Life on Earth: An Accident?

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

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by ERC, EXOTIC

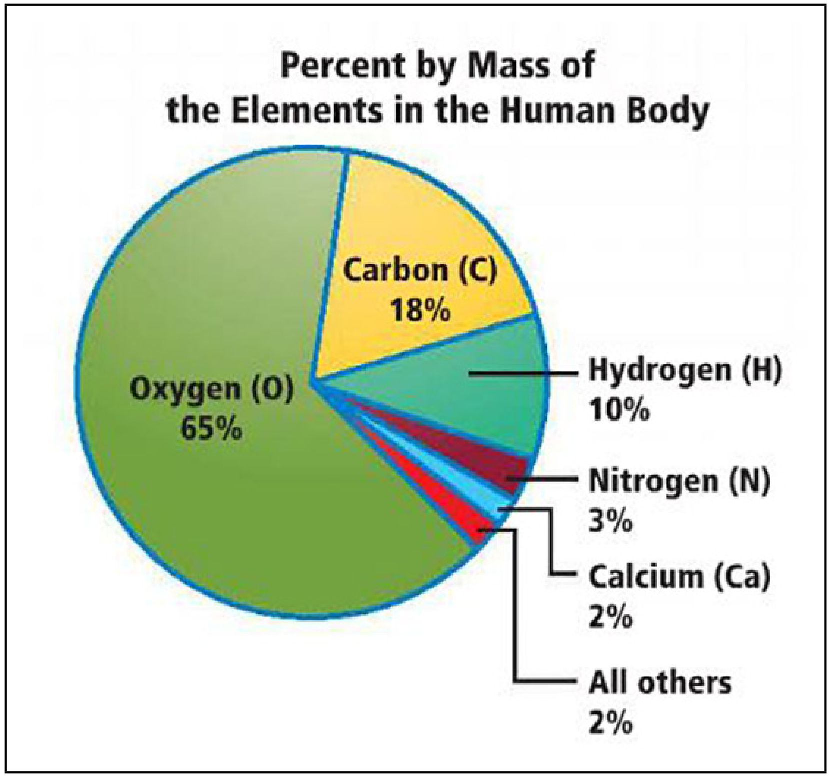
by NRW-FAIR

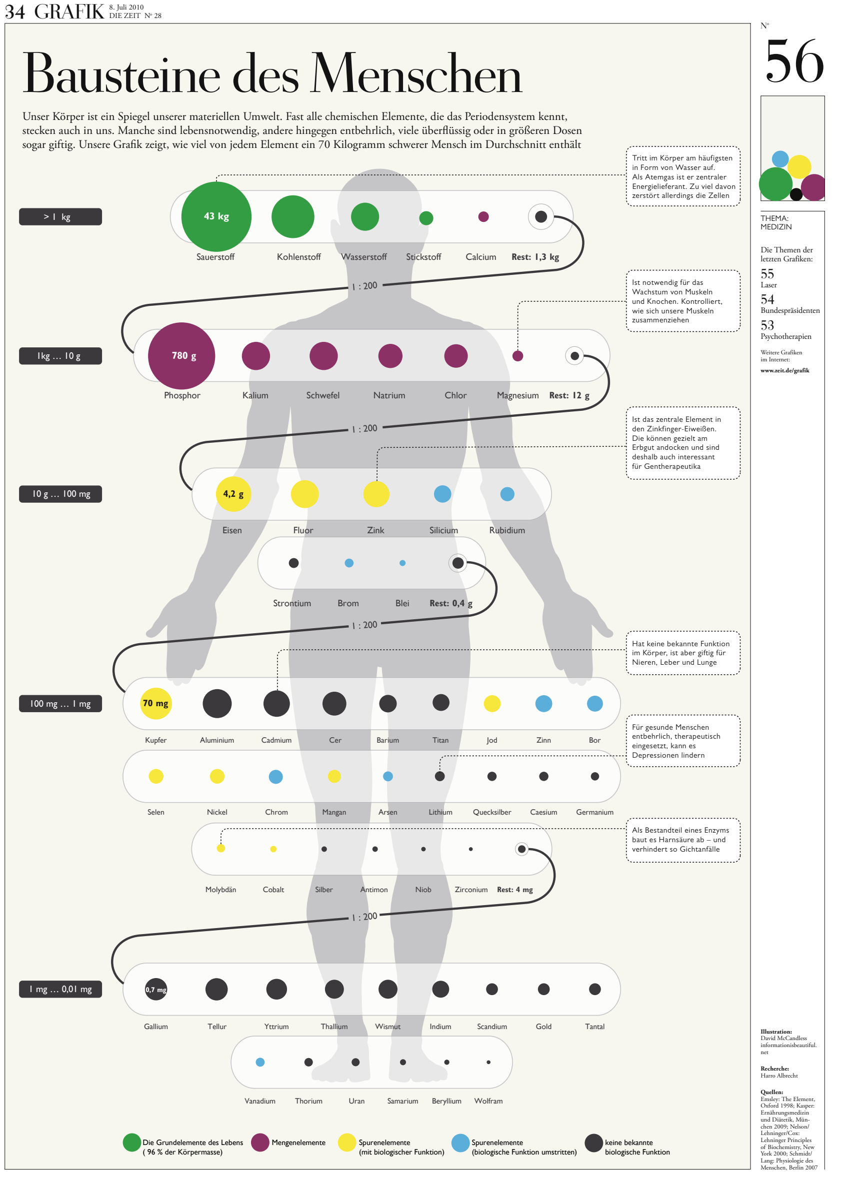
Contents

Introduction: Elements of life

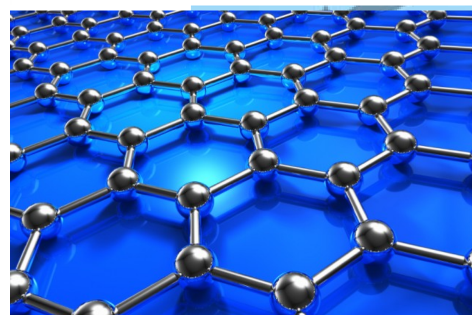
Human chemistry

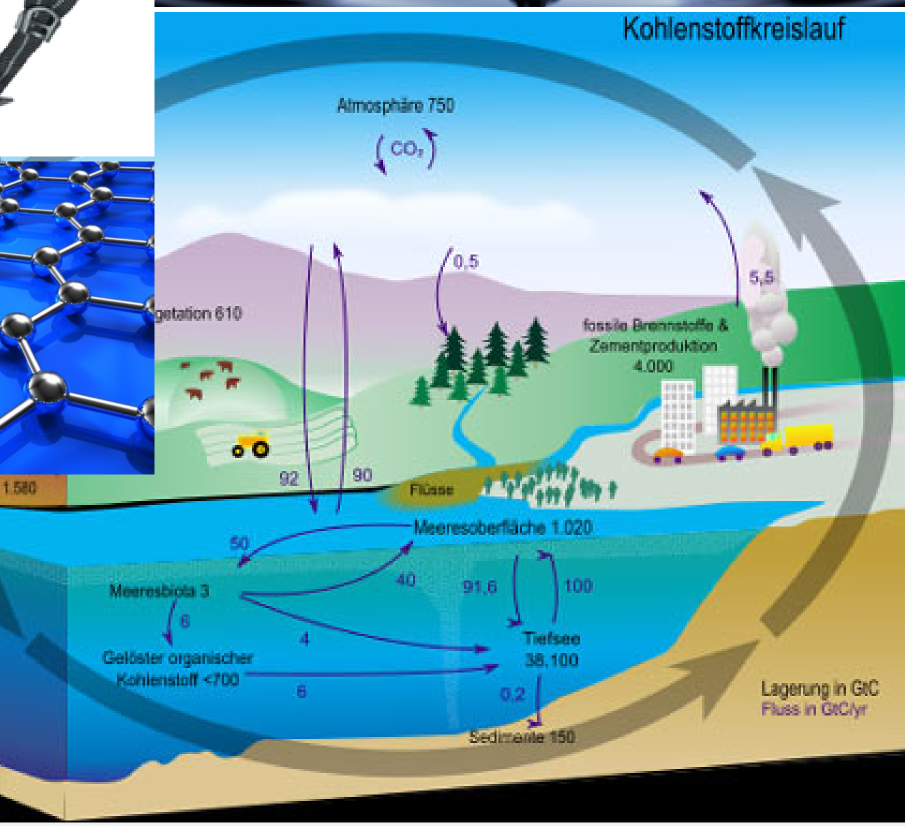
- The human body consists mostly of water (H_2O)
- All organic substances are based on **carbon (C)**





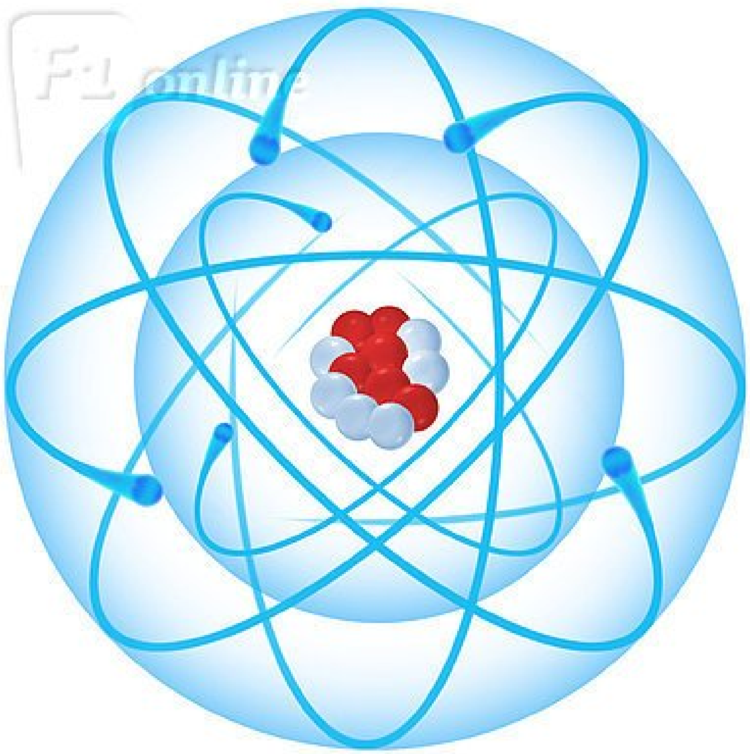
The many factes of carbon



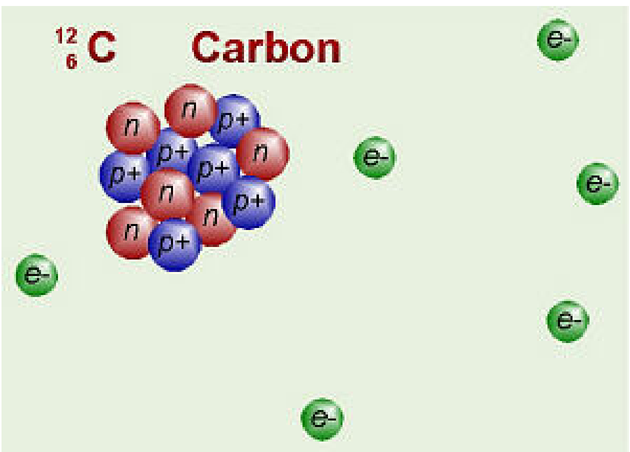


Structure of the carbon atom

- carbon atom



- carbon nucleus



6 protons (positively charged)

6 neutrons (no charge)

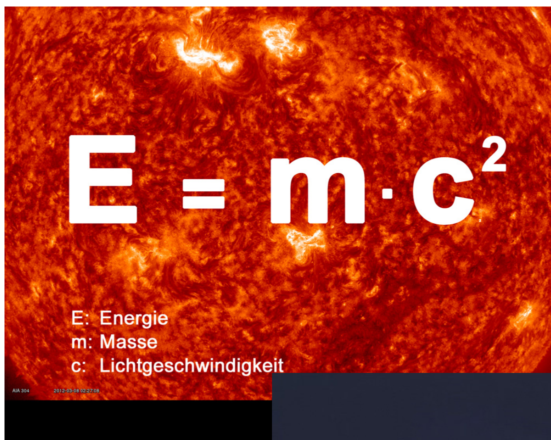
$\Rightarrow$ **atomic weight: 12 a.u.** $\simeq 2 \cdot 10^{-26}$ **kg**

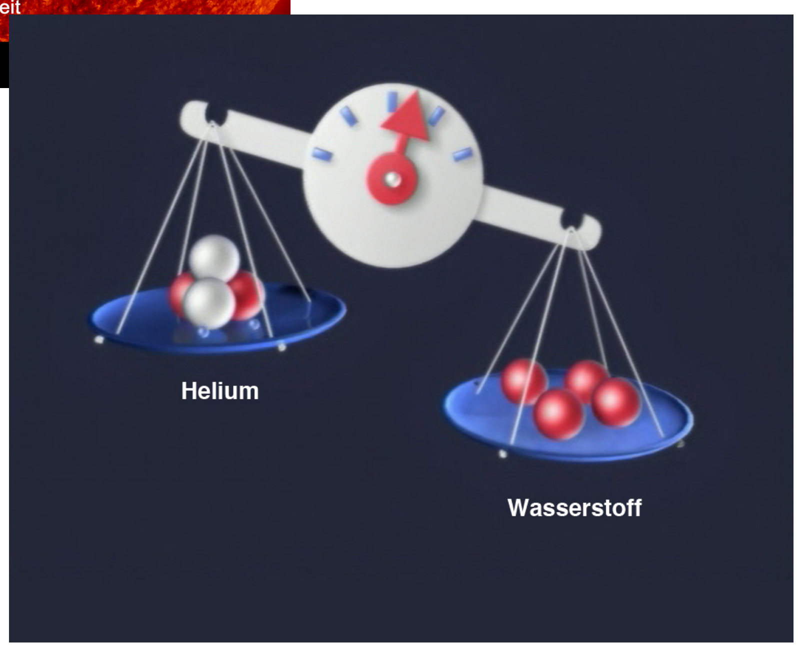
How is the carbon nucleus generated?

