Status of Project B.9
Lattice Nuclear Physics

Hermann Krebs, ***Thomas Luu***, Ulf-G. Meißner
Collaborative research center CRC 110
"*Symmetries and the emergence of structure in QCD*"

Personnel

Principle Investigators:

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Lukas Boverman (RUB)
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***Postdocs*:**

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***Collaborators*:**

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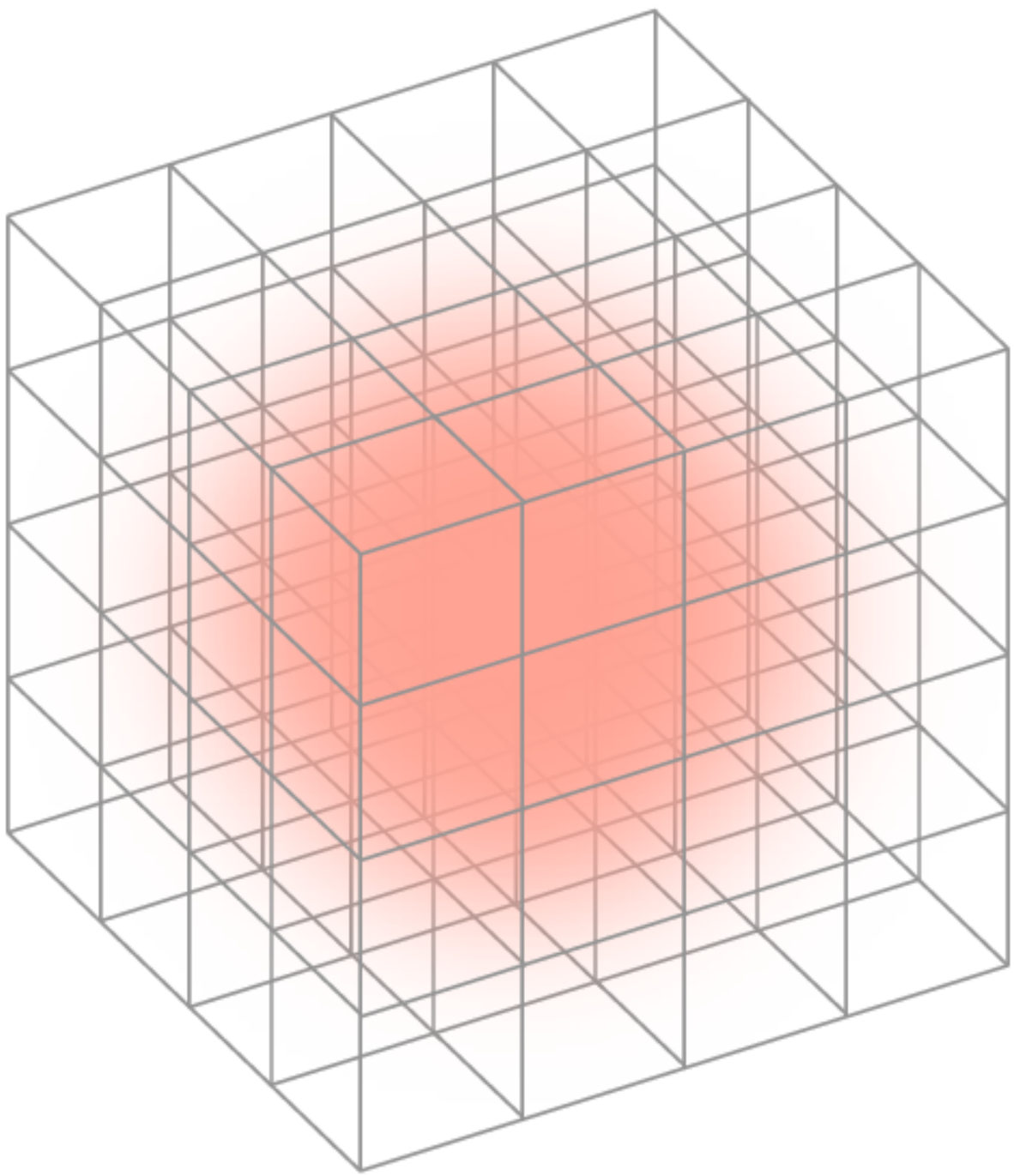
Andrea Shindler (FRIB/MSU), Evgeny Epelbaum (RUB)

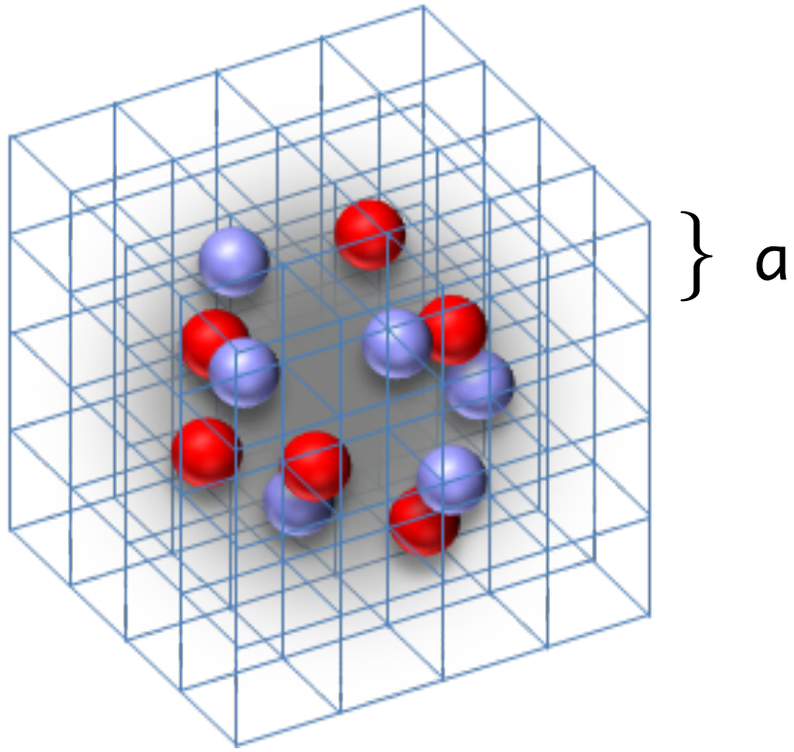
Overview of B.9



- **Discretized space and time**
- **Interactions depend on degrees of freedom (DoF)**
  - **Nucleon DoF—chiral EFT**
  - **Quarks & gluons—QCD**
- **Large HPC aspect**
  - **Algorithms**
- **Investigate nuclear structure**
  - **Binding energies**
  - **Matrix elements**
  - **NN, NY, NNN**
- **Overlap with A2/B4/B5**

highlight [arXiv:1702.05319] Eur.Phys.J. **A53** (2017) 83

Reducing the lattice spacing in NLEFT



$$H = T + V[C_i(a)]$$

coefficients tuned to low-energy observables (e.g. phase shifts)

lattice spacing

Partial wave channels and low-energy coefficients

order	fit channels	fit parameters
LO	${}^1S_0$, ${}^3S_1$	$C_{{}^1S_0}$, $C_{{}^3S_1}$, b_s
NLO	${}^1S_0$	$C_{{}^1S_0}$, $\widetilde{C}_1$
	${}^3S_1$, ϵ_1	$C_{{}^3S_1}$, $\widetilde{C}_2$, $\widetilde{C}_3$
	${}^1P_1$	$\widetilde{C}_4$
	${}^3P_0$, ${}^3P_1$, ${}^3P_2$	$\widetilde{C}_5$, $\widetilde{C}_6$, $\widetilde{C}_7$
NNLO	${}^1S_0$	$C_{{}^1S_0}$, $\widetilde{C}_1$
	${}^3S_1$, ϵ_1	$C_{{}^3S_1}$, $\widetilde{C}_2$, $\widetilde{C}_3$
	${}^1P_1$	$\widetilde{C}_4$
	${}^3P_0$, ${}^3P_1$, ${}^3P_2$	$\widetilde{C}_5$, $\widetilde{C}_6$, $\widetilde{C}_7$

