Happy the man who has been able to discern the cause of things

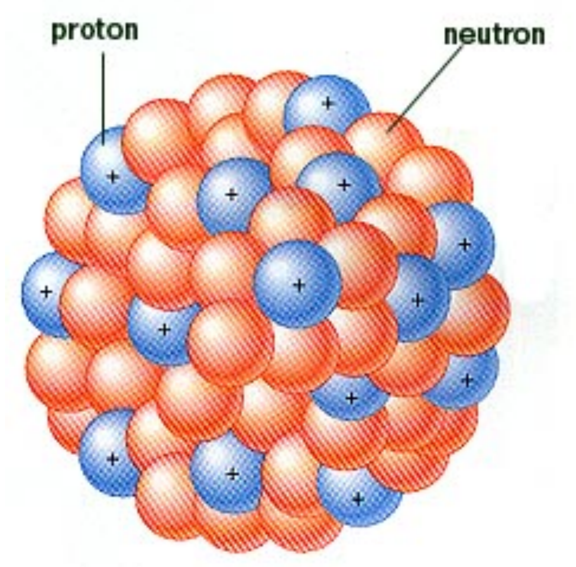
Virgil, Georgica

Theories
Models

- A first rate theory predicts
- A second rate theory forbids
- A third rate theory explains after the facts

Alexander I. Kitaigorodskii

Modeling the Atomic Nucleus



Theoretical bag of tricks…

The Nuclear Many-Body Problem

$$\hat{H}\Psi = E\Psi$$

$$\hat{H} = \hat{T} + \hat{V}$$

$\hat{T} = \sum_{i=1}^{A} \frac{\hat{p}_i^2}{2m_i},$	$\hat{V} = \sum_{i<i} \hat{V}_{2b}(i,j) + \sum_{i<i<k} \hat{V}_{3b}(i,j,k)$
one-body	**two-body** **three-body**
Kinetic energy	Potential energy

$$\Psi = \Psi\left(\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_A; s_1, s_2, \ldots, s_A; t_1, t_2, \ldots, t_A\right)$$

3A nucleon coordinates in r-space

nucleon spins: ±1/2

nucleon isospins (p or n): ±1/2

Eigenstate of angular momentum, parity, and ~isospin

Bottom line:

$$2^A \times \frac{A!}{N!Z!}$$

coupled integro-differential equations in 3A dimensions

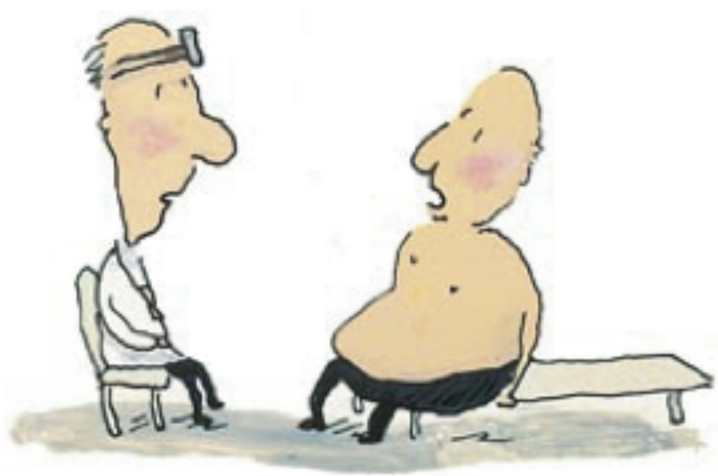
Weinberg's Laws of Progress in Theoretical Physics

From: "Asymptotic Realms of Physics" (ed. by Guth, Huang, Jaffe, MIT Press, 1983)

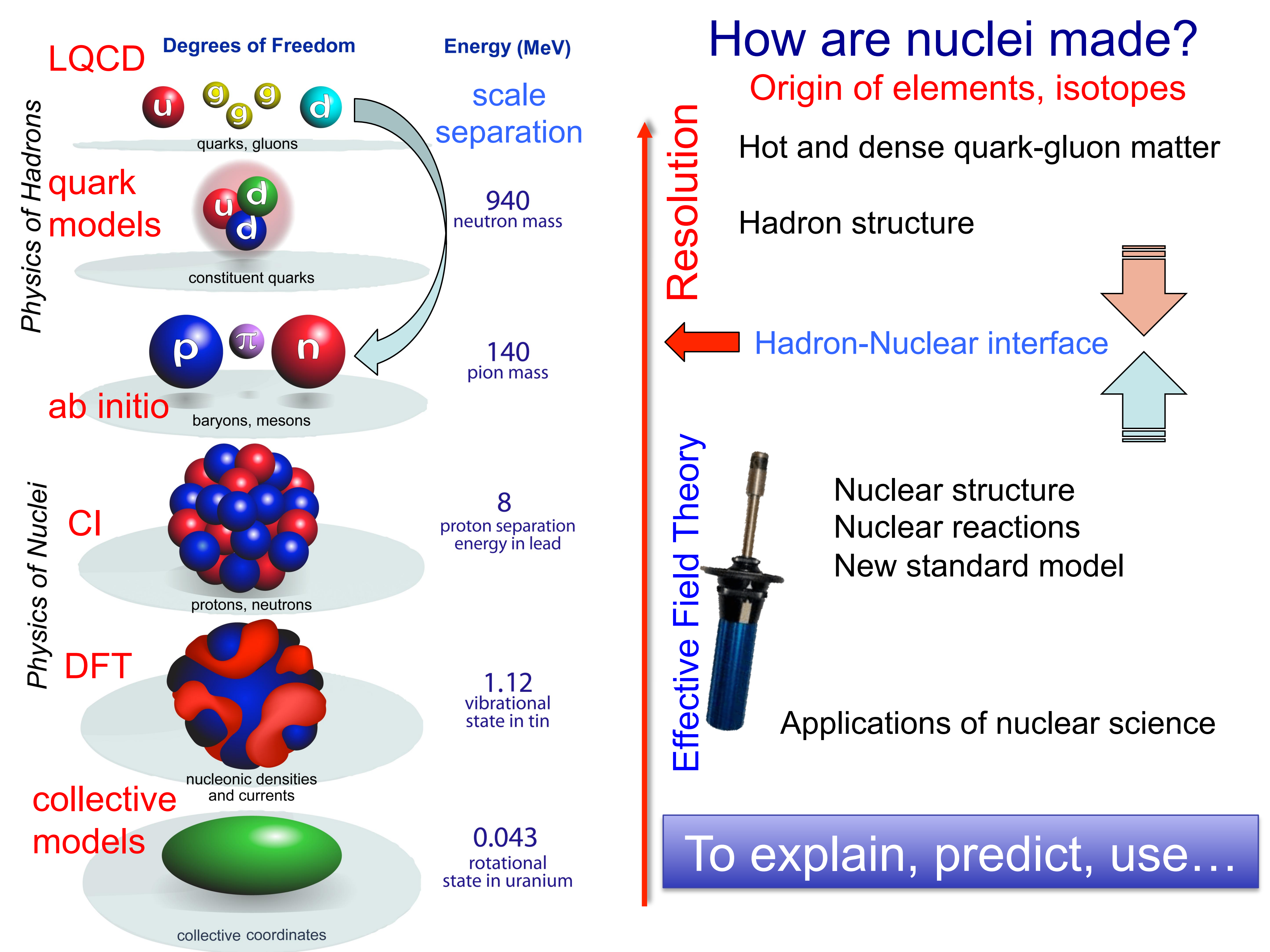
First Law: "The conservation of Information" (*You will get nowhere by churning equations*)

