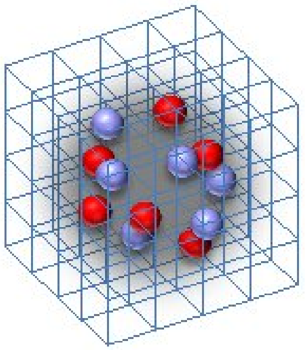
Anthropic Considerations in Nuclear Physics (B.7)

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



NLEFT

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- **Nuclear Lattice Effective Field Theory collaboration**

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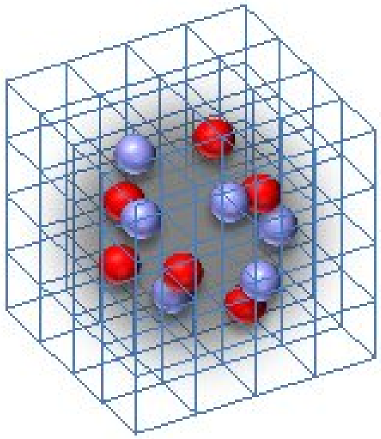


CONTENTS

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, . . .

⇒ 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, $\ldots$

$$
\begin{aligned}
&{}^4\mathrm{He} + {}^4\mathrm{He} \rightleftharpoons {}^8\mathrm{Be} \\
&{}^8\mathrm{Be} + {}^4\mathrm{He} \rightleftharpoons {}^{12}\mathrm{C}^* \rightarrow {}^{12}\mathrm{C} + \gamma \\
&{}^{12}\mathrm{C} + {}^4\mathrm{He} \rightleftharpoons {}^{16}\mathrm{O} + \gamma
\end{aligned}
$$

- 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
  $E - E(\mathrm{g.s.}) = 7.653 \pm 0.008$ MeV Dunbar et al. 1953, Cook et al. 1957

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

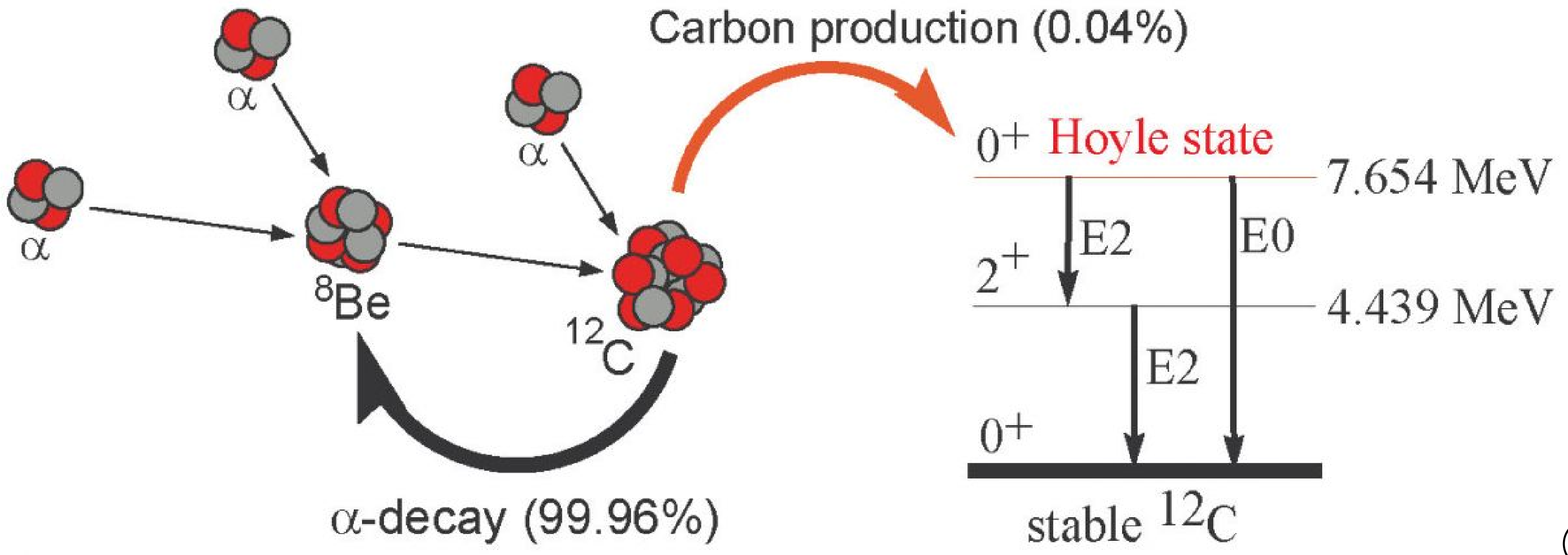
M. Chernykh et al., Phys. Rev. Lett. 98 (2007) 032501

- *ab initio* theory only during the last few years (part of **B.7**)

- 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 !

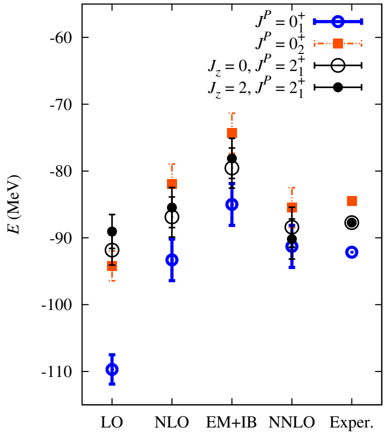
The RELEVANT QUESTION

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.

