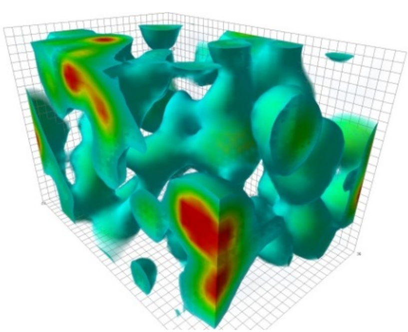
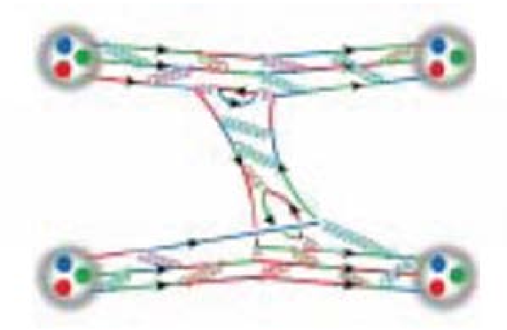
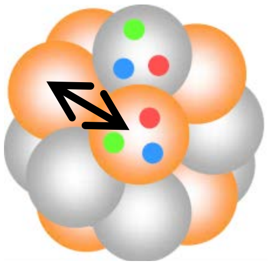
Baryon-Baryon Interactions from Lattice QCD

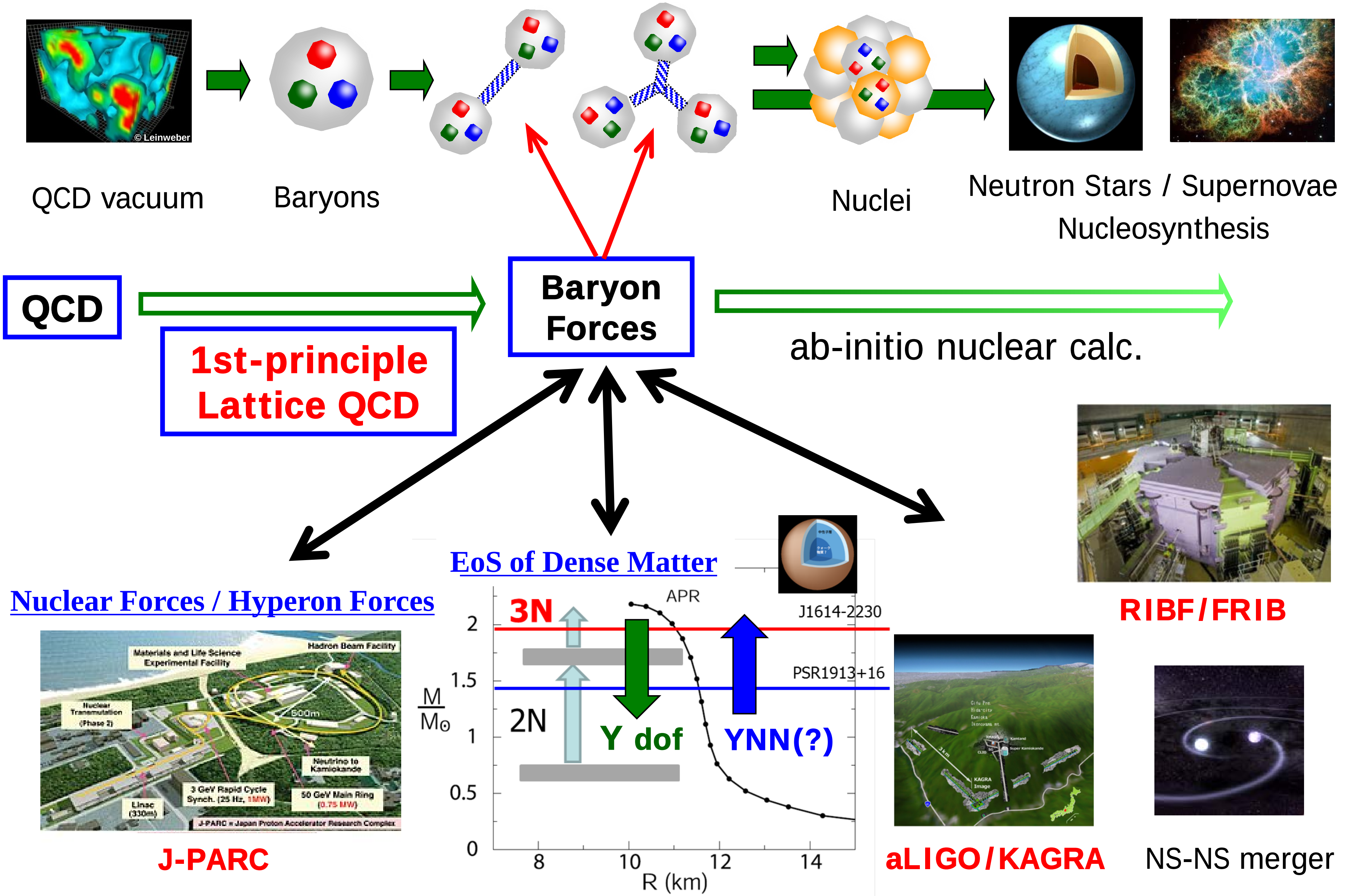
Takumi Doi
(Nishina Center, RIKEN)



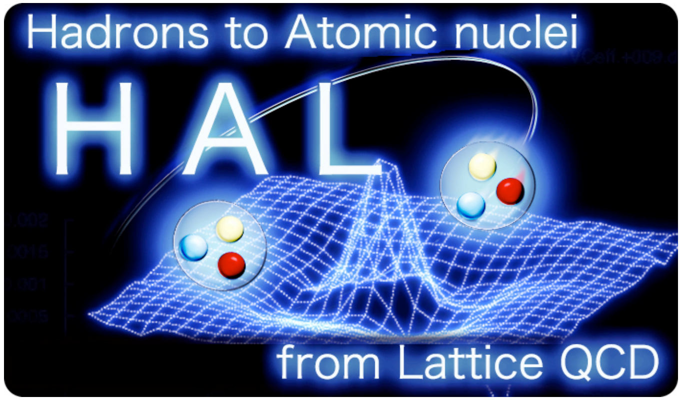




The Odyssey from Quarks to Universe



- **Outline**
  - ~~Introduction~~
  - Theoretical framework (HAL QCD method)
  - Results at heavy quark masses
  - Results at physical quark masses
  - Summary / Prospects

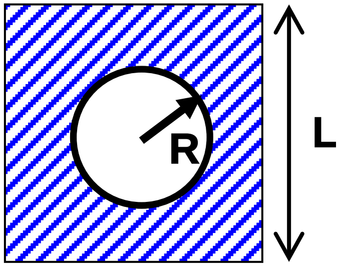


S. Aoki, D. Kawai,
T. Miyamato, K. Sasaki (YITP)
T. Doi, T. Hatsuda, T. Iritani (RIKEN)
F. Etminan (Univ. of Birjand)
S. Gongyo (Univ. of Tours)
Y. Ikeda, N. Ishii, K. Murano (RCNP)
T. Inoue (Nihon Univ.)
H. Nemura (Univ. of Tsukuba)

[HAL QCD method]

- Nambu-Bethe-Salpeter (NBS) wave function

$$\psi(\vec{r}) = \langle 0|\ N(\vec{r})N(\vec{0})\ |N(\vec{k})N(-\vec{k}); in\rangle$$



$$(\nabla^2 + k^2)\psi(\vec{r}) = 0, \quad r > R$$

  – phase shift at asymptotic region

$$\psi(r) \simeq A \frac{\sin(kr - l\pi/2 + \delta(k))}{kr}$$

M.Luscher, NPB354(1991)531
C.-J.Lin et al., NPB619(2001)467
N.Ishizuka, PoS LAT2009 (2009) 119
CP-PACS Coll., PRD71(2005)094504

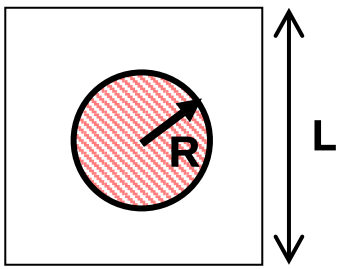
Extended to multi-particle systems

S. Aoki et al., PRD88(2013)014036

- Consider the wave function at "interacting region"

$$(\nabla^2 + k^2)\psi(\boldsymbol{r}) = m \int d\boldsymbol{r}' U(\boldsymbol{r}, \boldsymbol{r}')\psi(\boldsymbol{r}'), \quad r < R$$

  – U(r,r'): faithful to the phase shift by construction
    - U(r,r'): E-independent, while non-local in general
      – Non-locality ➔ derivative expansion

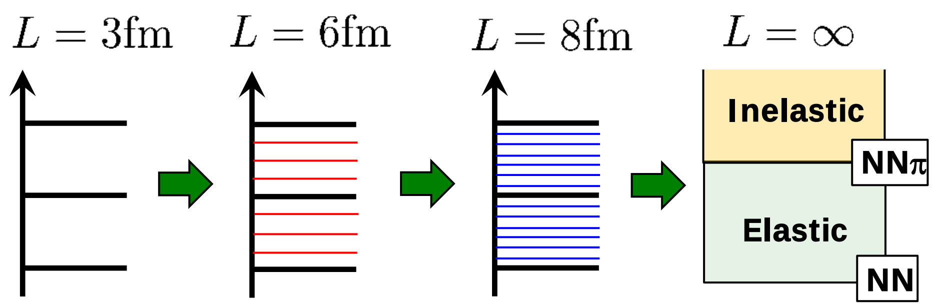


Aoki-Hatsuda-Ishii PTP123(2010)89

The Challenge in multi-baryons on the lattice

Almost No Excitation Energy

➔ LQCD method based on G.S. saturation unreliable



$S/N \propto$ 10^{-4} 10^{-13} 10^{-25}

Existence of elastic scattering states ➔ **System w/o Gap**

(except for very small binding energies)

Signal/Noise issue

G.S. saturation ➔ $t \gg 1/(E_1 - E_0)$ (excitation energy)

$$S/N \sim \exp[-\mathbf{A} \times (\mathbf{m_N} - \mathbf{3/2m_\pi}) \times \mathbf{t}]$$

Parisi, Lepage(1989)

Time-dependent HAL method

N.Ishii et al. (HAL QCD Coll.) PLB712(2012)437

E-indep of potential U(r,r') ➔ *(excited) scatt states share the same U(r,r')*

*They are **not contaminations**, **but signals***

Original (t-indep) HAL method

$$G_{NN}(\vec{r},t) = \langle 0|N(\vec{r},t)N(\vec{0},t)\overline{\mathcal{J}_{\rm src}(t_0)}|0\rangle$$

$$R(\boldsymbol{r},t) \equiv G_{NN}(\boldsymbol{r},t)/G_N(t)^2 = \sum_i A_{W_i}\psi_{W_i}(\boldsymbol{r})e^{-(W_i-2m)t}$$

🡐 Many states contribute

$$\int d\boldsymbol{r}'U(\boldsymbol{r},\boldsymbol{r}')\psi_{W_0}(\boldsymbol{r}') = (E_{W_0} - H_0)\psi_{W_0}(\boldsymbol{r})$$

$$\int d\boldsymbol{r}'U(\boldsymbol{r},\boldsymbol{r}')\psi_{W_1}(\boldsymbol{r}') = (E_{W_1} - H_0)\psi_{W_1}(\boldsymbol{r})$$

...

