格子QCD計算を用いた
核媒質中におけるハイペロンの研究

井上貴史　＠日本大学生物資源

サブ課題B　格子QCD

HALQCD Collaboratoin

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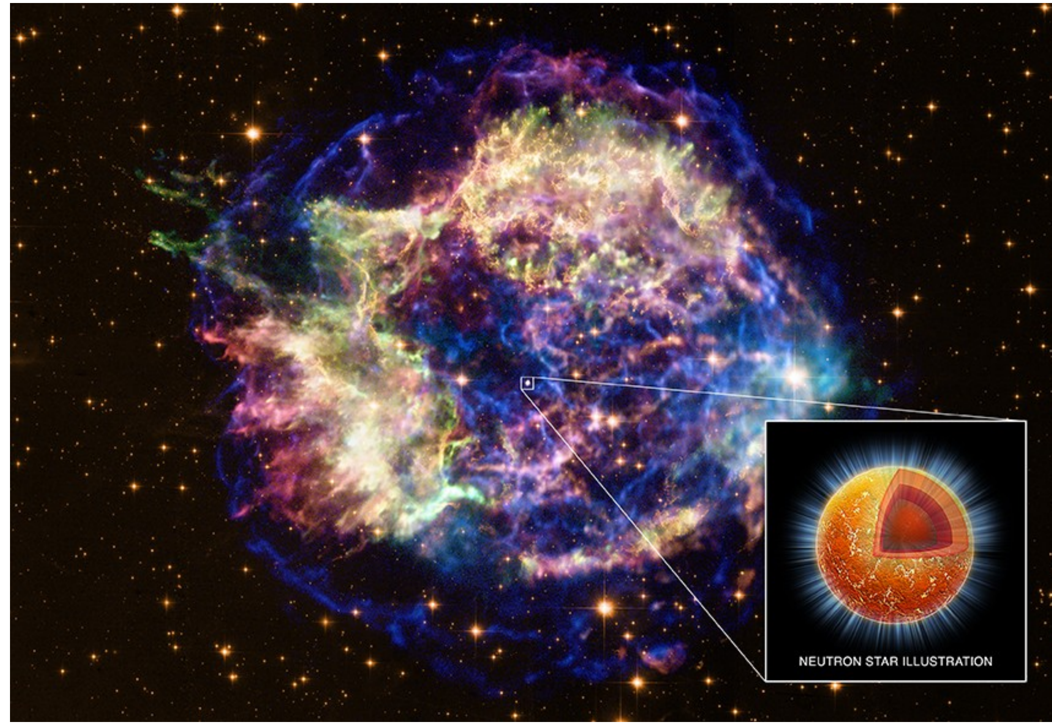
Hadrons to Atomic nuclei
HAL
from Lattice QCD

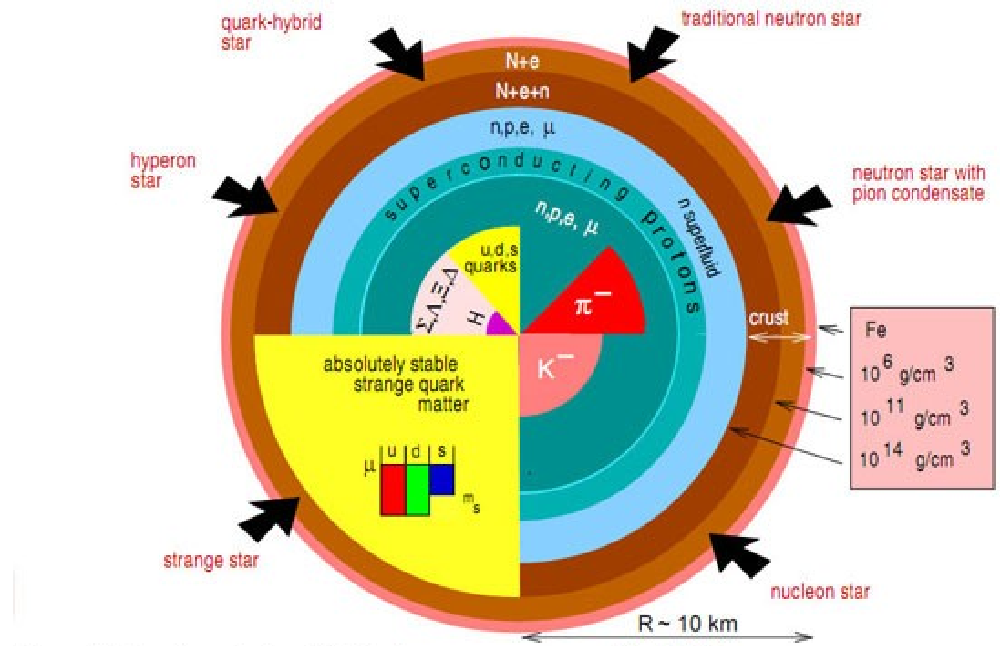
Introduction



- Neutron Star
  - is a compact star formed after supernova explosion of massive star.
  - Typically, $M = 1.5\, M_{\odot}$, $R = 10$ km.
  - Temperature T $\simeq 10^8$ [K] $\simeq$ 0.01 [MeV] $\simeq 0$
  - Density in core ρ = several $\times\ \rho_0$

is roughly 10^{15} [g/cm^3] !
Most dense in Universe!

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.
  - measure h-h NBS w.f. in lattice QCD simulation.
  - define & extract interaction “potential” from the w.f.

HALQCD applapch

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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.

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  - U_Y is crucial for hyperon chemical potential.

- Hypernuclear experiment suggest that 　　$@\rho = 0.17\,[\mathrm{fm}^{-3}]$, $x = 0.5$

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

attraction 　　 attraction small 　　 repulsion small

Outline

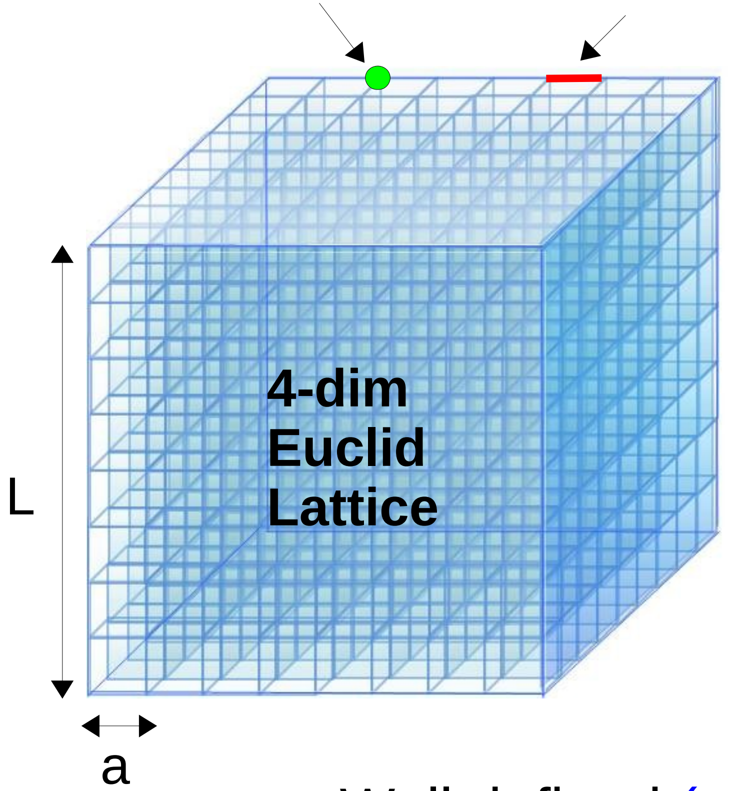
1. Introduction
2. HALQCD method & simulation setup
3. Hyperon interactions from QCD
4. Hyperon s.-p. potentials from QCD
5. Hyperon onset in NS core
6. Summary

Lattice QCD

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

quarks q on the sites

gluons $U=e^{iaA_\mu}$ on the links



Vacuum expectation value

$$\langle O(\bar{q},q,U)\rangle$$

path integral

$$=\int dU\,d\bar{q}\,dq\,e^{-S(\bar{q},q,U)}\,O(\bar{q},q,U)$$

$$=\int dU\,\det D(U)\,e^{-S_U(U)}\,O(D^{-1}(U))$$

quark propagator

$$=\lim_{N\to\infty}\frac{1}{N}\sum_{i=1}^{N}O(D^{-1}(U_i))$$

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

- Well defined (regularized)
- Manifest gauge invariance
- Fully non-perturvative
- 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

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

Therefor, in
the leading

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

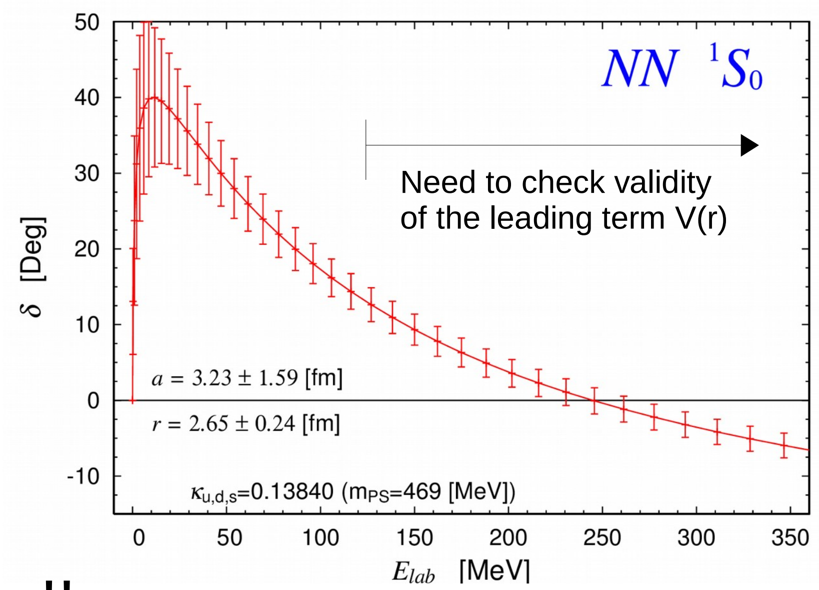
Multi-hadron in LQCD

- 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.



