Baryon interactions from lattice QCD with physical masses

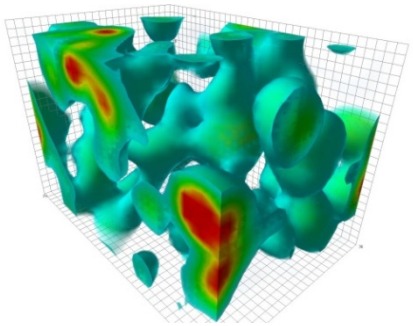
– Overview and S = 0, -4 sectors –

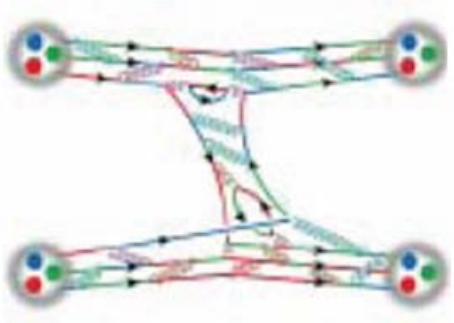
S = -6

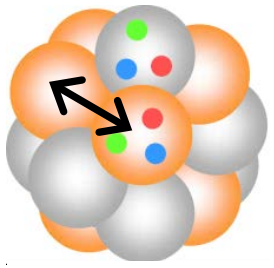
Takumi Doi

(Nishina Center, RIKEN)

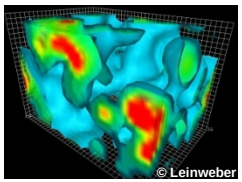
for HAL QCD Collaboration

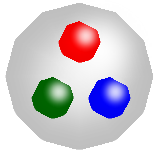


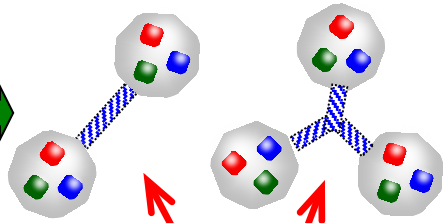


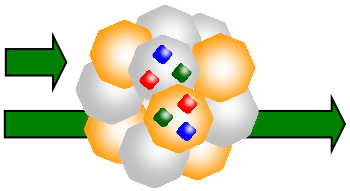


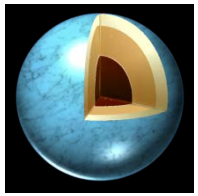
The Odyssey from Quarks to Universe

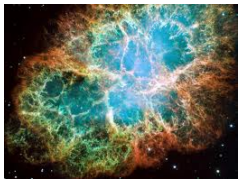












QCD vacuum Baryons Nuclei Neutron Stars / Supernovae Nucleosynthesis

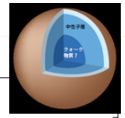
QCD → **1st-principle Lattice QCD** → **Baryon Forces** → ab-initio nuclear calc.

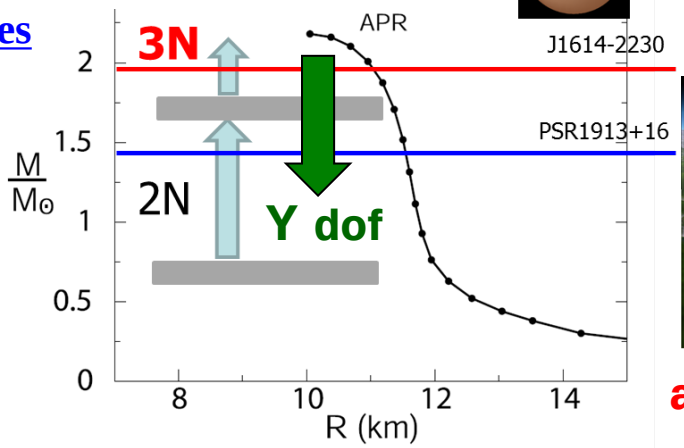
RIBF

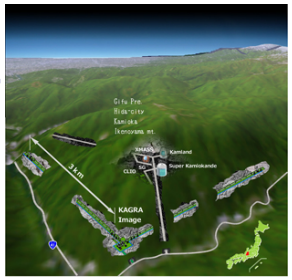
Nuclear Forces / Hyperon Forces

J-PARC

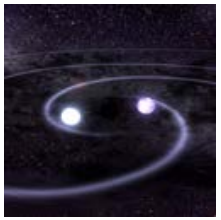
EoS of Dense Matter







aLIGO/KAGRA



NS-NS merger

The Odyssey from unphysical to physical quark masses

~2010

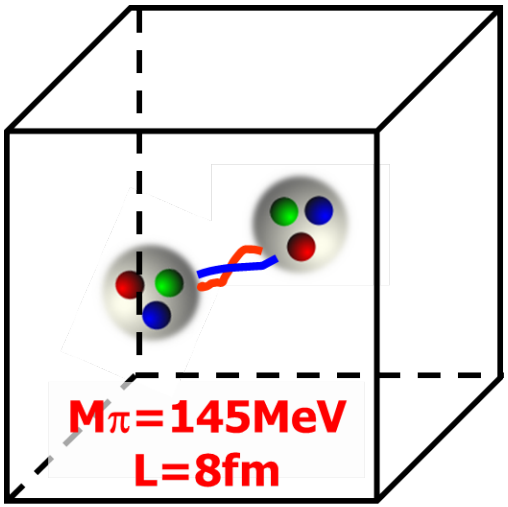
➔ lighter m_q

We were here

Mπ=800 MeV
L=2fm

K-computer [10PFlops]

