UNIVERSITÄT BONN

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CENTER FOR SCIENCE & THOUGHT

JÜLICH FORSCHUNGSZENTRUM

Life on Earth – an Accident ?

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Contents

The anthropic principle

The Anthropic Principle (AP)

- so **many** parameters in the Standard Model, the landscape of string theory, . . .

⇒ 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, . . .

⇒ can this be tested? / have physical consequences?

- Ex. 1: “Anthropic bound on the cosmological constant” Weinberg (1987) [1036 cites]
- Ex. 2: “The anthropic string theory landscape” Susskind (2003) [1126 cites]

A prime example of the AP

- 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

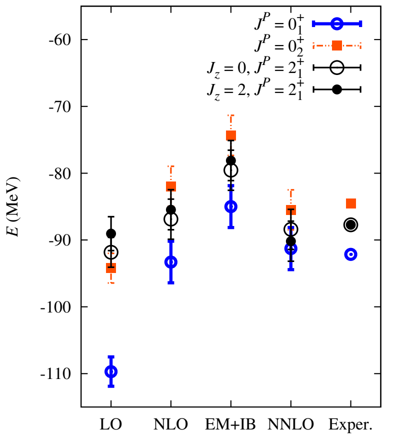
The relevant question

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.

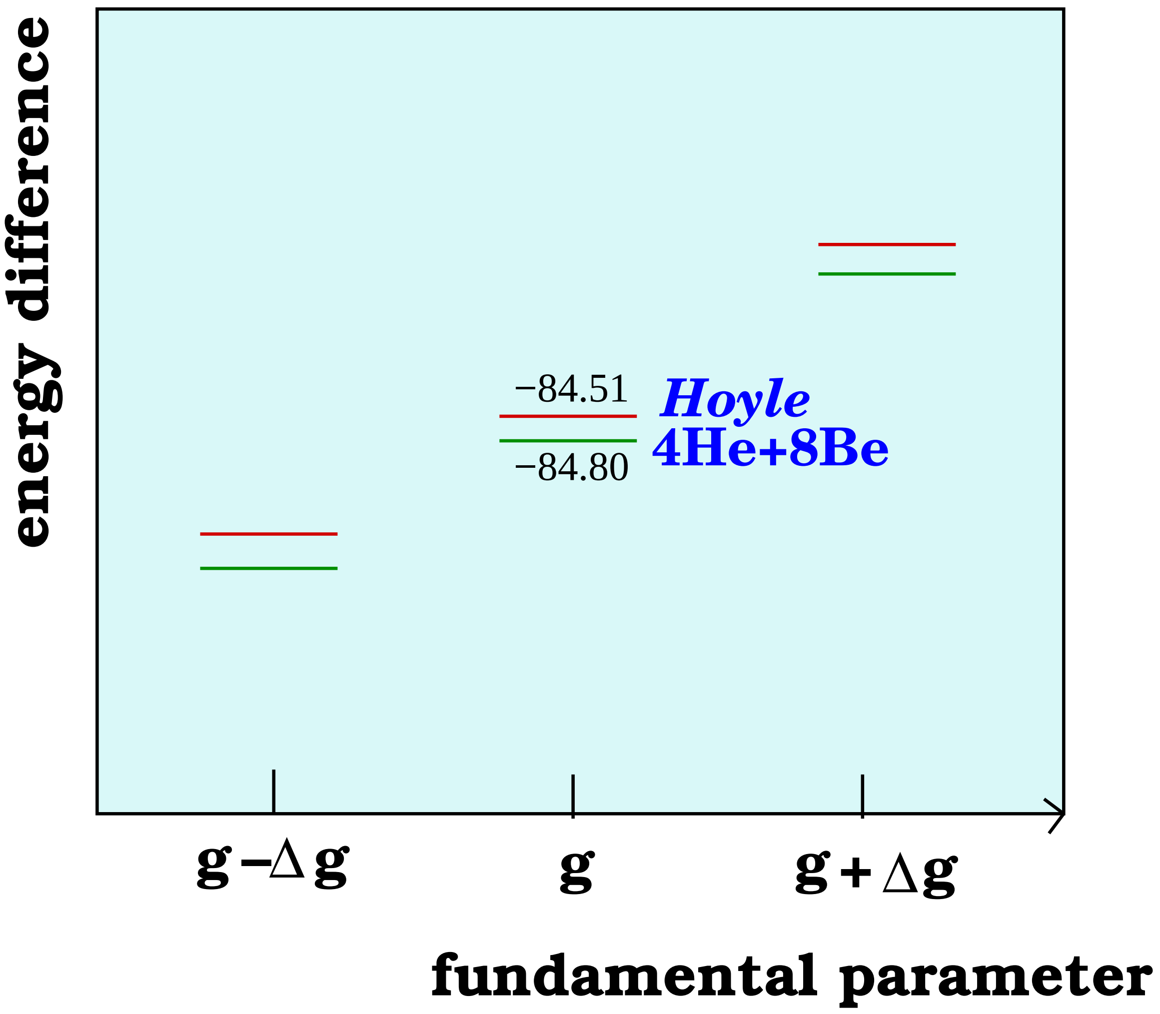
All best,
Steve Weinberg



- How does the Hoyle state move 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!*

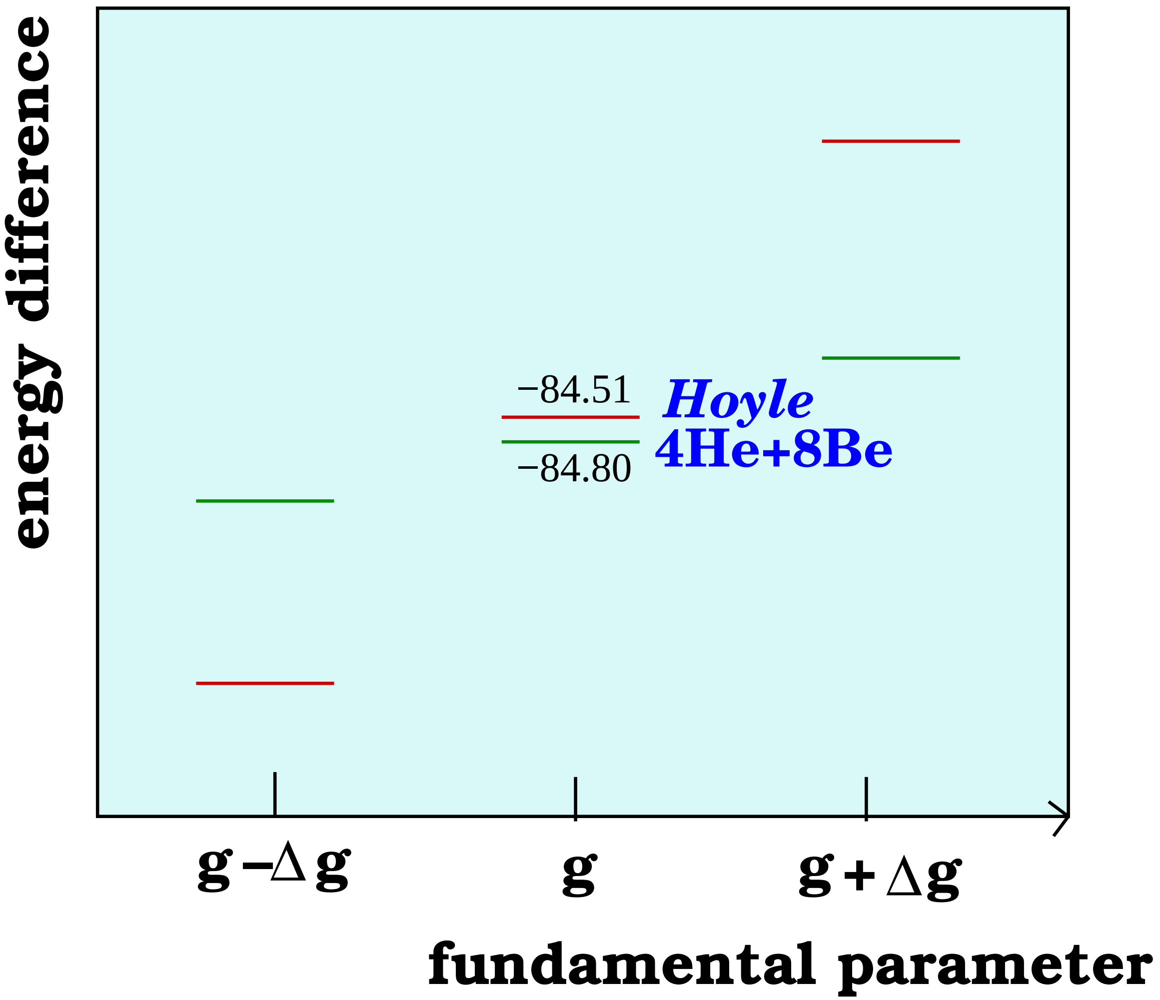
The non-anthropic scenario

- 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



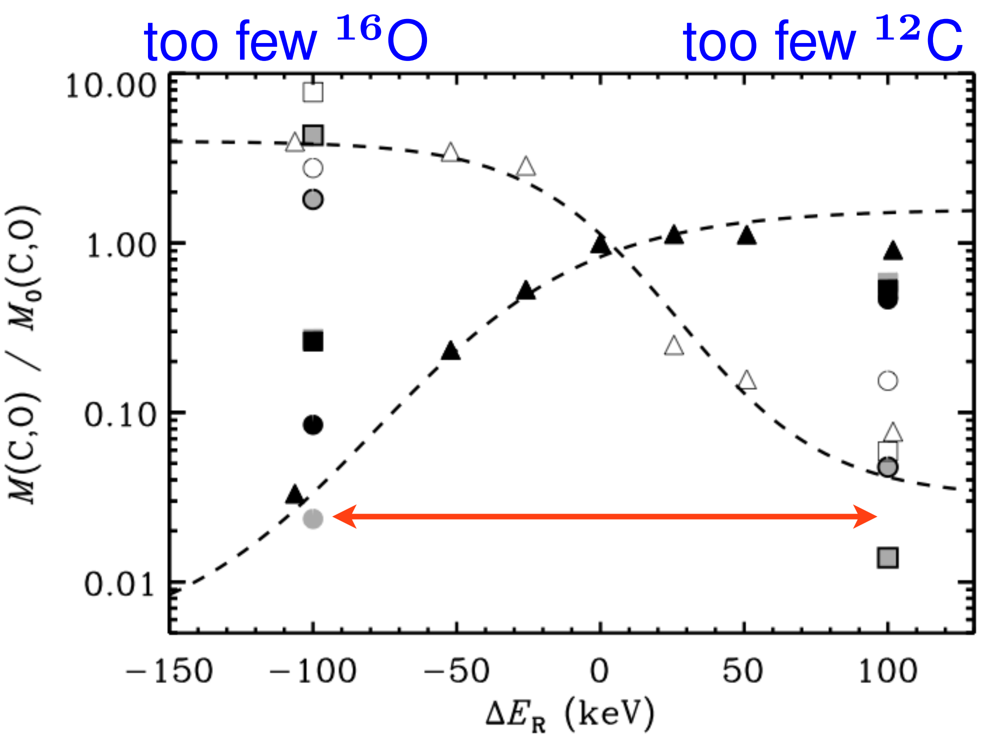
Earlier studies of the AP

- rate of the 3α-process: $r_{3\alpha} \sim \Gamma_\gamma \exp\left(-\frac{\Delta E_{h+b}}{kT}\right)$

$$\Delta E_{h+b} = E^\star_{12} - 3E_\alpha = 379.47(18)\text{ keV}$$

- how much can ΔE_{h+b} be changed so that there is still enough ^{12}C and ^{16}O?

$\Rightarrow$ $|\Delta E_{h+b}| \lesssim 100$ keV



Oberhummer et al., Science **289** (2000) 88
Csoto et al., Nucl. Phys. A **688** (2001) 560
Schlattl et al., Astrophys. Space Sci. **291** (2004) 27
[Livio et al., Nature **340** (1989) 281]

More recent stellar simulations

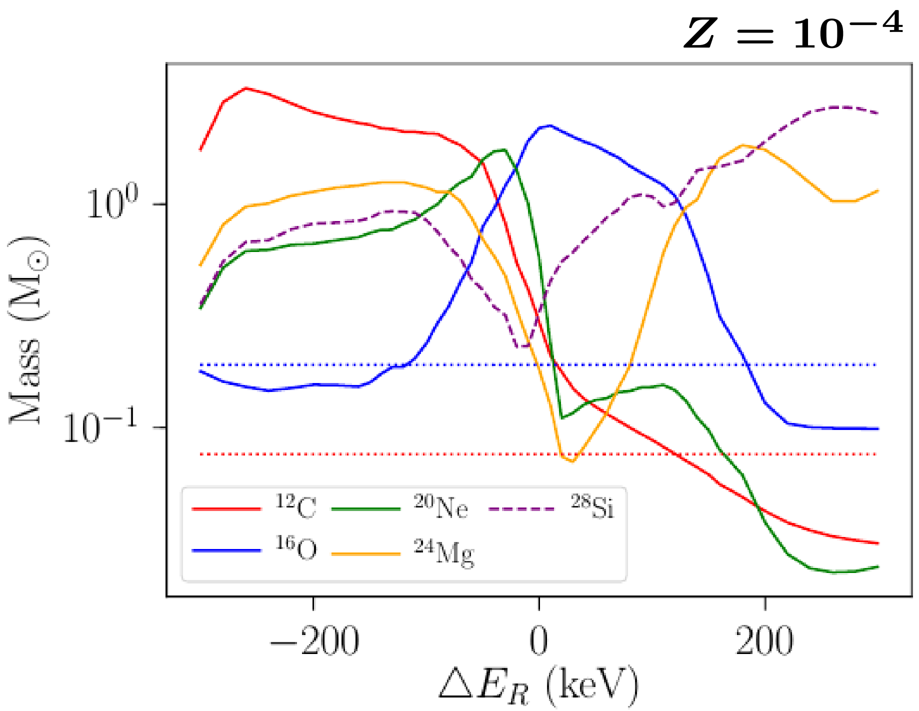
- Consider a larger range of masses $M_\star = (15 - 40)\, M_\odot$
- Consider low $Z = 10^{-4}$ and high $Z = Z_\odot \simeq 0.02$ metallicity
- changes depend on Z now

low Z: -300 keV $< \Delta E_R <$ 500 keV (C)