☆ 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

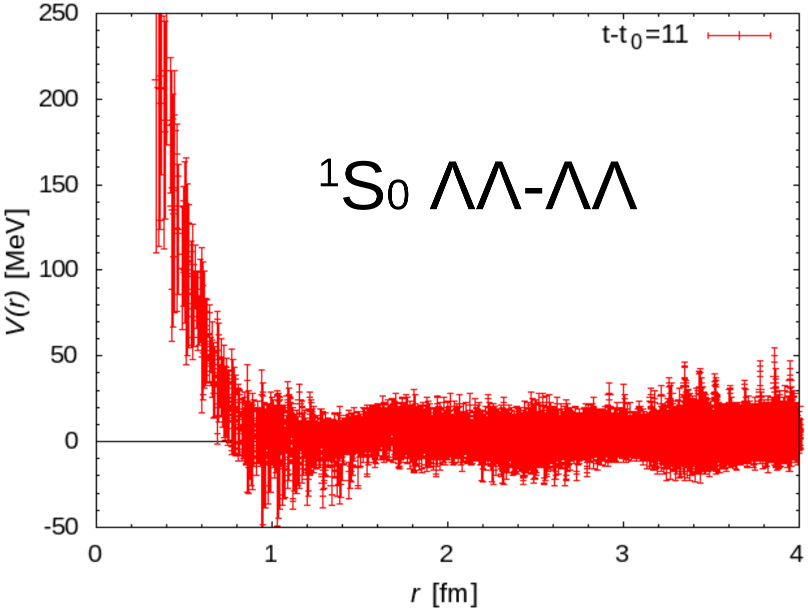
almost physical point

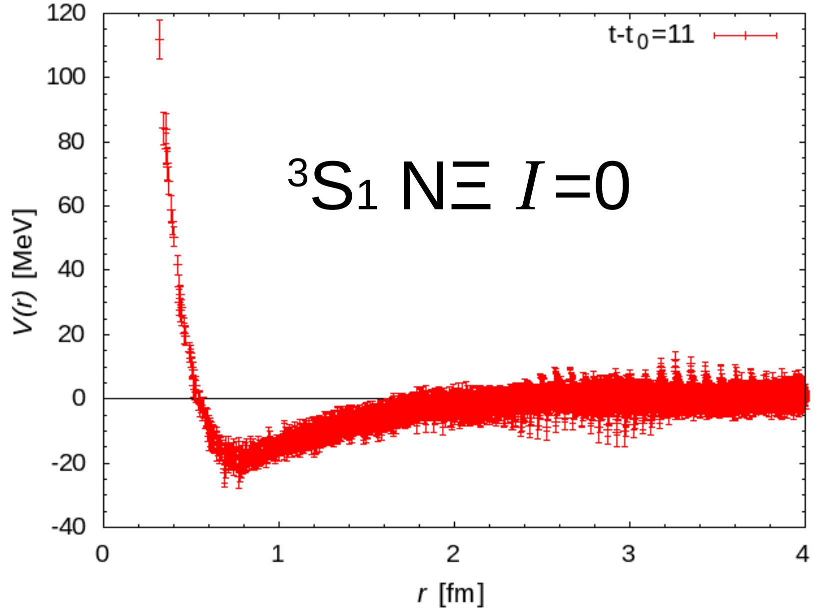
- Measurement
  - 4pt correlators: 52 channels in 2-octet-baryon (+ others)
  - Wall source w/ Coulomb gauge fixing
  - Dirichlet temporal BC to avoid the wrap around artifact
  - #stat = 414 confs $\times$ 4 rot $\times$ 28 src.

Not final. We are still increasing #stat.

Hyperon interactions from QCD

Hyperon int. potentials from LQCD





etc. for example

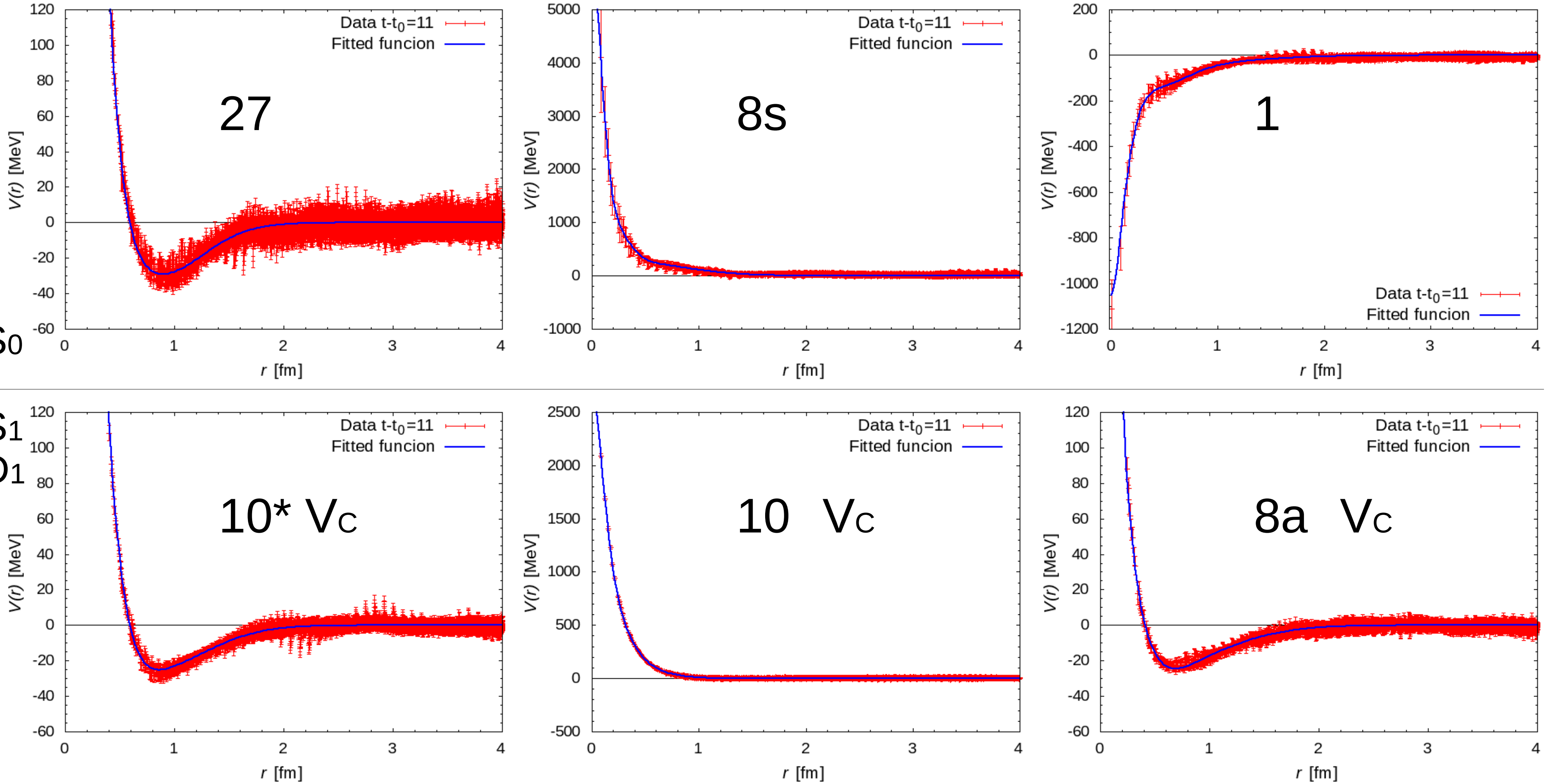
- There are many particle-base potentials. #≈100 in S-wave.
- For application, we need to parameterize potential data.
- It is tough to parameterize all needed potential data.
- So, today, for the moment, I use potential data rotated into the irreducible-representation base.

