Charmed Hadrons in Nuclei
from Few Body viewpoints

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Key questions to be answered

- **What are the roles of charm (heavy) quark embedded in Atomic Nuclei?**

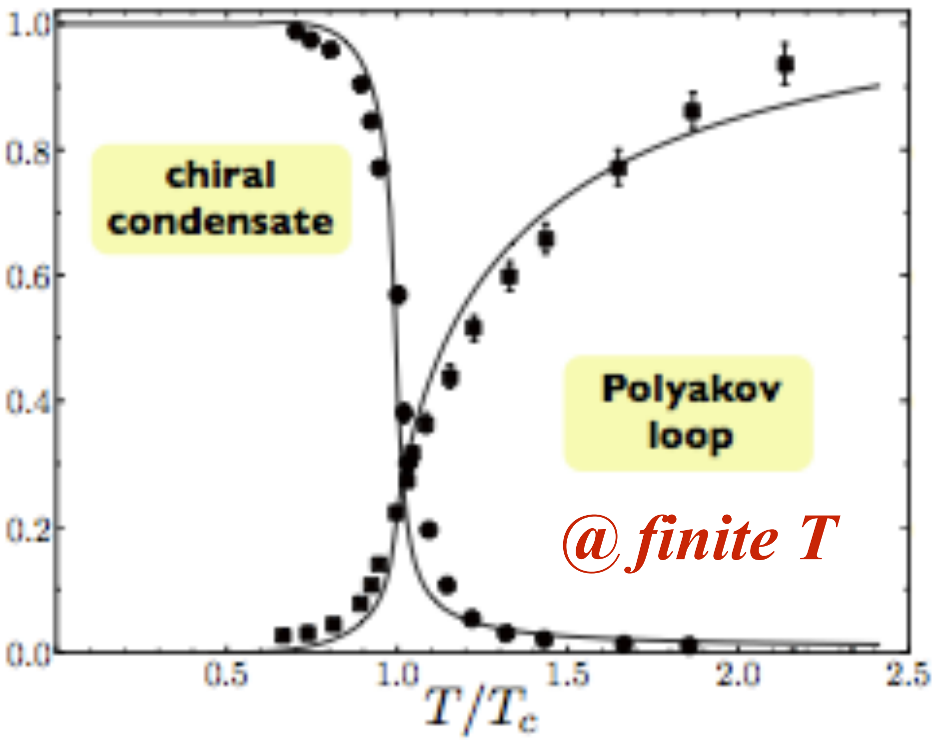
  As an impurity to change the properties of matter and nucleus
  => nuclear size, density, shape, decays and transitions
  anomalous phenomena ex. Kondo effect

  As a probe of the properties of dense matter
  => deconfinement and chiral symmetry restoration
  changes in quark and/or gluon distributions

  To study properties of heavy hadrons
  => structure of heavy hadrons, composite nature
  from how they are modified in medium

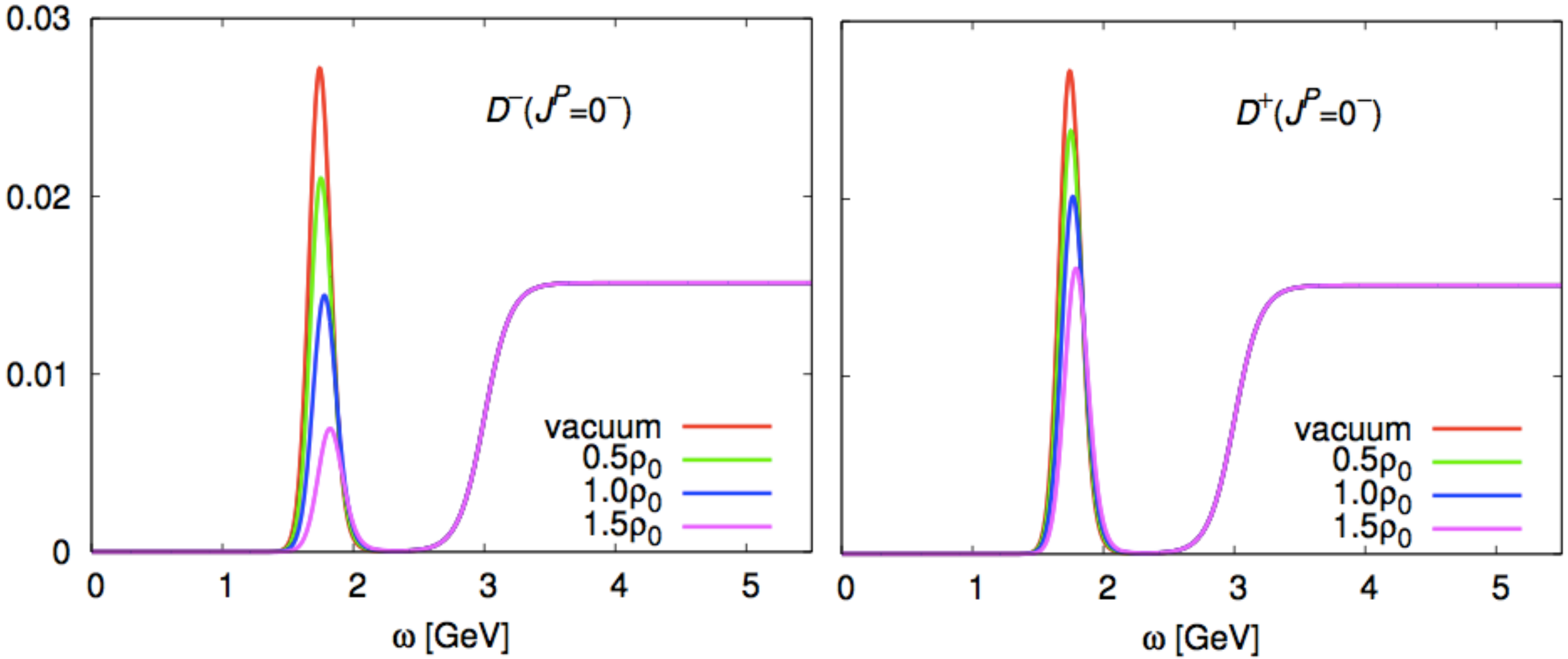
Hadrons in Matter

- Hadrons can probe the hadronic matter at finite T and/or ρ.
- Interplay of *chiral symmetry* and *quark confinement* at finite T and/or ρ is intriguing.



Hadrons in Matter

- **D and D^{bar} mesons at finite density**
  QCD sum rule with the Maximum Entropy Method
  K. Suzuki, P. Gubler, MO, PR C 93, 045209 (2016)



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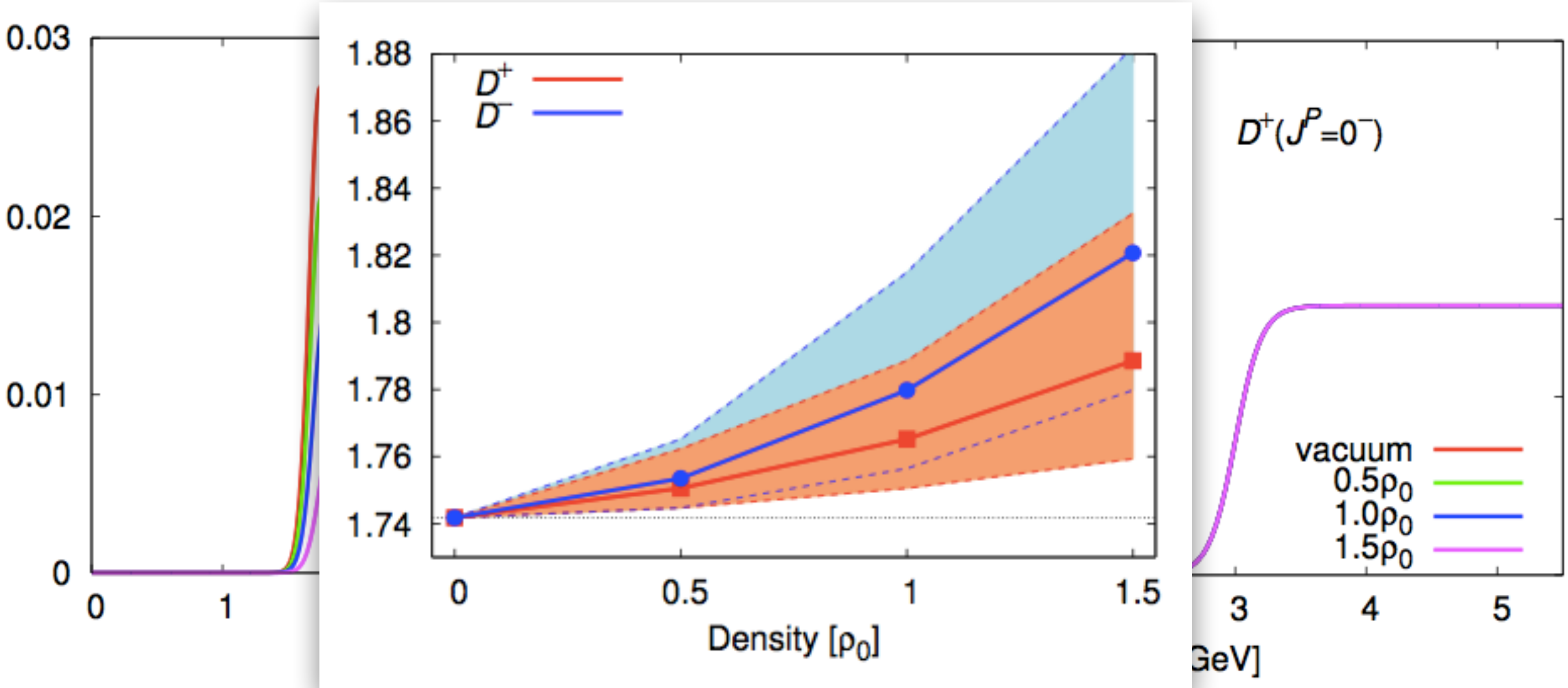
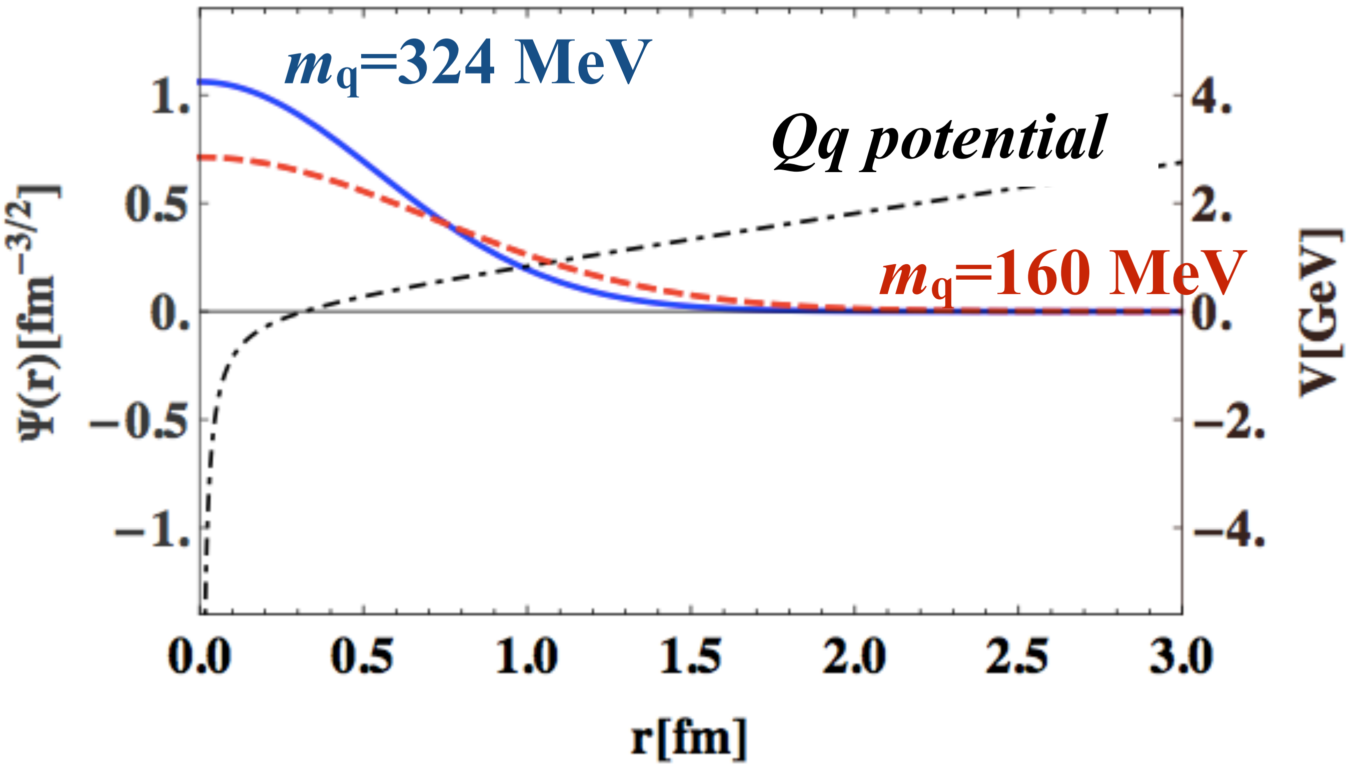
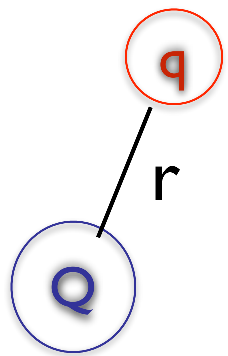


Hadrons in Matter

- **Interpretation in the constituent quark picture:**
  The wave function will extend to feel more repulsion.

