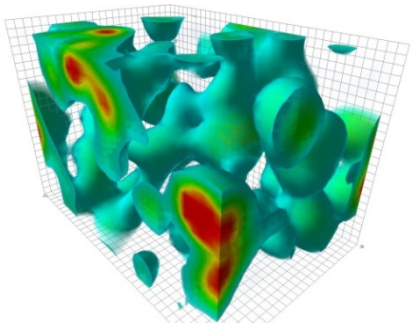
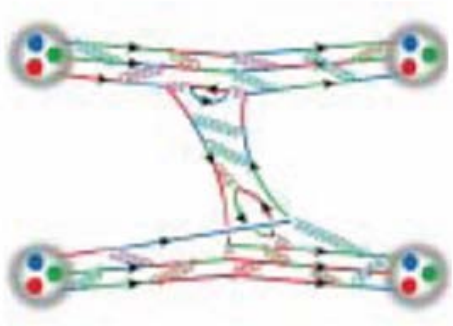
# 格子量子色力学を用いたバリオン間力の決定

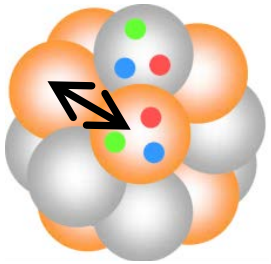

**土井琢身**

（理研仁科センター）

for HAL QCD Collaboration

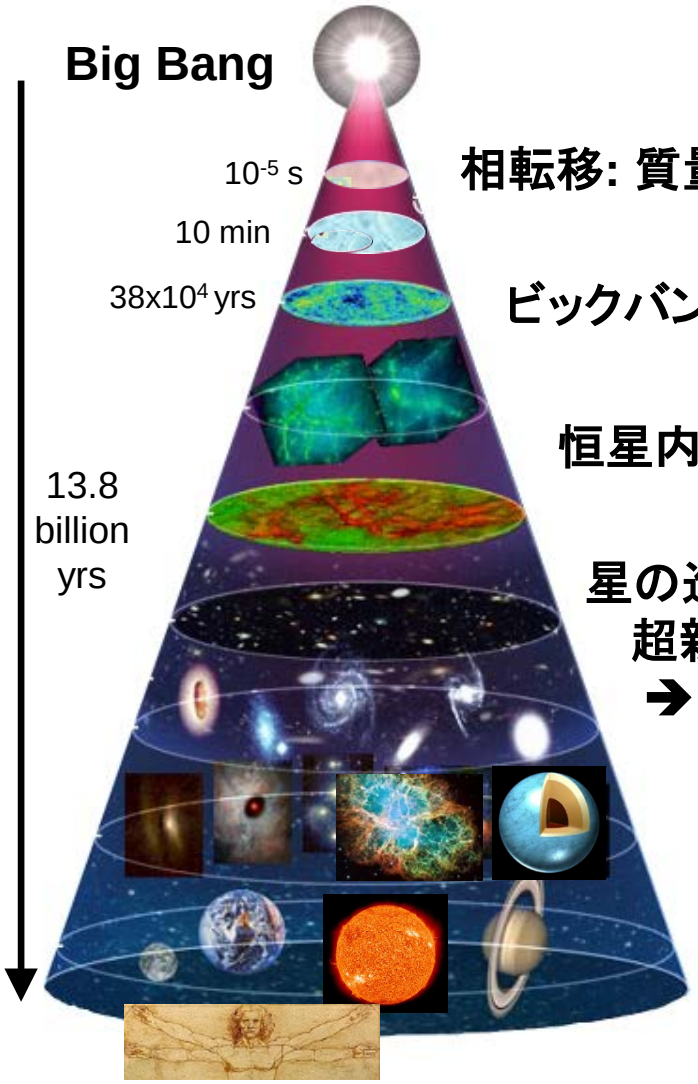







# 我々はどこから来てどこへ行くのか？

**宇宙における物質の創世史** ⟷ **物質のミクロな性質**



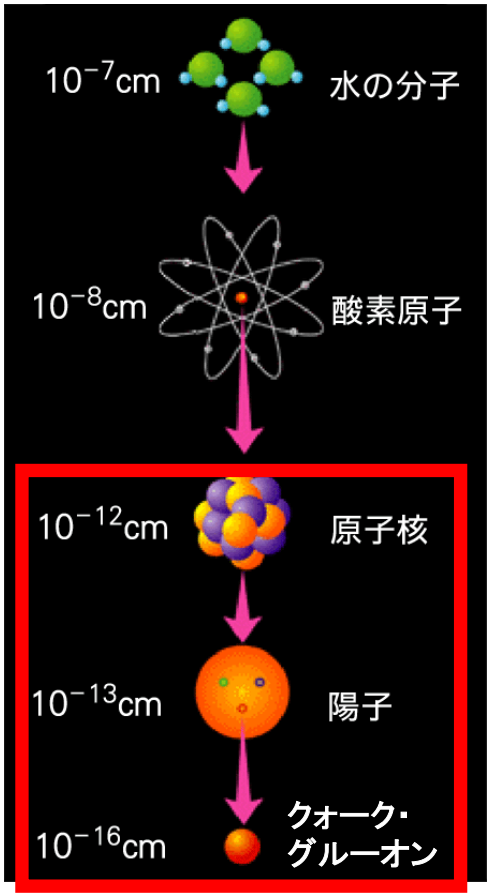

相転移: 質量の獲得

ビックバン元素合成

恒星内元素合成

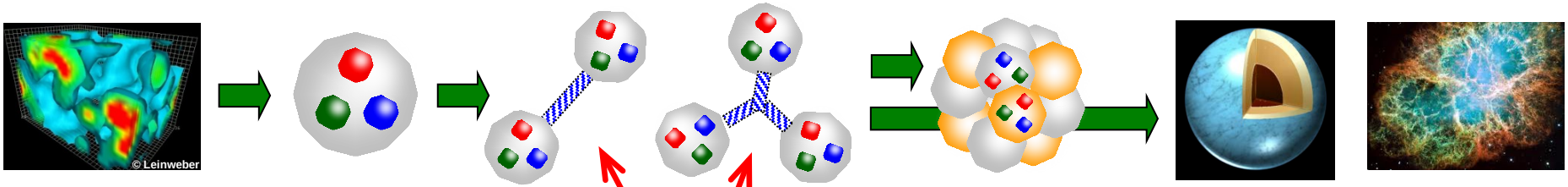
星の進化の終着点:
超新星爆発
➔ 中性子星 or ブラックホール

r過程元素合成




「強い力」 量子色力学(QCD)

# The Odyssey from Quarks to Universe




QCD vacuum  Baryons  Nuclei  Neutron Stars / Supernovae
Nucleosynthesis

**QCD** → **Baryon Forces** → ab-initio nuclear calc.

**1st-principles calc**

## Nuclear Forces

Yukawa model ➔ QCD
(u, d-quark only)

## Hyperon Forces

Interactions w/ hyperon
(u, d & s-quark)

