EFFECTIVE FIELD THEORY FOR LATTICE NUCLEI

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Supported by CNRS and US DOE

Outline

- QCD at Low Energies and the Lattice
- Nuclear Effective Field Theories
- EFT for Lattice Nuclei
- Outlook and Conclusion

Goal

Derivation of nuclear physics consistent with Standard Model (SM) of particle physics

- correct symmetries
- systematic

Why?

- Nucleus as the simplest complex system: quarks and gluons interacting strongly, yet exhibiting many regularities
  - QCD at large distances an unsolved part of the SM
  - tools for non-perturbative quantum (field) theories, *e.g.* cold atoms
- Nucleus as a laboratory: properties of the SM and beyond
  - nuclear matrix elements for symmetry tests
  - reaction rates for nucleosynthesis
  - equation of state for stellar structure
  - variation of parameters for cosmology
  - …

How?

Effective Field Theory

$$\begin{cases} T = T^{(\infty)}(Q \sim m \ll M) \sim \underbrace{N(M)}_{\text{normalization}} \sum_{\nu=\nu_{\min}}^{\infty} \sum_i \underbrace{\tilde{c}_{\nu,i}(\Lambda)}_{\text{“low-energy constants”}} \left[\frac{Q}{M}\right]^{\nu} \underbrace{F_{\nu,i}\left(\frac{Q}{m};\frac{\Lambda}{m}\right)}_{\text{non-analytic, from loops}} \\ \frac{\partial T}{\partial \Lambda} = 0 \end{cases}$$

arbitrary regulator

“power counting” → counting index depending on properties of interactions

For $Q \sim m$, truncate …

$$T = T^{(\bar{\nu})}\left[1 + \mathcal{O}\left(\frac{Q}{M}, \frac{Q}{\Lambda}\right)\right]$$

controlled

⇒ … consistently with RG invariance:

$$\frac{\Lambda}{T^{(\bar{\nu})}} \frac{\partial T^{(\bar{\nu})}}{\partial \Lambda} = \mathcal{O}\left(\frac{Q}{\Lambda}\right) \ll 1$$

model independent

<u>If so</u>
- want $\Lambda \gtrsim M$
- realistic estimate of errors comes from variation $\Lambda \in [M, \infty)$

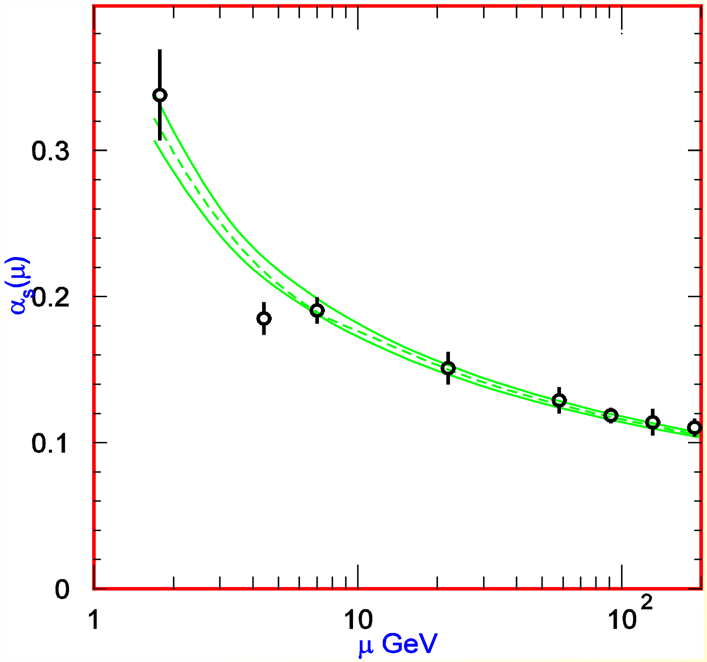
QCD

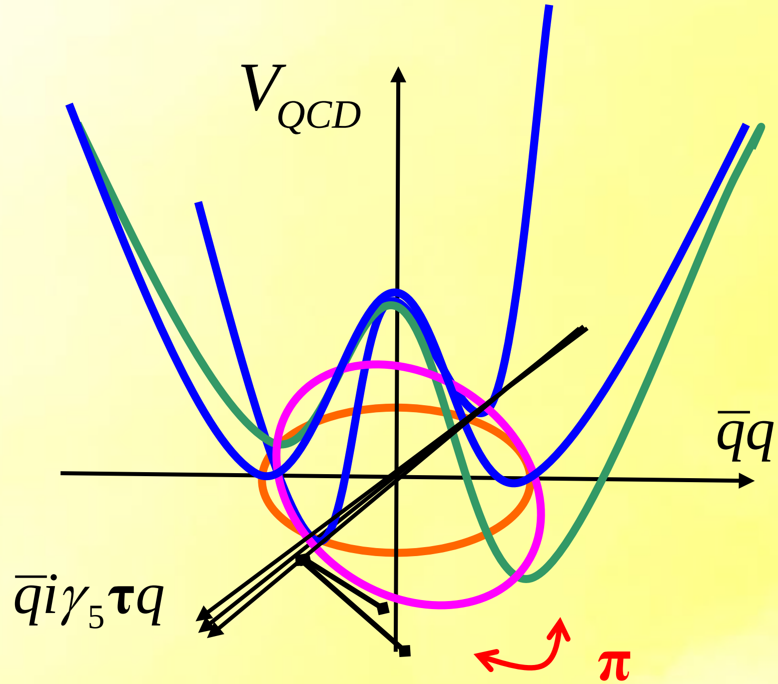
$$\mathcal{L}_{QCD} = \bar{q}\left(i\partial\!\!\!/ + g_s G\!\!\!/\right)q - \frac{1}{2}\mathrm{Tr}\, G^{\mu\nu}G_{\mu\nu} + \bar{m}\,\bar{q}\left(1-\varepsilon\tau_3\right)q + \dots$$

Basic mass scales

$M_{QCD} \sim m_N, m_\rho, 4\pi f_\pi, \dots$ $\sim 1\ \mathrm{GeV}$

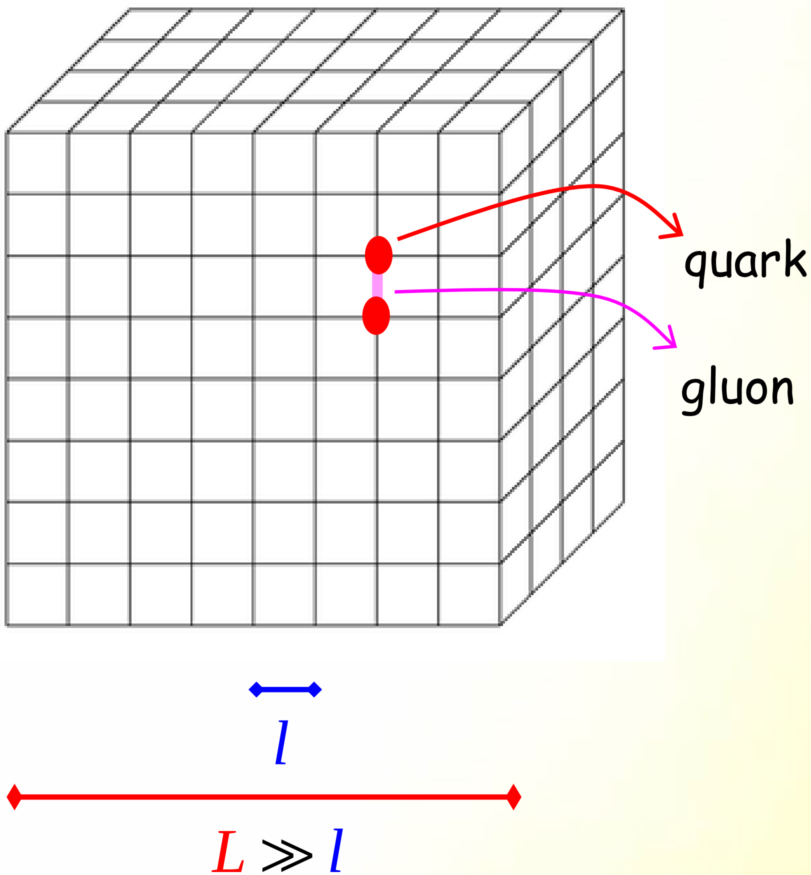
$m_\pi \sim \sqrt{\bar{m} M_{QCD}}$ $\simeq 140\ \mathrm{MeV}$





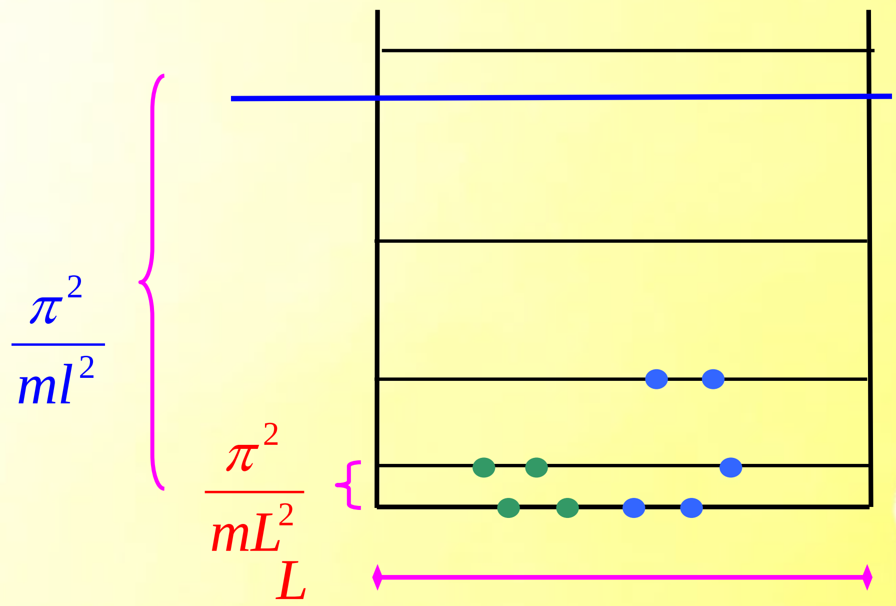
$$f_\pi \sim M_{QCD}/4\pi + \mathcal{O}(\bar{m}) \simeq 100\ \mathrm{MeV}$$

