Phases of QCD and holography

Matti Järvinen

Universiteit Utrecht

THOR meeting – Istanbul – 4 September 2019

in collaboration with Christian Ecker, Umut Gürsoy, Ioannis Iatrakis, Govert Nijs, Wilke van der Schee (Utrecht);
Niko Jokela, Jere Remes (Helsinki);
Takaaki Ishii (Kyoto); Juan Pedraza (Amsterdam); . . .

Outline

1. Introduction to holographic QCD
   - Holographic V-QCD models
2. Inverse magnetic catalysis
   - Modeling inverse catalysis holographically
   - Anisotropic inverse catalysis
3. Holographic dense QCD matter
   - Dense quark matter
   - Dense nuclear matter
   - Holographic neutron star mergers

1. Introduction

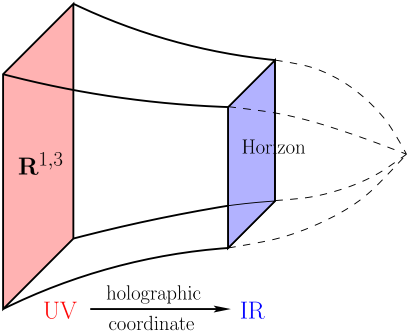
Gauge/gravity duality

- Gauge/gravity duality: at large N_c, strongly coupled field theory $\leftrightarrow$ classical higher dimensional gravity
- Well known example: $\mathcal{N} = 4$ Super Yang-Mills
  $\leftrightarrow$ type IIB supergravity on $AdS_5 \times S^5$
- Relatively easy classical analysis of strongly coupled phenomena $\Rightarrow$ apply to QCD?
- There are possible issues (QCD not conformal, no SUSY, and $N_c = 3$ is not that large ...) but since solving QCD is hard, it's worth trying

Gauge/gravity duality for QCD

Basic features:

- Geometrization of RG flow
- Deconfining (high T) phase: thermodynamics of QCD $\leftrightarrow$ thermodynamics of a planar bulk black hole
- Confining phase: horizonless geometry



- Operators $O_i(x^\mu) \leftrightarrow$ classical bulk fields $\phi_i(x^\mu, r)$
- Condensates in QCD $\langle O_i \rangle \leftrightarrow$ nontrivial extrema $\phi_i(r)$ in the bulk, e.g. black hole "hair"

Gauge/gravity duality for QCD: approaches

Top-down: models directly based on string theory

- Concrete, fixed string models in 10/11 d with brane configurations
- Control on what dual field theory is (it's not QCD though)
- E.g., Witten-Sakai-Sugimoto model: $D4$-$D8$-$\overline{D8}$

Bottom-up: models constructed "by hand"

- Follow generic ideas of holography, inspiration from top-down
- Introduce fields for most important operators (marginal)
- Lots of freedom $\to$ effective 5d description, no link to specific dual theory, comparison with QCD data essential
- Either a fixed geometry (AdS) or dynamical gravity

This talk: a rich bottom-up model; lots of input from string theory

- Goal: mimic QCD as closely as possible

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
- Relatively 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 these things by hand and generalize $\rightarrow$ arbitrary potentials
- Tune model to match QCD physics and data
- Effective description of QCD

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:
$\Rightarrow$ V-QCD models

[MJ, Kiritsis arXiv:1112.1261]

V-QCD at finite T, μ and B

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

$$\mathcal{S}_{\mathrm{V-QCD}} = N_c^2 M^3 \int d^5x \sqrt{g} \left[R - \frac{4}{3} \frac{(\partial\lambda)^2}{\lambda^2} + V_g(\lambda) \right]$$

$$- N_f N_c M^3 \int d^5x \; V_{f0}(\lambda) e^{-\tau^2}$$

$$\times \sqrt{-\det(g_{ab} + \kappa(\lambda)\partial_a\tau\partial_b\tau + w(\lambda)F_{ab})}$$

$$F_{rt} = \Phi'(r) \qquad \Phi(0) = \mu \qquad F_{xy} = B$$

[Alho, Kajantie, Kiritsis, MJ, Rosen, Tuominen; Gürsoy, Iatrakis, MJ, Nijs]

Effective model: choose potentials by comparing to QCD data

- Many potentials V_g, V_{f0}, w, κ – however need to be "simple" functions – still lot of predictivity!

