Nuclear Physics from Lattice QCD

Takumi Doi
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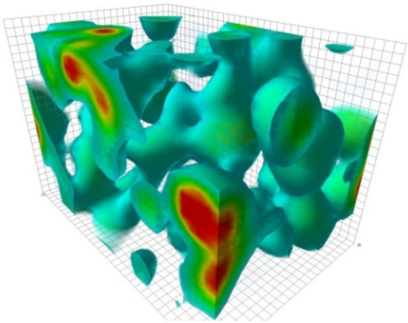
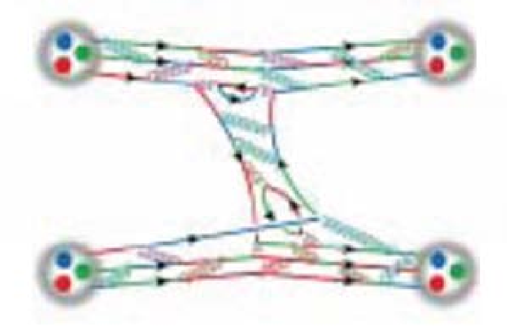
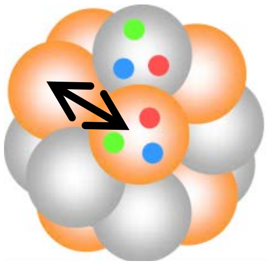
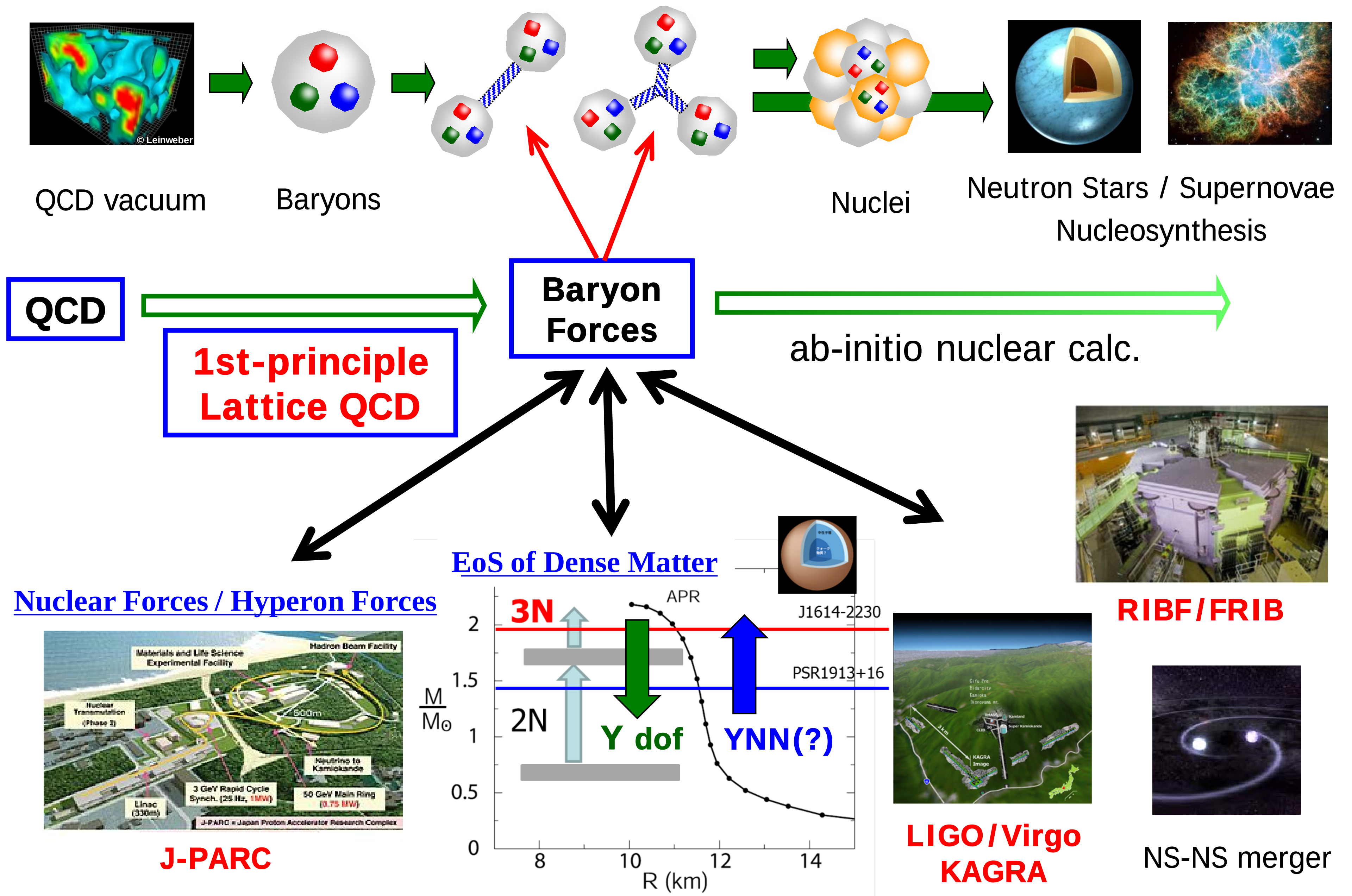


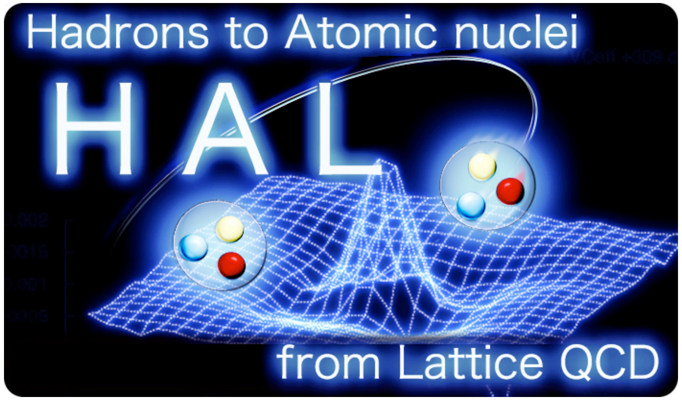




The Odyssey from Quarks to Universe



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



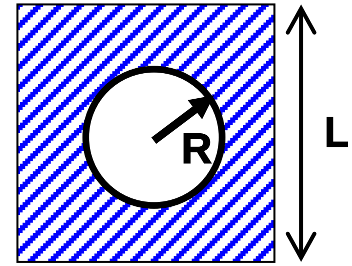
S. Aoki, T. Aoyama, D. Kawai,
T. Miyamato, K. Sasaki (YITP)
T. Doi, T. M. Doi, S. Gongyo,
T. Hatsuda, T. Iritani (RIKEN)
F. Etminan (Univ. of Birjand)
Y. Ikeda, N. Ishii, K. Murano,
H. Nemura (RCNP)
T. Inoue (Nihon Univ.)

[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

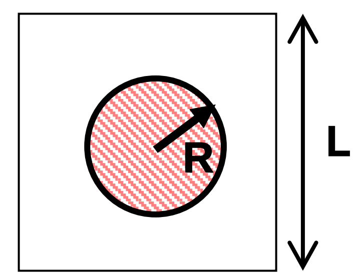
CP-PACS Coll., PRD71(2005)094504

Extended to multi-particle systems

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

- Consider the wave function at "interacting region"

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



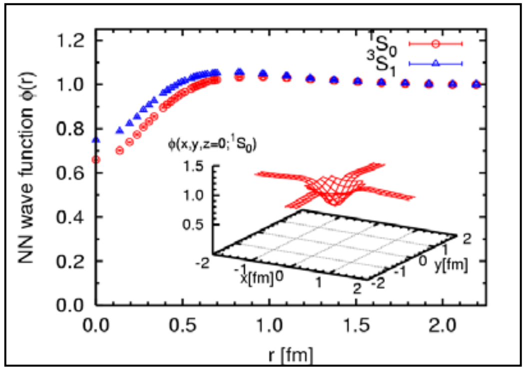
  – U(r,r'): faithful to the phase shift by construction
    - U(r,r'): E-independent, while non-local in general
      – Non-locality ➔ derivative expansion

Aoki-Hatsuda-Ishii PTP123(2010)89

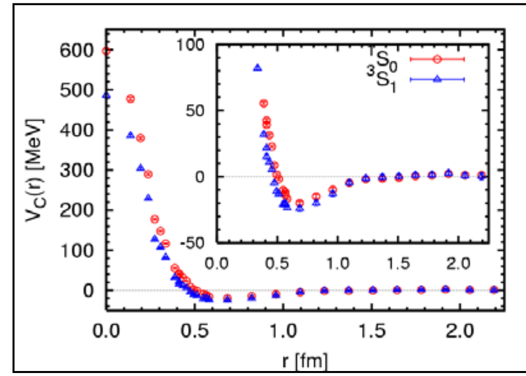
HAL QCD method

Lattice QCD

NBS wave func.



Lat Baryon Force



$$\psi_{NBS}(\vec{r}) = \langle 0|N(\vec{r})N(\vec{0})|N(\vec{k})N(-\vec{k}), in\rangle$$
$$\simeq A_k \sin(kr - l\pi/2 + \delta_l(k))/(kr)$$

(at asymptotic region)

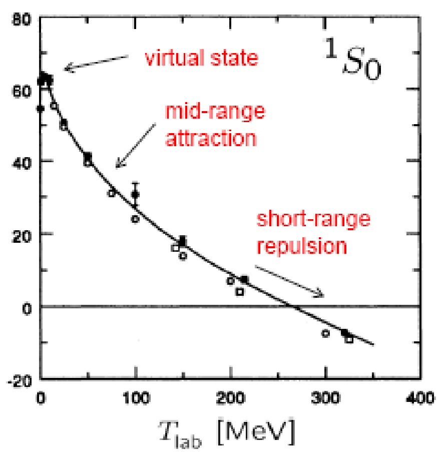
$$(k^2/m_N - H_0)\,\psi(\vec{r}) = \int d\vec{r}\,' U(\vec{r},\vec{r}\,')\psi(\vec{r}\,')$$

E-indep (& non-local) Potential:
Faithful to phase shifts

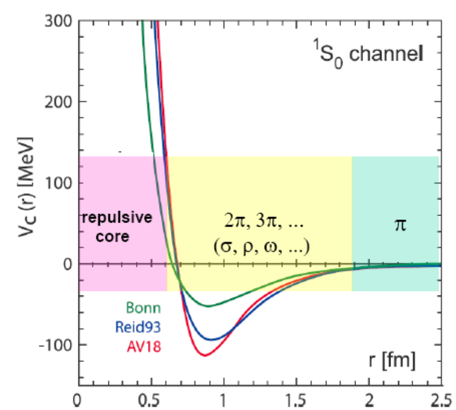
Analog to …

Scattering Exp.