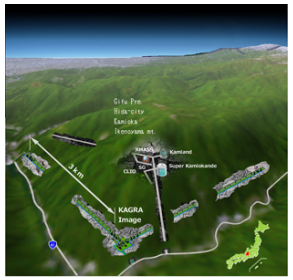
➔ **EoS of dense matter**

⇔

**Experiments & Observations**

**RIBF**


**J-PARC**




**aLIGO/KAGRA**

# How to solve QCD ?

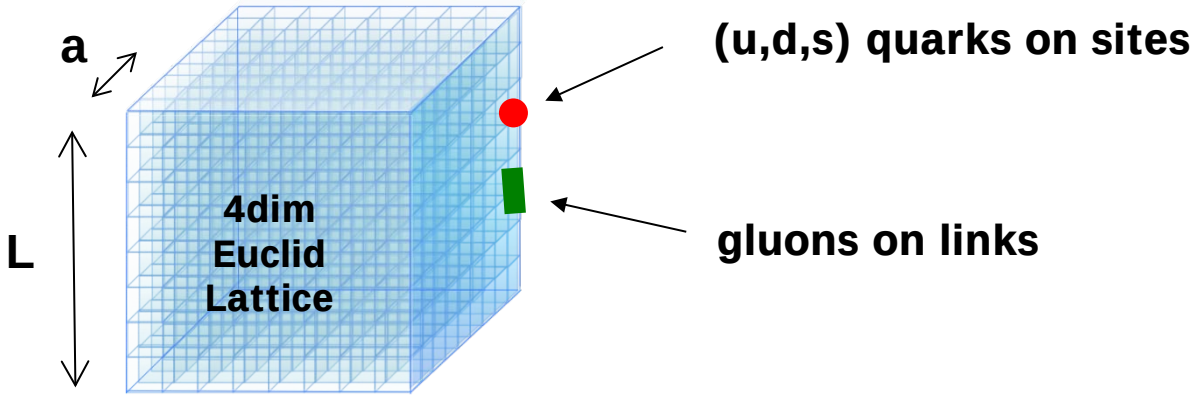
QCD $$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + \bar{q}\left[\gamma^\mu (i\partial_\mu - g A_\mu) - m\right] q$$

$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f_{abc} A^b_\mu A^c_\nu$$

**Simple & beautiful** but
**difficult to solve !**

**[only 4 parameters]**
quark masses ($m_u$, $m_d$, $m_s$)
coupling constant $\alpha_s = g^2/4\pi$

## Lattice QCD

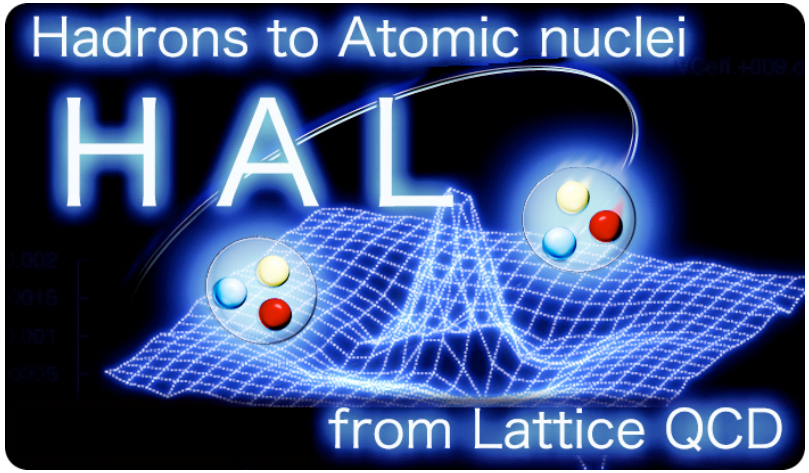



- Nonperturbative definition of QCD
- DoF ~ $10^9$ ➔ Monte-Carlo w/ Euclid time

$$Z = \int dU\, dq d\bar{q}\; e^{-S_E}$$

**LQCD :** single hadron spectrum reproduced
➔ Next Challenge: Prediction for multi-hadron systems

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




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

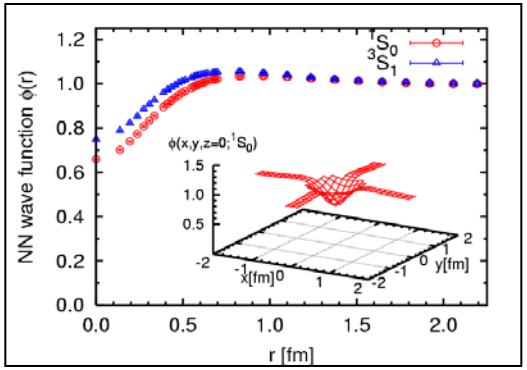
「20XX年宇宙の旅」

***from Quarks to Universe***

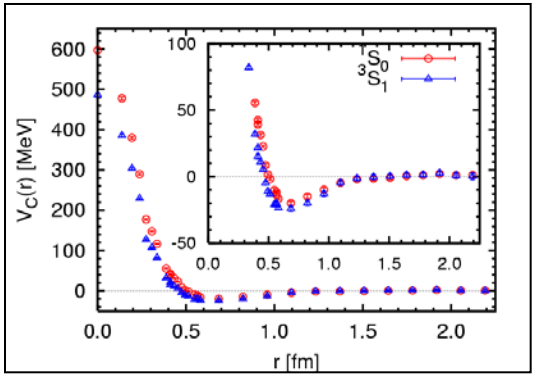

# How to define/calc Baryon Forces ?
# HAL QCD method

Lattice QCD

**NBS wave func.**




**Lat Baryon Force**




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

(at asymptotic region)

