Magnetically induced phenomena and Holographic QCD

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arXiv:1212.3894 with I. Iatrakis, E. Kiritsis, F. Nitti, A. O' Bannon
arXiv:1506.01350 with T. Drwenski and I. Iatrakis
arXiv:1607.XXXXX with I. Iatrakis, M. Jarvinen, G. Nijs

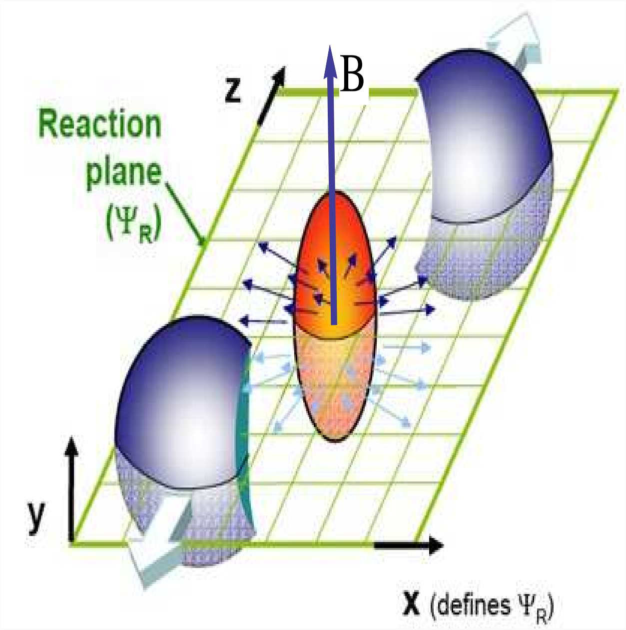
Interesting QCD Phenomena at large B

- Anomalous transport: Chiral magnetic effect, chiral vortical effect, chiral magnetic wave, etc D. Kharzeev, McLerran, Warringa '08
- Magnetic catalysis: B (de)catalyzes $\langle \bar{q} q \rangle$, $T_c(B)$ is complicated Gusynin, Miransky, Shovkovy '95Bali et al '12
- Magnetically generated electric currents in QGP U.G., D. Kharzeev, K. Rajagopal '14
- Schwinger pair production
- Possibility of new phases in $\mu - T - B$ diagram

Possible realizations in Nature:

- Off-central heavy ion collisions
- Compact stars: neutron stars, magnetars
- Primordial magnetic fields in cosmological evolution

Off-central HIC



- Initial magnitude of B
- Bio-Savart: $B_0 \sim \gamma Z e \frac{b}{R^3} \Rightarrow$ $\sim 10^{18}(10^{19})$ G at RHIC (LHC).
- $B_0 \sim 10^{10} - 10^{13}$G (neutron stars), 10^{15} (magnetars)
- More relevantly $eB \approx 5 - 15 \times m_\pi^2$ RHIC (LHC).

This talk:

- Part I: Chiral magnetic effect
- Part II: Inverse magnetic catalysis

Assumptions:

- Constant magnetic field
- Homogenenous Quark-Gluon Plasma with infinite extent
- Strong coupling

Methods:

- Lattice QCD: works at finite B, good for part II, not clear for part I
- Holographic QCD: Good for both at qualitative (perhaps quantitive) level

PART I: Chiral Magnetic Effect

U.G., I. Iatrakis, E. Kiritsis, F. Nitti, A. O' Bannon 1212.3894

U.G, T. Drwenski and I. Iatrakis 1506.01350

Chiral Anomaly in QCD

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- *massless* fermions are chiral: left and right-handed quarks.
- *Classically* QGP chiral symmetric: $N_L = N_R$
  as $T \approx 500$ MeV $\gg m_u,\ m_d$
- Axial current $\partial_\mu J^{\mu 5} = \partial_\mu \left(\langle \bar{\psi}\gamma^\mu \psi \rangle_L - \langle \bar{\psi}\gamma^\mu \psi \rangle_R \right) = 0$
- However there is a QM anomaly: $\partial_\mu j^{\mu 5} = -\frac{N_f g^2}{16\pi^2} \mathrm{Tr}(F_{\mu\nu}\tilde{F}^{\mu\nu})$.

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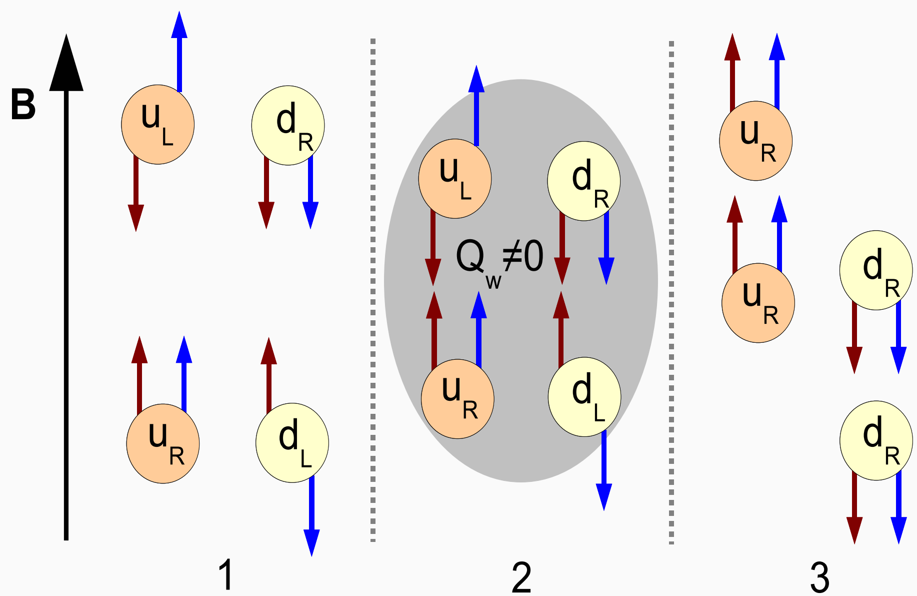
- Due to topologically non-trivial gluon configurations
- Gluon winding number: $Q_w = \frac{g^2}{32\pi^2} \int \mathrm{d}^4 x \, F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a \in \mathbb{Z}$.
- Atiyah-Singer index theorem: $\Delta(N_L - N_R) = 2 N_f Q_w$

Chiral Magnetic Current

Chiral Magnetic Current

- Under B spin degeneracy of quarks lifted due $H \sim -q\vec{s} \cdot \vec{B}$:



