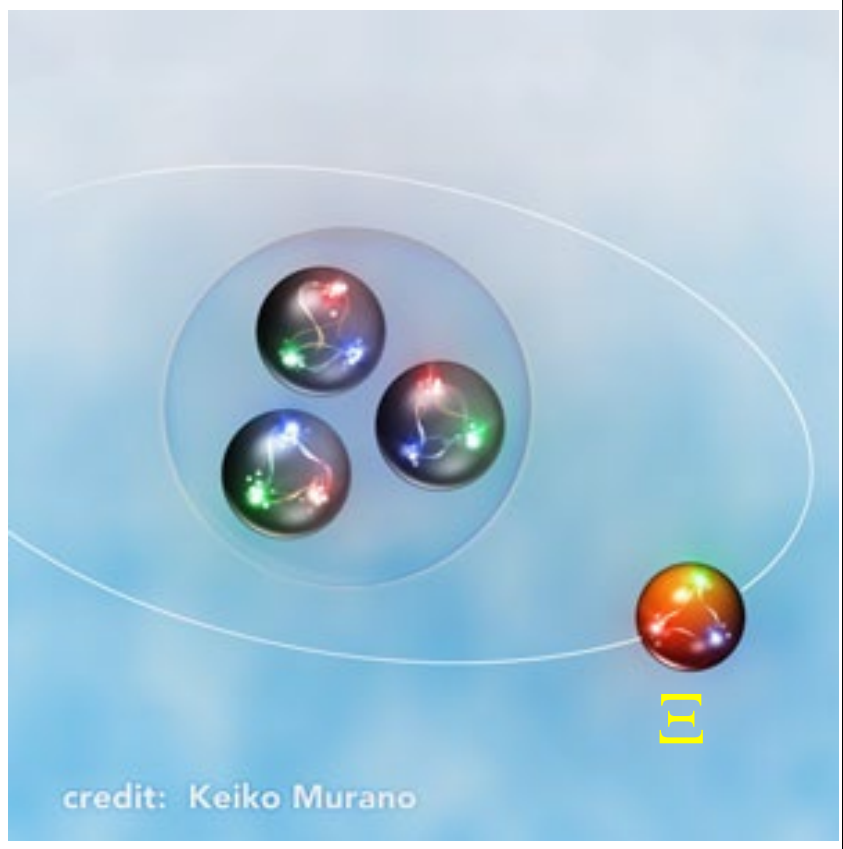
Hyperon interactions from Lattice QCD and Ξ hypernuclei



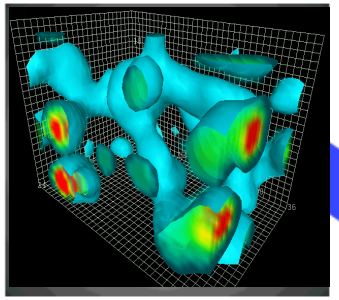
Tetsuo Hatsuda
(RIKEN iTHEMS)

RIKEN iTHEMS
RIKEN interdisciplinary Theoretical & Mathematical Sciences

Clustering as a Window on the Hierarchical Structure of Quantum Systems (CLUSHIQ2022)
(Oct. 31, 2022)

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + \bar{q}\gamma^\mu (i\partial_\mu - g t^a A^a_\mu) q - m\bar{q}q$$

QCD vacuum

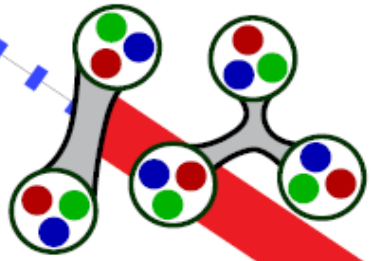


Lattice QCD

Monte Carlo method for
$10^{9\text{-}10}$ dim. QCD Integral

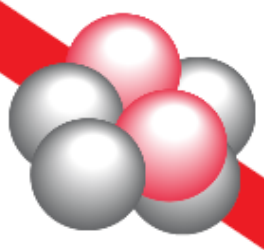
Baryons

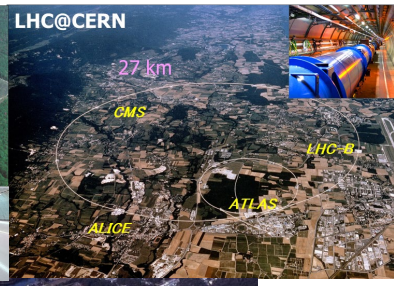
Interactions



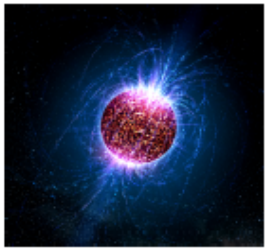
ab-initio nuclear calc.

Nuclei

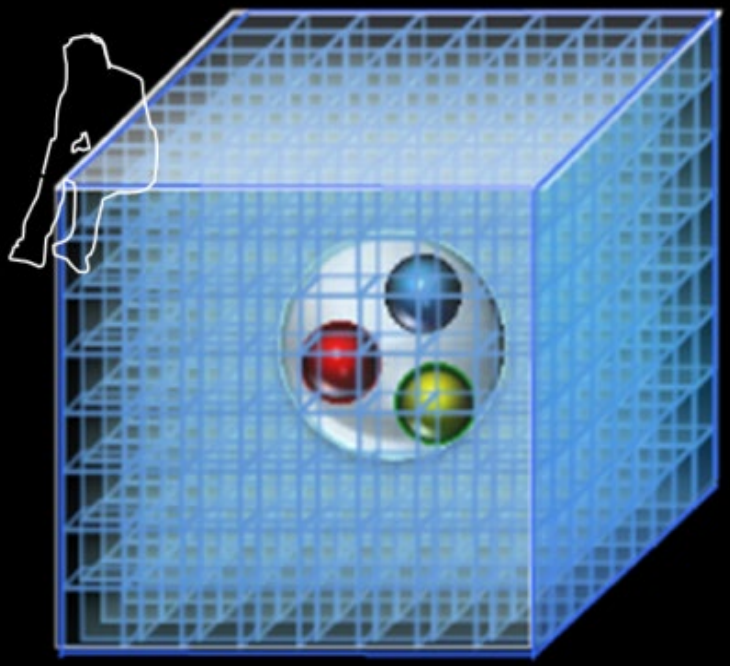




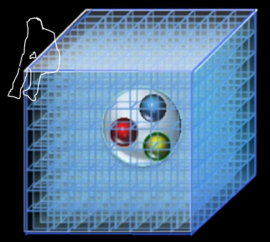
Neutron Stars
Supernovae
Nucleosynthesis