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

***Potential***

NBS wave function
Faithful to phase shifts

Potential
Faithful to phase shifts

Phase shifts: observable

Ishii-Aoki-Hatsuda PRL99(2007)022001

# *The impact of new supercomputers as FX100*

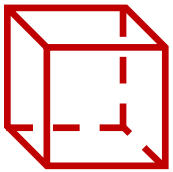
~2012

➔ lighter quark mass

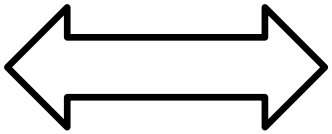
**We were here**

**Phys. point**

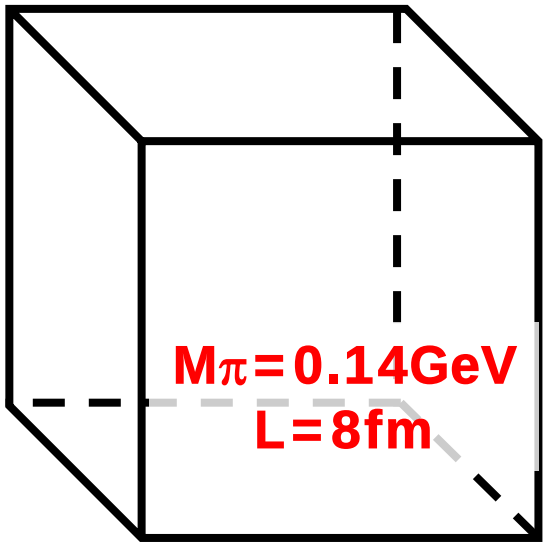
**Mπ=0.4 GeV**
**L=3fm**



**Simulation w/**
**Unrealistic QCD**



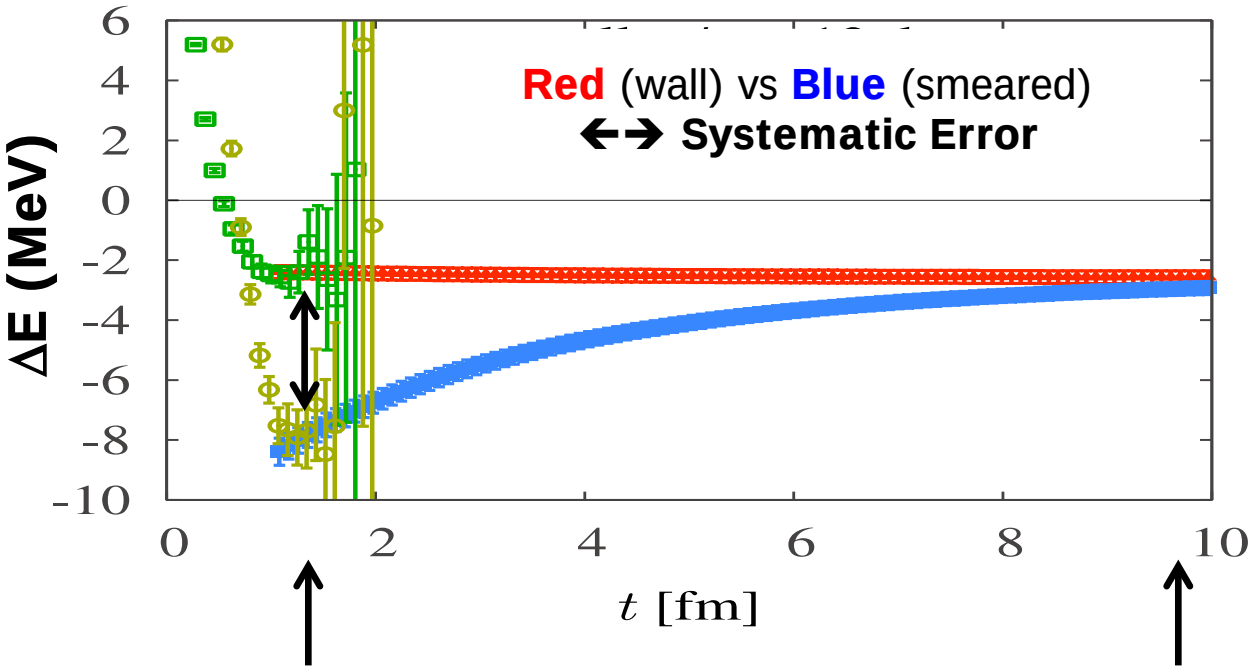
Tuning the quark mass w/ large comput. resources is NOT sufficient...




**Simulation w/**
**Realistic QCD**

# Towards physical quark masses, new theoretical development is also crucial

[Example]
naïve calc w/ traditional Luscher's method does NOT work




**[T. Iritani]**

(order estimate @ phys. point)

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

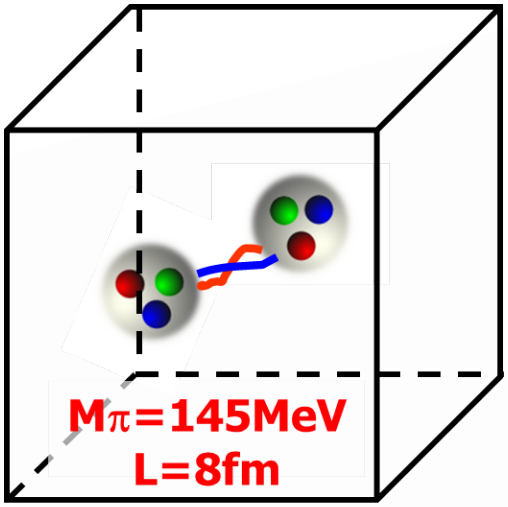
- **Coupled Channel systems** S. Aoki et al. (HAL Coll.) Proc.Jpn.Acad.B87(2011)509
  - **Coupled channel potentials** can be extracted above inelastic threshold

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

# 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: $96^4$ ~= $(8\ \mathrm{fm})^4$
  - 1/a ~= 2.3 GeV (a ~= 0.085 fm)
  - mπ ~= 145 MeV, $m_K$ ~= 525 MeV
  - #traj ~= 2000 generated

**HA-PACS (Tsukuba U.)**

**FX100 (RIKEN/Wako)**

**K-computer(RIKEN/AICS)**


## Baryon Forces

➔ **HAL QCD method**

# Strategy for phys point BB-forces calc

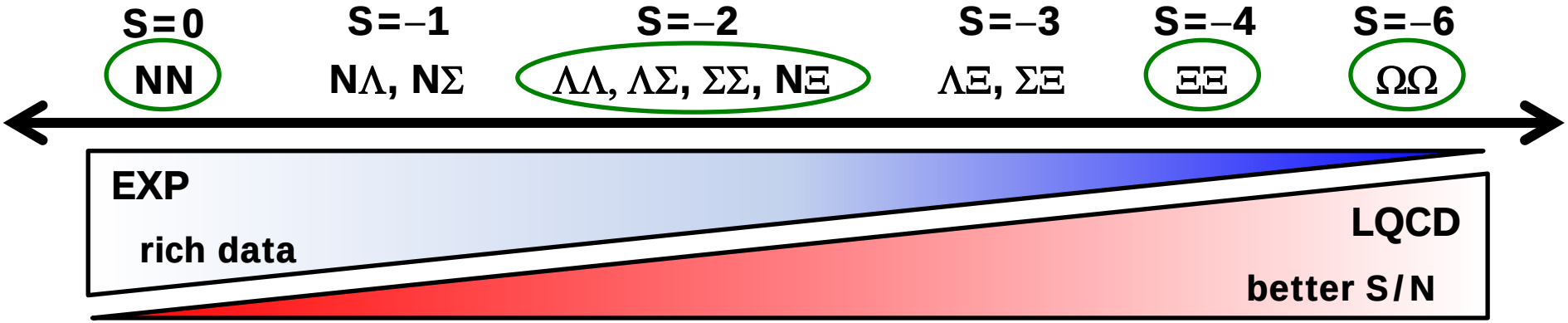
- Focus on the most important forces:
  - Central/tensor forces for all NN/YN/YY in P=(+) (S, D-waves)

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"**



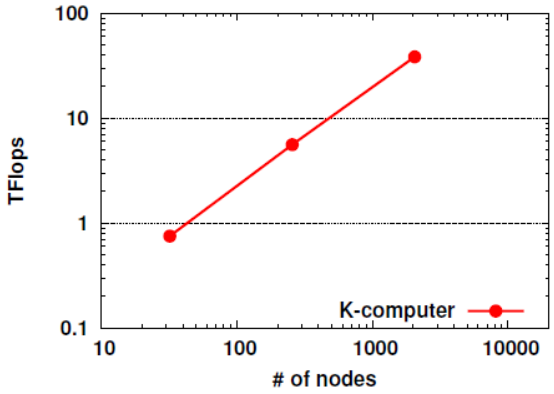

Hyperon in neutron star and EoS ? Exotic states ?

