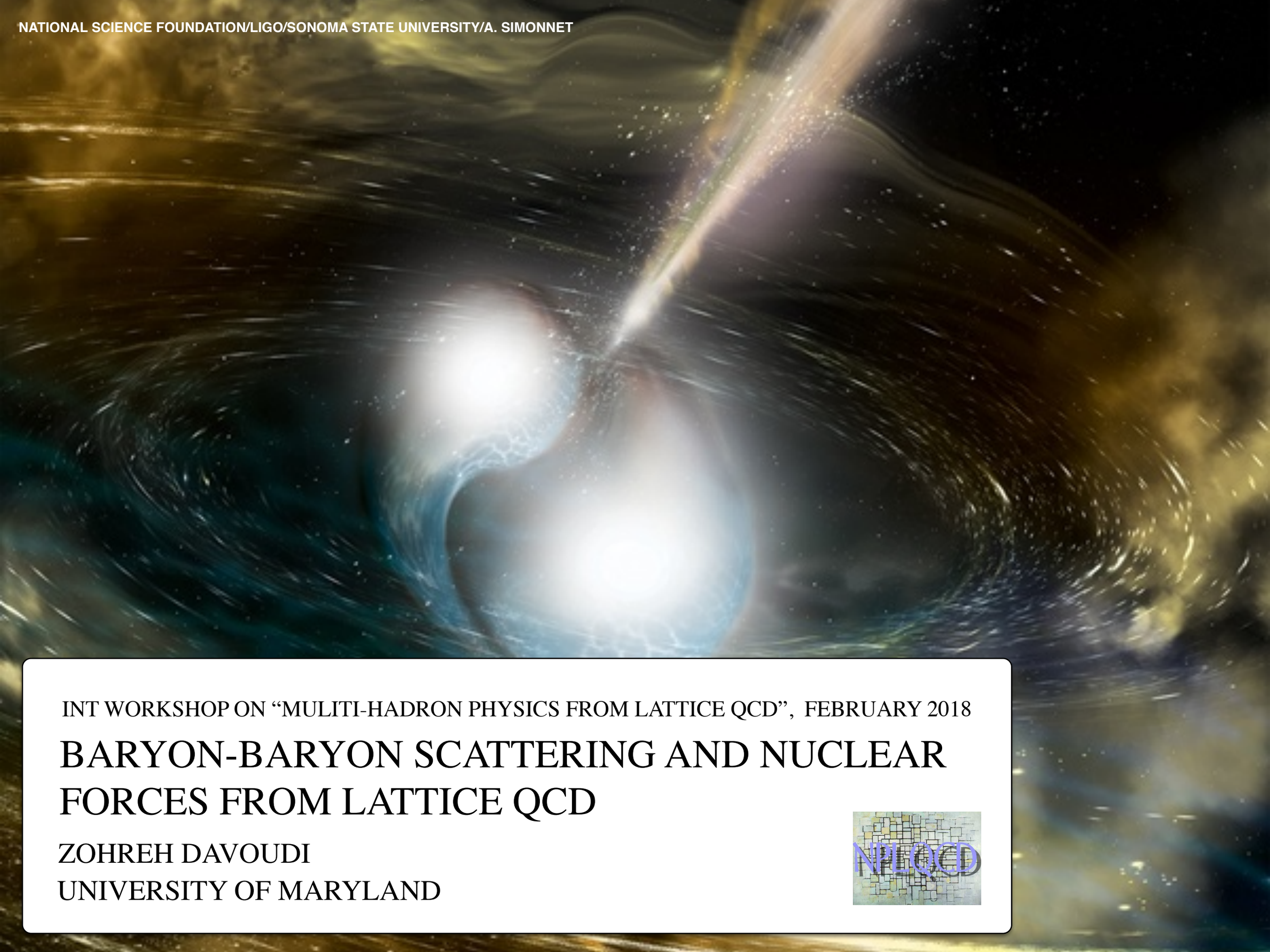
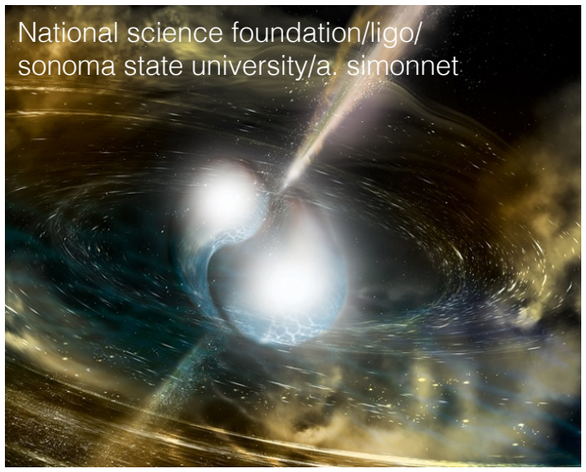


