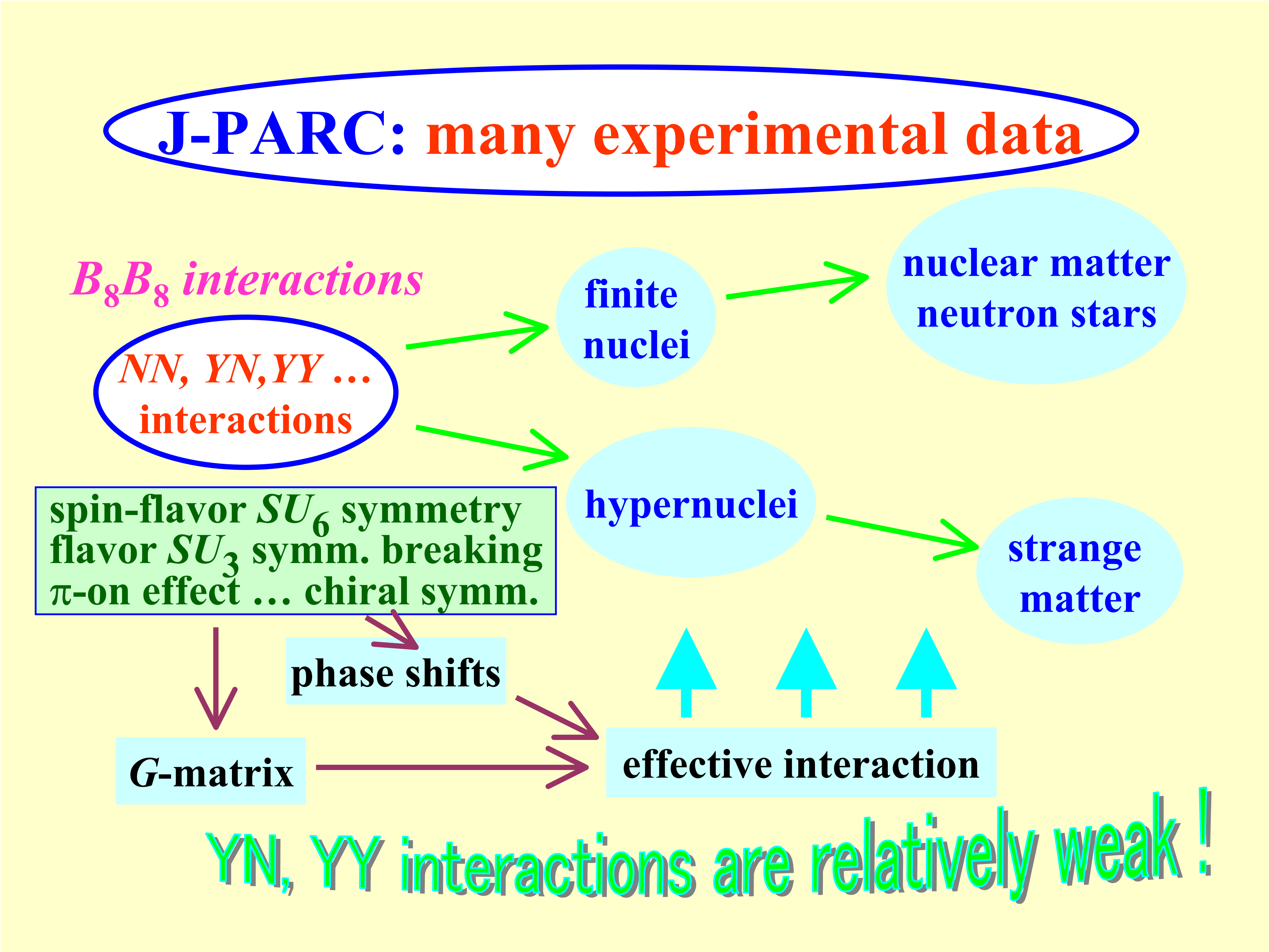
A Microscopic Approach to Hyperon-Nucleon and Hyperon-Hyperon Interactions in Hypernuclei

