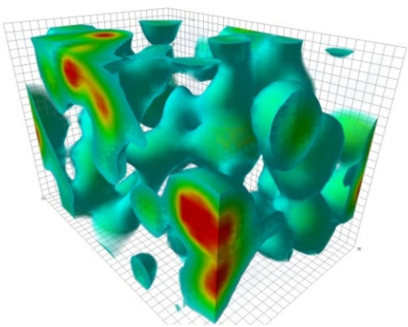
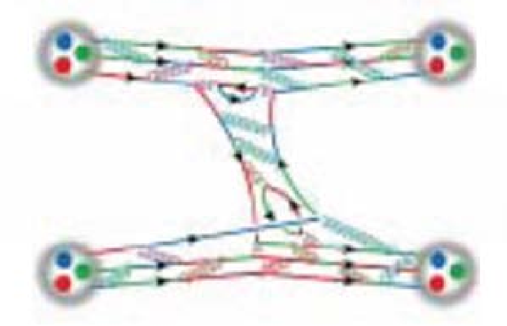
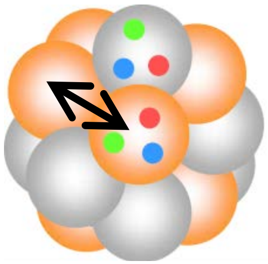
Hadron Interactions from Lattice QCD

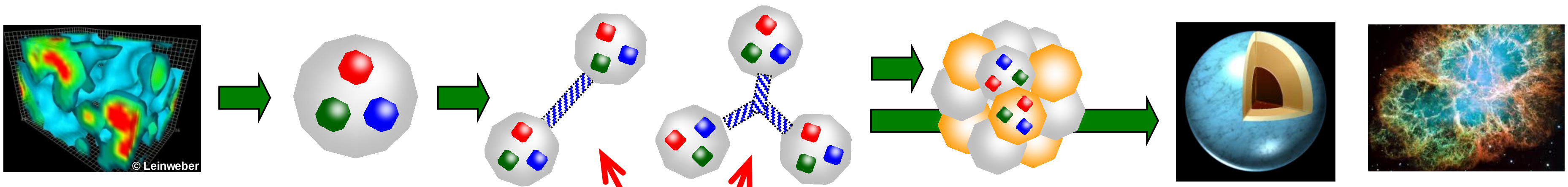
Takumi Doi

(RIKEN Nishina Center / iTHEMS)





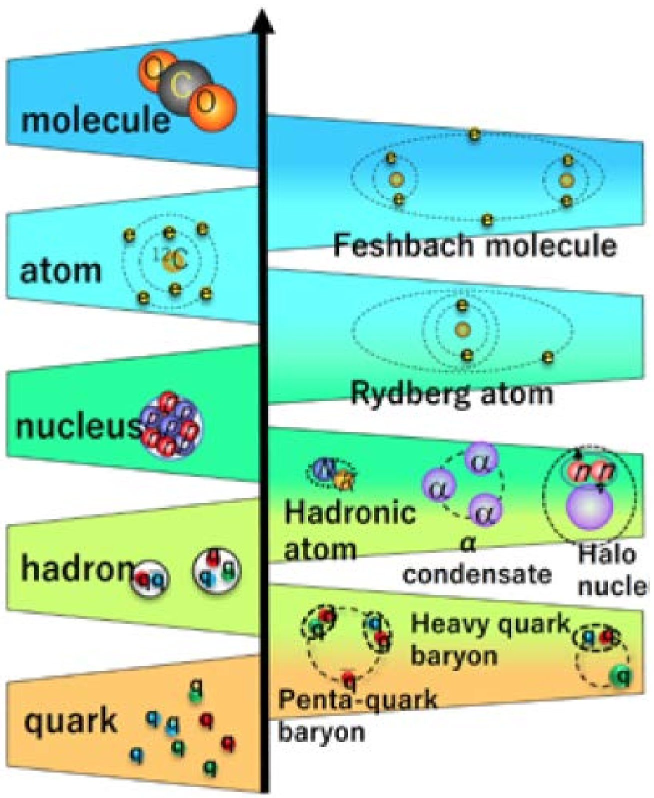




QCD vacuum | Hadrons | Nuclei | Neutron Stars / Supernovae Nucleosynthesis

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

Lattice QCD



Final State Interactions in HIC-exp [A01]

Interactions to form Exotic hadrons [A02, B01]

Hyperon interactions [B01]

3-body interactions [B02]

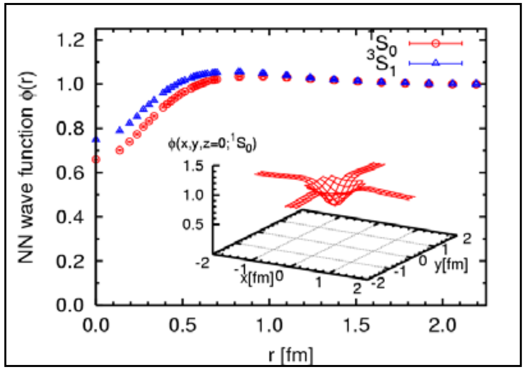
Numerical simulator
←→ cold-atom simulator [C01, C02]

Hyperon interactions → Hypernuclei [D01]
(Hiyama's talk)

HAL QCD method

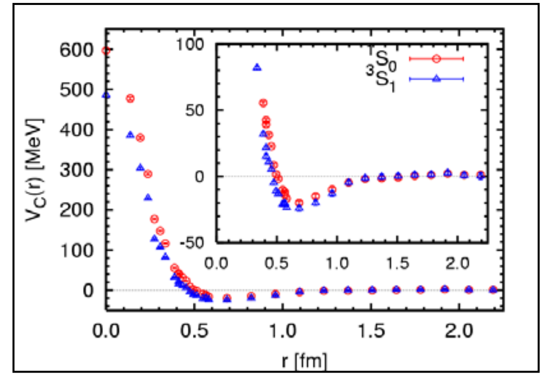
Lattice QCD

NBS wave func.



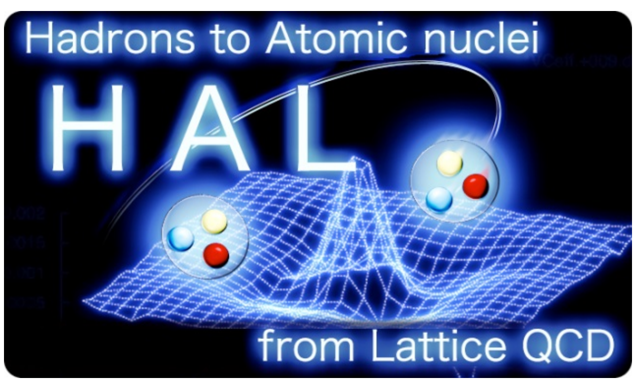
$$\psi_{NBS}(\vec{r}) = \langle 0|N(\vec{r})N(\vec{0})|N(\vec{k})N(-\vec{k}), in\rangle$$
$$\simeq A_k \sin(kr - l\pi/2 + \delta_l(k))/(kr)$$

Lat Baryon Force



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

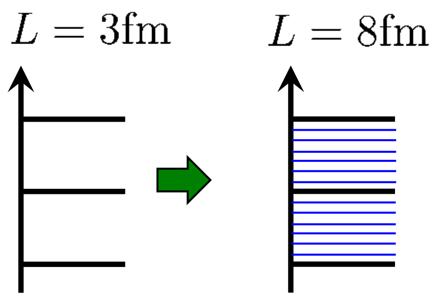
E-indep (& non-local) Potential:
Faithful to phase shifts



Y. Akahoshi, S. Aoki, T. Miyamato, K. Sasaki (YITP)
T. Aoyama (KEK)
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 Challenge in multi-baryons on the lattice

T. Iritani et al. JHEP1610(2016)101
T. Iritani et al. PRD96(2017)034521
T. Iritani et al. arXiv: 1805.02365
T. Iritani, EPJ Web Conf. 175(2018)05008



