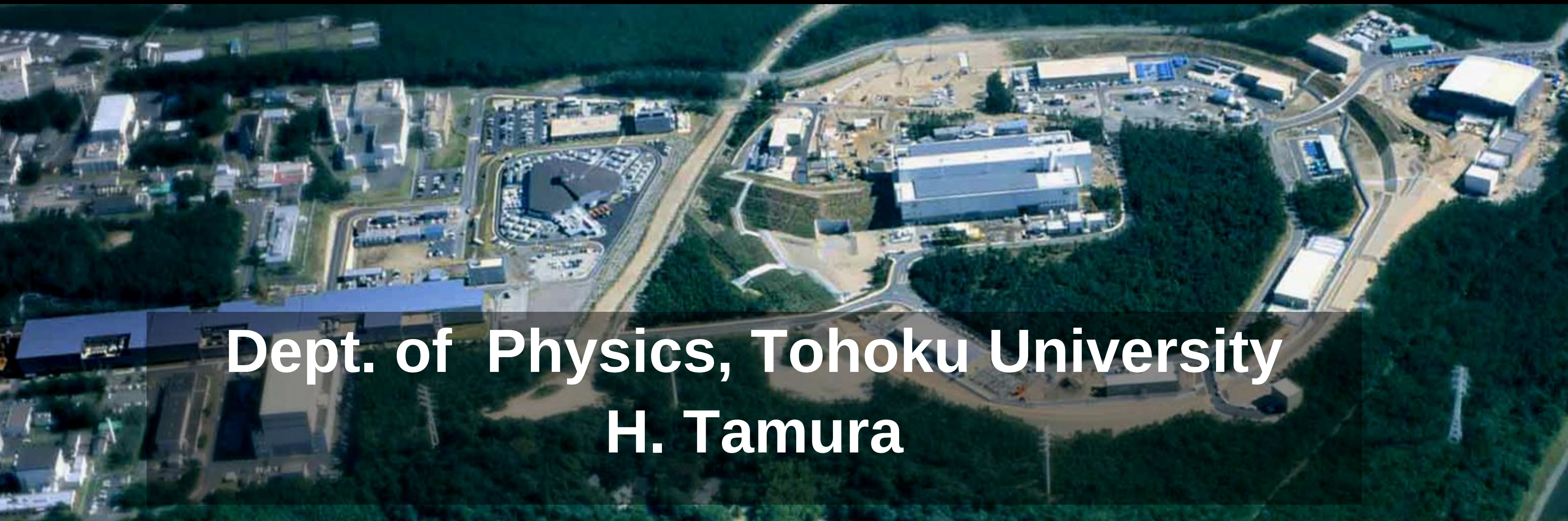
Seminar
at Nishina Center
2012. 6. 25

J-PARCでの ハイパー核物理の展開

Prospect of Hypernuclear Physics at J-PARC



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H. Tamura

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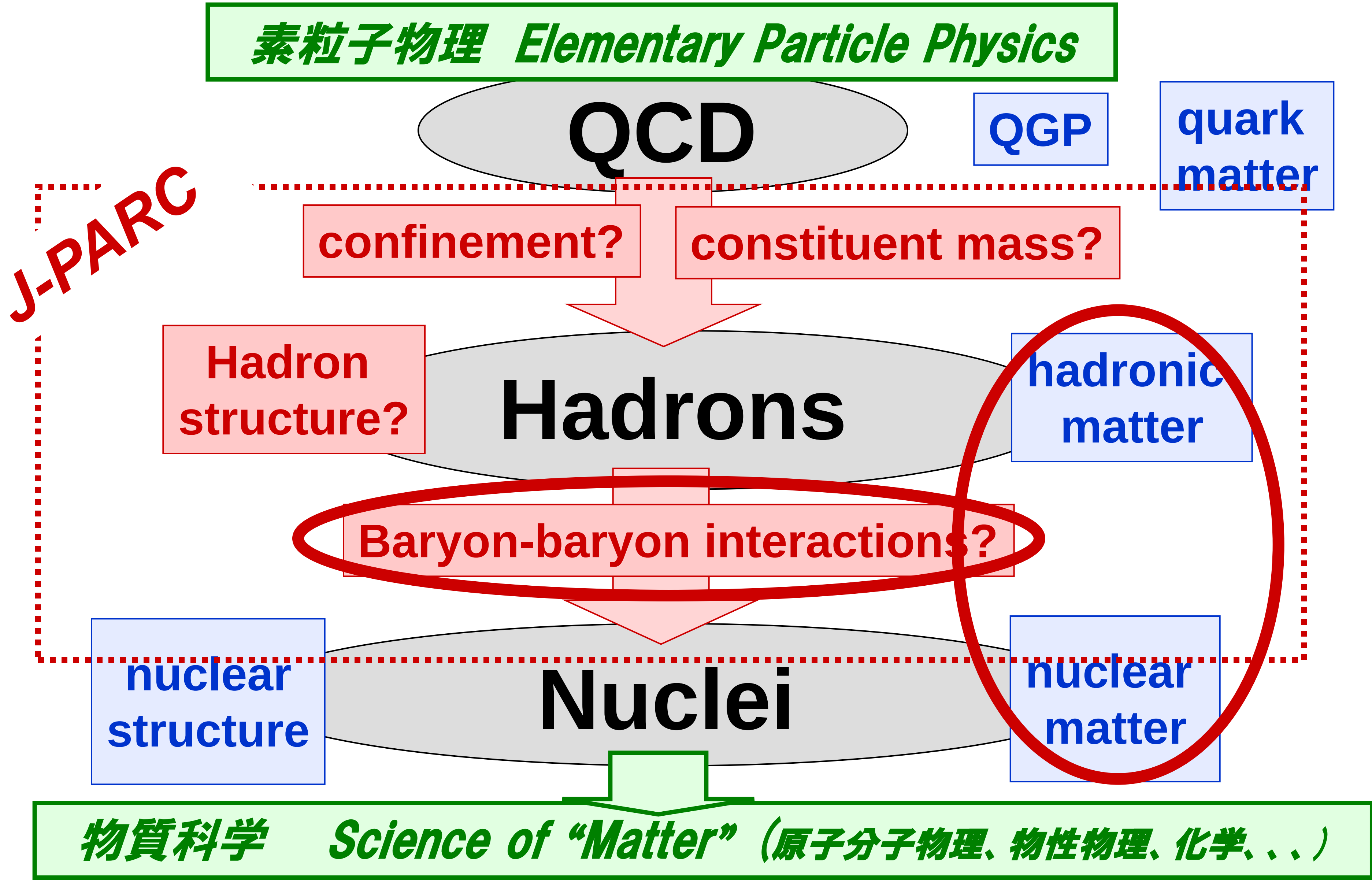
1. Introduction

J-PARC connects Elementary Particle Physics and Science of Matter



Origin of nuclear force

Nuclear force: the starting point of
"physics of matter"

Force between white (neutral) composite particles = complicated as molecular force
Short range parts not understood yet

- Repulsive core => stability of nucleus
- Spin-orbit force => magic numbers

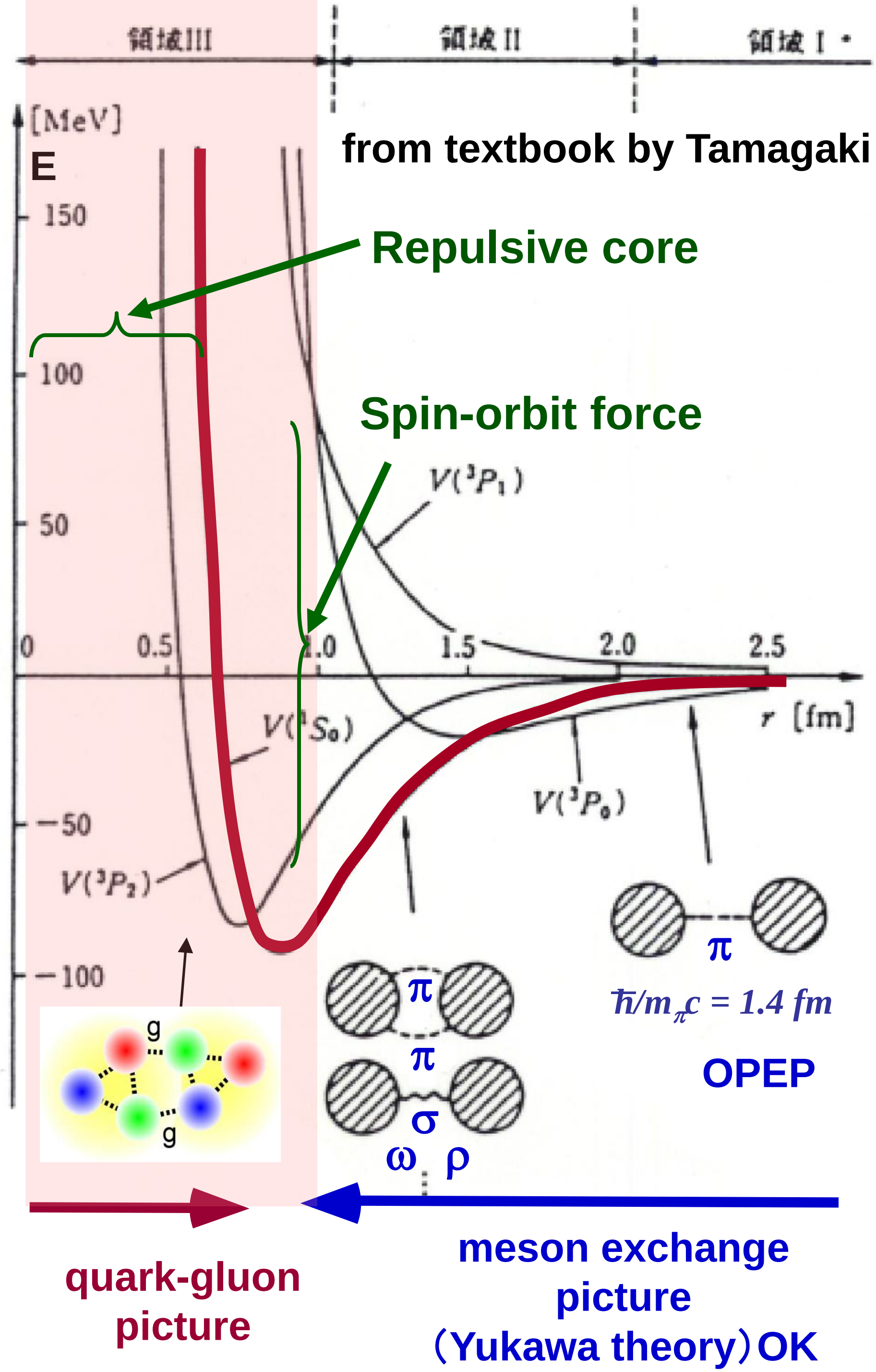
-> Abundance of elements

Meson exchange picture does not work.
Quark-gluon picture works well?

s quark gives a clue !

Hyperon forces are very different?
The miracle balance between attraction and repulsion in NN force is universal?

Extend nuclear force into u,d,s world and achieve unified understanding of baryon-baryon forces



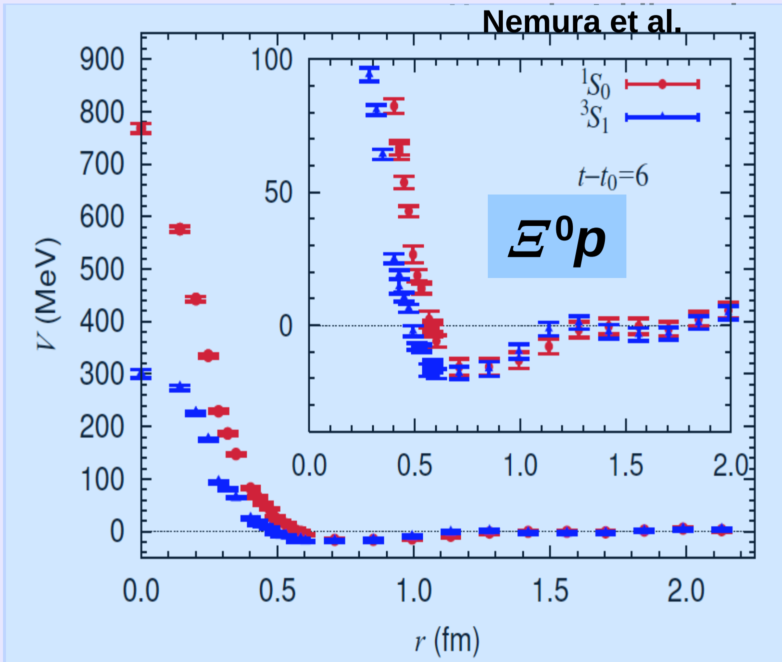
Origin of nuclear force

Nuclea

Force b
particle
Short r

- Repu
- Spin-

Meson
Qu

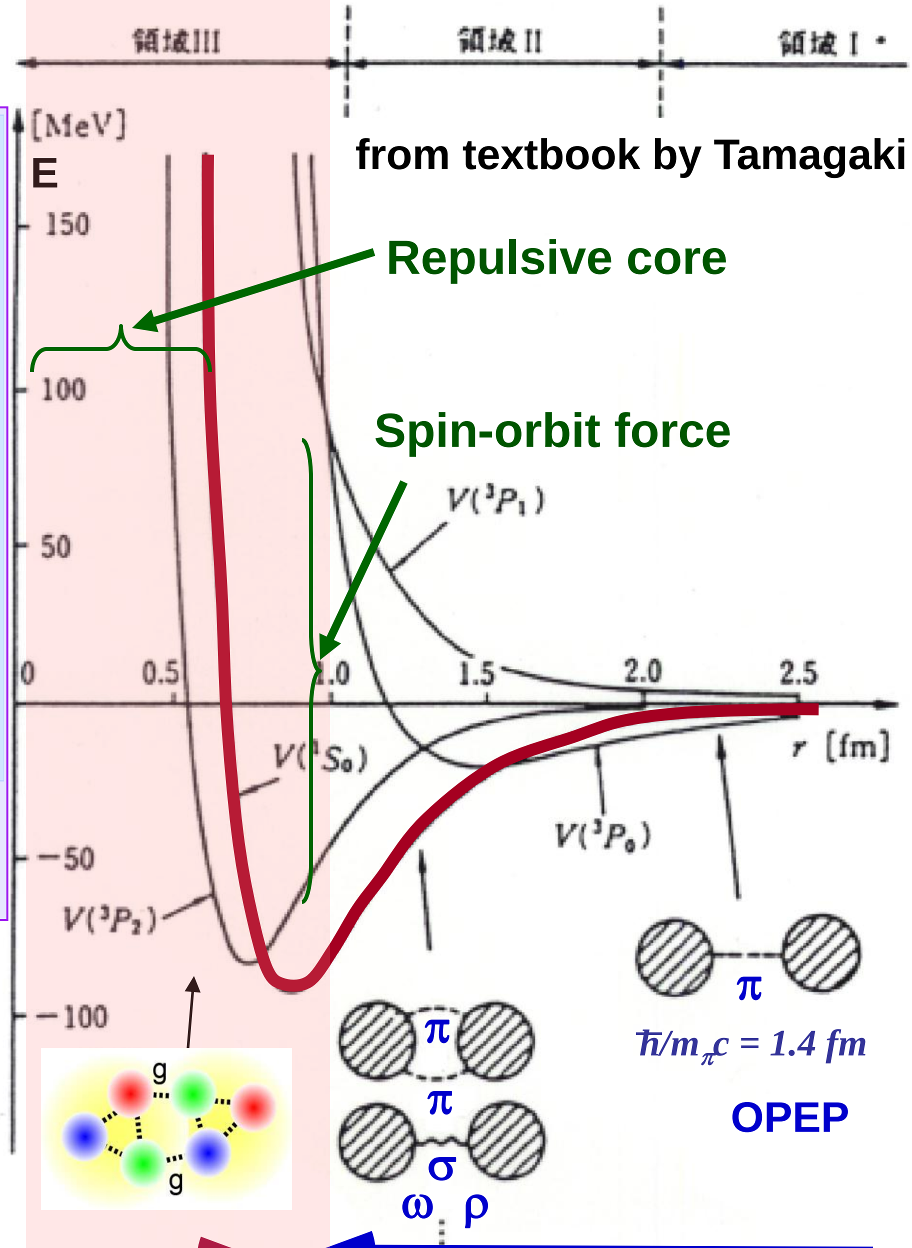


Lattice QCD can calculate B-B potentials.
Accuracy is getting better
→ can be compared with experimental data.

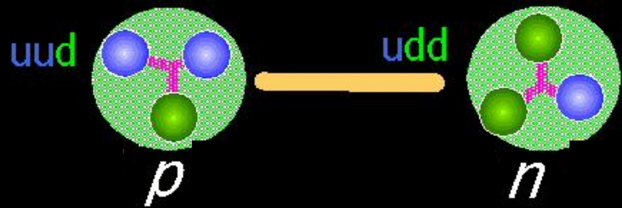
s quark gives a clue !

Hyperon forces are very different?
The miracle balance between attraction and repulsion in NN force is universal?

Extend nuclear force into u,d,s world and achieve unified understanding of baryon-baryon forces

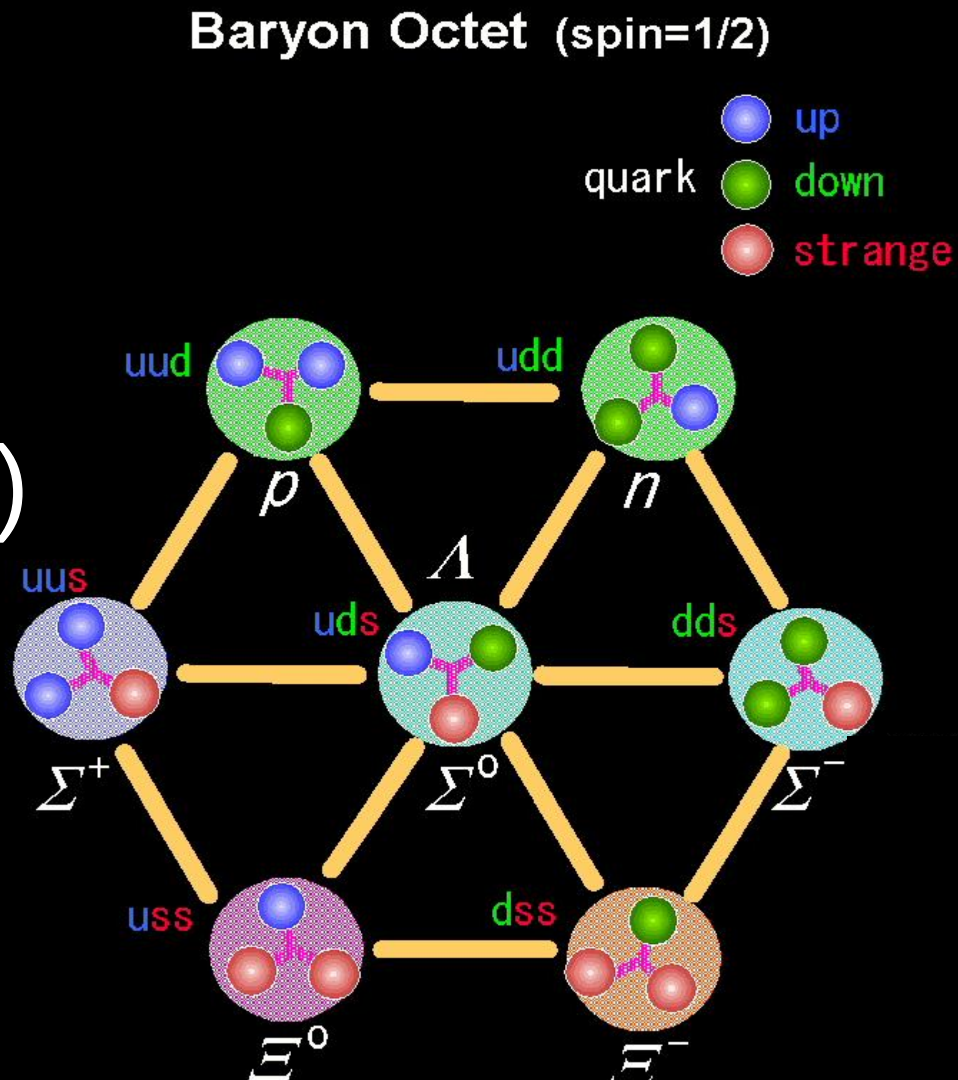


Nuclear force ($SU_f(2)$)



