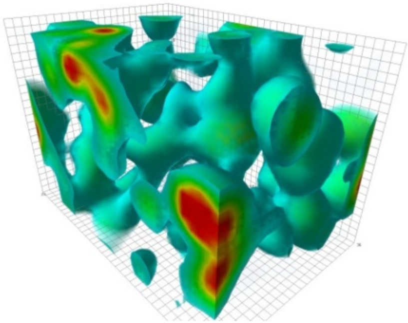
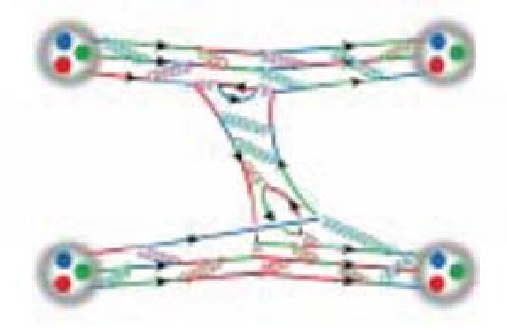
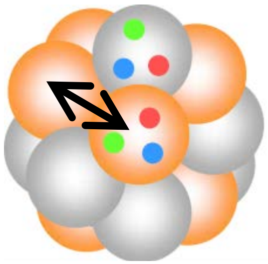
Baryon Interactions from Lattice QCD with physical masses

Takumi Doi
(Nishina Center, RIKEN)

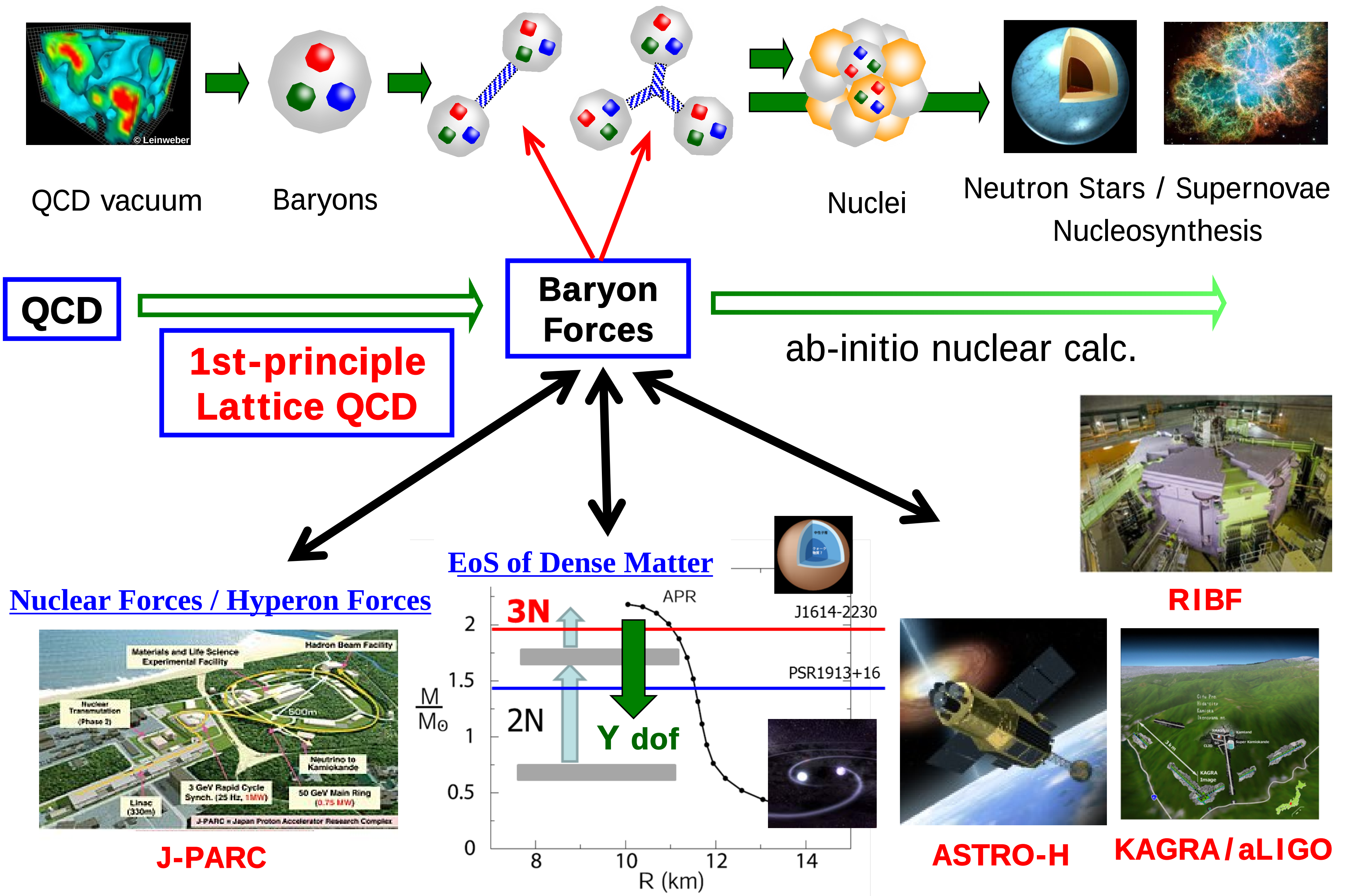
for HAL QCD Collaboration





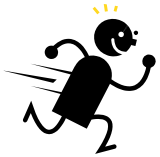


The journey from Quarks to Universe



The journey from unphysical to physical quark masses

~2012

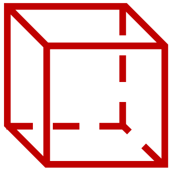


➔ lighter m_q

We were here

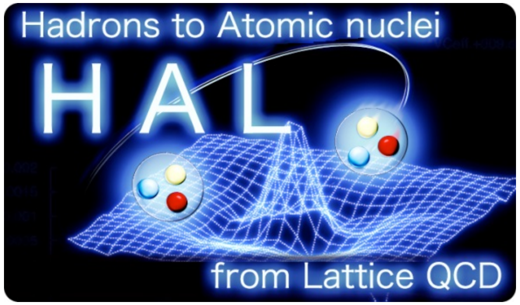
Phys. point

$M\pi$=0.4 GeV
L=3fm

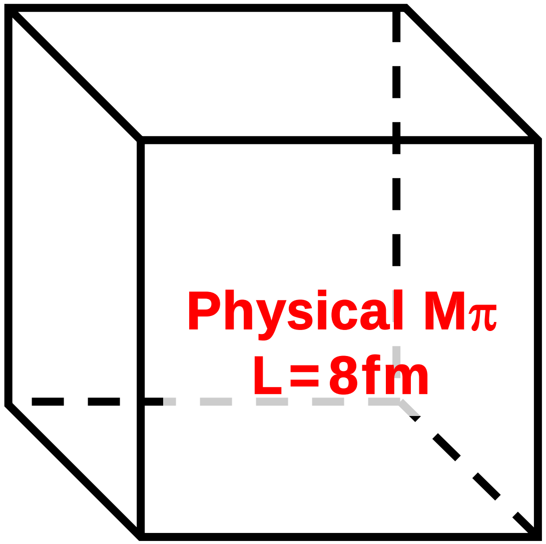


K-computer

Hadrons to Atomic nuclei from Lattice 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)



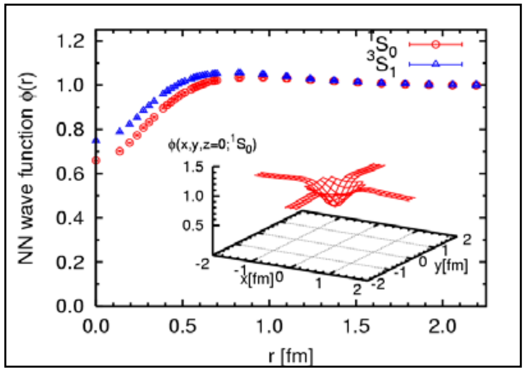
+ Collaboration in HPCI Field5 Project 1

- **Outline**
  - ~~Introduction~~
  - Theoretical framework
  - Results at heavy quark masses
  - Reliability test of LQCD methods
  - Results at physical quark masses
  - Summary / Prospects

HAL QCD method

Lattice QCD

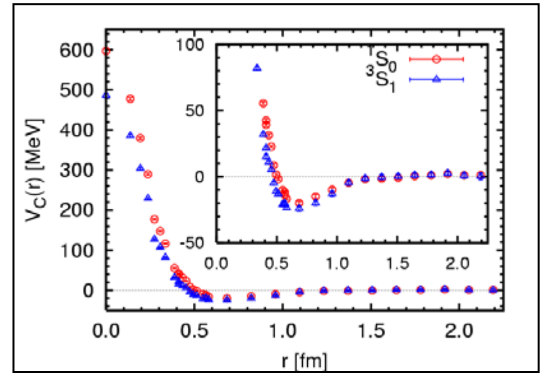
NBS wave func.



$$\psi_{NBS}(\vec{r}) = \langle 0|N(\vec{r})N(\vec{0})|N(\vec{k})N(-\vec{k}), in\rangle$$
$$\simeq e^{i\delta_l(k)}\sin(kr - l\pi/2 + \delta_l(k))/(kr)$$

(at asymptotic region)

Lat Nuclear Force



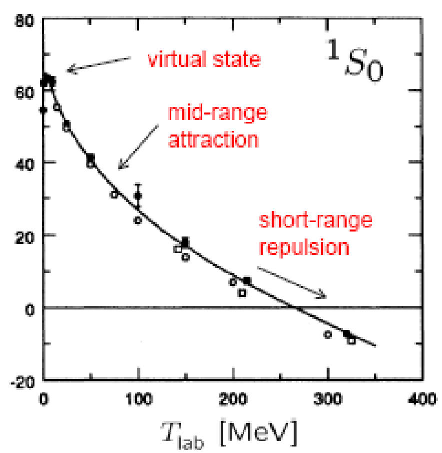
$$(k^2/m_N - H_0)\,\psi(\vec{r}) = \int d\vec{r}'\,U(\vec{r},\vec{r}')\psi(\vec{r}')$$

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

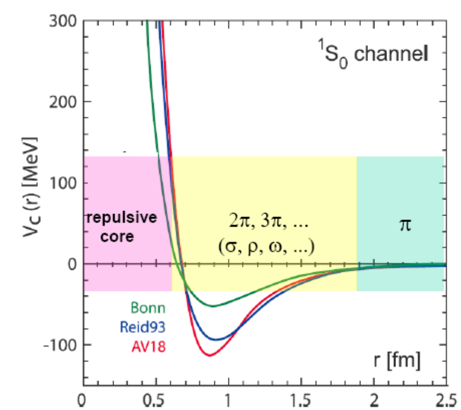
Analog to …

Scattering Exp.