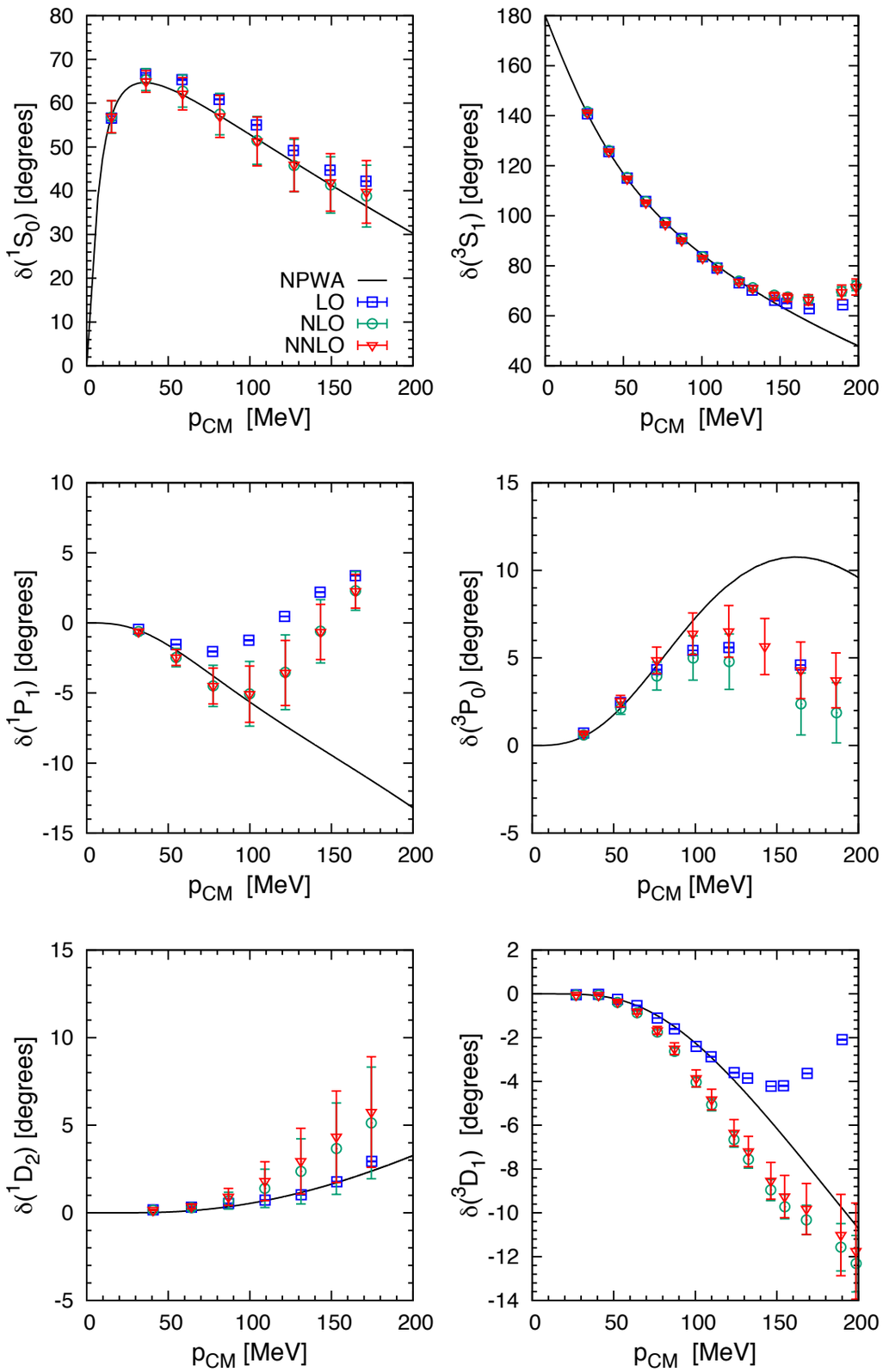
Past NLEFT calculations:

- Lattice spacing a=1.97 fm
- 2-pion exchange absorbed in contact terms (not explicit in V)

Would like to understand dependence of contact terms (and binding energies) with smaller lattice spacing

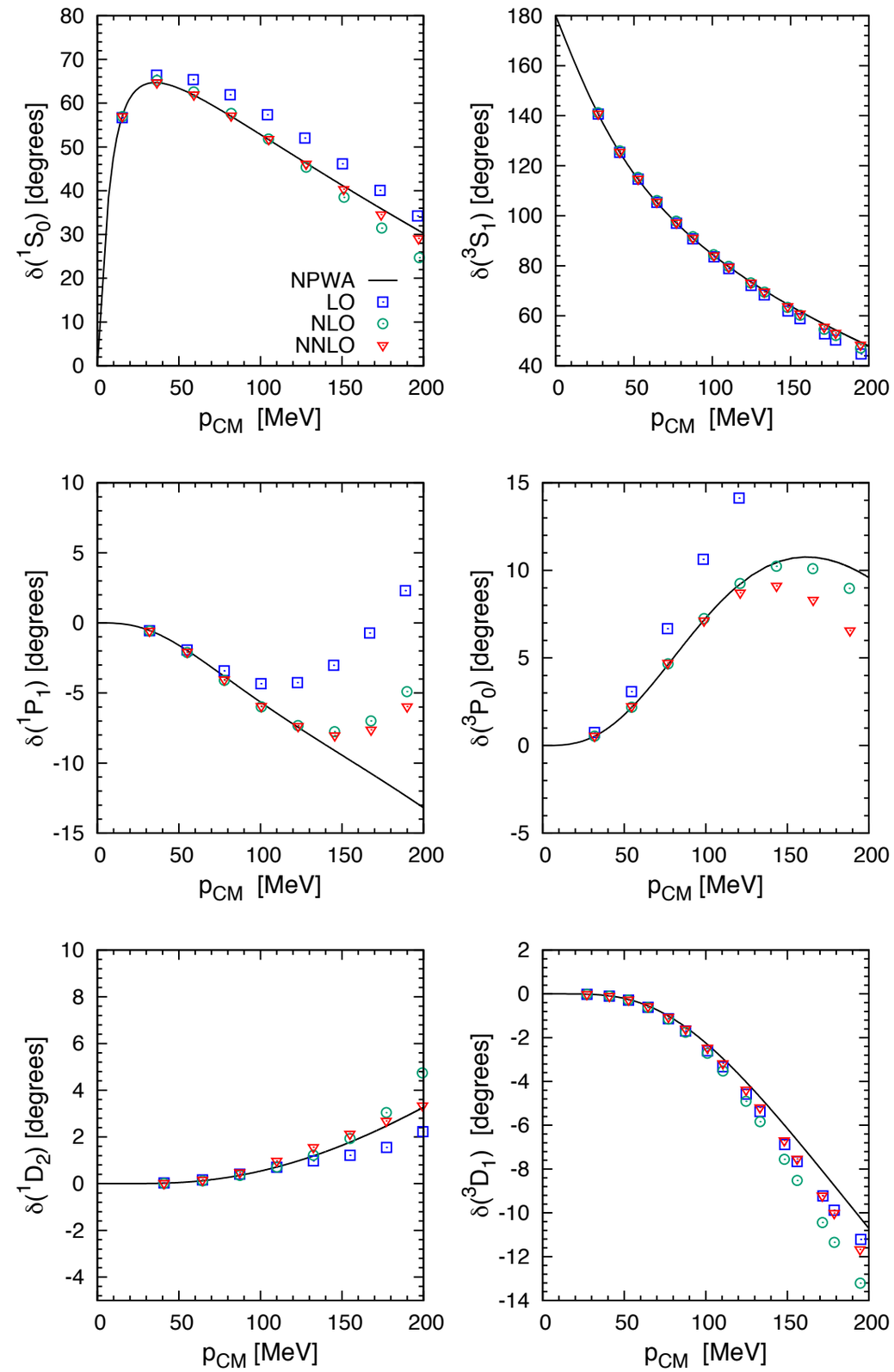
NN phase shifts

a=1.97 fm



also have for a=1.32 and 1.64 fm

a=0.98 fm



2-pion exchange now explicit, currently adapting in NLEFT

highlight [arXiv:1602.04539] Phys.Rev.Lett. **117** (2016) 132501

Controlling the alpha-alpha scattering length in simulations

LO interaction (w/o Coulomb)

