Hyperon single-particle potentials from QCD on lattice

Takashi Inoue @Nihon Univ.

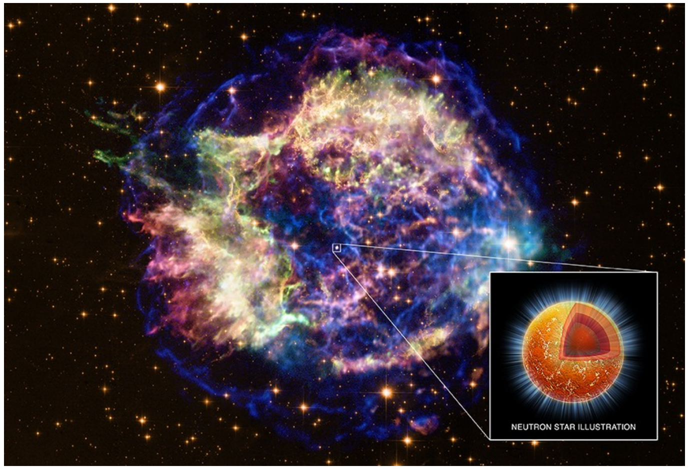
for

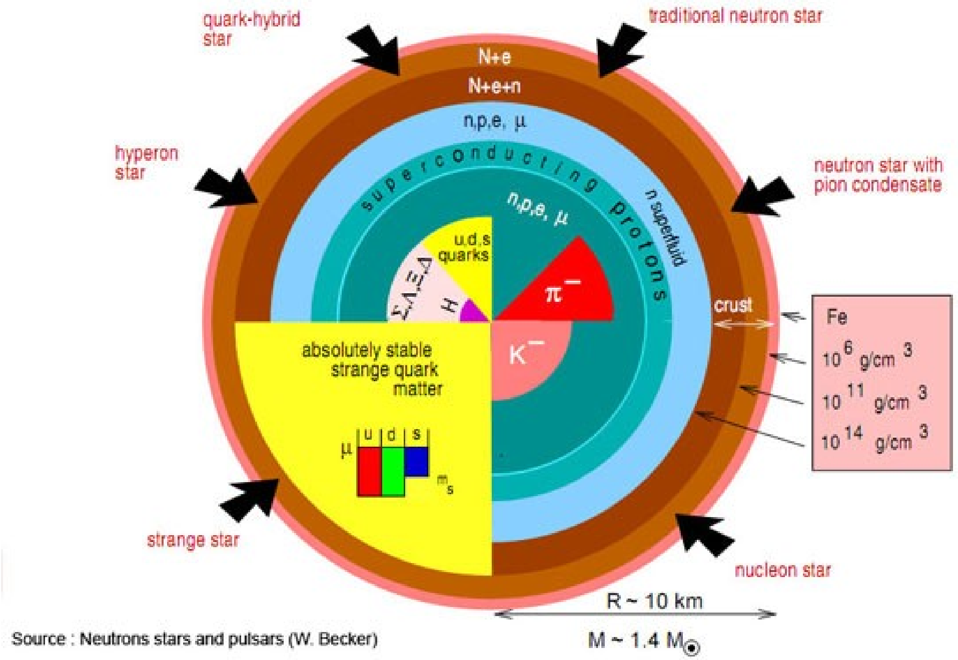
HAL QCD Collaboration

S. Aoki	YITP Kyoto Univ.
T. Doi	RIKEN Nishina
T. Hatsuda	RIKEN Nishina
Y. Ikeda	RCNP Osaka Univ.
T. I.	Nihon Univ.
N. Ishii	RCNP Osaka Univ.
K. Murano	RCNP Osaka Univ.
H. Nemura	Univ. Tsukuba
K. Sasaki	YITP Kyoto Univ.
F. Etminan	Univ. Birjand
T. Miyamoto	YITP Kyoto Univ.
T. Iritani	RIKEN NIshina
S. Gongyo	Univ. of Tours
D. Kawai	YITP Kyoto Univ.

Hadrons to Atomic nuclei
HAL
from Lattice QCD

Introduction





Source : Neutrons stars and pulsars (W. Becker)

- Hyperon is a serious subject in physics of NS.
  - Does hyperon appear inside neutron star core?
  - How EoS of NS mater can be so stiff with hyperon?

cf. PSR J1614-2230 1.97±0.04 $M_{\odot}$

- Tough problem due to ambiguity of hyperon forces
  - comes form difficulty of hyperon scattering experiment.

Introduction

- However, nowadays, we can study or predict hadron-hadron interactions from QCD.
    - mesure h-h NBS w.f. in lattice QCD simulation.
    - define & extract interaction “potential” from the w.f.

HALQCD
applapch

Introduction

- However, nowadays, we can study or predict hadron-hadron interactions from QCD.
  - mesure h-h NBS w.f. in lattice QCD simulation.
  - define & extract interaction “potential” from the w.f.

HALQCD applapch

- Today, we study hyperons in nuclear medium by basing on YN YY interactions predicted from QCD.
  - We calculate hyperon single-particle potential $U_Y(k;\rho)$
  - defined by $e_Y(k;\rho) = \frac{k^2}{2M_Y} + U_Y(k;\rho)$

$e_Y(k;\rho)$: sepectrum in medium

  - U_Y is crucial for hyperon chemical potential.

Introduction

- However, nowadays, we can study or predict hadron-hadron interactions from QCD.
  - mesure h-h NBS w.f. in lattice QCD simulation.
  - define & extract interaction "potential" from the w.f.

HALQCD
applapch

- Today, we study hyperons in nuclear medium by basing on YN YY interactions predicted from QCD.
  - We calculate hyperon single-particle potential $U_Y(k;\rho)$
  - defined by $$e_Y(k;\rho) = \frac{k^2}{2M_Y} + U_Y(k;\rho)$$ $e_Y(k;\rho)$: sepectrum in medium
  - U_Y is crucial for hyperon chemical potential.
- Hypernuclear experiment suggest that

$@\ \rho = 0.17\,[\mathrm{fm}^3]$
$x = 0.5$

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

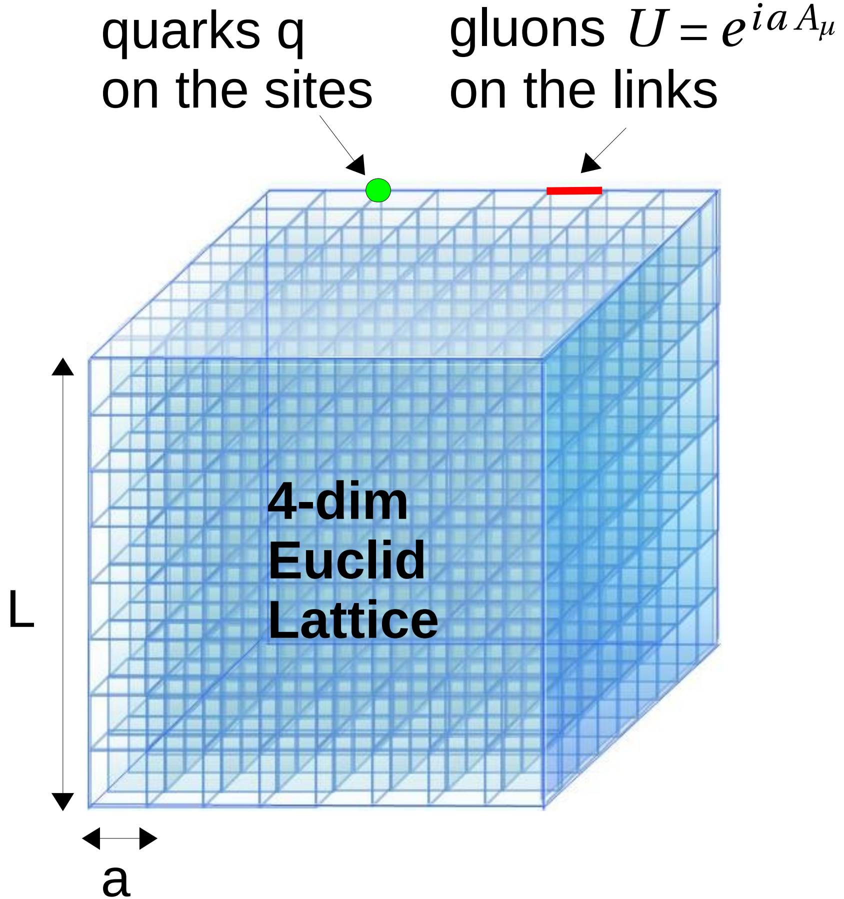
attraction   attraction small   repulsion small