Phase shifts



Phen. Potential



Recent Crucial Development

- **Time-dependent HAL method** N.Ishii et al. (HAL Coll.) PLB712(2012)437
  - **[Luscher's method]** (traditional) ➔ ground state saturation ➔ very bad S/N

    $$S/N \sim \exp[-\mathbf{A} \times (\mathbf{m_N} - \mathbf{3/2m_\pi}) \times \mathbf{t}]$$
  - **[HAL method]** ➔ ground state saturation NOT required w/ E-indep pot

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

- **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

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

- **<u>Outline</u>**
  - Introduction
  - Theoretical framework
  - Results at heavy quark masses
  - Reliability test of LQCD methods
  - Results at physical quark masses
  - Summary / Prospects

SU(3) study

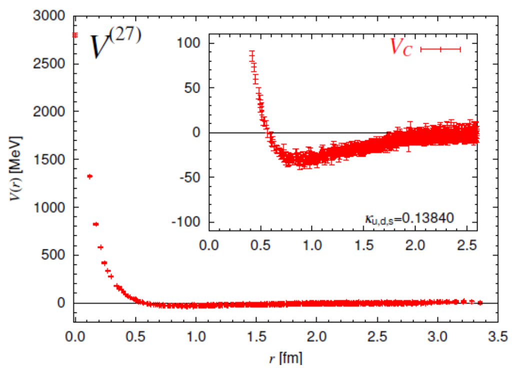
BB potentials

a=0.12fm, L=3.9fm,
m(PS)= 0.47-1.2GeV

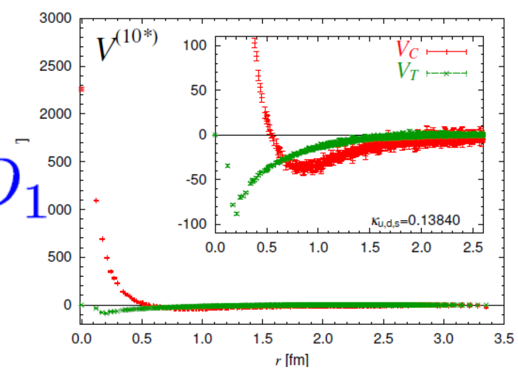
T.Inoue et al. (HAL.), NPA881(2012)28

NN sector

$^1S_0$



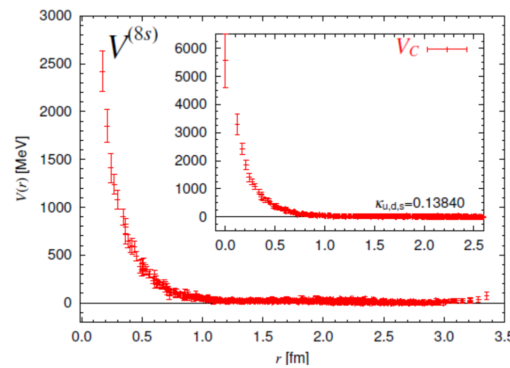
$^3S_1-^3D_1$

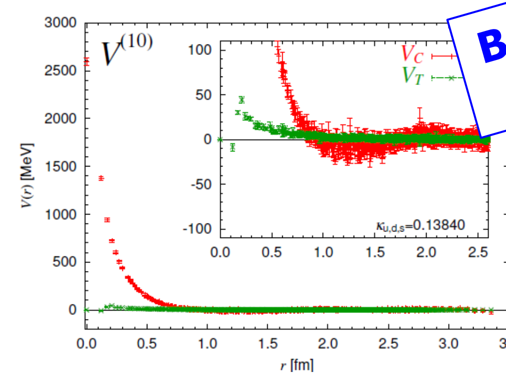


27,10*:
Same as NN

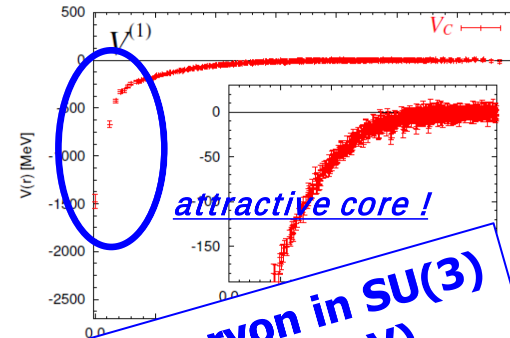
NN : unbound ($^1S_0$, $^3S_1$-$^3D_1$)

YN / YY sector



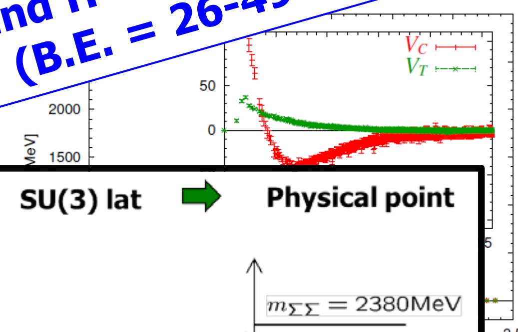


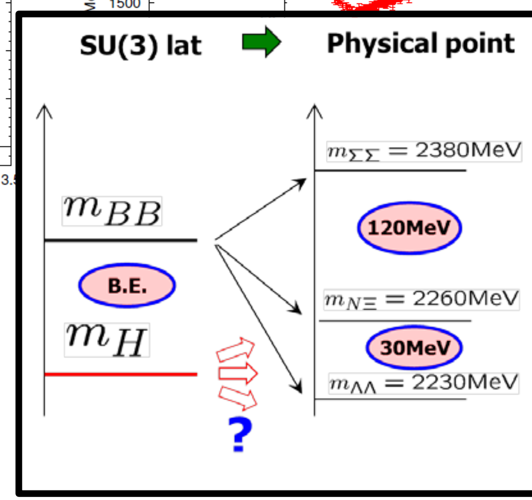
8s,10:
strong repulsive core



attractive core !

Bound H-dibaryon in SU(3)
(B.E. = 26-49 MeV)





Repulsive core
← Pauli principle !

M.Oka et al., NPA464(1987)700

- **Outline**
  - Introduction
  - Theoretical framework
  - Results at heavy quark masses
  - Reliability test of LQCD methods

NN ($^1S_0$, $^3S_1$) @ heavy masses: **HAL method (HAL) : unbound** **Luscher's method (Yamazaki et al. / NPL / CalLat) : bound**

  - Results at physical quark masses
  - Summary / Prospects

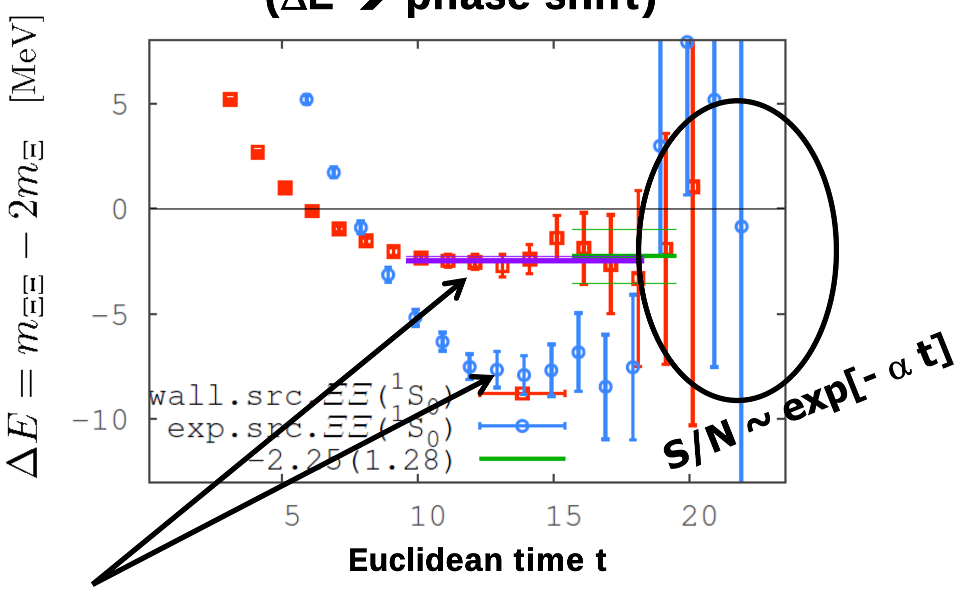
Reliability Test of LQCD methods

- High-stat study for BB-system (@m(pi)=0.5GeV) T. Iritani et al. (HAL Coll.)
  - Benchmark w/ two LQCD setup (wall & smeared src)

