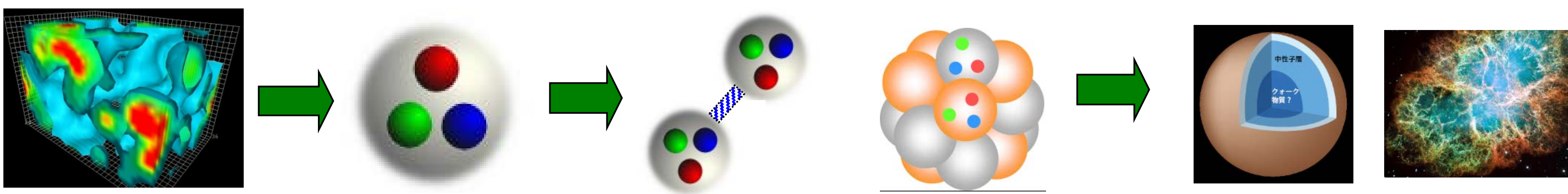
First results of baryon interactions from lattice QCD with physical masses (1)

– General overview and two-nucleon forces –

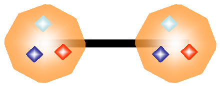
Takumi Doi

(Nishina Center, RIKEN)

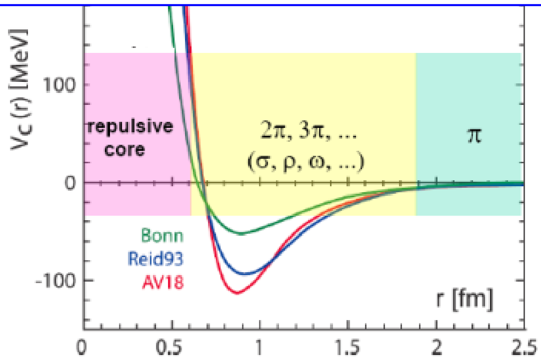
for HAL QCD Collaboration



LQCD outputs for Baryon Forces highly awaited

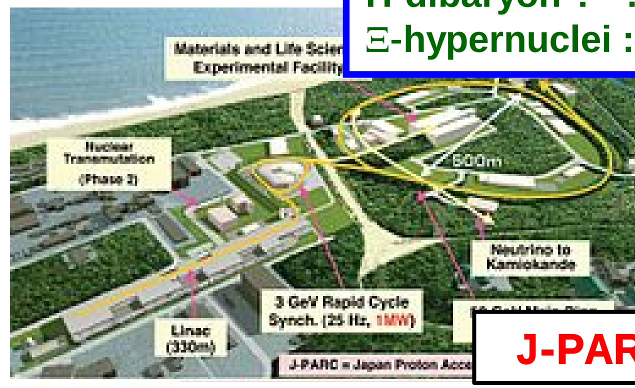


Nuclear Forces
➔ **Foundation of Nuclear Physics**



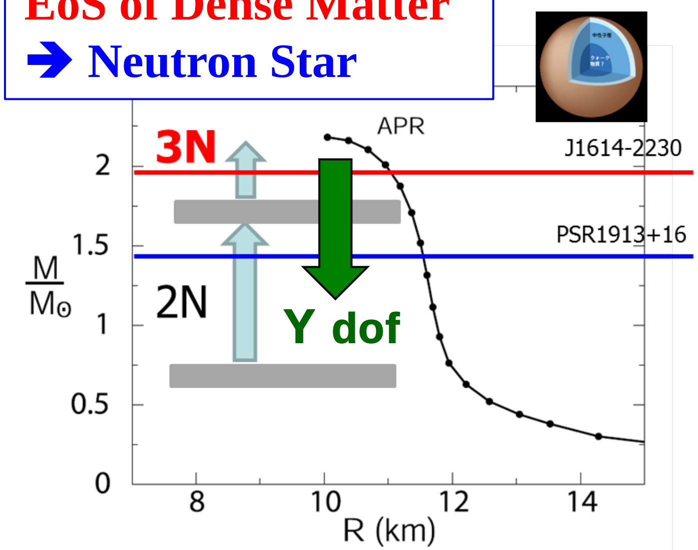
Hyperon Forces
➔ **Universal Picture for Baryon Forces**

H-dibaryon ? : NAGARA-event (2001)
Ξ-hypernuclei : KISO-event (2014)



J-PARC (coming back !)

EoS of Dense Matter
➔ **Neutron Star**



Neutron Star Merger
EoS / Nucleosynthesis

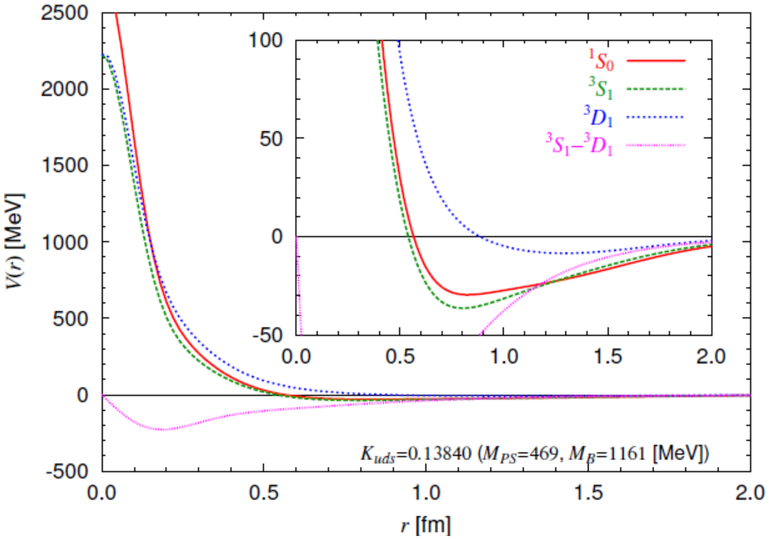
ASTRO-H
(FY2015-)

KAGRA
(2018-)

RIBF
(2007-)

