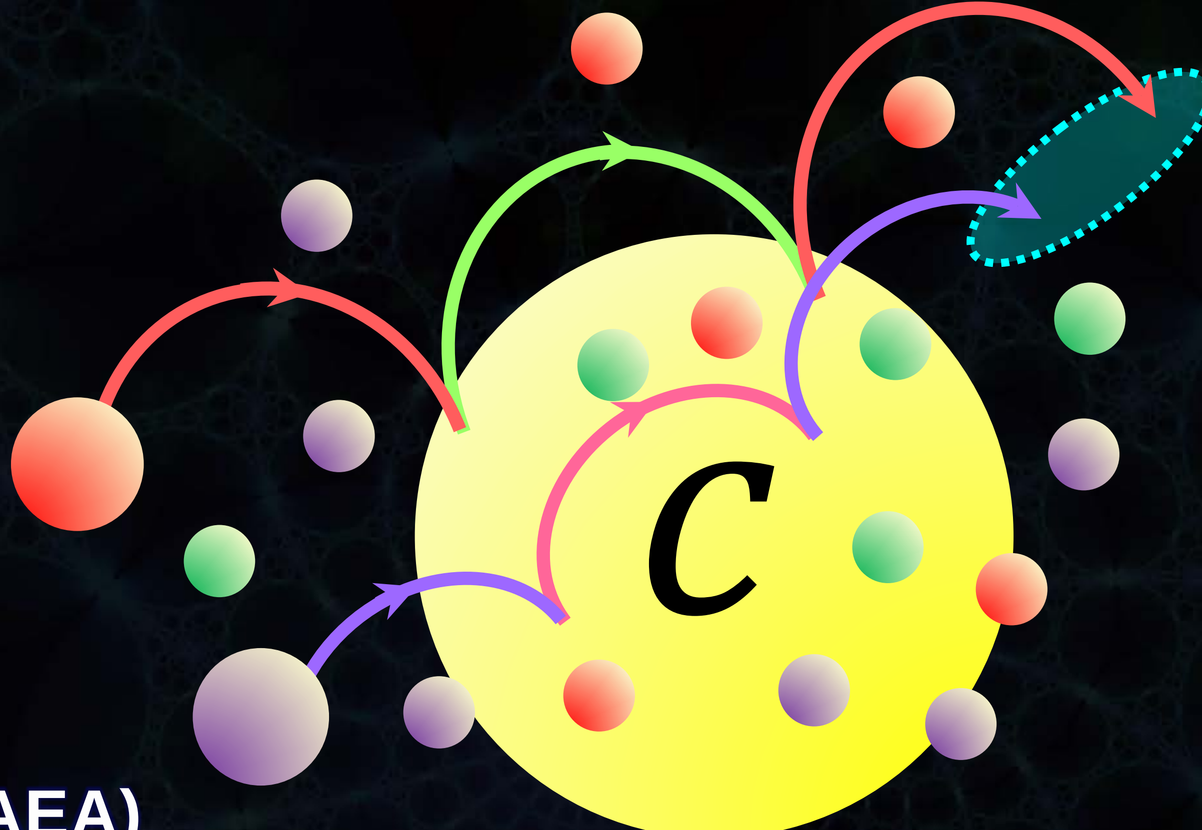
Quarks and Compact Stars (QCS2019)

A new phase and exciton modes in QCD Kondo effect

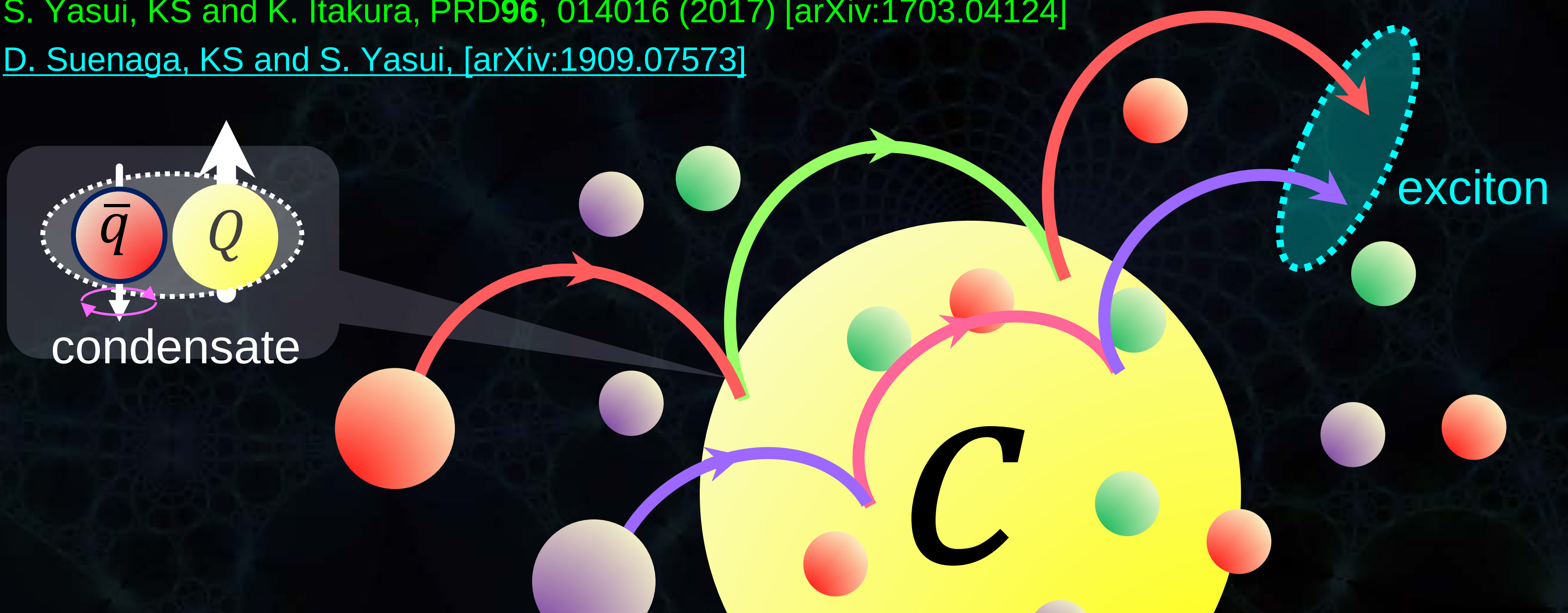


Kei Suzuki (JAEA)

Ref) D. Suenaga, K. Suzuki and S. Yasui, arXiv:1909.07573

Contents

1. QCD Kondo effect
   S. Yasui and K. Sudoh, PRC**88**, 135301 (2013) [arXiv:1301.6830]
   K. Hattori, K. Itakura, S. Ozaki and S. Yasui, PRD**92**, 065003 (2015) [arXiv:1504.07619]
2. QCD Kondo phase (Kondo condensate)
   S. Yasui, KS and K. Itakura, NPA**983**, 90 (2019) [arXiv:1604.07208]
3. QCD Kondo excitons
   S. Yasui, KS and K. Itakura, PRD**96**, 014016 (2017) [arXiv:1703.04124]
   D. Suenaga, KS and S. Yasui, [arXiv:1909.07573]



(Original) Kondo problem

At low temperature, the electrical resistance of a metal is enhanced by a heavy-impurity effect

