Chiral Thermodynamics with Charm

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Outline

- chiral doublers of heavy-light mesons, effective theory
- interplay between light and heavy quark dynamics
- fluctuations, transport coefficients, diffusion constant

in collaboration with K. Redlich

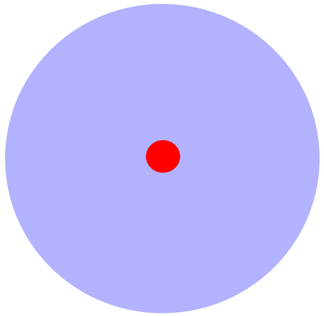
I. Chiral structure of heavy-light mesons

Symmetries of QCD in the heavy quark mass limit

- flavor symmetries

$$\text{chiral symmetry}: \quad m_{u,d}/\Lambda_{\rm QCD} \ll 1\,, \quad m_s/\Lambda_{\rm QCD} < 1\,.$$
$$\text{heavy quark symmetry}: \quad \Lambda_{\rm QCD}/m_{c,b} \ll 1\,.$$

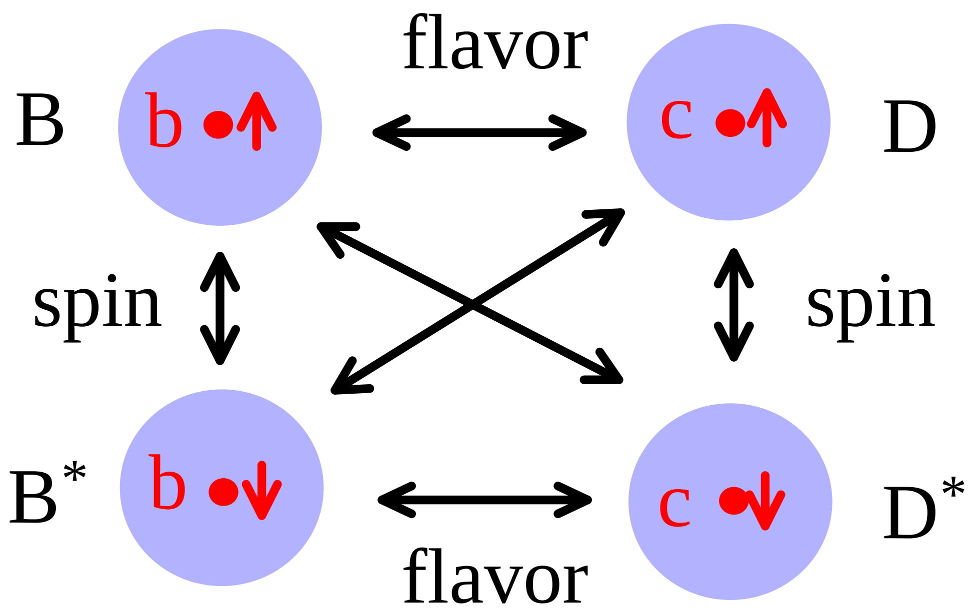
- heavy-light ($Q\bar{q}$) mesons Q : heavy quark and q : light quark
  e.g. D mesons: $Q = c$, $q = u, d, s$



- physical picture ($m_Q \to \infty$)
  - **flavor symmetry** ($c \leftrightarrow b$): cloud does not feel the flavor of Q.
  - **spin symmetry**: cloud does not feel the spin of Q.

Spin and flavor symmetries of heavy quarks are entangled!

- $SU(2N_{Qf})$ **spin-flavor symmetry**: [Isgur-Wise (89)]
light d.o.f. (q) do not feel the flavor and spin of the heavy quark (Q).