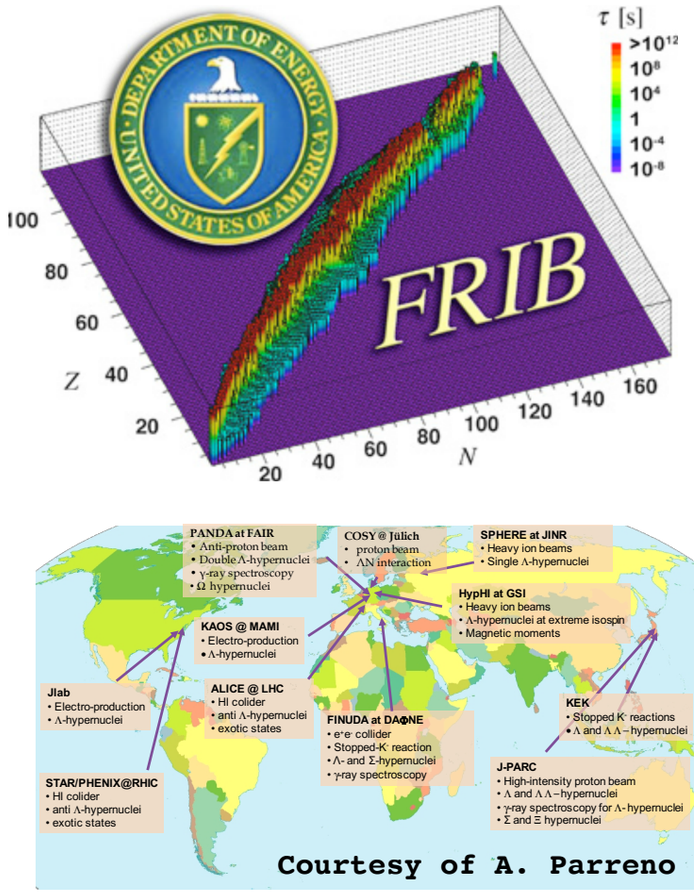
INT WORKSHOP ON "MULITI-HADRON PHYSICS FROM LATTICE QCD", FEBRUARY 2018

BARYON-BARYON SCATTERING AND NUCLEAR FORCES FROM LATTICE QCD

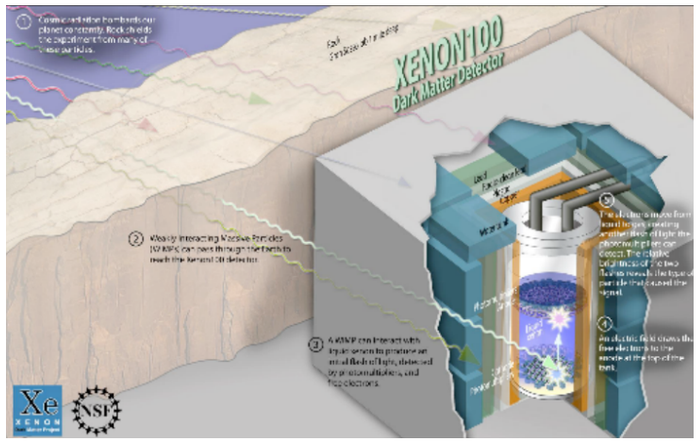
ZOHREH DAVOUDI
UNIVERSITY OF MARYLAND

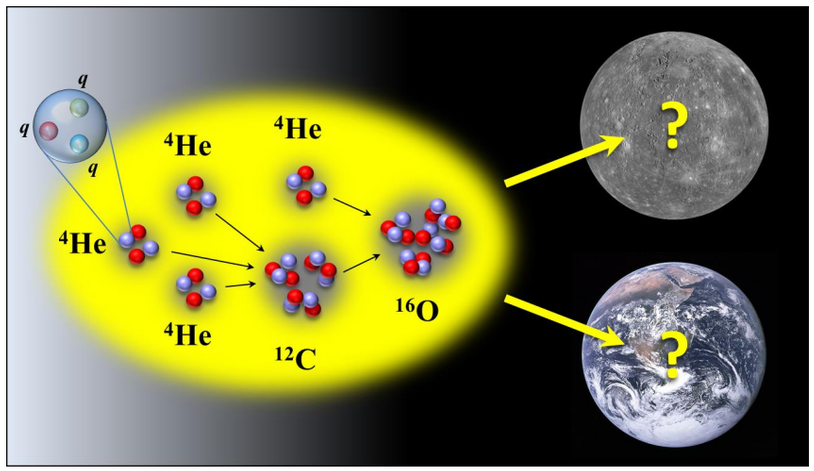
NUCLEAR FORCES ARE ESSENTIAL COMPONENTS OF NUCLEAR PHYSICS RESEARCH…





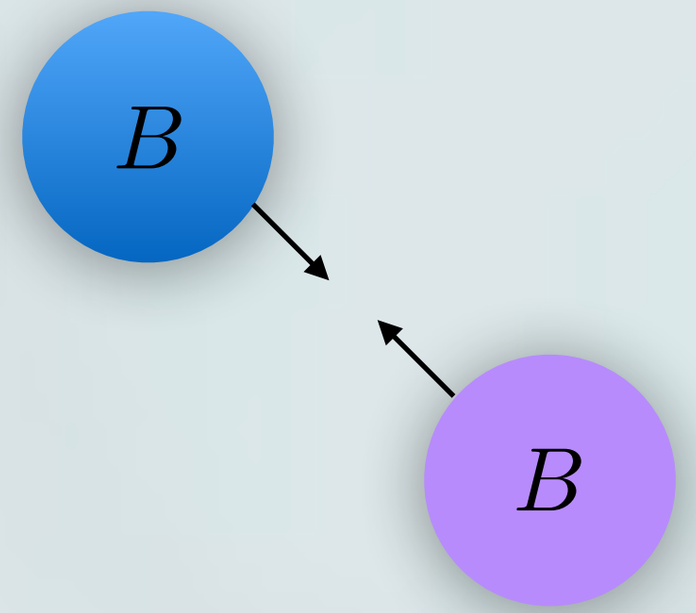
updated from J. Pochodzalla, Int. Journal Modern Physics E, Vol 16, no. 3 (2007) 925-936

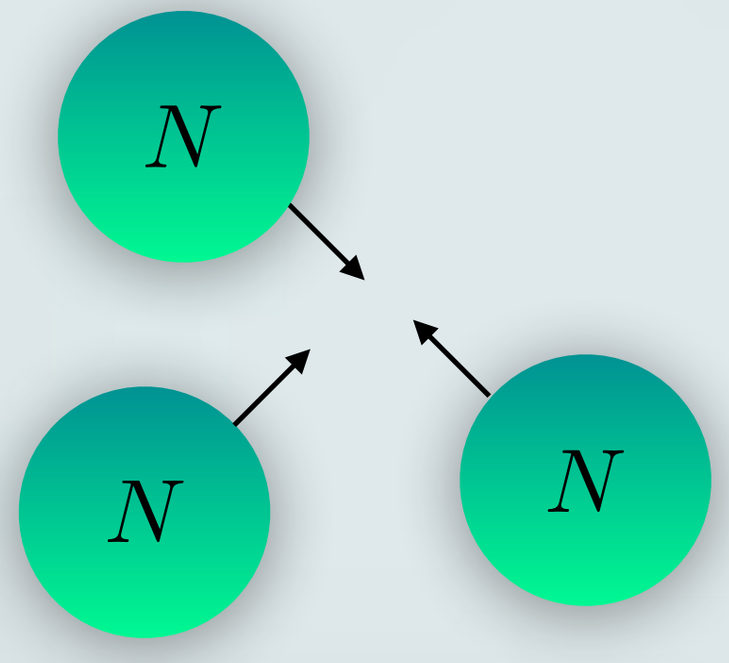




Courtesy of D. Lee

FIRST-PRINCIPLES APPROACH OF LQCD IS PROMISING TO CONSTRAIN THESE FROCES. OF IMPORTANCE TO THE COMMUNITY ARE THREE-NEUTRON FORCES AND HYPERON-NUCLEON FORCES.





COLLABORATION WAS FORMED IN 2004 WITH THE MISSION OF CONNECTING QCD TO NUCLEAR PHYSICS.

Lattice QCD and Nuclear Physics

… Let the Games Begin …

Lattice QCD studies of Nuclei and Multi-Hadron Systems are an important part of the future of Nuclear Physics.

Extracted from the talk by M. Savage, Bad Honnef (2004).

THOUGHT AND FORMALISM DEVELOPMENTS

Nucleon-nucleon interactions on the lattice

Beane and Savage, Phys.Lett. B535 177-180(2002).

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Beane et al(NPLQCD), Phys.Rev. D92 114512 (2015).

THOUGHT AND FORMALISM DEVELOPMENTS FOR >2 MESONS

n-Boson energies at finite volume and three-boson interactions

Beane, Detmold and Savage, Phys.Rev.D76 074507(2007).

The Energy of n Identical Bosons in a Finite Volume at O(L^{-7})

Detmold and Savage, Phys.Rev.D77 057502(2008).

A method to study complex systems of mesons in lattice QCD

Detmold and Savage, Phys.Rev.D82 014511(2010).

NUMERICAL DEVELOPMENETS FOR >2 MESONS

Multi-Pion Systems in Lattice QCD and the Three-Pion Interaction

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Multi-Pion States in Lattice QCD and the Charged-Pion Condensate

Detmold, Savage, Torok, Beane, Luu, Orginos and Parreno, Phys.Rev.D78:014507(2008).

Kaon Condensation with Lattice QCD

Detmold, Orginos, Savage and Walker-Loud, Phys.Rev.D78 054514(2008).

