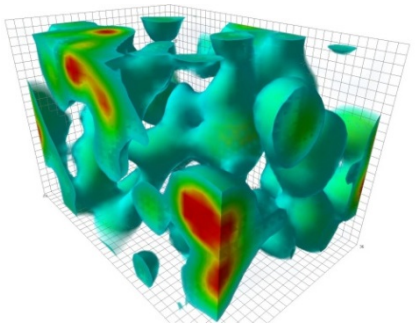
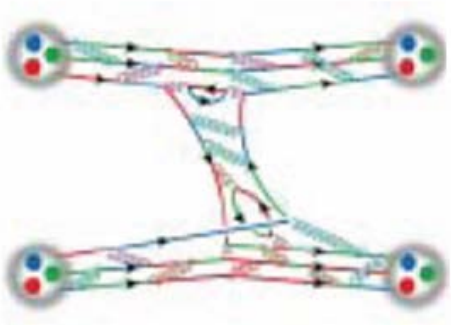
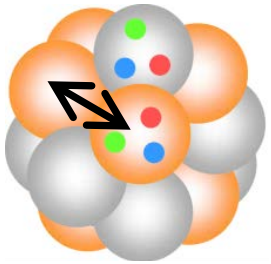
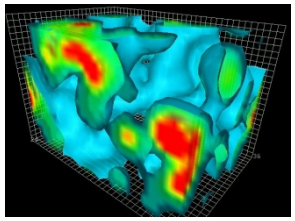
Towards lattice QCD baryon forces at the physical point: First results

Takumi Doi
(Nishina Center, RIKEN)
for HAL QCD Collaboration

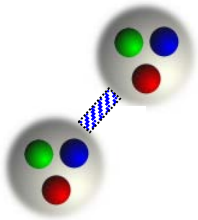




Nuclear- and Astro- physics based on QCD

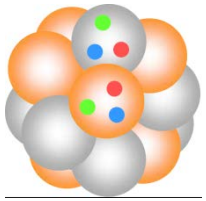


QCD Vacuum

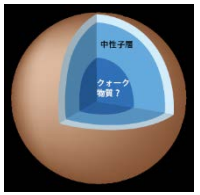
Baryon

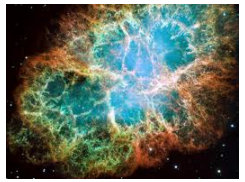


Few-Body



Nuclei





Neutron Star / Supernova
Nucleosynthesis

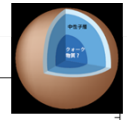
QCD → **1st-principle Lattice QCD** → **Baryon Forces** → ab-initio nuclear calc.