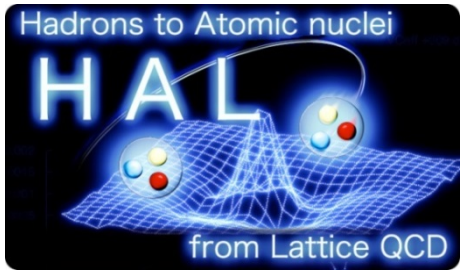
Phys. point



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

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

Staple Wilson-line
@ ~2000 BC

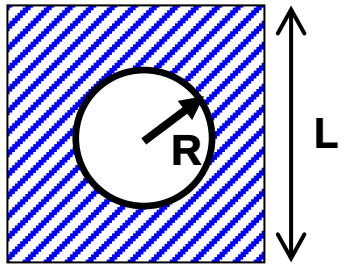


S. Aoki, T. Doi, F. Etminan, S. Gongyo,
T. Hatsuda, Y. Ikeda, T. Inoue, T. Iritani,
N. Ishii, D. Kawai, T. Miyamato,
K. Murano, H. Nemura, K. Sasaki

[HAL QCD method]

- Nambu-Bethe-Salpeter (NBS) wave function

$$\psi(\vec{r}) = \langle 0|\ N(\vec{r})N(\vec{0})\ |N(\vec{k})N(-\vec{k}); in\rangle$$



$$(\nabla^2 + k^2)\psi(\vec{r}) = 0, \quad r > R$$

– phase shift at asymptotic region

$$\psi(r) \simeq A\frac{\sin(kr - l\pi/2 + \delta(k))}{kr}$$

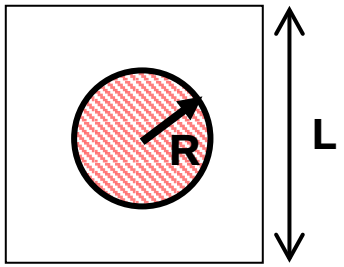
M.Luscher, NPB354(1991)531
C.-J.Lin et al., NPB619(2001)467
N.Ishizuka, PoS LAT2009 (2009) 119
CP-PACS Coll., PRD71(2005)094504

Extended to multi-particle systems

S. Aoki et al., PRD88(2013)014036

- Consider the wave function at "interacting region"

$$(\nabla^2 + k^2)\psi(\boldsymbol{r}) = m\int d\boldsymbol{r'}U(\boldsymbol{r},\boldsymbol{r'})\psi(\boldsymbol{r'}), \quad r < R$$



– U(r,r'): faithful to the phase shift by construction
  - U(r,r'): E-independent, while non-local in general
    – Non-locality ➔ derivative expansion

Aoki-Hatsuda-Ishii PTP123(2010)89

Crucial Theoretical Development

- **Time-dependent HAL method** N.Ishii et al. (HAL Coll.) PLB712(2012)437
  - Multi-baryon systems on large box w/ light mass ➔ **~ gapless (continuum)**
  - **[Luscher's method]** ➔ G.S. saturation required ➔ the S/N problem
  - **[HAL method]** ➔ G.S. saturation NOT required w/ E-indep pot

    ➔ **"exponential" S/N Improvement** $S/N \sim \exp[-\mathbf{A} \times (\mathbf{m_N - 3/2m_\pi}) \times \mathbf{t}]$

    ➔ **Talks by T. Iritani, S. Aoki (Thur.)** **T. Iritani et al. (HAL Coll.) arXiv:1607.06371**

- **Coupled Channel systems** S. Aoki et al. (HAL Coll.) Proc.Jpn.Acad.B87(2011)509
  - Extension above inelastic threshold by **Coupled channel potentials**

    ➔ Essential for YN/YY-forces

- **Unified Contraction Algorithm (UCA)** TD, M.Endres, CPC184(2013)117
  - Drastically faster algorithm by unifying Wick and color/spinor contractions

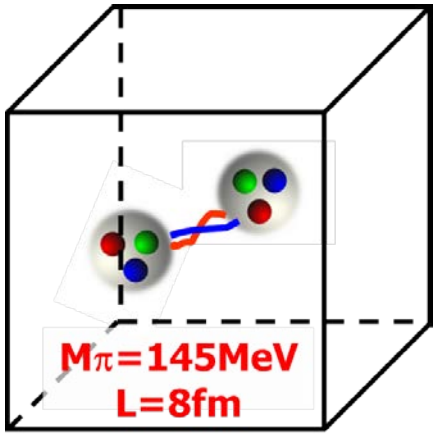
Speedup: $\times 192$ for ^{3}H/^{3}He, $\times 20736$ for ^{4}He, $\times 10^{11}$ for ^{8}Be

See also subsequent works: Detmold et al., PRD87(2013)114512
Gunther et al., PRD87(2013)094513

Setup of Lattice QCD

- **Nf = 2+1 full QCD**
  - Clover fermion + Iwasaki gauge action
  - Non-perturbatively O(a)-improved
  - APE-Stout smearing (α=0.1, n_{stout}=6)
  - m(pi) ~= 145 MeV, m(K) ~= 525 MeV
  - #traj ~= 2000 generated

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



96^4 box
(a~= 0.085fm)

- Measurement
  - Wall source w/ Coulomb gauge
  - K @ RIKEN/AICS, FX100 @ RIKEN/Wako, HA-PACS @ Tsukuba are used
    - Efficient UCA code + block solver ➔ ~25% efficiency on K @ 2048node
  - #stat = 200 confs x 4 rot x 44 (or 88) src ➔ x 4 (or 2) in FY2016
  - All results preliminary

