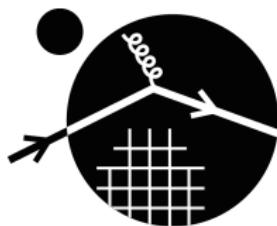


Pionless EFT for medium-mass nuclei

The case of ^{16}O

Alessandro Roggero

with: L. Contessi & F. Pederiva (UNITN), A. Lovato (ANL/INFN), J. Kirschner (CCNY), U. Van Kolck (UA/IPNO)



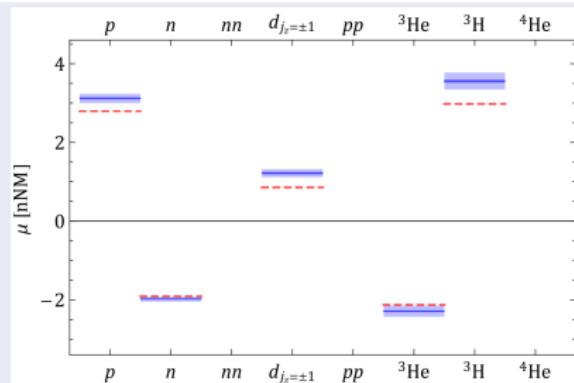
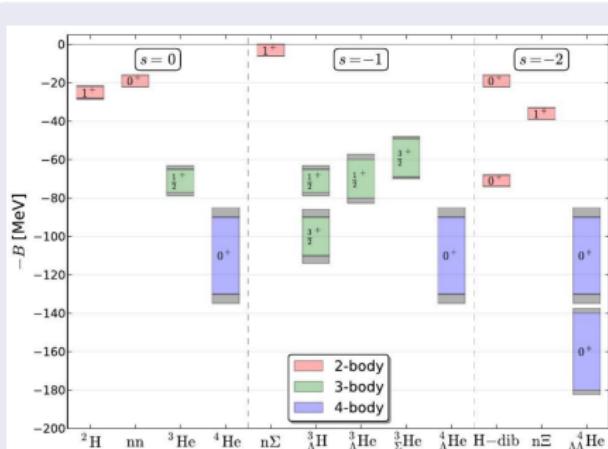
New Ideas in Constraining Nuclear Forces
ECT* - Trento - 08 June, 2018

Outline

- Motivations
- Many-body method
- Results for ^{16}O
- Why NLO (probably) won't be enough
- Conclusions

Motivations

- tremendous progress in LQCD for light nuclei at large m_π



NPLQCD (2013),(2015)

- exponential increase in difficulty as we increase baryon number A

Need a reliable way to extend LQCD predictions to larger systems
potential model: extract potential directly from the lattice [HALQCD]
EFT matching: use observables at small A to fix coupling of a proper EFT

The plan for EFT matching

- Use a theory with only nucleons and contact interactions (EFT(\not{p}))

Why we expect it's going to work:

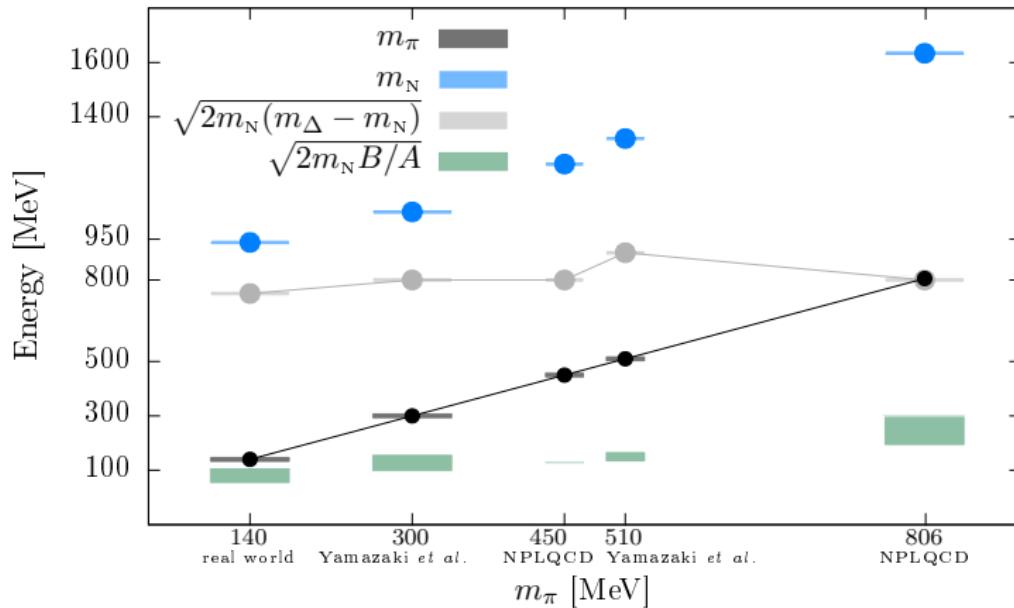


figure from: J. Kirscher, Int. J. Mod. Phys. E, 25, 1641001 (2016)

Pionless EFT

EFT(π)

[Chen,Rupak,Savage(1999), Bedaque&vanKolck (2002), Epelbaum,Hammer,Meißner(2009)]

- describe NN scattering for $q < m_\pi$ with contact interactions
- works better than expected for $A = 4$ [Platter,Hammer,Meißner(2005)]
- LO is renormalizable (at least) up to $A = 6$ [Stetcu,Barret,vanKolck(2007)]

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Applications of EFT(π) to lattice nuclei

- binding energies with A up to 6

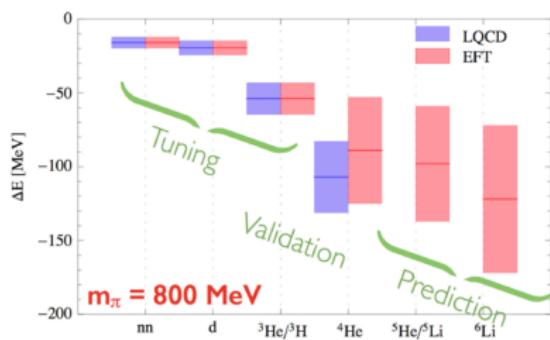
Barnea,Contessi,Gazit,Pederiva,vanKolck(2015)

- n-d scattering

Kirschner,Barnea,Gazit,Pederiva,vanKolck(2015)

- mag. moments & polarizabilities

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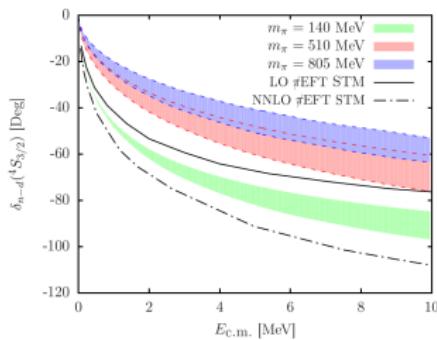
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large m_π by NPLQCD, Chang et al. (2015)

	$m_\pi = 137 \text{ MeV}$			$m_\pi = 806 \text{ MeV}$		
	deuteron	triton	helion	deuteron	triton	helion
shell model	0.879	2.793	-1.913	1.138	3.119	-1.981
LO	0.879	2.746	-1.862	1.138	3.118	-1.979
NLO	0.857	2.979	-2.130	1.220	3.405	-2.170
EXP/LQCD	0.857	2.979	-2.127	1.220(95)	3.56(19)	-2.29(12)

- polarizabilities not so good but strong regulator dependence

EFT(\not{p}) Hamiltonian at LO

$$\hat{H}_{LO} = - \sum_i^A \frac{\hbar^2}{2M} \nabla_i^2 + \sum_{i < j} [C_0^S + C_0^T \vec{\sigma}_i \cdot \vec{\sigma}_j] f_\Lambda(r_{ij}) \\ + D \sum_{i < j < k} \sum_{cyc} f_\Lambda(r_{ij}) f_\Lambda(r_{ik})$$

- $f_\Lambda(r) = \exp(-r^2 \Lambda^2 / 4)$ for $\Lambda = 2, 4, 6, 8 \text{ fm}^{-1}$

