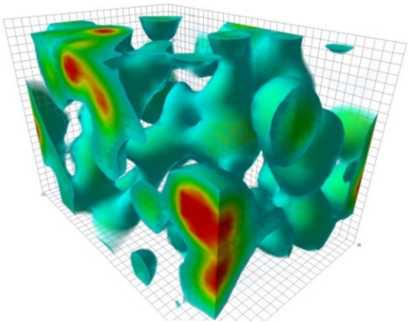
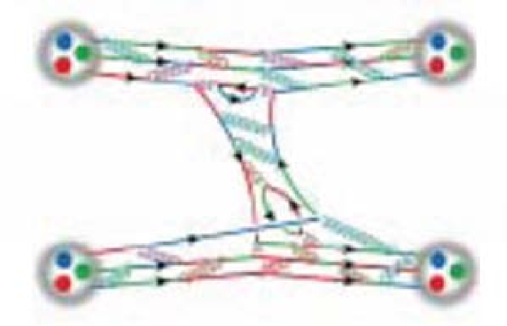
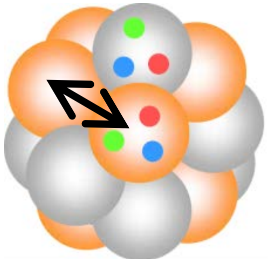
Nuclear Physics from Lattice QCD

Takumi Doi

(RIKEN Nishina Center / iTHEMS)

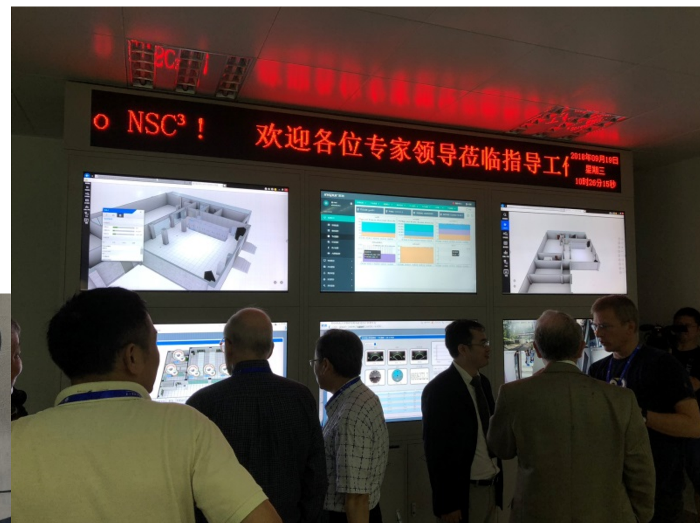




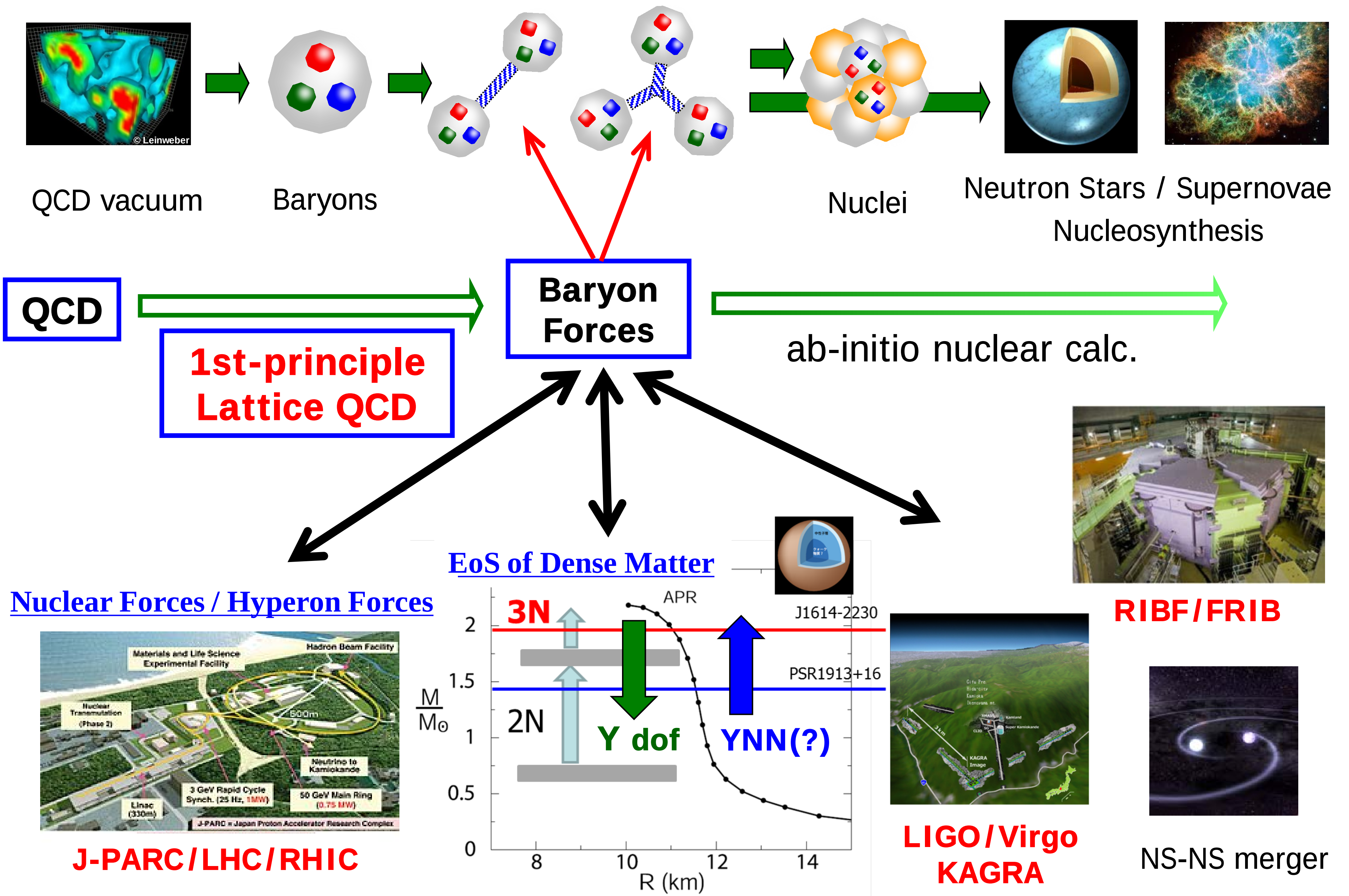


Congratulations for

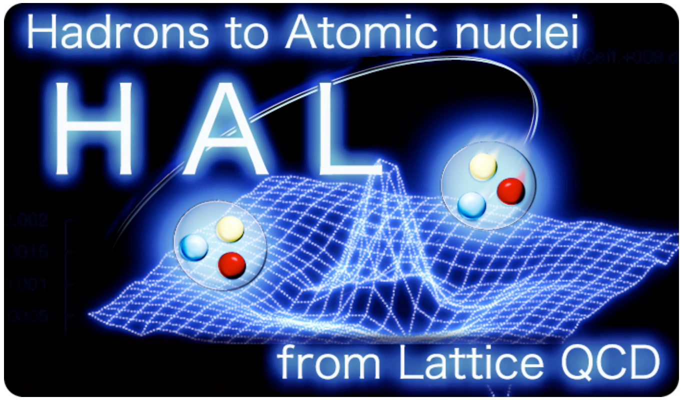
Nuclear Science Computing Center (NSC3) @ CCNU !



The Odyssey from Quarks to Universe



- **<u>Outline</u>**
  - ~~Introduction~~
  - Theoretical framework (HAL QCD method)
    - Reliability test for LQCD methods
  - Simulations at physical quark masses
    - HPC resources at Japan
    - Results for baryon forces & application to dense matter
  - Summary / Prospects

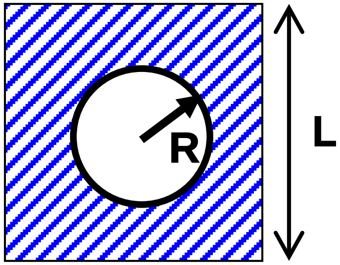


S. Aoki, T. Aoyama, T. Miyamato, K. Sasaki (YITP)
T. Doi, T. M. Doi, S. Gongyo, T. Hatsuda, T. Iritani (RIKEN)
F. Etminan (Univ. of Birjand)
Y. Ikeda, N. Ishii, K. Murano, H. Nemura (RCNP)
T. Inoue (Nihon Univ.)

[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

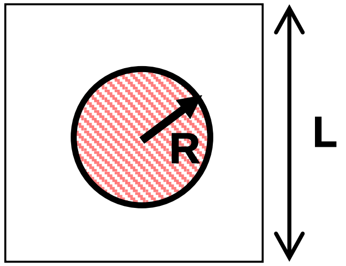
$$\psi(r) \simeq A\frac{\sin(kr - l\pi/2 + \delta(k))}{kr}$$

Extended to multi-particle systems

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

- Consider the wave function at "interacting region"

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



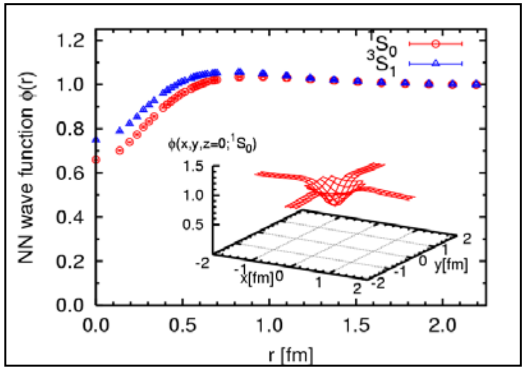
  – U(r,r'): faithful to the phase shift by construction
    - U(r,r'): E-independent, while non-local in general
      – Non-locality ➔ derivative expansion

Aoki-Hatsuda-Ishii PTP123(2010)89

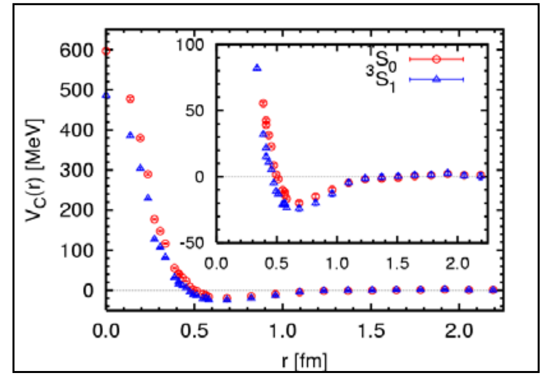
HAL QCD method

Lattice QCD

NBS wave func.



Lat Nuclear Force



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

(at asymptotic region)

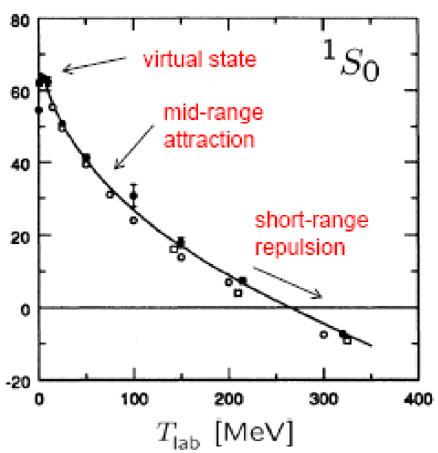
$$(k^2/m_N - H_0)\,\psi(\vec{r}) = \int d\vec{r}\,' U(\vec{r},\vec{r}\,')\psi(\vec{r}\,')$$

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

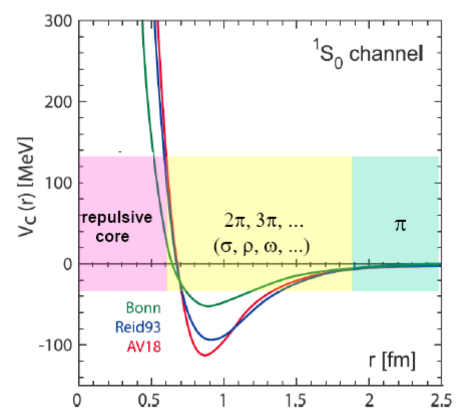
Analog to …

Scattering Exp.