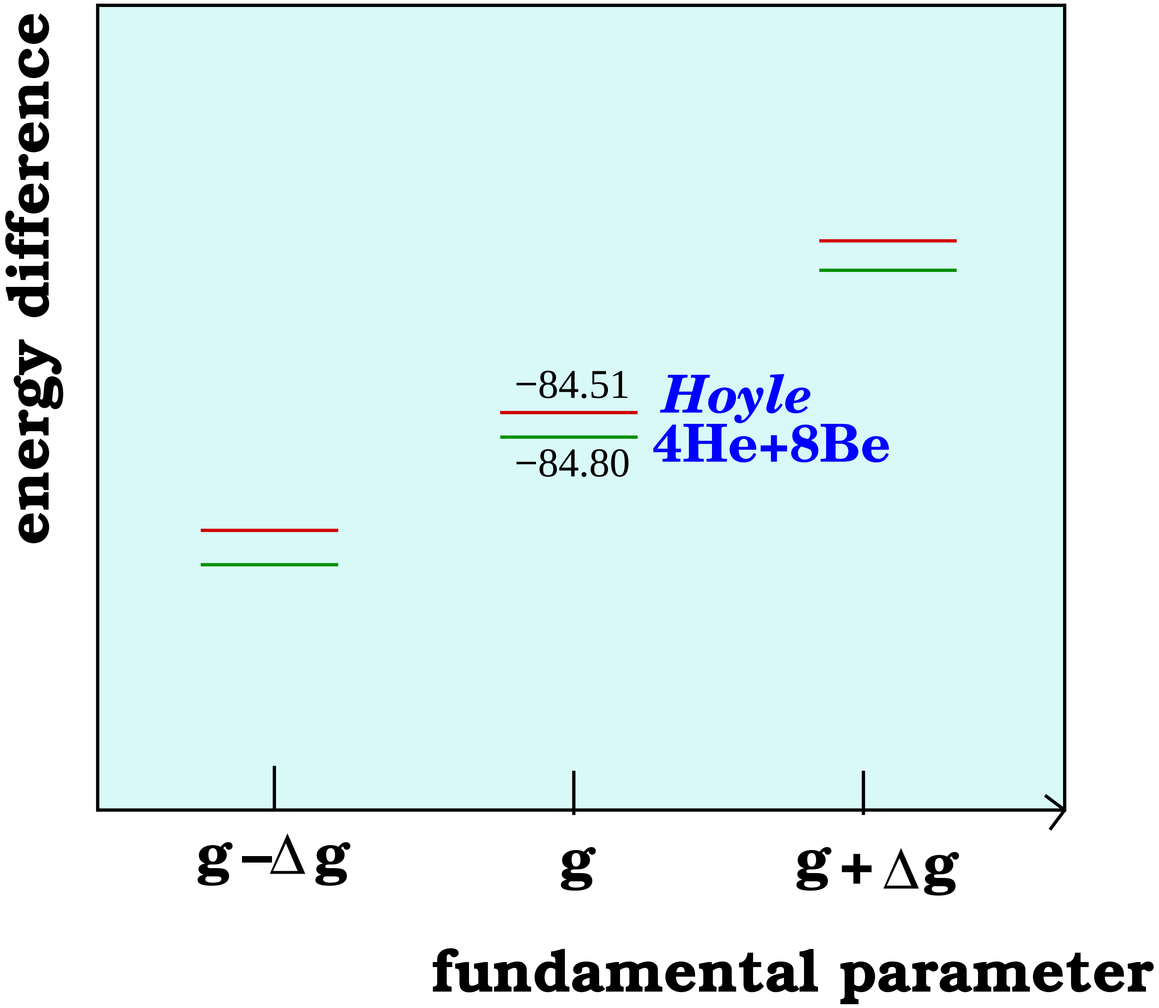
All best,
Steve Weinberg



- 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!*

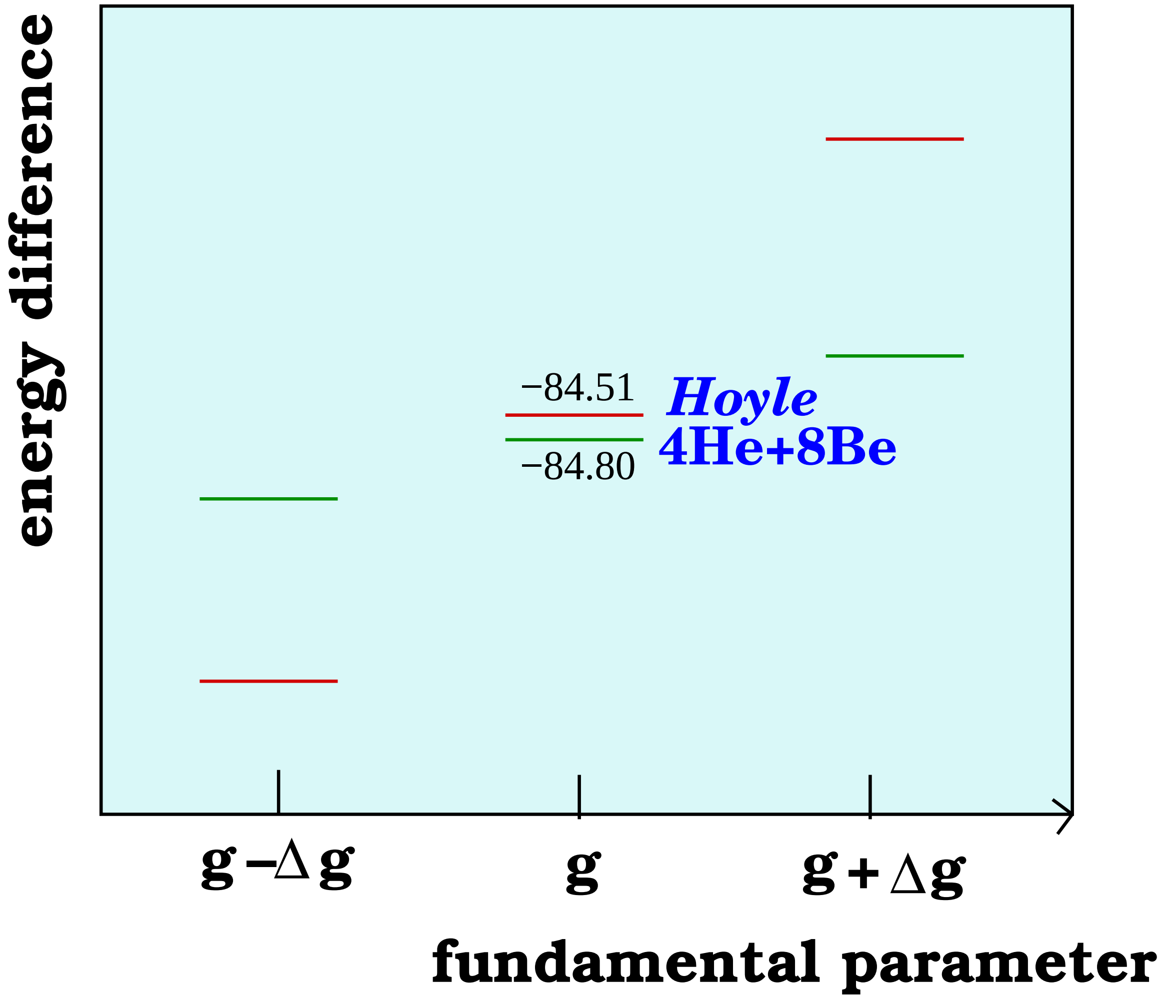
The NON-ANTHROPIC SCENARIO

- 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



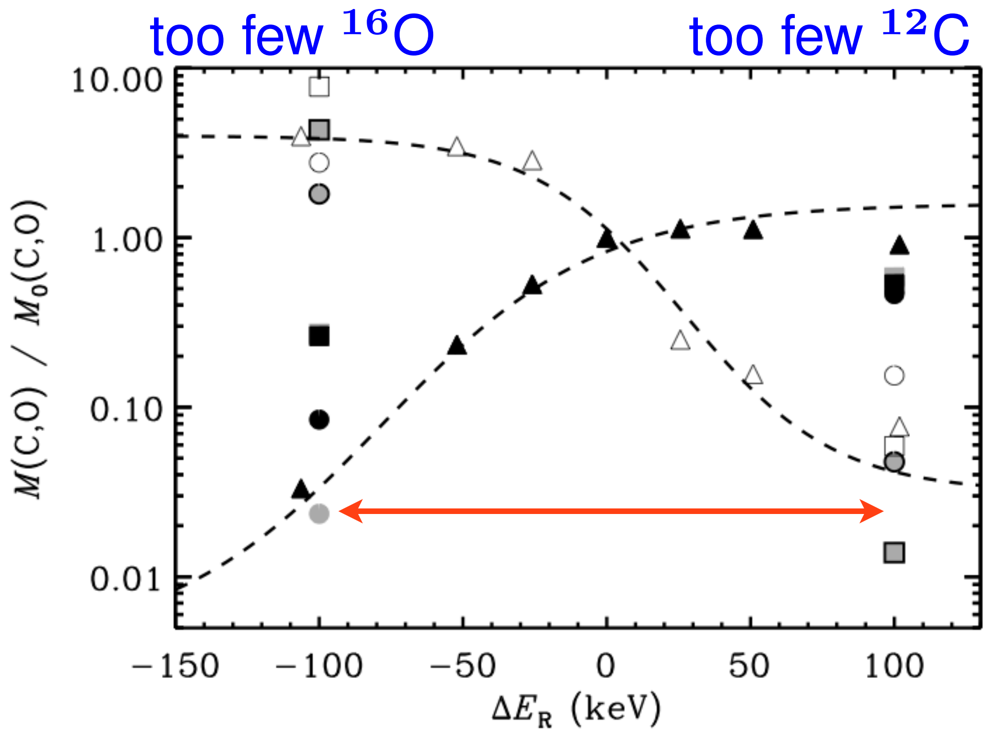
EARLIER STUDIES of the ANTHROPIC PRINCIPLE

- 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?

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



