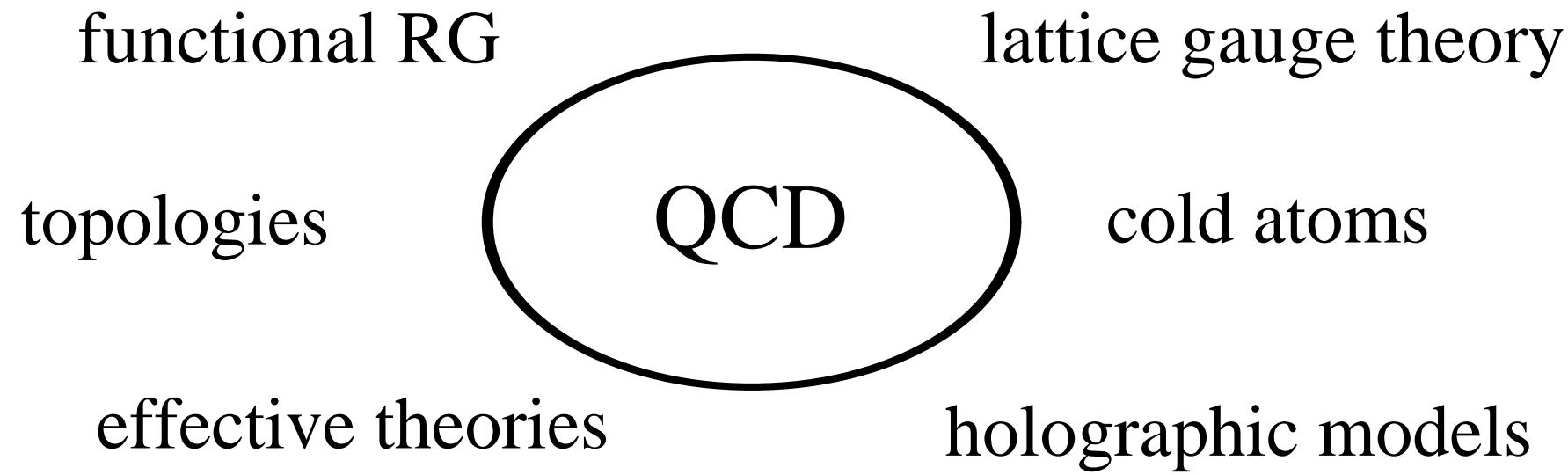


# **New Developments in Thermal Field Theory**

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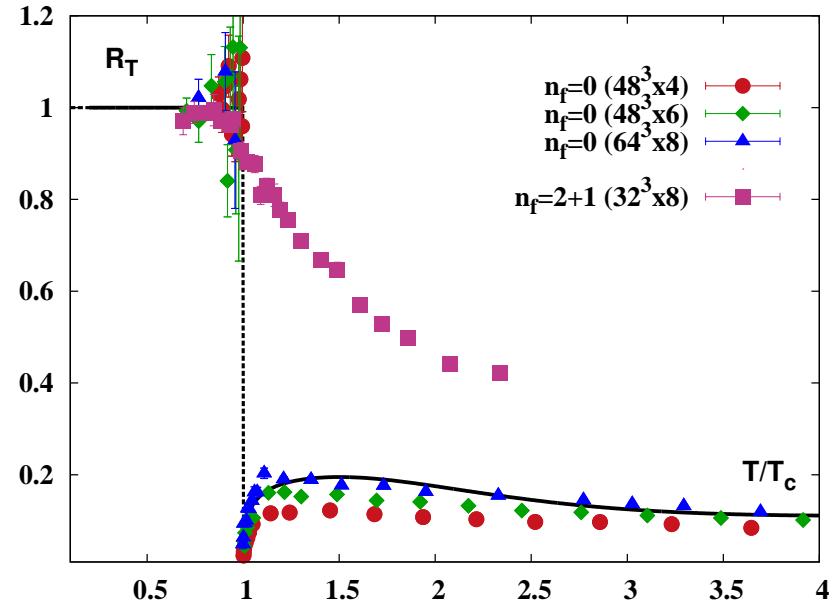
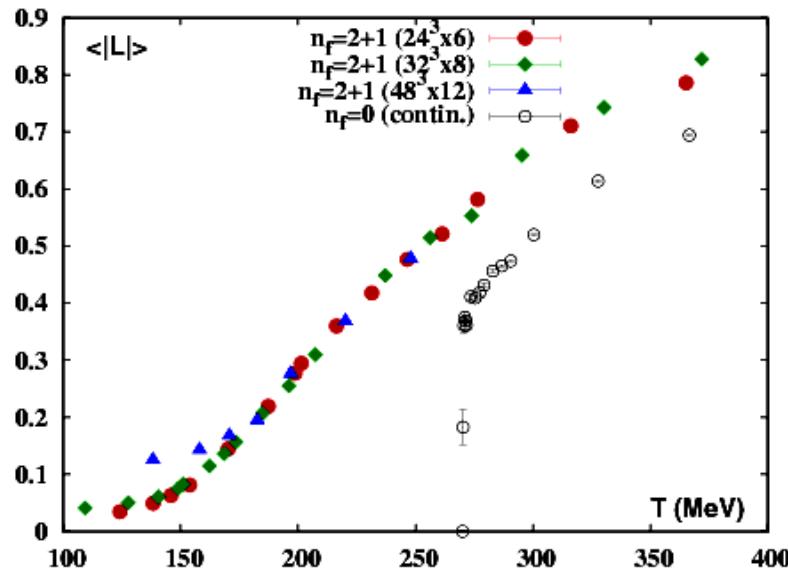
## **Selected Issues:**

- interplay between chiral symmetry breaking and confinement
- role of QCD trace anomaly
- hadrons near chiral symmetry restoration
- chiral thermodynamics of charmed mesons