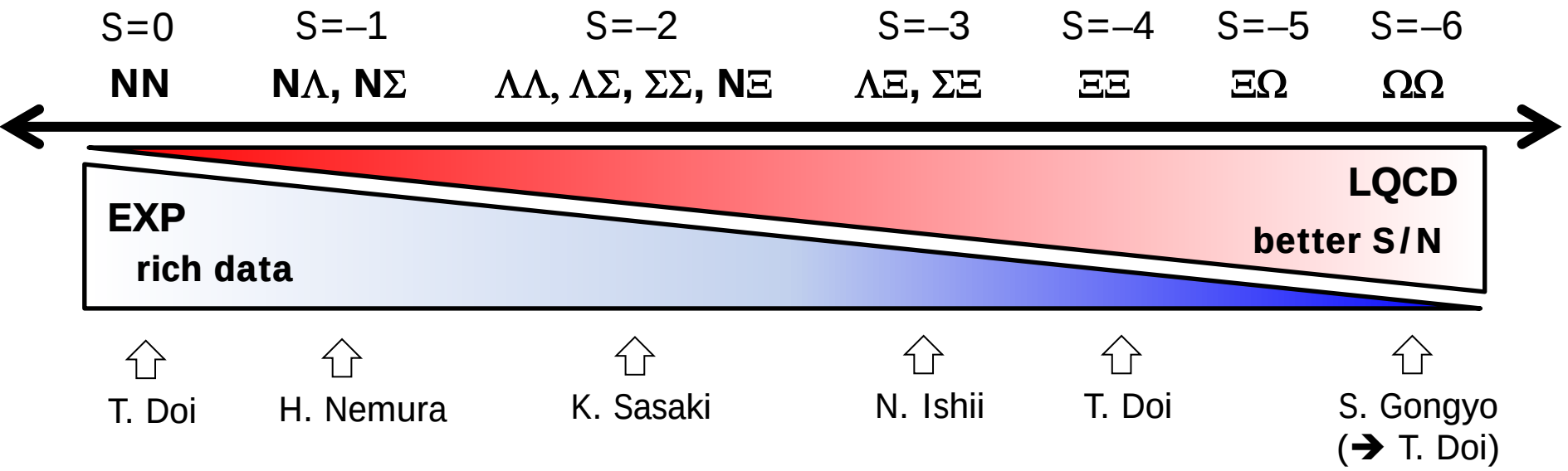
Target of Lattice QCD

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

Central Tensor

$$U(\vec{r},\vec{r'}) = V_c(r) + S_{12}V_T(r) + \vec{L}\cdot\vec{S}V_{LS}(r) + \mathcal{O}(\nabla^2)$$

LO LO NLO NNLO (derivative expansion)

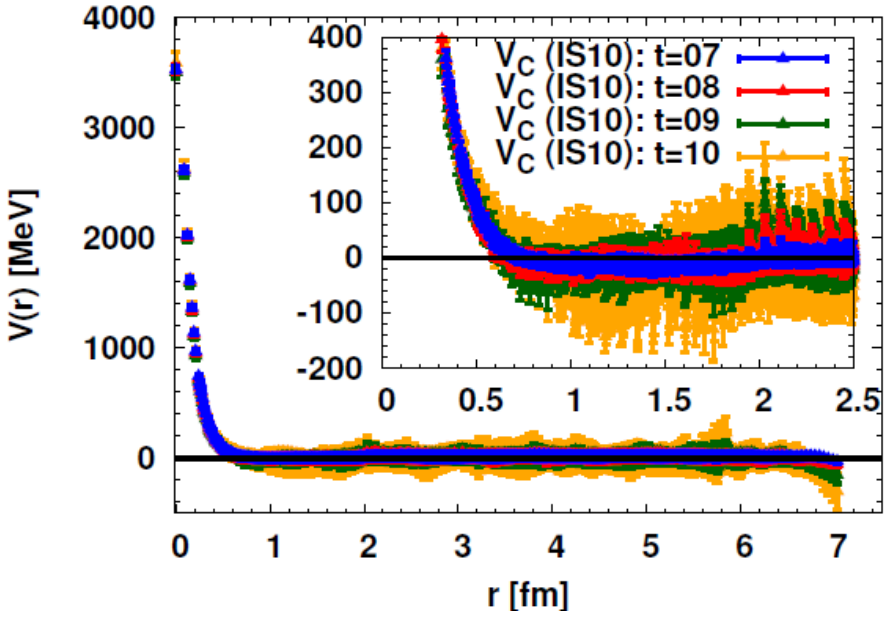


Hyperon forces provide precious predictions

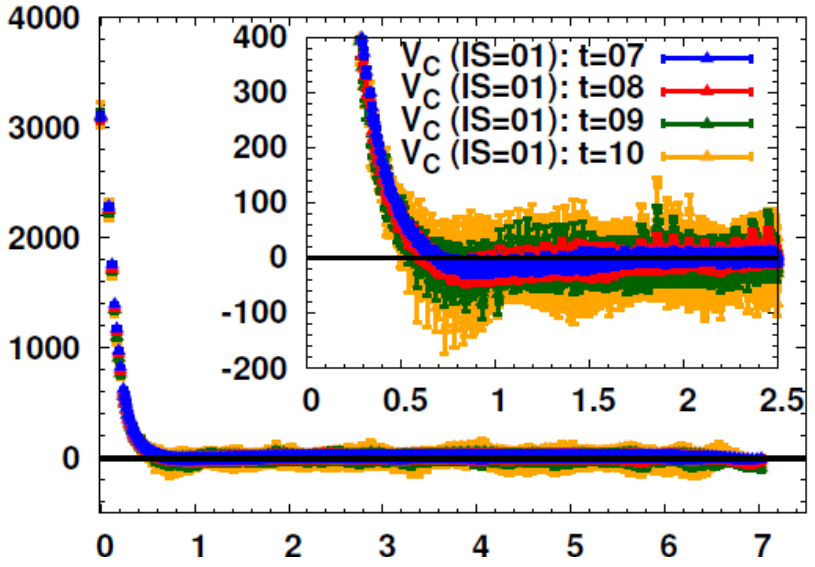
NN system (S= 0)