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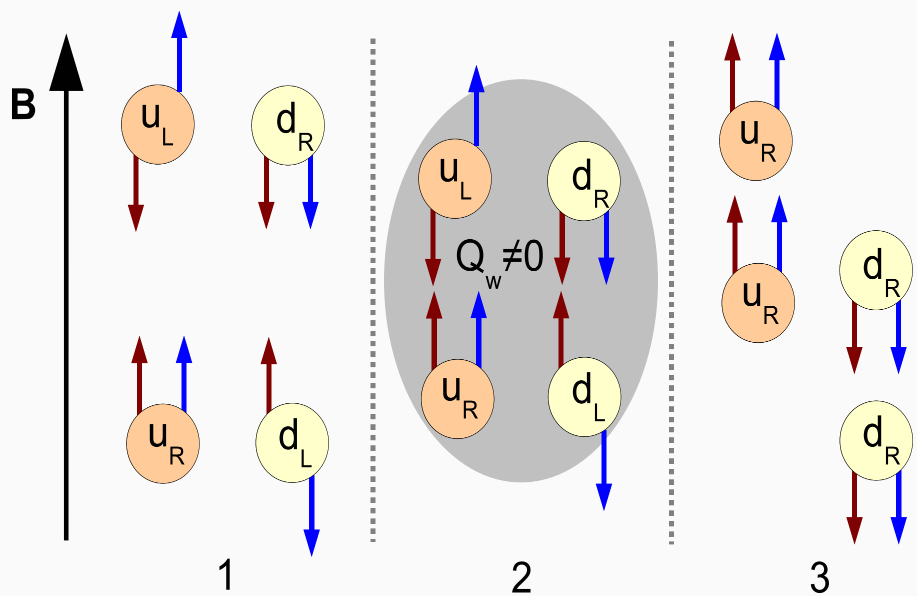
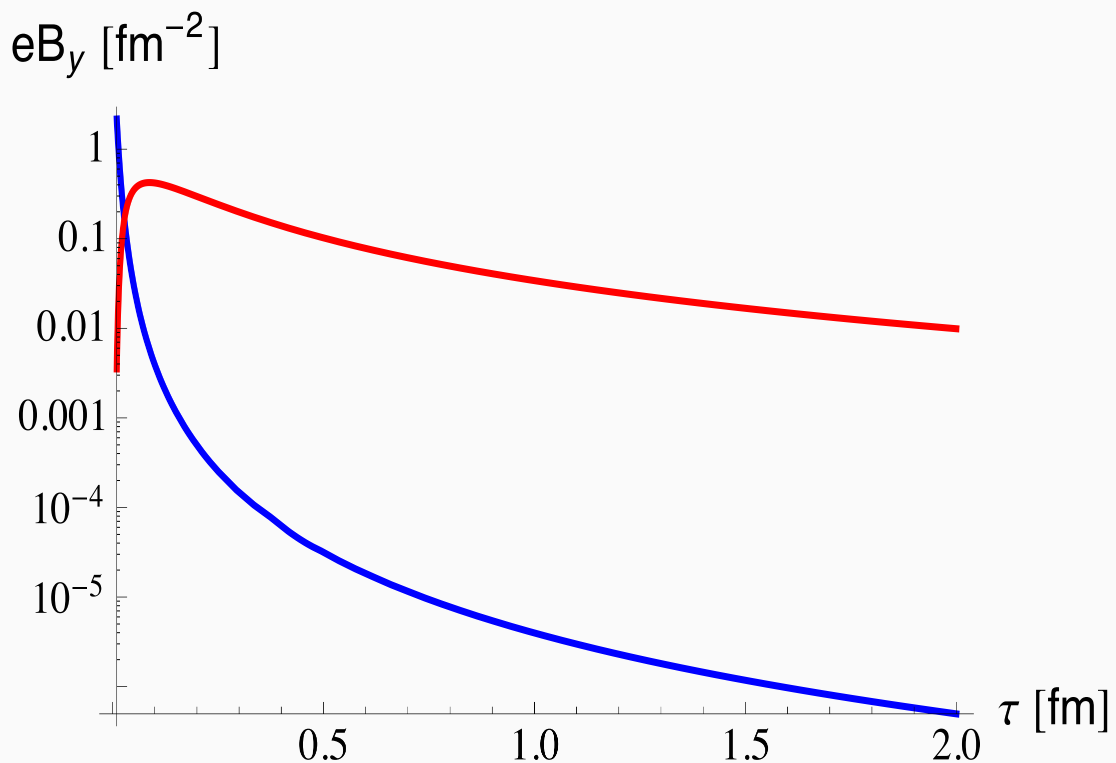


- Macroscopic manifestation of the axial anomaly
- Anomalous magnetohydrodynamics: $\vec{J} = \frac{e^2}{2\pi^2} \mu_5 \vec{B}$

  Kharzeev et al '07, Son, Surowka '09
- μ_5 encodes the imbalance $N_L \neq N_R$
- Chiral magnetic conductivity: $\sigma_B = \frac{e^2}{2\pi^2} \mu_5$

Time profile of B at LHC

U.G., D. Kharzeev, K. Rajagopal ’14



with $\sigma = 0.023\text{fm}^{-1}$ and with $\sigma = 0$

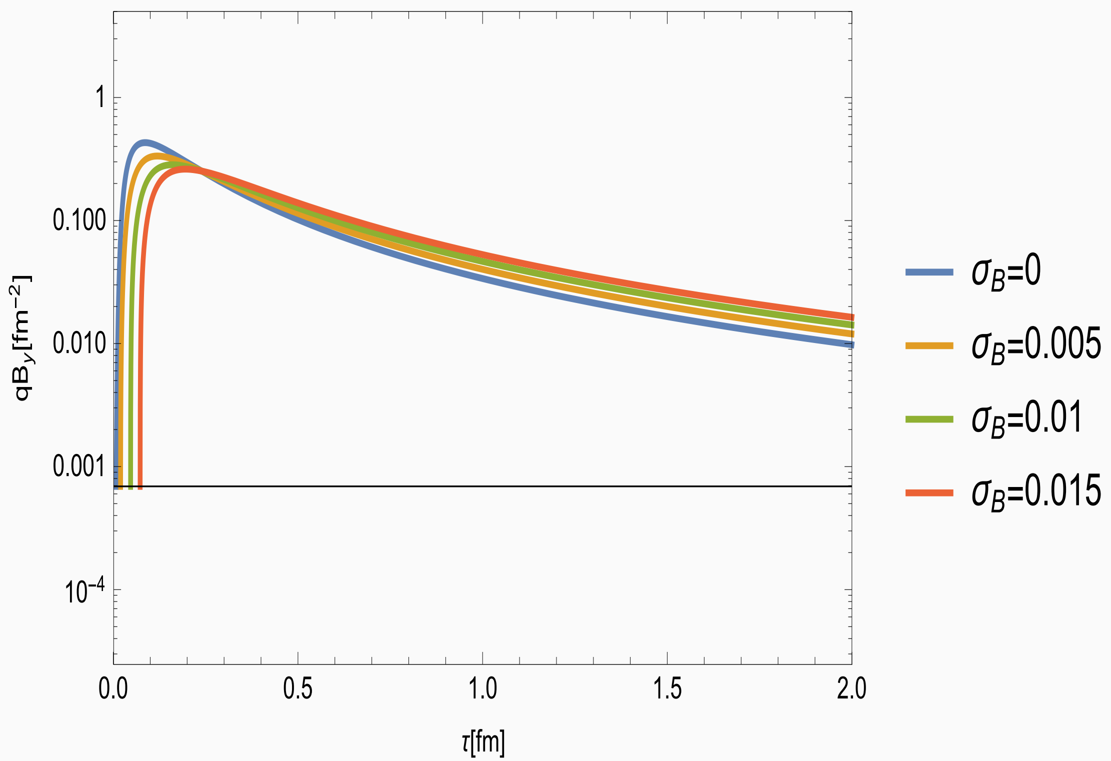
- Simplifying assumption hard-sphere distribution for spectators and participants
- For participants empirical distribution over Y: Kharzeev et al. 2007

  $f(Y_b) = (4\sinh(Y_0/2))^{-1}\, e^{Y_b/2}, \qquad -Y_0 \le Y_b \le Y_0$

B with non-vanishing σ and σ_5

H. Li, X. Sheng, Q. Wang '16; U.G., E. Marcus, C. van der Poel, ongoing

- Also include $\vec{J}_B = \sigma_B \vec{B}$ along with $\vec{J}_E = \sigma \vec{E}$ and $J_S = \int \rho_s(x) \vec{v}$



- σ_B delays the decay of B!