A. Park, P. Gubler, M. Harada, S.H. Lee, C. Nonaka, W. Park, PR D93, 054035 (2016)





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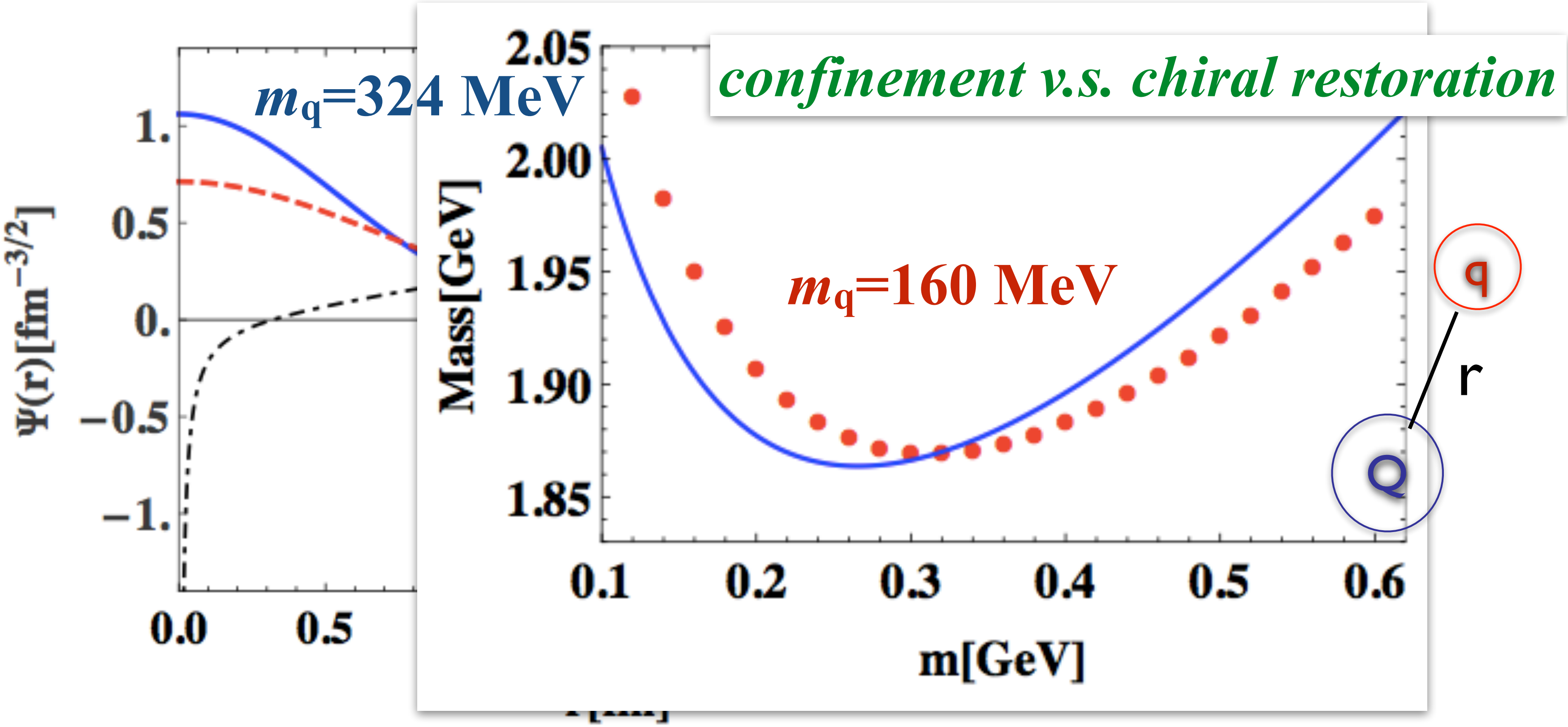


Key questions to be answered

- **What have we learned in Strangeness Nuclear Physics?**

  Hyperon does not melt in nuclei as the nucleon do not.

  <= single particle motions in nuclei

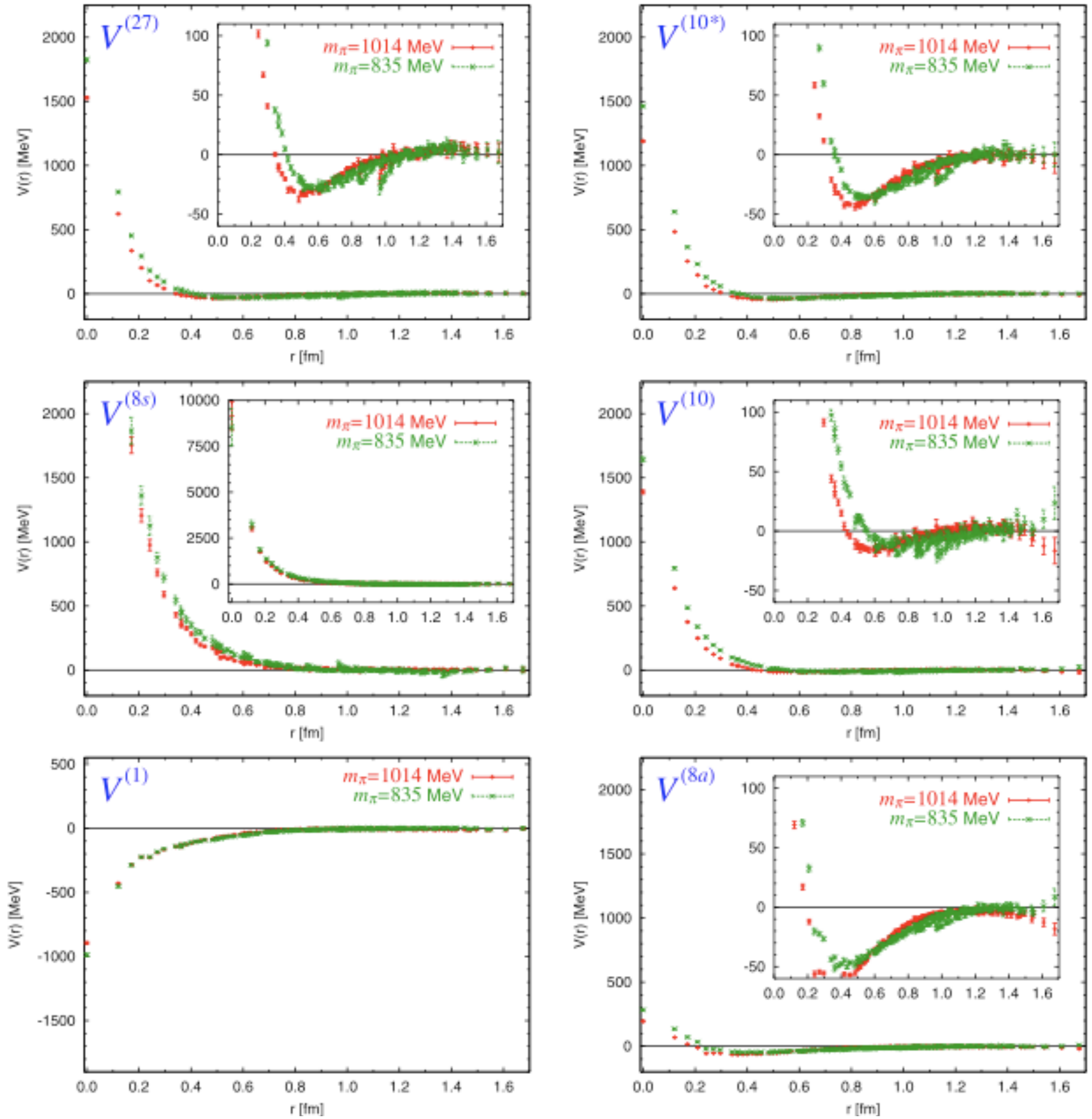
  YN and YY interactions are generalized nuclear force.

  => SU(3) symmetry, meson exchange interactions

  quark structure at short distances

HAL QCD Lattice calculation of the BB potentials (in SU(3) scheme) shows that the potentials have long-range meson exchange part plus short-range part consistent with the quark Pauli effects.

T. Inoue et al., (HAL QCD) PTP 124, 591 (2010)



Key questions to be answered

- **Most hadrons are protected from being dissociated into multi-quark compound in medium.**
  => Thanks to short-range repulsion due to the quark structure of hadrons
- **There are exceptions, which are very interesting.**
  K^{bar} *feels a strong attraction to* N, *forming a molecular bound state* Λ(1405).
  The flavor singlet BB interaction is attrative, giving H-dibaryon ($u^2d^2s^2$) which couples to* ΛΛ, NΞ, ΣΣ *channels.

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- **The strange hadron physics is mature now, and why do we need heavier hadrons?**

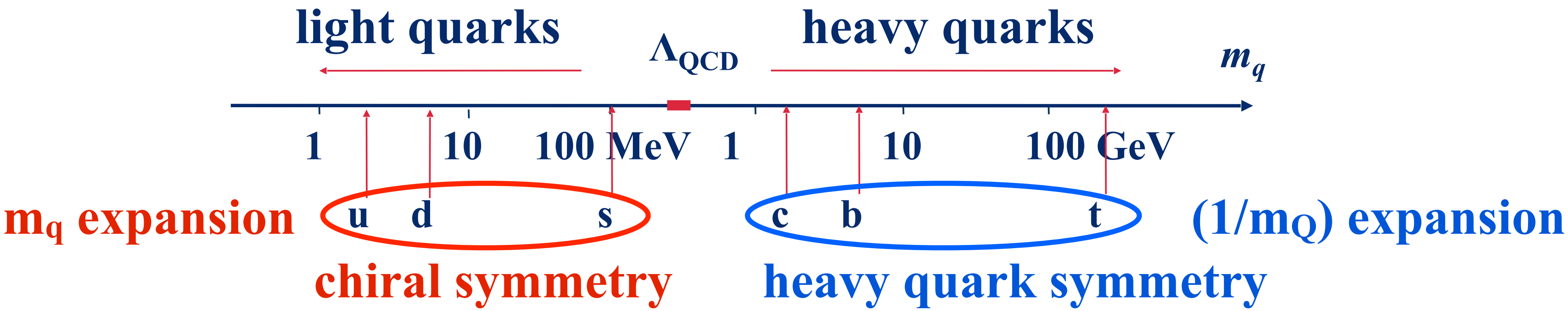
They are even more exciting!

Why Heavy Quarks?

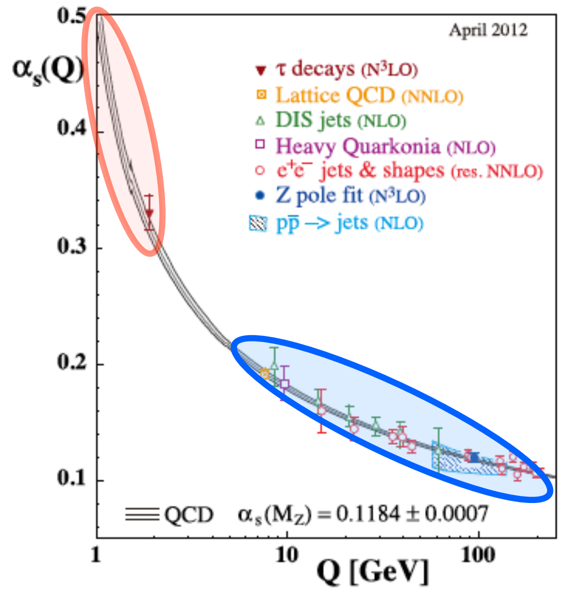
- **A goal of hadron physics:**
  – To clarify the relevant *effective degrees of freedom* of hadrons and hadron excitations.
- ***Heavy hadrons are simpler* =>**
  because the QCD coupling is small and heavy quarks are non-relativistic. They are separated from light quarks dynamically.

Heavy Quark

- QCD Lagrangian is flavor independent, but the coupling constant runs. $\Lambda_{QCD}(\sim 300\ \text{MeV}) \ll m_c(\sim 1.3\ \text{GeV}) \ll m_b(\sim 4.2\ \text{GeV})$



- Light quarks are nonperturbative/ relativistic.
- Heavy quarks are perturbative/ non-relativistic.

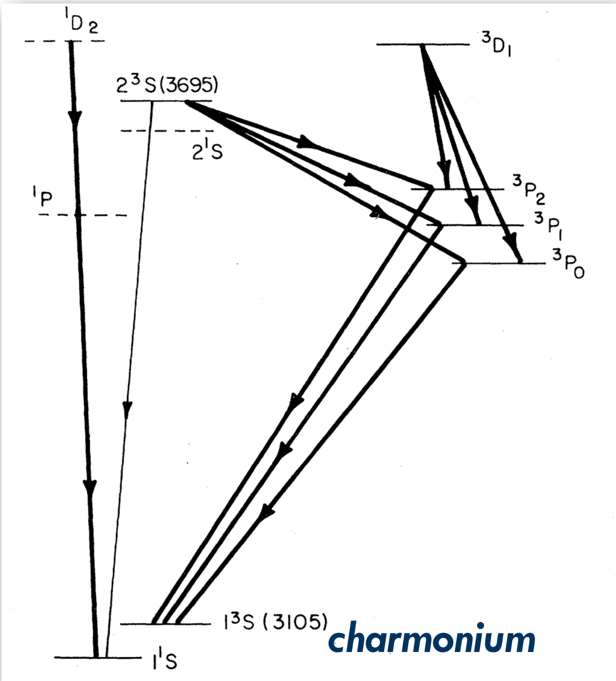


Charmonium

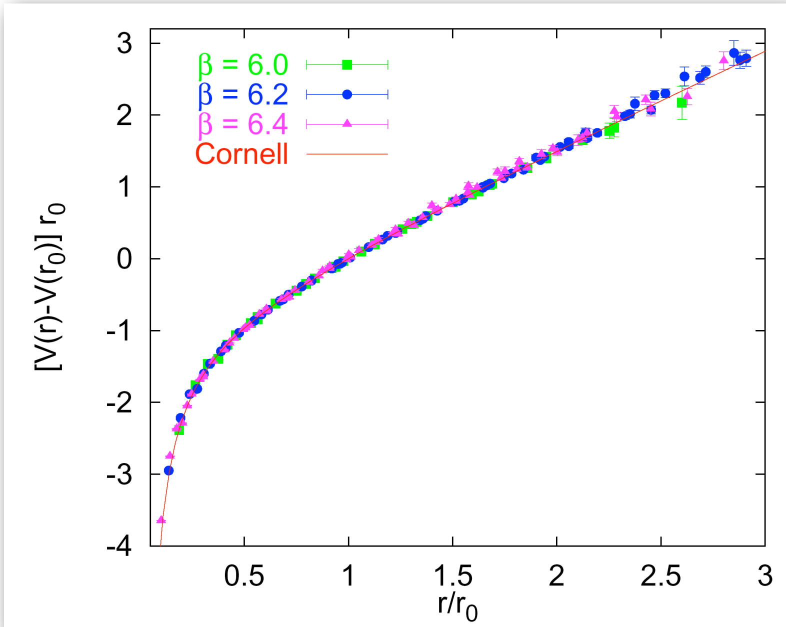
- Charmonium (1974) gave a firm evidence for quarks.
  - Hydrogen atom in QCD
  - NR quarks with an instantaneous potential
  - Linear + Coulomb (Cornell) potential

$$V(r) = -\frac{e}{r} + \sigma r$$

E. Eichten, et al., PRL 34 (1975) 369



G.S. Bali, Phys. Rept. 343 (2001) 1



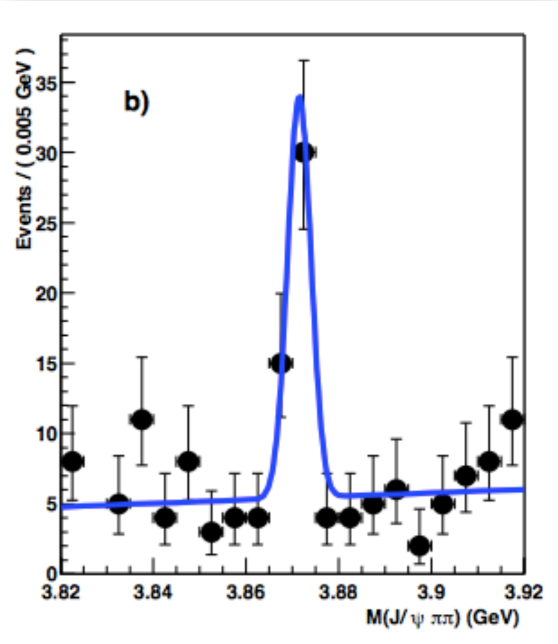
Why Heavy Quarks?