From LQCD to Nuclei / Neutron Star

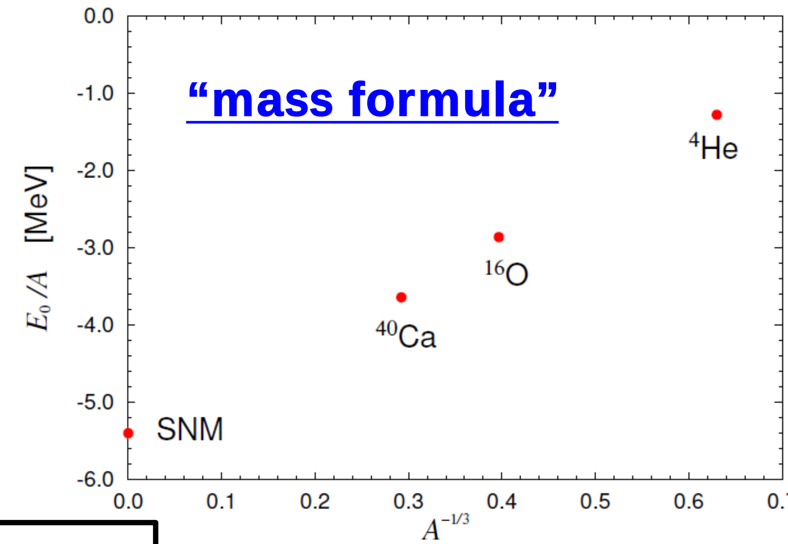
Lat NN forces



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

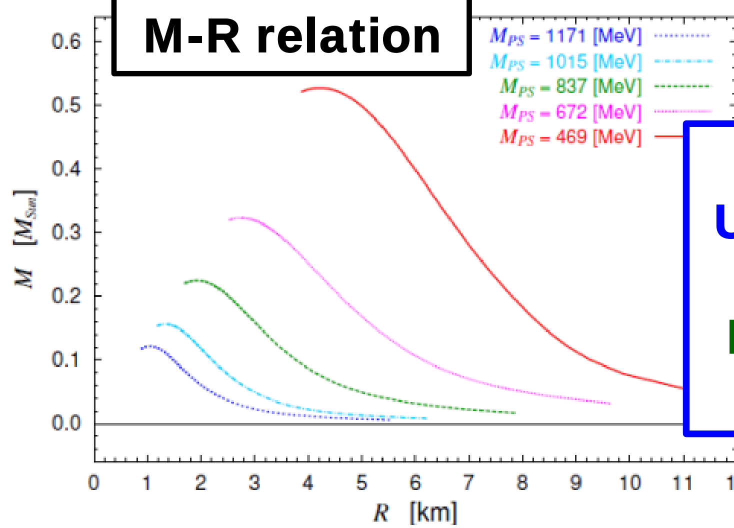
BHF

B.E. of medium-heavy nuclei



BHF & TOV

Neutron Star
M-R relation



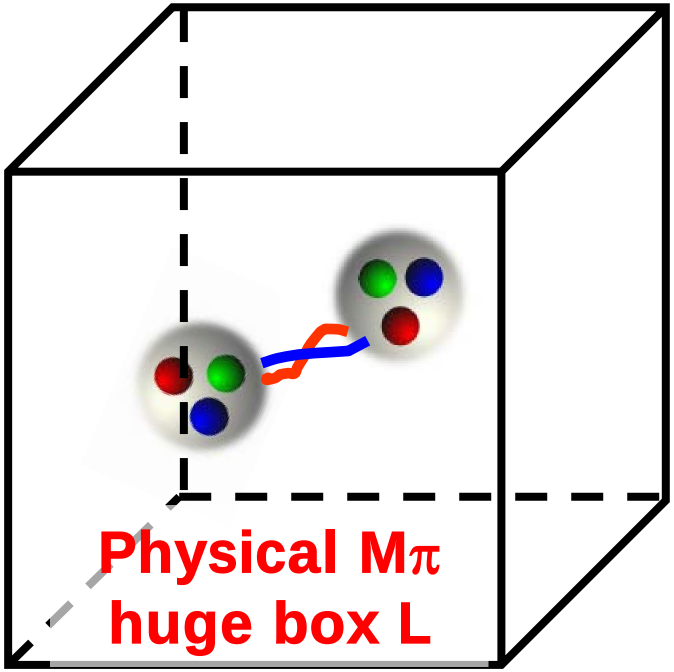
[LQCD]
Unphysical mass
[Missing]
Hyperon Forces
(& 3NF / 3BF)

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



K computer

Gauge Config Generation

➔ Talk by N. Ukita (7/14)

Baryon Forces

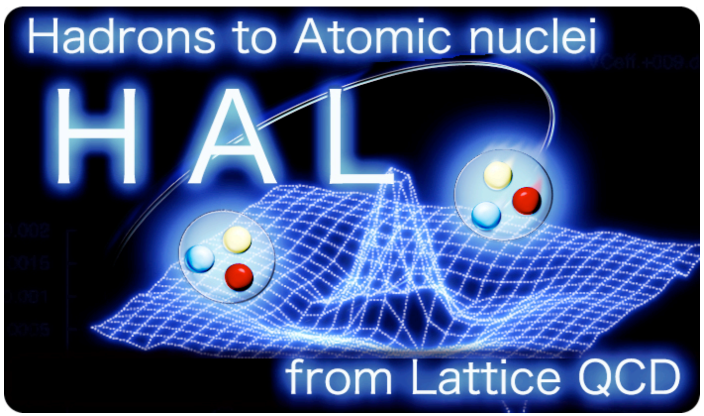
➔ HAL QCD method

3 talks now
(+ 1 talk by H. Nemura, 07/17)

- **Signal/Noise Issue**
  w/ (almost) continuum on Lat
- **Coupled Chanel Systems**
- **Computational Challenge**

c.f. Direct Nuclei: Talk by T. Yamazaki (07/15)

Hadrons to Atomic nuclei from Lattice QCD (HAL QCD Collaboration)



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

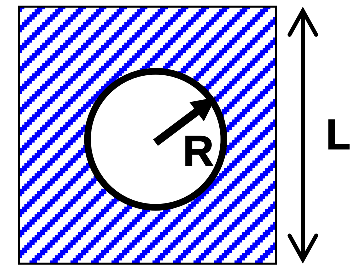
Gauge configs are generated in
HPCI Strategic Program Field 5 Project 1 Collaboration