Outline

1. Introduction
2. HALQCD method & simulation setup
3. Hyperon interactions from QCD
4. Hyperon s.-p. potentials from QCD
5. Summary

Lattice QCD

$$L = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + \bar{q} \gamma^\mu \left(i \partial_\mu - g t^a A^a_\mu \right) q - m \bar{q} q$$



Vacuum expectation value

path integral

$$\begin{aligned}
&\langle O(\bar{q}, q, U) \rangle \\
&= \int dU\, d\bar{q}\, dq\, e^{-S(\bar{q}, q, U)}\, O(\bar{q}, q, U) \\
&= \int dU \det D(U) e^{-S_U(U)}\, O(\underset{\uparrow}{D}^{-1}(U)) \\
&= \lim_{N \to \infty} \frac{1}{N} \sum_{i=1}^{N} O(D^{-1}(U_i))
\end{aligned}$$

quark propagator

{ U_i } : ensemble of gauge conf. U
generated w/ probability $\det D(U)\, e^{-S_U(U)}$

- Well defined (regularized)
- Manifest gauge invariance
- Fully non-perturbative
- Highly predictive

HAL method

S. Aoki, T. Hatsuda, N. Ishii, Prog. Theo. Phys. 123 89 (2010)
N. Ishii etal. [HAL QCD coll.] Phys. Lett. B712 , 437 (2012)

NBS wave function $\phi_{\vec{k}}(\vec{r}) = \sum_{\vec{x}} \langle 0 | B_i(\vec{x}+\vec{r},t) B_j(\vec{x},t) | B=2, \vec{k} \rangle$

Define a common potential U for all E eigenstates by a “Schrödinger” eq.

$$\left[-\frac{\nabla^2}{2\mu} \right] \phi_{\vec{k}}(\vec{r}) + \int d^3\vec{r}\,' U(\vec{r},\vec{r}\,') \phi_{\vec{k}}(\vec{r}\,') = E_{\vec{k}} \phi_{\vec{k}}(\vec{r})$$

Non-local but
energy independent
below inelastic threshold

Measure 4-point function in LQCD

$$\psi(\vec{r},t) = \sum_{\vec{x}} \langle 0 | B_i(\vec{x}+\vec{r},t) B_j(\vec{x},t)\ J(t_0) | 0 \rangle = \sum_{\vec{k}} A_{\vec{k}} \phi_{\vec{k}}(\vec{r}) e^{-W_{\vec{k}}(t-t_0)} + \cdots$$

$$\left[2M_B - \frac{\nabla^2}{2\mu} \right] \psi(\vec{r},t) + \int d^3\vec{r}\,' U(\vec{r},\vec{r}\,') \psi(\vec{r}\,',t) = -\frac{\partial}{\partial t} \psi(\vec{r},t)$$

∇ expansion
& truncation

$$U(\vec{r},\vec{r}\,') = \delta(\vec{r}-\vec{r}\,') V(\vec{r},\nabla) = \delta(\vec{r}-\vec{r}\,') [V(\vec{r}) + \cancel{\nabla + \nabla^2} ...]$$

Therefor, in
the leading

$$V(\vec{r}) = \frac{1}{2\mu} \frac{\nabla^2 \psi(\vec{r},t)}{\psi(\vec{r},t)} - \frac{\frac{\partial}{\partial t} \psi(\vec{r},t)}{\psi(\vec{r},t)} - 2M_B$$

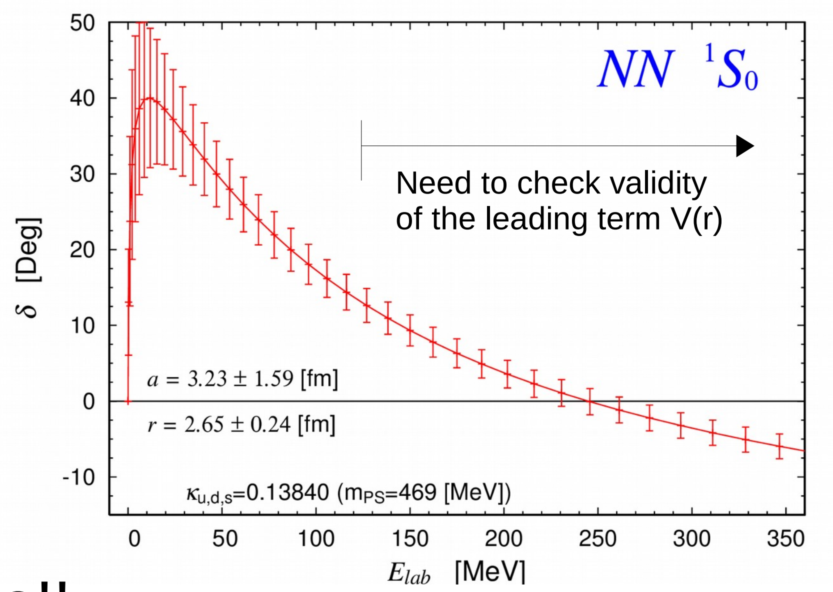
Multi-hadron in LQCD

- Direct：utilize energy eigenstates (eigenvalues).
  - Lüscher's finite volume method for phase-shifts
  - Infinite volume extrapolation for bound states
- HAL：utilize spatial correlation and “potential” *V(r)* + …

$$V(\vec{r}) = \frac{1}{2\mu}\frac{\nabla^2\psi(\vec{r},t)}{\psi(\vec{r},t)} - \frac{\frac{\partial}{\partial t}\psi(\vec{r},t)}{\psi(\vec{r},t)} - 2M_B$$

$\psi(\vec{r},t)$: 4-point function
contains NBS w.f.

- Advantages
  - No need to separate E eigenstate. Just need to measure $\psi(\vec{r},t)$
  - Then, potential can be extracted.
  - Demand a minimal lattice volume. No need to extrapolate to V=∞.
  - Can output more observables.



Need to check validity of the leading term V(r)

a = 3.23 ± 1.59 [fm]

r = 2.65 ± 0.24 [fm]

$\kappa_{u,d,s}$=0.13840 (m_{PS}=469 [MeV])

✯ We can attack hyperon in matter too!!

