Lattice QCD @ Spain
Palacio de la Magdalena
Santander, June 9-10, 2011

SAIL

Study of SubAtomic Interactions through Lattice QCD simulatons in Mare Nostrum

The overall goal of our project (and a central goal of nuclear physics) is to calculate important nuclear processes directly from quantum chromodynamics (QCD)

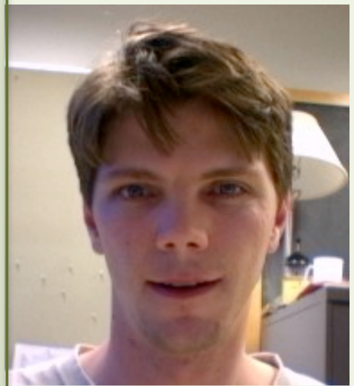
Assumpta Parreño, U Barcelona
Emmanuel Chang, U. Barcelona

(for the NPLQCD Collaboration)

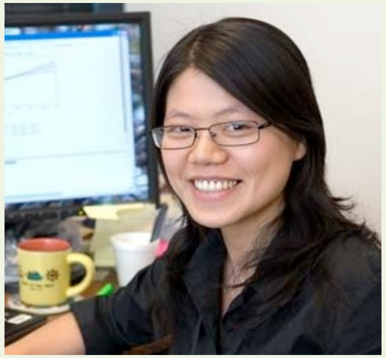
NPLQCD Collaboration

Silas R. Beane
New Hampshire

Emmanuel Chang
Barcelona



William Detmold
William & Mary



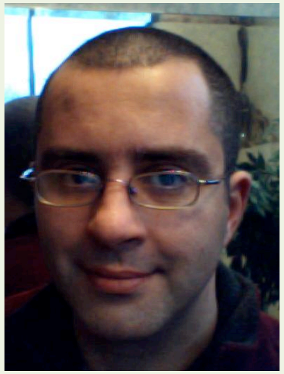
Huey-Wen Lin
U of Washington

Tom Luu
Livermore

Kostas Orginos
William & Mary

Assumpta Parreño
Barcelona

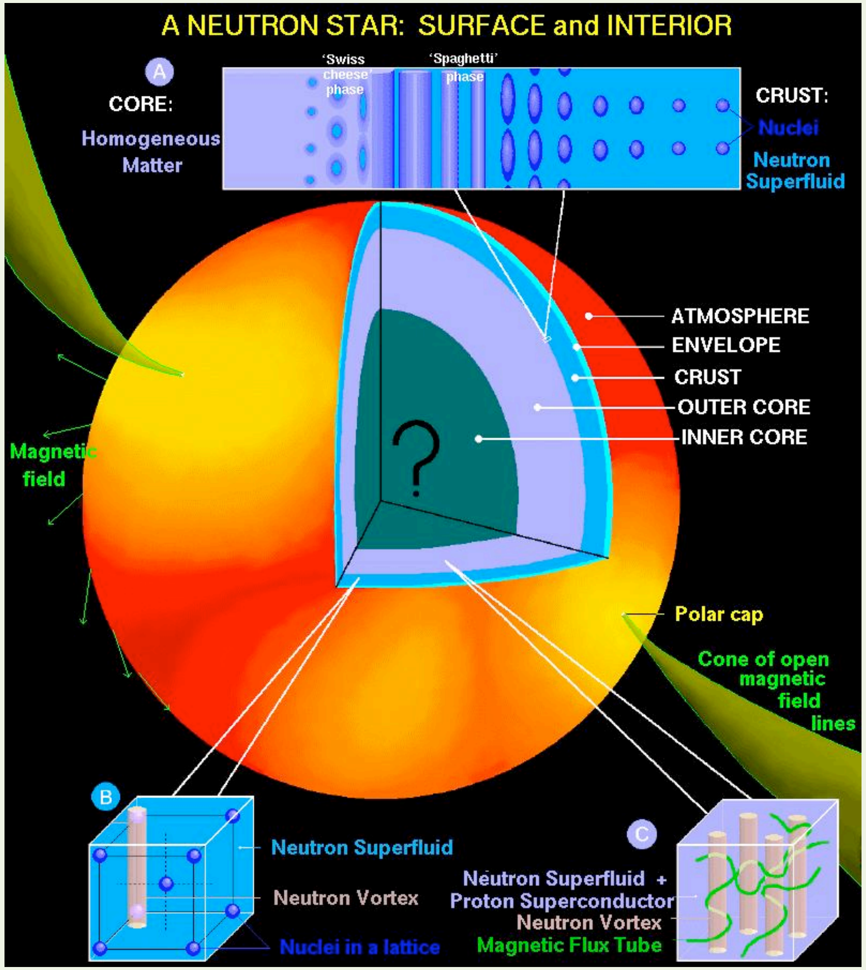
Martin J. Savage
U of Washington

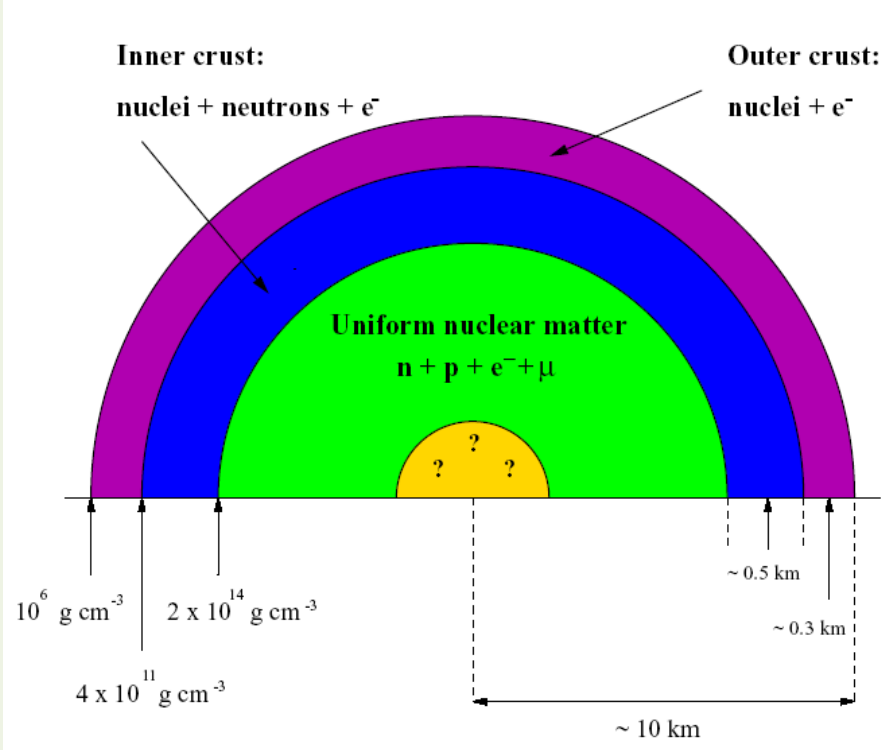


Aaron Torok
Indiana

André Walker-Loud
Berkeley

attending this meeting





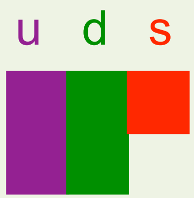
Dany P. Page, UNAM

¿Hyperon matter?