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

Irre.-rep. base diagonal potentials

$^1S_0$

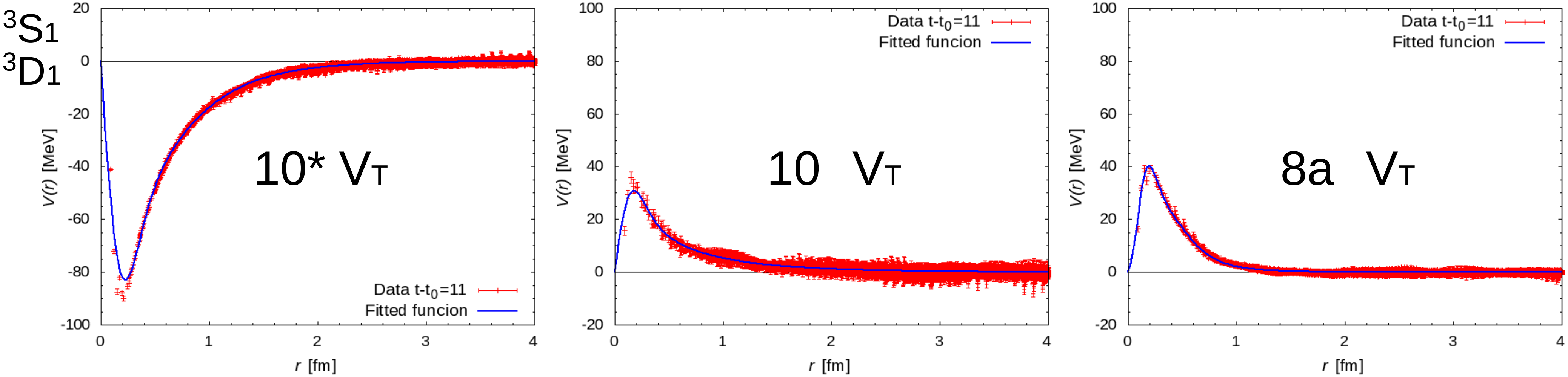
$^3S_1$
$^3D_1$



- 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



- 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)

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

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

in our study

limitation

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

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

- 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

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

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

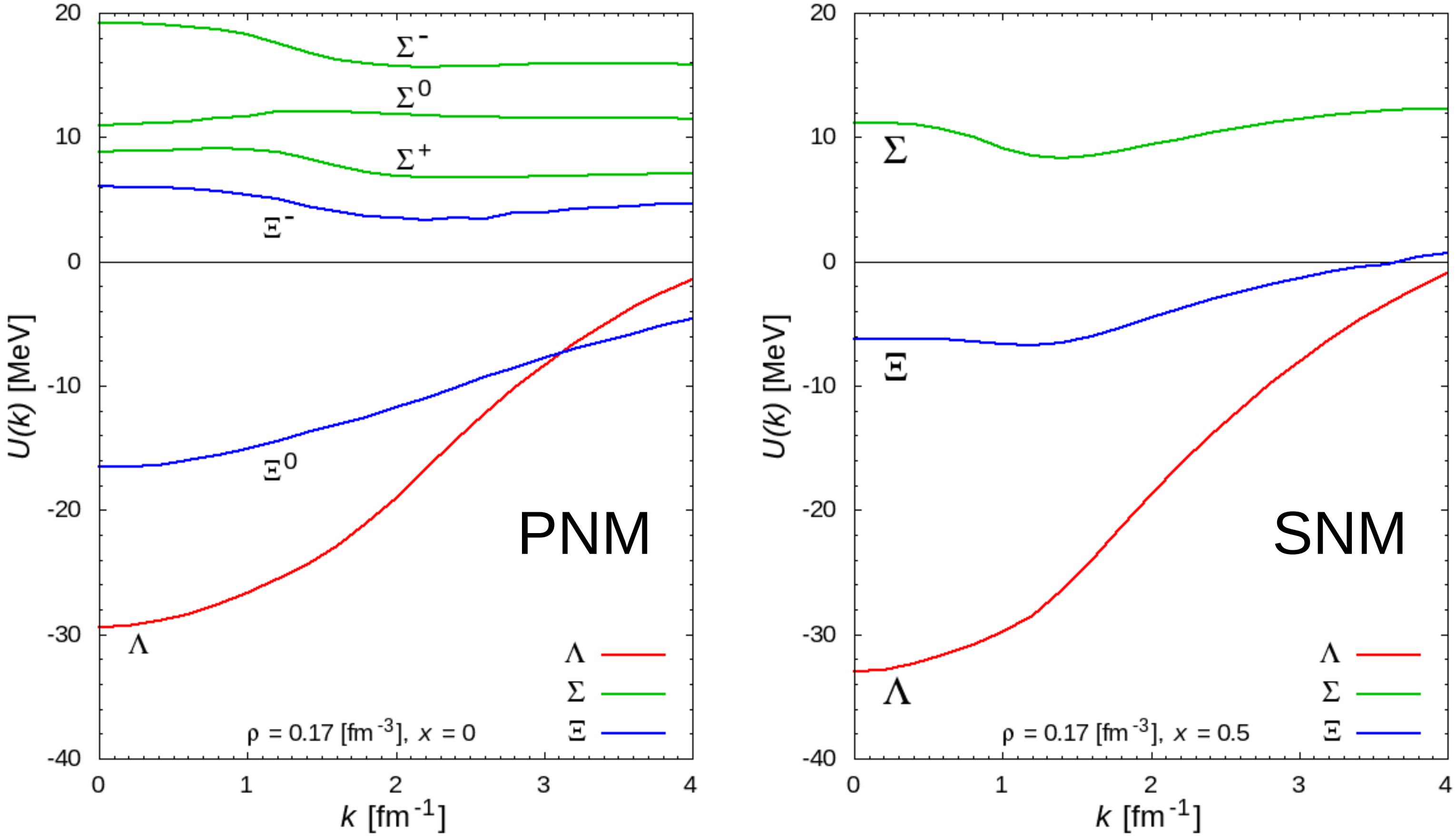
$$\begin{pmatrix} G^{SLJ}_{(\Xi^0 p)(\Xi^0 p)} & G_{(\Xi^0 p)(\Sigma^+\Sigma^0)} & G_{(\Xi^0 p)(\Sigma^+\Lambda)} \\ G_{(\Sigma^+\Sigma^0)(\Xi^0 p)} & G_{(\Sigma^+\Sigma^0)(\Sigma^+\Sigma^0)} & G_{(\Sigma^+\Sigma^0)(\Sigma^+\Lambda)} \\ G_{(\Sigma^+\Lambda)(\Xi^0 p)} & G_{(\Sigma^+\Lambda)(\Sigma^+\Sigma^0)}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

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

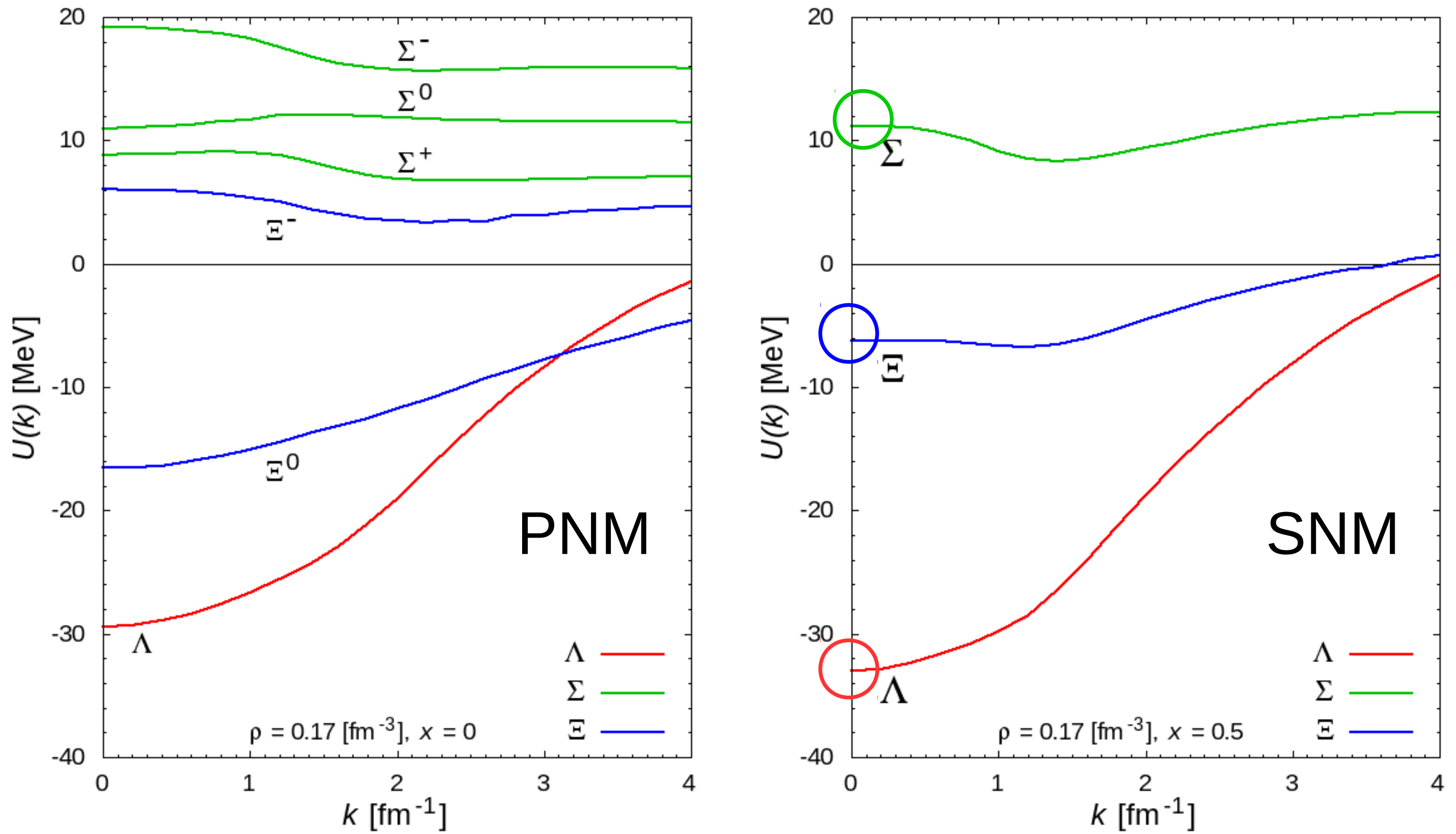


@$\rho = 0.17$ [fm^{-3}]

Preliminary

- obtained by using YN,YY forces form QCD.