Ground State saturation is exponentially difficult

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

QCD

Baryon Forces

Observables

HAL QCD method

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

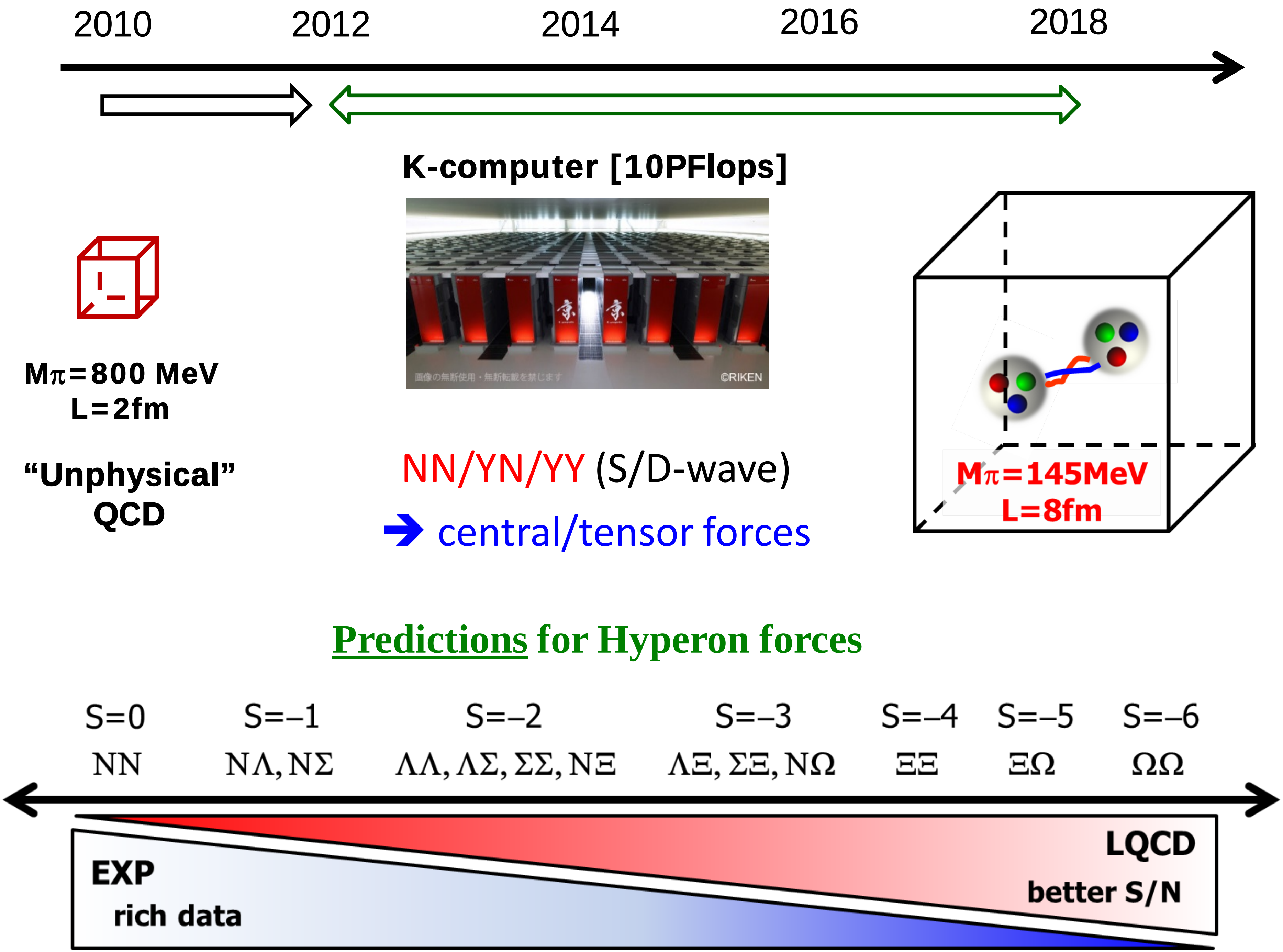
E-indep potential ➔ "Signal" from all (elastic) states

Explosion of Noise

Direct method

G.S. saturation required

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



2010
2012
2014
2016
2018
K-computer [10PFlops]
©RIKEN
Mπ=800 MeV
L=2fm
"Unphysical"
QCD
NN/YN/YY (S/D-wave)
➔ central/tensor forces
Mπ=145MeV
L=8fm
Predictions for Hyperon forces
S=0
NN
S=−1
NΛ, NΣ
S=−2
ΛΛ, ΛΣ, ΣΣ, NΞ
S=−3
ΛΞ, ΣΞ, NΩ
S=−4
ΞΞ
S=−5
ΞΩ
S=−6
ΩΩ
EXP
rich data
LQCD
better S/N

- 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]

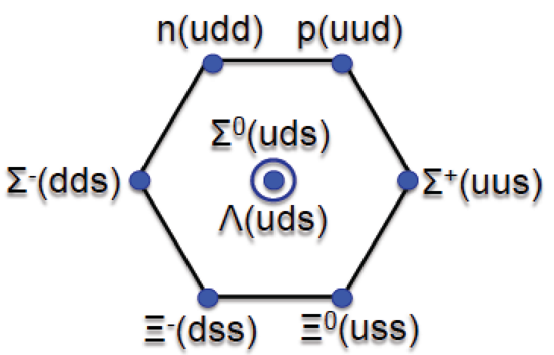
= Unified Contraction Algorithm

- Exponential speedup — Doi-Endres (2013)

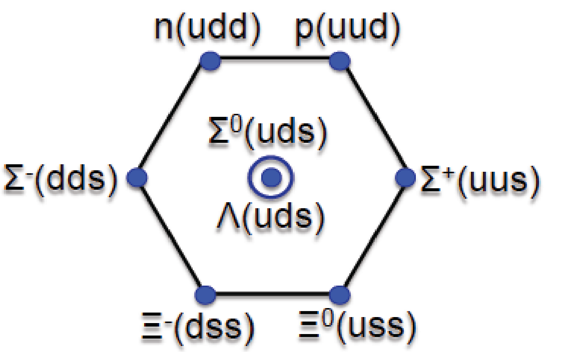
$$^3\mathrm{H}/^3\mathrm{He} \quad : \quad \times 192$$
$$^4\mathrm{He} \quad : \quad \times 20736$$
$$^8\mathrm{Be} \quad : \quad \times 10^{11}$$

Classification of baryon interactions

SU(3)-flavor



X



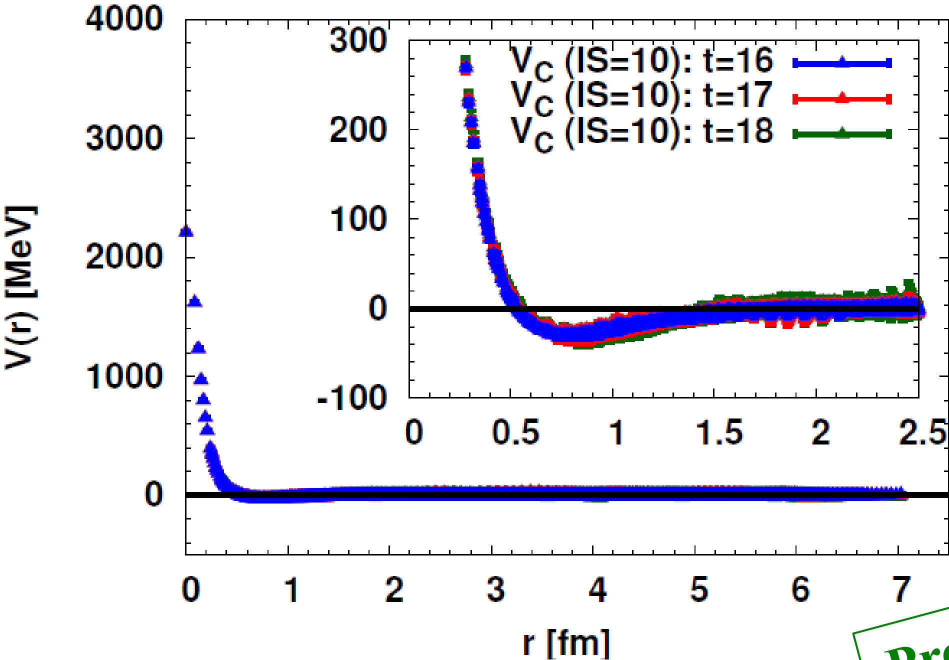
$$8 \times 8 = 27 + 8s + 1 + 10^* + 10 + 8s$$

Nuclear Forces

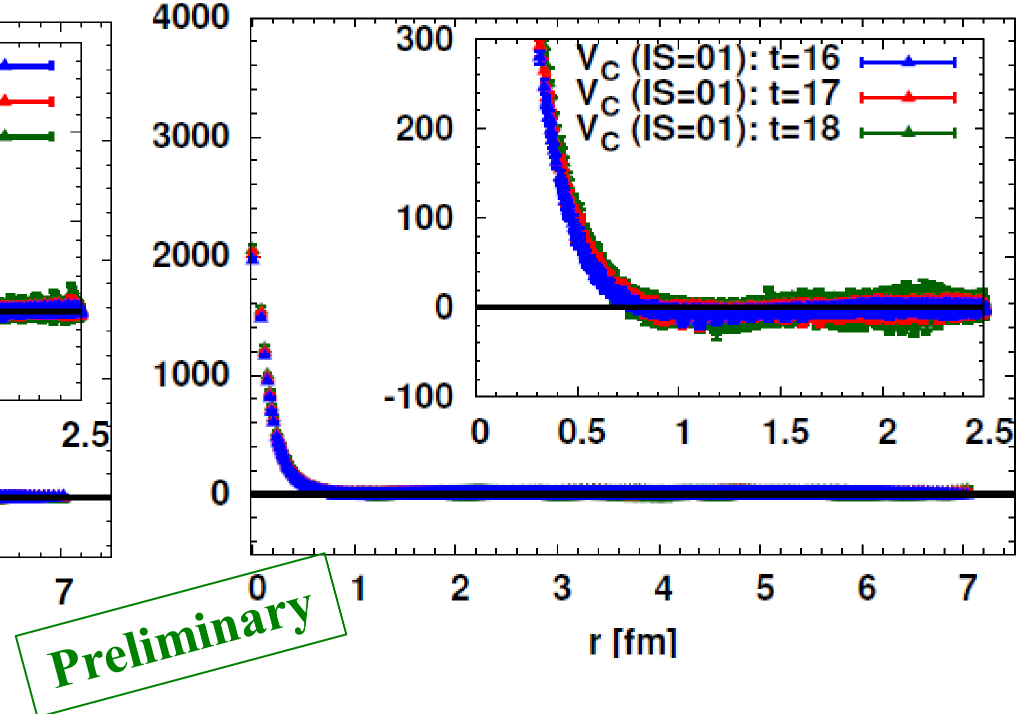
What is universal, and
what is individual in baryon forces ?