to

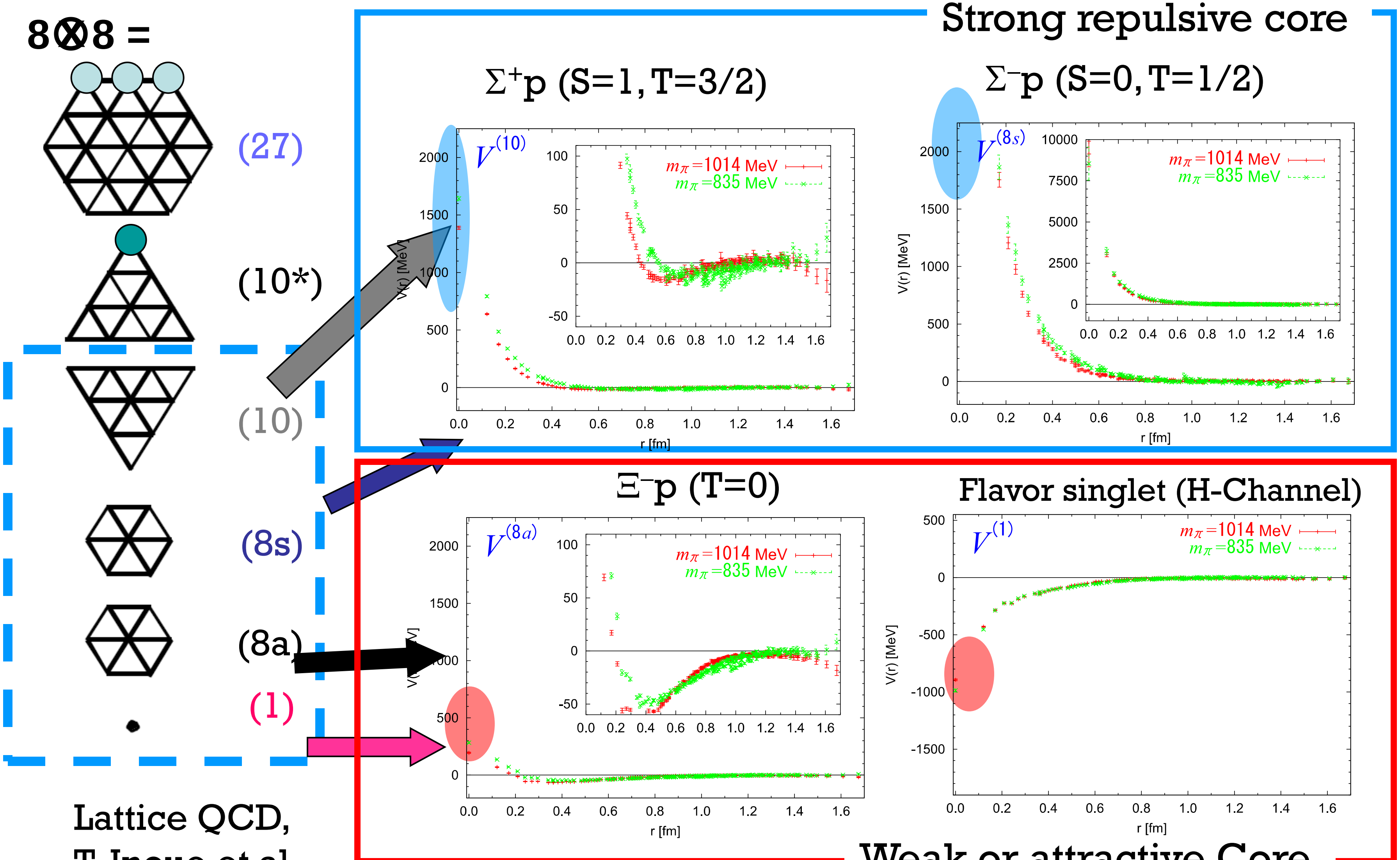
B-B force ($SU_f(3)$)



Slide by Koji Miwa

Baryon Baryon interaction by Lattice QCD

- 6 independent forces in flavor SU(3) symmetry



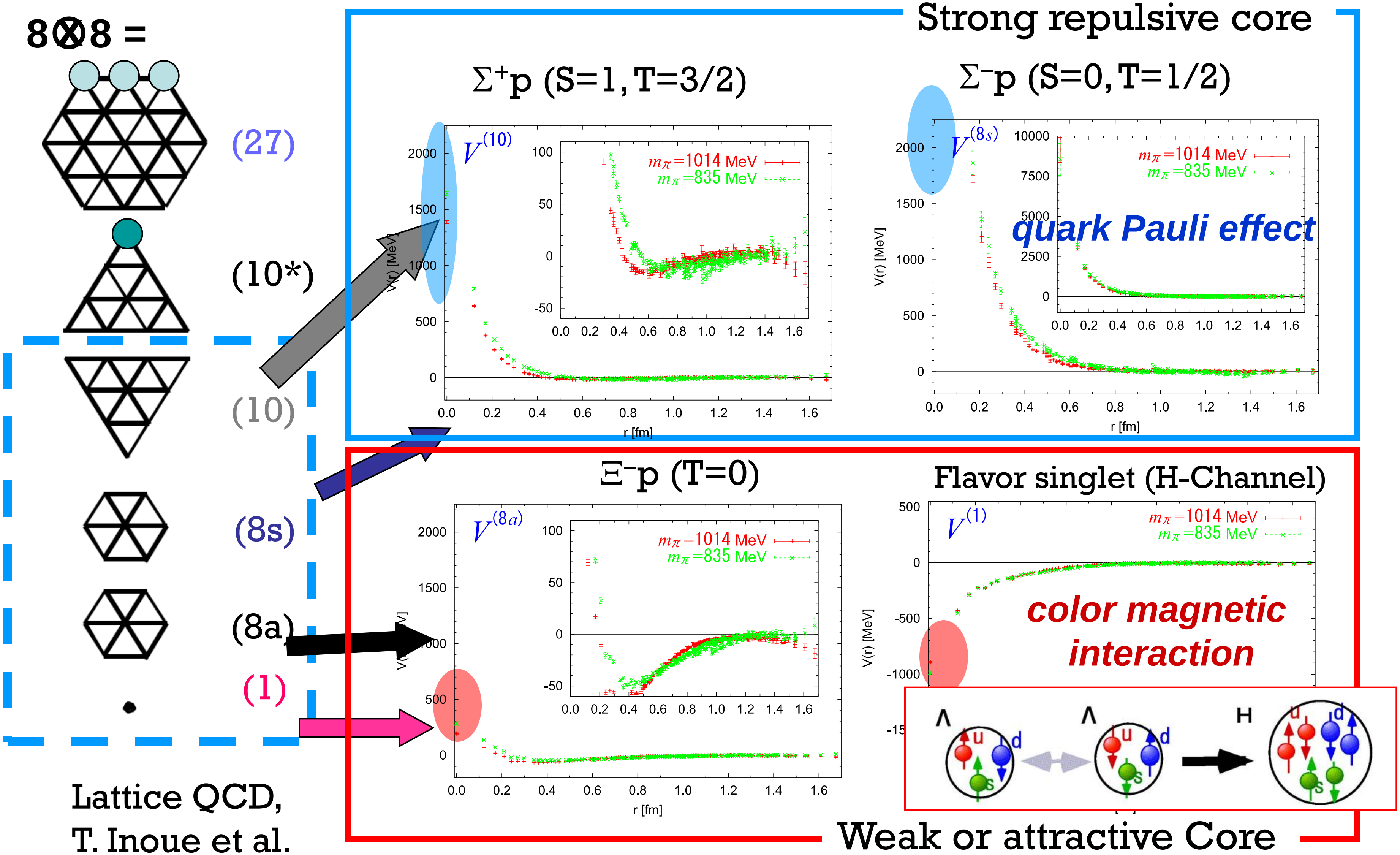
Lattice QCD,
T. Inoue et al.
Prog. Theor. Phys. 124 (2010) 4

Slide by Koji Miwa

Bary… ?

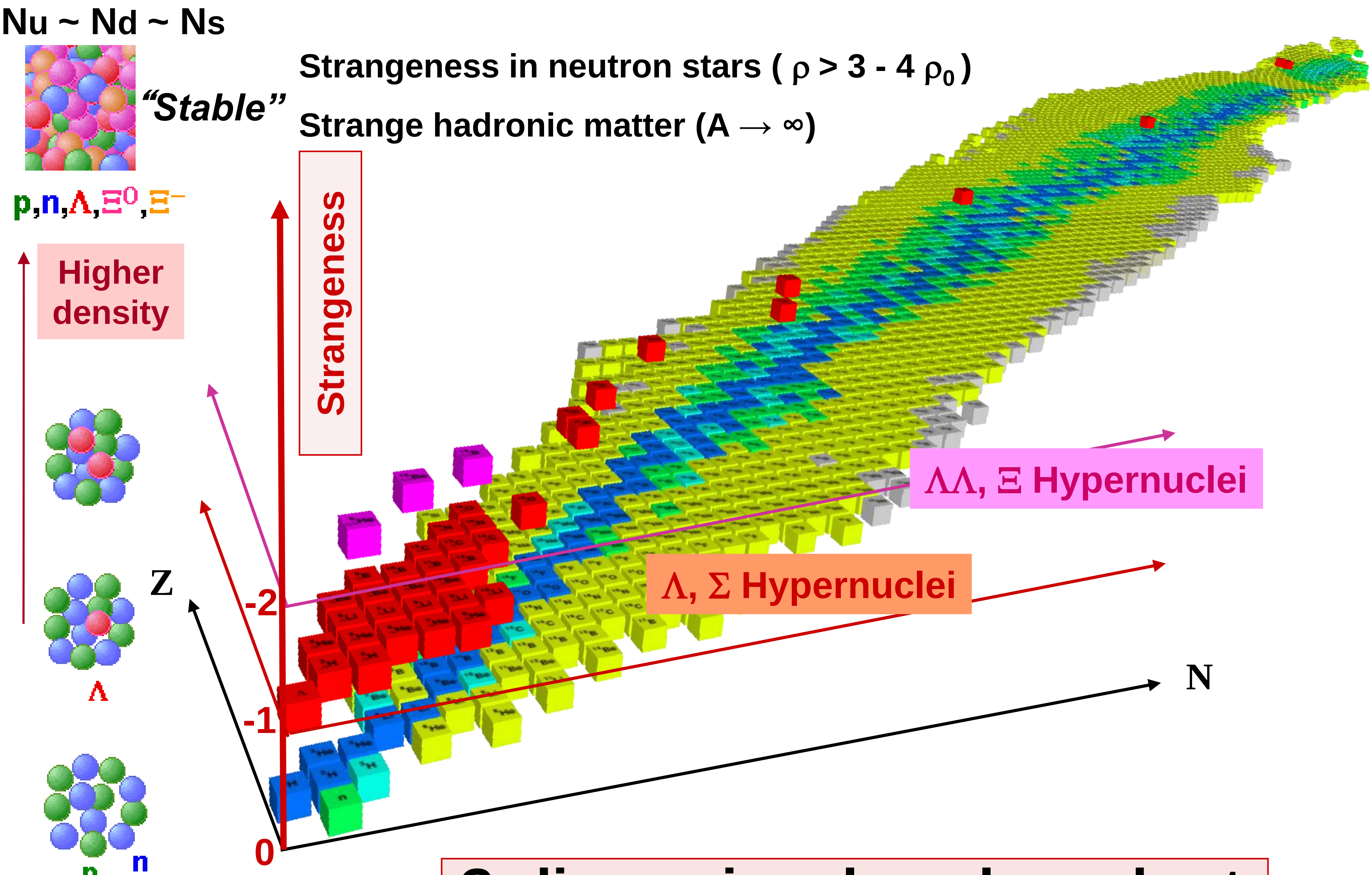
• 6…

The same behavior was already predicted by Oka-Yazaki's Quark Cluster Model



Lattice QCD,
T. Inoue et al.
Prog. Theor. Phys. 124 (2010) 4

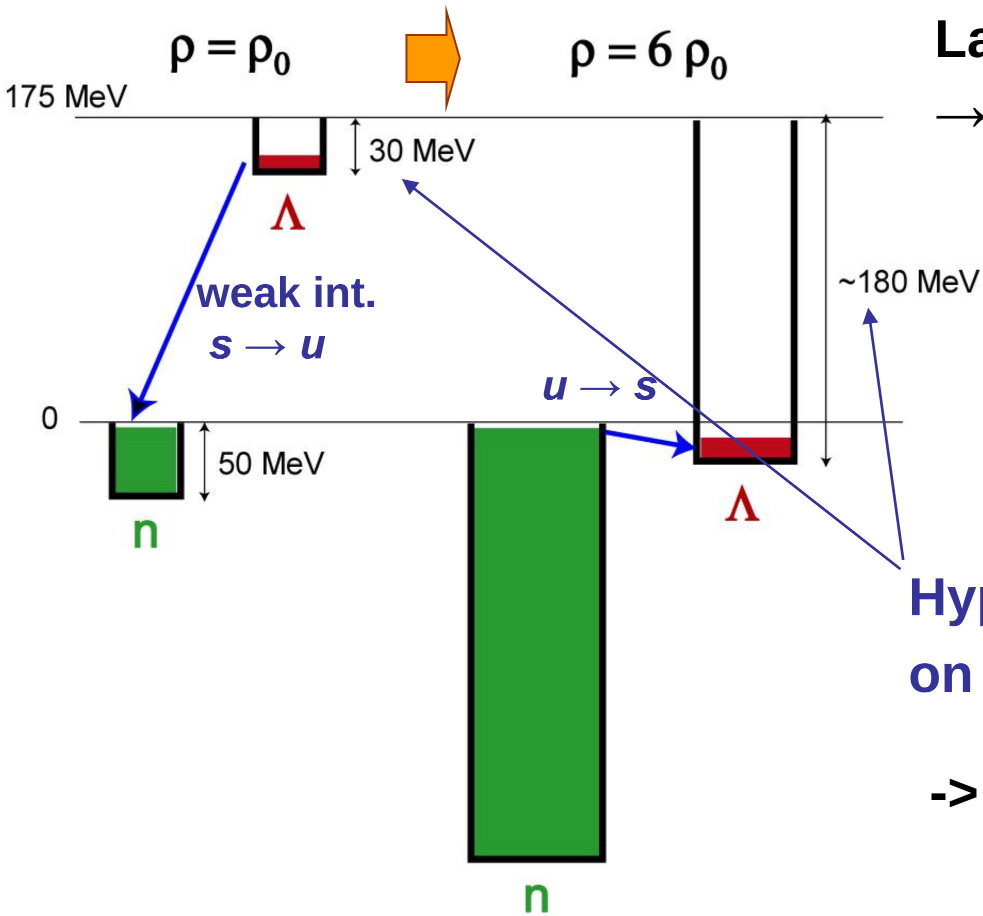
World of matter made of u, d, s quarks



3-dimensional nuclear chart

Motoba-Bando's diagram (designed by M. Kaneta)

Hyperon mixing in neutron stars



Large neutron Fermi energy

→ Hyperons appear

→ density up (softening of EOS)

→ cannot support n star

(→ black hole)

= smaller maximum mass of n star

Hyperon fraction depends sensitively on <u>YN, YY interactions</u>

-> Maximum mass, Cooling speed

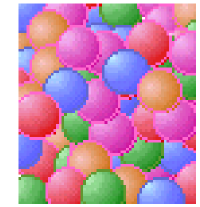
Recent hypernuclear data -> realistic calculations possible

High density matter in neutron stars

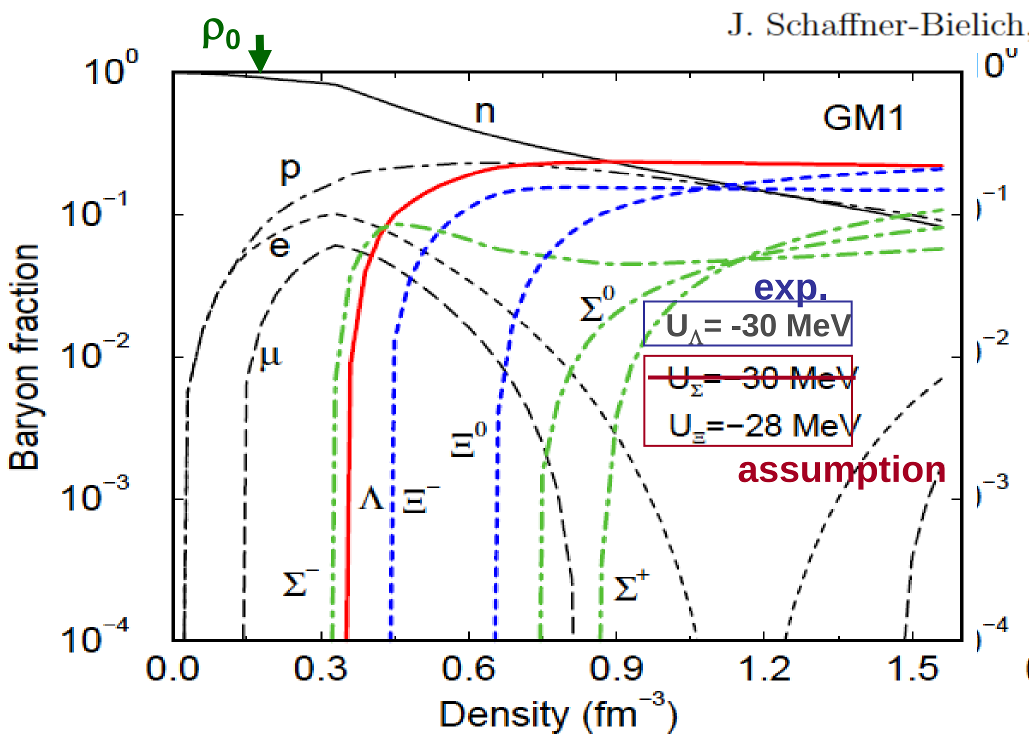
We still need
ΞN, ΛΛ, ΣN forces,
$\bar{K}$N forces,
ΛN p-wave force,
NNN and YNN force, …

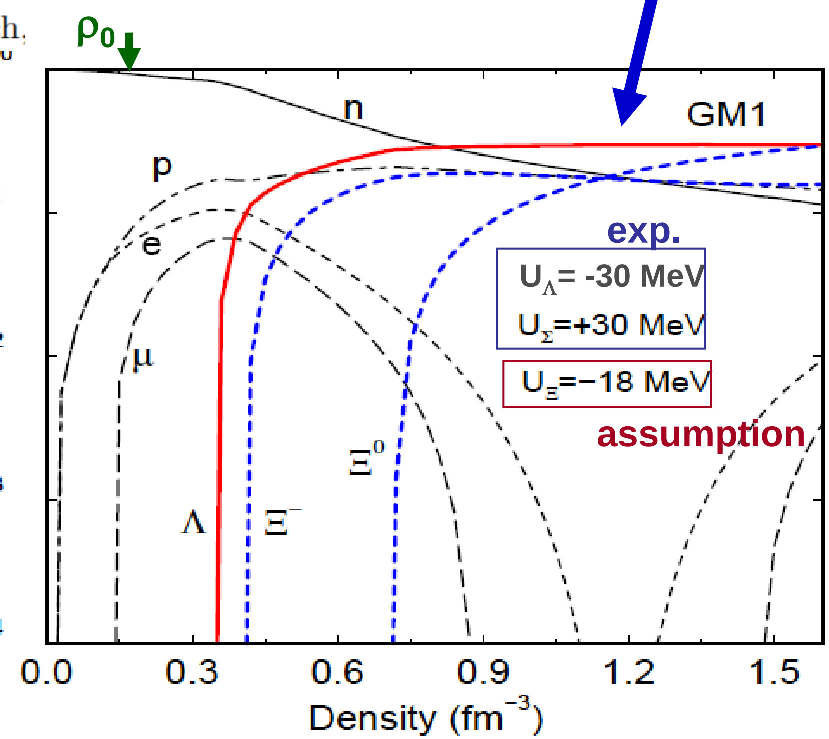
The heavy n-star (M=1.97 ± 0.04 $M_{\odot}$) can be supported?
Σ's appear?
K^{bar} appear?
Strange hadronic matter exists?
Quark matter exists?

Nu ~ Nd ~ Ns

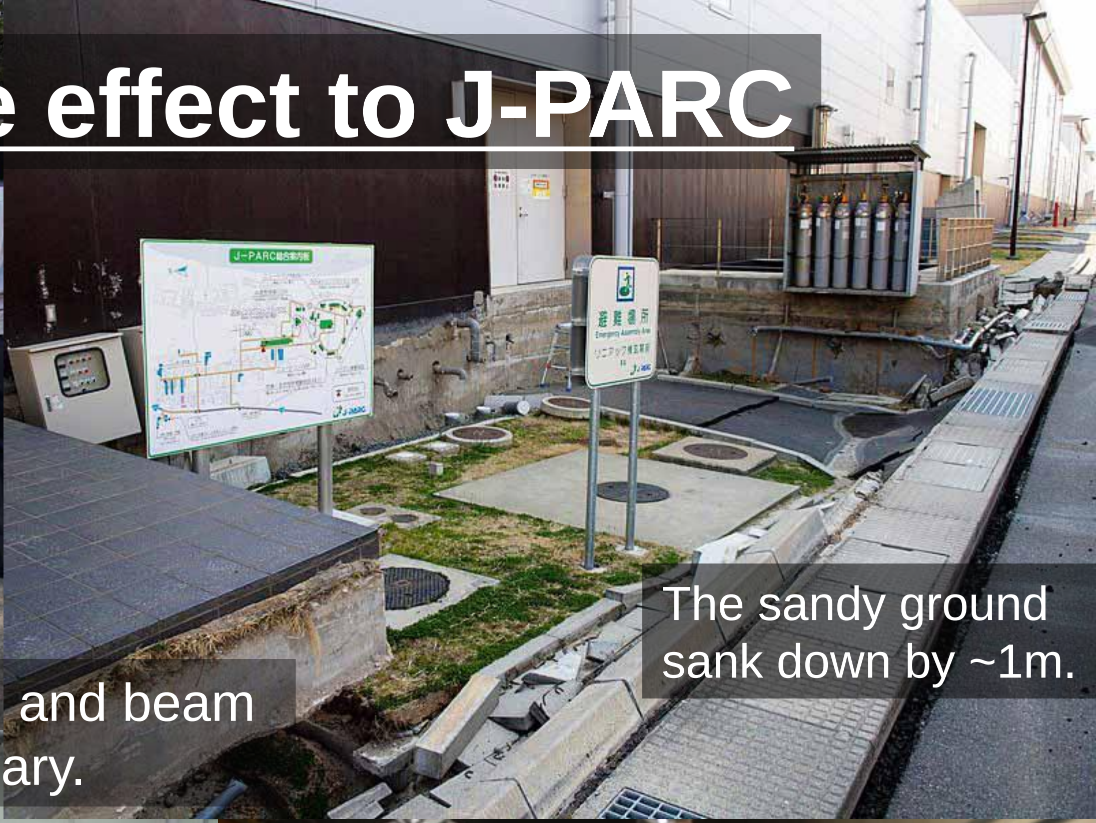


p,n,Λ,Ξ^0,Ξ^-





Earthquake effect to J-PARC



Re-alignment of all the Main Ring and beam line magnets were necessary.