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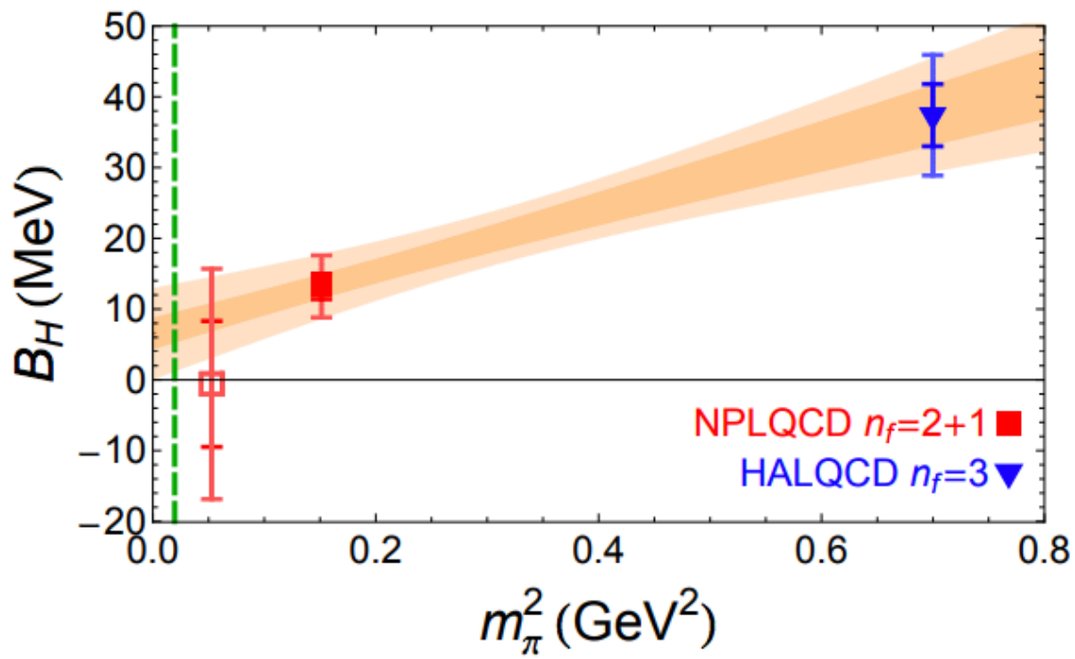
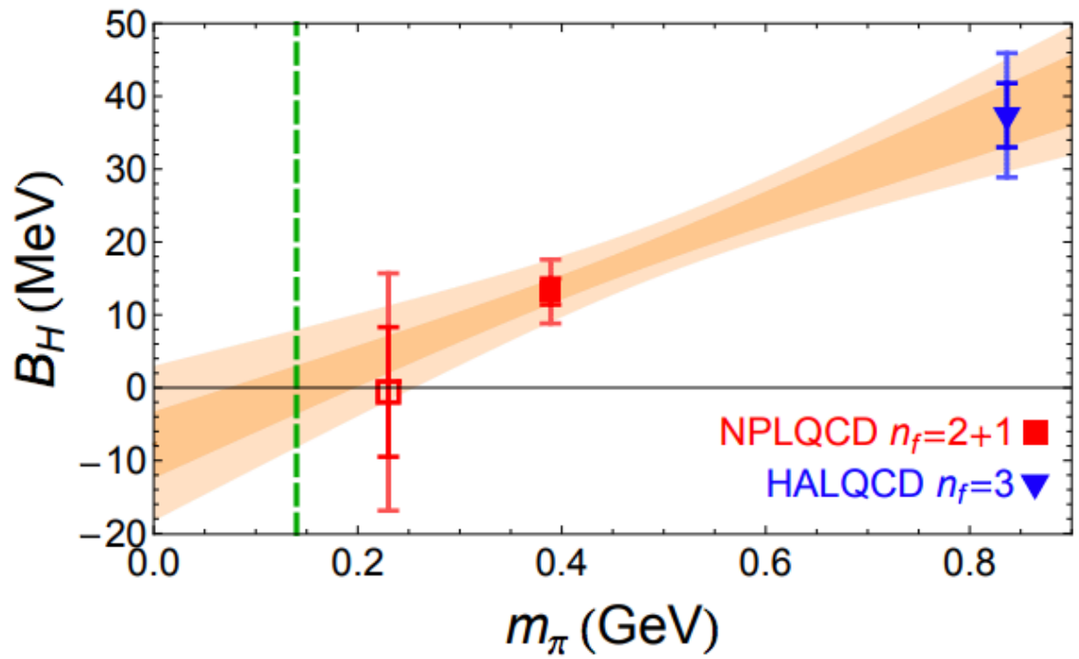
A POSSIBLE BOUND STATE IN THE S=-2, I=0, J=0 TWO-BARYON CHANNEL:

$$\frac{1}{\sqrt{3}}(\Sigma^+\Sigma^- + \Sigma^0\Sigma^0 + \Sigma^-\Sigma^+)/\frac{1}{\sqrt{2}}(\Xi^0 n + \Xi^- p)/\Lambda\Lambda$$





Beane et al(NPLQCD), Phys.Rev.Lett.106 162001(2011).

Inoue et al(HAL QCD), Phys.Rev.Lett.106 162002(2011).

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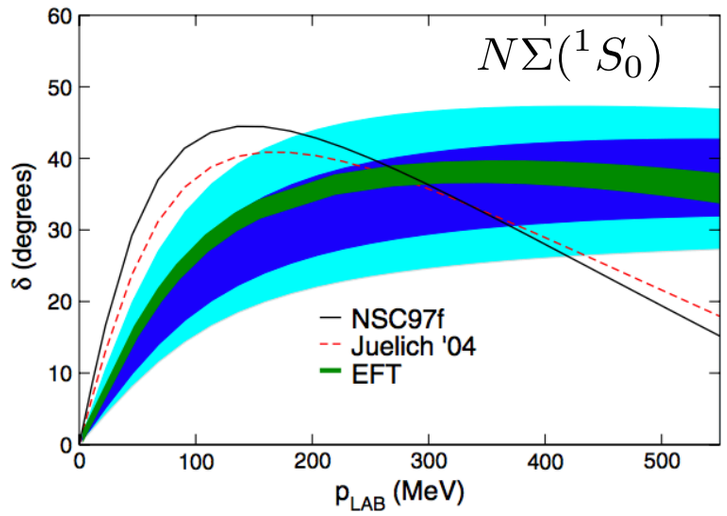
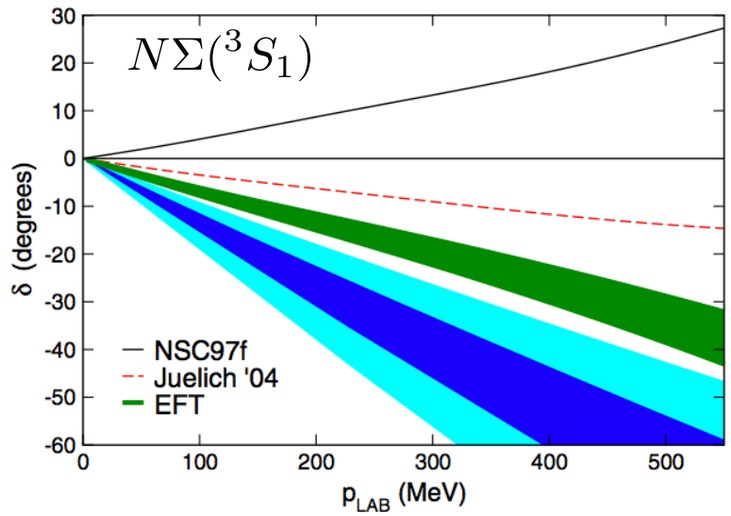
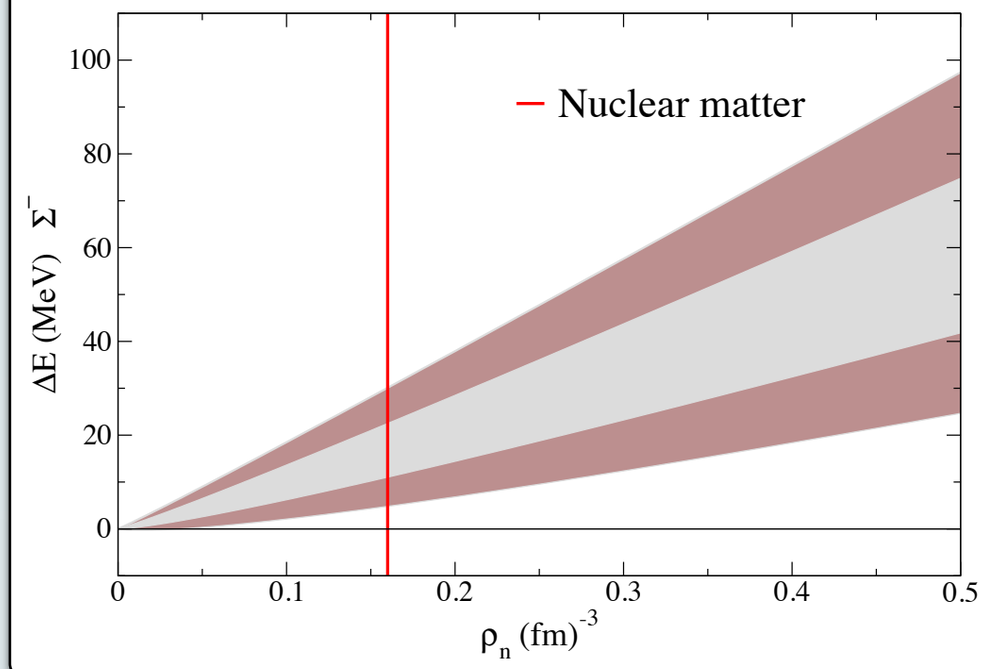
Beane et al(NPLQCD), Phys.Rev. D92 114512 (2015).