Task: solve saddle point configurations numerically

- Finite T black hole and horizonless "thermal gas" solutions
- Chiral symmetry breaking $\leftrightarrow$ "condensation" of τ in the bulk
- Here restrict to zero quark mass (no source for τ)

2. Inverse magnetic catalysis

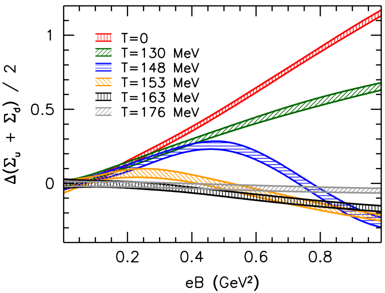
Inverse magnetic catalysis – a puzzle

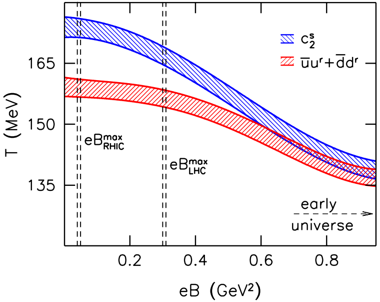
At low temperatures in QCD, $\langle\bar{q}q\rangle$ increases with B

- Magnetic catalysis: model independent, well understood

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

- T_c decreases with B [Bali et al., arXiv:1111.4956, arXiv:1206.4205]





Lattice: "Valence" quarks induce ordinary catalysis, but "sea" quarks can give inverse catalysis ⇒ backreaction important [Bruckmann, Endrodi, Kovacs, arXiv:1303.3972]

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

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

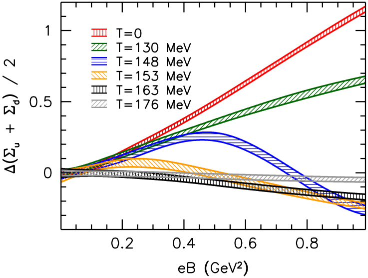
[Preis,Rebhan,Schmitt, arXiv:1012.4785]

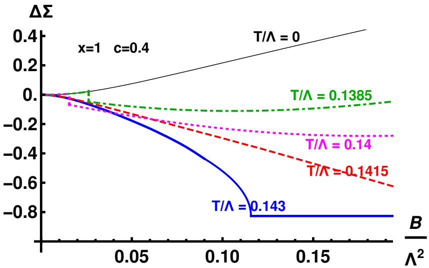
This talk: consider inverse catalysis in V-QCD

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

Chiral condensate in V-QCD

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





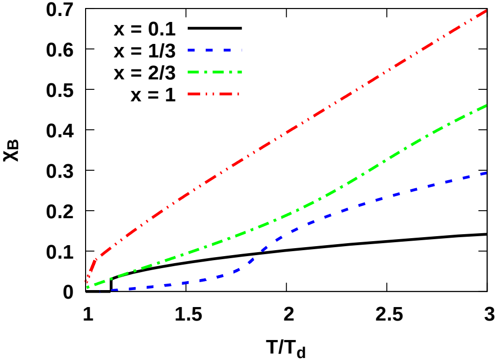
- Separate confinement and chiral transitions with $T_d < T_\chi$ give rise to a nontrivial behavior
- Qualitative agreement between lattice and V-QCD

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

Varying number of flavors

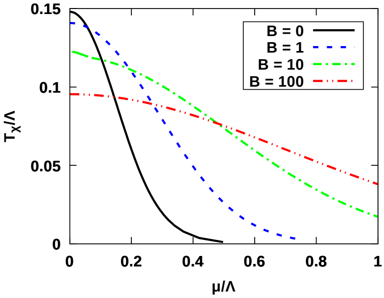
Magnetic susceptibility controls the dip in the critical temperature T_d through

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

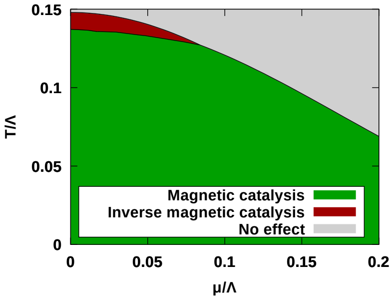


- Dip stronger at higher $x \leftrightarrow$ inverse catalysis
- Rough agreement with the picture arising from lattice: inverse catalysis arises due to backreaction
- Magnitude of χ_B in agreement with lattice

Inverse magnetic catalysis for $\mu > 0$



At $B \approx 0$



- Turning on μ suppresses inverse catalysis
- Increasing B enhances inverse catalysis at finite μ
  [Gürsoy, MJ, Nijs, PRL 120, 242002; arXiv:1707.00872]
- Effect found at small μ: accessible by lattice simulations?

