Hadron Interactions in HAL QCD method and Applications to Nuclear and Astro Physics

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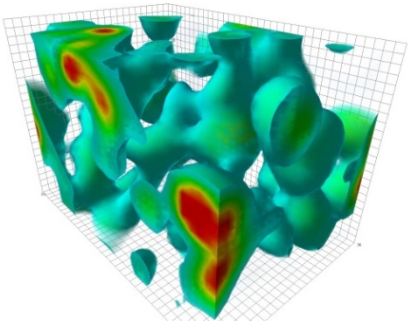
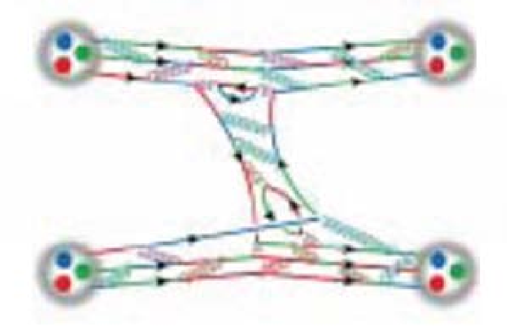
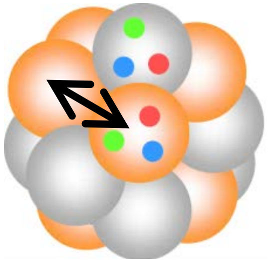
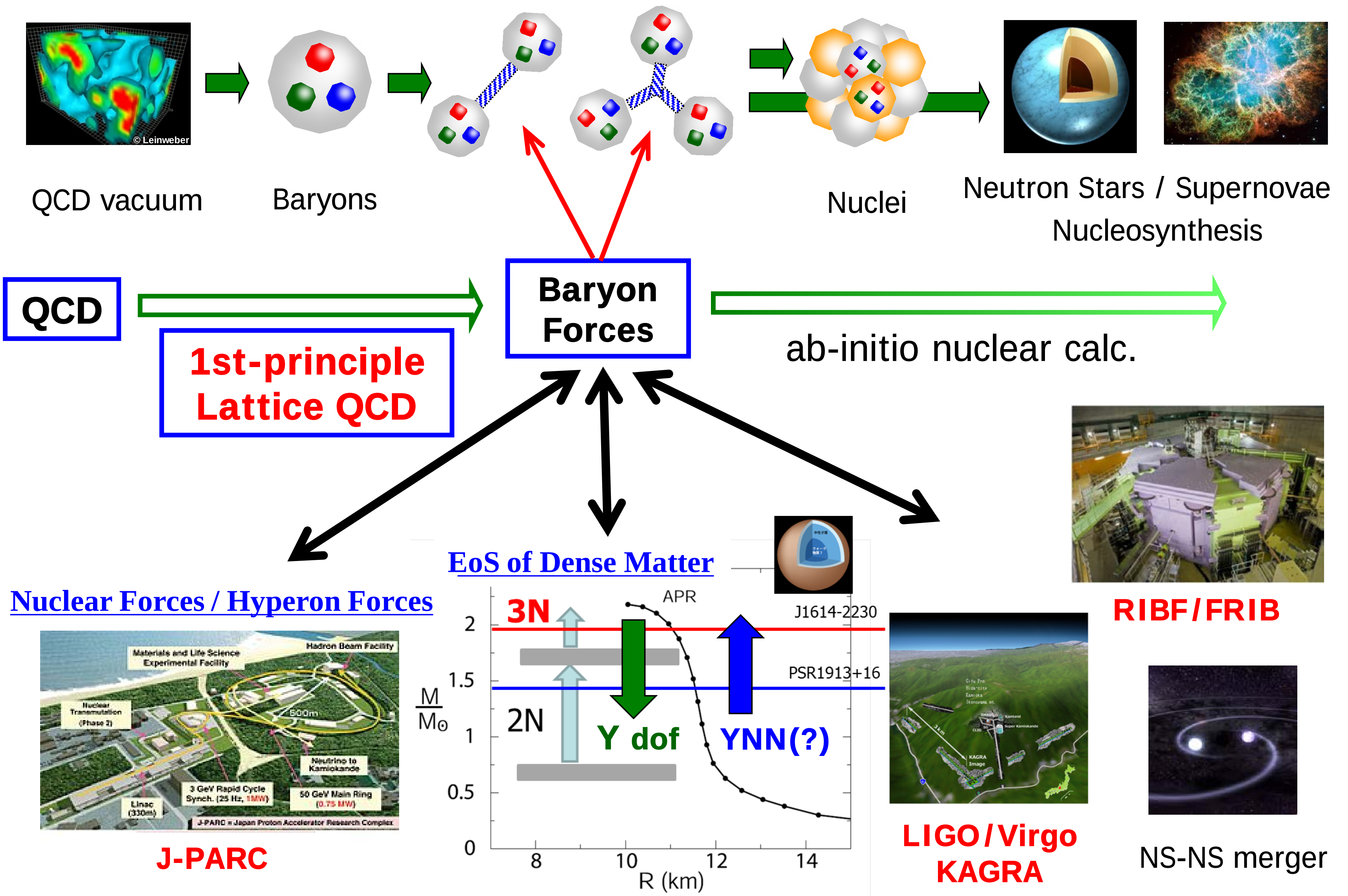




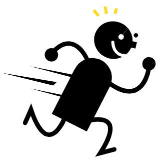


The Odyssey from Quarks to Universe



The Odyssey from unphysical to physical quark masses

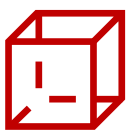
~2010



➔ lighter m_q

We were here

M_π=800 MeV
L=2fm

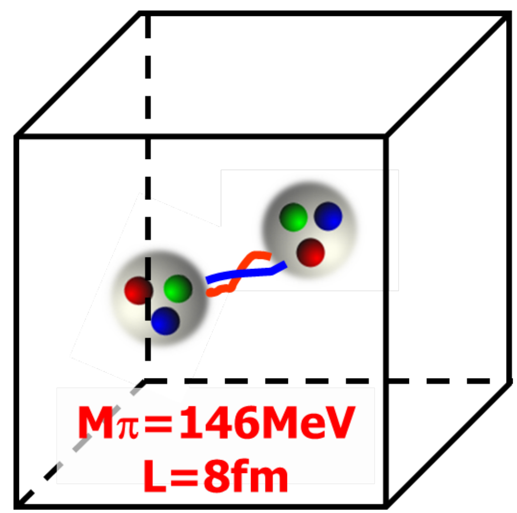


K-computer [10PFlops]

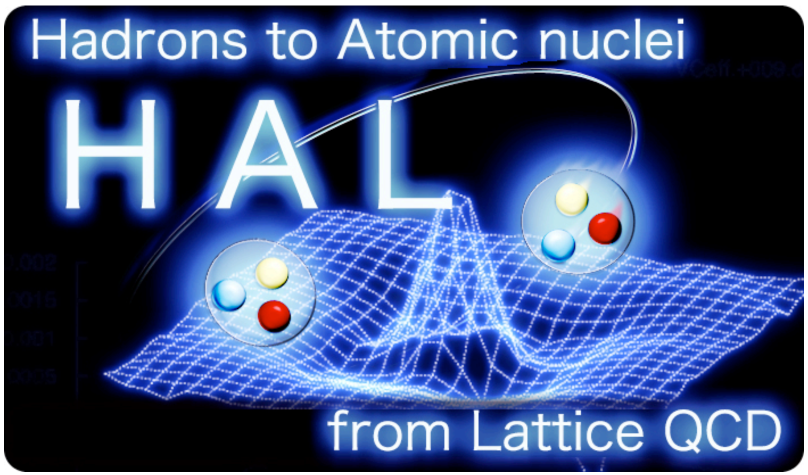
HPCI Program Field 5 **(FY2010-15)**

Priority Issue 9 **(FY2015-19)**

Phys. point



Hadrons to Atomic nuclei from Lattice QCD (HAL QCD Collaboration)



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.)

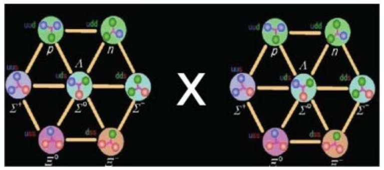
「20XX年宇宙の旅」

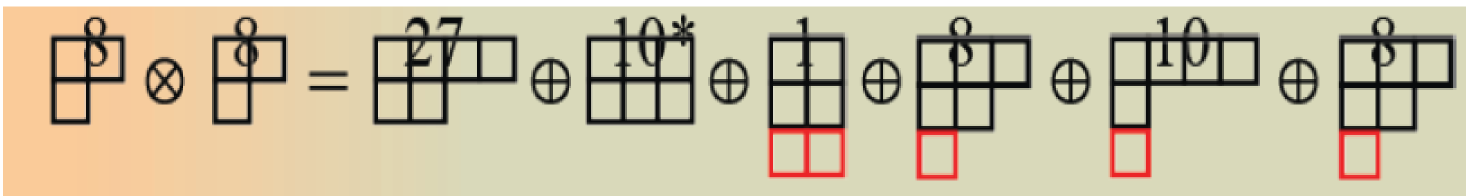
from Quarks to Universe

- **Outline**
  - ~~Introduction~~
  - Theoretical framework of the HAL QCD method
    - NBS wave function ➔ Energy-indep Potential faithful to phase shifts
    - time-dep HAL method ➔ g.s. saturation is NOT necessary
    - Extended to coupled channel system
    - Extended to n>=3 system (w/ non-rela approx.)
  - Results at heavy quark masses
  - Results at physical quark masses
  - Summary / Prospects

- **<u>Outline</u>**
  - Introduction
  - Theoretical framework of the HAL QCD method
  - Results at heavy quark masses
    - LQCD to NN/YN/YY forces
    - LQCD to EoS / Neutron stars
    - LQCD to Nuclei
  - Results at physical quark masses
  - Summary / Prospects