Phase shifts



Phen. Potential

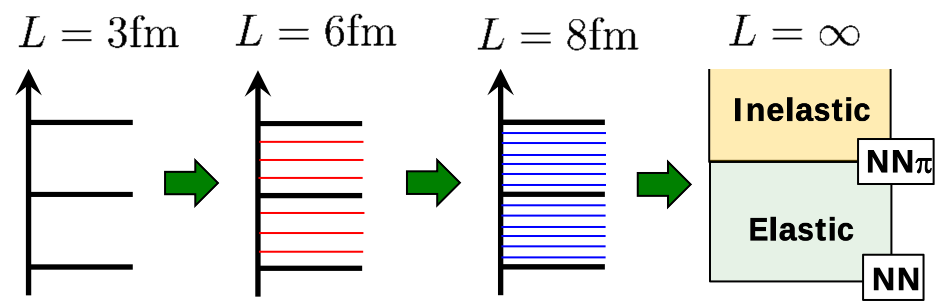


The Challenge in multi-baryons on the lattice

Existence of elastic scatt. states

➔ (almost) No Excitation Energy

➔ LQCD method based on G.S. saturation impossible



Signal/Noise issue

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

Parisi('84), Lepage('89)

L=8fm @ physical point $(E_1 - E_0) \simeq 25\mathrm{MeV} \Longrightarrow t > 10\mathrm{fm}$

$$S/N \sim 10^{-32}$$

Naïve plateau fitting at t ~ 1fm is unreliable ("mirage" of true signal)

T. Iritani et al. (HAL) JHEP1610(2016)101
T. Iritani et al. (HAL) PRD96(2017)034521

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

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

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

🡐 Many states contribute

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

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

. . .

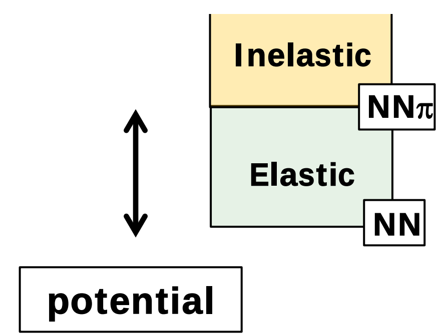
New t-dep HAL method

All equations can be combined as

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

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

[Exponential Improvement]



The Challenge in multi-baryons on the lattice

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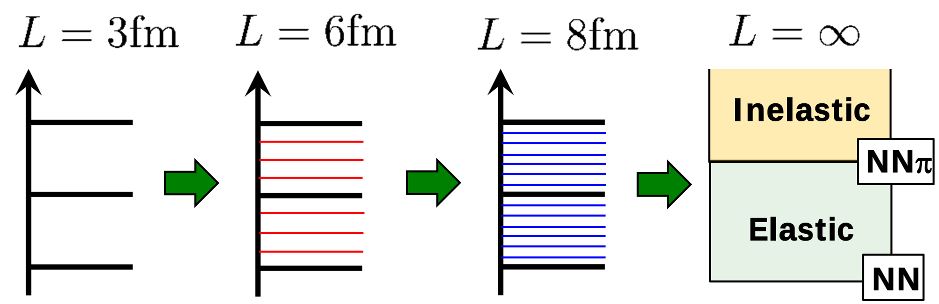


QCD

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

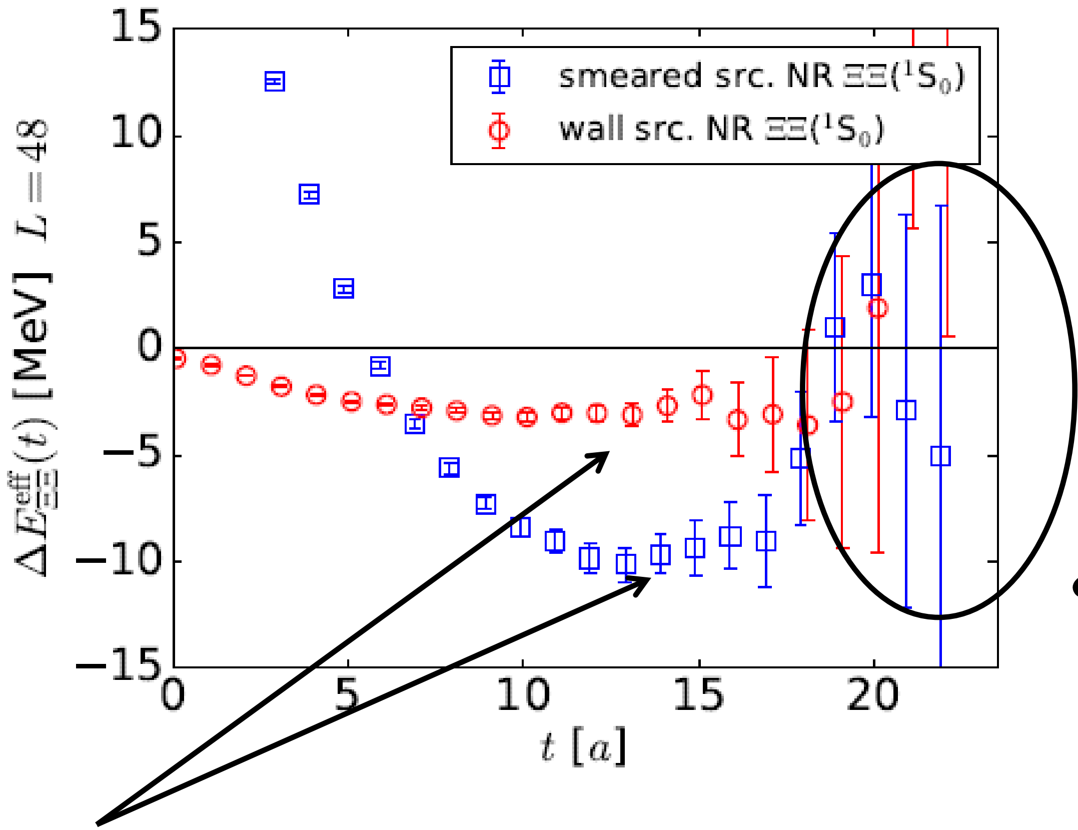
Savage et al. (NPL Coll.)
Yamazaki et al.

Example of failure of the direct method

$$R(t) = \sum_{\vec{r}} \sum_{\vec{x}} \langle 0 | B(\vec{r}+\vec{x},t) B(\vec{x},t) \overline{\mathcal{J}_{\rm src}(0)} | 0 \rangle / \{G_B(t)\}^2$$

T. Iritani et al. (HAL)
JHEP1610(2016)101

Physics should NOT depend on source op.



$\Xi\Xi$ ($^1S_0$)

(L=4.3fm)

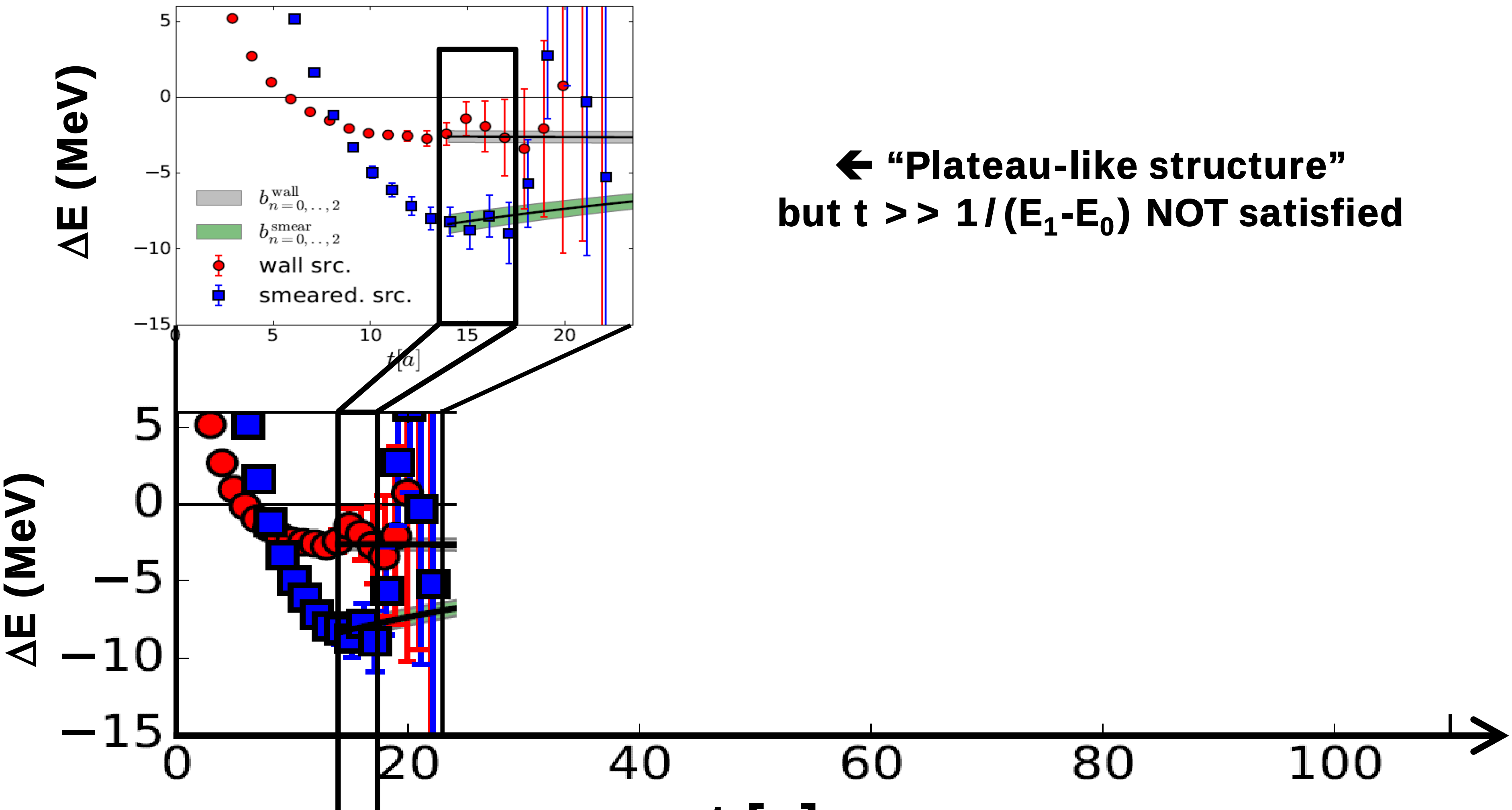
S/N ~ exp[- α t]
(a la Lepage)