Inverse Anisotropic catalysis

- Inverse magnetic catalysis conjectured to arise through the anisotropy caused by the magnetic field, rather than by the direct effect of the field

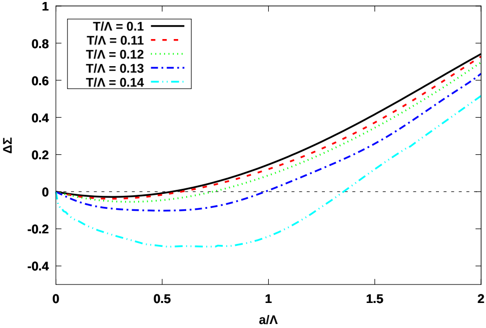
  [Giataganas, Gürsoy, Pedraza PRL 121, 121601]

- We checked this by turning on an anisotropy from a different source ($\sim \theta$ angle with spatial dependence) at zero B

  [Gürsoy, MJ, Nijs, Pedraza arXiv:1811.11724]

$\Delta\Sigma$ as a function of the anisotropy for various T

- Results (including parameter dependence) support the conjecture
- Can a similar setup be realized on the lattice?



3. Dense QCD matter

Fitting to lattice data ($\mu \approx 0$)

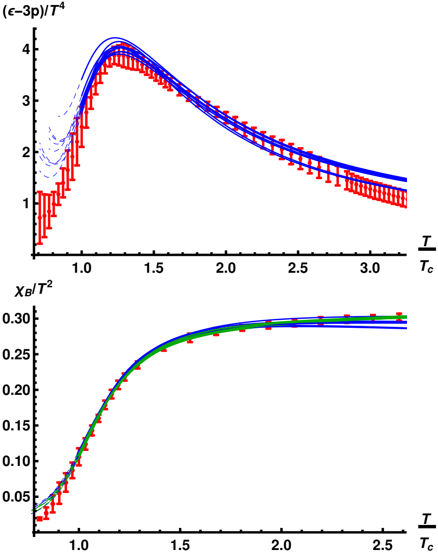
Stiff fit to lattice data near $\mu = 0$ (many parameters, but results quite insensitive to them) [Jokela, MJ, Remes, arXiv:1809.07770]

Interaction measure: constrains $V_{f0}(\lambda)$

Lattice data: Borsanyi et al. arXiv:1309.5258

Baryon number susceptibility: constrains $w(\lambda)$

Lattice data: Borsanyi et al. arXiv:1112.4416



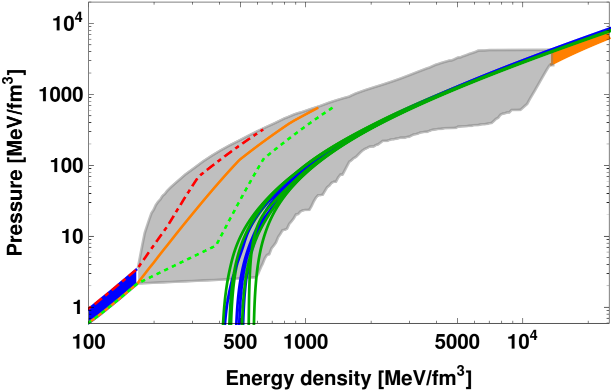
Extrapolated EoSs of cold QCD

The V-QCD quark matter result compared to

[Jokela, MJ, Remes, arXiv:1809.07770]

- Interpolated equations of state (EoSs) (gray band)
- Stiff, intermediate, and soft nuclear EoSs

  [K. Hebeler, J. M. Lattimer, C. J. Pethick, A. Schwenk arXiv:1303.4662]



Extrapolation works nicely ⇒ reasonable EoSs for all T and μ!