Strangeness

Confined

S, L, K

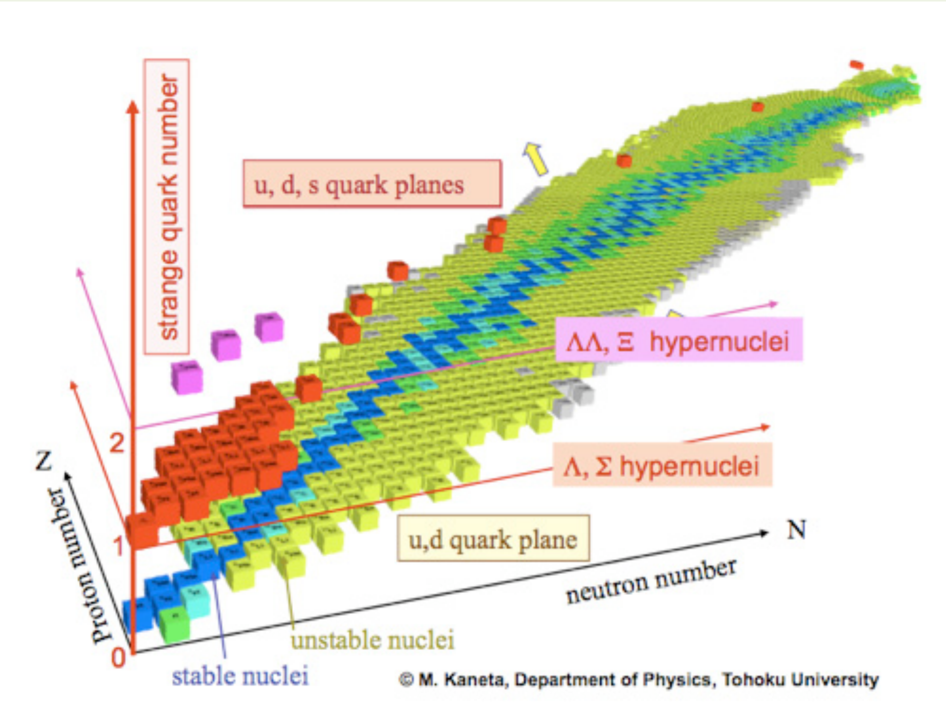


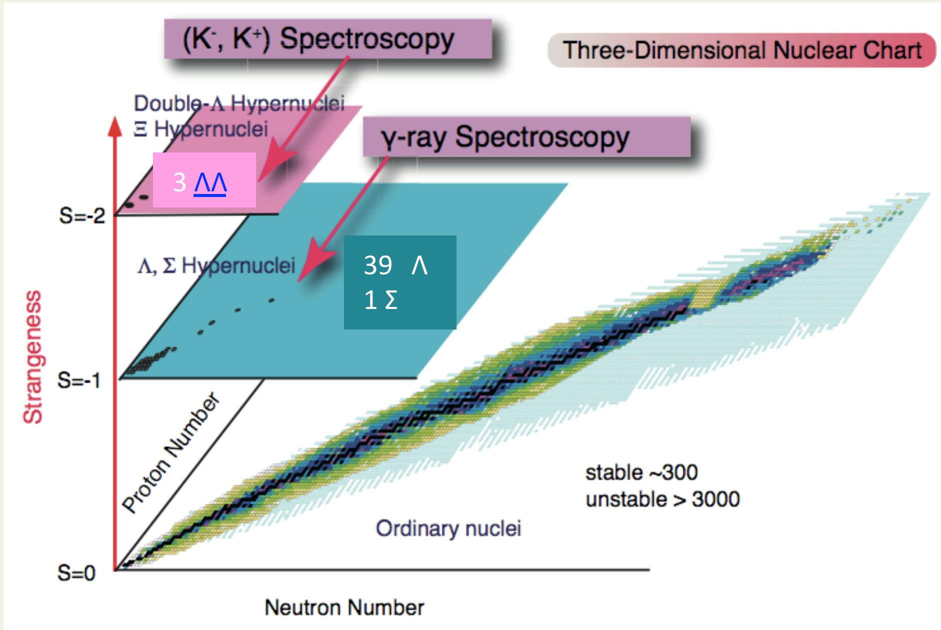
interaction among hadrons: why lattice?

First principle QCD calculation

Quantifiable uncertainties

Possibility of study processes which are not accessible experimentally

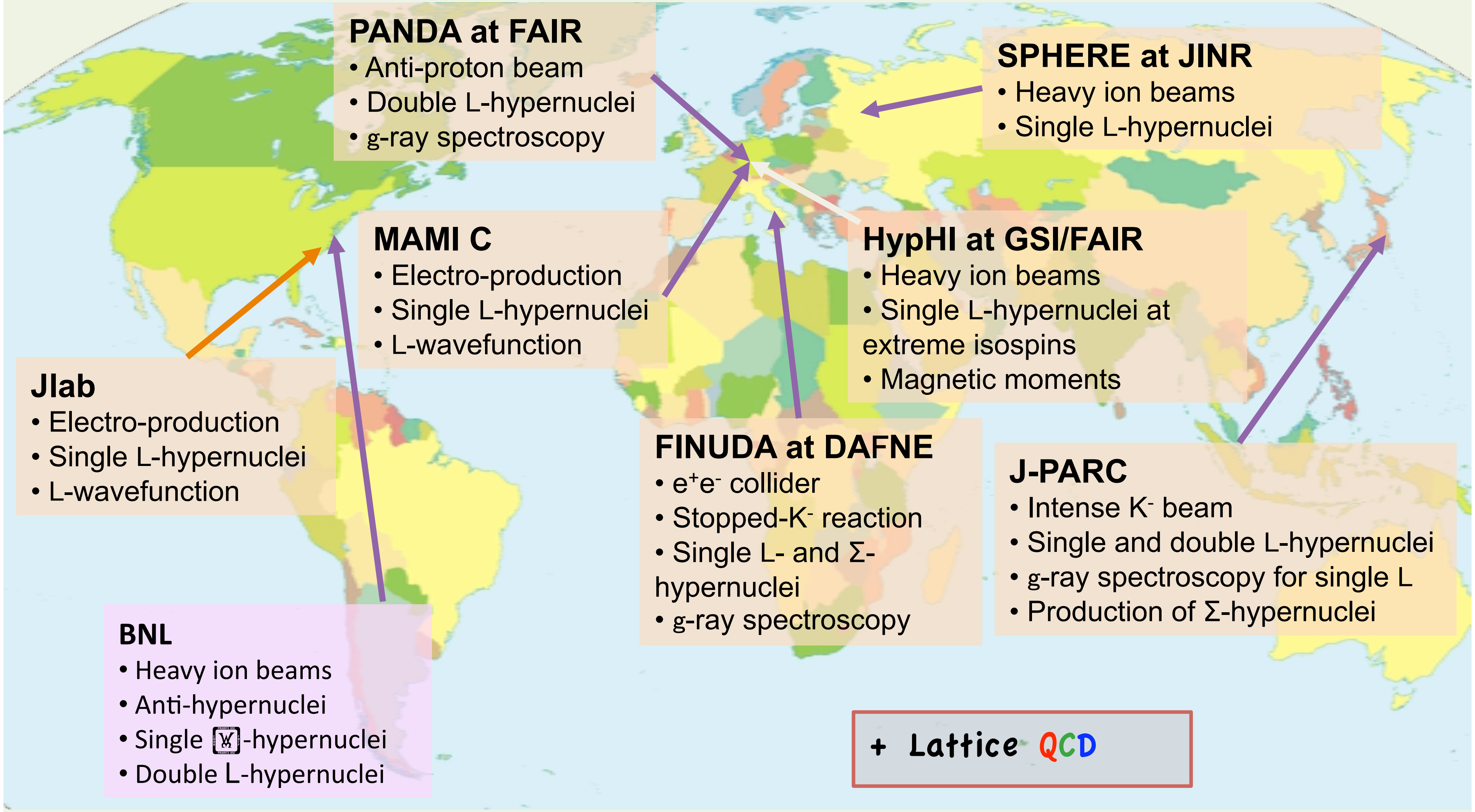




LQCD

EFT, GFMC, NCSM, SRG ...
many-body methods

“strange” Experimental program



PANDA at FAIR
- Anti-proton beam
- Double L-hypernuclei
- g-ray spectroscopy

SPHERE at JINR
- Heavy ion beams
- Single L-hypernuclei

MAMI C
- Electro-production
- Single L-hypernuclei
- L-wavefunction

HypHI at GSI/FAIR
- Heavy ion beams
- Single L-hypernuclei at extreme isospins
- Magnetic moments

Jlab
- Electro-production
- Single L-hypernuclei
- L-wavefunction

FINUDA at DAFNE
- e^+e^- collider
- Stopped-K^- reaction
- Single L- and Σ-hypernuclei
- g-ray spectroscopy

