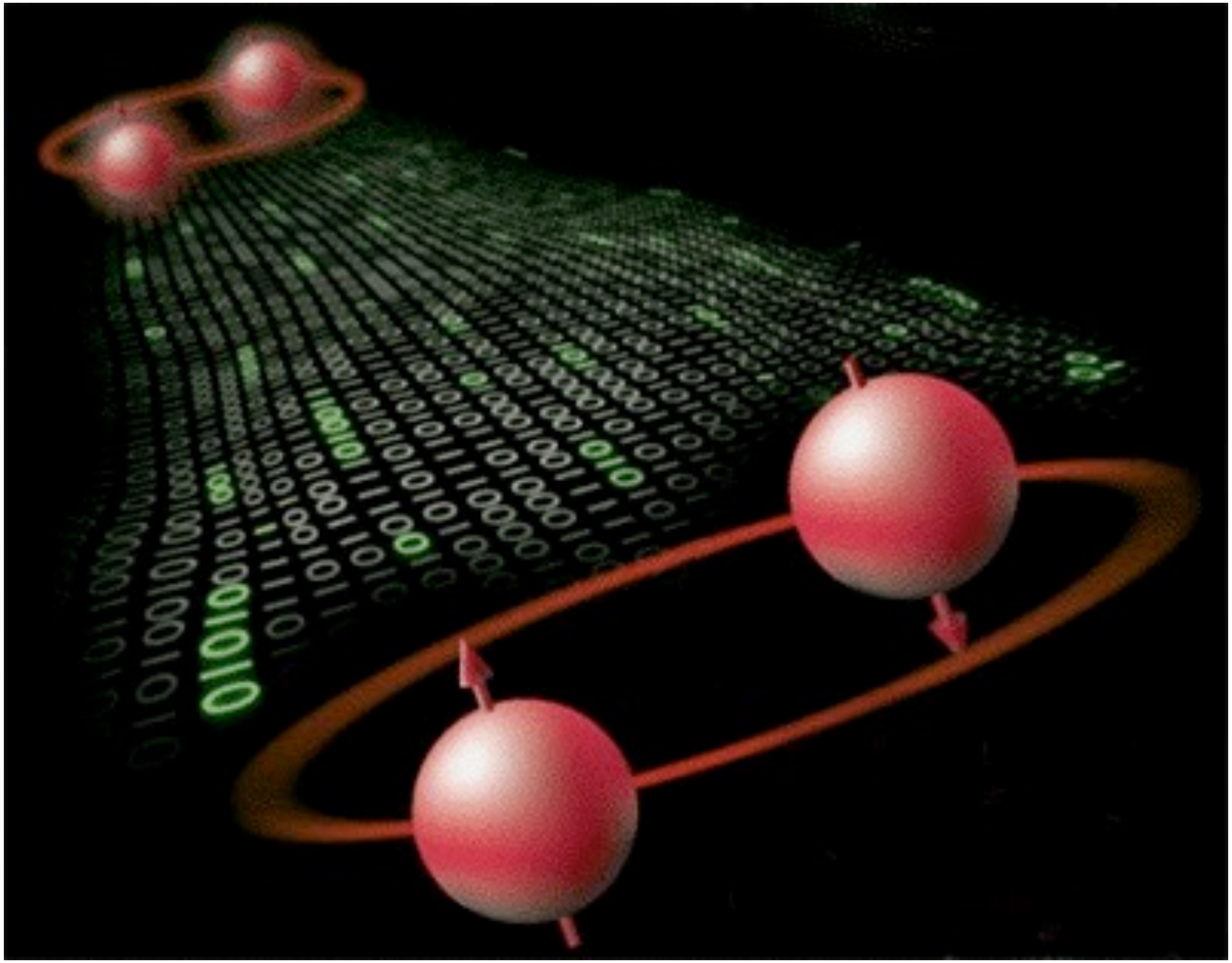


Hyperon Nucleon Interactions and Dense Matter

Martin J. Savage
University of Washington
June 2012, Lattice 2012
Cairns, Australia

NPLQCD

Oak Ridge National Laboratory

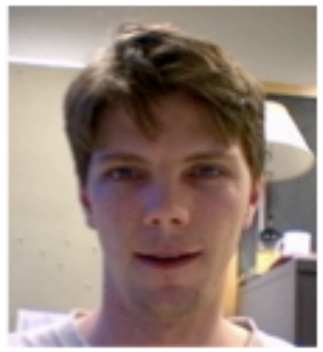
NERSC

TeraGrid

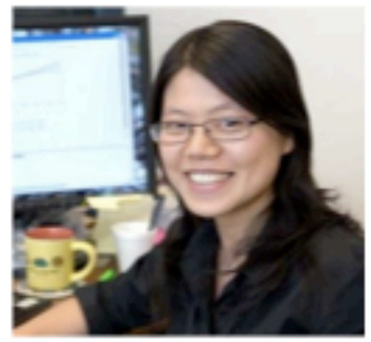
U.S. Department of Energy INCITE Leadership Computing

Silas Beane
New Hampshire

Emmanuel Chang
Barcelona



William Detmold
Willam+Mary



Huey-Wen Lin
U. of Washington

Tom Luu
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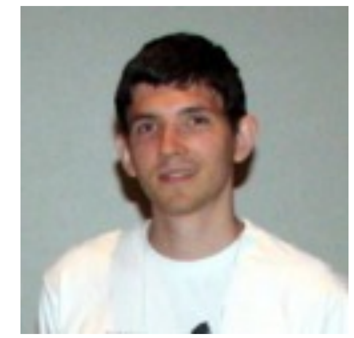

Saul Cohen
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Assumpta Parreno
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Marton Savage
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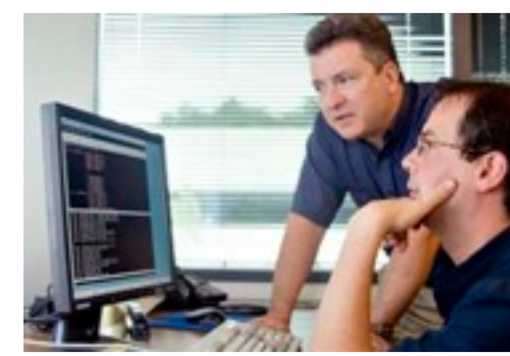
Aaron Torok
Indiana

Andre Walker-Loud
LBNL

+



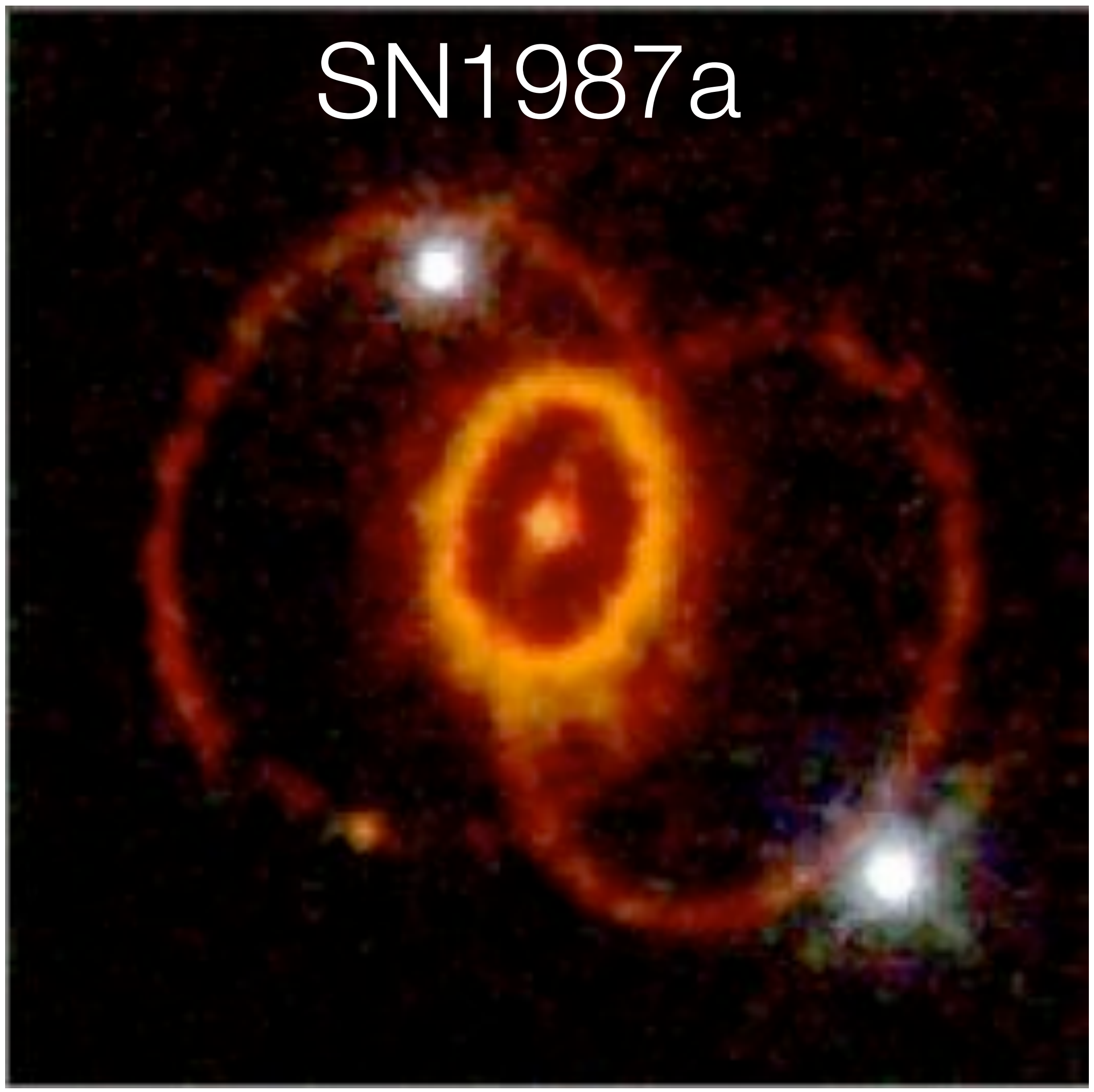
Jefferson Lab

... to make predictions for the structure and interactions of nuclei using lattice QCD.

USQCD

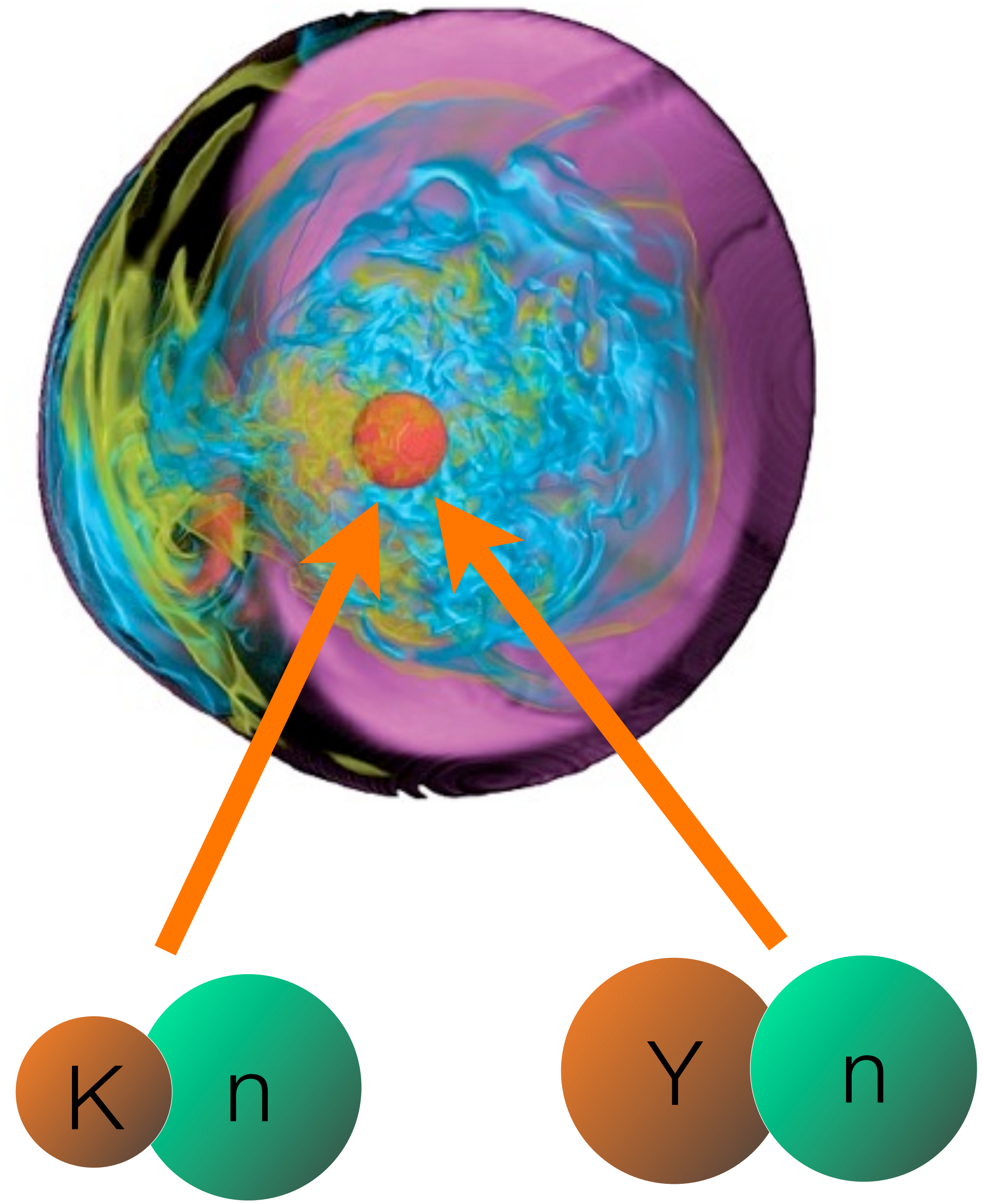
US Lattice Quantum Chromodynamics

Core-Collapse Supernova and the Heavy Elements



Black-Hole or Neutron Star ?