Second Law: "Do not trust arguments based on the lowest order of perturbation theory"

Third Law: "You may use any degrees of freedom you like to describe a physical system, but if you use the wrong ones, you'll be sorry!"

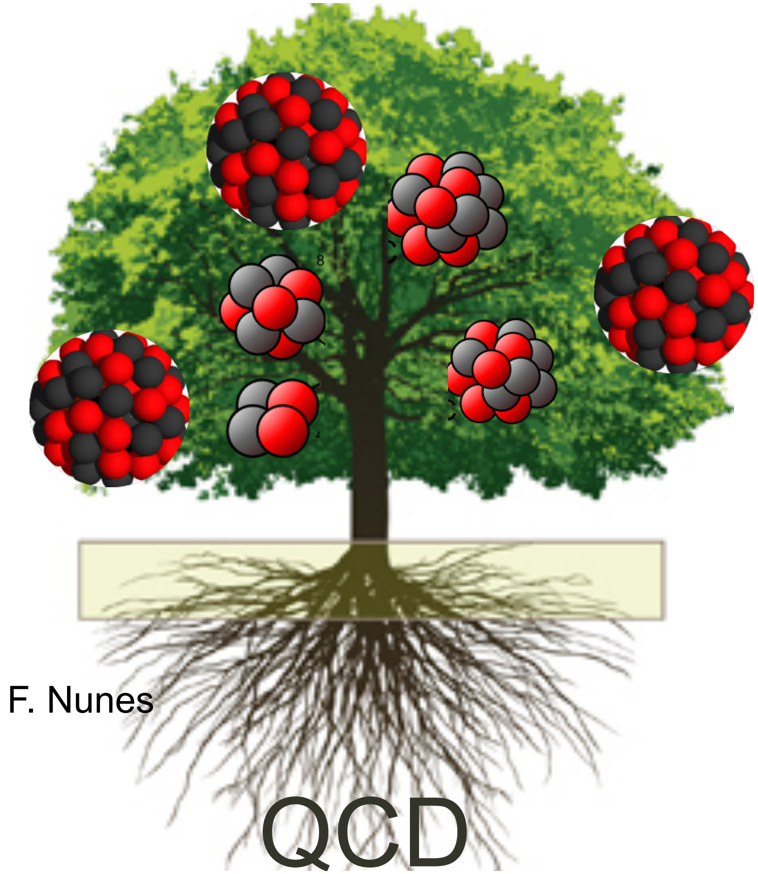


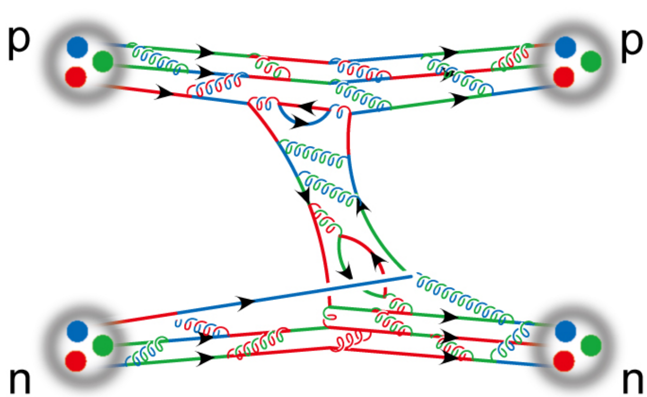
Patient: Doctor, doctor, it hurts when I do this!
Doctor: Then don't do that.