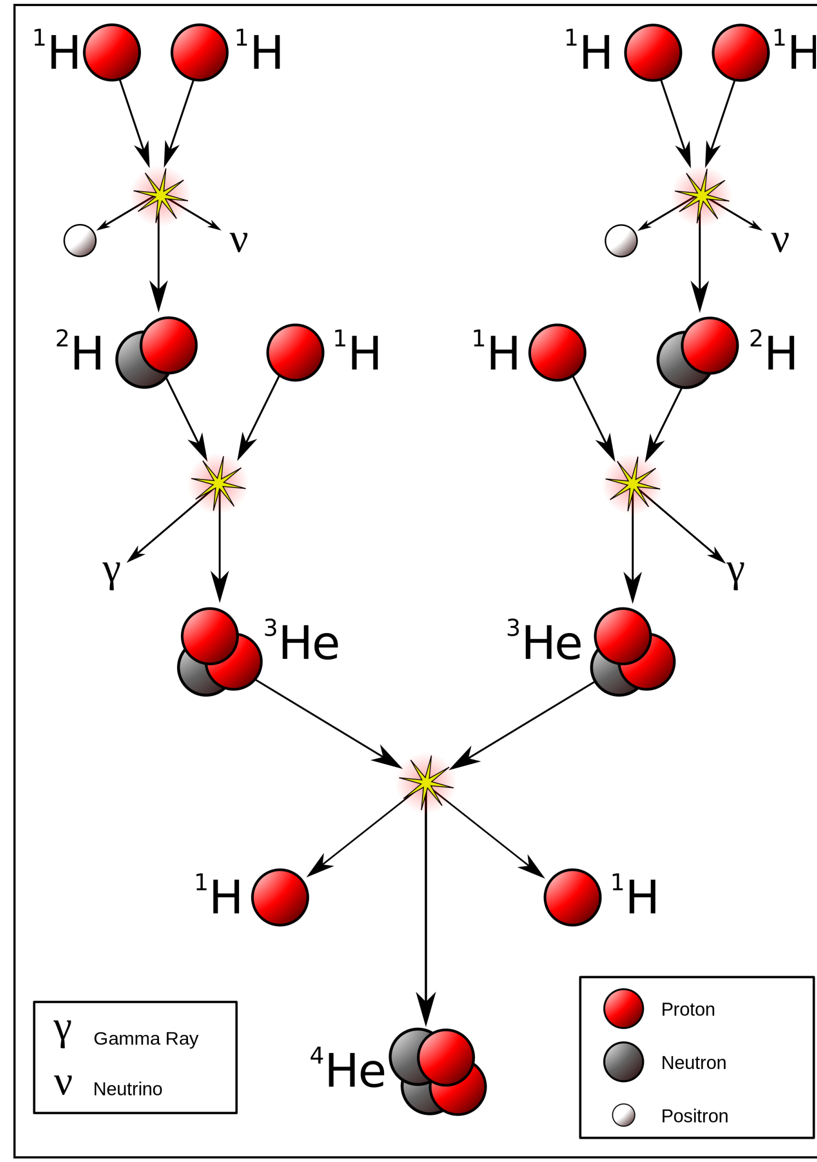
Nuclear fusion

- The elements are generated in the Big Bang
  & in stars through nuclear **fusion** processes

$\Rightarrow$ we are all made from stardust!



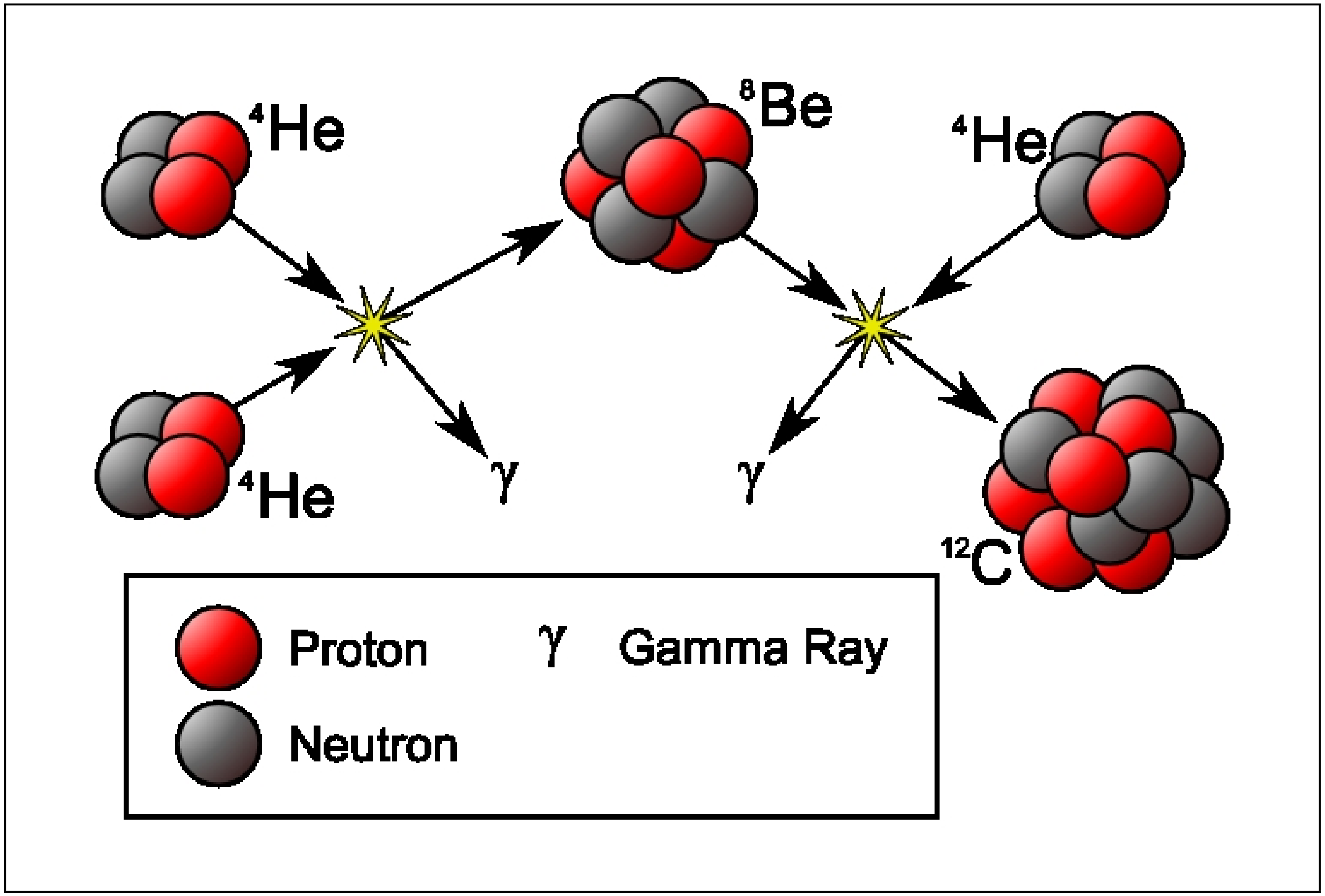




Carbon nucleosynthesis

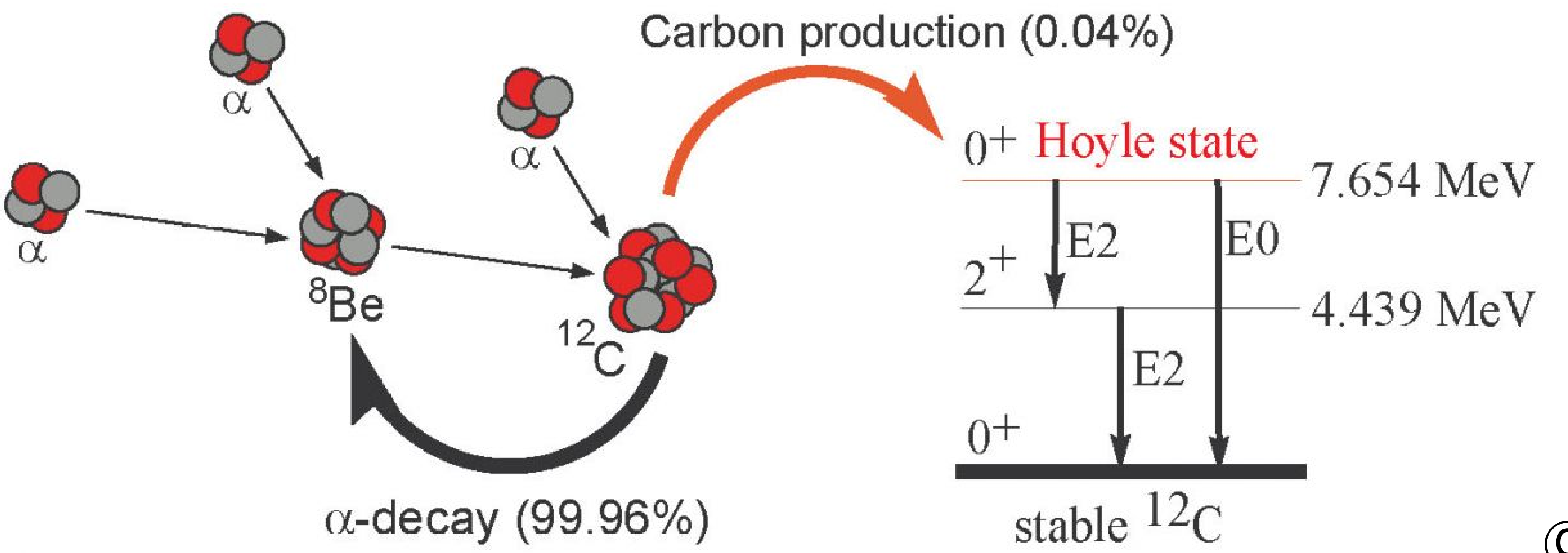
- Carbon is generated through the fusion of 3 helium nuclei (alpha-particles)

$\longrightarrow$ a short movie



@ Wikipedia

The triple-alpha process



2 fine-tunings!