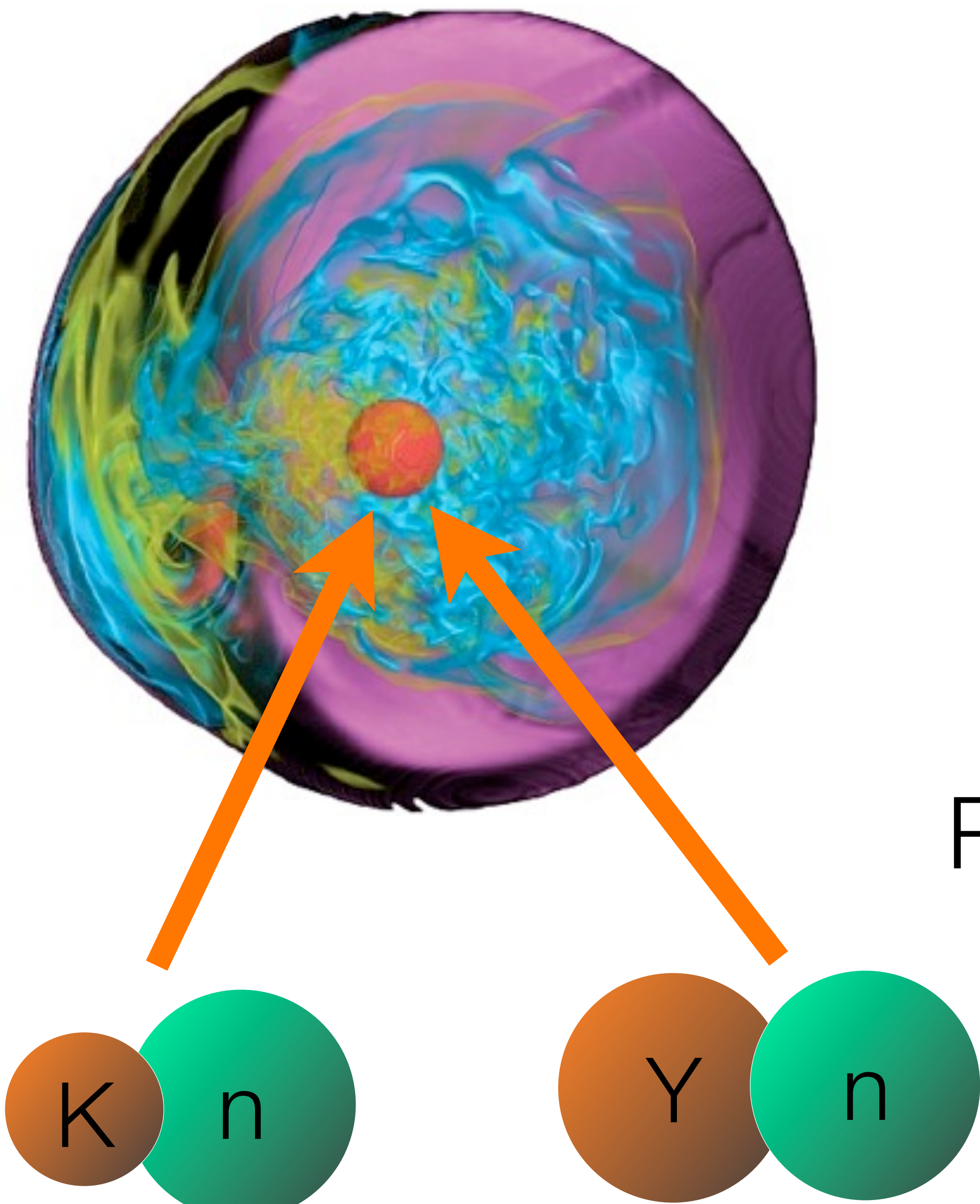
(Mezzacappa *et al*)



Nuclear EoS

Core-Collapse Supernova and the Heavy Elements

(Mezzacappa *et al*)

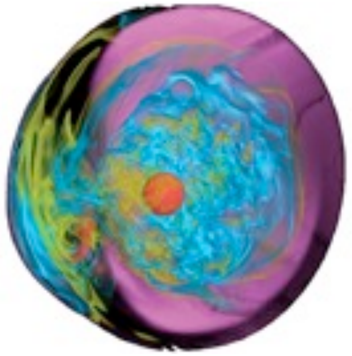


Nuclear EoS

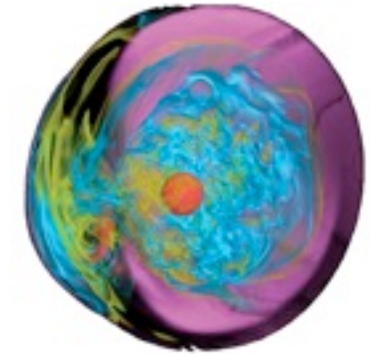
$e^- \rightarrow K^- + \text{neutrino}$

$n + e^- \rightarrow \Sigma^- + \text{neutrino}$

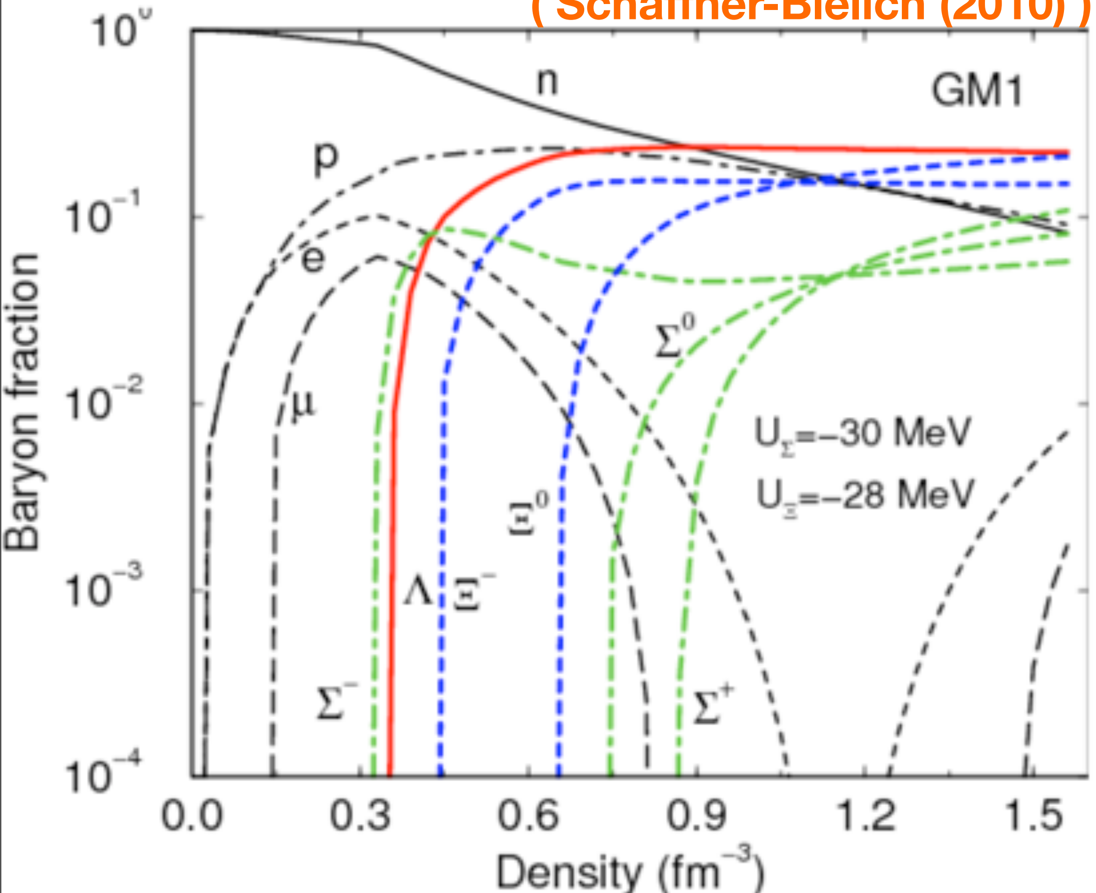
Role depends upon Interactions



Hyperons in Matter : Present Predictive Capability

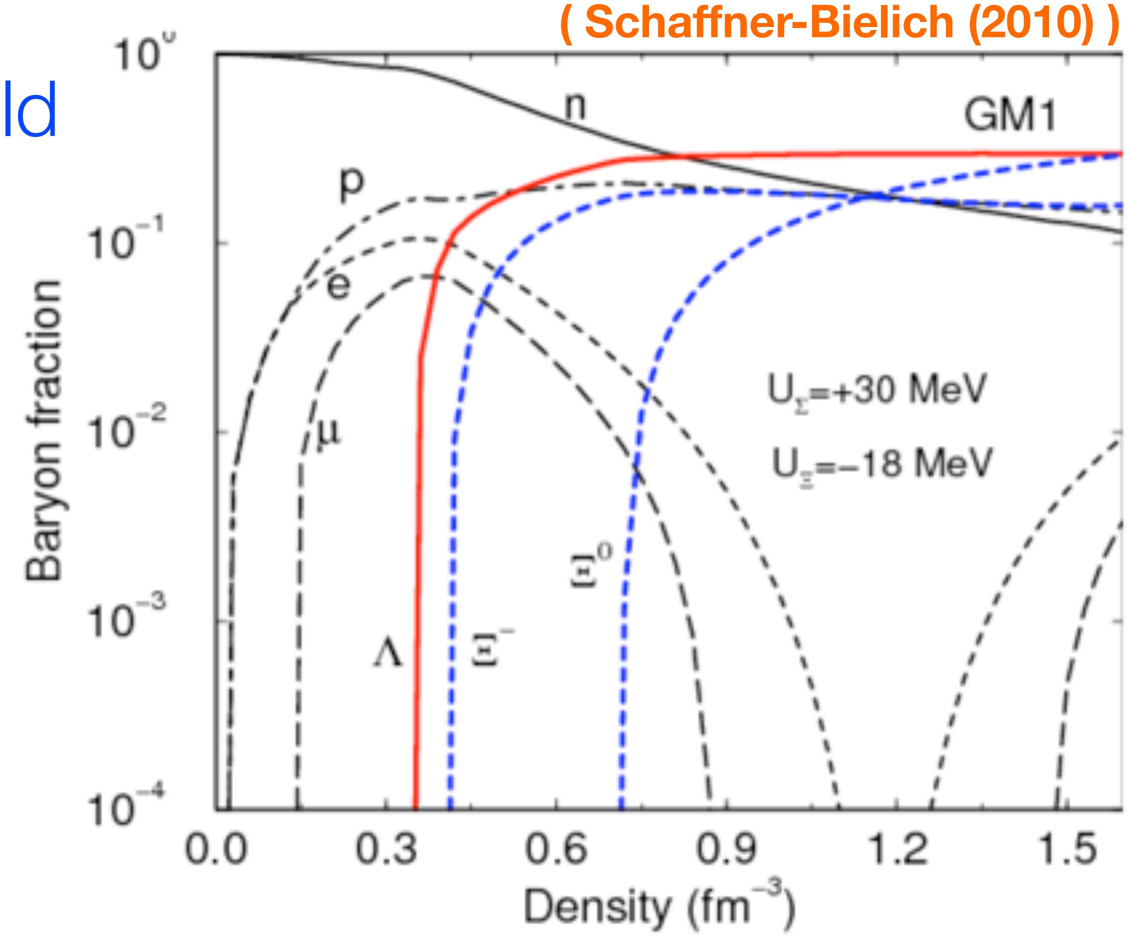


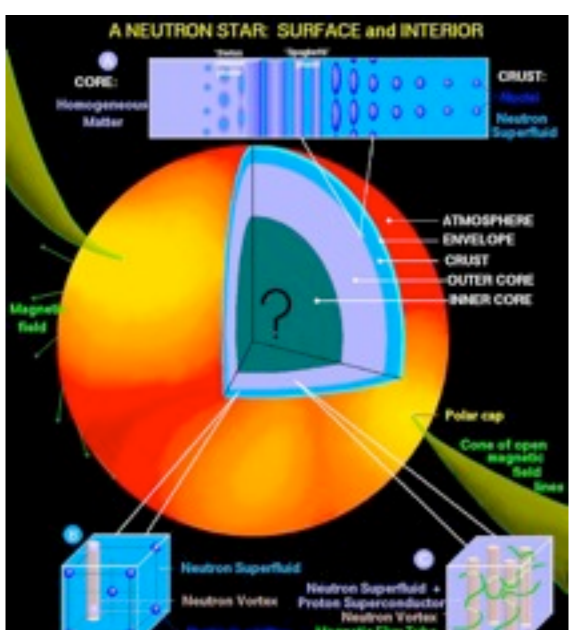
(Schaffner-Bielich (2010))

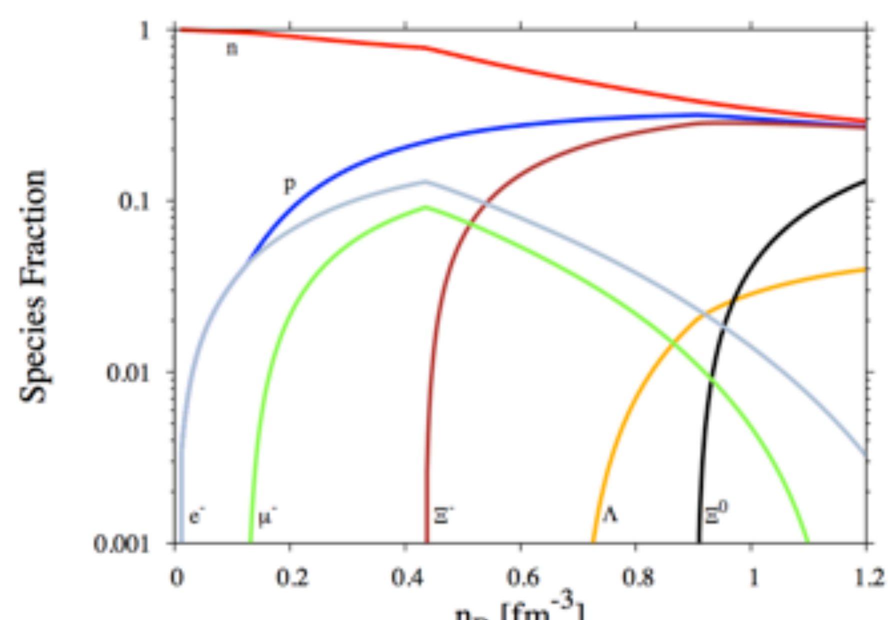


Mean-Field Models

(Schaffner-Bielich (2010))







(Whittenbury) (2012)