- If $Q_w \neq 0$ (or μ_5 finite)
- If there is an external magnetic field
- There exists $J^\mu \propto B$ due to chiral anomaly
- In QGP the main source of Q_w is sphalerons
- A effective μ_5 is generated by topological charge fluctuations due to Sphaleron decay:

$$\mu_5 \propto lim_{\omega\to 0}\langle \mathrm{Tr}F\tilde{F}(\omega)\mathrm{Tr}F\tilde{F}(\omega)\rangle$$

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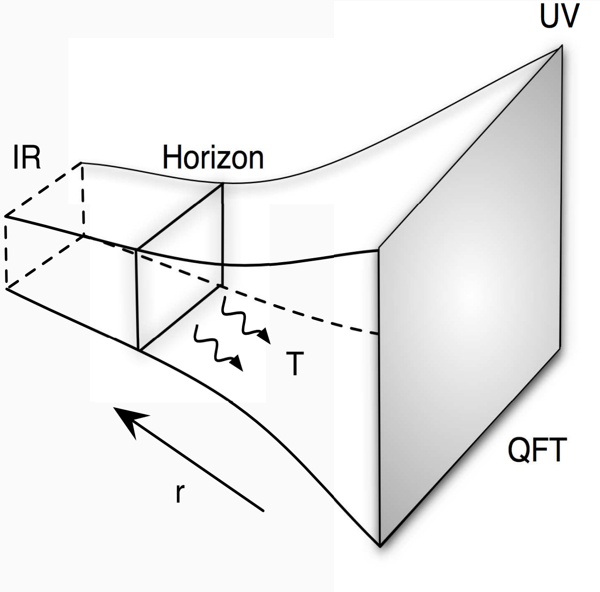
- However, QGP is strongly interacting, how to calculate μ_5?

Holographic calculation

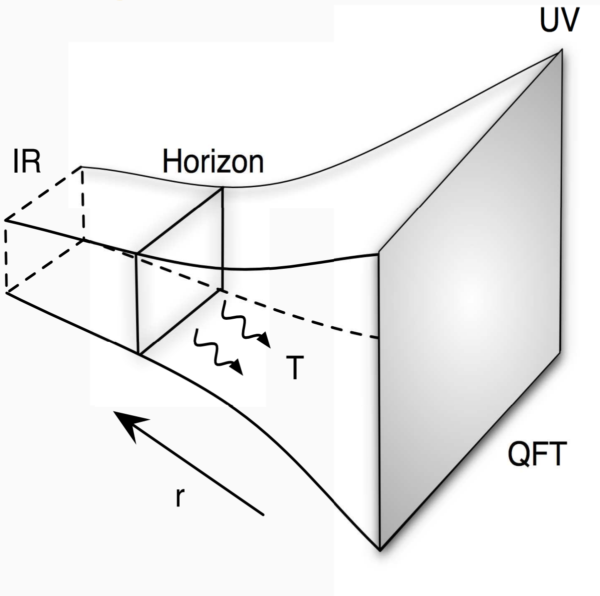


Finite T, $N_c \gg 1, \alpha_s \gg 1$ QFT $\Leftrightarrow$ GR on black holes in 5D

Maldacena '97; Witten; Gubser, Klebanov, Polyakov '98

1. $\langle \mathcal{O}(x_1)\mathcal{O}(x_2)\rangle$ computed from $\hat{\nabla}^2\phi = m^2\phi$ on the BH.

Holographic calculation



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1. $\langle \mathcal{O}(x_1)\mathcal{O}(x_2)\rangle$ computed from $\hat{\nabla}^2\phi = m^2\phi$ on the BH.
2. Recall $\omega J^{\mu 5}(\omega) \propto \mathrm{Tr} F\tilde{F}(\omega)$. Introduce CP odd axion $a(r,x)$
3. The source term $\int d^4x a_0(x) \mathrm{Tr} F\tilde{F}(x)$ with $a(r,x) \to a_0(x)$ at the boundary.

Holographic calculation of $\Delta(N_L - N_R)$

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AdS/CFT: $\Gamma_{CS} = \frac{(g^2 N_c)^2}{256\pi^3} T^4,$ Son, Starinets '02