Hyperon single-particle potentials



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

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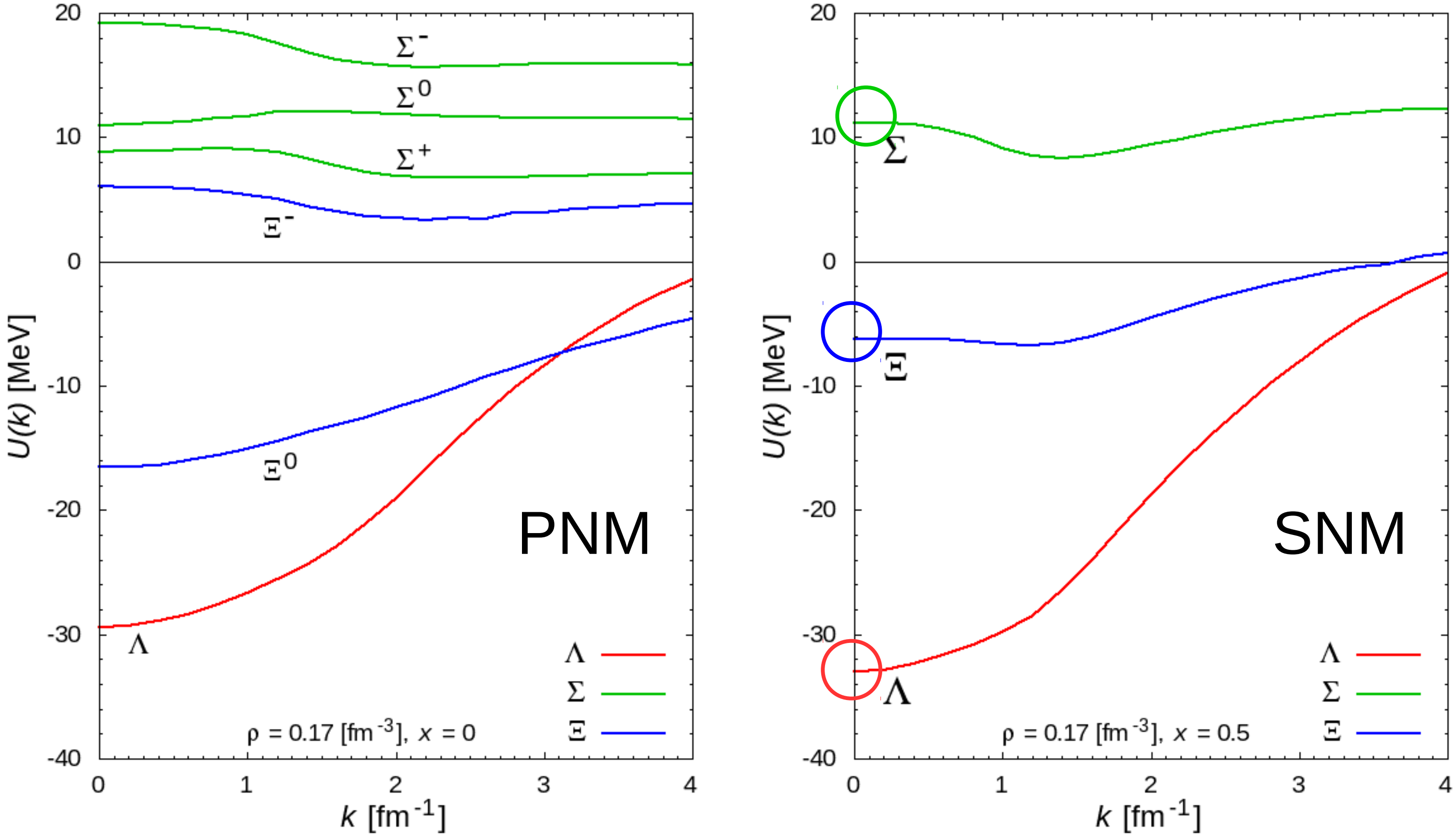
- Results agree with experimental data!

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

attraction — attraction small — repulsion small

Hyperon single-particle potentials



@ρ=0.17 [fm^{-3}]

Preliminary

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Remarkable.
Encouraging.

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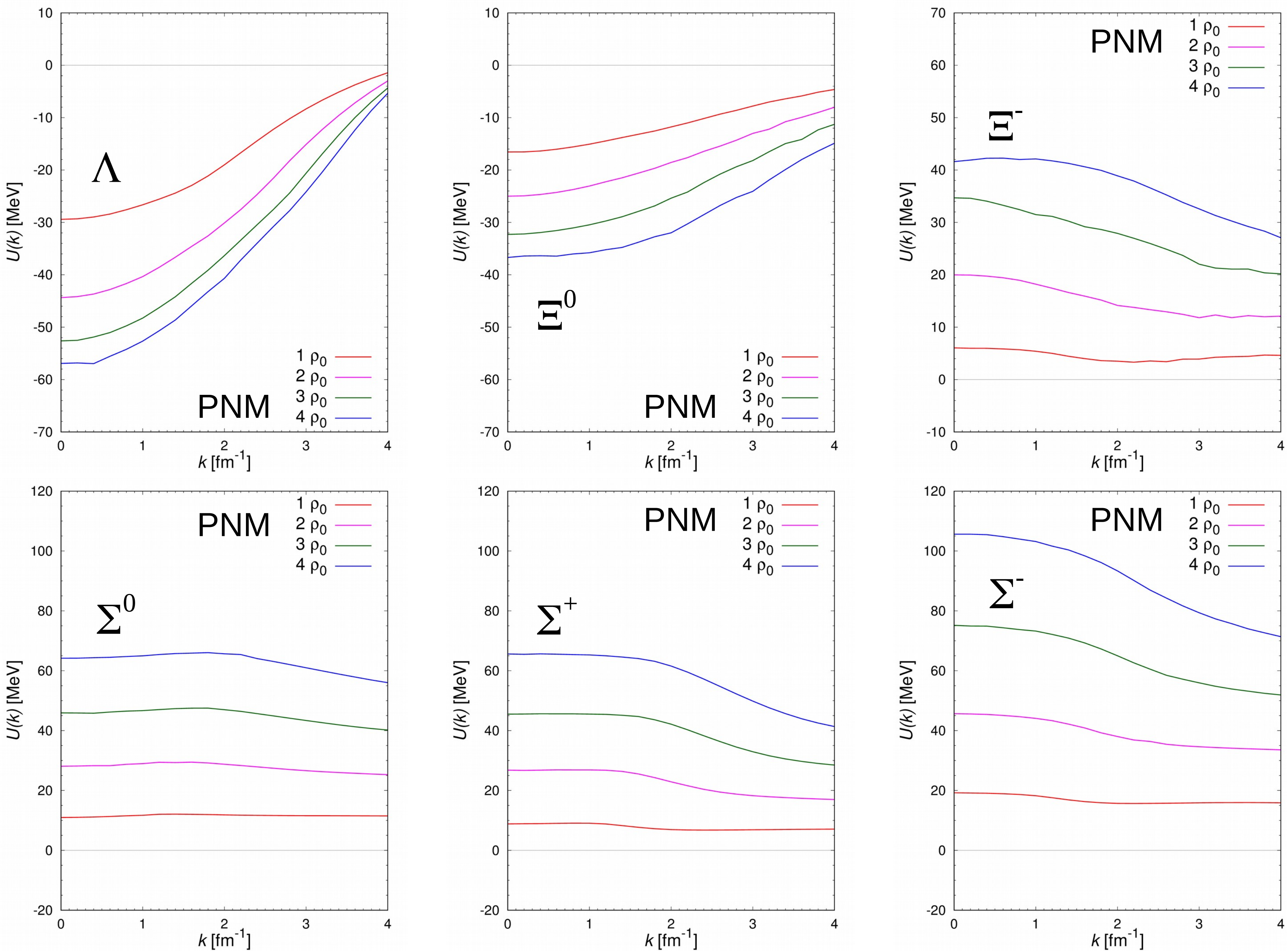
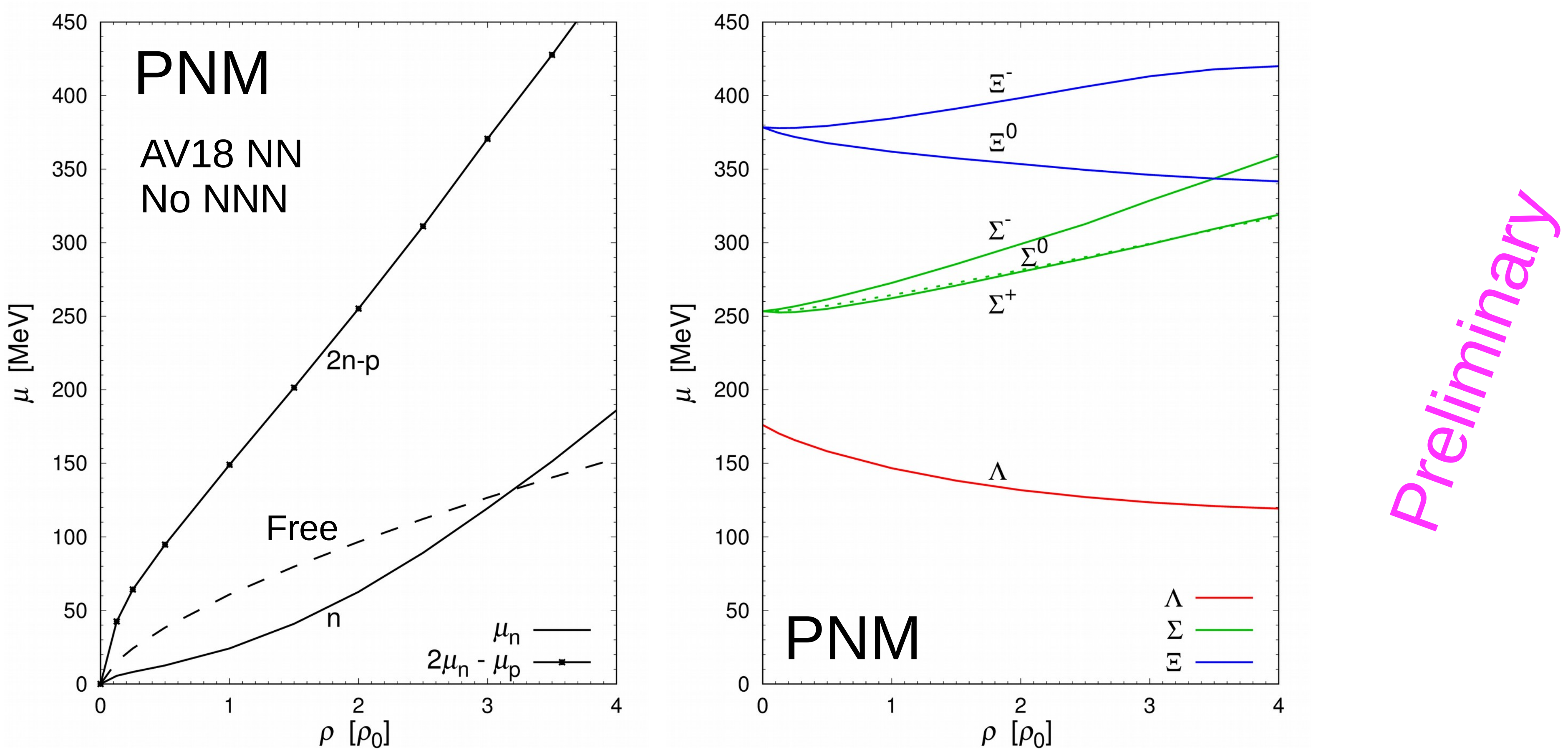
In high density PNM