Phase shifts



Phen. Potential

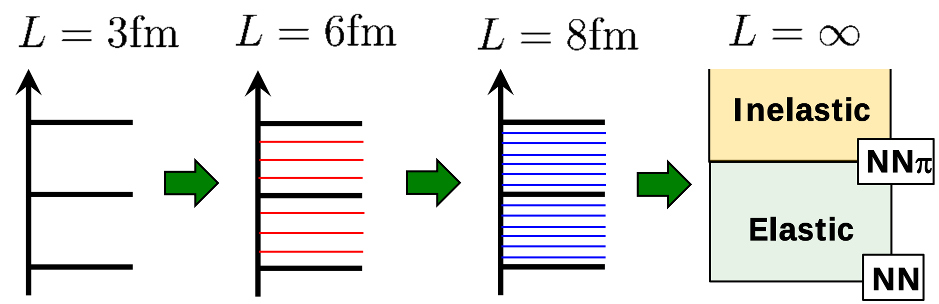


The Challenge in multi-baryons on the lattice

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 $(E_1 - E_0) \simeq 25\text{MeV} \Longrightarrow t > 10\text{fm}$

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

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

T. Iritani et al. (HAL) JHEP1610(2016)101
T. Iritani et al. (HAL) PRD96(2017)034521

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

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

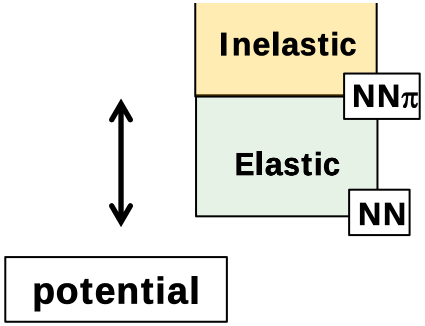
$$\int d\boldsymbol{r}' U(\boldsymbol{r},\boldsymbol{r}')\underline{\psi_{W_1}(\boldsymbol{r}')} = (\underline{E_{W_1}} - H_0)\underline{\psi_{W_1}(\boldsymbol{r})}$$

. . .

New t-dep HAL method

All equations can be combined as

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



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

[Exponential Improvement]

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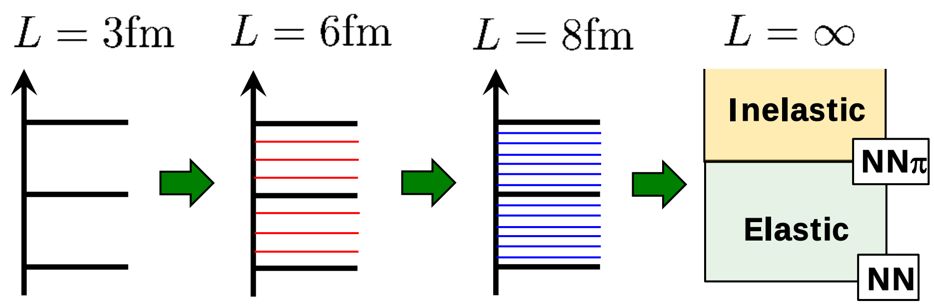


QCD

Baryon Forces

Experiments

HAL QCD method

"Time-dependent method" N.Ishii et al. PLB712(2012)437

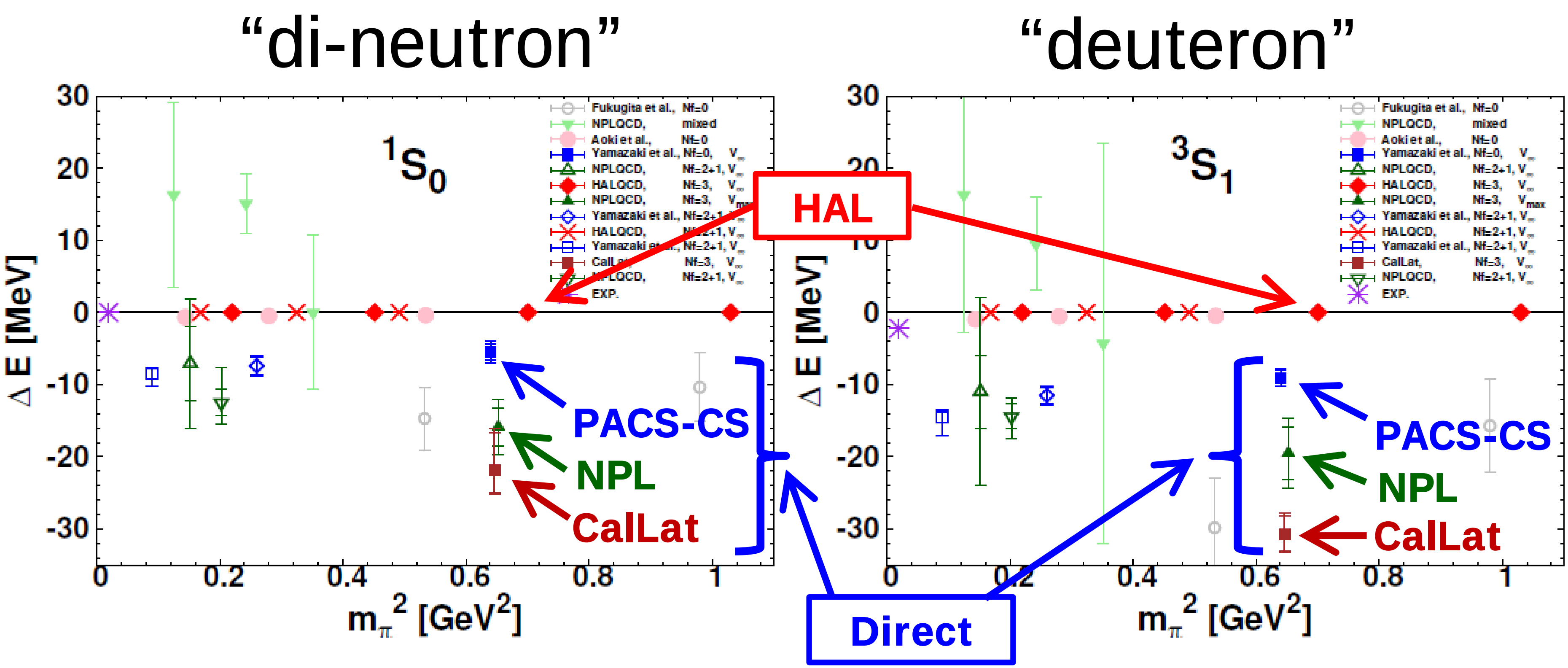
G.S. saturation NOT required w/ E-indep pot

Direct method

G.S. saturation required

Savage et al. (NPL Coll.)
Yamazaki et al.

Direct method vs HAL method



HAL method (HAL) : **unbound**

Direct method (PACS-CS (Yamazaki et al.) / NPL / CalLat): **bound**

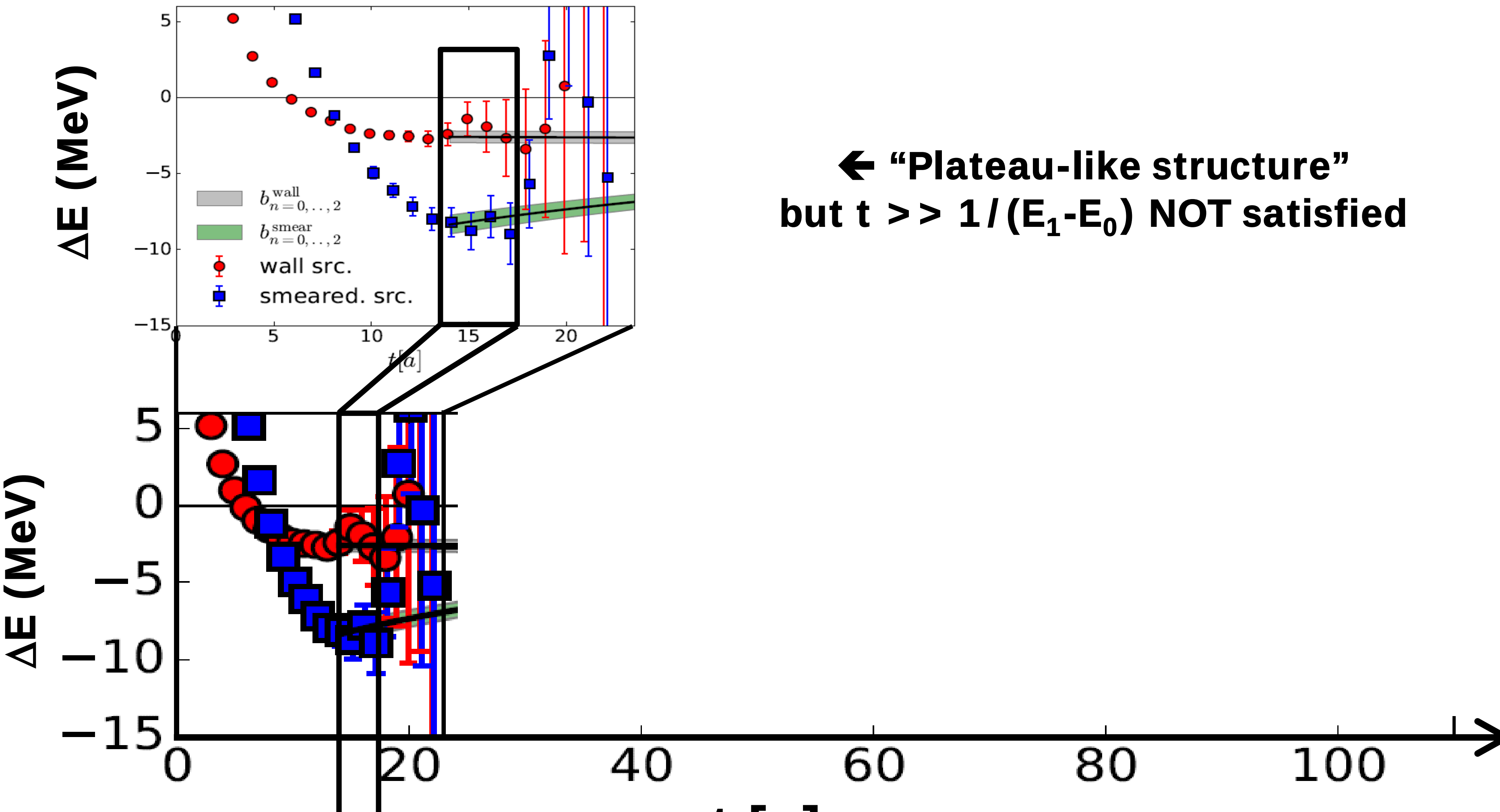
T. Iritani et al. (HAL Coll.) JHEP1610(2016)101