[Chesler, Jokela, Loeb, Vuorinen arXiv:1906.08440]

Homogeneous nuclear matter in V-QCD

Baryons in holography: solitons of gauge field in the bulk

Consider probe limit: consider full brane action $S = S_{\rm DBI} + S_{\rm CS}$ where

[Bigazzi, Casero, Cotrone, Kiritsis, Paredes; Casero, Kiritsis, Paredes]

$$S_{\rm DBI} = -\frac{1}{2}M^3 N_c\, \mathbb{T}r \int d^5x\, V_{f0}(\lambda)e^{-\tau^2}\left(\sqrt{-\det \mathbf{A}^{(L)}} + \sqrt{-\det \mathbf{A}^{(R)}}\right)$$

$$\mathbf{A}_{MN}^{(L/R)} = g_{MN} + \delta^r_M \delta^r_N \kappa(\lambda)\tau'(r)^2 + \delta^{rt}_{MN} w(\lambda)\Phi'(r) + w(\lambda)F_{MN}^{(L/R)}$$

gives the dynamics of the solitons (will be expanded in $F^{(L/R)}$) and

$$S_{\rm CS} = \frac{N_c}{8\pi^2}\int \Phi(r)e^{-b\tau^2} dt \wedge \left(F^{(L)} \wedge F^{(L)} - F^{(R)} \wedge F^{(R)} + \cdots\right)$$

sources the baryon number for the solitons

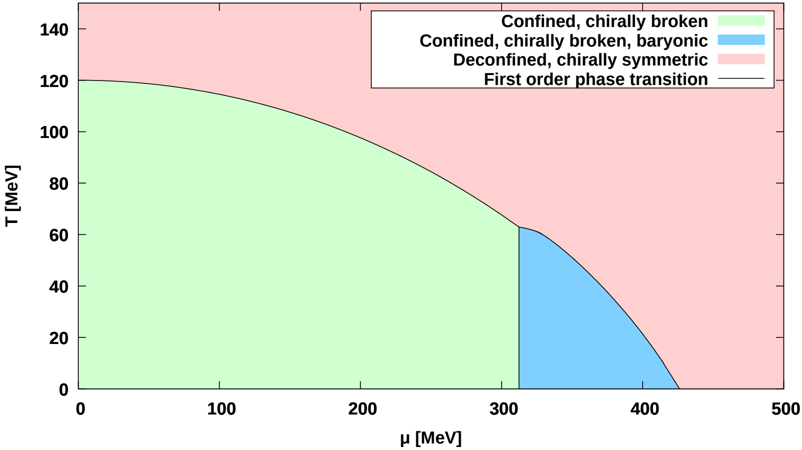
Set $N_f = 2$ and consider the homogeneous SU(2) Ansatz

[Rozali, Shieh, Van Raamsdonk, Wu]

$$A^i_L = -A^i_R = h(r)\sigma^i$$

- Good approximation at high densities, where traditional nuclear matter models do not work?

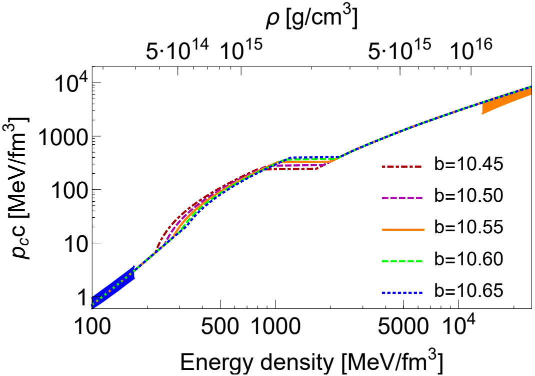
Phase diagram



- Baryons appear at medium μ in the confined phase
- Nontrivial nuclear and quark matter EoS from the same model

Hybrid Equation of State

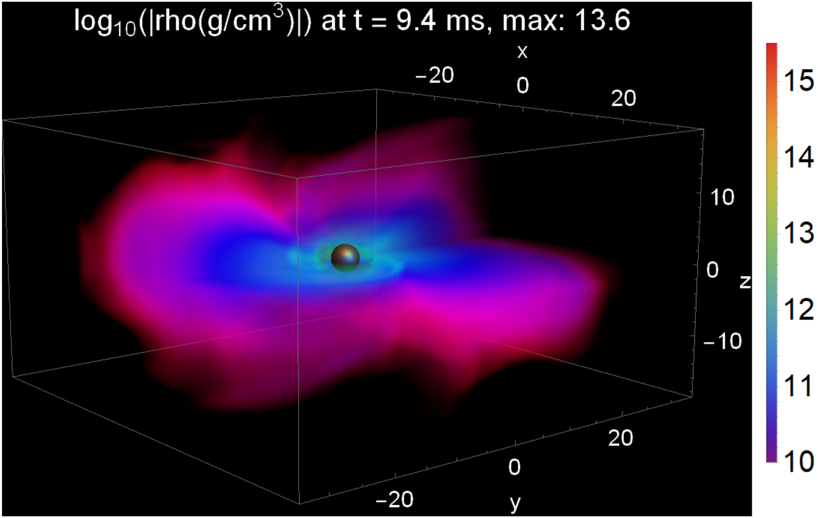
- Match SLy (low densities) with V-QCD (high densities)
  [SLy: Haensel, Pichon nucl-th/9310003, Douchin, Haensel astro-ph/0111092]
- V-QCD nuclear matter EoS stiff, as in Witten-Sakai-Sugimoto
  [Bitaghsir Fadafan, Kazemian, Schmitt arXiv:1811.08698]
- Easy to pass astrophysical constraints



- Strong first order nuclear to quark matter phase transition
- Same holographic model for baryon and quark phases!

