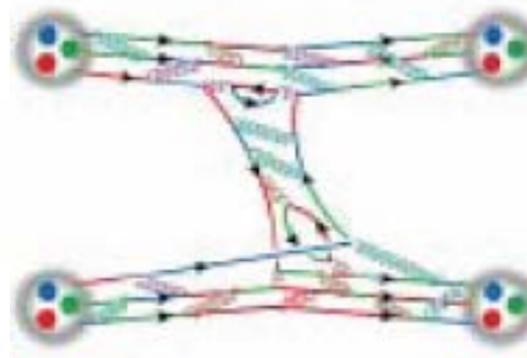


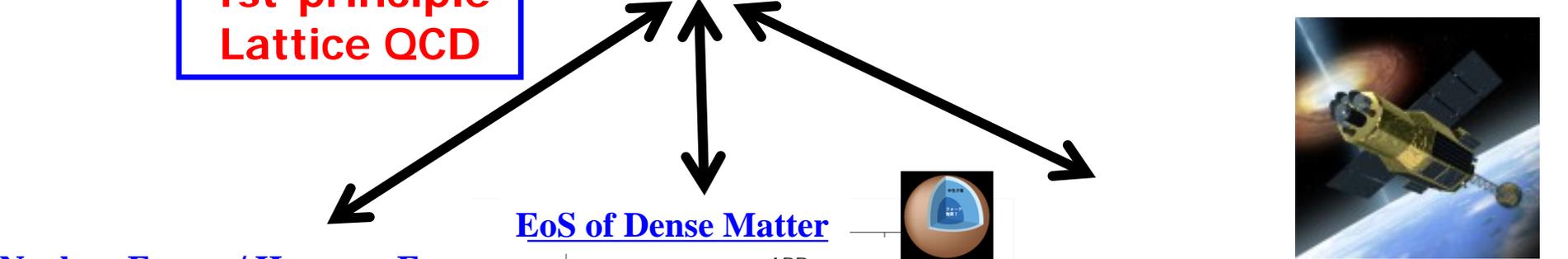
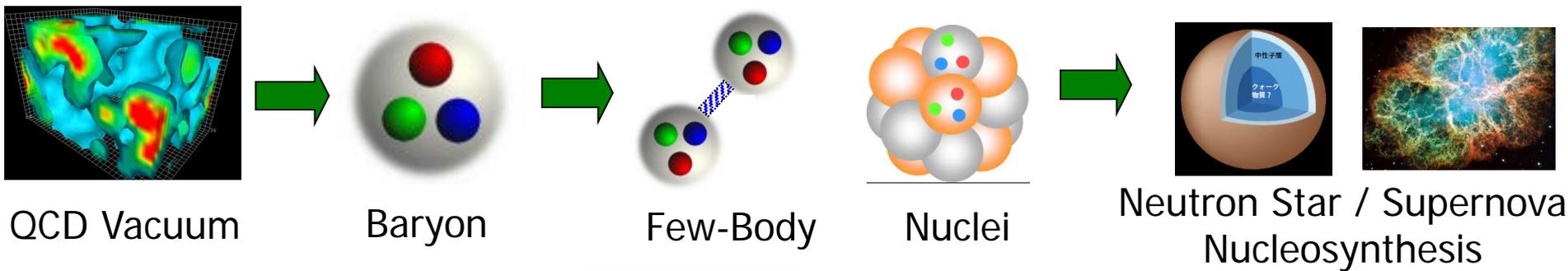
格子QCDによるバリオン間力の決定 — 現状と展望 —

土井 琢身
(理研・仁科センター)

