The Nuclear Many-Body Problem

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

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

$$\hat{T} = \sum_{i=1}^{A} \frac{\hat{p}_i^2}{2m_i},$$

one-body

Kinetic energy

$$\hat{V} = \sum_{i<i} \hat{V}_{2b}(i,j) + \sum_{i<i<k} \hat{V}_{3b}(i,j,k)$$

two-body three-body

Potential energy

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

Eigenstate of angular momentum, parity, and ~isospin

3A nucleon coordinates in r-space

nucleon spins: ±1/2

nucleon isospins (p or n): ±1/2

Bottom line:

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

coupled integro-differential equations in 3A dimensions

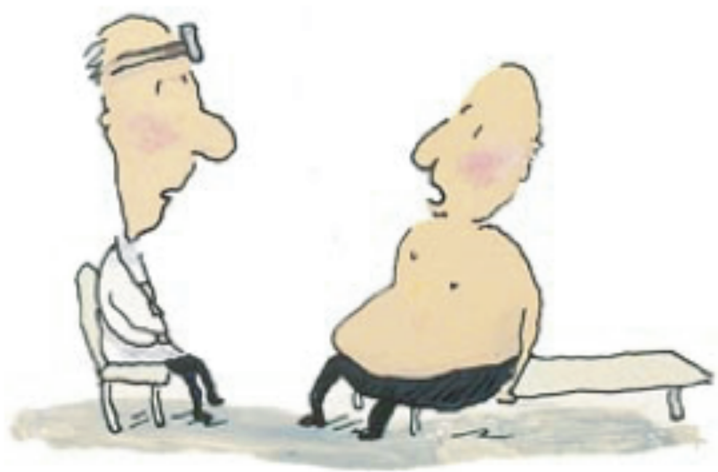
Weinberg's Laws of Progress in Theoretical Physics

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

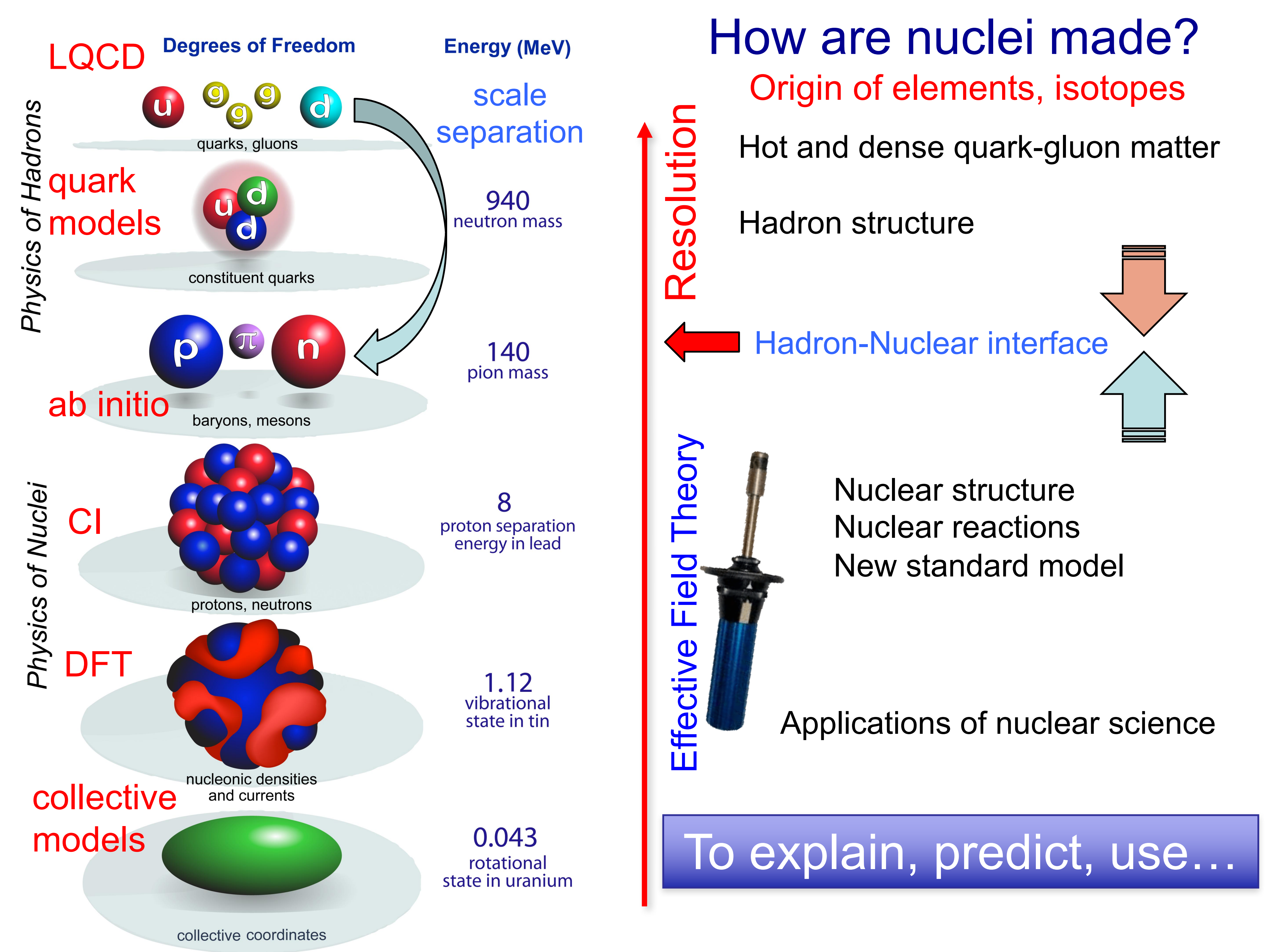
First Law: "The conservation of Information" (*You will get nowhere by churning equations*)