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]

Nuclear lattice simulations

NUCLEAR LATTICE SIMULATIONS

Frank, Brockmann (1992), Koonin, Müller, Seki, van Kolck (2000) , Lee, Borasoy, Schäfer, Phys.Rev. **C70** (2004) 014007, . . .
Borasoy, Krebs, Lee, UGM, Nucl. Phys. **A768** (2006) 179; Borasoy, Epelbaum, Krebs, Lee, UGM, Eur. Phys. J. **A31** (2007) 105

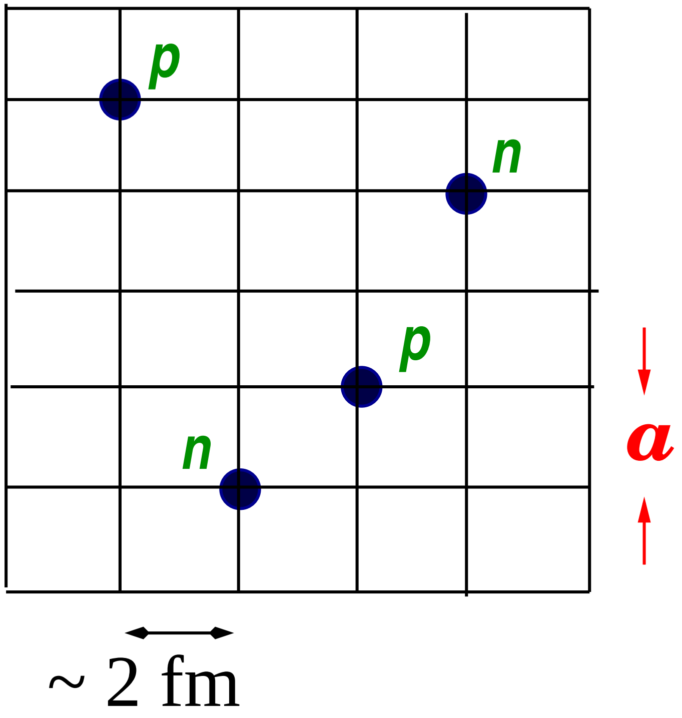
- *new method* to tackle the nuclear many-body problem