ΞΞ systems

$^1S_0$



$^3S_1$



~ 27-plet

$SU_f(3)$-partner of dineutron

~ 10-plet

$SU_f(3)$-partner of $\Sigma N(I=3/2, {}^3S_1)$

Repulsive core ←→ quark-Pauli + OGE

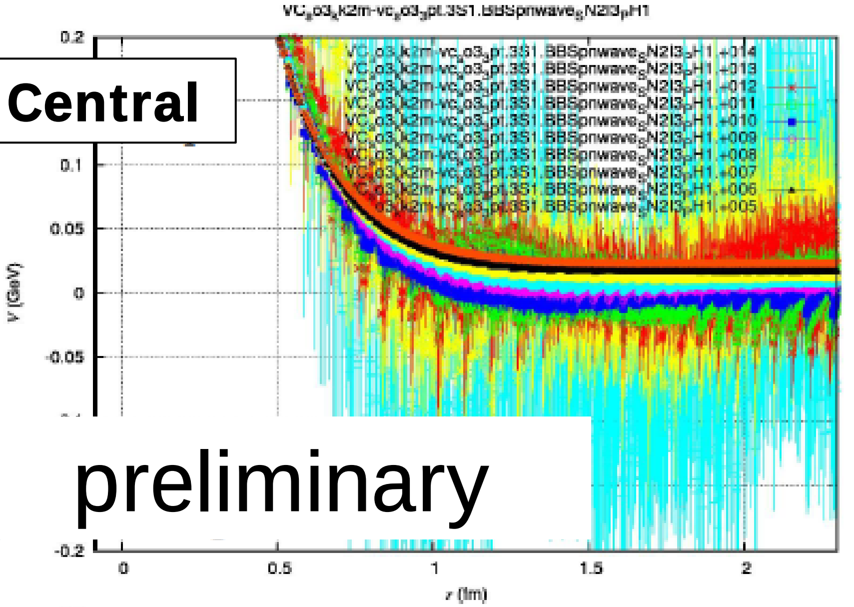
M.Oka et al., NPA464(1987)700

T.Inoue et al. (HAL.), PTP124(2010)591

ΣN (I=3/2) potential in $^3S_1$–$^3D_1$

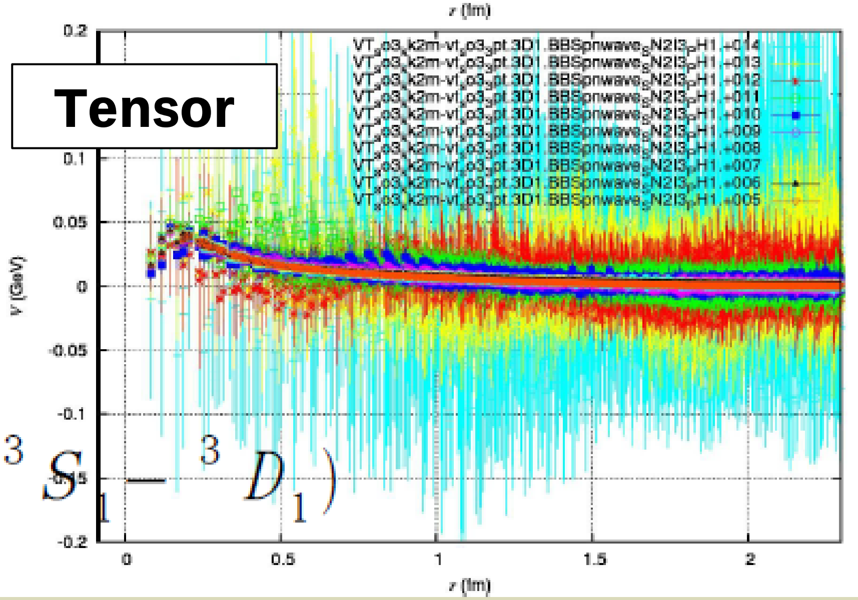
[H. Nemura]

Central



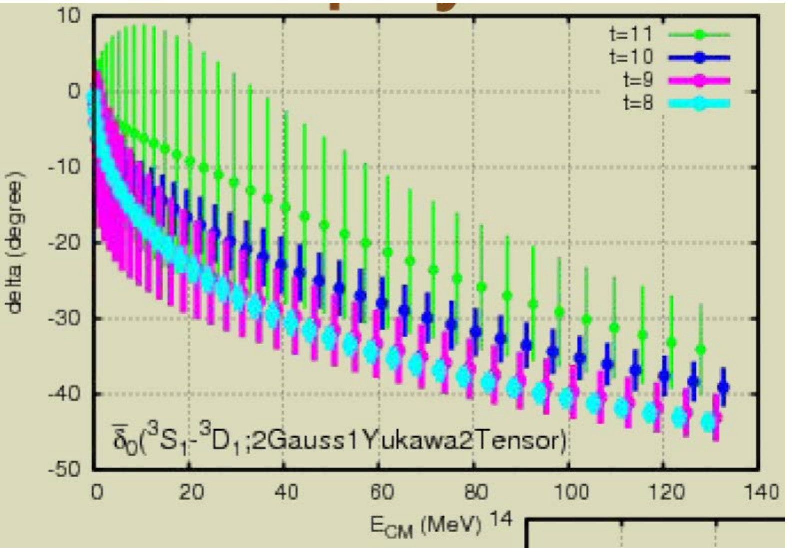
preliminary

Tensor



$^3S_1 - {}^3D_1)$

Phase shift $\bar{\delta}_0$



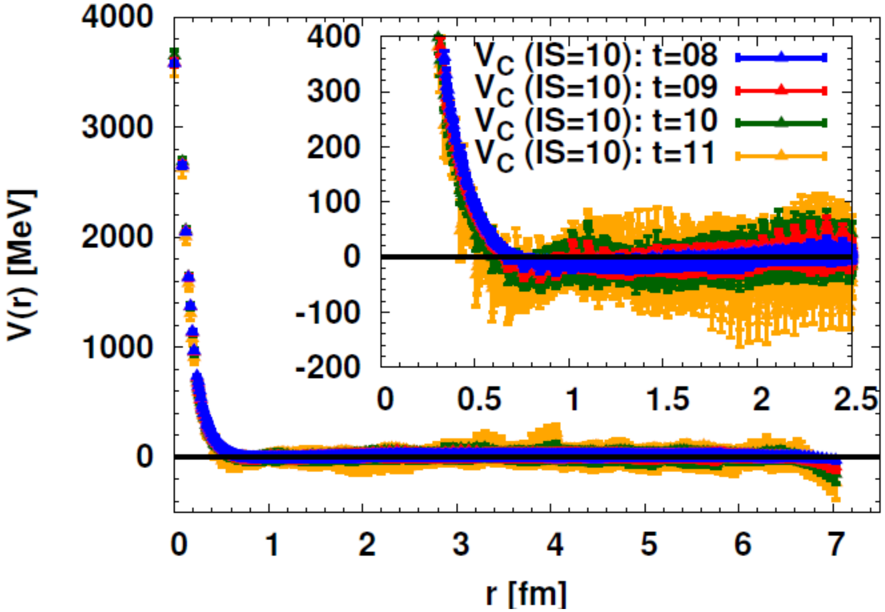
←→ J-PARC Exp (B01班)

- Σ^- in neutron star ?

