Part 2. Charm quark in quark matter

Content of Part 2

1. Heavy quark in quark matter
2. “Kondo phase” of heavy quark matter

   S.Y., K. Suzuki, K. Itakura, arXiv:1604.09229 [hep-ph]
3. Case of single heavy quark

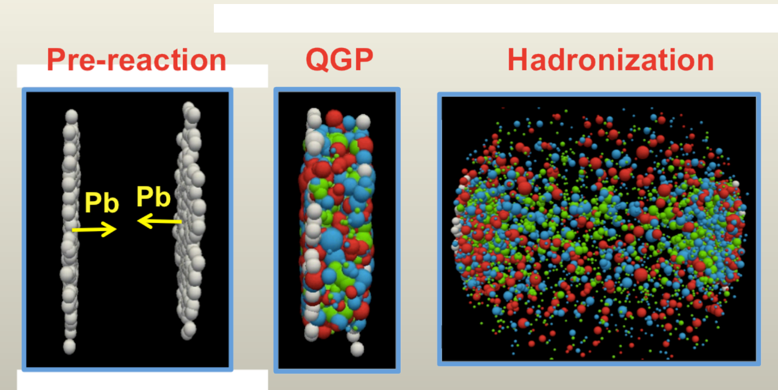
   S.Y., arXiv:1608.06450 [hep-ph]

1. Heavy quark in quark matter

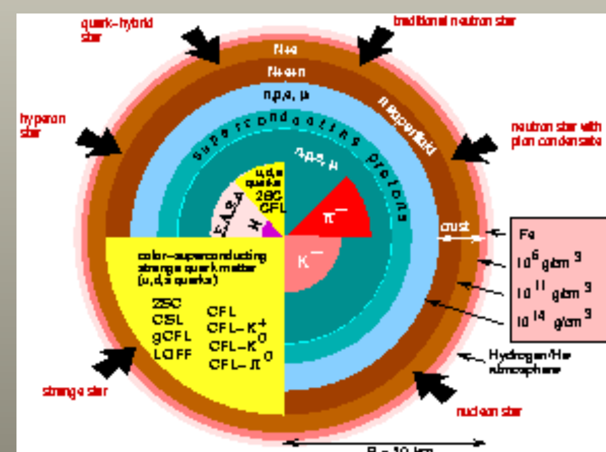
Charm quark in quark matter

Do charm/bottom quarks exist in quark matter?

① Charm quark production at initial (gluon) hard scatterings in relativistic heavy ion collisions (ex. J-PARC).

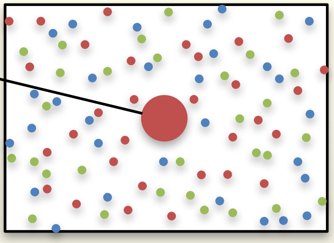


② Flavor change (ex. s→c) by high energy neutrinos in strange quark matter in neutron stars.



2. "Kondo phase" of heavy quark matter

Lagrangian

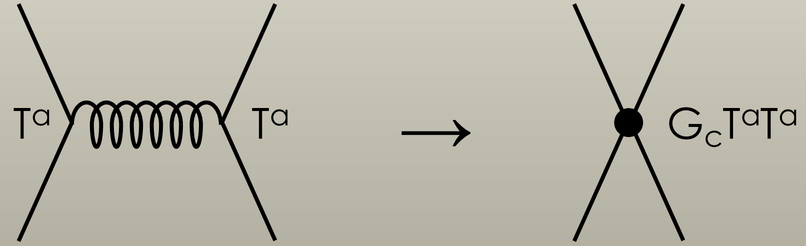


Light quark (u,d,s) ψ and heavy quark (c) Ψ

$$\mathcal{L} = \bar{\psi} i \partial\!\!\!/ \psi + \mu \bar{\psi} \gamma^0 \psi + \bar{\Psi} i \partial\!\!\!/ \Psi - m_Q \bar{\Psi} \Psi$$
$$- G_c \sum_a \left(\bar{\psi} \gamma^\mu T^a \psi \right) \left(\bar{\Psi} \gamma_\mu T^a \Psi \right) ,$$

Cf. NJL for light quark
$G_c=(9/2)2.0/\Lambda^2$
$\Lambda=0.65$ [GeV]

① Color-current interaction



Cf. S.Y., K. Sudoh, PRC88, 015201 (2013)
K. Hattori, K. Itakura, S. Ozaki, S.Y., PRD92, 065003 (2015)

② N_f flavor for light quark

$$\psi = (\psi^1, \ldots, \psi^{N_f})^{\mathrm{t}}$$

③ Heavy quark limit for charm quark $p^\mu = m_Q v^\mu + k^\mu$ $v^\mu v_\mu = 1$

$$\Psi \to \Psi_v = \frac{1}{2}(1+v\!\!\!/) e^{i m_Q v \cdot x} \Psi$$

← Heavy Quark Effective Theory
Cf. "Heavy Quark Physics", V. A. Manohar and M. B. Wise