# Computational Code

- **NBS correlator calc**
  - Many channels (> 50) w/ $L^3$ dof in NBS
  - Unified Contraction Algorithm (UCA)
  - Contraction: B/F ~ 0.5 (snk) & 1.6-6.4 (src)
  - Convolution by FFT
- **Propagator calc**
  - Sparse linear solver w/ domain-decomposed BiCGstab
  - Non-block ➔ block solver for multi-RHS

    T. Boku et al., PoS LAT2012,188, Y. Nakamura et al., CPC183(2012)34
  - Stencil calc: B/F ~ 0.7
  - Sloppy solver (c.f. AMA)

**Weak scaling @ K**
(NBS calc part, w/o solver, w/o IO)




**Total Performance**
~25% efficiency (~65 Tflops sustained)
@ K-2048 node (x 8core/node)

- **FX100**
  - Solver tuning & Memory usage reduction, etc.
  - FX100-256 node (x 32core/node) : compared w/ K (based on elapsed time)
    - FX100 is ~ 40% faster for the same # of core
    - FX100 is ~ 40% slower for the same peak perf (double prec) ←➔ ~18% efficiency
    - FX100 is much better in I/O
  - **Tips (?)**
    - -KHPC_ACE option (instead of -KHPC_ACE2) is sometimes faster (as much as x2)

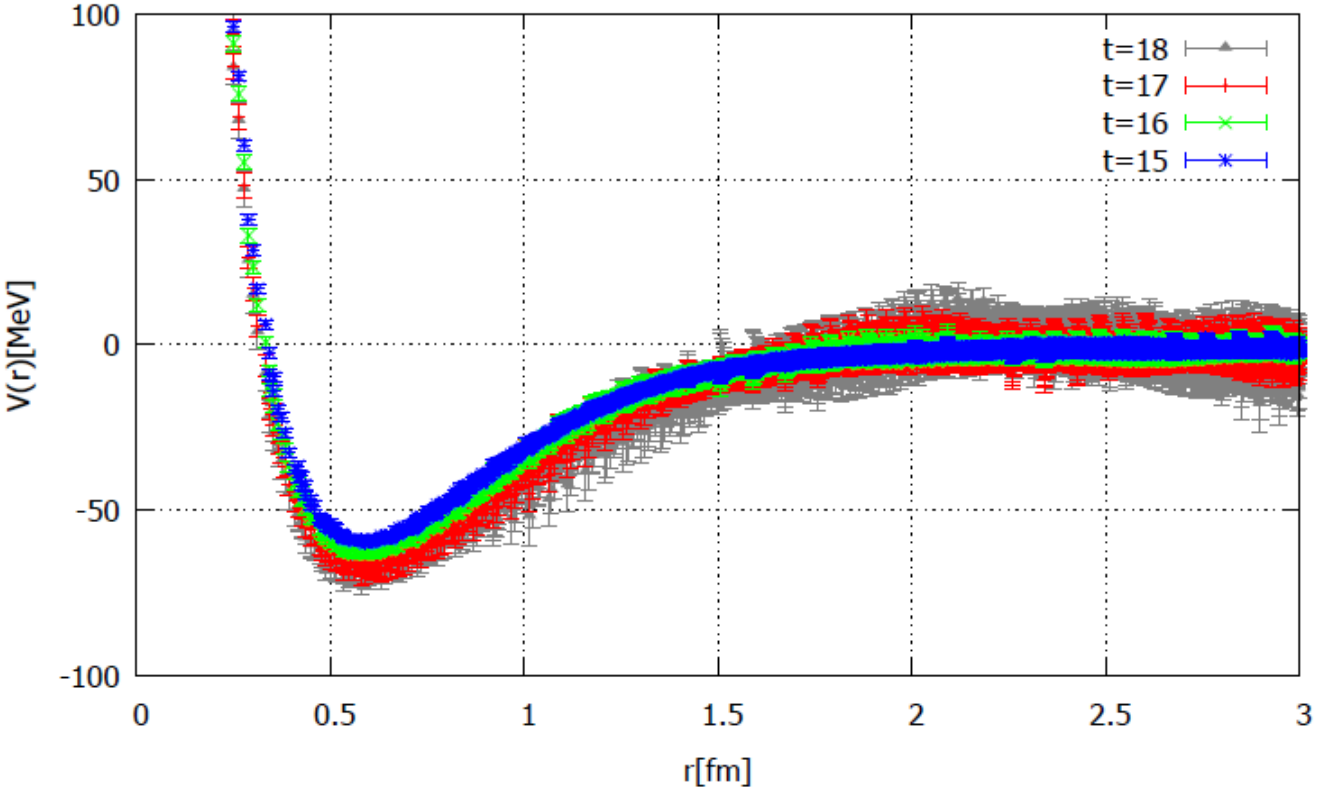
[S=–6]

# ΩΩ system ($^1S_0$)

spin=0
L=0 (S-wave)
J=0

## Potential

r




(200conf x 4rot x 72src)

**Preliminary**

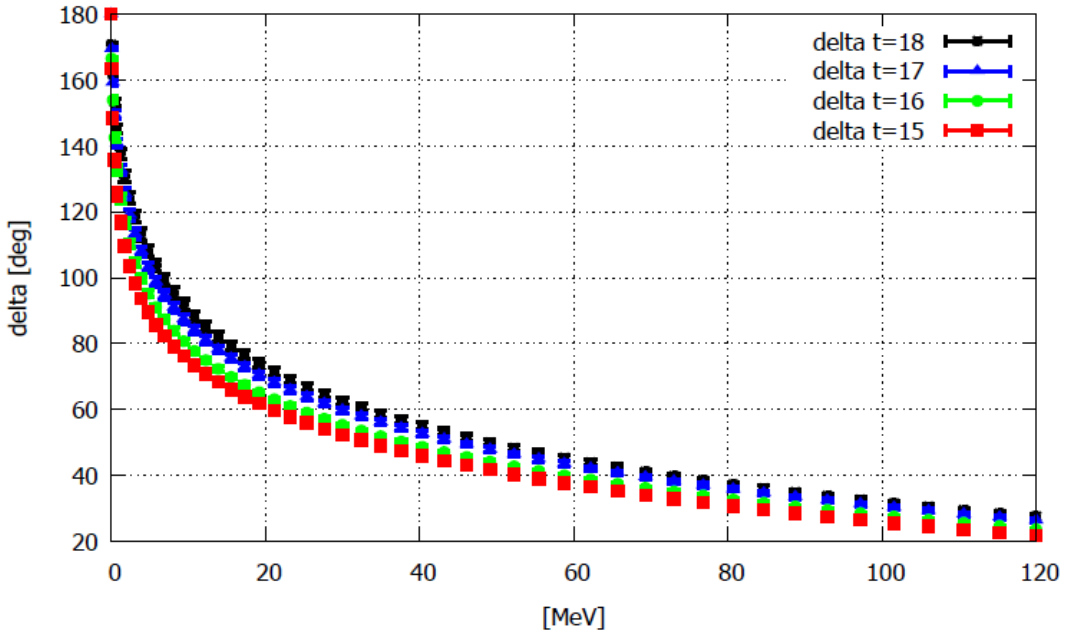
**[S. Gongyo / K. Sasaki]**

[S=–6]