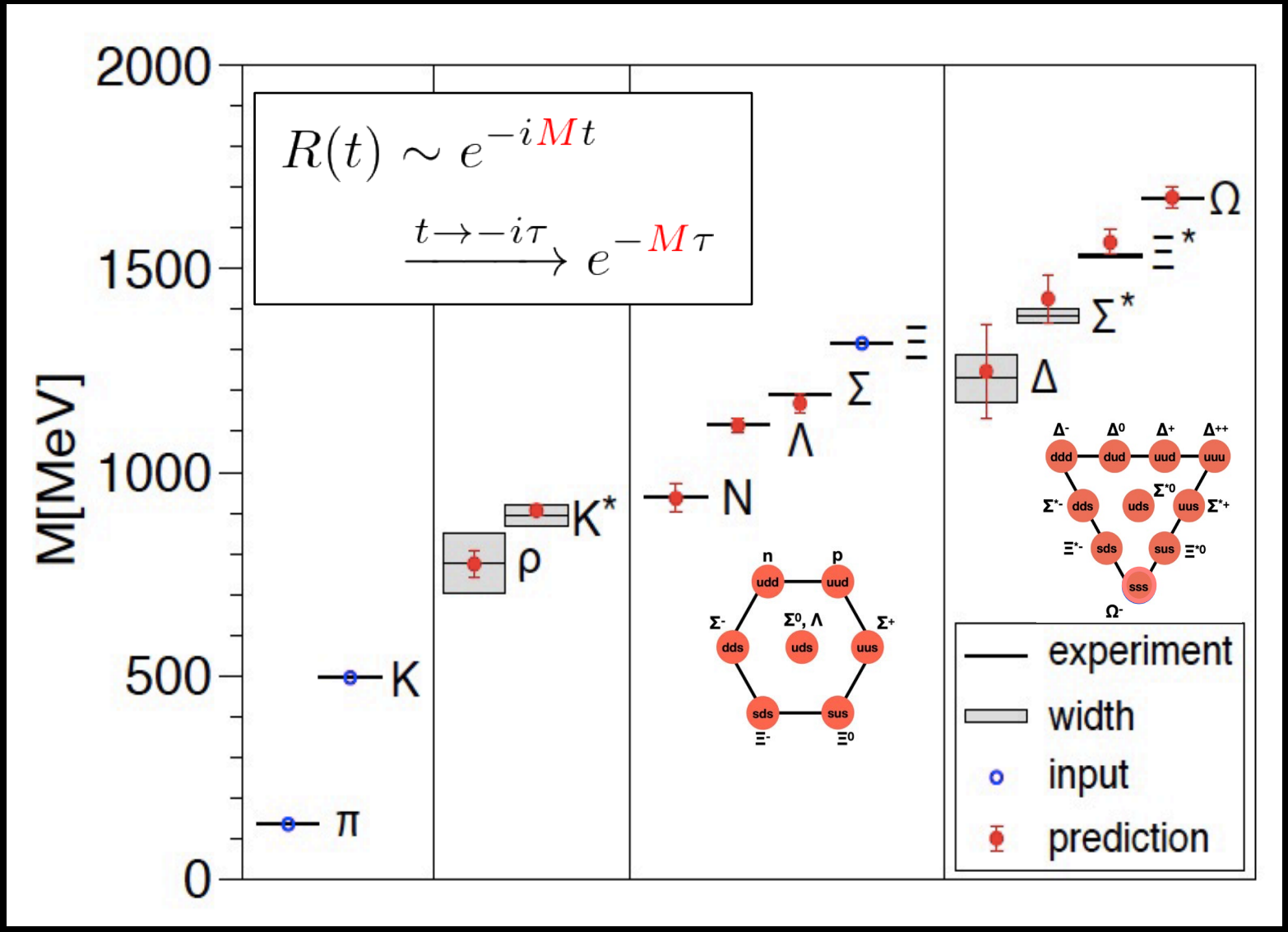


Single Baryon



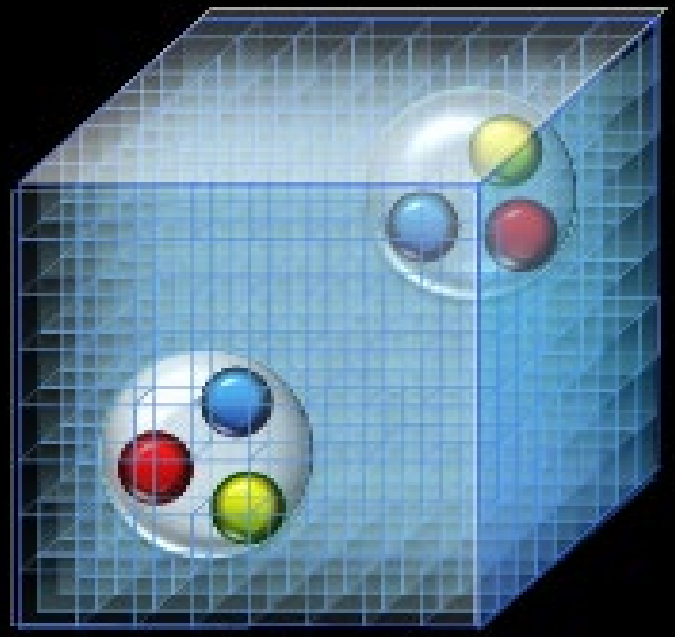
Hadron masses from LQCD





Review: Fodor and Hoelbling, Rev. Mod. Phys. 84 (2012) 449

Baryon Interactions

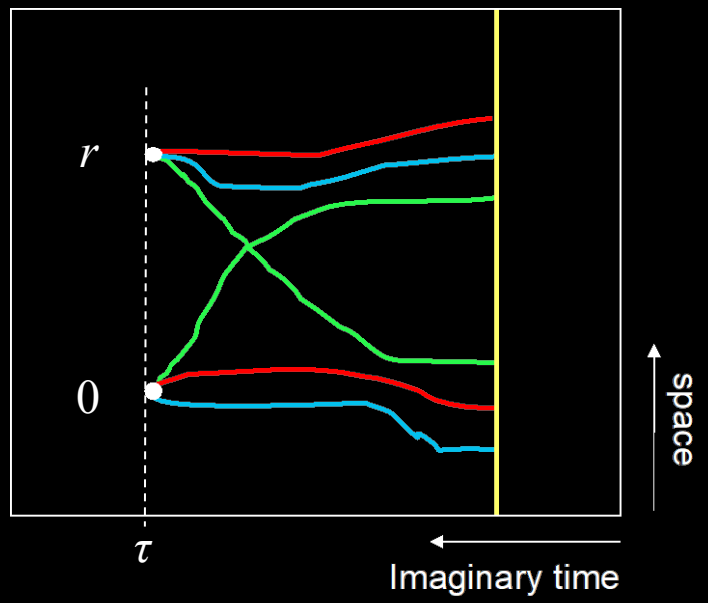


Femtoscopy
Hypernuclei
Neutron stars

Scattering of composite particles

- Haag–Nishijima–Zimmermann reduction formula (1958)
- Borchers Theorem (1960)

$$R(r,\tau) = \sum_n \Psi_n(r) e^{-E_n \tau}$$



HAL QCD Method

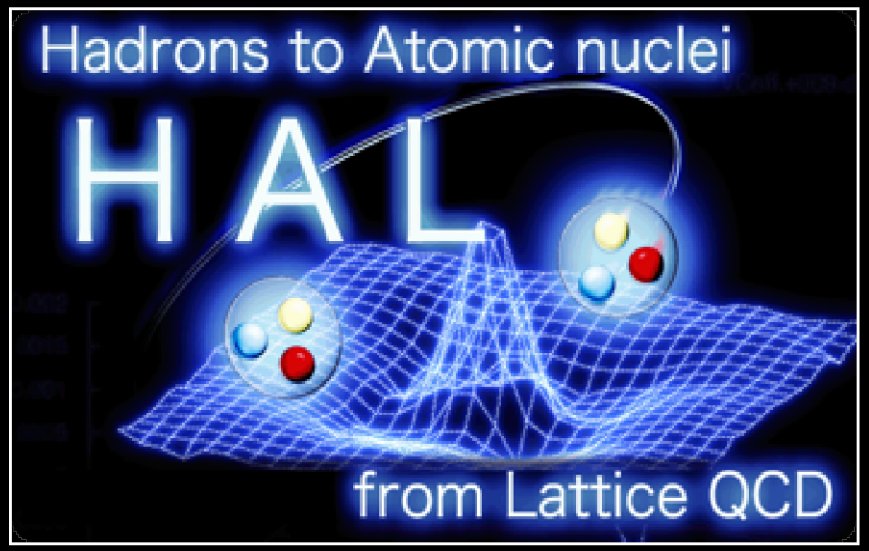
Ishii, Aoki & Hatsuda, PRL 99 (2007) 022001
Ishii+ [HAL QCD Coll.], PLB 712 (2012) 437

$R(r, \tau)$ → LS equation ($T = U + GUT$) → phase shift, binding energy

$$U(\mathbf{r},\mathbf{r}') = V(\mathbf{r},\mathbf{v})\delta(\mathbf{r}-\mathbf{r}'),$$

$$V(\mathbf{r},\mathbf{v}) = \underbrace{V_C(r) + V_T(r)S_{12}}_{\text{LO}} + \underbrace{V_{LS}(r)\mathbf{L}\cdot\mathbf{S}}_{\text{NLO}} + \underbrace{O(\mathbf{v}^2)}_{\text{N}^2\text{LO}} + \cdots$$

Large scale LQCD simulations for BB interactions



(KEK) T. Aoyama

(RIKEN) T. Doi, T. Hatsuda, T. Sugiura

(Nihon) T. Inoue

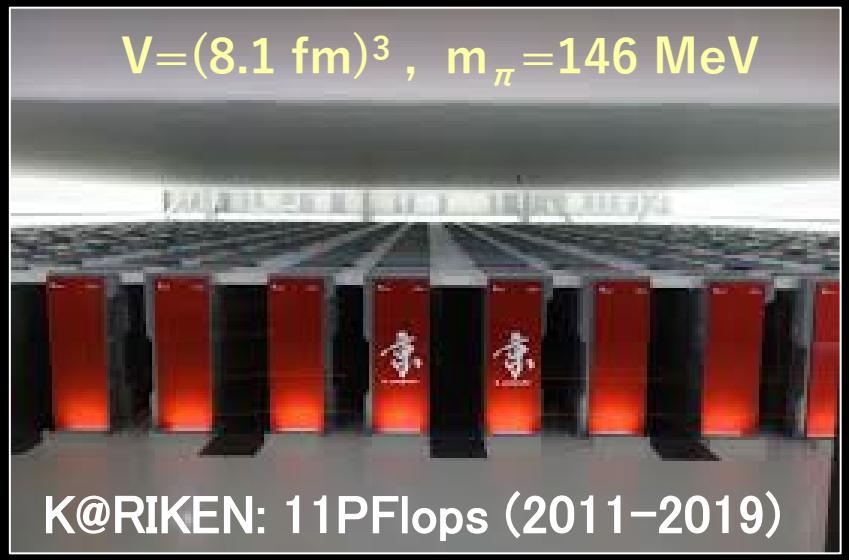
(YITP) Y. Akahoshi, S. Aoki, K. Murakami

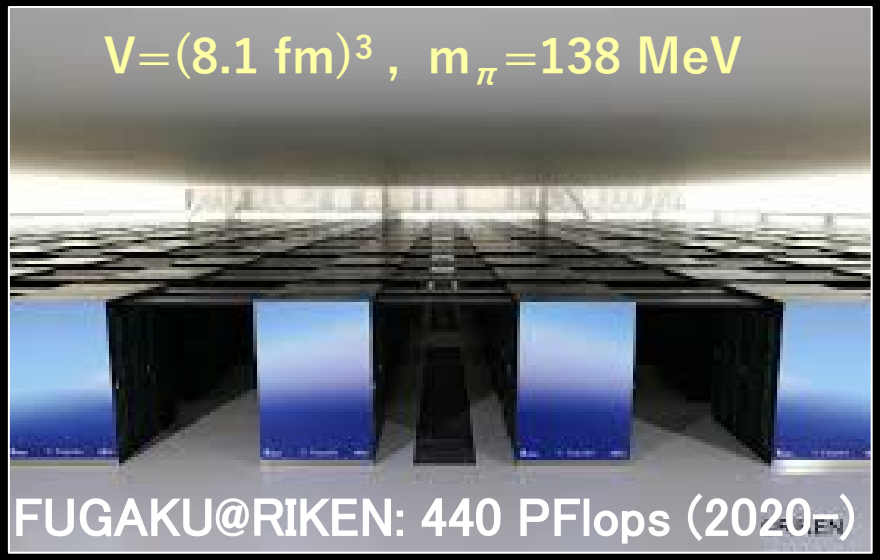
(RCNP) T. M. Doi, N. Ishii, K. Murano, H. Nemura

