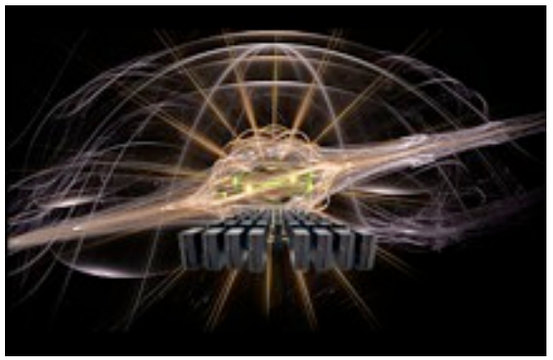
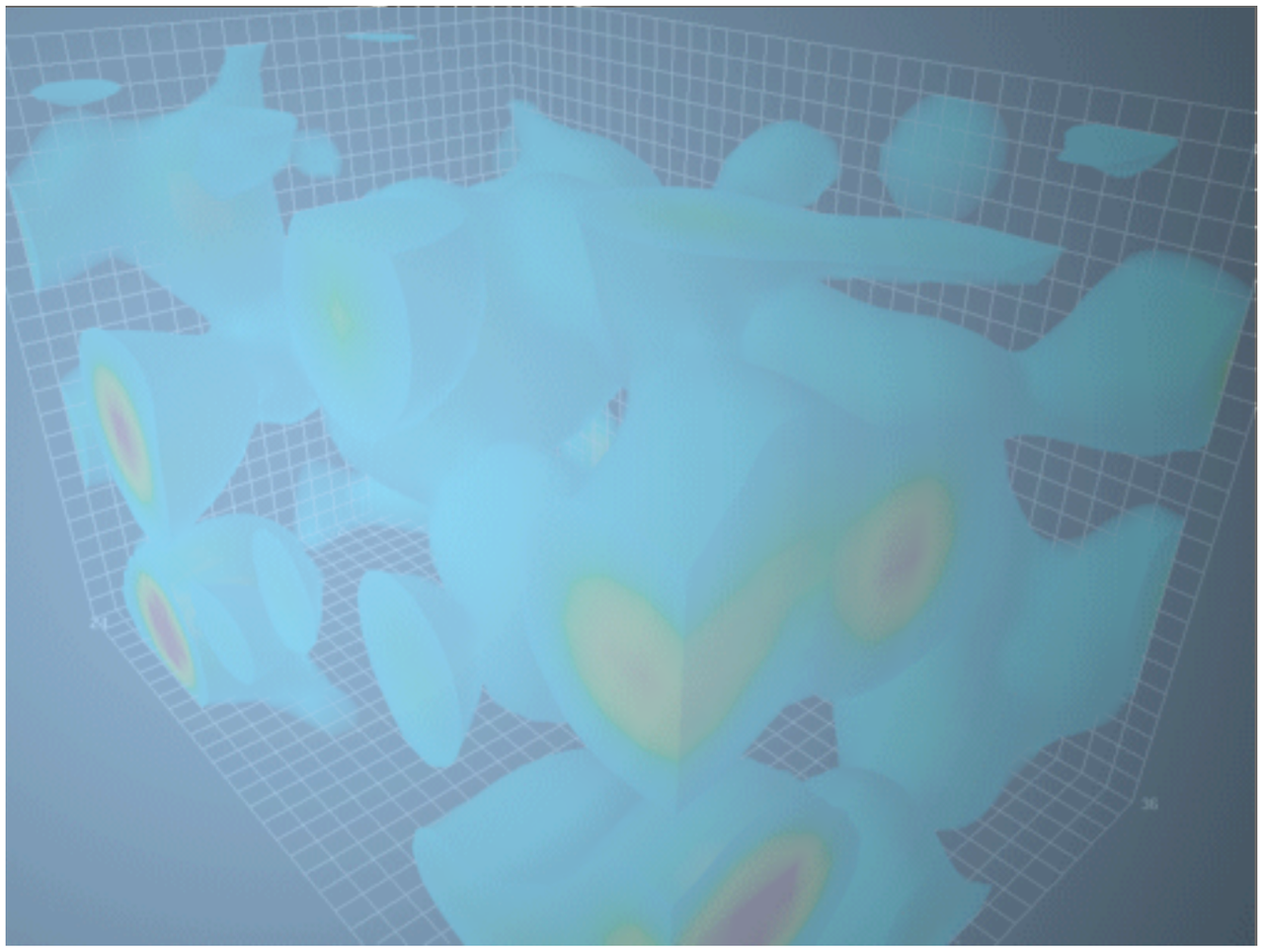
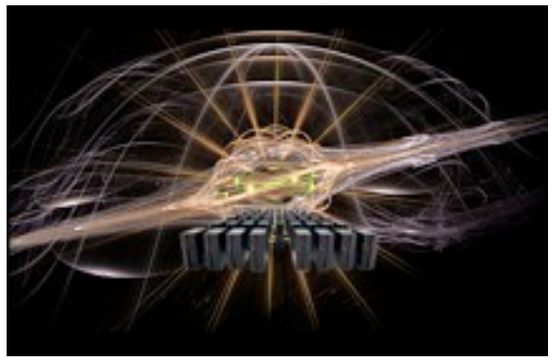




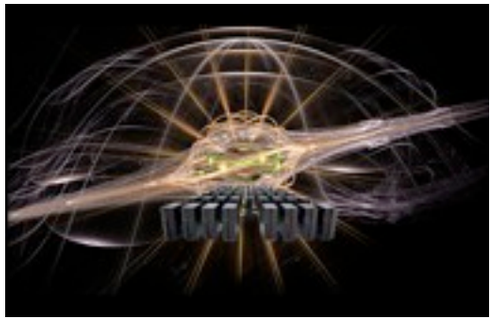


Nuclear Forces from Lattice Quantum Chromodynamics

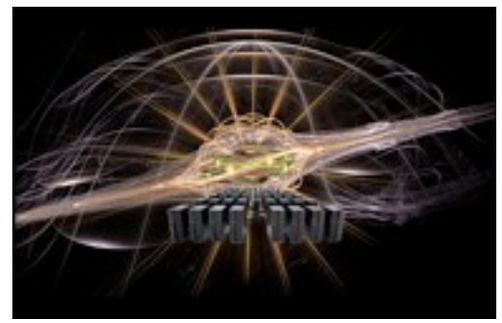
Martin J. Savage
University of Washington

International Conference on Nuclear Theory in the Supercomputing Era - 2013

Iowa , May 2013



Me and James : **197.327**



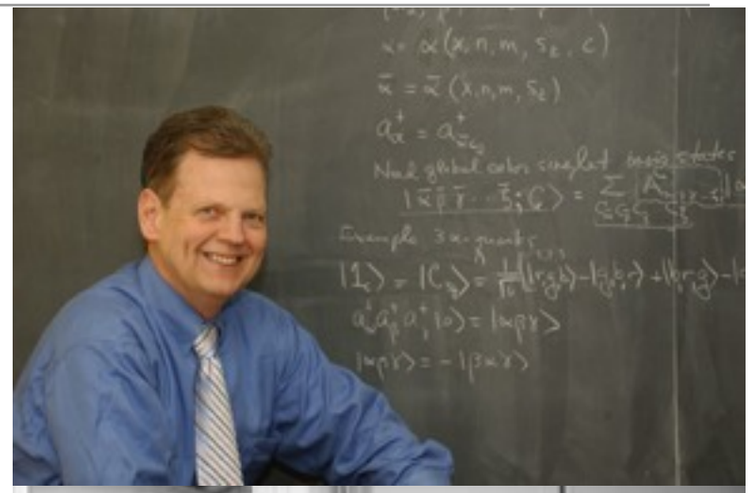
Caltech 1985-86

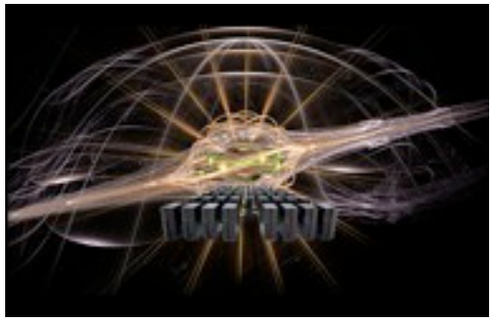
James : Visiting Professor

Me : first year grad student

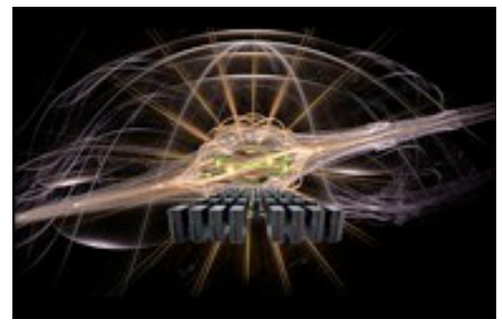
Computer : big old VAX

Result : I know **ħc** !

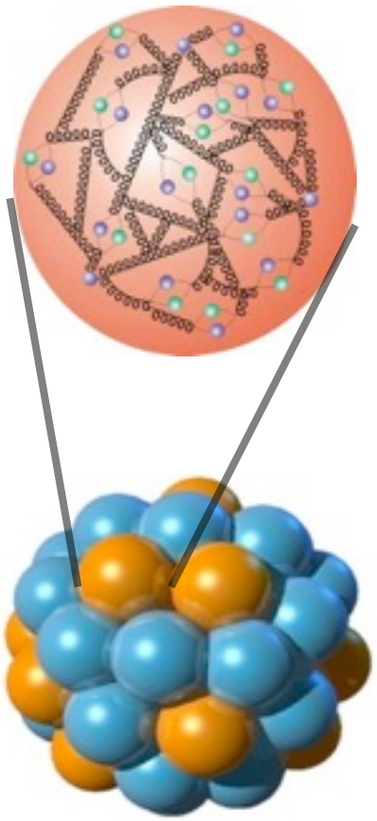




The Structure and Interactions of Matter from QCD

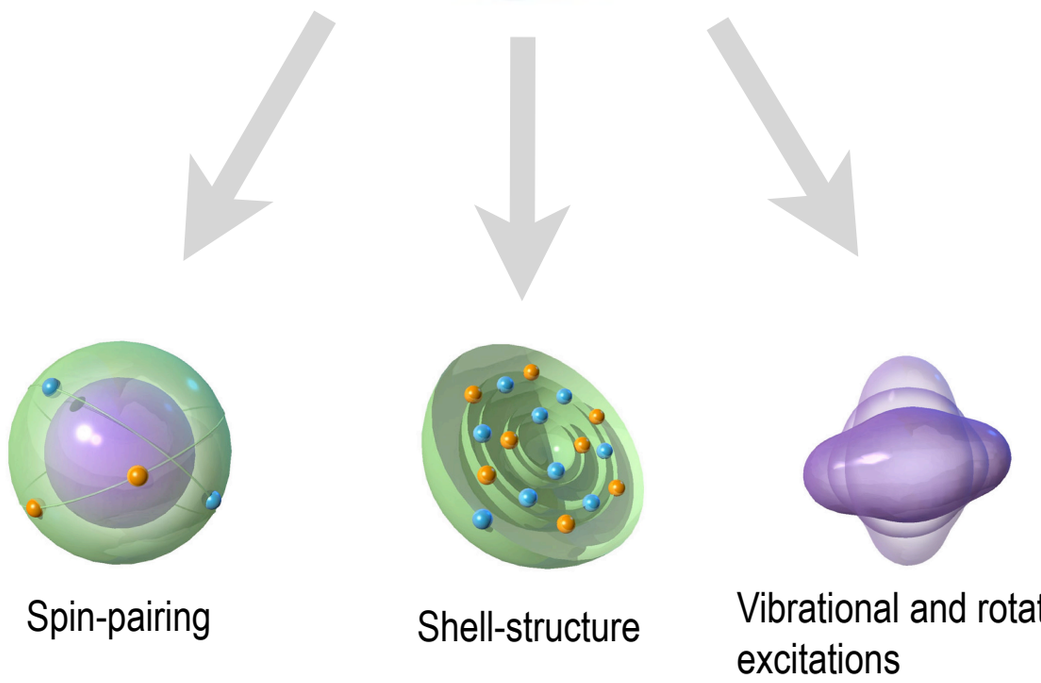


Proton



Quarks and Gluons

Nucleus



Spin-pairing

Shell-structure

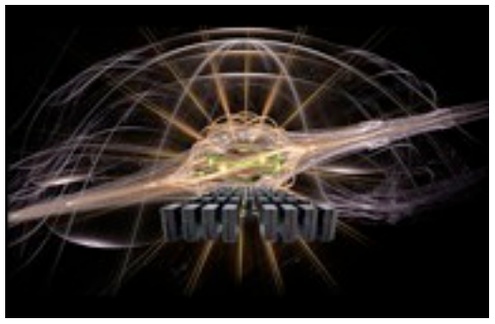
Vibrational and rotational excitations

$$\Lambda_{\mathrm{QCD}}$$

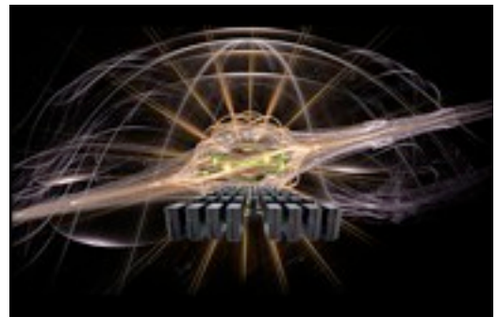
$$\frac{m_u}{\Lambda_{\mathrm{QCD}}} \qquad \frac{m_d}{\Lambda_{\mathrm{QCD}}} \qquad \frac{m_s}{\Lambda_{\mathrm{QCD}}}$$

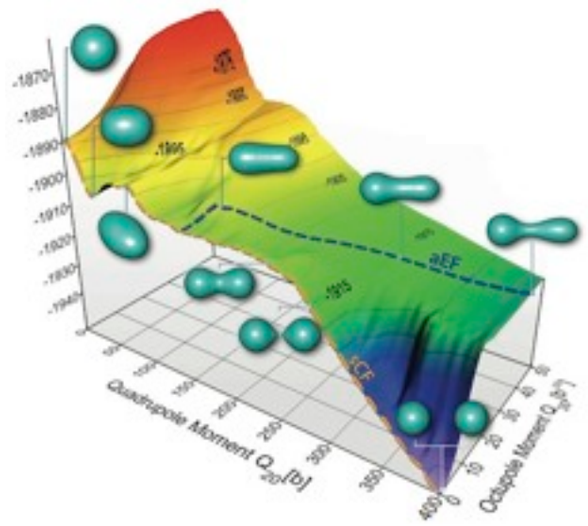
$$\alpha_e$$

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



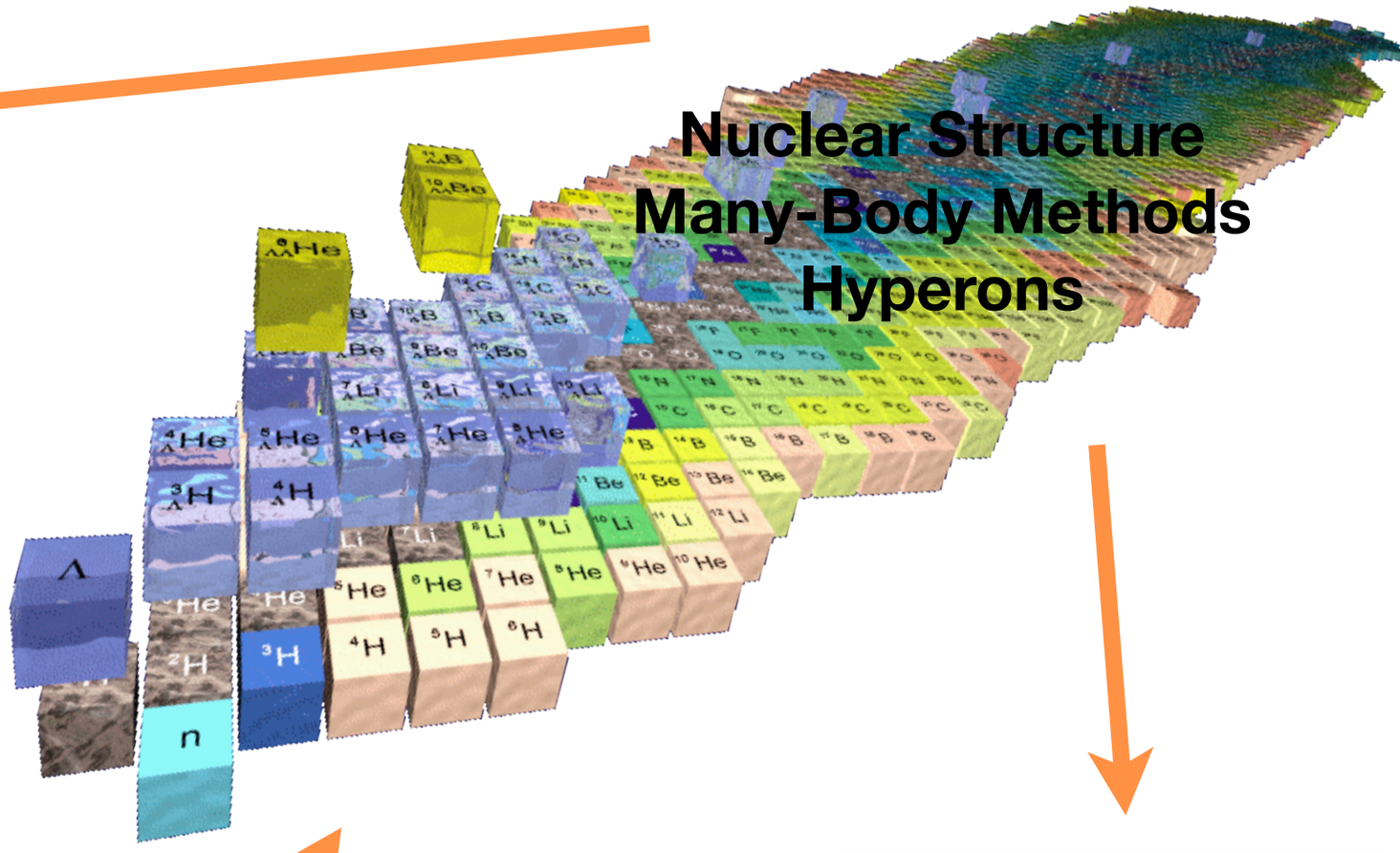
The Road from QCD



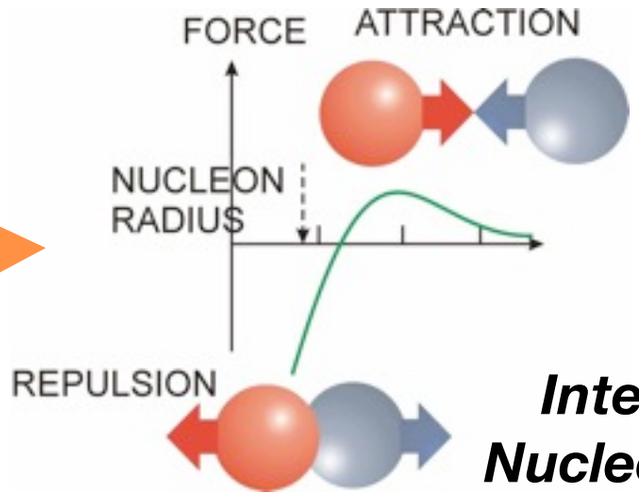


Spectrum and Structure of the Nucleon

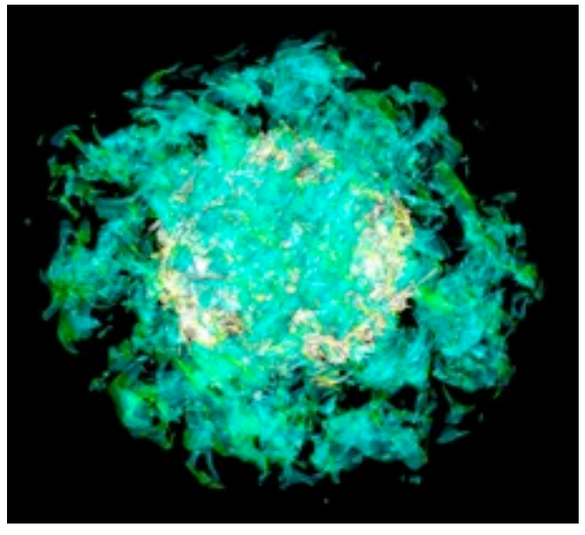
Nuclear Structure
Many-Body Methods
Hyperons

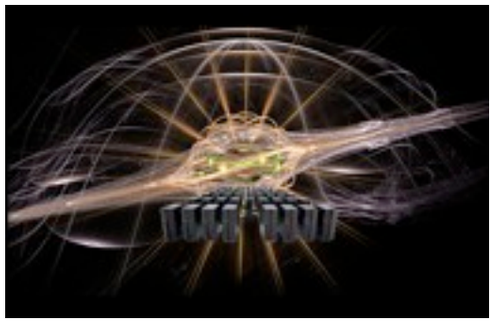


Solve QCD

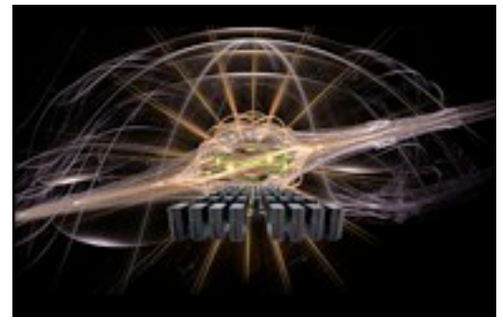


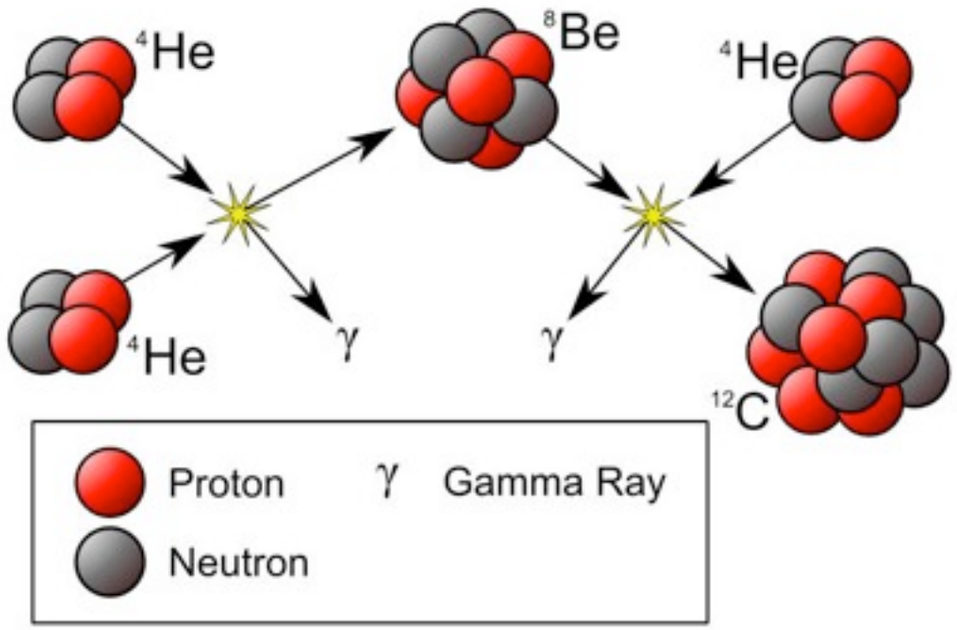
Interactions of the Nucleon and Hyperons

