Baryon interactions at physical quark masses in Lattice QCD

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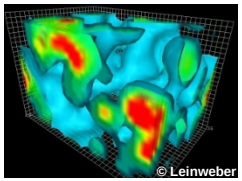
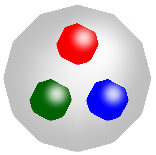
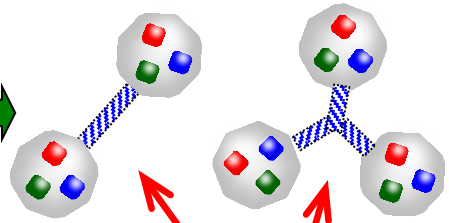
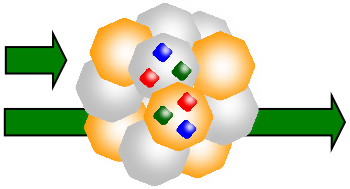
T. Inoue (Nihon Univ.)

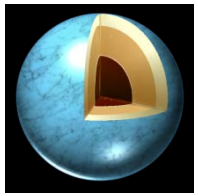
The Odyssey from Quarks to Universe

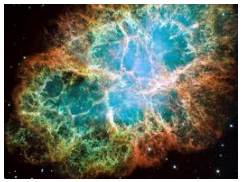












QCD vacuum

Baryons

Nuclei

Neutron Stars / Supernovae
Nucleosynthesis

QCD

1st-principle Lattice QCD

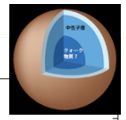
Baryon Forces

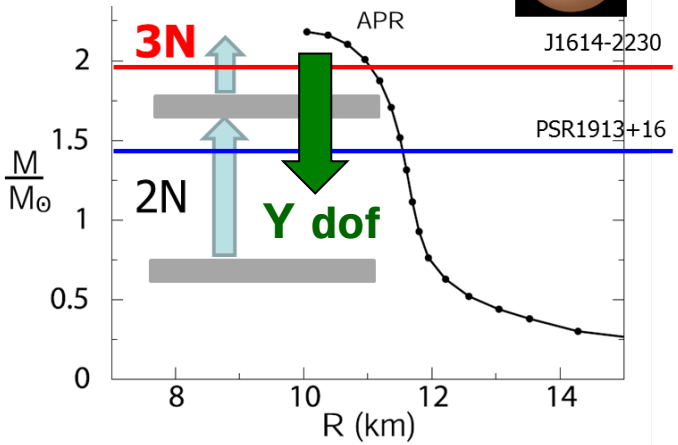
ab-initio nuclear calc.

J-PARC

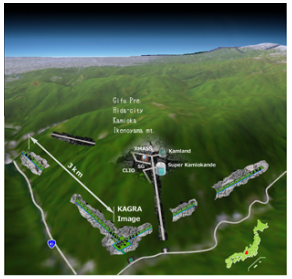
LHC/RHIC

EoS of Dense Matter





RIBF/FRIB

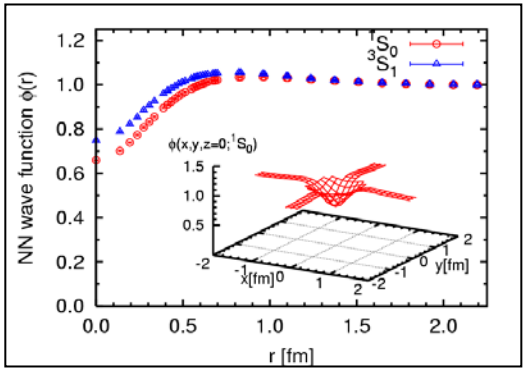


aLIGO/KAGRA

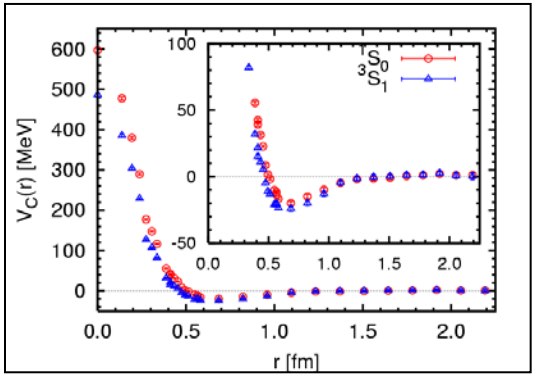
HAL QCD method

Lattice QCD

NBS wave func.



Lat Baryon Force



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

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

- **E-indep potentail from NBS w.f.** Aoki-Hatsuda-Ishii PTP123(2010)89
  - **Faithful to Phase Shifts by construction** (non-locality: derivative expansion)
- **Time-dependent HAL method** N.Ishii et al. (HAL Coll.) PLB712(2012)437
  - **G.S. saturation NOT required ←→ Fake plateaux in the Direct method**

    ➔ Iritani's talk
- **Coupled Channel formalism** S. Aoki et al. (HAL Coll.) Proc.Jpn.Acad.B87(2011)509
  - **Above inelastic threshold** ➔ Essential for **YN/YY-forces**

- 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

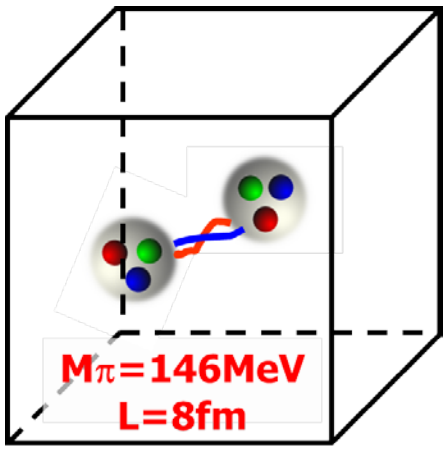
- Exponential speedup — Doi-Endres (2013)

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

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

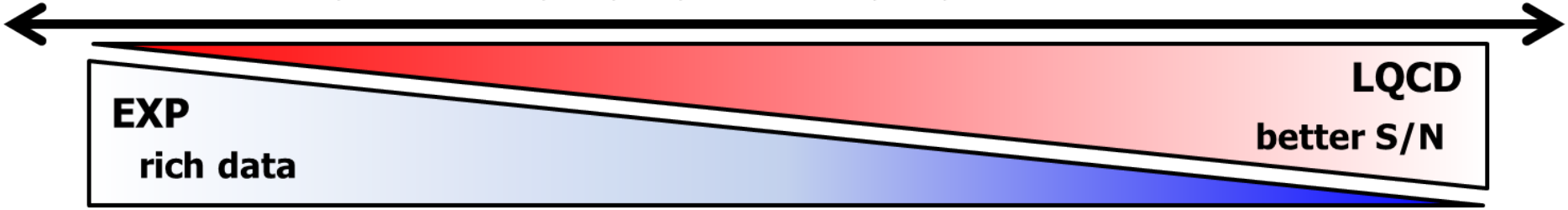
PACS Coll., PoS LAT2015, 075



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

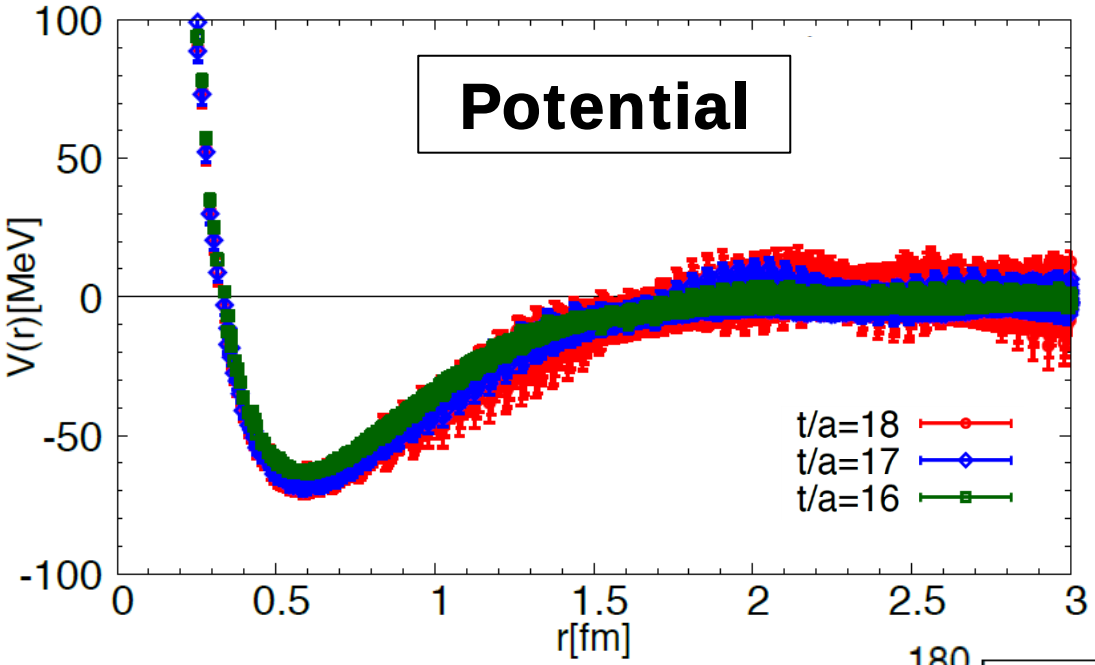
Predictions for Hyperon forces

S=0	S=–1	S=–2	S=–3	S=–4	S=–5	S=–6
NN	NΛ, NΣ	ΛΛ, ΛΣ, ΣΣ, NΞ	ΛΞ, ΣΞ, NΩ	ΞΞ	ΞΩ	ΩΩ

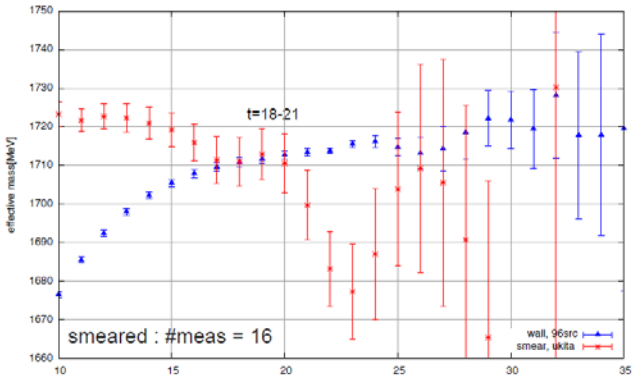


ΩΩ system ($^1S_0$)