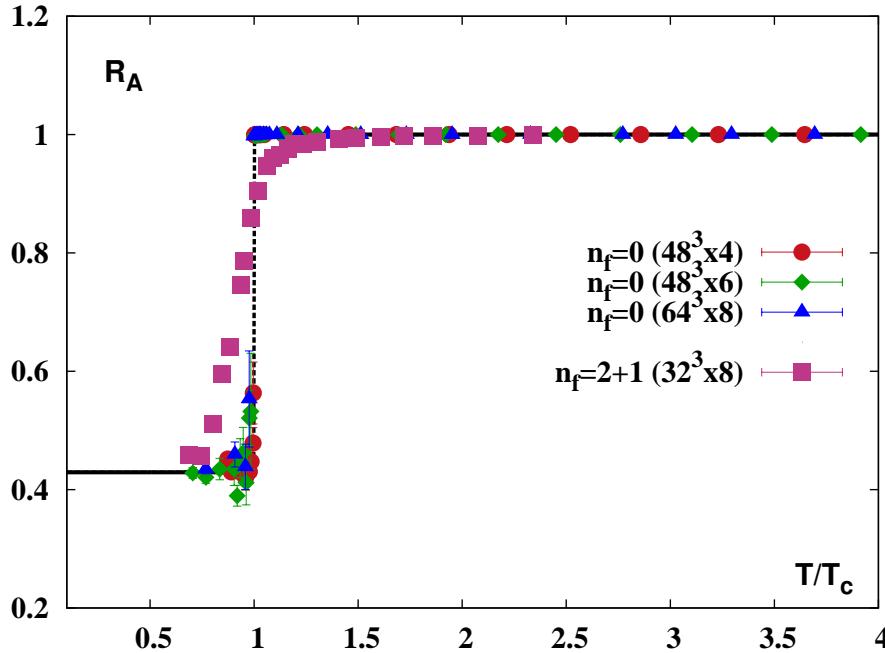


## **I. Chiral Symmetry Breaking vs. Confinement**

# Probing deconfinement with Polyakov-loop fluctuations

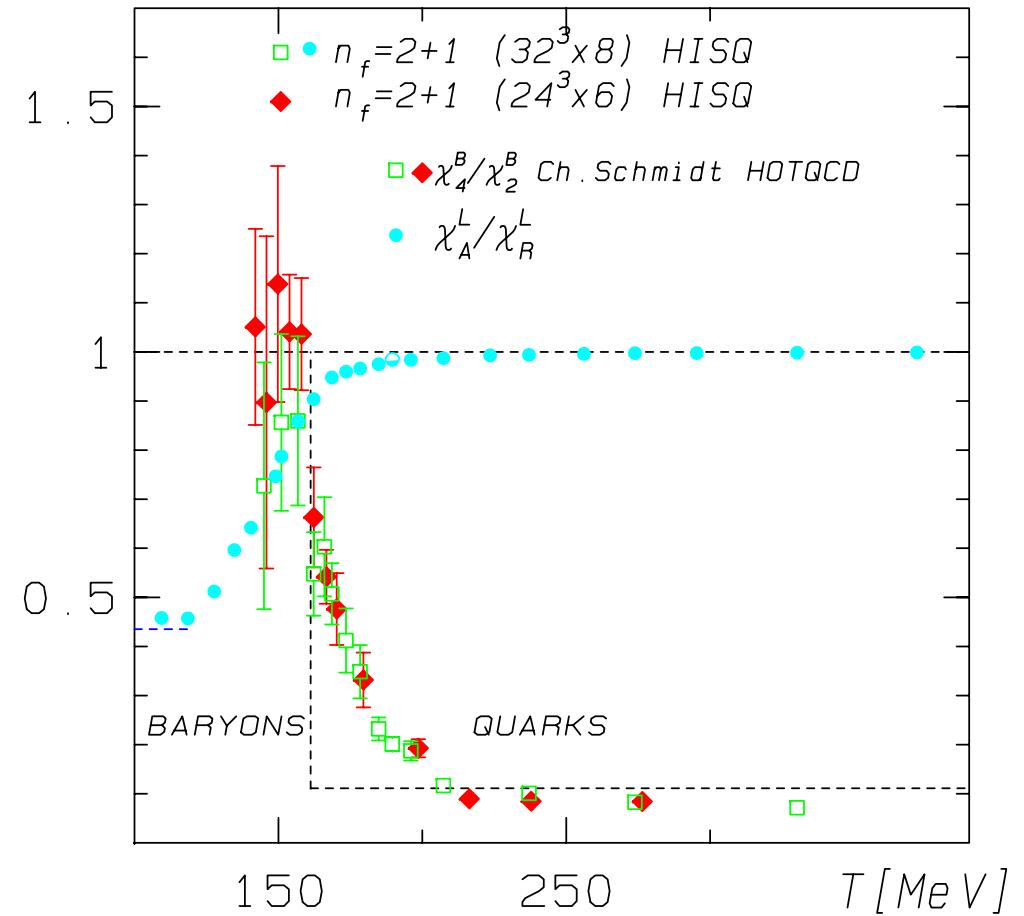


- Polyakov loop  $L$ : quite broaden in QCD [HotQCD Collaboration]
- susceptibilities of  $L$  and their ratios: [Lo, Friman, Kaczmarek, Redlich, CS ('13)]  
modulus (A), real (R) and imaginary (I) part of  $L$ :  $\chi_A, \chi_R, \chi_I$ 
  - ratios:  $R_A = \chi_A / \chi_R$ ,  $R_T = \chi_I / \chi_R$  vs.  $T$
  - ambiguity of renor. prescription can be avoided to large extent!
  - pure YM vs.  $N_f = 2 + 1$  QCD (HISQ) on lattice ( $T_{\text{chiral}} = 155$  MeV): broad  $R_T$  due to exp.  $Z(3)$  symmetry



[Lo, Friman, Kaczmarek, Redlich, CS ('13)]

[Lo, Friman, Kaczmarek, Karsch, Redlich, CS ('14)]



- a clear remnant of  $Z(3)$  in  $R_A$ ! pseudo-critical temperatures  $T_{\text{ch}} \simeq T_{\text{dec}}$ !
- quark number fluctuations: kurtosis measures fermion number  $B^2$

Lattice QCD:  $T_{\text{ch}} \sim T_{\text{dec}}$  at zero density [also talk by H.-T. Ding]

- Polyakov-loop model with quarks (a la PNJL/PQM) *does not* reproduce  $R_A, R_T \dots$  dynamics of confinement missed!

## Confinement vs. dynamical chiral symmetry breaking ( $D\chi SB$ )

to which extent does  $D\chi SB$  contain information on confinement?

- Banks-Casher relation: low-lying Dirac eigenmodes generate  $\langle \bar{q}q \rangle$ .