← **Physical outputs should NOT depend on these setup**

Luscher's method (traditional)

(ΔE → phase shift)



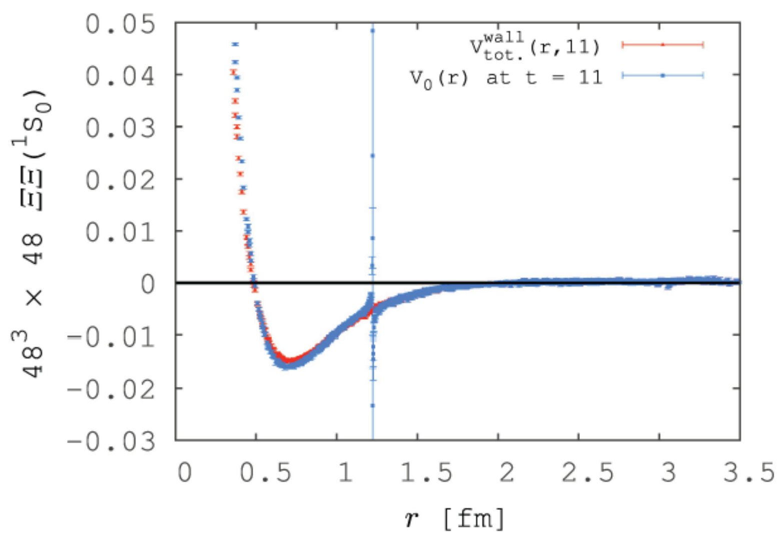
Inconsistent "signal" (red (wall) vs blue (smeared))

→ cannot judge which (or neither) is reliable

FAILED

HAL method (new !)

(V(r) → phase shift)

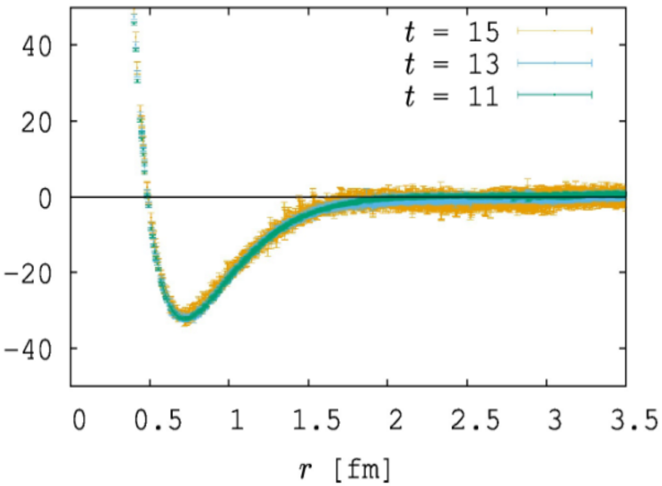


V^{eff}(r) from wall & V^{LO}(r) from wall+smeared are consistent

PASSED

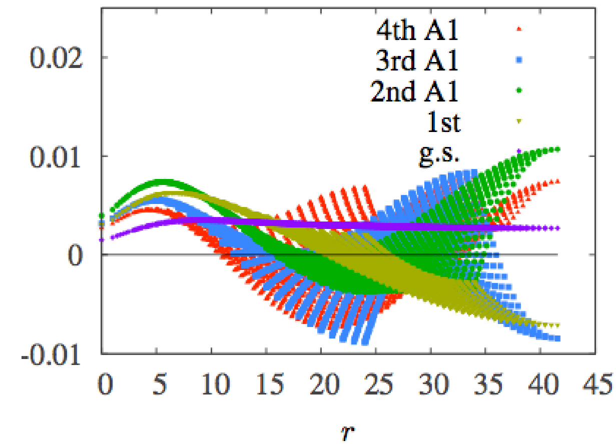
Understand the origin of "fake plateaux"

Potential



Solve Schrodinger eq. in Finite V

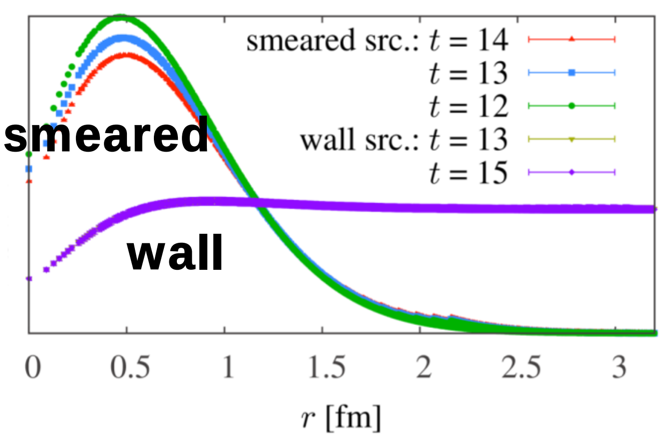
Eigen-wave functions



Eigen-energies

n-th A1	ΔE_n [MeV]
0	-2.58(1)
1	52.49(2)
2	112.08(2)
3	169.78(2)
4	224.73(1)

NBS correlator Ψ(r,t)



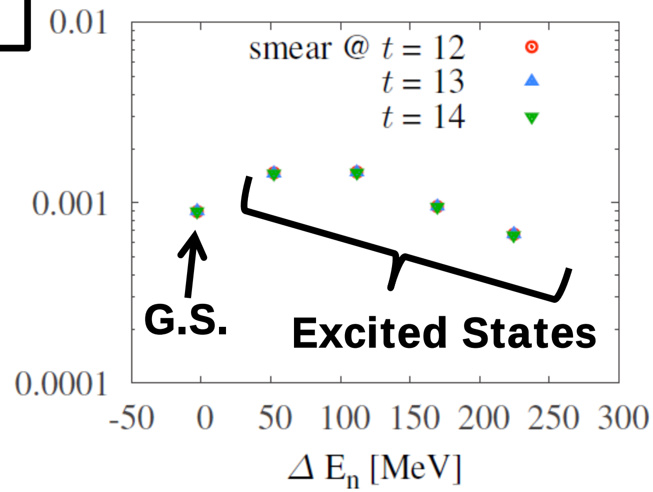
Decompose NBS correlator to each eigenstates

Decompose NBS correlator to each eigenstates

NBS correlator $\Psi(r,t)$

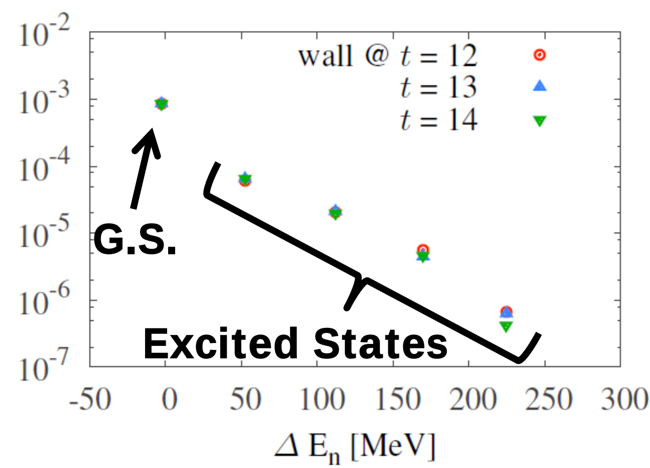
Contribution from each (excited) states (@ t=0)

smeared



excited states NOT suppressed

wall

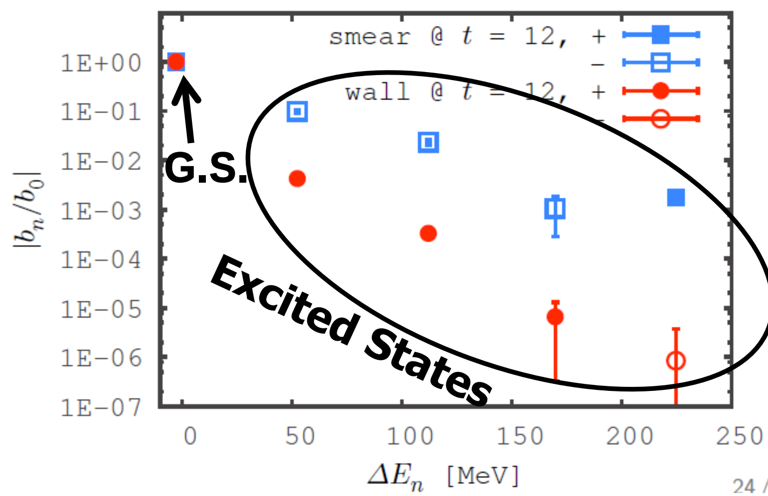


excited states suppressed

R-correlator
$R(t) = \Sigma_r \Psi(r,t)$

(R(t) w/ smeared has been used in Luscher's method)

Contribution from each (excited) states (@ t=0)