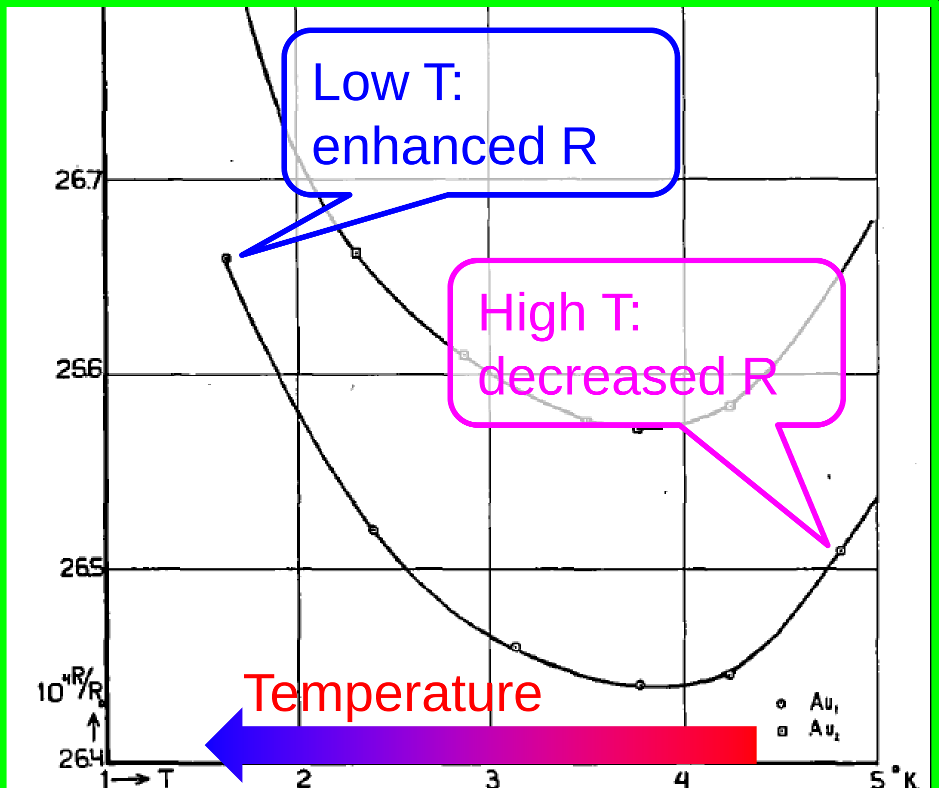
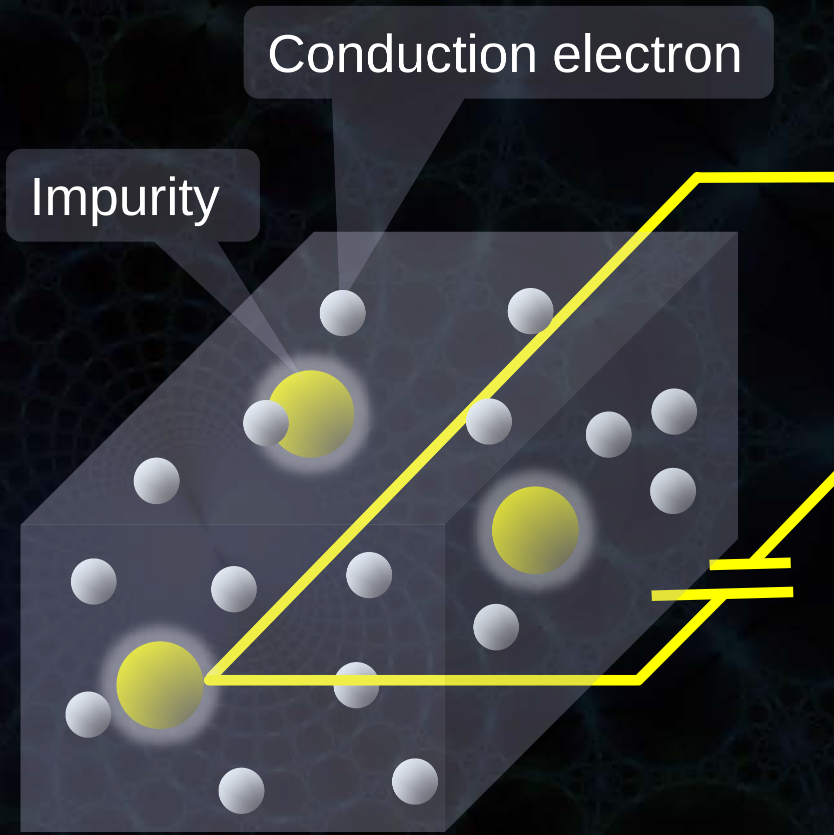
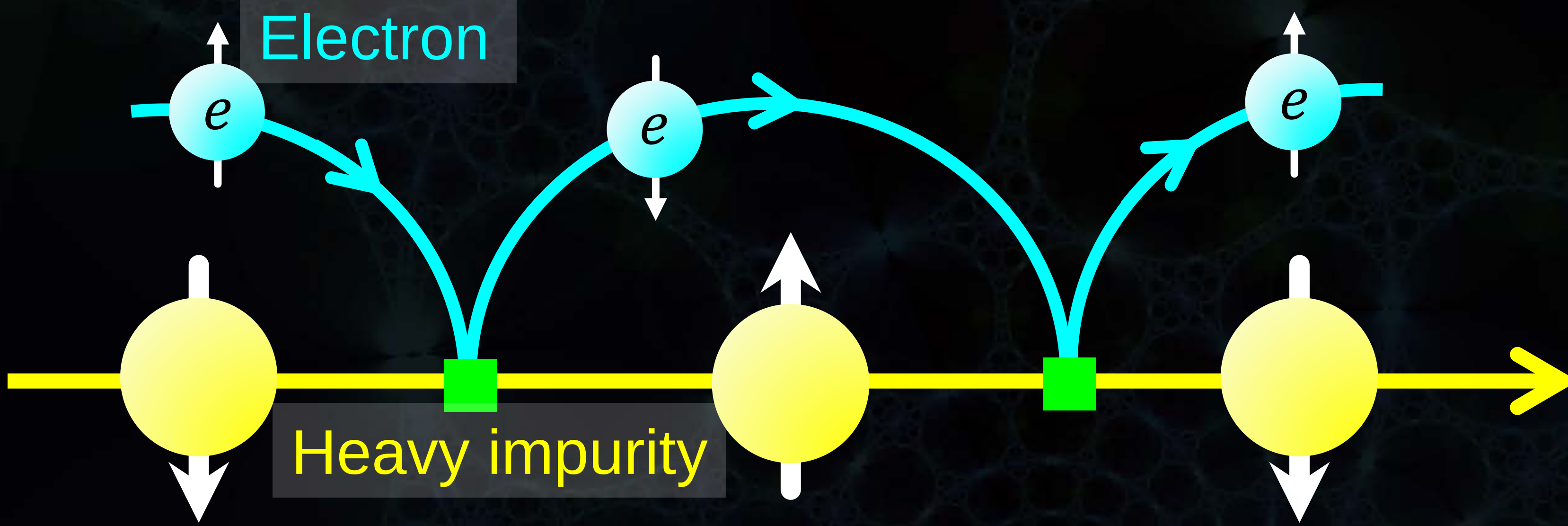


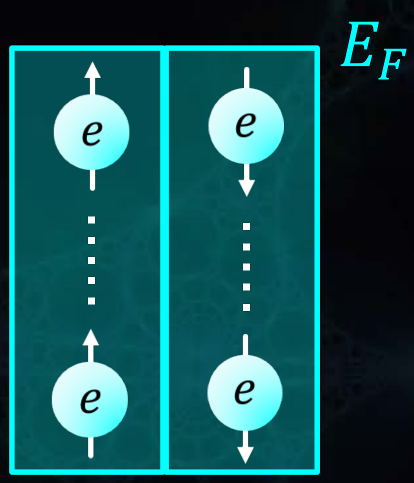
Fig. 1. Resistance of *Au* between 1°K. and 5°K.



J. Kondo, PTP32, 37 (1964)

Kondo effect (for electrons)



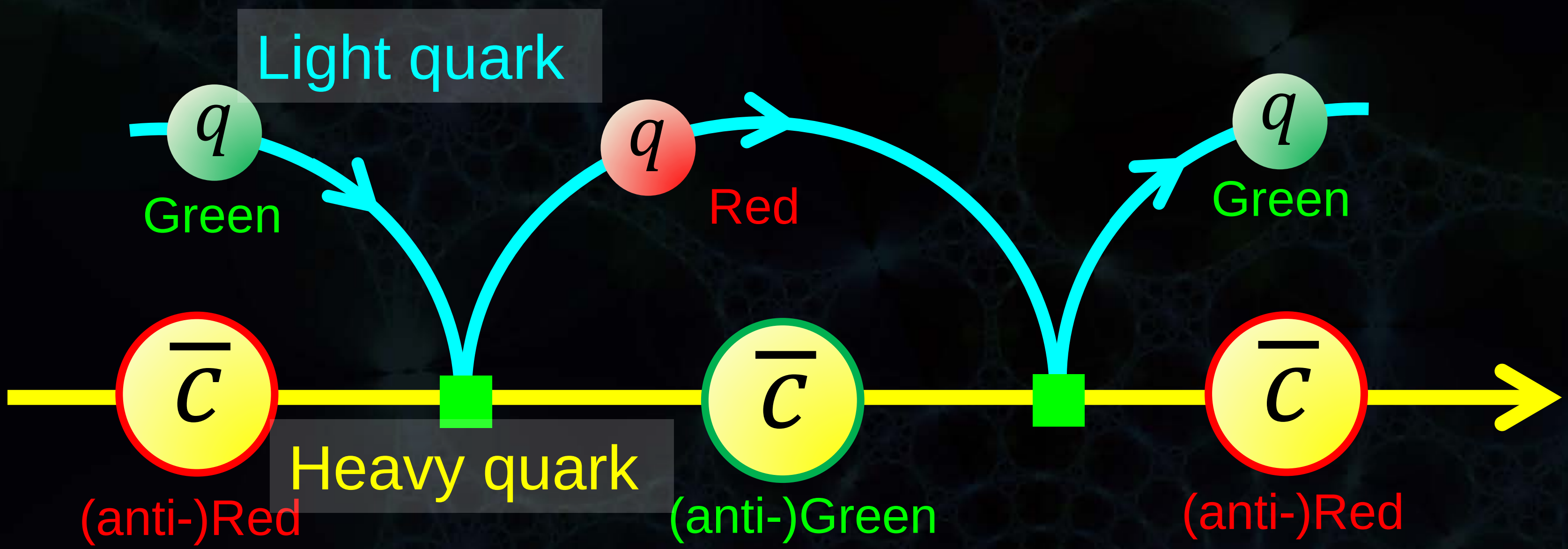


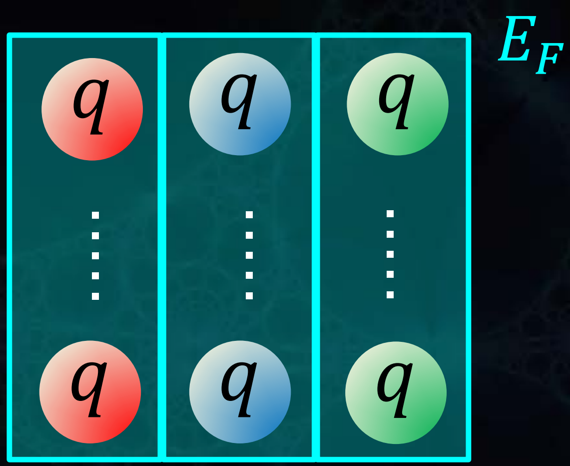
SU(2) spin exchange between a heavy impurity and a electron with Fermi surface

(⇒Scat. amplitude has a divergence of $-\log T$ at low T)

S. Yasui and K. Sudoh, PRC88, 135301 (2013) [arXiv:1301.6830]
K. Hattori, K. Itakura, S. Ozaki and S. Yasui, PRD92, 065003 (2015) [arXiv:1504.07619]

QCD Kondo effect



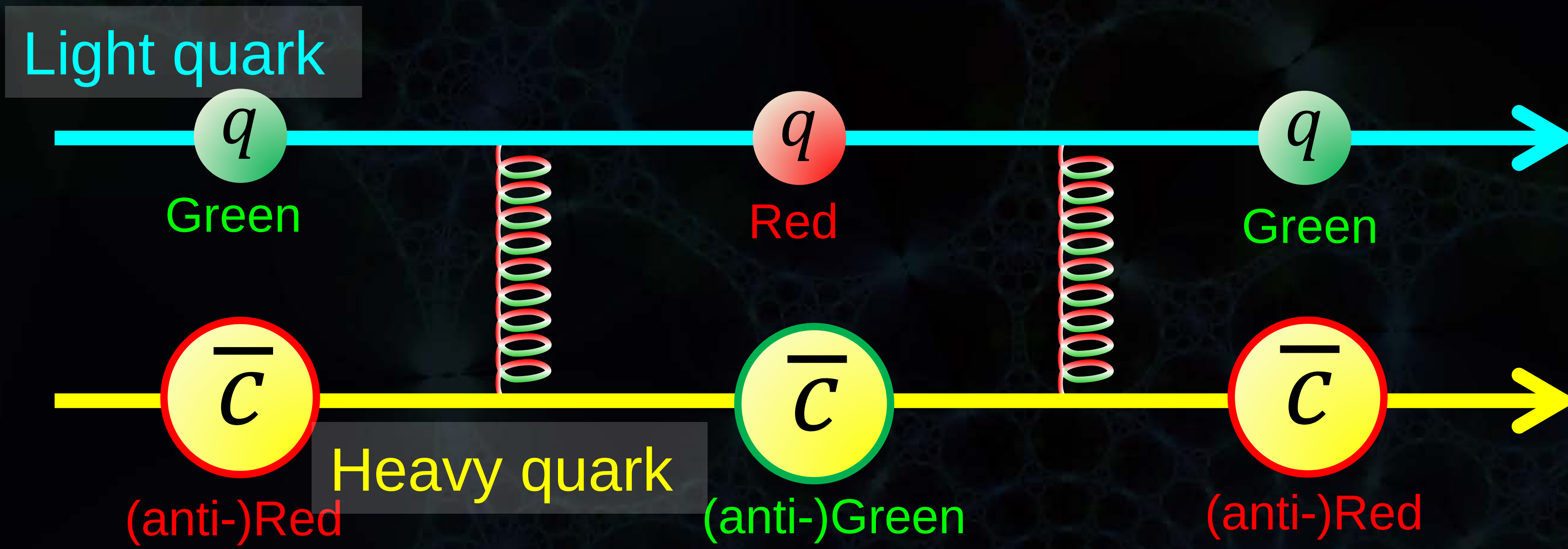


SU(3) color exchange between a heavy quark and a light quark with Fermi surface

(⇒Scat. amplitude has a divergence of $-\log T$ at low T)