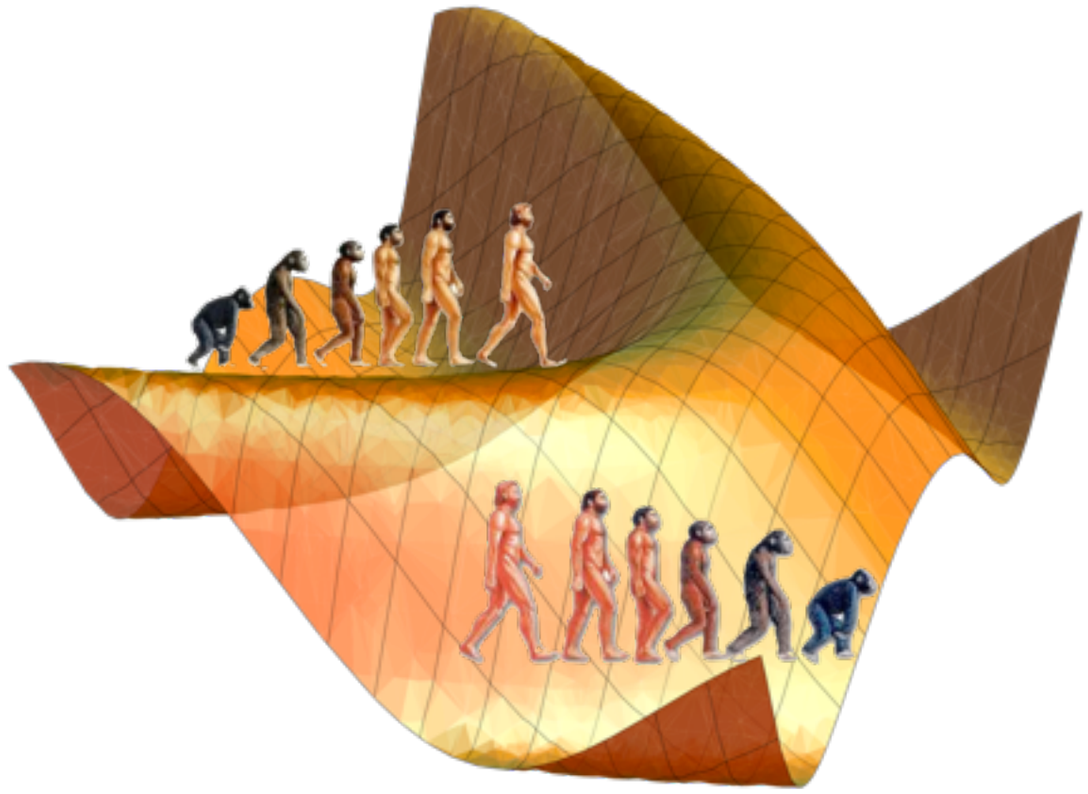




Fine-Tunings define our Universe

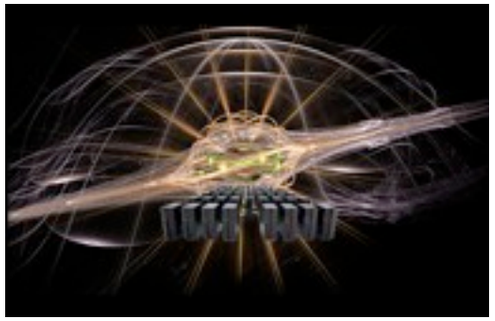






Parameter/Gauge Landscape

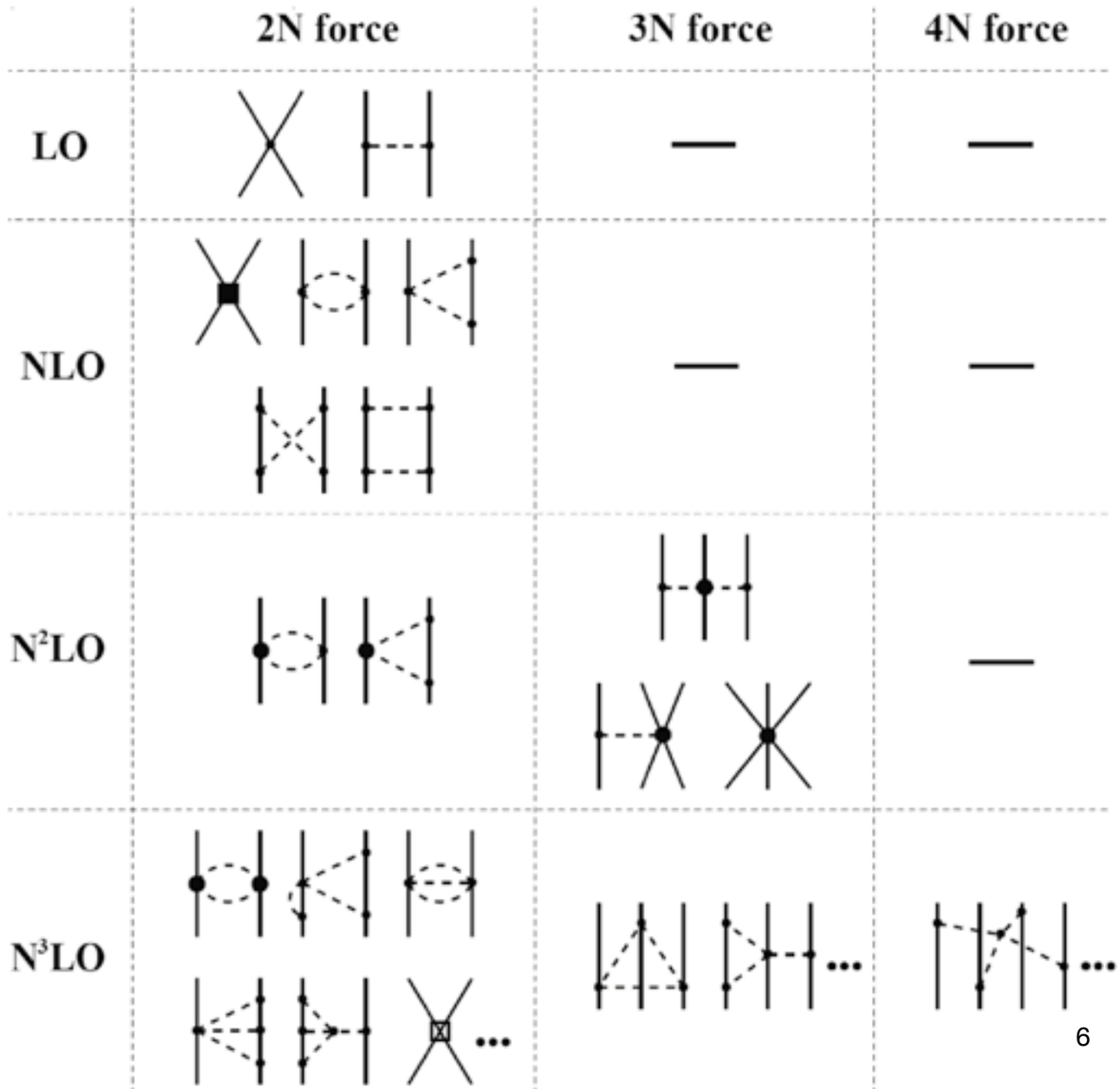
- Nuclear physics exhibits fine-tunings
  - *Why ??*
  - *Range of parameters to produce sufficient carbon ?*
- Need to calculate over a range of parameters to disentangle the chiral nuclear forces anyway!



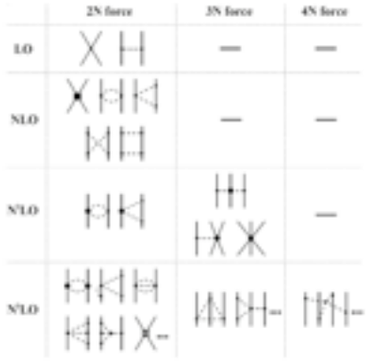
Organizing Nuclear Forces

Effective Field Theory introduced by Weinberg in the early 1990's to systematize nuclear forces

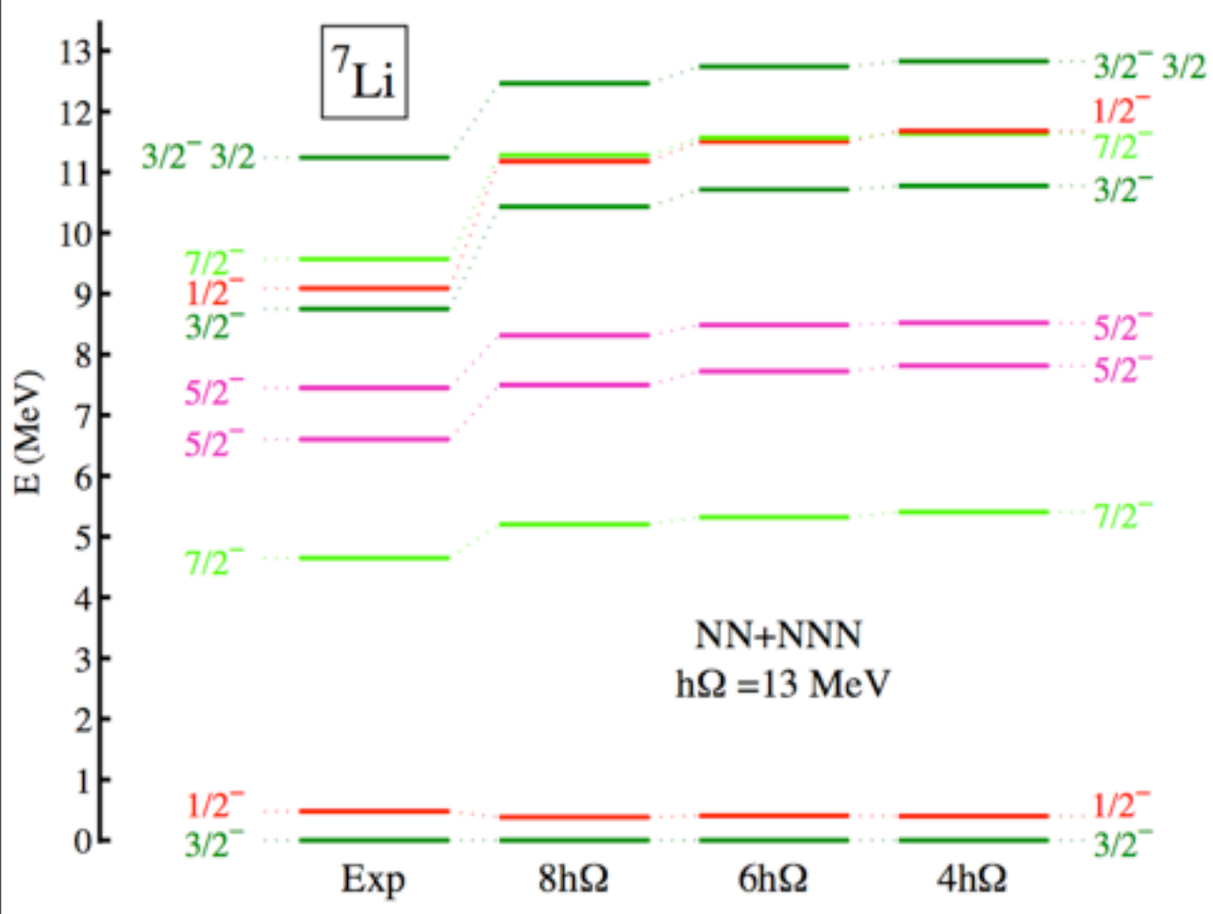
- Low-energy EFT of QCD
- Chiral symmetries of QCD
- Quark mass dependence
- Interesting RG behavior
- Softer Interactions
  - V_{lowk} , SRG
- Organization of multi-nucleon forces

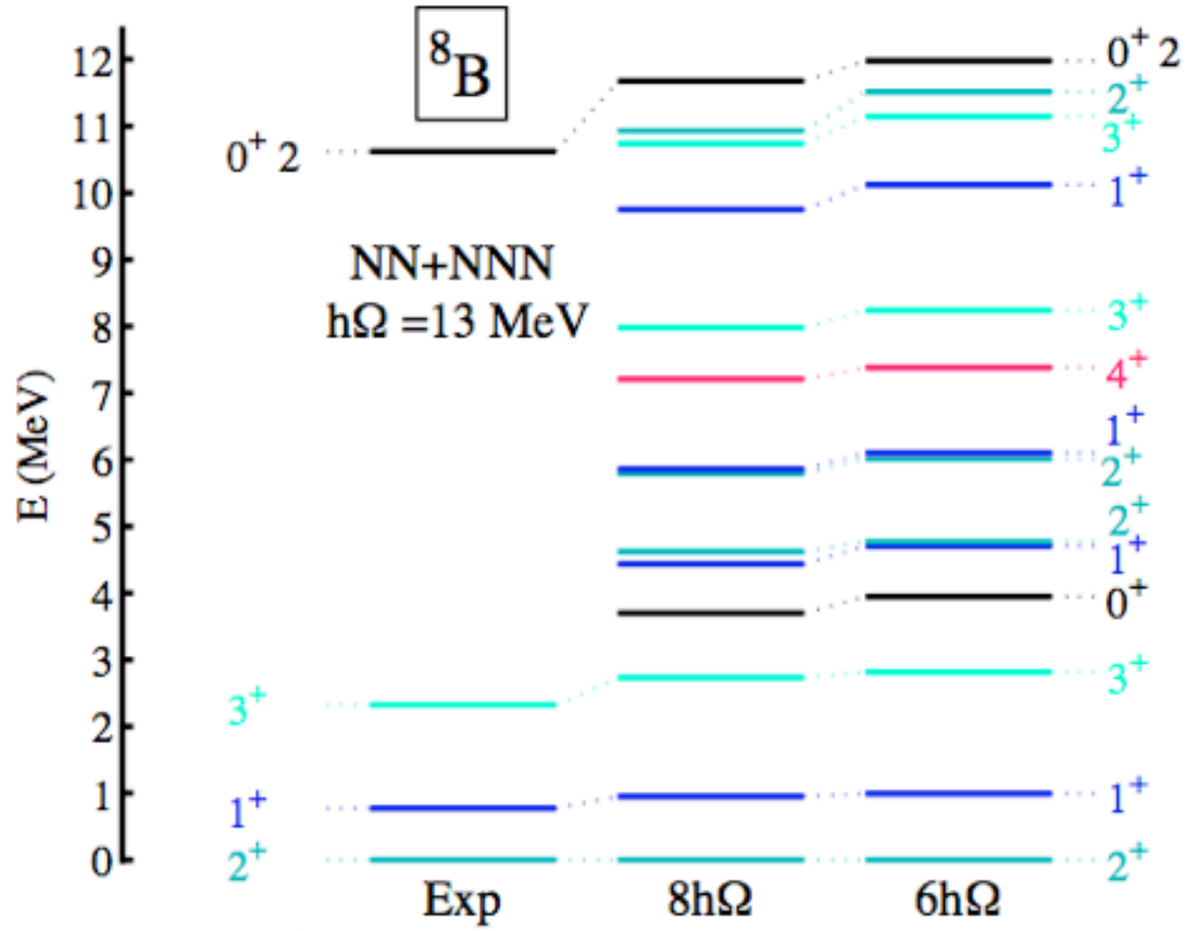


Chiral Interactions in Nuclear Calculations



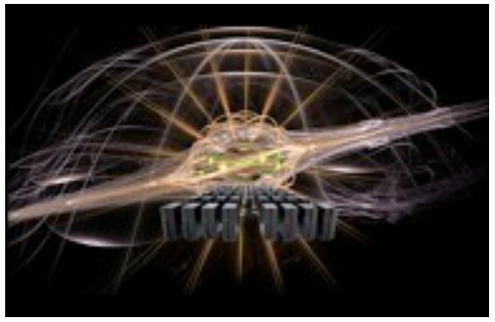
No-Core Shell Model Calculations with Chiral Forces



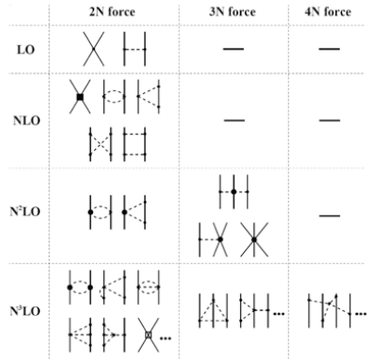


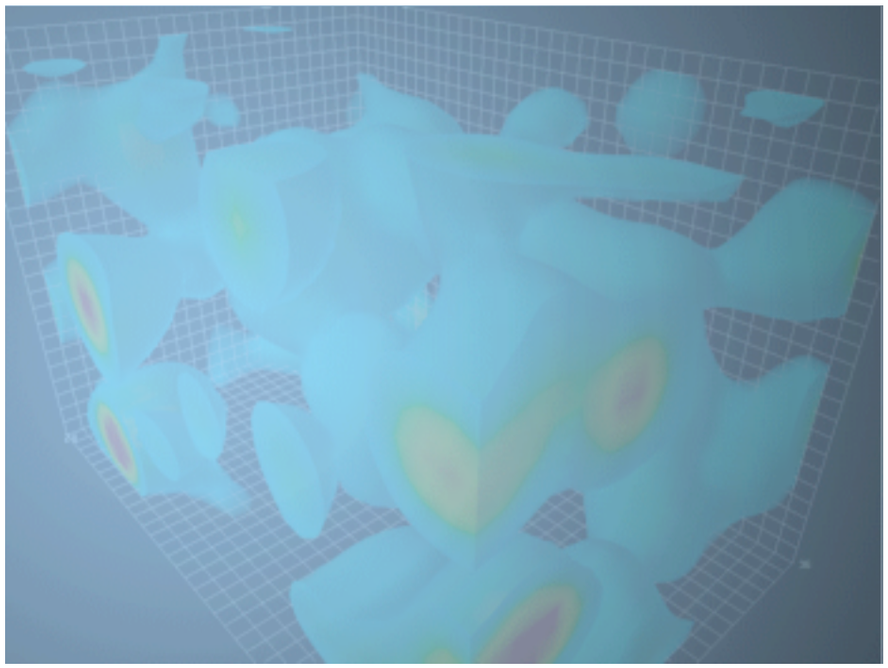
(Maris, Vary, Naratil, 2012)

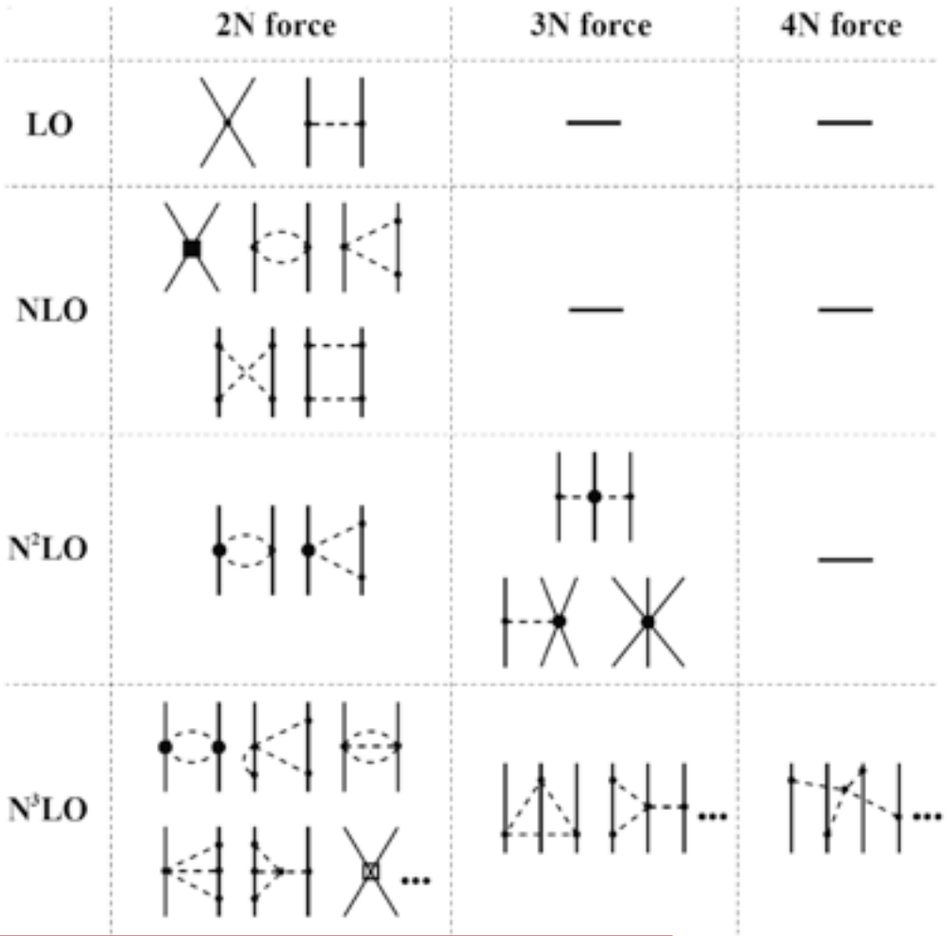
Experiments constrain counterterms leading to predictions for other observables at a given order in the EFT expansion



Refining Nuclear Forces and Multi-Nucleon Interactions: Enhancing Predictive Capabilities







QCD to constrain counterterms

i) Verification and/or better experiment (?)