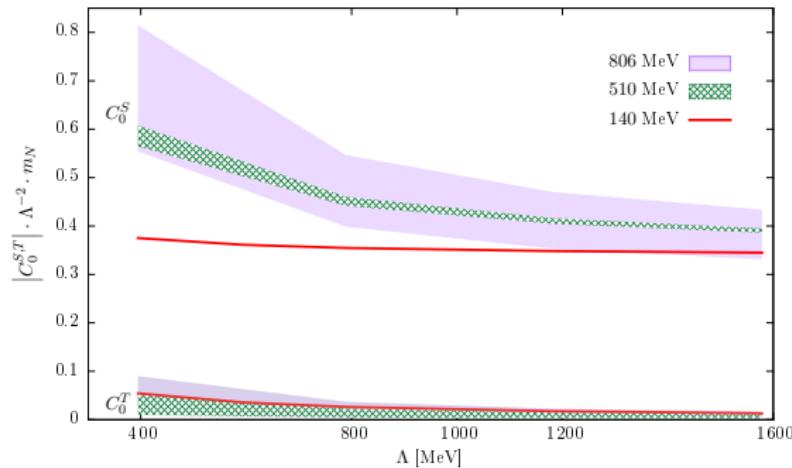


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Many Body calculation

Problem: to ensure renormalizability we need $\Lambda = 2, 4, 6, 8 \text{ fm}^{-1}$

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Auxiliary Field Diffusion Monte Carlo

[K.E.Schmidt & S.Fantoni (1999), J.Carlson et. al. (2015)]

Use projection operator on initial $|\Phi_T\rangle$ to get close to ground-state $|G\rangle$

$$e^{-\tau \hat{H}} |\Phi_T\rangle = |\Psi(\tau)\rangle \xrightarrow{\tau \rightarrow \infty} |G\rangle$$

- correlations explicitly built into “source” state $|\Phi_T\rangle$

pro: can deal efficiently with large Λ and moderate A

con: fundamentally limited by sign problem

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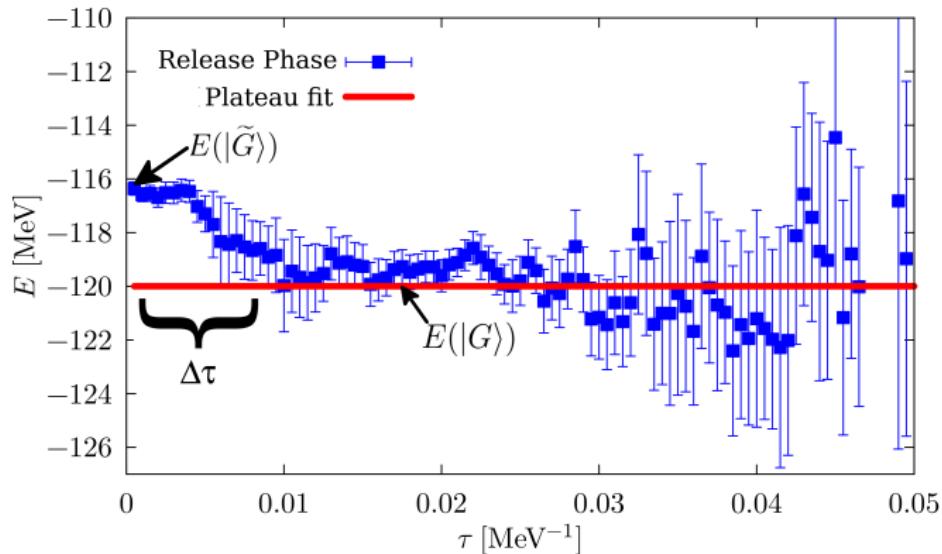
con: fundamentally limited by sign problem \rightarrow fixed-phase

$$\widetilde{e^{-\tau \hat{H}}} |\Phi_T\rangle = |\tilde{\Psi}(\tau)\rangle \xrightarrow{\tau \rightarrow \infty} |\tilde{G}\rangle \approx |G\rangle$$

[Ortiz, Ceperley and Martin (1993)]