From LQCD to NN/YN/YY forces





8 X 8 = 27 + 8s + 1 + 10* + 10 + 8a

symmetric

anti-symmetric

NN channel

SU(3) study

BB potentials

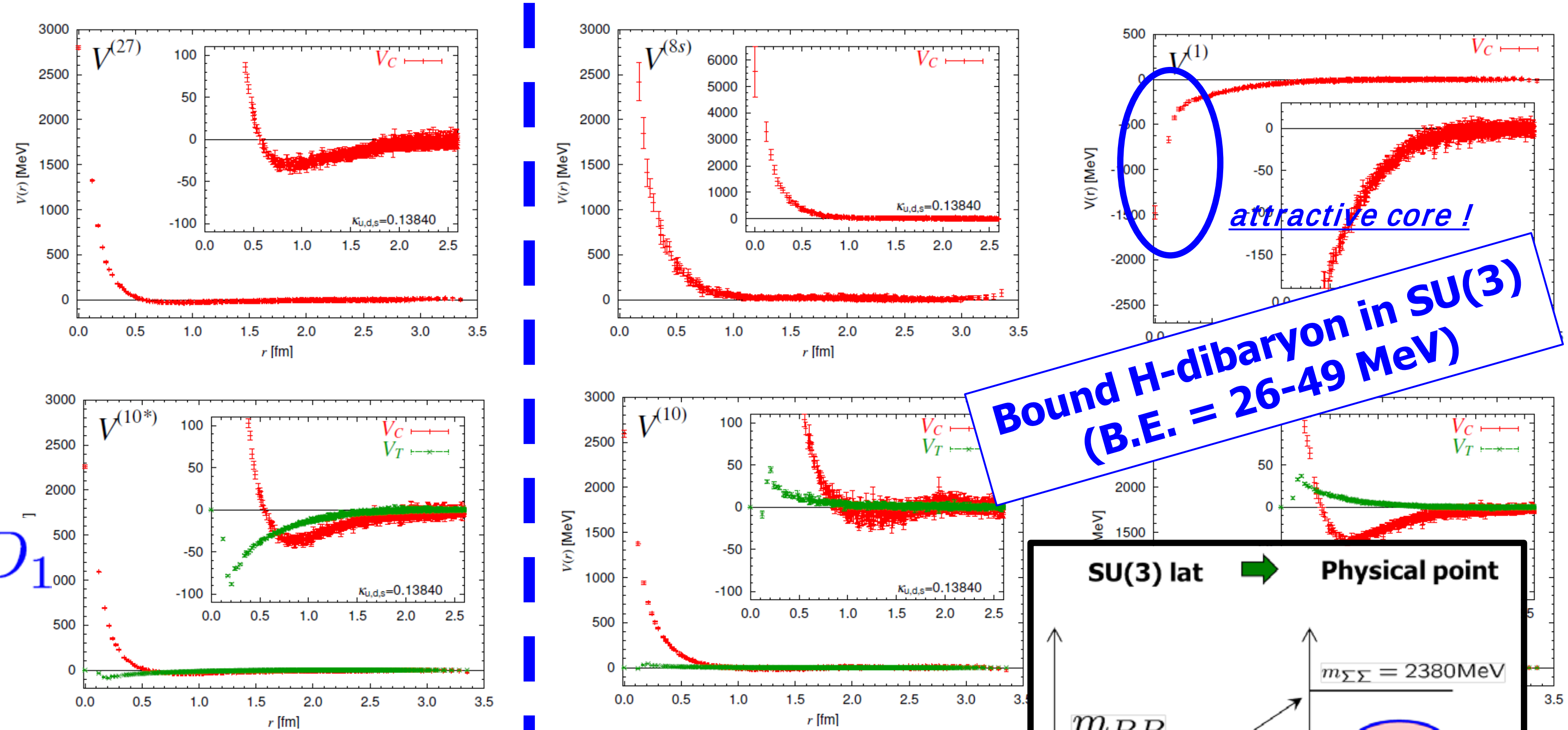
a=0.12fm, L=3.9fm, m(PS)= 0.47-1.2GeV

T.Inoue et al. (HAL.), NPA881(2012)28

NN sector | YN/YY sector

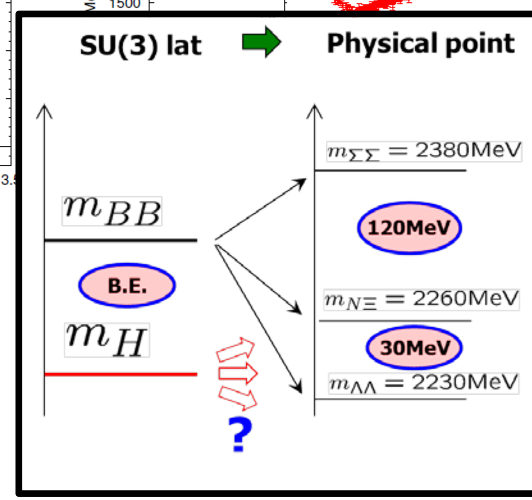
$^1S_0$

$^3S_1-^3D_1$



27,10*:
Same as NN

8s,10:
strong repulsive core

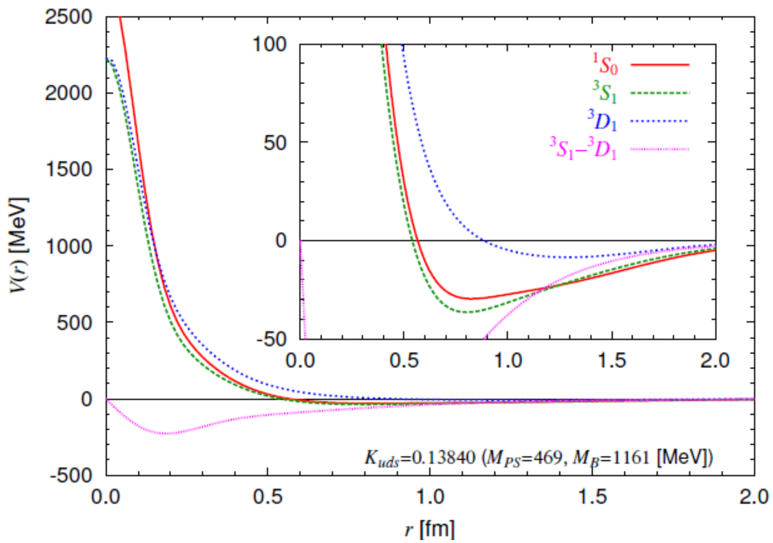


Repulsive core
← Pauli principle !

M.Oka et al., NPA464(1987)700

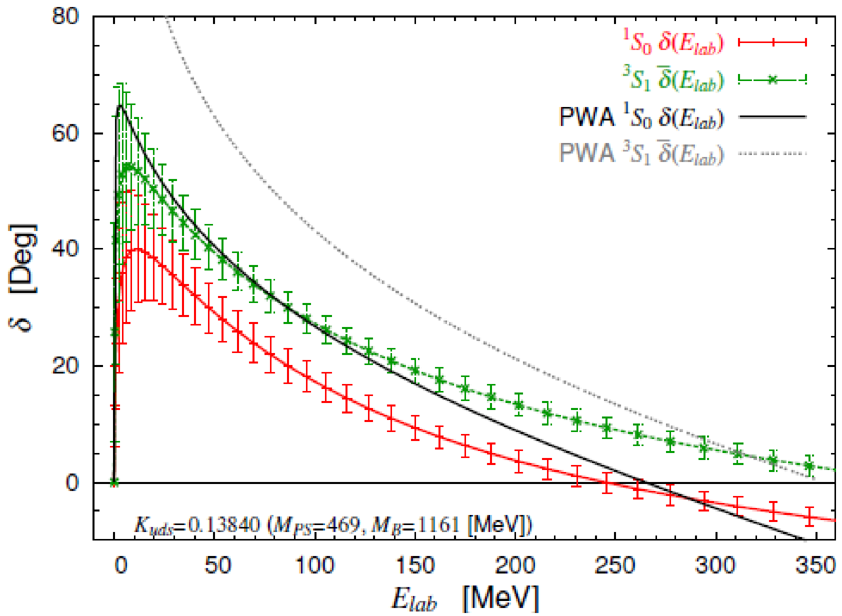
From LQCD to NN phase shifts

Lat NN forces



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

Phase shifts



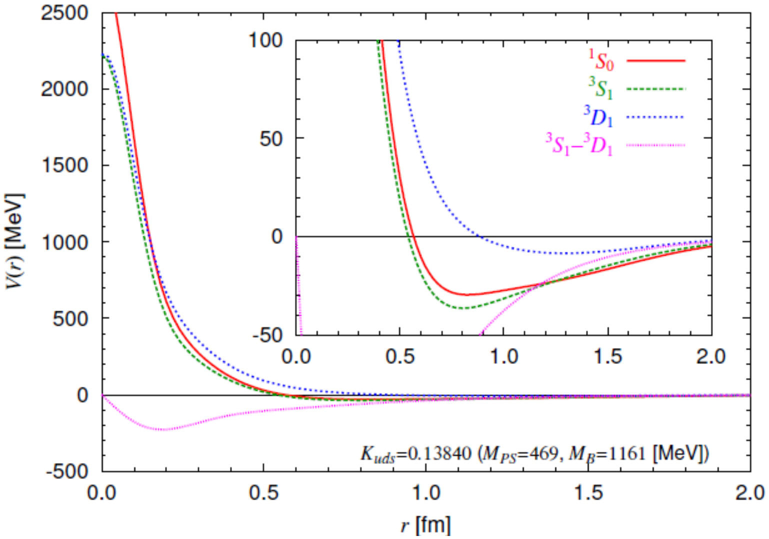
NN : unbound ($^1S_0$, $^3S_1$-$^3D_1$)

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

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

From LQCD to EoS / Neutron Star

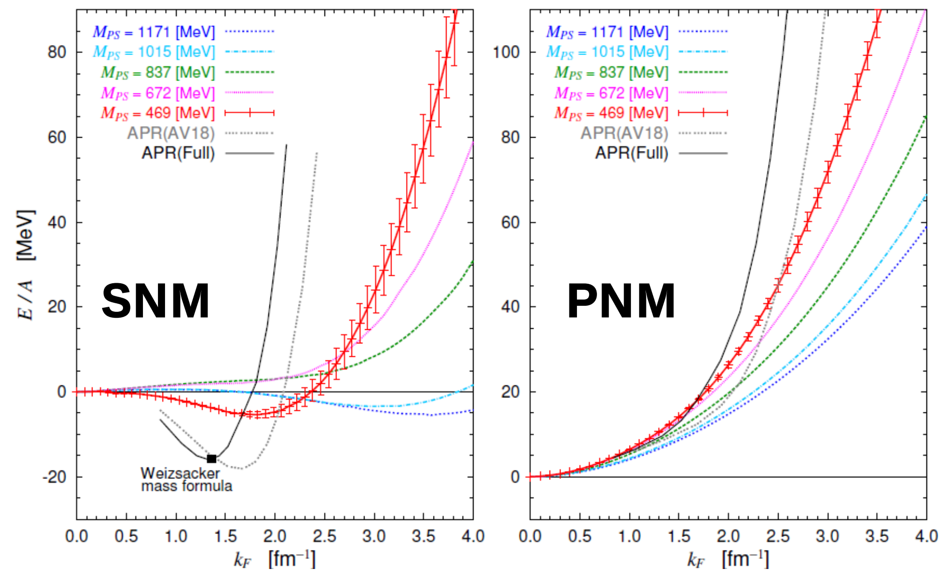
Lat NN forces



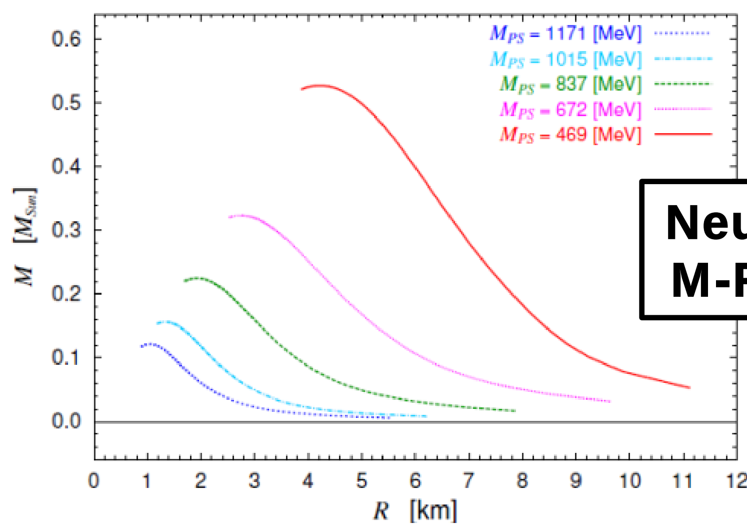
(SU(3), m(PS)=0.47GeV)

BHF

EoS of nuclear matter



TOV



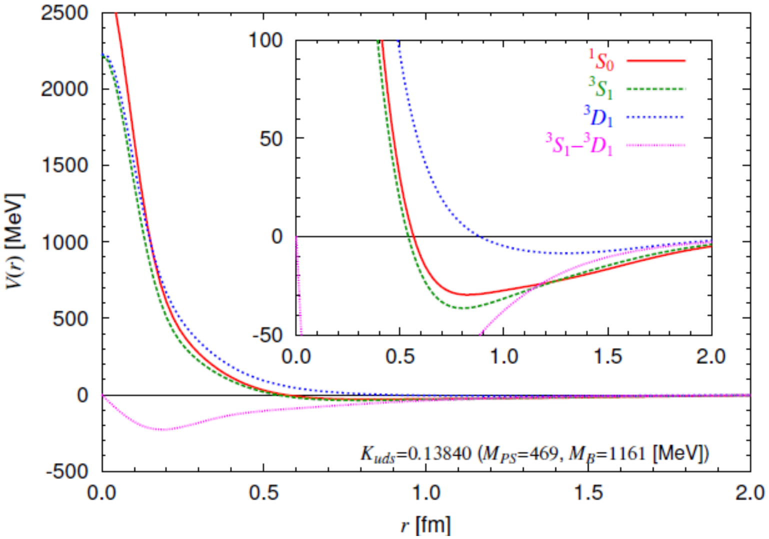
Neutron Star M-R relation

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

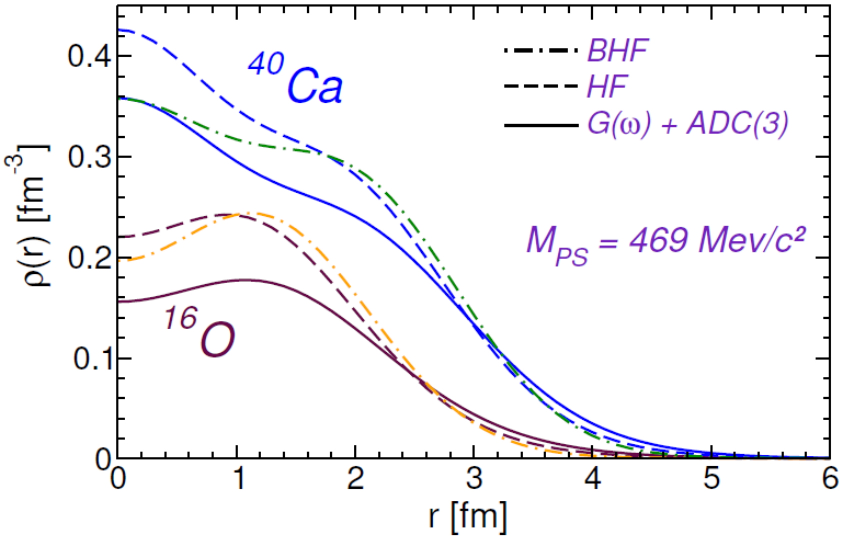


(SU(3), m(PS)=0.47GeV)

C. McIlroy et al., 1701.02607, PRC

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)

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

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

- **Outline**
  - Introduction
  - Theoretical framework of the HAL QCD method
  - Results at heavy quark masses
  - 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]

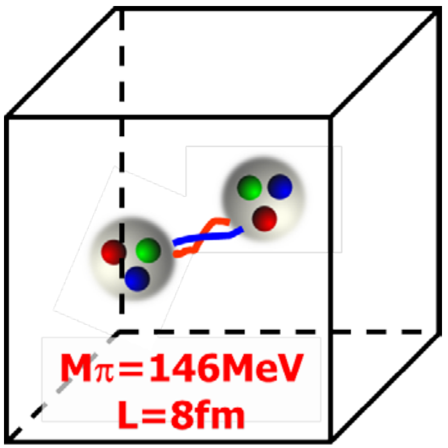
= Unified Contraction Algorithm

- 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

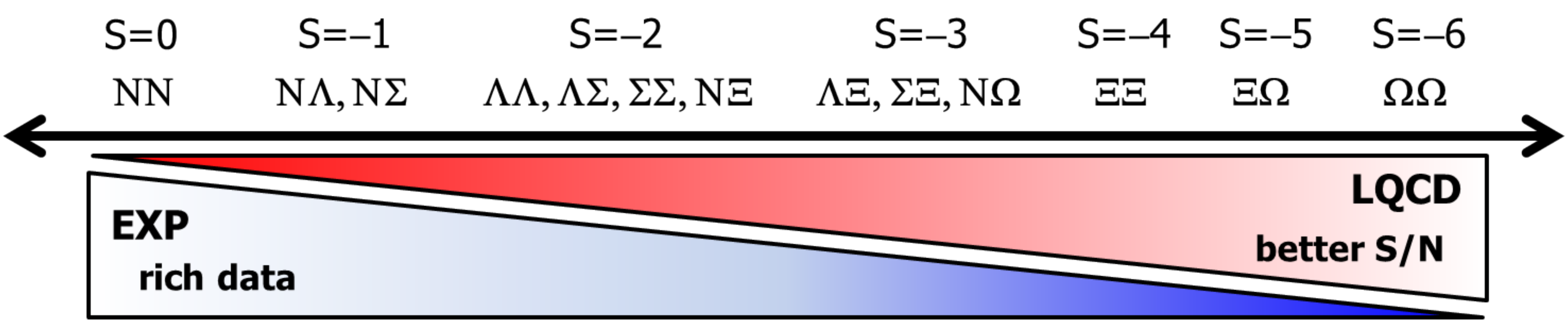
- **Nf = 2 + 1 gauge configs**
  - clover fermion + Iwasaki gauge w/ stout smearing
  - V=(8.1fm)^4, a=0.085fm (1/a = 2.3 GeV)
  - m(pi) ~= 146 MeV, m(K) ~= 525 MeV
  - #traj ~= 2000 generated