**removal of low-lying Dirac modes  $\Rightarrow$  NO  $D\chi SB$**   
**Q. does confinement disappear simultaneously?**

- linking Polyakov loop to spectral function of *lattice* Dirac operator

[Gattringer ('06); Bruckmann, Gattringer, Hagen ('07); Synatschke, Wipf, Langfeld ('08)]

manifestly gauge invariant formalism

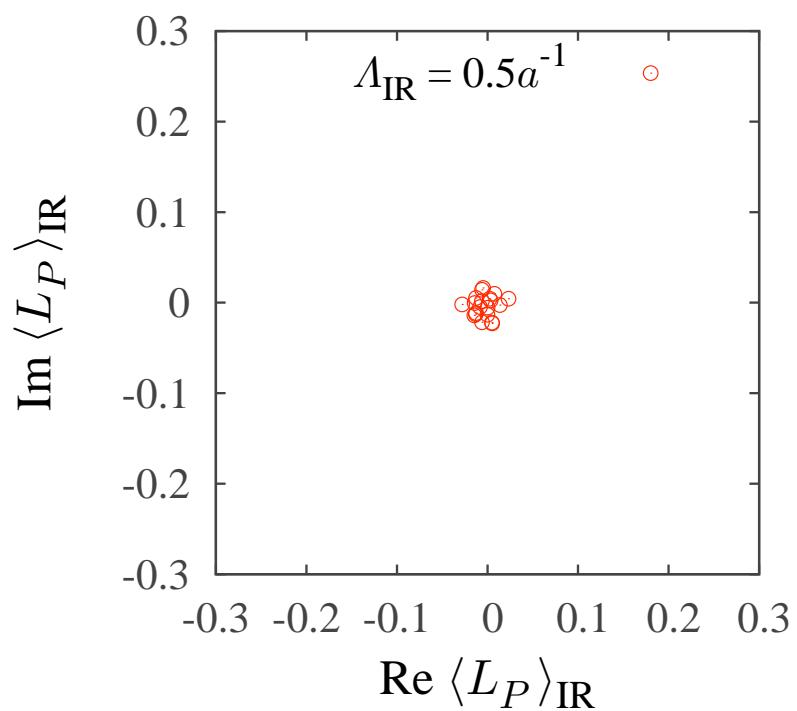
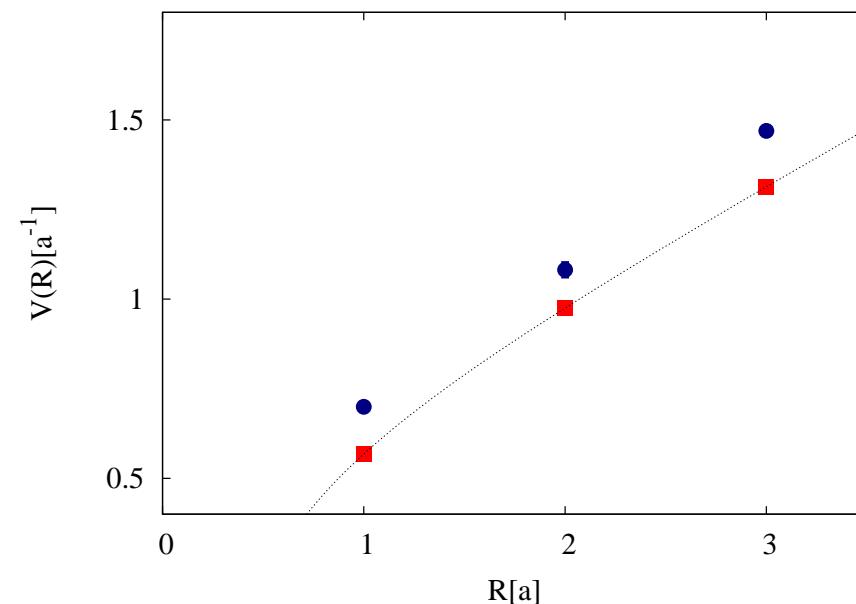
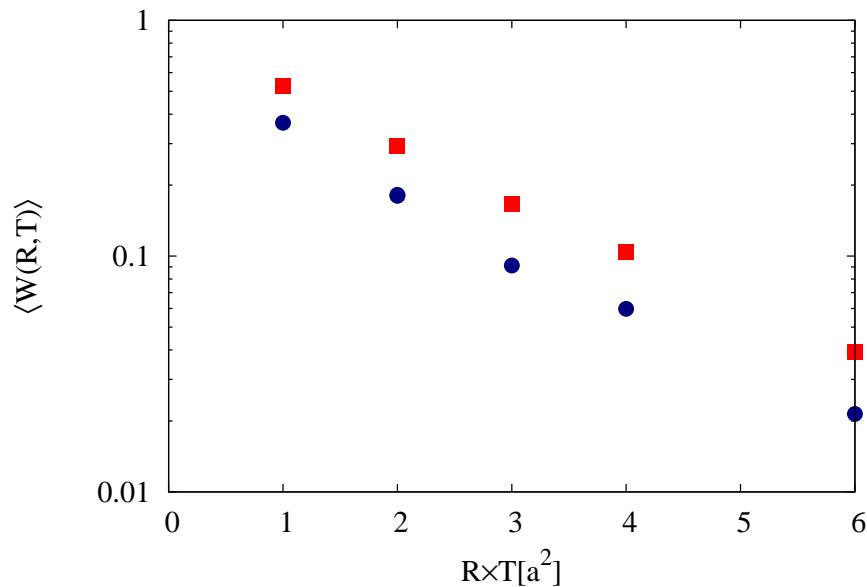
[Gongyo, Iritani, Suganuma ('12); Doi, Iritani, Suganuma ('13,14)]

$$\langle L \rangle = \frac{(2i)^{N_t-1}}{12V} \sum_n \lambda_n^{N_t-1} \langle n | \hat{U}_4 | n \rangle \quad (*)$$