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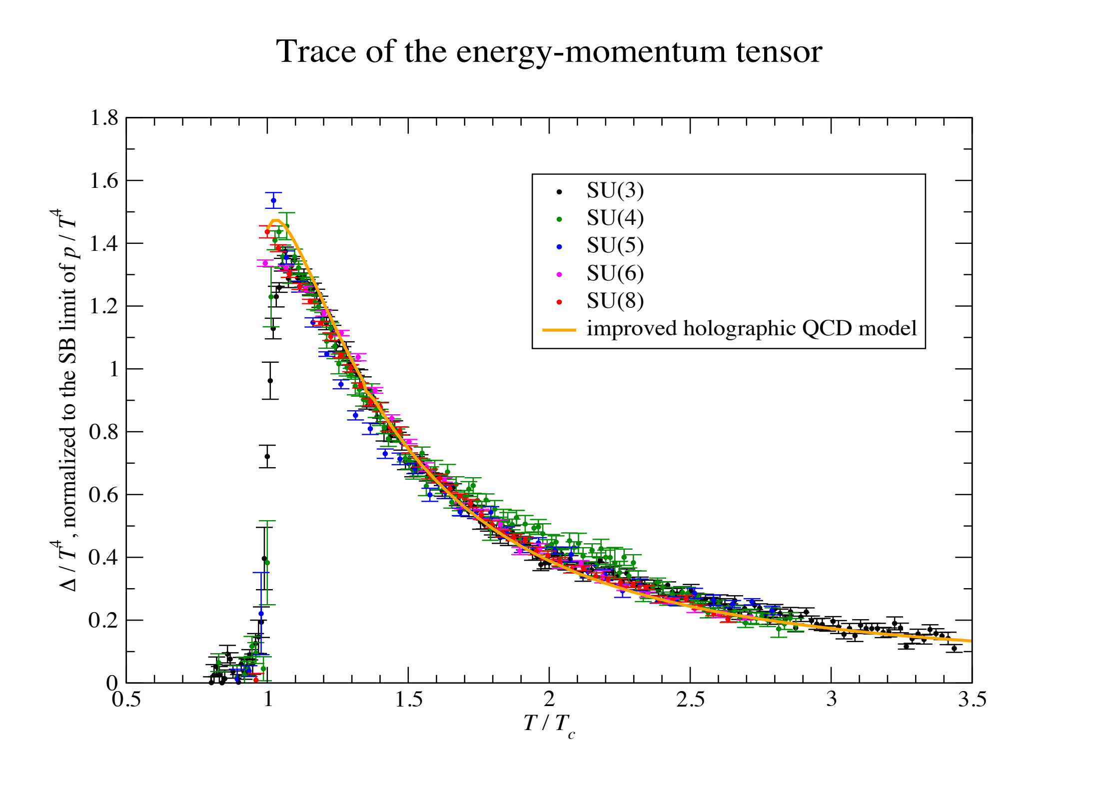
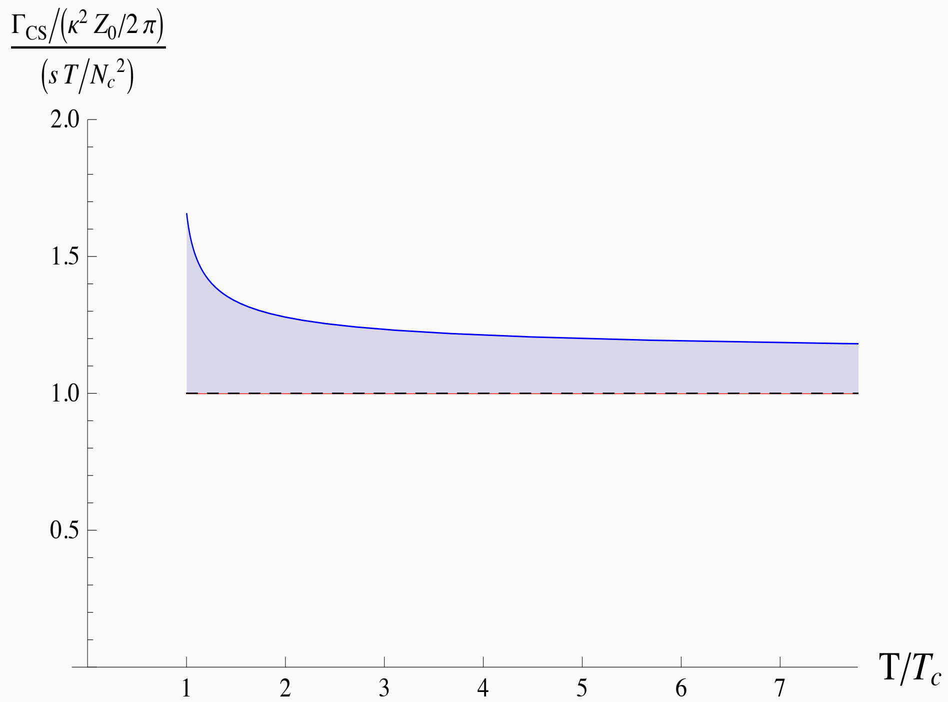
Phenomenologically interesting region $T \approx T_c$ where conformality breaks down:



Improved holographic QCD U.G., Nitti, Kiritsis '07

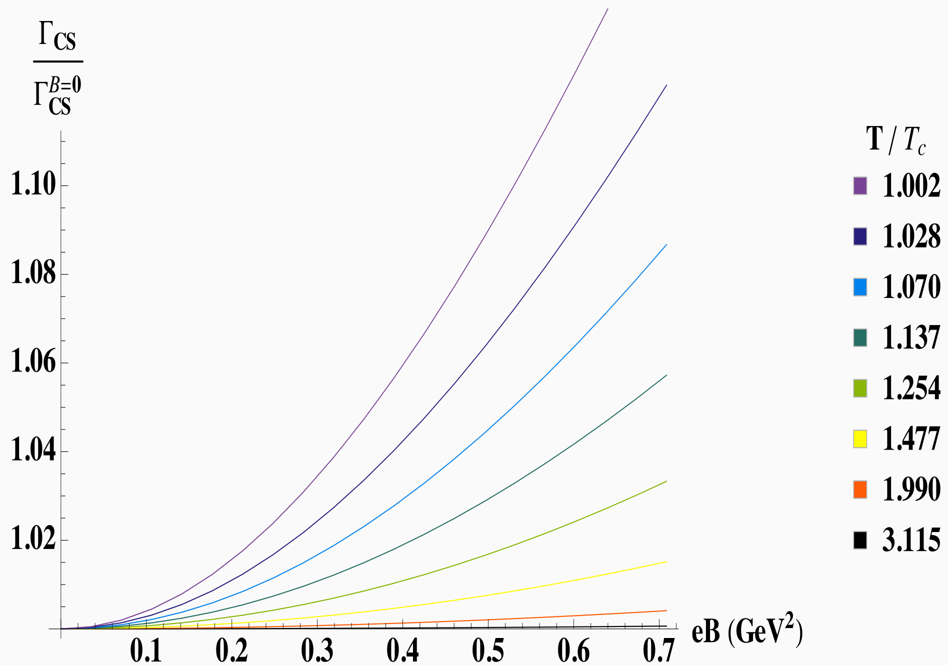
- $\frac{S_{GR}}{M_p^3 N_c^2} = \int d^5x\sqrt{-g}\left(R - (\partial\Phi)^2 + V(\Phi) - \frac{1}{2N_c^2}\, Z(\Phi)(\partial\alpha)^2\right)$
- Parametrize $Z(\lambda) = Z_0\left(1 + c_1\lambda + c_4\lambda^4\right)$
- Result: $\Gamma_{CS}(T_c) \geq C\, s(T_c)T_c\chi$ O'Bannon, U.G, Iatrakis, Kiritsis, Nitti '12
- where $\chi = \frac{\partial^2\epsilon(\theta)}{\partial\theta^2}$ is the topological susceptibility



for ihQCD to reproduce lattice 0^{+-} glueball spectrum within 1σ.

Dependence of Γ on the magnetic field

T. Drwenski, I. Iatrakis, U.G., '15



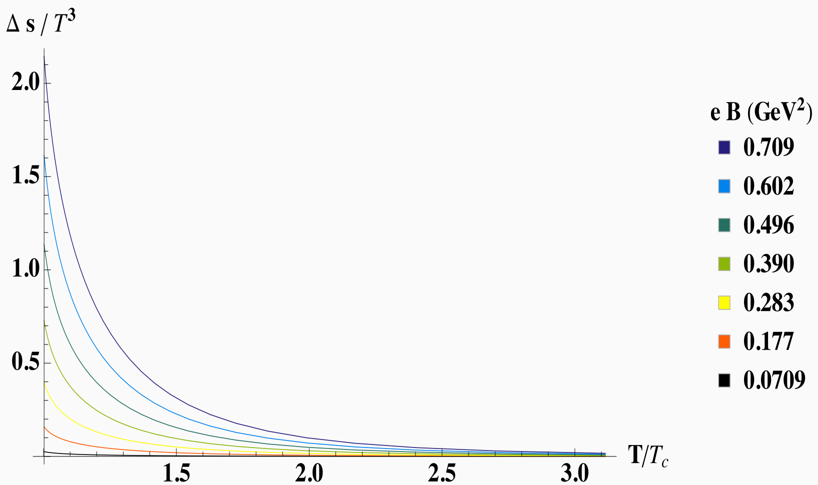
- Backreacted ihQCD with $N_f/N_c = 0.1$.