©ANU

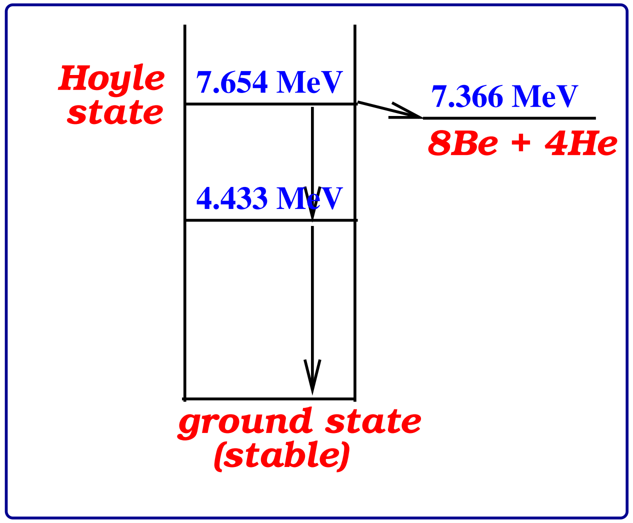
- The ^{8}Be nucleus is instable, long lifetime (10^{-16} s) → 3 alpha-particles must meet
- The Hoyle state is located just above the continuum threshold
  → the excited carbon nuclei decay in various ways

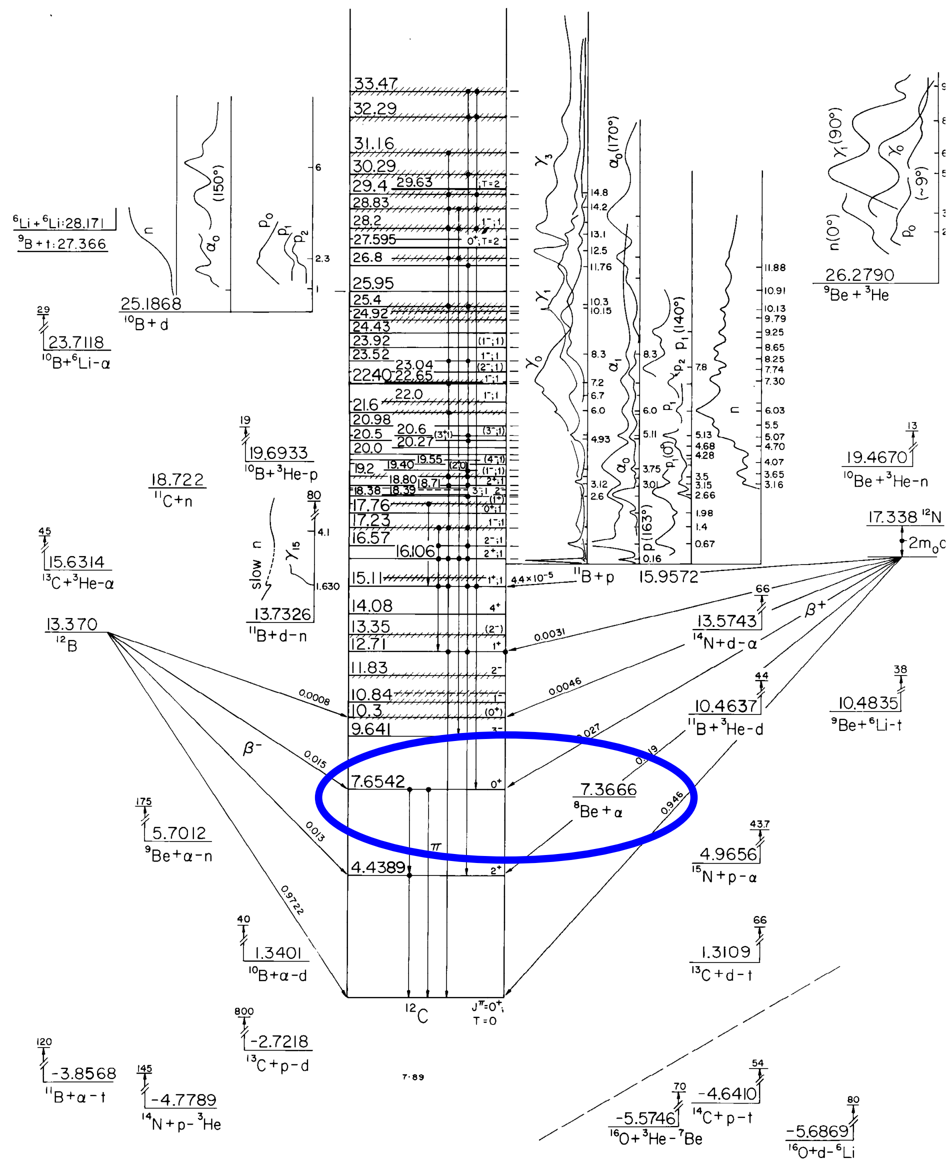
about 4 of 10000 decays produce stable carbon

The Hoyle state

- The rate for the generation of carbon in its ground state is orders of magnitude too small
- Fred Hoyle (1954): To generate a sufficient amount of carbon and oxygen, there must exist a **resonant** state in the carbon spectrum
  Hoyle, Astrophys. J. Suppl. Ser. 1 (1954) 121
- Resonance: Swing, bridge, . . .
- The Hoyle state was experimentally confirmed already in 1953 at Caltech
  Dunbar et al., Phys. Rev. 92 (1953) 649 [energy]
  Cook et al., Phys. Rev. 107 (1957) 508 [spin/parity]
- Without this state, there is no life on Earth
- But are we able to understand this state from **nuclear theory**?

UK astrophysicist, 1915-2001





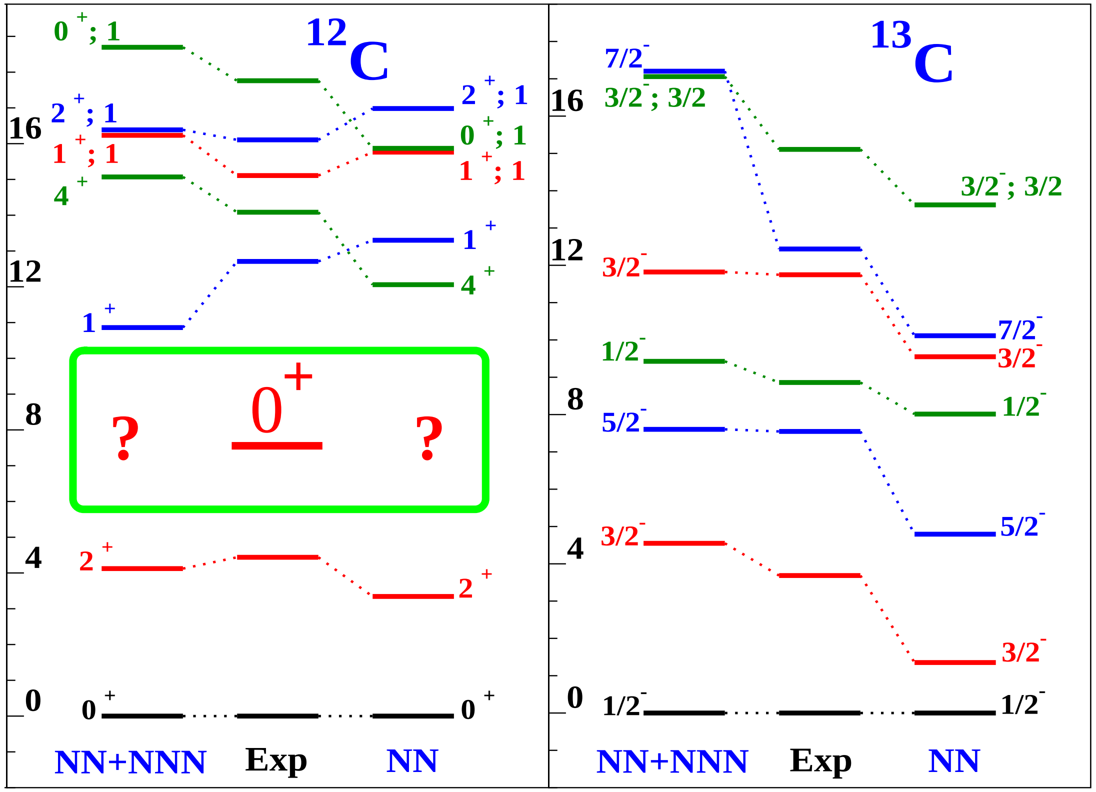
http://www.tunl.duke.edu/nucldata/fas/12_1959.pdf

Numerical simulations of the carbon nucleus

Nuclear theory and the Hoyle state

- Many-body theory (no-core-shell model) on a supercomputer:
  about 10^7 CPU hrs on JAGUAR (fastest computer in 2009/2010, 1.75 Pflops)

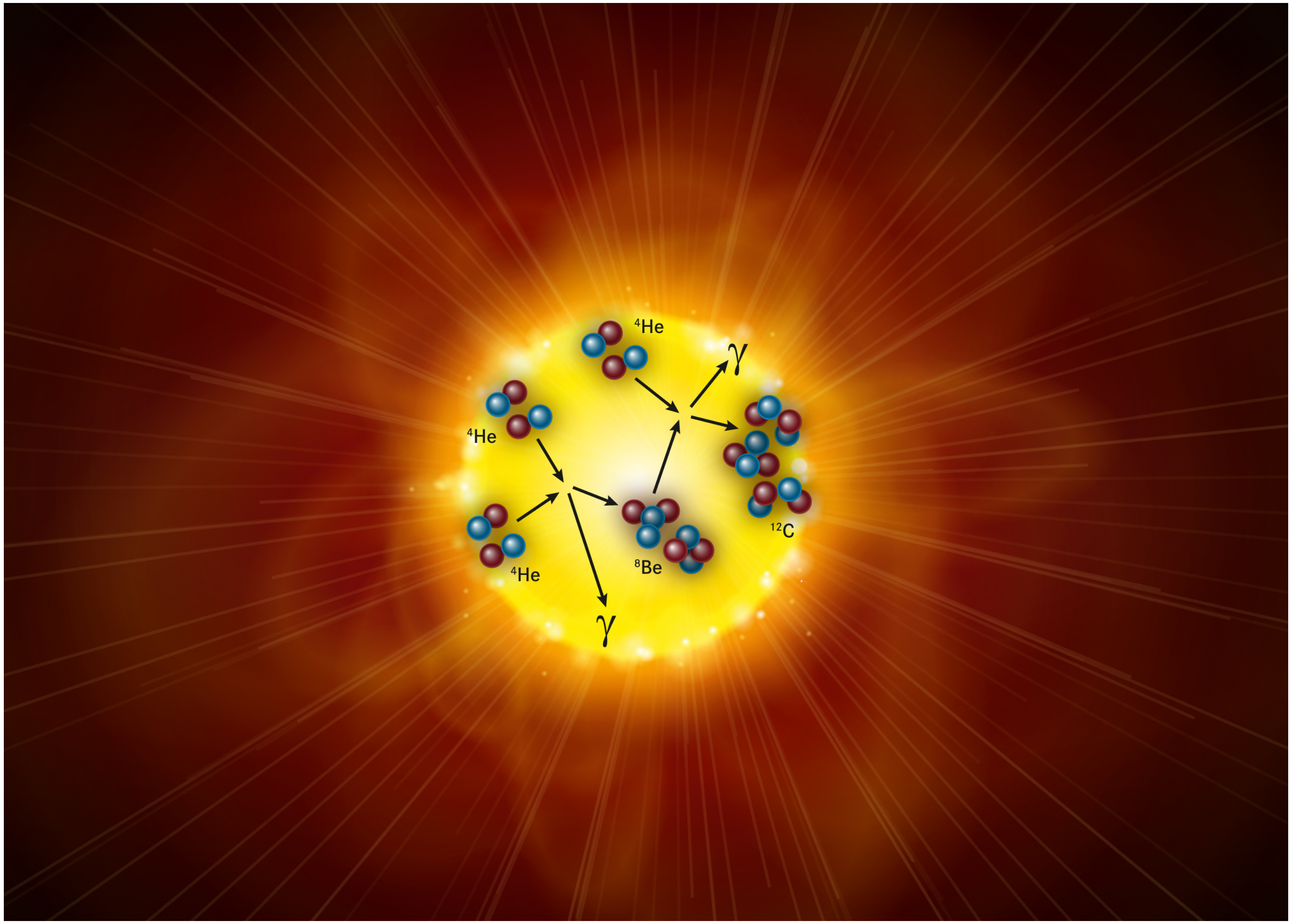
P. Navratil et al., Phys. Rev. Lett. **99** (2007) 042501; R. Roth et al., Phys. Rev. Lett. **107** (2011) 072501



⇒ Excellent description, but *no indication for the Hoyle state*

Ab initio calculation of the Hoyle state

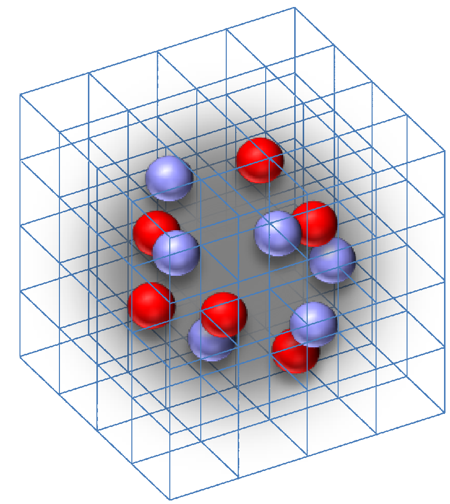
Epelbaum, Krebs, Lee, UGM, Phys. Rev. Lett. **106** (2011) 192501
Viewpoint: Hjorth-Jensen, Physics 4 (2011) 38



Tools

- improved theoretical *ansatz* (new many-body theory, novel nuclear forces)

- High Performance Computer = JUGENE (BlueGene/P/Q/...)