Preliminary

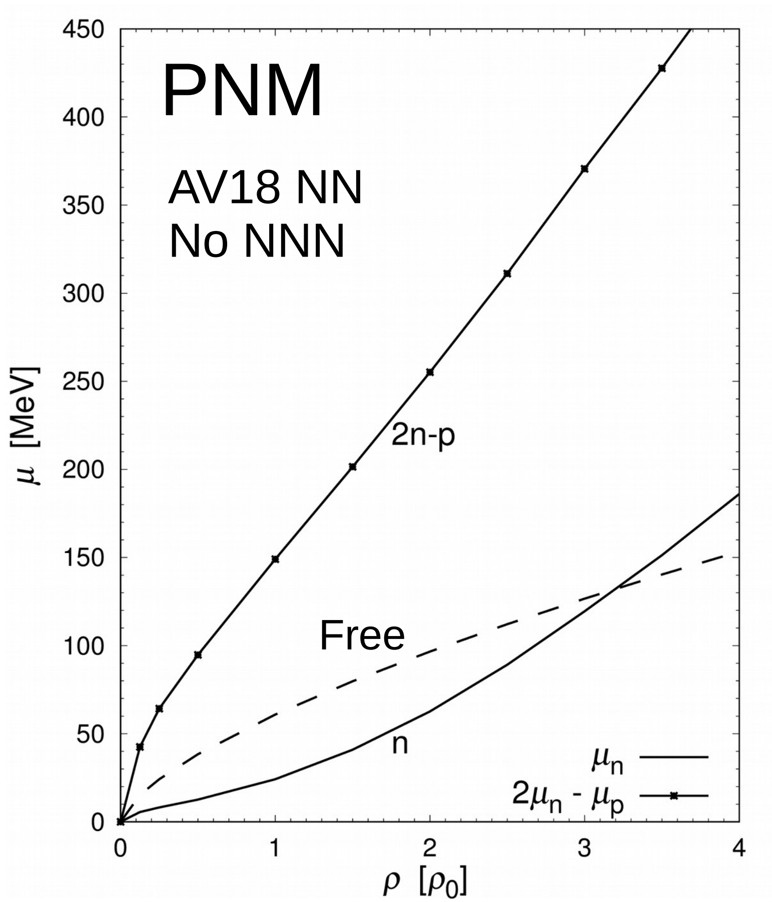
Chemical potentials

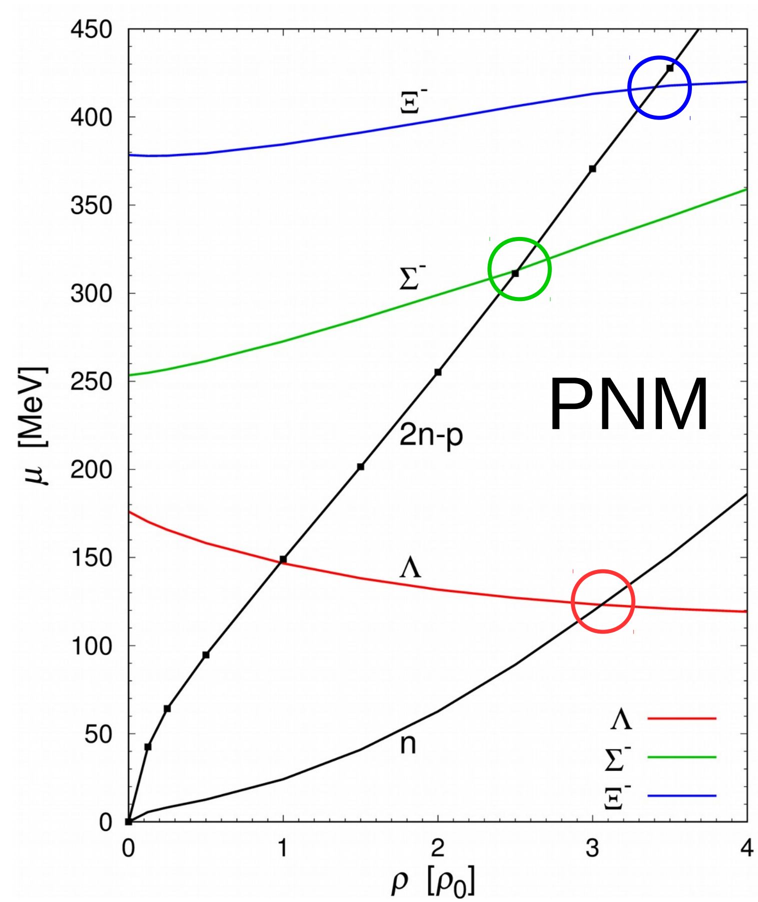


- Density dependence of chemical pot. of n & Y in PNM.
- Hyperon appear $n \rightarrow Y^0$ if $\mu_n > \mu_{Y^0}$

  $nn \rightarrow pY^-$ if $2\mu_n > \mu_p + \mu_{Y^-}$

Hyperon onset (just for a demonstration)





Preliminary

- First, Σ^- appear at 2.5 ρ_0. Next, Λ appear at 3.0 ρ_0.
  - NS matter is not PNM especially at high density.
  - We should compare with more sophisticated μ_n and μ_p.
  - P-wave YN force may be important at high density.