NN-Potentials

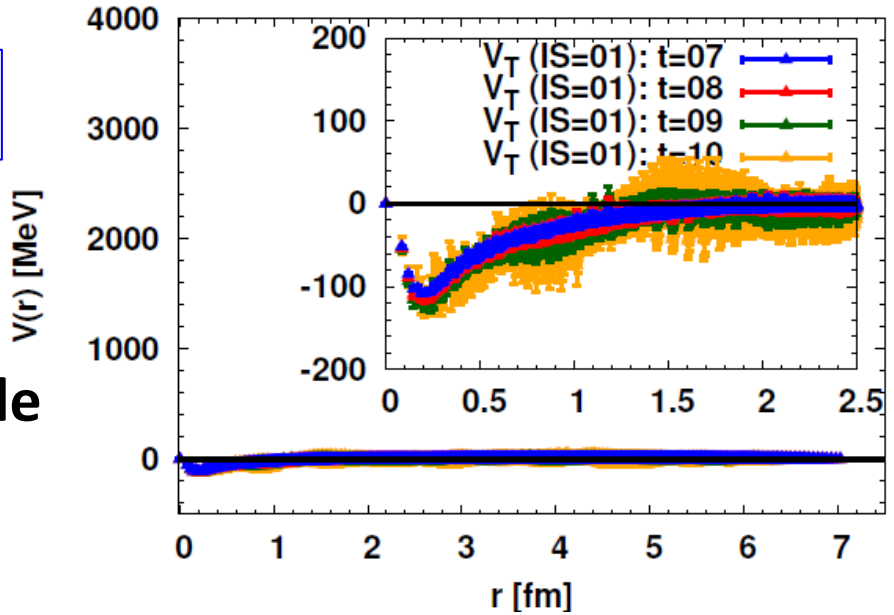
$^1S_0$



$^3S_1$-$^3D_1$



Central



Tensor

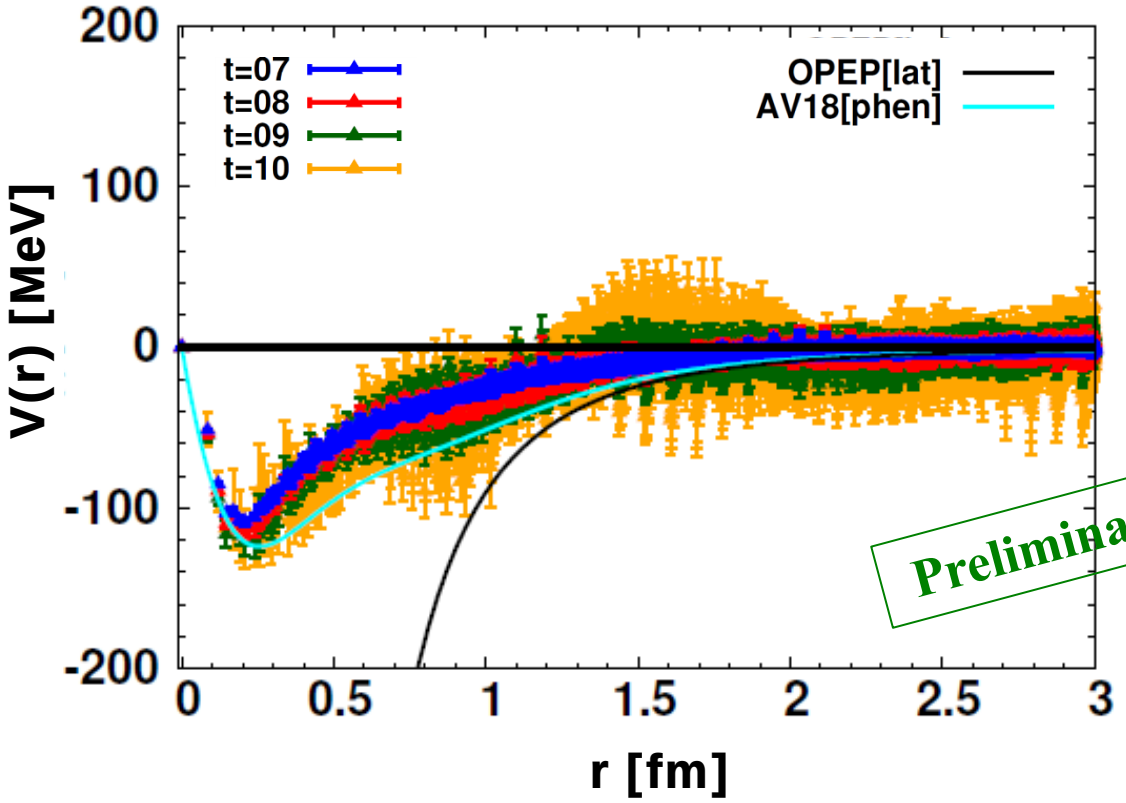
Preliminary

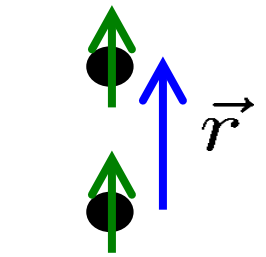
- **Vc: repulsive core**
  + long-range attraction
- **Vt: tensor force clearly visible**