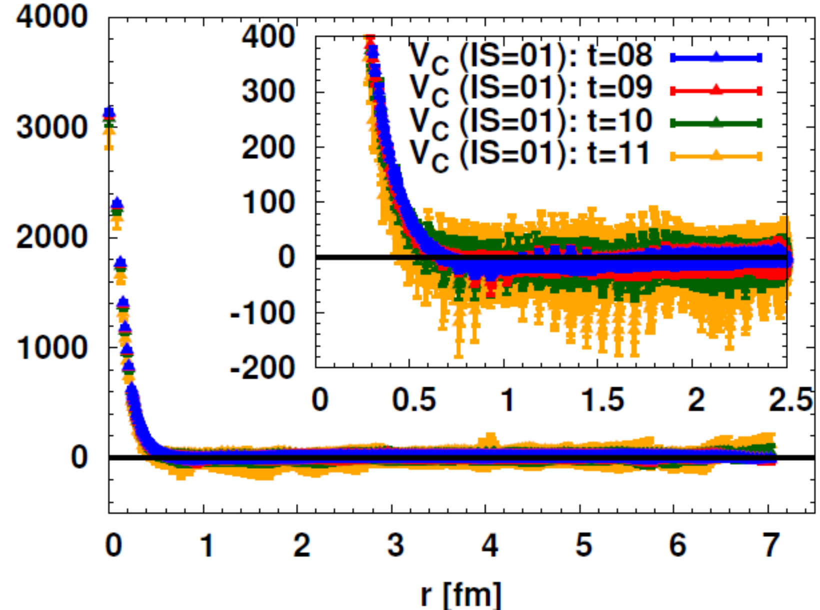
(400conf x 4rot x 96src)

NN-Potentials

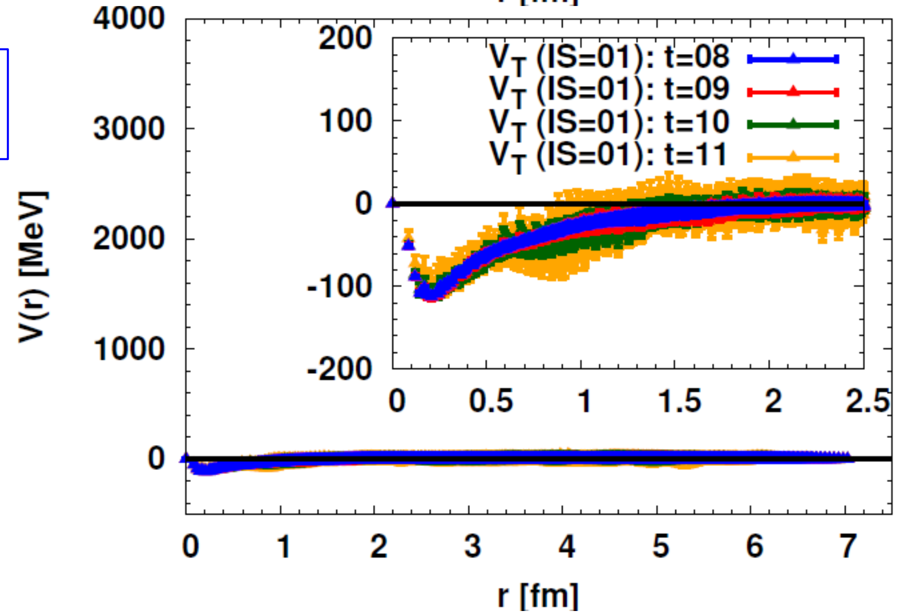
$^1S_0$



$^3S_1$-$^3D_1$



Central



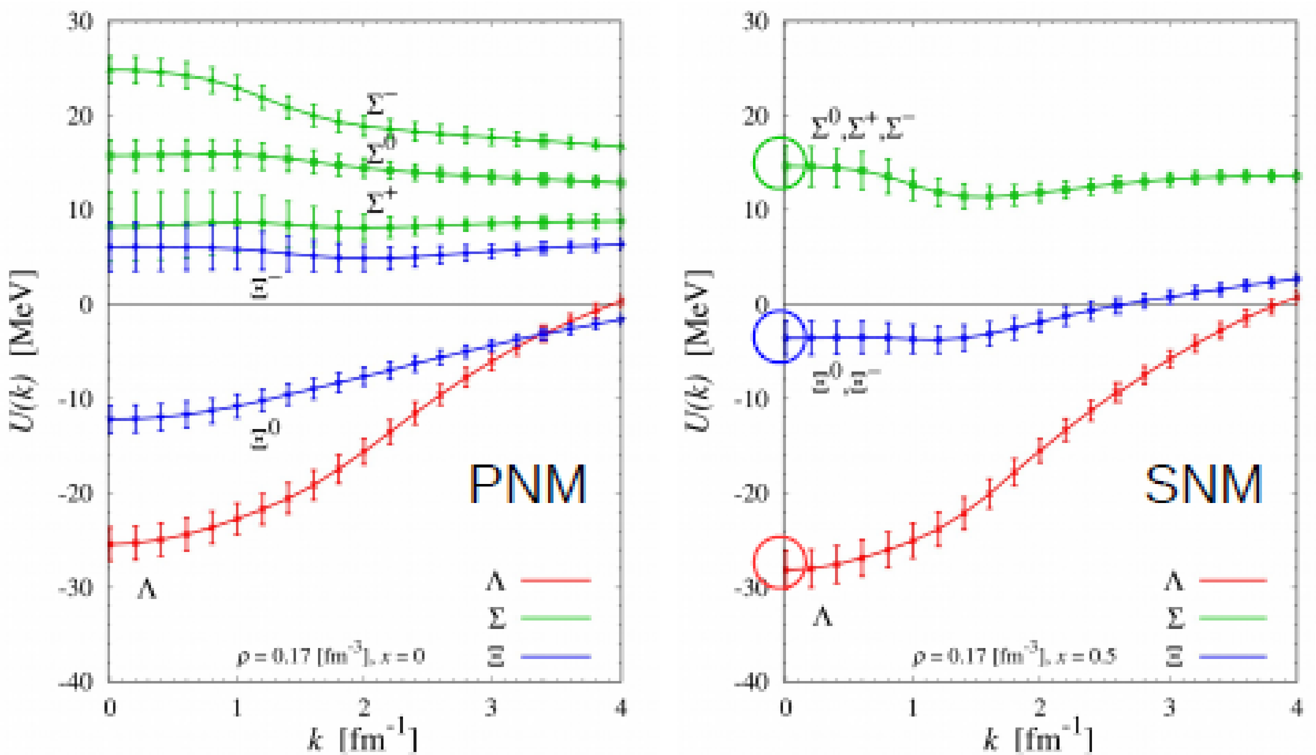
Tensor

Preliminary

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

(400conf x 4rot x 96src)

[Application to dense matter]
Hyperon single-particle potential



$@\rho = 0.17\,[\mathrm{fm}^{-3}]$

Preliminary

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

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

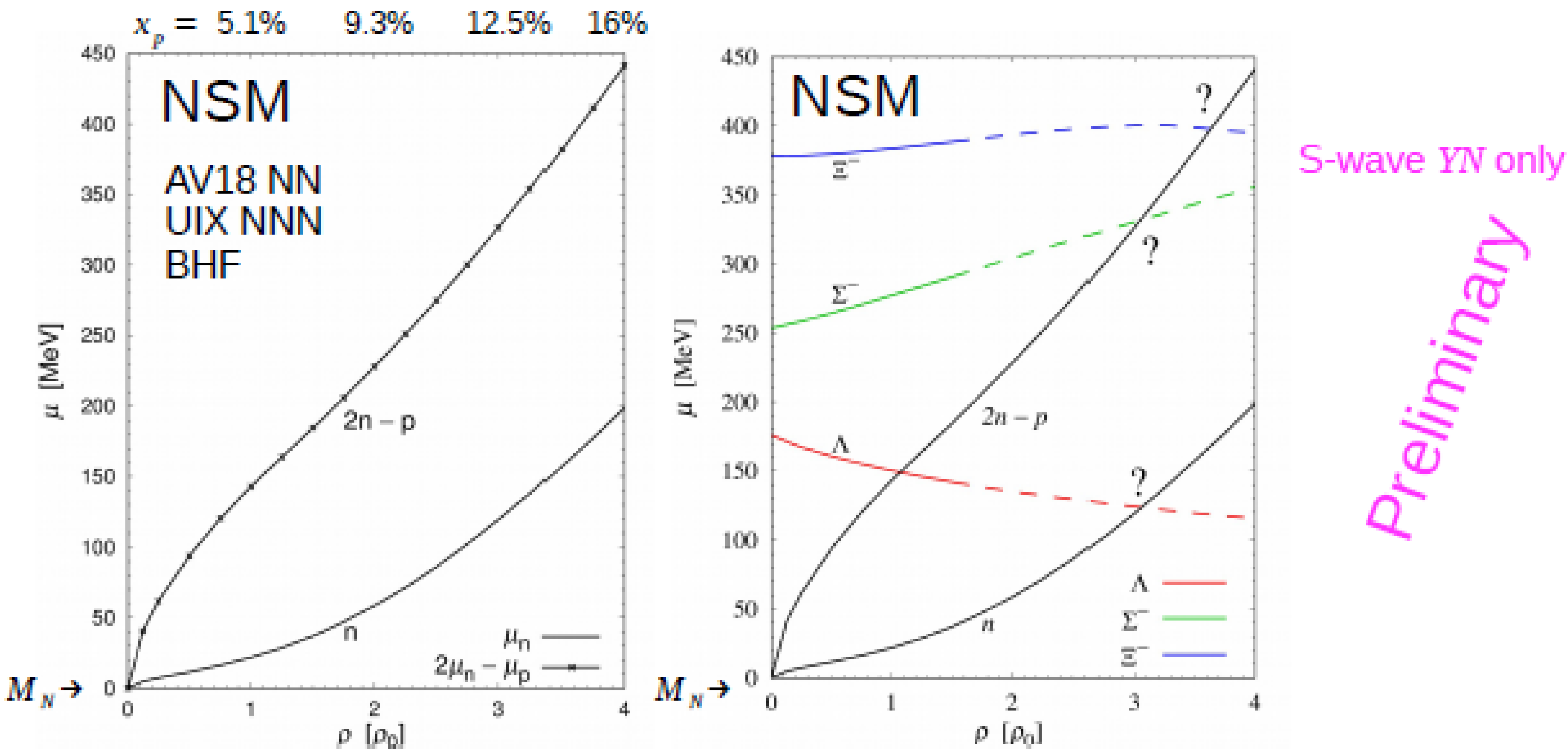
$$U_\Lambda^{\mathrm{Exp}}(0) \simeq -30, \quad U_\Xi(0)^{\mathrm{Exp}} \simeq -10\,?, \quad U_\Sigma^{\mathrm{Exp}}(0) \geq +20\,? \quad [\mathrm{MeV}]$$

attraction attraction small repulsion

49

[T. Inoue]

Hyperon onset in NSM (just for fun)



- Result indicate Λ, Σ^-, Ξ^- appear around $\rho = 3.0 - 4.0\ \rho_0$
- However,
  - $YN^{L=1,2...}$ and YNN force could be important at high density.
  - We may need to compare with more sop[...] BHF.