$N_f = 2+1,\ m_\pi \approx 389\ \text{MeV},\ a_s \approx 0.123\ \text{fm}, a_s/a_t = 3.5$





ARE HYPERONS EXPECTED TO OCCUR IN INTERIOR OF NEUTRON STARS?



REQUIRES THE KNOWLEDGE OF YN INTERACTIONS IN MEDIUM.

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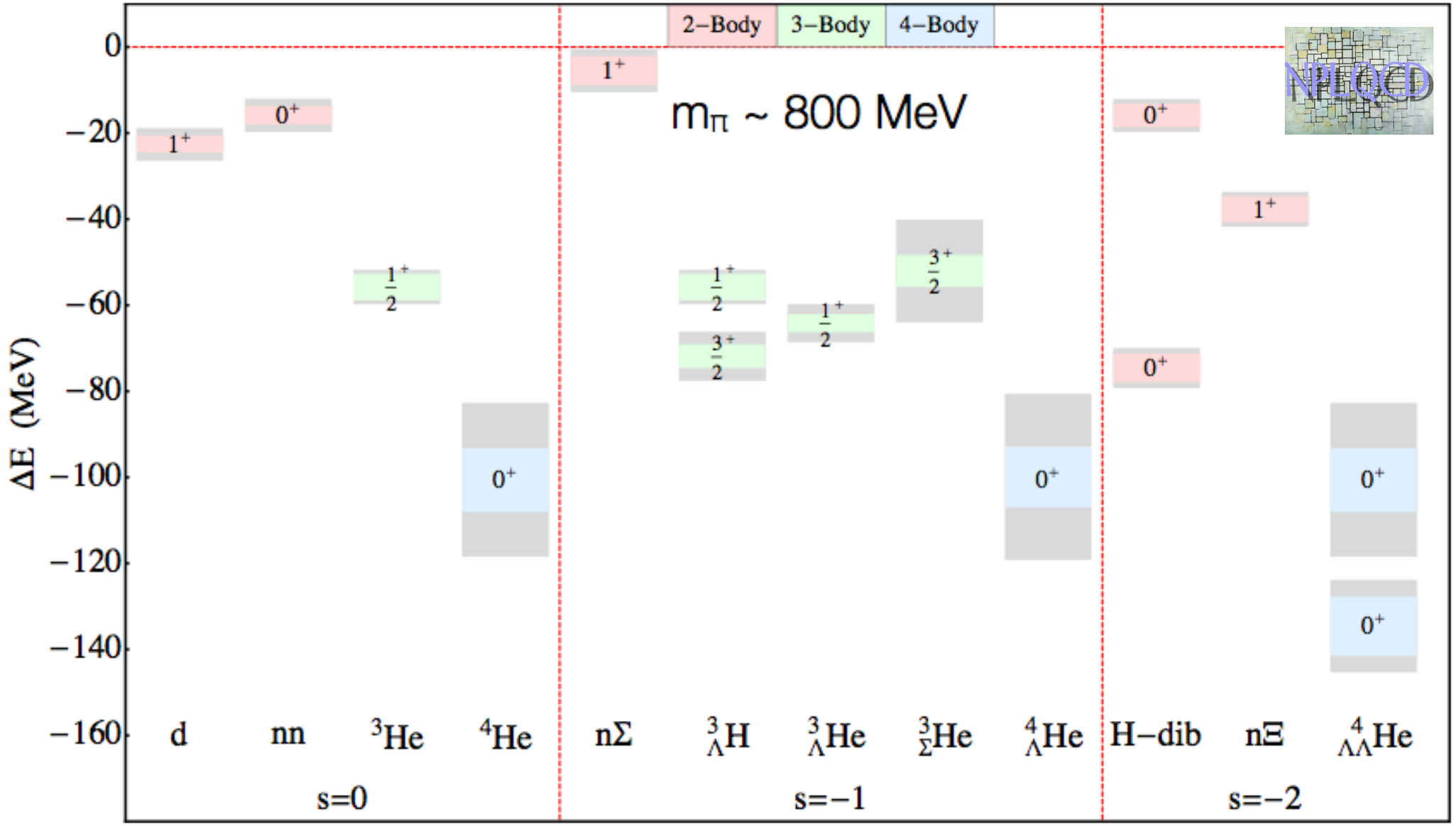
NUCLEI FROM QCD IN A WORLD WITH HEAVIER QUARKS

$N_f = 3,\ m_\pi = 0.806\ \text{GeV},\ a = 0.145(2)\ \text{fm}$



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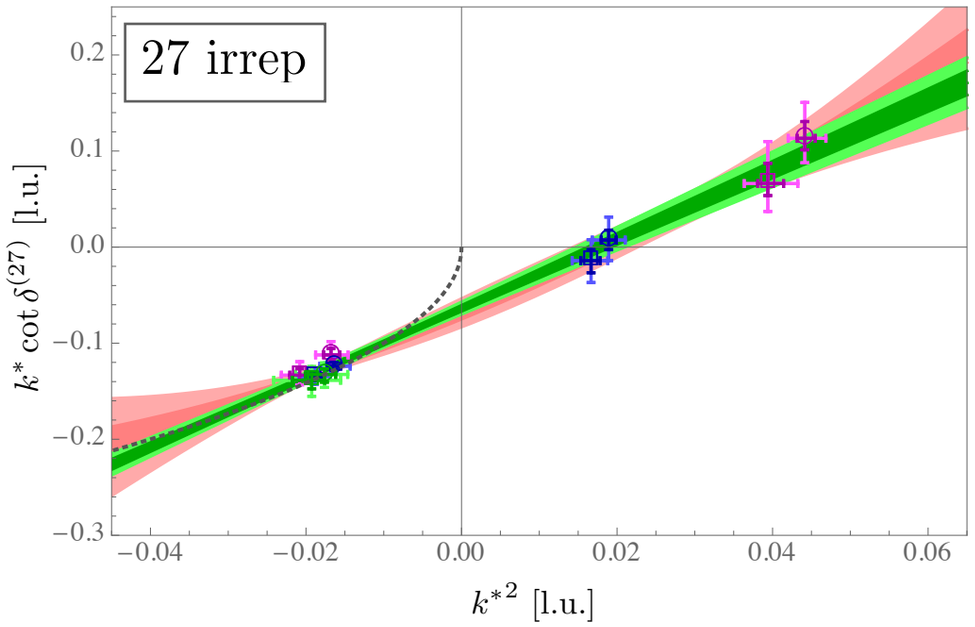