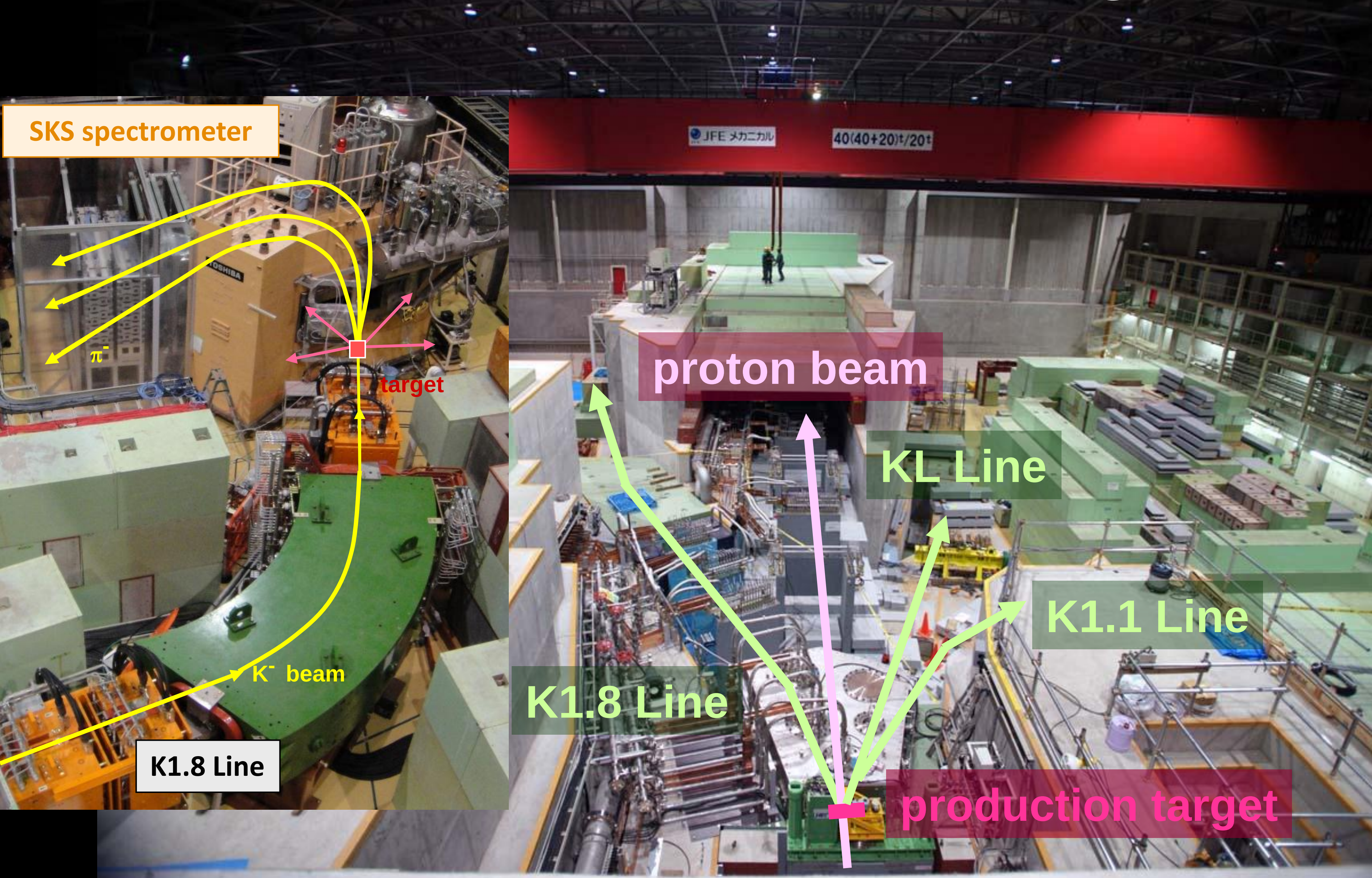
The sandy ground sank down by ~1m.

The beam came back in December, only 9 months after the disaster.

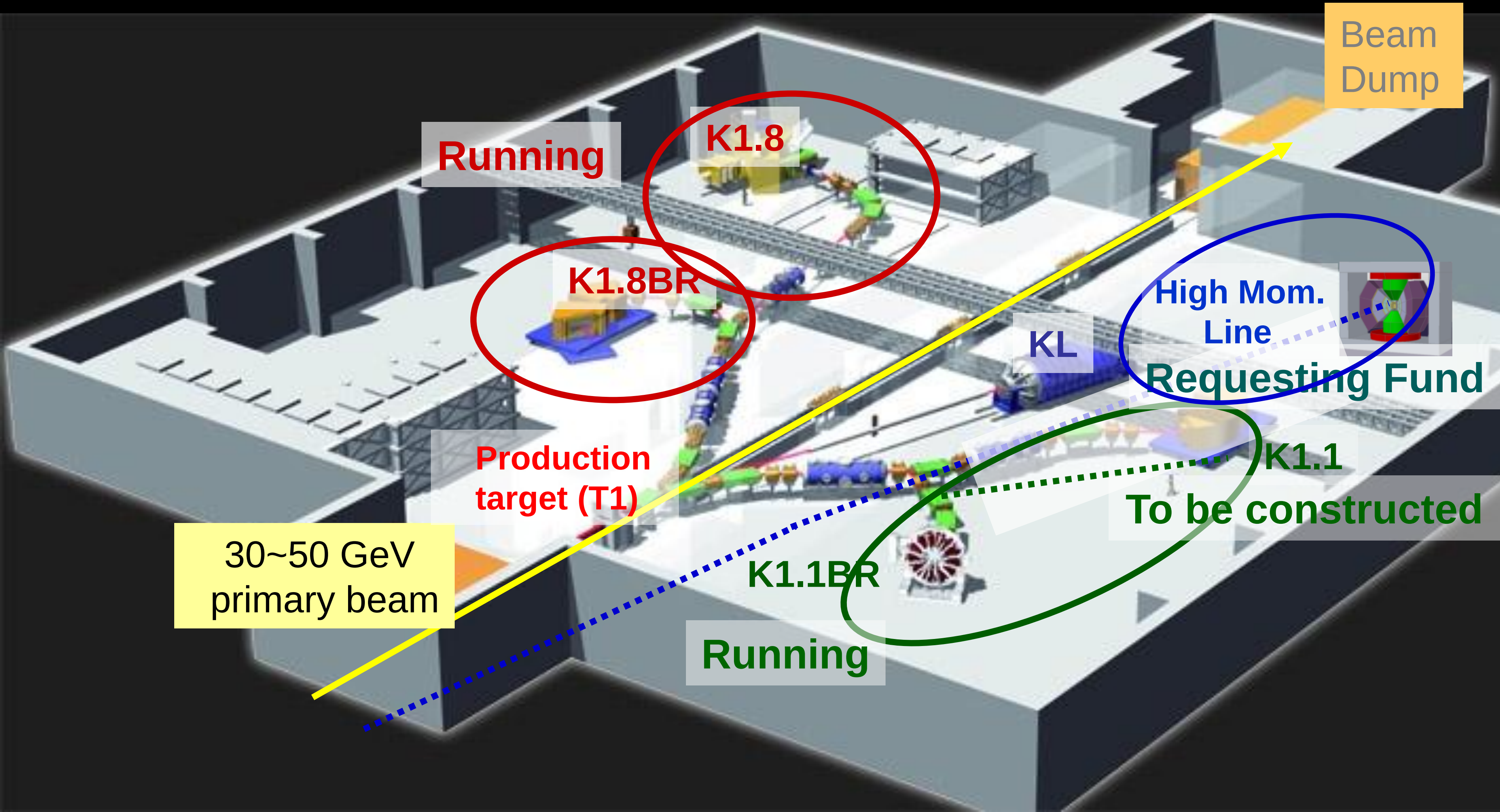
Roads, power/water stations, and pipes/cables to the accelerator facilities were heavily damaged.

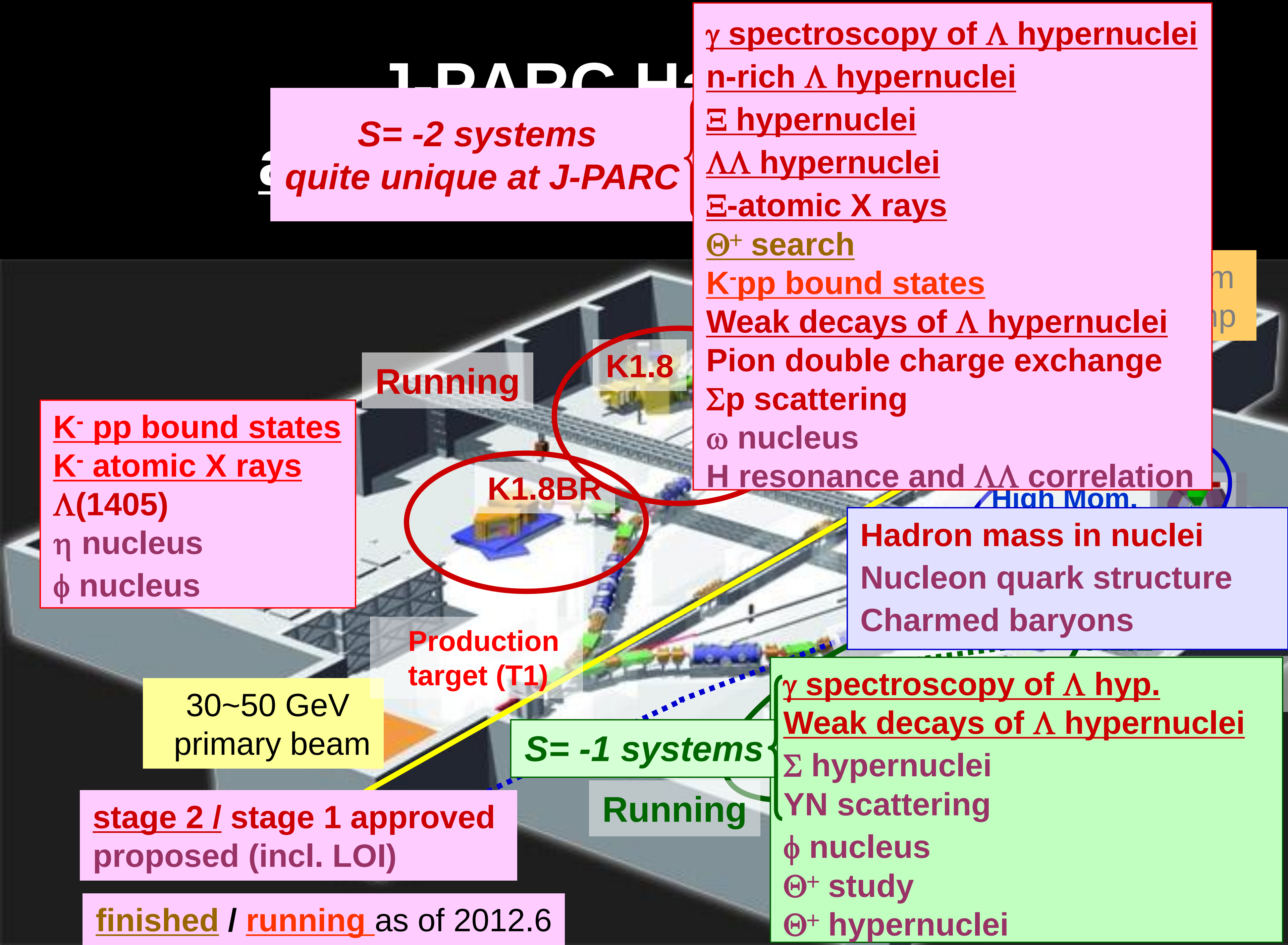
Underground water flew into LINAC.

J-PARC Hadron Hall: re-aligned



J-PARC Hadron Hall and nuclear/hadron physics





S= -2 systems
quite unique at J-PARC
γ spectroscopy of Λ hypernuclei
n-rich Λ hypernuclei
Ξ hypernuclei
ΛΛ hypernuclei
Ξ-atomic X rays
Θ+ search
K-pp bound states
Weak decays of Λ hypernuclei
Pion double charge exchange
Σp scattering
ω nucleus
H resonance and ΛΛ correlation
Running
K1.8
K1.8BR
K- pp bound states
K- atomic X rays
Λ(1405)
η nucleus
ϕ nucleus
High Mom.
Hadron mass in nuclei
Nucleon quark structure
Charmed baryons
Production
target (T1)
30~50 GeV
primary beam
S= -1 systems
γ spectroscopy of Λ hyp.
Weak decays of Λ hypernuclei
Σ hypernuclei
YN scattering
ϕ nucleus
Θ+ study
Θ+ hypernuclei
Running
stage 2 / stage 1 approved
proposed (incl. LOI)
finished / running as of 2012.6

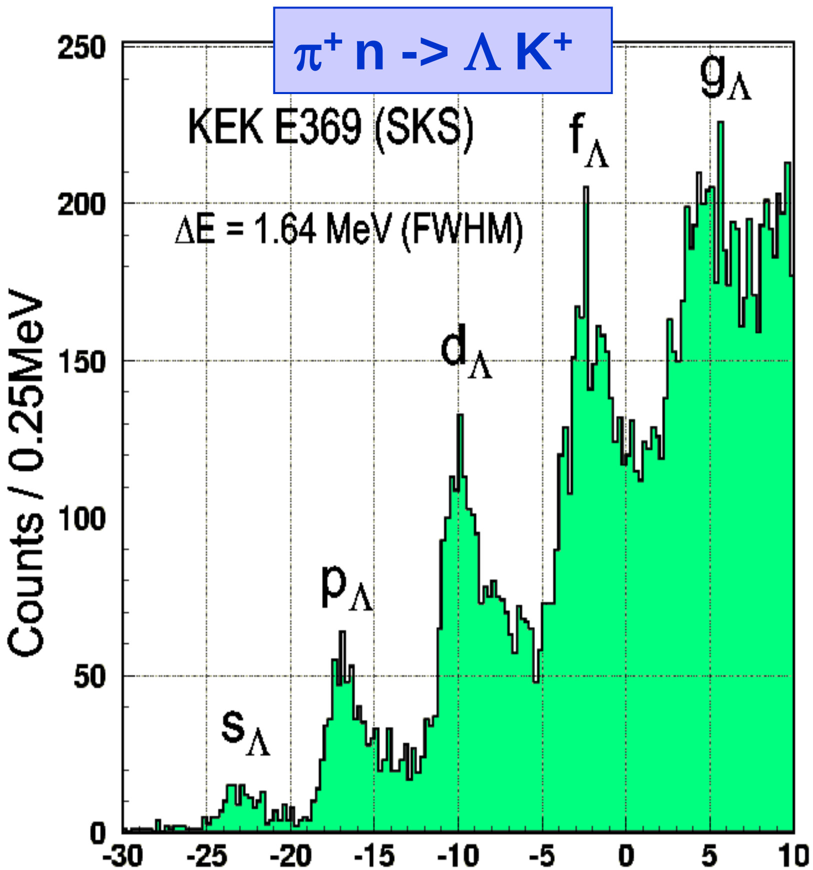
2. Baryon-baryon interactions

2.1 Λ hypernuclei and ΛN force

Previous (π^+,K^+) data and ΛN interaction

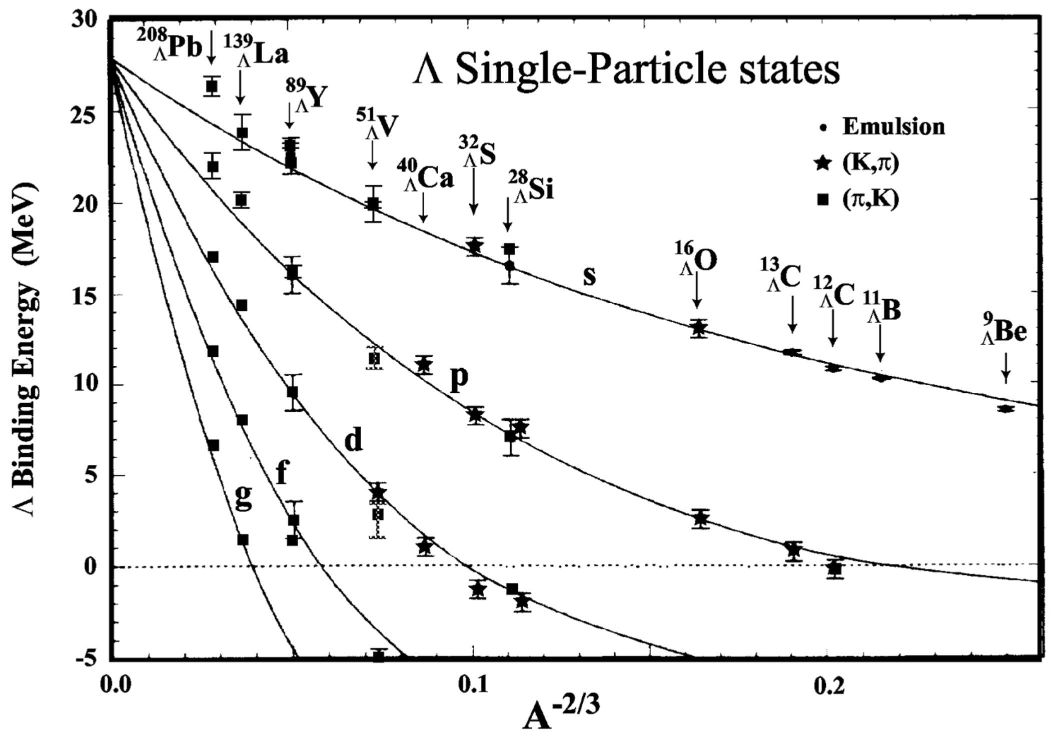
SKS at KEK-PS

^{89}Y (π^+,K^+) $^{89}{}_{\Lambda}Y$



Mass of hypernucleus -B_{Λ} (MeV)

Hotchi et al., PRC 64 (2001) 044302



-> Nuclear potential of Λ

U_{Λ} = - 30 MeV (c.f. U_N = -50 MeV)

<u>Better resolution</u> is necessary

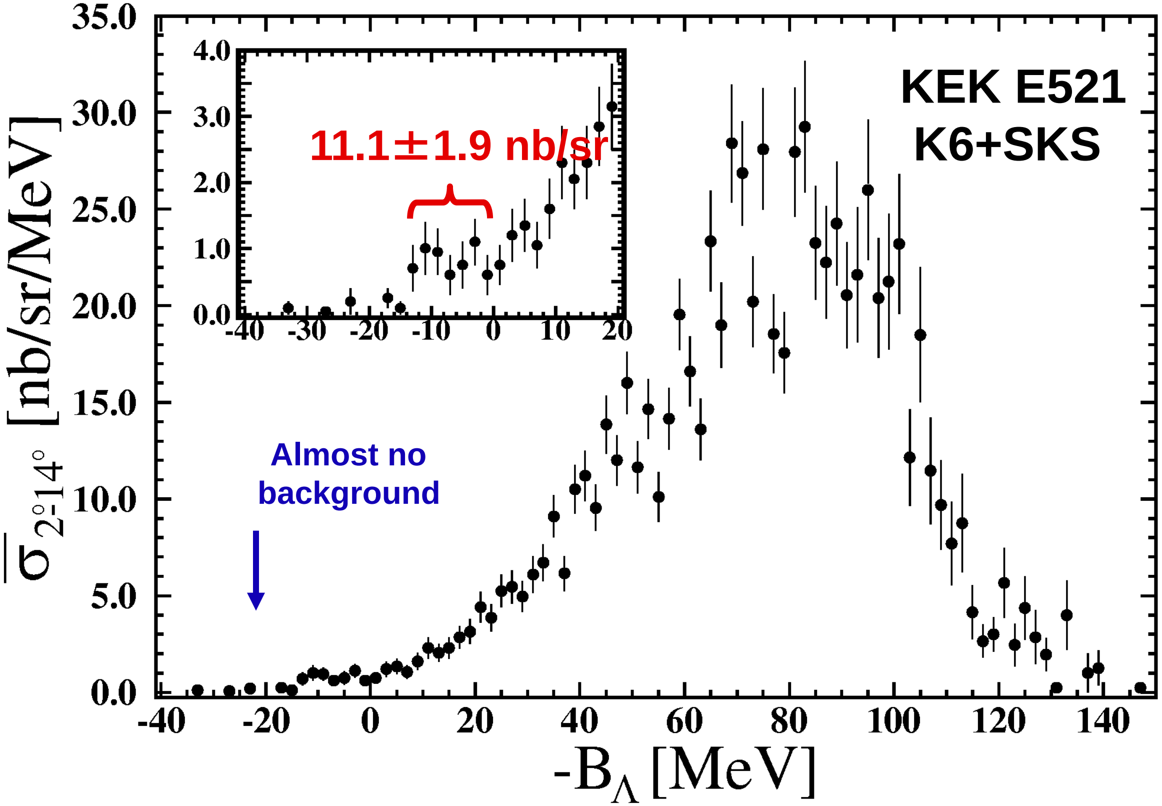
for ΛN spin-dependent forces, ΛN-ΣN force, ..