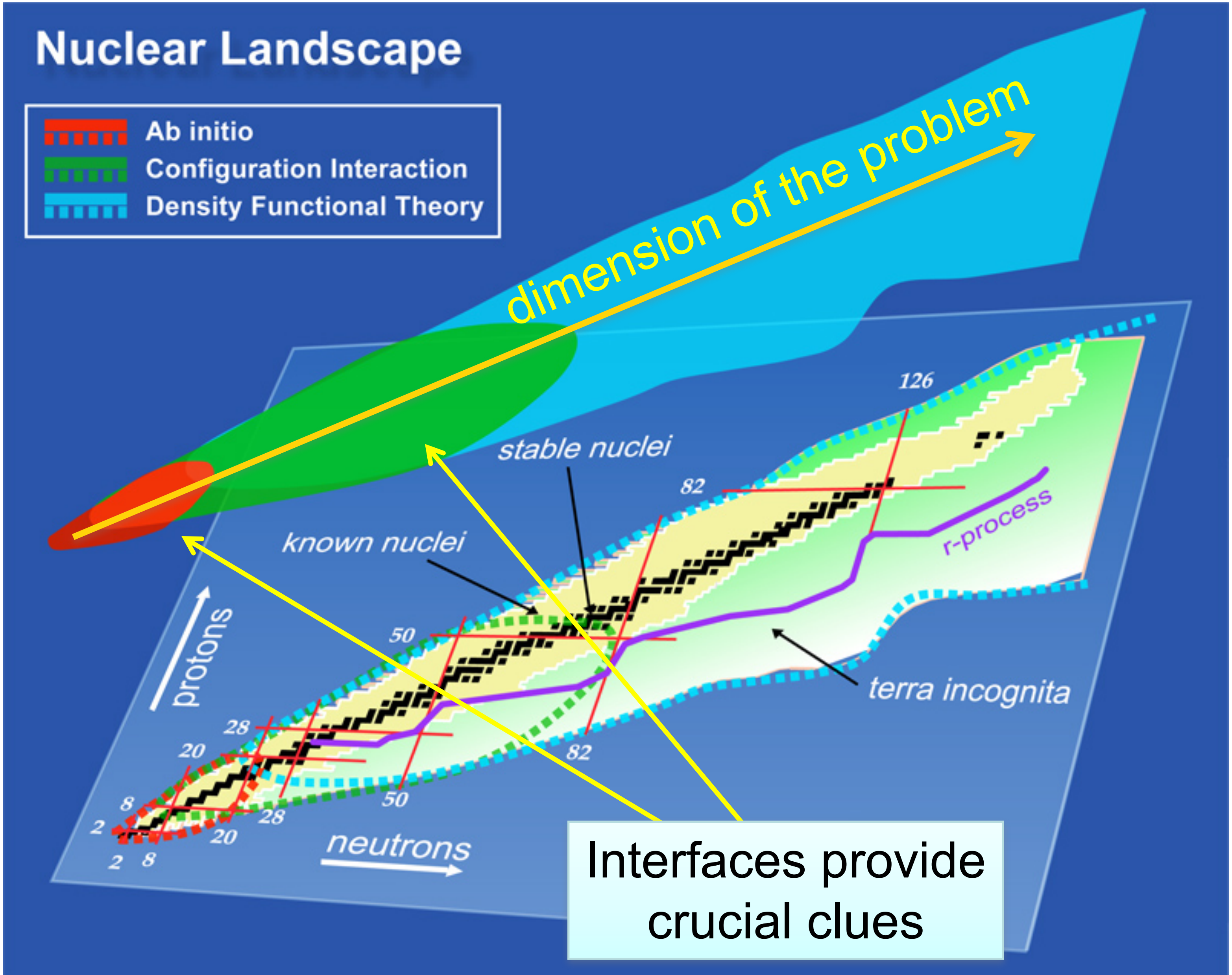
Second Law: "Do not trust arguments based on the lowest order of perturbation theory"

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
p
π
n
ab initio
baryons, mesons
140
pion mass
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
collective coordinates
0.043
rotational state in uranium
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…

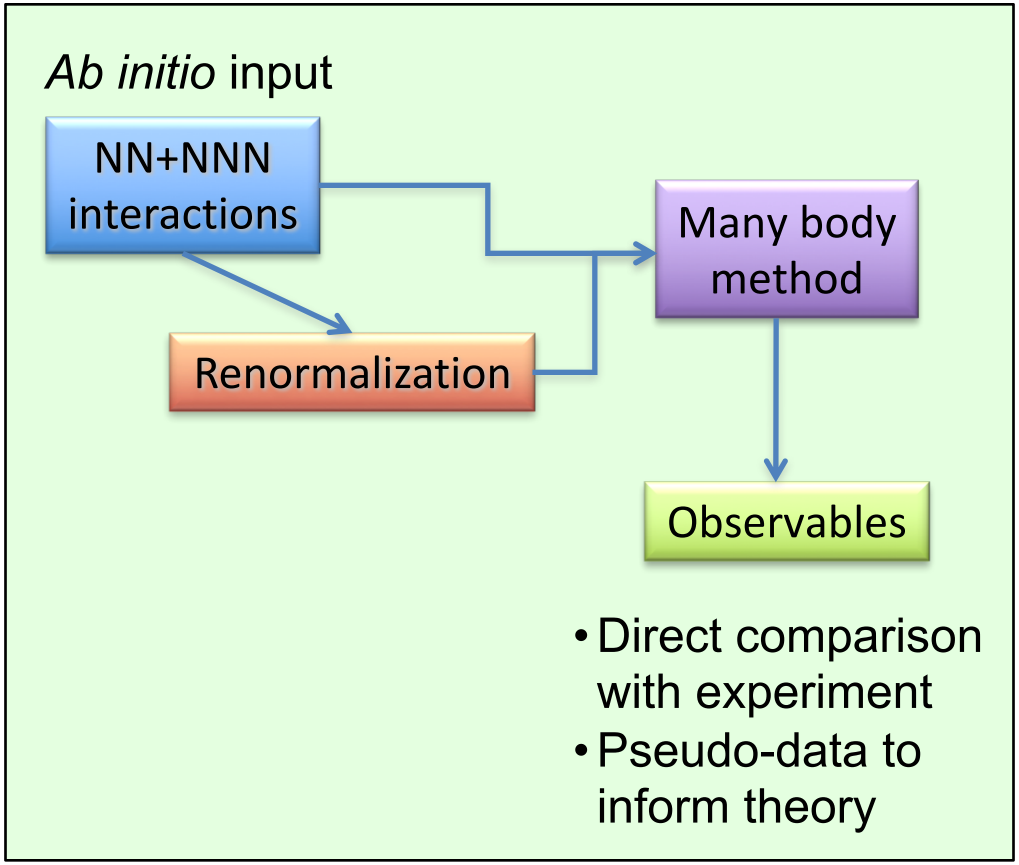


number of nuclei < number of processors!

