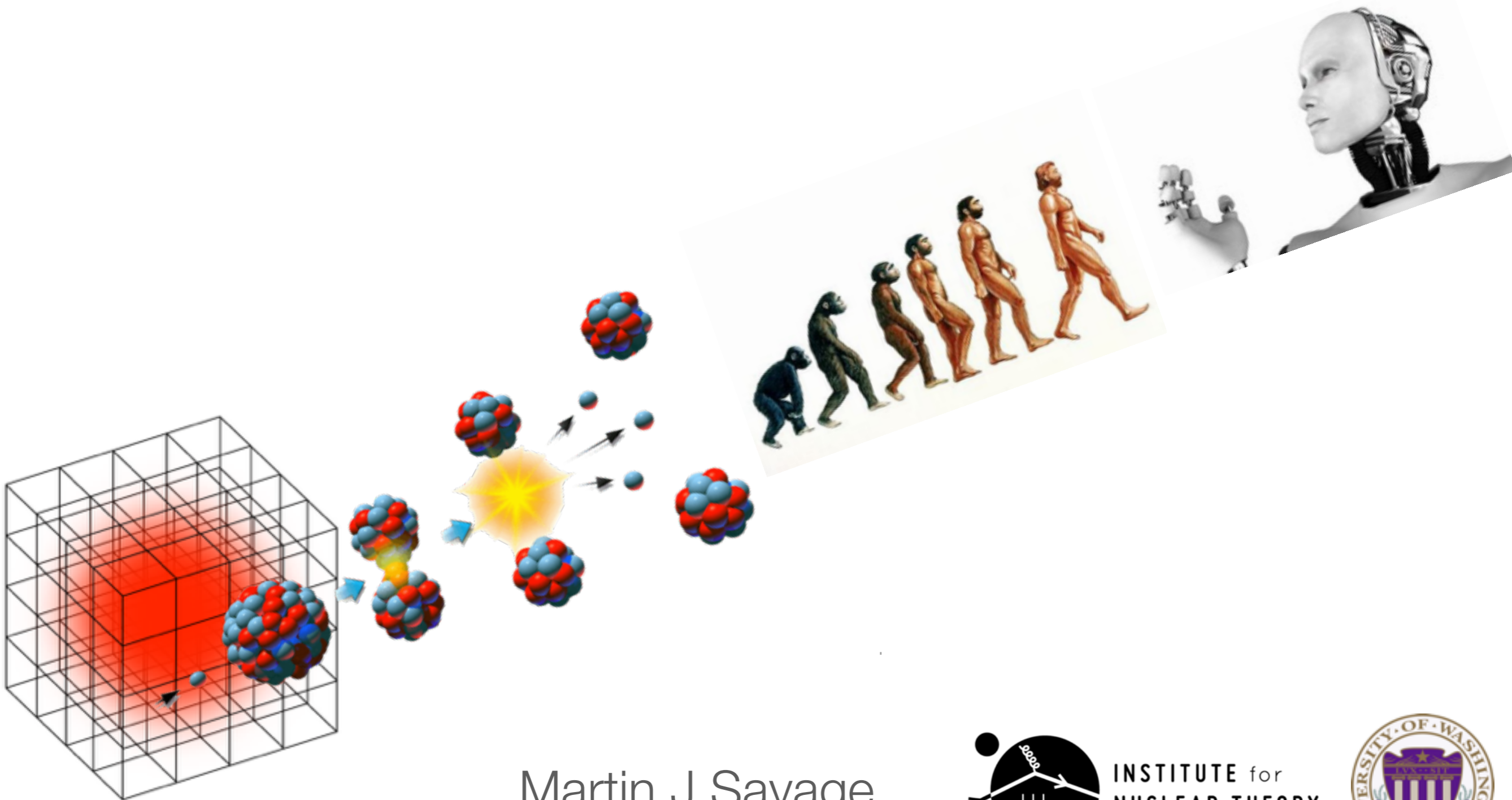


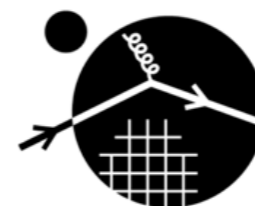


Kavli Institute for  
Theoretical Physics  
University of California, Santa Barbara

# Lattice QCD and Anthropic Arguments

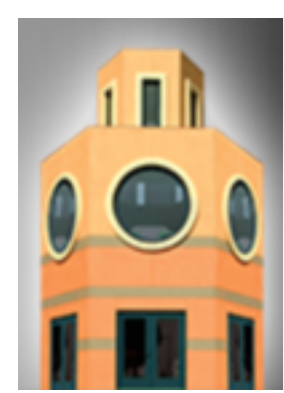


Martin J Savage

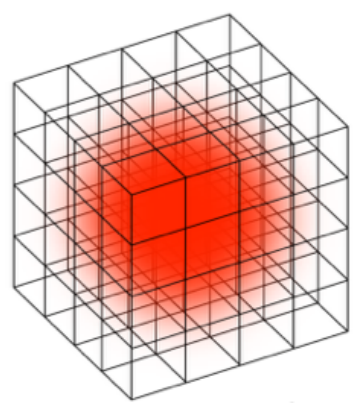


INSTITUTE for  
NUCLEAR THEORY



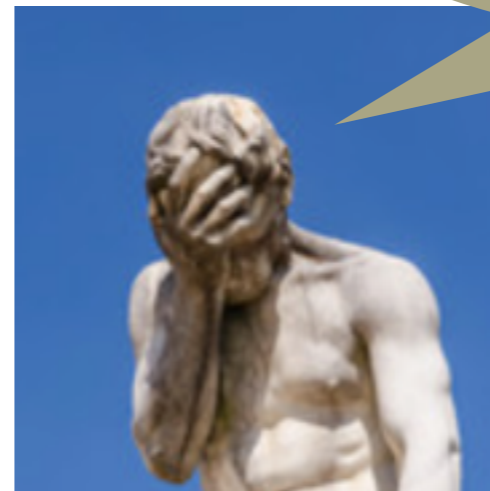


# Introduction



- David Gross gave a clear and critical introduction to the (Anti-)Anthropic Principle !

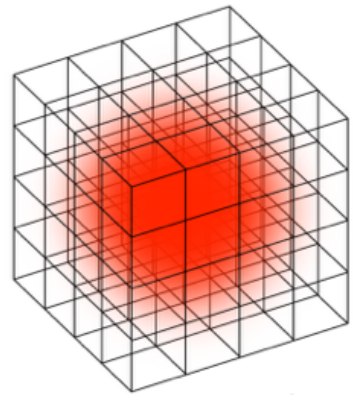
- refuge of the desperate ?



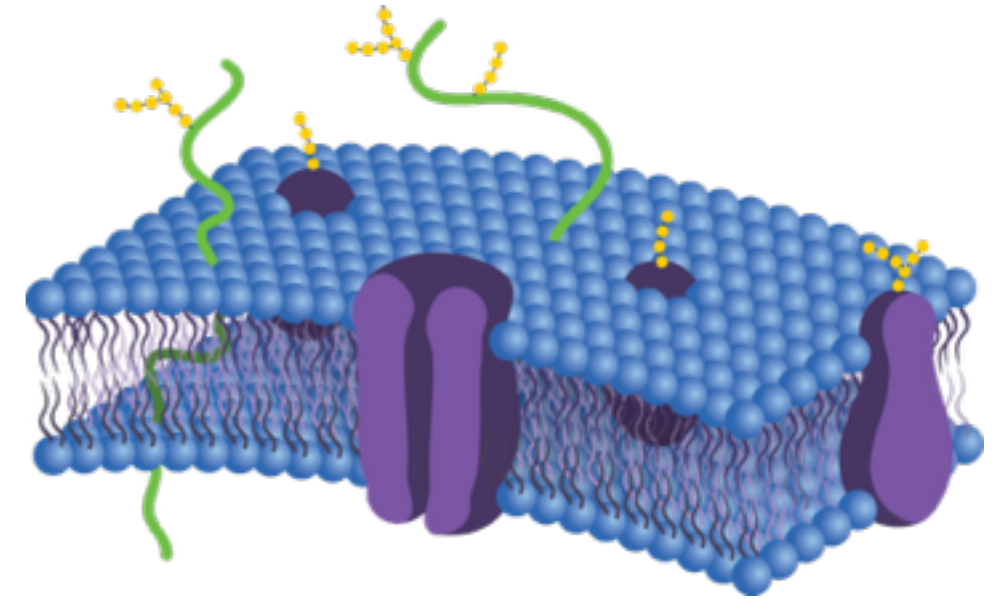
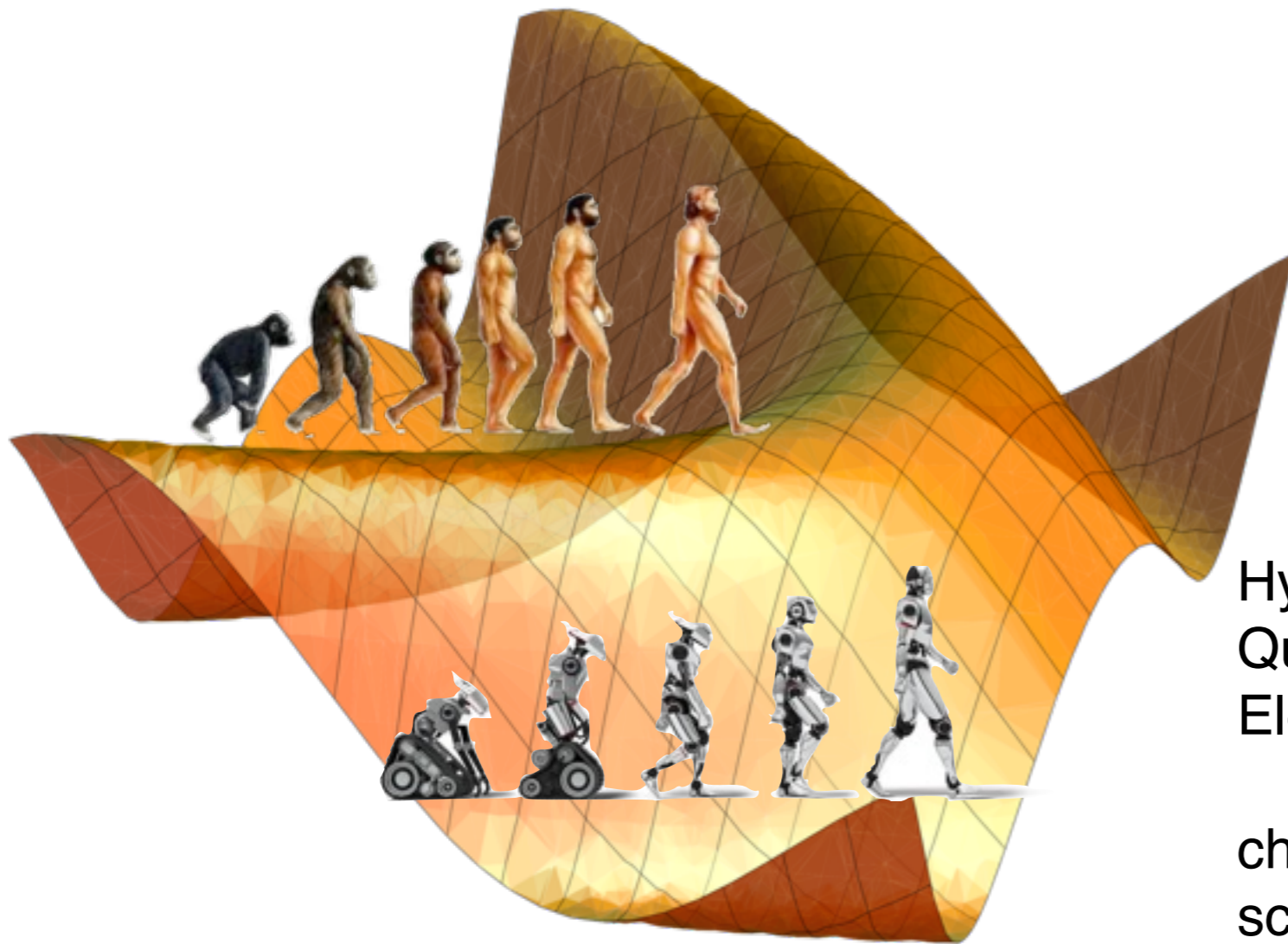
Oh no!  
- I don't know how to calculate it  
- anthropic argument?

- Dean Lee and Evgeni Epelbaum gave a wonderful discussion of EFT/Nuclear Structure/Hoyle-State status and future impacts

# Random Standard Model Parameters - What does Low-Energy Physics Look like ?



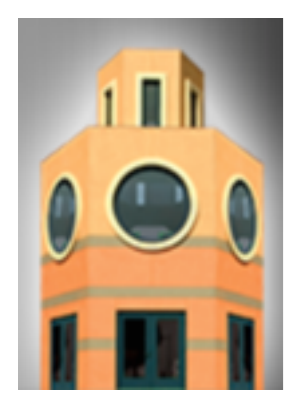
## The string landscape



Hydrogen, Carbon, Oxygen, Nitrogen  
Quantum Mechanics + Electromagnetism  
Electrons

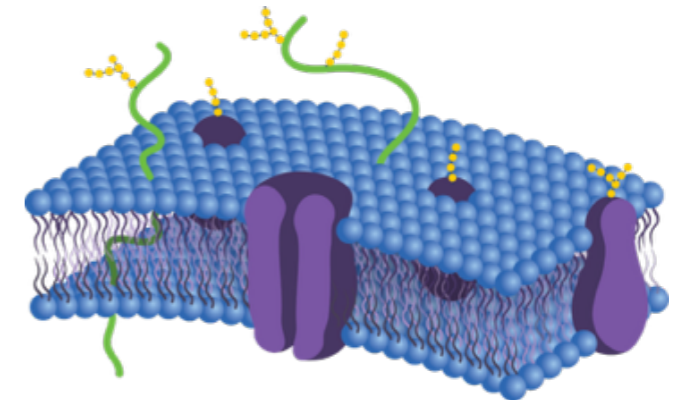
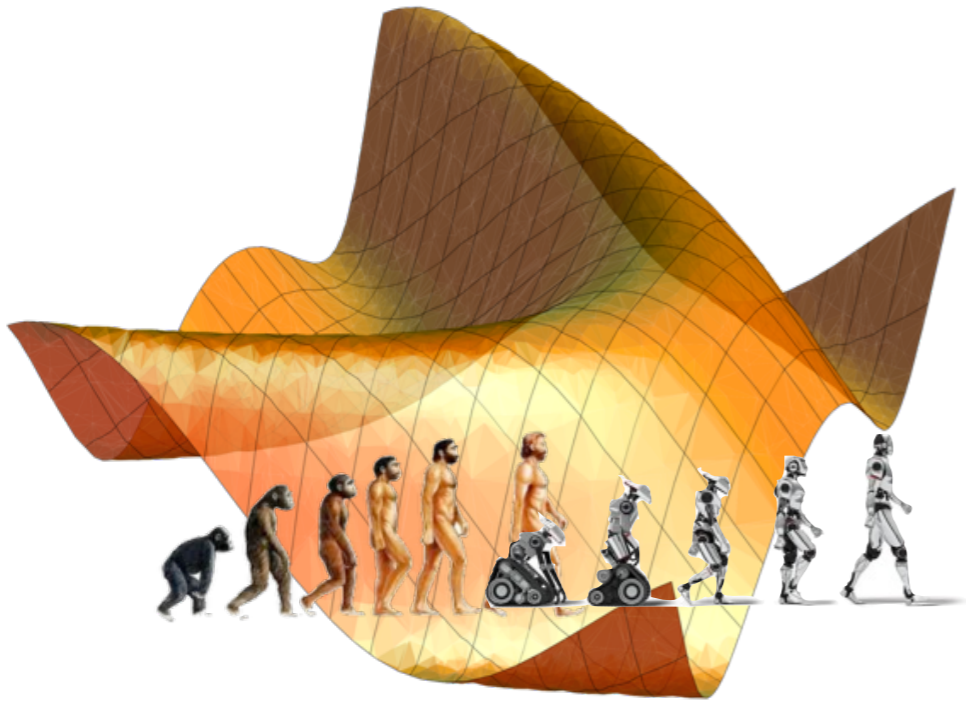
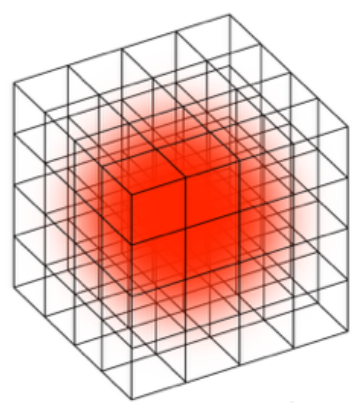
charges of nuclei, Pauli Principle, QM, EM  
scale set by  $\alpha_e m_e$   
a minimum amount of electronic complexity?