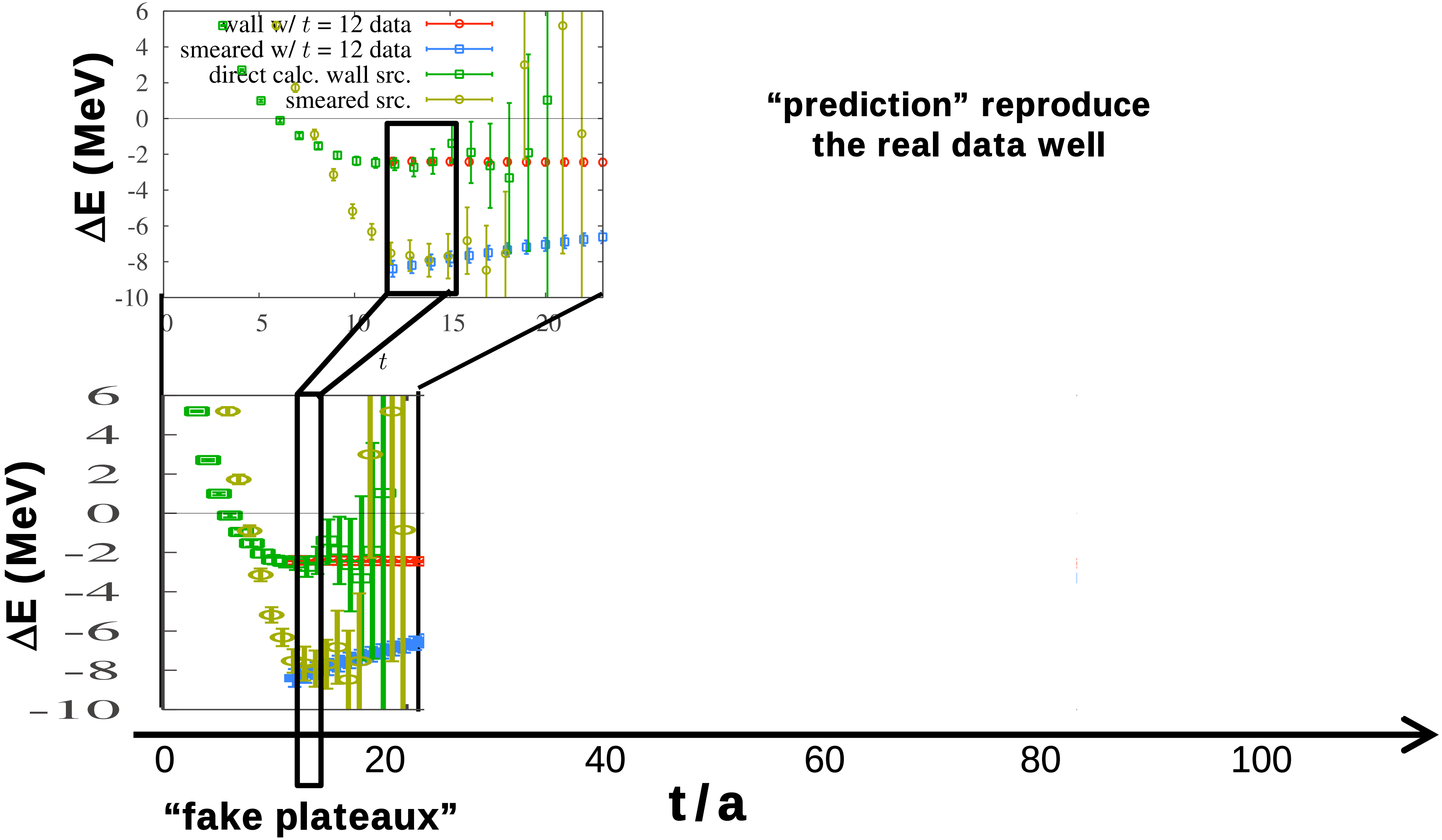


Blue: smeared

Red: wall

Understand the origin of "fake plateaux"

We are now ready to "predict" the behavior of m(eff) of ΔE at any "t"



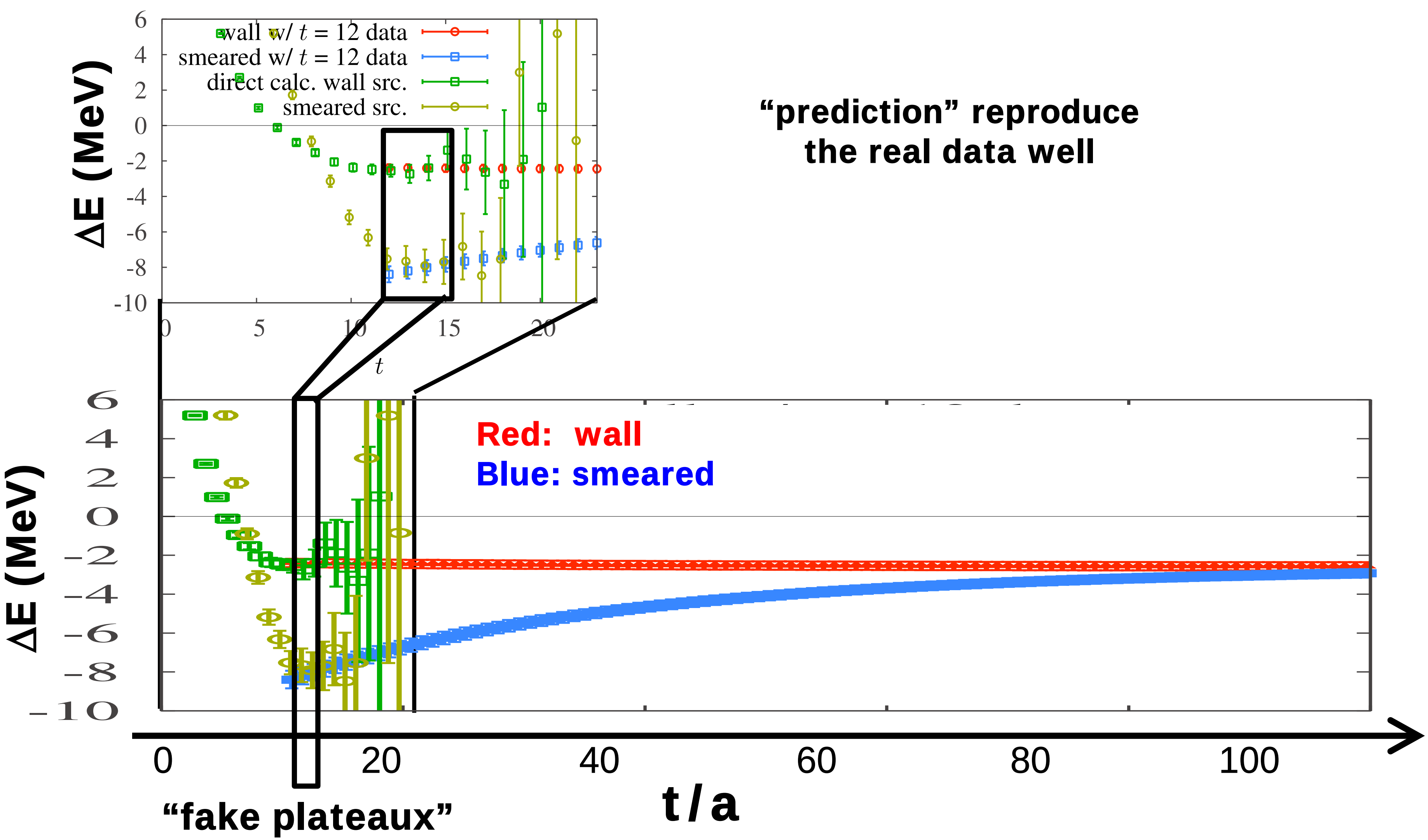
"prediction" reproduce the real data well

Extreme care is necessary for the results from the Luscher's method

To obtain a "real plateau", t/a >100 (t>10fm) is necessary

Understand the origin of "fake plateaux"

We are now ready to "predict" the behavior of m(eff) of ΔE at any "t"

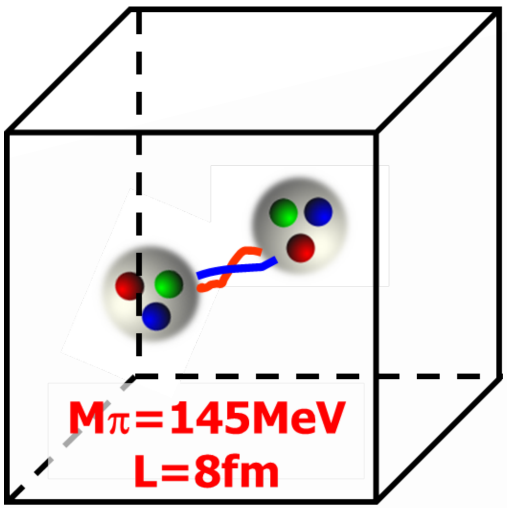


Extreme care is necessary
for the results from the Luscher's method

To obtain a "real plateau",
t/a >100 (t>10fm) is necessary

- **<u>Outline</u>**
  - Introduction
  - Theoretical framework
  - Results at heavy quark masses
  - Reliability test of LQCD methods
  - Results at physical quark masses
  - Summary / Prospects

Simulations w/ ~ physical masses



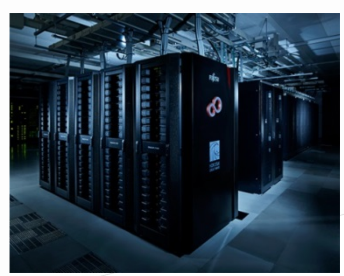
HPCI Strategic Program Field 5
"The origin of matter and the universe"
FY2010-15

Gauge Config Generation

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

(Nara)

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



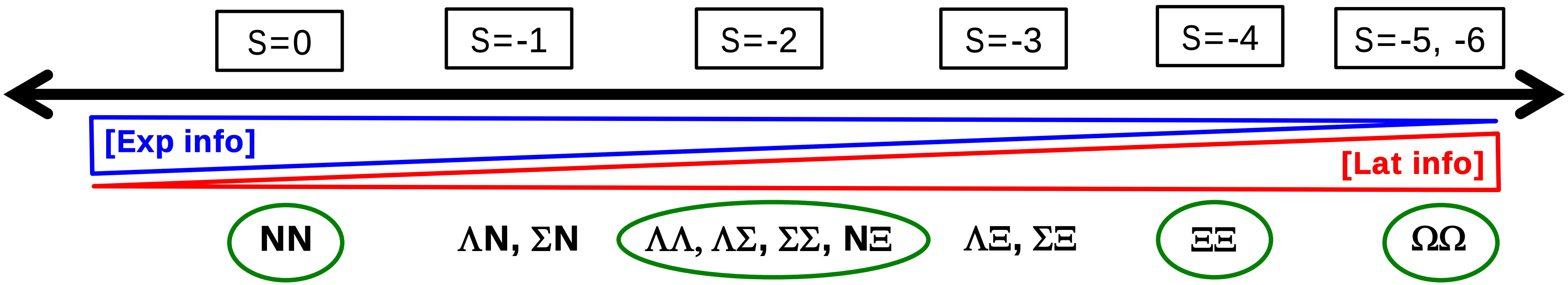
K-computer(RIKEN/AICS)

Baryon Forces

➔ HAL QCD method

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

New bound state(s) ?

