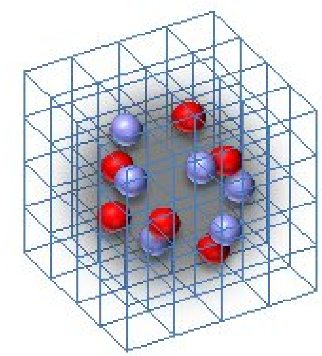
Testing the Anthropic Principle with Lattice Simulations

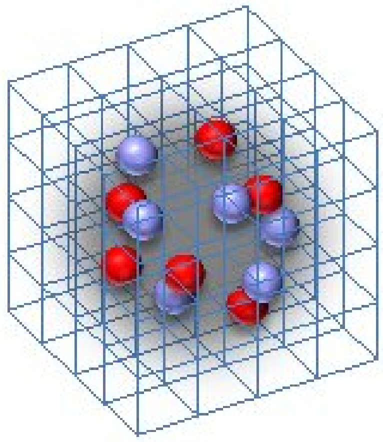
Ulf-G. Meißner, Univ. Bonn & FZ Jülich



NLEFT

Supported by DFG, SFB/TR-16 and by DFG, SFB/TR-110 and by EU, I3HP EPOS and by BMBF 06BN9006 and by HGF VIQCD VH-VI-417

- **N**uclear **L**attice **E**ffective **F**ield **T**heory collaboration



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- Introduction I: The Anthropic Principle & the Hoyle state
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- Nuclear lattice simulations: methods
- Nuclear lattice simulations: results
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- Summary & outlook

Introduction I: The Anthropic Principle & the Hoyle state

THE ANTHROPIC PRINCIPLE

- The anthropic principle:

"The observed values of all physical and cosmological quantities are not equally probable but they take on values restricted by the requirement that there exist sites where carbon-based life can evolve and by the requirements that the Universe be old enough for it to have already done so."

Carter 1974, Barrow & Tippler 1988, . . .

$\Rightarrow$ can this be tested? / have physical consequences?

- Ex. 1: "Anthropic bound on the cosmological constant" Weinberg (1987) [505 cites]
- Ex. 2: "The anthropic string theory landscape" Susskind (2003) [681 cites]

A PRIME EXAMPLE for the ANTHROPIC PRINCIPLE

- Hoyle (1953):

Prediction of an excited level in carbon-12 to allow for a sufficient production of heavy elements (^{12}C, ^{16}O,...) in stars

- was later heralded as a prime example for the AP:

"As far as we know, this is the only genuine anthropic principle prediction"
Carr & Rees 1989

"In 1953 Hoyle made an anthropic prediction on an excited state – 'level of life' – for carbon production in stars"
Linde 2007

"A prototype example of this kind of anthropic reasoning was provided by Fred Hoyle's observation of the triple alpha process..."
Carter 2006

A SHORT HISTORY of the HOYLE STATE

- Heavy element generation in massive stars: triple-α process

Bethe 1938, Öpik 1952, Salpeter 1952, Hoyle 1954, ...

$$^4\text{He} + {}^4\text{He} \rightleftharpoons {}^8\text{Be}$$
$$^8\text{Be} + {}^4\text{He} \rightleftharpoons {}^{12}\text{C}^* \rightarrow {}^{12}\text{C} + \gamma$$
$$^{12}\text{C} + {}^4\text{He} \rightleftharpoons {}^{16}\text{O} + \gamma$$

- Hoyle's contribution: calculation of relative abundances of ^{4}He, ^{12}C and ^{16}0
  $\Rightarrow$ need a resonance close to the ^{8}Be + ^{4}He threshold at $E_R = 0.35$ MeV
  $\Rightarrow$ this corresponds to a 0^+ excited state 7.7 MeV above the g.s.

- a corresponding state was experimentally confirmed at Caltech at
  $E - E(\text{g.s.}) = 7.653 \pm 0.008$ MeV Dunbar et al. 1953, Cook et al. 1957

- still on-going experimental activity, e.g. EM transitions at SDALINAC

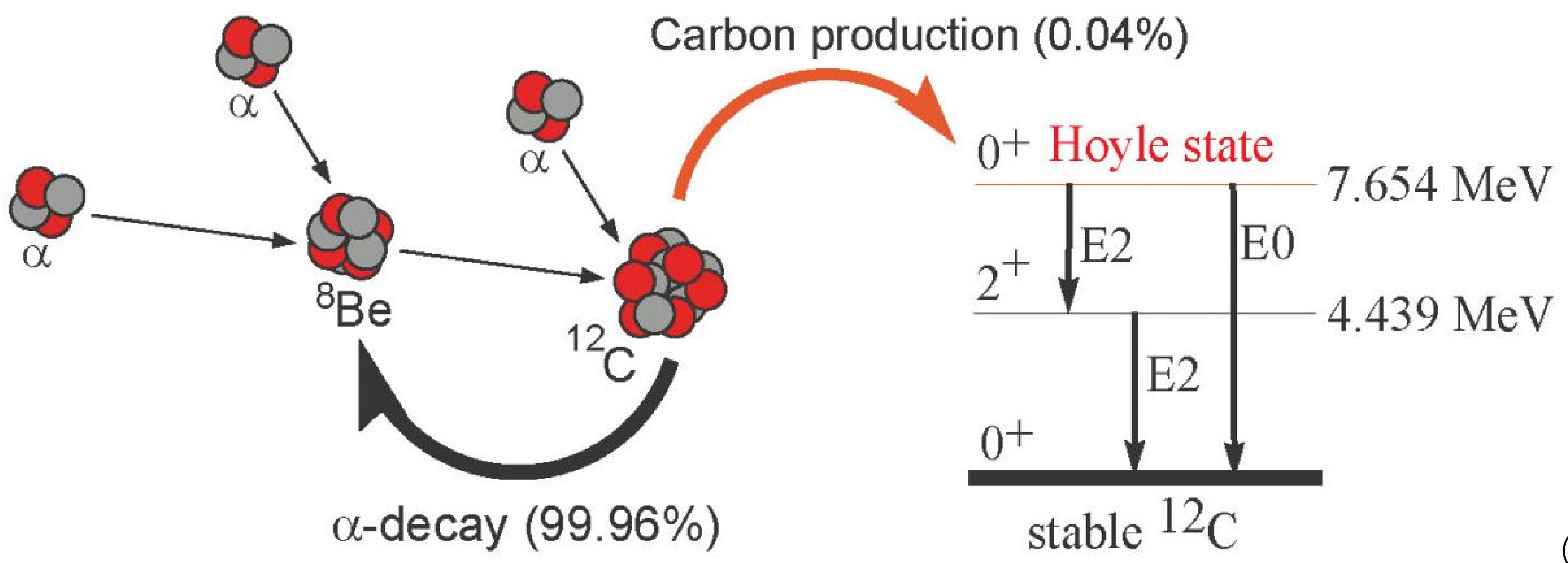
M. Chernykh et al., Phys. Rev. Lett. 98 (2007) 032501

- and how about theory ? $\rightarrow$ this talk

- side remark: NOT driven by anthropic considerations

H. Kragh, Arch. Hist. Exact Sci. 64 (2010) 721

THE TRIPLE-ALPHA PROCESS



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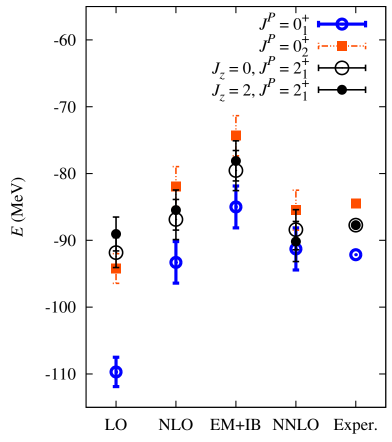
- the ^{8}Be nucleus is instable, long lifetime → 3 alphas must meet
- the Hoyle state sits just above the continuum threshold
  → most of the excited carbon nuclei decay
  (about 4 out of 10000 decays produce stable carbon)
- carbon is further turned into oxygen but w/o a resonant condition

⇒a triple wonder !

The RELEVANT QUESTION

Date: Sat, 25 Dec 2010 20:03:42 -0600
From: Steven Weinberg ⟨weinberg@zippy.ph.utexas.edu⟩
To: Ulf-G. Meissner ⟨meissner@hiskp.uni-bonn.de⟩
Subject: Re: Hoyle state in 12C



Dear Professor Meissner,

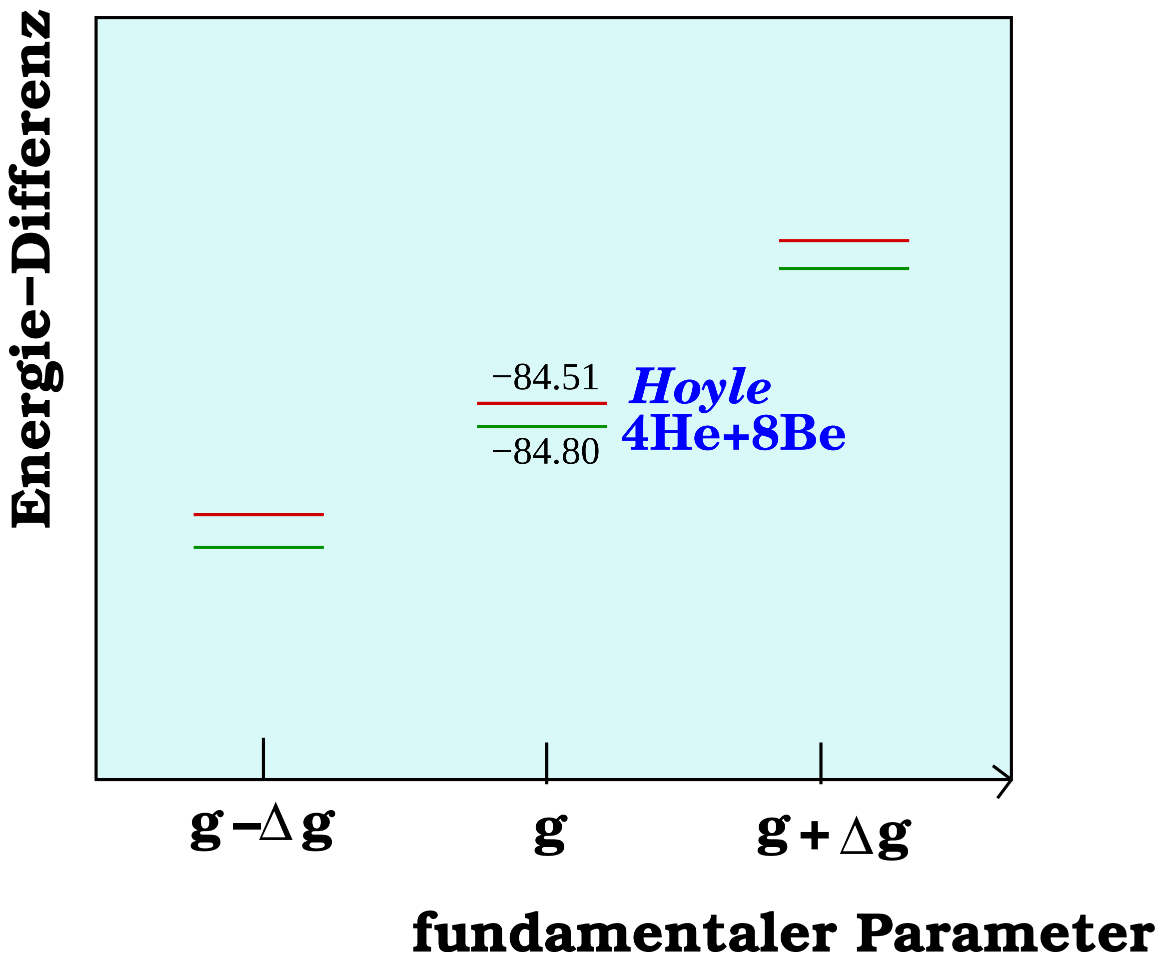
Thanks for the colorful graph. It makes a nice Christmas card. But I have a detailed question. Suppose you calculate not only the energy of the Hoyle state in C12, but also of the ground states of He4 and Be8. How sensitive is the result that the energy of the Hoyle state is near the sum of the rest energies of He4 and Be8 to the parameters of the theory? I ask because I suspect that for a pretty broad range of parameters, the Hoyle state can be well represented as a nearly bound state of Be8 and He4.