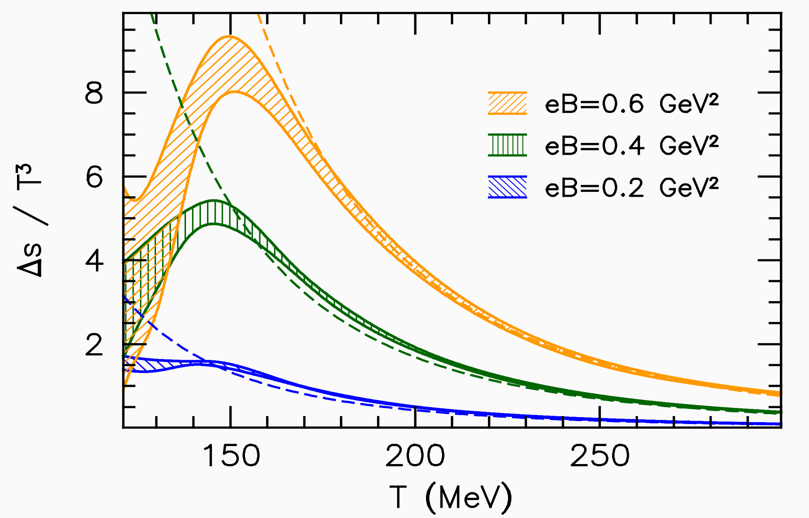
Thermodynamic functions

- Determine the entropy $S(B,T)$

  T. Drwenski, I. Iatrakis, U.G., '15

  Compare with lattice Bali et al, '14





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Summary - part I

- Calculated the Γ_{CS} in non-conformal holography
- CME is proportional to Γ_{CS}
- Comparison of AdS/CFT with non-AdS/non-CFT at T_c:
  $\Gamma_{CS}^{CFT} \approx 0.045 T_c^4$ vs. $\Gamma_{CS} > 1.64 T_c^4$
- Precise value at T_c ambiguous but a lower limit exists.
- Linear response $\Rightarrow \mu_5 \propto \frac{\sqrt{\Gamma_{CS}}}{V_3 \chi}$
- "Realistic" holography in favor of the chiral magnetic effect in HICs
- Decay rate increases with magnetic field
- Dependence of entropy on B agrees with lattice

Outlook

1. To fix the ambiguity, determine $Z(\phi) \Rightarrow$ compare $\mathrm{Tr} F \wedge F$ Euclidean correlators with lattice

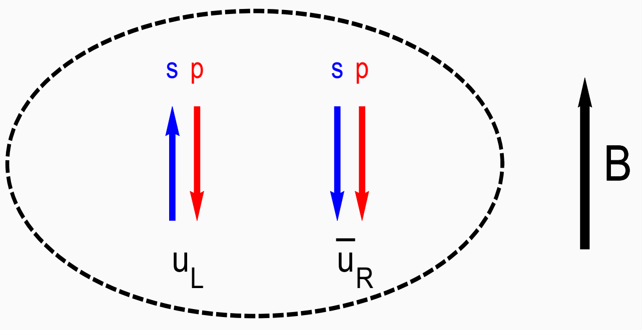
   U.G., E. Kiritsis, S. Mages, F. Nitti, A. Schafer, ongoing

2. What is μ_5 if generated far from equilibrium?
   Add the axion in a time-dependent thermalization background?

PART II: Inverse magnetic catalysis

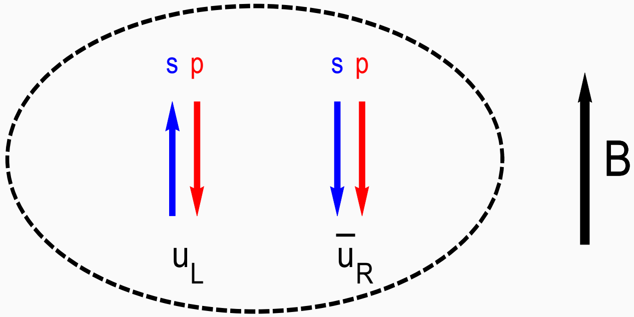
U.G., I. Iatrakis, M. Jarvinen, G. Nijs, 1607.XXXXX

Magnetic Catalysis **Gusynin, Miransky, Shovkovy '94**



- B increases $\langle \bar{q}q \rangle$ at $T = 0$
- Seems counter-intiutive in the light of BCS: B destroys the Cooper pair $\langle ee \rangle$
- Opposite charges important

Magnetic Catalysis Gusynin, Miransky, Shovkovy '94



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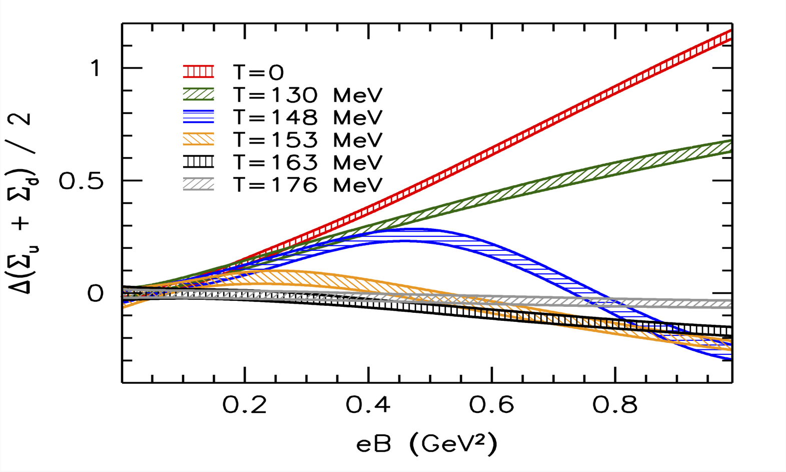
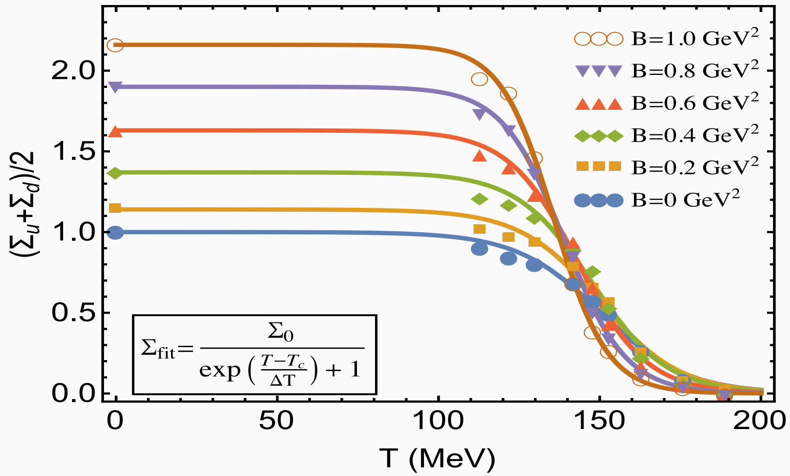
- Gusynin, Miransky, Shovkovy '94 studied in 3+1 NJL:
$$\langle \bar{q}q(B) \rangle^2 = \langle \bar{q}q(0) \rangle^2 \left(1 + \frac{|eB|^2}{3\langle \bar{q}q(0) \rangle^4 \ln(\Lambda / \langle \bar{q}q(0) \rangle^2} \right)$$
- Similar behavior for QCD at weak α_s
- Dimensional reduction $3+1 \rightarrow 1+1$ through Landau quantization $\Rightarrow$ IR dynamics stronger in lower D

