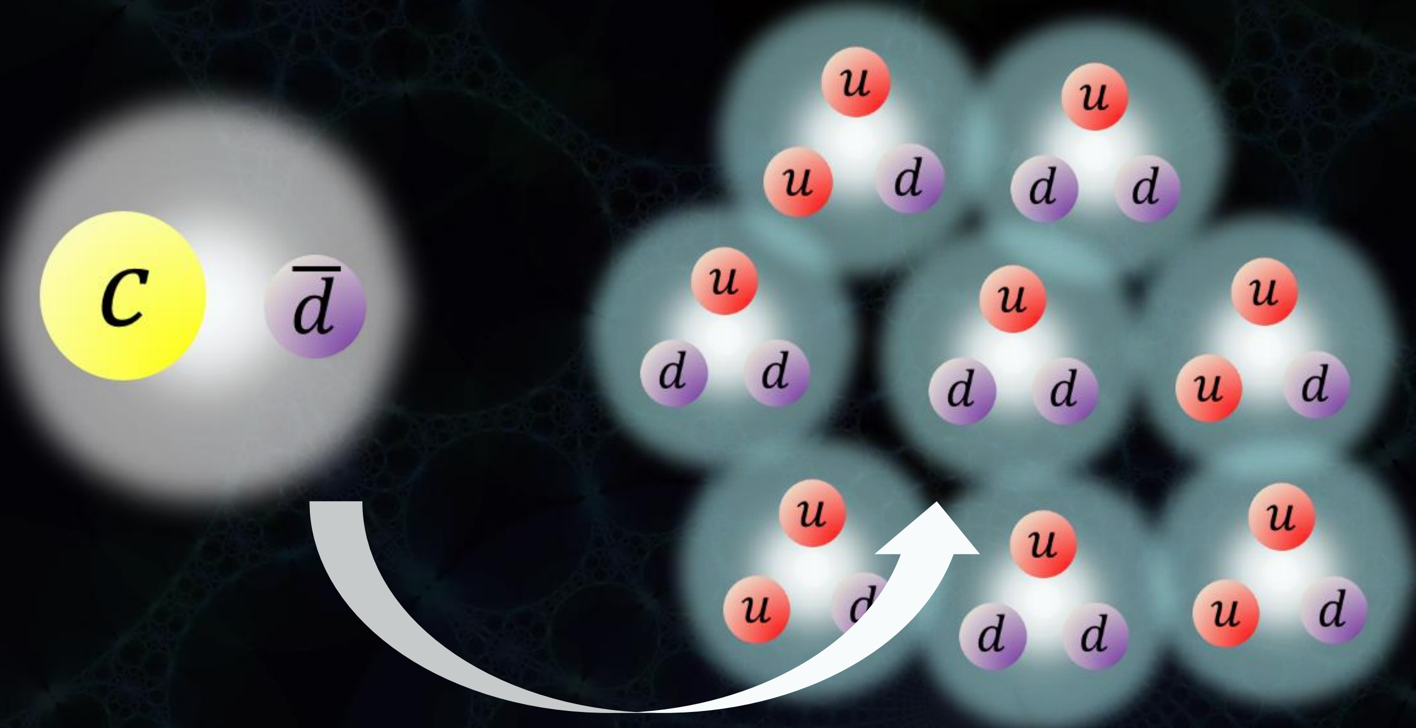
D meson properties in nuclear medium from QCD sum rules

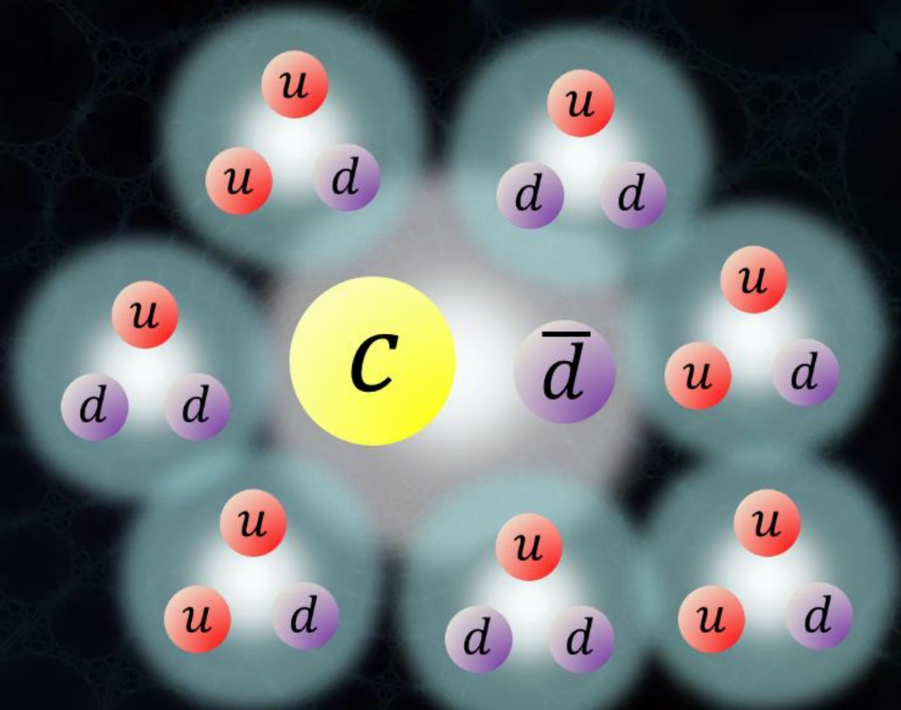


Kei Suzuki (RIKEN)

Collaboration with
Philipp Gubler (ECT*) and Makoto Oka (TITech)

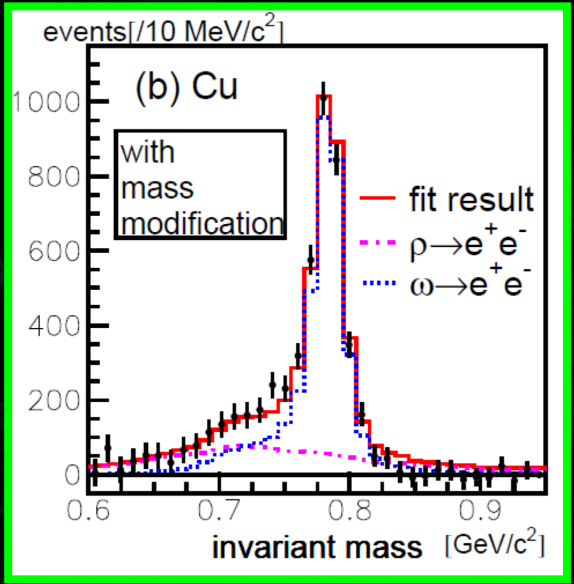
Outline of talk

1. Introduction - Hadrons **in nuclear matter**
   - Chiral symmetry restoration
   - Charge symmetry breaking
2. QCD sum rules **in nuclear matter**
3. Results and summary