Wall and Smeared are Inconsistent:

one cannot judge which (or neither) is reliable

“Anatomy” of sympton in direct method

T. Iritani (HAL Coll.), arXiv:1710.06147



🡐 “Plateau-like structure”
but t >> 1/(E$_1$-E$_0$) NOT satisfied

“fake plateaux”
at t ~ 1fm

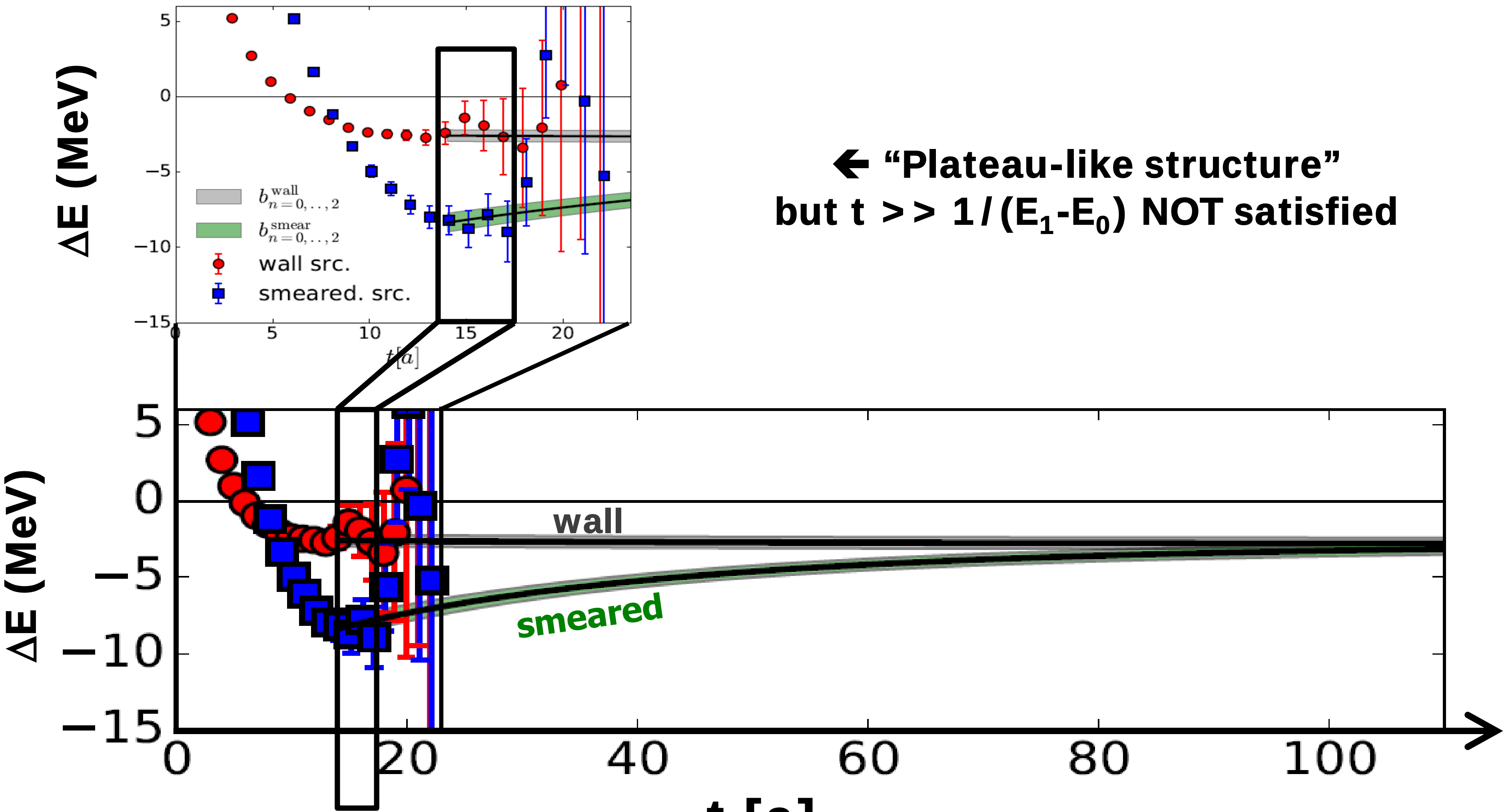
HAL method is crucial !

“real plateau”
at t ~ 10fm

(E$_1$-E$_0$=50MeV)

“Anatomy” of sympton in direct method

T. Iritani (HAL Coll.), arXiv:1710.06147



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

“fake plateaux” at t ~ 1fm

“real plateau” at t ~ 10fm

(E_1-E_0=50MeV)

HAL method is crucial !

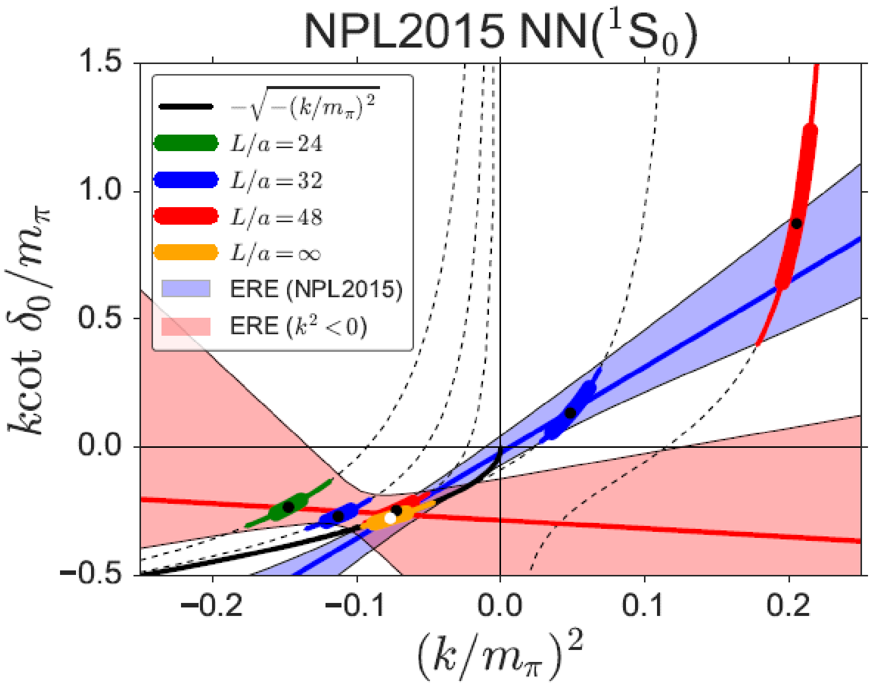
“Sanity Check” for results from direct method

T. Iritani et al. (HAL Coll.) PRD96(2017)034521

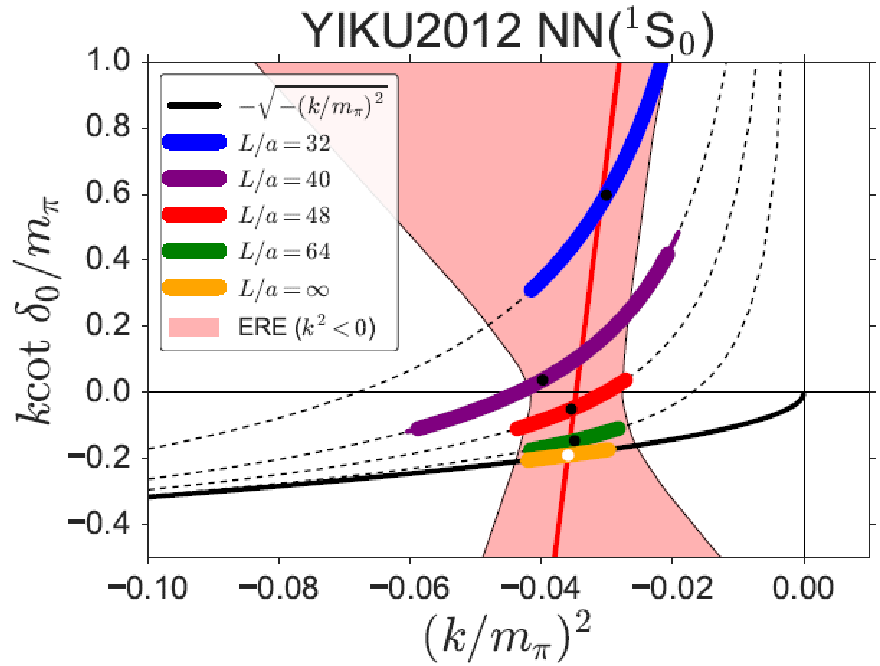
$k \cot \delta(k)$ vs k^2 plot

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

Data from NPL Coll. (‘15)



Data from Yamazaki et al (‘12)



Inconsistent ERE

Unphysical pole residue

FAILED

Singular behaviors

$r \simeq \pm\infty$

The fate of the direct method (check on NN)