The laws of nature in our vacuum are simple, yet complexity emerges rapidly with scale. What about other vacua?



# Lattice QCD Calculations

## What does Low-Energy Physics Look like ?

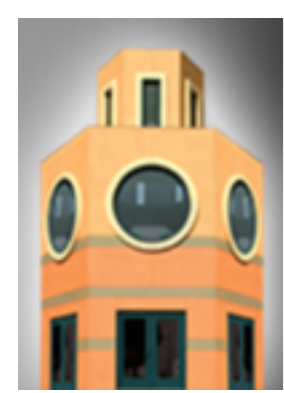


Hydrogen, Carbon, Oxygen, Nitrogen  
Quantum Mechanics + Electromagnetism  
Electrons

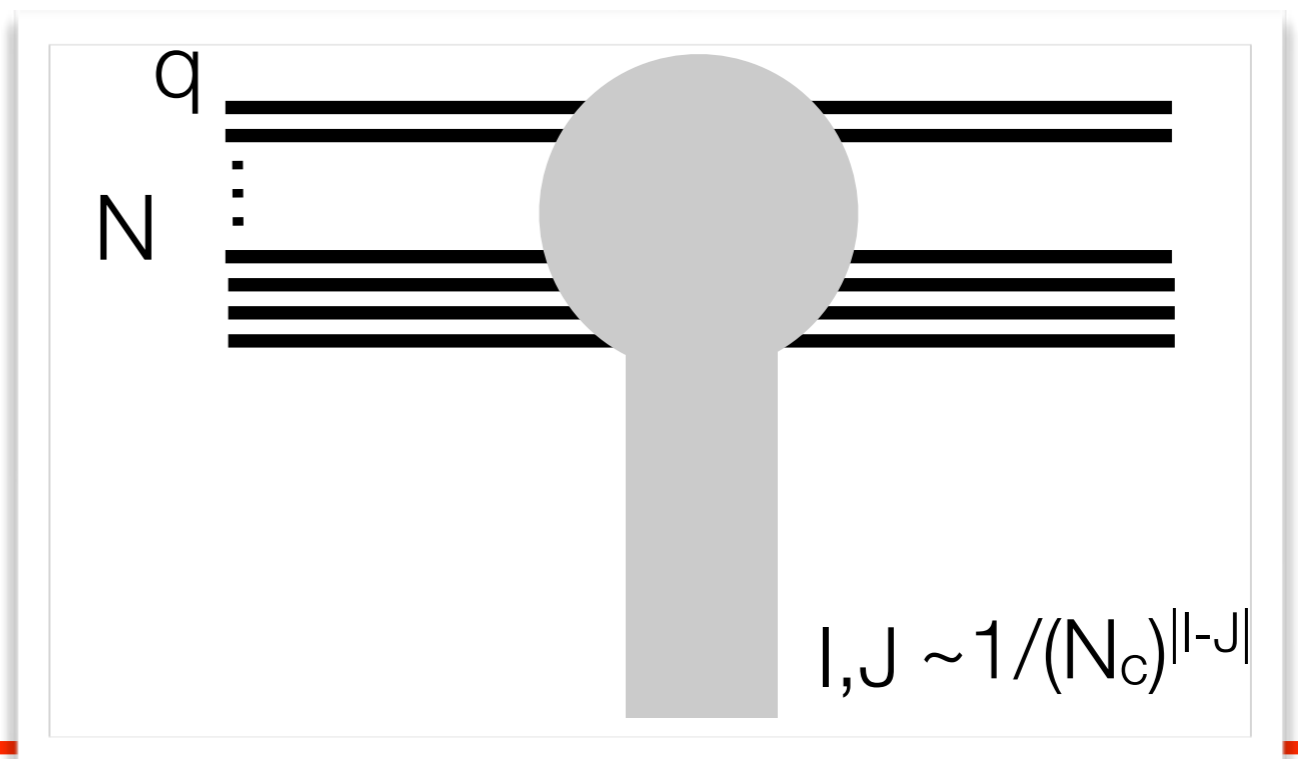
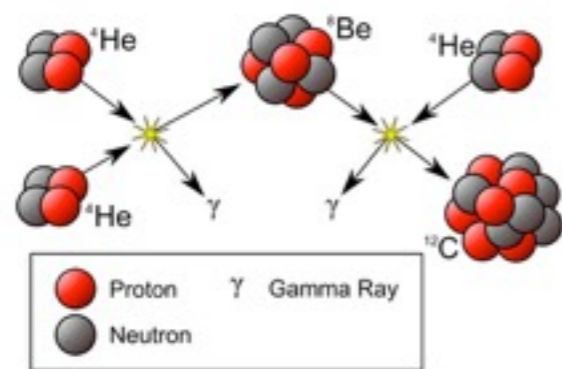
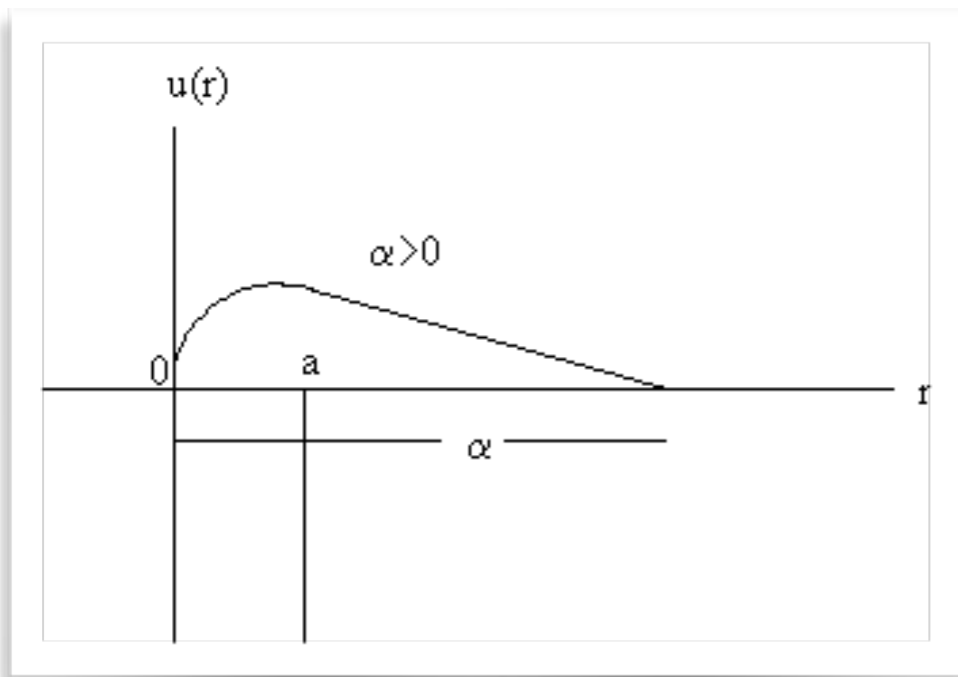
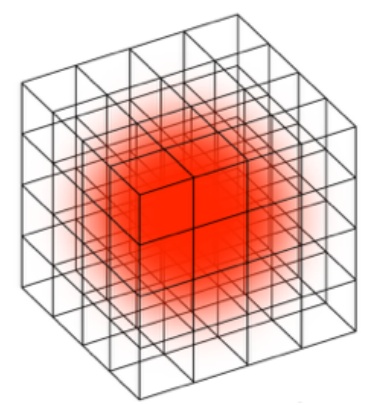
My personal angle on this is that of a "simple mechanic":

What is the space of standard model parameters that permit life ?

Lattice QCD (with  $N_c=3$ ) calculations of certain nuclear physics quantities can impact/improve these discussions  
(- removing ignorance)



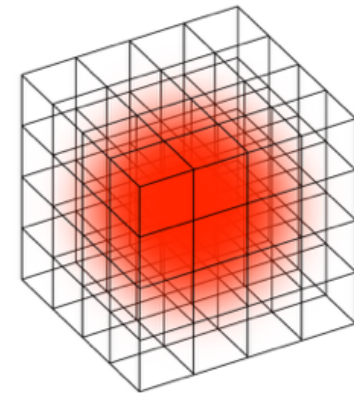
# Fine-Tunings in NP



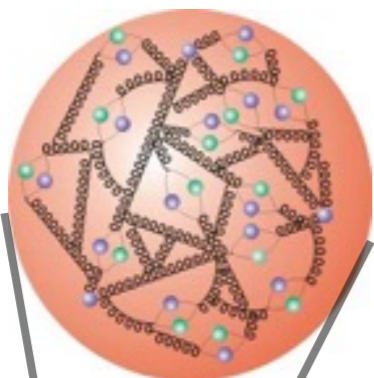
- Spin Independent up to  $1/Nc^2$
- SU(4) spin-flavor symmetry
- Near Unitarity

- Nuclear Physics exhibits unnatural and/or fine-tuned quantities, emergent symmetries
  - how? , robustness? , why (is the fine-tuning required)?
  - nonlinearities and quantum fluctuations trade off with quark masses
  - non-trivial fixed points in EFTs

# The Structure and Interactions of Matter from Quantum Chromodynamics

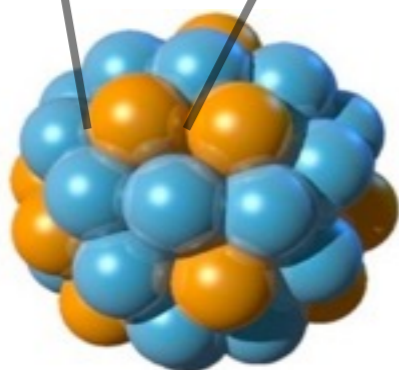


Proton



Quarks  
and  
Gluons

Nucleus



$$\Lambda_{\text{QCD}}$$

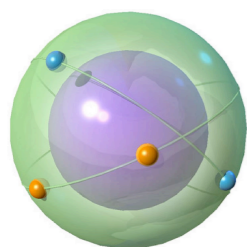
$$\frac{m_u}{\Lambda_{\text{QCD}}} \quad \frac{m_d}{\Lambda_{\text{QCD}}} \quad \frac{m_s}{\Lambda_{\text{QCD}}}$$

$$\alpha_e$$

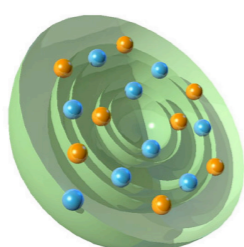
**Small number of input parameters responsible for all of strongly interacting matter**

**Dimensionless plus a scale**

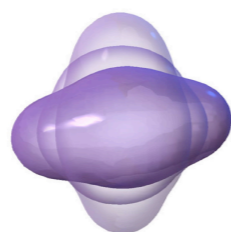
**LQCD - dimensionless**



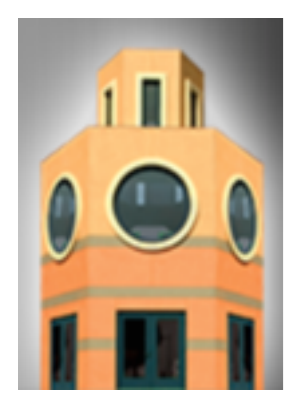
Spin-pairing



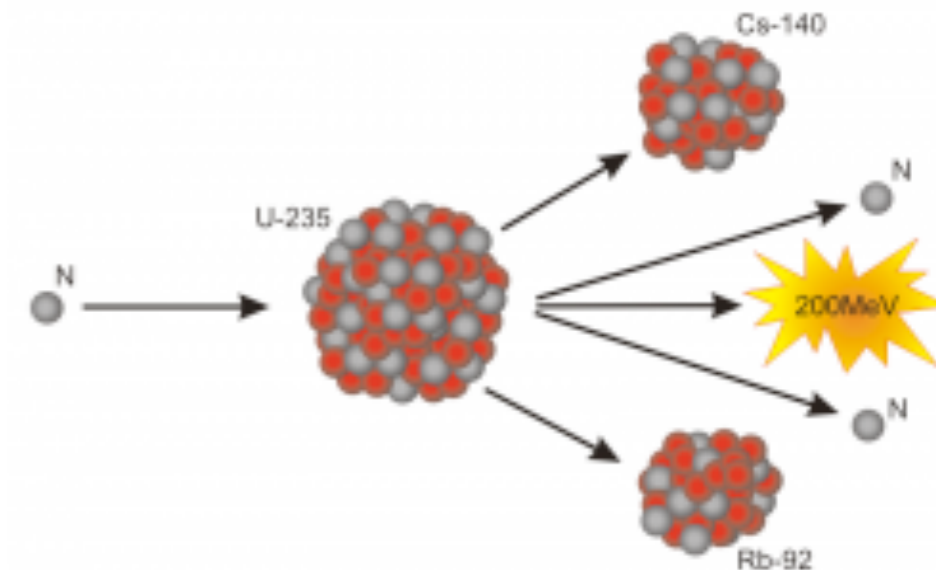
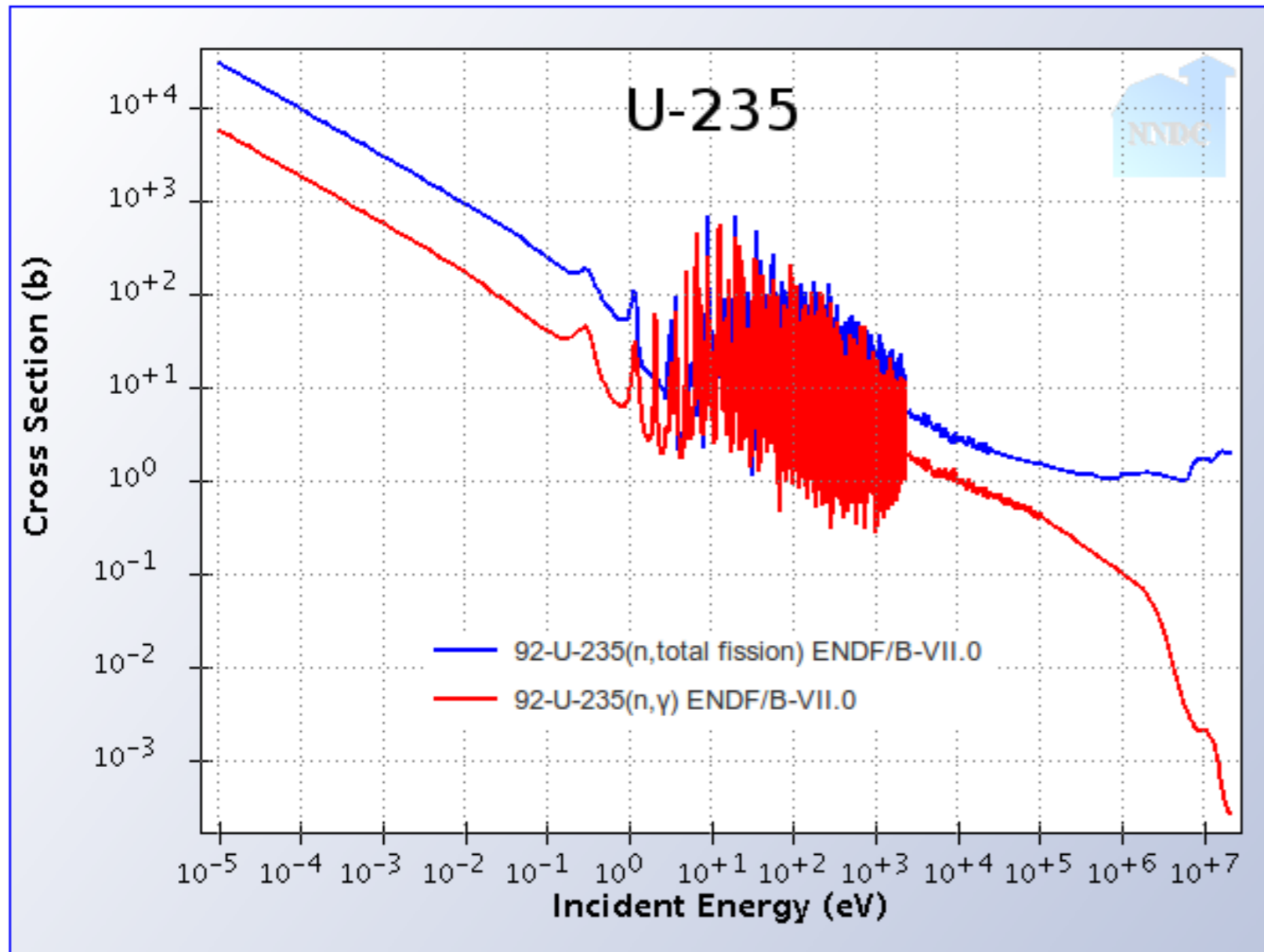
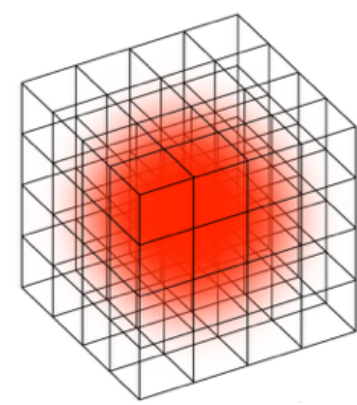
Shell-structure