New t-dep HAL method

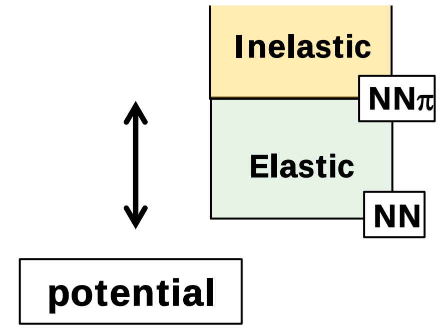
All equations can be combined as

$$\int d\boldsymbol{r}'U(\boldsymbol{r},\boldsymbol{r}')R(\boldsymbol{r}',t) = \left(-\frac{\partial}{\partial t} + \frac{1}{4m}\frac{\partial^2}{\partial t^2} - H_0\right)R(\boldsymbol{r},t)$$

~~G.S. saturation~~ ➔ "Elastic state" saturation

[Exponential Improvement]

System w/ Gap



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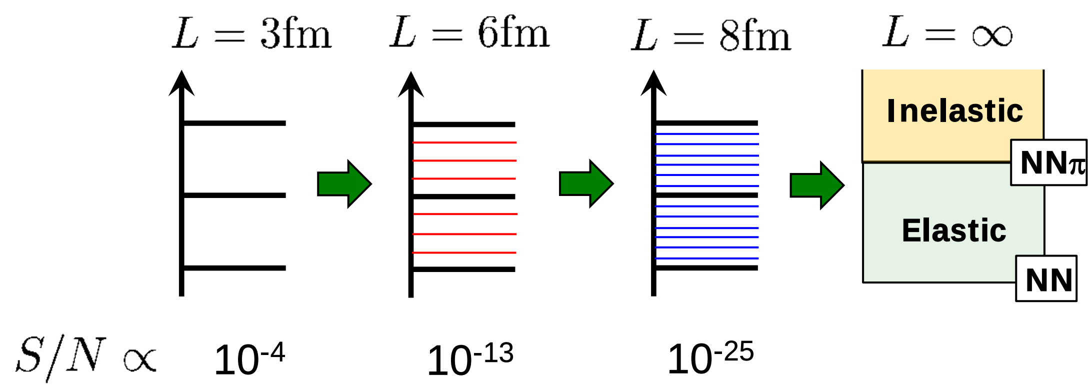


QCD

Baryon Forces

Experiments

HAL QCD method

"Time-dependent method" N.Ishii et al. PLB712(2012)437

G.S. saturation NOT required w/ E-indep pot

Direct method

G.S. saturation required

Yamazaki et al.

Savage et al. (NPL Coll.)

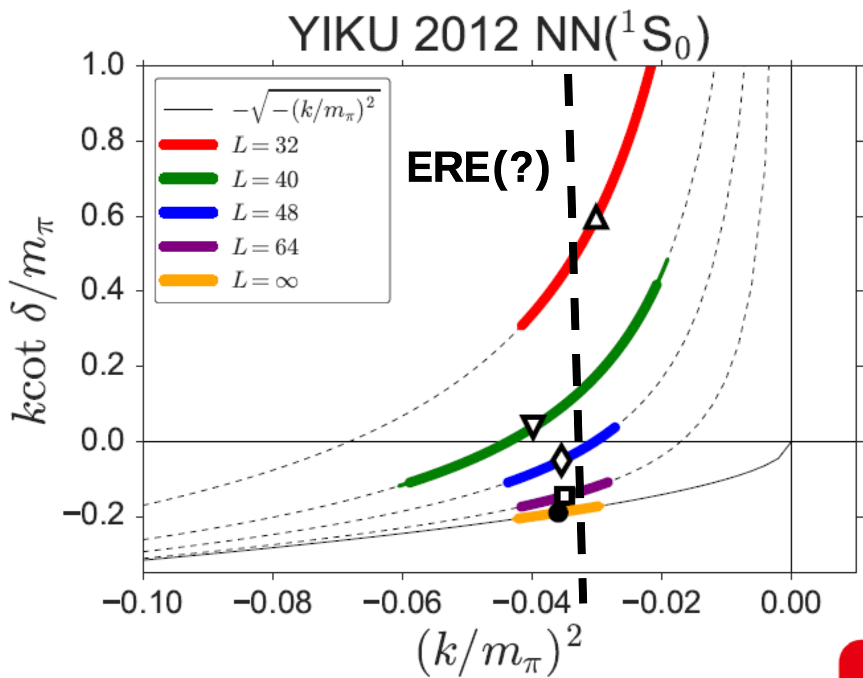
“Sanity Check” for results from direct method

Aoki-Doi-Iritani, arXiv:1610.09763

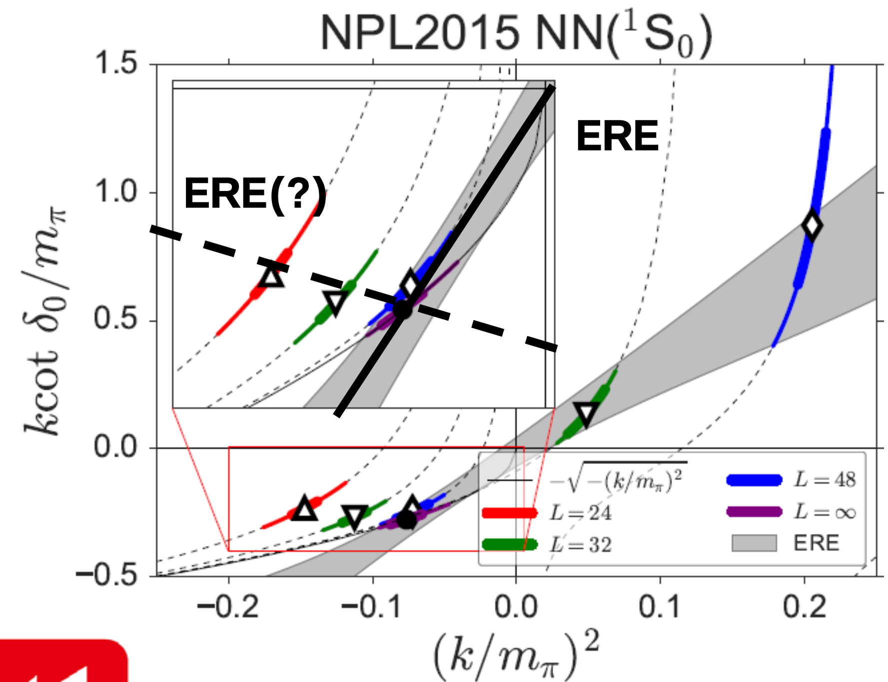
$k \cot\delta(k)$ vs k^2 plot

$$\text{ERE:}\quad k\cot\delta(k) = \frac{1}{\mathbf{a}} + \frac{1}{2}\,\mathbf{r}\,k^2 + \cdots$$

Data from Yamazaki et al (‘12)



Data from NPL Coll. (‘15)



Singular behaviors

$1/a \simeq -\infty \qquad r \simeq -\infty$

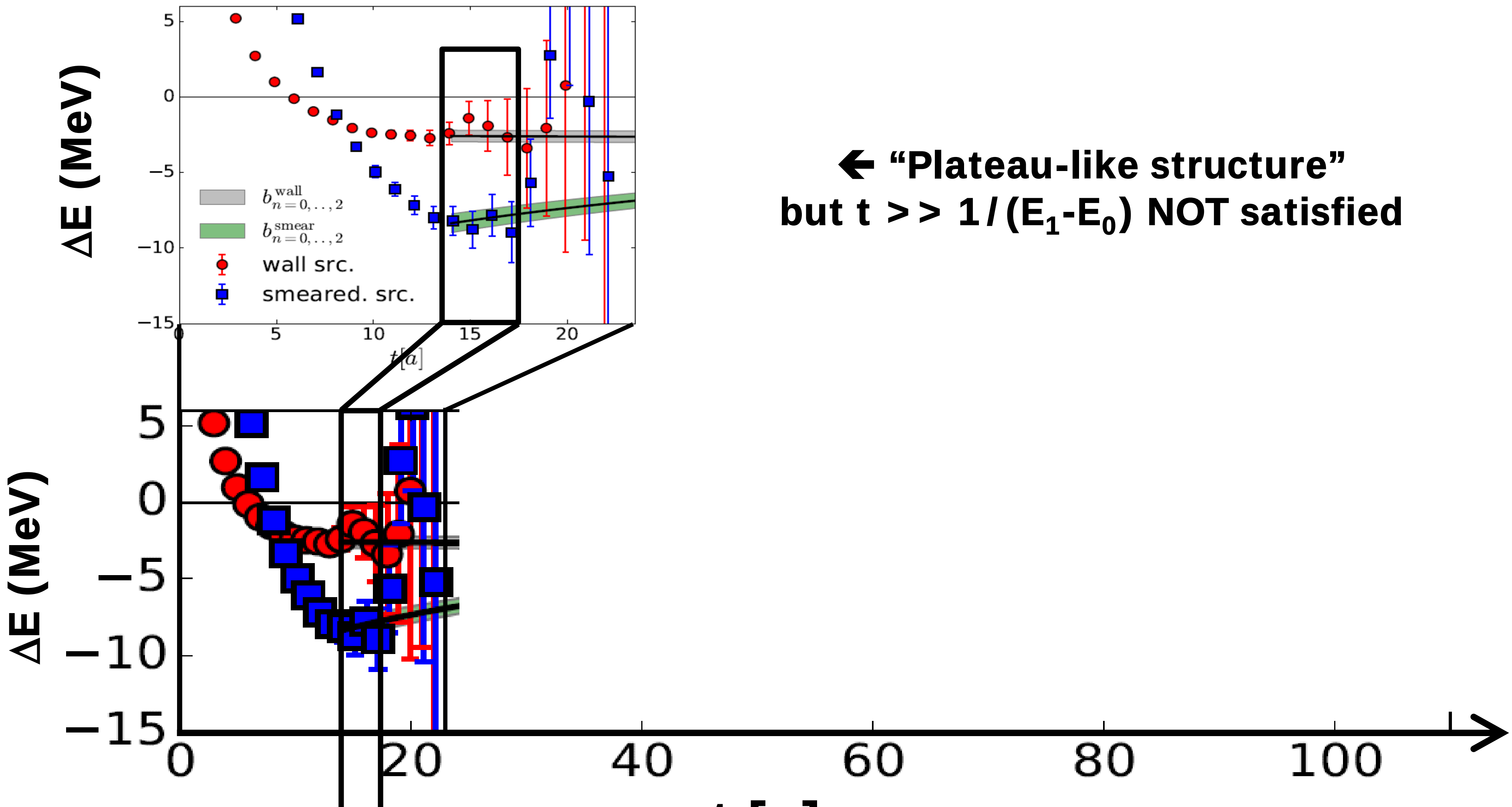
WARNING

Inconsistent ERE

$(k^2 < 0 \text{ vs. } k^2 > 0)$

“Anatomy” of sympton in direct method

T. Iritani (HAL Coll.), arXiv:1610.09779



🡐 “Plateau-like structure”
but t >> 1 / (E_1-E_0) NOT satisfied

“fake plateaux”
at t ~ 1fm

HAL method is crucial !

