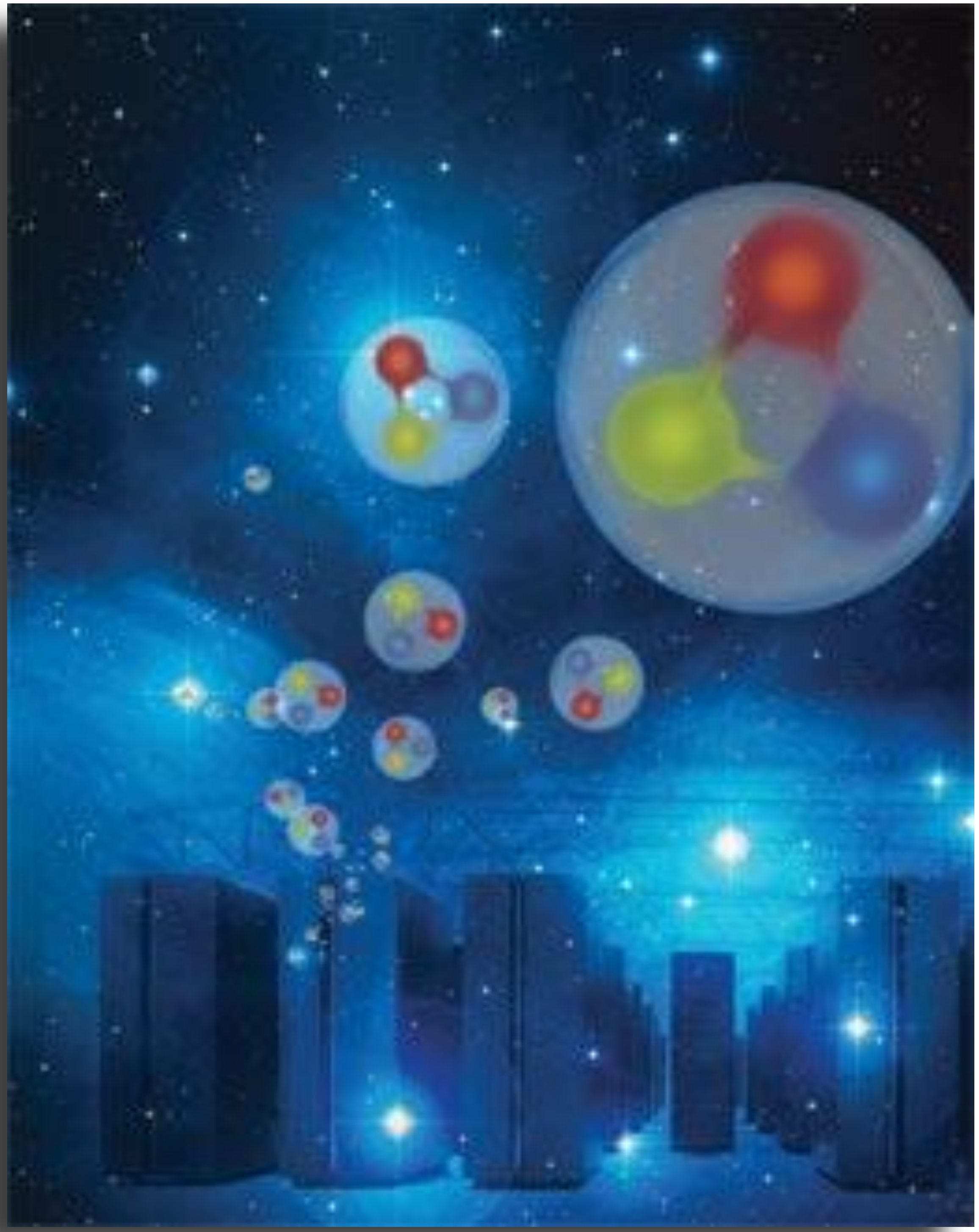


S. Durr *et al.*

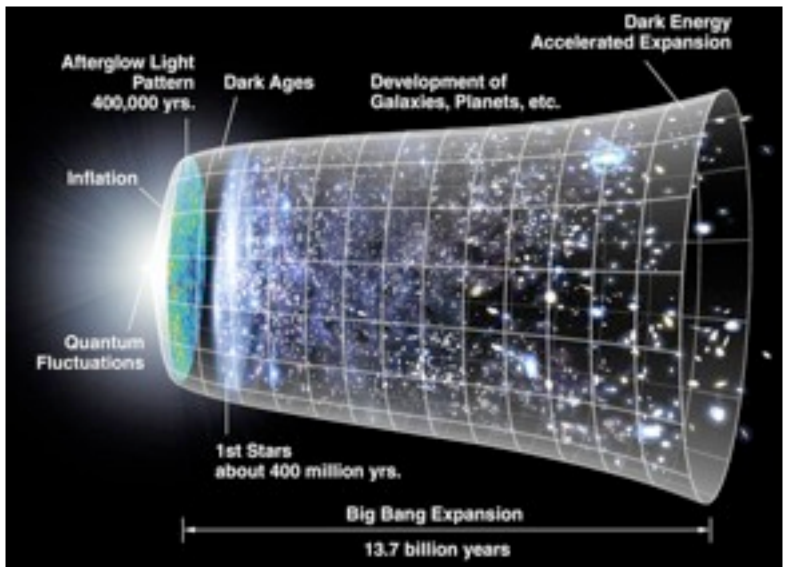
Science

Nuclear Physics from Lattice QCD

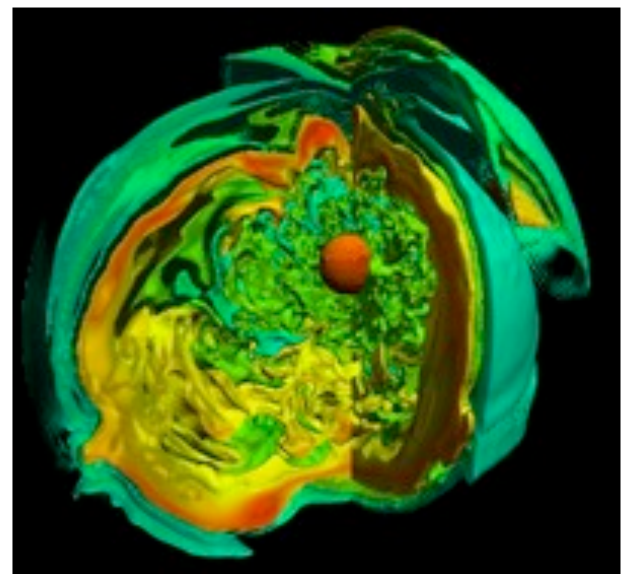
Martin J. Savage
September 2011
Erice, Sicily

Nuclear Physics Length Scales

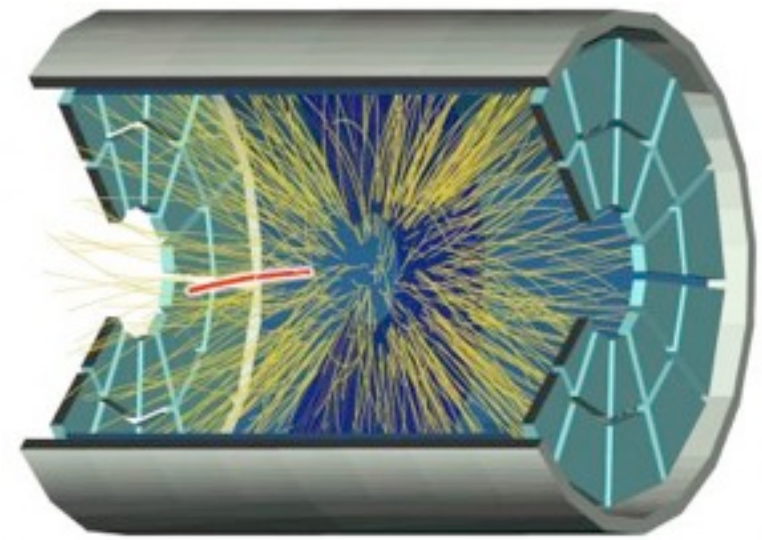
Phase transition(s) at early times, light sources at later times



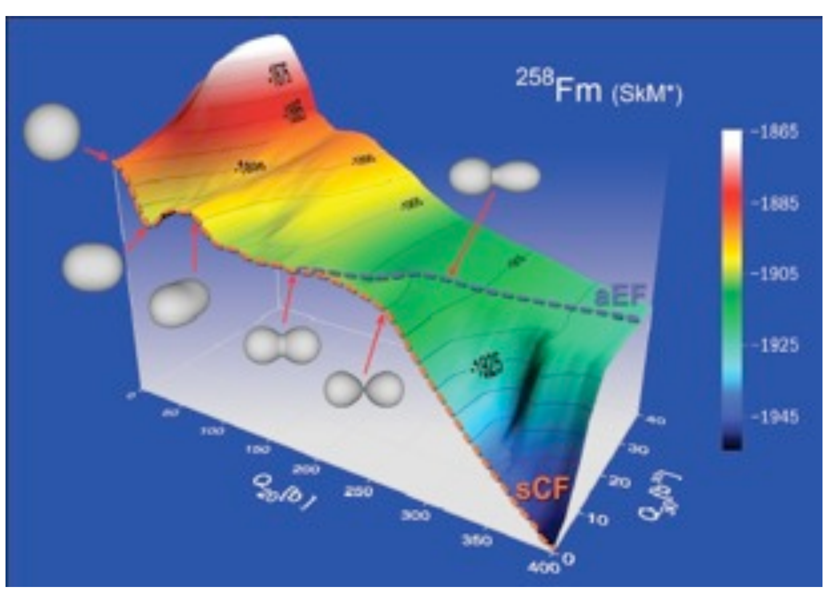
Production of most elements in the cosmos



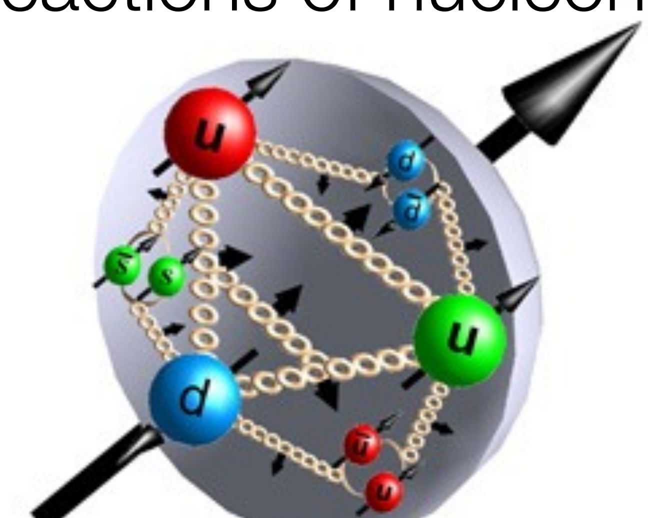
Matter under extreme conditions



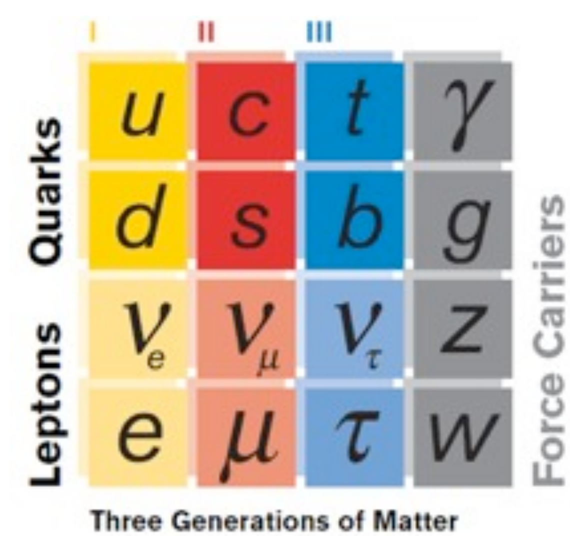
Nuclei and their reactions



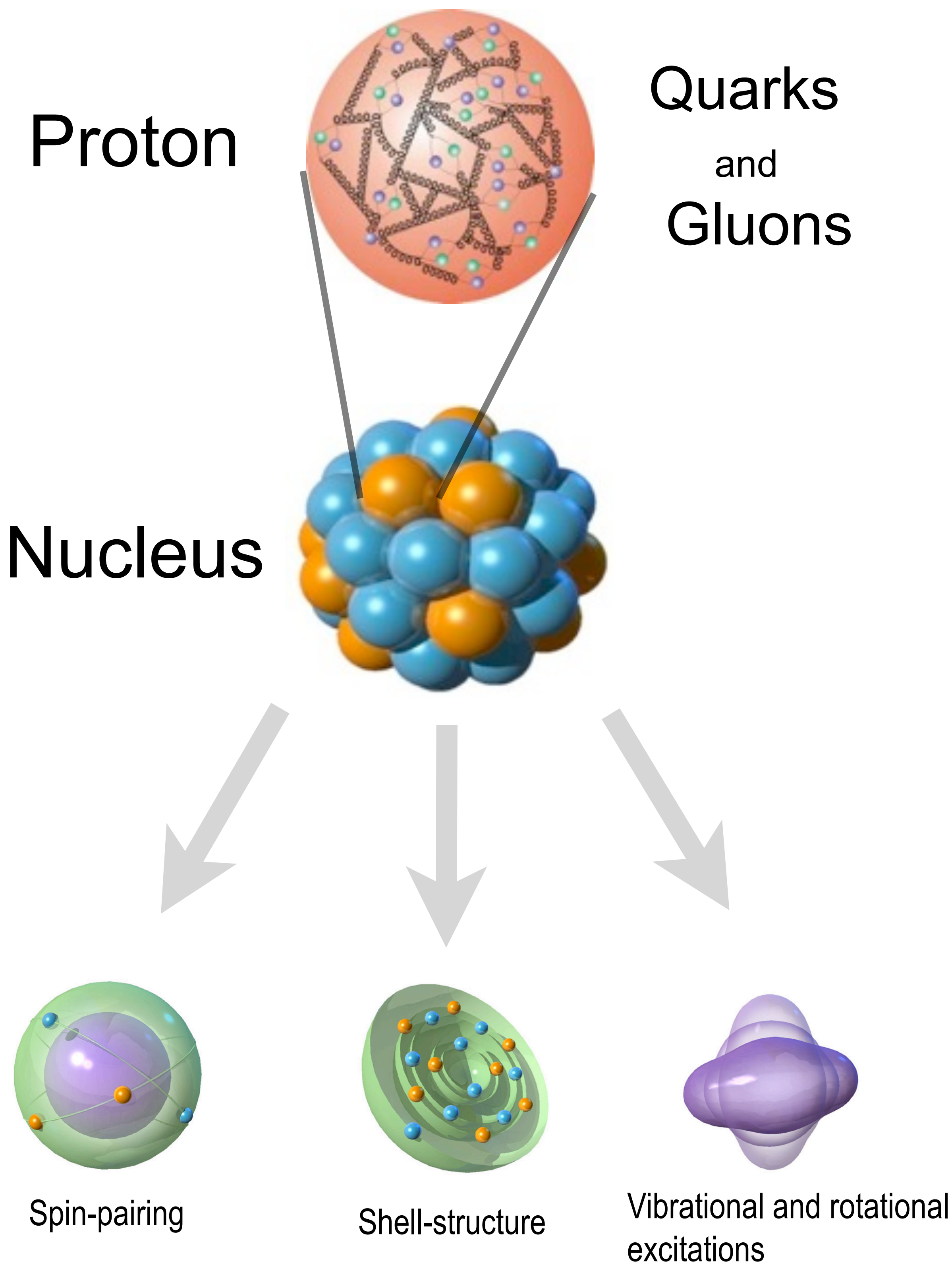
The structure and reactions of nucleons



Nature's building blocks



The Structure and Interactions of Matter from Quantum Chromodynamics



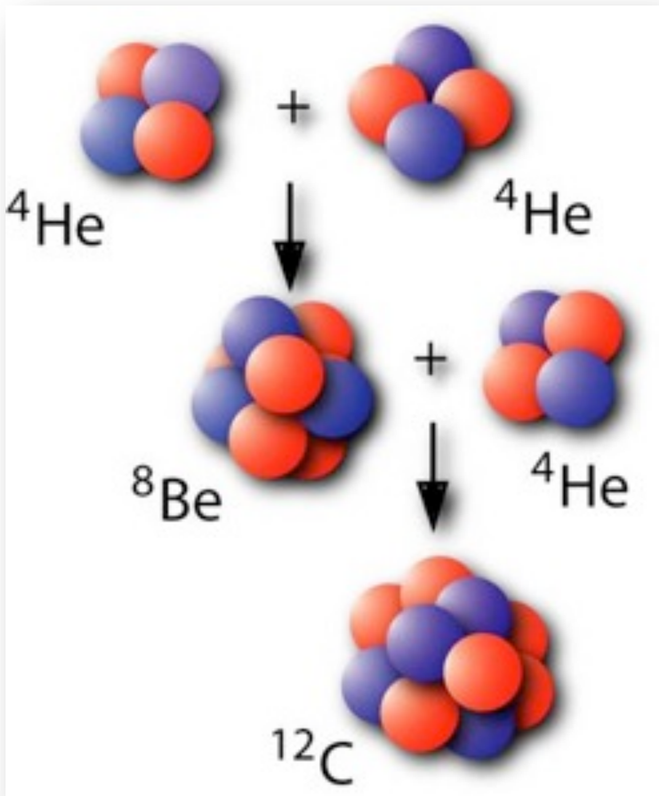
$$\Lambda_{\rm QCD}$$

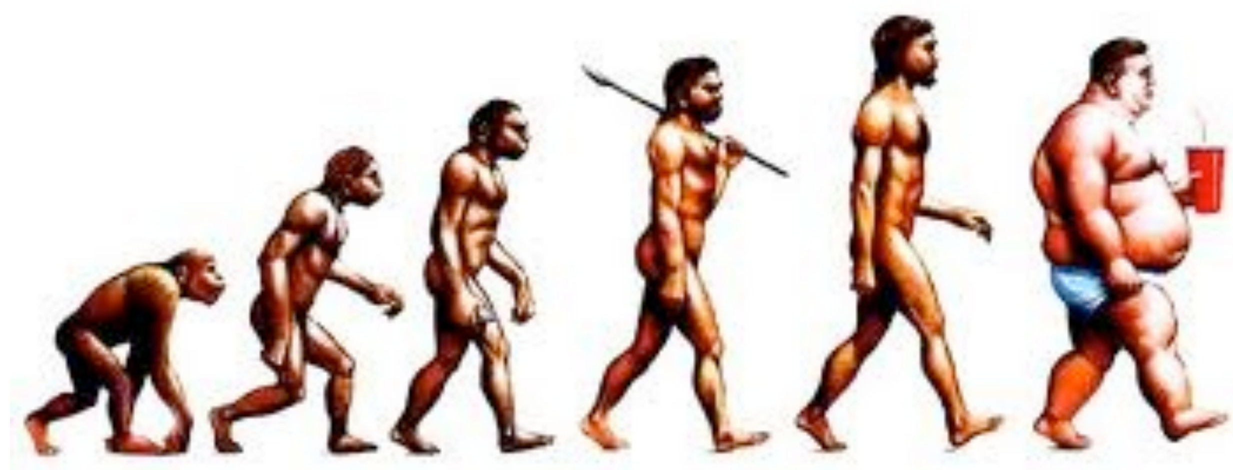
$$\frac{m_u}{\Lambda_{\rm QCD}} \quad \frac{m_d}{\Lambda_{\rm QCD}} \quad \frac{m_s}{\Lambda_{\rm QCD}}$$

$$\alpha_e$$

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

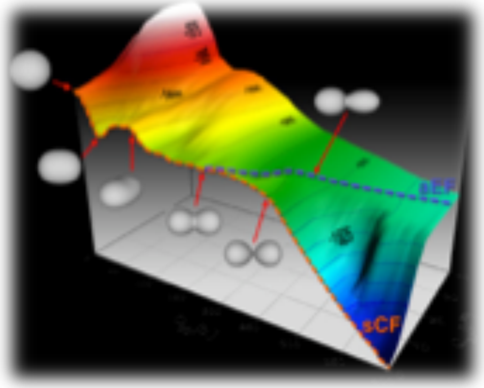
Fundamental Question(s) about our Universe