Ab initio theory for light nuclei and nuclear matter

Ab initio: QMC, NCSM, CCM,…

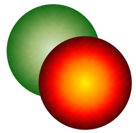
(nuclei, neutron droplets, nuclear matter)



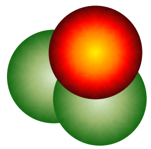
Input:

- 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

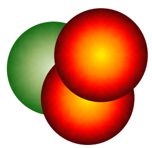
Few-nucleon systems



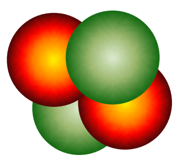
A=2: many years ago…



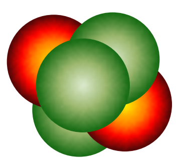
^{3}H: 1984 (1% accuracy)



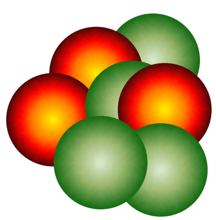
^{3}He: 1987



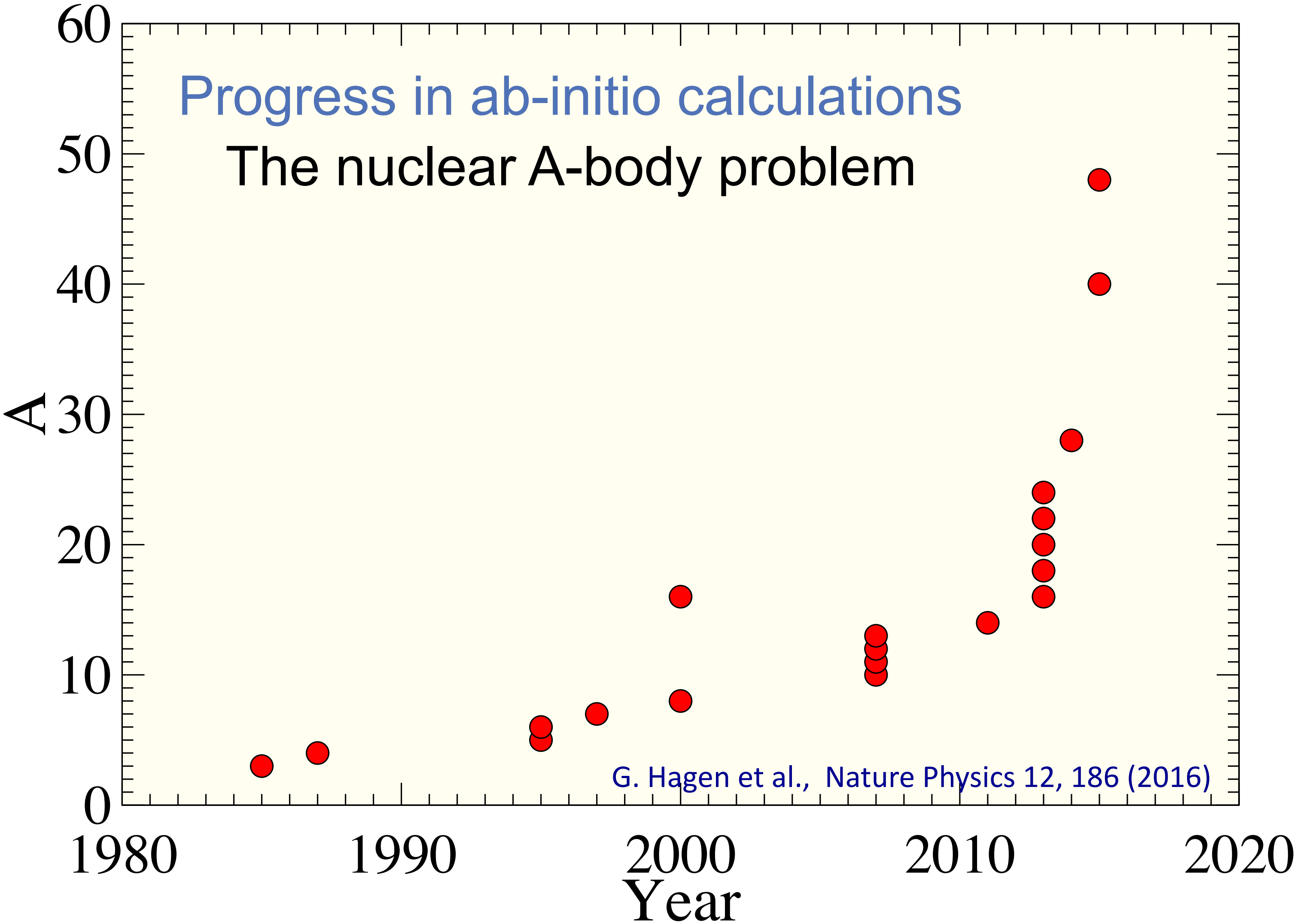
^{4}He: 1987



^{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)

