.50$

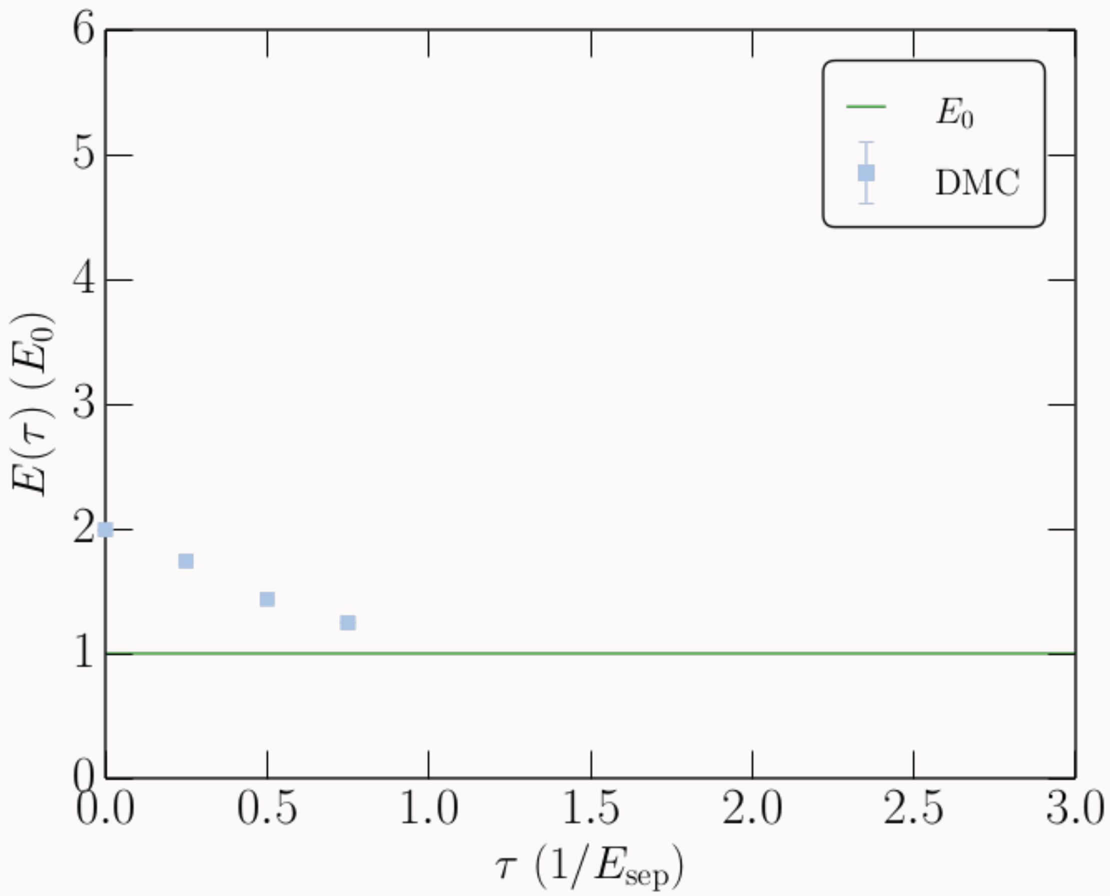


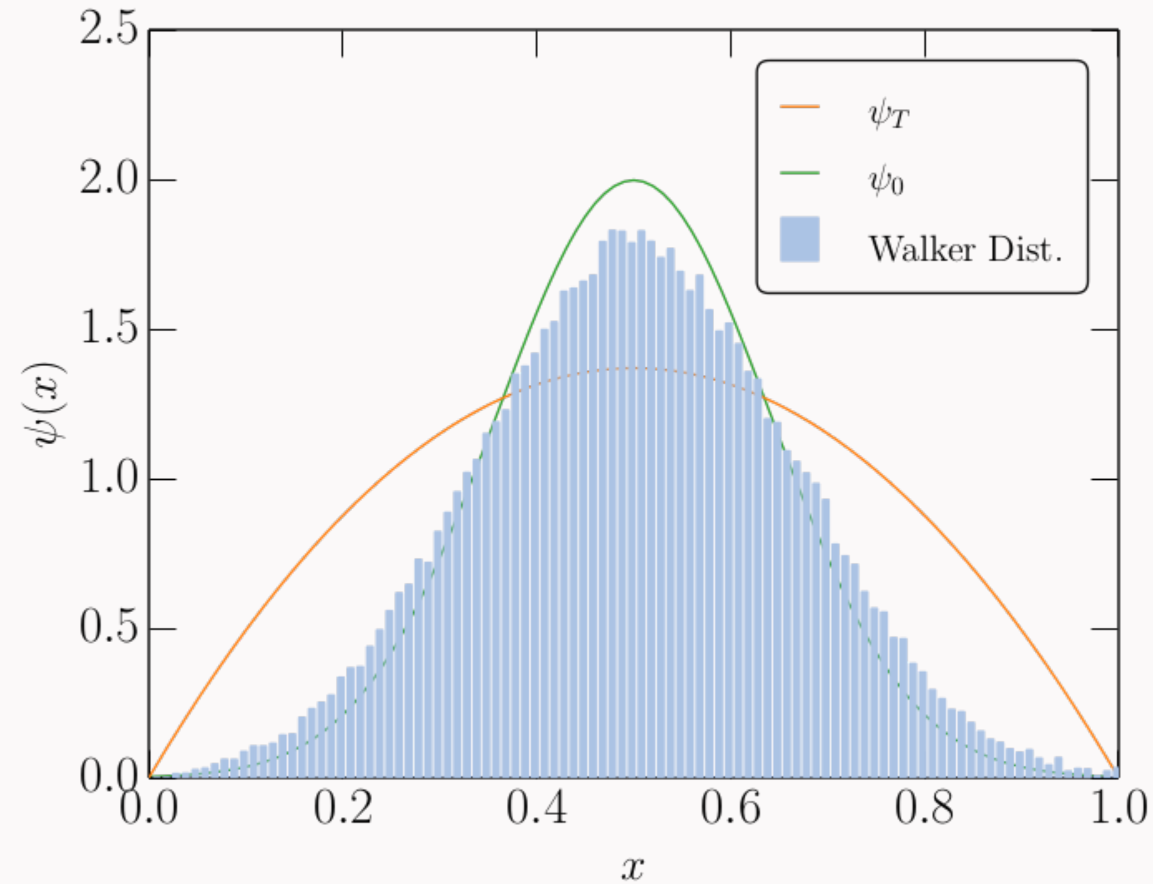


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 0.75$

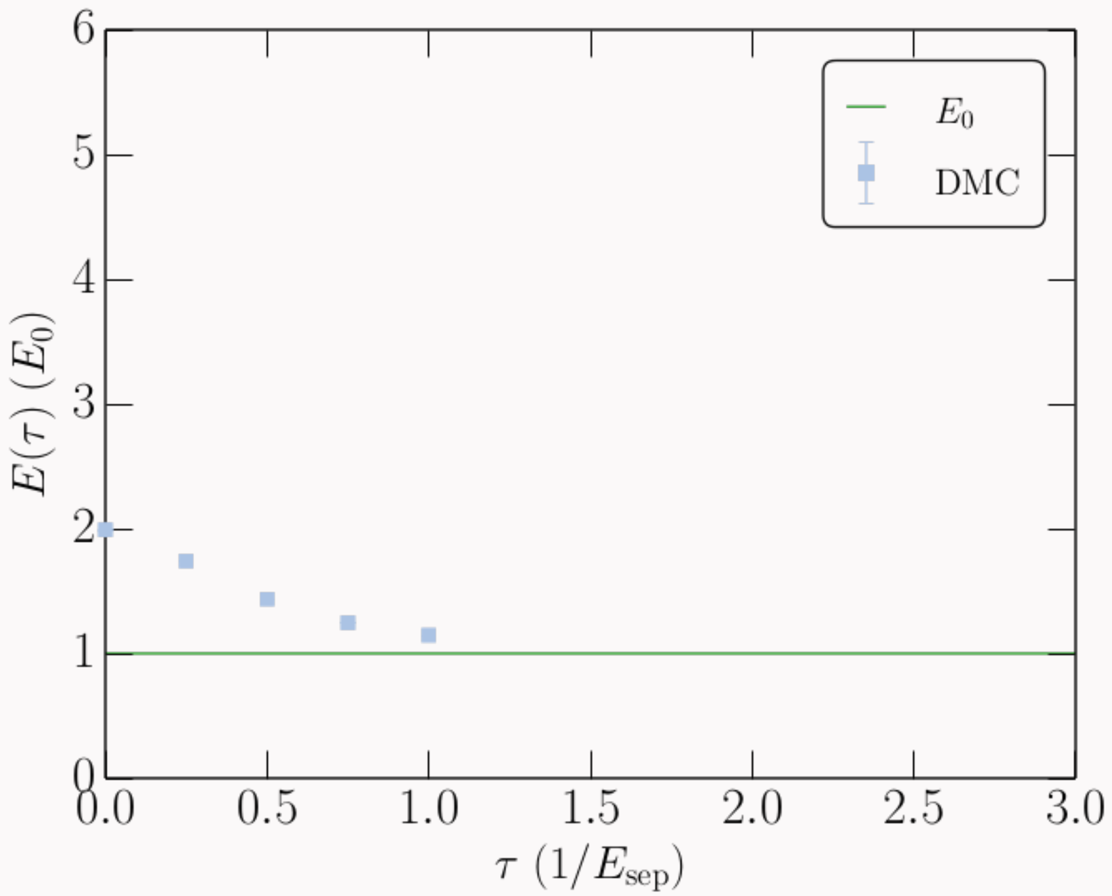


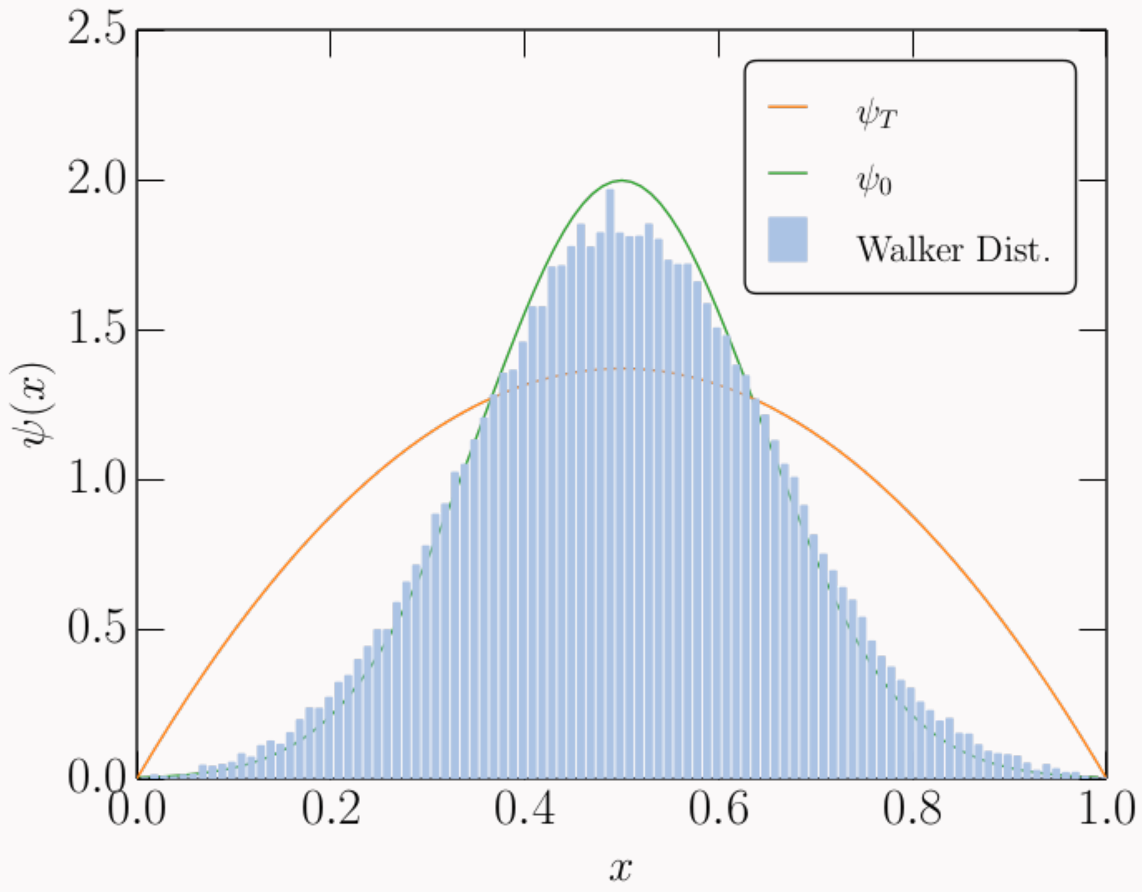


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 1.00$

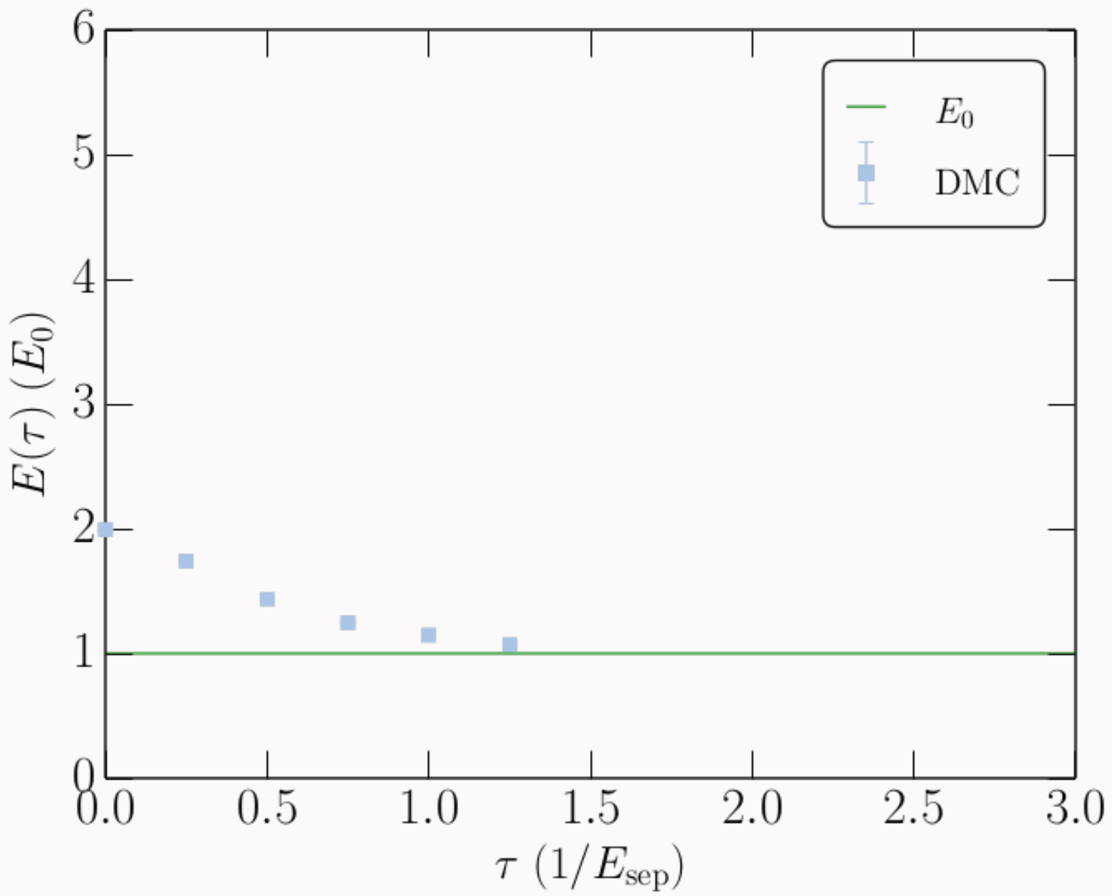


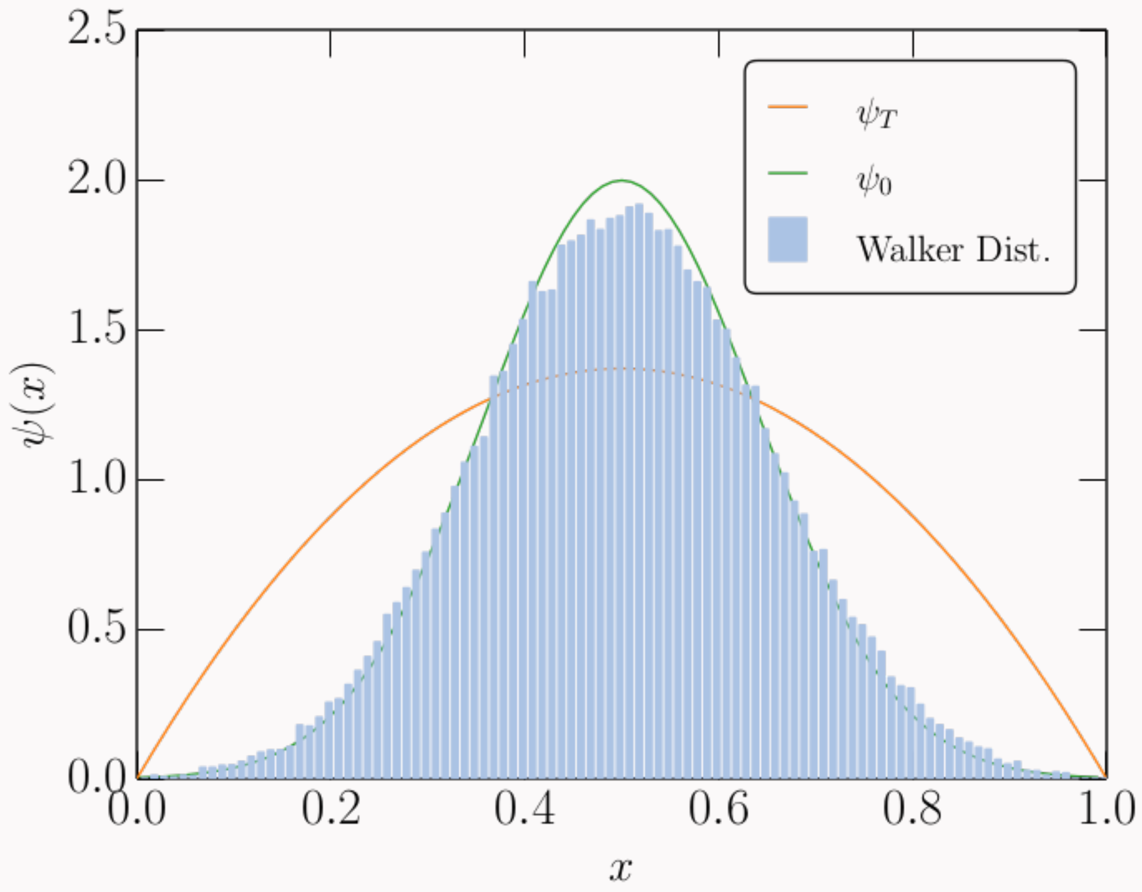