Simulation setup

- Nf = 2+1 full QCD
  - Clover fermion + Iwasaki gauge w/ staut smearing
  - Volume $96^4 \simeq (8\ \text{fm})^4$
  - 1/a = 2333 MeV, a = 0.0845 fm
  - $M_\pi \simeq 146$, $M_K \simeq 525$ MeV
    $M_N \simeq 956$, $M_\Lambda \simeq 1121$, $M_\Sigma \simeq 1201$, $M_\Xi \simeq 1328$ MeV
  - Collaboration in HPCI Strategic Program Field 5 Project 1

K-configuration

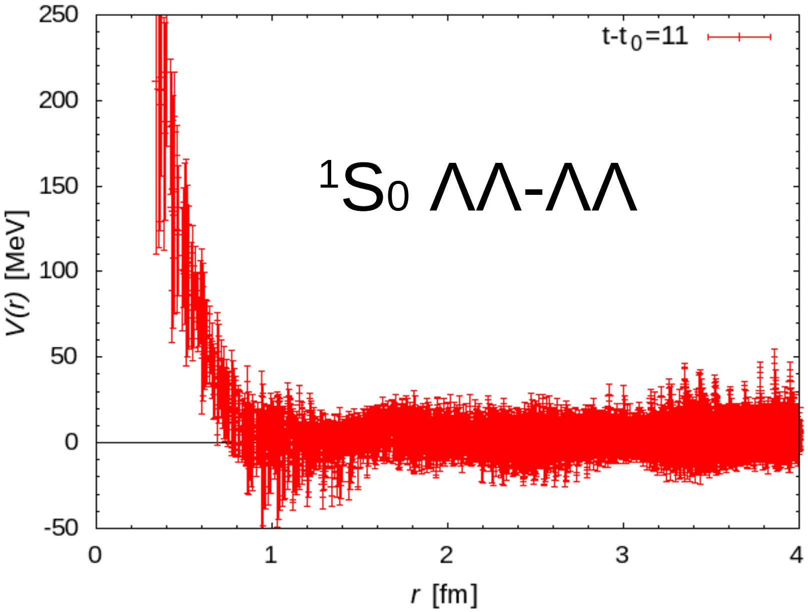
almost physical point

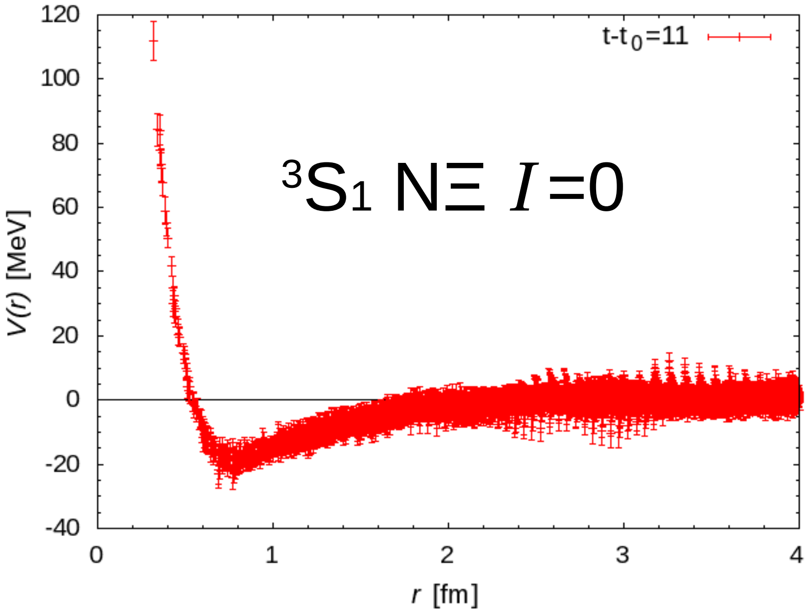
- Measurement
  - 4pt correlators: 52 channels in 2-octet-baryon (+ others)
  - Wall source w/ Coulomb gauge fixing
  - Dirichlet temporal BC to avoid the wrap around artifact
  - #stat = 414 confs × 4 rot × 28 src.

Not final. We are still increasing #stat.

Hyperon interactions from QCD

Hyperon int. potentials from LQCD



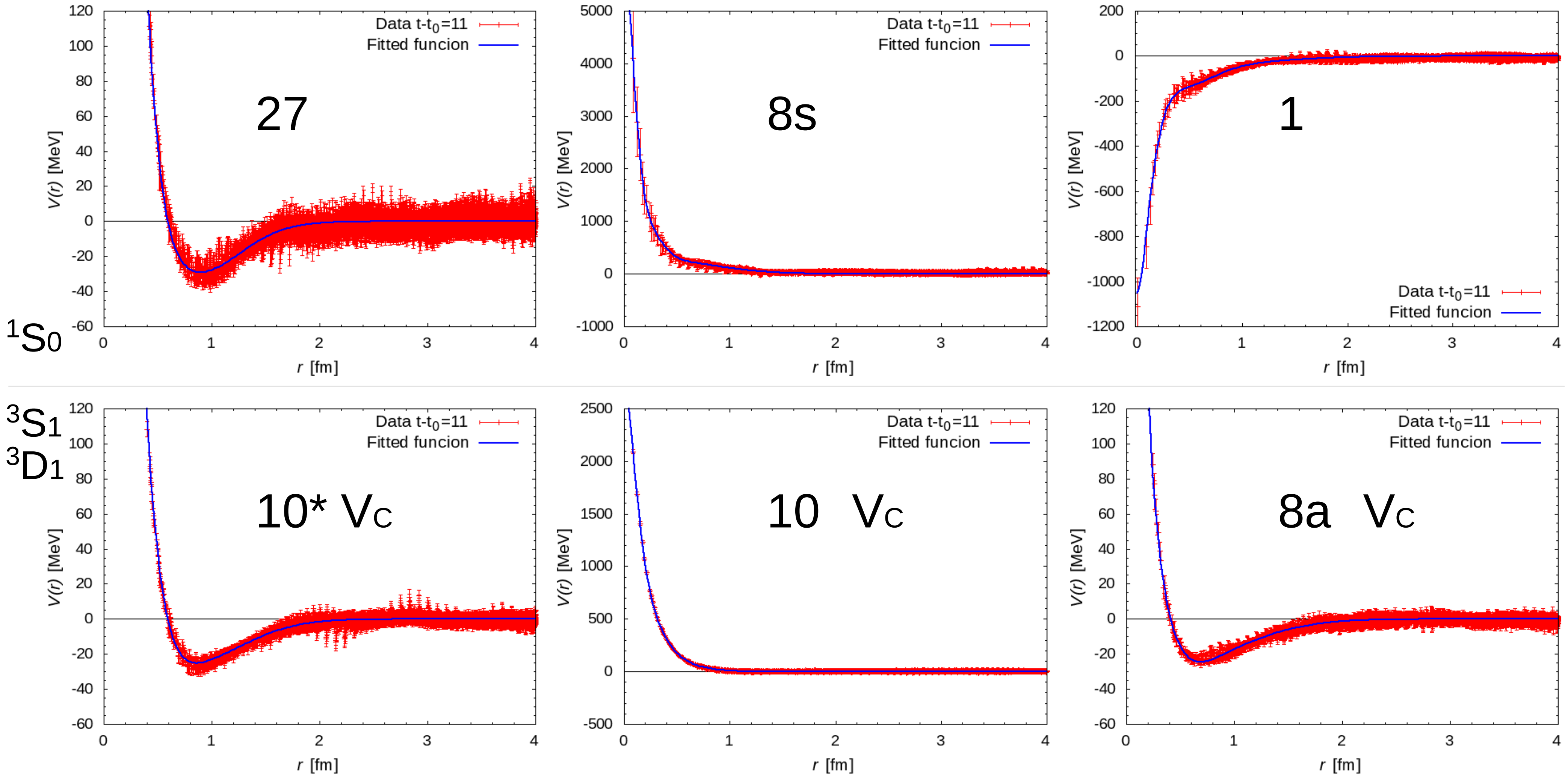


etc. for example

- There are many particle-base potentials. #≈100 in S-wave.
- For application, we need to parameterize potential data.
- It is tough to parameterize all needed potential data.
- So, today, for the moment, I use potential data rotated into the irreducible-representation base.