(Osaka) Y. Ikeda, K.Sasaki

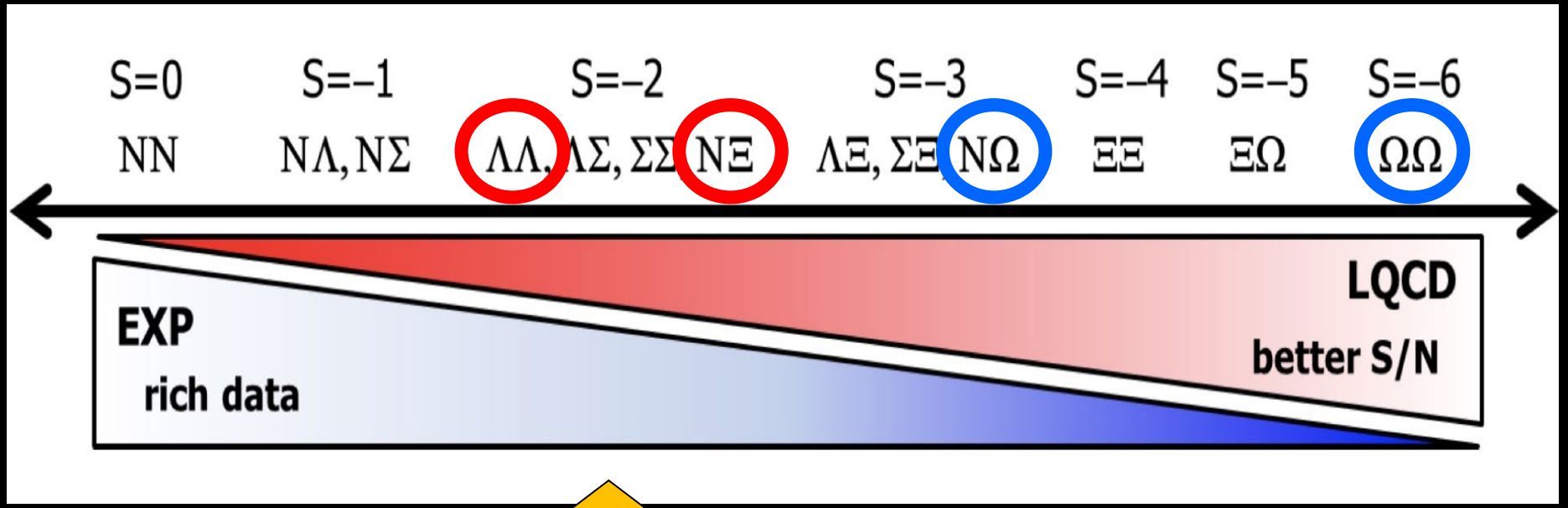
(Birjand) F. Etminan

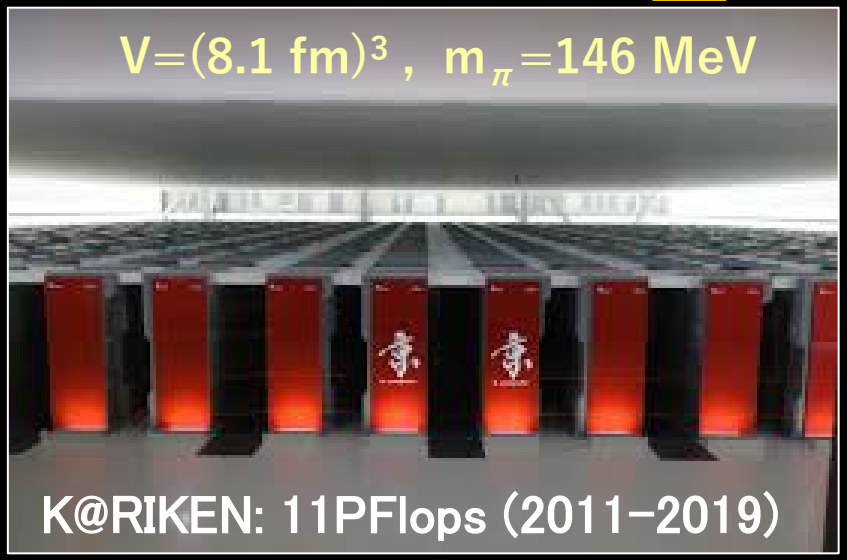
(Beijing) Yan Liu, Hui Tong

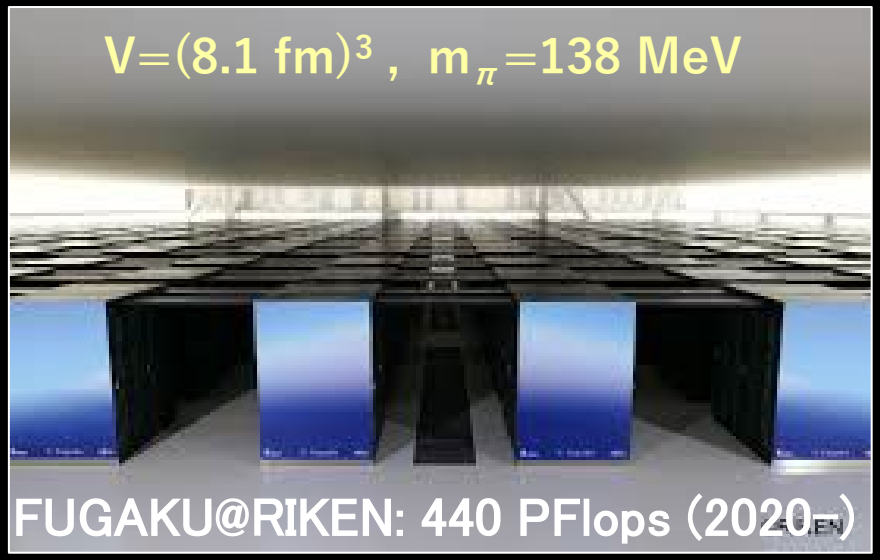




Large scale LQCD simulations for BB interactions





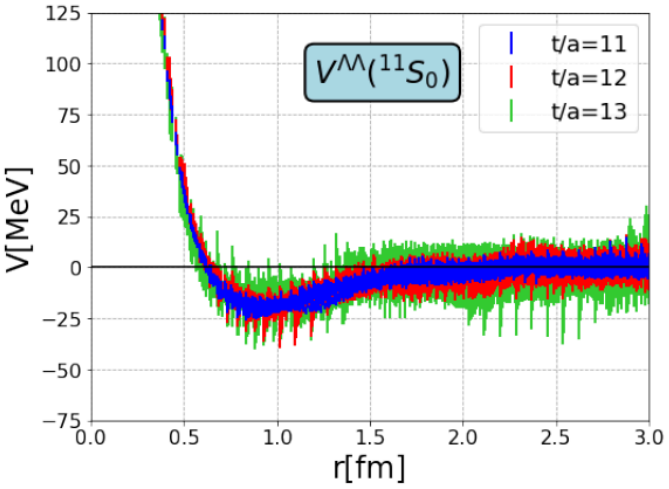


Coupled Channel S=-2 system

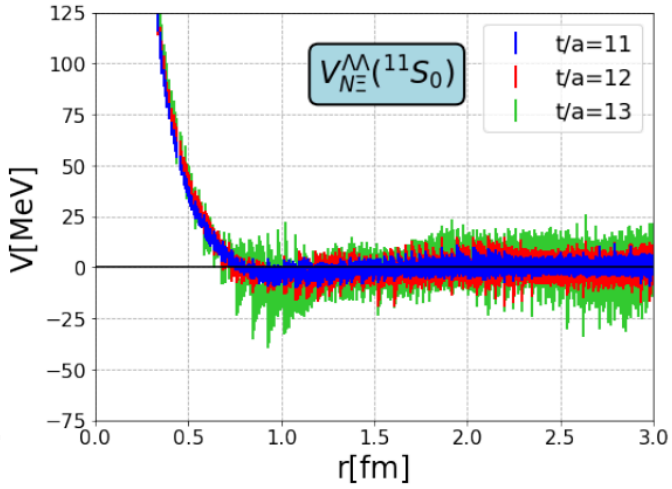
K. Sasaki+ [HAL QCD Coll.]
Nucl. Phys. A998 (2020)

Small ΛΛ attraction

Short-range NΞ-ΛΛ coupling

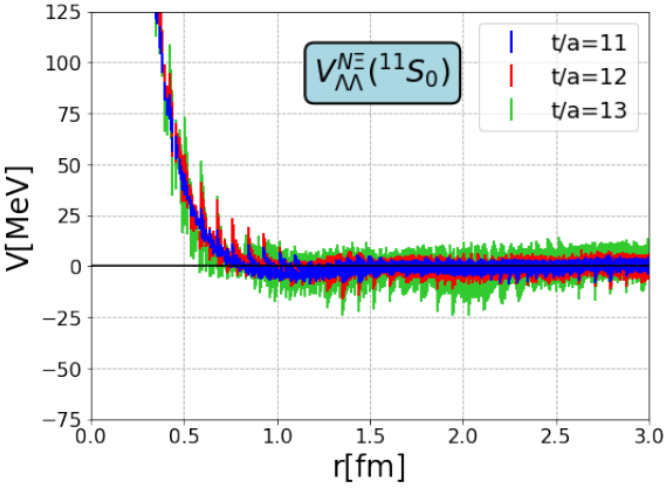


(a)



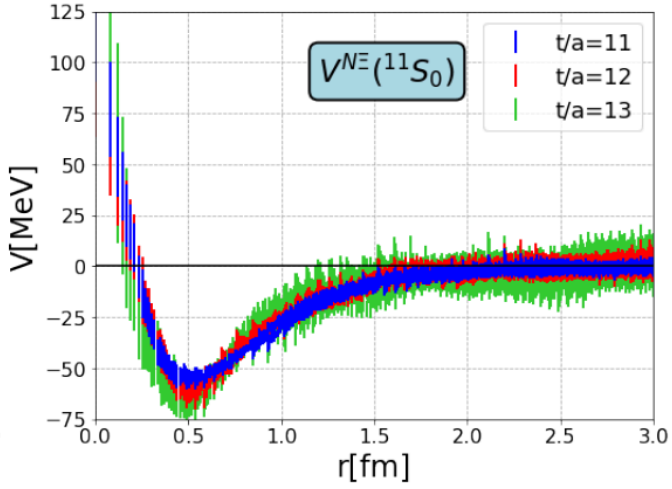
(b)