(200conf x 4rot x 44src)

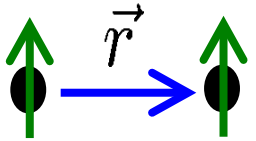
NN system ($^3S_1$-$^3D_1$)

Tensor Force





(attractive)



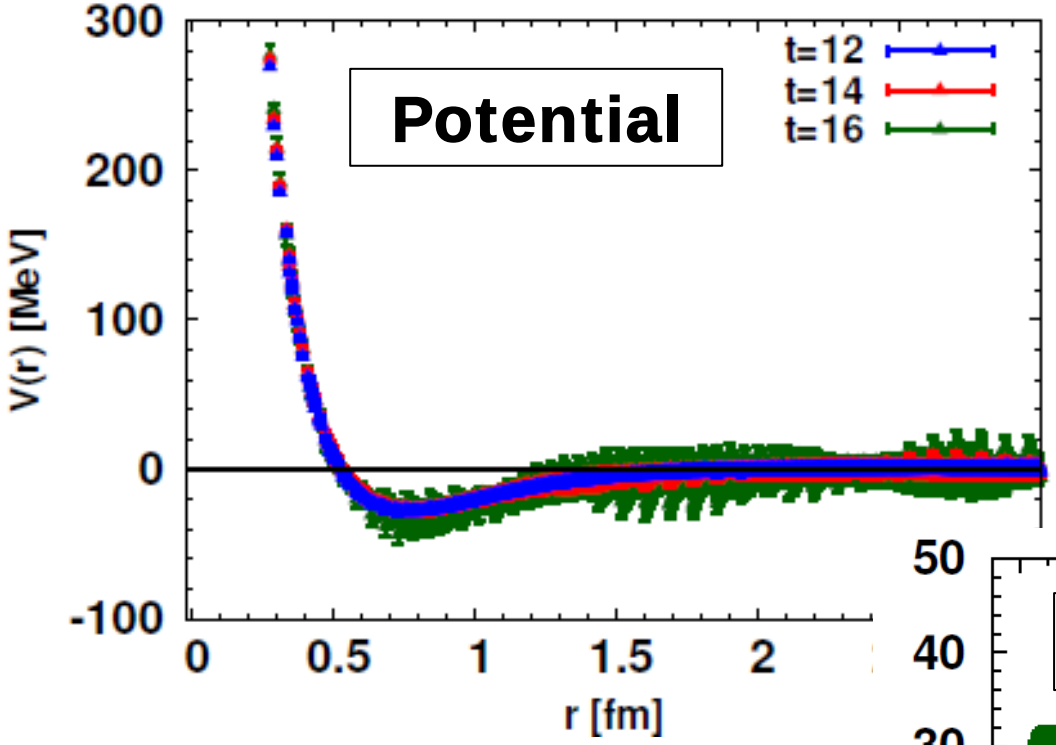
(repulsive)

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

m(eff) for single N: ~2-4% sys err for t = 8-10

ΞΞ system (S= –4)

ΞΞ system ($^1S_0$)