1. Introduction

Hadrons in nuclear matter



M. Naruki et al., (KEK E-325), PRL 96 (2006) 092301

ρ, ω, ϕ mesons in nuclear matter

- Probe of chiral symmetry restoration
- Many theoretical predictions
- Some experimental indications

D meson in nuclear matter

- Probe of chiral symmetry restoration, D-N ($\bar{D}$-N) interaction, mesic nuclei
- Many theoretical predictions
- No experiment (future at J-PARC/FAIR)

Many theoretical works for D meson in matter

Coupled chanel approach

L. Tolos, J. Schaffner-Bielich, and A. Mishra, PRC70, 025203 (2004)
M. Lutz and C. Korpa, PLB633, 43 (2006)
T. Mizutani and A. Ramos, PRC74, 065201 (2006)
L. Tolos, A. Ramos, and T. Mizutani, PRC77, 015207 (2008)
L. Tolos, C. Garcia-Recio, and J. Nieves, PRC80, 065202 (2009)
C. Jimenez-Tejero, A. Ramos, L. Tolos, and I. Vidana, PRC84, 015208 (2011)

Mean field approach

A. Mishra, E. Bratkovskaya, J. Schaffner-Bielich, S. Schramm, and H. Stoecker, PRC69, 015202 (2004)
A. Mishra and A. Mazumdar, PRC79, 024908 (2009)
A. Kumar and A. Mishra, PRC81, 065204 (2010)
A. Kumar and A. Mishra, EPJ. A47, 164 (2011)

Pion exchange model for Dbar -N

S. Yasui and K. Sudoh, PRC87, 015202 (2013)

QMC model

K. Tsushima, D.-H. Lu, A. W. Thomas, K. Saito, and R. Landau, PRC59, 2824 (1999)
A. Sibirtsev, K. Tsushima, and A. W. Thomas, EPJ. A6, 351 (1999)

QCD sum rules

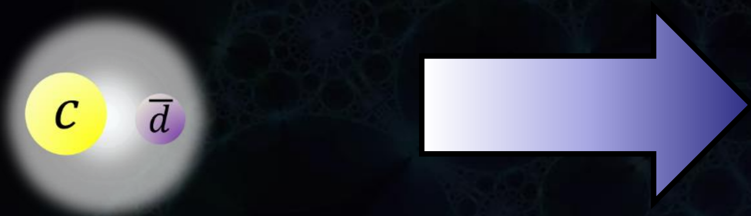
P. Morath, W. Weise, and S.-H. Lee (1999)
A. Hayashigaki, PLB487, 96 (2000)
T. Hilger, R. Thomas, and B. Kampfer, Phys. Rev. C79,025202 (2009)
K. Azizi, N. Er, and H. Sundu, EPJ. C74, 3021 (2014)
W.Z. Gang (2015) arXiv:1501.05093 [hep-ph]

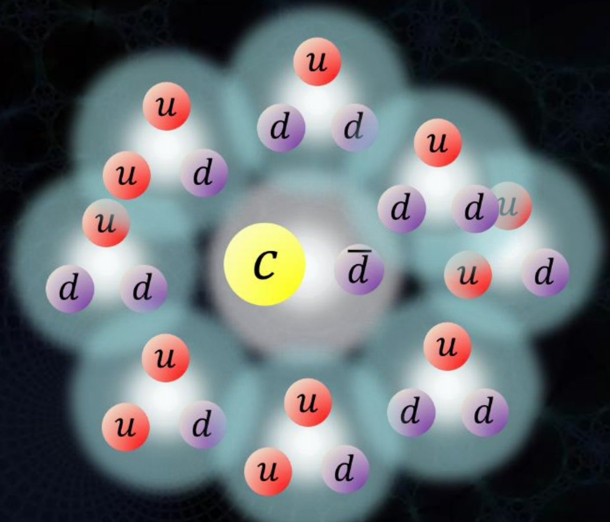
D meson in nuclear matter

If a D meson is put into nuclear matter, what will happen ?