All best,
Steve Weinberg

- How does the Hoyle state relative to the 4He+8Be threshold, if we change the fundamental parameters of QCD+QED?
- not possible in nature, *but on a high-performance computer!*

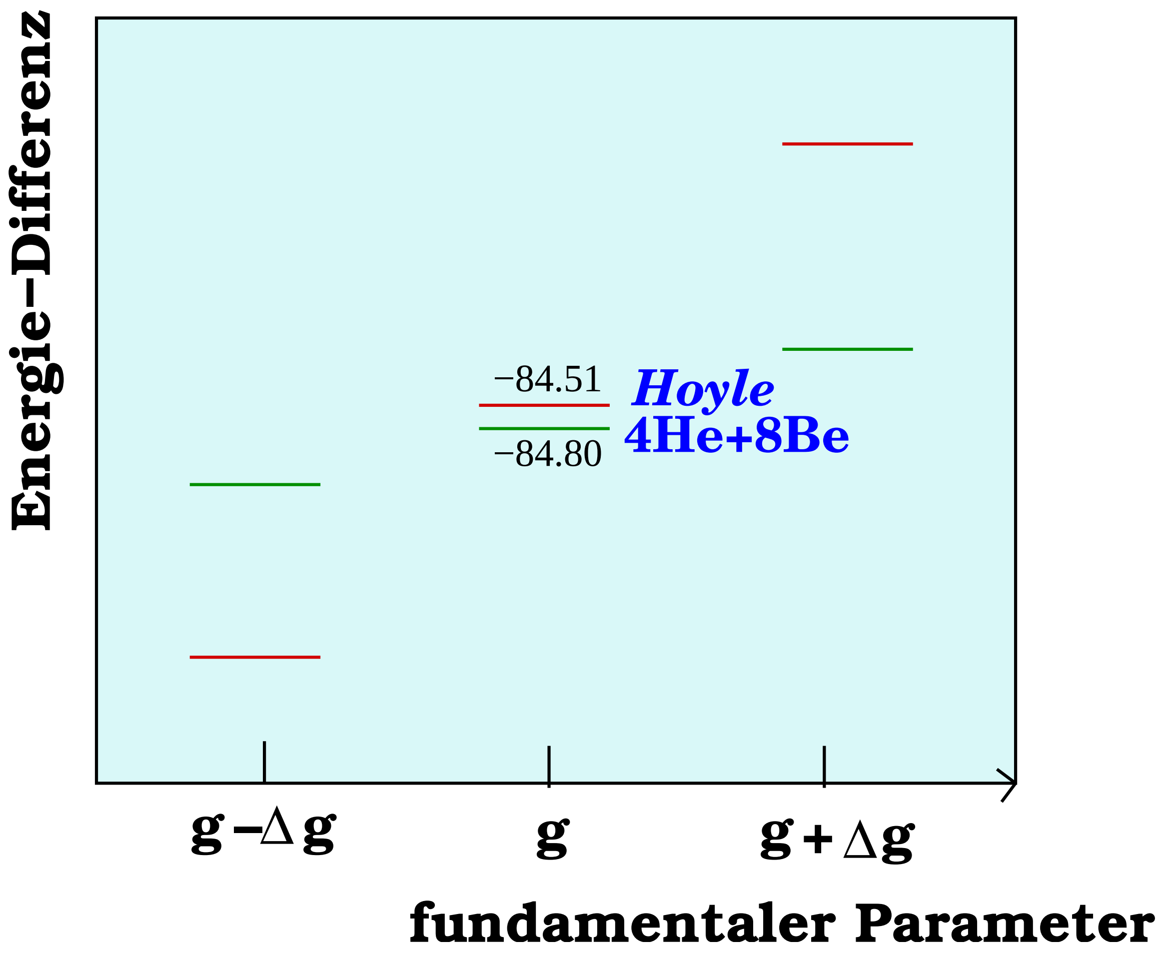
The NON-ANTHROPIC SCENARIO

- Weinberg's assumption: The Hoyle state stays close to the 4He+8Be threshold



The ANTHROPIC SCENARIO

- The AP strikes back: The Hoyle state moves away from the 4He+8Be threshold



EARLIER STUDIES of the AP

- By hand modification of the energy diff. & network calcs in massive stars

  Livio et al., Nature 340 (1989) 281

  ↪ a 60 keV increase does not significantly alter carbon production

  ↪ a 60 keV decrease roughly doubles the carbon production rate

  ↪ a $\pm\mathbf{277}$ keV change leaves essentially no carbon (just oxygen)

  ↪ weak conclusion: the strong AP might be in trouble

- Changing NN and em interactions in a microscopic model & network calcs

  Oberhummer et al., Science 289 (2000) 88

  ↪ modified NN strength & fine structure constant in $[\mathbf{0.996}, \mathbf{1.004}]$

  ↪ no influence on the width but on the relative position of the Hoyle state

  ↪ use up-to-date stellar evolution model

  ↪ more than $\mathbf{0.5}[\mathbf{4}]\%$ in the strong coupling $[\alpha_{\mathbf{QED}}]$ would destroy all carbon (oxygen) in stars

  ↪ "should be of interest to AP considerations"

Introduction II: Effective Field Theory for Nuclear Physics

only a brief reminder → details in

E. Epelbaum, H.-W. Hammer, UGM, Rev. Mod. Phys. **81** (2009) 1773 [arXiv:0811.1338 [nucl-th]]

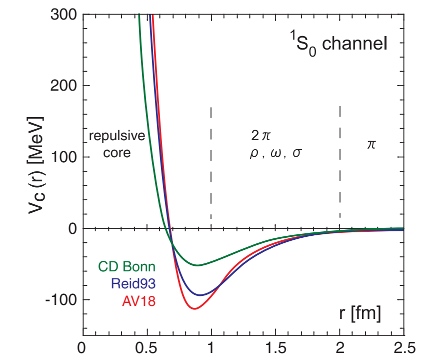
CHIRAL EFT FOR FEW-NUCLEON SYSTEMS

Gasser, Leutwyler, Weinberg, van Kolck, Epelbaum, Bernard, Kaiser, UGM, . . .

• Scales in nuclear physics:

Natural: $\lambda_\pi = 1/M_\pi \simeq 1.5$ fm (Yukawa 1935)

Unnatural: $|a_{np}(^1S_0)| = 23.8\,\text{fm}\,,\; a_{np}(^3S_1) = 5.4\,\text{fm} \gg 1/M_\pi$



• this can be analyzed in a suitable EFT based on

$$\mathcal{L}_{\rm QCD} \to \mathcal{L}_{\rm EFF} = \mathcal{L}_{\pi\pi} + \mathcal{L}_{\pi N} + \mathcal{L}_{NN} + \ldots$$

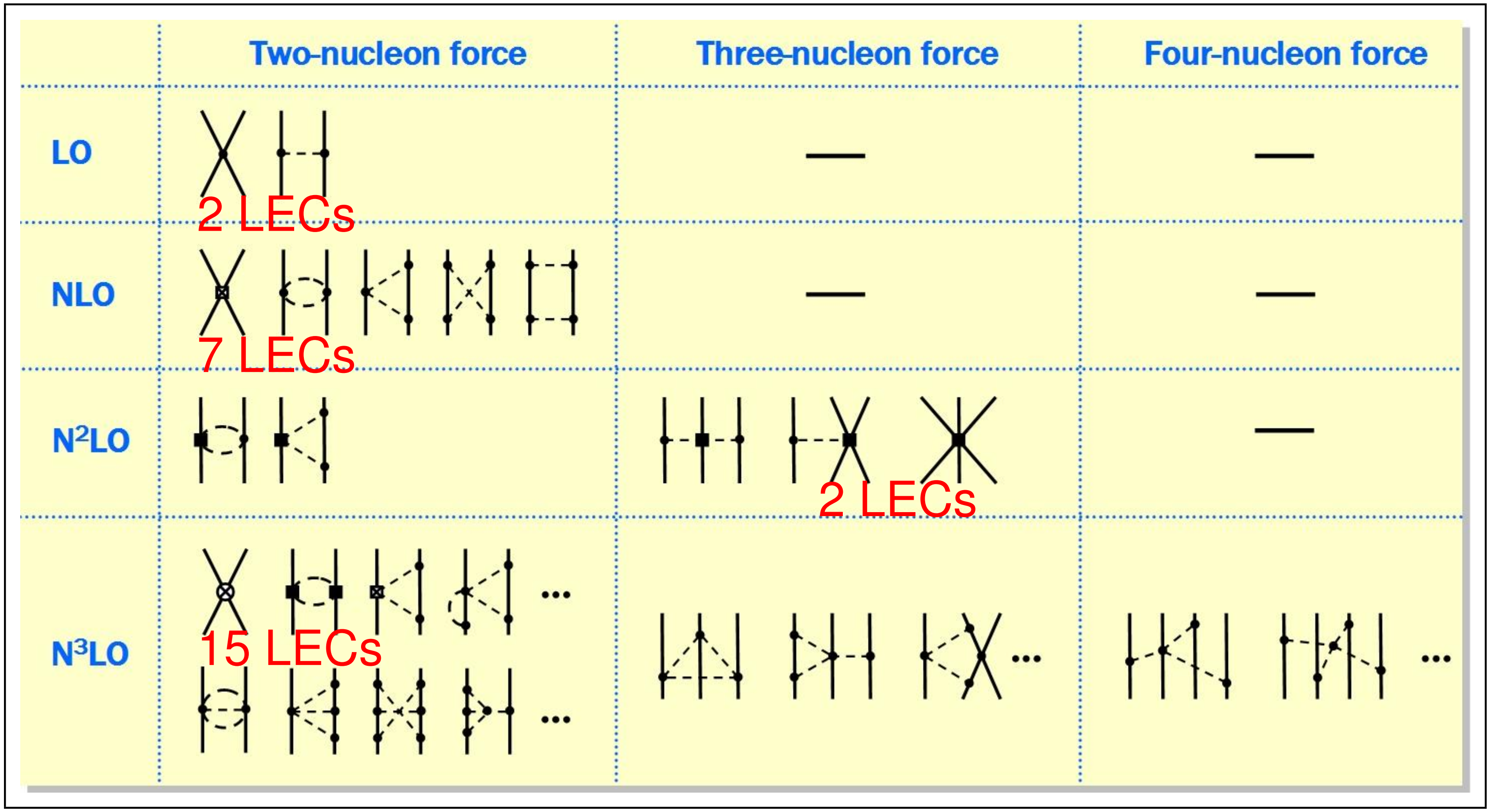
• pion and pion-nucleon sectors are perturbative in Q/Λ_χ → chiral perturbation th'y

• $\mathcal{L}_{NN}$ collects short-distance contact terms, to be fitted

• NN interaction requires non-perturbative resummation

→ chirally expand $\text{V}_{\rm NN(N)}$, use in regularized LS/FY equation

CHIRAL POTENTIAL and NUCLEAR FORCES



$\mathcal{O}((Q/\Lambda_\chi)^0)$

$\mathcal{O}((Q/\Lambda_\chi)^2)$

$\mathcal{O}((Q/\Lambda_\chi)^3)$

$\mathcal{O}((Q/\Lambda_\chi)^4)$

- explains naturally the observed hierarchy of nuclear forces
- MANY successfull tests in few-nucleon systems (continuum calc's)

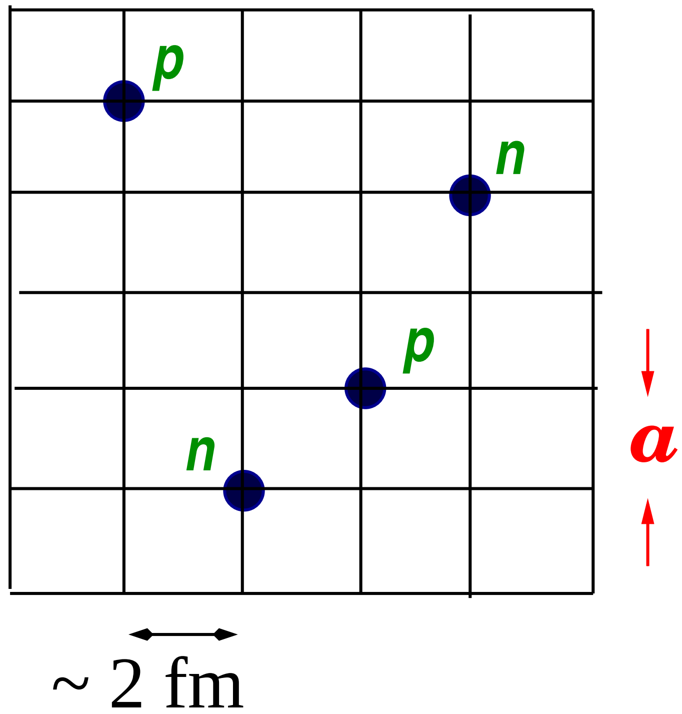
Nuclear lattice simulations – Formalism –