PACS Coll., PoS LAT2015, 075

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

Predictions for Hyperon forces



$\Omega\Omega$ system (S= –6)

$^1S_0$: Pauli allowed channel, candidate for exotic bound state

Model varies from bound state to repulsive interactions

HAL study @ m(pi)=0.7GeV: nearly bound (Unitary Region)

M. Yamada et al., PTEP2015, 071B01

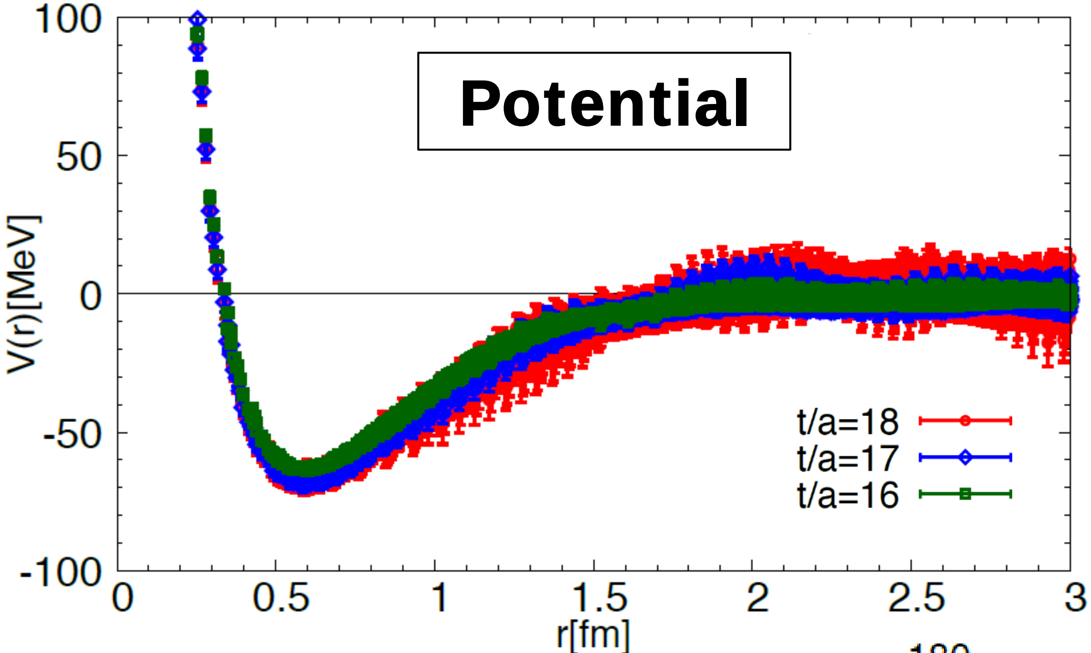
c.f. Luscher's method @ m(pi)=0.39GeV: weak repulsion

a = -0.16(22)fm

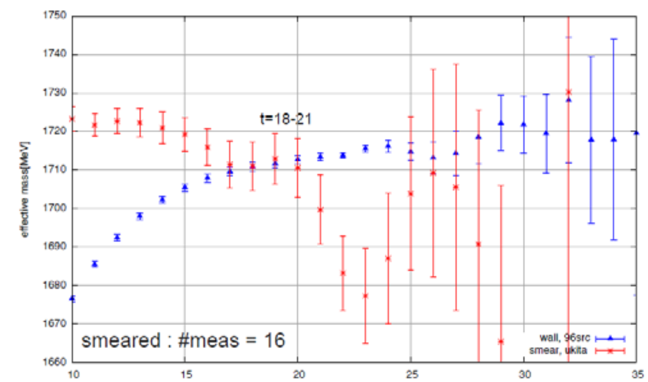
M. Buchoff et al, PRD85(2012)094511

$\Omega\Omega$ system ($^1S_0$)

(The "most strange" dibaryon system)

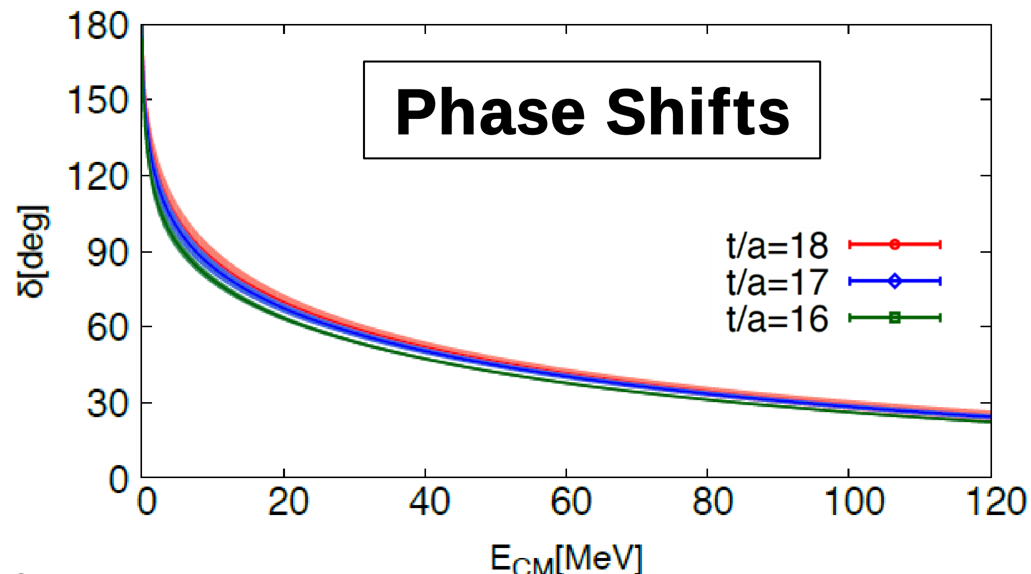


m(eff) for single Ω



t = 18 : ~0.2-0.3% sys error

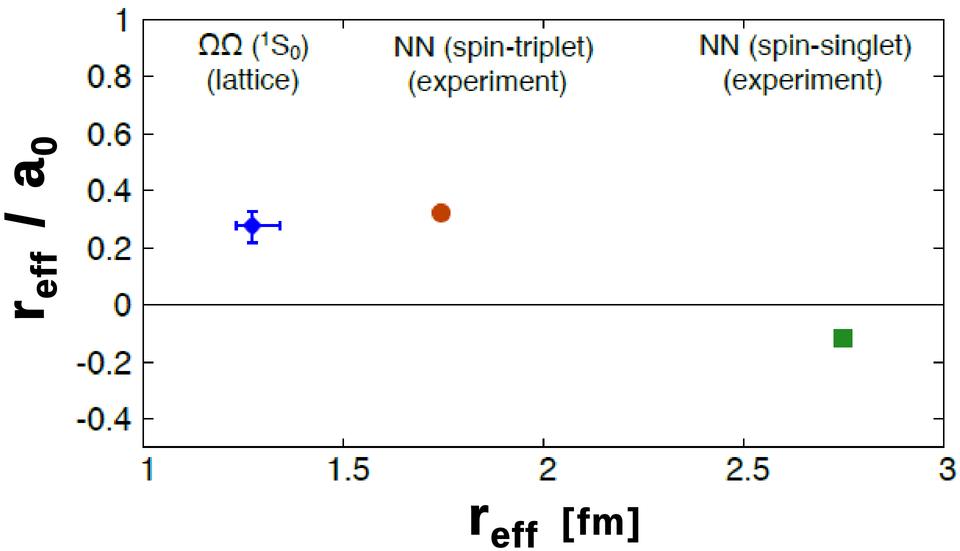
Strong Attraction

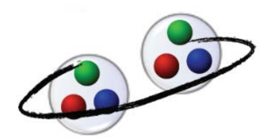


S. Gongyo et al. (HAL Coll.), arXiv:1709.00654

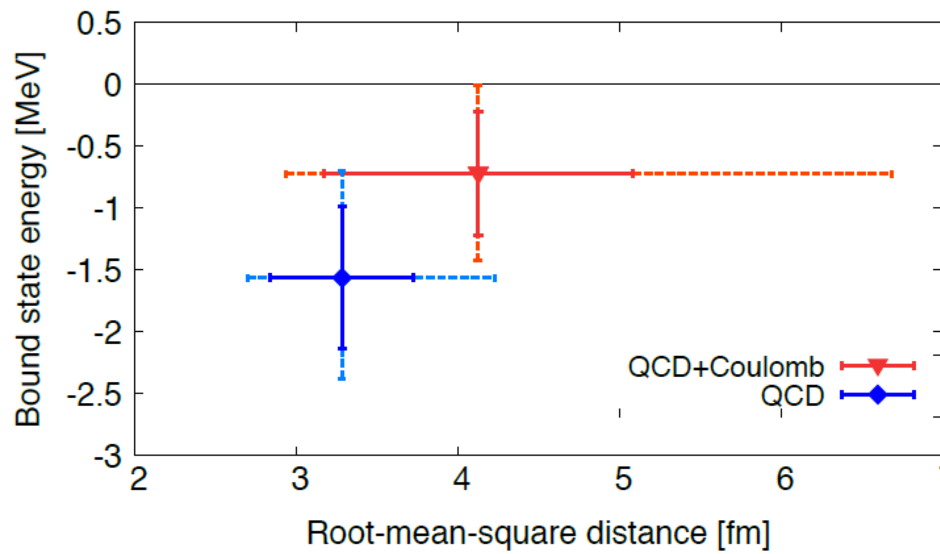
$\Omega\Omega$ system ($^1S_0$)

(The "most strange" dibaryon system)





$$B_{\mathrm{QCD}} = 1.6(6)(^{+0.7}_{-0.6})\ \mathrm{MeV}$$
$$B_{\mathrm{QCD+Coul.}} = 0.7(5)(5)\ \mathrm{MeV}$$



Vicinity of bound / unbound

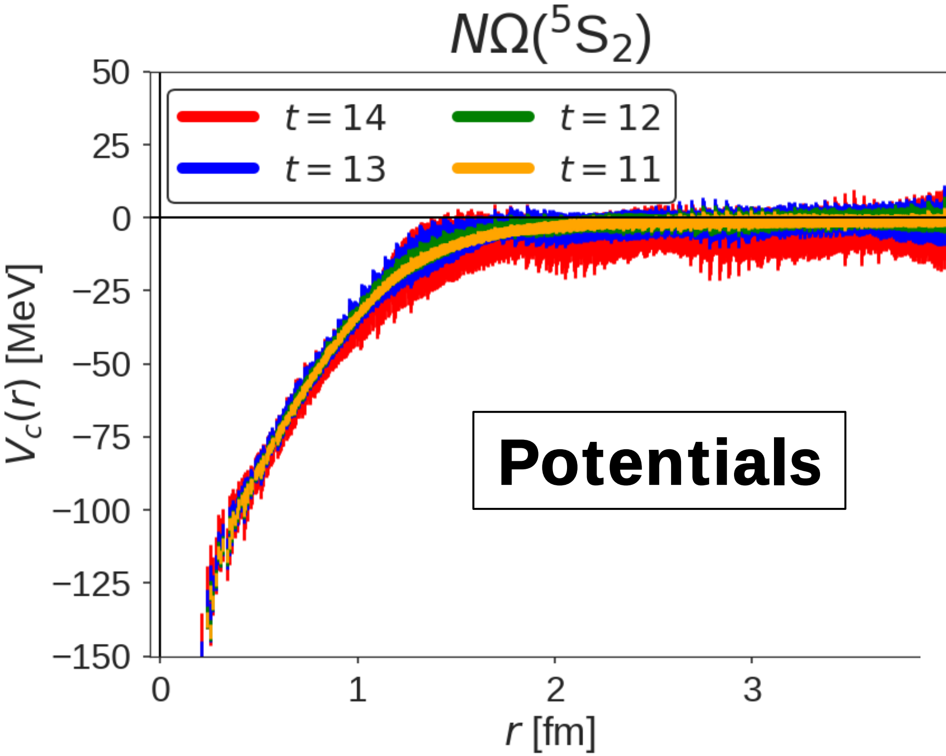
[~ Unitary limit]

⇔ $\Omega\Omega$ correlation in HIC exp.