Vibrational and rotational excitations



# QCD and EM Responsible for the Nuclear Energy Scales

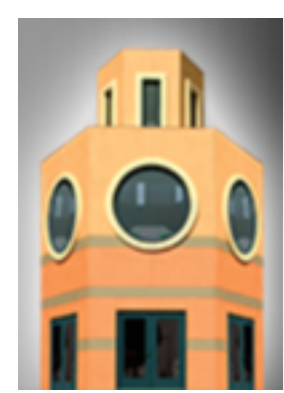


Interplay and delicate balancing between

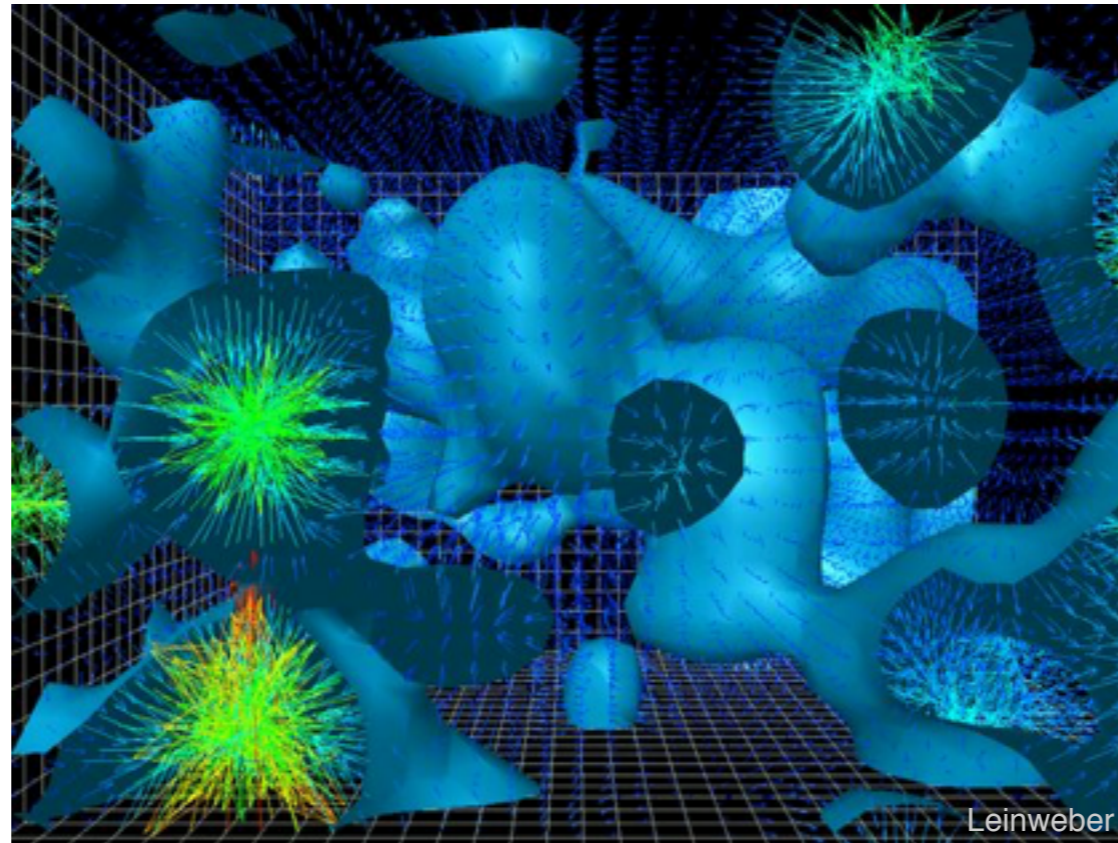
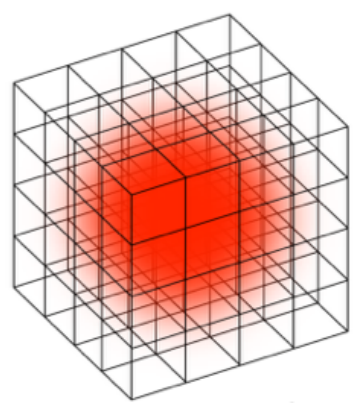
- classical,
- quantum,
- strong and
- electromagnetic

Mass  $^{235}\text{U} \sim 220\,900\text{ MeV}$

robustness of fission ?

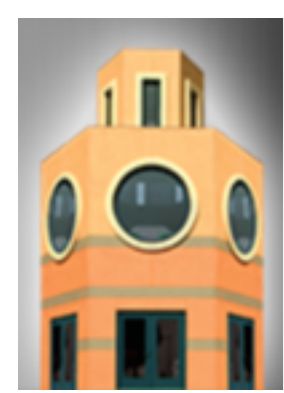


# Nuclear Physics and LQCD

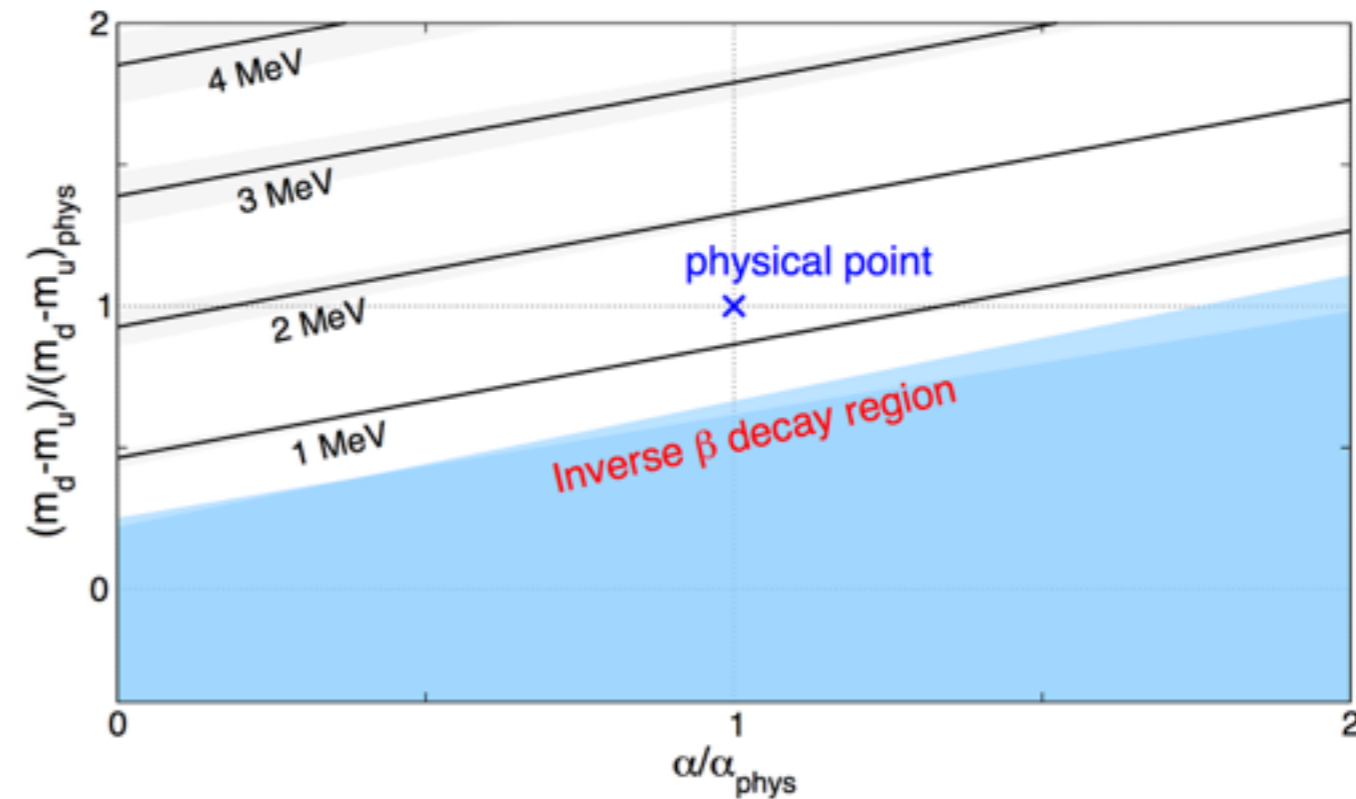
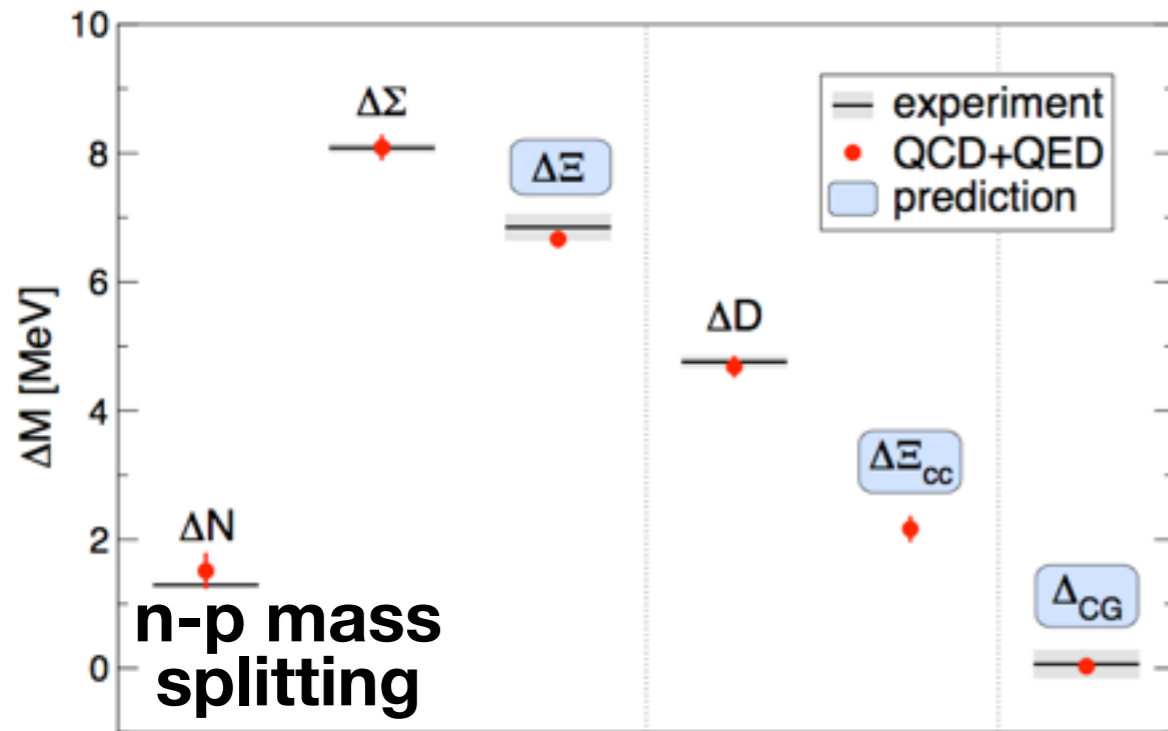
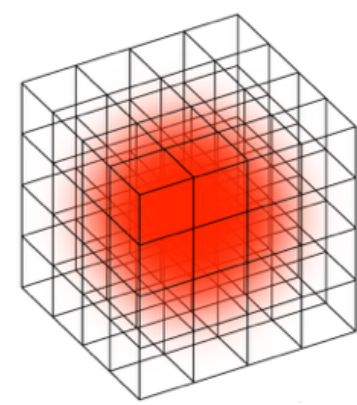


- Lattice QCD is a numerical technique with which to calculate the low-energy properties and interactions of hadrons
  - QCD+QED, with u,d,s,c quarks now possible.
- a means to address some of these questions
- what are the important quantities and the low-hanging fruit ?



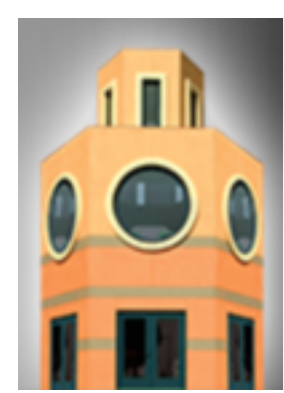


# State-of-the-Art Lattice QCD

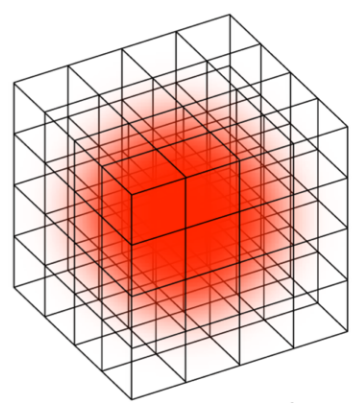


BMW collab

- Physical up, down, strange and charm quark masses
- Fully dynamical QCD+QED



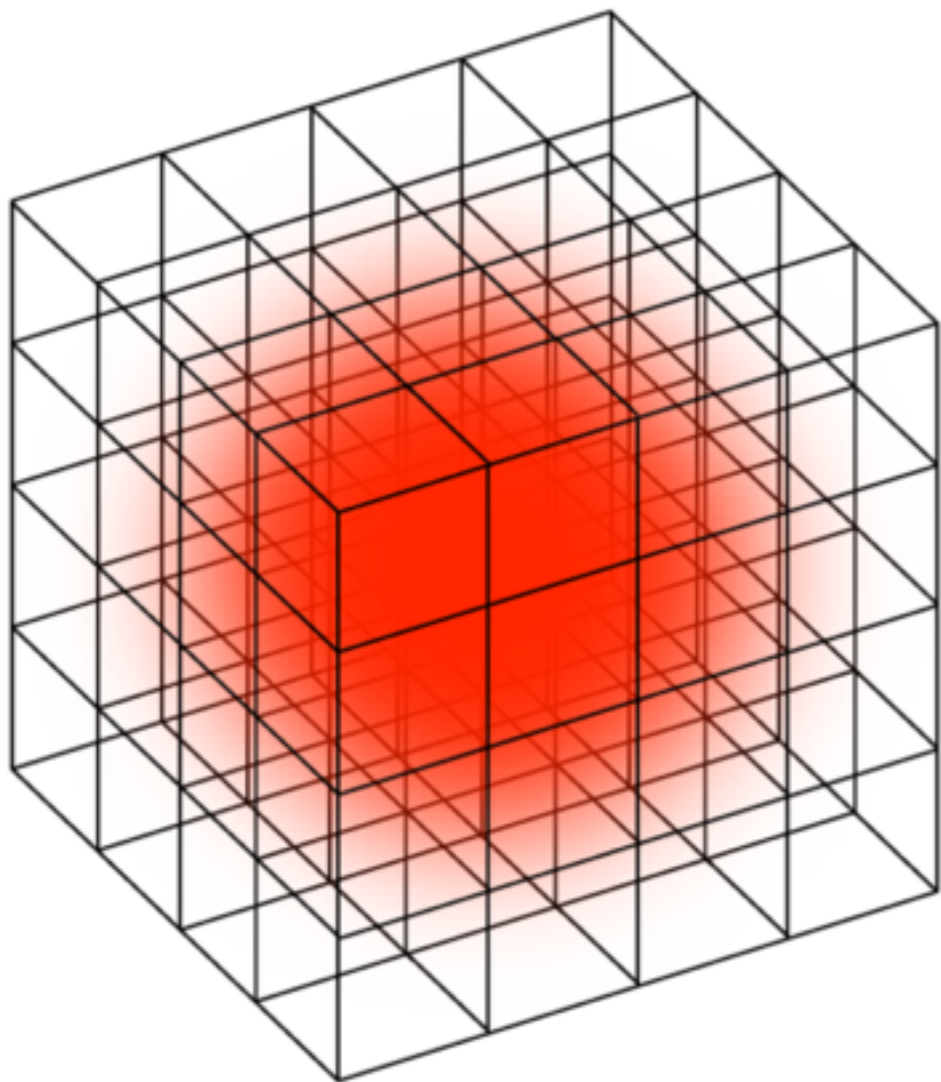
# Lattice QCD is a Method to Solve Low-Energy QCD



Ideally,

Use ratios of multiple quantities to fix UV parameters, improve action and operators

Then vary quark masses to map out observables( $m_q$ )



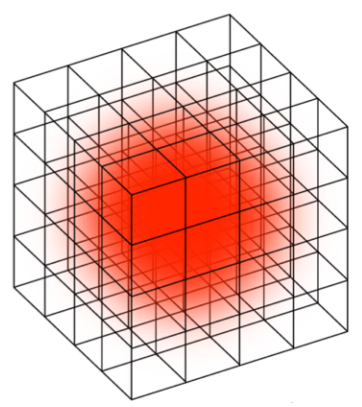
Would like this for  $t, b, c, s, d, u$  dynamical !