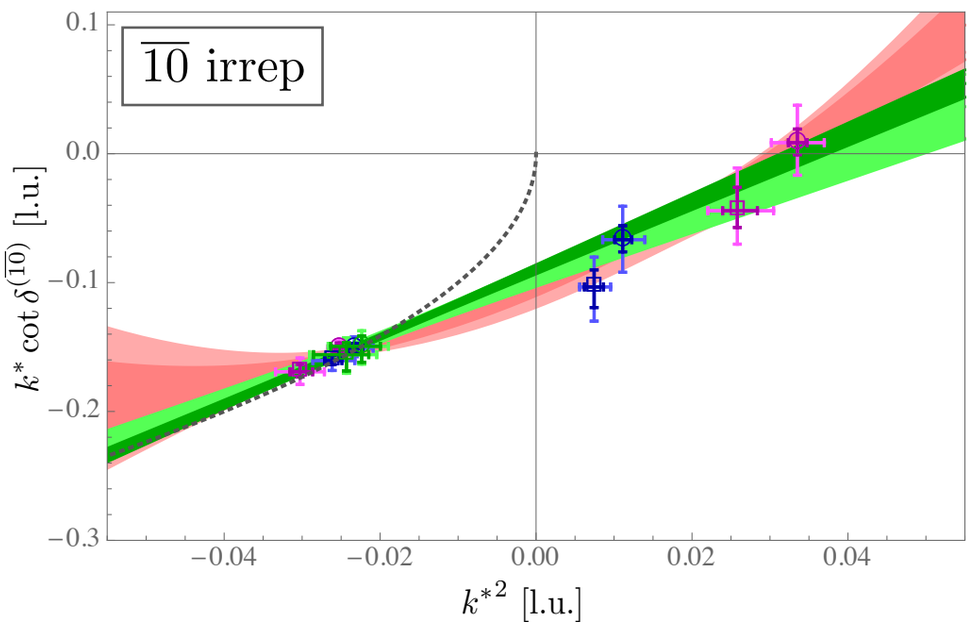

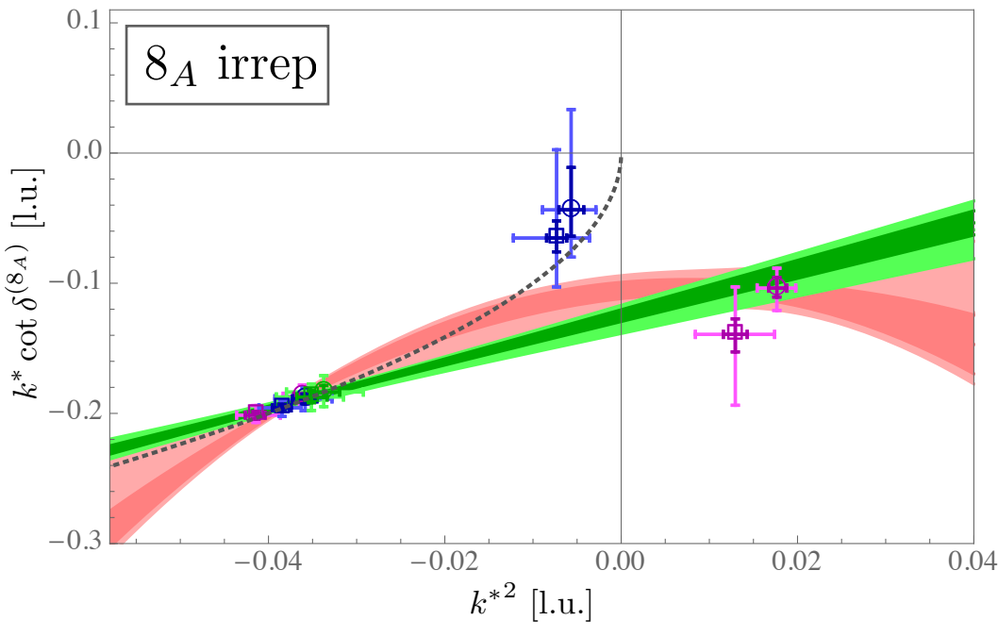

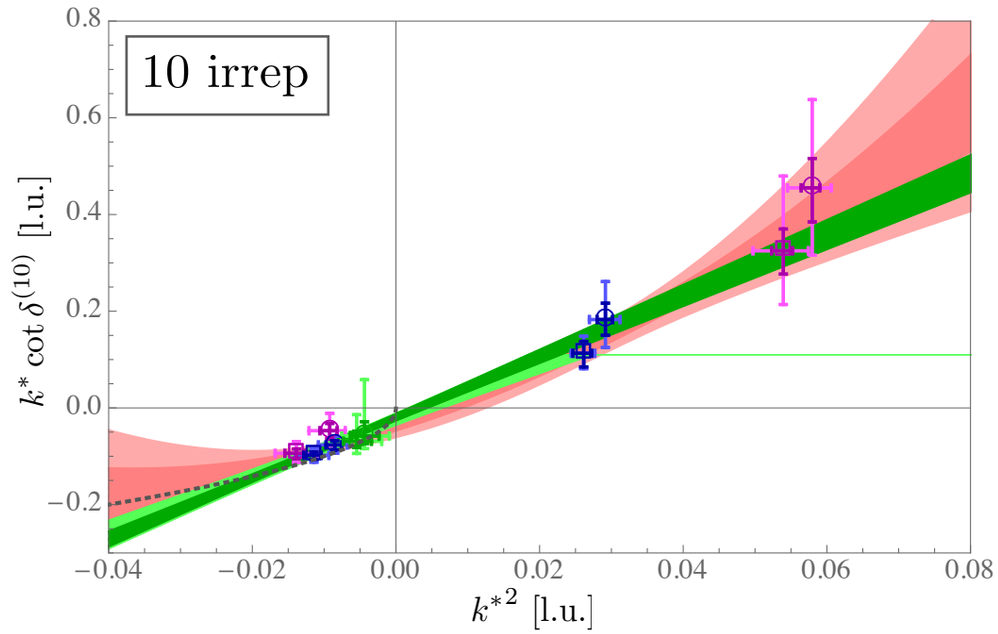

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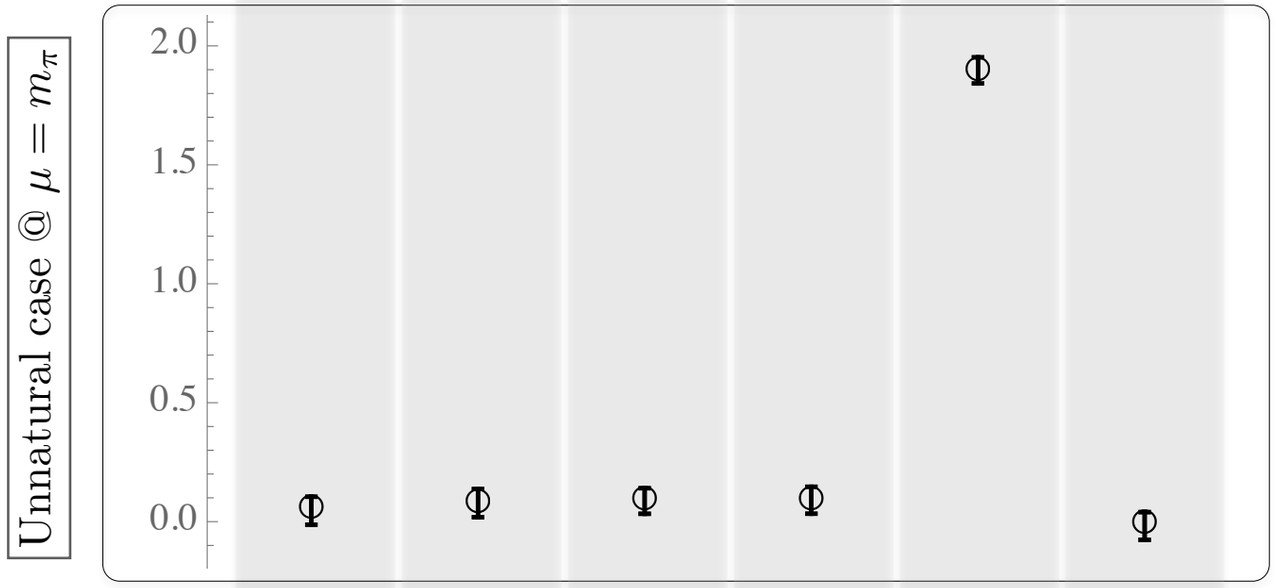