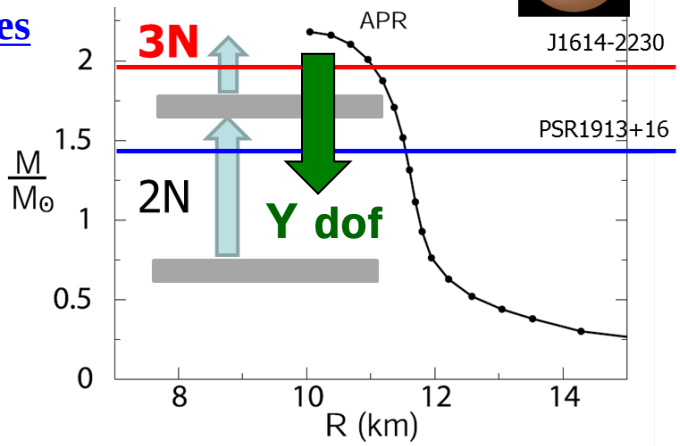
RIBF

Nuclear Forces / Hyperon Forces

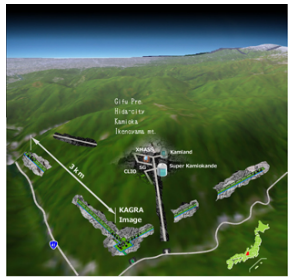
J-PARC

EoS of Dense Matter





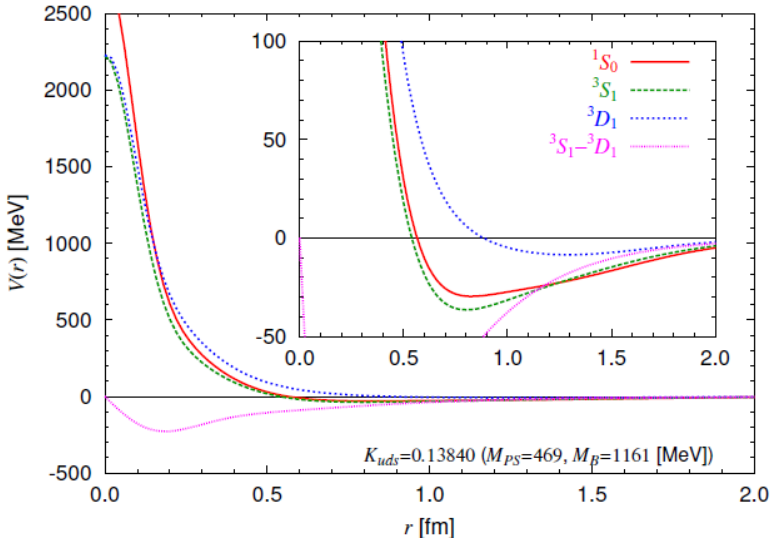
ASTRO-H



KAGRA

From LQCD to Nuclei / Neutron Star

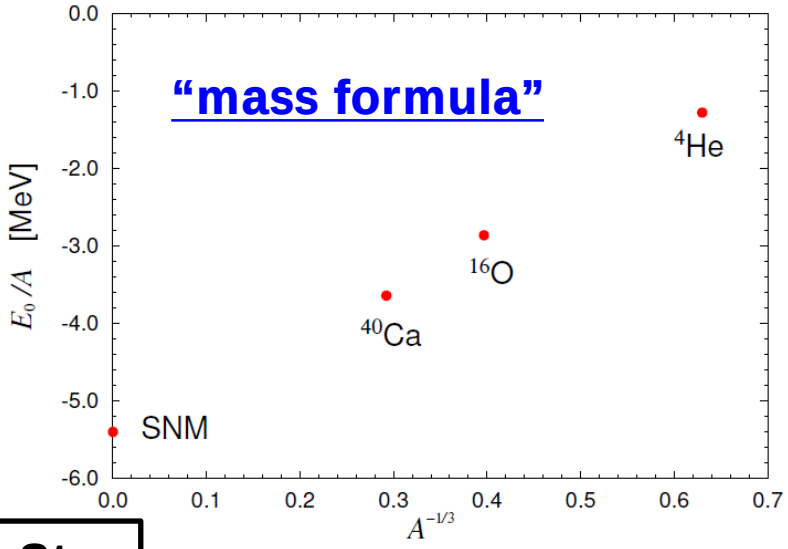
Lat NN forces



(SU(3), m(PS)=0.47GeV)

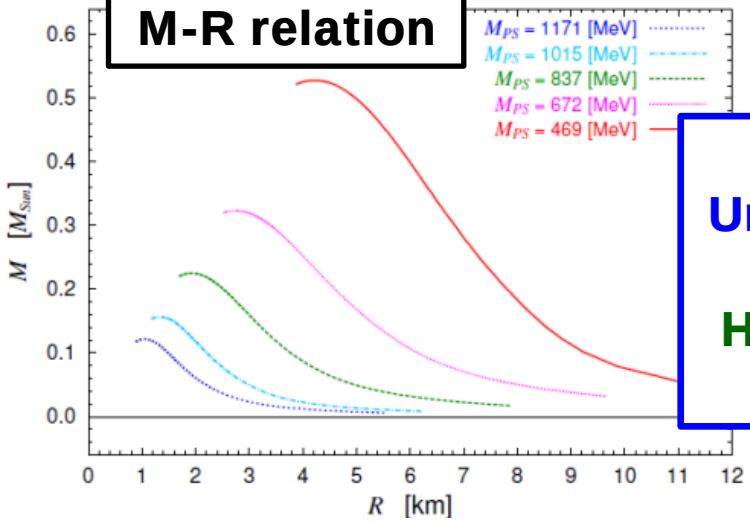
BHF

B.E. of medium-heavy nuclei



BHF & TOV

Neutron Star M-R relation

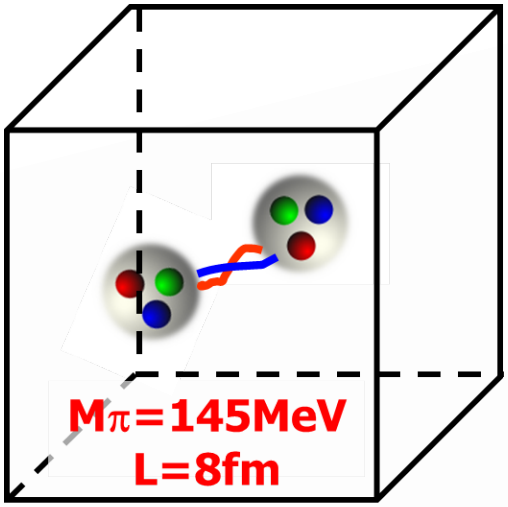


[LQCD]
Unphysical mass
[Missing]
Hyperon Forces
(& 3NF/3BF)

T.Inoue et al. (HAL Coll.) PRL111(2013)112503

T.Inoue et al. (HAL Coll.), PRC91(2015)011001

Towards realistic LQCD Baryon Forces



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

Gauge Config Generation

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

(Sendai)