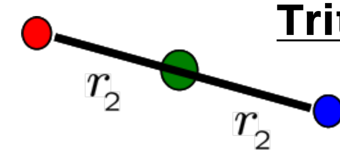
54

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

[T. Inoue]

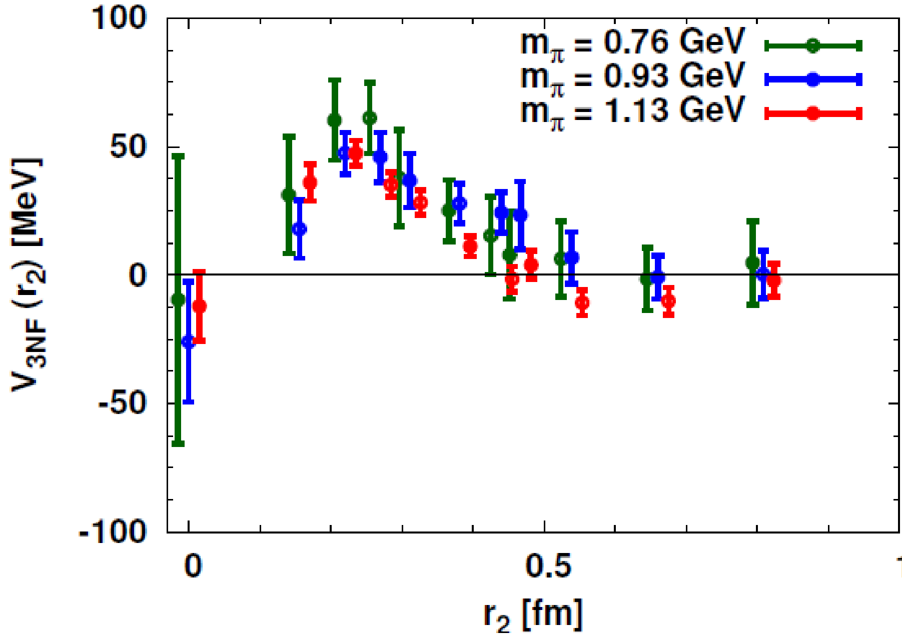
3N-forces (3NF)

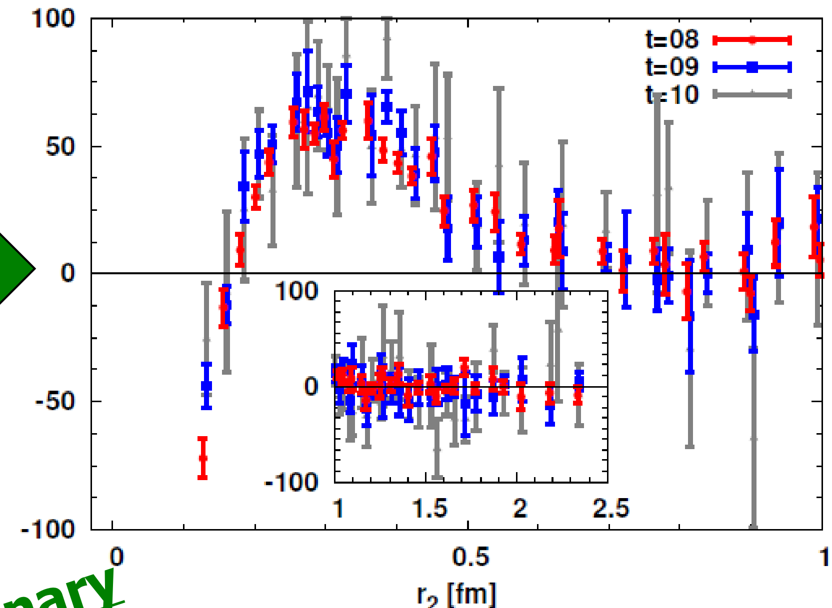
Triton channel



Nf=2, mπ=0.76-1.1 GeV

Nf=2+1, mπ=0.51 GeV





Preliminary

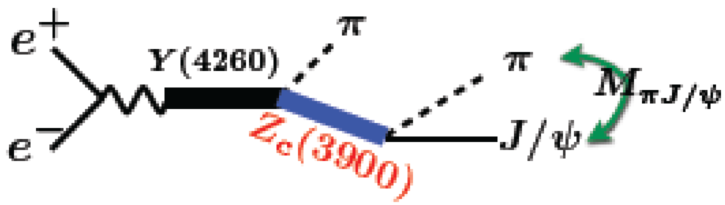
Magnitude of 3NF is similar for all masses
Range of 3NF seems to become longer for mπ =0.51GeV

←→ RIBF Exp (B02班)

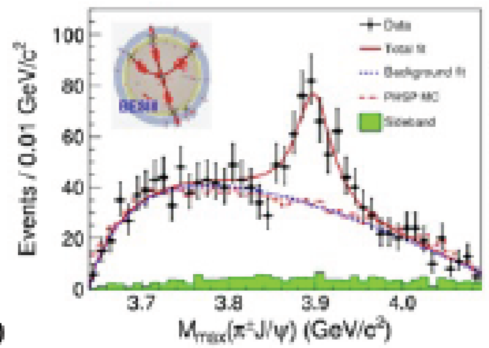
Fate of exotic candidate Zc(3900)[$u\bar{d}c\bar{c}$] -- coupled channel study --

[Y. Ikeda]

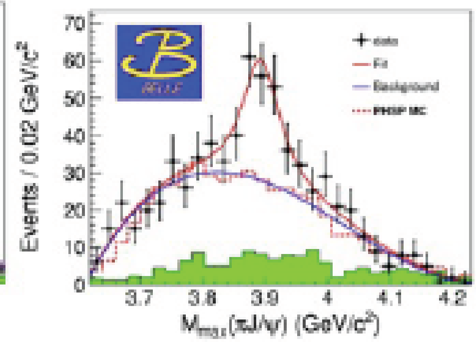
● Expt. observations



BESIII Coll., PRL110 (2013).



Belle Coll., PRL110 (2013).



$e^+ + e^- \to Y(4260) \to \pi + Z_c(3900)$

➡ $\pi^{+/-} + J/\psi$

- peak in **$\pi^{+/-}J/\psi$ invariant mass** (minimal quark content $c\bar{c}\,u\bar{d}$ <--> tetraquark candidate)
- M ~ 3900, Γ ~ 60 MeV (Breit-Wigner) --> just above $\bar{D}D^*$ threshold

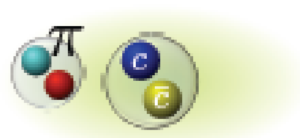
($J^P=1^+$ <--> couple to **s-wave** meson-meson continuum)

★ structure of $Z_c(3900)$ studied by models

tetraquark

Maiani et al.('13)

J/ψ + π atom



Voloshin('08)

$\bar{D}D^*$ molecule

Nieves et al.('11) + many others

$\bar{D}D^*$ threshold effect

Chen et al.('14), Swanson('15)

genuine state expected

kinematical origin

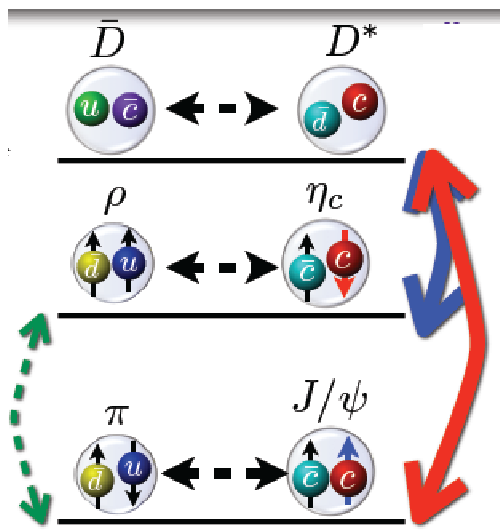
Fate of exotic candidate Zc(3900)[$ud^{bar}cc^{bar}$] -- coupled channel study --