1 Petaflop = 1.000.000.000.000.000 floating point operations per second

Literature

REVIEWS OF MODERN PHYSICS, VOLUME 81, OCTOBER–DECEMBER 2009

Modern theory of nuclear forces

E. Epelbaum*

Institut für Kernphysik (IKP-3) and Jülich Center for Hadron Physics, Forschungszentrum Jülich, D-52425 Jülich, Germany and Helmholtz-Institut für Strahlen- und Kernphysik (Theorie) and Bethe Center for Theoretical Physics, Universität Bonn, D-53115 Bonn, Germany

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(Published 21 December 2009)

Effective field theory allows for a systematic and model-independent derivation of the forces between nucleons in harmony with the symmetries of quantum chromodynamics. The foundations of this approach are reviewed and its application for light nuclei at various resolution scales is discussed. The extension of this approach to many-body systems is sketched.

DOI: 10.1103/RevModPhys.81.1773 PACS number(s): 21.30.−x, 21.45.−v, 12.38.Lg, 12.39.Fe

CONTENTS

I. QUANTUM CHROMODYNAMICS AND NUCLEAR FORCES

Within the standard model of particle physics, the strong interactions are described by quantum chromodynamics (QCD). QCD is a fascinating theory with many intriguing manifestations. Its structure and interactions are governed by a local non-Abelian gauge symmetry, namely, $SU(3)_{\text{color}}$. Its fundamental degrees of freedom, the quarks (the matter fields) and gluons (the force carriers), have never been observed in isolation (confinement). The strong coupling constant α_S exhibits a very pronounced running and is of order 1 in the typical energy scales of nuclear physics. The bound states made from the basic constituents are the hadrons, the strongly interacting particles. The particle spectrum shows certain regularities that can be traced back to the flavor symmetries related to the fermions building up these states. More precisely, there are six quark flavors. These can be grouped into two very different sectors. While the light quarks (u,d,s) are almost massless and thus have to be treated relativistically, bound states made from heavy quarks allow for a precise nonrelativistic treatment. In what follows, we consider only the light quarks at low energies, where perturbation theory in α_S is inapplicable (this regime is frequently called "strong QCD"). A further manifestation of strong QCD is the appearance of nuclei, shallow bound states composed of

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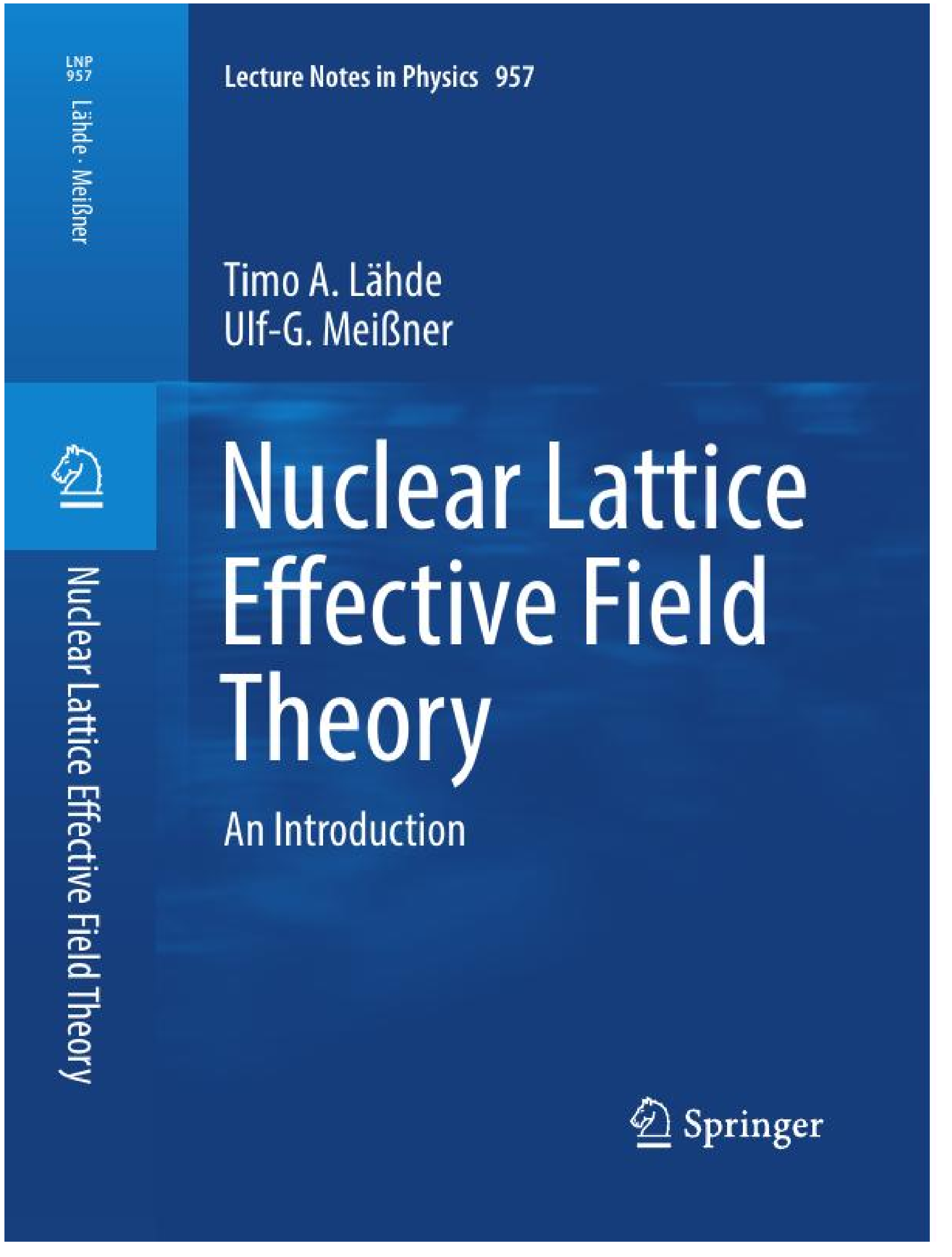
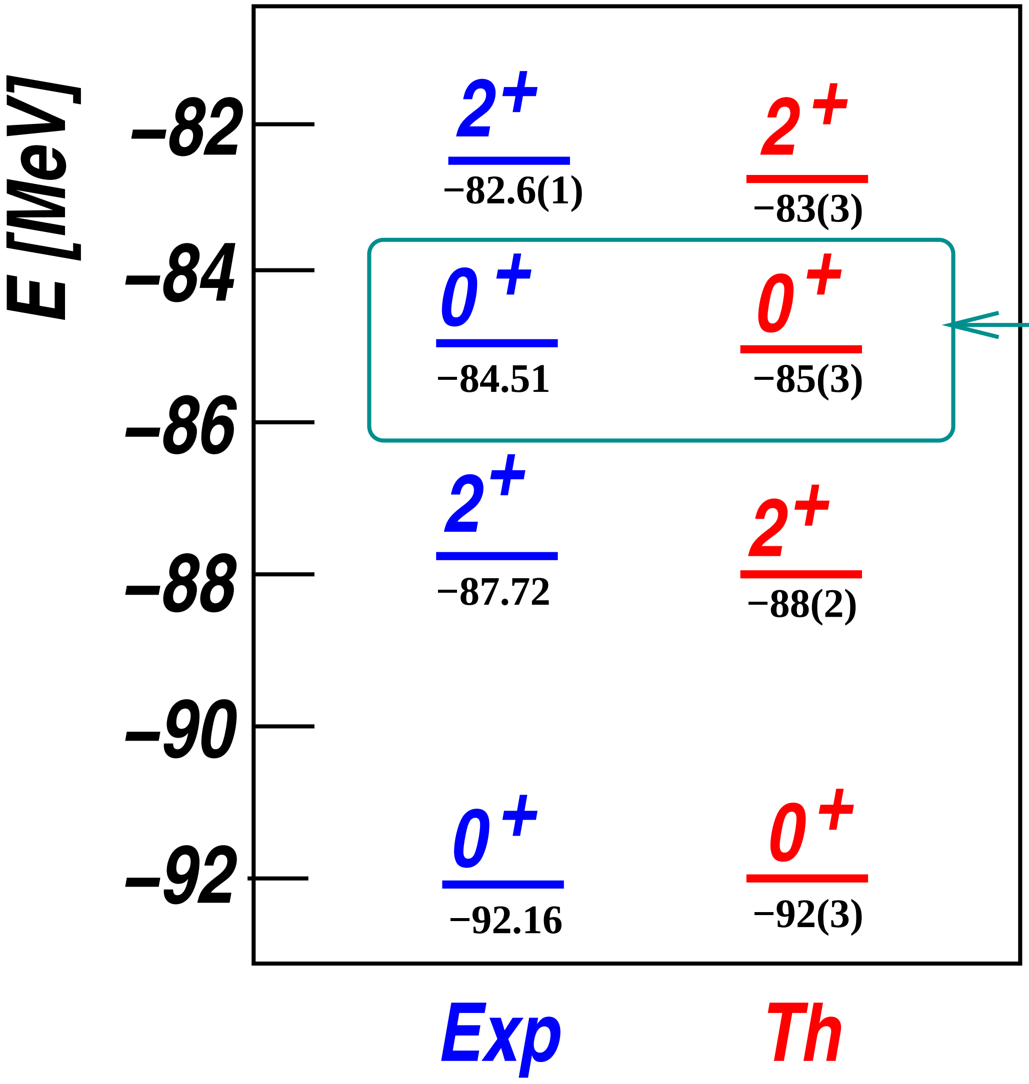
0034-6861/2009/81(4)/1773(53) 1773



The carbon-12 spectrum

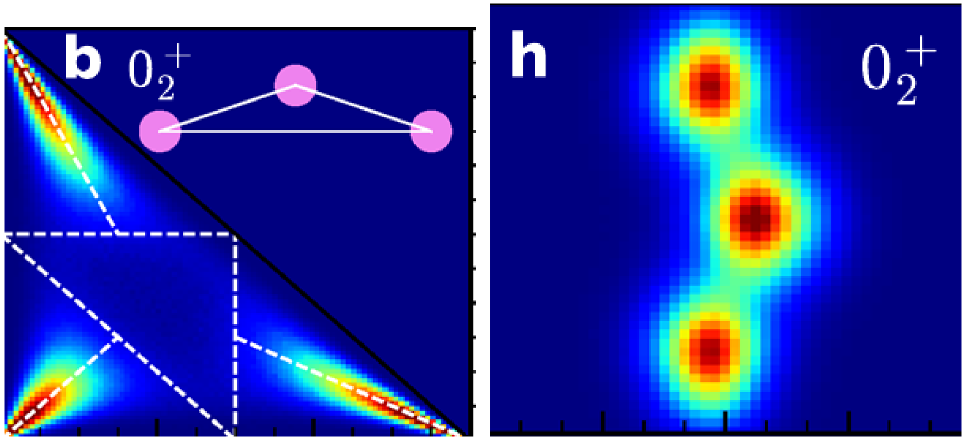
- After $4 \cdot 10^6$ CPU hours on JUGENE (and "a bit" of human work)