# ΩΩ system ($^1S_0$)

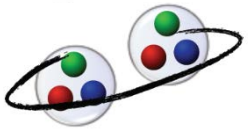
spin=0
L=0 (S-wave)
J=0

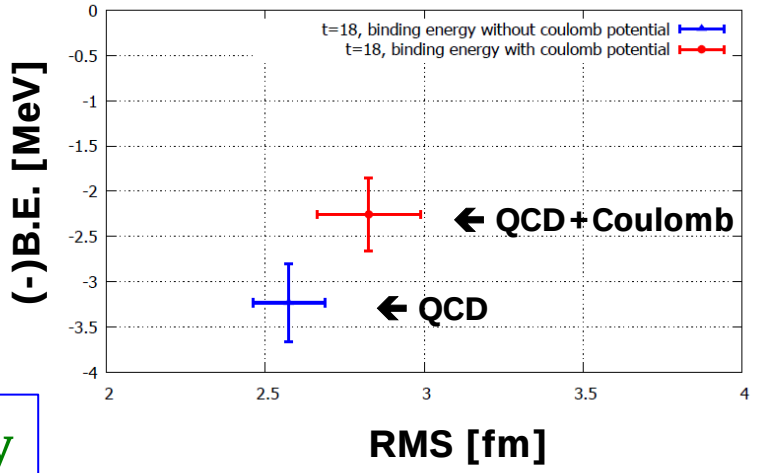
## Phase Shifts




**B.E. (QCD) ~= 3 MeV**

**B.E. (QCD+Coulomb) ~= 2MeV**






## The Most Strange Dibaryon

➔ HIC experiments ?

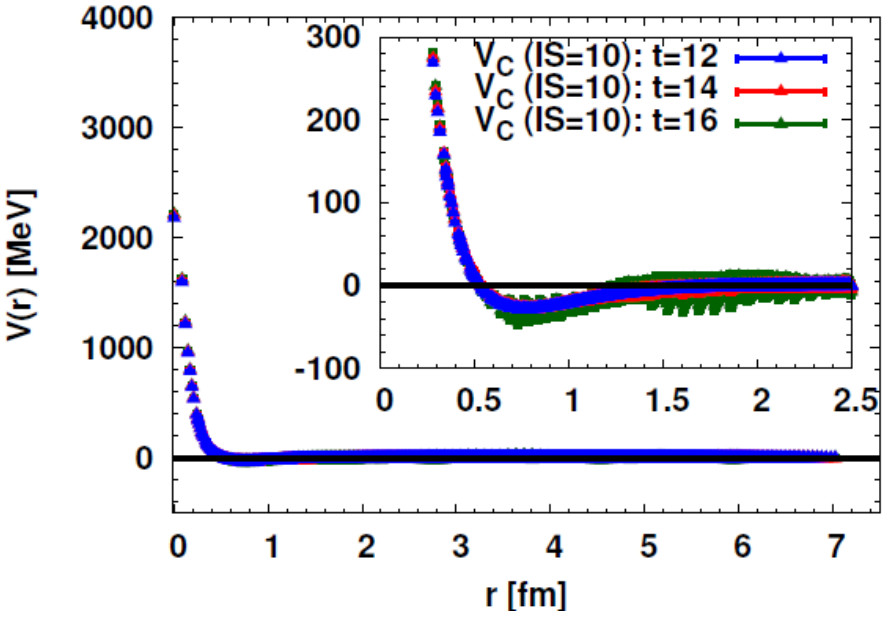
[S. Gongyo / K. Sasaki]

Preliminary

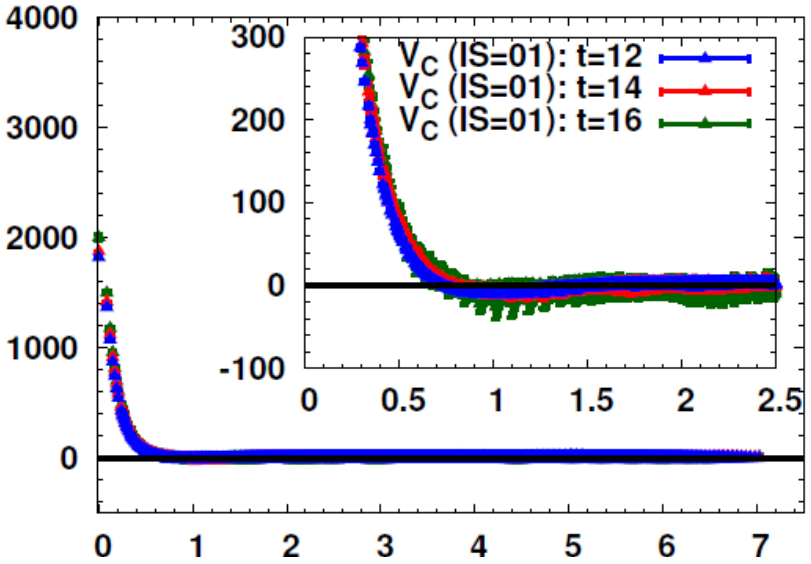
[S=–4]