T. Iritani et al. (HAL Coll.) PRD96(2017)034521

T. Iritani (HAL Coll.), EPJ Web. Conf. 175(2018)05008

"Anatomy" of sympton in direct method

T. Iritani (HAL Coll.), arXiv:1710.06147



← "Plateau-like structure"
but t >> 1/(E$_1$-E$_0$) NOT satisfied

"fake plateaux"
at t ~ 1fm

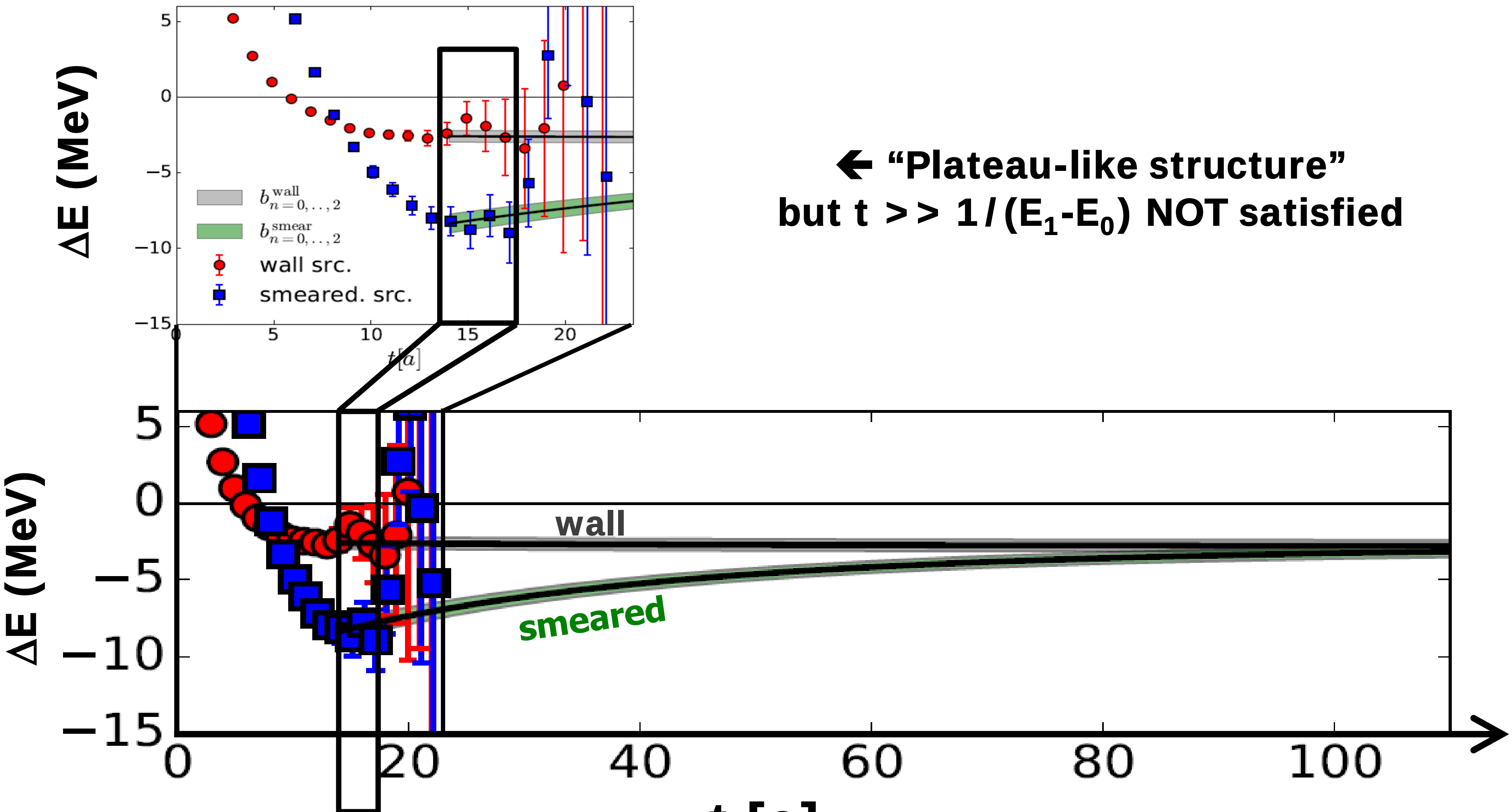
HAL method is crucial !

"real plateau"
at t ~ 10fm

(E$_1$-E$_0$=50MeV)

"Anatomy" of sympton in direct method

T. Iritani (HAL Coll.), arXiv:1710.06147



← "Plateau-like structure"
but t >> 1/(E_1-E_0) NOT satisfied

"fake plateaux"
at t ~ 1fm

HAL method is crucial !

"real plateau"
at t ~ 10fm

(E_1-E_0=50MeV)

The fate of the direct method (check on NN)

T. Iritani et al. (HAL Coll.) PRD96(2017)034521

	$NN(^1S_0)$				$NN(^3S_1)$			
Data	Source independence	Sanity check (i)	Sanity check (ii)	Sanity check (iii)	Source independence	Sanity check (i)	Sanity check (ii)	Sanity check (iii)
YKU2011 [24]	†	No	No	*	†	No	No	*
YIKU2012 [25]	No	†	No	*	No	†	No	*
YIKU2015 [26]	†	†	No	*	†	†	No	No
NPL2012 [27]	†	†	No	*	†	†	*	*
NPL2013 [28, 29]	No	*	*	No	No	[illegible]	[illegible]	[illegible]
NPL2015 [30]	†	No	*	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
CalLat2017 [31]	No	?	*	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Improved calc by Luscher's method

$NN(^1S_0)$ @ heavy mass is **unbound**

Mainz group, arXiv:1805.03966

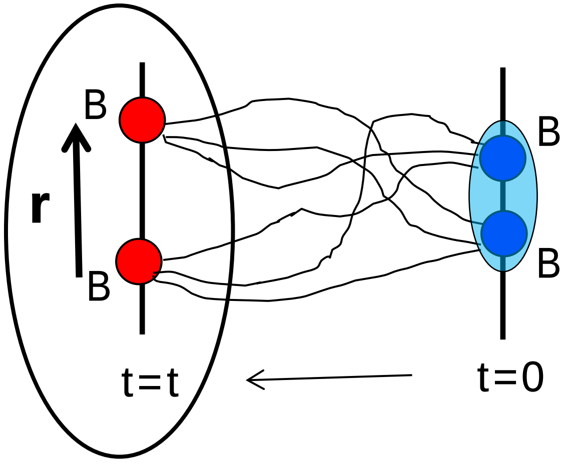
All NN data by the direct method fail these "minimum" tests so far

➔ Studies w/ the variational method are mandatory

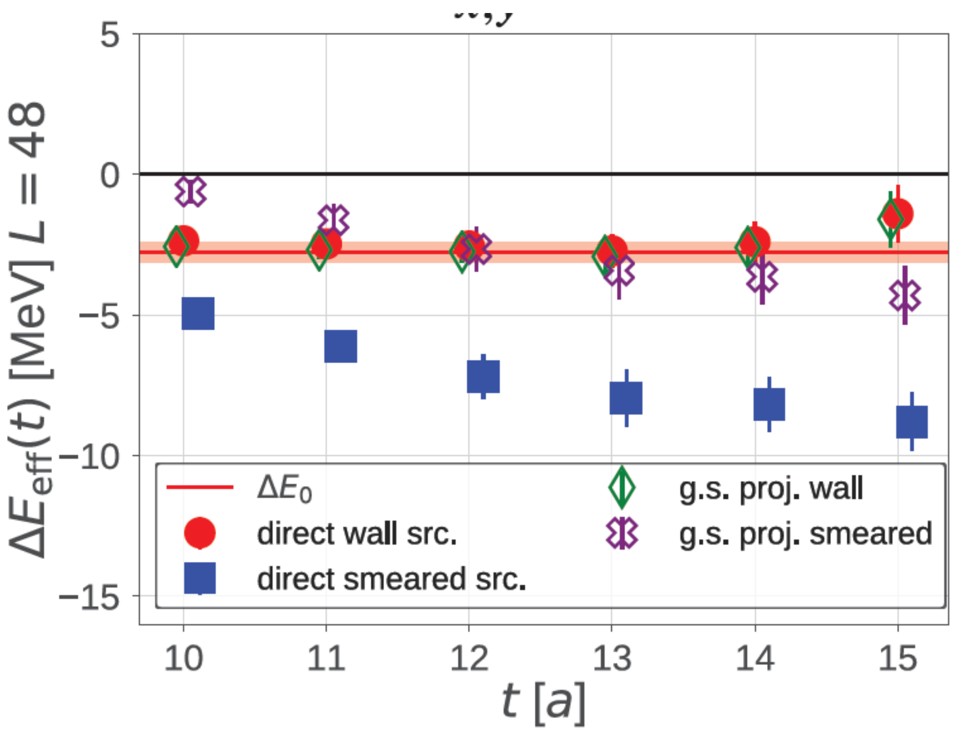
True plateau from the proper sink op projection

$$C_{2B}(t) = \langle 0|\mathrm{T}[\mathcal{J}^{2B}_{\mathrm{sink}}(t)\overline{\mathcal{J}}^{2B}_{\mathrm{src}}(0)]|0\rangle$$

$$\mathcal{J}^{2B}_{\mathrm{sink}} = \sum_{\vec{r}} g(r) \sum_{\vec{x}} B(\vec{r}+\vec{x})B(\vec{x})$$



Projection to the correct eignenmode
g(r) ➔ ψ(r) : wave func @ finite V



HAL QCD method

= Lushcer's method w/ proper projection

≠ Direct method w/ naïve plateau fitting

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    - HPC resources at Japan
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HPC resources at Japan

- **HPCI (High Performance Computing Infrastructure)**
  - K-computer + Supercomputers @ major universities/institutes
    - 45% of K-computer (11PFlops), 20% of Oakforest-PACS (25PFlops) etc.
  - Shared storage system (45PB in total)
  - Proposals (in all fields) are reviewed by the committee

    ➔ free charge for accepted proposals
  - for FY2018-A, ~10% of K-computer for HPCI (=2% of total) goes to LQCD

- **Each Univ/Inst. also control (some part of) their resources**
  - U. of Tsukuba: 1/3 of Oakforest-PACS
    - 30% (=10% of total) for accepted proposals for free, 30% for non-free
  - YITP, RCNP, (KEK)
    - free charge
  - Other in-house resources
    - RIKEN (Wako): 1.0+2.6 PFlops

      ➔ free charge (at this moment) for accepted proposals

K and post-K computer

- **K-computer (2012-2019(?)) : 11PFlops**
  - General Use (45%)
    - General Projects (25%) , Industrial Projects (15%), Junior Projects (5%)
  - 9 Priority Issues (+ 4 Exploratory Challenges) for Post-K (40%)
    - No.1, 2 : health & longevity, No.3, 4: earthquake/tsunami/climate
    - No.5, 6: energy problem, No.7, 8: industrial competitiveness
    - No.9 : basic science

      "Elucidation of the Fundamental Laws and Evolution of the Universe"

      (~1.5-2% for LQCD)
- **Post-K computer (2021/22-) : "Exascale"**
  - Co-design between hardware & applications (incl. LQCD)
  - Prioritized projects to be selected

- Baryon Forces from LQCD — Ishii-Aoki-Hatsuda (2007)
- Exponentially better S/N — Ishii et al. (2012)
- Coupled channel systems — Aoki et al. (2011,13)

[Theory] = HAL QCD method

Baryon Interactions at Physical Point

[Hardware]

= K-computer [10PFlops]

+ FX100 [1PFlops] @ RIKEN
+ HA-PACS [1PFlops] @ Tsukuba

- HPCI Field 5 “Origin of Matter and Universe”

[Software]