Going the last mile: release phase

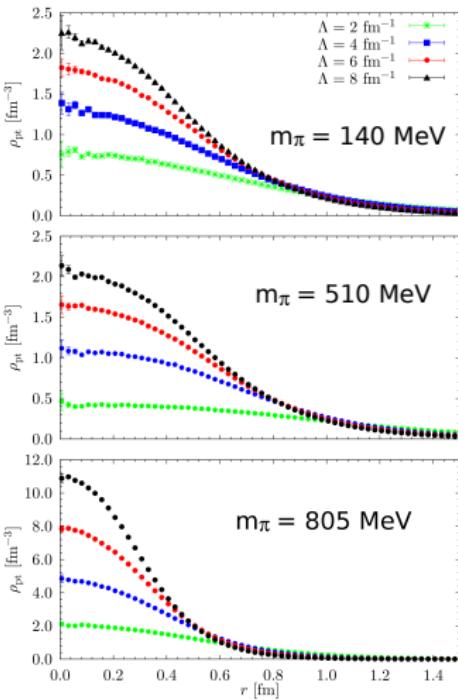
Release Phase: $e^{-\delta \hat{H}} |\tilde{G}\rangle = |\Psi_{RP}(\delta)\rangle \rightarrow |G\rangle + e^{-\delta(E_A - E_G)} |A\rangle + \dots$



KEY: time scale $\Delta\tau$ controlled by the quality of $|\Phi_T\rangle$

Benchmark for ^4He

L.Contessi,A.Lovato,F.Pederiva,A.R.,J.Kirschner,U.vanKolck (2017)