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 1.25$

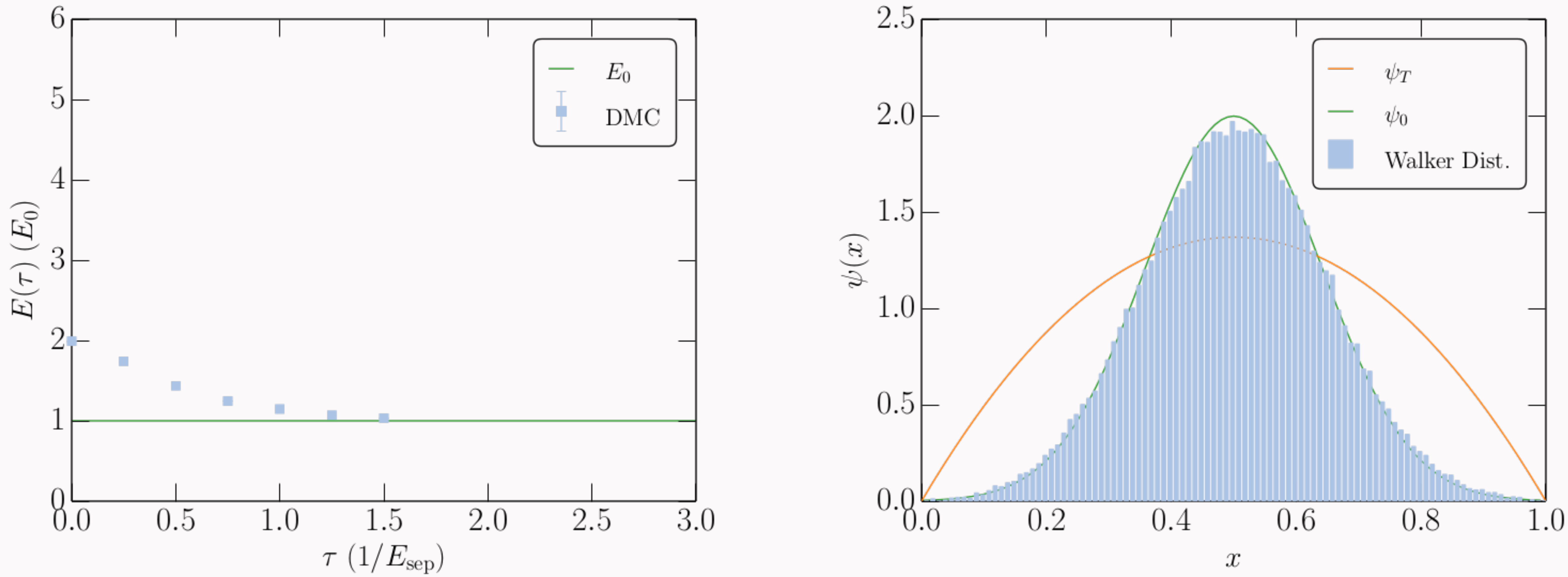




QMC Methods - An Example

Imaginary-time evolution:

$\tau = 1.50$



QMC Methods - An Example

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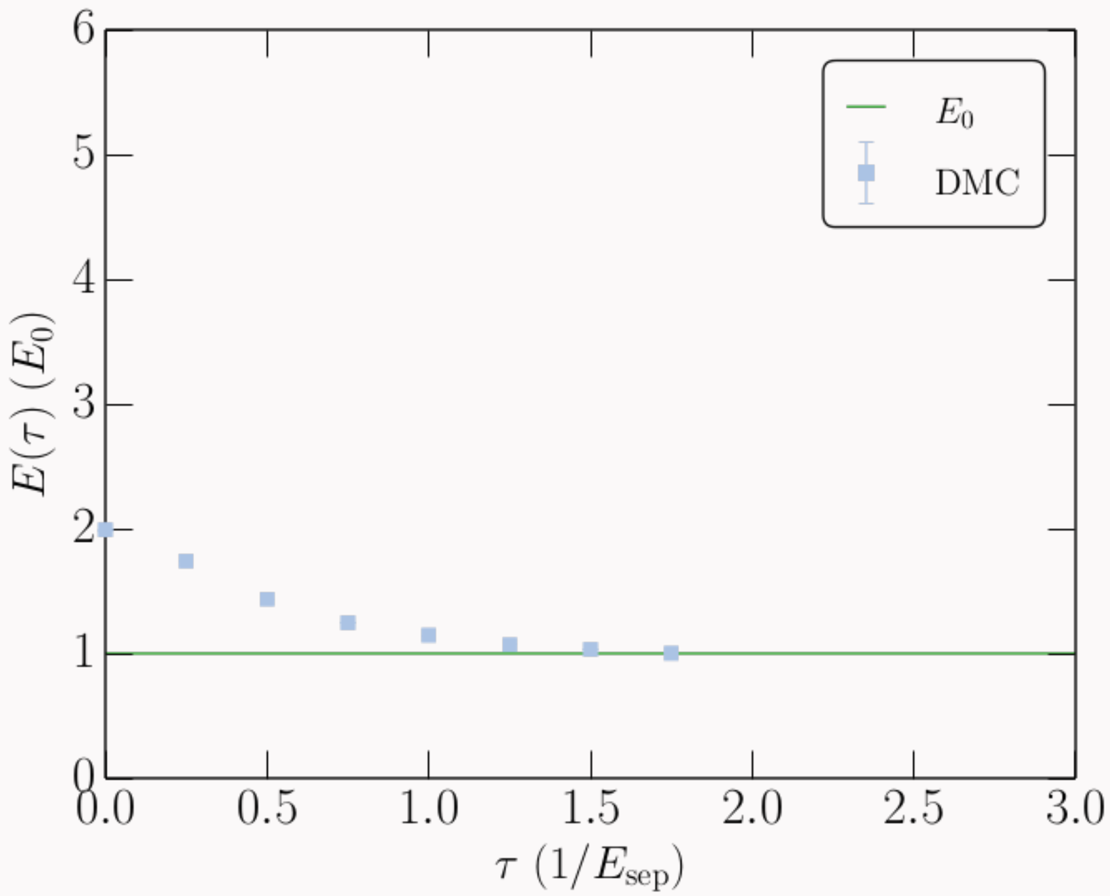
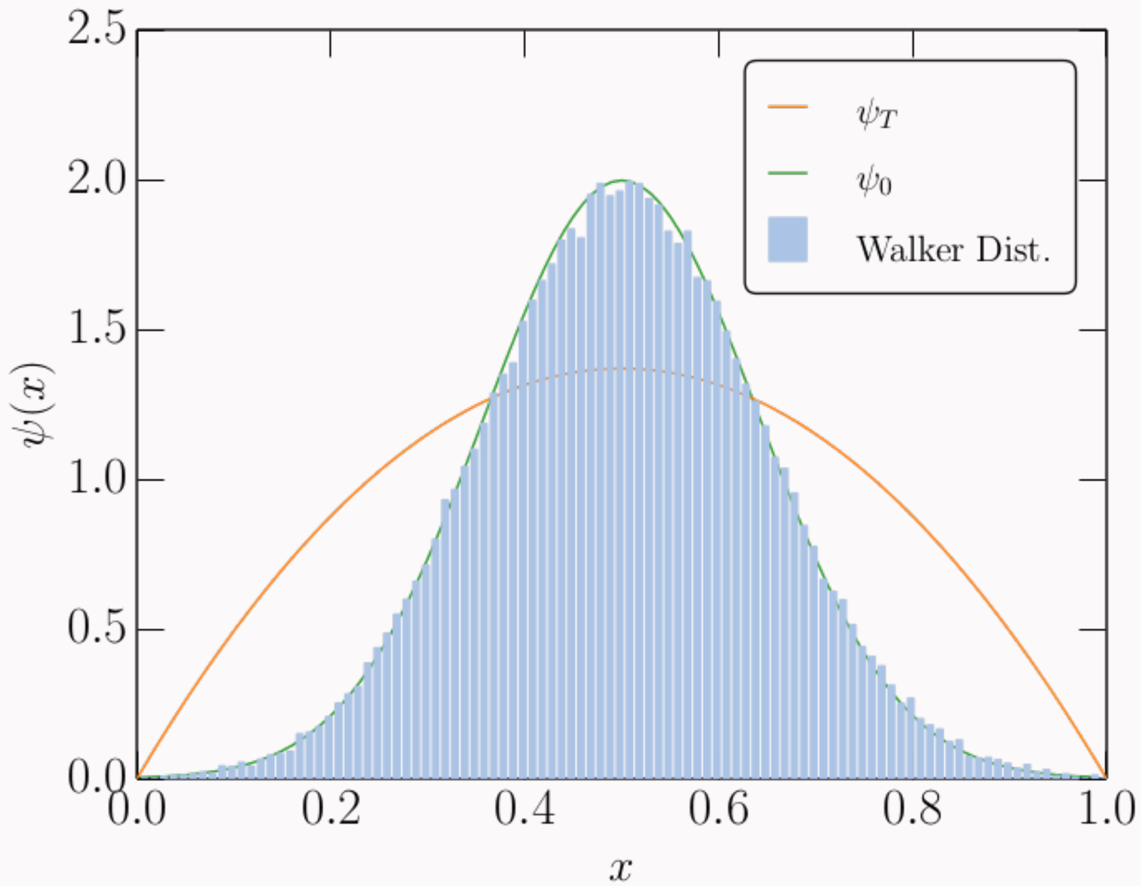
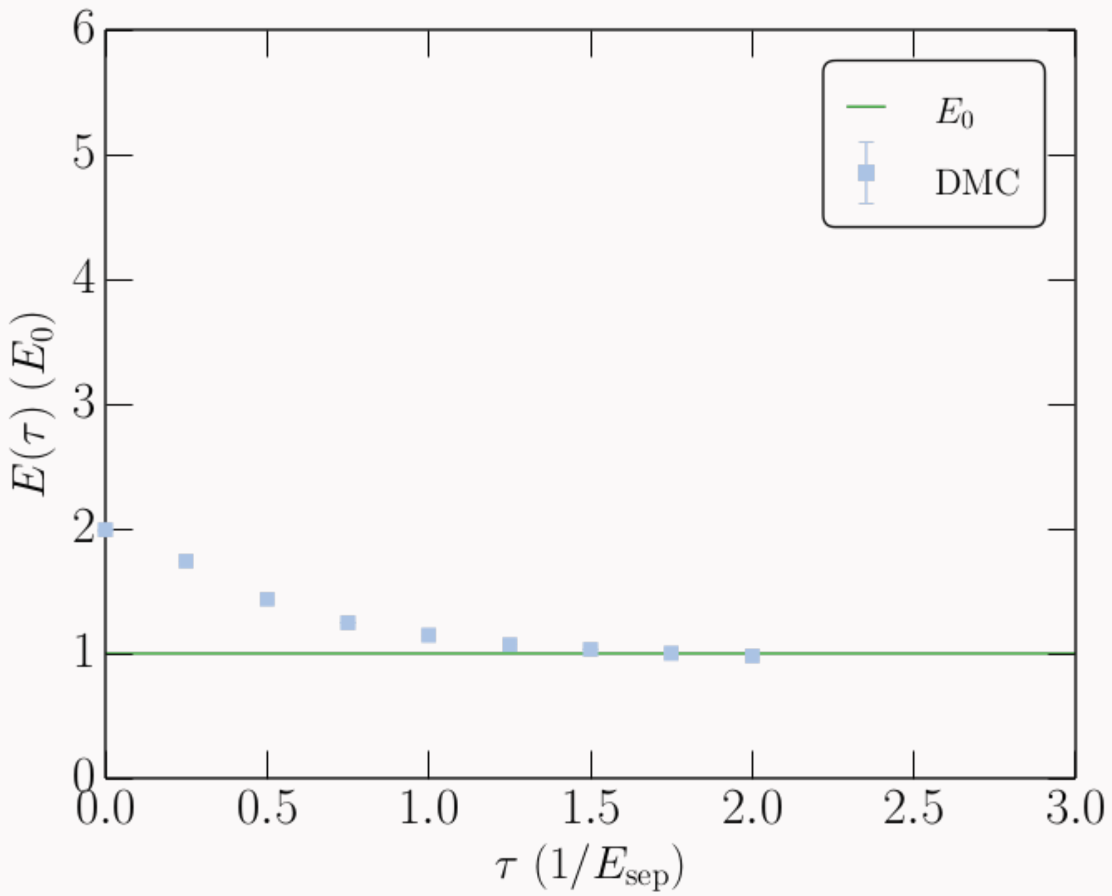


