Exotic nuclei with charm and bottom flavors

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KEK

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新学術領域
「多彩なフレーバーで探る新しいハドロン存在形態の包括的研究」
キックオフミーティング＠Nagoya University

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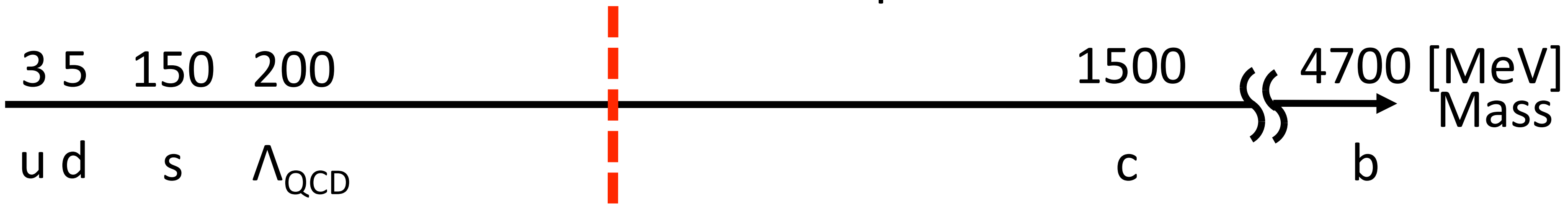
Why are heavy flavors interesting in QCD?

Mass scale of quarks



Chiral Symmetry

$SU(3)_L \times SU(3)_R$

Heavy Quark (Spin & Flavor) Symmetry

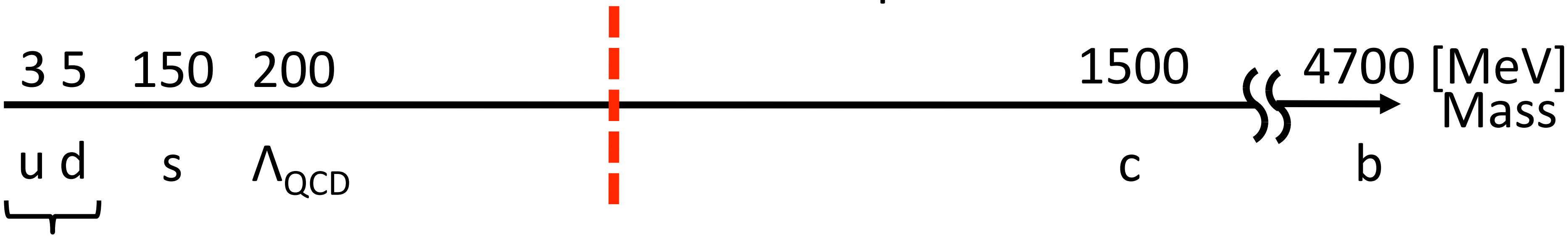
$SU(2)_{spin} \times SU(N_h)_{flavor}$

- ✔ New energy scale ($m_{c,b}$) is introduced in addition to Λ_{QCD}.
- ✔ New symmetry (heavy quark symmetry) appears.
- ✔ QCD Effective Theory (HQET, NRQCD, pNRQCD, ...)
- ✔ Lattice QCD approach

etc.

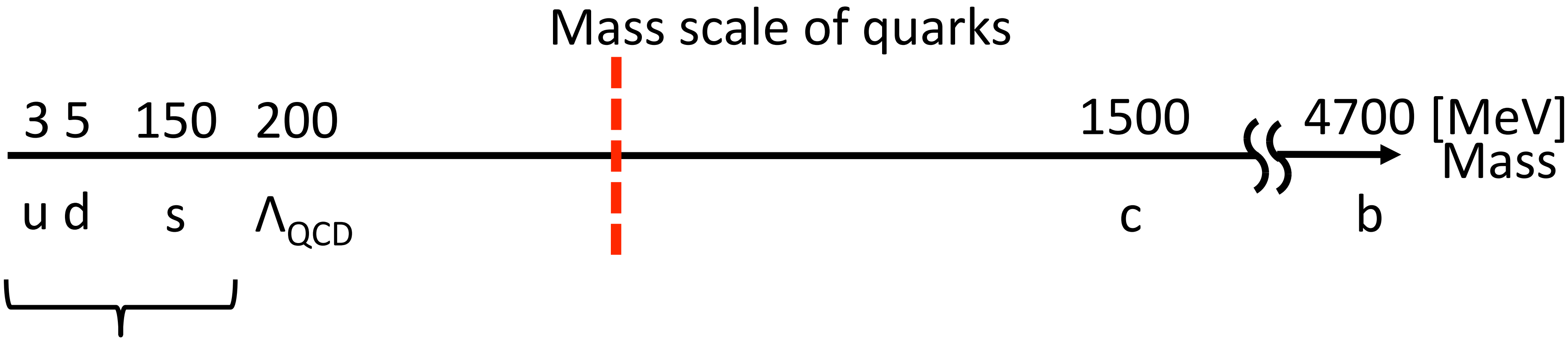
Why are heavy flavors interesting in QCD?

Mass scale of quarks



- Normal Nuclei
- Large Isospin Nuclei
  (neutron/proton rich)

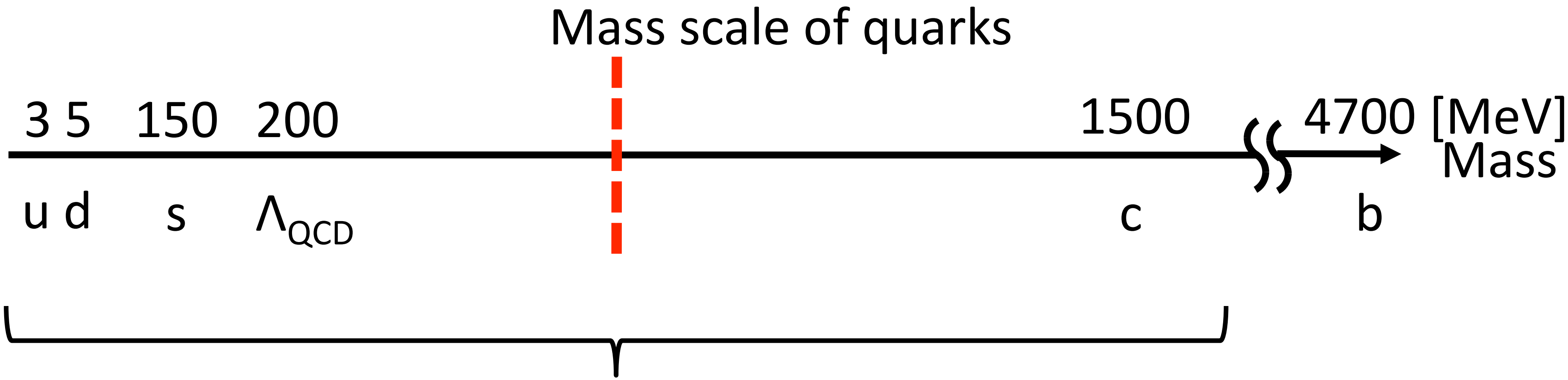
Why are heavy flavors interesting in QCD?



- Strangeness Nuclei @J-PARC

  (Hypernuclei/K-nuclei)

Why are heavy flavors interesting in QCD?

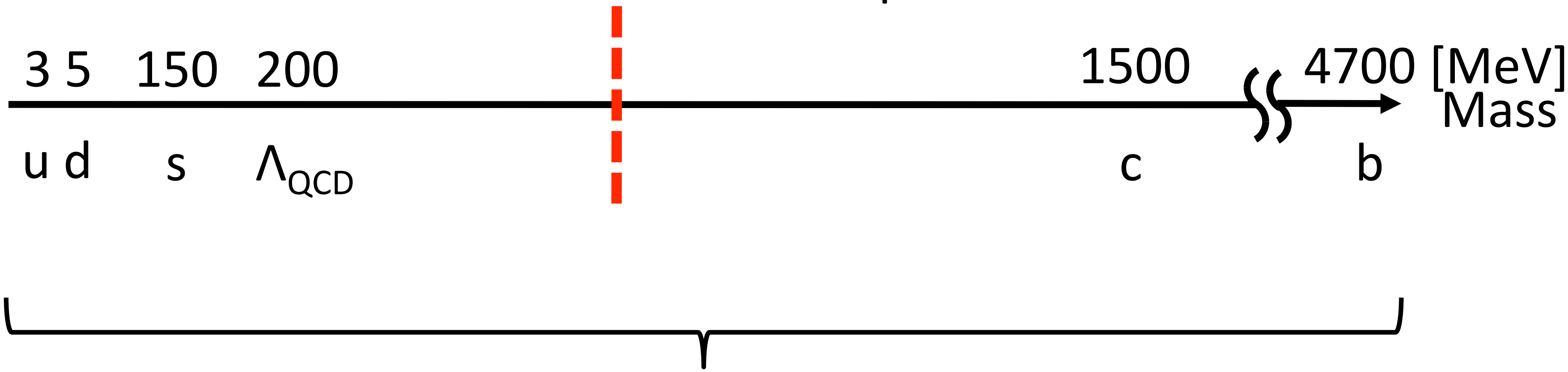


- Charmed Nuclei ? @J-PARC and GSI

(Charm baryon nuclei/D-nuclei)

Why are heavy flavors interesting in QCD?

Mass scale of quarks

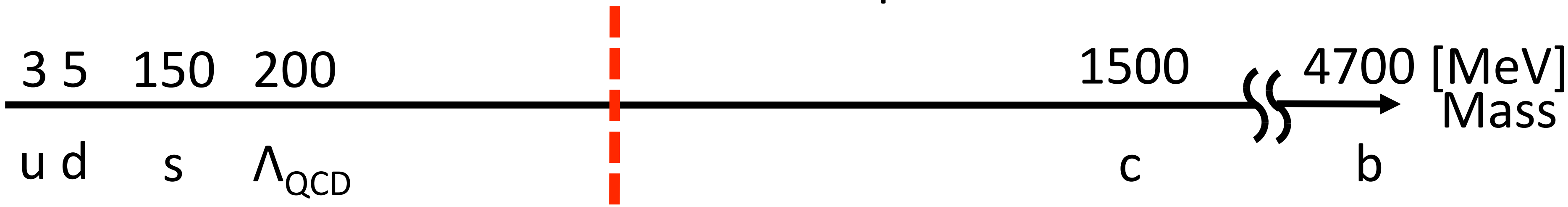


- Bottom Nuclei ??

  (Bottom baryon nuclei/B-nuclei)

Why are heavy flavors interesting in QCD?

Mass scale of quarks



Theory based on QCD

- Heavy Quark Symmetry
- QCD Effective Theory
  (HQET, NRQCD, pNRQCD, ...)
- Lattice QCD approach

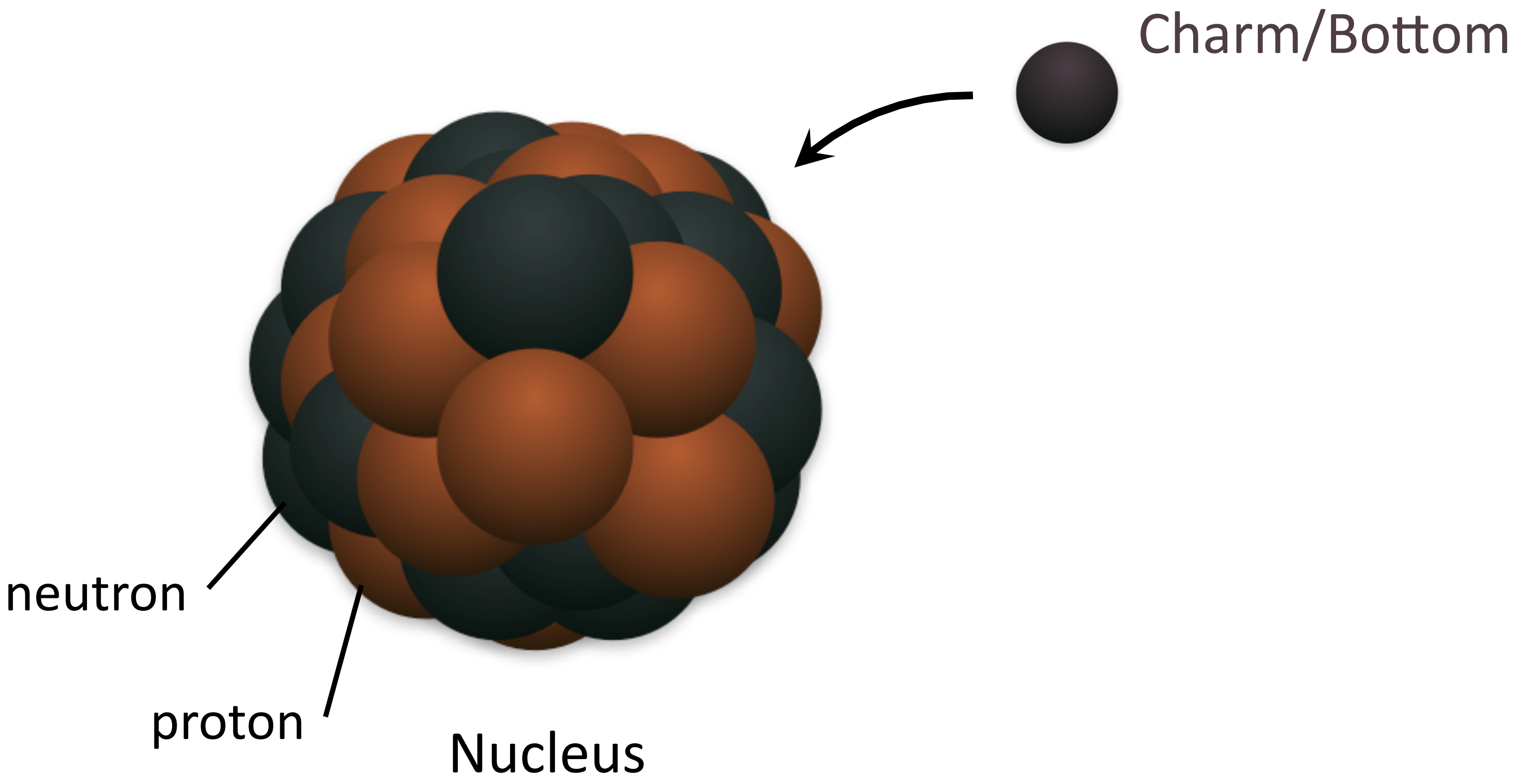
➡

Charm/Bottom Nuclei

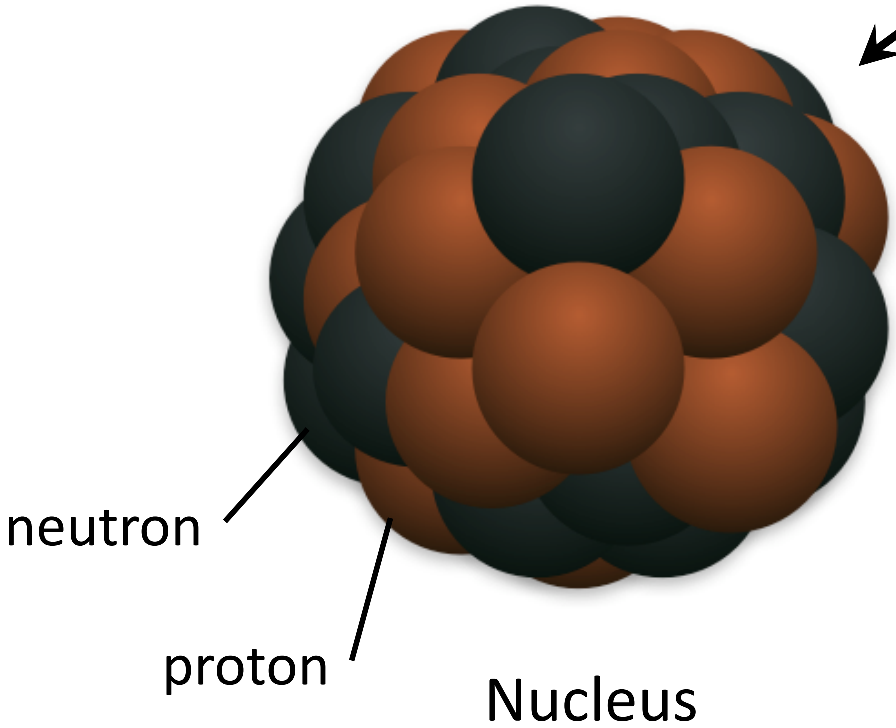
- New sates and properties
- Further understanding of exotic nuclei with flavors
- Confinement, χSB, ...