⇒ First ab initio calculation of the Hoyle state √

Hoyle

Structure of the Hoyle state:



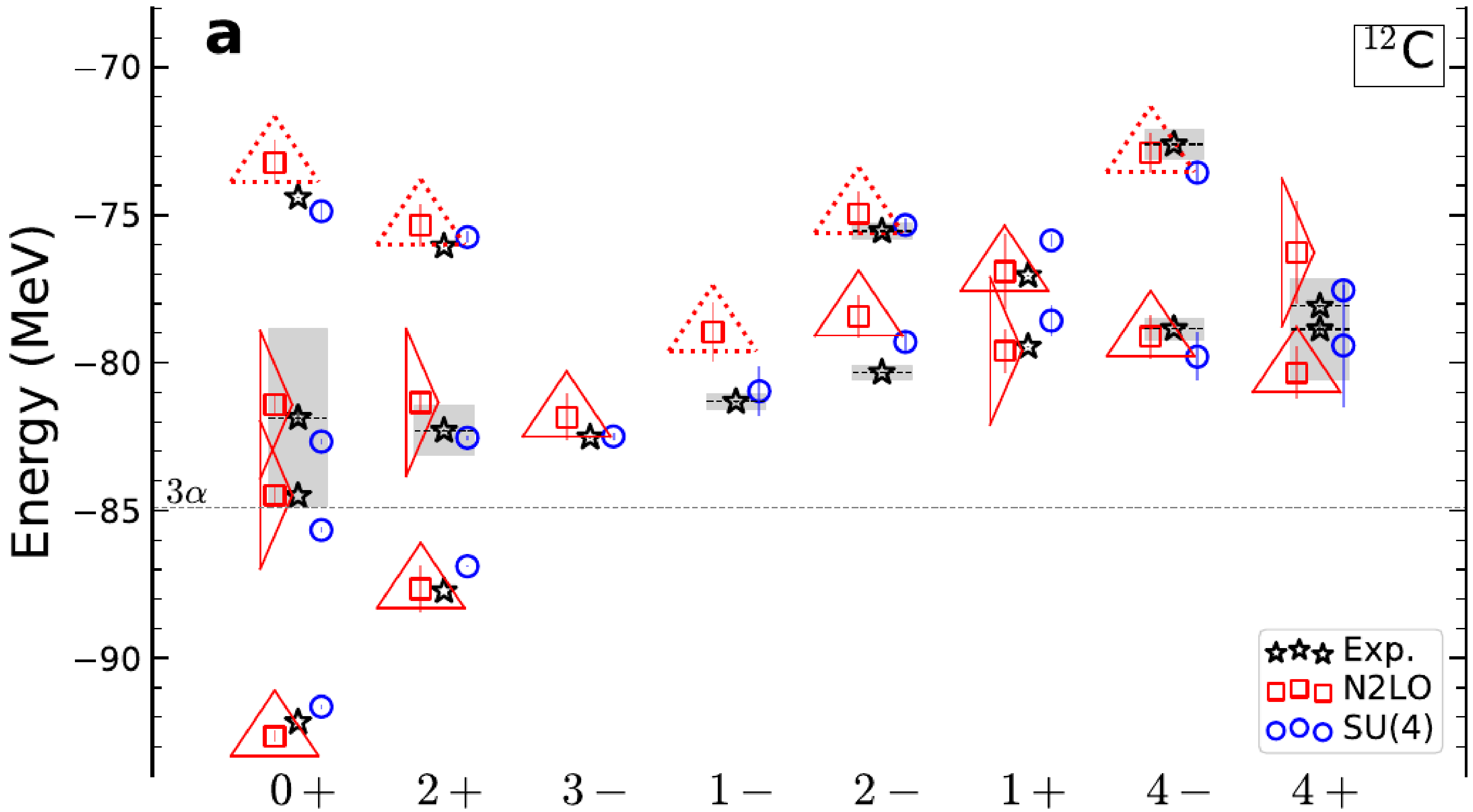
Epelbaum, Lähde, Lee, UGM, Phys. Rev. Lett. **109** (2012) 252501

Shen, Elhatisari, Lähde, Lee, Lu, UGM, Nat. Comm. **14** (2023) 2777

The carbon-12 spectrum: Update

Shen, Elhatisari, Lähde, Lee, Lu, UGM, Nat. Comm. **14** (2023) 2777

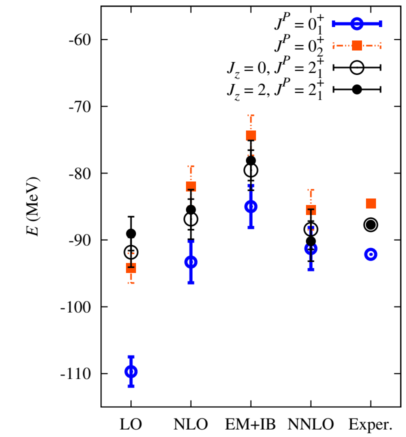
- With improved algorithms, we can now calculate the complete spectrum



↪ impressive agreement

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

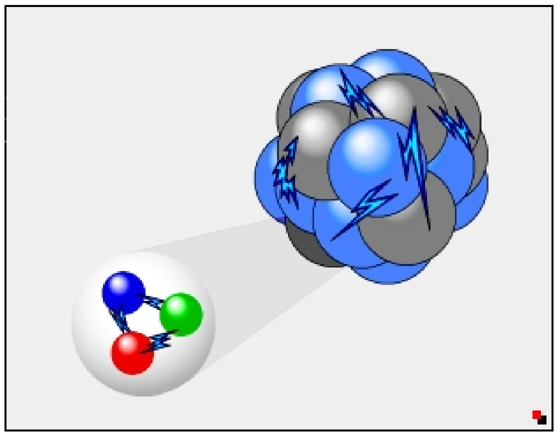
US physicist 1933-2021
Nobel prize 1979

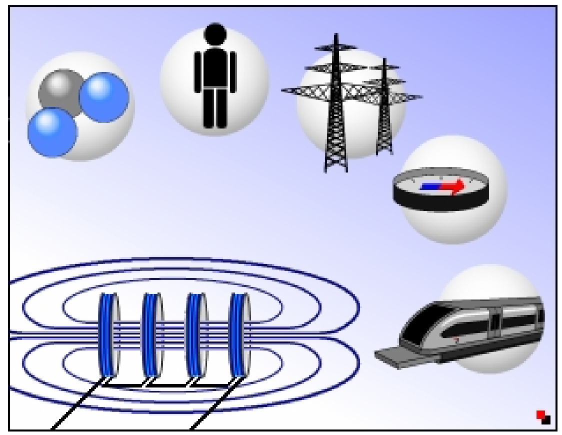
- How does the Hoyle state move w.r.t. the 4He+8Be threshold, when the parameters of the fundamental interactions are changed?
- In Nature, this is impossible to do, **but can be answered on a computer!**

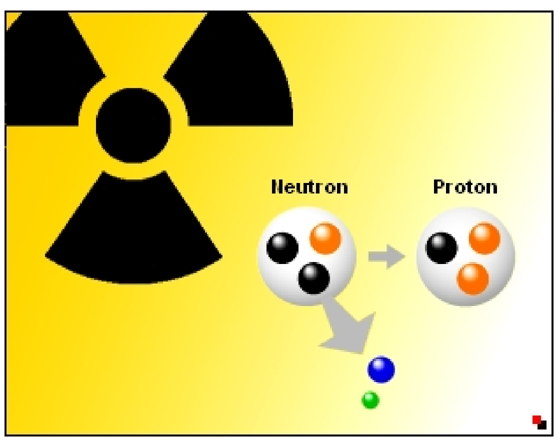
A dose of philosophy: The anthropic principle

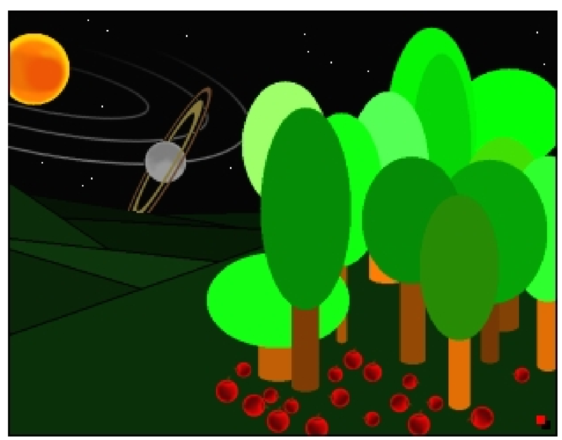
Forces in Nature

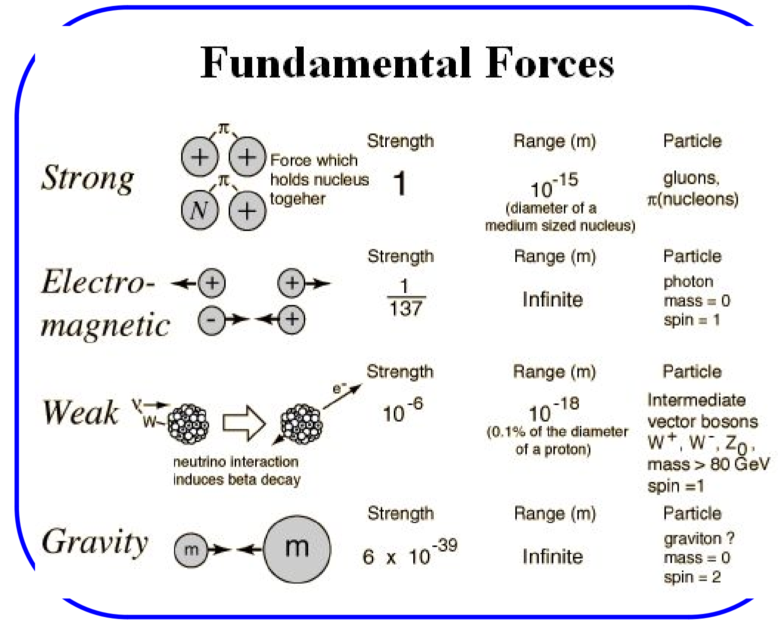
- 4 different forces: strong, electromagnetic, weak & gravitation











why these strengths?

why these masses?

why these parameters?

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, . . .

$\Rightarrow$ does this lead to physical/testable consequences?

Some examples of anthropic reasoning

VOLUME 59, NUMBER 22 PHYSICAL REVIEW LETTERS 30 NOVEMBER 1

Anthropic Bound on the Cosmological Constant

Steven Weinberg
Theory Group, Department of Physics, University of Texas, Austin, Texas 78712
(Received 5 August 1987)

In recent cosmological models, there is an "anthropic" upper bound on the cosmological constant Λ. It is argued here that in universes that do not recollapse, the only such bound on Λ is that it should not be so large as to prevent the formation of gravitationally bound states. It turns out that the bound is quite large. A cosmological constant that is within 1 or 2 orders of magnitude of its upper bound would help with the missing-mass and age problems, but may be ruled out by galaxy number counts. If so, we may conclude that anthropic considerations do not explain the smallness of the cosmological constant.

1099 citations

The Anthropic Landscape of String Theory

L. Susskind
Department of Physics
Stanford University
Stanford, CA 94305-4060

arXiv:hep-th/0302219v1 27 Feb 2003

Abstract

In this lecture I make some educated guesses, about the landscape of string theory vacua. Based on the recent work of a number of authors, it seems plausible that the lanscape is unimaginably large and diverse. Whether we like it or not, this is the kind of behavior that gives credence to the Anthropic Principle. I discuss the theoretical and conceptual issues that arise in developing a cosmology based on the diversity of environments implicit in string theory.

1167 citations

Nature *Vol. 278 12 April 1979* 605

review article

The anthropic principle and the structure of the physical world

B. J. Carr* & M. J. Rees
Institute of Astronomy, Madingley Road, Cambridge, UK

The basic features of galaxies, stars, planets and the everyday world are essentially determined by a few microphysical constants and by the effects of gravitation. Many interrelations between different scales that at first sight seem surprising are straightforward consequences of simple physical arguments. But several aspects of our Universe—some of which seem to be prerequisites for the evolution of any form of life—depend rather delicately on apparent 'coincidences' among the physical constants.