# ΞΞ-Potentials

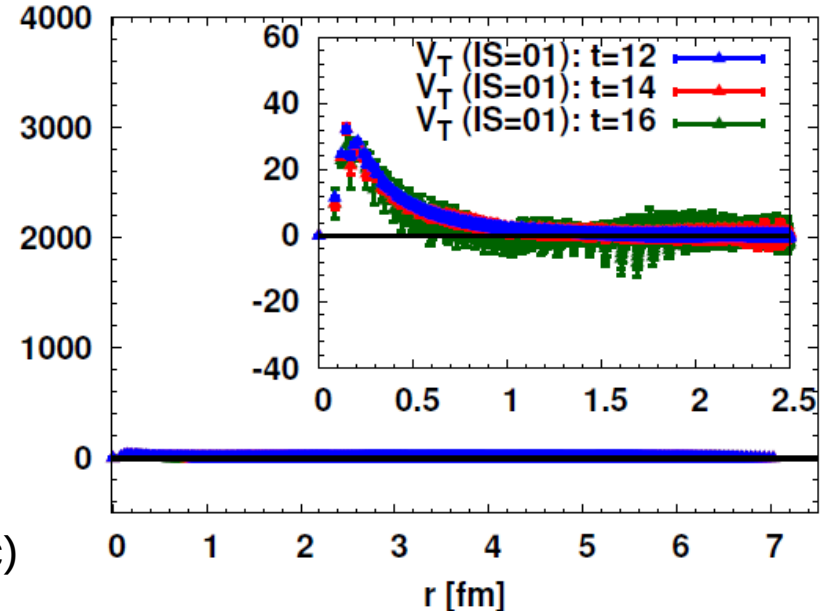
## $^1S_0$




## $^3S_1$-$^3D_1$




Central




Tensor

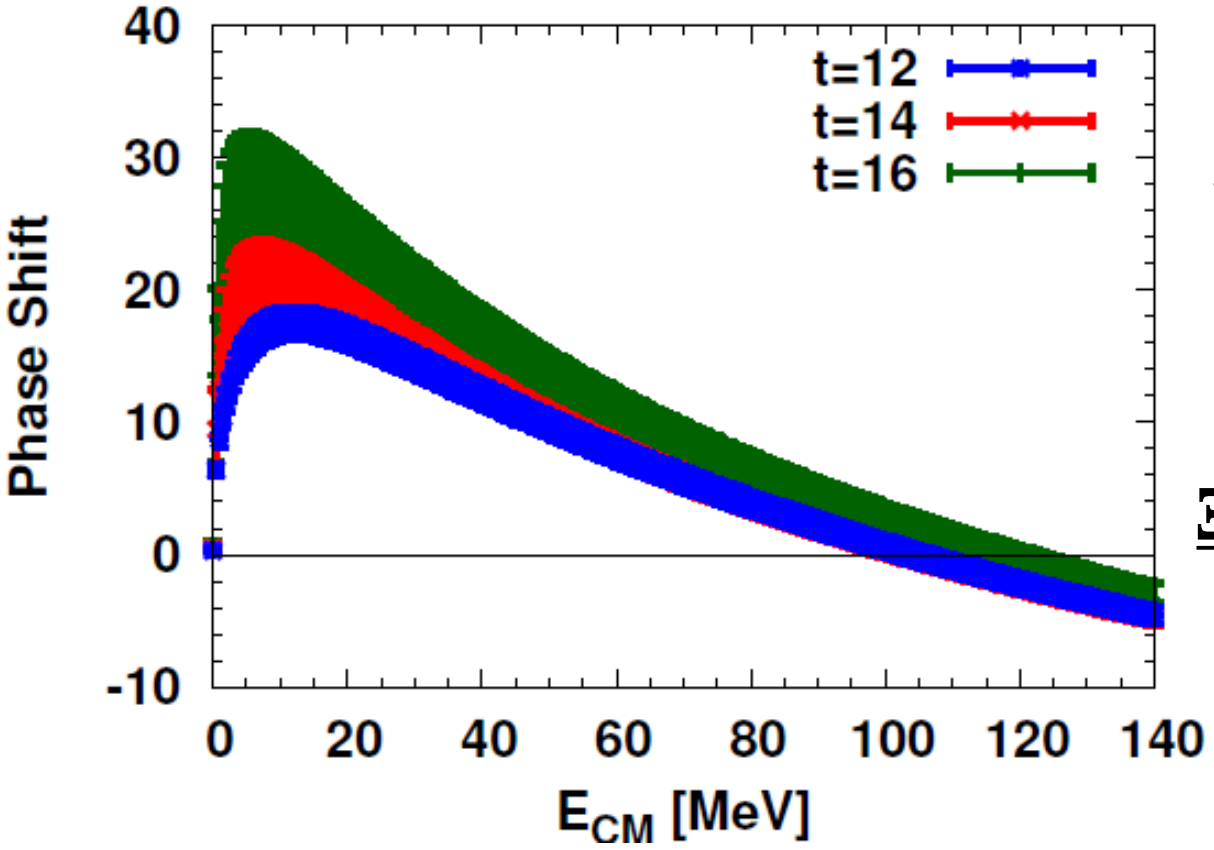
- $^1S_0$ ～ 27-plet
  ⇔ NN($^1S_0$) + SU(3) breaking
- $^3S_1$-$^3D_1$ ～ 10-plet
  ⇔ unique w/ hyperon DoF
  ⇔ $\Sigma^-$ in neutron star

**Preliminary**

(200conf x 4rot x 44src)

[S=–4]

# ΞΞ phase shifts ($^1S_0$)




**Scatt. Length**

a = 1.35(047) fm (t=14)

a = 1.97(113) fm (t=16)

**ΞΞ ($^1S_0$) is unbound**

➔ HIC experiments ?

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

(2-gauss + 2-OBEP fit)

(200conf x 4rot x 44src)

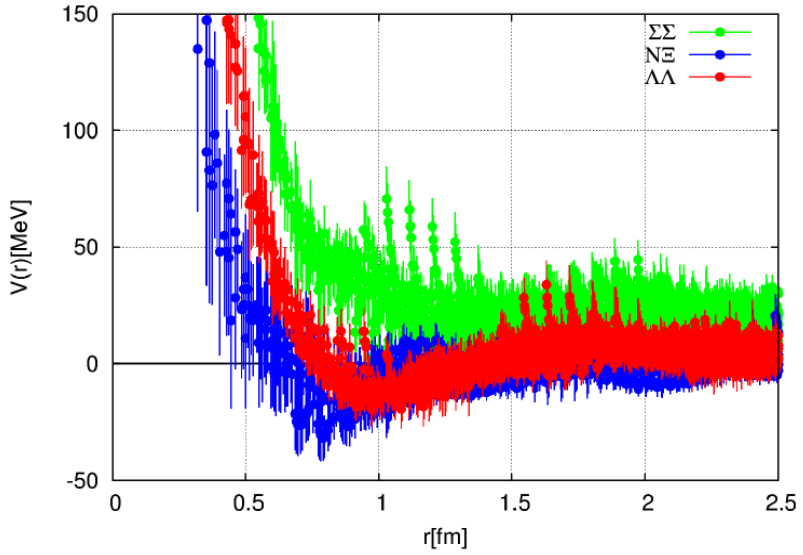
Preliminary

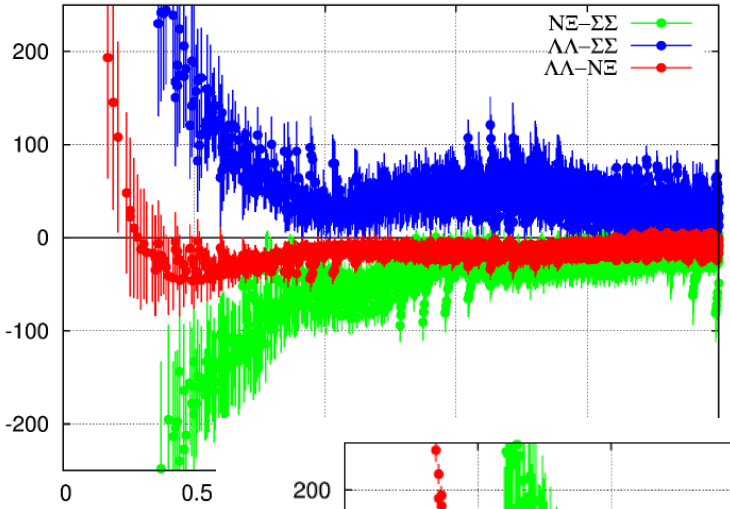
[S=−2] # ΛΛ–NΞ–ΣΣ coupled channel system ($^1S_0$)

**diagonal**

**off-diagonal**

[K. Sasaki]