2. "Kondo phase" of heavy quark matter

S.Y., K. Suzuki, K. Itakura, arXiv:1604.09229 [hep-ph]

Mean-field approximation

① Mean-field: mixing between light quark and heavy quark

$$(\bar{\psi}^i_\alpha \Psi_{v\delta})(\bar{\Psi}_{v\gamma}\psi^i_\beta) \to \langle \bar{\psi}^i_\alpha \Psi_{v\delta}\rangle \bar{\Psi}_{v\gamma}\psi^i_\beta + \langle \bar{\Psi}_{v\gamma}\psi^i_\beta\rangle \bar{\psi}^i_\alpha \Psi_{v\delta} - \langle \bar{\psi}^i_\alpha \Psi_{v\delta}\rangle\langle \bar{\Psi}_{v\gamma}\psi^i_\beta\rangle$$

i=light flavor; α,β,γ,δ=Dirac indices

↓

② Gap (color singlet)

$$\Delta^i_{\delta\alpha} \equiv \frac{G_c}{2}\langle \bar{\psi}^i_\alpha \Psi_{v\delta}\rangle \quad \to \quad \Delta^i_{\delta\alpha} = \Delta^i \left(\tfrac{1+\gamma_0}{2}(1-\hat{k}\cdot\vec{\gamma}) \right)_{\delta\alpha}$$

↓

③ Mean-field Lagrangian

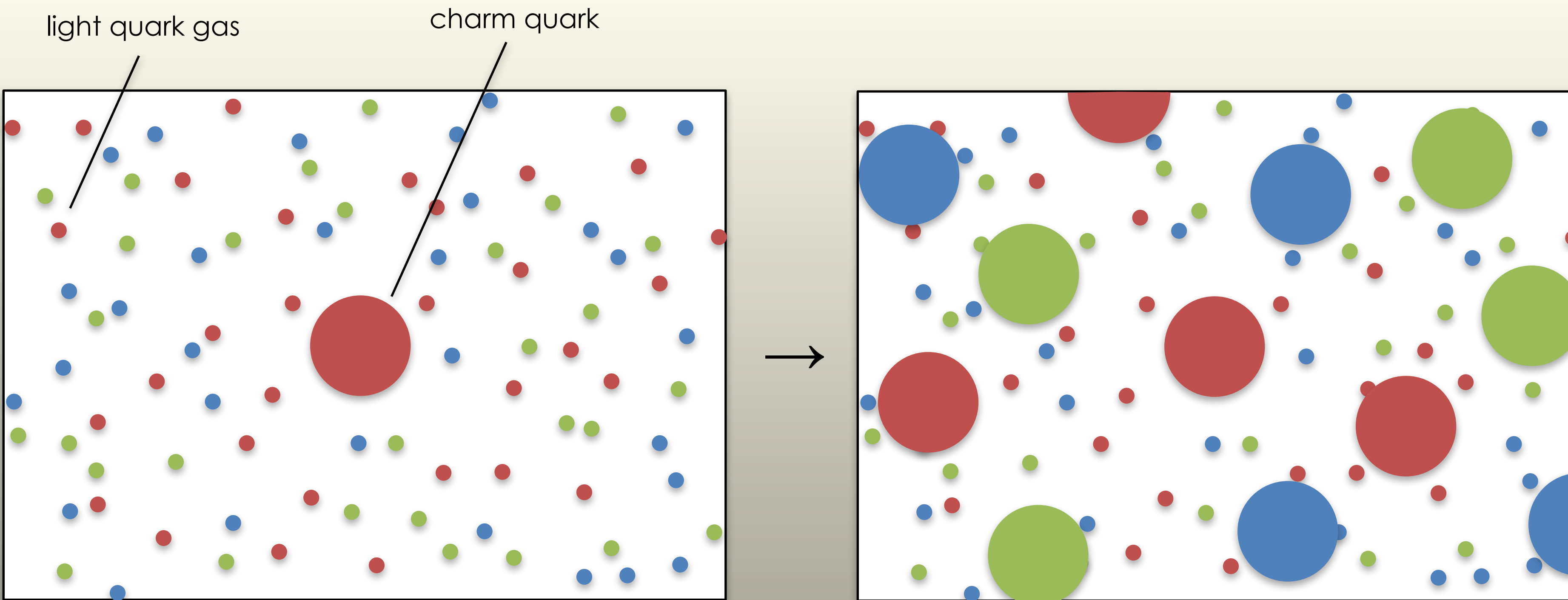
Lagrange multiplier for heavy quark density n_Q

$$\mathcal{L}^{\mathrm{MF}} = \bar{\psi}(\not{k} + \mu\gamma^0)\psi + \bar{\Psi}_v v\cdot k \Psi_v - \lambda(\Psi^\dagger_v \Psi_v - n_Q)$$
$$+ \sum_i \Delta^i \bar{\Psi}_v \frac{1+\gamma_0}{2}\left(1+\hat{k}\cdot\vec{\gamma}\right)\psi^i$$
$$+ \sum_i \Delta^{i*}\bar{\psi}^i \left(1+\hat{k}\cdot\vec{\gamma}\right)\frac{1+\gamma_0}{2}\Psi_v - \sum_i \frac{8}{G_c}|\Delta^i|^2$$

2. "Kondo phase" of heavy quark matter

Charm quark density n_Q (λ)

S.Y., K. Suzuki, K. Itakura,
arXiv:1604.09229 [hep-ph]



single charm quark

many charm quarks distributed randomly
(No Fermi surface)

Breaking of translational invariance...