Multi-Volume Study by NPLQCD
2009 - 2011

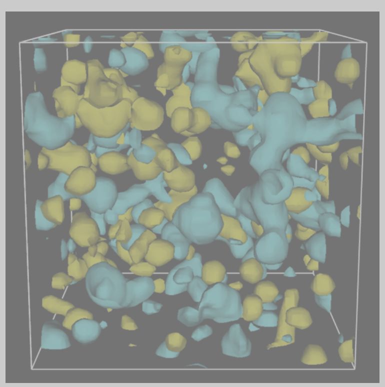
Jefferson Lab

lattice spacing : $b \sim 0.123$ fm

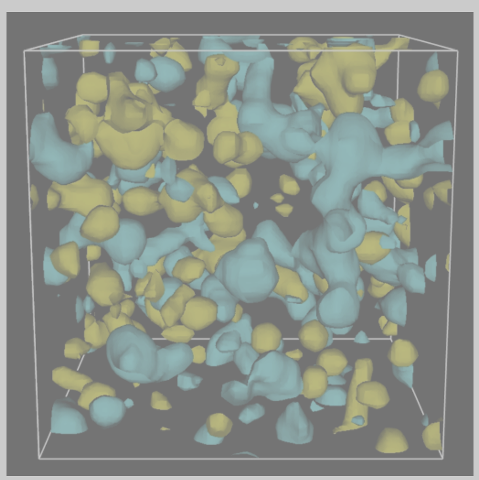
pion mass : $m_\pi \sim 390$ MeV

fermion action : Clover

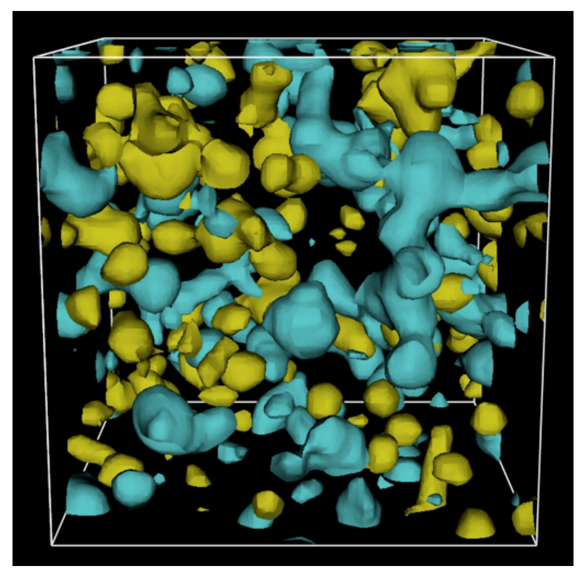
anisotropy : $\xi_t \sim 3.5$



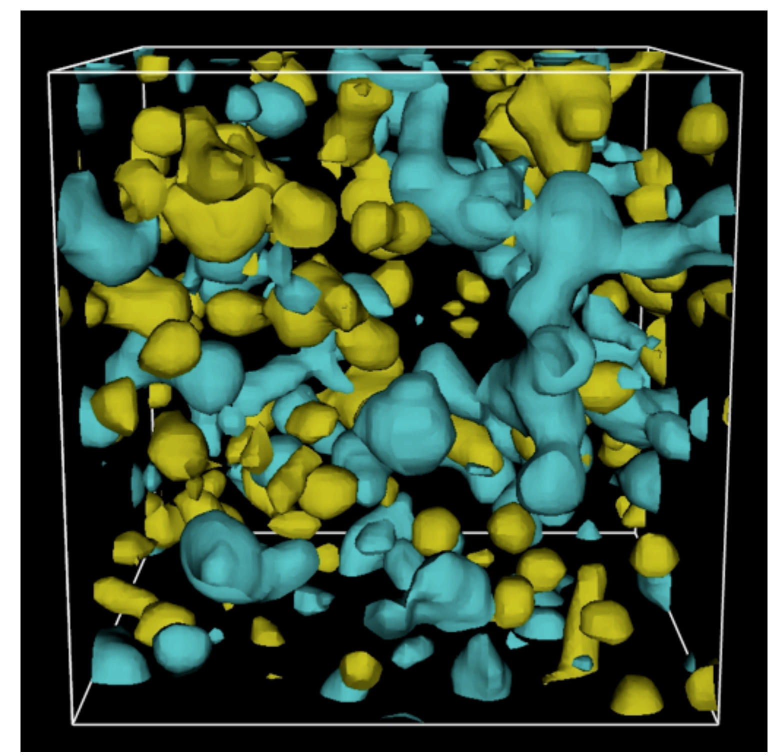
$L \sim 2$ fm



$L \sim 2.5$ fm



$L \sim 3$ fm

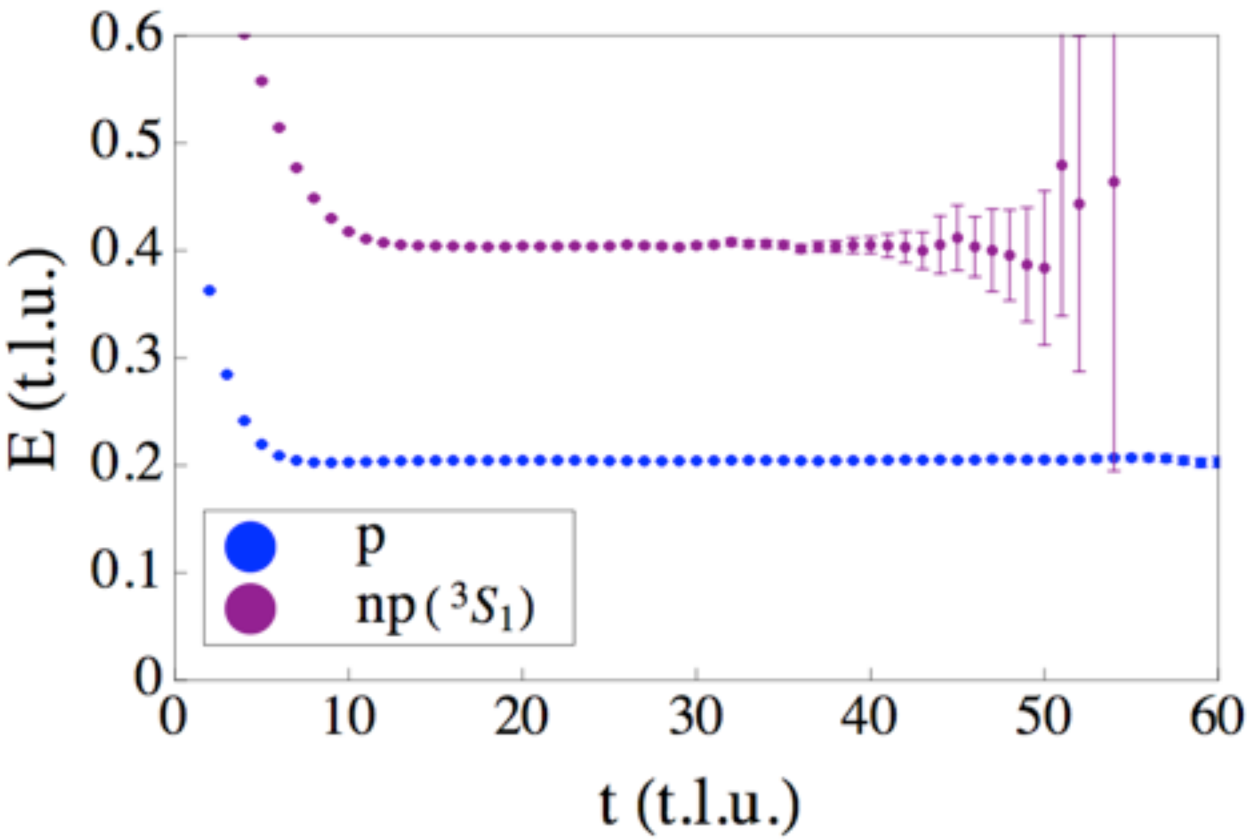


$L \sim 4$ fm

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

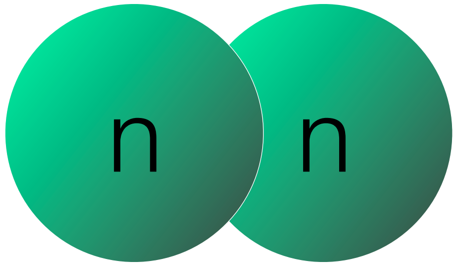
$m_\pi L \sim 4\ ,\ 5\ ,\ 6\ ,\ 8 \qquad m_\pi T \sim 9\ ,\ 9\ ,\ 9\ ,\ 18$

Multi-Volume Study by NPLQCD 2009 - 2011

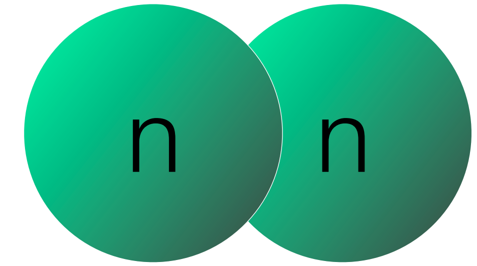


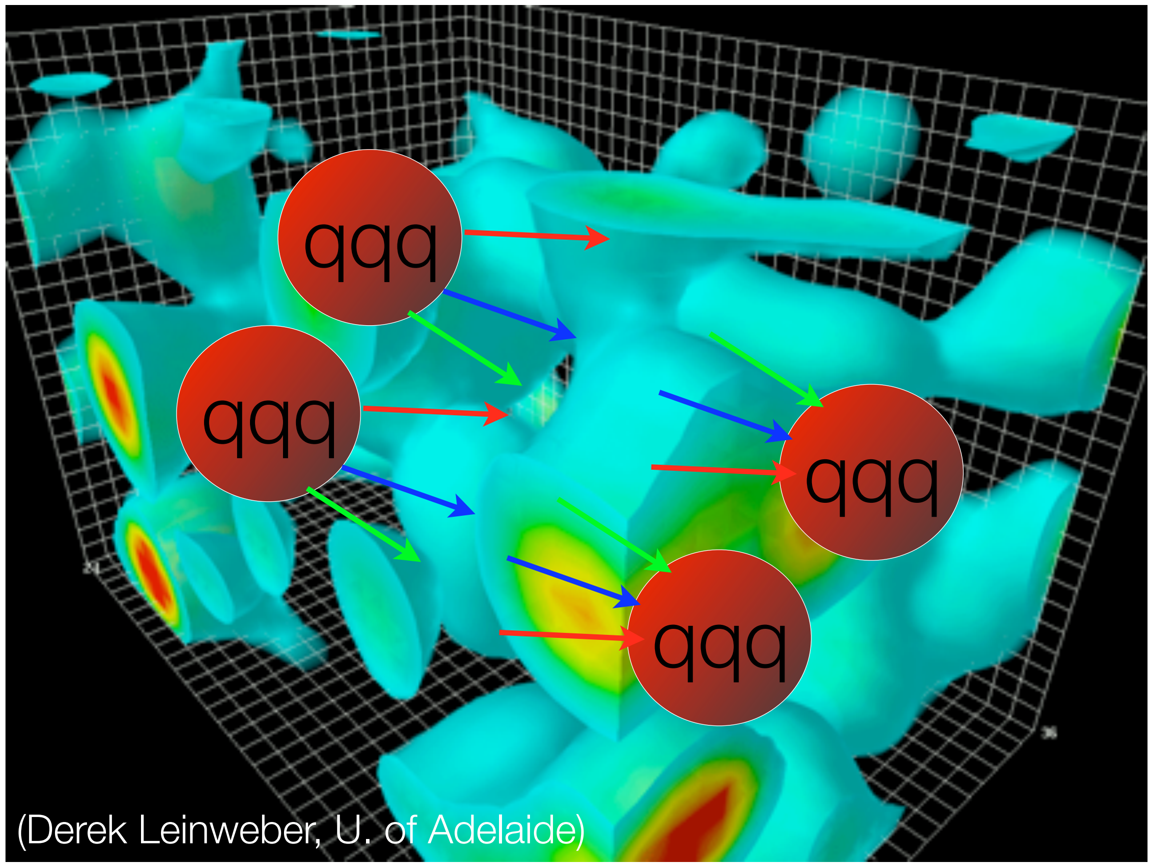
L	cfgs	srcs
24	2215	390,000
32	739	135,000

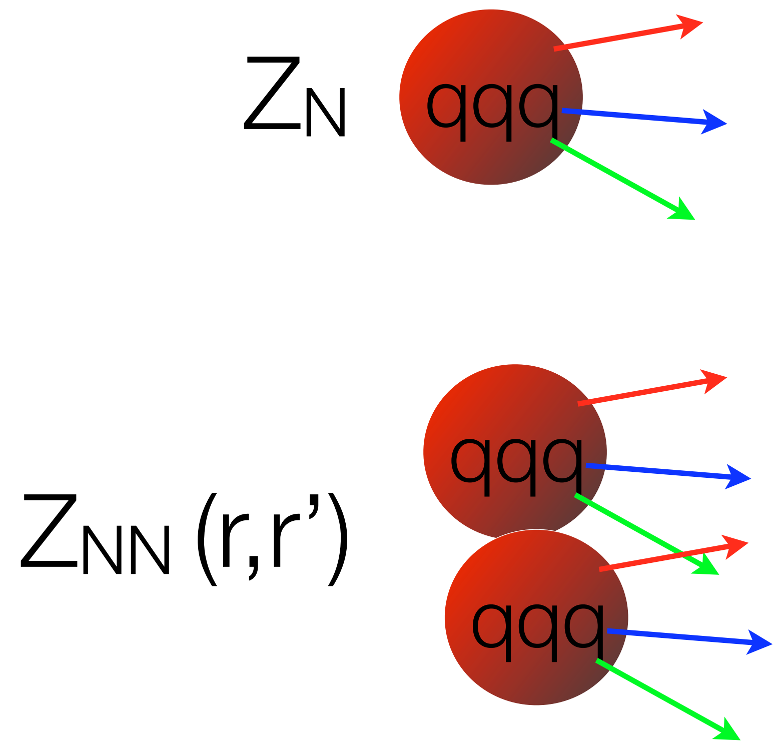
$L^3 \times T$	$16^3 \times 128$	$20^3 \times 128$	$24^3 \times 128$	$32^3 \times 256$	Extrapolation
L (fm)	~ 2.0	$\sim$2.5	$\sim$3.0	$\sim$4.0	∞
$m_\pi L$	3.86	4.82	5.79	7.71	∞
$m_\pi T$	8.82	8.82	8.82	17.64	∞
M_N (t.l.u.)	0.21004(44)(85)	0.20682(34)(45)	0.20463(27)(36)	0.20457(25)(38)	0.20455(19)(17)
M_Λ (t.l.u.)	0.22446(45)(78)	0.22246(27)(38)	0.22074(20)(42)	0.22054(23)(31)	0.22064(15)(19)
M_Σ (t.l.u.)	0.22861(38)(67)	0.22752(32)(43)	0.22791(24)(31)	0.22726(24)(43)	0.22747(17)(19)
M_Ξ (t.l.u.)	0.24192(38)(63)	0.24101(27)(38)	0.23975(20)(32)	0.23974(17)(31)	0.23978(12)(18)



Generic Calculations of 2-Body Interactions







1) Maiani-Testa Theorem

2) Luscher : Measure energy-eigenvalues of the two-hadron system

A Primer - 1990 : Luscher says ....