$m_{\Sigma\Sigma} = 2380\text{MeV}$

**120MeV**

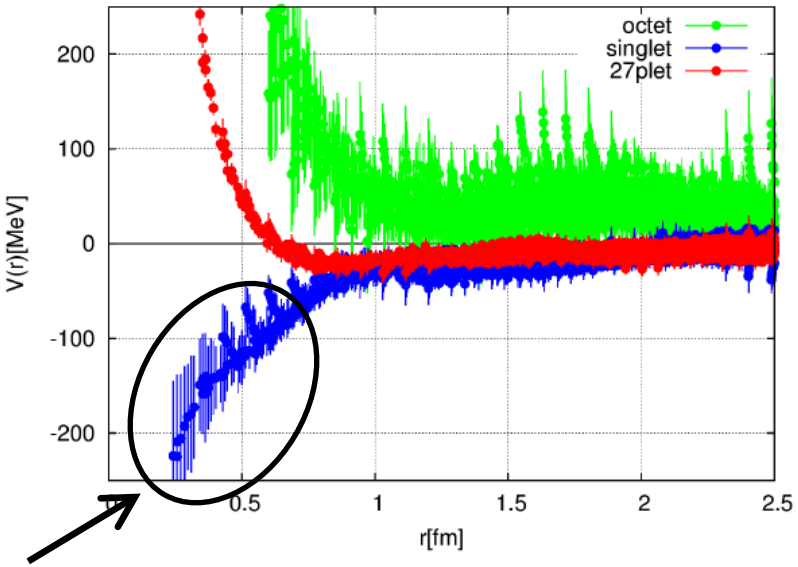
$m_{N\Xi} = 2260\text{MeV}$

**30MeV**

$m_{\Lambda\Lambda} = 2230\text{MeV}$

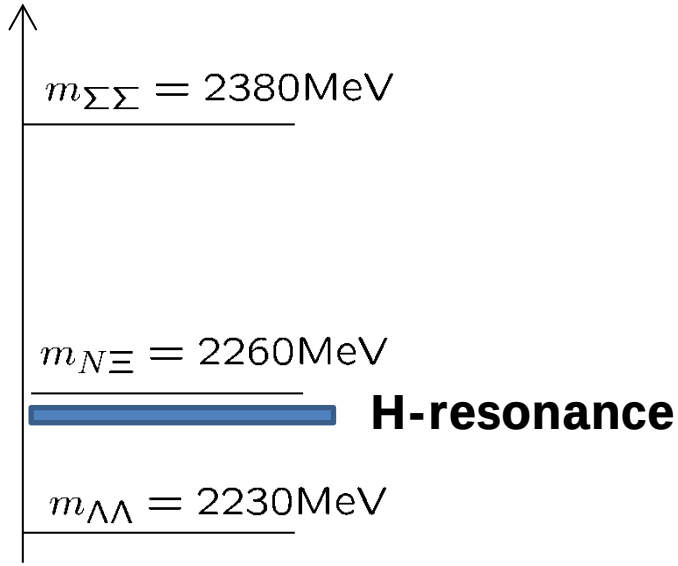
**diagonal in SU(3)-irrep base**

**Strong Attraction in flavor-singlet channel**

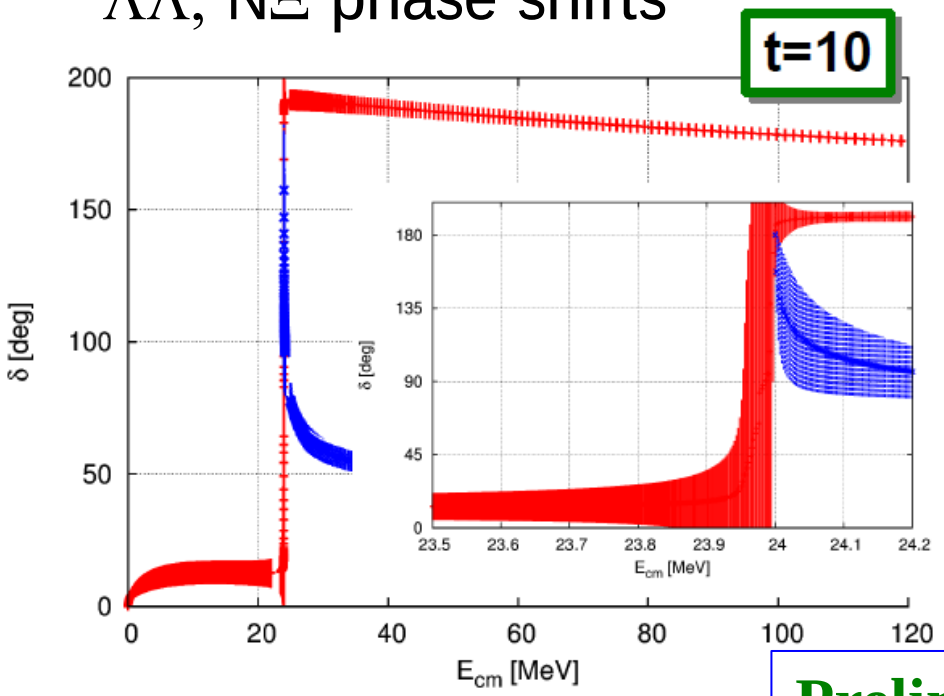



(200conf x 4rot x 20src, t=10)

**[S=–2]** # ΛΛ, NΞ 2x2 coupled channel analysis




ΛΛ, NΞ phase shifts




**Preliminary**

**“Perhaps a Resonant Dihyperon”**
(LQCD prediction)

**“Perhaps a Stable Dihyperon”**
(Jaffe(’77), quark model)

➔ **J-PARC experiment (E42)**

(N.B. t-dep should be checked)

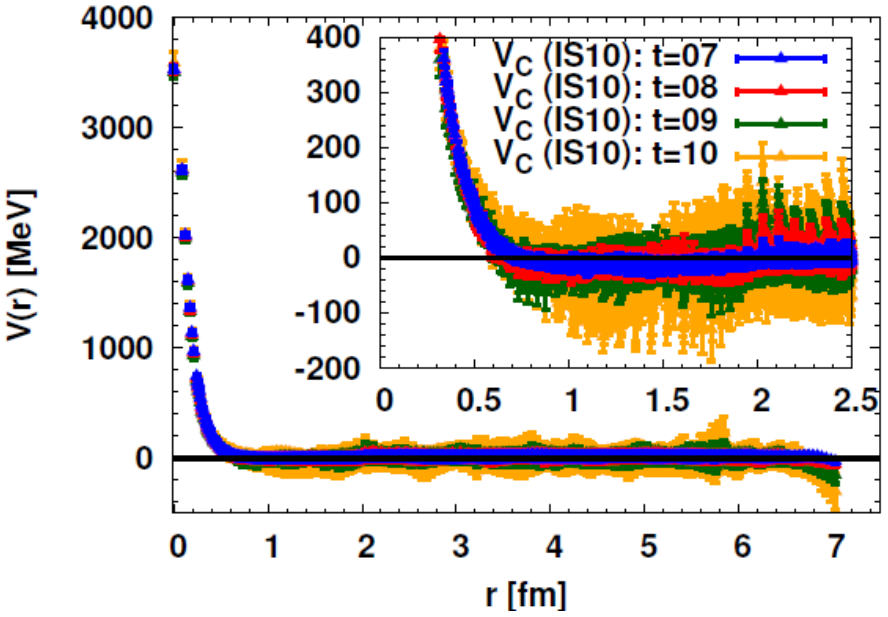
**[K. Sasaki]**

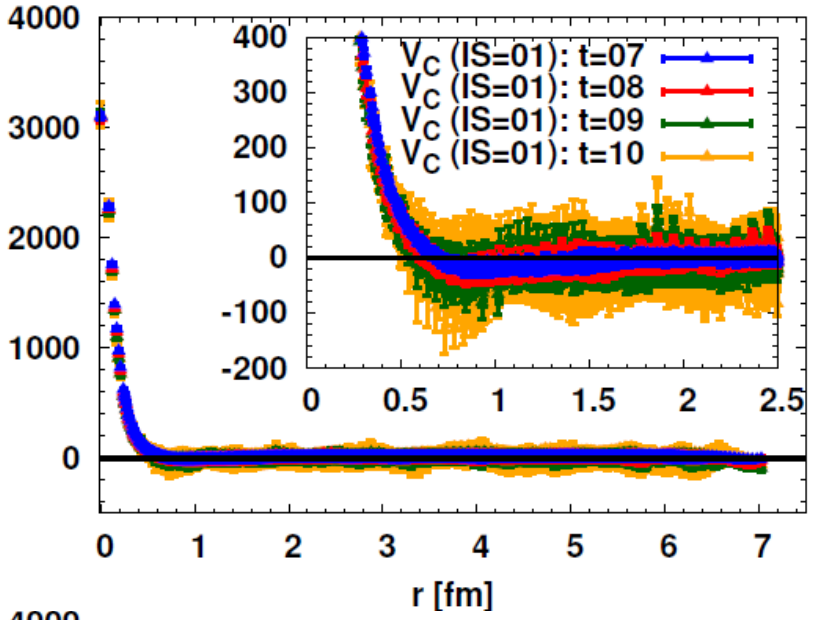
# NN-Potentials

[S=0]