Near-term reality  $c, s, d, u$  dynamical, followed by  $b$ , not  $t$



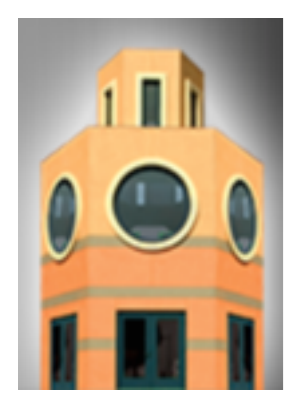
# Stages of a LQCD Project

... very roughly

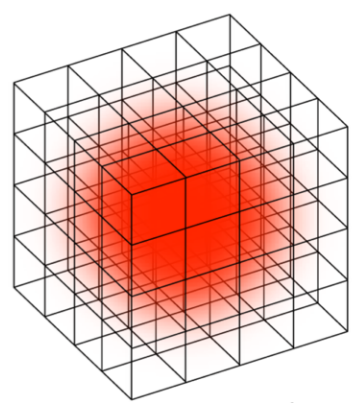


- physics concept(s)
- algorithms for including all important ingredients
- optimizing inclusion of all required ingredients
- reaching impactful precision point
- manufacturing phase





# Hadron Mass Decomposition



$$\mathcal{L} = \frac{1}{4} G^{\mu\nu} G_{\mu\nu} + \bar{q} (\not{D} + m_q) q$$

QCD

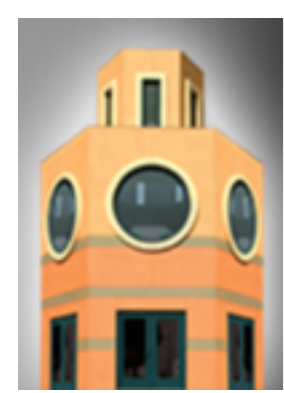
$$\mathcal{L} = \bar{N} (\not{\partial} + M_N) N$$

Nucleon

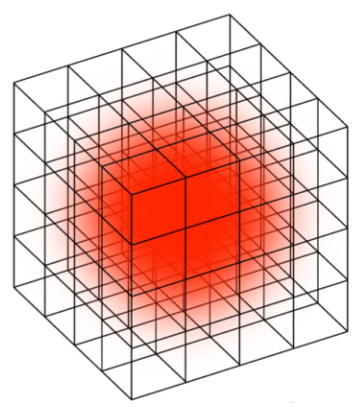
$$\partial^\mu s_\mu = T_\alpha^\alpha = \frac{\beta(\alpha)}{\alpha} \frac{1}{4} G^{\mu\nu} G_{\mu\nu} + (\gamma_m(\alpha) - 1) m_q \bar{q} q = -M_N \bar{N} N$$

Divergence of the Scale Current

Nucleon Mass comes **entirely** from the *divergence of the scale current*, which is the *trace of the energy-momentum tensor*.



# Hadron Mass Decomposition #1



$$\Delta M_{u,d} = M_H(m_\pi) - M_H(0)$$

generalizes to any number of the quarks

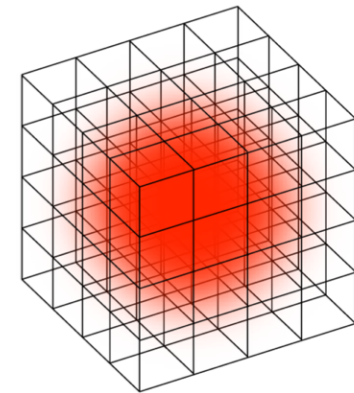
The difficulty determining the value for vanishing quark mass

- pion is special - the u,d masses are 100% of its mass
- Nucleon - LQCD and HB $\chi$ PT

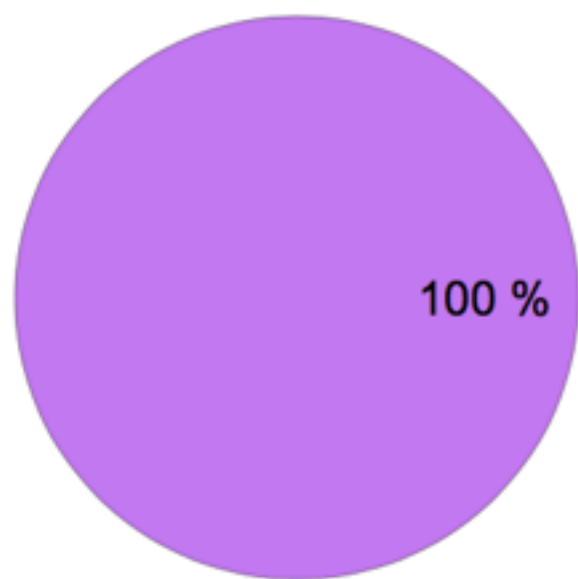
$$\Delta_m M_N^{n_f=2+1} = M_N(m_u, m_d, m_s)^{n_f=2+1} - M_N^{n_f=2+1}(0, 0, m_s) = 59(4)(7)(3) \text{ MeV}$$



# Hadron Mass Decomposition #1



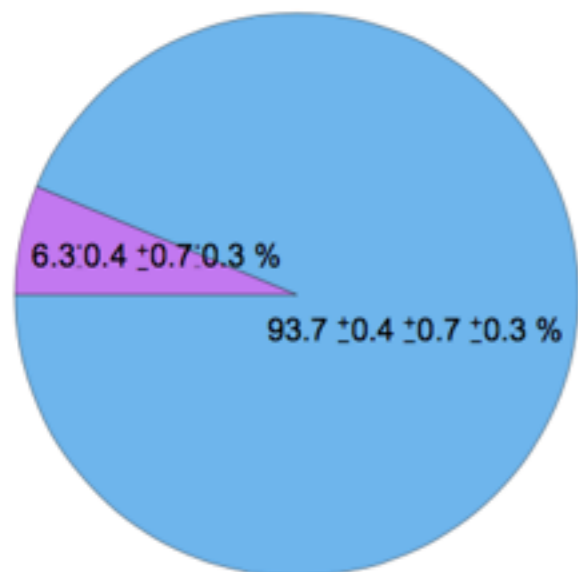
The Pion



- Total U and D Quark Mass Contribution
- U and D Chiral Limit

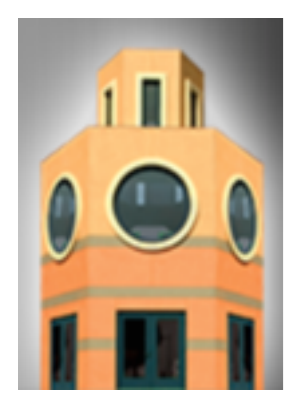
Symmetry

The Nucleon

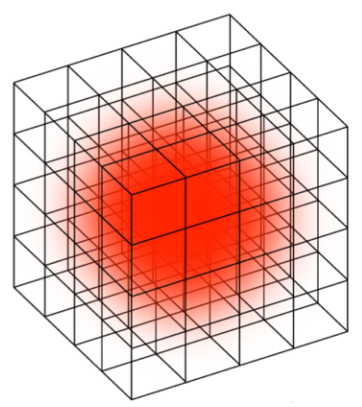


- Total U and D Quark Mass Contribution
- U and D Chiral Limit

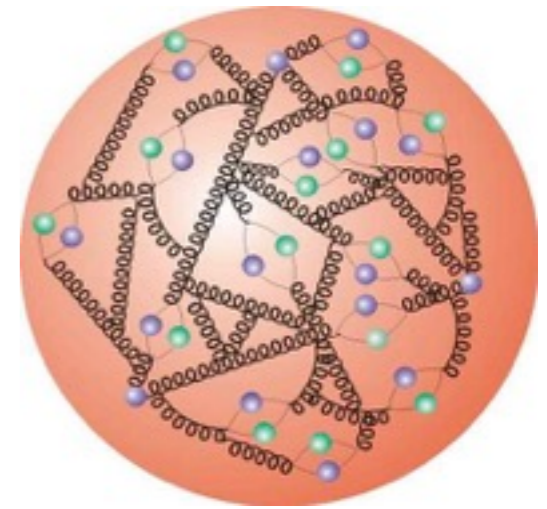
LQCD and HB $\chi$ PT

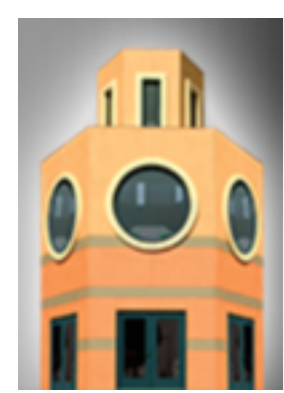


# Hadron Mass Decomposition #1

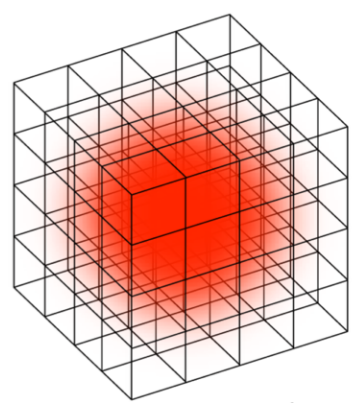


- Accounts for both the explicit dependence in the hamiltonian and implicit dependence in the states
- Hadron masses for massless (or near massless)  $u, d, s$ , or  $u, d, s, c$ , or ... remain to be calculated
  - interesting : higgs vev is lowered to zero
  - scale setting is the issue (in LQCD)
  - fix UV parameters at physical point, then change masses





# Hadron Mass Decomposition #2



$$\begin{aligned} M_N &= m_q \langle |\bar{q} m_q q| \rangle_{m_q} - m_q \left\langle \left| \frac{\beta(\alpha)}{\alpha} \frac{1}{4} G^{\mu\nu} G_{\mu\nu} + \gamma_m(\alpha) m_q \bar{q} q \right| \right\rangle_{m_q} \\ &= M_{\text{ExM}} + M_{\text{ExA}} = \sigma + M_{\text{ExA}} \end{aligned}$$



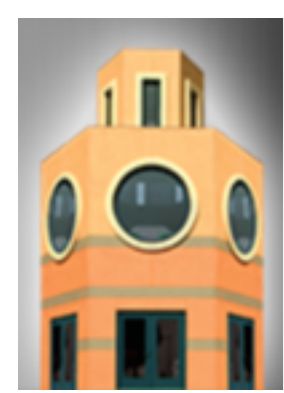
Derivative at the physical point

LQCD ( $\chi$ QCD collaboration results)

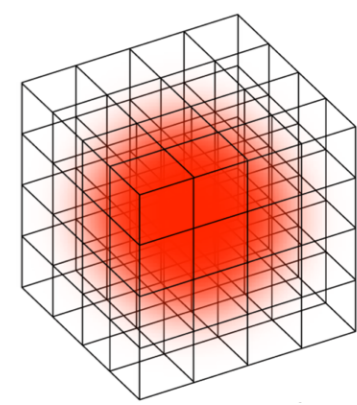
$$\sigma_{ud}^{n_f=2+1} = 44.4(3.2)(4.5)\text{MeV}, \quad \sigma_s^{n_f=2+1} = 32.3(4.7)(4.8)\text{MeV}$$

$$\sigma_{uds}^{n_f=2+1} = 76.7(6.4)(6.6)\text{MeV}$$



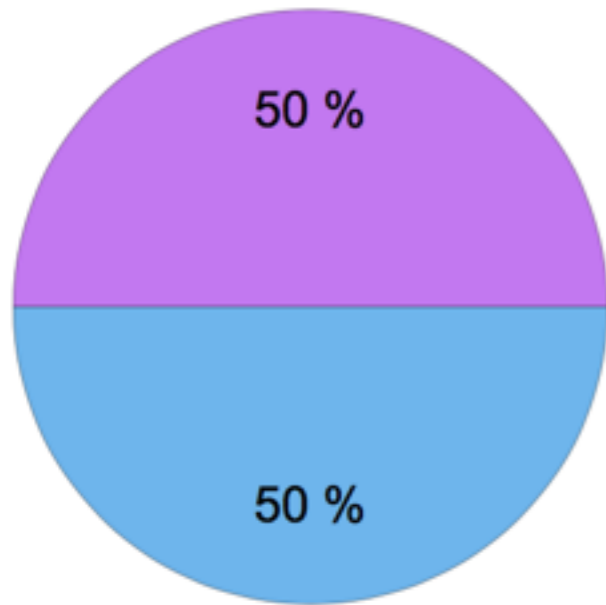


# Hadron Mass Decomposition #2



u- and d-quarks only

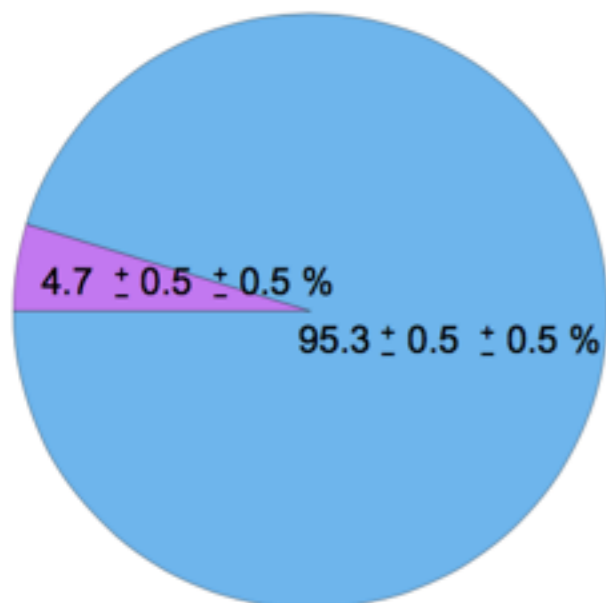
The Pion



- Explicit U and D Quark-Mass Contributions:  $\sigma_{ud}$ -Term
- Explicit Anomalous Contribution

GMOR

The Nucleon

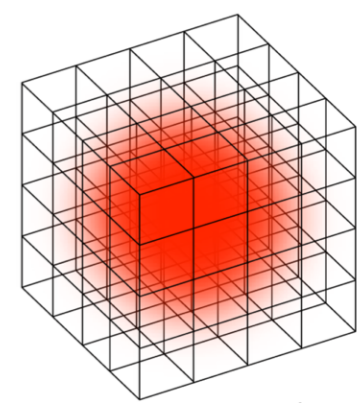


- Explicit U and D Quark-Mass Contributions:  $\sigma_{ud}$ -Term
- Explicit Anomalous Contribution