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

Irre.-rep. base diagonal potentials

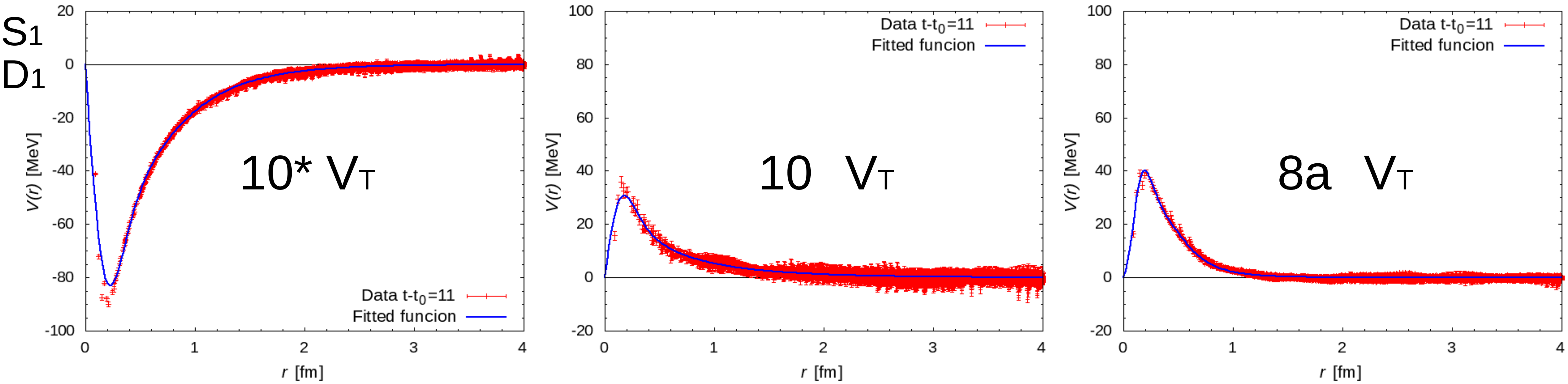


- Analitic function fitted to data

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

Irre.-rep. base diagonal potentials

$^3S_1$
$^3D_1$



- Analitic function fitted to data

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

- Since SU(3)$_F$ is broken at the physical point (K-conf.), there are irre.-rep. base off-diagonal potentials.
- But, I omit them and constract V_{YN}, V_{YY} with these irre.-rep. diagonal potentials and the C.G. coefficient.

Hyperon single-particle potentials

Brueckner-Hartree-Fock

LOBT

- Hyperon single-particle potential

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

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

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

in our study

limitation

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

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

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

Q=−1 $G^{SLJ}_{(\Sigma^- n)(\Sigma^- n)}$

Q = +2 $G^{SLJ}_{(\Sigma^+ p)(\Sigma^+ p)}$

Brueckner-Hartree-Fock

- Hyperon single-particle potential

$$U_{\Xi}(k)=\sum_{N=n,p}\sum_{SLJ}\sum_{k'\leq k_F}\langle k\,k'|\,G^{SLJ}_{(\Xi N)(\Xi N)}\big(e_{\Xi}(k)+e_N(k')\big)\,|k\,k'\rangle$$

- ΞN G-matrix using $V^{\mathrm{LQCD}}_{S=-2}$, $M^{\mathrm{Phys}}_{N,Y}$, $U^{\mathrm{AV18}}_{n,p}$, $U^{\mathrm{LQCD}}_{\Lambda,\Sigma}$ and, U^{LQCD}_{Ξ}

Flavor symmetric $^1S_0$ sectors

Q=0

$$\begin{pmatrix} G^{SLJ}_{(\Xi^0 n)(\Xi^0 n)} & G_{(\Xi^0 n)(\Xi^- p)} & G_{(\Xi^0 n)(\Sigma^+\Sigma^-)} & G_{(\Xi^0 n)(\Sigma^0\Sigma^0)} & G_{(\Xi^0 n)(\Sigma^0\Lambda)} & G_{(\Xi^0 n)(\Lambda\Lambda)} \\ G_{(\Xi^- p)(\Xi^0 n)} & G_{(\Xi^- p)(\Xi^- p)} & G_{(\Xi^- p)(\Sigma^+\Sigma^-)} & G_{(\Xi^- p)(\Sigma^0\Sigma^0)} & G_{(\Xi^- p)(\Sigma^0\Lambda)} & G_{(\Xi^- p)(\Lambda\Lambda)} \\ G_{(\Sigma^+\Sigma^-)(\Xi^0 n)} & G_{(\Sigma^+\Sigma^-)(\Xi^- p)} & G_{(\Sigma^+\Sigma^-)(\Sigma^+\Sigma^-)} & G_{(\Sigma^+\Sigma^-)(\Sigma^0\Sigma^0)} & G_{(\Sigma^+\Sigma^-)(\Sigma^0\Lambda)} & G_{(\Sigma^+\Sigma^-)(\Lambda\Lambda)} \\ G_{(\Sigma^0\Sigma^0)(\Xi^0 n)} & G_{(\Sigma^0\Sigma^0)(\Xi^- p)} & G_{(\Sigma^0\Sigma^0)(\Sigma^+\Sigma^-)} & G_{(\Sigma^0\Sigma^0)(\Sigma^0\Sigma^0)} & G_{(\Sigma^0\Sigma^0)(\Sigma^0\Lambda)} & G_{(\Sigma^0\Sigma^0)(\Lambda\Lambda)} \\ G_{(\Sigma^0\Lambda)(\Xi^0 n)} & G_{(\Sigma^0\Lambda)(\Xi^- p)} & G_{(\Sigma^0\Lambda)(\Sigma^+\Sigma^-)} & G_{(\Sigma^0\Lambda)(\Sigma^0\Sigma^0)} & G_{(\Sigma^0\Lambda)(\Sigma^0\Lambda)} & G_{(\Sigma^0\Lambda)(\Lambda\Lambda)} \\ G_{(\Lambda\Lambda)(\Xi^0 n)} & G_{(\Lambda\Lambda)(\Xi^- p)} & G_{(\Lambda\Lambda)(\Sigma^+\Sigma^-)} & G_{(\Lambda\Lambda)(\Sigma^0\Sigma^0)} & G_{(\Lambda\Lambda)(\Sigma^0\Lambda)} & G_{(\Lambda\Lambda)(\Lambda\Lambda)} \end{pmatrix}$$

Q=+1

$$\begin{pmatrix} G^{SLJ}_{(\Xi^0 p)(\Xi^0 p)} & G_{(\Xi^0 p)(\Sigma^+\Lambda)} \\ G_{(\Sigma^+\Lambda)(\Xi^0 p)} & G_{(\Sigma^+\Lambda)(\Sigma^+\Lambda)} \end{pmatrix}$$

Q=−1

$$\begin{pmatrix} G^{SLJ}_{(\Xi^- n)(\Xi^- n)} & G_{(\Xi^- n)(\Sigma^-\Lambda)} \\ G_{(\Sigma^-\Lambda)(\Xi^- n)} & G_{(\Sigma^-\Lambda)(\Sigma^-\Lambda)} \end{pmatrix}$$

Brueckner-Hartree-Fock

- ΞN G-matrix using $V^{\mathrm{LQCD}}_{S=-2}$, $M^{\mathrm{Phys}}_{N,Y}$, $U^{\mathrm{AV18}}_{n,p}$, $U^{\mathrm{LQCD}}_{\Lambda,\Sigma}$ and, U^{LQCD}_{Ξ}