- イン트로ダクション
- 「京」での成果
- 「ポスト京」に向けて



Nuclear- and Astro- physics based on QCD

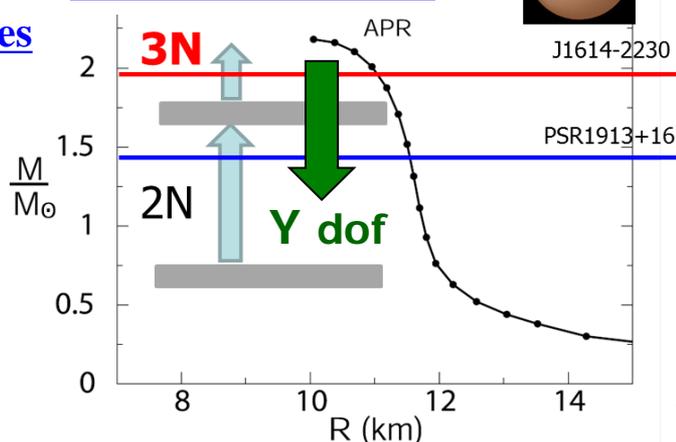


Nuclear Forces / Hyperon Forces



J-PARC

EoS of Dense Matter



aLIGO/KAGRA



RIBF

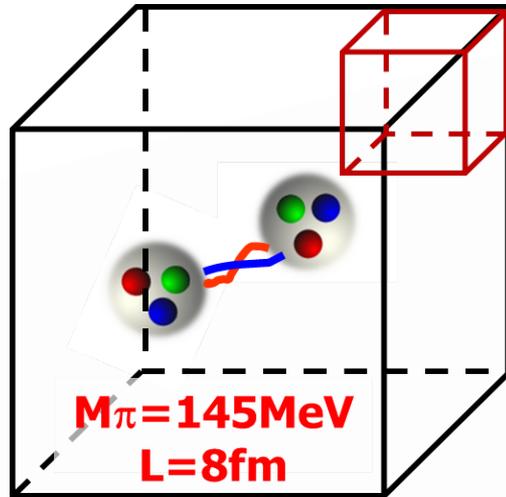
Towards realistic LQCD Baryon Forces

HPCI Strategic Program Field 5
"The origin of matter and the universe"
FY2010-15

Gauge Config Generation

- **$N_f = 2+1$ full QCD**
 - clover fermion + Iwasaki gauge w/ stout smearing
 - volume: $96^4 \approx (8 \text{ fm})^4$
 - $1/a \approx 2.3 \text{ GeV}$ ($a \approx 0.085 \text{ fm}$)
 - $m_\pi \approx 145 \text{ MeV}$, $m_K \approx 525 \text{ MeV}$
 - #traj ≈ 2000 generated

K.-I. Ishikawa et al., PoS LAT2015, 075



$M_\pi = 0.4 \text{ GeV}$
 $L = 3 \text{ fm}$

$M_\pi = 145 \text{ MeV}$
 $L = 8 \text{ fm}$

K-computer (RIKEN/AICS)



FX100 (RIKEN/Wako)
HA-PACS (Tsukuba U.)

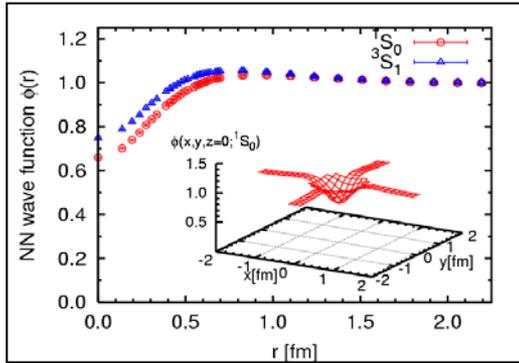


Baryon Forces

→ HAL QCD method

HAL QCD method

NBS wave func.

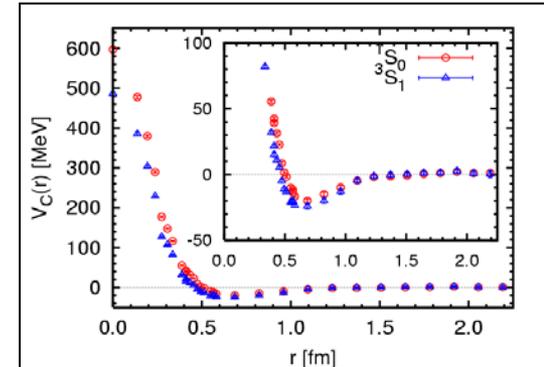


$$\psi_{NBS}(\vec{r}) = \langle 0 | N(\vec{r}) N(\vec{0}) | N(\vec{k}) N(-\vec{k}), in \rangle$$

$$\simeq e^{i\delta_l(k)} \sin(kr - l\pi/2 + \delta_l(k)) / (kr)$$

(at asymptotic region)

Lat Nuclear Force



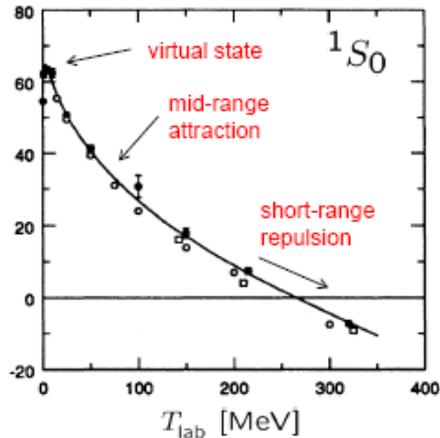
$$(k^2/m_N - H_0) \psi(\vec{r}) = \int d\vec{r}' U(\vec{r}, \vec{r}') \psi(\vec{r}')$$

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

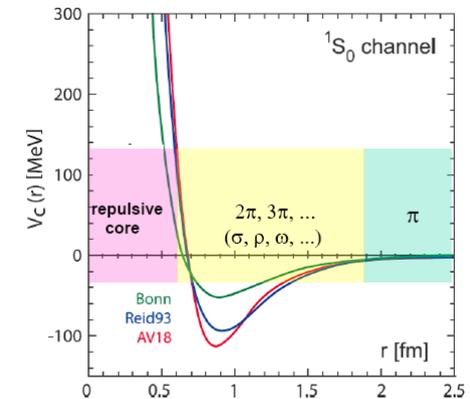
Analog to ...