Y. Fujiwara (Kyoto)　K. Miyagawa (Okayama)
M. Kohno (Kyushu Dental)　Y. Suzuki (Niigata)

1. Introduction
2. A strategy --- theoretical ---
3. Examples
   3.1. ${}_{\Lambda}^{3}$H Faddeev calculation
   3.2. Spin-orbit splitting of ${}_{\Lambda}^{9}$Be
   3.3. Nagara event: ${}_{\Lambda\Lambda}^{6}$He
4. Summary


J-PARC: many experimental data
B_8B_8 interactions
NN, YN, YY … interactions
finite nuclei
nuclear matter neutron stars
hypernuclei
strange matter
spin-flavor SU_6 symmetry
flavor SU_3 symm. breaking
π-on effect … chiral symm.
phase shifts
G-matrix
effective interaction
YN, YY interactions are relatively weak !

Different approaches to different categories

- ***s*-shell hypernuclei:** $_{\Lambda}^{3}H$, $_{\Lambda}^{4}H$, $_{\Lambda}^{4}He$, $_{\Lambda}^{5}He$ …
rigorous few-body calculations, using the bare interactions, are possible
- ***p*-shell hypernuclei:** $_{\Lambda}^{9}Be$, $_{\Lambda}^{6}Li$, $_{\Lambda}^{12}C$, ($_{\Lambda\Lambda}^{6}He$), $_{\Lambda\Lambda}^{10}Be$ … **α-cluster models are efficient**
- **medium and heavy hypernuclei:** $_{\Lambda}^{89}Y$ …
mean field approach based on *G*-matrix + Thomas Fermi approximation
- **strange matter and high density matter**
***G*-matrix and variational**

A small number of experimental data are essential : for example,

- $B_\Lambda({}^{3}_{\Lambda}\mathrm{H}) = 130 \pm 50$ keV: **triton binding energy**
- $B_\Lambda({}^{5}_{\Lambda}\mathrm{He}) = 3.12 \pm 0.02$ MeV: **overbinding problem**
- $\Delta B_{\ell s}(3/2^{+}\text{-} 5/2^{+}) = 43 \pm 5$ keV : **ℓs splitting of ${}^{9}_{\Lambda}\mathrm{Be}^{*}$**
- $\Delta B_{\Lambda\Lambda} = 1.01 \pm 0.20$ MeV : **Nagara event**
- . . .

To make the most of these experimental data, the OCM (orthogonality condition model) and simple boson models are not sufficient …

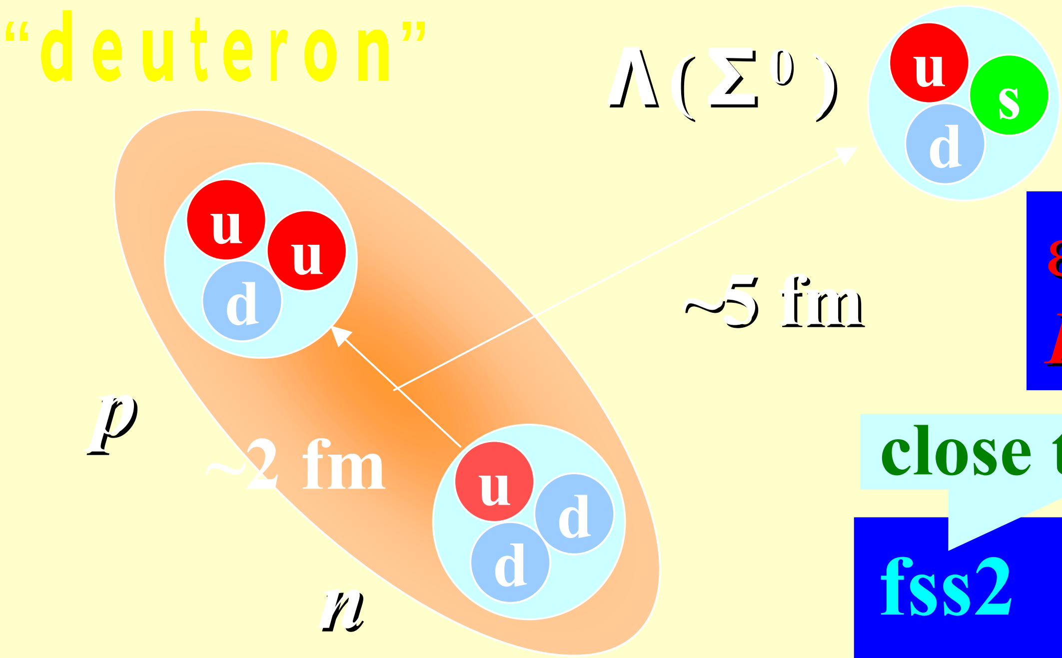
3-cluster Faddeev formalism using 2-cluster RGM kernels