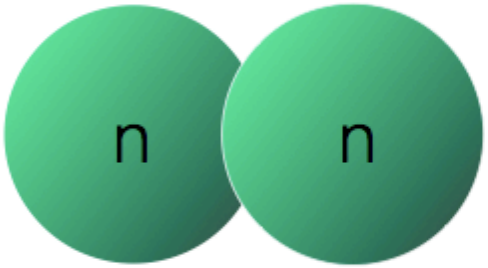
J-PARC
- Intense K^- beam
- Single and double L-hypernuclei
- g-ray spectroscopy for single L
- Production of Σ-hypernuclei

BNL
- Heavy ion beams
- Anti-hypernuclei
- Single [illegible]-hypernuclei
- Double L-hypernuclei

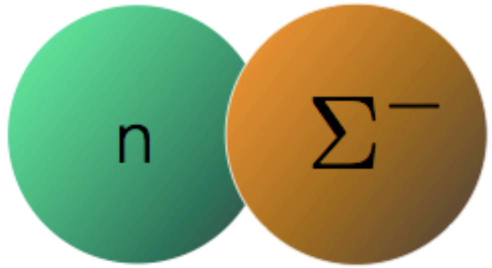
+ Lattice QCD

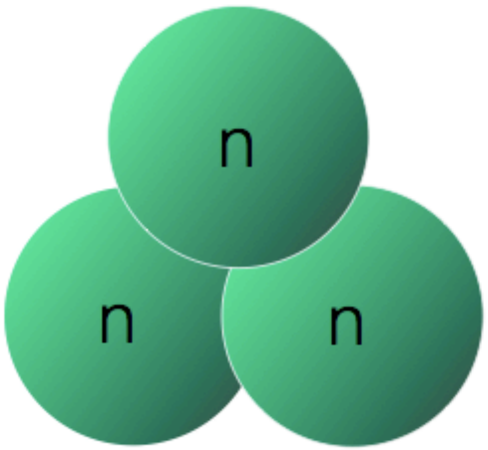
J. Pochodzalla, Int. Journal Modern Physics E, Vol 16, no. 3 (2007) 925-936

hadronic interactions

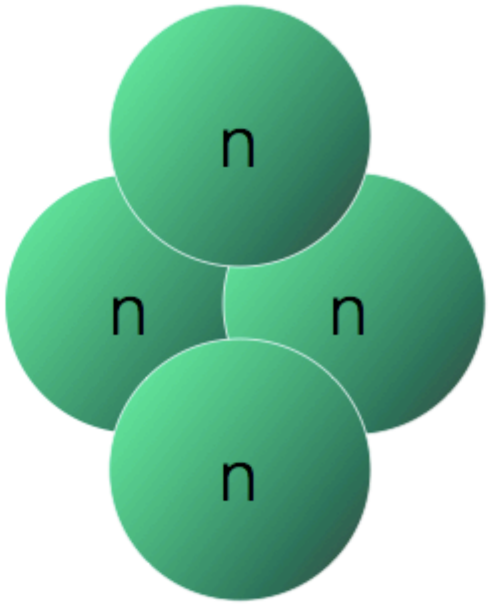


NN-interaction verification

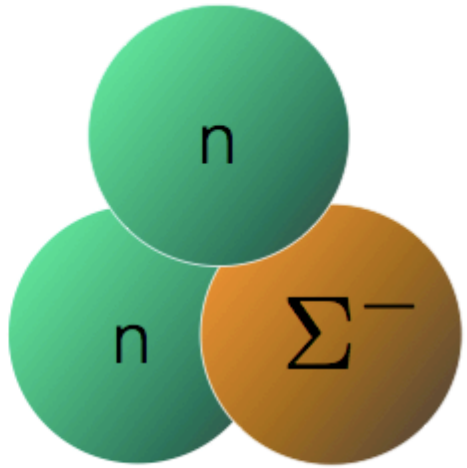




NNN



NNNN



YNN

The computation consists of generating quark propagators (up/downand strange) from gauge configurations and performing contractions to produce correlators with various meson and baryon (including non zero strangeness) states and study their interactions from first principles.

Configurations (HSC) ⇒ Compute propagators ⇒ Compute correlators

Code name: CHROMA, by Robert Edwards (edwards@jlab.org).

Our recent simulations (dynamical):

anisotropic lattices N_f=2+1 clover-improved Wilson fermion actions

L^3 x T	16^3 x 128	20^3 x 128	24^3 x 128	32^3 x 256
L (fm)	2.0	2.5	3.0	4.0
$m_\pi L$	3.86	4.82	5.79	7.71
exp($-m_\pi L$)	0.0205	00078	0.0030	0.00044
$m_\pi T$	8.82	8.82	8.82	17.64
exp($-m_\pi T$)	1.48 x 10^{-4}	1.48 x 10^{-4}	1.48 x 10^{-4}	2.18 x 10^{-8}

m_π ~ 390 MeV

To study the interaction of multi-meson/baryon states, a large number of contractions are required; in fact the number grows factorially with the number of particles involved.

Wick contractions to form the correlation function is naively $N_u!\ N_d!\ N_s!$

$$((A+Z)!\,(2A-Z)!)$$

→ cheapest 3-baryon system: $\Xi^0\Xi^0 n$, with 3! 2! 4! = 288 Wick contractions

The triton (nnp) naively involves 2880 (N_u=4 and N_d=5)

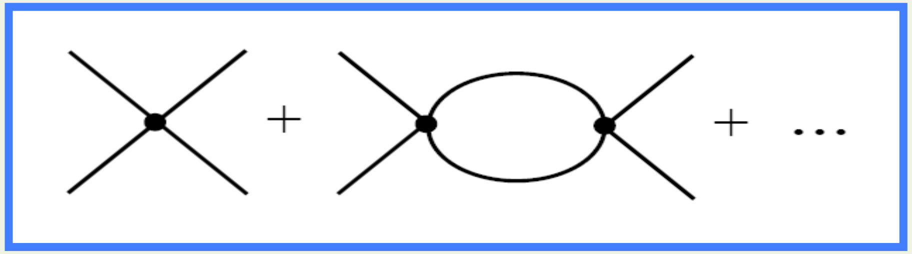
However some careful counting (or brute force numerical attack), can reduce this number to a smaller # of distinct contractions after anti-symmetrizing the proton block.

Recursive algorithms would be needed to study even the light nuclei. This has been tested with multi-meson systems *(Detmold & Savage, Phys.Rev. D82 (2010) 014511*). Work on multi-baryons is underway.

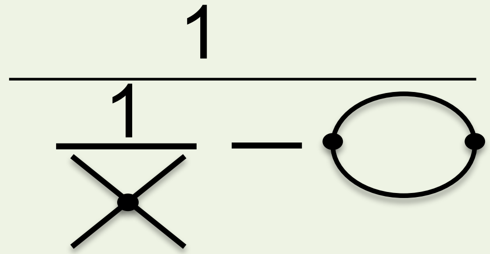
Scattering

Beane, Bedaque, Parreño, Savage, Phys. Lett. B 585,1-2, 106-114 (2004)
M. Lüscher, Commun. Math. Phys. 105, 153-188 (1986)

$i\mathcal{A} =$



$=$

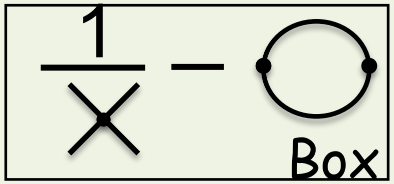


$$\mathcal{A} = \frac{\sum C_{2n} p^{2n}}{1 - I_0 \sum C_{2n} p^{2n}}$$

$$I_0 = \left(\frac{\mu}{2}\right)^{4-D} \int \frac{d^{D-1}\vec{q}}{(2\pi)^{D-1}} \frac{1}{E - \frac{|\vec{q}|^2}{M} + i\varepsilon}$$