S.Y., arXiv:1608.06450 [hep-ph]

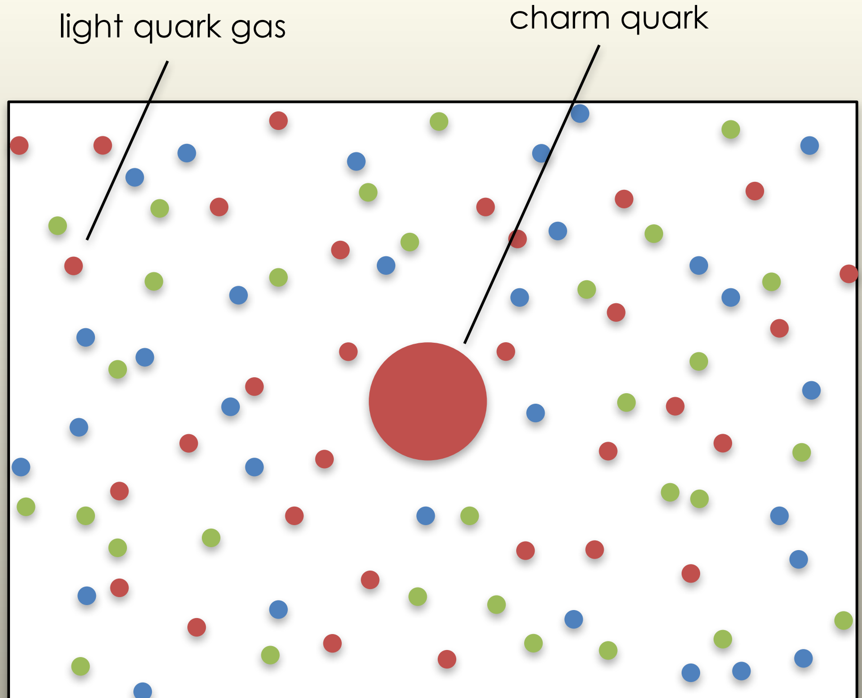
Conservation of translational invariance!

$$\Psi_v^\dagger(x)\Psi_v(x) = \sum_i \delta^{(3)}(\vec{x}-\vec{x}_i)$$

2. "Kondo phase" of heavy quark matter

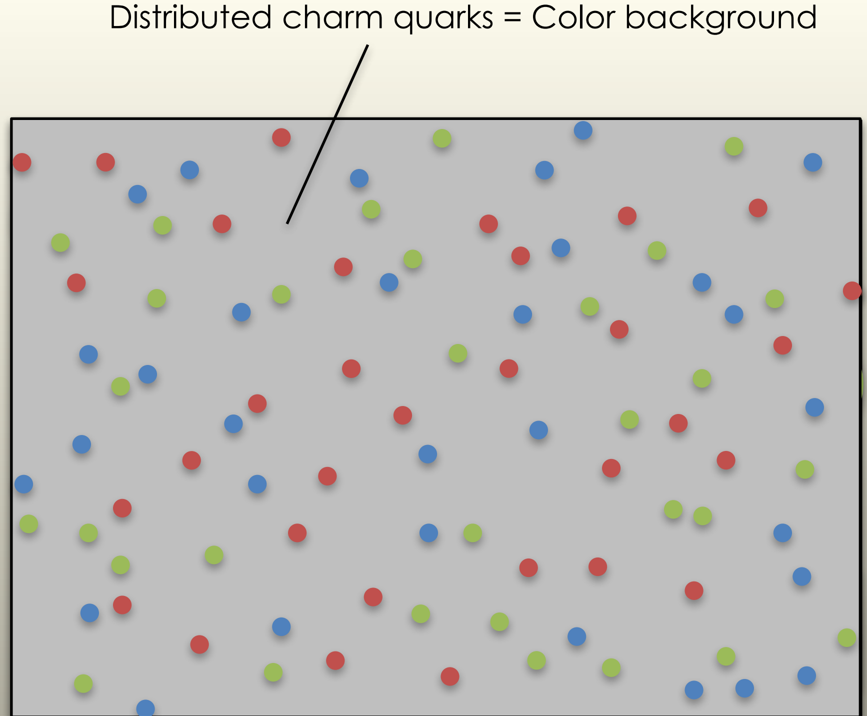
Charm quark density n_Q (λ)

S.Y., K. Suzuki, K. Itakura, arXiv:1604.09229 [hep-ph]



single charm quark

→



many charm quarks distributed randomly
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Breaking of translational invariance...

S.Y., arXiv:1608.06450 [hep-ph]

Conservation of translational invariance!

