Few-Neutron Resonances From Chiral EFT

Hirshegg 2018 - Multiparticle resonances in hadrons, nuclei, and ultracold atomic gases

TECHNISCHE UNIVERSITÄT DARMSTADT

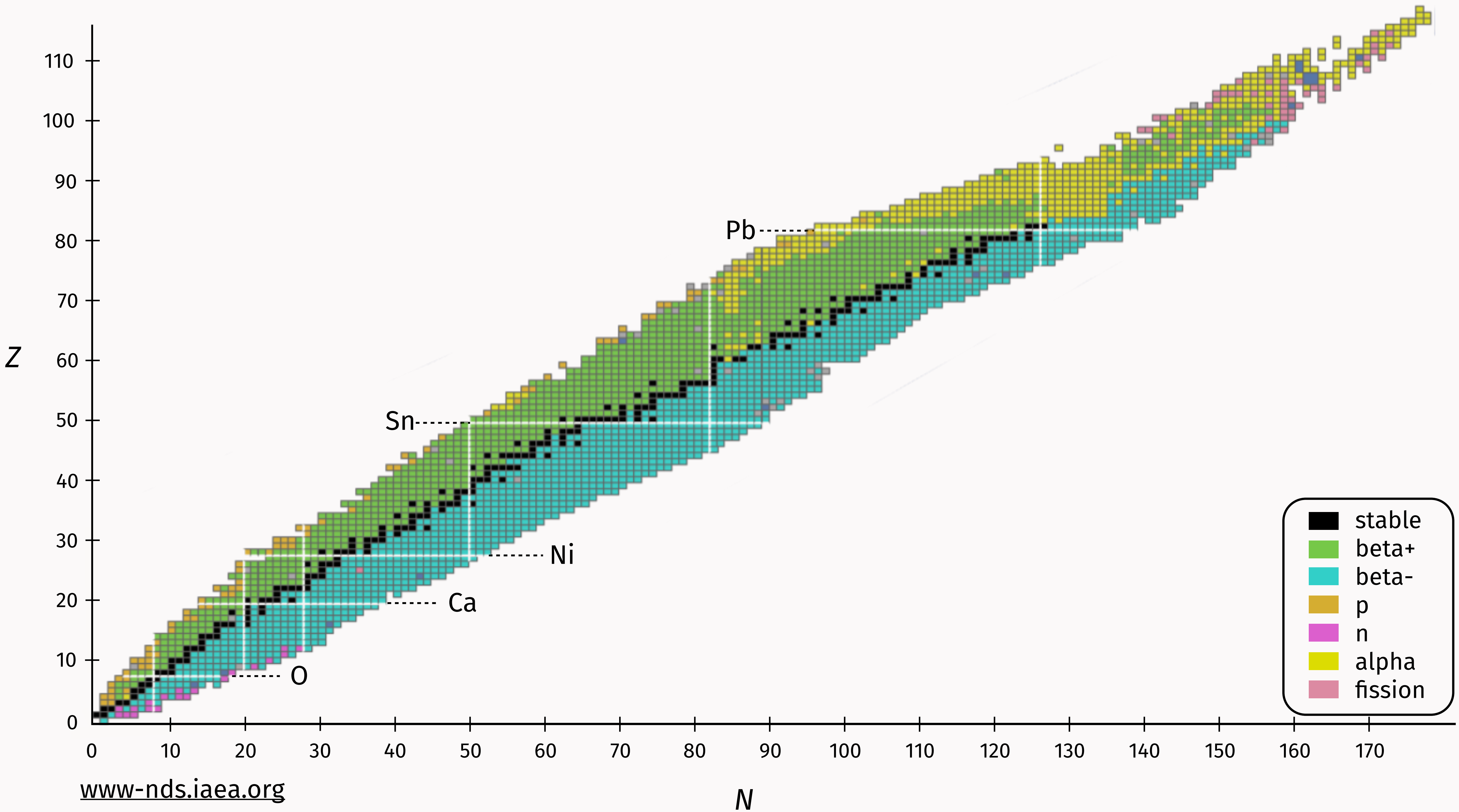
Bundesministerium für Bildung und Forschung

Joel E. Lynn

January 16, 2018

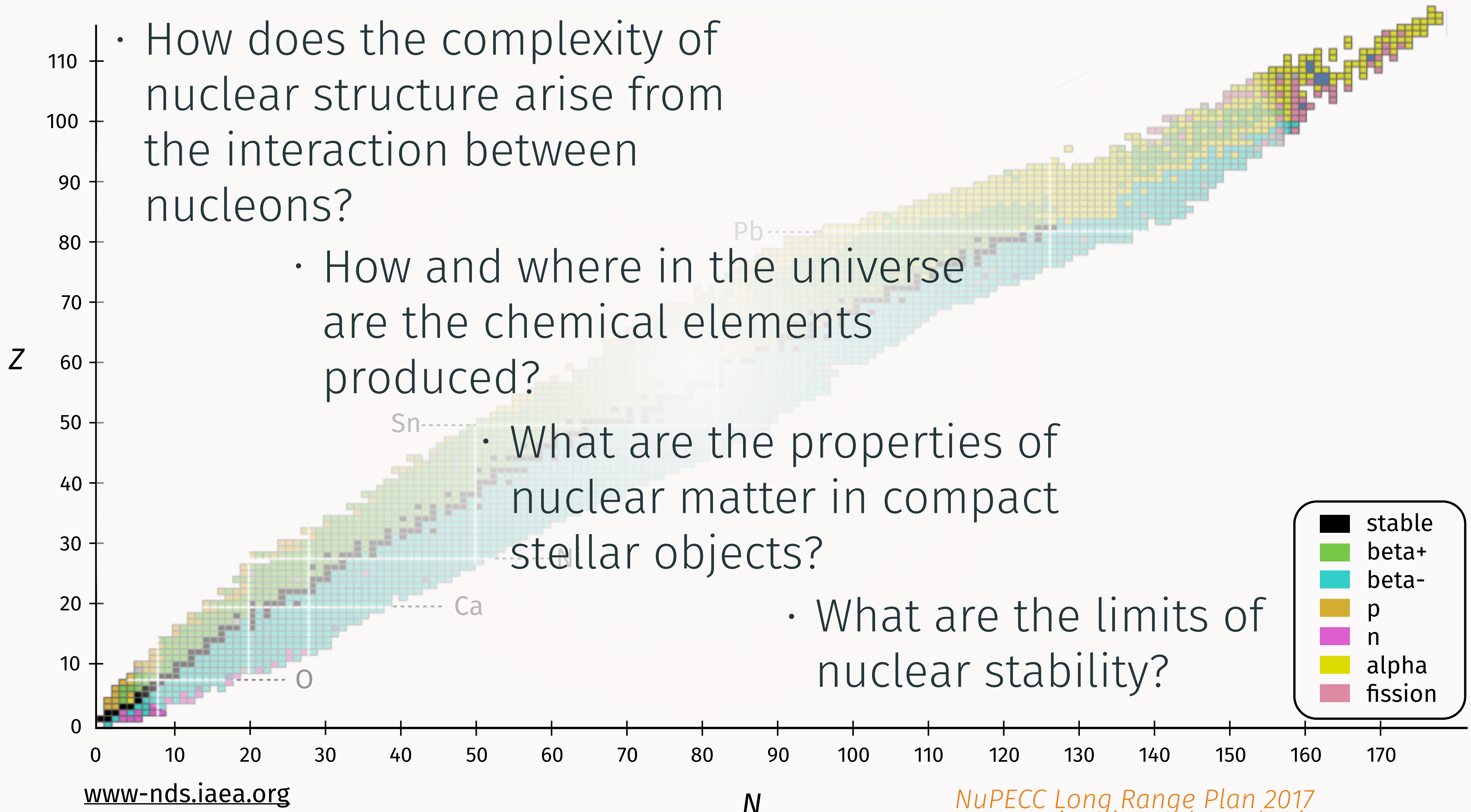
Motivation

The Nuclear Landscape



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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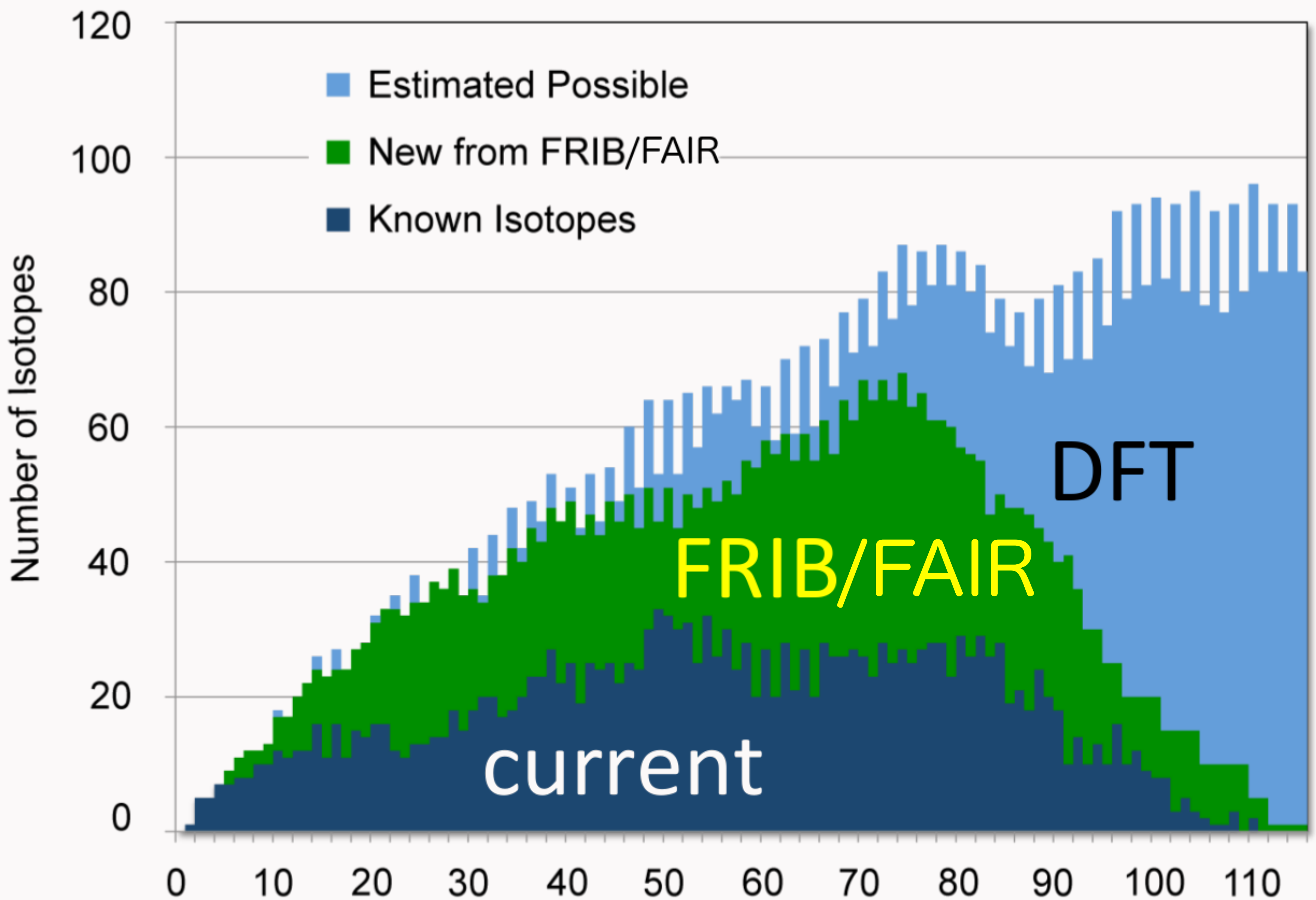
NuPECC Long Range Plan 2017
Perspectives in Nuclear Physics

Extending The Nuclear Landscape



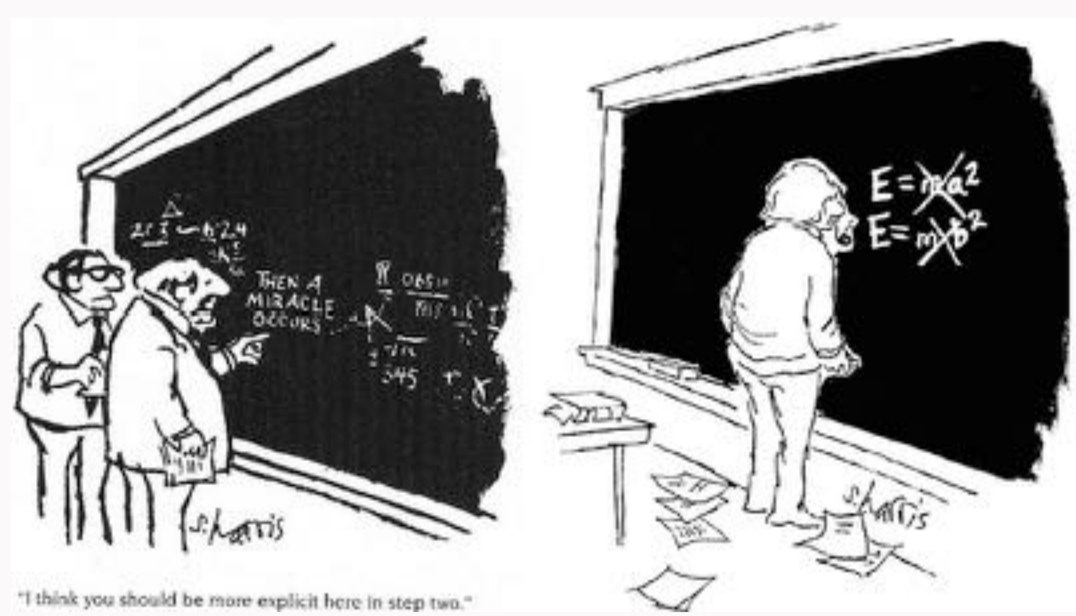
adapted from A. B. Balentekin et al., Mod. Phys. Lett. A, **29** 1430010 (2014)

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.



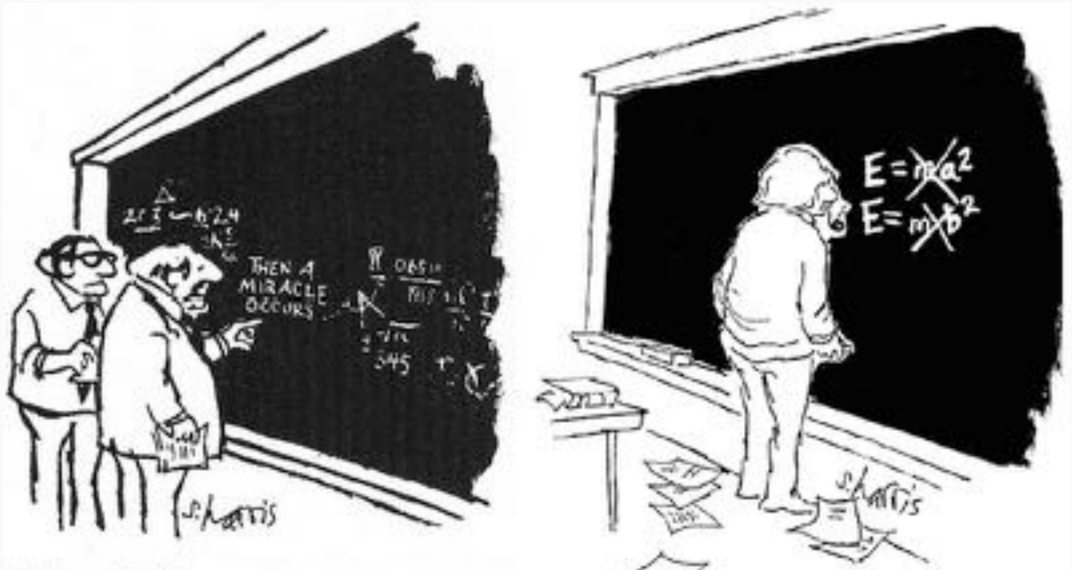
What Can Theory Offer?

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.

   work with protons + neutrons
   &
   controlled approximations

2. Chiral effective field
   interactions.

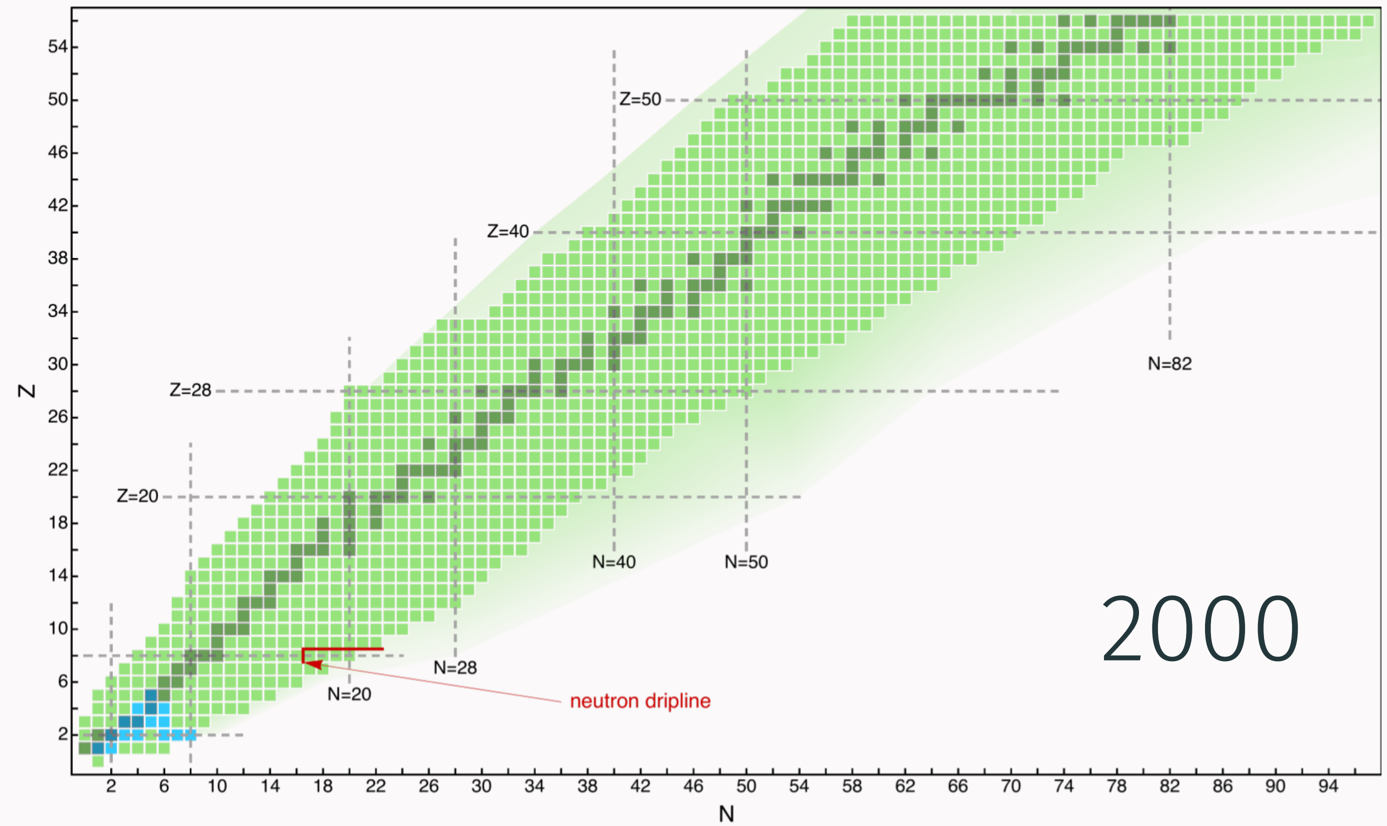


"I think you should be more explicit here in step two."

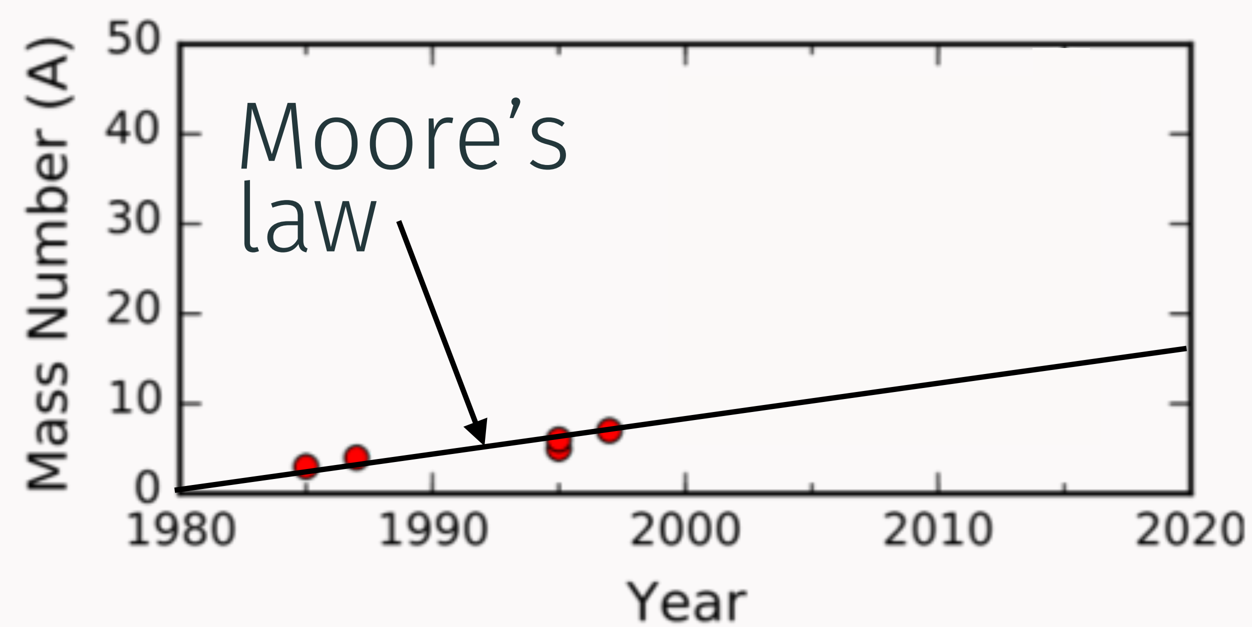
Reach Of *Ab Initio* Methods

- <u>1980s & 1990s:</u>
  Exact methods (exponential scaling) e.g. *Green's Function Monte Carlo Method*, *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*. Closed-shell nuclei around up to A = 40.



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



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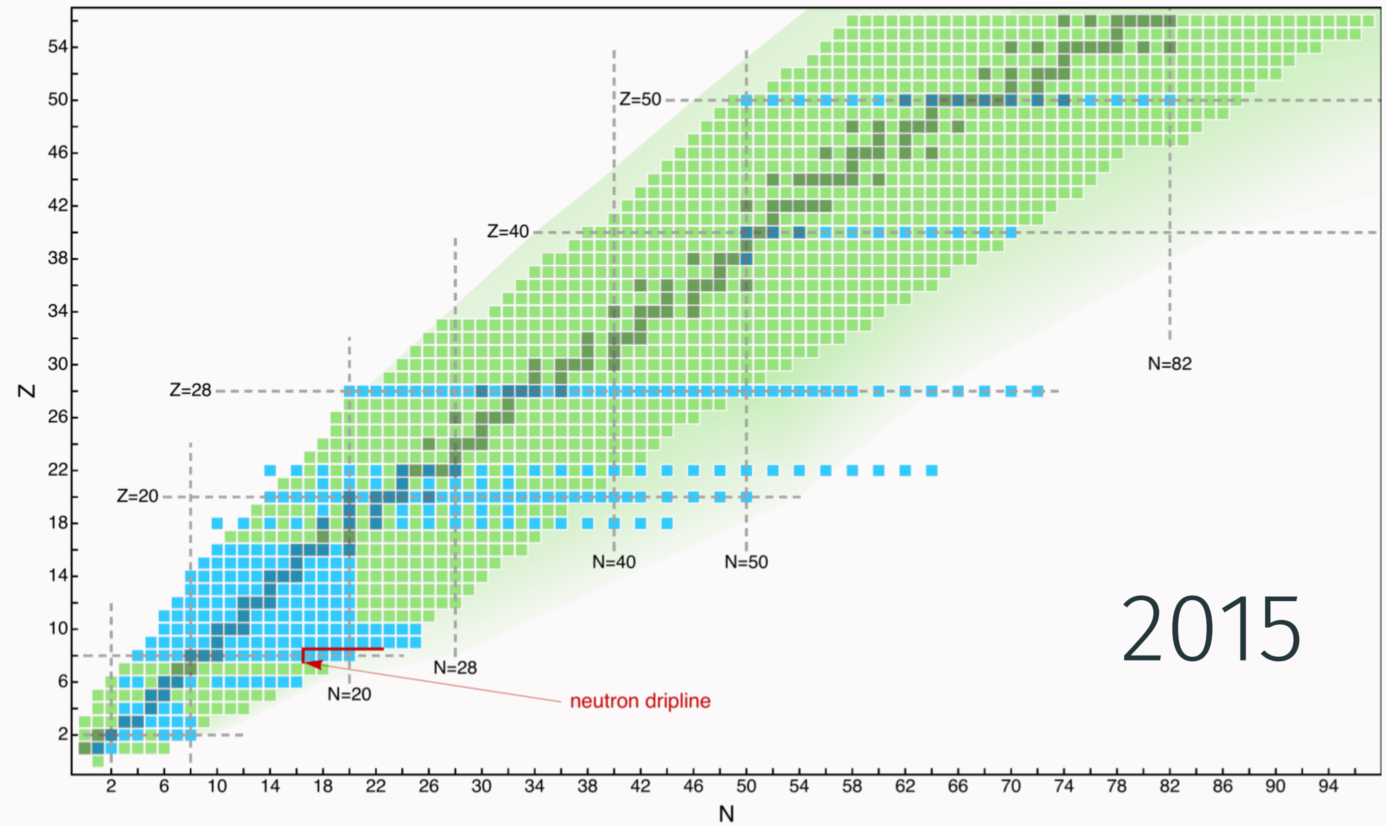

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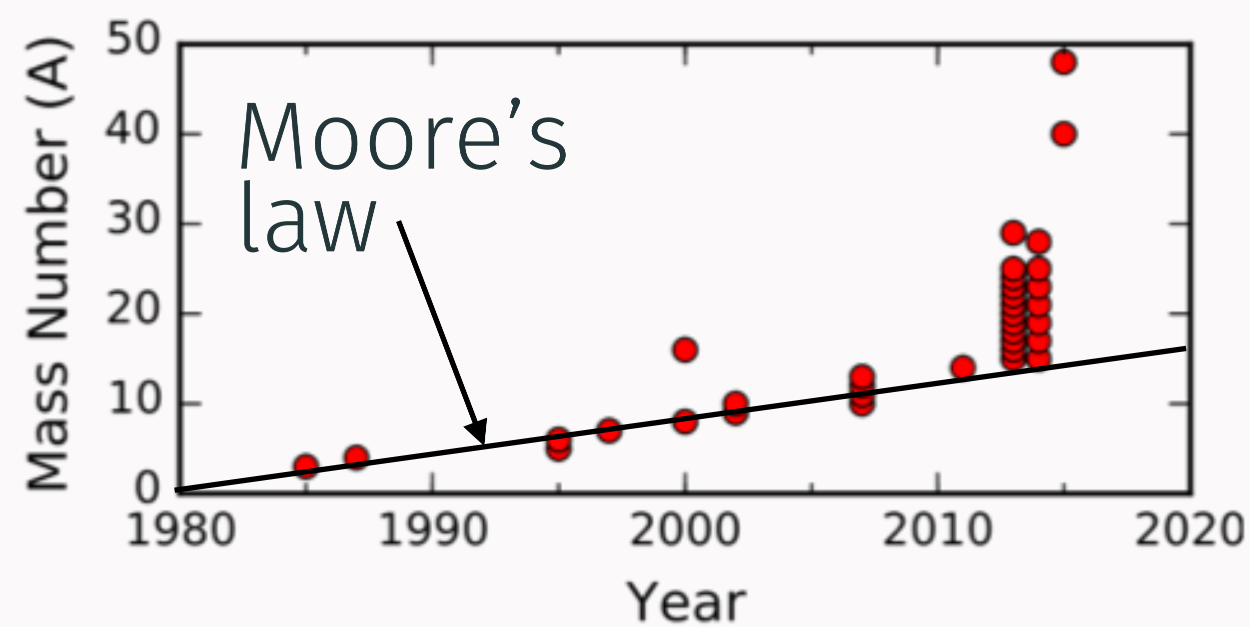

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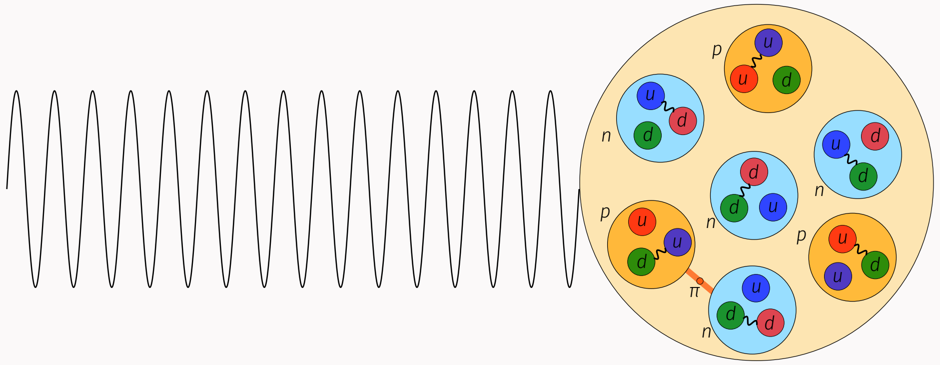
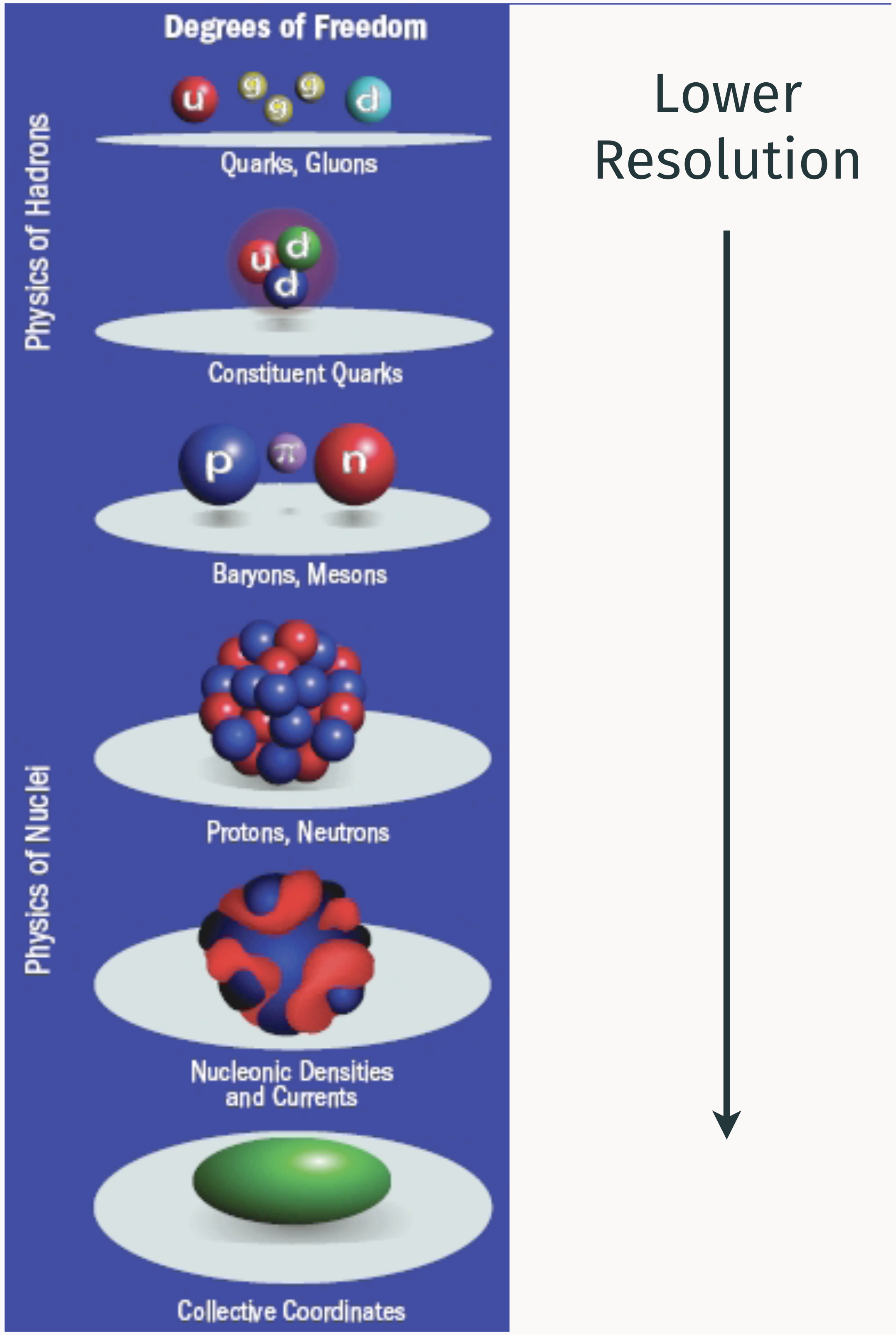
Chiral EFT



- 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.