Cf. Charmonium-Nucleon interaction from Lattice QCD; Hatsuda-Kawanai-Sasaki

What are charm/bottom nuclei?



What are charm/bottom nuclei?

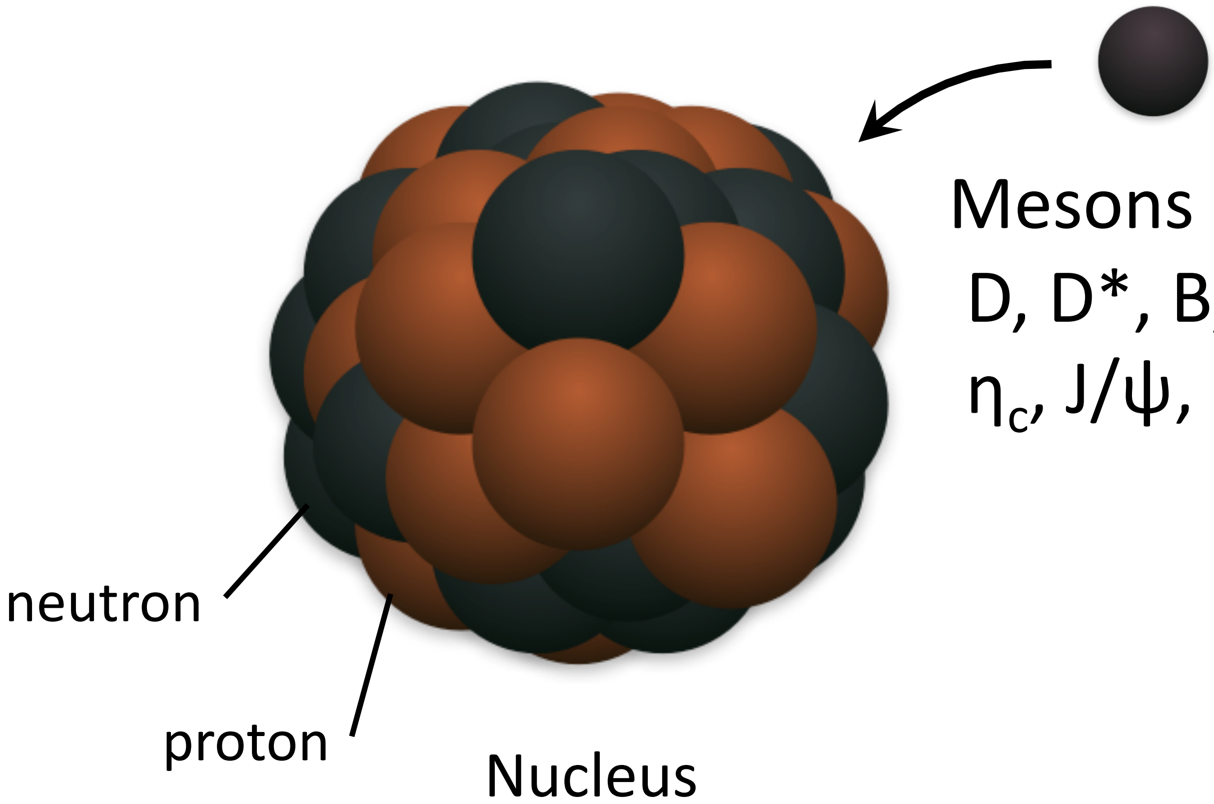


Baryons

Λ_c, Σ_c, Λ_b, Σ_b, …

Dover-Kahana (1977)
Iwao (1977)
Gatto-Paccanoni (1978)
Bando-Bando (1982)
…

What are charm/bottom nuclei?

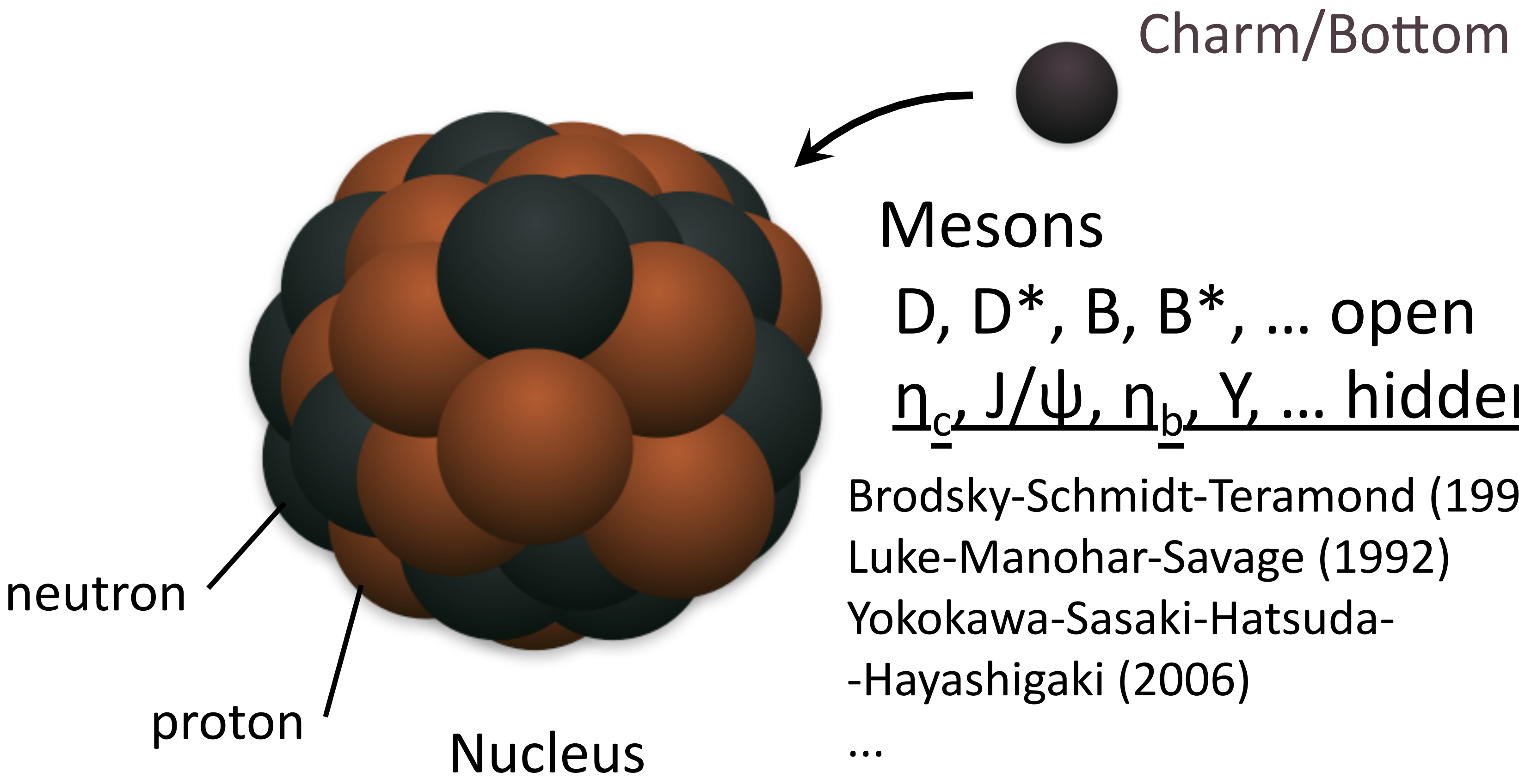


Mesons

D, D*, B, B*, … open

η_c, J/ψ, η_b, Υ, … hidden

What are charm/bottom nuclei?



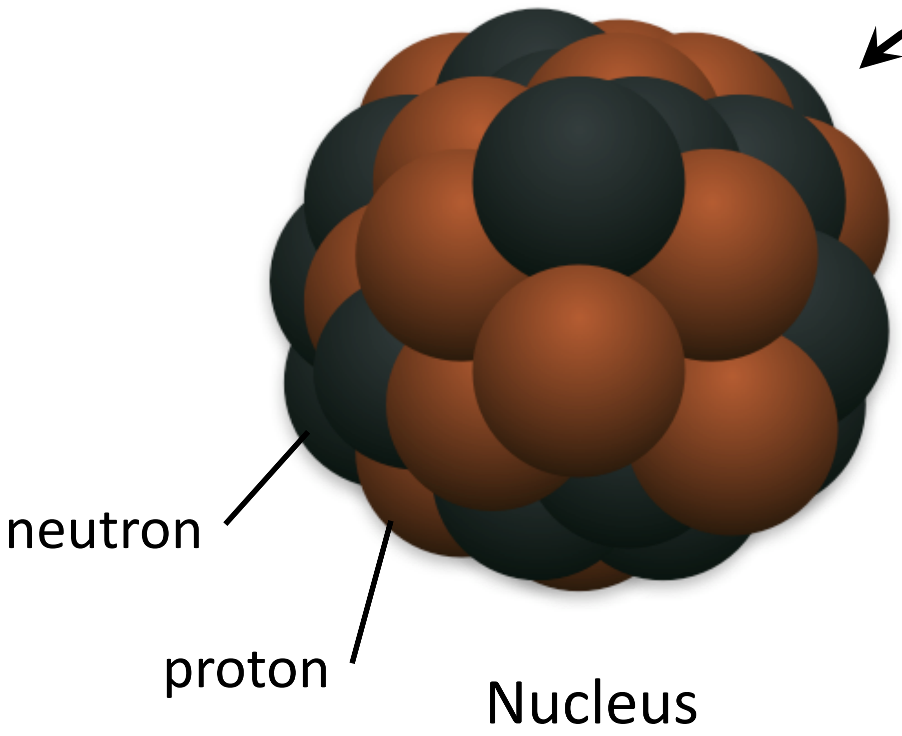
Mesons

D, D*, B, B*, … open

η_c, J/ψ, η_b, Υ, … hidden

Brodsky-Schmidt-Teramond (1990)
Luke-Manohar-Savage (1992)
Yokokawa-Sasaki-Hatsuda-
-Hayashigaki (2006)
…

What are charm/bottom nuclei?



Mesons

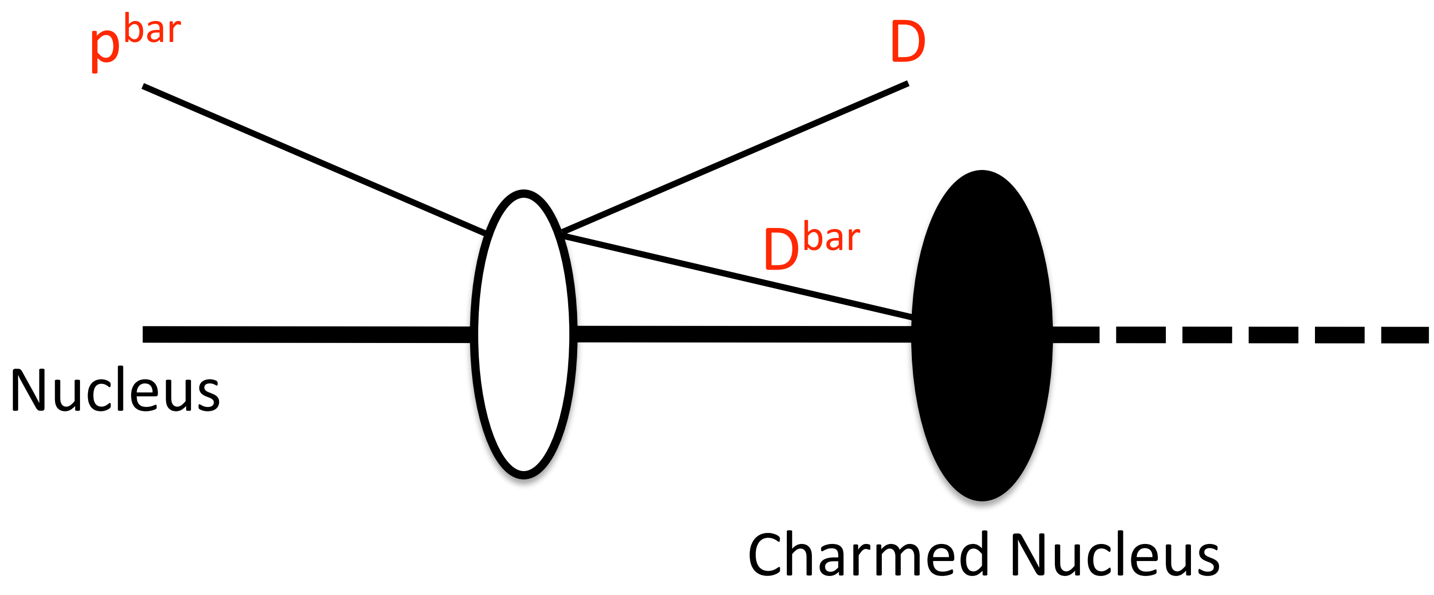
D, D*, B, B*, … open

η_c, J/ψ, η_b, Υ, … hidden

This is our subject in this study!

