# Baryon interactions from lattice QCD with physical masses

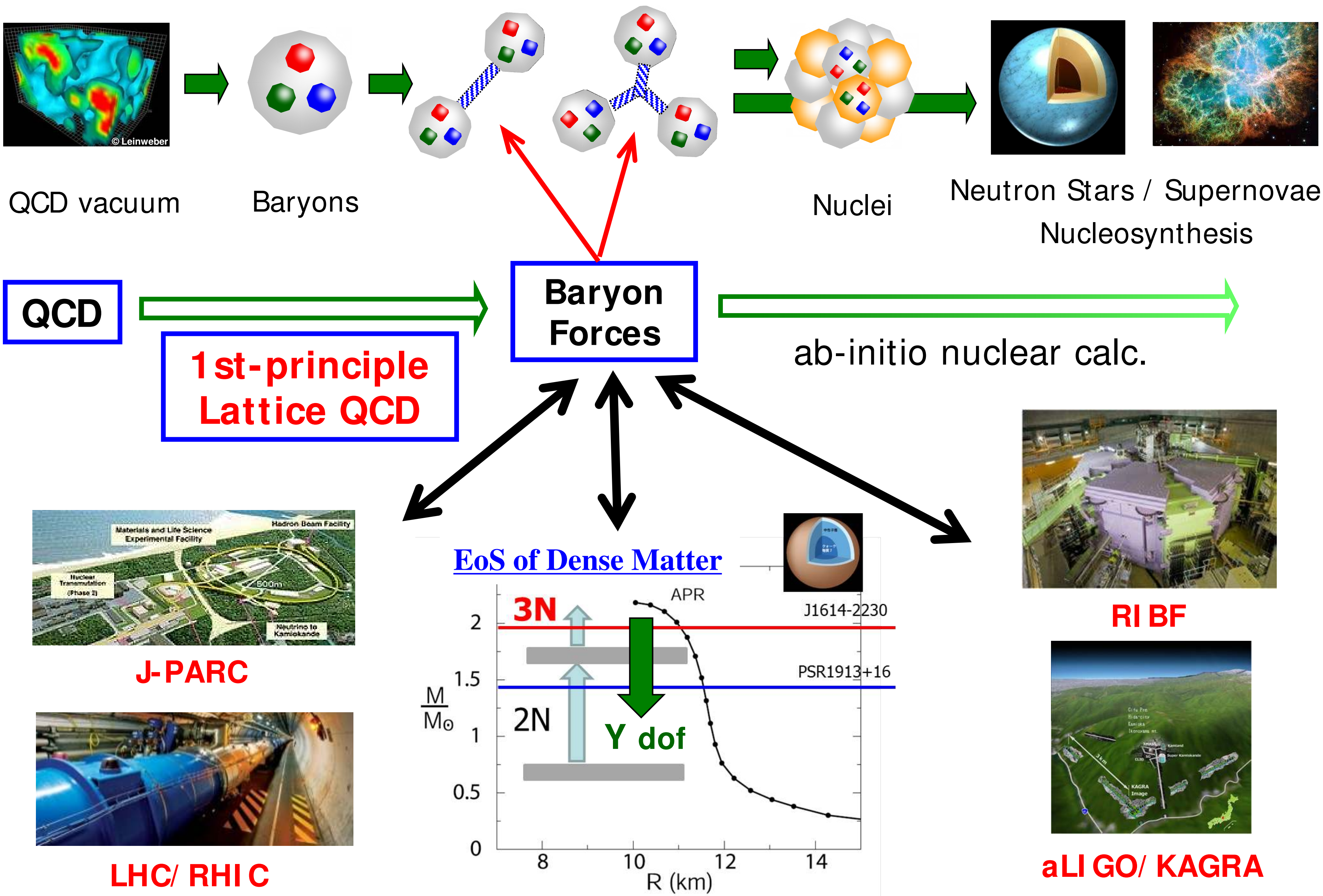
## *– Nuclear forces and $\Xi\Xi$ forces –*

*+ $N\Omega$ forces*

**Takumi Doi**
(Nishina Center, RIKEN)

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

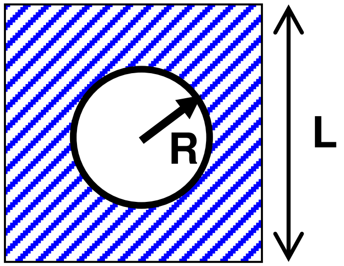
# The Odyssey from Quarks to Universe



# [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

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

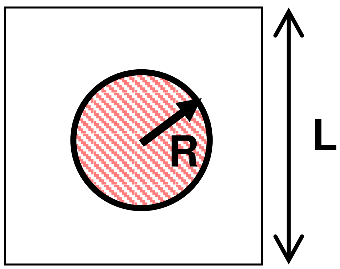
$$\psi(r) \simeq A \frac{\sin(kr - l\pi/2 + \delta(k))}{kr}$$

**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

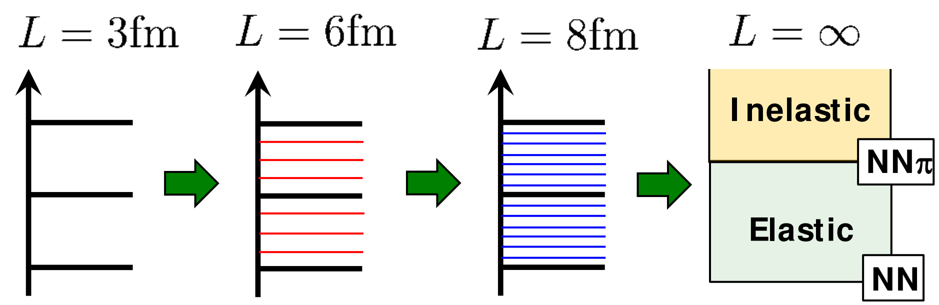
Aoki-Hatsuda-Ishii PTP123(2010)89

# *The Challenge in multi-baryons on the lattice*

Existence of elastic scatt. states

➔ (almost) No Excitation Energy

➔ LQCD method based on G.S. saturation impossible




Signal/Noise issue

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

Parisi, Lepage(1989)