-300 keV $< \Delta E_R <$ 300 keV (O)

$Z_\odot$: -500 keV $< \Delta E_R <$ 160 keV (C)

-150 keV $< \Delta E_R <$ 200 keV (O)



$\Rightarrow$ carbon constraints somewhat weakened

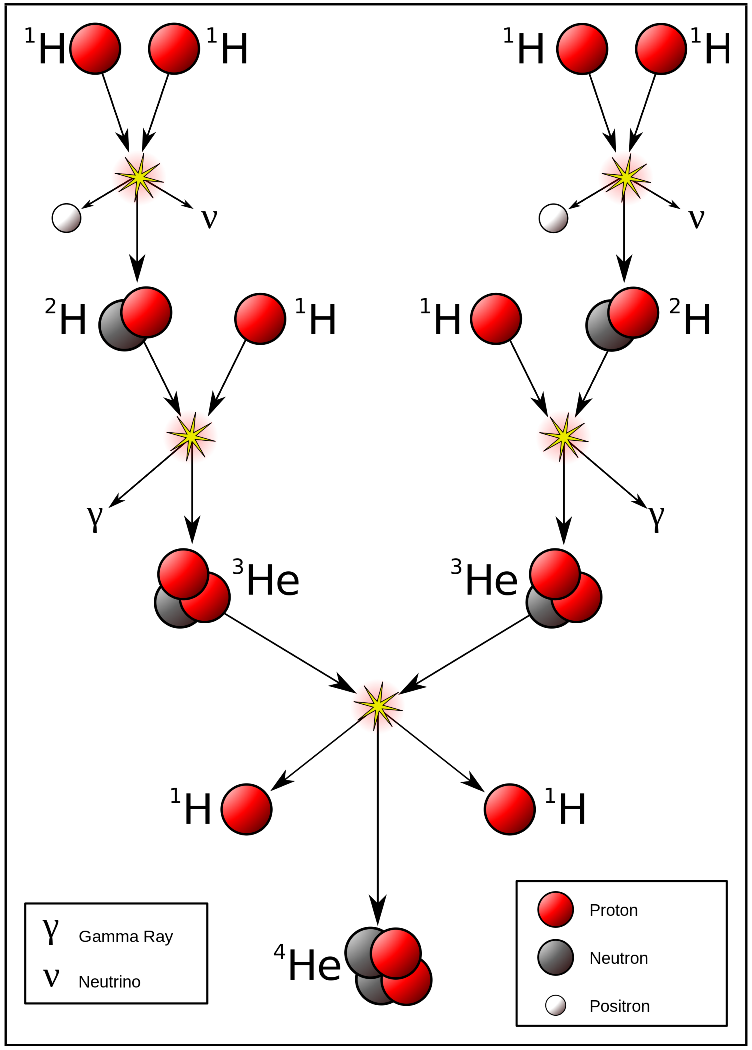
$\Rightarrow$ stronger constraints from oxygen production

Huang, Adams, Grohs, Astropart. Phys. **105** (2019) 13

Definition of the physics problem

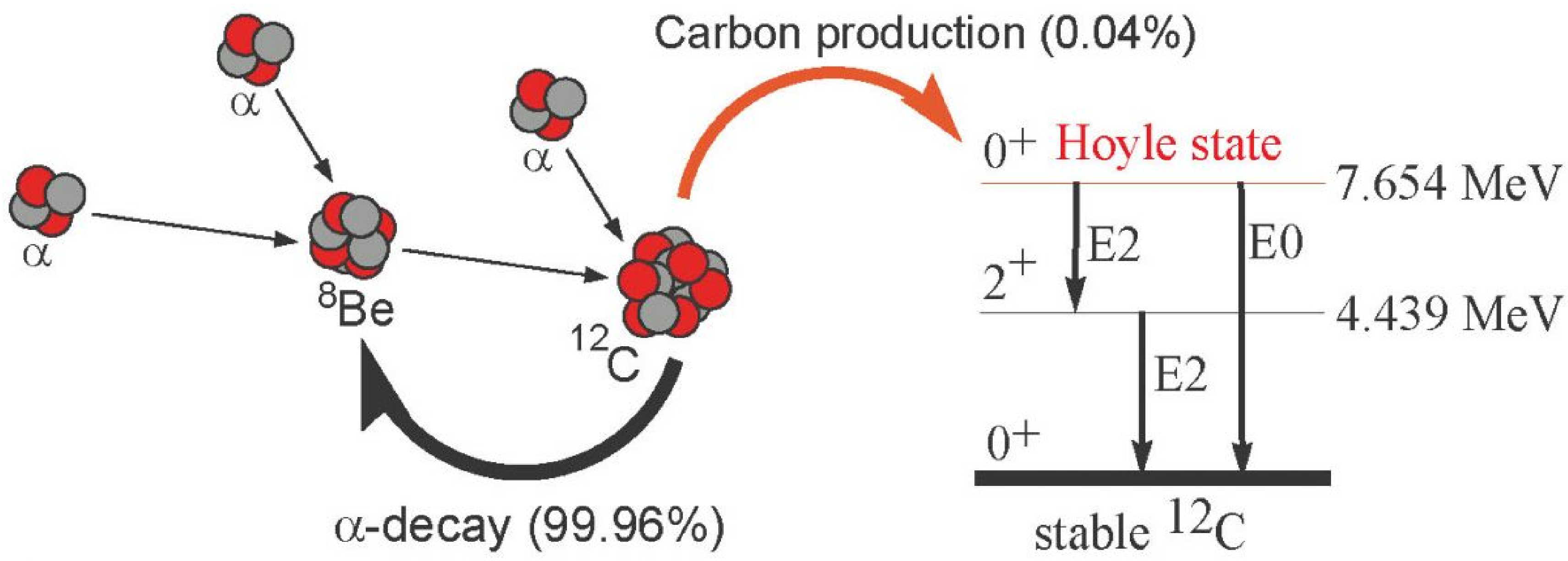
Element generation

- Elements are generated in the Big Bang & in stars through the **fusion** of protons & nuclei [pp chain or CNO-cycle]
- All is simple until ^{4}He
- Only elements up to Be are produced in the Big Bang [BBNucleosynthesis]
- **Life-essential** elements like ^{12}C and ^{16}O are generated in hot, old stars (triple-alpha reaction, see later)
- Note also that nuclei make up the visible matter in the Universe



[from Wikipedia]

The triple-alpha process



©ANU

- the ^{8}Be nucleus is instable, long lifetime $\rightarrow$ 3 alphas must meet
- the Hoyle state sits just above the continuum threshold
  $\rightarrow$ 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

$\Rightarrow$a triple wonder !

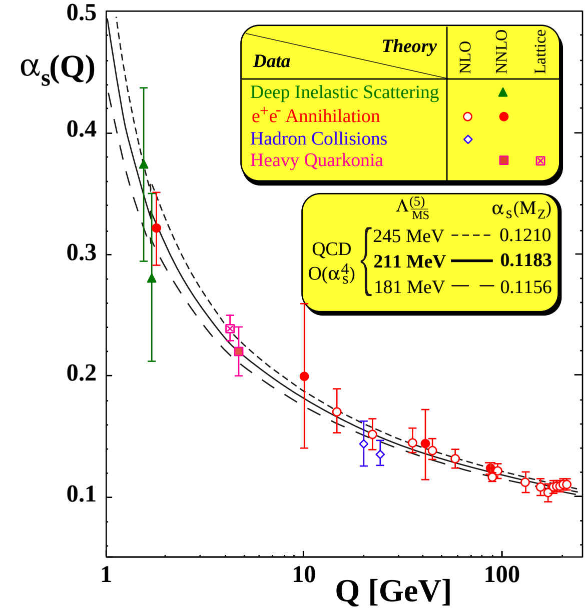
Emergence of structure in QCD

- The strong interactions are described by QCD:

$$\mathcal{L} = -\frac{1}{4g^2} G_{\mu\nu}G^{\mu\nu} + \sum_{f=u,d,s,c,b,t} \bar{q}_f \left(i\gamma_\mu D^\mu - m_f\right) q_f + \ldots$$

- **up** and **down** quarks are very light, a few MeV
- Quarks and gluons are confined within **hadrons**
- Protons and neutrons form **atomic nuclei**

⇒ This requires the inclusion of electromagnetism described by QED with $\alpha_{\rm EM} \simeq 1/137$



[from S. Bethge]

> So how sensitive are these strongly interacting composites to variations of the fundamental parameters of QCD+QED?
> or: how accidental is life on Earth?

Quark mass dependence of the nuclear forces

Berengut, Epelbaum, Flambaum, Hanhart, UGM, Nebreda, Pelaez,
Phys. Rev. D **87** (2013) 085018

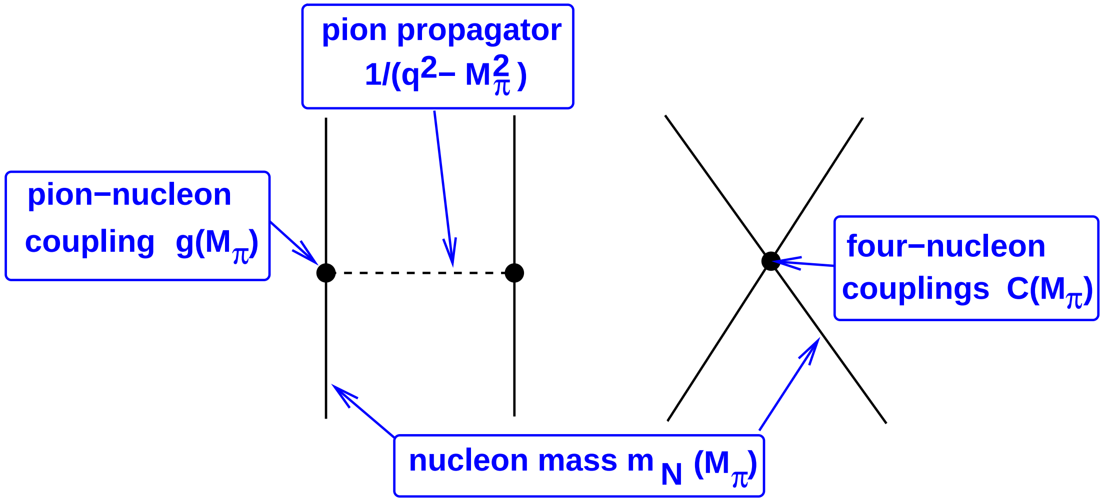
Ingredients

- Nuclear forces are given by chiral EFT based on Weinberg's power counting

Weinberg 1991

$\Rightarrow$ Pion-exchange contributions and short-distance multi-N operators

- graphical representation of the quark mass dependence of the LO potential



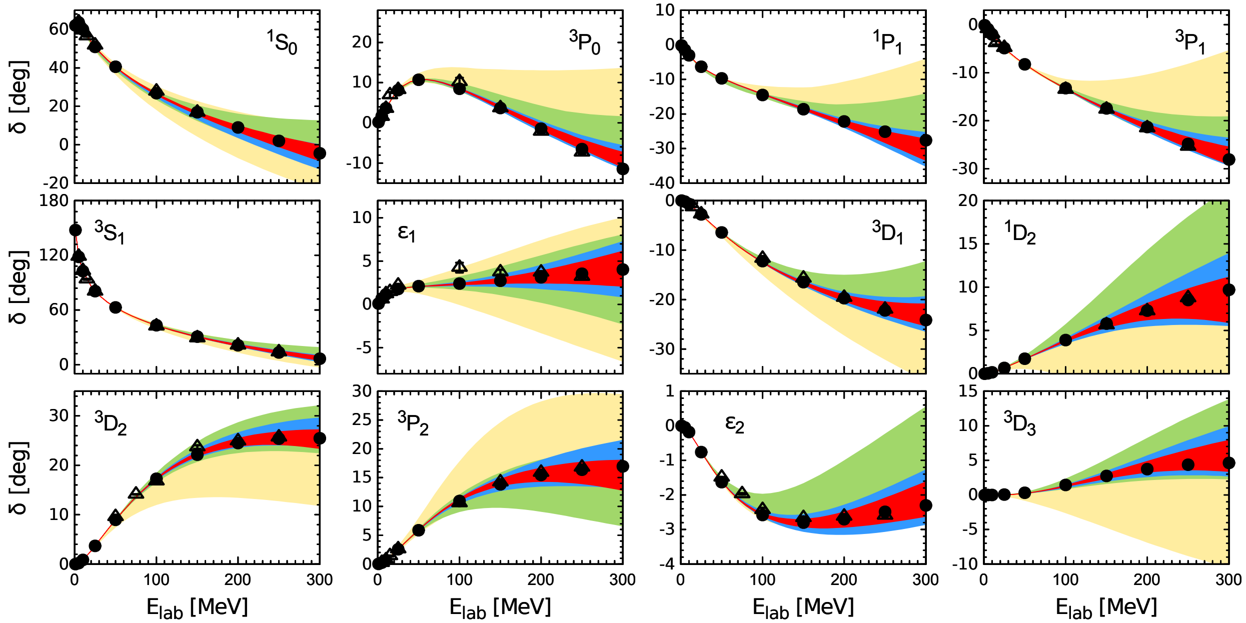
- always use the Gell-Mann–Oakes–Renner relation: $$M^2_{\pi^\pm} \sim (m_u + m_d)$$
- fulfilled to better than 94% in QCD — Colangelo, Gasser, Leutwyler 2001
- Strong isospin violation and electromagnetic effects can also be included