[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

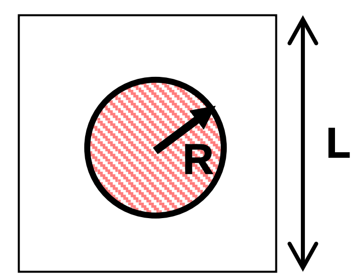
CP-PACS Coll., PRD71(2005)094504

Extended to multi-particle systems

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

- Consider the wave function at "interacting region"

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



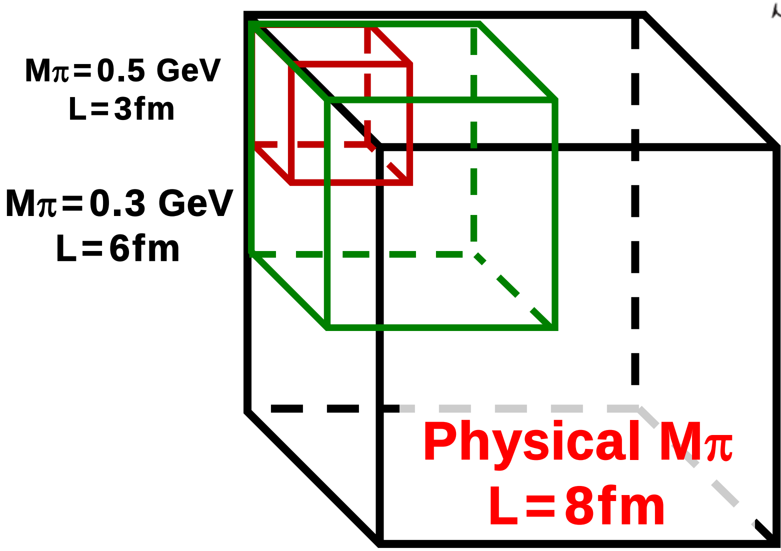
  – U(r,r'): faithful to the phase shift by construction
    - U(r,r'): E-independent, while non-local in general
      – Non-locality ➔ derivative expansion

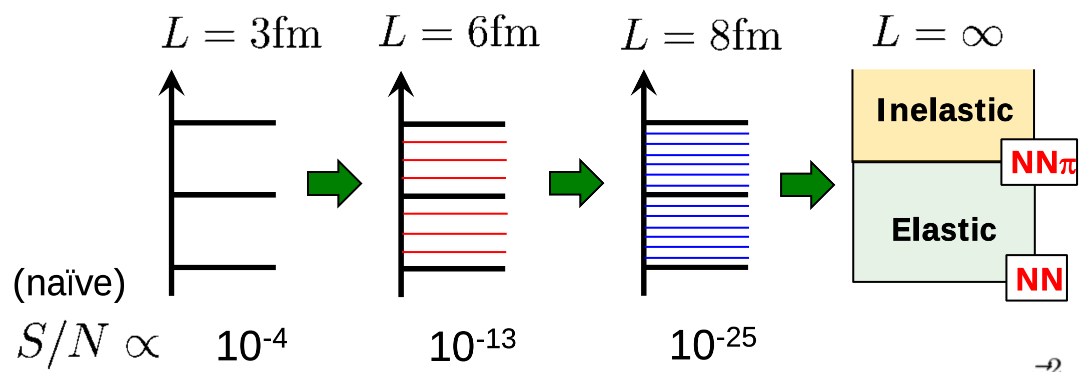
Aoki-Hatsuda-Ishii PTP123(2010)89

Signal/Noise issue w/ ～continuum on Lat

- Challenge in traditional Lat calc ➔ ground state saturation
  - S/N gets worse for larger mass number A & light quark mass & $t \to \infty$

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





$$1/t \simeq \Delta E \simeq \frac{\vec{p}^2}{m_N}$$

- Time-dependent HAL method

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

  - E-indep potential ←➔ (elastic) Excited states share the same potential

$$\left(-\frac{\partial}{\partial t} + \frac{1}{4m}\frac{\partial^2}{\partial t^2} - H_0\right) R(\boldsymbol{r}, t) = \int d\boldsymbol{r}' U(\boldsymbol{r}, \boldsymbol{r}') R(\boldsymbol{r}', t)$$

$$R(\boldsymbol{r}, t) \equiv C_{NN}(\boldsymbol{r}, t)/C_N(t)^2$$

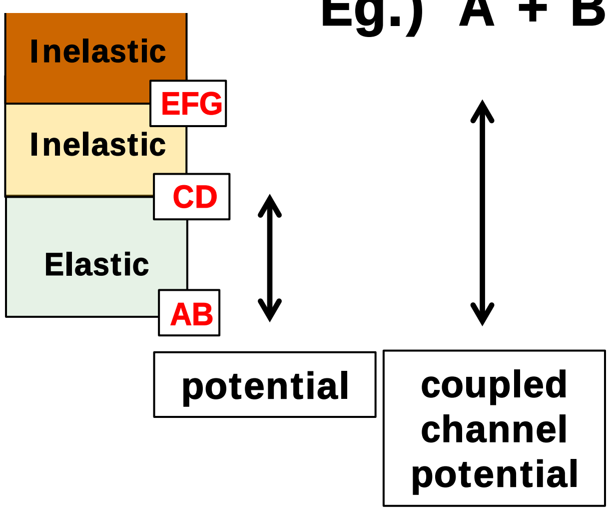
  - Ground state saturation ➔ Elastic states saturation

Coupled Channel systems

(beyond inelastic threshold)

- Essential in many interesting physics
  - H-dibaryon (ΛΛ-NΞ-ΣΣ), Zc-exotic mesons, etc.
- Coupled channel potentials in HAL method

Eg.) A + B ←→ C + D (←→ E + F + G, etc.)