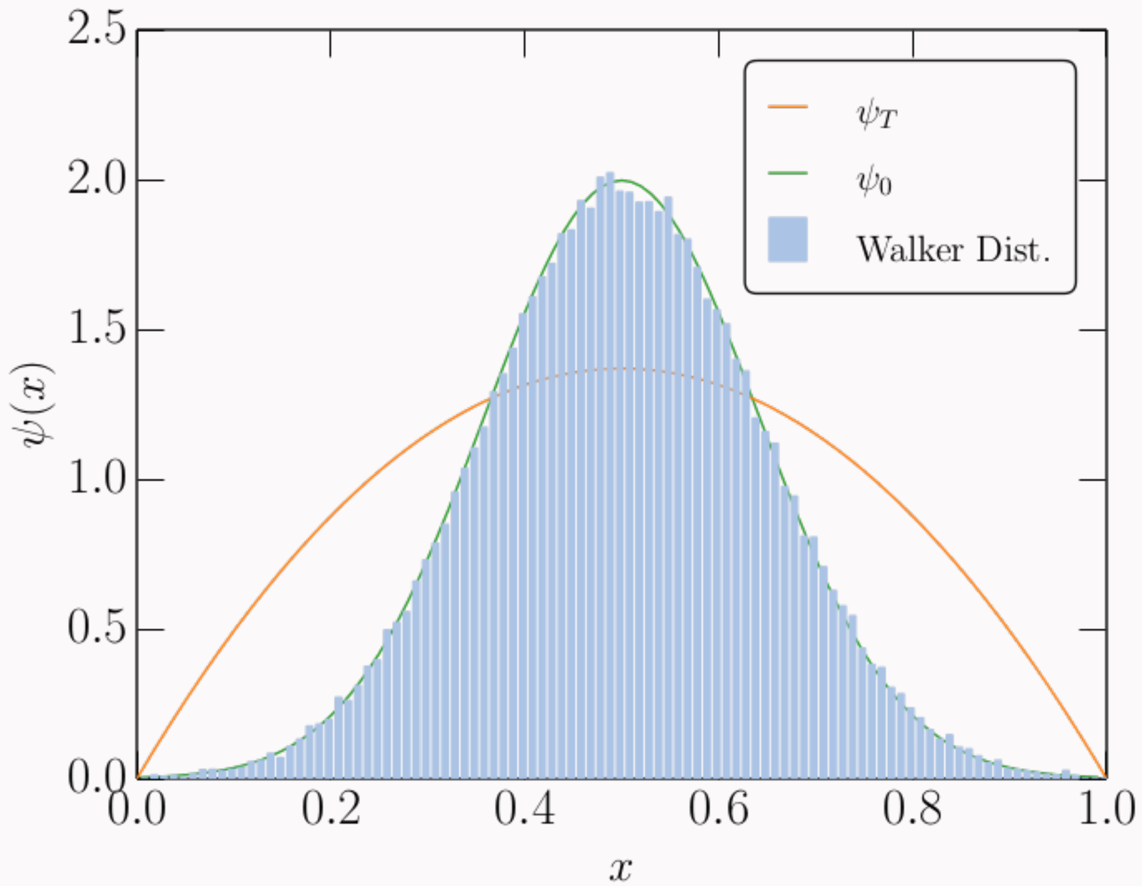


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 2.00$





QMC Methods - An Example

Imaginary-time evolution:

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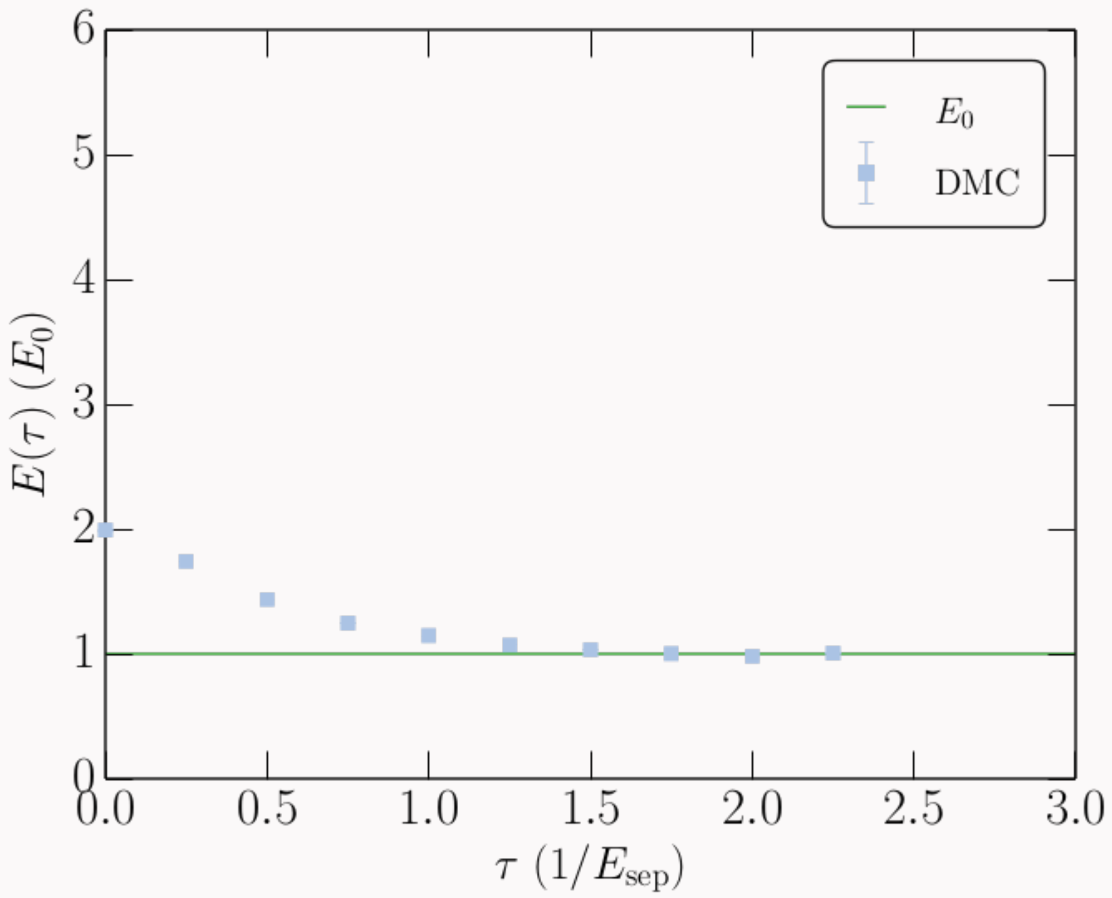

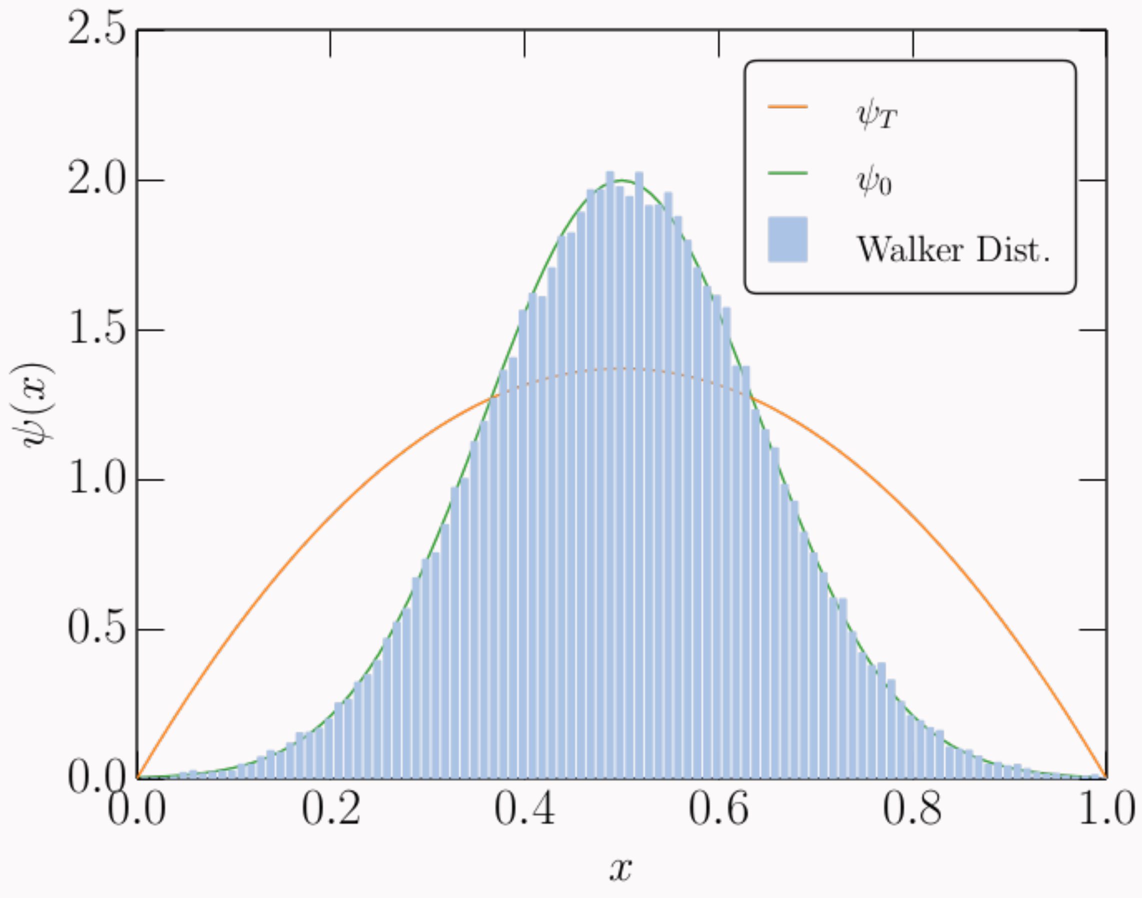

QMC Methods - An Example

Imaginary-time evolution:

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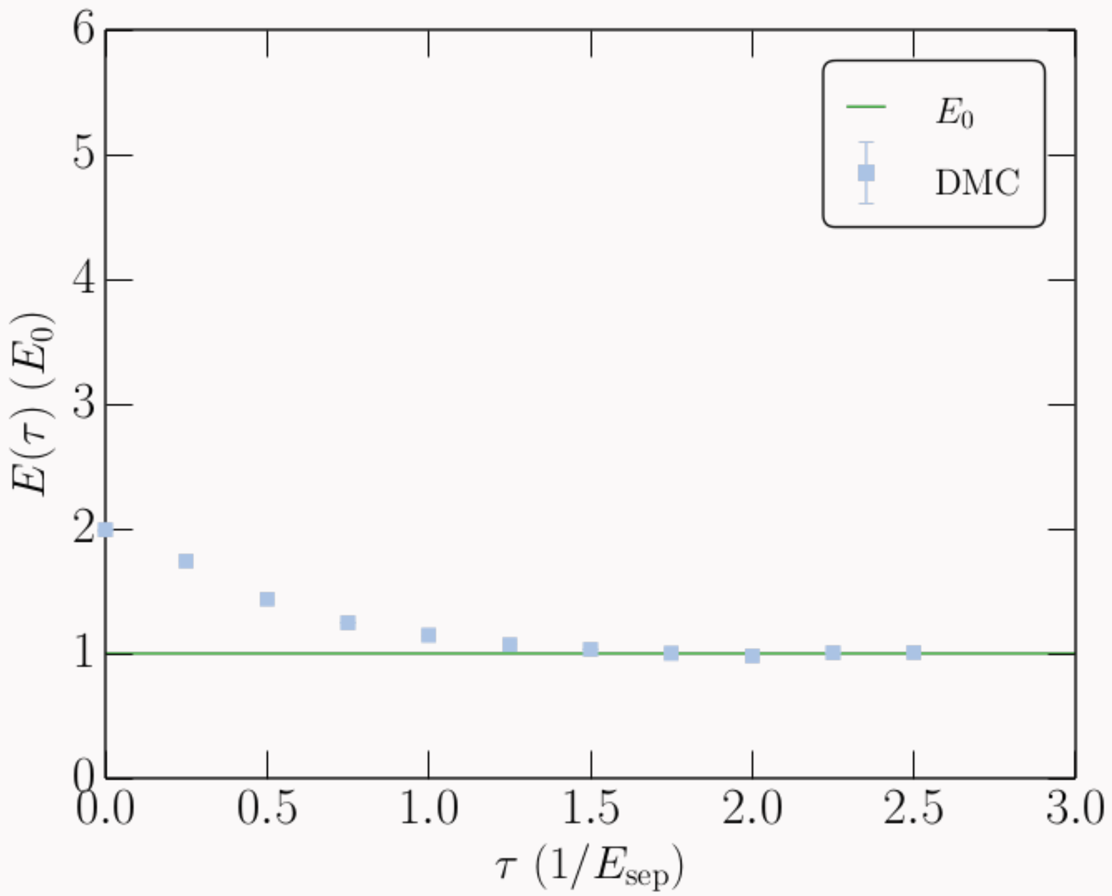
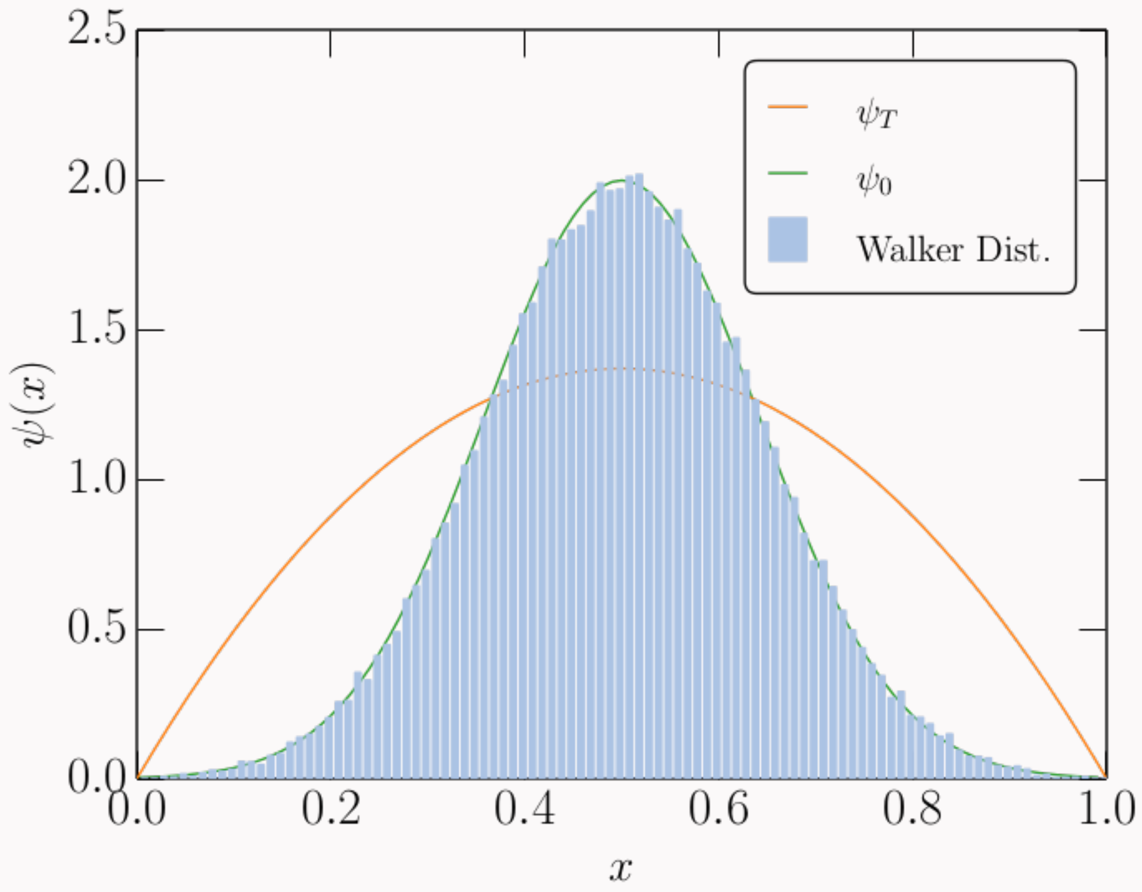
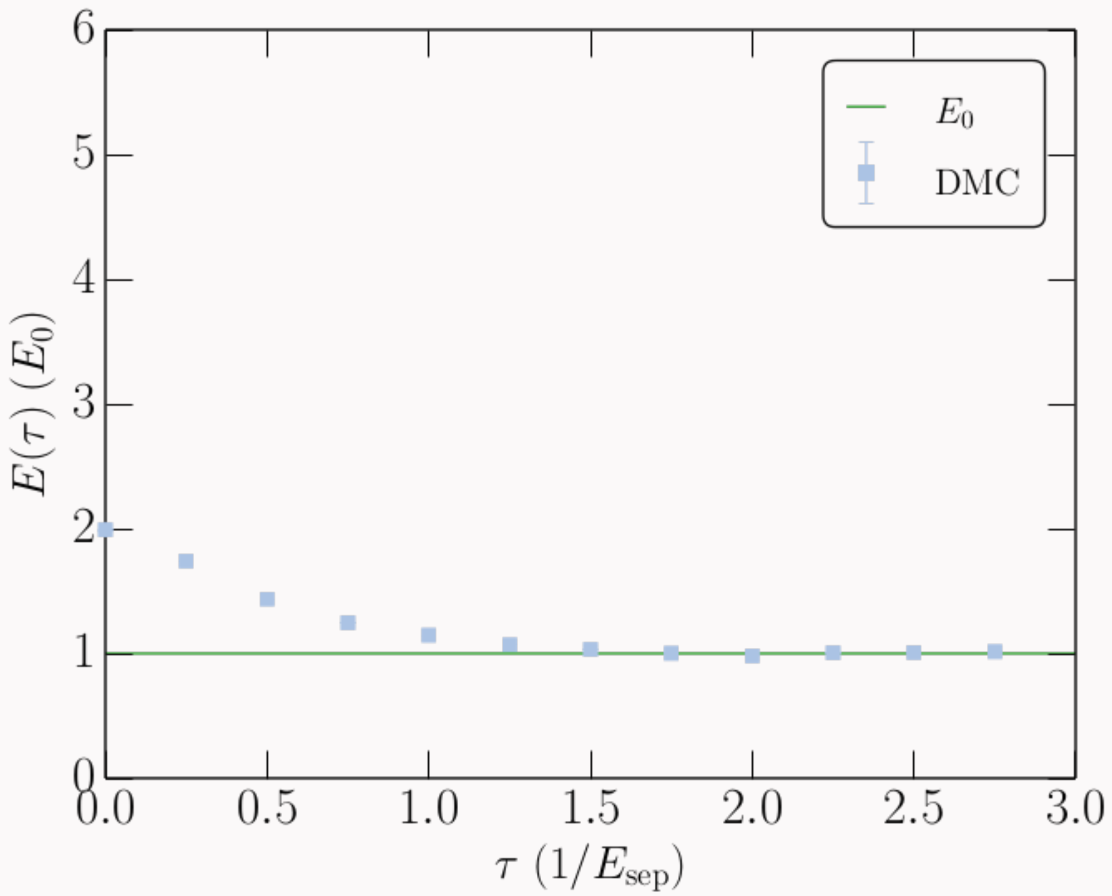