L=8fm @ physical point $(E_1 - E_0) \simeq 25\mathrm{MeV} \Longrightarrow t > 10\mathrm{fm}$

$$S/N \sim 10^{-32}$$

Naïve plateau fitting at t ~ 1fm is unreliable ("mirage" of true signal)

➔ Talks by S. Aoki & T. Iritani (next session)

T. Iritani et al. (HAL) JHEP1610(2016)101
T. Iritani et al. (HAL) arXiv:1703.07210

# Time-dependent HAL method

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

***E-indep of potential U(r,r')*** ➔ *(excited) scatt states share the same U(r,r')*

*They are* ***not contaminations, but signals***

## Original (t-indep) HAL method

$$G_{NN}(\vec{r},t) = \langle 0|N(\vec{r},t)N(\vec{0},t)\overline{\mathcal{J}_{\rm src}(t_0)}|0\rangle$$

$$R(\boldsymbol{r},t) \equiv G_{NN}(\boldsymbol{r},t)/G_N(t)^2 = \sum A_{W_i}\psi_{W_i}(\boldsymbol{r})e^{-(W_i-2m)t}$$

🡐 Many states contribute

$$\int d\boldsymbol{r}' U(\boldsymbol{r},\boldsymbol{r}')\underline{\psi_{W_0}(\boldsymbol{r}')} = (\underline{E_{W_0}} - H_0)\underline{\psi_{W_0}(\boldsymbol{r})}$$

$$\int d\boldsymbol{r}' U(\boldsymbol{r},\boldsymbol{r}')\underline{\psi_{W_1}(\boldsymbol{r}')} = (\underline{E_{W_1}} - H_0)\underline{\psi_{W_1}(\boldsymbol{r})}$$

...

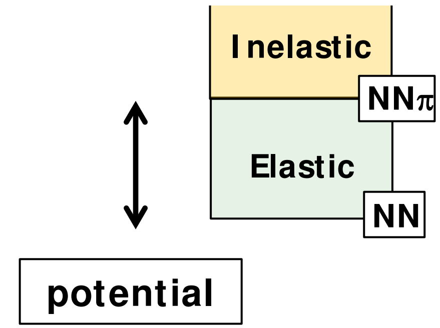
## New t-dep HAL method

All equations can be combined as

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

**~~G.S. saturation~~ ➔ "Elastic state" saturation**

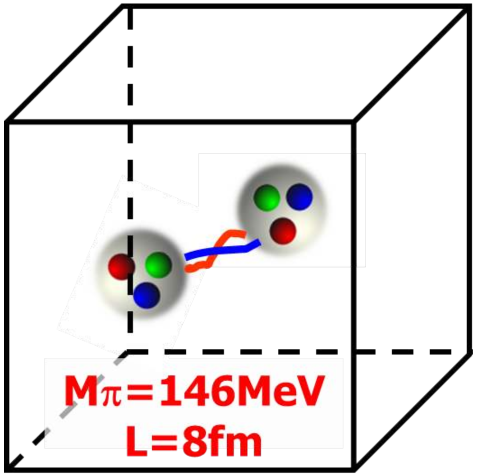
**[Exponential Improvement]**



# Setup of Lattice QCD

- **Nf = 2+1 full QCD**
  - Clover fermion + Iwasaki gauge action
  - Non-perturbatively O(a)-improved
  - APE-Stout smearing ($\alpha$=0.1, $n_{stout}$=6)
  - m(pi) ~= 146 MeV, m(K) ~= 525 MeV
  - #traj ~= 2000 generated

PACS Coll., PoS LAT2015, 075
(talk by Y. Kuramashi)




$96^4$ box
(a~= 0.085fm)

- Measurement
  - t-dep HAL method w/ coupled channel formalism
  - Unified Contraction Algorithm (UCA) for drastic speedup
    - ~25% efficiency on K @ 2048node (solver + UCA + I/O)
  - Wall source w/ Coulomb gauge
  - #stat (NN, $\Xi\Xi$) = [200 x 2] confs x 4 rot x 72 src
  - #stat ($N\Omega$) = [115 ] confs x 4 rot x 48 src
  - All results preliminary

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

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

TD, M.Endres, CPC184(2013)117

K-computer (10PFlops)

# Target of LQCD calc

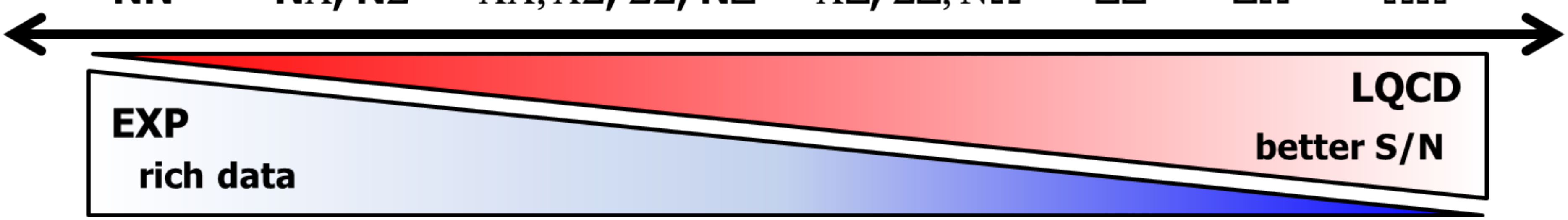
- All of NN/YN/YY for central/tensor forces in P=(+) (S, D-waves)

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)

| S=0 | S=−1 | S=−2 | S=−3 | S=−4 | S=−5 | S=−6 |
|---|---|---|---|---|---|---|
| NN | NΛ, NΣ | ΛΛ, ΛΣ, ΣΣ, NΞ | ΛΞ, ΣΞ, NΩ | ΞΞ | ΞΩ | ΩΩ |




T. Doi | H. Nemura | K. Sasaki | N. Ishii | T. Iritani (➔ T. Doi) | T. Doi

**Predictions for Hyperon forces**

# ΞΞ system (S= –4)

$^1S_0$ 27plet ⇔ Flavor SU(3)-partner of NN($^1S_0$)