$$\psi_{AB}(\boldsymbol{r},\boldsymbol{k}) = 1/\sqrt{Z_A Z_B}\cdot\langle 0|\phi_A(\boldsymbol{x}+\boldsymbol{r})\phi_B(\boldsymbol{x})|W\rangle$$

$$\psi_{CD}(\boldsymbol{r},\boldsymbol{q}) = 1/\sqrt{Z_C Z_D}\cdot\langle 0|\phi_C(\boldsymbol{x}+\boldsymbol{r})\phi_D(\boldsymbol{x})|W\rangle$$

$$W = \sqrt{m_A^2+k^2}+\sqrt{m_B^2+k^2} = \sqrt{m_C^2+q^2}+\sqrt{m_D^2+q^2}$$

$$(E_{k_i}^{AB}-H_0^{AB})\psi_{AB}(\boldsymbol{r},k_i) = \int d\boldsymbol{r}' U_{AB,AB}(\boldsymbol{r},\boldsymbol{r}')\psi_{AB}(\boldsymbol{r}',k_i) + \int d\boldsymbol{r}' U_{AB,CD}(\boldsymbol{r},\boldsymbol{r}')\psi_{CD}(\boldsymbol{r}',q_i)$$

$$(E_{q_i}^{CD}-H_0^{CD})\psi_{CD}(\boldsymbol{r},q_i) = \int d\boldsymbol{r}' U_{CD,AB}(\boldsymbol{r},\boldsymbol{r}')\psi_{AB}(\boldsymbol{r}',k_i) + \int d\boldsymbol{r}' U_{CD,CD}(\boldsymbol{r},\boldsymbol{r}')\psi_{CD}(\boldsymbol{r}',q_i)$$

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

S.Aoki et al. (HAL Coll.), PRD87(2013)034512

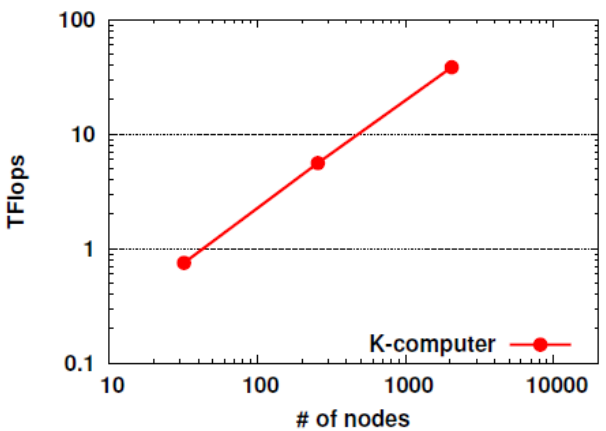
Computational Challenge

- **Enormous comput. cost for multi-baryons correlators**
  - Wick contraction (permutations) $\sim [(\frac{3}{2}A)!]^2$
  - color/spinor contractions $\sim 6^A \cdot 4^A$ or $6^A \cdot 2^A$
  - **Unified Contraction Algorithm (UCA)** TD, M.Endres, CPC184(2013)117
    - A novel method which unifies two contractions ➔ drastic speedup

$\times 192$ for ${}^3\mathrm{H}/{}^3\mathrm{He}$, $\times 20736$ for ${}^4\mathrm{He}$, $\times 10^{11}$ for ${}^8\mathrm{Be}$ (x add'l. speedup)

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

- **Code development**
  - Efficient implementation of UCA
  - Many channels w/ L^3 dof in NBS
  - Performance on K @ 2048 node
    - ~15% of peak (~40 TFlops sustained)



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

Strategy for phys point baryon forces

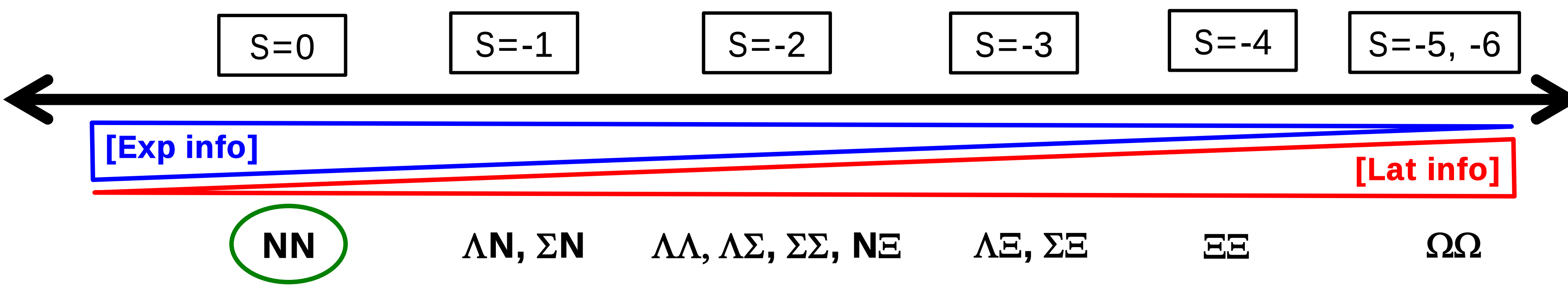
- Focus on the most important forces:
  - Notoriously noisy at phys point (even w/ t-dep HAL method)
  - Central and Tensor forces for all NN/YN/YY (2 octet baryons) in parity-even channel (S, D-waves)

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 (YN/YY) provide precious "prediction"



"milestone-postdiction"

Hypernuclear phys @ J-PARC

H-dibaryon ?, Ξ-hypernuclei

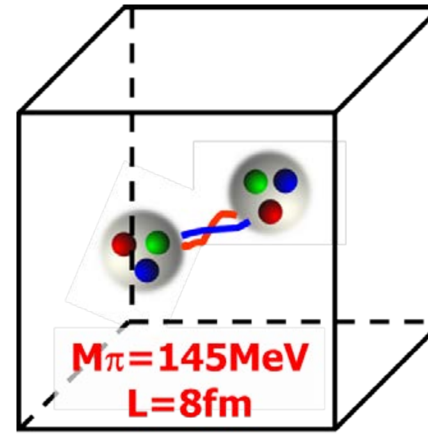
Λ appearance in NS & EoS ?

New bound state(s) ?