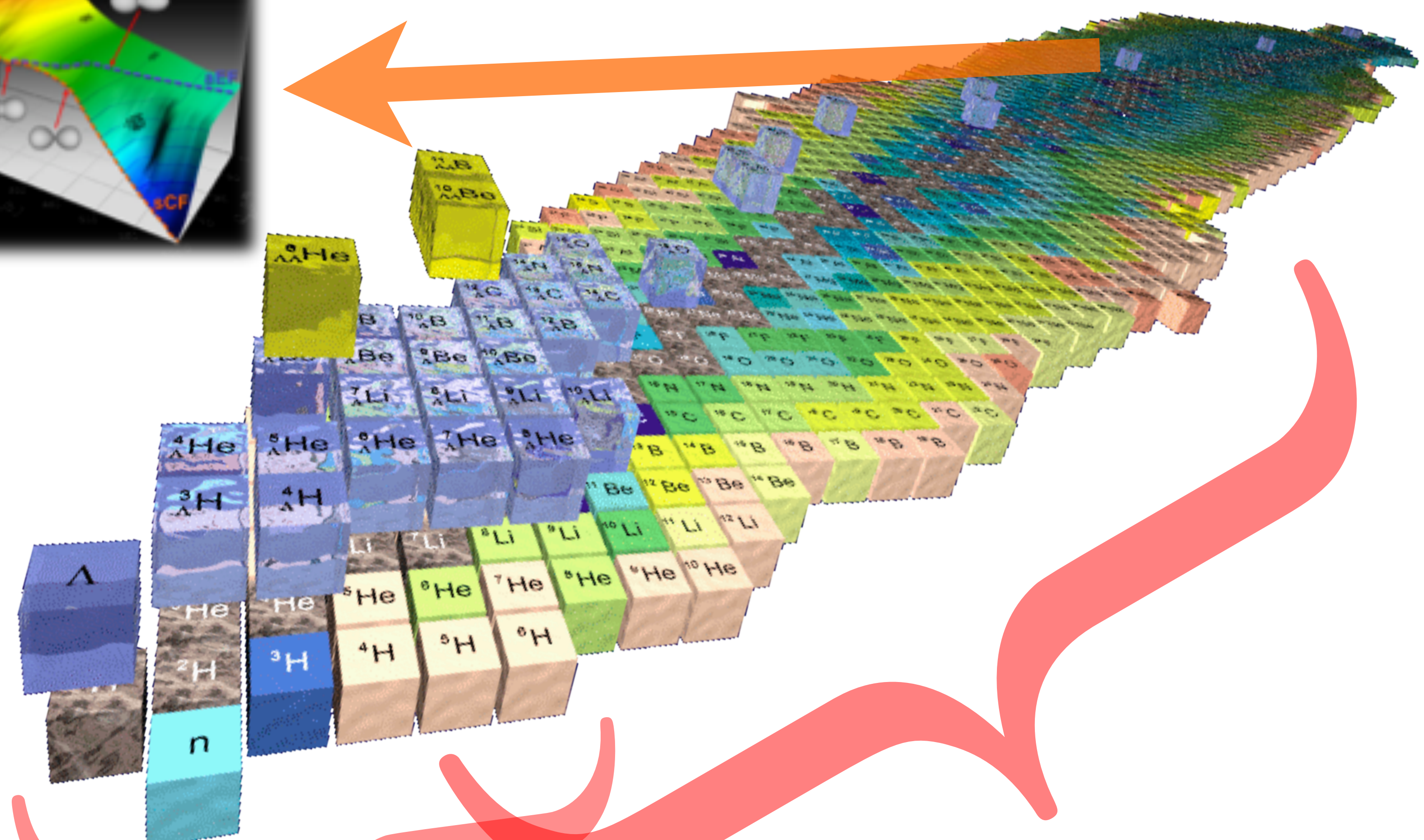




- Nuclear physics exhibits fine-tunings
    - *Why ??*
    - *Range of quark masses that can produce sufficient carbon ?*

(Partial) Unification of Nuclear Physics - Quantifiable Uncertainties



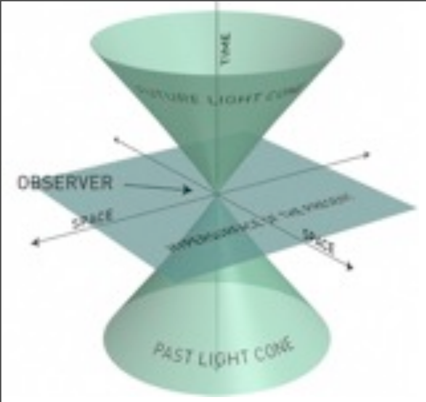


Lattice QCD

Many-Body Methods
EFT, LatticeEFT,
GFMC, NCSM

g_s m_u m_d m_s e

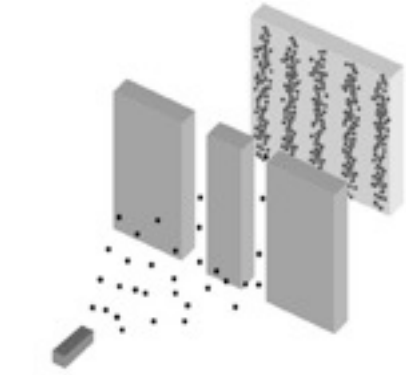
Other Universes ?



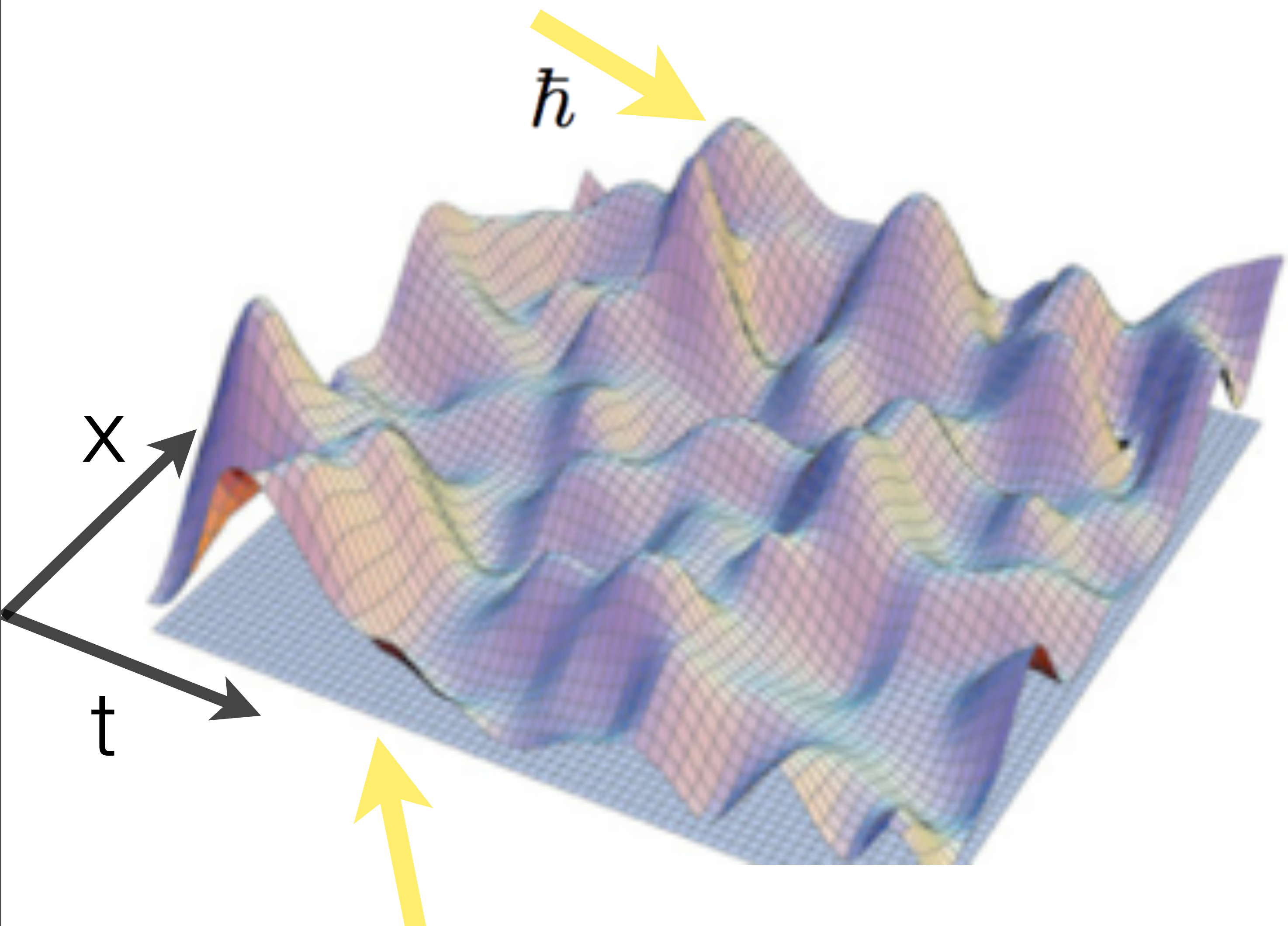
Quantum Field Theory

Scalar Field

a number at each point in space-time

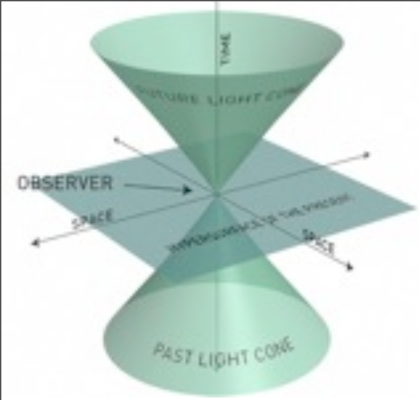


Quantum Vacuum



Classical Vacuum

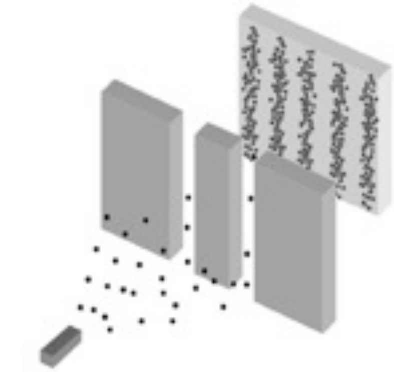
$$e^{\frac{i}{\hbar}S[\phi]}$$



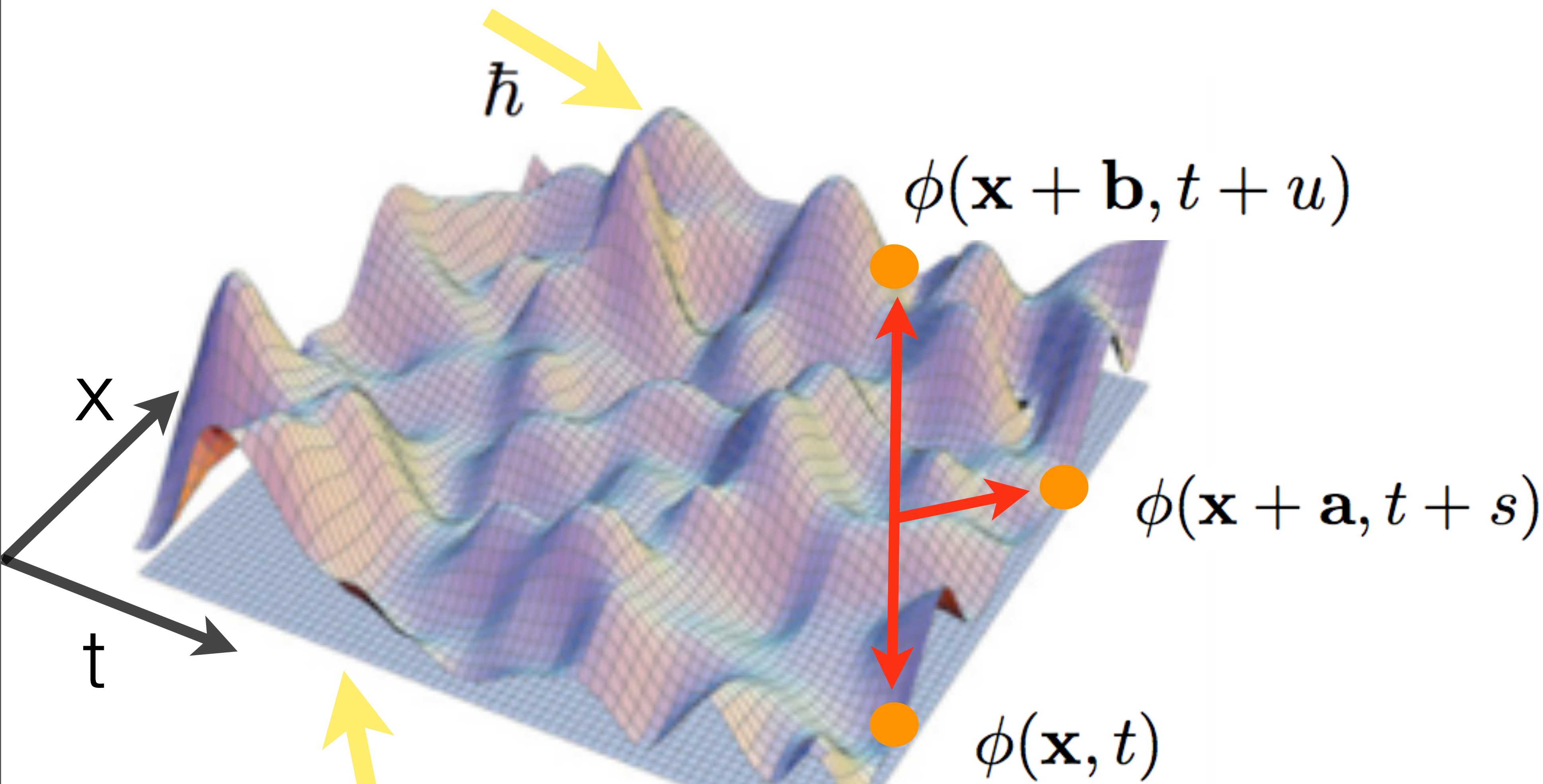
Quantum Field Theory

Scalar Field

a number at each point in space-time



Quantum Vacuum



$$e^{\frac{i}{\hbar} S[\phi]}$$

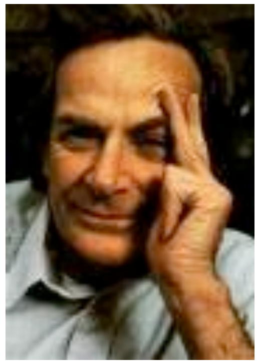
e.g. $\langle \phi(\mathbf{x}, t)\phi(\mathbf{x}+\mathbf{a}, t+s)\phi(\mathbf{x}+\mathbf{b}, t+u)\rangle$

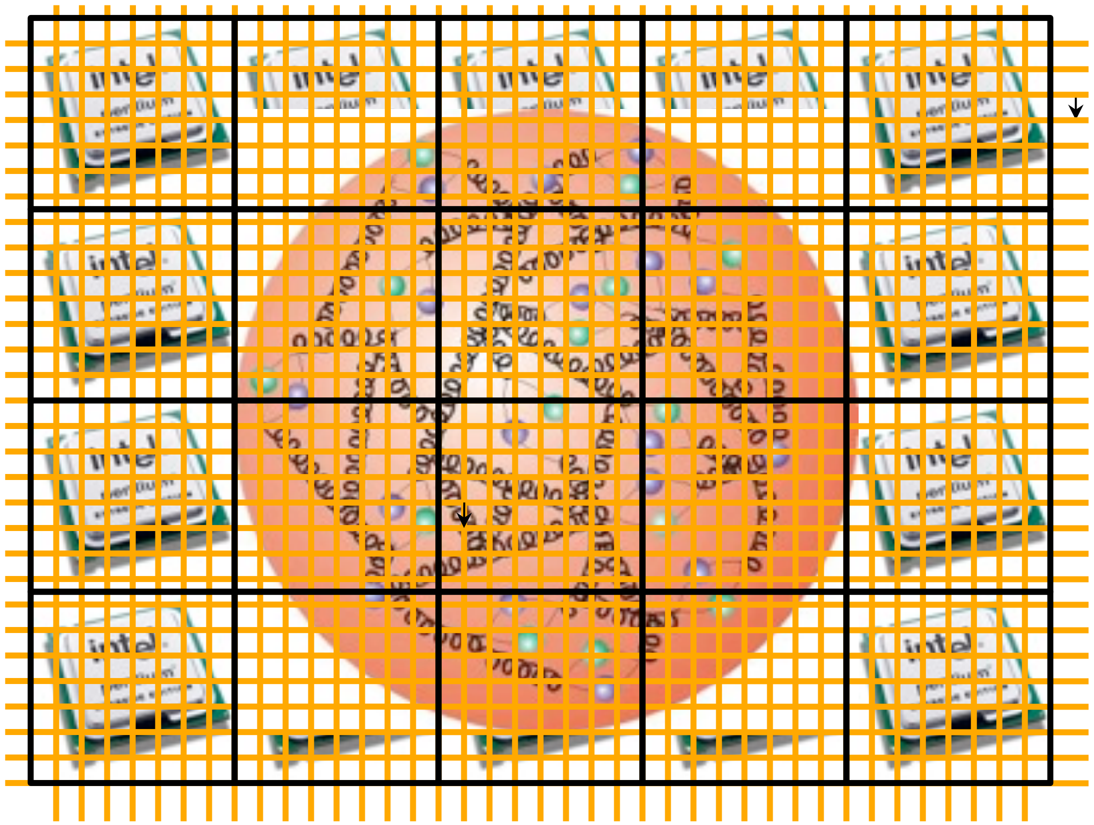
Classical Vacuum

$\boxed{\text{Quantum Fluctuations in the Vacuum Dictate Observables}}$

Lattice QCD

Monte-Carlo Evaluation of QCD Path Integral





Lattice Spacing :

a << $1/\Lambda\chi$

(Nearly Continuum)

Lattice Volume :

$m_\pi L >> 2\pi$

(Nearly Infinite Volume)