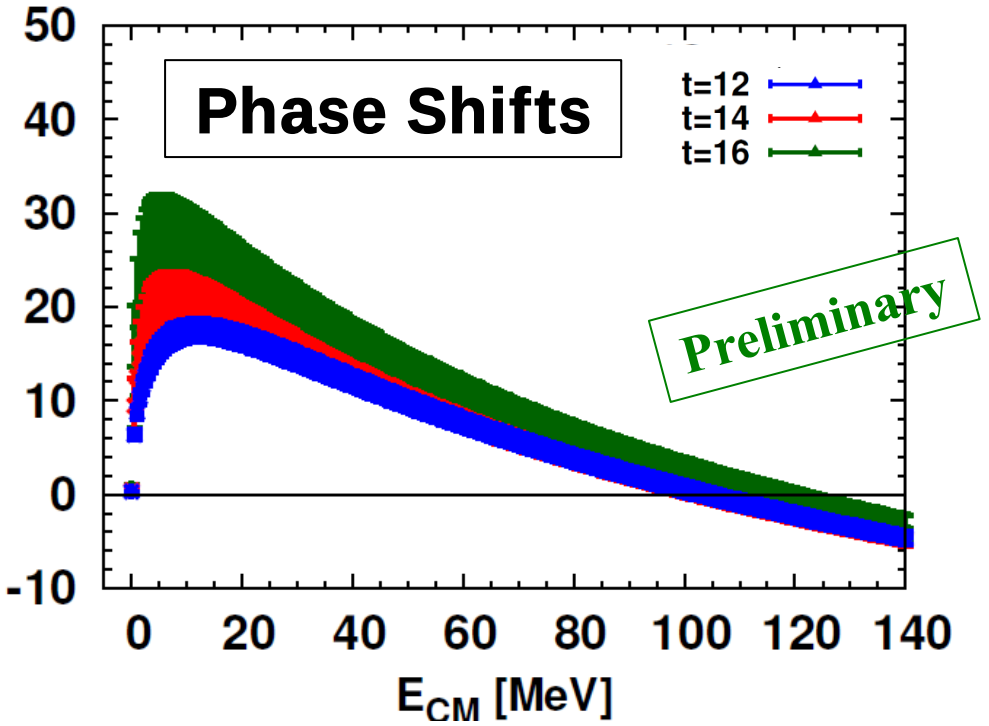
Flavor SU(3)-partner of dineutron

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

Strong Attraction

yet Unbound

⇔ **ΞΞ correlation in HIC**



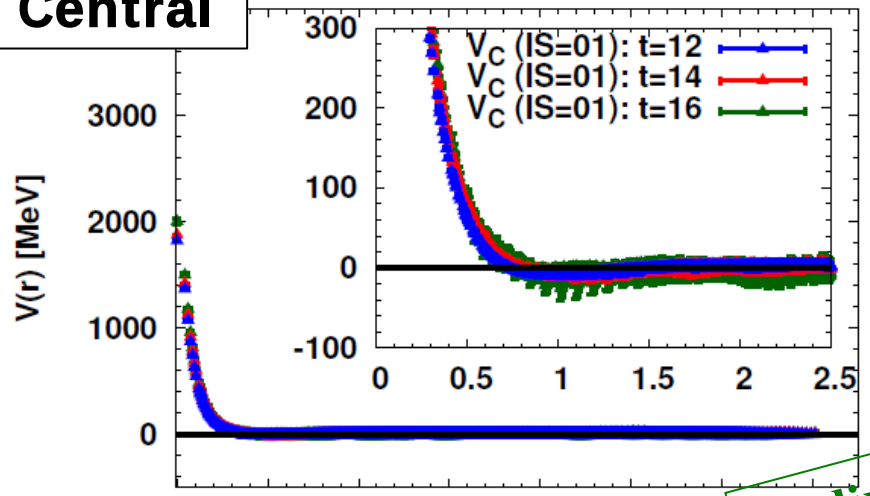
m(eff) for single Ξ: ~0.3-1% sys err for t=14-18

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

ΞΞ system ($^3S_1$-$^3D_1$)

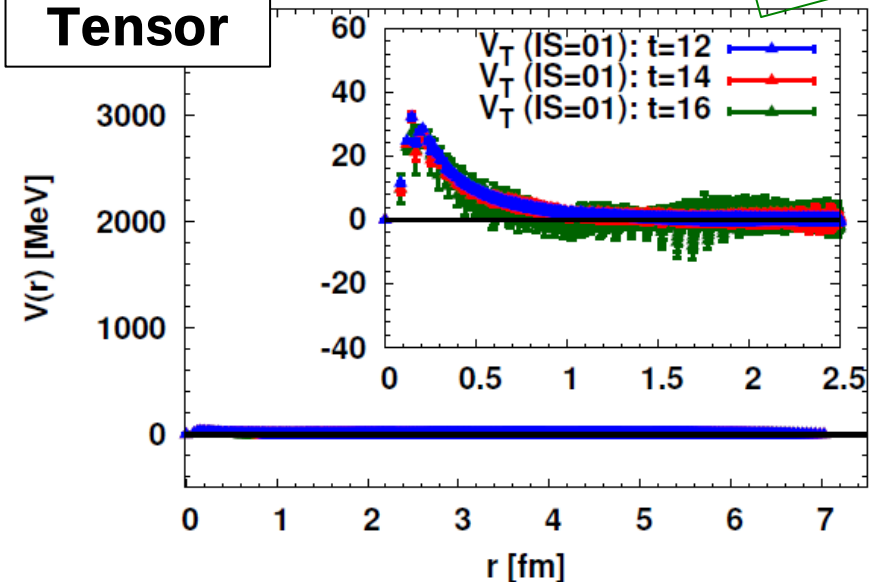
Potentials

Central



Preliminary

Tensor



10plet ⇔ unique w/ hyperon DoF

Flavor SU(3)-partner of Σ^- n

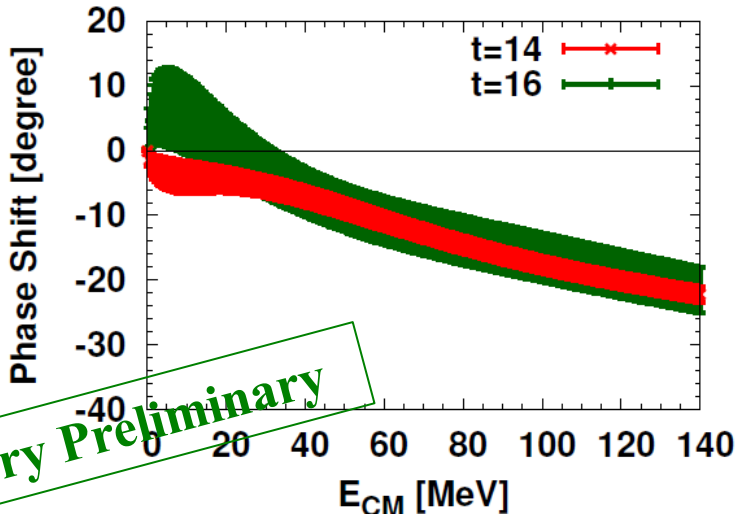
⇨ • Σ^- in neutron star ?