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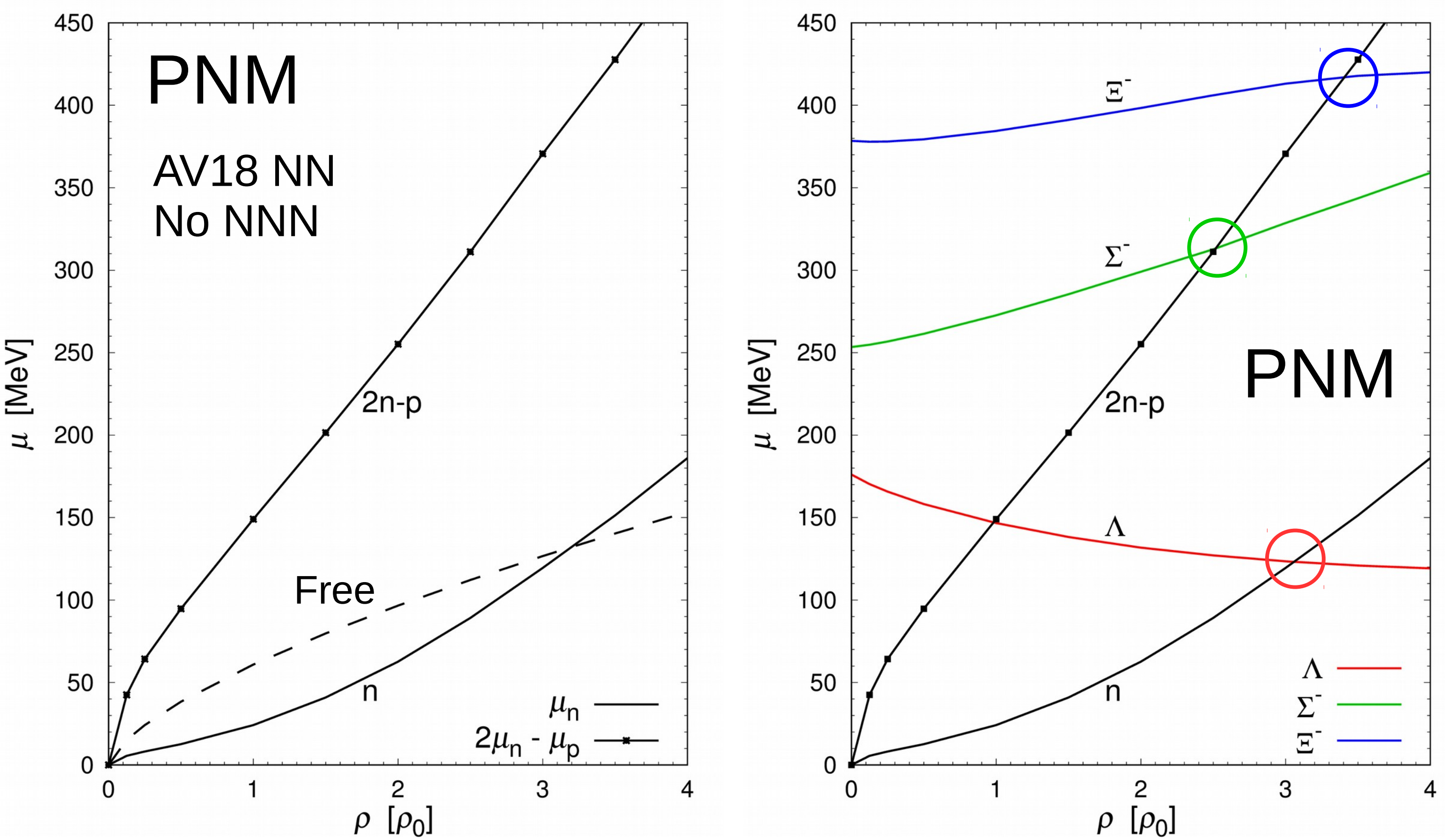

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Post K target

まとめ

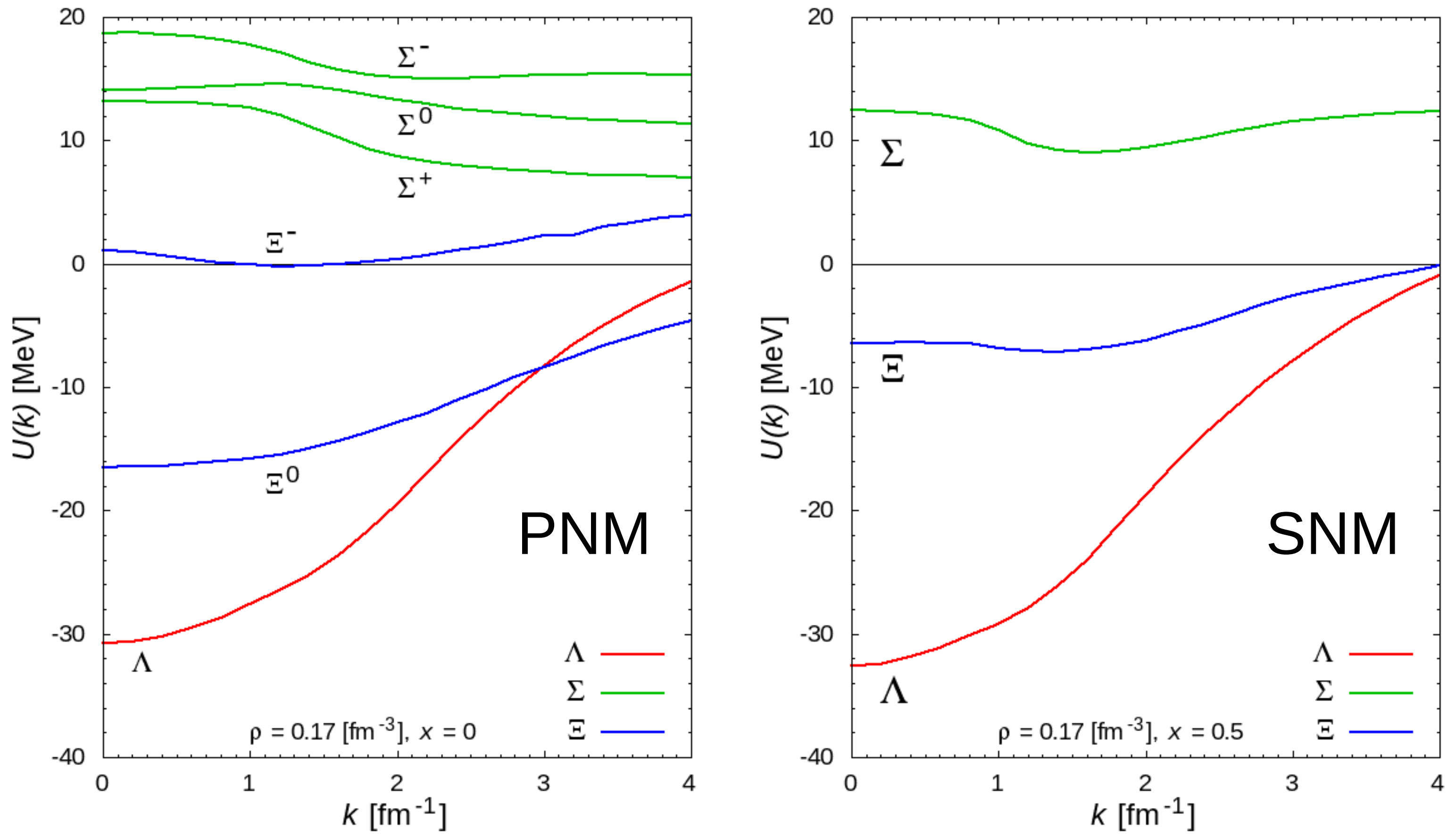
まとめと展望

- 中性子星におけるハイペロン問題を解くために、格子QCD計算を使った研究をしている。
  - ほぼ物理点での配位を用い、HALQCD 法によって、実験で未定なハイペロン相互作用（S波）を QCD から導出。
  - 格子QCDハイペロン力と現象論的核力を多体理論に適用し、核媒質中でのハイペロン一体ポテンシャルを計算。
- ハイパー核実験からの示唆を再現する結果が得られた。
  - 対称核物質中で、Λ と Ξ は引力を、Σ は斥力を受ける。
- 結果を用い、中性子星でのハイペロン出現を見積もった。
- 今後は、今より精密に、中性子星の研究を行いたい。
  - その為には、ハイペロンP波相互作用の導入が不可欠。
  - これを格子QCDから決定するには、ポスト京スパコンが要る。
  - 現実的な核力と三核子力も、格子QCDから得られるはず。

Thank you !!