(The "most strange" dibaryon system)

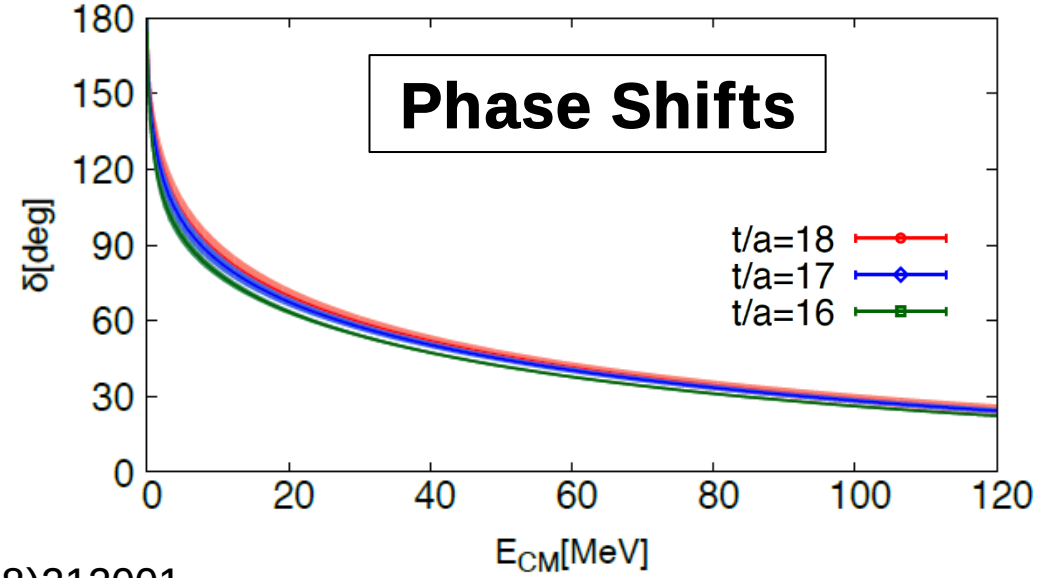


m(eff) for single Ω



t = 18 : ~0.2-0.3% sys error

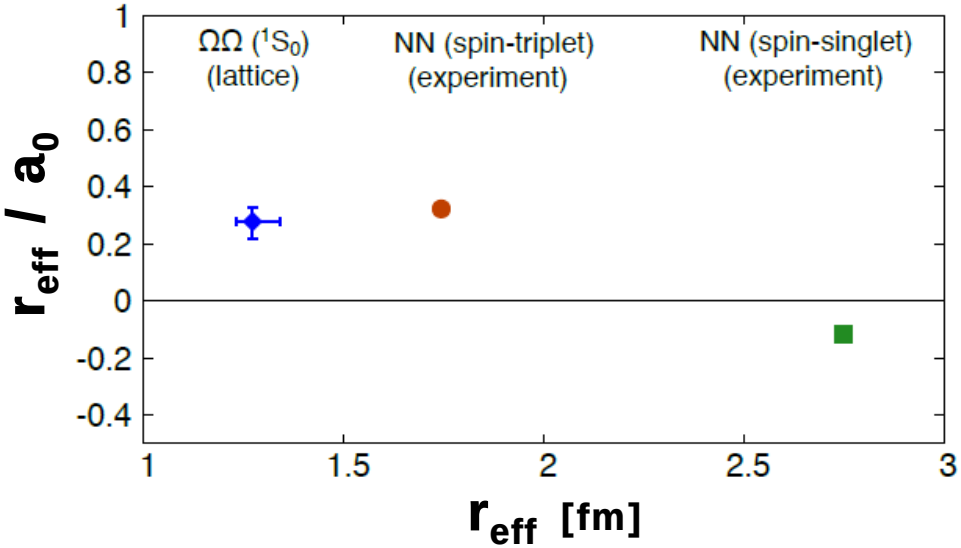
Strong Attraction



S. Gongyo et al. (HAL Coll.), PRL120(2018)212001

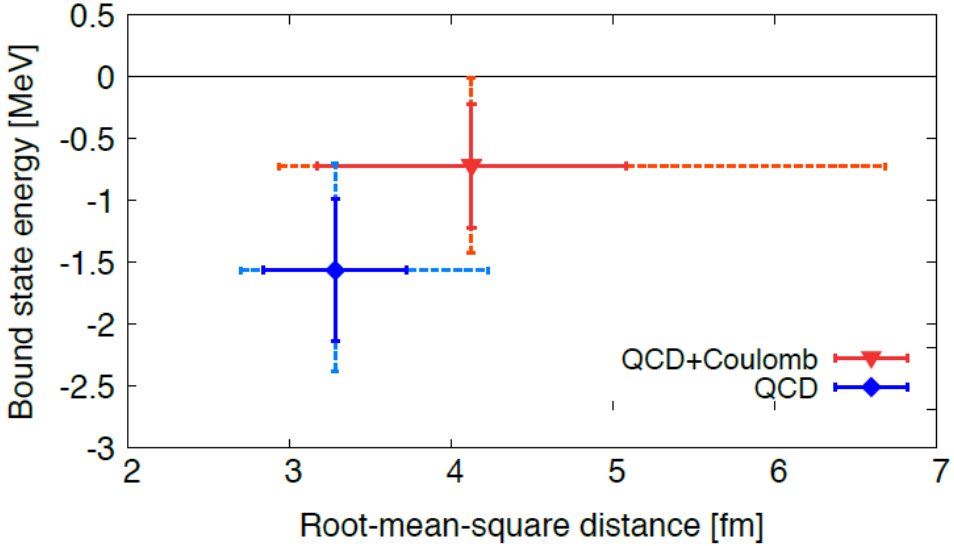
ΩΩ system ($^1S_0$)

(The "most strange" dibaryon system)



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

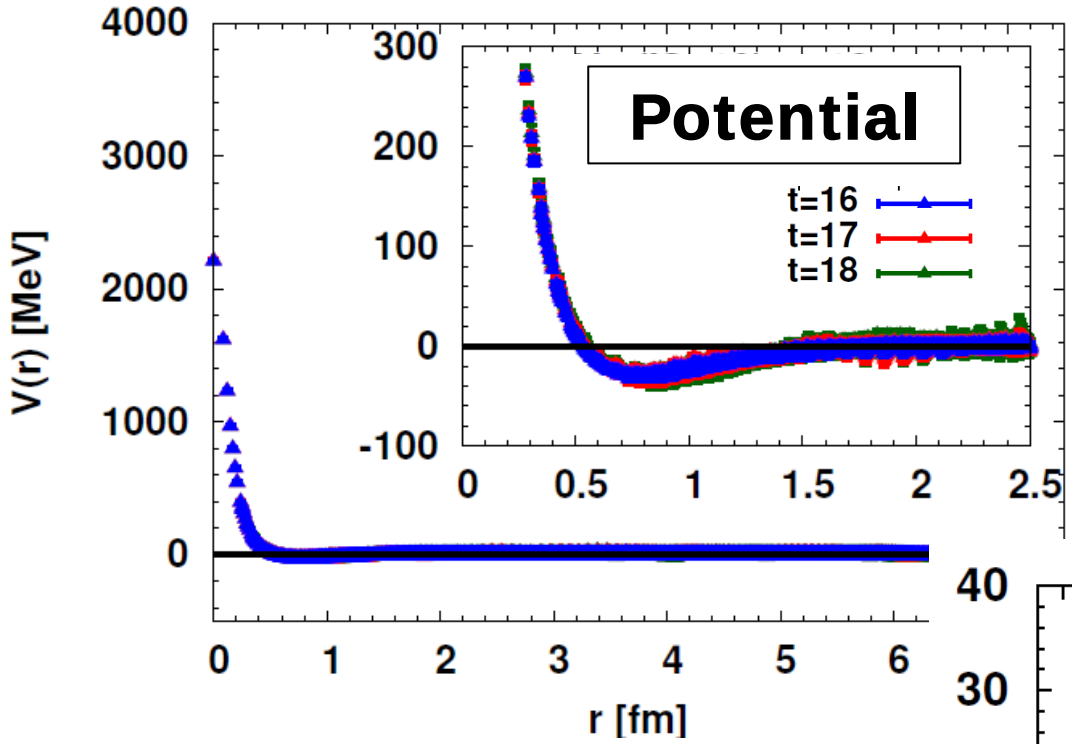
Vicinity of bound / unbound
[~ Unitary limit]



⟺ **ΩΩ correlation in HIC exp.**

S. Gongyo et al. (HAL Coll.), PRL120(2018)212001

ΞΞ system ($^1S_0$)