- **A goal of hadron physics:**
  – To clarify the relevant *effective degrees of freedom* of hadrons and hadron excitations.
- ***Heavy hadrons are simpler* =>**
  because the QCD coupling is small and heavy quarks are non-relativistic. They are separated from light quarks dynamically.
- ***Heavy hadrons are complex* =>**
  because many exotic multi-quark-like resonances are found.

HQ Exotic Hadrons

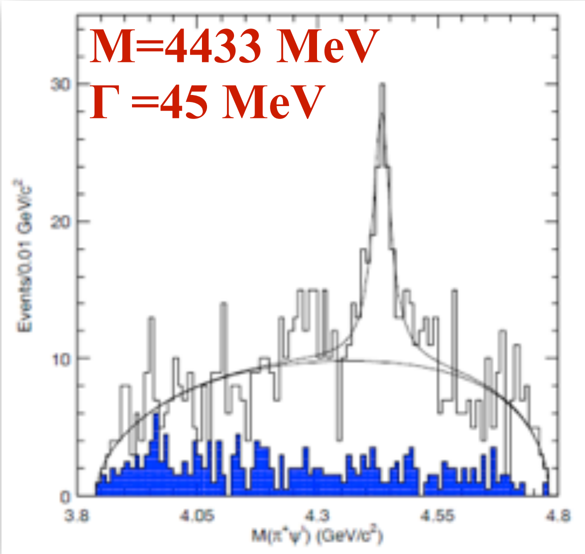
- X(3872) found in 2003 by Belle (KEK)
  → *not reproduced by lattice QCD using only q-q^{bar} operators.*
- Z(3900), Z(4430) etc. : charged hidden charm states

X(3872)
Belle



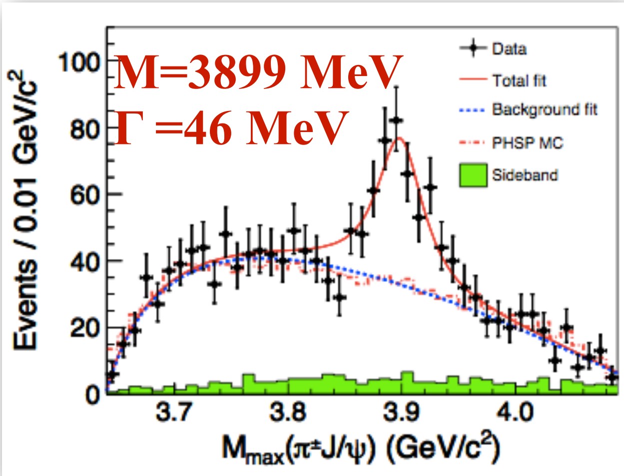
PRL 91 (2003) 262001

Z_c^+(4430)
Belle



PRL 100 (2008) 142001

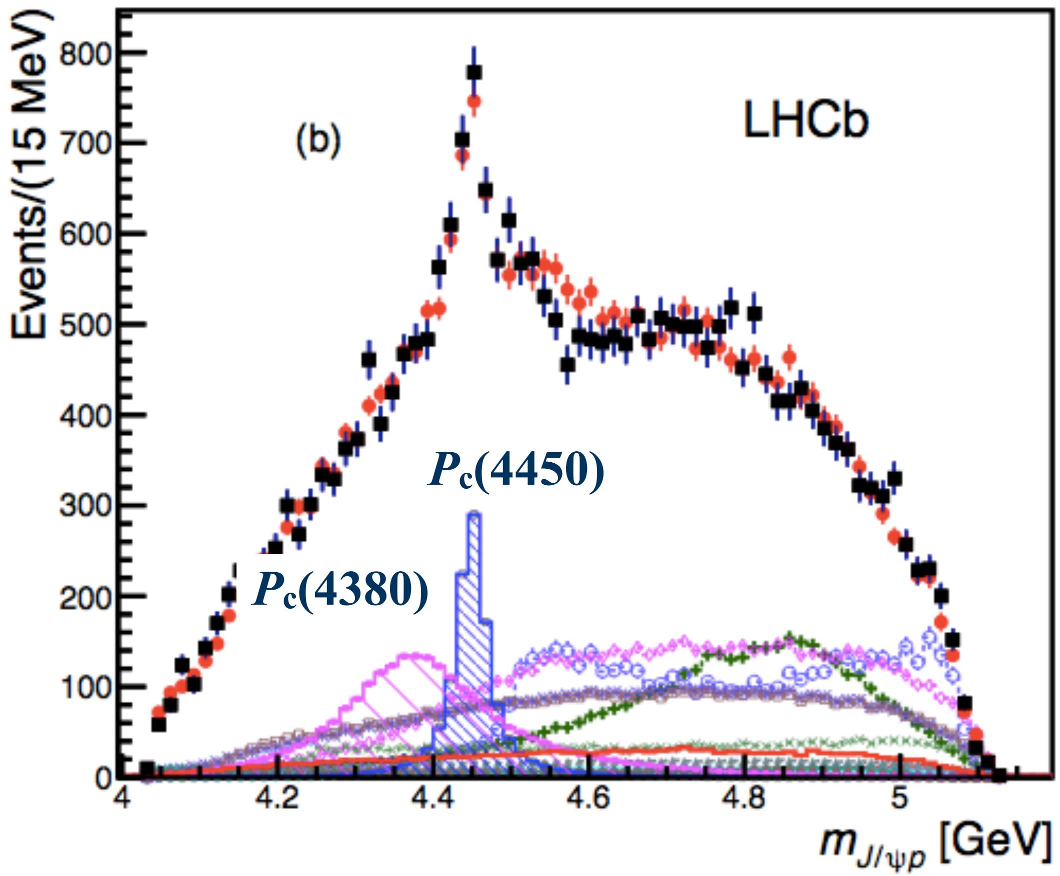
Z_c^+(3900)
BES III



PRL 110 (2013) 252001

HQ Exotic Hadrons

- $P_c \to J/\psi + p$ ($cc^{bar}uud$)
  LHCb (*PRL 115 (2015) 07201*) found two penta-quark states with hidden cc^{bar}.



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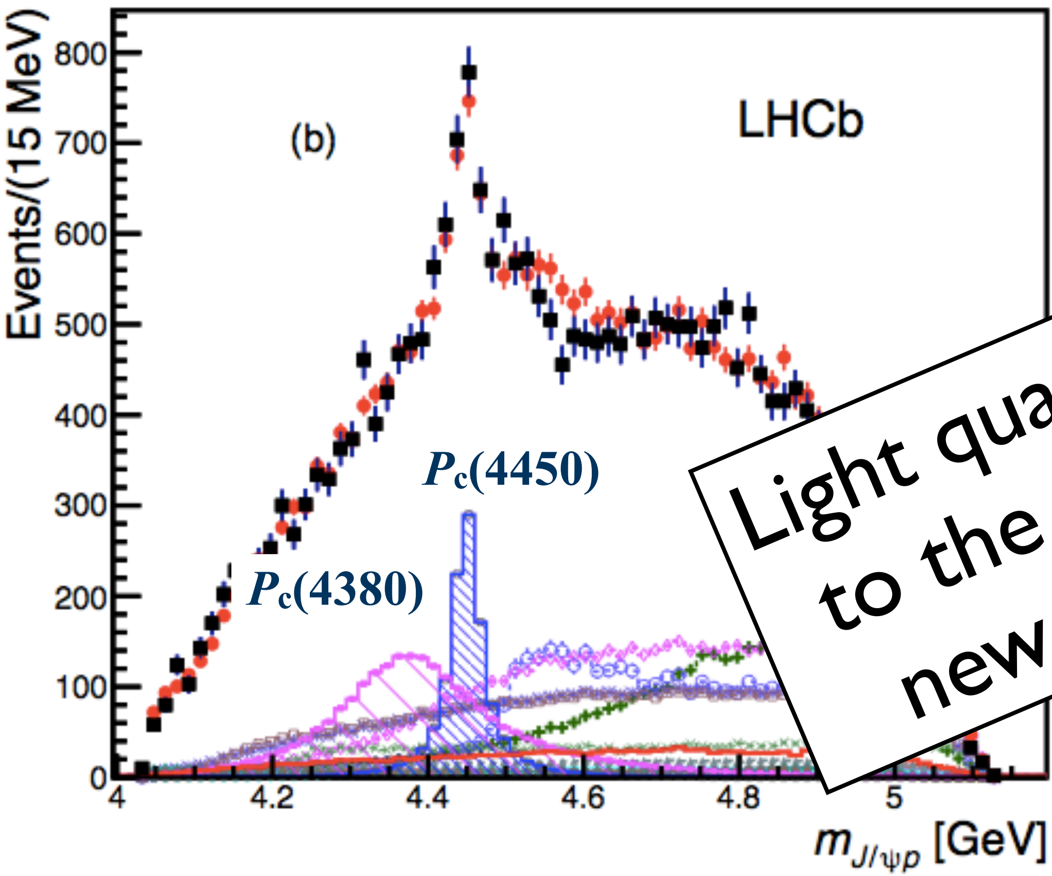


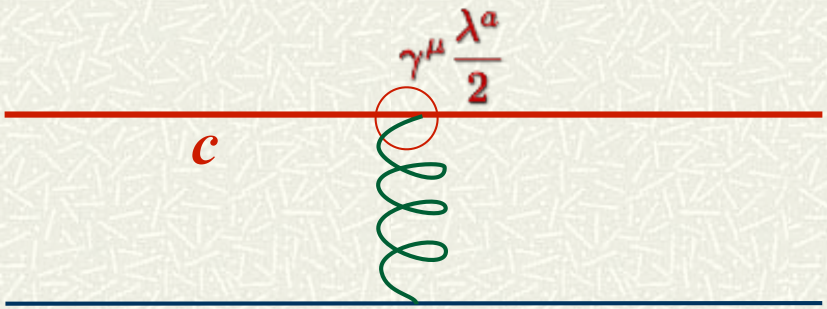
Light quarks tend to stick to the QQ^{bar} forming a new type of hadrons.

Many interesting questions in HQ hadrons

- **Does D meson melt in nuclei like π and K^{bar}?**
- **How does the heavy quark spin symmetry emerge and the chiral symmetry disappear?**
  When do the NG bosons turn into the heavy meson doublet?
  π-ρ, K-K* => D-D*, B-B*
- **Why are there many exotic resonance-like states appear in HQ sector? Are they compact states or just cusps?**
- **Are the interactions between Y_cN and Y_cY_c similar to hyperons? Are they described by meson exchanges plus short-range interaction?**
- **How does the heavy quark spin symmetry manifest in baryons? Can we study di-quark spectroscopy from the transition from strange to charm/bottom baryons?**

Heavy Quark Spin Symmetry

Magnetic gluon coupling is suppressed



$$\bar{\Psi}\gamma^\mu \frac{\lambda^a}{2}\Psi A^a_\mu \sim \Psi^\dagger \frac{\lambda^a}{2}\Psi A^a_0 - \Psi^\dagger \sigma \frac{\lambda^a}{2}\Psi \cdot \frac{1}{m_Q}(\nabla \times A^a)$$

(Color Electric coupling) ≫ (Color Magnetic coupling)

HQ spin-flip amplitudes are suppressed by ($1/m_Q$).