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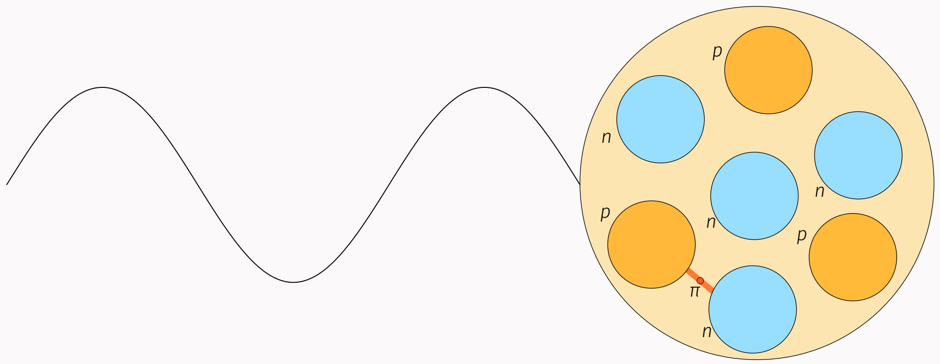

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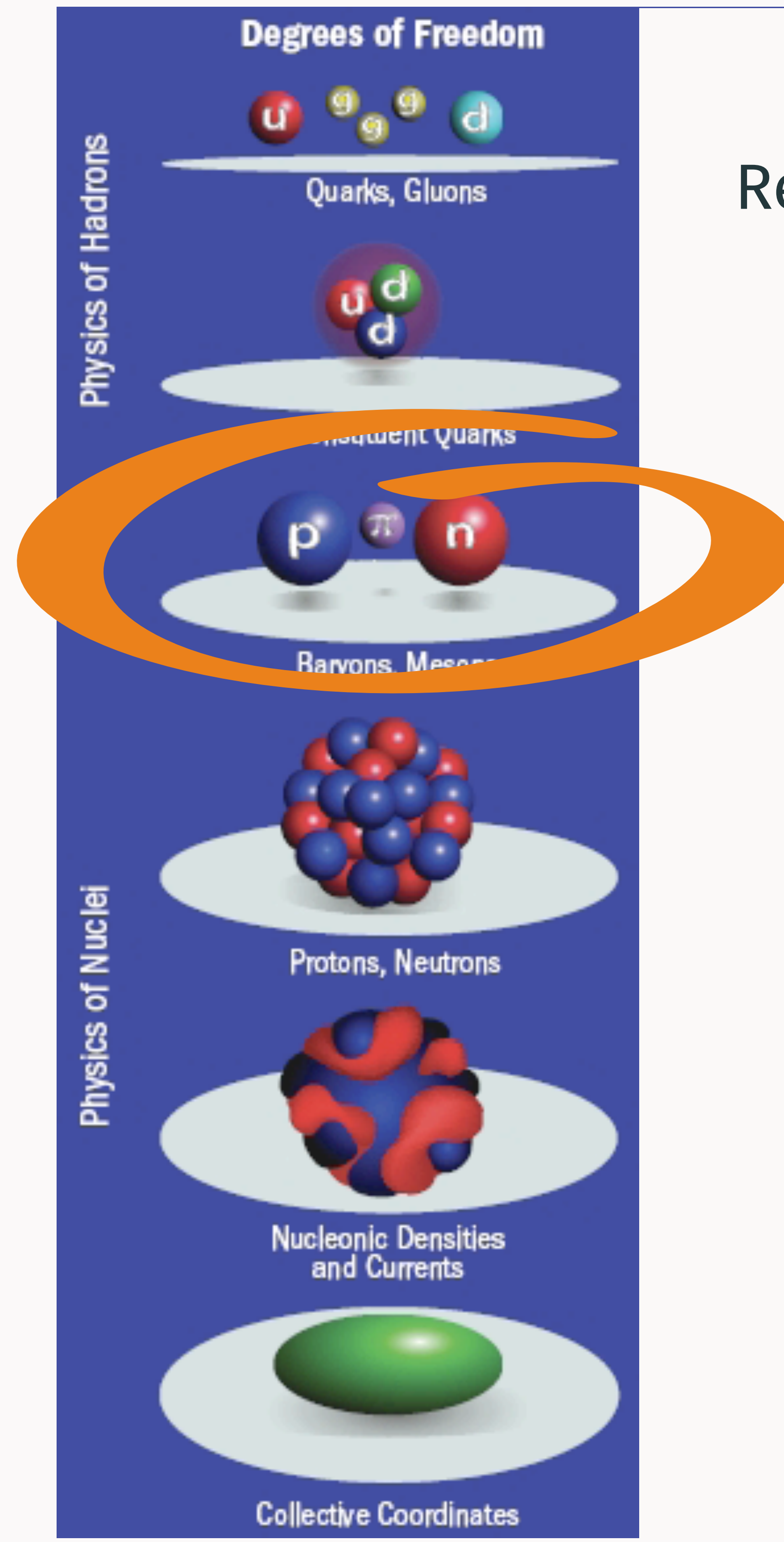
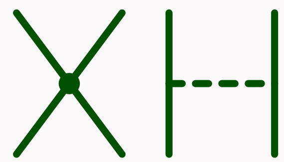
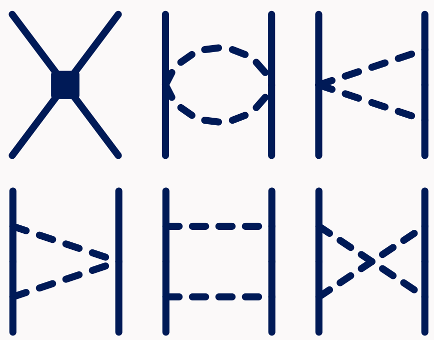
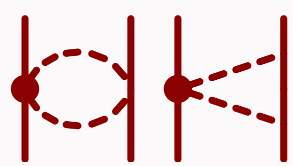
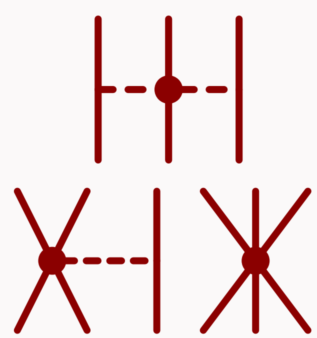
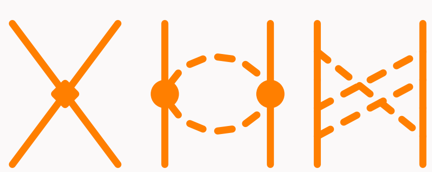


Lower Resolution

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

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.

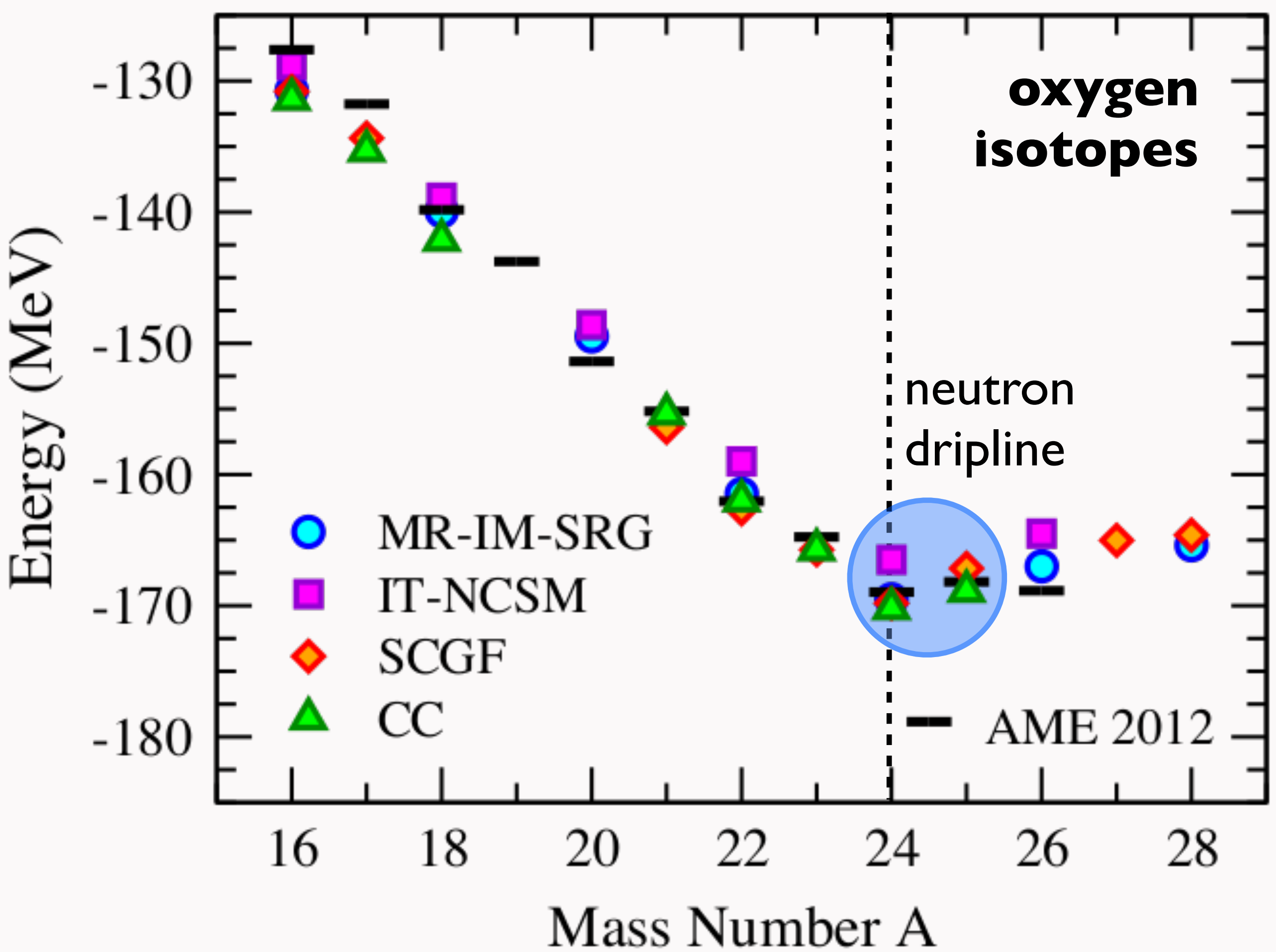
Chiral EFT - Some Highlights

New developments in

- power counting (van Kolck,...)
- uncertainty quantification (Furnstahl, Epelbaum,...)
- optimization (Ekström, Forssén,...)
- pushing the limits - latest interactions are up to next-to-next-to-next-to-next-to-leading order! (Epelbaum, Krebs, Meißner, Machleidt, Entem,...)
- Including Δ degrees of freedom (van Kolck, Piarulli, Ekström, ...)

Sensitivity Of Neutron-Rich Nuclei To Interaction

- Excellent agreement between different methods.
- Very nice agreement with experiment (for a specific interaction).
- Dripline very sensitive to *NNN* interaction.



adapted from K. Hebeler et al. , Ann. Rev. Nucl. Part. Sci. **165**, 457 (2015)

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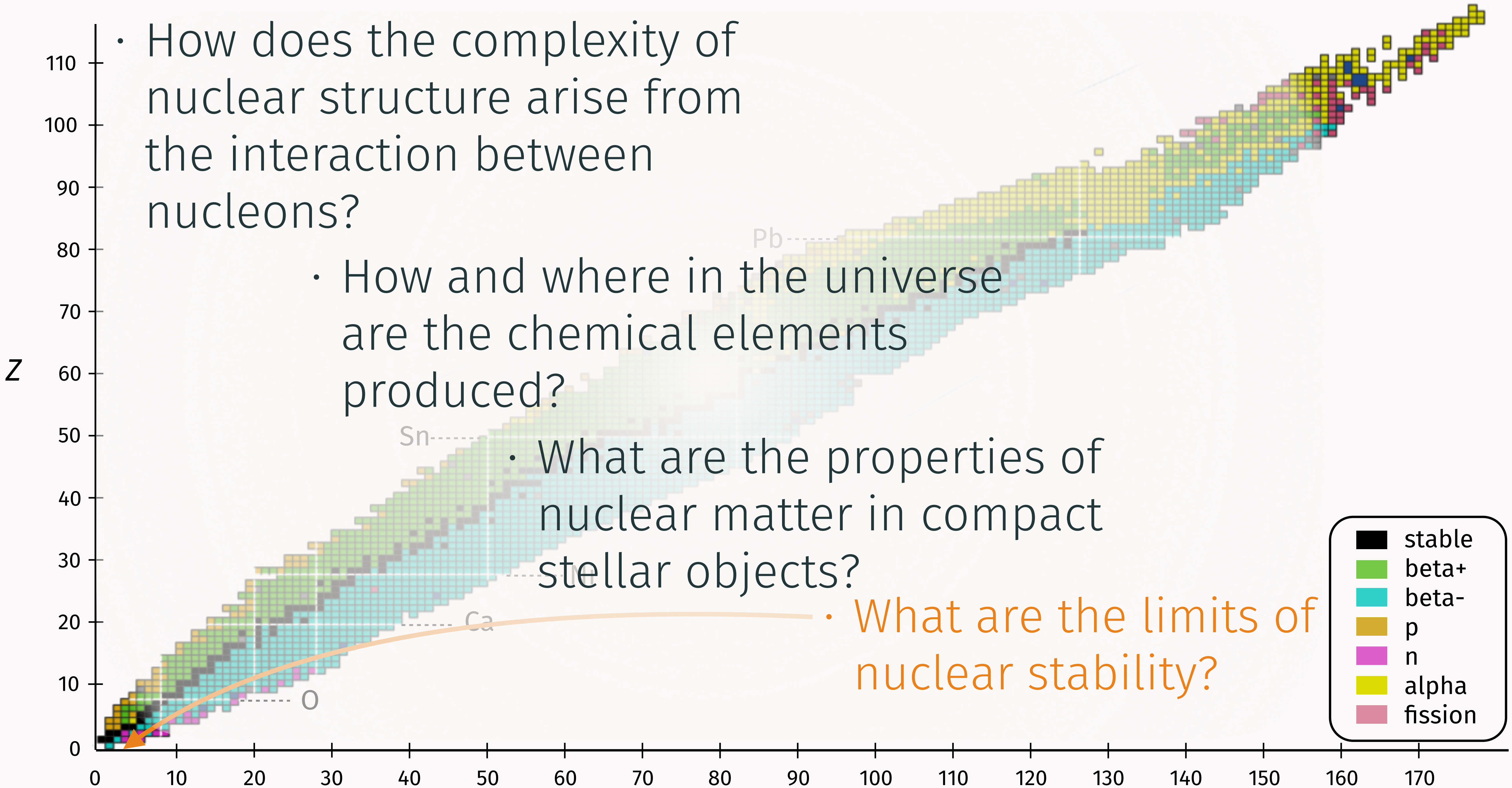

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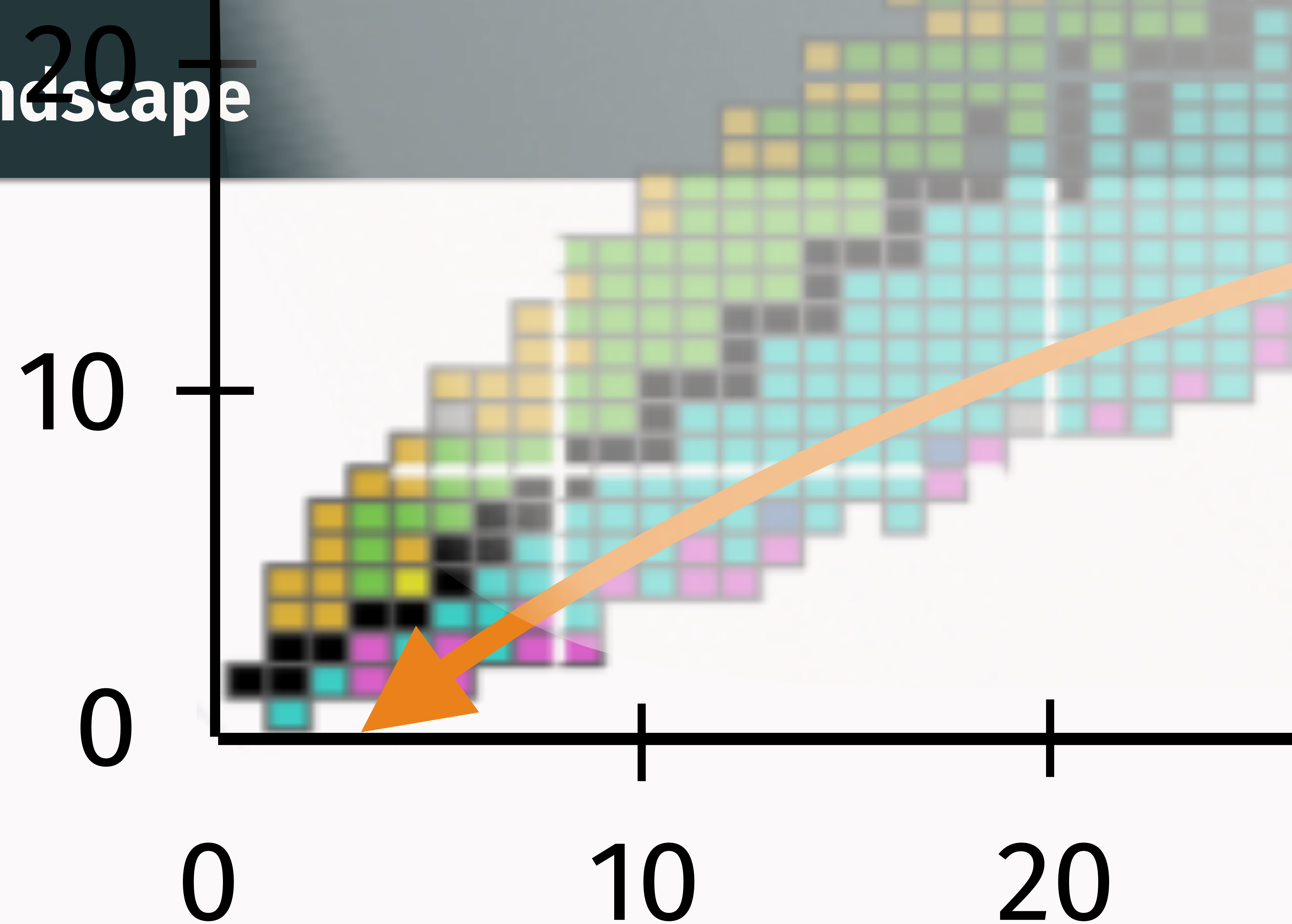

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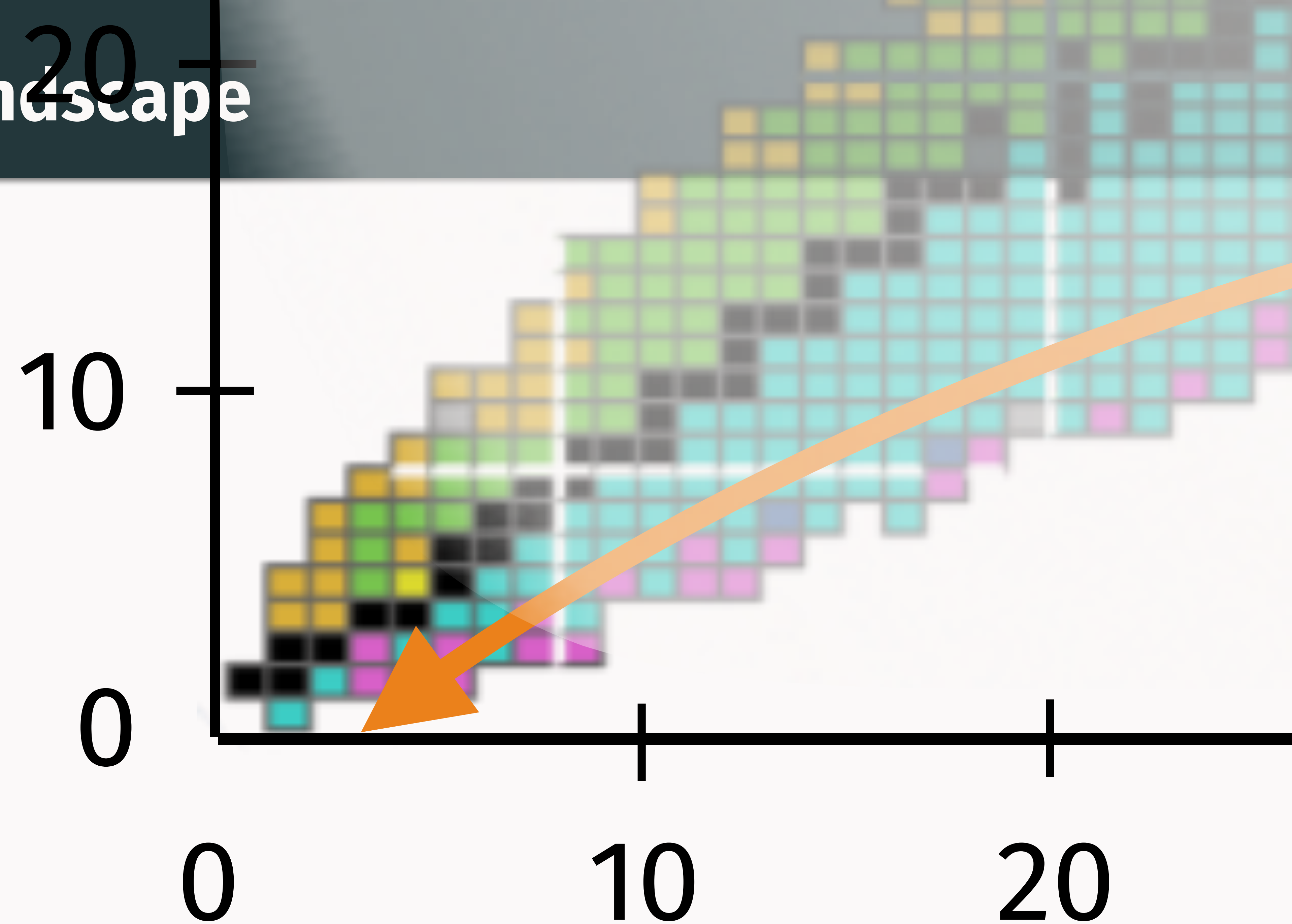

Few-neutron states?

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

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.