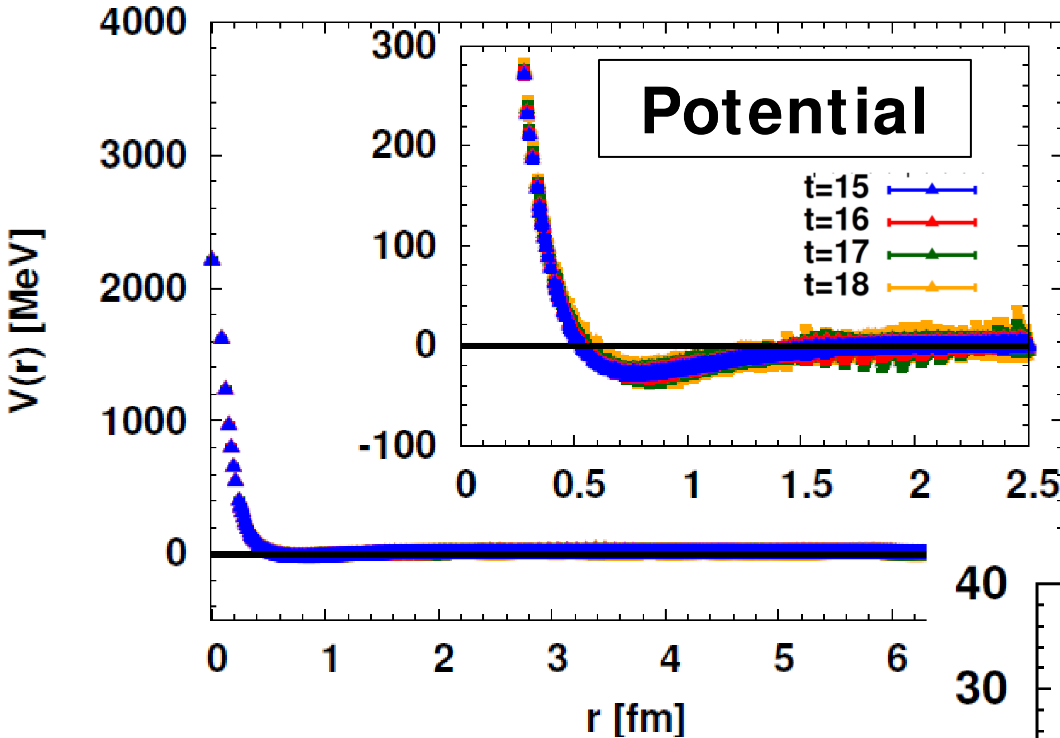
⇨
- Doorway to NN-forces
- Bound by SU(3) breaking ?

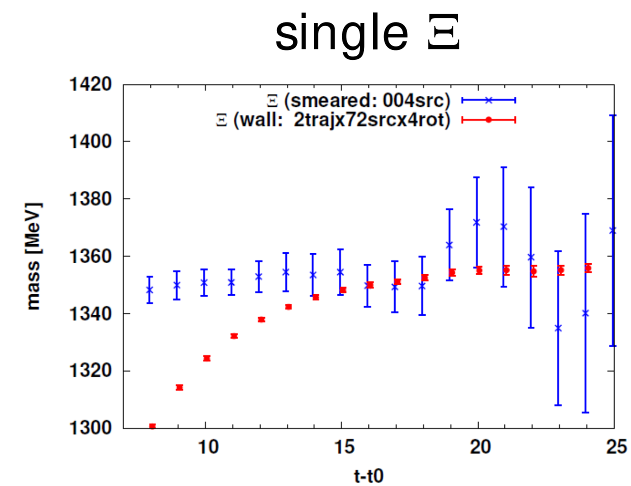
$^3S_1$-$^3D_1$ 10plet ⇔ unique w/ hyperon DoF

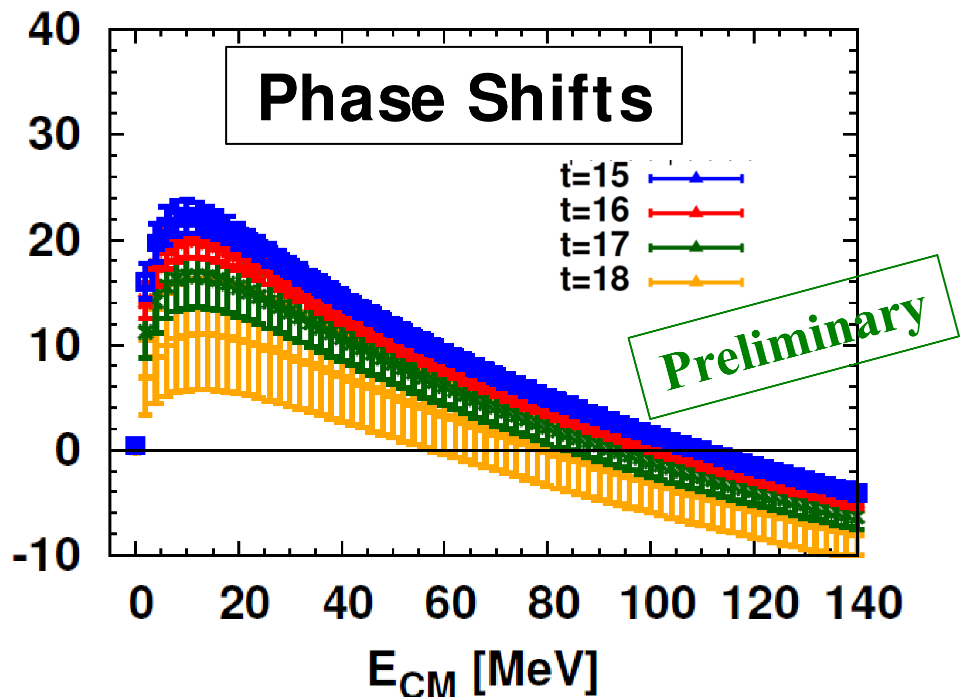
Flavor SU(3)-partner of $\Sigma^-$ n

⇨ • $\Sigma^-$ in neutron star ?