**NO particular Dirac-modes that crucially affect confinement!**



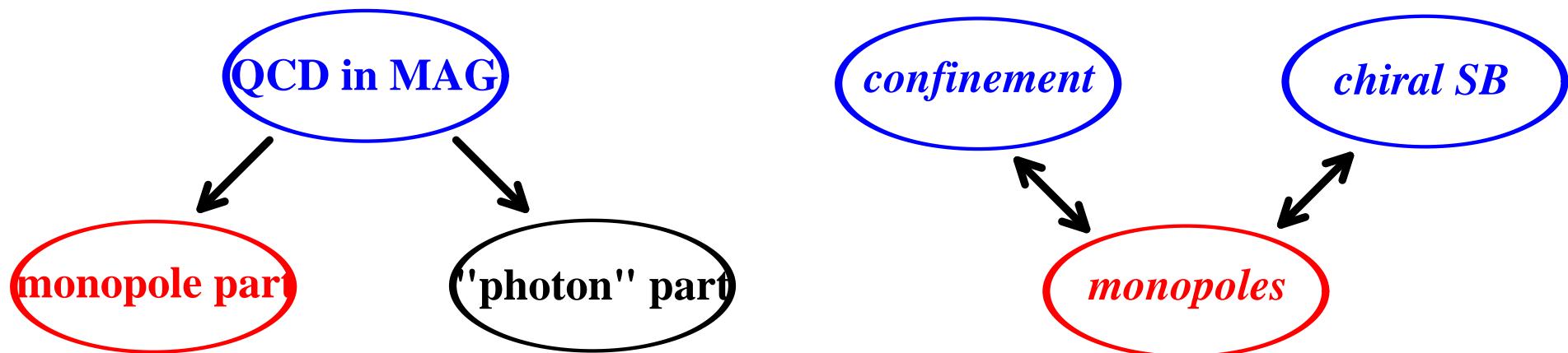
**disappearance of  $D\chi SB$  DOES NOT mean deconfinement?**



- full vs. ● w/o low-lying modes
- Wilson loop, quark potential:  
 $\langle W \rangle \propto e^{-\sigma RT}$ : slope parameter = string tension  $\Rightarrow$  unchanged!
- no D $\chi$ SB  $\neq$  no confinement
- survival hadrons in chiral symmetric phase
- NOTE: static quarks? but (\*)?

## Dual Ginzburg-Landau picture

[*'t Hooft ('75); Mandelstam ('76)*]



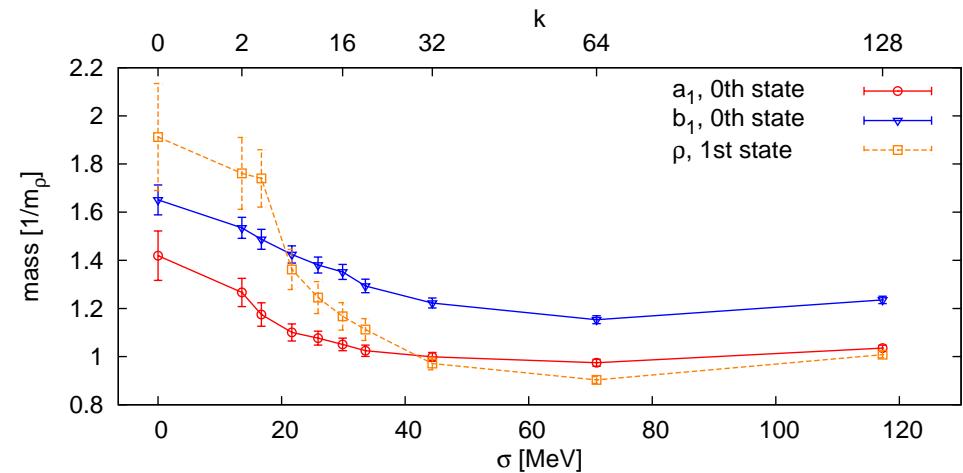
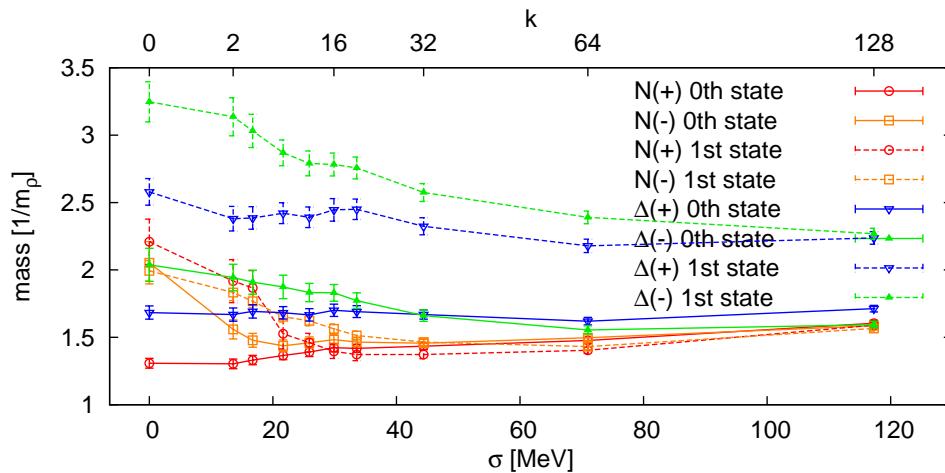
- dual Meissner effect  $\Rightarrow$  monopole condensation:  
QCD with Maximal Abelian Gauge (MAG) [*'t Hooft ('81); Ezawa, Iwasaki ('82)*]
  - monopole part: linear confinement potential,  $D\chi$ SB, instantons
  - Abelian part: trivial vacuum (no confinement, no  $D\chi$ SB)

**confinement and  $D\chi$ SB induced by monopole condensation**

- how monopoles and Dirac eigenmodes are related?
- effective theory in continuum?