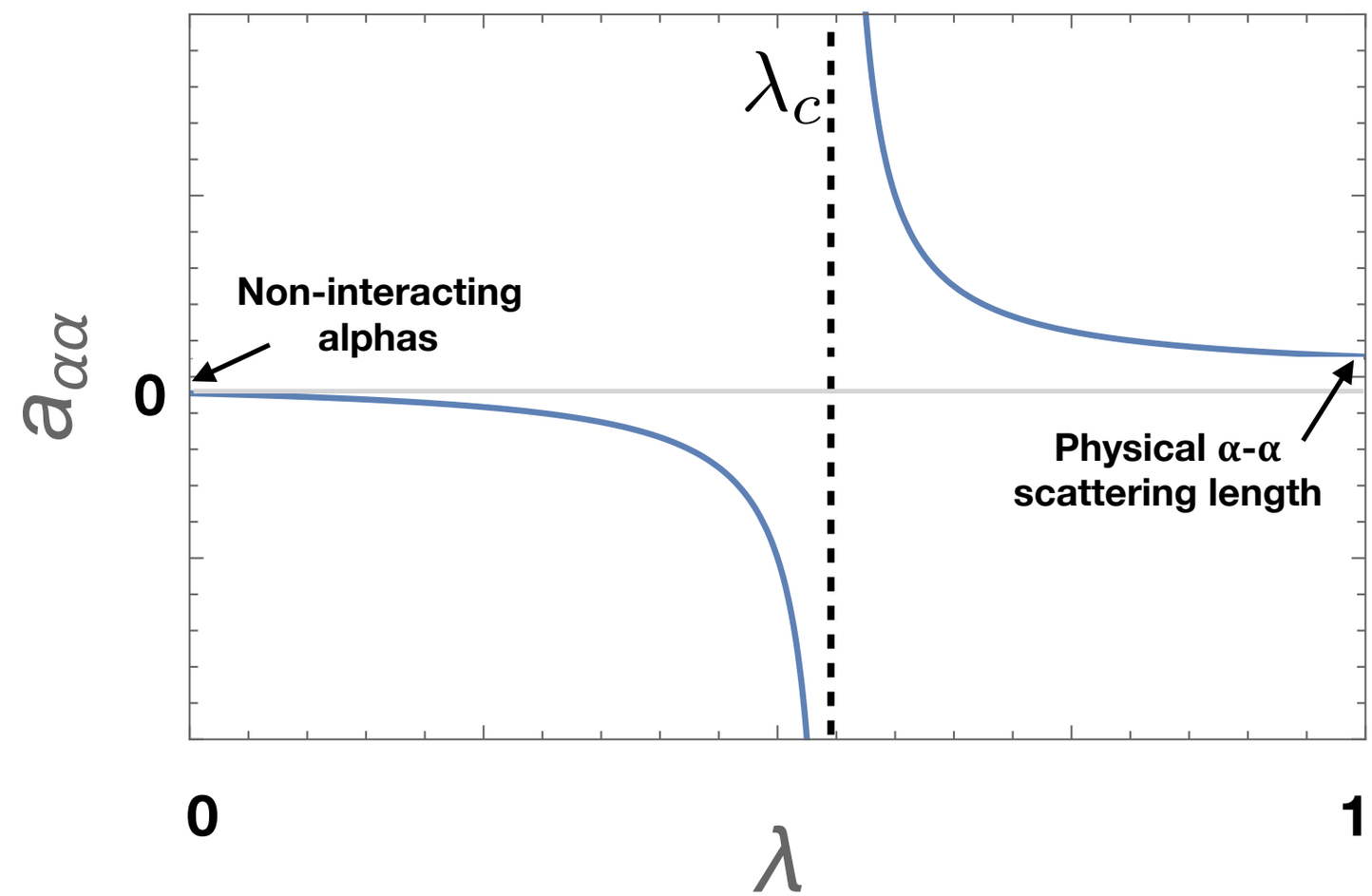
$$V_\lambda = (1-\lambda)V_A + \lambda V_B$$

V_A is purely non-local

V_B is has non-local AND local parts and reproduces s-wave alpha-alpha scattering

Both potentials reproduce low-energy NN phase shifts

Can drive alpha-alpha scattering through a "Feshbach resonance"

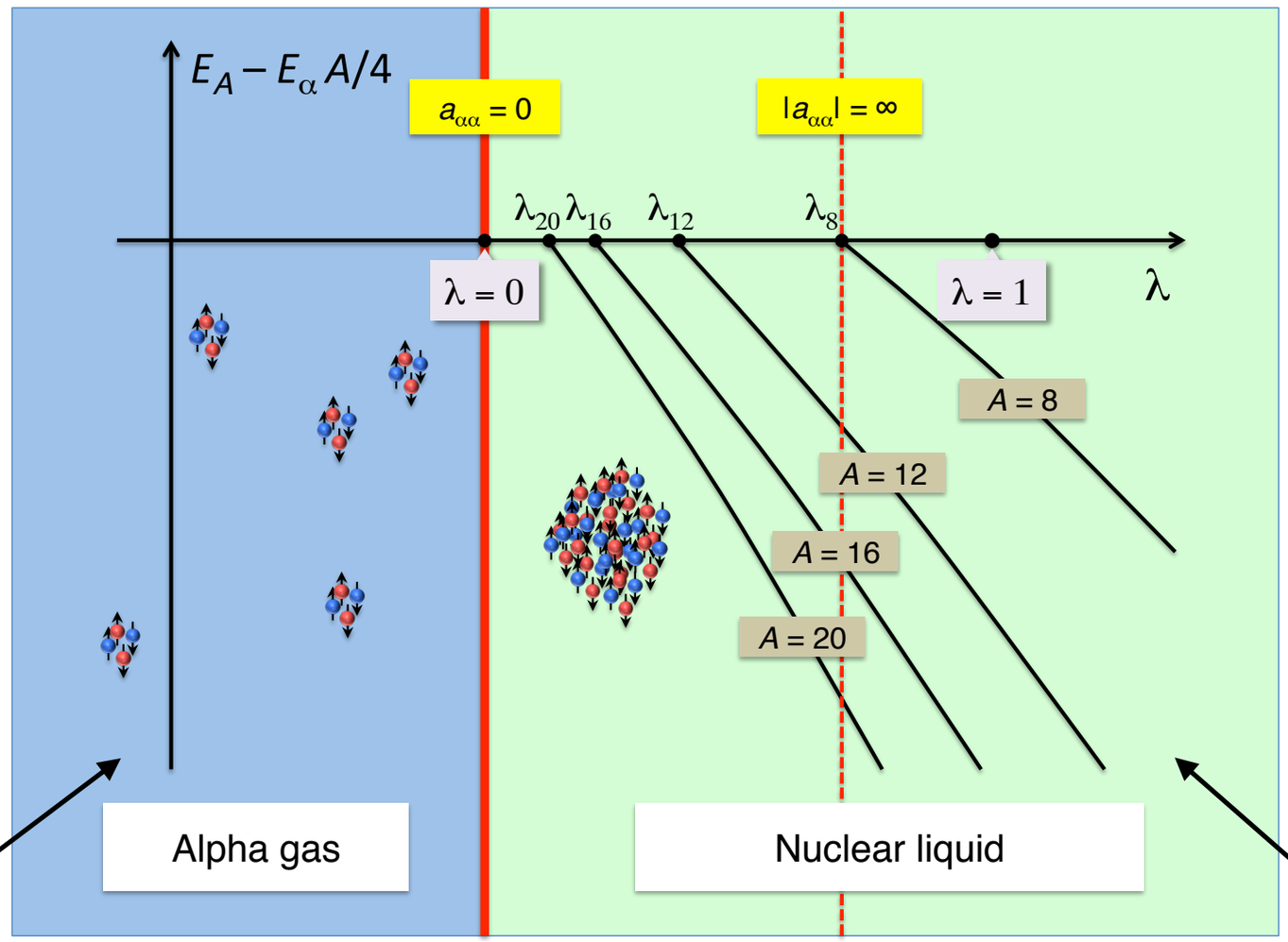


What does nuclear matter look like as one varies λ?

highlight [arXiv:1602.04539] Phys.Rev.Lett. **117** (2016) 132501

Nuclei near a Quantum Phase transition: alpha bose gas vs. nuclear liquid

Phase diagram as a function of λ



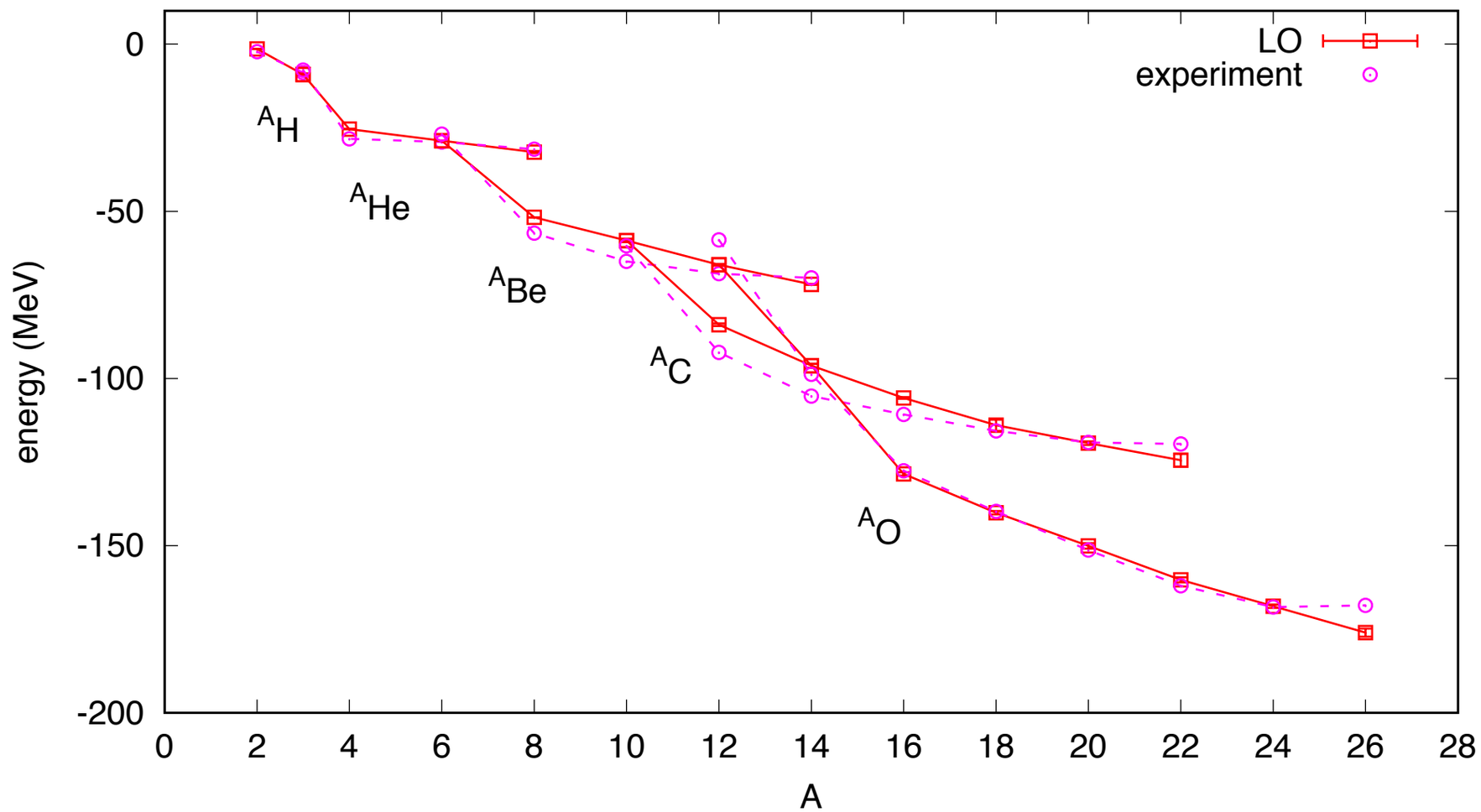
gas of attractive alpha (boson) particles