<u>(π,K^+) -> (e,e'K^+) at JLab</u>

<u>γ spectroscopy at KEK/BNL, J-PARC</u>

Neutron-rich hypernuclei

$^{10}B\ (\pi^-, K^+)\ ^{10}_{\Lambda}Li$ p_π~1.2 GeV/c



Saha et al., PRL 94 (2005) 052502

First data on n-rich hypernucleus

FINUDA data duggests $^{6}_{\Lambda}H$ by $^{6}Li(K^-_{stop},\pi^+)$

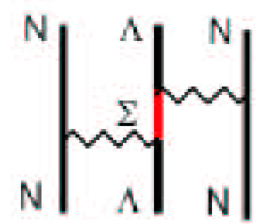
J-PARC E10: $^{6}_{\Lambda}H$ and $^{9}_{\Lambda}He$ by (π^-,K^+)

$\pi^- p\ p \rightarrow \Lambda\ n\ K^+$

2-step charge exchange
($\pi^- p \rightarrow \pi^0 n$, $\pi^0 p \rightarrow K^+\Lambda$ etc.)
Via Σ^- admixture in Λ hyp.
($\pi^- p \rightarrow \Sigma^- K^+$, $\Sigma^- p \leftrightarrow \Lambda n$)

Physics Interest

- **Λ–Σ coherent coupling -> ΛNN attraction**

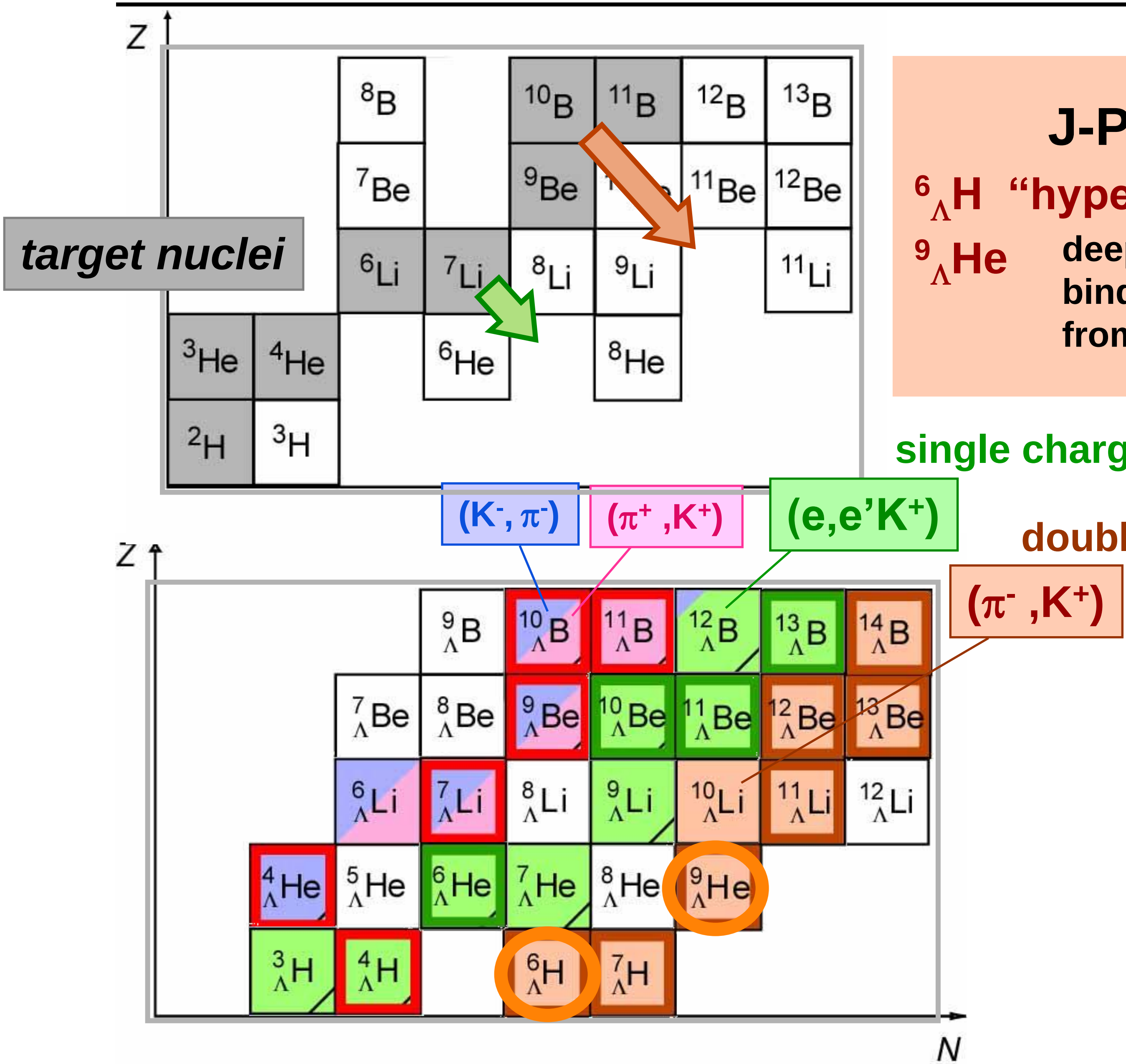


Akaishi et al., PRL 84 (2000) 3539

Coherently enhanced in large isospin environment -> important in neutron stars

- **Cross section sensitive to Σ^- admixture in Λ hyp.**
- **n-halo disappear by Λ ?**

How to extend S=-1 nuclear chart?



J-PARC E10

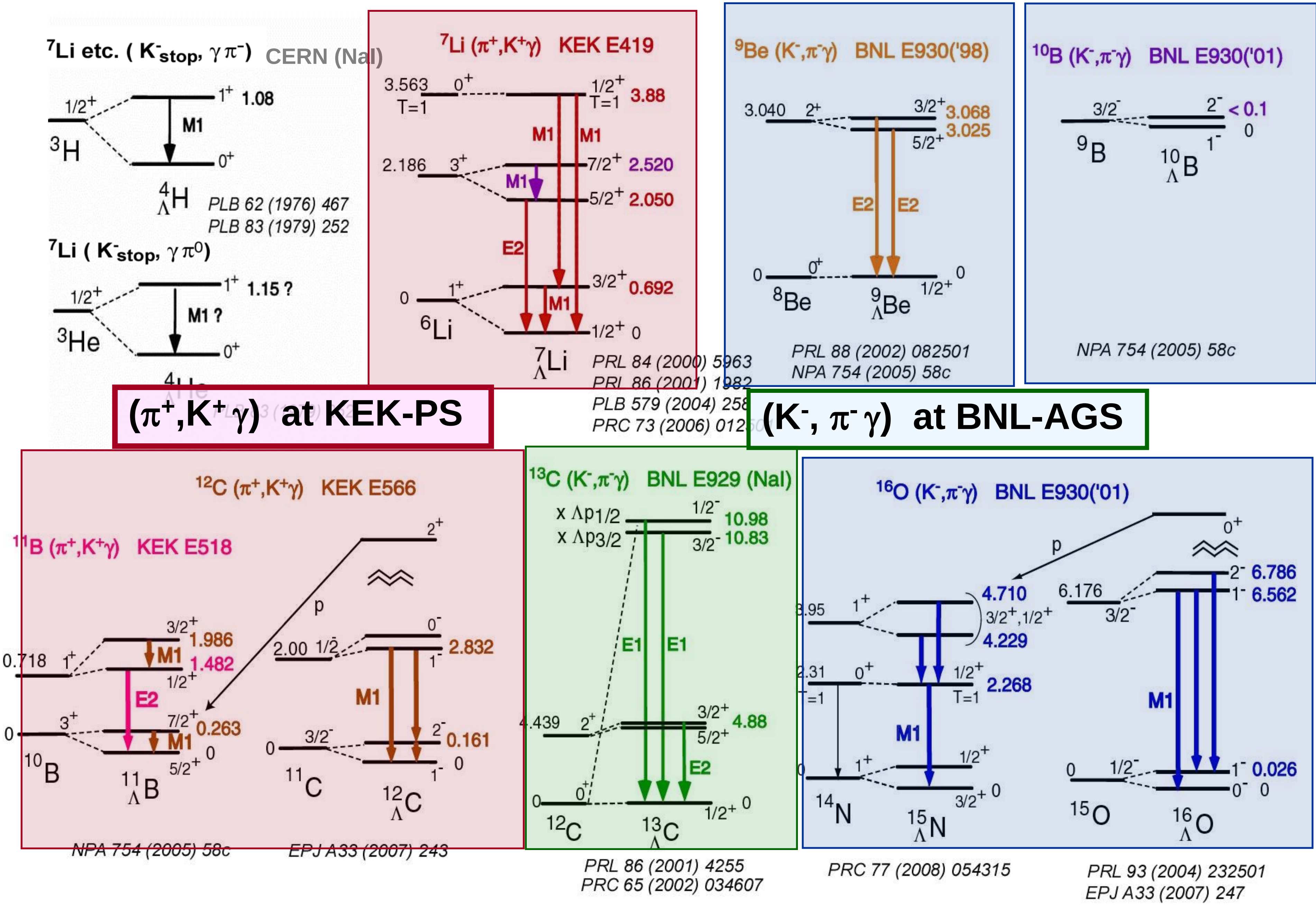
$^{6}_{\Lambda}H$ **"hyperheavy hydrogen"**

$^{9}_{\Lambda}He$ **deeply bound by additional binding (+1.4 MeV) from ΛNN force (Akaishi)**

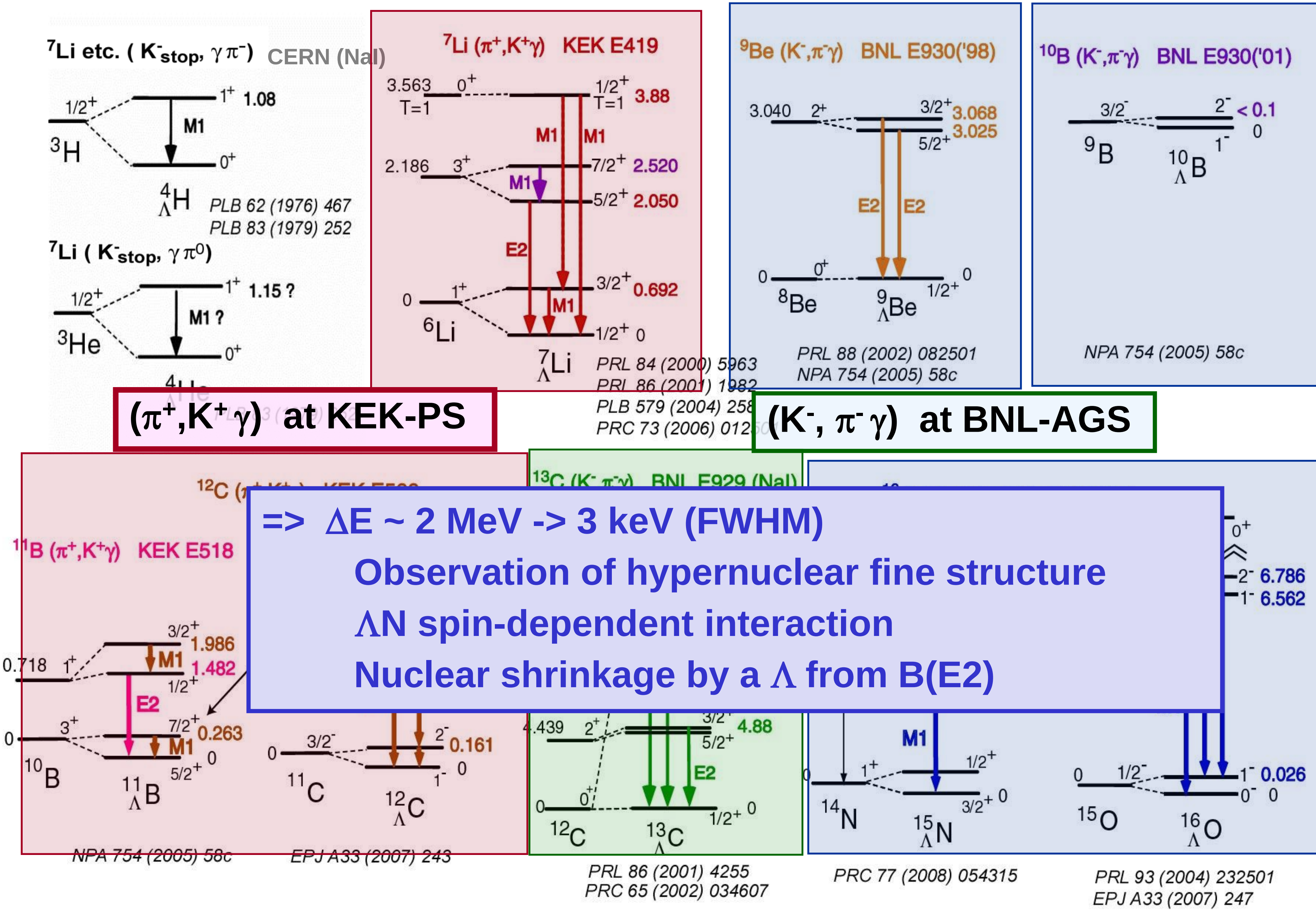
single charge exchange

double charge exchange

Hypernuclear γ-ray data



Hypernuclear γ-ray data



=> ΔE ~ 2 MeV -> 3 keV (FWHM)

Observation of hypernuclear fine structure

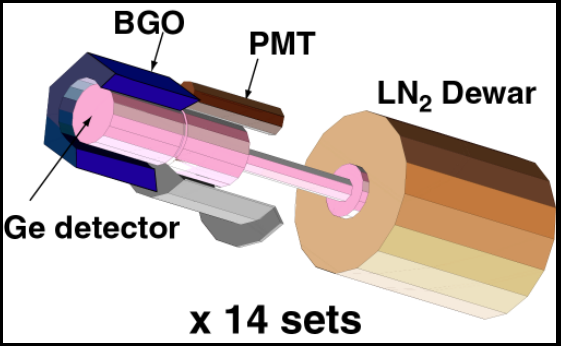
ΛN spin-dependent interaction

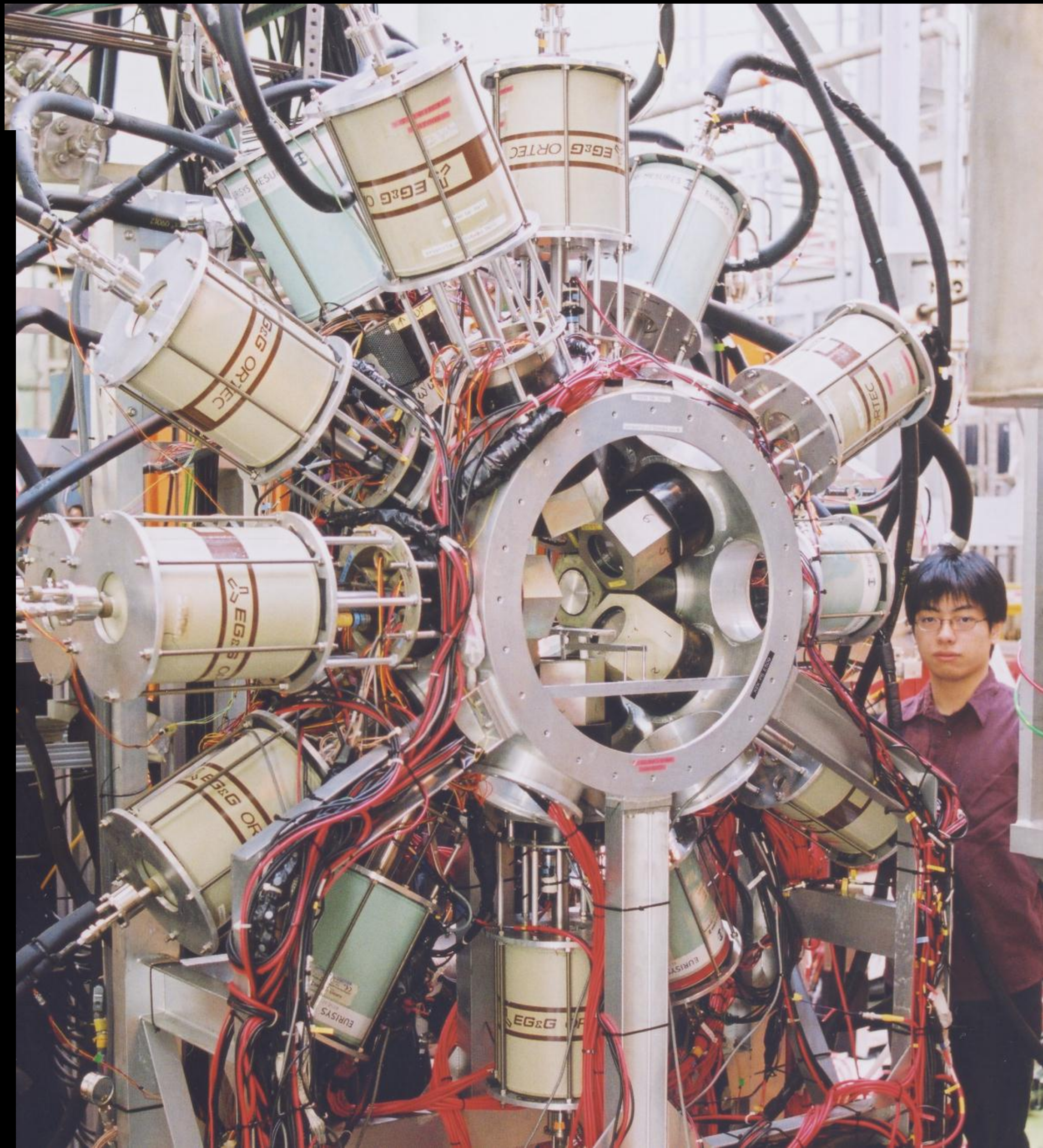
Nuclear shrinkage by a Λ from B(E2)

Ge detctor array: Hyperball

Constructed
by Tohoku/ KEK/ Kyoto
in 1998

- Large acceptance for small hypernuclear γ yields
  - Ge (r.e. 60%) x 14
    - Ω ~ 15%, ε ~ 3% at 1 MeV
- High-rate electronics for huge background
- BGO counters for π^0 and Compton suppression