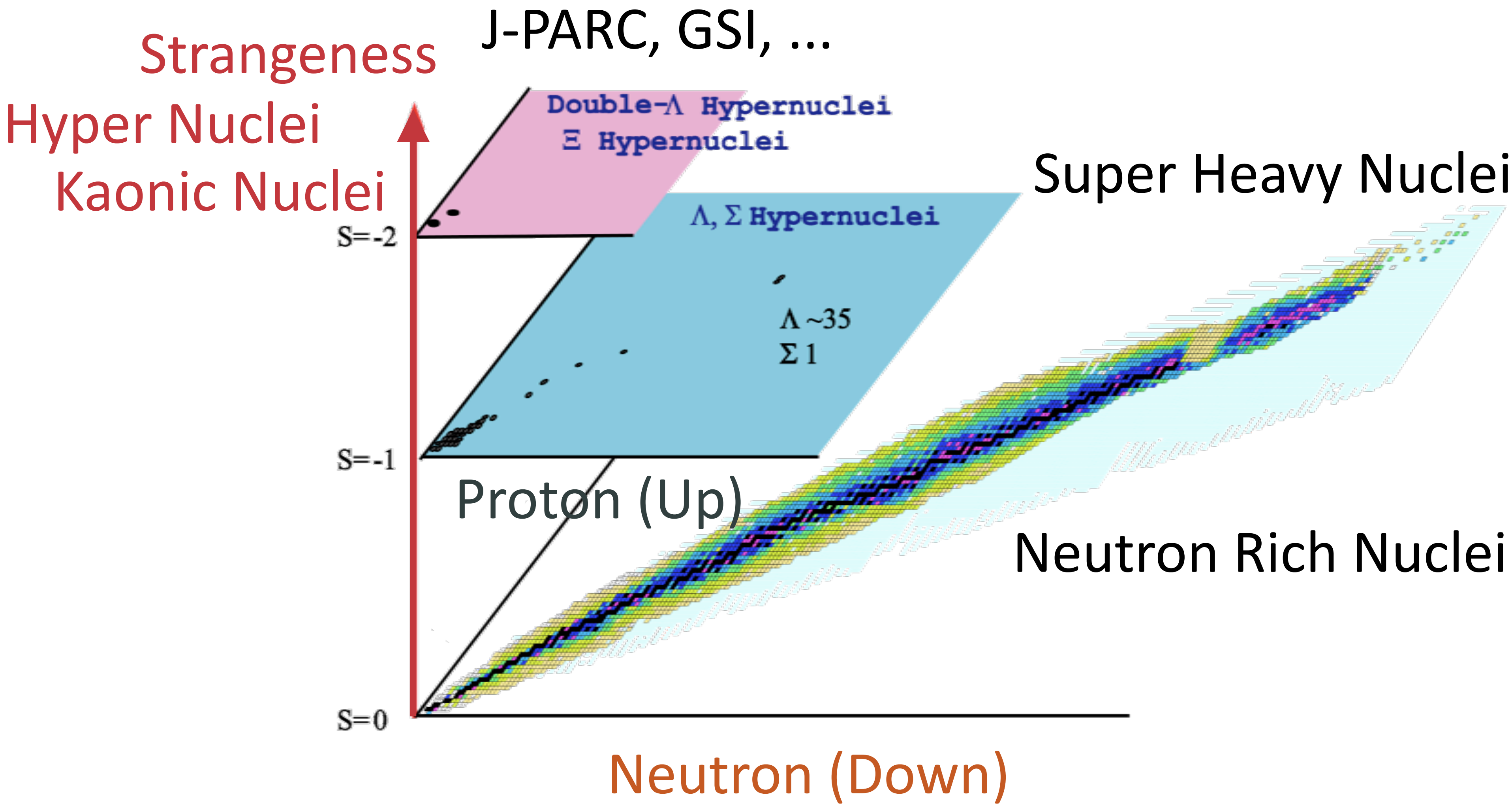
How to generate charm nuclei?

Possible experiments in J-PARC, GSI, ...

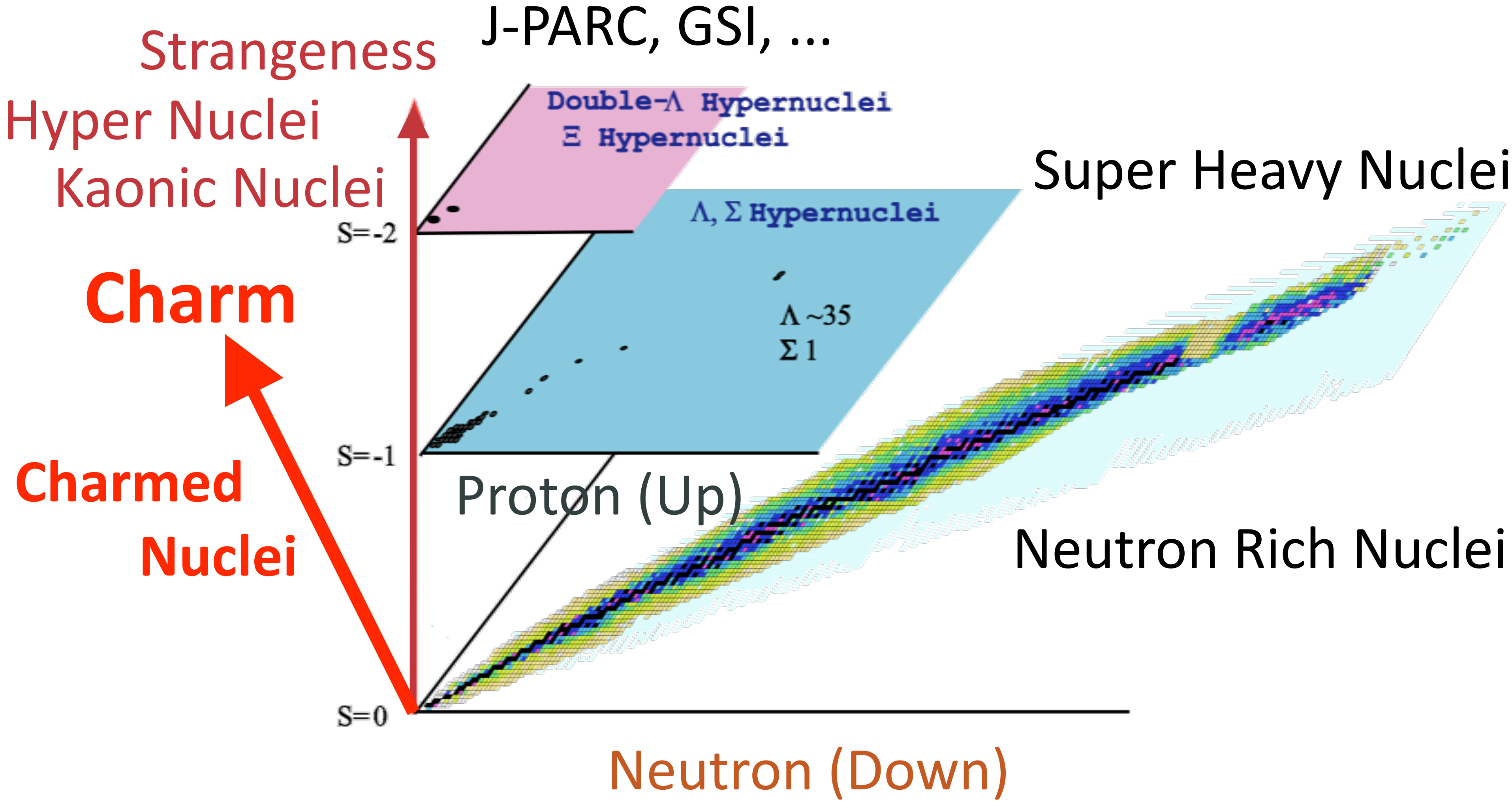


Report by PANDA@FAIR (Mar. 2009)
Krein's talk in FB19 (Sep. 2009)
Ohnishi's talk in HQP (Sep. 2009)

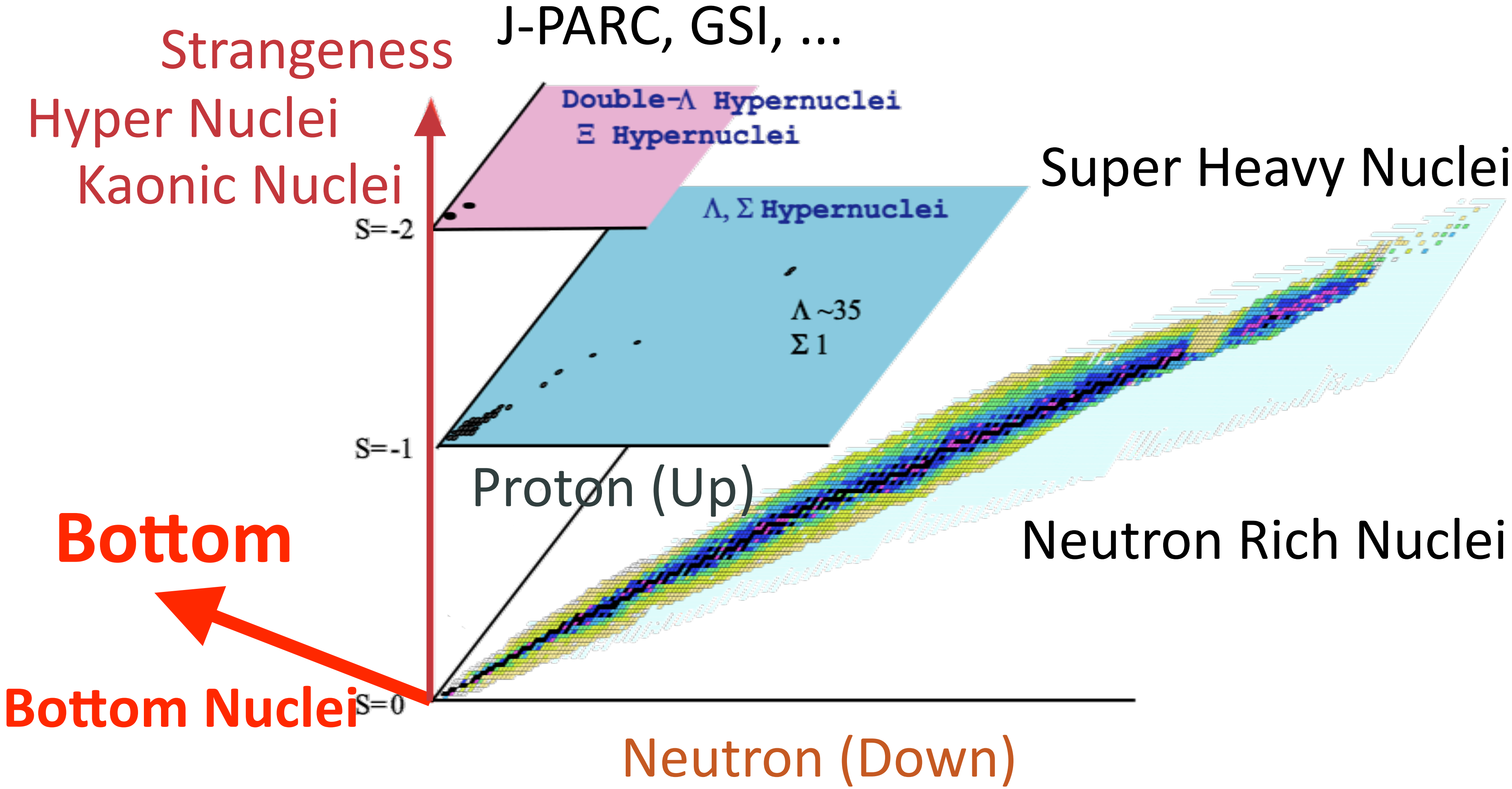
Multi-Favored Nuclear Chart



Multi-Favored Nuclear Chart

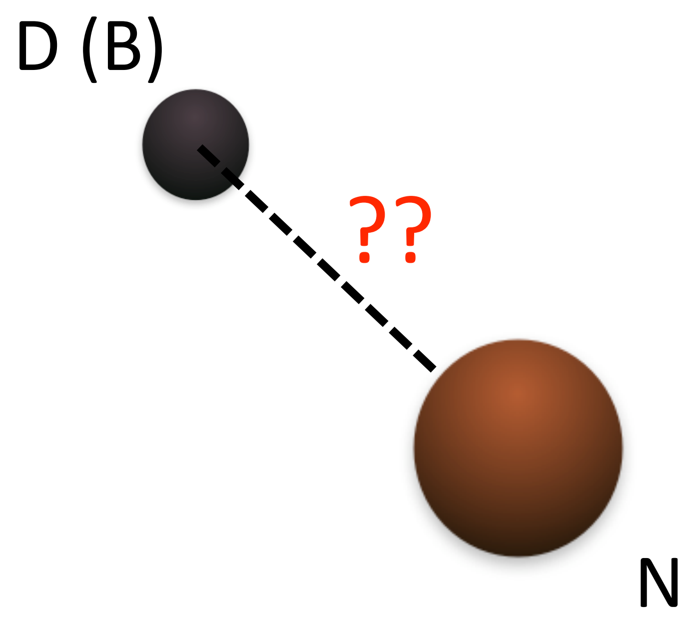


Multi-Favored Nuclear Chart



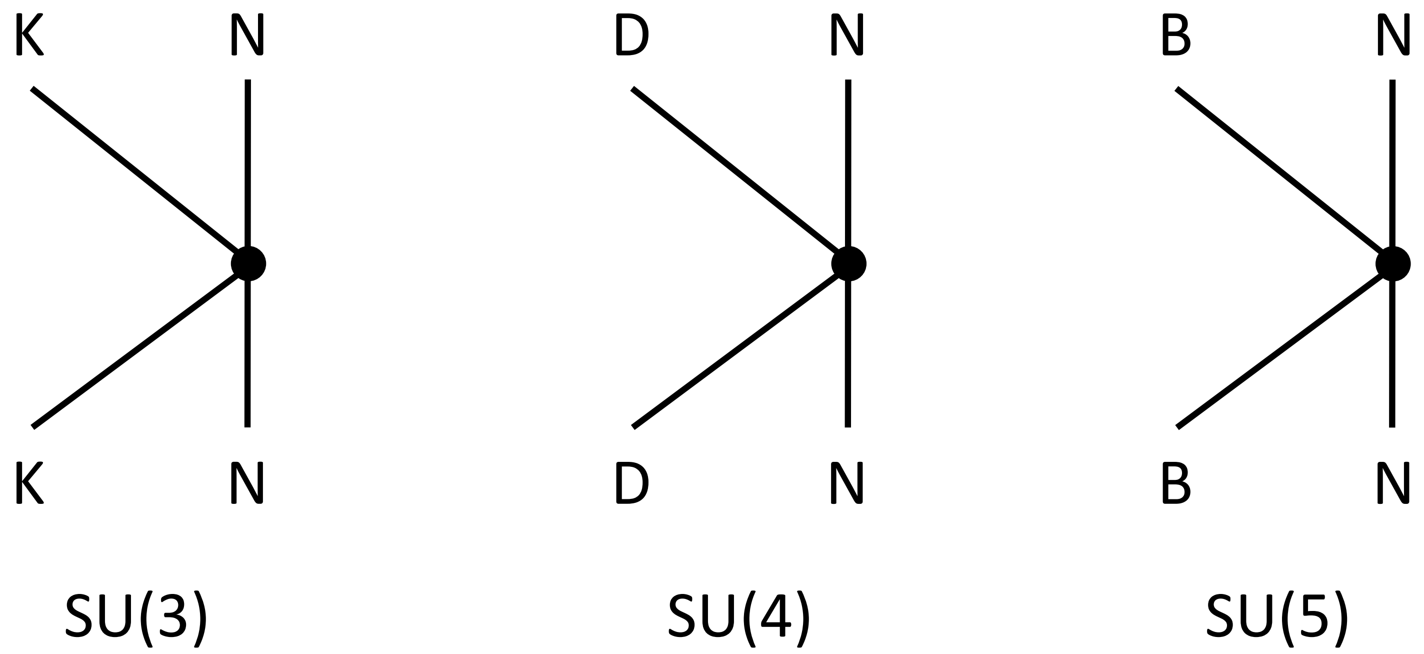
DN and BN potential

Q. What is the interaction between D (B) and N ?



DN and BN potential

Strangeness, Charm, Botom, ...