K. Hattori, K. Itakura, S. Ozaki and S. Yasui, PRD92, 065003 (2015) [arXiv:1504.07619]

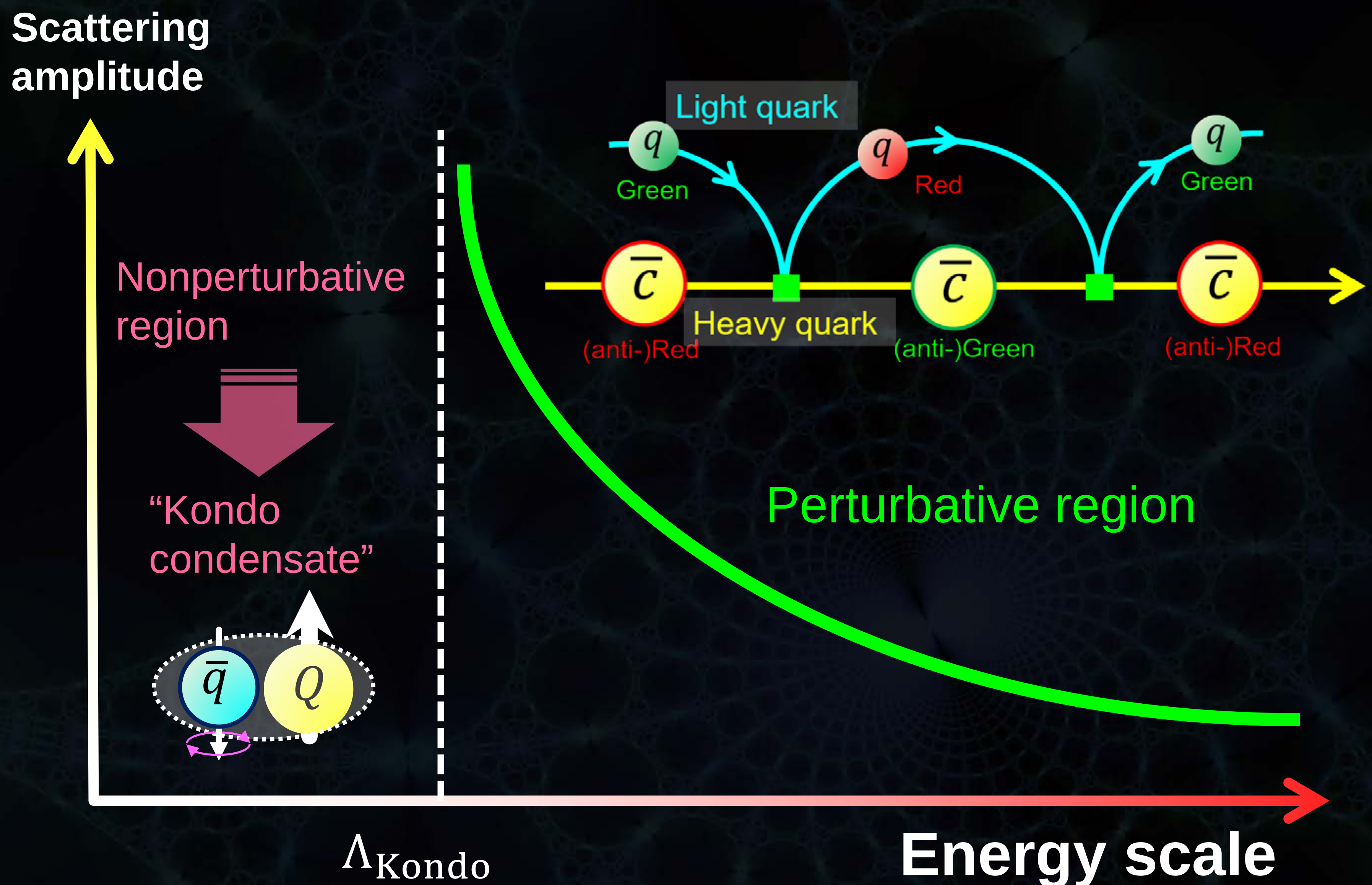
QCD Kondo effect (with gluon exchange)



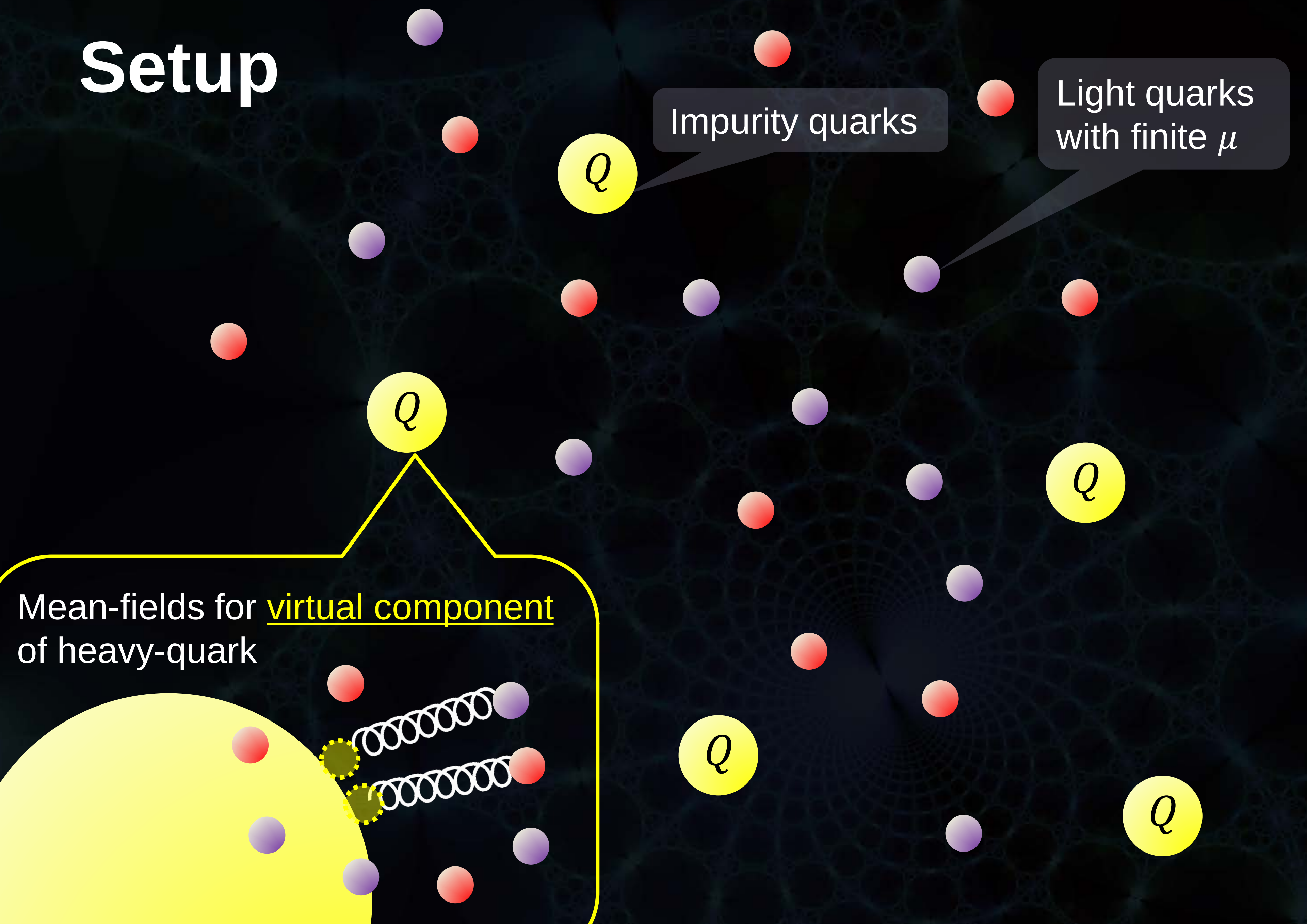
SU(3) color exchange between a heavy quark and a light quark with Fermi surface

(⇒Scat. amplitude has a divergence of $-\log T$ at low T)

Scale in Kondo effect



Setup

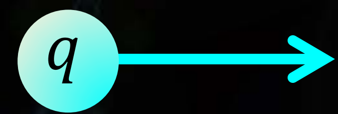


Impurity quarks
Light quarks with finite μ
Q
Q
Q
Q
Q
Mean-fields for virtual component of heavy-quark

S. Yasui, KS and K. Itakura, NPA983, 90 (2019)

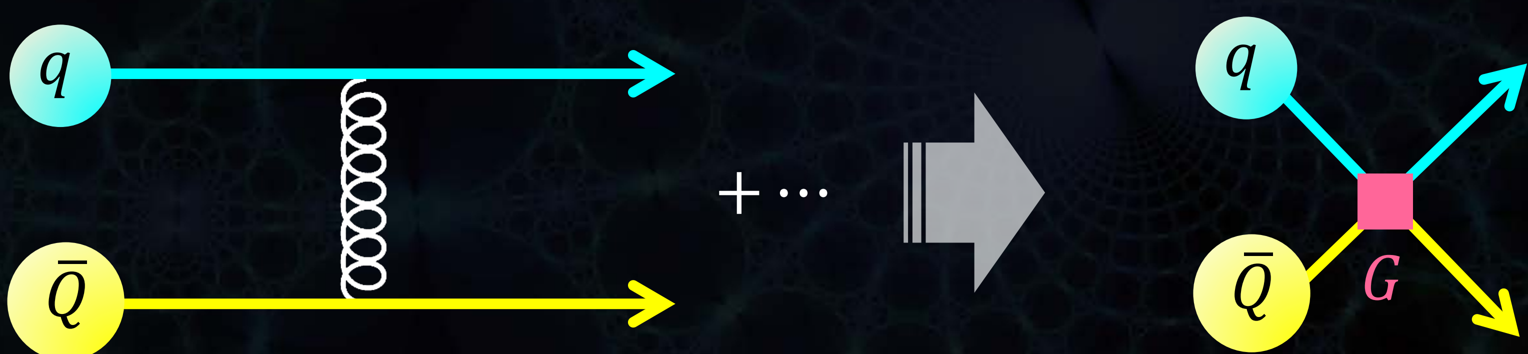
Our model: Light kinetic + Heavy kinetic + Heavy-light 4-point interaction

$$\mathcal{L}_{\mathrm{Light}} = \bar{\psi}\left(i\partial_\mu \gamma^\mu + \mu\gamma^0\right)\psi + \cdots$$



$$\mathcal{L}_{\mathrm{Heavy}} = \bar{\Psi}_v (v \cdot i\partial)\Psi_v - \lambda\left(\bar{\Psi}_v \Psi_v - n_Q\right)$$

$$\mathcal{L}_{\mathrm{H-L}} = -G_c \sum_a (\bar{\psi}\gamma^\mu T^a \psi)(\bar{\Psi}_v \gamma_\mu T^a \Psi_v)$$