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

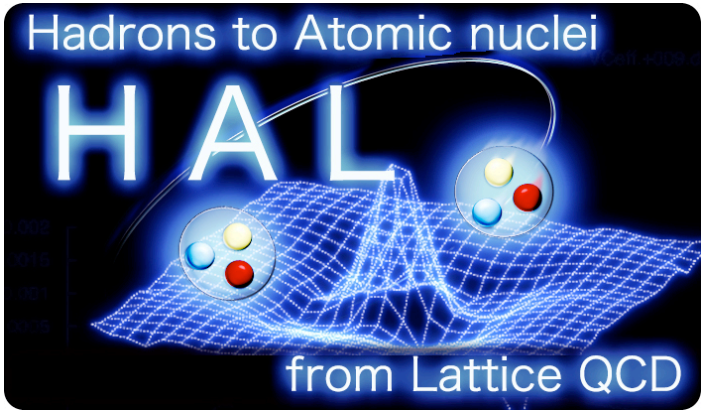
K-computer(RIKEN/AICS)

Baryon Forces

➔ **HAL QCD method**

3 talks now +
Plenary talk by N. Ishii (09/07)

Hadrons to **A**tomic nuclei from **L**attice QCD (**HAL** QCD Collaboration)



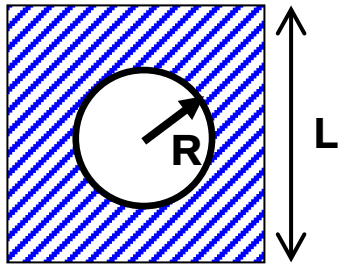
S. Aoki, S. Gongyo, D. Kawai, T. Miyamato (YITP)
T. Doi, T.Hatsuda, Y. Ikeda (RIKEN)
F. Etminan (Univ. of Birjand)
T. Inoue (Nihon Univ.)
T. Iritani (Stony Brook Univ.)
N. Ishii, K. Murano (RCNP)
H. Nemura, K. Sasaki (Univ. of Tsukuba)

Gauge configs are generated in
HPCI Strategic Program Field 5 Project 1 Collaboration

[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

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

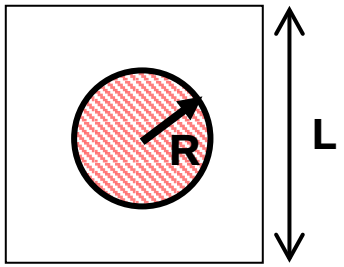
M.Luscher, NPB354(1991)531
C.-J.Lin et al., NPB619(2001)467
N.Ishizuka, PoS LAT2009 (2009) 119
CP-PACS Coll., PRD71(2005)094504

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

Recent Crucial Development

- **Reliable LQCD method: Time-dependent HAL method**

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

  - **Traditional LQCD method (Luscher's method)** ➔ ground state saturation
    - S/N gets worse for larger mass number A & light quark mass & $t \to \infty$

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

  - **t-dep HAL method w/ E-indep pot** ➔➔ Extract signal from excited states
    ➔ **ground state saturation unnecessary ("exponential" S/N Improvement)**

- **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**

- **Unified Contraction Algorithm (UCA)**

  TD, M.Endres, CPC184(2013)117

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

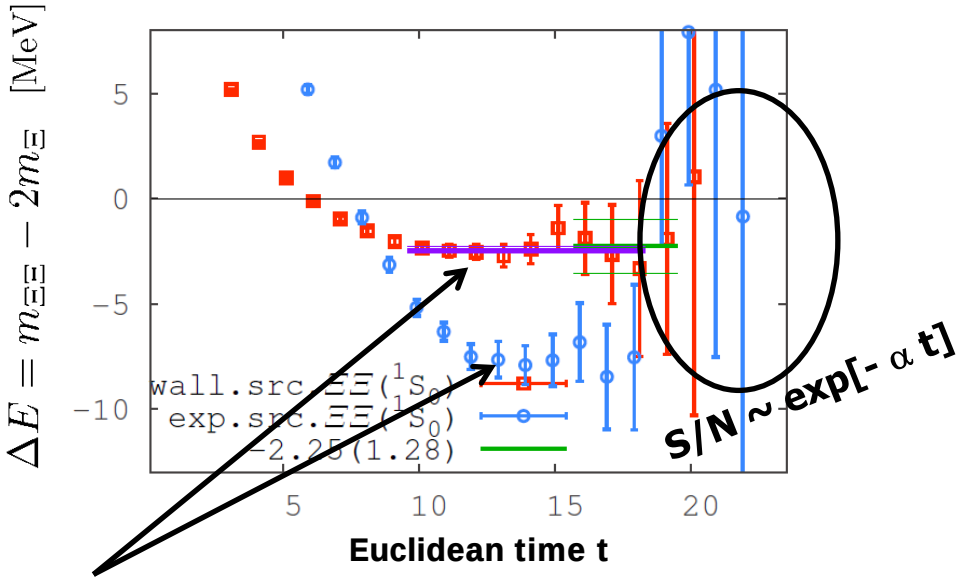
$\times 192$ for ^{3}H/^{3}He, $\times 20736$ for ^{4}He, $\times 10^{11}$ for ^{8}Be