Short-range NΞ-ΛΛ coupling



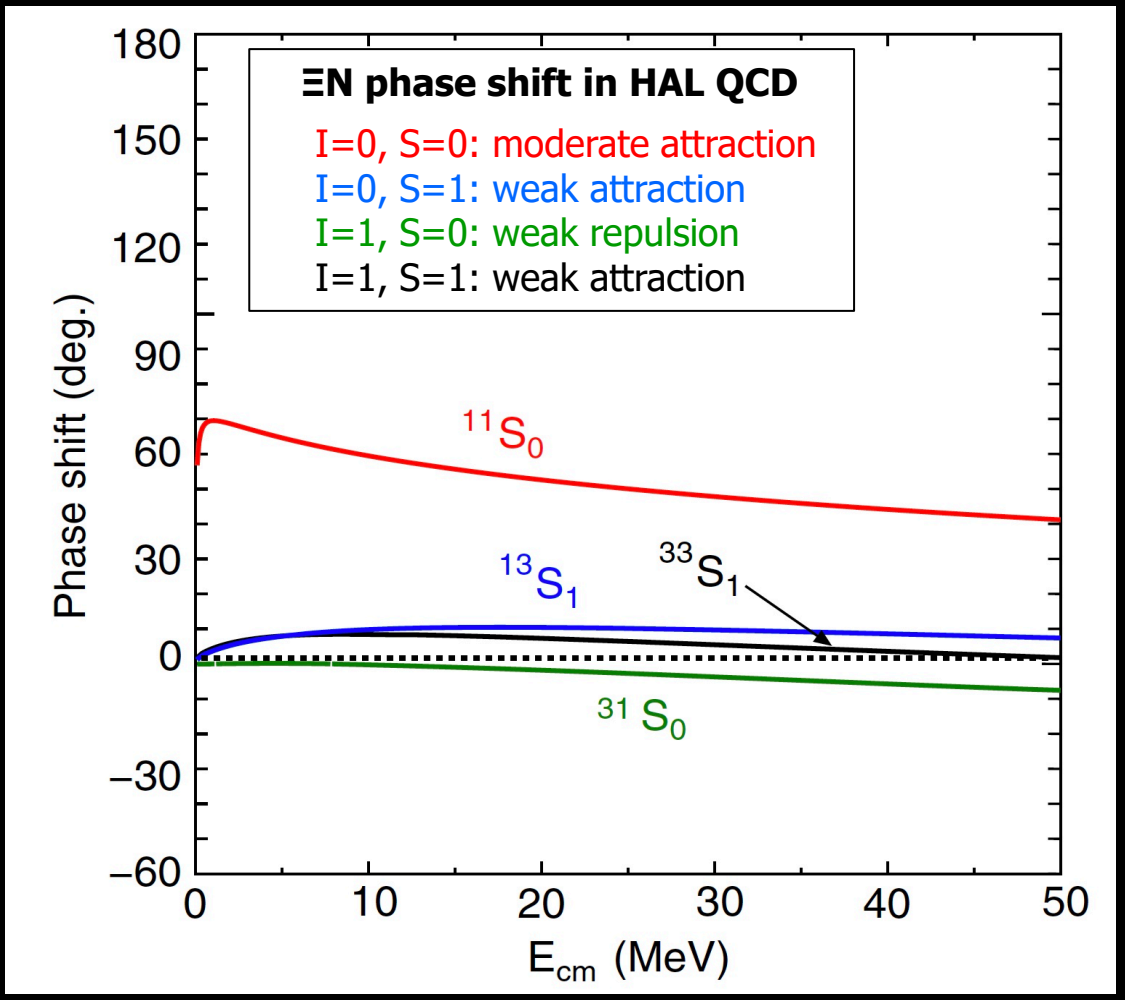
(c)

Large NΞ attraction



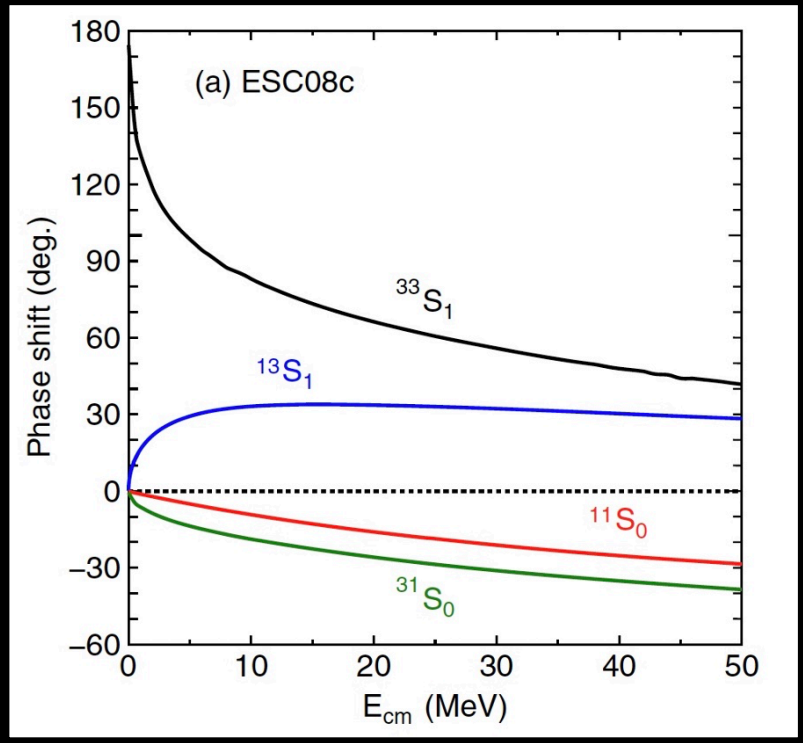
(d)

ΞN scattering phase shifts



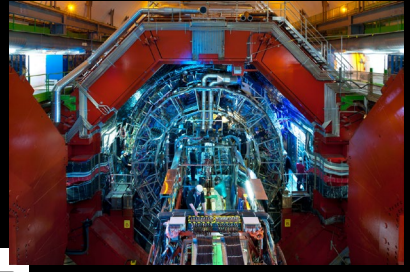
← Lattice QCD force
(∜∜ renormalized)