Lattice QCD



path integral solved with Monte Carlo methods, typically for unrealistically large quark masses

lattice "model space"



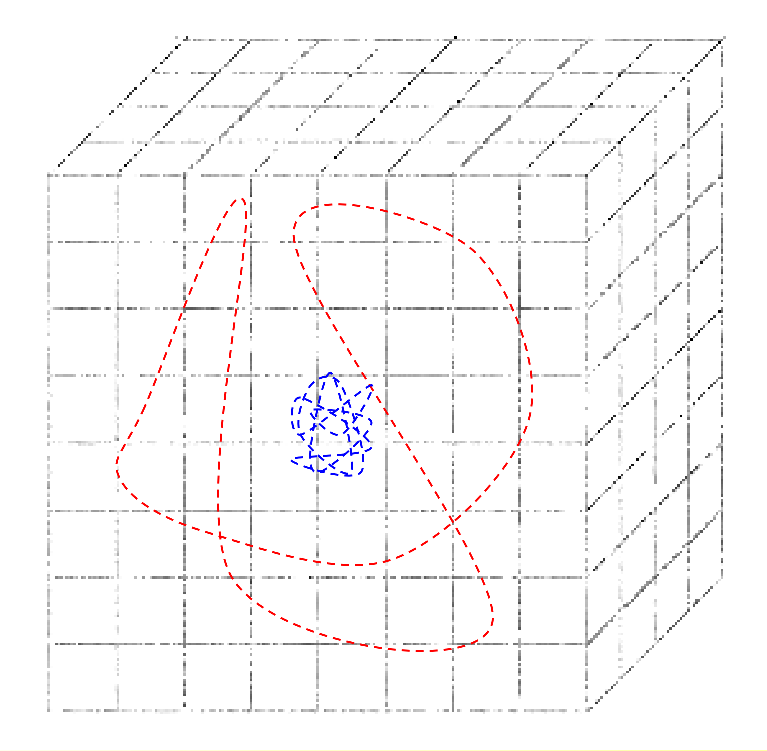
$$\cot\delta(E) = \frac{4}{\sqrt{mEL}}\left[\pi\sum_{\mathbf{n}}^{|\mathbf{n}|<L/l}\frac{1}{(2\pi\mathbf{n})^2 - mEL^2} - \frac{L}{l}\right]$$

Lüscher '91

nucleon

$l \ll 1/M_{QCD}$

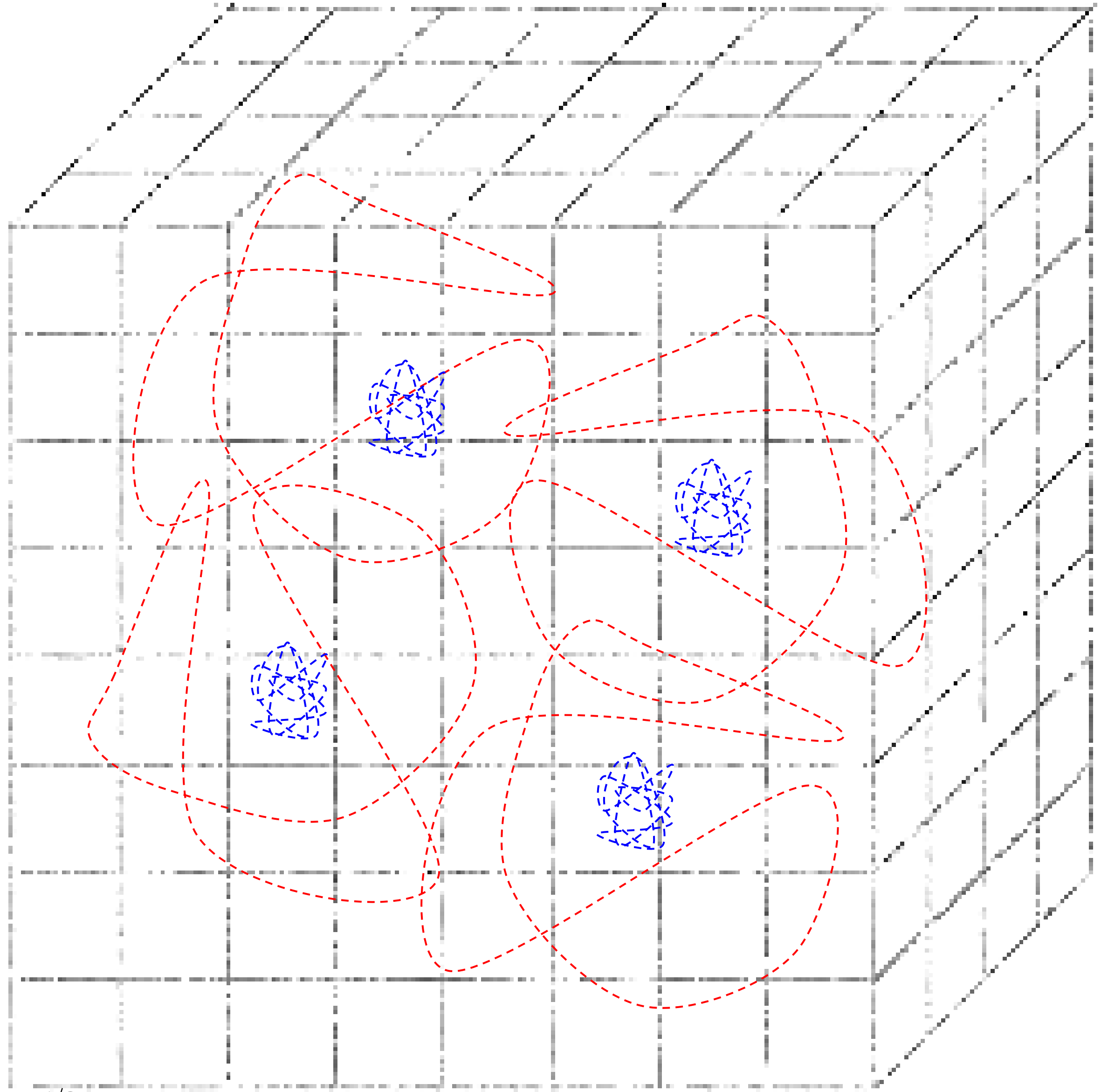
$1/M_{QCD} \approx 0.3 \text{ fm}$



$1/m_\pi \cong 1.4 \text{ fm}$

$L \gg 1/m_\pi$

nucleus



$l \ll 1/M_{QCD}$

$1/M_{QCD} \approx 0.3$ fm

$R \sim \rho\left(m_\pi / f_\pi\right) A^{1/3}/m_\pi \approx 1.2\ A^{1/3}\mathrm{fm}$