[Ecker,MJ,Nijs,van der Schee arXiv:1908.03213; in progress with Jokela,Nijs,Remes]

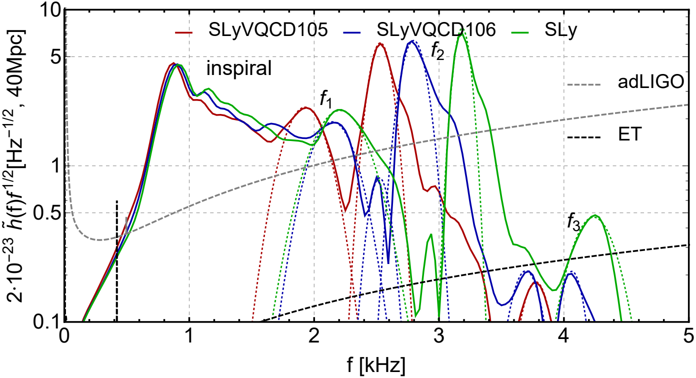
Neutron star merger with holographic EoS



[Ecker, MJ, Nijs, van der Schee arXiv:1908.03213]

Power spectral densities of gravitational waves

Power spectral density of the produced gravitational waves carries the imprint of the EoS



- Holographic EoSs predict relatively low frequencies f_2 of the strongest peak
- Signal should be visible at advanced LIGO for nearby mergers

Summary

- Holographic models are useful to study QCD in regimes (with strong coupling) where other approaches have difficulties
- We analyzed inverse magnetic catalysis:
  - Backreaction is important
  - Prediction at finite μ: inverse catalysis weakened
  - Inverse catalysis arises through anisotropy caused by the magnetic field (?)
- Simultaneous holographic modeling of dense quark and nuclear matter at $T = 0$
  - Stiff nuclear matter EoS
  - Predictions/constraints for gravitational wave spectrum in neutron star mergers

Extra slides

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

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]

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

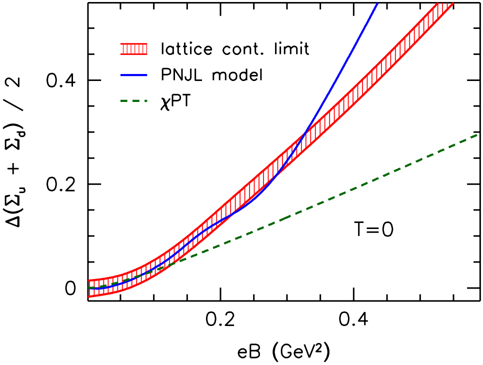
Apply here to QCD thermodynamics at finite μ and B: no lattice data available

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

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: $D = 3+1 \to 1+1$
  $\Rightarrow$ Stronger IR dynamics
  $\Rightarrow$ Enhanced $\langle \bar{q}q \rangle$
- Model independent

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

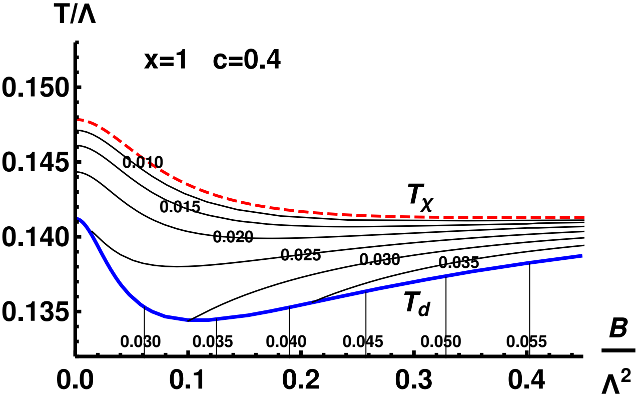
- "Valence" vs. "sea" quarks

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

- 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]