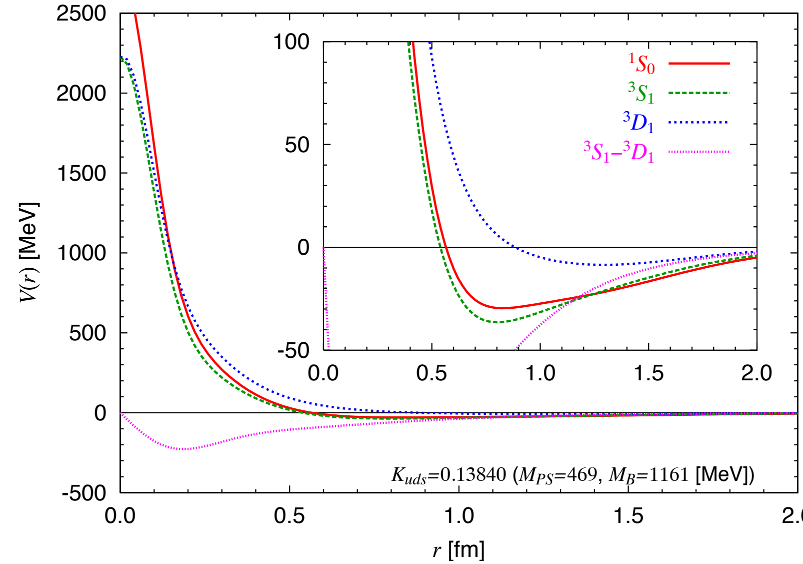


How are nuclei made?
Origin of elements, isotopes
LQCD
Degrees of Freedom
Energy (MeV)
quarks, gluons
scale
separation
Physics of Hadrons
quark
models
constituent quarks
940
neutron mass
140
pion mass
ab initio
baryons, mesons
Physics of Nuclei
CI
protons, neutrons
8
proton separation
energy in lead
DFT
nucleonic densities
and currents
1.12
vibrational
state in tin
collective
models
0.043
rotational
state in uranium
collective coordinates
Resolution
Effective Field Theory
Hot and dense quark-gluon matter
Hadron structure
Hadron-Nuclear interface
Nuclear structure
Nuclear reactions
New standard model
Applications of nuclear science
To explain, predict, use…