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

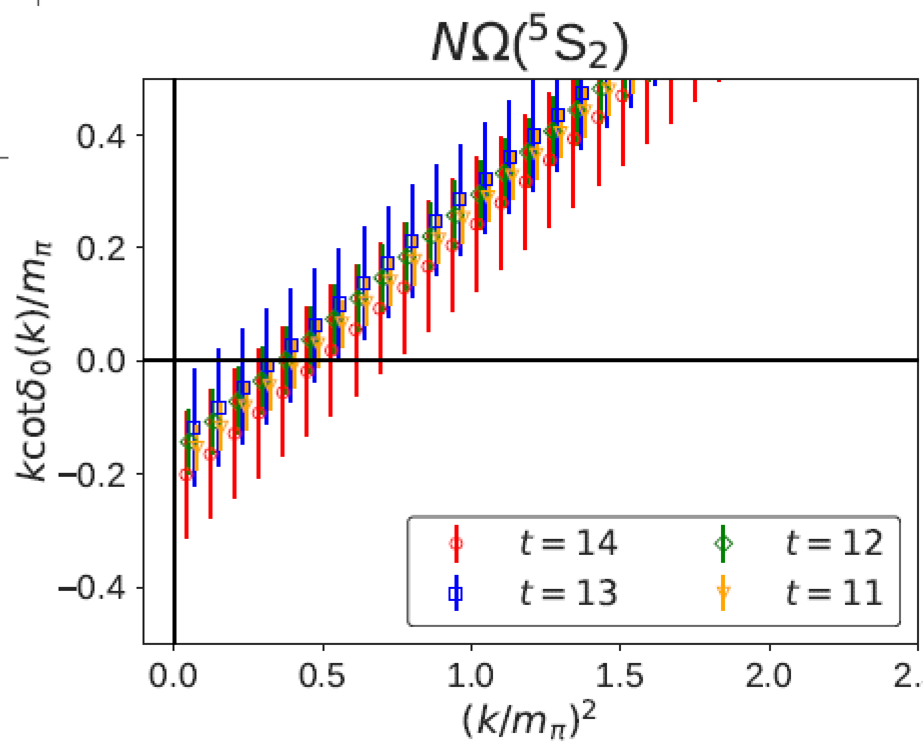
NΩ system ($^5S_2$)

preliminary



Potentials

Phase Shifts



Strong Attraction

possibly "Bound"

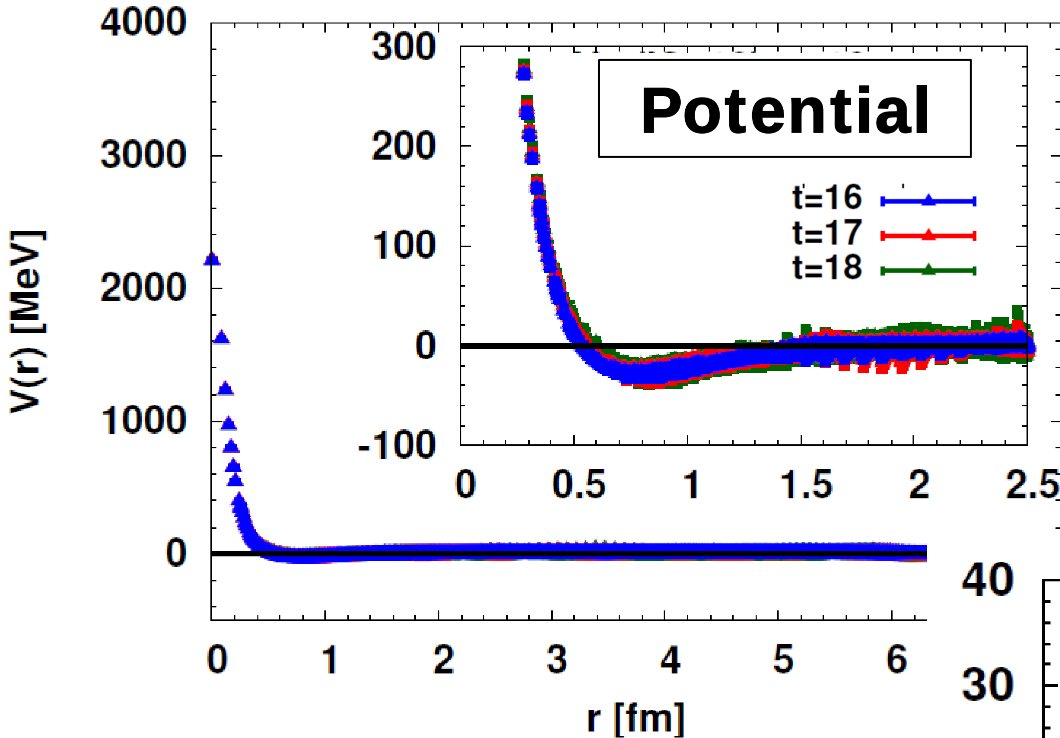
⟺ **NΩ correlation in HIC**

(200conf x 4rot x 48src)

[T. Iritani]

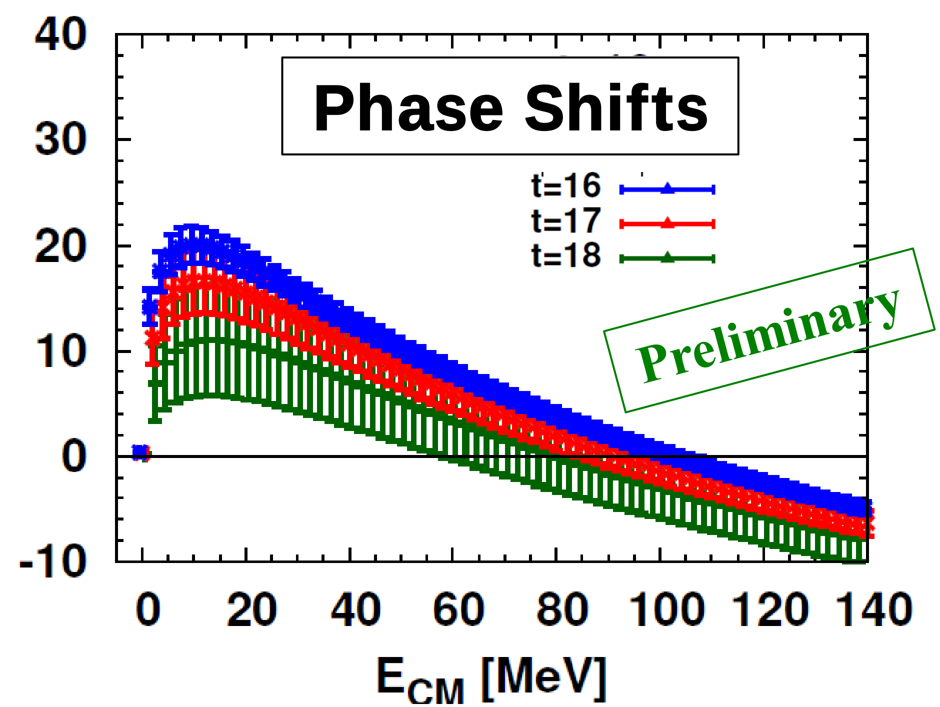
$\Xi\Xi$ system (S= –4)

ΞΞ system ($^1S_0$)



Flavor SU(3)-partner of dineutron

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



Strong Attraction

yet Unbound

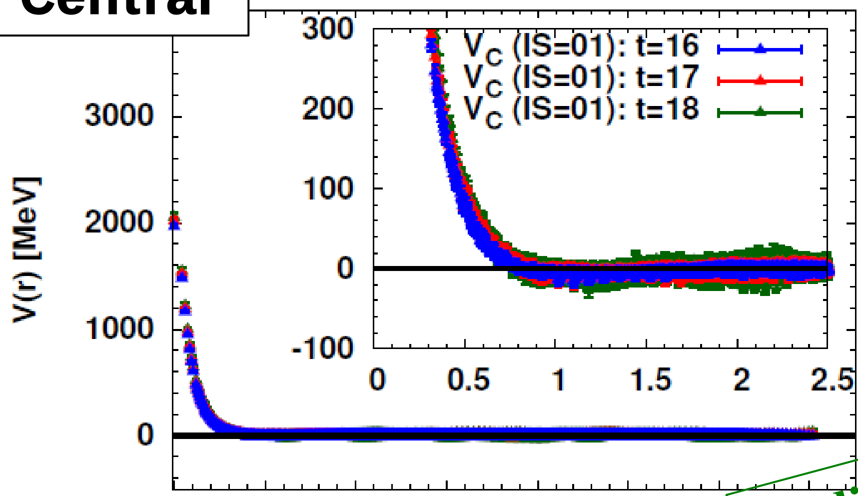
⟺ **ΞΞ correlation in HIC**

(2-gauss + 2-OBEP)

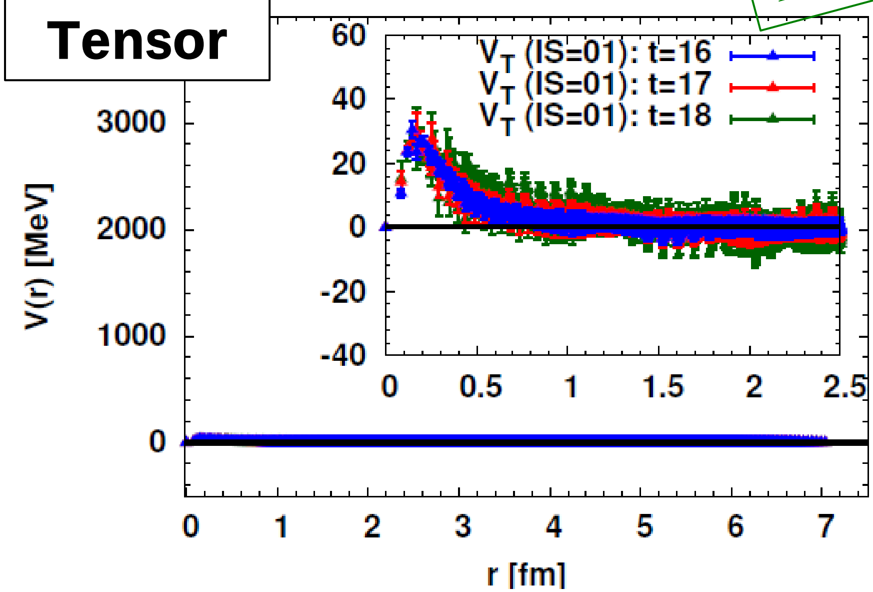
ΞΞ system ($^3S_1$-$^3D_1$)

Potentials

Central



Tensor



Preliminary

10plet ⇔ unique w/ hyperon DoF

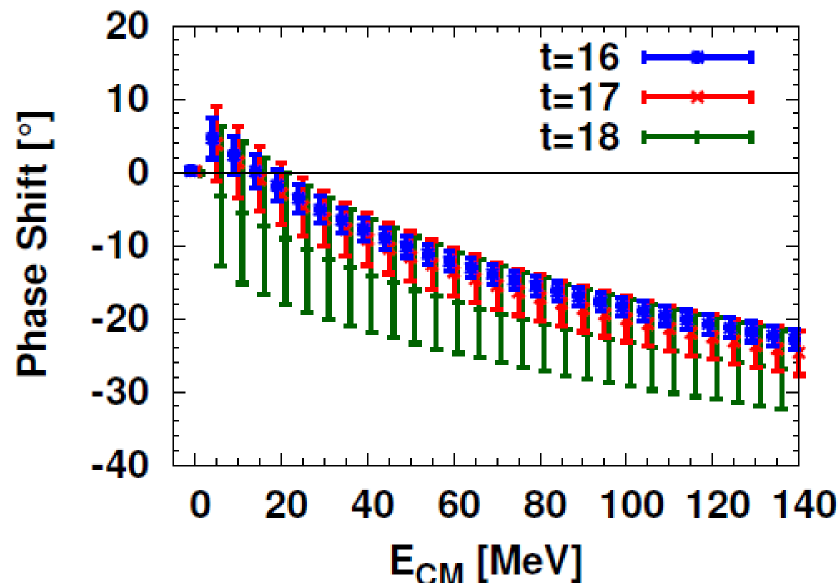
Flavor SU(3)-partner of Σ^- n

⇨ • Σ^- in neutron star ?

Central: Strong Repulsion

Tensor: Weak

Phase Shifts (eff. $^3S_1$)



(2-gauss + 2-OBEP)

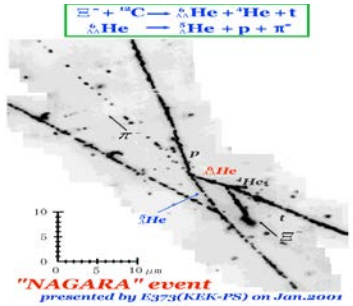
S = -2 channel (Coupled Channel)

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

R. Jaffe (1977), “Perhaps a Stable Dibaryon”

NAGARA-event (2001)

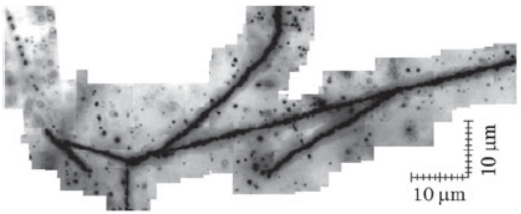
$$\Xi^- + {}^{12}\mathrm{C} \to {}_{\Lambda\Lambda}{}^{6}\mathrm{He} + {}^{4}\mathrm{He} + t$$



Ξ–hypernuclei

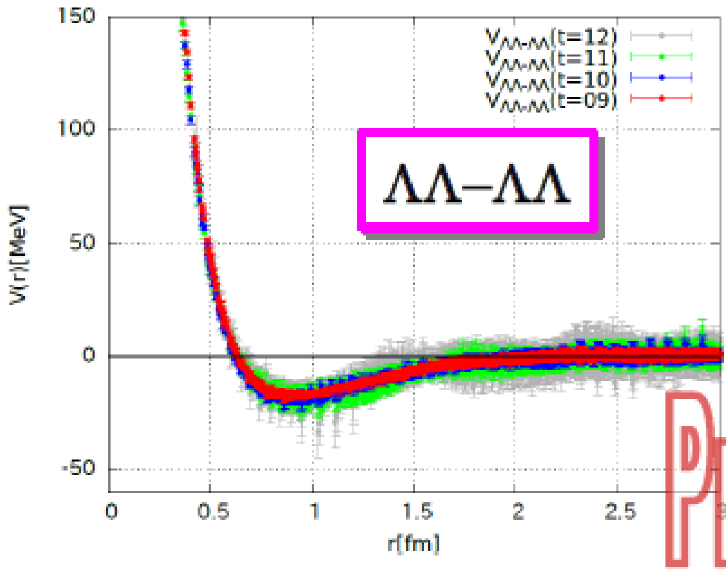
KISO-event (2014)