[Y. Ikeda]

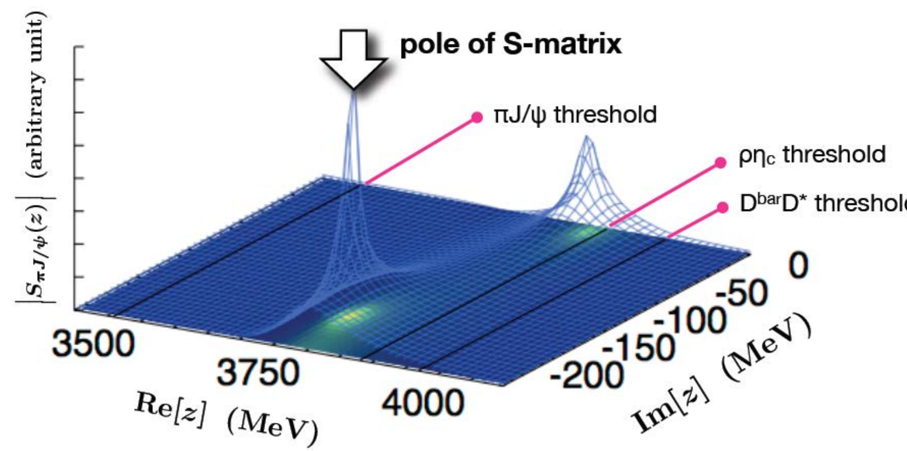
LQCD

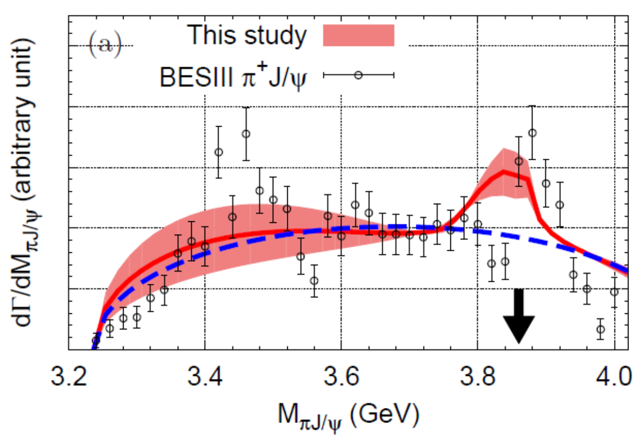
m(pi)=0.41GeV

Coupled channel potential



⇨

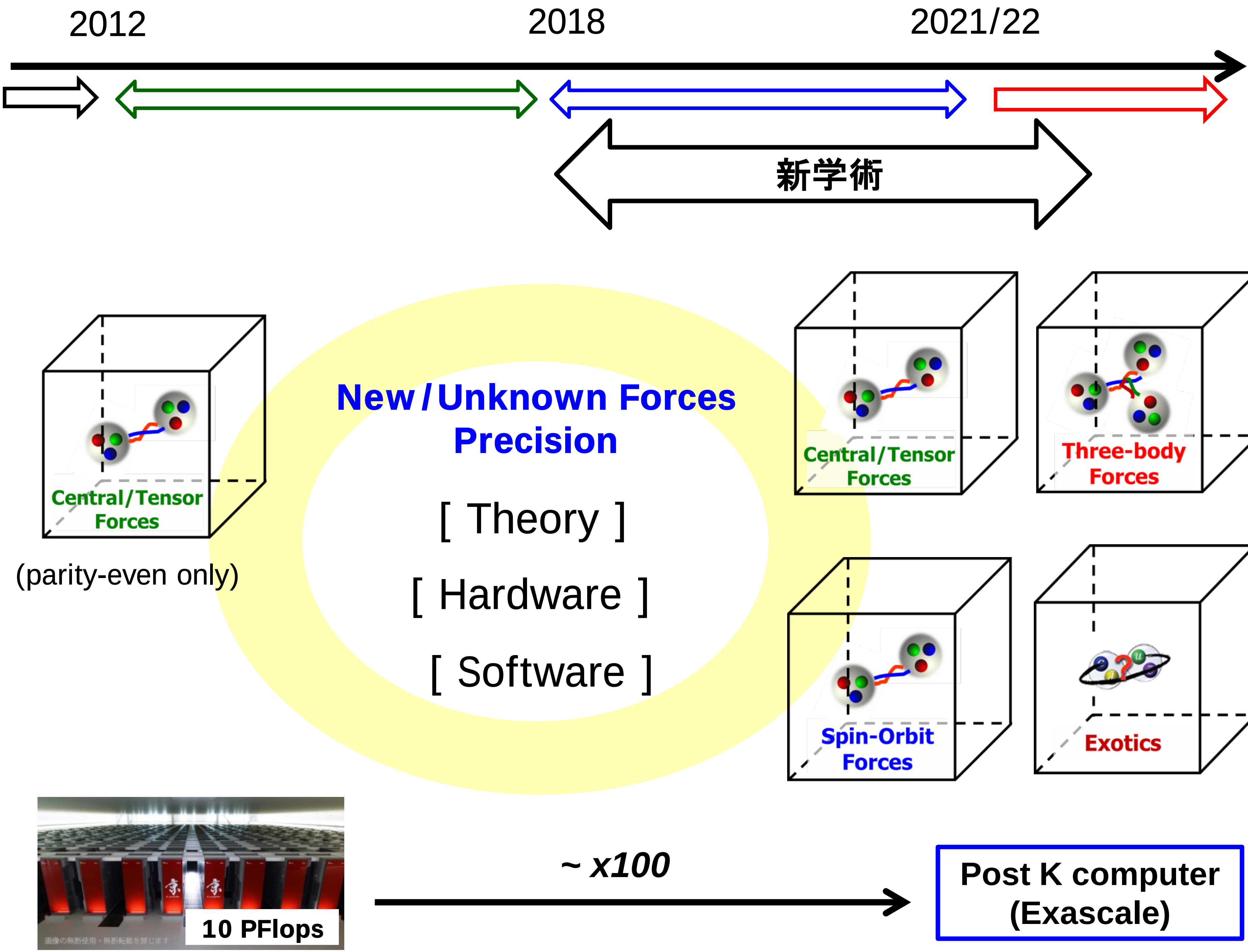




Zc(3900) is threshold cusp

Y. Ikeda et al., PRL117(2016)242001

←→ A02班


2012
2018
2021/22
新学術
Central/Tensor Forces
(parity-even only)
New/Unknown Forces
Precision
[Theory]
[Hardware]
[Software]
Central/Tensor Forces
Three-body Forces
Spin-Orbit Forces
Exotics
10 PFlops
~ x100
Post K computer
(Exascale)

R&D for better comput. framework

- **LapH method, all-to-all method, …**
- **Partial wave decomposition method**

Dominant origin of systematic/statistical errors
➔ contaminations of inelastic states

The challenge is to use the hadron-hadron operator which couples to elastic states

Study of general (exotic) resonances

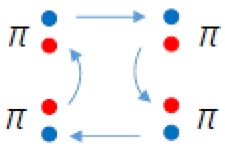
The challenge is the calculation of quark-antiquark creation/annihilation diagrams (disconnected diagram)

The use of all source to all sink quark propagator could meet these challenges

Resonances w/ disconnected diagrams

I=1 pipi scattering

D. Kawai (HAL Coll.) EPJ Web Conf. 175(2018)05007

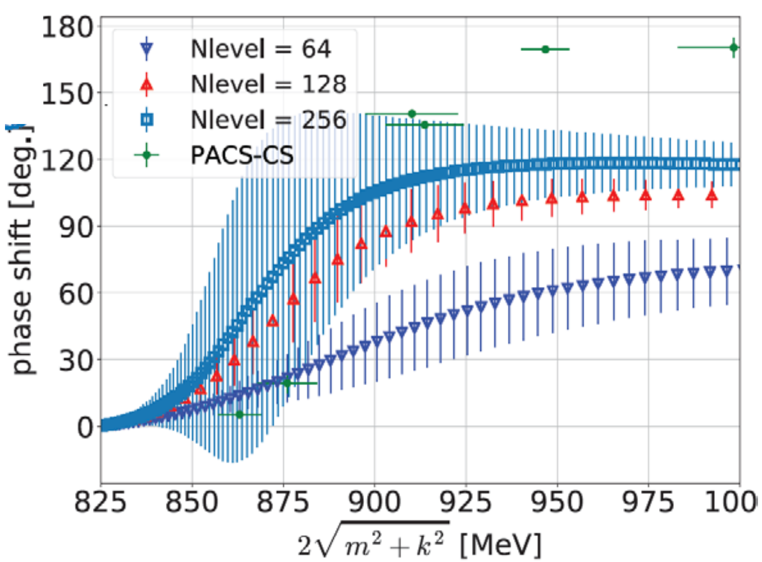


➡ We have to calculate all-to-all correlators to get NBS wave functions.

➡ It needs a lot of computational cost and time.