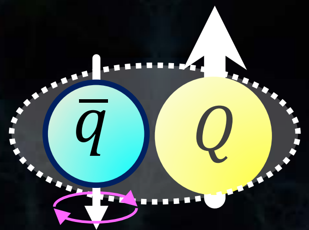
Mean-field approximation

$$(\bar{\psi}\Psi_v)(\bar{\Psi}_v\psi) = \langle\bar{\psi}\Psi_v\rangle\bar{\Psi}_v\psi + \langle\bar{\Psi}_v\psi\rangle\bar{\psi}\Psi_v - \langle\bar{\psi}\Psi_v\rangle\langle\bar{\Psi}_v\psi\rangle$$

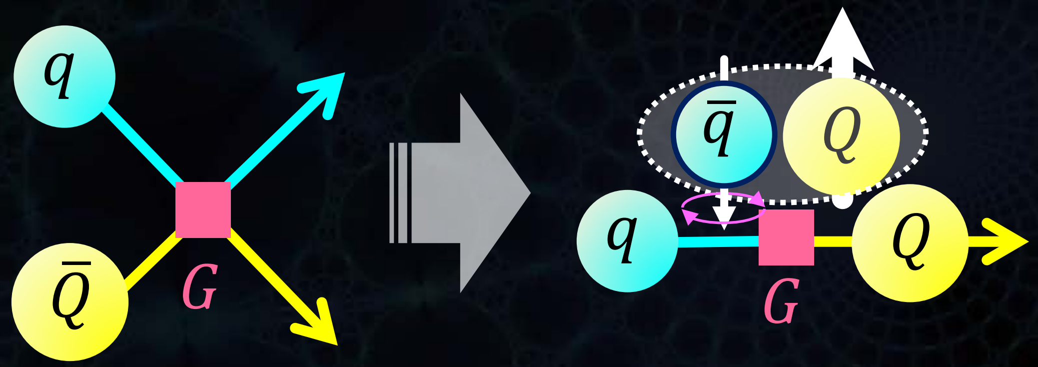
$$(\bar{\psi}\vec{\gamma}\Psi_v)(\bar{\Psi}_v\vec{\gamma}\psi) = \langle\bar{\psi}\vec{\gamma}\Psi_v\rangle\bar{\Psi}_v\vec{\gamma}\psi + \langle\bar{\Psi}_v\vec{\gamma}\psi\rangle\bar{\psi}\vec{\gamma}\Psi_v - \langle\bar{\psi}\vec{\gamma}\Psi_v\rangle\langle\bar{\Psi}_v\vec{\gamma}\psi\rangle$$

- Scalar + Hedgehog ansatz:

$$\langle\bar{\psi}\Psi_v\rangle \equiv \Delta, \qquad \langle\bar{\psi}\vec{\gamma}\Psi_v\rangle \equiv \vec{\Delta} \equiv \Delta\hat{p}$$



$$\langle\bar{\psi}\,(1+\hat{p}\cdot\vec{\gamma})\Psi_v\rangle$$



Mean-field Lagrangian

$$\mathcal{L}_{\rm MF} = \bar{\psi}(p_\mu \gamma^\mu + \mu\gamma^0)\psi + \bar{\Psi}_v (v\cdot p)\Psi_v - \lambda(\bar{\Psi}_v \Psi_v - n_Q)$$
$$+ \Delta\bar{\Psi}_v(1+\hat{p}\cdot\vec{\gamma})\psi + \Delta^* \bar{\psi}(1+\hat{p}\cdot\vec{\gamma})\Psi_v - \frac{8}{G_c}|\Delta|^2$$

Dispersion relations of quasiparticles

- Mixed (dressed) modes

$$E_\pm = \frac{1}{2}\left(p+\lambda-\mu \pm \sqrt{(p-\lambda-\mu)^2 + 8|\Delta|^2}\right)$$

- Decoupled (undressed) light-quarks

$$\tilde{E}_p = -p-\mu$$
$$E_p = p-\mu \ (\text{for } N_f \geq 2)$$

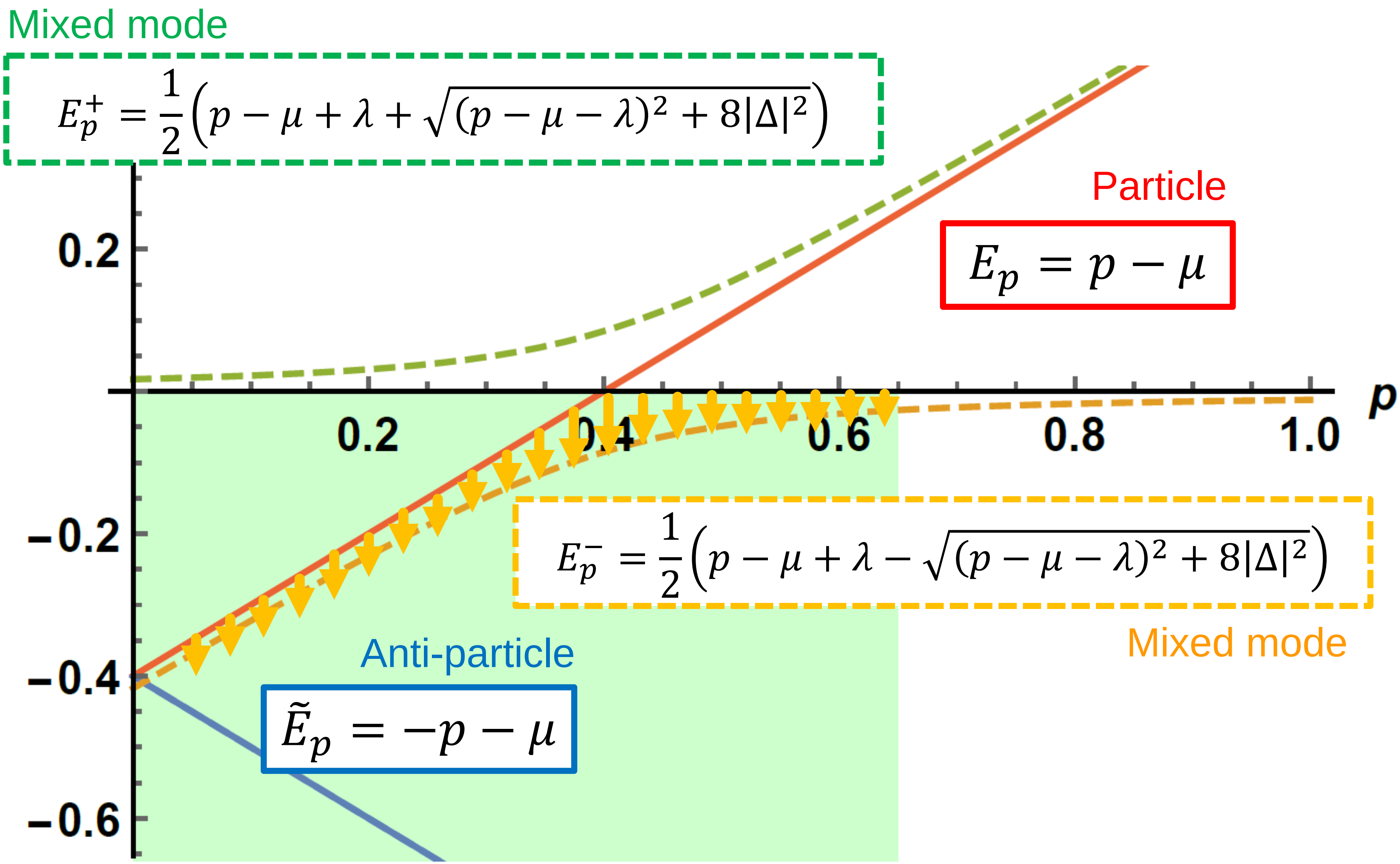
Thermodynamic potential

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

Gap equation: $\frac{\partial \Omega}{\partial \Delta} = 0$

⇒determination of Δ

Dispersion relation (high μ, $\Delta \neq 0$)