AN ACCIDENTAL SYMMETRY IN QCD WITH A "LARGE" NUMBER OF COLORS?

$$\mathcal{L}^{(0)}_{BB} = -c_1\mathrm{Tr}(B_i^\dagger B_i B_j^\dagger B_j) - c_2\mathrm{Tr}(B_i^\dagger B_j B_j^\dagger B_i) - c_3\mathrm{Tr}(B_i^\dagger B_j^\dagger B_i B_j)$$
$$-c_4\mathrm{Tr}(B_i^\dagger B_j^\dagger B_j B_i) - c_5\mathrm{Tr}(B_i^\dagger B_i)\mathrm{Tr}(B_j^\dagger B_j) - c_6\mathrm{Tr}(B_i^\dagger B_j)\mathrm{Tr}(B_j^\dagger B_i).$$

Savage and Wise (1996).

Kaplan and Savage (1998).

$$\begin{array}{ccccc} c_1 \ldots, c_6 & \longrightarrow & a, b & \longrightarrow & a \\ SU(N_f = 3) & \longrightarrow & SU(2N_f = 6) & \longrightarrow & SU(16) \end{array}$$

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Barnea at al, Phys.Rev.Lett.114 052501 (2015).

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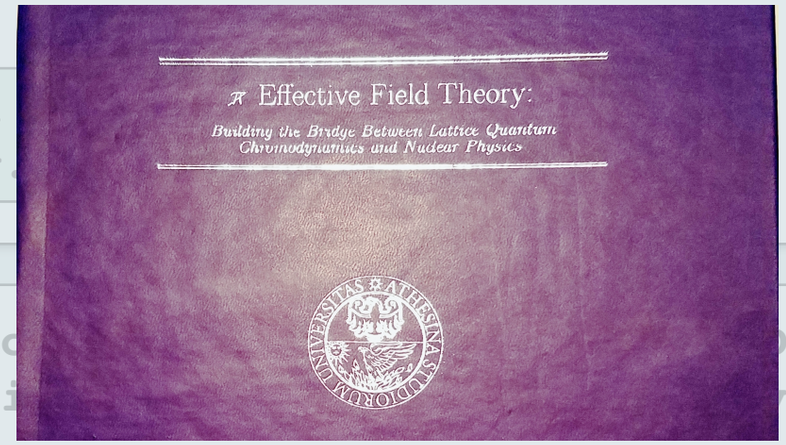
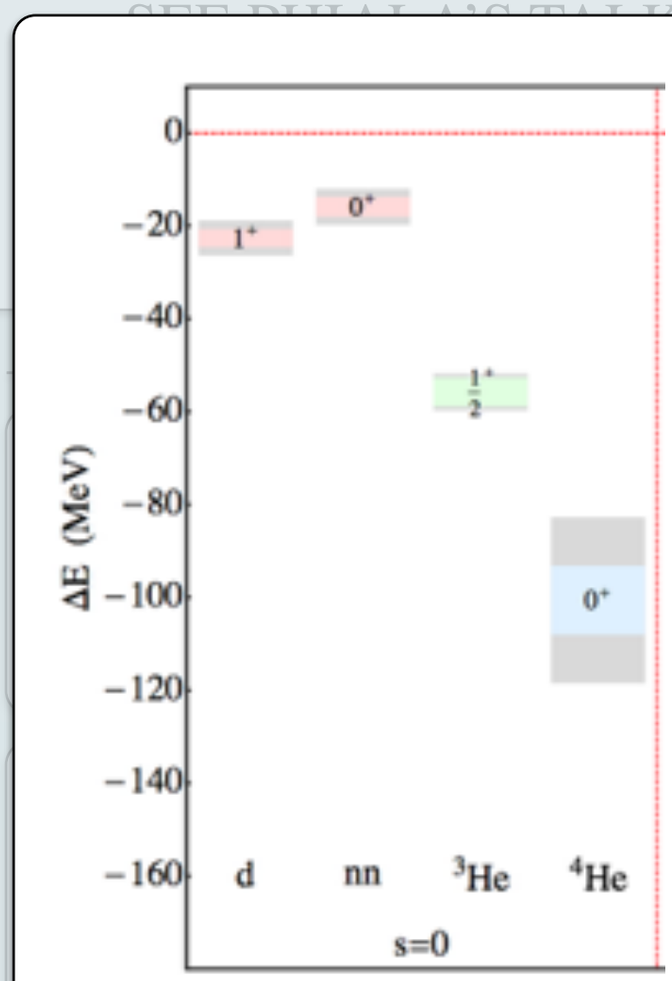
Nucleon-nucleon scattering at m_pi=450MeV from lattice QCD

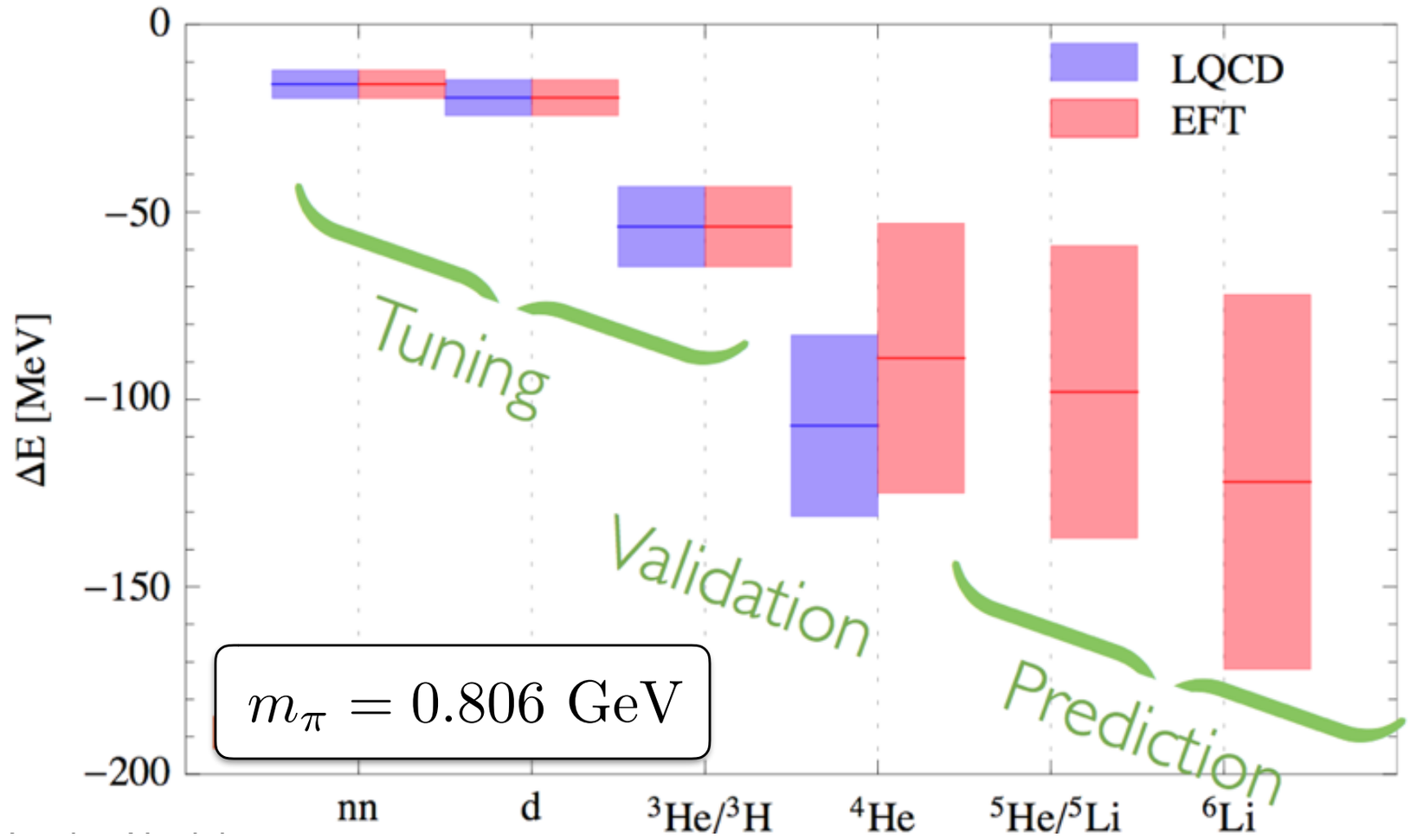
Beane et al(NPLQCD), Phys.Rev. D92 114512 (2015).