Weinberg-Tomozawa

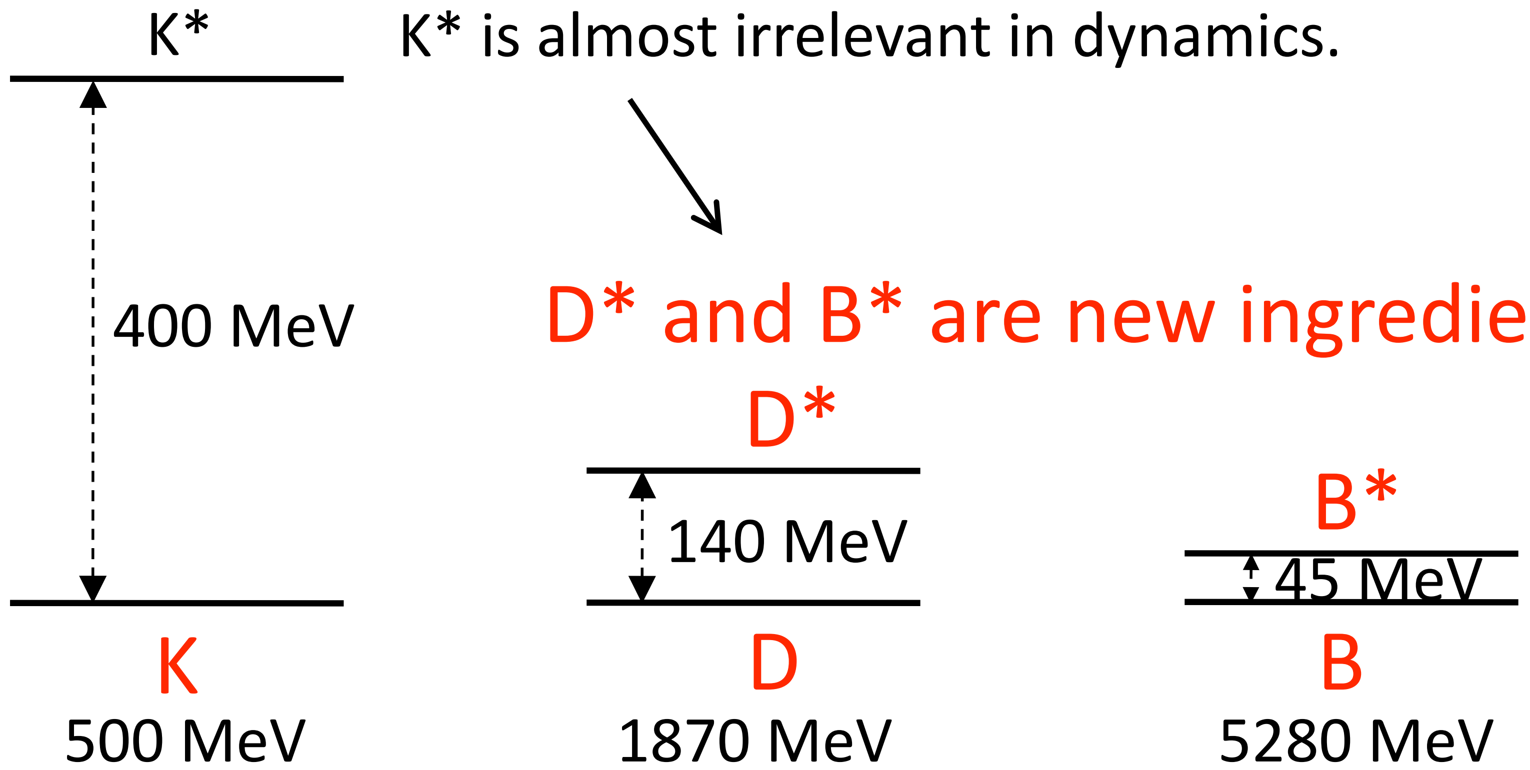
Lutz-Kolomeitsev (2004), Hoffmann-Lutz (2005), Mizutani-Ramos (2006), Gamermann-Oset-Strottman-Vacas (2007), Haidenbauer-Krein-Meissner-Sibirtsev (2007), ...

DN and BN potential

Strangeness, Charm, Botom, ...

K* is almost irrelevant in dynamics.

D* and B* are new ingredients!

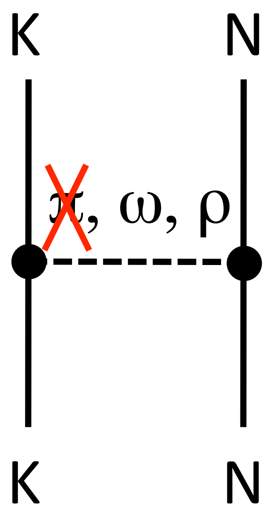


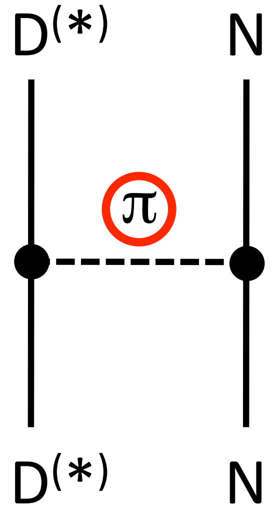
Chiral symmetry

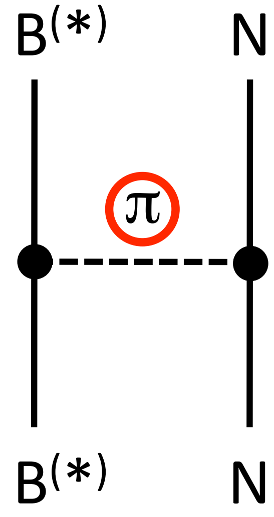
Heavy quark symmetry

DN and BN potential

One pion exchange potential







One pion is absent.
(short range force)

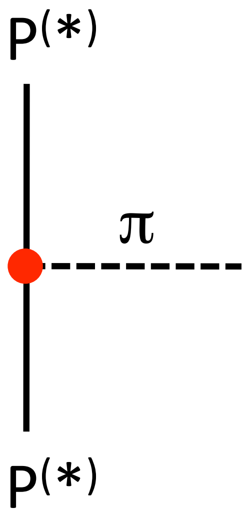
Weinberg-Tomozawa

One pion is present.
(long range force)

One pion exchange potential
(OPEP)

DN and BN potential

One pion exchange potential



P=D or B

$P^{(*)}P^{(*)}\pi$ vertex

Heavy quark symmetry

$$\mathcal{L}_{\pi HH} = g\,\mathrm{tr}\bar{H}_a H_b \gamma_\nu \gamma_5 A^\nu_{ba}$$

G. Burdman and J.F. Donoghue (1992)
M.B. Wise (1992)
T.-M. Yan, H.-Y. Cheng, C.-Y. Cheung,
G.-L. Lin, Y.C. Lin and H.-L. Yu (1997)

$$H_a = \frac{1+\not{v}}{2}\left[P^*_{a\mu}\gamma^\mu - P_a\gamma_5\right] \quad \text{with} \quad \bar{H}_a = \gamma_0 H_a^\dagger \gamma_0$$

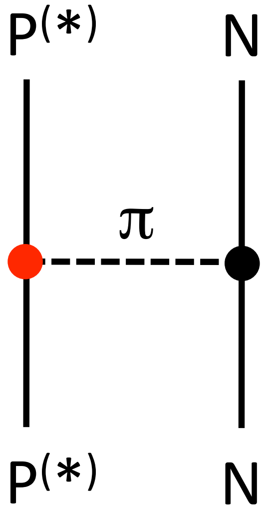
vector + pseudoscalar

$$A_\mu \simeq \frac{i}{f}\partial_\mu \mathcal{M} \quad \text{with} \quad \mathcal{M} = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix}$$

DN and BN potential

One pion exchange potential

S. Y. and K. Sudoh (2008)



PN-P*N and P*N-P*N potentials

$$V_{PN\to P^*N} = -\frac{g g_{\pi NN}}{\sqrt{2} m_N f}\frac{1}{4\pi}\frac{\mu^2}{3} \times \left[\vec{\varepsilon}^{(\lambda)\dagger}\cdot\vec{\sigma}\, C(r;\mu) + S^{\dagger}_{\varepsilon^{(\lambda)}}\, T(r;\mu)\right]\vec{\tau}_P\cdot\vec{\tau}_N$$

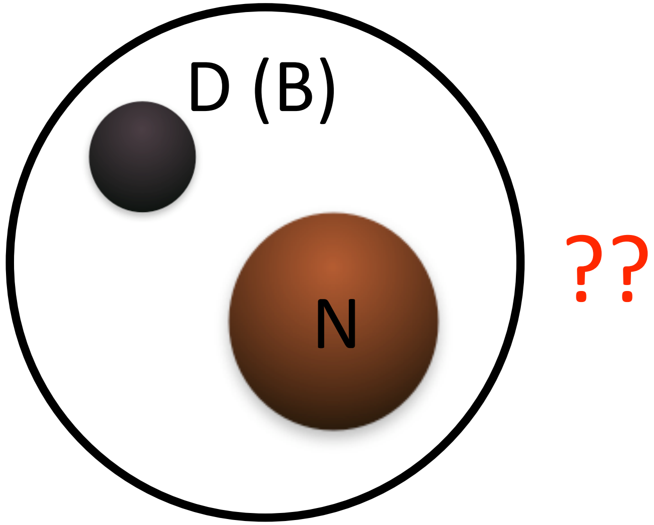
$$V_{P^*N\to P^*N} = \frac{g g_{\pi NN}}{\sqrt{2} m_N f}\frac{1}{4\pi}\frac{m_\pi^2}{3} \times \left[\vec{T}\cdot\vec{\sigma}\, C(r;m_\pi) + S_T\, T(r;m_\pi)\right]\vec{\tau}_P\cdot\vec{\tau}_N$$

$$\left[\begin{array}{lcl} T(r;m) &=& -\dfrac{4\pi}{m^2}\displaystyle\int\frac{\mathrm{d}^3p}{(2\pi)^3}\frac{\vec{q}^{\,2}}{\vec{q}^{\,2}+m^2}\left\{3(\vec{\sigma}_1\cdot\hat{q})(\vec{\sigma}_2\cdot\hat{q}) - \vec{\sigma}_1\cdot\vec{\sigma}_2\right\} e^{i\vec{q}\cdot\vec{r}}\,\frac{\Lambda_N^2-m^2}{\Lambda_N^2+\vec{q}^{\,2}}\frac{\Lambda_P^2-m^2}{\Lambda_P^2+\vec{q}^{\,2}} \\ C(r;m) &=& \dfrac{4\pi}{m^2}\displaystyle\int\frac{\mathrm{d}^3p}{(2\pi)^3}\frac{1}{\vec{q}^{\,2}+m^2} e^{i\vec{q}\cdot\vec{r}}\,\frac{\Lambda_N^2-m^2}{\Lambda_N^2+\vec{q}^{\,2}}\frac{\Lambda_P^2-m^2}{\Lambda_P^2+\vec{q}^{\,2}} \end{array}\right.$$

DN and BN bound states

DN and BN bound states

Q. Are there bound states of D (B) and N ?



DN and BN bound states

Classification of states

S. Y. and K. Sudoh (2008)

|state> = |PN>+ |P*N>   P=D^{bar} (c^{bar}q), B (b^{bar}q)

* No annihilation process

DN and BN bound states

Classification of states

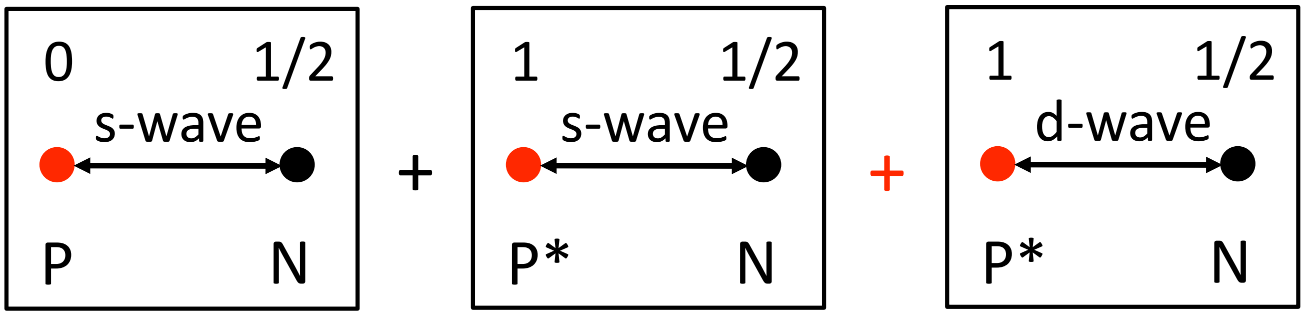
S. Y. and K. Sudoh (2008)

|state> = |PN>+ |P*N> $P=D^{bar}$ ($c^{bar}q$), B ($b^{bar}q$)