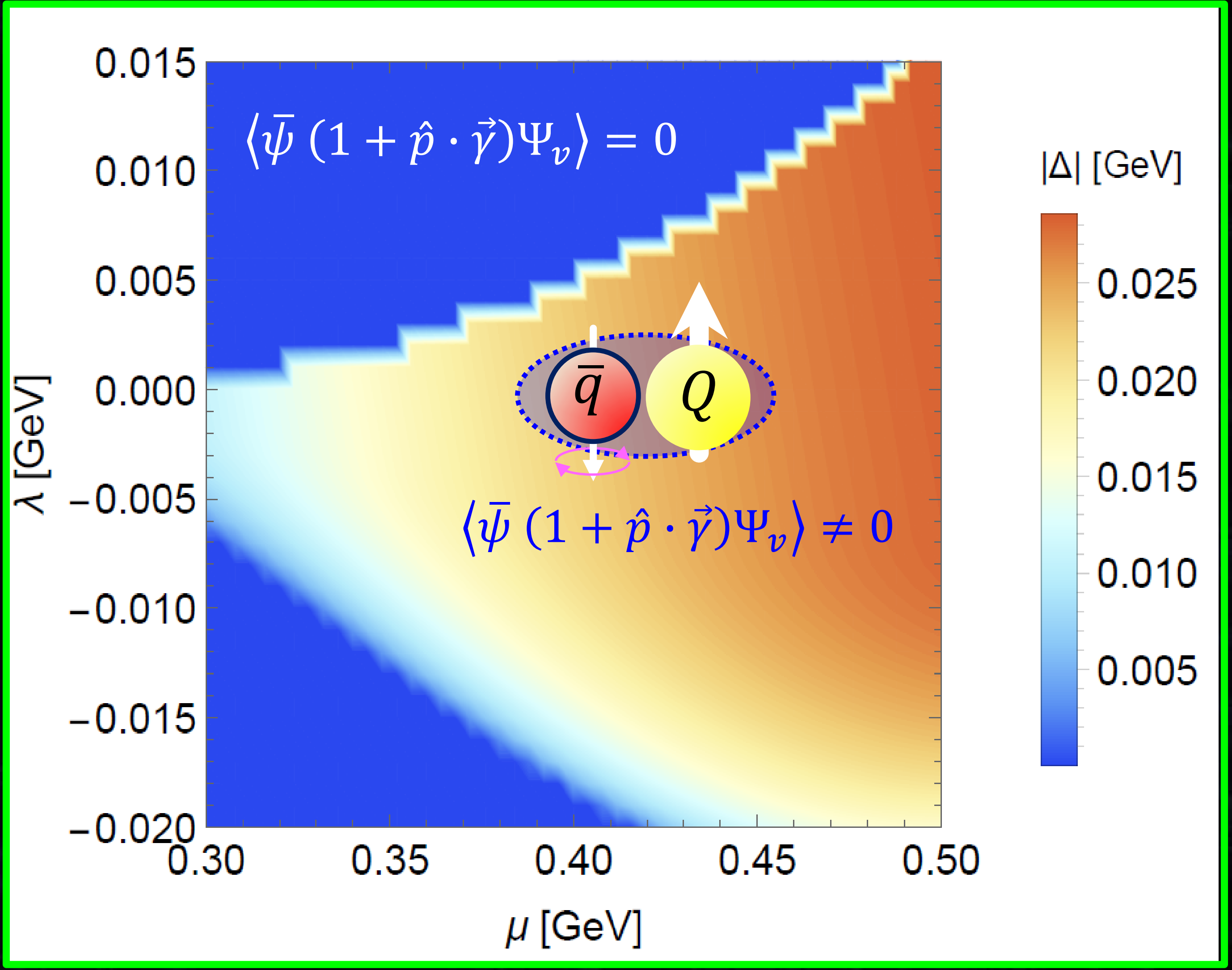


We got ground state spectra in mean field:

Next applications

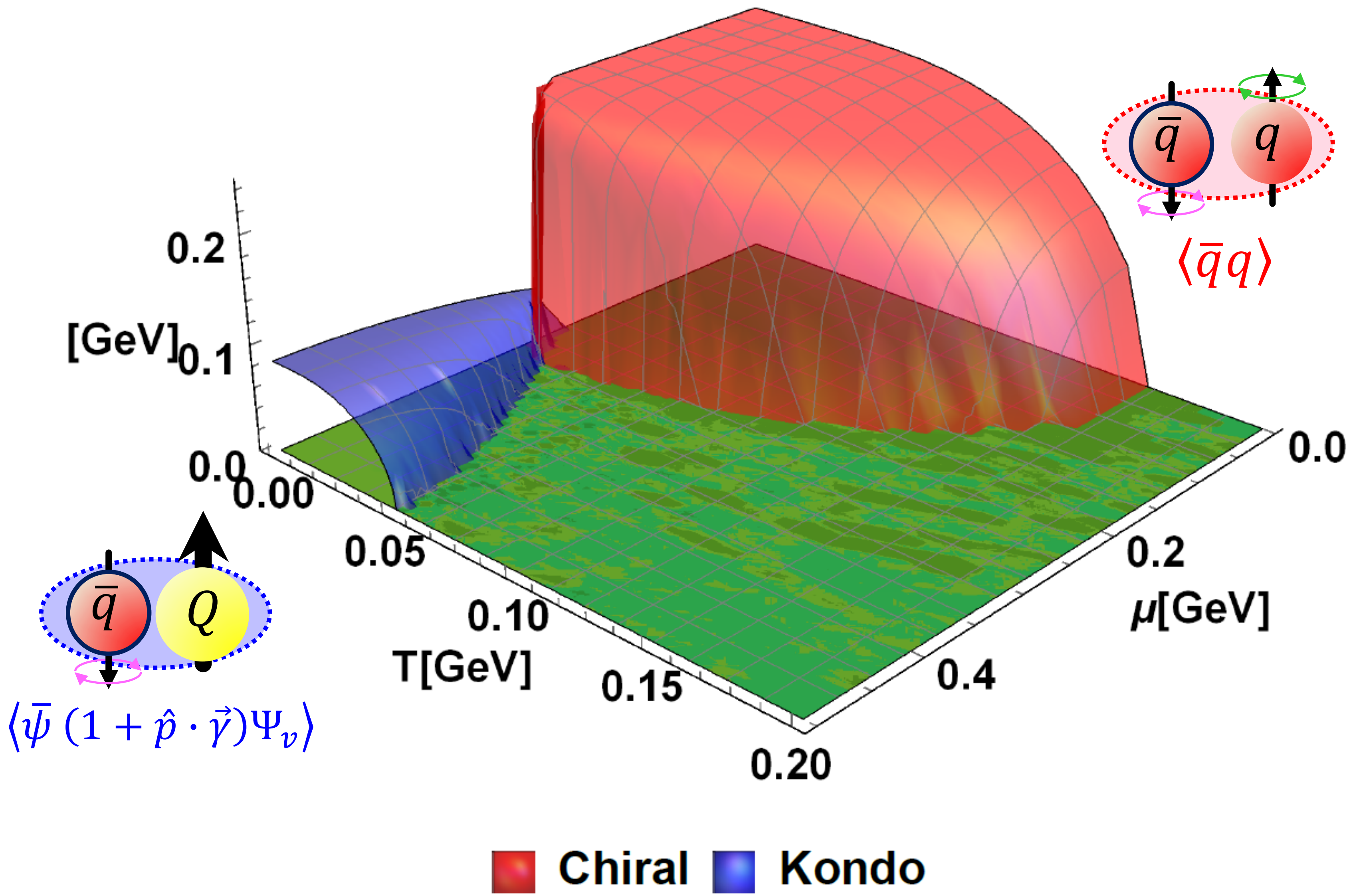
1. Thermodynamic potential and phase diagram
   S. Yasui, K. Suzuki, and K. Itakura, NPA**983**, 90 (2019)
2. Topology of ground state
   S. Yasui, K. Suzuki, and K. Itakura, PRD**96**, 014016 (2017)
3. Interplay with chiral condensate or color-super.
   K. Suzuki, S. Yasui, and K. Itakura, PRD**96**, 114007 (2017)
   T. Kanazawa and S. Uchino, PRD**94**, 114005 (2016)
4. Transport coefficients
   S. Yasui and S. Ozaki, PRD**96**, 114027 (2017)
5. Kondo stars
   J. C. Macías, F.S. Navarra, arXiv:1901.01623
6. Excited states (Kondo excitons)
   S. Yasui, K. Suzuki, and K. Itakura, PRD**96**, 014016 (2017)
   D. Suenaga, K. Suzuki, and S. Yasui, arXiv:1909.07573

Phase diagram (at μ-λ plane)



KS, S. Yasui and K. Itakura, PRD96, 114007 (2017)

Phase diagram (at μ-T plane)