- 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

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

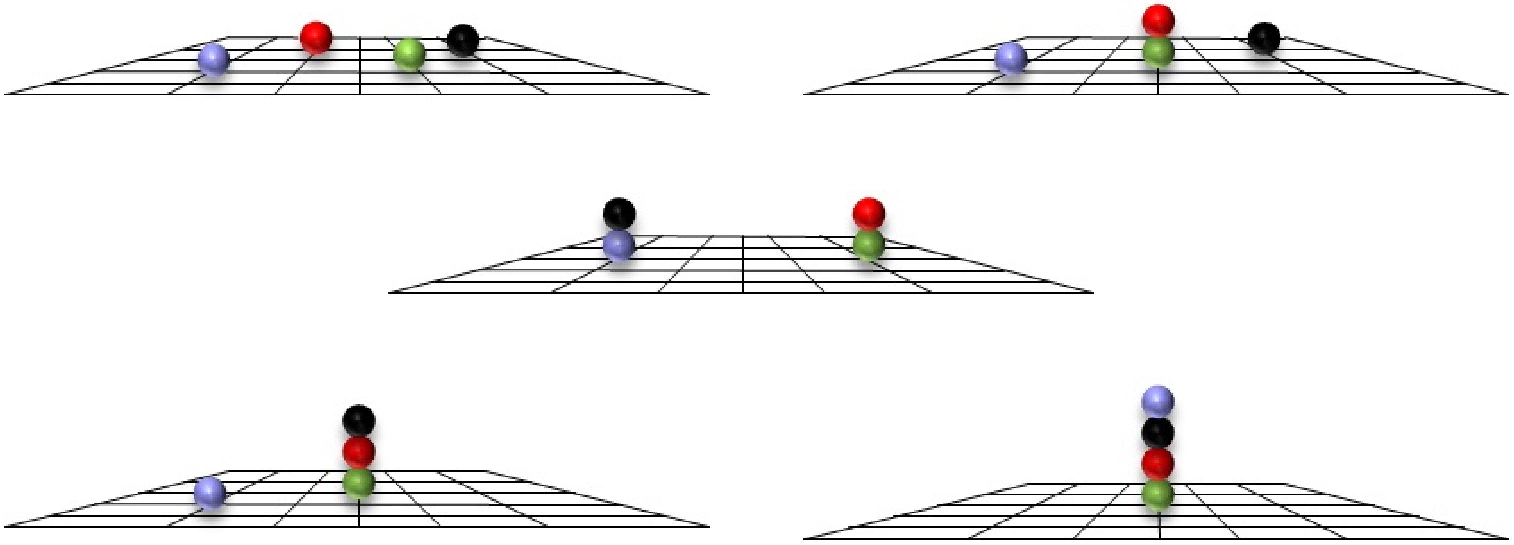


- strong suppression of sign oscillations due to approximate Wigner SU(4) symmetry

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*
- ⇒ perform *ab initio* calculations using only V_{NN} and V_{NNN} as input
- ⇒ grand challenge: the spectrum of ^{12}**C**