* No annihilation process

<u>$J^P=1/2^-$ (I=0 or 1)</u>

$|PN;\ ^2S_{1/2}> + |P^*N;\ ^2S_{1/2}> + |P^*N;\ ^4D_{1/2}>$



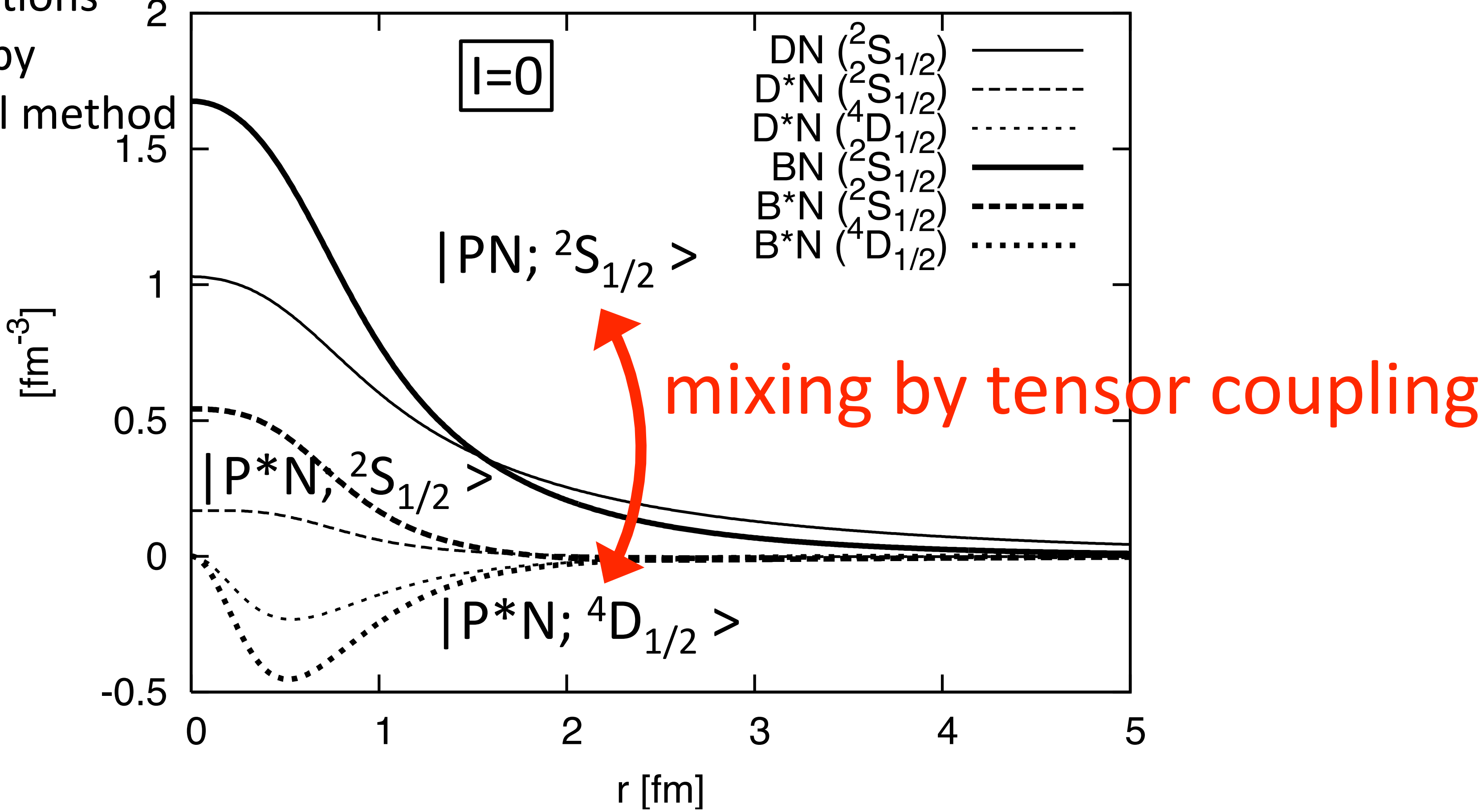
DN and BN bound states

$J^P=1/2^-$ (I=0 or 1)

S. Y. and K. Sudoh (2008)

$|PN;\,{}^2S_{1/2}> + |P^*N;\,{}^2S_{1/2}> + |P^*N;\,{}^4D_{1/2}>$

wave functions obtained by variational method



DN and BN bound states

$J^P = 1/2^-$ (I=0 or 1)

S. Y. and K. Sudoh (2008)

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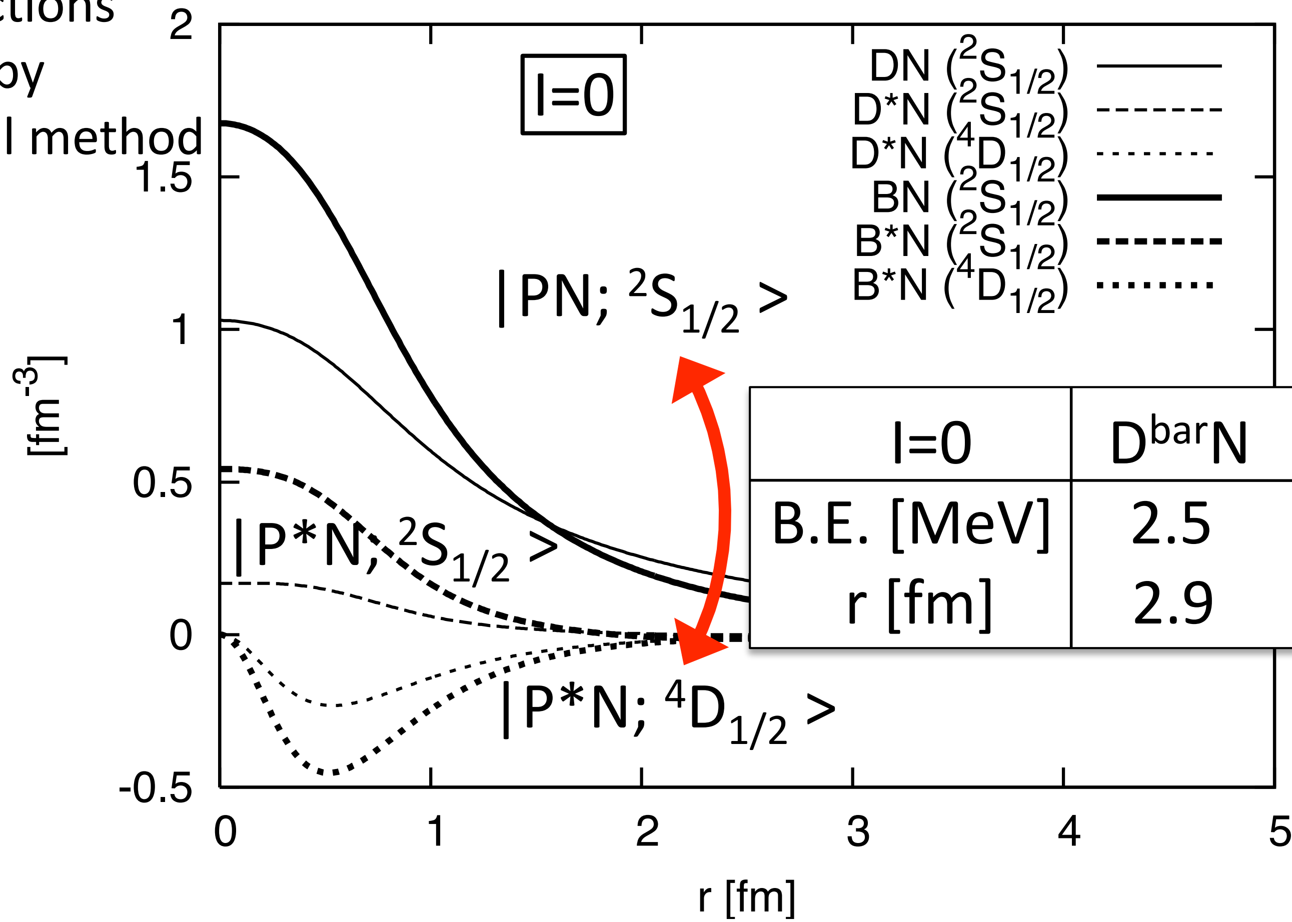
wave functions obtained by variational method

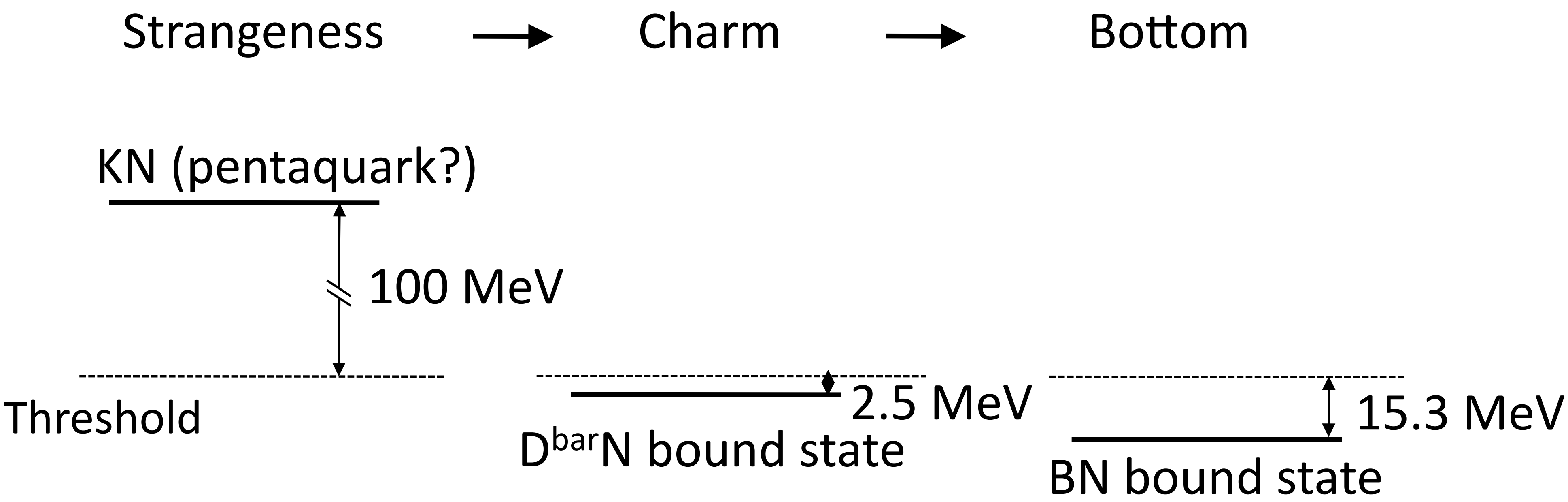


I=0	$D^{bar}N$	BN
B.E. [MeV]	2.5	15.3
r [fm]	2.9	1.4

oupling

DN and BN bound states

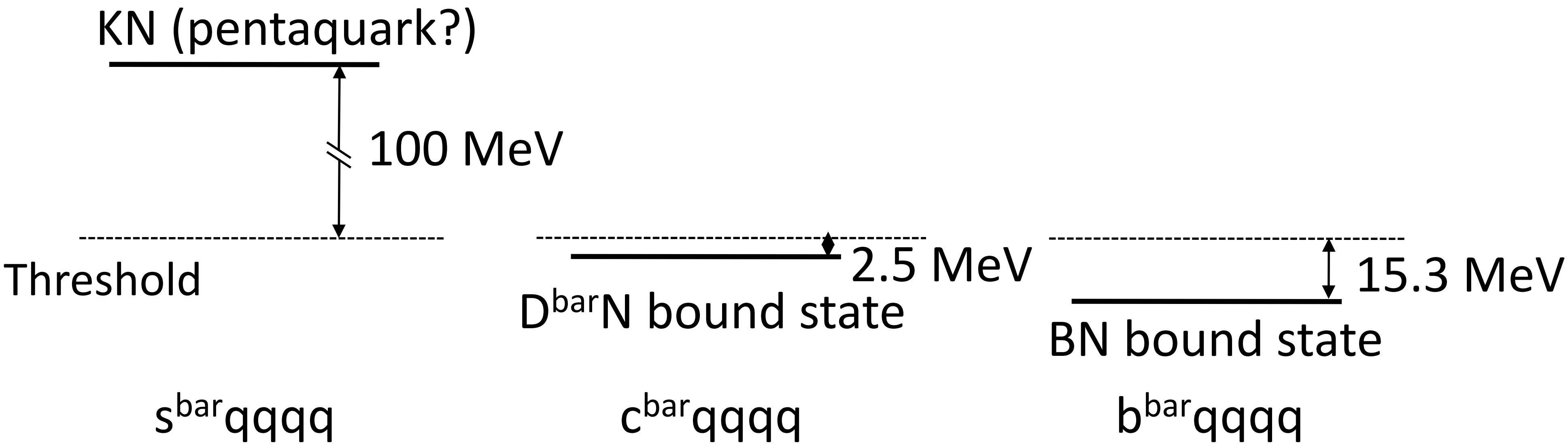
Transition from strangeness to charm and bottom systems?



DN and BN bound states

Transition from strangeness to charm and bottom systems?

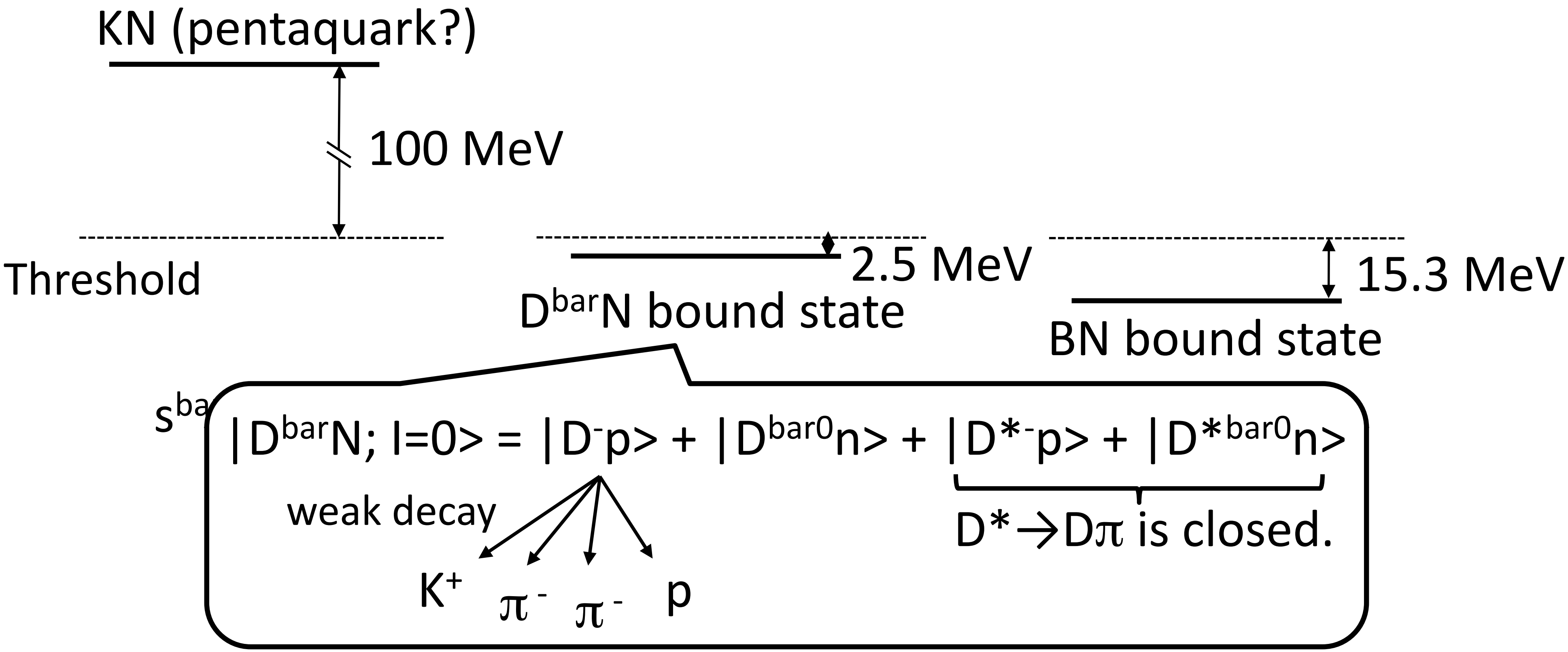
Strangeness → Charm → Bottom



DN and BN bound states

Transition from strangeness to charm and bottom systems?