2003

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Experiment

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2002

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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 $^8_2\mathrm{He} + ^4_2\mathrm{He} \rightarrow ^8_4\mathrm{Be} + ^4n$ measurement at the RIKEN radioactive ion beam factory (RIBF) suggests a tetraneutron resonance at **0.83±0.65(stat)±1.25(syst) MeV.**

Experiment

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Double-charge-exchange reaction

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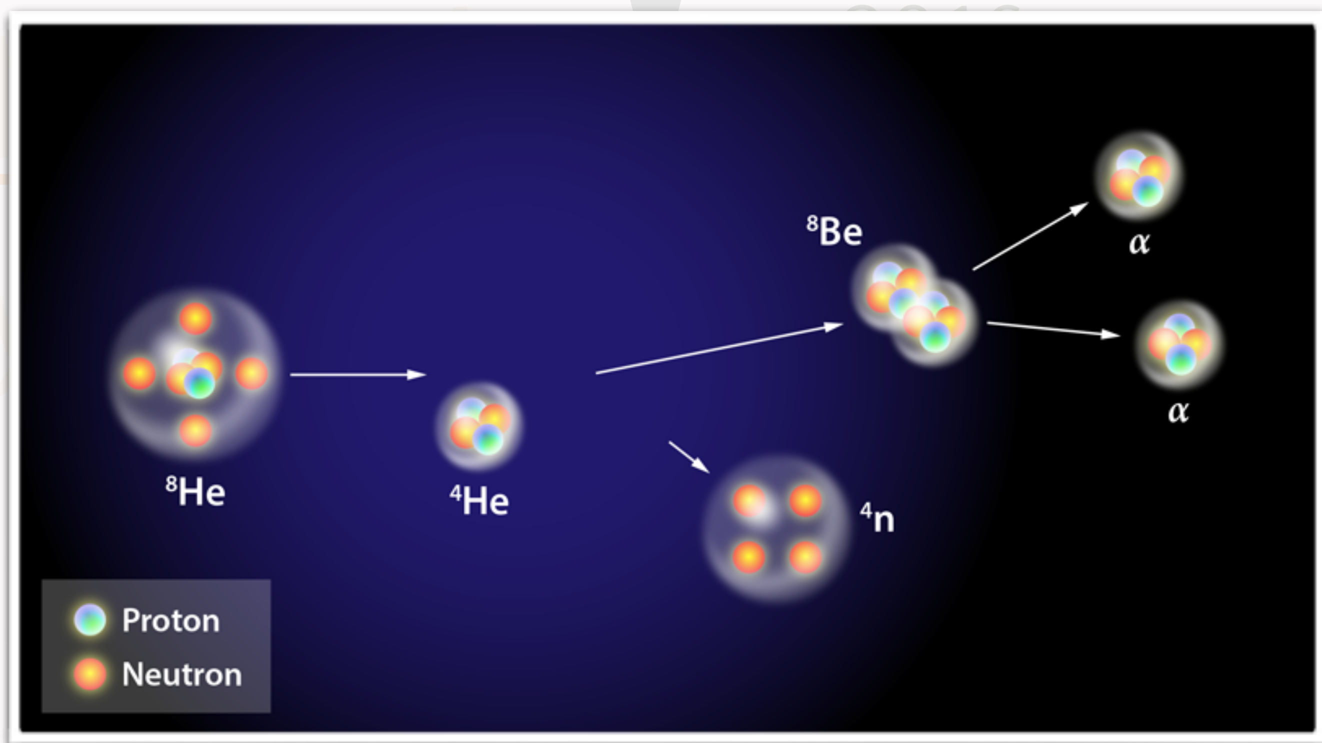

APS/Alan Stonebraker

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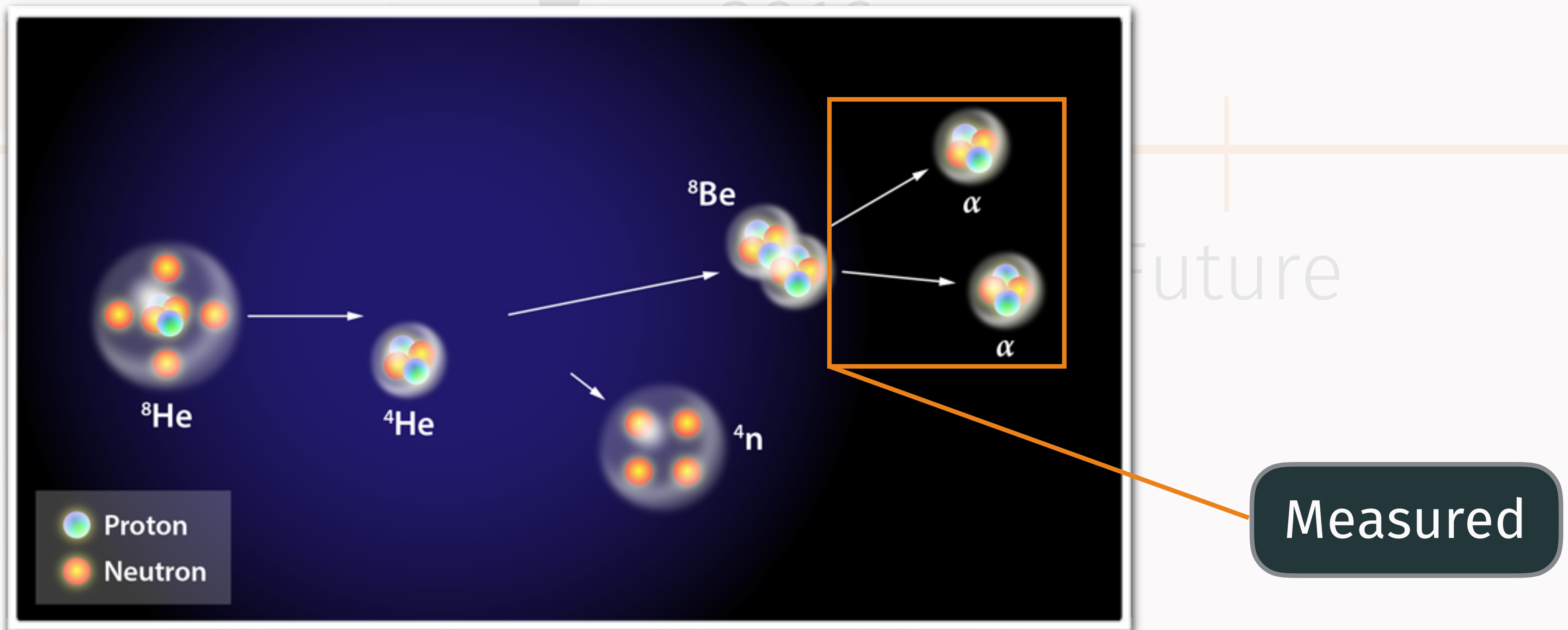

APS/Alan Stonebraker

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

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

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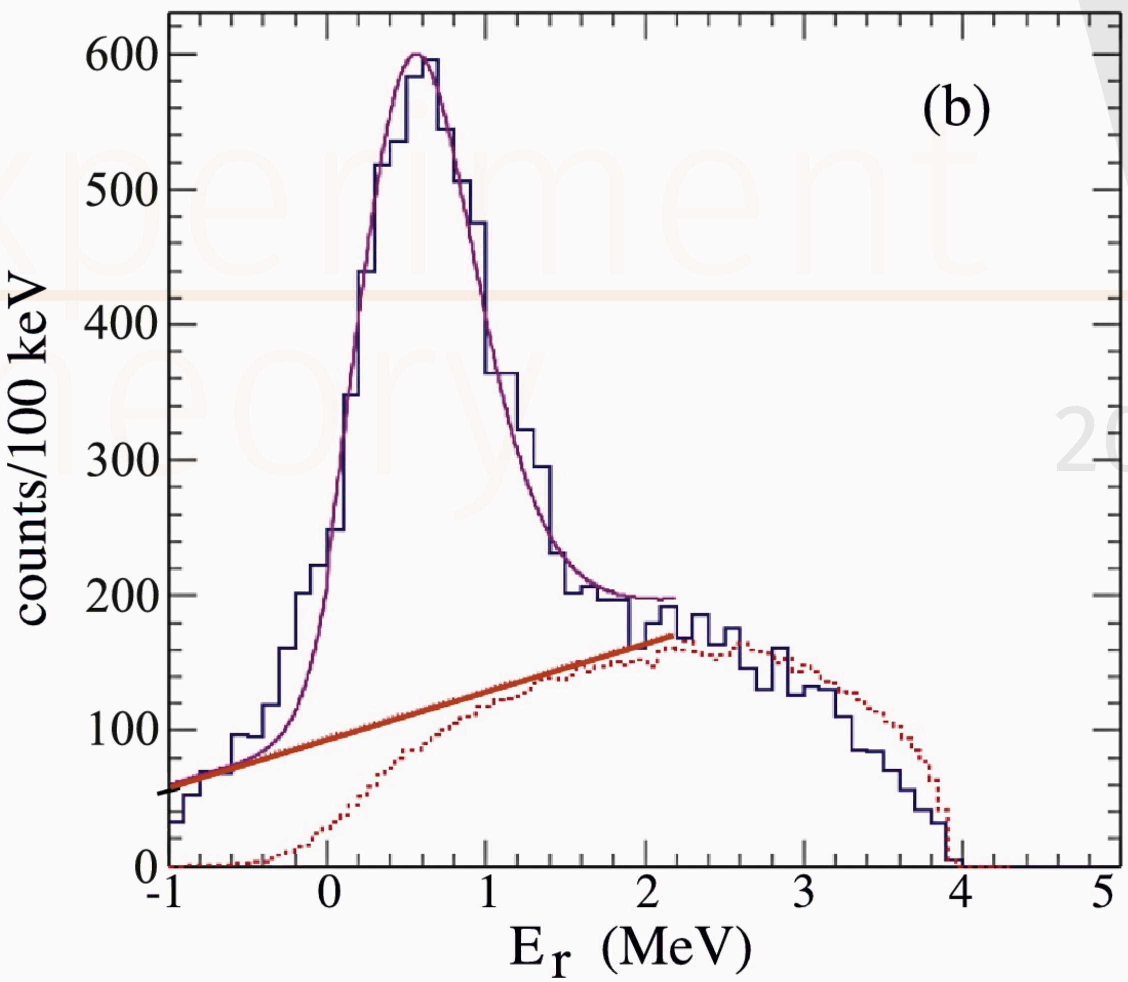
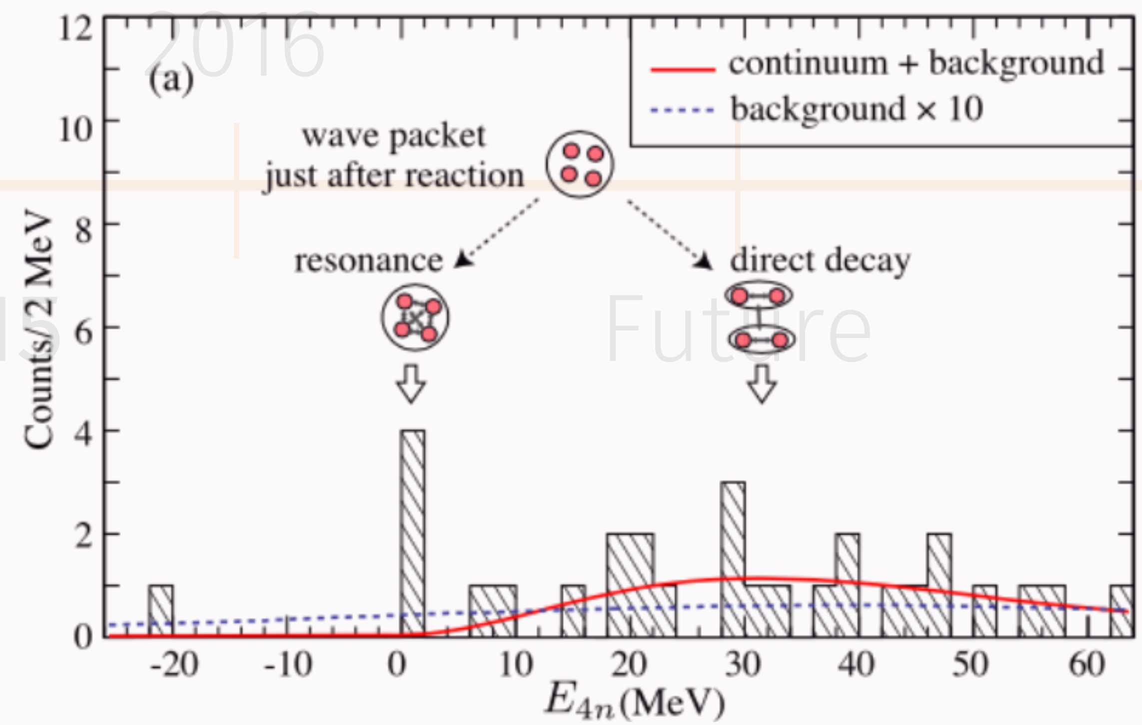


from A. Sanetullaev et al., Phys. Lett. B **755**, 481 (2016)



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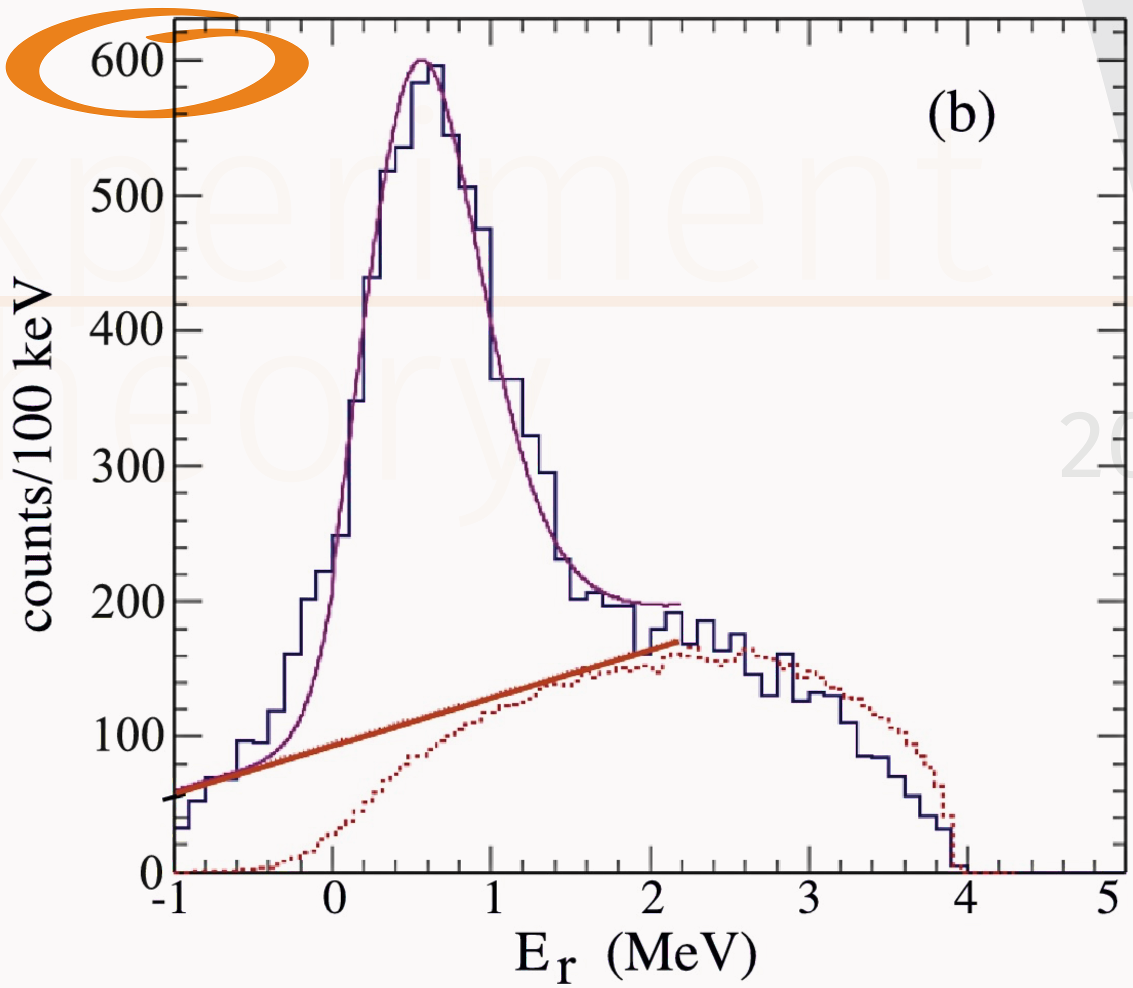
Relatively low statistics: More data needed!



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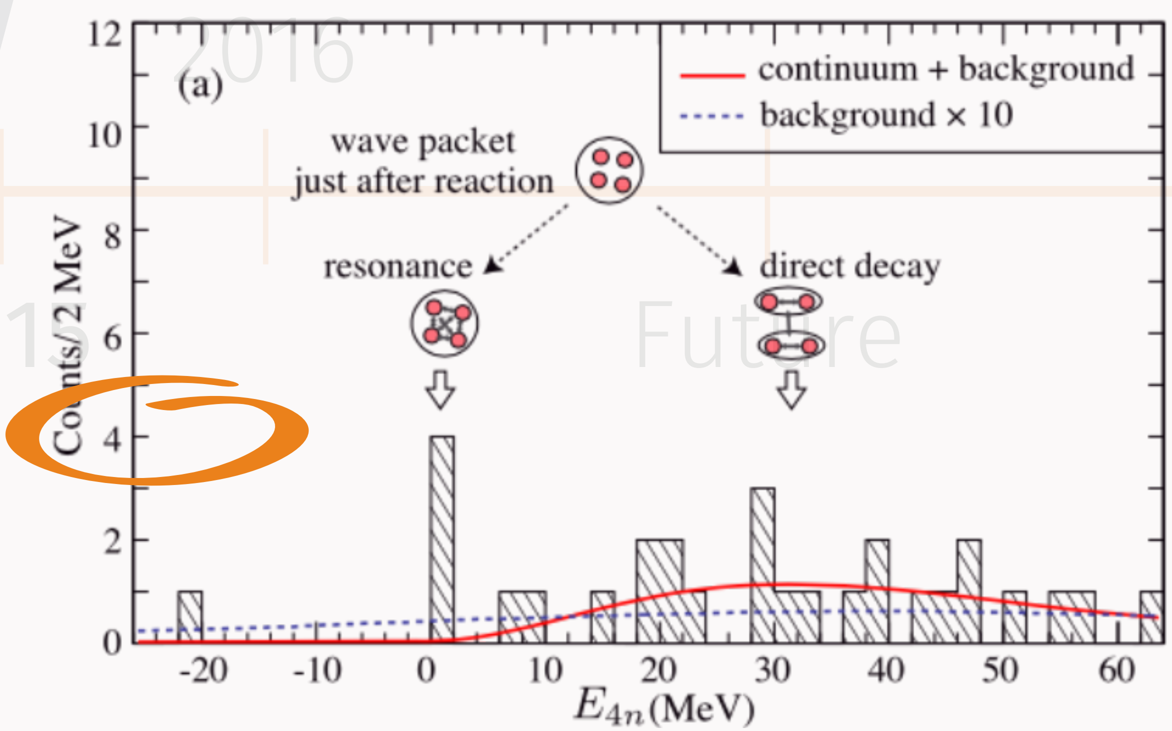

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Experiment

Theory

2016

2015

Present/Future

Experiment

Theory

2015

2016

Present/Future

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. **See Emiko Hiyama's talk, Friday 9:40.**

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2015 | **2016** | Present/Future

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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 HORSE. Compelling confirmation of a ^4n resonance at 0.8 MeV with **JISP** NN interaction. **See Andrey Shirokov's talk, Thursday 9:40.**

T. Aumann, D. Rossi, S. Shimoura, S. Paschalis et al., RIBF Experimental Proposal NP1406-SAMURAI19.

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

c.f. Tom Aumann's talk, Monday 17:00.

Experiment

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S. Shimoura et al., RIKEN-RIBF proposal "Tetraneutron resonance produced by exothermic double-charge exchange reaction," NP1512-SHARAQ10. **c.f. Shimoura-San's talk, just before.**

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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. **See Miguel Marqués's talk, Thursday 9:00,**

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Experiment

Theory

2015

2016

Present/Future

What's still missing?

Ab initio calculations with chiral *NN* and 3*N* interactions.

•Initial efforts using Quantum Monte Carlo calculations with chiral interactions. **(This talk!)**

•See talk by Sebastian König, Thursday 10:50, for finite-volume ideas.

•See talk by Stefan Alexa, Thursday 17:00, for more on the HORSE method.

•See also recent work by K. Fossez et al. PRL **119**, 032501 (2017), and A. Deltuva arXiv: 1801.02919 [nucl-th].

Outline

- Quantum Monte Carlo Methods
- Local Chiral EFT
- Three-Nucleon Interactions
- Few-body resonances
- Outlook and Conclusion

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

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

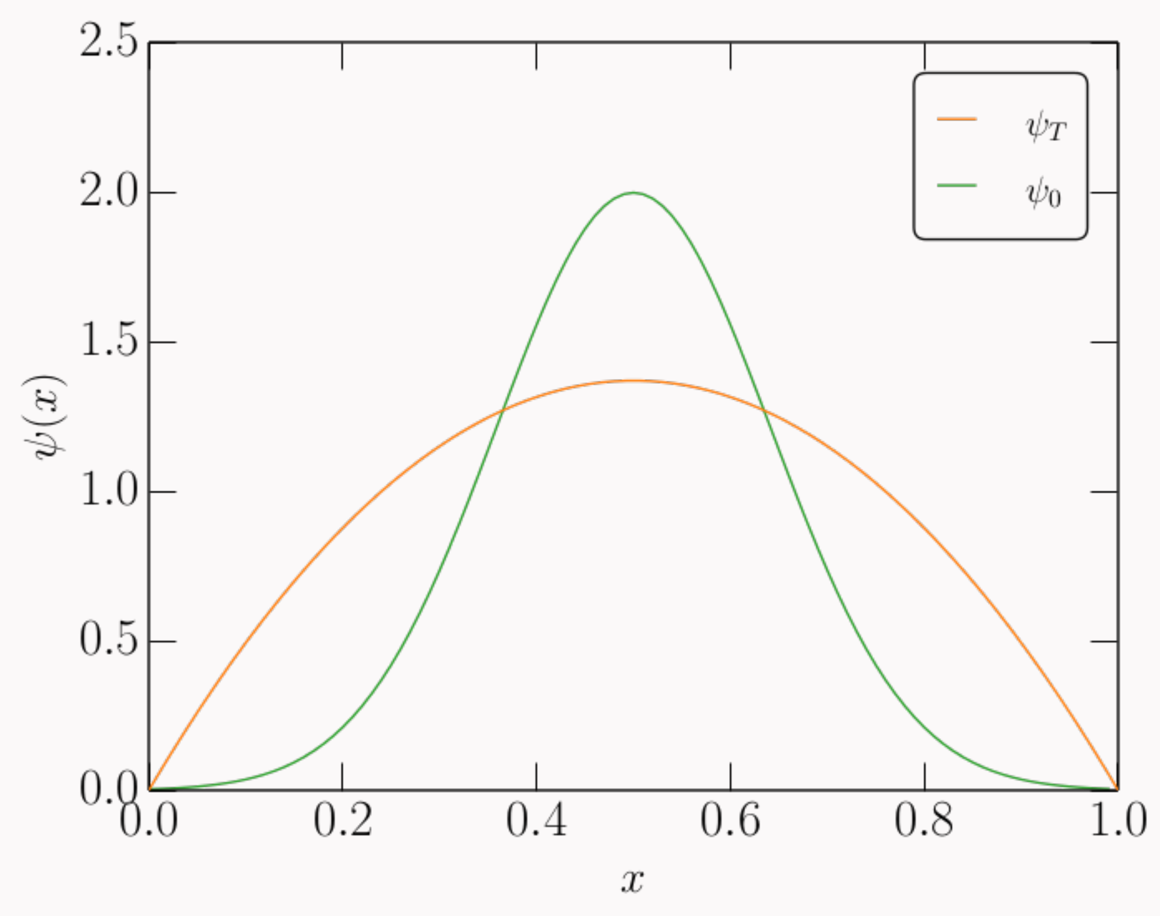
QMC Methods - An Example

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

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

Trial wave function; e.g.