  Flavor anti-symmetric $^3S_1$, $^3D_1$ sectors

Q=0

$$\begin{pmatrix} G^{SLJ}_{(\Xi^0 n)(\Xi^0 n)} & G_{(\Xi^0 n)(\Xi^- p)} & G_{(\Xi^0 n)(\Sigma^+\Sigma^-)} & G_{(\Xi^0 n)(\Sigma^0\Lambda)} \\ G_{(\Xi^- p)(\Xi^0 n)} & G_{(\Xi^- p)(\Xi^- p)} & G_{(\Xi^- p)(\Sigma^+\Sigma^-)} & G_{(\Xi^- p)(\Sigma^0\Lambda)} \\ G_{(\Sigma^+\Sigma^-)(\Xi^0 n)} & G_{(\Sigma^+\Sigma^-)(\Xi^- p)} & G_{(\Sigma^+\Sigma^-)(\Sigma^+\Sigma^-)} & G_{(\Sigma^+\Sigma^-)(\Sigma^0\Lambda)} \\ G_{(\Sigma^0\Lambda)(\Xi^0 n)} & G_{(\Sigma^0\Lambda)(\Xi^- p)} & G_{(\Sigma^0\Lambda)(\Sigma^+\Sigma^-)} & G_{(\Sigma^0\Lambda)(\Sigma^0\Lambda)} \end{pmatrix}$$

Q=+1

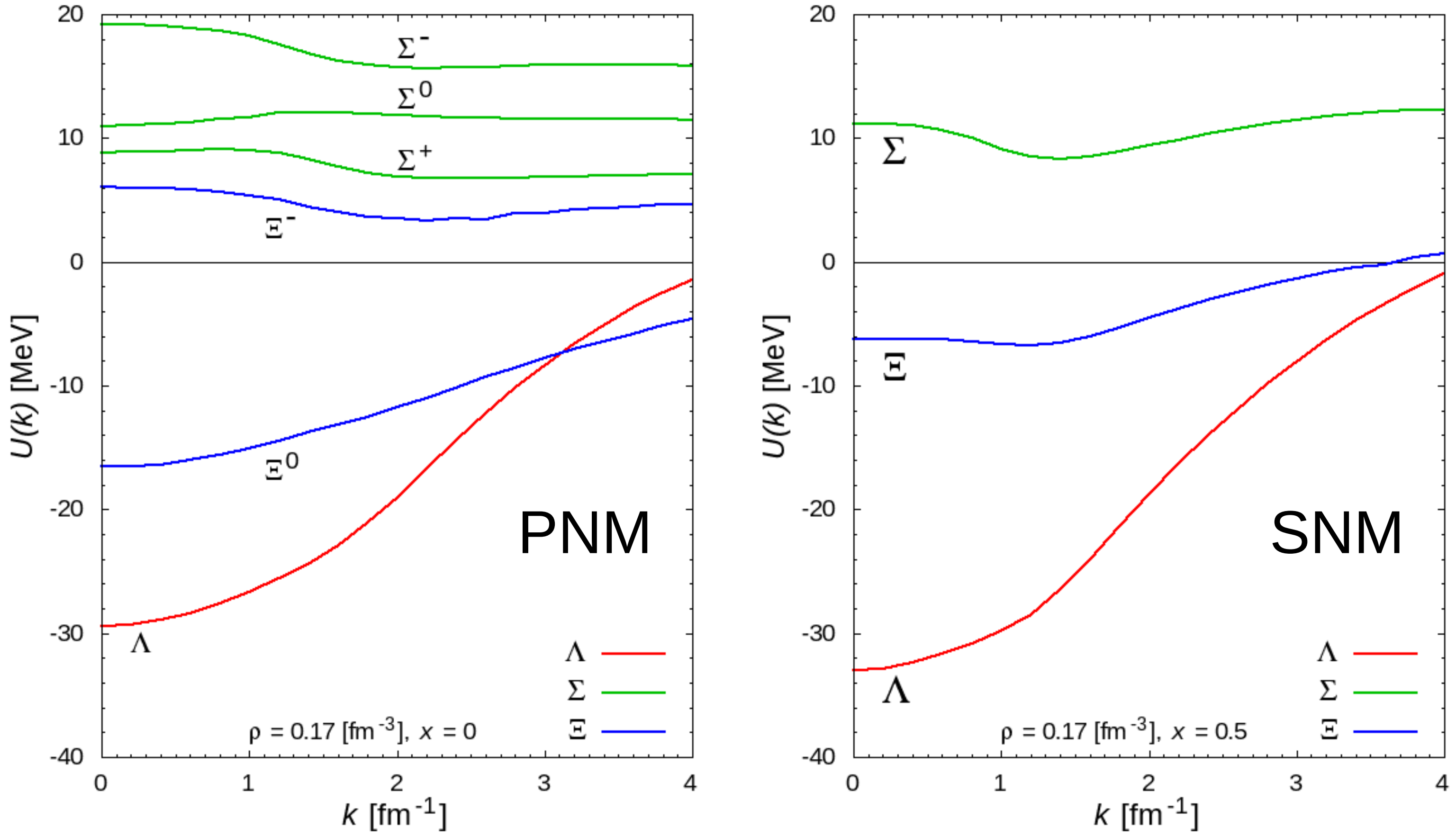
$$\begin{pmatrix} G^{SLJ}_{(\Xi^0 p)(\Xi^0 p)} & G_{(\Xi^0 p)(\Sigma^+\Sigma^0)} & G_{(\Xi^0 p)(\Sigma^+\Lambda)} \\ G_{(\Sigma^+\Sigma^0)(\Xi^0 p)} & G_{(\Sigma^+\Sigma^0)(\Sigma^+\Sigma^0)} & G_{(\Sigma^+\Sigma^0)(\Sigma^+\Lambda)} \\ G_{(\Sigma^+\Lambda)(\Xi^0 p)} & G_{(\Sigma^+\Lambda)(\Sigma^+\Sigma^0)} & G_{(\Sigma^+\Lambda)(\Sigma^+\Lambda)} \end{pmatrix}$$

Q=−1

$$\begin{pmatrix} G^{SLJ}_{(\Xi^- n)(\Xi^- n)} & G_{(\Xi^- n)(\Sigma^-\Sigma^0)} & G_{(\Xi^- n)(\Sigma^-\Lambda)} \\ G_{(\Sigma^-\Sigma^0)(\Xi^- n)} & G_{(\Sigma^-\Sigma^0(\Sigma^-\Sigma^0))} & G_{(\Sigma^-\Sigma^0)(\Sigma^-\Lambda)} \\ G_{(\Sigma^-\Lambda)(\Xi^- n)} & G_{(\Sigma^-\Lambda)(\Sigma^-\Sigma^0)} & G_{(\Sigma^-\Lambda)(\Sigma^-\Lambda)} \end{pmatrix}$$