PHYSICAL REVIEW D VOLUME 57, NUMBER 9 1 MAY 1998

Viable range of the mass scale of the standard model

V. Agrawal,[1] S. M. Barr,[1] John F. Donoghue,[2] and D. Seckel[1]
[1]*Bartol Research Institute, University of Delaware, Newark, Delaware 19716*
[2]*Department of Physics and Astronomy, University of Massachusetts, Amherst, Massachusetts 01003*
(Received 30 July 1997; published 1 April 1998)

In theories in which different regions of the universe can have different values of certain physical parameters, we would naturally find ourselves in a region where they take values favorable for life. We explore the range of such viable values of the mass parameter in the Higgs potential, μ^2. For $\mu^2<0$, the requirement that complex elements be formed suggests that the Higgs vacuum expectation value v must have a magnitude less than 5 times its observed value. For $\mu^2>0$, baryon stability requires that $|\mu| \ll M_P$, the Planck mass. Smaller values of $|\mu^2|$ may or may not be allowed depending on issues of element synthesis and stellar evolution. We conclude that the observed value of μ^2 appears reasonably typical of the viable range, and a multiple-domain scenario may provide a plausible explanation for the closeness of the QCD scale and the weak scale.
[S0556-2821(98)05509-X]

A prime exampe of the AP

- Hoyle (1953):

Prediction of an excited state in the carbon spectrum neccessary to generate a sufficient amount of heavy elements (^{12}C, ^{16}O,...) in stars

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

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

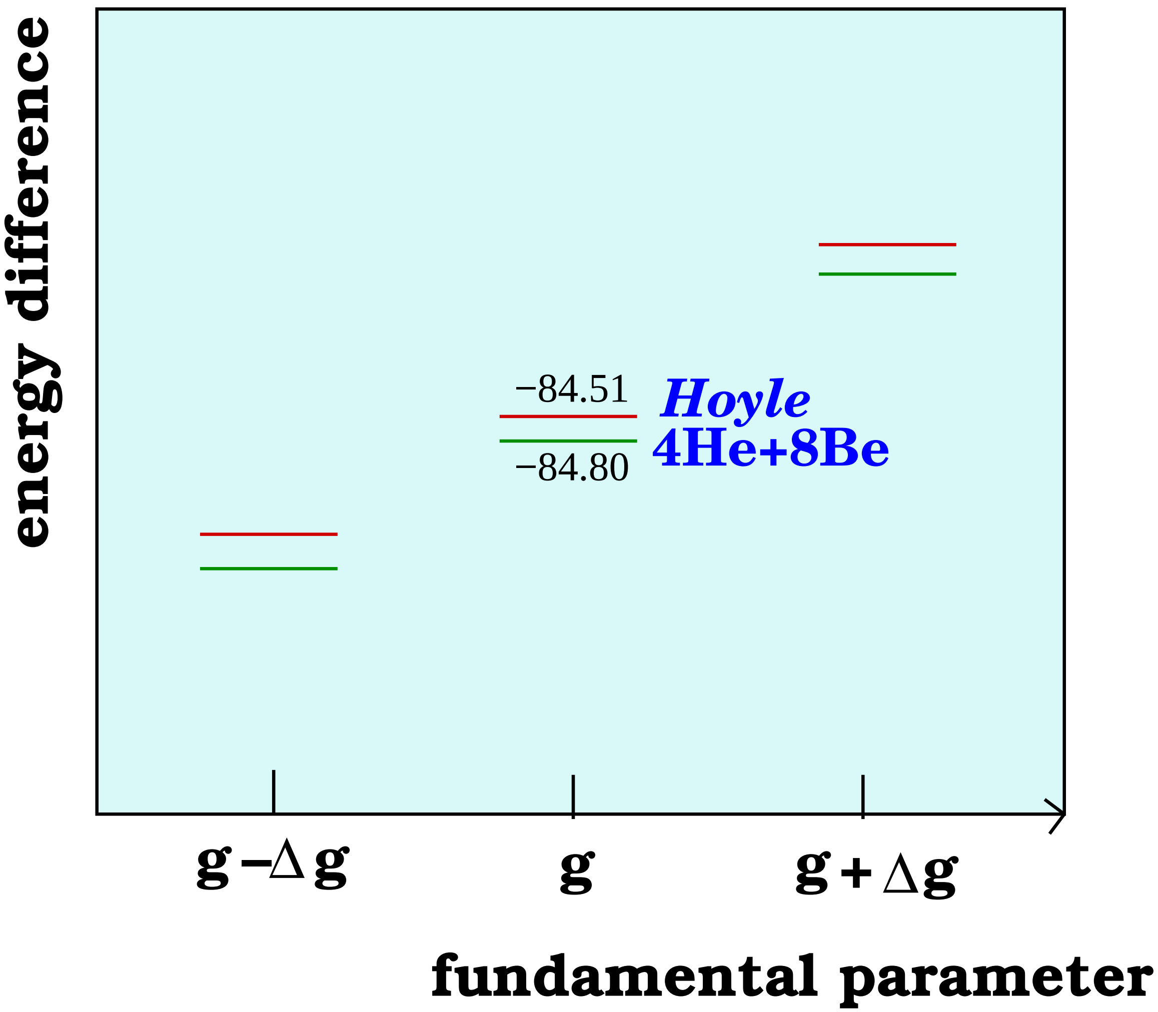
"In 1953 Hoyle made an anthropic prediction on an excited state – 'level of life' – for carbon production in stars"
Linde 2007

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

⇒ can we find out / test whether this is true?

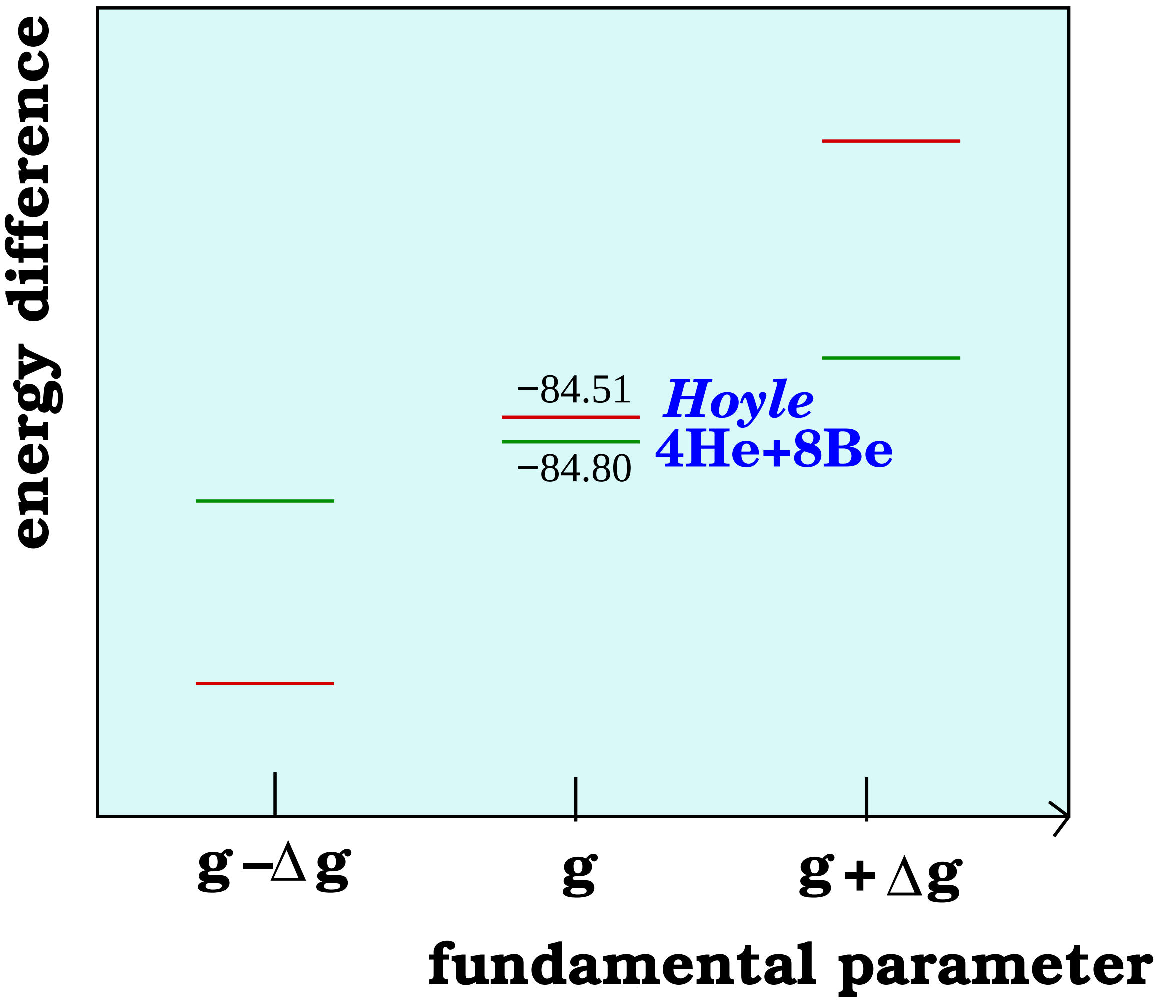
The non-anthropic scenario

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



The non-anthropic scenario

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



How accidental is life on Earth?

E. Epelbaum, H. Krebs, T. A. Lähde, D. Lee and UGM, “Viability of Carbon-Based Life as a Function of the Light Quark Mass,” Phys. Rev. Lett. **110** (2013) 112502

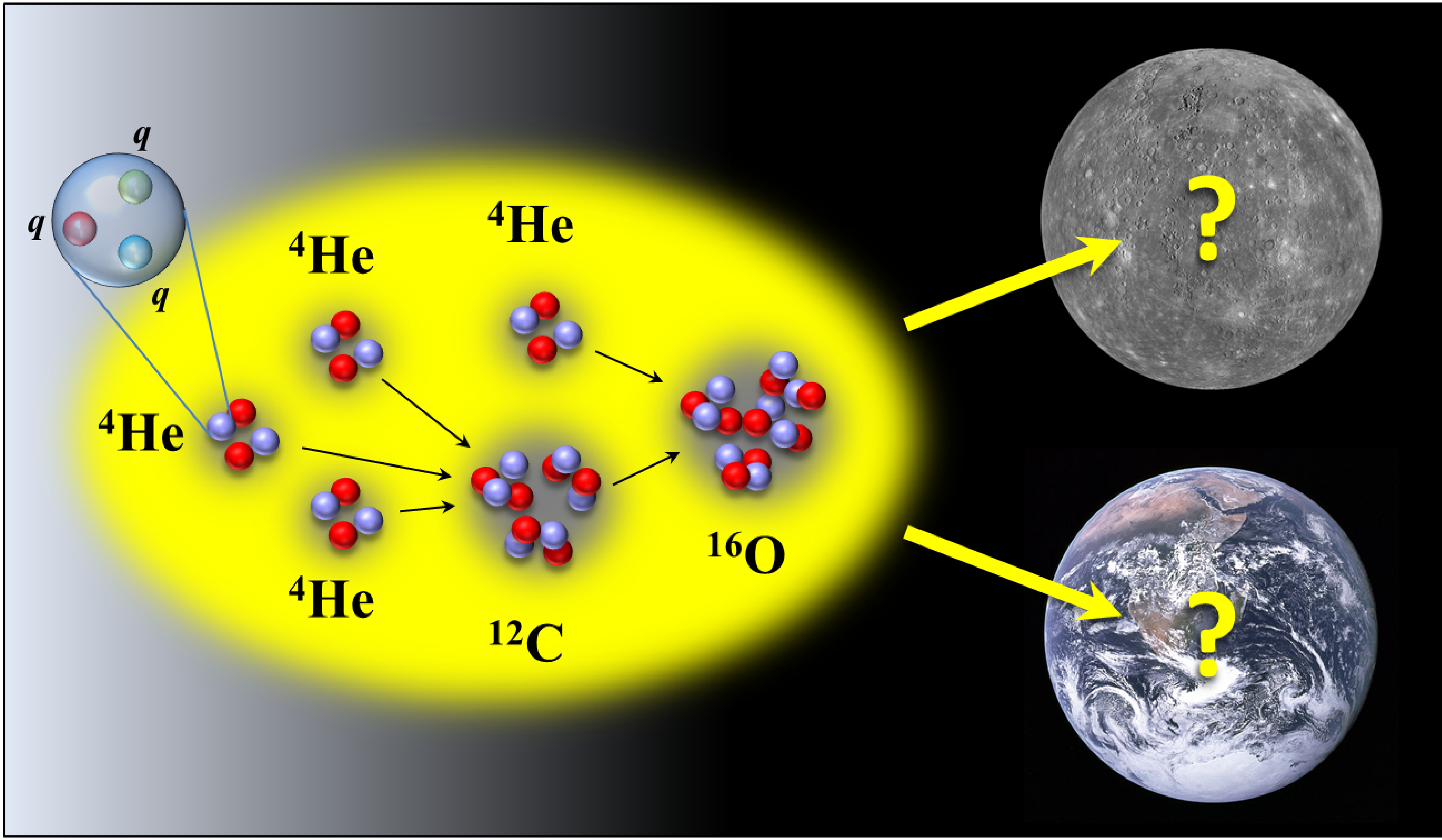
E. Epelbaum, H. Krebs, T. A. Lähde, D. Lee and UGM, “Dependence of the triple-alpha process on the fundamental constants of nature,” Eur. Phys. J. A **49** (2013) 82