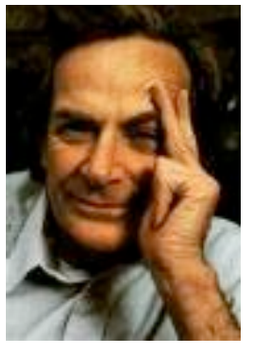
ii) Inaccessible to experiment, e.g. nnn, nnnn

iii) Number of counterterms for required level of precision

iii) and/or direct calculation of desired quantity

Lattice QCD

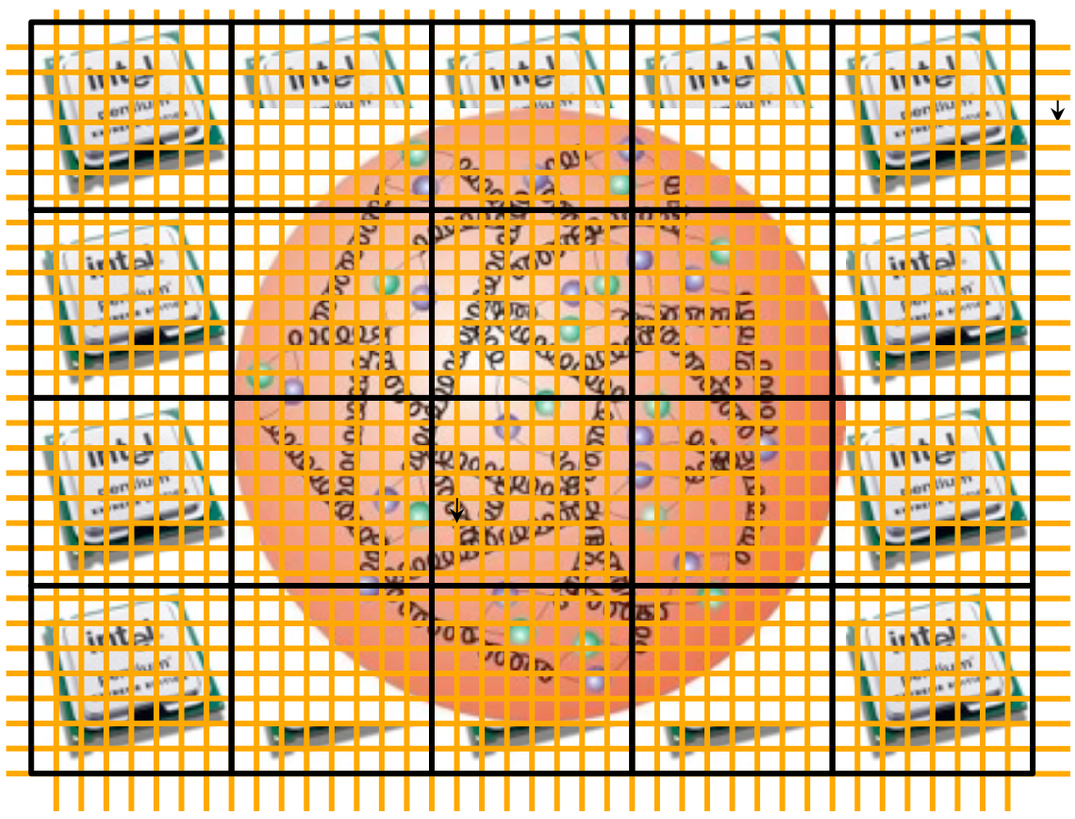
Monte-Carlo Evaluation of QCD Path Integral



Propagators Gauge Configurations

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

Prob(U) ~ exp(-S[U])



Not Quite QCD !

Lattice Spacing :

$a << 1/\Lambda\chi$

(Nearly Continuum)

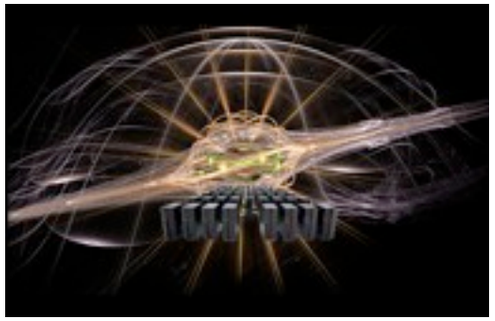
Lattice Volume :

$m_\pi L >> 2\pi$

(Nearly Infinite Volume)

Systematically Extrapolate to QCD

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



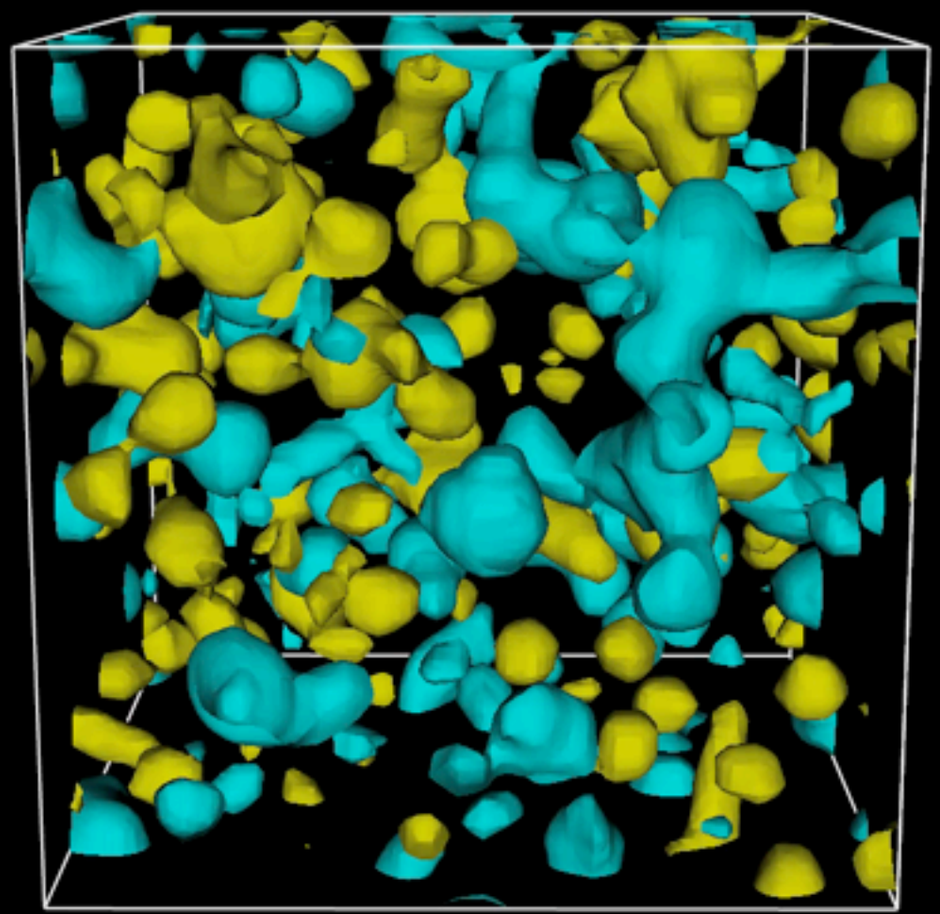
Gauge Field Configurations

The Vacuum is Complex

SciDAC
Scientific Discovery through Advanced Computing

USQCD

The Quantum Vacuum

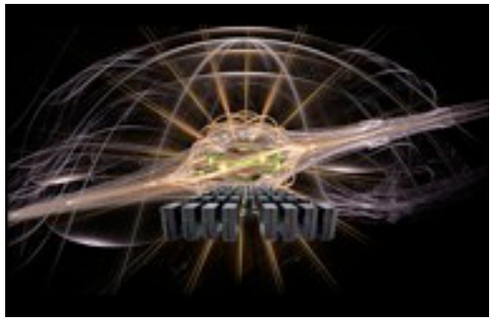


Topological Charge Density
(Massimo DiPierro)

$L \sim 4$ fm

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

"Pixelation" ~ (0.12 x 10^{-15} m)^3

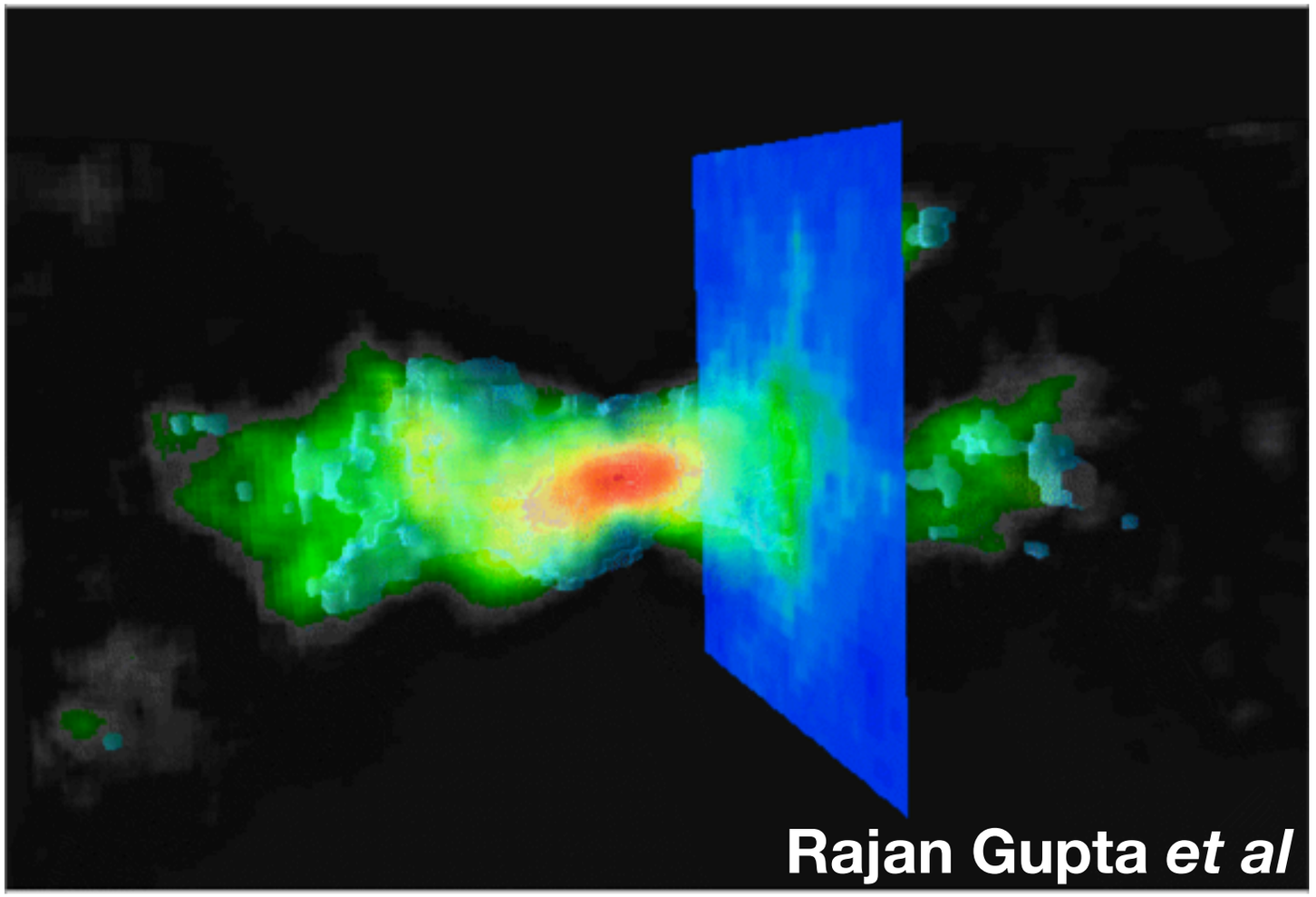


Quark Propagators

Quarks and Gluons are Confined (T=0)

SciDAC
Scientific Discovery through Advanced Computing

USQCD

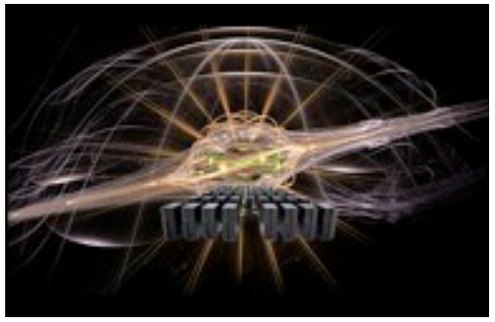


No isolated (free) quarks

Cancellation of Probability Amplitudes

Quark Propagator on One Gauge Configuration

Pion, Nucleon from same propagators

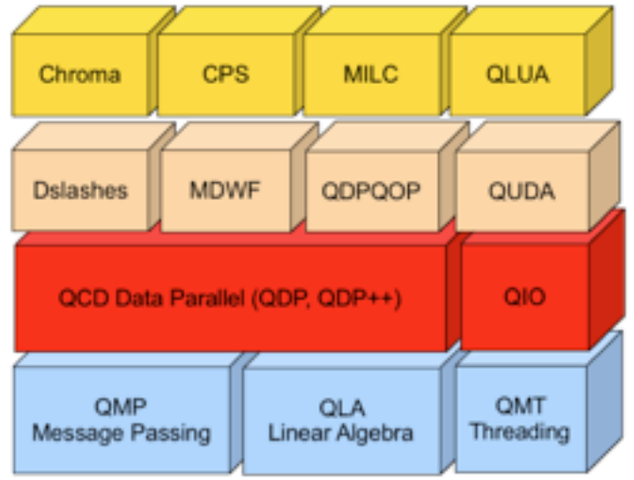


US Lattice Quantum Chromodynamics

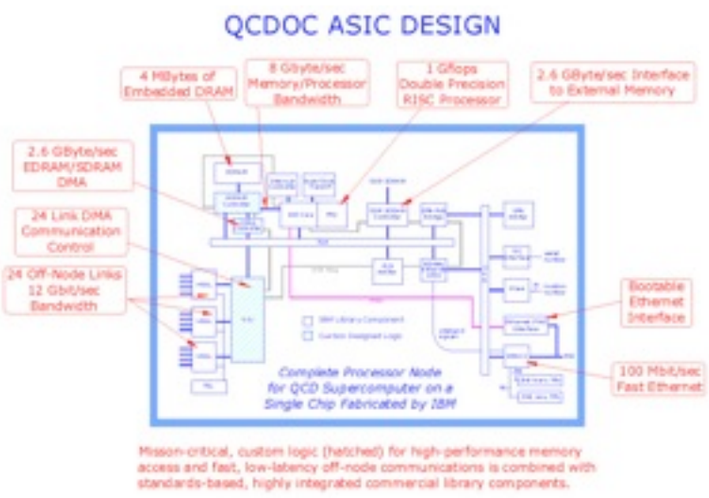
SciDAC
Scientific Discovery through Advanced Computing

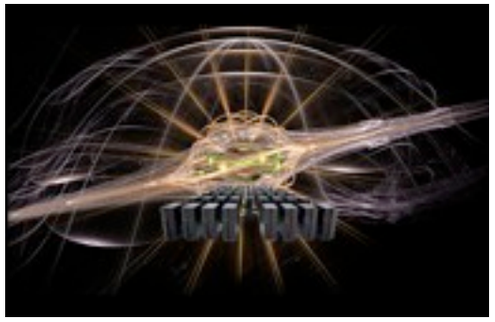
USQCD

SciDAC-3
NP/HEP



QCDSP : 1998 Gordon Bell Prize



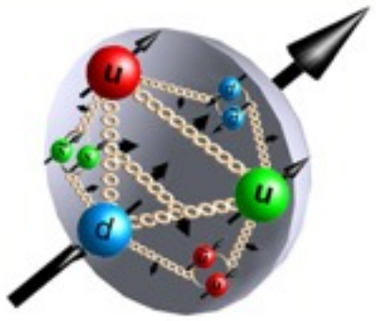


Cold Nuclear Physics

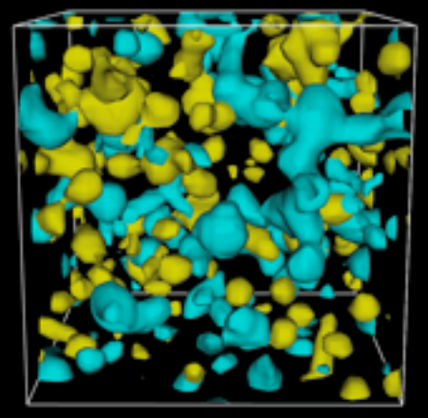
SciDAC
Scientific Discovery through Advanced Computing

USQCD

capacity resources



The Quantum Vacuum



Topological Charge Density

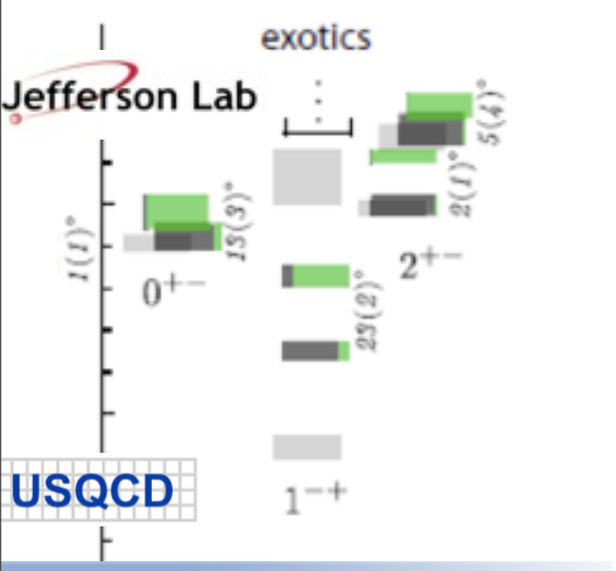
(Massimo DiPierro)

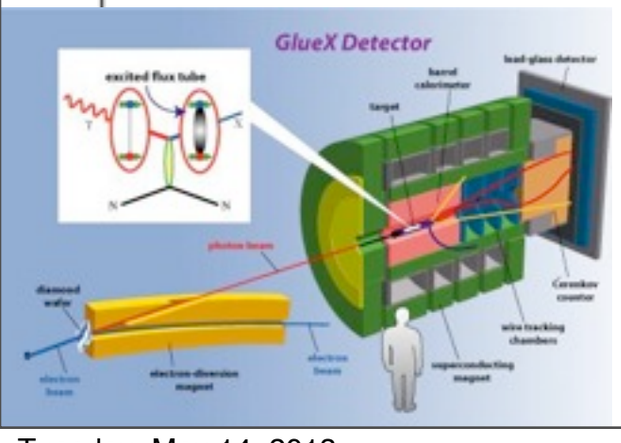
capability resources

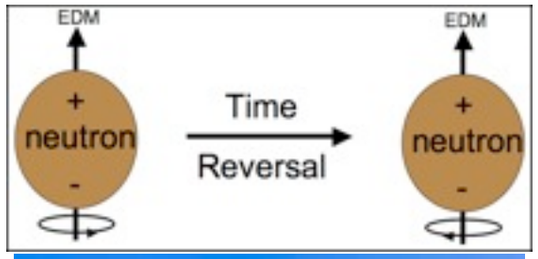
$L \sim 4$ fm

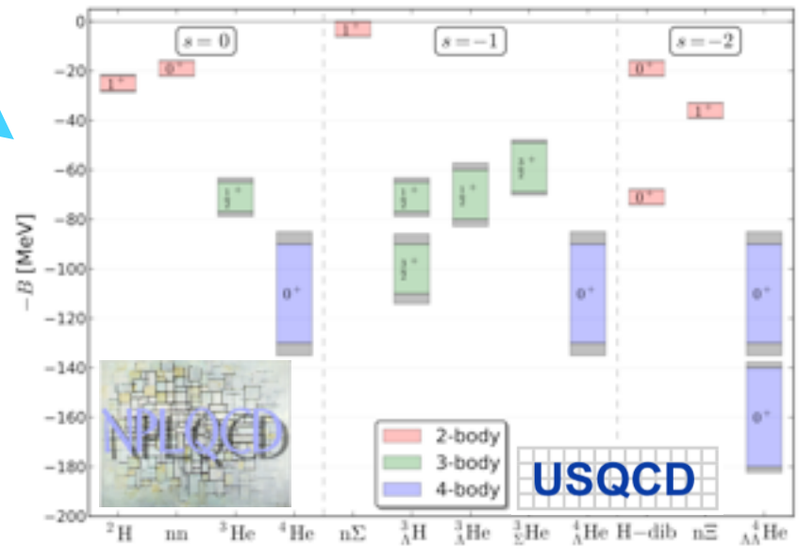
$\Delta t \sim 6 \times 10^{-24}$ s

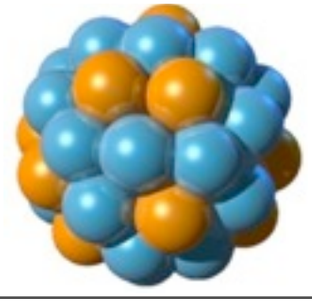
capacity resources

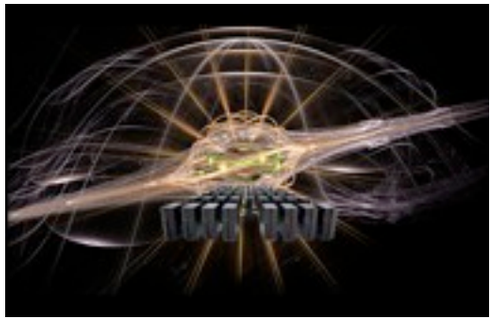








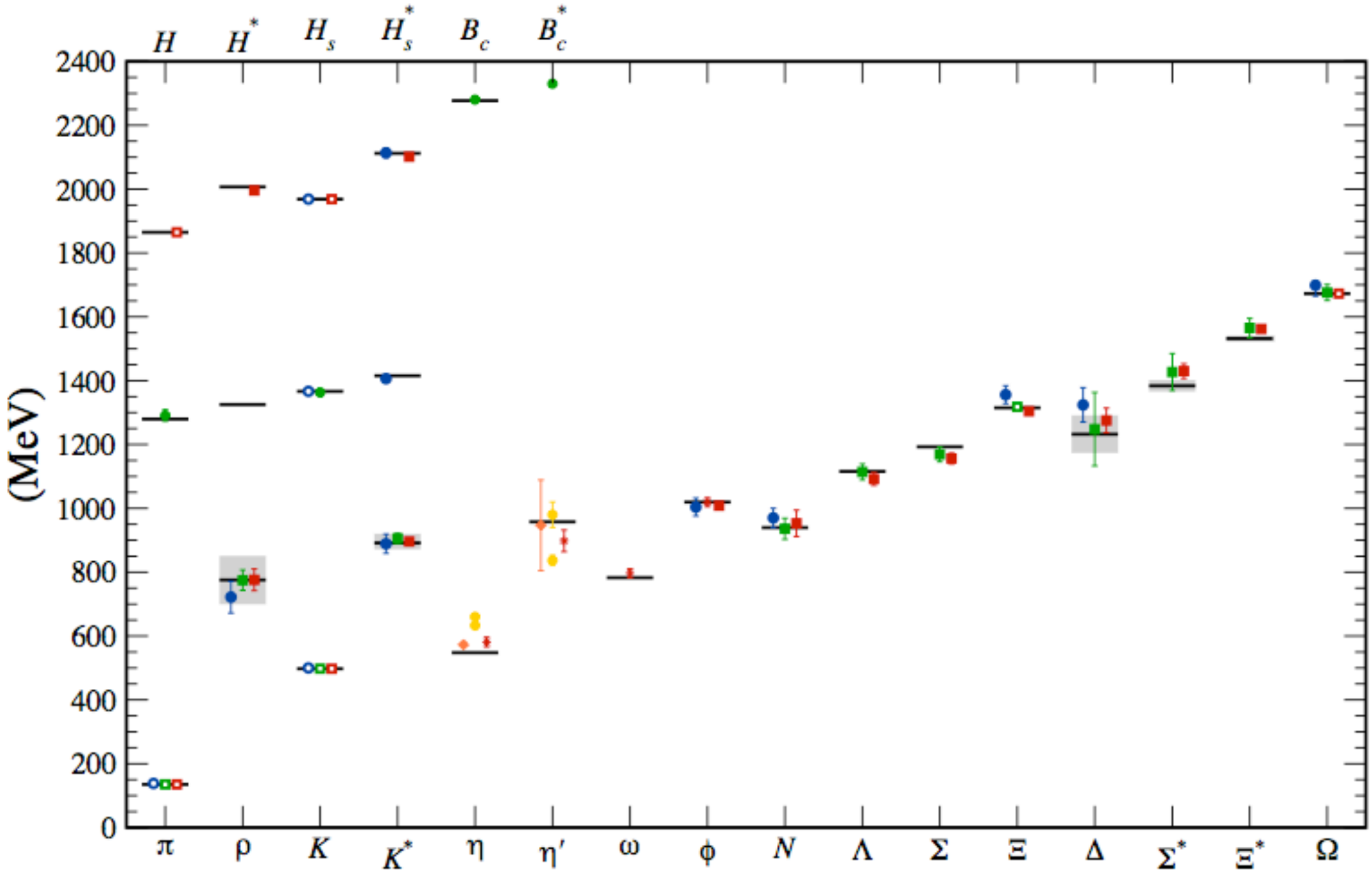




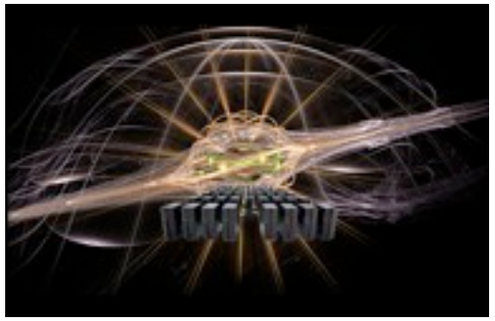
Masses of the Particles

SciDAC
Scientific Discovery through Advanced Computing

USQCD



(Kronfeld)