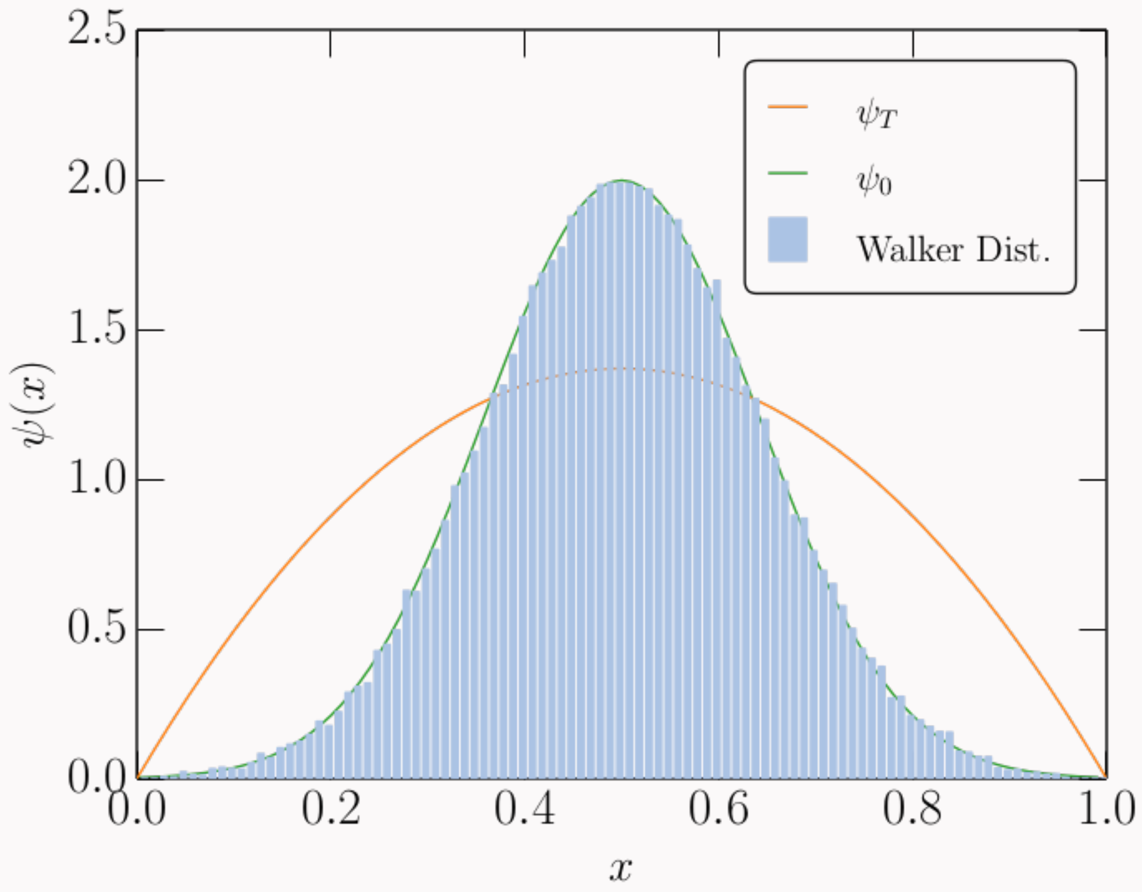


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 2.75$

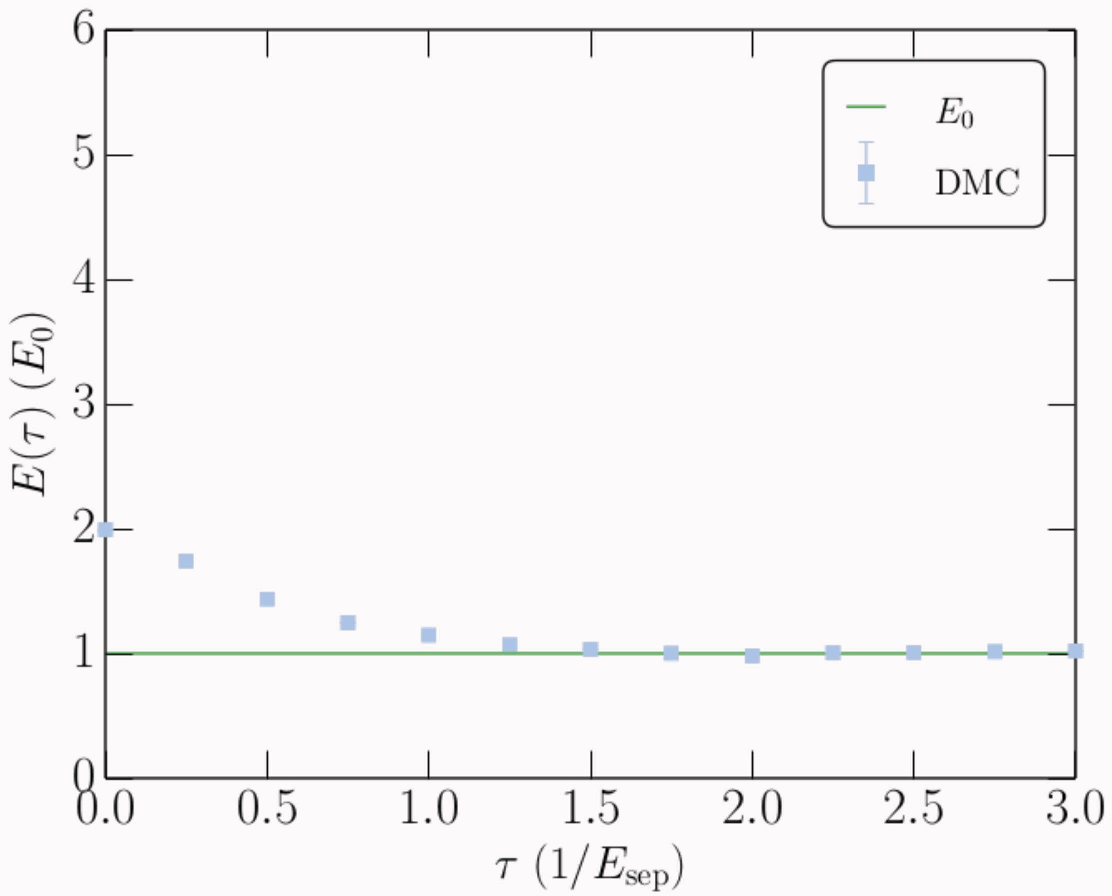


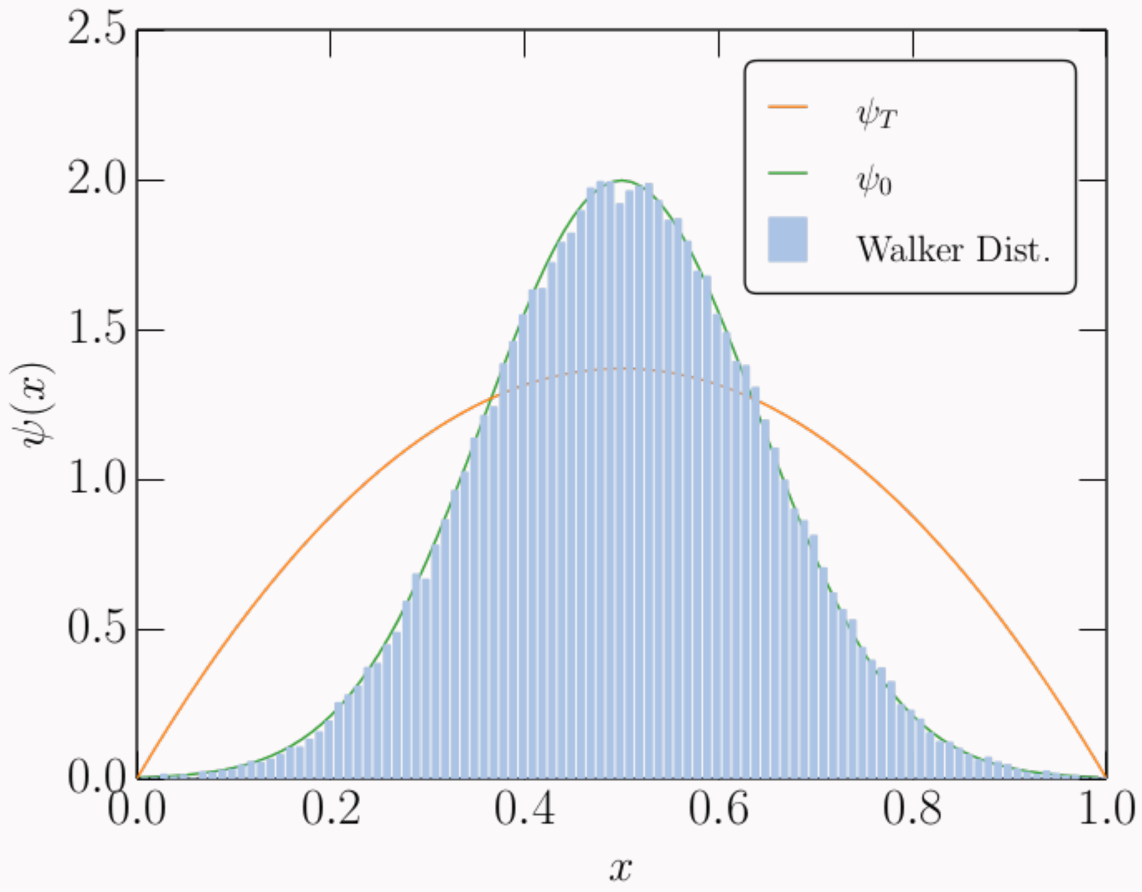


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 3.00$





QMC Methods - An Example

Imaginary-time evolution:

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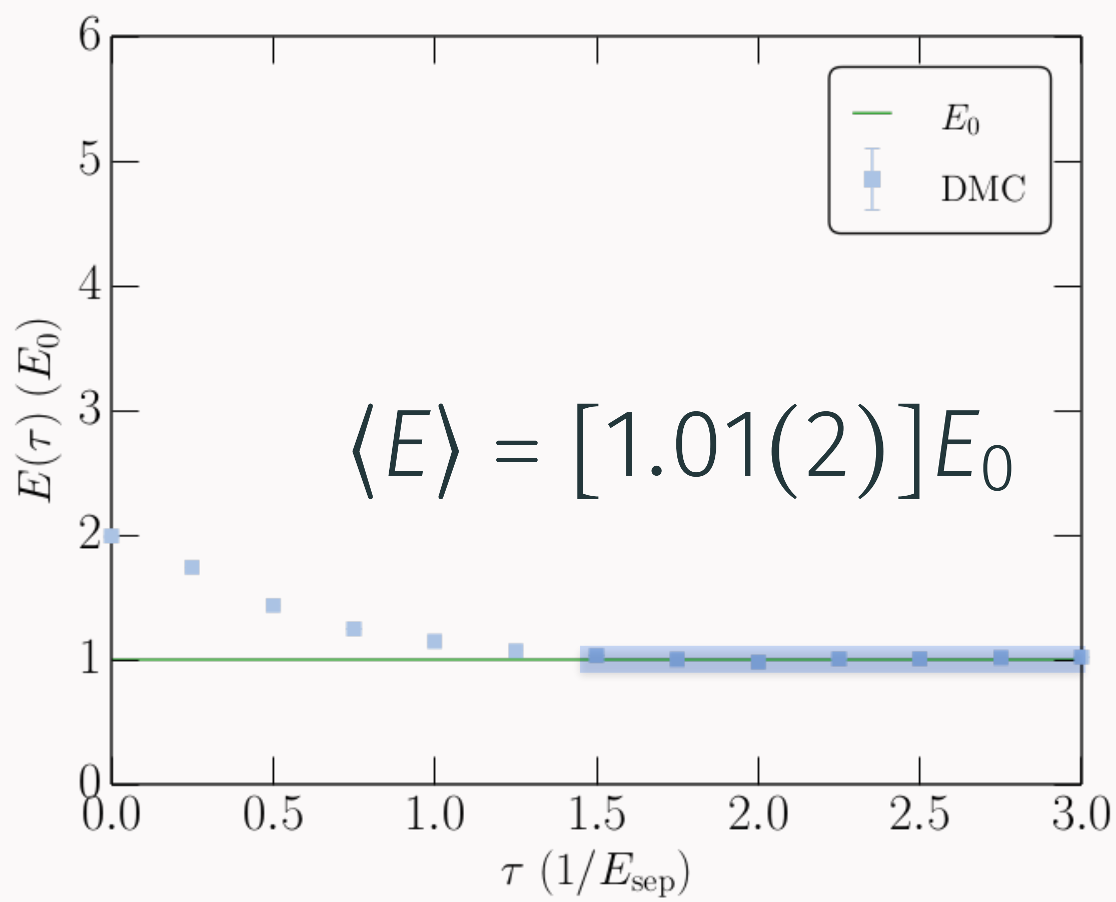
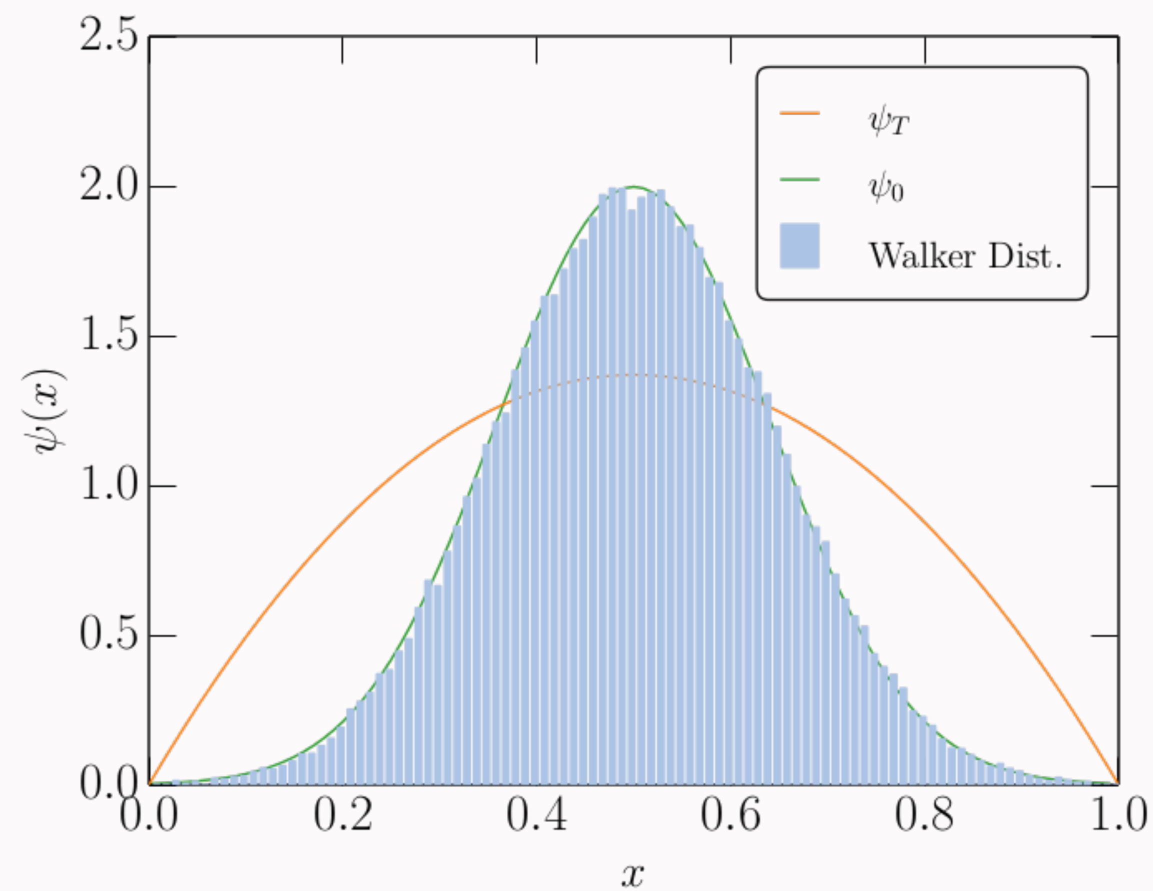




QMC Methods - The Rug

QMC Methods - Two Methods Used Below

Green's function Monte Carlo (GFMC)

- Among the most accurate nuclear many-body *ab initio* methods.
- Exponential scaling in A (sum over all spin-isospin states).

Auxiliary-field diffusion Monte Carlo (AFDMC)

- Still in development but now maturing quickly.
- Polynomial scaling in A (sample spin-isospin states).

The Hamiltonian

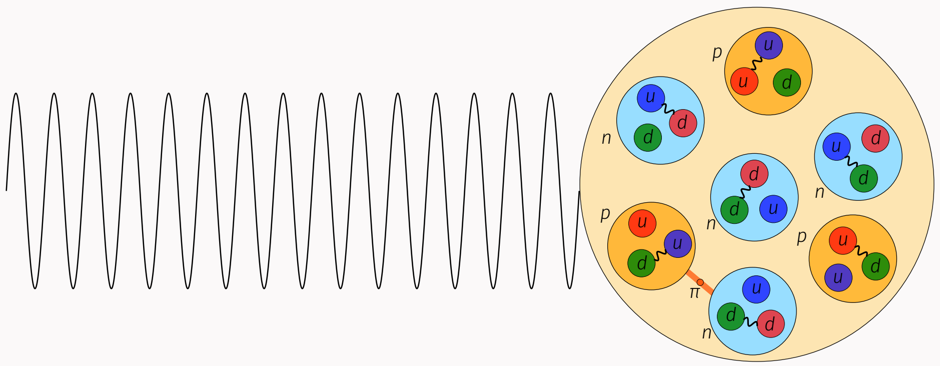
Of course, the nuclear Hamiltonian is complicated.

$$H = \sum_{i=1}^{A} \frac{\mathbf{p}_i^2}{2m_i} + \sum_{i<j}^{A} v_{ij} + \sum_{i<j<k}^{A} V_{ijk} + \cdots$$

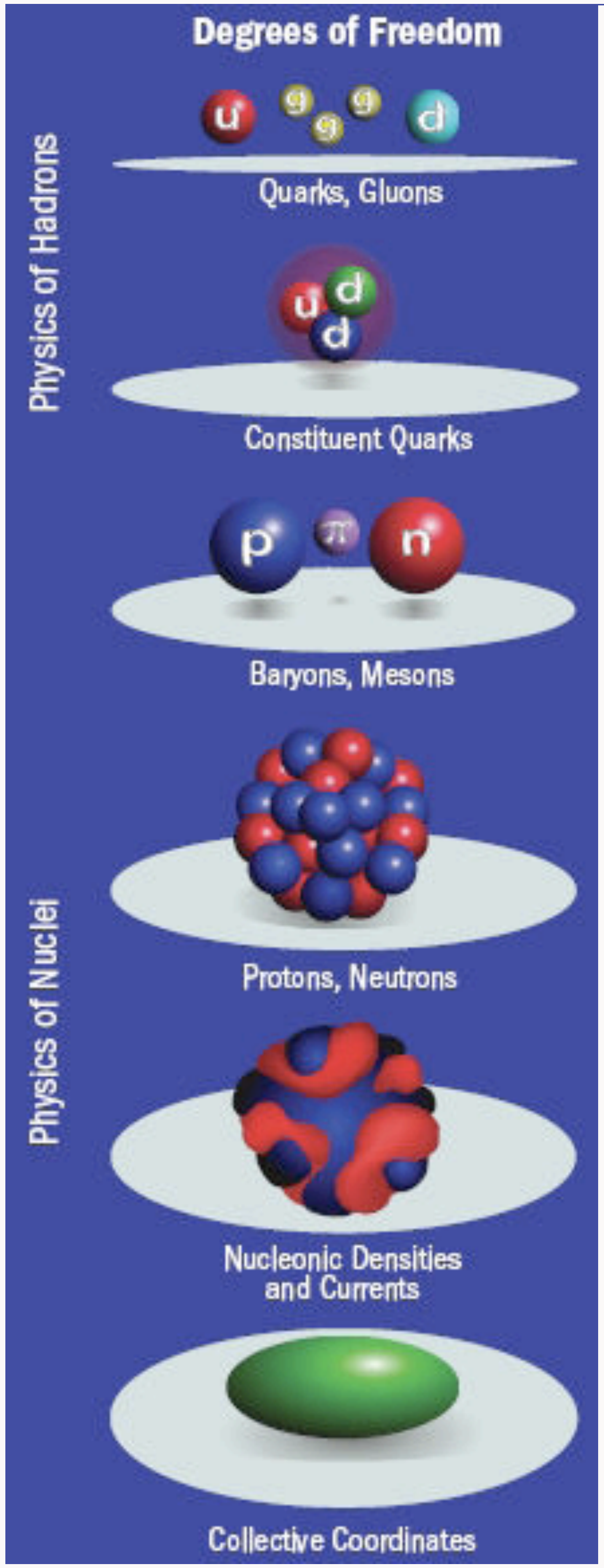
Where should it come from?

Chiral EFT

Motivation - Chiral EFT

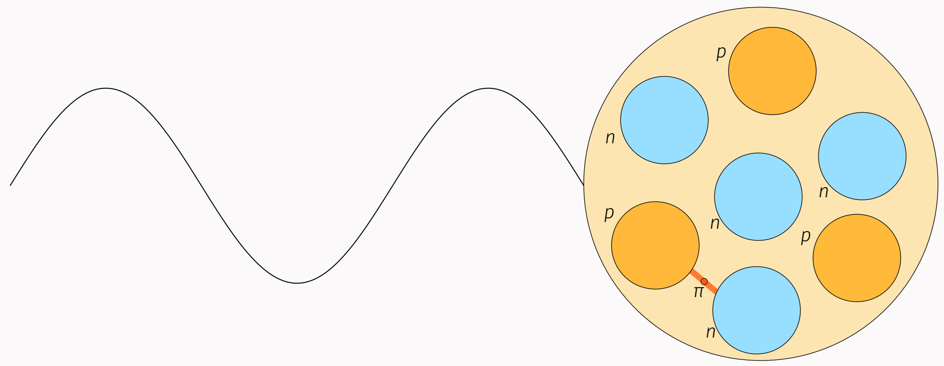


- If probed at high energies, substructure is resolved.
- At low energies, details are not resolved.
- Can replace fine structure by something simpler (think of multipole expansion): low-energy observables unchanged.



Lower Resolution

Motivation - Chiral EFT



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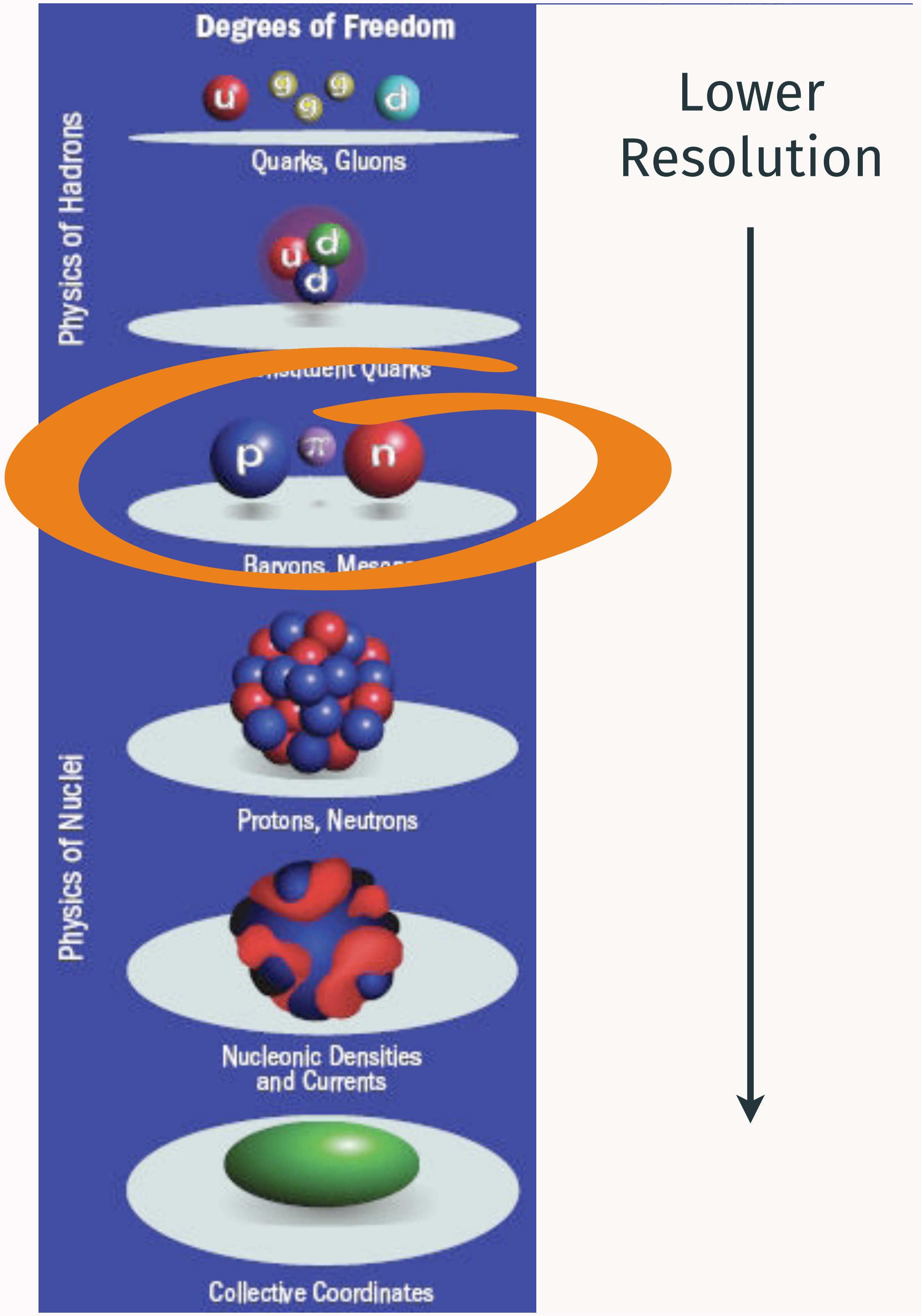
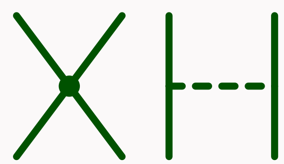
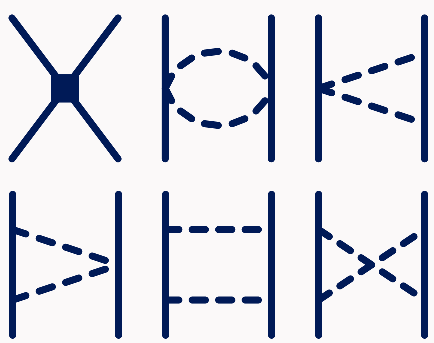
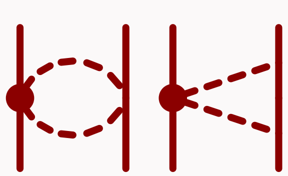
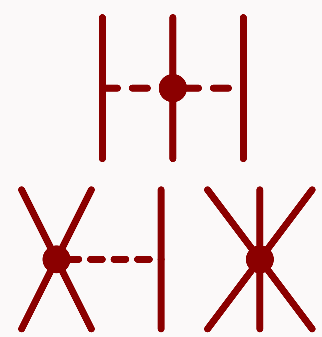
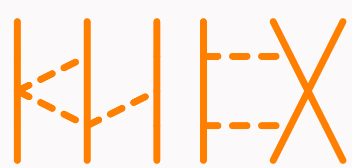