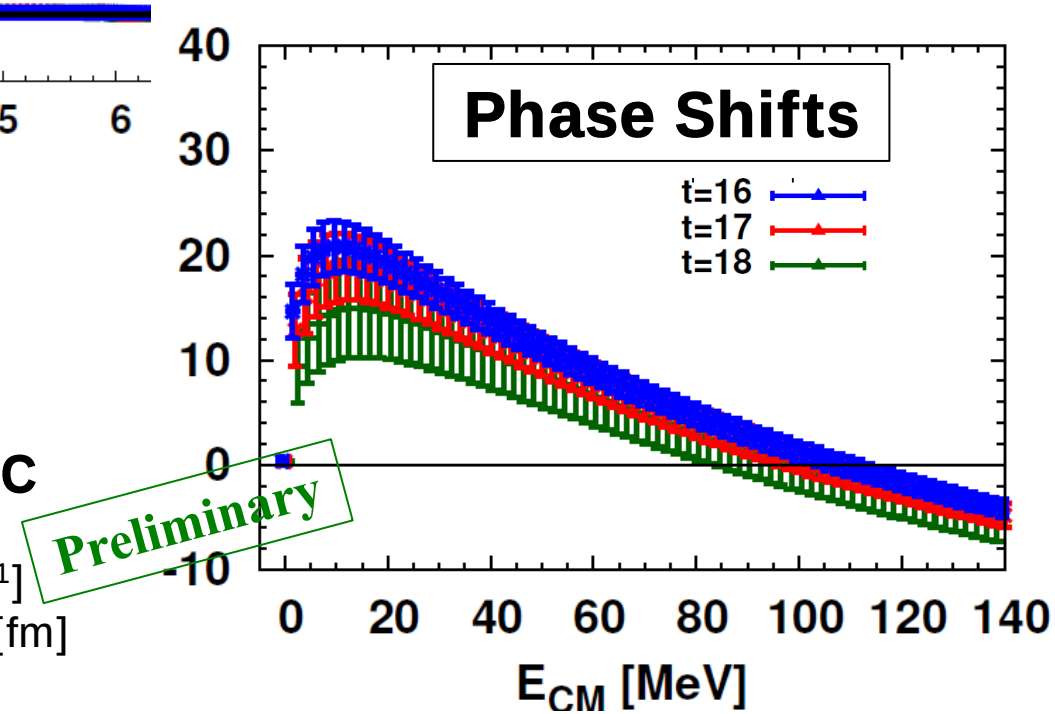
Flavor SU(3)-partner of dineutron

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

Strong Attraction

yet Unbound

⟺ **ΞΞ correlation in HIC**



a_0^{-1} = 1.03(32)(42) [fm^{-1}]
r_{eff} = 3.64(2.32)(0.44) [fm]

(2-gauss + 2-OBEP)

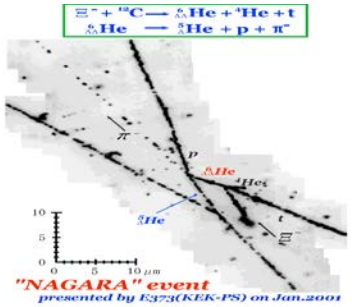
S = -2 channel (Coupled Channel)

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

R. Jaffe (1977), "Perhaps a Stable Dibaryon"

NAGARA-event (2001)

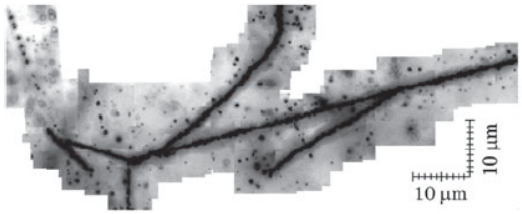
$$\Xi^- + {}^{12}\mathrm{C} \rightarrow {}_{\Lambda\Lambda}{}^{6}\mathrm{He} + {}^{4}\mathrm{He} + t$$



Ξ–hypernuclei

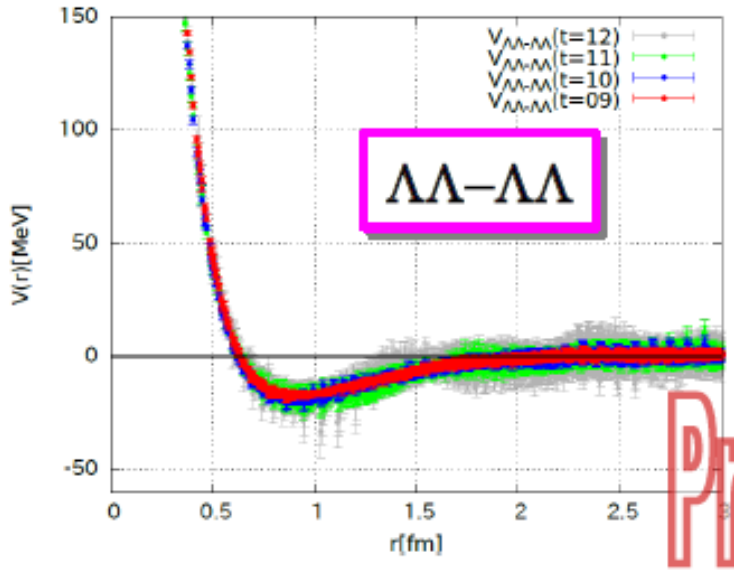
KISO-event (2014)

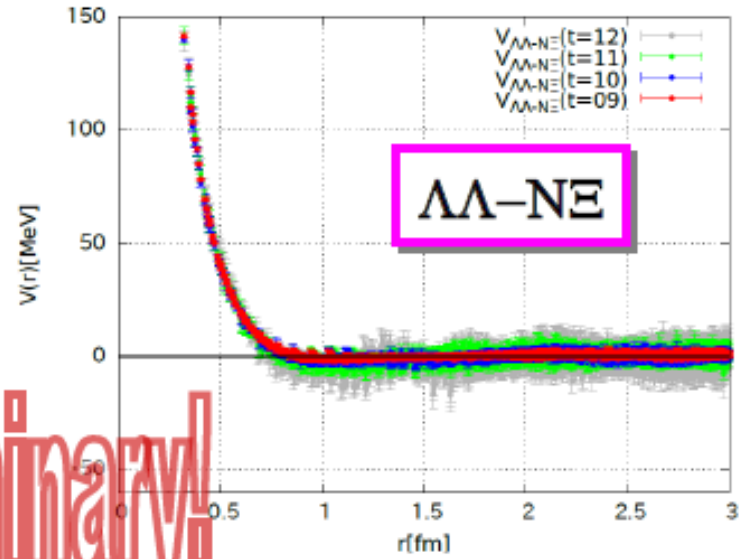
$$\Xi^- + {}^{14}\mathrm{N} \rightarrow {}_{\Lambda}{}^{10}\mathrm{Be} + {}_{\Lambda}{}^{5}\mathrm{He}$$



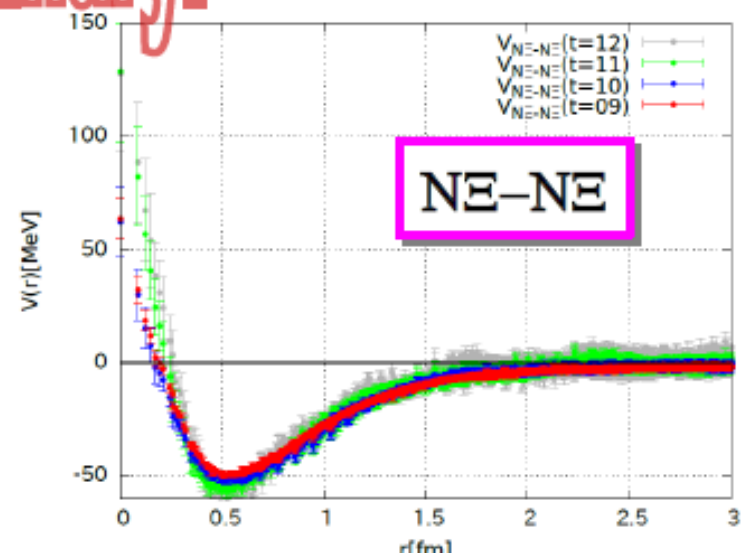
B.E. = 4.38(25) MeV
(or 1.11(25) MeV)

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





Preliminary!