- spin partners: $D(0^-)$ and $D(1^-)$, $B(0^-)$ and $B(1^-)$
- **reality**:
$m_{D^*} - m_D = 142$ MeV , $m_{B^*} - m_B = 46$ MeV $\ll \Lambda_{\rm QCD}$
$\cdots$ $1/m_Q$ corrections
$m_{Ds} - m_{Dd} = 100$ MeV , $m_{Bs} - m_{Bd} = 90$ MeV $\ll \Lambda_{\rm QCD}$
$\cdots$ m_q corrections

Role of light flavor (chiral) symmetry

- **observation**:

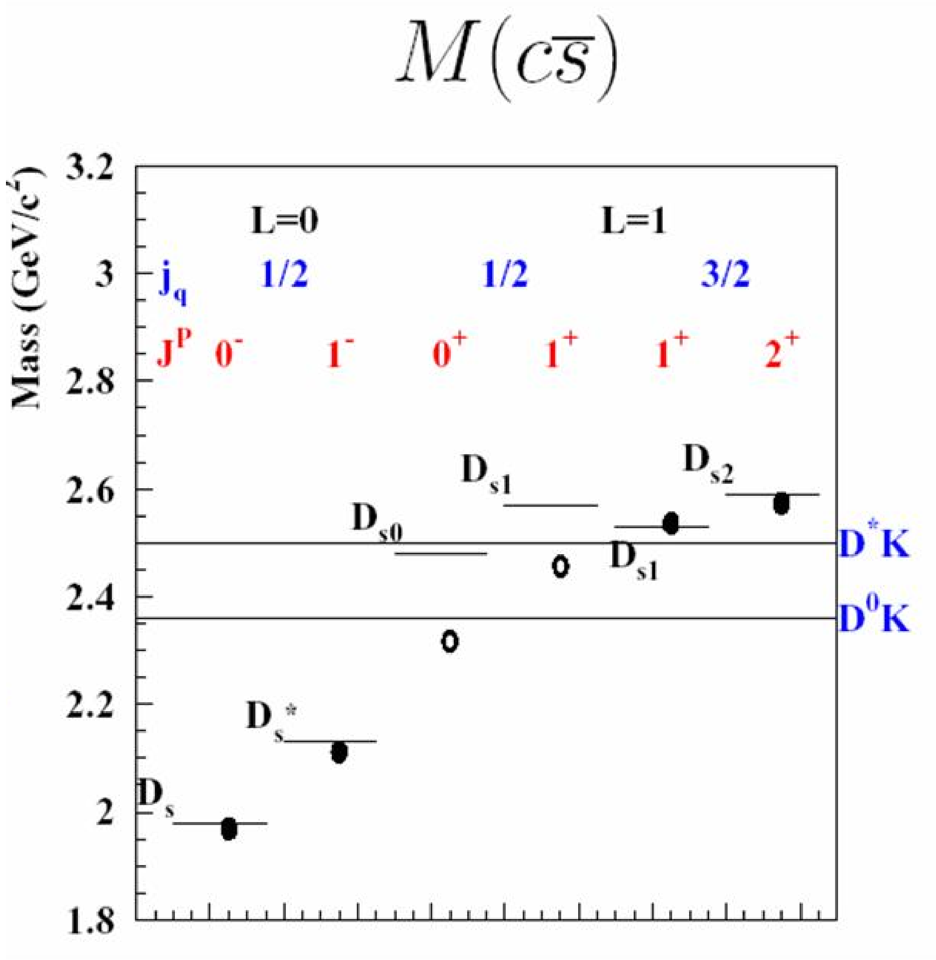
$$D_{u,d}(0^+) : 2308\,\text{MeV} \quad \text{[Belle (03)]}$$
$$D_{u,d}(1^+) : 2427\,\text{MeV} \quad \text{[Belle (03)]}$$
$$D_s(0^+) : 2317\,\text{MeV} \quad \text{[Babar (03)]}$$
$$D_s(1^+) : 2460\,\text{MeV} \quad \text{[CLEO (03)]}$$

- spin doublets: $D(0^+)$-$D(1^+)$
- mass difference:

$$m(0^+, 1^+) - m(0^-, 1^-) = 300 - 400\,\text{MeV} \sim \Lambda_{\text{QCD}}\,.$$