Results

Hyperon single-particle potentials

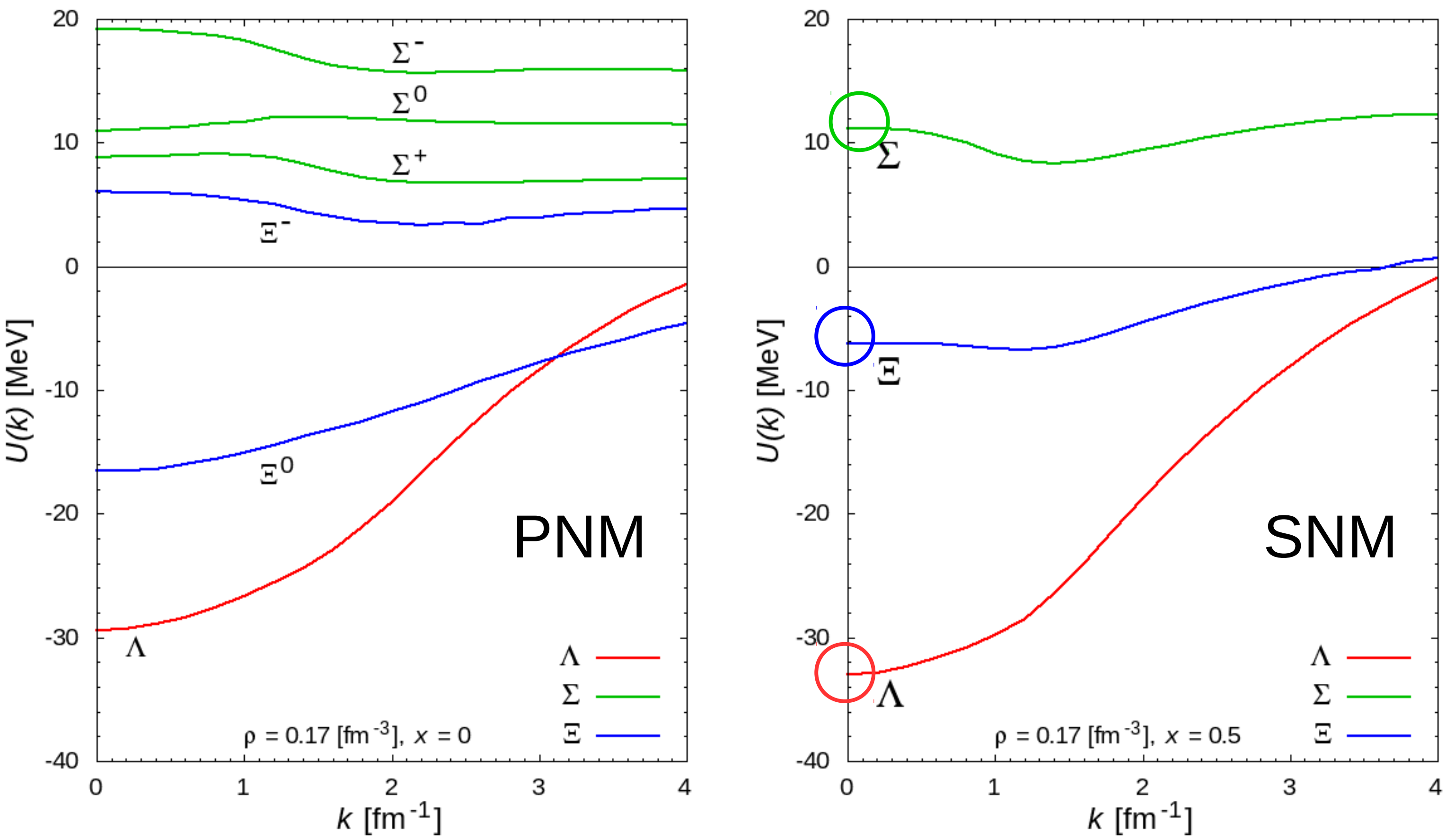


@$\rho = 0.17\,[\mathrm{fm}^3]$

Preliminary

- obtained by using YN,YY forces form QCD.

Hyperon single-particle potentials



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

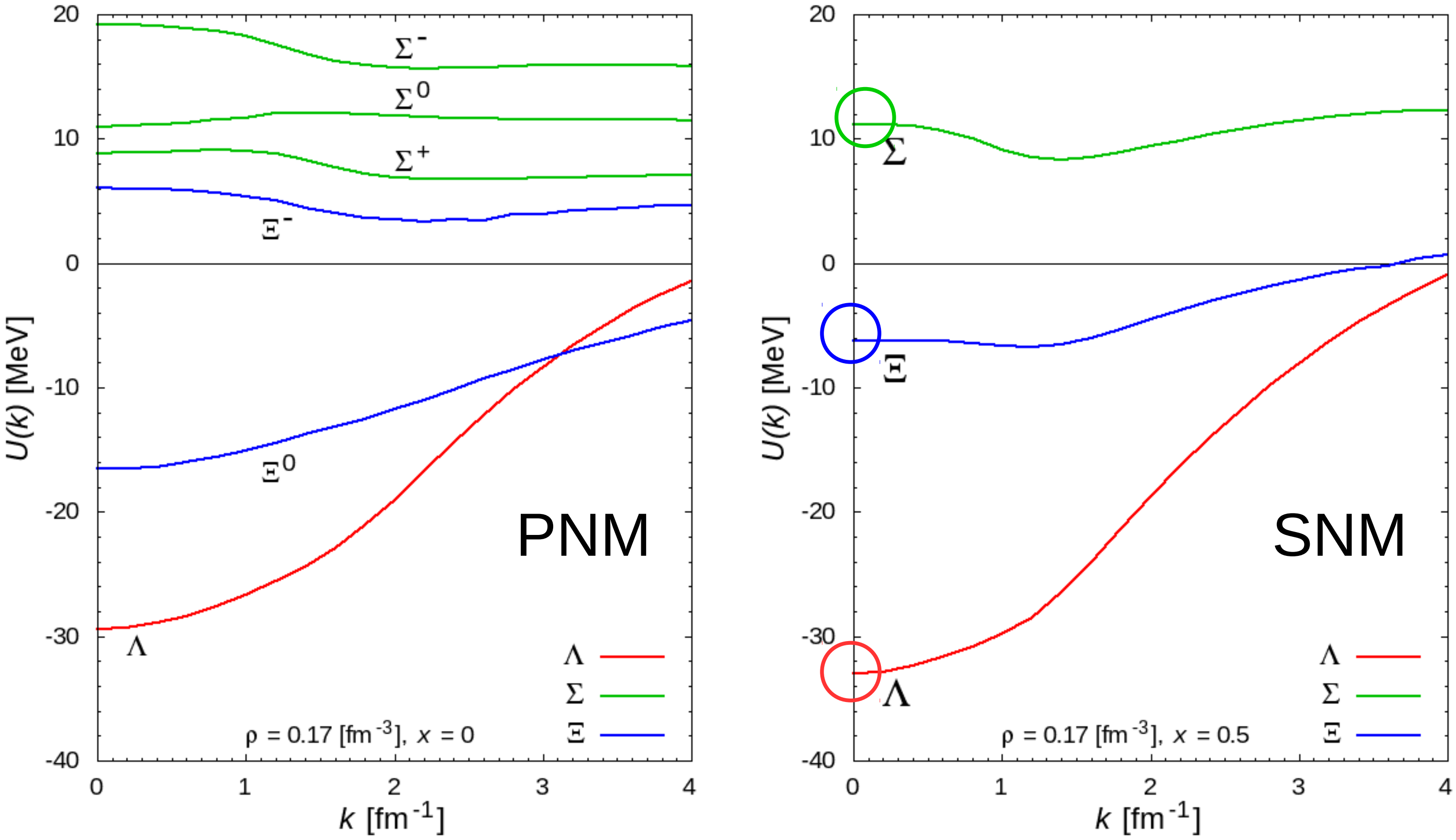
Preliminary

- obtained by using YN,YY forces form QCD.
- Results agree with experimental data!

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

attraction attraction small repulsion small

Hyperon single-particle potentials



@$\rho = 0.17$ [fm^3]

Preliminary

- obtained by using YN,YY forces form QCD.
- Results agree with experimental data!

Remarkable.
Encouraging.