Scattering Exp.

Phase shifts



Phen. Potential



Crucial Development for Phys Point calc

- Reliable LQCD method: Time-dependent HAL method

N.Ishii et al. (HAL Coll.) PLB712(2012)437

- [**Luscher's method**] → ground state saturation → very bad S/N
- [**HAL method**] → ground state saturation NOT required w/ E-indep pot

→ **“exponential” S/N Improvement** $S/N \sim \exp[-A \times (m_N - 3/2m_\pi) \times t]$

→ Talk by Ishii

- Coupled Channel systems

S. Aoki et al. (HAL Coll.) Proc.Jpn.Acad.B87(2011)509

- **Coupled channel potentials** can be extracted above inelastic threshold
- Essential for YN/YY-forces

→ Talk by Sasaki

- Unified Contraction Algorithm (UCA)

TD, M.Endres, CPC184(2013)117

- Drastically faster algorithm by unifying Wick and color/spinor contractions

Speedup: $\times 192$ for ${}^3\text{H}/{}^3\text{He}$, $\times 20736$ for ${}^4\text{He}$, $\times 10^{11}$ for ${}^8\text{Be}$

Strategy for phys point in “K-era”

- Central/tensor forces for all NN/YN/YY in P=(+) (S, D-waves)

$$U(\vec{r}, \vec{r}') = \underbrace{V_c(r)}_{\text{LO}} + \underbrace{S_{12}V_T(r)}_{\text{LO}} + \underbrace{\vec{L} \cdot \vec{S}V_{LS}(r)}_{\text{NLO}} + \mathcal{O}(\nabla^2)_{\text{NNLO (derivative expansion)}}$$



[Exp info]

[Lat info]



Code:

Efficient implementation of UCA

Performance on K @ 2048node:

~17% → ~25% of peak (~65 Tflops sustained)

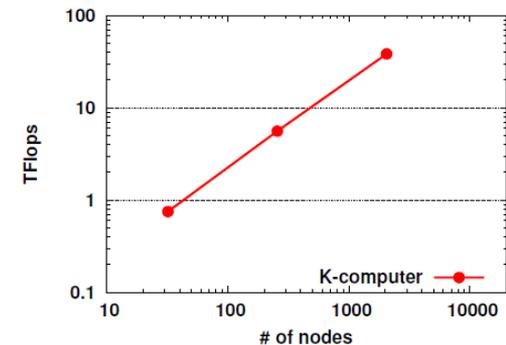
Setup:

Wall source w/ Coulomb gauge

#stat ~ = 200conf x 4rot x 44src → ~x2-4 in FY2015-16

Weak scaling

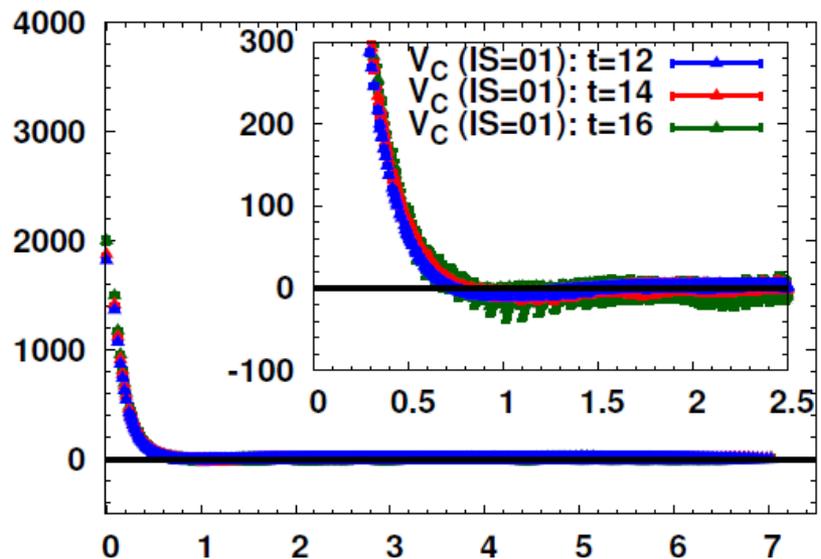
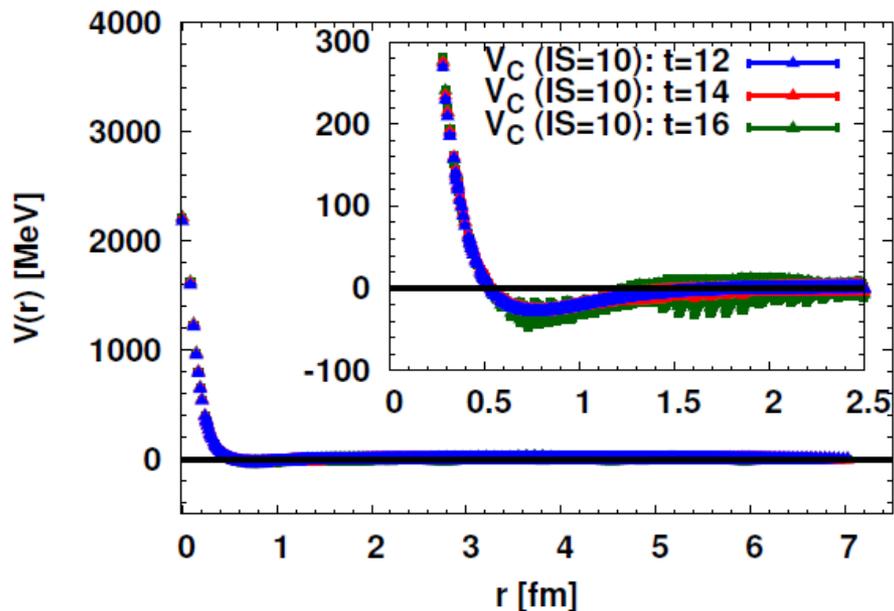
(total of Hadron-Force code, w/o IO)