Structure of the Nucleon

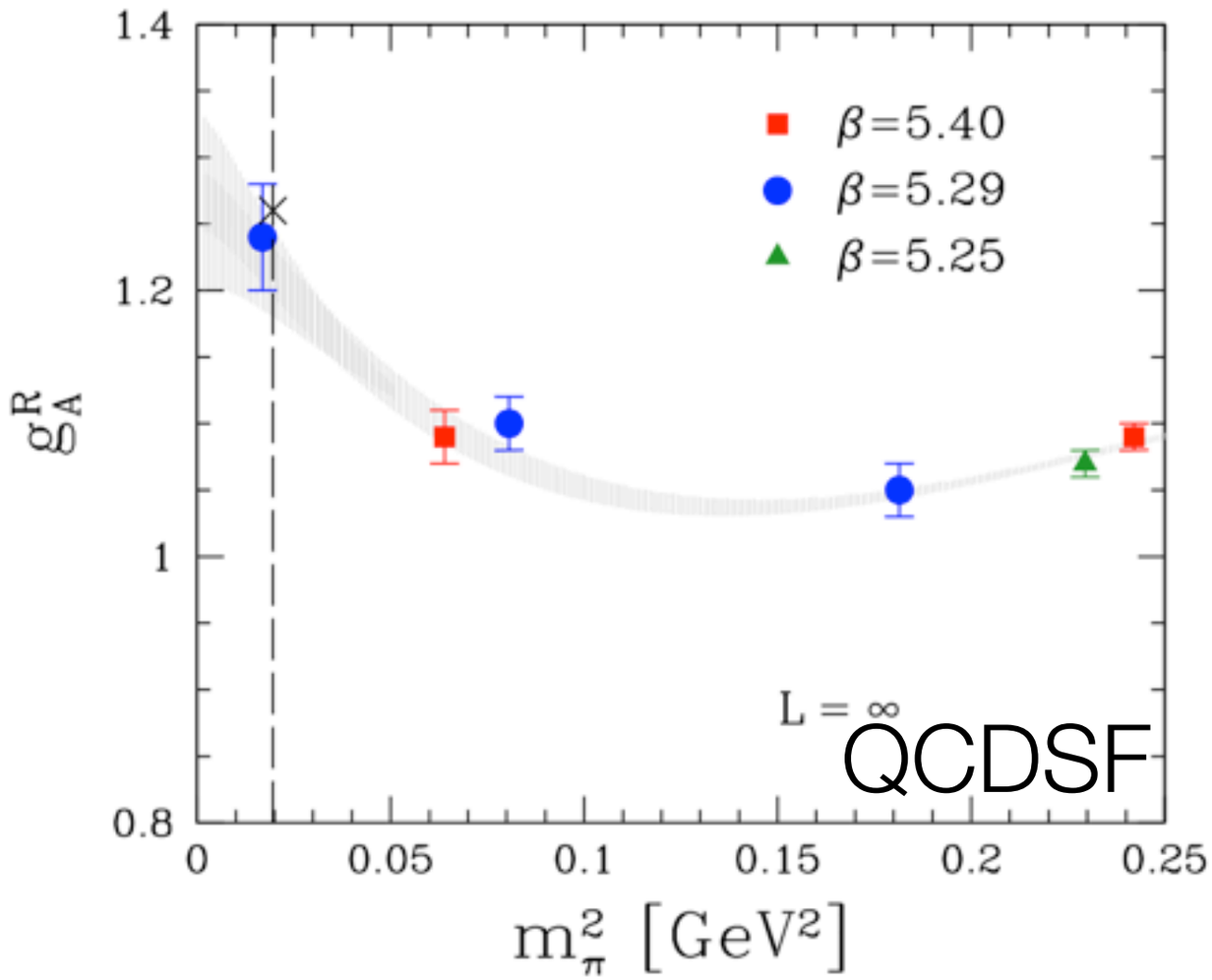
SciDAC
Scientific Discovery through Advanced Computing

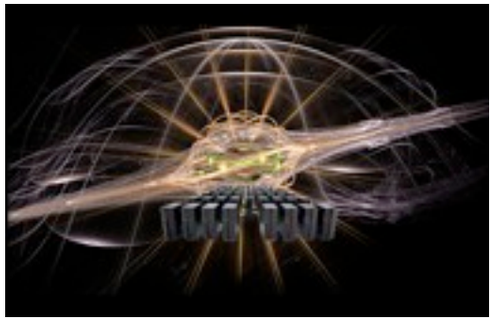
USQCD

- g_A and other $q^2=0$ matrix elements
- $\langle x^n \rangle$
- charge and magnetic radii, etc
- associated form factors

First calculations at physical pion mass during 2012

Precision is needed
(complete uncertainty quantification)



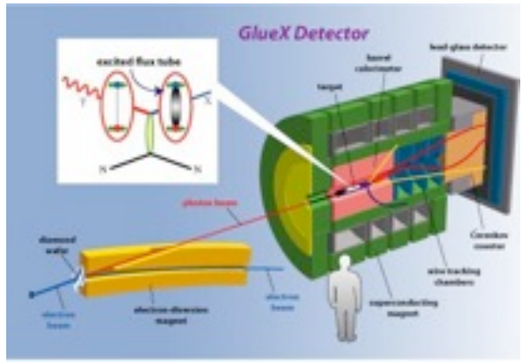


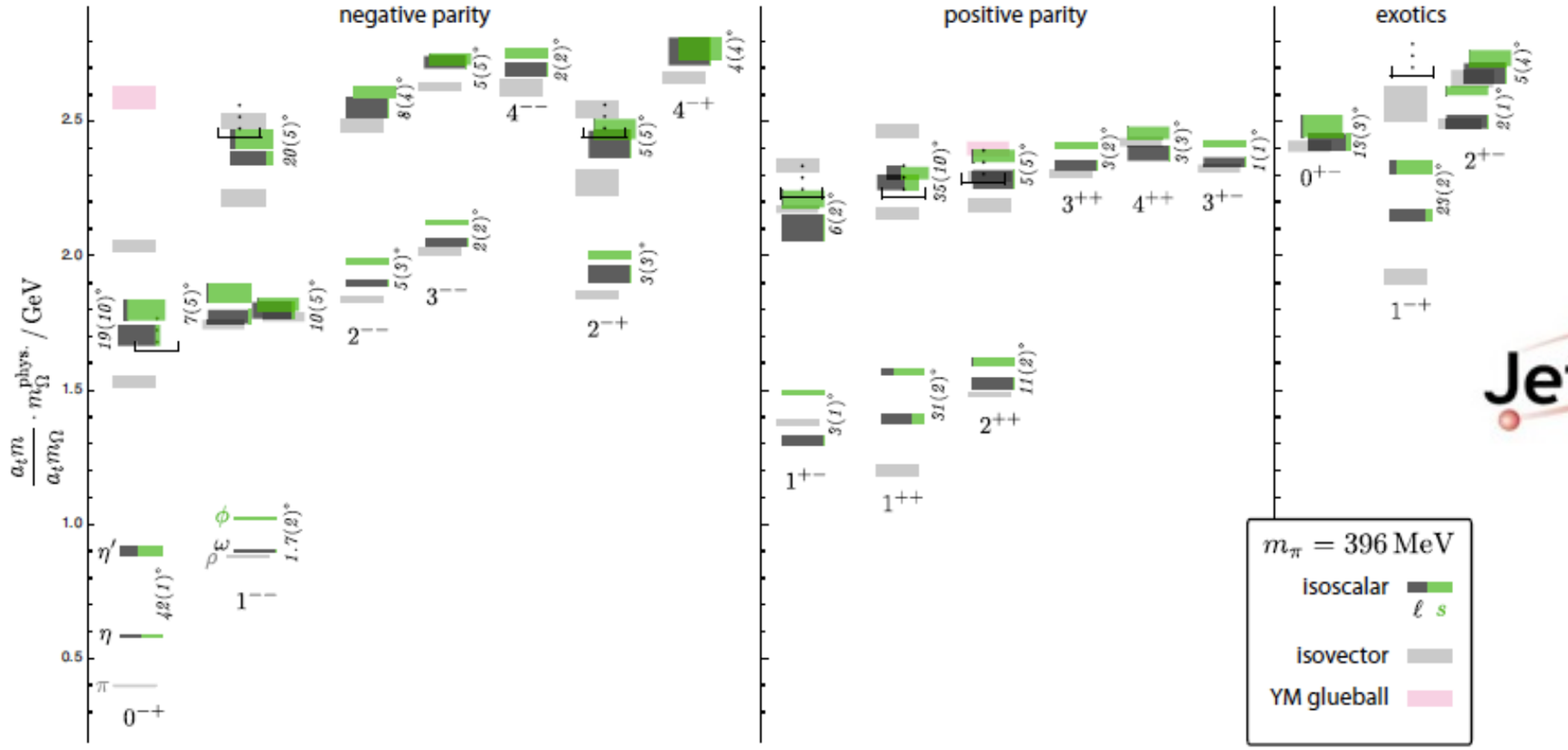
Spectrum of the Hadrons

SciDAC
Scientific Discovery through Advanced Computing

USQCD

- Spectrum of mesons and baryons
  - exotics, molecules
  - coupled channels, etc
  - provided motivation for 12 GeV upgrade



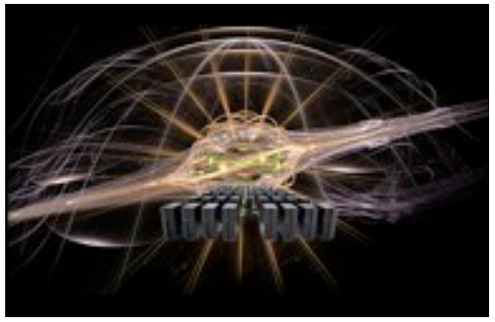


Jefferson Lab

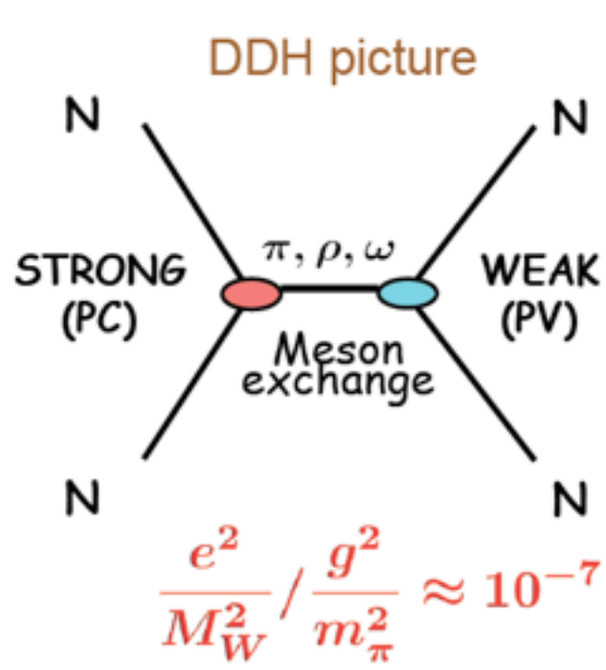
$m_\pi \sim 400$ MeV

Lattice QCD will predict the exotic spectrum before or during the GlueX experiment

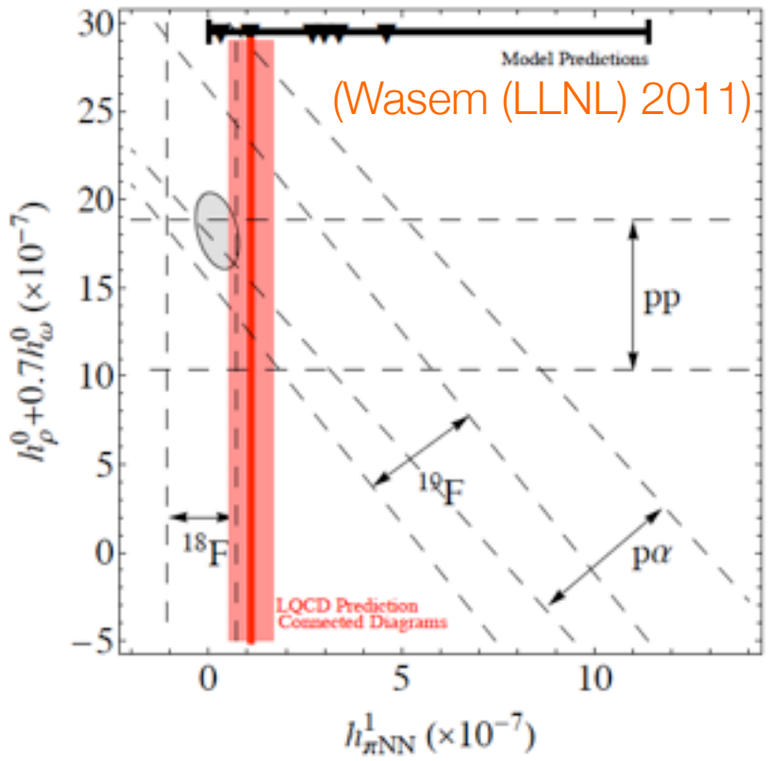
(with sufficient compute resources)