Explicitly, the stationary effective Schrödinger equation in the centre-of-mass frame reads

$$-\frac{1}{2\mu}\Delta\psi(\mathbf{r}) + \frac{1}{2}\int d^3r'\, U_E(\mathbf{r},\mathbf{r}')\psi(\mathbf{r}') = E\psi(\mathbf{r}), \qquad (7.1)$$

where the parameter E is related to the true energy W of the system through

$$W = 2\sqrt{m^2 + mE}. \qquad (7.2)$$

The "potential" $U_E(\mathbf{r},\mathbf{r}')$ is the Fourier transform of the modified Bethe-Salpeter kernel $\hat{U}_E(\mathbf{k},\mathbf{k}')$ introduced in ref.[3]. It depends analytically on

38

E in the range $-m < E < 3m$ and is a smooth function of the coordinates $\mathbf{r}$ and $\mathbf{r}'$, decaying exponentially in all directions †. Furthermore, the potential

EUTSCHES ELEKTRONEN – SYNCHROTRON DE

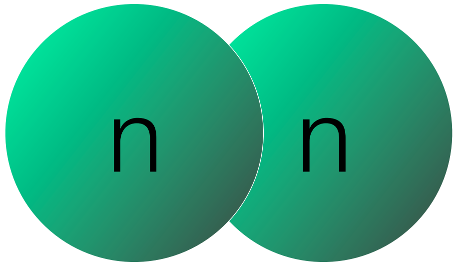
DESY 90-131
October 1990

Two-Particle States on a Torus and their Relation to the Scattering Matrix

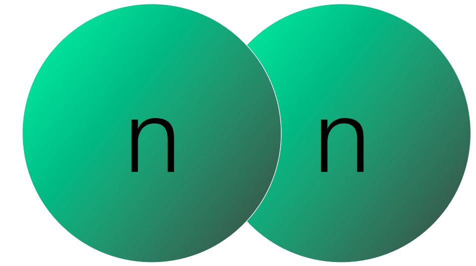
M. Lüscher
Deutsches Elektronen-Synchrotron DESY, Hamburg

It therefore follows that....

Taking U to be energy-independent is a model-dependent assertion and not a QCD prediction



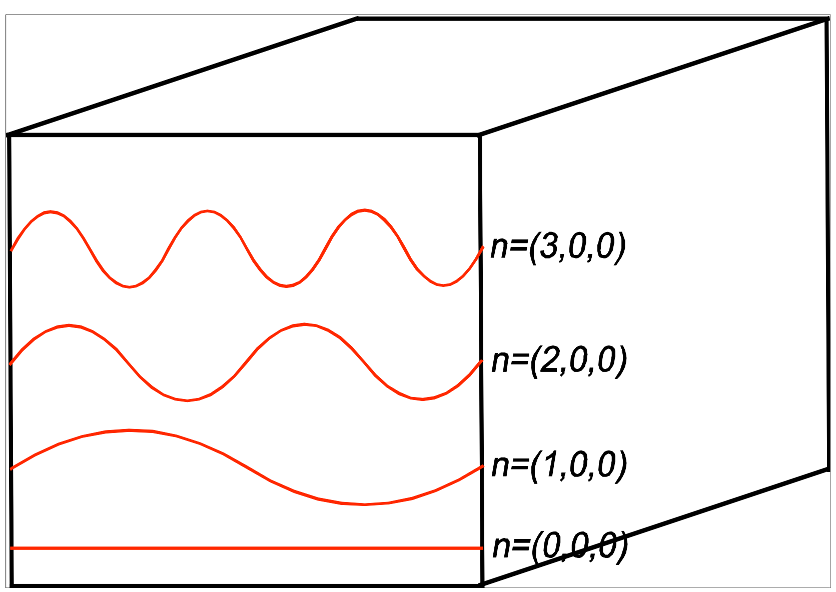
Two-Particle Energy Levels
(Luscher)



Below Inelastic Thresholds :

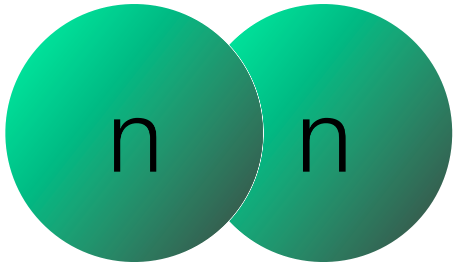
Measure on lattice ⇒ $$\delta E = 2\sqrt{p^2 + m^2} - 2m$$

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

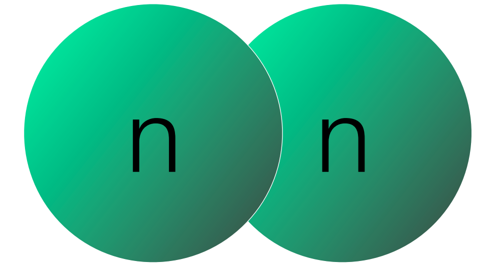


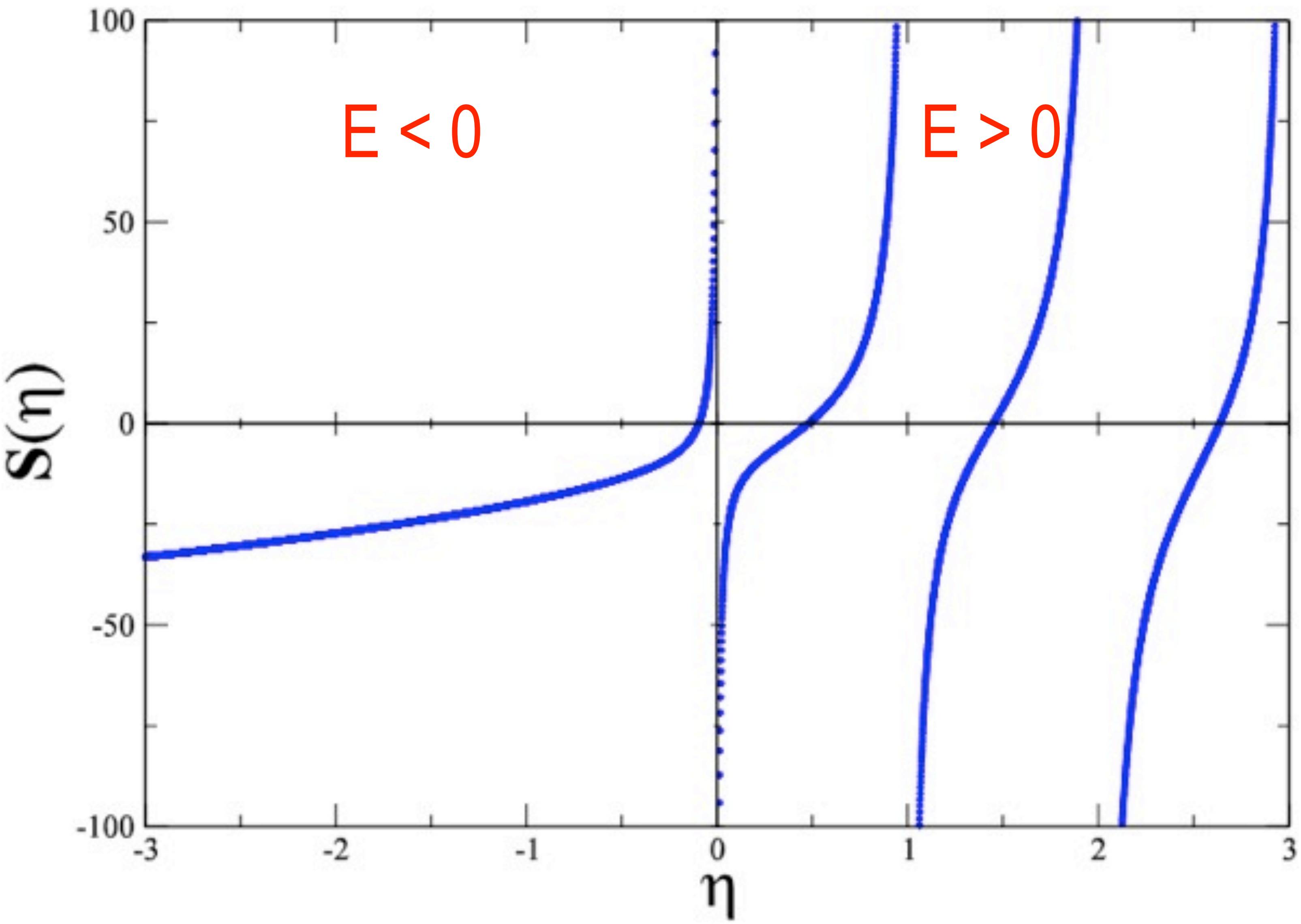
$$\mathbf{S}(\eta) \equiv \sum_{\mathbf{j}}^{\Lambda_j} \frac{1}{|\mathbf{j}|^2 - \eta} - 4\pi\Lambda_j$$

Gives the scattering amplitude at δE



Luscher Eigenvalue Relation





A_1^+

Bound-state or

Scattering state ?