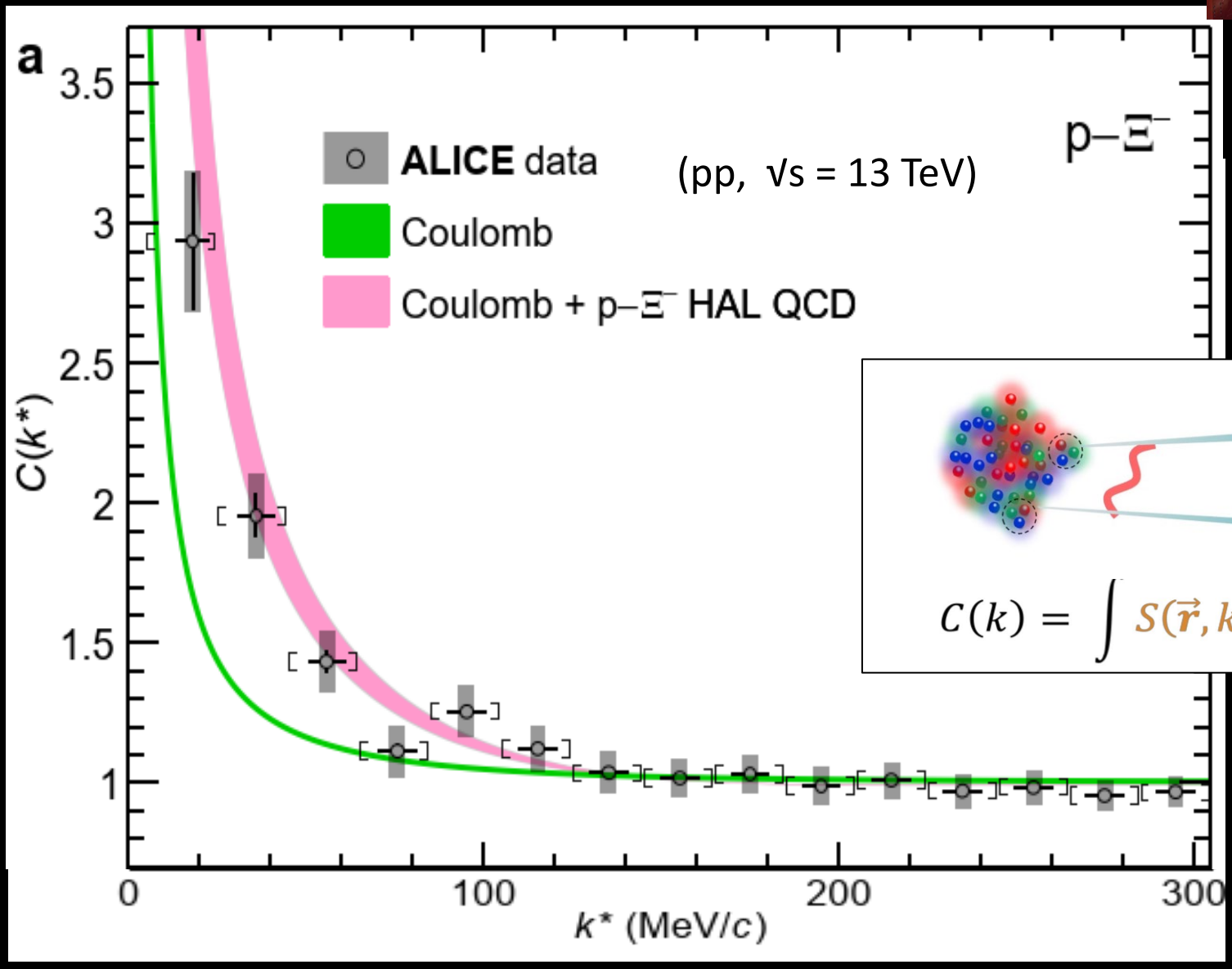
Phenomenological force
↓



Femtoscopy: NΞ pair in pp collisions

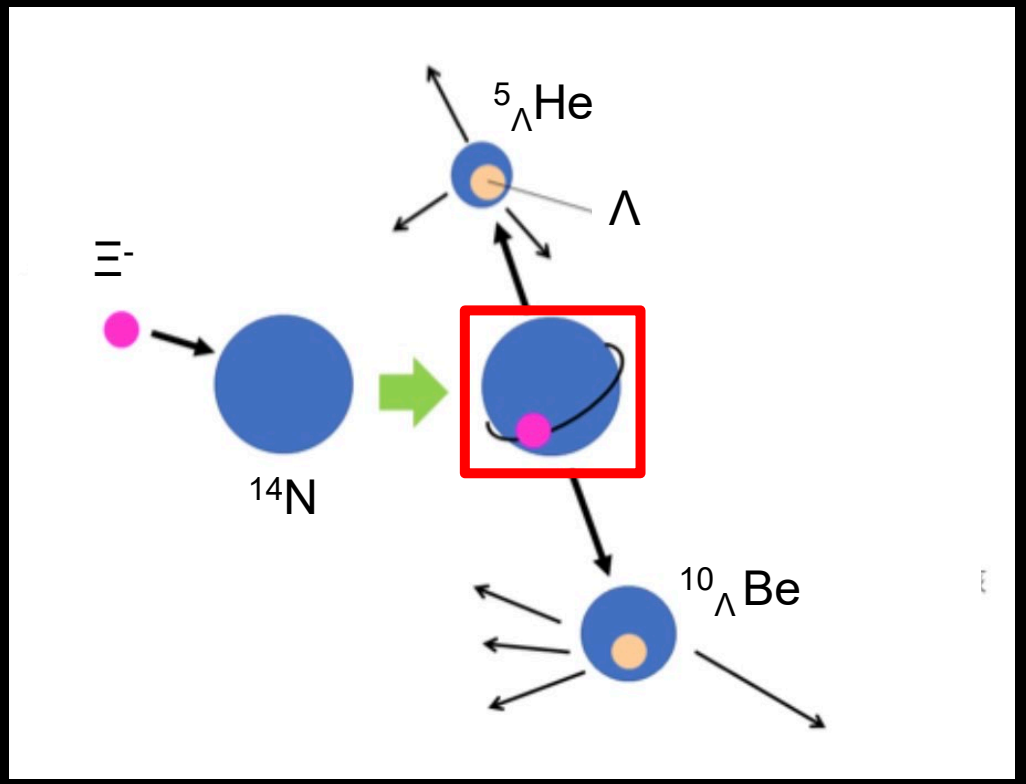
LHC ALICE Coll., Nature 588 (2020) 232





Ξ hypernuclei at J-PARC

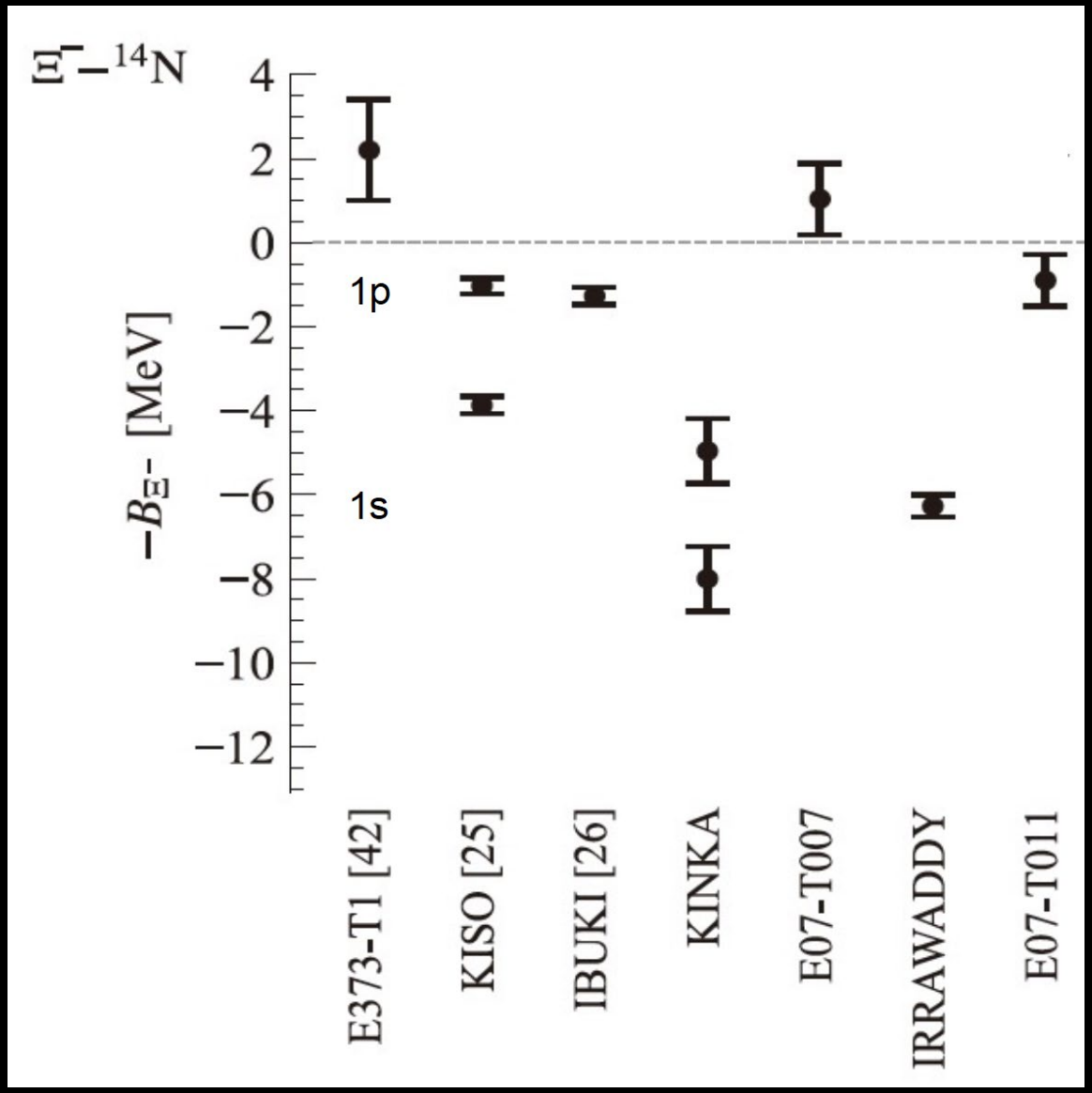
E07 Coll. at J-PARC,
Phys.Rev.Lett. 126 (2021) 062501



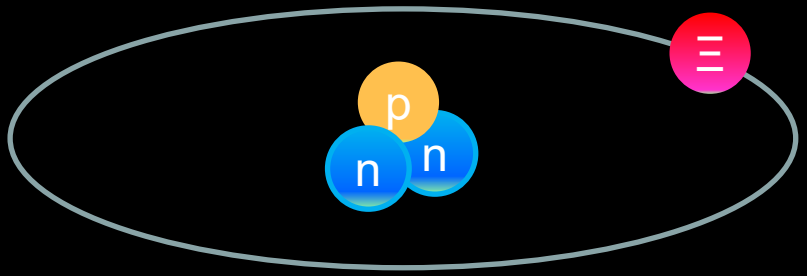
Attraction in NΞ
Weak NΞ- ΛΛ coupling

Ξ hypernuclei found so far

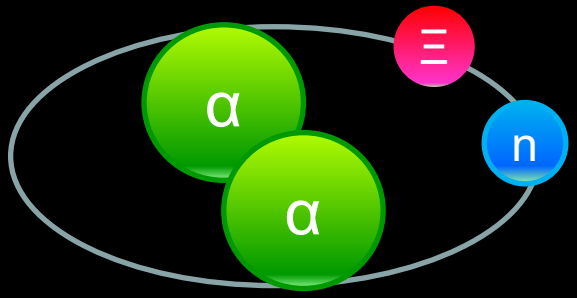
Yoshimoto+, PTEP 2021 (2021) 073D02



Q1. What is the lightest
Ξ hypernuclei?

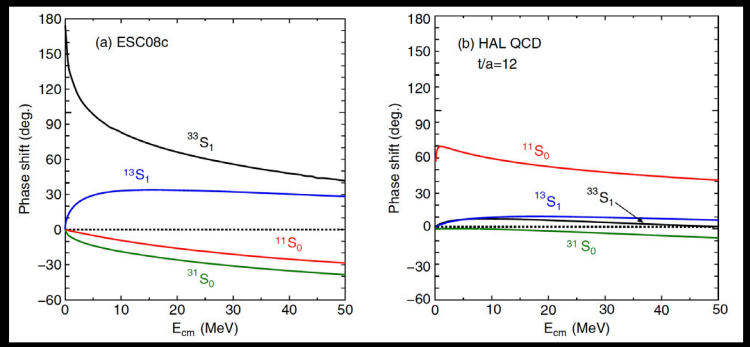


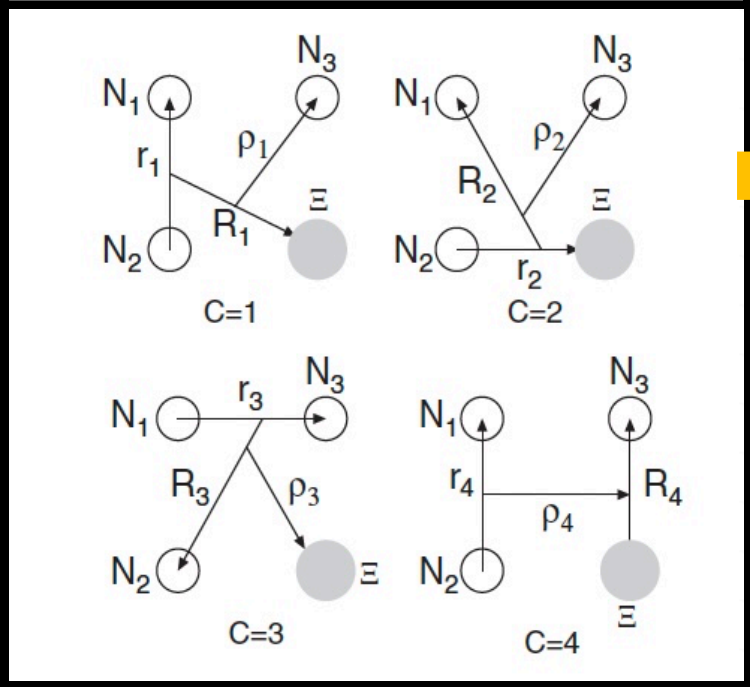
Q2. Can we test the
spin-isospin dependence
of ΞN int.?



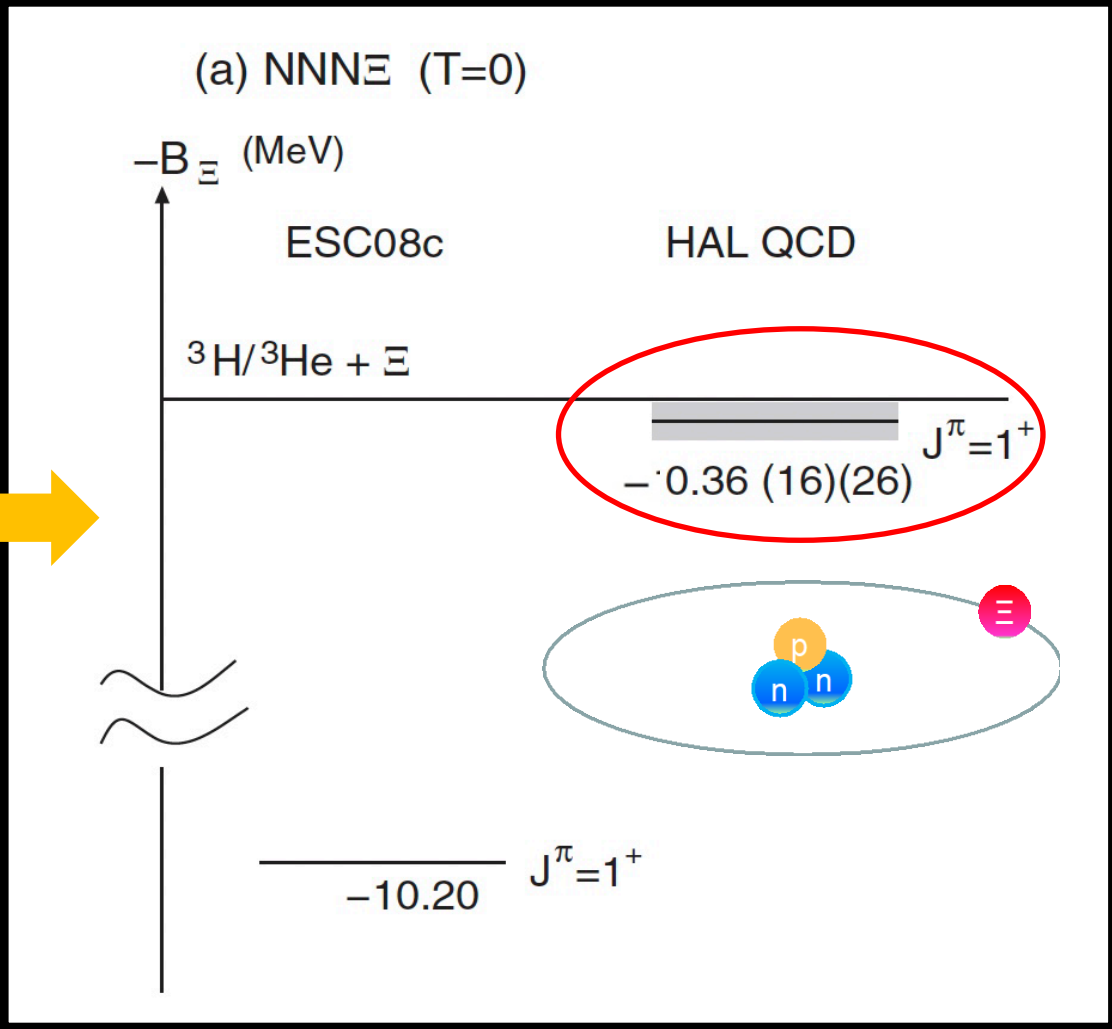
Q1. What is the lightest Ξ hypernuclei?