EE-Potentials

1S_0

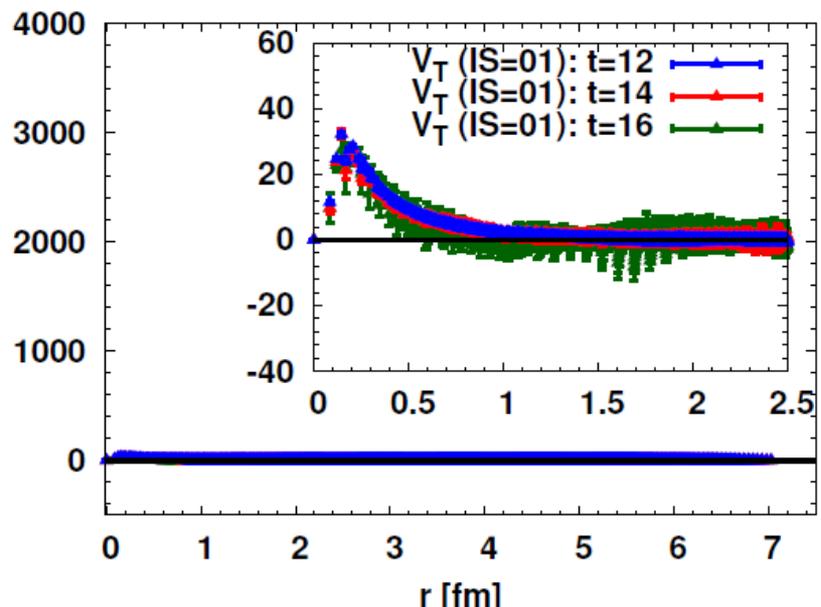
3S_1 - 3D_1



Central

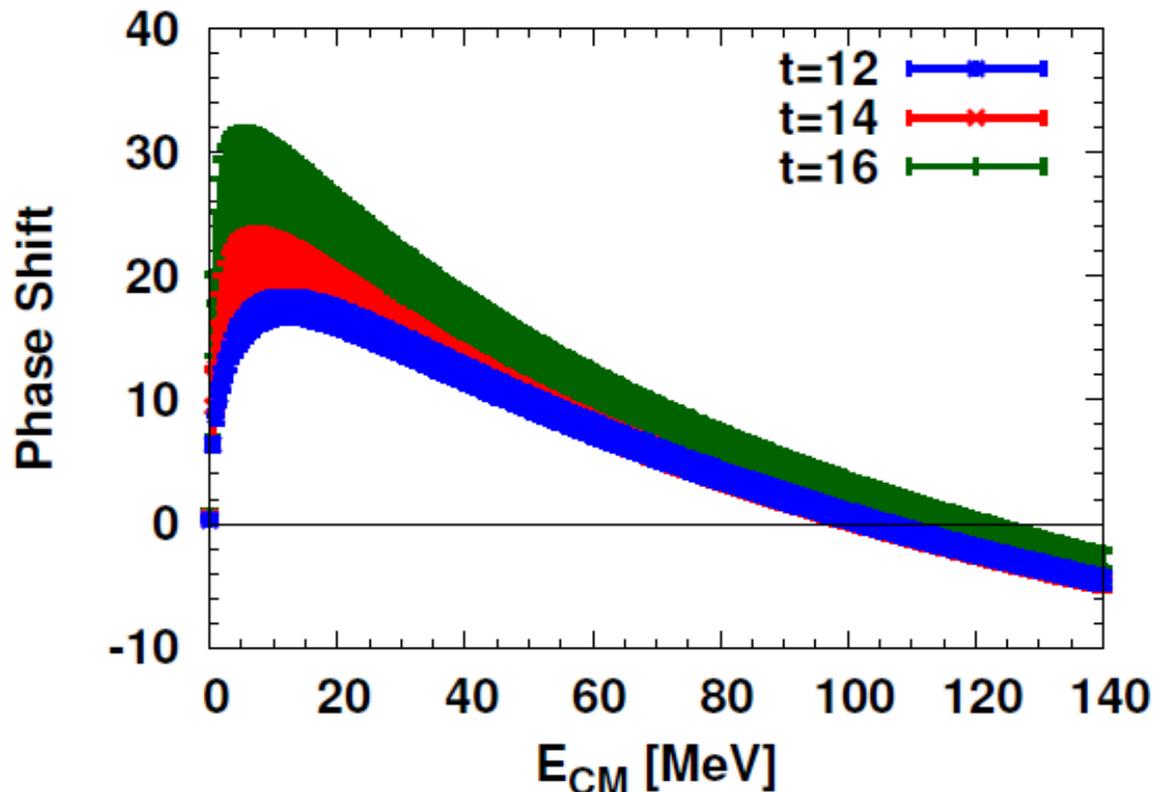
Preliminary

- $^1S_0 \sim 27$ -plet
 \Leftrightarrow NN(1S_0) + SU(3) breaking
- 3S_1 - $^3D_1 \sim 10$ -plet
 \Leftrightarrow unique w/ hyperon DoF
 $\Leftrightarrow \Sigma^-$ in neutron star



Tensor

EE phase shifts (1S_0)



EE (1S_0) is unbound

(t-dependence will be checked again w/ larger #stat)

→ HIC experiments ?

c.f. Phen. model (Nijmegen) : possibly bound

EFT (Haidenbauer et al. '14) : unbound favored

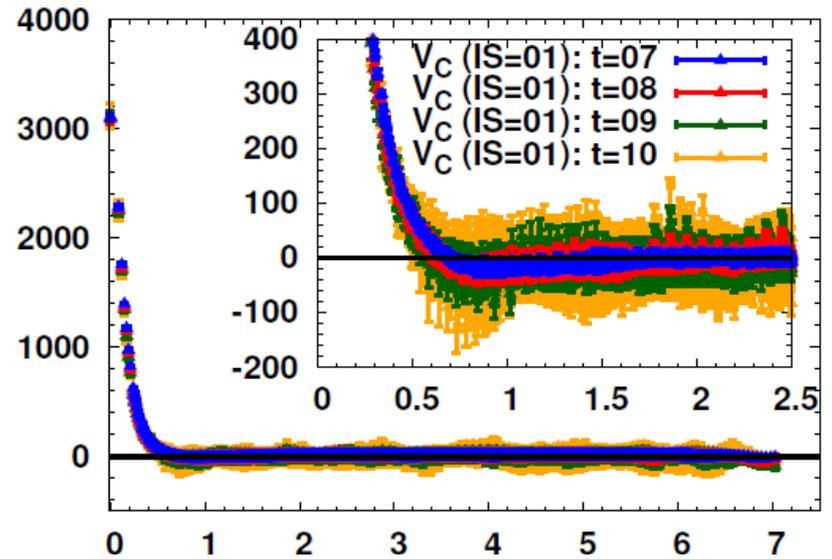
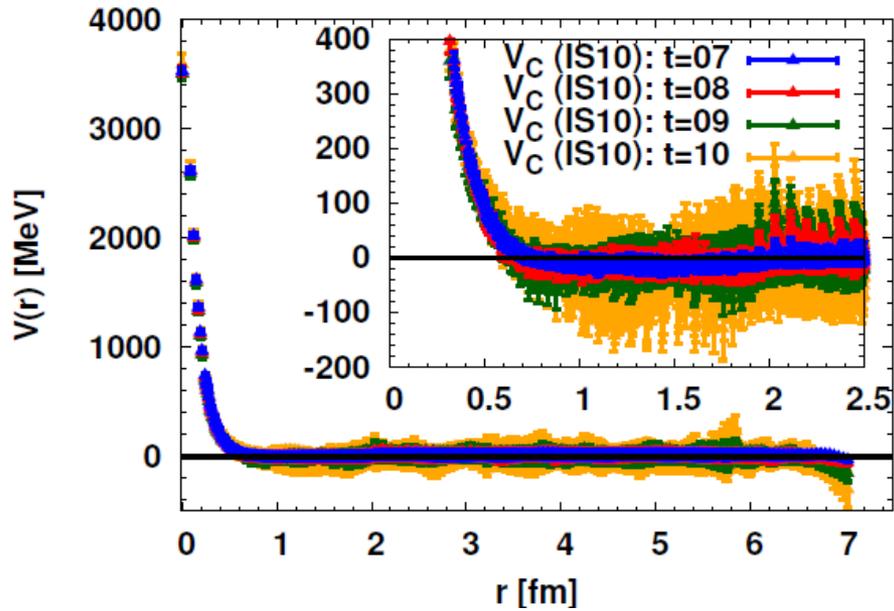
(2-gauss + 2-OBEP fit)