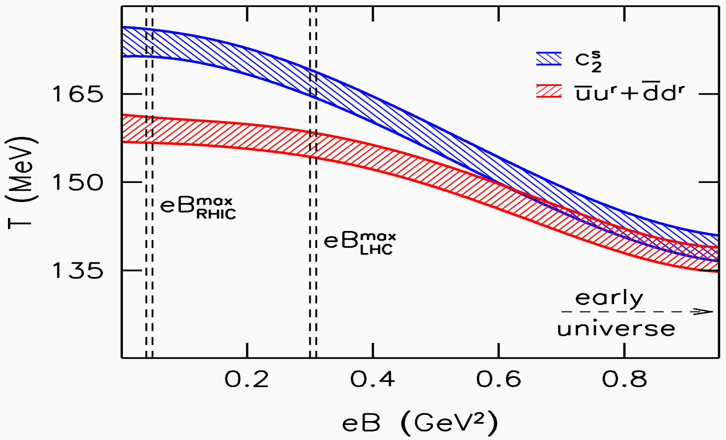
Inverse Magnetic Catalysis: a puzzle

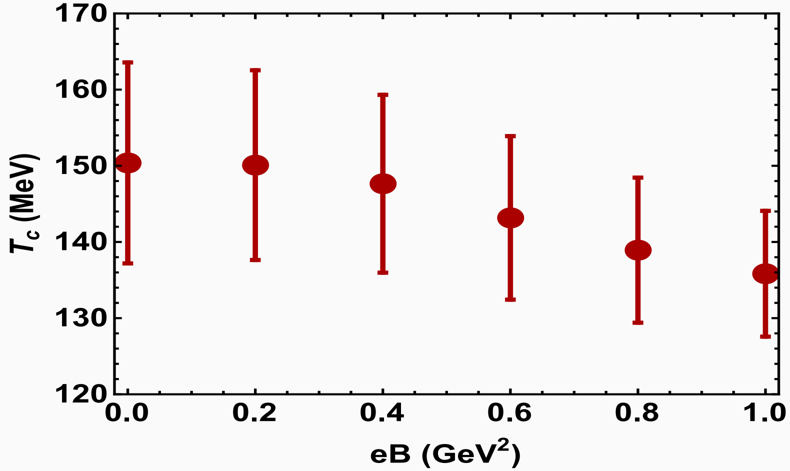
G. Bali et al '11, '12

- B destroys $\langle \bar{q}q \rangle$ around $T \sim T_c$
- T_c decreases with B









Possible Explanations

- "Valence" vs. "sea" quarks F. Bruckmann et al '13

$$\langle \bar{q}q \rangle = \int \mathcal{D}A e^{-S[A]} \mathsf{det}(D(A,B)+m) \mathsf{tr}(D(A,B)+m)^{-1}$$

  Valence $\Rightarrow$ enhances $\langle \bar{q}q \rangle$ for any B. Sea $\Rightarrow$ favors A configs. with larger Dirac eigenvalues $\Rightarrow$ suppresses $\langle \bar{q}q \rangle$ for larger B

- B effectively reduces $3+1 \to 1+1$, enhancing $\langle \bar{q}q \rangle$. But larger B reduces α_s by asymptotic freedom, diminishing $\langle \bar{q}q \rangle$.
- Clearly a result of non-trivial interplay between confinement and chiral symmetry breaking
- Should be able to observe in a phase deconfined with broken chiral symmetry
- This happens in holographic QCD in the Veneziano limit Jarvinen, Kiritsis '12

The gravitational action

$$S = M^3 N_c^2 \int \mathrm{d}^5x \left[\sqrt{g}\left(R - \frac{4}{3}\frac{(\partial\lambda)^2}{\lambda^2} + V_g(\lambda)\right) - xV_f(\lambda,\tau)\sqrt{\det(g_{\mu\nu} + w(\lambda)V_{\mu\nu} + \kappa(\lambda)\partial_\mu\tau\partial_\nu\tau)}\right],$$

with $V_{\mu\nu}$ the EM field tensor, $x = N_f/N_c = 1$ in Veneziano limit.
Ansatz:

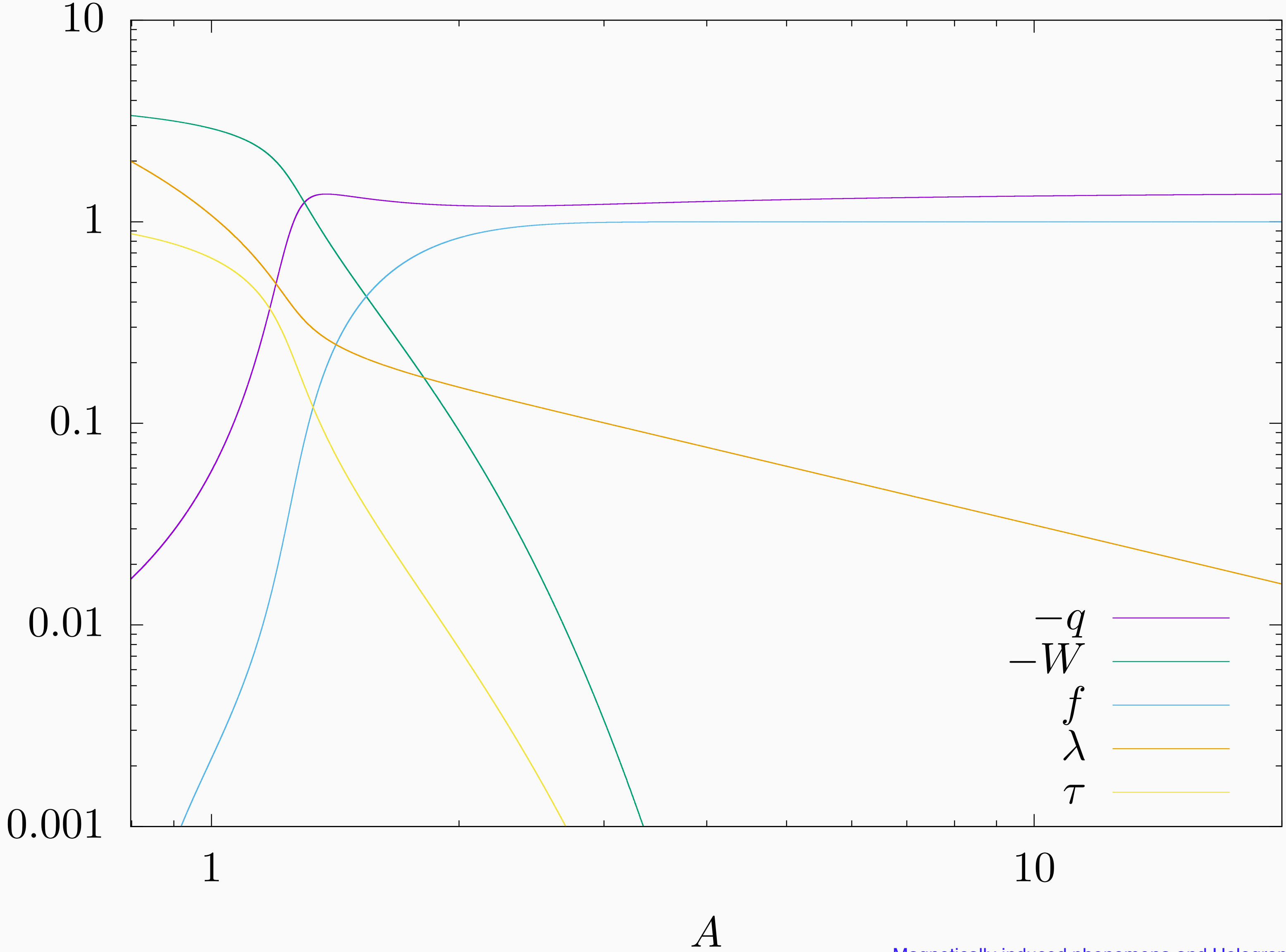
$$\mathrm{d}s^2 = e^{2A(r)}\left(\frac{\mathrm{d}r^2}{f(r)} + f(r)\,\mathrm{d}t^2 + \mathrm{d}x_1^2 + \mathrm{d}x_2^2 + e^{2W(r)}\,\mathrm{d}x_3^2\right).$$