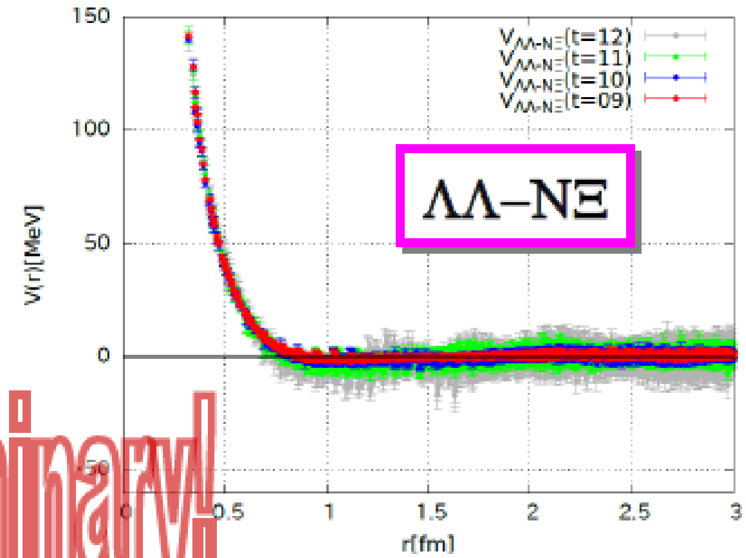
$$\Xi^- + {}^{14}\mathrm{N} \to {}_{\Lambda}{}^{10}\mathrm{Be} + {}_{\Lambda}{}^{5}\mathrm{He}$$



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

$\Lambda\Lambda$, $N\Xi$, ($\Sigma\Sigma$) coupled channel ➔ H-dibaryon channel





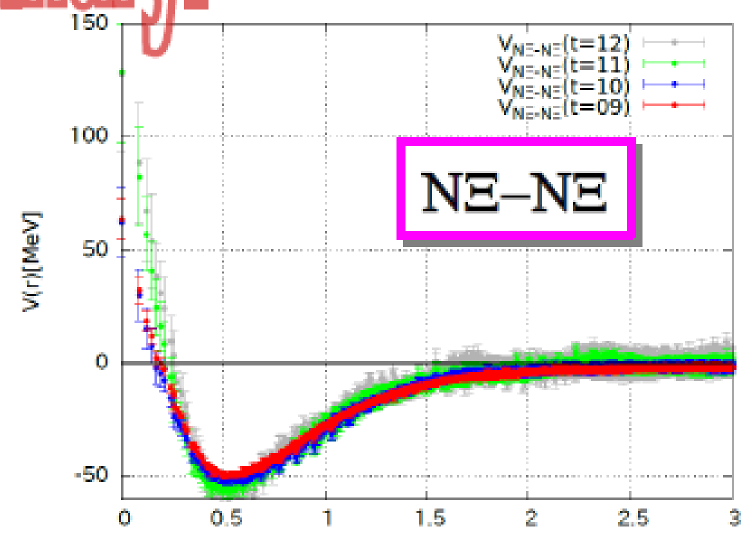
Preliminary!

$m_{\Sigma\Sigma} = 2380\text{MeV}$

$m_{N\Xi} = 2260\text{MeV}$

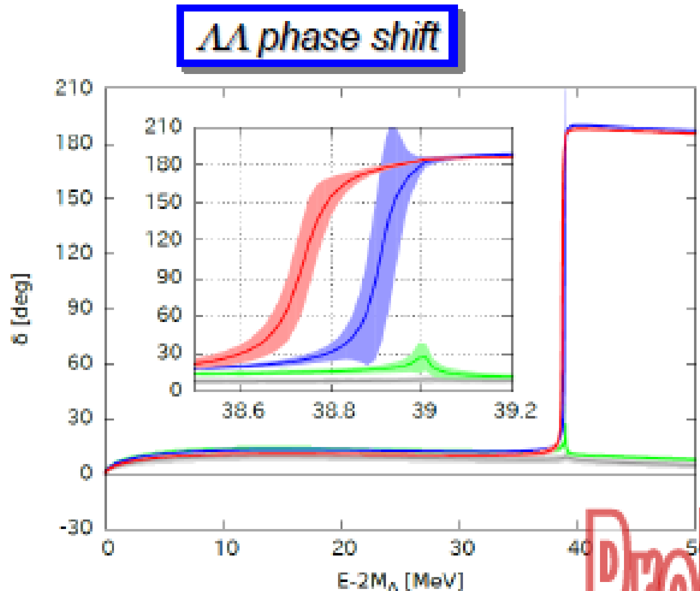
$m_{\Lambda\Lambda} = 2230\text{MeV}$

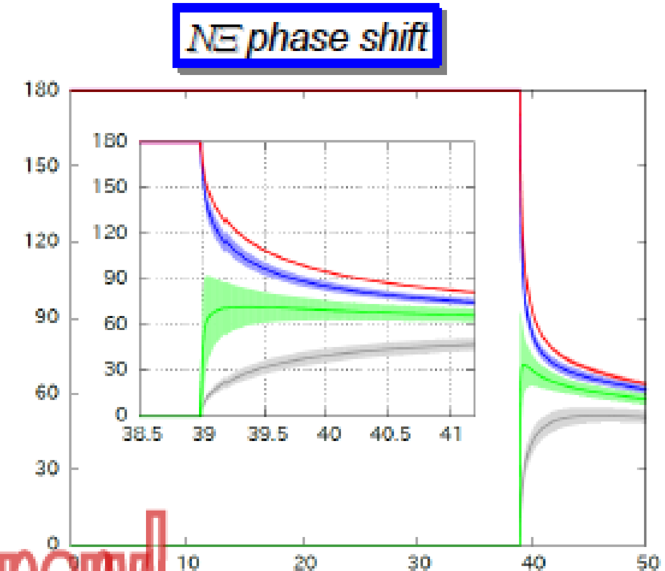
2x2 Potentials



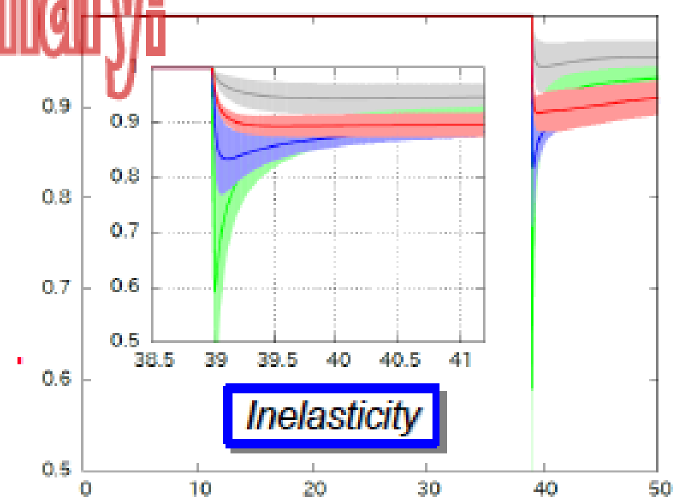
[K. Sasaki]

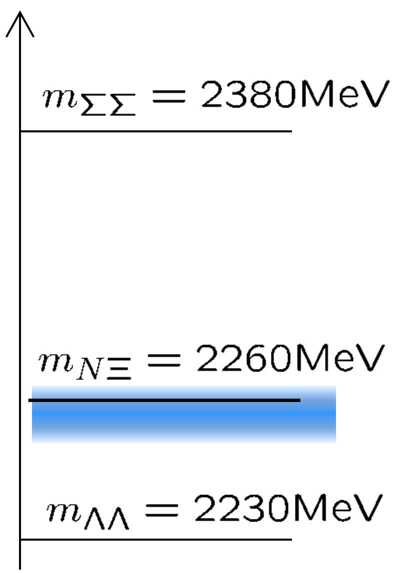
ΛΛ, NΞ (effective) 2x2 coupled channel analysis





Preliminary!





H-resonance (?)

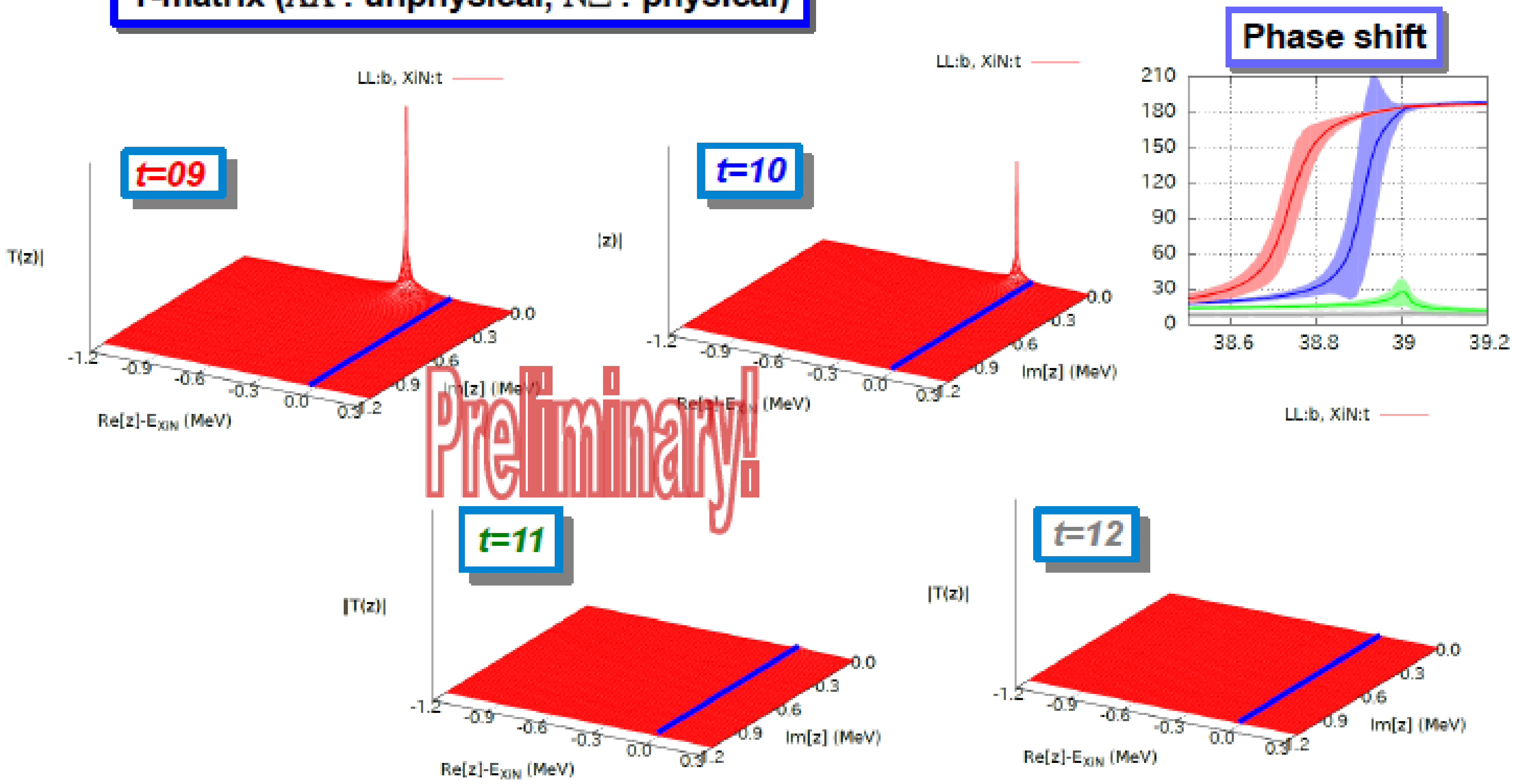
"Perhaps a Resonant Dibaryon"

[K. Sasaki]

Pole search

- N_f = 2+1 full QCD with L = 8.1fm, *m_π = 146 MeV*

T-matrix (ΛΛ : unphysical, NΞ : physical)

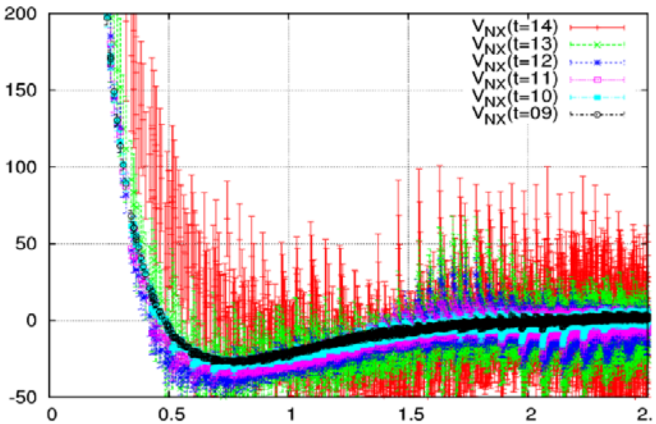


NΞ-Potentials

[K. Sasaki]

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

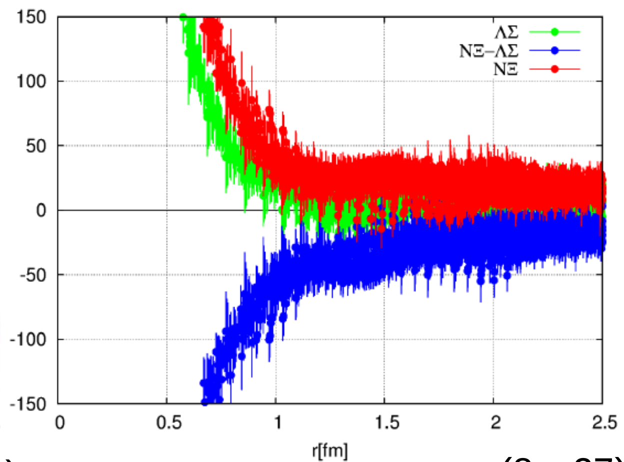
NΞ (I=0, $^3S_1$)