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

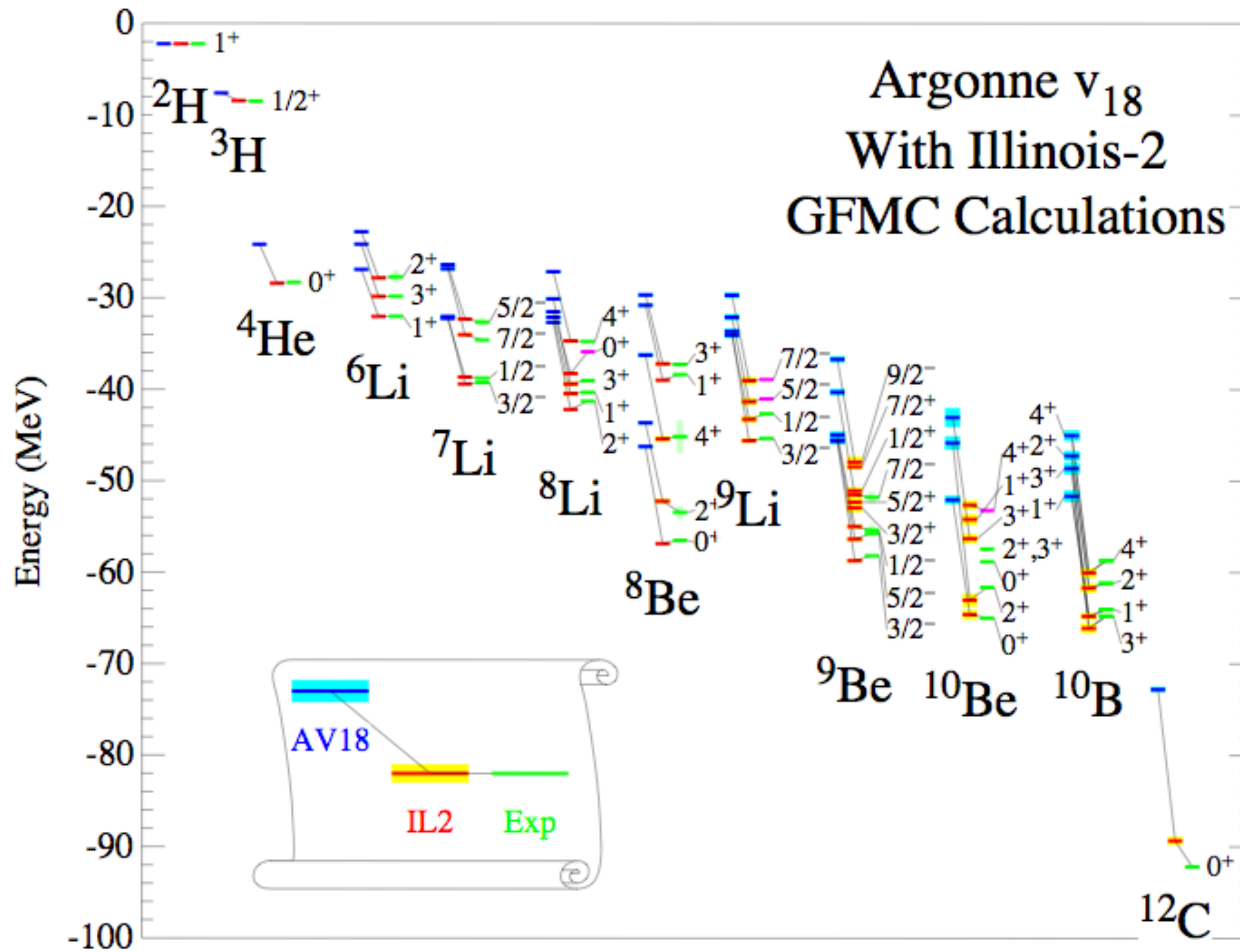
trial wave function

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

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

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

- 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
- …

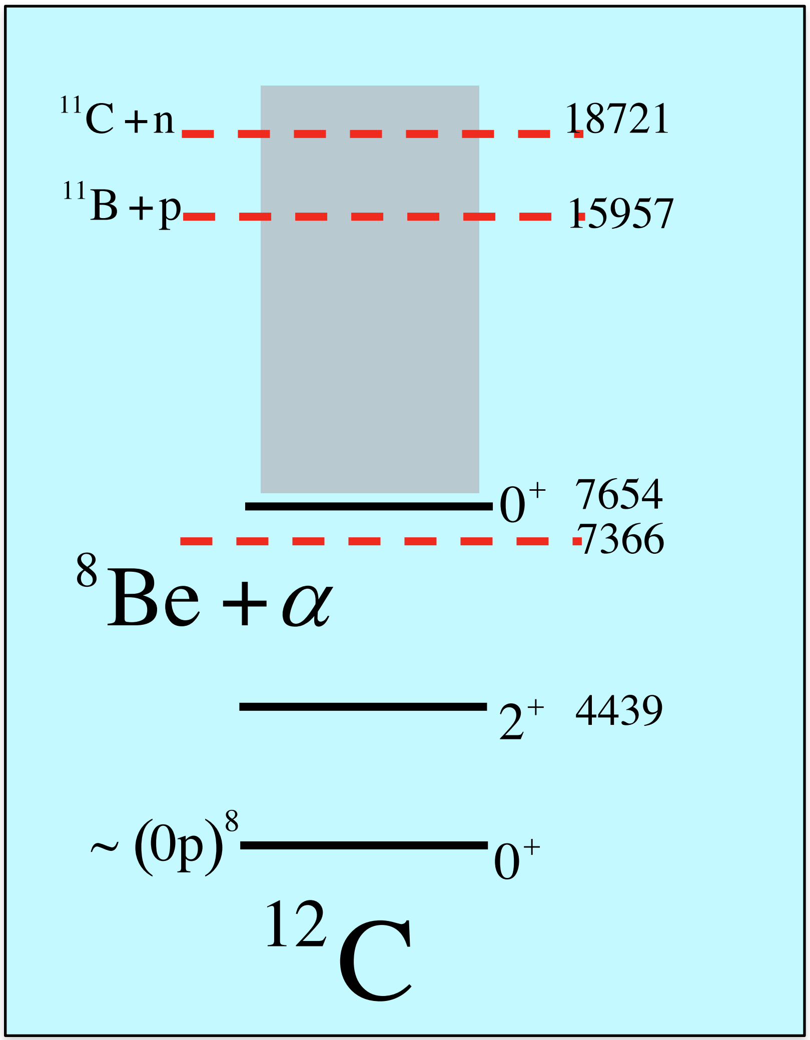


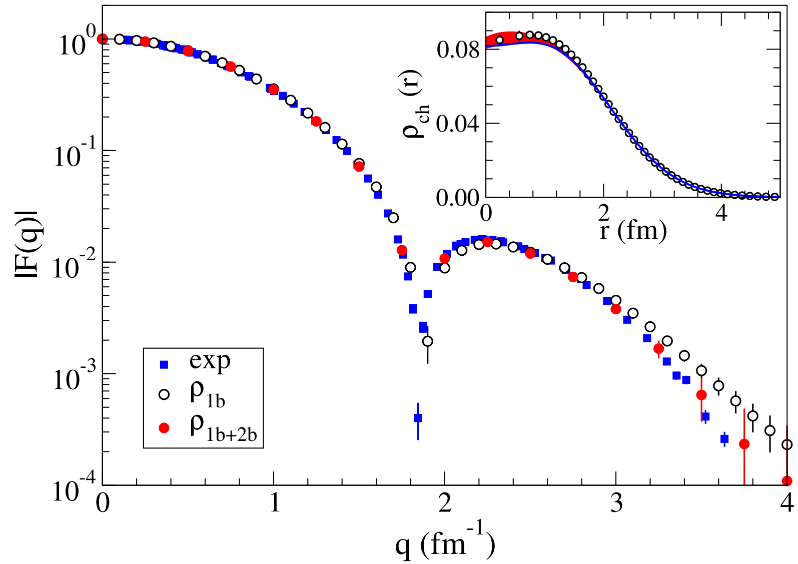
GFMC: S. Pieper, ANL

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

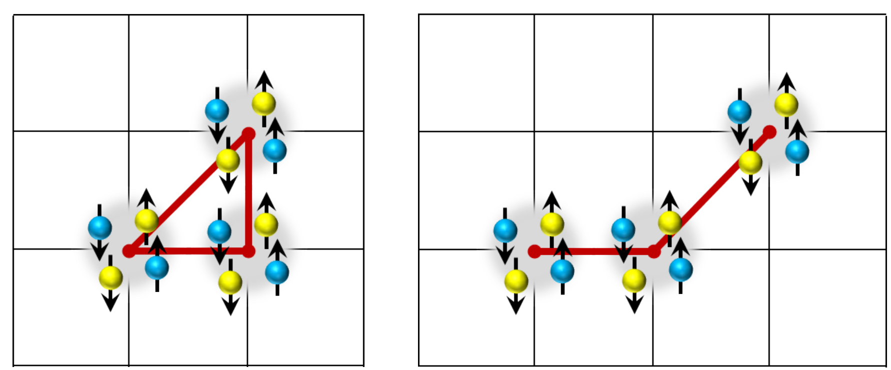
^{12}C structure: Ground-state and Hoyle-state