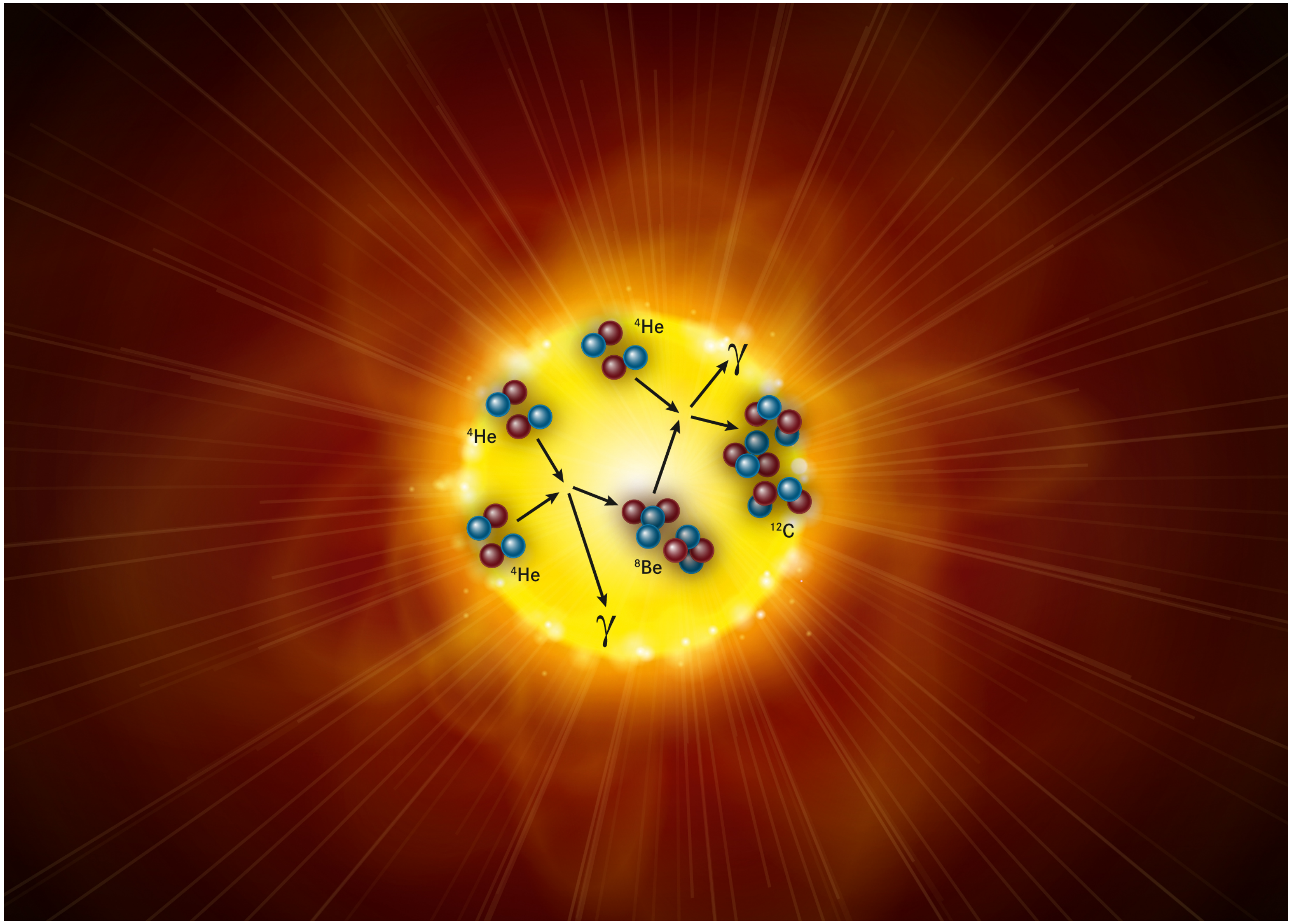
COMPUTATIONAL EQUIPMENT

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

6 Pflops

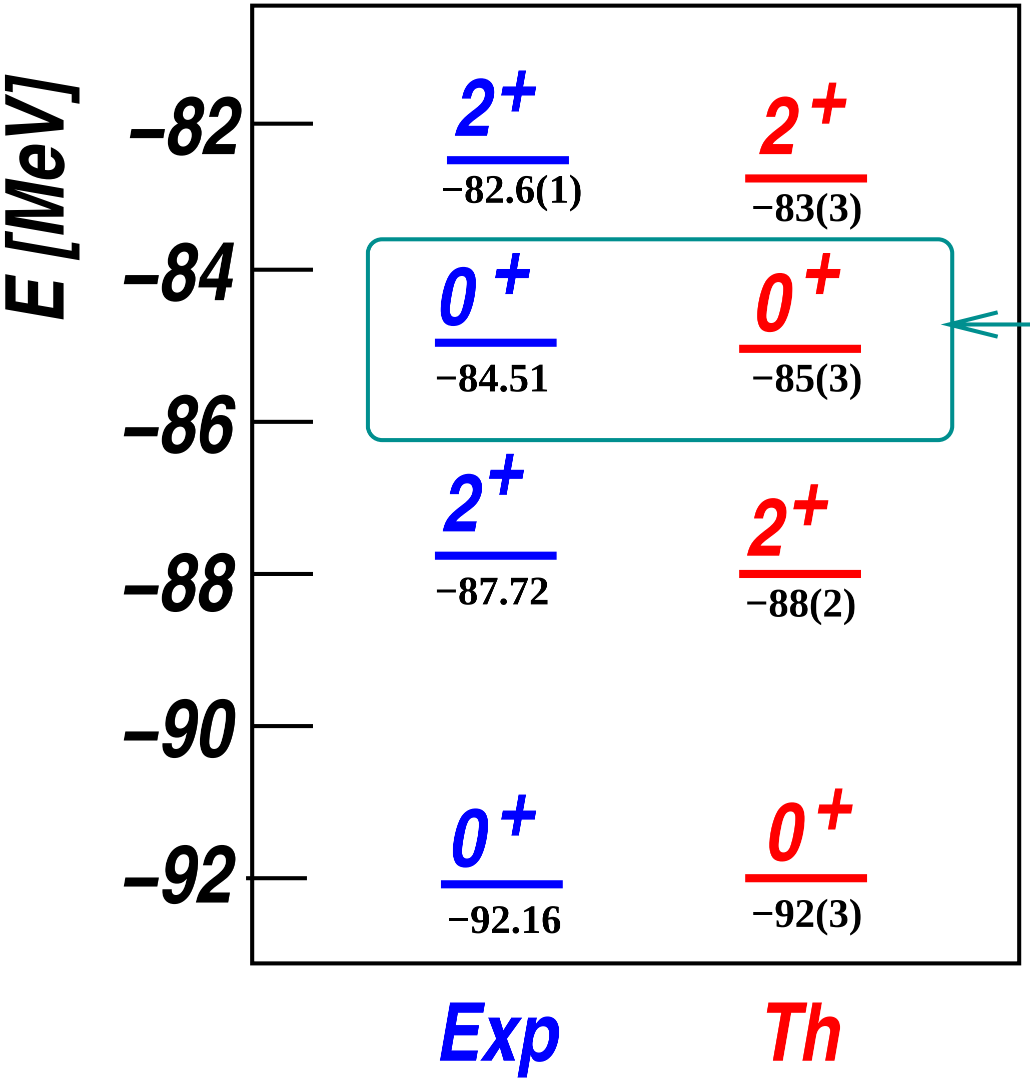
SPECTRUM OF ^{12}C & the HOYLE STATE

Epelbaum, Krebs, Lee, UGM, Phys. Rev. Lett. **106** (2011) 192501
Viewpoint: Hjorth-Jensen, Physics **4** (2011) 38
Epelbaum, Krebs, Lähde, Lee, UGM, Phys. Rev. Lett. **109** (2012) 252501