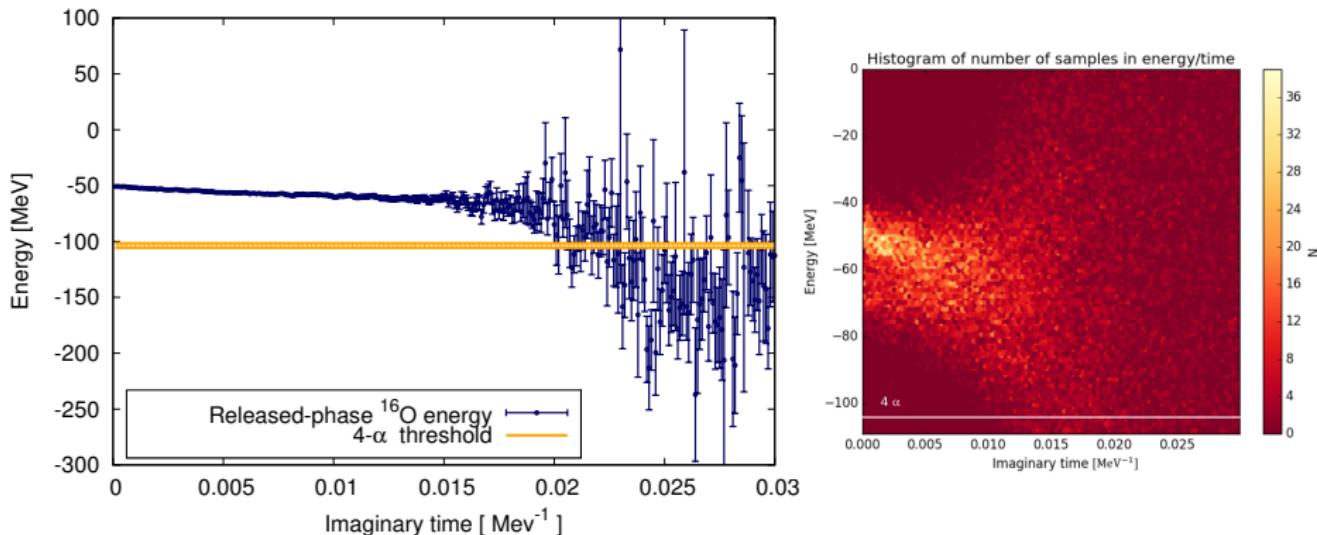


Λ	$m_\pi = 140$ MeV	$m_\pi = 510$ MeV	$m_\pi = 805$ MeV
2 fm ⁻¹	-23.17 ± 0.02	-31.15 ± 0.02	-88.09 ± 0.01
4 fm ⁻¹	-23.63 ± 0.03	-34.88 ± 0.03	-91.40 ± 0.03
6 fm ⁻¹	-25.06 ± 0.02	-36.89 ± 0.02	-96.97 ± 0.01
8 fm ⁻¹	-26.04 ± 0.05	-37.65 ± 0.03	-101.72 ± 0.03
$\rightarrow \infty$	$-30^{+0.3}_{-2} (\text{sys})$ $\pm 2 (\text{stat})$	$-39^{+1}_{-2} (\text{sys})$ $\pm 2 (\text{stat})$	$-124^{+3}_{-1} (\text{sys})$ $\pm 1 (\text{stat})$
Exp. LQCD	-28.30	—	—
	—	-43.0 ± 14.4	-107.0 ± 24.2

- consistent with prev studies: no 4N needed!
- at physical m_π close to experiment
- at larger m_π match LQCD predictions for any cutoff Λ ! Plateau identification seems consistent [vs. Iritani et al. (2016)]

Puzzles with ^{16}O

Release-Phase run at $m_\pi = 140$ MeV, $\Lambda = 8 \text{ fm}^{-1}$ [similar in ALL cases]

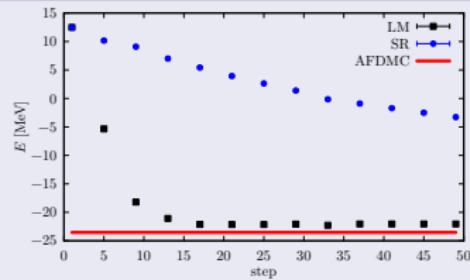


- seems to suggest ^{16}O is unstable for breakup BUT:
 - noise too strong to estimate $E(|G\rangle)$ reliably
 - poor constrained projection $E(\tilde{|G\rangle}) \approx -50\text{MeV} \Rightarrow$ improve $|\Phi_T\rangle$

New results for ^{16}O with better optimizer

Wave-Function optimizer for AFDMC: find minimum of $\langle \Phi_T | \hat{H} | \Phi_T \rangle$

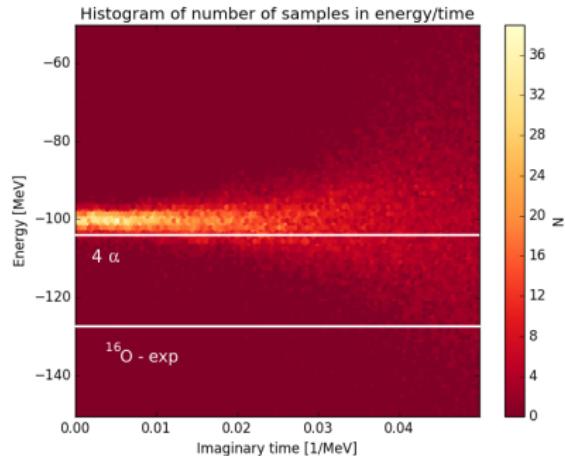
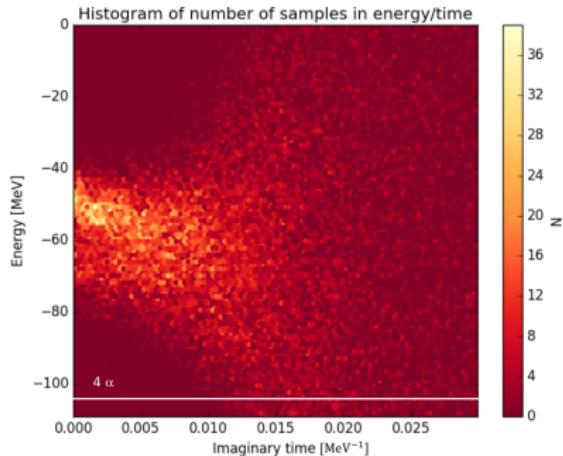
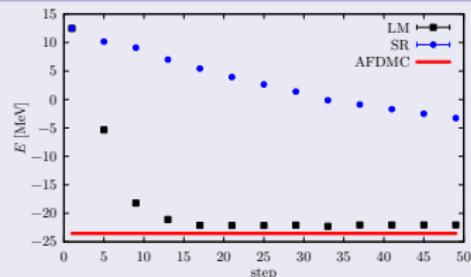
- based on Linear Method from quantum chemistry [Toulouse&Umrigar(2007)]
- flexible cubic spline representation
- reasonably robust with very noisy data