Central: Strong Repulsion

Tensor: Weak

Phase Shifts

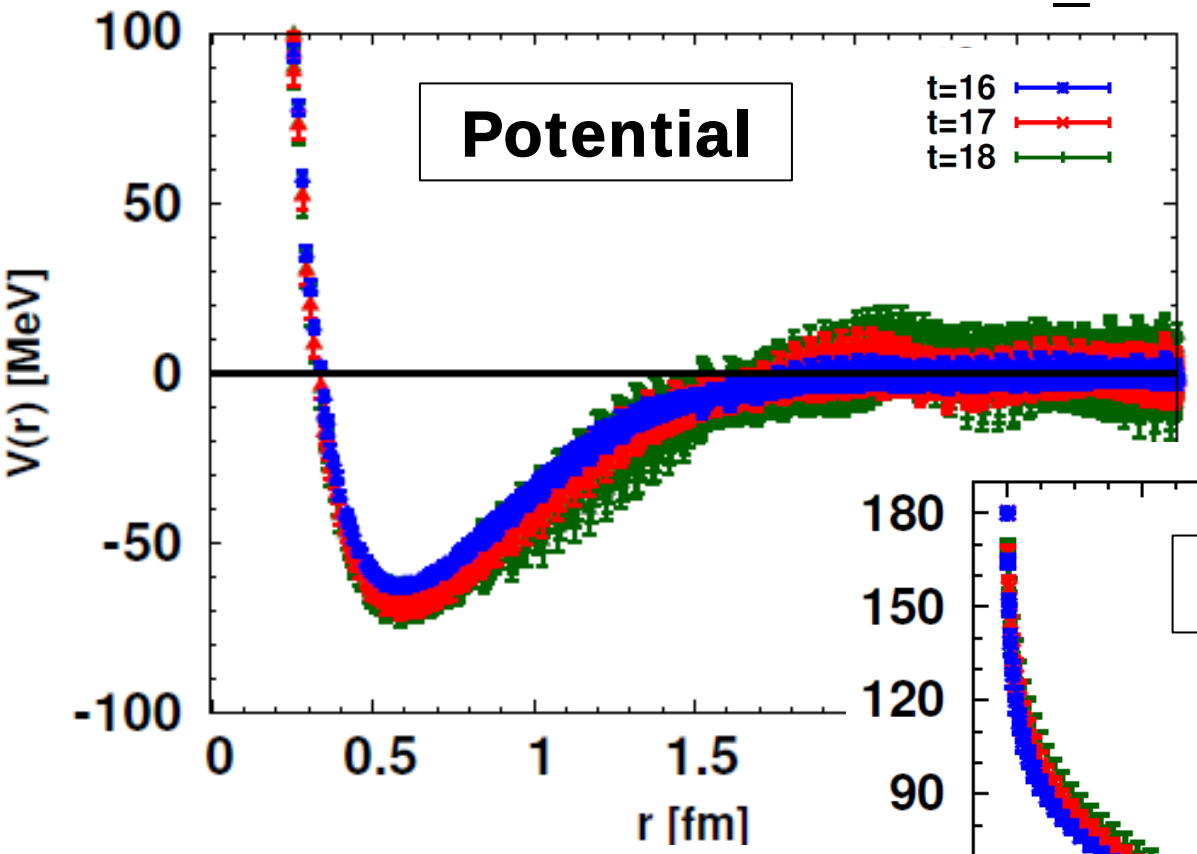
(effective $^3S_1$)



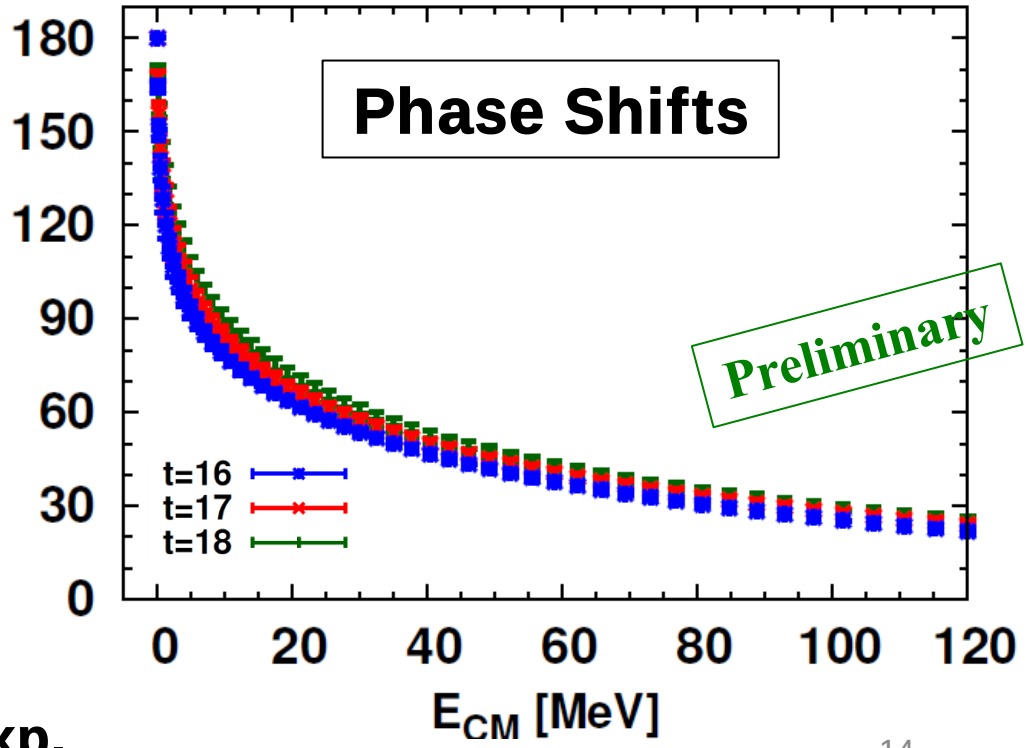
Very Preliminary

ΩΩ system ($^1S_0$)

The "most strange" dibaryon system



[S. Gongyo / K. Sasaki]



Strong Attraction

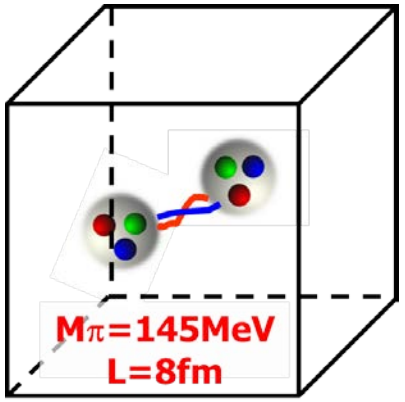
➔ **Vicinity of bound / unbound**

[~ Unitary limit]