⇨ Heavy Quark Spin Symmetry

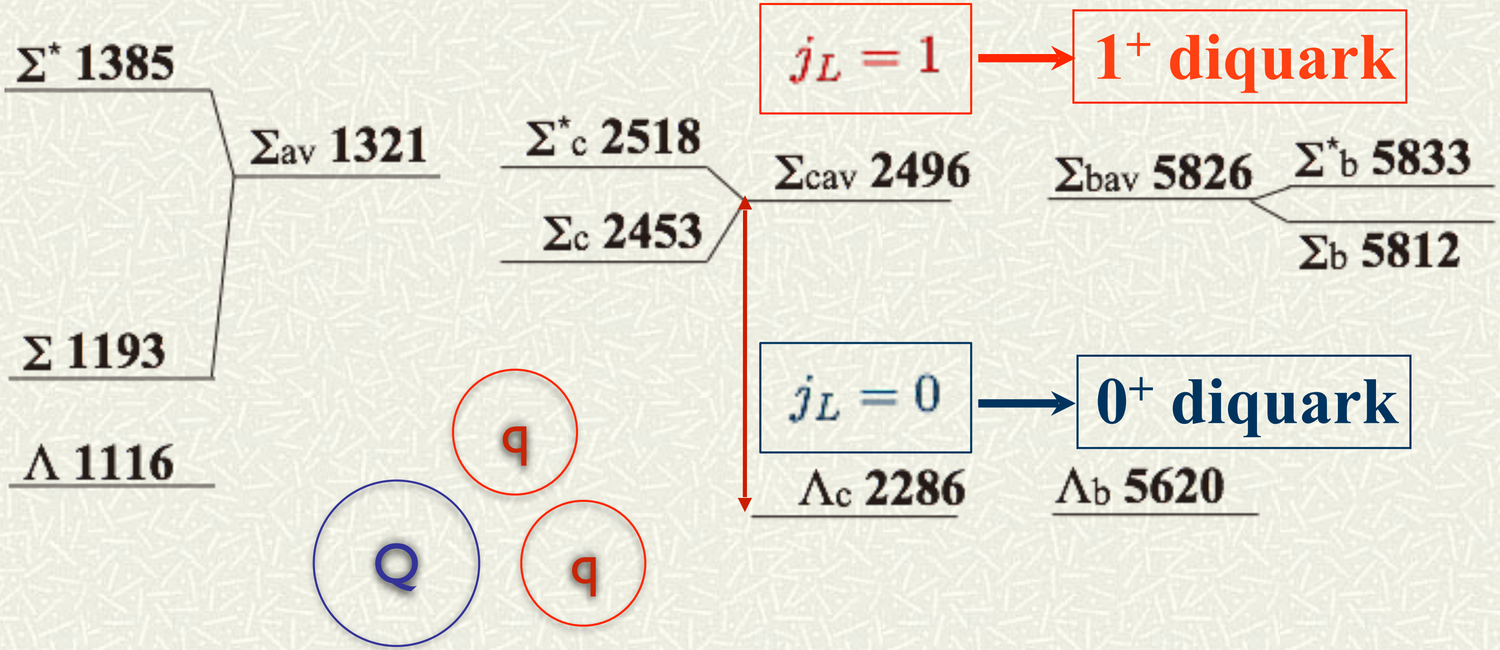
Heavy Quark Spin Symmetry

HQ spin symmetry $[S_Q, H] = O\left(\frac{1}{m_Q}\right)$

Q
qq

$\vec{J} = \vec{S}_Q + \vec{j}_L \qquad \vec{j}_L = \vec{S}_q + \vec{L}_q$

$J = j_L \pm \frac{1}{2}$ **states are degenerate in the HQ limit.**



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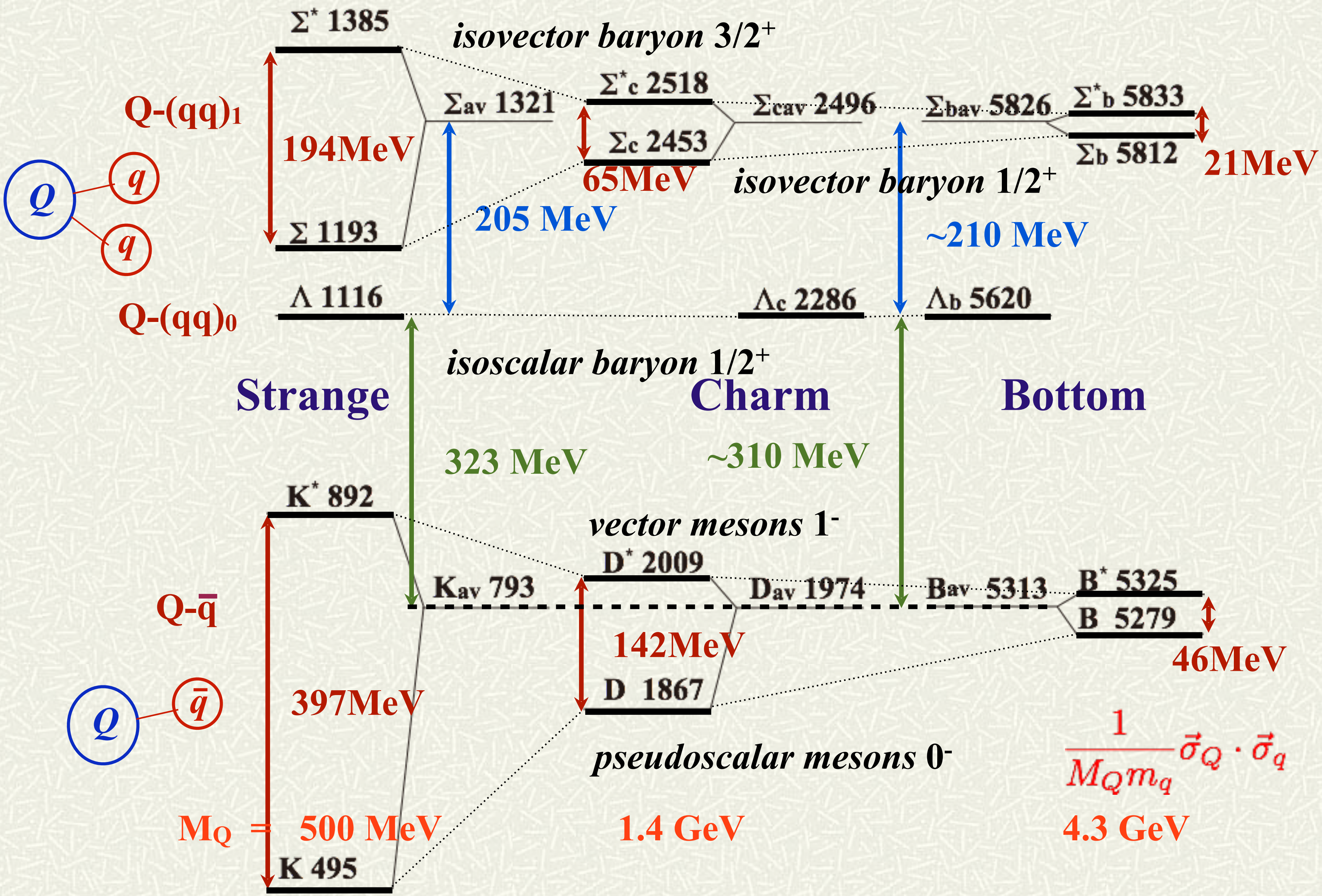


$$\frac{1}{M_Q m_q}\vec{\sigma}_Q \cdot \vec{\sigma}_q$$

Heavy Hadron in Nuclei

- D (=cq^{bar}) (<= K^{bar}) bound in DNN system
- D^{bar} (=c^{bar} q) in nuclear medium (Yasui, Sudoh)
- Charmonium J/ψ, η_c in nuclei
  Charmonium bound in nuclei (Yokota et al.)
- Charmed dibaryons and nuclei
  $\Lambda_c$pn bound state (YR Liu et al., Maeda, et al.)

DN system and D in nuclei

- D (=c u^{bar}, c d^{bar}) in medium compared to K^{bar} (=s u^{bar}, s d^{bar})
  Does DN have a strong attraction and couple strongly to $\Lambda_c(1/2^-)$?
  Contact TW-type interaction is strongly attractive.
  OπE couples D and D* strongly.

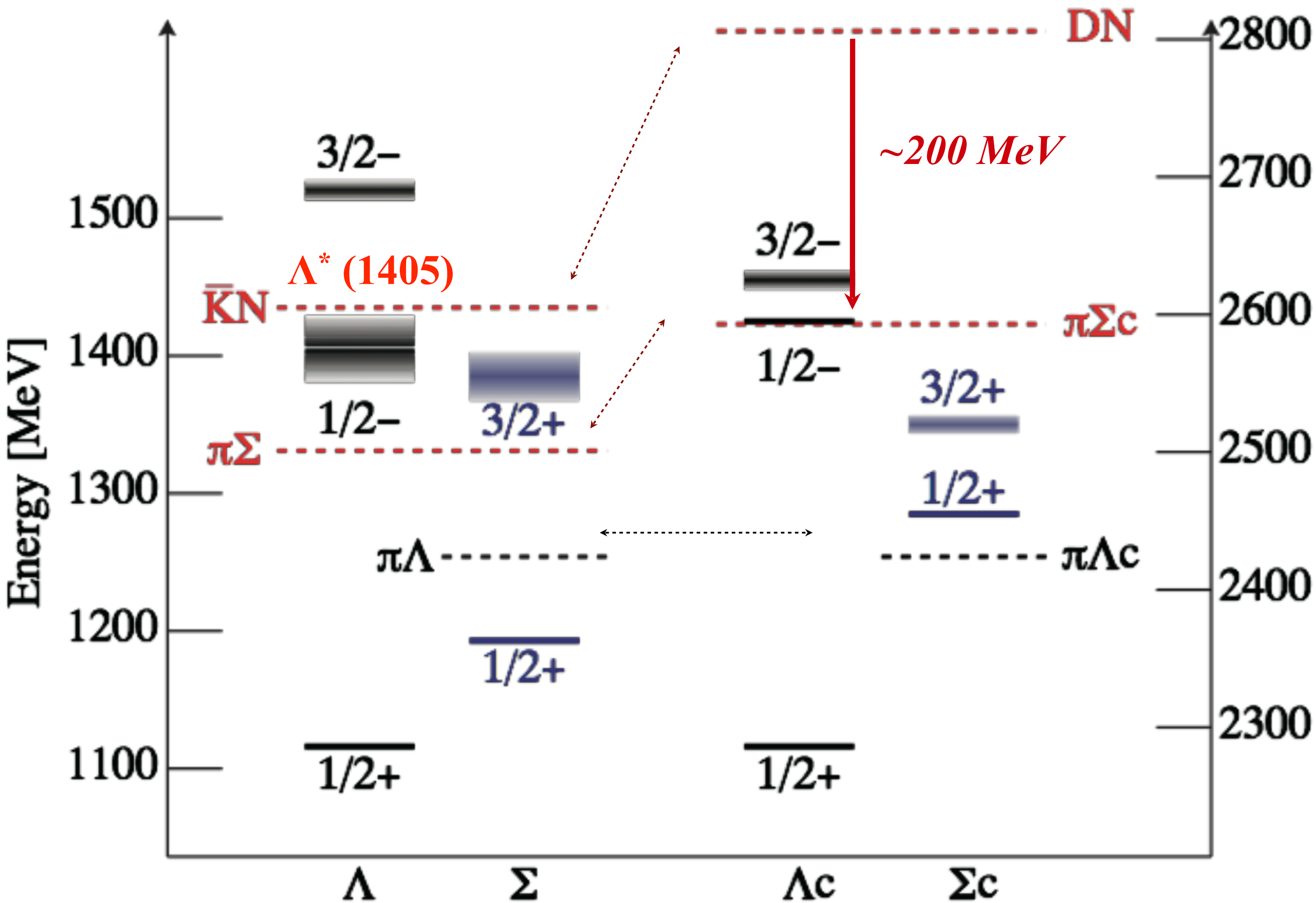
  J.Hofmann, M.F.M.Lutz (2005), T.Mizutani, A.Ramos (2006),
  C. Garcia-Recio, et al. (2009), Y. Yamaguchi, et al. (2013),

- If Λ_c(2595) is a bound DN state, there may be a deeply bound DNN state and D-nuclei.

  M. Bayar et al. (2004)

DN system and D nuclei

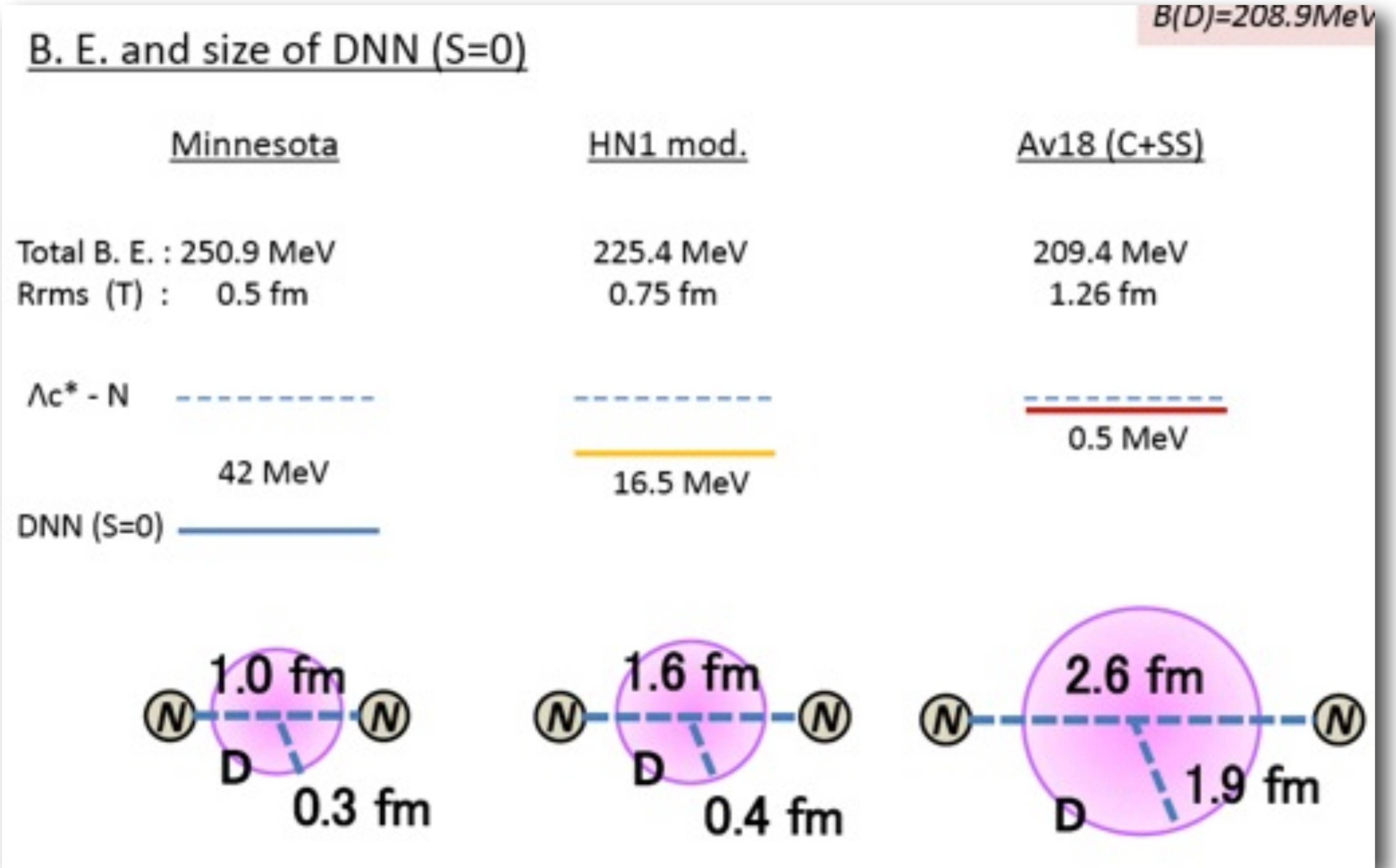
- **Negative-parity charmed baryon as DN ← Λ(1405) as K^{bar}N**