(8a)

Attractive

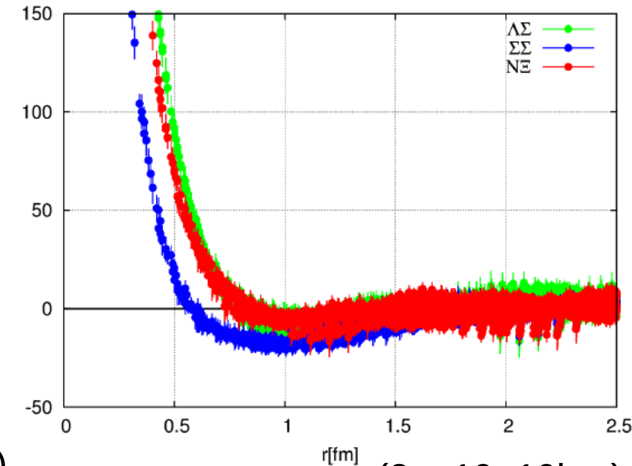
NΞ–ΛΣ (I=1, $^1S_0$)



(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 !

c.f. Net attractive @ m(pi)=0.66-88GeV (K. Sasaki et al., PTEP2015, 113B01)

S= –1 systems

←→ strangeness nuclear physics (Λ-hypernuclei @ J-PARC)

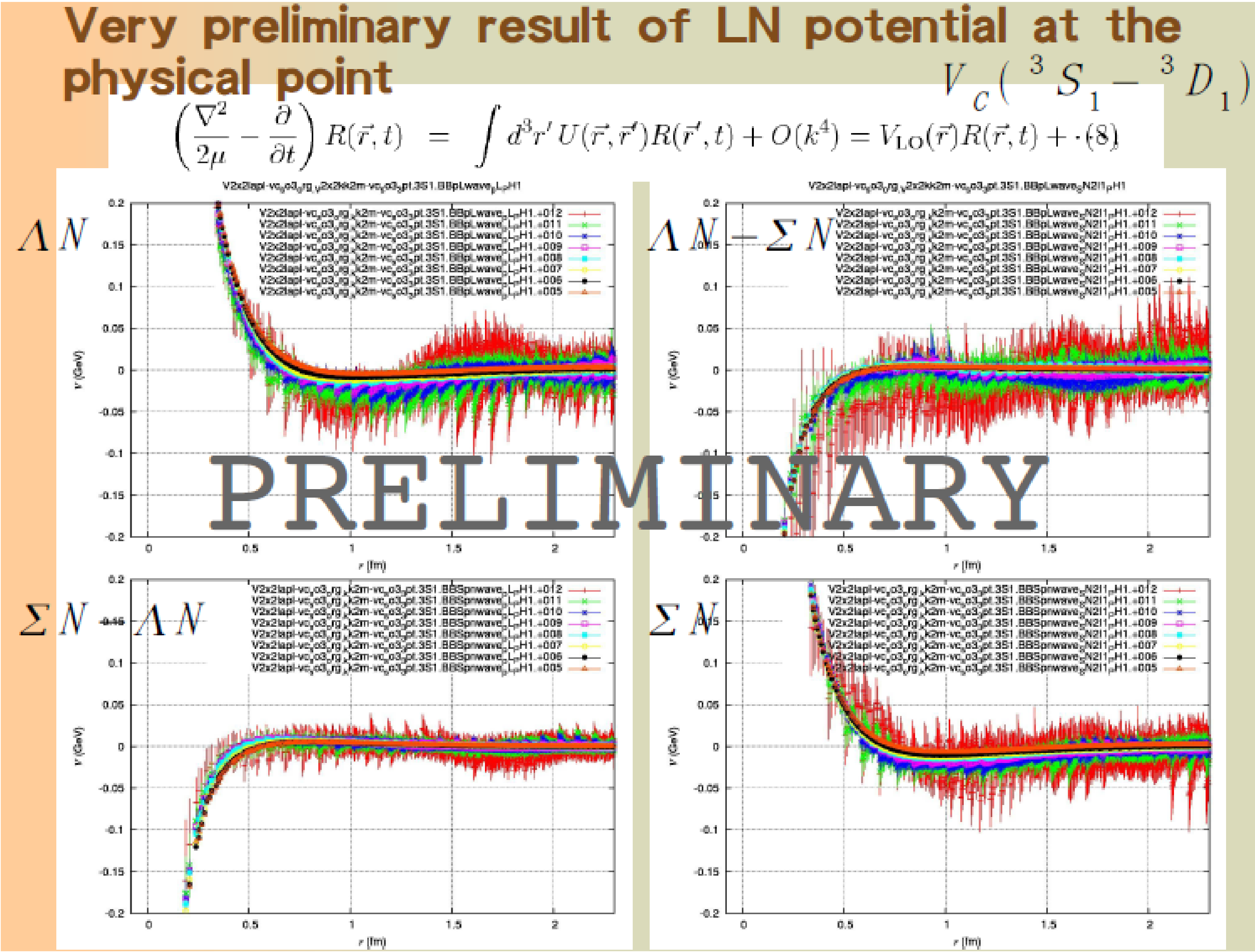
Λ should (?) appear in the core of Neutron Star

←→ Huge impact on EoS of high dense matter

- **ΛN–ΣN (I=1/2) : coupled channel**
  - **$^1S_0$ ∼ 27-plet & 8s-plet**
  - **$^3S_1$-$^3D_1$ ∼10*-plet & 8a-plet**
- **ΣN (I=3/2)**
  - **$^1S_0$ ∼ 27-plet**
    ⇔ NN($^1S_0$) + SU(3) breaking
  - **$^3S_1$-$^3D_1$ ∼10-plet**

ΛN–ΣN Vc potential in $^3S_1$–$^3D_1$

[H. Nemura]



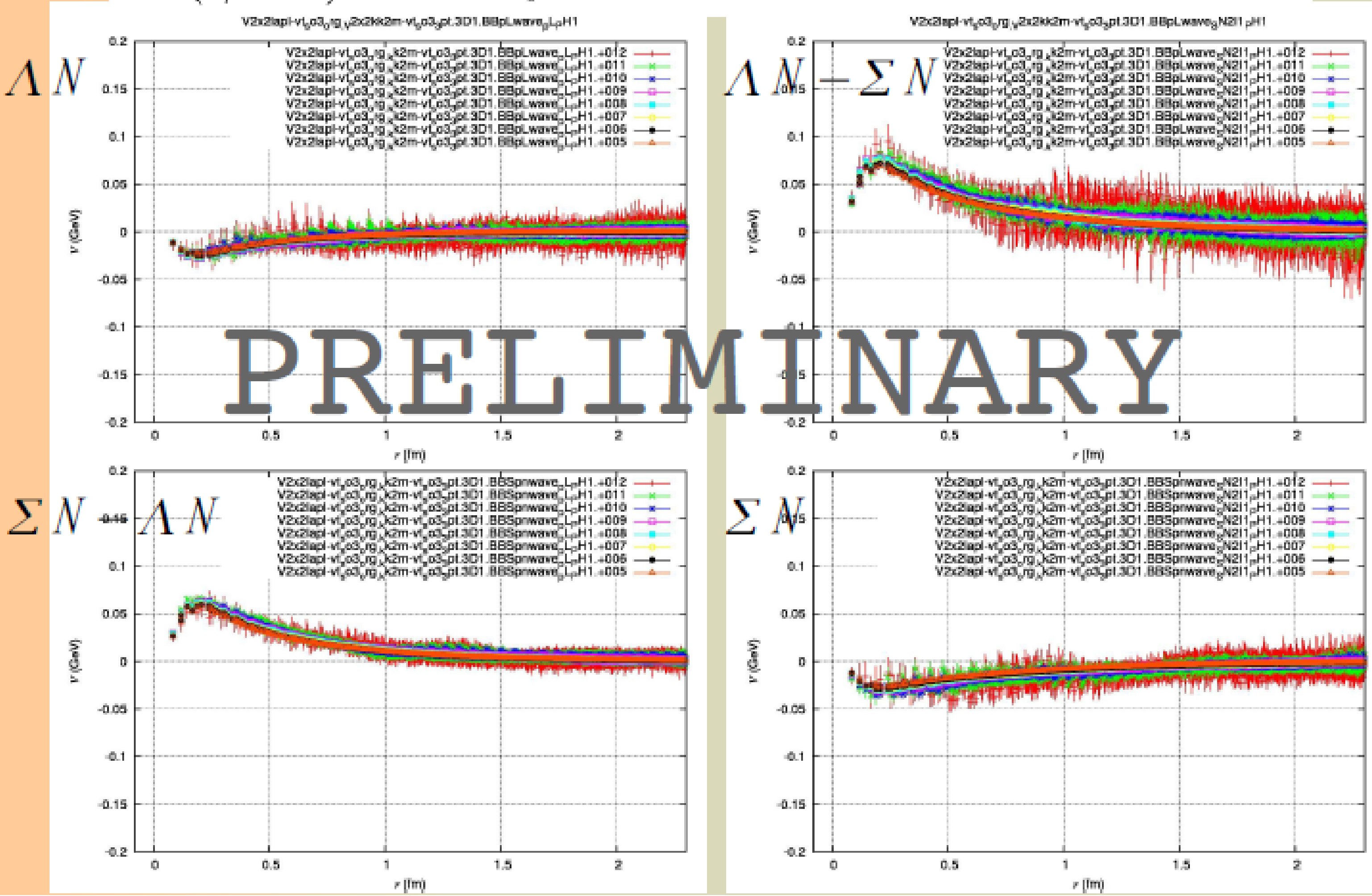
(200conf x 4rot x 52src)

ΛN–ΣN Vt potential in $^3S_1$–$^3D_1$ [H. Nemura]

Very preliminary result of LN potential at the physical point

$V_T(^3S_1 - ^3D_1)$

$$\left(\frac{\nabla^2}{2\mu} - \frac{\partial}{\partial t}\right) R(\vec{r},t) = \int d^3r' \, U(\vec{r},\vec{r}')R(\vec{r}',t) + O(k^4) = V_{\rm LO}(\vec{r})R(\vec{r},t) + \cdot (8)$$

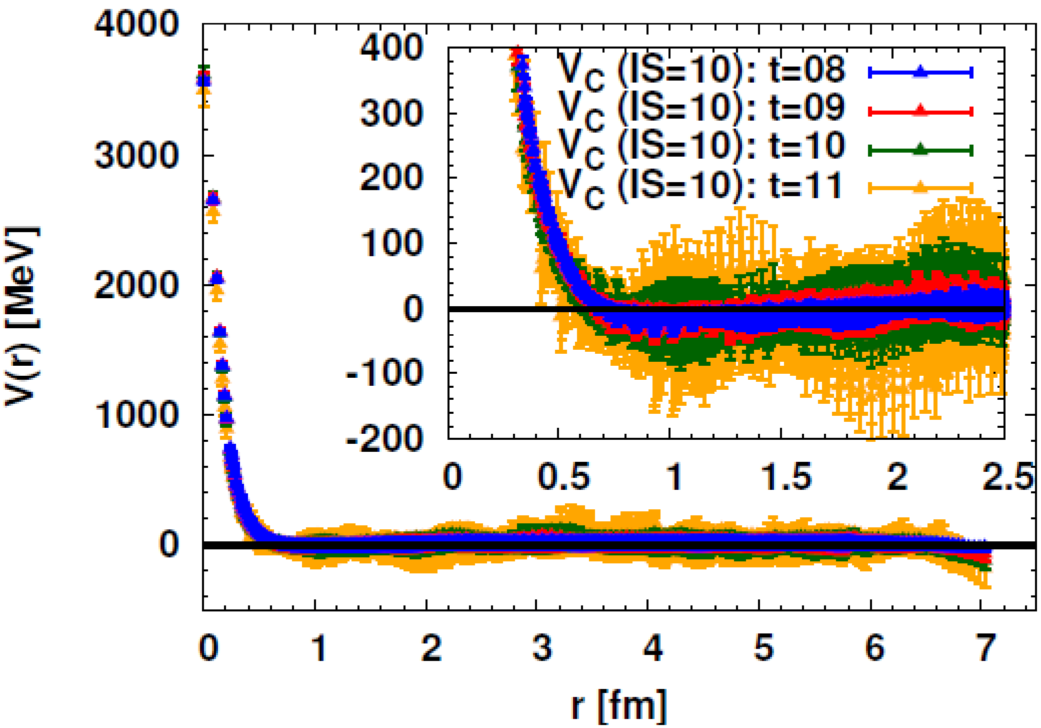


(200conf x 4rot x 52src)

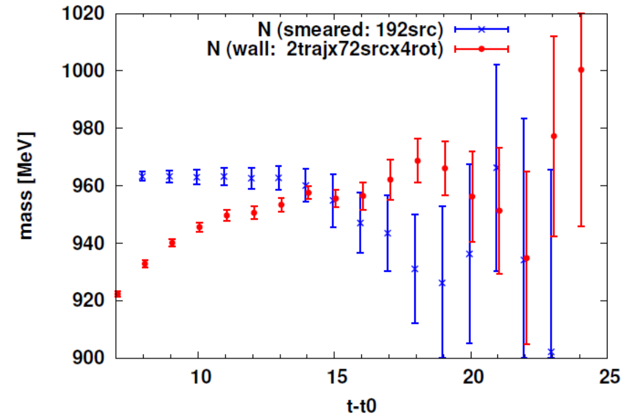
NN system (S = 0)

- **$^1S_0$ channel**
  - Central Force
- **$^3S_1$-$^3D_1$ channel**
  - Central Force
  - Tensor Force

Central Potential NN ($^1S_0$)