LQCD

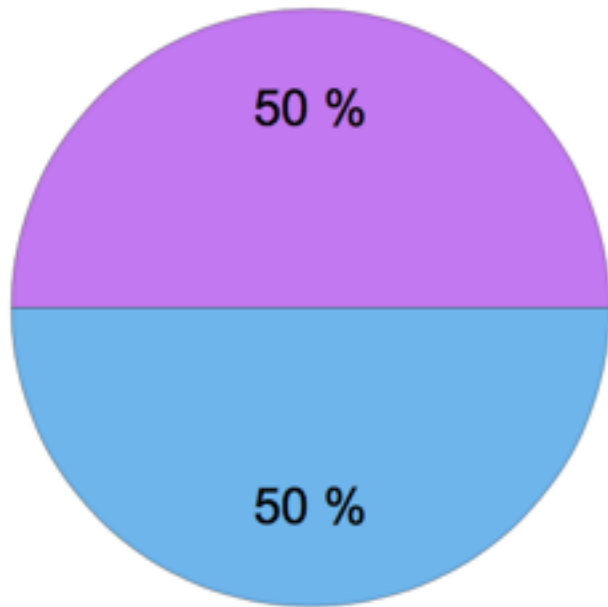


# Hadron Mass Decomposition #2



u-, d- and s-quarks only

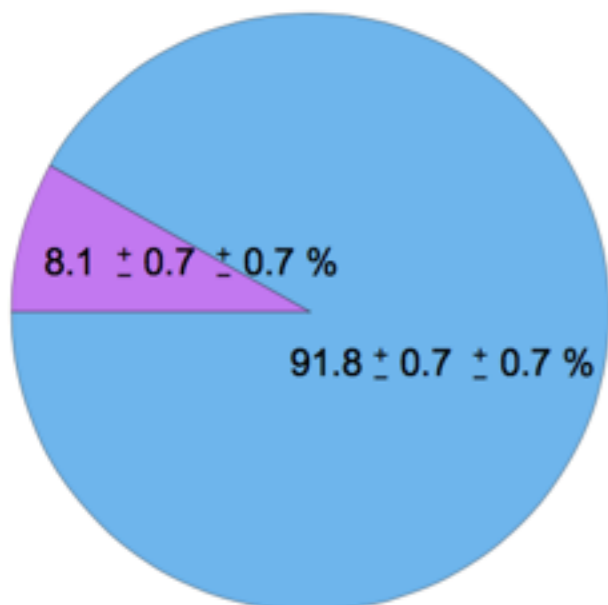
The Pion



- Explicit U, D, and S Quark-Mass Contributions:  $\sigma_{uds}$ -Term
- Explicit Anomalous Contribution

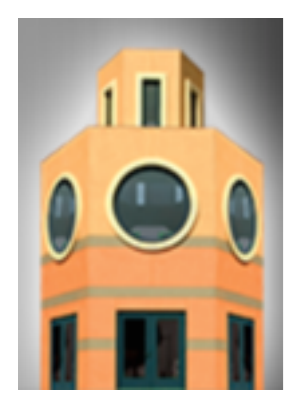
GMOR

The Nucleon



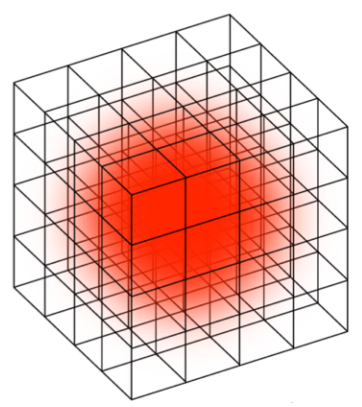
- Explicit U, D, and S Quark-Mass Contributions:  $\sigma_{uds}$ -Term
- Explicit Anomalous Contribution

LQCD

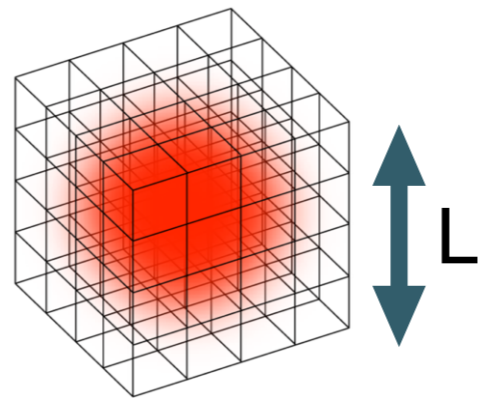


# Hadron Mass

## Chiral Limit from LQCD?



Interesting question - but challenging ...



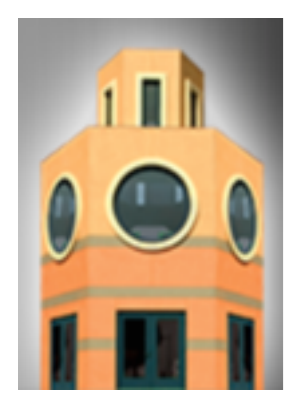
$$L^{-3} m_{\pi}^{-2}$$

Resum zero modes in path integral  $L m_{\pi} \ll 2 \pi$

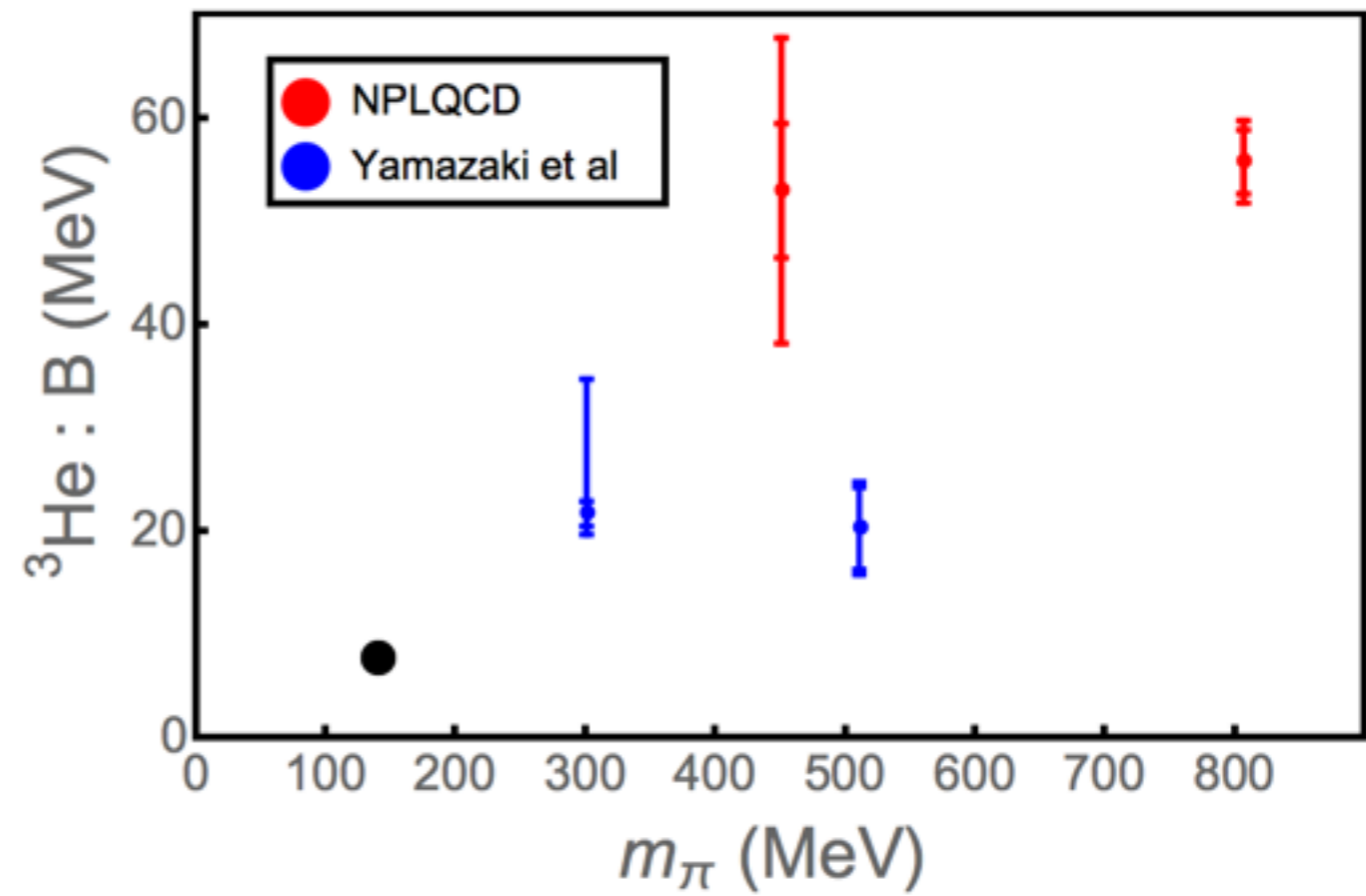
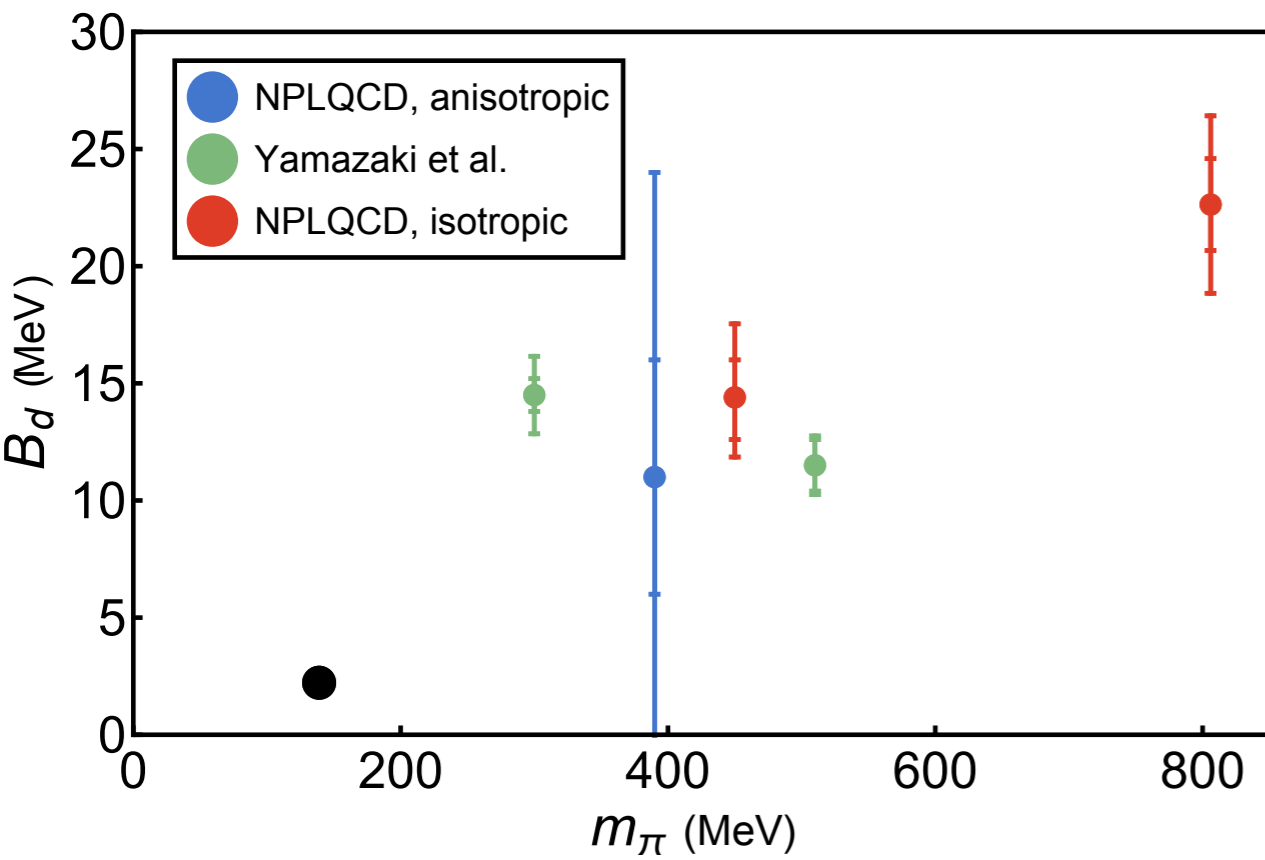
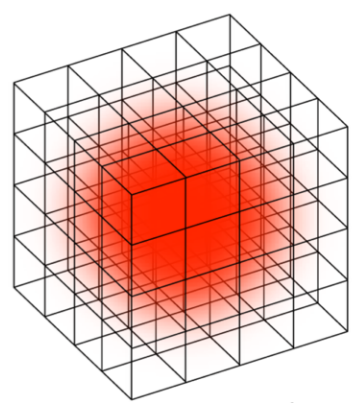
Becomes unclear!

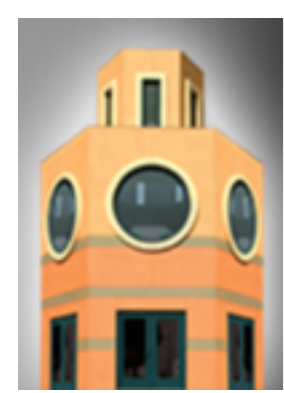
Want lattice volumes such that  $L m_{\pi} > 2 \pi$