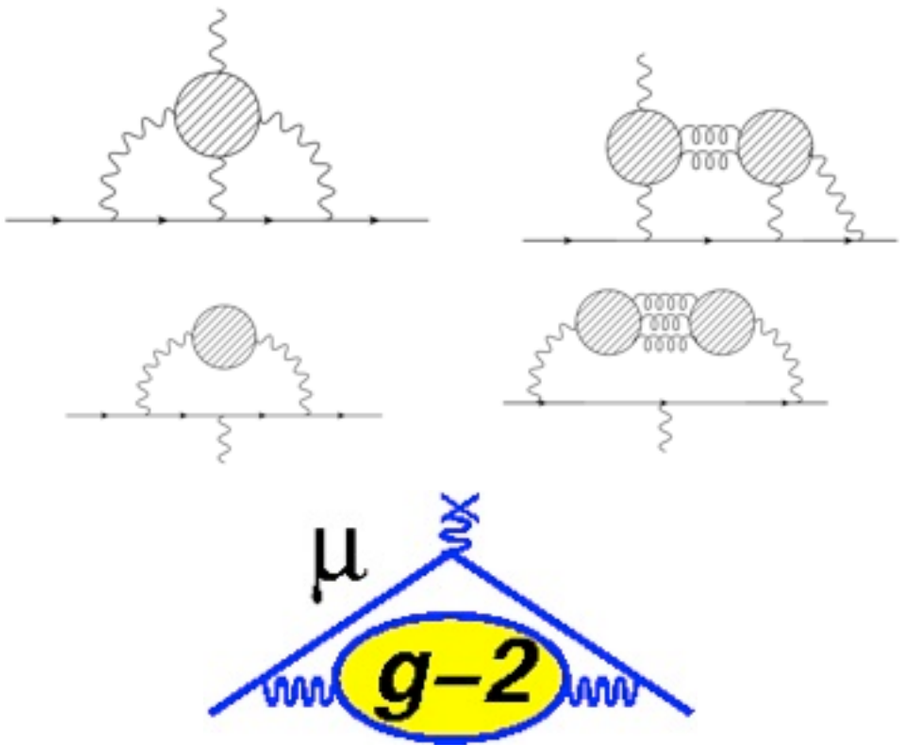


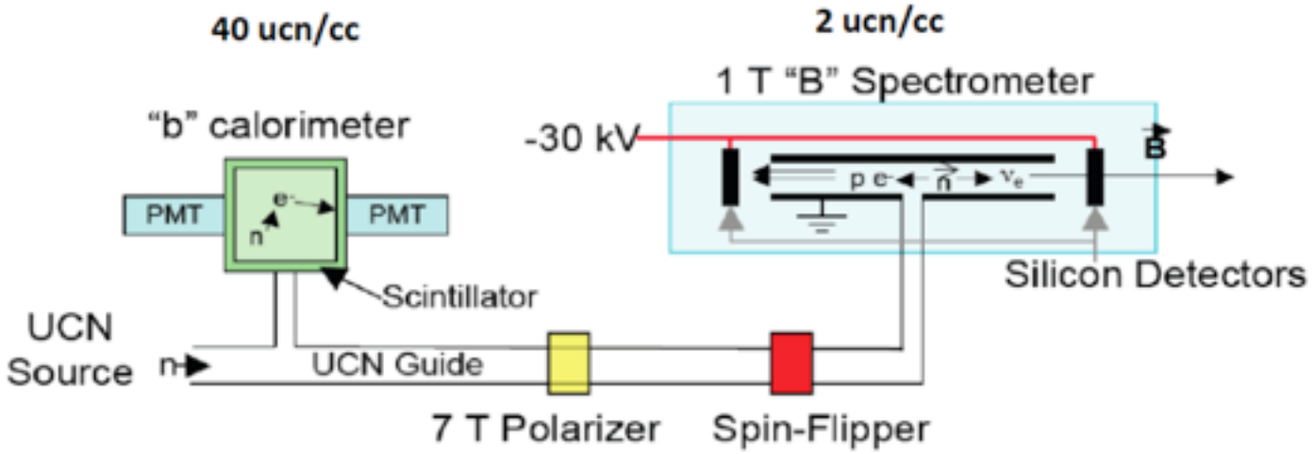
Fundamental Interactions

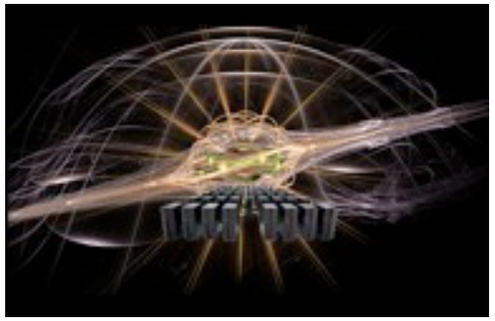


$$\frac{e^2}{M_W^2} / \frac{g^2}{m_\pi^2} \approx 10^{-7}$$

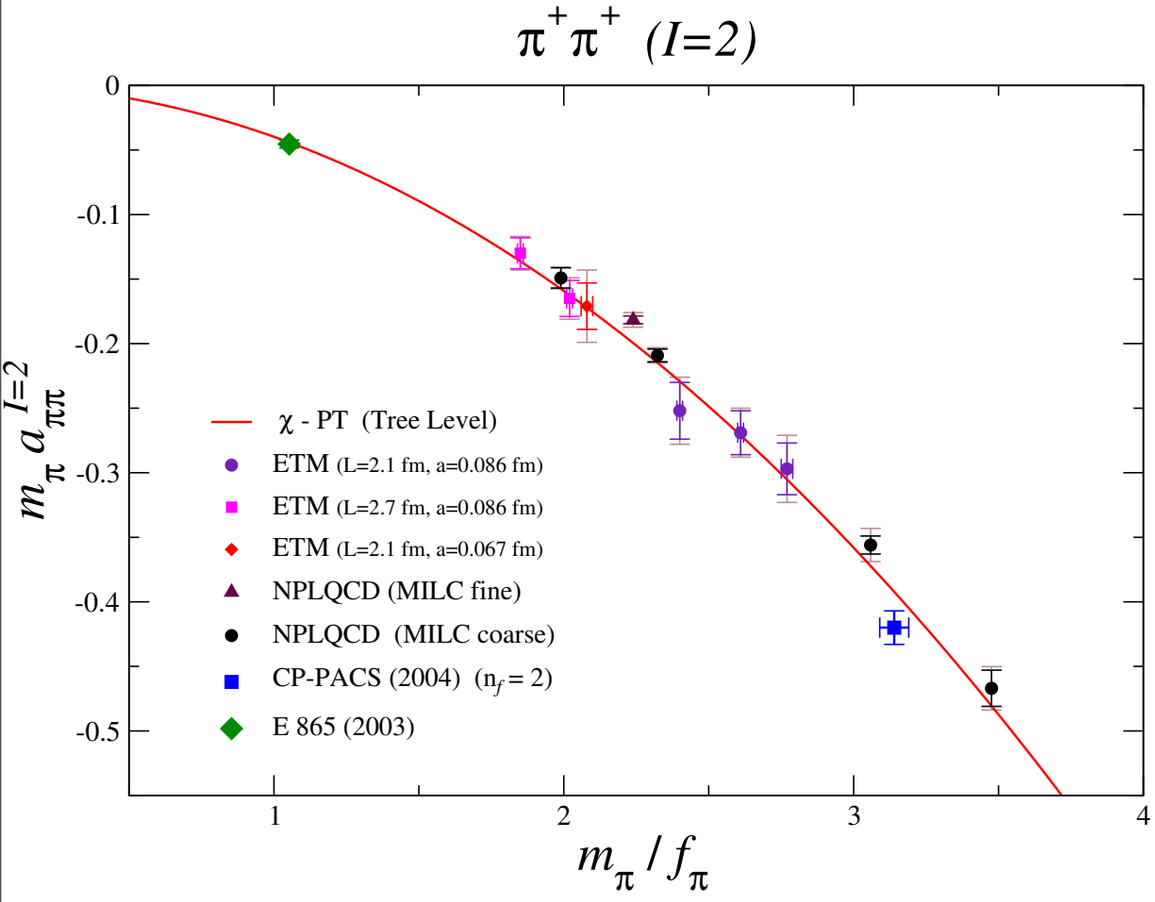


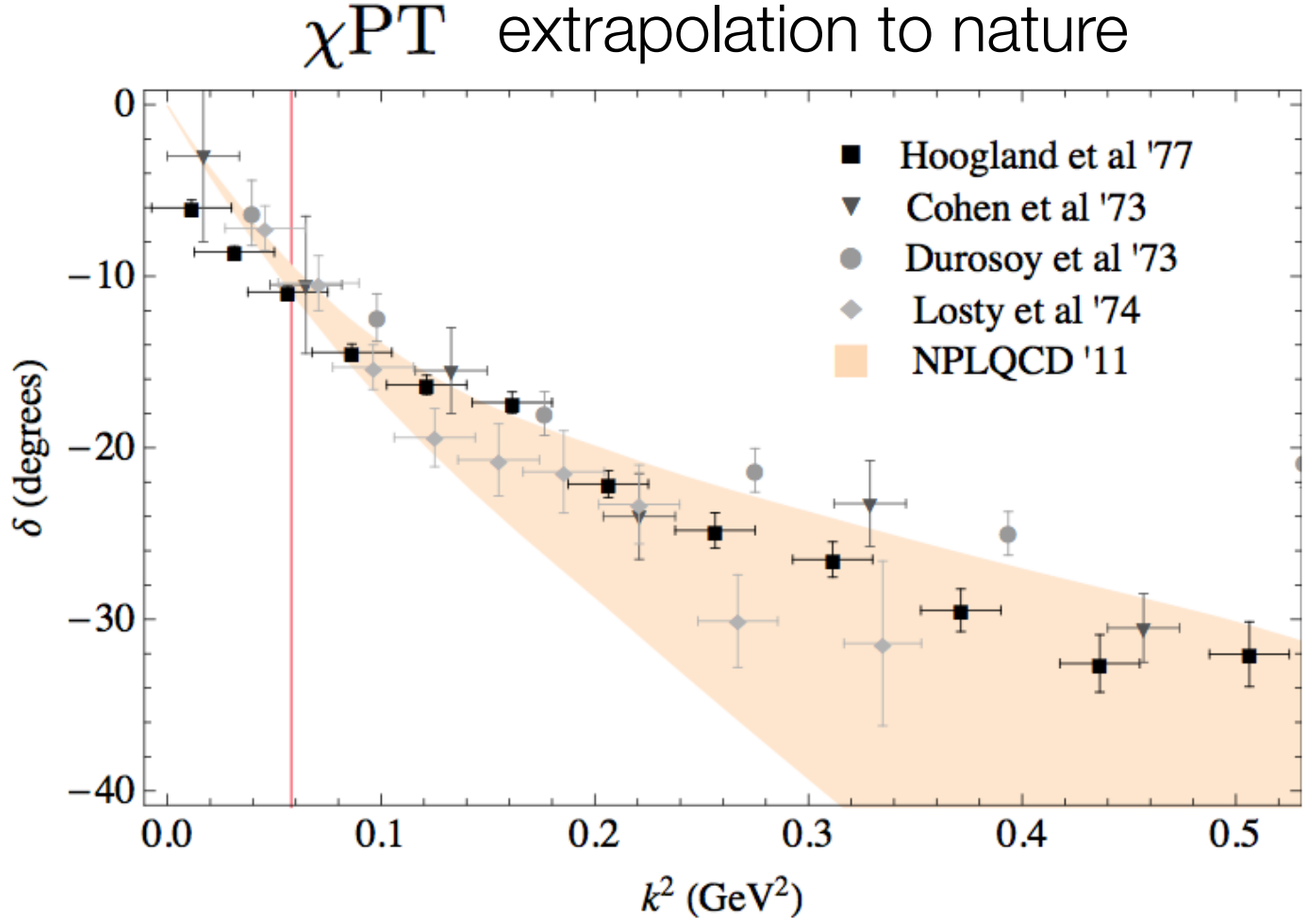


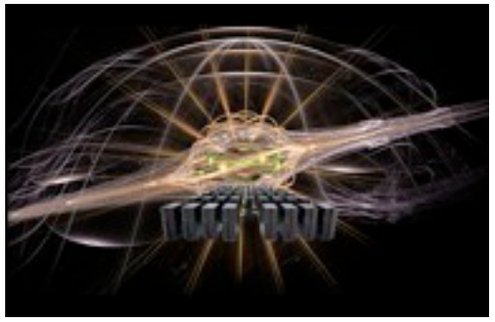




Non Resonant Phase Shifts
I=2 pion-pion

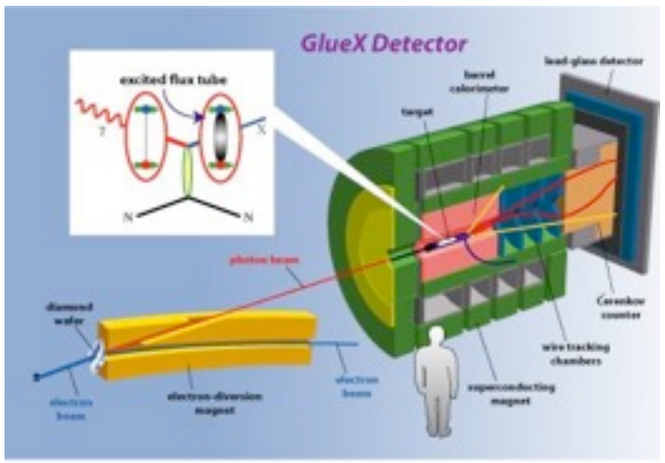


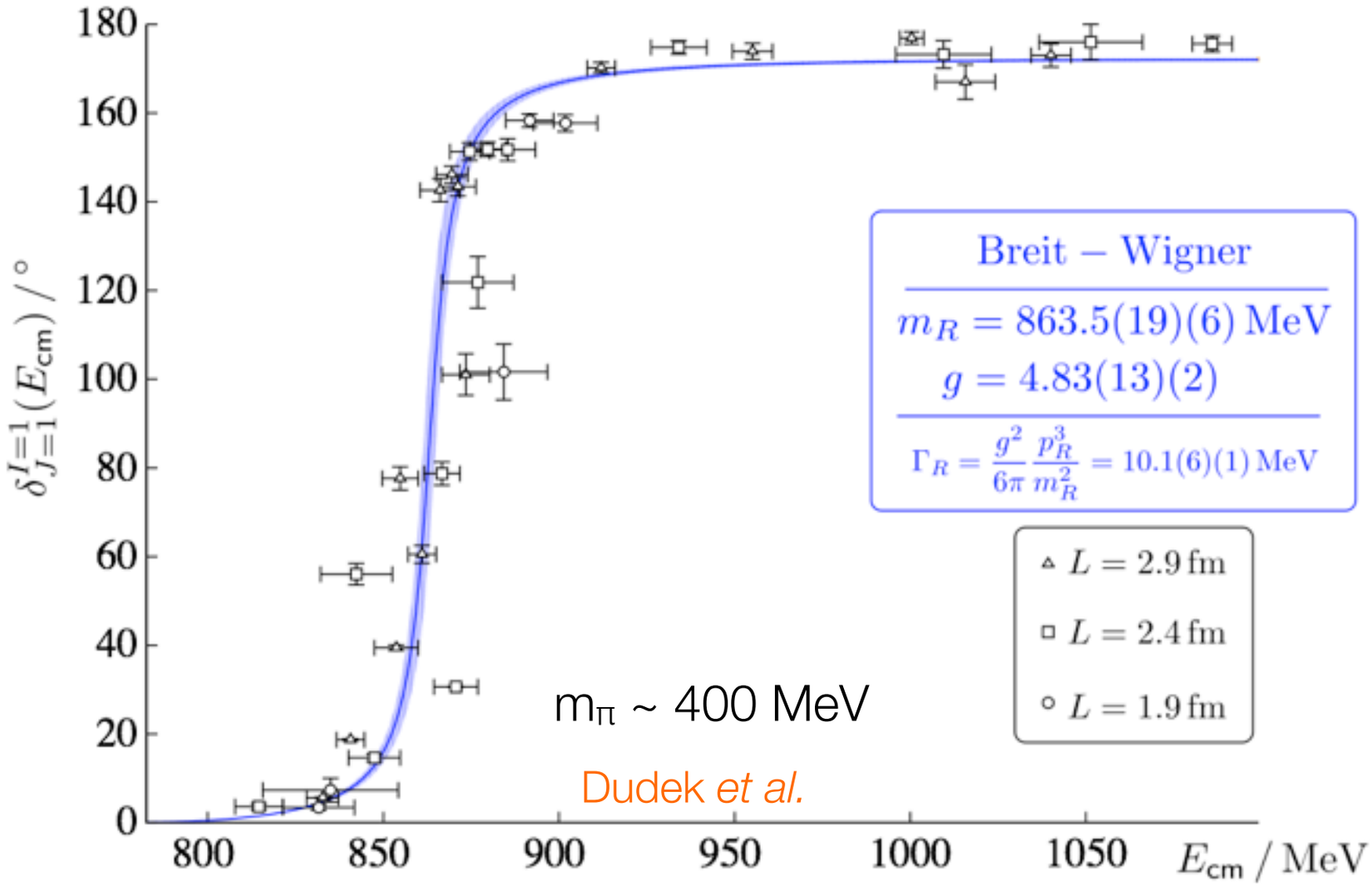




Resonant Phase Shifts
I=1 pion-pion

Jefferson Lab

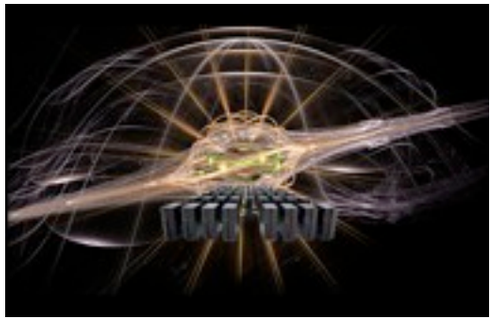




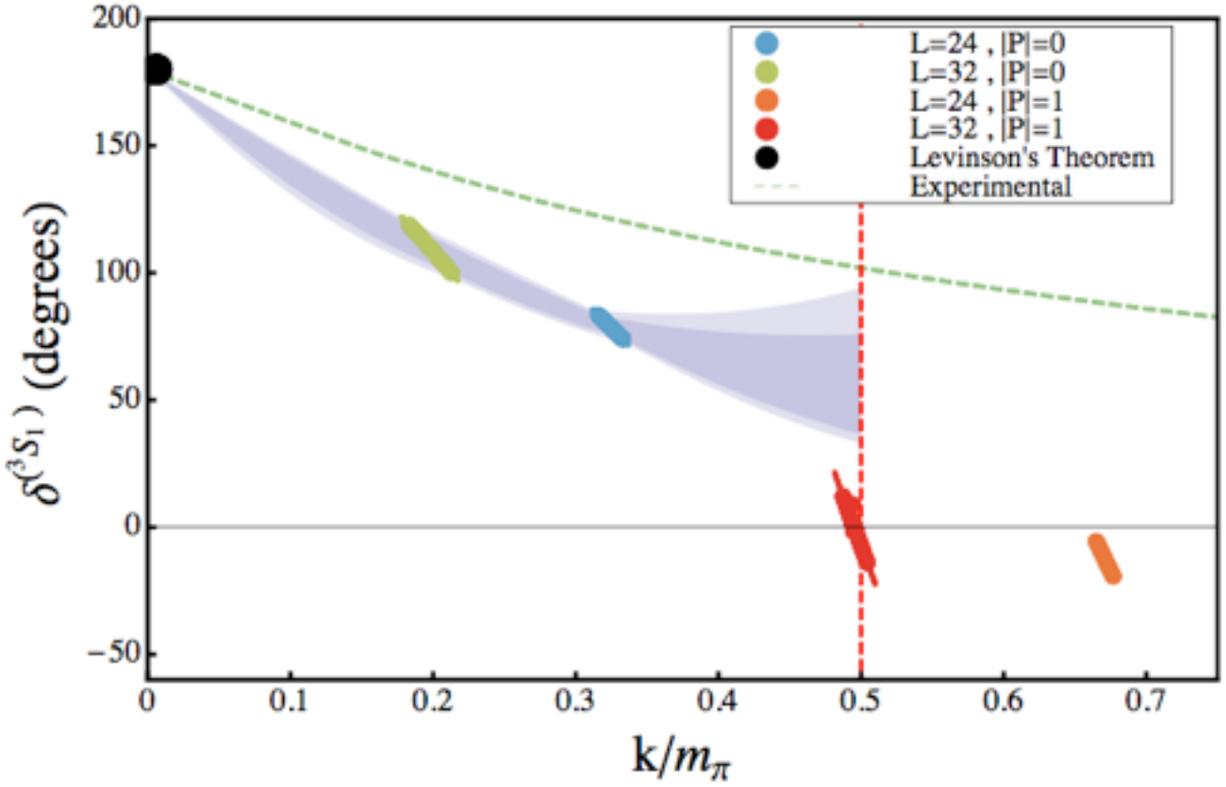
m_π ~ 400 MeV

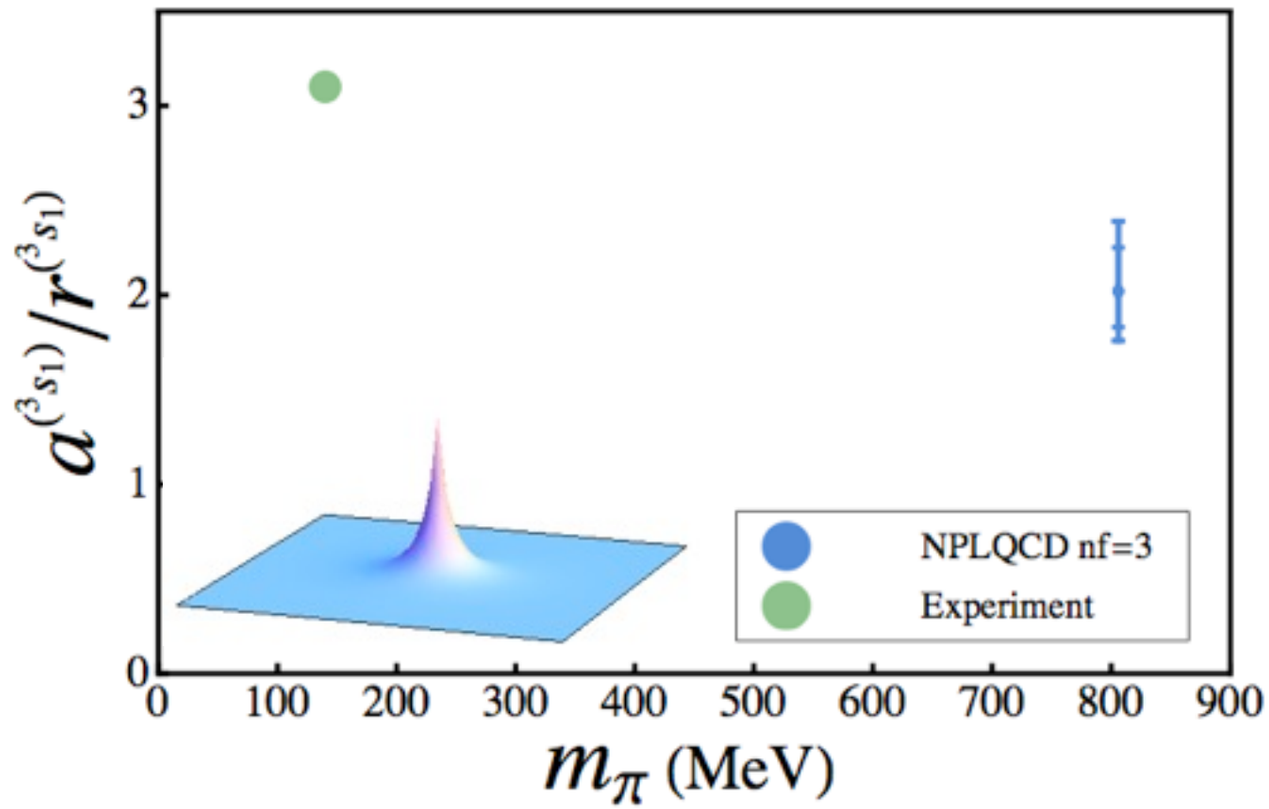
Dudek *et al.*

ρ- resonance successfully determined



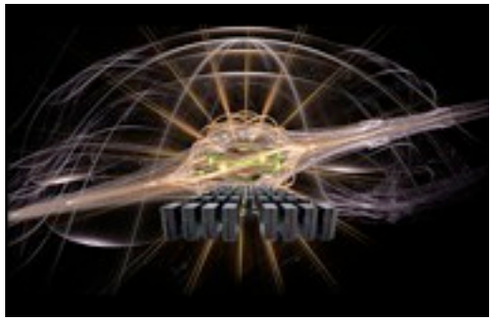
NN Interactions





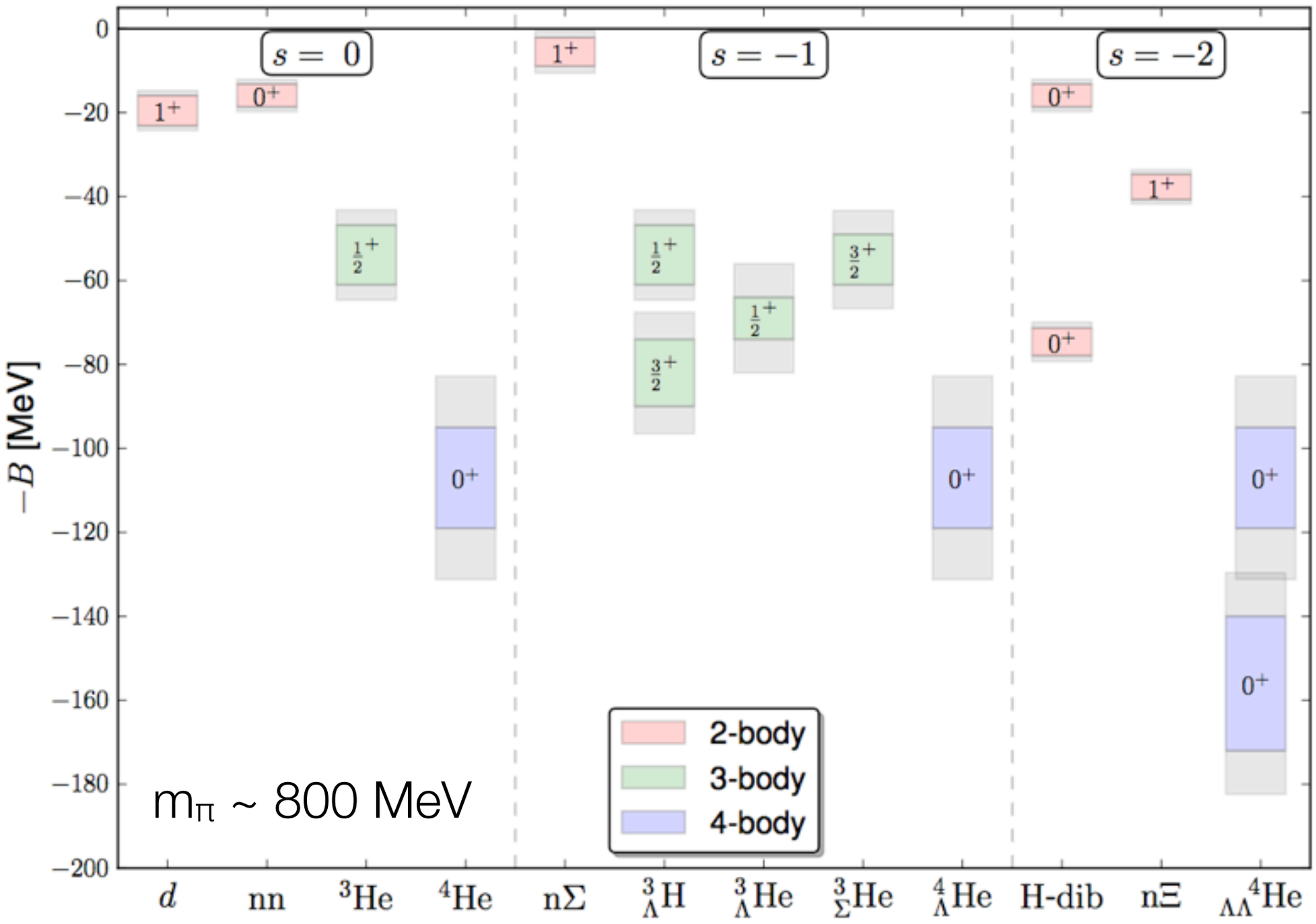
$m_\pi \sim 800$ MeV

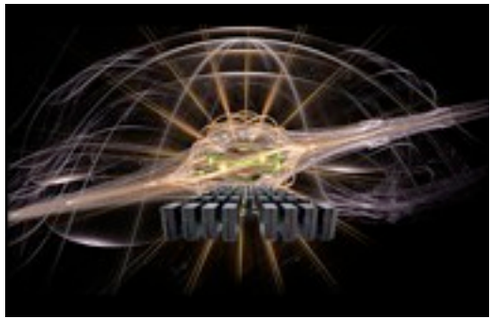
Deuteron appears to be unnatural but not finely-tuned ??
Generic feature of YM with $n_f=3$