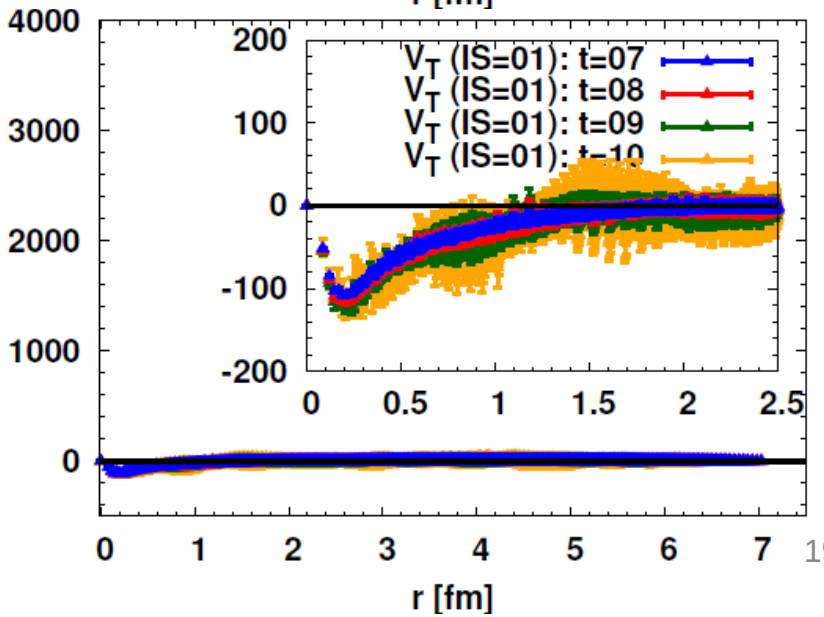
$^1S_0$

$^3S_1$-$^3D_1$




Central




Tensor

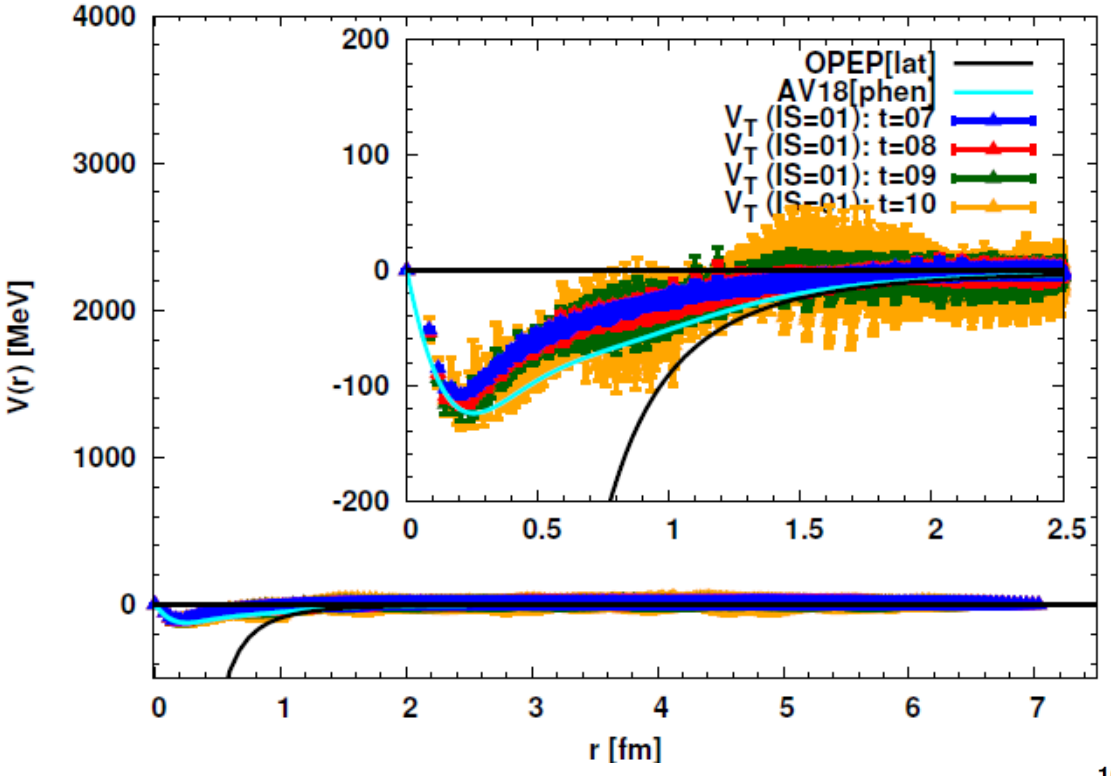
- **Vc: repulsive core**
  **+ long-range attraction**
- **Vt: tensor force clearly visible**

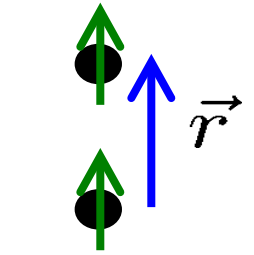
**Preliminary**

(200conf x 4rot x 44src)

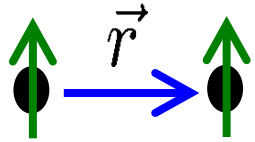
[S=0]

# NN-Potentials (tensor)



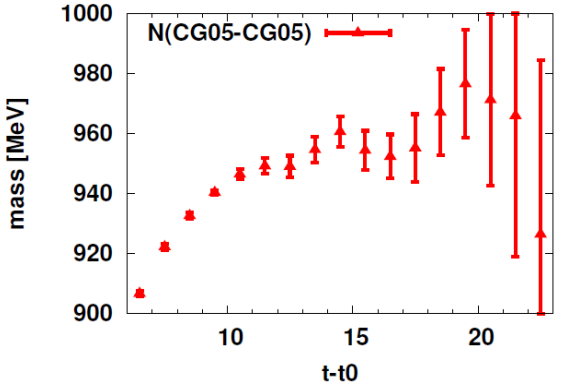

(attractive)




(repulsive)

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

m(eff) for single N




t = 8-10 : ~2-4% sys error

# Summary

- Nuclear Physics from LQCD: the new era is dawning
- The 1st LQCD for 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
- Prospects
  - FY2016: Increase #stat x2 (FX100 & K)
  - R&D of new methods in progress
  - Exascale computing Era ~ 2020
  - LS-forces, P=(-) channel, 3-baryon forces, etc., & EoS