In vacuum

In nuclear matter

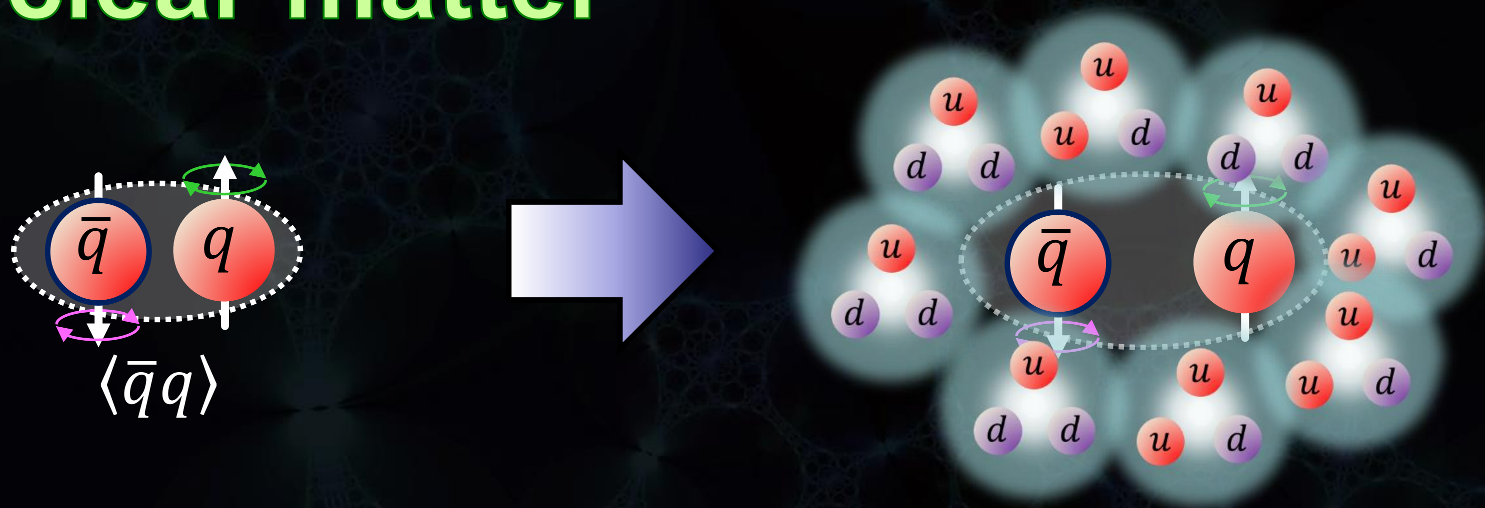




Key points

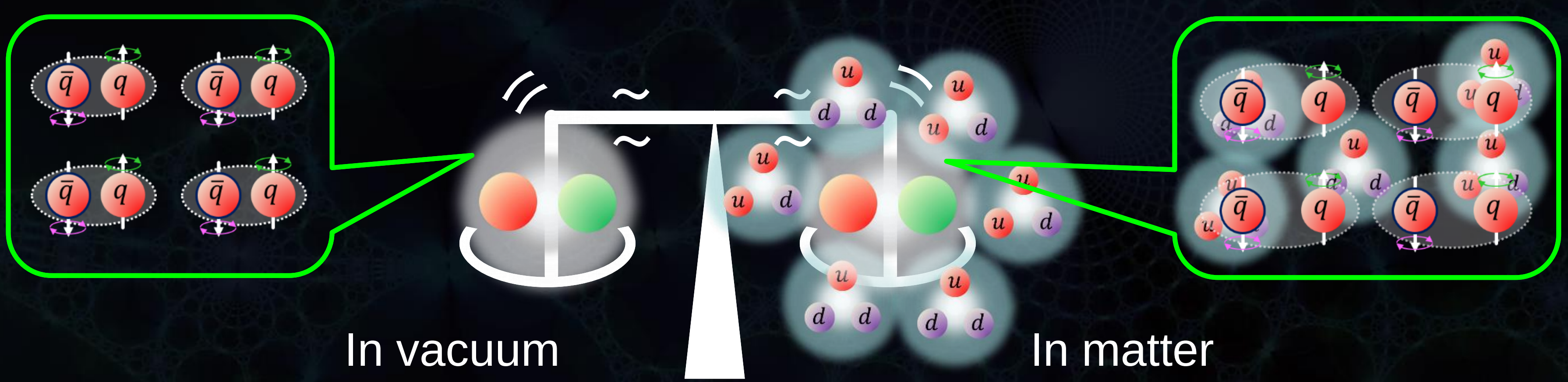
1. Chiral symmetry restoration (χSR)
2. Charge symmetry breaking (CSB)
   = Particle - anti-particle symmetry

Chiral symmetry restoration in nuclear matter



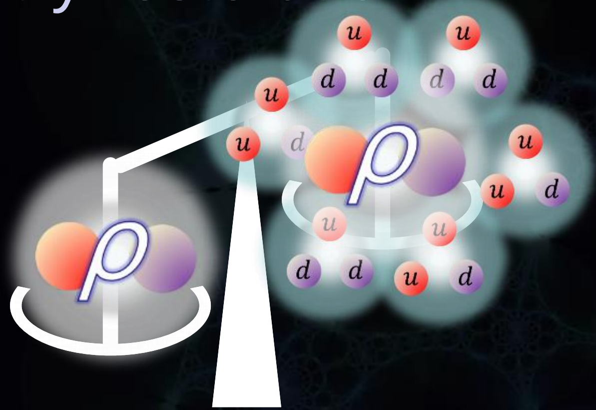
⇒Chiral condensate is reduced in NM

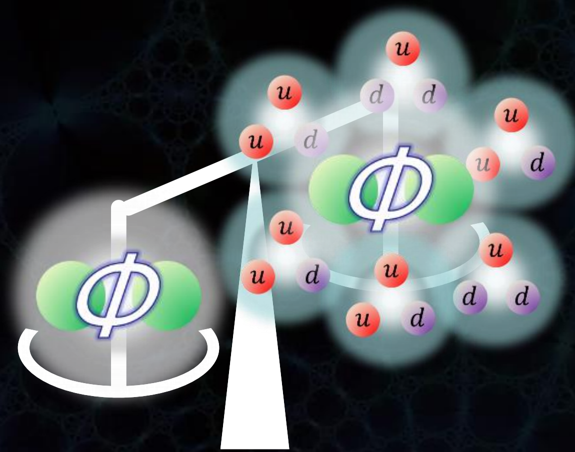
- Chiral symmetry restoration changes hadron masses



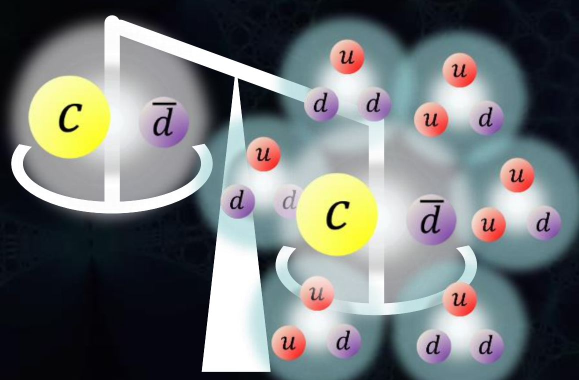
Different hadron mass shifts by Chiral symmetry restoration

- ρ and ϕ meson masses are decreased by chiral symmetry restoration



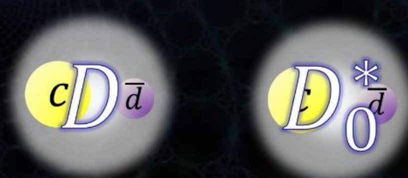


- D meson mass is <u>increased</u> by chiral symmetry restoration



cf.) Chiral partner:

<u>Pseudoscalar ⇔ Scalar</u>

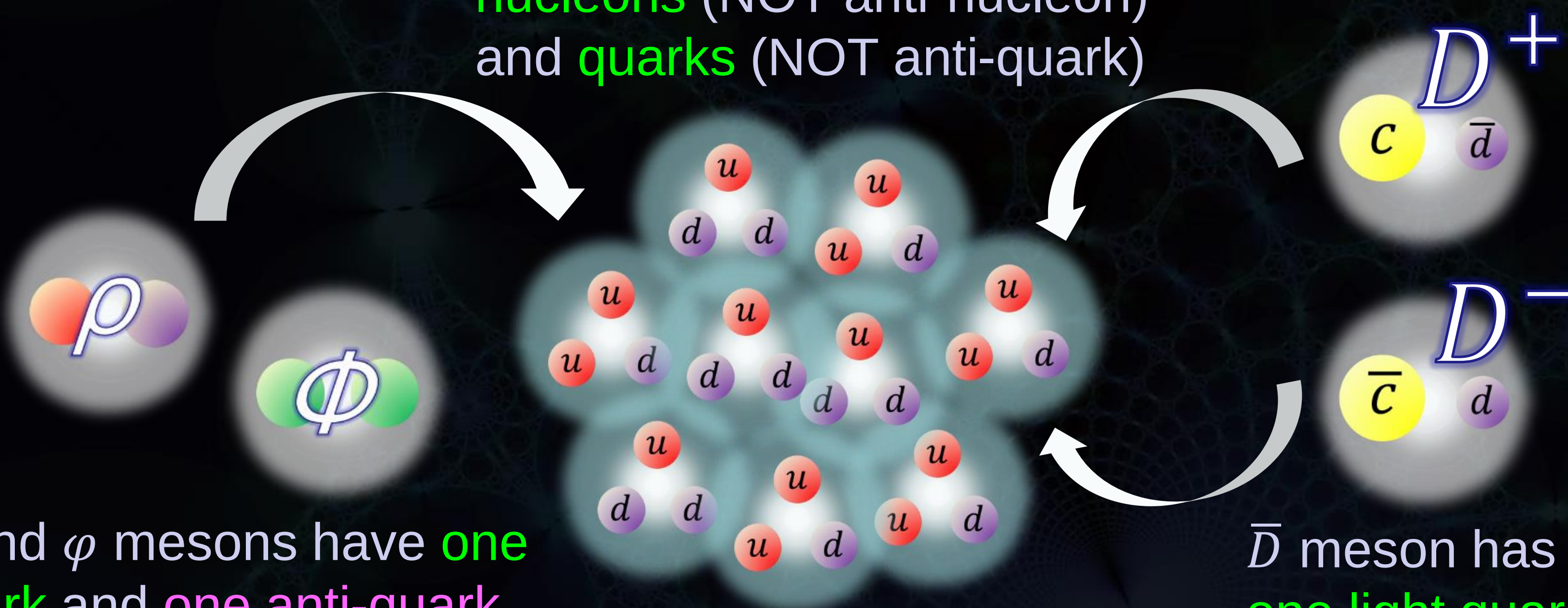


Chiral partner degenerates by chiral symmetry restoration

Charge Symmetry Breaking = imbalance b/w particle and anti-particle

Nuclear matter has only nucleons (NOT anti-nucleon) and quarks (NOT anti-quark)

D meson has only one light anti-quark



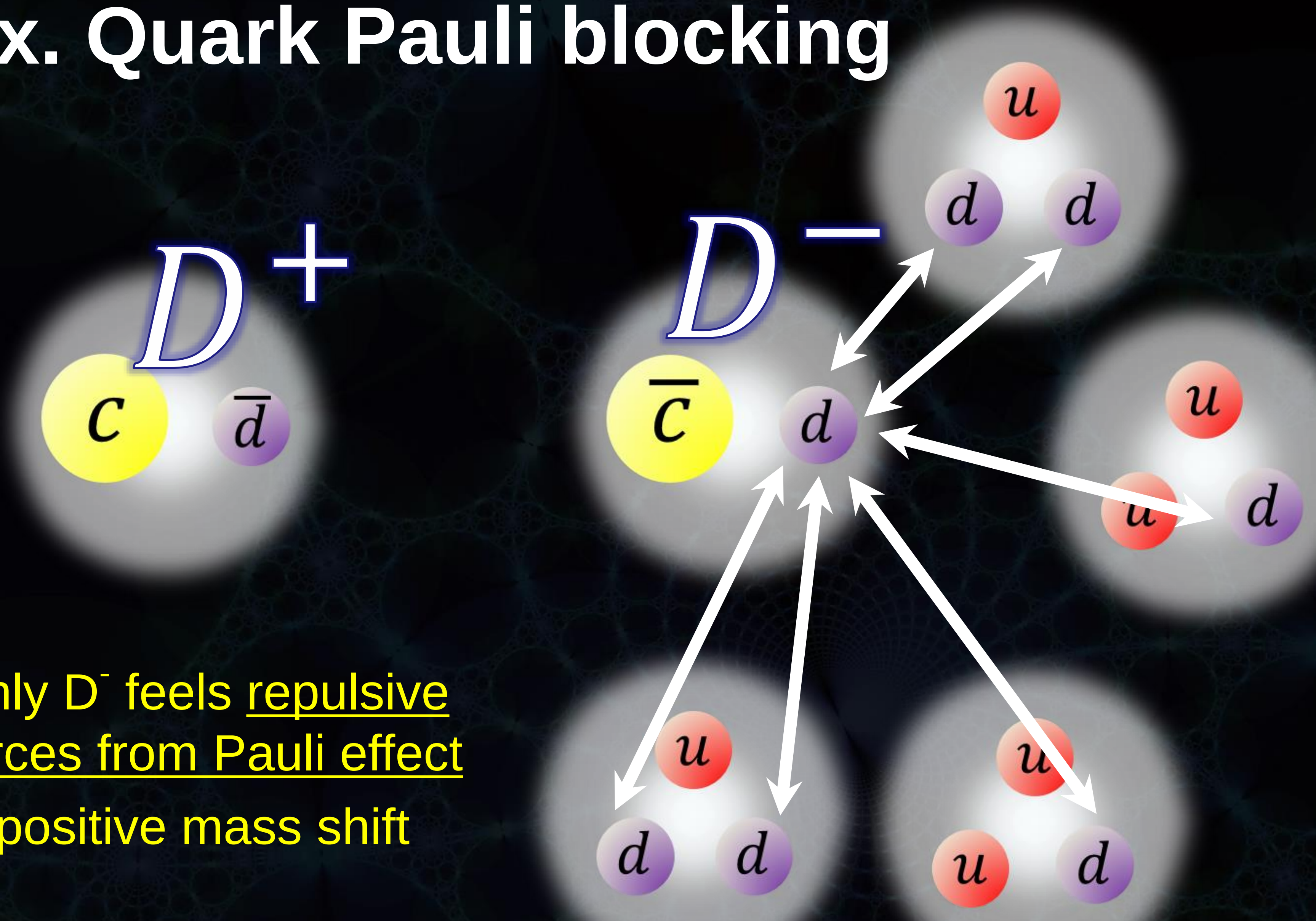
ρ and φ mesons have one quark and one anti-quark

$\bar{D}$ meson has only one light quark

⇒ρ and φ mesons in NM : NOT probe of charge symmetry breaking

⇒Heavy-light meson in NM: a <u>probe of charge symmetry breaking</u>

Ex. Quark Pauli blocking



Only D$^-$ feels <u>repulsive forces from Pauli effect</u>

⇒positive mass shift

2. QCD sum rule in nuclear medium

M.A. Shifman, A.I. Vainshtein, and V.I. Zakharov, Nucl. Phys. B**147**, 385 (1979); B**147**, 448 (1979)

QCD sum rule

Relation between operator product expansion (OPE) of QCD correlation function and hadron spectral function

$$\Pi_{\mathrm{OPE}}(M^2) = \int_0^\infty K(s, M^2)\,\rho(s)\,ds$$

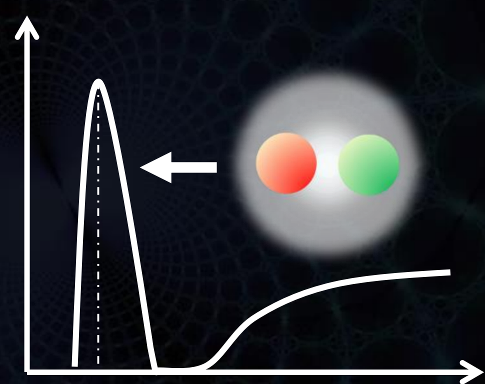
Quark and Gluon dynamics

QCD vacuum condensates

$\langle \bar{q}q \rangle$ $\langle G_{\mu\nu}G^{\mu\nu} \rangle$

etc…

Hadron properties (mass, width…)