= Unified Contraction Algorithm

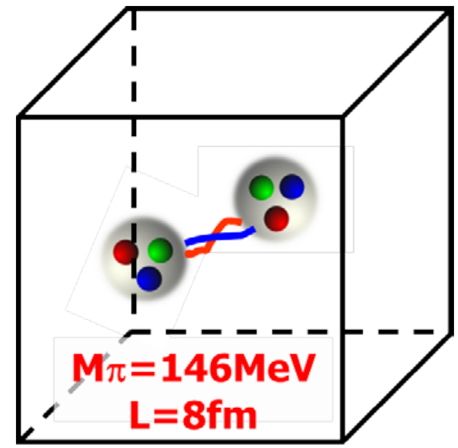
- Exponential speedup — Doi-Endres (2013)

$$^3\mathrm{H}/^3\mathrm{He} \quad : \quad \times 192$$
$$^4\mathrm{He} \quad : \quad \times 20736$$
$$^8\mathrm{Be} \quad : \quad \times 10^{11}$$

Lattice QCD Setup

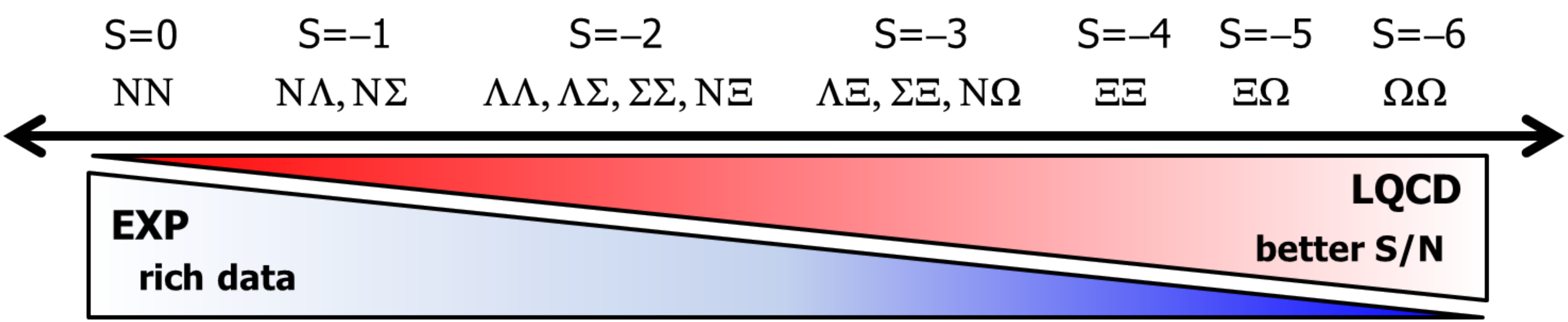
- **Nf = 2 + 1 gauge configs**
  - clover fermion + Iwasaki gauge w/ stout smearing
  - V=(8.1fm)^4, a=0.085fm (1/a = 2.3 GeV)
  - m(pi) ~= 146 MeV, m(K) ~= 525 MeV
  - #traj ~= 2000 generated

PACS Coll., PoS LAT2015, 075



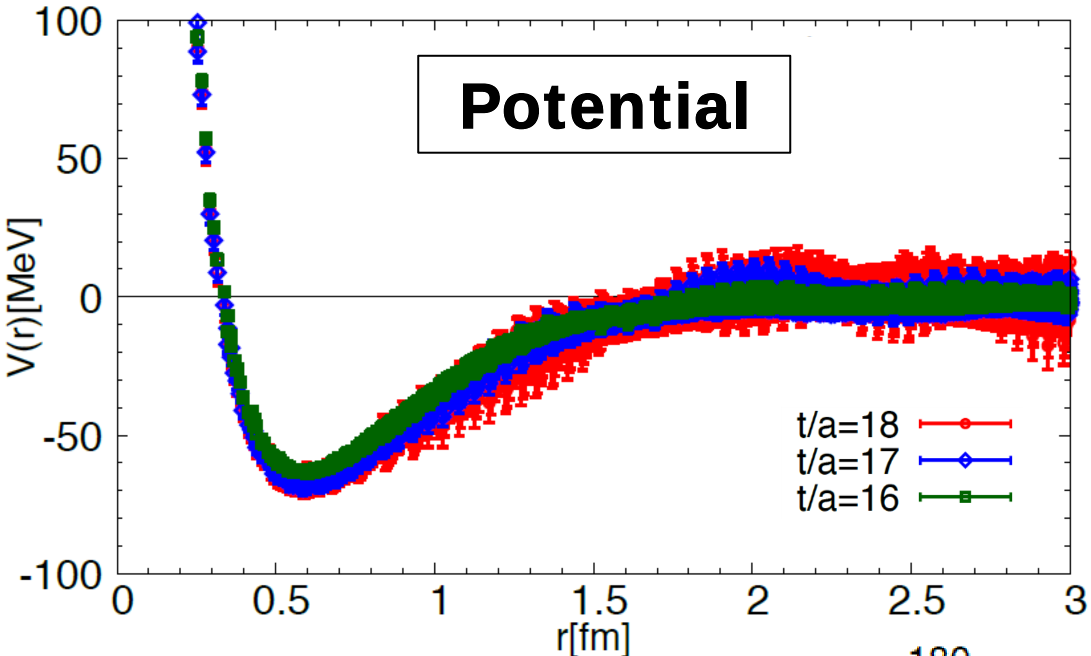
- **Measurement**
  - All of NN/YN/YY for central/tensor forces in P=(+) (S, D-waves)

Predictions for Hyperon forces

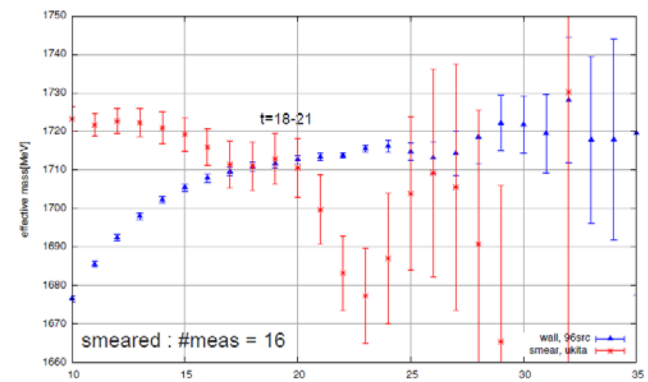


ΩΩ system ($^1S_0$)

(The "most strange" dibaryon system)

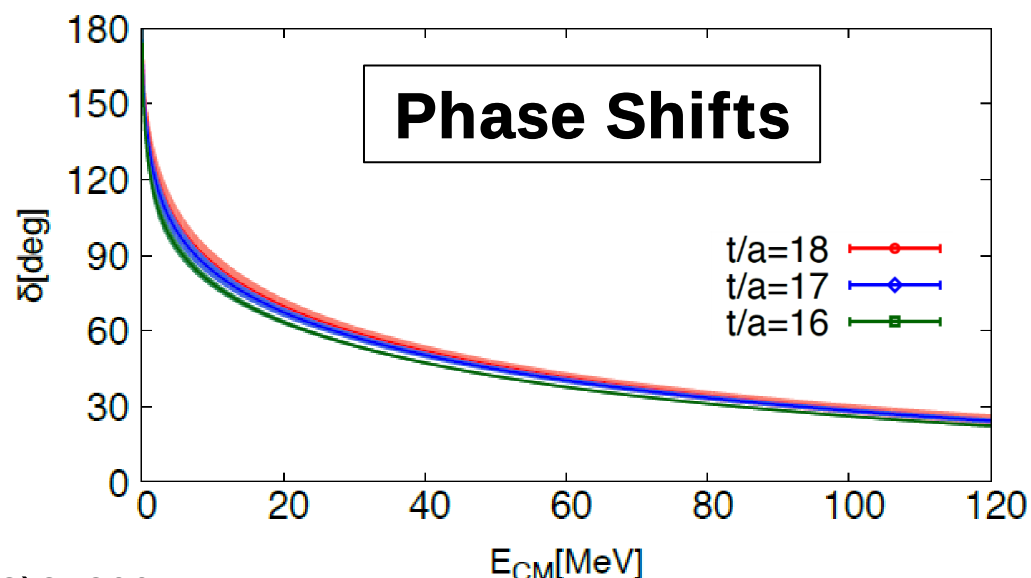


m(eff) for single Ω



t = 18 : ~0.2-0.3% sys error

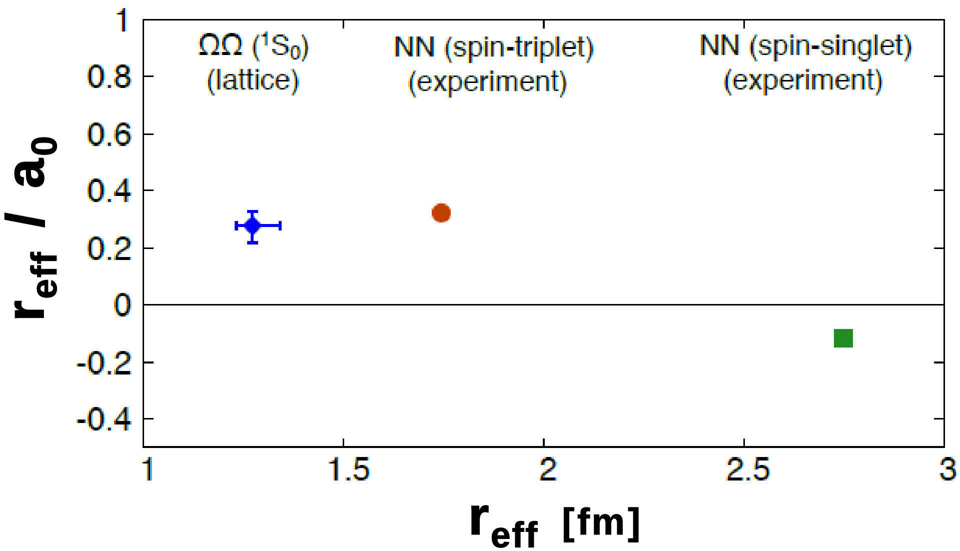
Strong Attraction

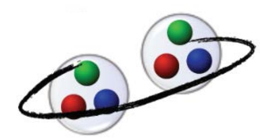


S. Gongyo et al. (HAL Coll.), PRL120(2018)212001

ΩΩ system ($^1S_0$)

(The "most strange" dibaryon system)

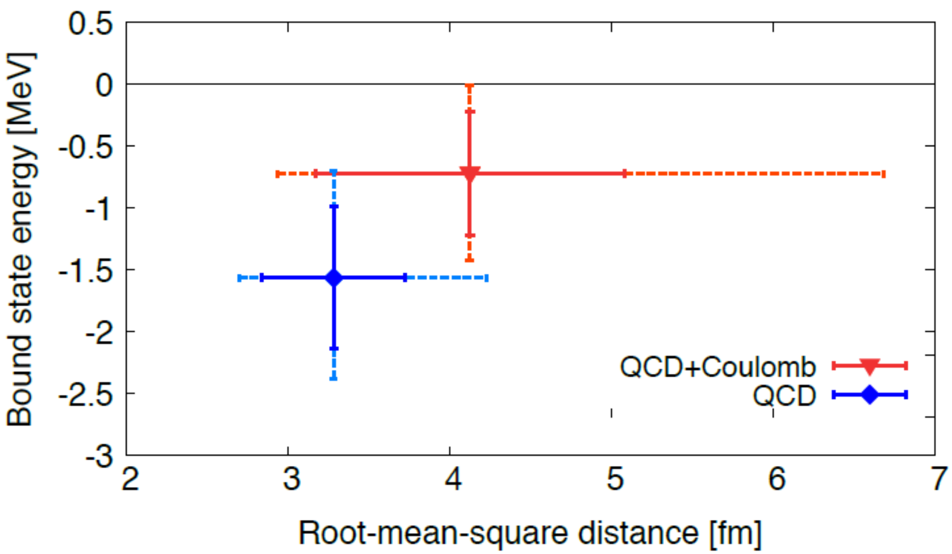




$$B_{\rm QCD} = 1.6(6)(^{+0.7}_{-0.6})\ {\rm MeV}$$
$$B_{\rm QCD+Coul.} = 0.7(5)(5)\ {\rm MeV}$$