NUCLEAR LATTICE SIMULATIONS

Frank, Brockmann (1992), Koonin, Müller, Seki, van Kolck (2000) , Lee, Schäfer (2004), . . .
Borasoy, Krebs, Lee, UGM, Nucl. Phys. **A768** (2006) 179; Borasoy, Epelbaum, Krebs, Lee, UGM, Eur. Phys. J. **A31** (2007) 105

- *new method* to tackle the nuclear many-body problem
- discretize space-time $V = L_s \times L_s \times L_s \times L_t$:
  nucleons are point-like fields on the sites
- discretized chiral potential w/ pion exchanges
  and contact interactions
- typical lattice parameters

$$\Lambda = \frac{\pi}{a} \simeq 300\,\text{MeV [UV cutoff]}$$

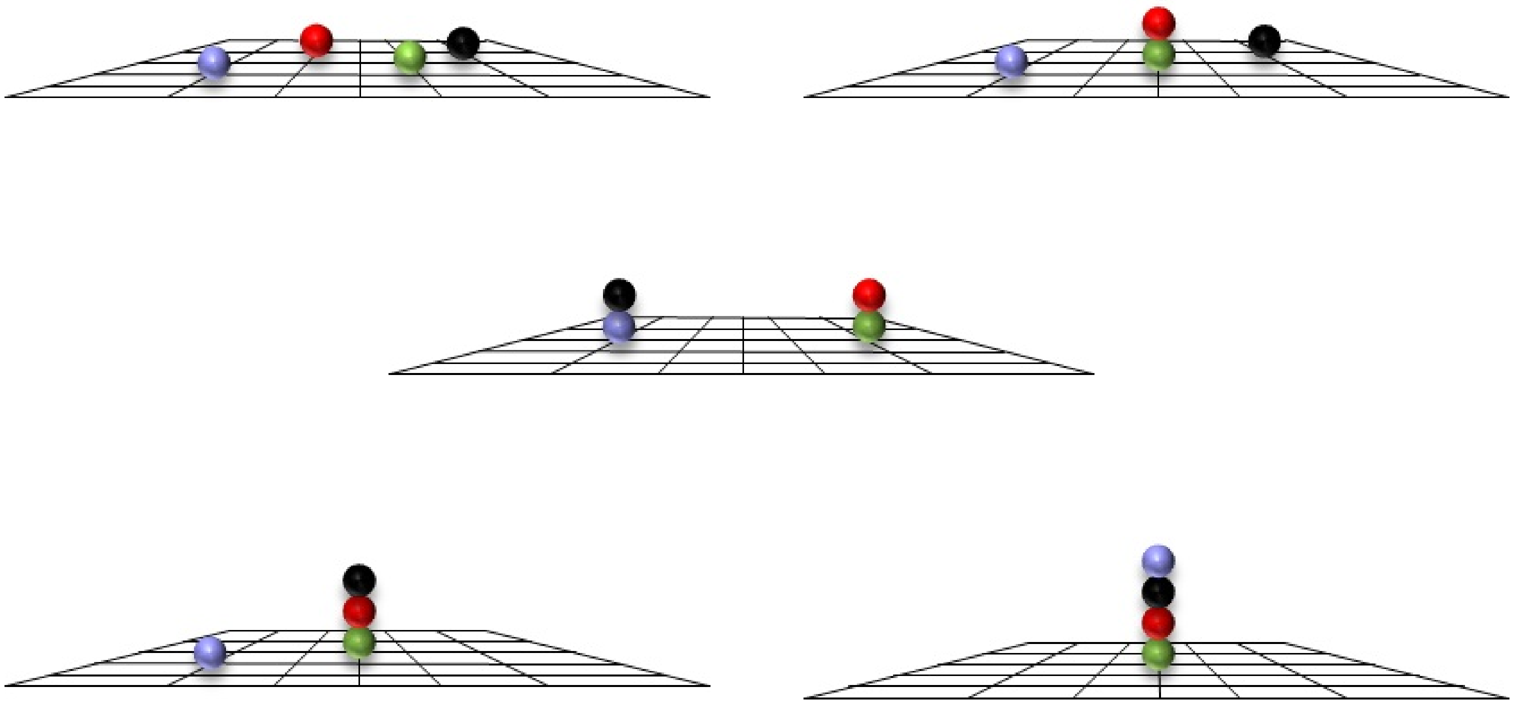


- strong suppression of sign oscillations due to approximate Wigner SU(4) symmetry

J. W. Chen, D. Lee and T. Schäfer, Phys. Rev. Lett. **93** (2004) 242302

- hybrid Monte Carlo & transfer matrix (similar to LQCD)

CONFIGURATIONS



⇒ all *possible* configurations are sampled

⇒ *clustering* emerges *naturally*

TRANSFER MATRIX METHOD

- Correlation–function for A nucleons: $Z_A(t) = \langle\Psi_A|\exp(-tH)|\Psi_A\rangle$

  with Ψ_A a Slater determinant for A free nucleons

Euclidean time

- Ground state energy from the time derivative of the correlator

$$E_A(t) = -\frac{d}{dt}\ln Z_A(t)$$

$\to$ ground state filtered out at large times: $E_A^0 = \lim_{t\to\infty} E_A(t)$

- Expectation value of any normal–ordered operator $\mathcal{O}$

$$Z_A^{\mathcal{O}} = \langle\Psi_A|\exp(-tH/2)\,\mathcal{O}\,\exp(-tH/2)\,|\Psi_A\rangle$$

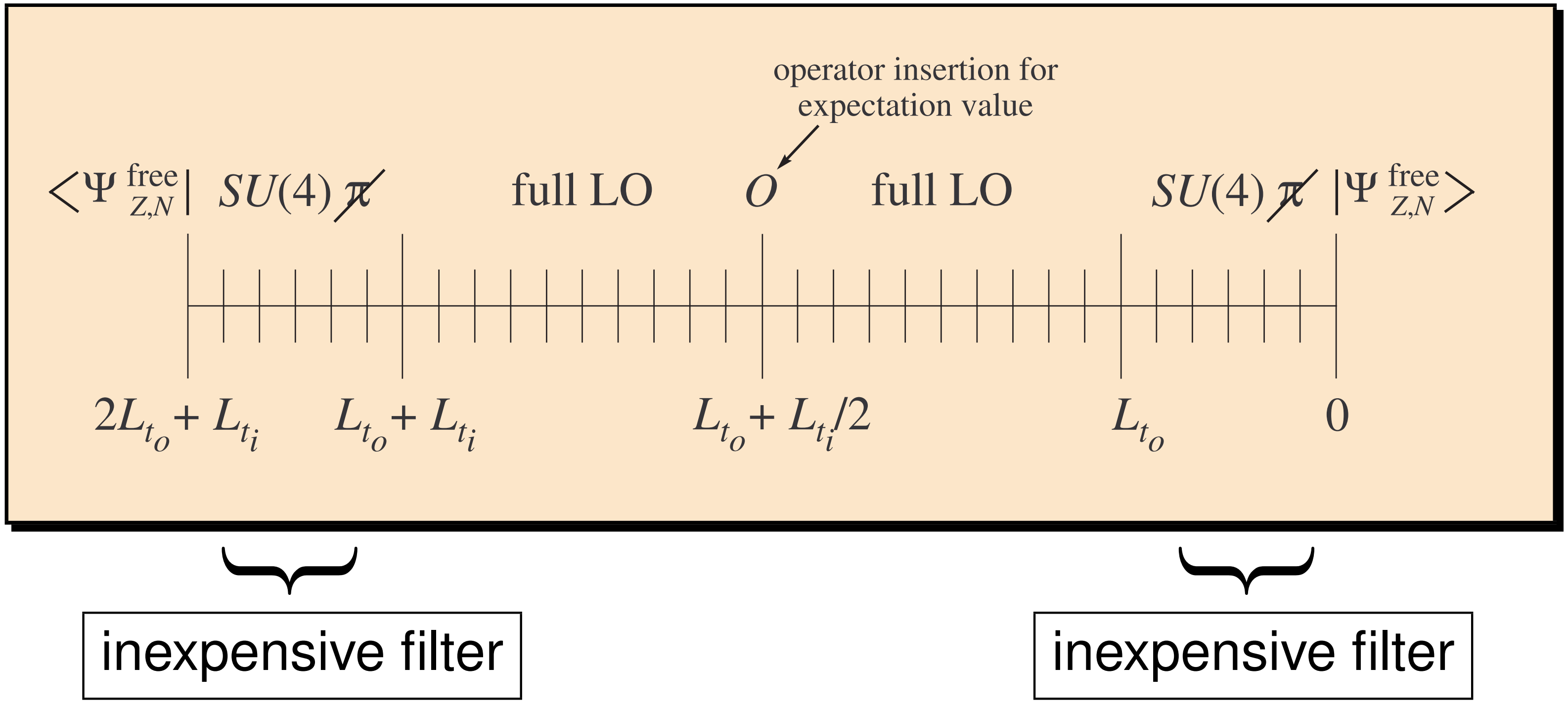
$$\lim_{t\to\infty}\frac{Z_A^{\mathcal{O}}(t)}{Z_A(t)} = \langle\Psi_A|\mathcal{O}\,|\Psi_A\rangle$$

TRANSFER MATRIX CALCULATION

- Expectation value of any normal–ordered operator $\mathcal{O}$

$$\langle \Psi_A | \mathcal{O} | \Psi_A \rangle = \lim_{t\to\infty} \frac{\langle \Psi_A | \exp(-tH/2)\, \mathcal{O}\, \exp(-tH/2) | \Psi_A \rangle}{\langle \Psi_A | \exp(-tH) | \Psi_A \rangle}$$