${}^{3}_{\Lambda}$H (hypertriton)

PRC 70, No. 2 (2004)

ΛN on-shell properties are directly reflected

${}^{1}S_{0}$ / ${}^{3}S_{1}$ relative strength



exp't

ε_d = 2.22 MeV

B_Λ=130 ±50 keV

close to NSC89

		P_Σ (%)
fss2	289 keV	0.80
FSS	878 keV	1.36

150 channel calculation

ε_{NN} = 19.37 – 21.03 = −1.66

$|\varepsilon_d|$ = 17.50 – 19.72 = −2.22

(MeV)

ΛN $^1S_0$ and $^3S_1$ effective range parameters

model	a_s (fm)	r_s (fm)	a_s (fm)	r_t (fm)	B_Λ(keV)	P_Σ(%)
FSS	−5.41	2.26	−1.03	4.20	878	1.36
fss2	−2.59	2.83	−1.60	3.01	289	0.80
NSC89	−2.59	2.90	−1.38	3.17	143	0.5
"fss2"	−2.15	3.05	−1.80	2.87	145	0.53

"fss2": $m_\kappa c^2 = 936$ MeV → 1,000 MeV

favorable for $_\Lambda^4$H (1^+) ?

B_Λ (keV)	fss2	"fss2"
6 ch (*S*)	137	44
15 ch (*SD*)	198	85
102 ch ($J\leq4$)	288	145
150 ch ($J\leq6$)	289	145