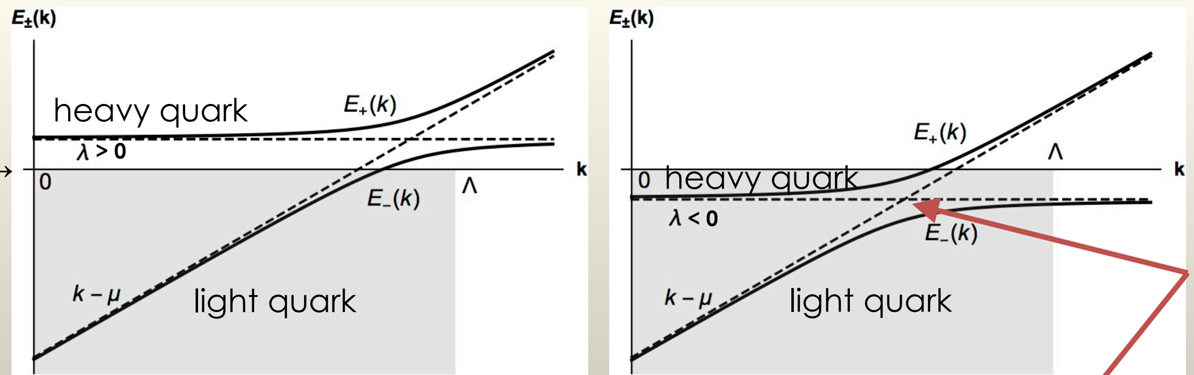
$$\Psi_v^\dagger(x)\Psi_v(x) = \sum_i \delta^{(3)}(\vec{x}-\vec{x}_i)$$

$$\rightarrow n_Q \equiv \overline{\sum_i \delta^{(3)}(\vec{x}-\vec{x}_i)}$$

2. "Kondo phase" of heavy quark matter

Energy-momentum dispersion & thermodynamic potential

Fermi surface →



"Gap" Δ

"mixing" mode $E_{\pm}(k) \equiv \frac{1}{2}\left(k+\lambda-\mu\pm\sqrt{(k-\lambda-\mu)^2+8N_f|\Delta|^2}\right)$,

"free" mode
$$\begin{cases} E(k) \equiv E_i = k-\mu & [i=1,\cdots,N_f-1], \\ \tilde{E}(k) \equiv \tilde{E}_i = -k-\mu & [i=1,\cdots,N_f], \end{cases}$$

$k = |\vec{k}|$

$\Delta^i = \Delta$

Thanks to Kanazawa-san's comments.

$$\Omega(T,\mu,\lambda;\Delta) = 2N_c\int_0^{\Lambda} f(T,\mu,\lambda;k)\frac{k^2\mathrm{d}k}{2\pi^2} + \frac{8N_f}{G_c}|\Delta|^2 - \lambda\, n_Q$$

$$f(T,\mu,\lambda;k) \equiv -\beta^{-1}\ln[(1+\mathrm{e}^{-\beta E_+(k)})(1+\mathrm{e}^{-\beta E_-(k)})(1+\mathrm{e}^{-\beta E(k)})^{N_f-1}]$$

① $\frac{\partial}{\partial\Delta^*}\Omega(T,\mu,\lambda;\Delta)=0$ ② $-\frac{\partial}{\partial\mu}\Omega(T,\mu,\lambda;\Delta)=n_q$ ③ $\frac{\partial}{\partial\lambda}\Omega(T,\mu,\lambda;\Delta)=0$

2. "Kondo phase" of heavy quark matter

S.Y., K. Suzuki, K. Itakura,
arXiv:1604.09229 [hep-ph]

Gap equation @λ=0

$$\Delta = \frac{1}{2} N_c G_c \int_0^{\Lambda} \frac{\Delta}{\sqrt{(k-\mu)^2 + 8N_f |\Delta|^2}} \frac{k^2 \mathrm{d}k}{2\pi^2}$$ @λ=0, T=0