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

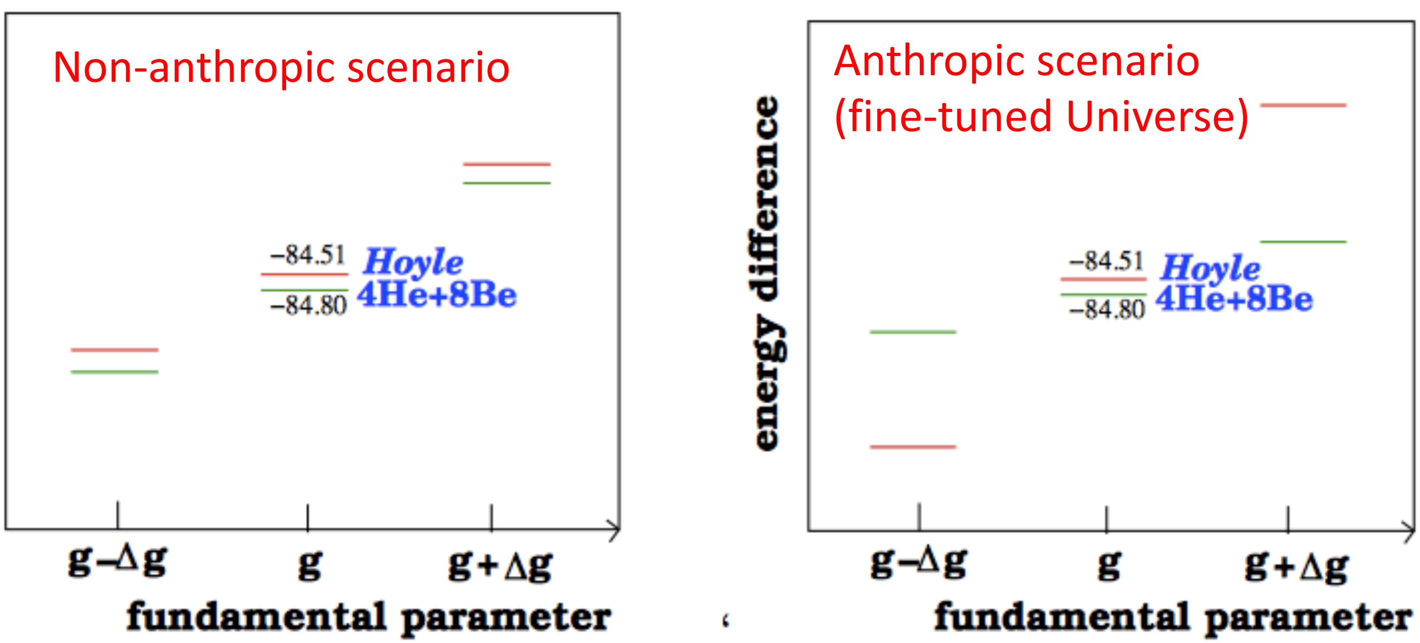
Anthropic Principle

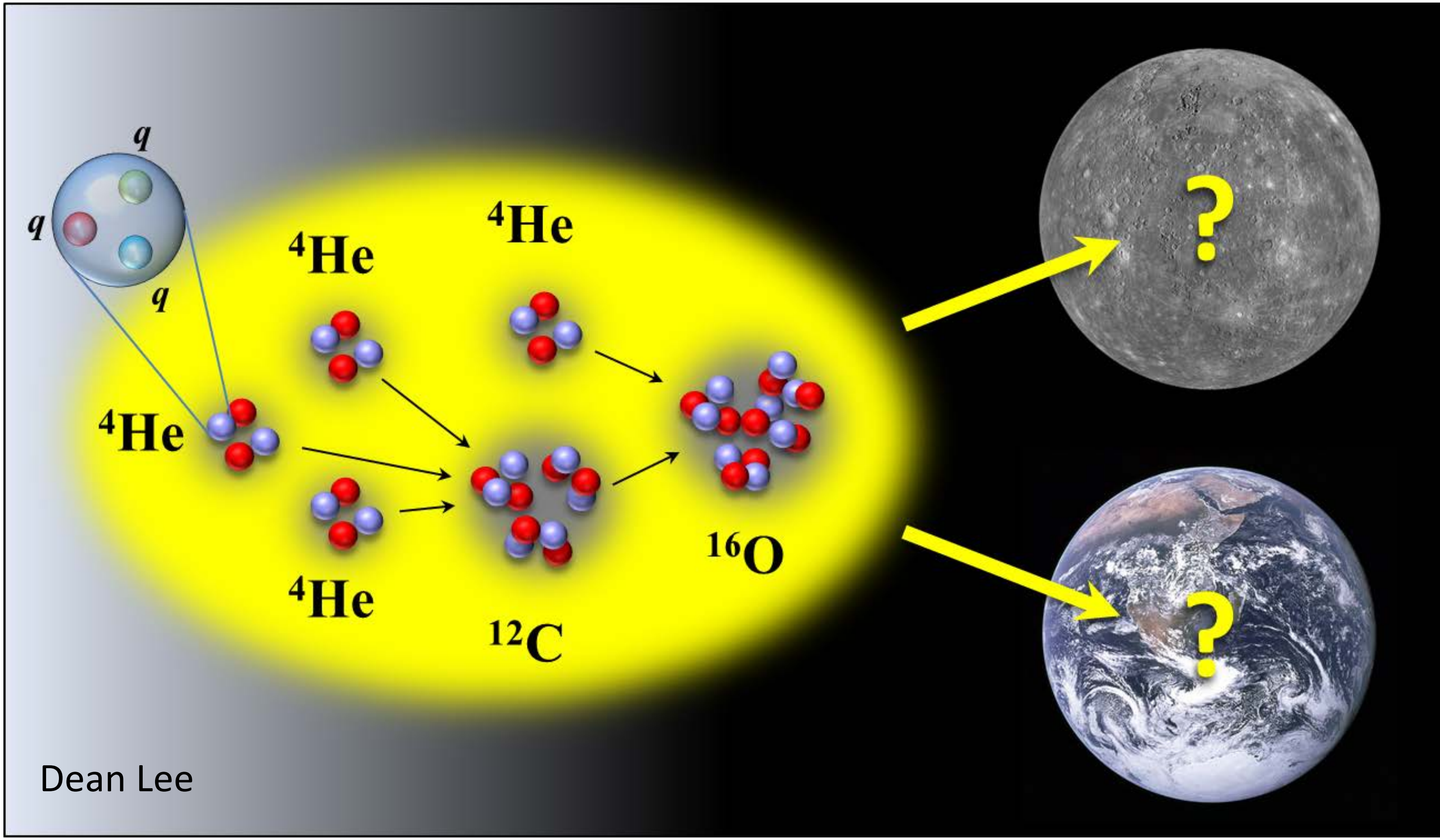
http://en.wikipedia.org/wiki/Anthropic_principle

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

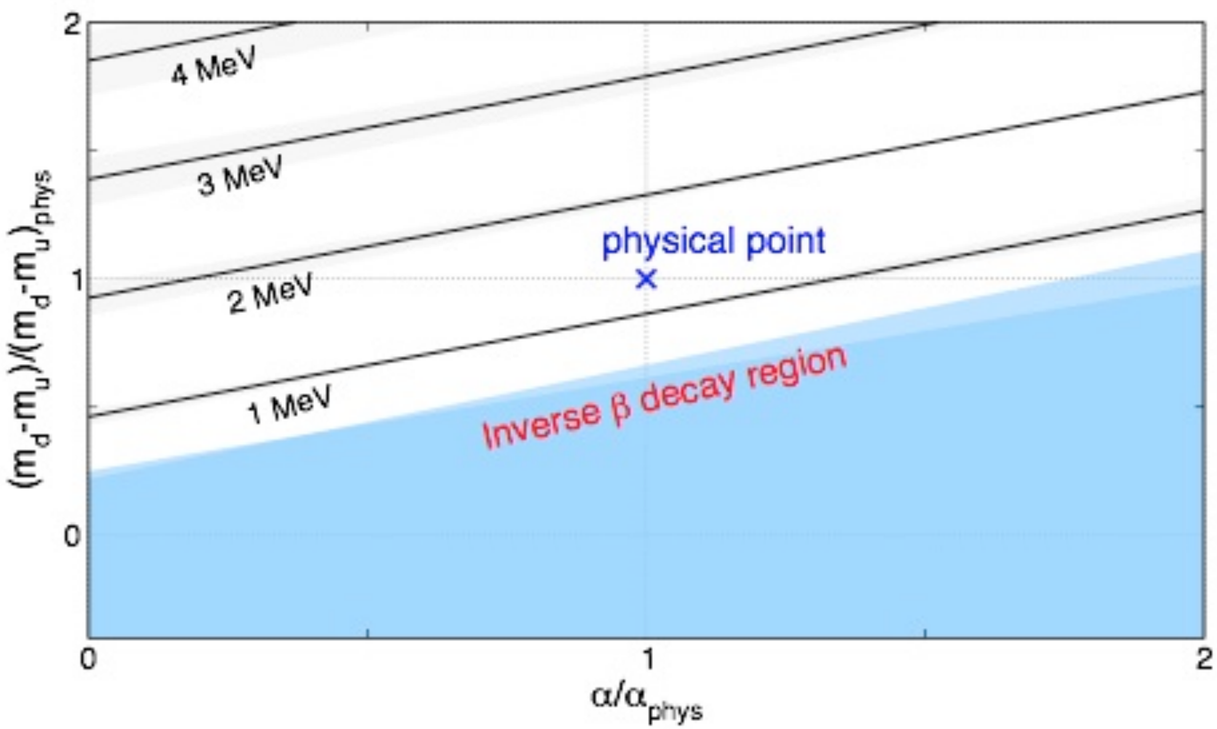




- "Viability of Carbon-Based Life as a Function of the Light Quark Mass", Phys. Rev. Lett. 110 (2013) 112502
- "Dependence of the triple-alpha process on the fundamental constants of nature", Eur. Phys. J. A 49 (2013) 82
- "Varying the light quark mass: impact on the nuclear force and Big Bang nucleosynthesis",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