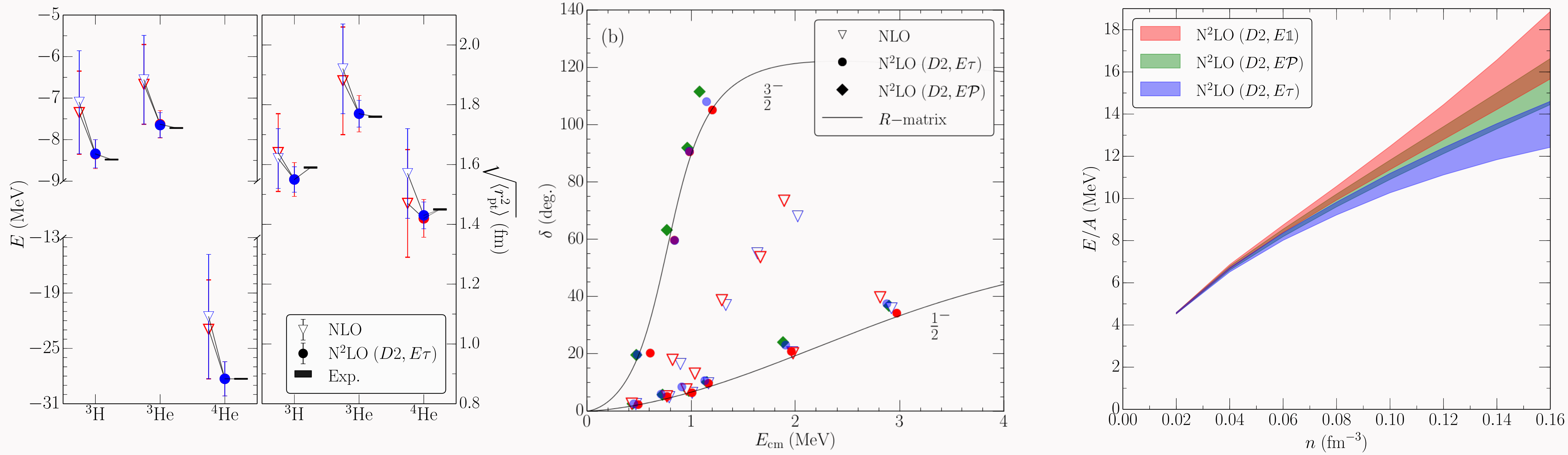
Chiral EFT

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

- 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 × LECs.
- Many-body forces & currents enter systematically.

Results

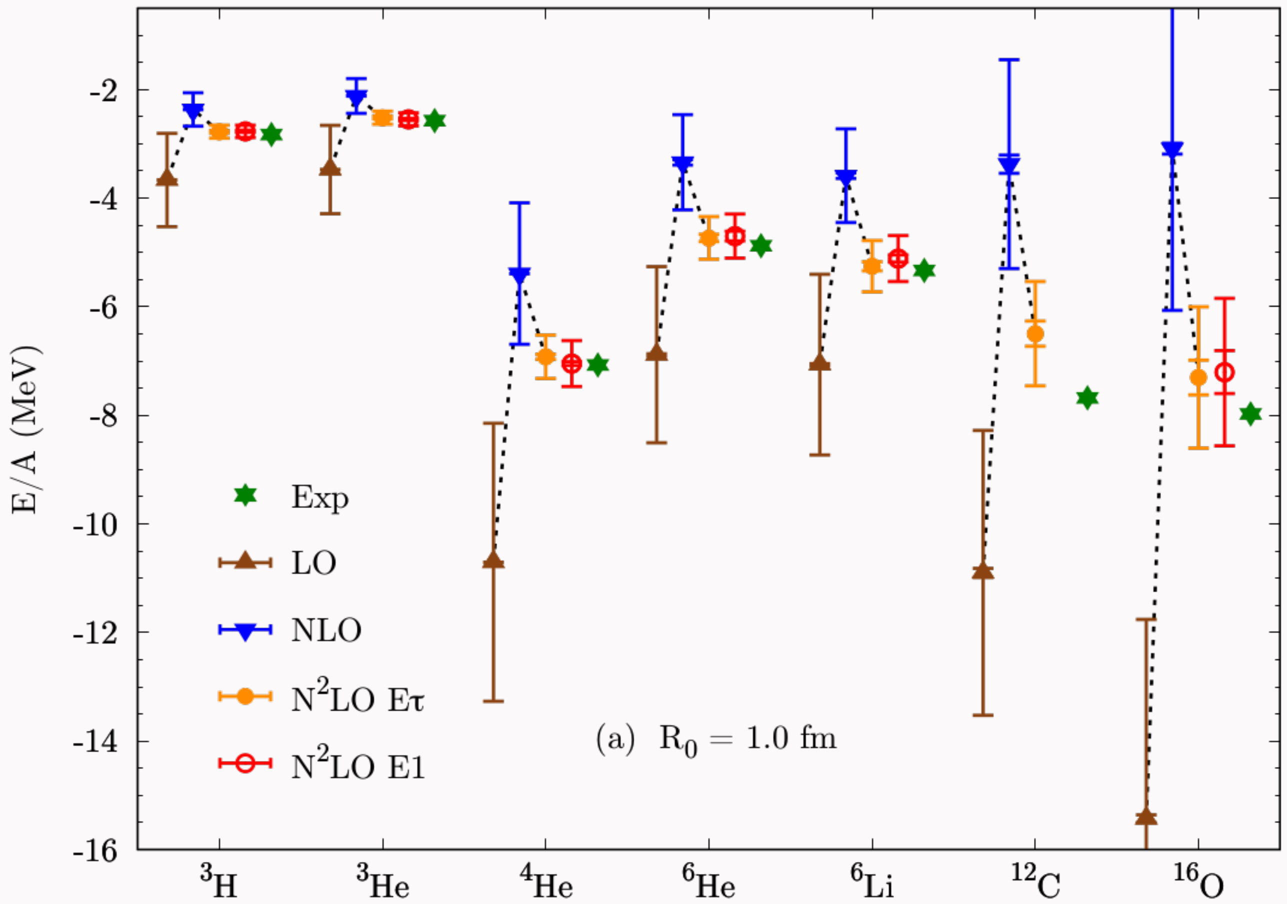
A simultaneous description of properties of light nuclei, n-α scattering and neutron matter is possible. Uncertainty analysis as in E. Epelbaum et al, EPJ **A51**, 53 (2015).

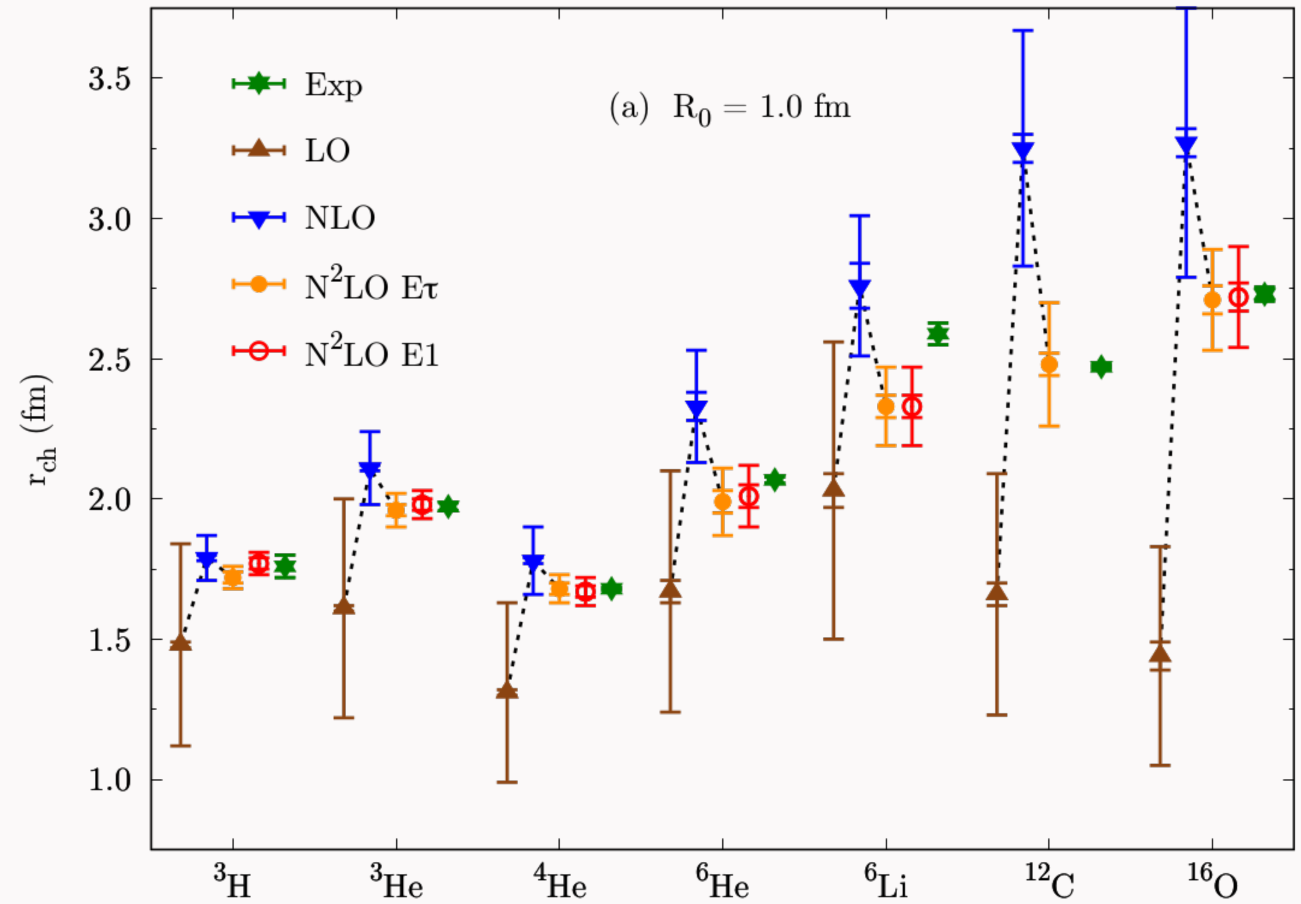


JEL et al, PRL **116**, 062501 (2016)

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, PRL **120**, 122502 (2018)

SRCs & EMC Effect

Some History And Definitions

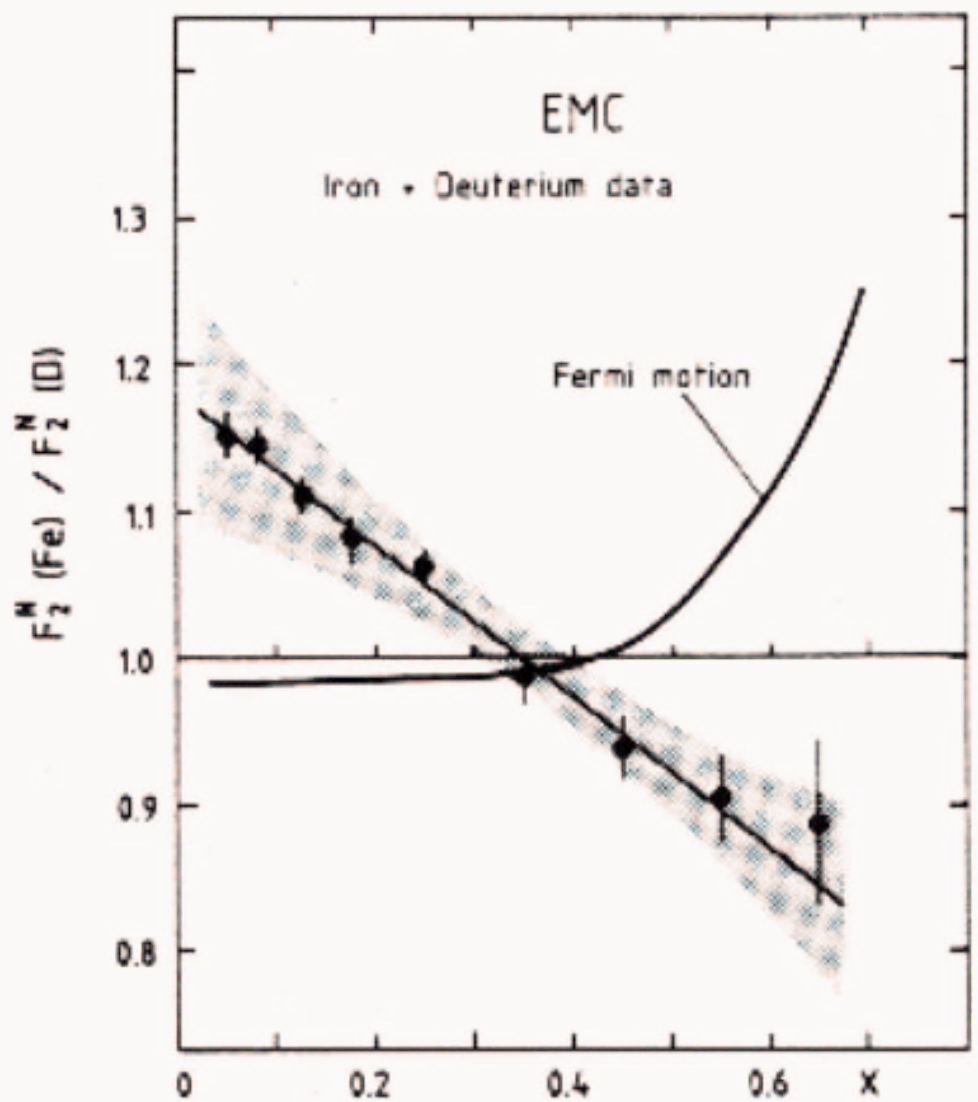
Deep inelastic scattering (DIS) cross section for EM interactions of charged leptons with nuclear targets:

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

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.