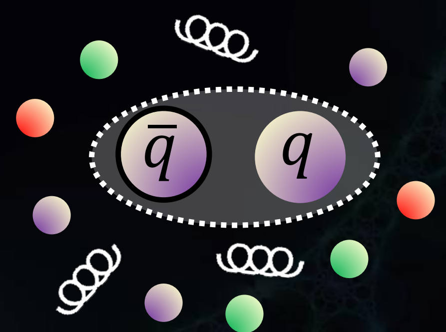


QCD sum rules in medium

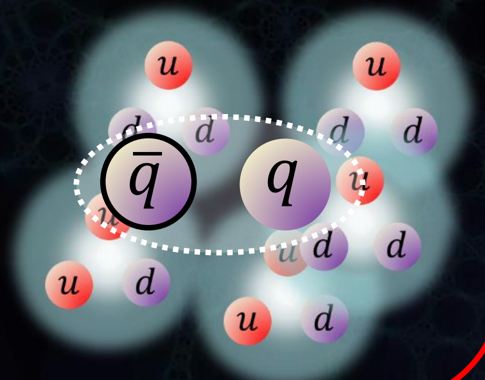
$$\Pi_{\mathrm{OPE}}(M^2) = \int_0^\infty K(s, M^2)\, \rho(s)\, ds$$

Medium modification of OPE INPUT

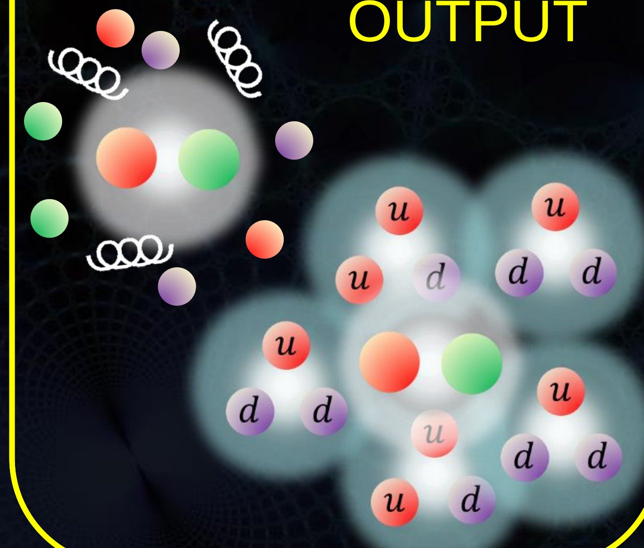
T- depend.
(ex. in hot π gas, QGP)



density depend.
(ex. in nuclear matter)



Hadron modification
OUTPUT



⇒QCD sum rule relates modification of OPE (or condensate) to modification of hadron state

QCD sum rules in nuclear matter

QCD sum rule

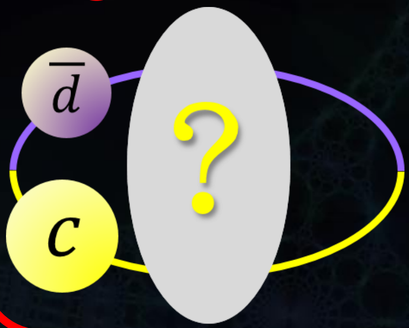
$$\Pi_{\mathrm{OPE}}(M) = \int_0^\infty K(s,M)\,\rho(t)\,ds$$

② Kernel

Weight of spectral function

- Gaussian sum rule

① OPE



- **dens.-dependence** of condensates up to dim.5

③ Output spectral function

- Maximum entropy method (MEM)

P. Gubler and M. Oka, PTP124 (2010) 995

- Charge-conjugate projection

cf.) D. Jido, N. Kodama, and M. Oka, PR**D54**, 4532 (1996)

cf.) A. Hayashigaki, PLB487 (2000) 96
T. Hilger, R. Thomas, B. Kampfer, PRC79 (2009) 025202

Condensates in nuclear matter

- Chiral-symmetry-breaking condensates

$\langle\bar{q}q\rangle_n = \langle\bar{q}q\rangle_{vac} + \frac{\sigma_N}{2m_q}n$	$\langle\bar{q}g\sigma Gq\rangle_n = \lambda^2\langle\bar{q}q\rangle_n$

- Others (Gluon cond. , Twist cond. , …)

$\left\langle\frac{\alpha_s}{\pi}G^2\right\rangle_n = \left\langle\frac{\alpha_s}{\pi}G^2\right\rangle_{vac} - \frac{8M_N^0}{9}n$	$\left\langle\frac{\alpha_s}{\pi}\left(\frac{(vG)^2}{v^2} - \frac{G^2}{4}\right)\right\rangle_n = (-0.05\mathrm{GeV})n$
$\left\langle q^\dagger iD_0 q\right\rangle_n = \frac{3}{8}M_N A_2^q(\mu^2)n$	$\left[\left\langle\bar{q}D_0^2 q\right\rangle_n - \frac{1}{8}\langle\bar{q}g\sigma Gq\rangle_n\right] = -\frac{3}{4}M_N^2 e_2^q(\mu^2)n$