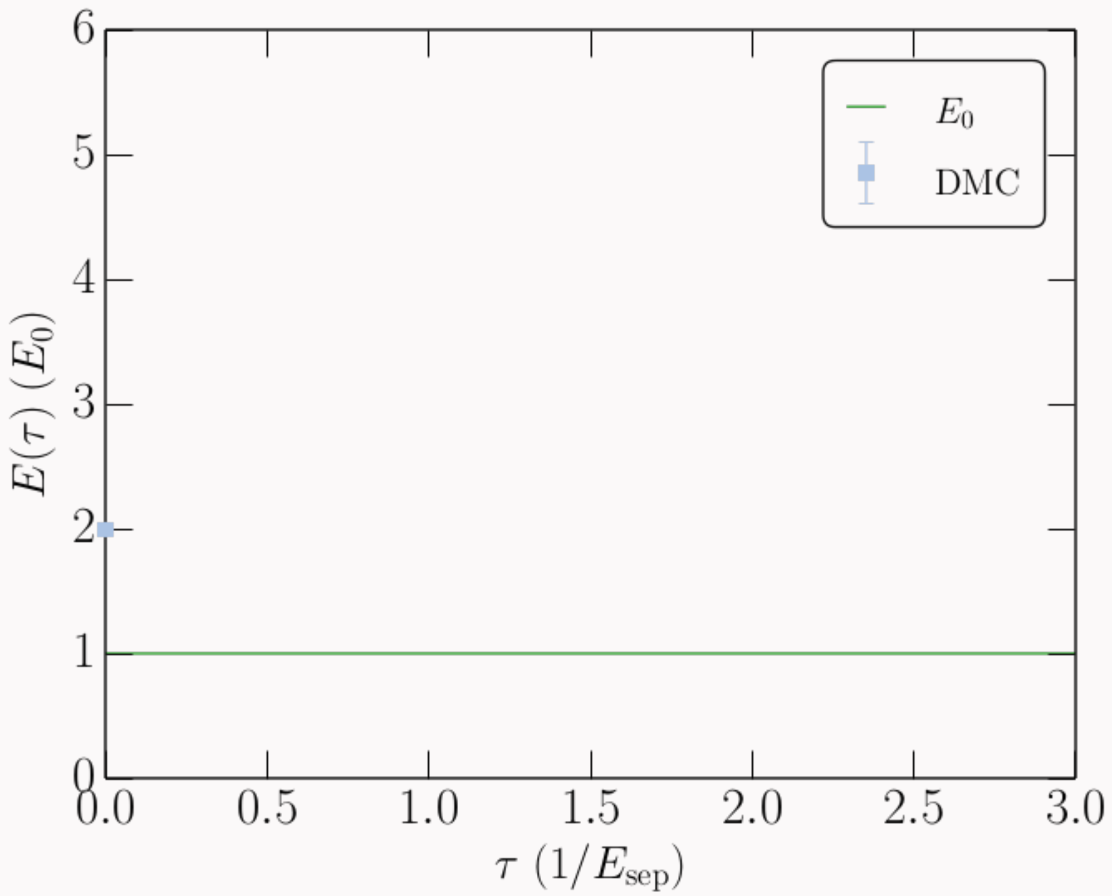
$$\Psi_T(x) = \sqrt{30}x(1-x).$$

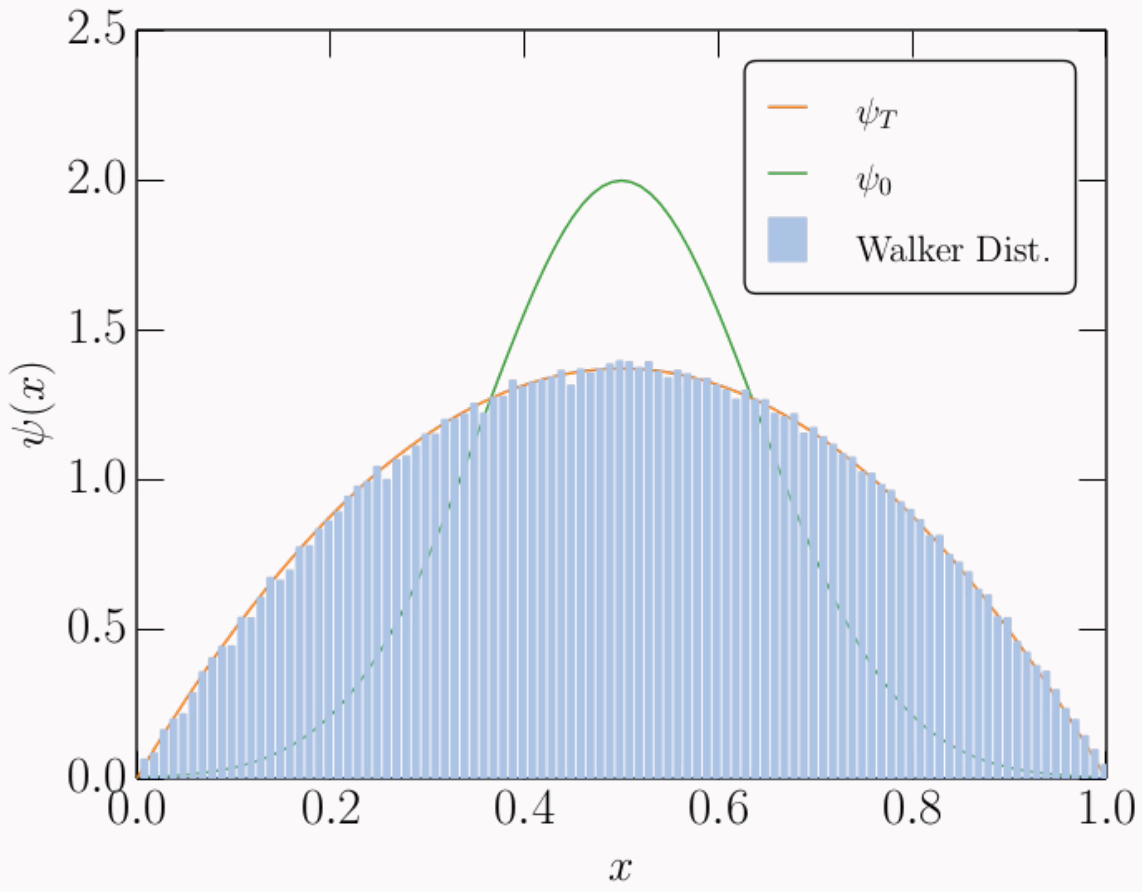


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 0.00$

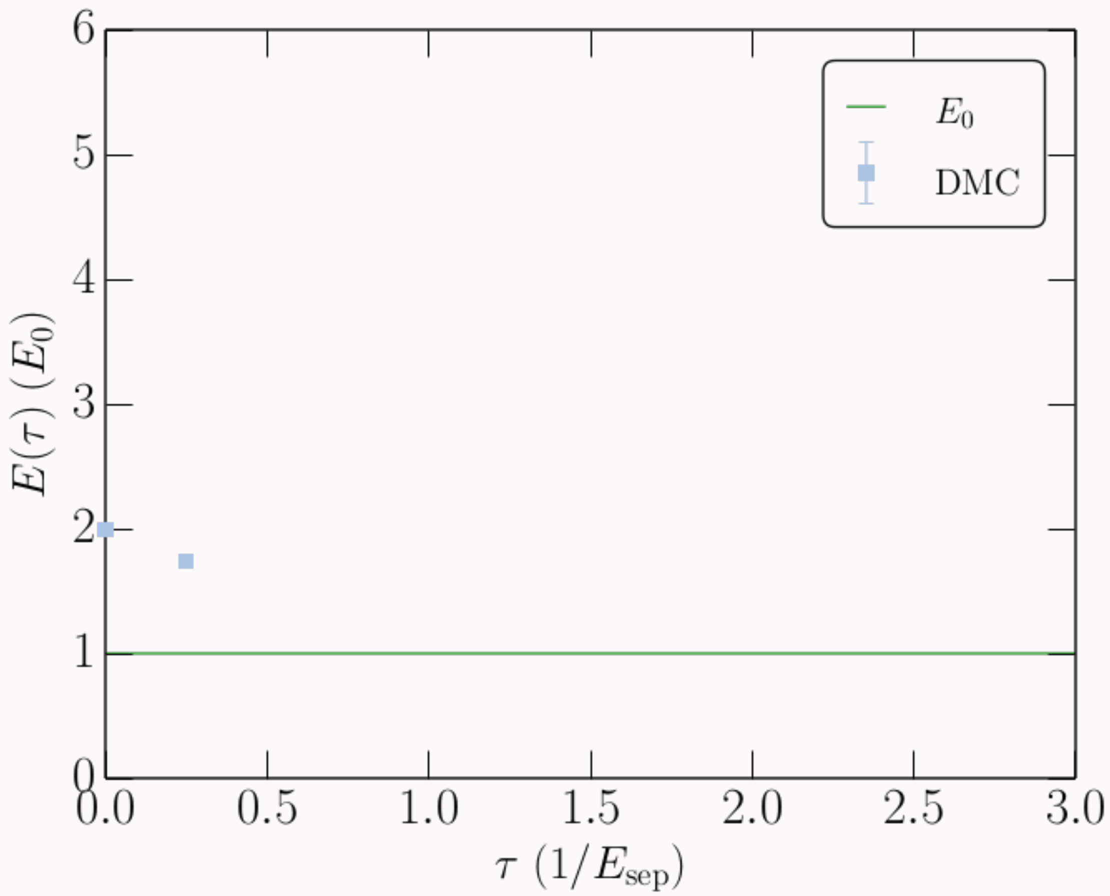


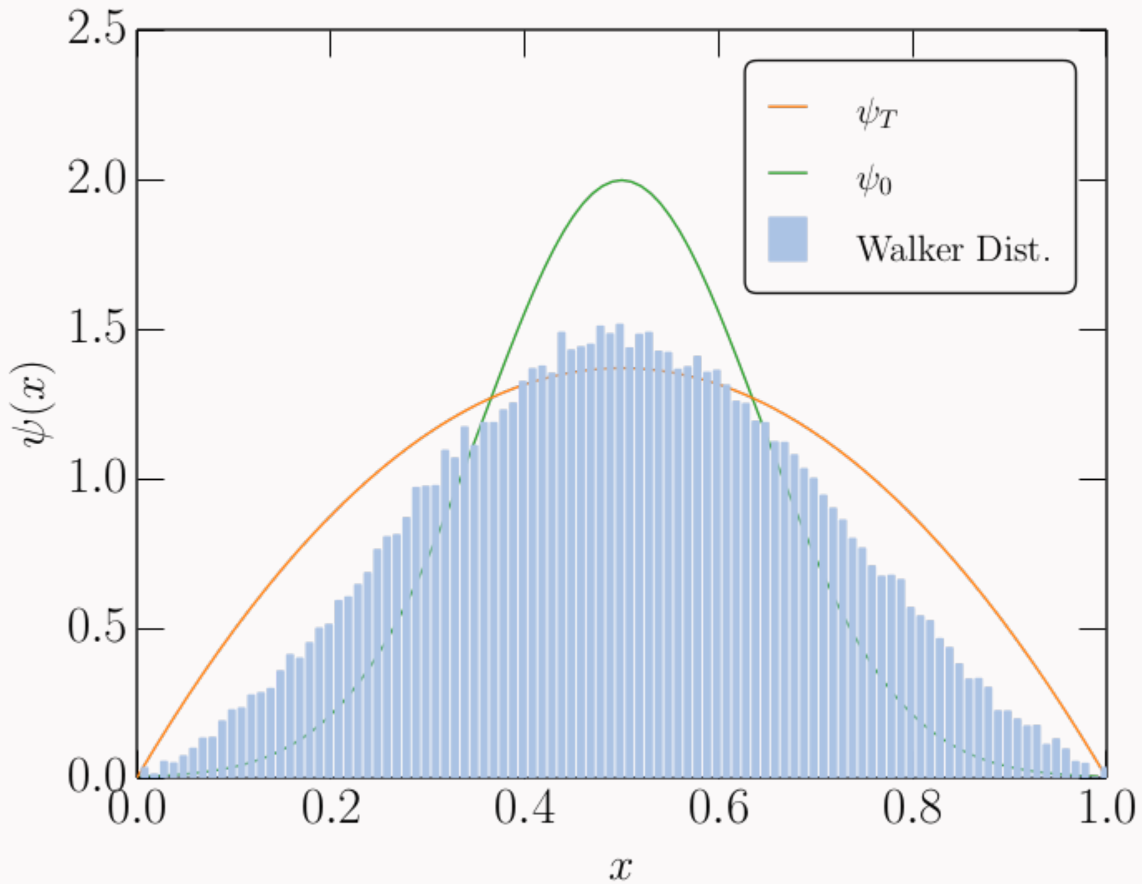


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 0.25$

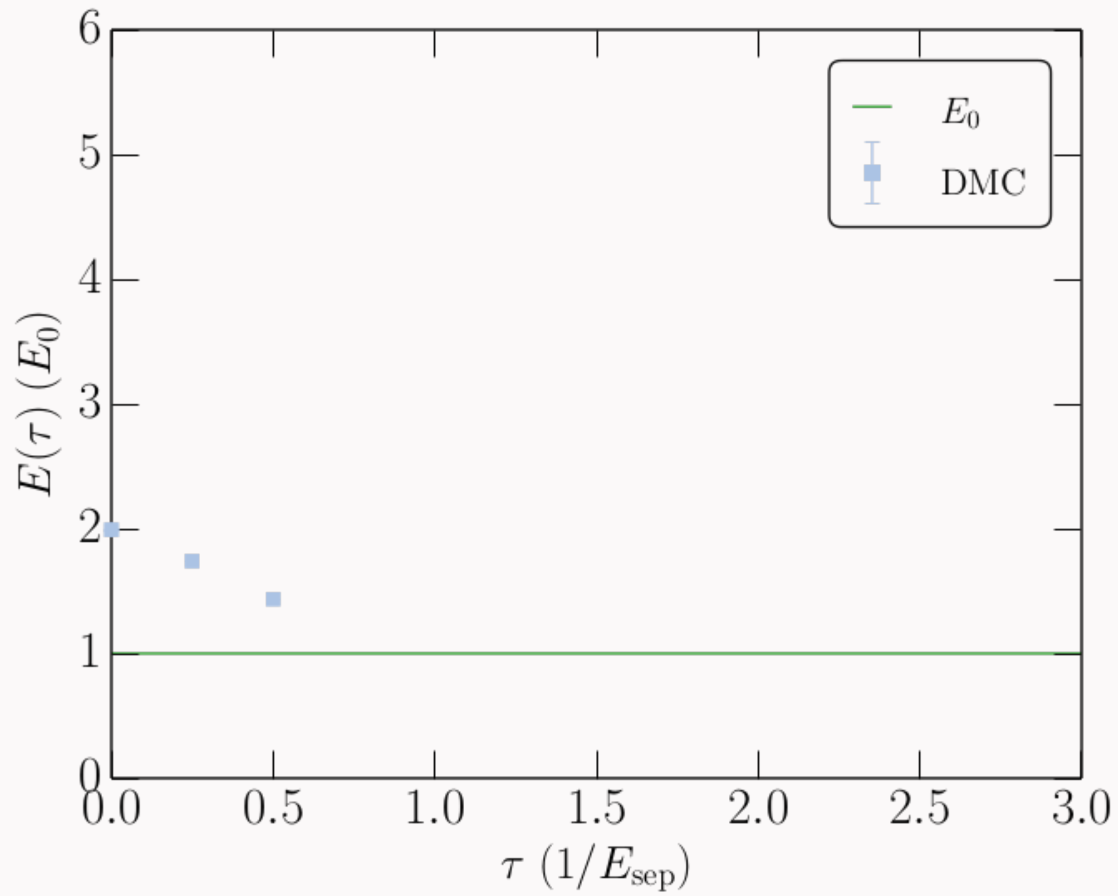


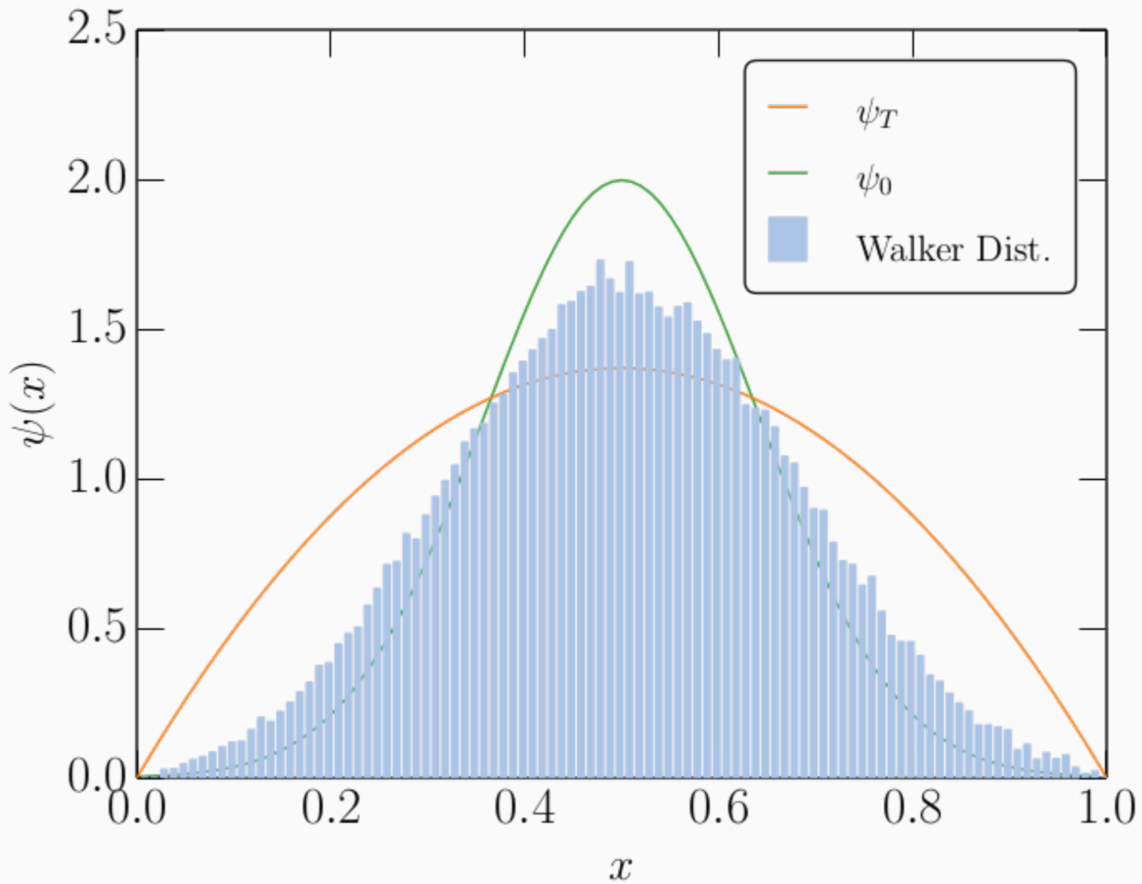


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 0.50$

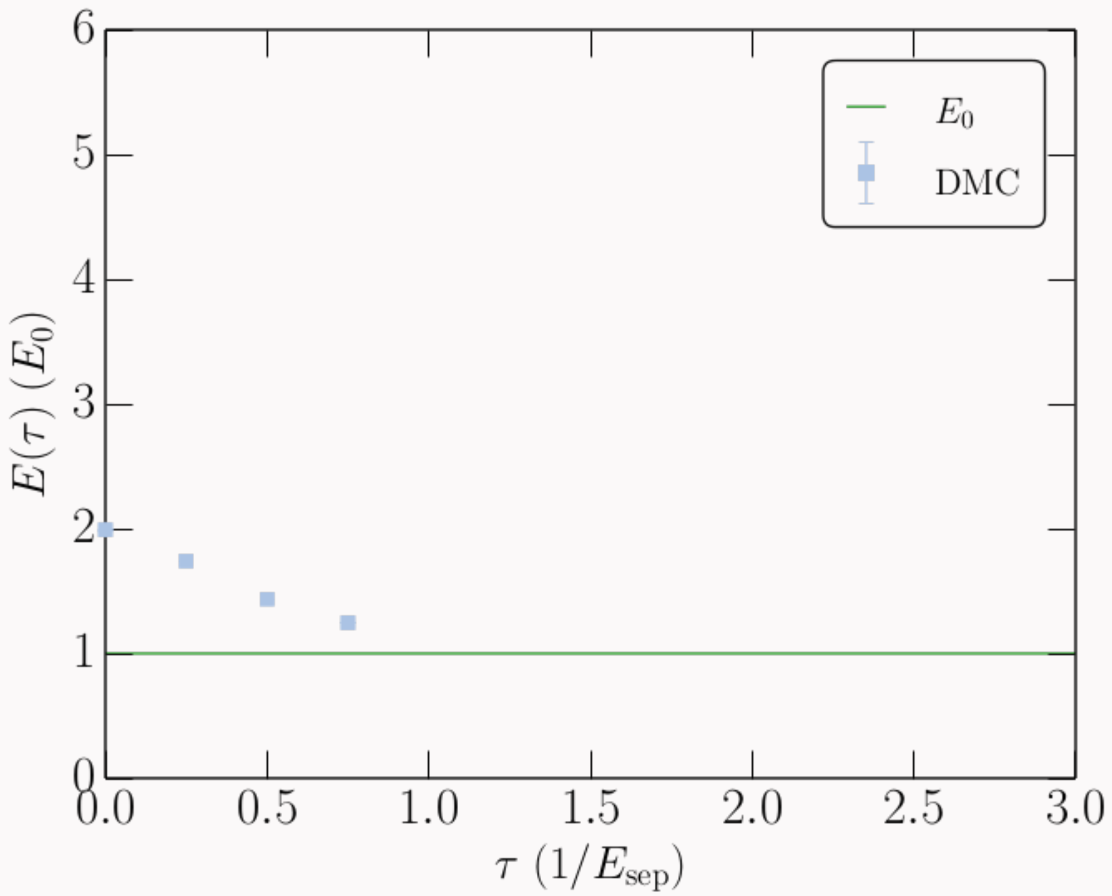


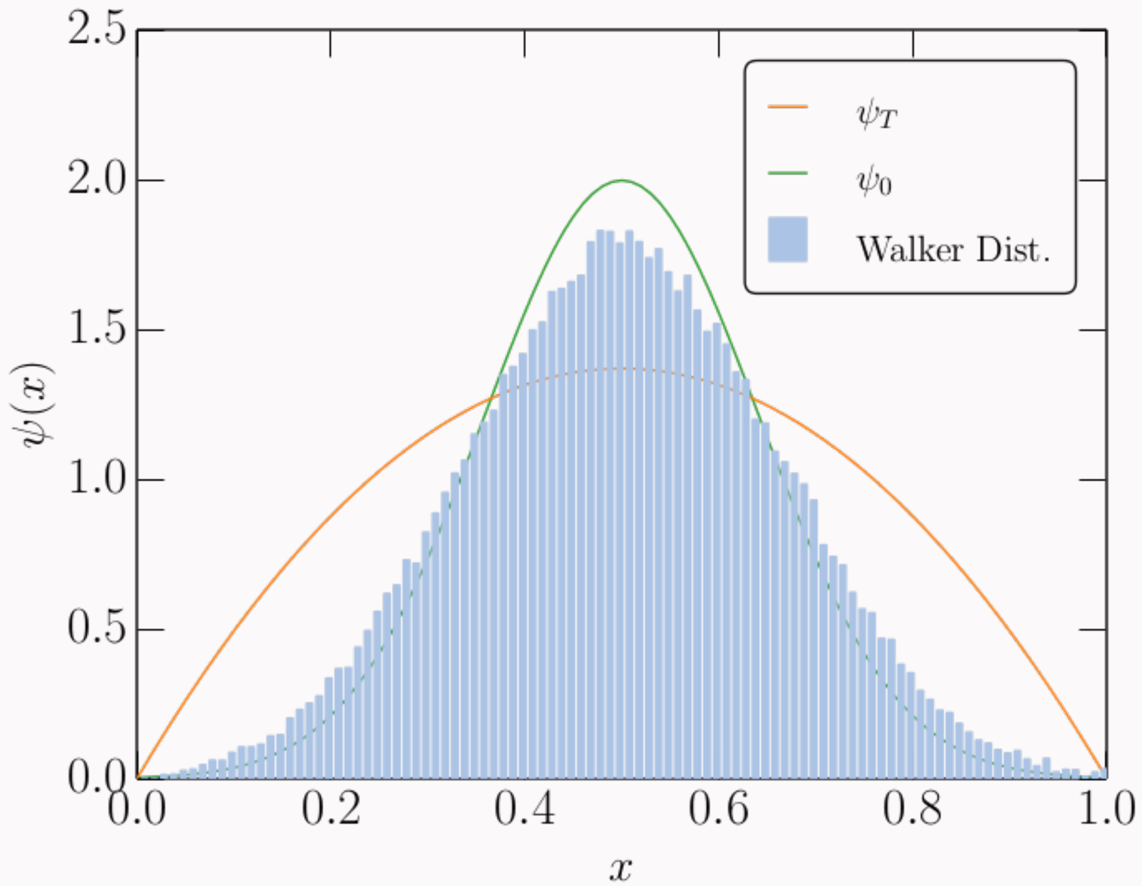


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 0.75$

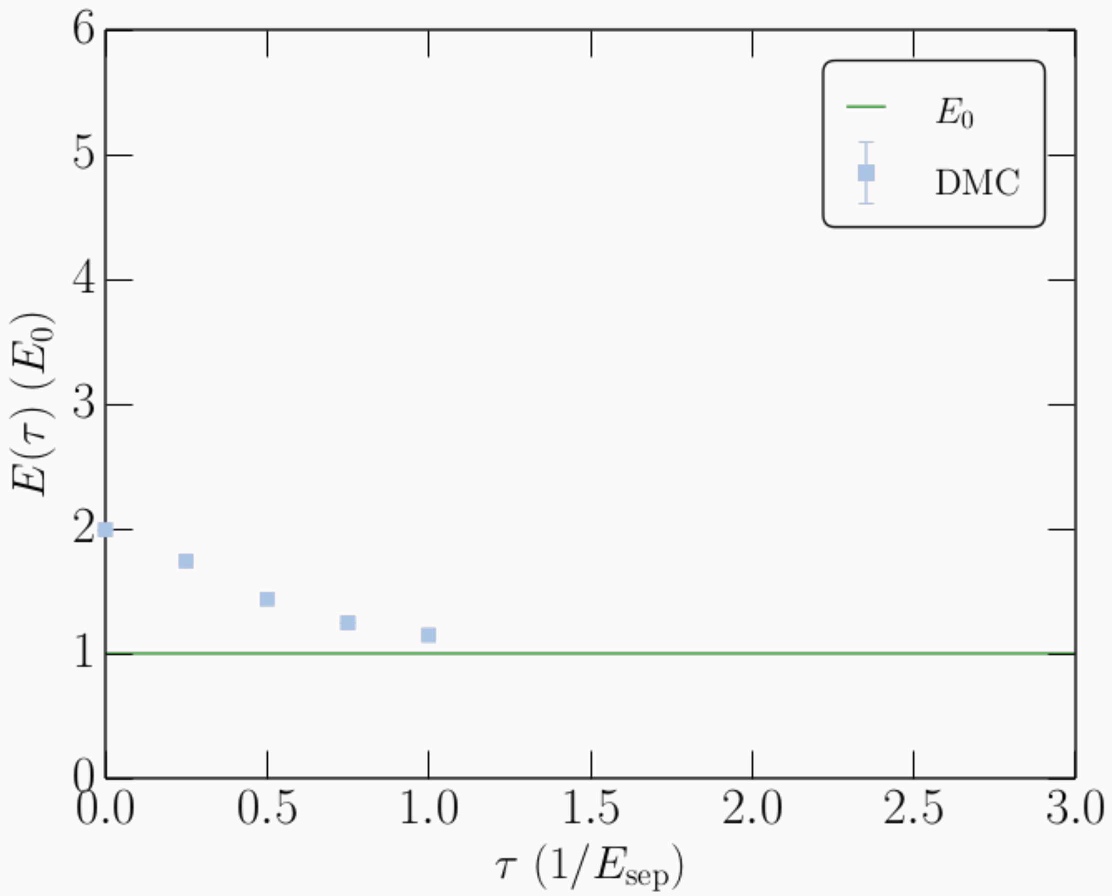


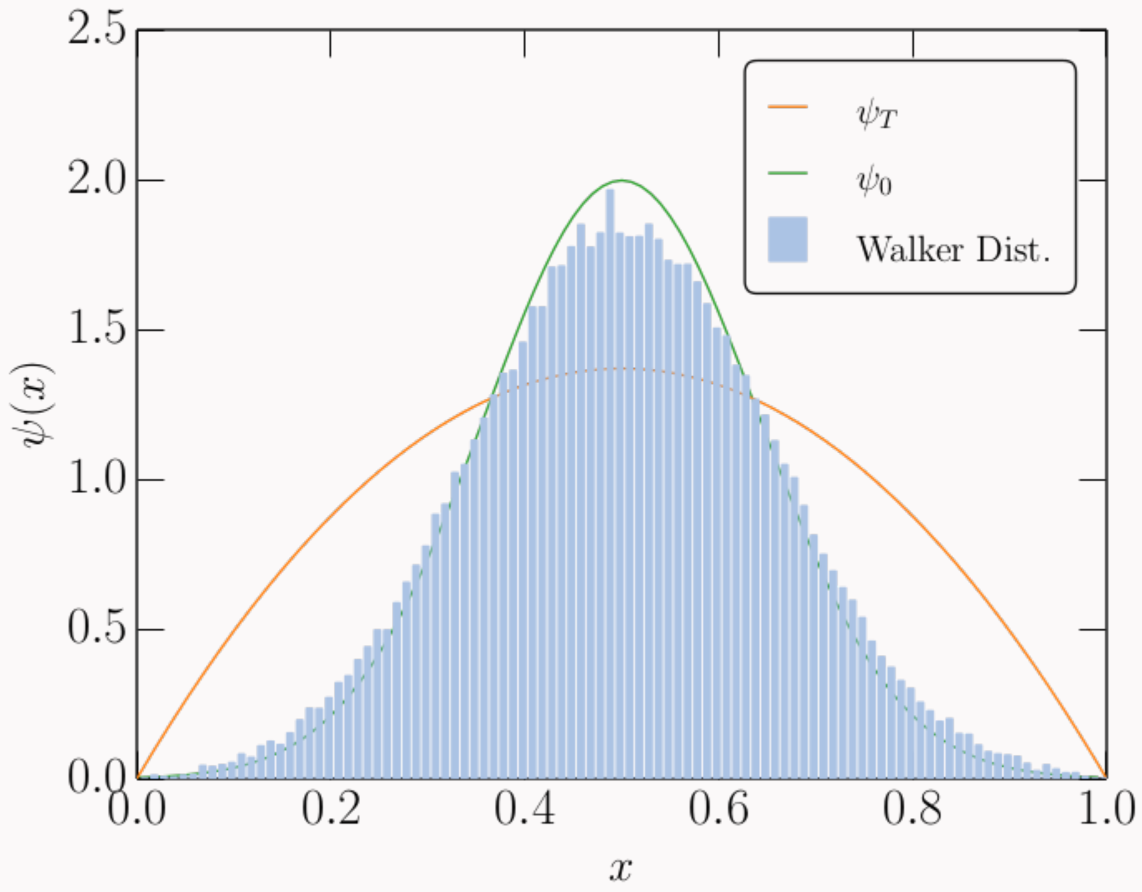


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 1.00$

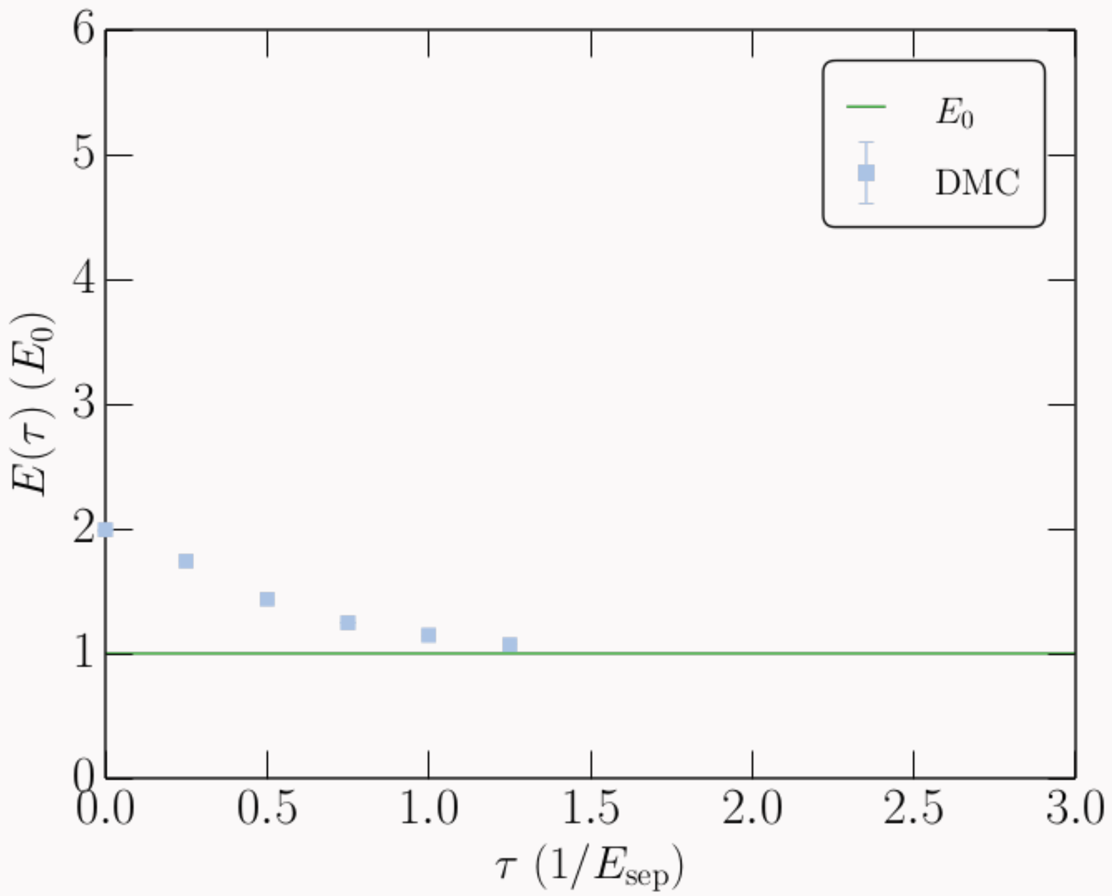


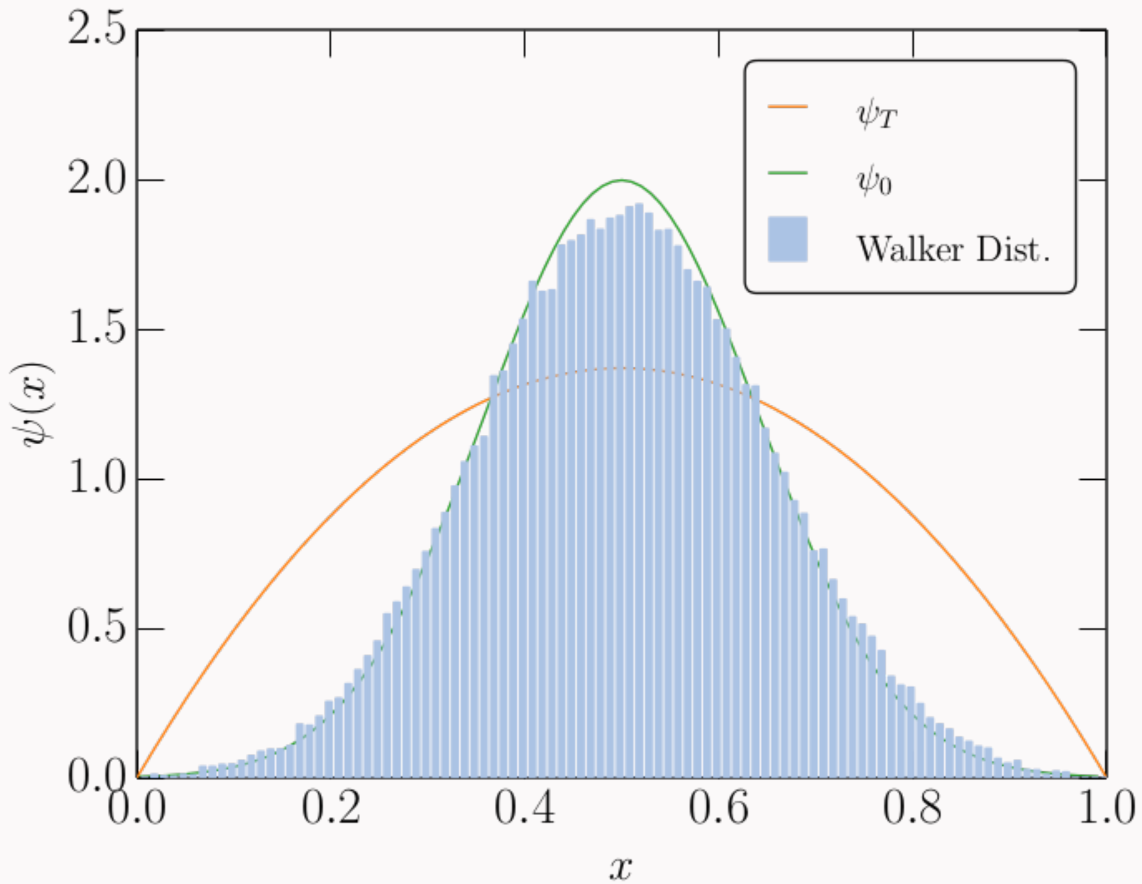


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 1.25$





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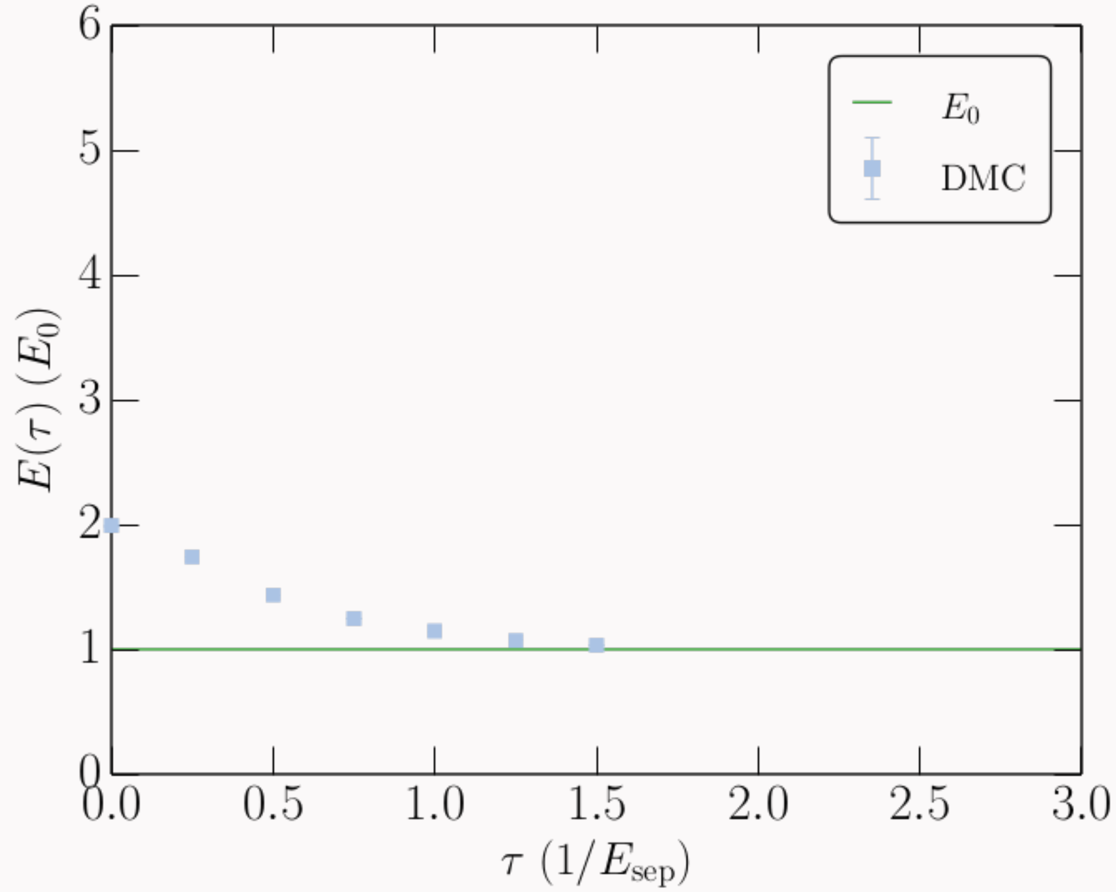