“real plateau”
at t ~ 10fm

(E_1-E_0=50MeV)

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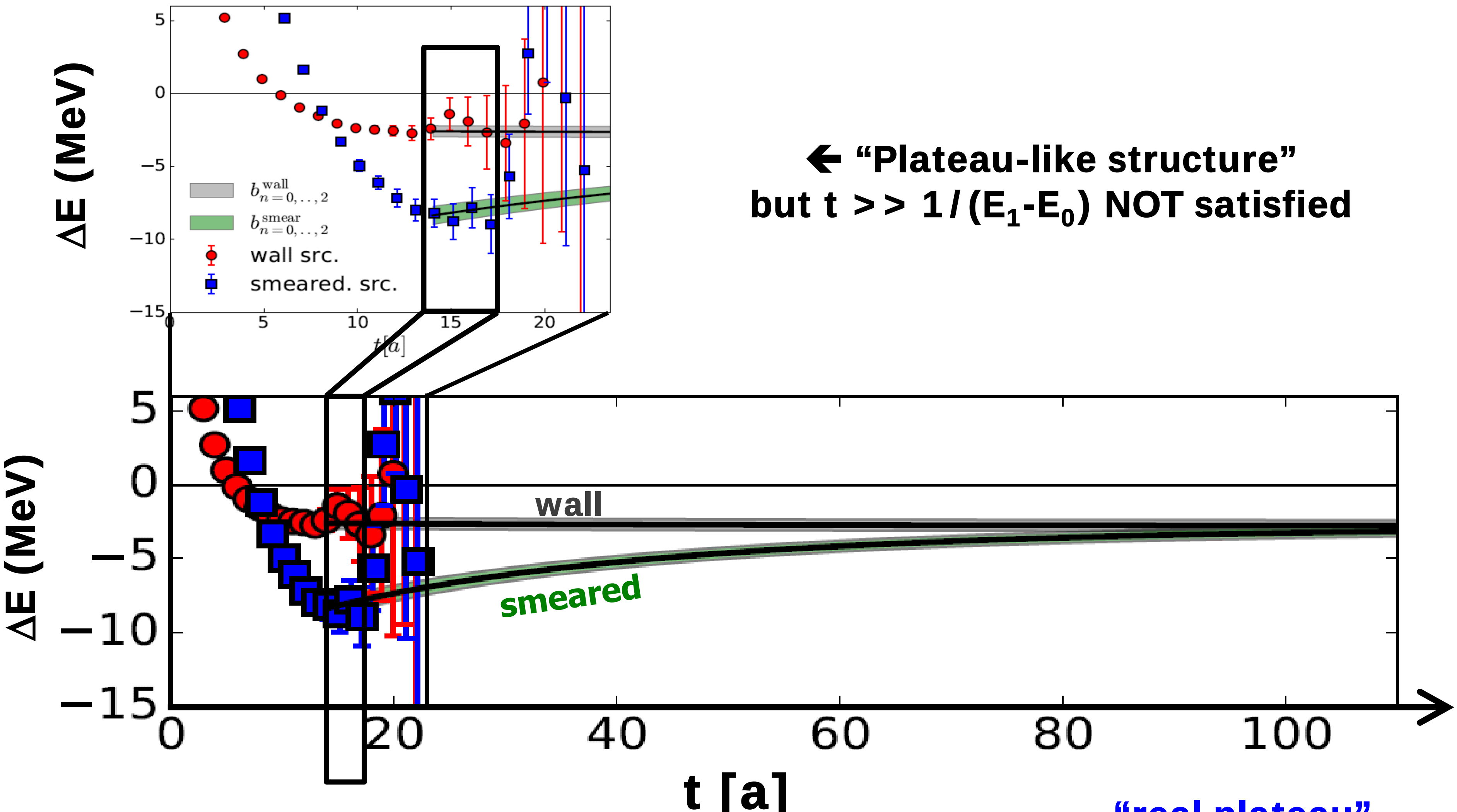
T. Iritani (HAL Coll.), arXiv:1610.09779



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at t ~ 10fm

(E_1-E_0=50MeV)

The fate of the direct method (check on NN)

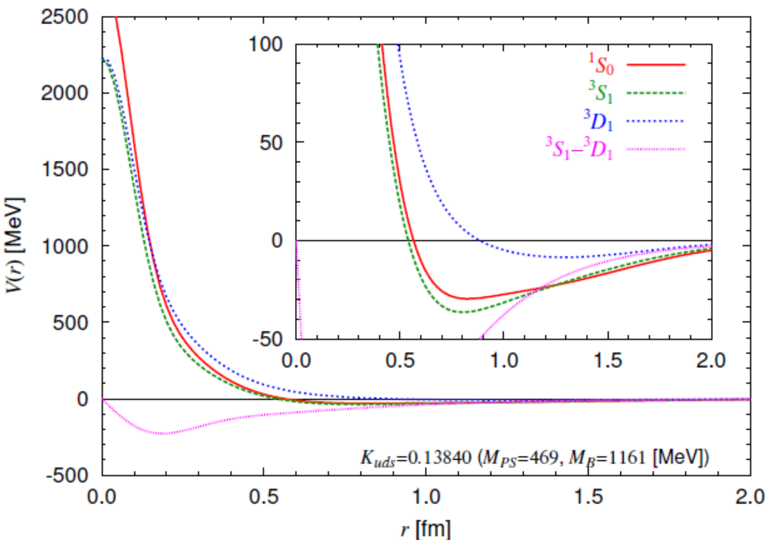
T. Iritani et al. (HAL Coll.) JHEP1610(2016)101 + more papers in prep.

	single baryon	double baryon				Overall Verdict
	plateau check	mirage plateau	src-dep check	sink-dep check	Effective Range expansion check	
YKU 2011	○	×	△	Not checked	×	**False**
YIKU 2012	○	×	×	×	×	**False**
YIKU 2015	○	×	Not checked	Not checked	×	**False**
NPL 2012	○	×	Not checked	Not checked	×	**False**
NPL 2013	○	×	Not checked	Not checked	△	**False**
NPL 2015	△	×	Not checked	Not checked	×	**False**

- **Outline**
  - Introduction
  - Theoretical framework
  - Results at heavy quark masses w/ HAL method
    - LQCD to EoS / Neutron stars
    - LQCD to Nuclei
    - LQCD to Exotic Hadrons
  - Results at physical quark masses
  - Summary / Prospects

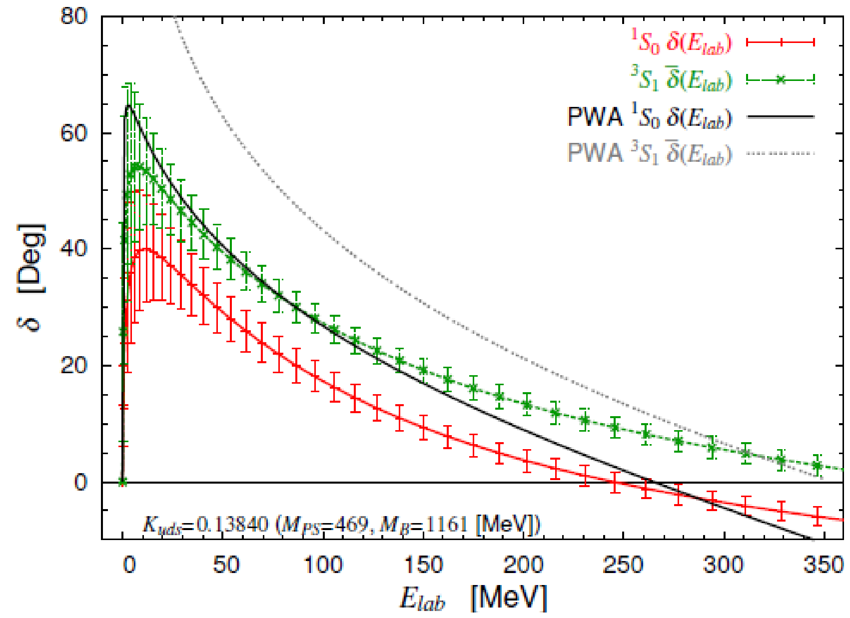
From LQCD to NN-forces

Lat NN forces



(SU(3), m(PS)=0.47GeV)

Phase shifts

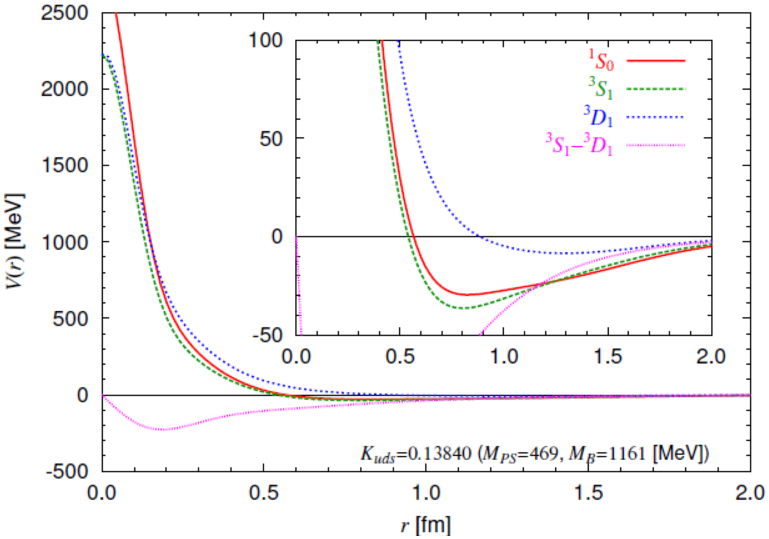


Strong Attraction in both of NN($^1S_0$), NN($^3S_1$)
(but they do not bound @ heavy quark masses)

T.Inoue et al. (HAL Coll.) PRL111(2013)112503
T.Inoue et al. (HAL Coll.), NPA881(2012)28

From LQCD to EoS / Neutron Star

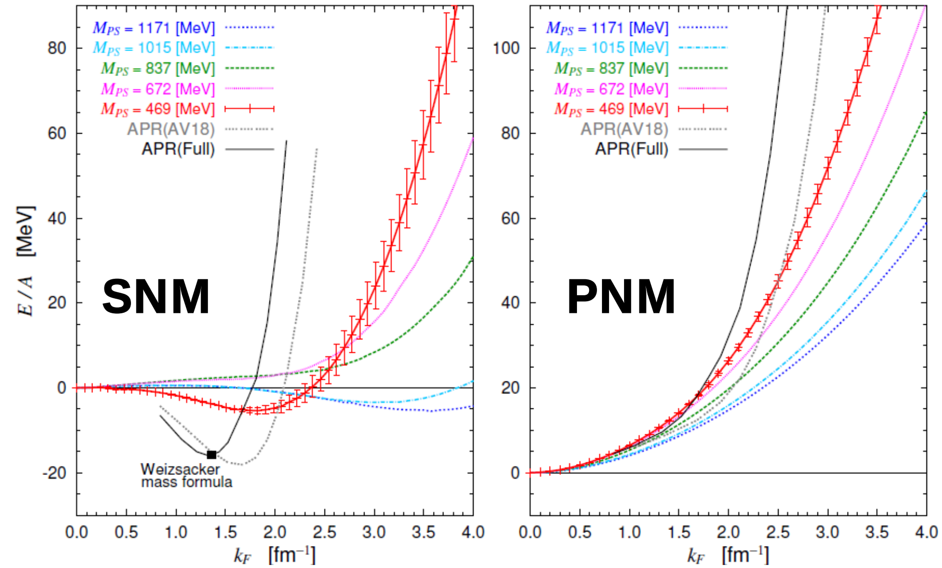
Lat NN forces



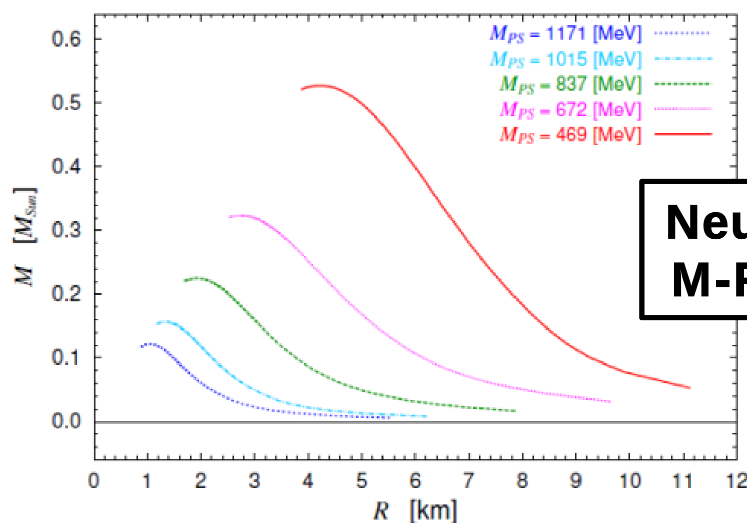
(SU(3), m(PS)=0.47GeV)

BHF

EoS of nuclear matter



TOV



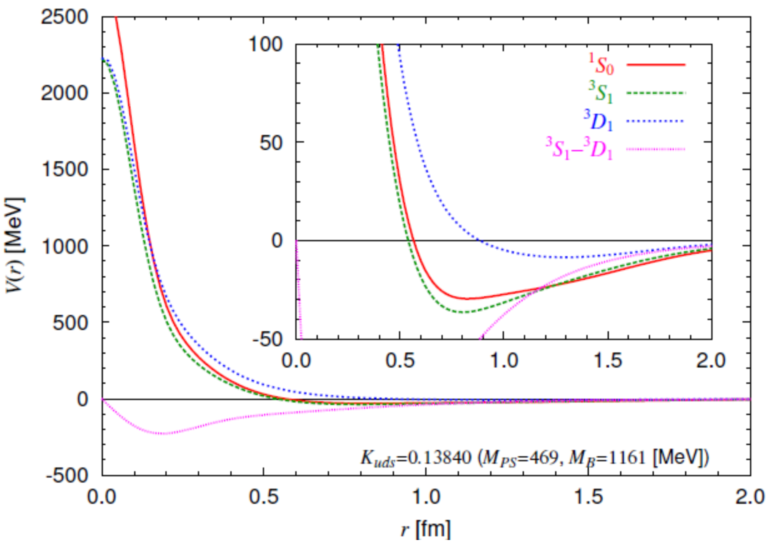
Neutron Star M-R relation

T.Inoue et al. (HAL Coll.) PRL111(2013)112503

T.Inoue et al. (HAL Coll.), PRC91(2015)011001

From LQCD to Nuclei (^{16}O, ^{40}Ca)