UGM, “Anthropic considerations in nuclear physics,” Sci. Bull. **60** (2015) 43

T. A. Lähde, UGM and E. Epelbaum, “An update on fine-tunings in the triple-alpha process,” Eur. Phys. J. A **56** (2020) 89

S. Elhatisari, T. A. Lähde, D. Lee, UGM and T. Vonk, “Alpha-alpha scattering in the Multiverse,” JHEP **02** (2022), 001

Two very different scenarios



Earlier studies of the AP

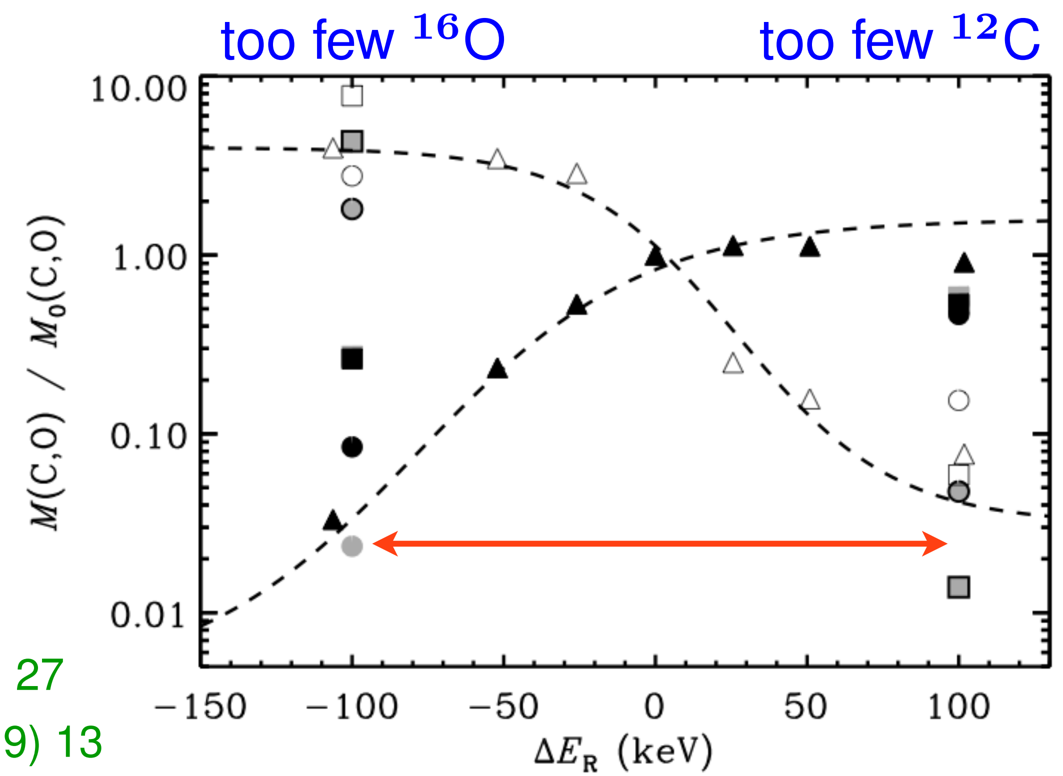
- rate of the 3α-process: $r_{3\alpha} \sim \Gamma_\gamma \exp\left(-\frac{\Delta E_{h+b}}{kT}\right)$

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

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

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

$\Rightarrow$ not very fine-tuned!



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

Update: Huang et al., Astropart. Phys. **105** (2019) 13

More recent stellar simulations

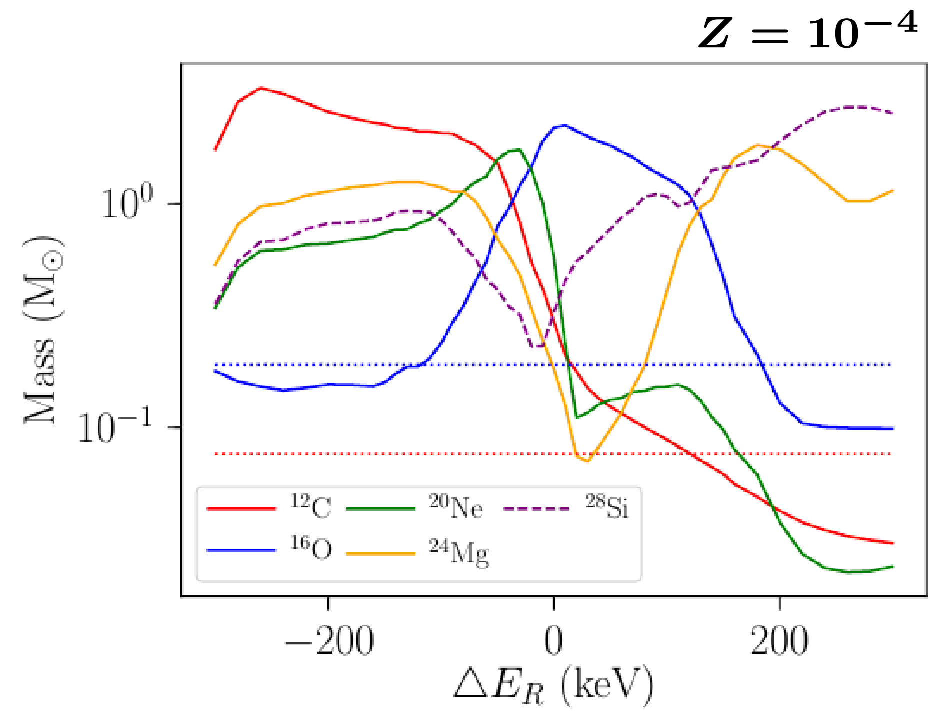
- Consider a larger range of masses $M_\star = (15 - 40)\, M_\odot$
- Consider low $Z = 10^{-4}$ and high $Z = Z_\odot \simeq 0.02$ metallicity
- changes depend on Z now

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)



⇒ carbon constraints somewhat weakened

⇒ stronger constraints from oxygen production

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

The relevant parameters

- Which fundamental parameters play a role?

- Strong force: Protons and neutrons are made of light quarks

$\Rightarrow$ the quark masses play no role for the total mass of the nucleon

$$m_{\text{proton}} = m_{\text{neutron}} = 939\ \text{MeV}\ , \quad m_{\text{quark}} \simeq 3\ \text{MeV}$$

$\Rightarrow$ but are of the same magnitude as the binding energies

$$\text{energy gain per nucleon} \lesssim 8\ \text{MeV}$$

- Electromagnetic force: Strength of the repulsion of the protons

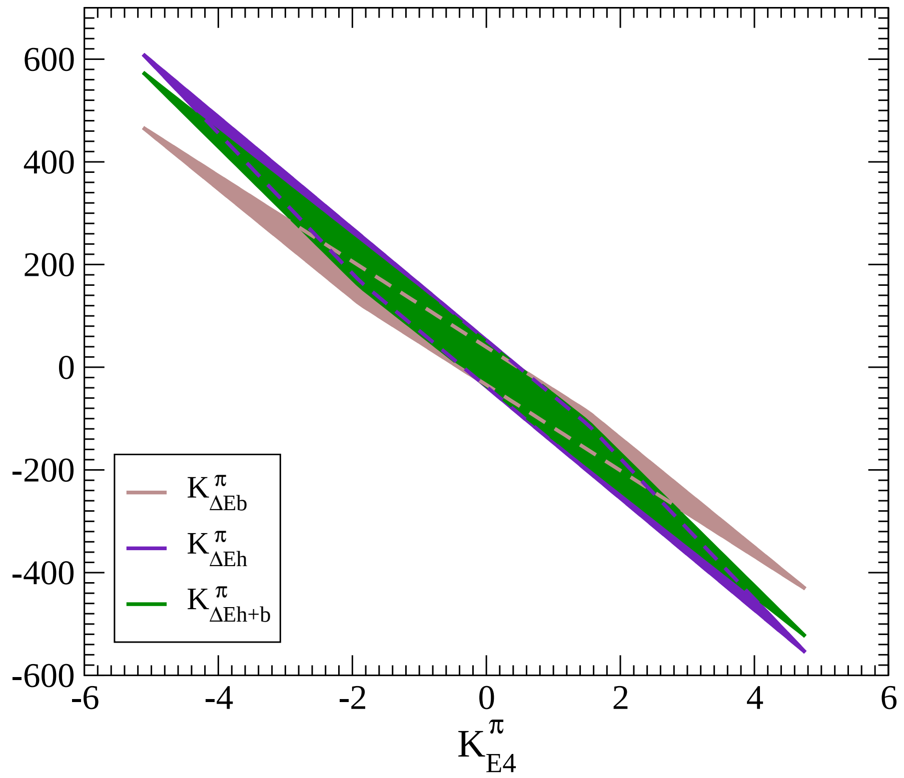
$$e^2 = 4\pi/137 \simeq 0.09$$

$\Rightarrow$ which variations of m_{quark} and e^2 are compatible with life on Earth?

Correlations

- Pion mass dependence of NN contact terms not well known

- make prediction by varying the ^{4}He mass within natural bounds



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

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

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

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

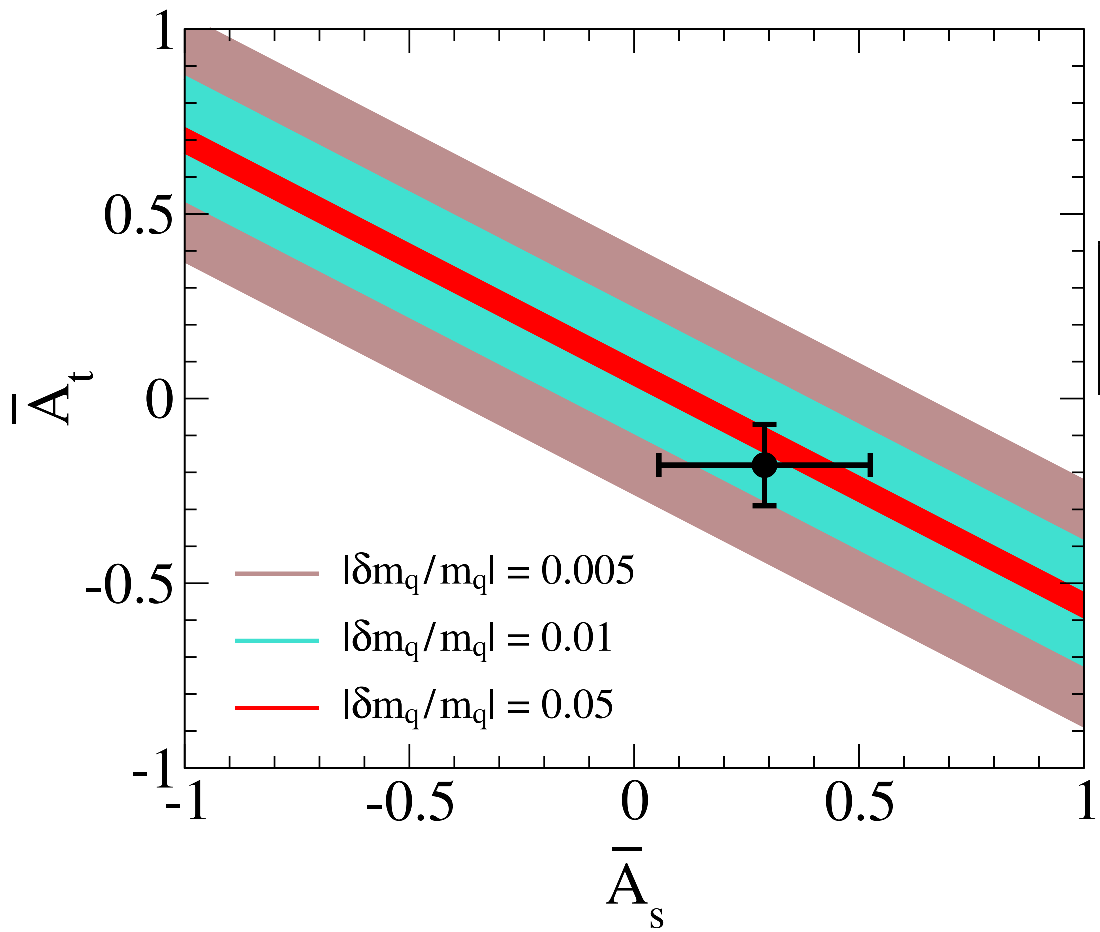
- the fine-tunings in the triple-alpha process are **correlated** [as speculated]