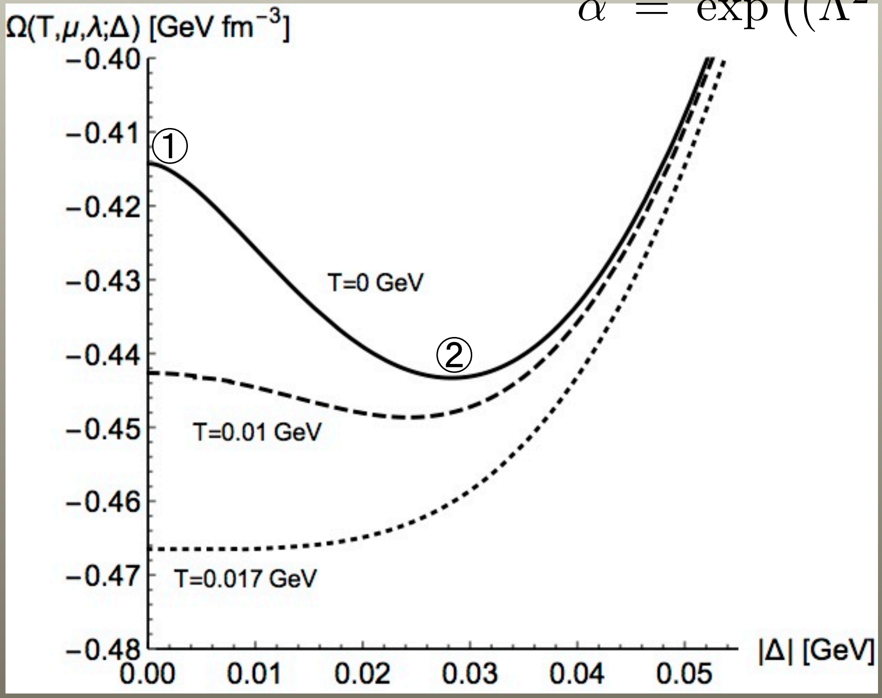
① trivial solution

$$|\Delta| = 0$$

② non-trivial solution

$$|\Delta| \simeq \alpha \sqrt{\frac{\mu(\Lambda-\mu)}{2N_f}} \exp\left(-\frac{2\pi^2}{N_c \mu^2 G_c}\right)$$

$$\alpha = \exp\left((\Lambda^2 + 2\Lambda\mu - 6\mu^2)/4\mu^2\right)$$



2. "Kondo phase" of heavy quark matter

"Kondo phase" @T=0

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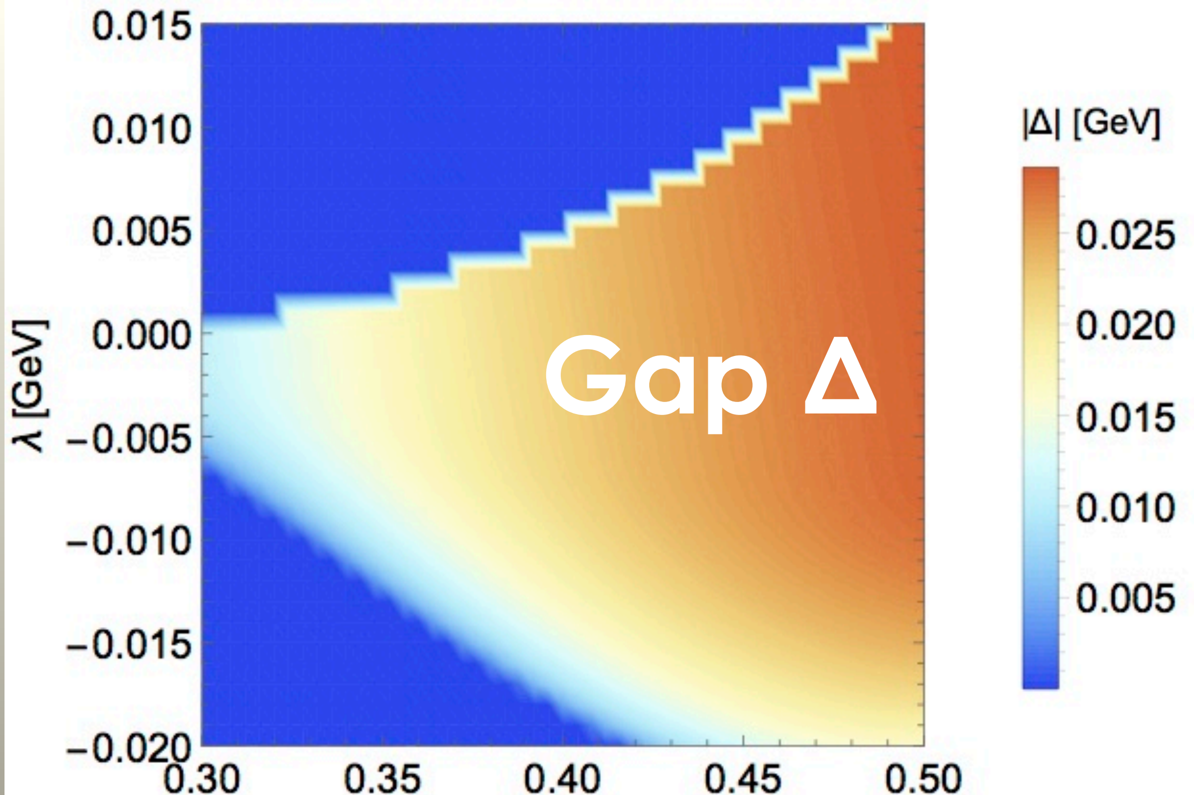
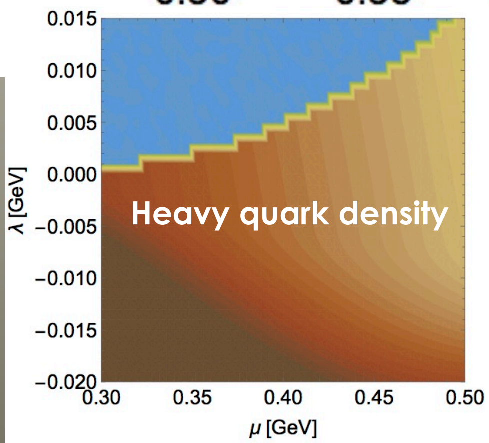
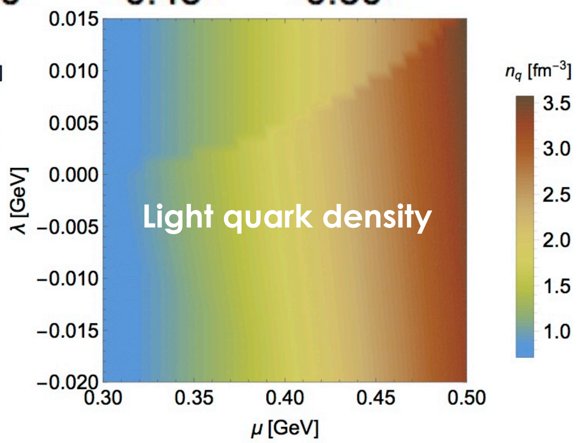
arXiv:1604.09229 [hep-ph]