Hiyama, Sasaki, Miyamoto, Doi, Hatsuda, Yamamoto, Rijken,
Phys.Rev.Lett.124 (2020) 092501





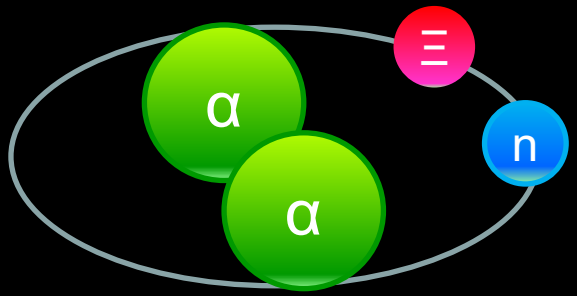
Gaussian expansion method
(Hiyama et al., 2003)

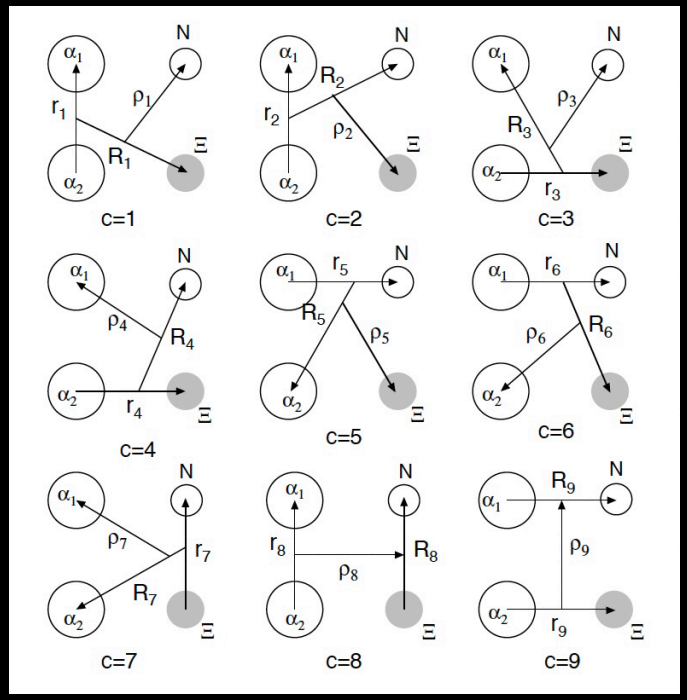


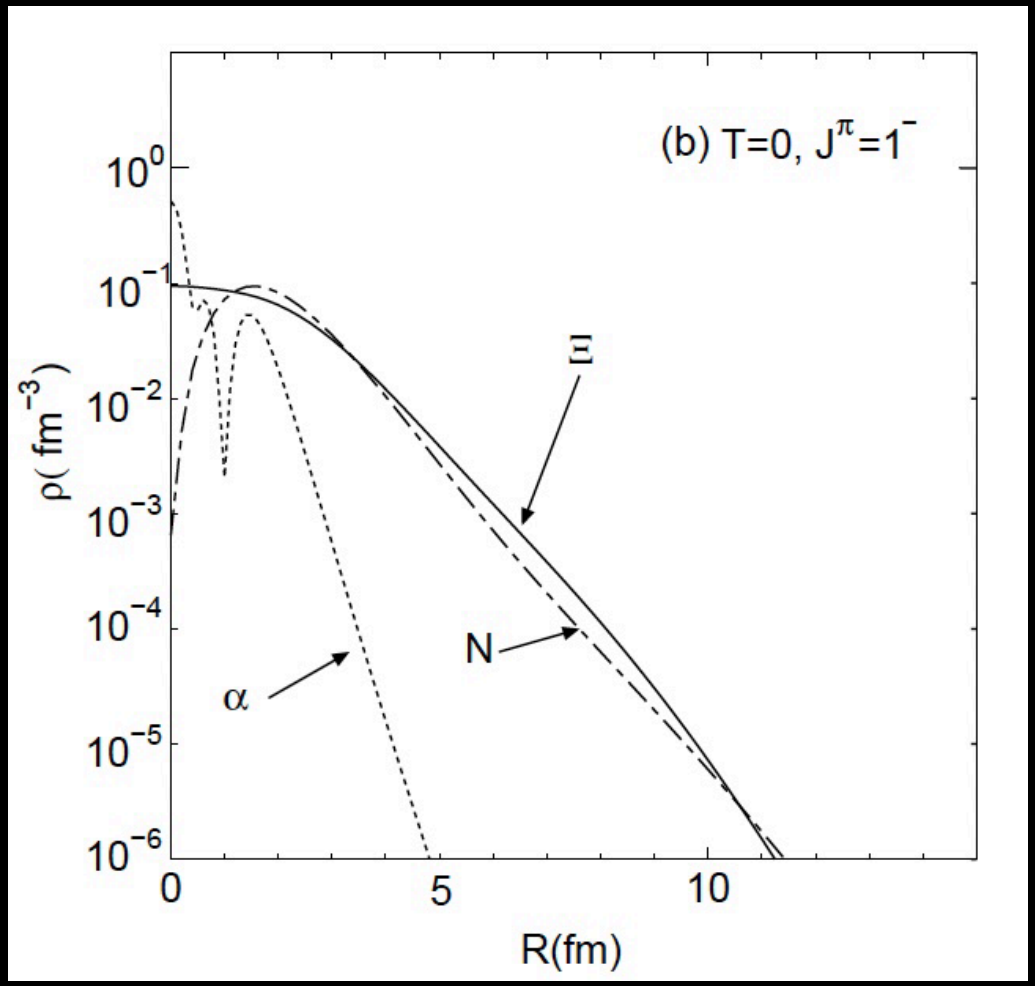
Γ ~ 60 keV

Q2. Can we test the spin-isospin dependence of ΞN int.?

Hiyama, Isaka, Doi, Hatsuda, arXiv:2209.06711 [nucl-th]