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

attraction　　attraction small　　repulsion small

Summary and Outlook

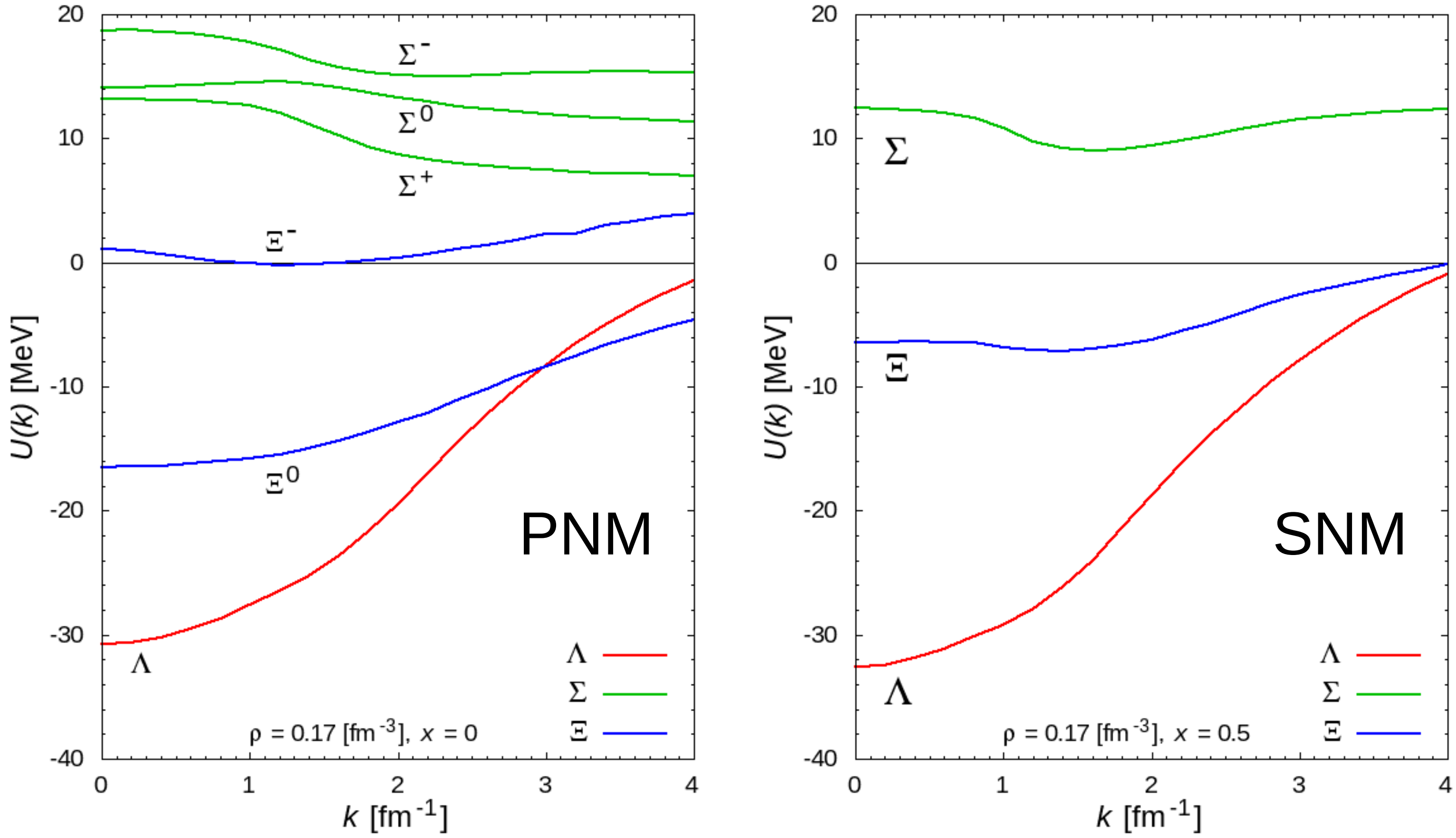
Summary and outlook

- We deduced hyperon forces from QCD on lattice.
- We calculated hyperon s.p. potentials using them.
  - This time, I used rotated data diagonal in the irre.-rep. base.
- Obtained U_Y are compatible with experiment!
  - In SNM, Λ and Ξ feel attracsion, while Σ feels repulsion.
  - I need to confirm this agreement since I used simplifications.
- This is remarkable success, at least encouraging.
  - Recall that we've never used any experimental data about hepron forces, but we used only QCD.
- We continue to improve this study.
  - We have to estimate statistical error & systematic uncertainty.
  - We try to reduce them as possible.
- In near future, we will be able to reproduce hypernuclei from QCD and reveal hyperons in NS from QCD.

Thank you !!

Back up

Hyperon single-particle potentials



@$\rho=0.17\,[\text{fm}^3]$

Preliminary

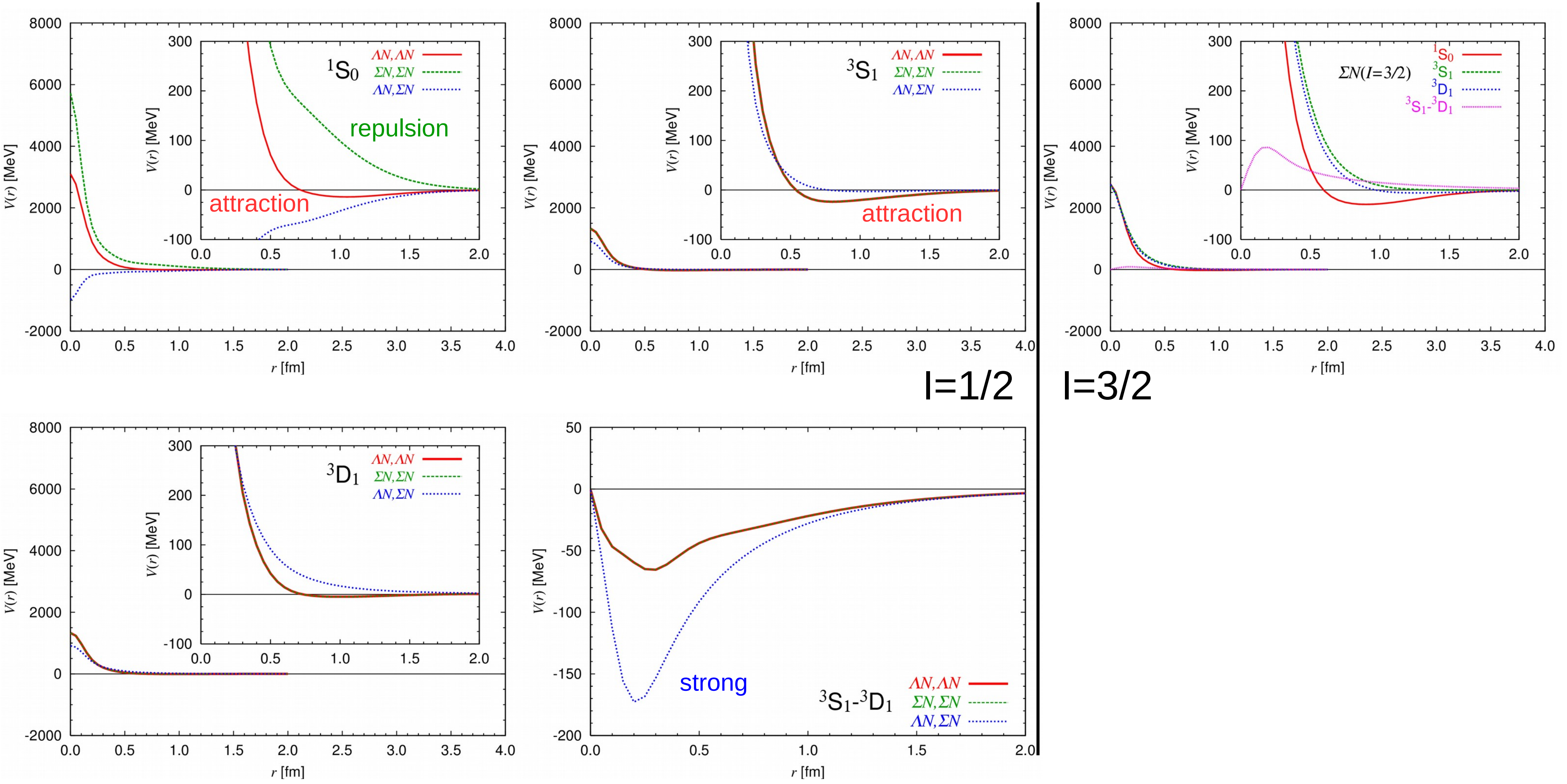
- obtained with LQCD YN,YY pot. + $M_{N,Y}^{\text{LQCD}}$ + $U_{n,p}^{\text{LQCD},\text{BHF}}$

	N	Λ	Σ	Ξ
M_B [MeV]	956	1121	1201	1328

- YN,YY pot. are essential. M_B and $U_{n,p}$ have minor effect.