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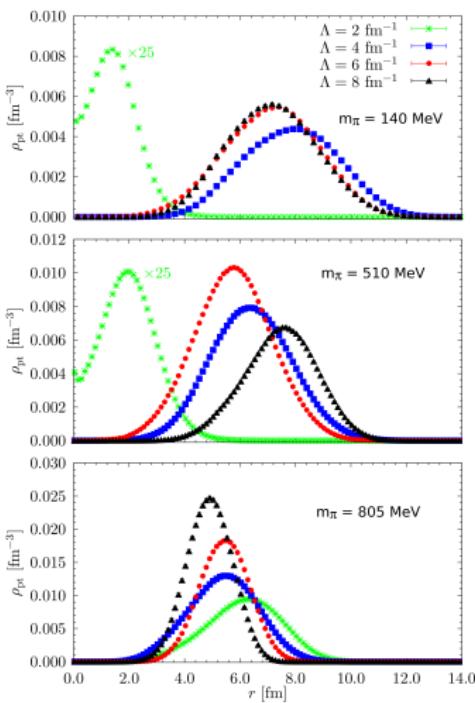
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Clusterized state of ^{16}O

L.Contessi,A.Lovato,F.Pederiva,A.R.,J.Kirschner,U.vanKolck (2017)

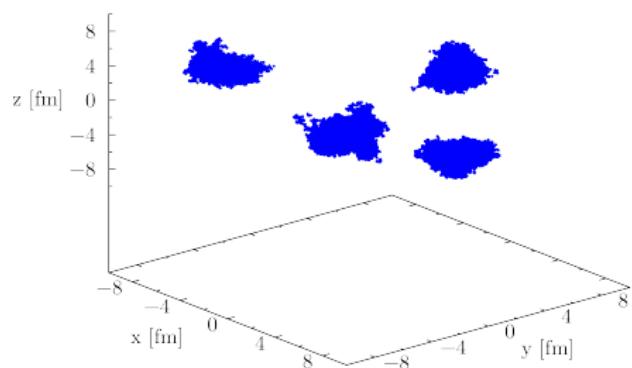
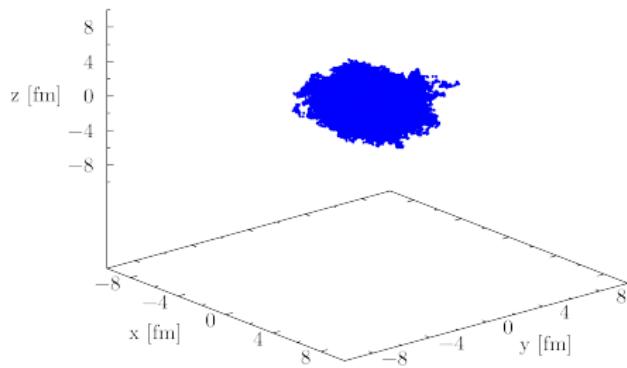


Λ	$m_\pi = 140 \text{ MeV}$	$m_\pi = 510 \text{ MeV}$	$m_\pi = 805 \text{ MeV}$
2 fm^{-1}	-97.19 ± 0.06	-116.59 ± 0.08	-350.69 ± 0.05
4 fm^{-1}	-92.23 ± 0.14	-137.15 ± 0.15	-362.92 ± 0.07
6 fm^{-1}	-97.51 ± 0.14	-143.84 ± 0.17	-382.17 ± 0.25
8 fm^{-1}	-100.97 ± 0.20	-146.37 ± 0.27	-402.24 ± 0.39
$\rightarrow \infty$	$-115_{\pm 1}^{\pm 1} (\text{sys})$ $\pm 8 (\text{stat})$	$-151_{\pm 10}^{\pm 2} (\text{sys})$ $\pm 10 (\text{stat})$	$-504_{\pm 12}^{\pm 20} (\text{sys})$ $\pm 12 (\text{stat})$
Exp.	-127.62	—	—
4α thresh.	-120 ± 8	-156 ± 12	-496 ± 16

- extrapolated energies compatible with 4α
→ agrees with NN only calculation with HAL-QCD [McIlroy et al. arXiv:1701.02607]
see Carlo's talk
- at large Λ the nucleon density doesn't look like a spherical nucleus at all! Are we actually producing separate clusters?