Reliability Test of LQCD methods

- High-stat study for BB-system (@m(pi)=0.5GeV) T. Iritani et al. (HAL Coll.)
  - Luscher's method w/ wall & smeared setup
  - t-dep HAL method w/ wall & smeared setup

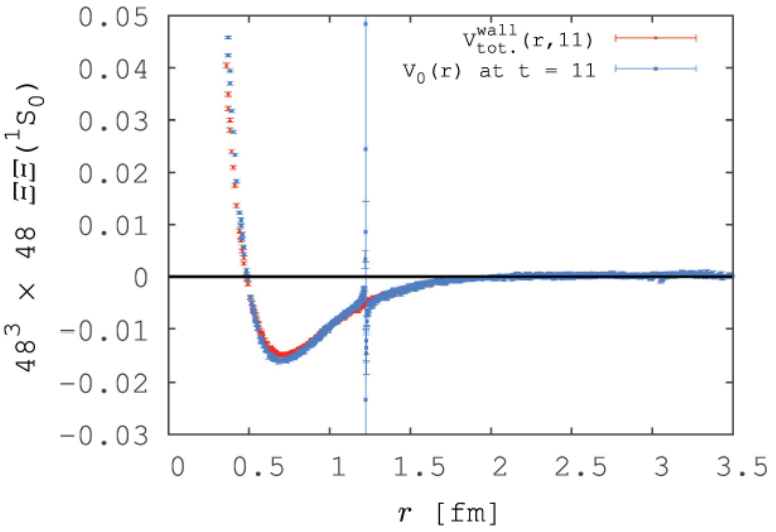
← Physical outputs should not depend on wall/smeared

Luscher's method



Inconsistent "signal" (red (wall) vs blue (smeared))
➔ cannot judge which (or neither) is reliable

HAL method



$V^{LO}(r)$ from wall & $V^{LO}(r)$ from wall+smeared are consistent

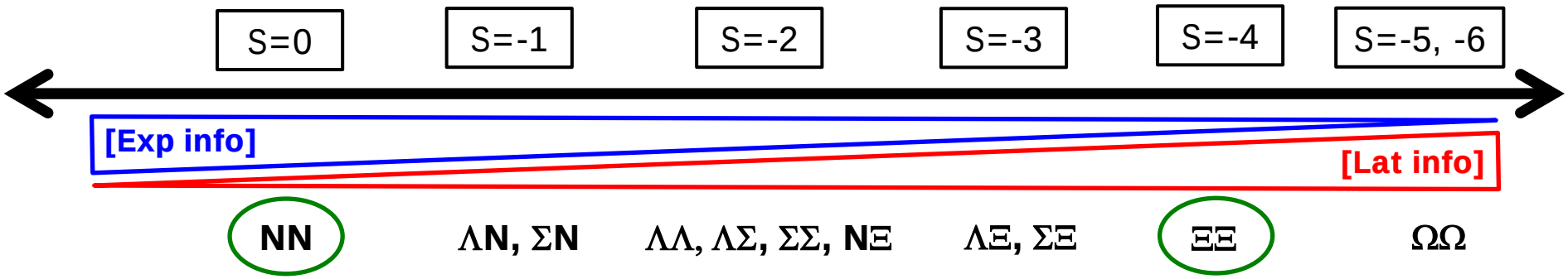
Spectrum from V(r) is found to be consistent w/ Luscher's wall src "plateau"

Through "potentials", phase shifts can be reliably extracted in LQCD

(more in Ishii's plenary talk)

Strategy for phys point BB-forces calc

- Focus on the most important forces:
  - Central/tensor forces for all NN/YN/YY in P=(+) (S, D-waves)
    - Hyperon forces provide precious "predictions"



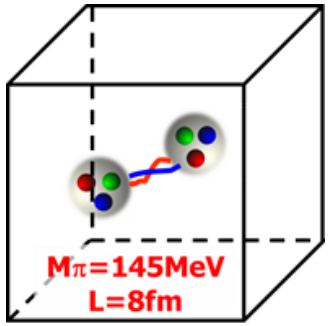
"milestone-postdiction"

Hypernuclear phys @ J-PARC
H-dibaryon ?, Ξ-hypernuclei

Λ appearance in NS & EoS ?

New bound state(s) ?