Vicinity of bound / unbound

[~ Unitary limit]

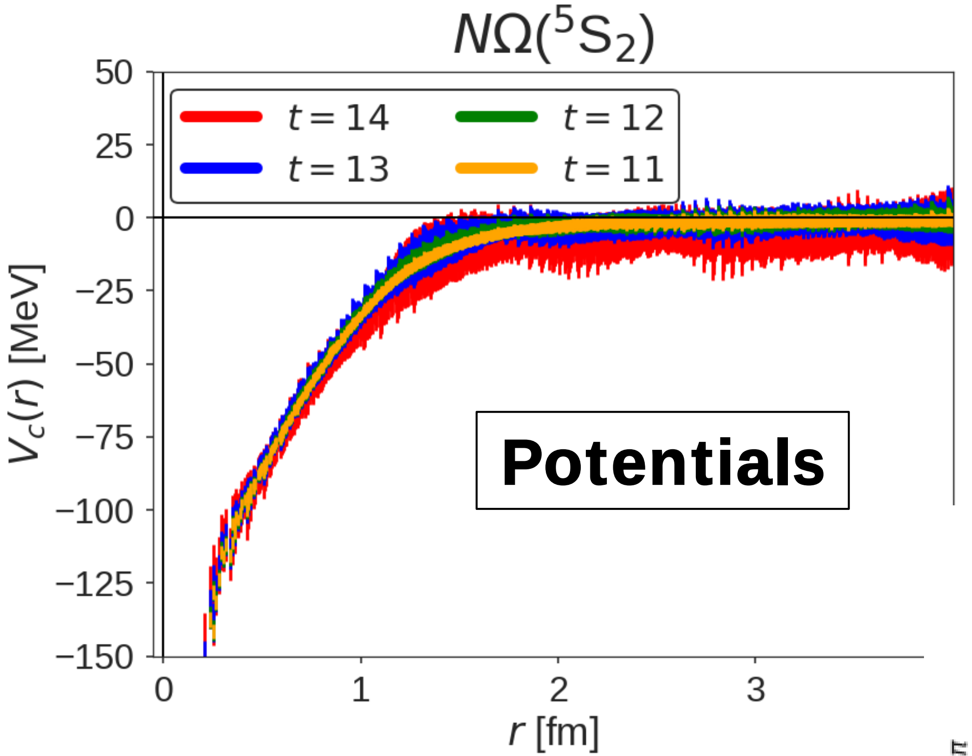


⟺ **ΩΩ correlation in HIC exp.**

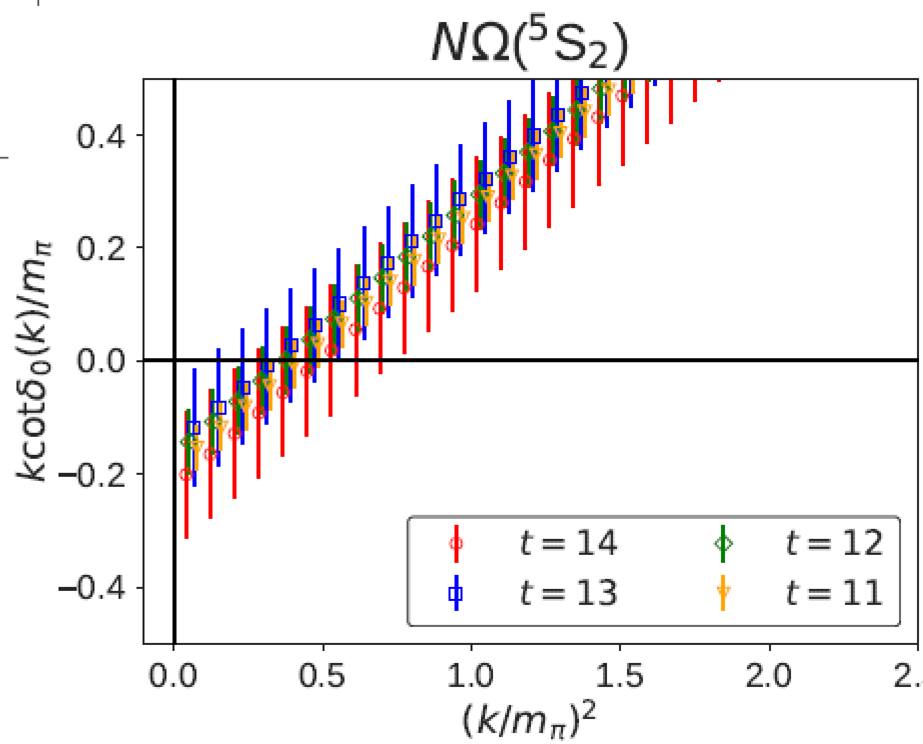
S. Gongyo et al. (HAL Coll.), PRL120(2018)212001

NΩ system ($^5S_2$)

preliminary



Phase Shifts



Possibly (quasi) Bound state

~ in the unitary limit

B.E. (QCD) =~ 1MeV

⟺ **NΩ correlation in HIC**

(200conf x 4rot x 48src) **[T. Iritani]**

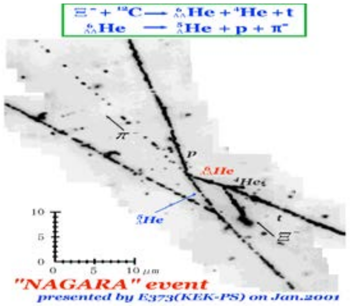
S = -2 channel (Coupled Channel)

H-dibaryon ($^1S_0$, $\Lambda\Lambda$–$N\Xi$–$\Sigma\Sigma$)

R. Jaffe (1977), “Perhaps a Stable Dibaryon”

NAGARA-event (2001)

$$\Xi^- + {}^{12}\text{C} \to {}_{\Lambda\Lambda}{}^{6}\text{He} + {}^{4}\text{He} + t$$

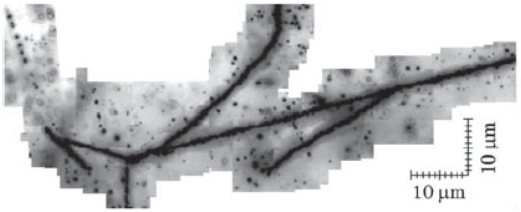


Ξ–hypernuclei

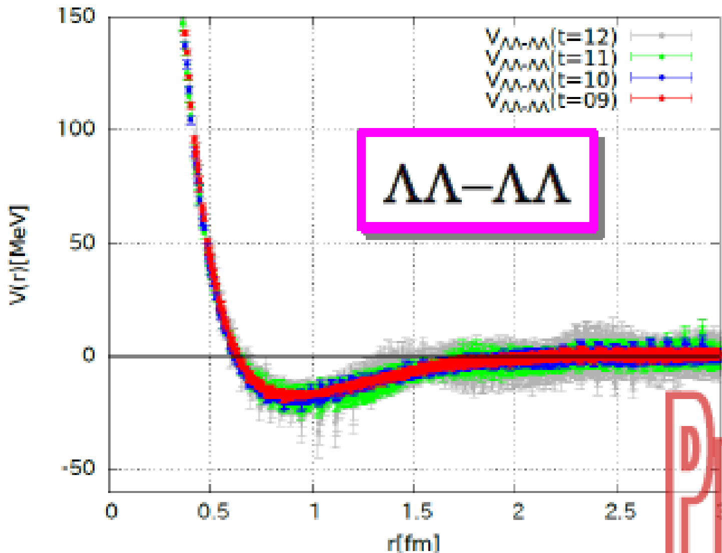
KISO-event (2014)

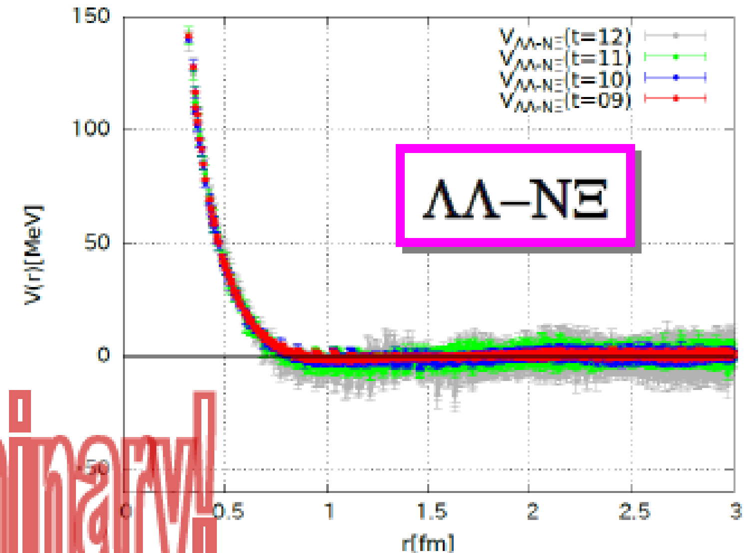
$$\Xi^- + {}^{14}\text{N} \to {}_{\Lambda}{}^{10}\text{Be} + {}_{\Lambda}{}^{5}\text{He}$$

B.E. = 4.38(25) MeV
(or 1.11(25) MeV)



ΛΛ, NΞ, (ΣΣ) coupled channel ➔ H-dibaryon channel





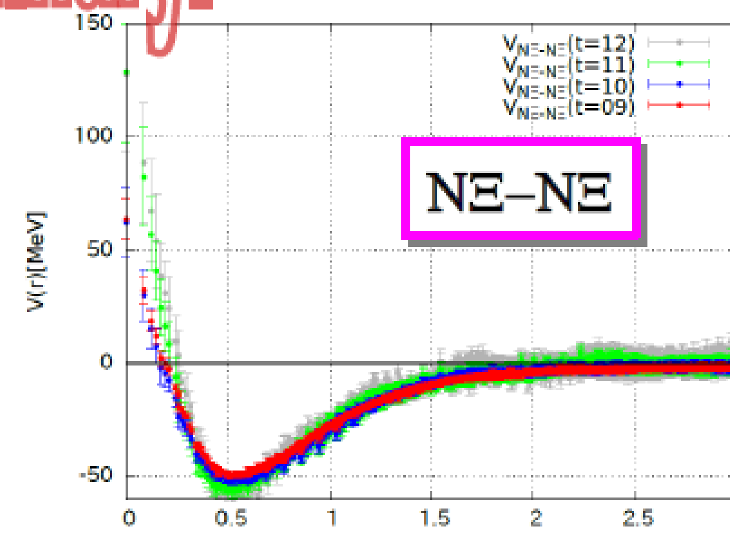
Preliminary!