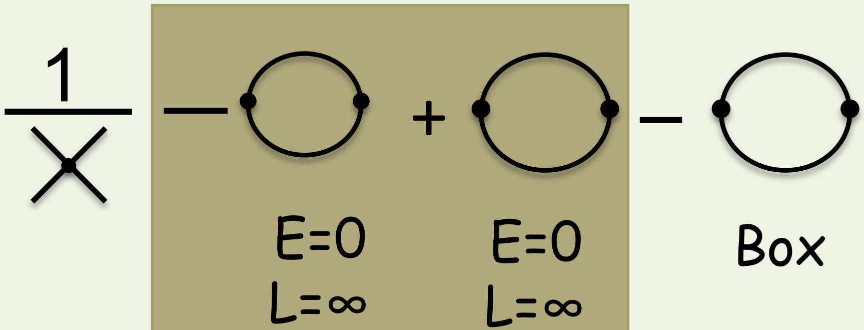
Energy eigenvalues:
zeros of Re[1/A]

$$0 = \mathrm{Re}[(i\mathcal{A})^{-1}] \quad = \mathrm{Re}$$



$$\frac{1}{\sum C_{2n} p^{2n}} - \mathrm{Re}(I_0) = 0$$

$$I_0 \rightarrow \frac{1}{L^3} \sum_{\vec{k}} \frac{1}{E - \frac{|\vec{k}|^2}{M} + i\varepsilon}$$



Scattering

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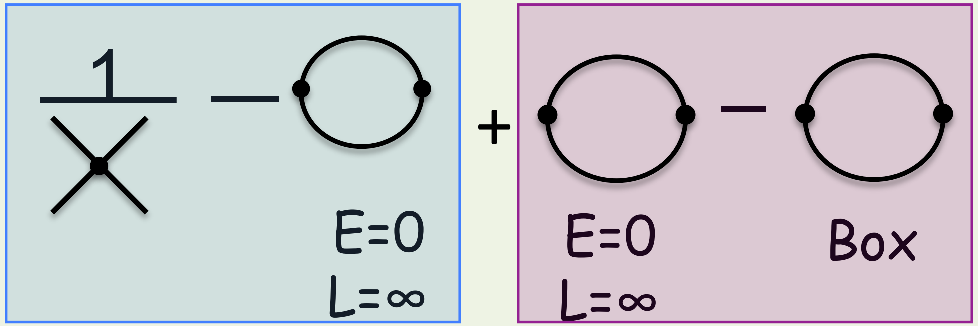


$$p\cot\delta(p) = -\frac{1}{\pi L} S\left(\frac{p^2 L^2}{4\pi^2}\right)$$

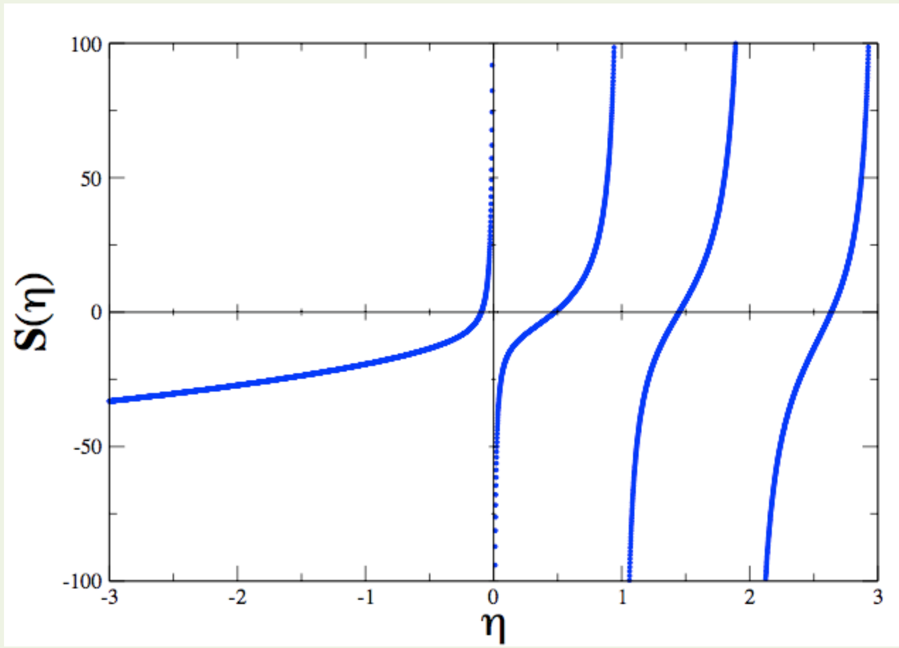
$$p\cot\delta(p)$$

$$\frac{1}{\pi L}\sum_{\vec{j}} \frac{1}{|\vec{j}|^2 - \left(\frac{Lp}{2\pi}\right)^2} - \frac{4\Lambda}{L}$$

$$\mathcal{A} = \frac{4\pi}{M}\,\frac{1}{p\cot\delta - ip}$$

$$p = \sqrt{ME}$$

$$p\cot\delta = -\frac{1}{a} + \frac{1}{2} r p^2 + \ldots$$



Lattice simulations Evaluation of vacuum correlation functions:

$$C_{B_1B_2,\Gamma}(\vec{p}_1,\vec{p}_2,t)=\sum_{\vec{x}_1\vec{x}_2} e^{i\vec{p}_1\vec{x}_1} e^{i\vec{p}_2\vec{x}_2}\Gamma^{\beta_1\beta_2}_{\alpha_1\alpha_2}\left\langle B_{1,\alpha_1}(\vec{x}_1,t)B_{2,\alpha_2}(\vec{x}_2,t)\overline{B}_{1,\beta_1}(x_0,0)\overline{B}_{2,\beta_2}(x_0,0)\right\rangle$$

spin tensor

baryon interpolating operator

away from the source, i.e. at large t

source located at t=0

$$C_{H_AH_B}(\vec{p},-\vec{p},t)\sim\sum_n Z^{(i)}_{n;AB}(\vec{p})Z^{(f)}_{n;AB}(\vec{p})e^{-E^{AB}_n(\vec{0})t}$$

$$\frac{C_{H_AH_B}(\vec{p},-\vec{p},t)}{C_{H_A}(\vec{0},t)C_{H_B}(\vec{0},t)}\xrightarrow{t\to\infty}\sum_n \tilde{Z}^{(i)}_{0;AB}(\vec{p})\tilde{Z}^{(f)}_{0;AB}(\vec{p})e^{-\Delta E^{AB}_0(\vec{0})t}\quad\sim\quad G(t)$$

Effective Mass method

$$\log\frac{G(t)}{G(t+1)}\to\text{extract}\quad\Delta E$$

$$\Delta E^{(AB)}_n\equiv\Delta E^{(AB)}_n(\vec{0})\equiv E^{(AB)}_n(\vec{0})-m_A-m_B$$

$$=\sqrt{q_n^{\;2}+m_A^2}+\sqrt{q_n^{\;2}+m_B^2}-m_A-m_B=\frac{q_n^2}{2\mu_{AB}}+\ldots$$

obtained from the simulation

(below inelastic thresholds)

$$p\cot\delta = -\frac{1}{a} + \frac{1}{2} r p^2 + \dots$$

$$p\cot\delta(p) = \frac{1}{\pi L} S(\eta) = \frac{1}{\pi L} \sum_{\vec{j}}^{|\vec{j}|<\Lambda} \frac{1}{|\vec{j}|^2 - \eta^2} - \frac{4\Lambda}{L} \quad \text{with} \quad \eta = \frac{L}{2\pi} p$$

If one retains only the scattering length in the tan(δ) expansion and performing a perturbative expansion on the momentum p^2 (and playing a bit with the sums...)

$$E = \frac{p^2}{M} = \frac{4\pi a}{ML^3}\left[1 - c_1 \frac{a}{L} + \left(c_1^2 - \frac{1}{\pi^2}\sum_{\vec{j}\neq 0}\frac{1}{|\vec{j}|^4}\right)\left(\frac{a}{L}\right)^2 + \dots\right] \quad \text{with} \quad c_1 = \frac{1}{\pi}\sum_{\substack{\vec{j}\in Z^3 \\ \vec{j}\neq \vec{0}}} \frac{1}{|\vec{j}|^2}$$