Nuclei

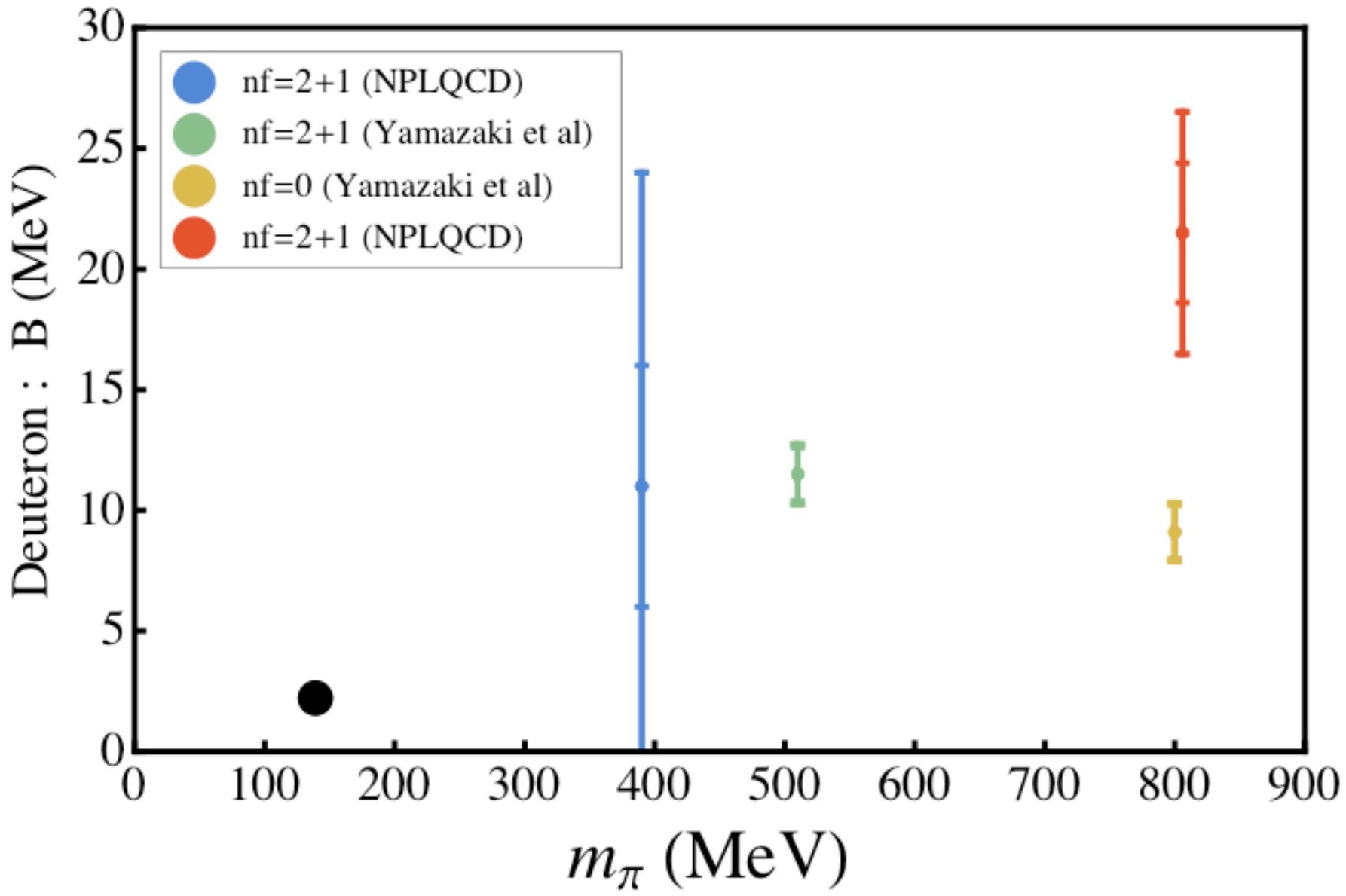

NPLQCD

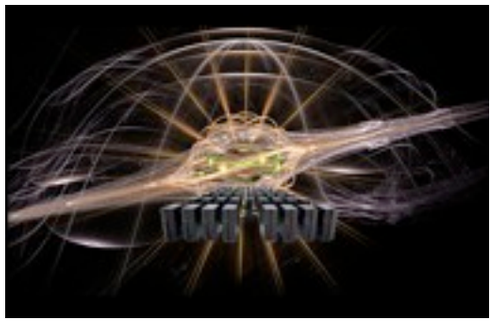

$s = 0$
$s = -1$
$s = -2$
$-B$ [MeV]
0
−20
−40
−60
−80
−100
−120
−140
−160
−180
−200
1^+
0^+
$\frac{1}{2}^+$
$\frac{3}{2}^+$
d
nn
^{3}He
^{4}He
nΣ
$^3_\Lambda$H
$^3_\Lambda$He
$^3_\Sigma$He
$^4_\Lambda$He
H-dib
nΞ
$^{4}_{\Lambda\Lambda}$He
2-body
3-body
4-body
m_π ~ 800 MeV



Deuteron

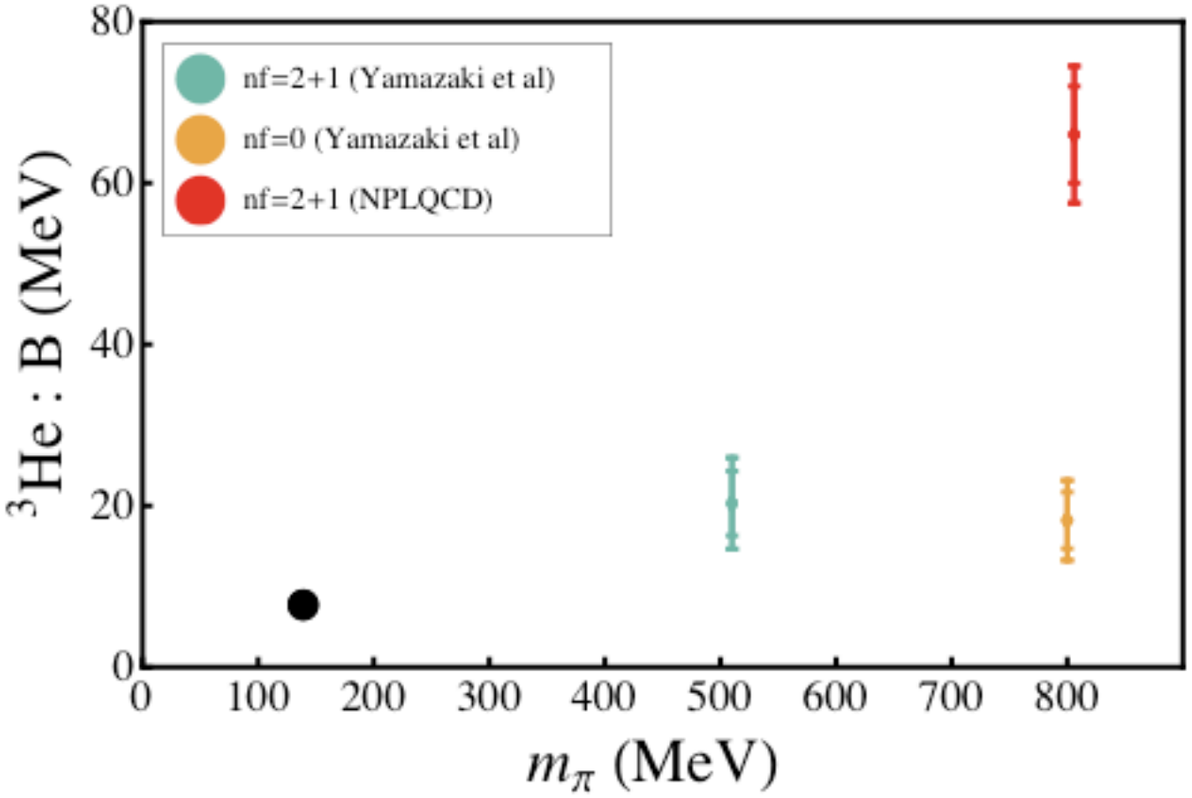

NPLQCD

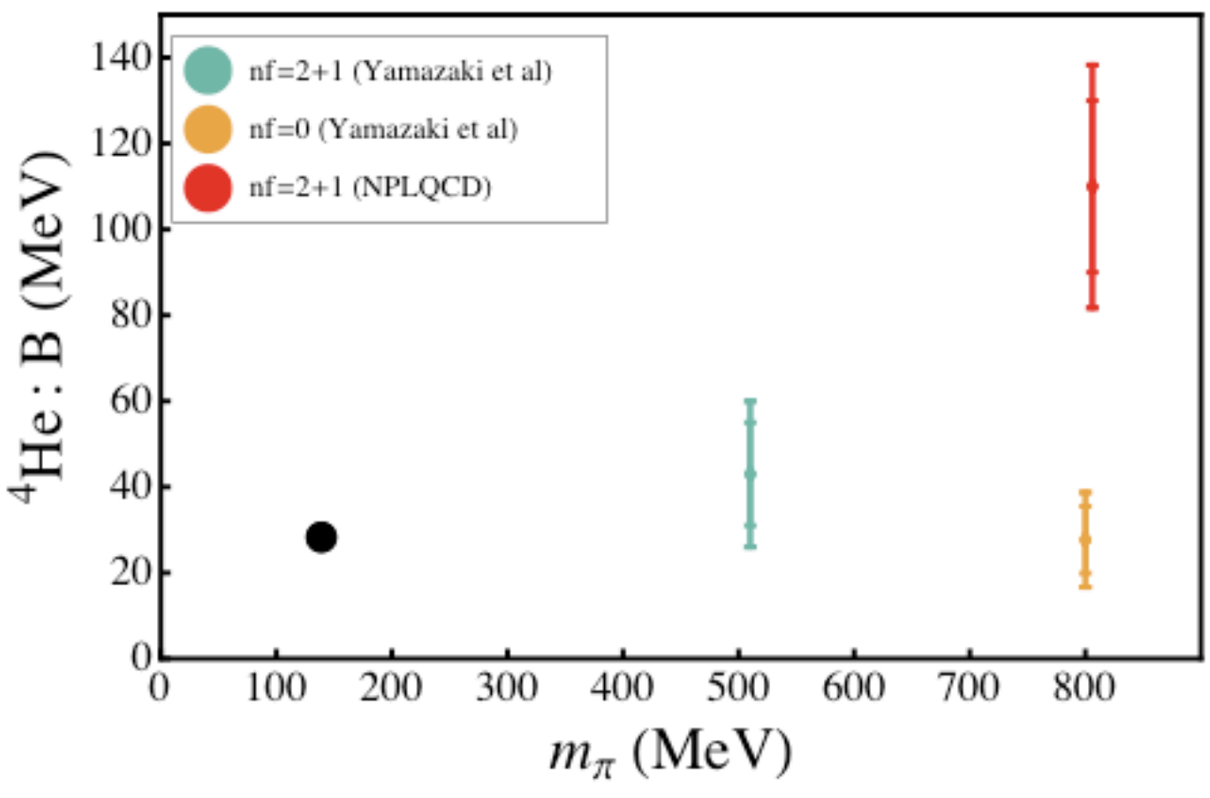

nf=2+1 (NPLQCD)
nf=2+1 (Yamazaki et al)
nf=0 (Yamazaki et al)
nf=2+1 (NPLQCD)
Deuteron : B (MeV)
m_π (MeV)
0
5
10
15
20
25
30
0
100
200
300
400
500
600
700
800
900

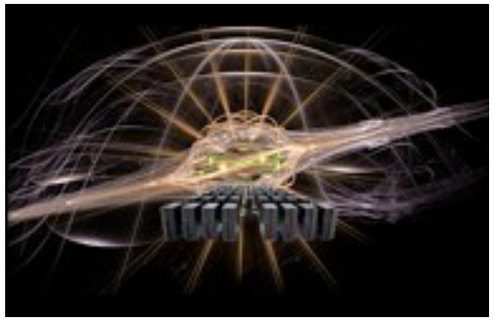


Helium

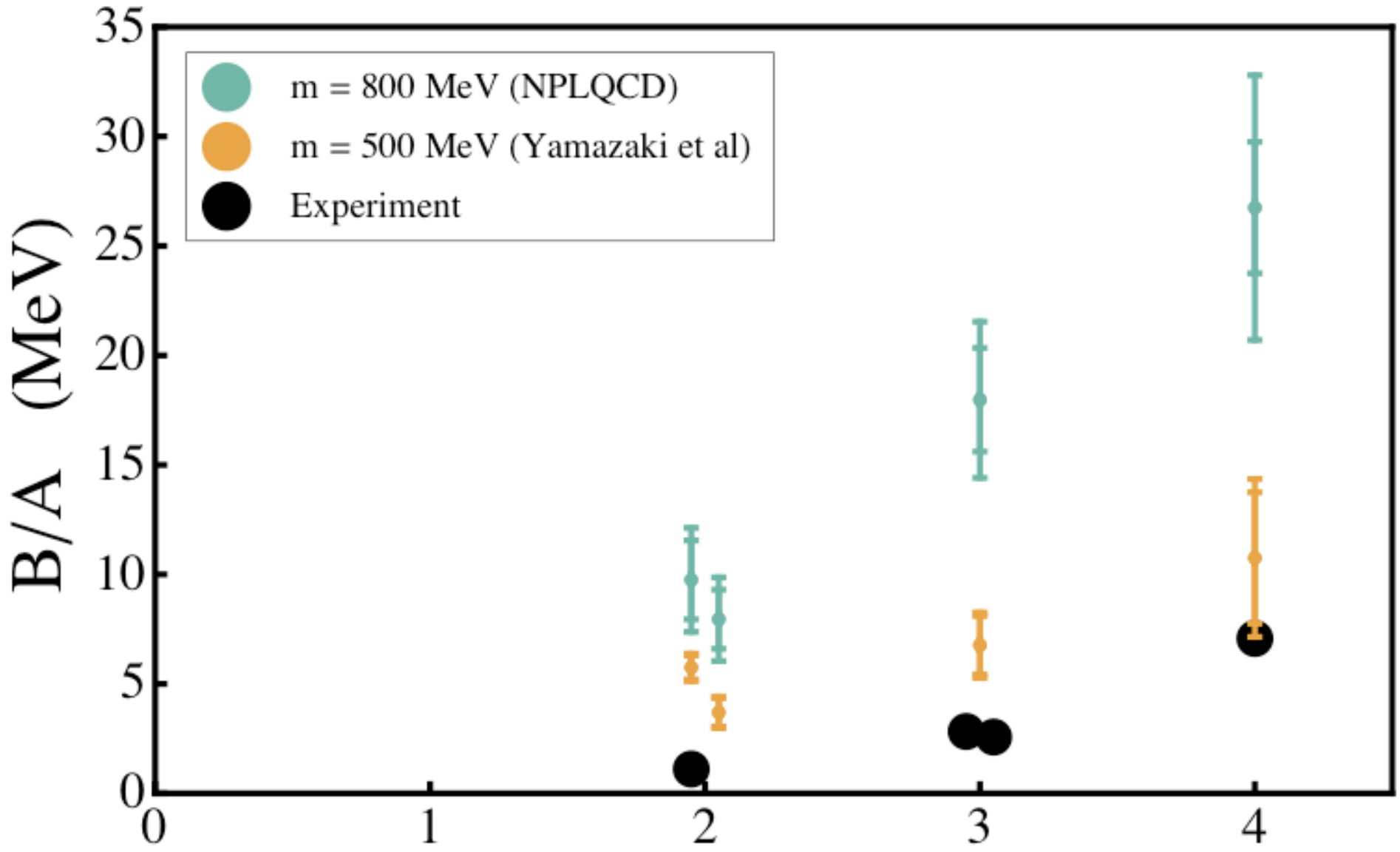

NPLQCD


nf=2+1 (Yamazaki et al)
nf=0 (Yamazaki et al)
nf=2+1 (NPLQCD)
^{3}He : B (MeV)
m_π (MeV)
0
20
40
60
80
0
100
200
300
400
500
600
700
800

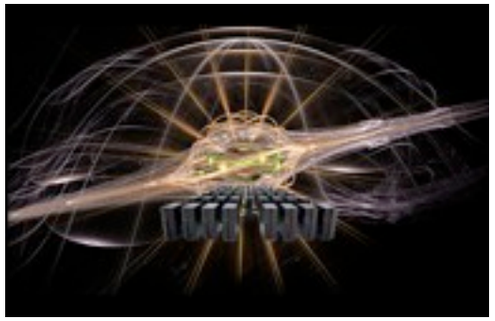

nf=2+1 (Yamazaki et al)
nf=0 (Yamazaki et al)
nf=2+1 (NPLQCD)
^{4}He : B (MeV)
m_π (MeV)
0
20
40
60
80
100
120
140
0
100
200
300
400
500
600
700
800



B/A

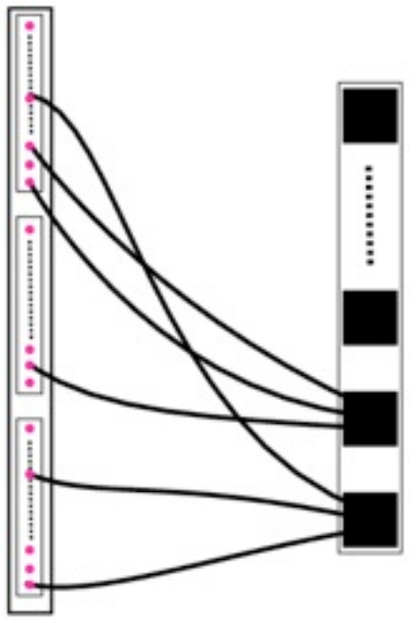


No EM and No isospin breaking



Roadblocks of the Past

NPLQCD

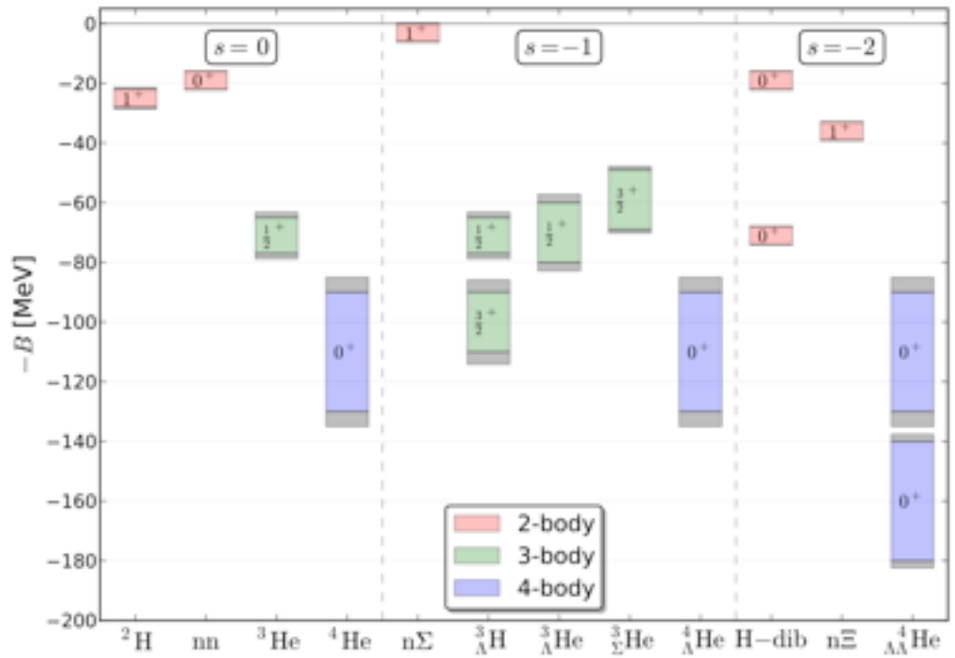


Contractions - 2012

no longer an issue for light nuclei

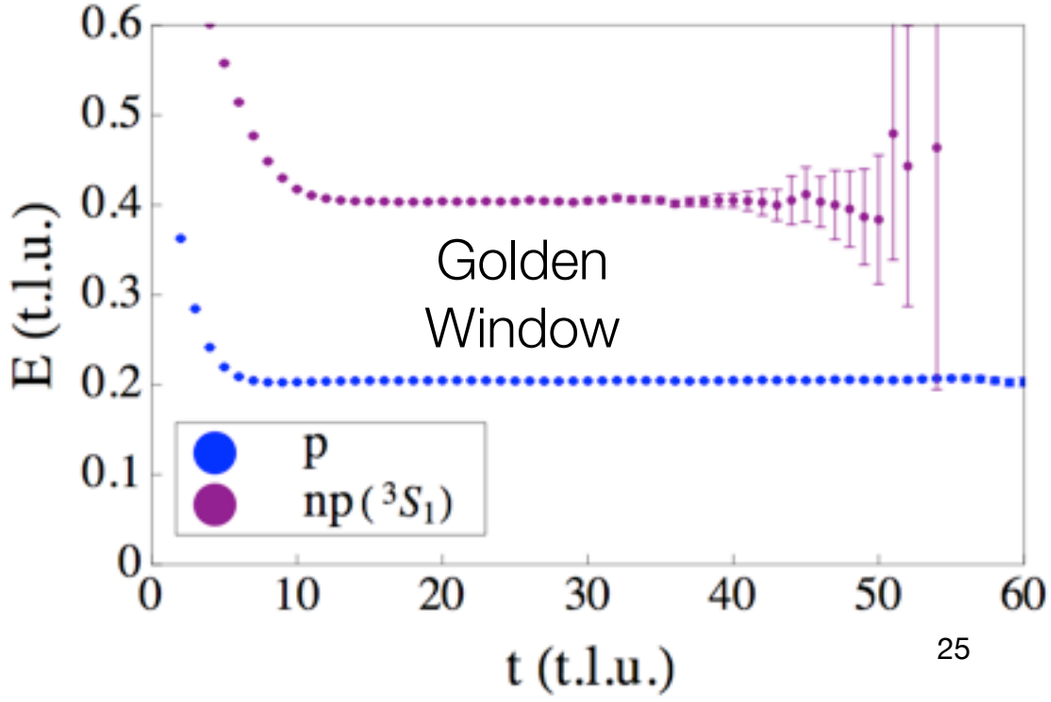
e.g. He-4 : 0.8 core-seconds per time-slice