Rooting nuclei in QCD

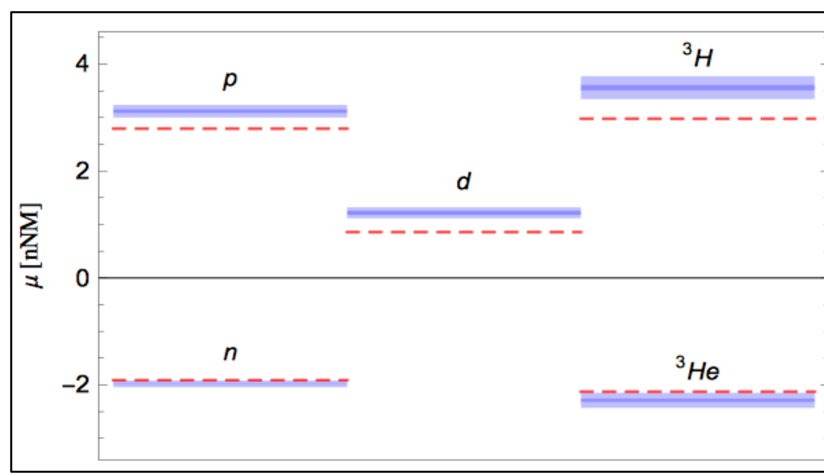






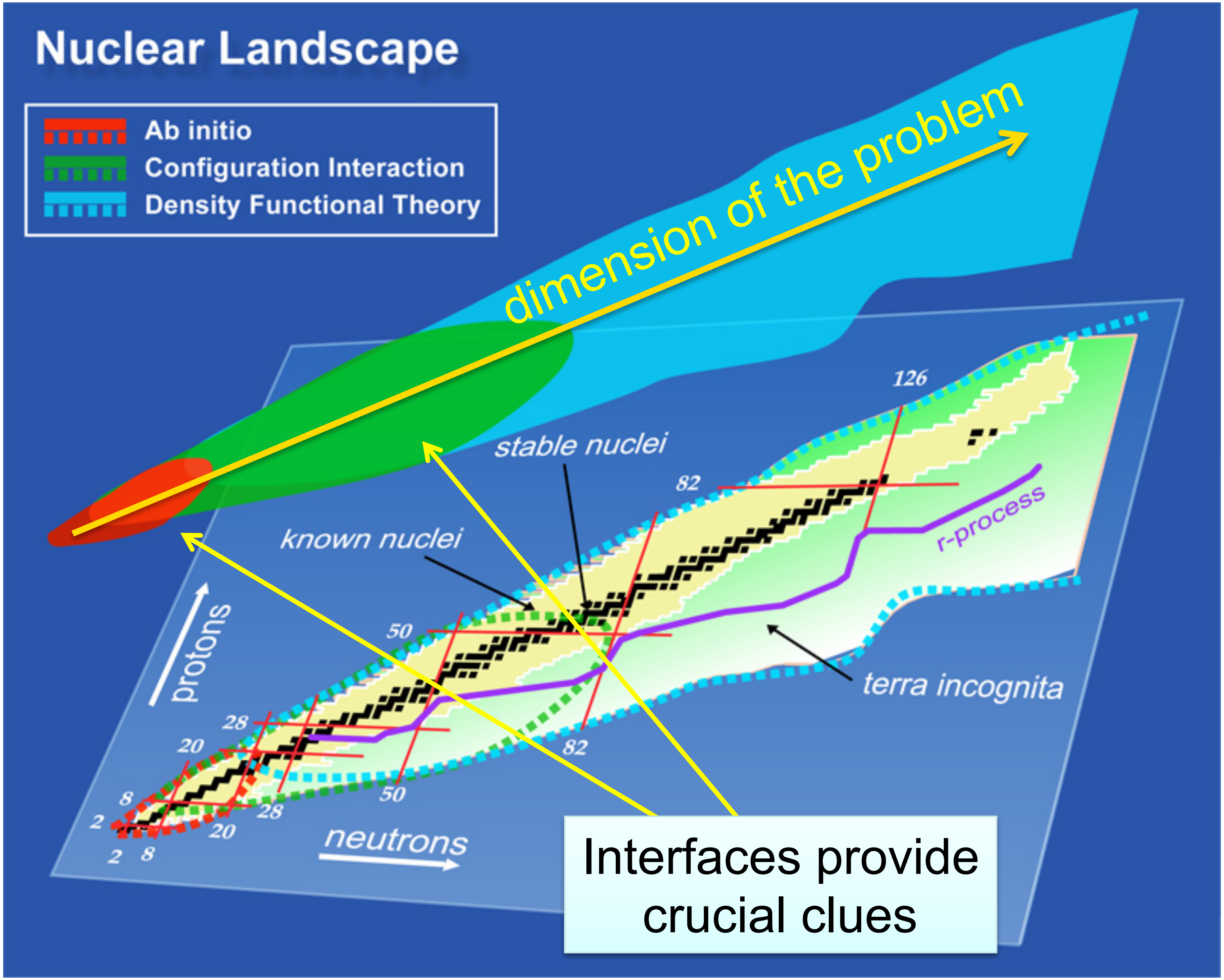
Nuclear Force from Lattice QCD

Inoue et al. PRL 111, 112503 (2013); HALQCD/HPCI



LQCD predictions for magnetic moments A<4

Beane et al., PRL113, 252001 (2014); NPLQCD



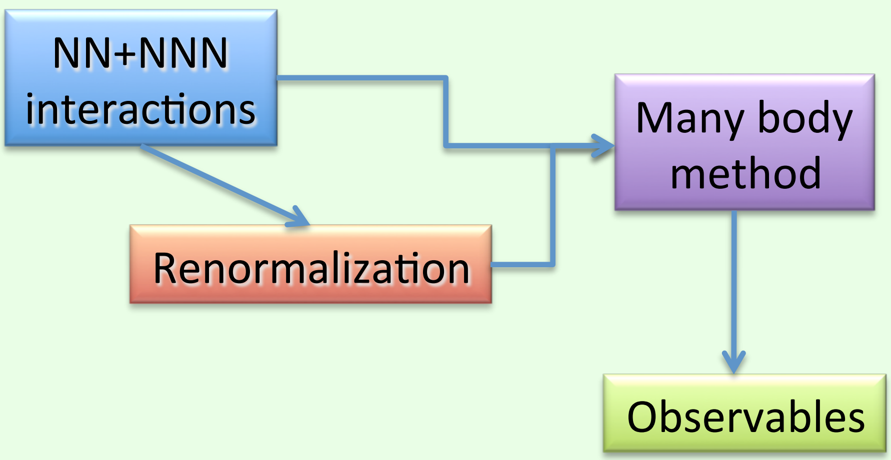
number of nuclei < number of processors!

Ab initio theory for light nuclei and nuclear matter

Ab initio: QMC, NCSM, CCM,…

(nuclei, neutron droplets, nuclear matter)

Ab initio input

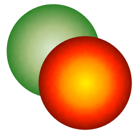


- Direct comparison with experiment
- Pseudo-data to inform theory

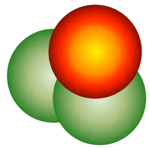
Input:

- Excellent forces based on the phase shift analysis and few-body data
- EFT based nonlocal chiral NN and NNN potentials
- SRG-softened potentials based on bare NN+NNN interactions

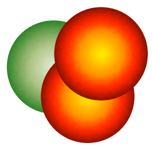
Few-nucleon systems



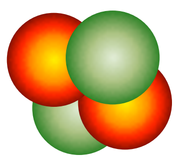
A=2: many years ago…



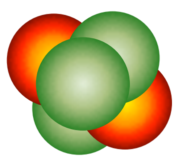
^{3}H: 1984 (1% accuracy)