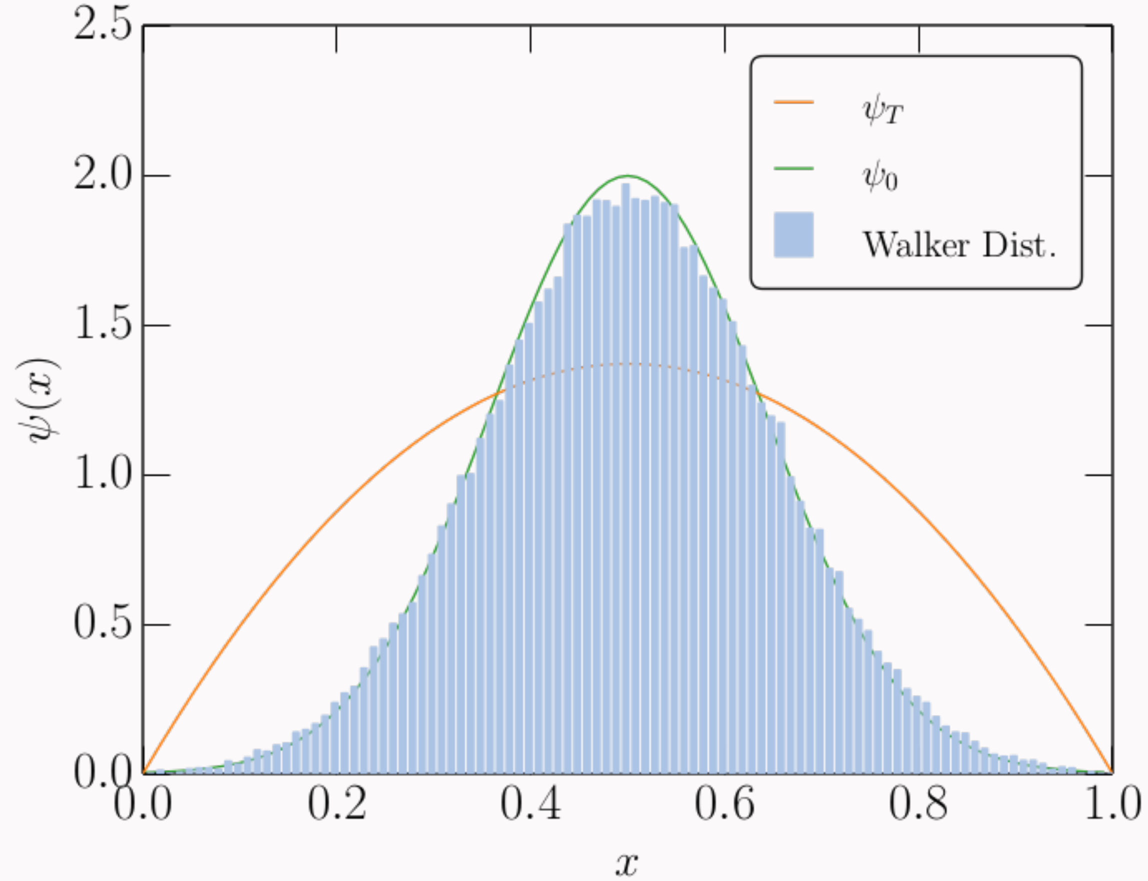

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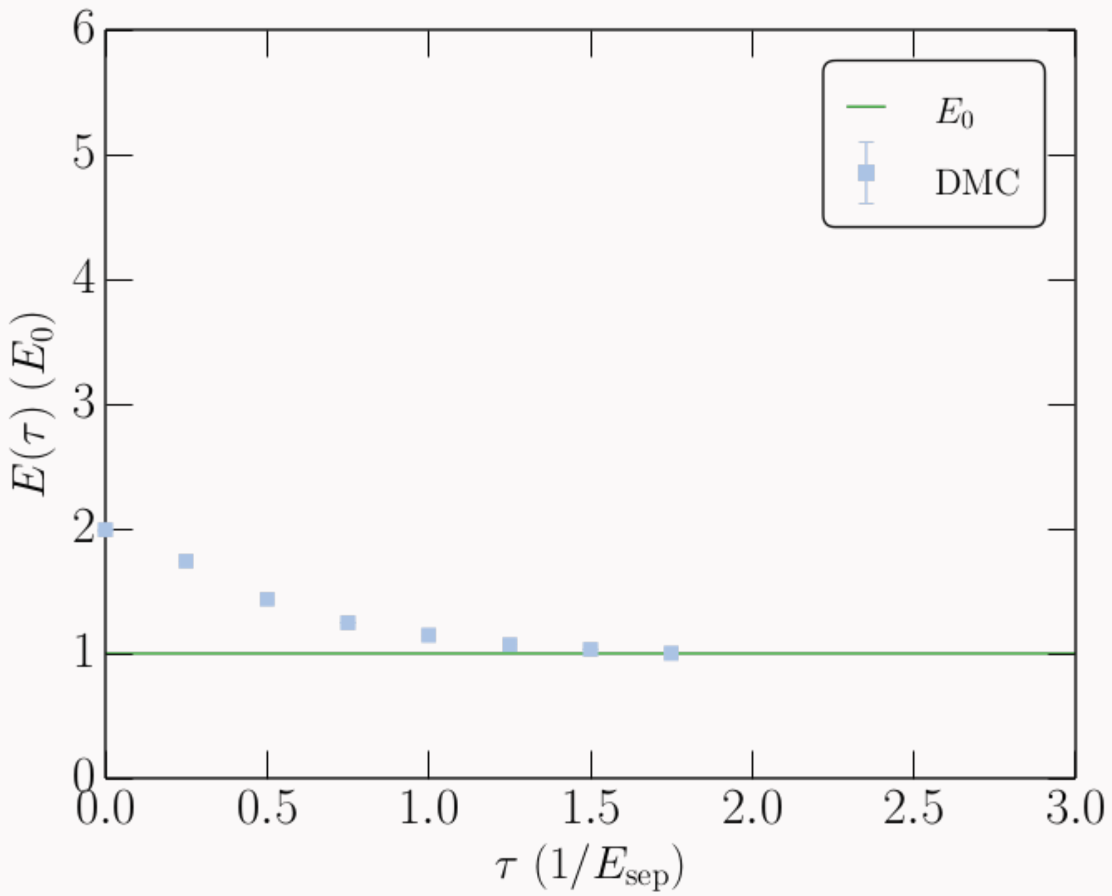
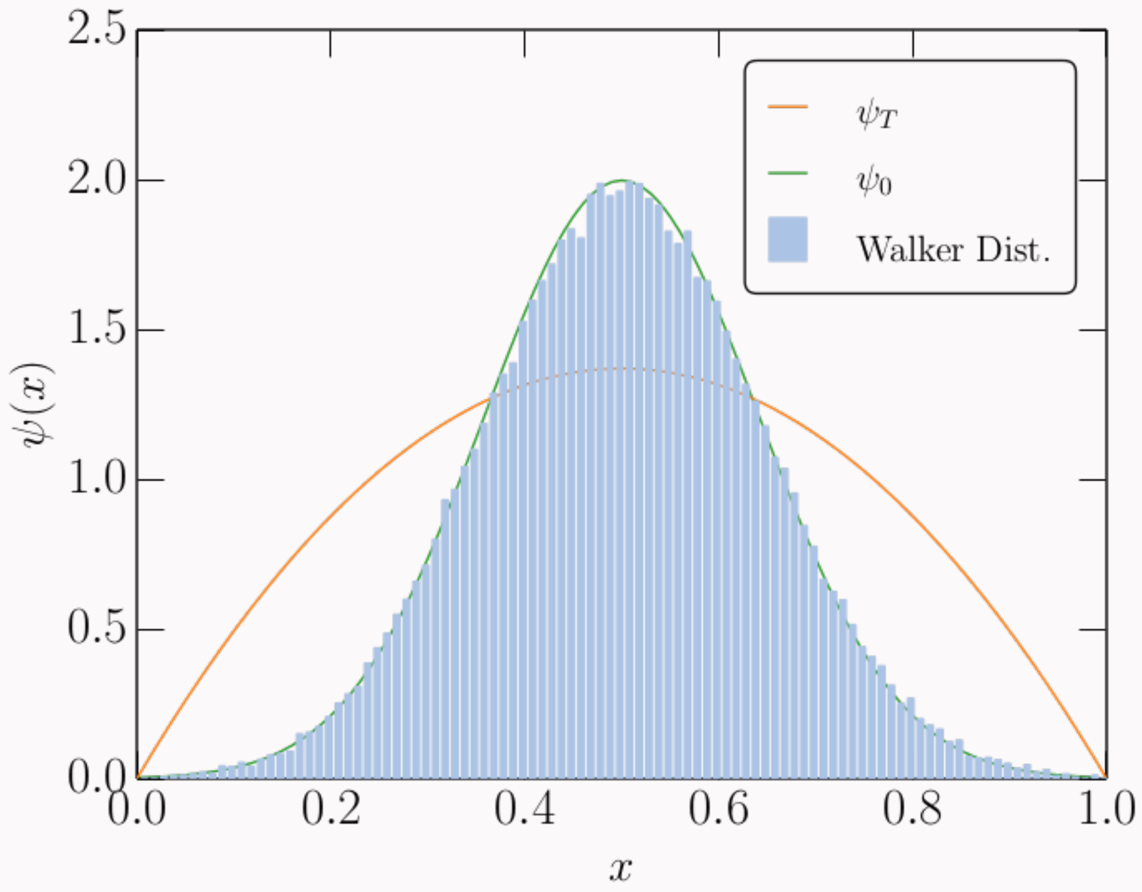
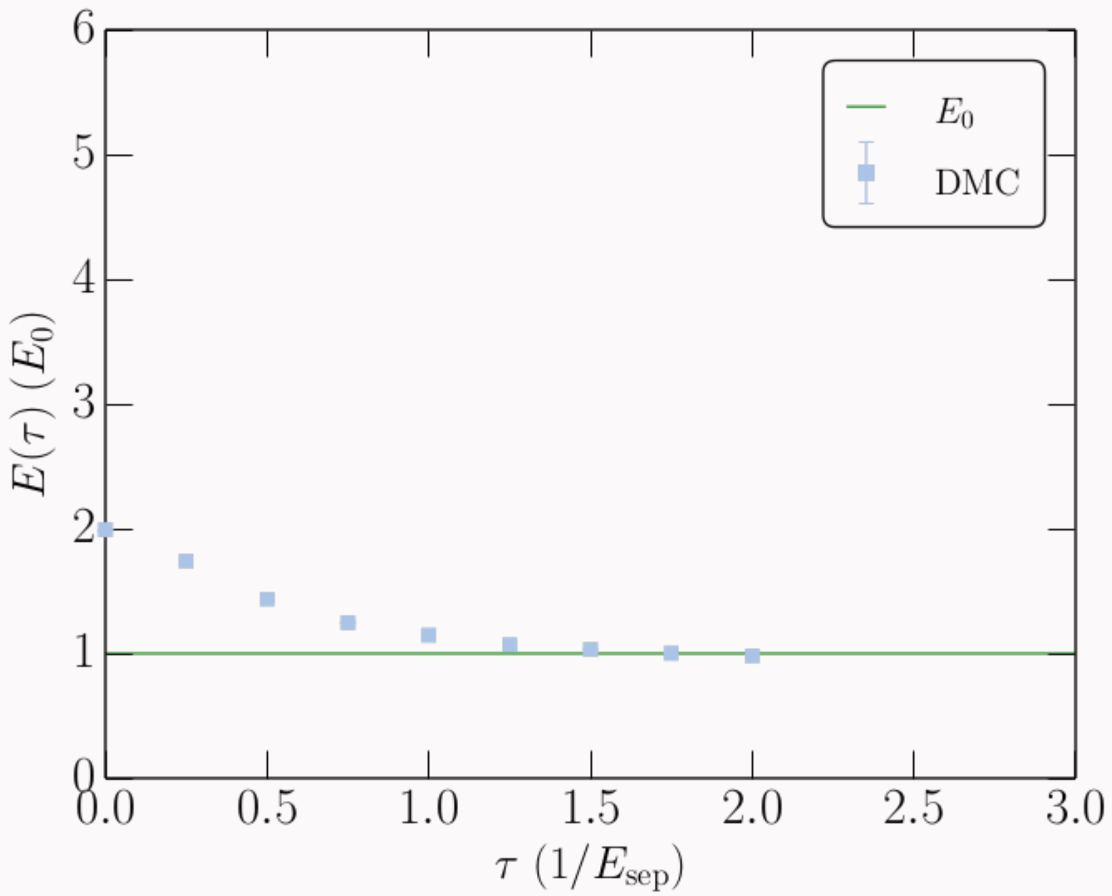


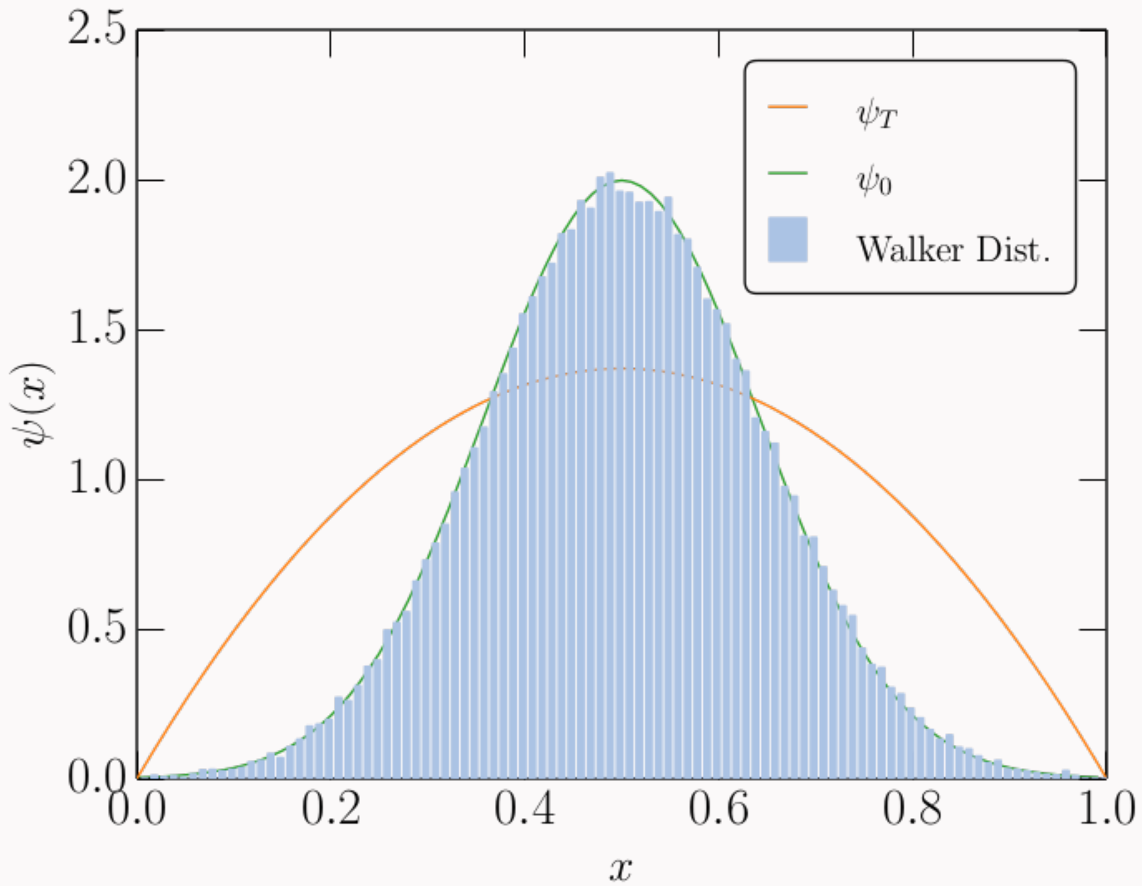


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 2.00$





QMC Methods - An Example

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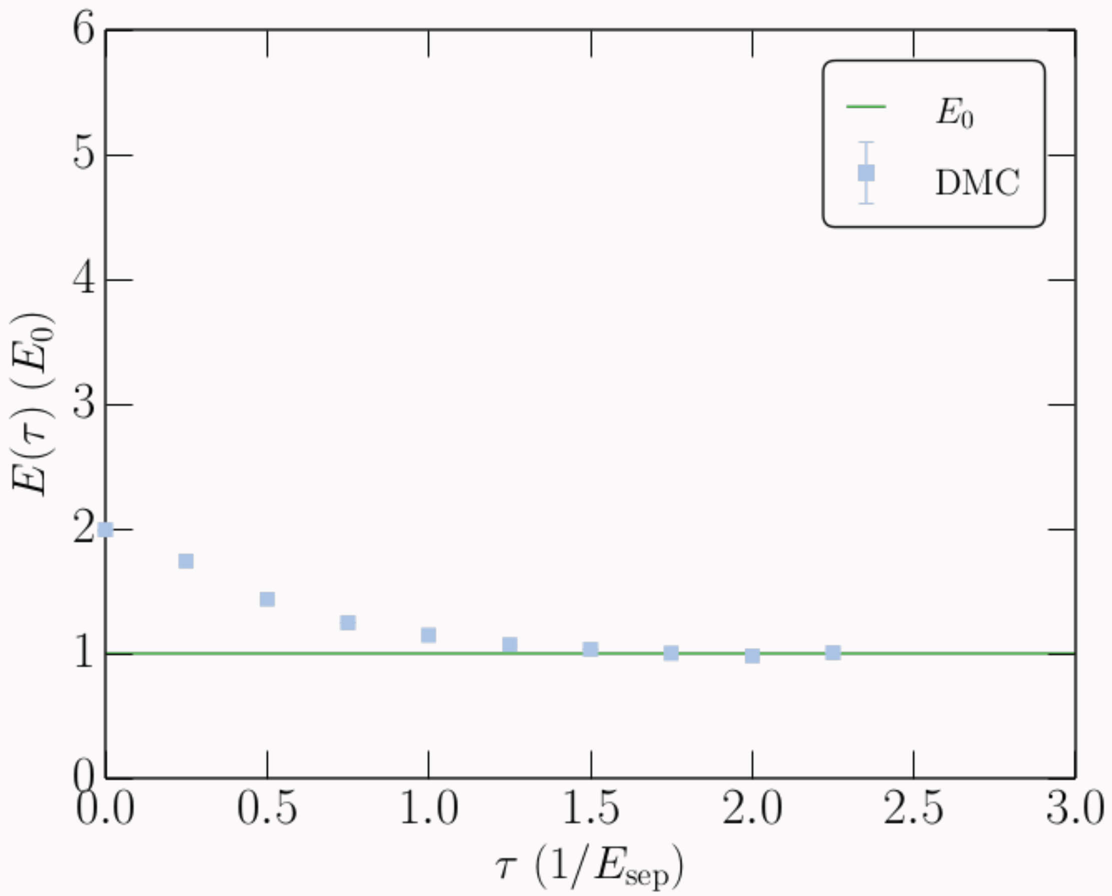

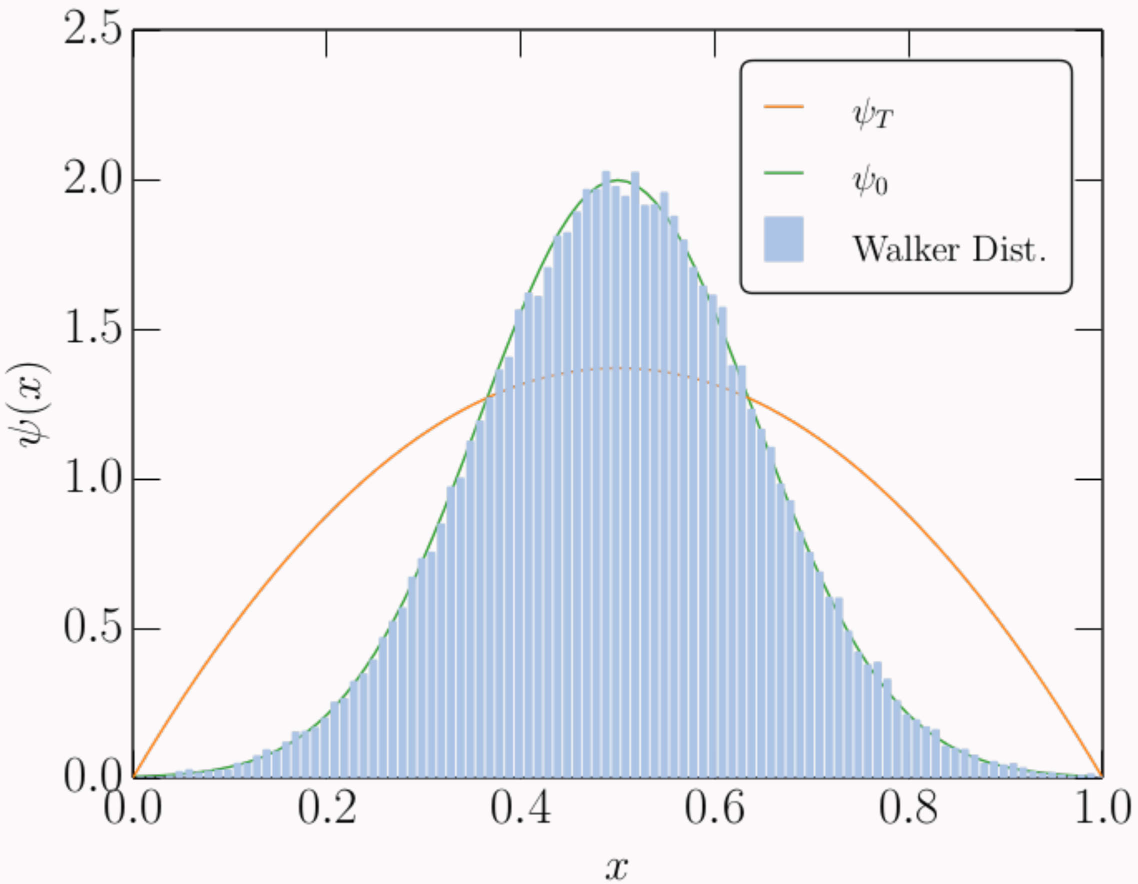

QMC Methods - An Example

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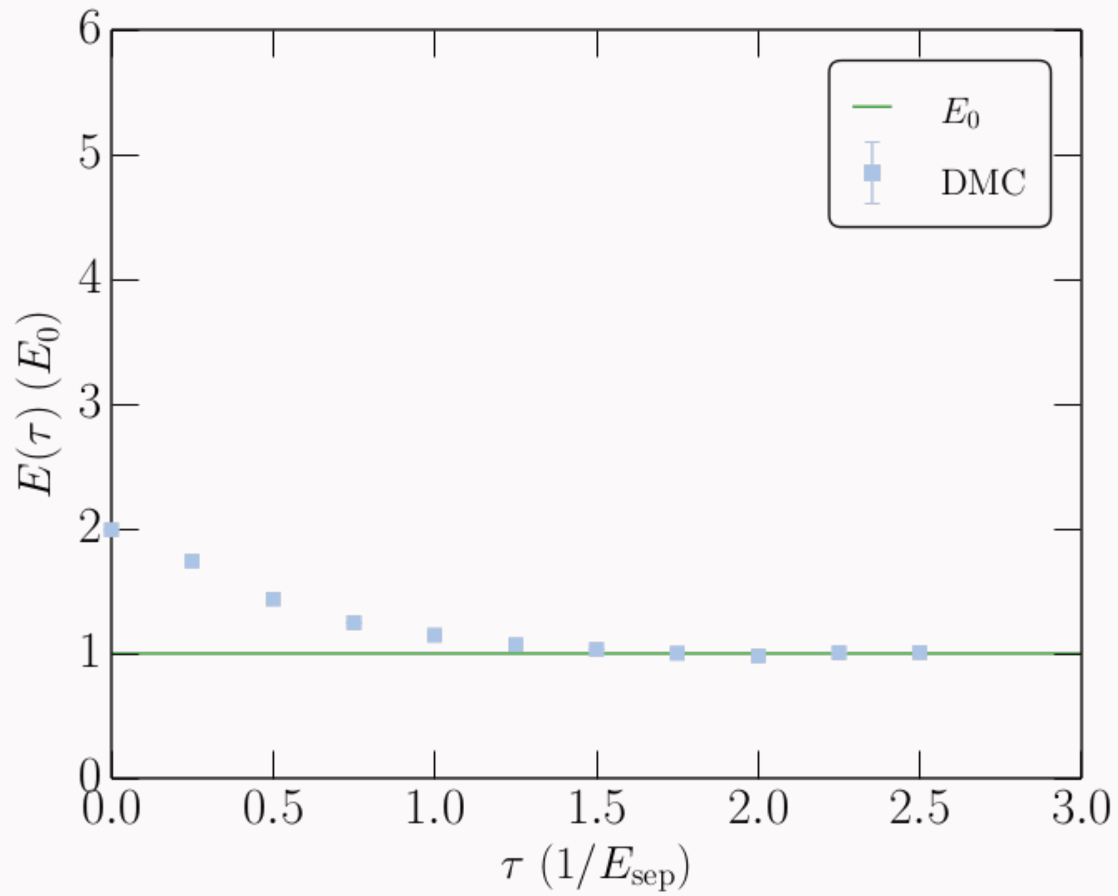