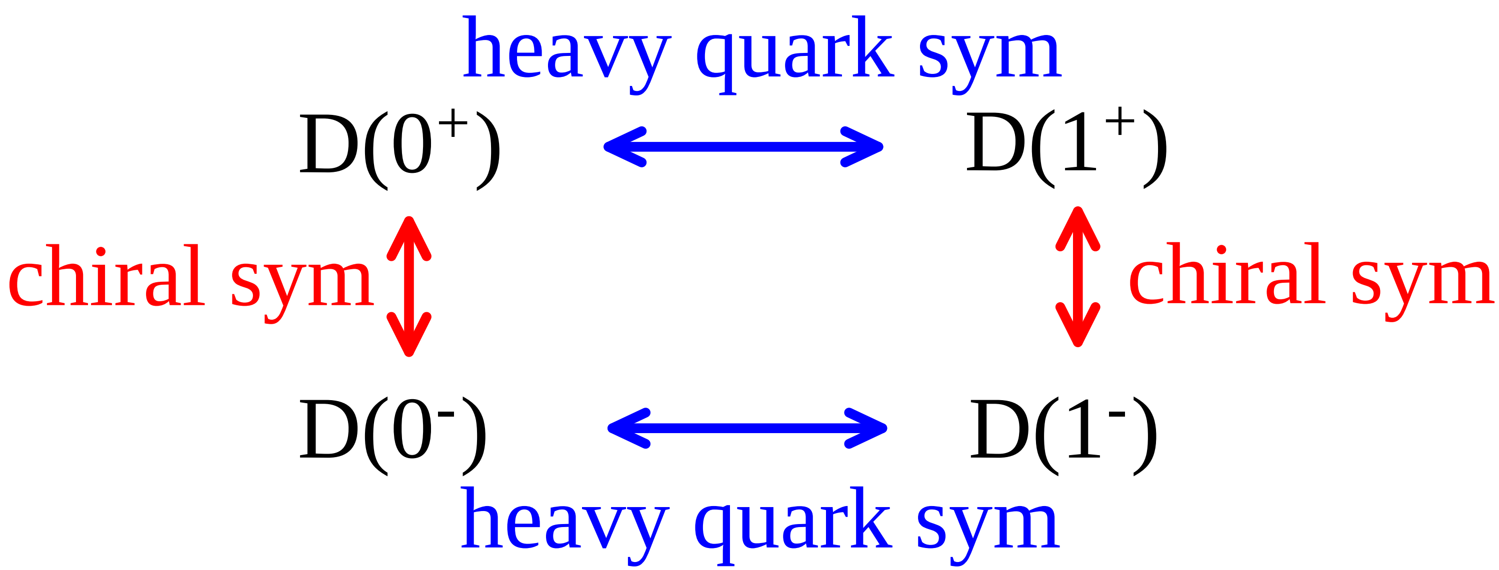
Why is Δm so small?

• potential model for D mesons   cf. hydrogen atom



what is missing? — chiral symmetry!!

- chiral doubling [Nowak-Rho-Zahed (92); Bardeen-Hill (93)]



chiral partners:

$$m(0^+) - m(0^-)\,, \quad m(1^+) - m(1^-) \propto \langle \bar{q} q \rangle \sim m_{\text{const}}$$

- 4-fermi (qqQQ) theory: heavy modes integrated out
  $\Rightarrow$ an effective Lagrangian for HL mesons

effective theory for heavy-light system based on the two relevant symmetries

- confirmed by the measurements in 2003!

Questions

How does the presence of charmed chiral doublers influence over thermodynamics around $T_{\rm ch}$?

- interplay between light and heavy quark sector
- susceptibilities and higher-order fluctuations
- heavy-ion exp.: transport coefficients, diffusion of D mesons

$\Rightarrow$ effective theory for L AND HL mesons:
NRZ/BH $plus$ additional terms in the potential [CS-Redlich 2013-14]

II. Extension of LSM: from $N_f = 2 + 1$ to $N_f = 2 + 1 + 1$

Constructing effective Lagrangian

- heavy fermion reduction

$$p_Q^\mu = m_Q v^\mu + k^\mu \,, \quad k^\mu \sim \mathcal{O}(\Lambda_{\rm QCD})\,.$$