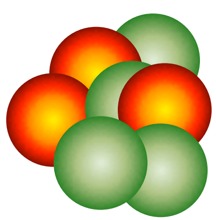
^{3}He: 1987



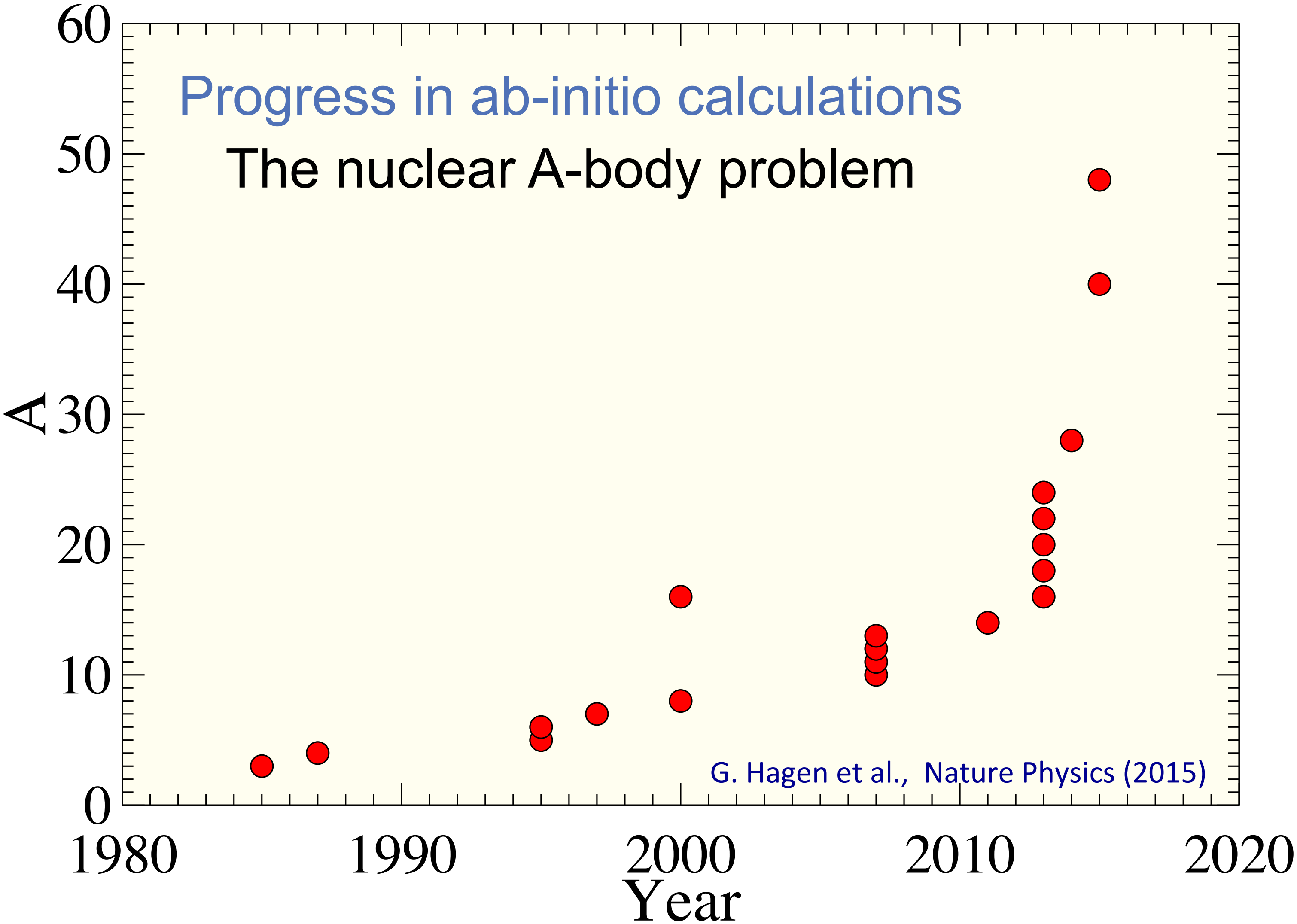
^{4}He: 1987



^{5}He: 1994 (n-α resonance)



A=6,7,..12: 1995-2011



In the early decades, the progress was approximately linear in A because the computing power, which increased exponentially according to Moore's law, was applied to exponentially expensive numerical algorithms. In recent years, new-generation algorithms, which exhibit polynomial scaling in A, have greatly increased the reach.

Green's Function Monte Carlo (imaginary-time method)

$$|\psi_0\rangle = \lim_{\tau\to\infty} e^{-(\hat{H}-E_0)\tau}|\psi_V\rangle$$

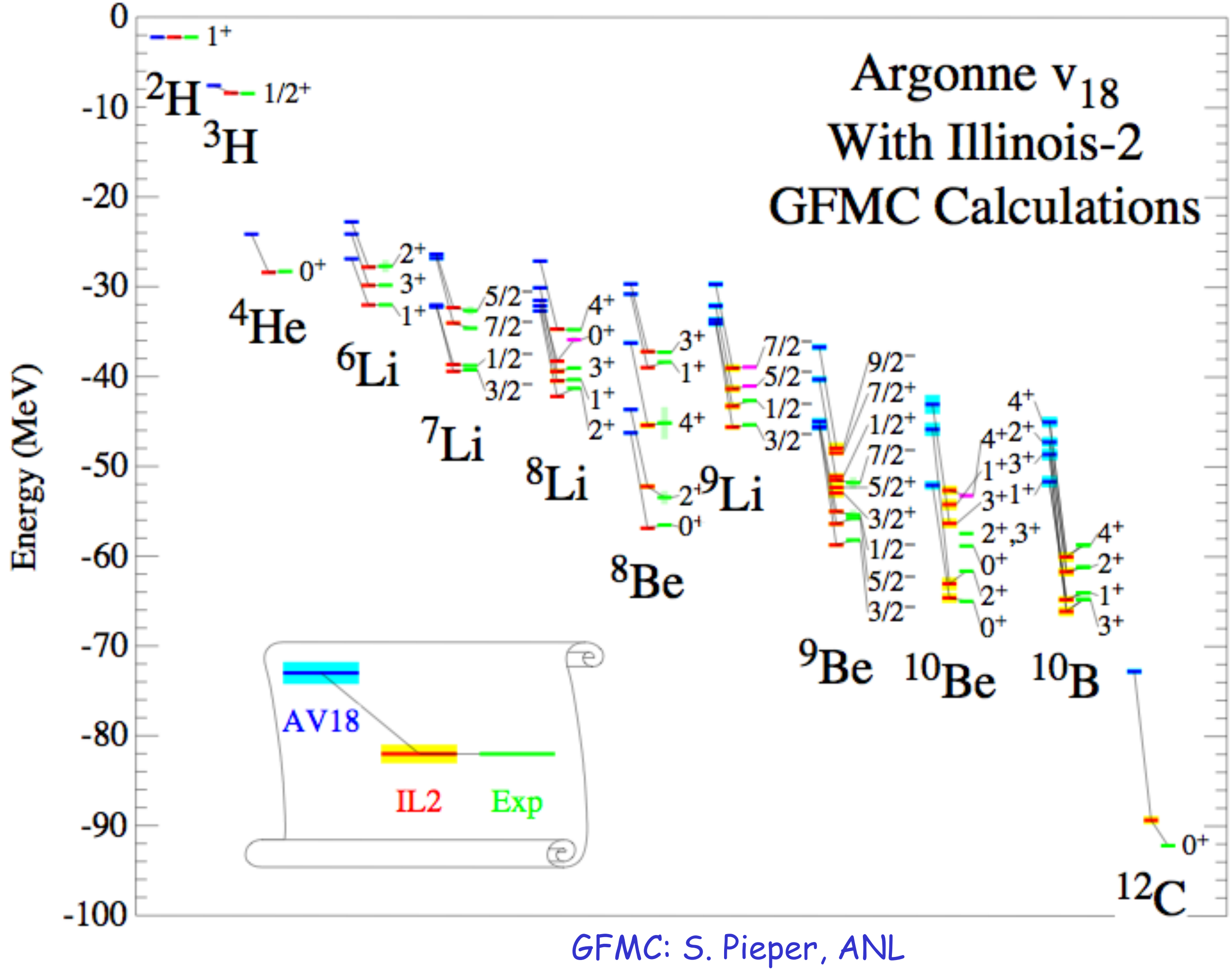
trial wave function

$$|\psi(\tau)\rangle = e^{-(\hat{H}-E_0)\tau}|\psi_V\rangle$$

$$|\psi(0)\rangle = |\psi_V\rangle, \quad |\psi(\infty)\rangle = |\psi_0\rangle$$

$$\tau = n\Delta\tau \quad \Rightarrow \quad |\psi(\tau)\rangle = \left[e^{-(\hat{H}-E_0)\Delta\tau}\right]^n |\psi_V\rangle$$