# ΞΞ system ($^1S_0$)




**Strong Attraction**

**yet Unbound**

⟺ **ΞΞ correlation in HIC**

(2-gauss + 2-OBEP)

# ΞΞ system ($^3S_1$-$^3D_1$)

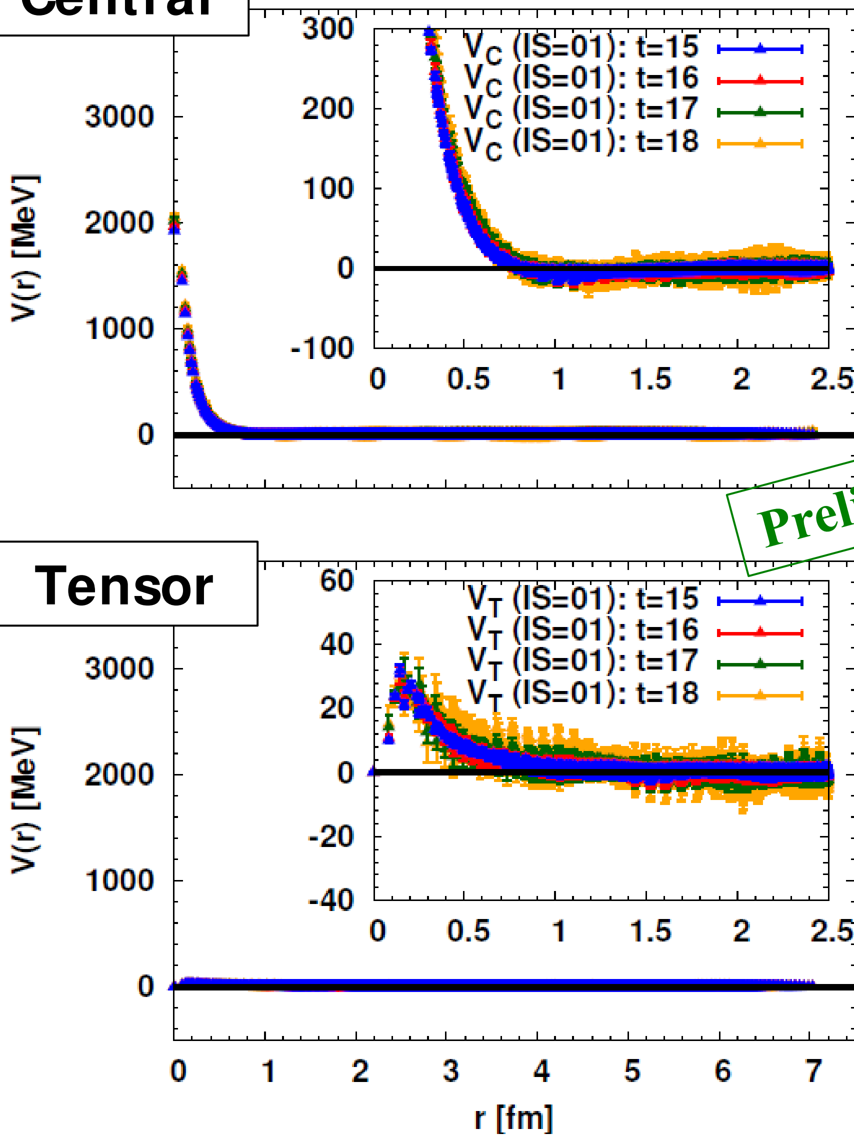
**Potentials**

**Central**

**Central: Strong Repulsion**

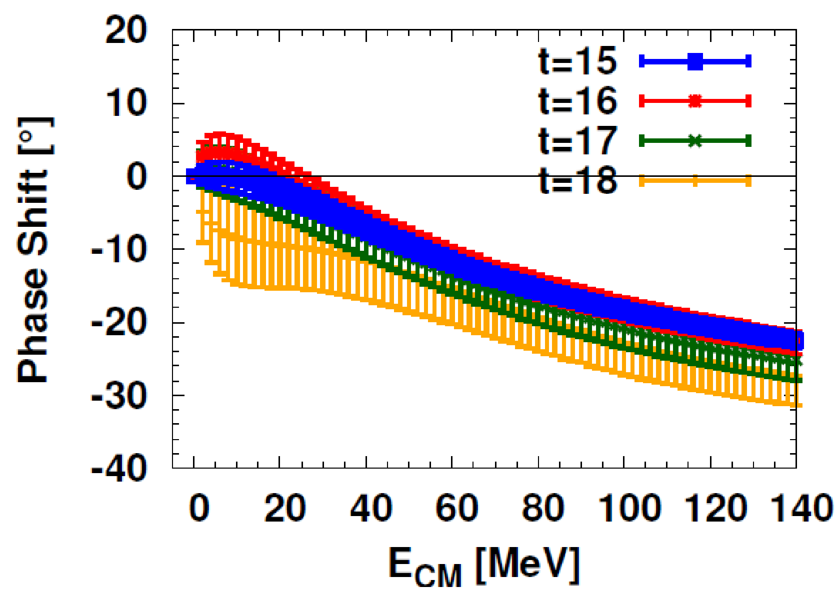
**Tensor: Weak**

**Tensor**




Preliminary

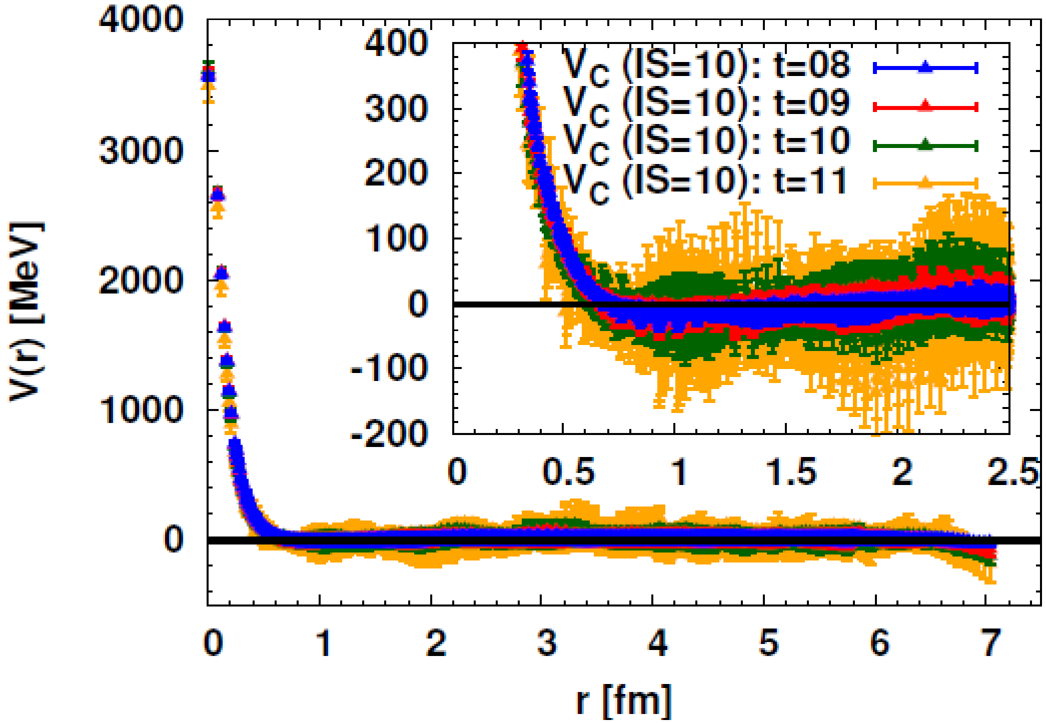
**Phase Shifts** (effective $^3S_1$)



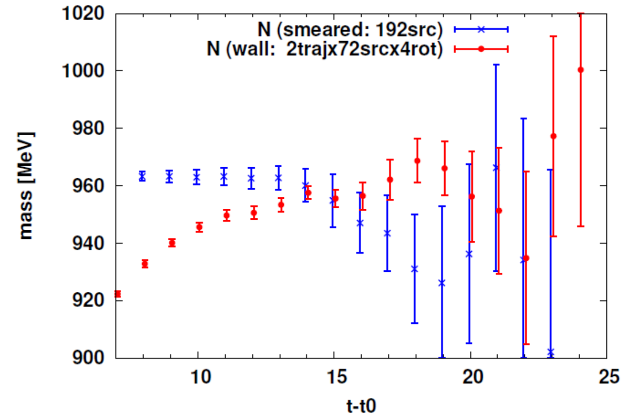
# NN system (S = 0)

- **$^1S_0$ channel**
  - Central Force
- **$^3S_1$-$^3D_1$ channel**
  - Central Force
  - Tensor Force