(recovering Lüscher's formula, M. Lüscher, Commun. Math. Phys. 105, 153 (1986))

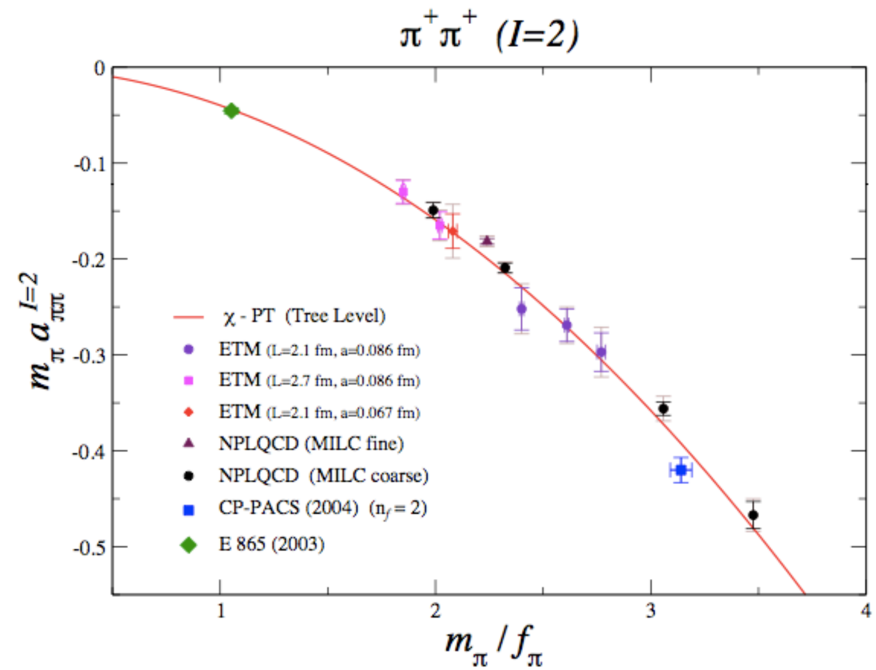
For negatively energy shifted states (in the lattice volume):

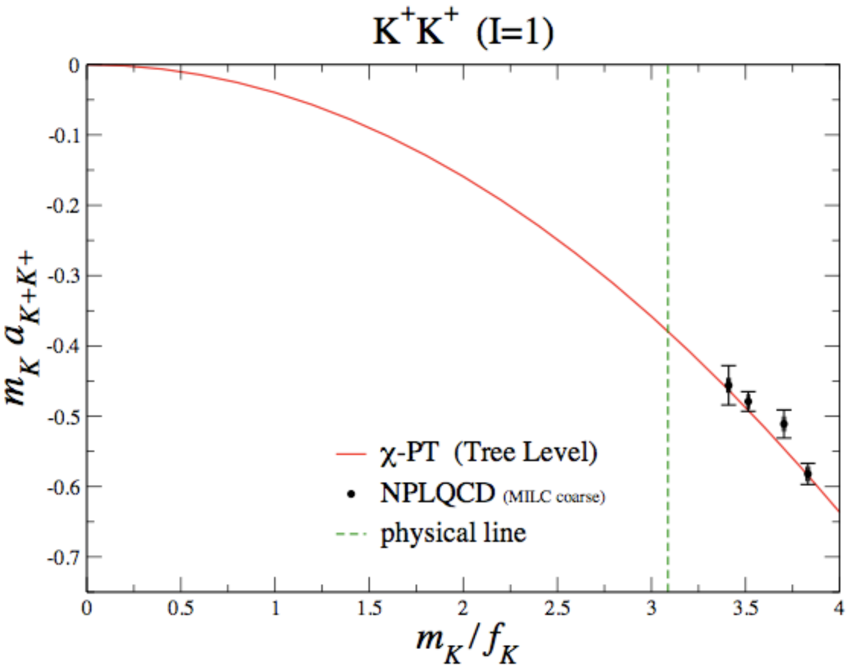
$$p = \mathrm{i}\,\kappa, \qquad \kappa = \gamma + \frac{g_1}{L}\left(e^{-\gamma L} + \sqrt{2}e^{-\sqrt{2}\gamma L} + \dots\right) \qquad \text{with } \gamma << m_\pi \qquad B.E._{\infty} = \frac{\gamma^2}{M}$$

(finite volume dependence suppressed exponentially by the binding momentum)

With simulations performed at two or more lattice volumes (with $p^2 < 0$) it is possible to perform an extrapolation to determine the b.e. at infinite volume, and at this pion mass.

Simplest hadronic interactions
(with mixed action: DWF on staggered)