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

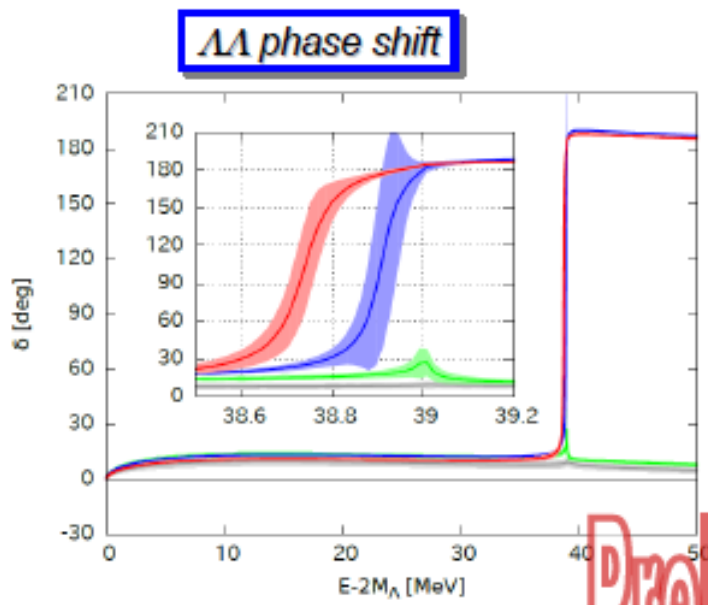
$m_{N\Xi} = 2260\text{MeV}$

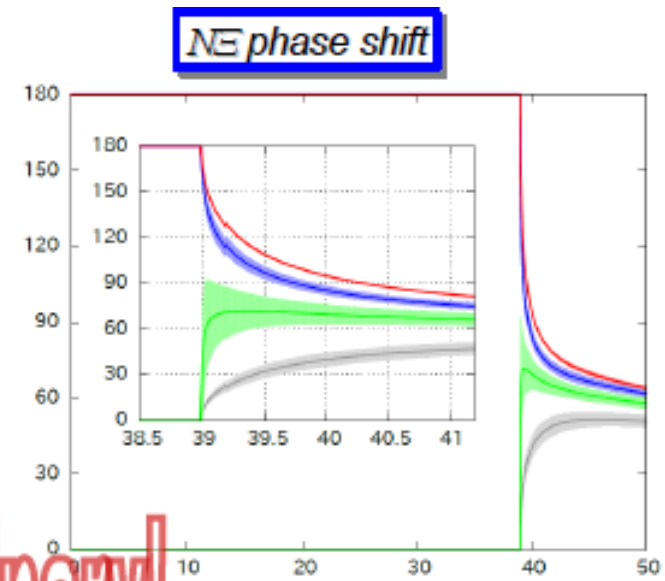
$m_{\Lambda\Lambda} = 2230\text{MeV}$

2x2 Potentials

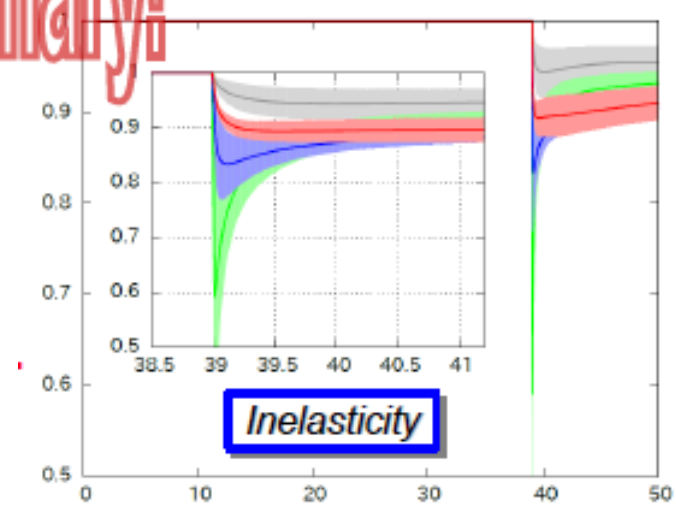
[K. Sasaki]

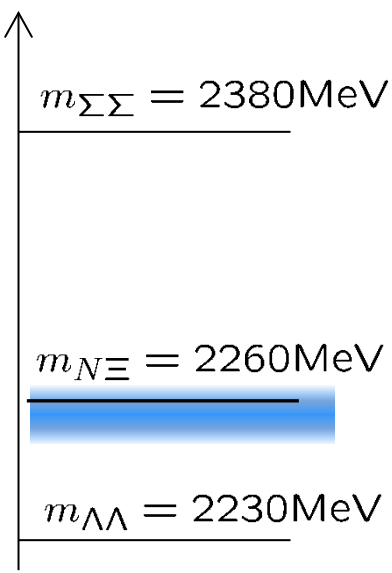
ΛΛ, NΞ (effective) 2x2 coupled channel analysis





Preliminary!



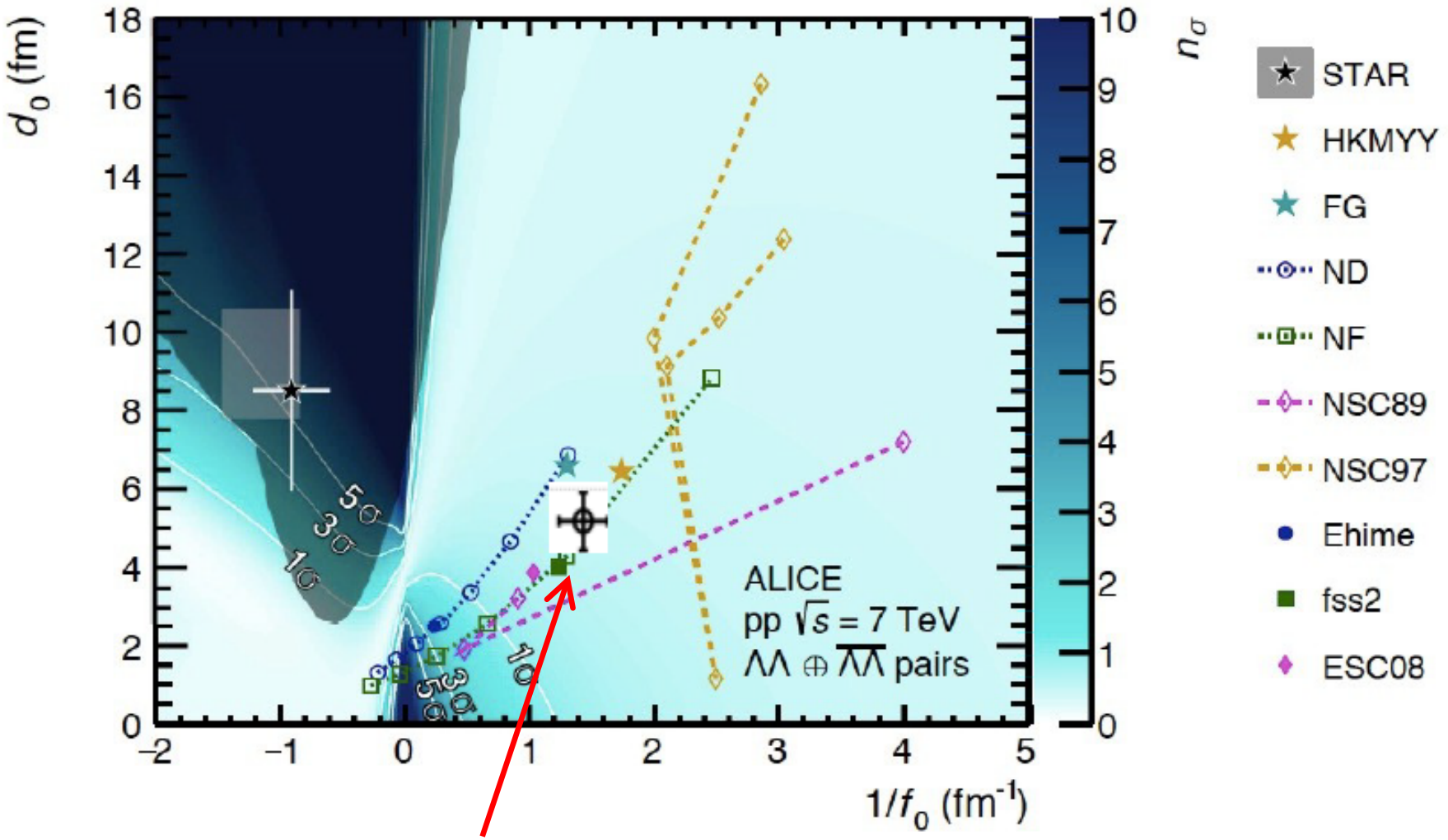


H-resonance (?)

"Perhaps a Resonant Dibaryon"

[K. Sasaki]

ΛΛ : LQCD prediction meets HIC exp



ALICE Coll., arXiv:1805.12455

S= –1 systems

🡐🡒 strangeness nuclear physics (Λ-hypernuclei @ J-PARC)