$L \gg \rho\, A^{1/3}/m_\pi$

two-step strategy

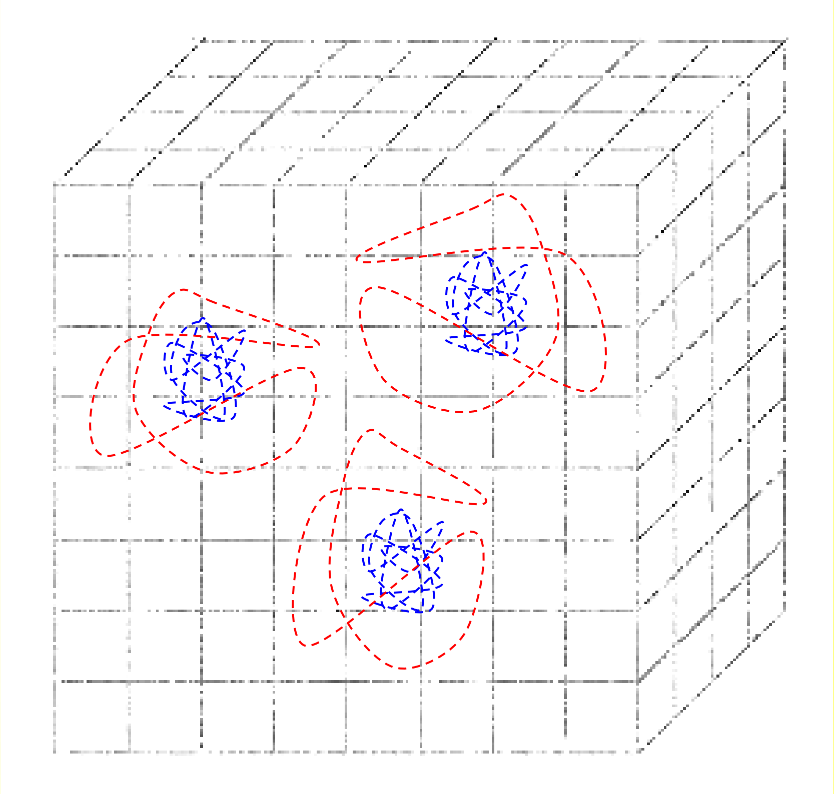
I) fit LECs for

$$A \le a \sim 3, 4$$

$$m_\pi \ge M_\pi \sim 300, 400 \text{ MeV}$$

$$l \ll 1/M_{QCD}$$

$$1/M_{QCD} \approx 0.3 \text{ fm}$$



$$1/M_\pi$$

$$\rho\left(M_\pi / f_\pi\right) a^{1/3} / M_\pi$$

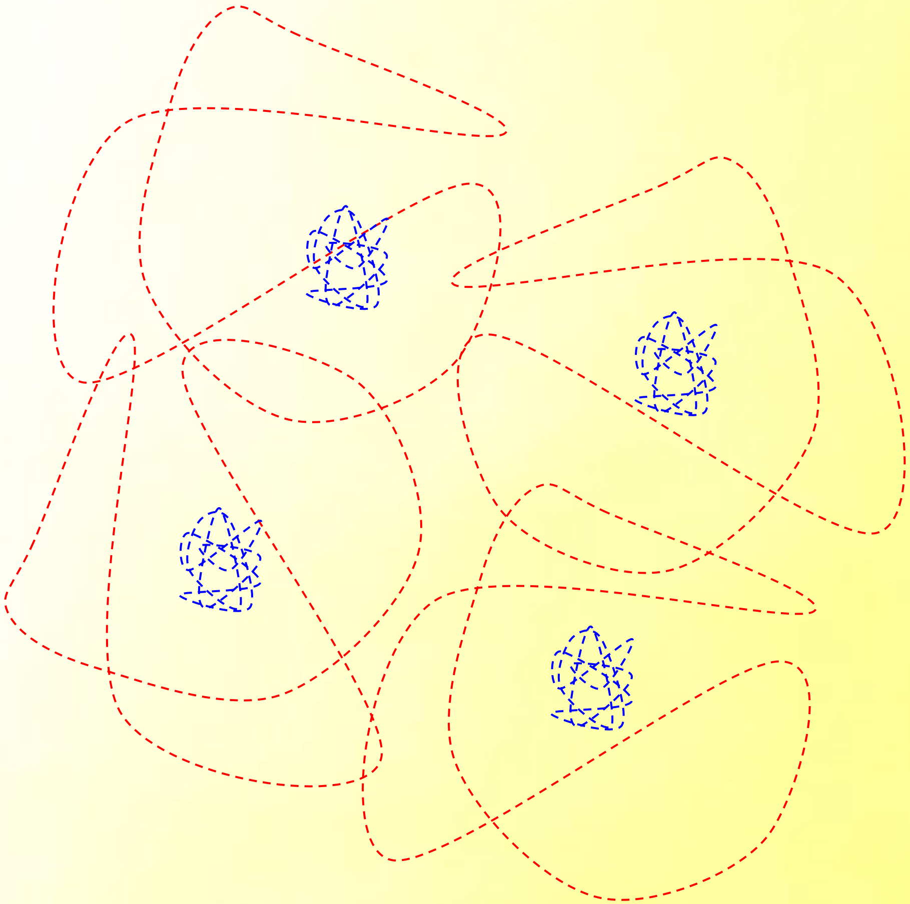
$$L \gg \rho\left(M_\pi / f_\pi\right) a^{1/3} / M_\pi$$

two-step strategy

II) solve EFT for

any A

any m_π



$1/M_{QCD} \approx 0.3$ fm

$1/m_\pi$

$\rho(m_\pi/f_\pi)\, A^{1/3}/m_\pi$

Extrapolation in pion mass

Pionful (Chiral) EFT $Q \sim m_\pi \ll M_{QCD}$

- degrees of freedom: nucleons, pions, Deltas (+ Roper + ?)

$$m_\Delta - m_N \sim 2m_\pi \quad \left(m_{N'} - m_N \sim 3m_\pi, \ldots\right)$$

- symmetries: Lorentz, ~~P~~, ~~T~~, ~~chiral~~ $\quad D_\mu = \left(1+\boldsymbol{\pi}^2/4f_\pi^2\right)^{-1}\partial_\mu \quad \mathcal{D}_\mu = \partial_\mu + \frac{i}{2f_\pi^2}\left(\boldsymbol{\pi}\times D_\mu\boldsymbol{\pi}\right)\cdot\mathbf{t}^{(I)}$

$$\mathcal{L}_{EFT} = \frac{1}{2}D_\mu\boldsymbol{\pi}\cdot D^\mu\boldsymbol{\pi} - \frac{m_\pi^2}{2}\frac{\boldsymbol{\pi}^2}{1+\boldsymbol{\pi}^2/4f_\pi^2} + N^+\left(i\mathcal{D}_0 + \frac{\vec{\mathcal{D}}^2}{2m_N}\right)N + \frac{g_A}{2f_\pi}N^+\vec{S}\boldsymbol{\tau}N\cdot\cdot\vec{D}\boldsymbol{\pi}$$

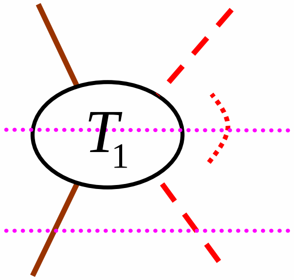
$$+C_0\,N^+N\,N^+N + C_2'\,N^+N\left(\vec{\mathcal{D}}N^+\right)\cdot\vec{\mathcal{D}}N + \ldots$$

other spin/isospin ,
more derivatives,
powers of pion mass,
Deltas (Ropers, …),
few-body forces,
etc.

- expansion in:

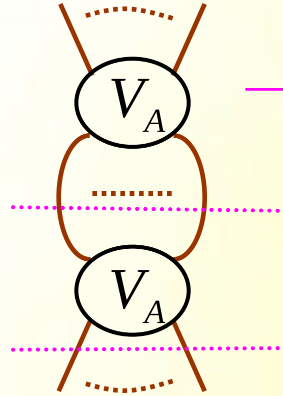
$$\frac{Q}{M_{QCD}} \sim \begin{cases} Q/m_N & \text{non-relativistic} \\ Q/m_\rho, \ldots & \text{multipole} \\ Q/4\pi f_\pi & \text{pion loop} \end{cases} \sim \frac{1}{5}$$

Weinberg '90, '92
Ordonez + v.K. '92
...



$$\frac{1}{\Delta E} \sim \frac{1}{Q}$$

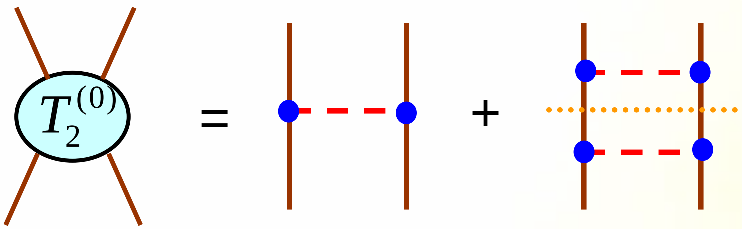
vs.



A-nucleon irreducible

A-nucleon reducible:

$$\frac{1}{\Delta E} \sim \frac{m_N}{Q^2}$$ infrared enhancement



$$+ \ldots = \mathcal{O}\left(\frac{1}{f_\pi^2}\right) \frac{1}{1-\mathcal{O}\left(\frac{Q}{f_\pi}\right)}$$

bound-state pole at

$$\sim \frac{1}{f_\pi^2} f_1(Q/m_\pi) \quad \sim \frac{1}{f_\pi^2}\frac{Q}{\mu_\pi} f_2(Q/m_\pi)$$

$$\sim \frac{4\pi f_\pi}{m_N} f_\pi \approx f_\pi$$

$$Q \sim f_\pi f(m_\pi / f_\pi)$$

$$-E \sim \frac{f_\pi^2}{M_{QCD}} f^2(m_\pi / f_\pi)$$

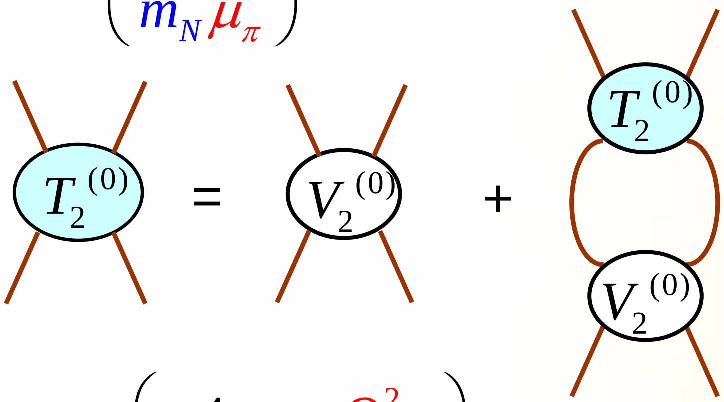
(modulo renormalization...)

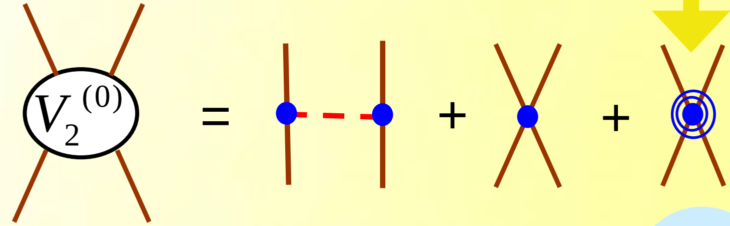
$$M_{nuc} = \mu_\pi \approx f_\pi \ll M_{QCD}$$

Nuclear scale arises in QCD due to spontaneous chiral symmetry breaking

Nogga, Timmermans + v.K. '05
Pavón + Ruiz-Arriola '06
...