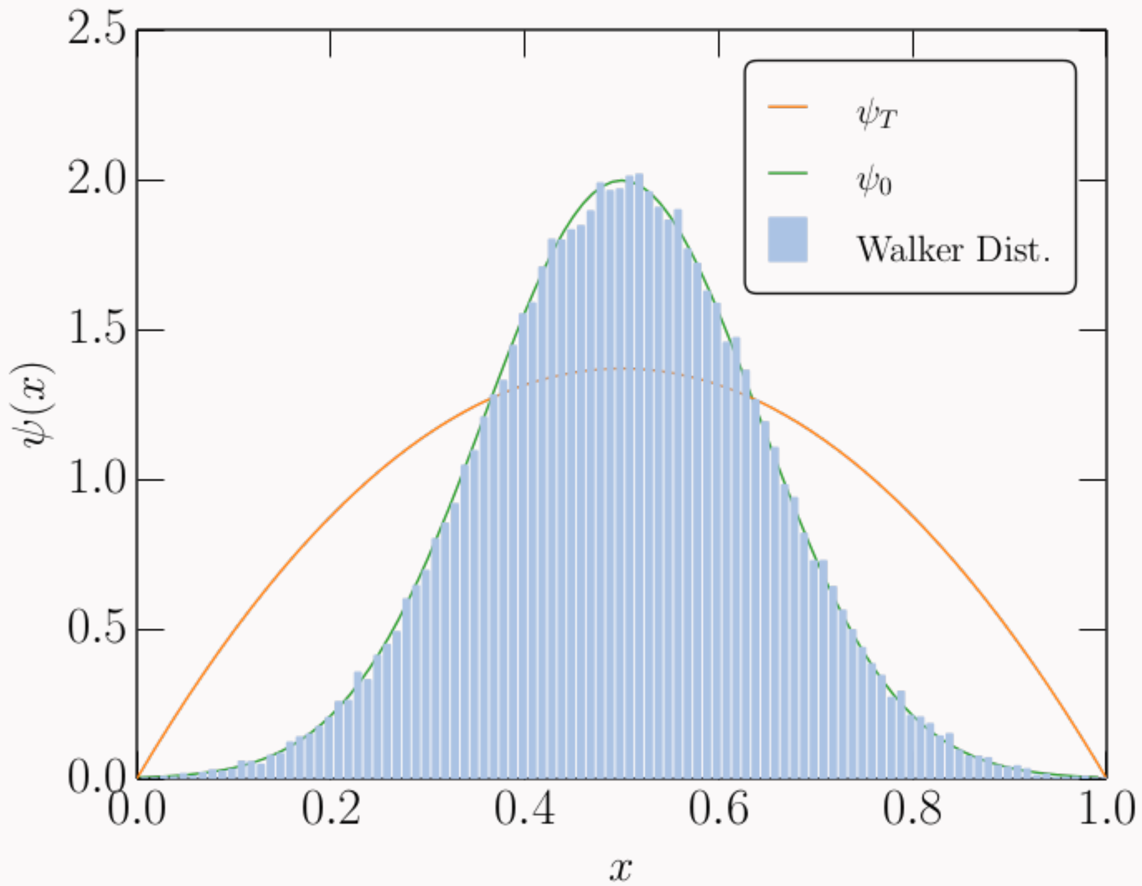

QMC Methods - An Example

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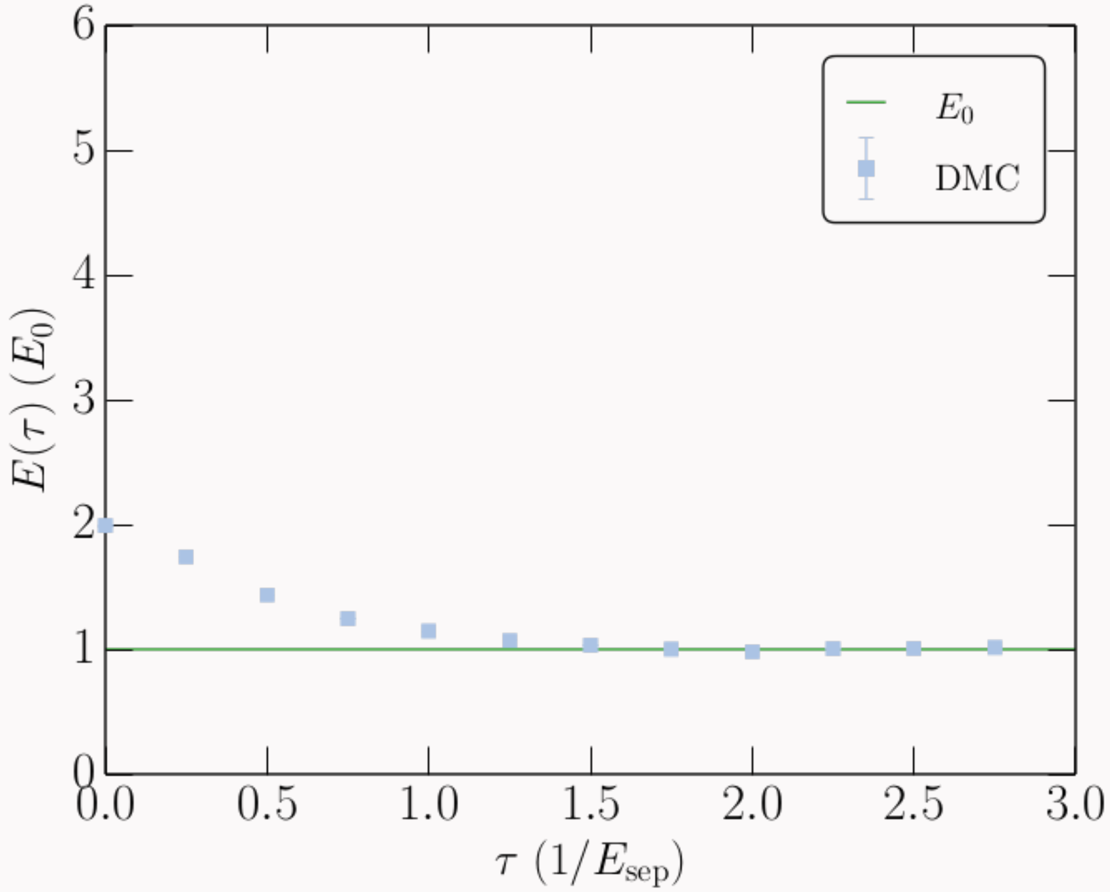
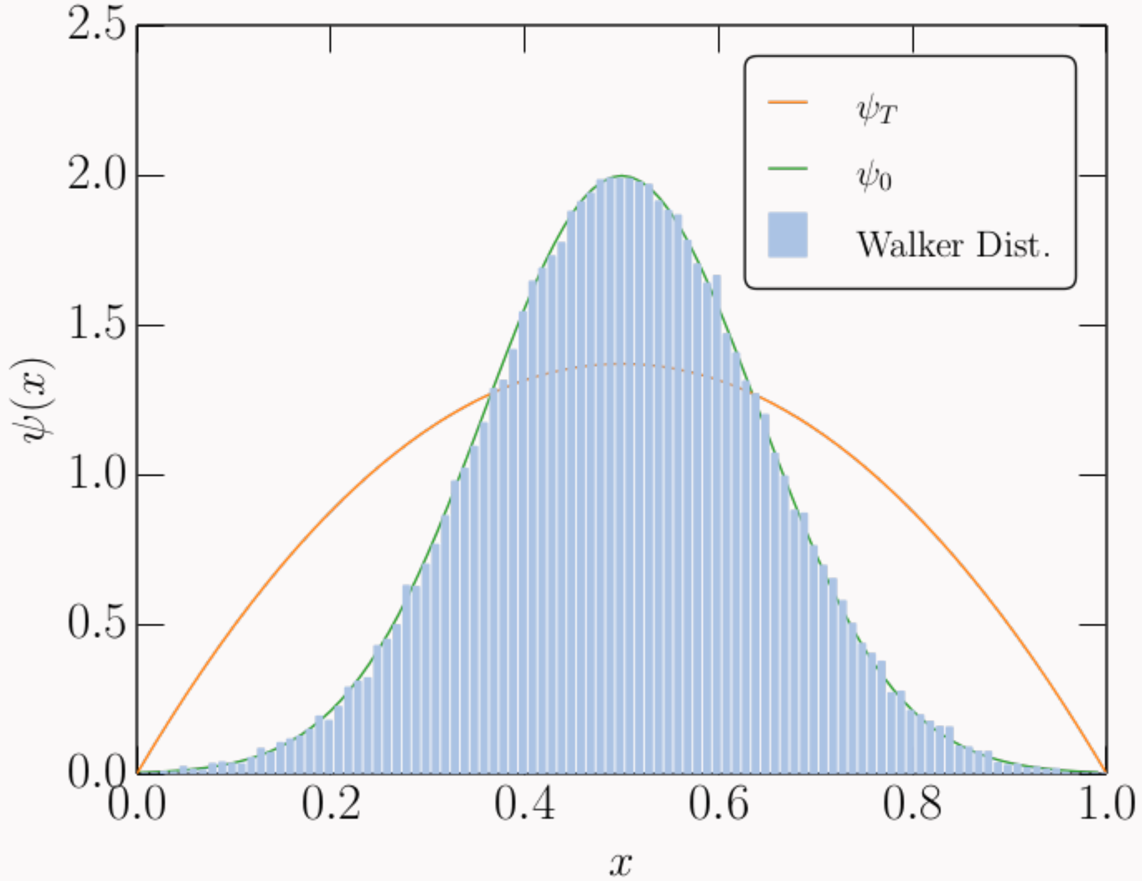
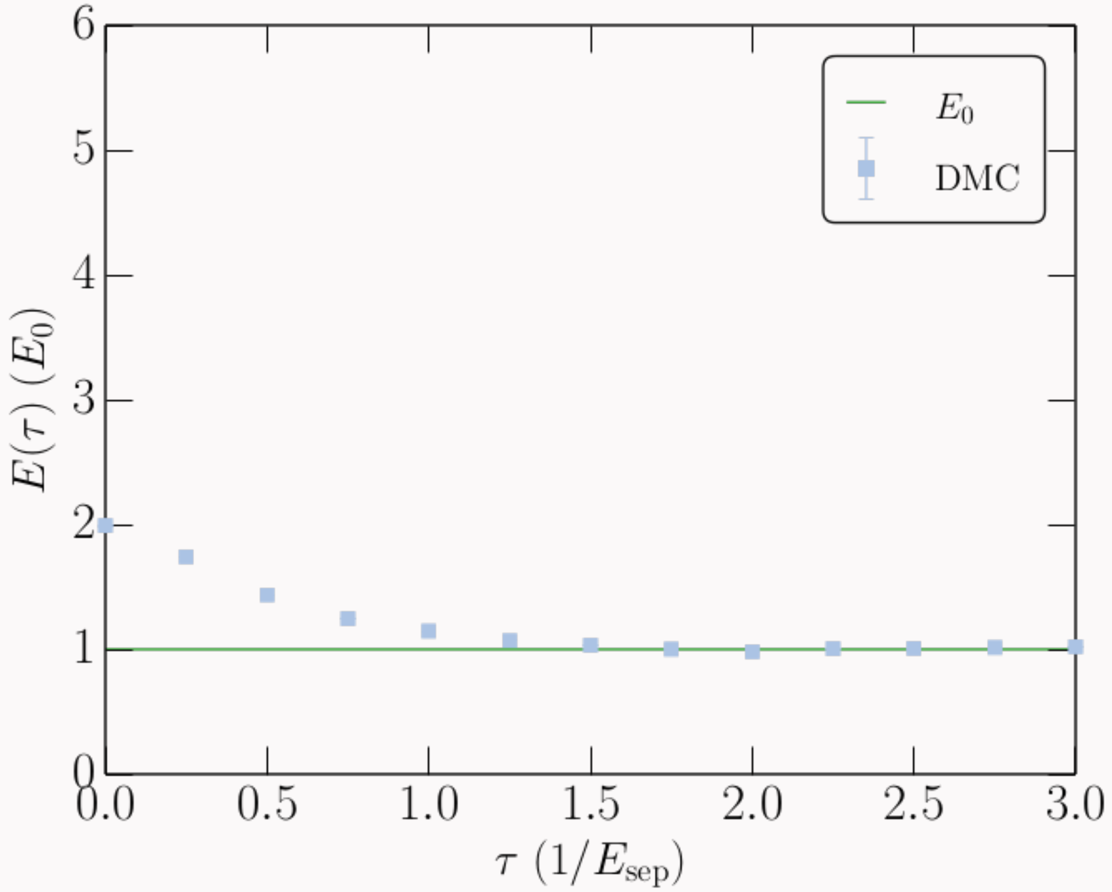


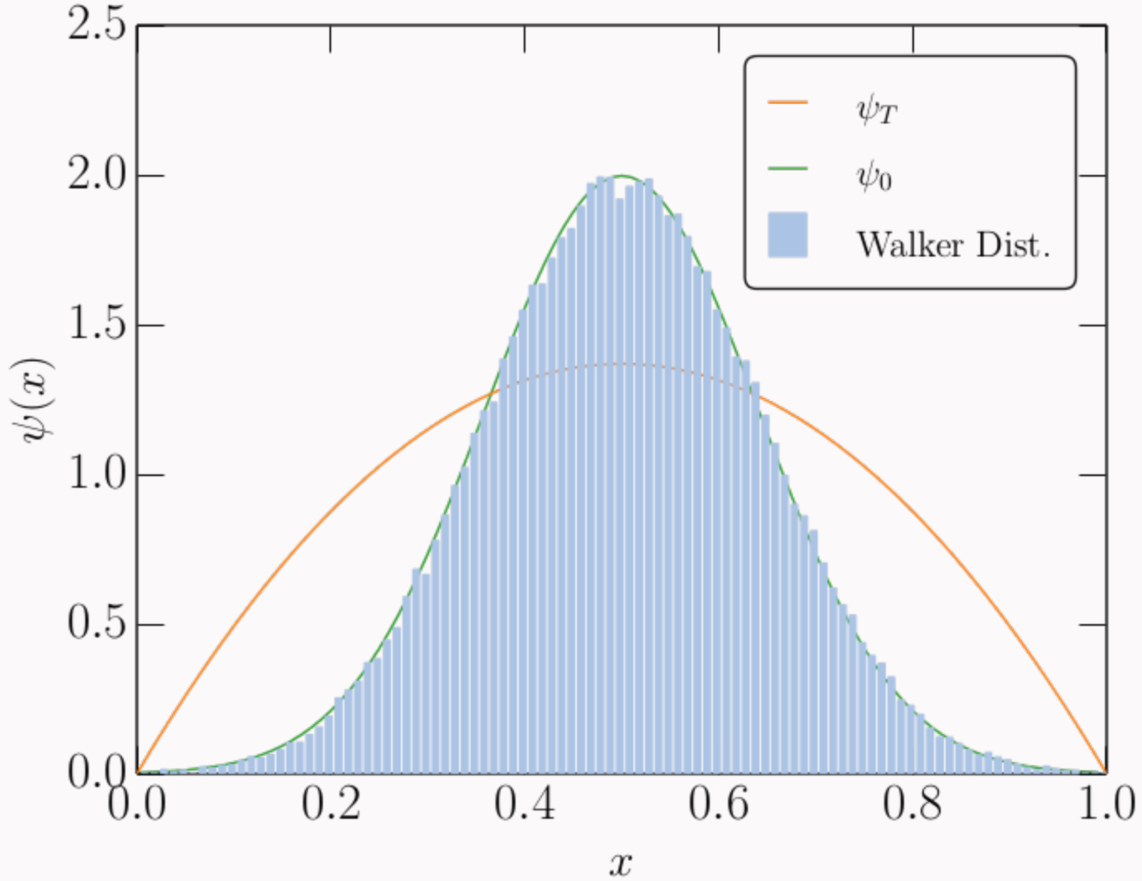


QMC Methods - An Example

Imaginary-time evolution:

$\tau = 3.00$





QMC Methods - An Example

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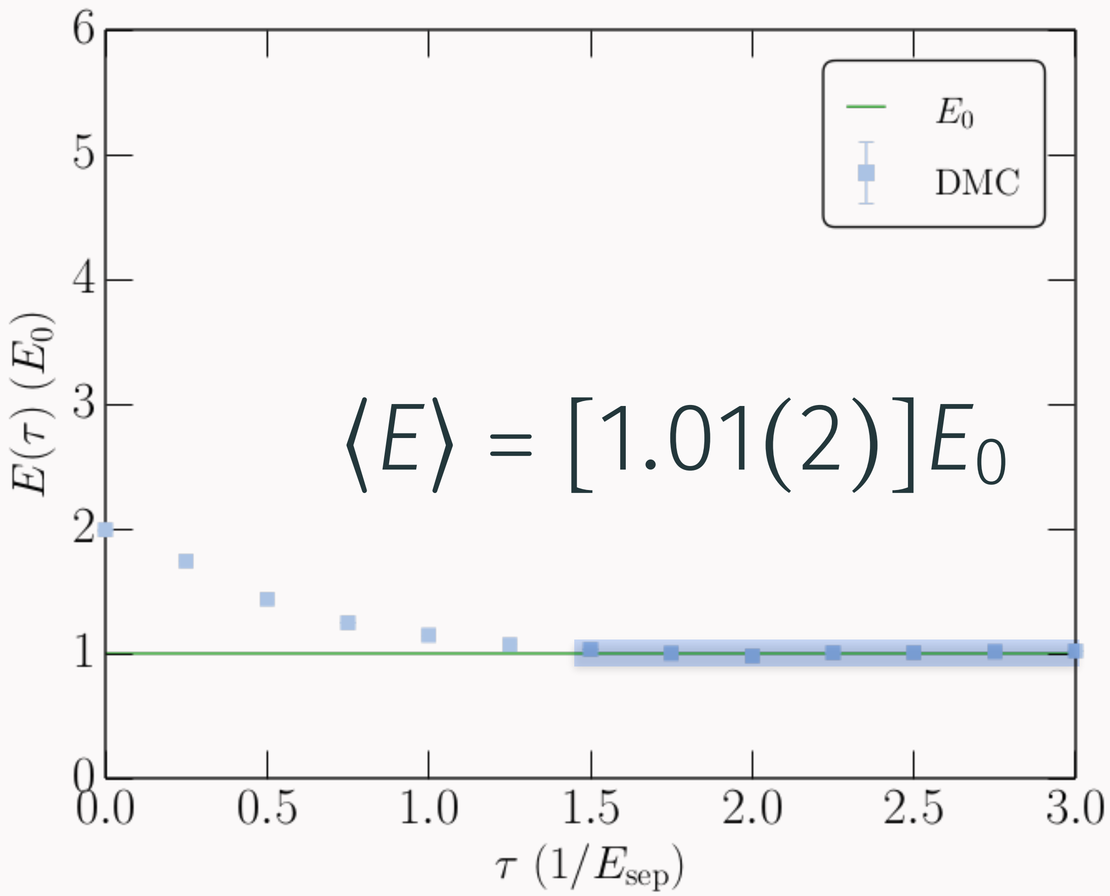

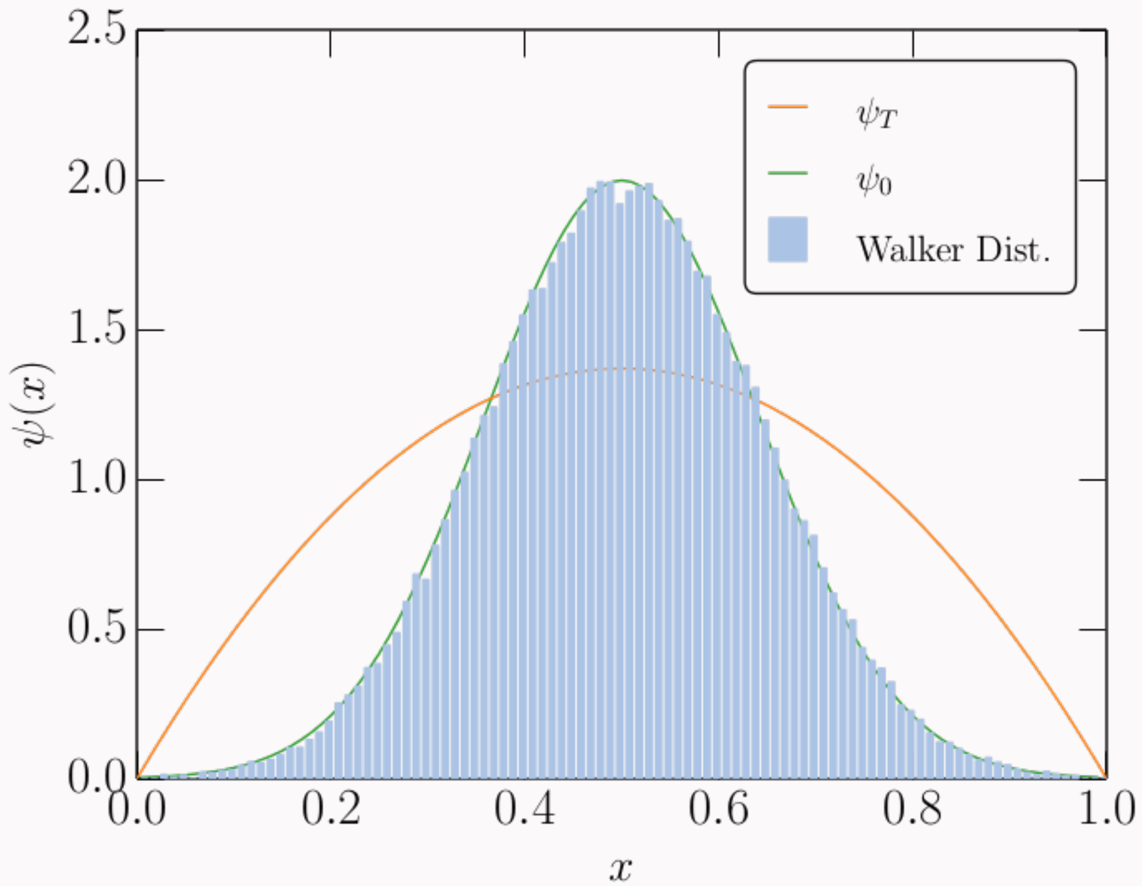

Local Chiral EFT

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:

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

Contacts:

$\propto$ **q** and **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)

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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:

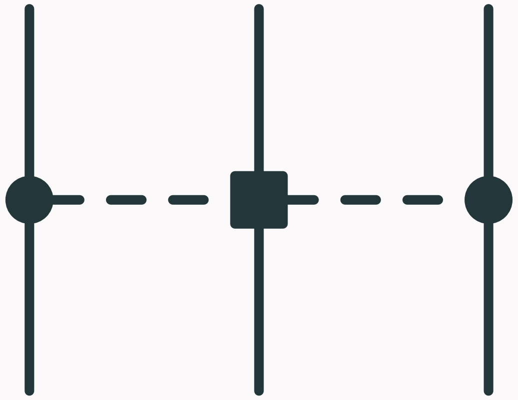
$\cancel{\propto \mathbf{q} \text{ and } \mathbf{k}}$

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

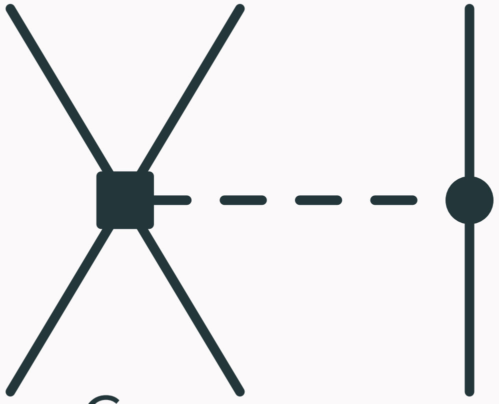
[1] A. Gezerlis et al, PRL **111** 032501 (2013); JEL et al, PRL **113** 192501 (2014); A. Gezerlis et al, PRC **90** 054323 (2014)

Three-Nucleon Interactions

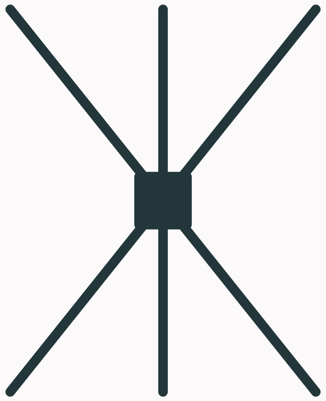
Three-Nucleon Interaction



$c_1,\ c_3,\ c_4$

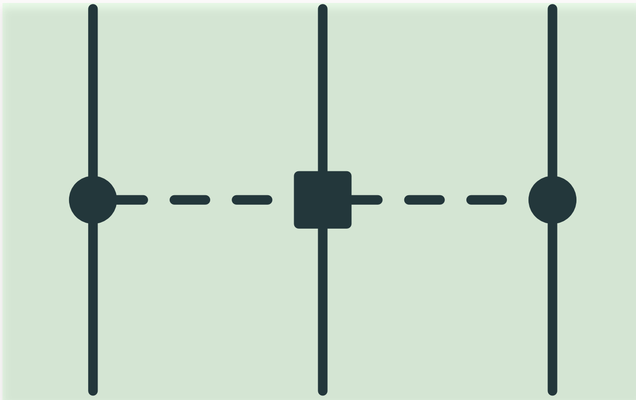


c_D



c_E

Three-Nucleon Interaction



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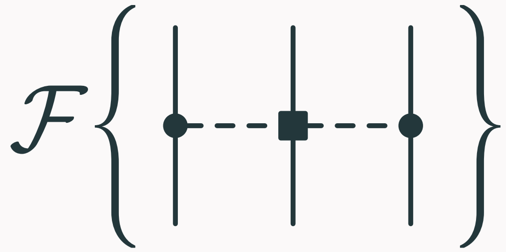
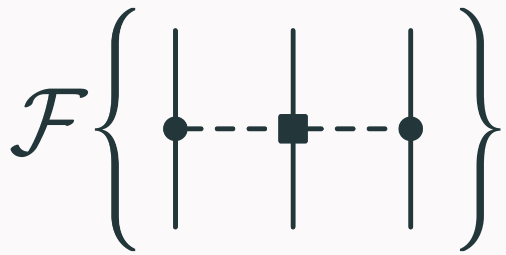


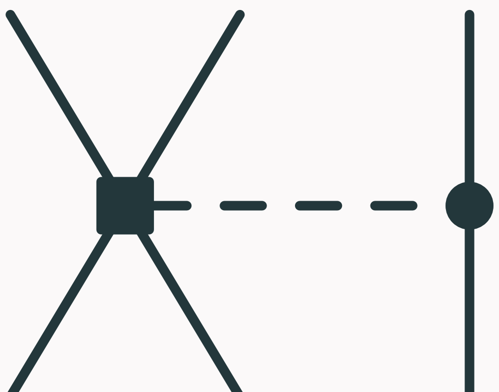
c_1

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

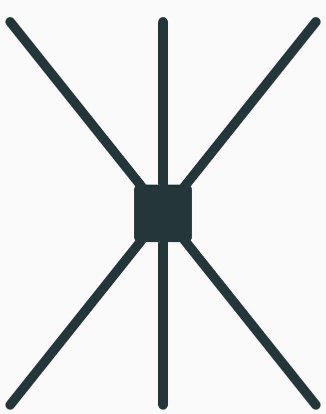


$c_3,\ c_4$

$\rightarrow\sim$ Fujita-Miyazawa

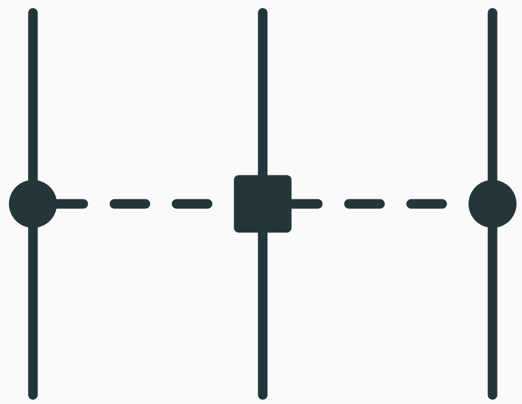


c_D

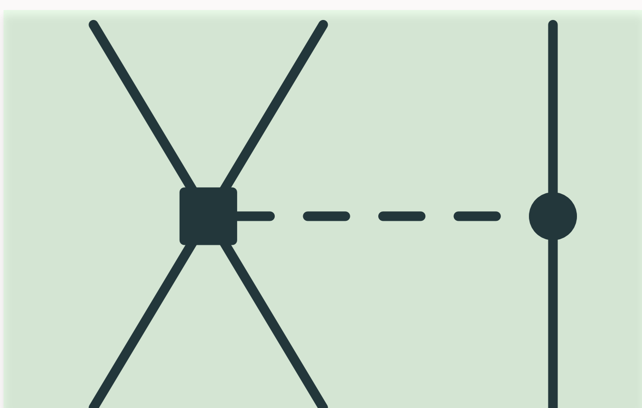


c_E

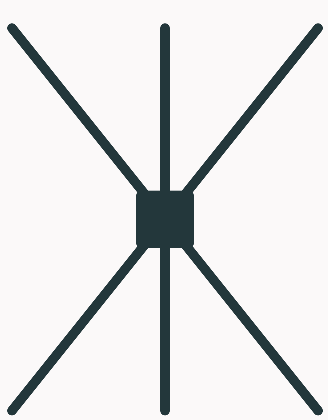
Three-Nucleon Interaction



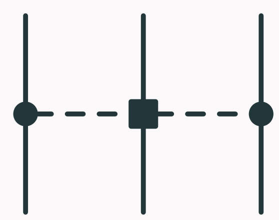
$c_1,\ c_3,\ c_4$



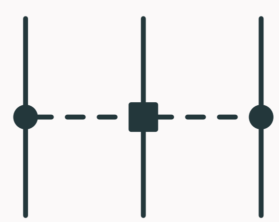
c_D



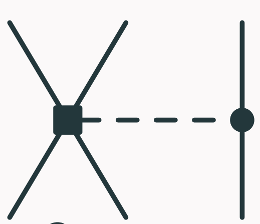
c_E

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

c_1

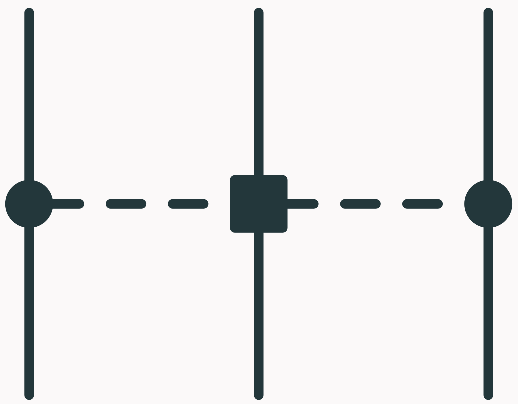
$\mathcal{F}\Big\{$  $\Big\}$ $\rightarrow\sim$ Fujita-Miyazawa

$c_3,\ c_4$

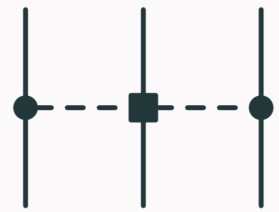
$\mathcal{F}\Big\{$  $\Big\}$ $\rightarrow$ 1π-Exchange + Contact

c_D

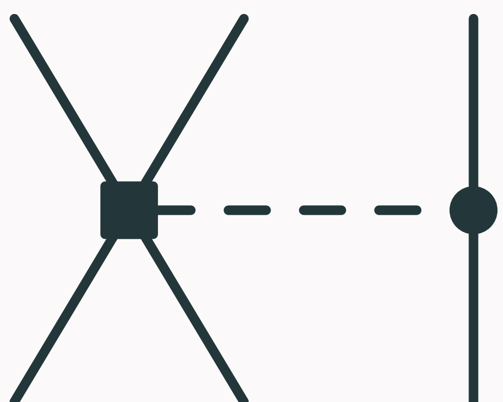
Three-Nucleon Interaction



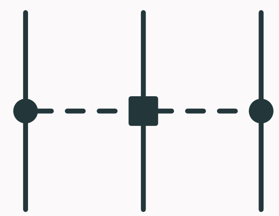
$c_1,\ c_3,\ c_4$

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

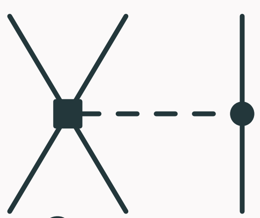
c_1



c_D

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

$c_3,\ c_4$

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

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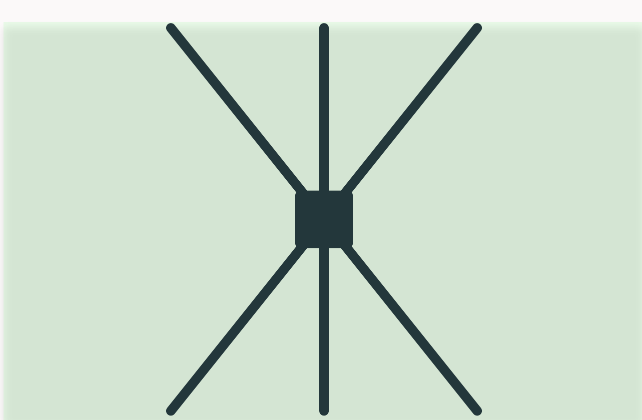
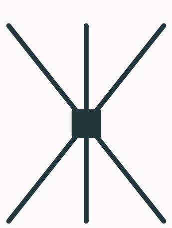


c_E

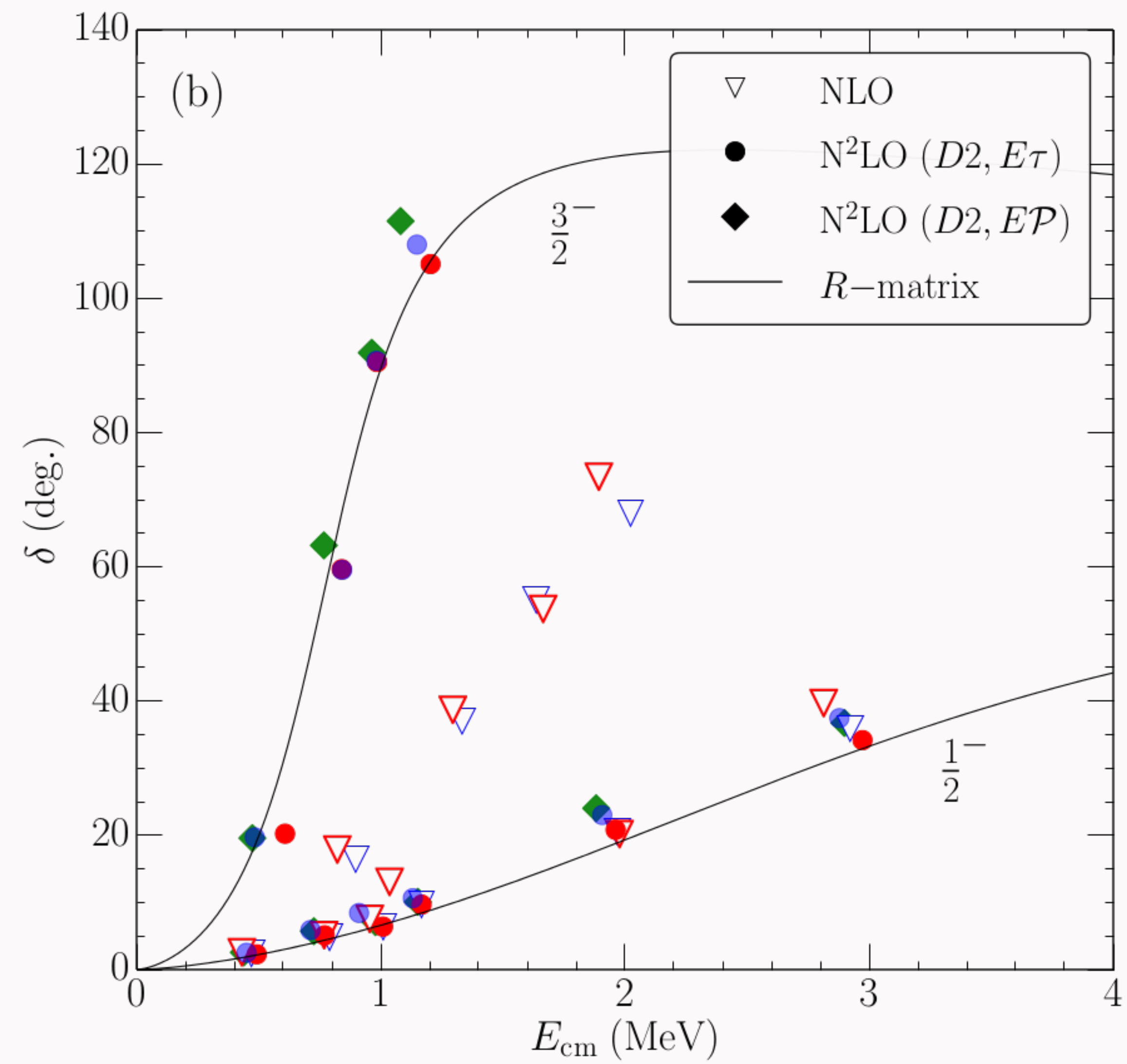
$\mathcal{F}\Big\{$  $\Big\}$ $\rightarrow$ Contact

c_E

Choosing Observables

What to fit c_D and c_E to?