⇒Same sign contribution to D and $\bar{D}$ meson

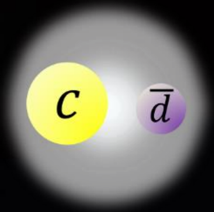
- Charge-symmetry-breaking condensates

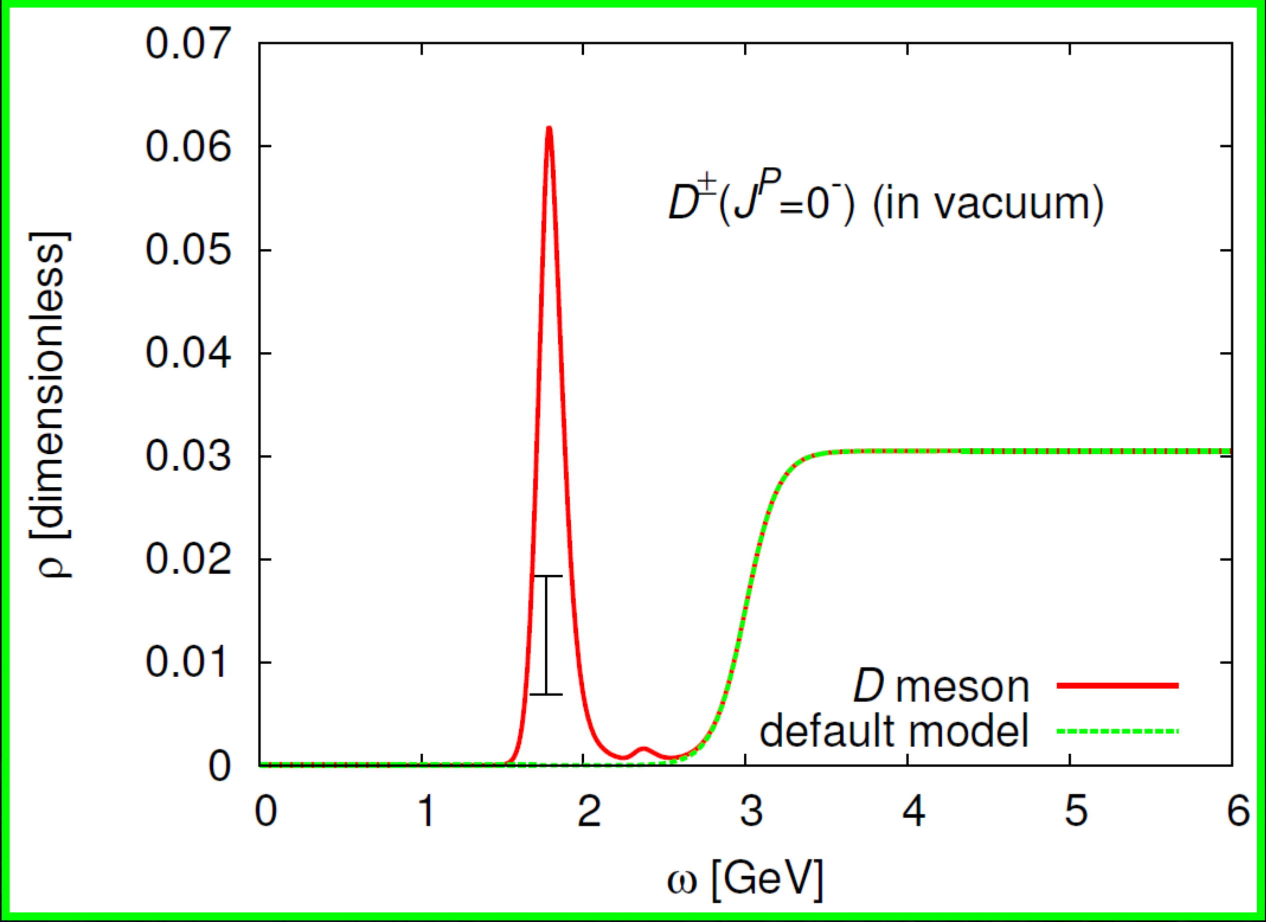
$\left\langle q^\dagger q\right\rangle_n = \frac{3}{2}n$	$\left\langle q^\dagger g\sigma Gq\right\rangle_n = (0.33\mathrm{GeV}^2)n$	$\left\langle q^\dagger D_0^2 q\right\rangle_n = -\frac{1}{4}M_N^2 A_3^q(\mu^2)n + \frac{1}{12}\left\langle q^\dagger g\sigma q\right\rangle_n$

⇒Opposite sign contribution to D and $\bar{D}$ meson

KS, P. Gubler and M. Oka

D meson spectral function (in vacuum)

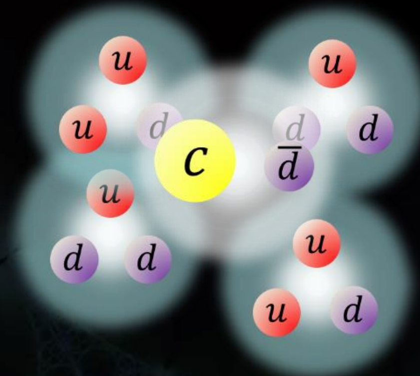




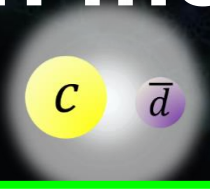
Mass : 1.78GeV Exp. : 1.87GeV

KS, P. Gubler and M. Oka

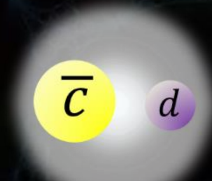
D meson spectral function (in medium)