Λ appearance in NS & EoS ?

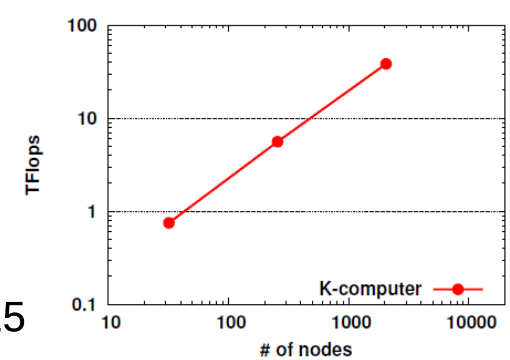
Code:

Efficient implementation of UCA
Performance on K @ 2048node:
~25% of peak (~65 Tflops sustained)

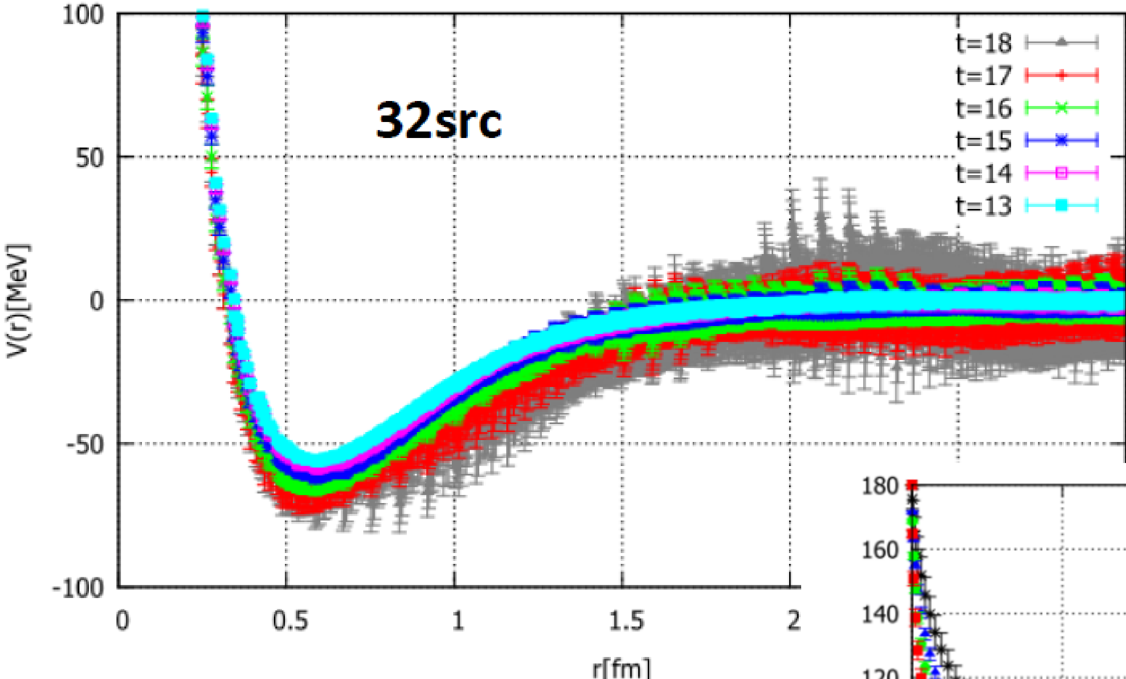
Setup:

Wall source w/ Coulomb gauge + temporal DBC
#stat ~= 200conf x 4rot x 20-44src ➔ ~x2-4 in FY2015

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

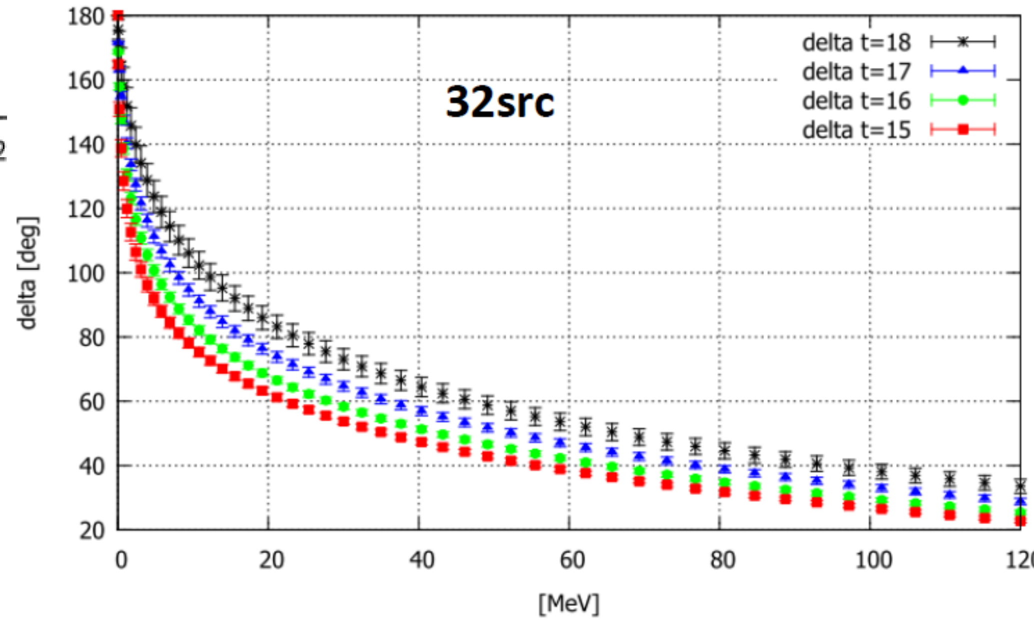


ΩΩ system in $^1S_0$



Preliminary

phase shifts



A new exotic dibaryon

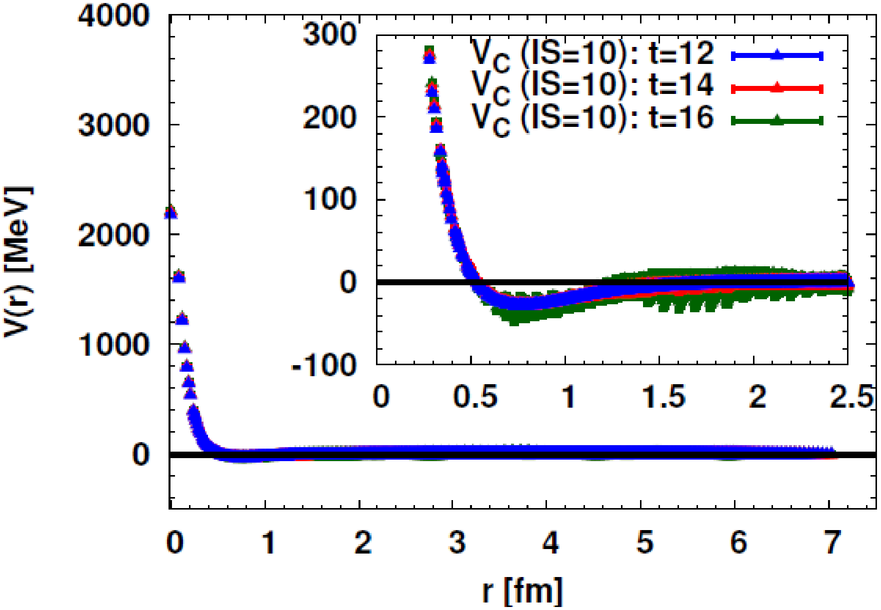
➔ HIC experiments ?