# Central Potential NN ($^1S_0$)




Single N

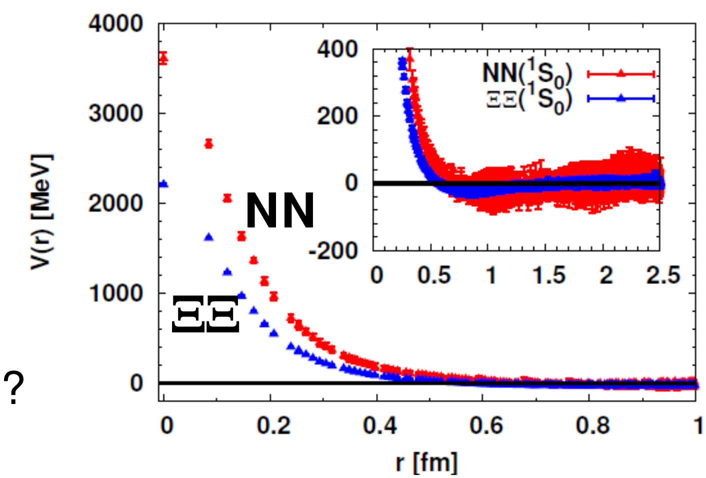



**Repulsive core observed**

**Attraction at mid-long range**

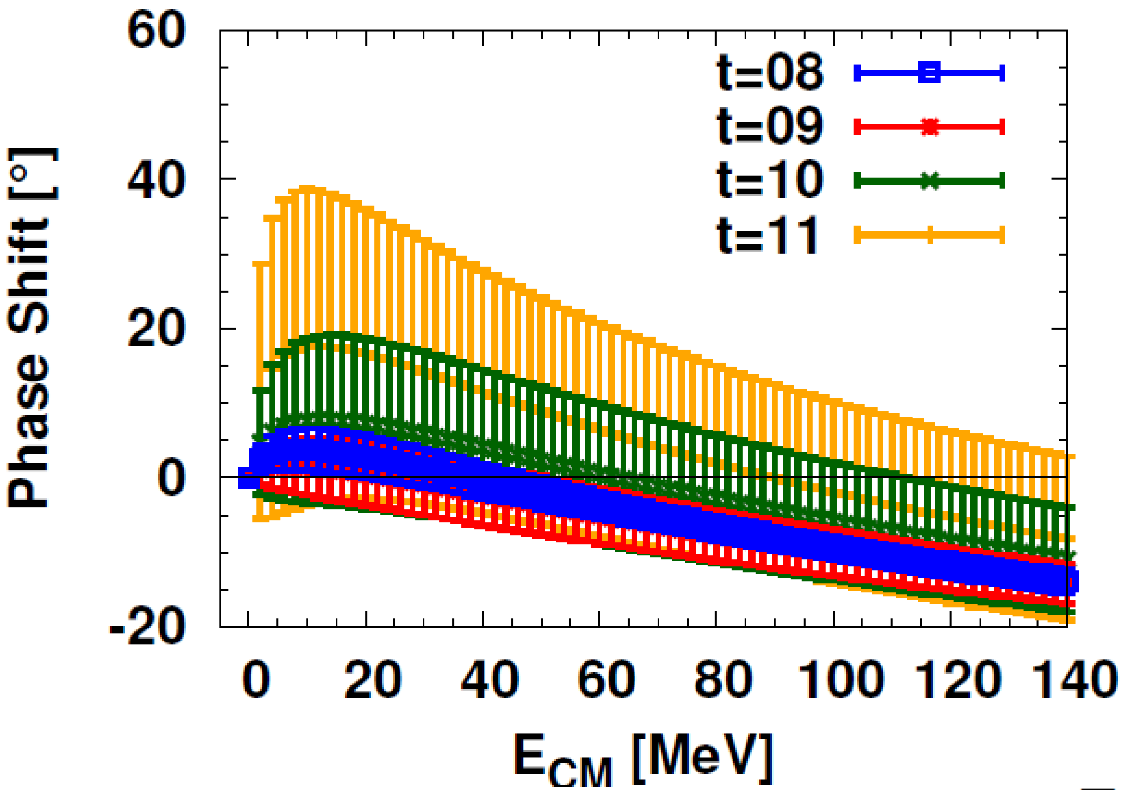
## The effect of SU(3)f breaking

NN($^1S_0$) and ΞΞ($^1S_0$) belong to 27-plet



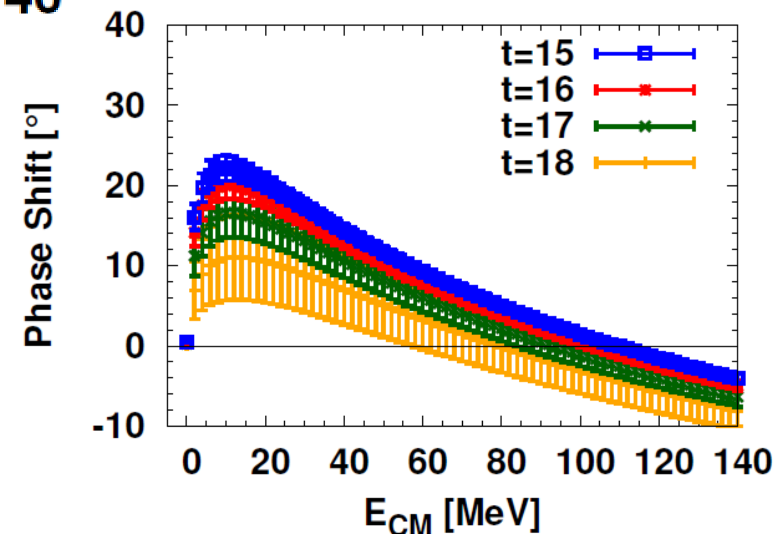

Repulsive core enhanced
for lighter quark mass ? ←→ OGE ?

# Phase Shifts NN($^1S_0$)



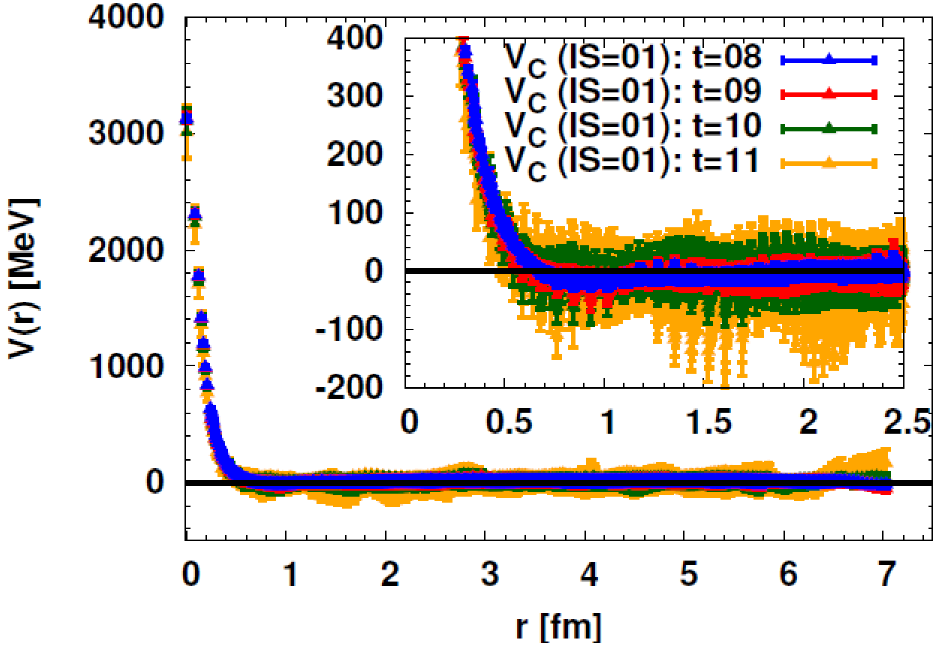

**preliminary**

ΞΞ ($^1S_0$)