clustering of alpha particles into nuclei

Light-nucleus scattering sensitive to non-locality of NN interaction

highlight [arXiv:1702.05177]

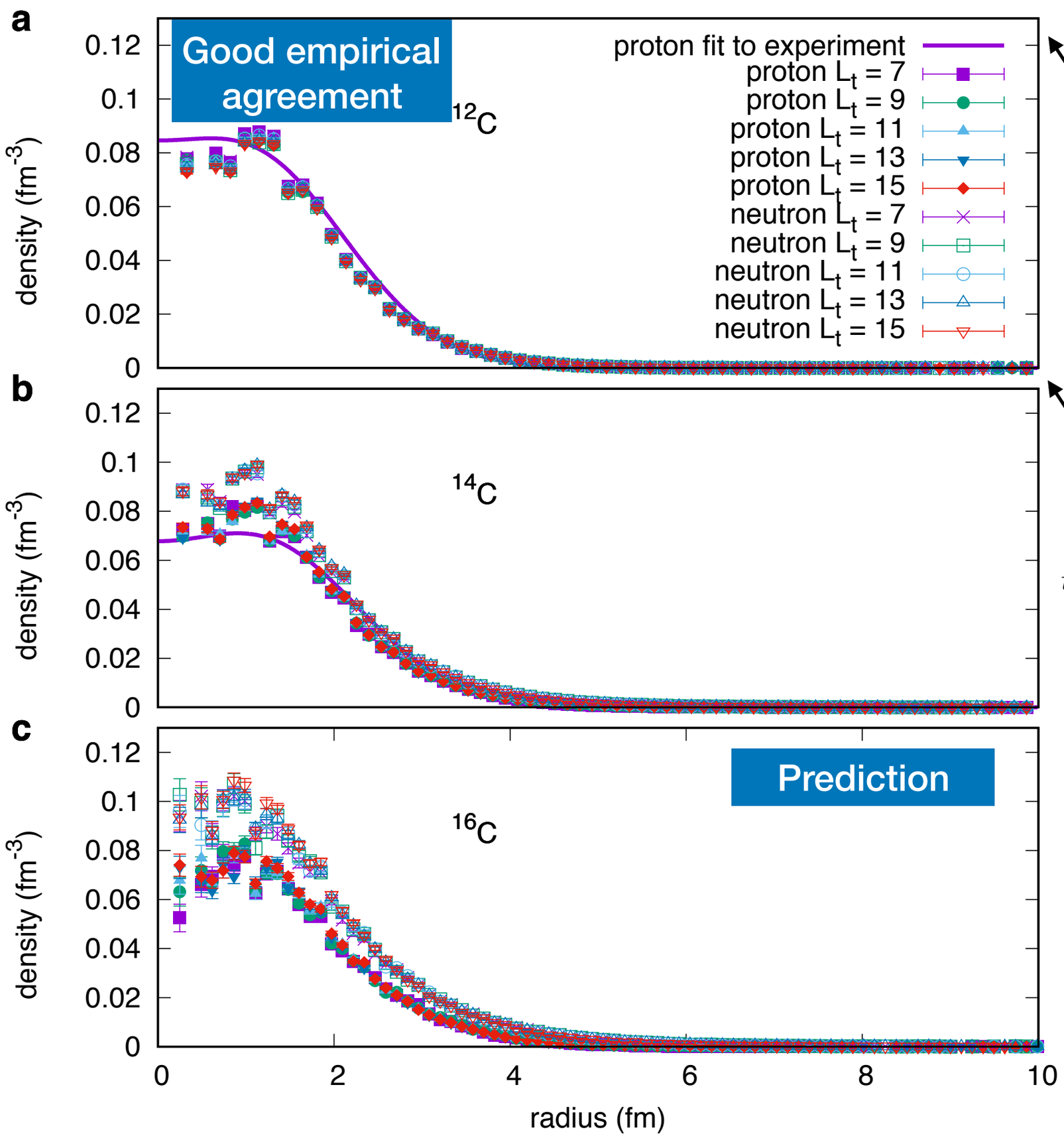
The Nature of Nuclear Clustering at Leading Order

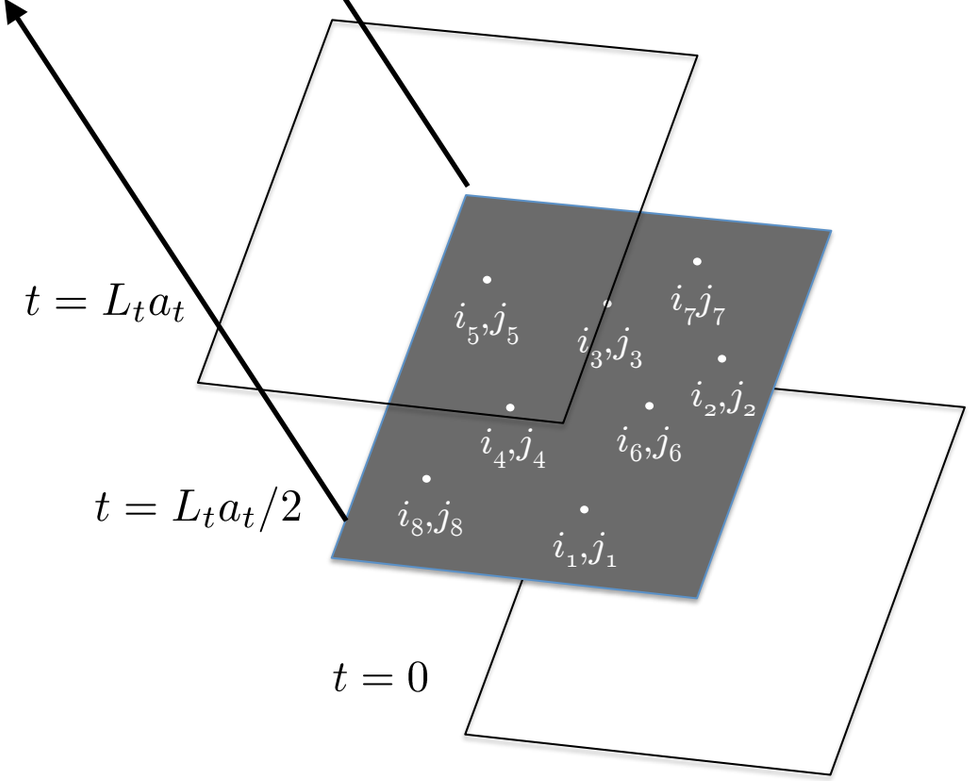


The binding energies of isotopic chains of H, He, Be, C, and O are surprisingly well described by *LO+Coulomb* (with appropriate smearing)

highlight [arXiv:1702.05177]