DN system and D nuclei

- **A narrow DNN bound state is predicted.**

M. Bayar et al., **PR C86 (2012) 044004**



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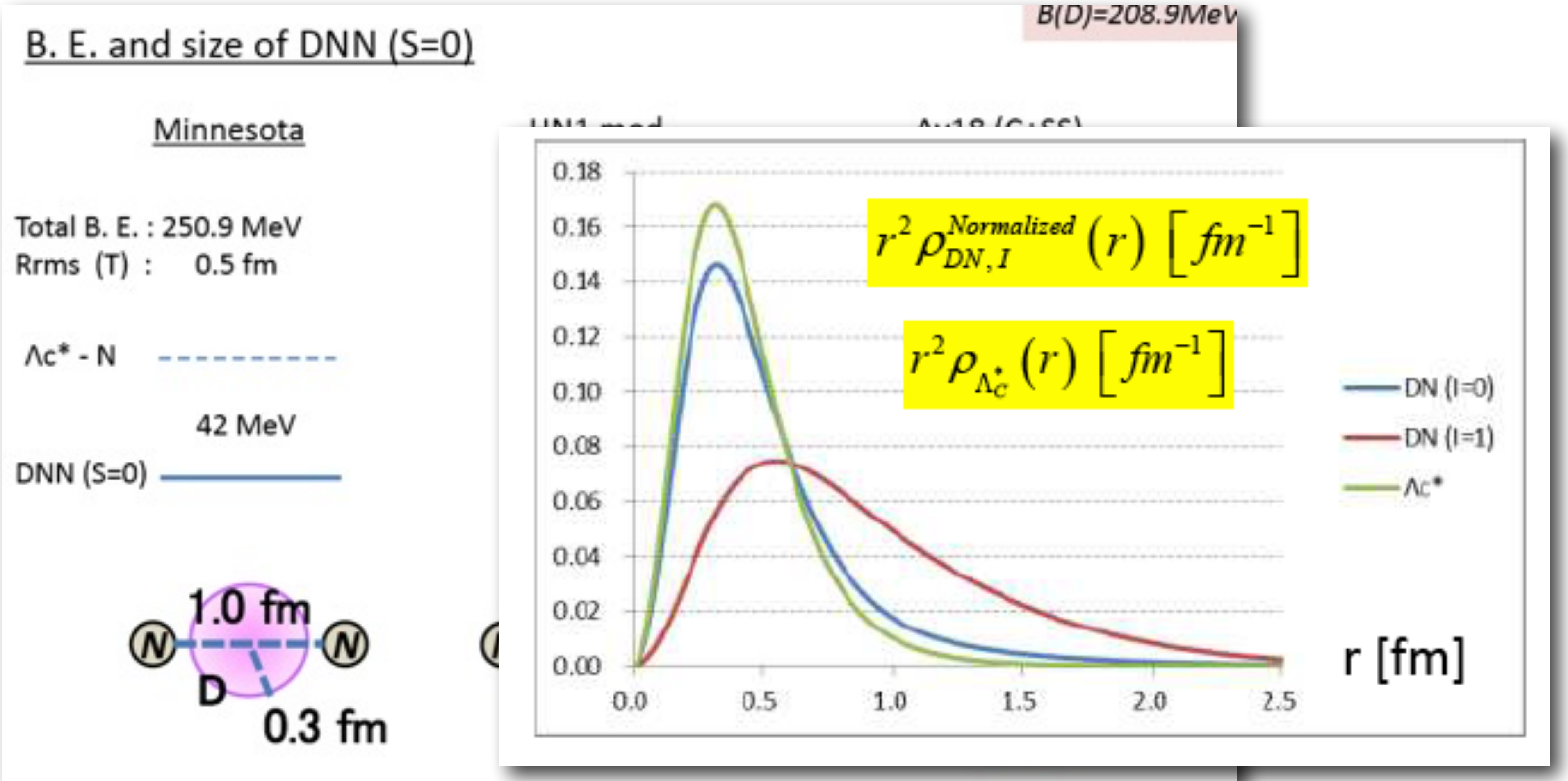


DN system and D in nuclei

- **D in matter shows two branches: deep bound and repulsive**

  K. Tsushima, et al. (1999), A. Mishra A. Mazumdar, (2009)
  M.F.M. Lutz, C.L.Korpa (2006), C. Garcia-Recio, et al. (2010)

- **The strong attaction seems inconsistent with the QCD SR.**

  T. Hilger, et al. (2009), K. Suzuki, P. Gubler, MO (2016)

DN system and D nuclei

- ***This is still an open problem. It is important to see how K and D are different from the viewpoint of chiral symmetry.***
- ***As studies of $K^{bar}NN$ system is powerful in understanding the nature of Λ(1405) and $K^{bar}N$ interaction, DNN and D in nuclei should help us to understand the nature of the DN interactions.***

D^{bar} (B) mesons in nuclei

S. Yasui, K. Sudoh, Phys. Rev. C89 (2014) 015201

The $1/m_Q$ expansion of heavy hadron ($\overline{D}^{(*)}$, $B^{(*)}$) masses in QCD

$$M_{\rm H} = m_{\rm Q} + \bar{\Lambda} - \frac{\lambda_1}{2m_{\rm Q}} + 4\vec{S}_{\rm Q}\cdot\vec{S}_{\rm L}\frac{\lambda_2(m_{\rm Q})}{2m_{\rm Q}} + \mathcal{O}(1/m_{\rm Q}^2),$$

M.E. Luke, A.V. Manohar (1992)

$$\frac{1}{2M_{\rm H}}\langle\tilde{\rm H}_{v_r}|\frac{\beta(\alpha_s)}{4\alpha_s}G^2|\tilde{\rm H}_{v_r}\rangle = \bar{\Lambda},$$ scale anomaly

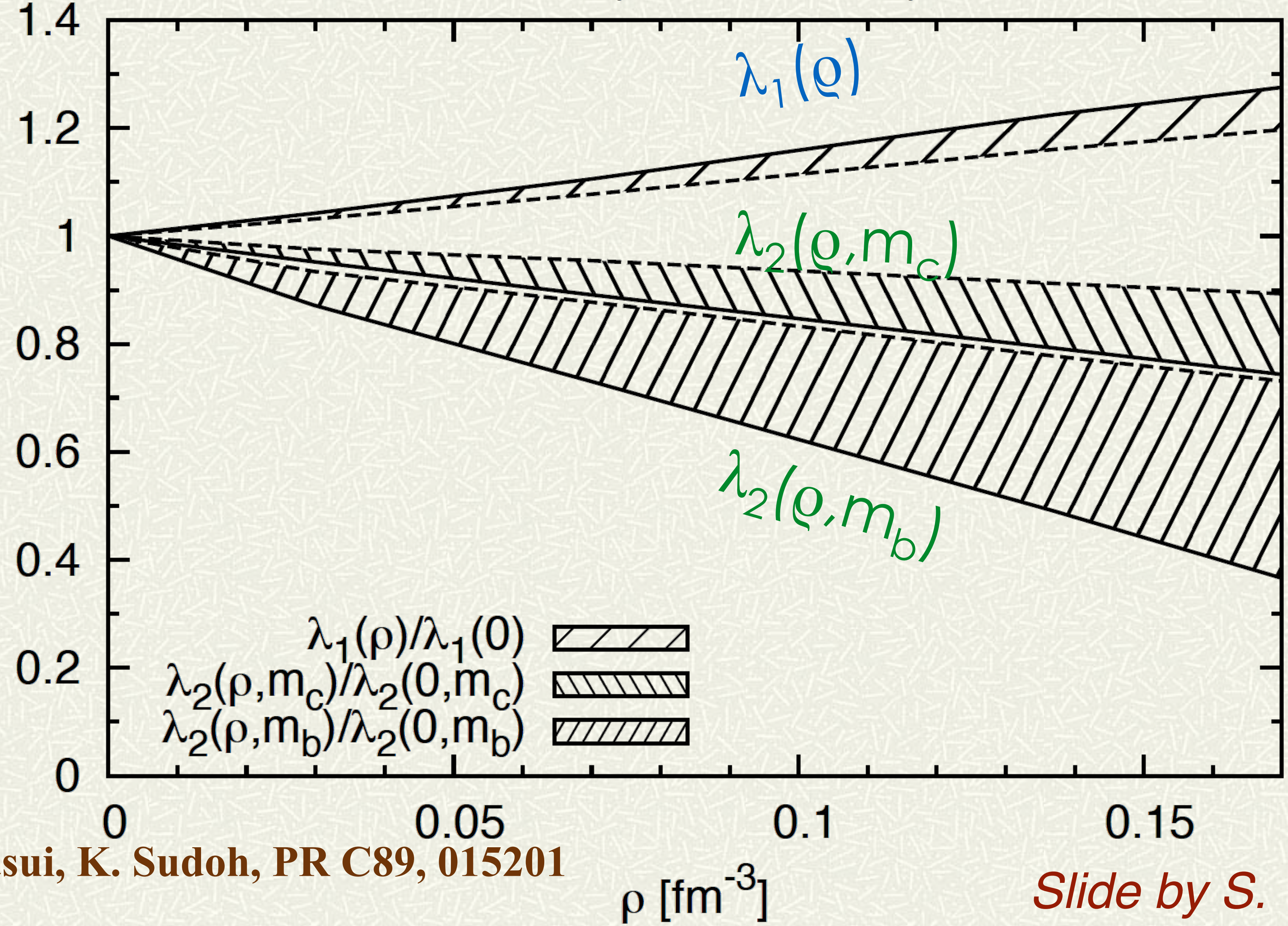
$$\langle{\rm H}_{v_r}|\overline{Q}_{v_r}g_s\vec{x}\cdot\vec{E}Q_{v_r}|{\rm H}_{v_r}\rangle = -\frac{\lambda_1}{m_{\rm Q}},$$ color electric

$$\frac{1}{2}c(\mu)\langle{\rm H}_{v_r}|\overline{Q}_{v_r}g_s\vec{\sigma}\cdot\vec{B}Q_{v_r}|{\rm H}_{v_r}\rangle = 8\vec{S}_{\rm Q}\cdot\vec{S}_{\rm L}\lambda_2(m_{\rm Q}),$$ color magnetic

M. Neubert (1994)

Properties of heavy hadrons in nuclear medium will directly be connected to the QCD matrix elements of gluon fields.

$$M_{\rm H}(\rho) = m_{\rm Q} + \bar{\Lambda}(\rho) - \frac{\lambda_1(\rho)}{2m_{\rm Q}} + 4\vec{S}\cdot\vec{j}\,\frac{\lambda_2(\rho;m_{\rm Q})}{2m_{\rm Q}} + \mathcal{O}(1/m_{\rm Q}^2)$$



S. Yasui, K. Sudoh, PR C89, 015201

Slide by S. Yasui

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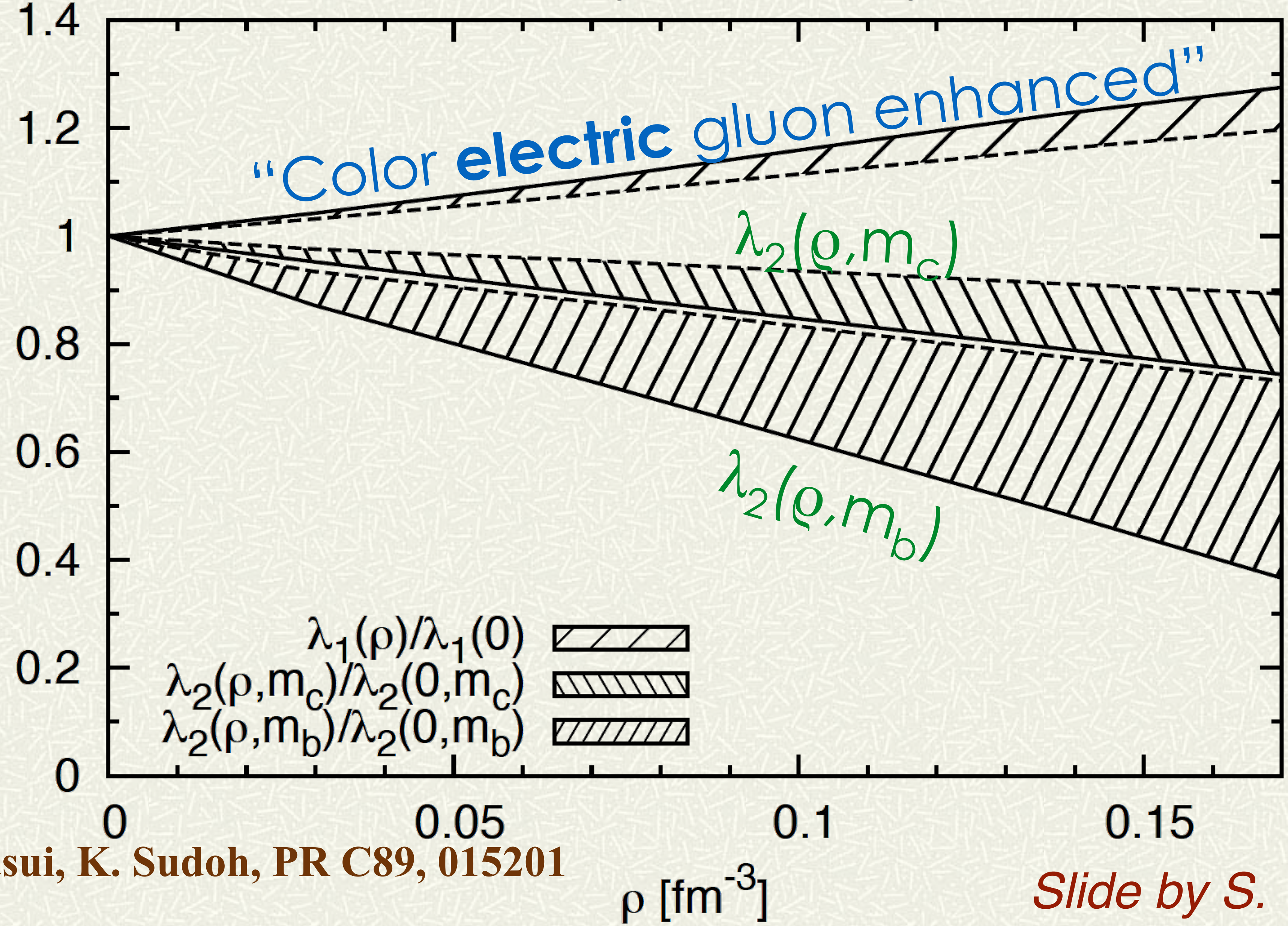