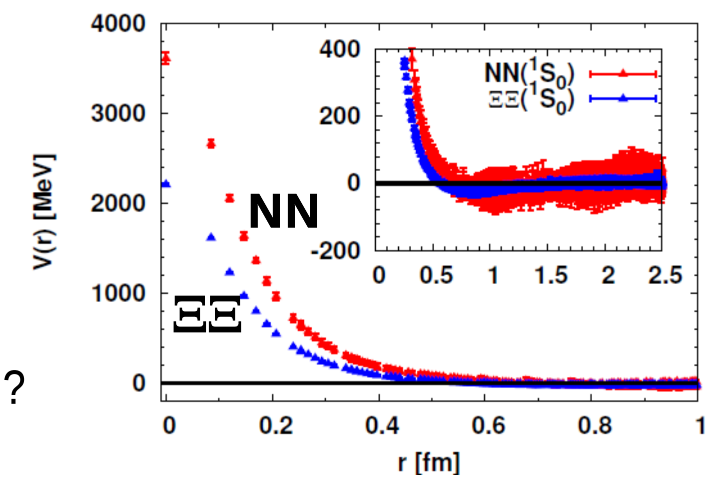


Single N



The effect of SU(3)f breaking

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



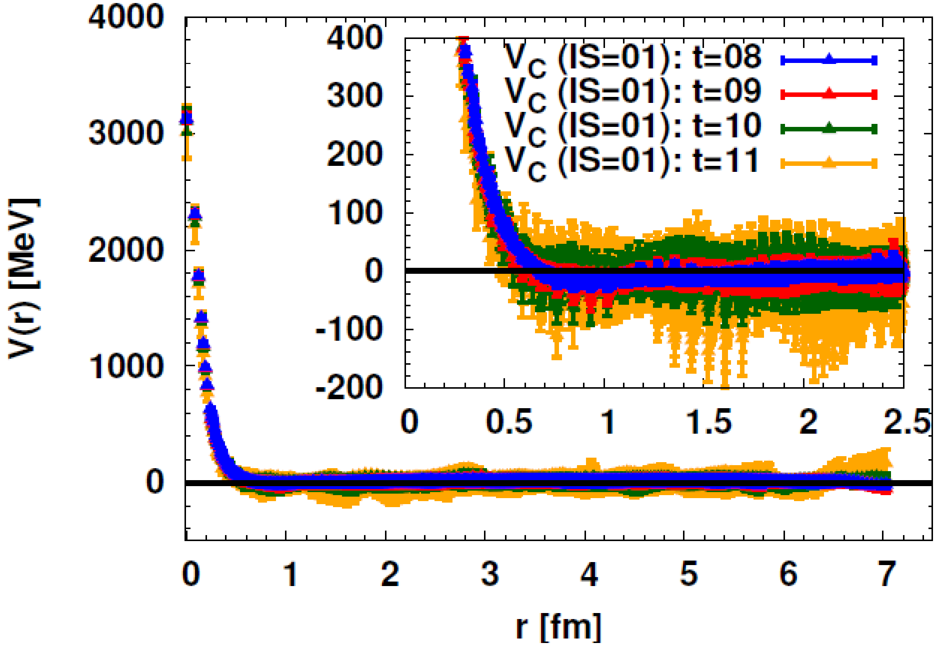
Repulsive core observed

Attraction at mid-long range

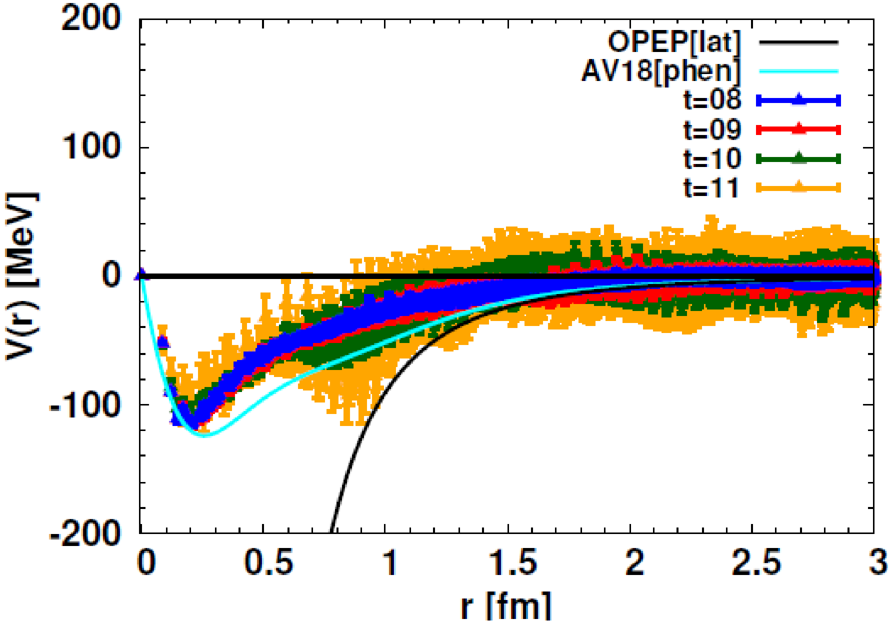
Repulsive core enhanced
for lighter quark mass ? ←→ OGE ?

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)

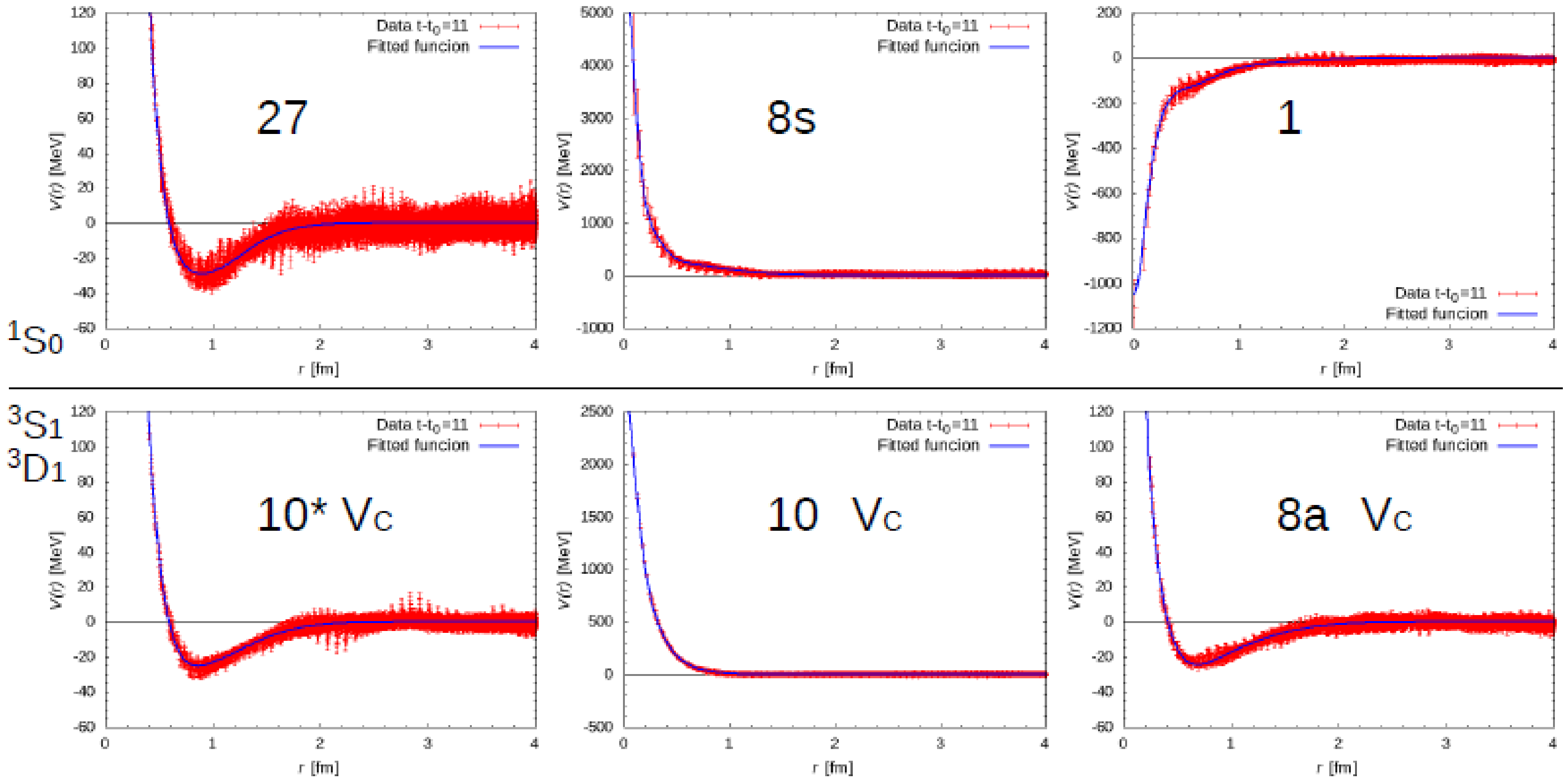
➔ Single-particle energy of Hyperon in nuclear matter

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

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

Central Force in Irrep-base (diagonal)

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



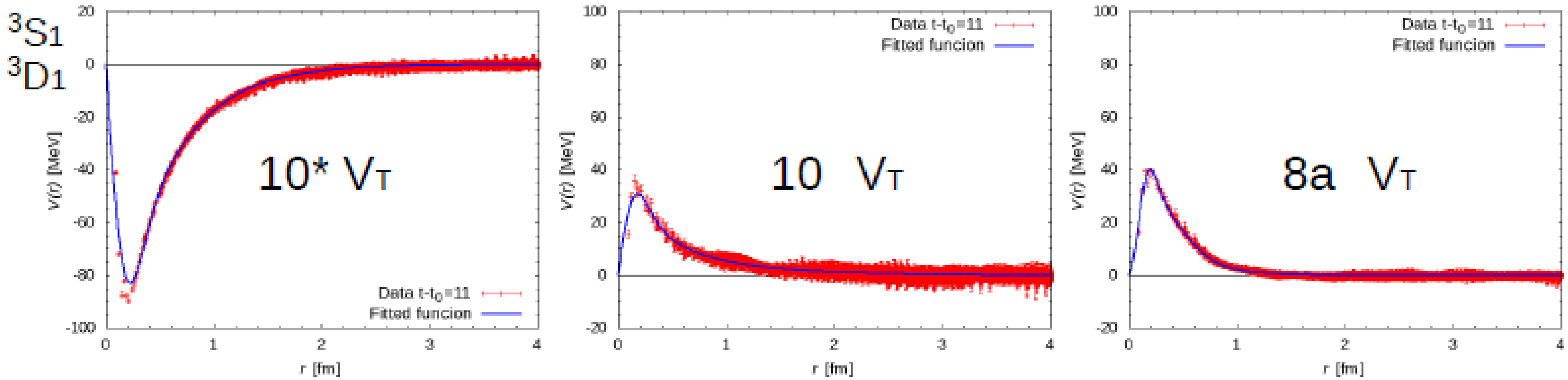
(off-diagonal component is small)

[K. Sasaki]

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

Tensor Force in Irrep-base (diagonal)

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



➔ We calculate single-particle energy of hyperon in nuclear matter w/ LQCD baryon forces

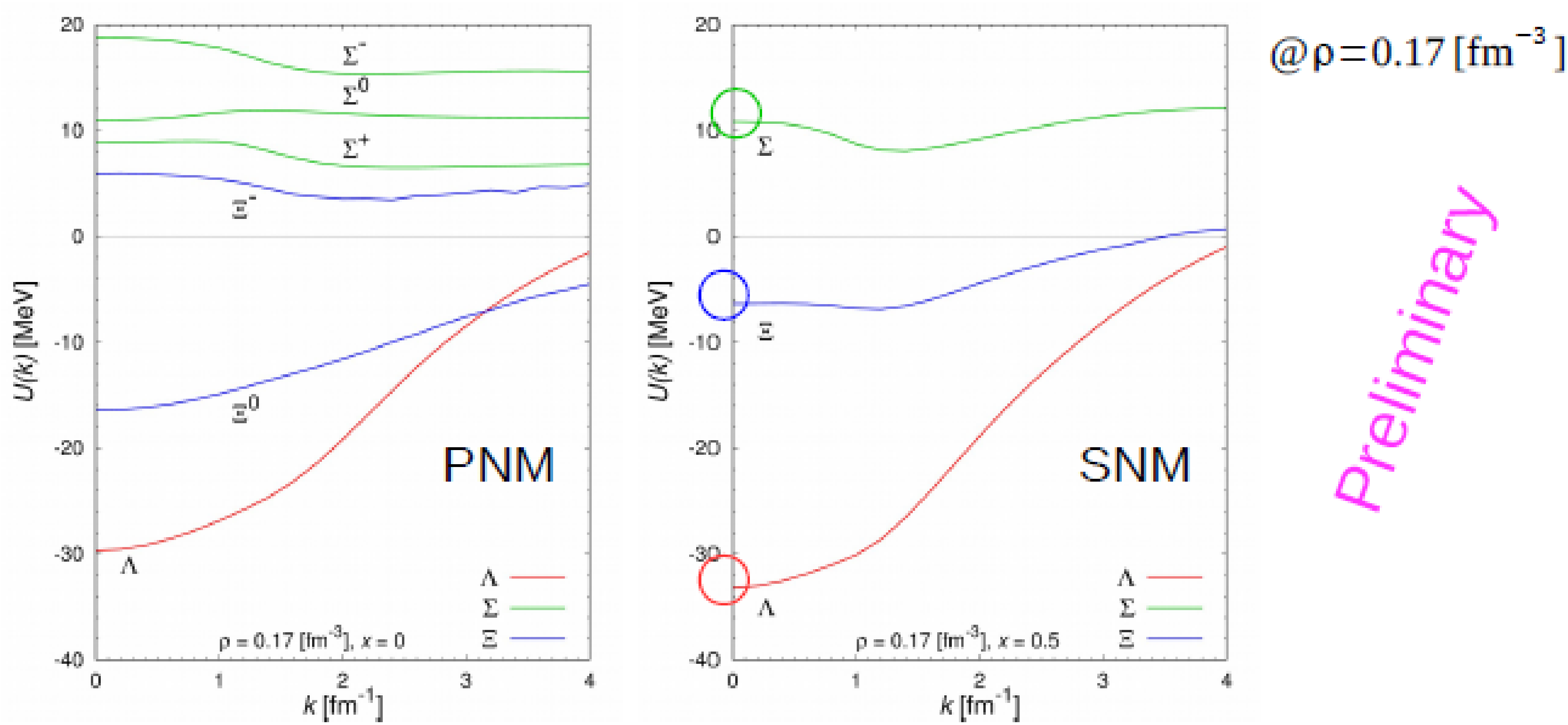
(off-diagonal component neglected)