Development of Pinhole algorithm to measure densities relative to Center of Mass





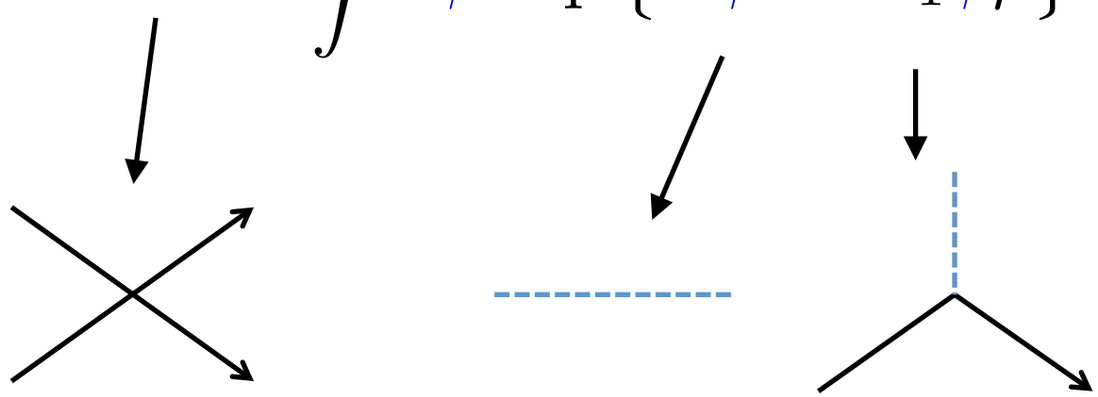
Application of Pinhole algorithm should have wide applications to hadronic, nuclear, condensed matter, and ultracold atomic simulations

highlight [arXiv:1706.06494]

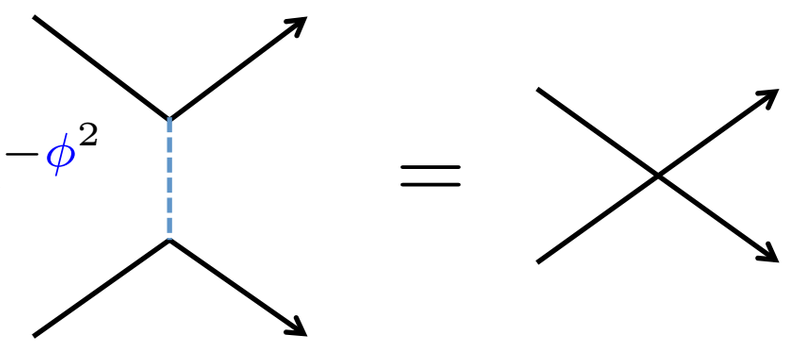
General Hubbard-Stratonovich transformation for 3-body (and higher) forces

The transformation we all know and love:

$$e^{-V_2\hat{\rho}^2} \propto \int d\phi \exp\left\{-\phi^2 - c_1\phi\hat{\rho}\right\}$$



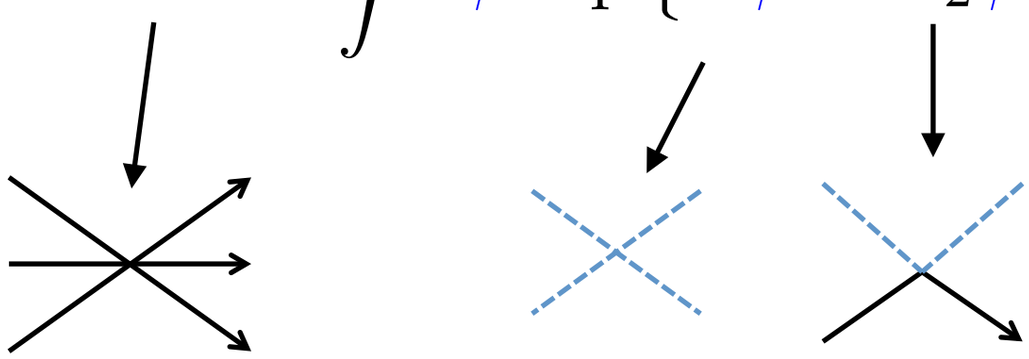
$$\int d\phi\, e^{-\phi^2}$$



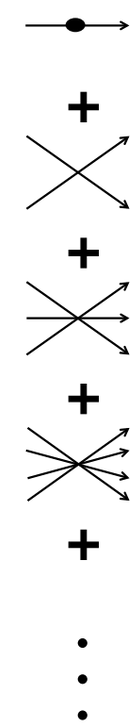
Can we do the same for 3-body interactions?

(simplest generalisation)

$$e^{-V_3\hat{\rho}^3} \overset{??}{\propto} \int d\phi \exp\left\{-\phi^4 - c_2\phi^2\hat{\rho}\right\}$$



after integrating out HS field =

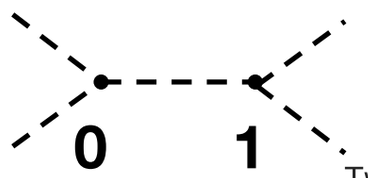


Infinite number of interactions are induced!

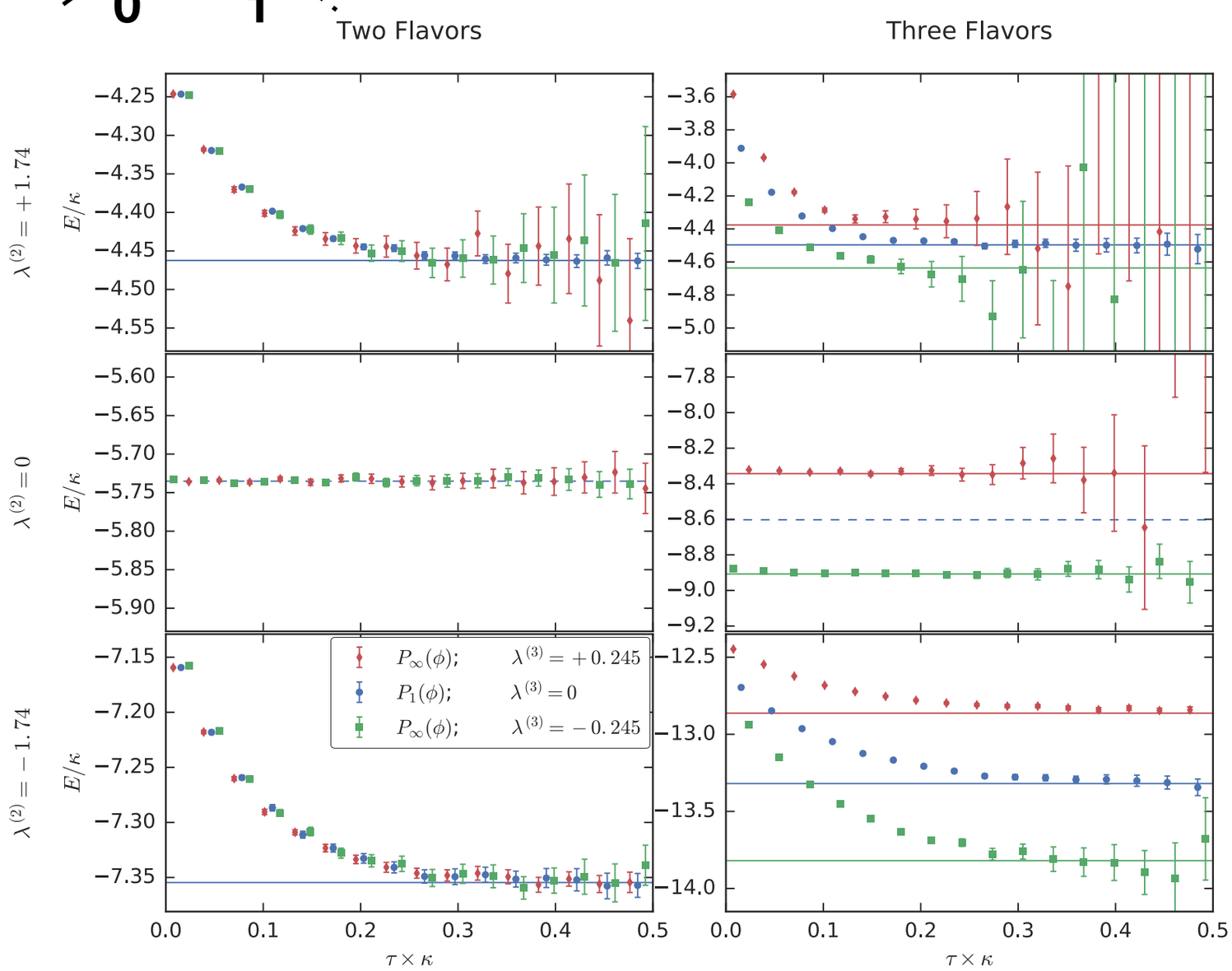
highlight [arXiv:1706.06494]

The strength of induced interactions can be systematically controlled

Two-site model



$$\hat{H} = \kappa \left(-3 \sum_{f=1}^{3} \sum_{\langle i,j \rangle} \hat{a}_{f,i} \hat{a}^{\dagger}_{f,j} + \lambda^{(2)} \sum_{i \in \{0,1\}} \hat{\rho}_i^2 + \lambda^{(3)} \sum_{i \in \{0,1\}} \hat{\rho}_i^3 \right)$$



repulsive two-body

no two-body

attractive two-body

repulsive three-body

no three-body

attractive three-body

Proof of principle

What we promised. . .