➔ Distillation method (LapH)

Peardon et al. (2009)



Efficient use of "low-mode" quark propagator
Operator is effectively smeared

Resonant behavior is observed !

2+1 clover, m(pi)=0.41GeV

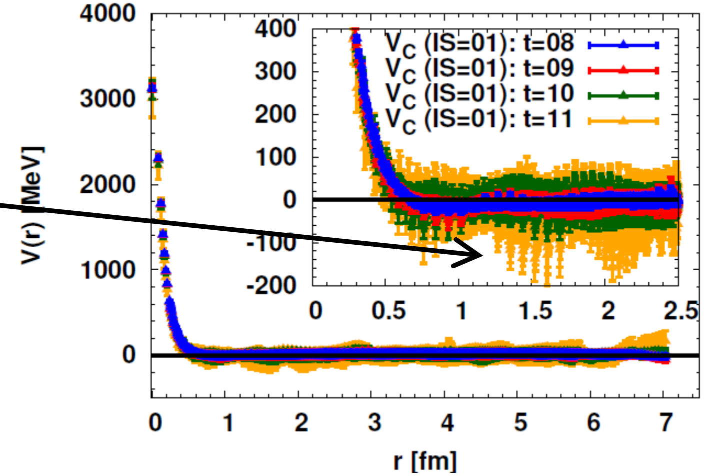
➔ Work w/ all-to-all method in progress (Y. Akahoshi)

R&D for better comput. framework

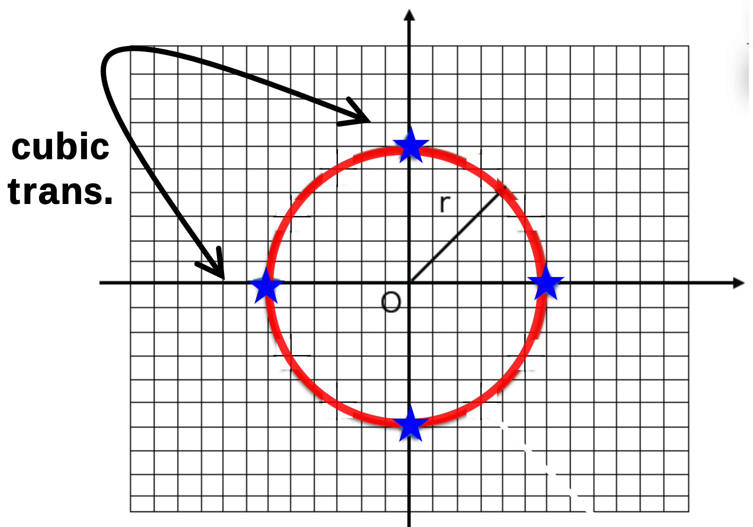
- **LapH method, all-to-all method, ...**
- **Partial wave decomposition method**

multi-valued in r

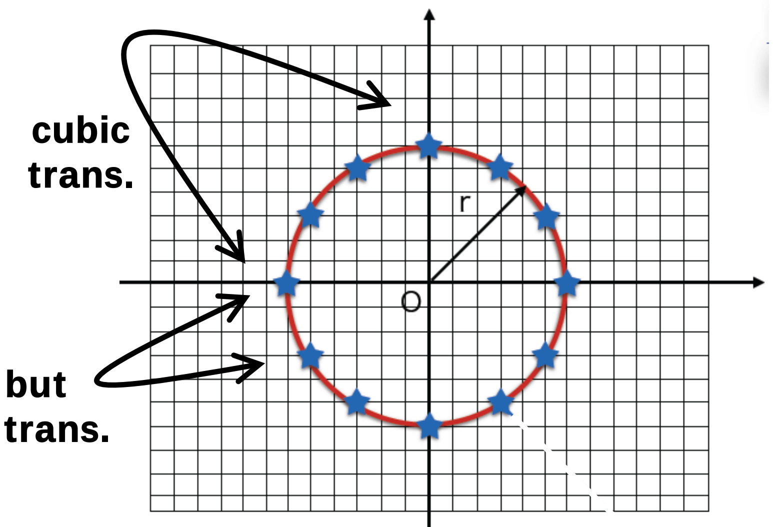
➔ Contaminations of higher partial waves ?



A_1^+ -irrep in cubic group
⟷ L=0, 4, ...



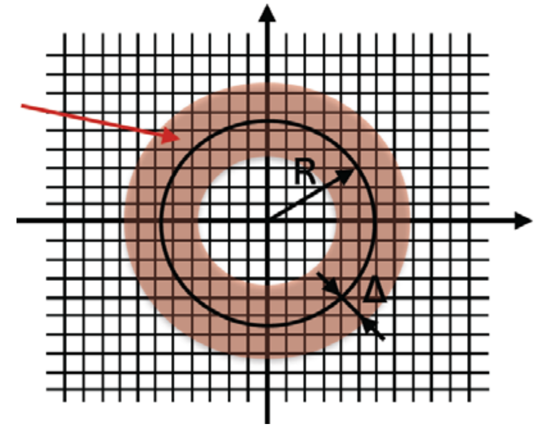
We have more info !



➔ Partial wave decomposition

R&D for better comput. framework

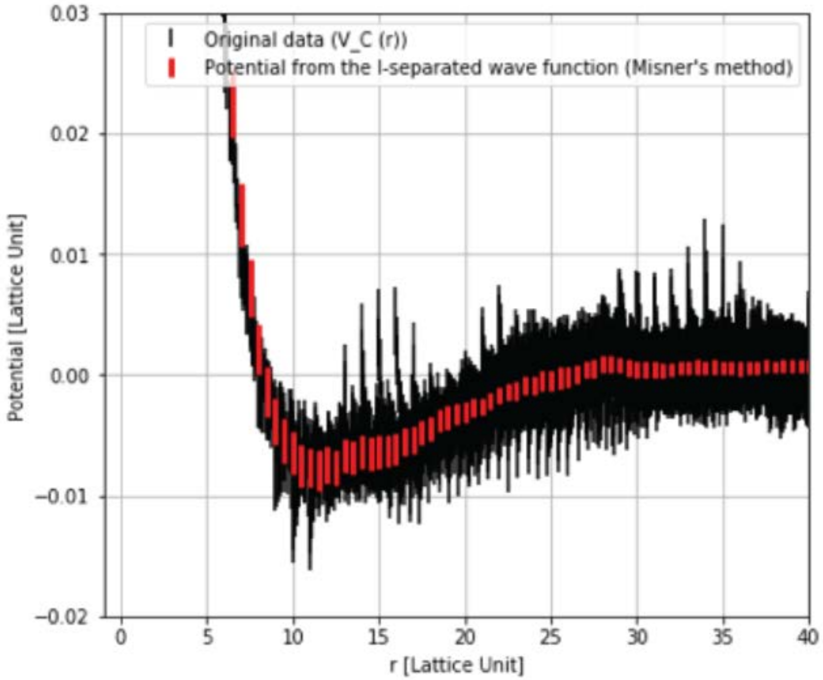
- **Partial wave decomposition method**



C. W. Misner, Class. Quantum Grav. 21 (2004) S243-S247

Sophisticated decomposition w/ binning of “r”

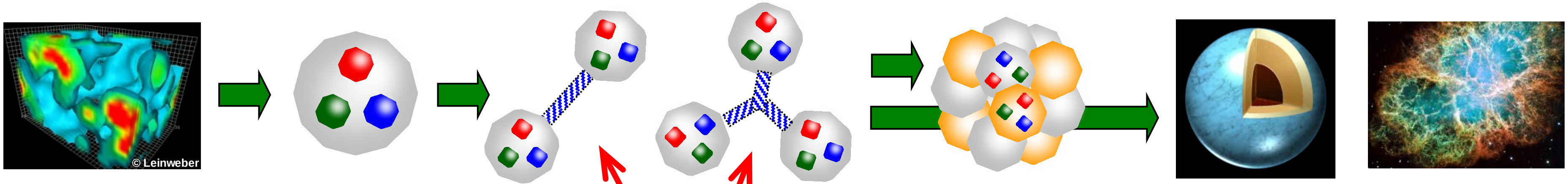
Example of the improvement



The method works well !