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

$$k = \frac{2\pi}{L}n$$

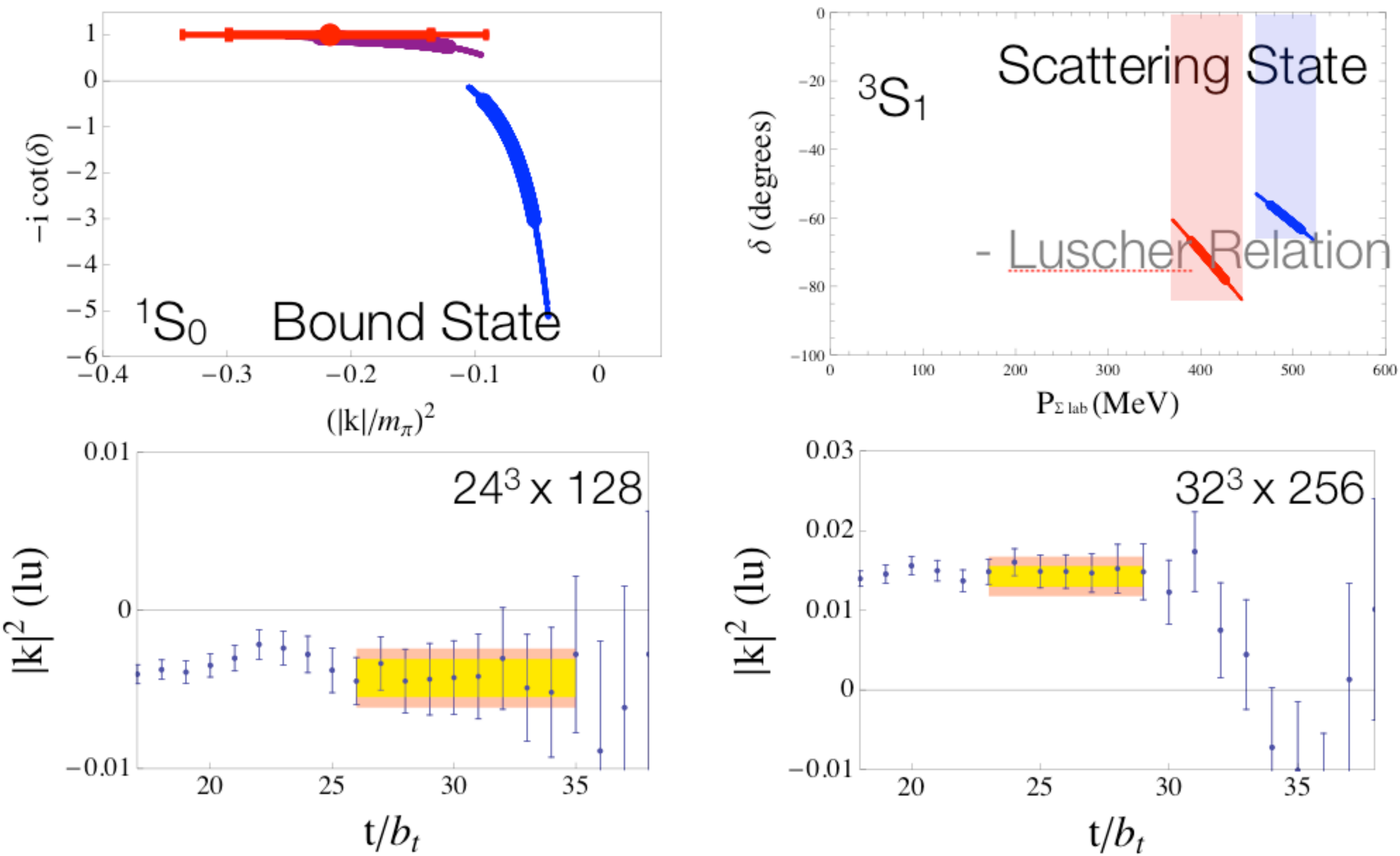
$$n = (nx, ny, nz)$$

Non-interacting particles

$$V = 0 \quad \rightarrow \quad a = r = 0$$

$$S = \infty$$

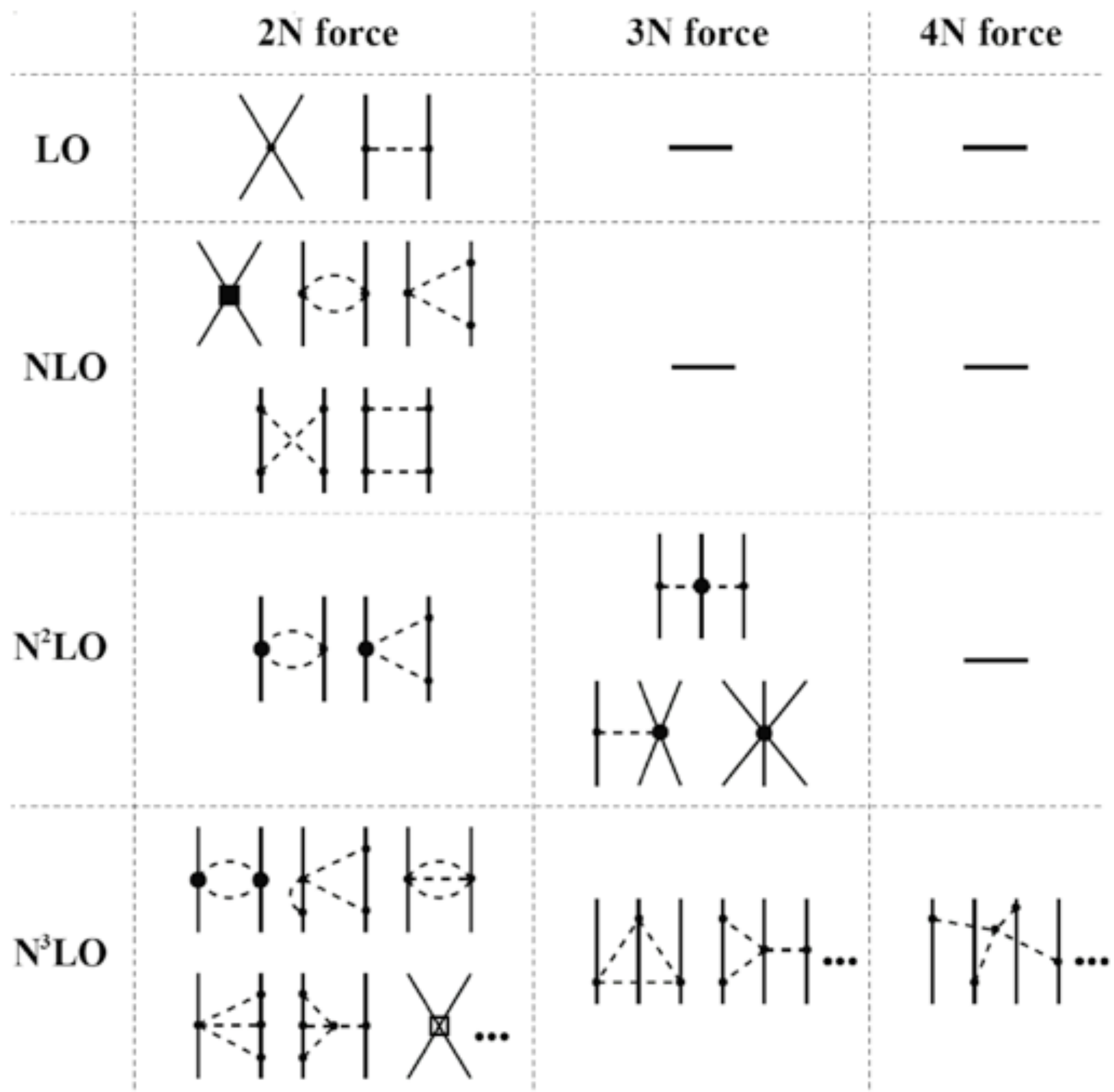
$n\Sigma^-$ at a pion mass of ~390 MeV



QCD-Based Organization of Nuclear Forces

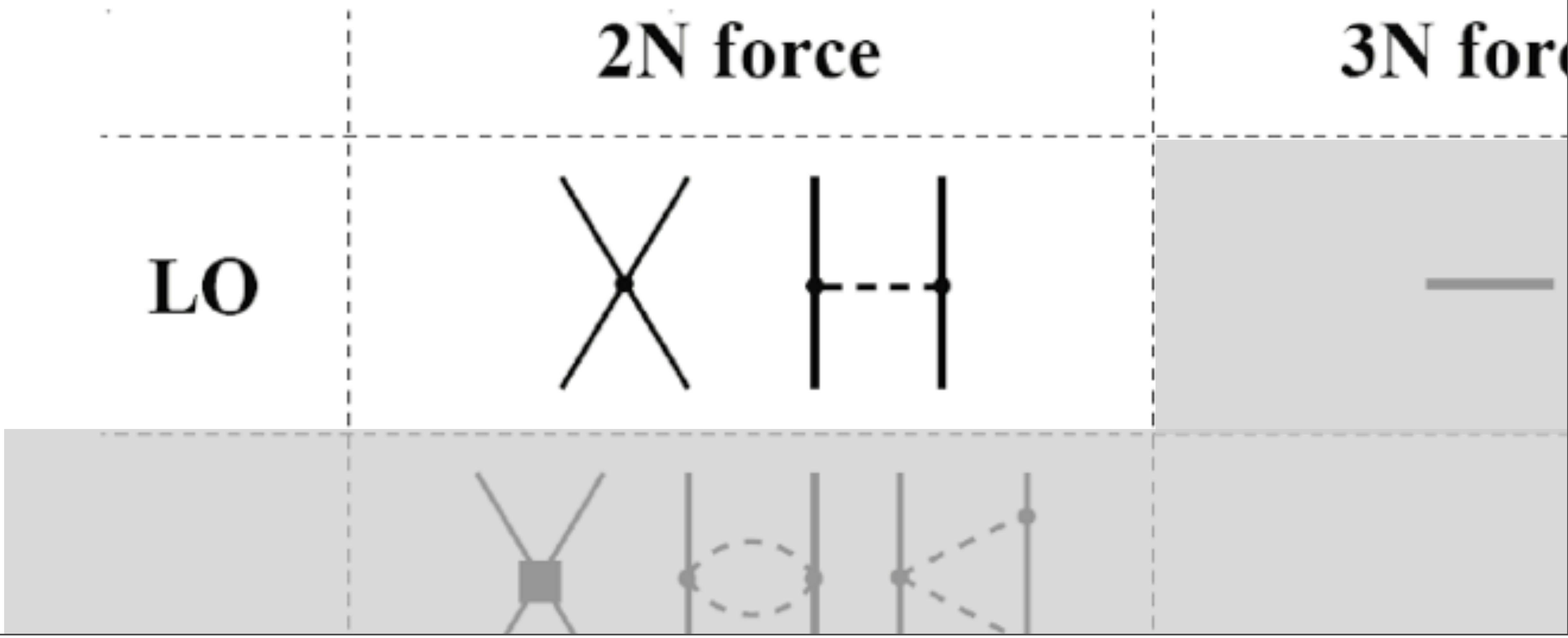
Effective Field Theory introduced by Weinberg in the early 1990's to systematize nuclear forces

- Low-energy EFT of QCD
- Chiral symmetries of QCD
- Quark mass dependence
- Renormalization Group
- Softer Interactions
  - V_{lowk} , SRG



LO Weinberg in $n\Sigma^-$

1 : local 4-baryon contact interaction (1 parameter)
2 : one meson exchange (0 new parameters)



Convergence of (Systematic) Expansions of Potentials

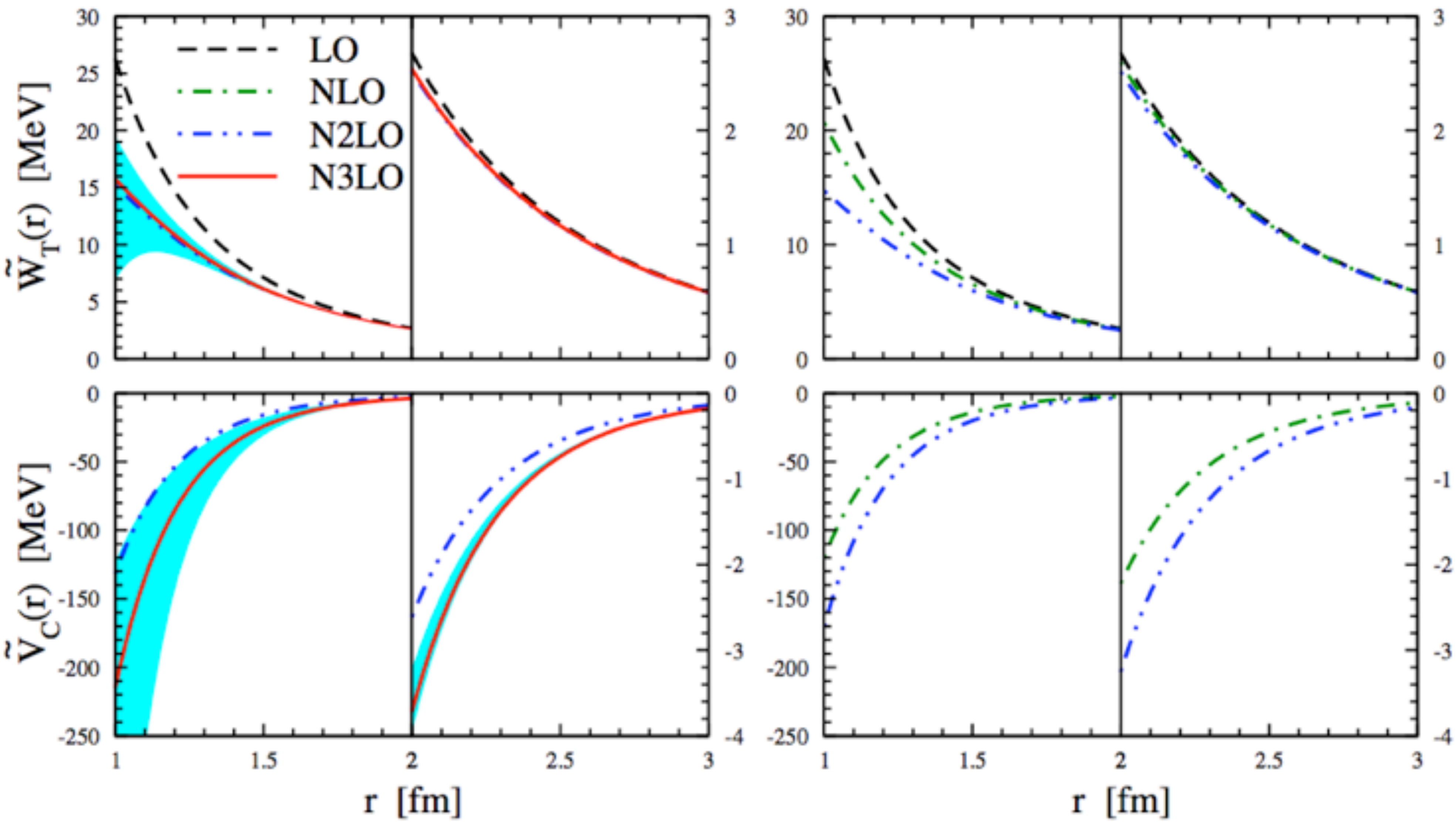
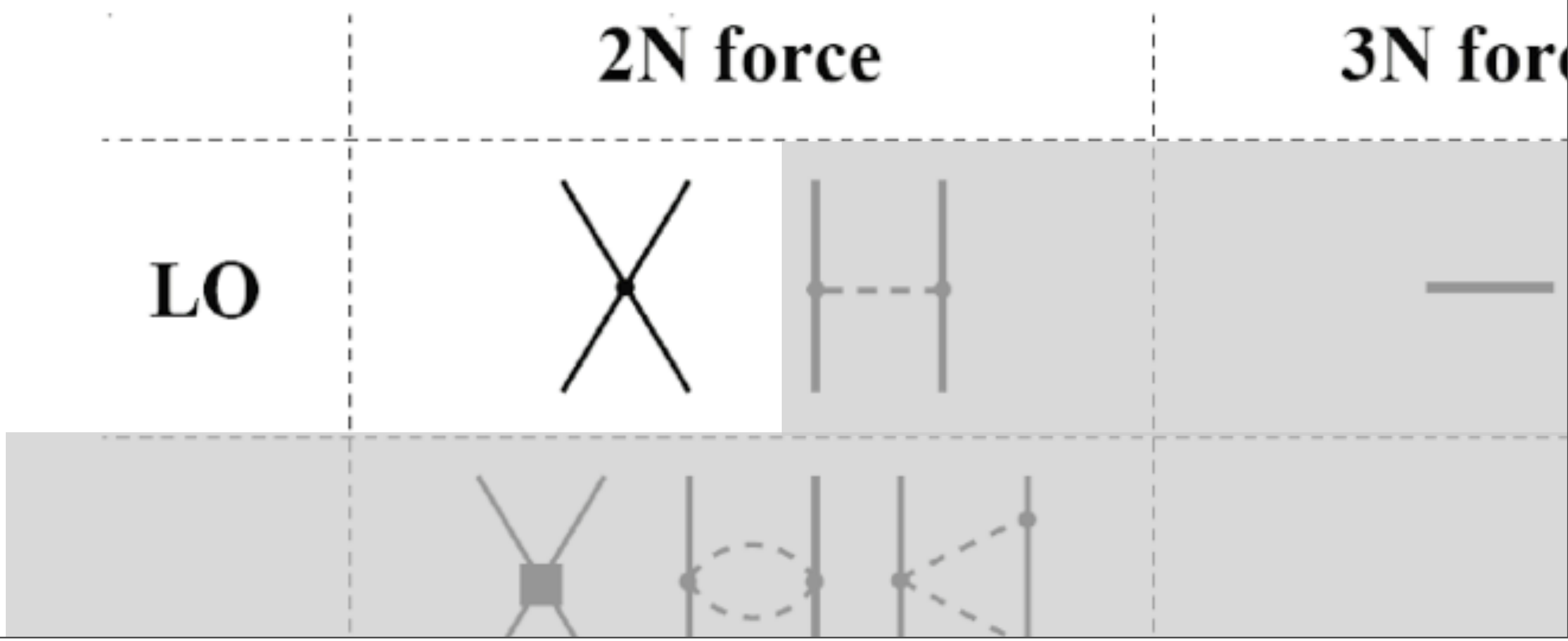


Figure 3: Chiral expansion of the isovector-tensor (upper row) and isoscalar central (lower row) long-range potentials $\tilde{W}_T(r)$ and $\tilde{V}_C(r)$, respectively. The left (right) panel shows the results for the EFT without (with) explicit $\Delta(1232)$ degrees of freedom. The light-shaded band shows the estimation of the intrinsic model dependence associated with the short-range components as explained in the text (only shown for the theory without deltas).