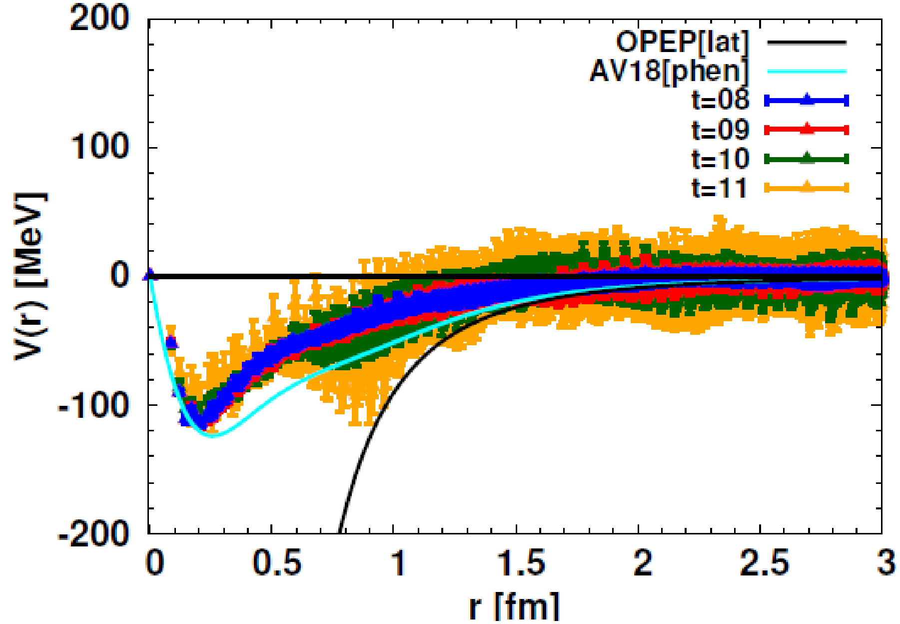


# Central/Tensor Potentials NN ($^3S_1$-$^3D_1$)

Central




Tensor




**Repulsive core observed**

**Attraction at mid-long range**

**Strong Tensor Force is clearly visible !**

**preliminary**

Either of bound/unbound is possible within uncertainties

# NΩ system (S= –3)

$^5S_2$

- Candidate for exotic dibaryon system
- No Pauli blocking
- S-wave decay to octet-octet baryon (ΛΞ etc.) is forbidden
- Bound state found in LQCD at heavy masses