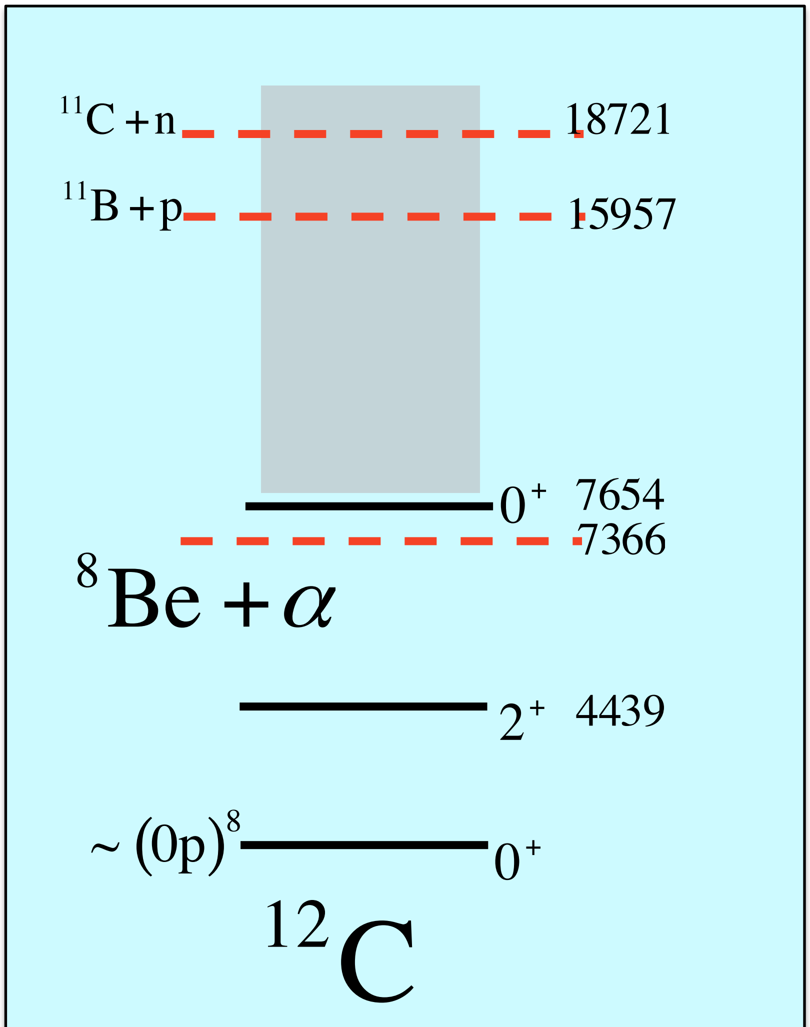
- Quantum Monte Carlo (GFMC) **^{12}C**
- No-Core Shell Model **^{14}F, ^{14}C**
- Faddeev-Yakubovsky
- Lattice EFT **^{12}C (Hoyle)**
- Coupled-Cluster Techniques **^{17}F, ^{56}Ni**
- Fermionic Molecular Dynamics
- …

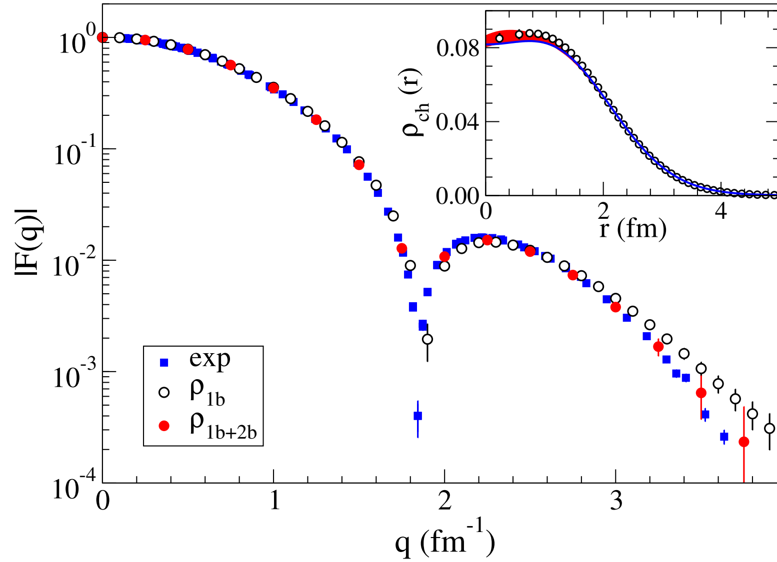


1-2% calculations of A = 6 – 12 nuclear energies are possible
excited states with the same quantum numbers computed

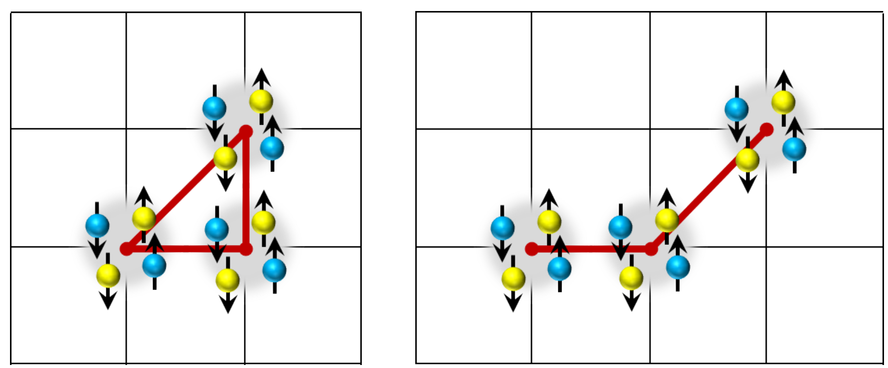
^{12}C structure: Ground-state and Hoyle-state

In 1954, Hoyle postulated that a7.65 MeV carbon state. This state plays a crucial role in the hydrogen burning of stars heavier than our sun and in the production of carbon and other elements necessary for life.