2016/2

- Development of contraction codes for multi-neutron systems
  - Chiral NN and NNN forces to higher orders on the lattice

in progress

2017

- First calculations of three-N and four-N systems with lattice QCD
  - Extension of contraction codes to select nuclei and hyperons
  - Spectrum and structure of Beryllium-10
  - Spectrum and structure of Carbon-12 at finer lattice spacings

latter half of 2017/ beginning of 2018

no longer relevant since (see next slide)

in progress

2018

- Begin calculations of select NNY, NYY, and YYY systems with lattice QCD
  - Continue development of contraction codes for light hyper-nuclear systems
  - Continue calculations of 3-N and 4-N systems with lattice QCD
  - Calculation of elastic ^{4}He-neutron/proton scattering
  - Calculation of the binding energies of the carbon isotope chain

done

Status of B.9

LQCD:

Behind on development of contraction codes due to late hires (November 2016) of Berkowitz and Wynen

Plan to run first test of NNN contraction codes later in 2017

Received 36 +18 million cpu-hour awards on JUQUEEN/JURECA

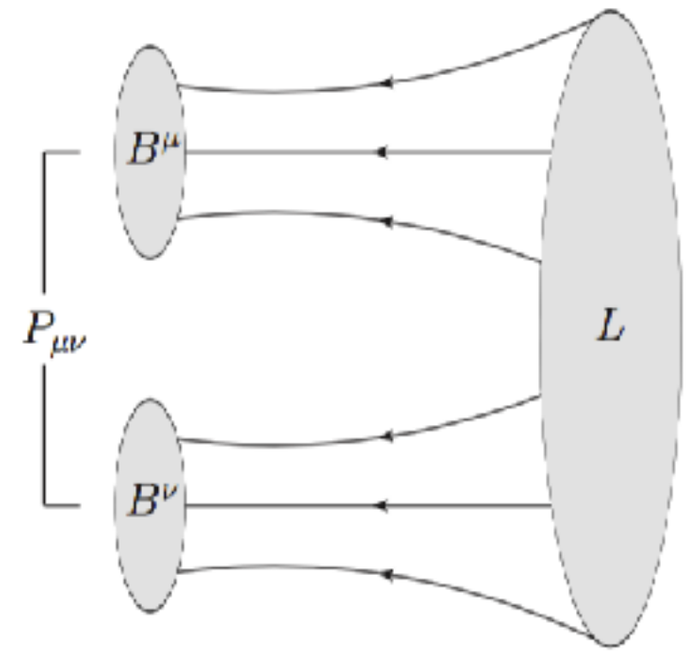


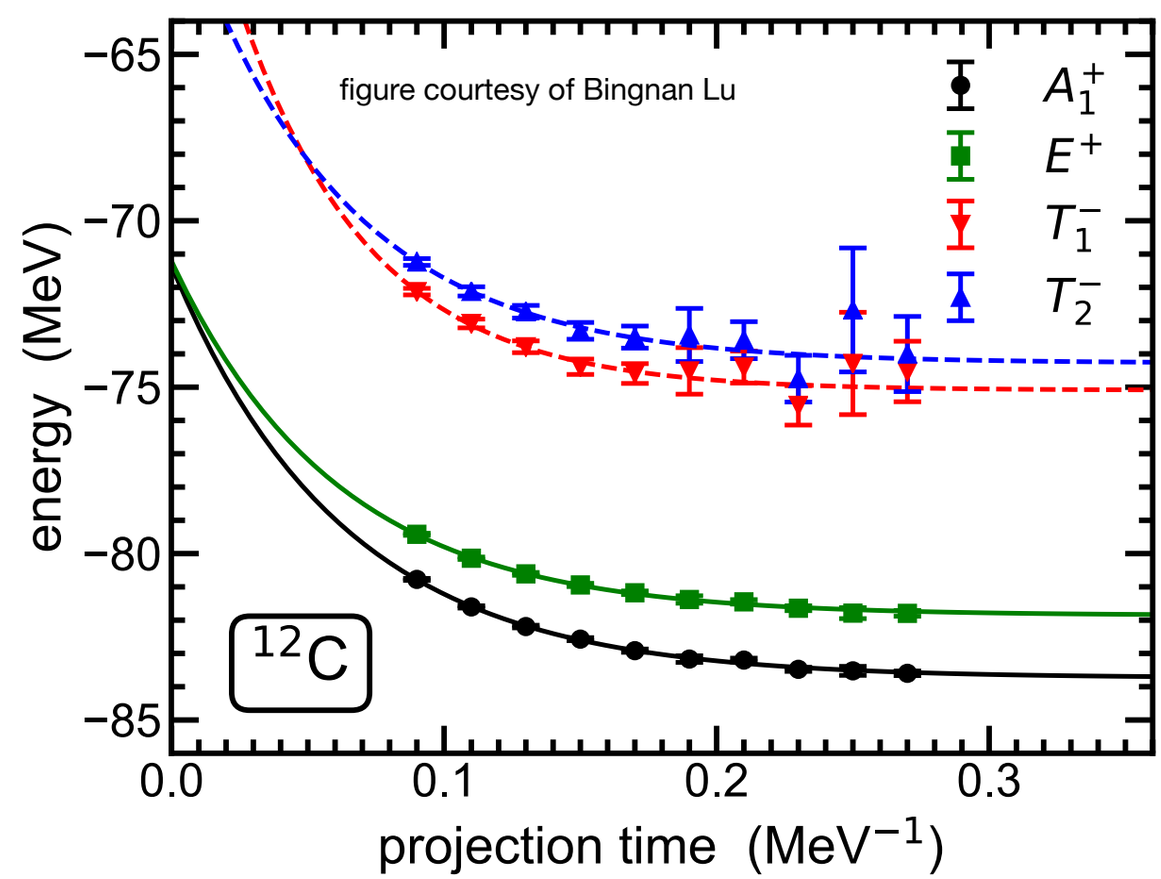
figure courtesy of Evan Berkowitz

NLEFT:

Awarded 44 million cpu hours on JUQUEEN

Instead of Beryllium calculation (2017), did calculation of the whole carbon isotope chain (2018)

Adapting NLEFT code with higher-order interactions is ongoing (ie N3LO TPE and contact terms)



Overall healthy program

Publications/Submissions

Martin Freer, Hisashi Horiuchi, Yoshiko Kanada-En'yo, Dean Lee,Ulf-G. Meißner
"Microscopic Clustering in Nuclei" , May 17, 2017. 50 pp.
[arXiv:1705.06192 [nucl-th]]

★ Jose Manuel Alarcón, Dechuan Du, Nico Klein, Timo A. Lähde, Dean Lee, Ning Li, Bing-Nan Lu, Thomas Luu, Ulf-G. Meißner
"Neutron-proton scattering at next-to-next-to-leading order in Nuclear Lattice Effective Field Theory"
Eur.Phys.J. A53 (2017) no.5, 83
[arXiv:1702.05319 [nucl-th]]

★ Serdar Elhatisari, Evgeny Epelbaum, Hermann Krebs, Timo A. Lähde, Dean Lee, Ning Li, Bing-nan Lu, Ulf-G. Meißner, Gautam Rupak
"Ab initio calculations of the isotopic dependence of nuclear clustering"
Feb 16, 2017. 14 pp.
[arXiv:1702.05177 [nucl-th]]

Serdar Elhatisari, Kris Katterjohn, Dean Lee, Ulf-G. Meißner, Gautam Rupak.
"Universal dimer–dimer scattering in lattice effective field theory"
Phys.Lett. B768 (2017) 337-344
[arXiv:1610.09095 [nucl-th]]

Serdar Elhatisari, Dean Lee, Ulf-G. Meißner, Gautam Rupak
"Nucleon-deuteron scattering using the adiabatic projection method "
Eur.Phys.J. A52 (2016) no.6, 174
[arXiv:1603.02333 [nucl-th]]

★ Serdar Elhatisari et al.
"Nuclear binding near a quantum phase transition"
Phys.Rev.Lett. 117 (2016) no.13, 132501
[arXiv:1602.04539 [nucl-th]]

Bing-Nan Lu, Timo A. Lähde, Dean Lee, Ulf-G. Meißner
"Precise determination of lattice phase shifts and mixing angles"
Phys.Lett. B760 (2016) 309-313
[arXiv:1506.05652 [nucl-th]]

Alexander Rokash, Evgeny Epelbaum, Hermann Krebs, Dean Lee
"Effective forces between quantum bound states"
Phys.Rev.Lett. 118 (2017) no.23, 232502

★ Christopher Körber, Evan Berkowitz, Thomas Luu
"Sampling General N-Body Interactions with Auxiliary Fields " Jun 20, 2017. 5 pp.
[arXiv:1706.06494 [nucl-th]]