Chiral nuclear EFT: Results

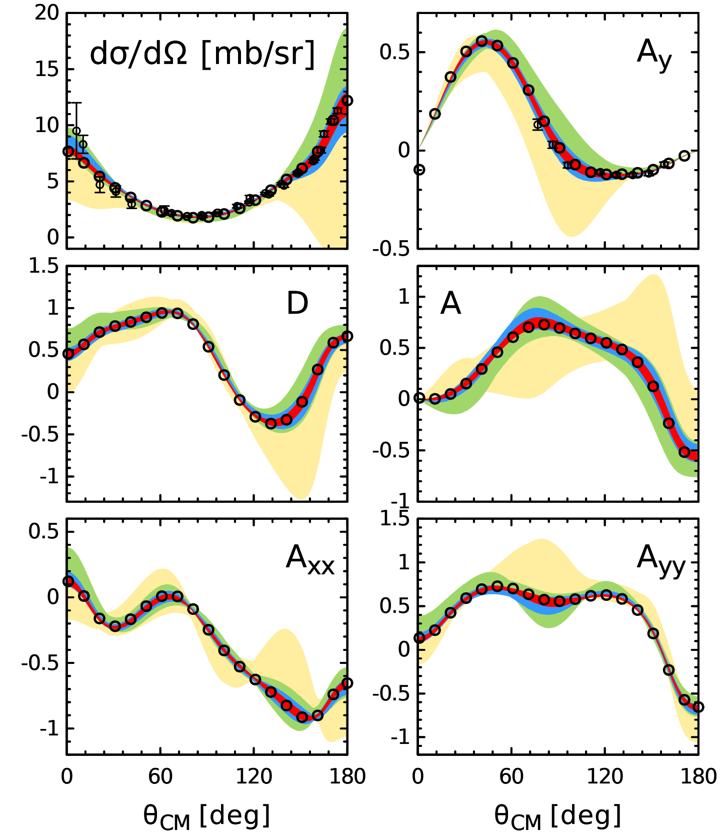
- Expansion to fifth order in the chiral expansion [Weinberg's power counting]

Epelbaum, Krebs, UGM, Phys.Rev.Lett. **115** (2015) 122301; Eur. Phys. J. A **51** (2015) 53

- phase shifts



- np scattering at 200 MeV



NLO N2LO N3LO N4LO

⇒ now a precision tool in nuclear physics

see e.g. Epelbaum, Krebs, Reinert, Front. in Phys. **8** (2020) 98

Quark mass dependence of hadron masses etc

- Quark mass dependence of hadron properties:

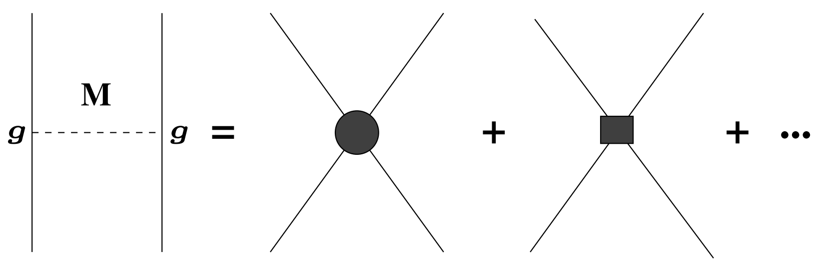
$$\frac{\delta O_H}{\delta m_f} \equiv K_H^f \frac{O_H}{m_f}\,, \quad f = u, d, s$$

- Pion and nucleon properties from lattice QCD combined with CHPT

- Contact interactions modeled by heavy meson exchanges + unitarized CHPT

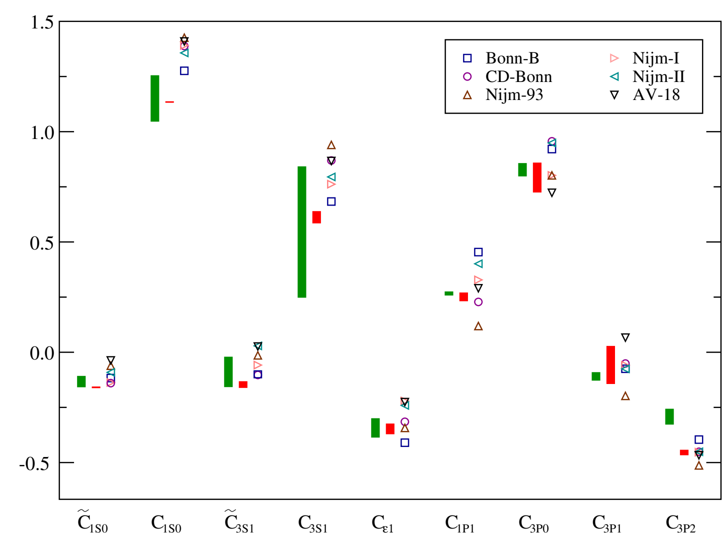
Epelbaum, UGM, Glöckle, Elster (2002)

Hanhart, Pelaez, Rios (2008)



$$\frac{g^2}{t-M^2} = -\frac{g^2}{M^2} - \frac{g^2\, t}{M^4} + \ldots$$

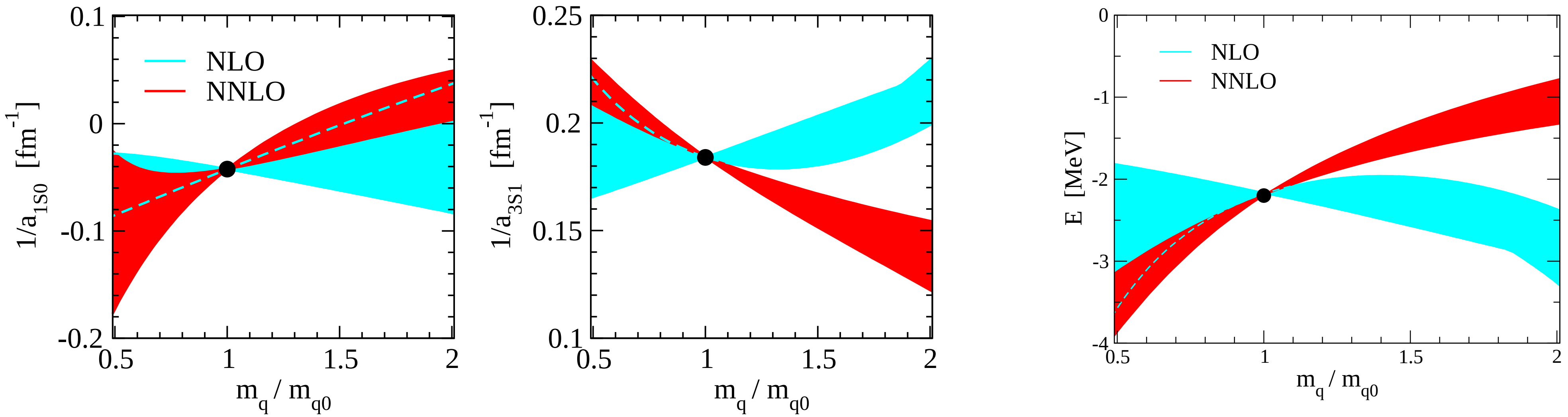
$\hookrightarrow$



Results for the NN system

- Putting pieces together for the two-nucleon system:

$$K^q_{a,1S0} = 2.3^{+1.9}_{-1.8}, \quad K^q_{a,3S1} = 0.32^{+0.17}_{-0.18}, \quad K^q_{\rm B(deut)} = -0.86^{+0.45}_{-0.50}$$



- Extends and improves earlier work based on EFTs and models

Beane, Savage (2003), Epelbaum, UGM, Glöckle (2003), Mondejar, Soto (2007), Flambaum, Wiringa (2007), Bedaque, Luu, Platter (2011) [BLP], . . .

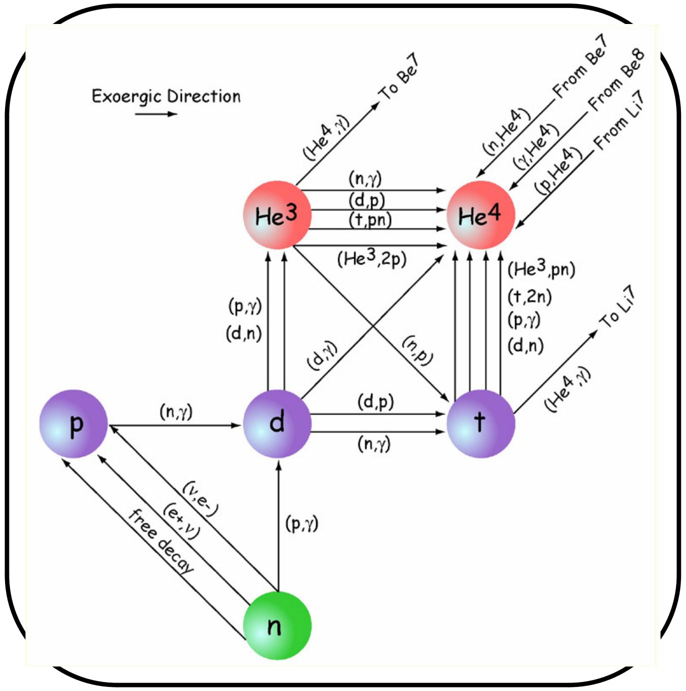
- connection to lattice QCD results → later

Impact on BBN

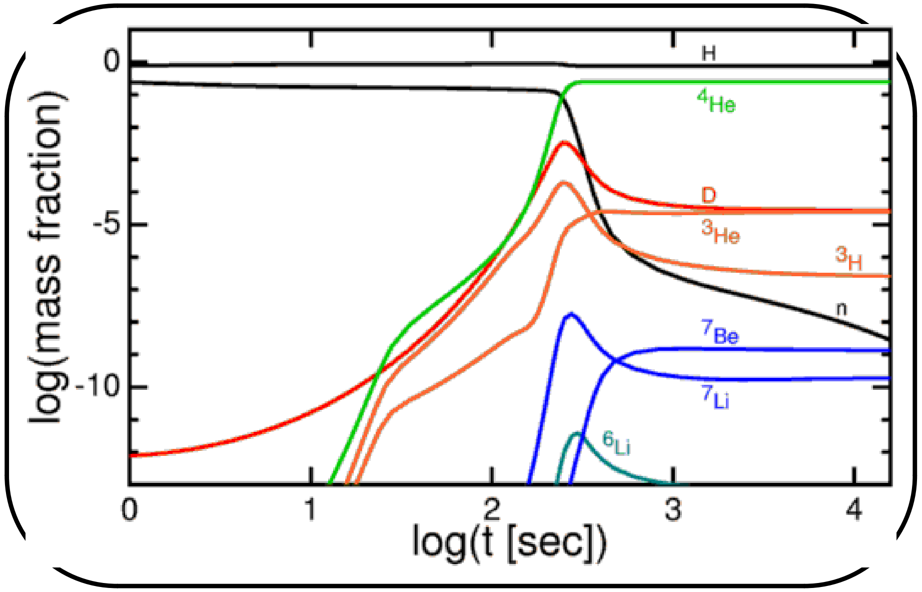
quark masses:
Berengut, Epelbaum, Flambaum, Hanhart, UGM, Nebreda, Pelaez,
Phys. Rev. D **87** (2013) 085018

fine-structure constant:
UGM, Metsch, Meyer, [arXiv:2305.15849 [hep-th]]

BBN network & element abundances



from Cococubed.com



from Burles, Nollett & Turner

- consider element generation up to ^{7}Li, ^{7}Be
- how does this network / the abundances of the elements change under variations of the quark masses/ the fine-structure constant?
- use the KAWANO code [NUC123] Kawano, FERMILAB-PUB-92-004-A

Quark mass variations of heavier nuclei

- In BBN, we also need the variation of ^{3}He and ^{4}He. All other BEs are kept fixed.

- use the method of BLP: Bedaque, Luu, Platter, PRC 83 (2011) 045803

$$K^q_{^A\mathrm{He}} = K^q_{a,\,1S0} K^{a,\,1S0}_{^A\mathrm{He}} + K^q_{\mathrm{deut}} K^{\mathrm{deut}}_{^A\mathrm{He}}\ , \quad A = 3, 4$$

with

$$K^{a,\,1S0}_{^3\mathrm{He}} = 0.12 \pm 0.01\ , \quad K^{\mathrm{deut}}_{^3\mathrm{He}} = 1.41 \pm 0.01$$

$$K^{a,\,1S0}_{^4\mathrm{He}} = 0.037 \pm 0.011\ , \quad K^{\mathrm{deut}}_{^4\mathrm{He}} = 0.74 \pm 0.22$$

so that

$$\Rightarrow \boxed{K^q_{^3\mathrm{He}} = -0.94 \pm 0.75, \quad K^q_{^4\mathrm{He}} = -0.55 \pm 0.42}$$

$\Rightarrow$ calculate BBN response matrix of primordial abundances Y_a at fixed baryon/photon ratio [first in the isospin limit]

Limits for the quark mass variation

- Average of ^{2}H and ^{4}He:

$$\frac{\delta m_q}{m_q} = 0.02 \pm 0.04$$

- in contrast to earlier studies, we provide reliable error estimates (EFT)
- but: BLP find a stronger constraint due to the neutron life time (affects $Y(^4\mathrm{He})$)
- re-evaluate this under the model-independent assumption that *all* quark & lepton masses vary with the **Higgs VEV** v (CHPT w/ virtual photons)

$\Rightarrow$ results are dominated by the ^{4}He abundance:

$$\left|\frac{\delta v}{v}\right| = \left|\frac{\delta m_q}{m_q}\right| \leq 0.9\%$$

- Presently updated: larger networks, 4 BBN codes and improved m_q variations

UGM, Metsch, Meyer, on-going

Fine-structure constant dependence in BBN I

UGM, Metsch, Meyer, 2305.15849 [hep-th]

- Many places where $\alpha_{\rm EM}$ appears directly or indirectly

$\hookrightarrow$ reaction rates, Coulomb penetration, β-decays, Q-values, ... note T-dep.