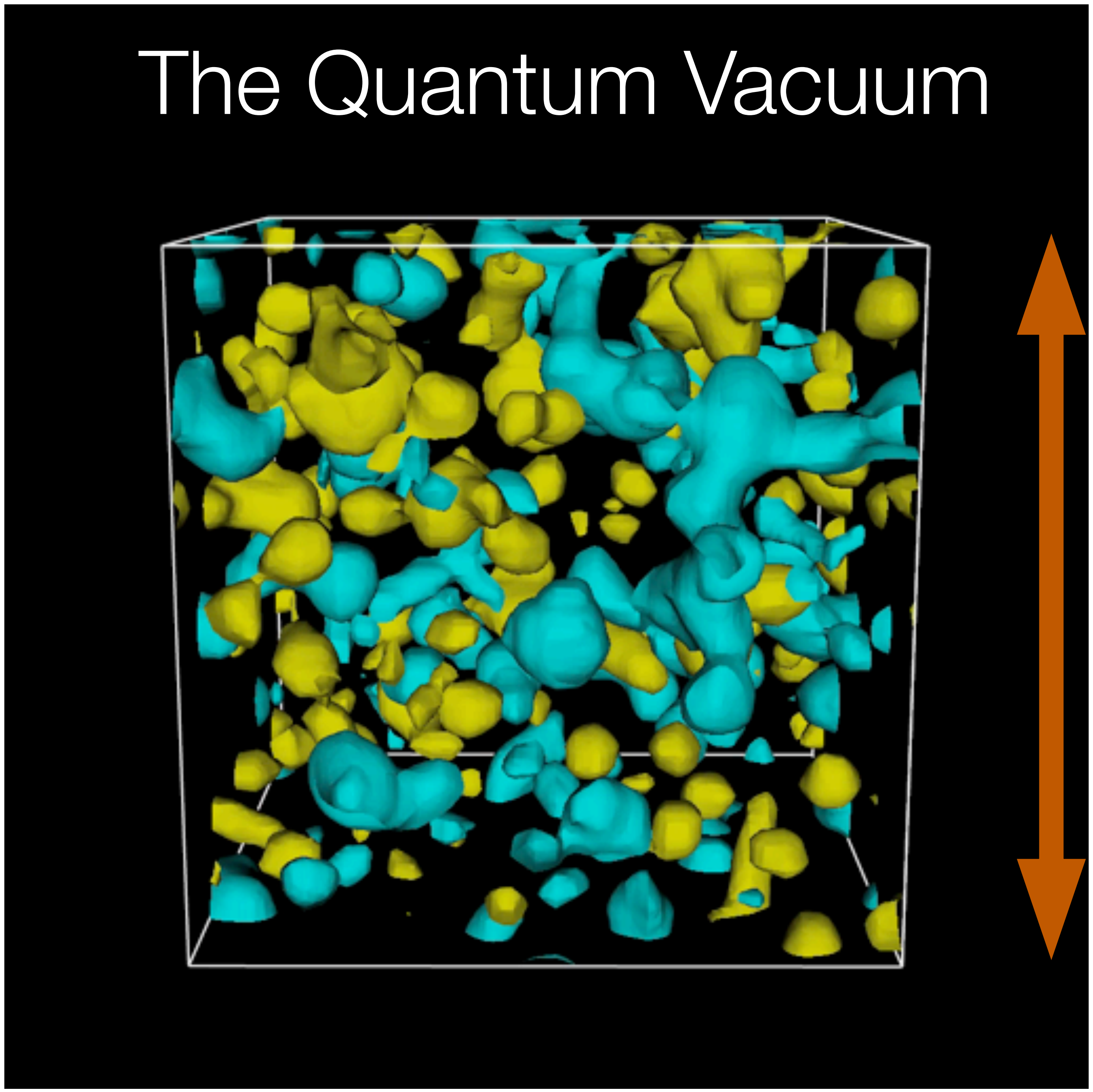
Effective Field Theory gives form of extrapolation $a = 0$ and $L = \infty$

Propagators Gauge Configurations

$$\langle\hat{\theta}\rangle \sim \int \mathcal{D}\mathcal{U}_\mu \, \hat{\theta}[\mathcal{U}_\mu] \, \det[\kappa[\mathcal{U}_\mu]] \, e^{-S_{YM}} \rightarrow \frac{1}{N} \sum_{\text{gluon cfgs}}^{N} \hat{\theta}\,[\mathcal{U}_\mu]$$

At the Heart of Visible Matter

The Vacuum is Complex

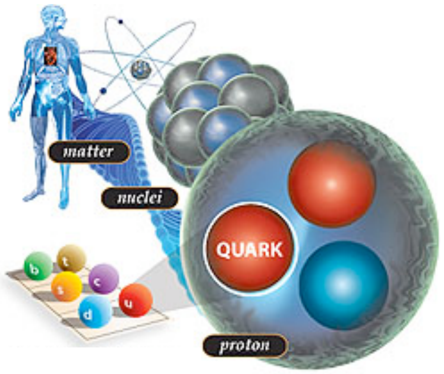


$L \sim 4 \text{ fm}$

$\Delta t \sim 6 \times 10^{-24}\ s$

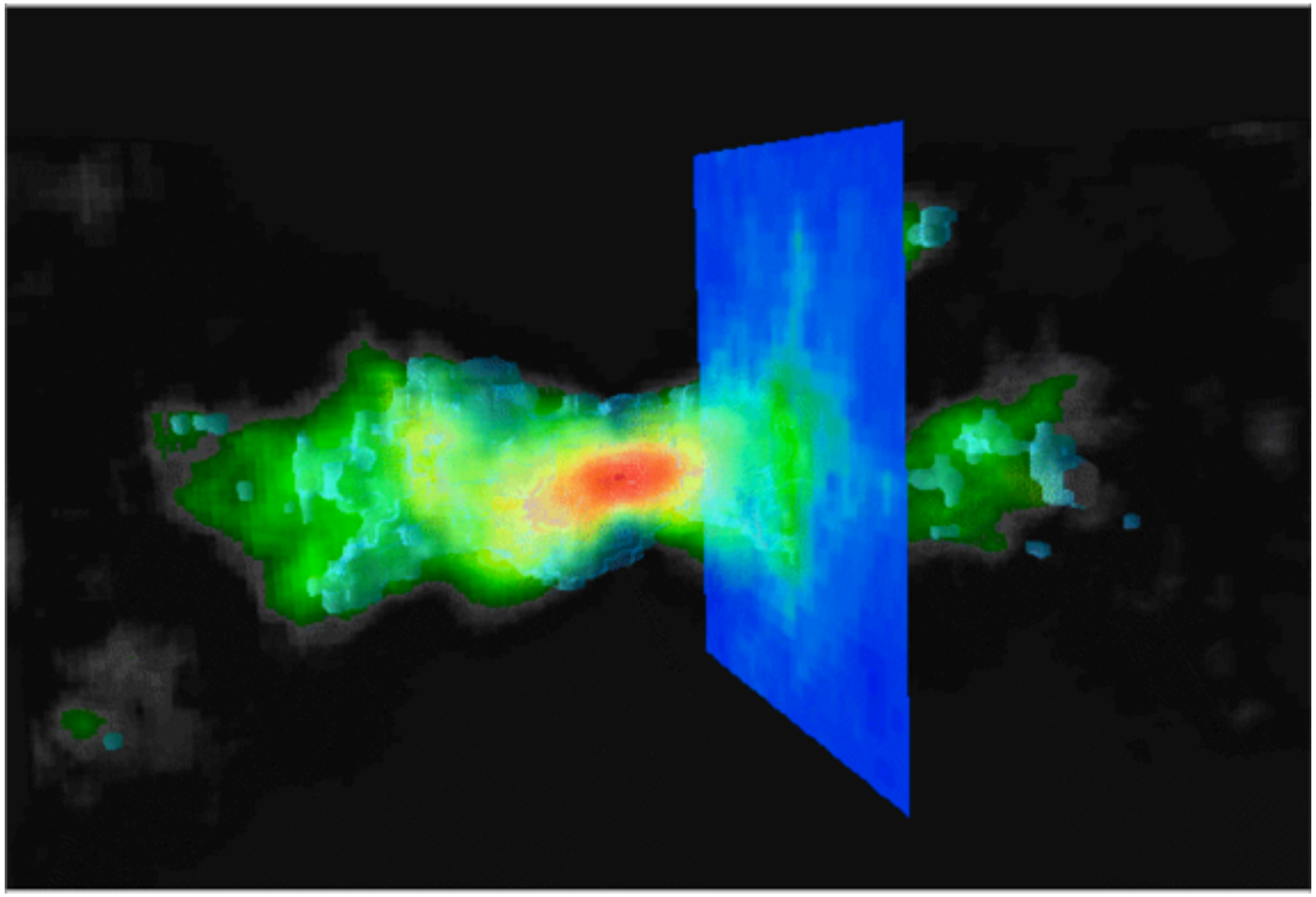
"Pixelation" ~ $(0.12 \times 10^{-15}\ \mathrm{m})^3$

Topological Charge Density
Massimo DiPierro



At the Heart of Visible Matter

Quarks and Gluons are Confined (T=0)



Rajan Gupta *et al*

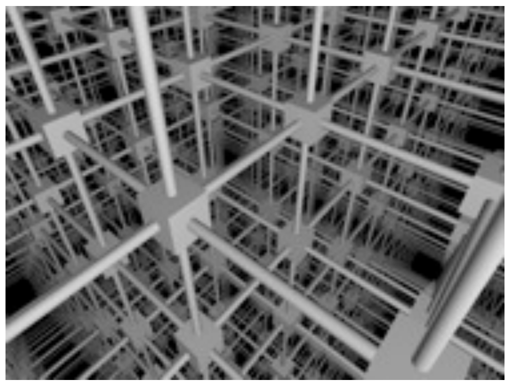
Quark Propagator on One Gauge Configuration

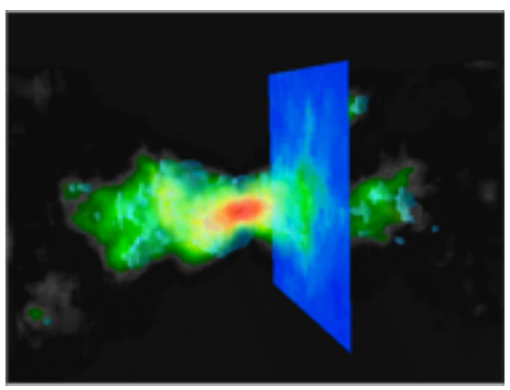
No isolated (free) quarks

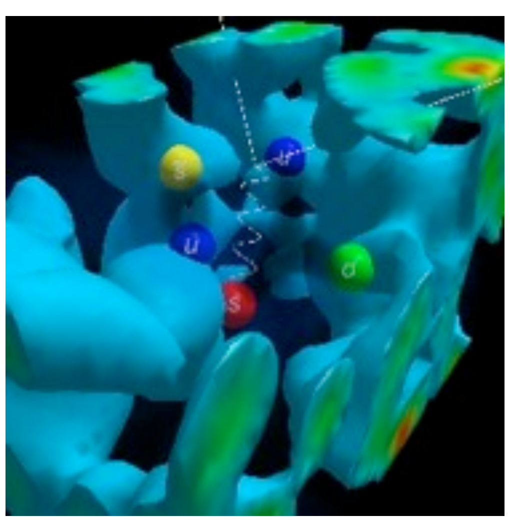
Cancellation of Probability Amplitudes

Pion, Nucleon from same propagators

LQCD Calculations Today





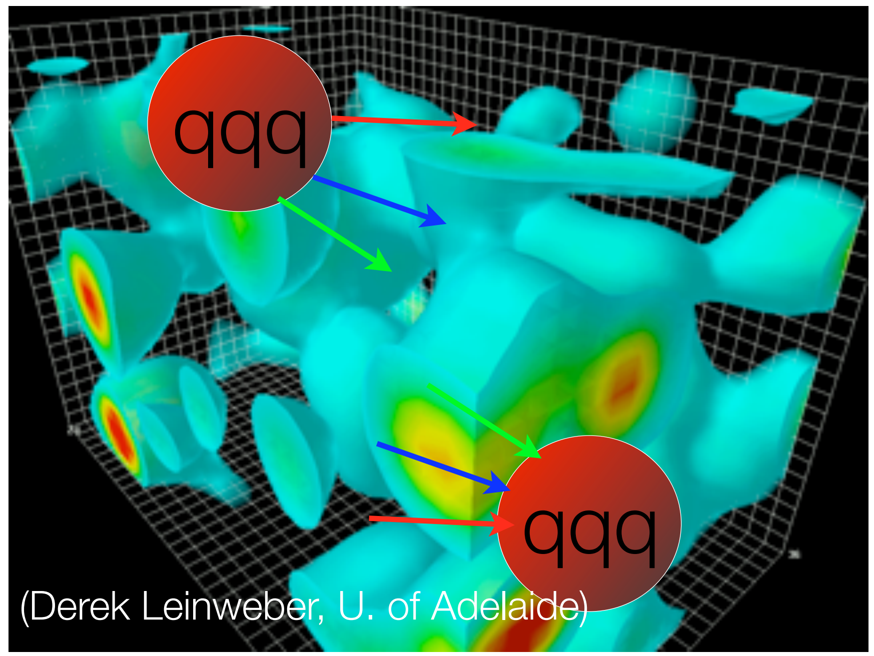


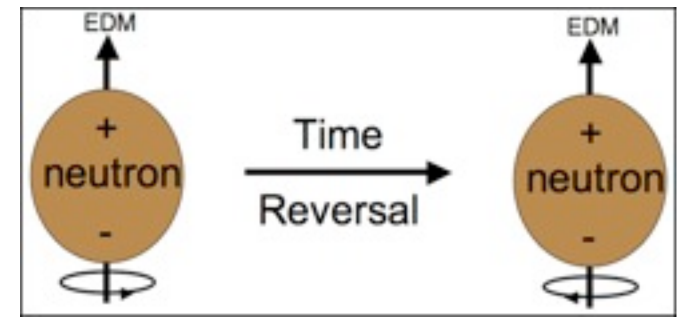
- Configurations
  - HMC, 2+1 (+1) flavors , isotropic or anisotropic
  - Domain-Wall, Clover, Staggered : det of matrix >> 10^8 x 10^8
  - >= physical quark masses
  - L from ~2.5 fm to > 12 fm , a from ~0.1 fm to < 0.05 fm
  - No EM and degenerate light quarks
  - <~ 128K cpu cores , ~10K trajectories, ~ 1K cfgs , < 10 GB/cfg
  - generated once, saved for use by many (USQCD)

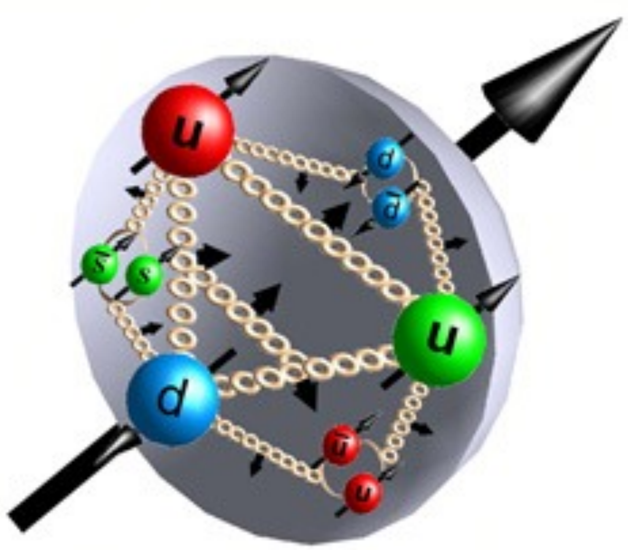
- Propagators
  - <~64K cpu and ~256 gpu (parallel code)
  - generated, used for correlation functions, deleted
  - < 100 GB
  - 1 (HEP) to 500 (NP) propagators per cfg
  - invert Dirac operator : deflation, multi-grid, ...

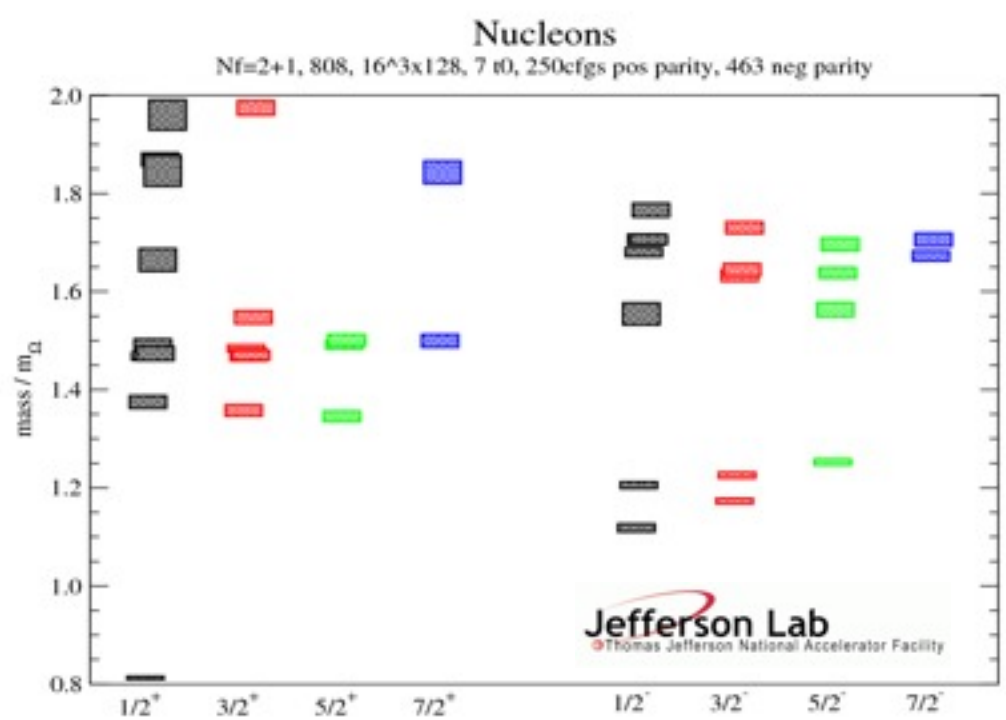
- Contractions
  - Hundreds of different correlation functions per propagator
  - permutations - recursion - needs algorithmic development, arprec
  - one xml file saved for subsequent analysis