⇔ **ΩΩ correlation in HIC exp.**

Summary

- The 1st LQCD for Baryon Forces at ~ phys. point
  - m(pi) ~= 145 MeV, L ~= 8fm, 1/a ~= 2.3GeV
  - Predictions in particular for Hyperon Forces

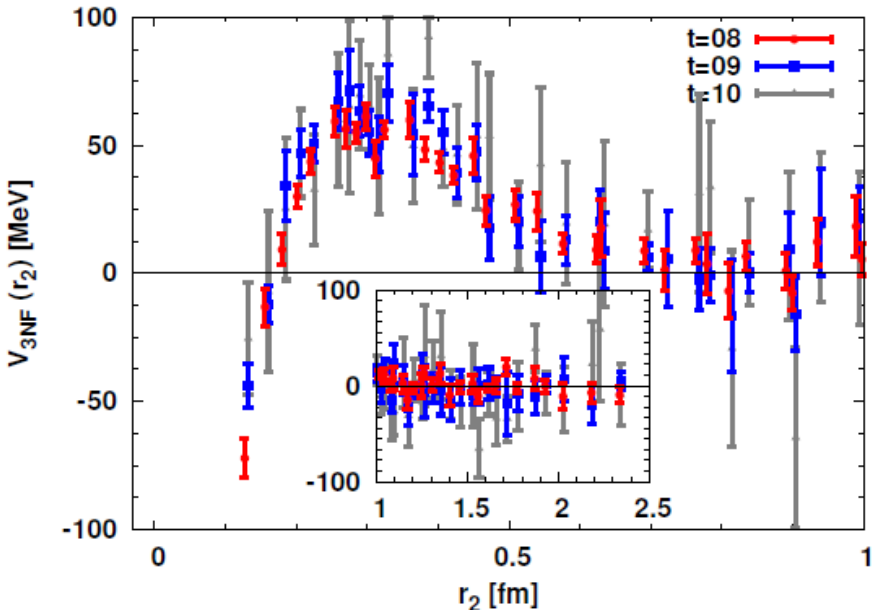


- NN systems
  - Tensor forces clearly visible
- ΞΞ systems
  - $^1S_0$: strong attraction but unbound
  - $^3S_1$: strong repulsion ⇔ Σ^- in neutron stars unlikely
- ΩΩ system
  - $^1S_0$: strong attraction; ~ unitary limit system
- Prospects
  - #stat will be ~ x2-4 in FY2016
  - Exascale computing Era ~ 2020
  - LS-forces, Parity-odd channel, Three-body forces ➔ LQCD EoS

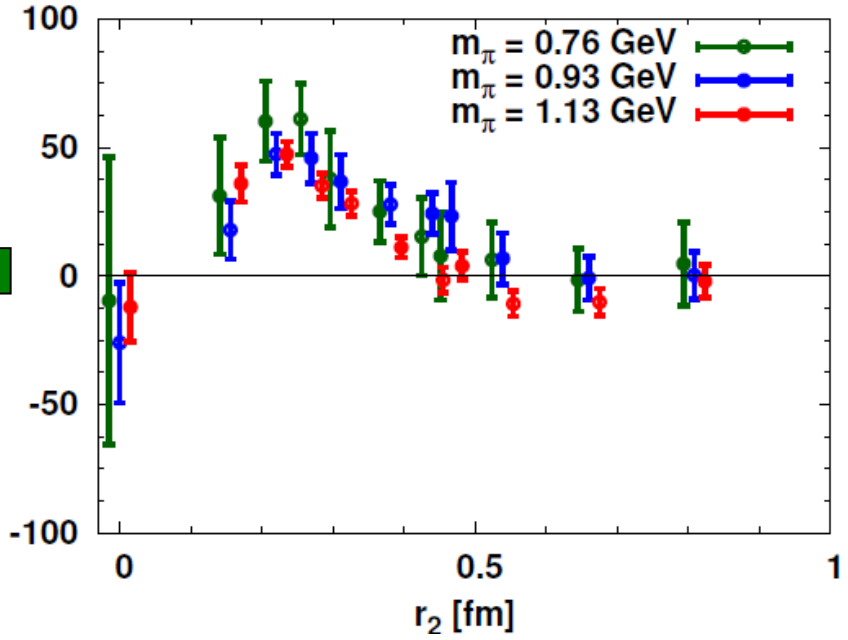
3N-forces (3NF)

Preliminary

Nf=2+1, mπ=0.51 GeV



Nf=2, mπ=0.76-1.1 GeV



Short-range repulsive 3NF

Kernel (B/F~=4): ~50% efficiency achieved !

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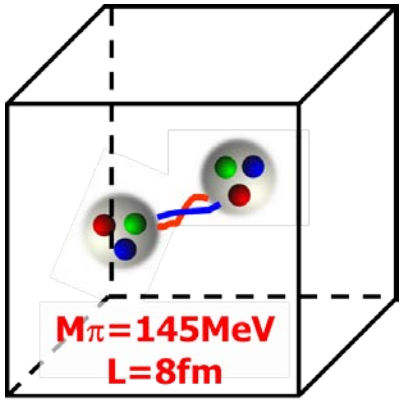

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  - LS-forces, Parity-odd channel, Three-body forces ➔ LQCD EoS

Nuclear Physics from LQCD
New Era is dawning !