We fit by

$$V(r) = a_1\, e^{-a_2 r^2} + a_3\, e^{-a_4 r^2} + a_5 \left[\left(1 - e^{-a_6 r^2}\right) \frac{e^{-a_7 r}}{r} \right]^2 \quad \text{(central)}$$

$$V(r) = a_1 \left(1 - e^{-a_2 r^2}\right)^2 \left(1 + \frac{3}{a_3 r} + \frac{3}{(a_3 r)^2}\right) \frac{e^{-a_3 r}}{r} + a_4 \left(1 - e^{-a_5 r^2}\right)^2 \left(1 + \frac{3}{a_6 r} + \frac{3}{(a_6 r)^2}\right) \frac{e^{-a_6 r}}{r} \quad \text{(tensor)}$$

Hyperon single-particle potentials



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

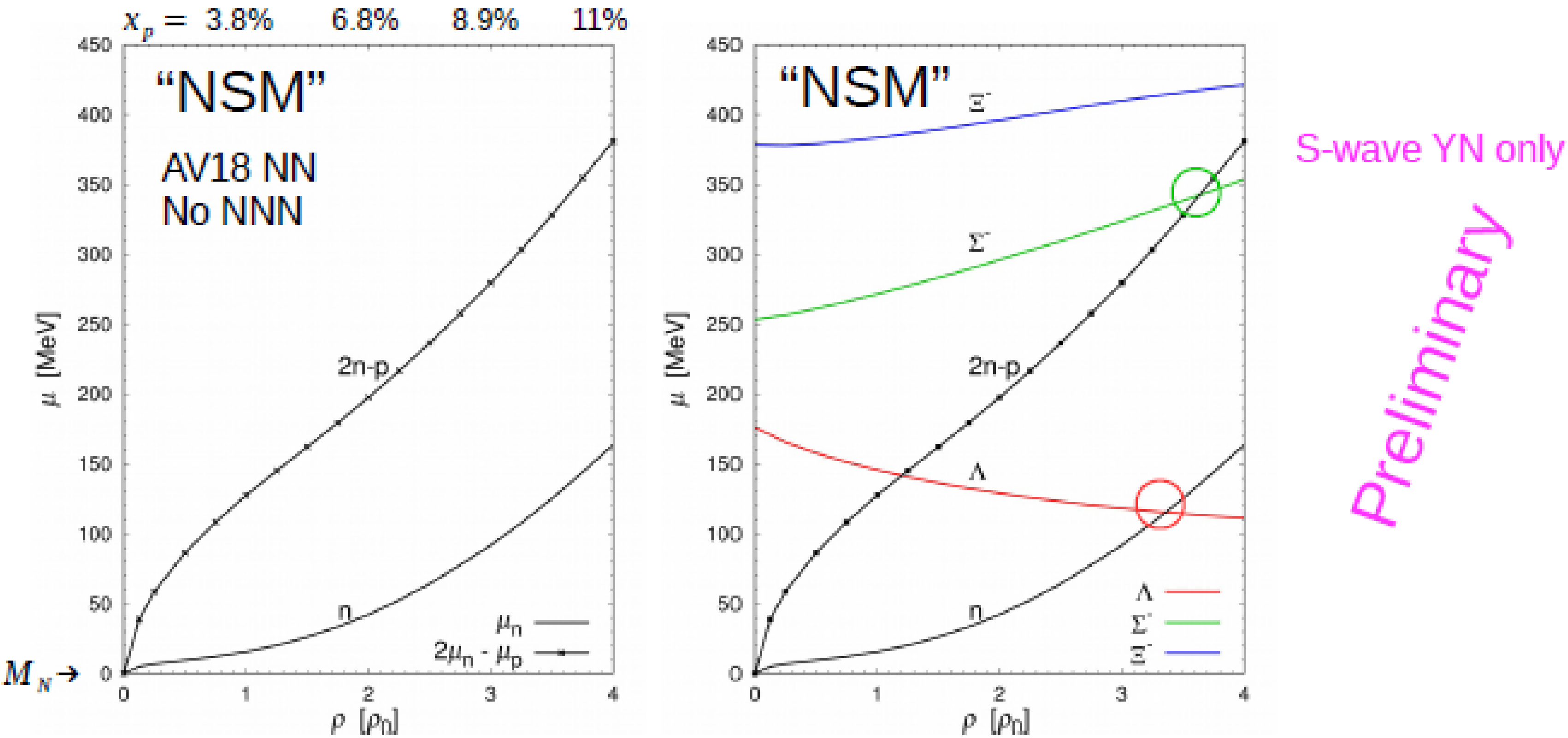
$$U_\Lambda^{\rm Exp}(0) \simeq -30\,, \quad U_\Xi(0)^{\rm Exp} \simeq -10\,, \quad U_\Sigma^{\rm Exp}(0) \geq +20 \quad [\mathrm{MeV}]$$

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

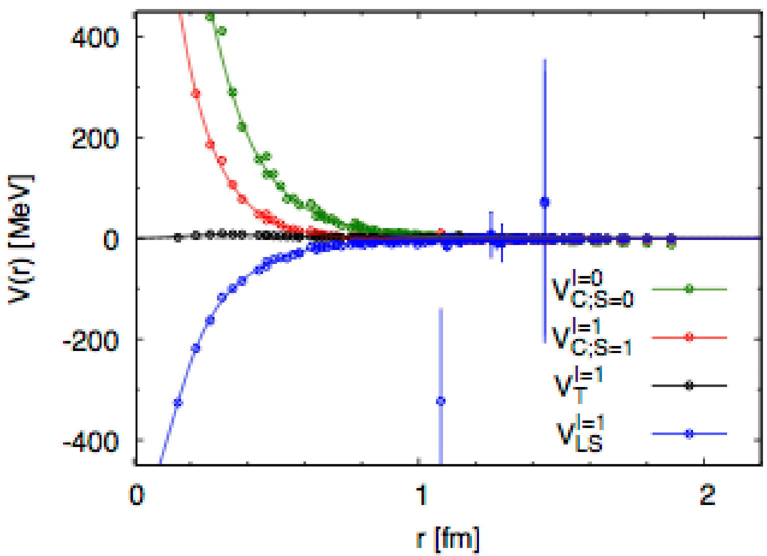
[T. Inoue]

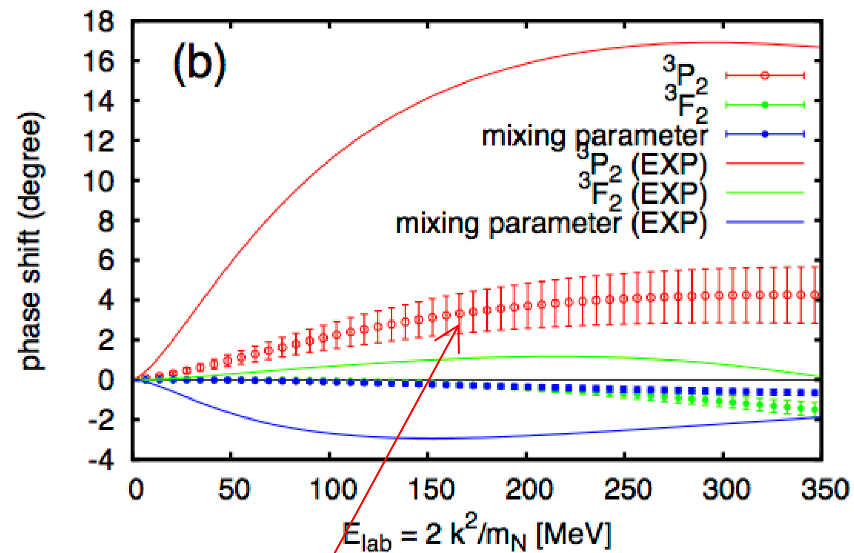
NN-forces in P=(−) channel (mπ=1.1 GeV)

- Central, tensor & LS forces

$$^1P_1,\ ^3P_0,\ ^3P_1,\ ^3P_2\text{–}^3F_2$$

Phase shifts





Superfluidity $^3P_2$ in neutron star
←→ neutrino cooling

Attractive in $^3P_2$

←→ observation of Cas A NS

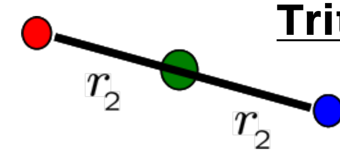
Qualitatively good, but strength is weak
(We also observe potentials glow by lighter mass)

K.Murano et al., PLB735(2014)19

c.f. CalLat Coll. PLB765(2017)285

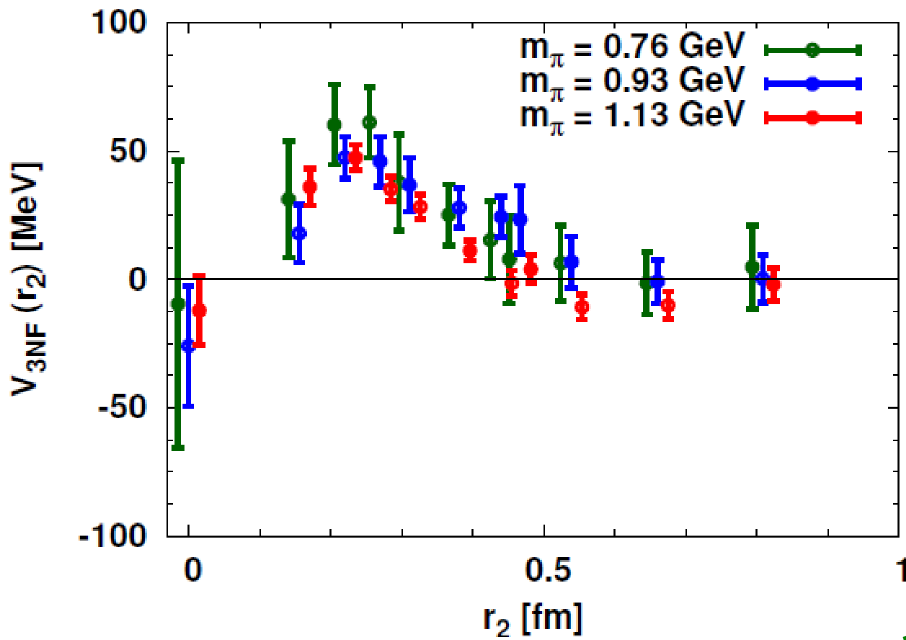
3N-forces (3NF)

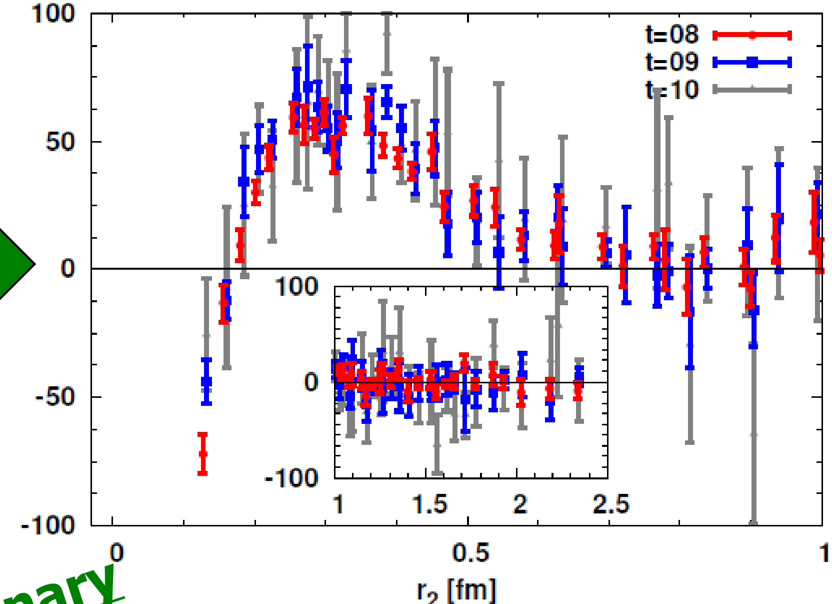
Triton channel



Nf=2, mπ=0.76-1.1 GeV

Nf=2+1, mπ=0.51 GeV





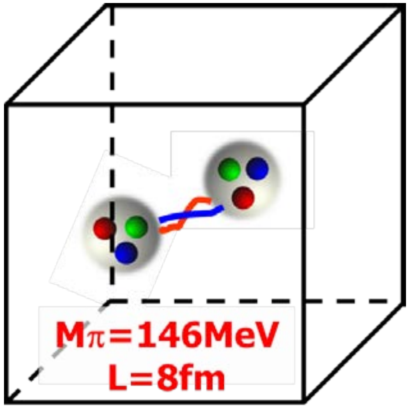
Preliminary

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

- Hadron Int.: Bridge between particle/nuclear/astro-physics
- HAL QCD method : reliable calculation w/o g.s. saturation
- LQCD at heavy masses: QCD ➔ EoS, nuclei, exotics
- 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