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

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

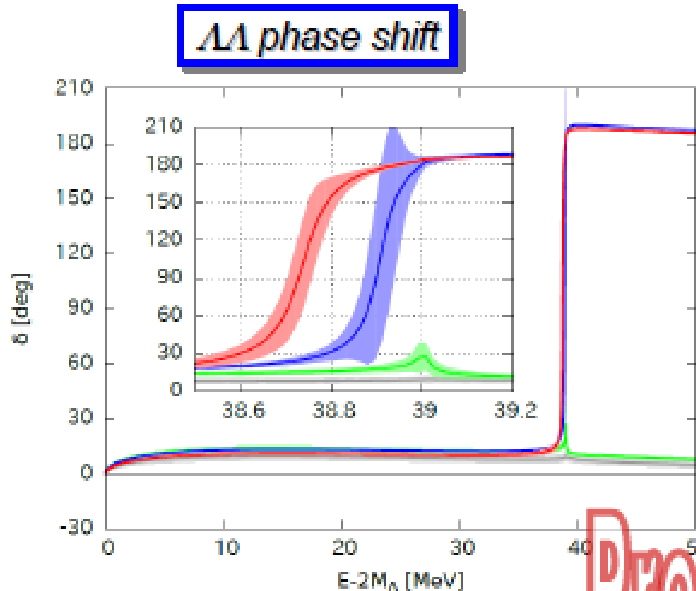
$m_{\Lambda\Lambda} = 2230\text{MeV}$

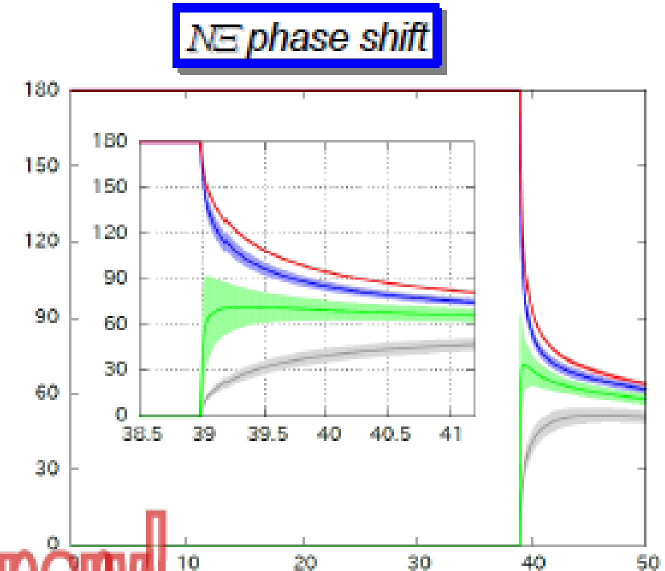
2x2 Potentials



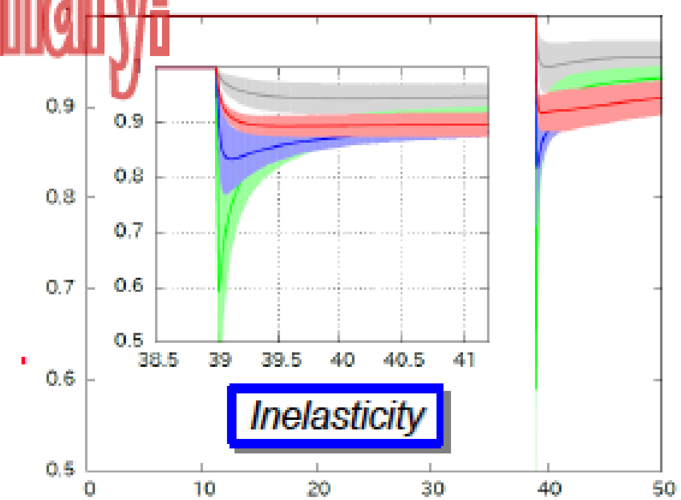
[K. Sasaki]

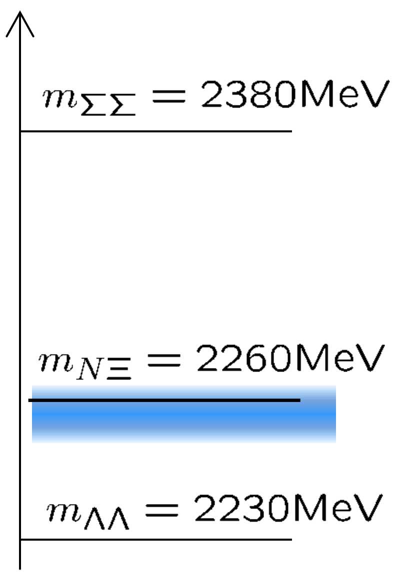
ΛΛ, NΞ (effective) 2x2 coupled channel analysis





Preliminary!



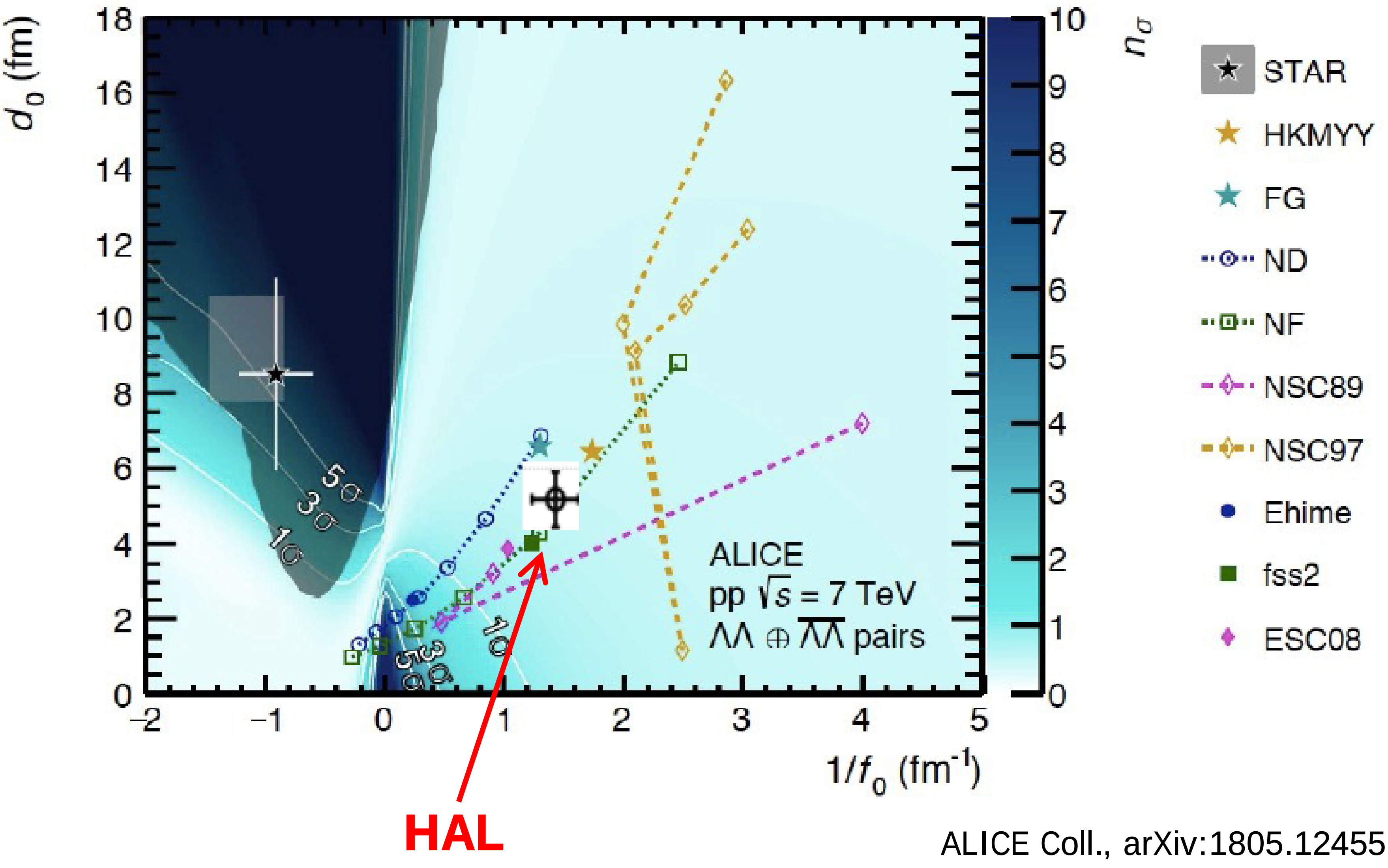


H-resonance (?)

“Perhaps a Resonant Dibaryon”

[K. Sasaki]

ΛΛ : LQCD prediction meets HIC exp



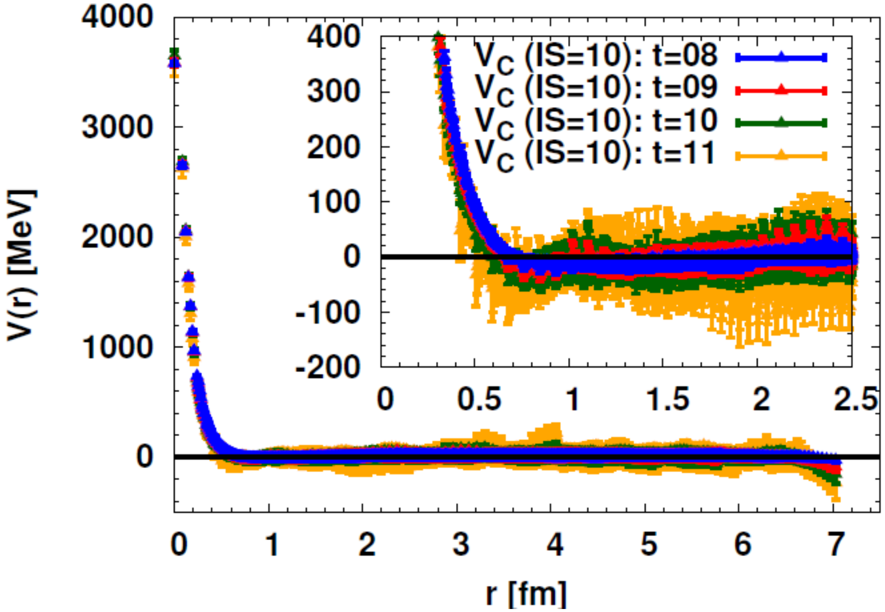
ALICE Coll., arXiv:1805.12455

NN system (S = 0)

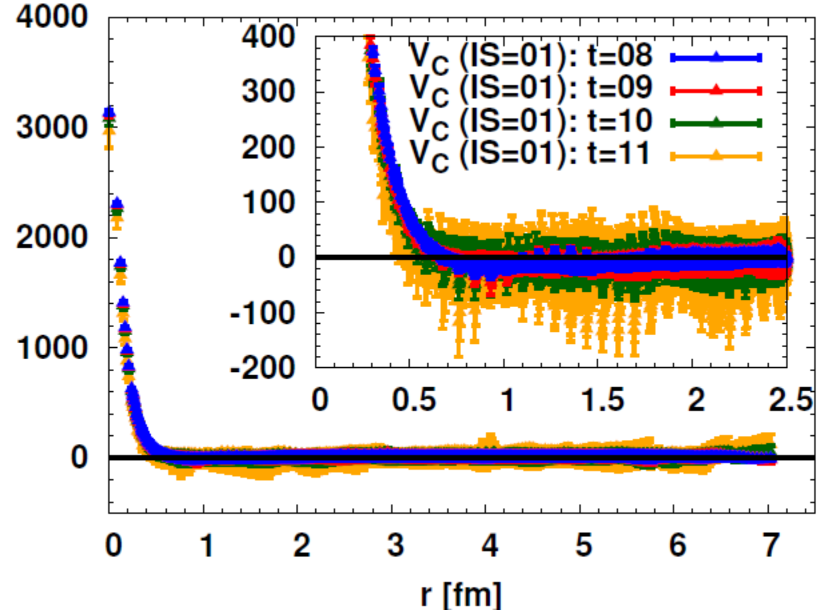
- **$^{1}S_{0}$ channel**
  - Central Force
- **$^{3}S_{1}$-$^{3}D_{1}$ channel**
  - Central Force
  - Tensor Force