T. Iritani et al. (HAL Coll.) PRD96(2017)034521

	$NN(^1S_0)$				$NN(^3S_1)$			
Data	Source independence	Sanity check (i)	(ii)	(iii)	Source independence	Sanity check (i)	(ii)	(iii)
YKU2011 [24]	†	No	No	*	†	No	No	*
YIKU2012 [25]	No	†	No	*	No	†	No	*
YIKU2015 [26]	†	†	No	*	†	†	No	No
NPL2012 [27]	†	†	No	*	†	†	*	*
NPL2013 [28, 29]	No	*	*	No	No	*	*	?
NPL2015 [30]	†	No	*	No	†	No	*	No
CalLat2017 [31]	No	?	*	No	No	?	*	No

All data for NN by the direct method fail these “minimum” tests so far

➔ Studies w/ the variational method are mandatory

- **Outline**
  - Introduction
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  - Results at physical quark masses
    - Nuclear forces and Hyperon forces
    - Impact on dense matter
  - Summary / Prospects

- Baryon Forces from LQCD Ishii-Aoki-Hatsuda (2007)
- Exponentially better S/N Ishii et al. (2012)
- Coupled channel systems Aoki et al. (2011,13)

[Theory] = HAL QCD method

Baryon Interactions at Physical Point

[Hardware]

= K-computer [10PFlops]

+ FX100 [1PFlops] @ RIKEN
+ HA-PACS [1PFlops] @ Tsukuba

- HPCI Field 5 "Origin of Matter and Universe"

[Software]

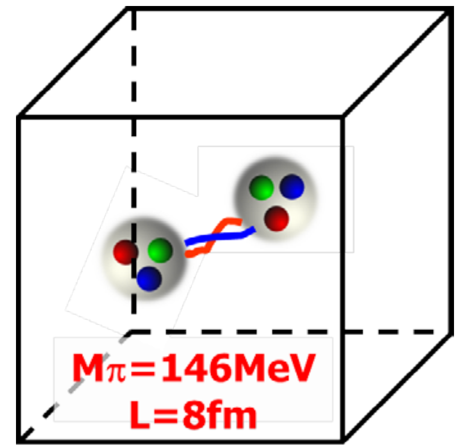
= Unified Contraction Algorithm

- Exponential speedup Doi-Endres (2013)

$$^3\mathrm{H}/^3\mathrm{He} \quad : \quad \times 192$$
$$^4\mathrm{He} \quad : \quad \times 20736$$
$$^8\mathrm{Be} \quad : \quad \times 10^{11}$$

Lattice QCD Setup

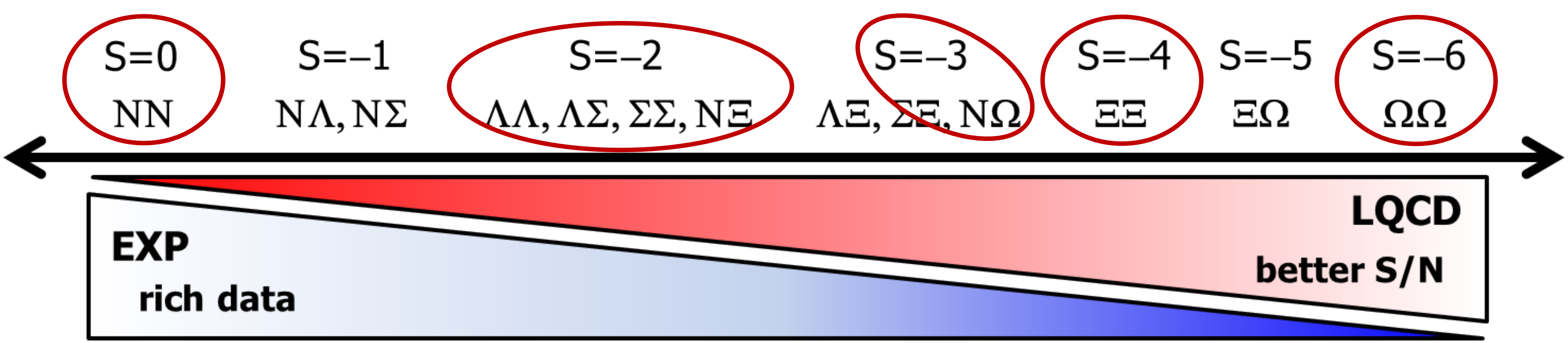
- **Nf = 2 + 1 gauge configs**
  - clover fermion + Iwasaki gauge w/ stout smearing
  - V=$(8.1\text{fm})^4$, a=0.085fm (1/a = 2.3 GeV)
  - m(pi) ~= 146 MeV, m(K) ~= 525 MeV
  - #traj ~= 2000 generated



PACS Coll., PoS LAT2015, 075

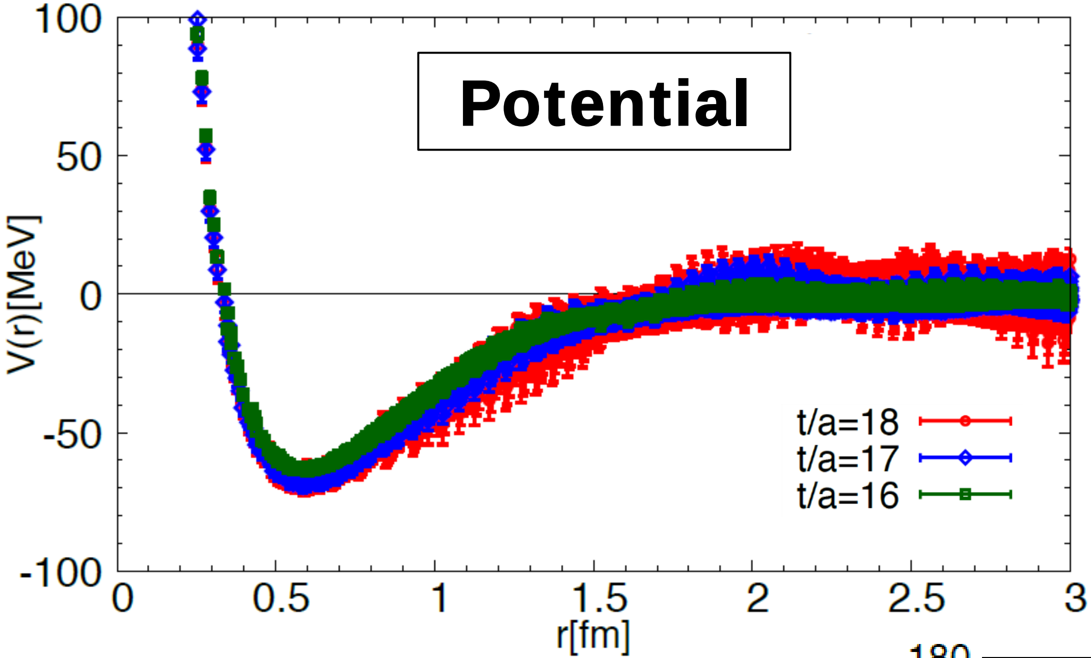
- **Measurement**
  - All of NN/YN/YY for central/tensor forces in P=(+) (S, D-waves)

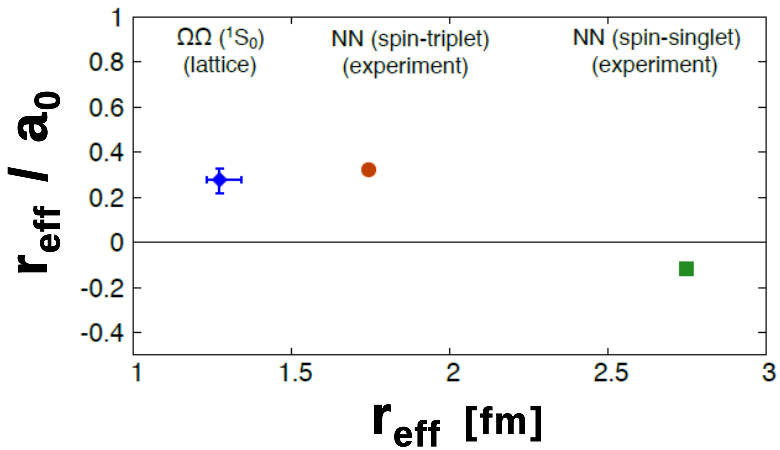
Predictions for Hyperon forces



ΩΩ system ($^1S_0$)

(The "most strange" dibaryon system)