- New ingredients:

$\hookrightarrow$ 4 different BBN codes

PRIMAT, PArthENoPE, AlterBBN, NUC123

$\hookrightarrow$ new value $(m_n - m_p)^{\rm QED}$

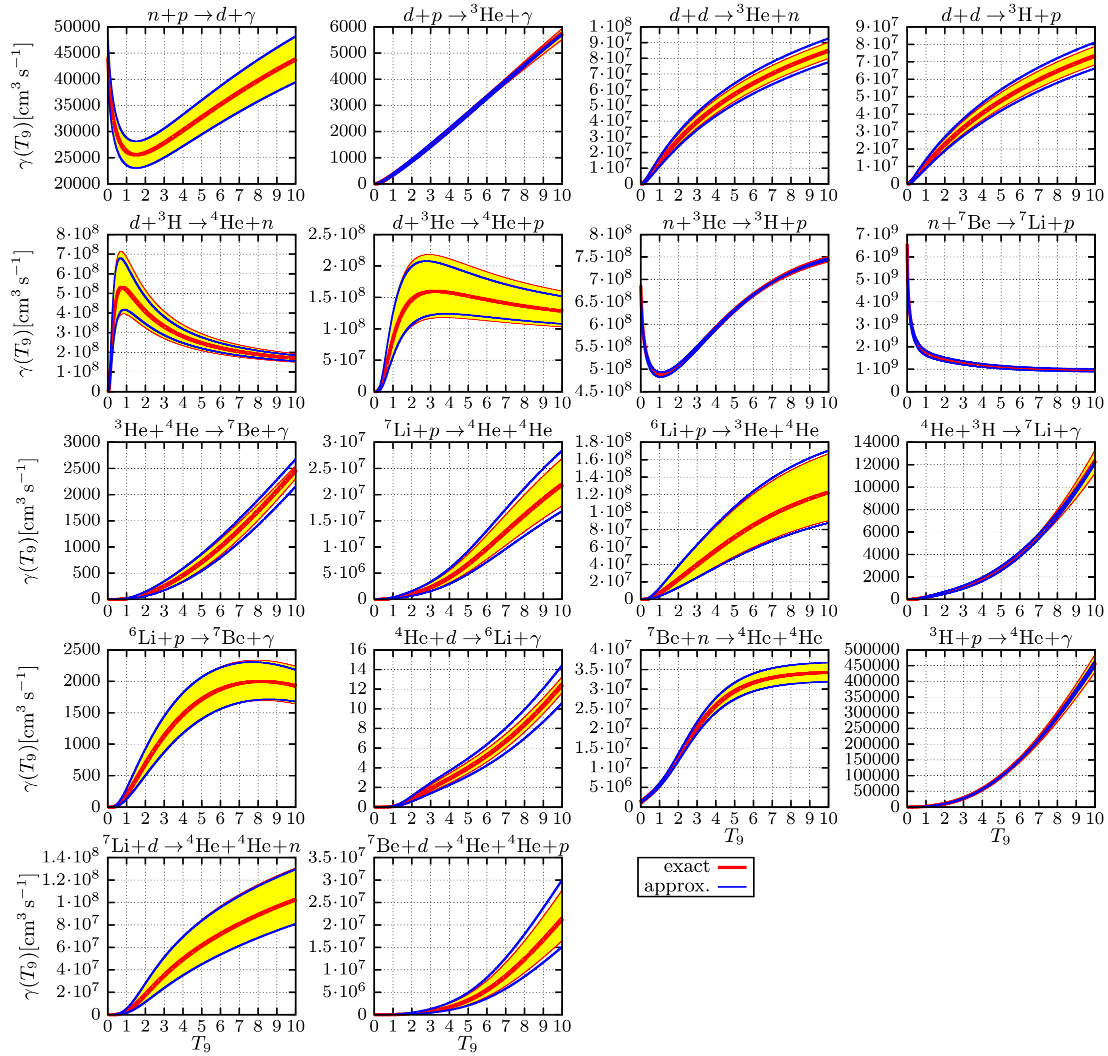
Gasser et al., Phys. Lett.B **814** (2021) 136087

$\hookrightarrow$ Coulomb energies from NLEFT

Elhatisari et al., 2210.17488 [nucl-th]

$\hookrightarrow$ modelling of reaction rates

$\Rightarrow$ $\alpha_{\rm EM}$-dependence of the rates for $\delta\alpha_{\rm EM} = \pm 10\%$



Fine-structure constant dependence in BBN II

UGM, Metsch, Meyer, 2305.15849 [hep-th]

- Baryon-to-photon ratio η from PDG

  $\hookrightarrow \boldsymbol{\eta = 6.18 \cdot 10^{-10}}$

- Neutron lifetime $\boldsymbol{\tau_n = 879.4}$ s

- Compare w/ measured abundances

  $\hookrightarrow$ from ^{2}H + ^{4}He:

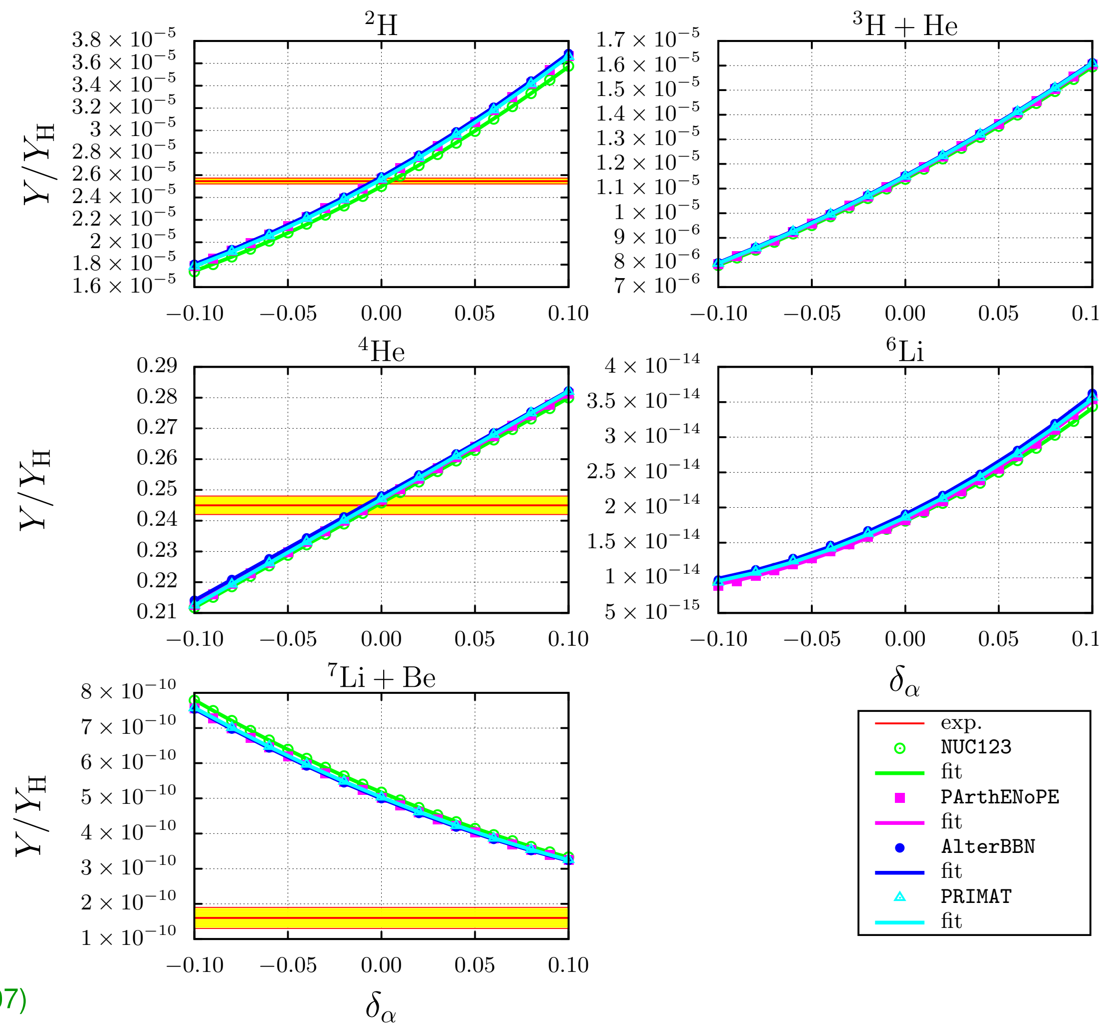
$$\left|\frac{\delta\alpha_{\rm EM}}{\alpha_{\rm EM}}\right| < 0.02$$

- 4 codes give consistent results

- improves on earlier works

  Bergstrem et al. (1999), Nollett, Lopez (2002), Coc et al. (2007), Dent et al. (2007)

- Y(^{7}Li) is overpredicted (“Lithium-problem”)



The fate of carbon-based life as a function of the quark mass

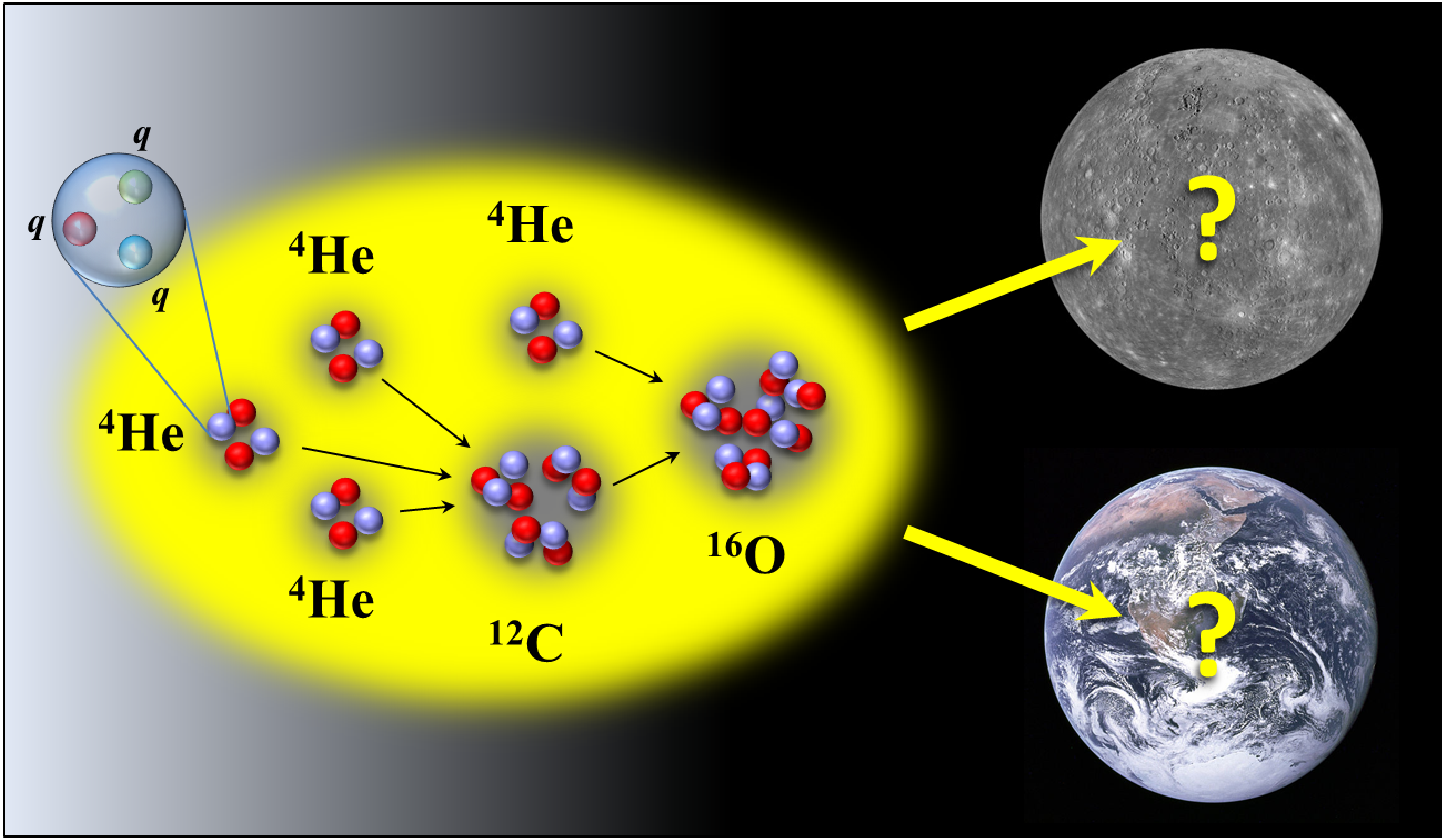
Epelbaum, Krebs, Lähde, Lee, UGM
Phys. Rev. Lett. **110** (2013) 112502; Eur. Phys. J. **A 48** 82 (2013)

update: Lähde, UGM, Epelbaum, Eur. Phys. J. **A 56** (2020) 89

review: UGM, Sci. Bull. **60** (2015) 43

Fine-tuning of the fundamental parameters

Fig. courtesy Dean Lee



The tool: Nuclear lattice effective field theory

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

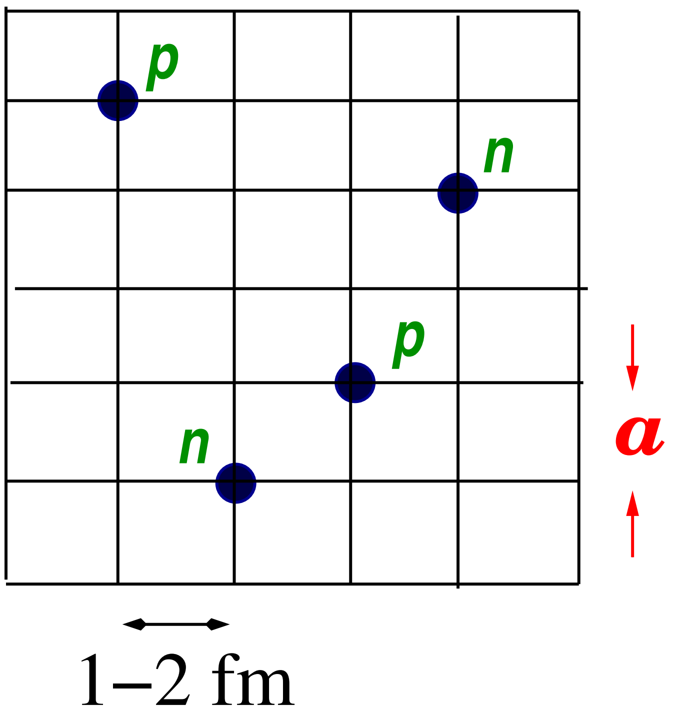
- discretize space-time $V = L_s \times L_s \times L_s \times L_t$:
  nucleons are point-like particles on the sites