NN-Potentials

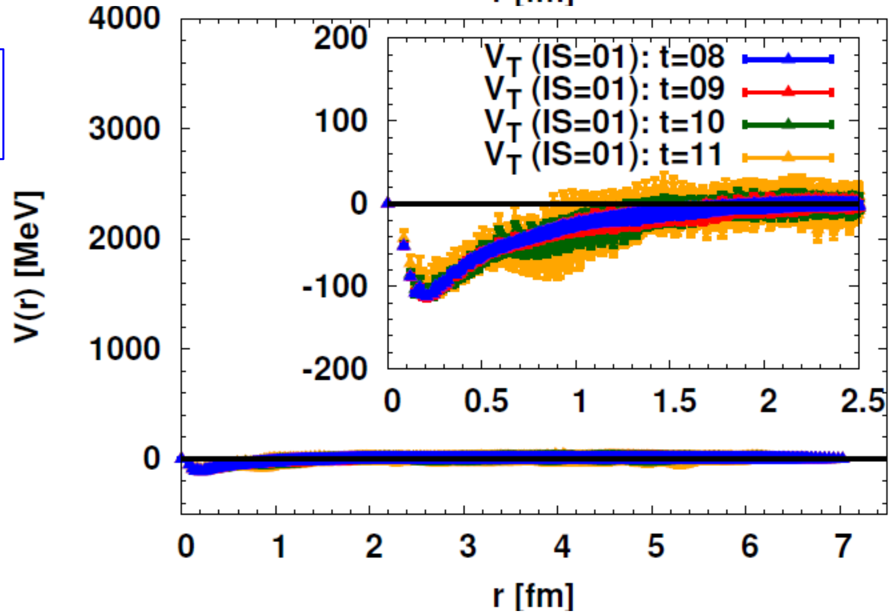
$^1S_0$



$^3S_1$-$^3D_1$



Central



Tensor

Preliminary

- **Vc: repulsive core + long-range attraction**
- **Vt: strong tensor force !**

(400conf x 4rot x 96src)

Impact on dense matter

LQCD YN/YY-forces + Phen NN-forces (AV18)
used in Brueckner-Hartree-Fock (BHF)

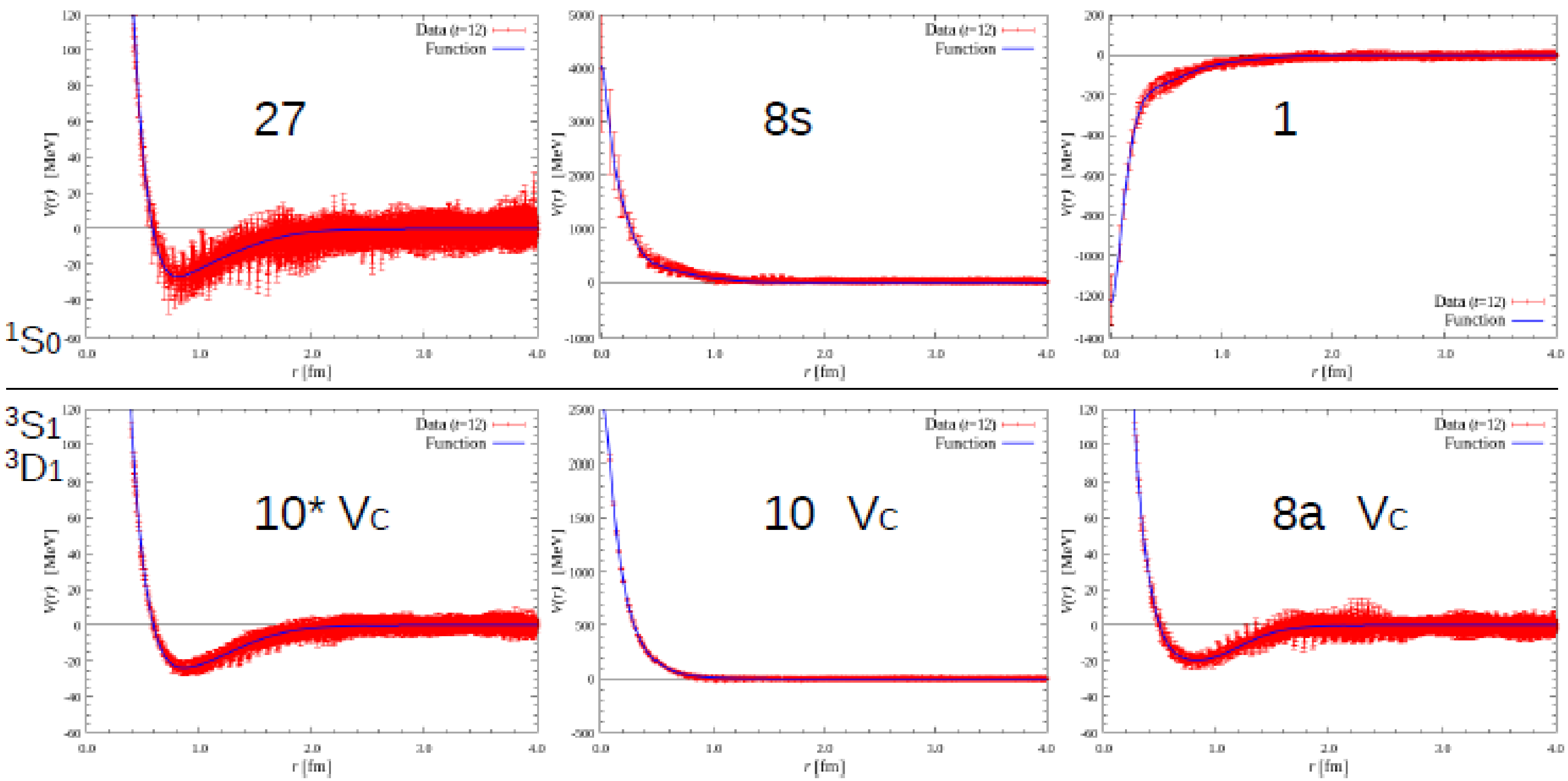
➔ Single-particle energy of Hyperon in nuclear matter

(Only diagonal YN/YY forces in SU(3) irrep used)
(400conf x 4rot x 96src)

S=-2 interactions suitable to grasp whole NN/YN/YY interactions

Central Force in Irrep-base (diagonal)

$$8 \times 8 = \underbrace{27 + 8s + 1}_{^1S_0} + \underbrace{10^* + 10 + 8a}_{^3S_1\,,\ ^3D_1}$$



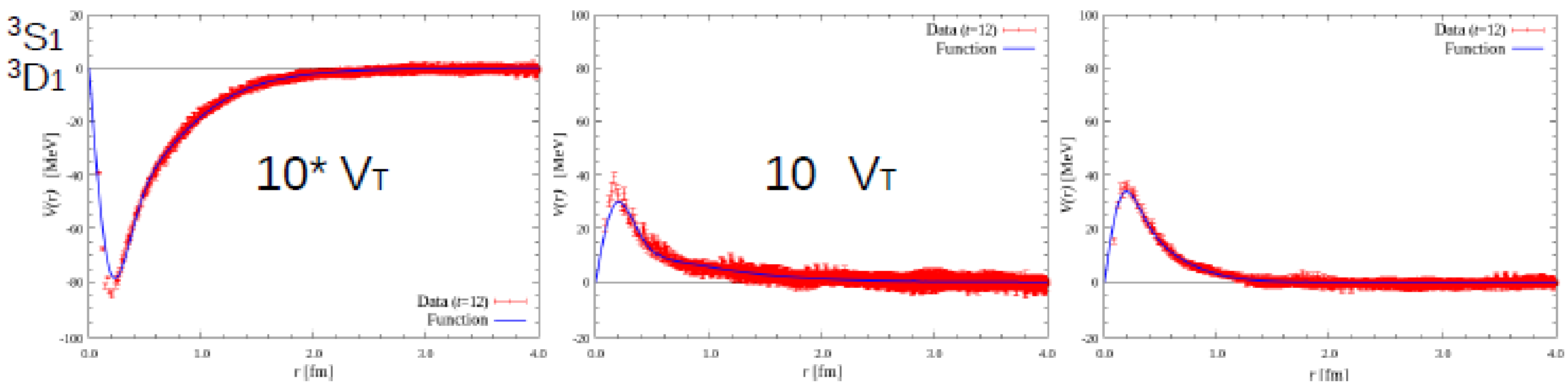
(off-diagonal component is small)

[K. Sasaki]

S=-2 interactions suitable to grasp whole NN/YN/YY interactions

Tensor Force in Irrep-base (diagonal)

$$8 \times 8 = \underbrace{27 + 8s + 1}_{^1S_0} + \underbrace{10^* + 10 + 8a}_{^3S_1,\ ^3D_1}$$



➔ We calculate single-particle energy of hyperon in nuclear matter w/ LQCD baryon forces

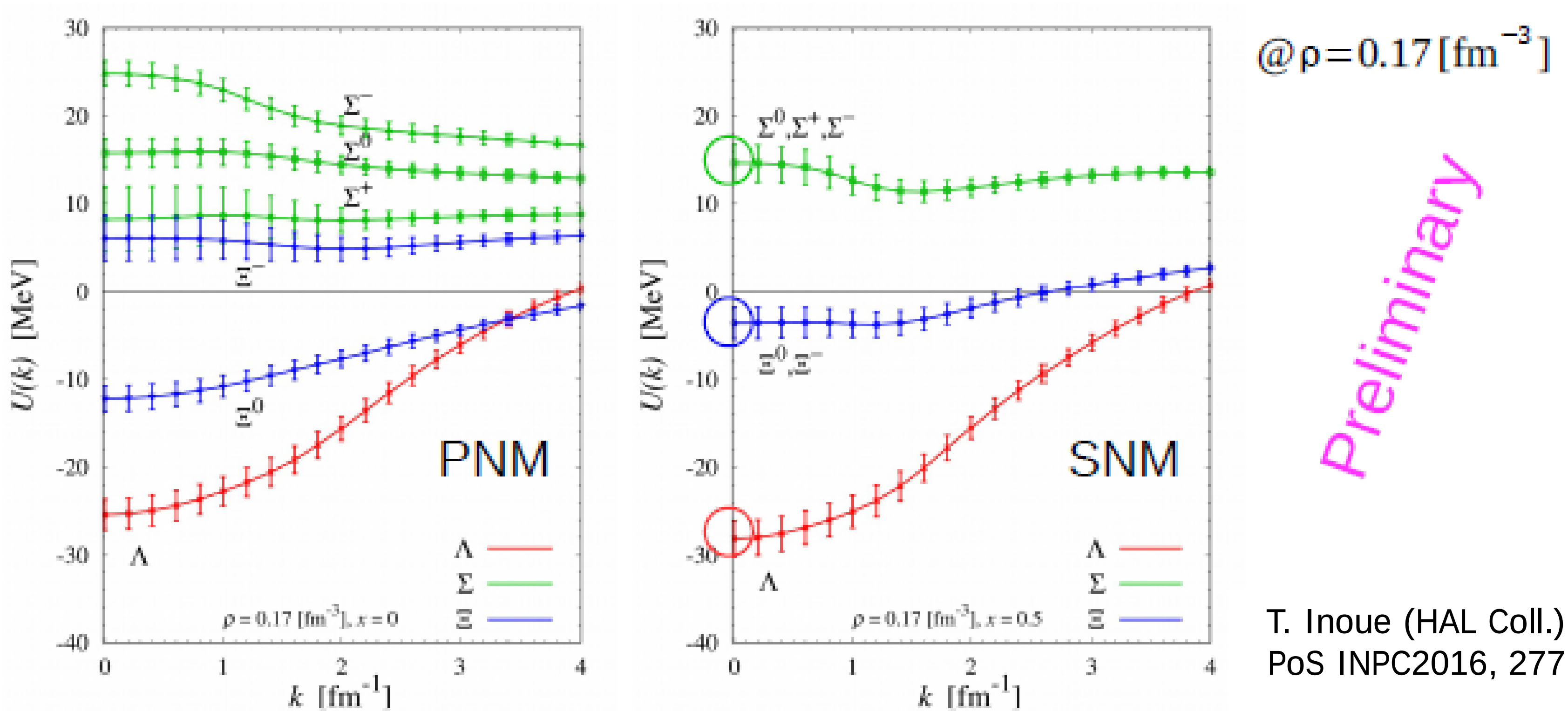
(off-diagonal component neglected)