The SPECTRUM of CARBON-12

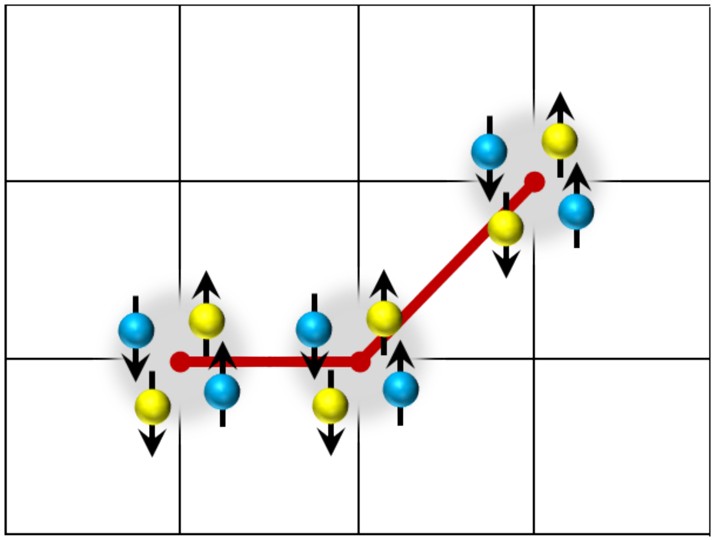
- After $8 \cdot 10^6$ hrs JUGENE/JUQUEEN (and “some” human work)



Hoyle

⇒ First ab initio calculation
of the Hoyle state ✓

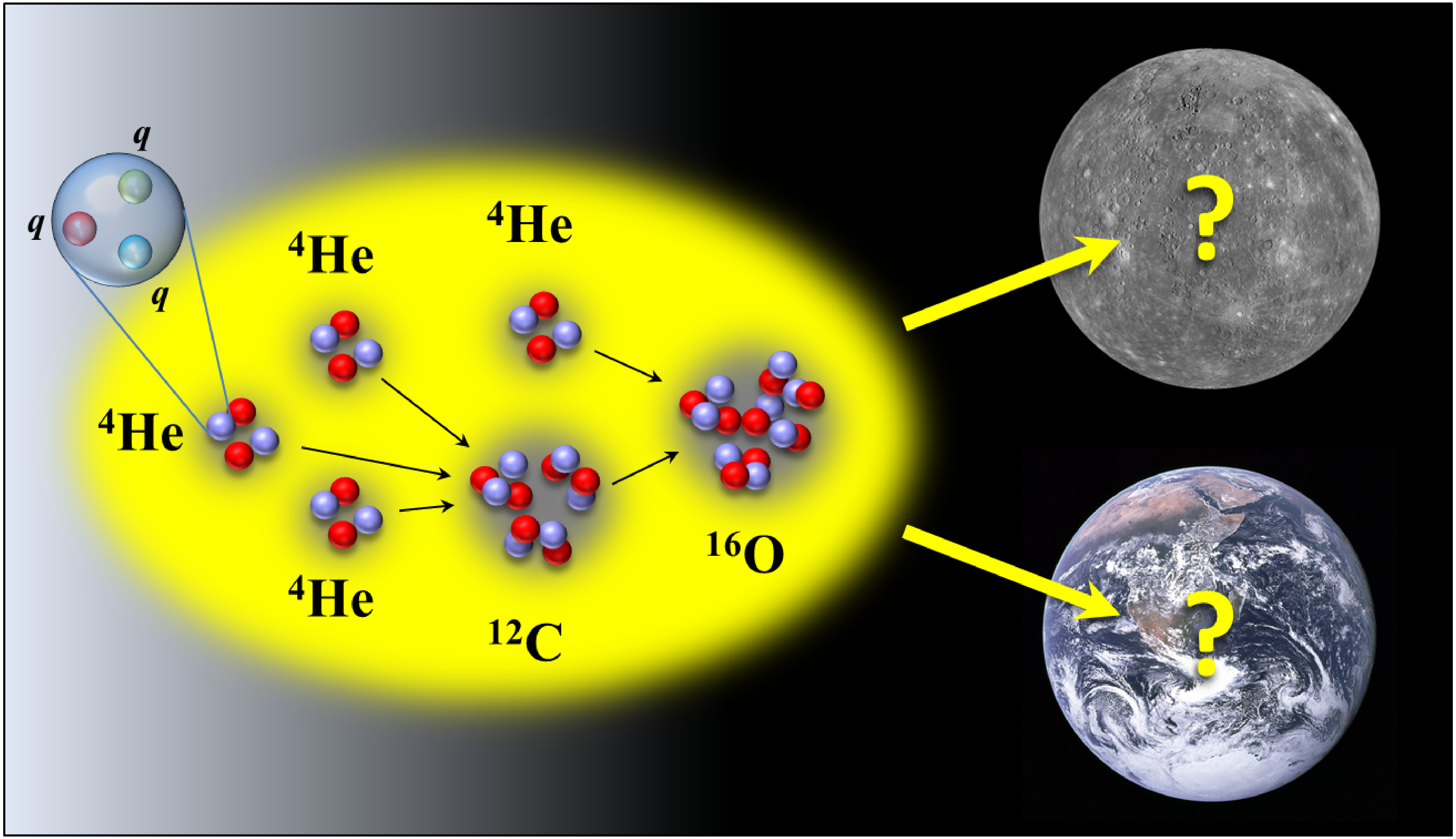
Structure of the Hoyle state:



Testing the Anthropic Principle

FINE-TUNING of FUNDAMENTAL PARAMETERS

Fig. courtesy Dean Lee



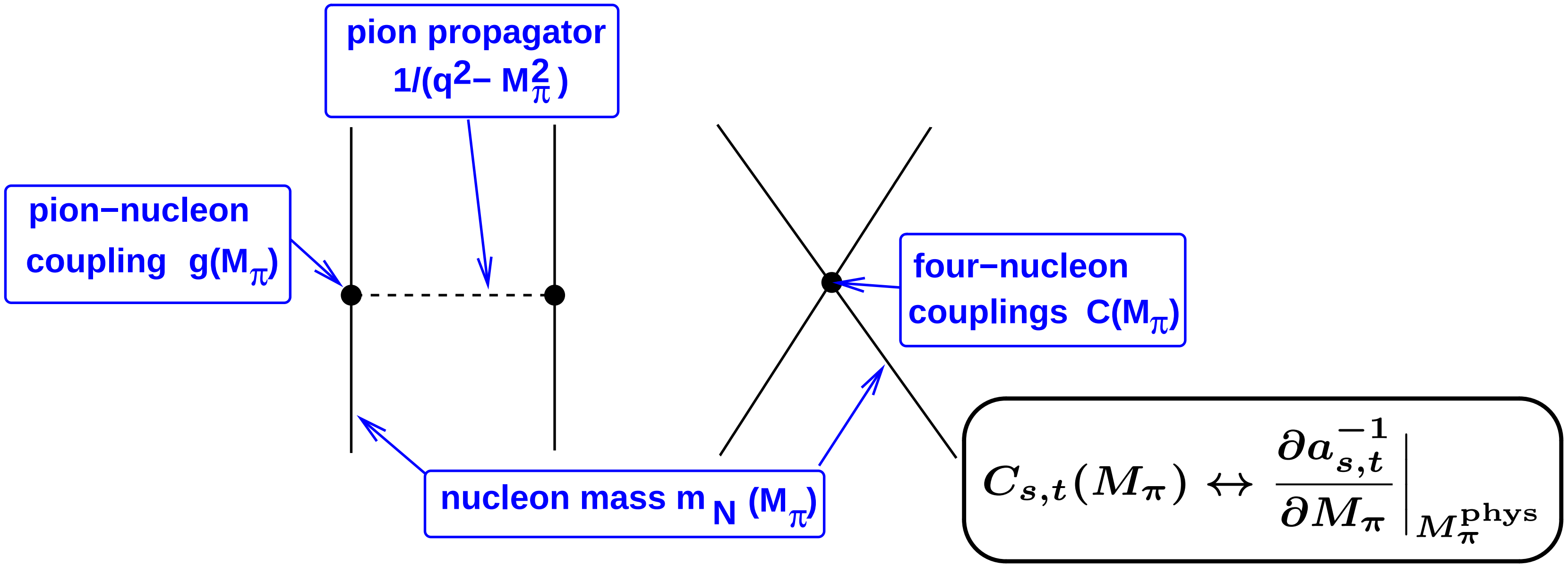
FINE-TUNING: MONTE-CARLO ANALYSIS

Epelbaum, Krebs, Lähde, Lee, UGM, PRL **110** (2013) 112502, Eur. Phys. J. **A49** (2013) 82

- simulations allow to vary $m_{\rm quark}$ and α_{EM}
- quark mass dependence $\equiv$ pion mass dependence: $\boxed{M^2_{\pi^\pm} \sim (m_u + m_d)}$

Gell-Mann, Oakes, Renner (1968)

- explicit and implicit pion mass dependences



pion propagator $1/(q^2 - M_\pi^2)$

pion−nucleon coupling $g(M_\pi)$

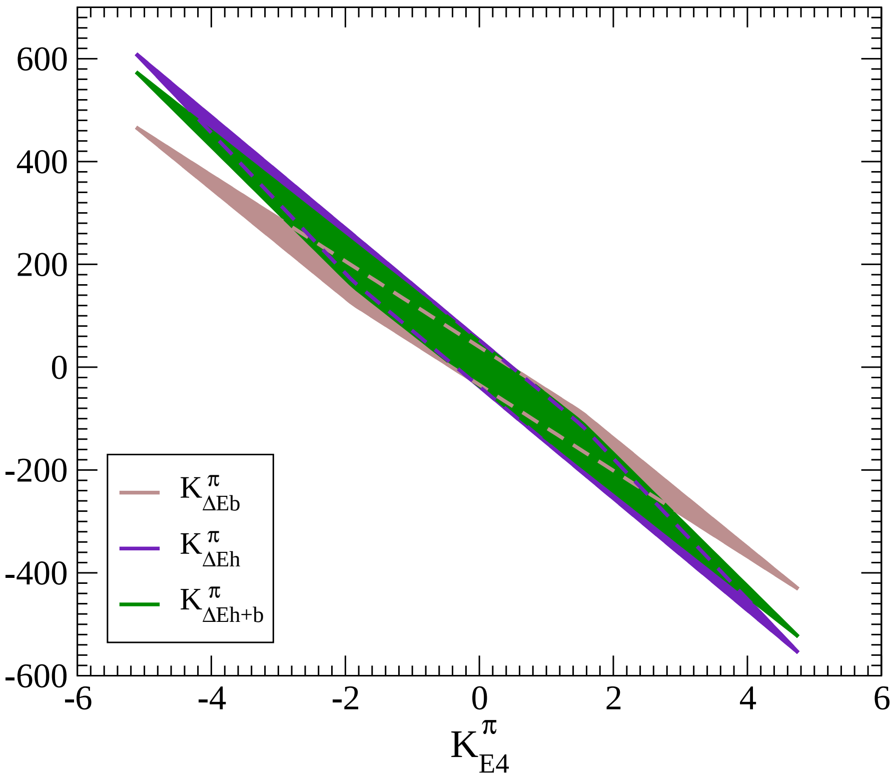
four−nucleon couplings $C(M_\pi)$

nucleon mass $m_N(M_\pi)$

$$C_{s,t}(M_\pi) \leftrightarrow \left.\frac{\partial a^{-1}_{s,t}}{\partial M_\pi}\right|_{M_\pi^{\rm phys}}$$

