Inverse magnetic catalysis in holographic QCD

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Outline

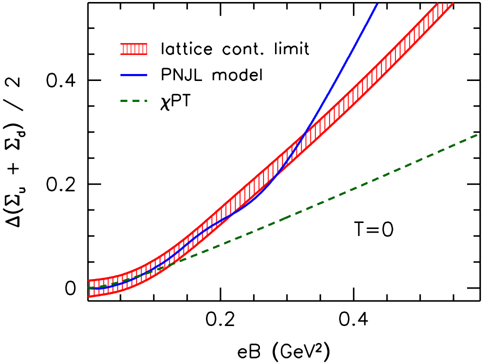
1. Introduction to Inverse Magnetic Catalysis
2. The V-QCD models
3. Inverse Magnetic Catalysis in V-QCD
4. Predictions at finite μ

1. Introduction

Background: Magnetic catalysis

At low temperatures in QCD, $\langle \bar{q}q \rangle$ increases with B

- Studied in NJL models, χPT, Dyson-Schwinger, large N_c, lattice QCD

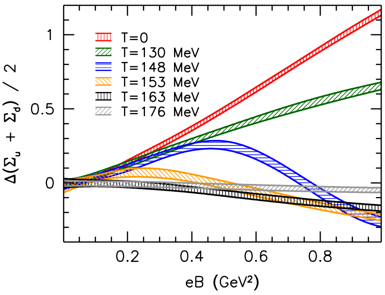


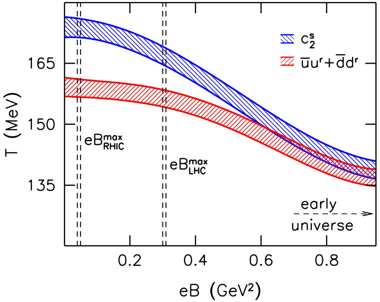
[Bali et al.]

- At strong B lowest Landau level: $D = 3+1 \rightarrow 1+1$ $\Rightarrow$ Stronger IR dynamics $\Rightarrow$ Enhanced $\langle \bar{q}q \rangle$
- Model independent

Inverse magnetic catalysis – a puzzle

Lattice results for $N_f = 2 + 1$, physical quark masses





[Bali et al., arXiv:1111.4956, arXiv:1206.4205]

- Near $T \simeq T_c$, $\langle \bar{q}q \rangle$ suppressed with increasing B: a surprise!
- T_c decreases with B

Lattice analysis of two competing contributions to $\langle \bar{q}q \rangle$

- "Valence" vs. "sea" quarks

$$\langle \bar{q}q \rangle = \int \mathcal{D}A \; e^{-S[A]} \, \mathrm{det}(\not{D}(B) + m) \; \mathrm{tr}(\not{D}(B) + m)^{-1}$$

- Valence $\Rightarrow$ enhances $\langle \bar{q}q \rangle$ with $B \Rightarrow$ Catalysis
- Sea $\Rightarrow$ favors A configs. with larger Dirac eigenvalues $\Rightarrow$ suppresses $\langle \bar{q}q \rangle$ with increasing $B \Rightarrow$ Inverse catalysis

[Bruckmann, Endrodi, Kovacs, arXiv:1303.3972]

Holographic inverse catalysis

Inverse magnetic catalysis has been found in some holographic models for QCD, e.g.:

- Backreacted "Hard-wall" and $\mathcal{N} = 4$ SYM on $\mathbb{R}^3 \times S^1$
  [Mamo, arXiv:1501.03262]
- "Tailored" D3-D7 models
  [Evans,Miller,Scott, arXiv:1604.06307]

but not some in others . . .

Originally "inverse magnetic catalysis" meant a different effect seen in Witten-Sakai-Sugimoto model at finite μ and small T

[Preis,Rebhan,Schmitt, arXiv:1012.4785]

This talk: consider a rich and realistic bottom-up model (V-QCD)

- Properly treated backreaction of the quarks $\Rightarrow$ capture the sea quark contributions
- Better modeling, understanding of physics?