LO $\mathcal{O}\left(\frac{4\pi}{m_N \mu_\pi}\right)$

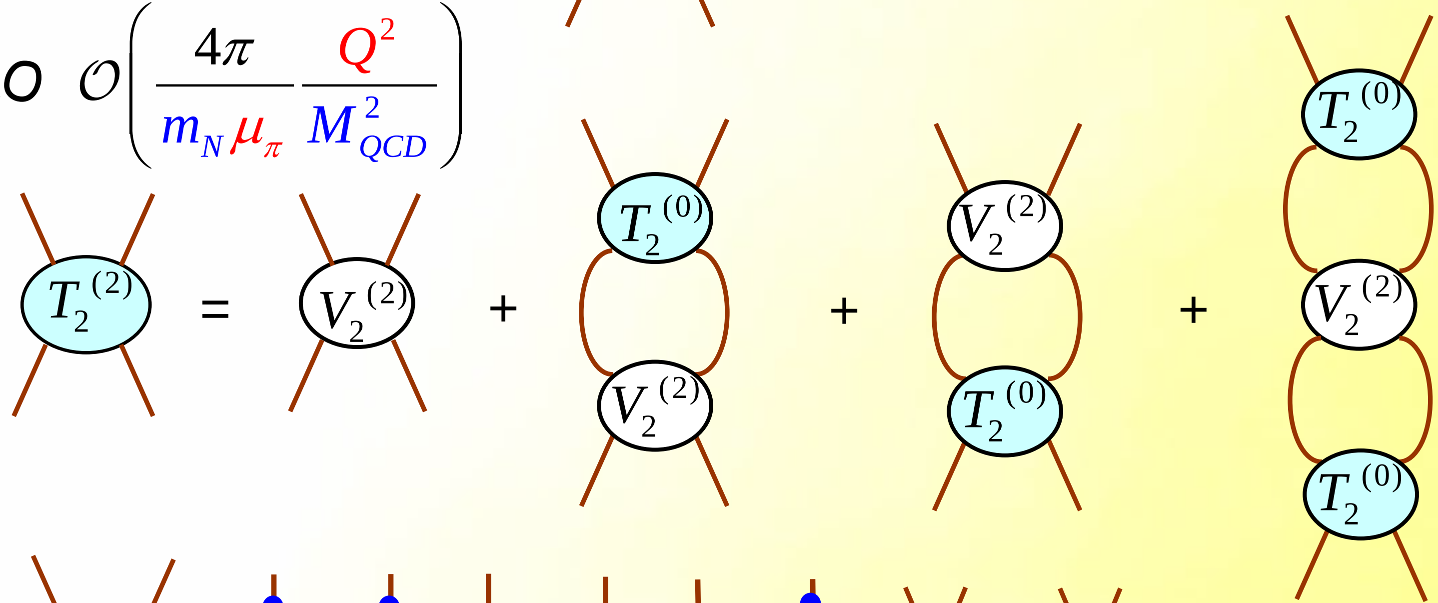


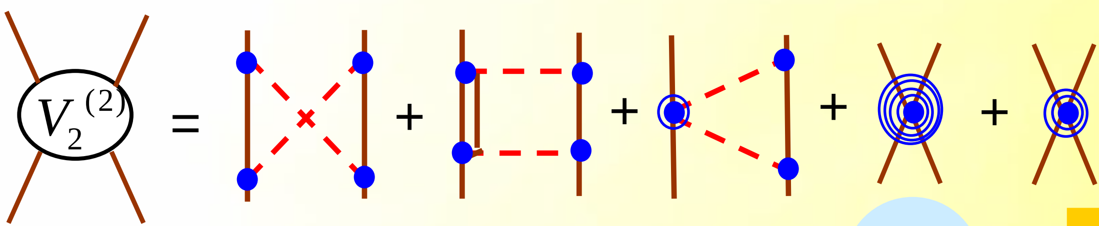


needed to renormalize OPE

$s=1$
$l \leq 2$

NLO $\mathcal{O}\left(\frac{4\pi}{m_N \mu_\pi}\frac{Q^2}{M_{QCD}^2}\right)$





Long + v.K. '07
Pavón '11
...

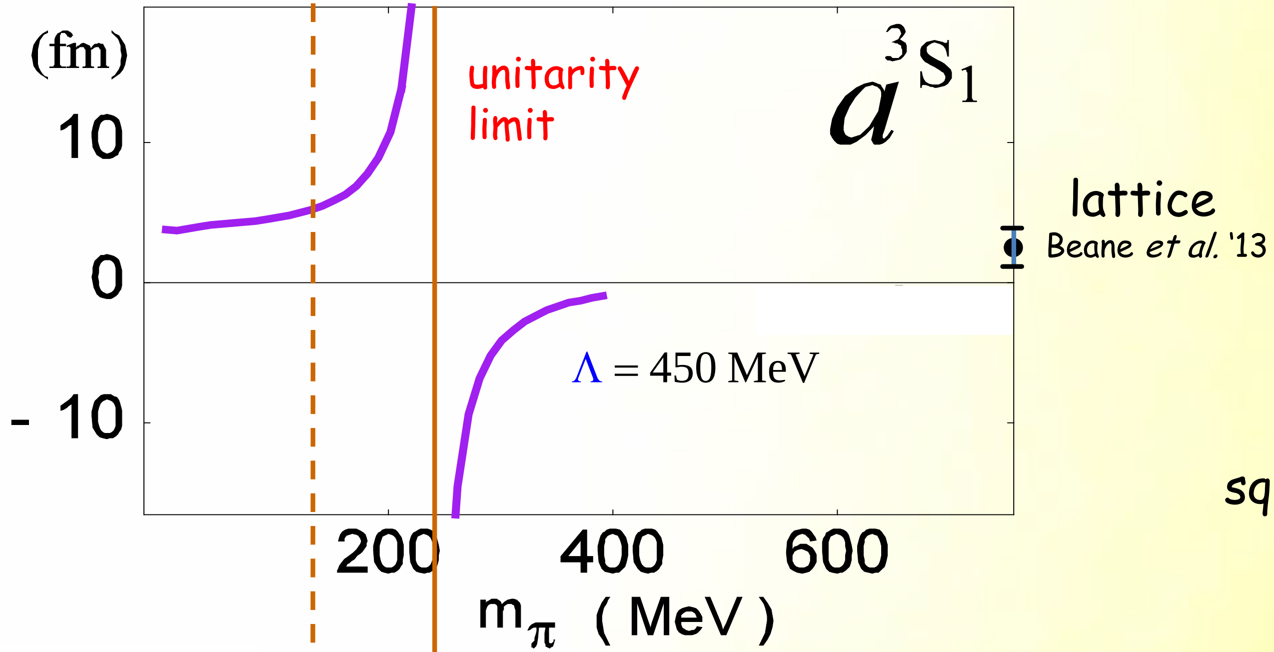
etc.

few-body forces?

$s=1$
$l \leq 2$

enough to renormalize singular perturbations

Beane, Bedaque, Savage + v.K. '02
Beane + Savage '03
Epelbaum + Meissner '03
...

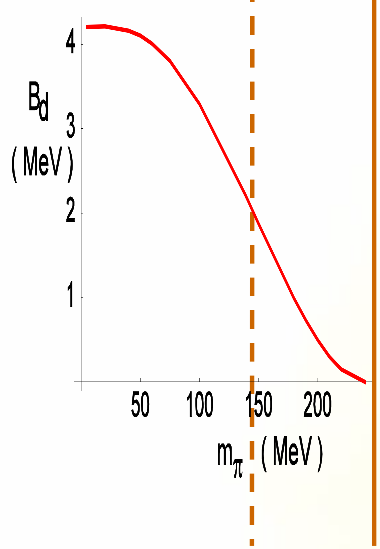


incomplete NLO

square-well regularization

range $1/\Lambda$

$\Lambda = 800$ MeV



$m_\pi \simeq 140$ MeV $m_\pi^*\left(M_{QCD}\right)$

varying only explicit pion mass, BUT

$$f_\pi = f\left[1+\left(\frac{m_\pi}{4\pi f_\pi}\right)^2 \bar{l}_4 + \mathcal{O}\left(\frac{m_\pi}{M_{QCD}}\right)^4\right]$$

$\bar{l}_4 = 4.4 \pm 0.2$ Colangelo *et al.* '01

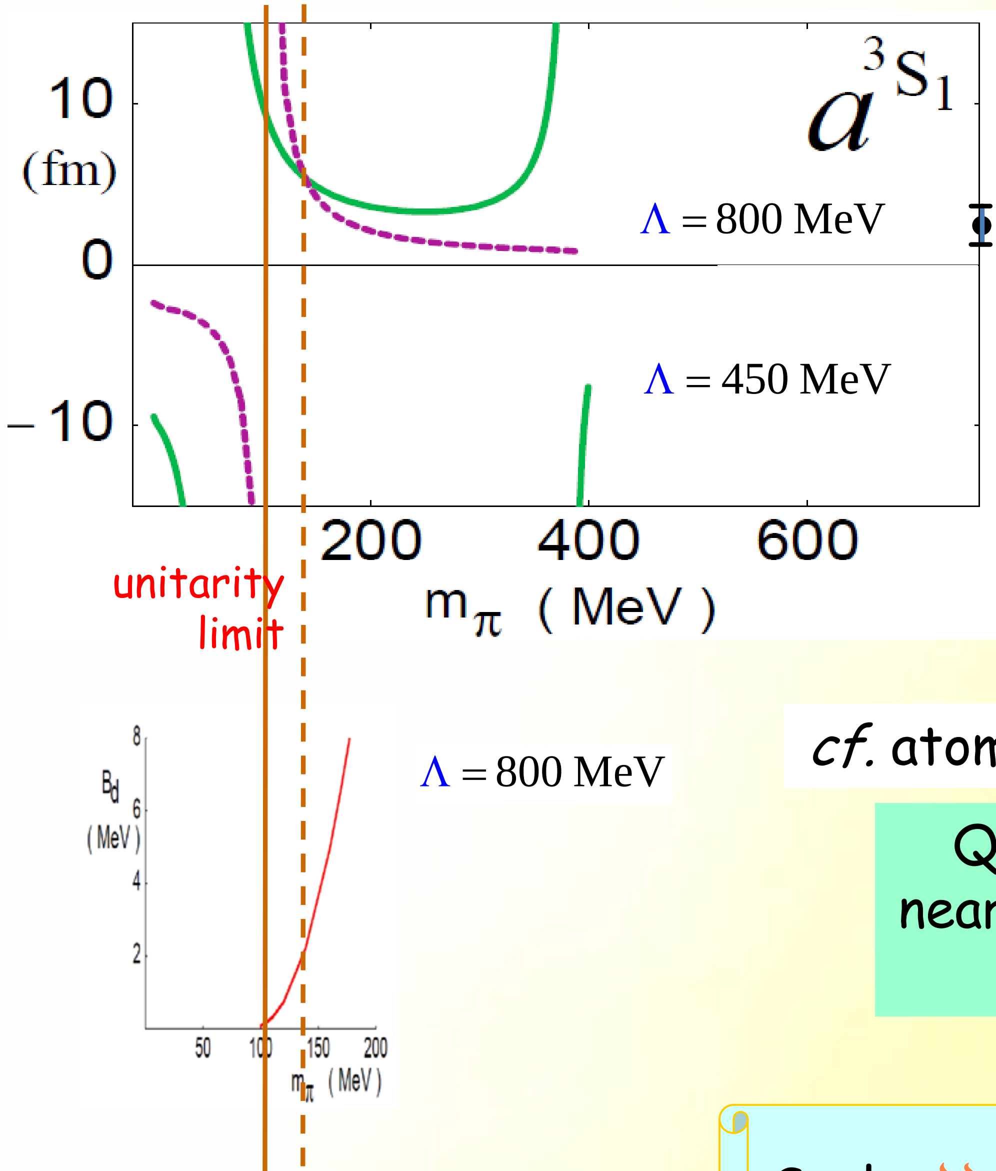
$$m_N = m_0\left[1-4\left(\frac{m_\pi}{4\pi f_\pi}\right)^2 \frac{(4\pi f_\pi)^2 c_1}{m_0} + \mathcal{O}\left(\frac{m_\pi}{M_{QCD}}\right)^3\right]$$