Effect of the higher partial waves

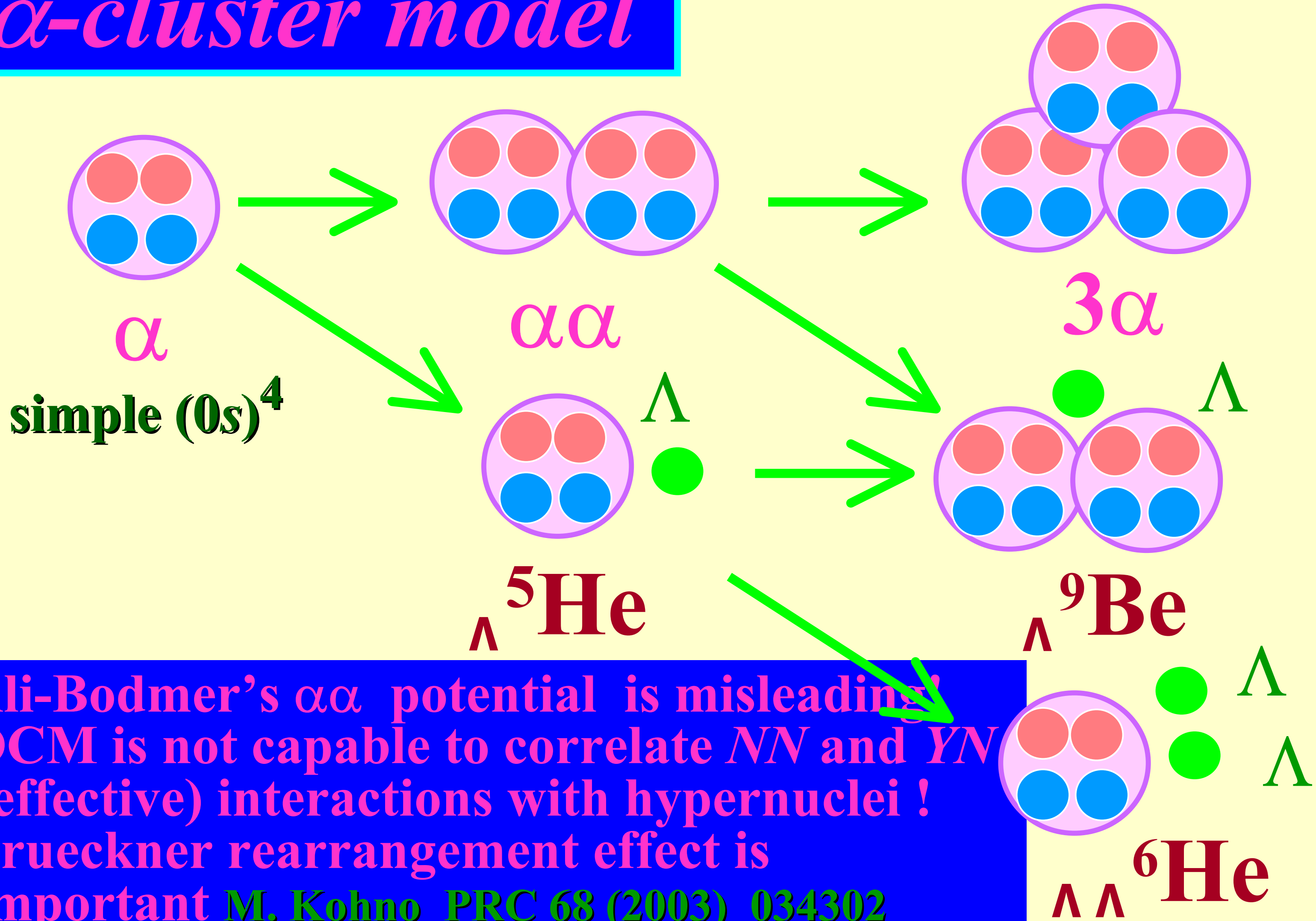
B_Λ^{exp}=130 ±50 keV

$V_{\Lambda N}$	a_s (fm)	a_t (fm)	B_Λ (keV)
NSC89	−2.59	−1.38	143
NSC97f	−2.51	−1.73	80
NSC97e	−2.10	−1.83	23
NSC89(S)	−3.39	−1.38	$0.37 \cdot 10^3$
NSC97f(S)	−2.82	−1.72	$0.18 \cdot 10^3$
NSC97e(S)	−2.37	−1.83	$0.10 \cdot 10^3$
exp’t			130 ± 50

upper: Faddeev by A. Nogga et al. Phys. Rev. Lett. 88, 172501 (2002)
lower: variaton by H. Nemura et al. Phys. Rev. Lett. 89, 142504 (2002)

Simulated potentials in *s*-shell Λ-hypernuclei are misleading!

α-cluster model



- Ali-Bodmer's αα potential is misleading!
- OCM is not capable to correlate *NN* and *YN* (effective) interactions with hypernuclei !
- Brueckner rearrangement effect is important M. Kohno PRC 68 (2003) 034302

3α Faddeev for $^{12}C(0_1^+)$

Cut-off Coulomb with R_C=10 fm in Faddeev

Ali-Bodmer

Fad.