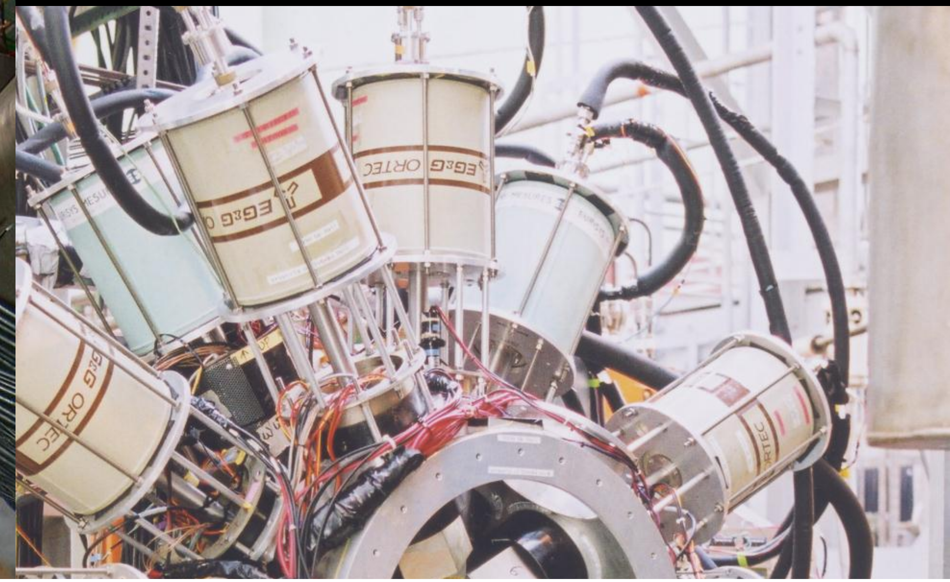


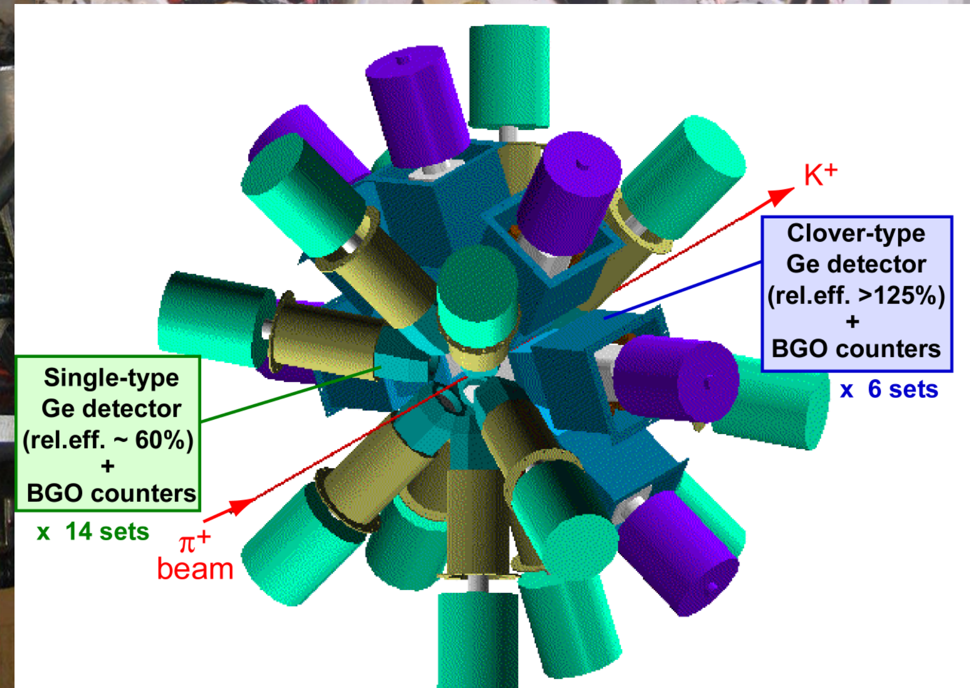


Ge detctor array: Hyperball

Upgraded to Hyperball2 in Tohoku (2005~)

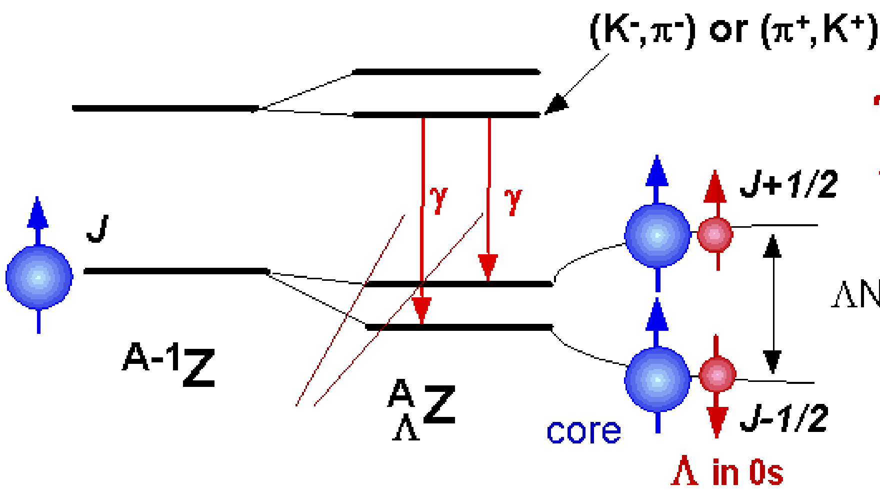
Efficiency 2.4% -> ~4%





ΛN spin-dependent interactions

- **Low-lying levels of Λ hypernuclei**



"Hypernuclear Fine Structure"

split by ΛN spin-dependent interactions $\lesssim$ 0.1 MeV

Level spacing: Linear combination of Δ, S_Λ, S_N, T

- **Two-body ΛN effective interaction**

Dalitz and Gal, Ann. Phys. 116 (1978) 167
Millener et al., Phys. Rev. C31 (1985) 499

$$V^{eff}_{\Lambda N} = V_0(r) + V_\sigma(r)\,\vec{s}_\Lambda \vec{s}_N + V_\Lambda(r)\,\vec{l}_{\Lambda N}\vec{s}_\Lambda + V_N(r)\,\vec{l}_{\Lambda N}\vec{s}_N + V_T(r)\,S_{12}$$

$\bar{V}$ Δ S_Λ S_N T

Well known from U_Λ = - 30 MeV

p-shell: 5 radial integrals for $s_\Lambda p_N$ w.f.

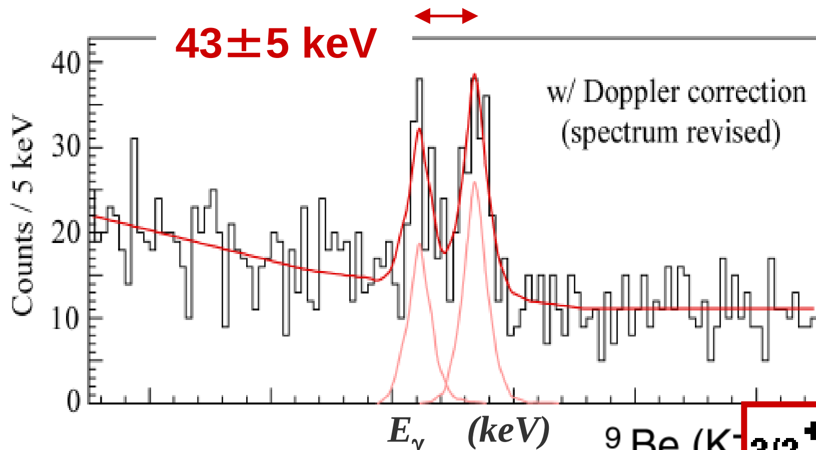
$$\Delta = \int V_\sigma(r)\,|u(r)|^2 r^2 dr, \quad \boldsymbol{r} = \boldsymbol{r}_{s_\Lambda} - \boldsymbol{r}_{p_N}$$

γ–ray data => Δ = 0.33 (0.43 for A=7), S_Λ = -0.01, S_N = -0.4, T= 0.03 [MeV]
Small spin-dependent forces have been established.

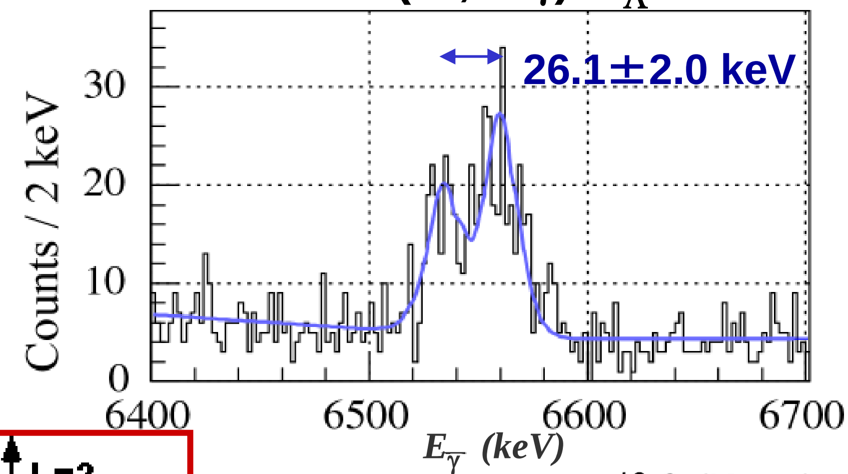
Observation of "Hypernuclear Fine Structure"

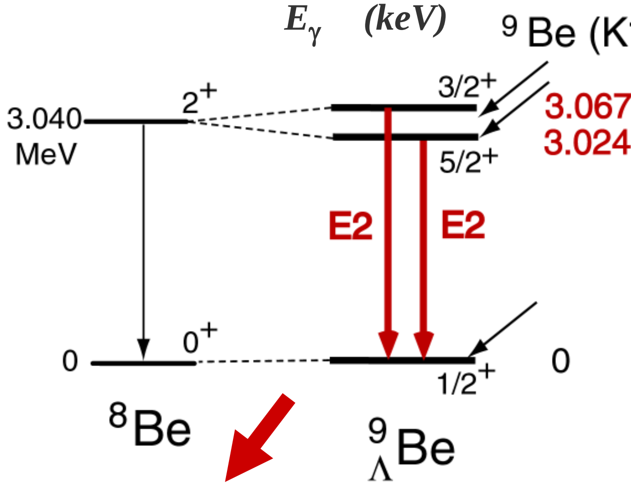
BNL E930 (AGS D6 line + Hyperball)

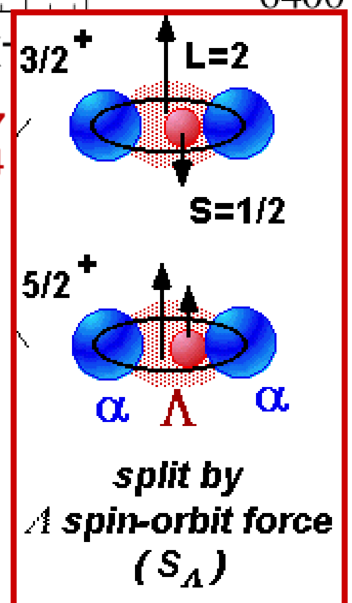
$^{9}Be\ (K^-, \pi^-\gamma)\ ^{9}_{\Lambda}Be$

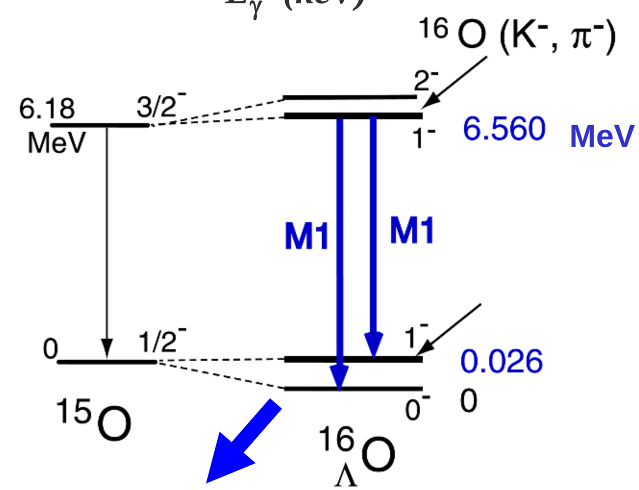


$^{16}O\ (K^-, \pi^-\gamma)\ ^{16}_{\Lambda}O$









S_{Λ} = -0.01 MeV

PRL 88 (2002) 082501

T = 0.03 MeV

PRL 93 (2004) 232501

consistent with Quark Cluster Model

consistent with Meson Exch. Model

D.J. Millener, J.Phys.Conf.Ser. 312 (2011) 022005

Nijmegen meson-exchange models

Via G-matrix calc.

Feedback to YN interaction models

	Δ	S_Λ	S_N	T (MeV)
ND	-0.048	-0.131	-0.264	0.018
NF	0.072	-0.175	-0.266	0.033
NSC89	1.052	-0.173	-0.292	0.036
NSC97f	0.421	-0.149	-0.238	0.055
ESC04a	0.381	-0.108	-0.236	0.013
ESC08a	0.146	-0.074	-0.241	0.055
("Quark"		0.0	-0.4	)
Exp.	0.4	-0.01	-0.4	0.03

Strength equivalent to quark-model LS force by Fujiwara et al.

spin-spin:

Δ = 0.33--0.43 MeV **=> *NSC97f selected* (consistent with $^4_\Lambda H(1^+,0^+)$)**

spin-orbit:

S_Λ = -0.01 MeV
(SLS+ALS)

S_N = -0.4 MeV
(SLS-ALS)

=> *All Nijmegen models fail. Quark model looks OK.*

$^9_\Lambda Be = \alpha\alpha\Lambda$ model
Hiyama et al., PRL 85 (2000) 270
Fujiwara et al. Prog.Part.Nucl.Phys.58 (2007) 439.

tensor:

T = 0.03 MeV

=> *Nijmegen models OK*

Reproduction of hypernuclear level energies

Millener's parameter set

J-PARC E13

A=7~9	$\Delta = 0.430$	$S_\Lambda = -0.015$	$S_N = -0.390$	$T = 0.030$,	MeV
A=10~16	$\Delta = 0.330$	$S_\Lambda = -0.015$	$S_N = -0.350$	$T = 0.0239$.	

Calculated from G-matrix using ΛN–ΣN force in NSC97f

doublet spacing

			contribution of each term (keV)					keV	
	J^π_u	J^π_l	$\Lambda\Sigma$	Δ	S_Λ	S_N	T	ΔE^{th}	ΔE^{exp}
$^{7}_{\Lambda}$Li	$3/2^+$	$1/2^+$	72	628	−1	−4	−9	693	692
$^{7}_{\Lambda}$Li	$7/2^+$	$5/2^+$	74	557	−32	−8	−71	494	471
$^{8}_{\Lambda}$Li	2^-	1^-	151	396	−14	−16	−24	450	(442)
$^{9}_{\Lambda}$Li	$5/2^+$	$3/2^+$	116	530	−17	−18	−1	589	
$^{9}_{\Lambda}$Li	$3/2^+_2$	$1/2^+$	−80	231	−13	−13	−93	−9	
$^{9}_{\Lambda}$Be	$3/2^+$	$5/2^+$	−8	−14	37	0	28	44	43
$^{10}_{\Lambda}$B	2^-	1^-	−15	188	−21	−3	−26	120	< 100
$^{11}_{\Lambda}$B	$7/2^+$	$5/2^+$	56	339	−37	−10	−80	267	264
$^{11}_{\Lambda}$B	$3/2^+$	$1/2^+$	61	424	−3	−44	−10	475	505
$^{12}_{\Lambda}$C	2^-	1^-	61	175	−12	−13	−42	153	161
$^{15}_{\Lambda}$N	$1/2^+_1$	$3/2^+_1$	44	244	34	−8	−214	99	
$^{15}_{\Lambda}$N	$3/2^+_2$	$1/2^+_2$	65	451	−2	−16	−10	507	481
$^{16}_{\Lambda}$O	1^-	0^-	−33	−123	−20	1	188	23	26
$^{16}_{\Lambda}$O	2^-	1^-_2	92	207	−21	1	−41	248	224

D.J. Millener, J.Phys.Conf.Ser. 312 (2011) 022005

Reproduction of hypernuclear level energies

Can we derive the effect of ΣN-ΛN coupling force?
–> NSC97f looks good, but we need more data.

J-PARC E13

A=7~9	$\Delta = 0.430 \quad S_\Lambda = -0.015 \quad S_N = -0.390 \quad T = 0.030$,
A=10~16	$\Delta = 0.330 \quad S_\Lambda = -0.015 \quad S_N = -0.350 \quad T = 0.0239$.

MeV

Calculated from G-matrix using ΛN–ΣN force in NSC97f

doublet spacing

			contribution of each term (keV)					keV	
	J^π_u	J^π_l	$\Lambda\Sigma$	Δ	S_Λ	S_N	T	ΔE^{th}	ΔE^{exp}
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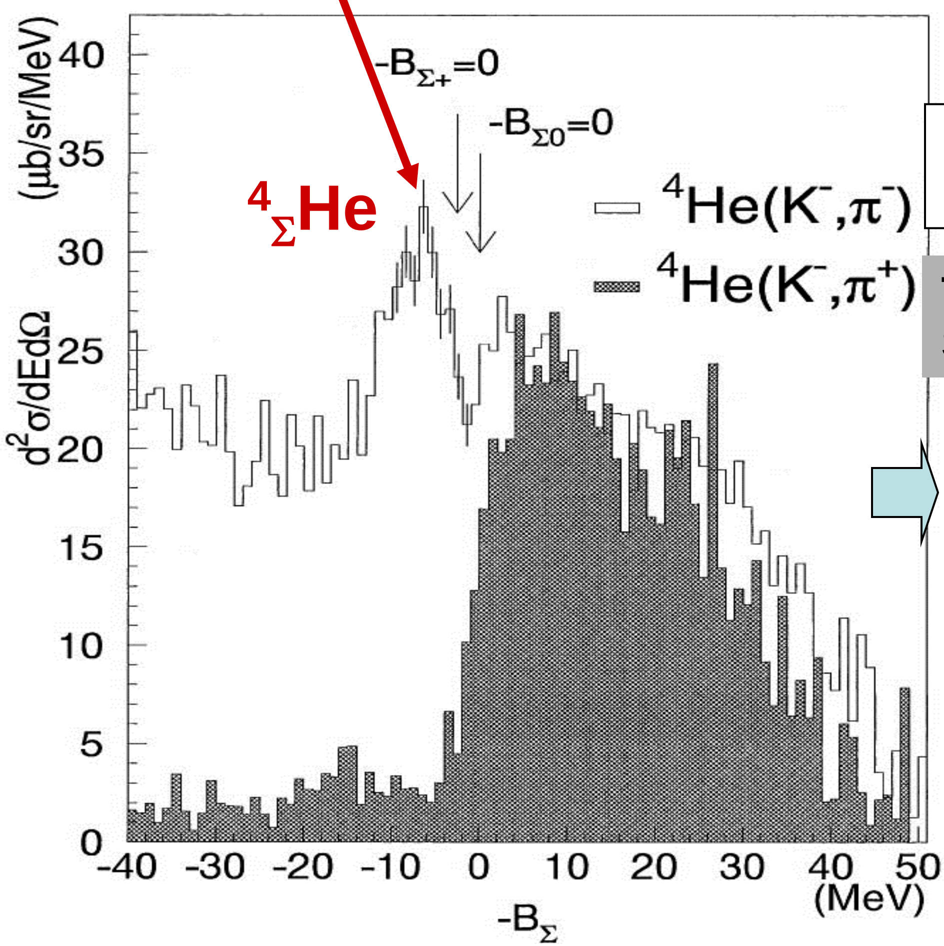
D.J. Millener, J.Phys.Conf.Ser. 312 (2011) 022005

2.2 Σ-nuclear systems
and ΣN force

The only Σ-nuclear bound state so far observed

Substitutional (ΔL=0) state: $n(s_{1/2})^{-1}\Lambda(s_{1/2}1)$

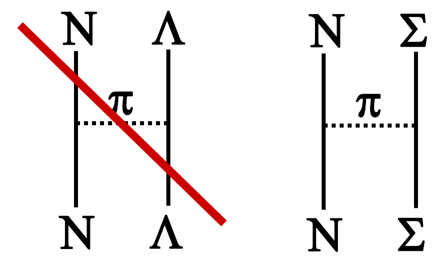


BNL-AGS, Nagae et al., PRL 80 (1995) 1605

***T*: total isospin**

***T*=1/2, 3/2**
***S*=0**

T=3/2 only
S=0



One pion exchange
plays important role in ΣN

Large spin-isospin dependence in ΣN int.

(*I*,*S*) = (3/2,0), (1/2,1) attractive
(3/2,1), (1/2,0) repulsive

-- Consistent with meson exchange models

OPEP:

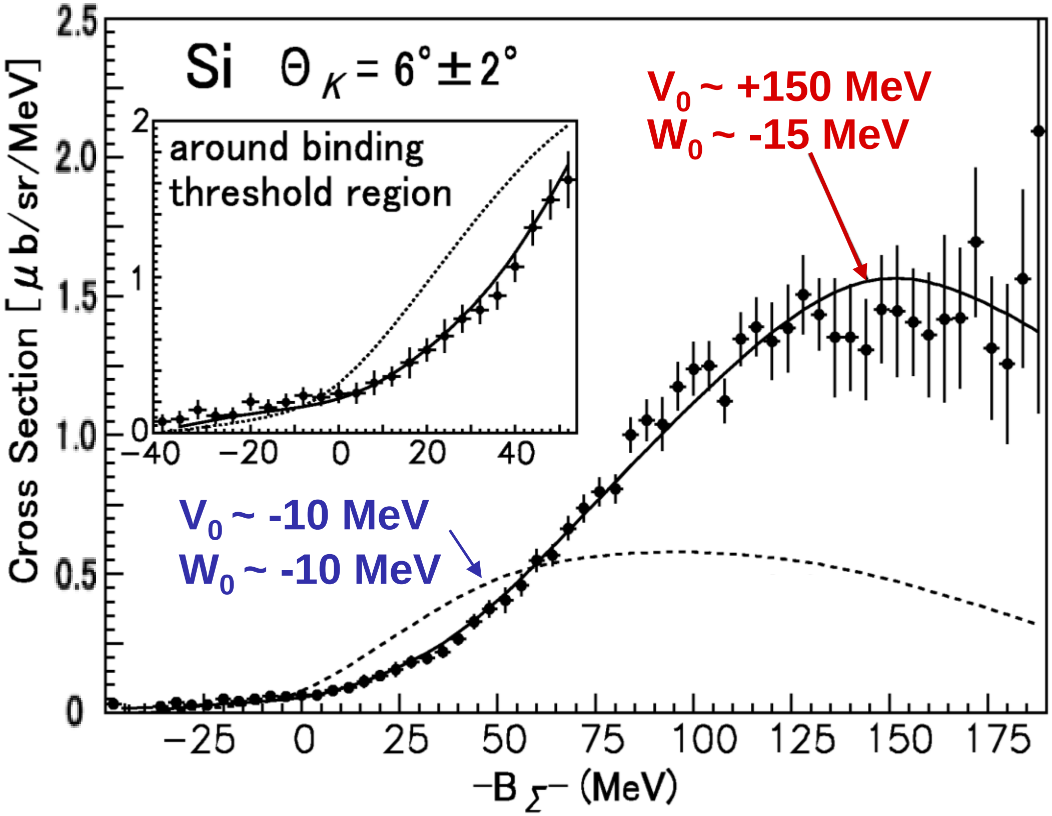
$$\propto (\tau_1\cdot\tau_2)\{(\sigma_1\cdot\sigma_2)+Z(r/m)\,S_{12}\}\,e^{-r/m}/r$$

No Σ bound states observed in other (heavier) Σ hypernuclei

How about spin-isospin averaged pot.?
Σ in neutron stars?