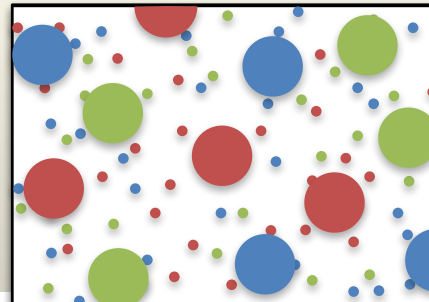


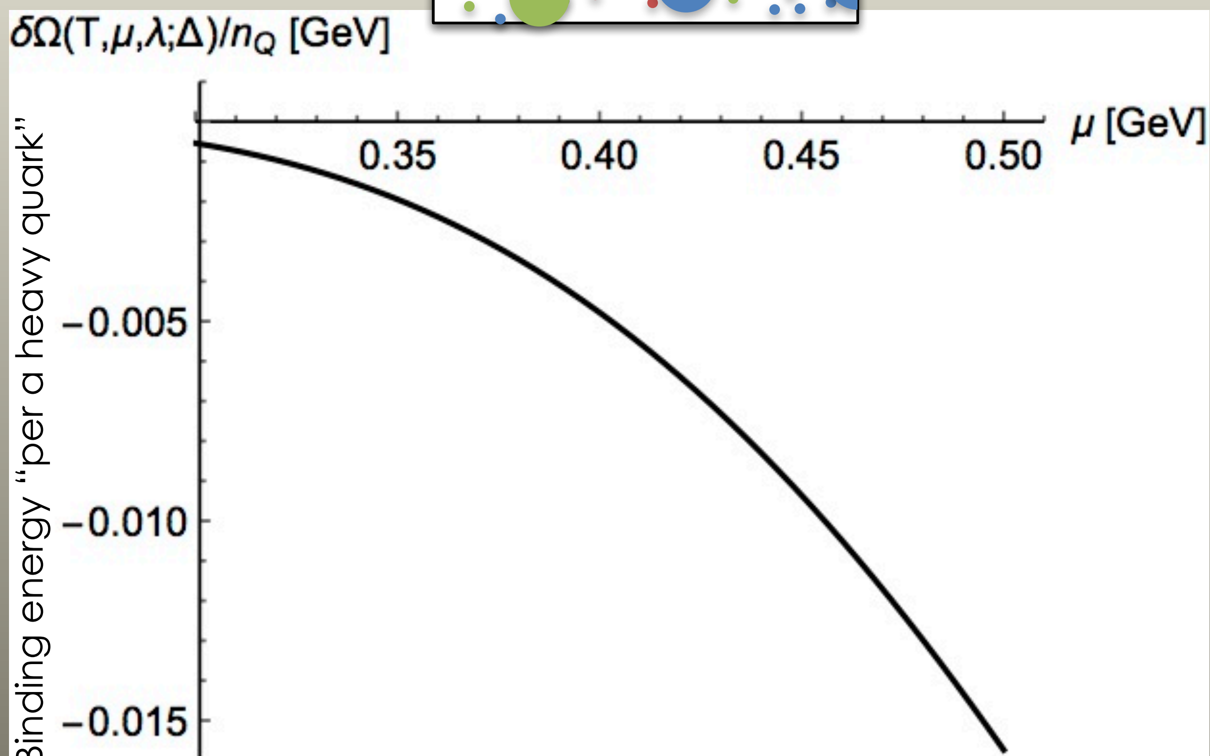
2. "Kondo phase" of heavy quark matter

S.Y., K. Suzuki, K. Itakura,
arXiv:1604.09229 [hep-ph]

Energy-gain "per a heavy quark"

$\delta\Omega(T,\mu,\lambda;\Delta)/n_Q$ with $\delta\Omega(T,\mu,\lambda;\Delta) = \Omega(T,\mu,\lambda;\Delta) - \Omega(T,\mu,\lambda;0)$