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

🡐🡒 Huge impact on EoS of high dense matter

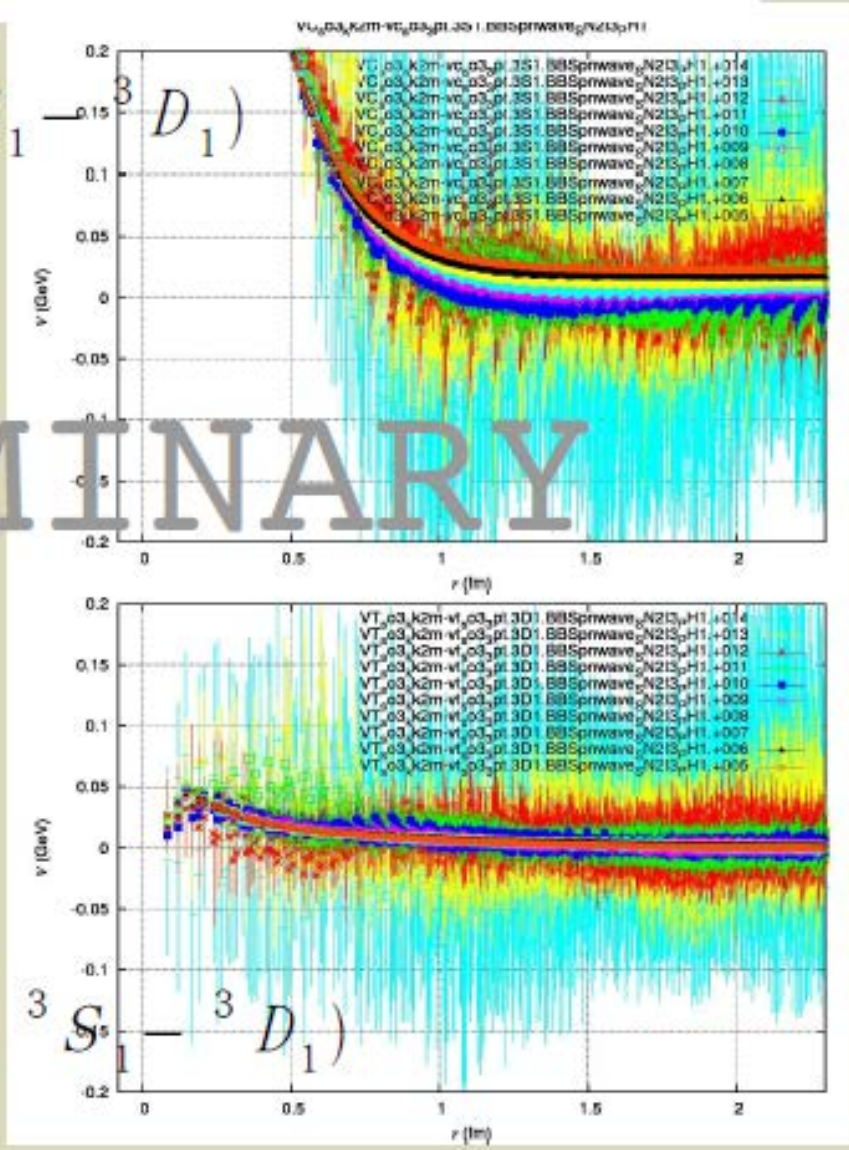
- **ΛN–ΣN (I=1/2) : coupled channel**
  - **$^1S_0$ ~ 27-plet & 8s-plet**
  - **$^3S_1$-$^3D_1$ ~10*-plet & 8a-plet**

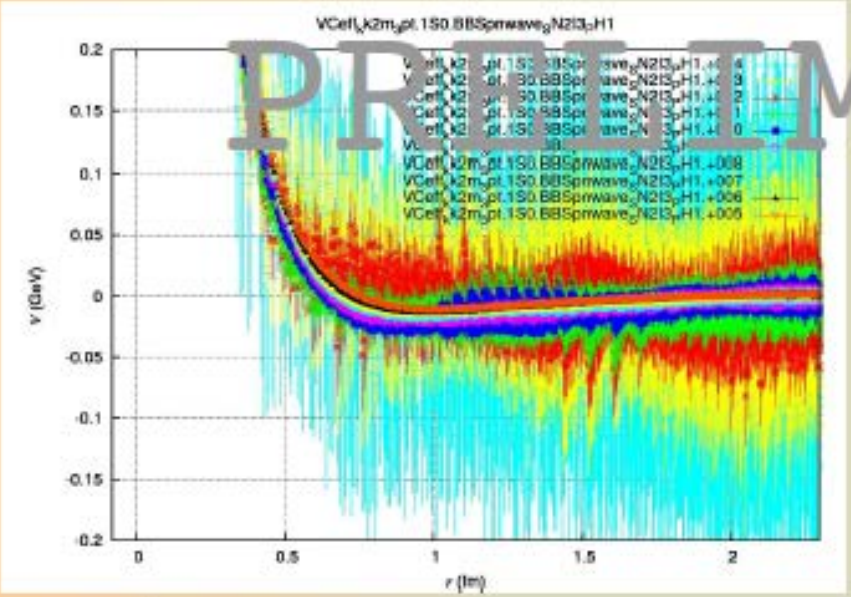
- **ΣN (I=3/2)**
  - **$^1S_0$ ~ 27-plet**
    ⇔ NN($^1S_0$) + SU(3) breaking
  - **$^3S_1$-$^3D_1$ ~10-plet**
    ⇔ Σ^- in Netron Star

ΣN (I=3/2) potential in $^1S_0$, $^3S_1$–$^3D_1$ [H. Nemura]

$\Sigma N(I=3/2)$

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





PRELIMINARY

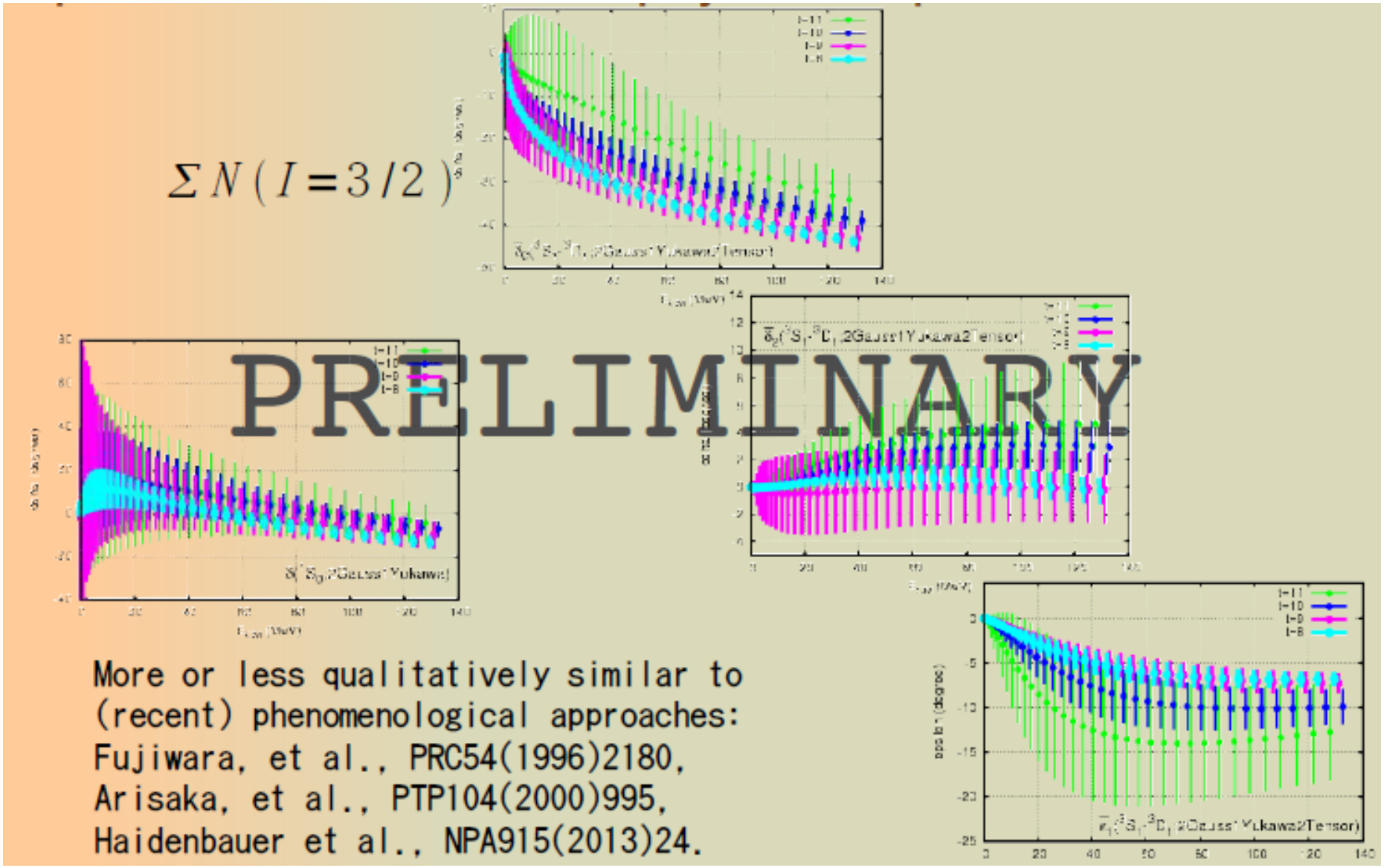
$V_c(^1S_0)$

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

(400conf x 4rot x 96src)

ΣN (I=3/2) phase shifts in $^1S_0$, $^3S_1$–$^3D_1$ [H. Nemura]

$\Sigma N(I=3/2)$



More or less qualitatively similar to (recent) phenomenological approaches:
Fujiwara, et al., PRC54(1996)2180,
Arisaka, et al., PTP104(2000)995,
Haidenbauer et al., NPA915(2013)24.