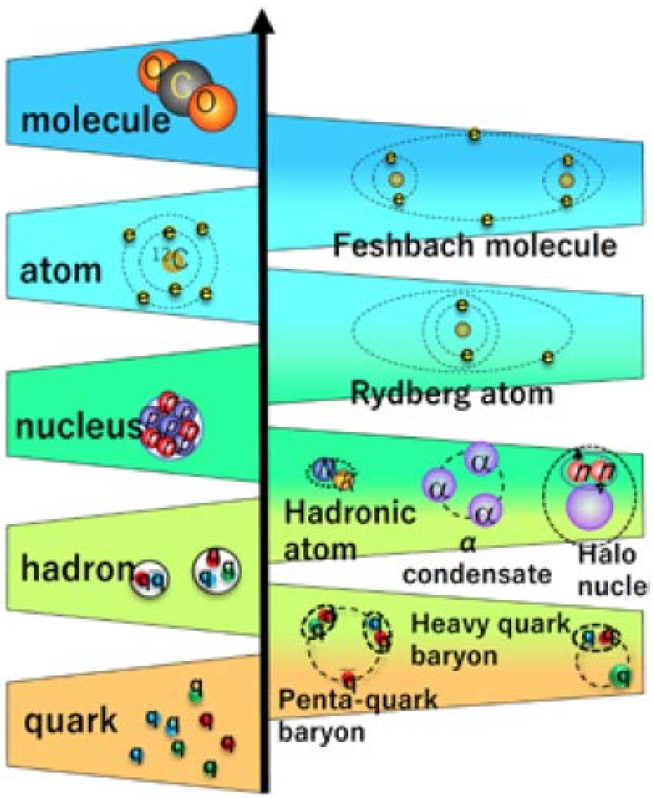
N.B. a part of the improvement (average of V(r) for the same “r”) was already taken into account even in previous studies

[T. Miyamoto]



QCD vacuum → Hadrons → Nuclei → Neutron Stars / Supernovae, Nucleosynthesis

QCD → **Lattice QCD** → **Hadron Forces** → ab-initio nuclear calc.



Final State Interactions in HIC-exp [A01]

Interactions to form Exotic hadrons [A02, B01]

Hyperon interactions [B01]

3-body interactions [B02]

Numerical simulator
←→ cold-atom simulator [C01, C02]

Hyperon interactions → Hypernuclei [D01]
(Hiyama's talk)

Backup Slides

Tcc, Tcs states w/ good diquark

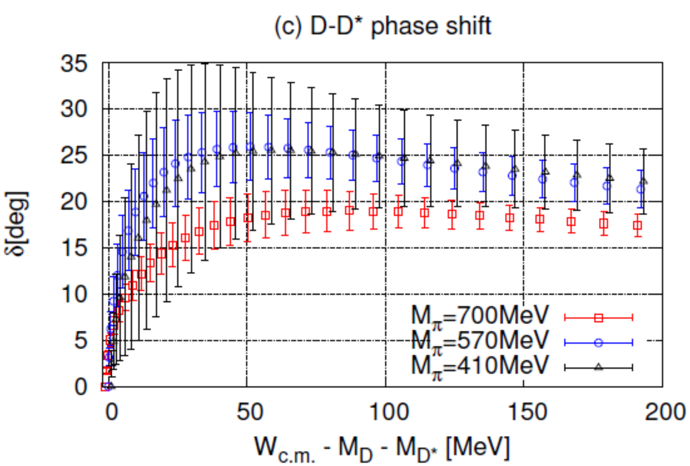
Phase Shift

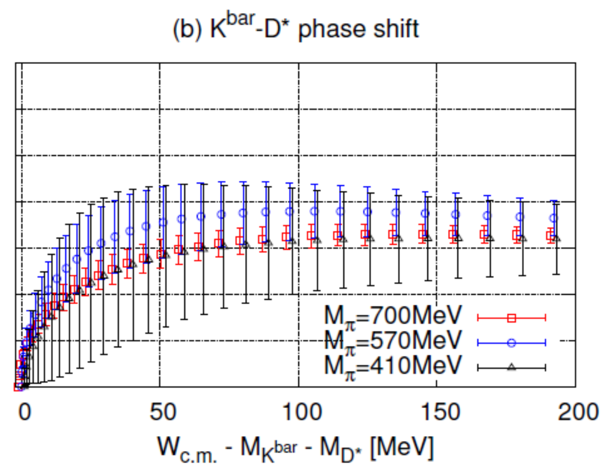
Tcc ($ccu^{bar}d^{bar}$), Tcs($csu^{bar}d^{bar}$)

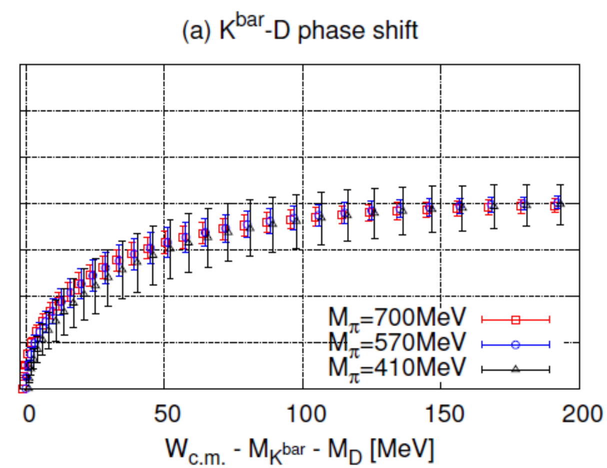
Tcc ($J^P=1^+, I=0$) ⇔ D-D*

Tcs ($J^P=1^+, I=0$) ⇔ K^{bar}-D*

Tcs ($J^P=0^+, I=0$) ⇔ K^{bar}-D





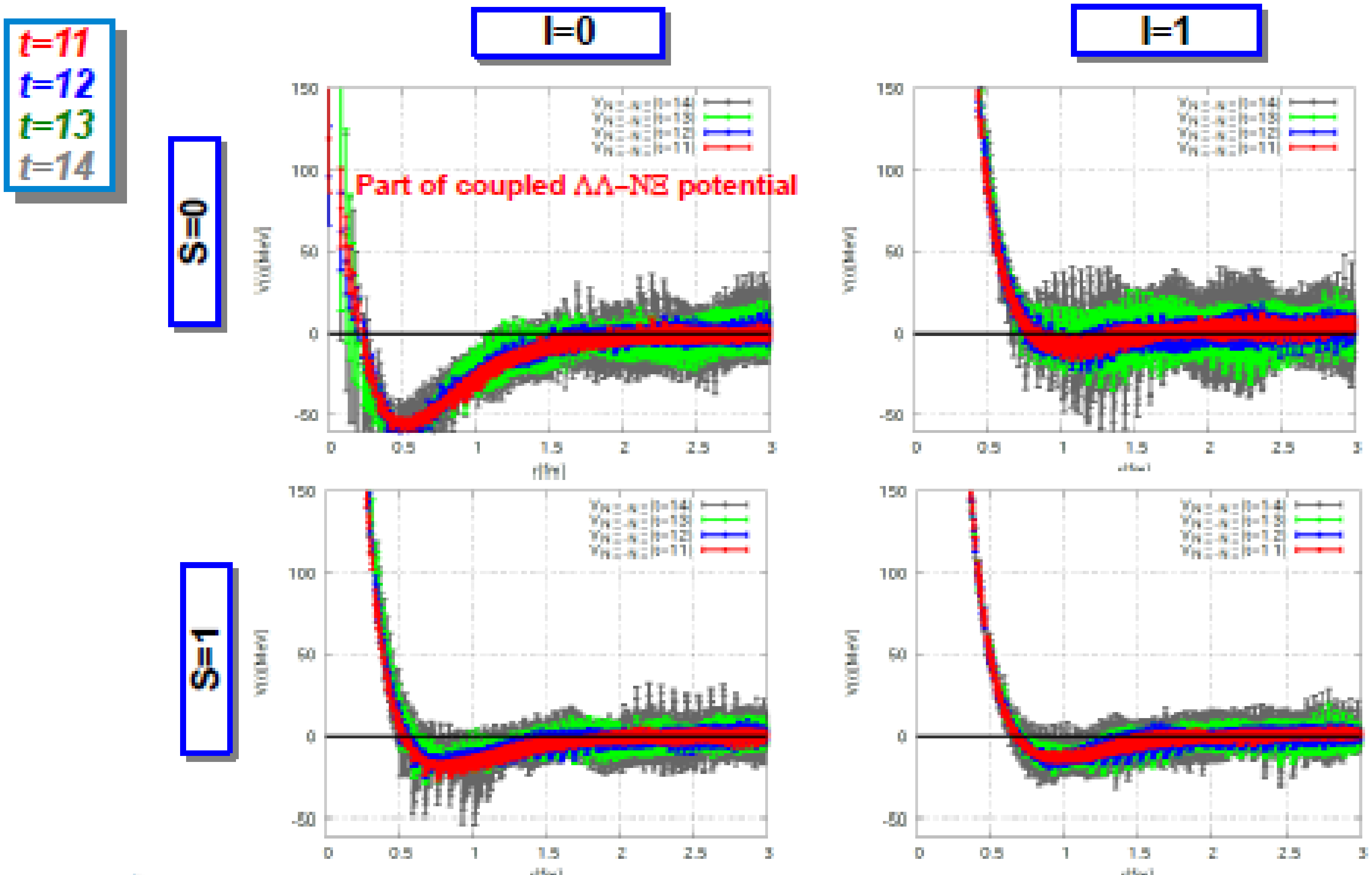


- Strong Attraction, but no bound state for $m\pi$ > 400MeV
- More attractive for lighter quark mass
- T_{bb} has a bound state if we combine m_b & potential in Tcc

Y. Ikeda et al. (HAL QCD), PLB729(2014)85

Spin and Isospin dependence of NΞ potentials

▶ Effective NΞ potentials are plotted. (tensor potential is involved)



▶ Strong attraction can be seen in S=0 I=0 state

[K. Sasaki]