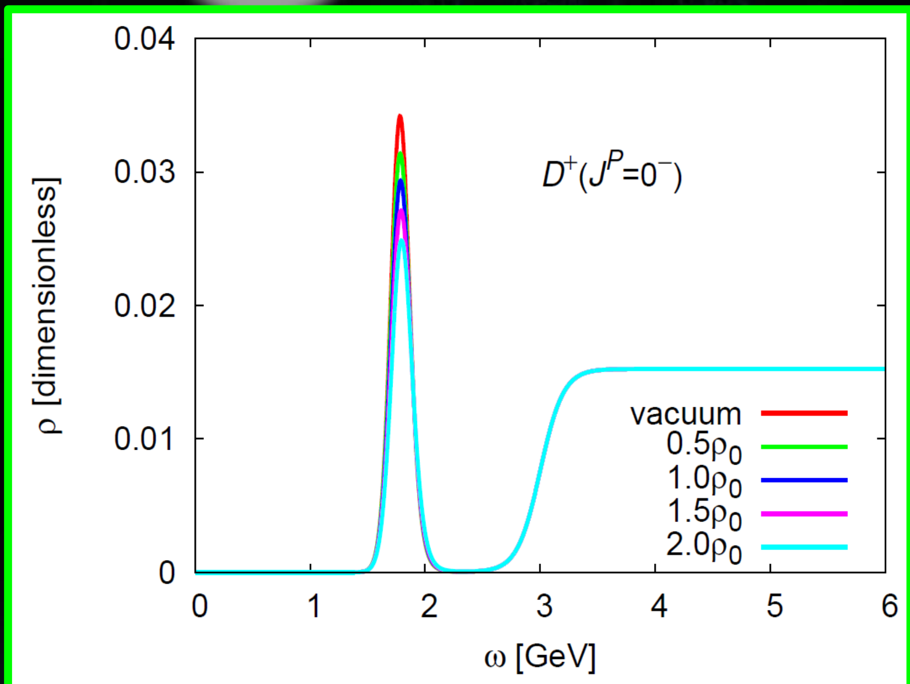


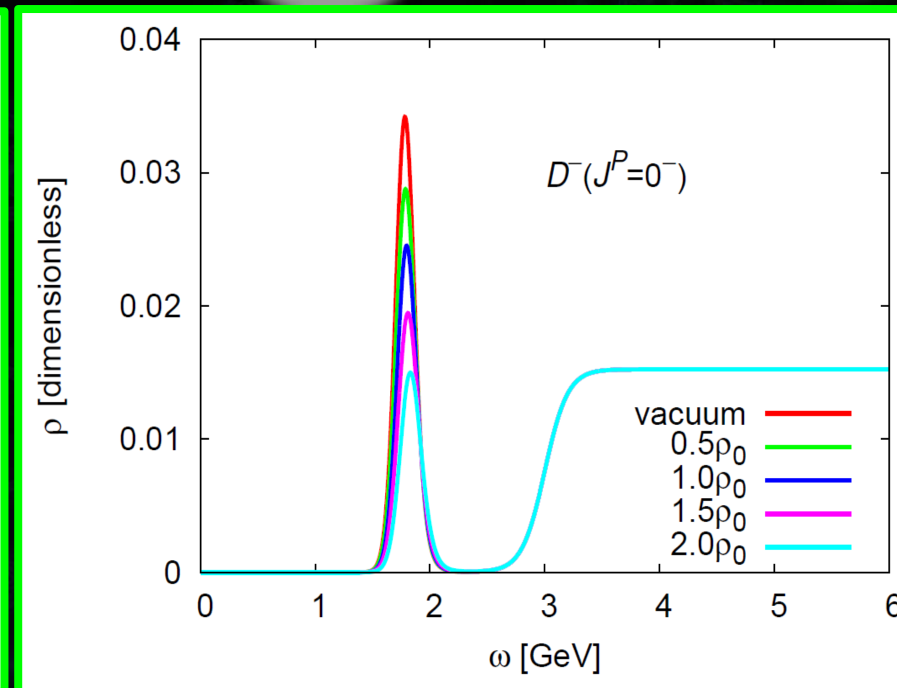
D^+



D^-



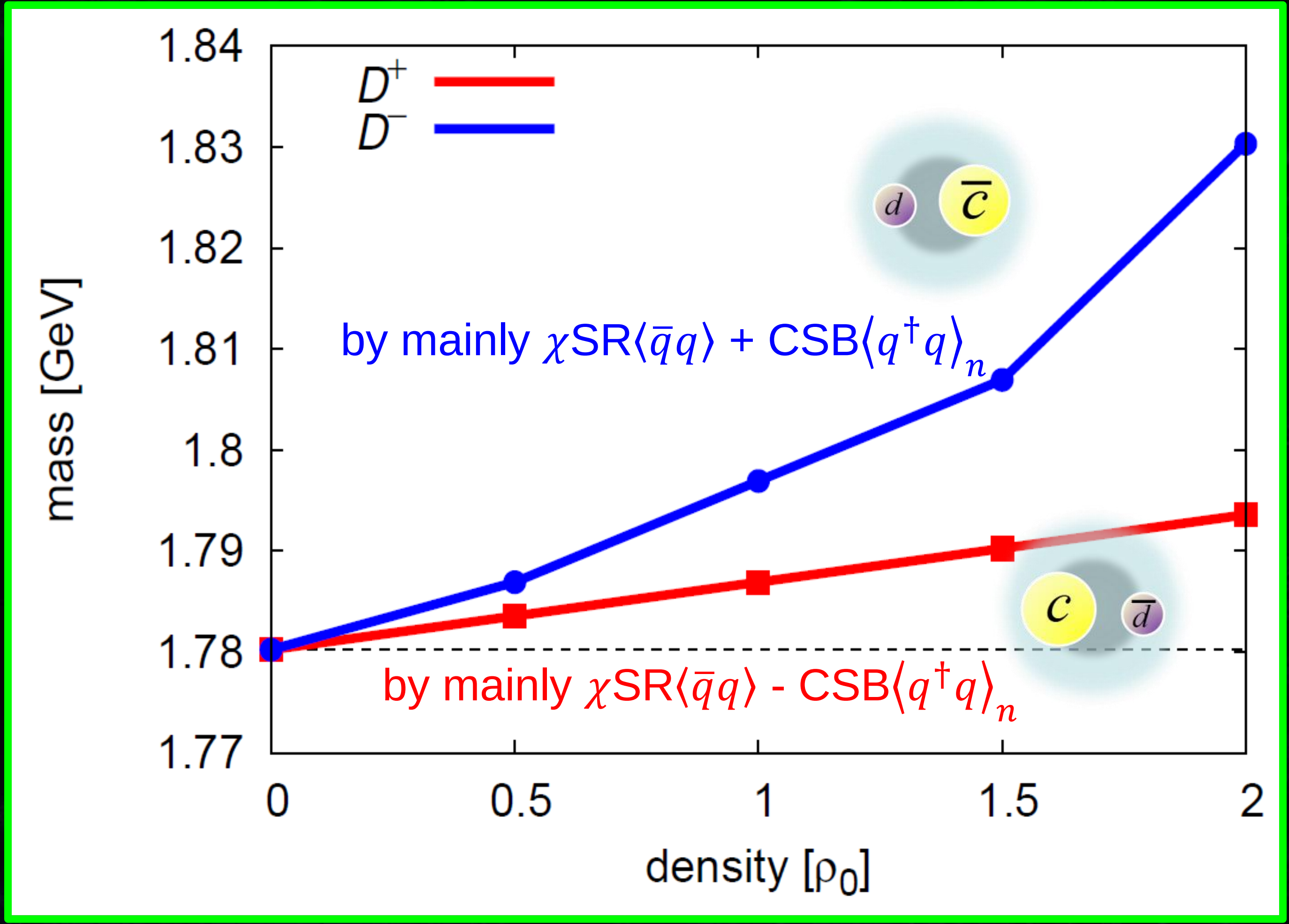




⇒Peak position in $D^{\pm}$ shifts to higher energy side with increasing density (D^+: ~5MeV D^-: ~15MeV at ρ_0)

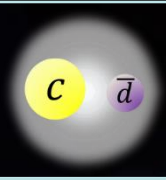
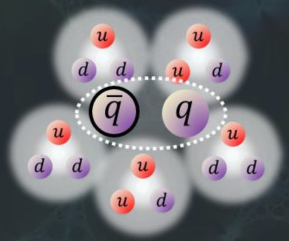
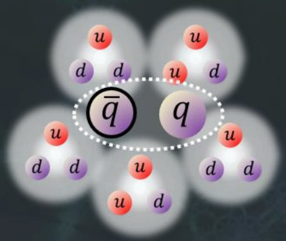
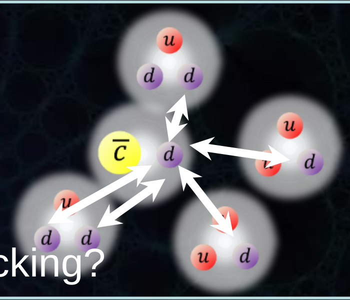
KS, P. Gubler and M. Oka

Comparison of D^+ and D^-



⇒D^+-D^- mass splitting is about 10 MeV at ρ_0

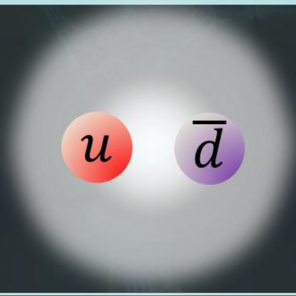
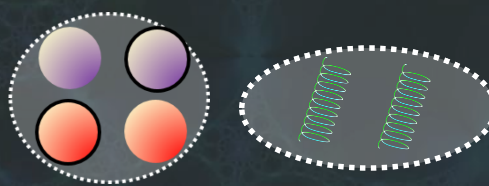
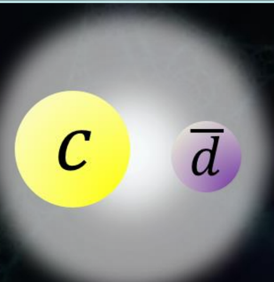
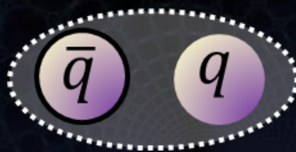
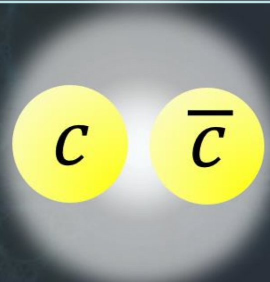
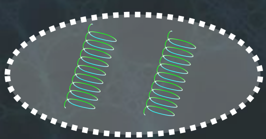
Summary of D meson in nuclear matter