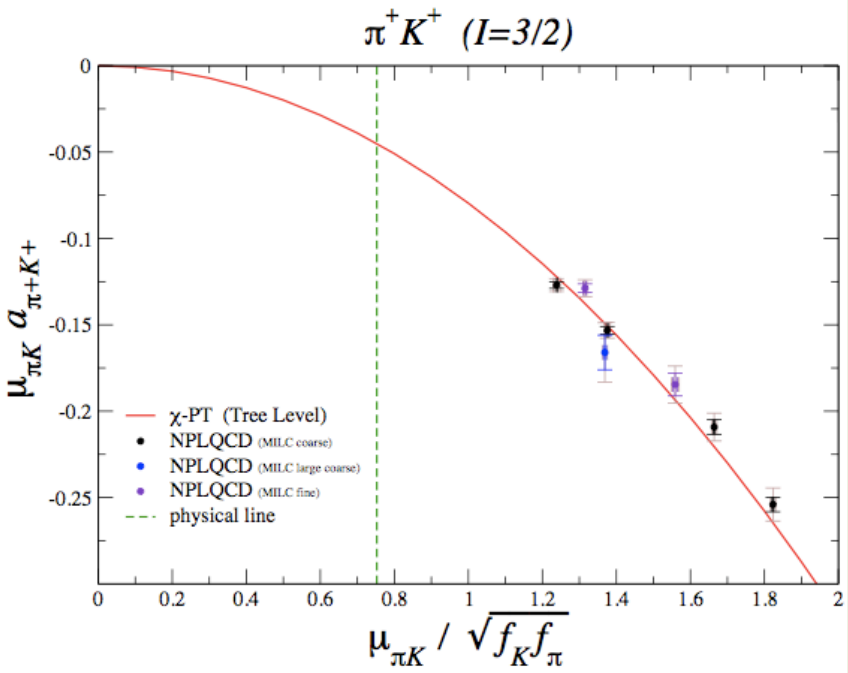


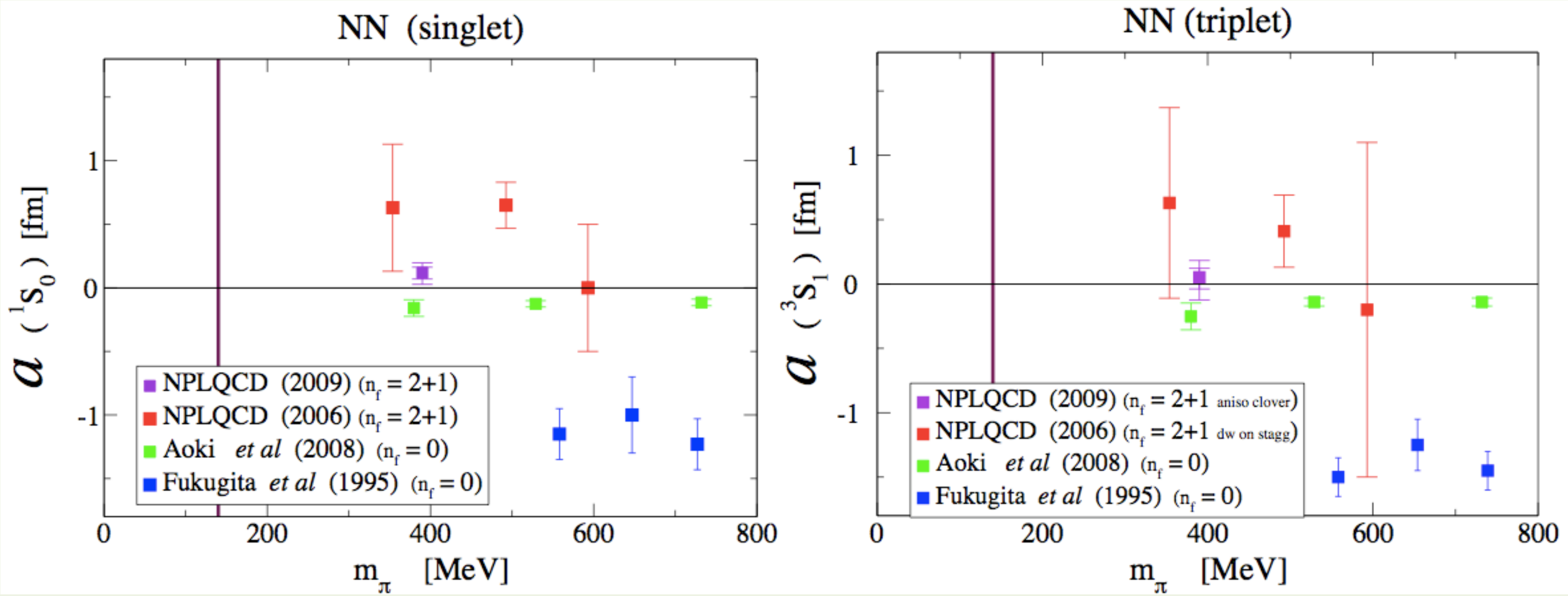


$20^3 \times 64$ ($L_5 = 16$)

b = 0.125 fm L = 2.5 fm

	m_p (MeV)	m_K (MeV)	no. conf x no. src
m_l=030 m_s=050	591	675	564 x 8
m_l=020 m_s=050	491	640	486 x 8
m_l=010 m_s=050	352	595	769 x 8
m_l=007 m_s=050	291	580	1039 x 8





physical values

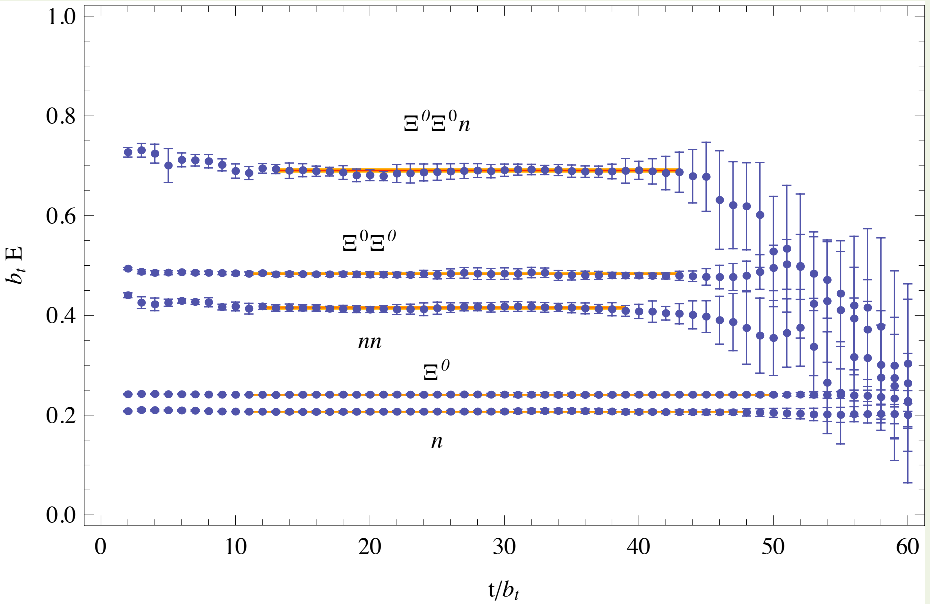
$$a_s^{^1S_0} = -23.714 \text{ fm}$$
$$a_s^{^3S_1} = 5.425 \text{ fm}$$

$$\frac{\text{noise}}{\text{signal}} \xrightarrow[t\to\infty]{} \frac{1}{\sqrt{N}} e^{A\left(m_p - \frac{3}{2} m_\pi\right)t}$$

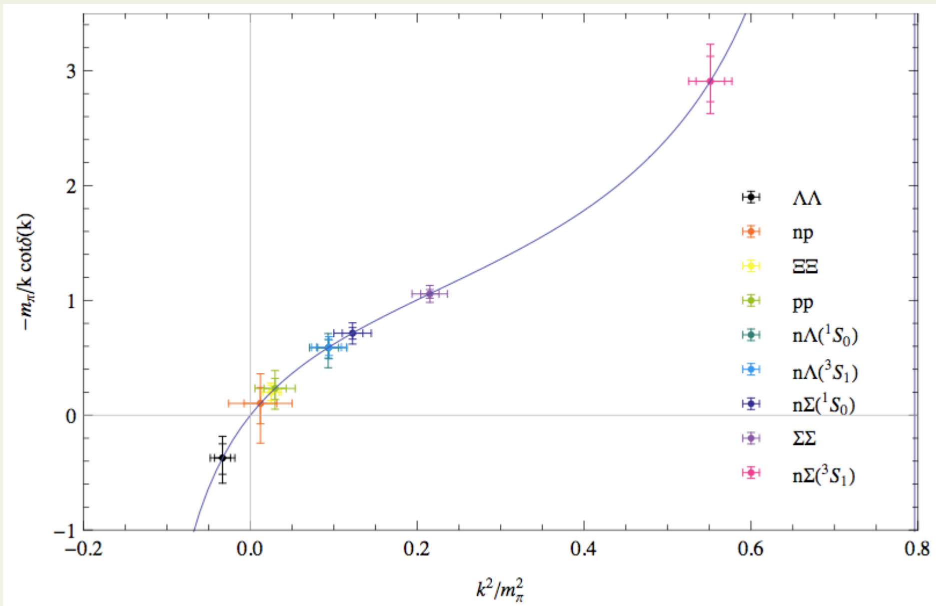
(but only asymptotically)

A → system with A nucleons

$20^3 \times 128$ b ≈ 0.123 fm $m_\pi \sim 390$ MeV



Phys. Rev. D. 80, 074501 (2009)



Phys. Rev. D 81, 054505 (2010)

H-dibaryon
I=0 J=0 s=-2 uuddss

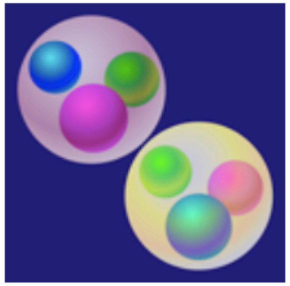
Evidence for a Bound *H* Dibaryon from Lattice QCD

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)

***Physics:* Binding baryons on the lattice**

April 26, 2011



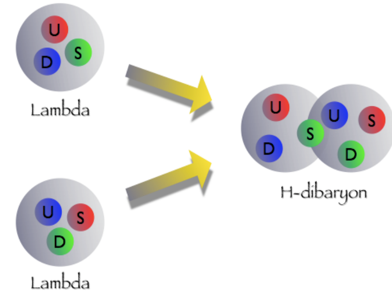
State of the art computer simulations provide the first indication of a dibaryon bound state.
[Synopsis on Phys. Rev. Lett. **106**, 162001 (2011)]
[Synopsis on Phys. Rev. Lett. **106**, 162002 (2011)]