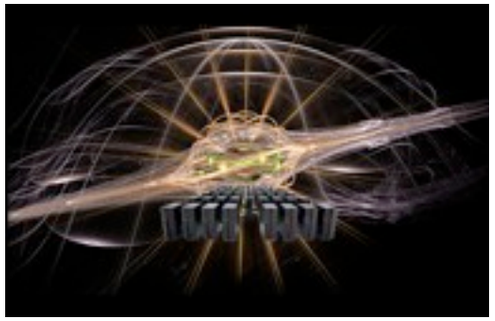
Orginos+Detmold algorithm



Signal to noise

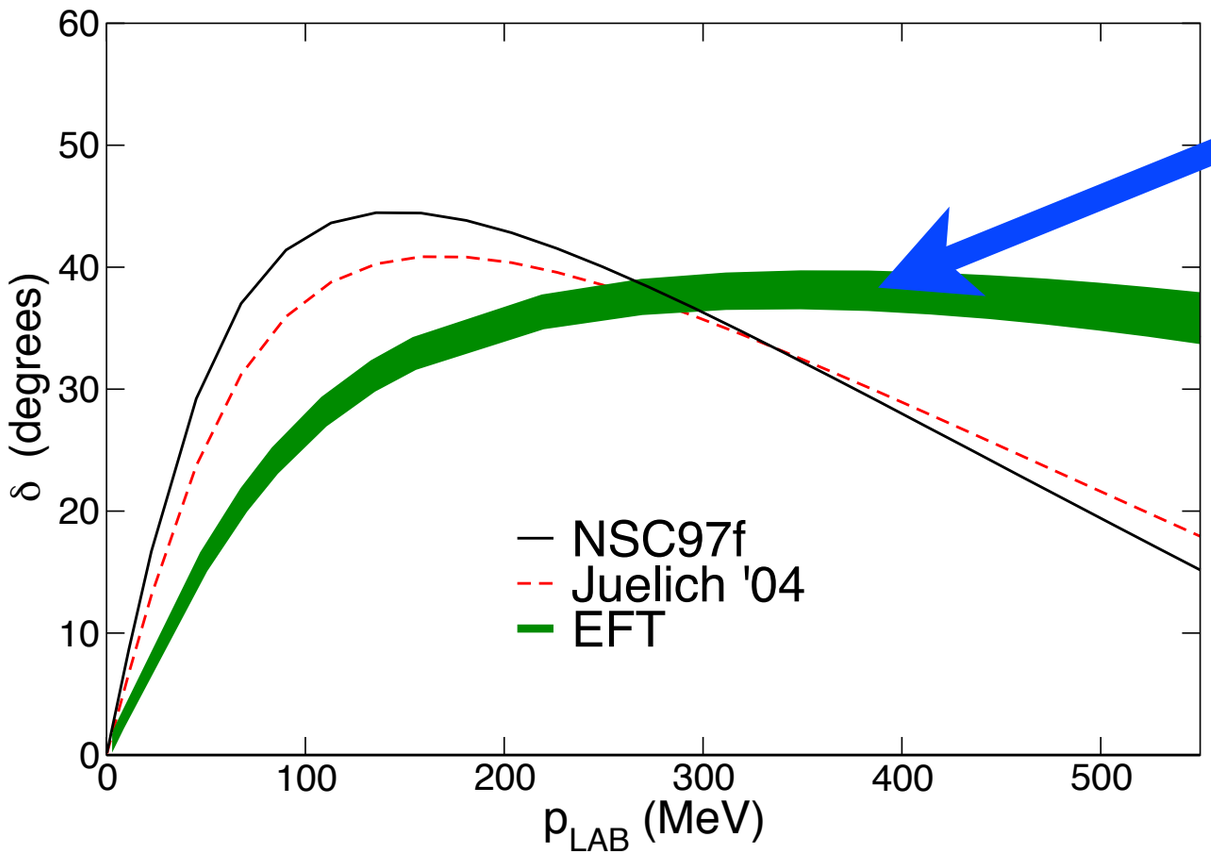
Large numbers of measurements

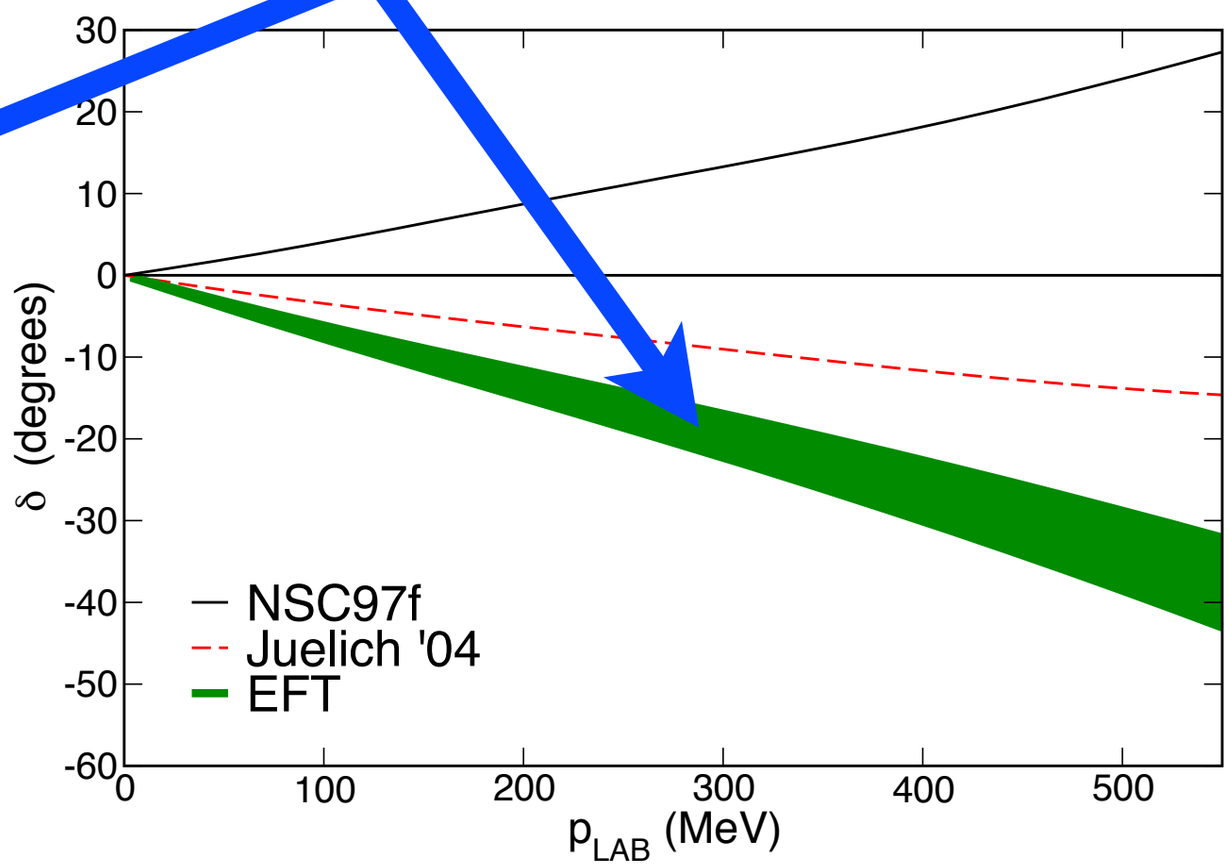




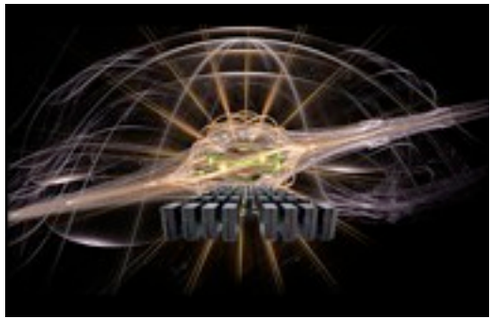
Hyperon Nucleon Interactions

Meissner+Haidenbauer - Experiment + YN-EFT (LO)



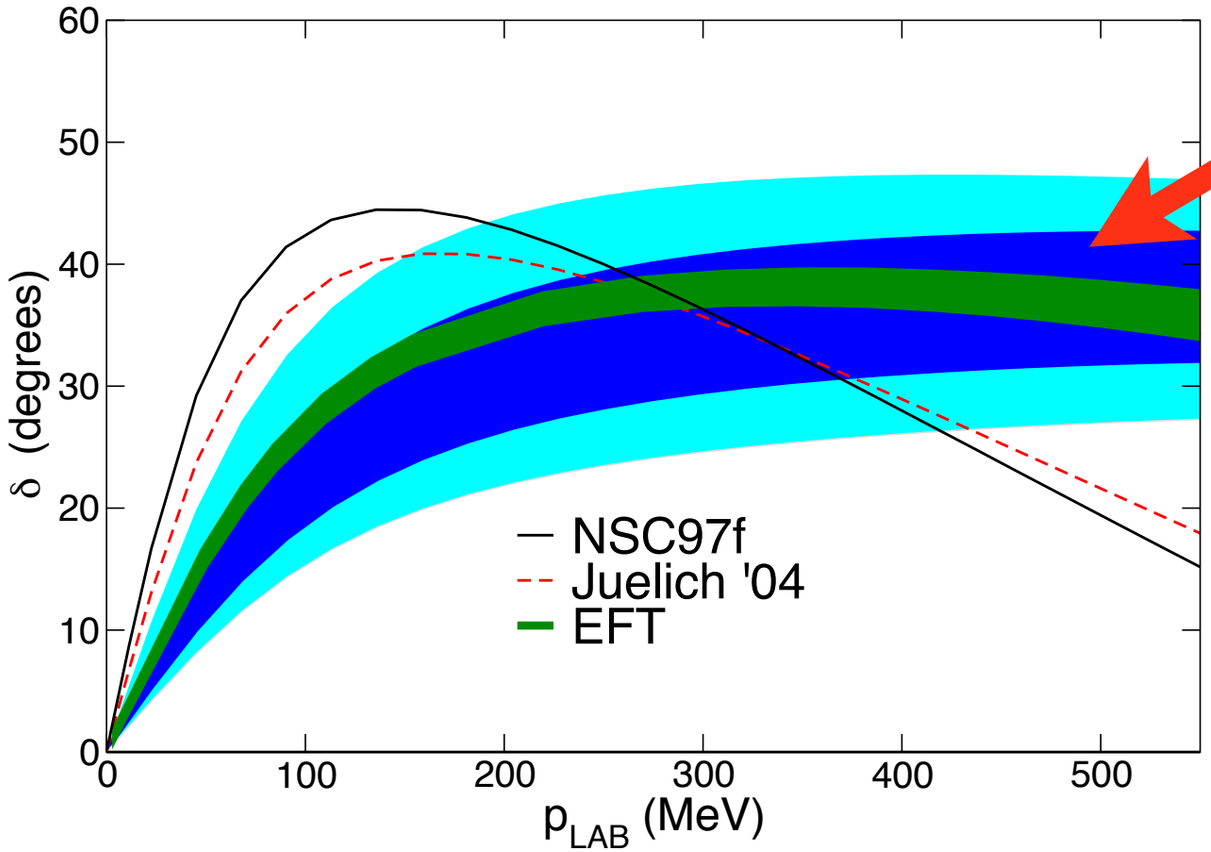


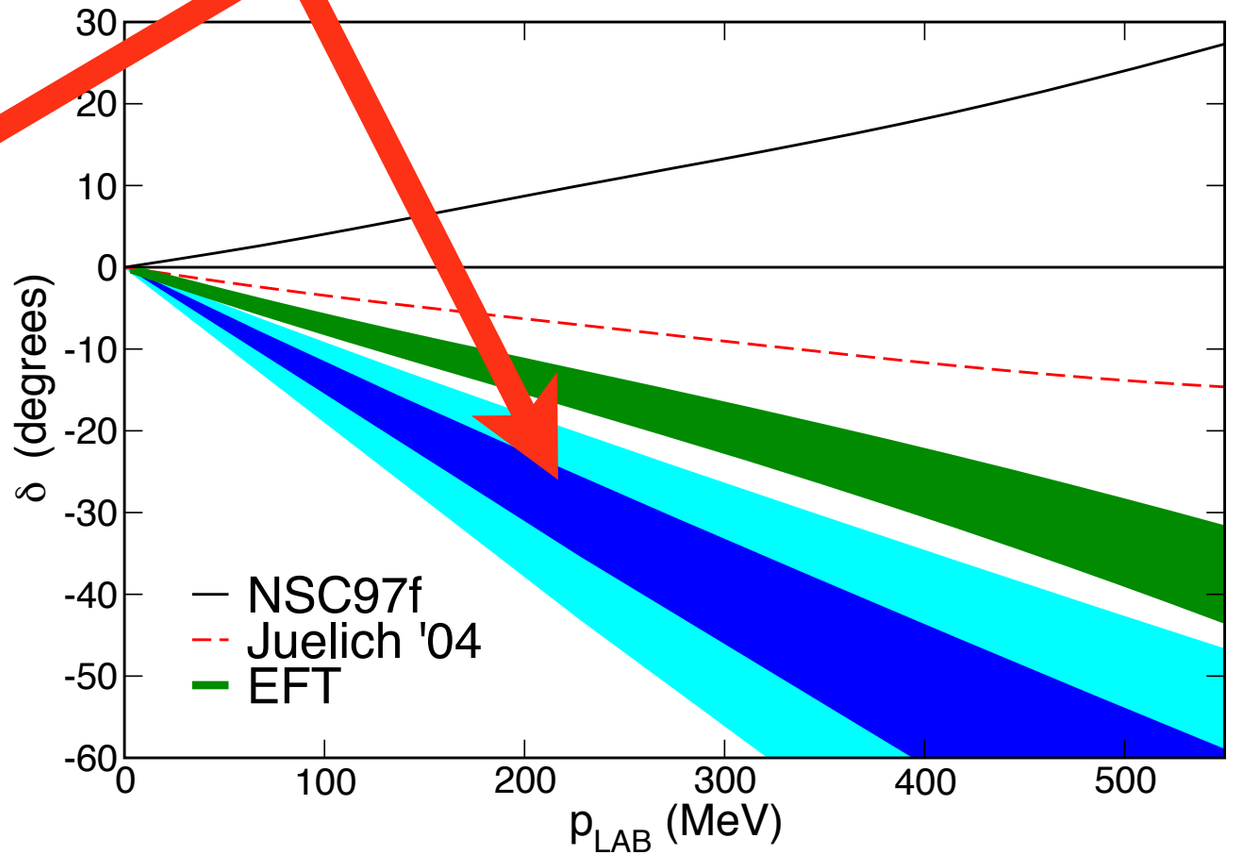
Cancellation between channels in dense matter
energy-shift of hyperon



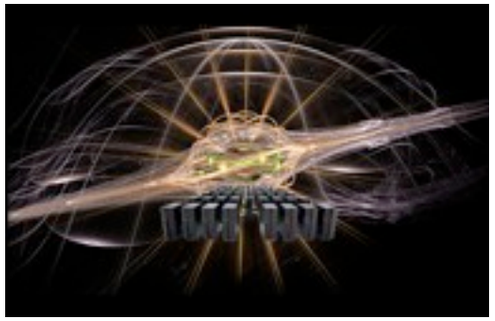
Hyperon Nucleon Interactions

NPLQCD - Lattice QCD + YN-EFT (LO)





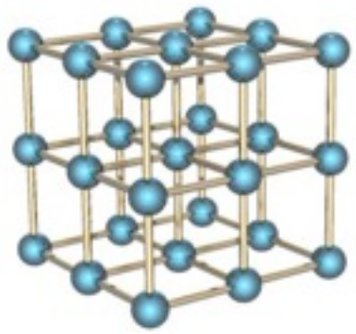
Cancellation between channels in dense matter energy-shift of hyperon



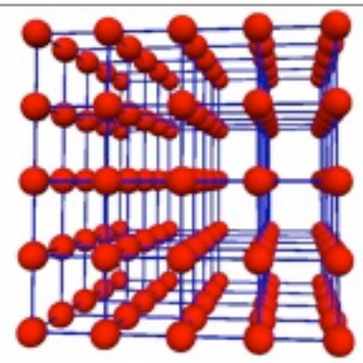
Future Cold Nuclear Physics Program : Physical Pion Mass

SciDAC
Scientific Discovery through Advanced Computing

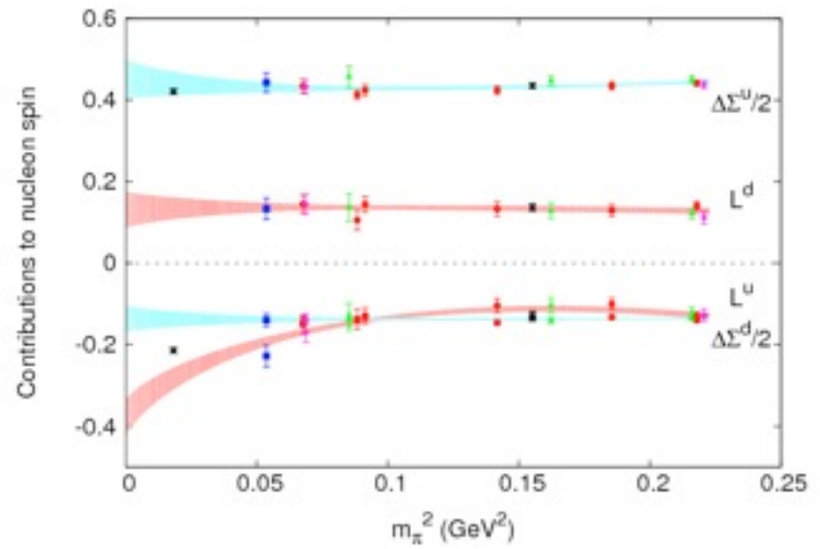
USQCD

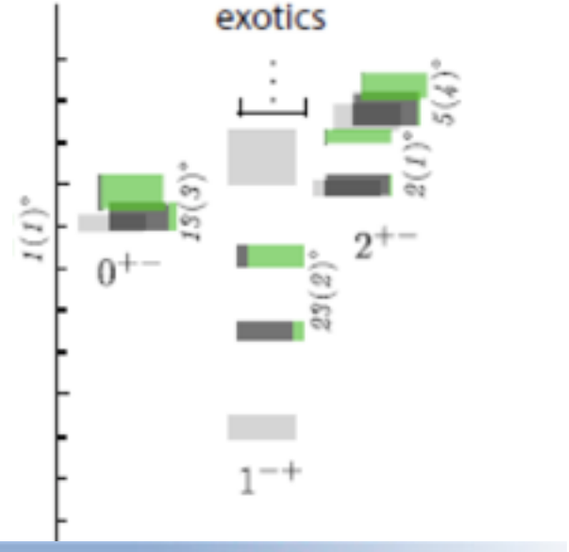


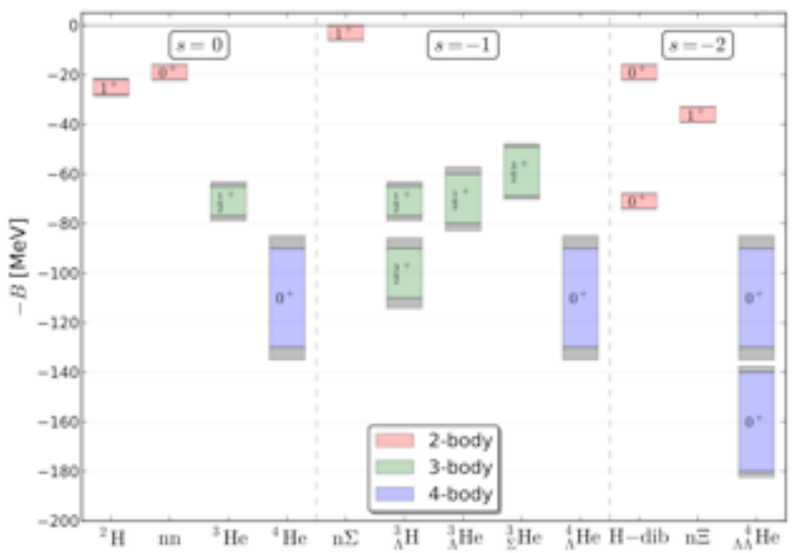
Domain-wall
Overlap

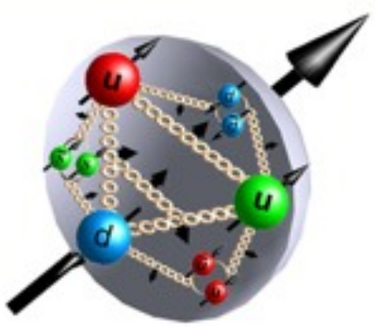


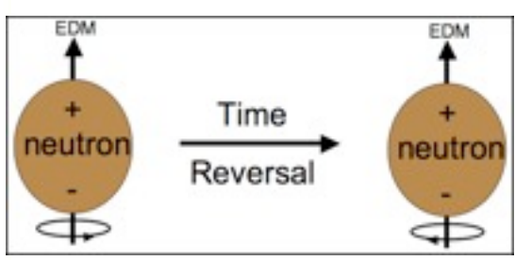
Isotropic clover : small enough lattice spacings

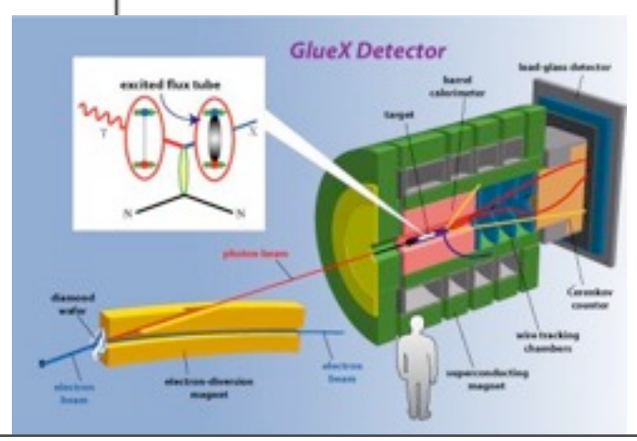










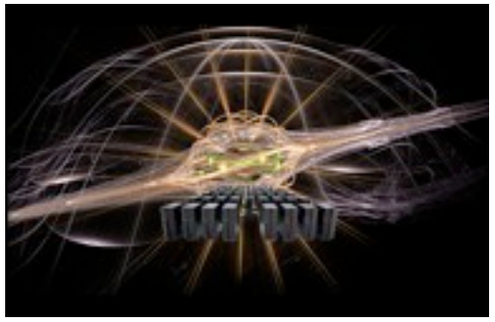


USQCD Proposed Production 2014-2019

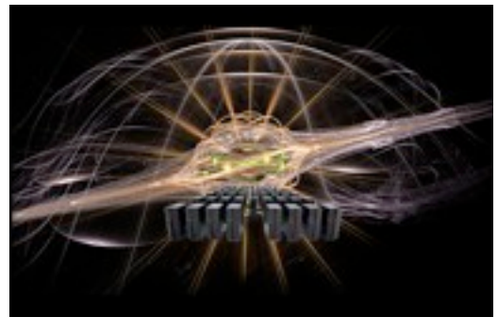


$N_s^3 \times N_t$	Action	a fm	m_π MeV	$m_\pi L$	$m_\pi T$	Traj.	Configs. (TF-yrs)	Str-A (TF-yrs)	Str-B	HSp	HI
$64^3 \times 128$	W	0.076	250	6.1	12.3	5×10^3	8				
$64^3 \times 128$	W	0.09	200	5.8	11.7	5×10^3	9			167	27
$32^3 \times 512$	AW	0.12	200	3.8	17.6	1×10^4	44			41	
$48^3 \times 512$	AW	0.12	200	5.8	17.6	1×10^4	197			142	
$48^3 \times 192$	W	0.09	140	3.0	12.3	5×10^3	7	40			
$64^3 \times 192$	W	0.09	140	4.1	12.3	5×10^3	21	40			
$96^3 \times 64$	W	0.09	140	6.1	4.1	5×10^3	24	13			
$96^3 \times 96$	W	0.09	140	6.1	6.1	5×10^3	40	20			
$96^3 \times 192$	W	0.076	140	6.1	12.3	5×10^3	96	40	350*	334	288
$128^3 \times 192$	W	0.076	140	6.9	10.4	5×10^3	323	67		792	970
$48^3 \times 96$	DWF	0.110	140	3.9	7.8	5×10^3		28	360†		
$64^3 \times 128$	DWF	0.086	140	3.9	7.8	5×10^3		64	844†		

Assume current funding levels throughout period - NP 50% partner

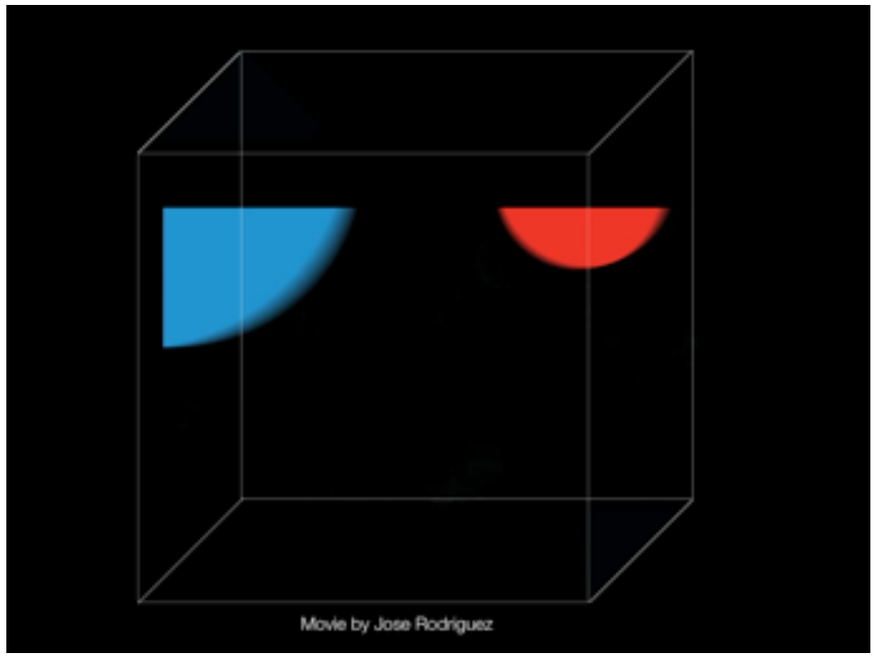


Beyond Computational : Formal Issues

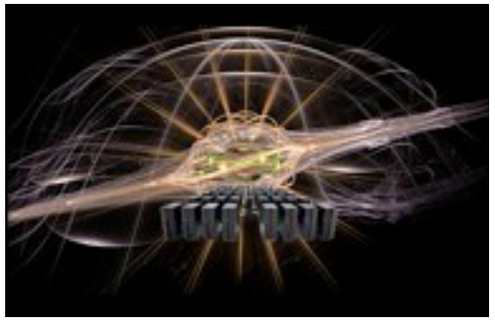


- What Lattice QCD calculations are required to predict multi-body nuclear reactions ?
  - Coupled channels extension of Luscher - underway

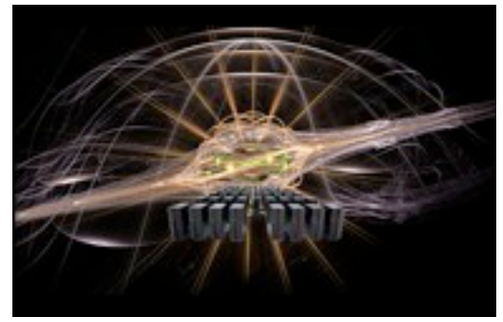
Nuclear Reactions from Lattice QCD
Briceno, Davoudi, Luu
http://www.int.washington.edu/PROGRAMS/13-53w/



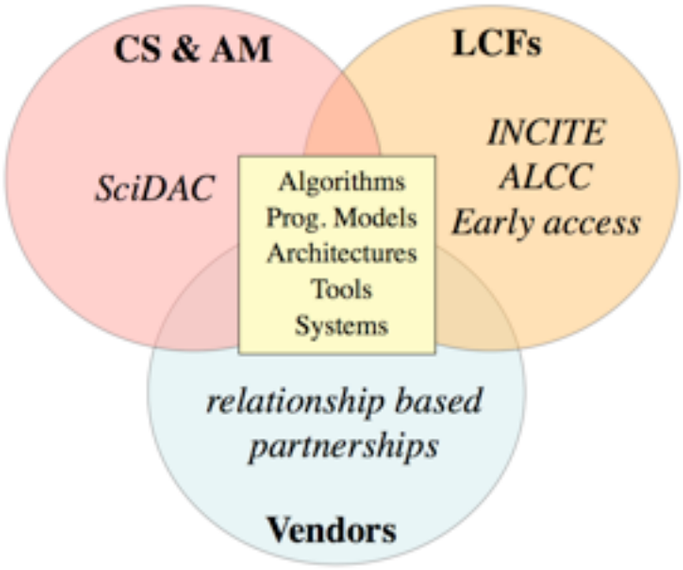
- How to optimally match to nuclear many-body technology ?
  - do we simply pass along energy eigenvalues ?