(200conf x 4rot x 44src)

NN-Potentials

1S_0

$^3S_1 - ^3D_1$



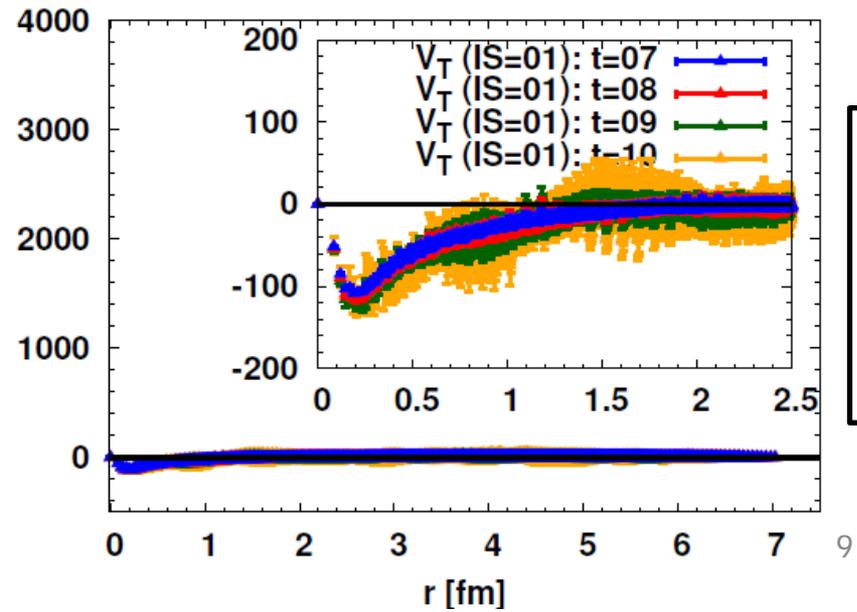
Central

Preliminary

- **Vc:** repulsive core + long-range attraction
- **Vt:** tensor force clearly visible