Lovato et al., Phys. Rev. Lett. 111, 092501 (2013). Quantum Monte Carlo



Epelbaum et al., Phys. Rev. Lett. 109, 252501 (2012). Lattice EFT

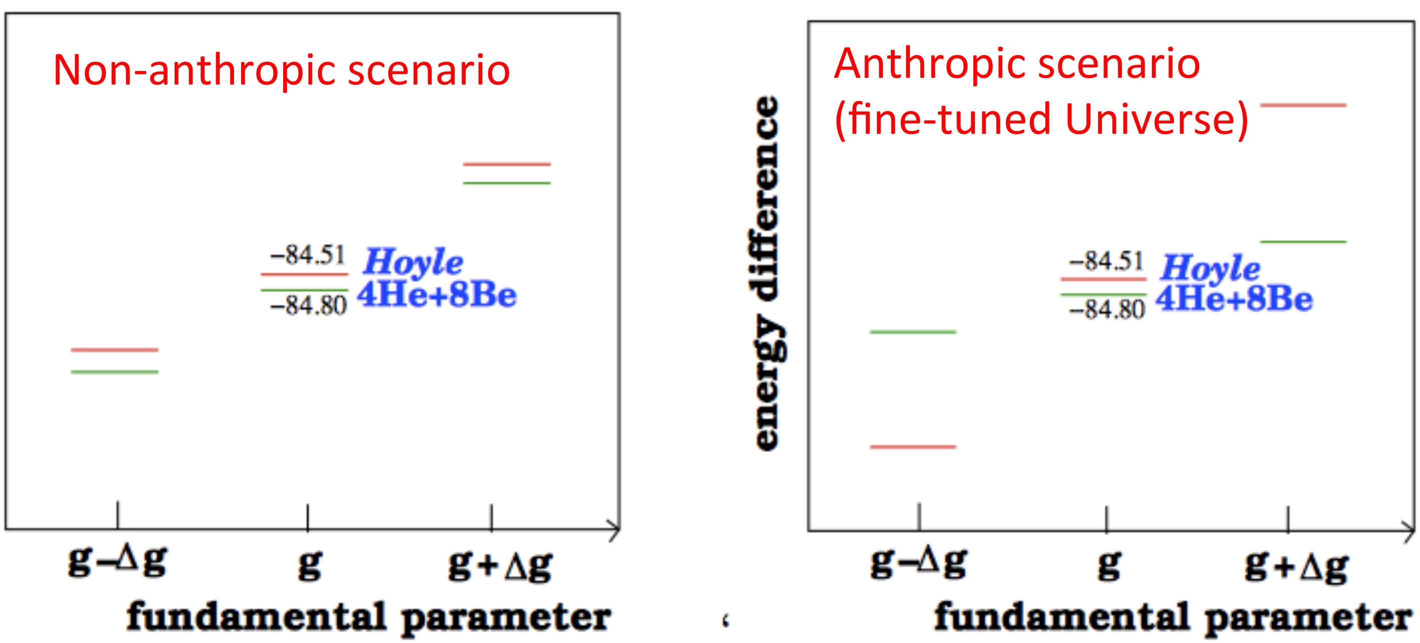
Anthropic Principle

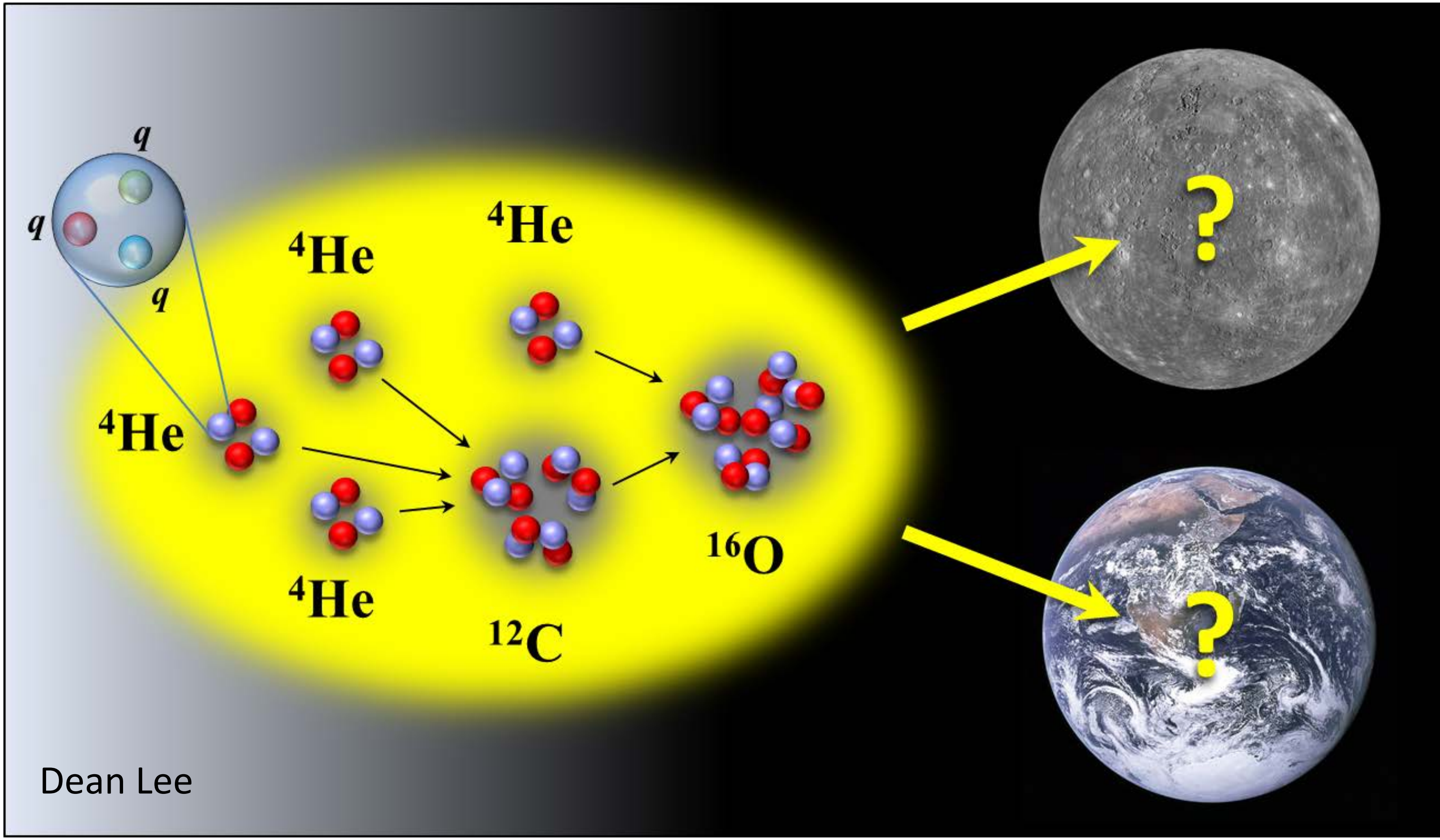
http://en.wikipedia.org/wiki/Anthropic_principle