-1.53

RGM	Fad.	GCM	Fad.	SVM	Fad.
Fukushima Kamimura (1977)		Uegaki (1977)		Suzuki (2002)	
-7.5	-5.97	-6.9	-5.37	-11.34	-9.59

Exp: -7.3 MeV

3 cluster exchange effect is small !

effective *NN* force

VN2	VN1	MN(3R)	
-0.245	0.18	0.14 MeV	for $E_{2\alpha}(0^+)$

Fujiwara, Miyagawa, Kohno, Suzuki, Baye, Sparenberg, PRC 70, No. 2 (2004)

$2\alpha\Lambda$ Faddeev for ${}^{9}_{\Lambda}$Be

PRC 70, No. 2 (2004)

(3.04 MeV) 2+

(0) 92 keV 0+

$\alpha+\alpha+\Lambda$

^{8}Be

-3.12±0.02 MeV

$\alpha + {}_{\Lambda}{}^{5}$He

exp't

(u = 0 SB)
MN+SB forces

(3067±3±1 keV) $3/2^+$ (2.92 MeV)

(3024±3±1 keV) $5/2^+$

-6.62±0.04 MeV

$1/2^+$ -6.84 MeV

${}_{\Lambda}{}^{9}$Be

calc.

Ali-Bodmer's αα potential
leads to overbinding !