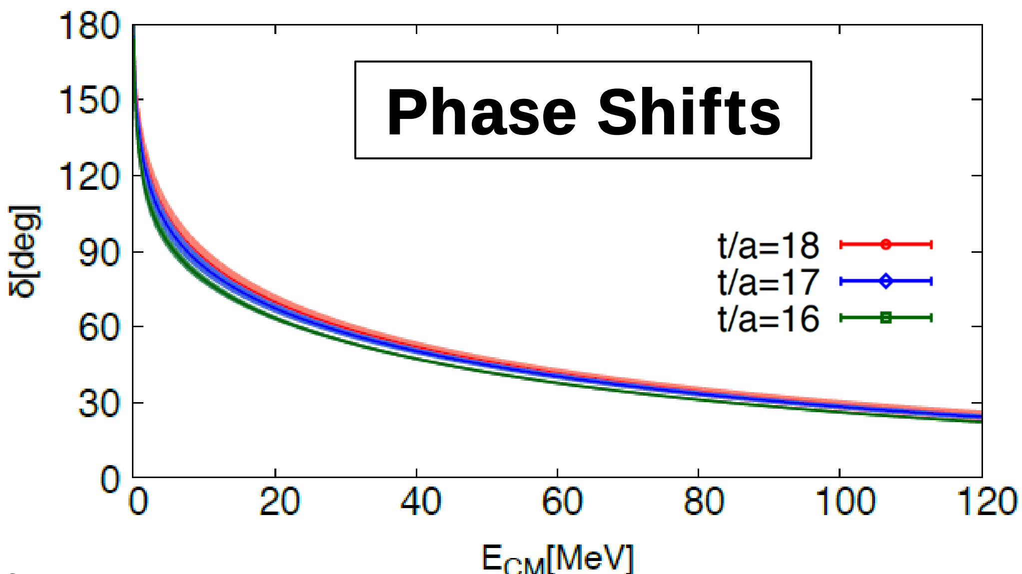




Strong Attraction

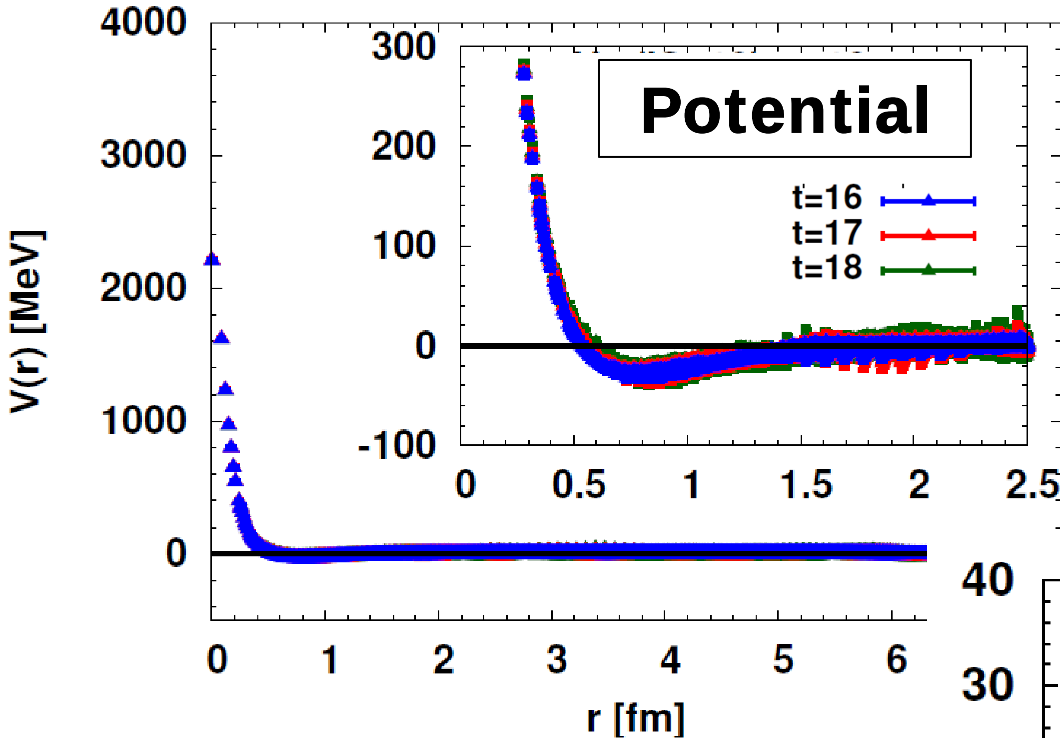
➔ **Vicinity of bound / unbound**

[~ Unitary limit]



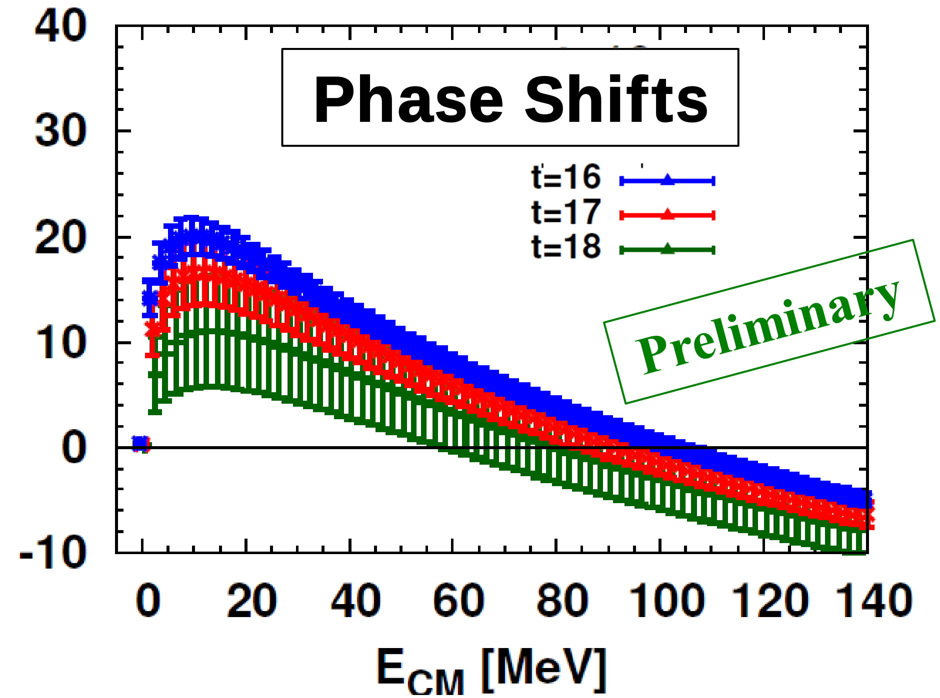
S. Gongyo et al. (HAL Coll.), arXiv:1709.00654

ΞΞ system ($^1S_0$)



Flavor SU(3)-partner of dineutron

⇨ • "Doorway" to NN-forces
• Bound by SU(3) breaking ?



Strong Attraction

yet Unbound

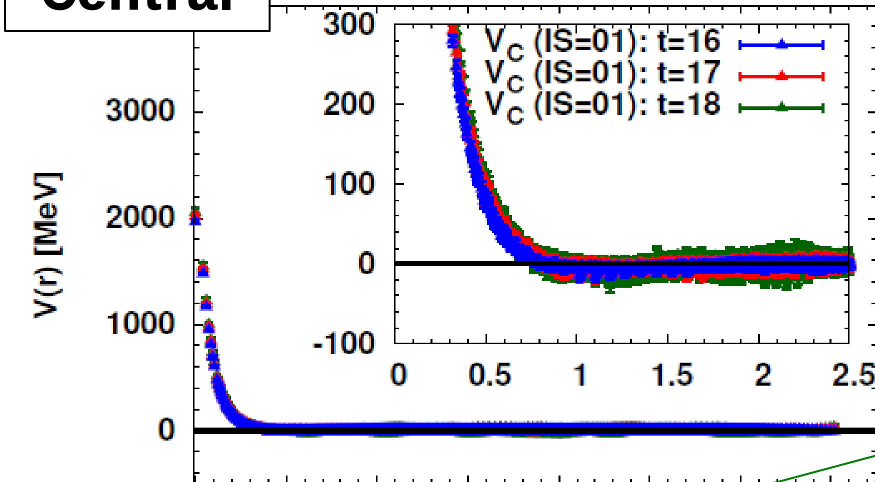
⟺ ΞΞ correlation in HIC

(2-gauss + 2-OBEP)

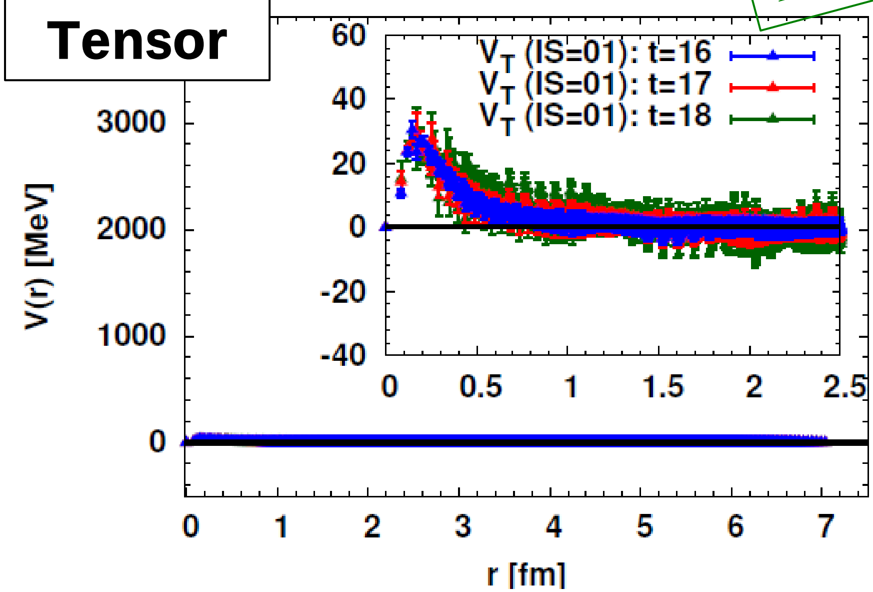
ΞΞ system ($^3S_1$-$^3D_1$)

Potentials

Central



Tensor



Preliminary

10plet ⇔ unique w/ hyperon DoF

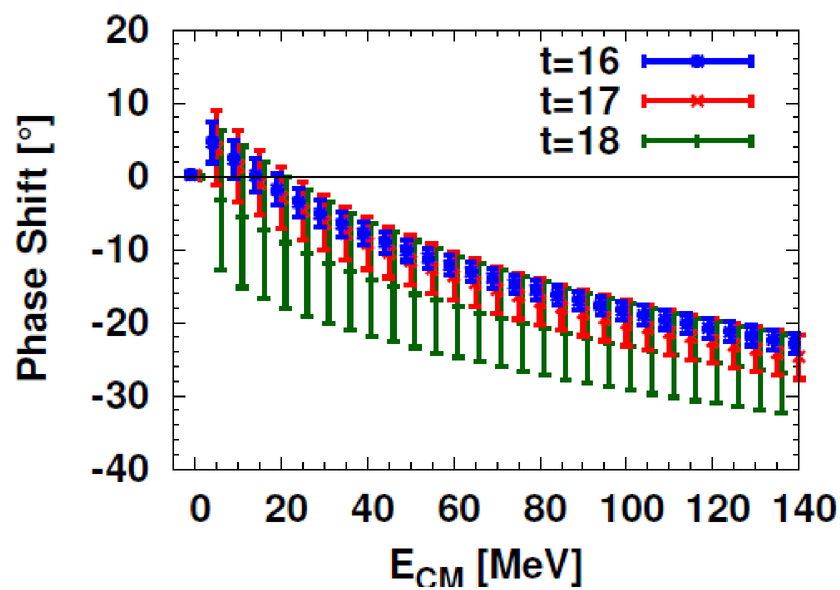
Flavor SU(3)-partner of Σ^- n

⇨ • Σ^- in neutron star ?