Σ^--^{28}Si Nuclear potential (KEK E438)

^{28}Si (π^-,K$^+$) at 1.2GeV/ with SKS

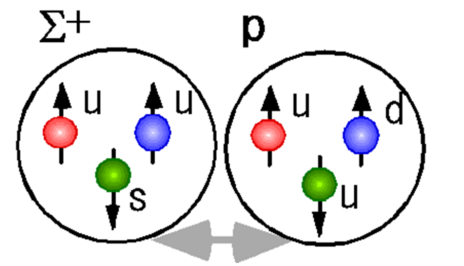


Noumi et al., PRL 87(2002) 072301

Strongly repulsive potential ($U_\Sigma \sim +30$ MeV)

How repulsive are
(I,S) = (3/2,1), (1/2,0) channels?

- **Strong repulsion coming from Pauli effect between quarks?**
  Quark Cluster Model
  Lattice QCD



ΣN (I,S) = (3/2,1)

- **Σ's never appear in n-stars?**

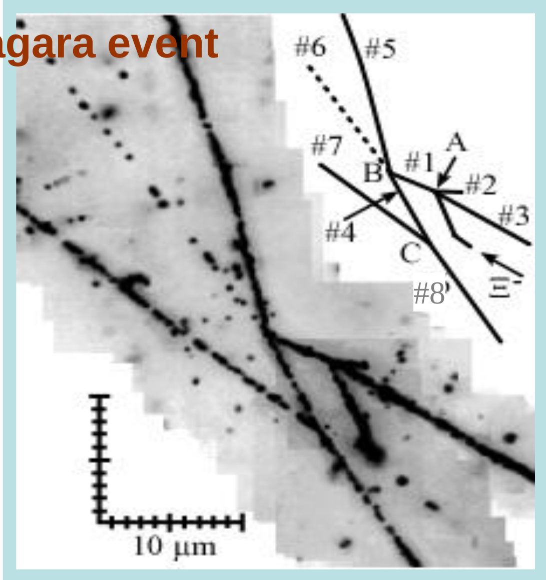
High statistics
Σ^+p/ Σ^-p scattering experiment
planned at J-PARC (E40)

2.3 ΛΛ, Ξ hypernuclei and ΛΛ, ΞN forces

Slide by Nakazawa

$\Lambda\Lambda$ hypernuclei via emulsion+counter hybrid method (KEK E373)

Nagara event



$^{6}_{\Lambda\Lambda}$He

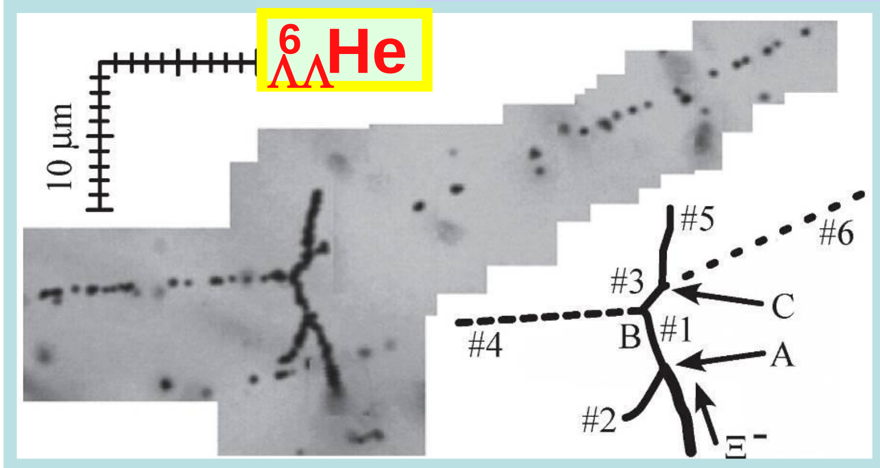
(unique and accurate)

$\Delta B_{\Lambda\Lambda}$= 0.67±0.17 MeV

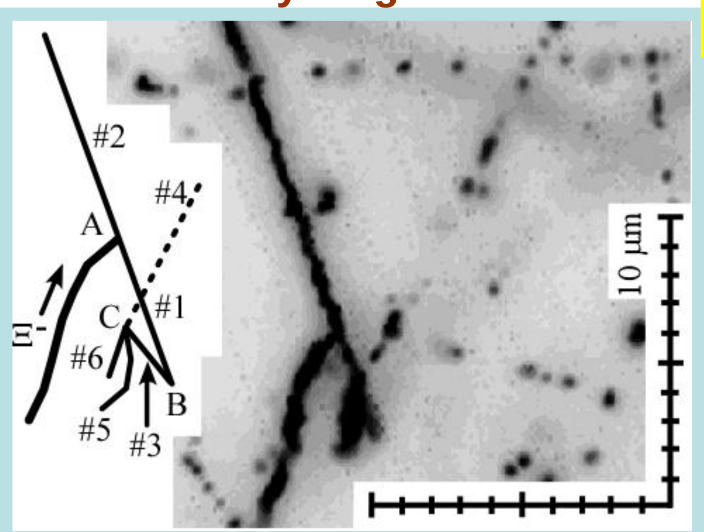
Mikage event

$\Delta B_{\Lambda\Lambda}$= 3.82 ±1.72 MeV

$^{6}_{\Lambda\Lambda}$He



Demachi-yanagi event



$^{10}_{\Lambda\Lambda}$Be*

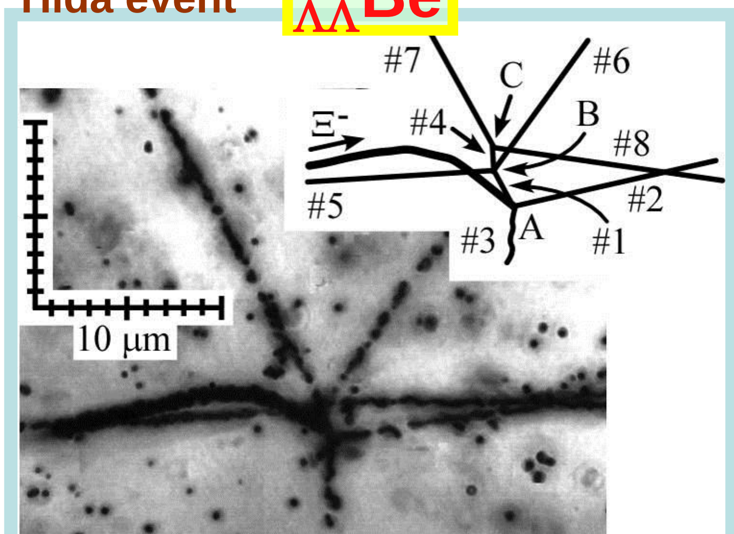
(w/ theoretical help)

$\Delta B_{\Lambda\Lambda}$= -1.52 ±0.15 + 3.0

cf. Ex = 3.0

Hida event

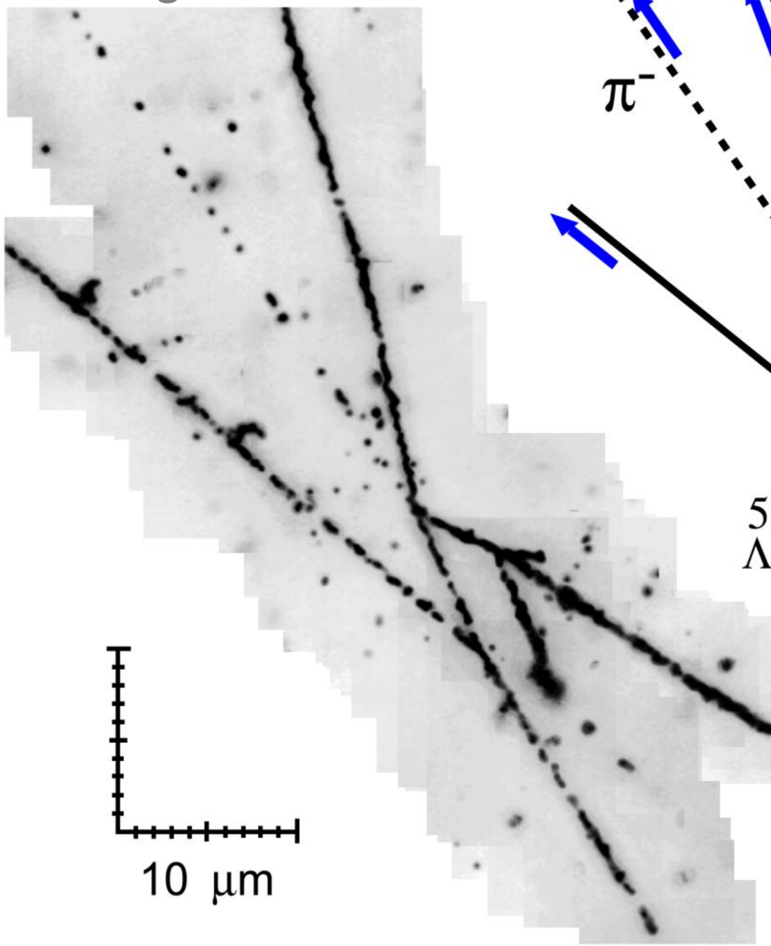
$^{11}_{\Lambda\Lambda}$Be



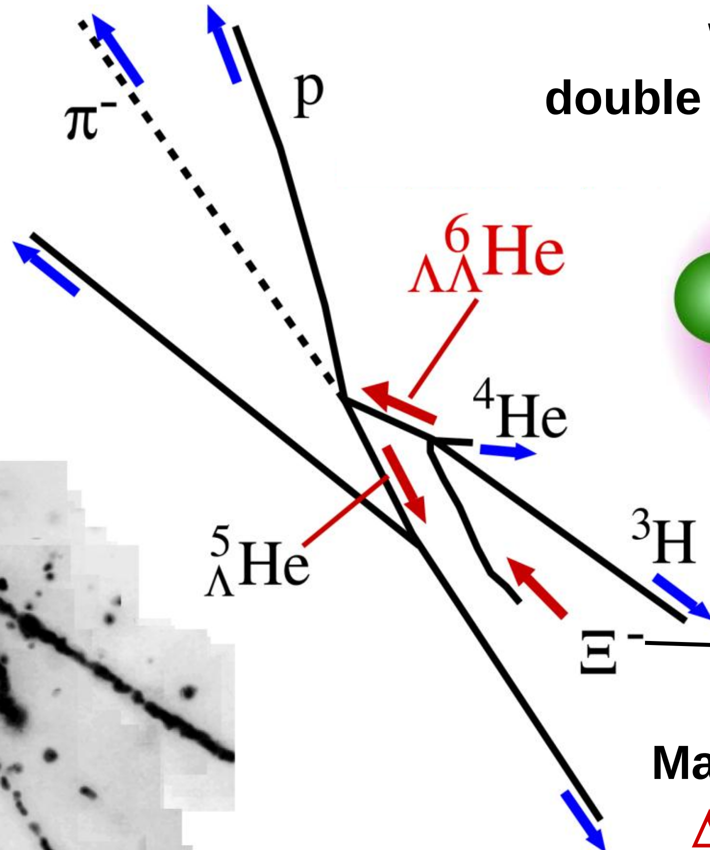
$\Delta B_{\Lambda\Lambda}$= 2.27 ±1.23 MeV

ΛΛ interaction strength

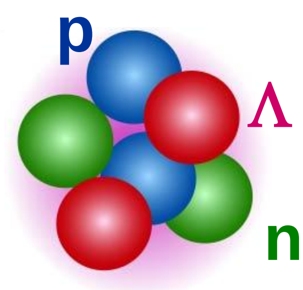
Nagara event



Takahashi et al., PRL 87 (2001) 212502



Well-identified double Λ hypernucleus event



produced from $K^- p \to \Xi K^+$ reaction

Mass ->

$\Delta B_{\Lambda\Lambda} = 0.67 \pm 0.17$ MeV

Interaction between ΛΛ is weekly attractive
Bound H dibaryon does not exist.

⇕

quark model prediction: strongly attractive and makes H dibaryon

Theoretical prediction and J-PARC experiment

HIYAMA, KAMIMURA, MOTOBA, YAMADA, AND YAMAMOTO — PHYSICAL REVIEW C **66**, 024007 (2002)

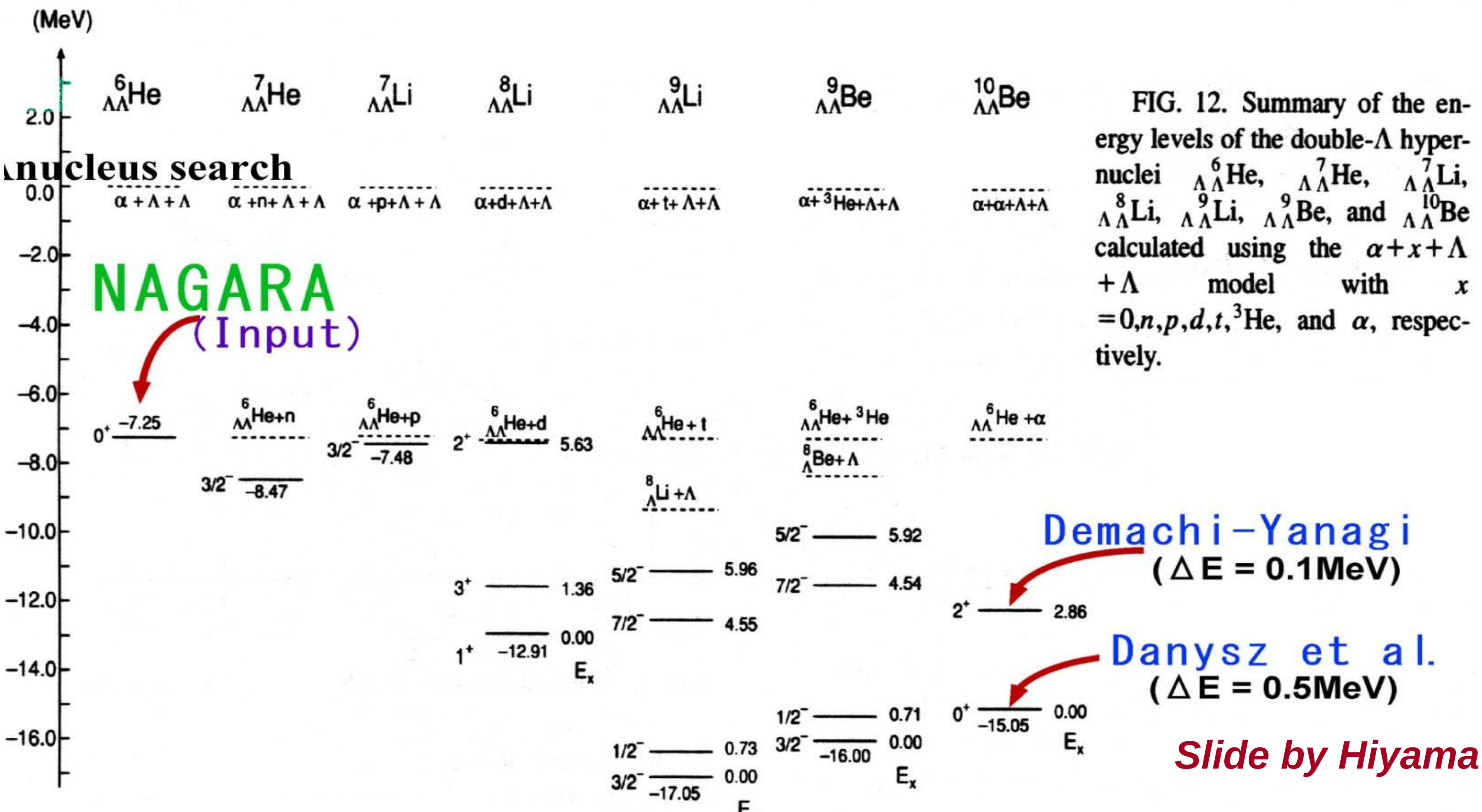


FIG. 12. Summary of the energy levels of the double-Λ hypernuclei $^{6}_{\Lambda\Lambda}$He, $^{7}_{\Lambda\Lambda}$He, $^{7}_{\Lambda\Lambda}$Li, $^{8}_{\Lambda\Lambda}$Li, $^{9}_{\Lambda\Lambda}$Li, $^{9}_{\Lambda\Lambda}$Be, and $^{10}_{\Lambda\Lambda}$Be calculated using the $\alpha+x+\Lambda+\Lambda$ model with $x=0,n,p,d,t,{}^{3}$He, and α, respectively.

~10 times more ΛΛ hypernuclear events (10^2 evens) at J-PARC (E07)

=> ・Precise data for ΛΛ interaction w/o nuclear effect

・ΛΛ -> ΣN decay to search for ΛΛ correlation in a nucleus

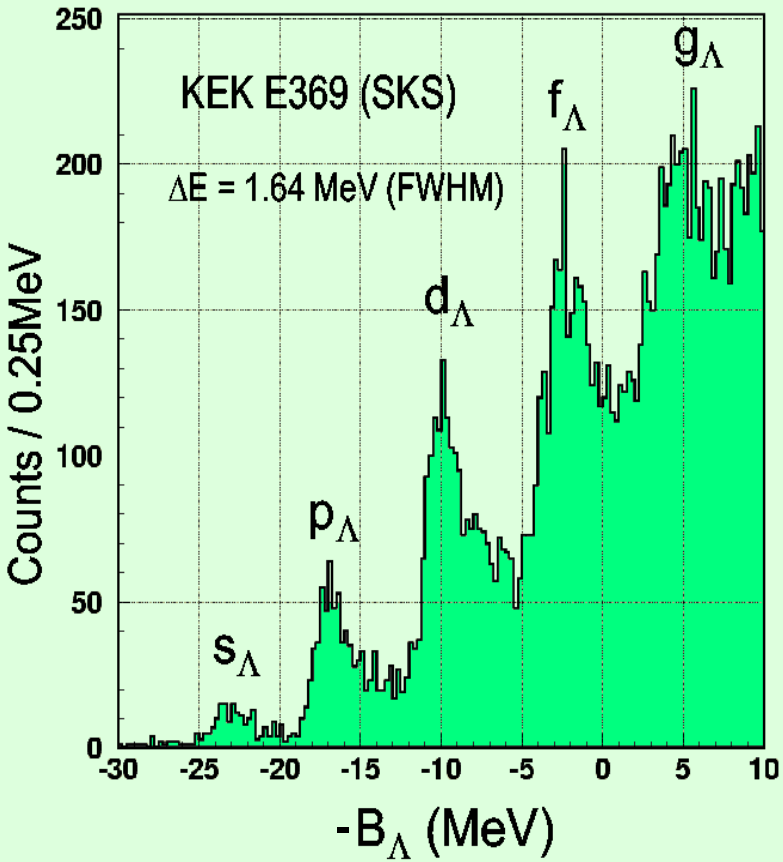
From (π^+,K^+) to (K^-,K^+) reaction

p K^- -> Ξ^- K^+

J-PARC E05

PRC 64 (2001) 044302

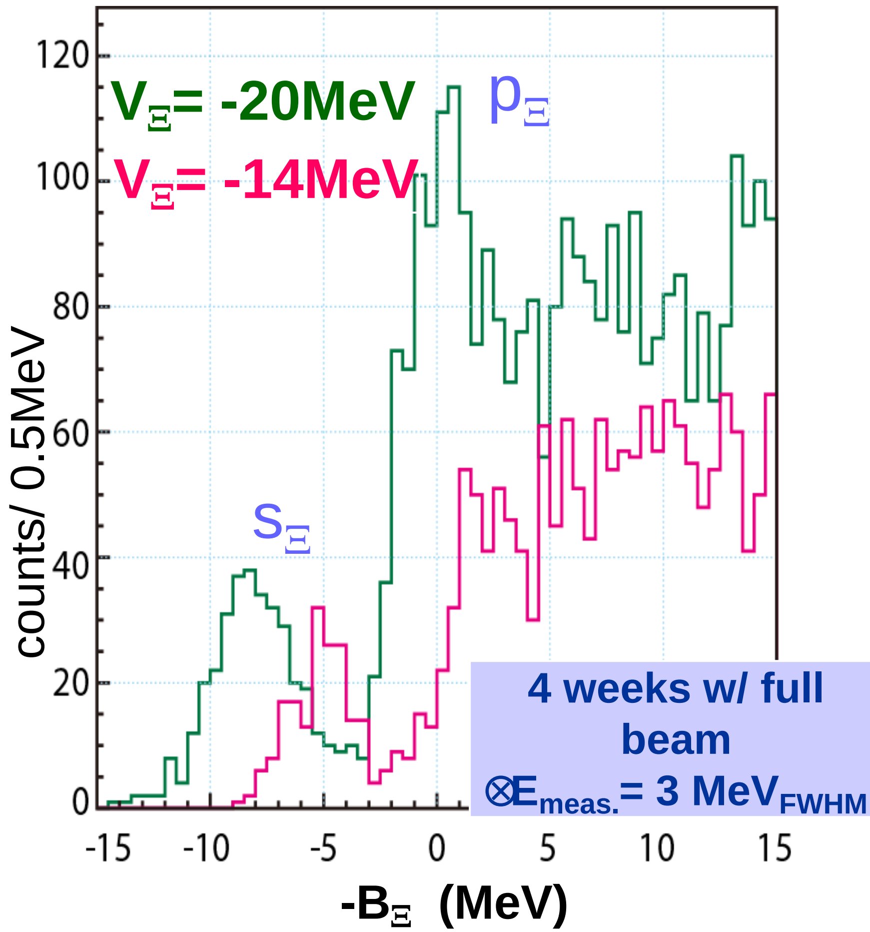
^{89}Y (π^+,K^+) $^{89}{}_{\Lambda}Y$



-> U_Λ = - 30 MeV

How about (K^-,K^+) reaction?