@λ=0, T=0

3. Case of single heavy quark

Energy-gain of a heavy quark

S.Y., arXiv:1608.06450 [hep-ph]

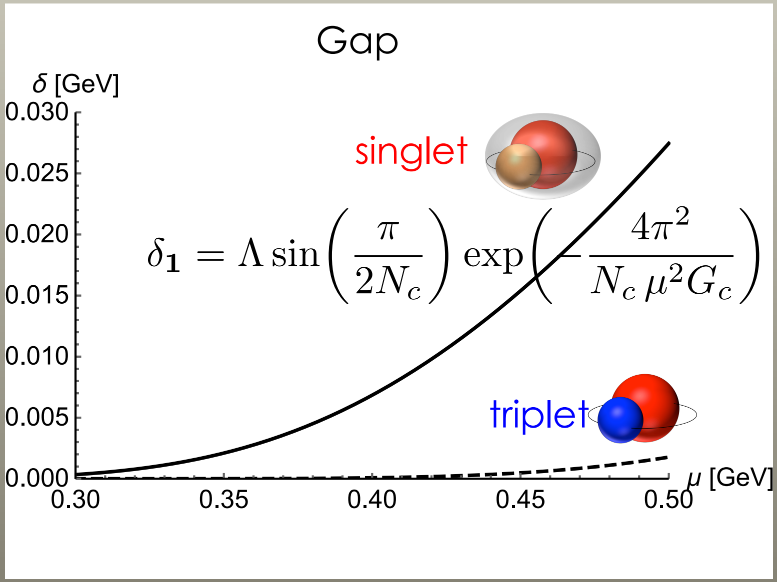
Energy: $\Omega_{\mathbf{1}}(\lambda, \Delta_{\mathbf{1}}) = -\frac{1}{\beta}\int_{-\infty}^{+\infty} \ln\left(1+e^{-\beta\omega}\right) 2N_c \rho_{\mathbf{1}}(\omega) d\omega + \frac{8N_f|\Delta_{\mathbf{1}}|^2}{G_c} V - \lambda$

Density of state: $\rho_{\mathbf{1}}(\omega) = -\frac{1}{\pi}\mathrm{Im}\frac{\partial}{\partial\omega}\ln\left(\omega_+ - \lambda - \sum_{\vec{q}} \frac{2N_f|\Delta_{\mathbf{1}}|^2}{\omega_+ + \mu - q}\right)$

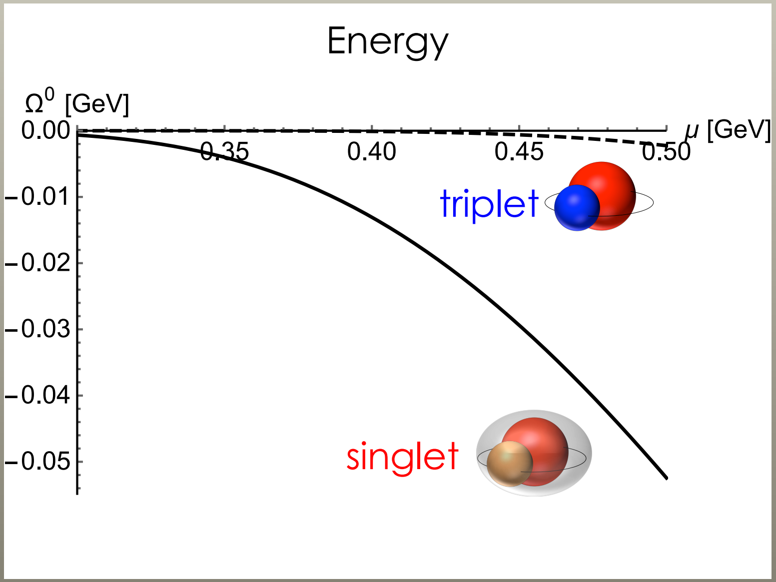
$$= \frac{1}{\pi}\frac{\delta_{\mathbf{1}}}{(\omega-\lambda_{\mathbf{1}})^2 + \delta_{\mathbf{1}}^2}$$

$$\sum_{\vec{q}} \frac{2N_f|\Delta_{\mathbf{1}}|^2}{\omega_+ + \mu - q} \simeq -\frac{iN_f}{\pi}\mu^2|\Delta_{\mathbf{1}}|^2 V \equiv -i\delta_{\mathbf{1}}$$

(approximation)



$$\delta_{\mathbf{1}} = \Lambda \sin\left(\frac{\pi}{2N_c}\right)\exp\left(-\frac{4\pi^2}{N_c\,\mu^2 G_c}\right)$$