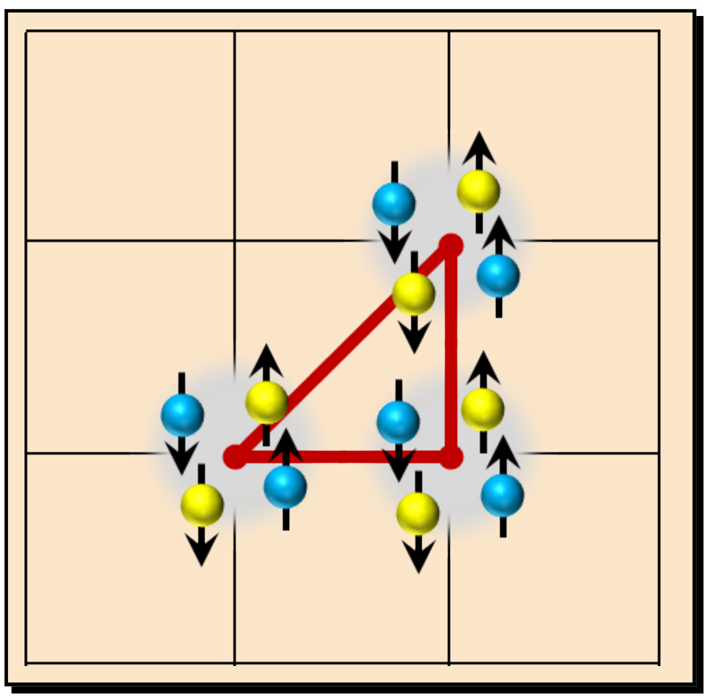
- Anatomy of the transfer matrix

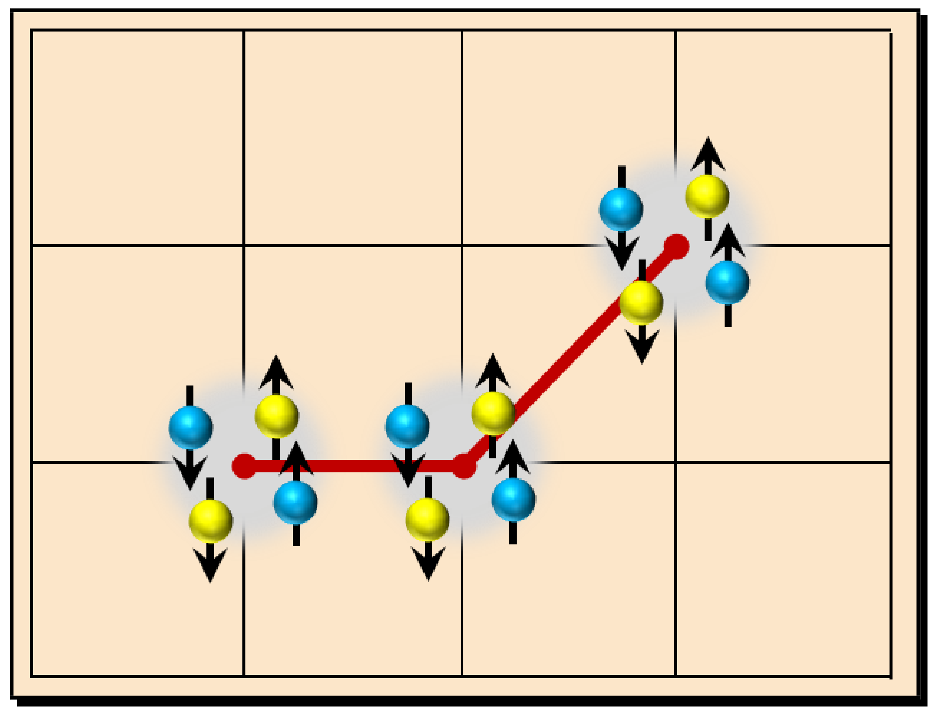


PROJECTION MONTE CARLO TECHNIQUE

- Insert clusters of nucleons at initial/final states (spread over some time interval)
  $\rightarrow$ allows for all type of wave functions (shell model, clusters, ...)
  $\rightarrow$ removes directional bias

- Example: two basic configurations in the spectrum of ^{12}C

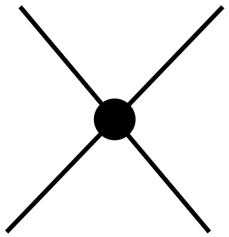




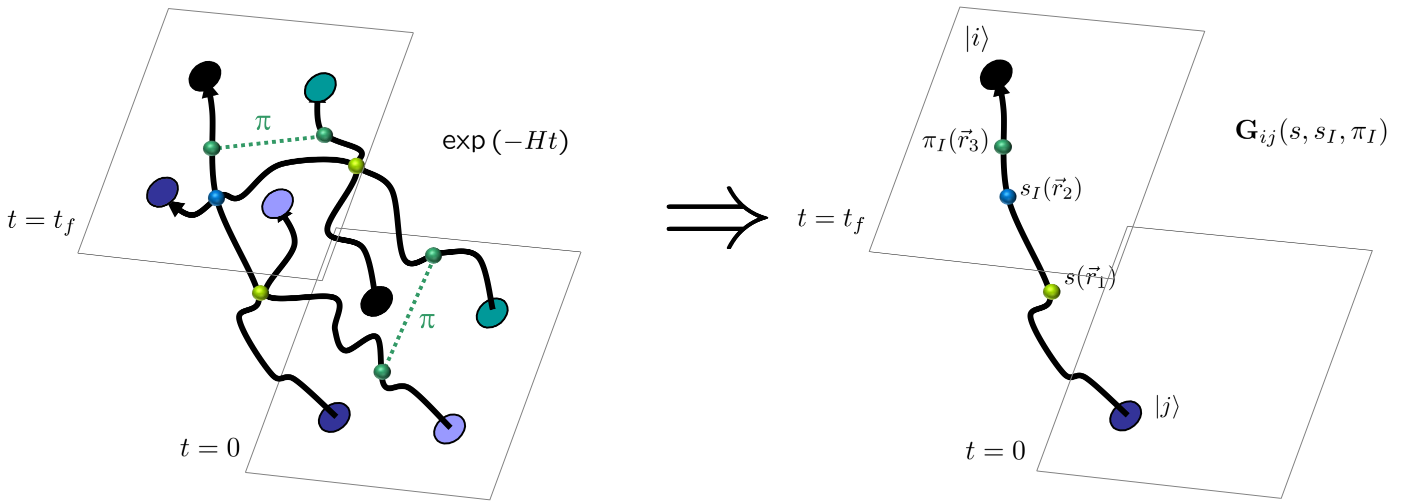
MONTE CARLO with AUXILIARY FILEDS

- Contact interactions represented by auxiliary fields s, s_I

$$\exp(\rho^2/2) \propto \int_{-\infty}^{+\infty} ds\, \exp(-s^2/2 - s\rho)\ , \quad \rho \sim N^\dagger N$$



- Correlation function = path-integral over pions & auxiliary fields

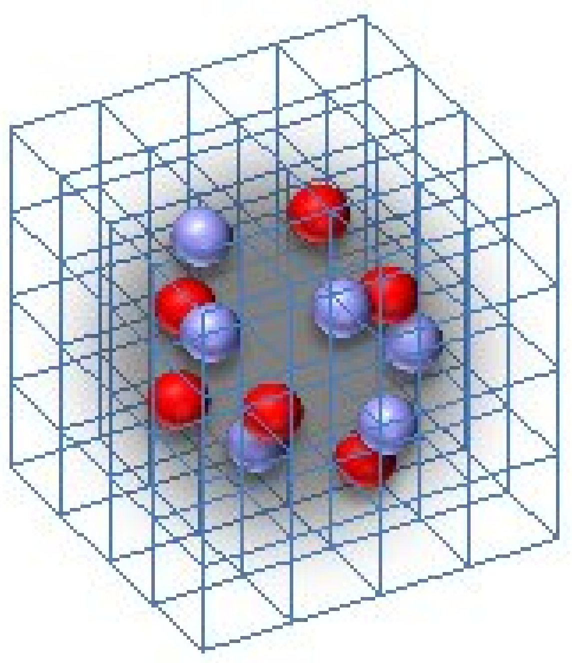


COMPUTATIONAL EQUIPMENT

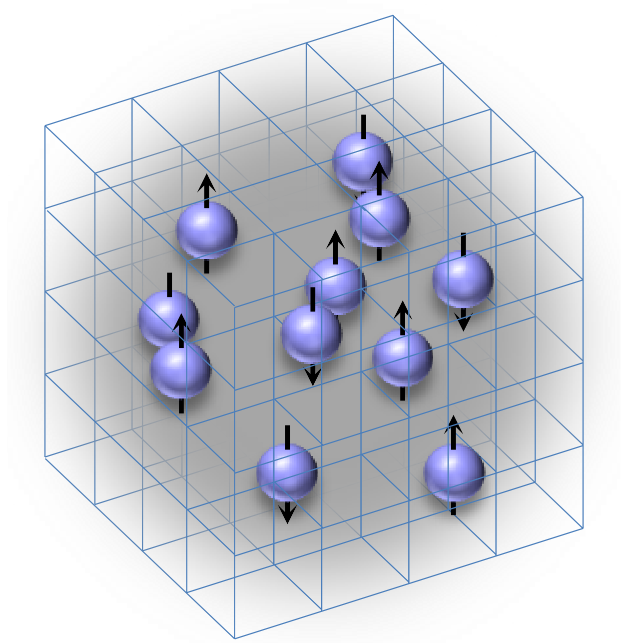
- Past = JUGENE (BlueGene/P)
- Present = JUQUEEN (BlueGene/Q)

Nuclear lattice simulations – Results –

nuclei



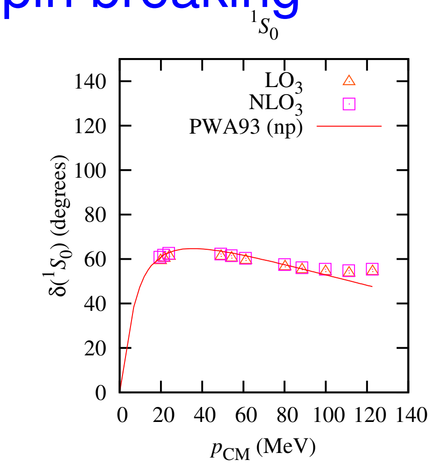
neutron matter

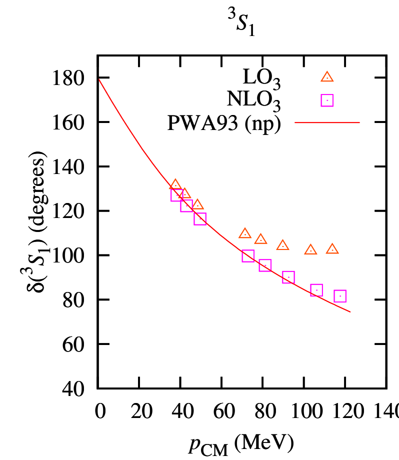


FIXING PARAMETERS & FIRST PREDICTIONS

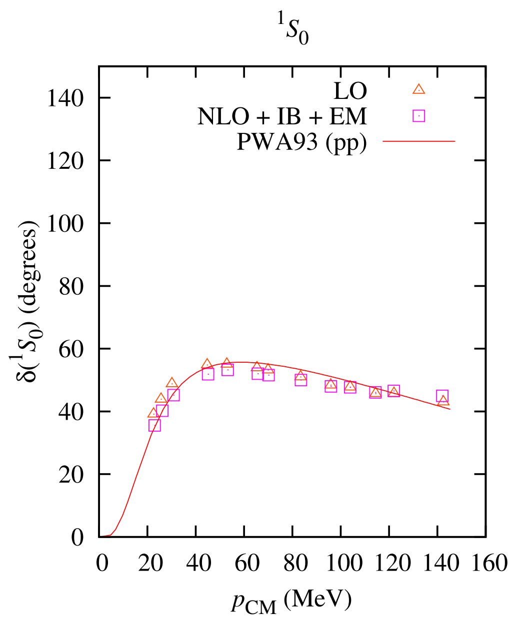
- work at NNLO including strong and em isospin breaking
- 9 NN LECs from np scattering and Q_d
- 2 LECs for isospin-breaking (np, pp, nn)
- 2 LECs D, E related to the leading 3NF

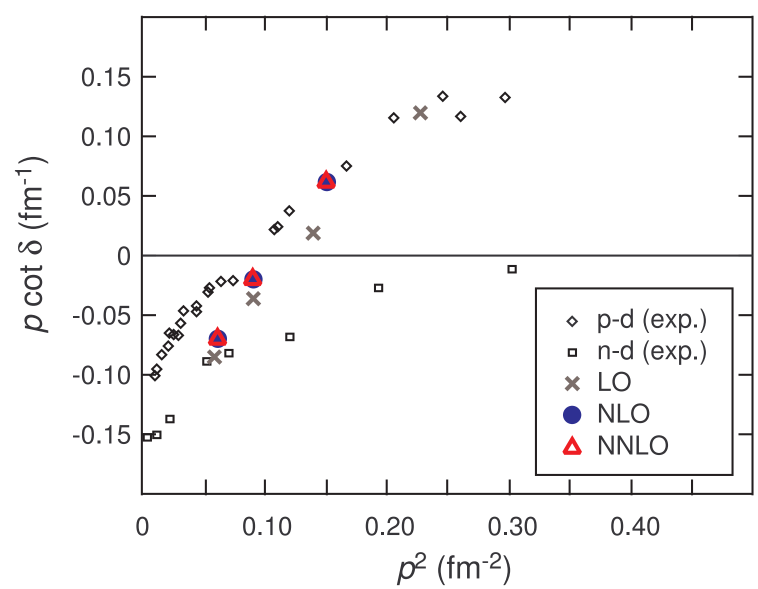
$\Rightarrow$ make predictions





- pp vs np scattering
- nd spin-3/2 quartet channel
- . . .