Expected ^{12}C (K^-,K^+) $^{12}{}_{\Xi}Be$ Spectrum



First step to multi-strangeness baryon systems

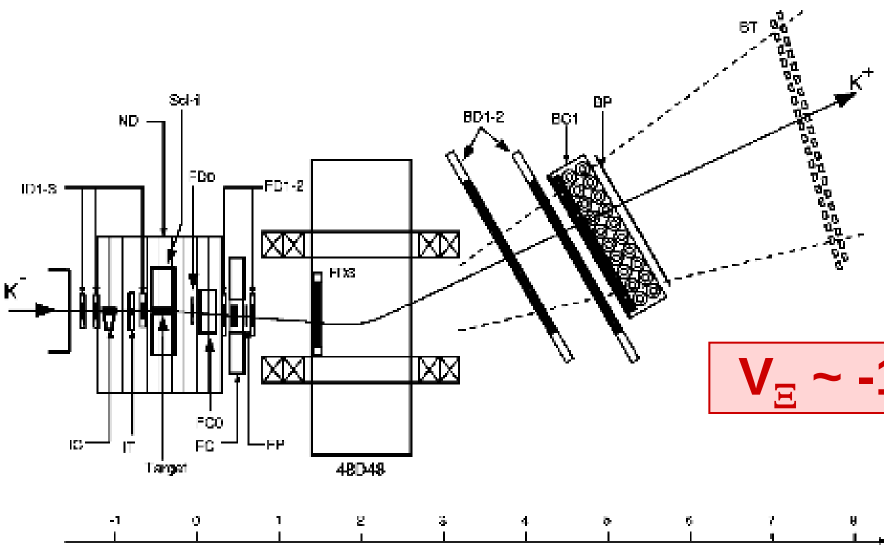
Previous data on ΞN interaction

(BNL AGS E855)

P_K=1.8 GeV/c
⊗M=9.9 MeV/c² (FWHM)
for p(K□,K⁺)∈□

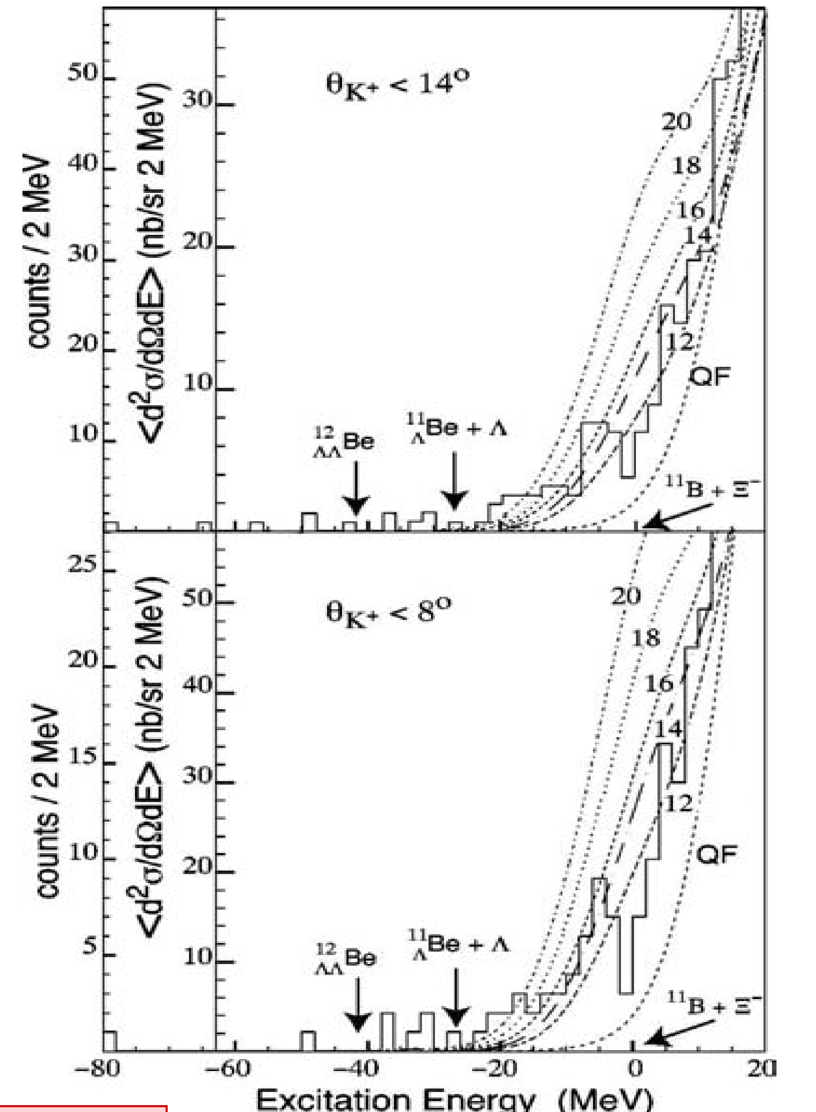
□20 < $E_{\in}$ < 0 MeV
89±14 nb/sr ⎝< 8°
42± 5 nb/sr ⎝<14°

P. KHAUSTOV *et al.*



P. Khaustov et al., PRC61 (2000) 054603

PHYSICAL REVIEW C 61 054603

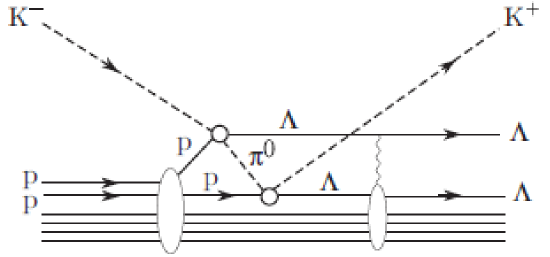


V$_{\Xi}$ ~ -14 MeV?

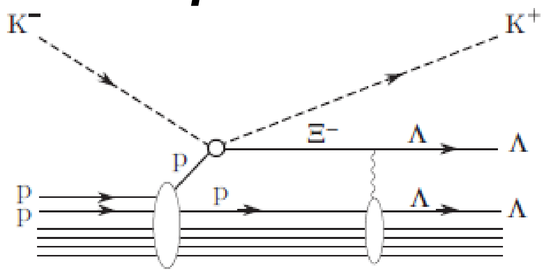
...tation-energy spectra from E885 for ^{12}C(K^-,K^+)X for $\theta_{K^+}<14°$ (top figure) and $\theta_{K^+}<8°$ (bottom figure) along with $^{12}_{\Xi}$Be production theoretical curves for $V_{0\Xi}$ equal to 20, 18, 16, 14, and 12 MeV. The results of a quasifree Ξ production calculation are also shown (curve QF). The expected location of the ground state of $^{12}_{\Lambda\Lambda}$Be and the thresholds for $^{11}_{\Lambda}$Be+Λ and ^{11}B+Ξ^- production are indicated with arrows.

Ξ–ΛΛ hypernuclear mixing states

Harada et al., PLB690 (2010) 363

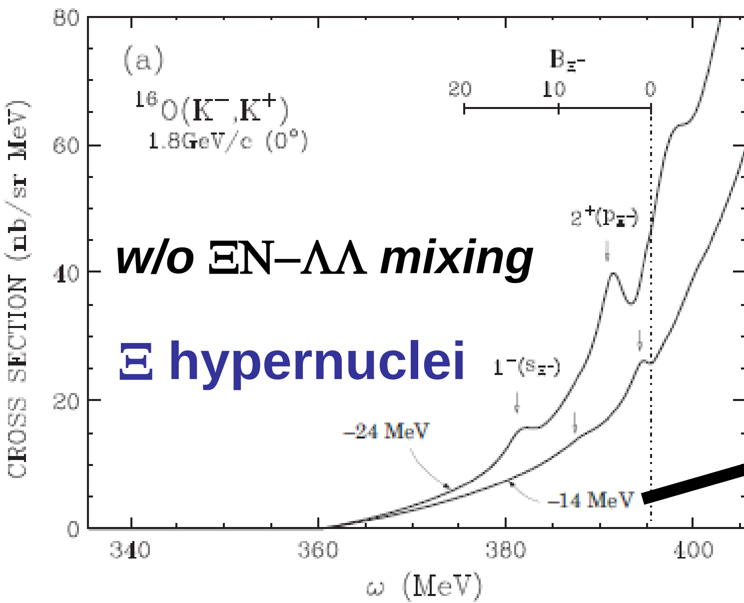


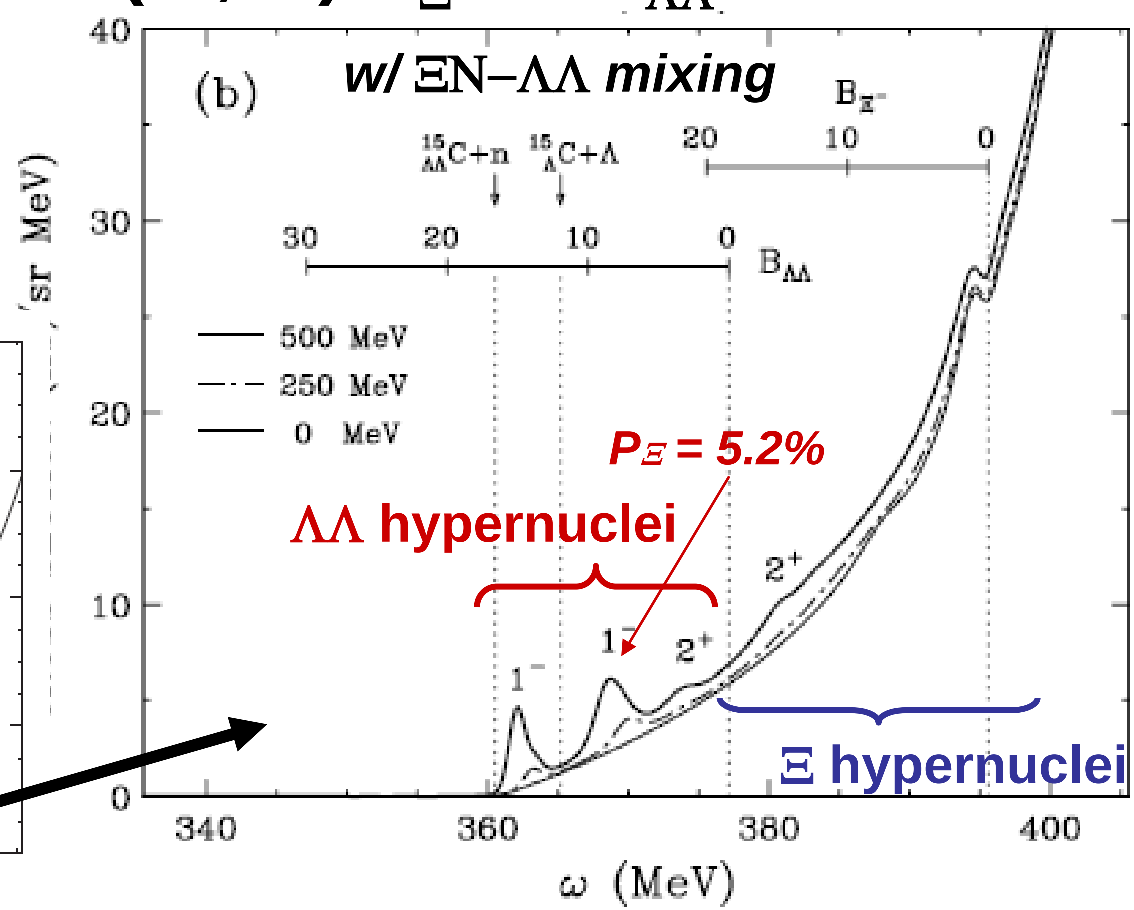
2 step (a)



1 step (b)

$^{16}O\ (K^-,K^+)\ ^{16}{}_{\Xi}C + {}^{16}{}_{\Lambda\Lambda}C$





Summary for the YN, YY interactions

Established   Suggested   Unknown

- **ΛN**

  Attractive (~ 2/3 of NN force)   <- $_{\Lambda}Z$ Λ-single particle orbit data

  Very small LS force, small spin-spin/ tensor forces <- $_{\Lambda}Z$ p-shell γ-ray data etc.

  ΛN–ΣN coupling force   <- s-shell Λ hypernuclei

  p-wave force?   Charge symmetry breaking (Λp Λn)??

- **ΣN**

  Strong isospin dependence (attractive for T=3/2,S=0 and T=1/2,S=1)   <- $^{4}_{\Sigma}He$

  Strongly repulsive in average   <- ^{28}Si (π^-,K^+) spectrum

  How large is the repulsive (T=3/2,S=1) channel?

- **ΛΛ**

  Weakly attractive   <- $^{6}_{\Lambda\Lambda}He$

  ΛΛ-ΞN-ΣΣ coupling force ???

- **ΞN**

  Weakly attractive??   <- ^{12}C (K^-,K^+) spectrum

  Isospin dependence???

- **ΛΣ, ΣΣ, ΞΛ, ΞΣ, ΞΞ; ΩN**   Unknown at all ???

J-PARC
will answer

3 How to approach nuclear matter in neutron stars

Neutron Star Matter

- **Final form of matter in matter evolution in the universe**

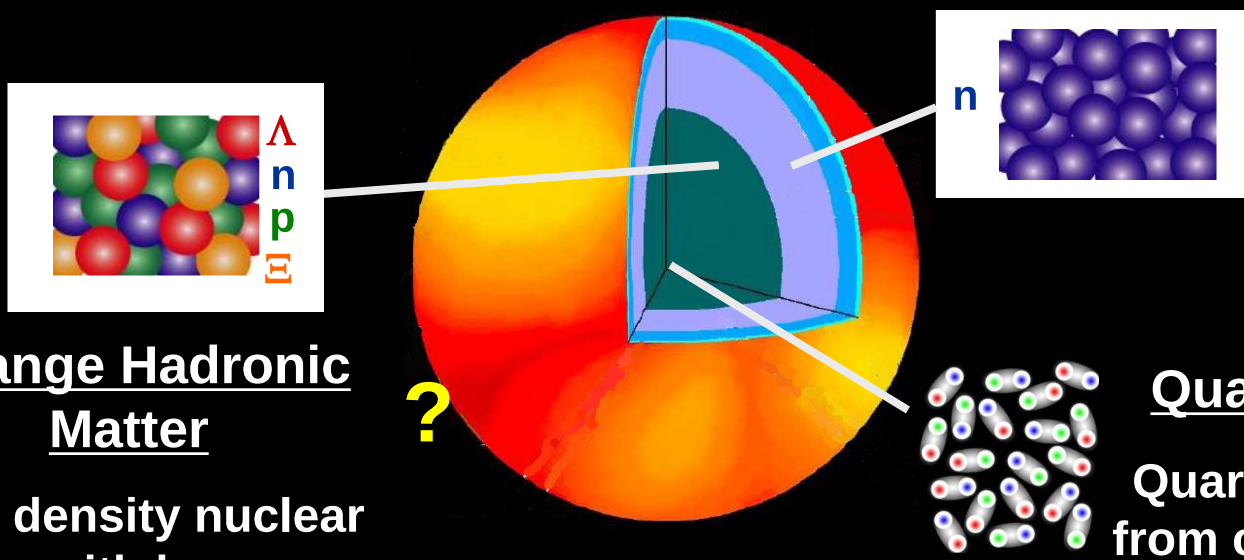
  Supernova explosion, Many samples as X-ray pulsars

- **Highest density matter in the universe**

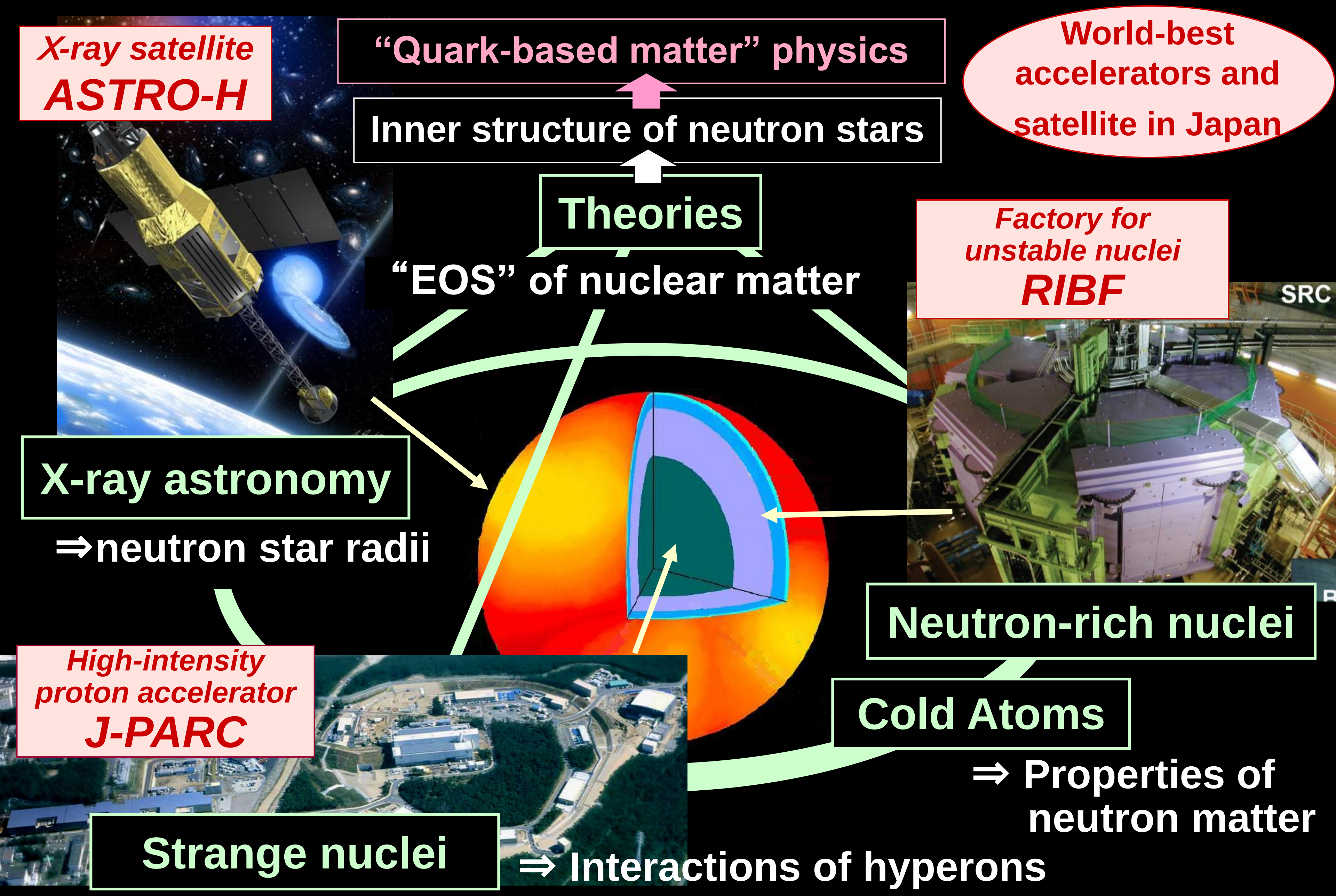
  Mass = 1~2 $M_{\odot}$, R~ 10 km? (no direct observation)