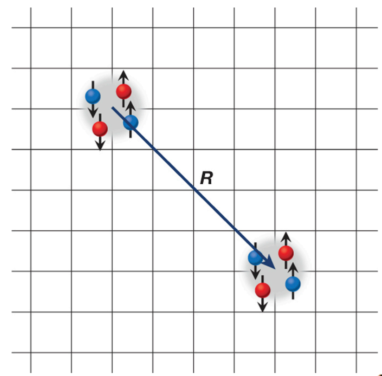
Ab initio calculation of the neutron-proton mass difference

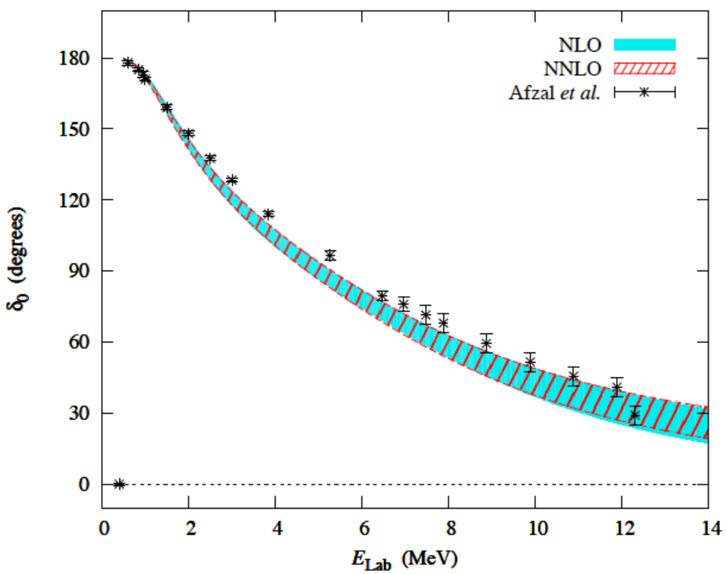
Science 347, 1452 (2015)

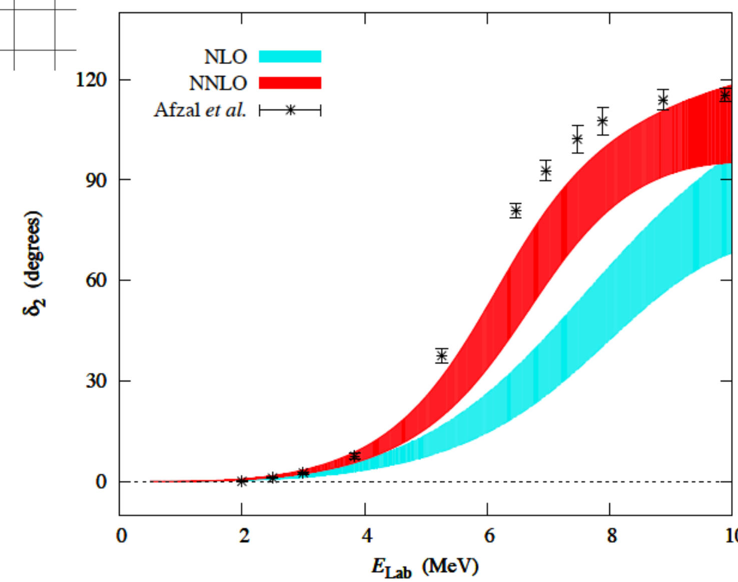


"The result of the neutron-proton mass splitting as a function of quark-mass difference and electromagnetic coupling. In combination with astrophysical and cosmological arguments, this figure can be used to determine how different values of these parameters would change the content of the universe. This 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."

ab-initio alpha-alpha scattering







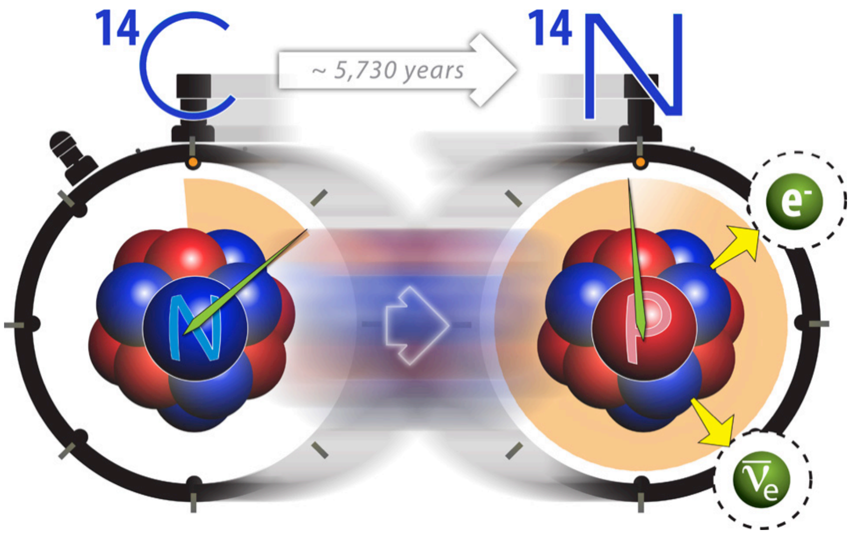
Elhatisari et al., Nature 528, 111 (2015)