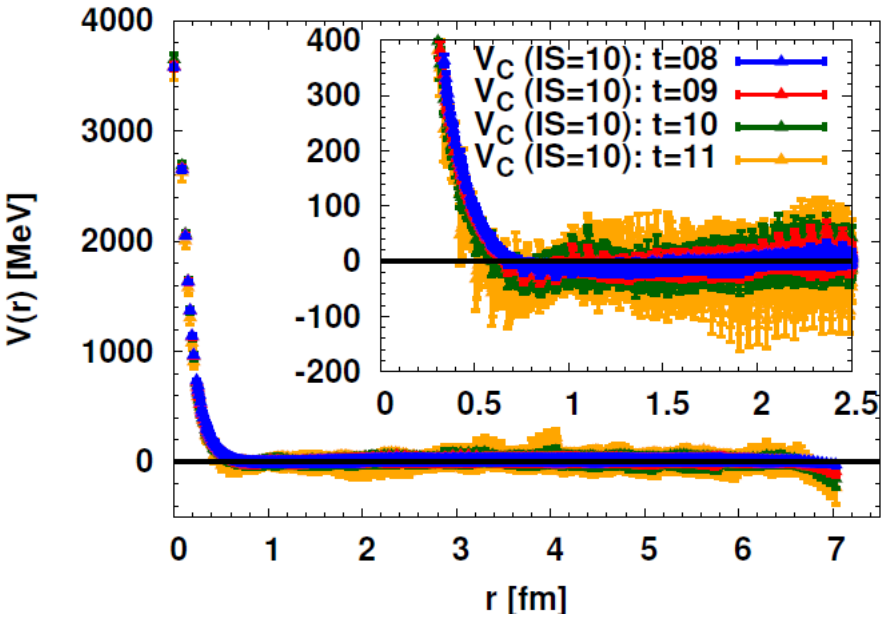
(400conf x 4rot x 96src)

NN system (S = 0)

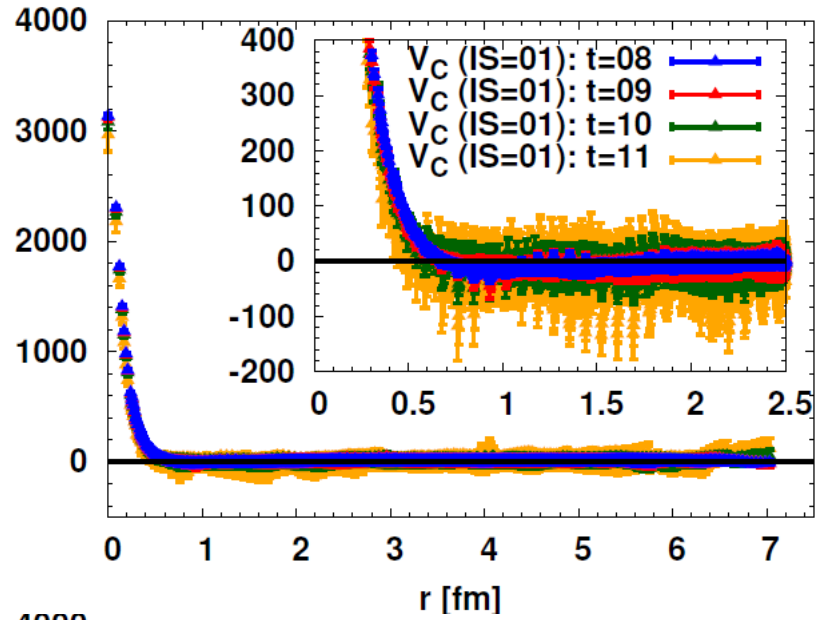
- **$^1S_0$ channel**
  - Central Force
- **$^3S_1$-$^3D_1$ channel**
  - Central Force
  - Tensor Force

NN-Potentials

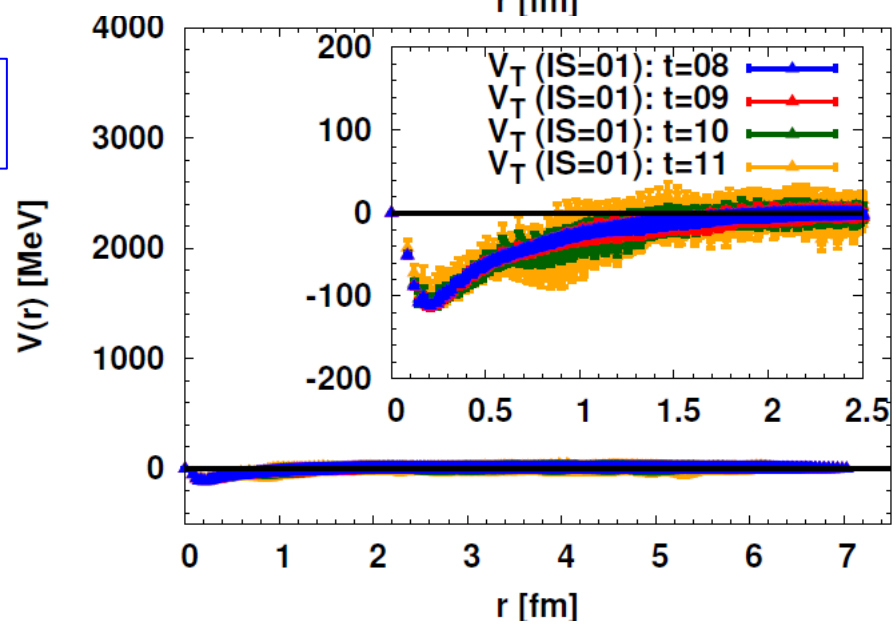
$^1S_0$



$^3S_1$-$^3D_1$



Central



Tensor

Preliminary

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

(400conf x 4rot x 96src)

Impact on dense matter

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

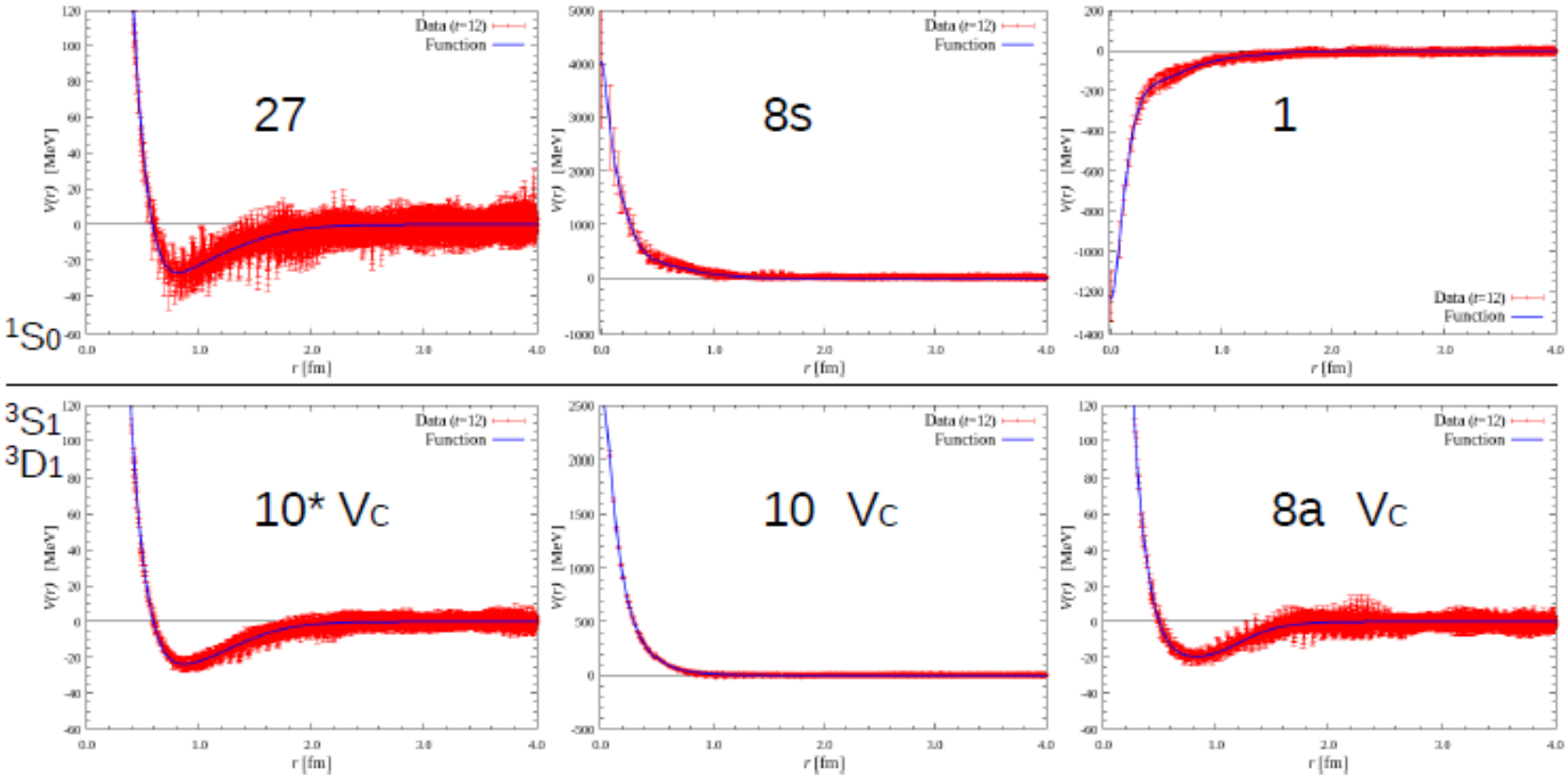
➔ Single-particle energy of Hyperon in nuclear matter

(Only diagonal YN/YY forces in SU(3) irrep used)
(400conf x 4rot x 96src)

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

Central Force in Irrep-base (diagonal)