Simulation Setup

- Nf = 2+1 clover fermion + Iwasaki gauge action
  - Stout smearing
  - Volume: 96^4 ~= $(8\ \mathrm{fm})^4$
  - 1/a ~= 2.3 GeV (a ~= 0.085 fm)
  - m(pi) ~= 145 MeV, m(K) ~= 525 MeV
  - #traj ~= 2000 generated

(For details ➔ Ukita's talk)



- Measurements
  - 4pt correlators for all 2-baryon systems are calculated
    - 52 channels in octet-baryon particle base (+ other hadron-hadron)
  - Wall source
    - Coulomb gauge fixing after stout smearing
  - Dirichlet BC (at t = Nt/2) to avoid the wrap around artifact
    - Forward/backward average is taken
  - Sloppy solver (almost exact compared to statistical err)
  - Relativistic correction term omitted in this preliminary analysis
  - #stat = 203 configs x 4 rotation x 12 src in this talk
    - (Objective: 400 configs x 4 rotation x 48 src)

2-nucleon forces

$^{2S+1}L_J$

$^3S_1 – {}^3D_1 \ (I=0)$ "deuteron" channel — **bound (2.2MeV)**

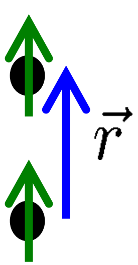
$^1S_0 \ (I=1)$ "di-neutron" channel — **unbound**

$^3S_1 – {}^3D_1 \ (I=0)$		$^1S_0 \ (I=1)$
$V_C^{IS=01}(r)$	**Central Force**	$V_C^{IS=10}(r)$
$V_T^{IS=01}(r)S_{12}(\hat{\boldsymbol{r}})$	**Tensor Force**	(none)

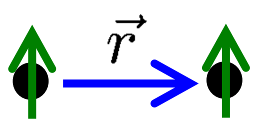
-2 MeV (B.E.) ~= 20 MeV (K.E.) – 5 MeV (Central) – 17 MeV (Tensor)

[AV8' phen. pot]

$$S_{12}(\hat{x}) = 3(\boldsymbol{\sigma}_1 \cdot \hat{\boldsymbol{x}})(\boldsymbol{\sigma}_2 \cdot \hat{\boldsymbol{x}}) - (\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)$$



(attractive)



(repulsive)

Tensor Force is the driving force for deuteron binding

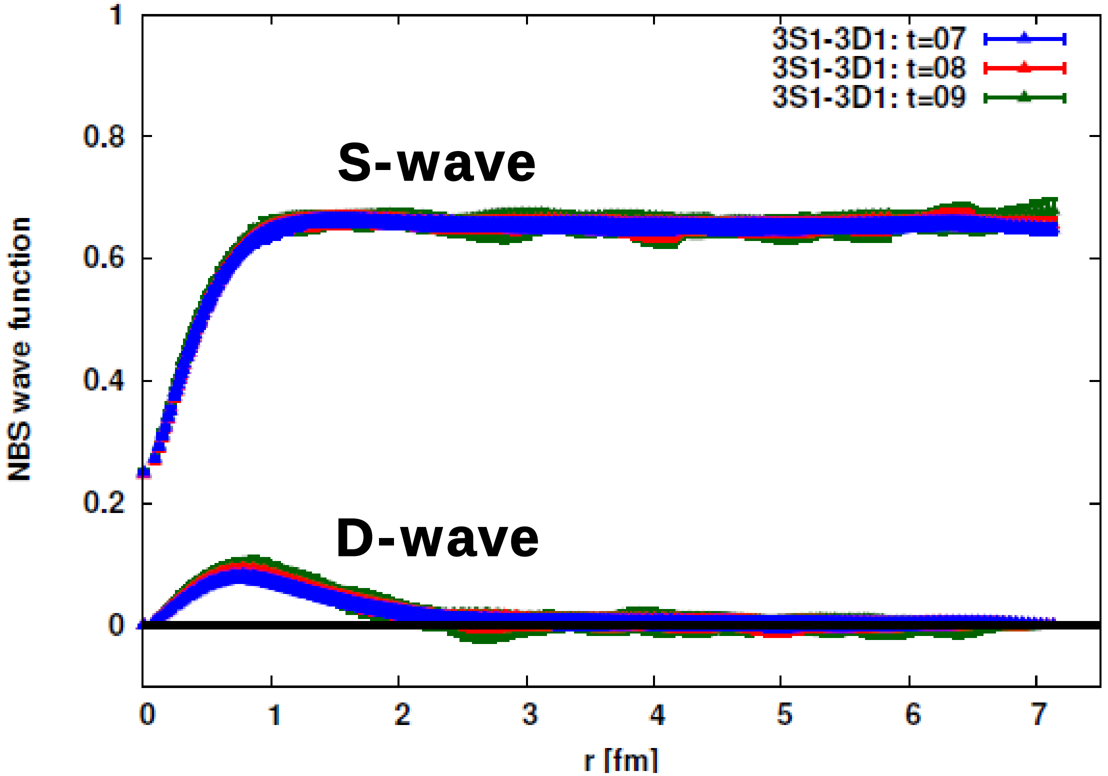
Role in nuclei is being rediscovered

Coupled channel system ($^3S_1$-$^3D_1$)

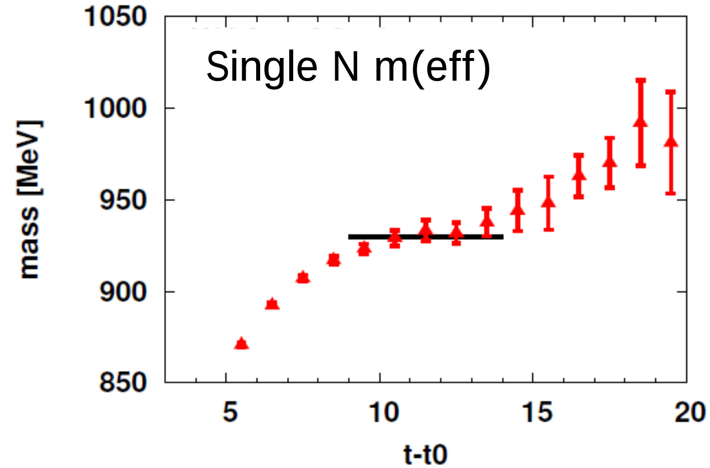
$$(H_0 + V_C + V_T S_{12})\psi = E\psi$$