Central: Strong Repulsion

Tensor: Weak

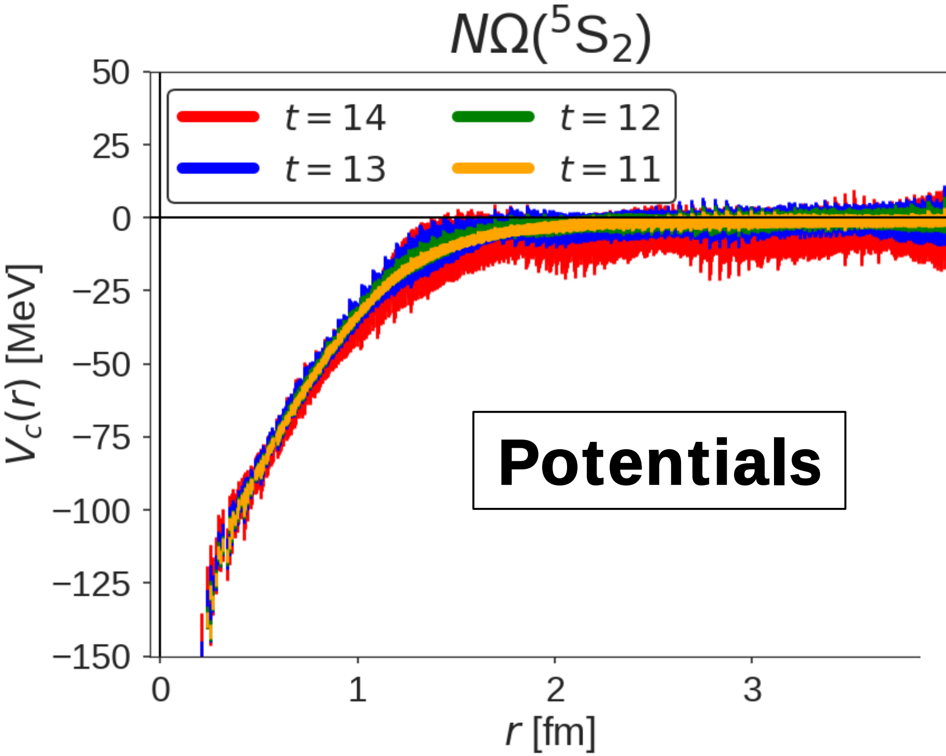
Phase Shifts (eff. $^3S_1$)



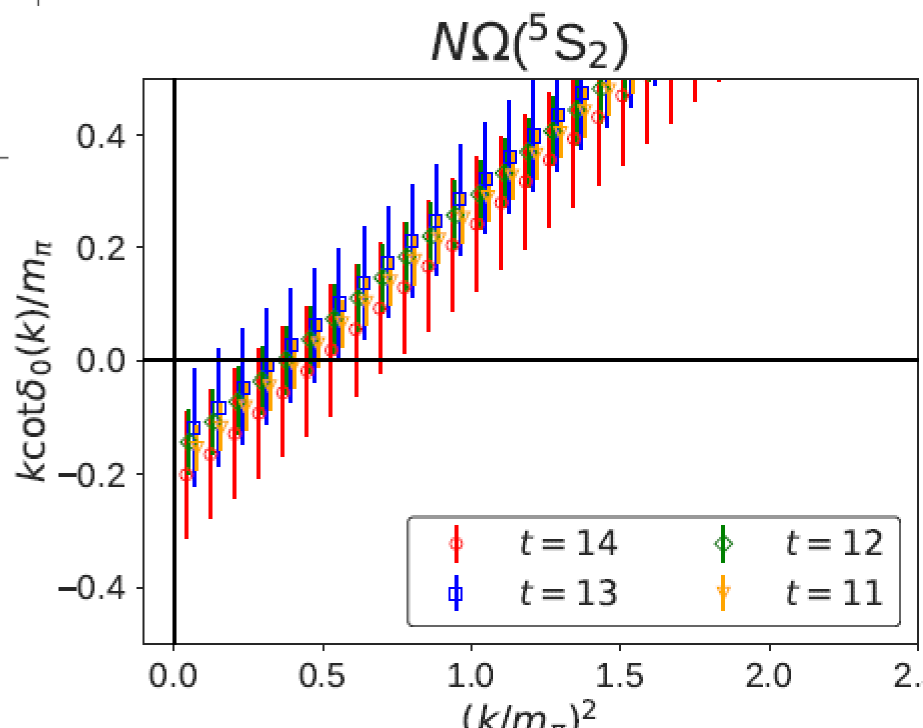
(2-gauss + 2-OBEP)

NΩ system ($^5S_2$)

preliminary



Phase Shifts



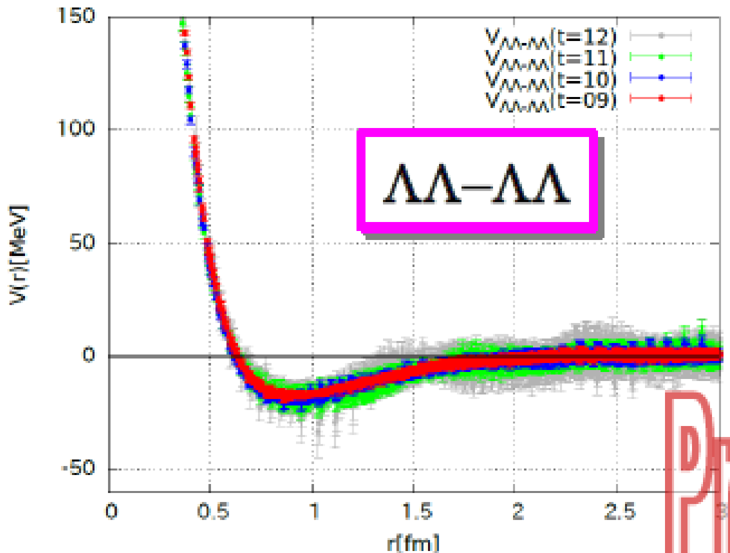
Strong Attraction

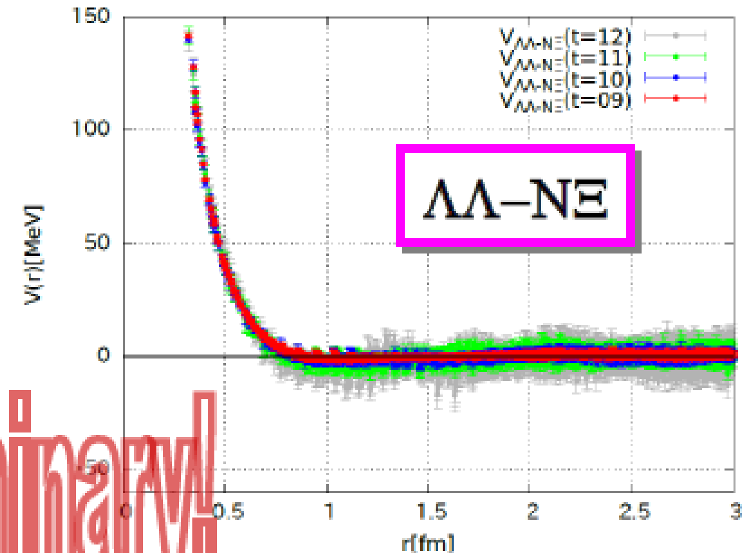
possibly "Bound"

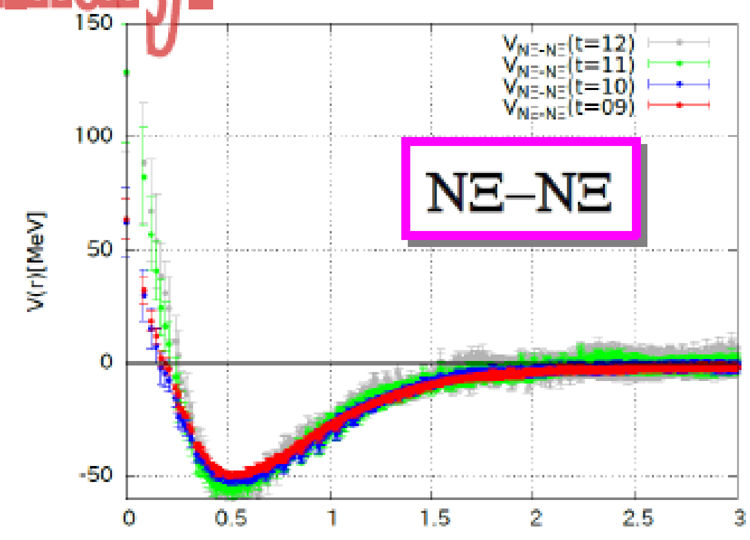
⟺ NΩ correlation in HIC

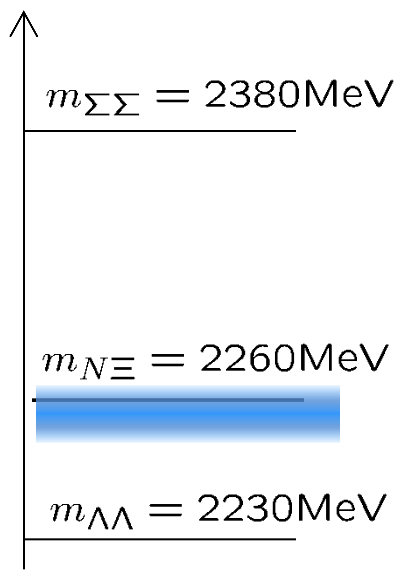
(200conf x 4rot x 48src) **[T. Iritani]**