Ground states

Epelbaum, Krebs, Lähde, Lee, UGM, arxiv:1208.1328

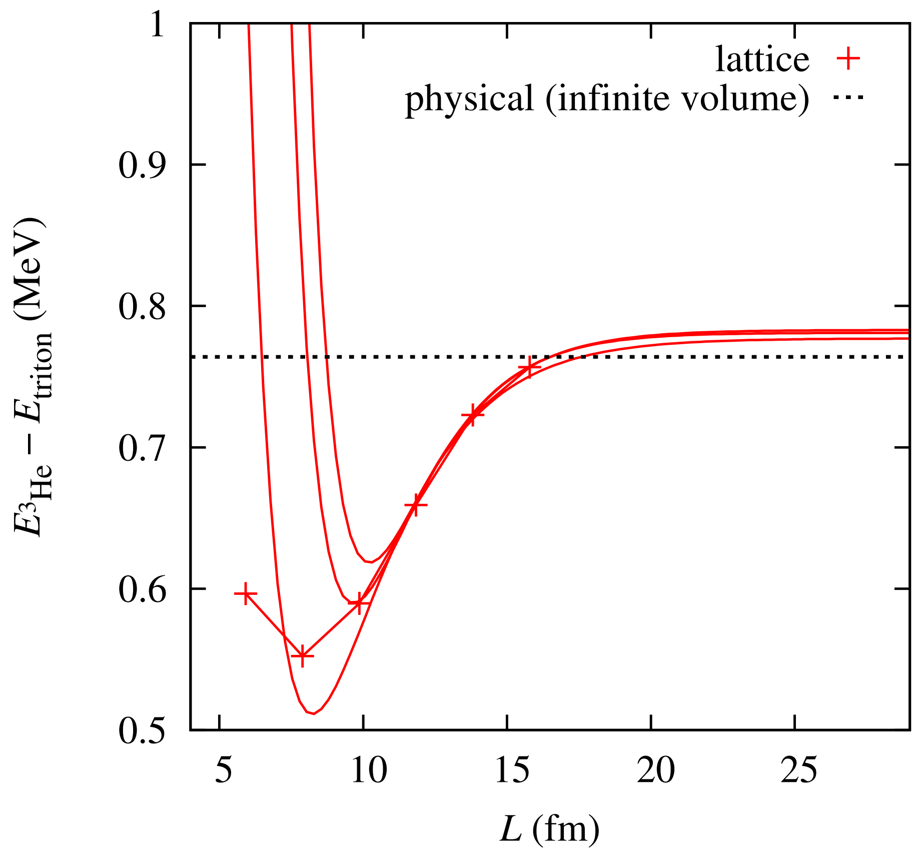
PREDICTIONS: TRITON & HELIUM-3

Epelbaum, Krebs, Lee, UGM, Phys. Rev. Lett. **104** (2010) 142501; Eur. Phys. J. **A 45** (2010) 335

- binding energies of 3N systems: $E(L) = \text{B.E.} - \frac{a}{L}\exp(-bL)$

see also Hammer, Kreuzer (2011)

$\Rightarrow$ predict the energy difference $E(^3He) - E(^3H)$

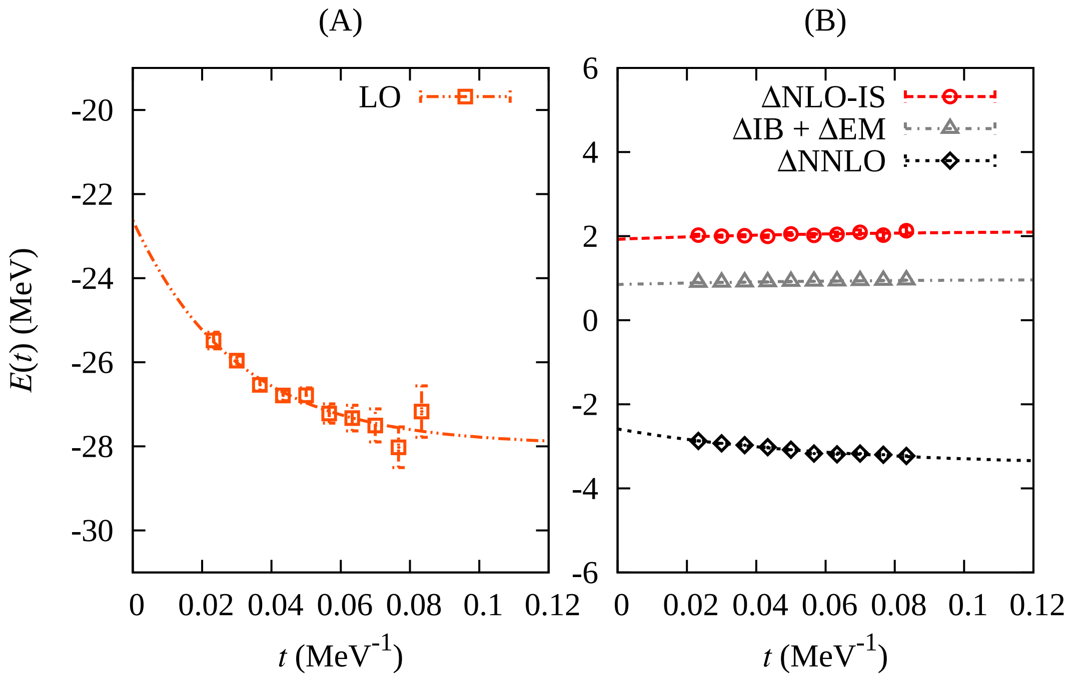


0.78(5) MeV

0.76 MeV [exp.]

Ground state of ^{4}He

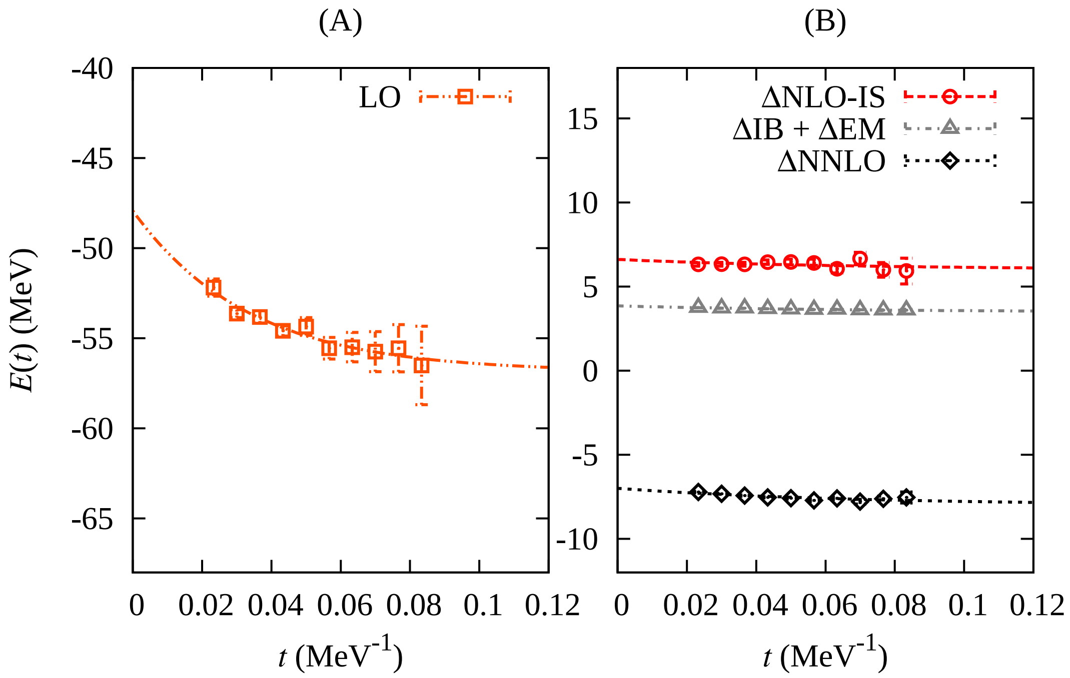
$$L = 11.8 \text{ fm}$$



LO ($\mathcal{O}(Q^0)$)	$-28.0(3)$ MeV
NLO ($\mathcal{O}(Q^2)$)	$-24.9(5)$ MeV
NNLO ($\mathcal{O}(Q^3)$)	$-28.3(6)$ MeV
Exp.	-28.3 MeV

Ground state of ^{8}Be

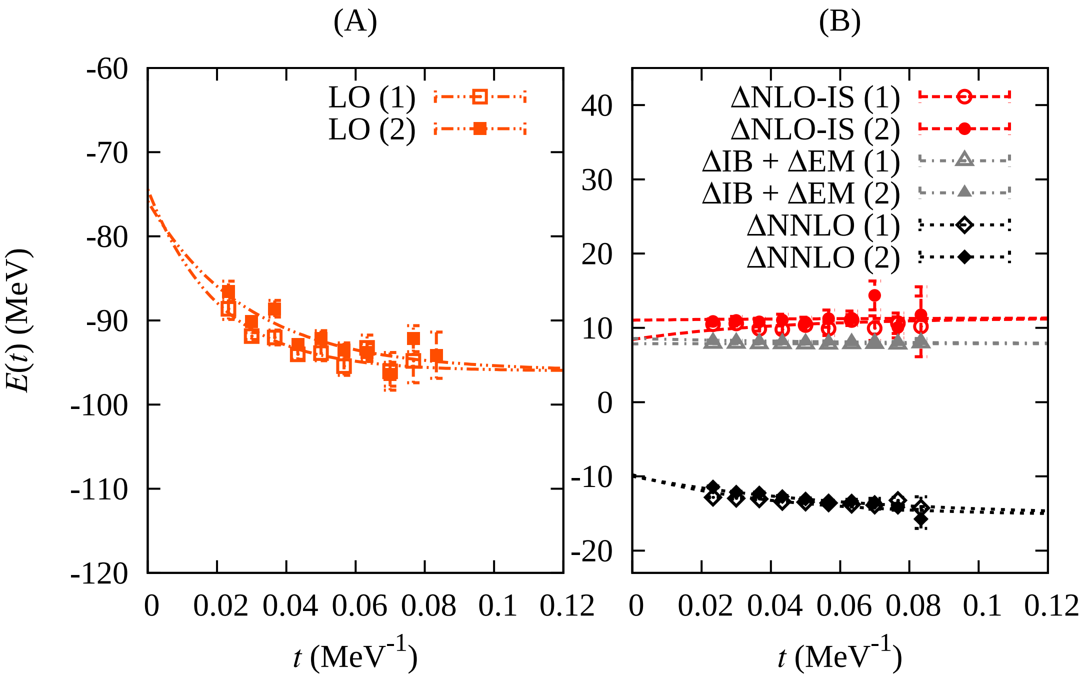
$$L = 11.8 \text{ fm}$$



LO ($\mathcal{O}(Q^0)$)	$-57(2)$ MeV
NLO ($\mathcal{O}(Q^2)$)	$-47(2)$ MeV
NNLO ($\mathcal{O}(Q^3)$)	$-55(2)$ MeV
Exp.	-56.5 MeV