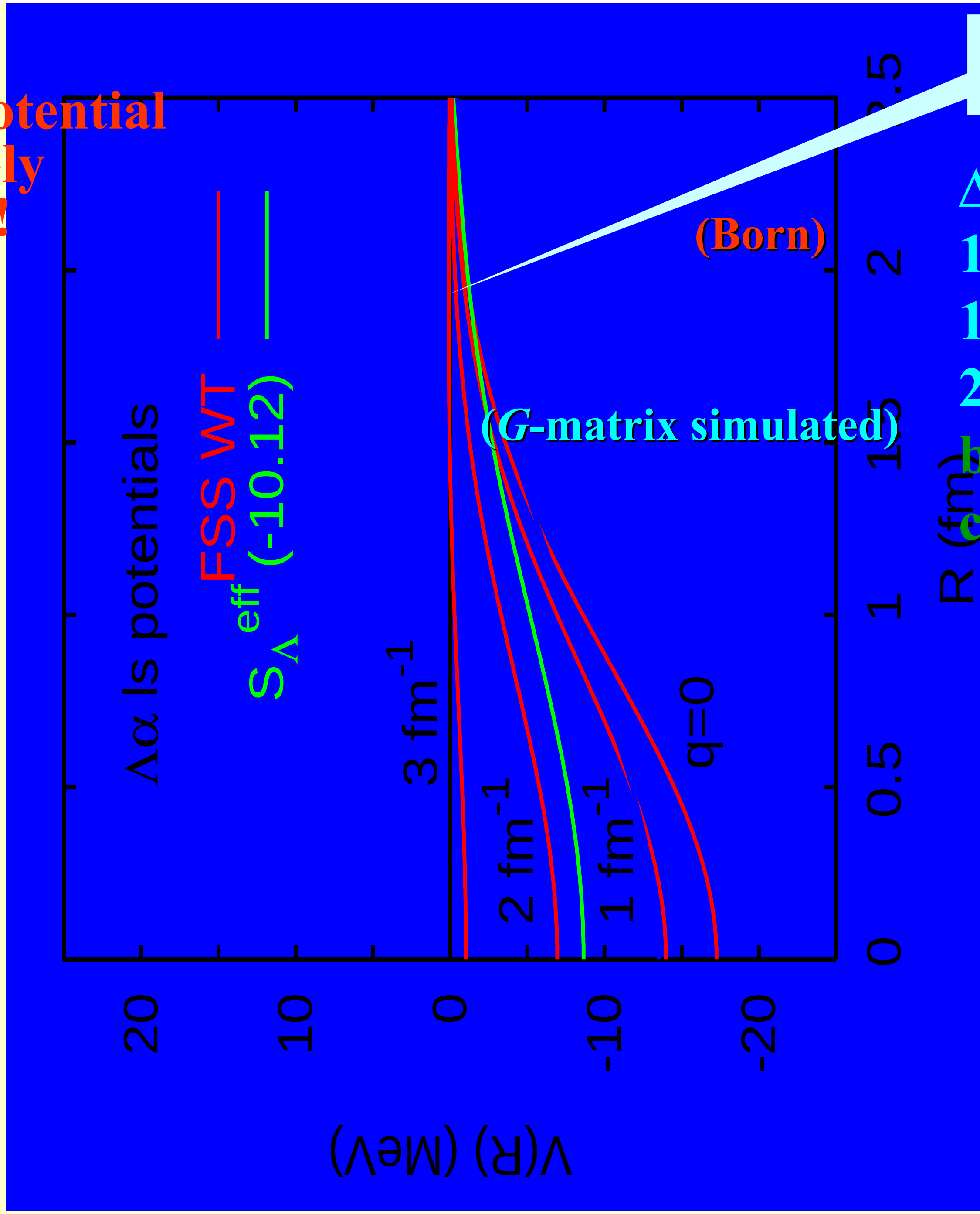
$\Delta E(3/2^+ - 5/2^+)$ = 43±5 keV

Akikawa et al.
PRL 88 (2002) 082501

198 keV (fss2 quark (86 keV) + EMEP) → ~40 keV
137 keV (FSS) by Born kernel
(u = 0.82 SB)

in short-range
correlations ?

Folding potential is extremely non-local !



$S_\Lambda^{eff}=(1+M_\Lambda/4M_N)\times S_\Lambda$

(Born)

(*G*-matrix simulated)

$\Delta E_{\ell s}$=

137 keV

147 keV

209 keV

by Faddeev calculations

Scheerbaum factors S_Λ in symmetric nuclear matter (k_F=1.07 fm^{-1}) by G-matrix calculations