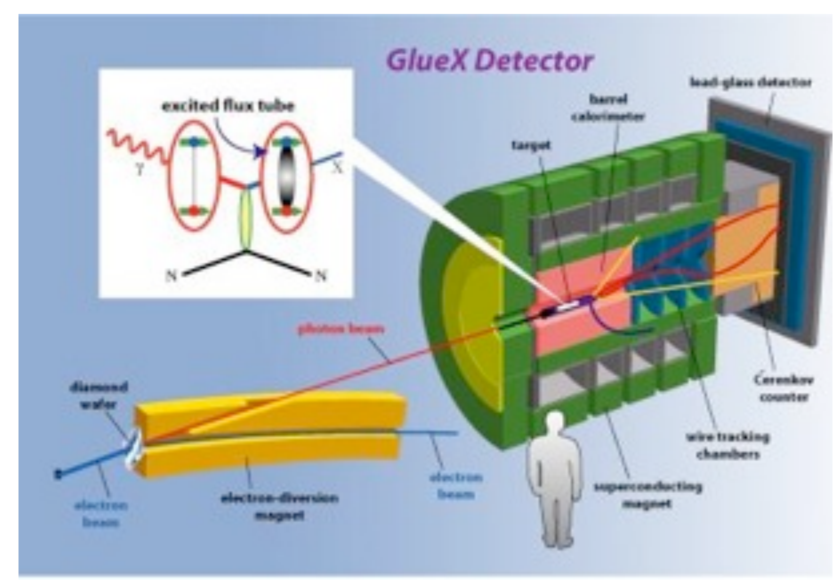
The Structure of Hadrons



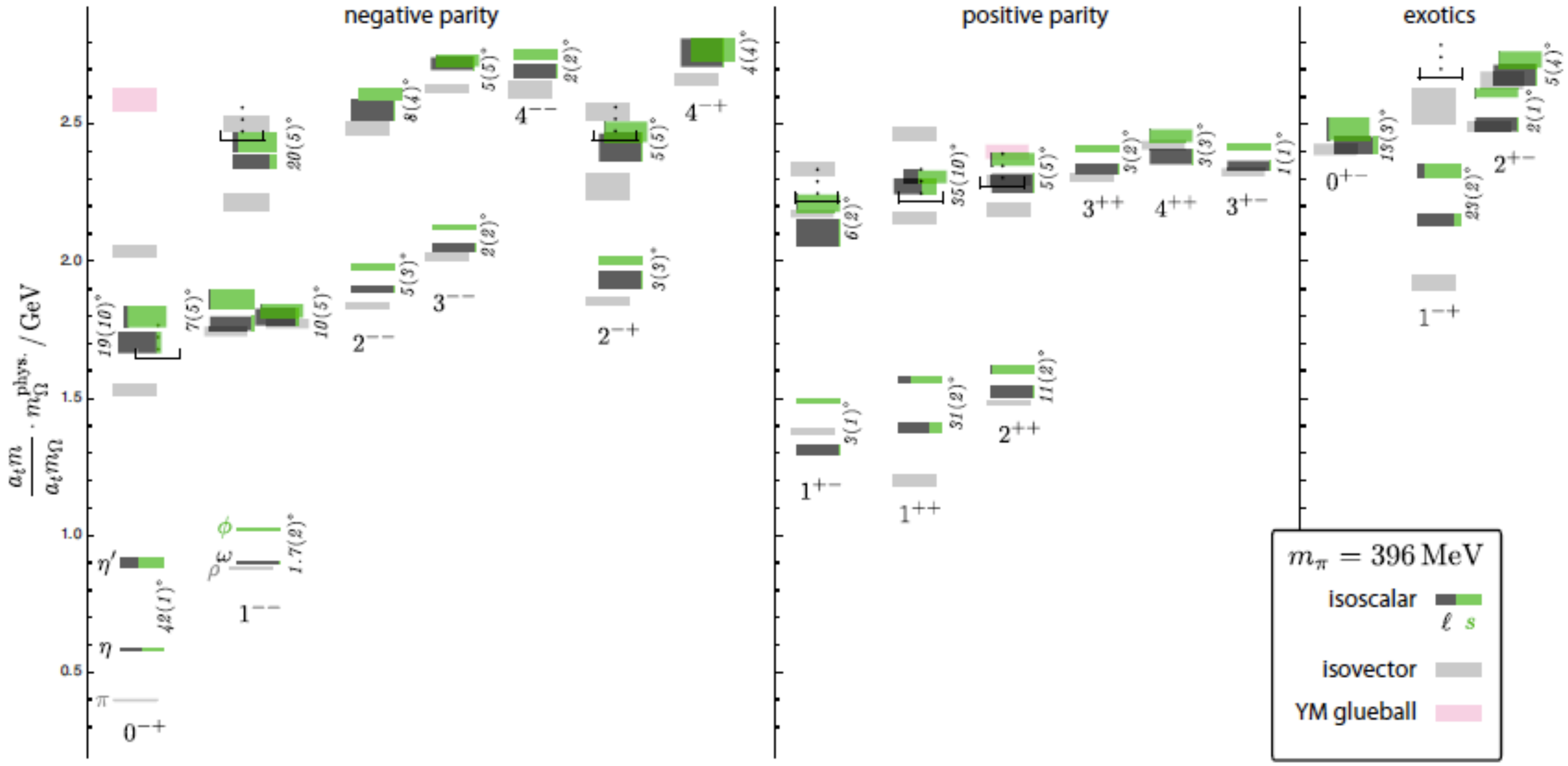


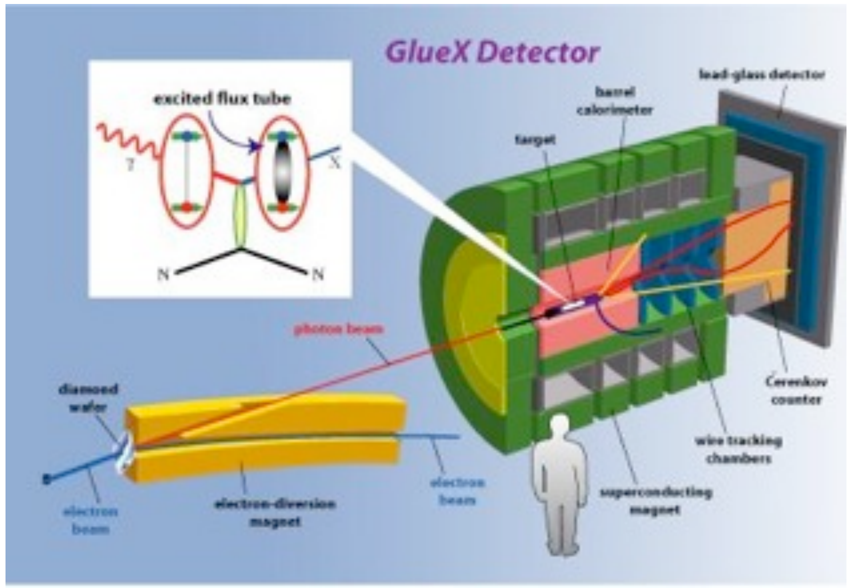






Excited Meson Spectrum
Exotics





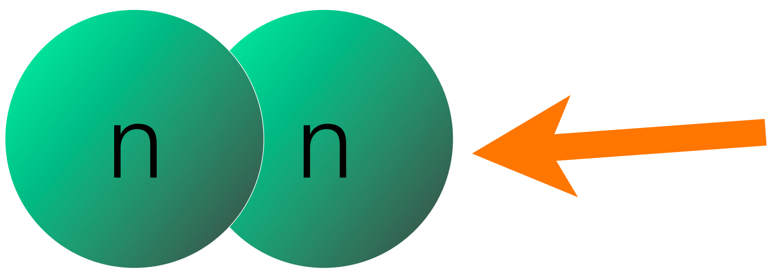
Dudek *et al* , arXiv:1102.4299

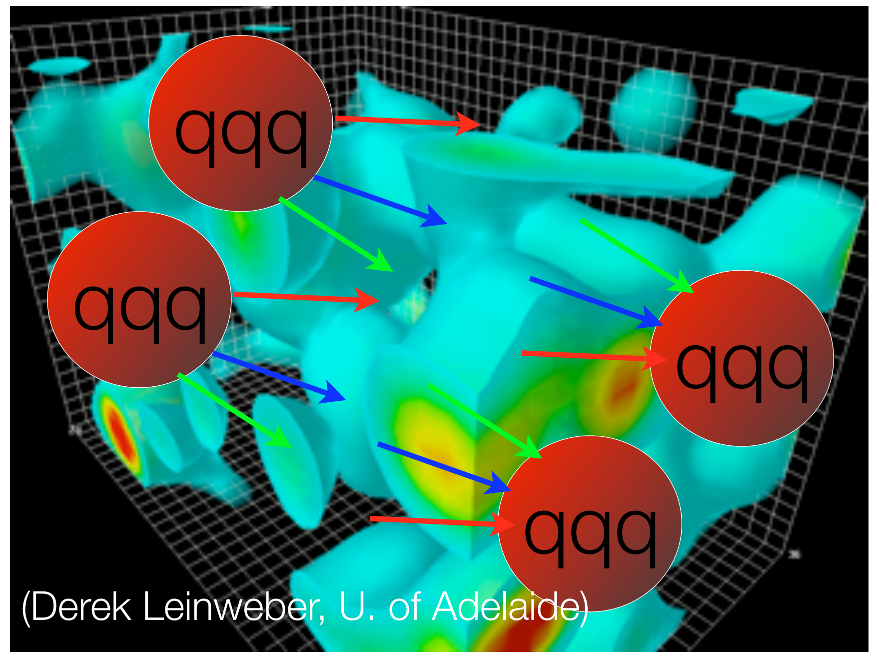
Lattice QCD will predict the exotic spectrum before or during the GlueX experiment
(with sufficient compute resources)

NSAC Milestone 2018 HP15: The first results on the search for exotic mesons using photon beams will be completed.

Multi-Hadron Systems

NN-interaction verification

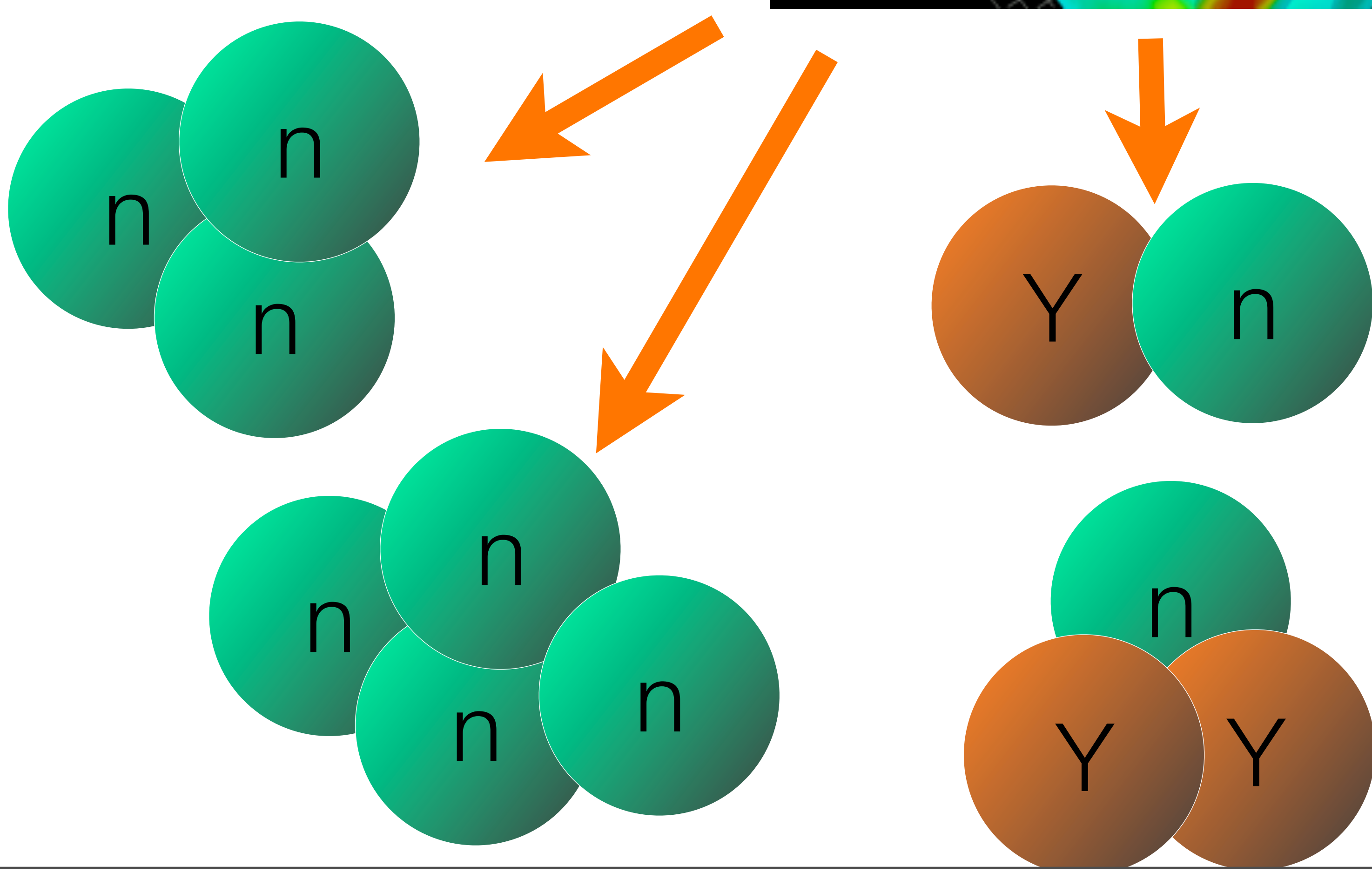


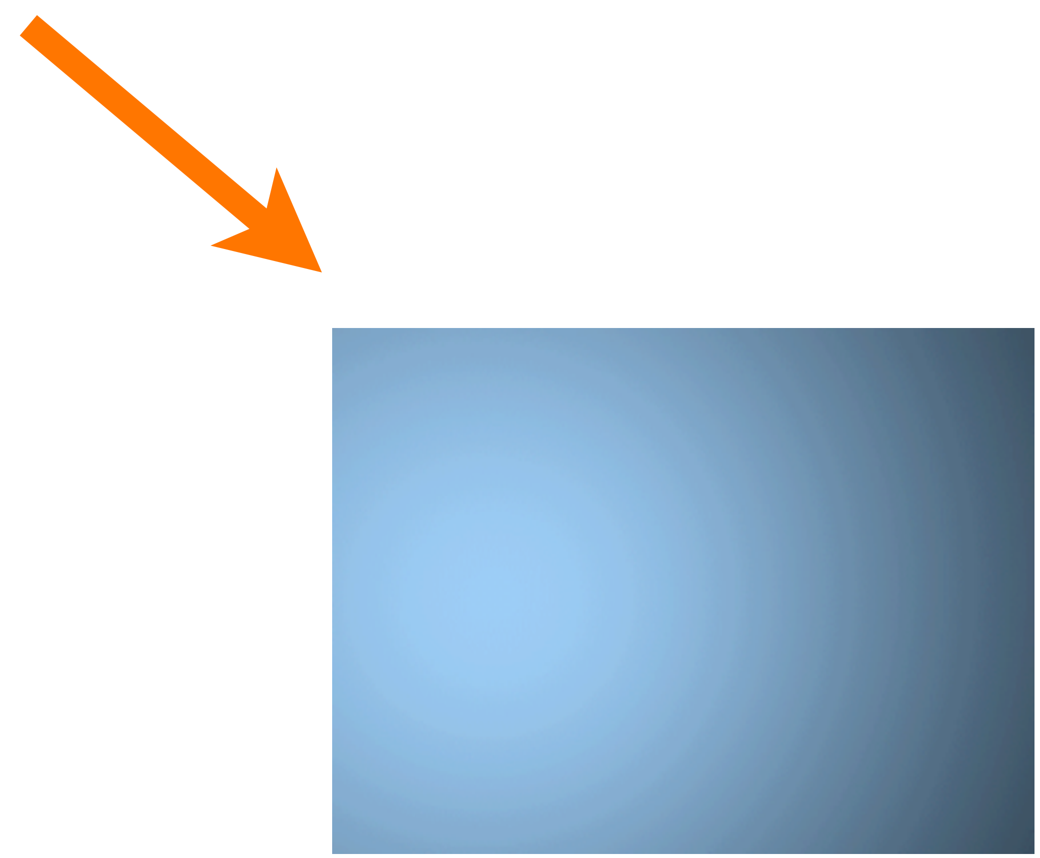


Hadron-Hadron

1) T-Matrix (E) ala Luscher
NPLQCD

2) $U(E, \mathbf{r}, \mathbf{r}', \mathrm{sink})$
HALQCD





Energy Eigenvalues and the Luscher Relation

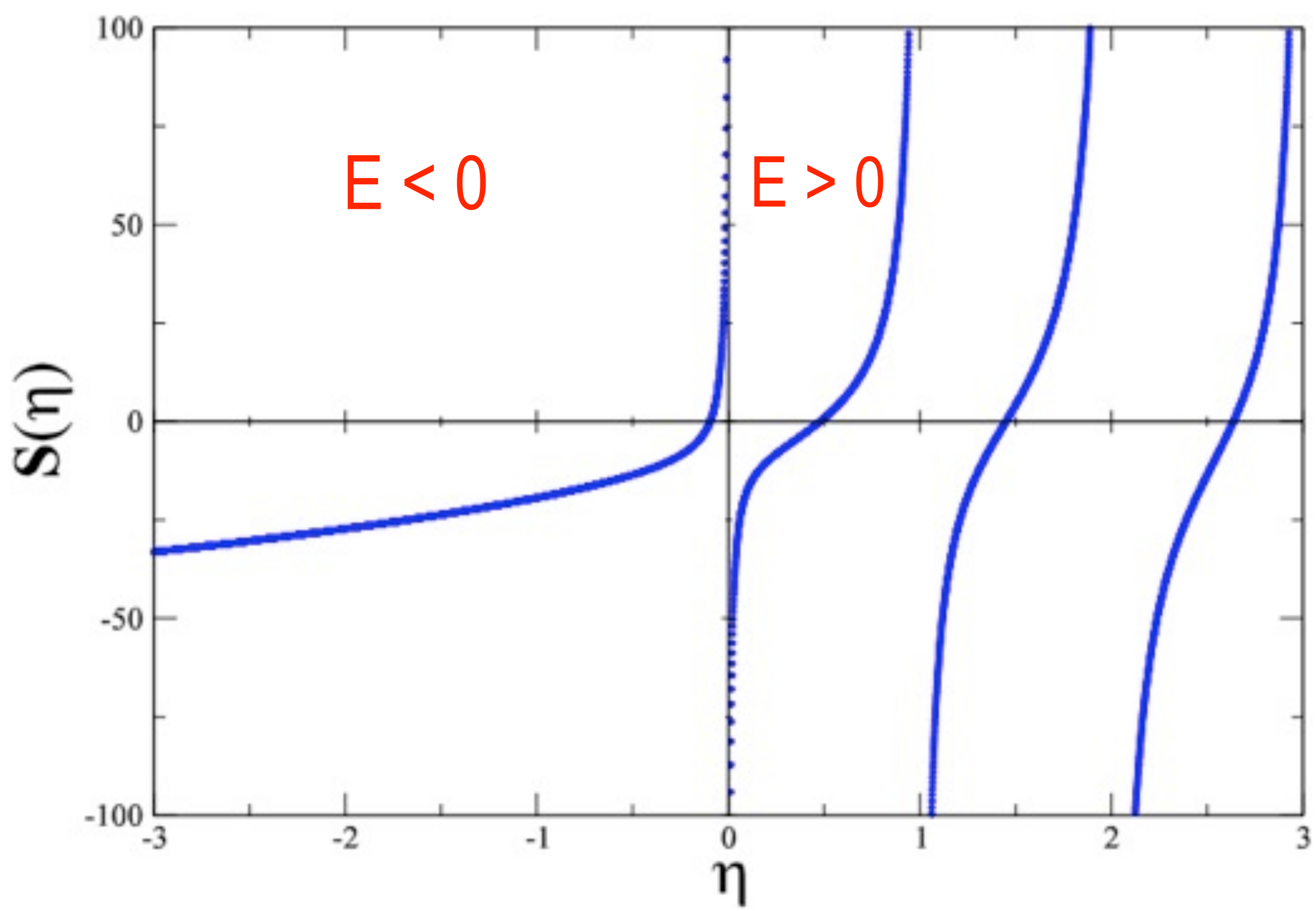
Below Inelastic Thresholds :