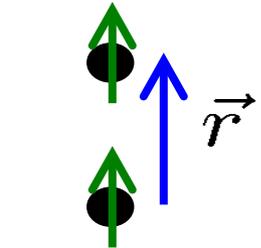
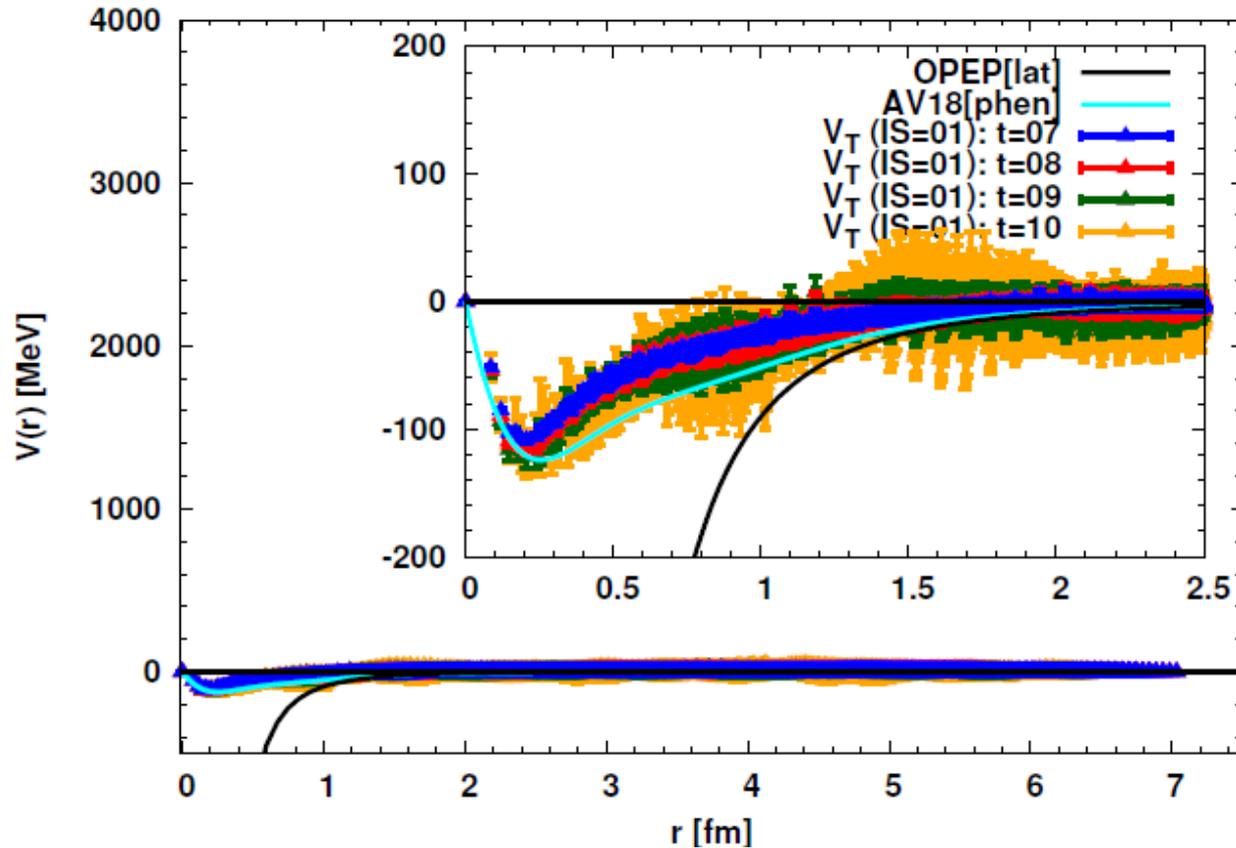
(200conf x 4rot x 44src)

V(r) [MeV]

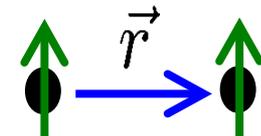


Tensor

NN-Potentials (tensor)



(attractive)



(repulsive)

- Qualitatively similar attractive tail as OPEP force
- Larger t w/ larger #stat is desirable

Objectives in “Post-K-era”

- Semi-quantitative results (small $|S|$) \rightarrow quantitative results
- Central/tensor forces & **spin-orbit forces (LS/ALS)** for all NN/YN/YY in $P=(+)$ & $P=(-)$ channels

“K”

$$U_+(\vec{r}, \vec{r}') = \underbrace{V_c(r)}_{\text{LO}} + \underbrace{S_{12}V_T(r)}_{\text{LO}} + \underbrace{\vec{L} \cdot \vec{S}V_{LS}(r)}_{\text{NLO}} + \dots \quad P=(+)$$

$$U_-(\vec{r}, \vec{r}') = \underbrace{V_c(r)}_{\text{LO}} + \underbrace{S_{12}V_T(r)}_{\text{LO}} + \underbrace{\vec{L} \cdot \vec{S}V_{LS}(r)}_{\text{NLO}} + \dots \quad P=(-)$$

LO

LO

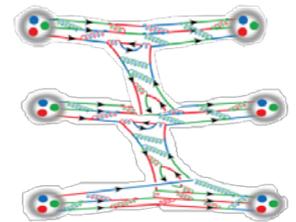
NLO

“Post-K”

- Magic number
- Superfluidity 3P_2 in neutron star

- **3-body forces**

- Stable & unstable nuclei
- Properties of high dense matter (w/ hyperon DoF)