CORRELATIONS

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



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

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

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

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

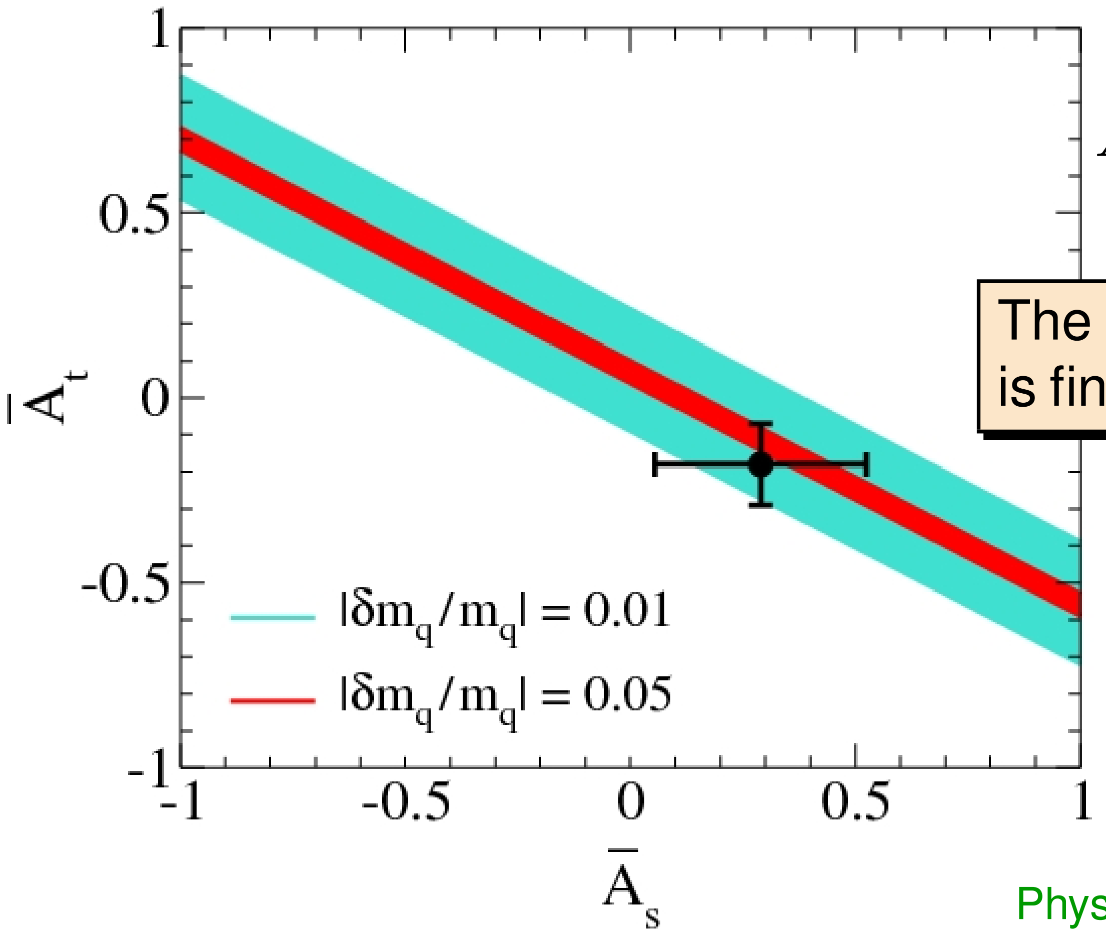
- clear correlations: α-particle BE and the energies/energy differences

⇒ 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 Schlattl et al. (2004)

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



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

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

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

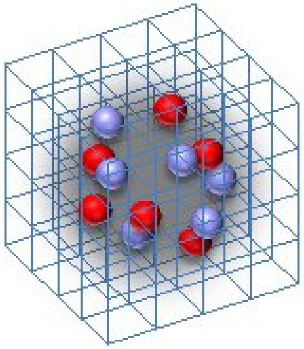
Berengut et al., Phys. Rev. **D 87** (2013) 085018

SUMMARY & OUTLOOK

- Nuclear lattice simulations as a new quantum many-body approach
- Formulate continuum EFT on space-time lattice $\boldsymbol{V = L_s \times L_s \times L_s \times L_t}$
- Fix parameters in few-nucleon systems $\rightarrow$ predictions
- ^{12}C spectrum and strcuture at NNLO $\rightarrow$ Hoyle state & $\mathbf{2^+}$ excitation
- Testing the anthropic principle $\rightarrow$ few percent fine-tuning

  $\Rightarrow$ need better determination of $\boldsymbol{\partial a_{s,t}^{-1}/\partial M_\pi \big|_{M_\pi^{\rm phys}}}$
- also done: spectrum and structure of ^{16}O $\checkmark$
- taming the sign problem: nuclei with $\boldsymbol{Z \neq N}$ $(\checkmark)$

  $\Rightarrow$ on a good way to overachieve in this part of **B.7**



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