Back up

Hyperon single-particle potentials



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

Preliminary

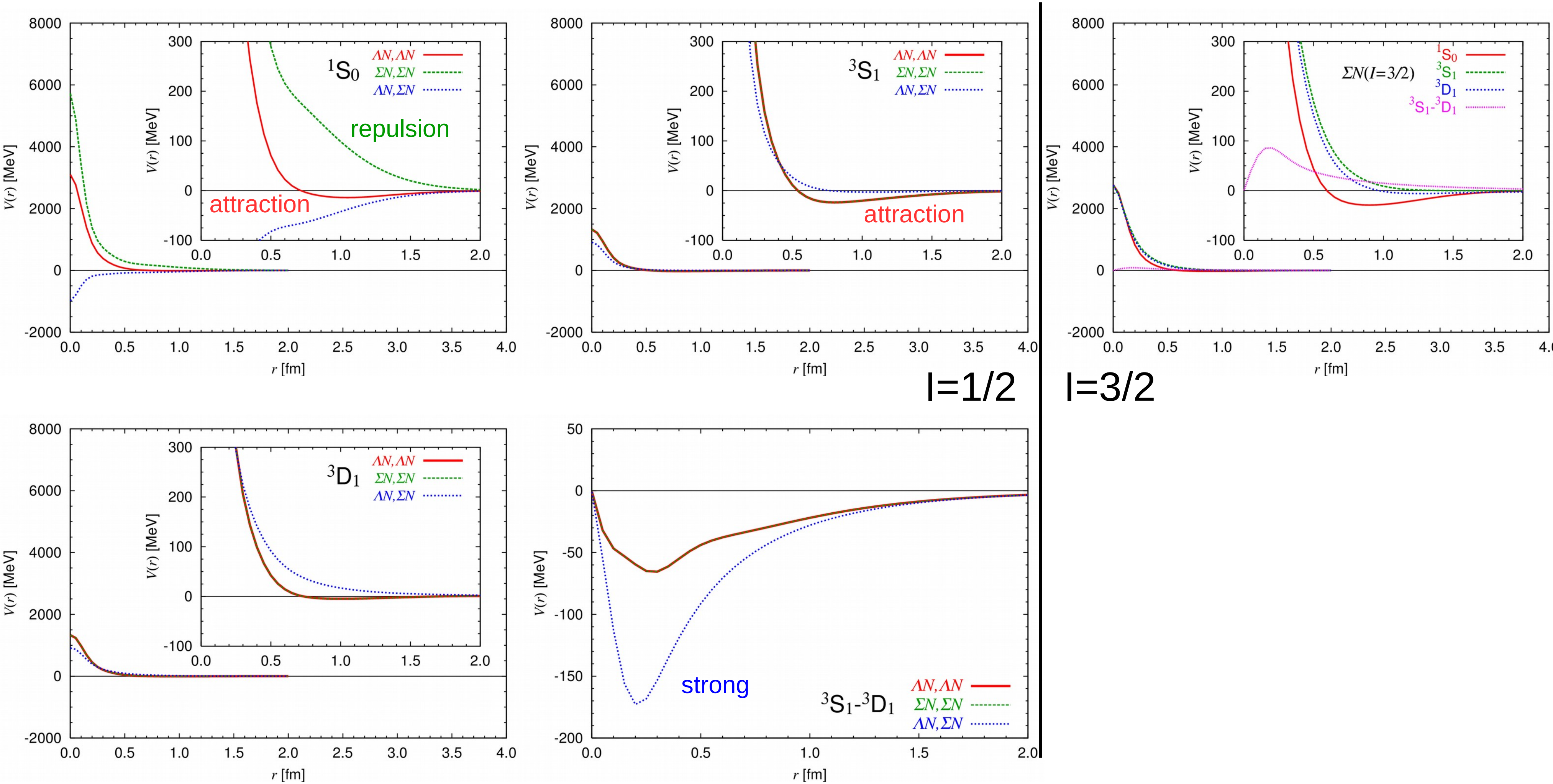
- obtained with LQCD YN,YY pot. + $M_{N,Y}^{\mathrm{LQCD}}$ + $U_{n,p}^{\mathrm{LQCD},\mathrm{BHF}}$

	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

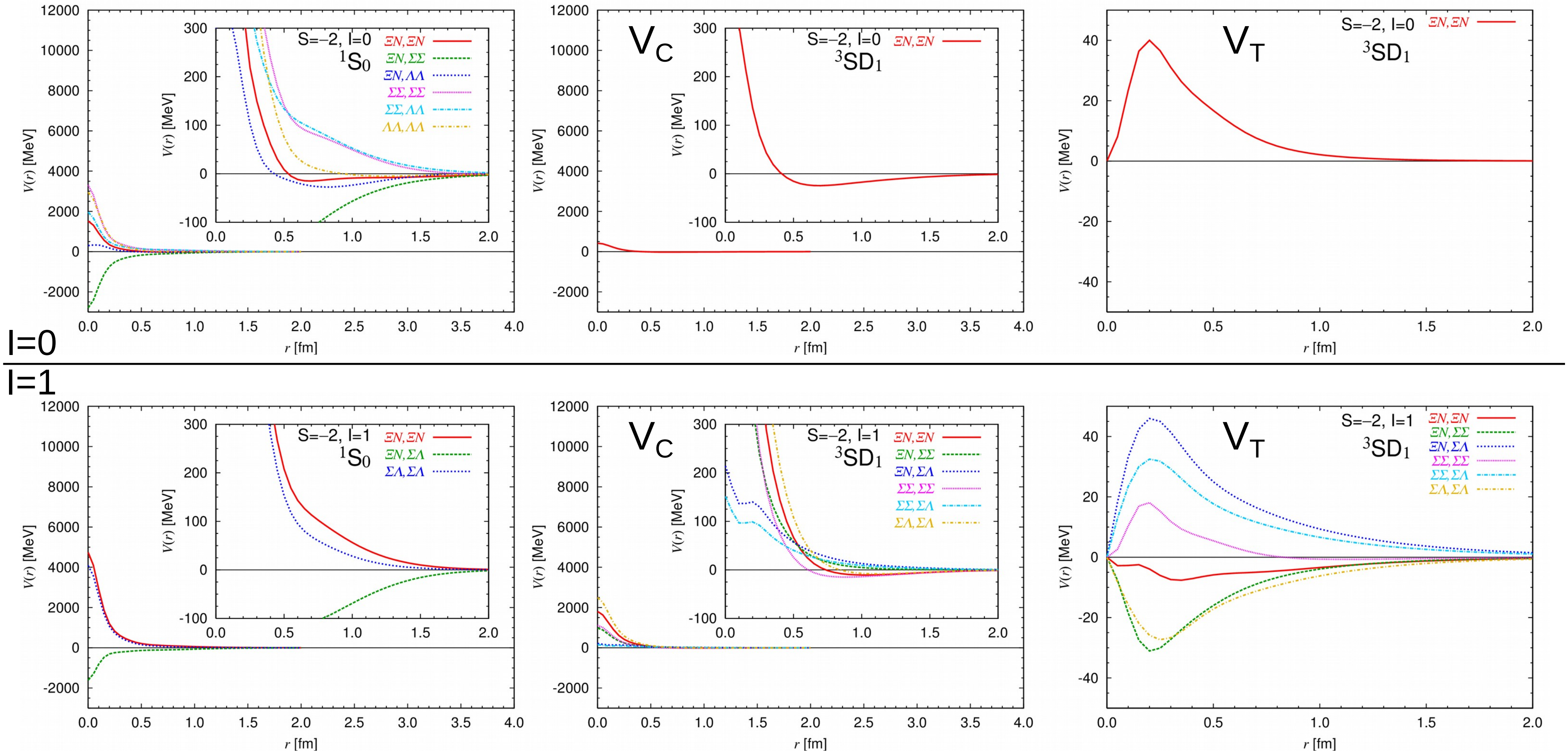
From K-conf. but rotated from the irr.-rep. base diagonal potentials.



- 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

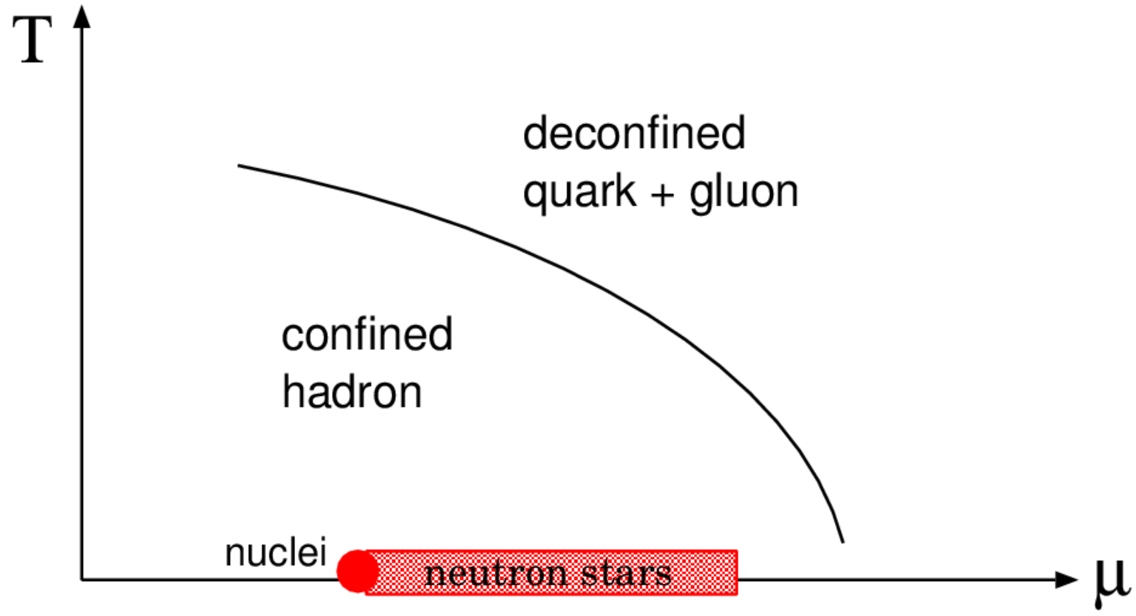
From K-conf. but rotated from the irr.-rep. base diagonal potentials.