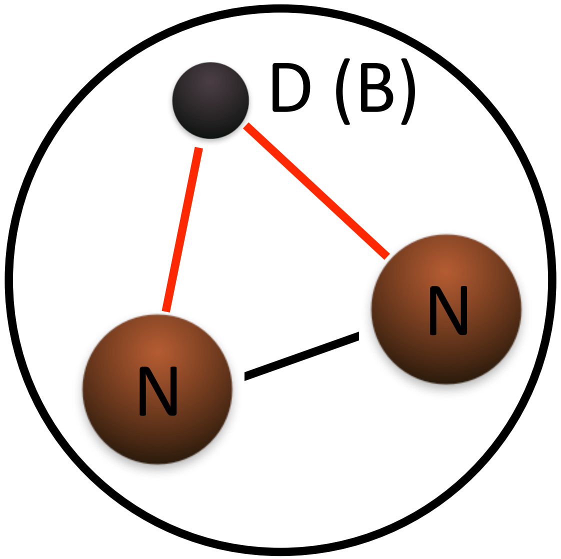
Strangeness → Charm → Bottom



Exotic charm/bottom nuclei

Exotic charm/bottom nuclei

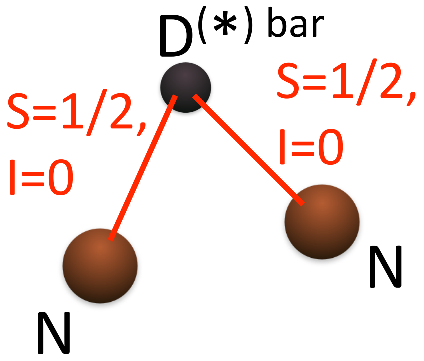
Q. Are there exotic nuclei with D (B) ?



A=2 charmed (bottom) nucleus ?

Exotic charm/bottom nuclei

$D^{(*)bar}NN$ and $B^{(*)}NN$ systems



Classification of states

$J^P=0^-$

I=1/2 $|D(NN)_{S=0,I=1}\rangle + |D^*(NN)_{S=1,I=0}\rangle$

I=3/2 $|D(NN)_{S=0,I=1}\rangle$

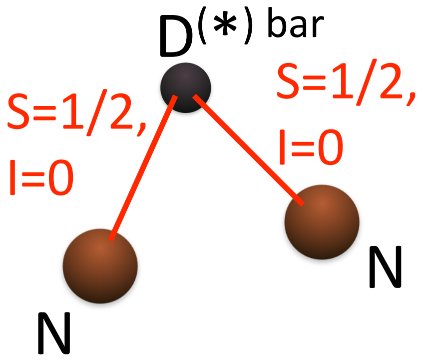
$J^P=1^-$

I=1/2 $|D(NN)_{S=1,I=0}\rangle + |D^*(NN)_{S=1,I=0}\rangle + |D^*(NN)_{S=0,I=1}\rangle$

I=3/2 $|D(NN)_{S=0,I=1}\rangle$

Exotic charm/bottom nuclei

$D^{(*)bar}NN$ and $B^{(*)}NN$ systems



Classification of states — Fraction of $(D^{(*)bar}N)_{S=1/2,I=0}$

$J^P=0^-$

I=1/2 $|D(NN)_{S=0,I=1}\rangle + |D^*(NN)_{S=1,I=0}\rangle$

3/4 — 1/4

I=3/2 $|D(NN)_{S=0,I=1}\rangle$

0

$J^P=1^-$

I=1/2 $|D(NN)_{S=1,I=0}\rangle + |D^*(NN)_{S=1,I=0}\rangle + |D^*(NN)_{S=0,I=1}\rangle$

1/4 — 1/6 — 1/4

I=3/2 $|D(NN)_{S=0,I=1}\rangle$

0

Conclusion & Perspective

- We discuss $D^{(*)bar}N$ and $B^{(*)}N$ bound states with respect to heavy quark symmetry.

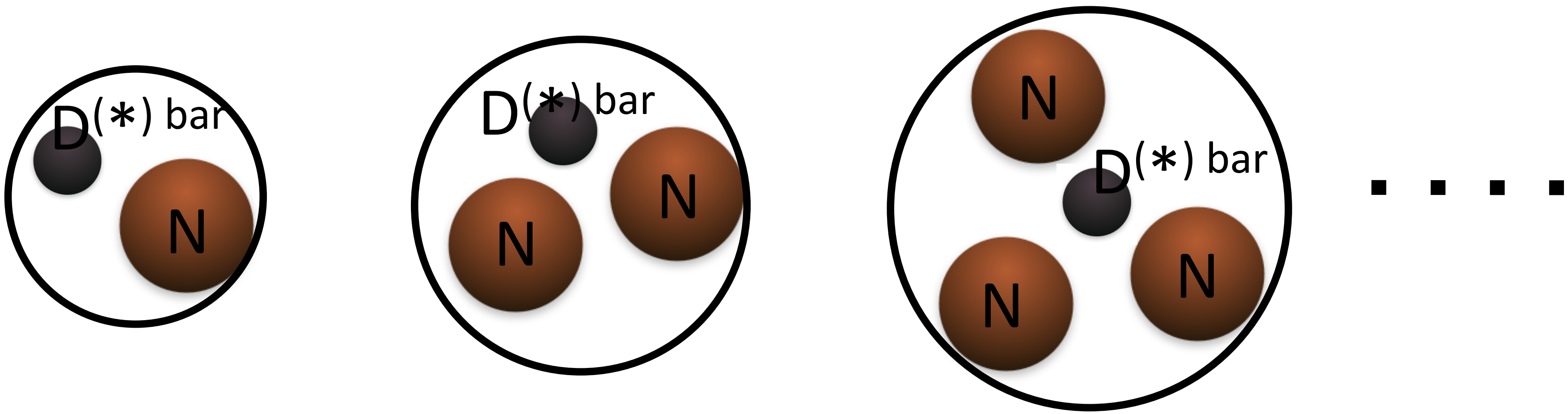
$J^P=1/2^-, I=0$	$D^{bar}N$	BN
B.E. [MeV]	2.5	15.3
r [fm]	2.9	1.4

- DN-D*N (BN-B*N) mixing with tensor coupling is important.

- Charmed nuclei will be studied in experiments (J-PARC, GSI, ...).

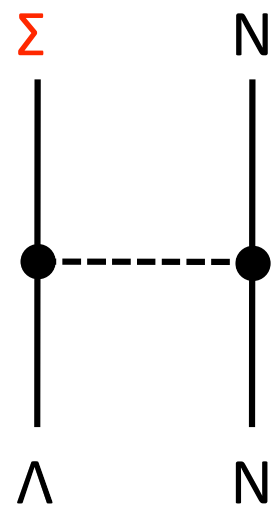
Conclusion & Perspective

- Further studies;
  - Short range potentials (under progress)
    - Phenomenological approach (vector meson/chiral loop)
    - Lattice QCD
  - $D^{(*)bar}NN$ and $B^{(*)}NN$ systems (under progress)
  - Nuclei with more baryon number (in near future)



Perspective

Hypernuclei

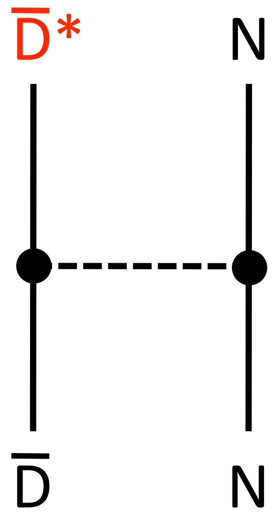


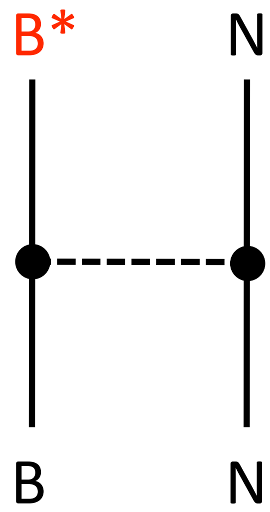
$m_\Lambda \approx m_\Sigma$

Λ-Σ mixing

Hiyama *et al.*

D (B) meson nuclei





$m_D \approx m_{D^*}$ $m_B \approx m_{B^*}$

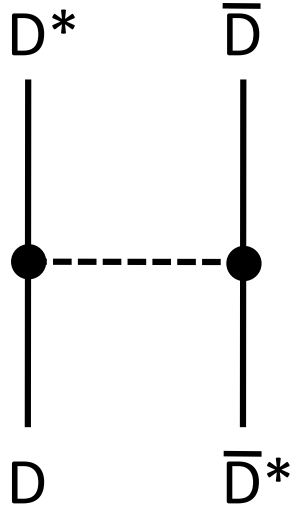
D-D* (B-B*) mixing

This work

Perspective

D-$\bar{D}^*$ molecule

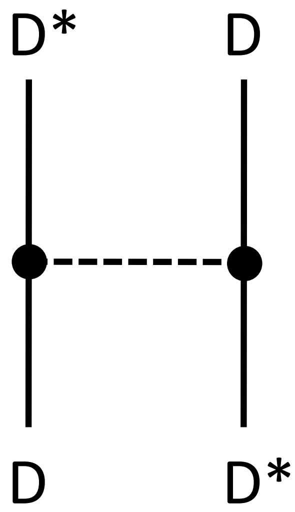
X(3872)



Tornqvist (1994)

D-D^* molecule

Tcc (?)



Manohar and Wise (1992)

D-D^* mixing

Perspective

Diquark model; S. H. Lee and S. Y. (2009)

✓ Tetraquark T_{cc} ($c^{bar}c^{bar}ud$; C=+2)

	$ud\bar{c}\bar{c}$	$us\bar{c}\bar{c}$	$ds\bar{c}\bar{c}$
T^1_{cc}	-74.9	-4.3	-4.3
	$\bar{D}^0 + D^{*-}$, $\bar{D}^{*0} + D^-$	$\bar{D}^0 + D_s^{*-}$	$D^- + D_s^{*-}$
	$ud\bar{b}\bar{b}$	$us\bar{b}\bar{b}$	$ds\bar{b}\bar{b}$
T^1_{bb}	-123.8	-61.4	-61.4
	$B^+ + B^{*0}$, $B^{*+} + B^0$	$B^+ + B_s^{*0}$	$B^0 + B_s^{*0}$

MeV

✓ Pentaquark Θ_{cs} ($udusc^{bar}$; S=-1, C=+1)

	config. of Θ	config. of $M+B$	$\bar{u}$	$\bar{s}$	$\bar{c}$	$\bar{b}$
Θ_{qs}	$ud\,us\,\bar{q}$	$ud\,s+u\bar{q}$	389.4	198.9	8.4	-56.4
Θ_{qss}	$us\,ds\,\bar{q}$	$ds\,s+u\bar{q}$	389.4	198.9	8.4	-56.4
		$ud\,s+s\bar{q}$	256.8	142.5	28.4	-10.7

MeV

Perspective

Diquark model; S. H. Lee and S. Y. (2009)

✓ Tetraquark T_{cc} ($c^{bar}c^{bar}ud$; C=+2)

	$ud\bar{c}\bar{c}$	$us\bar{c}\bar{c}$	$ds\bar{c}\bar{c}$
T^1_{cc}	-74.9 $\bar{D}^0 + D^{*-}$, $\bar{D}^{*0} + D^-$	-4.3 $\bar{D}^0 + D_s^{*-}$	-4.3 $D^- + D_s^{*-}$
	$ud\bar{b}\bar{b}$	$us\bar{b}\bar{b}$	$ds\bar{b}\bar{b}$
T^1_{bb}	-123.8 $B^+ + B^{*0}$, $B^{*+} + B^0$	-61.4 $B^+ + B_s^{*0}$	-61.4 $B^0 + B_s^{*0}$

MeV

✓ Pentaquark Θ_{cs} ($udusc^{bar}$; S=-1, C=+1)

	config. of Θ	config. of $M+B$	$\bar{u}$	$\bar{s}$	$\bar{c}$	$\bar{b}$
Θ_{qs}	$ud\,us\,\bar{q}$	$ud\,s{+}u\bar{q}$	389.4	198.9	8.4	-56.4
Θ_{qss}	$us\,ds\,\bar{q}$	$ds\,s{+}u\bar{q}$	389.4	198.9	8.4	-56.4
		$ud\,s{+}s\bar{q}$	256.8	142.5	28.4	-10.7

MeV

✓ H dibaryon H_c (udusuc)

Diquark model; S. H. Lee and S. Y. (2009)