ΛΛ, NΞ, (ΣΣ) coupled channel ➔ H-dibaryon channel







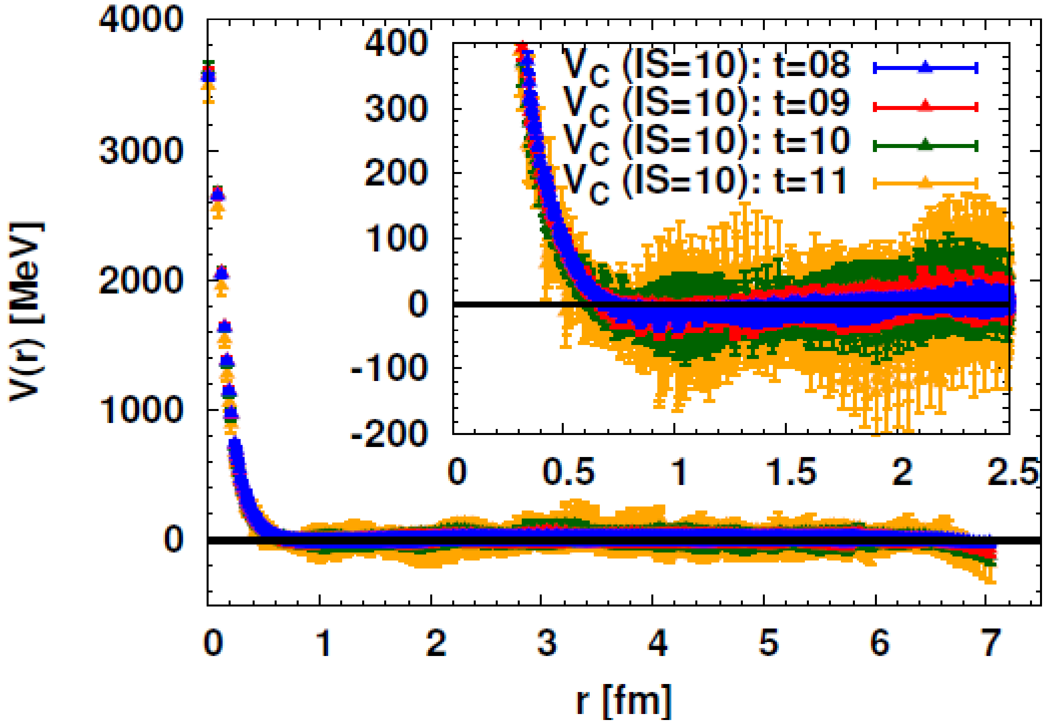


H-resonance (?)

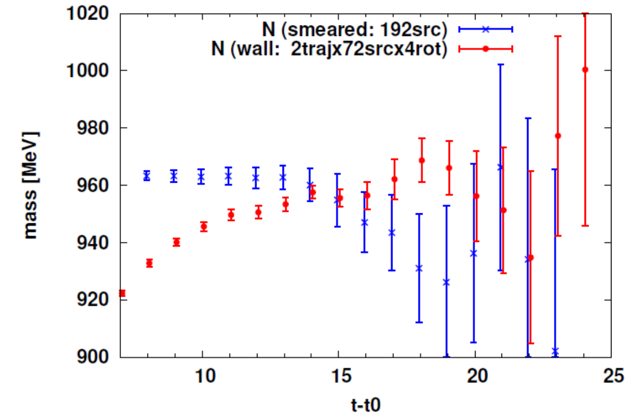
2x2 Potentials

[K. Sasaki]

Central Potential NN ($^1S_0$)



Single N

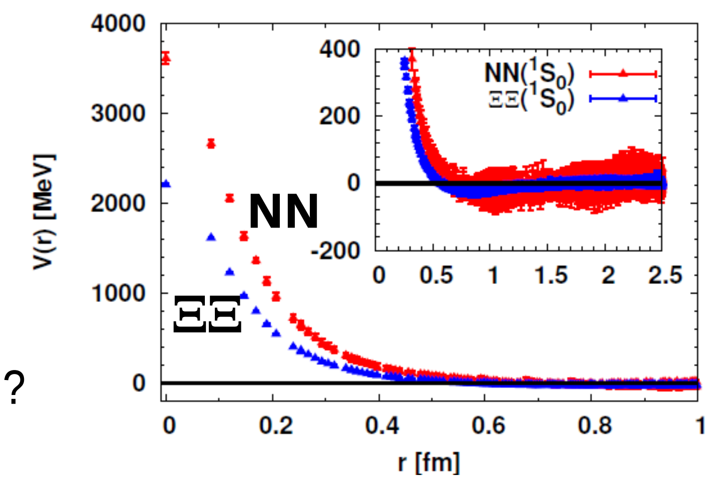


Repulsive core observed

Attraction at mid-long range

The effect of SU(3)f breaking

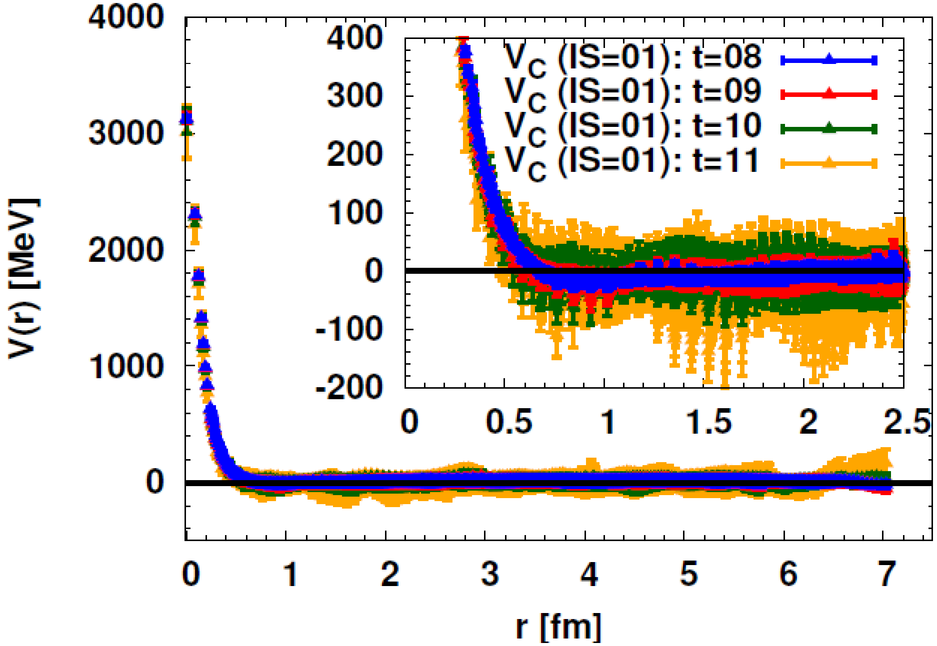
NN($^1S_0$) and ΞΞ($^1S_0$) belong to 27-plet



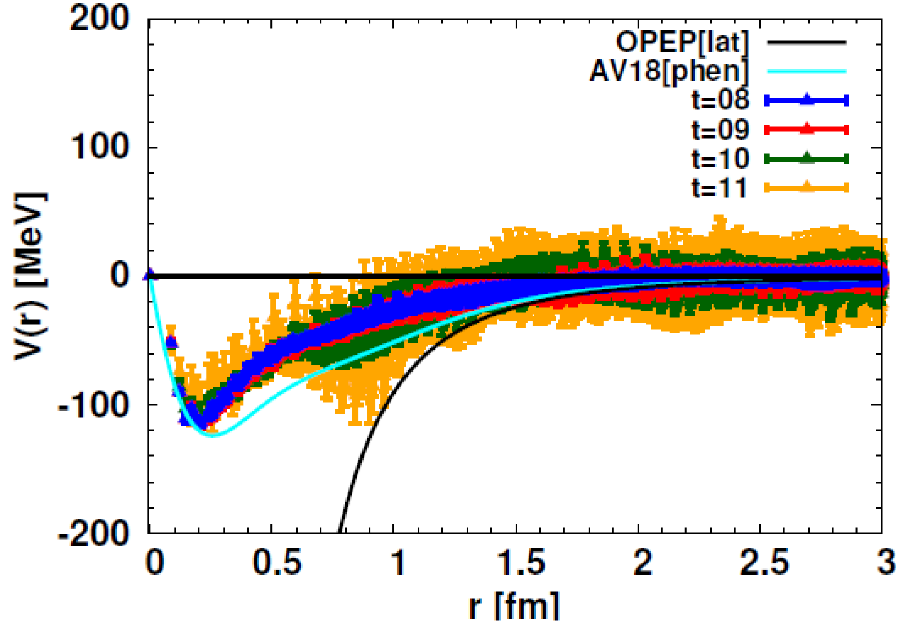
Repulsive core enhanced
for lighter quark mass ? ←→ OGE ?

Central/Tensor Potentials NN ($^3S_1$-$^3D_1$)

Central



Tensor



Repulsive core observed

Attraction at mid-long range

Strong Tensor Force is clearly visible !