Xiaonu Xiong, Thomas Luu, Ulf-G. Meißner
"Quasi-Parton Distribution Function in Lattice Perturbation Theory " Apr 29, 2017. 22 pp.
[arXiv:1705.00246 [hep-ph]]

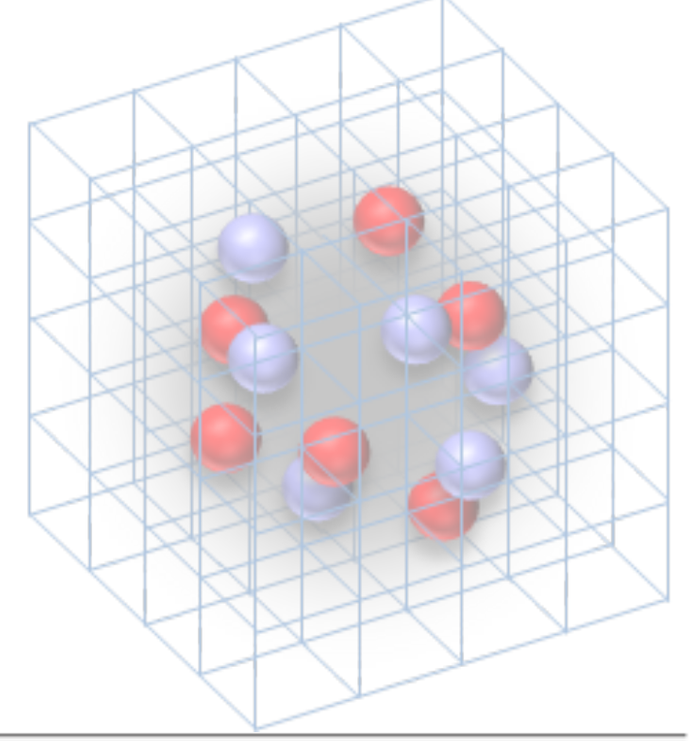
T. Luu and A. Shindler
"Lattice Quantum Chromodynamics: Symmetries and Applications"
Emergent Phenomena in Atomic Nuclei from Large-Scale Modeling
A Symmetry-Guided Perspective (World Scientific)
ISBN: 978-981-3146-04-4 (hardcover); ISBN: 978-981-3146-06-8 (ebook).