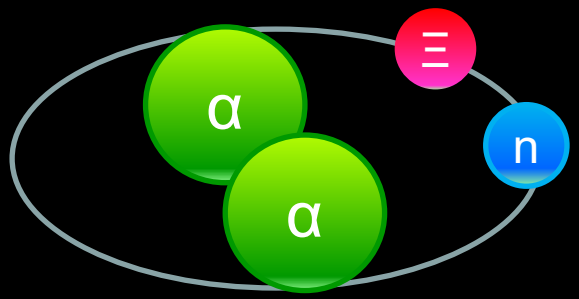




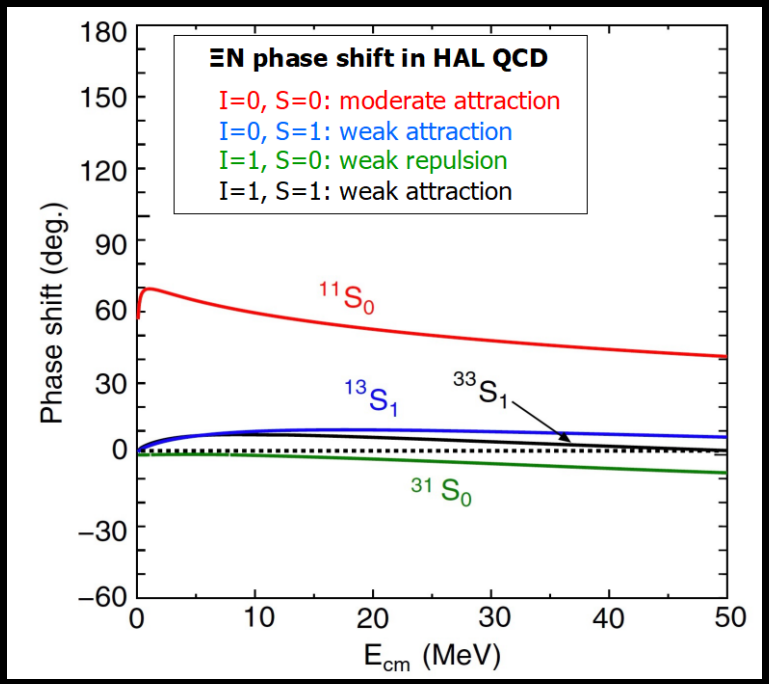


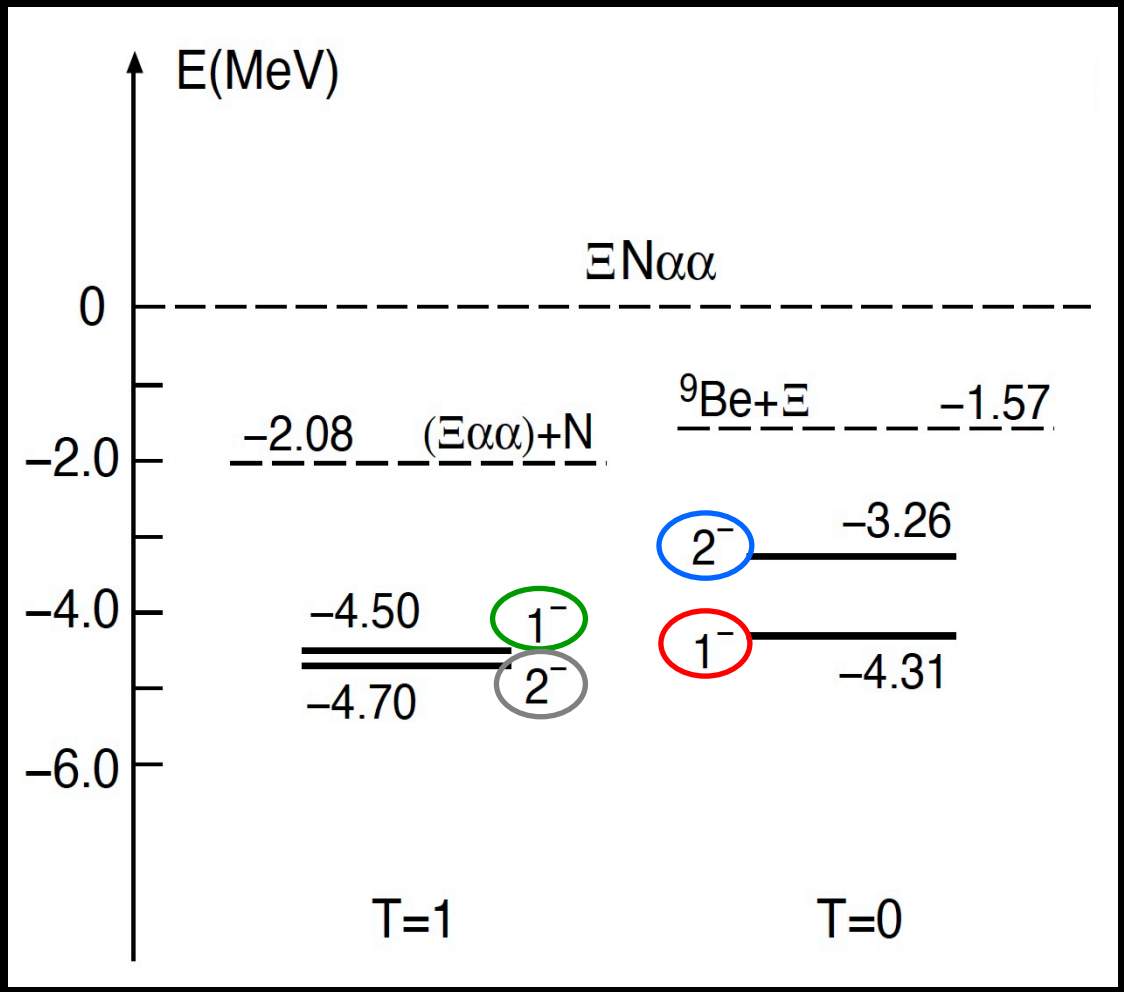
Gaussian expansion method (Hiyama et al., 2003)

Inversion of spin-doublets in ΞNαα system



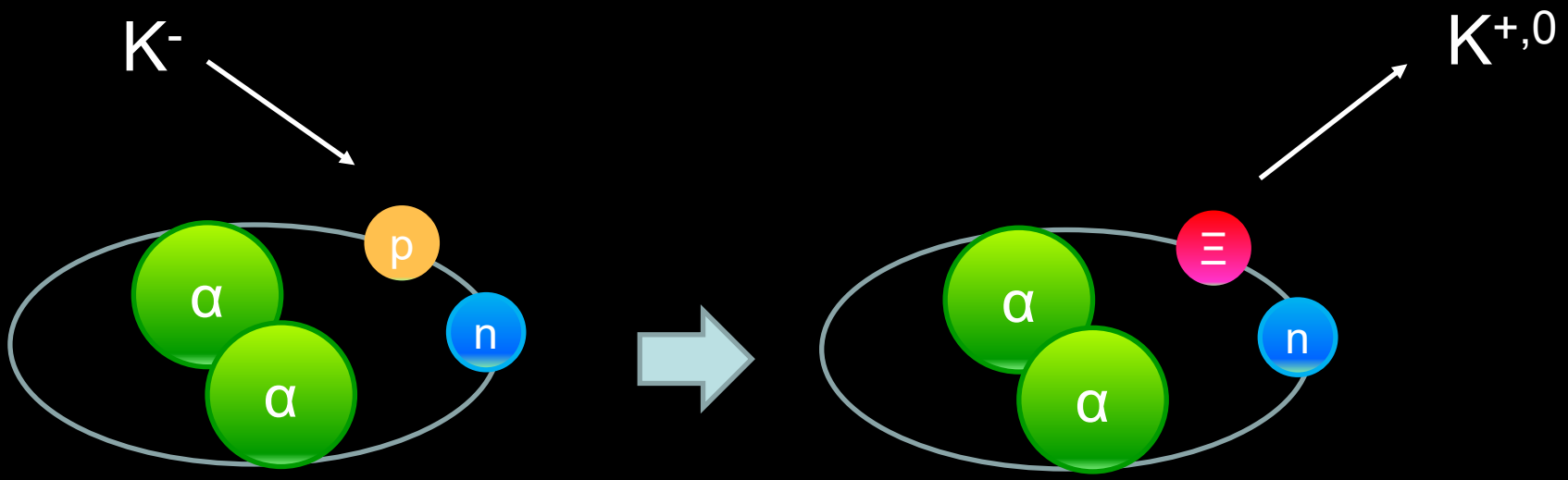
Hiyama, Isaka, Doi, Hatsuda,
arXiv:2209.06711 [nucl-th]





Γ=20-40 keV

Q3. How to create bound ΞNαα systems



^{10}Be (K^-,K^+) $[\Xi N\alpha\alpha]_{T=1}$

^{10}Be (K^-,K^0) $[\Xi N\alpha\alpha]_{T=0}$

Conclusions

1. LQCD simulations for YN and YY interactions at m_π=146MeV (K) and at 138 MeV (FUGAKU). [HAL QCD Coll.]

2. LQCD data vs. and femtoscopy data. [ALICE Coll. at LHC]

3. Hypernuclei using few-body method (GEM) + LQCD.

   -- What is the lightest Ξ hypernuclei ?
   NΞ, NNΞ none, NNNΞ possible

   Hiyama et al.,
   PRL 124 (2020) 092501

   -- Can we test the spin-isospin dep. of ΞN int.?
   Ξ hypernuclei wirh α cores

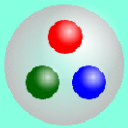
   Hiyama, Isaka, Doi, Hatsuda,
   arXiv:2209.06711 [nucl-th]

   -- Possible expt. to study ΞNαα.
   K^- induced reactions

Thank you !

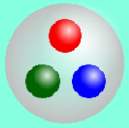
Hyperon embedded in cold nuclear matter (HAL QCD + BHF)

hyperon

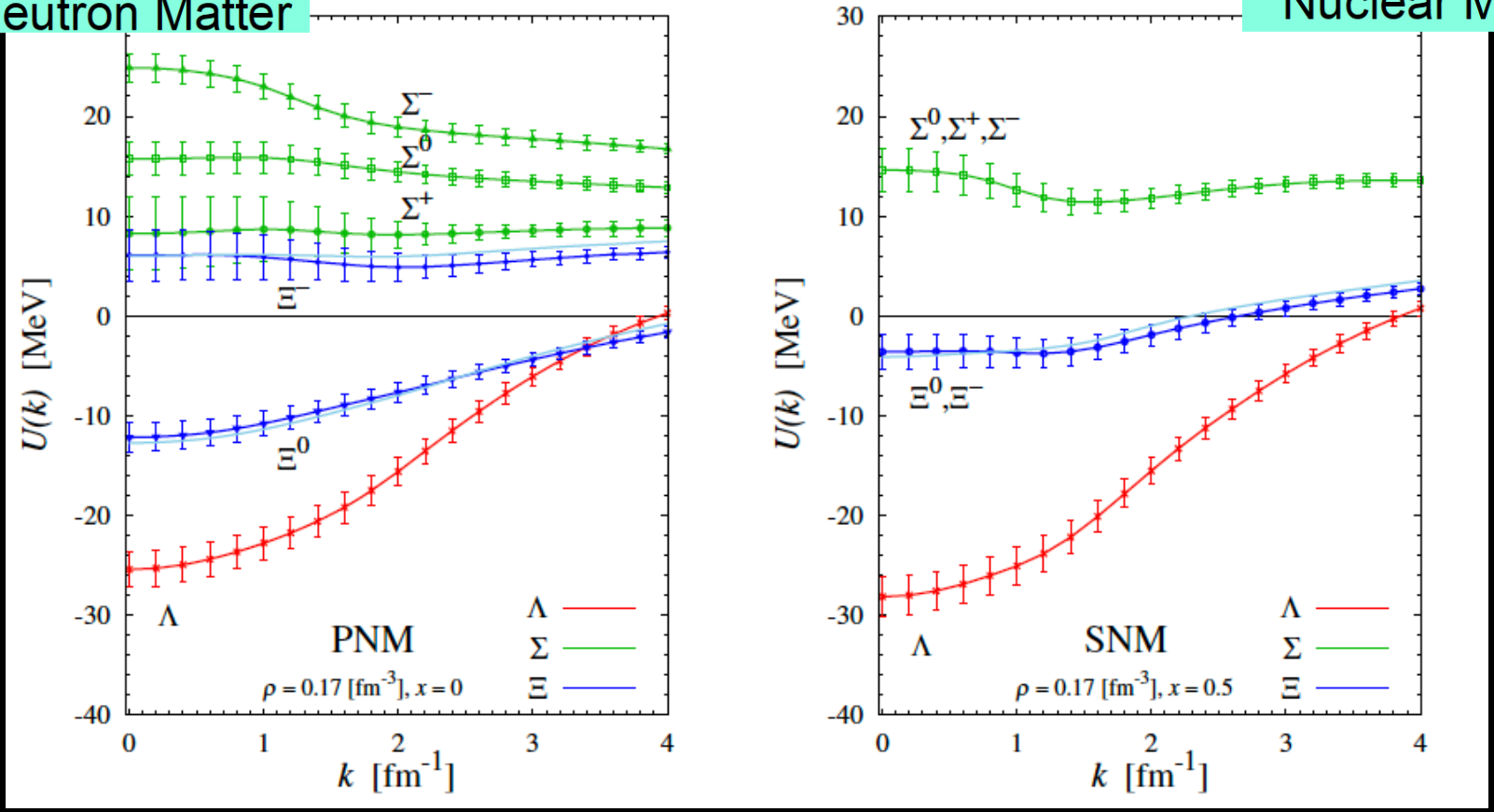


Neutron Matter

hyperon



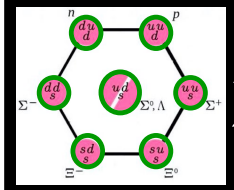
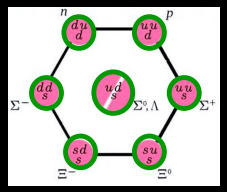
Nuclear Matter