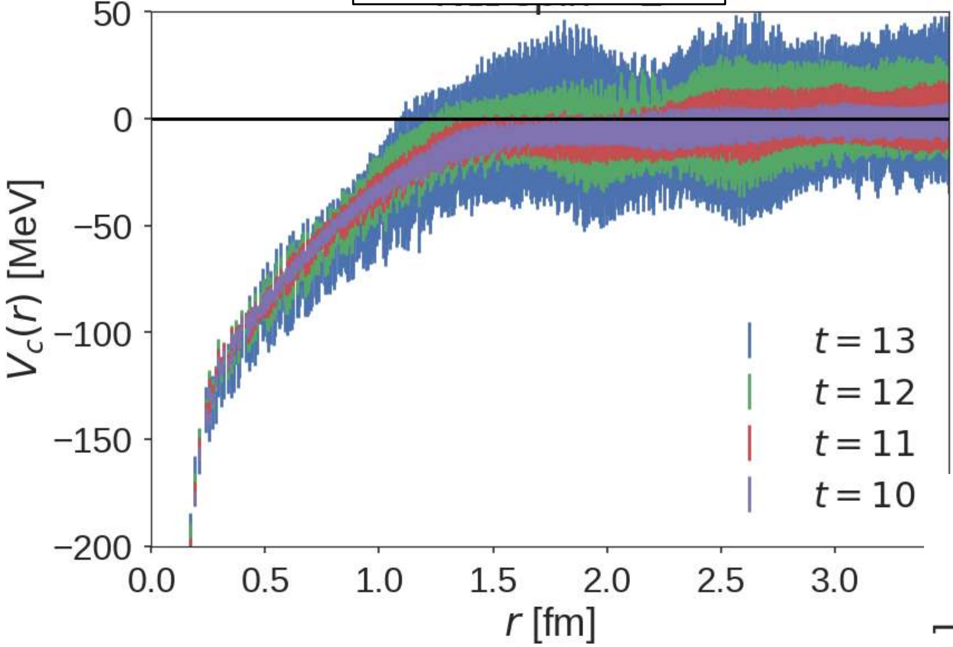
F. Etminan et al. (HAL Coll.) NPA928(2014)89

- Experimental study in HIC possible

K. Morita et al. PRC94(2016)031901

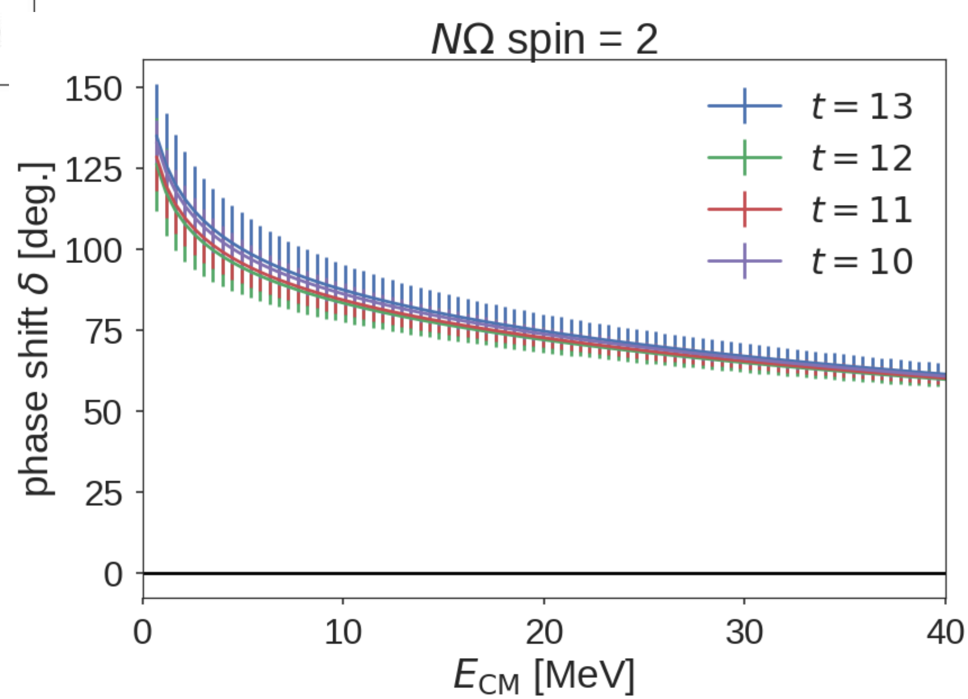
# NΩ system ($^5S_2$)

**Potentials**




**preliminary**

**Phase Shifts**




**Strong Attraction**

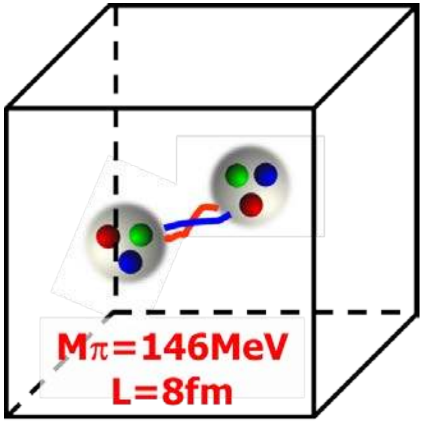
**possibly "Bound"**

**⟺ NΩ correlation in HIC**

(115conf x 4rot x 48src)