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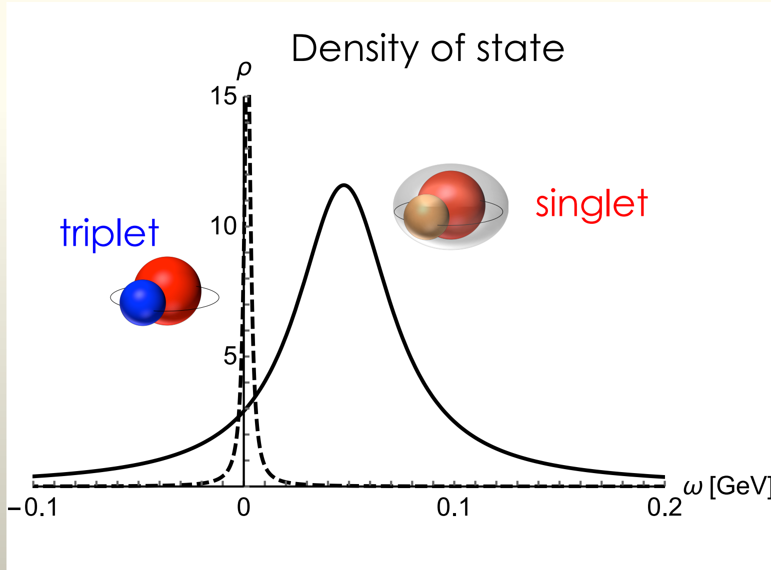
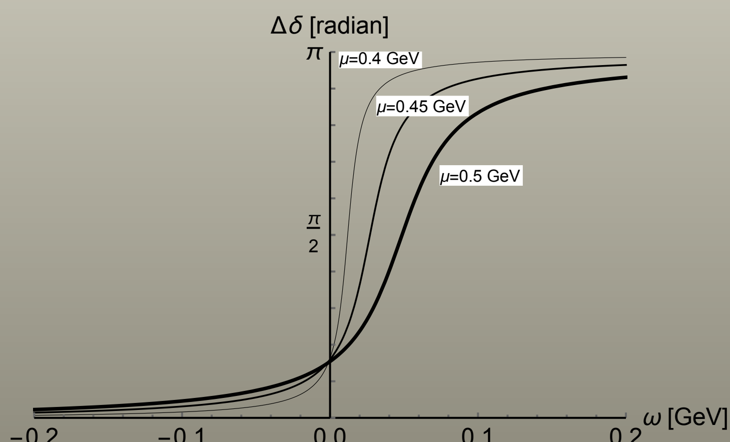
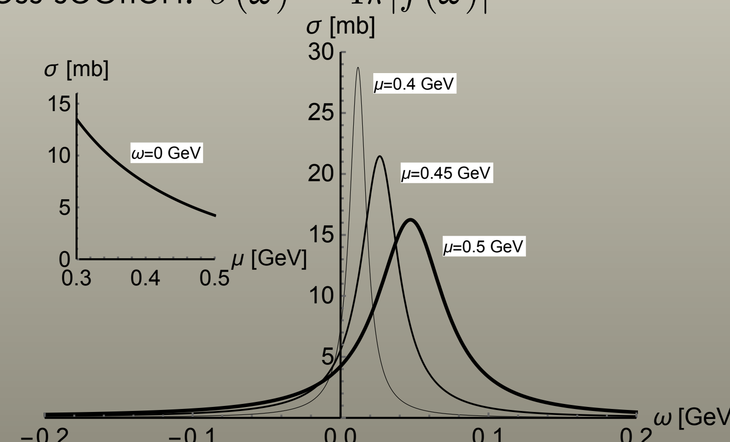


Phase shift: $\Delta\delta(\omega) = \pi \int_{-\Lambda}^{\omega} \rho_{\mathbf{1}}(\omega')\mathrm{d}\omega'$

Amplitude: $f(\omega) = e^{i\Delta\delta(\omega)} \sin\Delta\delta(\omega)/k$

Cross section: $\sigma(\omega) = 4\pi |f(\omega)|^2$





Comparable (strongly correlated system)

Mean free path: $\tau \simeq (\sigma\, n_q/N_f)^{-1}$

$\tau \simeq 1.3 - 0.91$ fm for $\mu = 0.3 - 0.5$ GeV

Mean distance:

$\ell \simeq n_q^{-1/3} = 0.96 - 0.58$ fm

Conclusion of Part 1

① We study the Kondo effect of $\bar{D}s/\bar{D}s^*$ meson

$\bar{D}s/\bar{D}s^*$ meson in nuclear matter

x HQS interaction

= "Kondo resonance"

nucleon in the ground state.

Future works:

1. Application to *realistic* $\bar{D}s/\bar{D}s^*$ meson-nucleon interaction.
2. Application to other heavy hadrons.
3. Observables and reactions for experiments.
4. etc.

Conclusion of Part 2

① We study Kondo effect by color exchange for charm quark in quark matter.

② The color-current interaction is considered.

③ It leads to a nontrivial ground state with mixing between light quark and heavy quark ("Kondo phase").

Future prospects:
1. Realization in QCD phase diagram.
2. Observables in experiments.
3. Comparison to condensed matter physics. etc.

Related references

HQS doublet/singlet in exotic hadrons and nuclei

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$\bar{D}^{(*)}N$, $\bar{D}^{(*)}NN$ hadronic molecules

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