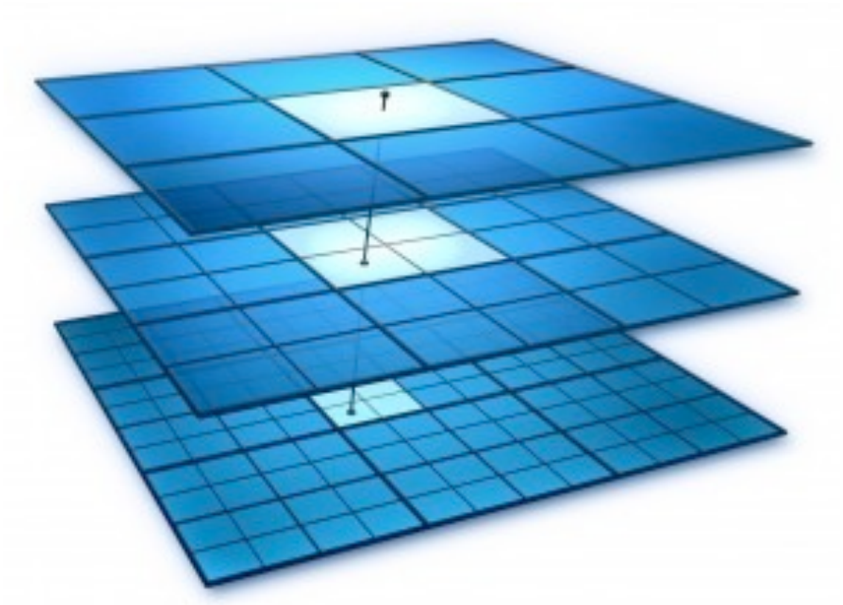


Collaboration is Crucial



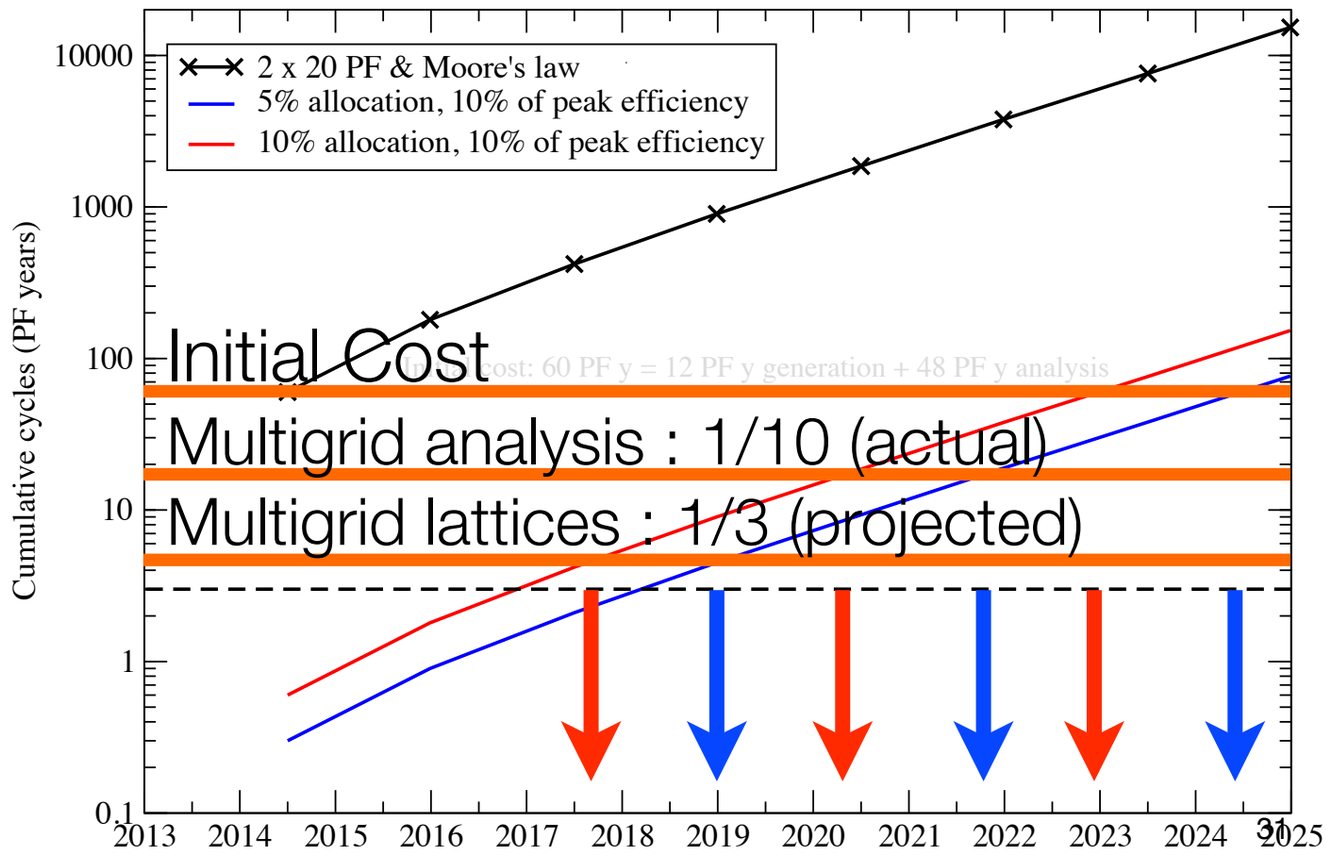
SciDAC
Scientific Discovery through Advanced Computing

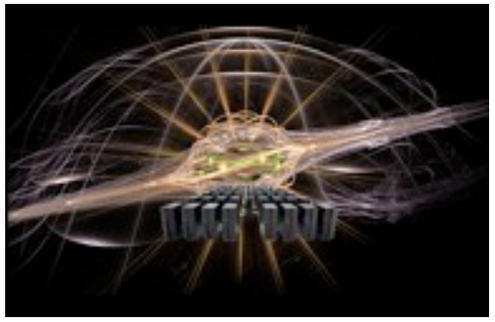




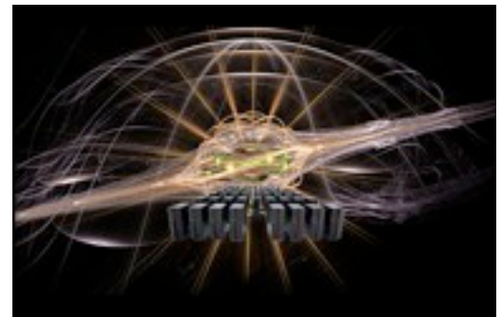
e.g. How to solve **optimally** ?

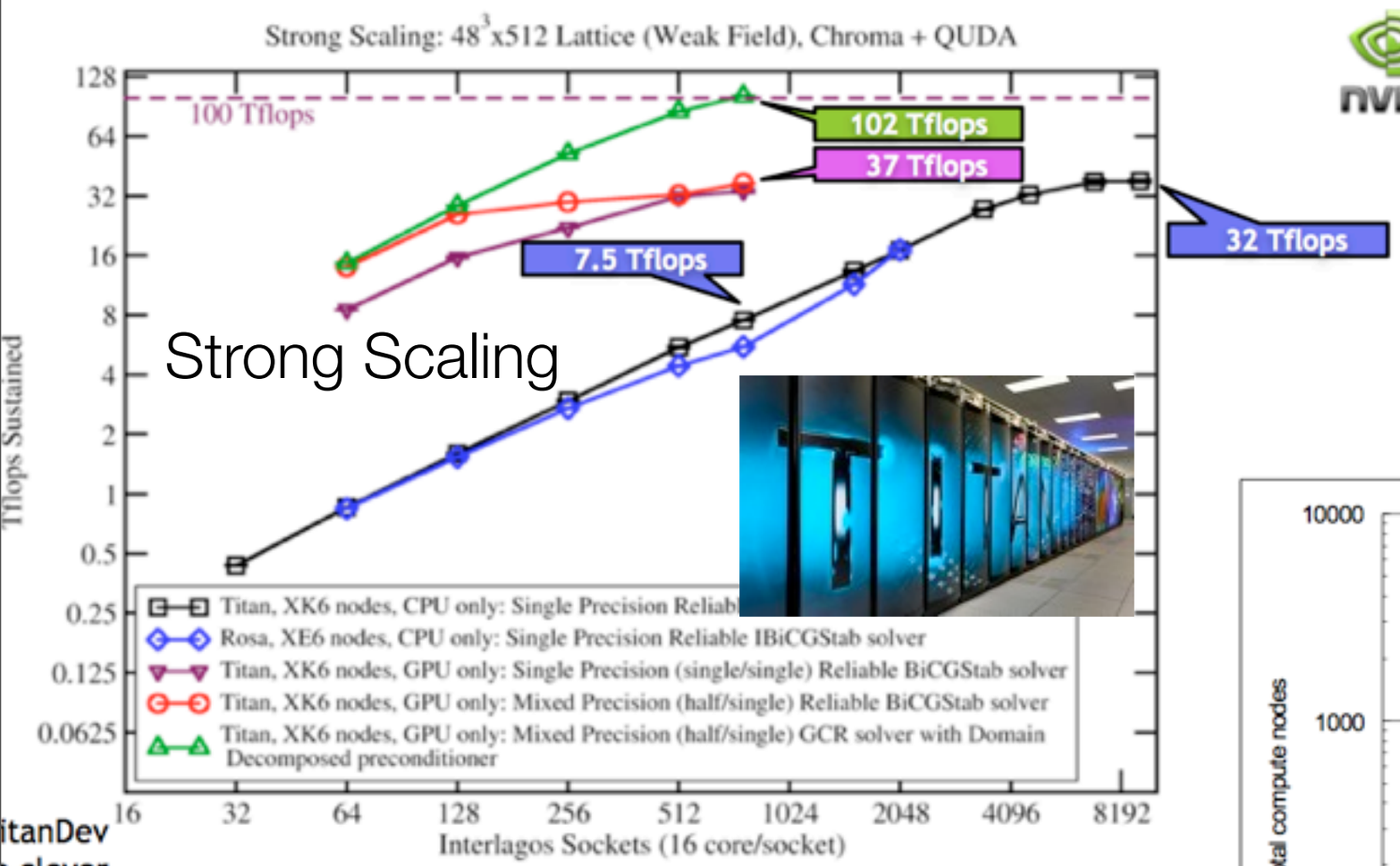
A.x=b

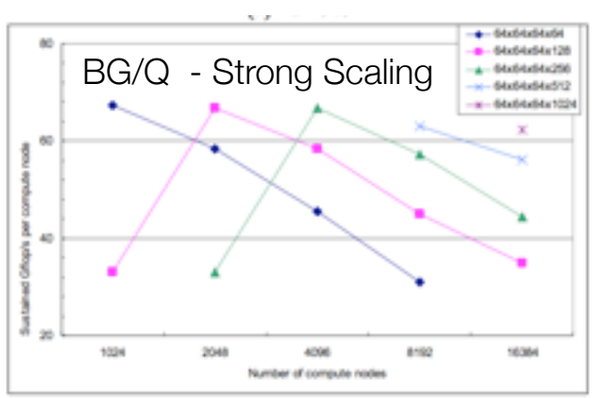




LQCD Codes on the Latest Hardware







(b) Even-odd preconditionning

Figure 13. Strong scaling measurement of the sustained performance per compute node for 64x64x64x16n lattices

16 racks
1.08 Pflops sustained
~ 32% peak

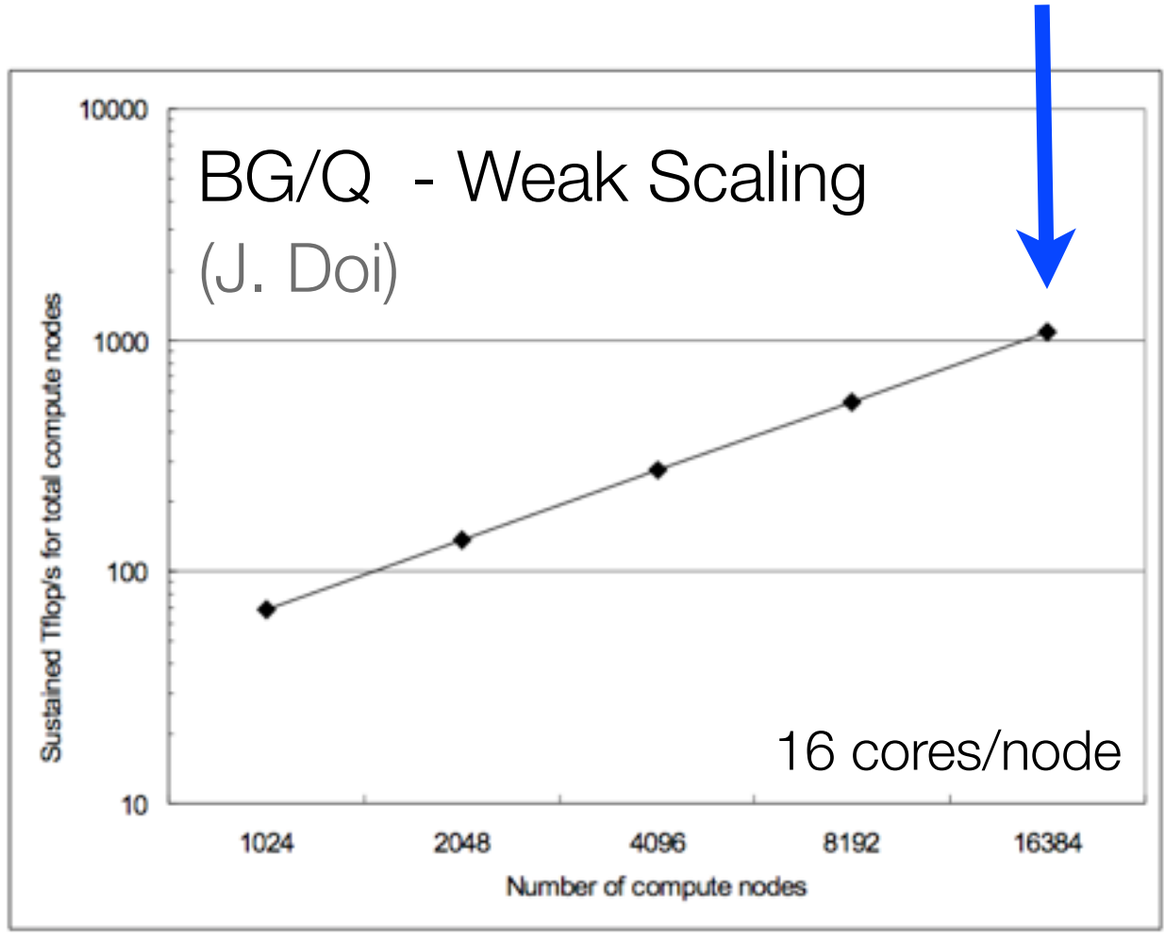
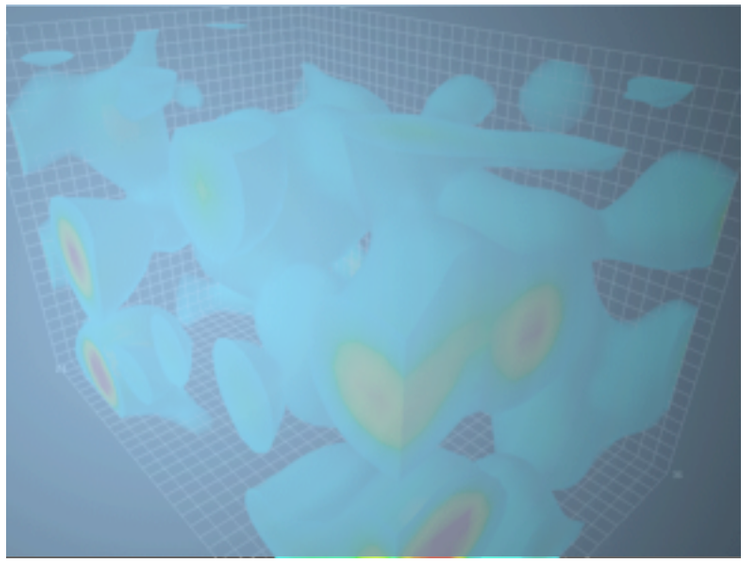
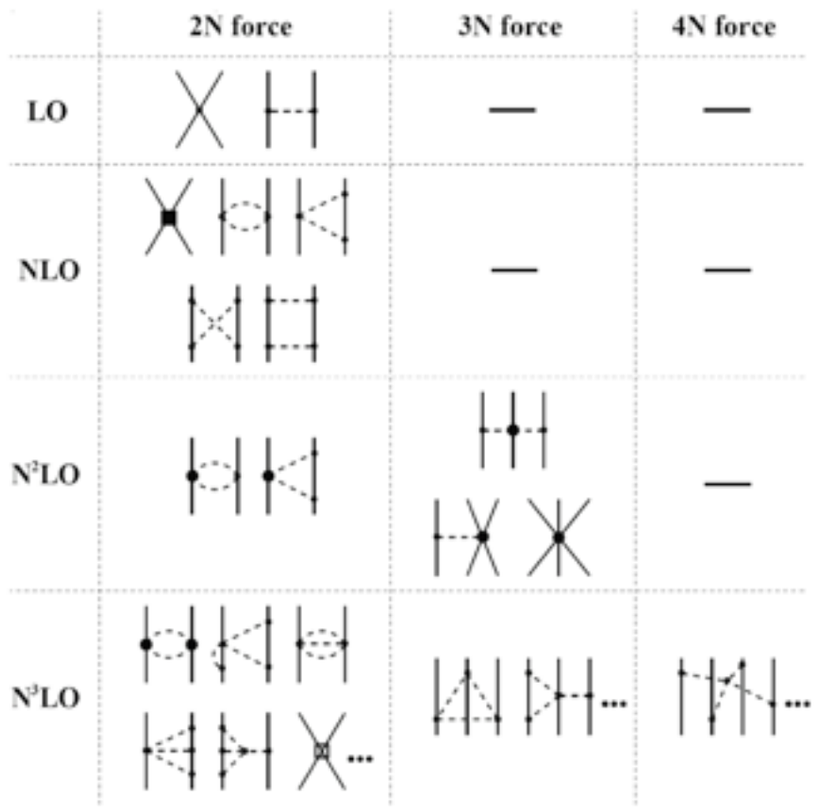


Figure 17. Scaling of the total sustained Tflop/s of lattice QCD (Even-odd preconditionning) on a Blue Gene/Q supercomputer

Closing Remarks

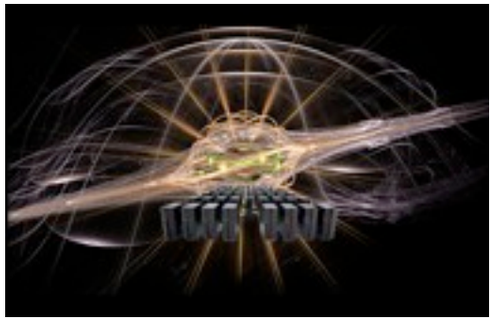




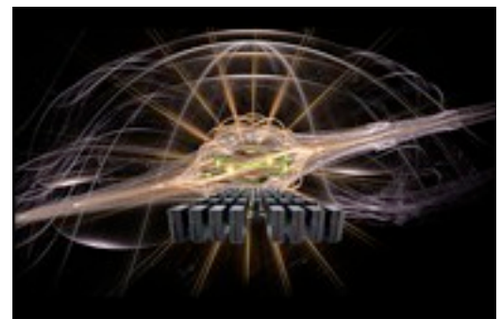
Lattice QCD, combined with chiral EFT and nuclear many-body techniques, will provide first principles predictive capabilities for Nuclear Physics

Enable calculations with **quantifiable uncertainties** of the nuclear forces and of processes occurring in nuclei and astrophysical environments where experiments are not possible.

Matching to nuclear many-body machinery is beginning



Happy Birthday James



THE END