4-velocity in the rest frame of Q: $v^\mu = (1, \vec{0})$

- heavy-light meson fields $H : (0^-, 1^-)$, $G : (0^+, 1^+)$

$$H = \frac{1+\not{v}}{2}\left[P_\mu \gamma^\mu + iP\gamma_5\right] \,, \quad G = \frac{1+\not{v}}{2}\left[-iQ_\mu\gamma^\mu\gamma_5 + Q\right] \,.$$

$\Leftrightarrow$ chiral eigenstates

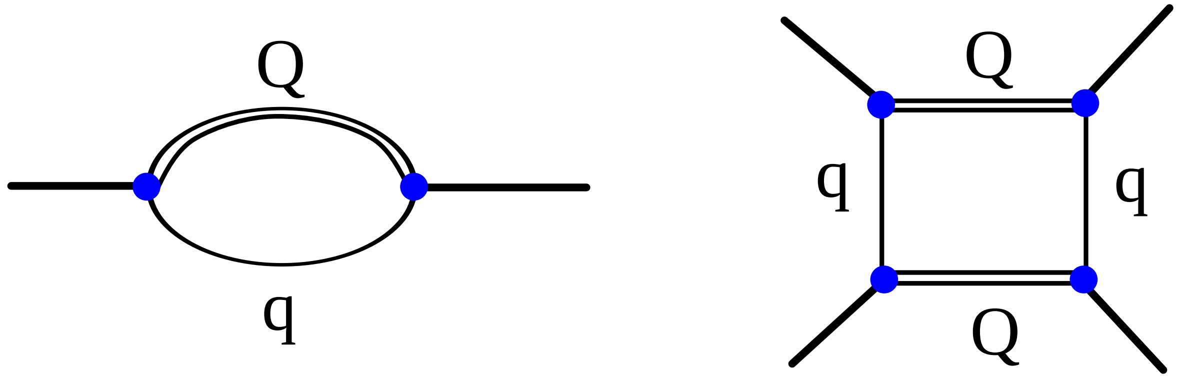
$$\mathcal{H}_{L,R} = \frac{1}{\sqrt{2}}(G \pm iH\gamma_5) \to S\mathcal{H}_{L,R}g_{L,R}^\dagger \,,$$

with

$$g_{L,R} \in SU(3)_{L,R} \,, \quad S \in SU(2)_{Q=c} \,.$$

- HL Lagrangian w/ chiral SU(3) symmetry

$$\mathcal{L}_{\rm HL} = \frac{1}{2}{\rm Tr}\left[-\bar{H} i v\cdot\partial H + \bar{G} i v\cdot\partial G\right] - V_{\rm HL}\,,$$
$$V_{\rm HL} = V_{\rm HL}^{(2)}\left(\mathcal{H}^2,\Sigma\right) + V_{\rm HL}^{(4)}\left(\mathcal{H}^4,\Sigma\right)\,.$$
$$\Rightarrow\ \mathcal{L} = \mathcal{L}_{\rm L} + \mathcal{L}_{\rm HL}\,.$$



- mean field approximation *plus* isospin-inv.

$$\Sigma^a \to \sigma^0,\sigma^8 \to \sigma_q,\sigma_s\,,\quad H\to 0\,,\quad G\to\frac{1+\not{v}}{2}D\,,$$
$$D = (D_u,D_d,D_s) = (D_q,D_q,D_s)\,.$$

- 7 parameters $\Leftarrow M_{D,D_s}(0^-)$, $M_{D,D_s}(0^+)$, F_{D,D_s}, $\Gamma(D^* \to D\pi)$
- thermodynamic potential

$$\Omega = \Omega_{f=u,d,s,c} + V_{\rm L} + V_{\rm HL} \,.$$

$$\frac{\partial \Omega}{\partial \sigma_q} = \frac{\partial \Omega}{\partial \sigma_s} = \frac{\partial \Omega}{\partial D_q} = \frac{\partial \Omega}{\partial D_s} = 0 \,.$$