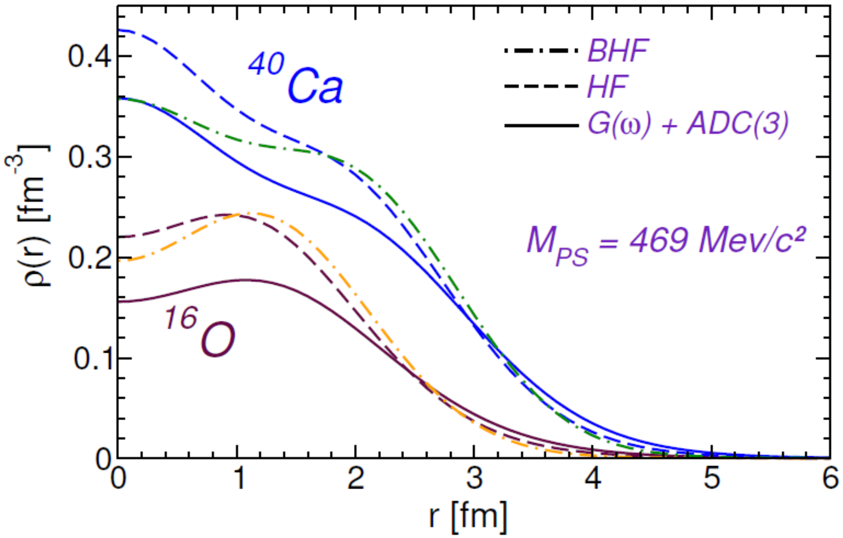
Lat NN forces



(SU(3), m(PS)=0.47GeV)

Ab initio SCGF

Density Distribution



E_0^A [MeV]	^{4}He	^{16}O	^{40}Ca
BHF [22]	-8.1	-34.7	-112.7
G(ω) + ADC(3)	-4.80(0.03)	-17.9 (0.3) (1.8)	-75.4 (6.7) (7.5)
Exact Result [51]	-5.09	–	–
Separation into ^{4}He clusters:		-2.46 (0.3) (1.8)	24.5 (6.7) (7.5)

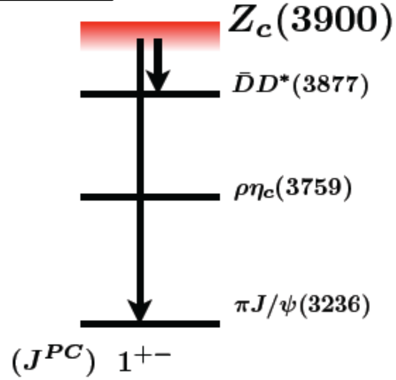
C. McIlroy et al.,
submitted to PRL

Particle Physics
First-principles LQCD calc
HAL Coll. @ Japan

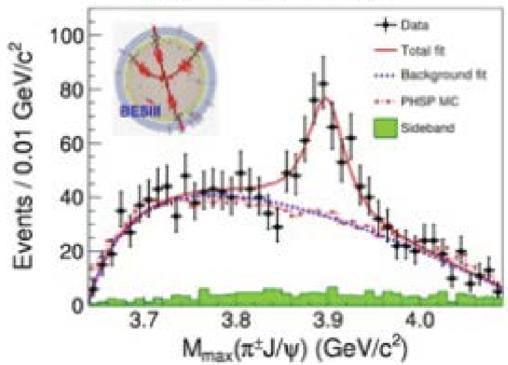
Nuclear Physics
Ab initio many-body calc
Univ. of Surrey @ UK

Fate of exotic candidate Zc(3900)[$ud^{bar}cc^{bar}$] -- coupled channel study --

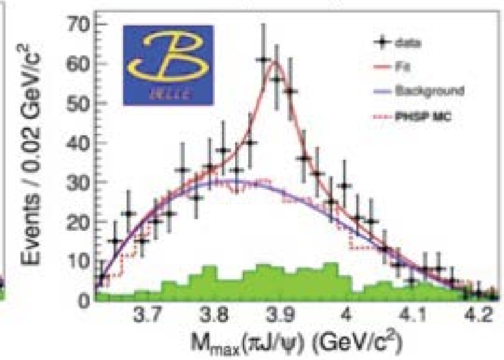
Exp



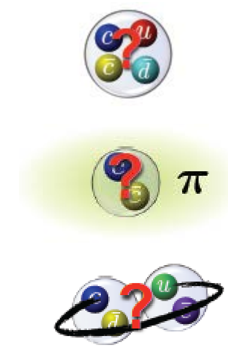
BESIII (2013).



Belle (2013).



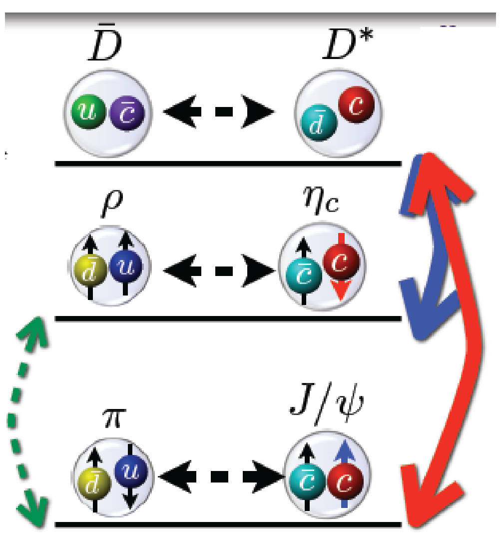
Models

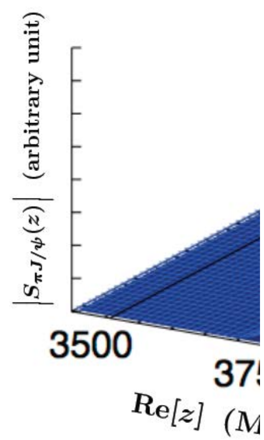


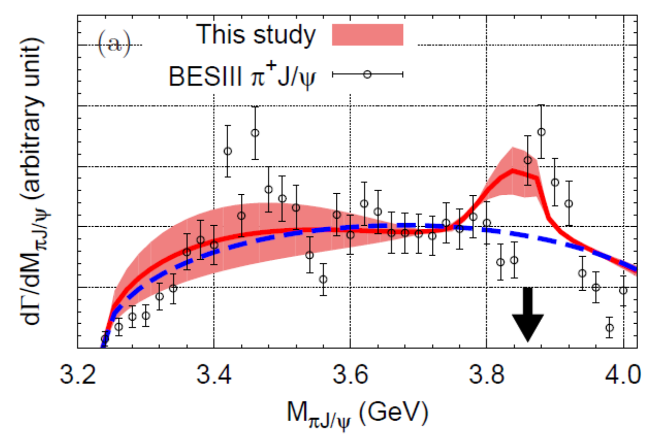
LQCD

m(pi)=0.41GeV

Coupled channel potential







Zc(3900) is threshold cusp

Y. Ikeda et al., PRL117(2016)242001

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  - Introduction
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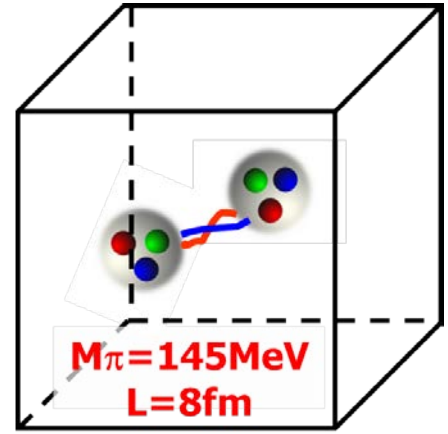
  - Results at heavy quark masses
  - Results at (almost) physical quark masses
    - Nuclear forces and Hyperon forces
    - Impact on dense matter
  - Summary / Prospects

Lattice QCD Setup

- **Nf = 2 + 1 gauge configs**
  - clover fermion + Iwasaki gauge
  - V=(8.1fm)^4, a=0.085fm (1/a = 2.3 GeV)
  - m(pi) ~= 145 MeV, m(K) ~= 525 MeV

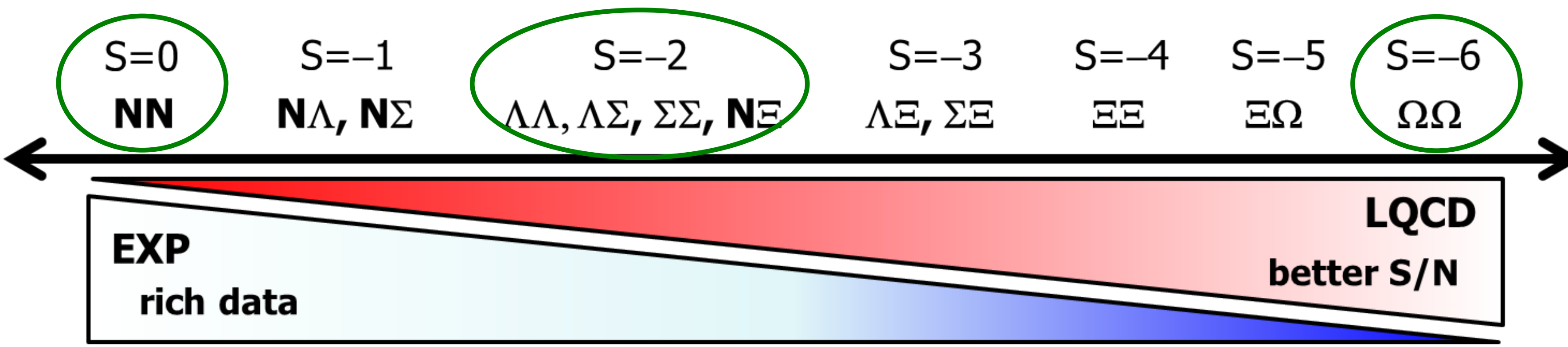
K.I. Ishikawa et al., PoS LAT2015, 075



- **Measurement**
  - NN/YN/YY for central/tensor forces in P=(+) (S, D-waves)
  - Unified Contraction Algorithm (UCA) ➔ drastic speedup in calc