Tachyon:

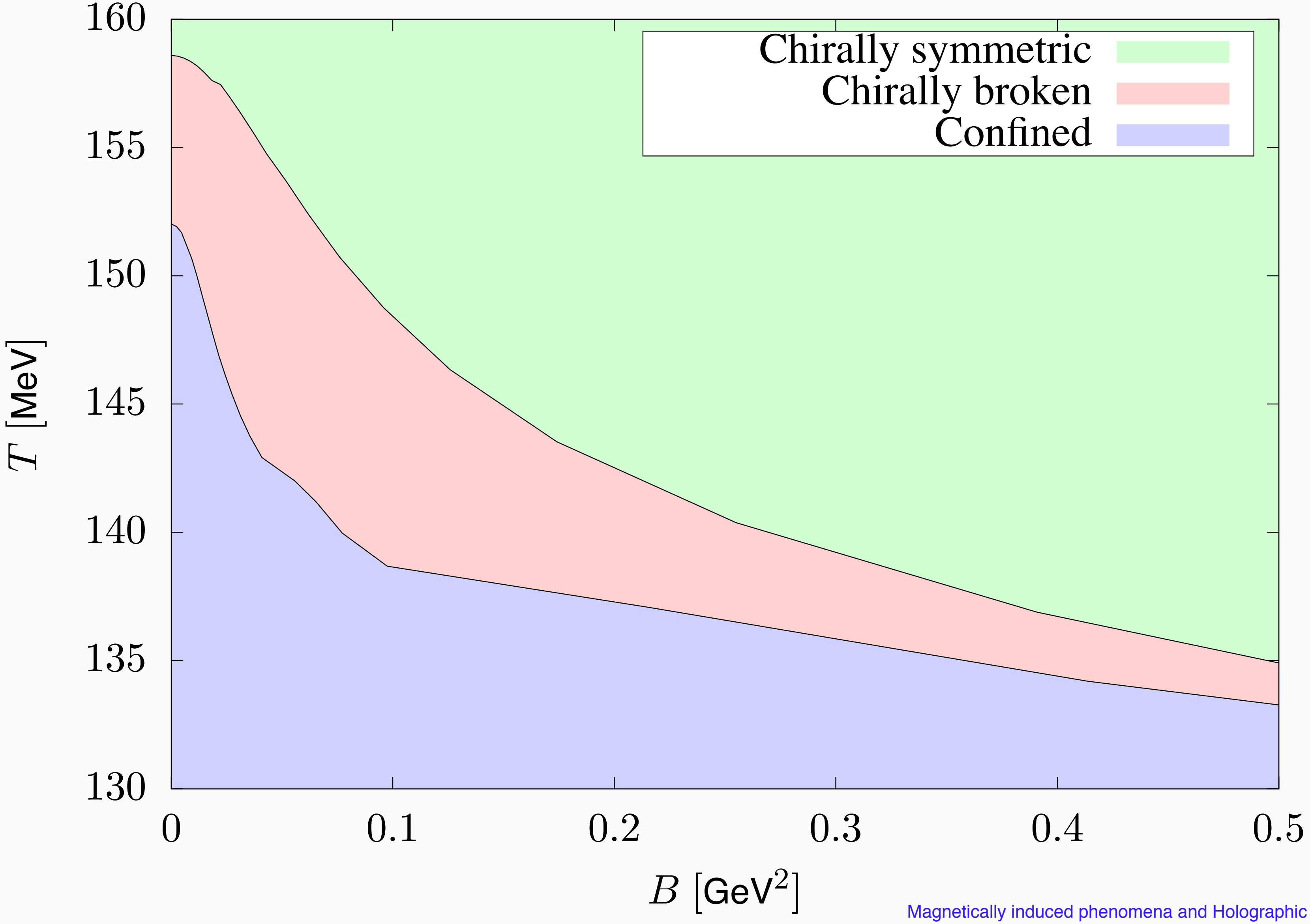
$$\frac{\tau}{\mathcal{L}_{\mathsf{UV}}} = m_q r\left(-\log(\Lambda r)\right)^{-\gamma_0/b_0} + \langle\bar{q}q\rangle r^3\left(-\log(\Lambda r)\right)^{\gamma_0/b_0}$$

V_f, V_g, κ and w chosen to satisfy known properties of QCD. Set $m_q = 0$. Define $q = e^A \frac{dr}{dA}$