- discretized chiral potential w/ pion exchanges
  and contact interactions + Coulomb

  → see Epelbaum, Hammer, UGM, Rev. Mod. Phys. **81** (2009) 1773

- typical lattice parameters

$$p_{\max} = \frac{\pi}{a} \simeq 315 - 630 \text{ MeV [UV cutoff]}$$



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

  E. Wigner, Phys. Rev. **51** (1937) 106; T. Mehen et al., Phys. Rev. Lett. **83** (1999) 931; J. W. Chen et al., Phys. Rev. Lett. **93** (2004) 242302

- physics independent of the lattice spacing for $a = 1 \ldots 2$ fm

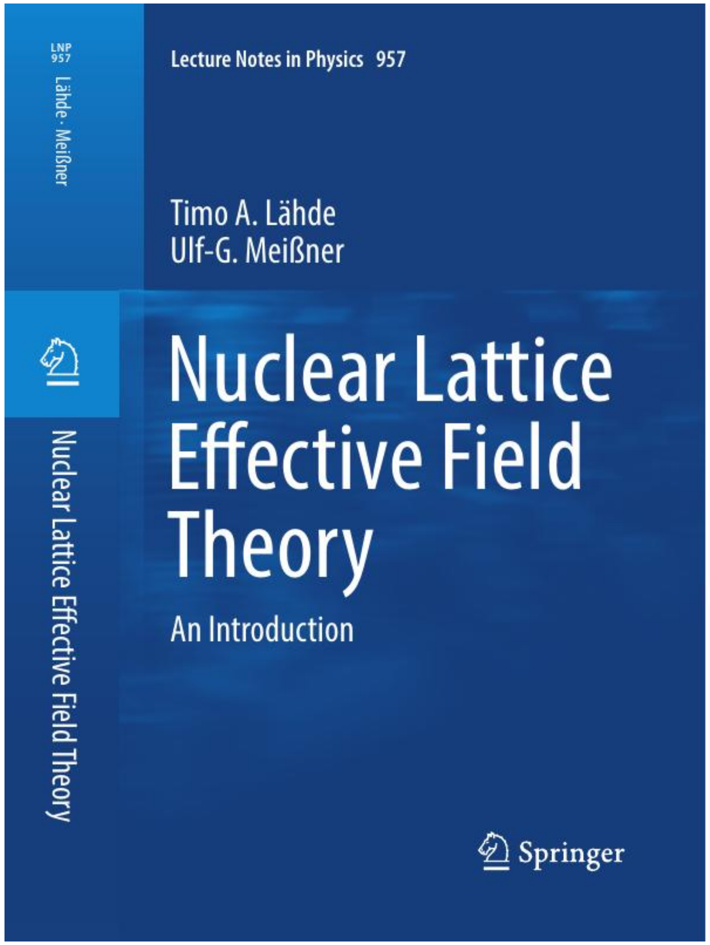
  Alarcon, Du, Klein, Lähde, Lee, Li, Lu, Luu, UGM, EPJA **53** (2017) 83; Klein, Elhatisari, Lähde, Lee, UGM, EPJA **54** (2018) 121

The tool: Nuclear lattice effective field theory II

- For all details on chiral EFT on a lattice

T. Lähde & UGM
Nuclear Lattice Effective Field Theory - An Introduction
Springer Lecture Notes in Physics **957** (2019) 1 - 396

- Computational equipment



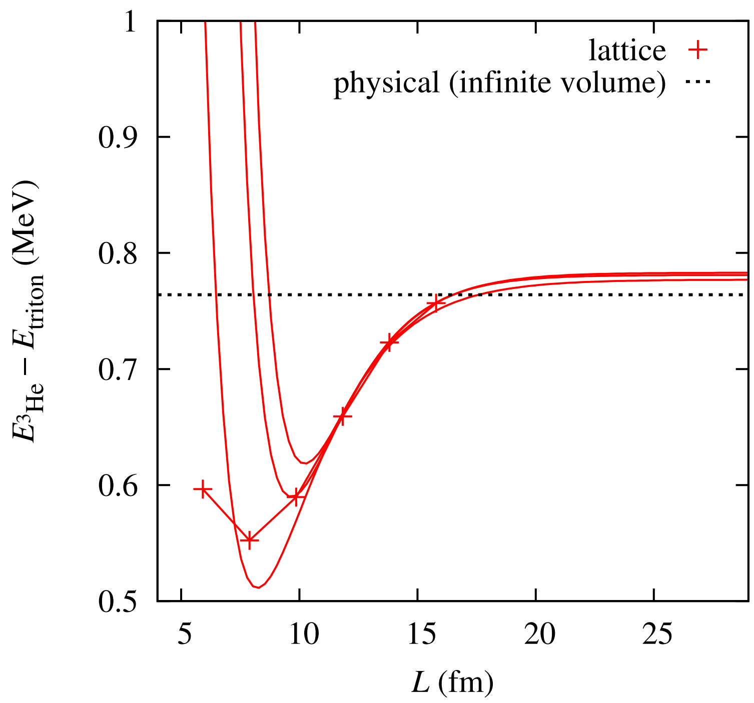
Some early results: Validation of the method

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

Lähde, Epelbaum, Krebs, Lee, UGM, Rupak, Phys. Lett. B **732** (2014) 110; Phys. Rev. Lett. **112** (2014) 102501

- Some groundstate energies and differences

E [MeV]	NLEFT	Exp.
^{3}He - ^{3}H	0.78(5)	0.76
^{4}He	−28.3(6)	−28.3
^{8}Be	−55(2)	−56.5
^{12}C	−92(3)	−92.2
^{16}O	−131(1)	−127.6
^{20}Ne	−166(1)	−160.6
^{24}Mg	−198(2)	−198.3
^{28}Si	−234(3)	−236.5

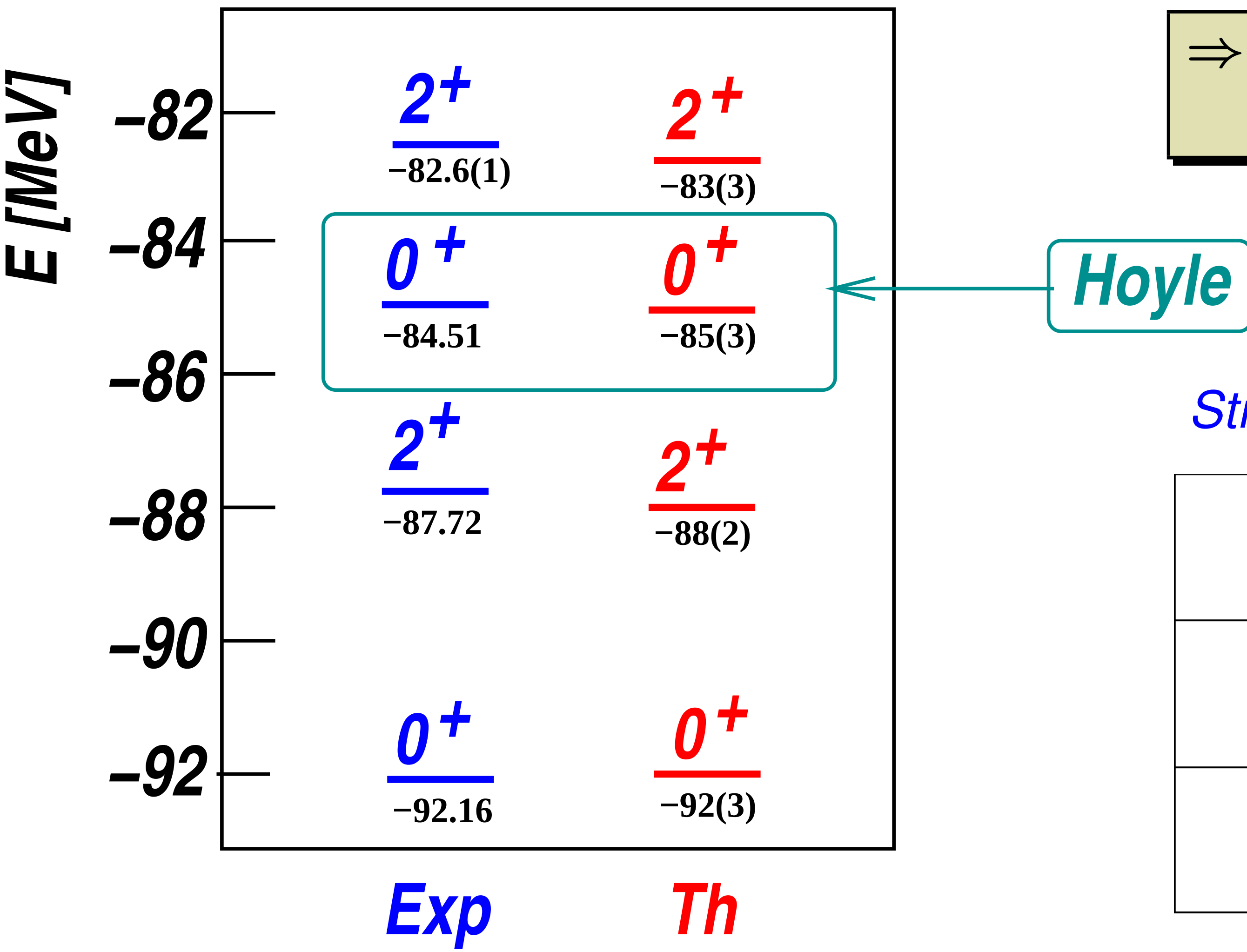


- promising results [much improved by now]

- excited states more difficult, but also doable

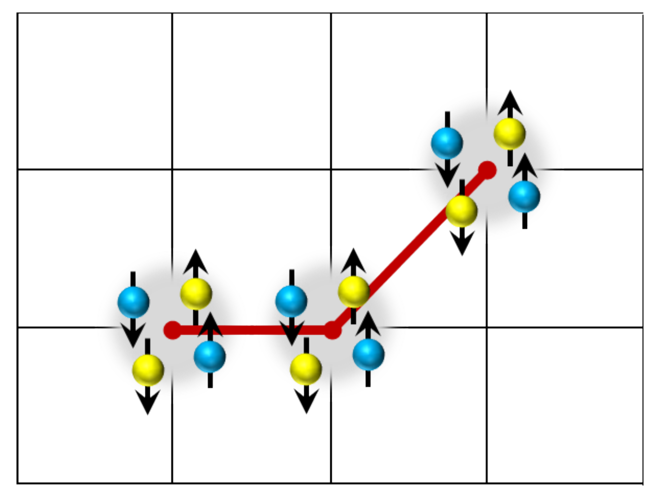
The spectrum of carbon-12 A.D. 2011

- After $8 \cdot 10^6$ hrs JUGENE/JUQUEEN (and “some” human work)



⇒ First ab initio calculation of the Hoyle state √

Structure of the Hoyle state:



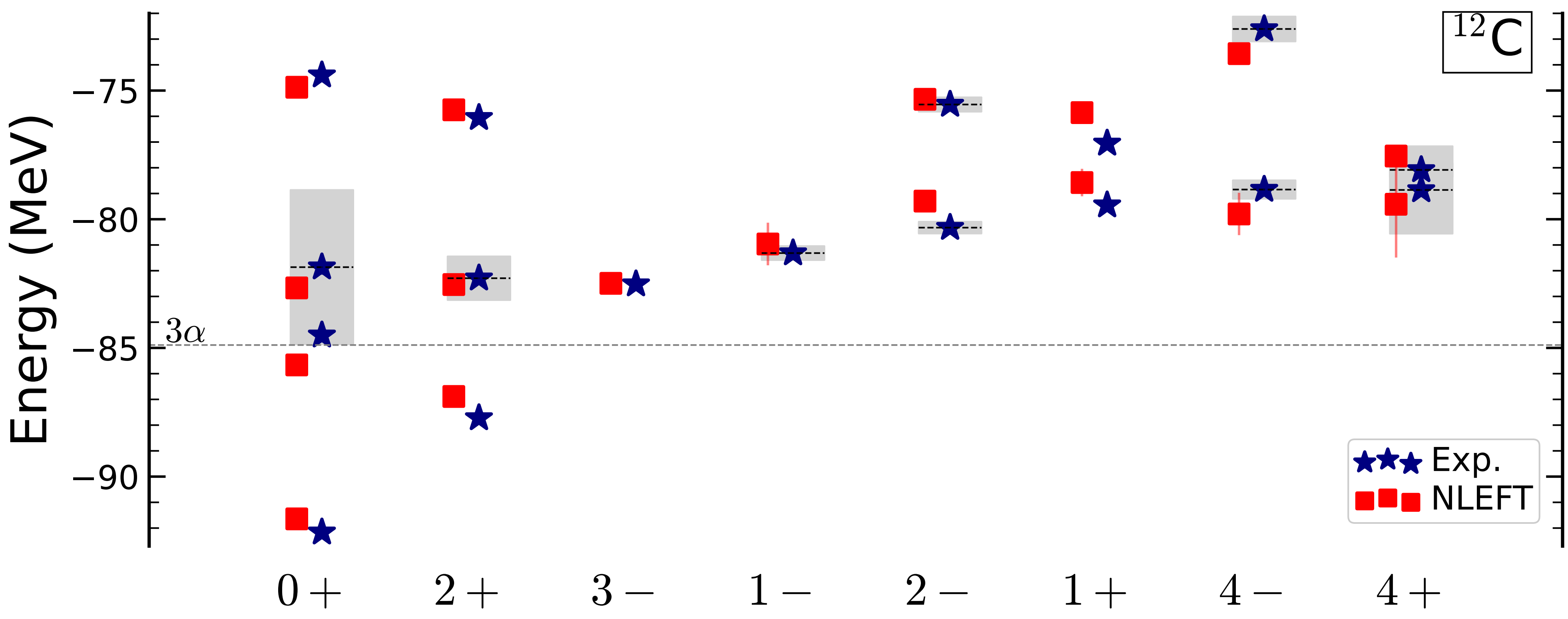
Epelbaum, Krebs, Lee, UGM, Phys. Rev. Lett. **106** (2011) 192501