QCD input → Few-body EFT interactions → Many-body calculations of nuclei and hypernuclei

Lorenzo Contessi's PhD thesis







Ground-State Properties of 4He and 16O Extrapolated from Lattice QCD with Pionless EFT: Contessi et al, arXiv:1701.06516.

Electroweak matrix elements in the two-nucleon sector from lattice QCD

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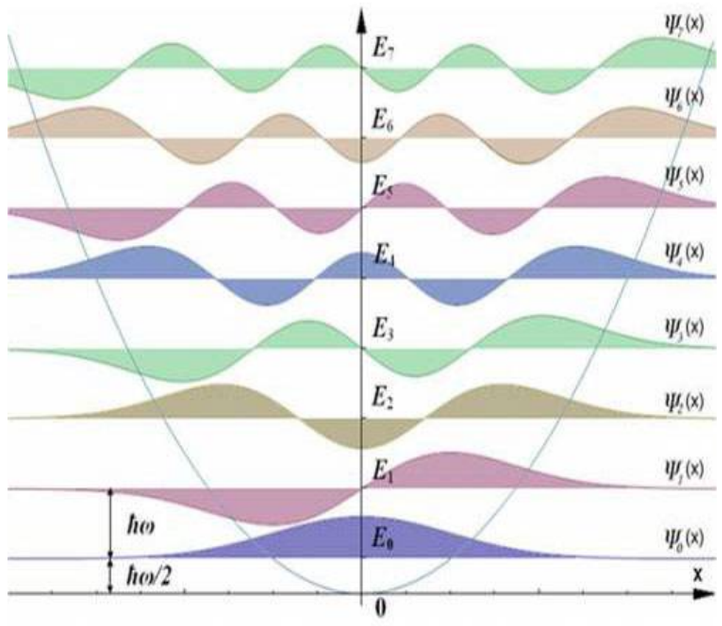
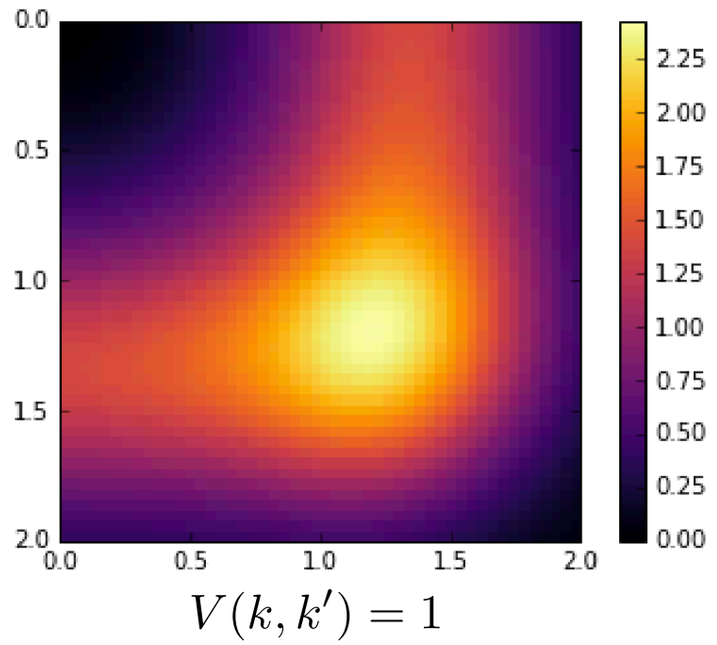
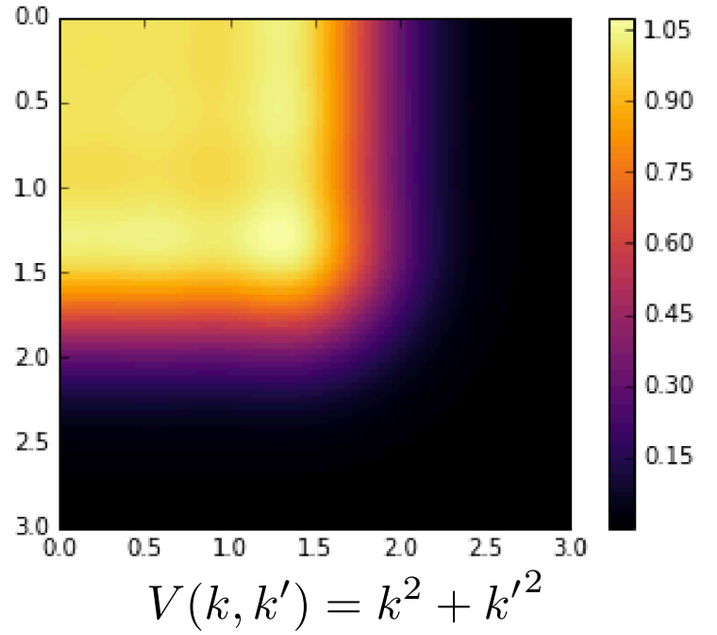




$V(k,k') = 1$



$V(k,k') = k^2 + k'^2$

$m_\pi = 0.806$ GeV

		^{16}O		^{40}Ca	
$\hbar\omega$	Λ	$N_1, N_3 = 12$	$N_1, N_3 = 14$	$N_1, N_3 = 12$	$N_1, N_3 = 14$
22	642.96	429.5	429.5	1187.0	1168.5
40	866.97	547.8	546.0	1252.0	1422.0

A semi-empirical mass formula: $E(A) = a_V A - a_S A^{2/3}$

$a_V \approx 35$ to 40 MeV
$a_S \approx 14$ to 22 MeV

Cool application: DVR of the deuteron used to calculate its binding energy on a quantum computer for the first time: Dumitrescu et al, arXiv:1801.03897[quant-ph]