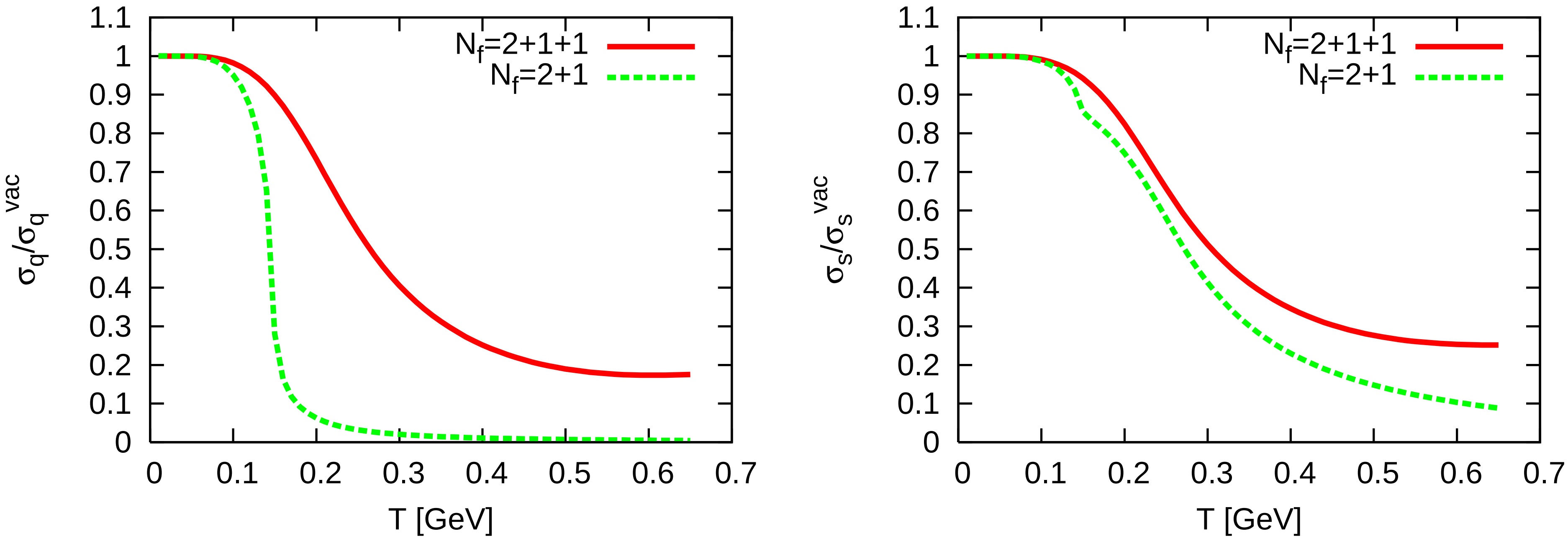
- **explicit SU(3) breaking**
  - light: $m_K - m_\pi = 358$ MeV
  - HL (0^+): $m_{D_s} - m_D = 25$ MeV! [QCDSR: Narison (05)]
  - PDG: $m_{D_s} = 2317.8 \pm 0.6$ MeV , $m_D = 2318 \pm 29$ MeV

much smaller SU(3) breaking in HL sector!

$\Rightarrow$ non-trivial modification of $\langle \sigma_{q,s} \rangle$ at finite temperature

III. Thermodynamics

• VEV of light scalar mesons ($N_f = 2+1$ vs. $N_f = 2+1+1$)