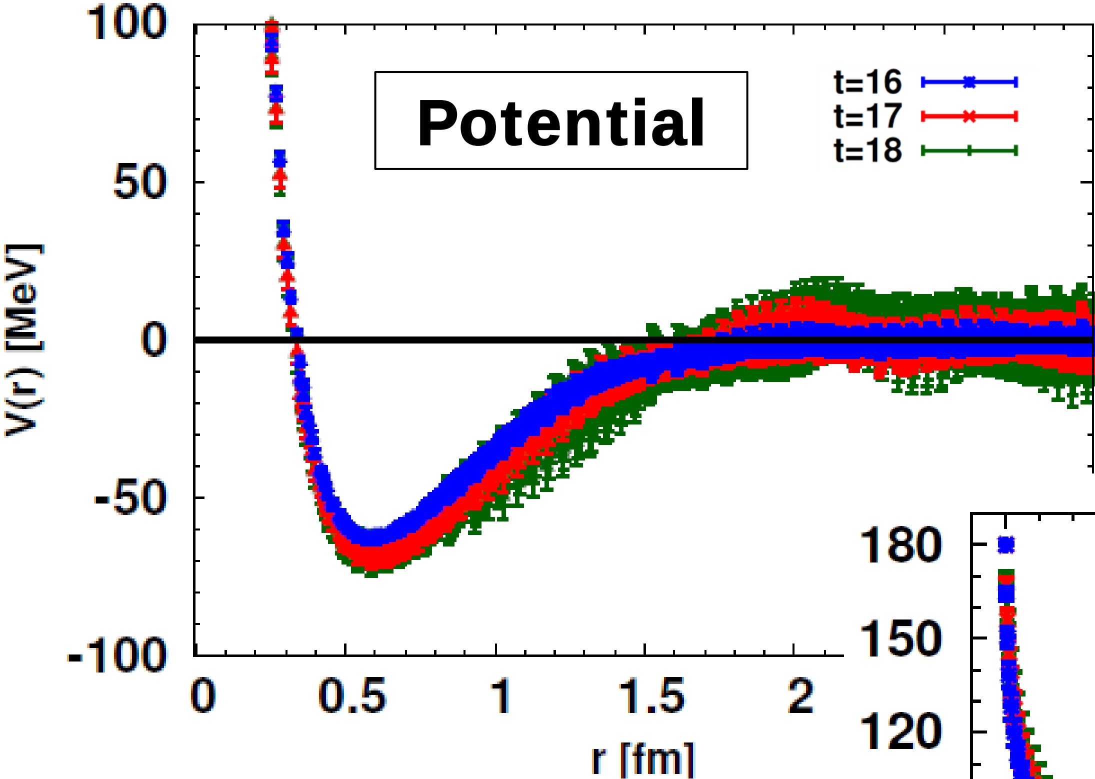
TD and M. Endres, CPC184(2013)117

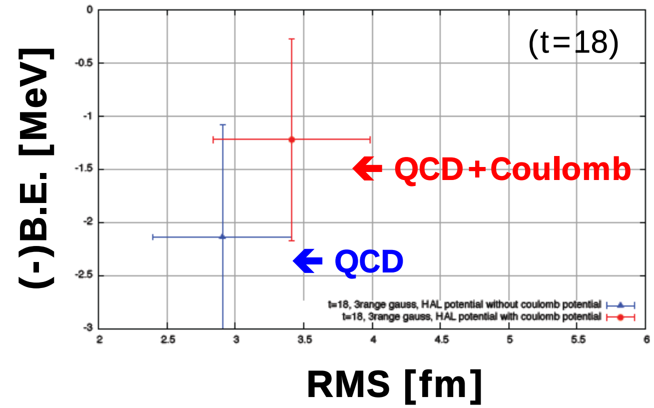
Predictions for Hyperon forces

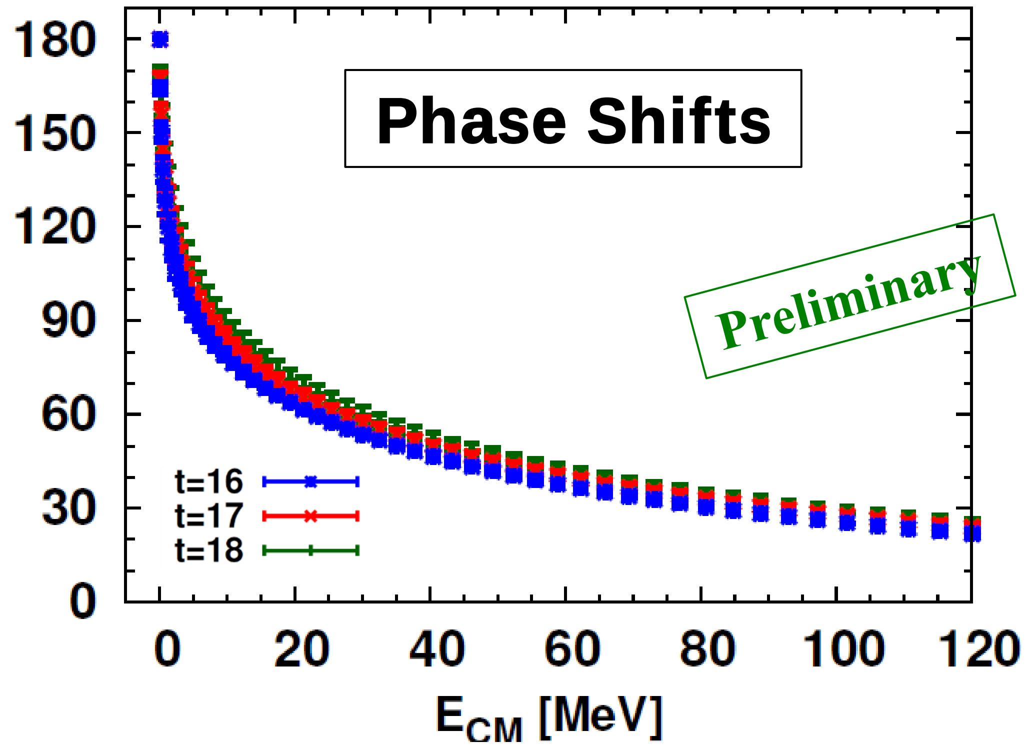


ΩΩ system ($^1S_0$)

(The "most strange" dibaryon system)







Strong Attraction

➔ **Vicinity of bound / unbound**

[~ Unitary limit]

⟺ **ΩΩ correlation in HIC exp.**

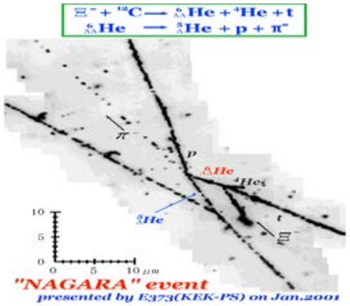
[S. Gongyo / K. Sasaki]

S = -2 channel (Coupled Channel)

H-dibaryon ($^1S_0$, $\Lambda\Lambda$–$N\Xi$–$\Sigma\Sigma$)

NAGARA-event (2001)

$$\Xi^- + {}^{12}\mathrm{C} \to {}_{\Lambda\Lambda}{}^{6}\mathrm{He} + {}^{4}\mathrm{He} + t$$

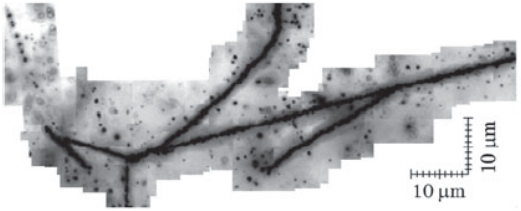


Ξ–hypernuclei

KISO-event (2014)

$$\Xi^- + {}^{14}\mathrm{N} \to {}_{\Lambda}{}^{10}\mathrm{Be} + {}_{\Lambda}{}^{5}\mathrm{He}$$

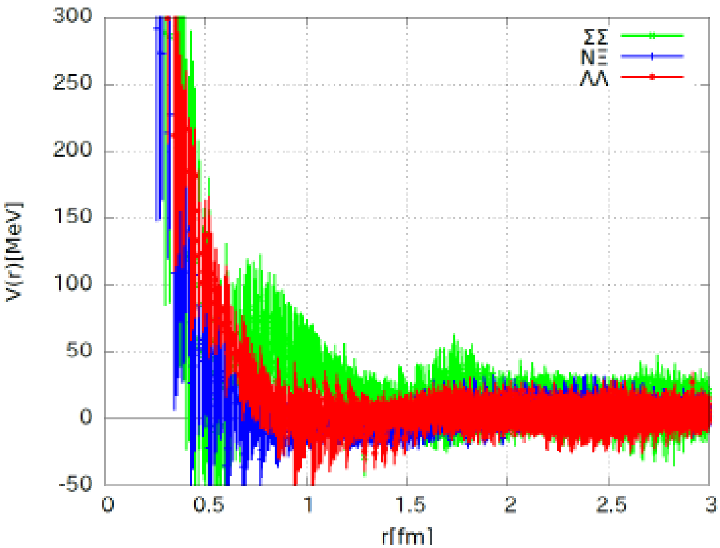
B.E. = 4.38(25) MeV
(or 1.11(25) MeV)



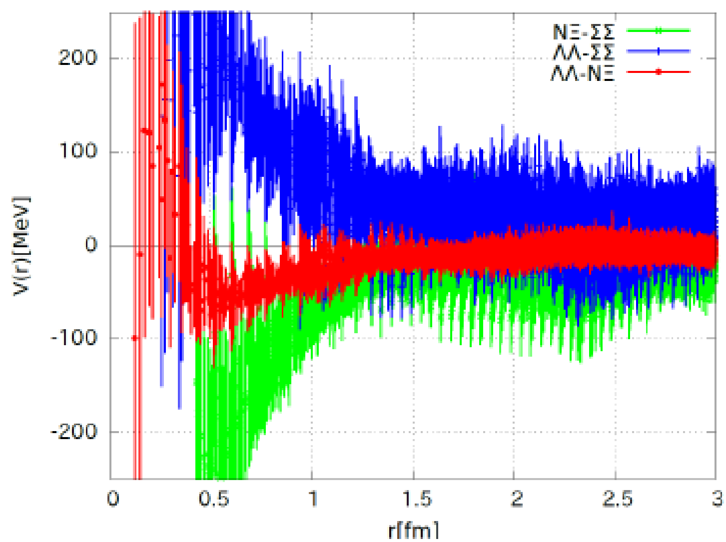
H-dibaryon @ Nf=2+1, m_π=146 MeV

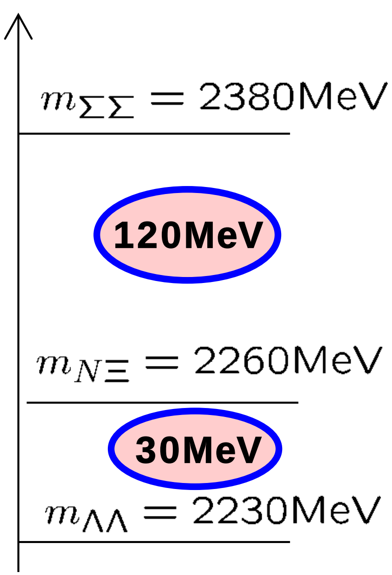
[K. Sasaki]

diagonal



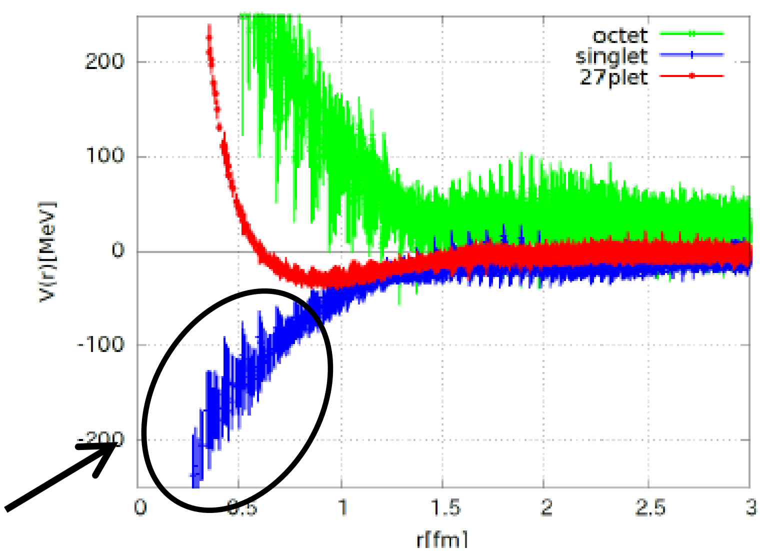
off-diagonal





diagonal in SU(3)-irrep base

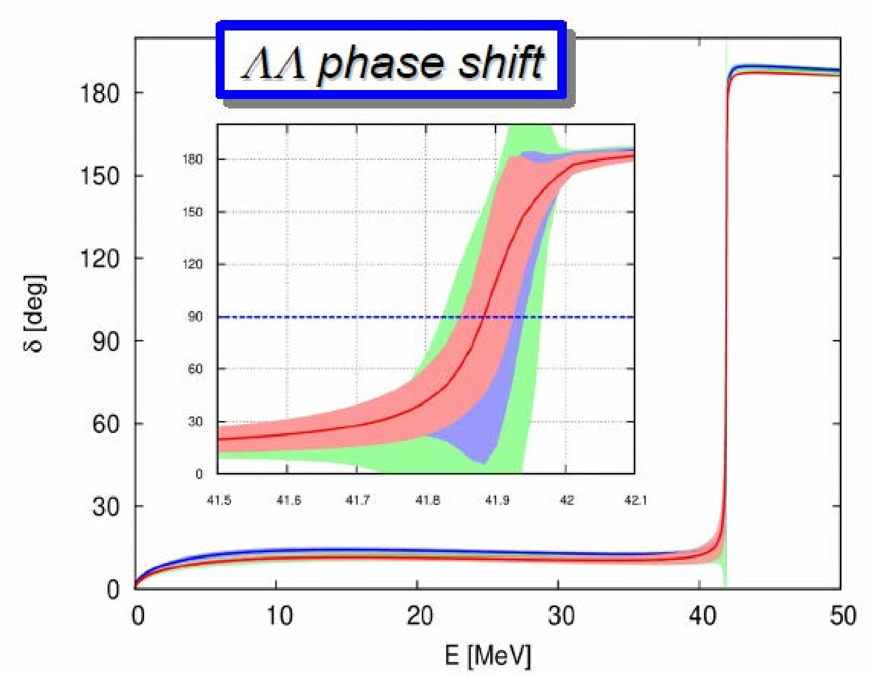
Strong Attraction in flavor-singlet channel