Weinberg (2000)

The end-of-the-world plot

- $|\delta(\Delta E_{h+b})| < 100$ keV [exp: 387 keV] — Oberhummer et al., Science (2000)

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



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

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 (limit on the Higgs vev)

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 $\bar{A}_{s,t}$:

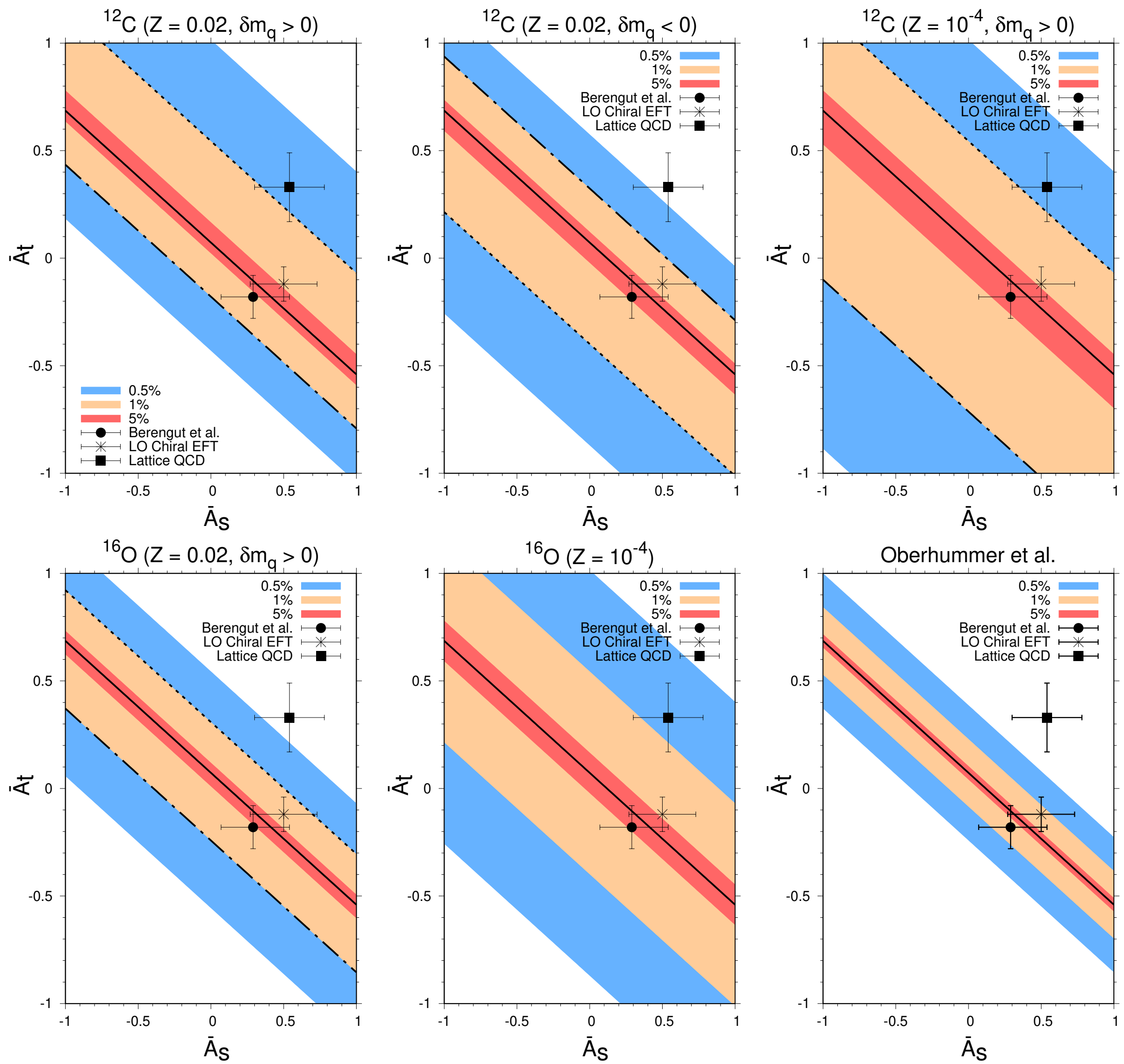
  The light quark mass is fine-tuned to $\simeq 0.5\,\%$

- 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!



Discussion & outlook

- The various fine-tunings in the triple-alpha-process are all correlated

- A sufficient amount of carbon and oxygen ($\alpha+{}^{12}$C$\to{}^{16}$O$+\gamma$) is generated for variations in the quark masses and the electromagnetic force by about 0.5-5%

$\Rightarrow$ is this an **argument in favor of the anthropic principle**?

$\Rightarrow$ is a 0.5-5% variation very fine-tuned?

$\Rightarrow$ we can simulate different worlds $\to$ more input from lattice QCD needed

$\Rightarrow$ we are on the way to answer the initial question – stay tuned

- Stronger constraints from Big Bang nucleosynthesis (but this is another talk)

- Computer simulations are a fascinating tool, that allows for **completely novel** insights!

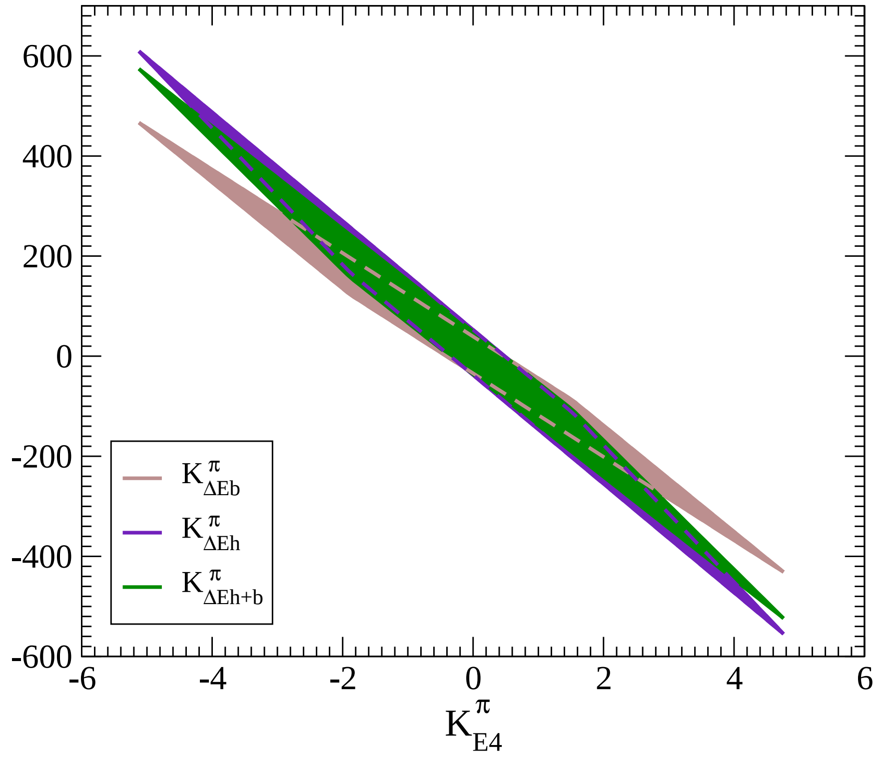
SPARES

RESULTS: CORRELATIONS

- vary the quark masses

⇒ strong correlations:

the fine-tuning of the energy differences
E(8Be) - 2E(alpha) and E(Hoyle) - 3E(alpha)
behaves *exactly* as the change
in the mass fo the alpha-particle E(alpha)
(this is called a *correlation*)



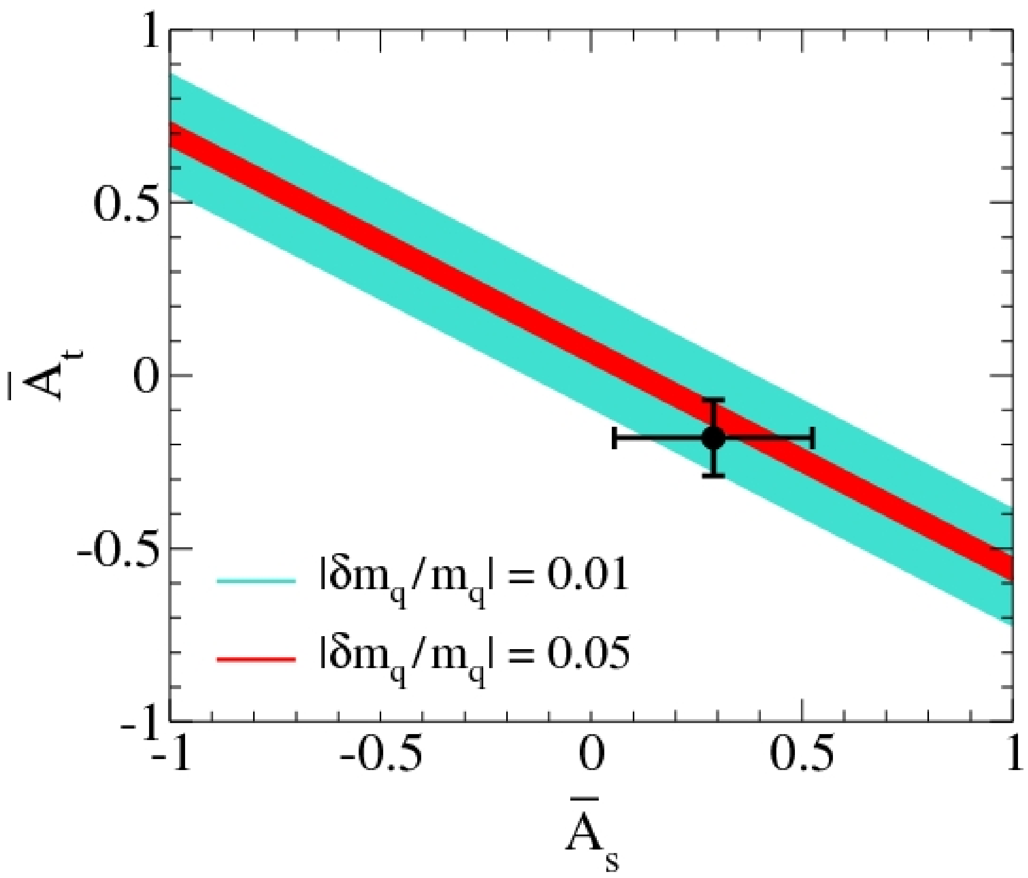
- Also: the production rate of ^{12}C and ^{16}O is sensitive to the difference E(Hoyle)-3E(alpha): maximal allowed change about 1/4 of the exp. value [based on nucleosynthesis calculations of Schlattl et al, 2004]

⇒ what can we deduce about the possible variations of the fundamental parameters?

- The variation of E(alpha) depends on two parameters (Nucleon-nucleon interaction)

⇒ The variation of these parameters can be calculated (approximatively)

⇒ Survival bands: for which variations in the quark masses enough C and O is generated?



⇒ Only a variation of $m_{\mathbf{quark}}$ by about 2% and of e^2 by about 2% is compatible with life of Earth!