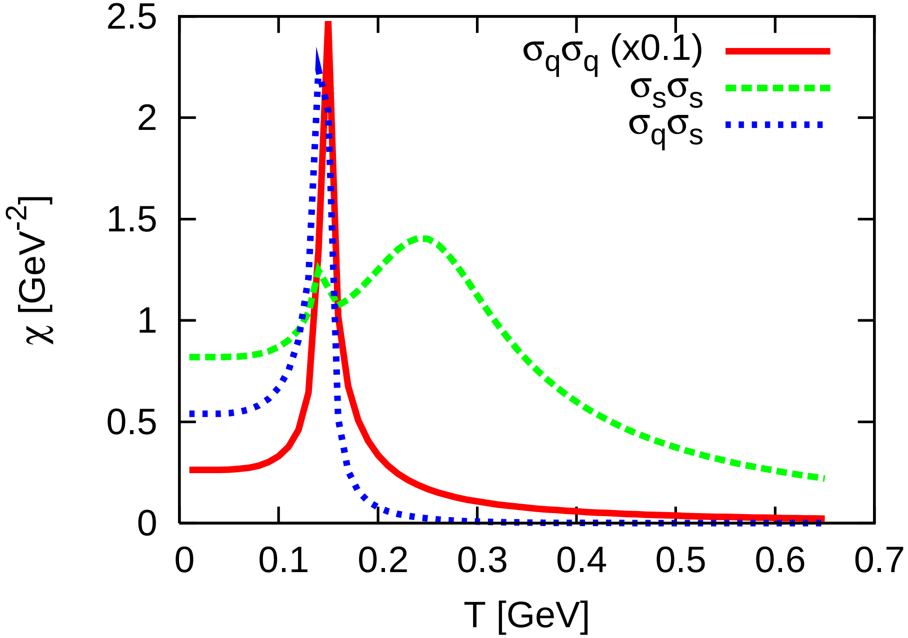
much stronger crossover!

– the presence of HL mean fields ∼ explicit chiral SU(3) breaking
  ⇒ strong interference between light and heavy quark dynamics

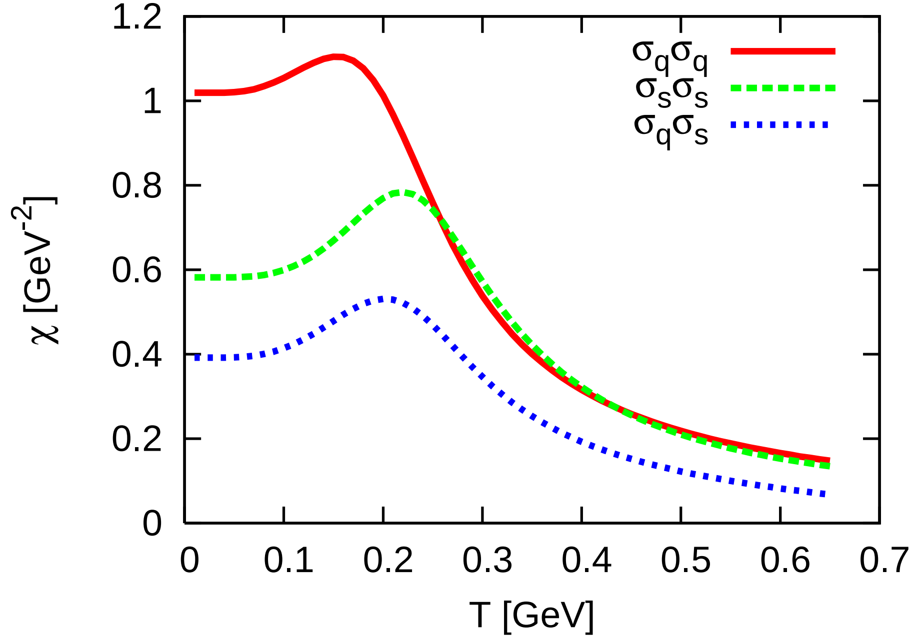
– strong interference between (u, d) and s sector