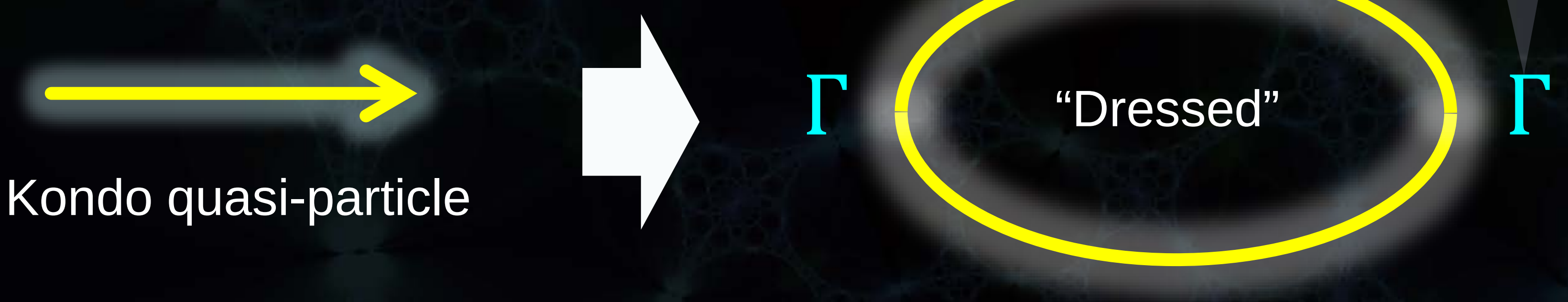
exciton = particle-hole pair

S. Yasui, KS and K. Itakura, PRD96, 014016 (2017)
D. Suenaga, KS and S. Yasui, arXiv:1909.07573

Kondo excitons for $N_f = 1$

$\Gamma = P, S, V, A$

1. Dressed Kondo excitons



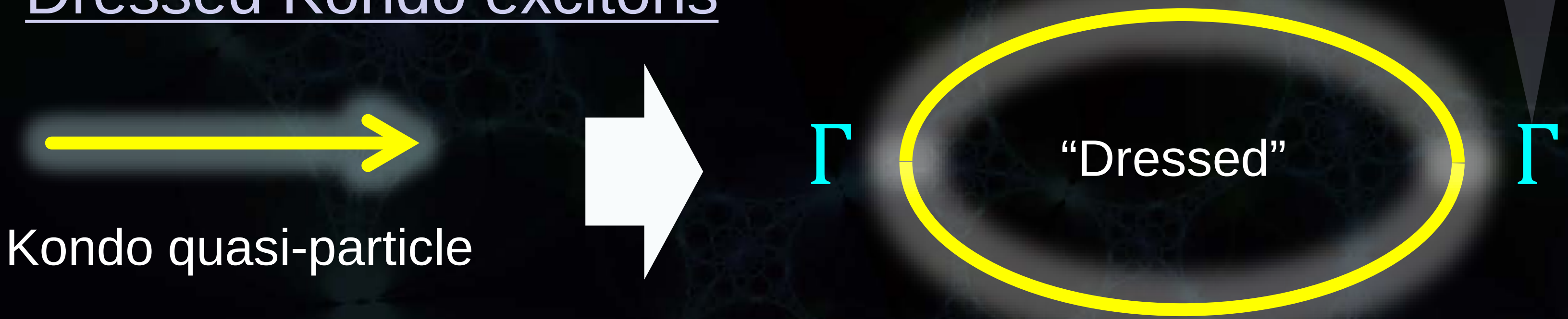
exciton = particle-hole pair

S. Yasui, KS and K. Itakura, PRD96, 014016 (2017)
D. Suenaga, KS and S. Yasui, arXiv:1909.07573

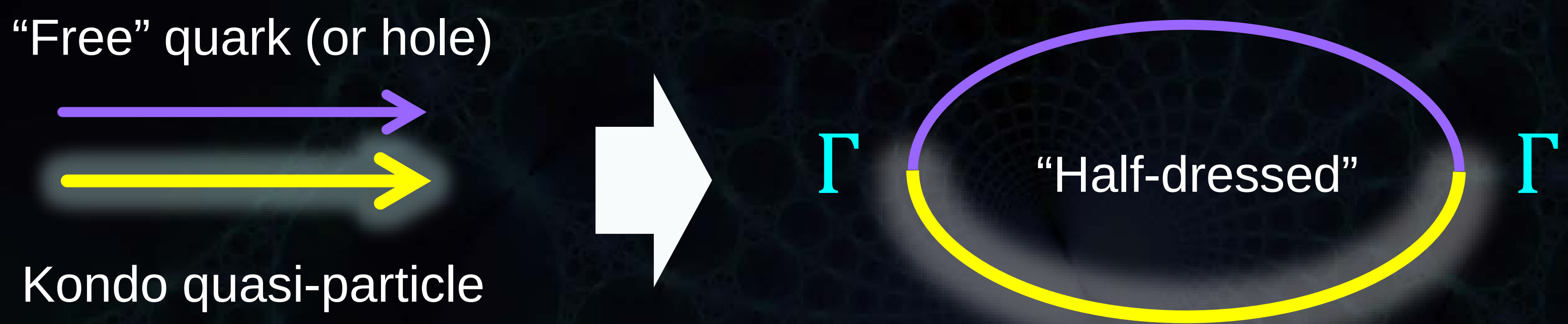
Kondo excitons for $N_f = 2$

$\Gamma = P, S, V, A$

1. Dressed Kondo excitons



2. Half-dressed Kondo excitons



Cf.) Flavor-doublet for Kondo condensate: $g \begin{pmatrix} \Delta_u \\ \Delta_d \end{pmatrix} \to \begin{pmatrix} \sqrt{\Delta_u^2 + \Delta_d^2} \\ 0 \end{pmatrix} \equiv \begin{pmatrix} \Delta \\ 0 \end{pmatrix}$

D. Suenaga, KS and S. Yasui, arXiv:1909.07573

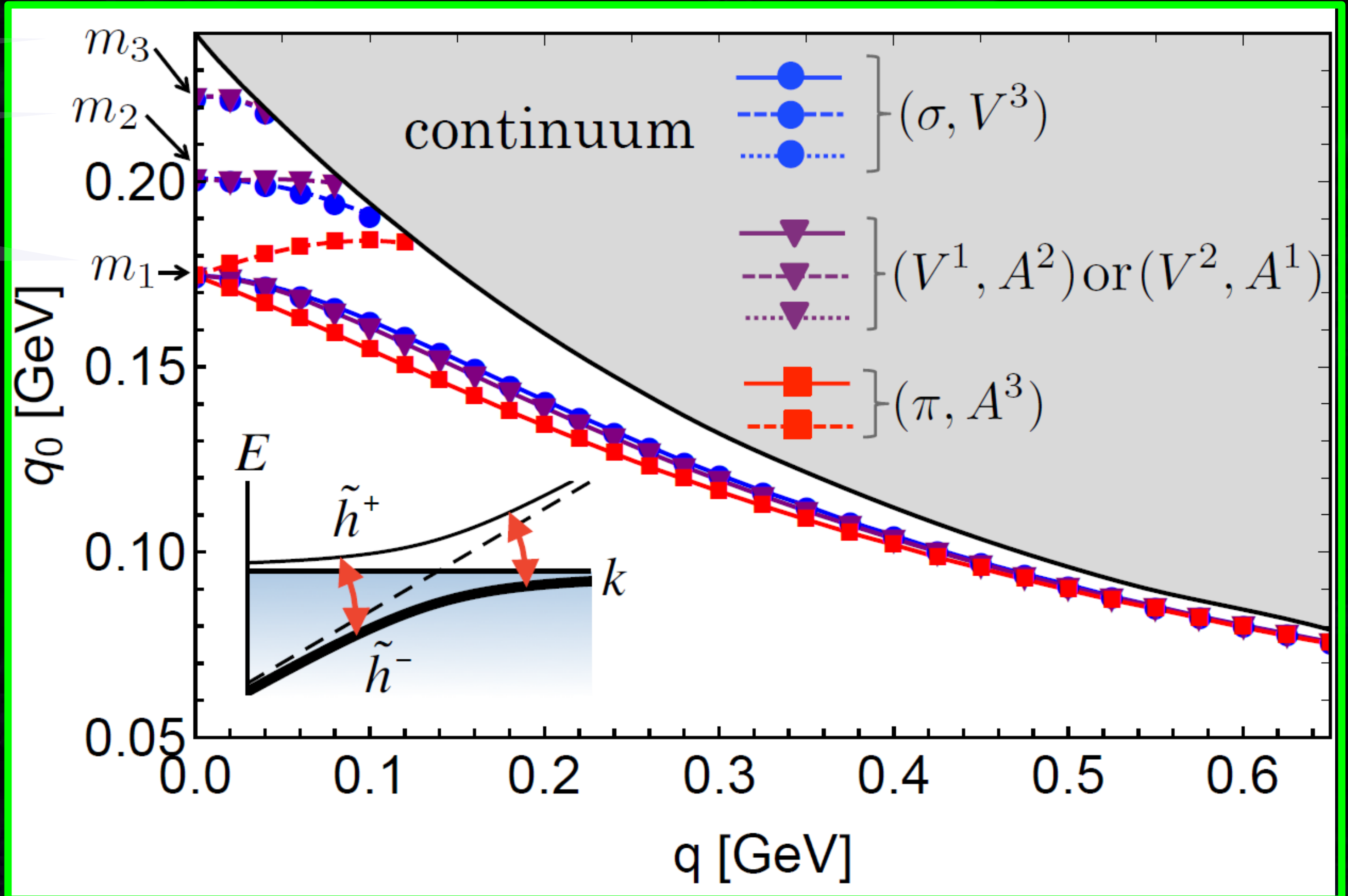
Numerical results:

Kondo excitons (Dressed)

$m_3: V_{1,2,3}$

$m_2: V_{1,2,3}$

$m_1: P, S, A_{1,2,3}$



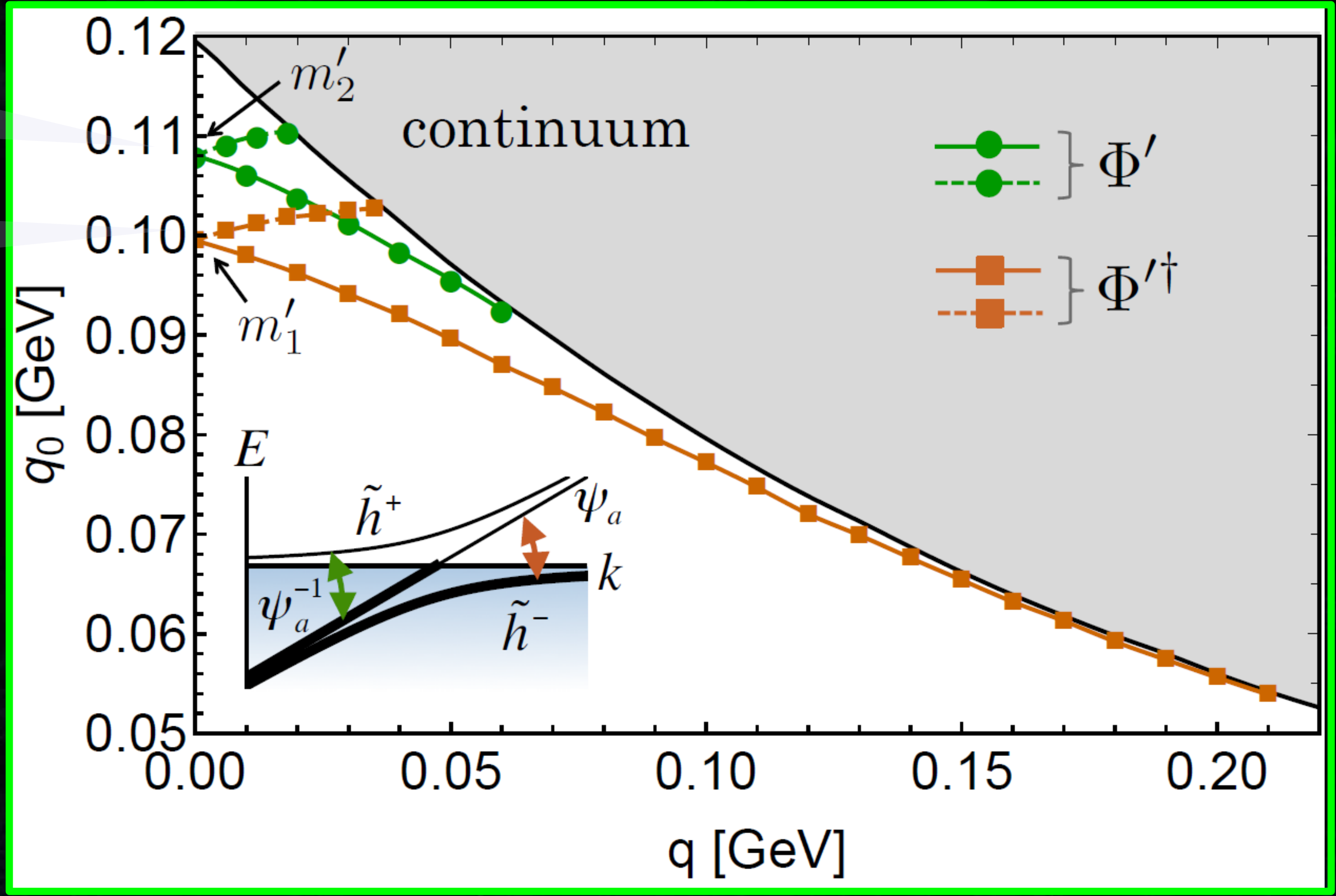
⇒We got bound states (stable w.r.t strong interactions)

Numerical results:

Kondo excitons (Half-dressed)

m'_2: $P^\dagger, S^\dagger, V^\dagger_{1,2,3}, A^\dagger_{1,2,3}$

m'_1: $P, S, V_{1,2,3}, A_{1,2,3}$



D. Suenaga, KS and S. Yasui, arXiv:1909.07573

Properties of excitons:

Mixing for S-V_3, P-A_3, V_1-A_2, V_2-A_1

Condensate: Parity sym.