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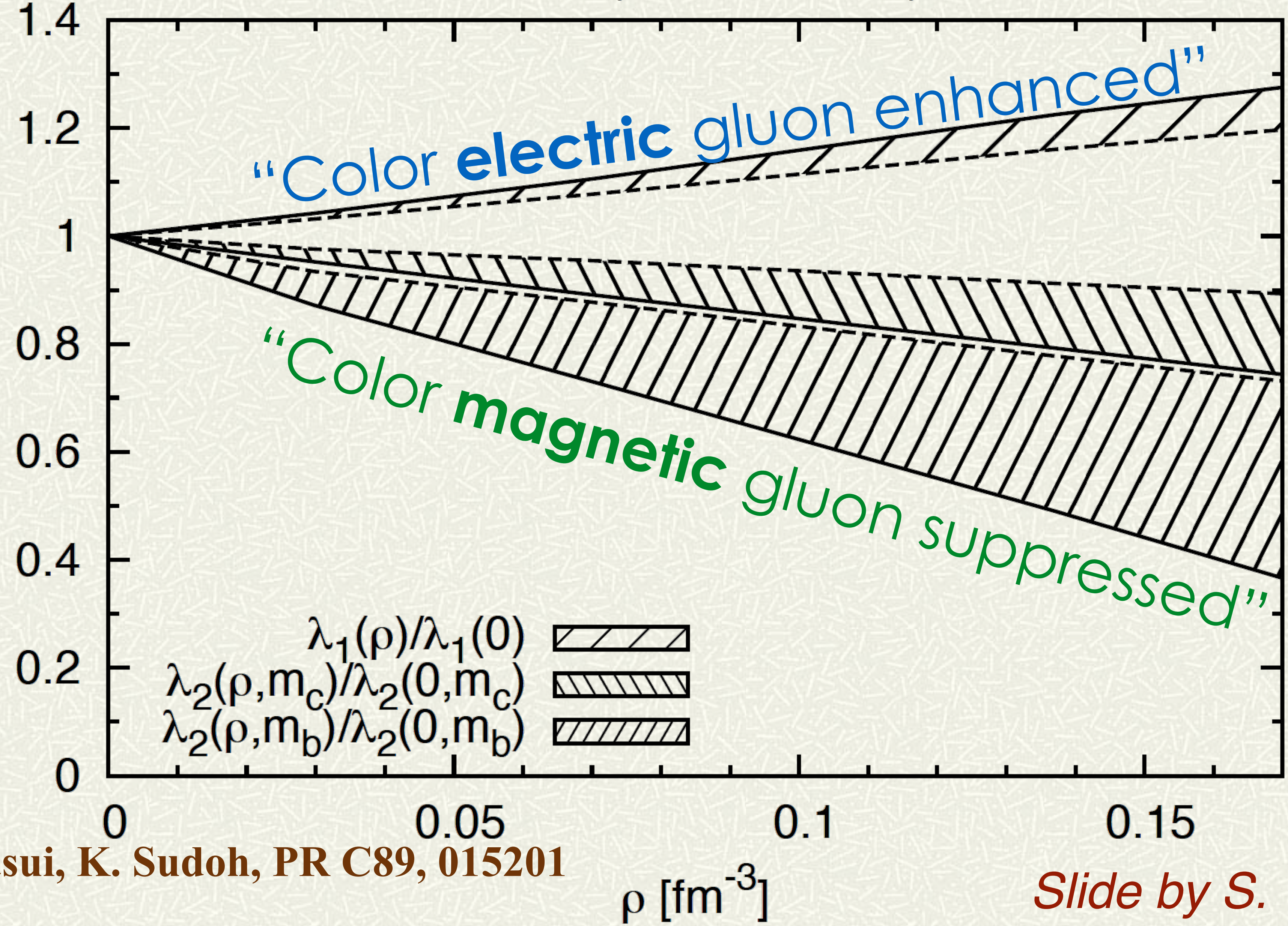
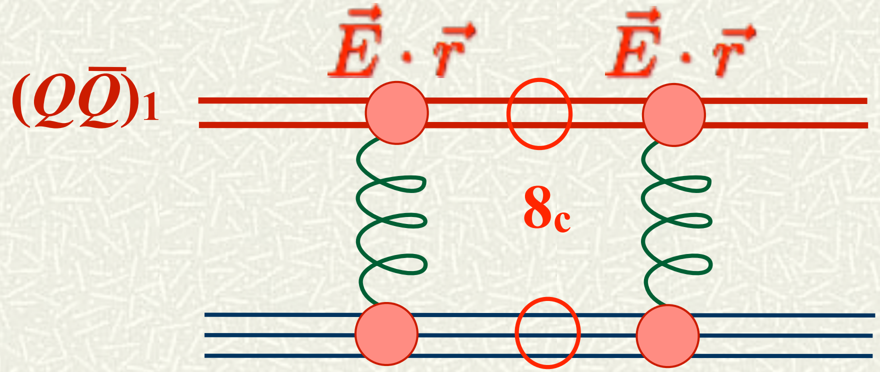


S. Yasui, K. Sudoh, PR C89, 015201

Slide by S. Yasui

Charmonium in Nuclei

Pure HQ hadrons have attractive interaction with matter.

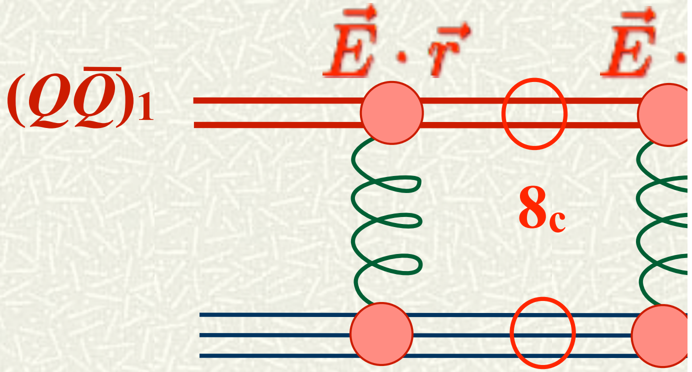


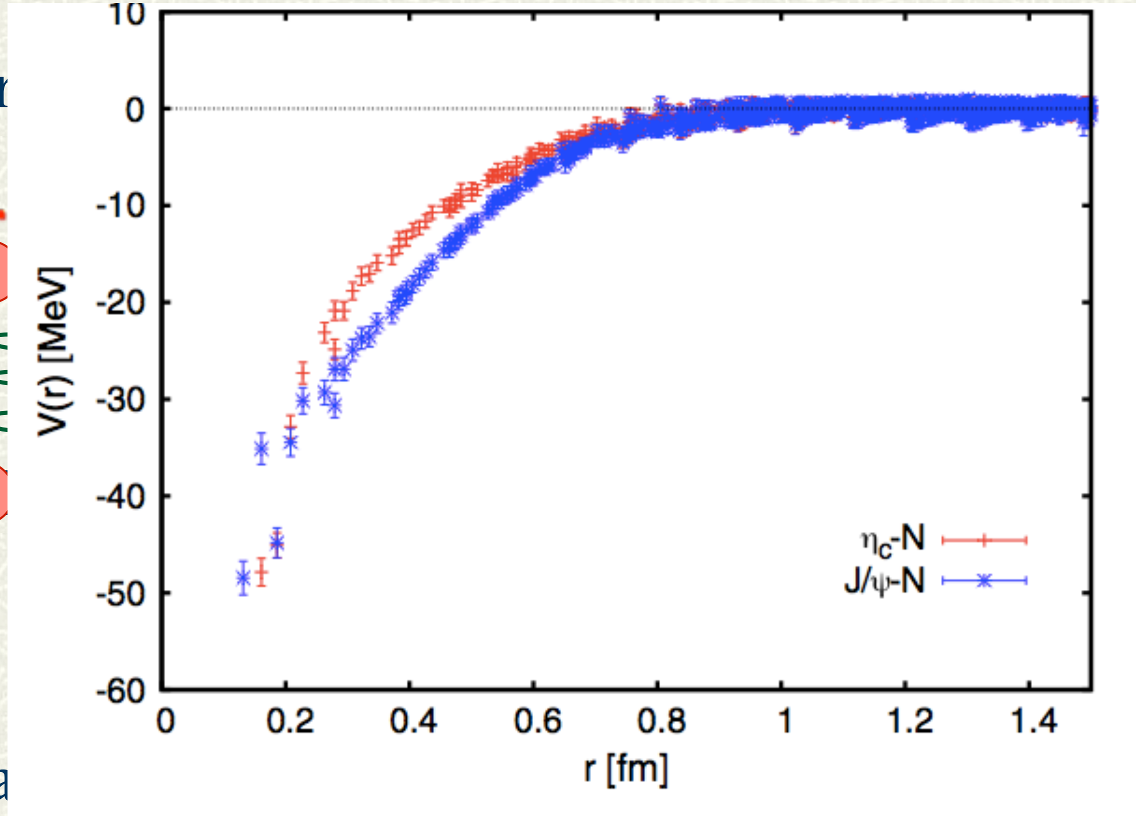
Color-van-der-Waals force (second order perturbation) is (weakly) attractive.

Lattice QCD (quenched) calculation:
T. Kawanai, S. Sasaki, PRD82, 091501 (2010)
shows attractive potential with screening at large distances.
This results favors J/ψ bound states in light nuclei.

Charmonium in Nuclei

Pure HQ hadrons have attr





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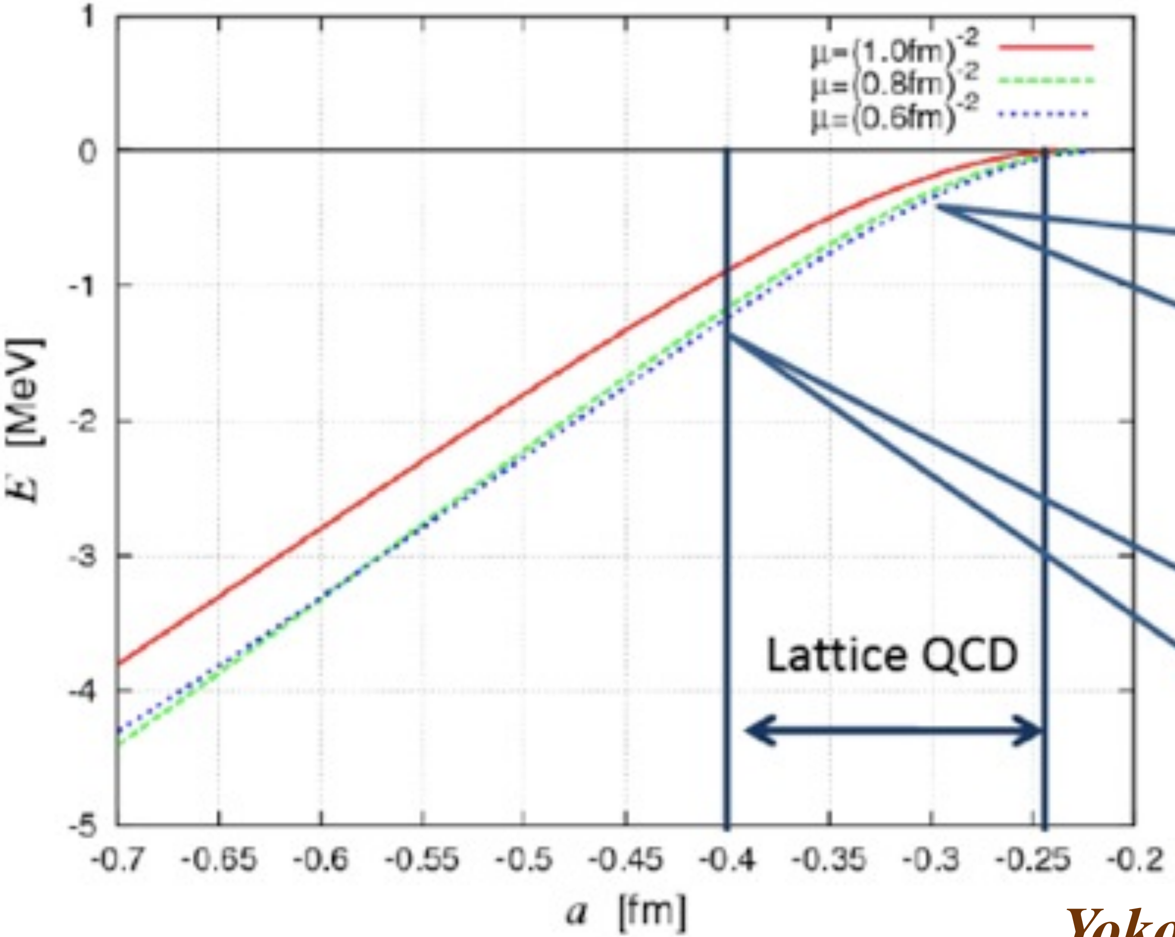
Charmonium in Nuclei