$c_1 \approx -1\,\mathrm{GeV}^{-1}$ Meissner '00

$$g_{\pi N} = g_A\left\{1-2\left(\frac{m_\pi}{4\pi f_\pi}\right)^2\left[\frac{(4\pi f_\pi)^2}{g_A}\bar{d}_{18} + \left(2g_A^2+1\right)\ln\frac{m_\pi}{\mu}\right] + \mathcal{O}\left(\frac{m_\pi}{M_{QCD}}\right)^3\right\}$$

$\bar{d}_{18} \approx -1\,\mathrm{GeV}^{-2}$ Fetter + Meissner '00

Beane, Bedaque, Savage + v.K. '02
Beane + Savage '03
Epelbaum + Meissner '03
...



lattice
Beane *et al.* '13

incomplete
NLO

square-well regularization

range $1/\Lambda$

$m_\pi^*(M_{QCD})$ $m_\pi \simeq 140$ MeV

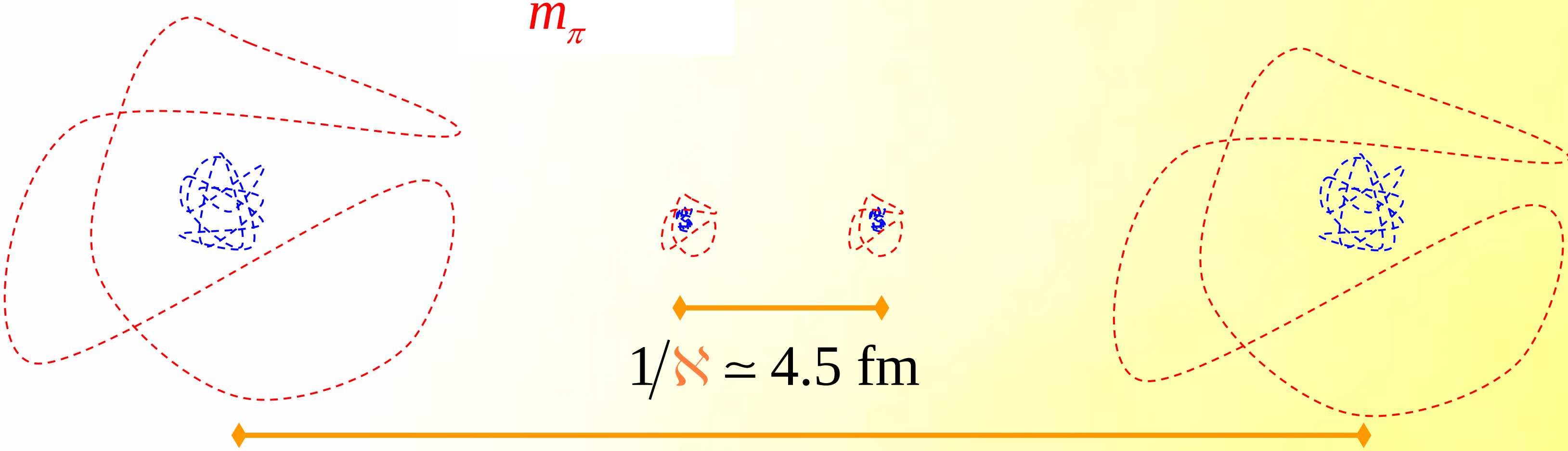
cf. atoms as magnetic field varies

QCD with $m_\pi \simeq 140$ MeV
near a Feshbach resonance
in pion mass

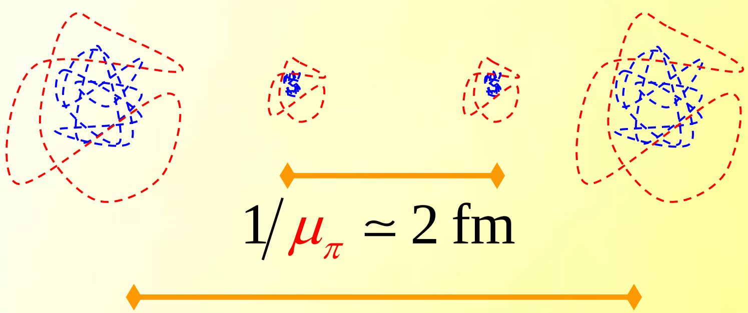
Scale $\aleph \sim \frac{m_\pi - m_\pi^*}{m_\pi^*} \mu_\pi \lesssim \mu_\pi$ emerges

$$Q \sim \aleph \sim \frac{m_\pi - m_\pi^*}{m_\pi^*}\,\mu_\pi < m_\pi$$

$$\frac{m_\pi - m_\pi^*}{m_\pi^*} < 1$$ e.g. $m_\pi \simeq 140\ \text{MeV}$



$\mu_\pi < m_\pi$ e.g. $m_\pi \sim 500\ \text{MeV}$



Pionless EFT $Q \sim M_{lo} \ll M_{hi}$

- degrees of freedom: nucleons
- symmetries: Lorentz, $\not{P}$, $\not{T}$

$$\mathcal{L}_{EFT} = N^{+}\left(i\partial_0 + \frac{\nabla^2}{2m_N}\right)N - \frac{C_0}{2}N^{+}N\,N^{+}N - \frac{D_0}{6}N^{+}N\,N^{+}N\,N^{+}N$$

$$+ N^{+}\frac{\nabla^4}{8m_N^3}N - \frac{C_2}{4}N^{+}N\,\nabla^2 N^{+}N + \ldots$$

omitting spin, isospin

- expansion in: $\frac{Q}{M_{hi}} = \begin{cases} Q/m_N \\ Q/m_\pi, \ldots \end{cases}$ non-relativistic / multipole

Universality: first orders apply also to neutral atoms

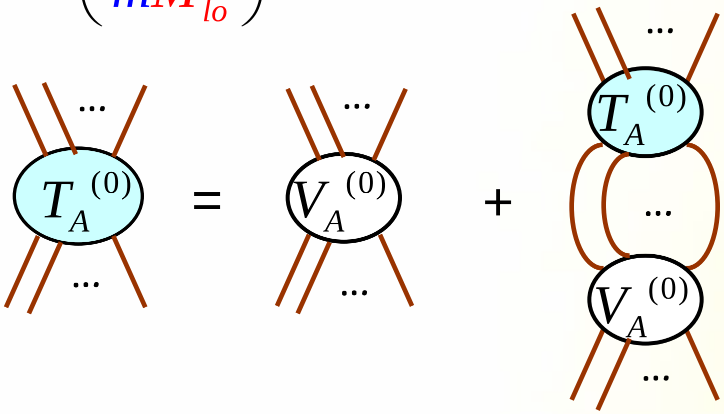
$M_{hi} \sim 1/l_{vdW}$ *where* $V(r) = -\frac{l_{vdW}^4}{2m_{at}r^6} + \ldots$

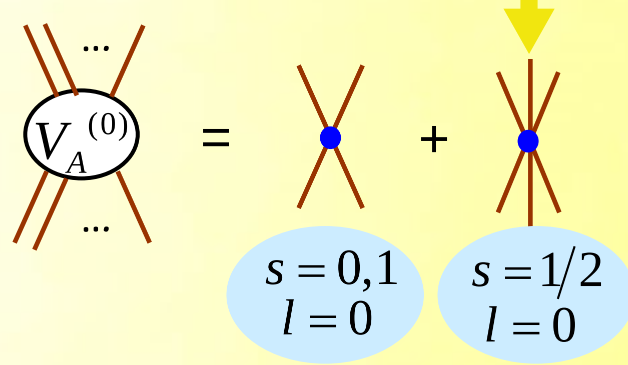
Bedaque, Hammer + v.K. '99 '00
Bedaque, Braaten + Hammer '01
...

Bedaque + v.K. '97
…

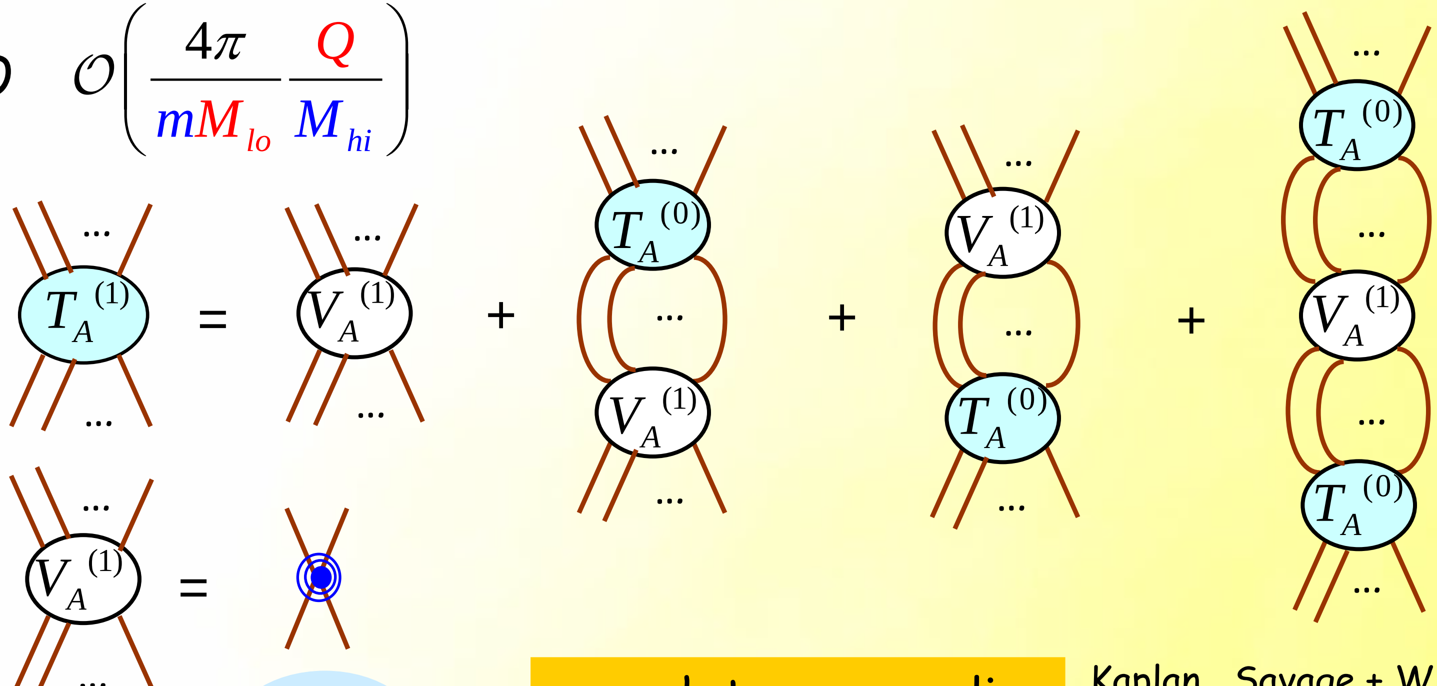
LO $\mathcal{O}\left(\frac{4\pi}{mM_{lo}}\right)$

needed to renormalize three-body system





NLO $\mathcal{O}\left(\frac{4\pi}{mM_{lo}}\frac{Q}{M_{hi}}\right)$



$s=0,1$
$l=0$

enough to renormalize singular perturbations

Kaplan, Savage + Wise '98
v.K. '98
…

etc.

v.K. '97
Kaplan, Savage +Wise '98
…

$A=2$ in each S-wave channel with shallow b.s.