Measure on lattice

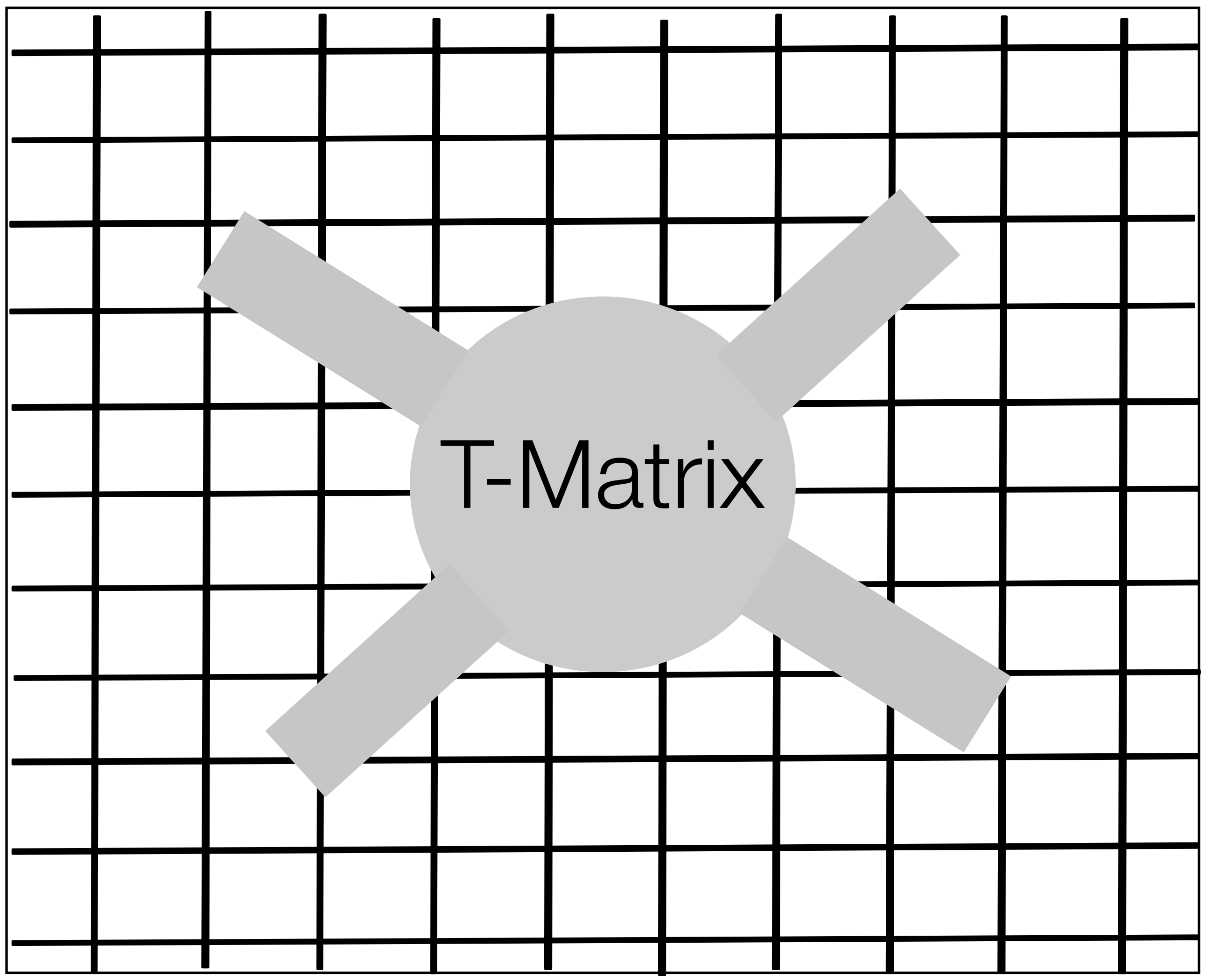
$$\delta E = 2\sqrt{p^2 + m^2} - 2m$$

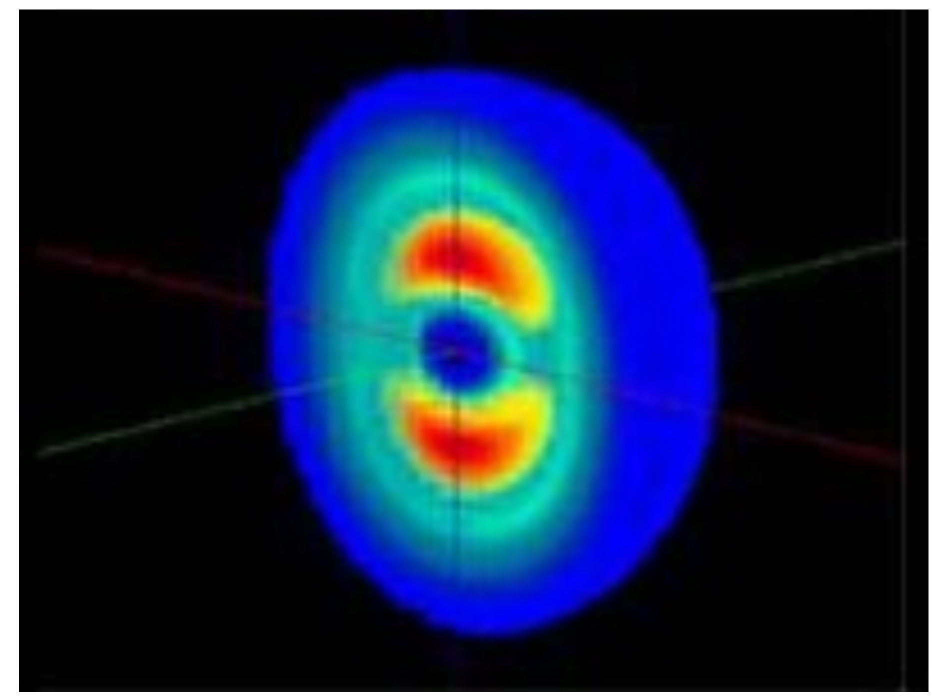
$$\boxed{p \cot \delta(p) \;=\; \frac{1}{\pi L}\, \mathbf{S}\left(\left(\frac{Lp}{2\pi}\right)^2 \right)}$$

A_1^+



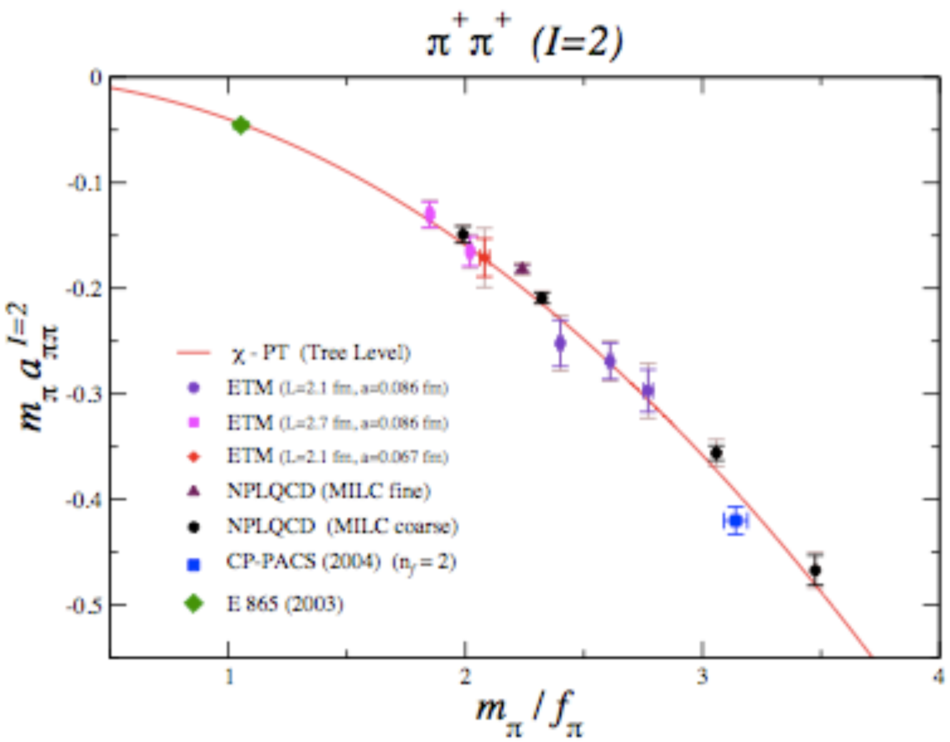
Large Scattering Lengths are OK !

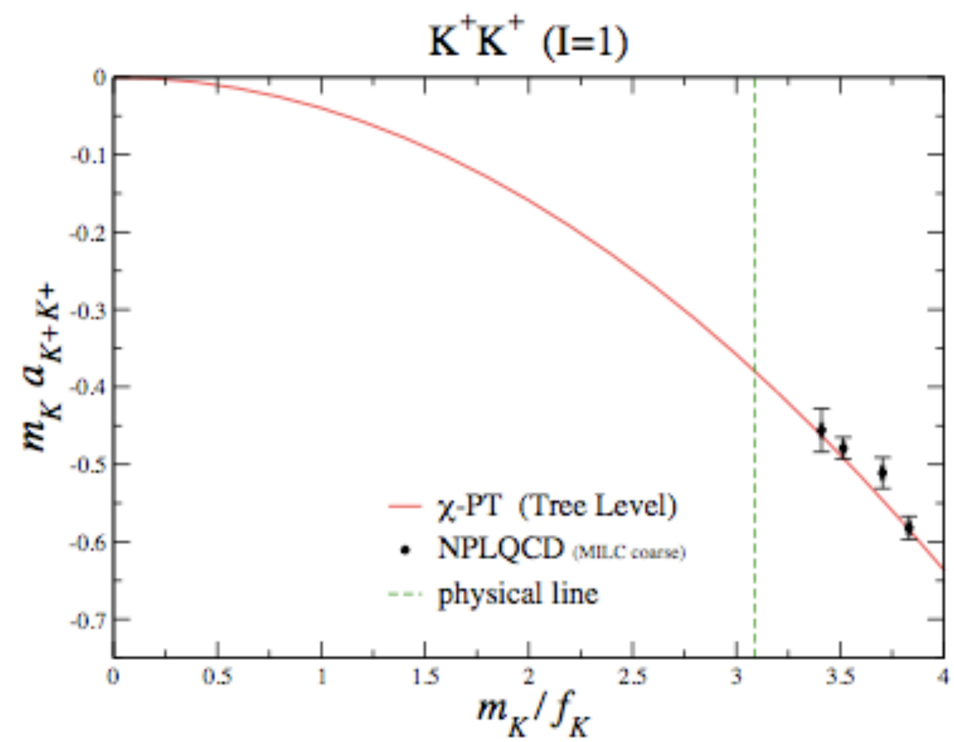


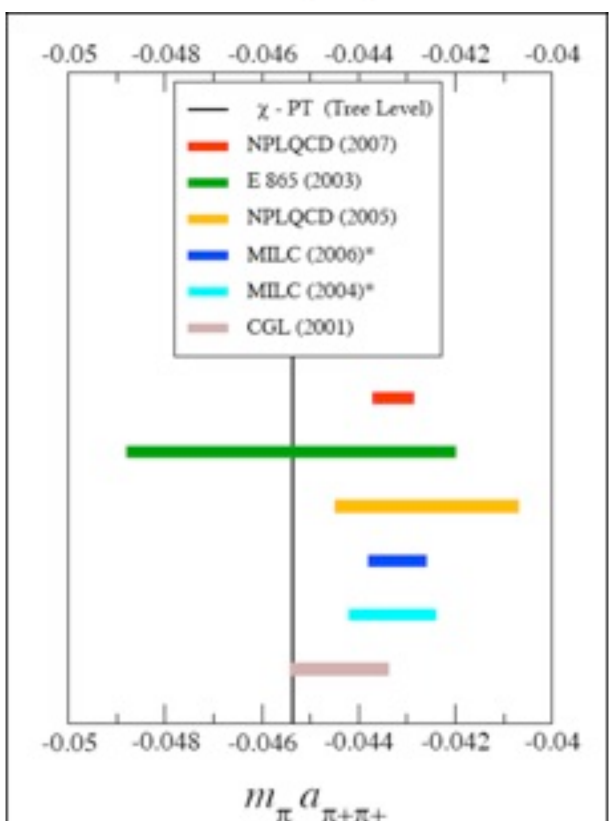


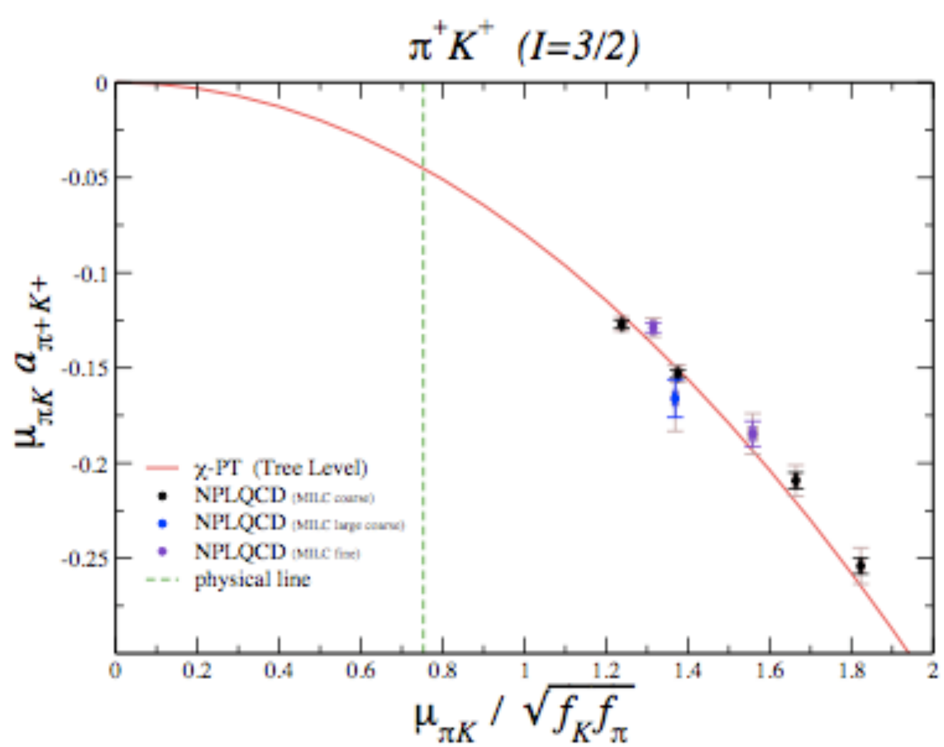
Require : $L >> r_0$ but ANY a

Lattice QCD and the Simplest Hadronic Interactions



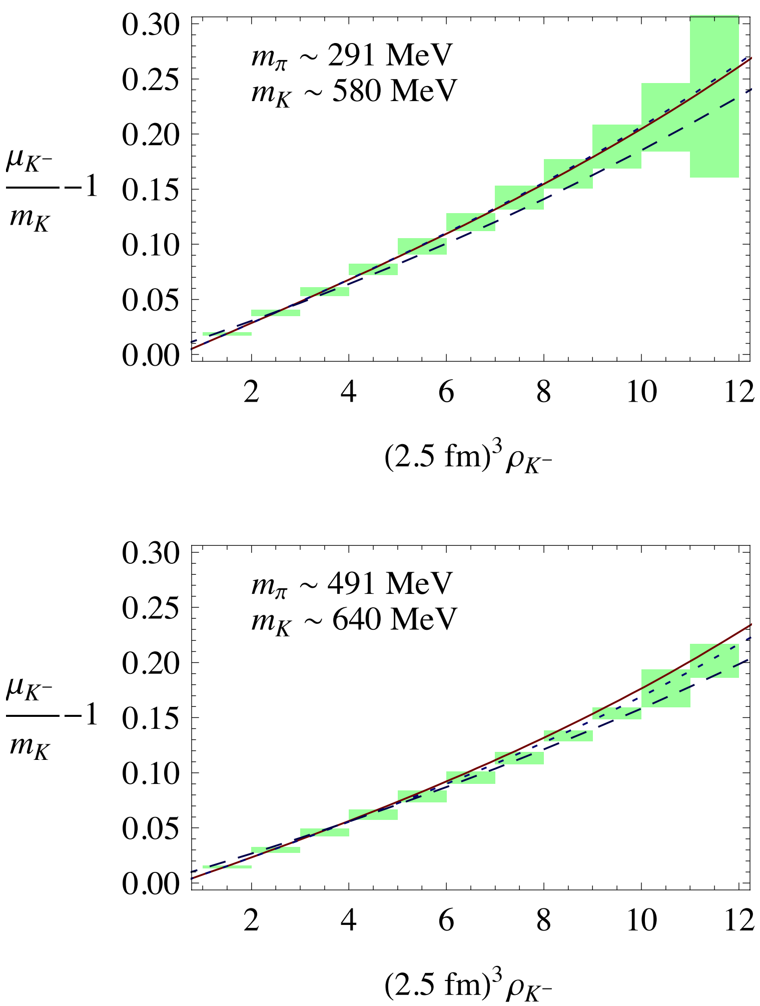




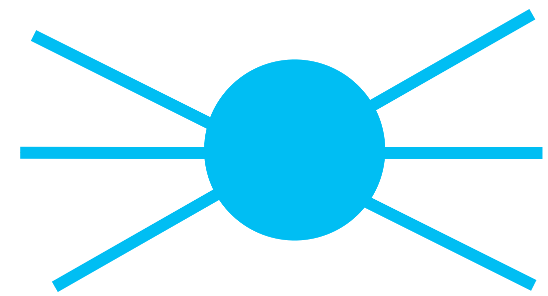


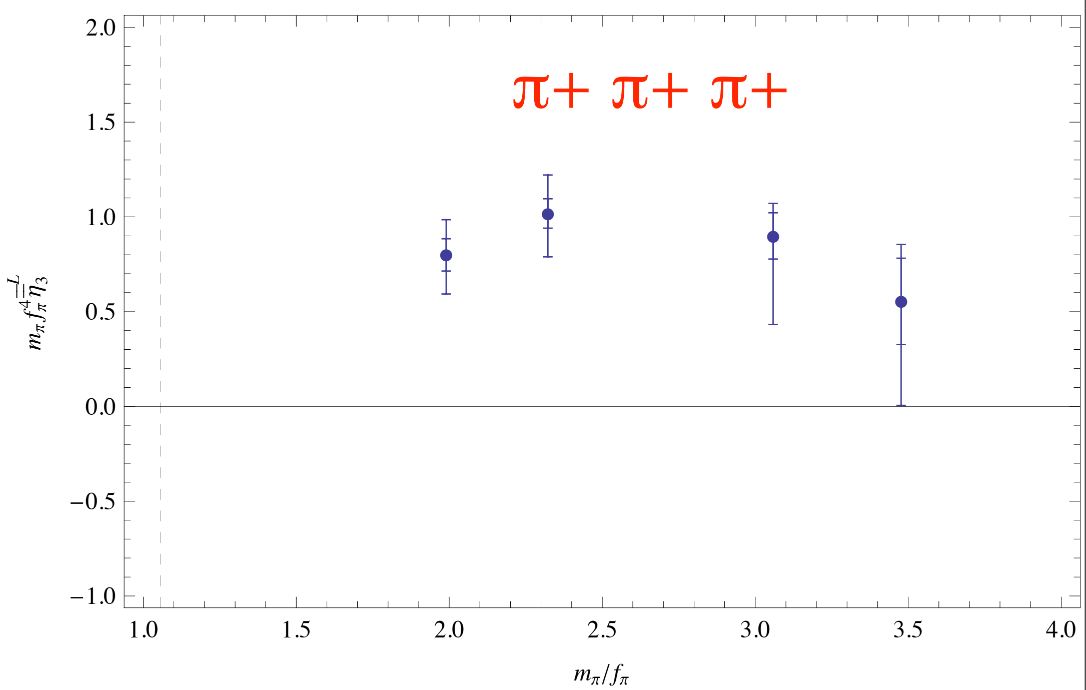
Bose-Einstein Condensates of pions and kaons : Many-Body Physics