## **II. Role of QCD Trace Anomaly**

# Fate of hadron masses toward chiral symmetry restoration

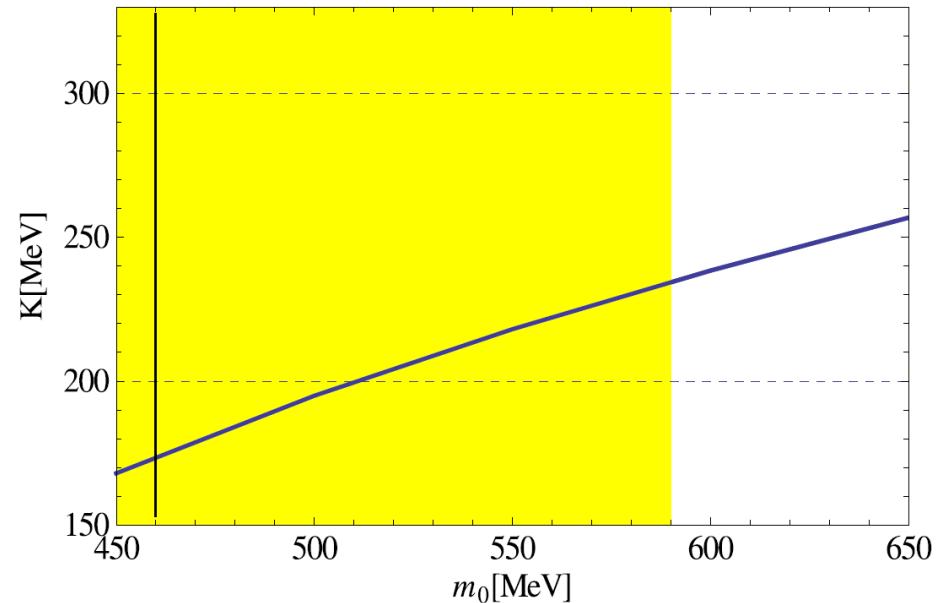
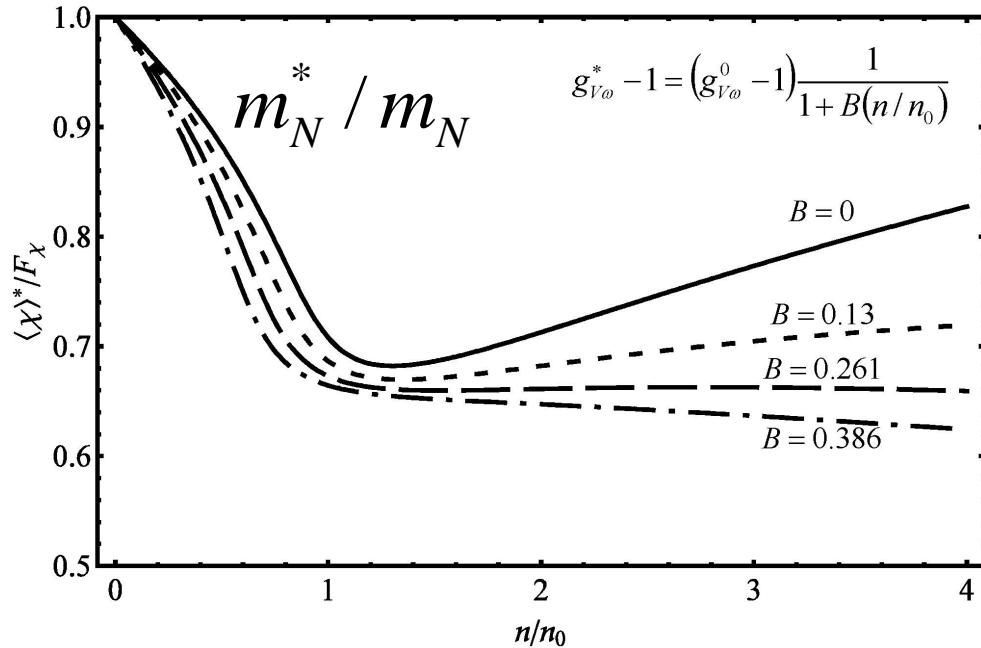


- hadron masses vs. truncation level on lattice [Glozman, Lang, Schrock ('12)]
  - removal of lowest Dirac-eigenmodes  $\Leftrightarrow$  NO  $\langle\bar{q}q\rangle$   
 $\Rightarrow$  parity partners degenerate *and* stay quite massive!
  - no universal scaling ( $m_{\text{meson}} \sim 2m$ ,  $m_{\text{baryon}} \sim 3m$ ) found  
 $\Rightarrow$  the system remains confined!
- origin of a scale in  $\chi$ -sym. phase? ... trace anomaly  $T_\mu^\mu \sim \langle \frac{\alpha_s}{\pi} G^2 \rangle$ 

$$\frac{d}{dm_q} \frac{\alpha_s}{\pi} \langle G^2 \rangle = \frac{-24 \langle \bar{q}q \rangle}{\frac{11}{3} N_c - \frac{2}{3} N_f}$$

[Novikov, Shifman, Vainstein, Zakharov ('81)]

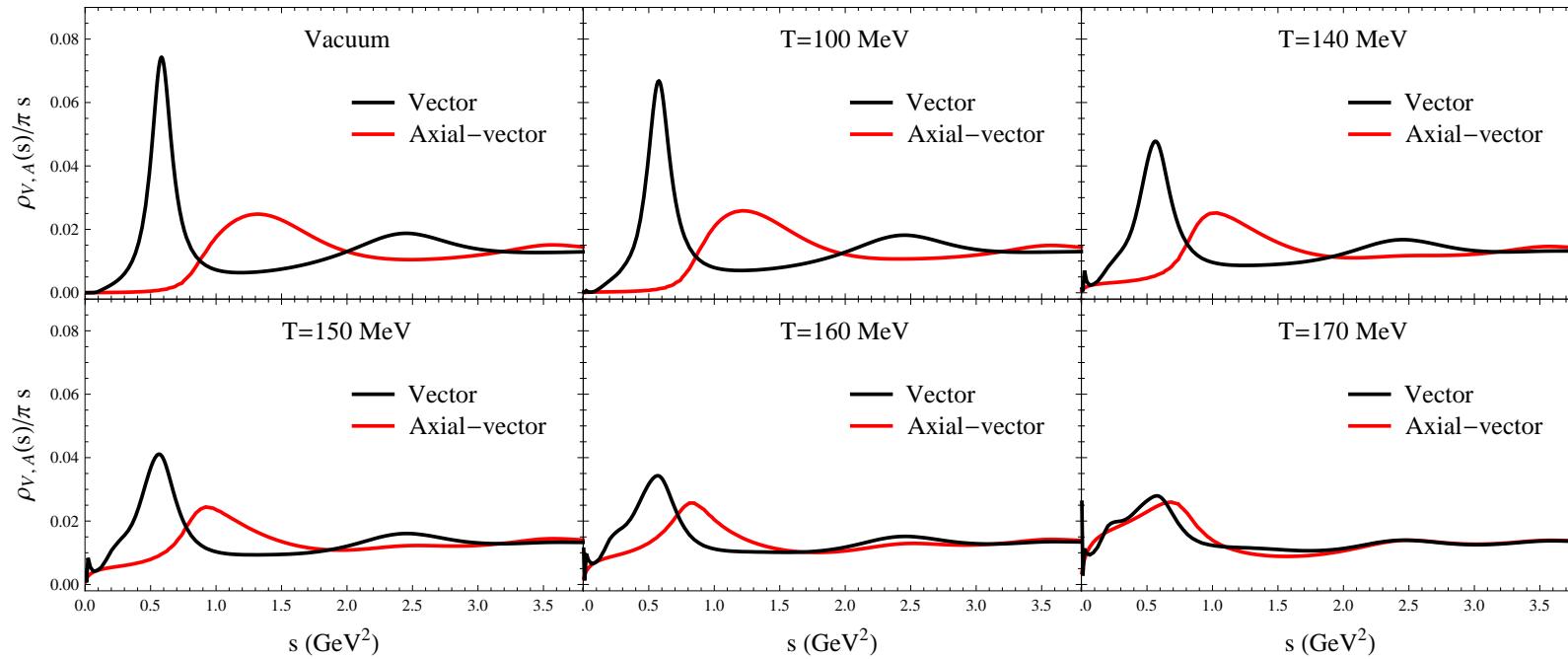
$\Rightarrow$  in-medium gluon condensate: melting toward  $T_{\text{ch}}$ , but non-vanishing