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



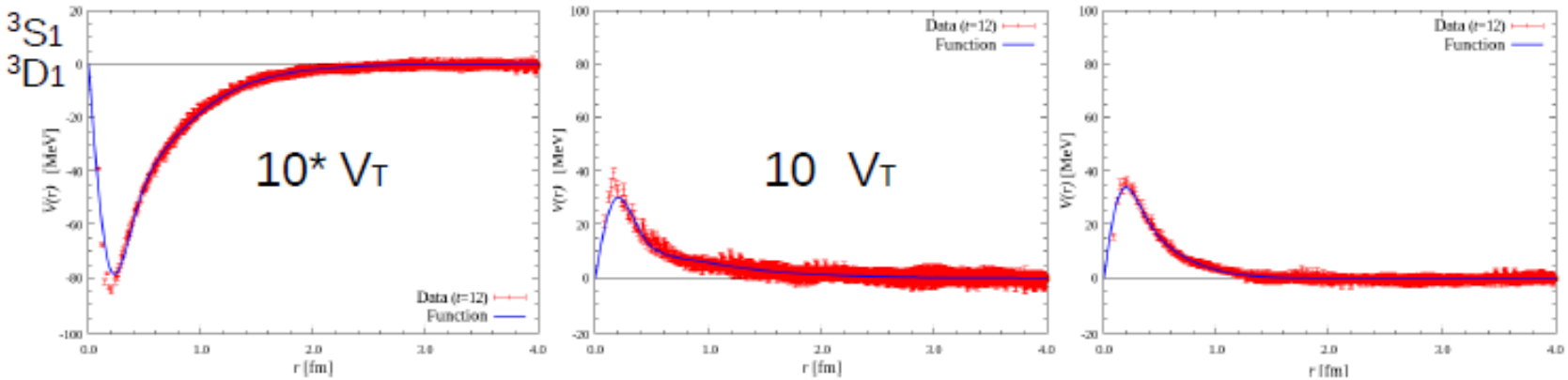
(off-diagonal component is small)

[K. Sasaki]

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

Tensor Force in Irrep-base (diagonal)

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



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

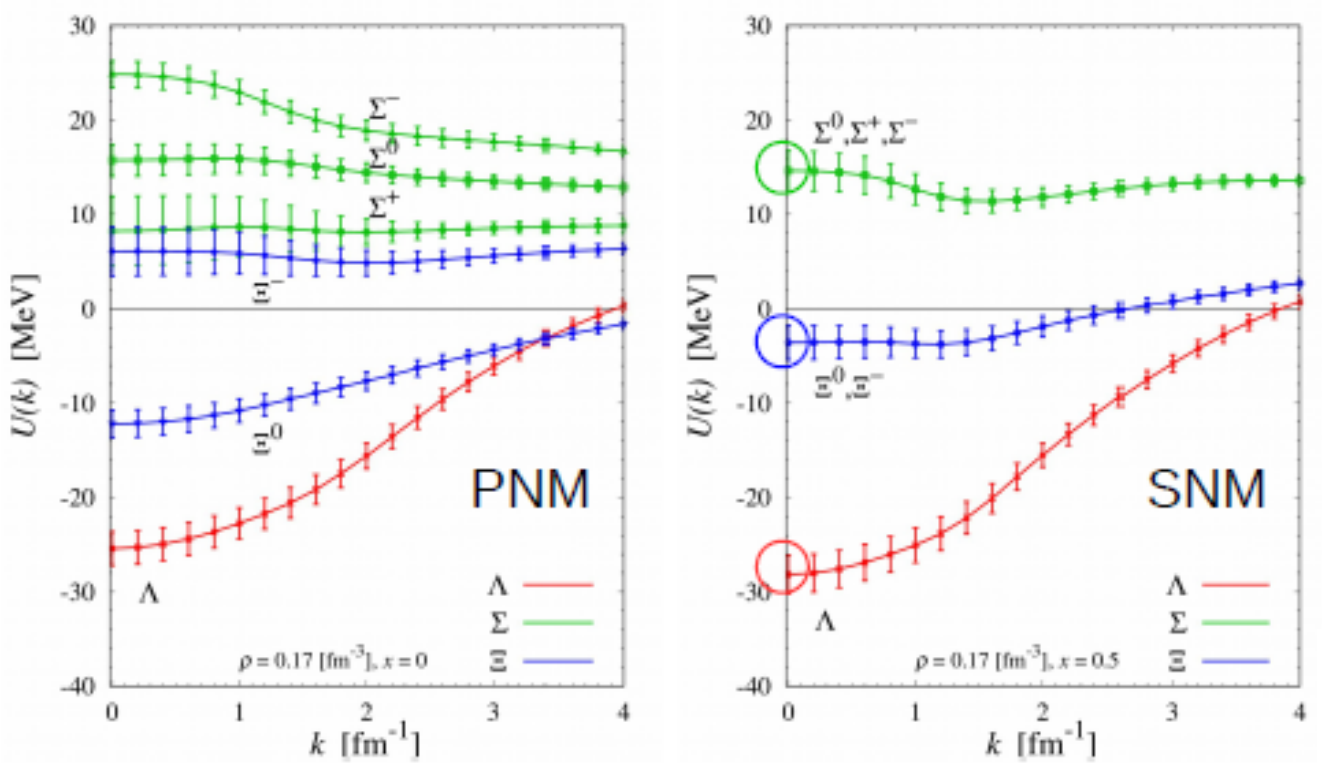
(off-diagonal component neglected)

We fit by

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

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

Hyperon single-particle potentials



@ρ=0.17 [fm^{-3}]

Preliminary

T. Inoue (HAL Coll.)
PoS INPC2016, 277

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

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

attraction — attraction small — repulsion

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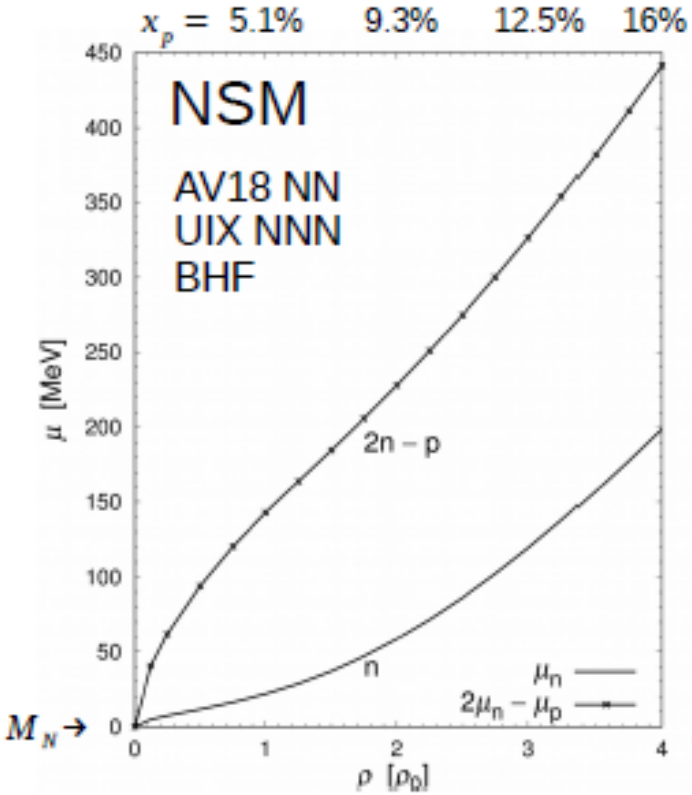
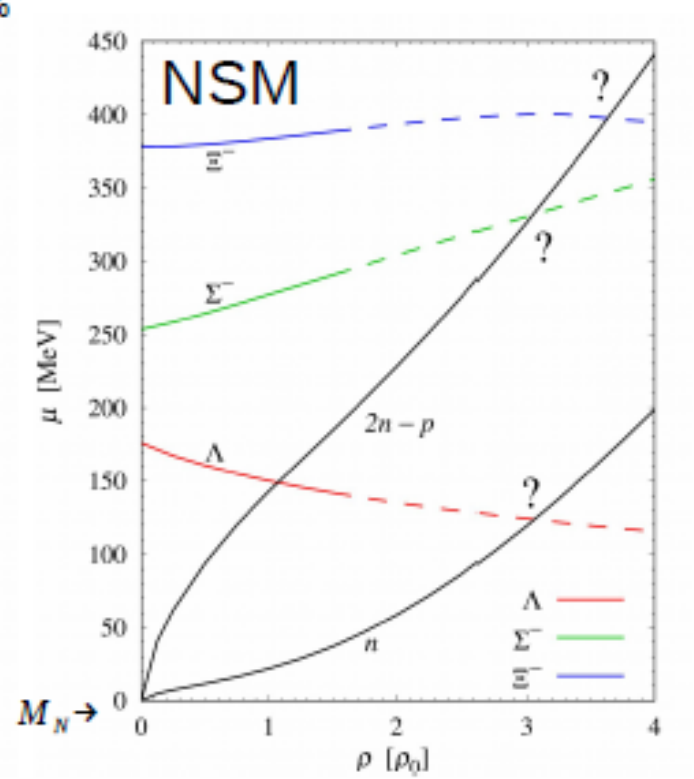
[T. Inoue]

Hyperon onset in NSM (just for fun)





S-wave YN only

Preliminary

- Result indicate Λ, Σ^-, Ξ^- appear around ρ = 3.0 - 4.0 ρ_0
- However,
  - $YN^{L=1,2...}$ and YNN force could be important at high density.
  - We may need to compare with more sophisticated μ_n, μ_p than BHF.