1983 EMC Paper

One-picture/One-sentence summary



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

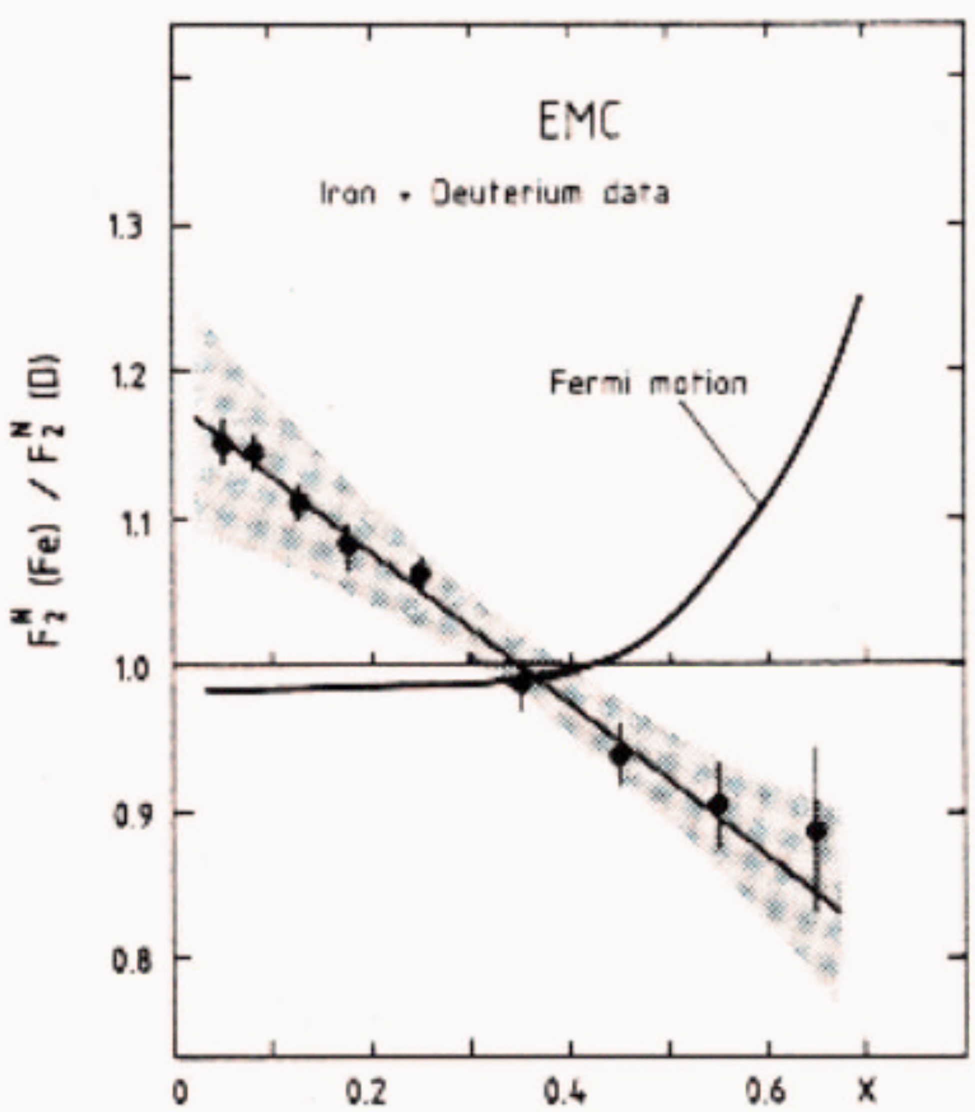
J. J. Aubert et al. (EMC), Phys. Lett. B. **123**, 275

“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:

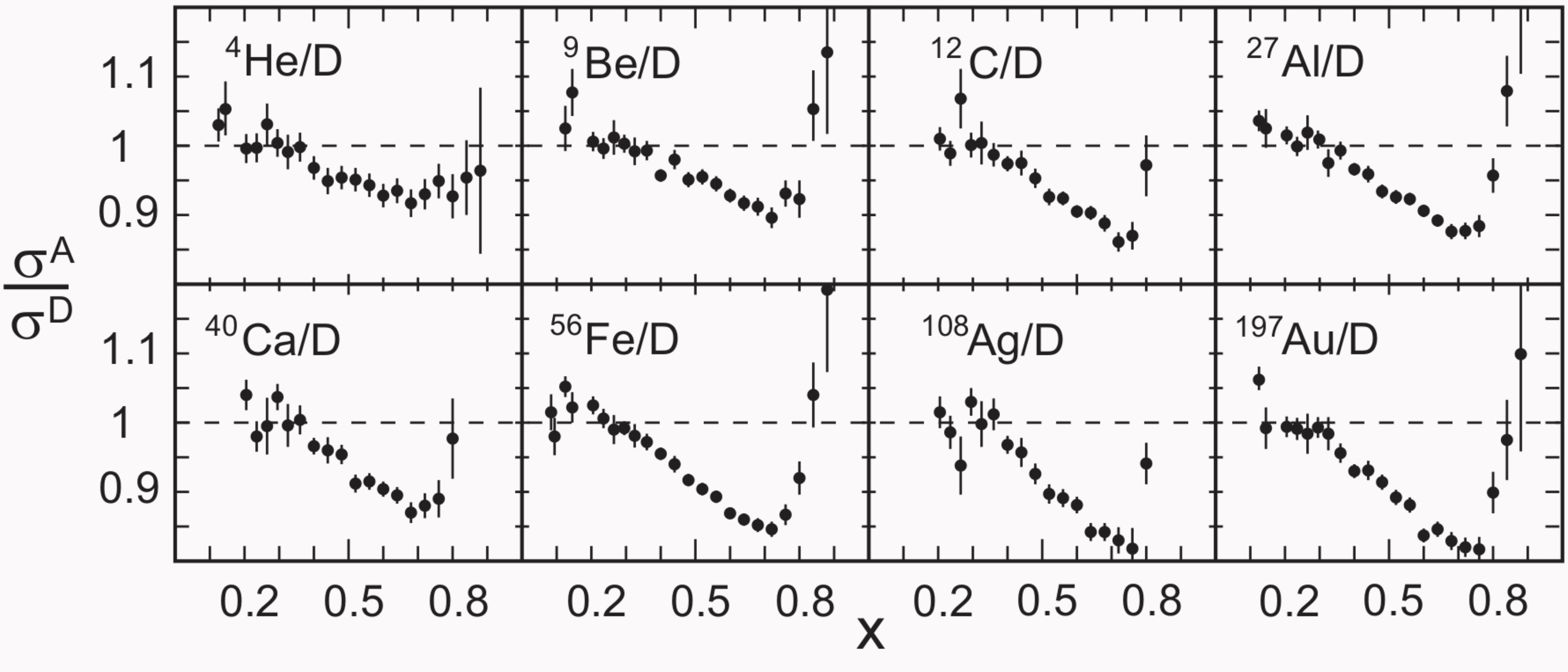
$$dR_{\mathrm{EMC}}(A,x)/dx|_{0.35<x<0.7} \sim d\left(\sigma^A/\sigma^d\right)/dx|_{0.35<x<0.7}$$



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

Some History And Definitions

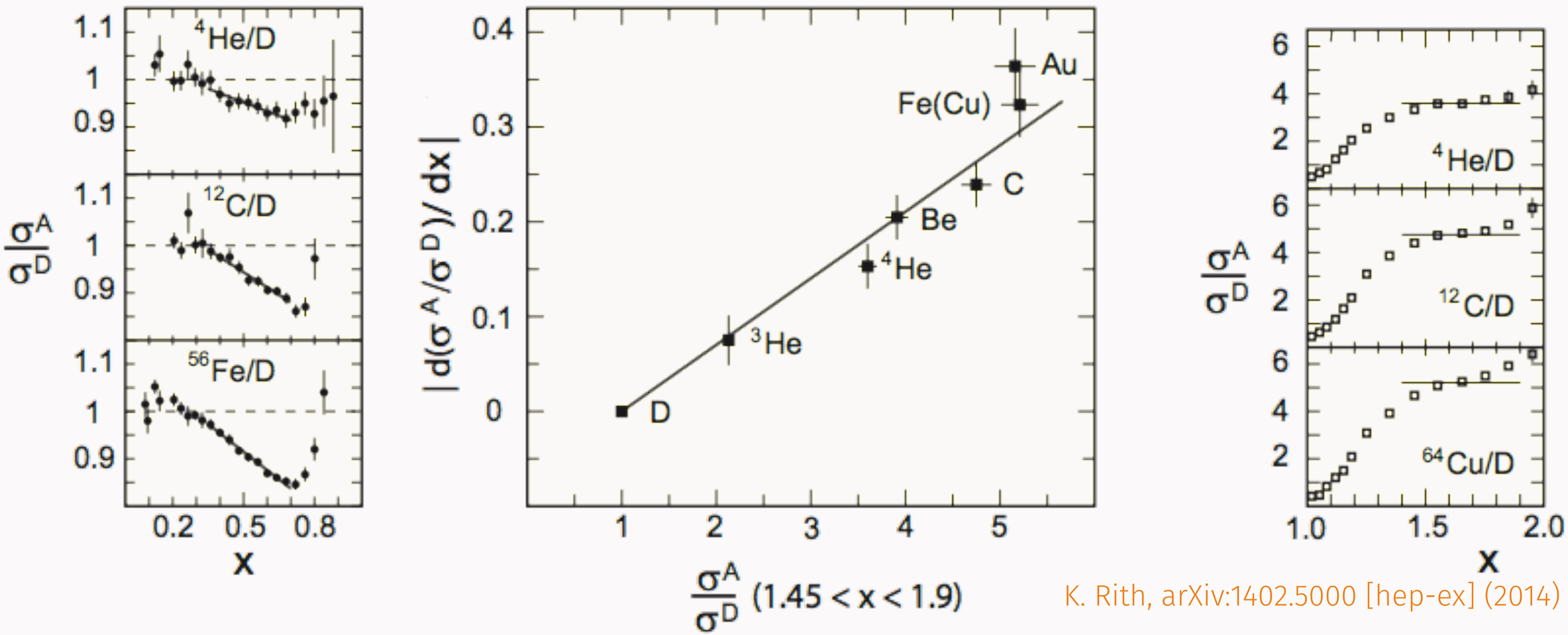
The ratio $R_{\text{EMC}}(A, x) = \frac{2F_2^A(x,Q^2)}{AF_2^d(x,Q^2)} \sim \frac{2\sigma^A}{A\sigma^d}$ plays an important role.



Later (~2000 And Beyond) Higher x Data

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

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



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

Implications Of EFT

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

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

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

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

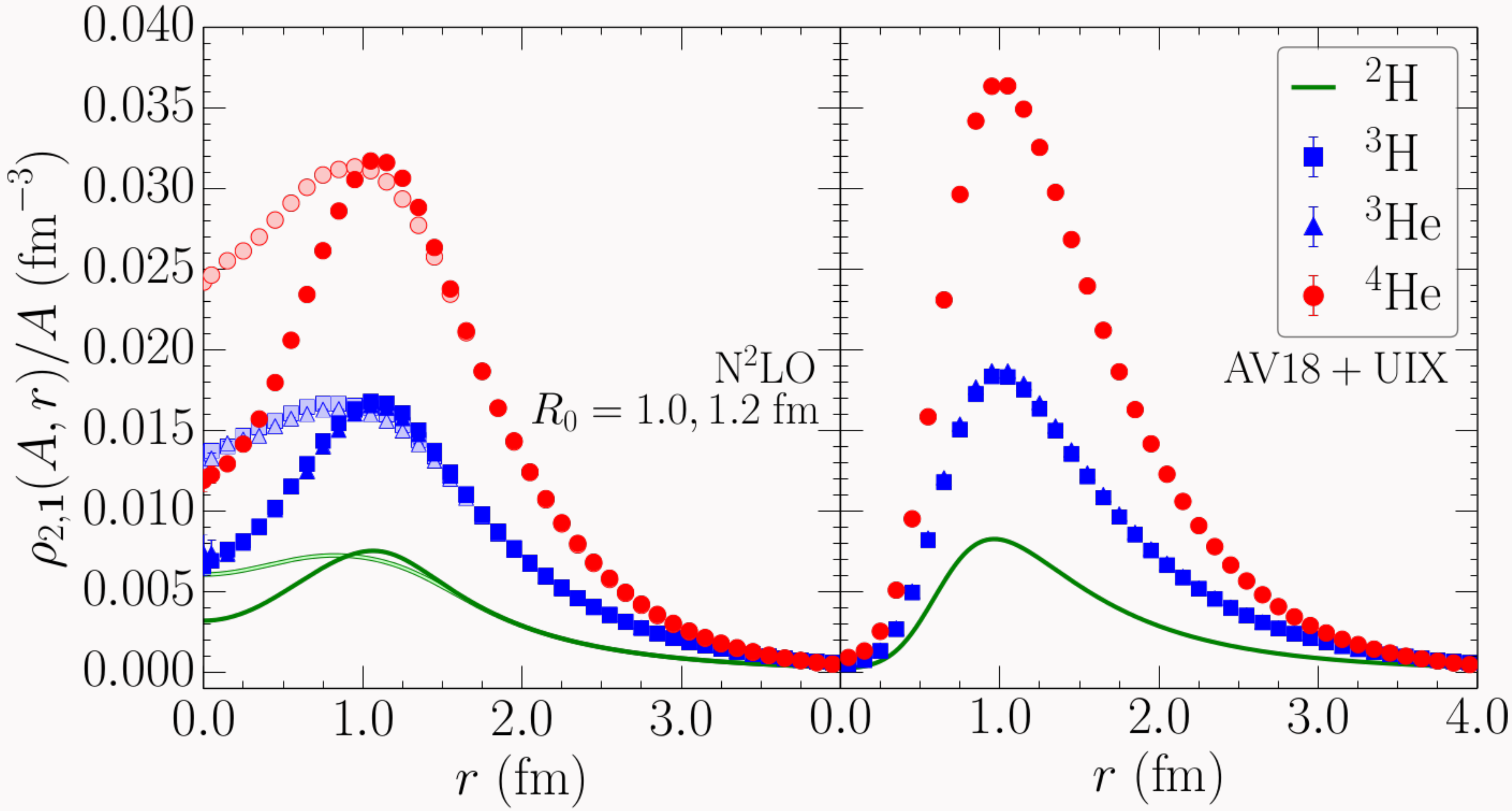
J.-W. Chen, W. Detmold, JEL, A. Schwenk,
PRL **119**, 262502, (2017):

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

Two-Body Distribution Functions (g_2)

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

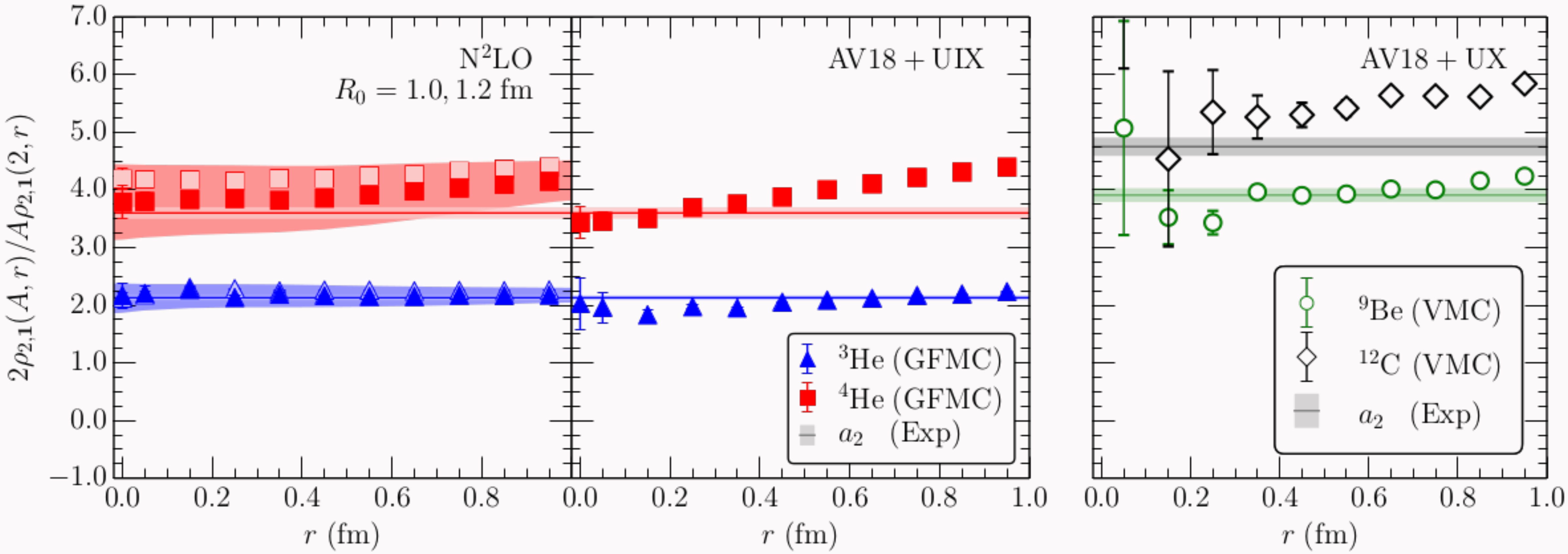
Scale and scheme dependent



SRC 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*!