- **embedding gluon condensate:**  $U(1)$  vs.  $SU(2)$  [Paeng, Lee, Rho, CS ('13)]
  - RGE analysis:  $\rho NN$ -int. “runs” whereas  $\omega NN$ -int. “walks” with  $n_B$ ! IR fixed point (cf. walking techni-color model)
  - $m_N^* \sim \text{const.}$ : emergence of a  $\chi$ -inv. mass!
- **tetra-quark states in chiral transition:**
  - crucial to nuclear compressibility  $K(n_0)$  [Gallas, Giacosa, Pagliara ('11)]
  - new CP? intermediate phase? enlarged symmetry? [Heinz, Struber, Giacosa, Rischke ('08); Harada, CS, Takemoto ('09); Mukherjee, Huang ('13)]

### **III. Hadrons near Chiral Symmetry Restoration**

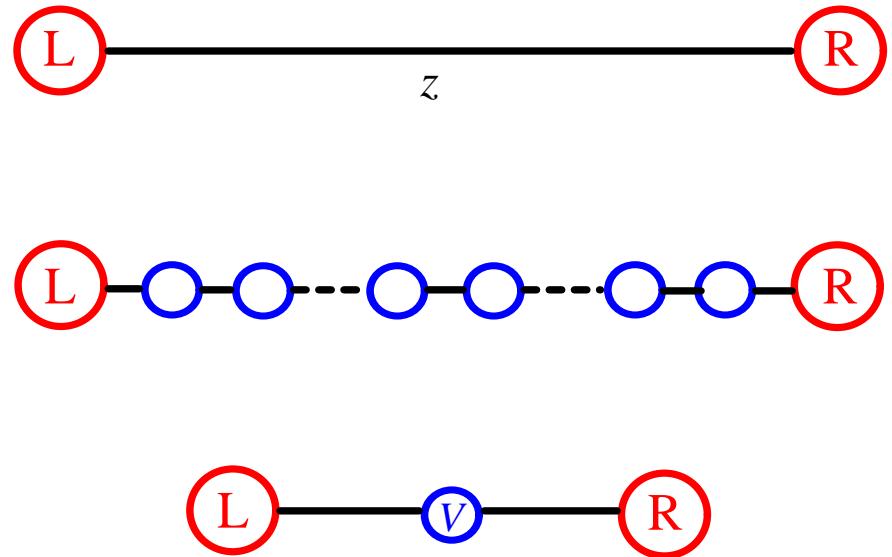
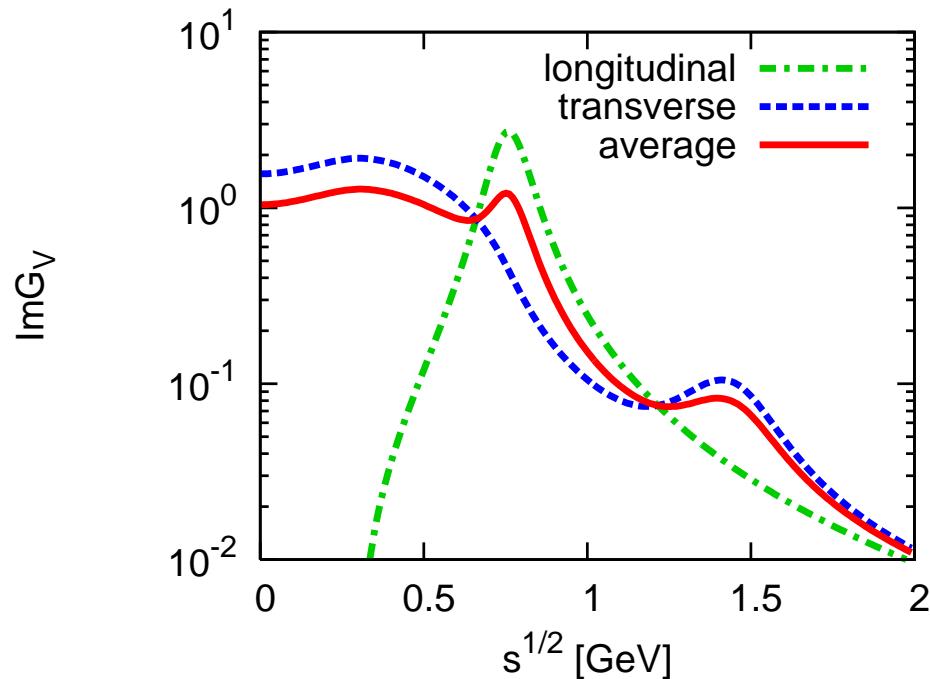
# Chiral symmetry restoration and in-medium axial-vector spectrum



[Hohler, Rapp ('14)]