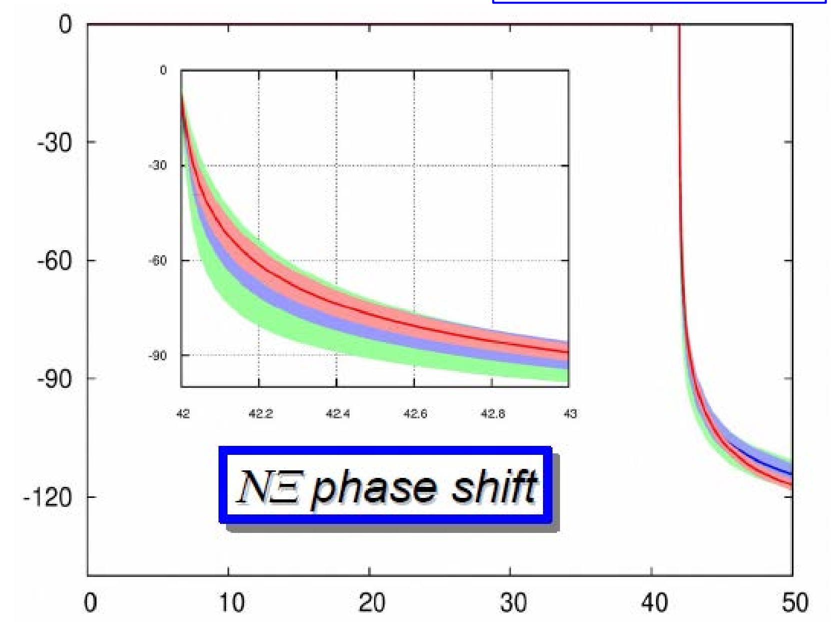


(400conf x 4rot x 28src, t=11)

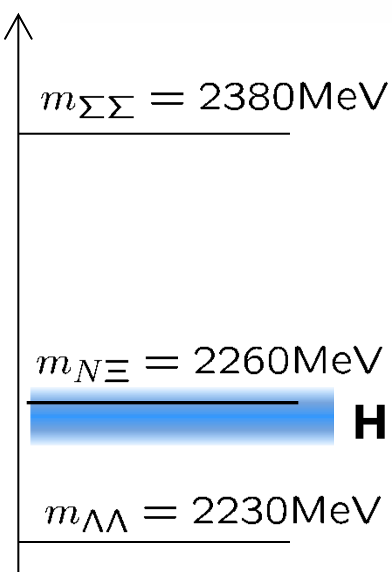
ΛΛ, NΞ (effective) 2x2 coupled channel analysis

Preliminary





(t=9,10,11)



H-resonance (?)

A Resonant Dihyperon (?)

pole analysis on going

➔ **J-PARC experiment (E42)**

N.B. t-dep should be checked;
single m_B has ~3% sys @ t=10

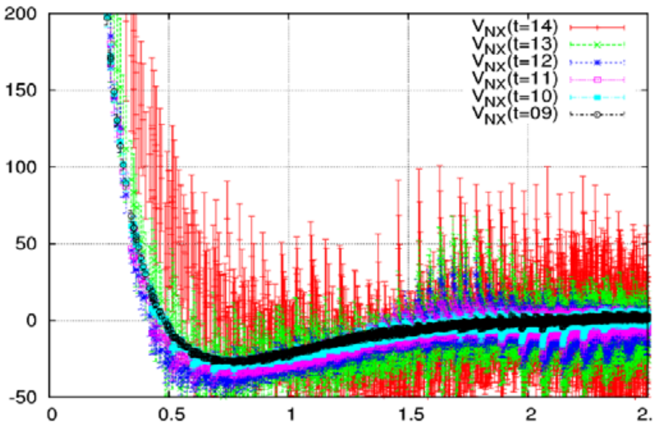
[K. Sasaki]

NΞ-Potentials

[K. Sasaki]

⇔ Ξ–hypernuclei

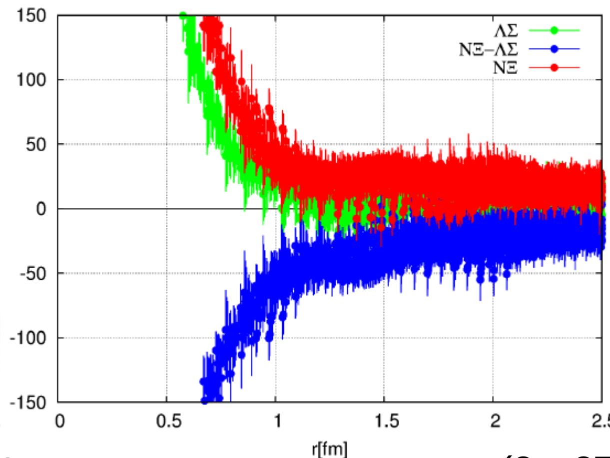
NΞ (I=0, $^3S_1$)



(8a)

Attractive

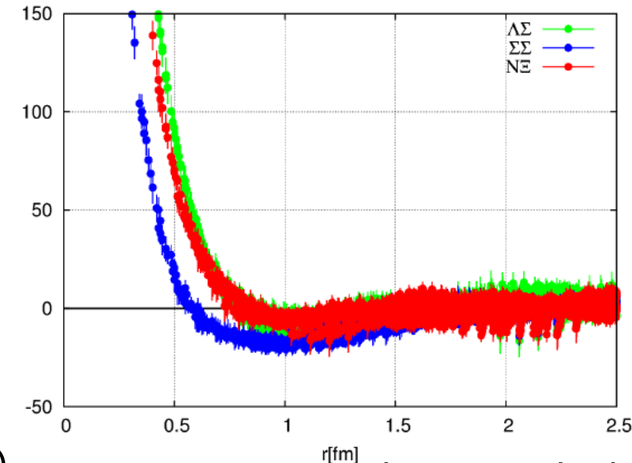
NΞ–ΛΣ (I=1, $^1S_0$)



(8s, 27)

Repulsive

NΞ–ΛΣ–ΣΣ (I=1, $^3S_1$)



(8a, 10, 10bar)

Attractive

(ΛΛ–NΞ–ΣΣ (I=0, $^1S_0$))

Is interaction net attractive ? Stay tuned !

(200conf x 4rot x 20src, t=10)

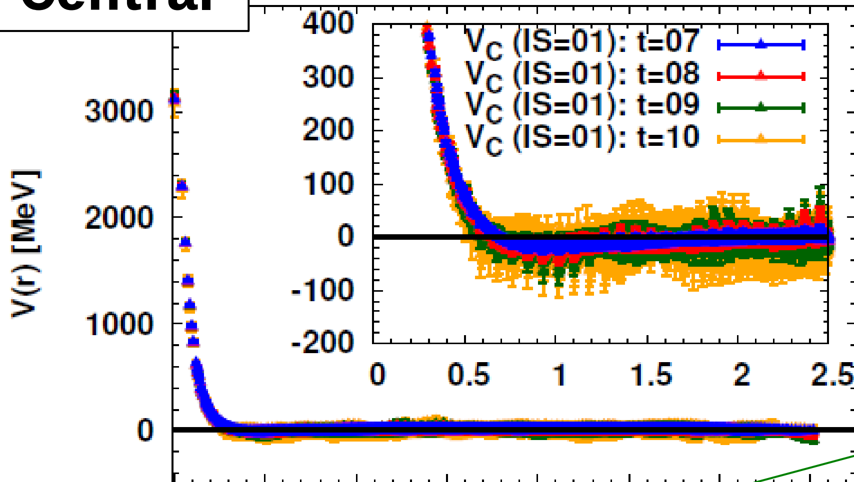
NN system (S = 0)

NN system ($^3S_1$-$^3D_1$)

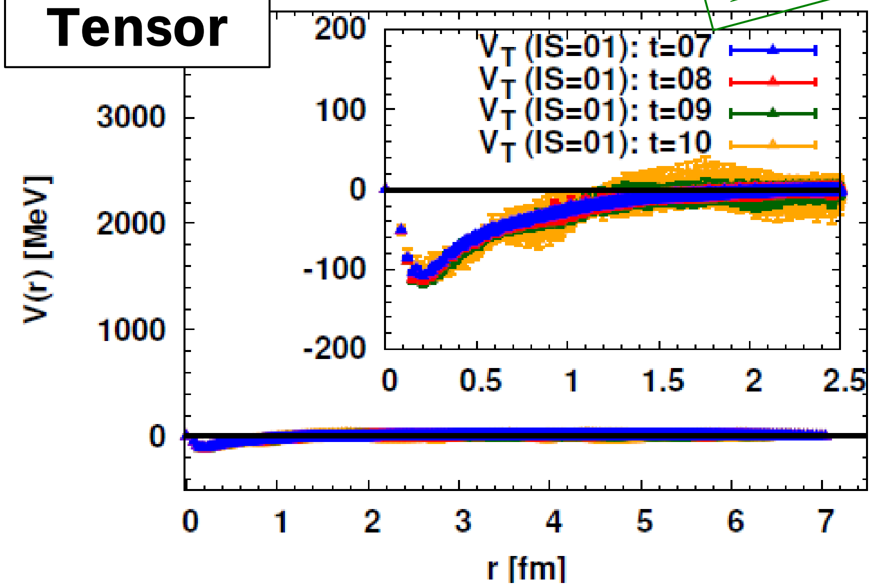
Potentials

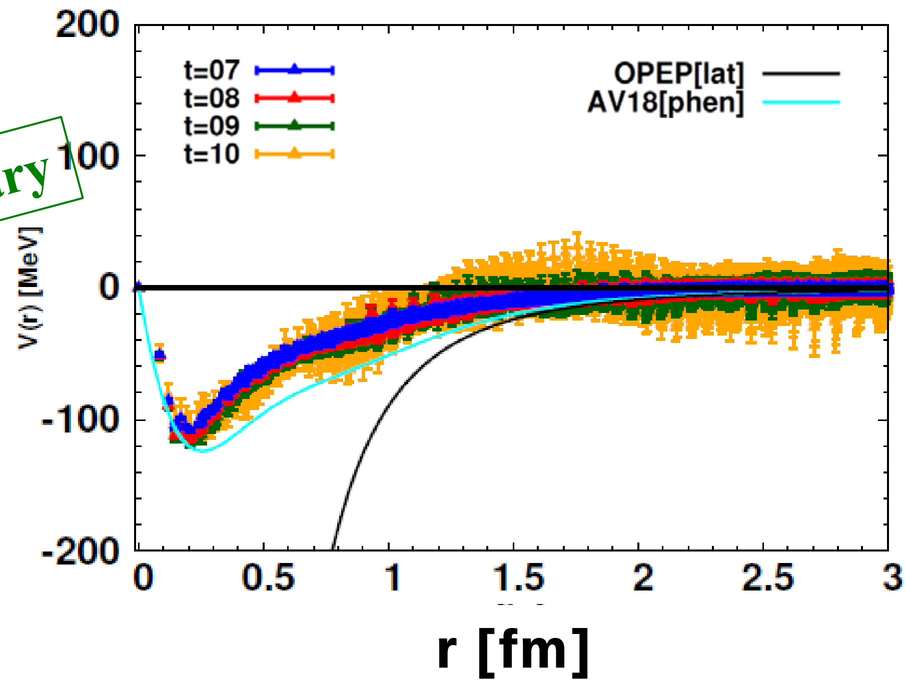
- **Vc: repulsive core + long-range attraction**
- **Vt: strong tensor force !**