B.E.(QCD) ~= a few – 10 MeV

[S. Gongyo / K. Sasaki]

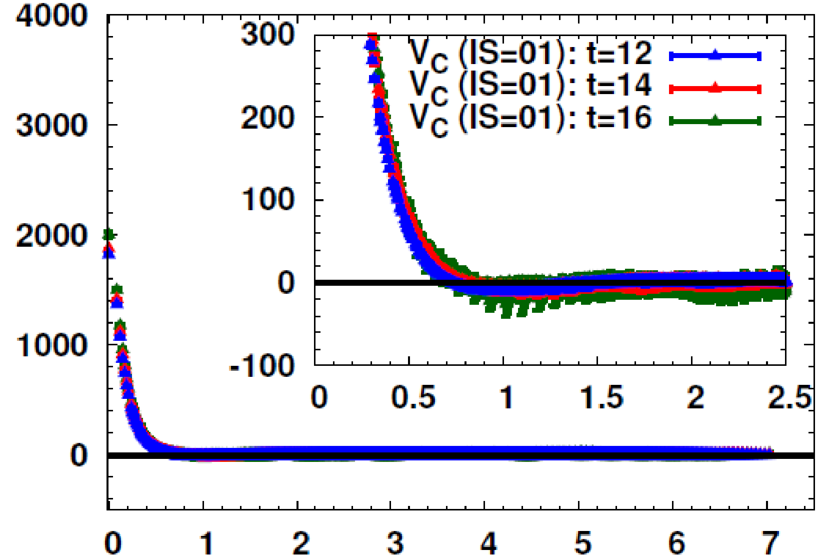
ΞΞ-Potentials

$^1S_0$

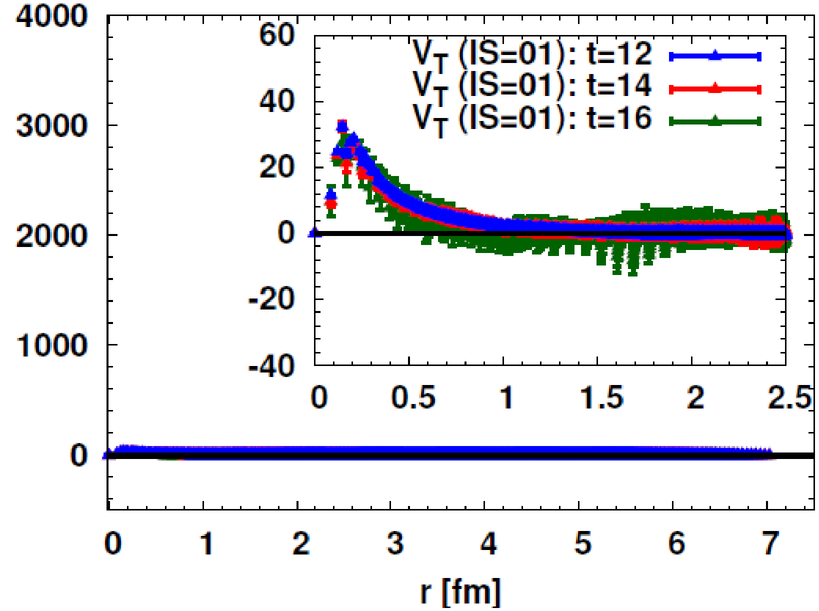


$^3S_1$-$^3D_1$

Central



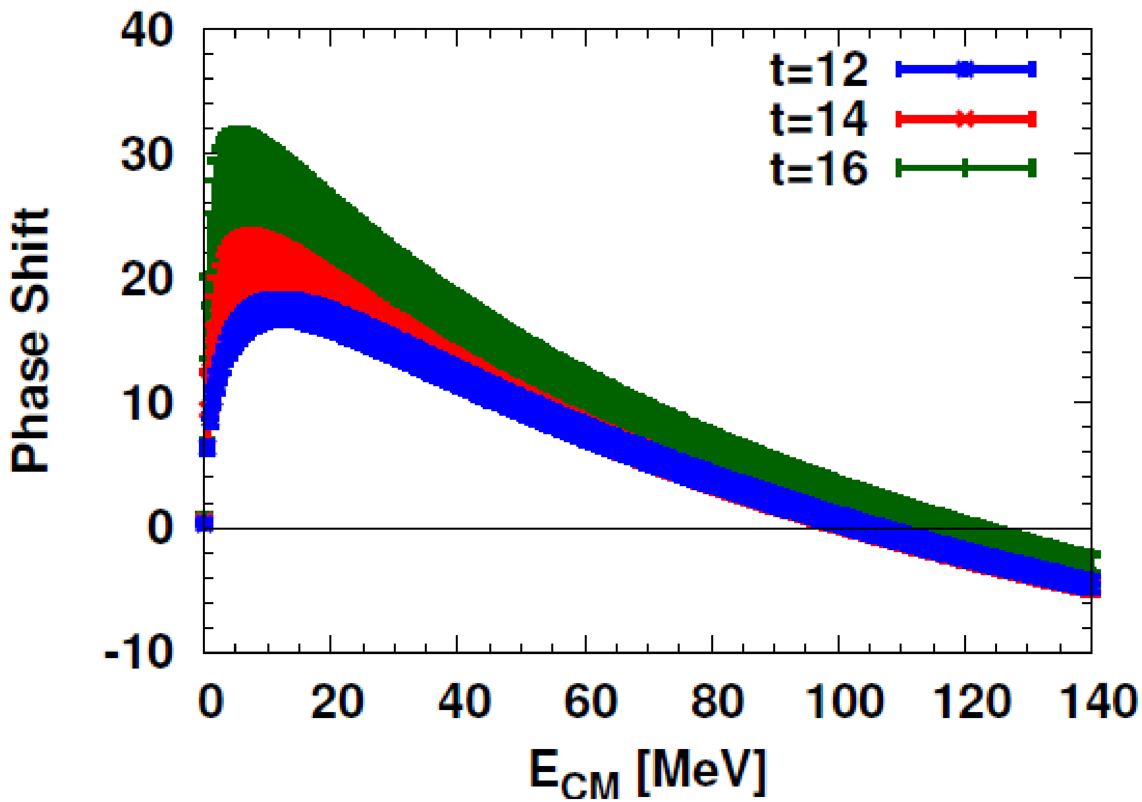
Tensor



Preliminary

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

ΞΞ phase shifts ($^1S_0$)



ΞΞ ($^1S_0$) 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

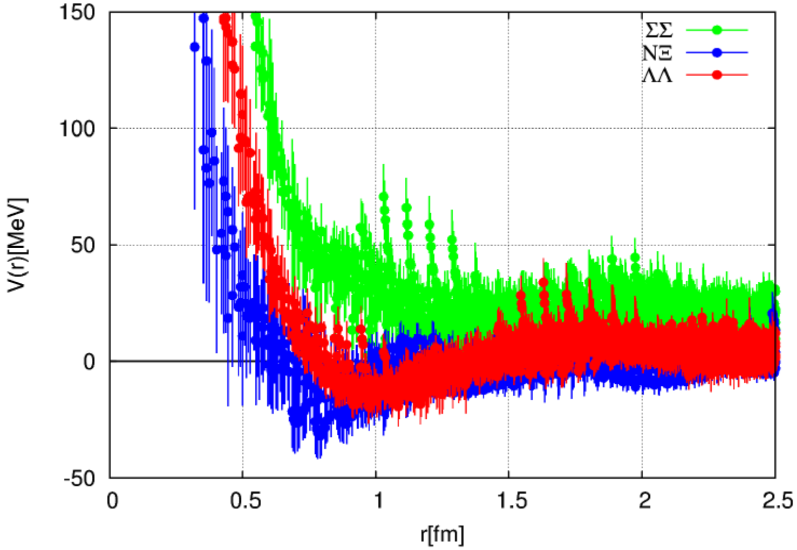
(2-gauss + 2-OBEP fit)

(200conf x 4rot x 44src)

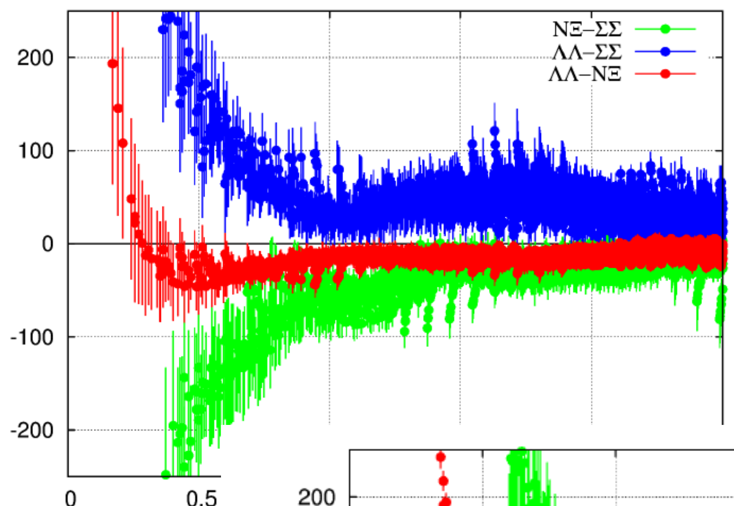
$\Lambda\Lambda$, $N\Xi$, $\Sigma\Sigma$ coupled channel (I=0) $^1S_0$