LQCD ΛN-ΣN

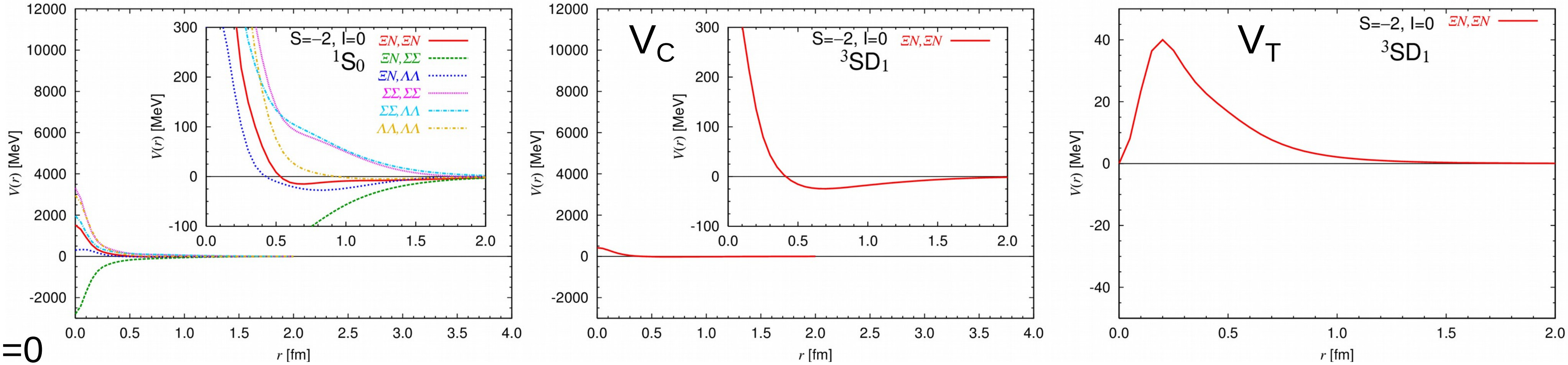
From K-conf. but rotated from the irr.-rep. base diagonal potentials.



- In I=1/2, $^1S_0$ channel, ΛN has an attraction, while ΣN is repulsive.
- In I=1/2, $^3S_1$ channel, both ΛN and ΣN have an attraction. ↔ No attraction in Nijmegen
- In I=1/2, strong tensor coupling in flavor off-diagonal.

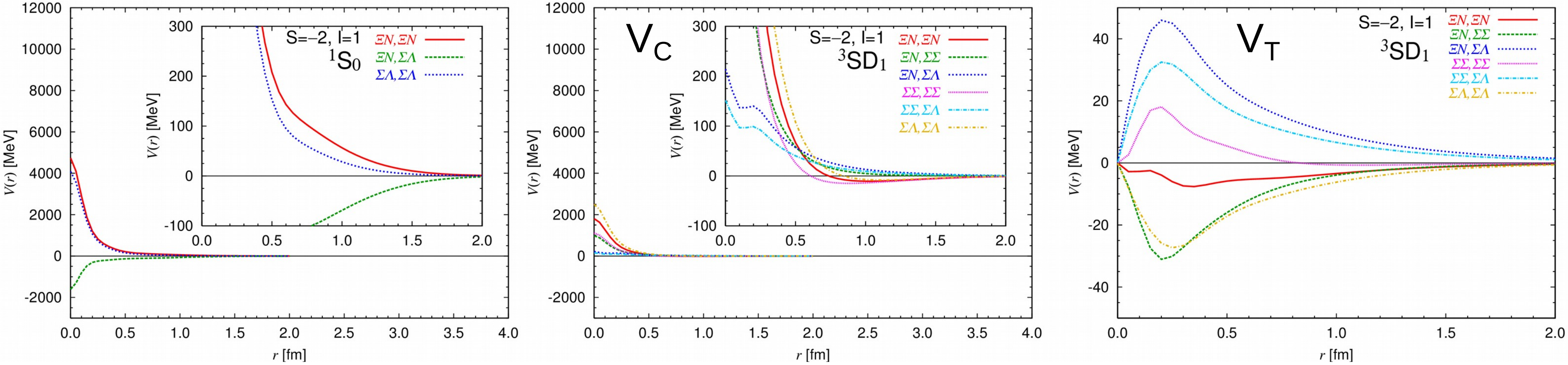
LQCD ΞN-YY

From K-conf. but rotated from the irr.-rep. base diagonal potentials.



I=0

I=1



- Many experimentally unknown coupled-channel potentials.
- One can see predictive power of the HALQCD method.

Source and sink operator

- NBS wave function and 4-point function

$$\phi_{\vec{k}}(\vec{r}) = \sum_{\vec{x}} \langle 0 | B_i(\vec{x}+\vec{r}, \overbrace{t) B_j(\vec{x}, t}^{\text{equal}}) | B=2, \vec{k} \rangle_{\text{QCD eigenstate}}$$

$$\psi(\vec{r}, t) = \sum_{\vec{x}} \langle 0 | \underbrace{B_i(\vec{x}+\vec{r}, t) B_j(\vec{x}, t)}_{\text{sink}} \ \underbrace{J(t_0)}_{\text{source}} | 0 \rangle = \sum_{\vec{k}} A_{\vec{k}} \phi_{\vec{k}}(\vec{r}) e^{-W_{\vec{k}}(t-t_0)} + \cdots$$

- Point type octet baryon field operator at sink

$$p_\alpha(\underline{x}) = \epsilon_{c_1 c_2 c_3} (C\gamma_5)_{\beta_1 \beta_2} \delta_{\beta_3 \alpha} \, u(\xi_1) d(\xi_2) u(\xi_3) \quad \text{with} \quad \xi_i = \{c_i, \beta_i, \underline{x}\}$$

$$\Lambda_\alpha(x) = -\epsilon_{c_1 c_2 c_3} (C\gamma_5)_{\beta_1 \beta_2} \delta_{\beta_3 \alpha} \sqrt{\frac{1}{6}} \left[d(\xi_1) s(\xi_2) u(\xi_3) + s(\xi_1) u(\xi_2) d(\xi_3) - 2u(\xi_1) d(\xi_2) s(\xi_3) \right]$$

- Wall type source of two-baryon state

e.g. $$\overline{BB}^{(1)} = -\sqrt{\frac{1}{8}} \, \overline{\Lambda} \overline{\Lambda} + \sqrt{\frac{3}{8}} \, \overline{\Sigma} \overline{\Sigma} + \sqrt{\frac{4}{8}} \, \overline{N} \overline{\Xi}$$ for flavor-singlet

FAQ

1. Does your potential depend on the choice of source?

2. Does your potential depend on choice of operator at sink?

3. Does your potential $U(r,r')$ or $V(r)$ depends on energy?

FAQ

1. Does your potential depend on the choice of source?

- ➔ No. Some sources may enhance excited states in 4-point func. However, it is no longer a problem in our new method.

2. Does your potential depend on choice of operator at sink?

- ➔ Yes. It can be regarded as the “scheme” to define a potential. Note that a potential itself is not physical observable.
  We will obtain unique result for physical observables irrespective to the choice, as long as the potential $U(r,r')$ is deduced exactly.

FAQ

3. Does your potential $U(r,r')$ or $V(r)$ depends on energy?

- ➔ By definition, $U(r,r')$ is non-local but energy independent. While, determination and validity of its leading term $V(r)$ depend on energy because of the truncation.

  However, we know that the dependence in NN case is very small (thanks to our choice of sink operator = point) and negligible at least at $E_{lab.}$ = 0 – 90 MeV. We rely on this in our study.

  If we find some dependence, we will determine the next leading term of the expansion from the dependence.