Interesting calculations to do

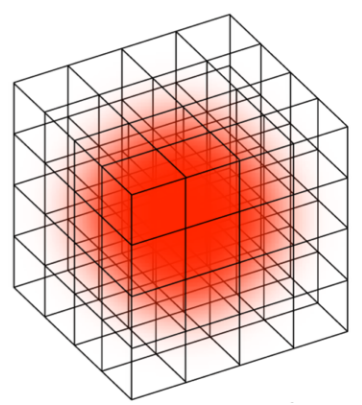


# Light Nuclei : Quark Mass Effects

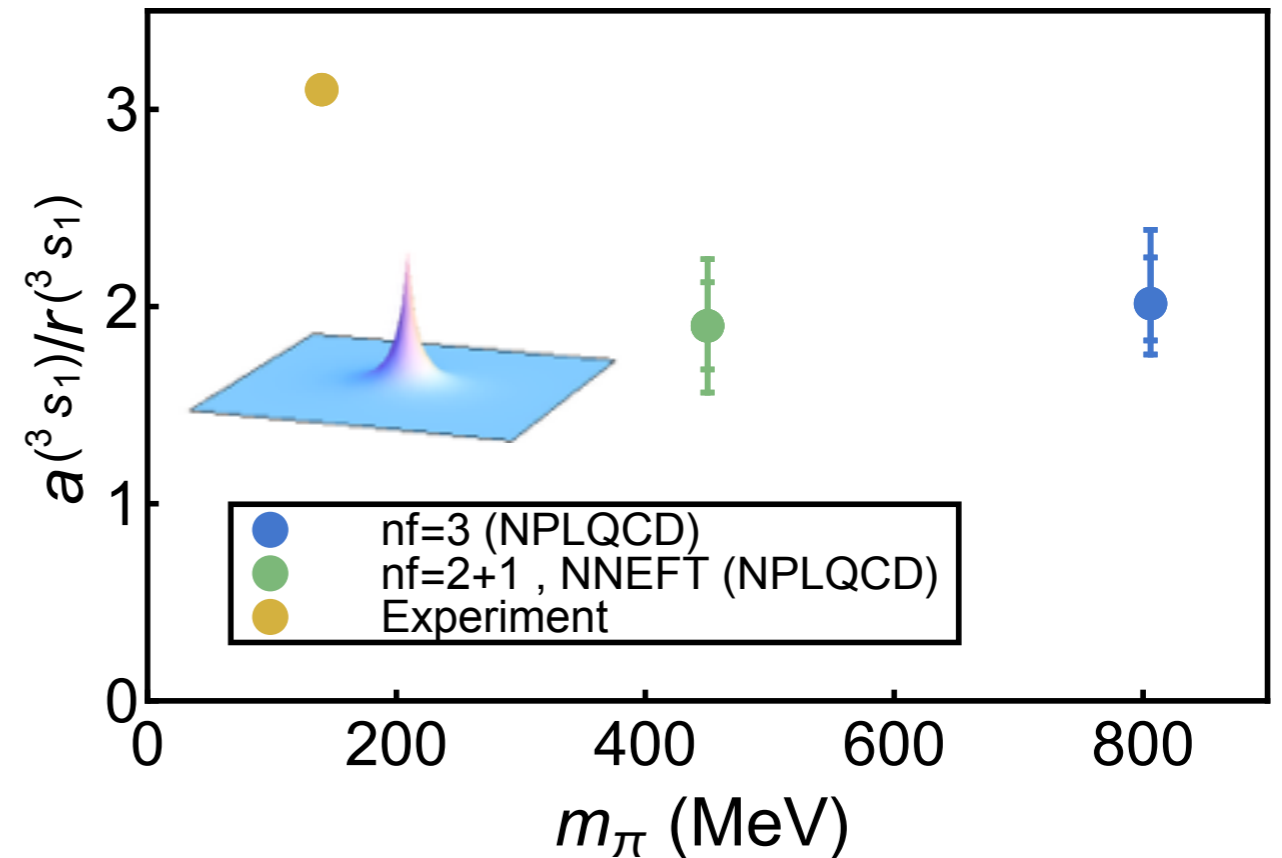
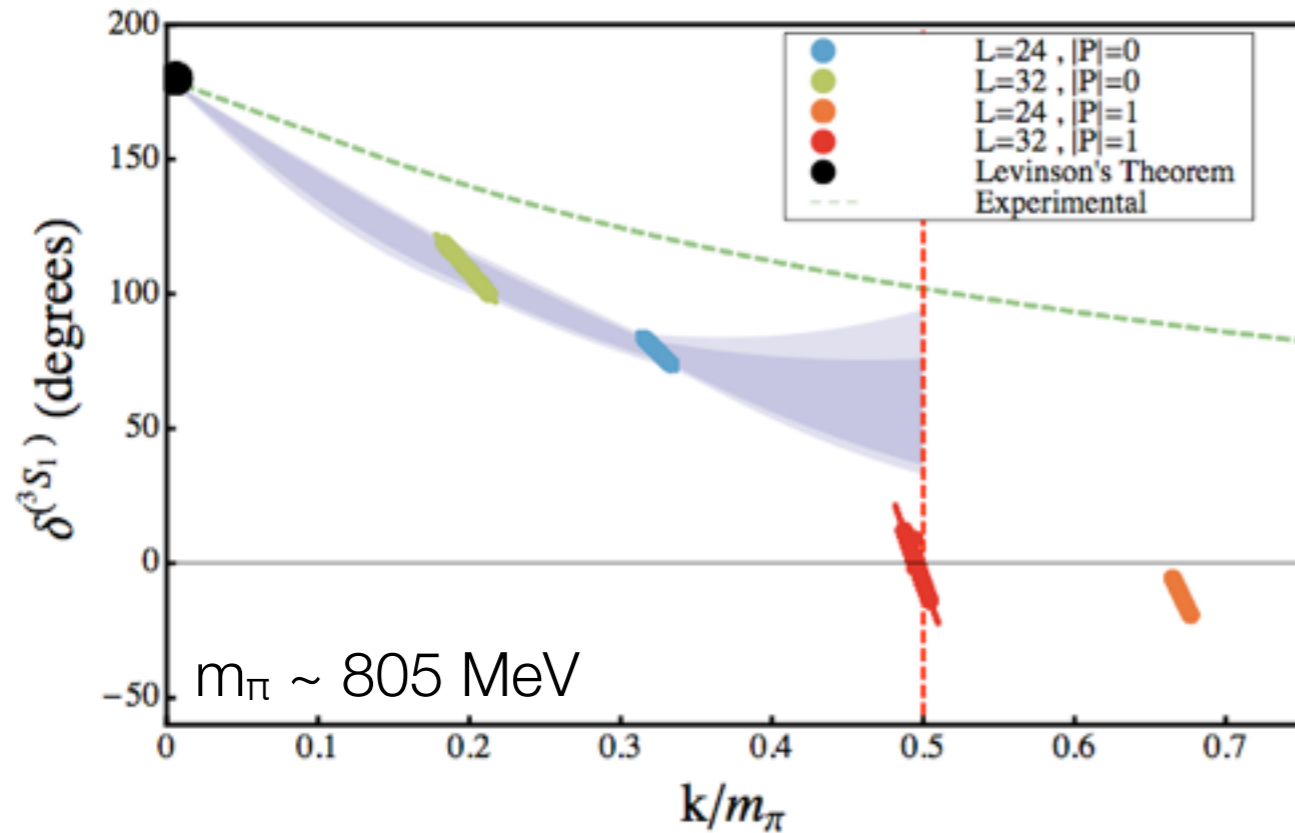




# NN Scattering



Beane *et al*, Phys.Rev. D87 (2013) 3, 034506, Phys.Rev. C88 (2013) 2, 024003

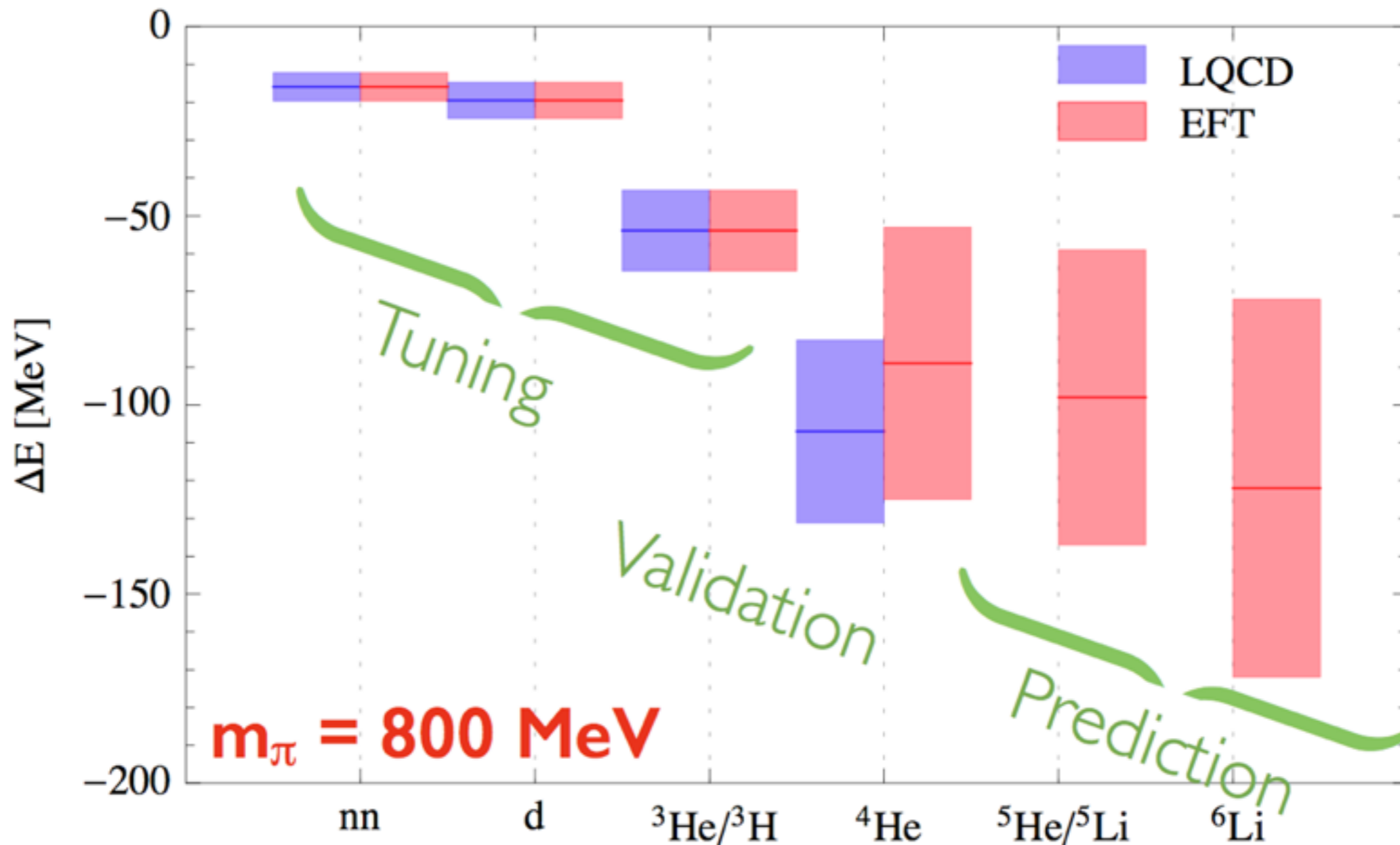
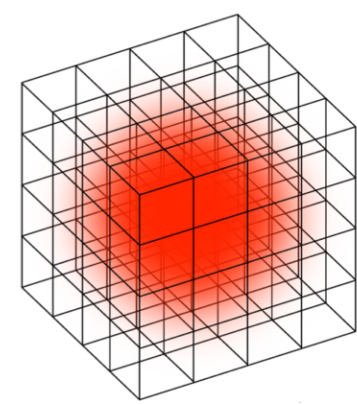


Deuteron appears to be unnatural but not finely-tuned ??  
 Generic feature of YM with  $n_f=3$

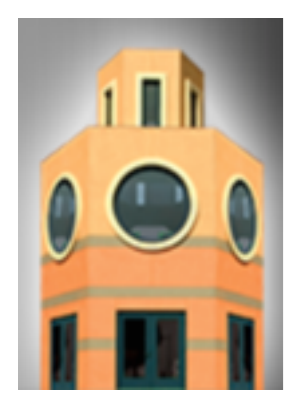
Why is this the case - simply "the result" or is there a "need" for a fluffy deuteron ?



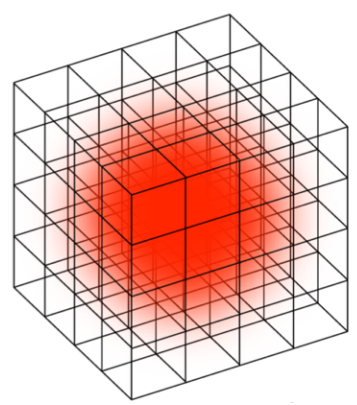
# The Periodic Table as a function of the quark masses



Enhances the scope of the Lattice Calculations



# The Periodic Table as a function of the quark masses



Effective Field Theory for Lattice Nuclei , [N. Barnea](#) et al, Nov 20, 2013. 5 pp. , Phys. Rev. Lett. 114 (2015) 5, 052501

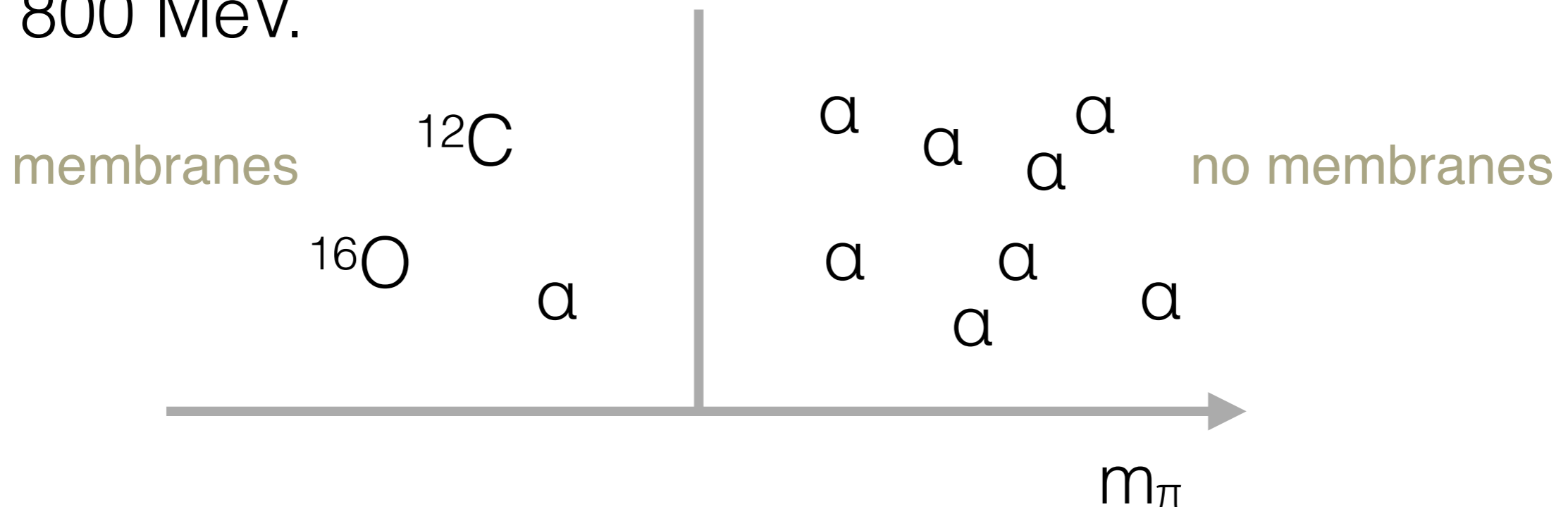
Spectra and Scattering of Light Lattice Nuclei from Effective Field Theory

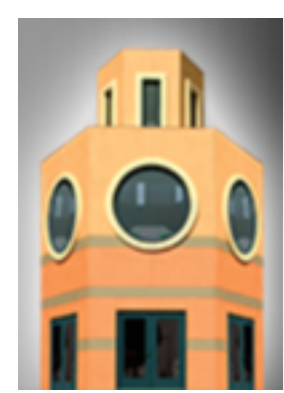
[Johannes Kirscher](#), [Nir Barnea](#), [Doron Gazit](#), [Francesco Pederiva](#), [Ubirajara van Kolck](#),

Phys.Rev. C92 (2015) no.5, 054002

Preliminary calculations suggest that  $^{16}\text{O}$  is unbound.  
The  $\alpha$ 's are so deeply bound that  $^{16}\text{O}$  is unstable

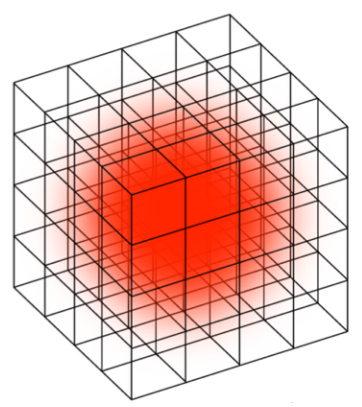
Very exciting - the Periodic Table terminates without the possibility to produce water or membranes for  $m_\pi \sim 800$  MeV.



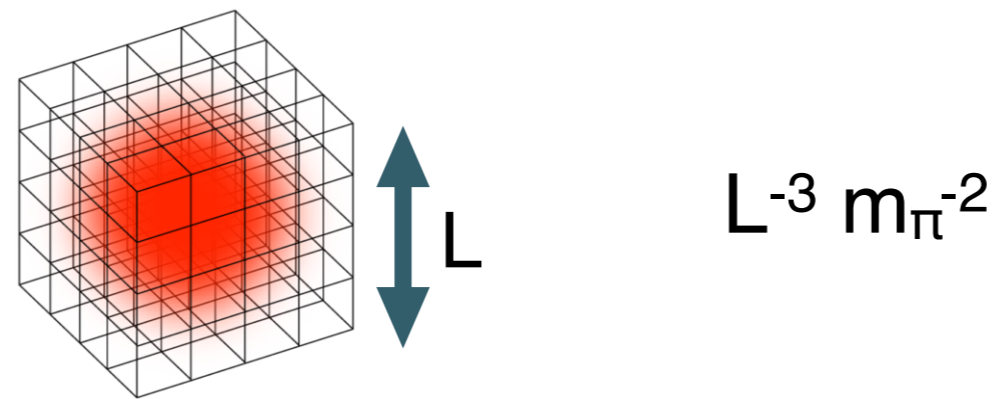


# Nuclei

## Chiral Limit from LQCD?



Interesting question - but challenging ...



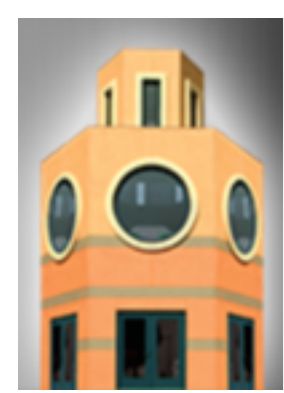
Nuclear force - no long range, only  $\delta(r)$  and  $r^{-3}$  from  $\pi$ .