SRC Factors

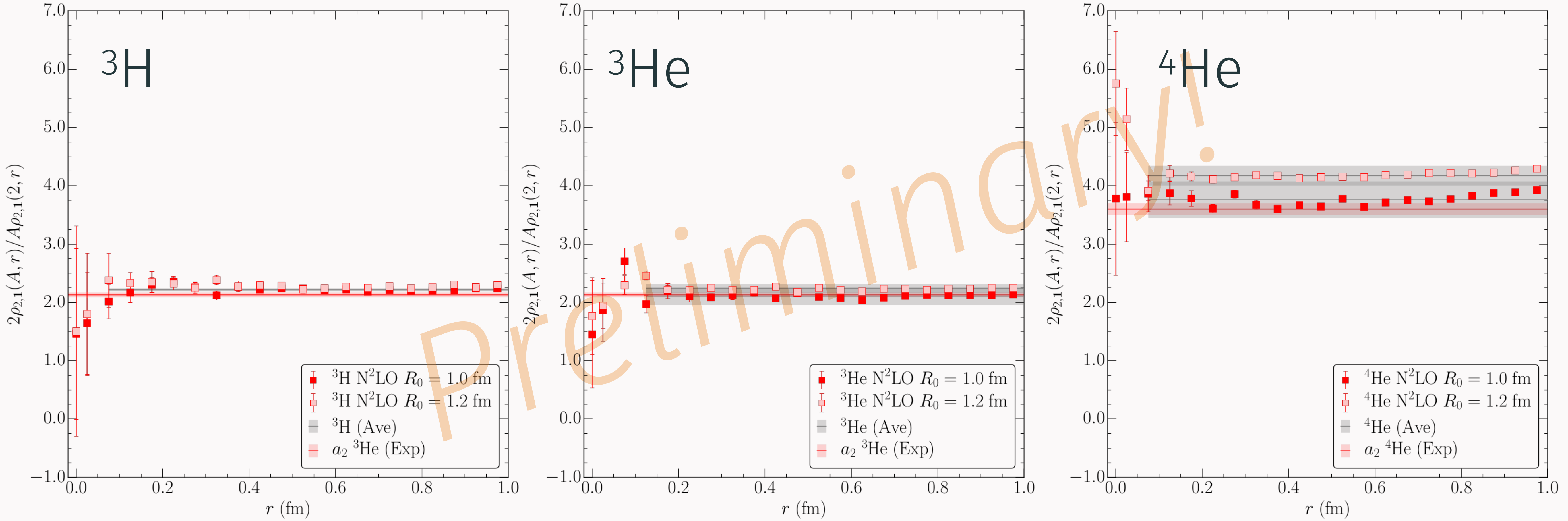
Detailed comparison of experiment and theory

	N^2LO ($R_0 = 1.0 - 1.2$ fm)	AV18+UIX	Exp
^3H	2.1(2) – 2.3(3)	2.0(4)	
^3He	2.1(2) – 2.1(3)	2.0(4)	2.13(4)
^4He	3.8(7) – 4.2(8)	3.4(3)	3.60(10)

SRC Factors From AFDMC

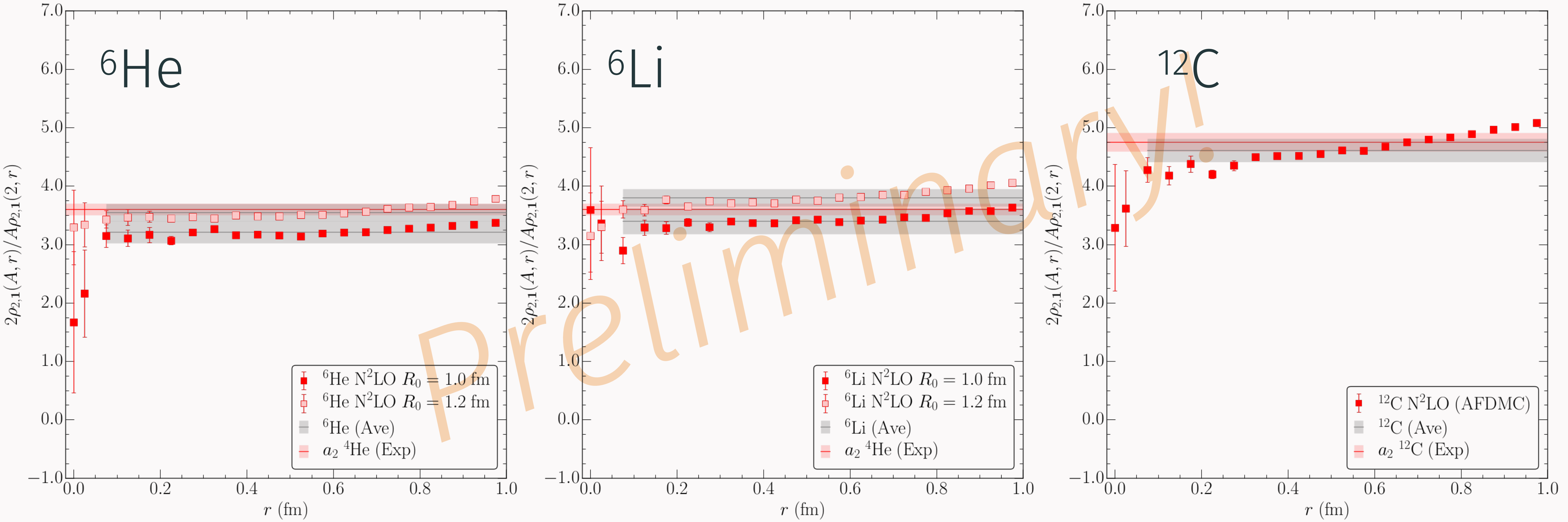
$$a_2 \equiv \lim_{r \to 0} \frac{2\rho_{2,1}(A,r)}{A\rho_{2,1}(2,r)}$$

Values extracted for a_2 identical to GFMC results.



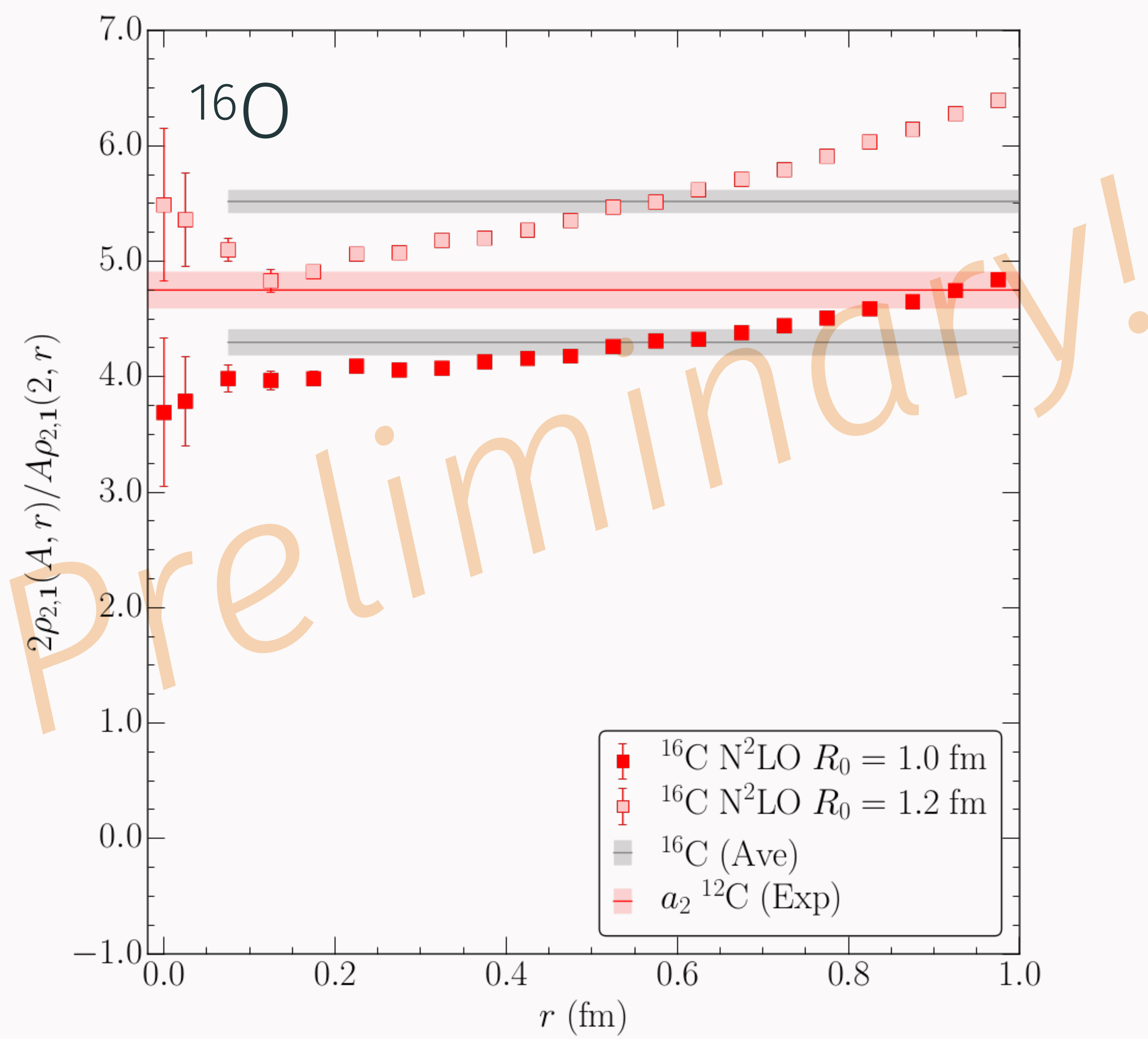
SRC Factors From AFDMC

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



SRC Factors From AFDMC

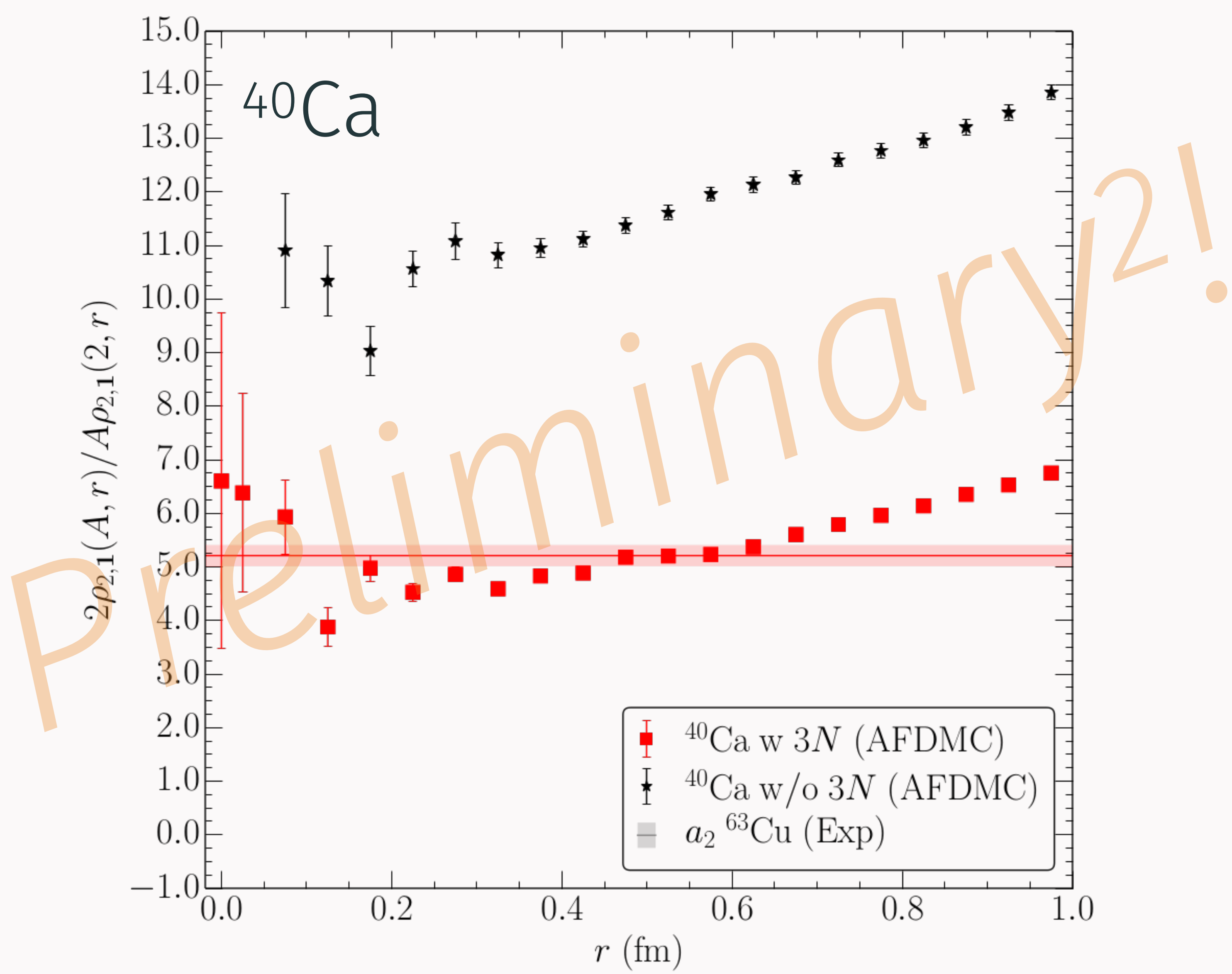
$$a_2 \equiv \lim_{r \to 0} \frac{2\rho_{2,1}(A,r)}{A\rho_{2,1}(2,r)}$$



SRC Factors From AFDMC

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

^{40}Ca w/simplified interaction: a_2 saturates as expected.



SRC Factors From AFDMC

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

	N^{2}LO ($R_0 = 1.0 - 1.2$ fm)	Exp.*
^{3}H	2.2(3) – 2.3(3)	
^{3}He	2.1(2) – 2.2(1)	2.13(4)
^{4}He	3.8(3) – 4.2(2)	3.60(10)
^{6}He	3.2(2) – 3.5(2)	
^{6}Li	3.4(2) – 3.8(2)	
^{12}C	4.6(2)–	4.75(16)
^{16}O	4.3(1) – 4.5(1)	

*O. Hen, G. A. Miller, E. Piasetzky, L. B. Weinstein, RMP **89**, 045002 (2017)

Preliminary!

Summary

- QMC methods + chiral EFT: A powerful combination.
- EFT predicts (postdicts) the linear relationship between R_{EMC} and a_2.
- Two-body distributions are **scheme and scale dependent**, but ratios are observable.
- Our results for a_2 seem to depend on the inclusion of $3N$ interactions.
- EFT can shed light on the existence of a_3 or the isospin dependence of the EMC effect.
- Values for a_2 might provide an **uncorrelated observable** for fitting nuclear interactions.

Acknowledgments

Collaborators

- J. Carlson, S. Gandolfi, D. Lonardoni — Los Alamos National Laboratory
- A. Schwenk — Technische Universität Darmstadt
- I. Tews — Institute for Nuclear Theory
- J.-W Chen — 國立臺灣大學 National Taiwan University
- A. Gezerlis — University of Guelph
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Thank you for your attention!