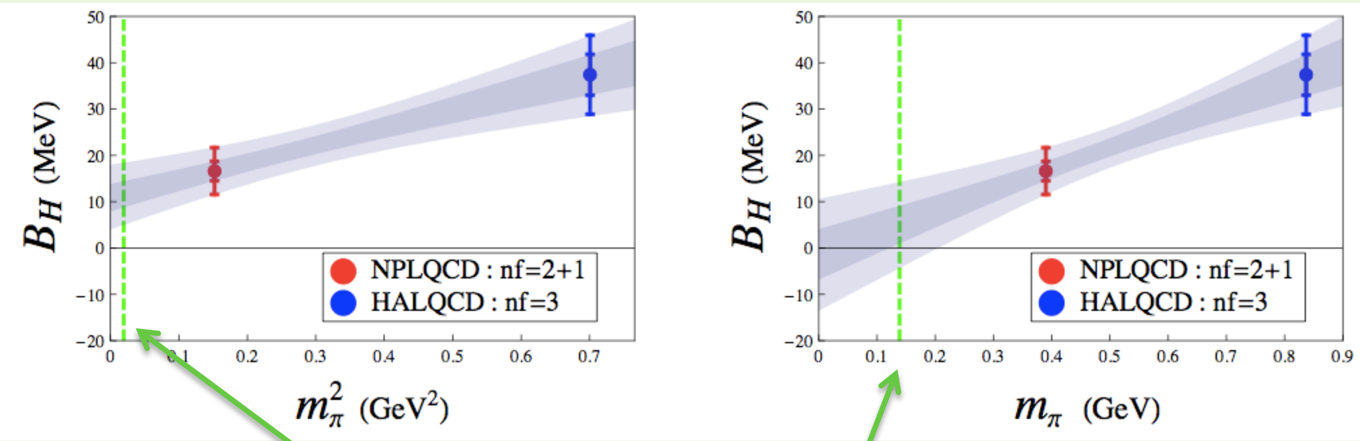
Read Article | More Synopses

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)





physical pion mass

$$B(m_\pi) = B_0 + d_1\, m_\pi^2$$

$$B_H^{quad} = +11.5 \pm 2.8 \pm 6 \text{ MeV}$$

$$B(m_\pi) = B_0 + c_1\, m_\pi$$

$$B_H^{lin} = +4.9 \pm 4.0 \pm 8.3 \text{ MeV}$$

e-Print: arXiv:1103.2821 [hep-lat]

Project SAIL in MN (BSC)

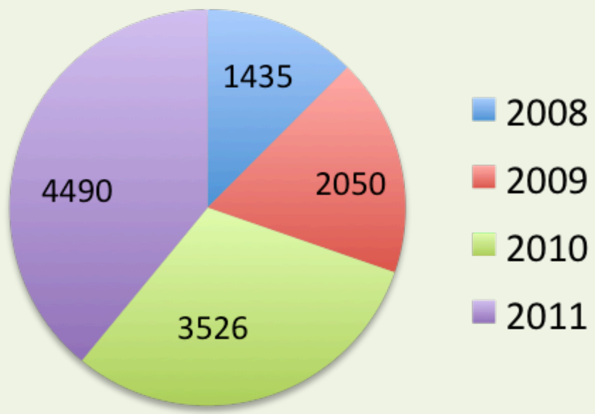
- NPLQCD Coll in MN

  PowerPC Cluster, 10k cores, Myrinet interconnect.

  Partnership 2006 to present day (15 periods)
- Current period ~ 5% share of total resource.
- Steady increase in time allocated over the years.
- Computing power in the upcoming years ?

  The more the merrier?

RES-Mare Nostrum



Example

- Propagator generation :

  solve a sparse matrix equation iteratively

  M x = b, size of M ~ L^4 by L^4

  2400 configurations “M”

- 180 sources “b” at 4 volumes

- ... at current rate (30 mins per prop / 256 cores)

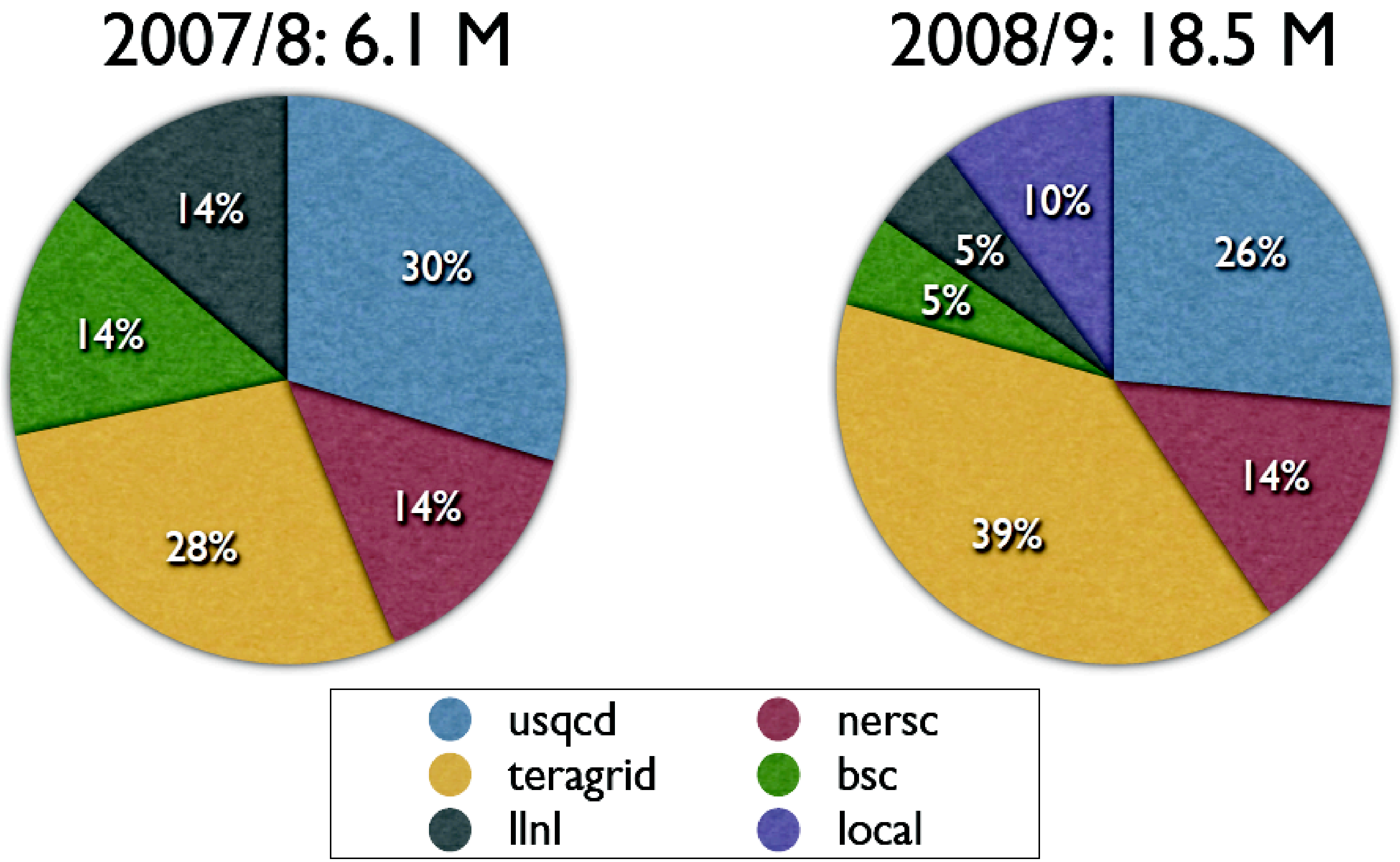
  800 configurations x 90 inversions x 1 volume

  ~ 5% (of total resource at BSC) => non-stop 2 years

- Factor of 20 increase in total resource at Mare Nostrum to reach 0.1% stats. error and perform volume extrapolation.