  => ρ (center) = 3~10 ρ_0

- **Various forms of matter made of quarks**

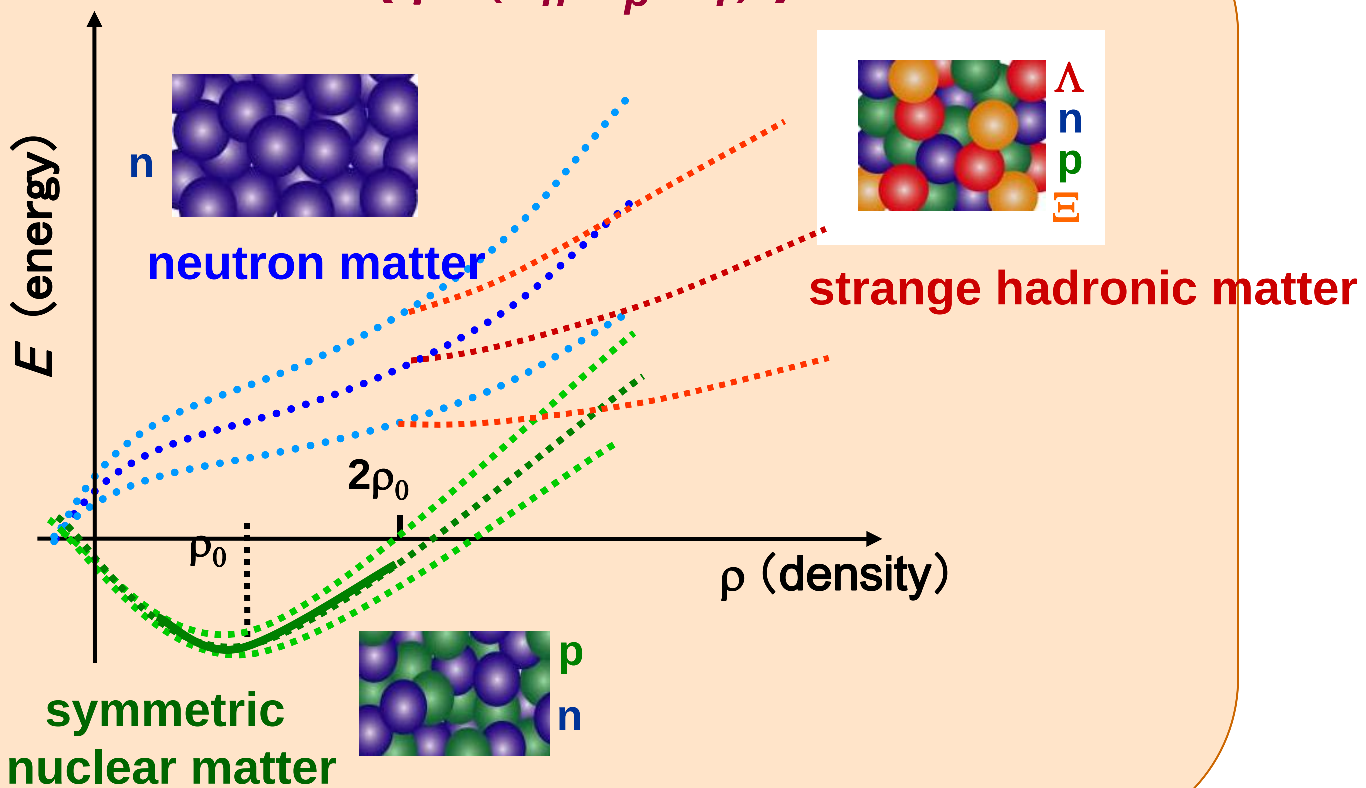


Joint research to reveal neutron star matter



Equation of state (EOS) for nuclear matter

$E = F(\rho, (n_n, n_p, n_Y))$



EOS ➡ inner structure of n-star

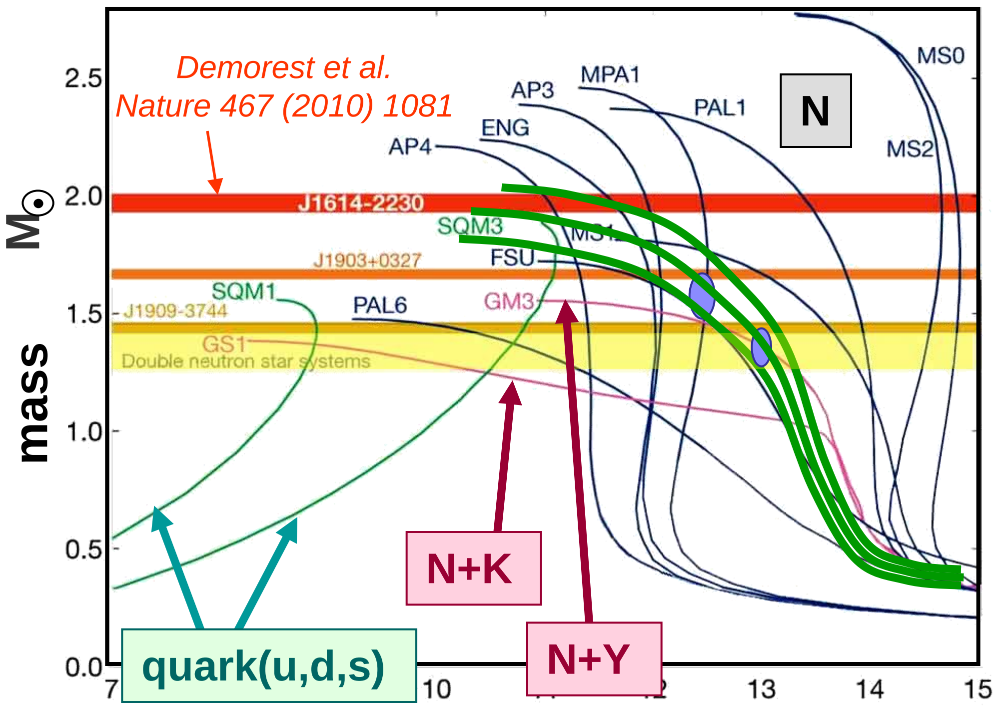
Why experiment-observation joint research?

EOS of nuclear matter

$E = F(\rho, (n_n, n_p, n_Y))$

unique correspondence ⇕ by gravity-pressure balance

Mass-Radius relation



n-star radius (km)
no direct measurement

experimental info on nucl. matter + theory ⇒ **determine EOS**

+

measurement of radius by X-ray satellite ⇒ **confirm EOS**

⇓

establish the EOS

Also establish theoretical framework existence of quark matter

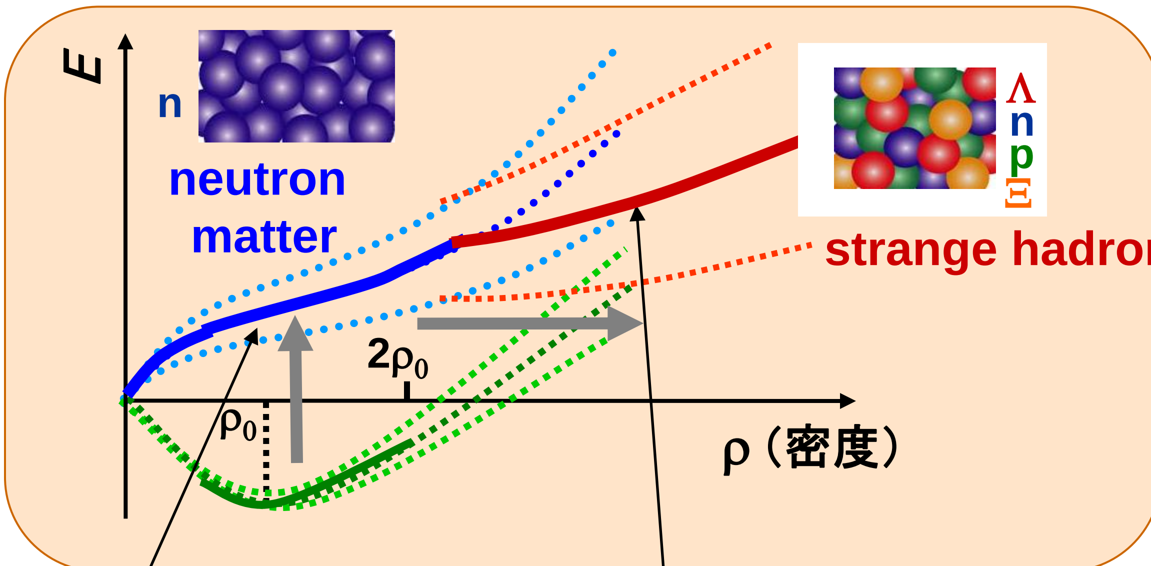
How to determine EOS from experiments

■ **Inner crust, outer core($\rho < 2\rho_0$)**

How EOS changes when going to neutron richer matter?

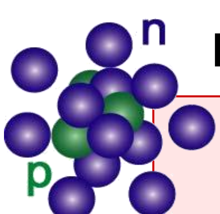
■ **Inner core ($\rho > 2\rho_0$)**

How much and which hyperons appear?

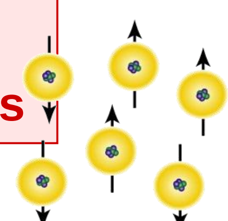


EOS for neutron matter

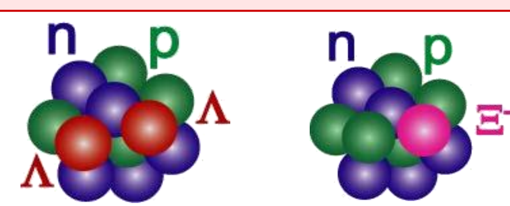
YN, YY interactions used as input for EOS



n-rich nuclei@RIBF
+
Ultra-cold Fermi atom gas

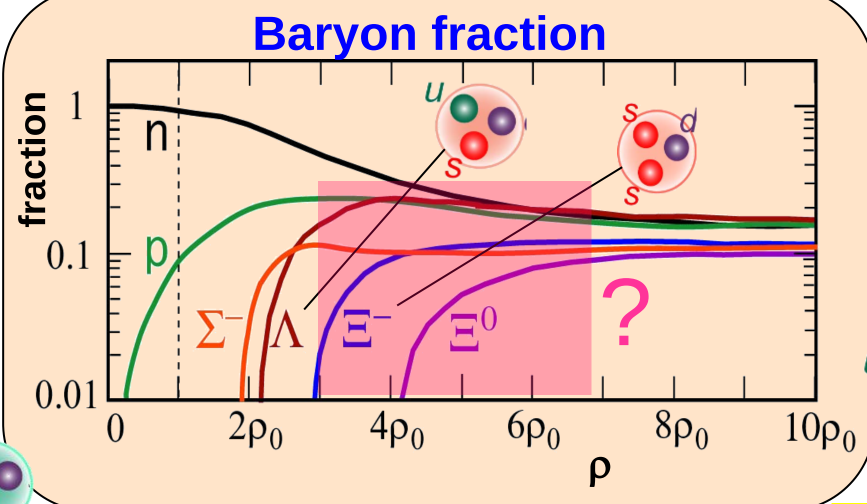


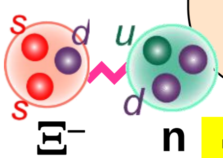
Various hypernuclei@J-PARC



B-B interactions of multi-strange systems

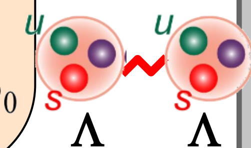
Determine hyperon mixing in centeral region ($\rho > 3\rho_0$) -> EOS





ΞN int.

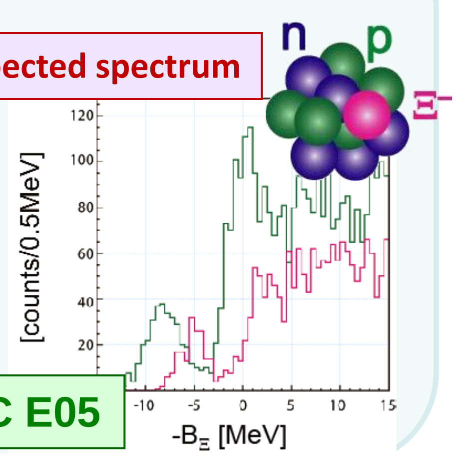
ΞN→ΛΛ int.



ΛΛ int.

Ξ hyp. spectroscopy

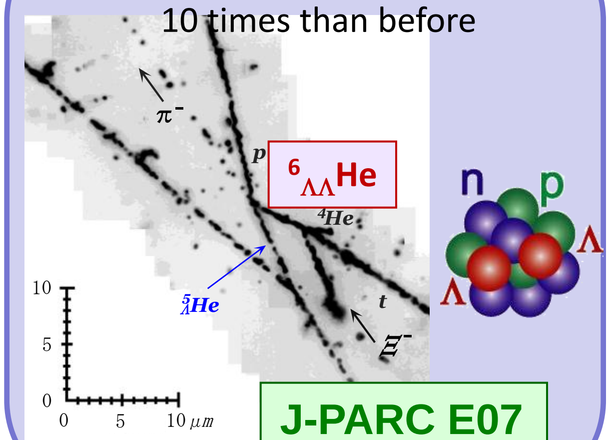
$^{12}_{\Xi}$Be expected spectrum



J-PARC E05

ΛΛ hyp. emulsion exp.

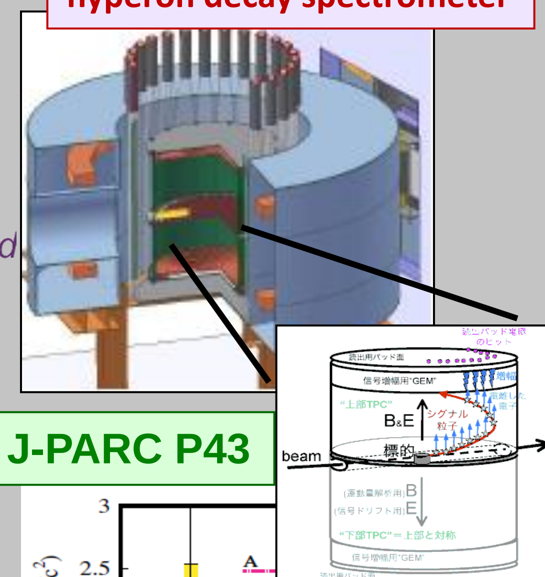
10 times than before



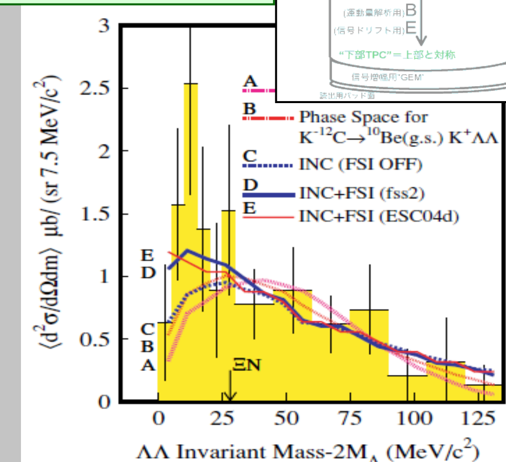
J-PARC E07

ΛΛ correlation

hyperon decay spectrometer



J-PARC P43

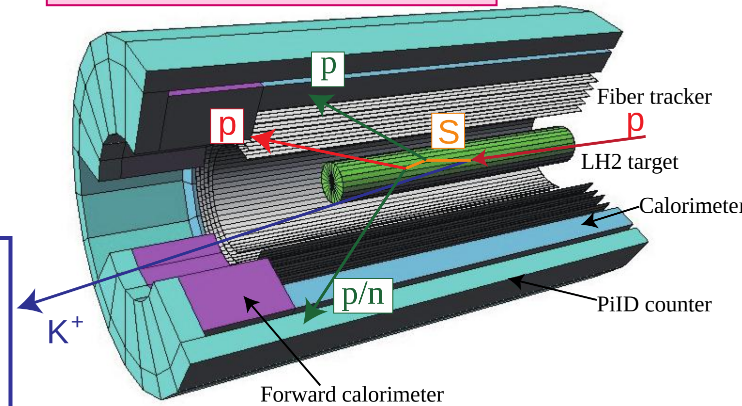


ΛΛ invariant mass

Strangeness in neutron-rich environment

Strangeness mixing by S=-1 hadrons
in $\rho = 2\sim3\rho_0$ region

proton scattering detector

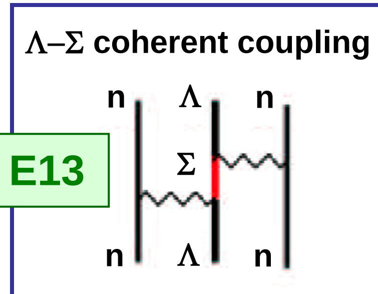


Σ^+p scattering exp.

J-PARC E40

-> Σ^-n (= Σ^+p) interaction

=> Existence of Σ^- in n-star
Confirm “quark Pauli effect”



Λ hyp. γ-spectroscopy

J-PARC E13

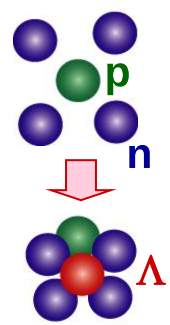
-> ΛN, ΛNN (ΛN-ΣN) interaction

Neutron-rich Λ hyp. spectroscopy

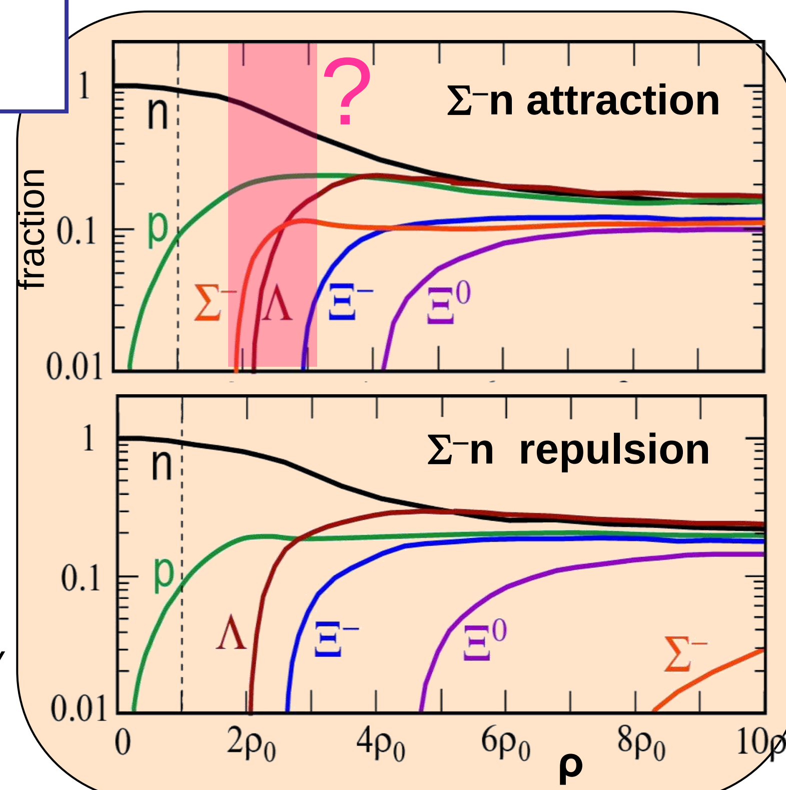
-> Λnn interaction
in neutron-rich environment

J-PARC E10

=> Λ fraction in neutron matter



$^{6}_{\Lambda}$H
Hyper-heavy hydrogen

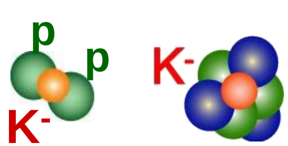


K⁻ nuclear bound states

-> How large is the K^{bar}N interaction

=> Determine existence of Kaon
condensation in n star

J-PARC E15, E27



5. Summary

- **J-PARC connects QCD and nuclear physics through studies of BB forces and high density nuclear matter with strangeness**
- **Study of YN and YY forces via strange nuclear systems enables unified understanding of BB forces including their short rage parts, and then, high density nuclear matter in neutron stars.**
- **ΛN force has been well studied via (π,K$^+$) spectroscopy and γ-spectroscopy. Further study of neutron-rich Λ hypernuclei is necessary for ΛNN force.**
- **ΣN force looks strongly repulsive probably due to quark Pauli effect. It will be confirmed by a Σp scattering experiment.**
- **$\Lambda\Lambda$ force was found to be weakly attractive. More data necessary to precisely determine the force and investigate $\Lambda\Lambda$ correlation/ H resonance.**
- **ΞN force will be studied from Ξ hypernuclei via (K$^-$, K$^+$) reaction.**
- **Joint research together with neutron-rich nuclei, ultra-cold atoms, X-ray astronomy, and theories will reveal the neutron star matter.**
- **Impurity effects and baryon properties and behavior in nuclei can be also investigated by strangeness nuclear physics.**