Central



Tensor



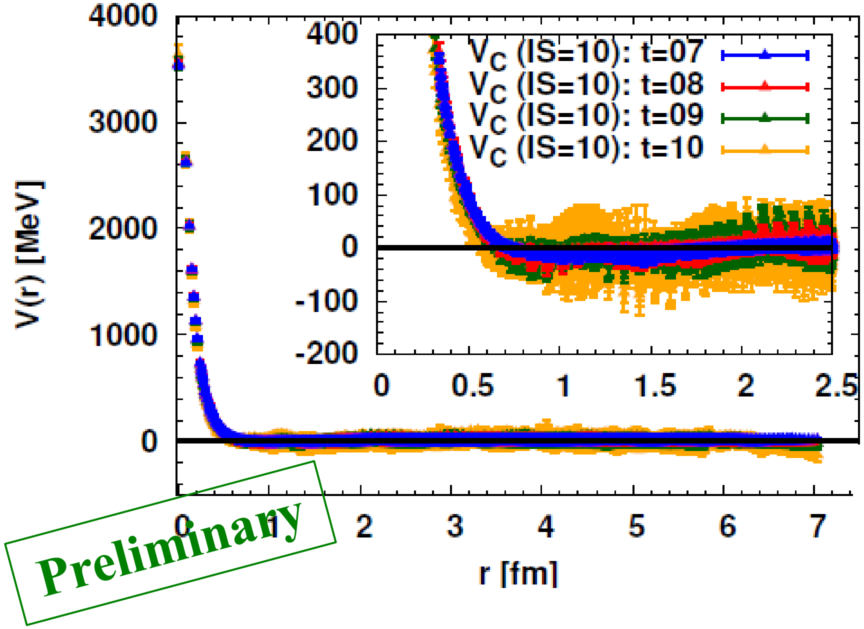


m(eff) for single N: ~2-4% sys err for t = 8-10

(400conf x 4rot x 48src)

NN system ($^1S_0$)

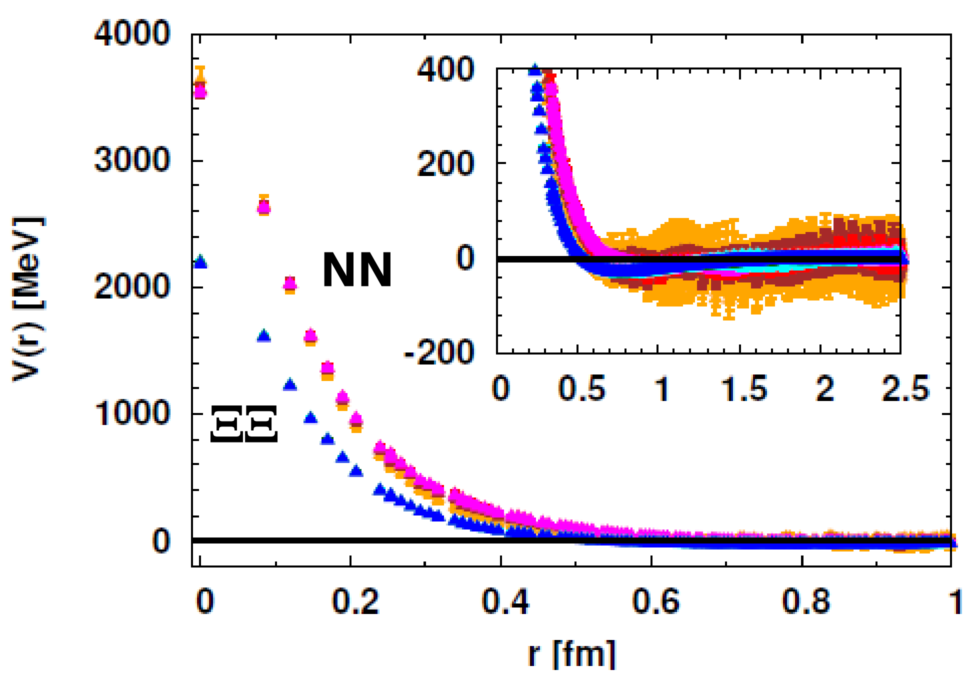
Potentials



- **Vc: repulsive core**
  + long-range attraction

The effect of SU(3)f breaking

NN($^1S_0$) and ΞΞ($^1S_0$) : 27-plet



Repulsive core enhanced
for lighter quark mass ? ←→ OGE ?

N.B. Sys error in NN may be underestimated

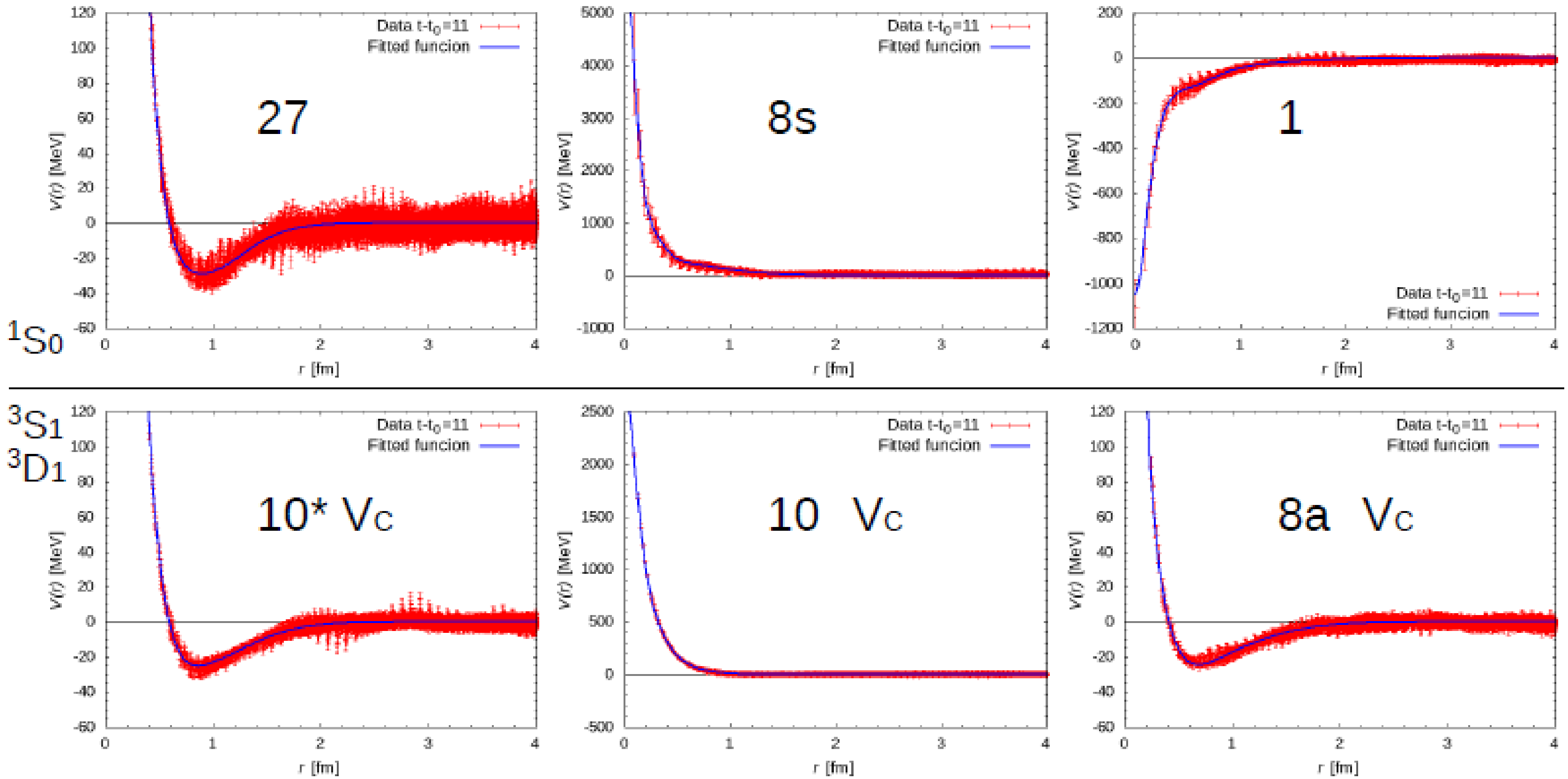
(400conf x 4rot x 48src)

Impact on dense matter

S=-2 interactions suitable to grasp whole NN/YN/YY interactions

Central Force in Irrep-base (diagonal)

$$8 \times 8 = \underbrace{27 + 8s + 1}_{^1S_0} + \underbrace{10^* + 10 + 8a}_{^3S_1,\ ^3D_1}$$



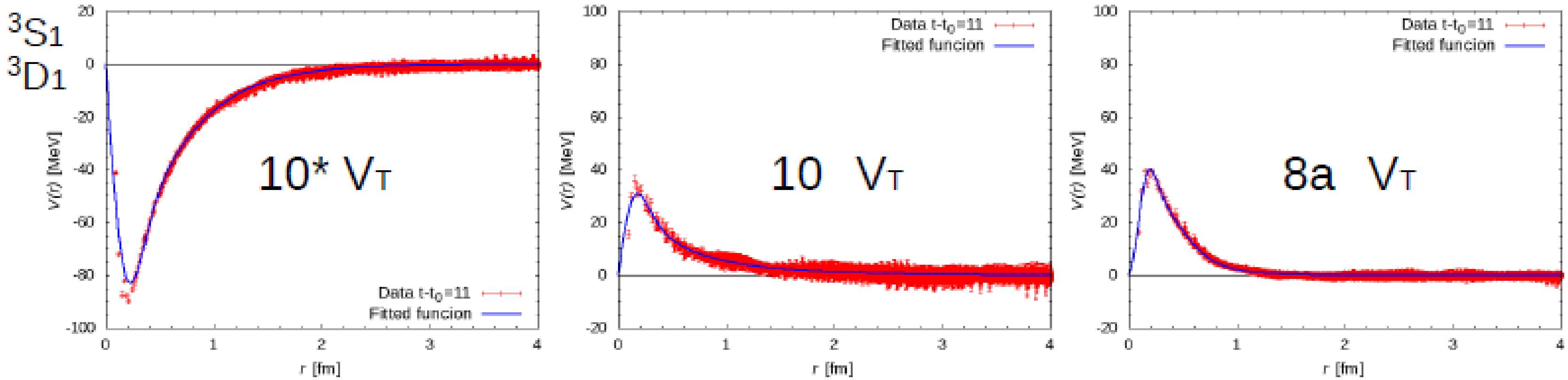
(off-diagonal component is small)

[K. Sasaki]

S=-2 interactions suitable to grasp whole NN/YN/YY interactions

Tensor Force in Irrep-base (diagonal)

$$8 \times 8 = \underbrace{27 + 8_s + 1}_{^1S_0} + \underbrace{10^* + 10 + 8_a}_{^3S_1,\ ^3D_1}$$