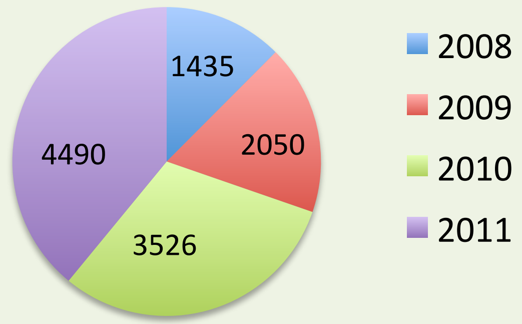
NPLQCD Resources

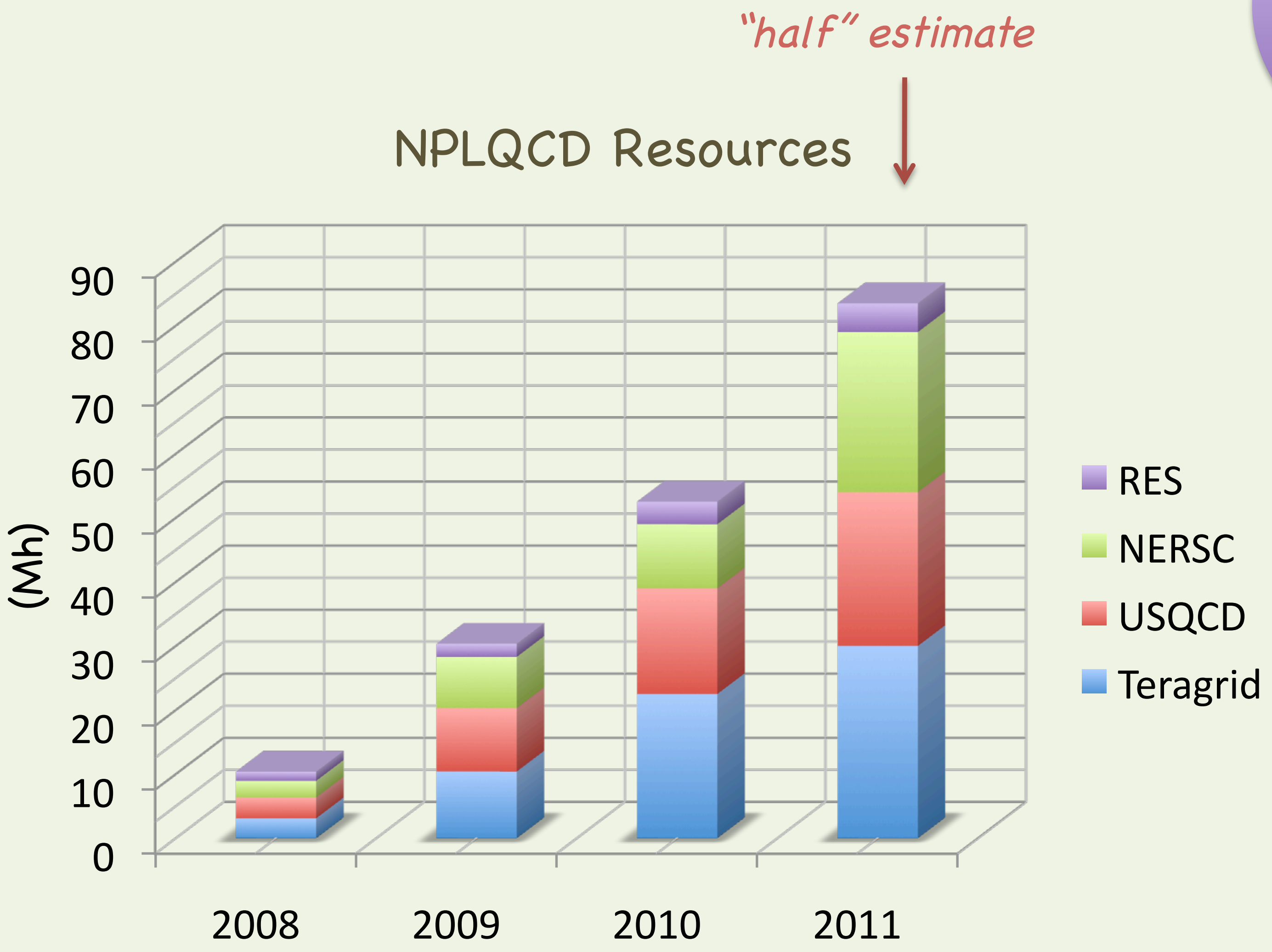
6n node-hours



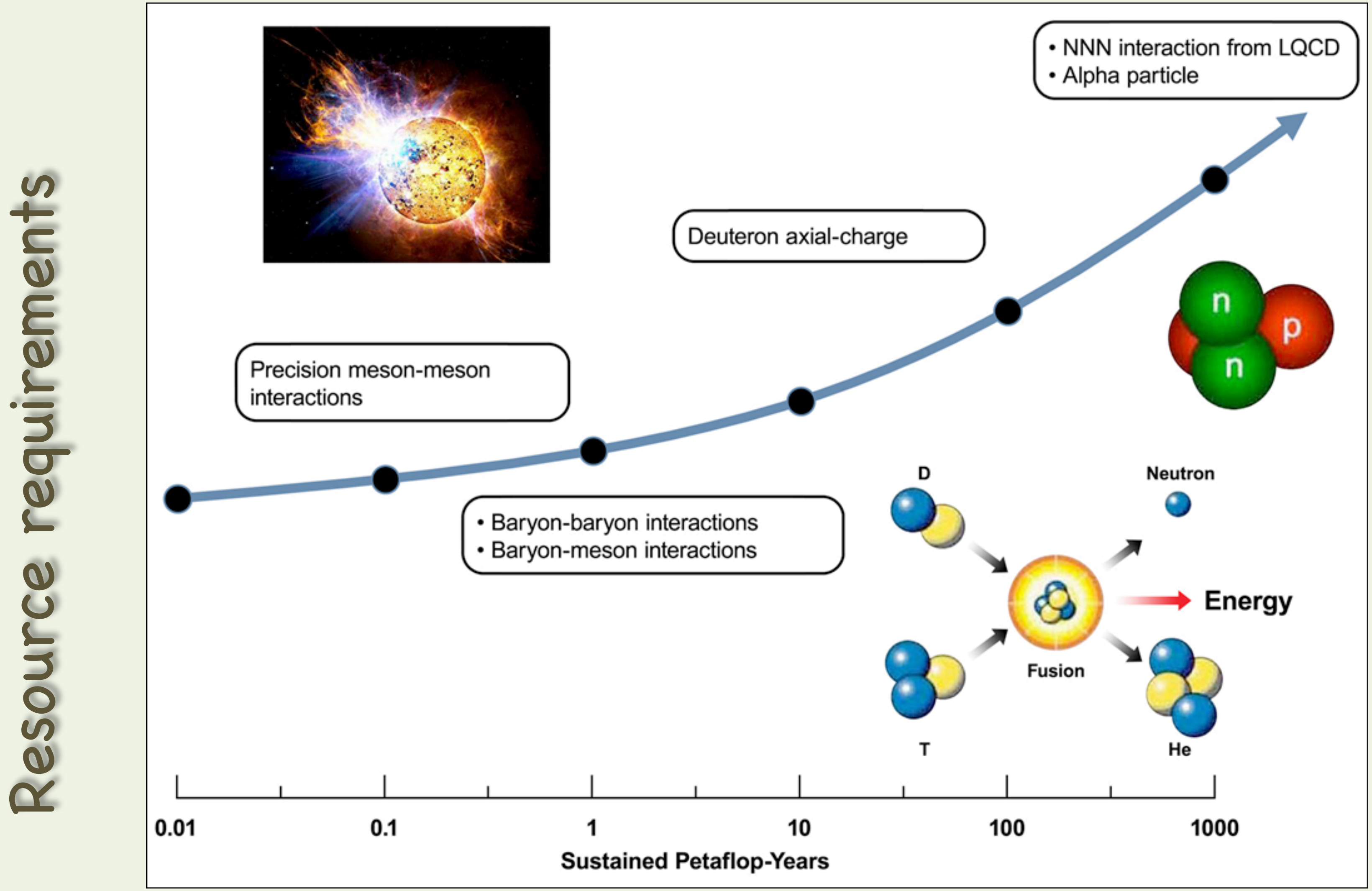
Period from 1st Jan. to 31 Dec.
(2011 projection based on current period
and application for next period)

RES-Mare Nostrum
(in Kh)





From QCD to Nuclei



Scientific Grand Challenges: Forefront Questions in Nuclear Science and the Role of Computing at the Extreme Scale, http://extremecomputing.labworks.org/nuclearphysics/report.stm