Ground state of ^{12}C

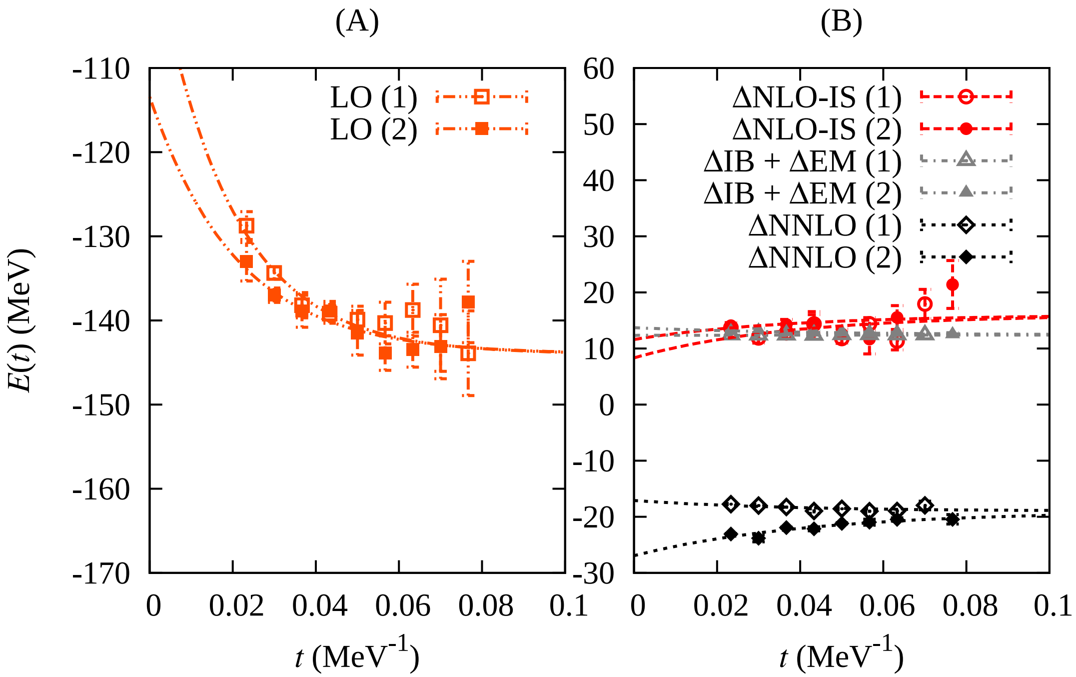
$$L = 11.8 \text{ fm}$$



LO ($\mathcal{O}(Q^0)$)	$-96(2)$ MeV
NLO ($\mathcal{O}(Q^2)$)	$-77(3)$ MeV
NNLO ($\mathcal{O}(Q^3)$)	$-92(3)$ MeV
Exp.	-92.2 MeV

Ground state of ^{16}O

$$L = 11.8 \text{ fm}$$

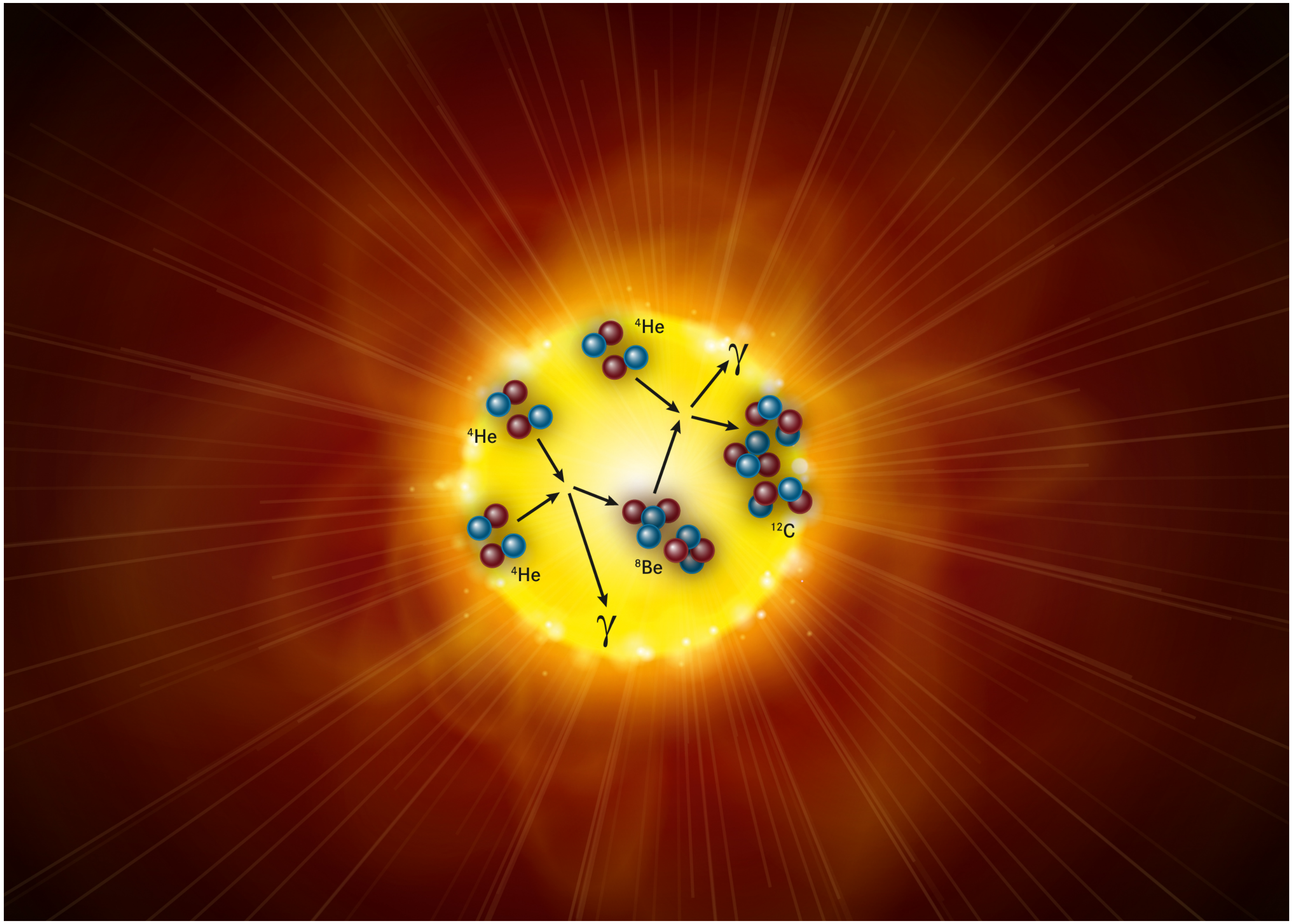


to be published

LO ($\mathcal{O}(Q^0)$)	$-144(4)$ MeV
NLO ($\mathcal{O}(Q^2)$)	$-116(6)$ MeV
NNLO ($\mathcal{O}(Q^3)$)	$-135(6)$ MeV
Exp.	-127.6 MeV

SPECTRUM OF ^{12}C & the HOYLE STATE

Epelbaum, Krebs, Lee, UGM, Phys. Rev. Lett. **106** (2011) 192501
Viewpoint: Hjorth-Jensen, Physics **4** (2011) 38
Epelbaum, Krebs, Lähde, Lee, UGM, arxiv:1208.1328 (numbers from this ref.)

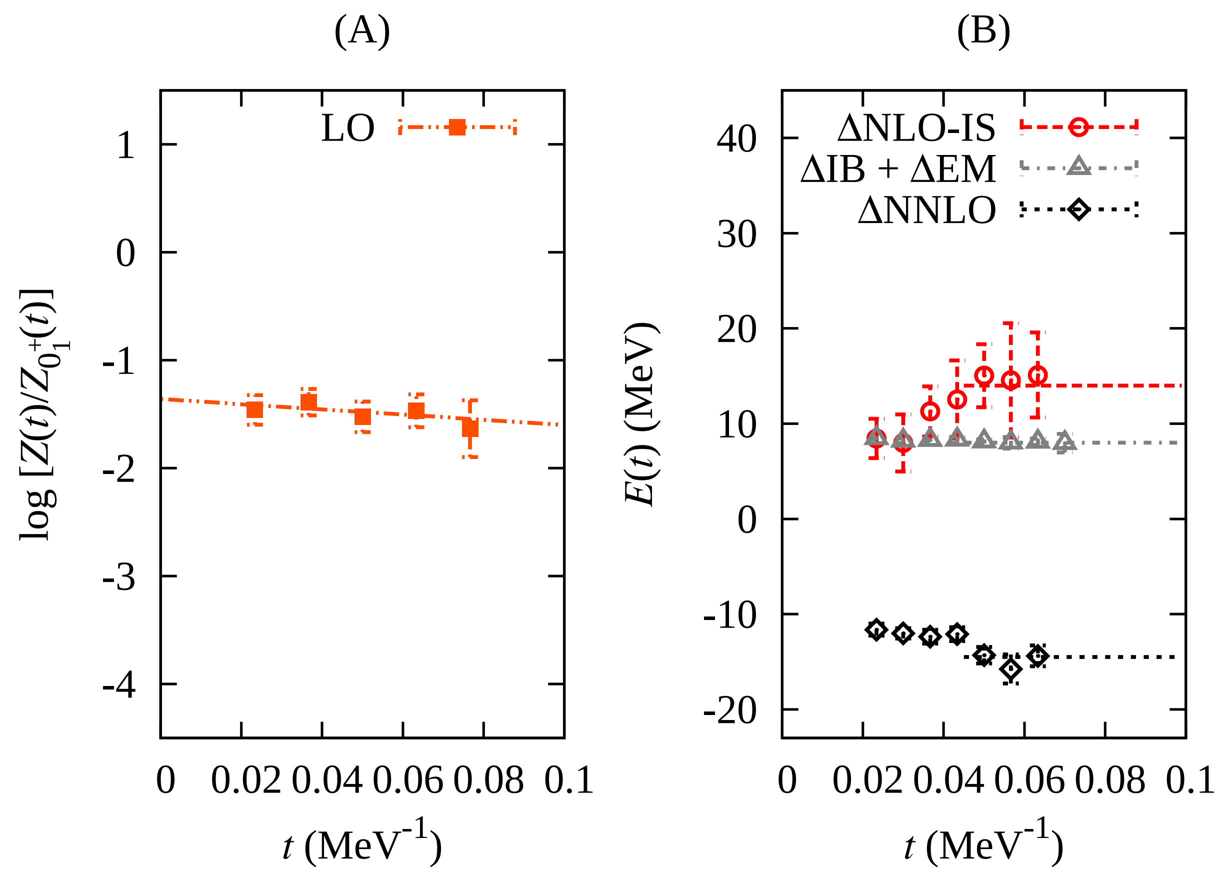


EXCITED STATES of ^{12}C

- Lowest excited state is $\mathbf{2_1^+}$ (as in nature)

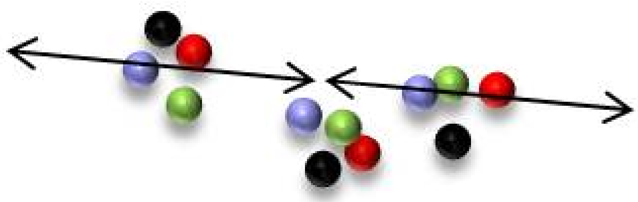
$$E(2_1^+) = -89(3)\ \text{MeV}$$

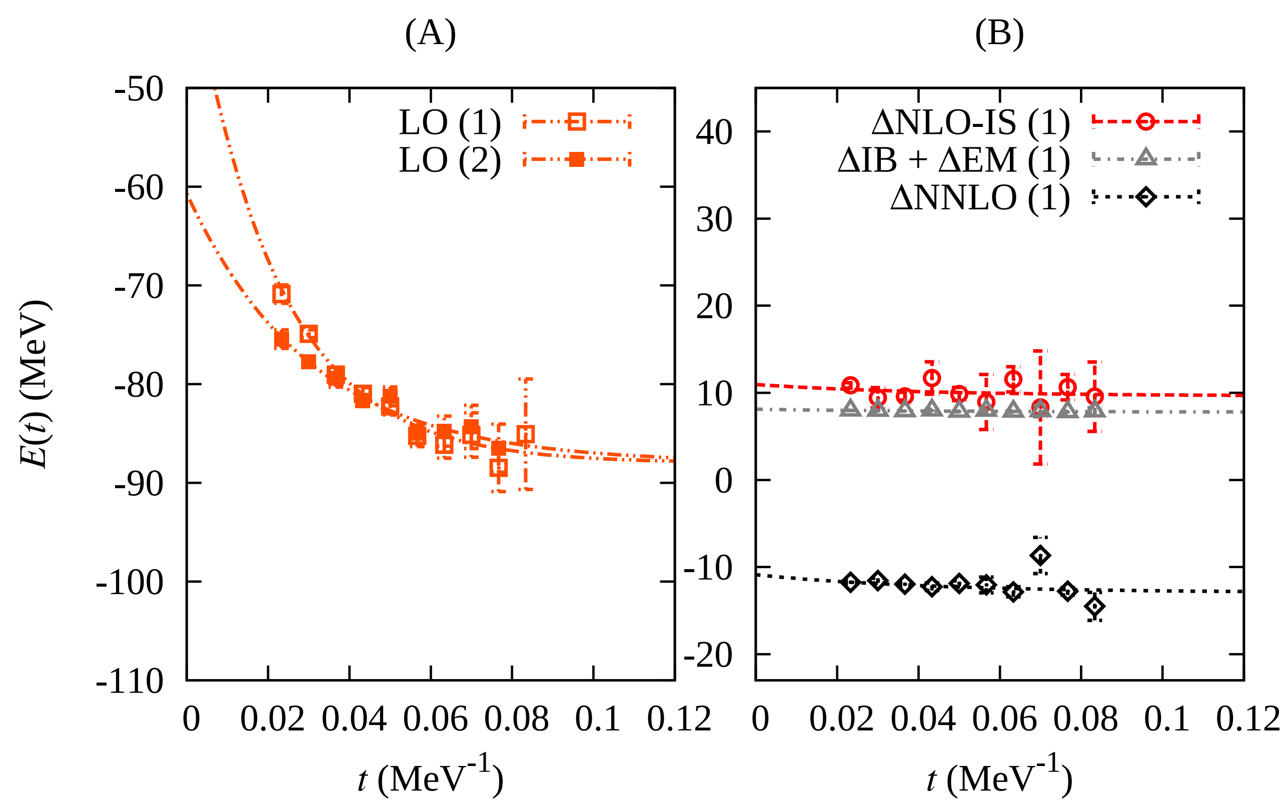
$$[-87.7\ \text{MeV}]$$



THE HOYLE STATE (0_2^+)