E. Berkowitz et al.,
"An accurate calculation of the nucleon axial charge with lattice QCD"
[arXiv:1704.01114 [hep-lat]]

★ **Highlighted in talk**

Backup Slides

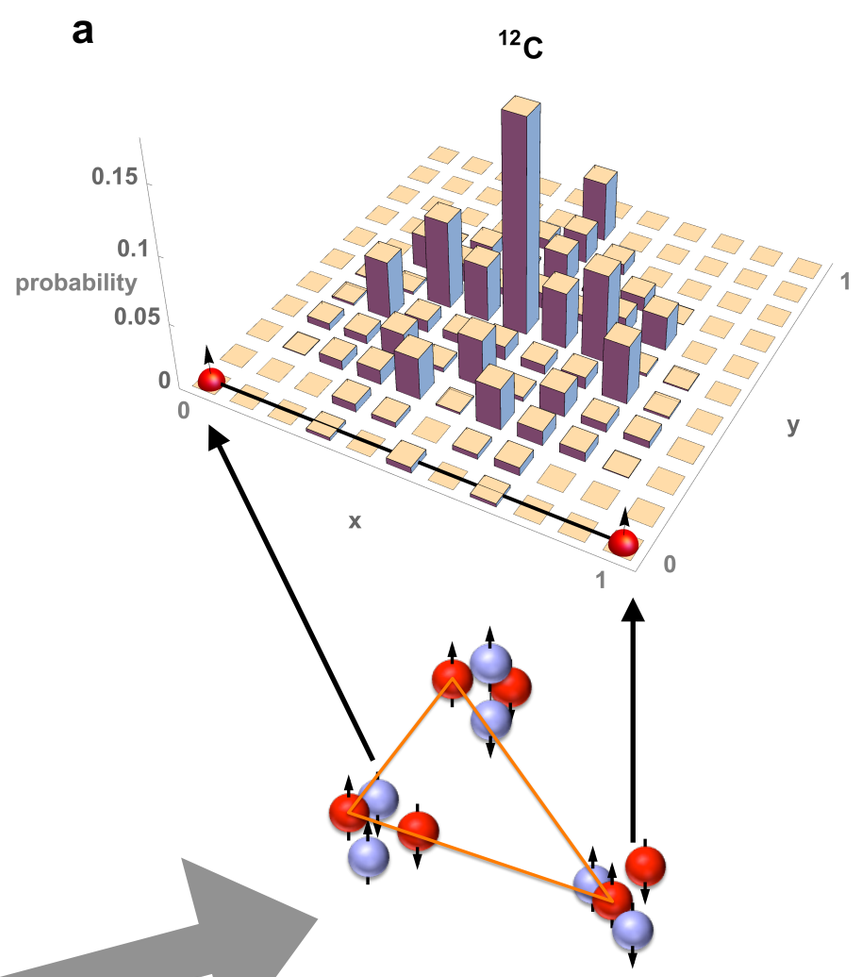
Evolution of LECs

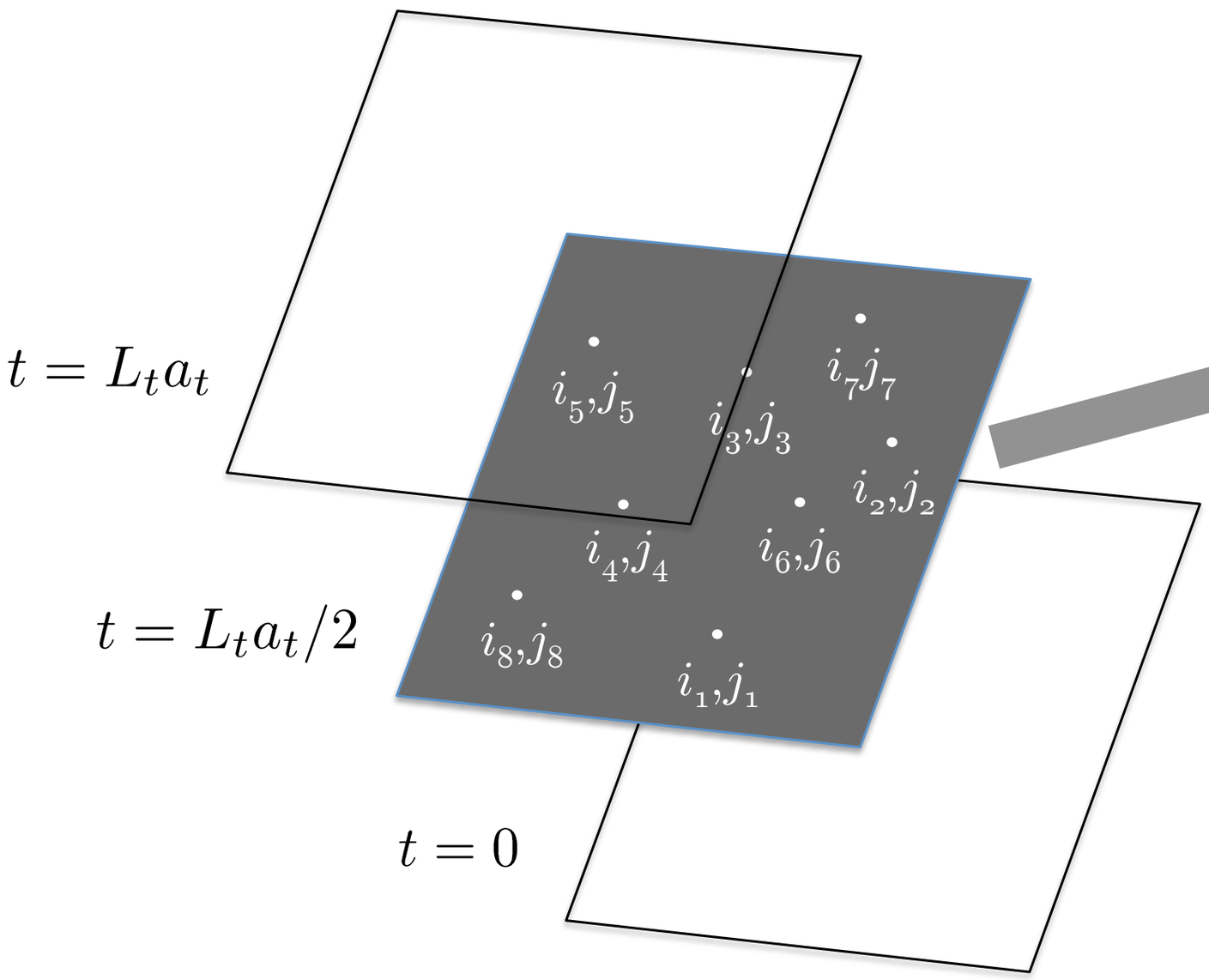


Order	LECs	$a = 1.98$ [fm]	$a = 1.64$ [fm]	$a = 1.32$ [fm]
LO	$C_{^1S_0}$	−0.4676(2)	−0.3290(7)	−0.201(5)
	$C_{^3S_1}$	−0.6377(2)	−0.4482(2)	−0.265(5)
	b_s [a]	0.0524(2)	0.0917(2)	0.173(6)
NLO	$C_{^1S_0}$	−0.5(1)	−0.35(2)	−0.220(2)
	$C_{^3S_1}$	−0.44(7)	−0.21(1)	−0.152(4)
	C_{q^2}	−0.05(3)	−0.032(9)	−0.006(1)
	C_{I^2,q^2}	0.08(2)	0.075(2)	0.052(1)
	C_{S^2,q^2}	−0.06(3)	−0.046(3)	−0.0341(7)
	C_{S^2,I^2,q^2}	0.03(2)	0.029(2)	0.0081(2)
	$C_{(q\cdot S)^2}$	0.11(2)	0.091(4)	0.0553(2)
	$C_{I^2,(q\cdot S)^2}$	−0.11(2)	−0.074(4)	−0.0240(8)
	$C^{I=1}_{(q\times S)\cdot k}$	0.037(8)	0.026(4)	0.019(2)
NNLO	$C_{^1S_0}$	−0.5(1)	−0.33(4)	−0.21(2)
	$C_{^3S_1}$	−0.5(1)	−0.22(1)	−0.15(2)
	C_{q^2}	0.08(3)	0.093(7)	0.118(7)
	C_{I^2,q^2}	0.07(2)	0.0668(4)	0.045(4)
	C_{S^2,q^2}	−0.06(3)	−0.05(2)	−0.036(7)
	C_{S^2,I^2,q^2}	0.01(2)	0.005(3)	−0.014(4)
	$C_{(q\cdot S)^2}$	0.10(3)	0.086(7)	0.056(4)
	$C_{I^2,(q\cdot S)^2}$	−0.10(3)	−0.055(4)	−0.006(4)
	$C^{I=1}_{(q\times S)\cdot k}$	0.031(8)	0.025(4)	0.018(2)

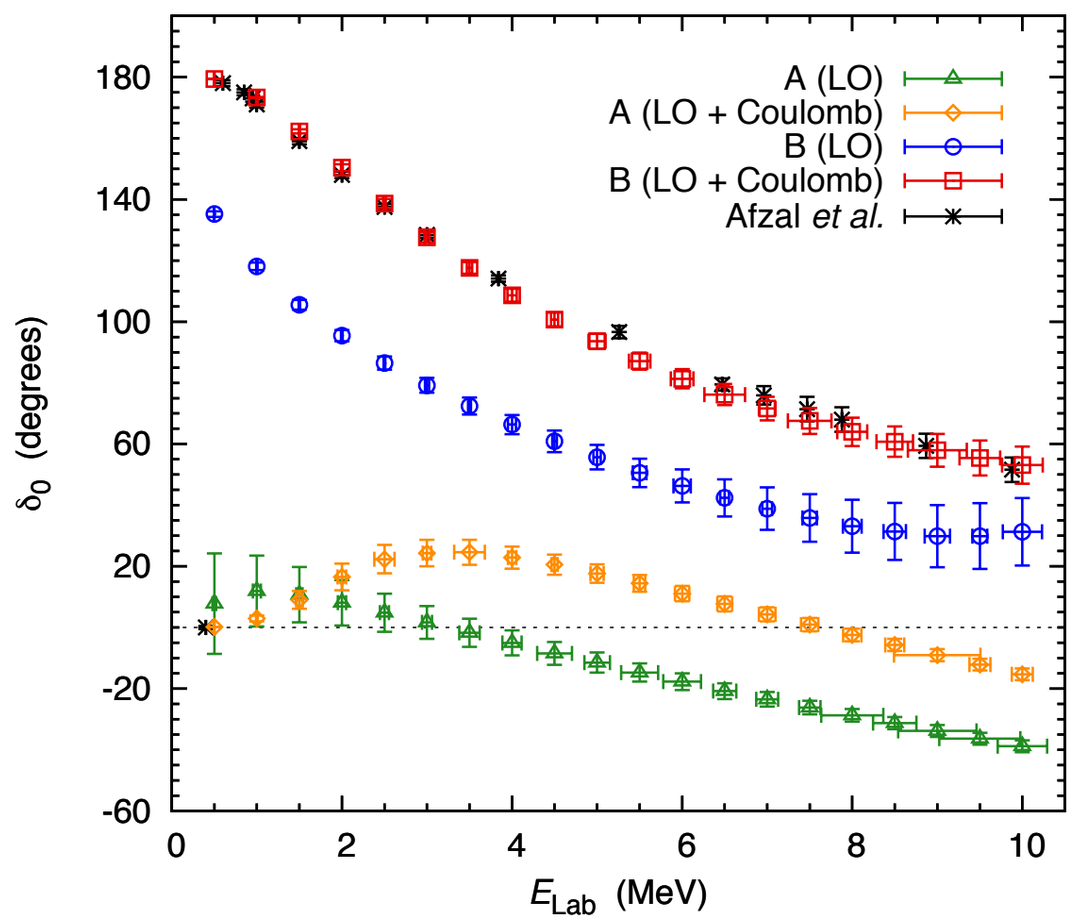
[a] The value of g_s is fitted at LO and kept unchanged at NLO and NNLO.

Pinhole algorithm & Alpha clustering

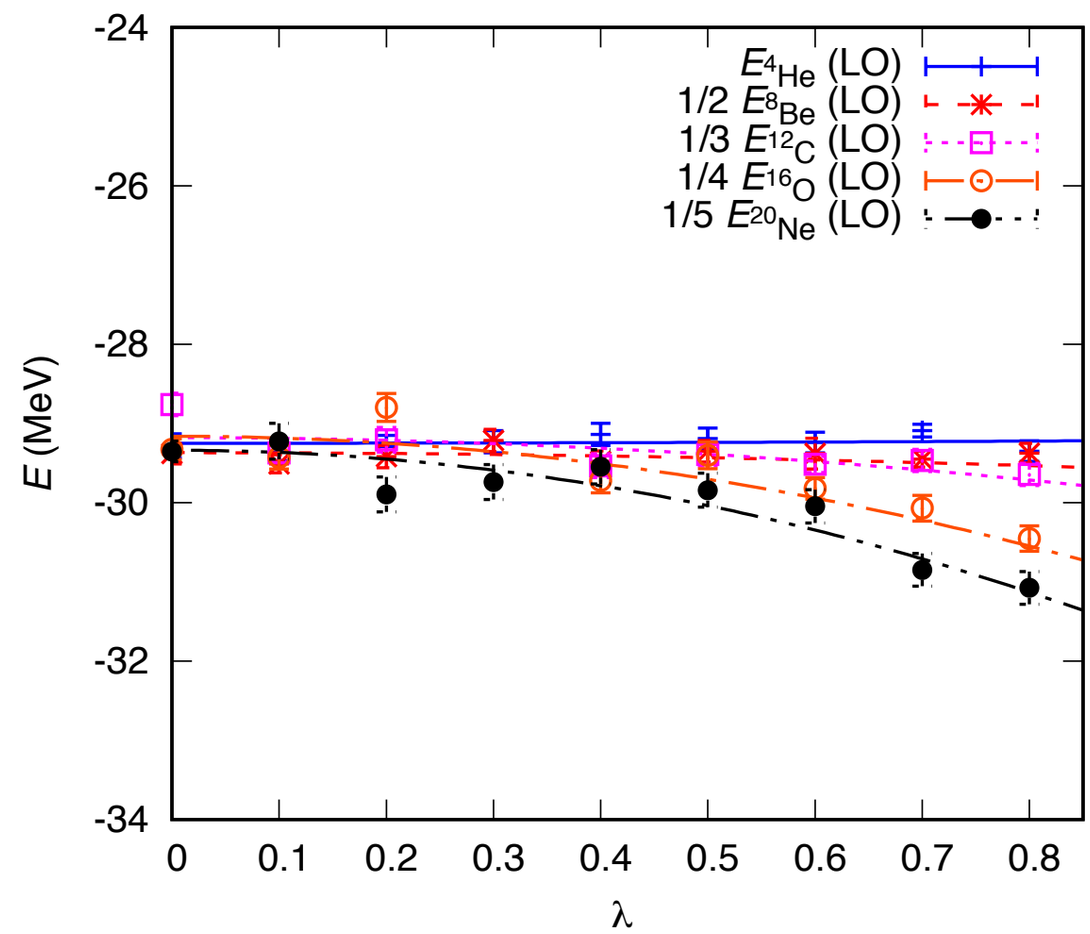




Alpha-Alpha scattering and alpha-nuclei binding energies



Calculated alpha-alpha s-wave phase shift for A and B potentials



Alpha-nuclei binding energies as a function of lambda