$\langle \bar{\psi}\, (1 + \hat{p} \cdot \vec{\gamma}) \Psi_v \rangle$

Anomalous coupling at finite momentum:

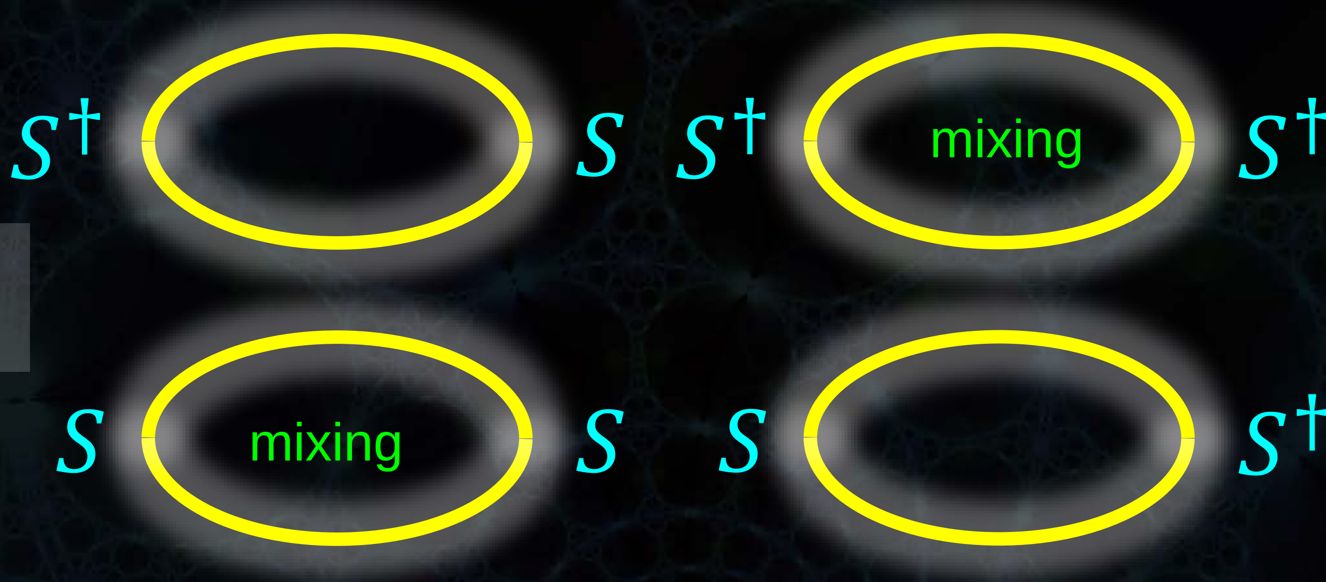
$\partial^3 S V_3$ $\partial^3 P A_3$ $\varepsilon^{ijk} \partial^i V^j A^k$

D. Suenaga, KS and S. Yasui, arXiv:1909.07573

Properties of excitons:

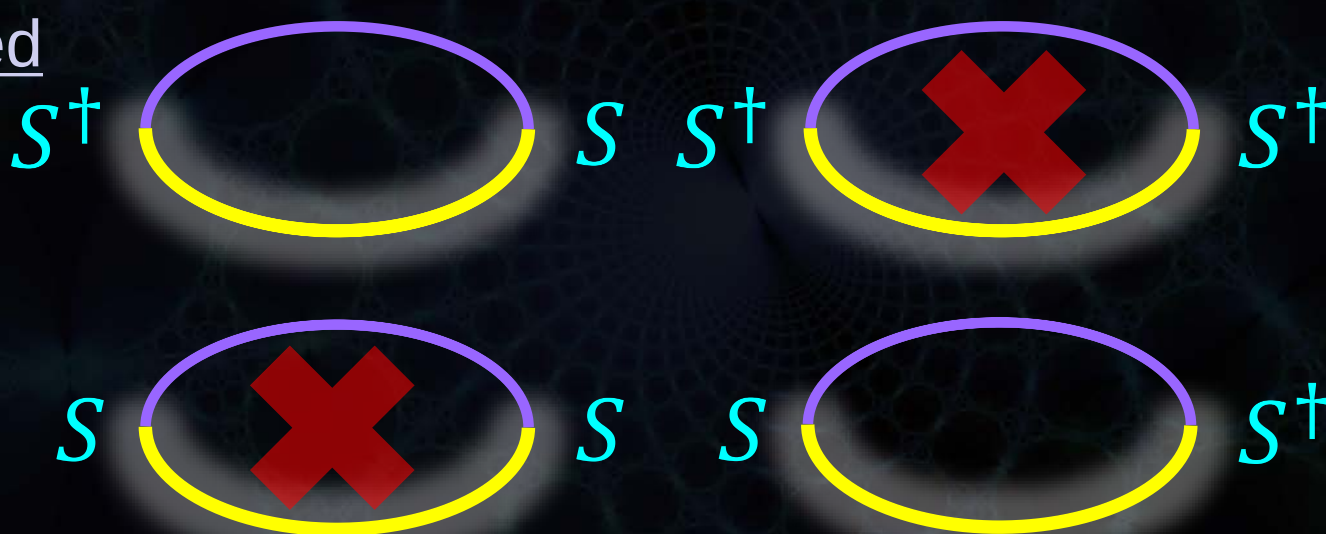
Mixing for flavor violation

1. Dressed



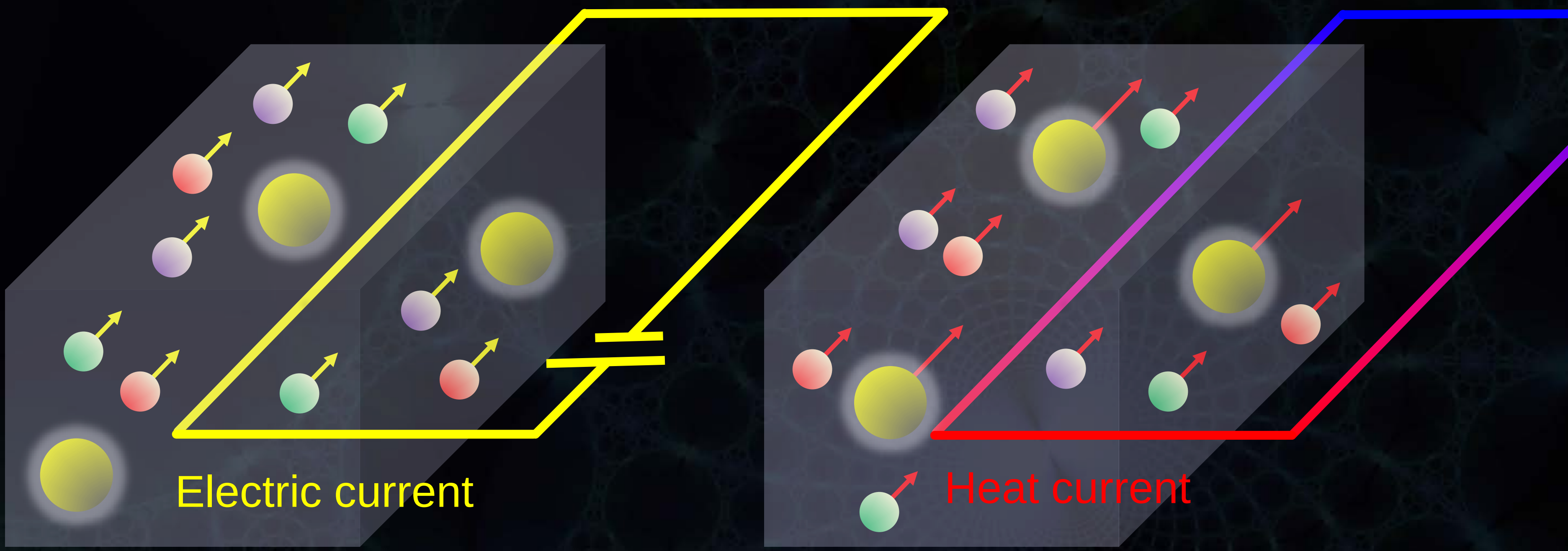
Cf.) π^+-π^- mixing in pion condensation