# Summary

- Baryon Forces from LQCD at ~ phys. point
  - m(pi) ~= 146 MeV, L ~= 8fm, 1/a ~= 2.3GeV
  - Predictions in particular for Hyperon Forces



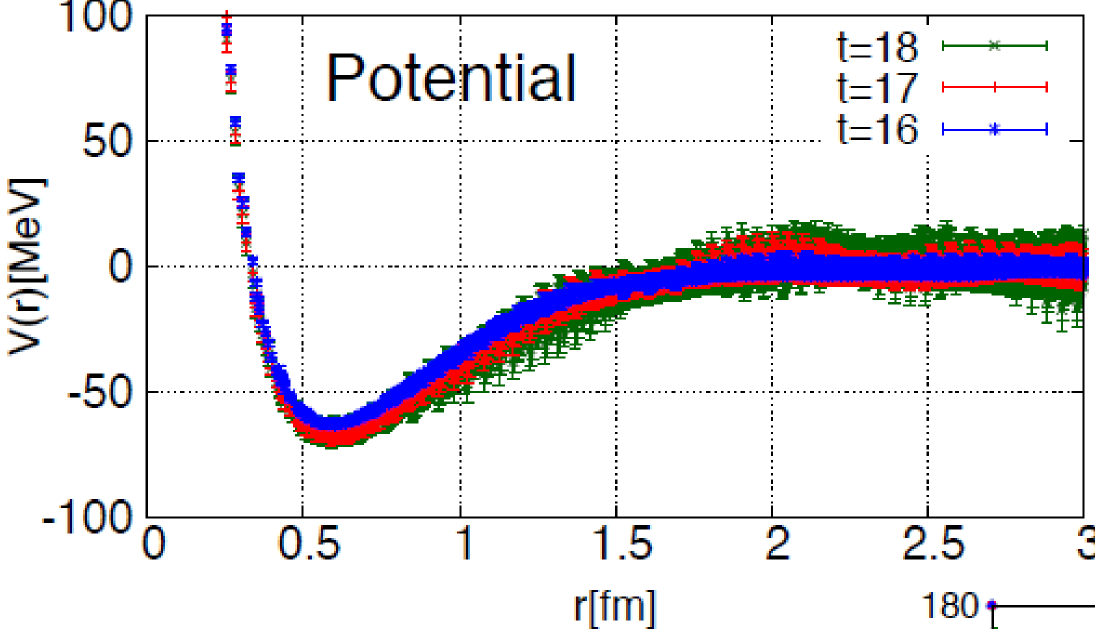

- ΞΞ systems
  - $^1S_0$: strong attraction but unbound
  - $^3S_1$-$^3D_1$: strong repulsive core, weak tensor force
- NN systems
  - Strong tensor forces, repulsive core + long-range attraction in central
- NΩ system
  - $^5S_2$: strong attraction, possibly bound
- Prospects
  - Full #stat (~ x 1.3) achieved soon
  - Exascale computing Era ~ 2020
  - LS-forces, Parity-odd channel, Three-body forces → LQCD EoS

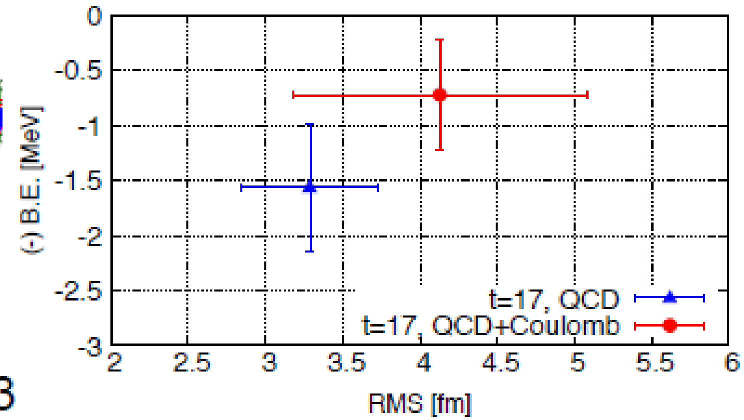
# Backup Slides

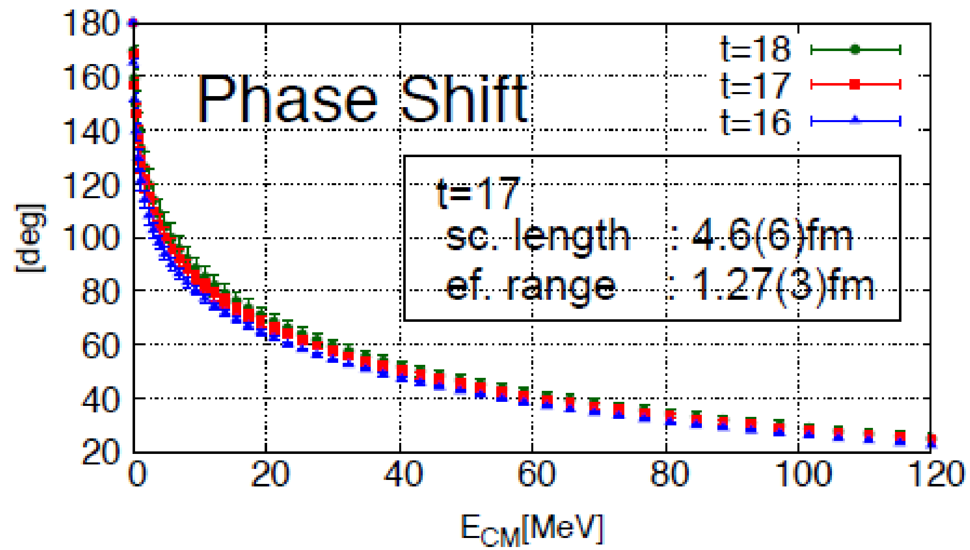
# ΩΩsystem in $^1S_0$

Ω(sss)

**Preliminary**




**Strong attraction**
**→ weak bound or unitary limit**

**[S. Gongyo]**