- Weinberg sum rules:  $f_\pi \Leftrightarrow \rho_{V,A}(s)$  [Weinberg ('67); Kapusta, Shuryak ('94)]
- **strategy:** phenomenologically accepted  $\rho_V(T)$  & ansatz for  $m_{a_1}(T), \Gamma_{a_1}(T)$   
 $\stackrel{\text{WSRs}}{\Rightarrow}$  in-medium  $\rho_A(T)$ 
  - smooth reduction of  $m_{a_1} \rightarrow m_\rho$  and broader width
  - importance of higher-lying states:  $\rho', a'_1, \dots$

# V-A mixing at finite density



- no charge-conjugation inv. at finite density  $\Rightarrow \rho$ - $a_1$  mixing at tree level

$$\mathcal{L}_{\text{mix}} = 2C\epsilon^{0\nu\lambda\sigma} \text{tr} [\partial_\nu V_\lambda \cdot A_\sigma + \partial_\nu A_\lambda \cdot V_\sigma]$$

$$\text{transv: } p_0^2 - \vec{p}^2 = \frac{1}{2} \left[ m_\rho^2 + m_{a_1}^2 \pm \sqrt{(m_{a_1}^2 - m_\rho^2)^2 + 16C^2 \vec{p}^2} \right]$$

- mixing strength:  $\chi$ EFT [Harada, CS ('09)] vs. AdS/QCD [Domokos, Harvey ('07)]

$C = 0.1 \text{ GeV}$  vs.  $1 \text{ GeV}$  at  $n_B = n_0$ !

$C = 1 \text{ GeV} \Rightarrow$  vector-meson condensation at  $n_0$ !?

- why  $C(n_0) = 1$  GeV in AdS/QCD?

$$C_\omega \ll C = C_\omega + C_{\omega'} + C_{\omega''} + \dots ?$$

- role of infinite KK modes in nuclear potential from Sakai-Sugimoto model

[Hashimoto, Sakai, Sugimoto ('09)]

- repulsive core, tensor force, spin/isospin dep.,  $V(r) \propto 1/r^2$
- **truncation vs. integrating-out**  $\dots$  different  $r$  dependence!

$$V_\infty(r) = \frac{1}{r} + \frac{e^{-r}}{r} + \frac{e^{-2r}}{r} + \dots \underset{\text{small } r}{\sim} \frac{1}{r^2}$$

$$V_N(r) = \frac{1}{r} + \frac{e^{-r}}{r} + \frac{e^{-2r}}{r} + \dots + \frac{e^{-Nr}}{r} \underset{\exp[-mr] \sim 1}{\sim} \frac{N}{r}$$

## Role of higher-lying hadronic states near phase transitions

increasing  $T$  and  $n_B$  toward QCD phase transition:

**More and more hadronic states activated!  
... How to handle them?**

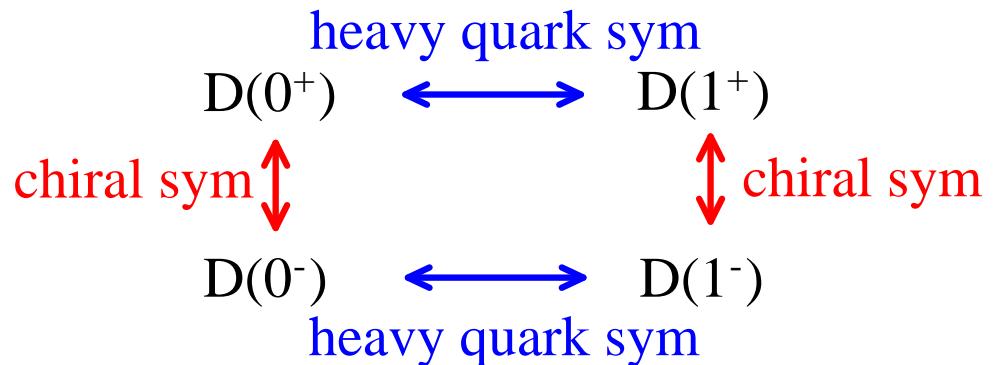
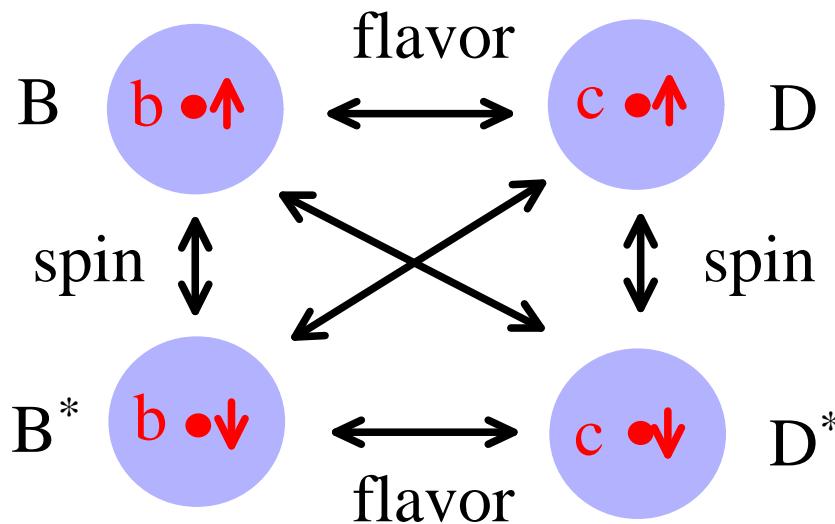
- holographic QCD models:  $1/N_c$  corrections?
- 4d effective field theories:  
unknown interactions among higher-lying states?  
if renormalized/integrated out,  $T, n_B$ -dep. interactions?

$$\mathcal{L}_\infty(\pi, \rho, \omega, \dots) \sim \mathcal{L}_{\text{low-lying}}(\pi, \rho, \omega, \dots; g(T, n_B))$$

... might be bridged via DS eq. and FRG?