Kaon Condensates



Pion 3-Body Interaction





- Systems with kaons and pions : Detmold + Smigielski

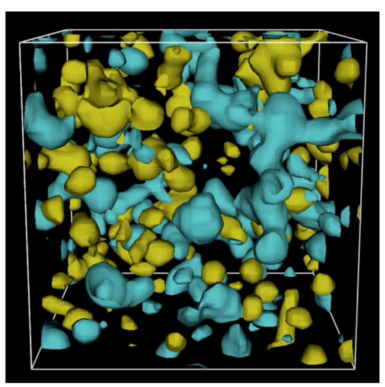
Multi-Volume Study by NPLQCD : 2009 - 2011

lattice spacing : $b \sim 0.123$ fm

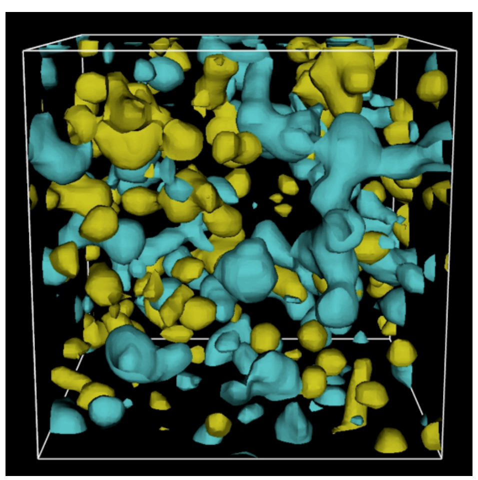
pion mass : $m_\pi \sim 390$ MeV

fermion action : Clover

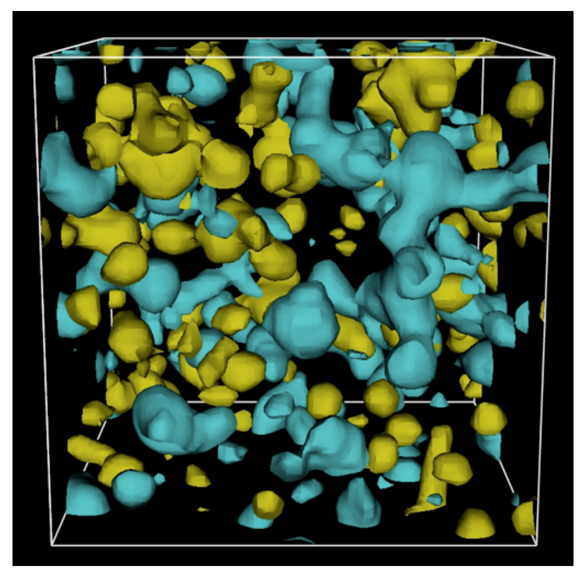
anisotropy : $\xi_t \sim 3.5$



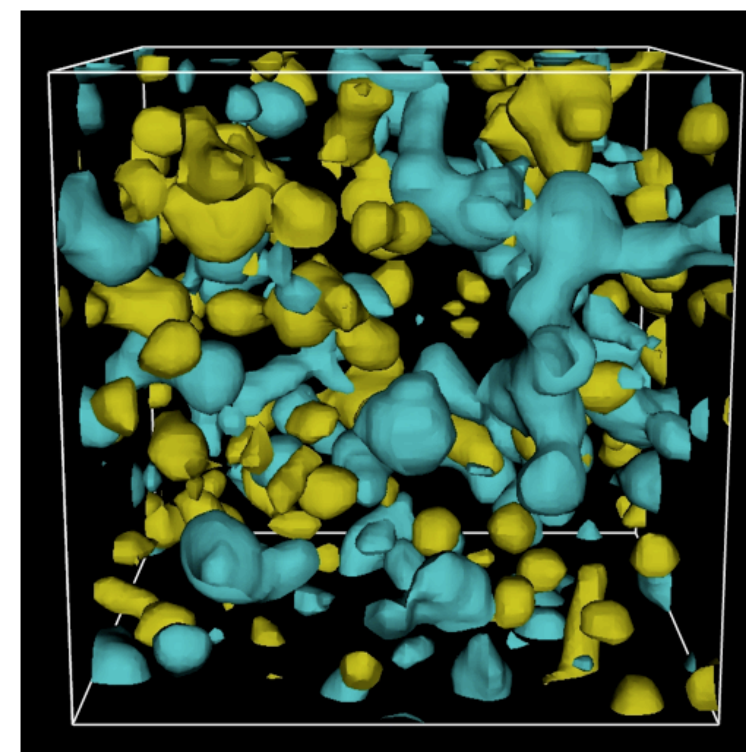
$L \sim 2$ fm



$L \sim 2.5$ fm



$L \sim 3$ fm

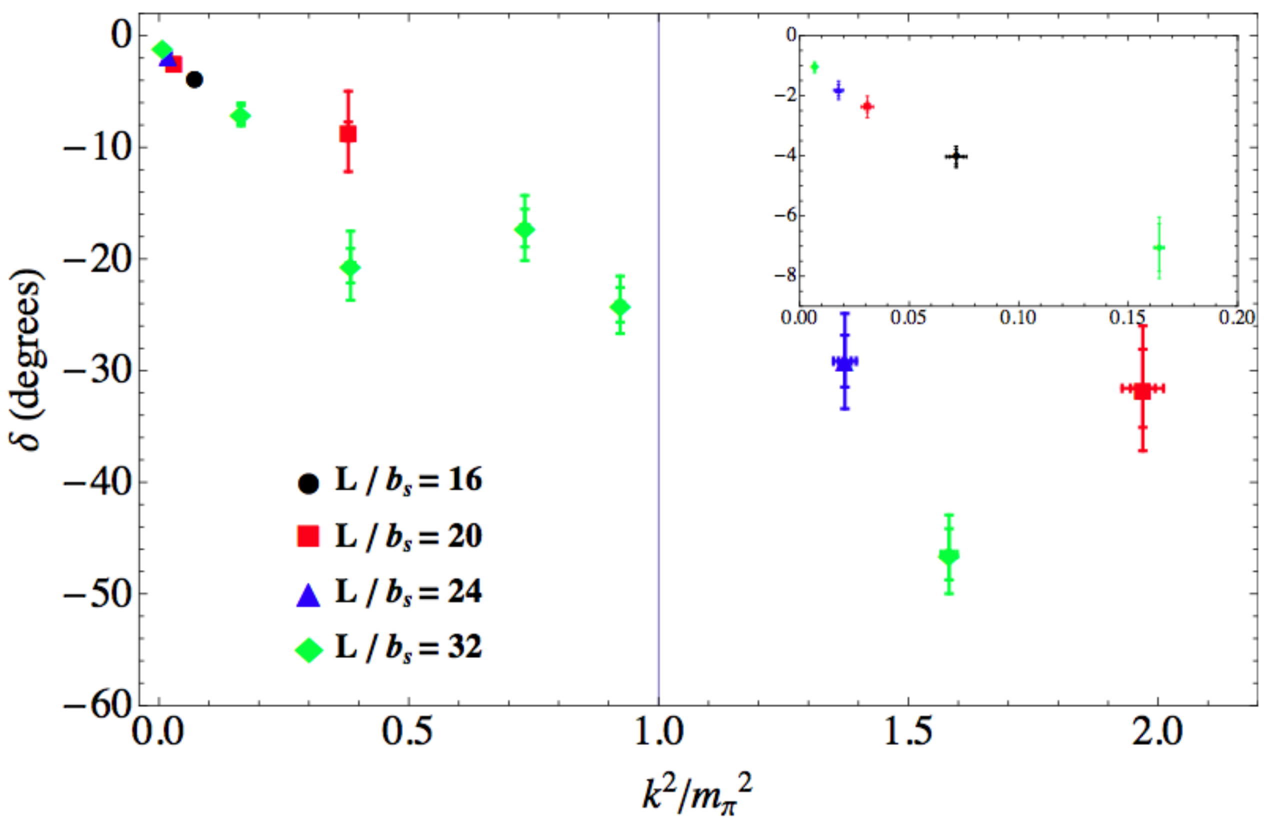


$L \sim 4$ fm

resources :$\sim 80 \times 10^6$ core hrs

$m_\pi L \sim 4\ ,\ 5\ ,\ 6\ ,\ 8 \quad m_\pi T \sim 9\ ,\ 9\ ,\ 9\ ,\ 18$

$I=2$ $\pi\pi$ Scattering Phase-Shift

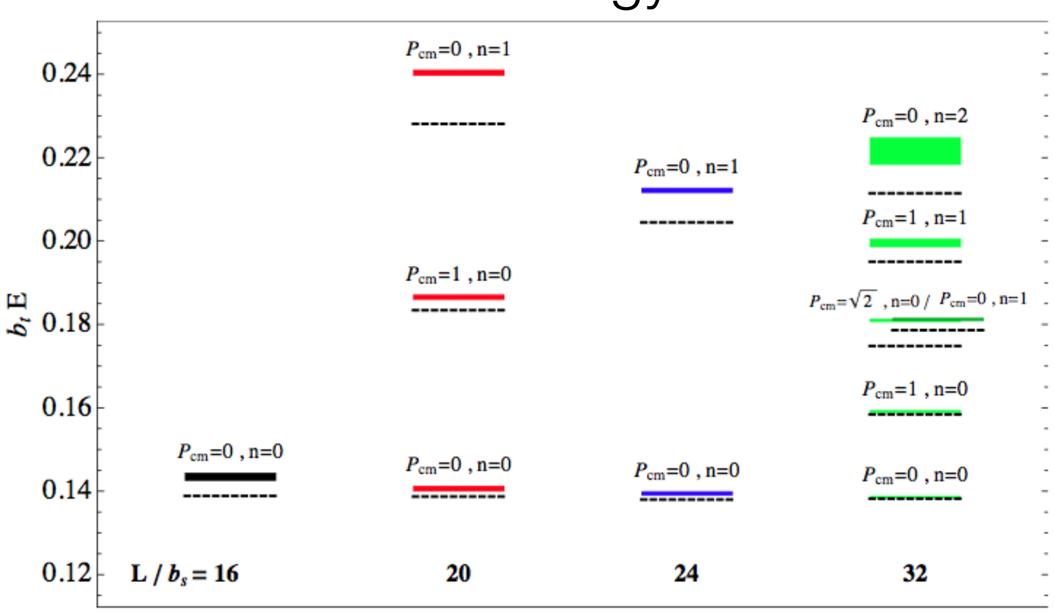


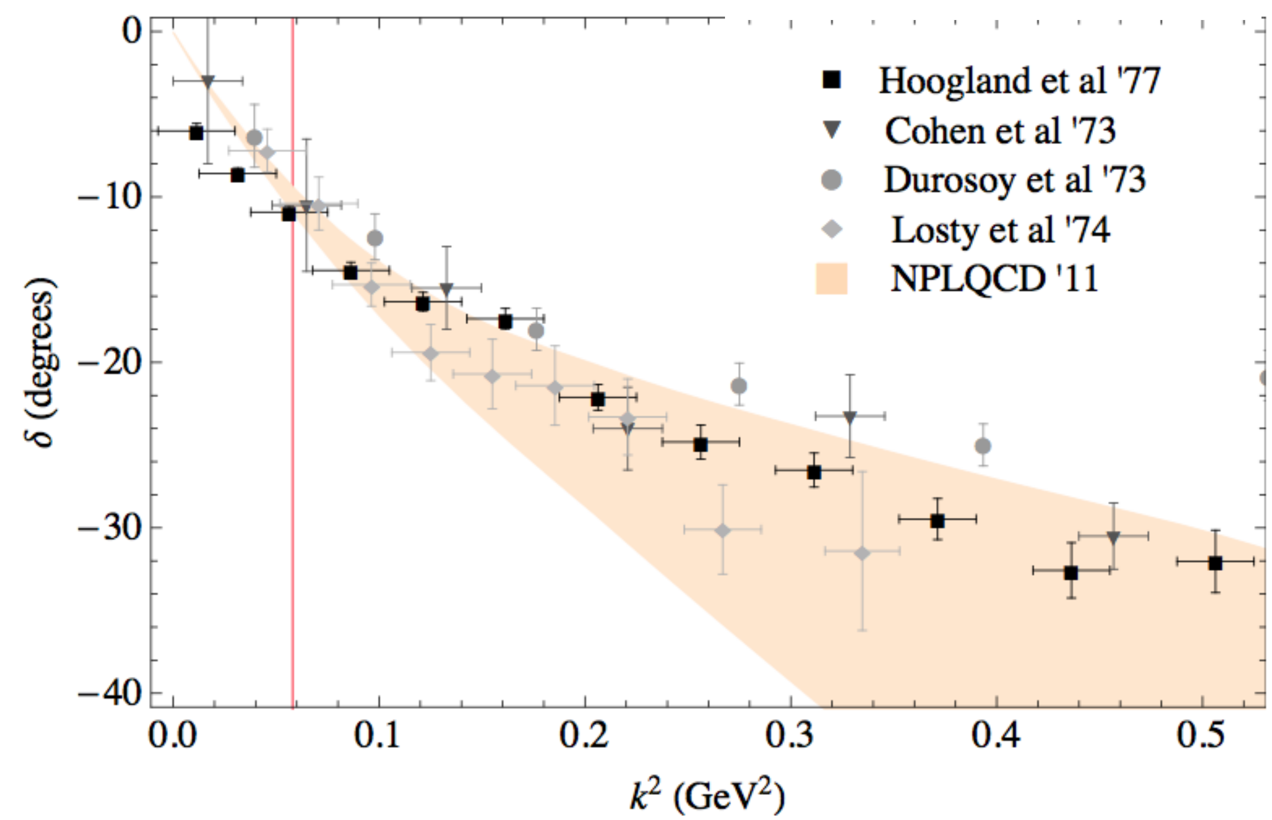
χPT

$m_\pi \sim 390$ MeV

$m_\pi \sim 139$ MeV

lattice energy-levels

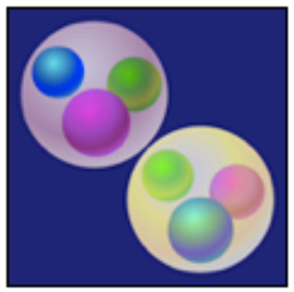




H-Dibaryon
An Exotic Nucleus

sics » Synopses » Binding baryons on the lattice

Binding baryons on the lattice



Credit: Alan Stonebraker

Evidence for a Bound *H* Dibaryon from Lattice QCD

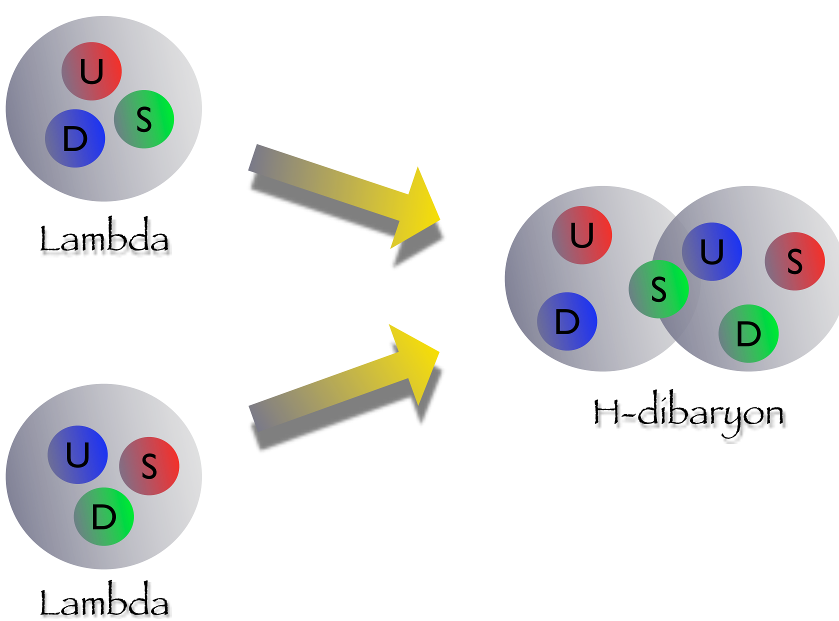
S. R. Beane, E. Chang, W. Detmold, B. Joo, H. W. Lin, T. C. Luu, K. Orginos, A. Parreño, M. J. Savage, A. Torok, and A. Walker-Loud (NPLQCD Collaboration)

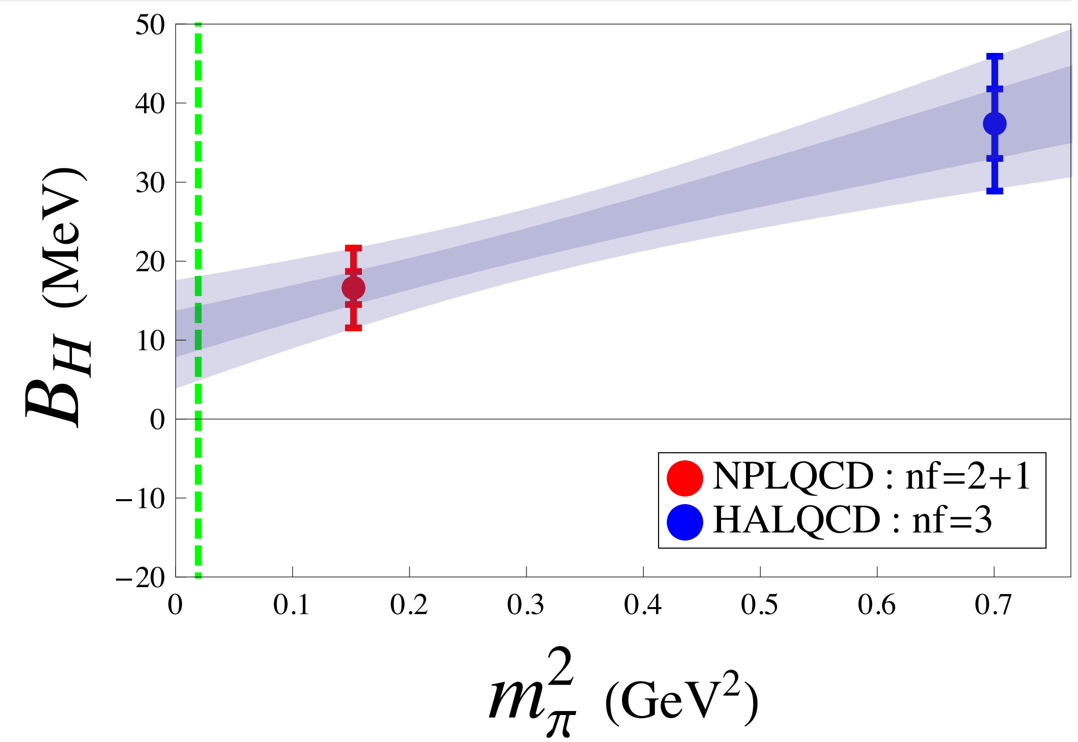
Phys. Rev. Lett. **106**, 162001 (Published April 20, 2011)

Bound *H* Dibaryon in Flavor SU(3) Limit of Lattice QCD

Takashi Inoue, Noriyoshi Ishii, Sinya Aoki, Takumi Doi, Tetsuo Hatsuda, Yoichi Ikeda, Keiko Murano, Hidekatsu Nemura, and Kenji Sasaki (HAL QCD Collaboration)

Phys. Rev. Lett. **106**, 162002 (Published April 20, 2011)

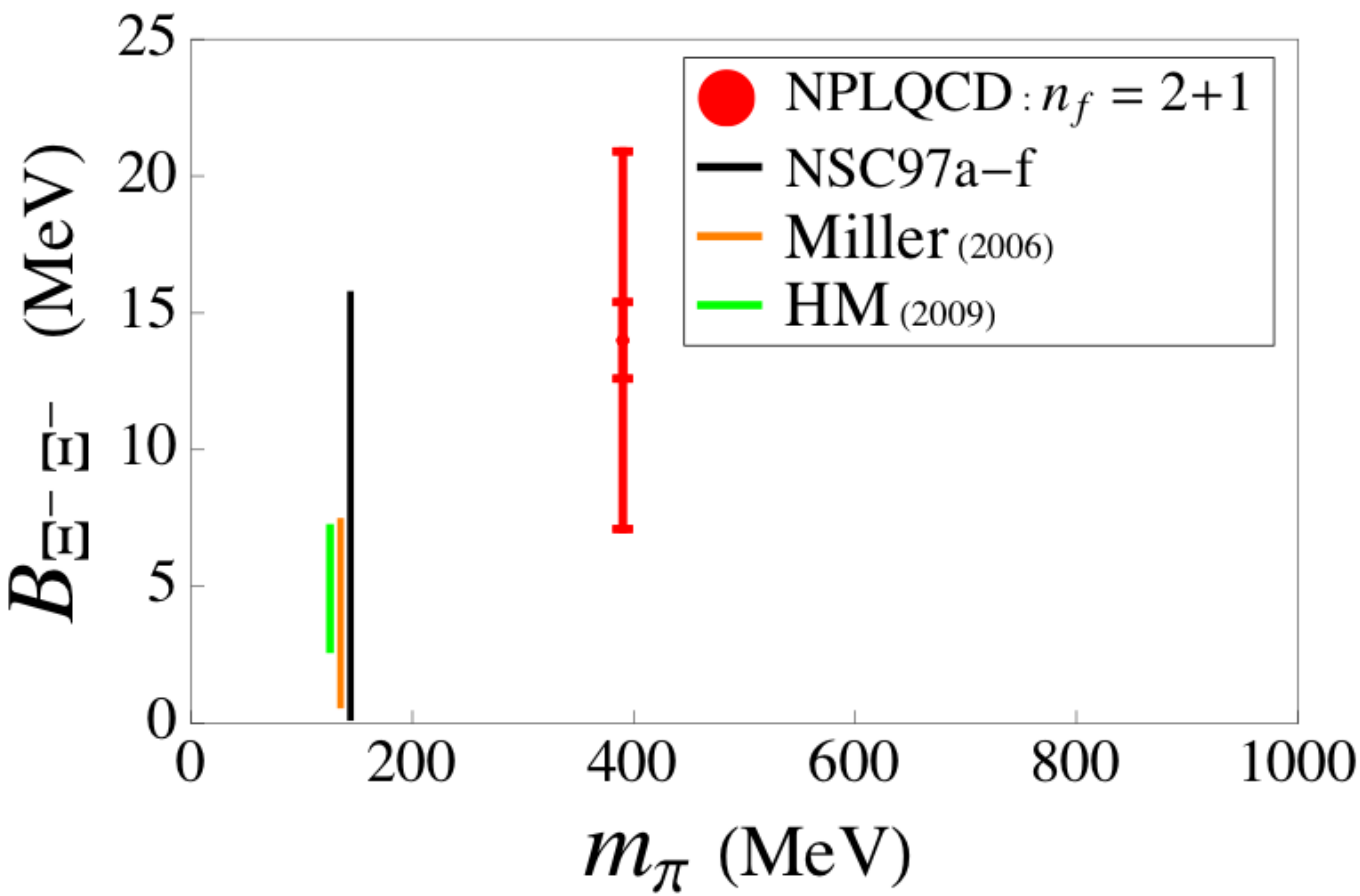




NSAC Milestone 2014 HP10: Carry out *ab initio* microscopic studies of the structure and dynamics of light nuclei based on two-nucleon and many-nucleon forces and lattice QCD calculations of hadron interaction mechanisms relevant to the origins of the nucleon-nucleon interaction