- \rightarrow EoS based on LQCD baryon forces

\rightarrow Talk by Inoue

Strategy in FY2016

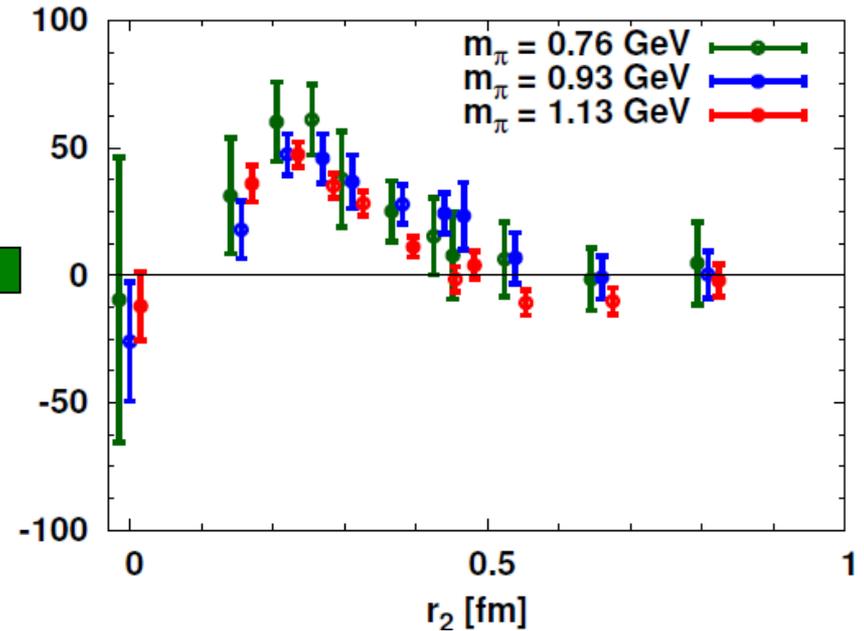
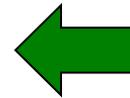
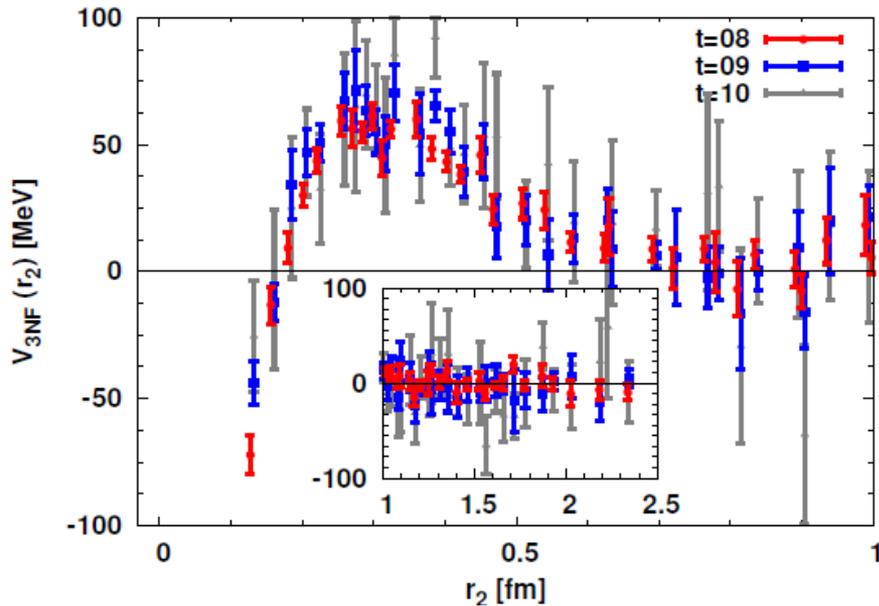
- $P=(+)$ forces, central & tensor
 - Improve #stat by x2
 - R&D of new methods to improve S/N
- $P=(-)$ forces and LS/ALS forces
 - Systematic studies in SU(3) limit @ heavy masses
 - SU(3) breaking effect @ heavy masses
- 3-body forces
 - Quark mass dependence for 3-nucleon forces
 - 3-baryon forces w/ hyperon in SU(3) limit
- Collaboration w/ LQCD group @ Berkeley, USA
- Collaboration w/ NP group @ Surrey, UK

3N-forces (3NF)

Preliminary

Nf=2+1, $m_\pi=0.51$ GeV

Nf=2, $m_\pi=0.76-1.1$ GeV



Short-range repulsive 3NF

Kernel (B/F ~ 4): $\sim 50\%$ efficiency achieved !

Summary

- **LQCD Baryon Forces at ~ phys. point in [K-era]**
 - $m(\pi) \approx 145 \text{ MeV}$, $L \approx 8 \text{ fm}$, $1/a \approx 2.3 \text{ GeV}$
 - **Central & Tensor forces** calculated for **all NN/YN/YY** in $P=(+)$ channel
 - Key formula / algorithm
 - t-dep HAL QCD method
 - Coupled channel formalism
 - Unified contraction algorithm (UCA)
- **$\Xi\Xi$ -forces**
 - 1S_0 : strong attraction but unbound
- **NN-forces**
 - Tensor force is clearly visible
- **Prospects**
 - Measurement in progress \rightarrow #stat will be $\sim x2 - x4$ in FY2015-16
 - New techniques to improve S/N are under R&D
 - **[Post-K Exascale-Era]** LS-forces, $P=(-)$ channel, 3-baryon forces etc