- susceptibilities

$N_f = 2+1$



$N_f = 2+1+1$



– broadened but peaked in a similar T range

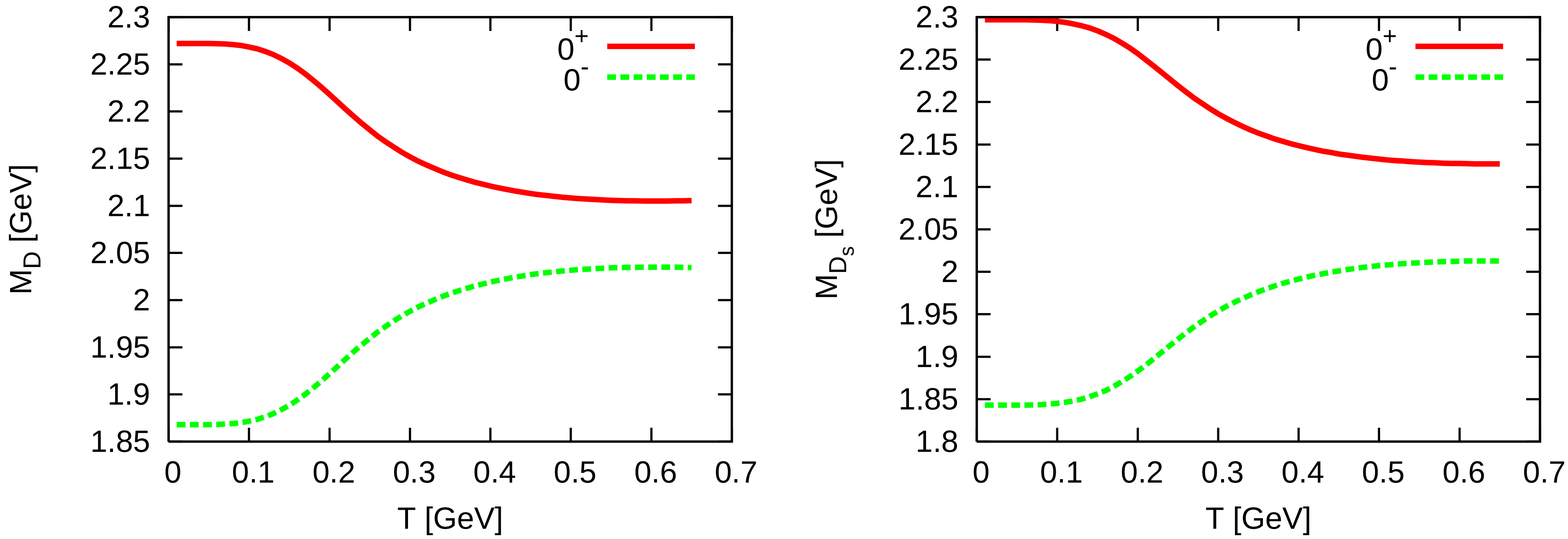
$N_f = 2+1+1$: $T_c^{qq} \sim 160$ MeV, $T_c^{qs} \sim 200$ MeV $T_c^{ss} \sim 220$ MeV

$N_f = 2+1$: $T_c^{qq} \sim 150$ MeV, $T_c^{qs} \sim 150$ MeV $T_c^{ss} \sim 240$ MeV

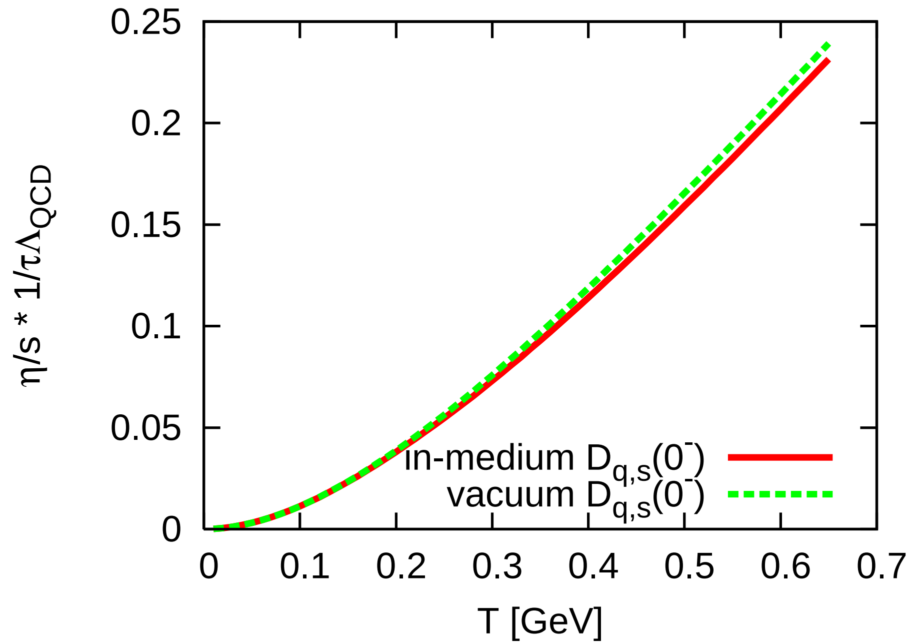
– higher-order fluctuations $c_n = \partial^n (P/T^4)/\partial(\mu/T)^n|_{\mu=0}$