(+ t-dep HAL method)

$$(4\text{pt})/(2\text{pt})^2 \simeq \text{NBS}$$



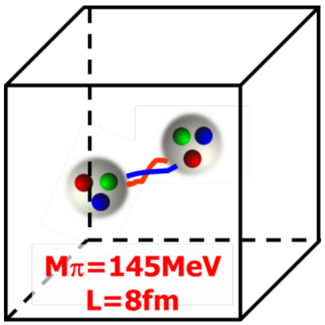
S/D-wave mixing
↔ tensor force

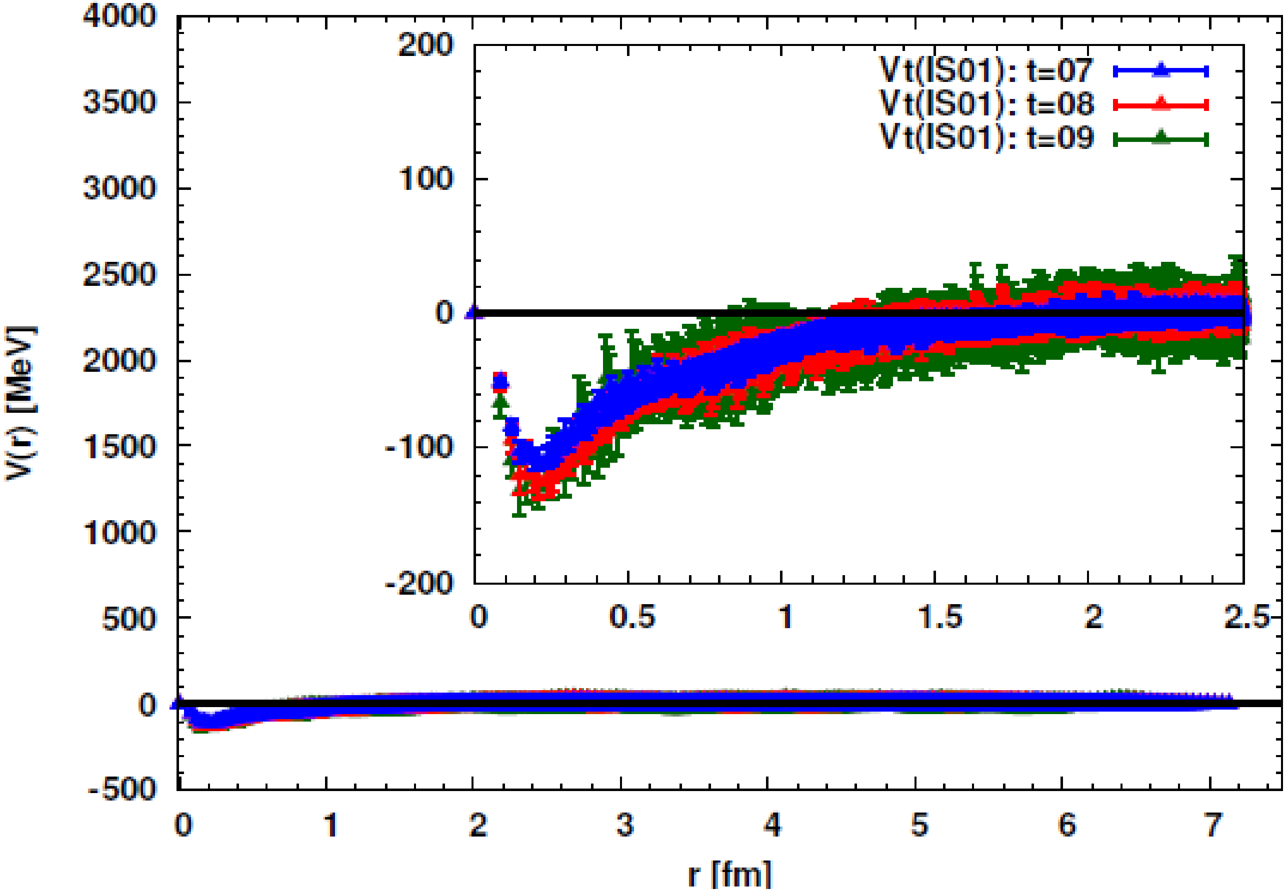


$$t \geq 9 \sim 10$$

preliminary

Tensor Potential ($^3S_1$-$^3D_1$)