Inoue [HAL QCD Coll.], Few-body Syst. 62 (2021) 106

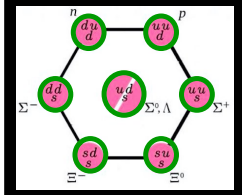
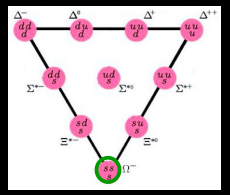
Hiyama, Sasaki, Miyamoto, Doi, Hatsuda, Yamamoto, and Rijken, PRL 124 (2020) 092501

$SU(3)_F$ classification of BB system


x


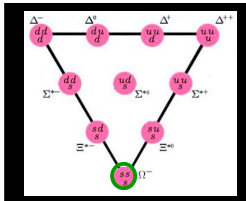
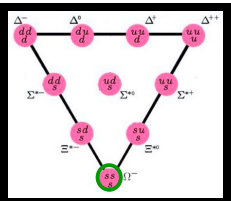
$$8 \times 8 = 27 + 8_s + 1 + 10^* + 10 + 8_a$$

$NN(^1S_0)$ $H(^1S_0)$ Jaffe (1977) $NN(^3S_1)$ deuteron


x


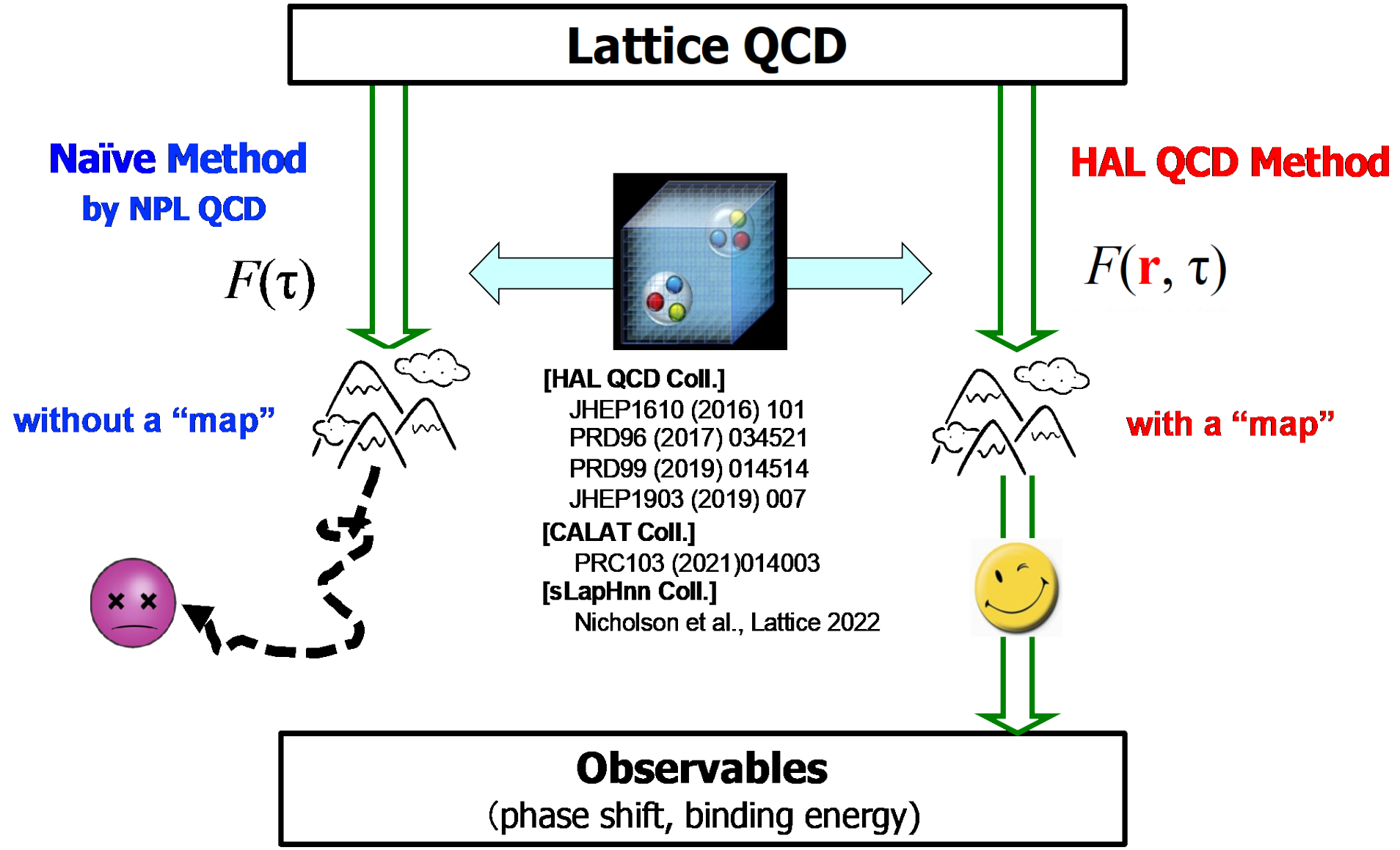
$$8 \times 10 = 35 + 8 + 10 + 27$$

$N\Omega\ (^5S_2)$ Goldman+ (1987) Oka (1988)

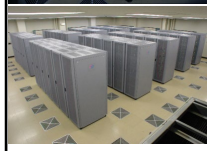

x


$$10 \times 10 = 28 + 27 + 35 + 10^*$$

Kopeliovich+ (1990) $\Omega\Omega(^1S_0)$ $\Delta\Delta(^7S_3)$ Dyson+ (1964)


Lattice QCD
Naïve Method
by NPL QCD
$F(\tau)$
HAL QCD Method
$F(\mathbf{r}, \tau)$
without a "map"
with a "map"
[HAL QCD Coll.]
JHEP1610 (2016) 101
PRD96 (2017) 034521
PRD99 (2019) 014514
JHEP1903 (2019) 007
[CALAT Coll.]
PRC103 (2021)014003
[sLapHnn Coll.]
Nicholson et al., Lattice 2022
Observables
(phase shift, binding energy)

HAL QCD Lattice data



CP-PACS @Tsukuba
0.6 Tflops
(1996-2005)

PACS-CS @Tsukuba
14 TFlops
(2006-2011)

3-flavor & (2+1)-flavor
V~(3 fm)^3 , m_π > 400 MeV

BB	Inoue+, PTP 124 ('10)
H	Inoue+, PRL 106 ('11) NPA 881 ('12)
BB	Sasaki+, PTEP 2015 ('15)
NΩ	Etminan+, NPA 928 ('14)
ΩΩ	Yamada+, PTEP 2015 ('15)
KN, πΣ	Ikeda+, PoS Lat ('11)
KN	Murakami+, PTEP 2020 ('20)
T_{cc}	Ikeda+, PLB 729 ('14)
Z_c	Ikeda+, PRL 117 ('16)
D^{bar}-N	Ikeda+, HAL internal rep. ('16)
J/ψ-N	Sugiura+, PoS Lat ('18)
$Λ_c$-N	Miyamoto+, NPA 971 ('18)

K computer
@ RIKEN
10 PFlops
(2011-2019)

(2+1)-flavor
V=(8.1 fm)^3 , m_π=146 MeV

S=-1 (ΛN, ΣN)	Nemura+, EPJ conf. 175 ('18)
S=-3 (ΞΣ, ΞΛ-ΞΣ)	Ishii+, EPJ conf. 175 ('18)
S=-4 (ΞΞ)	Doi+, EPJ conf, 175 ('18)
SU(3) basis	Inoue+, AIP conf. 2130 ('19)
S=-2 (ΛΛ, NΞ)	Sasaki+, NPA 998 ('20)
S=-3 (NΩ)	Iritani+, PLB 792 ('19)
S=-6 (ΩΩ)	Gongyo+, PRL 120 ('18)
C=+6 ($Ω_{ccc}Ω_{ccc}$)	Tong+, PRL 127 ('21)
φN	Lyu+, 2205.10544 ('22)

Fugaku
@RIKEN
440 PFlops
(2020-)

(2+1)-flavor
V=(8.1 fm)^3 , m_π=138 MeV

BB: Octet x Octet
BB: Octet x Decuplet
BB: Octet x Charmed

BB: LS force

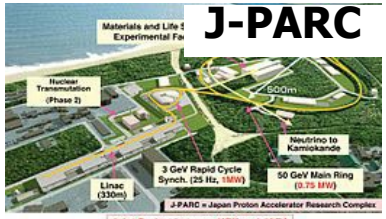
MB: KN, φN , DN, J/ψ-N, ⋯

MM: ππ , πK, DD*, J/ψ-J/ψ , ⋯

BBB

Phase I: exploratory studies ⇨ **Phase II: almost physical point** ⇨ **Phase III: physical point**

2019 2020 2021 2022 2030s



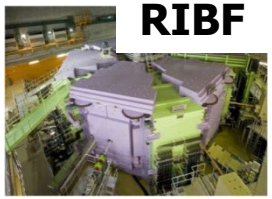
YN, YY, (YNN)
Exotic hypernuclei

J-PARC ExHEF (2028(?)-)

HIAF (2024-)

LIGO/Virgo
KAGRA

GW in NS merger
NS radius ➔ EoS



3NF (I=1/2, 3/2)
r-process in NS merger

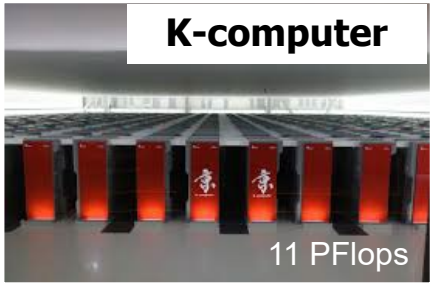
FRIB (2022-)

FAIR (2025(?)-)

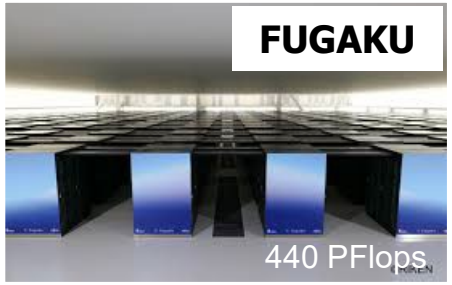
Femtoscopy
Exotic hadrons

LHC RUN3 (2022-24)

Exotic hadrons



BB, MB
strange, charm



LS, BBB
charm,bottom