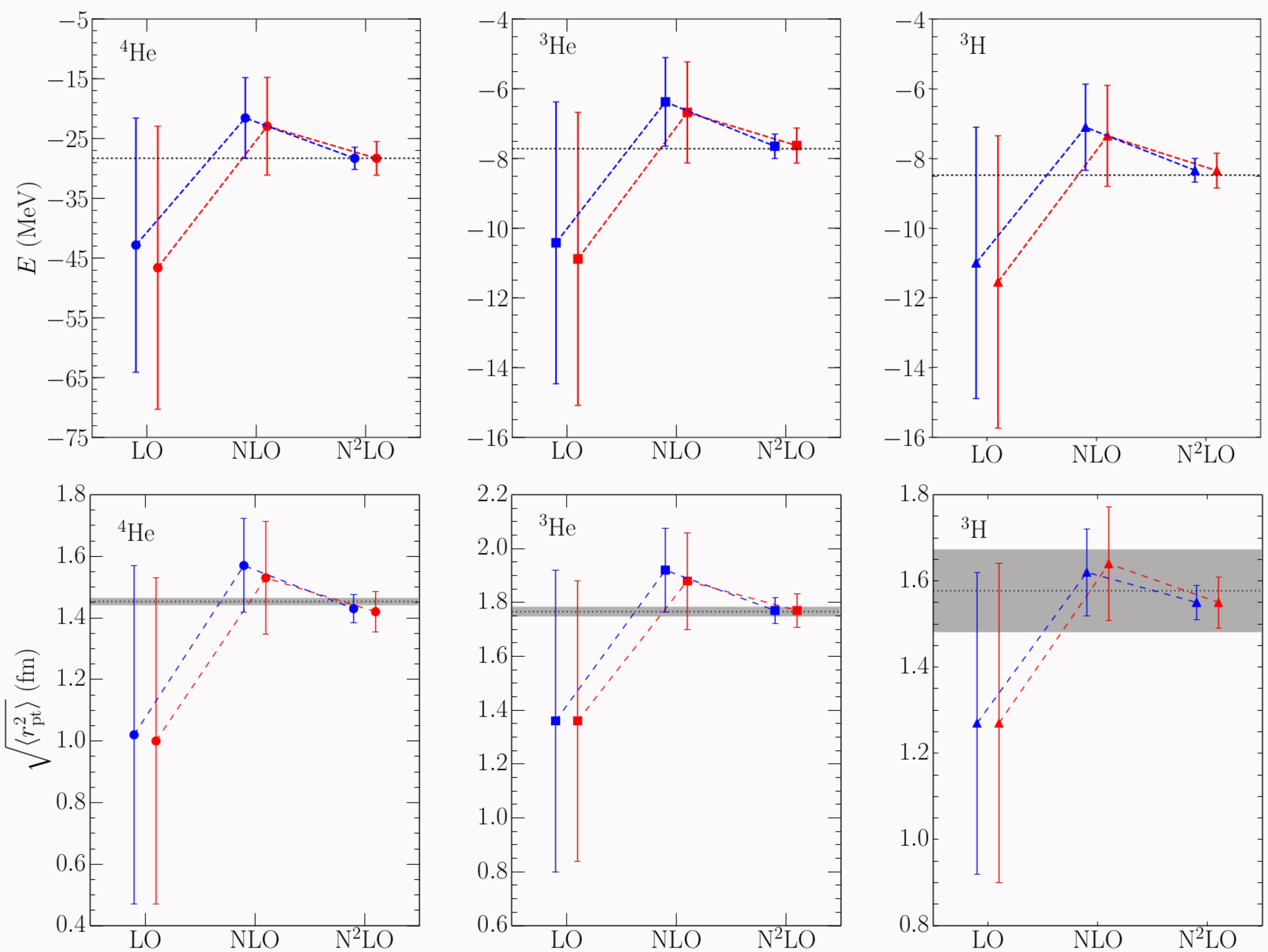
- Uncorrelated observables.
- Probe properties of light nuclei: ^{4}He E_B.
- Probe $T = 3/2$ physics: n-α scattering phase shifts.

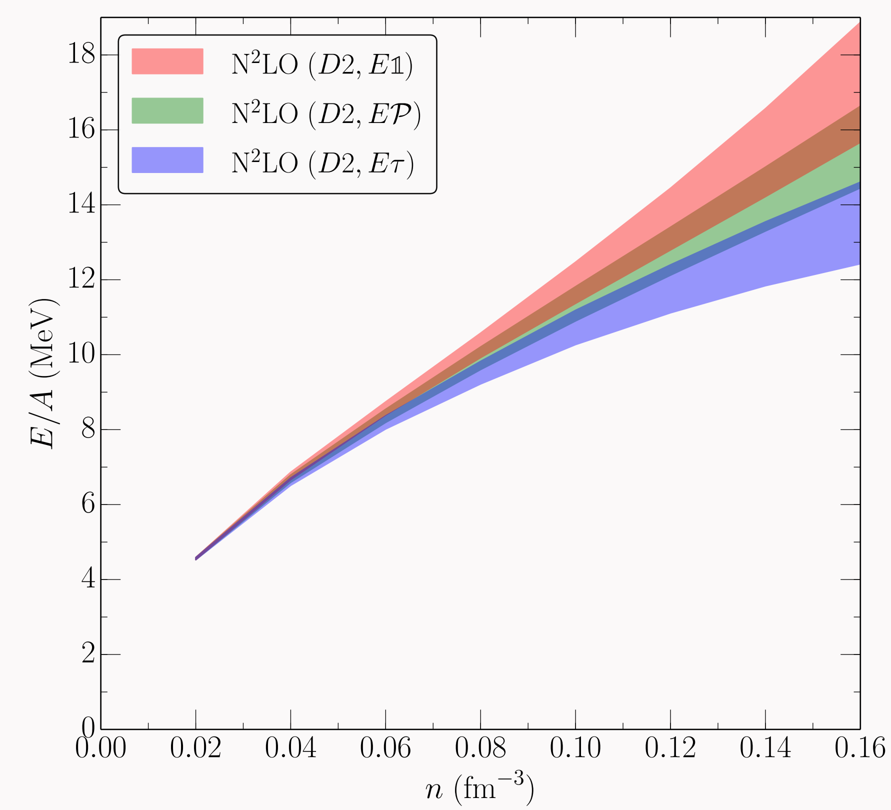


JEL et al, PRL **116**, 062501 (2016)

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)

$3n$, $4n$ Resonances

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

Simulating Unbound Systems?

QMC methods are ideal for simulating bound states.

What can we learn about unbound systems from a bound-state method?

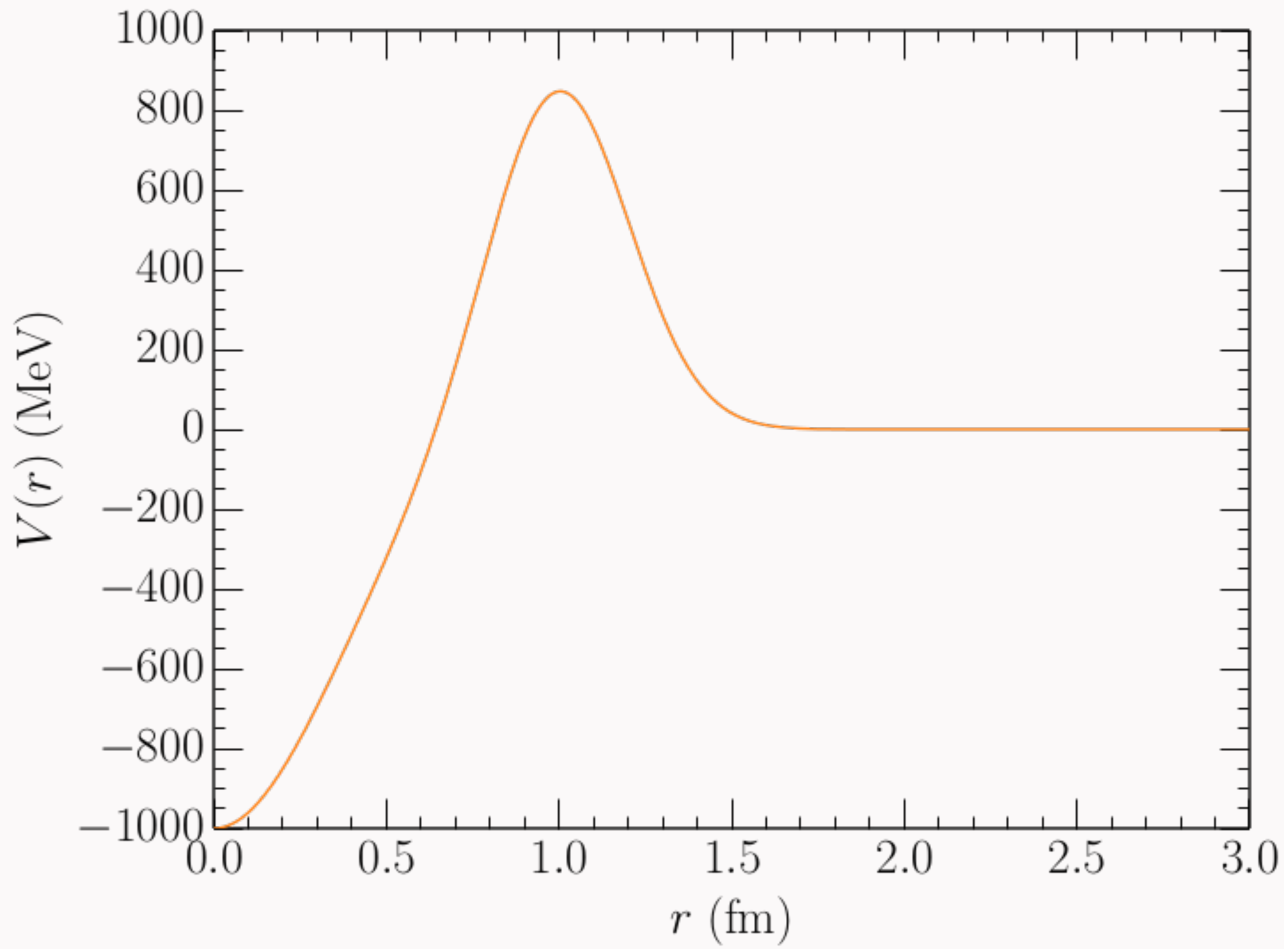
A Two-Body Test

A simple S-wave potential:

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

$$V_1 = -1000\ \text{MeV},\ \ R_1 = 0.4981\ \text{fm},$$

$$V_2 = 865\ \text{MeV},\ \ R_2 = 0.2877\ \text{fm},\ \ r_2 = 0.9972\ \text{fm}$$



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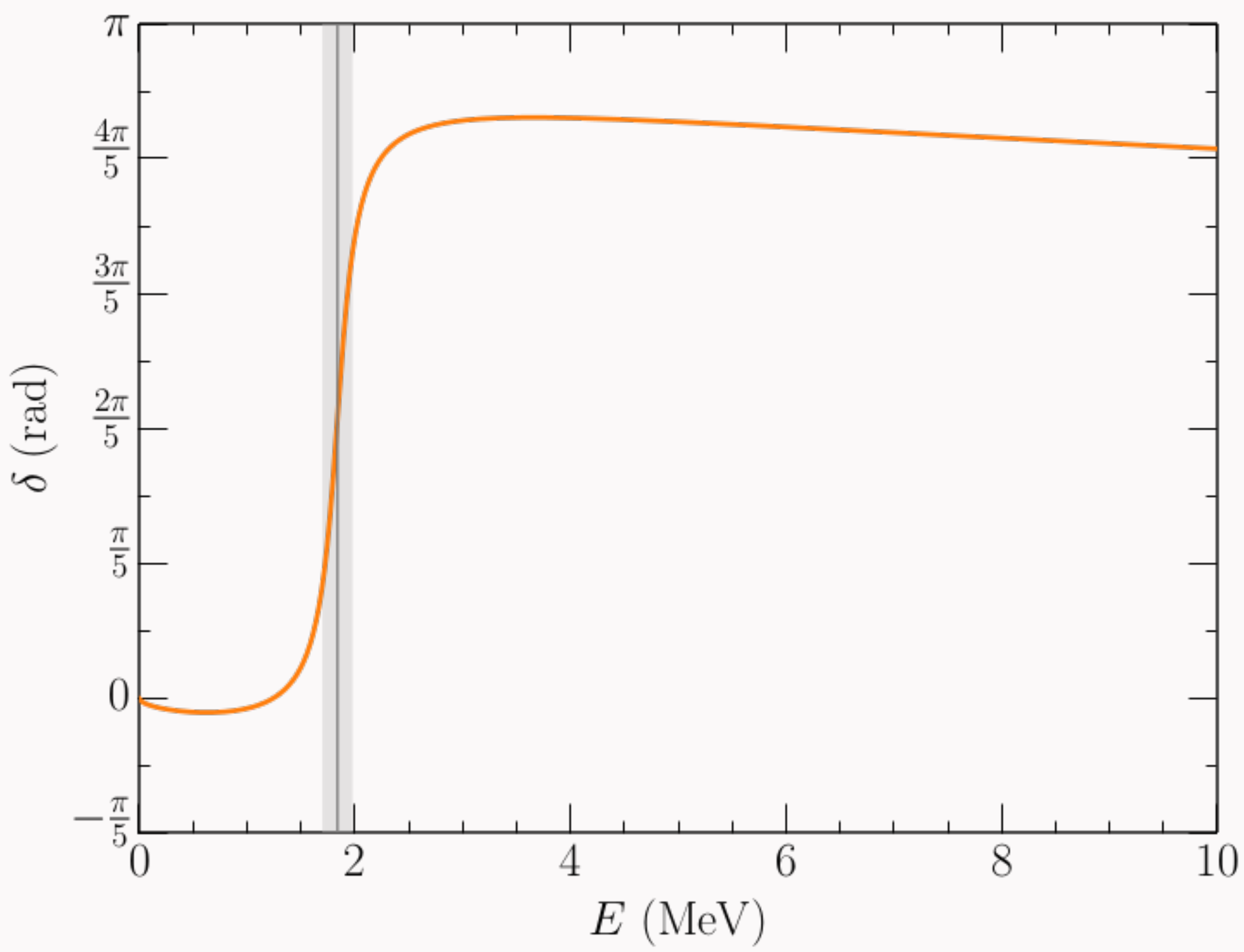
$$E_R = 1.84\ \text{MeV},\ \ \Gamma = 0.282\ \text{MeV}$$

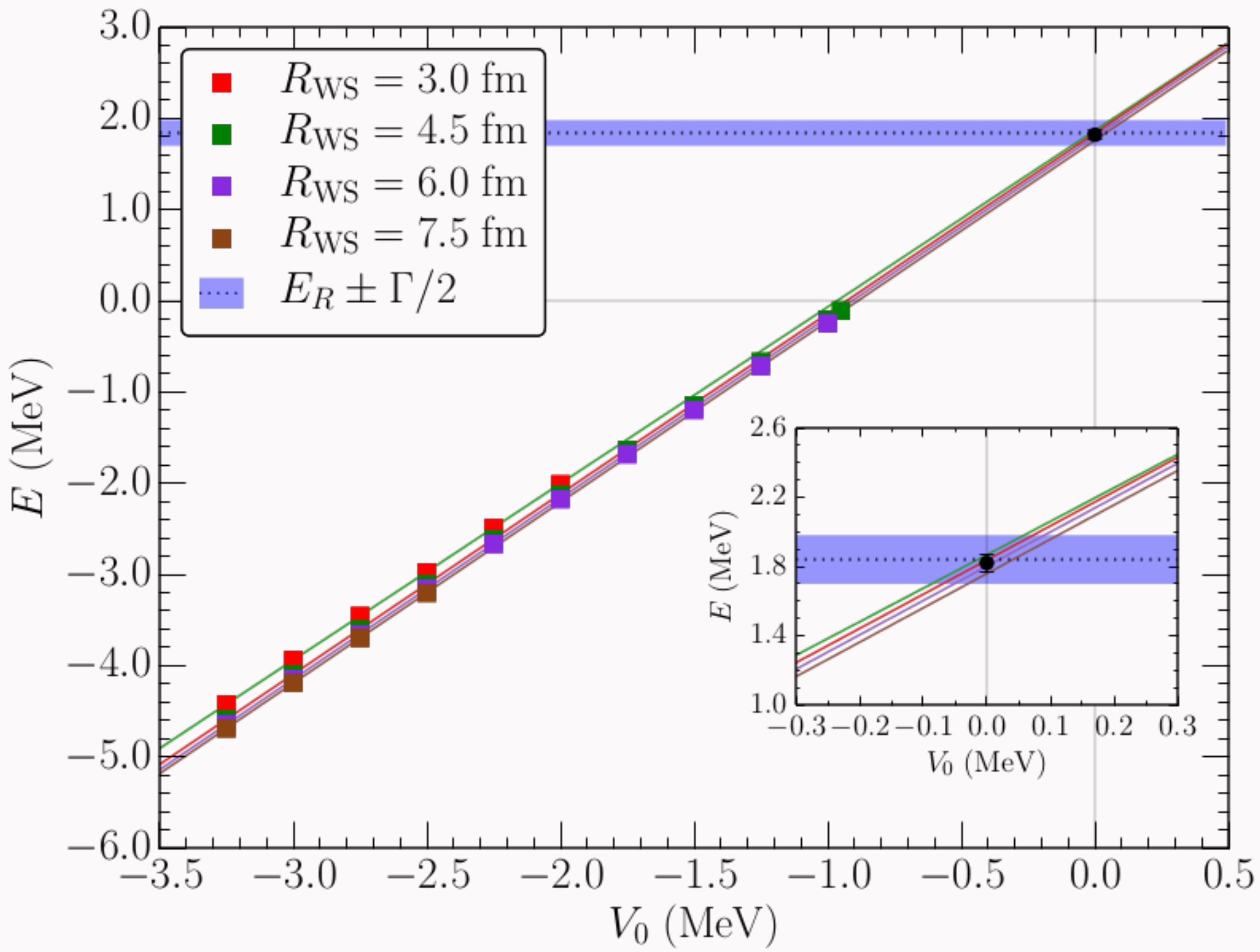


A Two-Body Test

A simple S-wave potential + Woods-Saxon:

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

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



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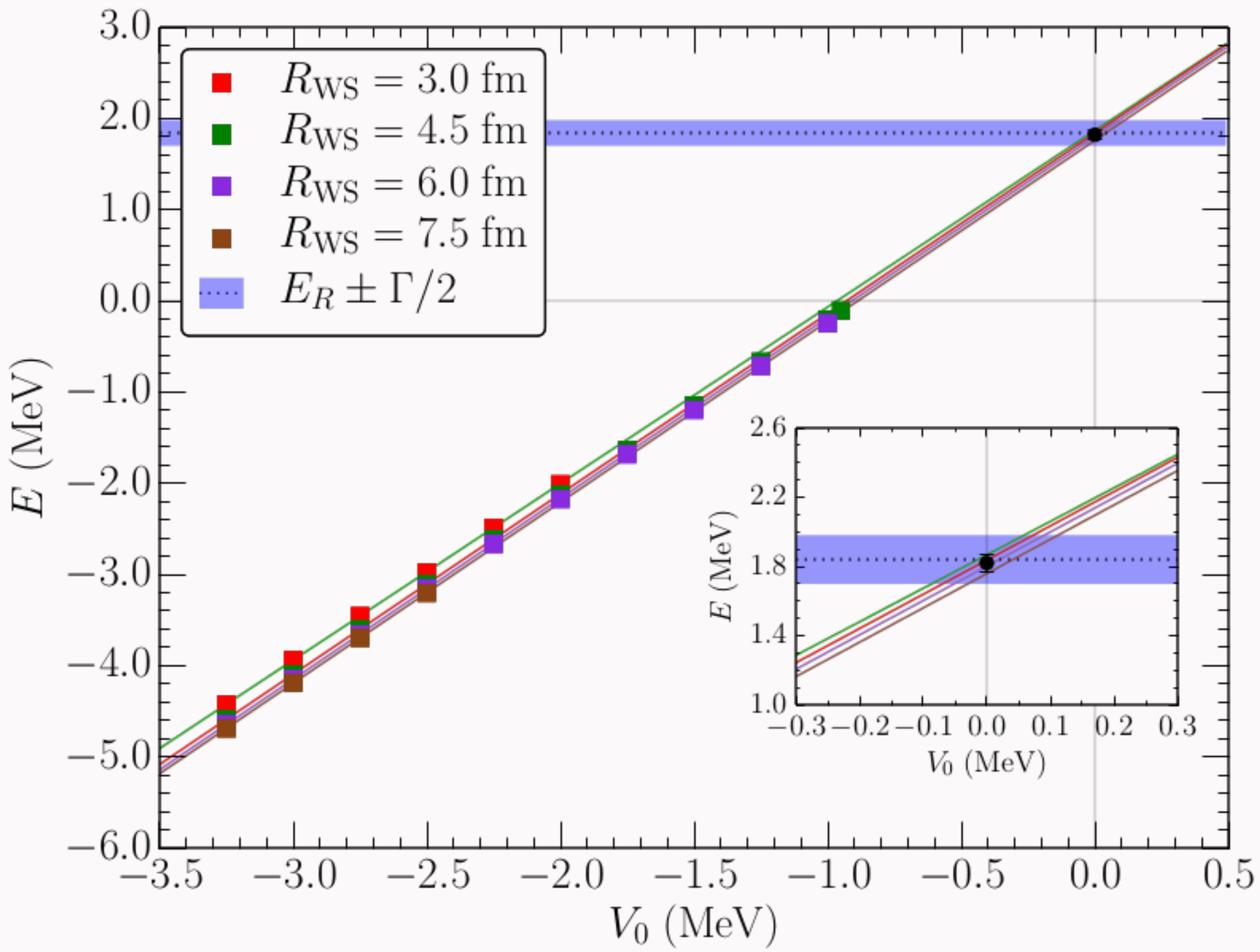
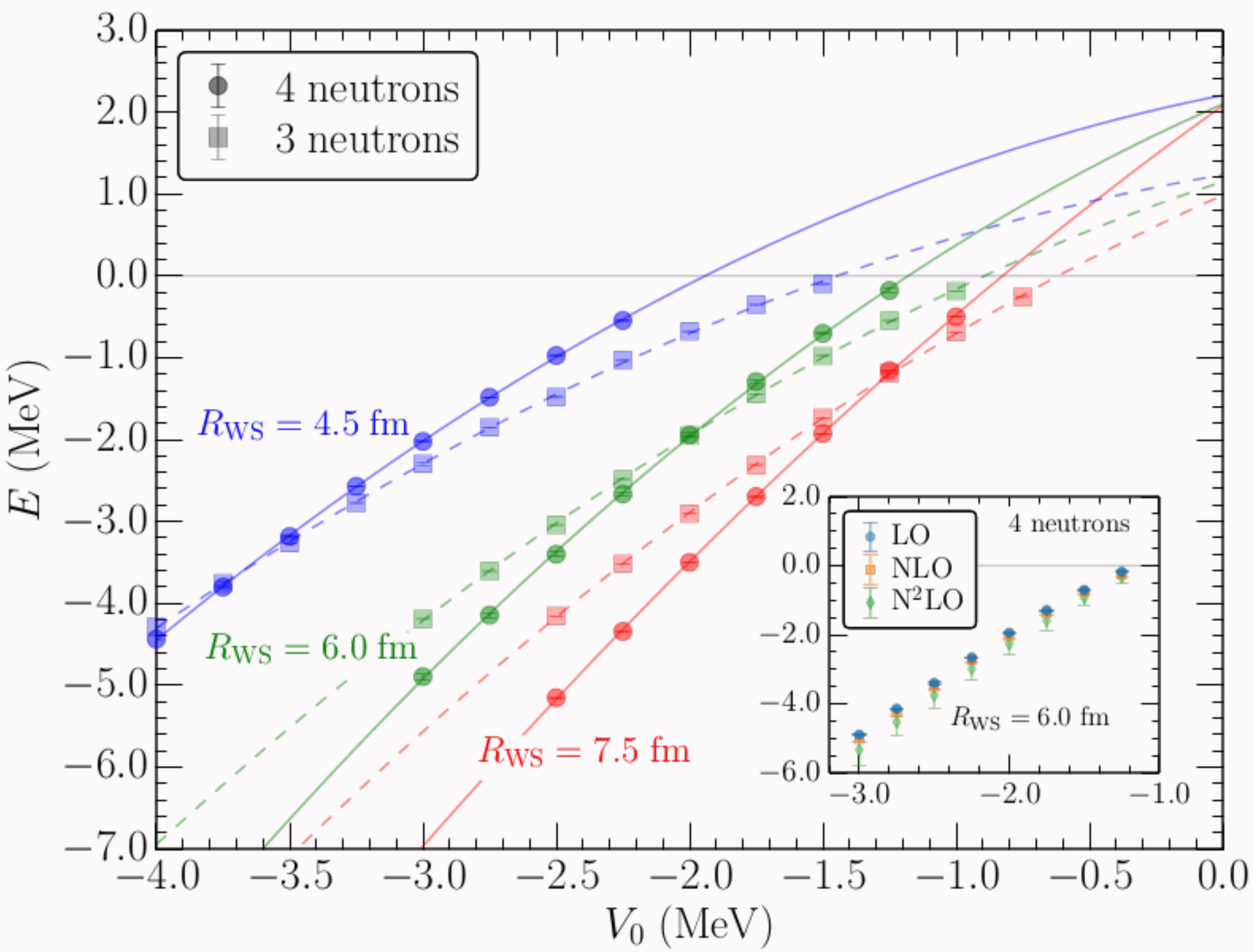
- Different Woods-Saxon radii: Independence of trap geometry.
- Extrapolations give 1.83(5) MeV. (Compare to 1.84 MeV).



Neutrons In A Trap

Now confine 3 & 4 neutrons in the external potential.