Short-range couplings modified

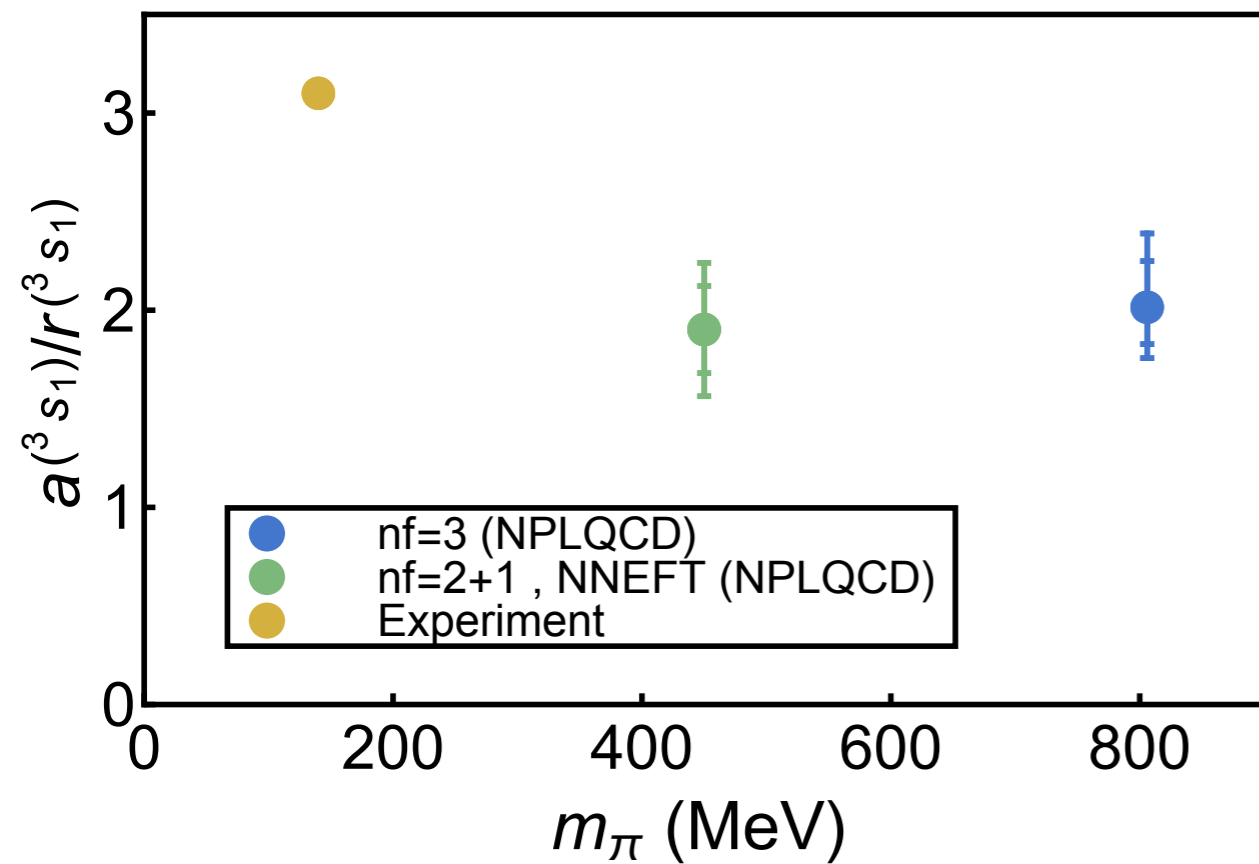
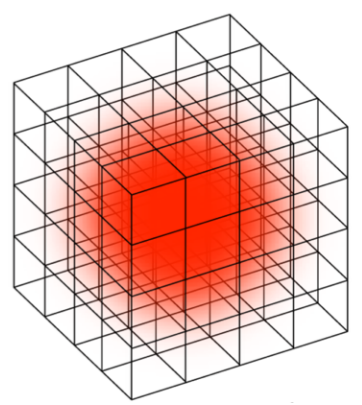
Radiation  $\pi$ 's need to be included

Currently do not know if nuclei exist near the chiral limit.

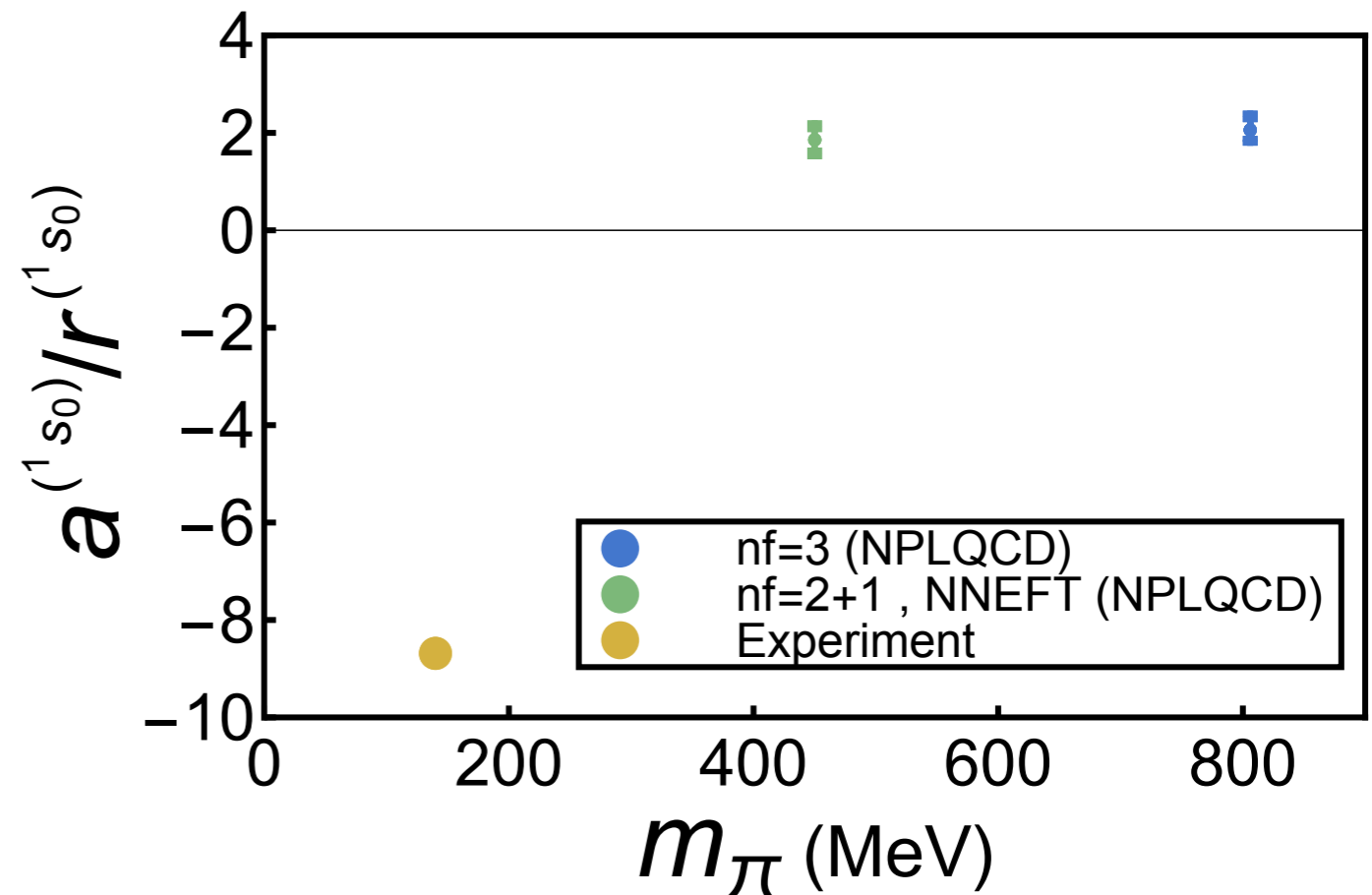




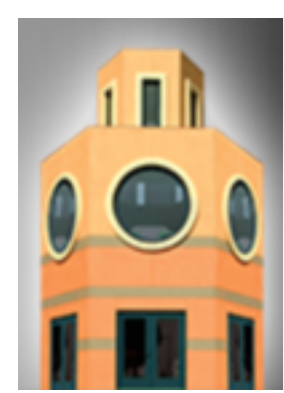
# Fine Tunings Vs Unnaturalness



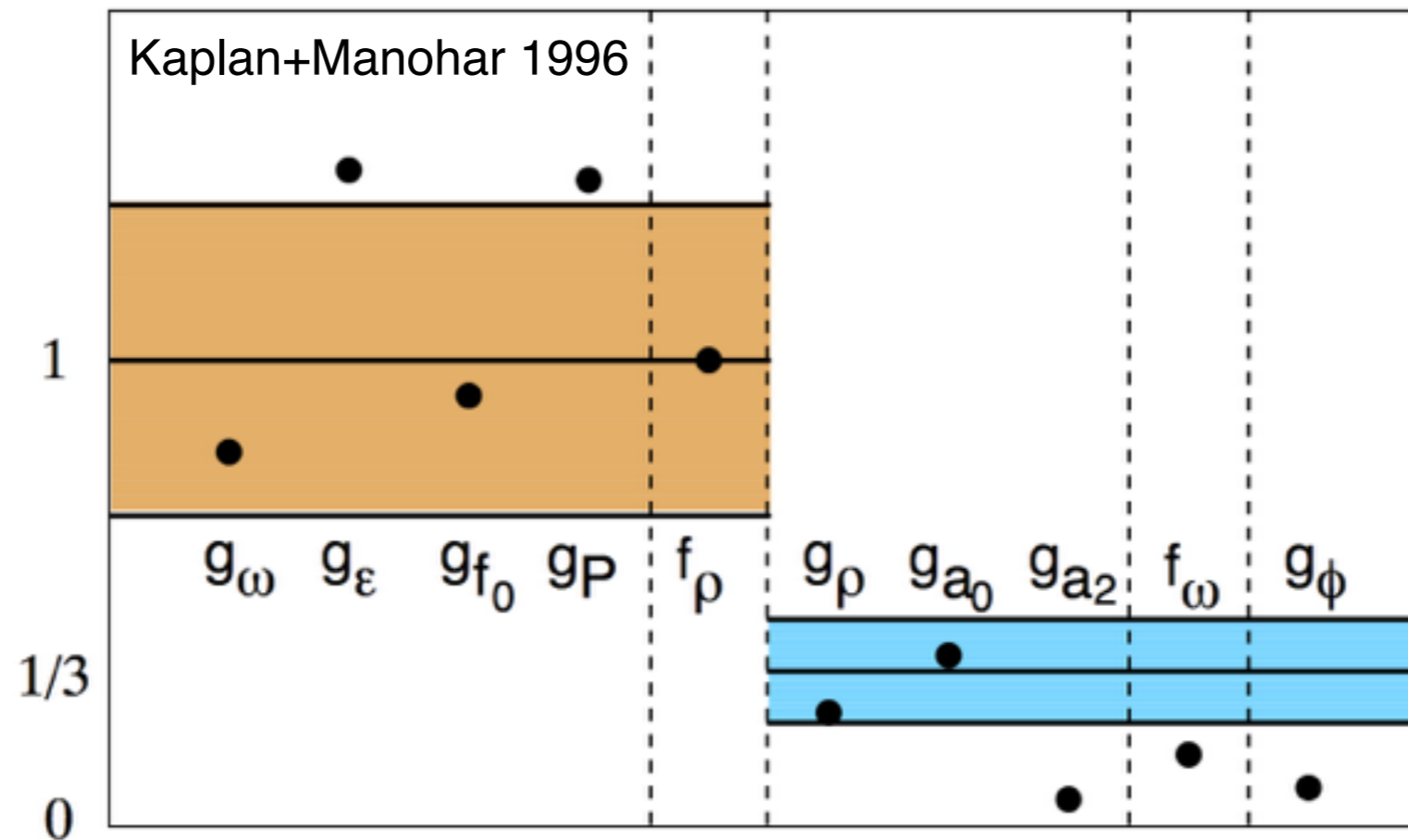
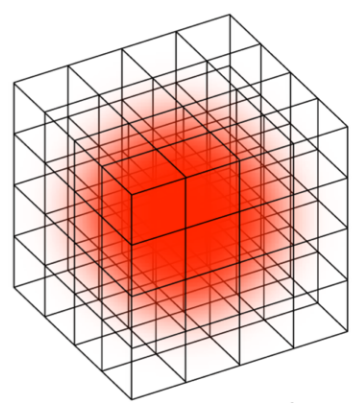
unnatural



unnatural and finely tuned



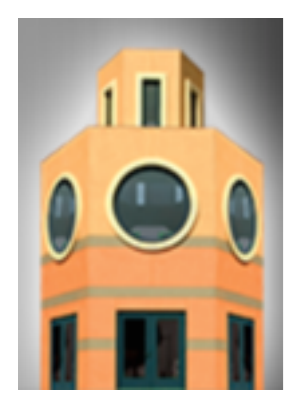
# Large- $N_c$ Nuclear Forces



Don't think anyone has solved nuclear many-body problem simply by changing the relative weights of the NN potential and scaling the nucleon mass.

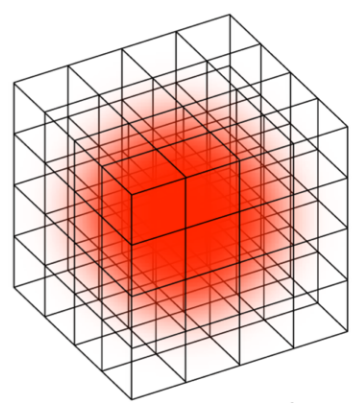
Large- $N_c$  scaling of 3-body forces now exists

Phillips+Schat (2013)



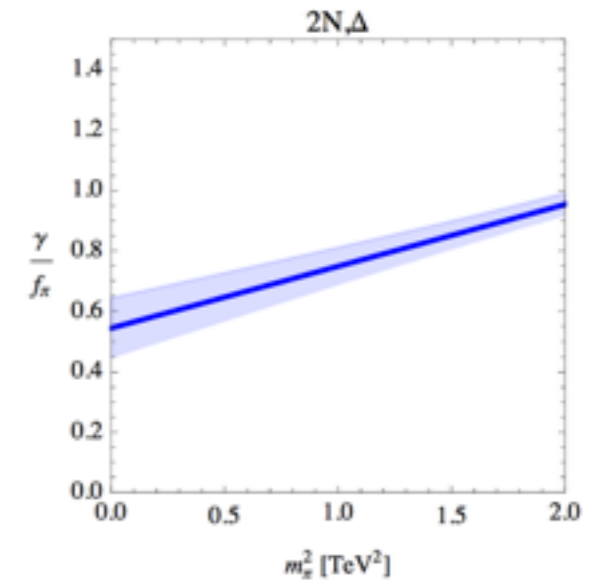
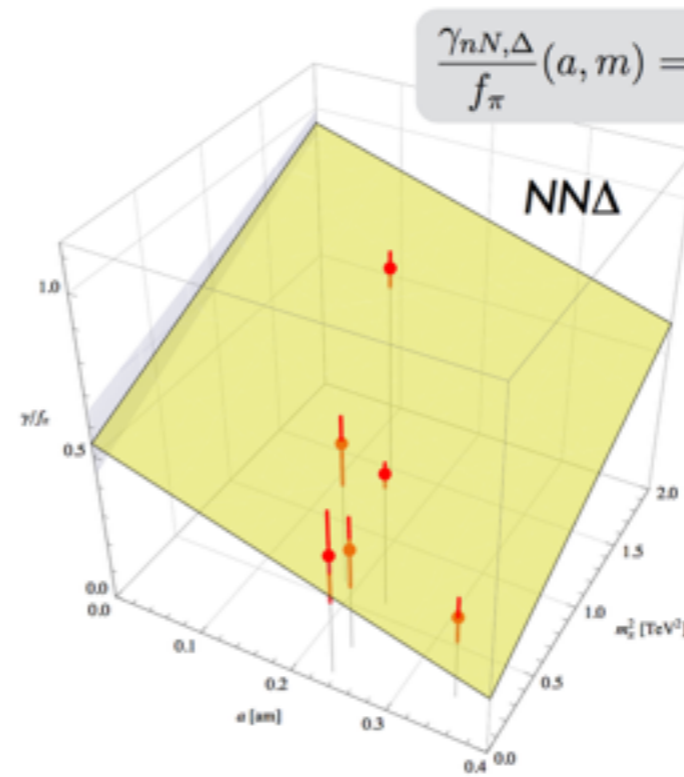
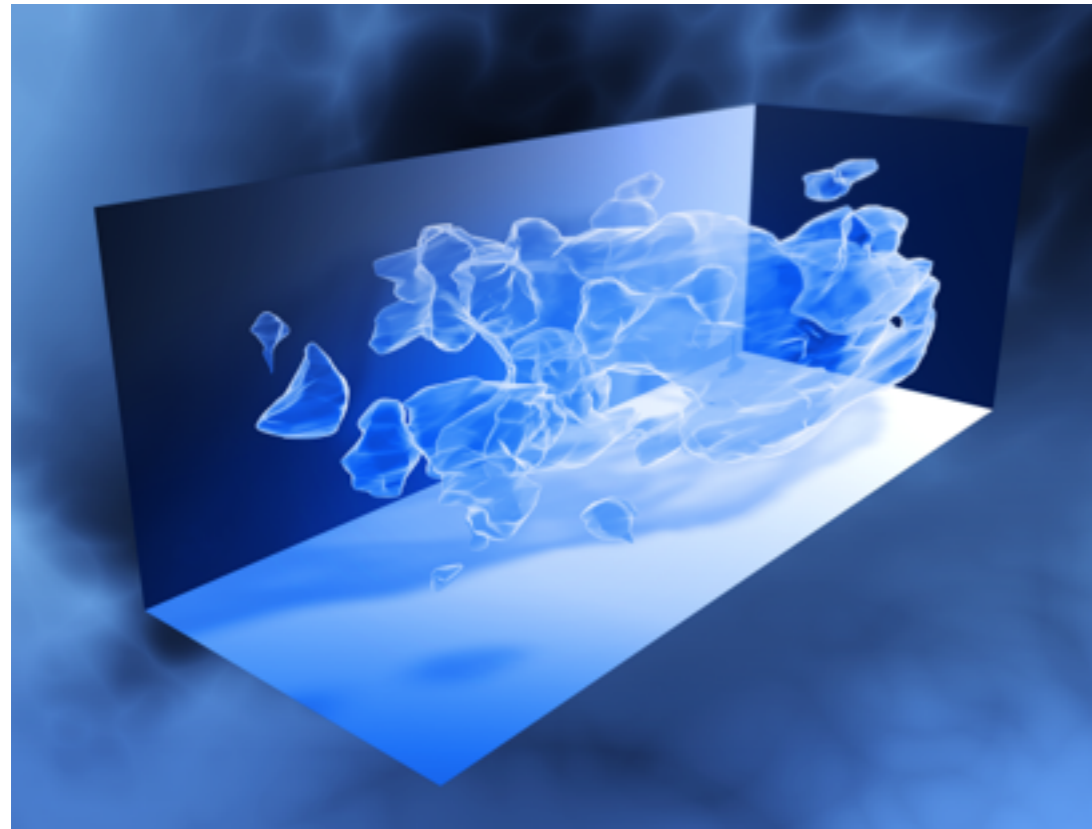
# Dark Nuclei

## A (Possible) Challenge for NEFTs



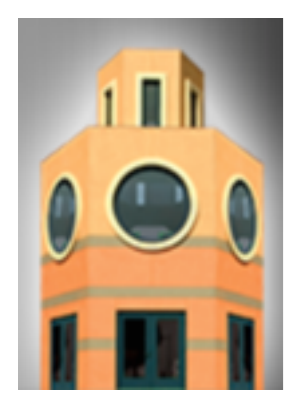
### BSM Nuclei as Dark Matter ?