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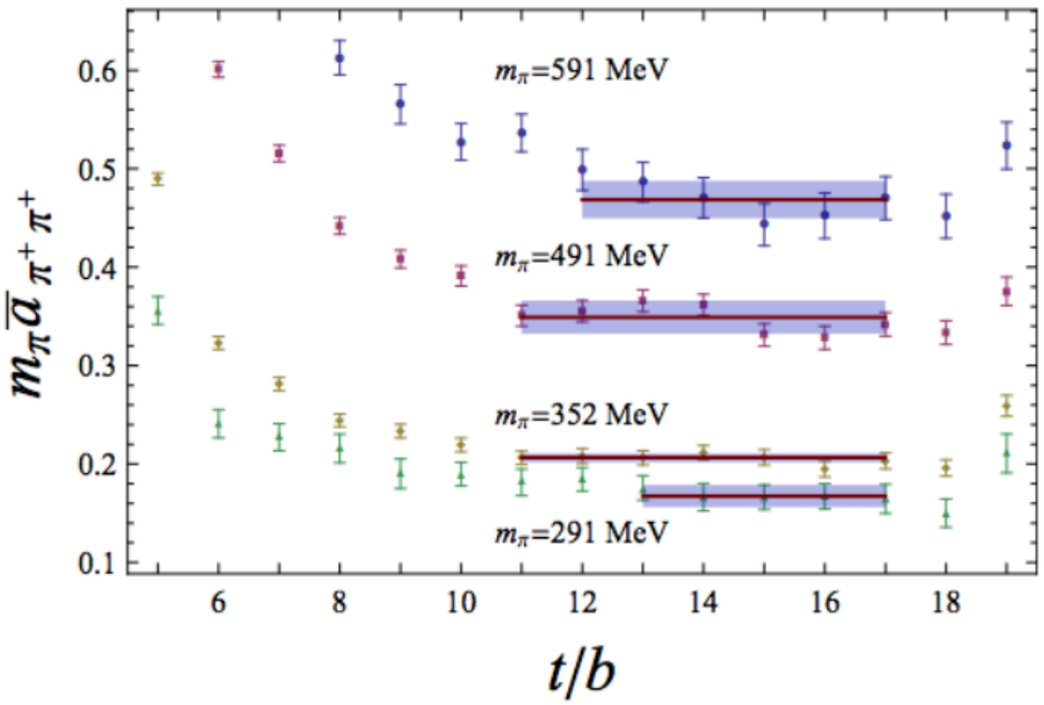
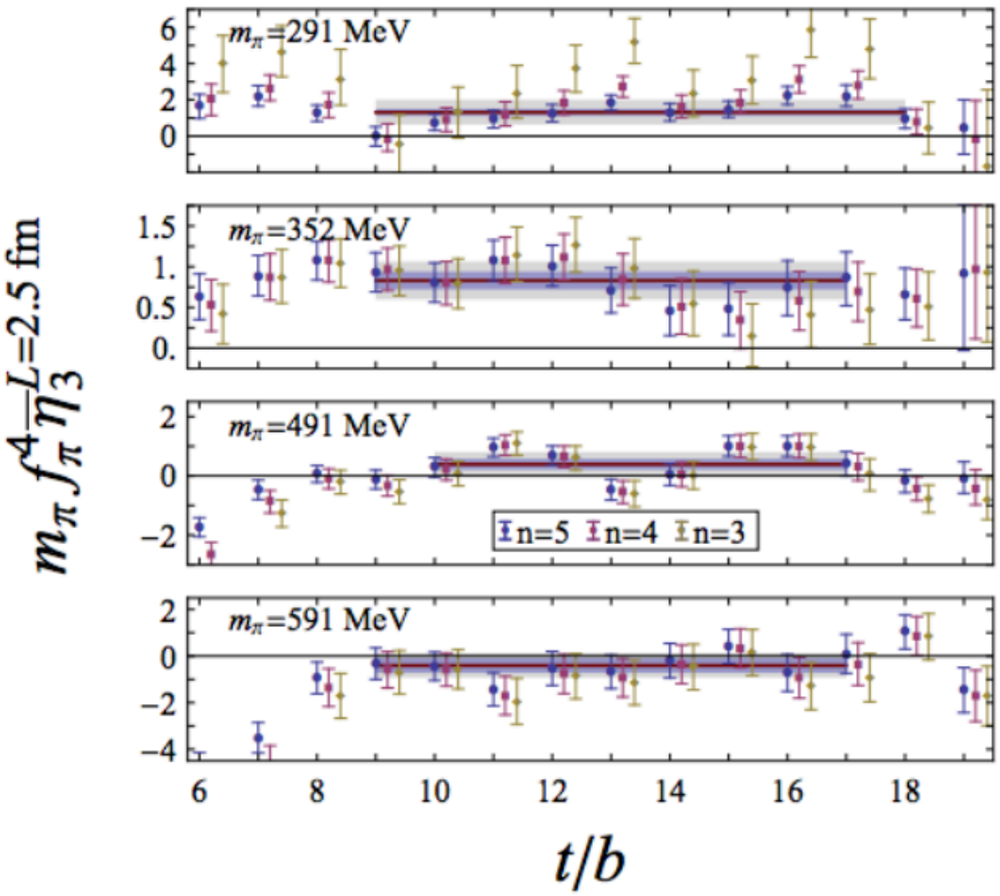
THOUGHT AND FORMALISM

NUMERICAL DEVELOPMENTS

TWO-BODY PHYSICS



THREE-BODY PHYSICS



of mesons in lattice QCD

Detmold and Savage, Phys.Rev.D82

$$\frac{L^3 M(\Delta E_n m(m^2-3m+2)-\Delta E_m n(n^2-3n+2))}{2(m-1)m(m-n)(n-1)n\pi}$$
$$=\overline{a}\left\{1-\frac{\overline{a}}{\pi L}\mathcal{I}+\left(\frac{\overline{a}}{\pi L}\right)^2[\mathcal{I}^2-\mathcal{J}]+\left(\frac{\overline{a}}{\pi L}\right)^3\right.$$
$$\left.\times\left[-\mathcal{I}^3+3\mathcal{I}\mathcal{J}+(19+5mn-10(n+m))\mathcal{K}\right]\right\},$$

Kaon Condensation with Lattice QCD

Detmold, Orginos, Savage and Walker-Loud, Phys.Rev.D78

$$\overline{\eta}_3^L = L^6\binom{n}{3}^{-1}\left\{\Delta E_n-\binom{n}{2}\Delta E_2-6\binom{n}{3}M^2\Delta E_2^3\ (\right.$$
$$\left.\times\left(\frac{L}{2\pi}\right)^4\left[\mathcal{J}+\frac{L^2M\,\Delta E_2}{2\pi^2}(\mathcal{I}\mathcal{J}-(5n-31)\mathcal{K})\right]\right\}$$

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OUTLOOK. WHAT DOES FUTURE LOOK LIKE?

WE UNDERSTAND OUR CURRENT LIMITATIONS. IMPROVEMENT IS IN HORIZON.

- ALMOST ALL OUR EXTRACTIONS OF SPECTRUM AND MEs ARE AT A SINGLE LATTICE SPACING - NEED AT LEAST 2 (3?) TO CONTROL UNCERTAINTIES.

- OUR INTERPOLATORS OPTIMAL SO FAR FOR DEEPLY BOUND NUCLEI AND LOWEST-LYING SCATTERING LEVELS. A MORE COMPLETE OPERATOR BASIS NEEDED FOR MORE COMPLEX SYSTEMS (HIGHER PARTIAL WAVES, COUPLED SYSTEMS, 3N SYSTEMS, ETC.) AND TOWARDS THE PHYSICAL POINT.

- NEED TO GO BEYOND GETTING JUST THE BINDINGS IN >2-PARTICLE SYSTEMS. THREE-NEUTRON FORCES ARE IMPORTANT FOR US.

- LOWERING PION MASS MEANS MORE INVOLVED ANALYSIS THAN WE HAVE DONE AT HEAVY QUARK MASSES TO OBTAIN MATRIX ELEMENTS IN MULTI-HADRON STATES.

THE NUCLEAR AND HYPERNUCLEAR FORCES PROGRAM WITHIN NPLQCD IS ON TRACK TO DELIVER ESSENTIAL QUANTITIES TO THE NUCLEAR PHYSICS BROADER COMMUNITY.

CURRENT MEMBERS OF THE NPLQCD COLLABORATION:

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- WILLIAM DETMOLD, MIT
- KOSTAS ORGINOS, JLAB/W&M
- ASSUMPTA PARRENO, U OF BARCELONA
- MARTIN SAVAGE, INT
- PHIALA SHANAHAN, JLAB/W&M
- BRIAN TIBURZI, CUNY
- MICHAEL WAGMAN, MIT
- FRANK WINTER, JLAB

THANK YOU