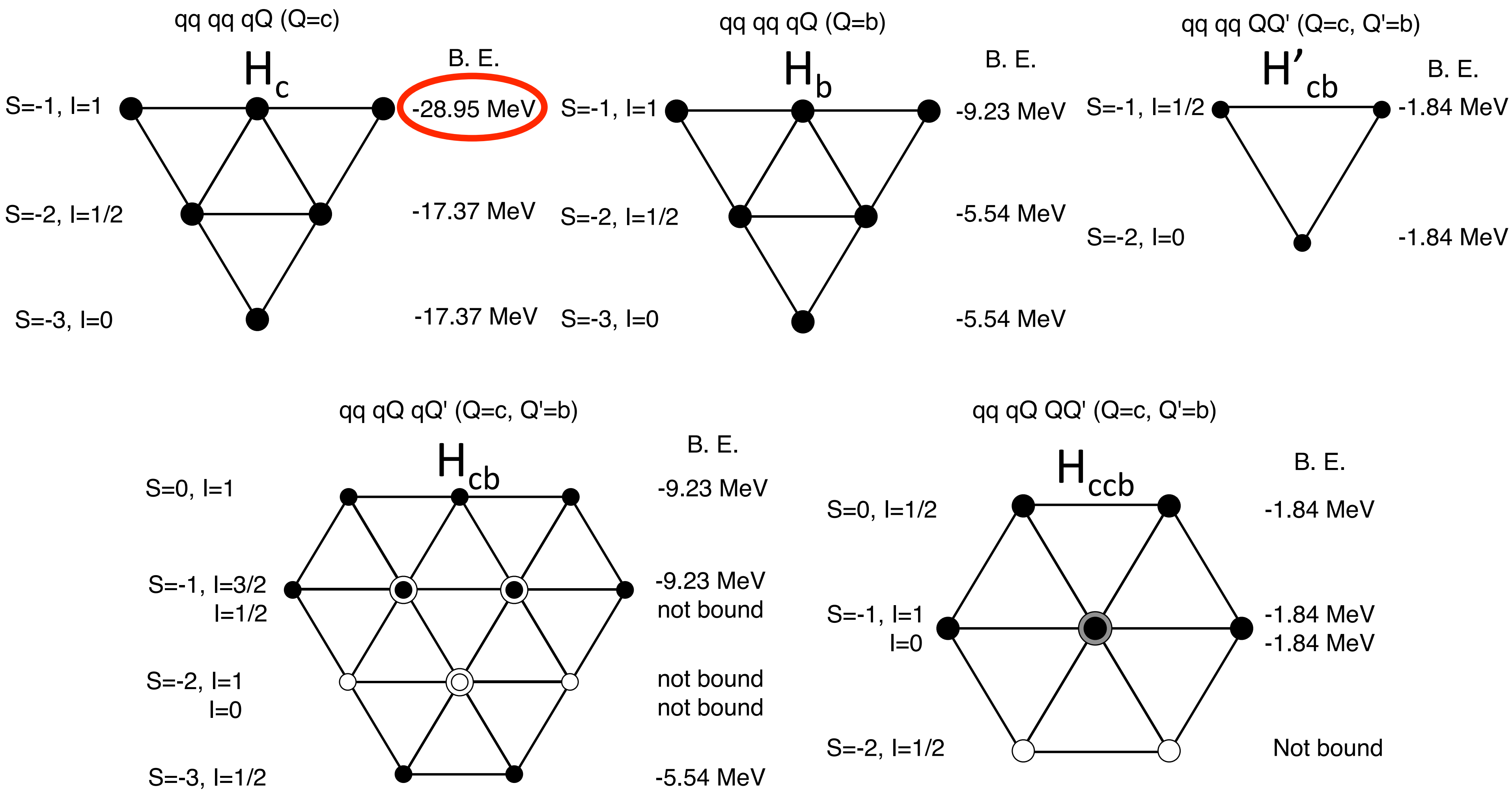
		flavor	config. of H	I	I_z	S	config. of $B+B'$	B_H [MeV]
H	$qq\,qq\,qq$	22200	$ud\,us\,ds$	0	0	-2	$ud\,s + ud\,s$	-28.95
H_c	$qq\,qq\,qQ$ $(Q=c)$	31110	$ud\,us\,uc$	1	1	-1	$ud\,c + us\,u,\ ud\,u + us\,c$	
		22110	$ud\,\frac{1}{\sqrt{2}}(us\,dc + ds\,uc)$	1	0	-1	$ud\,s + ud\,c,\ ud\,s + ud\,c$	-28.95
		13110	$ud\,ds\,dc$	1	-1	-1	$ud\,c + ds\,d,\ ud\,d + ds\,c$	
		21210	$ud\,us\,sc$	1/2	1/2	-2	$ud\,c + us\,s,\ ud\,s + us\,c$	-17.37
		12210	$ud\,ds\,sc$	1/2	-1/2	-2	$ud\,c + ds\,s,\ ud\,s + ds\,c$	
		11310	$\frac{1}{\sqrt{2}}(us\,ds - ds\,us)\,sc$	0	0	-3	$us\,s + ds\,c,\ us\,c + ds\,s$	-17.37
H_b	$qq\,qq\,qQ$ $(Q=b)$	31101	$ud\,us\,ub$	1	1	-1	$ud\,u + us\,b,\ ud\,b + us\,u$	
		22101	$ud\,\frac{1}{\sqrt{2}}(us\,db + ds\,ub)$	1	0	-1	$ud\,s + ud\,b,\ ud\,s + ud\,b$	-9.23
		13101	$ud\,ds\,db$	1	-1	-1	$ud\,b + ds\,d,\ ud\,d + ds\,b$	
		21202	$ud\,us\,sb$	1/2	1/2	-2	$ud\,b + us\,s,\ ud\,s + us\,b$	-5.54
		12201	$ud\,ds\,sb$	1/2	-1/2	-2	$ud\,b + ds\,s,\ ud\,s + ds\,b$	
		11301	$\frac{1}{\sqrt{2}}(us\,ds - ds\,us)\,sb$	0	0	-3	$us\,b + ds\,s,\ us\,s + ds\,b$	-5.54
H_{cb}	$qq\,qQ\,qQ'$ $(Q,\,Q'=c,\,b)$	31011	$ud\,uc\,ub$	1	1	0	$ud\,b + uc\,u,\ ud\,u + uc\,b$	
		22011	$ud\,\frac{1}{\sqrt{2}}(uc\,db + dc\,ub)$	1	0	0	$ud\,b + uc\,u,\ ud\,u + uc\,b$	-9.23
		13011	$ud\,dc\,db$	1	-1	0	$ud\,b + dc\,d,\ ud\,d + dc\,b$	
		30111	$us\,uc\,ub$	3/2	3/2	-1	$us\,u + uc\,b,\ us\,b + uc\,u$	
		21111	$\frac{1}{\sqrt{3}}((us\,dc + ds\,uc)\,ub + us\,uc\,db)$	3/2	1/2	-1	$ud\,b + us\,c,\ ud\,c + us\,b$	-9.23
		12111	$\frac{1}{\sqrt{3}}((us\,dc + ds\,uc)\,db + ds\,dc\,ub)$	3/2	-1/2	-1	$ud\,b + ds\,c,\ ud\,c + ds\,b$	
		03111	$ds\,dc\,db$	3/2	-3/2	-1	$ds\,b + dc\,d,\ ds\,d + dc\,b$	
		10311	$us\,sc\,sb$	1/2	1/2	-3	$us\,b + sc\,s,\ us\,s + sc\,b$	-5.54
		01311	$ds\,sc\,sb$	1/2	-1/2	-3	$ds\,b + sc\,s,\ ds\,s + sc\,b$	
H'_{cb}	$qq\,qq\,QQ'$ $(Q,\,Q'=c,\,b)$	21111	$ud\,us\,cb$	1/2	1/2	-1	$ud\,b + us\,c,\ ud\,c + us\,b$	-1.84
		12111	$ud\,ds\,cb$	1/2	-1/2	-1	$ud\,b + ds\,c,\ ud\,c + ds\,b$	
		11211	$\frac{1}{\sqrt{2}}(us\,ds - ds\,us)\,cb$	0	0	-2	$us\,b + ds\,c,\ us\,c + ds\,b$	-1.84
H_{ccb}	$qq\,qQ\,QQ'$ $(Q,\,Q'=c,\,b)$	21021	$ud\,uc\,cb$	1/2	1/2	0	$ud\,b + uc\,c,\ ud\,c + uc\,b$	-1.84
		12021	$ud\,dc\,cb$	1/2	-1/2	0	$ud\,b + dc\,c,\ ud\,c + dc\,b$	
		20121	$us\,uc\,cb$	1	1	-1	$us\,b + uc\,c,\ us\,c + uc\,b$	
		11121	$\frac{1}{\sqrt{2}}(us\,dc + ds\,uc)\,cb$	1	0	-1	$us\,b + dc\,c,\ us\,c + dc\,b$	-1.84
		02121	$ds\,dc\,cb$	1	-1	-1	$ds\,b + dc\,c,\ ds\,c + dc\,b$	
		11121	$ud\,sc\,cb$	0	0	-1	$ud\,b + sc\,c,\ ud\,c + sc\,b$	-1.84

MeV

Diquark model; S. H. Lee and S. Y. (2009)

✓ H dibaryon H_c (udusuc)

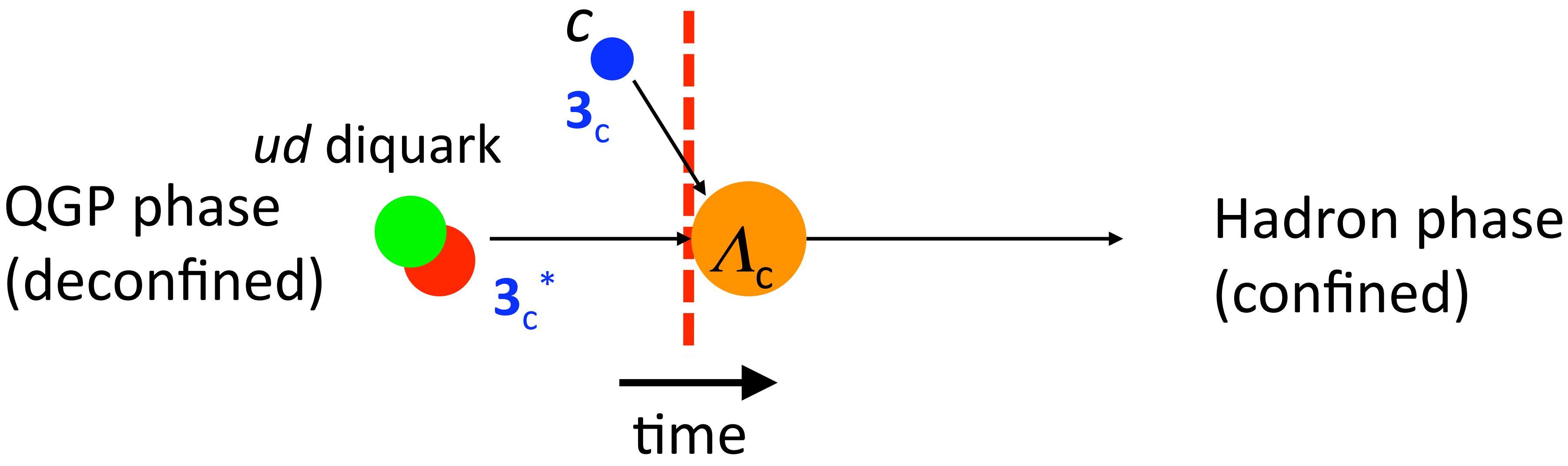
multiplets of $SU(3)_f$.



→ H dibaryons (H, H_c, H_b, ...) are stable as 3_f multiplet of $SU(3)_f$.