William Detmold, Matthew McCullough, and Andrew Pochinsky, *Phys. Rev. D* **90**, 115013 (2014), *Phys. Rev. D* **90**, 114506 (2014).

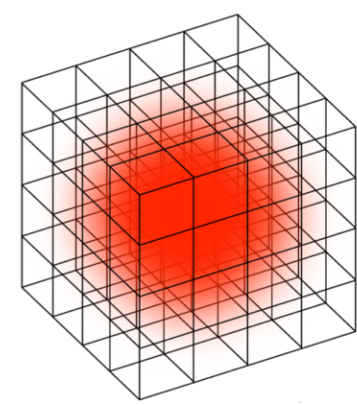


Use QCD technology for  $SU(2)_c$  color - bound states.

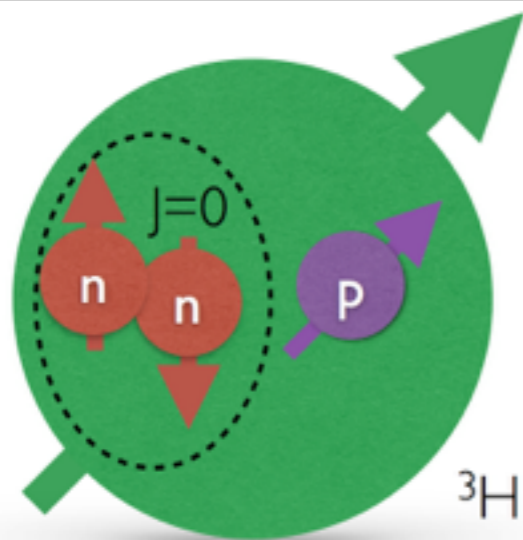
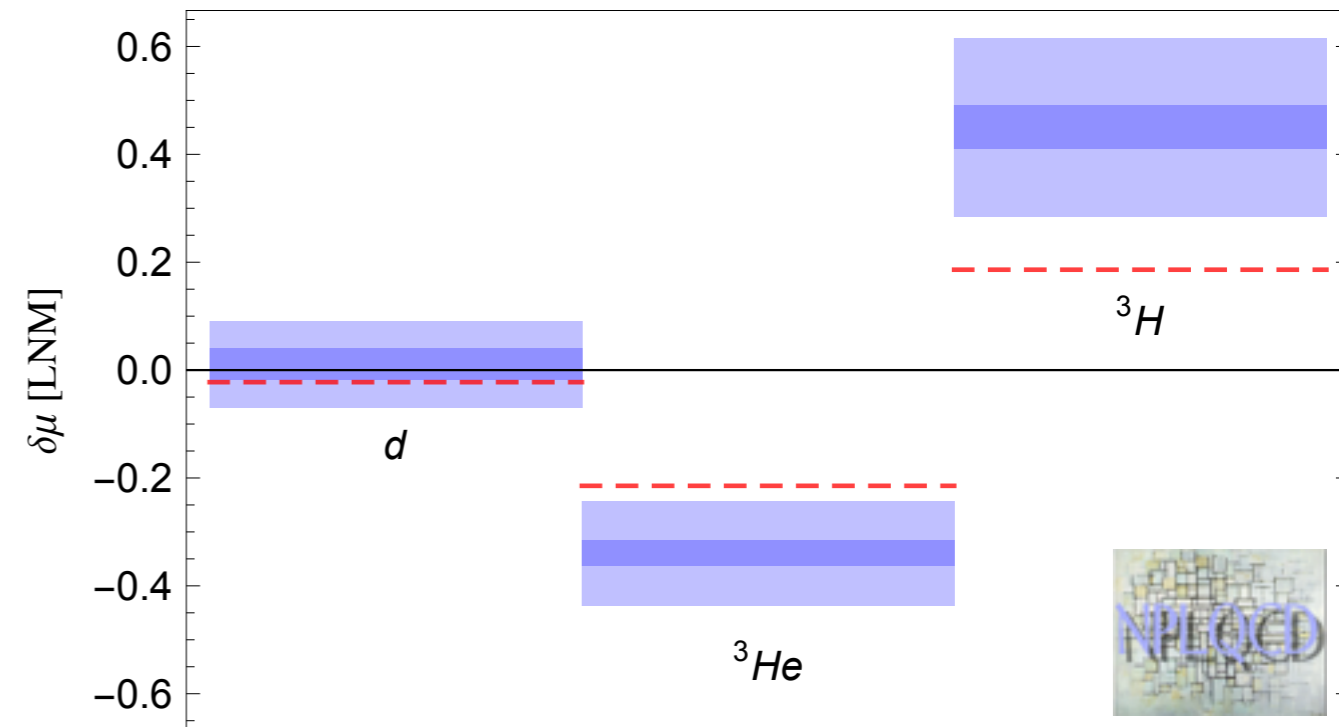
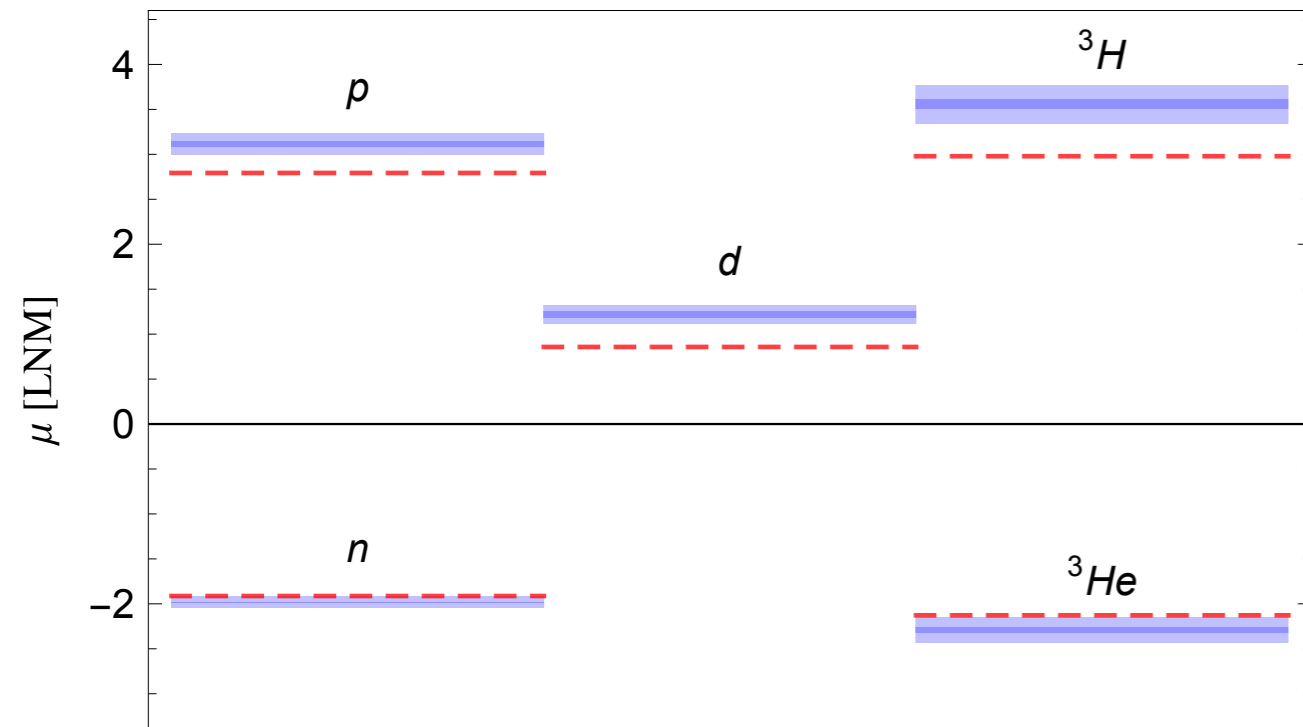
- 1/ Define NEFT for  $SU(2)_c$
- 2/ Extract counterterms from limited LQCD results
- 3/ Predict Periodic Table and cross sections (with error bars)
- 4/ Compare with complete LQCD results



# The Magnetic Structure of Nuclei : Magnetic Moments

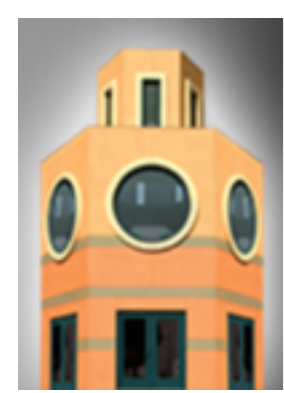


S.R. Beane *et al.*, Phys.Rev.Lett. 113 (2014) 25, 252001

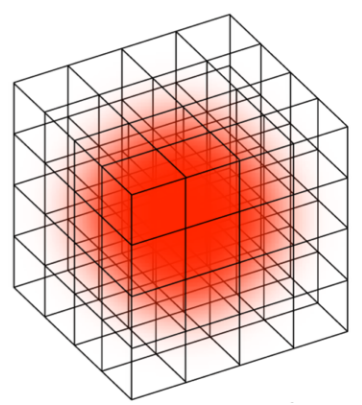


$m_\pi \sim 800 \text{ MeV}$  Vs Nature

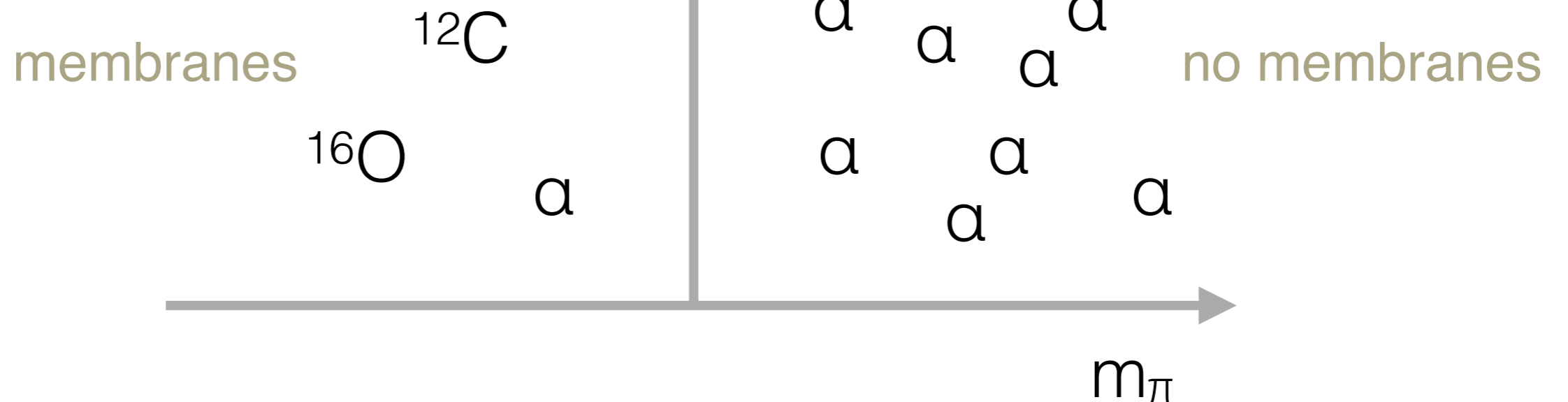
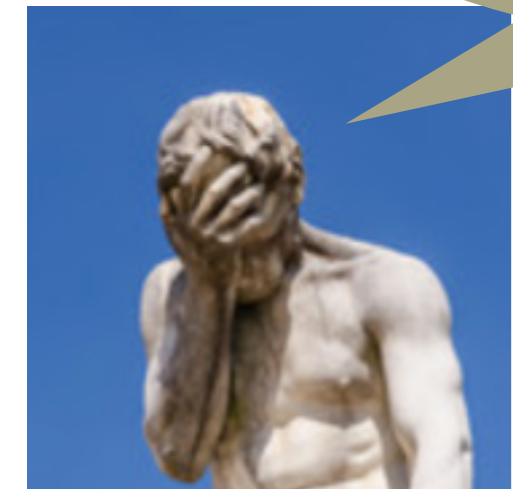
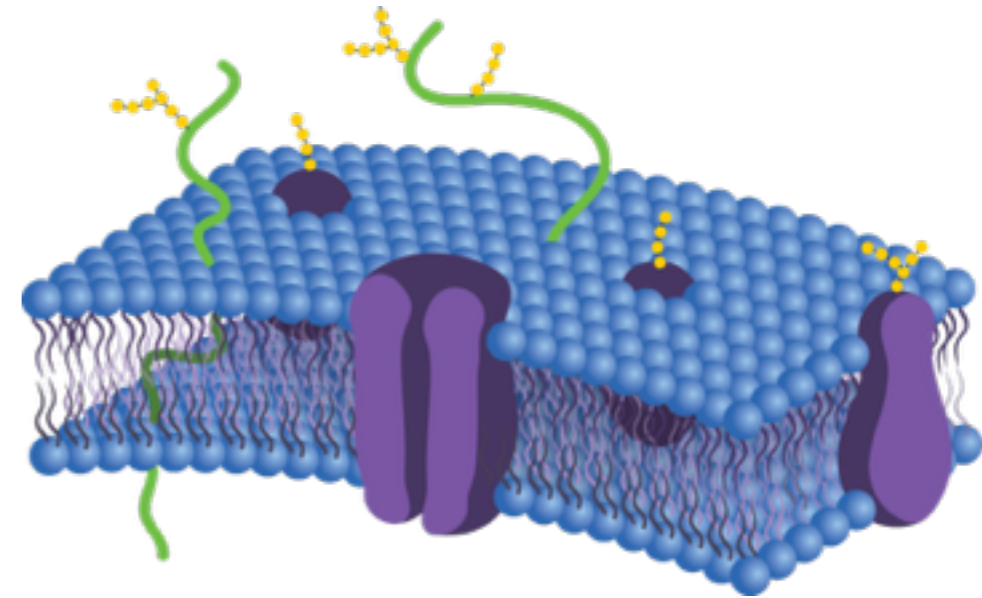
Nuclei are (nearly) collections of nucleons  
- shell model phenomenology!



# Closing Remarks



Oh no!  
- I don't know how to calculate it  
- anthropic argument?



Lattice QCD combined with Nuclear Many-body calculations can explore impact of a significant range of fundamental constants

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FIN