- energy: $E(0_2^+) = -85(3)$ MeV
- close to $E(^4\mathrm{He}) + E(^8\mathrm{Be}) = -83.3(2.0)$ MeV
- structure: “bent” alpha-chain like (not “BEC”)





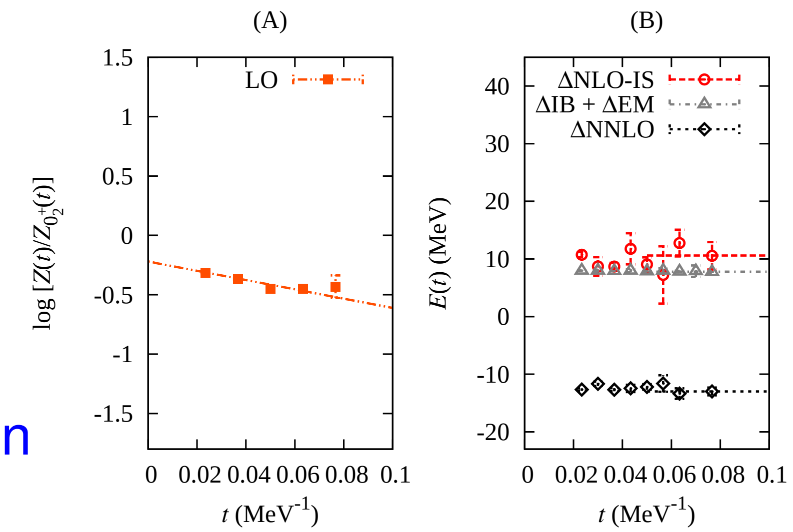
A HOYLE STATE EXCITATION (2_2^+)

- a 2^+ state 2 MeV above the Hoyle state

- interpretation:

  a rotational band of the Hoyle state

  generated from excitations of the alpha-chain



- what's in the data ?

  a 2^+ state 3.51 MeV above the Hoyle state seen in $^{11}B(d,n)^{12}C$
  not included in the level scheme! Ajzenberg-Selove, Nucl. Phys. A506 (1990) 1

  a 2^+ state 3.8(4) MeV above the Hoyle state seen in $^{12}C(\alpha,\alpha)^{12}C$
  Bency John et al., Phys. Rev. C 68 (2003) 014305

- and much more, see next slide and: $\rightarrow$ talk by Henry Weller

$\Rightarrow$ ab initio prediction requires experimental confirmation

SPECTRUM OF ^{12}C

- Summarizing the results for carbon-12:

	0_1^+	2_1^+	0_2^+	2_2^+
LO NLO NNLO	$-96(2)$ MeV $-77(3)$ MeV $-92(3)$ MeV	$-94(2)$ MeV $-74(3)$ MeV $-89(3)$ MeV	$-89(2)$ MeV $-72(3)$ MeV $-85(3)$ MeV	$-88(2)$ MeV $-70(3)$ MeV $-83(3)$ MeV
Exp.	-92.16 MeV	-87.72 MeV	-84.51 MeV	$-82.6(1)$ MeV [1,2] $-82.32(6)$ MeV [3] $-81.1(3)$ MeV [4] $-82.13(11)$ MeV [5]

[1] Freer et al., Phys. Rev. C 80 (2009) 041303
[2] Zimmermann et al., Phys. Rev. C 84 (2011) 027304
[3] Hyldegaard et al., Phys. Rev. C 81 (2010) 024303
[4] Itoh et al., Phys. Rev. C 84 (2011) 054308
[5] Weller et al., in preparation

- importance of consistent 2N & 3N forces
- good agreement w/ experiment, can be improved

Testing the Anthropic Principle

MC ANALYSIS of the AP

- consider QCD only $\rightarrow$ calculate $\partial \Delta E / \partial M_\pi$
- relevant quantities (energy *differences*)

$$\boxed{\Delta E_h \equiv E_{12}^* - E_8 - E_4, \quad \Delta E_b \equiv E_8 - 2E_4} \qquad \Delta E_c \equiv E_{12}^* - E_{12}$$

- energy differences depend on parameters of QCD (LO analysis)

$$\boxed{E_i = E_i\left(M_\pi^{\rm OPE}, m_N(M_\pi), \tilde{g}_{\pi N}(M_\pi), C_0(M_\pi), C_I(M_\pi)\right)}$$

$$\tilde{g}_{\pi N} \equiv \frac{g_A}{2F_\pi}$$

- remember: $M_{\pi^\pm}^2 \sim (m_u + m_d)$

$\Rightarrow$ quark mass dependence $\equiv$ pion mass dependence

PION MASS VARIATIONS

- consider pion mass changes as *small perturbations*

$$\left.\frac{\partial E_i}{\partial M_\pi}\right|_{M_\pi^{\rm phys}} = \left.\frac{\partial E_i}{\partial M_\pi^{\rm OPE}}\right|_{M_\pi^{\rm phys}} + x_1 \left.\frac{\partial E_i}{\partial m_N}\right|_{m_N^{\rm phys}} + x_2 \left.\frac{\partial E_i}{\partial \tilde g_{\pi N}}\right|_{\tilde g_{\pi N}^{\rm phys}} + x_3 \left.\frac{\partial E_i}{\partial C_0}\right|_{C_0^{\rm phys}} + x_4 \left.\frac{\partial E_i}{\partial C_I}\right|_{C_I^{\rm phys}}$$

with

$$x_1 \equiv \left.\frac{\partial m_N}{\partial M_\pi}\right|_{M_\pi^{\rm phys}} , \; x_2 \equiv \left.\frac{\partial \tilde g_{\pi N}}{\partial M_\pi}\right|_{M_\pi^{\rm phys}} , \; x_3 \equiv \left.\frac{\partial C_0}{\partial M_\pi}\right|_{M_\pi^{\rm phys}} , \; x_4 \equiv \left.\frac{\partial C_I}{\partial M_\pi}\right|_{M_\pi^{\rm phys}}$$

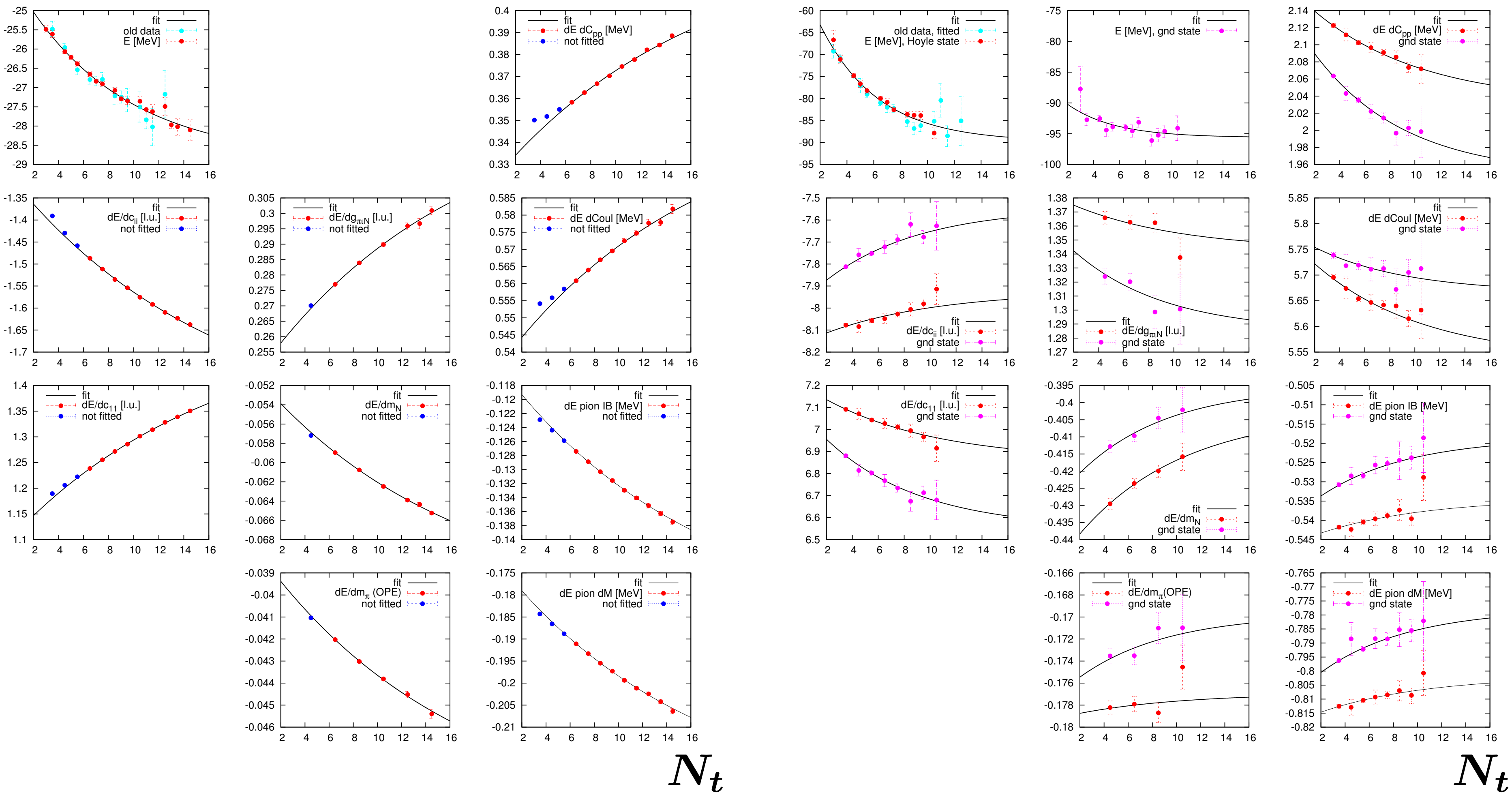
$\Rightarrow$ problem reduces to the calculation of the various derivatives using AFQMC and the determination of the x_i

- x_1 and x_2 can be obtained from LQCD plus CHPT
- x_3 and x_4 can be obtained from two-body scattering and its M_π-dependence

AFQMC RESUTS for the DERIVATIVES

- ^{4}He
- ^{12}C(0_2^+)

$$E(N_t) = E(\infty) + \text{const}\ \exp(-N_t/\tau)$$



DETERMINATION of the x_i

- x_1 from the quark mass expansion of the nucleon mass: $x_1 \simeq 0.8 \pm 0.2$
- x_2 from the quark mass expansion of the pion decay constant and the nucleon axial-vector constant: $x_2 \simeq -0.056 \ldots 0.008$
- x_3 and x_4 can be obtained from a two-nucleon scattering analysis & can be deduced from:

$$-\frac{\partial a^{-1}}{\partial M_\pi} \equiv \frac{A}{aM_\pi} = \frac{1}{\pi L} S'(\eta) \frac{\partial \eta}{\partial M_\pi}\ , \quad \eta \equiv m_N E \left(\frac{L}{2\pi}\right)^2$$

$\Rightarrow$ while this can straightforwardly be computed, we prefer to use a representation that substitutes x_3 and x_4 by:

$$\left.\frac{\partial a_s^{-1}}{\partial M_\pi}\right|_{M_\pi^{\rm phys}}, \quad \left.\frac{\partial a_t^{-1}}{\partial M_\pi}\right|_{M_\pi^{\rm phys}}$$