LO NLO

$$C_0(\Lambda)=\frac{C_0^{(R)}}{1-\#\frac{m}{2\pi^2}C_0^{(R)}\Lambda}\left(1-\#\frac{m}{2\pi^2}C_2(\Lambda)\Lambda^3+\ldots\right)$$

regularization-dependent numbers

$$C_2(\Lambda)=\left(1-\#\frac{m}{2\pi^2}C_0^{(R)}\Lambda\right)^{-2}\left[C_2^{(R)}+\#\frac{mC_0^{(R)2}(\Lambda)}{2\pi^2\Lambda}\left(1-\#\frac{m}{2\pi^2}C_0^{(R)}\Lambda\right)^{-2}\right]+\ldots$$

NLO

renormalized LECs

$$C_0^{(R)}\sim\frac{4\pi}{mM_{lo}}$$

$$C_2^{(R)}\sim\frac{4\pi}{mM_{hi}M_{lo}^2}$$

LO NLO

$$T_2(k)=\frac{4\pi}{m}\left(-\frac{4\pi}{mC_0^{(R)}}-ik\right)^{-1}\left[1-\left(-\frac{4\pi}{mC_0^{(R)}}-ik\right)^{-1}\frac{16\pi C_2^{(R)}}{mC_0^{(R)2}}\frac{k^2}{2}+\mathcal{O}\left(\frac{M_{lo}^2}{M_{hi}^2}\right)\right]$$

scattering length $=\frac{1}{a_2}\sim M_{lo}$

$=\frac{r_2}{2}\sim\frac{1}{M_{hi}}$ effective range

b.s. at $Q\sim M_{lo}$

effective-range expansion

Bedaque, Hammer + v.K. '99 '00
...

$A = 3$ { bosons
fermions with more than two states

$$T^{(0)}_{2+1}(\Lambda \gg p \gg M_{lo}) \approx A \cos\left(s_0 \ln \frac{p}{\Lambda} + \delta \right) \Rightarrow \frac{\Lambda}{T^{(0)}_{2+1}} \frac{\partial T^{(0)}_{2+1}}{\partial \Lambda} (p \sim M_{lo}) \sim 1 \quad \text{unless} \quad D_0^{(R)} \sim \frac{(4\pi)^2}{m M_{lo}^4}$$

approximate scale invariance

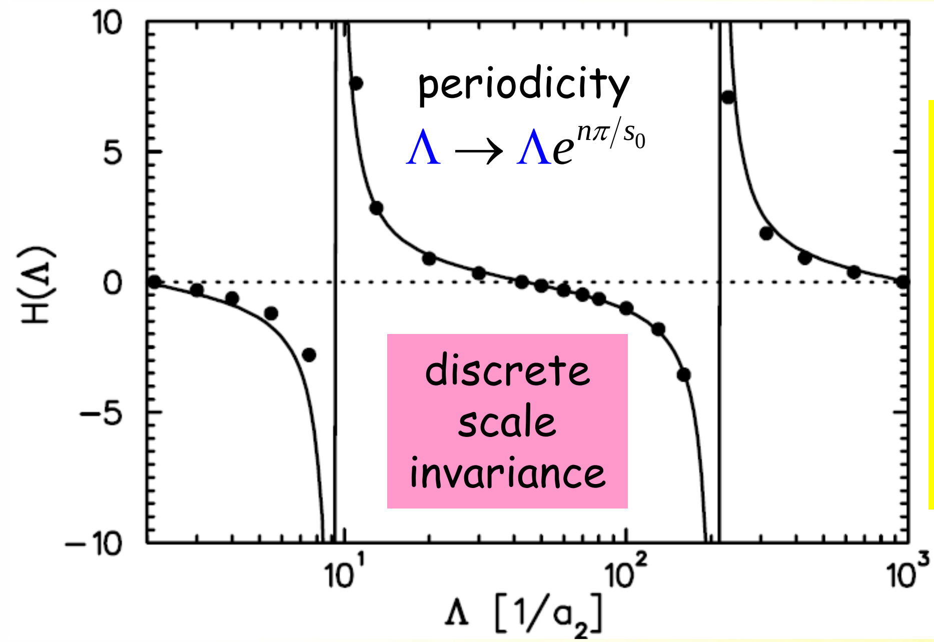
$s_0 = 1.0064...$

not *just* the effective-range expansion

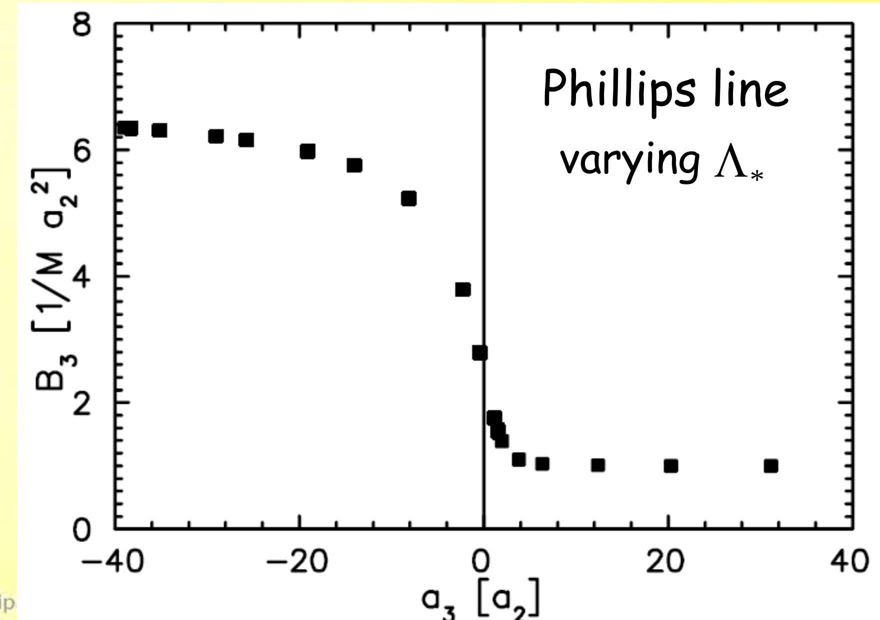
LO

$$H(\Lambda) \equiv \frac{\Lambda^2 D_0(\Lambda)}{2\mu C_0^2(\Lambda)} \simeq \frac{\sin\left(\ln(\Lambda/\Lambda_*) + \arctan(1/s_0)\right)}{\sin\left(\ln(\Lambda/\Lambda_*) - \arctan(1/s_0)\right)}$$

dimensionful parameter (dimensional transmutation)



RG limit cycle!



Extrapolation in nucleon number

$m_\pi \ll M_{QCD}$ → Pionful EFT, Pionless EFT

Pionless EFT ← $m_\pi \sim M_{QCD}$

+ any "exact" *ab initio* method

That is,

1) truncate EFT expansion at desired order
2) solve Schrödinger equation for low *A* at fixed cutoff (exactly for LO, subLOs in perturbation theory)
3) fit LECs to selected *lattice* input
4) solve Schrödinger equation for larger *A*
5) repeat steps 2-4 at other cutoffs
6) obtain observables at large cutoffs

Experimental and LQCD data

m_π	140	510	805
Nucleus	[Nature]	[5]	[6]
n	939.6	1320.0	1634.0
p	938.3	1320.0	1634.0
nn	-	7.4 ± 1.4	15.9 ± 3.8
D	2.224	11.5 ± 1.3	19.5 ± 4.8
^{3}n	-		
^{3}H	8.482	20.3 ± 4.5	53.9 ± 10.7
^{3}He	7.718	20.3 ± 4.5	53.9 ± 10.7
^{4}He	28.30	43.0 ± 14.4	107.0 ± 24.2
^{5}He	27.50		
^{5}Li	26.61		
^{6}Li	32.00		

[5] Yamazaki *et al.* '12
[6] Beane *et al.* '12

Beane *et al.* '13

$$a^{(^1S_0)} = 2.33^{+0.19+0.27}_{-0.17-0.20}\ \text{fm} \quad , \quad r^{(^1S_0)} = 1.130^{+0.071+0.059}_{-0.077-0.063}\ \text{fm}$$

$$a^{(^3S_1)} = 1.82^{+0.14+0.17}_{-0.13-0.12}\ \text{fm} \quad , \quad r^{(^3S_1)} = 0.906^{+0.068+0.068}_{-0.075-0.084}\ \text{fm}$$

$\text{Scales}\ (\text{MeV})$

m_N	940	1320	1630
$\sqrt{m_N(m_\Delta - m_N)}$	530	630	540
m_π	140	500	800
$\sqrt{m_N\ B/A}\ (A = 2 \mapsto 4)$	$30 \mapsto 80$	$90 \mapsto 120$	$130 \mapsto 210$