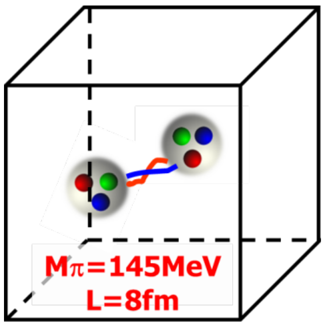


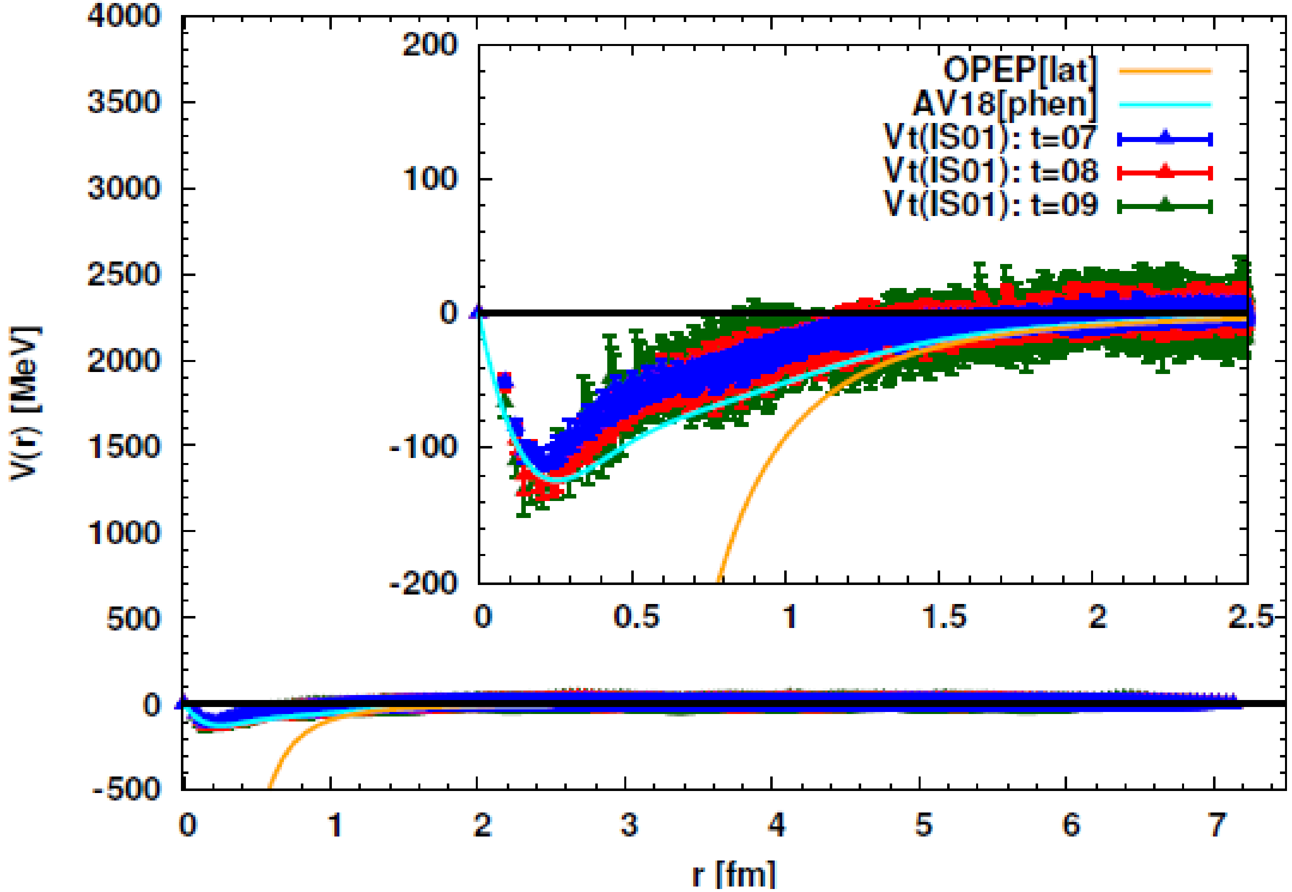


Tensor Force is clearly visible !

preliminary

Tensor Potential ($^3S_1$-$^3D_1$)





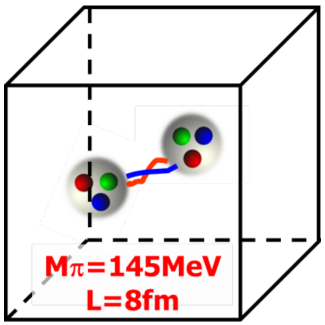
Tensor Force is clearly visible !

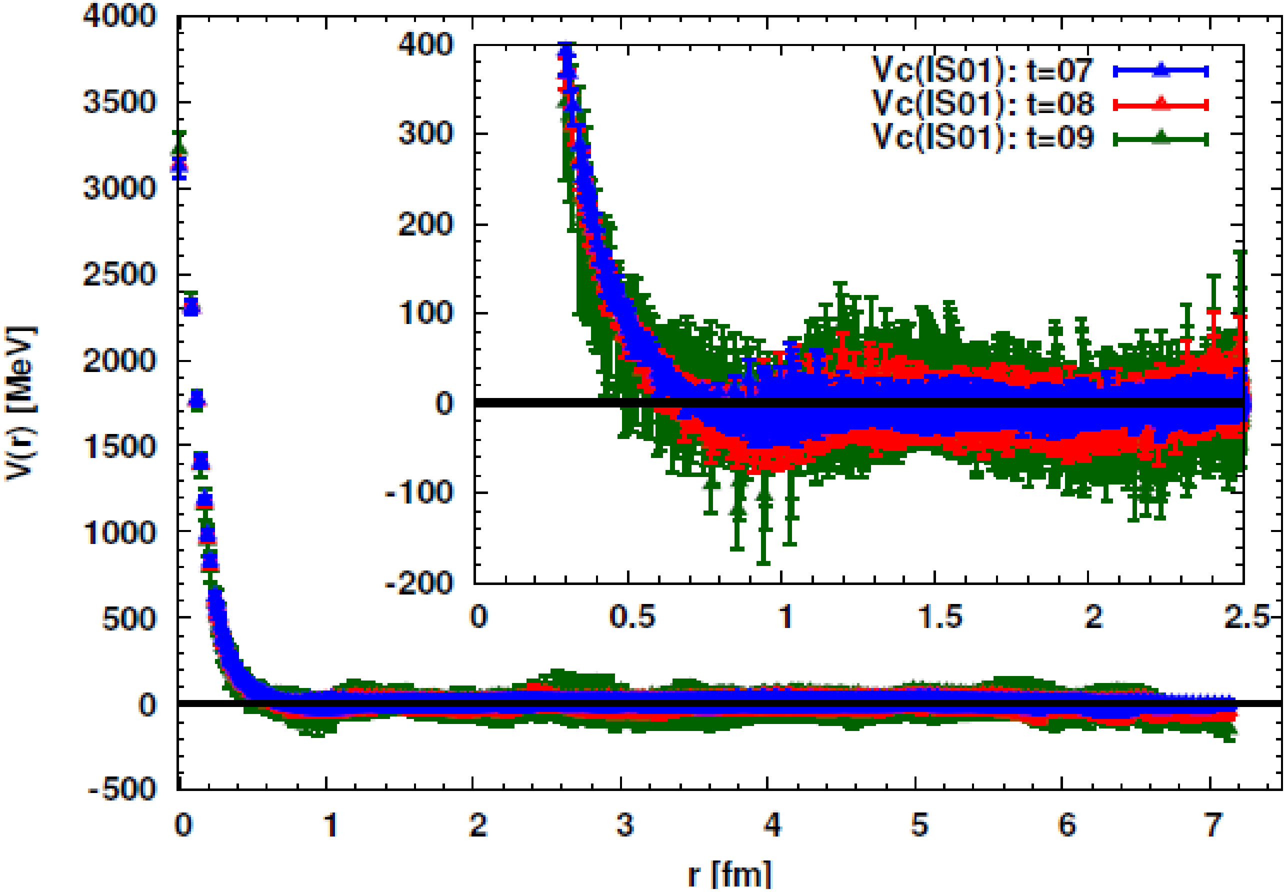
OPEP int !?
(further study in progress)