J/ψ in ^{4}He



$J/\psi -^4 He$ bound state is made when

$$a_{J/\psi N} \leq -0.24\text{fm} \quad (\mu = (1.0\text{fm})^{-2})$$
$$a_{J/\psi N} \leq -0.23\text{fm} \quad (\mu = (0.8\text{fm})^{-2})$$
$$a_{J/\psi N} \leq -0.22\text{fm} \quad (\mu = (0.6\text{fm})^{-2})$$

If $a_{J/\psi N} = -0.3\text{fm}$

$$E = -0.22\text{MeV} \ (\mu = (1.0\text{fm})^{-2})$$
$$E = -0.36\text{MeV} \ (\mu = (0.8\text{fm})^{-2})$$
$$E = -0.44\text{MeV} \ (\mu = (0.6\text{fm})^{-2})$$

If $a_{J/\psi N} \sim -0.4\text{fm}$

$$E = -1.03\text{MeV} \ (\mu = (1.0\text{fm})^{-2})$$
$$E = -1.18\text{MeV} \ (\mu = (0.8\text{fm})^{-2})$$
$$E = -1.29\text{MeV} \ (\mu = (0.6\text{fm})^{-2})$$

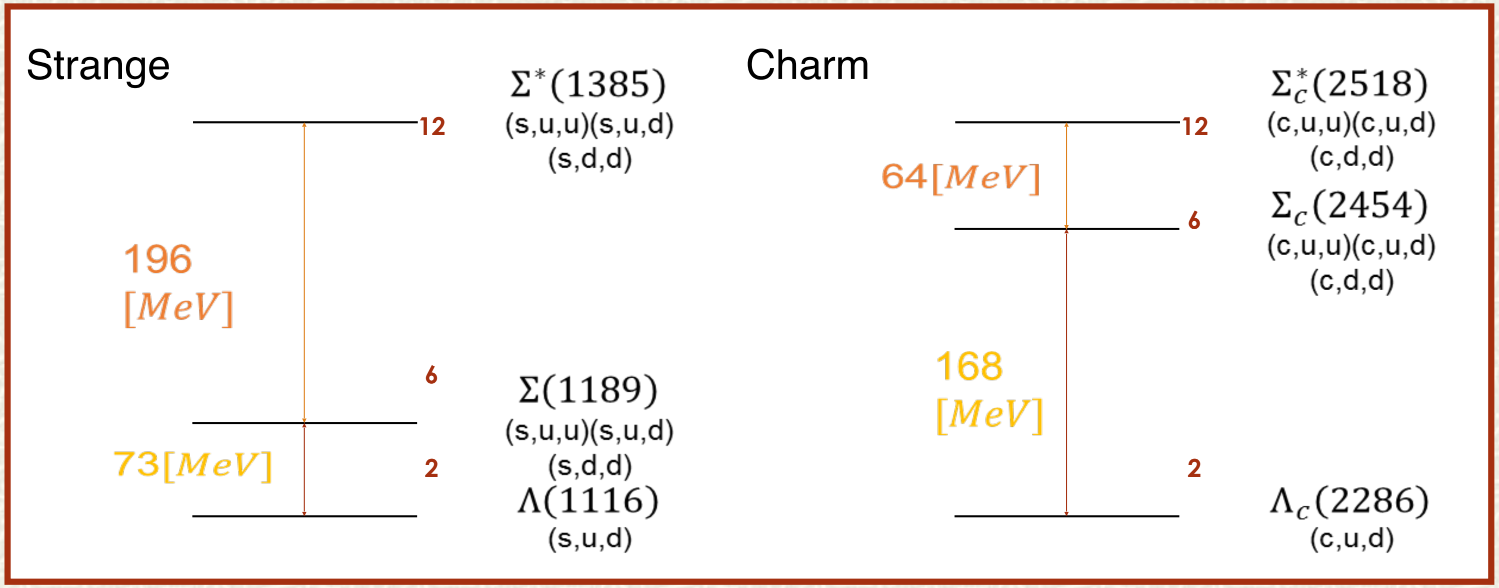
Yokota, Hiyama, MO, PTEP (2013)

Y_cN interaction

- Various approaches for Λ_cN interaction/Λ_c in matter
  - Lattice QCD T. Miyamoto (HAL-QCD) (2015)
  - QCD sum rule (finite density) K. Ohtani et al. (2017)
  - Chiral Effective Lagrangian approach
    Haidenbauer (2017)
  - Phenomenological Meson Exchange Model
    – SU(4): Tyapkin (1975), Dover, Kahana (1977), Bando, Nagata (1983)
    – HQ effective theory: Y.R. Liu, MO (2012), Gal et al. (2014),Maeda et al. (2016)
    – Mean field: Tsushima, Khanna (2003)

Heavy dibaryons

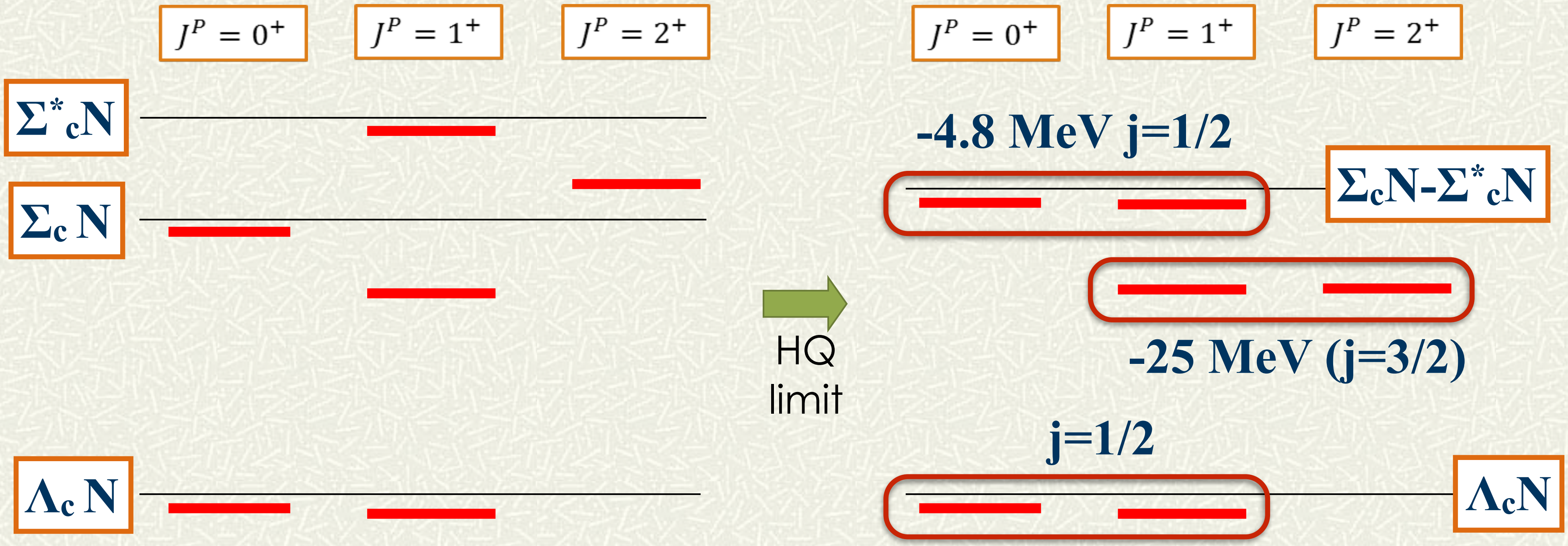
- Couplings between $\Sigma_c N$ and $\Sigma_c^* N$ channels are strong.



- Coupled channel calculation of $\Lambda_c N$ - $\Sigma_c N$ - $\Sigma_c^* N$ bound/ resonance states:
  S. Maeda, M. Oka, A. Yokota, E. Hiyama, Y.R. Liu, PTEP (2016) 023D02 and in preparation.

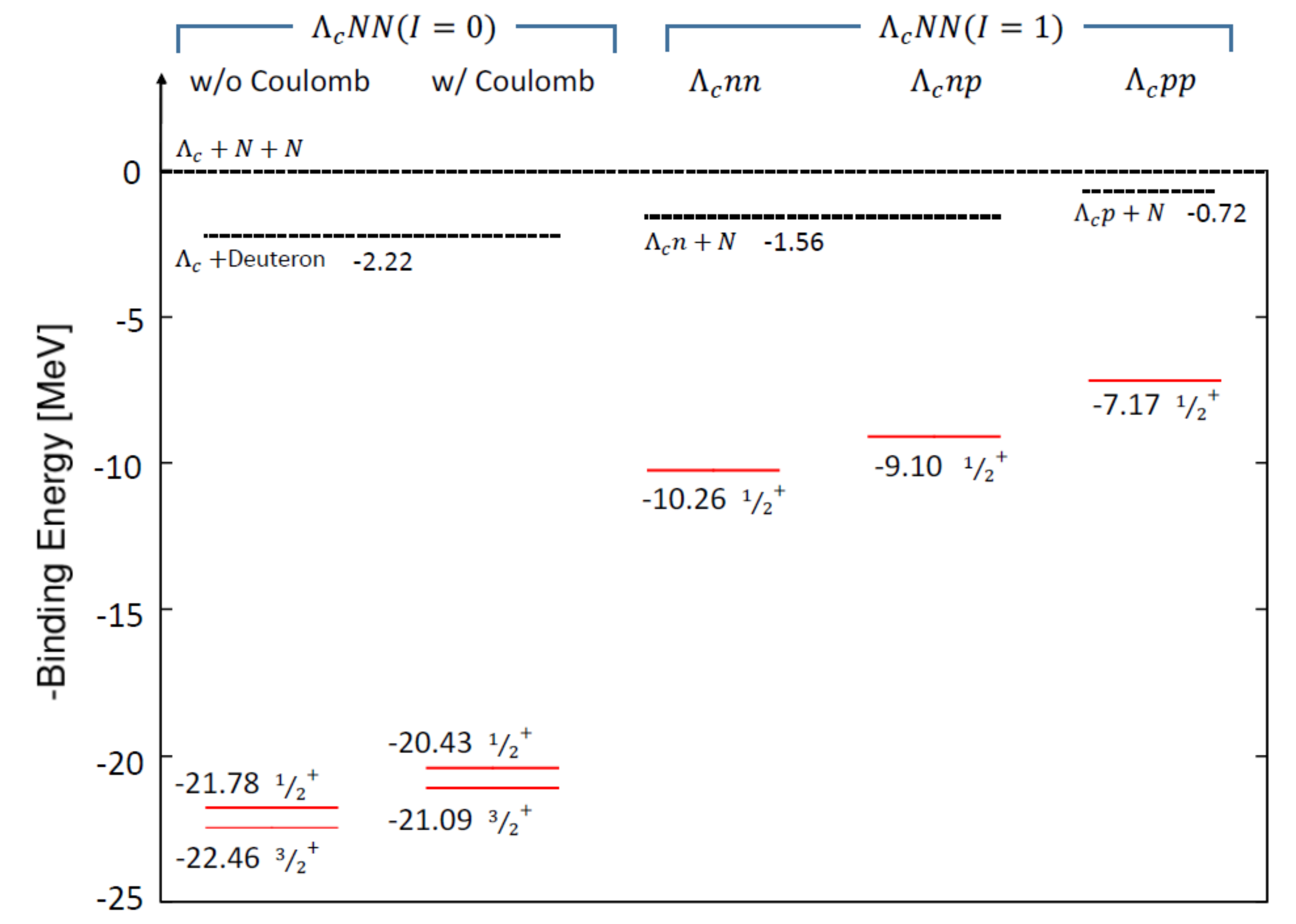
Charmed dibaryons

- **HQ doublets**
  A shallow bound state of Λ_c N with j=1/2
  A shallow (j=1/2) and deep bound (j=3/2) state of $\Sigma^{(*)}_c$ N.



S. Maeda et al.,
Prog. Theor. Exp. Phys. (2016) 023D02 and in preparation.

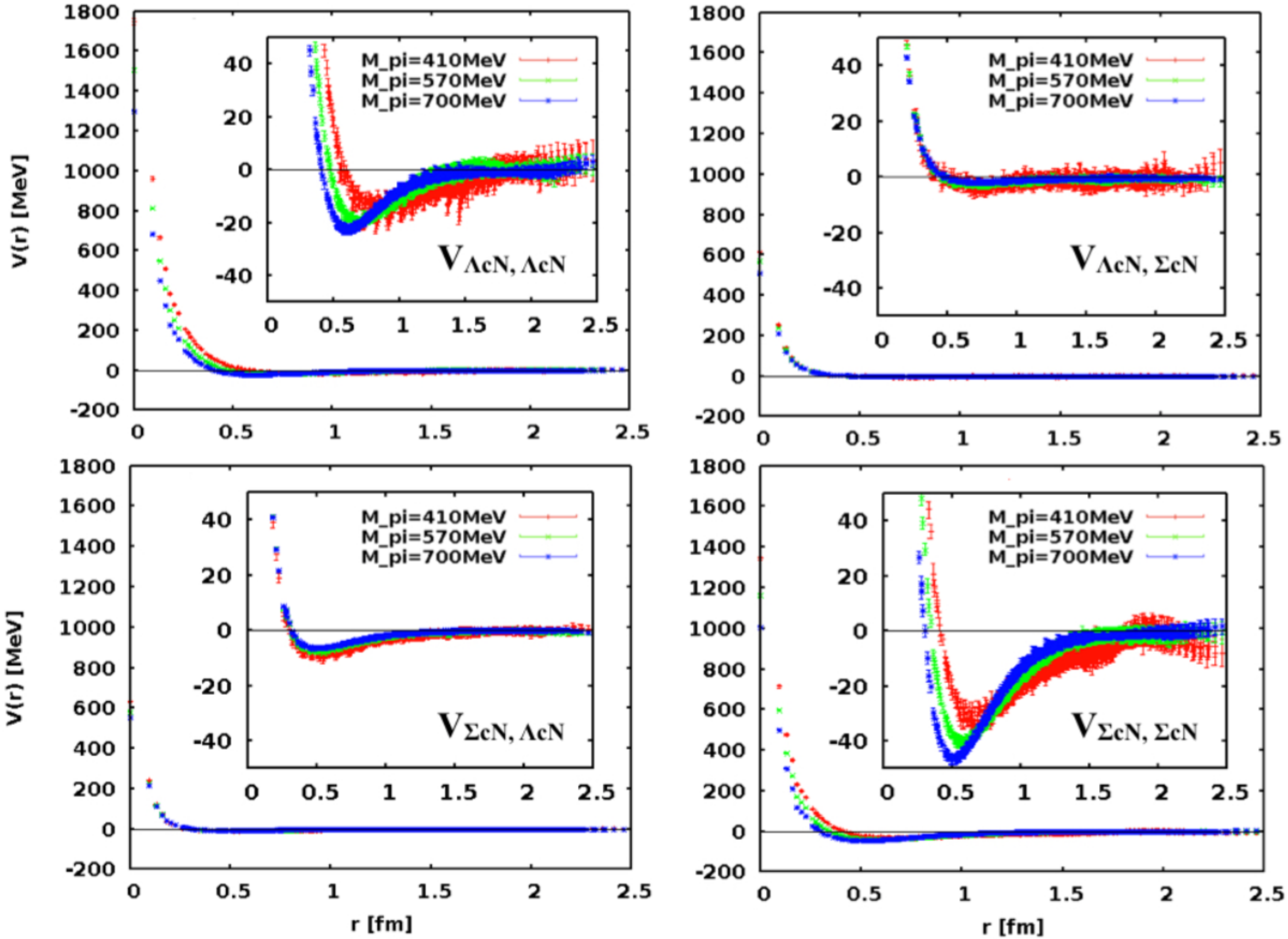
$\Lambda_c NN$ charm nuclei



M.Oka (Tokyo Tech. and JAEA)

T. Miyamoto (HAL QCD), PoS (LATTICE2016) 117

$\Lambda_c N$ -$\Sigma_c N$ coupled channel : I (J^P) = 1 (1^+)



Pion exchanges are still not fully included with large quark masses.