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

Introduction

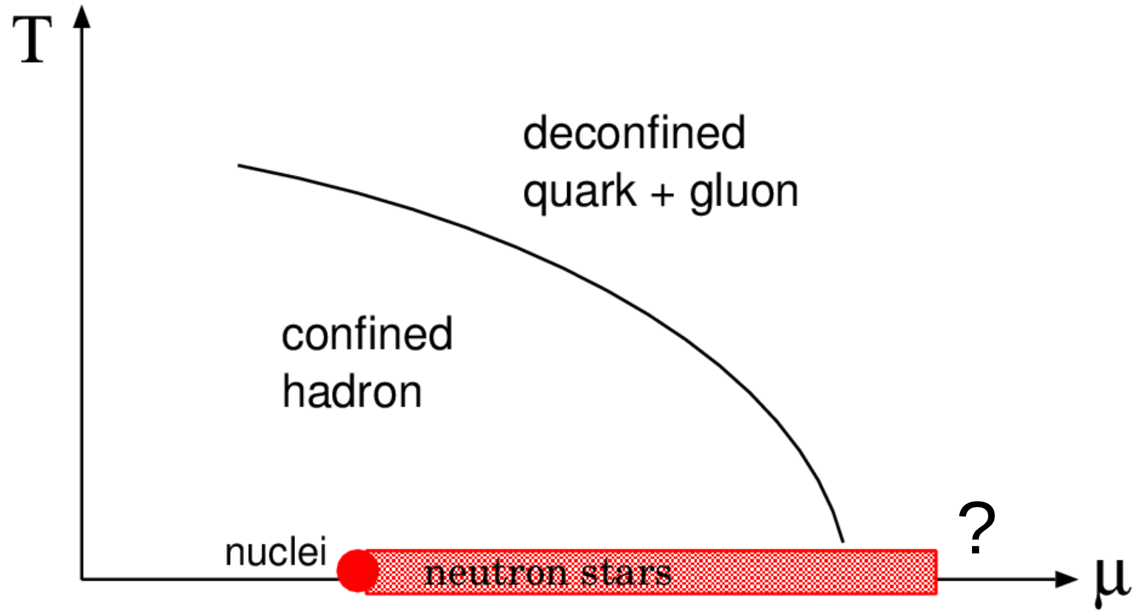
- QCD phase diagram



- NS matter has ρ = several x ρ_0 and T ≈ 0,
  and corresponds to [red box] on the QCD phase-diagram.

Introduction

- QCD phase diagram



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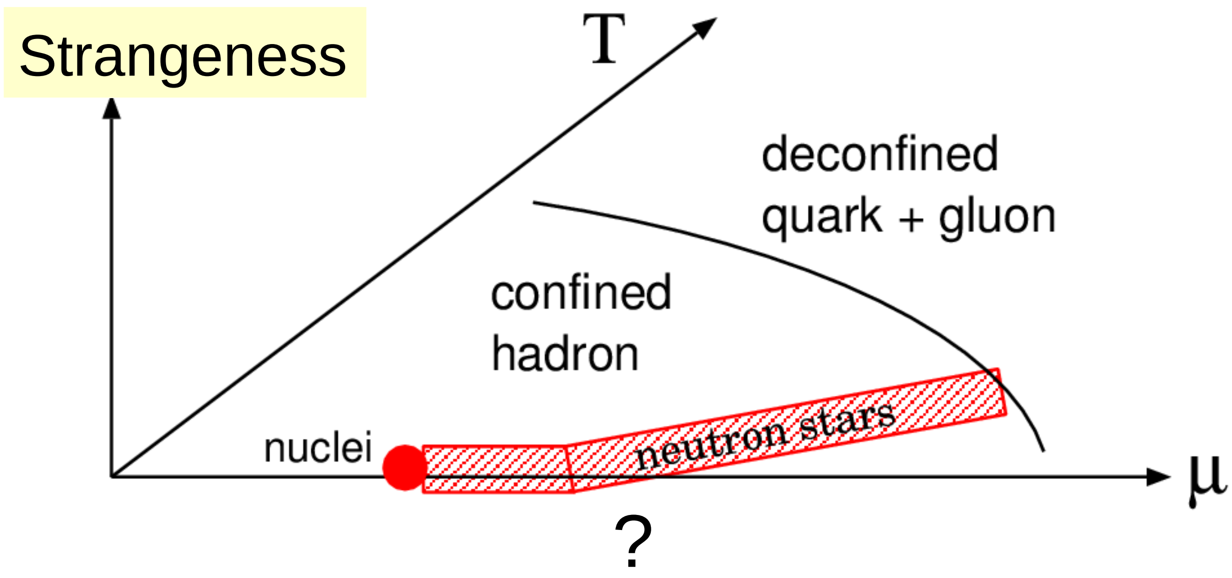
- Perhaps, it touches the deconfined QGP phase.

Introduction

✯ QCD phase diagram



- NS matter has ρ = several x ρ_0 and T ≈ 0, and corresponds to [red box] on the QCD phase-diagram.
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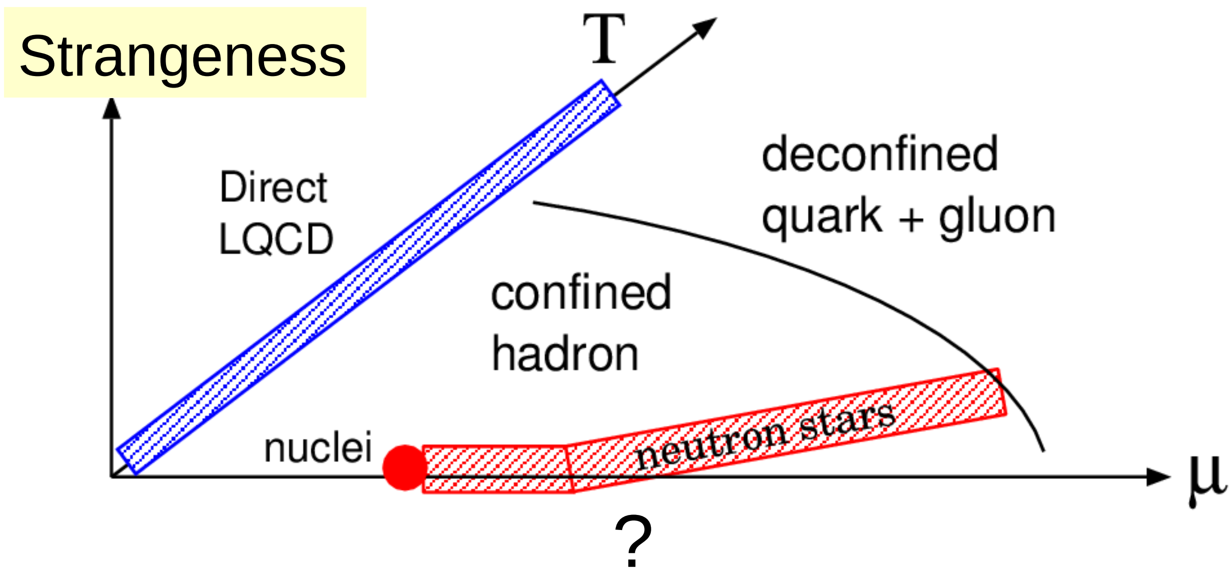
- Probably, it goes to finite strangeness direction.

Introduction

- QCD phase diagram



- NS matter has ρ = several x ρ_0 and T ≈ 0, and corresponds to [red box] on the QCD phase-diagram.
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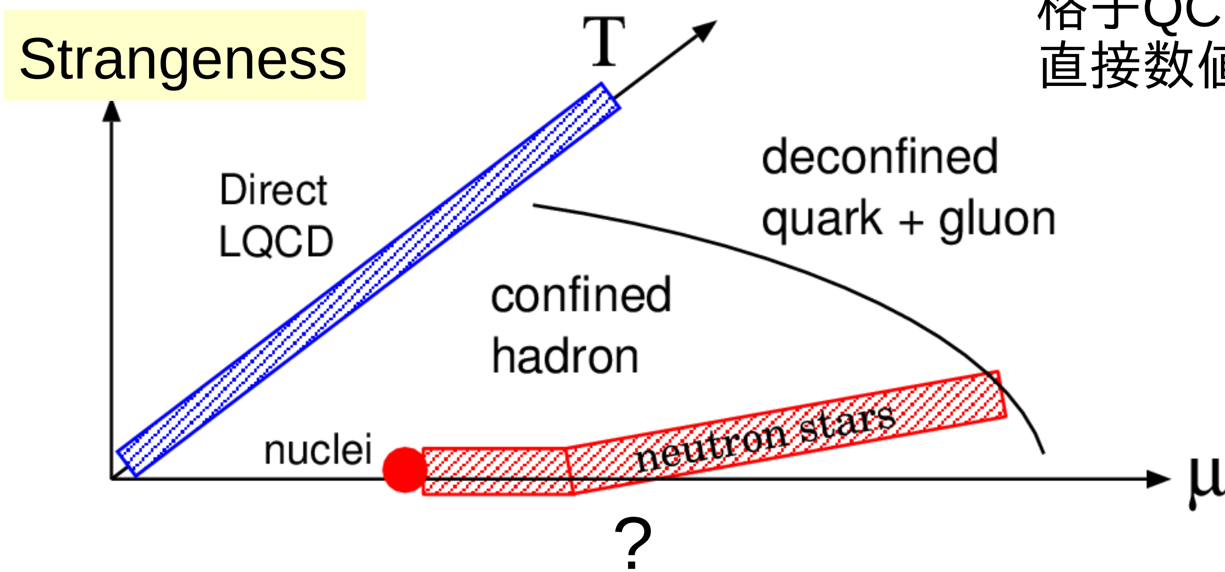
Introduction

* QCD phase diagram

格子QCDから中性子星を攻めるには、
直接数値計算とは別のアプローチが必要！



- NS matter has ρ = several x ρ_0 and T ≈ 0, and corresponds to [pink box] on the QCD phase-diagram.
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- Probably, it goes to finite strangeness direction.
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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.