Epelbaum, Krebs, Lähde, Lee, UGM, Phys. Rev. Lett. **109** (2012) 252501

The spectrum of carbon-12 A.D. 2023

- with much improved algorithms and methods:

Shen, Lähde, Lee, UGM, Nature Commun. **14** (2023) 2777



→ solidifies earlier NLEFT statements about the structure of the $\mathbf{0_2^+}$ and $\mathbf{2_2^+}$ states

Pion mass dependence from MC simulations

- Consider pion mass changes as *small perturbations* for an energy (difference) E_i

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

with

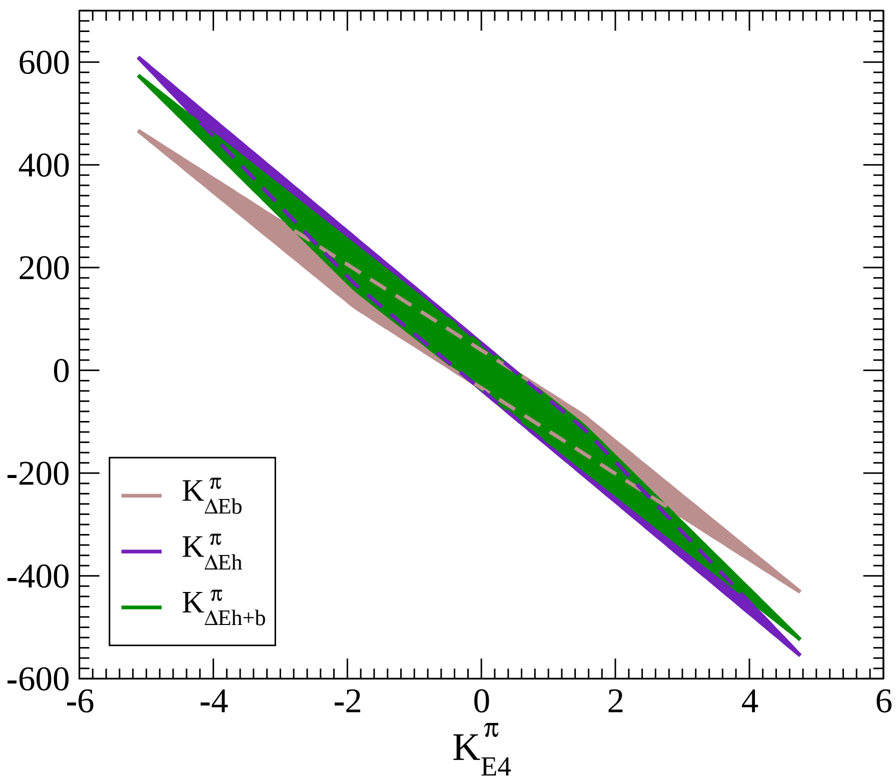
$$x_1 \equiv \left.\frac{\partial m_N}{\partial M_\pi}\right|_{M_\pi^{\rm phys}},\ x_2 \equiv \left.\frac{\partial g_{\pi N}}{\partial M_\pi}\right|_{M_\pi^{\rm phys}},\ x_3 \equiv \left.\frac{\partial C_0}{\partial M_\pi}\right|_{M_\pi^{\rm phys}},\ x_4 \equiv \left.\frac{\partial C_I}{\partial M_\pi}\right|_{M_\pi^{\rm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

$\Rightarrow$ 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 NN scattering and its M_π-dependence $\to \bar{A}_{s,t}$

Correlations

- vary the quark mass derivatives of $\bar{A}_{s,t} = \partial a_{s,t}^{-1}/\partial M_\pi|_{M_\pi^{\rm phys}}$ within $-1, \ldots, +1$:



$$\Delta E_b = E(^8{\rm Be}) - 2E(^4{\rm He})$$

$$\Delta E_h = E(^{12}{\rm C}^*) - E(^8{\rm Be}) - E(^4{\rm He})$$

$$\Delta E_{h+b} = E(^{12}{\rm C}^*) - 3E(^4{\rm He})$$

$$\boxed{\frac{\partial O_H}{\partial M_\pi} = K_H^\pi \frac{O_H}{M_\pi}}$$

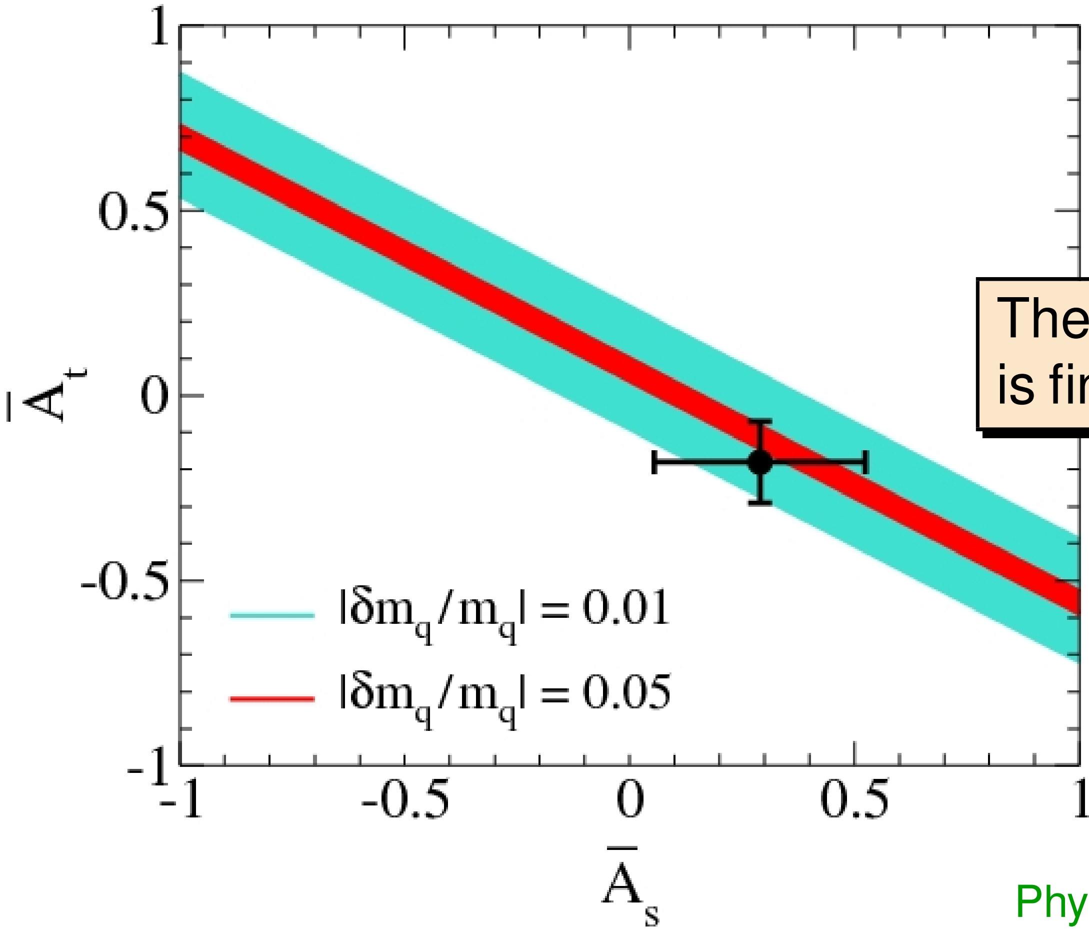
- clear correlations: the two fine-tunings are not independent

⇒ has been speculated before but could not be calculated Weinberg (2001)

The end-of-the-world plot I

- $|\delta(\Delta E_{h+b})| < 100$ keV   Oberhummer et al., Science (2000)

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



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

The light quark mass is fine-tuned to $\simeq 2-3\,\%$

Similarly: $\alpha_{\rm EM}$ is fine-tuned to $\simeq 2.5\%$

Berengut et al., Phys. Rev. **D 87** (2013) 085018

An update on fine-tunings in the triple-alpha process

Lähde, UGM, Epelbaum, Eur. Phys. J **A 56** (2020) 89

- Use lattice data to determine $\bar{A}_s$ and $\bar{A}_t$:

$$\bar{A}_s = 0.54(24)\ , \quad \bar{A}_t = 0.33(16)$$

$\hookrightarrow$ $\bar{A}_s$ is consistent w/ earlier determination

$\hookrightarrow$ $\bar{A}_t$ changes sign compared to earlier determination

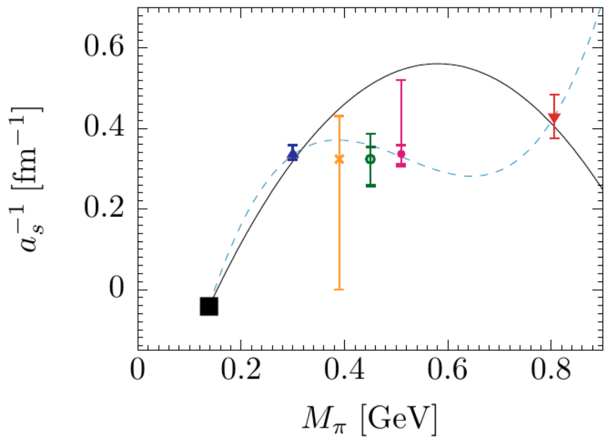
- update x_1 and x_2 using better LQCD data:

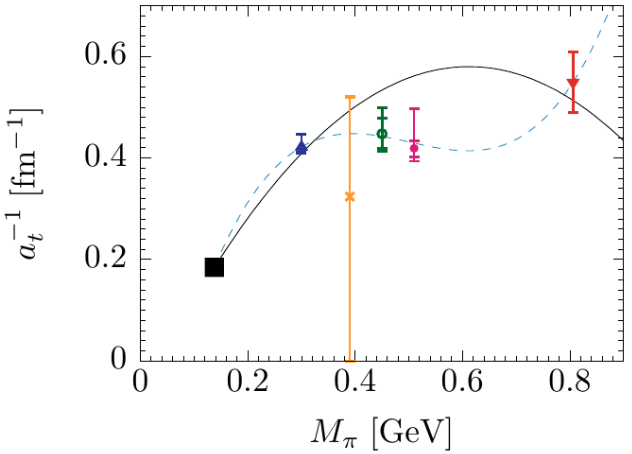
$$x_1 = 0.84(7)\ , \quad x_2 = -0.053(16)$$

$\hookrightarrow$ x_1 and x_2 more precise

$\hookrightarrow$ x_2 now has a definite sign

$\Rightarrow$ update end-of-the-world plot





Beane et al. (2012)
Yamazaki et al. (2015)
Orginos et al. (2015)
Beane et al. (2013)
Yamazaki et al. (2012)

New end-of-the-world plots

Lähde, UGM, Epelbaum, Eur. Phys. J **A 56** (2020) 89

- Constraints now depend on Z, the nucleus and the sign of δm_q

- lattice values for $\bar{A}_{s,t}$:

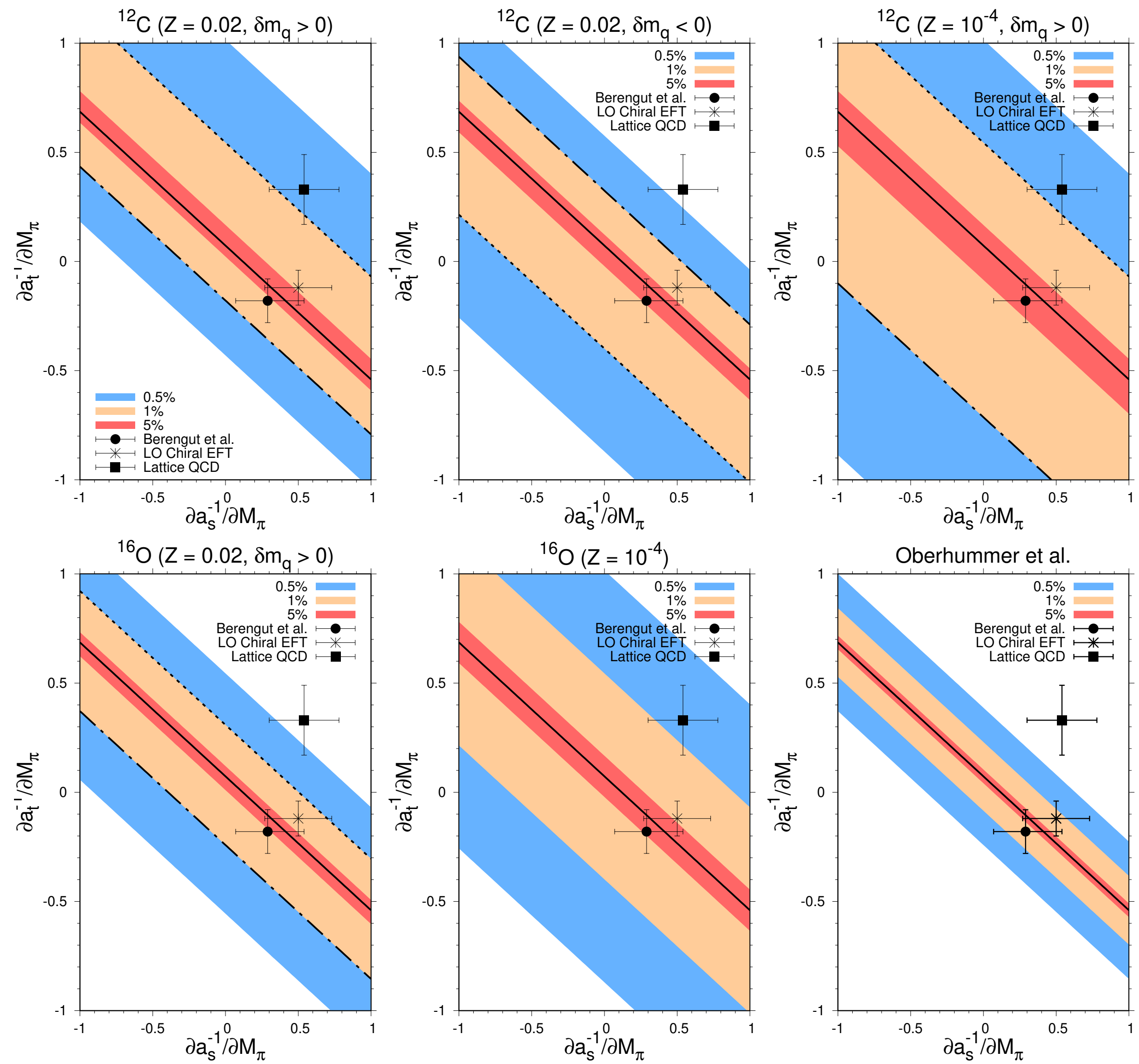
> The light quark mass is fine-tuned to $\simeq 0.5\,\%$