Perspective

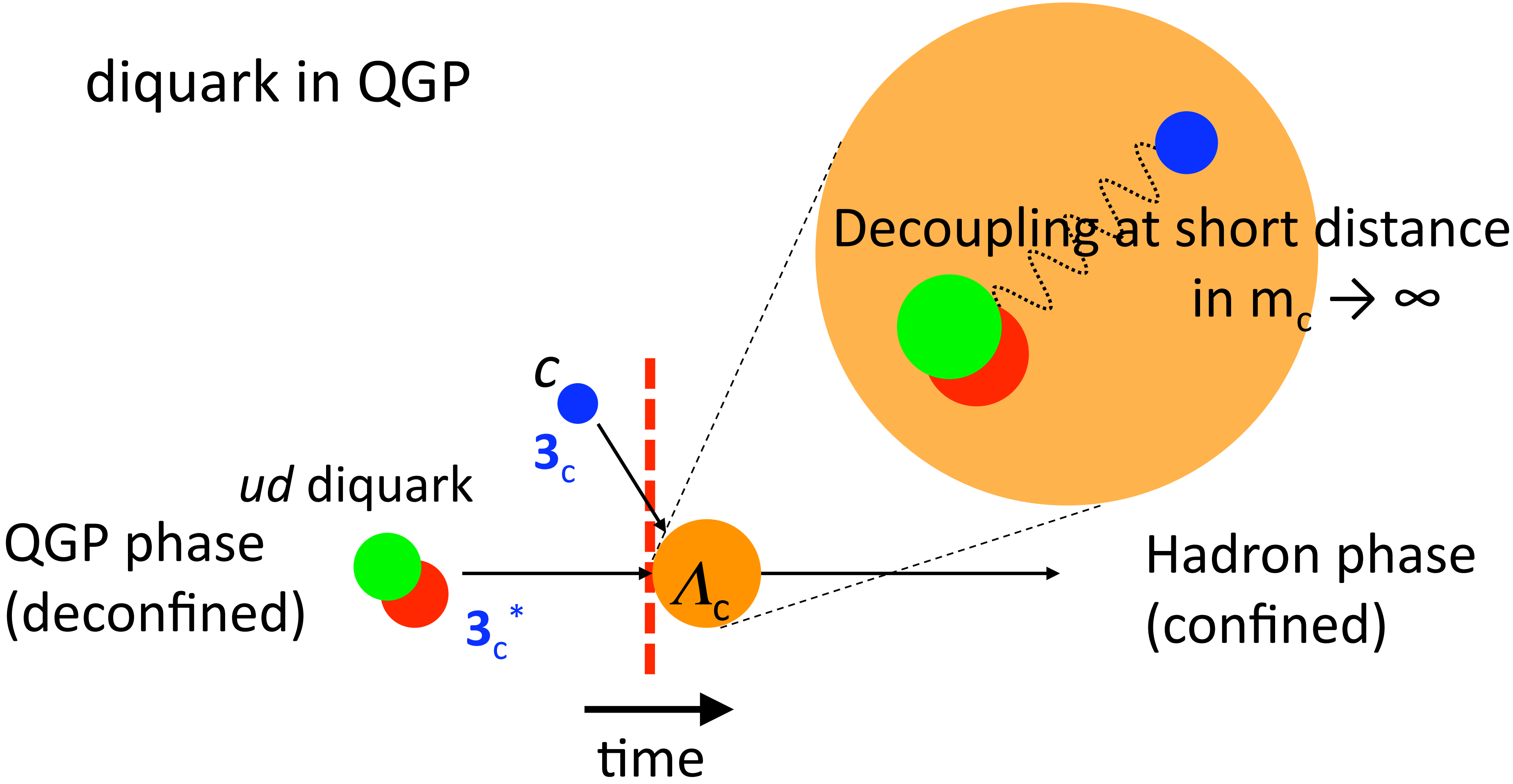
diquark in QGP



S. H. Lee, K. Ohnishi, S. Y., I. K. Yoo, C. M. Ko (2008)
S. H. Lee, Y. Oh, C. M. Ko, S. Y. (2009)

Perspective

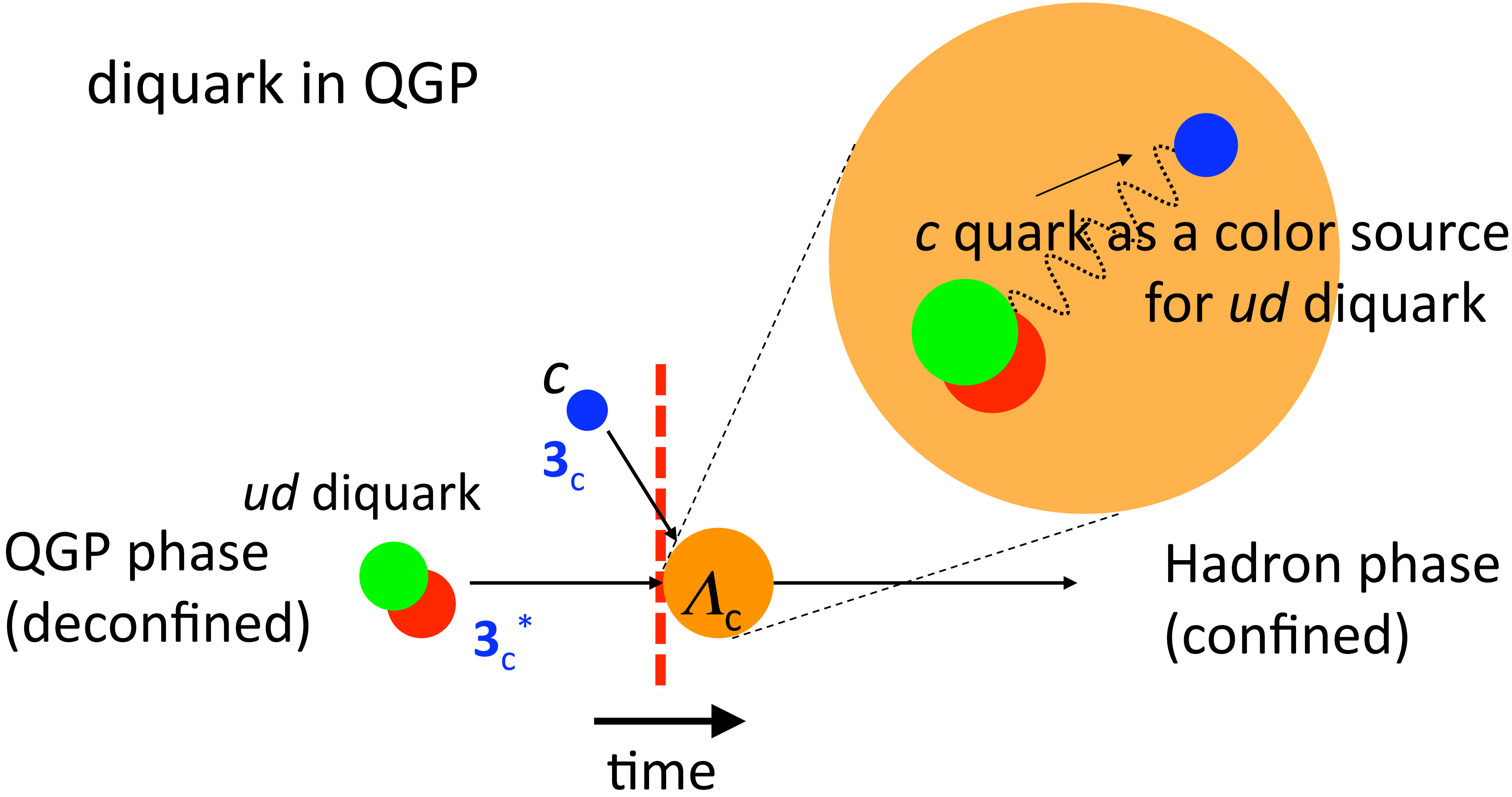
diquark in QGP



S. H. Lee, K. Ohnishi, S. Y., I. K. Yoo, C. M. Ko (2008)
S. H. Lee, Y. Oh, C. M. Ko, S. Y. (2009)

Perspective

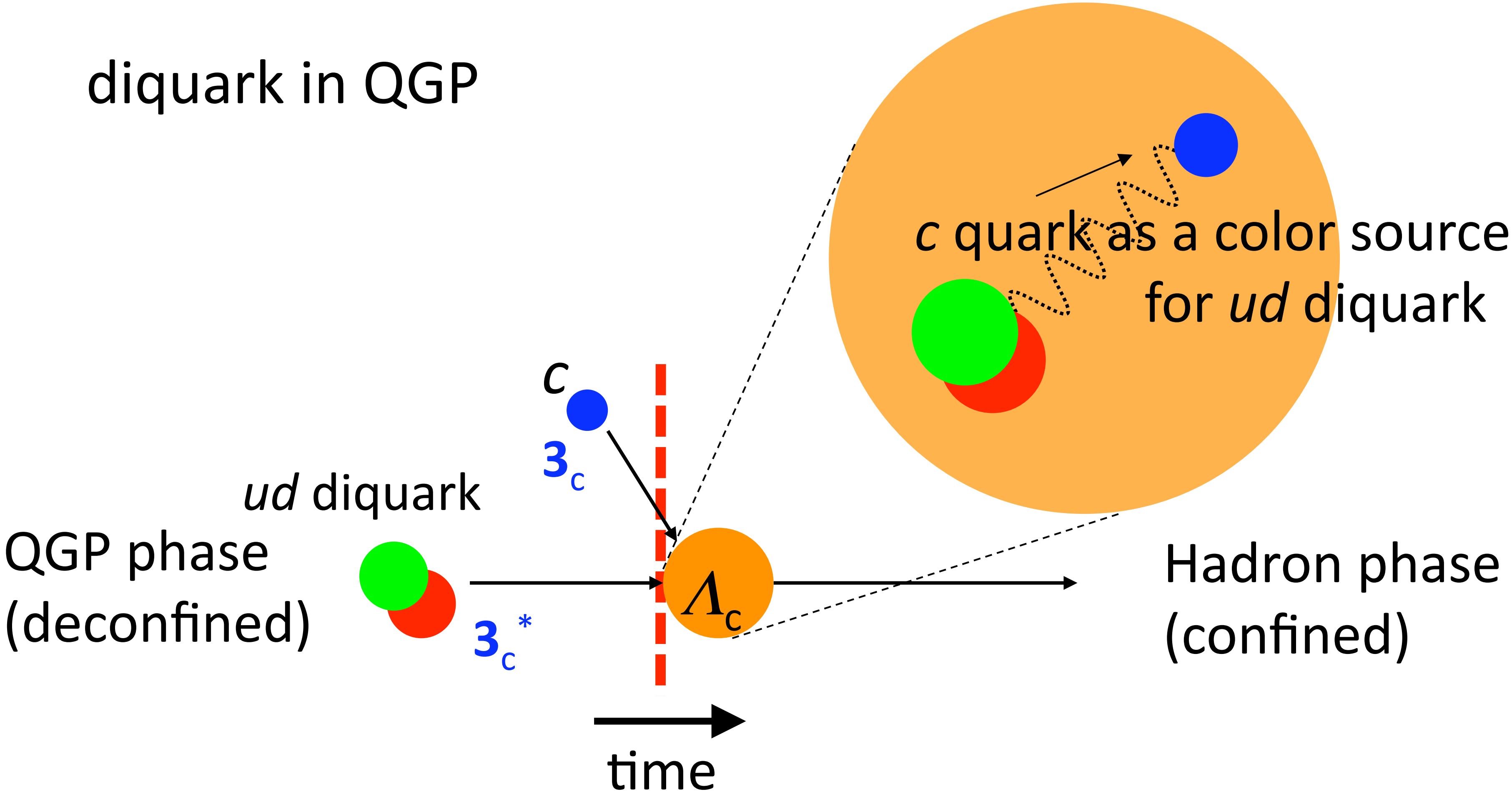
diquark in QGP



S. H. Lee, K. Ohnishi, S. Y., I. K. Yoo, C. M. Ko (2008)
S. H. Lee, Y. Oh, C. M. Ko, S. Y. (2009)

Perspective

diquark in QGP



☑ ***ud* diquark** ⟺ Λ_c

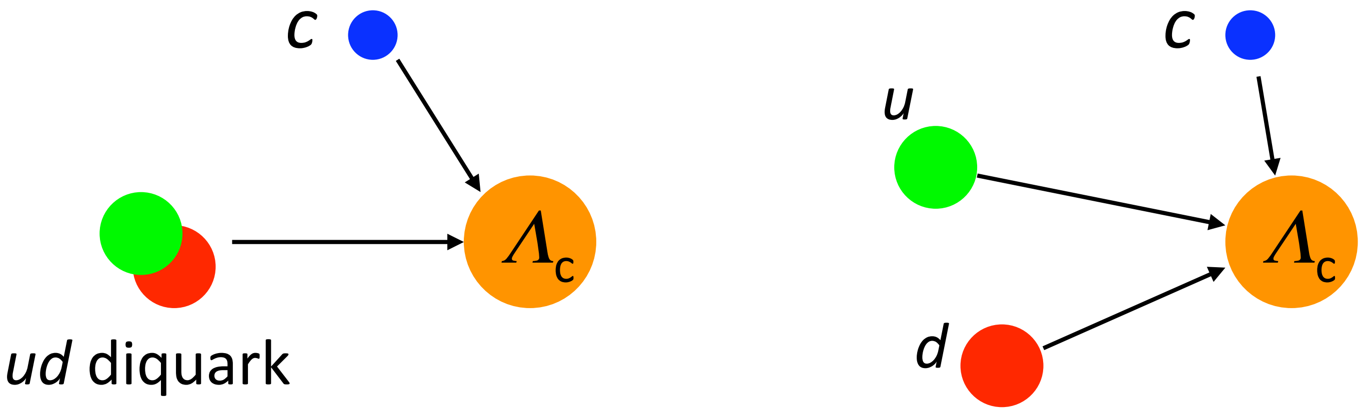
S. H. Lee, K. Ohnishi, S. Y., I. K. Yoo, C. M. Ko (2008)
S. H. Lee, Y. Oh, C. M. Ko, S. Y. (2009)

Perspective

In the process of yielding Λ_c ...

a) With diquark

b) Without diquark



Kinematically

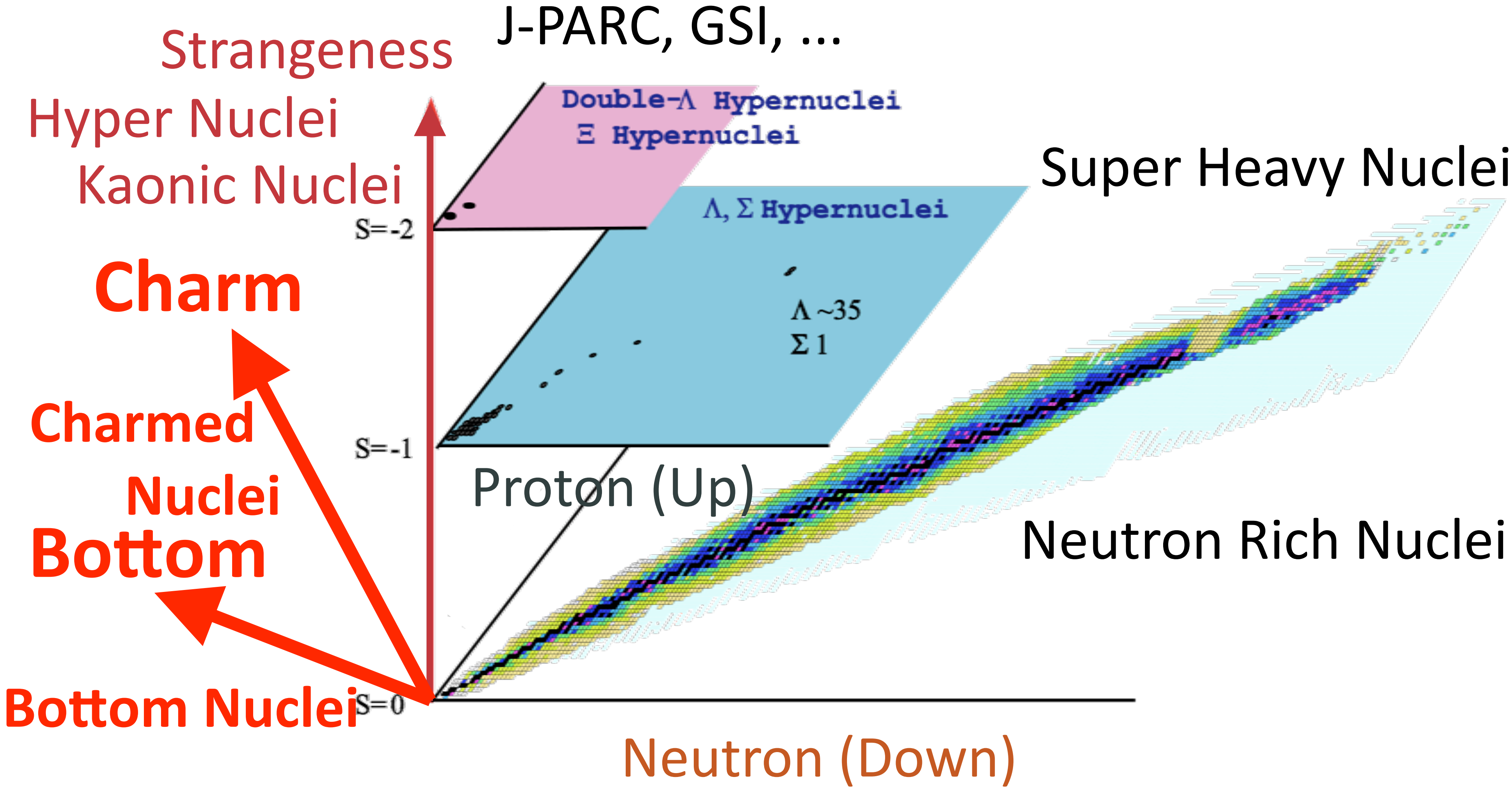
2 body collision >> 3 body collision

→ *ud* diquark enhances Λ_c yield by more than 2 times.

S. H. Lee, K. Ohnishi, S. Y., I. K. Yoo, C. M. Ko (2008)

S. H. Lee, Y. Oh, C. M. Ko, S. Y. (2009)

Multi-Favored Nuclear Chart



DN and BN bound states

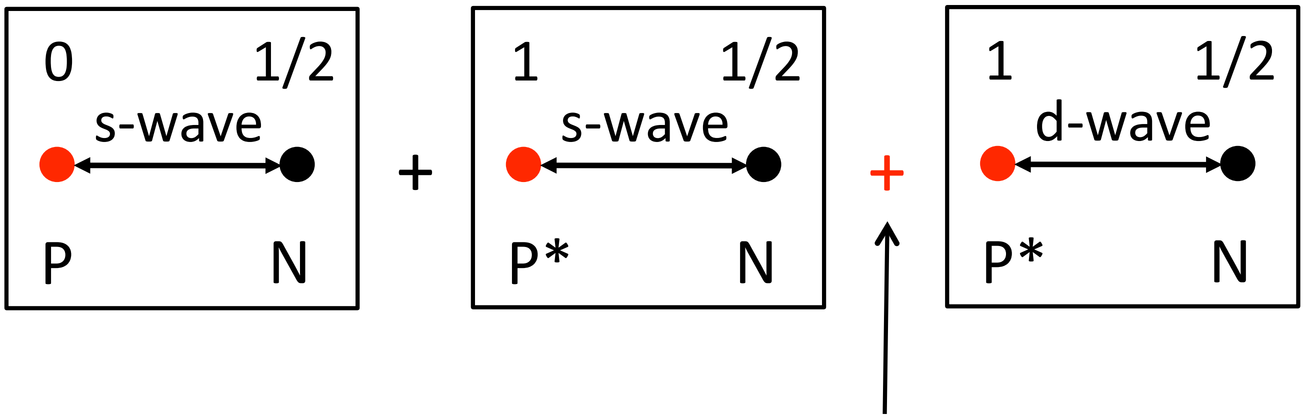
Classification of states

$|\text{state}\rangle = |PN\rangle + |P^*N\rangle$ $P = D^{bar}\ (c^{bar}q)$, $B\ (b^{bar}q)$

* No annihilation process

<u>$J^P = 1/2^-$ (I=0 or 1)</u>

$|PN;\ {}^2S_{1/2}\rangle + |P^*N;\ {}^2S_{1/2}\rangle + |P^*N;\ {}^4D_{1/2}\rangle$



This was missing in Cohen-Hohler-Lebed (2005).

DN and BN bound states

Classification of states

$|\text{state}\rangle = |PN\rangle + |P^*N\rangle$ $P = D^{bar}$ ($c^{bar}q$), B ($b^{bar}q$)

* No annihilation process

Case 1. $J^P = 1/2^-$ (I=0 or 1)

$|PN; {}^2S_{1/2}\rangle + |P^*N; {}^2S_{1/2}\rangle + |P^*N; {}^4D_{1/2}\rangle$

Case 2. $J^P = 3/2^-$ (I=0 or 1)

$|PN; {}^2D_{3/2}\rangle + |P^*N; {}^4S_{3/2}\rangle + |P^*N; {}^4D_{3/2}\rangle + |P^*N; {}^2D_{3/2}\rangle$