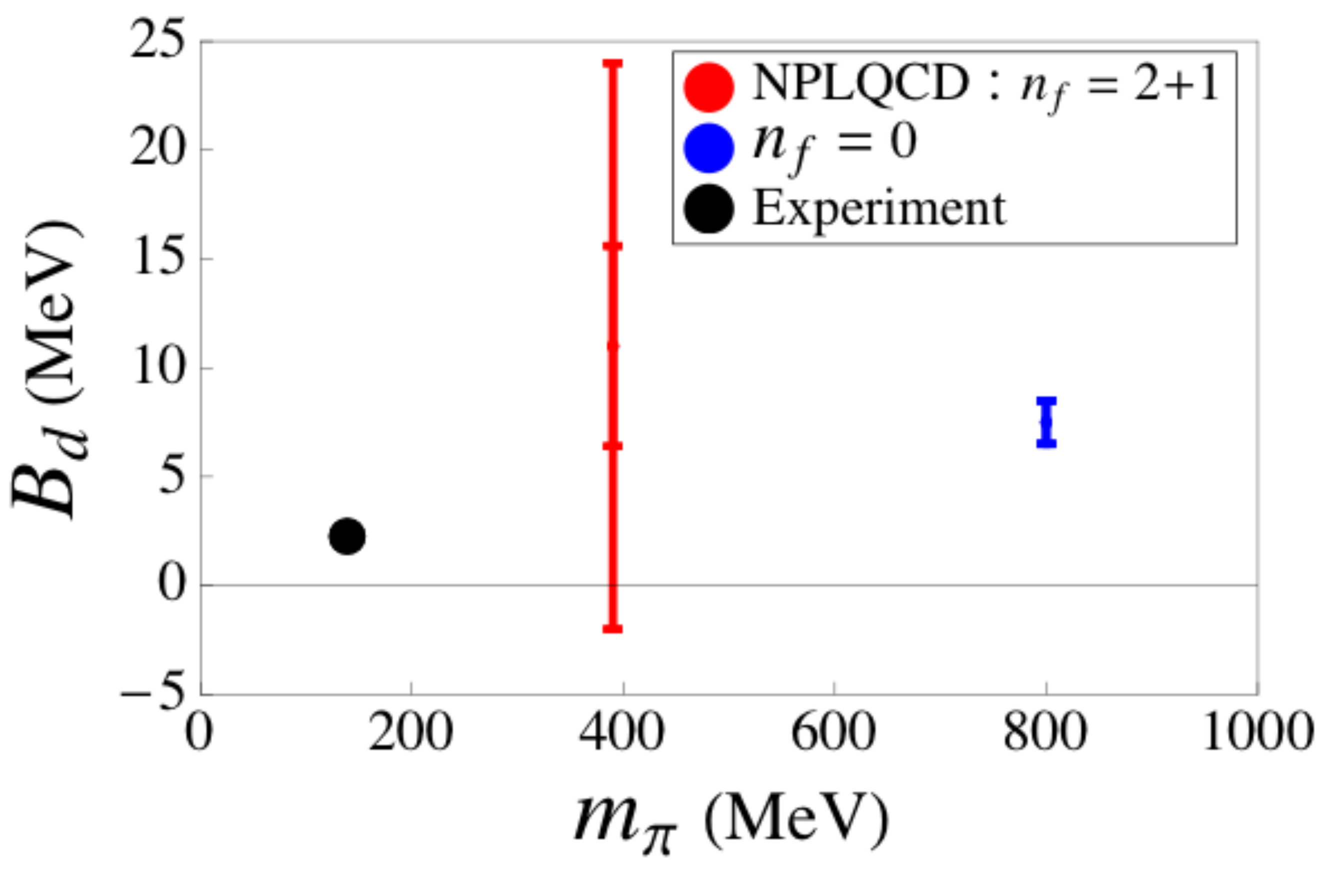
$\Xi^-\Xi^-$ Bound State

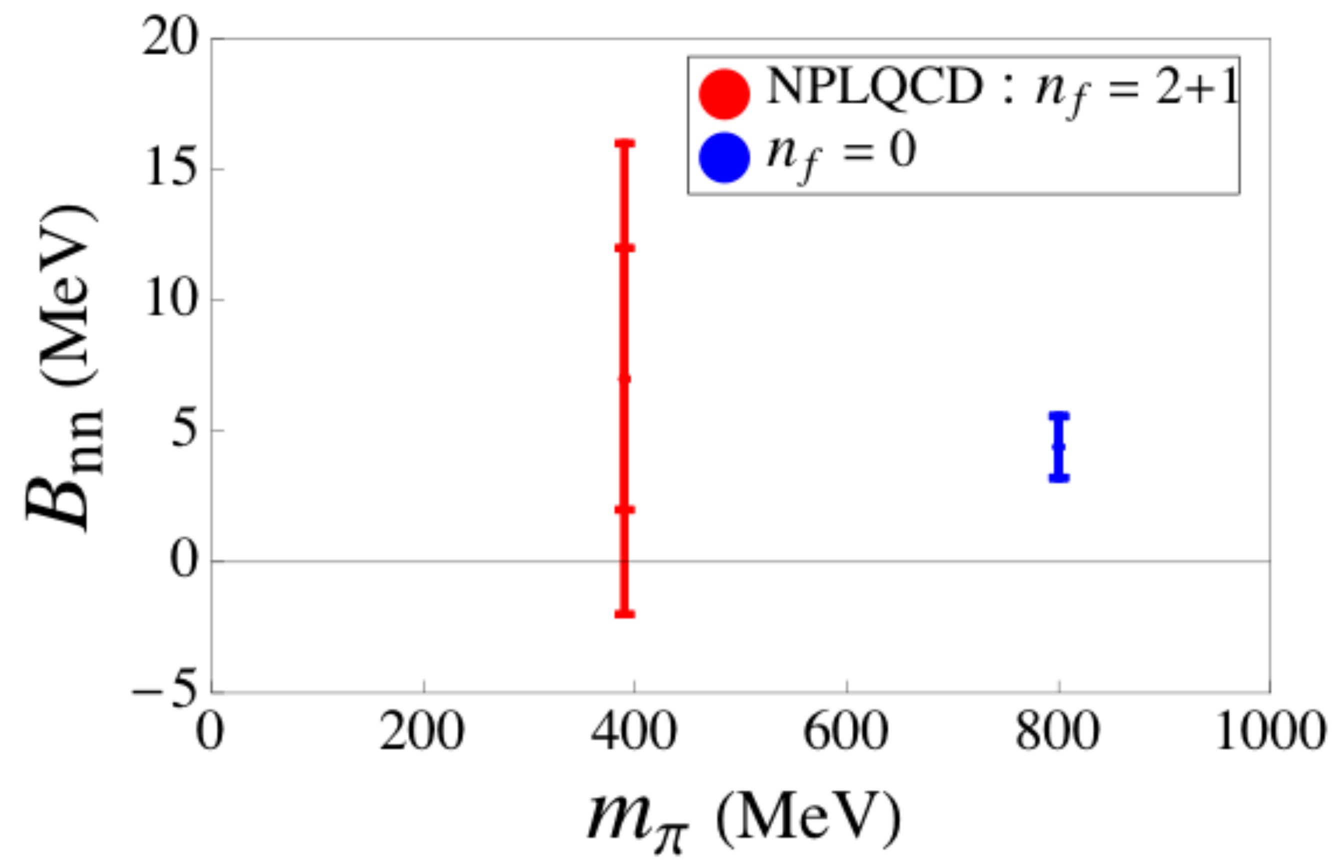
NPLQCD arXiv:1109.2889 – **this week!**



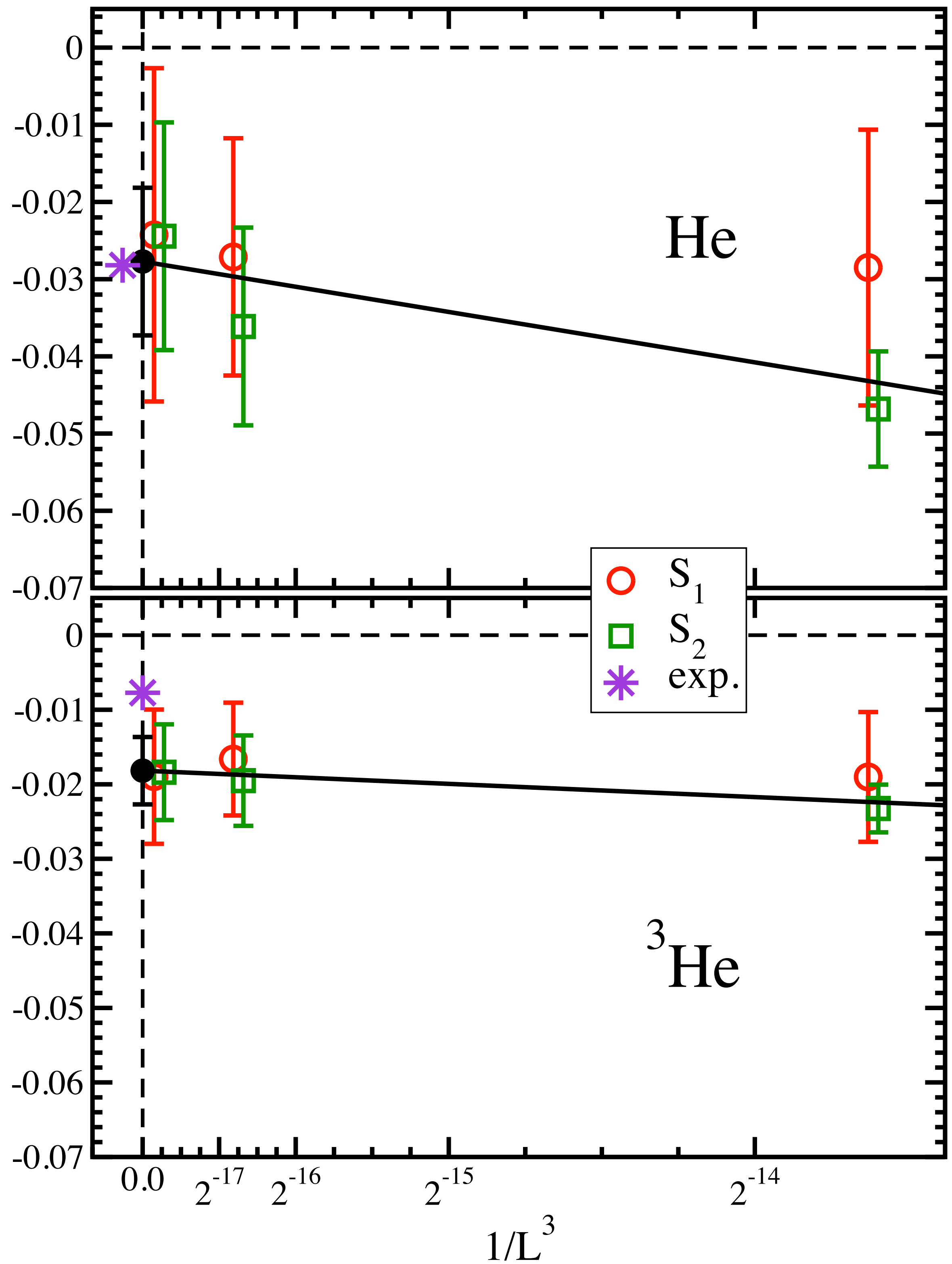
NN Bound States

NPLQCD arXiv:1109.2889 – **this week!**



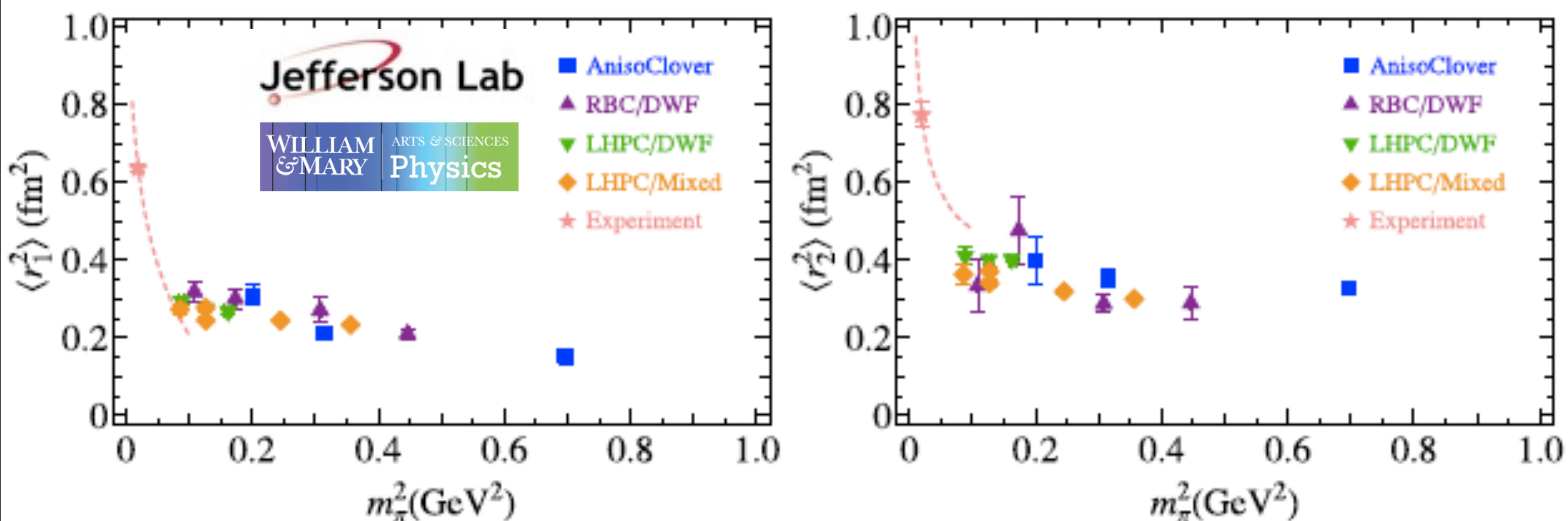


Quenched A = 3 and 4 , m_π~800 MeV

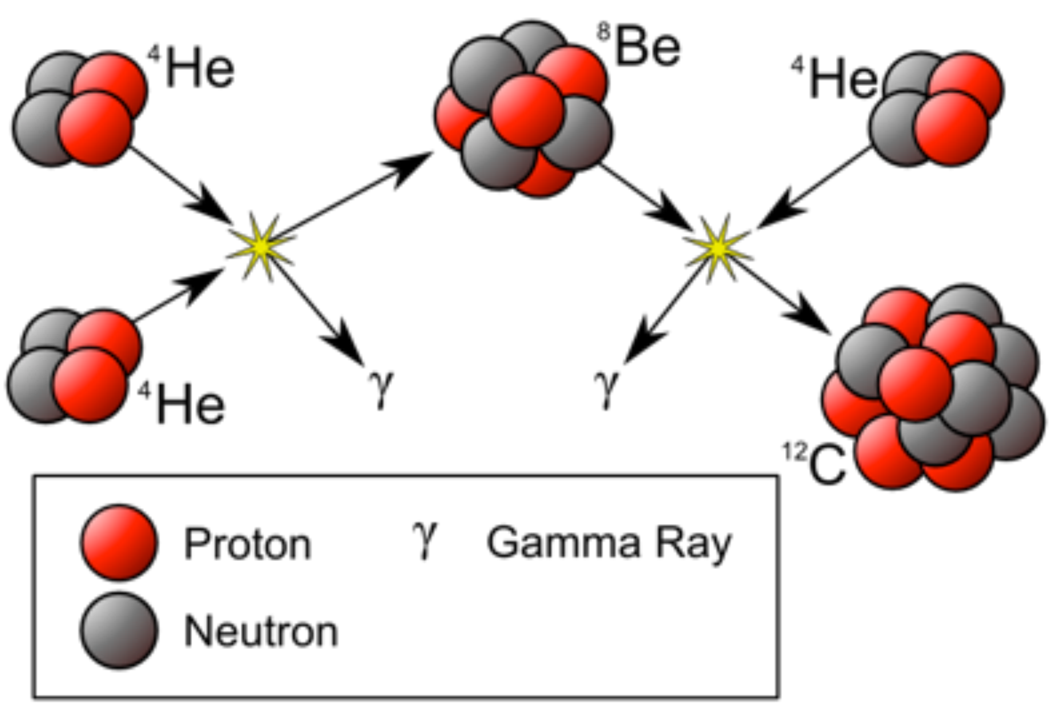


PACS-CS
2009

Nuclear Physics at the Physical Pion Mass



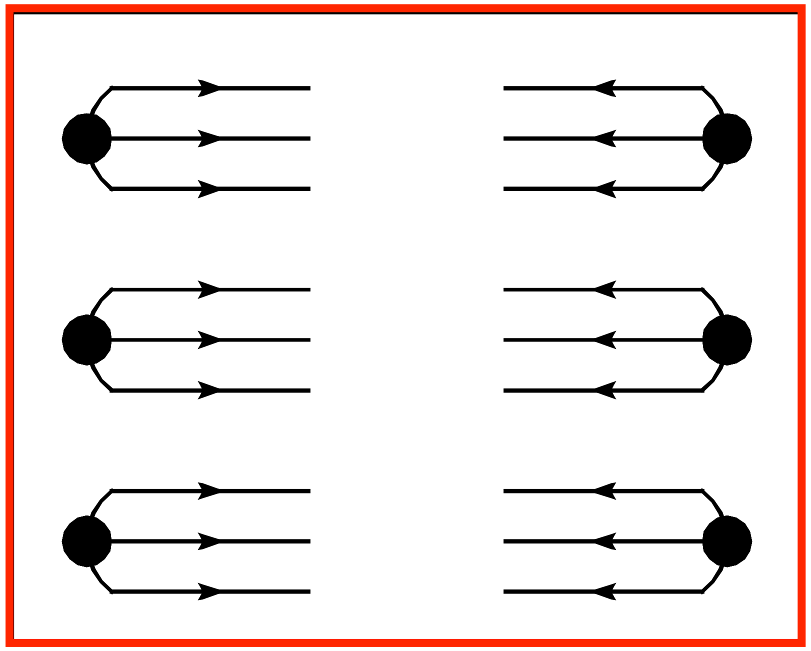
Chiral Behavior
-QCD symmetries



Nuclear Physics is Fine-Tuned
-QCD input parameters
-Our universe is special ?