- chiral EFT values for $\bar{A}_{s,t}$:

> The light quark mass is fine-tuned to $\simeq 5\,\%$

- Bound on $\alpha_{\rm EM}$ softened ($\sim 7.5\,\%$)

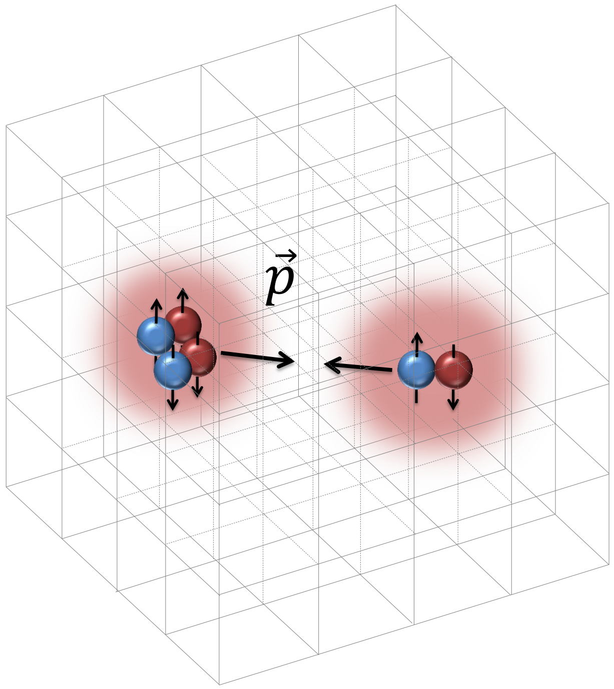
$\Rightarrow$ need better determinations of $\bar{A}_{s,t}$ from lattice QCD with pion masses closer to the physical point!



Quark mass dependence of alpha-alpha scattering

Nucleus-nucleus scattering on the lattice

- Processes involving α-particles and α-type nuclei comprise a major part of stellar nucleosynthesis, and control the production of certain elements in stars



- Ab initio calculations of scattering and reactions using continuum methods suffer from very unfavorable computational scaling with the number of nucleons A in the clusters (either factorial or exponential in A)

- This is very different in NLEFT:

Lattice EFT computational scaling $\Rightarrow$ $(A_1 + A_2)^2$

Rupak, Lee, Phys. Rev. Lett. **111** (2013) 032502
Pine, Lee, Rupak, Eur. Phys. J. A **49** (2013) 151
Elhatisari, Lee, Phys. Rev. C **90** (2014) 064001
Elhatisari et al., Phys.Rev. C **92** (2015) 054612
Elhatisari, Lee, UGM, Rupak, Eur. Phys. J. A **52** (2016) 174

Ab initio alpha-alpha scattering

Elhatisari, Lee, Rupak, Epelbaum, Krebs, Lähde, Luu, UGM, Nature **528** (2015) 111

- Construct the so-called adiabatic Hamiltonian

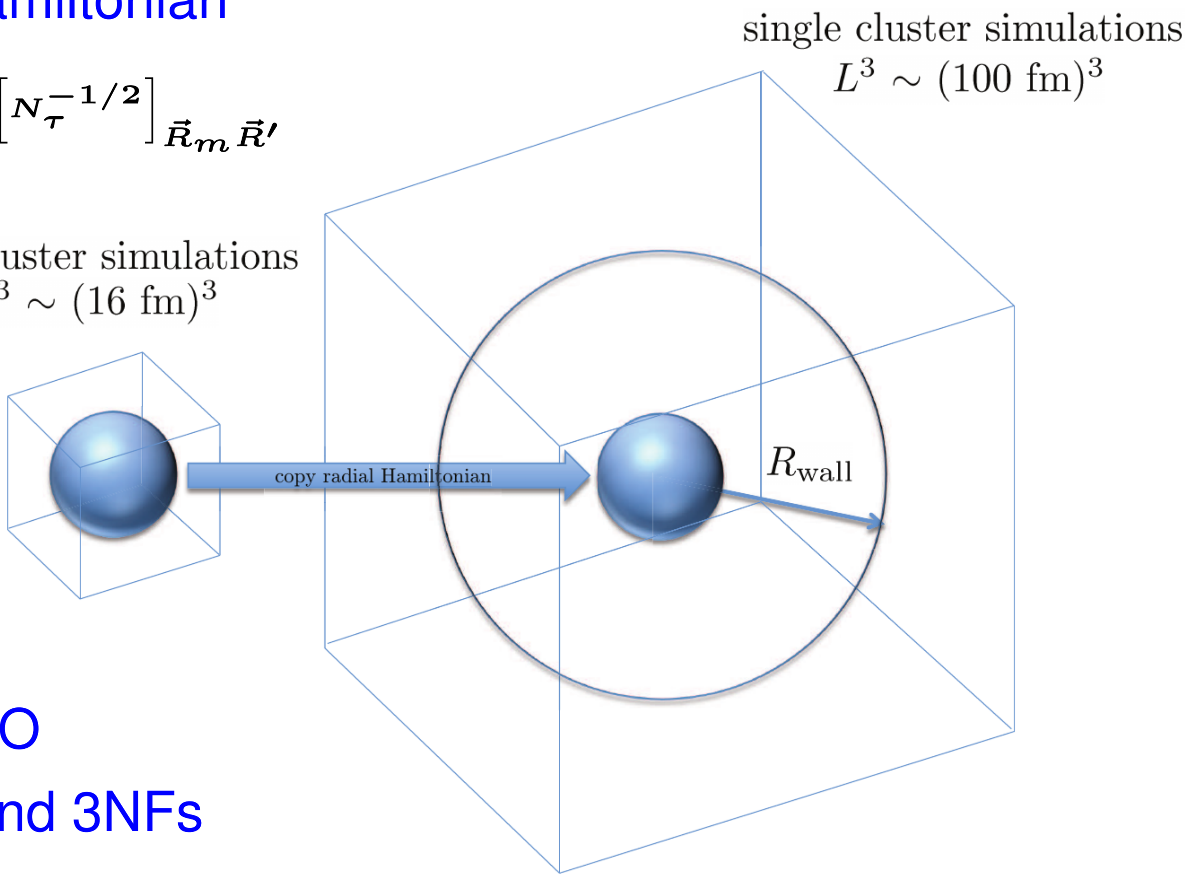
$$[H_\tau^a]_{\vec{R}\vec{R}'} = \sum_{\vec{R}_n \vec{R}_m} \left[N_\tau^{-1/2}\right]_{\vec{R}\vec{R}_n} \left[H_\tau\right]_{\vec{R}_n \vec{R}_m} \left[N_\tau^{-1/2}\right]_{\vec{R}_m \vec{R}'}$$

↪ two-cluster simulations

- Long-range Coulomb via spherical wall method (huge box)

Lu, Lähde, Lee, UGM, Phys. Lett. B **760** (2016) 309

↪ single cluster simulations



- Same action as used for ^{12}C and ^{16}O chiral N2LO Lagrangian w/ 2NFs and 3NFs

↪ all LECs determined before in NN and NNN systems

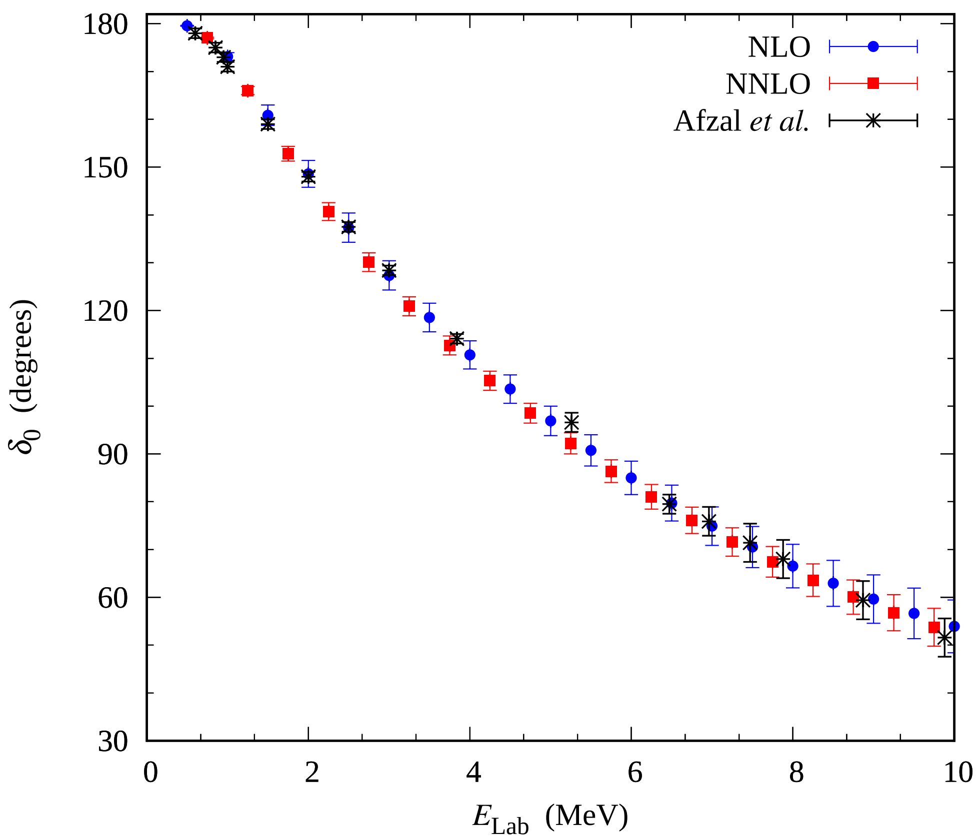
↪ parameter-free predictions

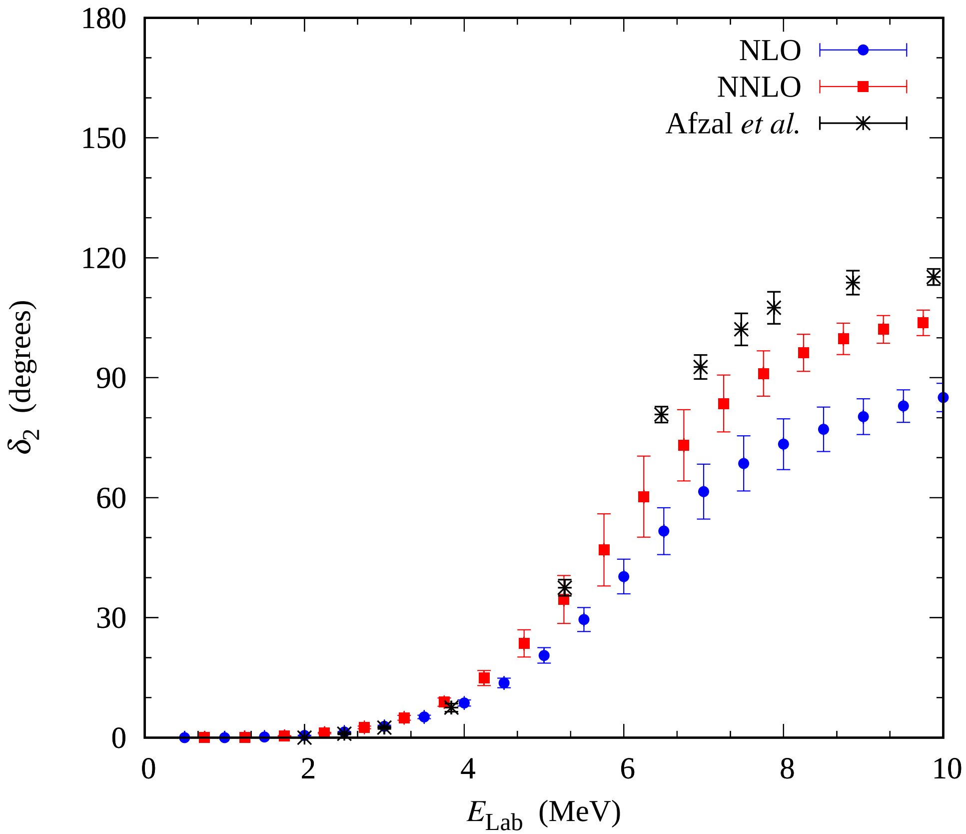
↪ first ever *ab initio* calculation of α-α scattering

Phase shifts of alpha-alpha scattering

- S-wave and D-wave phase shifts, updated in 2022

Elhatisari, Lähde, Lee, UGM, Vonk, JHEP **02** (2022) 001





$$E_R^{\rm NNLO} = -0.11(1)\ \text{MeV} \quad [+0.09\ \text{MeV}]$$

$$E_R^{\rm NNLO} = 2.93(5)\ \text{MeV} \quad [2.92(18)\ \text{MeV}]$$

$$\Gamma_R^{\rm NNLO} = 2.00(16)\ \text{MeV} \quad [1.35(50)\ \text{MeV}]$$

Afzal et al., Rev. Mod. Phys. **41** (1969) 247 [data]