Experimental and LQCD data

LO pionless fit:

m_N, C_{01}, C_{10}, D_1

Stetcu, Barrett + v.K. '06

m_π	140	510	805
Nucleus	[Nature]	[5]	[6]
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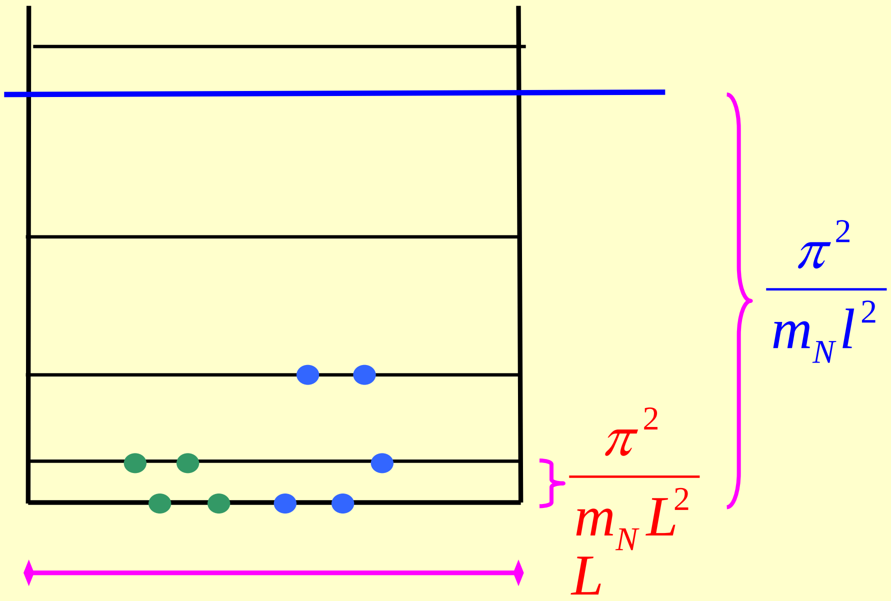
$A \gtrsim 4$ As A grows, given computational power limits number of accessible one-nucleon states → IR cutoff

Lattice Box



Mueller *et al.* '99

nuclear matter

Lee *et al.* '05

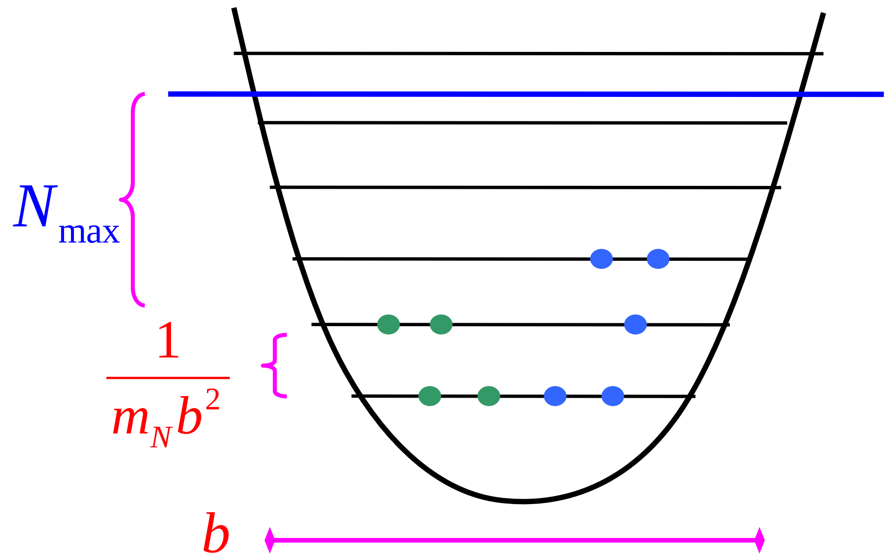
few nucleons

…

$$\cot\delta(E) = \frac{4}{\sqrt{m_N E L}}\left[\pi \sum_{\mathbf{n}}^{|\mathbf{n}|<L/l} \frac{1}{(2\pi\mathbf{n})^2 - m_N E L^2} - \frac{L}{l}\right]$$

Lüscher '91

Harmonic Oscillator "No-Core Shell Model"



Stetcu *et al.* '06

…

finite nuclei

$$\cot\delta(E) = -\frac{2}{\sqrt{m_N E b}} \frac{\Gamma\left(\frac{3}{4} - \frac{m_N E b^2}{2}\right)}{\Gamma\left(\frac{1}{4} - \frac{m_N E b^2}{2}\right)}$$

Busch *et al.* '99

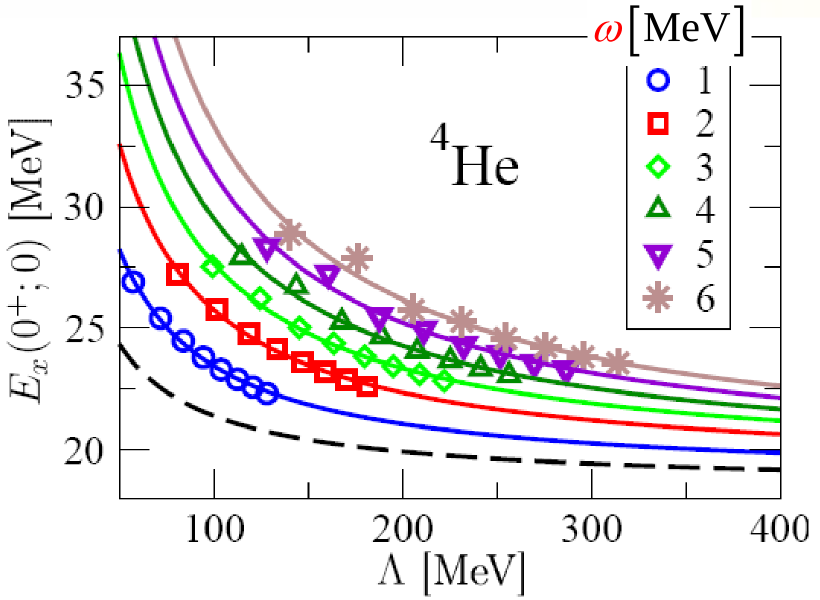
…

Stetcu, Barrett + v.K. '06

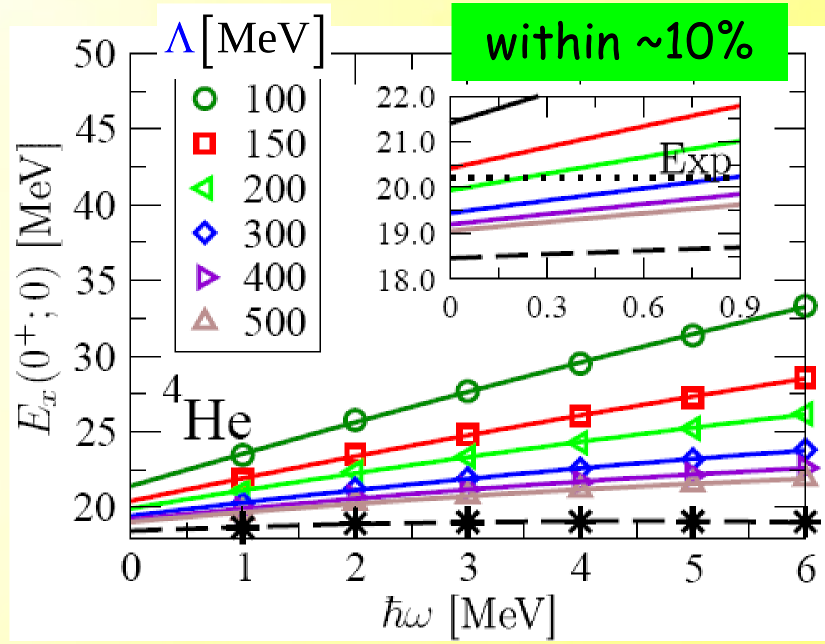
Pionless EFT: LO

(parameters fitted to d, t, α ground-state binding energies)

$N_{max} \leq 16$

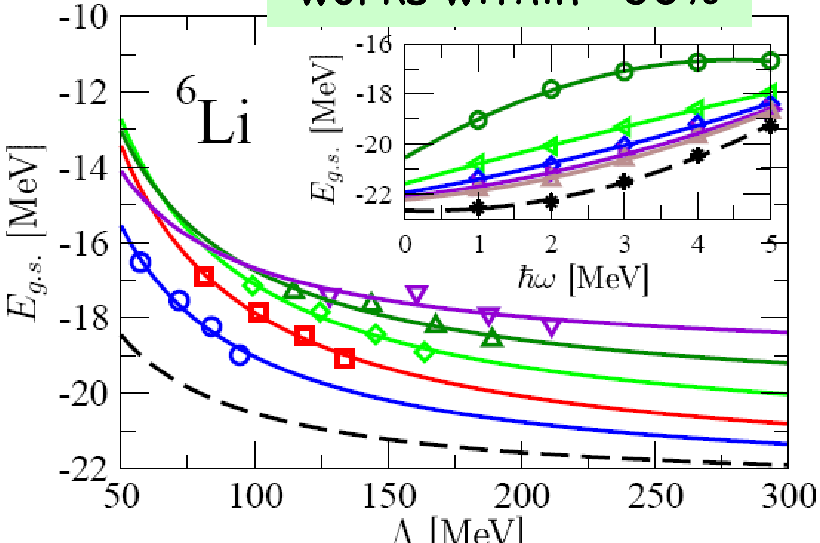


within ~10%



works within ~30%

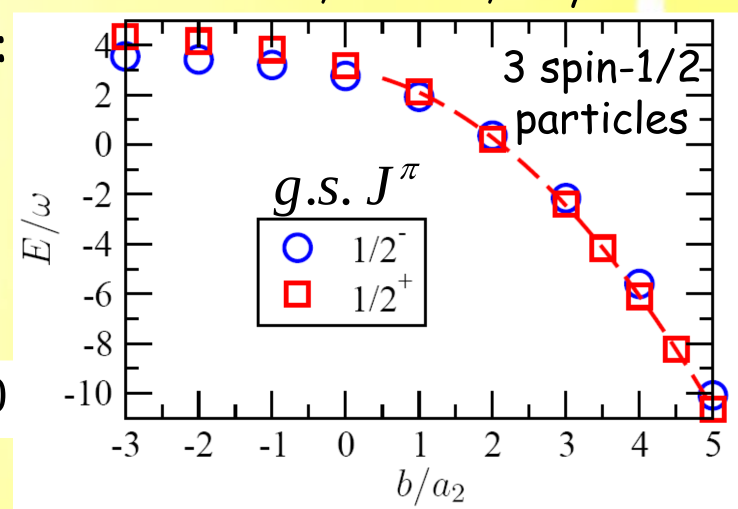
$N_{max} \leq 8$



Stetcu, Barrett , Vary + v.K. '08

Bonus:

$N_{max} \lesssim 30$



Experimental and LQCD data

m_π	140	510	805	
Nucleus	[Nature]	[5]	[6]	
n	939.6	1320.0	1634.0	
p	938.3	1320.0	1634.0	*
nn	-	7.4 ± 1.4	15.9 ± 3.8	*
D	2.224	11.5 ± 1.3	19.5 ± 4.8	*
^{3}n	-			
^{3}H	8.482	20.3 ± 4.5	53.9 ± 10.7	
^{3}He	7.718	20.3 ± 4.5	53.9 ± 10.7	*
^{4}He	28.30	43.0 ± 14.4	107.0 ± 24.2	
^{5}He	27.50			
^{5}Li	26.61			
^{6}Li	32.00			

[5] Yamazaki *et al.* '12
[6] Beane *et al.* '12

LO pionless fit:

m_N, C_{01}, C_{10}, D_1

Barnea, Contessi, Gazit + Pederiva + v.K. '13

Beane *et al.* '13

$$a^{(^1S_0)} = 2.33^{+0.19+0.27}_{-0.17-0.20}\ \mathrm{fm}, \quad r^{(^1S_0)} = 1.130^{+0.071+0.059}_{-0.077-0.063}\ \mathrm{fm}$$

$$a^{(^3S_1)} = 1.82^{+0.14+0.17}_{-0.13-0.12}\ \mathrm{fm}, \quad r^{(^3S_1)} = 0.906^{+0.068+0.068}_{-0.075-0.084}\ \mathrm{fm}$$

Ab initio methods employed

- Effective-Interaction Hyperspherical Harmonics (EIHH) Barnea *et al.* '00' 01
  - ✓ hyperspherical coordinates: hyperradius + 3*A*-4 hyperangles
  - ✓ model space: hyperangular momentum $K \leq K_{max}$
  - ✓ wavefunction: expanded in antisymmetrized spin/isospin states
  - ✓ effective interaction: Lee-Suzuki projection to subspace "in medium"
  - ✓ extrapolation: $K_{max} \to \infty$

- Auxiliary-Field Diffusion Monte Carlo (AFDMC) Schmidt + Fantoni '99
  - ✓ integral equation for evolution of wavefunction in imaginary time τ in terms of Green's function (diffusion)
  - ✓ two- and more-body operators linearized by auxiliary fields (Hubbard-Stratonovich transformation)
  - ✓ trial wavefunction probed stochastically with weight given by the Green's function
  - ✓ lowest-energy state with symmetry of trial wavefunction projected onto as $\tau \to \infty$

Barnea, Contessi, Gazit, Pederiva + v.K. '13

$$H^{(0)} = -\frac{1}{2m_N}\sum_i \nabla_i^2 + \frac{1}{4}\sum_{i<j}\left[\left(3C_{10}(\Lambda)+C_{01}(\Lambda)\right)+\left(C_{10}(\Lambda)-C_{01}(\Lambda)\right)\vec{\sigma}_i\cdot\vec{\sigma}_j\right]e^{-\Lambda^2 r_{ij}^2/4} + \sum_{i<j<k}\sum_{cyc} D_1(\Lambda)\,\boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_j\, e^{-\Lambda^2\left(r_{ij}^2+r_{jk}^2\right)/4}$$

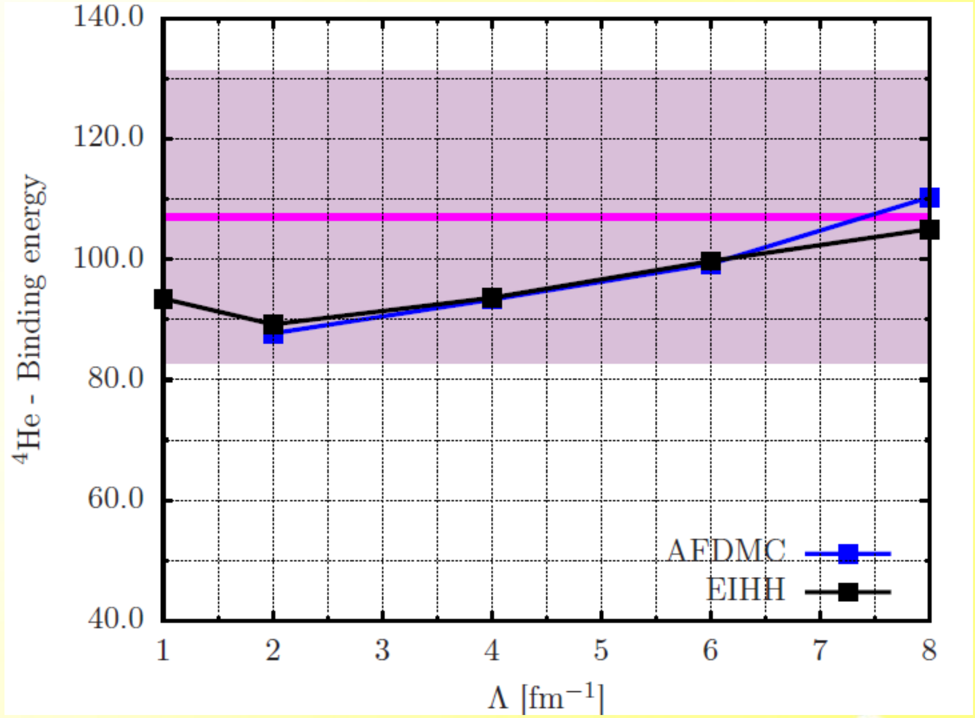
TABLE III. The LO LECs [GeV] for lattice nuclei at m_π = 805 MeV, as a function of the momentum cutoff Λ [fm^{-1}].

Λ	$C_{1,0}$	$C_{0,1}$	D_1
2	−0.1480	−0.1382	−0.07515
4	−0.4046	−0.3885	−0.3902
6	−0.7892	−0.7668	−1.147
8	−1.302	−1.273	−2.648

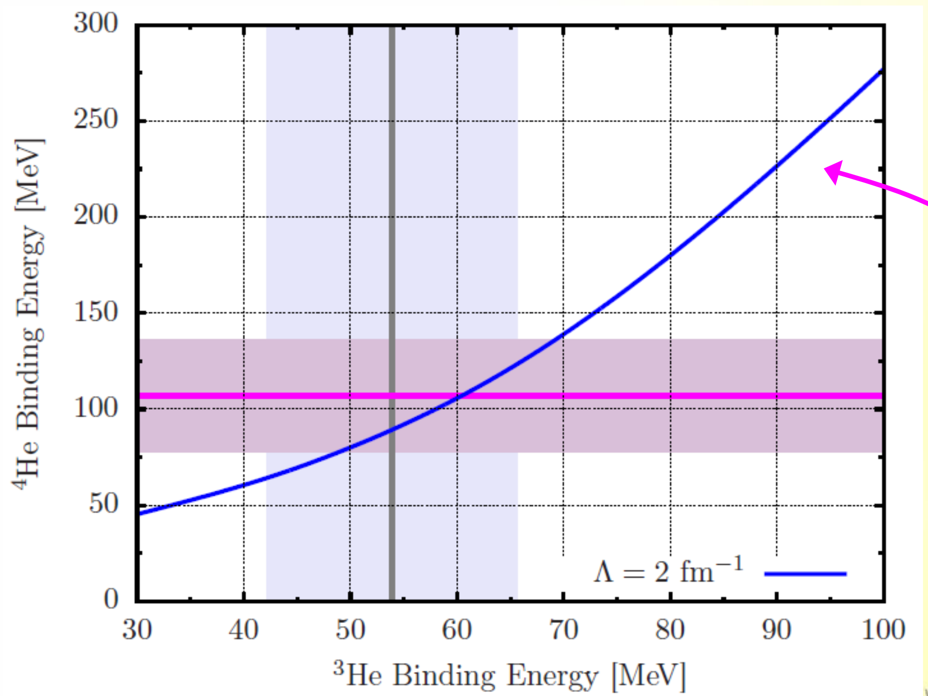
Barnea, Contessi, Gazit, Pederiva + v.K. '13

$$a^{(^3S_1)} = \underbrace{(1.2 \pm 0.5)}\ \mathrm{fm}$$

cutoff variation 2 to 14 fm^{-1}



Tjon line



varying D_1

at fixed C_{01}, C_{10}

Barnea, Contessi, Gazit, Pederiva + v.K. '13

- no excited states for A =2,3,4
- no ^{3}n droplet

m_π Nucleus	140 [Nature]	510 [5]	805 [6]	805 [This work]
n	939.6	1320.0	1634.0	1634.0 *
p	938.3	1320.0	1634.0	1634.0
nn	-	7.4 ± 1.4	15.9 ± 3.8	15.9 ± 3.8 *
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^{3}He	7.718	20.3 ± 4.5	53.9 ± 10.7	53.9 ± 10.7
^{4}He	28.30	43.0 ± 14.4	107.0 ± 24.2	89 ± 36
^{5}He	27.50			98 ± 39
^{5}Li	26.61			98 ± 39
^{6}Li	32.00			122 ± 50

predictions (^{4}He, ^{5}He, ^{5}Li, ^{6}Li, This work)

[5] Yamazaki *et al.* '12
[6] Beane *et al.* '12
[This work] Barnea *et al.* '13

What next?

- NLO at m_π = 805 MeV
- LO at m_π = 510 MeV
- larger A with AFDMC
- hypernuclei
- chiral EFT at lower pion masses when available
- …

Conclusion

- EFT is constrained *only* by symmetries and thus can be matched onto lattice QCD
- EFT allows controlled extrapolations of lattice results in both pion mass *and* nucleon number
- First, proof-of-principle calculation carried out at $m_\pi \approx 800$ MeV with pionless EFT
- World at large pion mass *might* be just a denser version of ours