- ΞΞ interaction
  - $^1S_0$ ~ 27-plet : NN($^1S_0$) + SU(3) breaking
    - Bound or Unbound ?
    - Phen. Pot (Nijmegen), EFT (Haidenbauer et al.), etc.
    - HIC experiment ?
  - $^3S_1$-$^3D_1$ ~ 10-plet : Unique w/ hyperon DoF
    - Σ^- in neutron star : to be or not to be



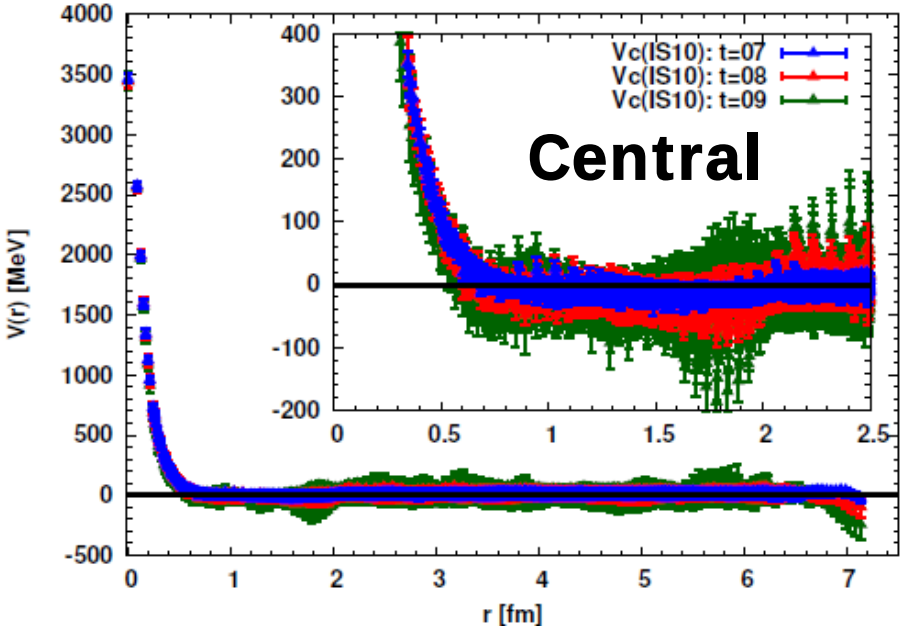
NN and ΞΞ-Potentials

(Single Channel)

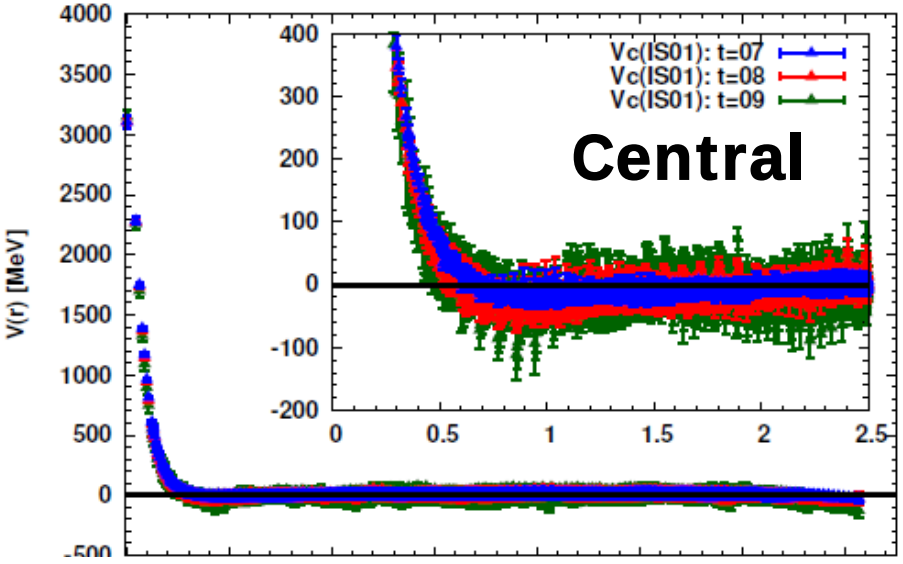
- Measurements
  - Wall quark source w/ Coulomb gauge
  - Dirichlet (temporal) boundary condition to avoid the wrap around artifact
  - (Relativistic correction omitted in this preliminary analysis)
  - **#stat = 203 configs x 4 rotation x 20 src in this talk**
    - **Objective: 400 configs x 4 rotation x 48 src ➔ stat error will be ~ x1/2**