$\Rightarrow$ no significance in $c_{2,4}$ but strong modification in c_6

- masses of chiral doublers



- shear viscosity for D mesons (w/ relaxation time approx.)

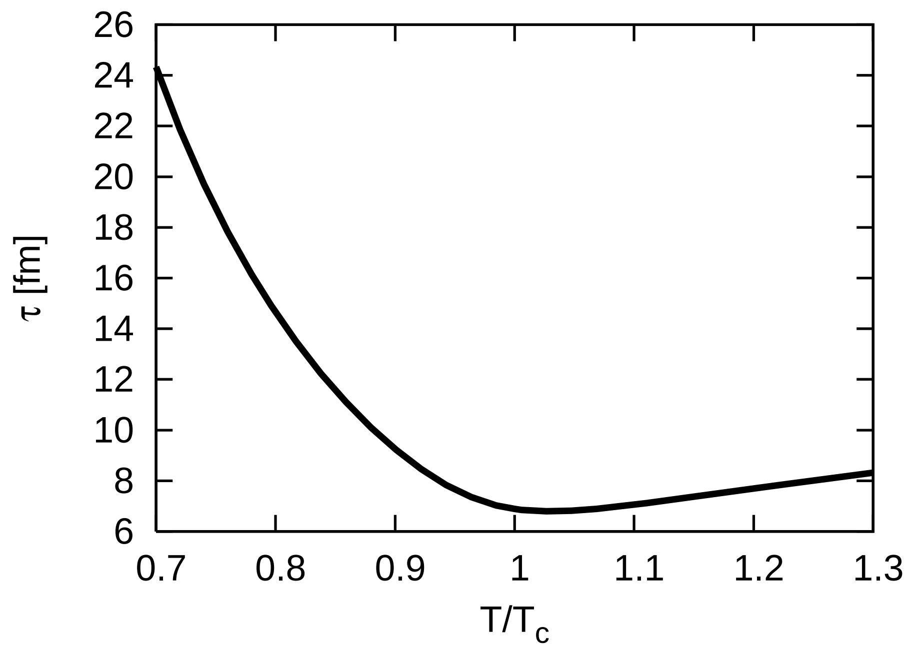


$$\frac{\eta}{\tau} = \frac{d_{\mathrm{d.o.f.}}}{15T} \int \frac{d^3p}{(2\pi)^3} \frac{\vec{p}^4}{E^2} n_D \left(1 + n_D\right) .$$

τ: relax. time $\Leftarrow$ dynamics!

cf. $N_f = 2$ NJL, $\tau \sim (n \cdot \sigma)^{-1}$
critical scattering σ around T_c

in-medium D mesons:
$\Rightarrow$ more significance in τ expected
$\Rightarrow$ diffusion constant $TD_s \sim \eta/s$
signals of χ-restoration!



Summary and Remarks

- **Interplay between light and heavy quark dynamics**
  - formulation made at $\mu_q = 0$
  - strong chiral crossover
  - SU(3) breaking effectively reduced
  - susceptibilities feel chiral crossover.
  - more important in c_6 vs. remnant of O(4) in QCD?
- **Issues**
  - fluctuations, application to finite μ
  - relaxation time, diffusion constant
  - spectral functions, role of light vector mesons cf. Harada-Rho-CS (03)

strong gauge dynamics: fluctuations and correlations for better discrimination