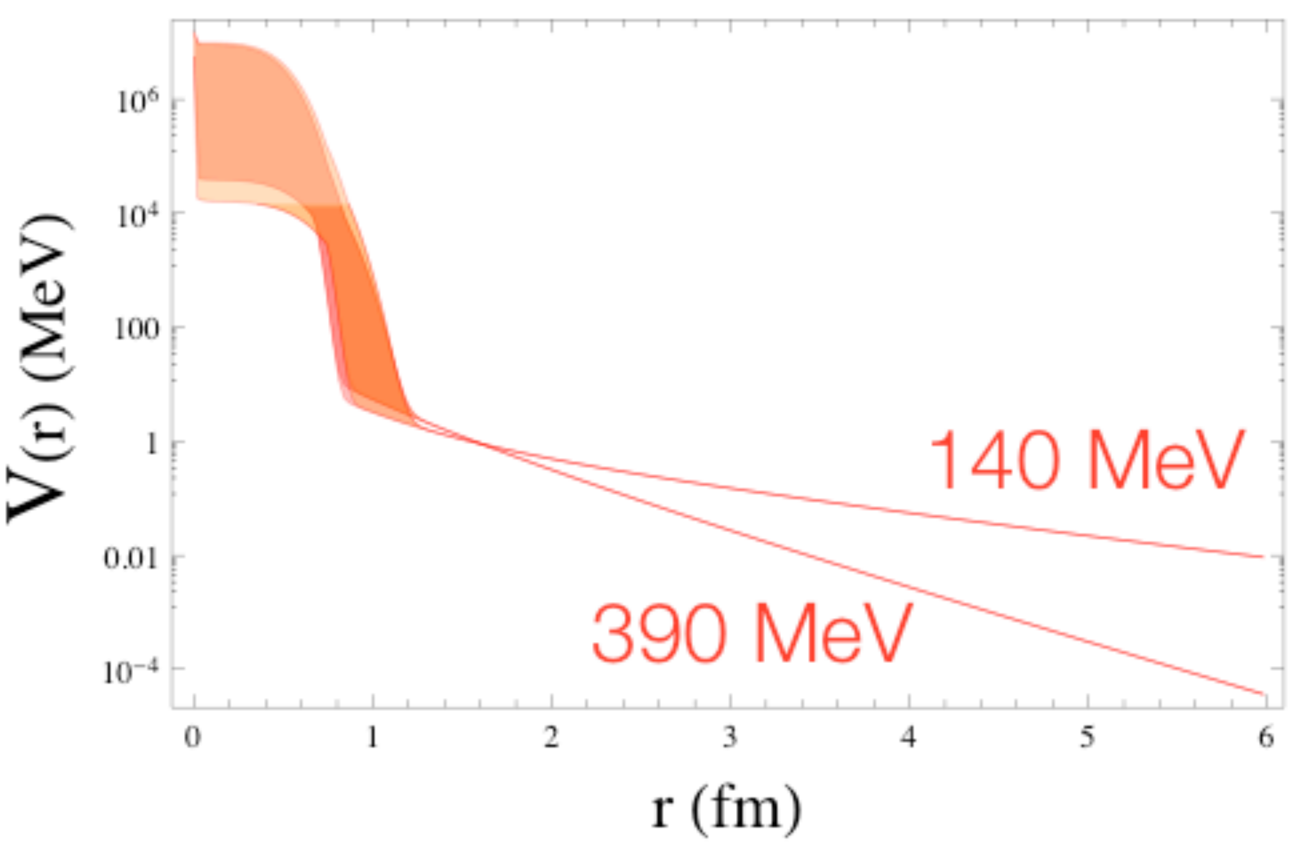
LO Weinberg in $n\Sigma^-$

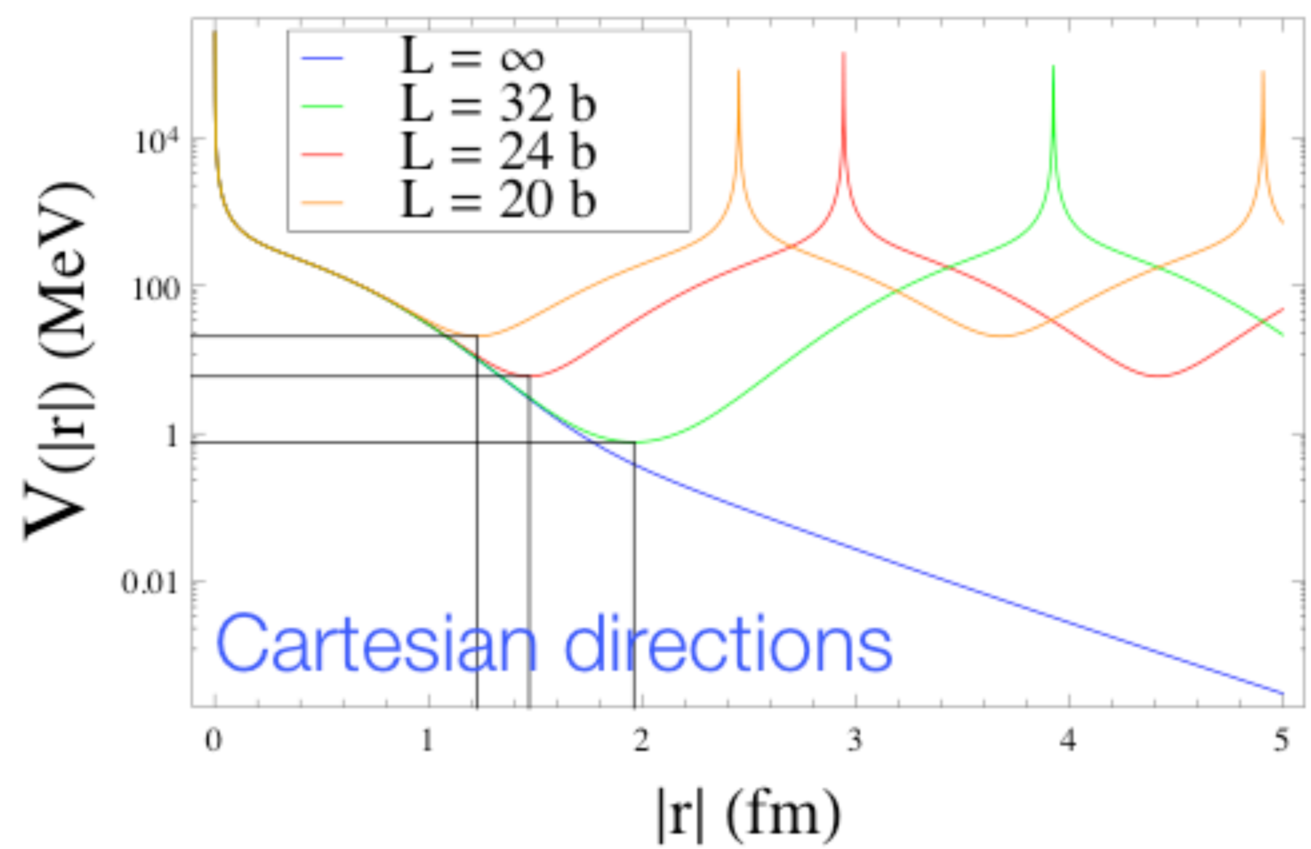
Require regulation - use simple compact shape
- square-well, Gaussian, exponential
- one length scale, one coupling



$^3S_1$: 3-d Schrodinger, Modifications to Luscher's Relation ?

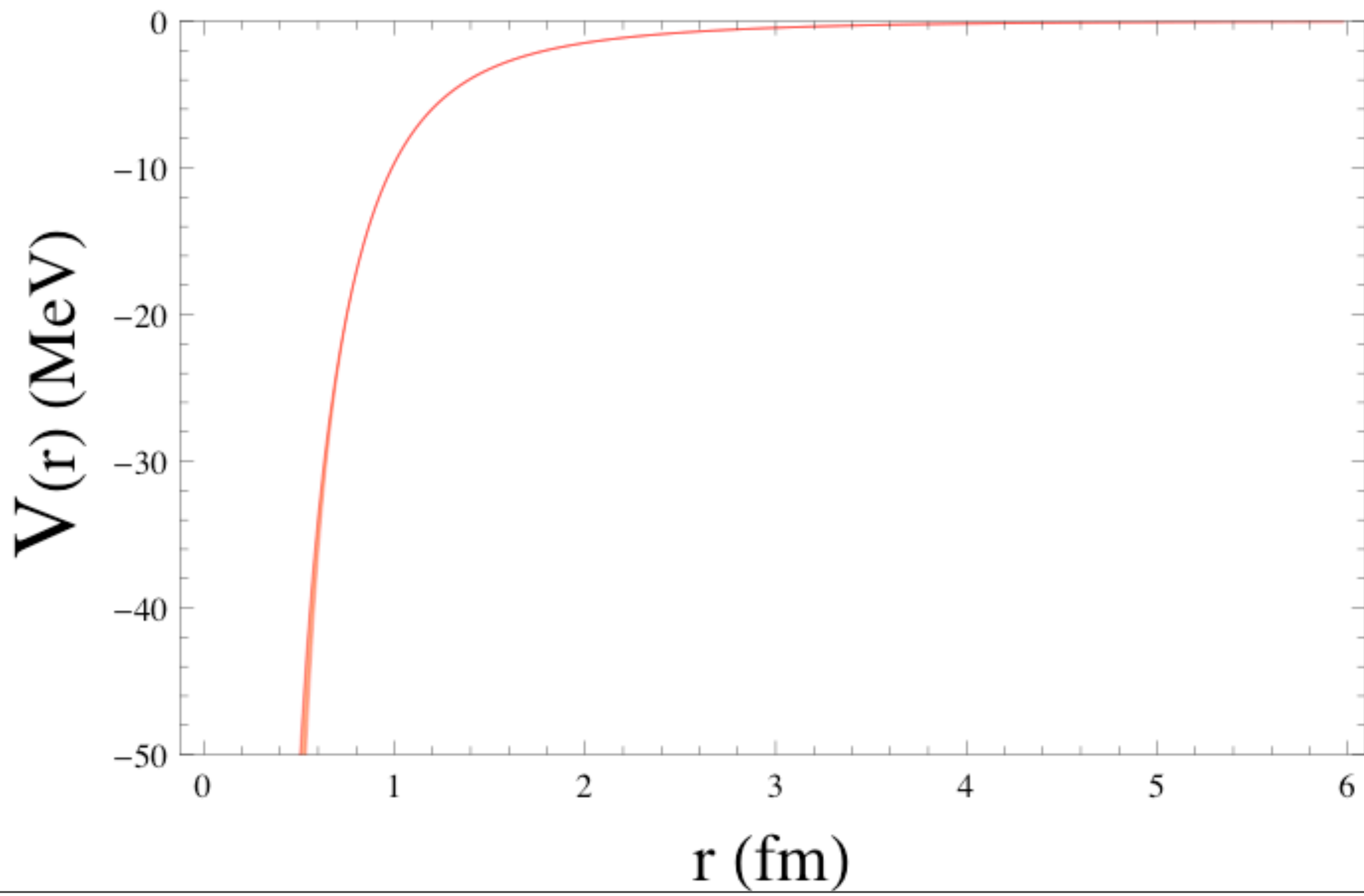
- diagonalize H in full 3-d mom. space (constrained by L and a)
- choose $R <<1/m_{mes}$ and fix C_0 to energy-eigenvalue
- extended repulsive core - Luscher ?
- use both Luscher and Weinberg EFT
  - phase-shifts are same within uncertainties!

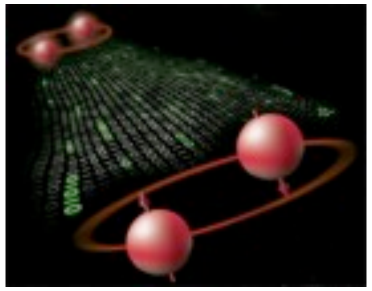




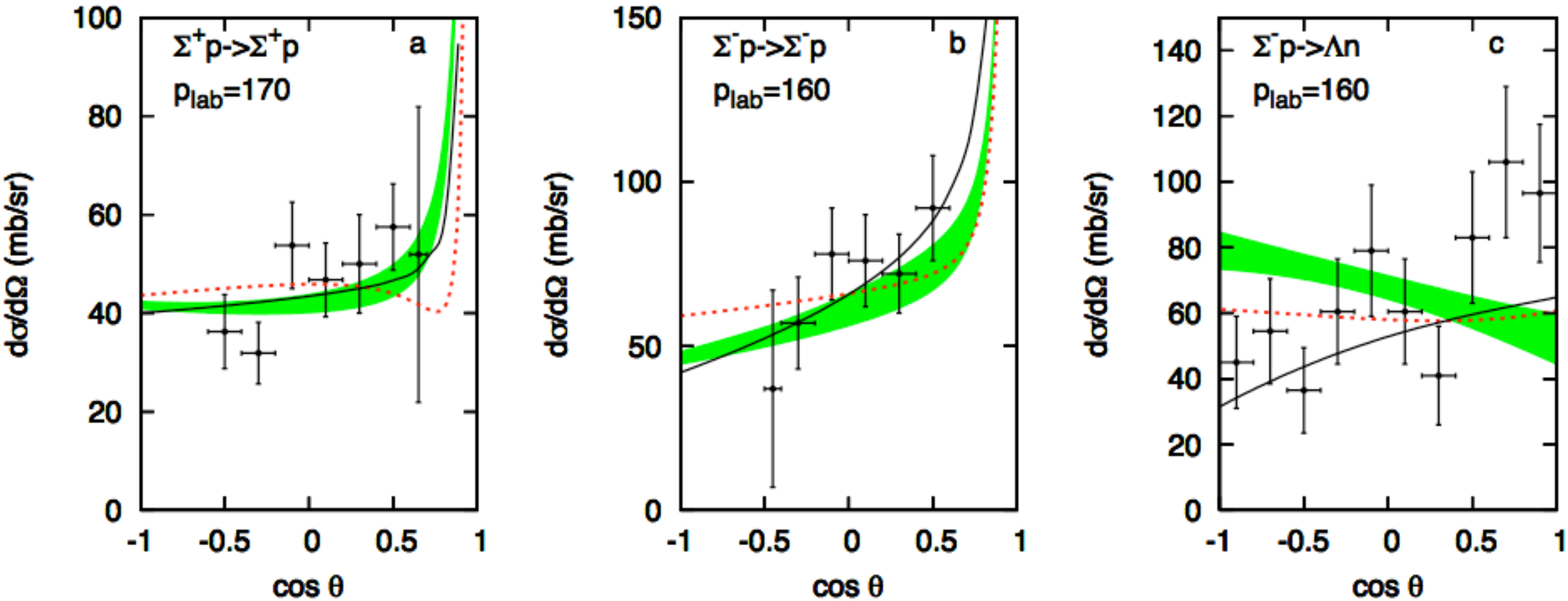
$^1S_0$: 3-d Schrodinger, Modifications to Luscher's Relation ?

Attractive core is compact - Luscher's relation is valid

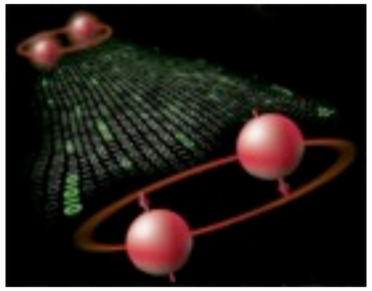




Hyperon Nucleon Interactions

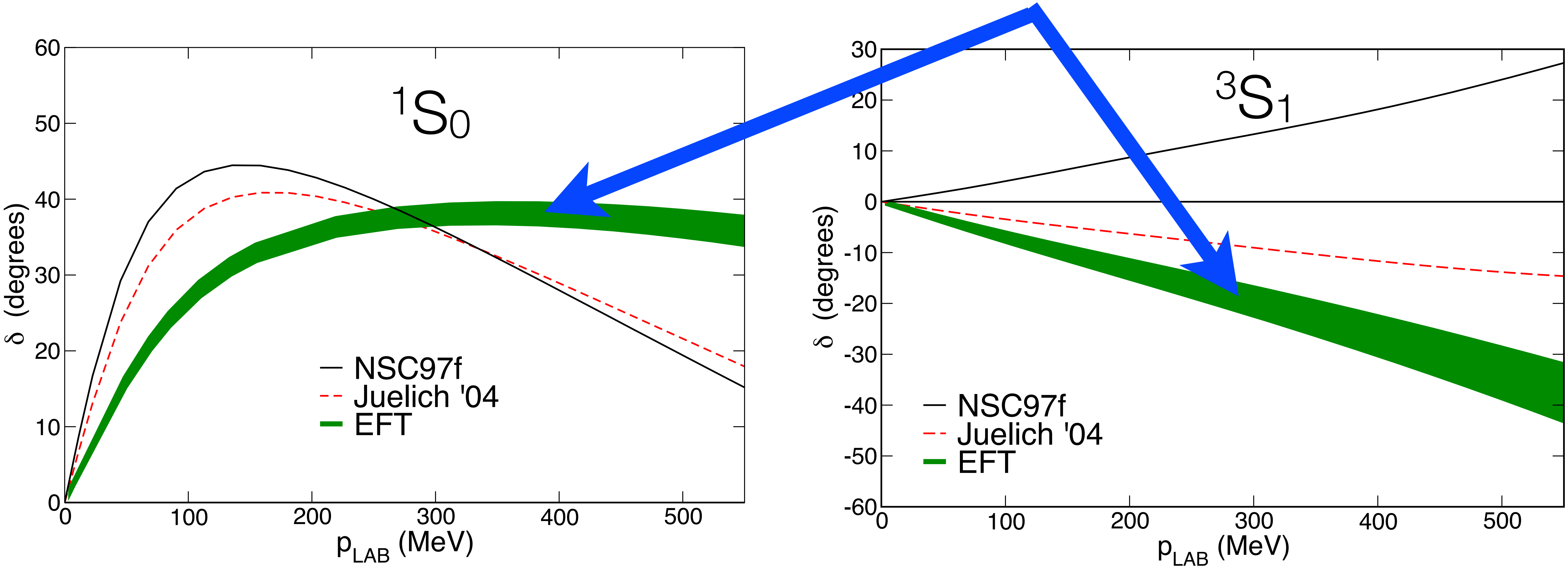


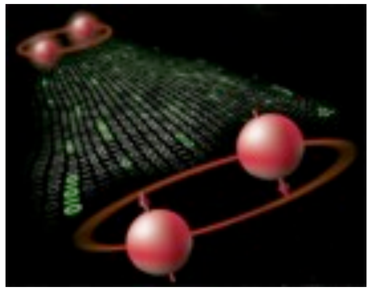
Haidenbauer and Meissner (2007)