$\Rightarrow$ we are ready to study the pertinent energy differences

RESULTS

- putting pieces together:

$$\left.\frac{\partial \Delta E_h}{\partial M_\pi}\right|_{M_\pi^{\rm phys}} = -0.455(35) \left.\frac{\partial a_s^{-1}}{\partial M_\pi}\right|_{M_\pi^{\rm phys}} - 0.744(24) \left.\frac{\partial a_t^{-1}}{\partial M_\pi}\right|_{M_\pi^{\rm phys}} + 0.056(10)$$

$$\left.\frac{\partial \Delta E_b}{\partial M_\pi}\right|_{M_\pi^{\rm phys}} = -0.117(34) \left.\frac{\partial a_s^{-1}}{\partial M_\pi}\right|_{M_\pi^{\rm phys}} - 0.189(24) \left.\frac{\partial a_t^{-1}}{\partial M_\pi}\right|_{M_\pi^{\rm phys}} + 0.012(9)$$

$$\left.\frac{\partial \Delta E_c}{\partial M_\pi}\right|_{M_\pi^{\rm phys}} = - 0.07(3) \left.\frac{\partial a_s^{-1}}{\partial M_\pi}\right|_{M_\pi^{\rm phys}} - 0.14(2) \left.\frac{\partial a_t^{-1}}{\partial M_\pi}\right|_{M_\pi^{\rm phys}} + 0.017(9)$$

- x_1 and x_2 only affect the small constant terms
- also calculated the shifts of the individual energies (not shown here)

INTERPRETATION

- $(\partial \Delta E_h / \partial M_\pi) / (\partial \Delta E_b / \partial M_\pi) \simeq 4$
  $\Rightarrow$ ΔE_h and ΔE_b cannot be independently fine-tuned

- Within error bars, $\partial \Delta E_h / \partial M_\pi$ & $\partial \Delta E_b / \partial M_\pi$ appear unaffected by the choice of x_1 and x_2 $\rightarrow$ indication for α-clustering

- For ΔE_h & ΔE_b, the dependence on M_π is small when

$$\boxed{\partial a_s^{-1} / \partial M_\pi \simeq -1.6 \times \partial a_t^{-1} / \partial M_\pi}$$

- the triple alpha process is controlled by :

$$\Delta E_{h+b} \equiv \Delta E_h + \Delta E_b = E_{12}^\star - 3E_4$$

$$\boxed{\left.\frac{\partial \Delta E_{h+b}}{\partial M_\pi}\right|_{M_\pi^{\rm phys}} = -0.571(14) \left.\frac{\partial a_s^{-1}}{\partial M_\pi}\right|_{M_\pi^{\rm phys}} - 0.934(11) \left.\frac{\partial a_t^{-1}}{\partial M_\pi}\right|_{M_\pi^{\rm phys}} + 0.069(6)}$$

$\Rightarrow$ so what can we say about the quark mass dependence of the scattering lengths?

CONSTRAINTS on the SCATTERING LENGTHS

- Quark mass dependence of hadron properties: $\displaystyle\frac{\delta O_H}{\delta m_f} \equiv K_H^f \frac{O_H}{m_f}\,, \quad f = u, d, s$

- NN scattering lengths as a function of M_π: $\displaystyle -\frac{\partial a_{s,t}^{-1}}{\partial M_\pi} \equiv \frac{A_{s,t}}{a_{s,t} M_\pi}, \quad A_{s,t} \equiv \frac{K^q_{a_{s,t}}}{K^q_\pi}$

- earlier determinations from chiral EFT at NLO

Beane, Savage (2003), Epelbaum, Glöckle, UGM (2003)

- new determination at NNLO:

Epelbaum et al. (2012)

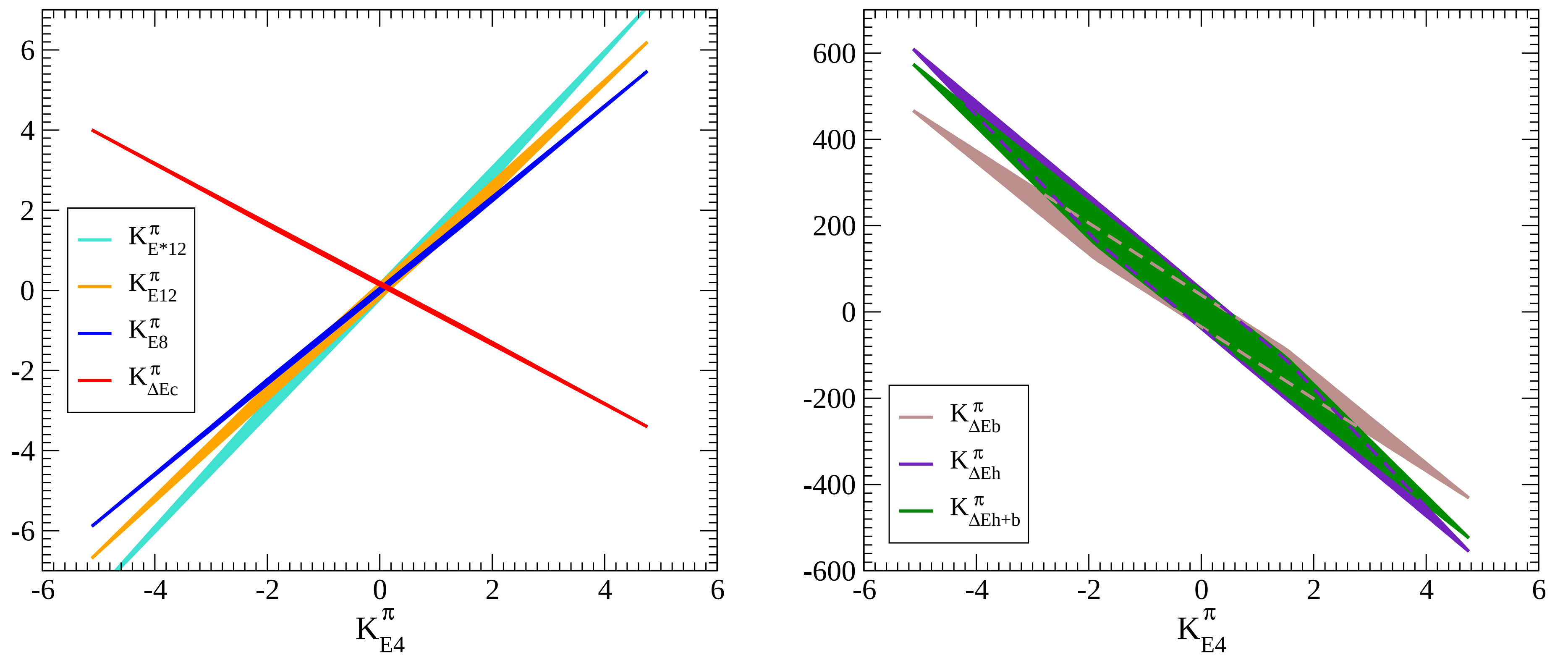
$$K^q_{a_s} = 2.3^{+1.9}_{-1.8}\,,\; K^q_{a_t} = 0.32^{+0.17}_{-0.18} \to \frac{\partial a_t^{-1}}{\partial M_\pi} = -0.18^{+0.10}_{-0.10}\,,\; \frac{\partial a_s^{-1}}{\partial M_\pi} = 0.29^{+0.25}_{-0.23}$$

- note the *magical* central value:

$$\boxed{\frac{\partial a_s^{-1}/\partial M_\pi}{\partial a_t^{-1}/\partial M_\pi} \simeq -1.6^{+1.0}_{-1.7}}$$

CORRELATIONS

- vary the quark mass derivatives of $a_{s,t}^{-1}$ within $-1, \ldots, +1$:



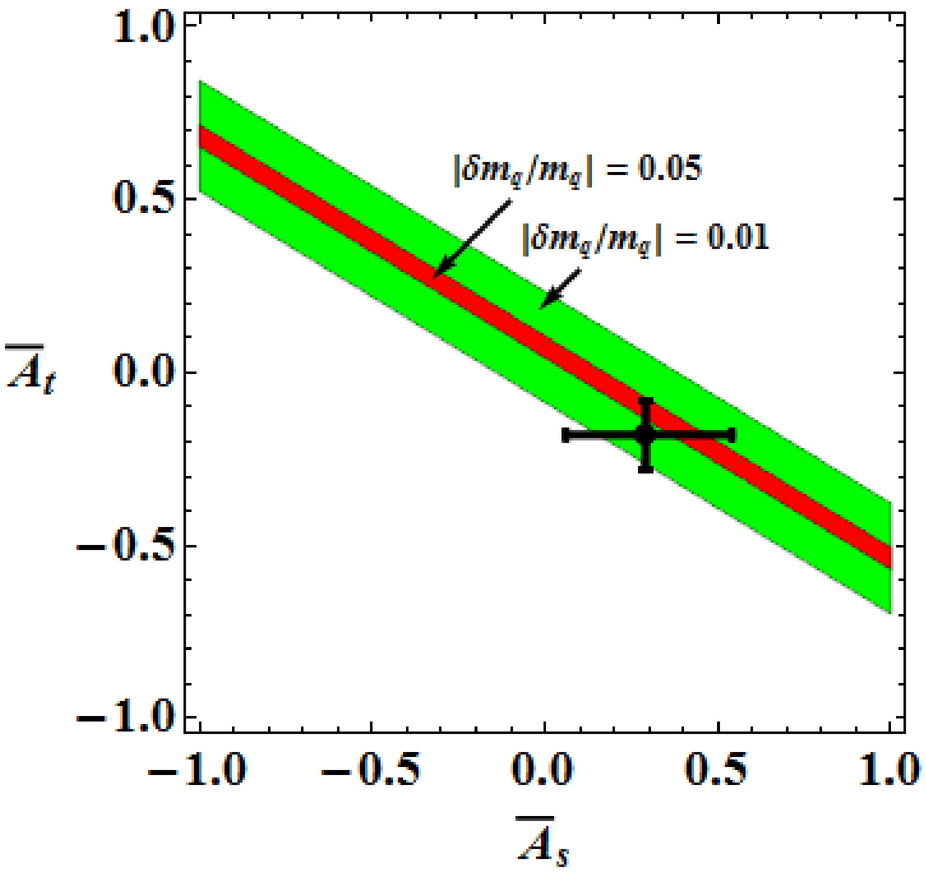
- clear correlations: α-particle BE and the energies/energy differences

$\Rightarrow$ anthropic or non-anthropic scenario depends on whether the ^{4}He BE moves!

THE END-OF-THE-WORLD PLOT

- $|\delta(\Delta E_{h+b})| < 100$ keV

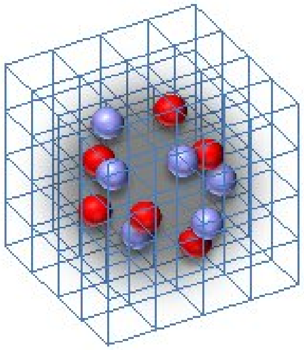
$$\rightarrow \boxed{\left|\left(0.571(14)\,\bar{A}_s + 0.934(11)\,\bar{A}_t - 0.069(6)\right)\frac{\delta m_q}{m_q}\right| < 0.0015}$$



$$\bar{A}_{s,t} \equiv \left.\frac{\partial a_{s,t}^{-1}}{\partial M_\pi}\right|_{M_\pi^{\rm phys}}$$

SUMMARY & OUTLOOK

- Nuclear lattice simulations as a new quantum many-body approach
- Formulate continuum EFT on space-time lattice $V = L_s \times L_s \times L_s \times L_t$
- New method to extract phase shifts & mixing angles
- Fix parameters in few-nucleon systems $\to$ predictions
- Promising results for $A = 2, 3, 4, 8, 12, 16$ at NNLO
- ^{12}C spectrum at NNLO $\to$ Hoyle state & 2^+ excitation
- First ever ab initio MC calculation of ^{16}O
- Testing the anthropic principle $\to$ strong correlations of α-cluster type
  $\Rightarrow$ the Hoyle state does not appear anthropic (Coulomb to be done)



$\Rightarrow$ larger A and higher precision