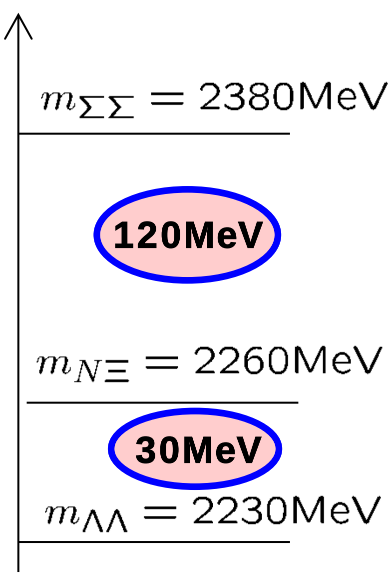
H-dibaryon channel

diagonal

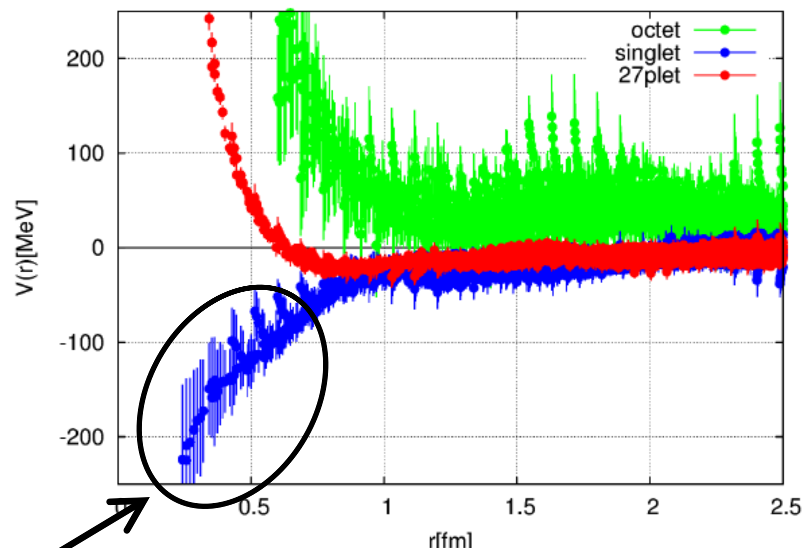


off-diagonal





diagonal in SU(3)-irrep base

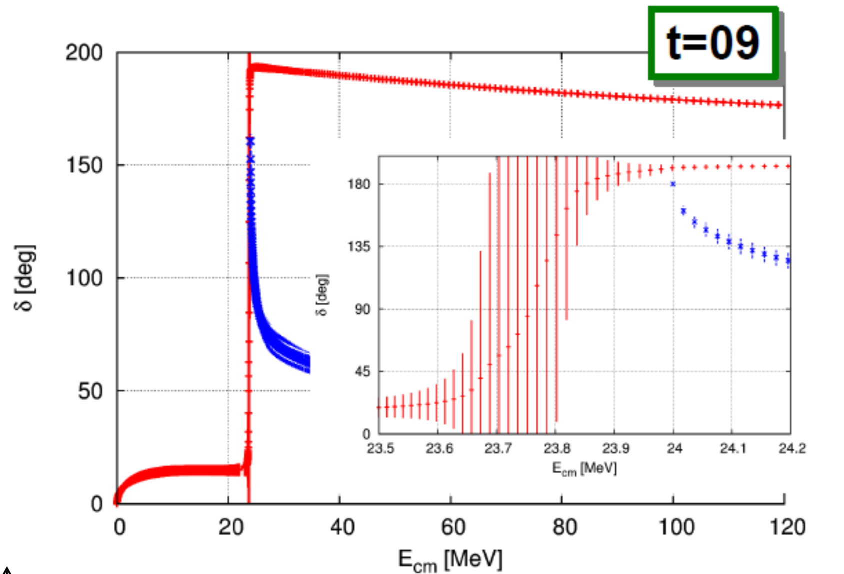


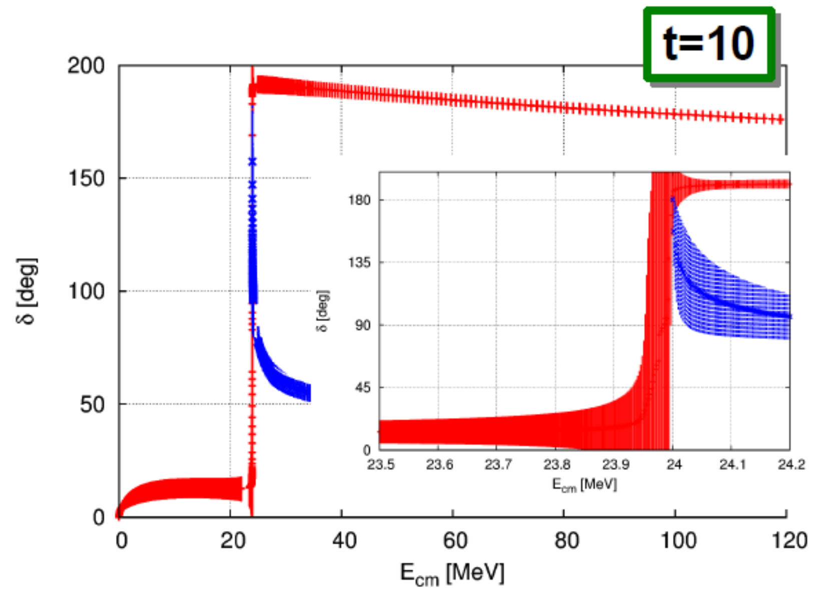
Strong Attraction in flavor-singlet channel

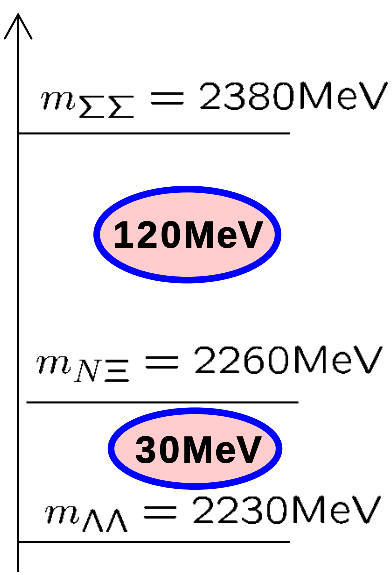
[K. Sasaki]

ΛΛ, NΞ (effective) 2x2 coupled channel analysis

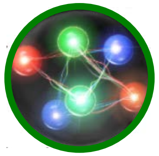
ΛΛ, NΞ phase shifts







H-dibaryon may exist as a resonance just below NΞ threshold



N.B. systematics from time-dependence should be checked

Preliminary

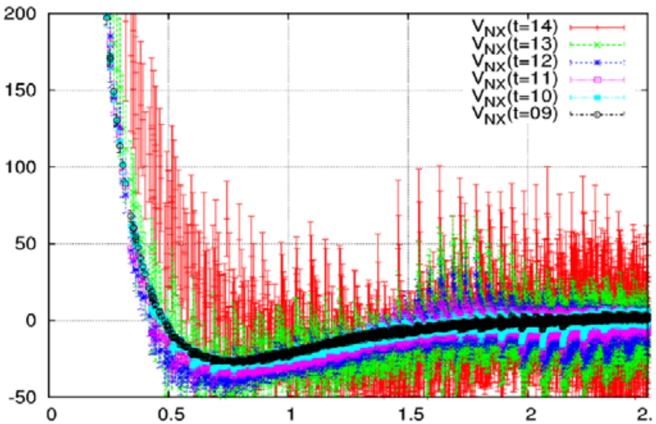
[K. Sasaki]

NΞ-Potentials

[K. Sasaki]

KISO-event (2014): Ξ^{-}–^{14}N : B.E. = 4.38(25) MeV (or 1.11(25) MeV)

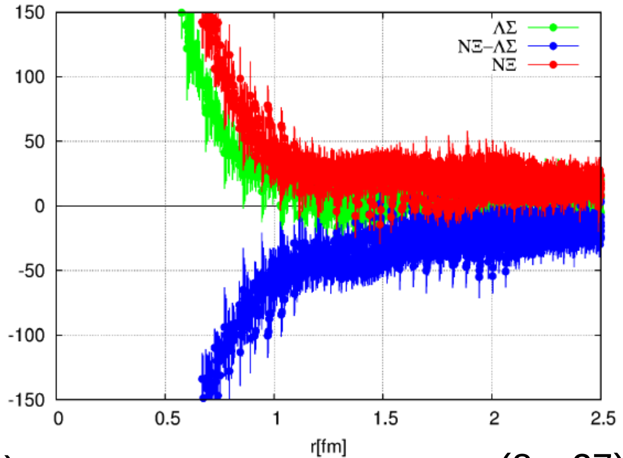
NΞ (I=0, $^3S_1$)



(8a)

Attractive

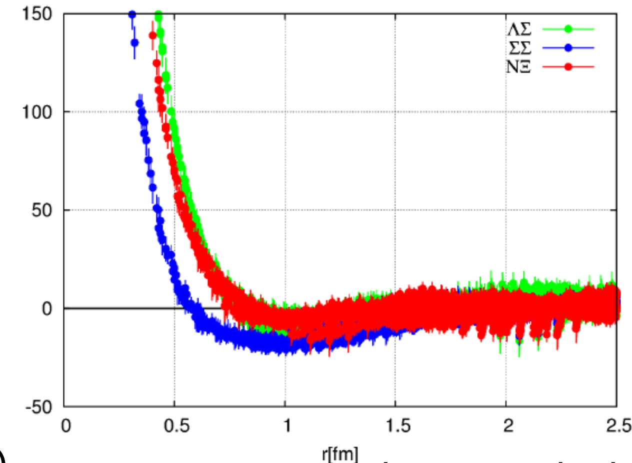
NΞ–ΛΣ (I=1, $^1S_0$)



(8s, 27)

Repulsive

NΞ–ΛΣ–ΣΣ (I=1, $^3S_1$)



(8a, 10, 10bar)

Attractive

(ΛΛ–NΞ–ΣΣ (I=0, $^1S_0$))

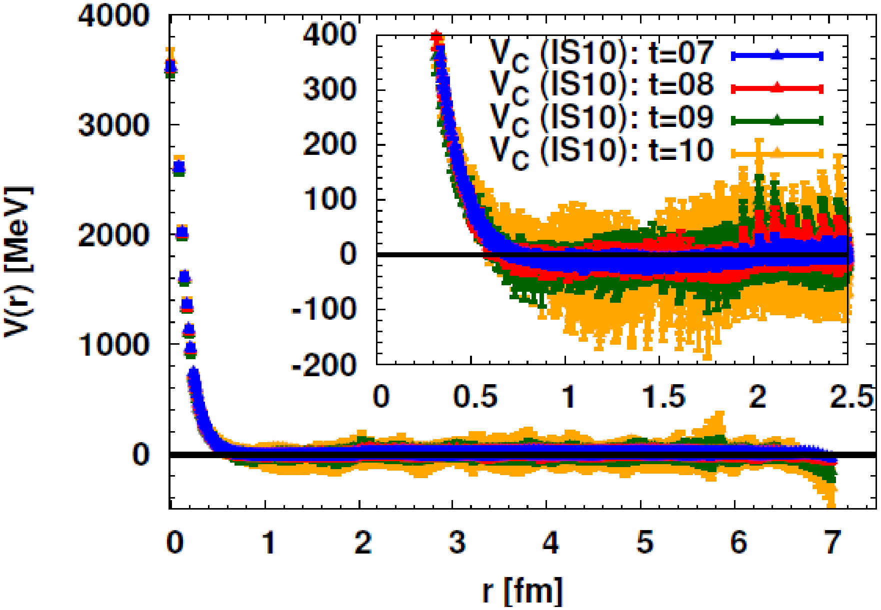
Is interaction net attractive ? Stay tuned !