Many Nucleons (Baryons)

Large number of Wick contractions



Proton : N ^{cont} = 2

^{235}U : N ^{cont} = 10^{1494}

$$
\begin{aligned}
N_{\text{cont.}} &= u!d!s! \quad (\text{Naive}) \\
&= (A+Z)!(2A-Z)!s! \\
&\sim A^3 \ (\text{Kaplan})
\end{aligned}
$$

Symmetries provide significant reduction

$$^3\text{He} \ : \ 2880 \rightarrow 93$$

Recursion Relations

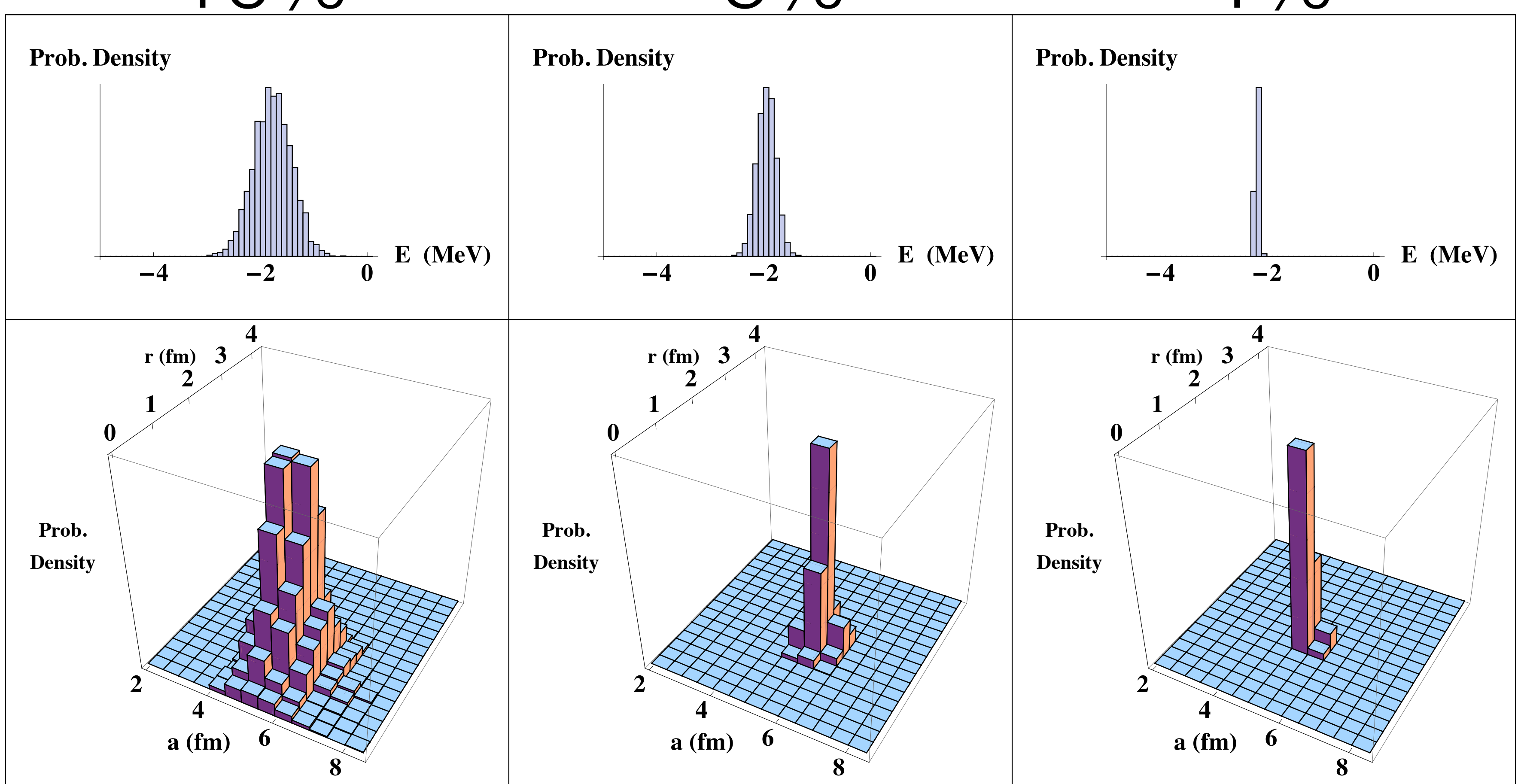
Simulated Calculations of the Deuteron

(NOT actual calculations)

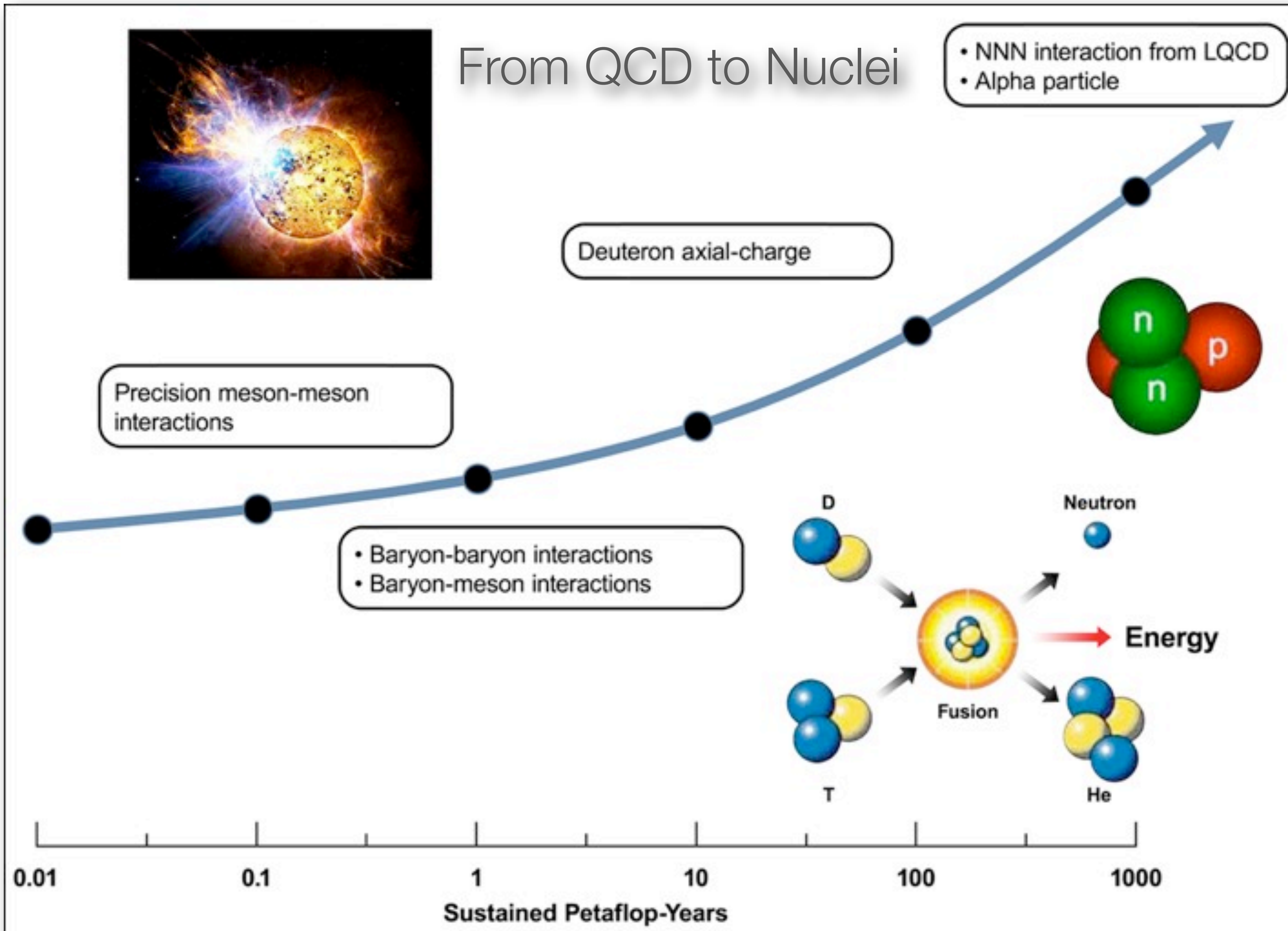
Precision Level of Energy Shift	Bound State Energy (MeV)	1^{st} ContinuumLevel (MeV)
0%	-3.147	4.005
1%	-3.111 ± 0.031	4.015 ± 0.040
5%	-2.95 ± 0.16	4.24 ± 0.20
10%	-2.66 ± 0.31	3.65 ± 0.40

$$E_D \sim 2\ \mathrm{GeV}$$
$$\Delta E_D \sim 2\ \mathrm{MeV}$$

10% 5% 1%



Computational Requirements

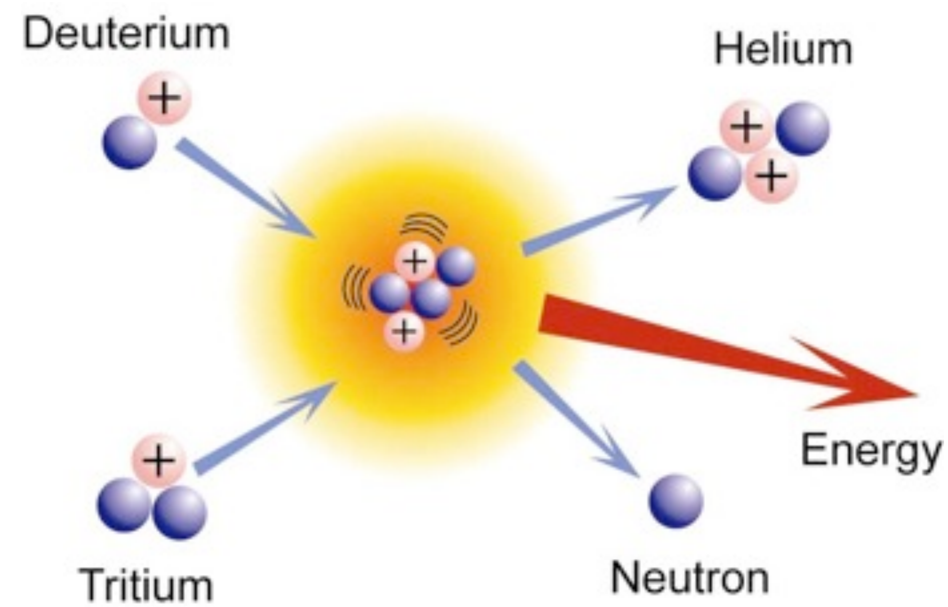



Scientific Grand Challenges
FOREFRONT QUESTIONS IN NUCLEAR SCIENCE AND THE ROLE OF COMPUTING AT THE EXTREME SCALE
January 26-28, 2009 • Washington, D.C.
U.S. DEPARTMENT OF ENERGY

Electromagnetism
Isospin Breaking
The Real Deal !

Beyond Computational Requirements: Formal Issues , e.g.

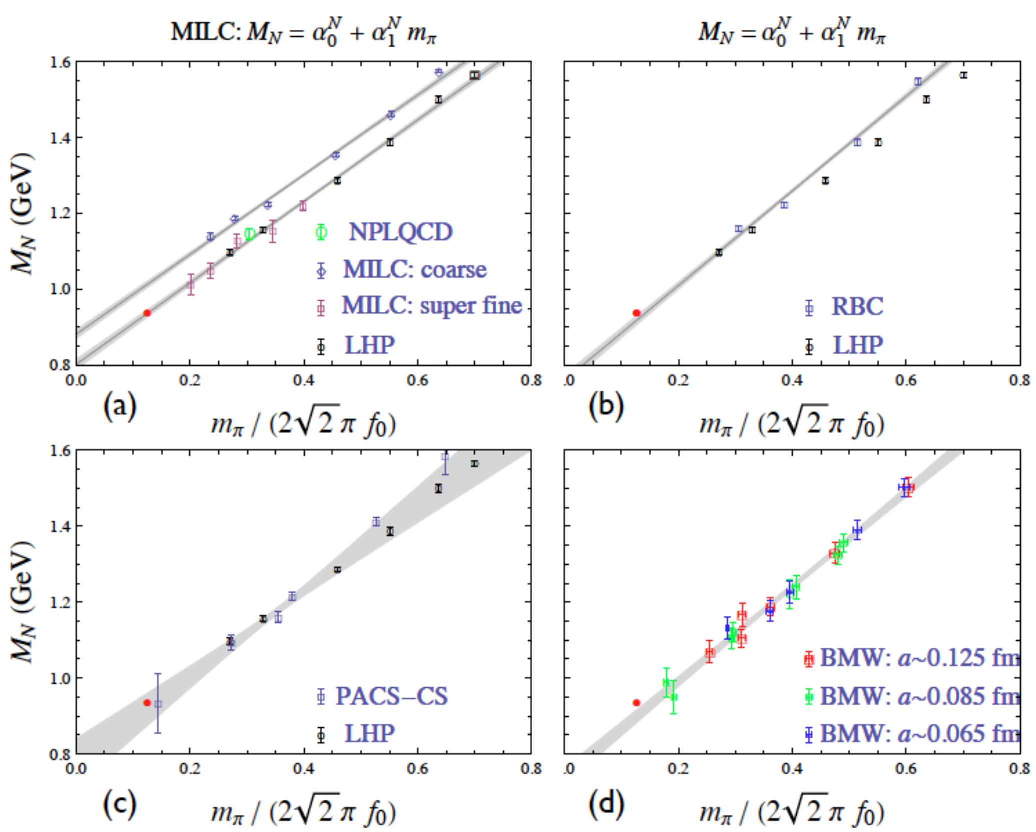
What Lattice QCD calculations are required to predict multi-body nuclear reactions ?



What length-scales determine the convergence of EFT expansions ?

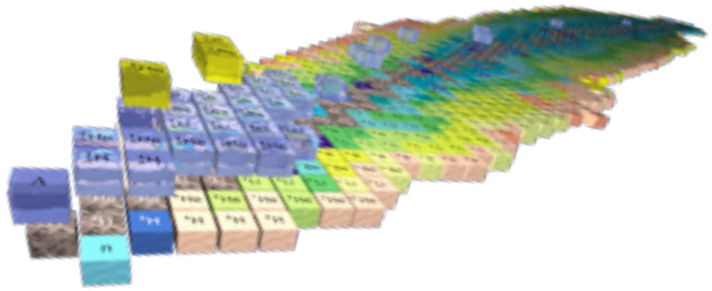
(to predict more complex systems than LQCD can access)

(quark masses, number of flavors?)

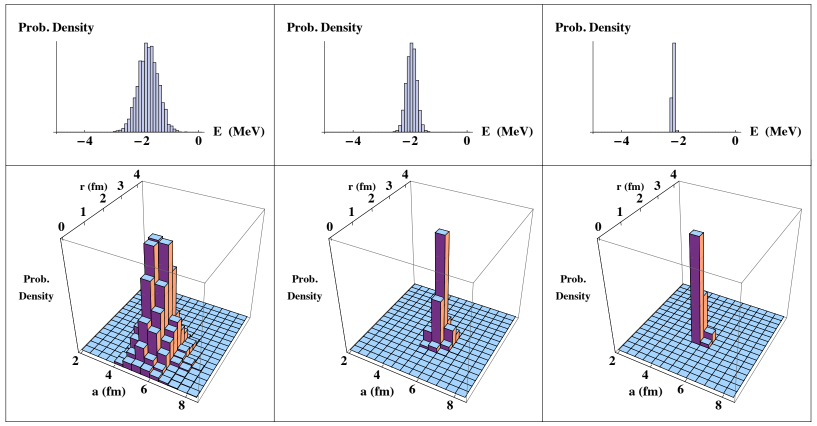


(A. Walker-Loud)

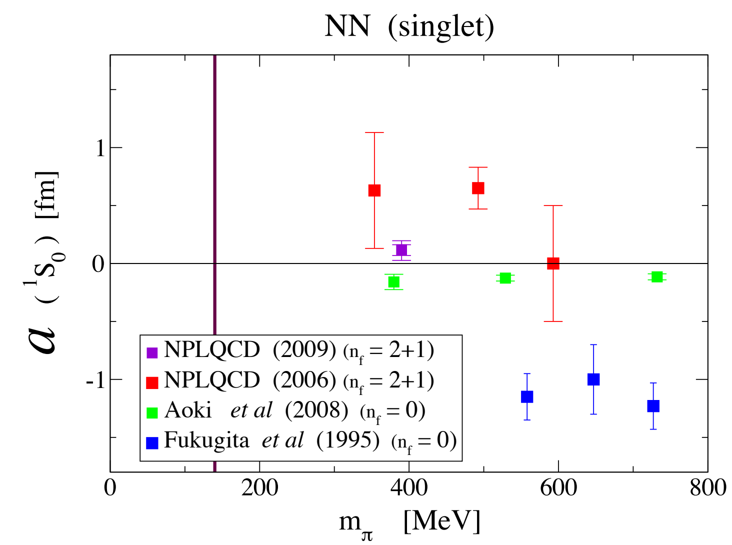
Nuclear Theory Needs (physical m_π)



- What do we expect to observe in LQCD calculations in a finite volume
  - Need 3-body and 4-body spectrum (cubic volumes)
    - With and without background electroweak fields

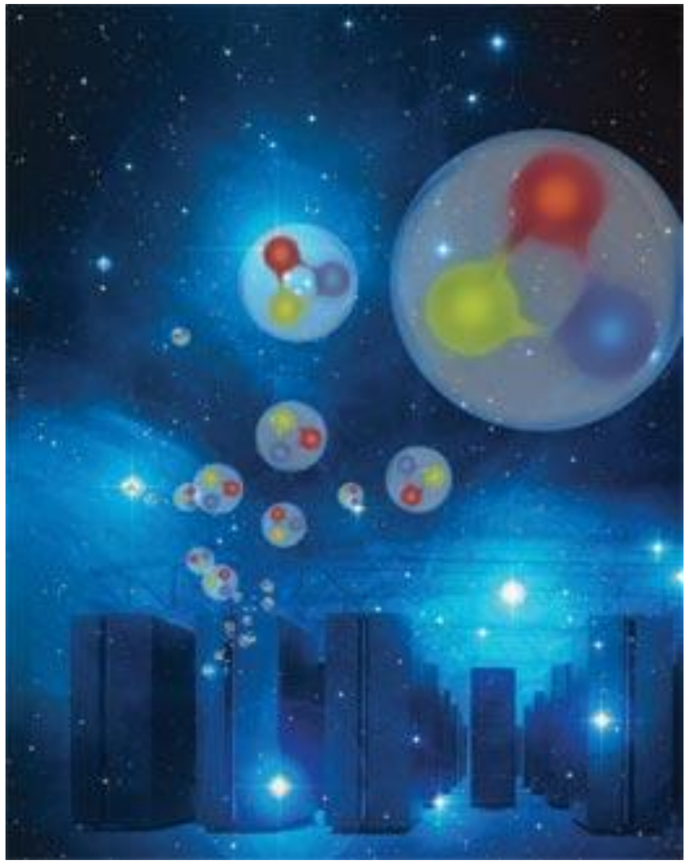


- How to optimally invert lattice data
  - what volumes should we calculate with ?



- Quark-mass dependence
  - Higher orders in EFT for few-body systems

Closing Remarks



- Close to discovering how hadrons and nuclei emerge from quarks and gluons using Lattice QCD

- Moving toward light nuclear systems with quantifiable and removable uncertainties
  - input into larger scale nuclear calculations

Organizers : Thank You

END