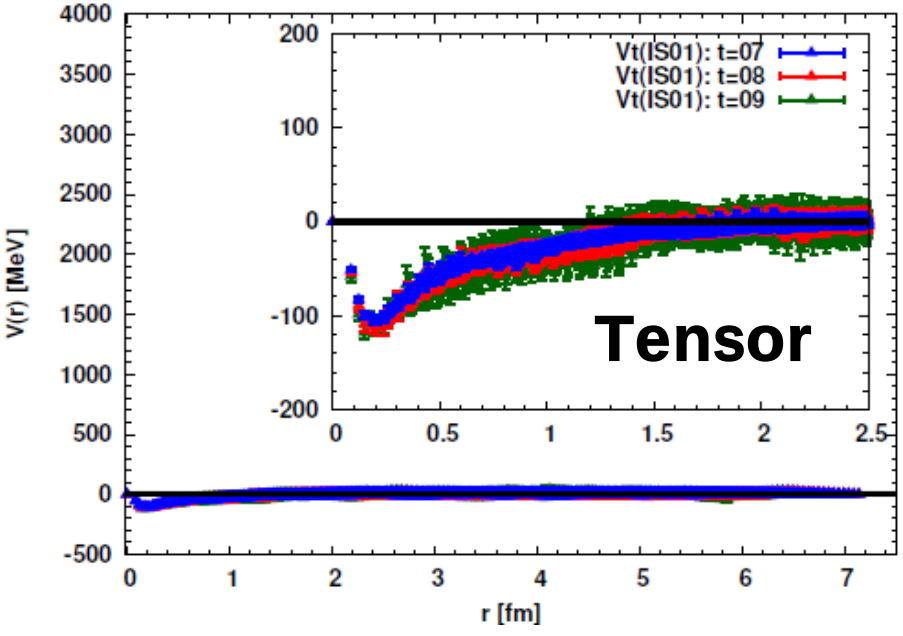
NN-Potentials

$^1S_0$



$^3S_1$-$^3D_1$

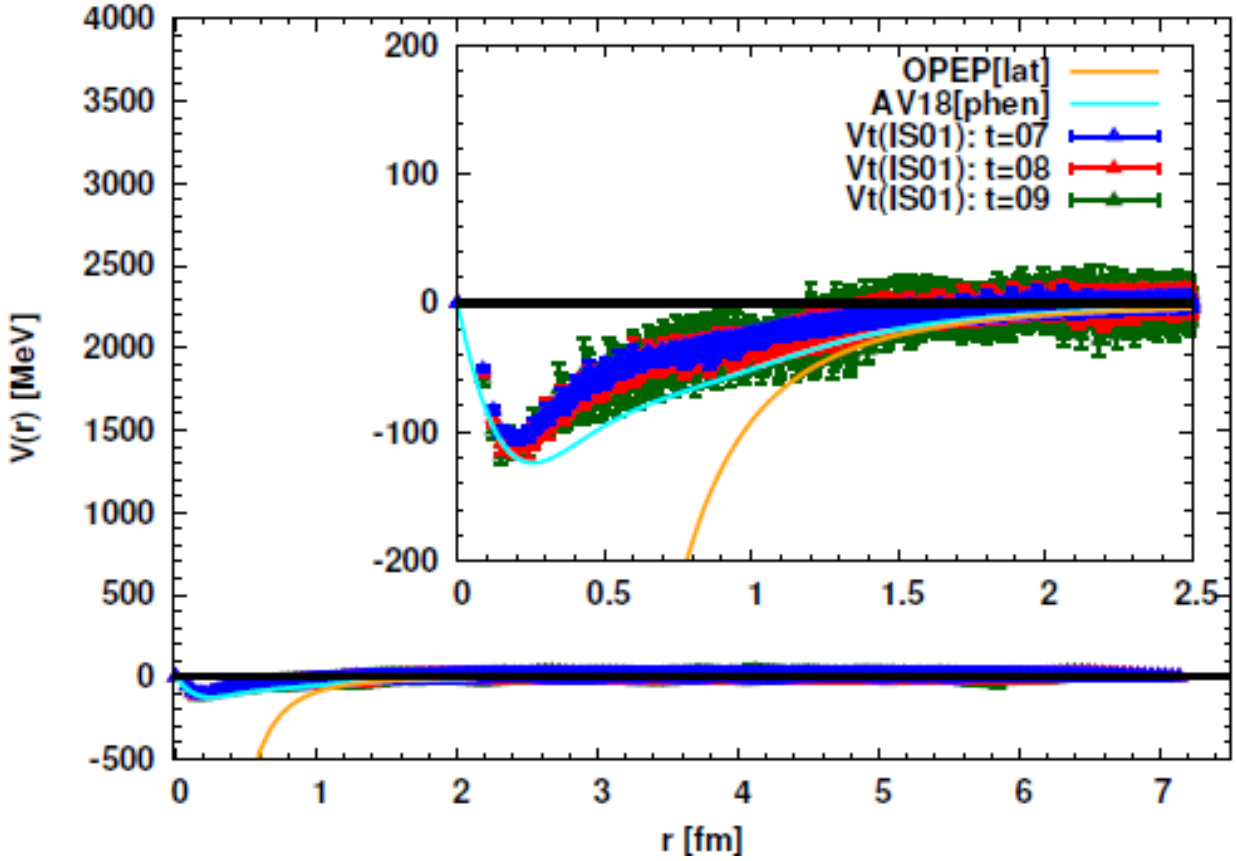




Preliminary

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