Clusterized state of ^{16}O

Trajectories for $m_\pi = 140$ MeV and $\Lambda = 2$ (left), 8 (right) fm $^{-1}$:



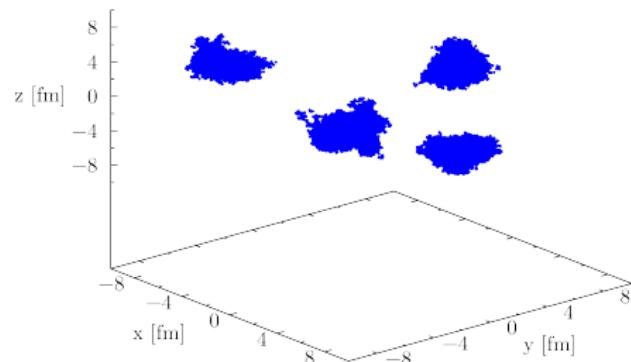
- finite range interaction seems critical for stability of oxygen

Why NLO corrections will (probably) not be enough

- ground-state of LO hamiltonian

$$|^{16}O_{LO}\rangle \sim |^4He_{LO}\rangle \otimes |^4He_{LO}\rangle \\ \otimes |^4He_{LO}\rangle \otimes |^4He_{LO}\rangle$$

- effective interaction among clusters is mildly repulsive
(see also Dean's talk)
- 4 clusters are not going to infinity only due to numerical artifacts



at NLO: $\Delta E_{^{16}O} = \langle ^{16}O_{LO} | V_{NLO} | ^{16}O_{LO} \rangle \equiv 4\Delta E_{^4He}$

→ the 4α threshold moves together with the ^{16}O energy

Conclusions and future directions

What have we seen?

- confirm that α -particle described reasonably well at LO
 - indirect evidence of correct identification of plateau in LQCD
- LO EFT(π) well behaved up to $A = 16$ [no need for A-body contact]
- unbound ^{16}O at LO for all values of m_π [maybe just barely at physical]

Future directions

- can NLO or NNLO calculations save ^{16}O ?
- how about the stability of ^8Be , ^{12}C and ^{40}Ca ?
 - non-perturbative NLO binds both ^{16}O and ^{40}Ca [Bansal et al (2018)]
- proper error propagation including errors in LEC (so far only cut-off and AFDMC), maybe with better LQCD data?

Wave-function optimization with Linear Method

- Slater-Jastrow wave function

$$\Phi_T(X) \equiv \langle X | \Phi_T \rangle = \langle X | \left(\prod_{i < j < k} U_{ijk} \right) \left(\prod_{i < j} F_{ij} \right) | D \rangle$$

- set of M parameters $\vec{\alpha}$ to be optimized using: $E(\vec{\alpha}) = \frac{\langle \Phi_T | \hat{H} | \Phi_T \rangle}{\langle \Phi_T | \Phi_T \rangle}$

Linear Method

J. Tolouse & C. Umrigar, J. Chem. Phys. 126(8), 084102 (2007)

- at each step expand: $\frac{|\Phi(\vec{\alpha})\rangle}{\sqrt{\langle \Phi(\vec{\alpha}) | \Phi(\vec{\alpha}) \rangle}} = |\Phi(\vec{\alpha}_k)\rangle + \sum_i^M \delta_i |\Phi_i(\vec{\alpha}_k)\rangle + \dots$
- find optimal update solving for

$$\nabla_{\vec{\delta}} E^{lin}(\vec{\alpha}_k, \delta) = \nabla_{\vec{\delta}} \frac{\langle \Phi^{lin}(\vec{\alpha}_k, \delta) | \hat{H} | \Phi^{lin}(\vec{\alpha}_k, \delta) \rangle}{\langle \Phi^{lin}(\vec{\alpha}_k, \delta) | \Phi^{lin}(\vec{\alpha}_k, \delta) \rangle} = 0$$