Hyperon Nucleon Interactions

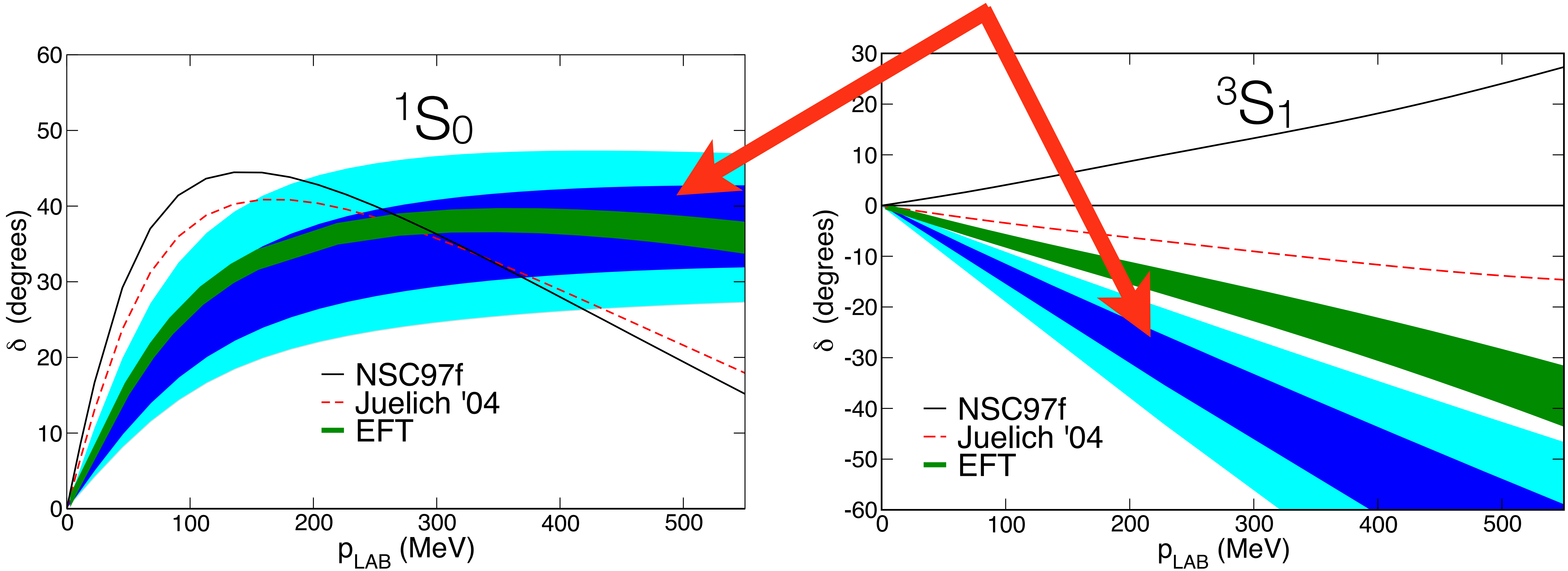
Meissner+Haidenbauer - Experiment + YN-EFT (LO)



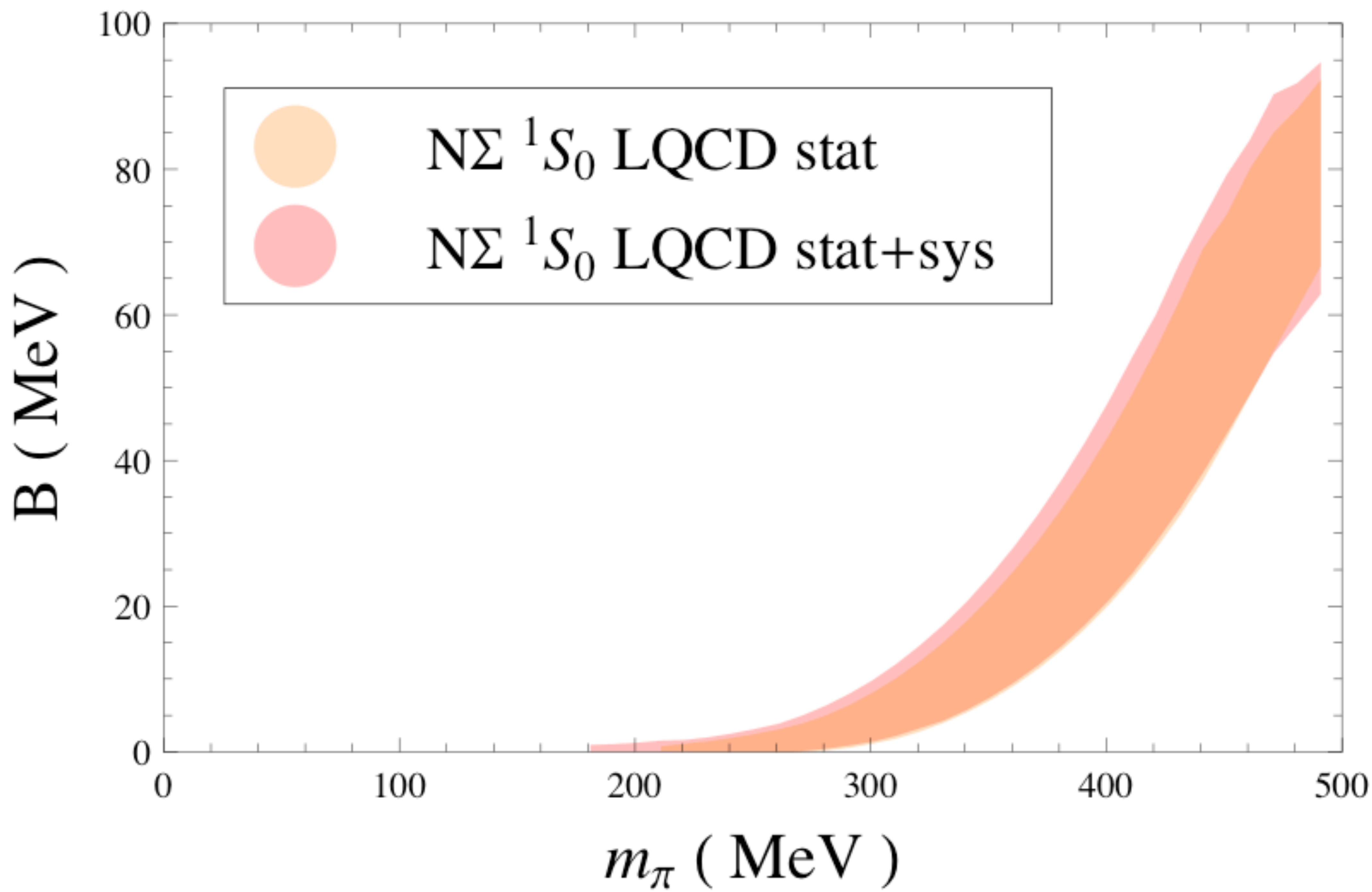


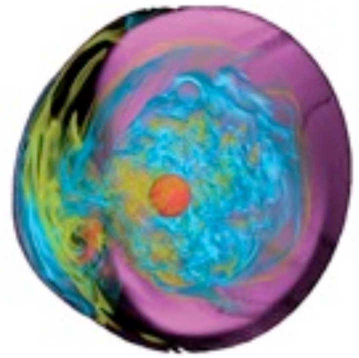
Hyperon Nucleon Interactions

NPLQCD - Lattice QCD + YN-EFT (LO)

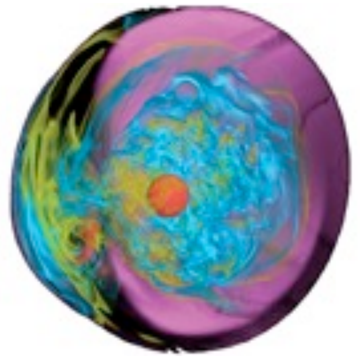


Binding in the Singlet Channel

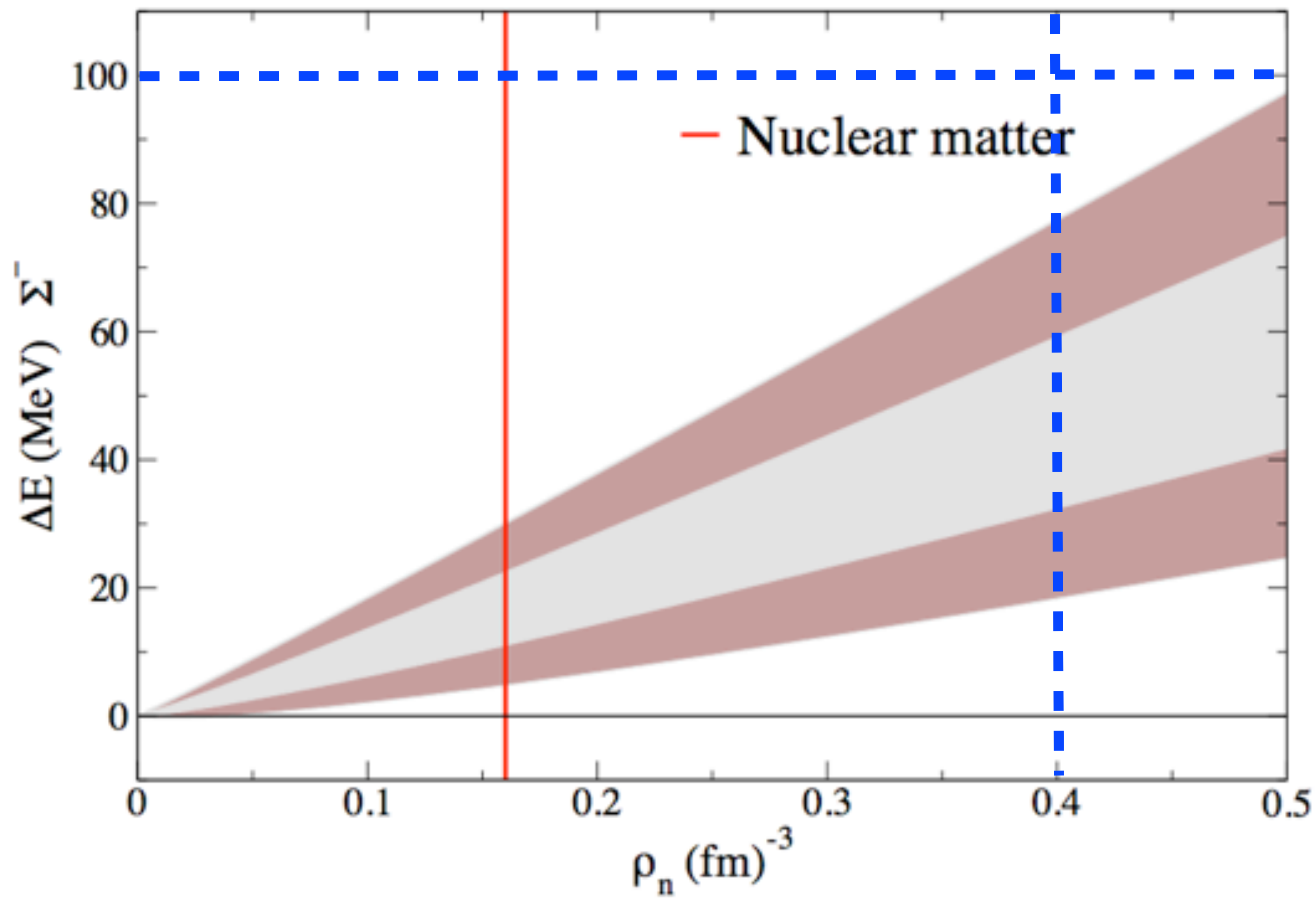




Σ^- in Dense Matter
Fumi Limit Approx. (assertions)

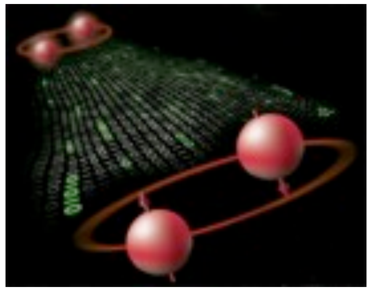


$$\Delta E = -\frac{1}{\pi\mu}\int_0^{k_f} dk\, k \left[\frac{3}{2}\delta_{^3S_1}(k) + \frac{1}{2}\delta_{^1S_0}(k) \right]$$