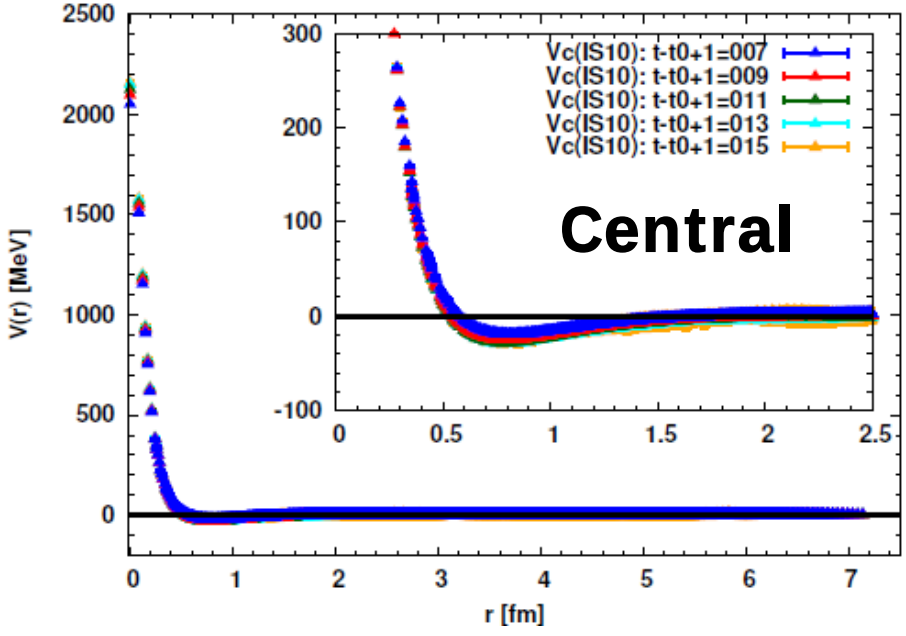
NN-Potentials (tensor)



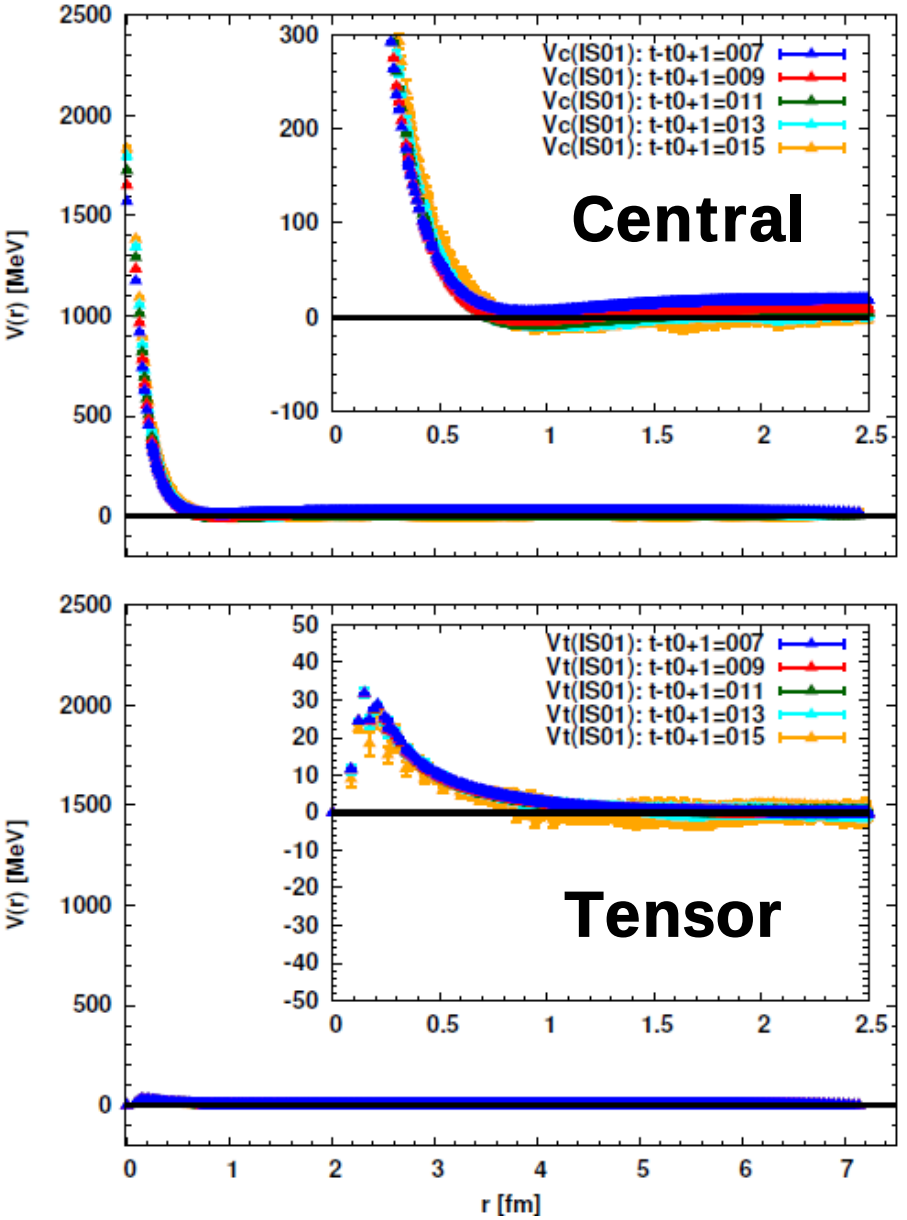
- **We may be able to extract OPEP tail from tensor force**
- **Fit analysis etc. in progress**