Λ_c in medium from QCD sum rules

QCD sum rules applied to Heavy baryons

E. V. Shuryak, Nucl. Phys. **B198**, 83 (1982)

E. Bagan et al., Phys. Lett. **B287**, 176 (1992)

. . .

In vacuum

Z.-G. Wang, Eur. Phys. J. **C71**, 1816 (2011)

K. Azizi, N. Er, H. Sundu, NP A960 (2017) 147, A962 (2017) 122

In nuclear matter

	in vacuum	in medium	in vacuum	in medium		
	λ_{Λ_c} [GeV^3]	$\lambda^*_{\Lambda_c}$ [GeV^3]	m_{Λ_c} [GeV]	$m^*_{\Lambda_c}$ [GeV]	$\Sigma^\nu_{\Lambda_c}$ [MeV]	$\Sigma^S_{\Lambda_c}$ [MeV]
K. Azizi et al.	0.044 ± 0.012	0.023 ± 0.007	2.235 ± 0.244	1.434 ± 0.203	327 ± 98	-801
Z. G. Wang	0.022 ± 0.002	0.021 ± 0.001	$2.284^{+0.049}_{-0.078}$	$2.335^{+0.045}_{-0.072}$	34 ± 1	51

K. Ohtani, K-J. Araki, MO, arXiv:1704.04902 [hep-ph]

⇒
- α_s corrections (NLO) S. Groote, et al., Eur. Phys. J. C58, 355 (2008)
- dimension 8 condensates
- parity projection

Λ_c in medium from QCD sum rules

Correlation function:

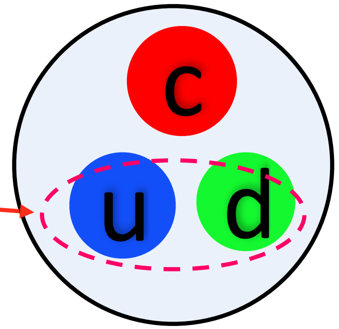
$$\Pi(q) = i\int e^{iqx}\langle\Psi_0(\rho,u^\mu)|T[J_{\Lambda_c}(x)\overline{J}_{\Lambda_c}(0)]|\Psi_0(\rho,u^\mu)\rangle d^4x$$

$$= \not{q}\,\Pi_1(q_0,|\vec{q}|) + \Pi_2(q_0,|\vec{q}|) + \not{u}\,\Pi_3(q_0,|\vec{q}|)$$

$\Psi_0(\rho,u^\mu)$: Ground state of Nuclear medium u^μ velocity of medium

Λ_c interpolating operator: $J_{\Lambda_c} = \epsilon^{abc}(u^{Ta}C\gamma_5 d^b)c^c$

Scalar 0^+ diquark



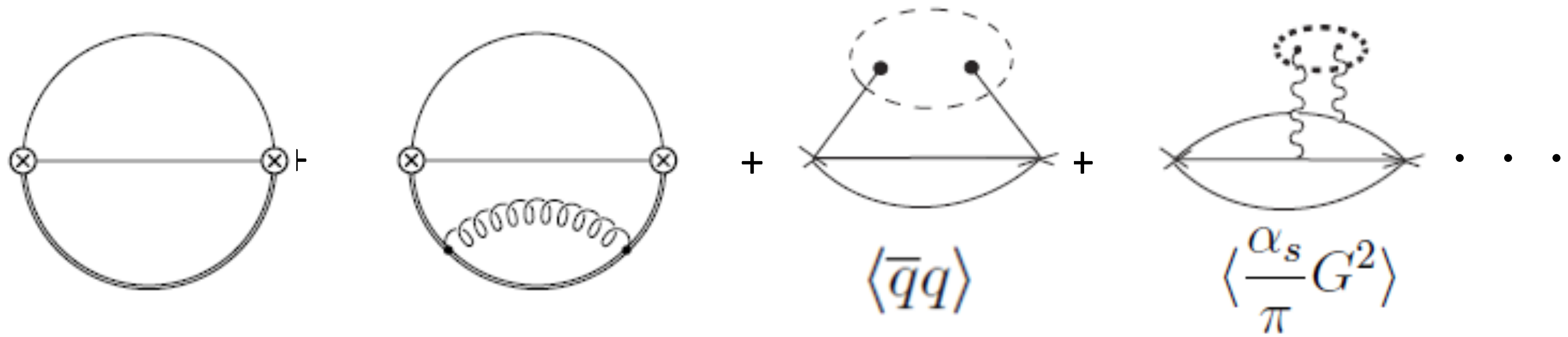
Parity Projection + Gaussian sum rule

$$G_{OPE}(\tau) = \int_0^\infty \frac{1}{\sqrt{4\pi\tau}}\exp\left(-\frac{(q_0^2-m_c^2)^2}{4\tau}\right)\rho(q_0)dq_0$$

Λ_c in medium from QCD sum rules

Operator Product Expansion

$G_{OPE}(\tau)$ =



Quark, Gluon Condensates contain non-perturbative (long-distance) contribution

$\langle \bar{q}q \rangle_0$ $\langle \frac{\alpha_s}{\pi} G^2 \rangle_0$ $\langle \bar{q}q\bar{q}q \rangle_0$ $\cdots$ in vacuum

Effects of the medium are taken into account as density dependences of the condensates.

$\langle \bar{q}q \rangle_m$ $\langle \frac{\alpha_s}{\pi} G^2 \rangle_m$ $\langle \bar{q}q\bar{q}q \rangle_m$ $\cdots$ in medium

Linear density dependence

$$\langle \bar{q}q \rangle_m = \langle \bar{q}q \rangle_0 + \rho \frac{\sigma_N}{2m_q}$$

$$\langle q^\dagger q \rangle_m = \rho \frac{3}{2}$$

$\cdots$

Λ_c in medium from QCD sum rules

Density dependence of the four-quark condensate

Factorization (F-type)

$$\text{“}\langle \overline{q}q\overline{q}q\rangle_m\text{”} = -\frac{1}{6}\left(\langle \overline{q}q\rangle_m^2 + \langle q^\dagger q\rangle_m^2\right)$$
$$= -\frac{1}{6}\left(\langle \overline{q}q\rangle_0^2 + \rho\frac{\sigma_N}{m_q}\langle \overline{q}q\rangle_0 + \left(\frac{\sigma_N^2}{4m_q^2} + \frac{9}{4}\right)\rho^2\right)$$

~ 10

Factorization predicts a strong density dependence.

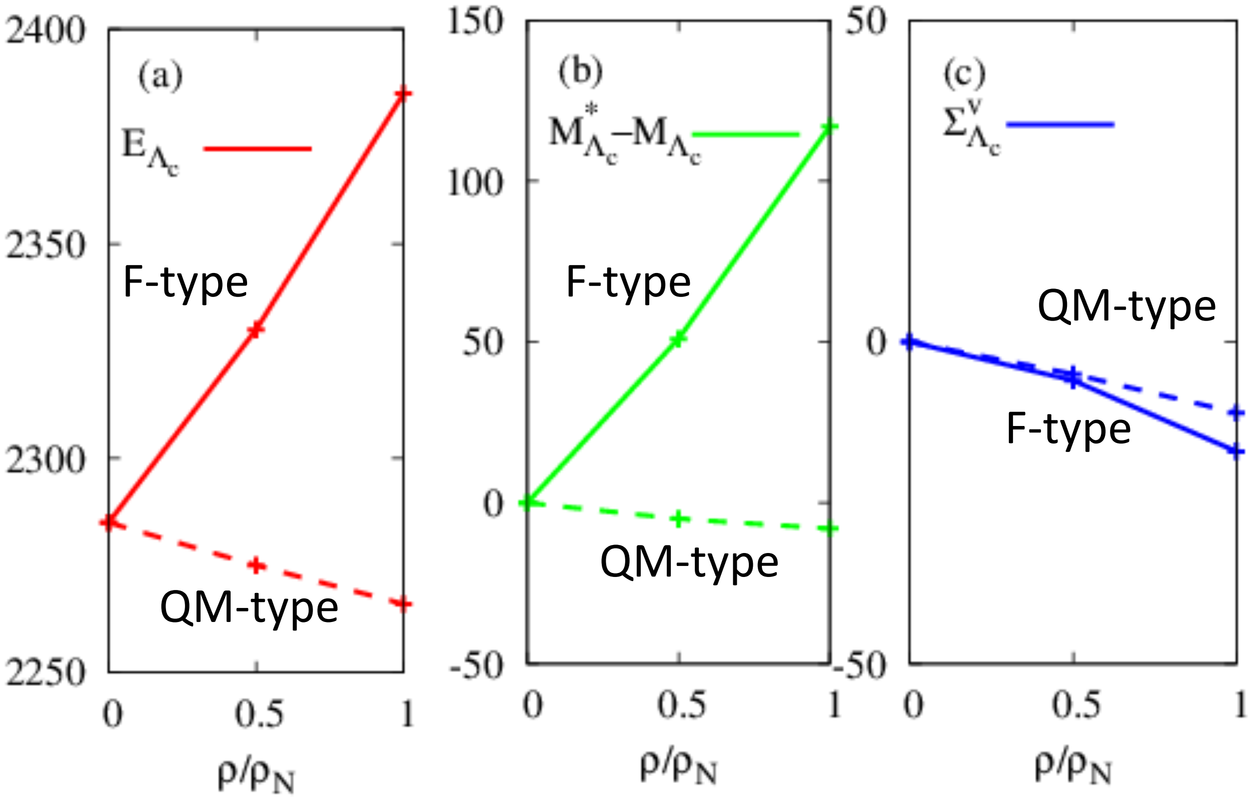
Model calculation in Perturbative chiral quark model (QM-type)

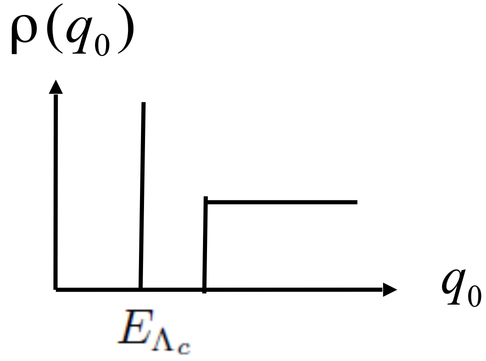
E.G. Drukarev, et al., Phys. Rev. D **68** 054021 (2003).
R. Thomas, T. Hilger, and B. Kampfer, Nucl. Phys. **A795**, 19 (2007).

$$\text{“}\langle \overline{q}q\overline{q}q\rangle_m\text{”} = -\frac{1}{6}\langle \overline{q}q\rangle_0^2 - \rho\frac{1}{4}0.935\langle \overline{q}q\rangle_0 + \mathcal{O}(\rho^2)$$

The coefficient of the linear-density term is much smaller.

Λ_c in medium from QCD sum rules





$$E_{\Lambda_c} = \Sigma_v + \sqrt{M^{*2}_{\Lambda_c} + \vec{q}^2}$$

Density dependence of the 4-quark condensate in the factorization scheme seems too strong.

The perturbative chiral quark model gives milder dependence.
At the normal nuclear density $\Delta E_{\Lambda_c} \approx -20\mathrm{MeV}$

Summary

- **We are in the era of new discoveries and development of heavy hadron spectroscopy in vacuum and also in matter.**
- **New forms of atomic nuclei with heavy flavor hadrons are very interesting. Heavy hadrons can probe the properties of hadronic matter.**
- **Heavy hadrons in matter provide us with information of the heavy hadron structure.**

Sincere thanks to

Qiang Zhao

Wei-Hong Liang

and All the members of LOC

for wonderful hospitality.

As a member of IAC, I am honored to announce

APFB2020

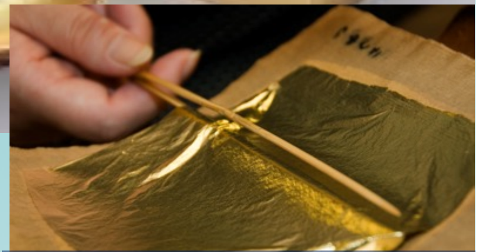
APFB2020

in Kanazawa, Japan

Chair: Emiko Hiyama (RIKEN/Kyushu Univ.)
Vice-Chair: Atsushi Tamii (RCNP, Osaka Univ.)

Kaga Yuzen Dyeing of Fabric

Tea Ceremony



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Tea Ceremony

Kaga Yuzen Dyeing of Fabric

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See you in Kanazawa, in 2020