Alpha-alpha scattering in the multiverse

Elhatisari, Lähde, Lee, UGM, Vonk, JHEP **02** (2022) 001

- Now vary the light quark mass m_q and the fine-structure constant $\alpha_{\rm EM}$

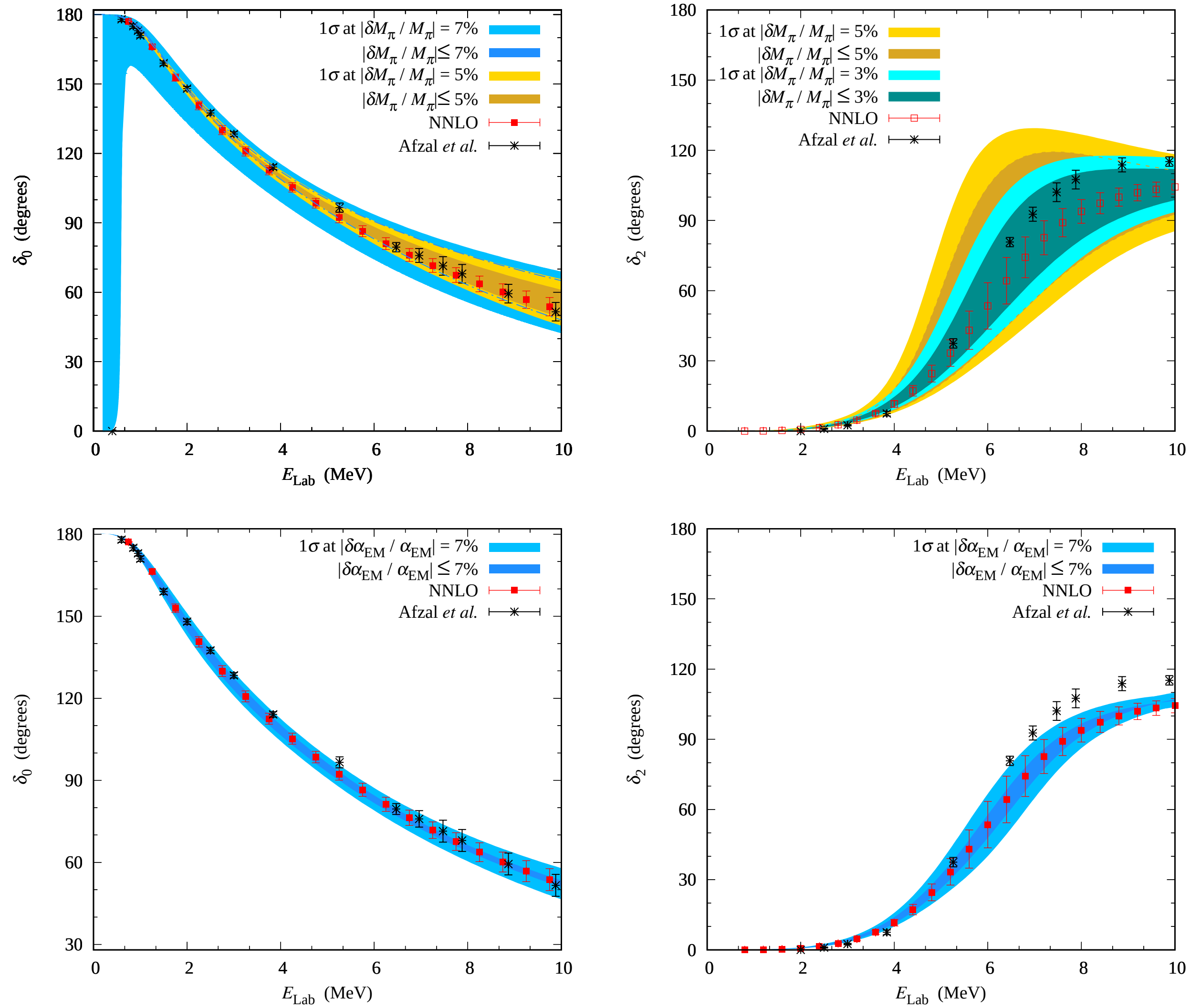
$\Rightarrow$ Dramatic effect in the S-wave for $\delta M_\pi/M_\pi \simeq 7\%$

$\Rightarrow$ D-wave resonance requires $\delta M_\pi/M_\pi \lesssim 3\%$

$\Rightarrow$ S- and D-wave phase shifts tolerate $\delta\alpha_{\rm EM}/\alpha_{\rm EM} \lesssim 7\%$

$\Rightarrow$ weaker bounds as given by the position of the Hoyle state but independet of stellar modelling!

- in a next step, consider $\alpha+{}^8$Be$\to{}^{12}$C as function of m_q and $\alpha_{\rm EM}$



Summary & outlook

- Chiral nuclear EFT: best approach to nuclear forces and few-body systems
- Study of the nuclear force as a function of the quark masses & $\alpha_{\rm EM}$
  $\to$ pion-exchanges straightforward, contact interactions require modeling / LQCD
- Impact on BBN: $|\delta m_q/m_q| \le 0.9\%$ $\hookrightarrow$ requires update
- Variations of $\alpha_{\rm EM}$: many sources, new input $\to$ $|\delta\alpha_{\rm EM}/\alpha_{\rm EM}| \le 2\%$
- Nuclear lattice simulations as a new quantum many-body approach
  $\to$ allow to vary the parameters of QCD+QED
  $\to$ investigate changes in nuclear properties + scattering can also be done
- Fine-tuning of $m_{\rm quark}$ and $\alpha_{\rm EM}$ $\to$ viability of carbon-oxygen based life
  $\Rightarrow$ changes in m_q of about 0.5 % and in $\alpha_{\rm EM}$ of about 7.5% are allowed
  $\Rightarrow$ LQCD required to reduce the uncertainties! $\hookrightarrow$ challenge!
  $\Rightarrow$ Sensitivity of α-α scattering to m_q and $\alpha_{\rm EM}$ worked out

$\Rightarrow$ conditions for life are fine-tuned

SPARES

QUARK MASS DEP. of the SHORT-DISTANCE TERMS

- Consider a typical OBEP with $M = \sigma, \rho, \omega, \delta, \eta$
- Quark mass dependence of the sigma and rho from unitarized CHPT

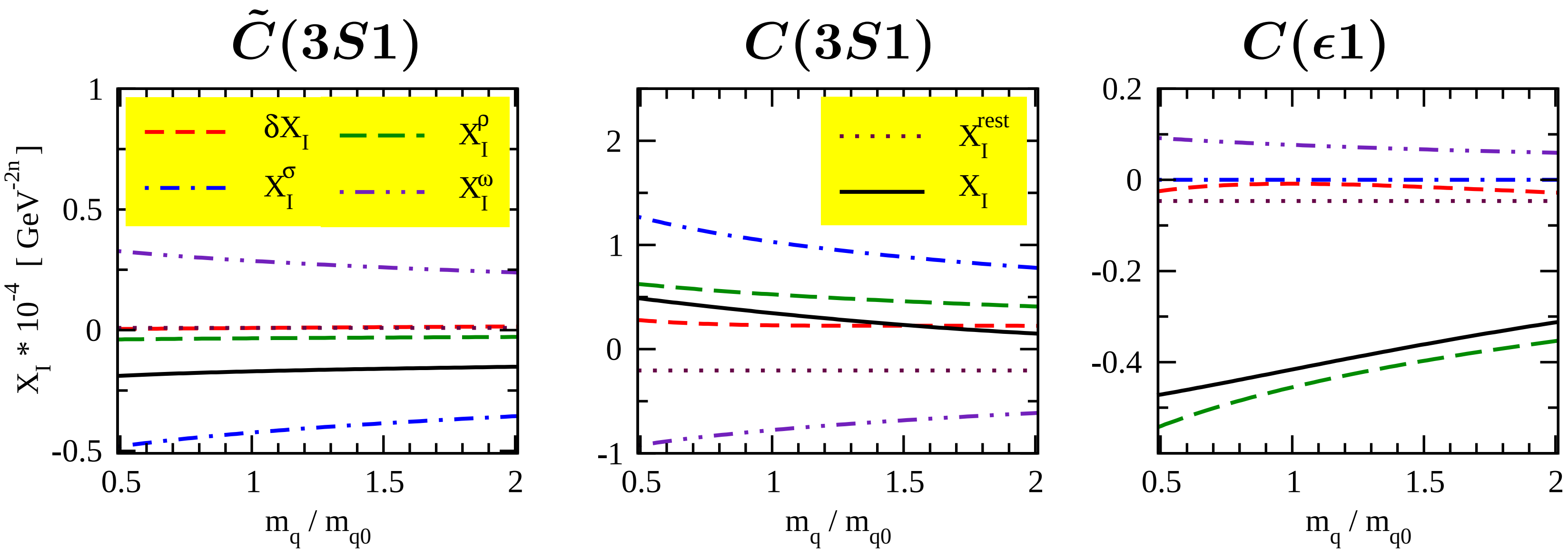
Hanhart, Pelaez, Rios (2008)

$\Rightarrow$ $K^q_{M_\sigma} = 0.081 \pm 0.007, \quad K^q_{M_\rho} = 0.058 \pm 0.002$

$\Rightarrow$ couplings appear quark mass independent (requires refinement in the future)

- assume a) that $K^q_\omega = K^q_\rho$ and b) neglect dep. of δ, η

$\Rightarrow$



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 $J^P = 0^+$ 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

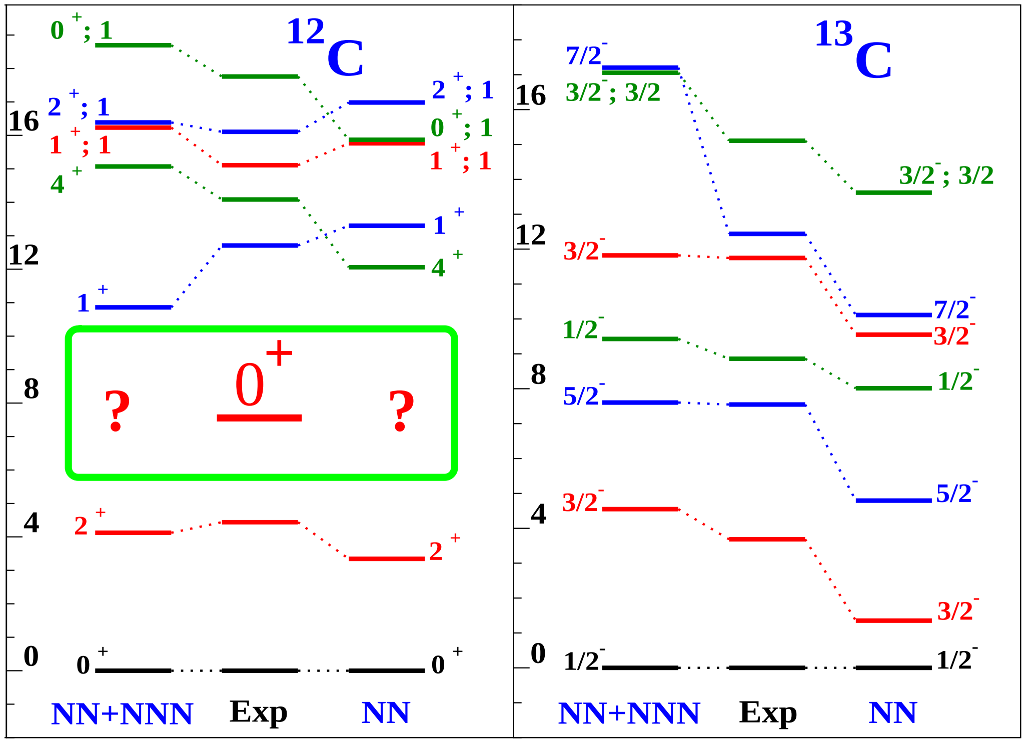
- and how about theory ? $\rightarrow$ this talk
- side remark: NOT driven by anthropic considerations

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

AN ENIGMA for NUCLEAR THEORY

- Ab initio calculation in the no-core shell model: $\approx 10^7$ CPU hrs on JAGUAR

P. Navratil et al., Phys. Rev. Lett. **99** (2007) 042501; R. Roth et al., Phys. Rev. Lett. **107** (2011) 072501



⇒ excellent description, but no trace of the Hoyle state

RESULTS for HEAVIER NUCLEI

- calculate BBN response matrix of primordial abundances Y_a at fixed baryon/photon ratio :

$$\frac{\delta \ln Y_a}{\delta \ln m_q} = \sum_{X_i} \frac{\partial \ln Y_a}{\partial \ln X_i} K^q_{X_i}$$

$\Rightarrow$

X	d	^{3}He	^{4}He	^{6}Li	^{7}Li
a_s	−0.39	0.17	0.01	−0.38	2.64
$B_{\rm deut}$	−2.91	−2.08	0.67	−6.57	9.44
$B_{\rm trit}$	−0.27	−2.36	0.01	−0.26	−3.84
$B_{^3\rm He}$	−2.38	3.85	0.01	−5.72	−8.27
$B_{^4\rm He}$	−0.03	−0.84	0.00	−69.8	−57.4
$B_{^6\rm Li}$	0.00	0.00	0.00	78.9	0.00
$B_{^7\rm Li}$	0.03	0.01	0.00	0.02	−25.1
$B_{^7\rm Be}$	0.00	0.00	0.00	0.00	99.1
τ	0.41	0.14	0.72	1.36	0.43

updated Kawano code

Kawano, FERMILAB-Pub-92/04-A

RESULTS

- putting pieces together:

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

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

- 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

- the triple alpha process is controlled by :

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

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

$\Rightarrow$ quark mass dependence of the scattering lengths discussed earlier