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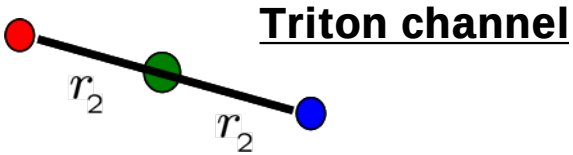
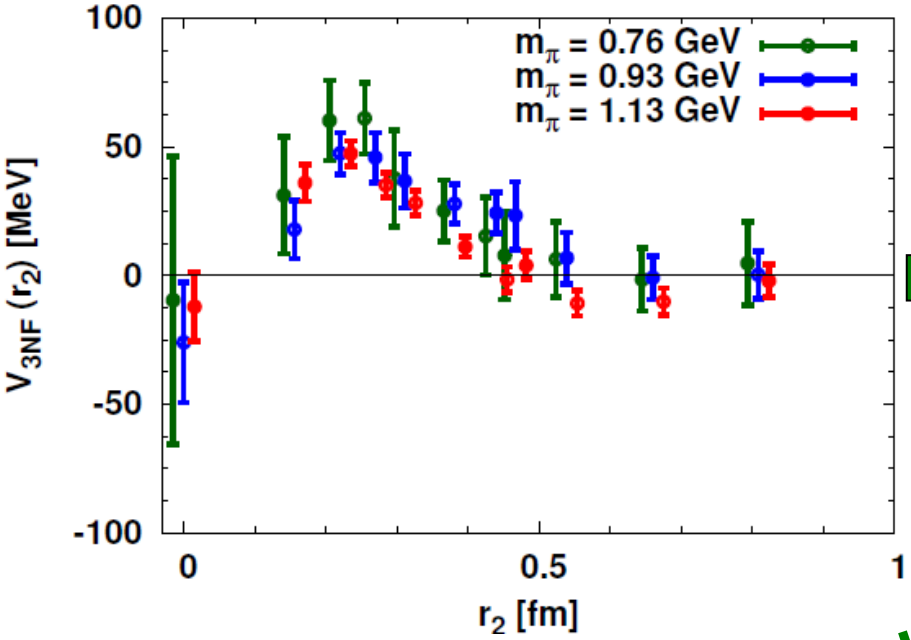
[T. Inoue]

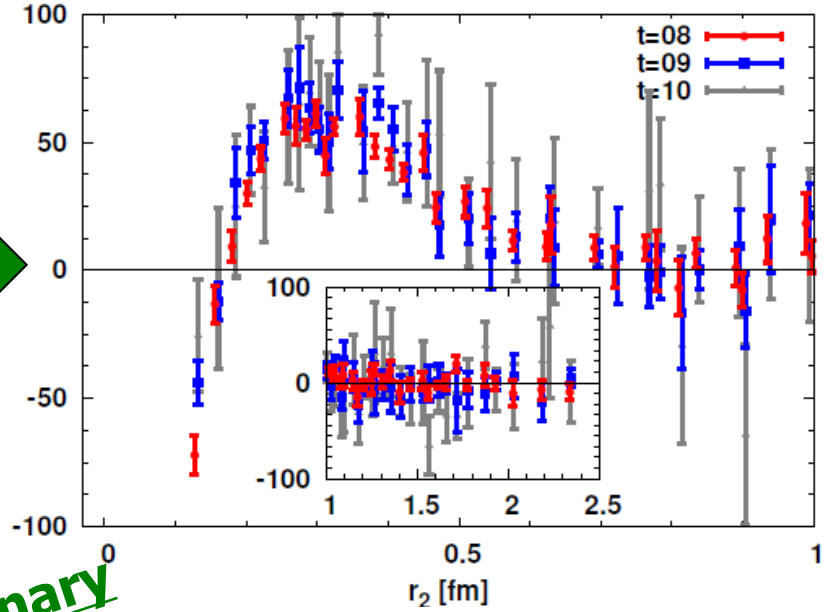
3N-forces (3NF)



Nf=2, mπ=0.76-1.1 GeV

Nf=2+1, mπ=0.51 GeV





Preliminary

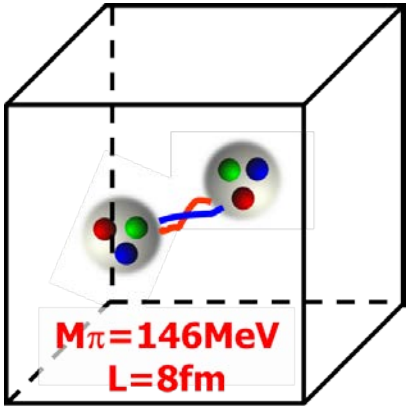
Magnitude of 3NF is similar for all masses
Range of 3NF tend to get longer (?) for m(pi)=0.5GeV

Kernel: ~50% efficiency achieved !

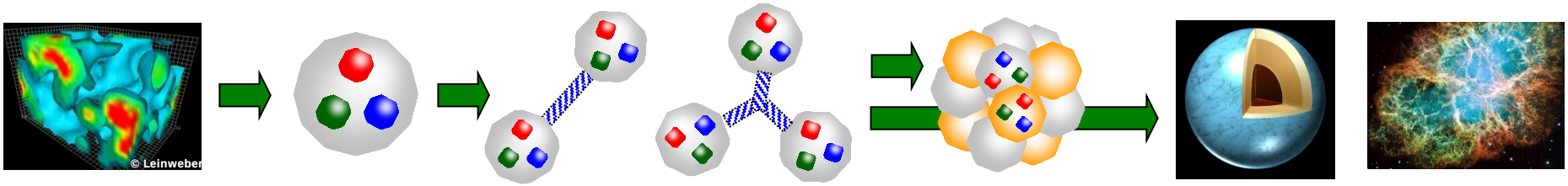
Summary

- 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
  - HAL QCD method is crucial

- Predictions for YN/YY forces ←→ Experiments/Observations
  - Exotic di-baryon states, Hypernuclei
  - Baryon-baryon correlation in HIC
  - Properties of dense matter



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



Backup Slides

Brueckner-Hartree-Fock LOBT

M.I. Haftel and F. Tabakin, Nucl. Phys. A158(1970) 1-42

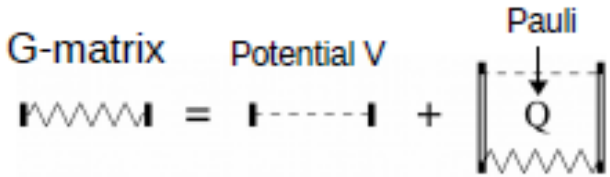
- Ground state energy in BHF framework

$$E_0 = \gamma \sum_k^{k_F} \frac{k^2}{2M} + \frac{1}{2} \sum_i^{N_{ch}} \sum_{k,k'}^{k_F} \mathrm{Re}\langle G_i(e(k)+e(k')) \rangle_A$$

- Bethe Goldston eq.

AV18 + "UIX"

$$\langle k_1 k_2 | G(\omega) | k_3 k_4 \rangle = \langle k_1 k_2 | V | k_3 k_4 \rangle + \sum_{k_5, k_6} \frac{\langle k_1 k_2 | V | k_5 k_6 \rangle Q(k_5, k_6) \langle k_5 k_6 | G(\omega) | k_3 k_4 \rangle}{\omega - e(k_5) - e(k_6)}$$



- Single particle spectrum & potential

$$e(k) = \frac{k^2}{2M_N} + U(k)$$

Physical

$$U(k) = \sum_i \sum_{k' \le k_F} \mathrm{Re}\langle k k' | G_i(e(k)+e(k')) | k k' \rangle_A$$

- Partial wave decomposition $^{2S+1}L_J = {}^1S_0, {}^3S_1, {}^3D_1, {}^1P_1, {}^3P_J \cdots$
- Continuous choice w/ effective mass approx. Angle averaged Q-operator

Brueckner-Hartree-Fock LOBT

- Hyperon single-particle potential

M. Baldo, G.F. Burgio, H.-J. Schulze, Phys. Rev. C58, 3688 (1998)

$$U_Y(k) = \sum_{N=n,p} \sum_{SLJ} \sum_{k' \le k_F} \langle kk' | G^{SLJ}_{(YN)(YN)} \left(e_Y(k) + e_N(k') \right) | kk' \rangle$$

$$^{2S+1}L_J = {}^1S_0,\ {}^3S_1,\ {}^3D_1, \Big|\ {}^1P_1,\ {}^3P_J\ \cdots$$

in our study

limitation

- YN G-matrix using $M^{\text{Phys}}_{N,Y}$, $U^{\text{AV18+UIX}}_{n,p}$, $V^{\text{LQCD}}_{S=-1}$ and, U^{LQCD}_{Y}

$$Q=0 \quad \begin{pmatrix} G^{SLJ}_{(\Lambda n)(\Lambda n)} & G_{(\Lambda n)(\Sigma^0 n)} & G_{(\Lambda n)(\Sigma p)} \\ G_{(\Sigma^0 n)(\Lambda n)} & G_{(\Sigma^0 n)(\Sigma^0 n)} & G_{(\Sigma^0 n)(\Sigma^- p)} \\ G_{(\Sigma^- p)(\Lambda n)} & G_{(\Sigma^- p)(\Sigma^0 n)} & G_{(\Sigma^- p)(\Sigma^- p)} \end{pmatrix} \qquad Q=+1 \quad \begin{pmatrix} G^{SLJ}_{(\Lambda p)(\Lambda p)} & G_{(\Lambda p)(\Sigma^0 p)} & G_{(\Lambda p)(\Sigma^+ n)} \\ G_{(\Sigma^0 p)(\Lambda p)} & G_{(\Sigma^0 p)(\Sigma^0 p)} & G_{(\Sigma^0 p)(\Sigma^+ n)} \\ G_{(\Sigma^+ n)(\Lambda p)} & G_{(\Sigma^+ n)(\Sigma^0 p)} & G_{(\Sigma^+ n)(\Sigma^+ n)} \end{pmatrix}$$

$$Q=-1 \quad G^{SLJ}_{(\Sigma^- n)(\Sigma^- n)} \qquad Q=+2 \quad G^{SLJ}_{(\Sigma^+ p)(\Sigma^+ p)}$$