2. Half-dressed



Importance in transport phenomena

1. Excitons can be (color and electric) charge neutral
2. Difference btw electric and heat currents



3. Excitons are bosonic transport

Neutral current In condensed matter

Y. Sato et al., Nature Physics 15, 954 (2019)

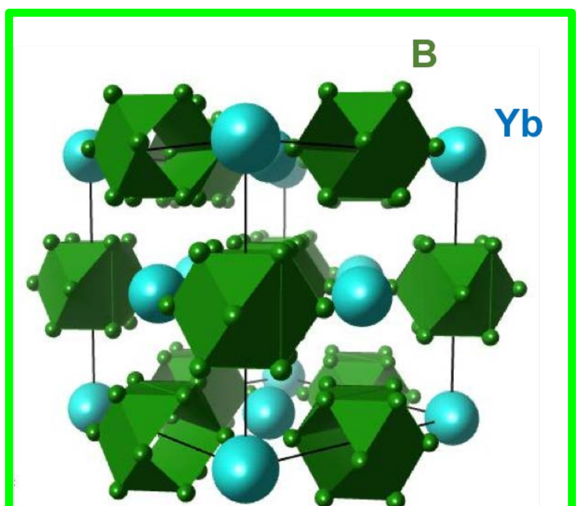
日本経済新聞

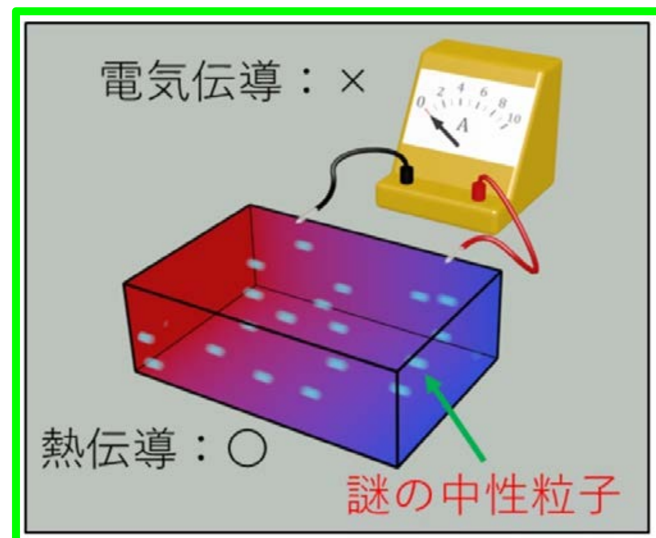
2019年9月28日（土）

プレスリリース

京大・東大・茨城大など、絶縁体の内部を動き回る未知の中性粒子を発見

2019/7/2 0:05

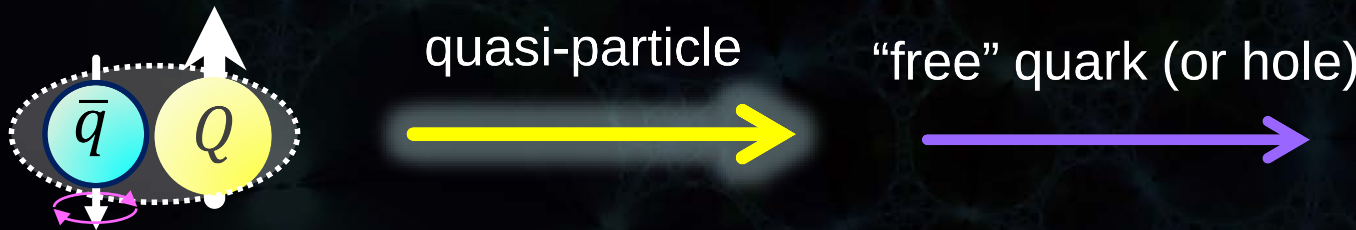




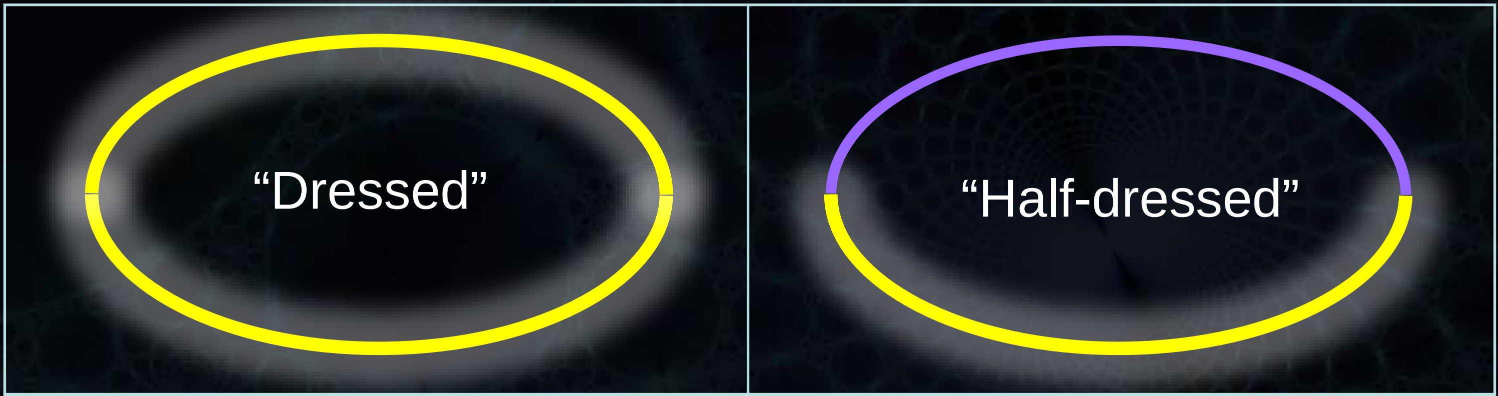
D. Suenaga, KS and S. Yasui, arXiv:1909.07573

Summary and outlook

- Ground state (QCD Kondo phase, quasi-particles)



- Excited states (QCD Kondo excitons)

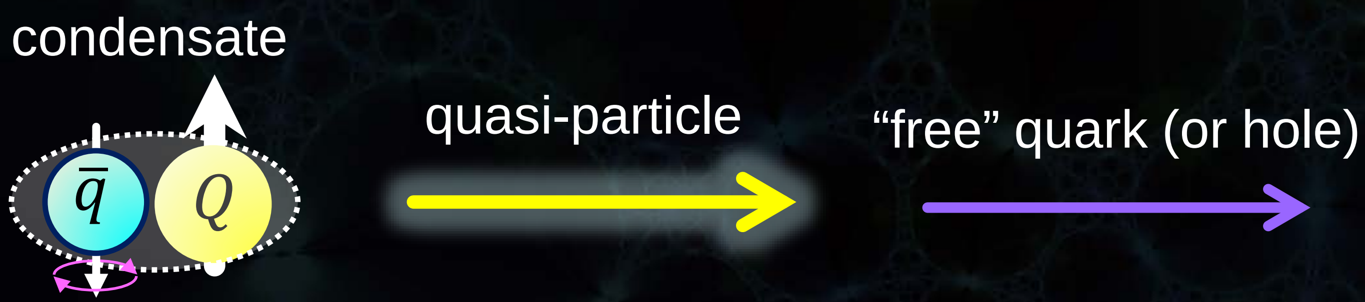


S-V_3,V_1-A_2,V_2-A_1,P-A_3 mixing Particle-Antiparticle mixing	S-V_3,V_1-A_2,V_2-A_1,P-A_3 mixing

D. Suenaga, KS and S. Yasui, arXiv:1909.07573

Summary and outlook

- Ground state (QCD Kondo phase, quasi-particles)



- Excited states (QCD Kondo excitons)

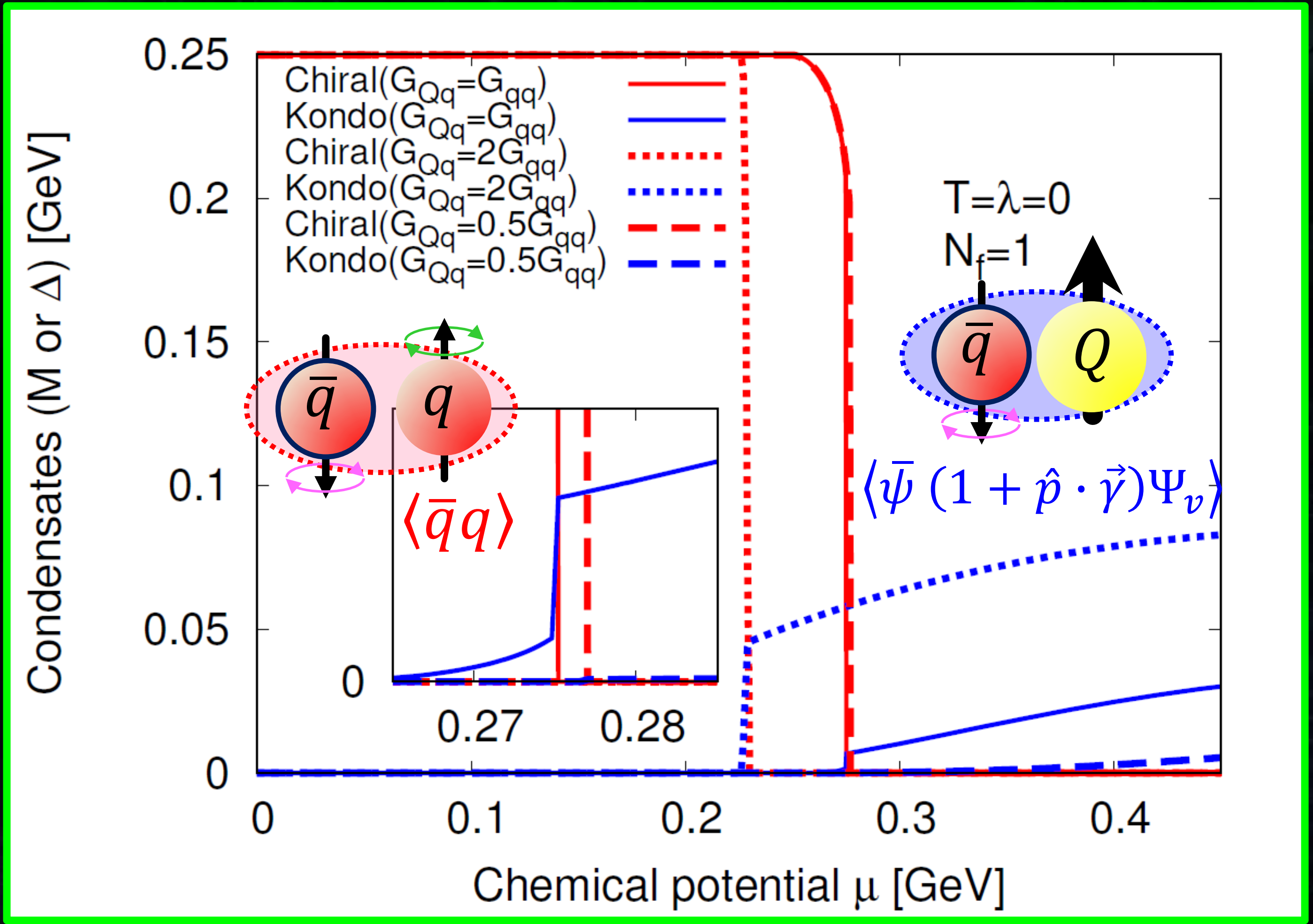
1. They can induce color-neutral current ⇒ Transport phenomena w/o charges (heat/sound-wave)
2. Lattice QCD sim. with isospin chemical potential
3. Continuity with hadronic phase
4. Compact stars with Kondo phase (Charm stars)

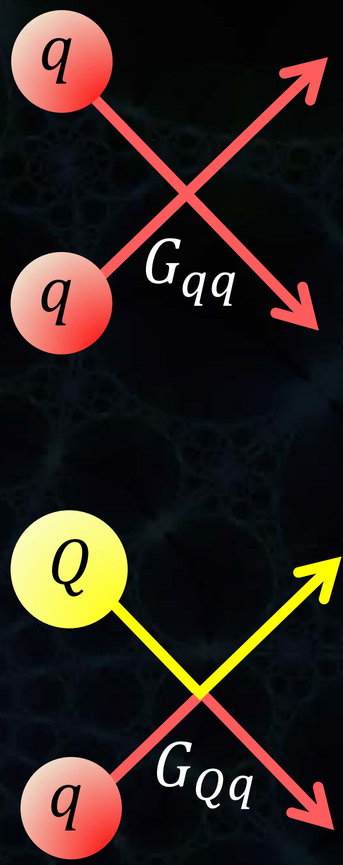
Cf.) J. C. Macías, F.S. Navarra, arXiv:1901.01623

Backup

KS, S. Yasui and K. Itakura, PRD96, 114007 (2017)

Phase diagram (at μ-axis)





⇒Kondo condensate realizes at high μ