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



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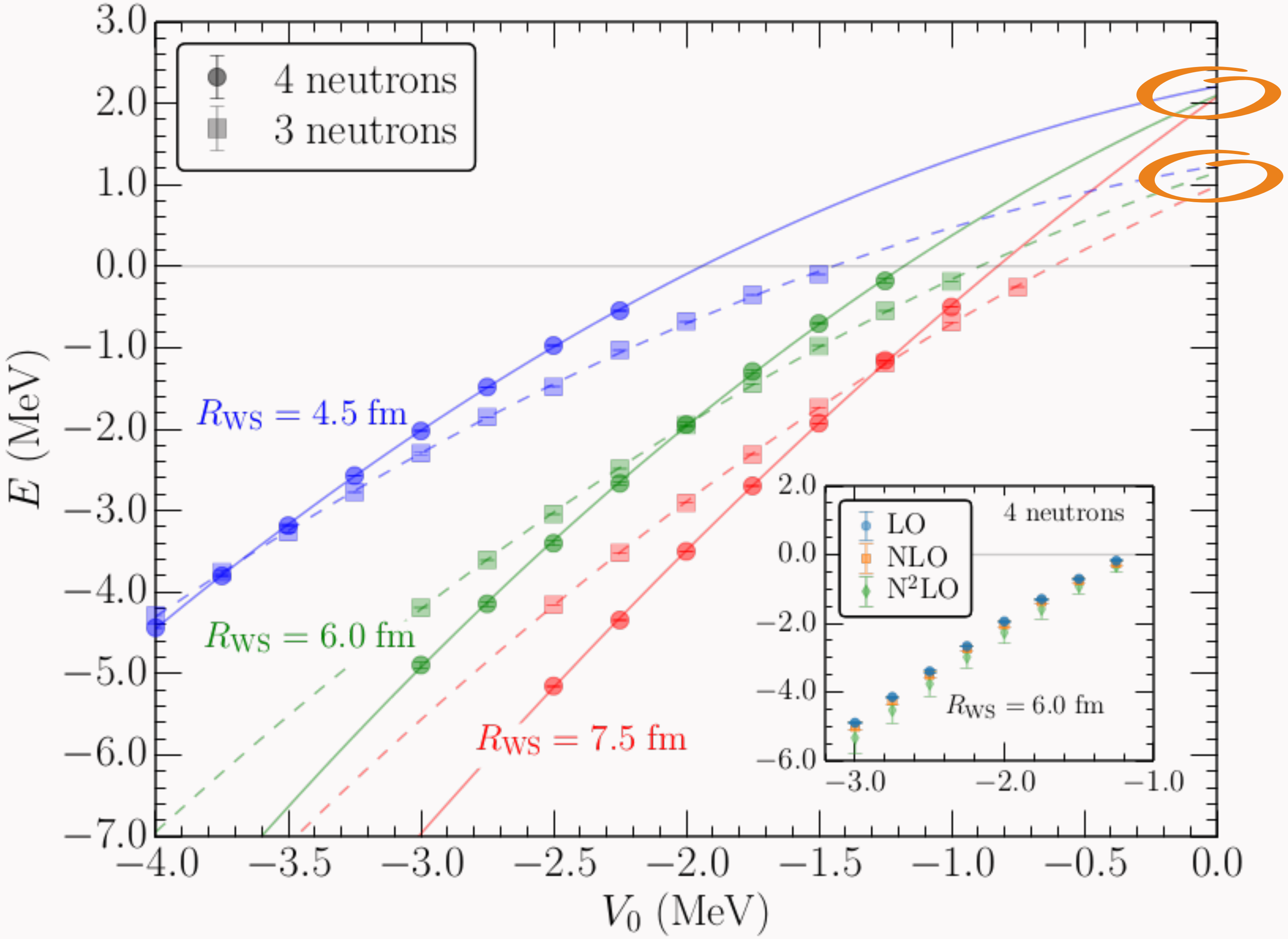
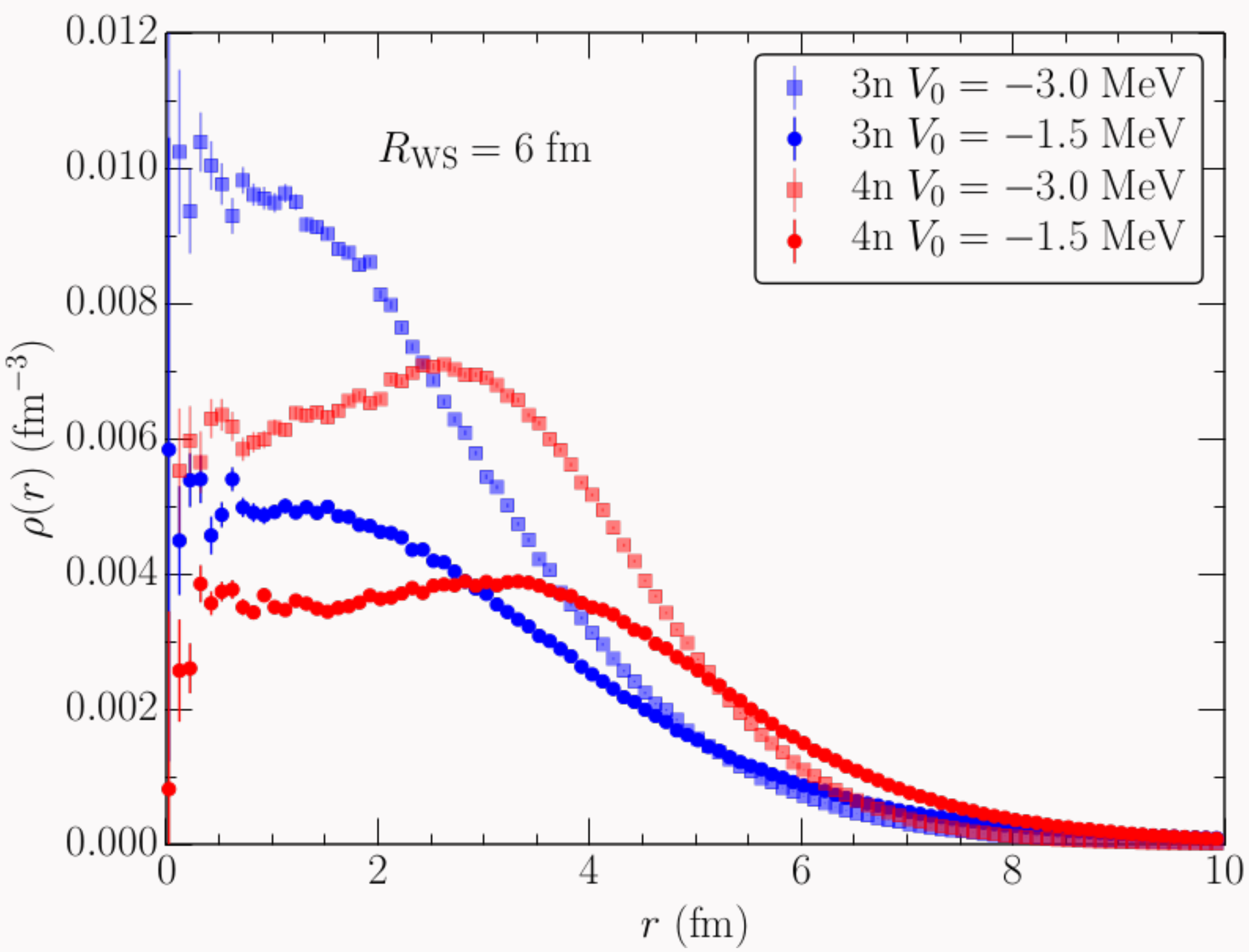


- E_{4n} = 2.1(2) MeV,
  E_{3n} = 1.1(2) MeV.
- ^3n resonance lower than ^4n resonance!
- Changing cutoff/ removal of 3N interaction gives indistinguishable results.

One-Body Densities

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



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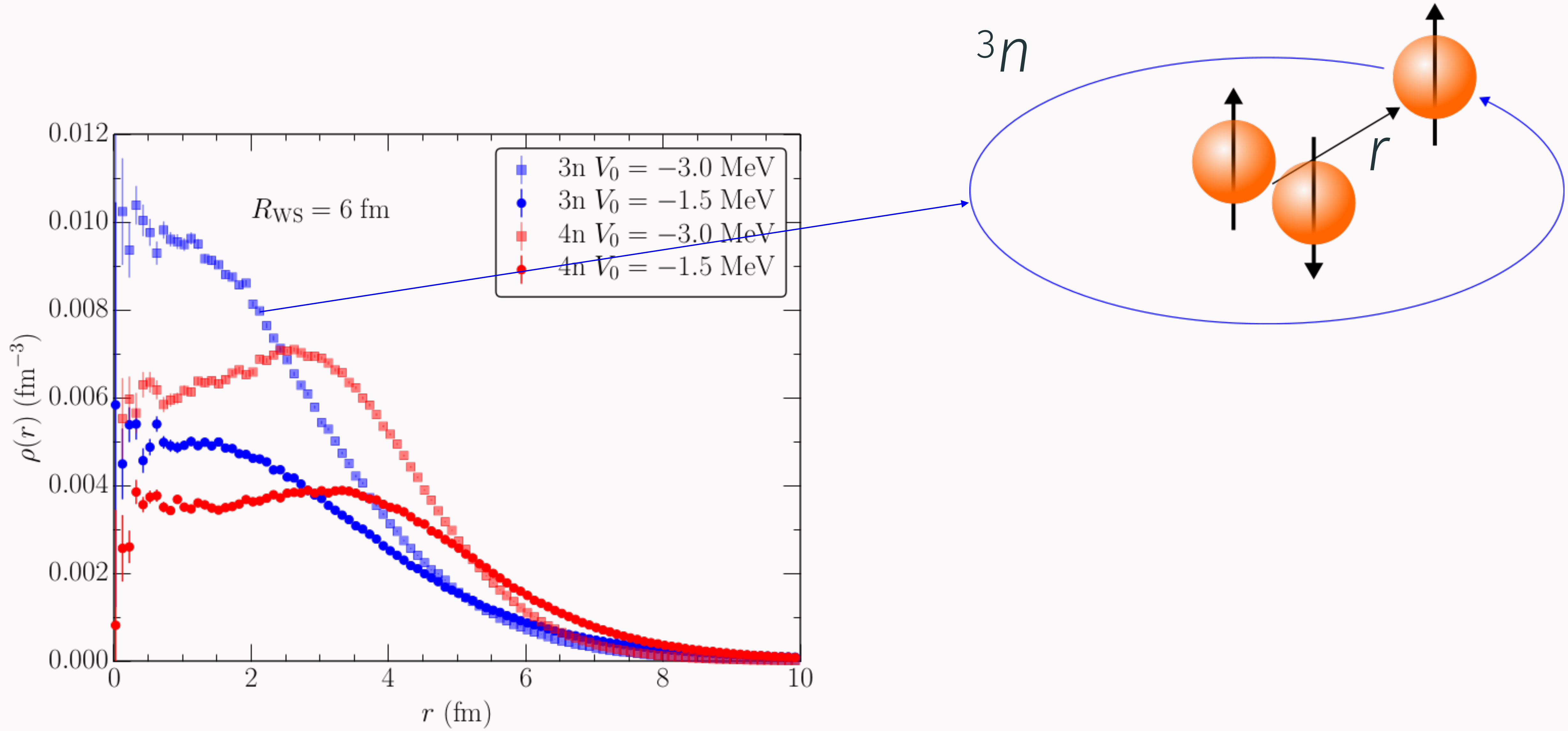
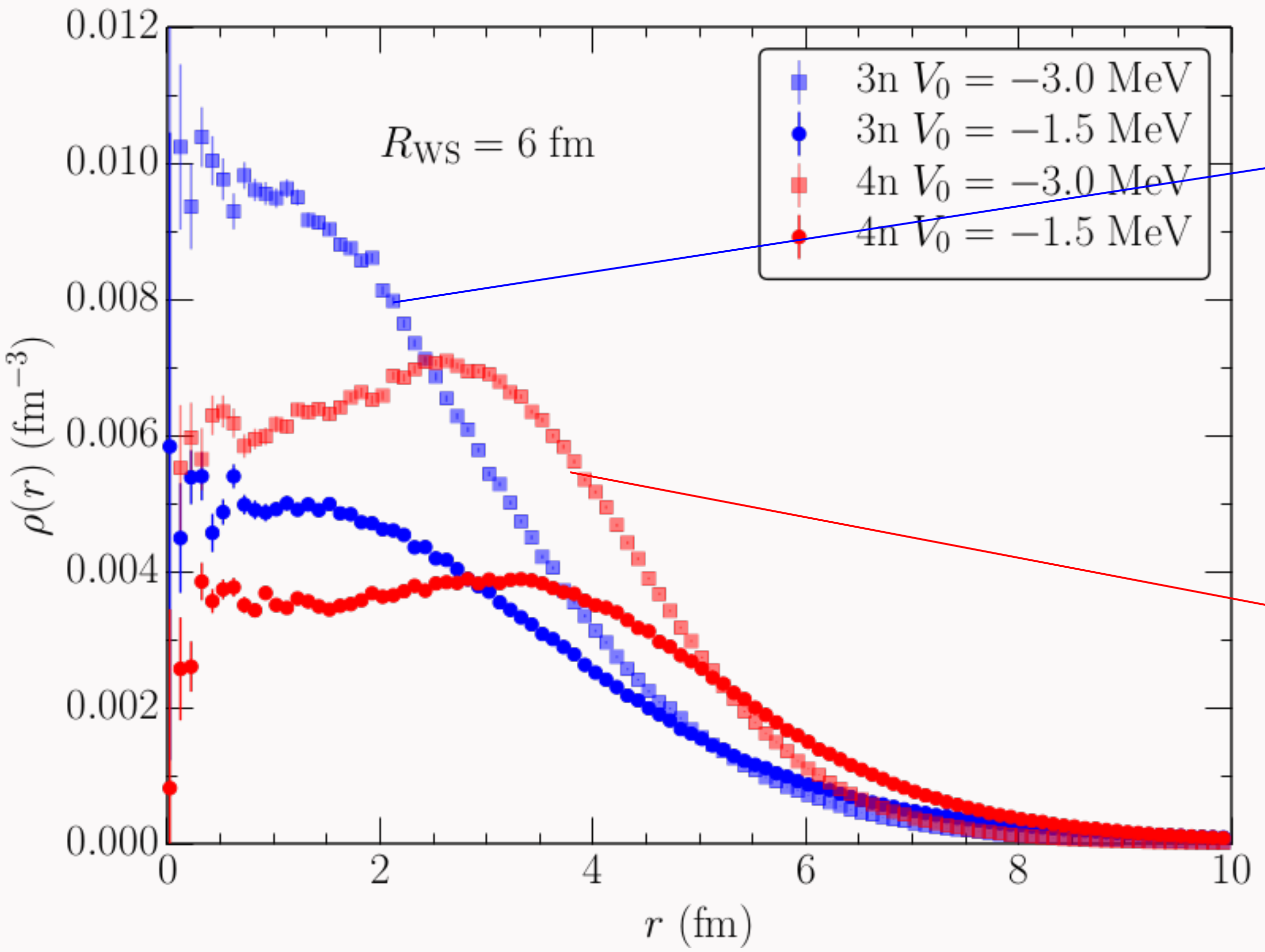
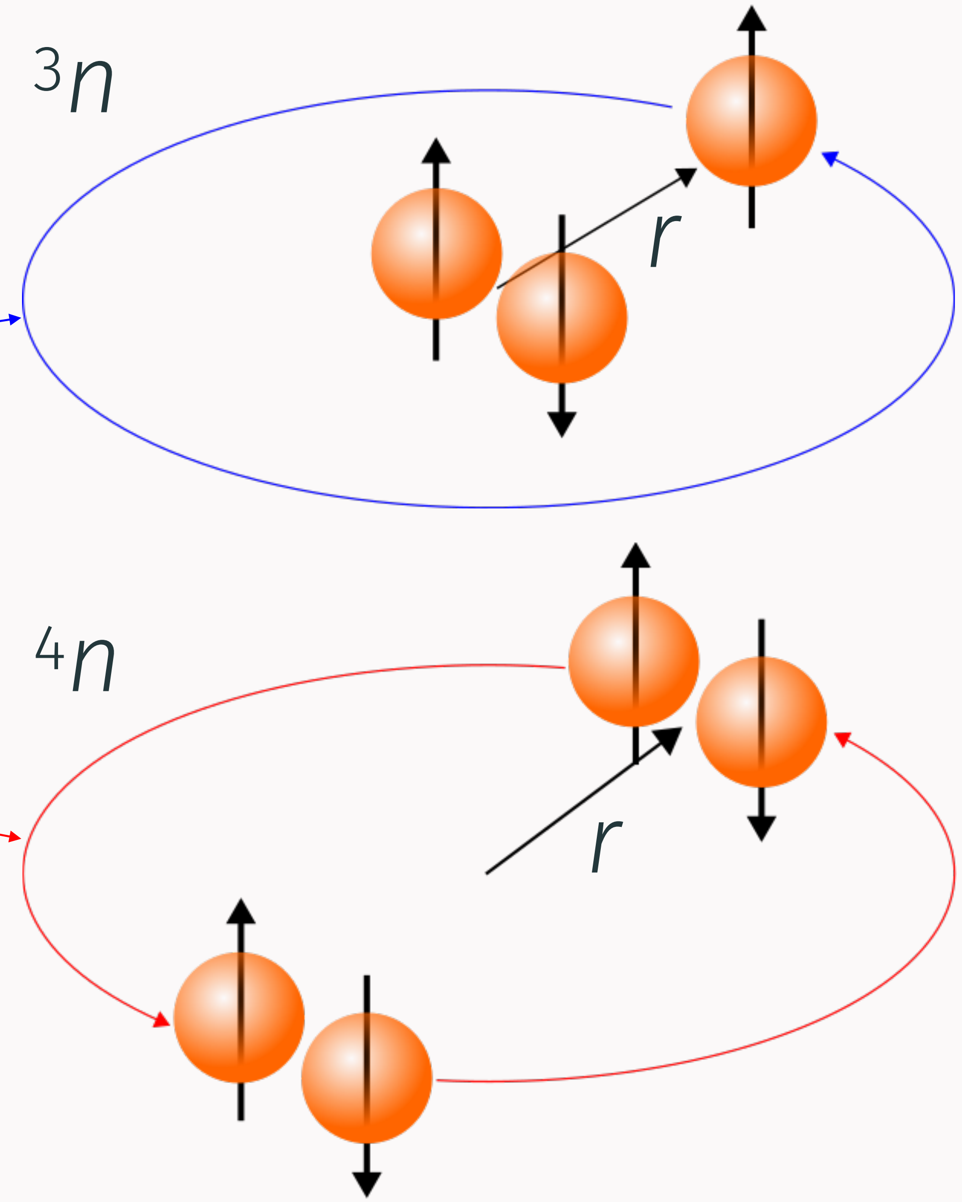
- The ${}^3n$ and ${}^4n$ systems are very dilute.
- ${}^3n$ and ${}^4n$ systems show different short-distance structure.



One-Body Densities

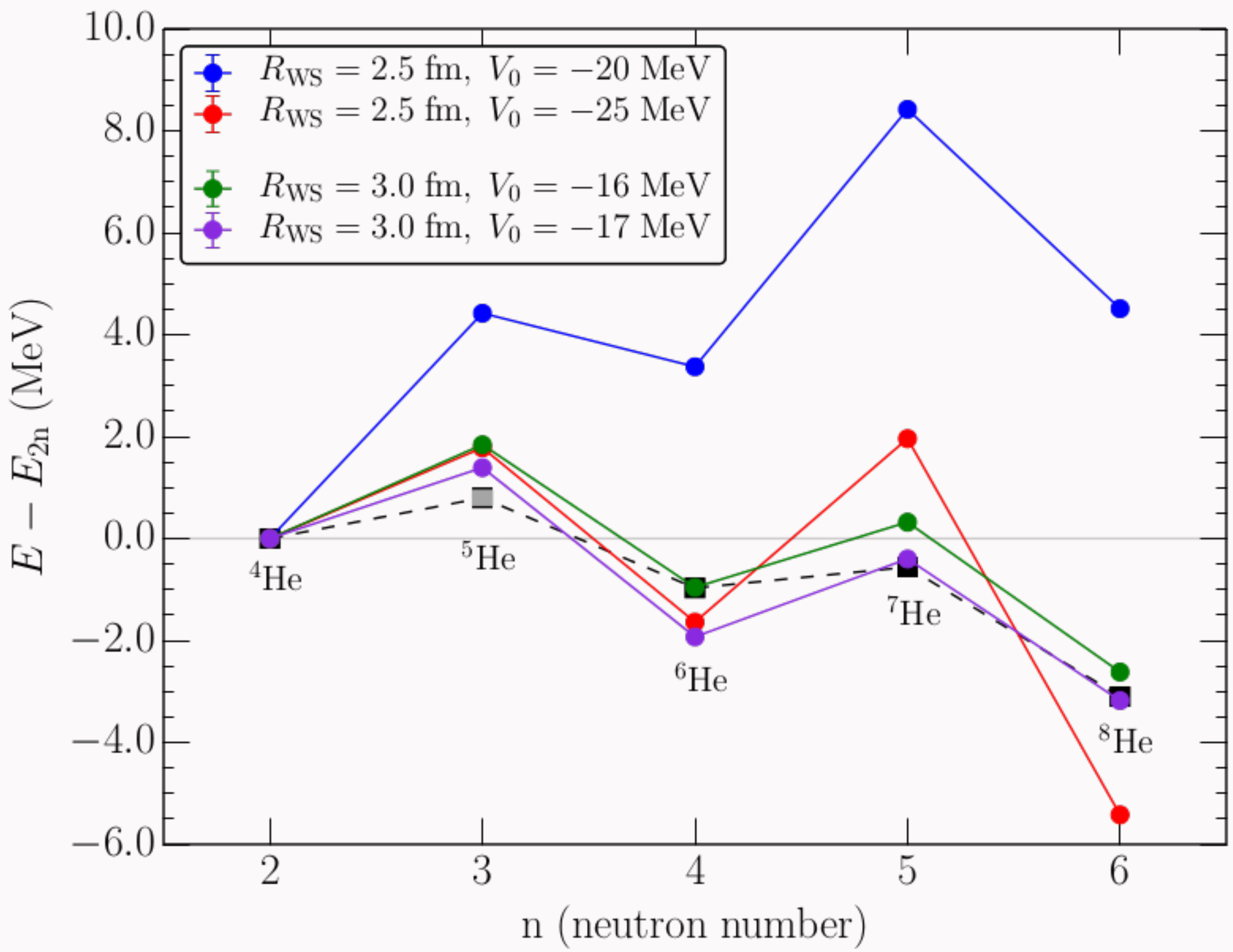
- The ^3n and ^4n systems are very dilute.
- ^3n and ^4n systems show different short-distance structure.





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.

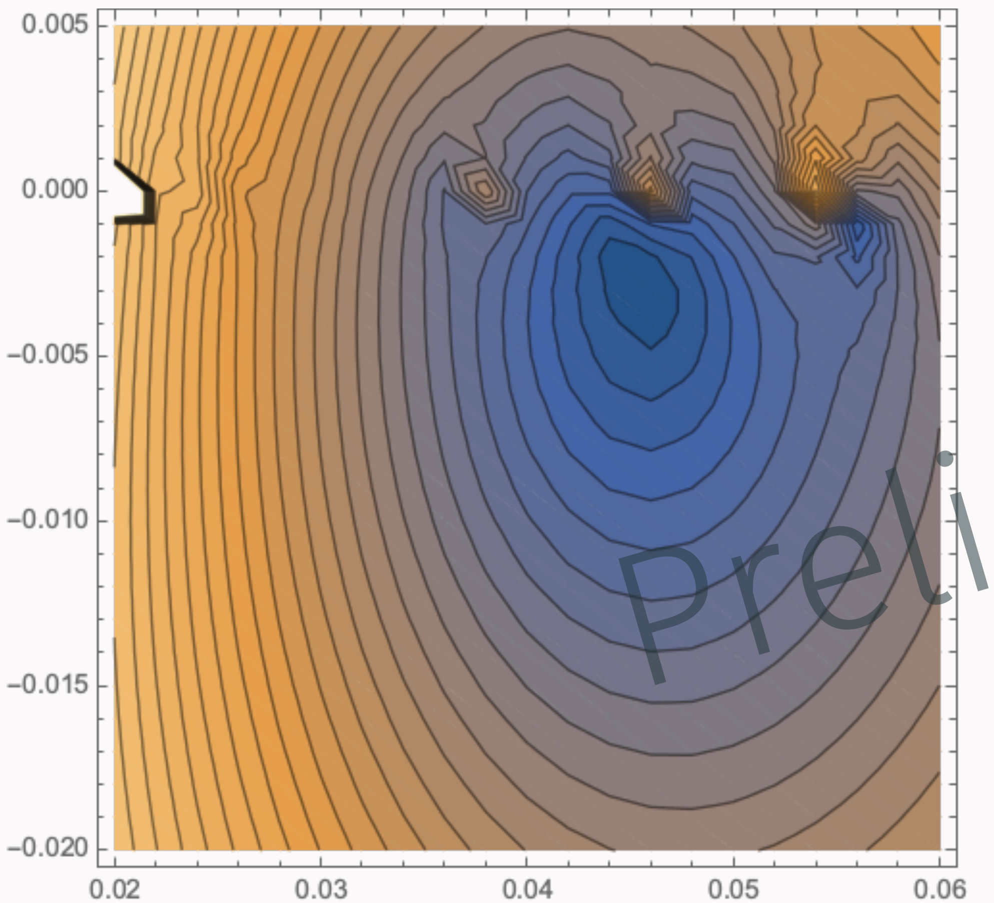


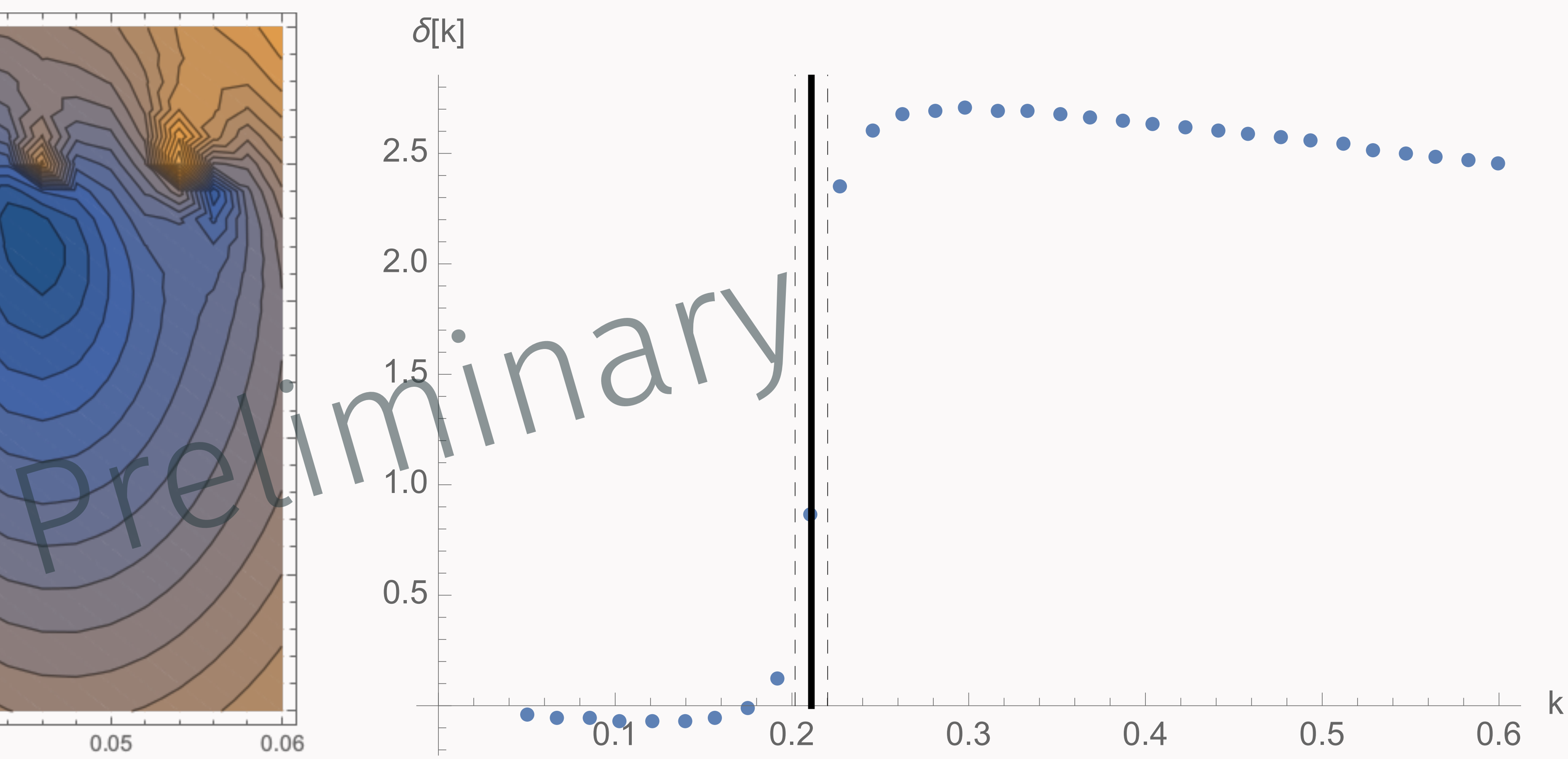
Cold Atoms Connections

- 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.

S-Matrix Poles

Future work with S. König, S. Dietz, and H.-W. Hammer: Tracing the pole in the S matrix and analytic structure of the S matrix for $3n$ from pionless EFT.





Summary

- An exciting time in nuclear physics thanks to new experiments, advances in many-body methods, and chiral EFT.
- A recent experiment suggests the possibility of a low-lying tetraneutron resonance. (More experiments are needed: Just waiting on analysis now!)
- Chiral two- and three-nucleon interactions at N^2LO support a tetraneutron resonance at 2.1(2) MeV compatible with the experimental claim.
- A trineutron resonance might be lower in energy than a tetraneutron resonance and therefore might be observable as well.

Acknowledgments

Collaborators

- S. Gandolfi, J. Carlson

Los Alamos NATIONAL LABORATORY EST. 1943

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Thank you for your attention!