2. V-QCD

V-QCD approach: general idea

A holographic bottom-up model for QCD in the Veneziano limit (large N_f, N_c with $x = N_f/N_c$ fixed)

- Bottom-up, but trying to follow principles from string theory as closely as possible
- Complicated model (because QCD is complicated)

More precisely:

- Derive the model from five dimensional noncritical string theory with certain brane configuration
  $\Rightarrow$ some things do not work (at small coupling)
- Fix model by hand and generalize $\rightarrow$ arbitrary potentials
- Tune model to match QCD physics and data
- Effective description of QCD

Last steps so far incomplete: model not yet tuned to match any QCD data (but soon will be)

Holographic V-QCD: the fusion

The fusion:

1. IHQCD: model for glue inspired by string theory (dilaton gravity)

   [Gursoy, Kiritsis, Nitti; Gubser, Nellore]

2. Adding flavor and chiral symmetry breaking via tachyon brane actions

   [Klebanov,Maldacena; Bigazzi,Casero,Cotrone,Iatrakis,Kiritsis,Paredes]

Consider 1. + 2. in the Veneziano limit with full backreaction:
$N_c \to \infty$ and $N_f \to \infty$ with $x_f \equiv N_f/N_c$ fixed
$\Rightarrow$ V-QCD models

[MJ, Kiritsis arXiv:1112.1261]

V-QCD at finite T and B

Two bulk scalars: $\lambda \leftrightarrow g^2 N_c$, $\tau \leftrightarrow \bar{q}q$

$$\mathcal{S}_{\mathrm{V-QCD}} = N_c^2 M^3 \int d^5x \sqrt{g} \left[R - \frac{4}{3} \frac{(\partial\lambda)^2}{\lambda^2} + V_g(\lambda) \right]$$
$$- N_f N_c M^3 \int d^5x \; V_f(\lambda,\tau)$$
$$\times \sqrt{-\det(g_{ab} + \kappa(\lambda)\partial_a\tau\partial_b\tau + w(\lambda)F_{ab})}$$

$$F_{xy} = B \qquad\qquad V_f(\lambda,\tau) = V_{f0}(\lambda)e^{-\tau^2}$$

Metric Ansatz (A, f to be determined from EoMs)

$$ds^2 = e^{2A(r)} \left(\frac{dr^2}{f(r)} - f(r)dt^2 + d\mathbf{x}_\perp^2 + e^{2W(r)}dz^2 \right)$$

- Choice of $w(\lambda)$ important for magnetic effects

Task: solve saddle point configurations numerically

- Use standard dictionary to compute observables
- Here restrict to zero quark mass (no source for τ)

3. Inverse magnetic catalysis in V-QCD

Choice of $w(\lambda)$

Most important potential for dependence on B: the coupling of the bulk gauge fields, $w(\lambda)$

- UV correlators: $w \to \mathrm{const.}$ as $\lambda \to 0$
- IR: from string theory, expect $\kappa \sim w \sim \lambda^{-4/3}$ as $\lambda \to \infty$
  - $\kappa \sim \lambda^{-4/3}$ also supported by the analysis of meson spectrum

Therefore we choose

[Gürsoy, Iatrakis, MJ, Nijs arXiv:1611.06339]

$$w(\lambda) = \kappa(c\lambda)$$

with $c = $ constant

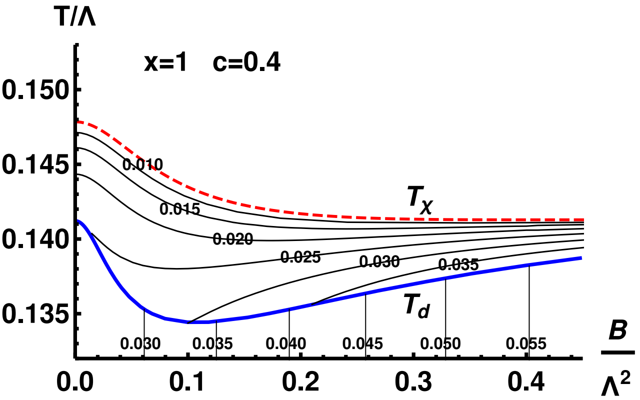
Explicit choice

$$w(\lambda) = \frac{(1 + \log(1 + c\lambda))^{-1/2}}{(1 + \kappa_1 c\lambda)^{4/3}}$$

- $\kappa_1 = 3/4((115 - 16x)/27 - 1/2) \leftrightarrow$ perturbation theory
- Other potentials as in earlier work

[Alho,MJ,Kajantie,Kiritsis,Tuominen, arXiv:1210.4516]