We fit by

$$V(r) = a_1 e^{-a_2 r^2} + a_3 e^{-a_4 r^2} + a_5 \left[\left(1 - e^{-a_6 r^2}\right) \frac{e^{-a_7 r}}{r} \right]^2 \quad \text{(central)}$$

$$V(r) = a_1 \left(1 - e^{-a_2 r^2}\right)^2 \left(1 + \frac{3}{a_3 r} + \frac{3}{(a_3 r)^2}\right) \frac{e^{-a_3 r}}{r} + a_4 \left(1 - e^{-a_5 r^2}\right)^2 \left(1 + \frac{3}{a_6 r} + \frac{3}{(a_6 r)^2}\right) \frac{e^{-a_6 r}}{r} \quad \text{(tensor)}$$

Hyperon single-particle potentials



T. Inoue (HAL Coll.)
PoS INPC2016, 277

- obtained by using YN,YY S-wave forces form QCD.
- Results are compatible with experimental suggestion.

$$U_{\Lambda}^{\mathrm{Exp}}(0) \simeq -30, \quad U_{\Xi}(0)^{\mathrm{Exp}} \simeq -10\,?, \quad U_{\Sigma}^{\mathrm{Exp}}(0) \geq +20\,? \quad [\mathrm{MeV}]$$

attraction | attraction small | repulsion

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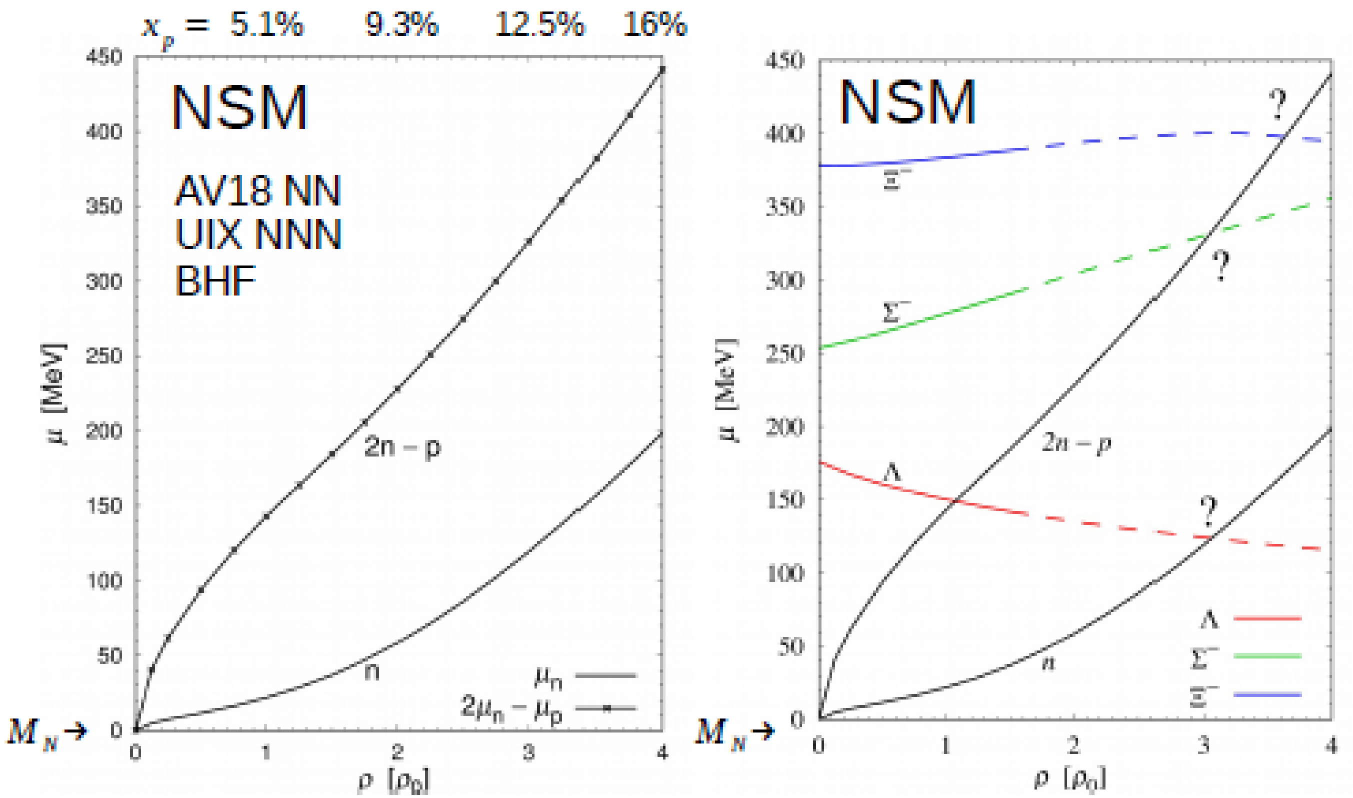
[T. Inoue]

Hyperon onset in NSM (just for fun)



S-wave *YN* only

Preliminary

- Result indicate Λ, Σ^-, Ξ^- appear around ρ = 3.0 - 4.0 ρ_0
- However,
  - $YN^{L=1,2...}$ and YNN force could be important at high density.
  - We may need to compare with more sop[...] BHF.

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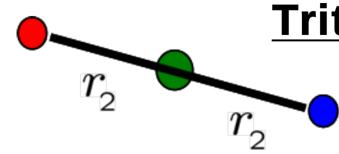
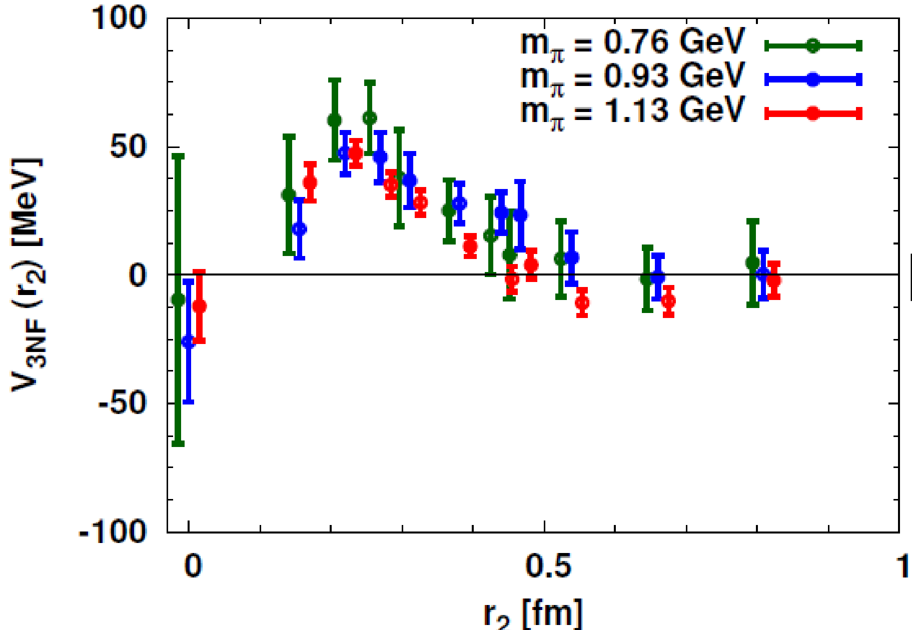
[Missing]
P-wave / LS forces
3-baryon forces

[T. Inoue]

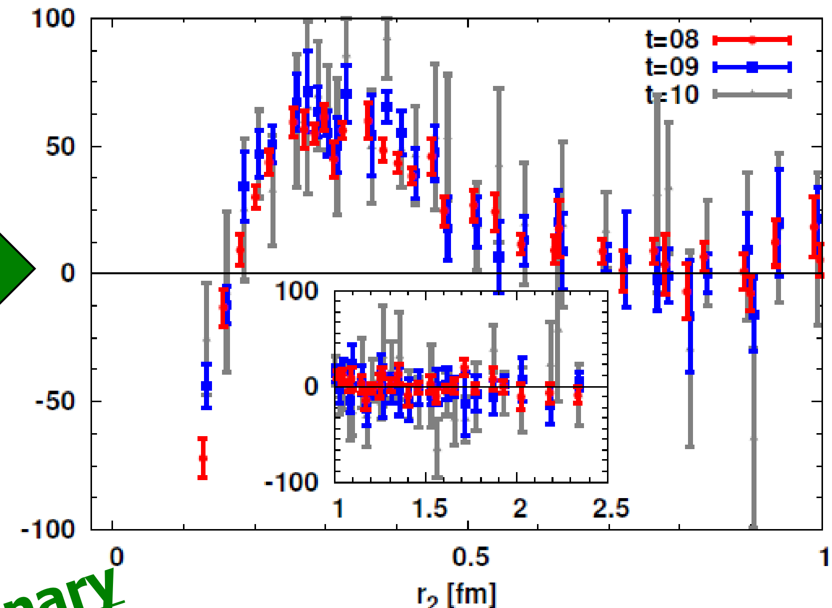
3N-forces (3NF)



Nf=2, mπ=0.76-1.1 GeV



Nf=2+1, mπ=0.51 GeV



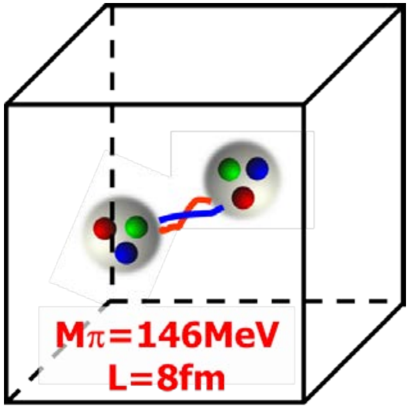
Preliminary

Magnitude of 3NF is similar for all masses
Range of 3NF tend to get longer (?) for m(pi)=0.5GeV

Kernel: ~50% efficiency achieved !

Summary

- Baryon forces: Bridge between particle/nuclear/astro-physics
- HAL QCD method crucial for a reliable calculation
  - Direct method suffers from excited state contaminations
- The 1st LQCD for Baryon Interactions at ~ phys. point
  - m(pi) ~= 146 MeV, L ~= 8fm, 1/a ~= 2.3GeV
  - Central/Tensor forces for NN/YN/YY in P=(+) channel



Nuclear Physics from LQCD
New Era is dawning !

- Prospects
  - Exascale computing Era ~ 2020
  - LS-forces, P=(-) channel, 3-baryon forces, etc., & EoS