ΞΞ-Potentials

$^1S_0$



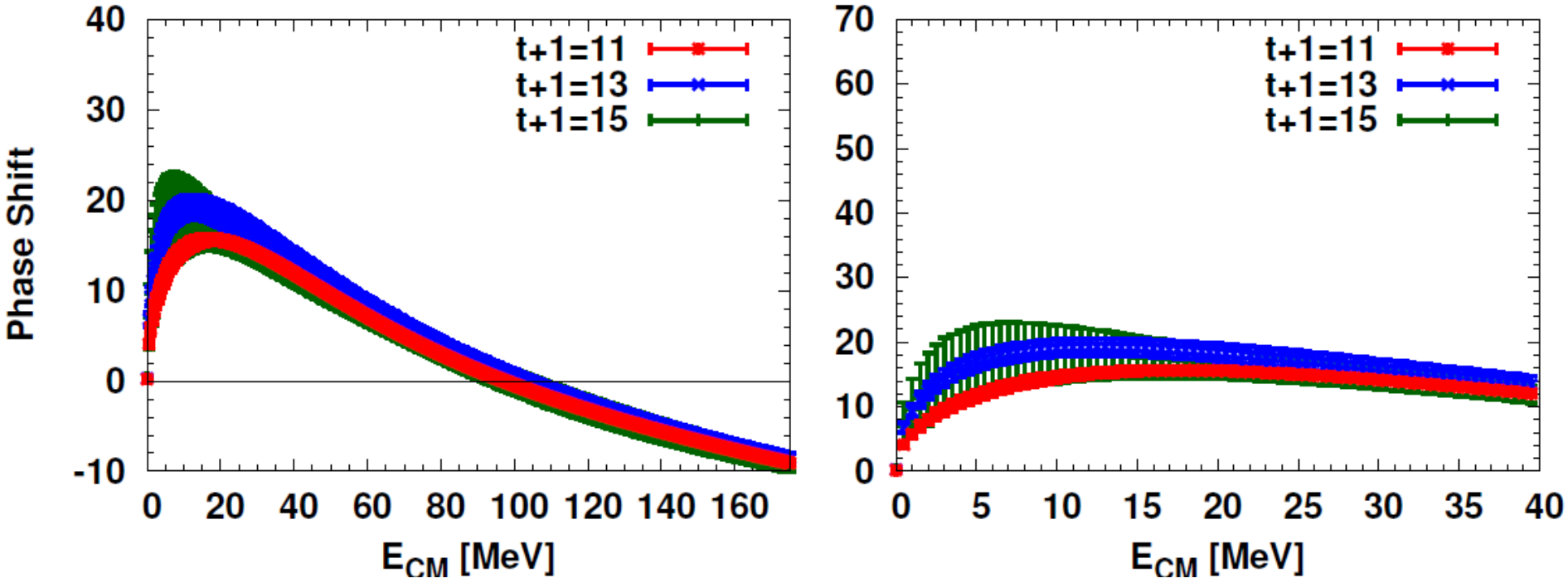
$^3S_1$-$^3D_1$



Preliminary

- $^1S_0$ ～ 27-plet
  ⇔ NN($^1S_0$) + SU(3) breaking
- $^3S_1$-$^3D_1$ ～ 10-plet
  ⇔ unique w/ hyperon DoF

Phase shift ($^1S_0$)



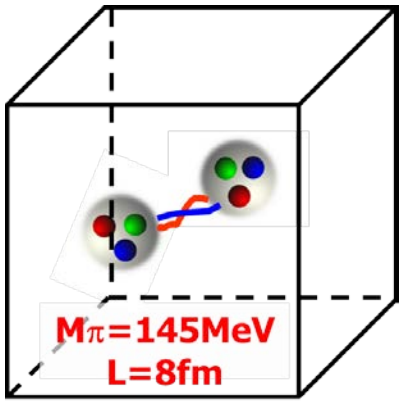
Zoom In

Preliminary

(Naïve spline fit for pot is used)

Summary

- **The 1st LQCD calc of Baryon Interactions at ~ phys. point**
  - m(pi) ~= 145 MeV, L ~= 8fm, 1/a ~= 2.3GeV
  - Central & Tensor forces calculated for all NN/YN/YY in P=(+) channel
- **HAL QCD method**
  - t-dep HAL method avoids S/N issue by g.s. saturation
  - Suitable for coupled channel systems
  - Unified contraction algorithm for computations



- **NN-forces**
  - Tensor force is clearly visible
- **ΞΞ-forces**
  - Precision prediction possible: $^1S_0$ strong attraction, $^3S_1$-$^3D_1$ repulsion
- YN/YY forces w/ coupled channel study ➔ next talks
- **Prospects**
  - Measurement in progress ➔ stat error will be ~x1/2 in FY2015
  - LS-forces, P=(-) channel, 3-baryon forces + other int. in future