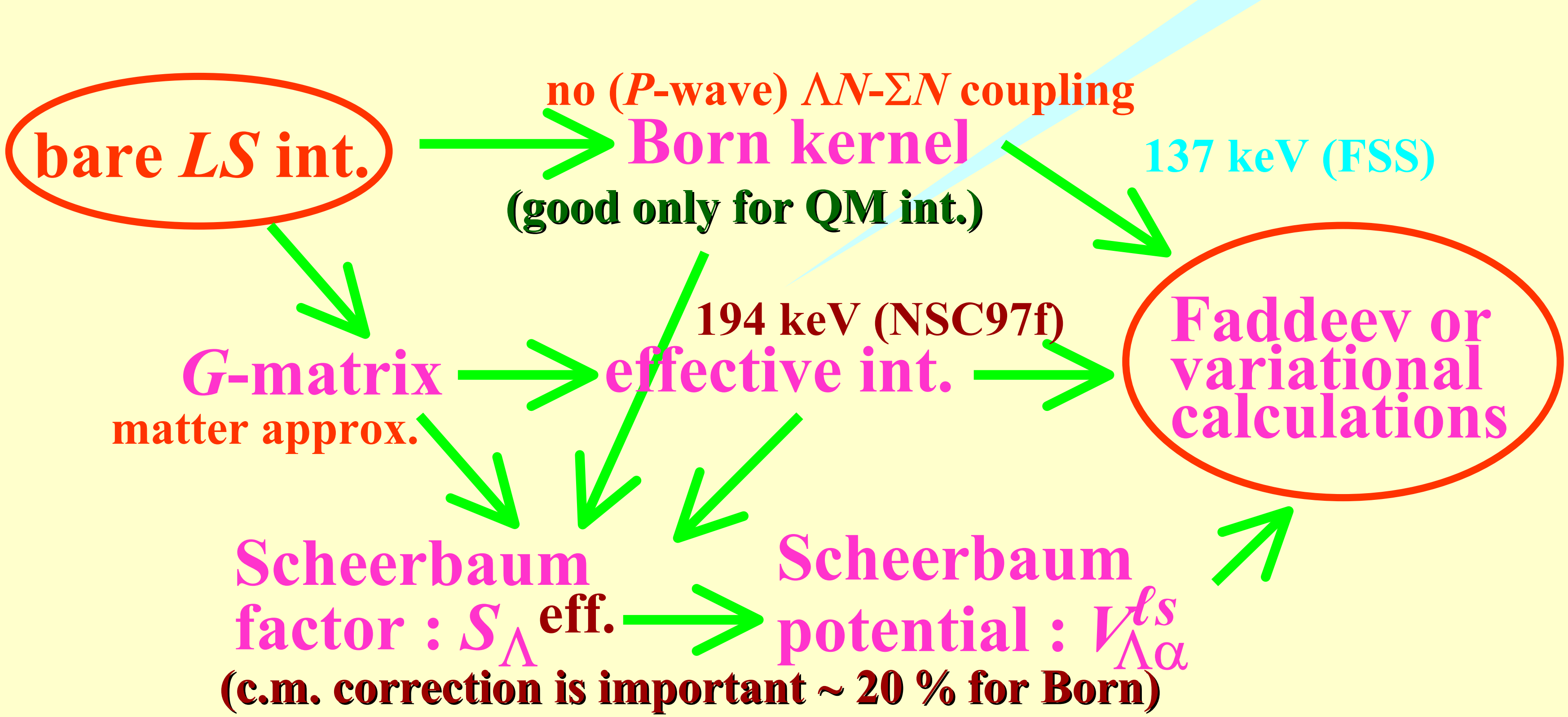
$^1P_1$ - $^3P_1$

model		full		*P*-wave ΛN-ΣN coupling off	
		odd	even	odd	even
FSS	*LS*	−17.36	0.38	−19.70	0.30
	$LS^{(-)}$	24.83	0.22	8.37	0.26
	total	−1.93		−10.77	
fss2	*LS*	−19.97	−0.14	−21.04	−0.20
	$LS^{(-)}$	8.64	0.21	6.12	0.23
	total	−11.26		−14.89	

EMEP *LS* force is unfavorable !

Unit: MeV·fm^5

Comparison of different methods



Results are different in all the cases !
Comparison in the same condition is necessary.

$2\Lambda\alpha$ Faddeev for ${}_{\Lambda\Lambda}{}^{6}$He using $\Lambda\Lambda$ RGM *T*-matrices of fss2 and FSS

$\Delta B_{\Lambda\Lambda} = B_{\Lambda\Lambda}({}_{\Lambda\Lambda}{}^{6}\mathrm{He}) - 2B_{\Lambda}({}_{\Lambda}{}^{5}\mathrm{He}) = 1.01 \pm 0.20$ MeV

H. Takahashi et al. PRL 87 (2001) 21250

1.14 in SC

$V_{\Lambda N}$	$V_{\Lambda\Lambda}$(3G)	FSS	fss2	SB (2G)
SB	3.62	3.65	1.41	1.90

PRC 70, No. 3 (2004)

Effects not considered

1. $(\alpha\Lambda\Lambda)$-$(\alpha\Xi N)$-$(\alpha\Sigma\Sigma)$ CC effect (fss2, FSS) ~ 0.5 MeV ?
2. Brueckner rearrangement effect of α-cluster (starting energy dependence of the ΛN interaction) ~ −1 MeV

   M. Kohno PRC 68 (2003) 034302
3. quark Pauli effect by Suzuki and Nemura < −0. 2 MeV

   PTP 102 (1999) 203

fss2 is consistent with the Nagara event !

Summary

We should use most appropriate approaches to the systems considered. For the *s*-shell hypernuclei, the bare interactions should be used without alteration. For *p*-shell hypernuclei, advantages and disadvantages of various approaches should be critically examined. The linkage between the effective interactions and the bare interactions is usually very difficult. However, the 3-cluster Faddeev formalism using 2-cluster RGM kernels provides a useful framework, not only for using the quark-model baryon-baryon interactions in the study of few-baryon systems, but also for studying cluster structure of light hypernuclei. Characteristic features of this formalism are 1) the input is closer to the bare *YN* and *YY* interactions and 2) the Faddeev results exactly coincide with the variational calculations as long as the full model space is used.