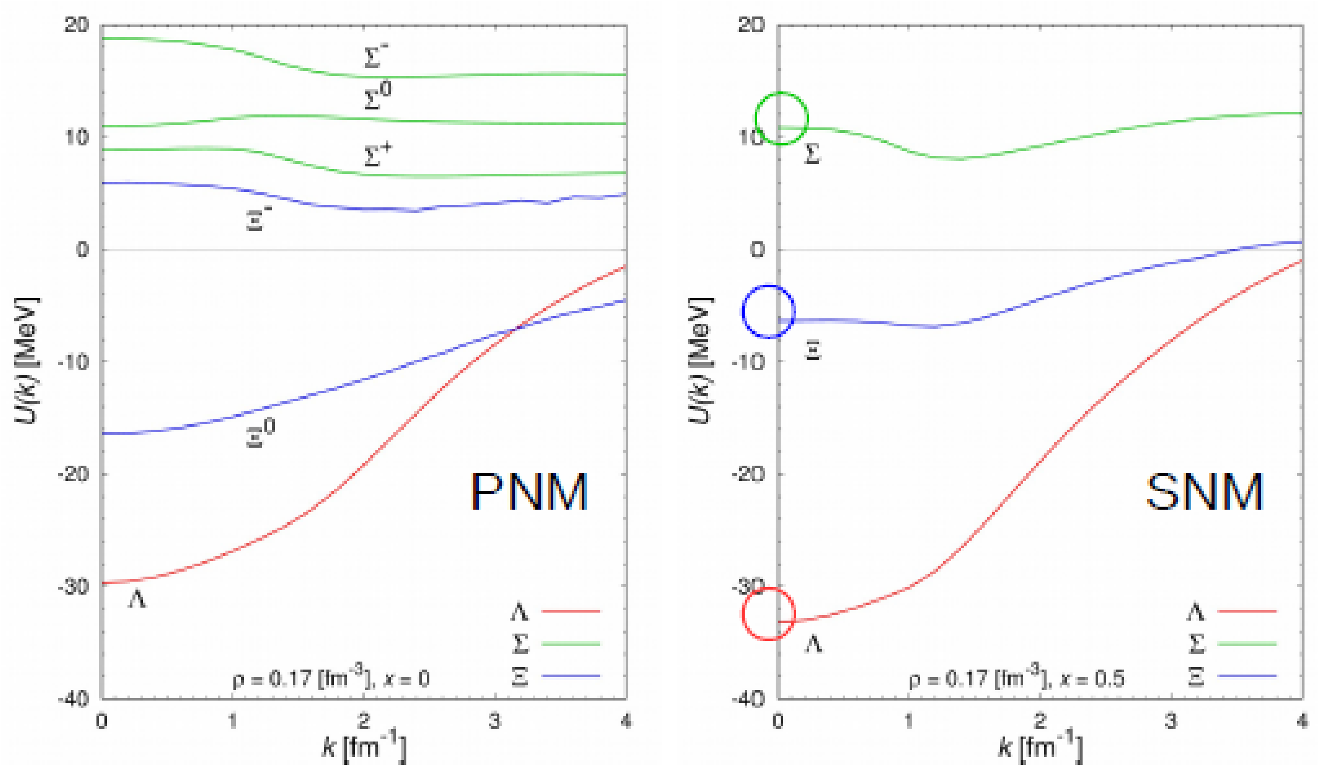
➔ LQCD YN/YY forces are used to study nuclear matter

(off-diagonal component neglected)

Brueckner-Hartree-Fock (BHF)
w/ Phen NN-forces (AV18) + LQCD YN/YY-forces

➔ single-particle energy of hyperon in nuclear matter

Hyperon single-particle potentials



@ρ=0.17 [fm^{-3}]

Preliminary

- obtained by using YN,YY forces form QCD.
- Results are compatible with experimental suggestion.

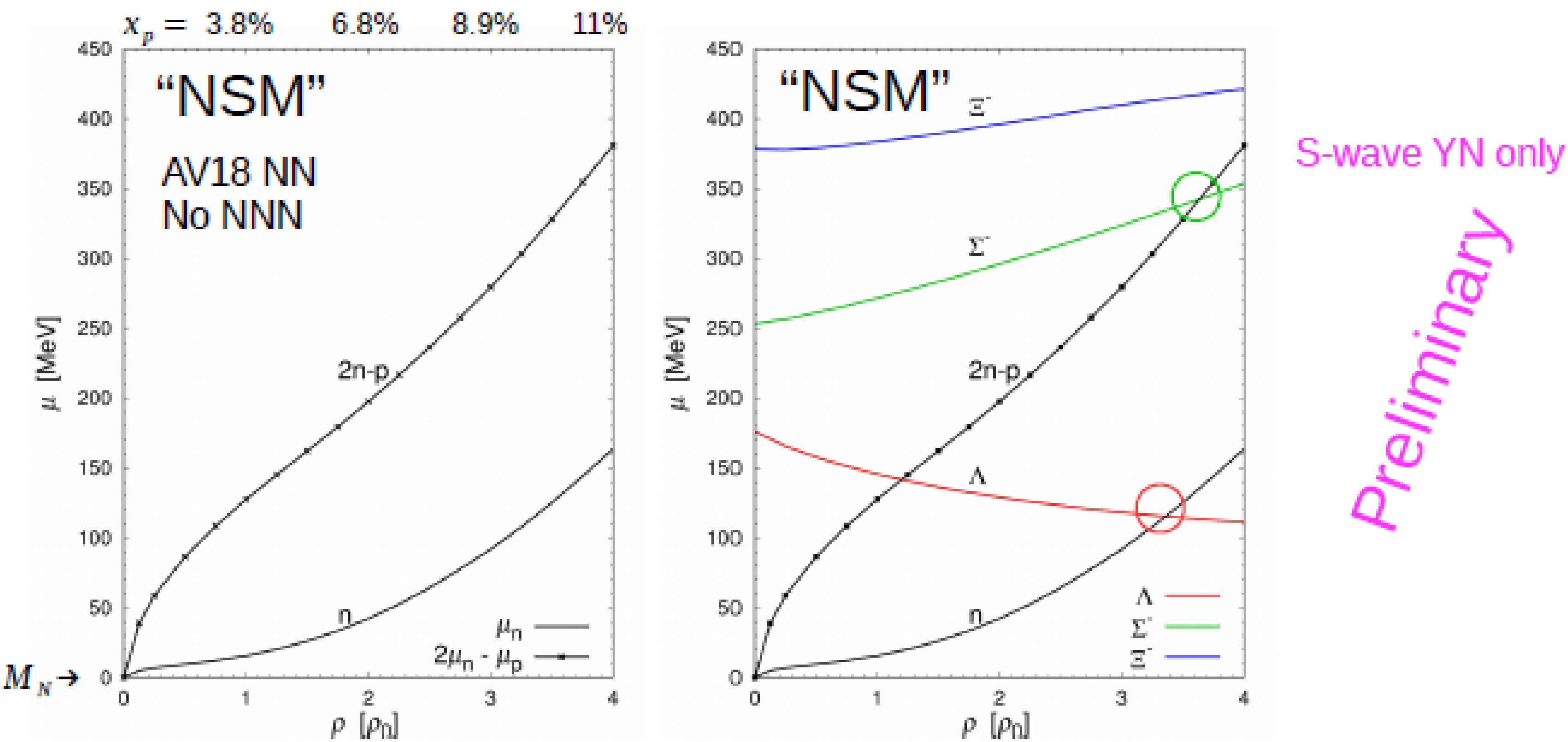
$$U_\Lambda^{\text{Exp}}(0) \simeq -30\,, \quad U_\Xi(0)^{\text{Exp}} \simeq -10\,, \quad U_\Sigma^{\text{Exp}}(0) \geq +20 \quad [\text{MeV}]$$

attraction   attraction small   repulsion

1

[T. Inoue]

Hyperon onset (just for a demonstration)



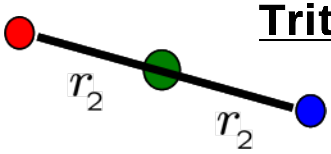
- "NSM" is matter w/ n, p, e, μ under β-eq and Q=0.

[Missing]
P-wave / LS forces
3-baryon forces

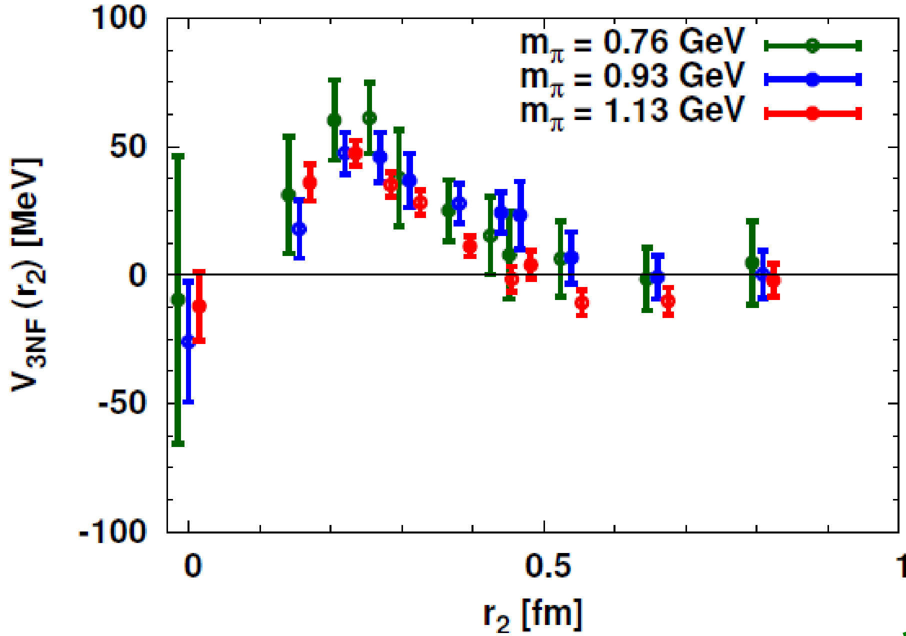
[T. Inoue]

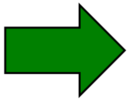
4

3N-forces (3NF)

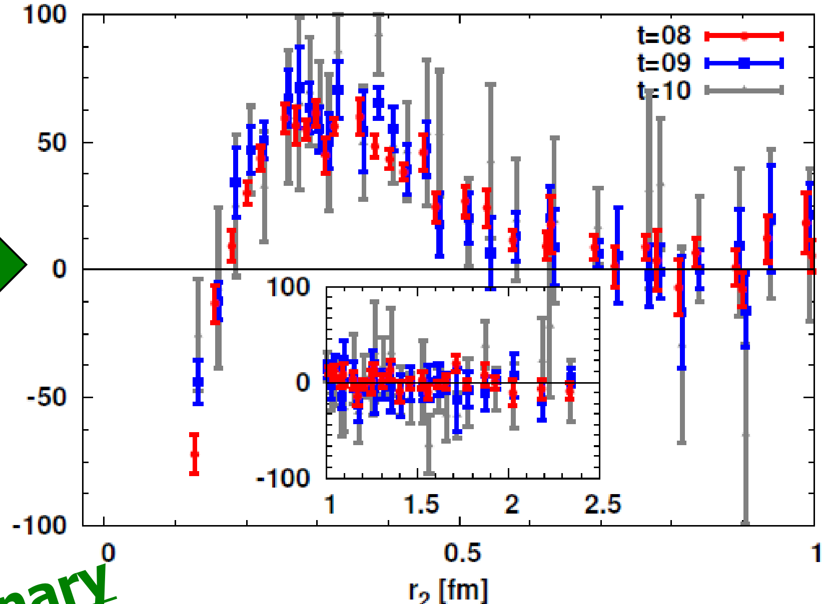


Nf=2, mπ=0.76-1.1 GeV





Nf=2+1, mπ=0.51 GeV



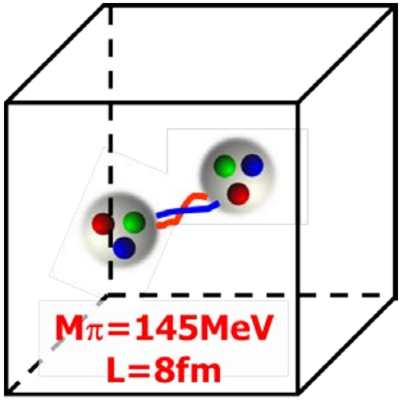
Preliminary

Magnitude of 3NF is similar for all masses
Range of 3NF tend to get longer (?) for m(pi)=0.5GeV

Kernel: ~50% efficiency achieved !

Summary

- Baryon forces: Bridge between particle/nuclear/astro-physics
- HAL QCD method crucial for a reliable calculation
  - Direct method suffers from excited state contaminations
- The 1st LQCD for Baryon Interactions at ~ phys. point
  - m(pi) ~= 145 MeV, L ~= 8fm, 1/a ~= 2.3GeV
  - Central/Tensor forces for NN/YN/YY in P=(+) channel



Nuclear Physics from LQCD
New Era is dawning !

- Prospects
  - Exascale computing Era ~ 2020
  - LS-forces, P=(-) channel, 3-baryon forces, etc., & EoS