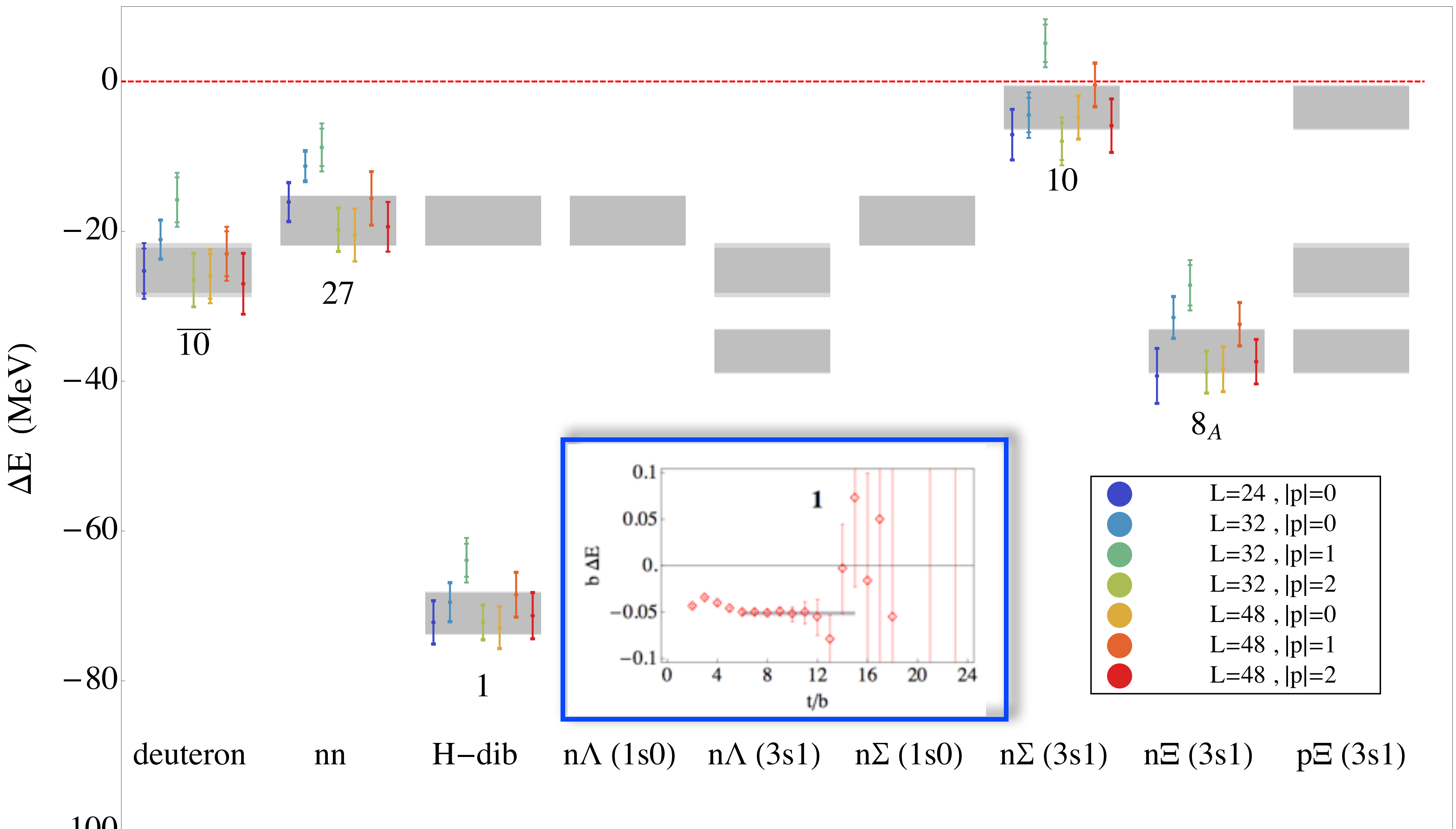


$\mu_n + \mu_{e^-}$ - M_Σ

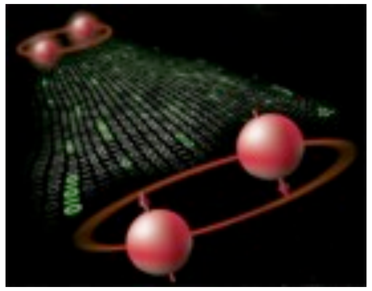
Cancellation between channels in dense matter energy-shift of hyperon



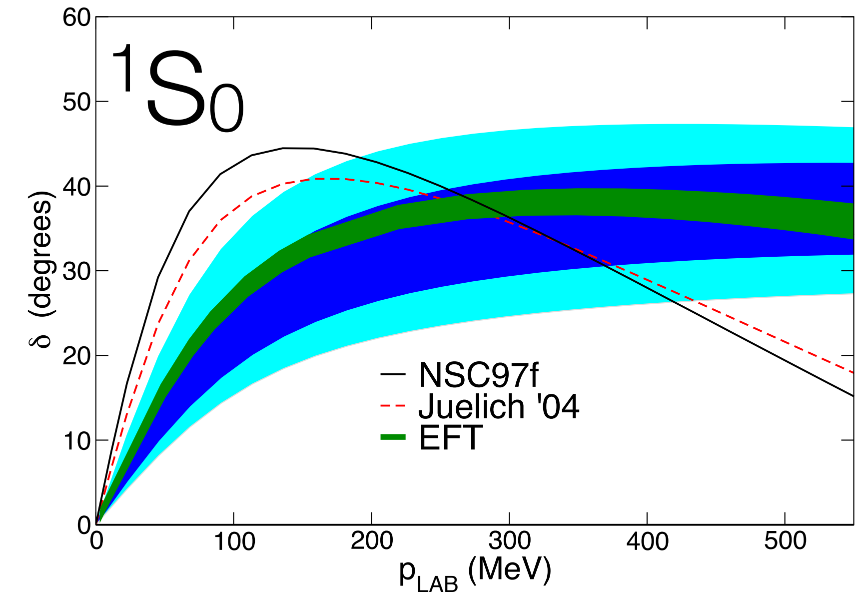
SU(3) Limit - Isotropic Clover

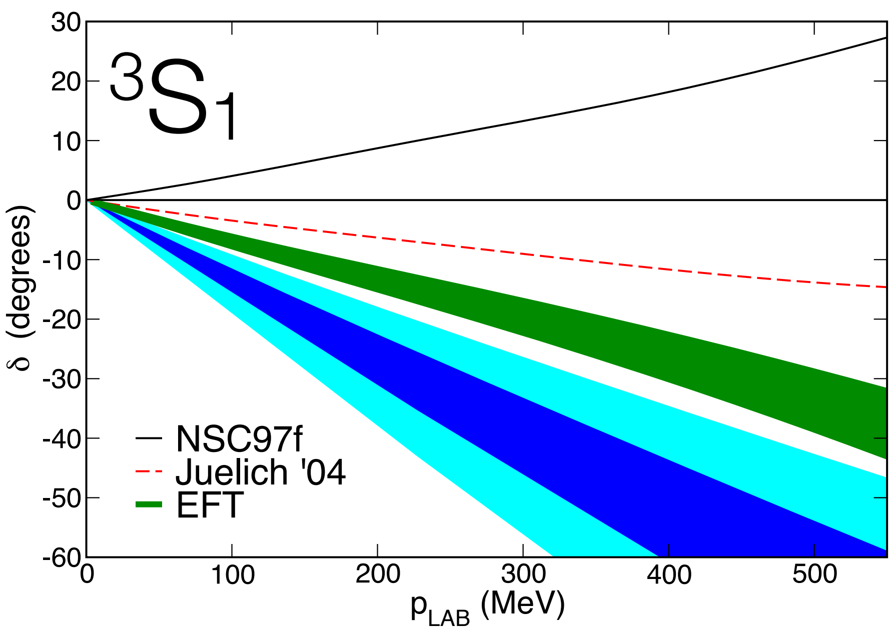


NPLQCD : e-Print: **arXiv:1206.5219 [hep-lat]**



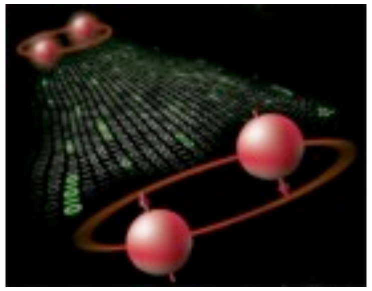
Closing Remarks



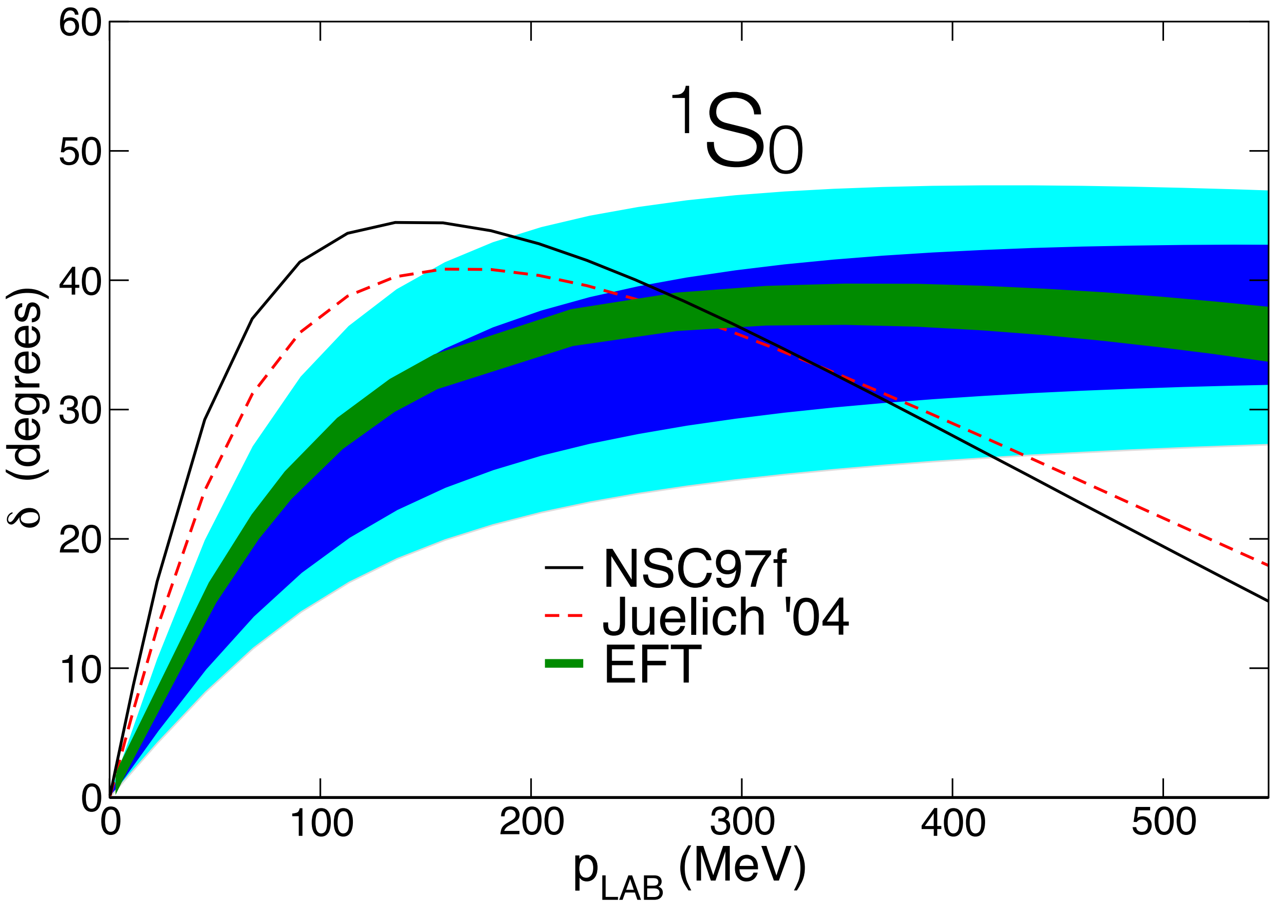


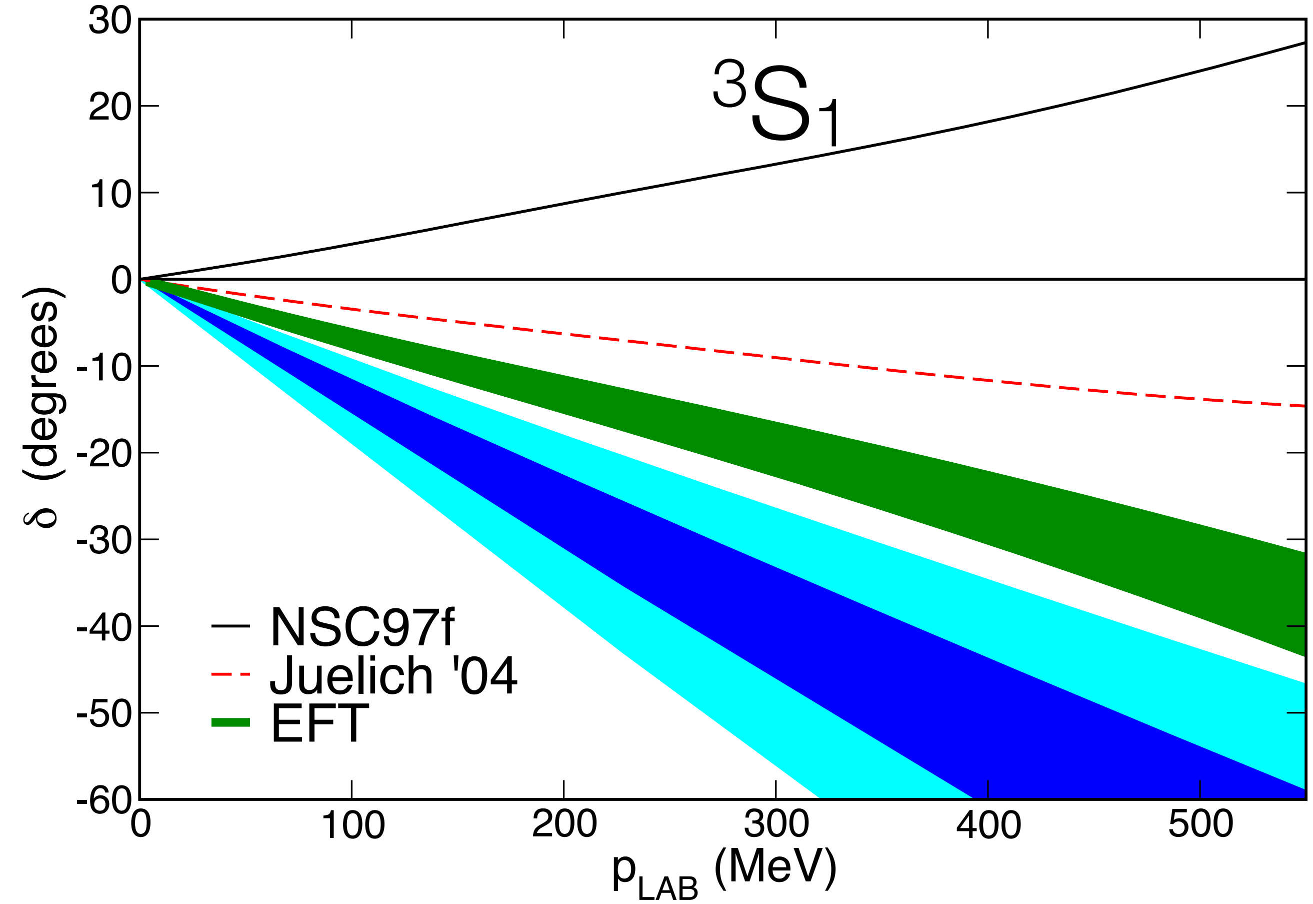
- LQCD calculations of $n\Sigma^-$
- Luscher and 3-d SE consistent
- Extrapolation with (W)EFT
- Consistent with phase-shift analysis of (limited) expt data
- Future LQCD calculations will supersede experiment
- Refine understanding of dense matter
  - Further theoretical developments required

END



Hyperon Nucleon Interactions





- LQCD + (W)EFT consistent with limited data sets
- Next generation of LQCD will be more precise than expt