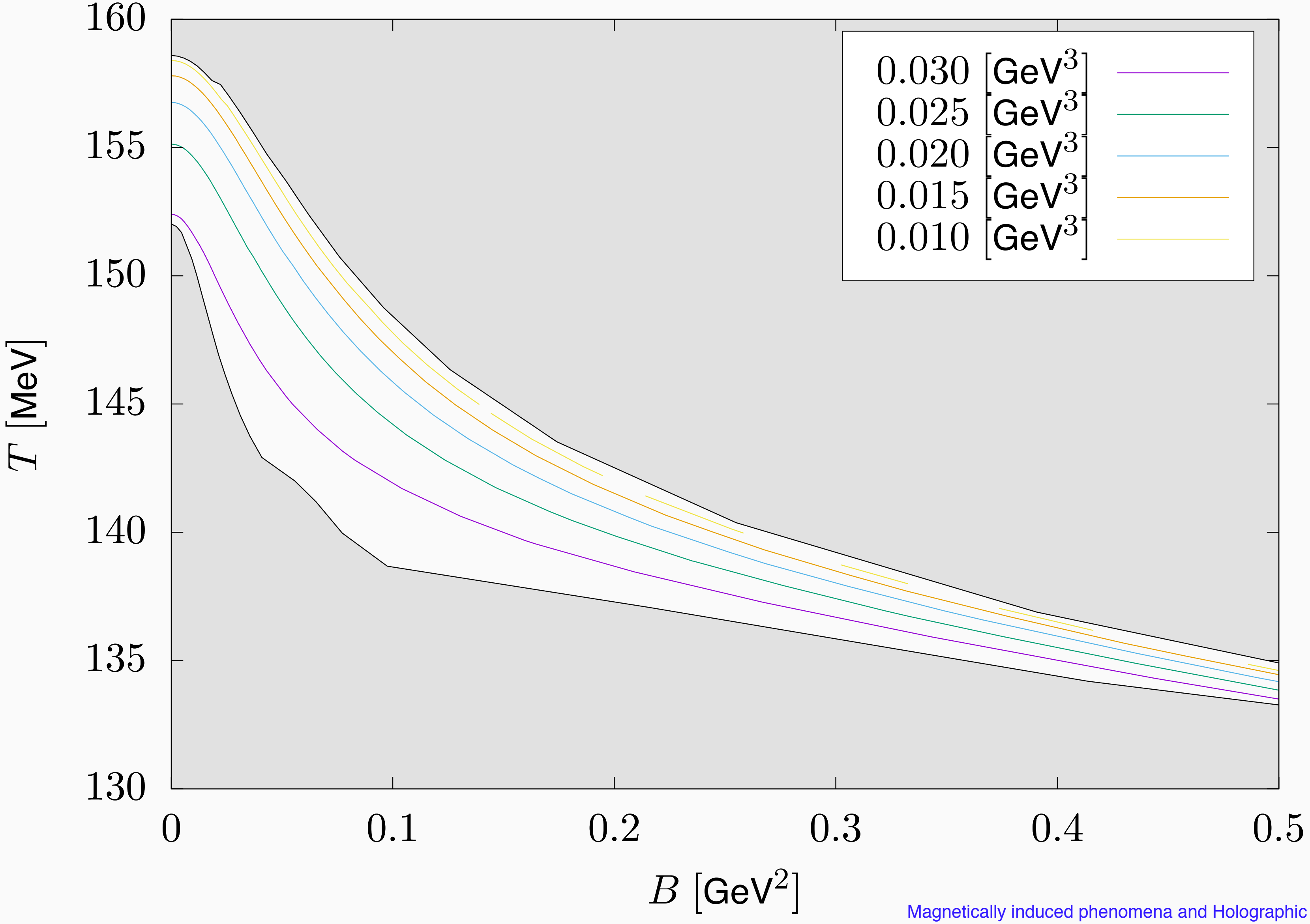
Example solution



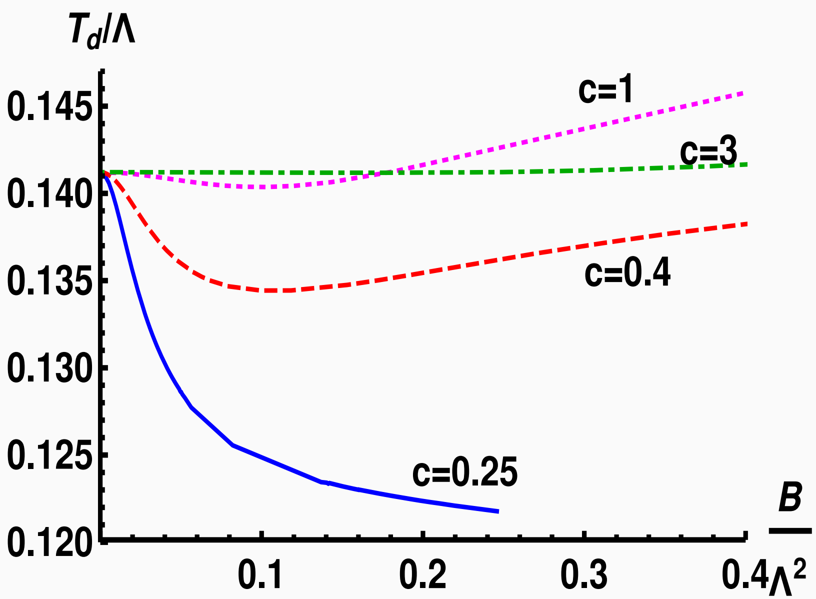
Deconfinement and χSB

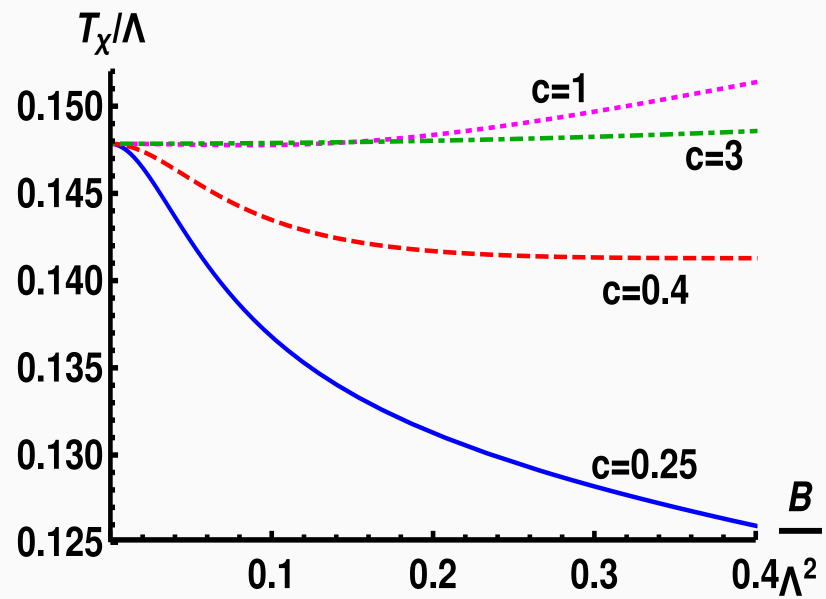


Condensate


0.030 [GeV^3]
0.025 [GeV^3]
0.020 [GeV^3]
0.015 [GeV^3]
0.010 [GeV^3]
T [MeV]
160
155
150
145
140
135
130
0
0.1
0.2
0.3
0.4
0.5
B [GeV^2]

- Playing with c in $w(\lambda) = \frac{\sqrt{1+\log(1+c\,\lambda)}}{\left(1+\frac{3}{4}\left(\frac{115-16x}{27}+\frac{1}{2}\right)c\,\lambda\right)^{4/3}}$ produce different qualitative behavior





- Decreasing c reduces the effect of λ in the B-sector of the DBI action

Summary - part II

- Found in Inverse Magnetic catalysis in a realistic model for non-conformal holography
- Realized in the phase deconfined with broken chiral symmetry
- Similar observations were made by Freis, Rebhan, Schmitt '12 in Sakai-Sugimoto but with finite μ
- Recently in Hard-wall K. Mamo '15 and in "tailored" D7 N. Evans et al '16 observes inverse magnetic catalysis
- More analysis needed to pinpoint the holographic mechanism behind IMC.

THANK YOU !