The anthropic principle (from Greek anthropos, meaning "human") is the philosophical consideration that observations of the physical Universe must be compatible with the conscious life that observes it. Some proponents of the anthropic principle reason that it explains why the universe has the age and the fundamental physical constants necessary to accommodate conscious life.

Anthropic considerations in nuclear physics: U. Meissner. http://arxiv.org/abs/1409.2959

The nucleosynthesis of carbon-12 and Hoyle state

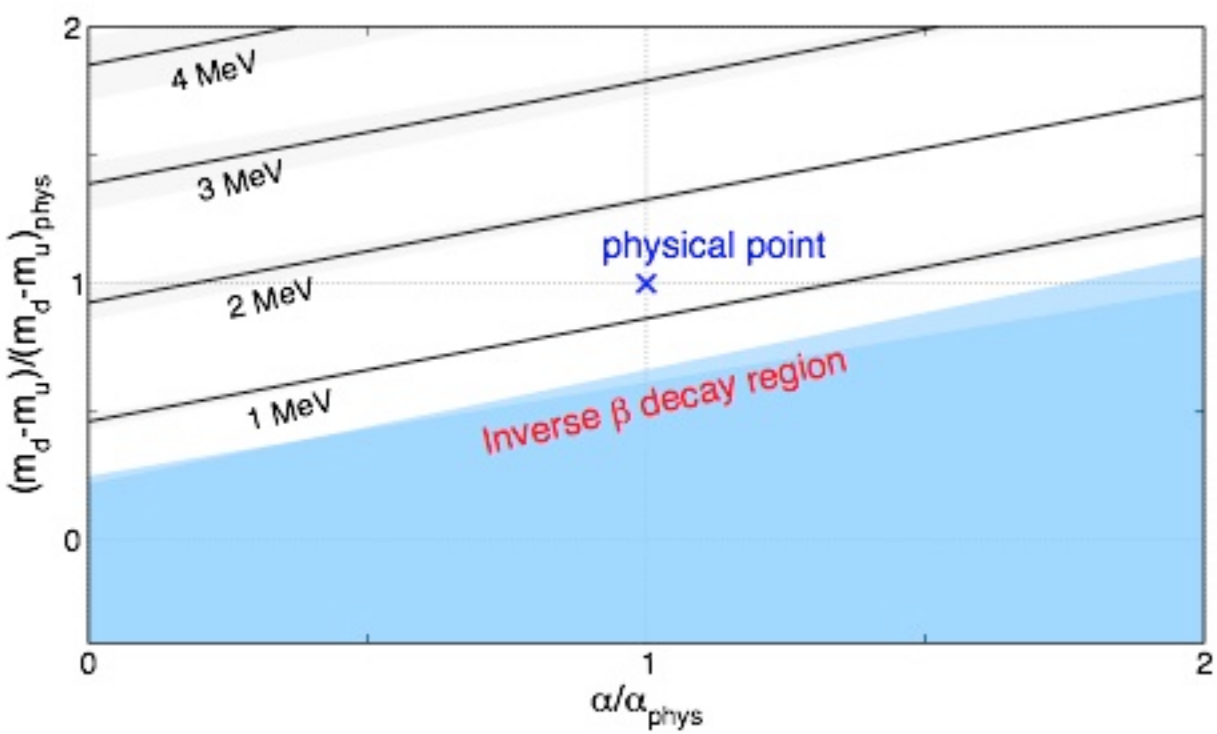




- "Viability of Carbon-Based Life as a Function of the Light Quark Mass", Phys. Rev. Lett. 110 (2013) 112502
- "Dependence of the triple-alpha process on the fundamental constants of nature", Eur. Phys. J. A 49 (2013) 82
- "Varying the light quark mass: impact on the nuclear force and Big Bang nucleosynthesis", Phys. Rev. D 87 (2013) 085018

Ab initio calculation of the neutron-proton mass difference

Science 347, 1452 (2015)



"The result of the neutron-proton mass splitting as a function of quark-mass difference and electromagnetic coupling. In combination with astrophysical and cosmological arguments, this figure can be used to determine how different values of these parameters would change the content of the universe. This in turn provides an indication of the extent to which these constants of nature must be fine-tuned to yield a universe that resembles ours."