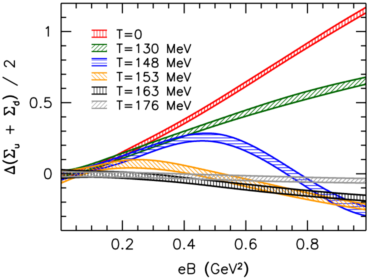
Transition temperatures and chiral condensate

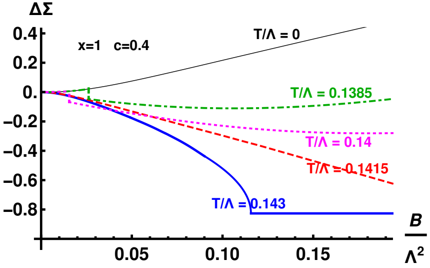


- Separate chiral and deconfinement transitions
- Clear inverse catalysis observed in the transition regime

Chiral condensate

$$\Delta\Sigma(T,B) = \frac{\langle\bar{q}q\rangle(T,B) - \langle\bar{q}q\rangle(T,0)}{\langle\bar{q}q\rangle(0,0)}$$



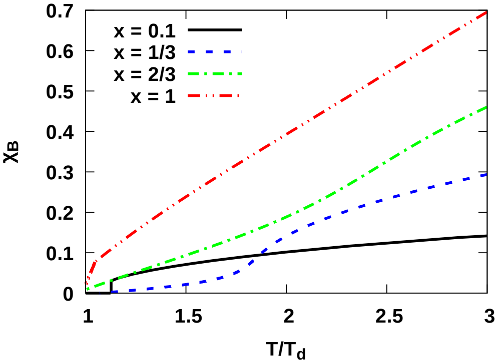


- Qualitative agreement between lattice and V-QCD

Varying number of flavors

Magnetic susceptibility controls the dip in T_d through

$$\frac{dT_d}{dB} = -\frac{\chi_B B}{S}$$



- Order parameter for inverse magnetic catalysis [Ballon-Bayona,Ihl,Shock,Zoakos, arXiv:1706.05977]
- Dip stronger at higher $x \leftrightarrow$ inverse catalysis
- Rough agreement with the picture arising from lattice: inverse catalysis arises due to backreaction
- Magnitude of χ_B in agreement with lattice

4. Predictions at finite μ

Turning on a chemical potential

An example of a generic idea:

1. "Fit" holographic model to observables easy to compute on the lattice
2. Use the model to compute harder observables

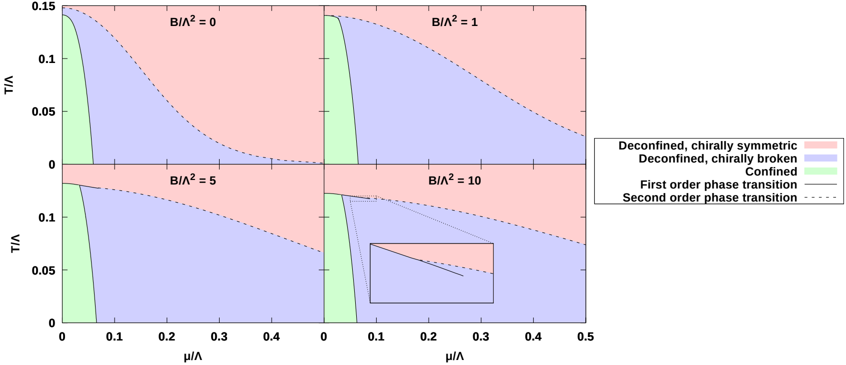
Apply here to QCD thermodynamics at finite μ and B: no lattice data available

- Pick model giving best results at $\mu = 0$, then turn on μ

[Gürsoy, MJ, Nijs, PRL 120, 242002; arXiv:1707.00872]

The phase diagram at finite B and μ

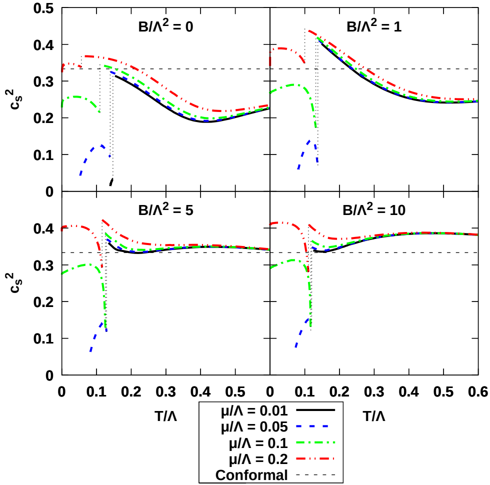
$x_f = 1$



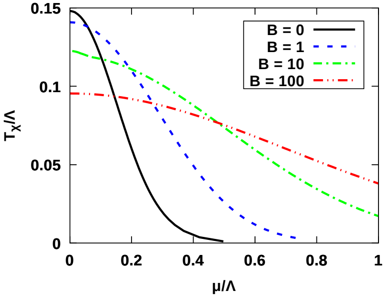
- Main effect: increasing B enhances the intermediate phase