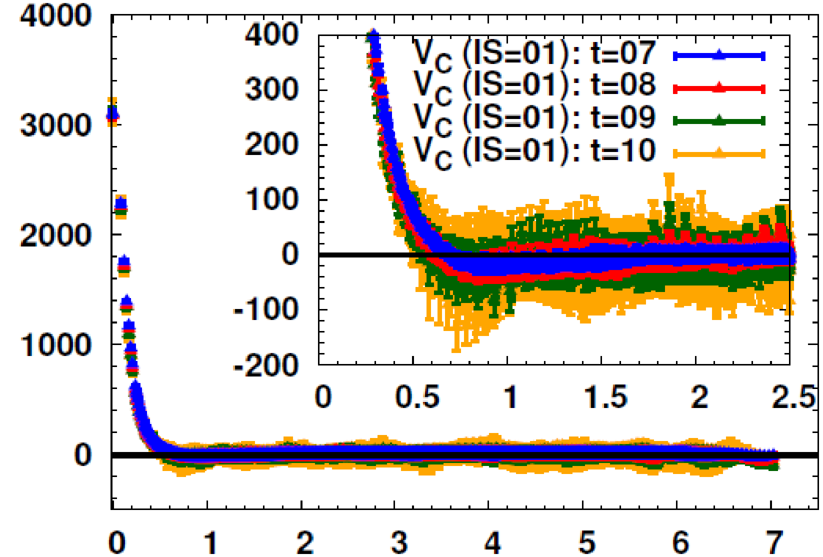
(net attractive @ m(pi)=0.66-88GeV)

NN-Potentials

$^1S_0$

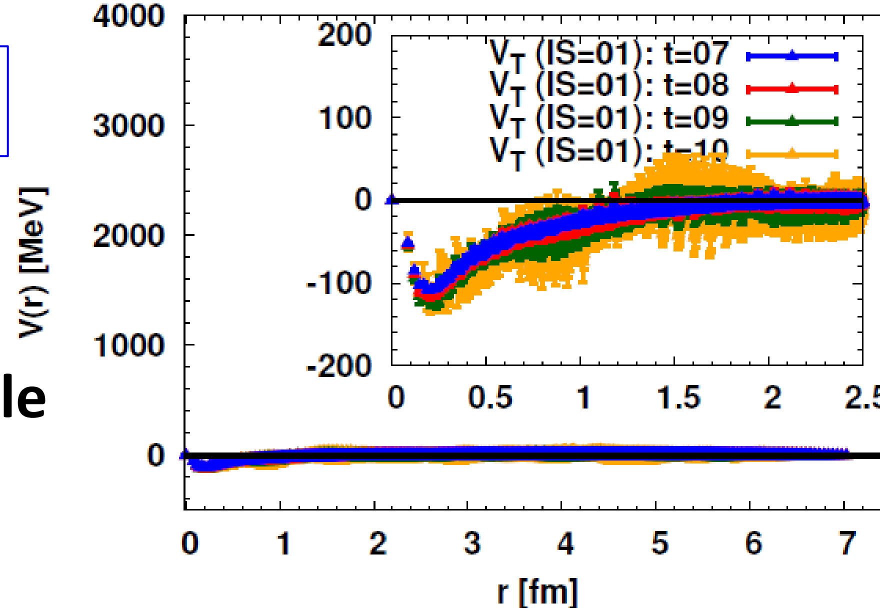
$^3S_1$-$^3D_1$





Central

Preliminary

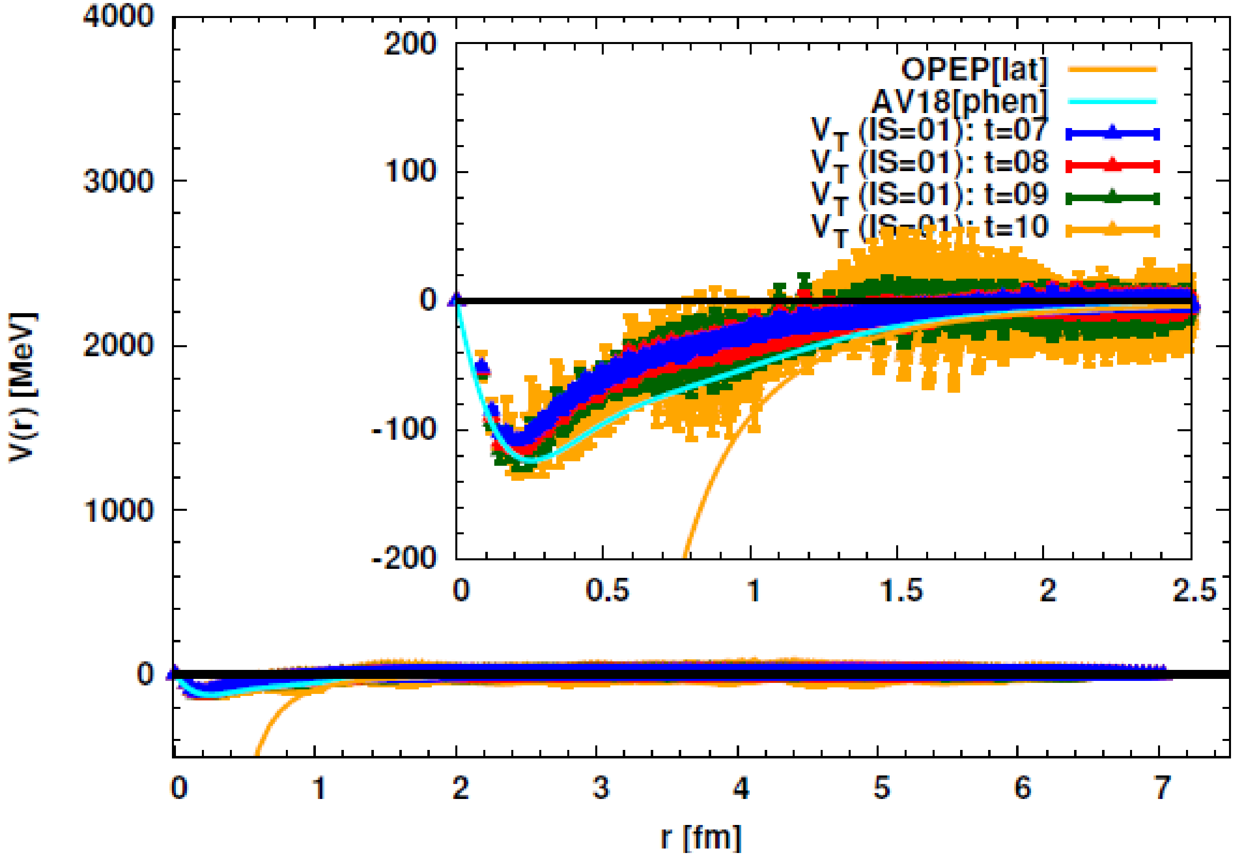


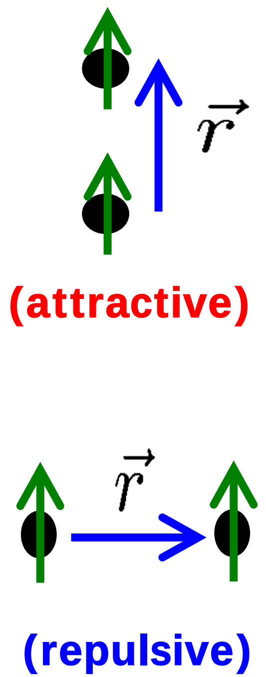
Tensor

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

(200conf x 4rot x 44src)

NN-Potentials (tensor)



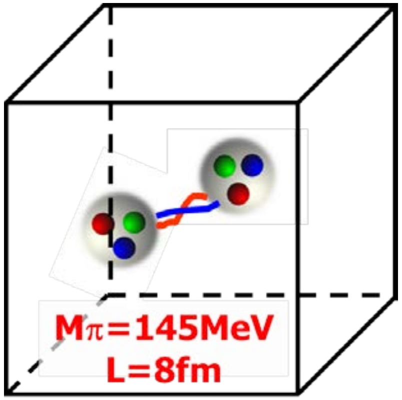


- **Similar structure to phenomenological potential**
- **Larger t w/ larger #stat is desirable**

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
  - **Various exciting results** from precise prediction to semi-quantitative arguments

- **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
  - (Difficulty in Lushcer's method shown explicitly)



- **Prospects**
  - Measurement in progress ➔ #stat will be ~x2-4 in FY2015
  - LS-forces, P=(-) channel, 3-baryon forces ➔ towards post K
  - Resonances / Exotics (talk by Y. Ikeda, on Tue.) & more