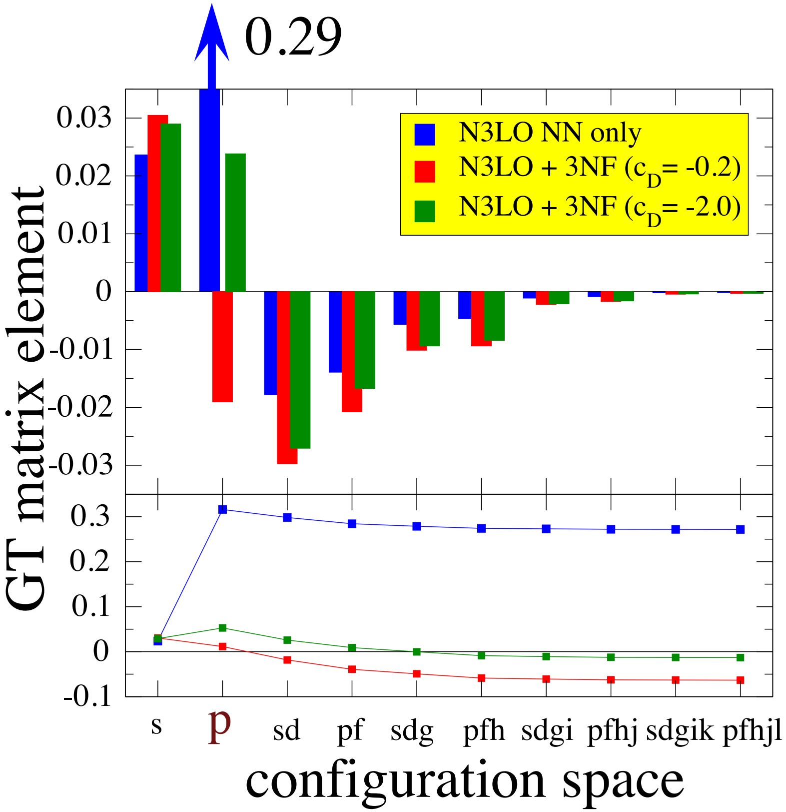
http://www.nature.com/nature/journal/v528/n7580/full/nature16067.html
http://www.nature.com/nature/journal/v528/n7580/abs/528042a.html

http://phys.org/news/2015-12-insights-creation-heavy-elements-simulate.html

Anomalous Long Lifetime of ^{14}C

Determine the microscopic origin of the suppressed β-decay rate: 3N force



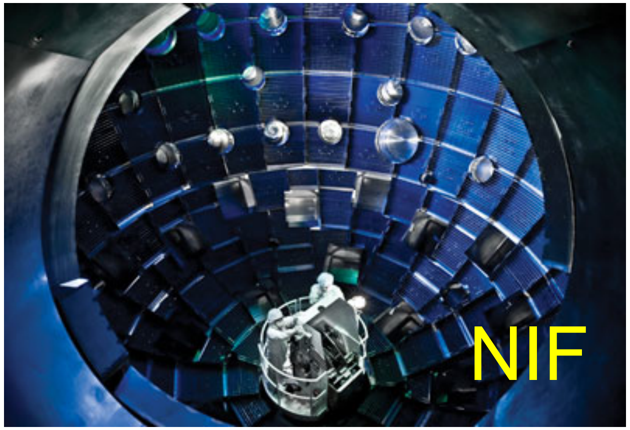


Maris et al., PRL 106, 202502 (2011)

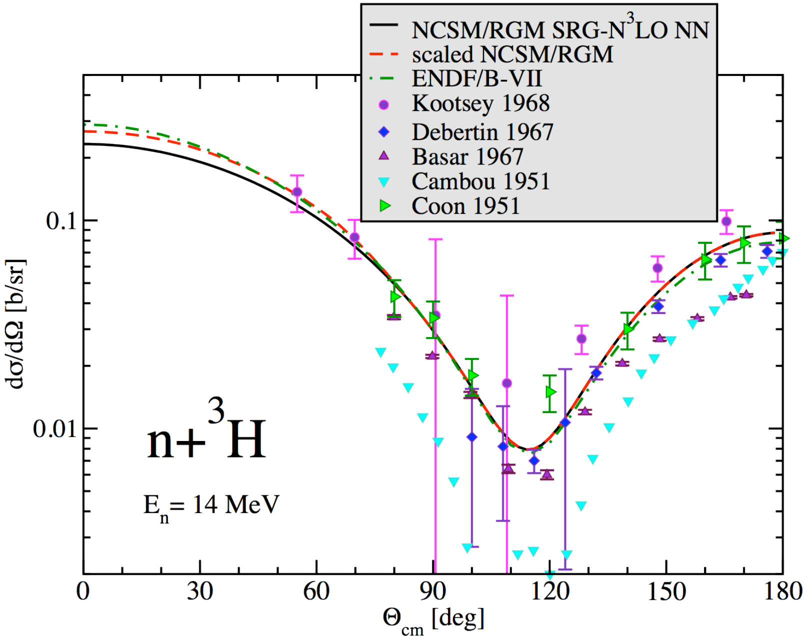
Dimension of matrix solved for 8 lowest states ~ 10^9
Solution took ~ 6 hours on 215,000 cores on Cray XT5 Jaguar at ORNL

Fusion of Light Nuclei

Computational nuclear physics enables us to reach into regimes where experiments and analytic theory are not possible, such as the cores of fission reactors or hot and dense evolving environments such as those found in inertial confinement fusion environment.



Ab initio theory reduces uncertainty due to conflicting data



- The n-^{3}H elastic cross section for 14 MeV neutrons, important for NIF, was not known precisely enough.
- Delivered evaluated data with required 5% uncertainty and successfully compared to measurements using an Inertial Confinement Facility
- "First measurements of the differential cross sections for the elastic n-^{2}H and n-^{3}H scattering at 14.1 MeV using an Inertial Confinement Facility", by J.A. Frenje *et al.*, Phys. Rev. Lett. **107,** 122502 (2011)

http://physics.aps.org/synopsis-for/10.1103/PhysRevLett.107.122502