Larger #stat (w/ larger t) desirable

preliminary

Central Potential ($^3S_1$-$^3D_1$)





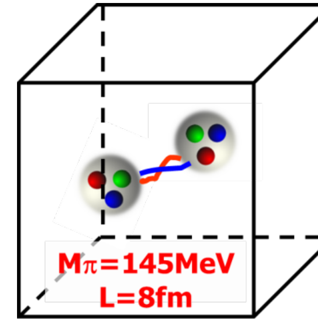
Repulsive core observed

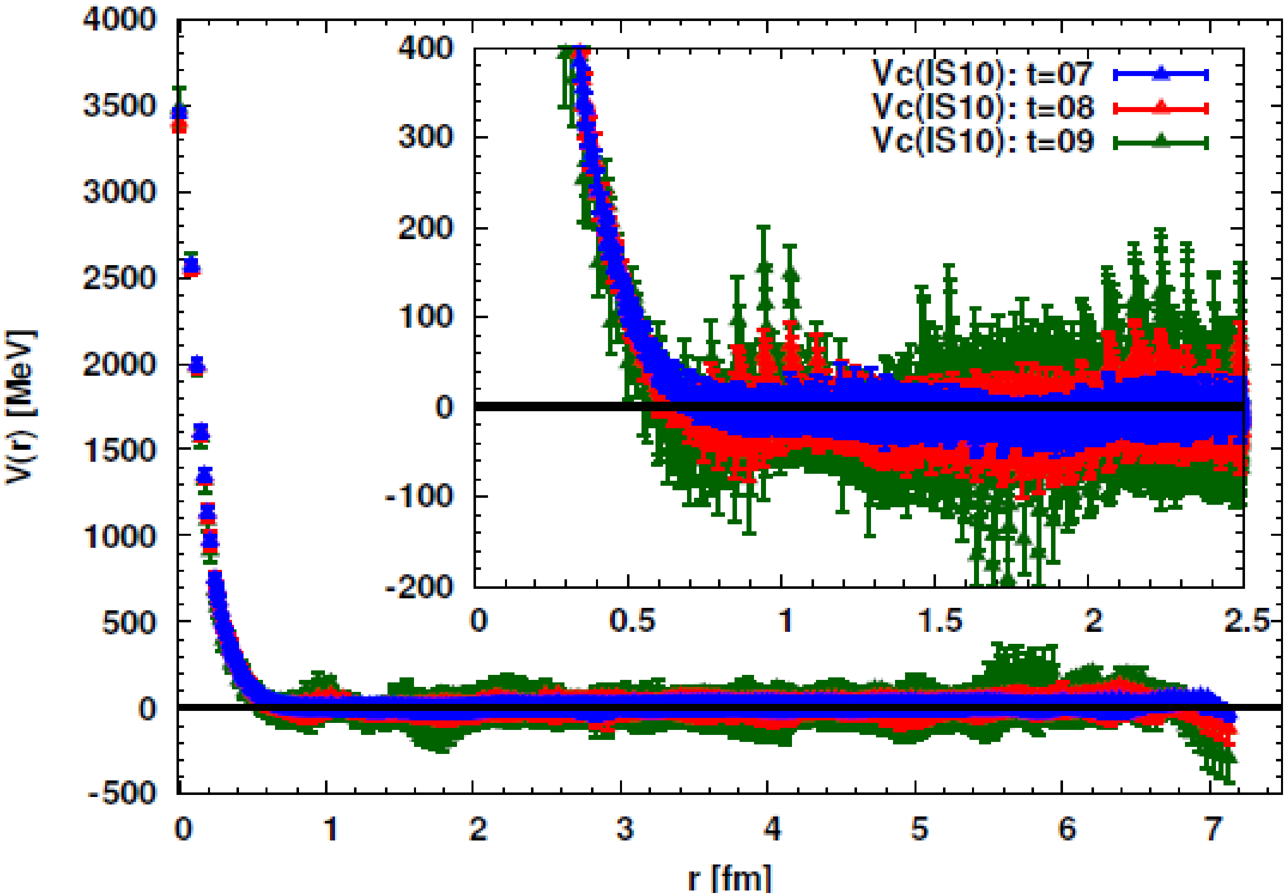
Long-range int still noisy

Larger #stat (w/ larger t) desirable

preliminary

Central Potential ($^1S_0$)





Repulsive core observed

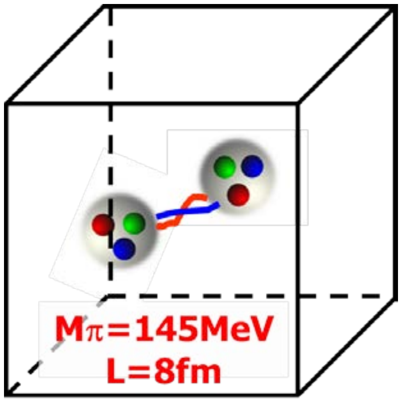
Long-range int still noisy

Larger #stat (w/ larger t) desirable

preliminary

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
  - Repulsive core in Central forces, more #stat needed
- YN/YY-forces ➔ next talks
- Prospects
  - Measurement in progress ➔ #stat will be increased ~x8 in FY'15
  - LS-forces, P=(-) channel, 3-baryon forces + other int. in future