preliminary

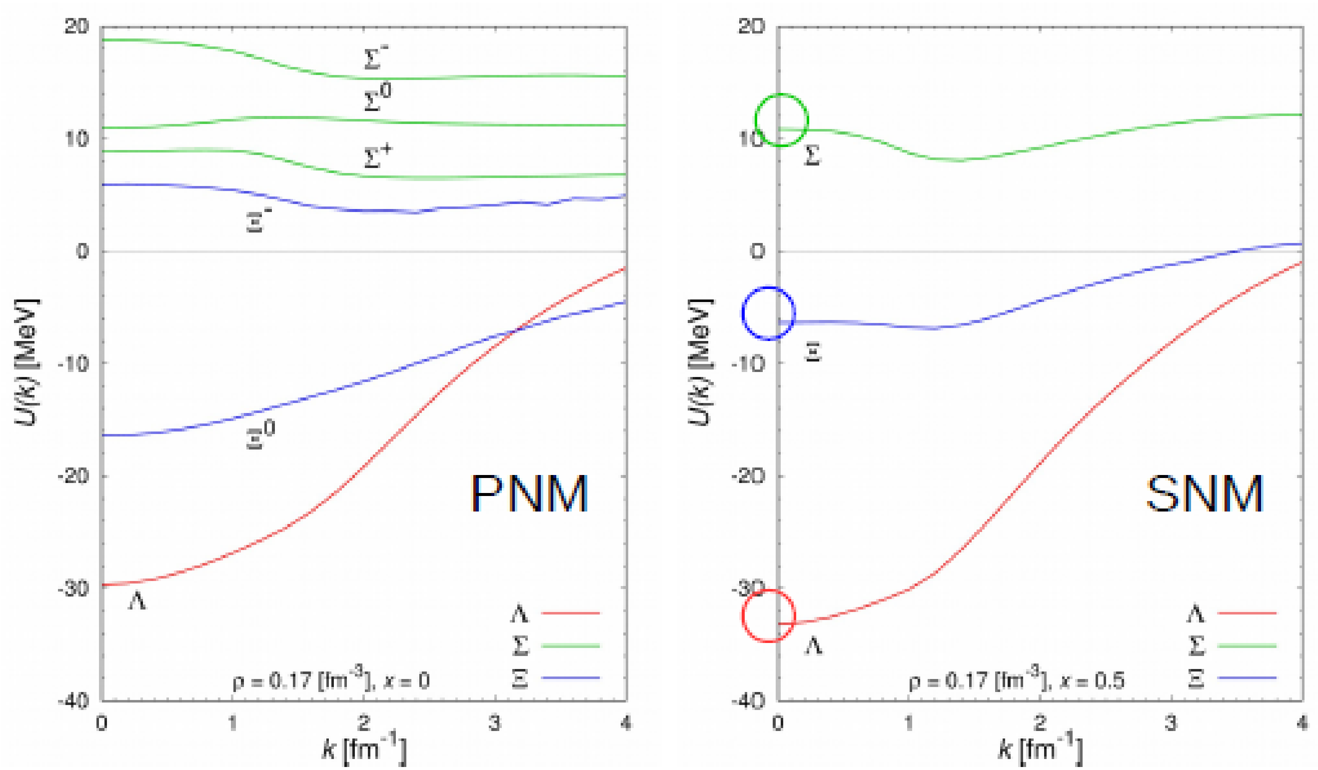
Impact on dense matter

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

➔ Single-particle energy of Hyperon in nuclear matter

(Only diagonal YN/YY forces in SU(3) irrep used)

Hyperon single-particle potentials



$@\rho = 0.17\ [\mathrm{fm}^{-3}]$

Preliminary

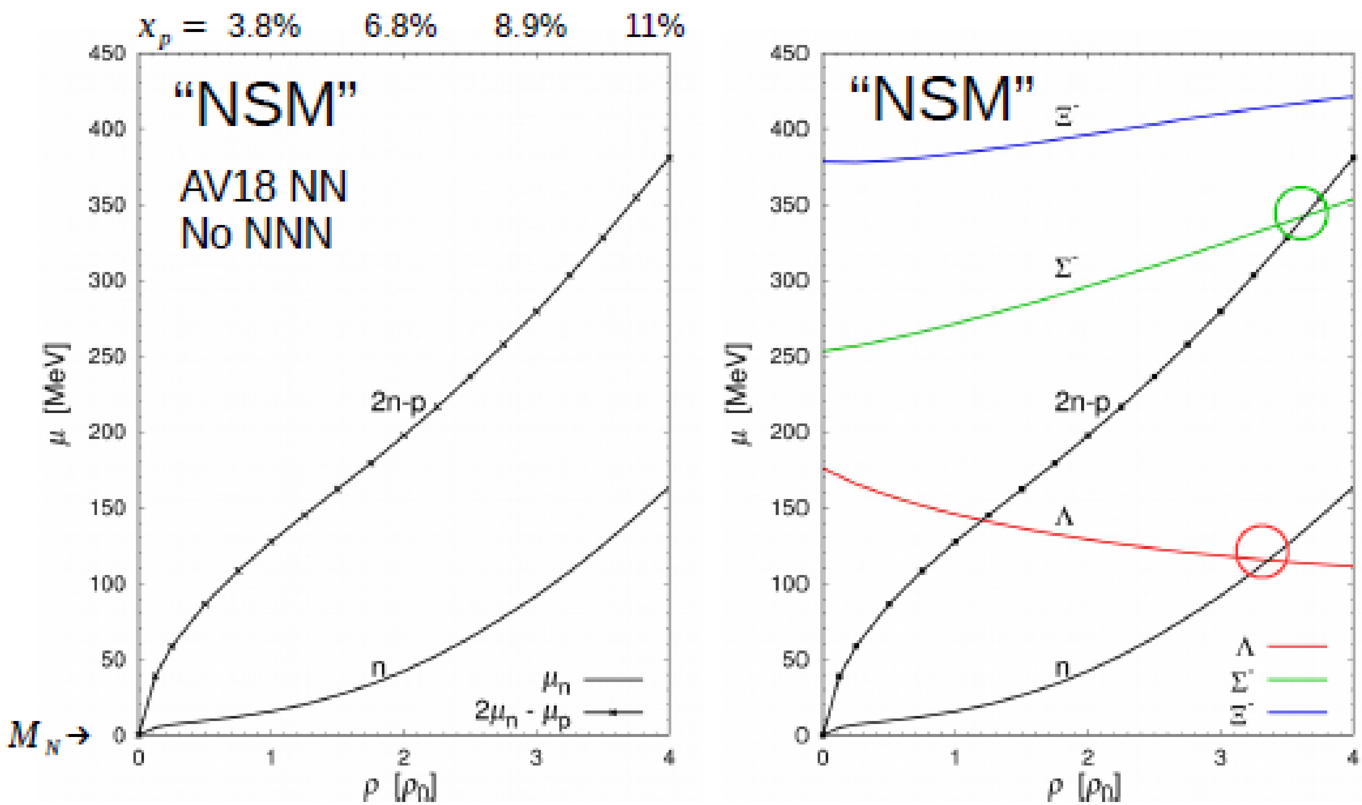
- obtained by using YN,YY forces form QCD.
- Results are compatible with experimental suggestion.

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

attraction   attraction small   repulsion   1

[T. Inoue]

Hyperon onset (just for a demonstration)



S-wave YN only

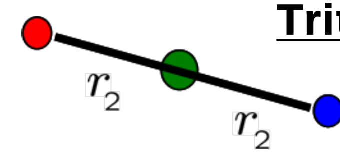
Preliminary

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

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

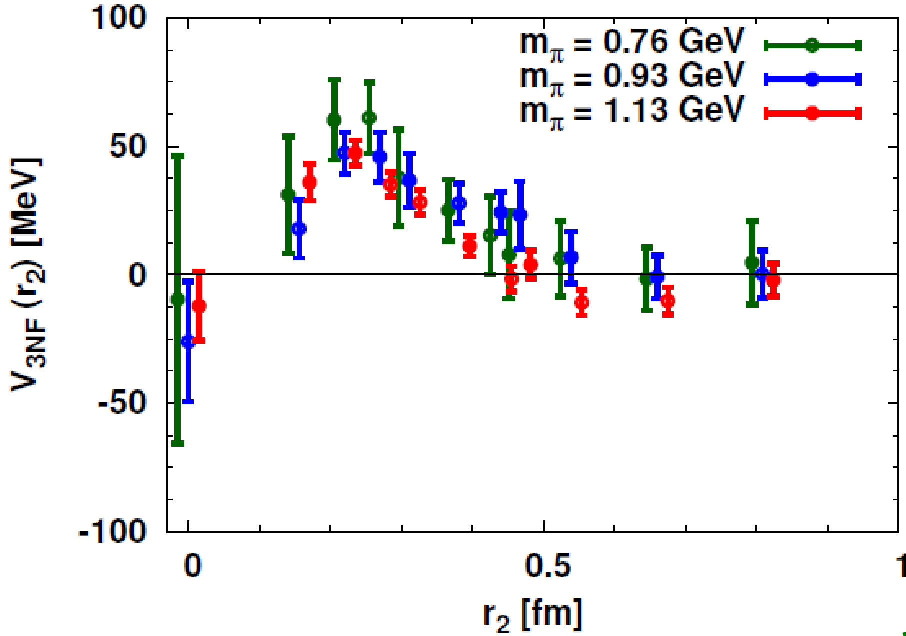
[T. Inoue]

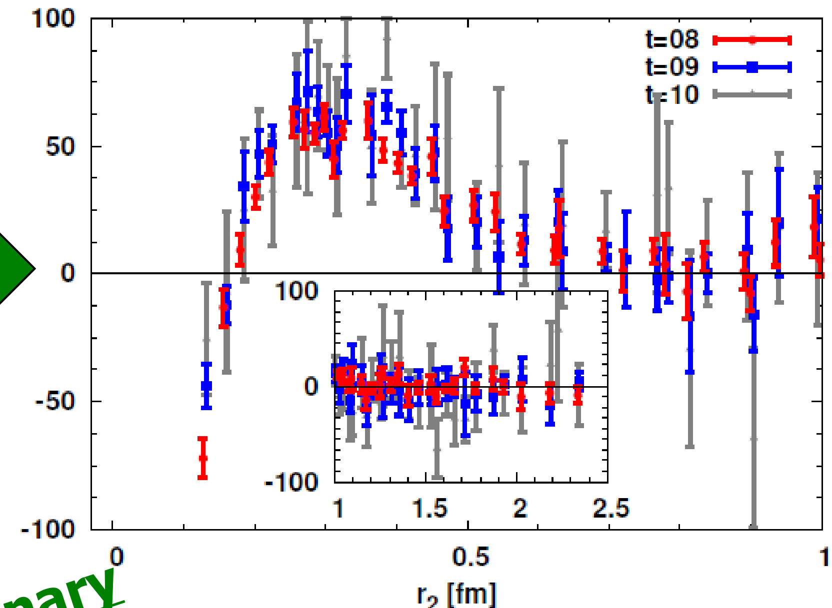
3N-forces (3NF)



Nf=2, mπ=0.76-1.1 GeV

Nf=2+1, mπ=0.51 GeV





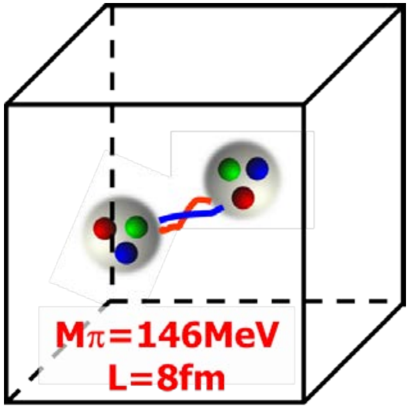
Preliminary

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) ~= 146 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 ~ 2020s
  - LS-forces, P=(-) channel, 3-baryon forces, etc., & EoS