	D+ 	D- 
χSR = $\langle \bar{q}q \rangle$ reduction	Increase↑↑ 	Increase↑↑ 
CSB effect	Decrease↓	Increase↑ 
Our results	Increase↑ (~5MeV)	More increase↑↑(~15MeV)

⇒D meson is a good probe of χSR and CSB

Backup

Difference of meson systems

Meson	Dominant contributions in vacuum
Light-Light (ρ, ω meson) 	Probe of 4-quark and gluon condensates (2-quark condensate is suppressed as $m_q\langle\bar{q}q\rangle$) 
Light-Heavy (D, B meson) 	Probe of 2-quark condensate as $m_c\langle\bar{q}q\rangle$  $\langle\bar{q}q\rangle$
Heavy-Heavy (J/ψ, Υ) 	Almost perturbative object (Probe of gluon condensate)  $\left\langle\frac{\alpha_s}{\pi}G^{\mu\nu}G_{\mu\nu}\right\rangle$

D meson OPE (in vacuum)

$$\Pi_{\mathrm{OPE}}(M^2) = \text{perturbative term}$$

$$+e^{-m_c^2/M^2}\left[-m_c\langle\bar{q}q\rangle + \frac{1}{2}\left(\frac{m_c^2}{2M^4} - \frac{1}{M^2}\right)m_c\langle\bar{q}g\sigma Gq\rangle\right.$$

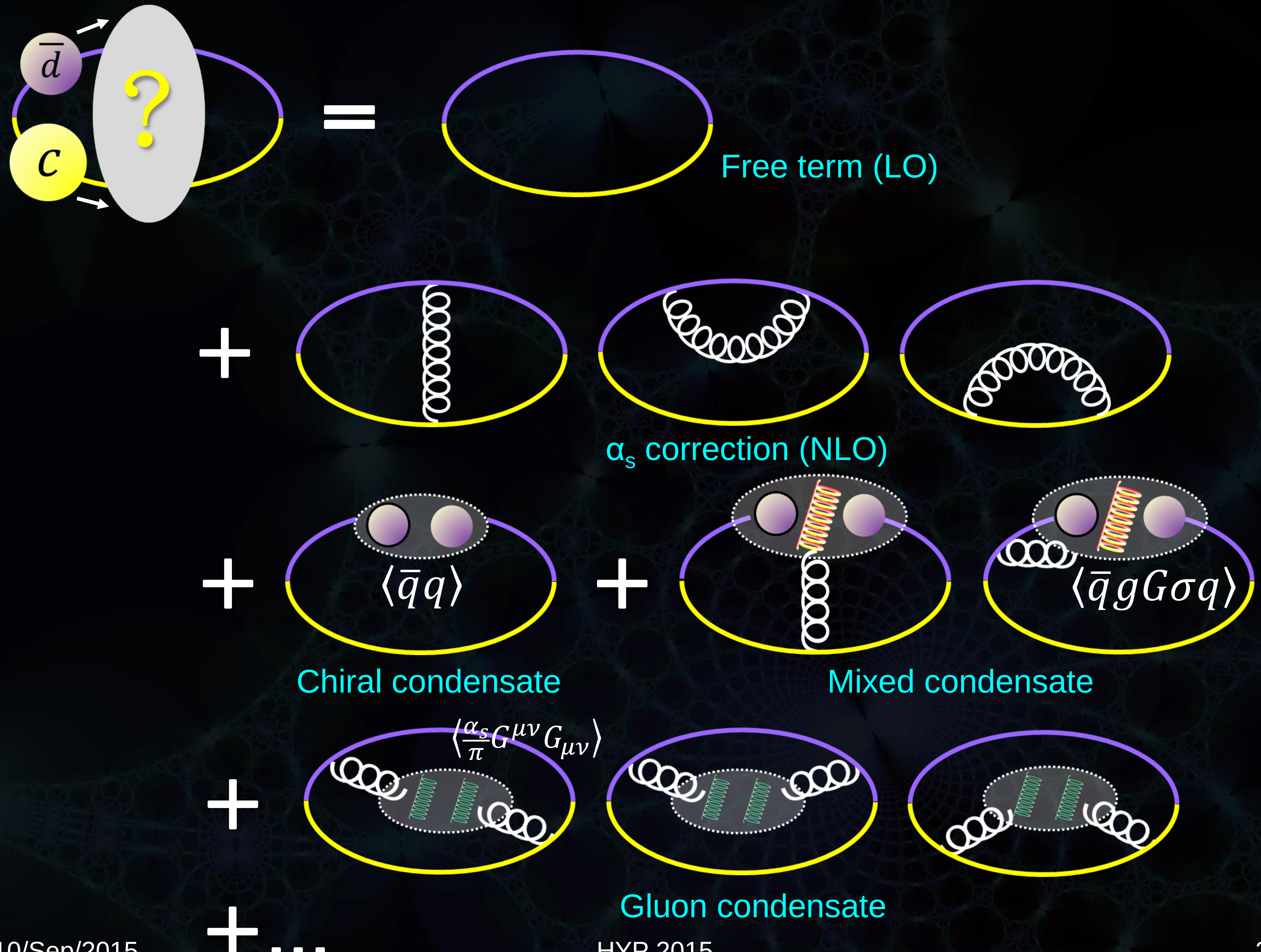
$$\left.+\frac{1}{12}\left\langle\frac{\alpha_s}{\pi}G^2\right\rangle - \frac{16\pi}{27}\frac{1}{M^2}\left(1 + \frac{1}{2}\frac{m_c^2}{M^2} - \frac{1}{12}\frac{m_c^4}{M^4}\right)\alpha_s\langle\bar{q}q\rangle^2\right]$$

1. Chiral condensate
2. Mixed condensate

Coefficients are proportional to charm quark mass
⇒These terms are enhanced

3. Gluon condensate
4. 4-quark condensate

Other condensates are relatively suppressed



$\bar{d}$
c
?
=
Free term (LO)
+
α_s correction (NLO)
+
$\langle \bar{q}q \rangle$
+
$\langle \bar{q}gG\sigma q \rangle$
Chiral condensate
Mixed condensate
$\langle \frac{\alpha_s}{\pi} G^{\mu\nu} G_{\mu\nu} \rangle$
+
Gluon condensate
+ ...