## **IV. Chiral Thermodynamics with Charm**

## Fine splitting of D-meson masses



[Nowak, Rho, Zahed ('93); Bardeen, Hill ('94)]

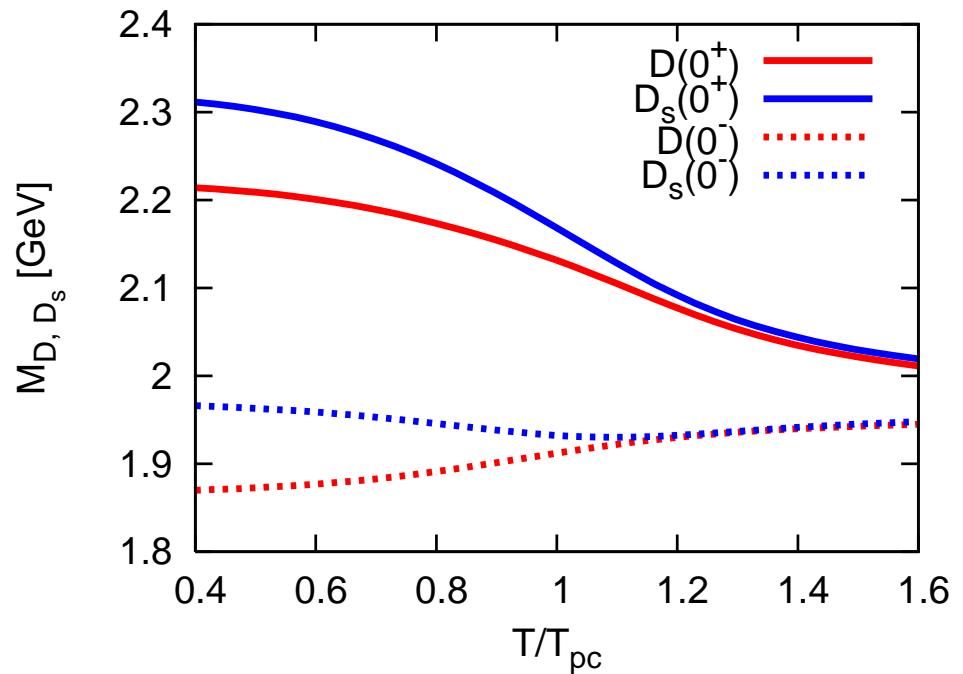
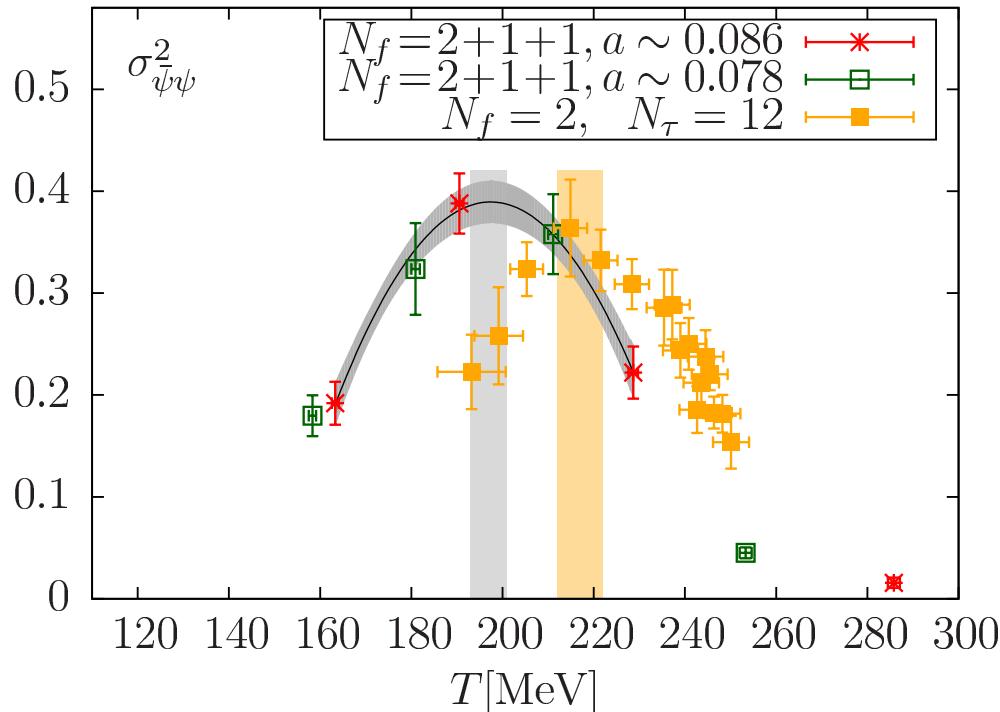
- no charge-conjugation inv. at  $n_B \neq 0 \Rightarrow m_{D^-} - m_{D^+} \sim 50$  MeV
- spontaneous chiral symmetry breaking:  
chiral doublers  $D(0^-, 1^-)$  and  $D(0^+, 1^+) \Rightarrow \delta m_D \sim 350$  MeV
- flavor symmetries

chiral symmetry :  $m_{u,d}/\Lambda_{\text{QCD}} \ll 1$ ,  $m_s/\Lambda_{\text{QCD}} < 1$ .

heavy quark symmetry :  $\Lambda_{\text{QCD}}/m_{c,b} \ll 1$ .

when  $m_Q \rightarrow \infty$ ,

light d.o.f. (q) do not feel the flavor and spin of the heavy quark (Q).



- $N_f = 2 + 1 + 1$  LQCD simulations: downward shift of  $T_{\text{ch}}$  by 20 MeV (ETMC,  $m_\pi \sim 400$  MeV) [Poster A-11 by Burger, Hotzel, Muller-Preussker, Ilgenfritz, Lombardo]
- chiral MF theory with heavy quark symmetry: [CS, Redlich ('14)]  
⇒  $D$ - $D_s$  splitting effectively reduced toward  $T_{\text{ch}}$ :  $h_q \ll h_s \rightarrow h_q^* \lesssim h_s^*$
- D,B mesons in nuclear matter: modifications of color-electric and color-magnetic gluon condensates [Yasui, Sudoh ('14)]

**interesting testing ground of quark-gluon interplay in matter!**

## Summary

- Polyakov-loop ratio & quark number fluc. suggest  $T_{\text{ch}} \sim T_{\text{dec}}$  at  $\mu = 0$   
survival hadrons in confined phase at  $\mu \neq 0$ ?
- importance of higher-lying states near phase transitions
- $N_f = 2 + 1 + 1$  lattice QCD simulations: a downward shift of  $T_{\text{ch}}$
- effective theories: reduction of  $D-D_s$  splitting, gluon dynamics in hot/dense matter

**More to come from Exp, LQCD, EFTs!**  
**Exciting moments in nuclear/hadron physics!**