Speed of sound

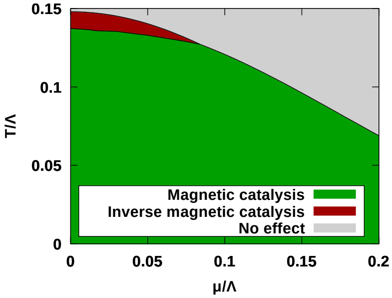
- Conformal bound broken
- c_s^2 increases with B: agreement with lattice



Inverse magnetic catalysis for $\mu > 0$



At $B \approx 0$



- Turning on μ suppresses inverse catalysis
- Increasing B enhances inverse catalysis at finite μ

Summary

- Chiral condensate decreases with B near the critical temperature of QCD: "inverse magnetic catalysis"
- Inverse magnetic catalysis reproduced in V-QCD: results support importance of sea quarks and backreaction
- Turning on chemical potential destroys inverse catalysis

Outlook

Ongoing work:

- Tuning the model to match with experimental/lattice QCD data
- Implications at $T = 0$ and neutron stars
  [Niko Jokela's talk]
- Baryon physics in V-QCD
- Spatially asymmetric (magnetic) plasma

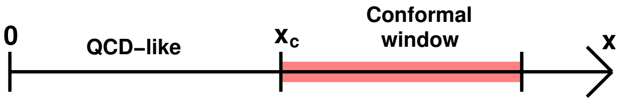
Future projects:

- Flavor dependence
- . . .

Extra slides

QCD phases in the Veneziano limit

Veneziano limit: large N_f, N_c with $x = N_f/N_c$ fixed



In the Veneziano limit (discrete) N_f replaced by (continuous) $x = N_f/N_c$

- Transition expected at some $x = x_c$

Computations near the transition difficult

- Schwinger-Dyson approach, ...
- Lattice QCD
- Holography (?)

Dictionary

In the flavor/CP-odd sector

1. The tachyon: $T^{ij} \leftrightarrow \bar{\psi}^i_R \psi^j_L$; $(T^\dagger)^{ij} \leftrightarrow \bar{\psi}^i_L \psi^j_R$
   - Source: the (complex) quark mass matrix M^{ij}
     Note: the phase of the tachyon sources the phase of the mass
2. The gauge fields $A^{ij}_{\mu,L/R} \leftrightarrow \bar{\psi}^i_{L/R}\gamma_\mu \psi^j_{L/R} \equiv J^{(L/R)}_\mu$
   - Sources: chemical potentials and background fields (not turned on in this study)
3. The bulk axion $\mathfrak{a} \leftrightarrow \mathbb{T}\mathrm{r}\, G \wedge G$
   - Source: (normalized) theta angle θ/N_c

In the glue sector

1. The dilaton $\lambda \leftrightarrow \mathbb{T}\mathrm{r}\, G^2$
   - Source: the 't Hooft coupling $g^2 N_c$

Choosing the potentials

In the UV ($\lambda \to 0$), where holography not reliable:

- UV expansions of potentials matched with perturbative QCD beta functions $\Rightarrow$

$$\lambda(r) \simeq -\frac{1}{\beta_0 \log r}, \quad \tau(r) \simeq m_q(-\log r)^{-\gamma_0/\beta_0} r + \sigma(-\log r)^{\gamma_0/\beta_0} r^3$$

  with the 5th coordinate $r \sim 1/\Lambda \to 0$

- Best boundary conditions for IR physics

In the IR ($\lambda \to \infty$):

- Glue sector: existence of "good" IR singularity, confinement
- Flavor sector: tachyon divergence, linear (radial) meson trajectories
- Working potentials string-inspired power-laws of λ, multiplied by logarithmic corrections (i.e, first guesses usually work!)

In the middle ($\lambda \sim 1$): compare to data