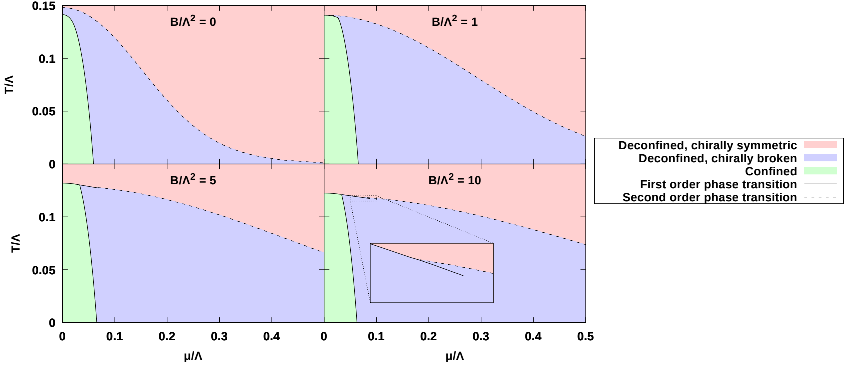
Transition temperatures and chiral condensate



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

The phase diagram at finite B and μ

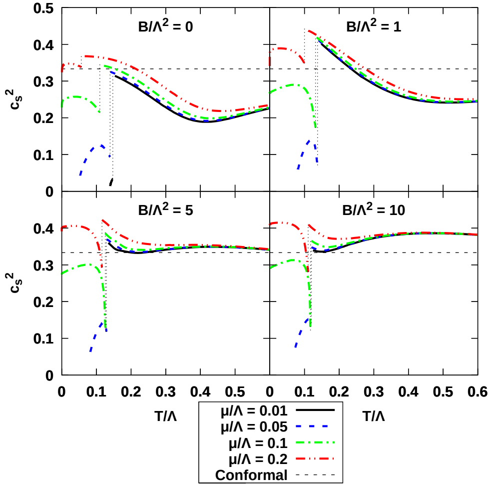
$$x_f = 1$$



- Main effect: increasing B enhances the intermediate phase

Speed of sound

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



Ansatz for potentials, $(x = 1)$

$$V_g(\lambda) = 12\left[1+V_1\lambda+\frac{V_2\lambda^2}{1+\lambda/\lambda_0}+V_{\rm IR}e^{-\lambda_0/\lambda}(\lambda/\lambda_0)^{4/3}\sqrt{\log(1+\lambda/\lambda_0)}\right]$$

$$V_{f0}(\lambda) = W_0 + W_1\lambda + \frac{W_2\lambda^2}{1+\lambda/\lambda_0} + W_{\rm IR}e^{-\lambda_0/\lambda}(\lambda/\lambda_0)^2$$

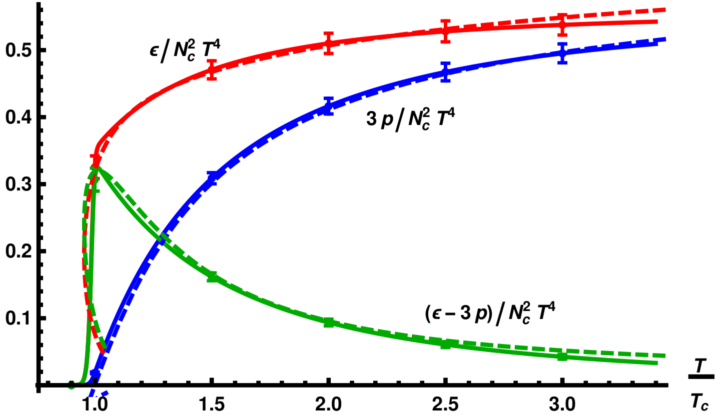
$$\frac{1}{w(\lambda)} = w_0\left[1 + \frac{w_1\lambda/\lambda_0}{1+\lambda/\lambda_0} + \bar{w}_0 e^{-\lambda_0/\lambda w_s}\frac{(w_s\lambda/\lambda_0)^{4/3}}{\log(1+w_s\lambda/\lambda_0)}\right]$$

$$V_1 = \frac{11}{27\pi^2}\ , \qquad V_2 = \frac{4619}{46656\pi^4}$$

$$W_1 = \frac{8+3\,W_0}{9\pi^2}\ ; \qquad W_2 = \frac{6488+999\,W_0}{15552\pi^4}$$

Fixed UV/IR asymptotics $\Rightarrow$ fit parameters only affect details in the middle

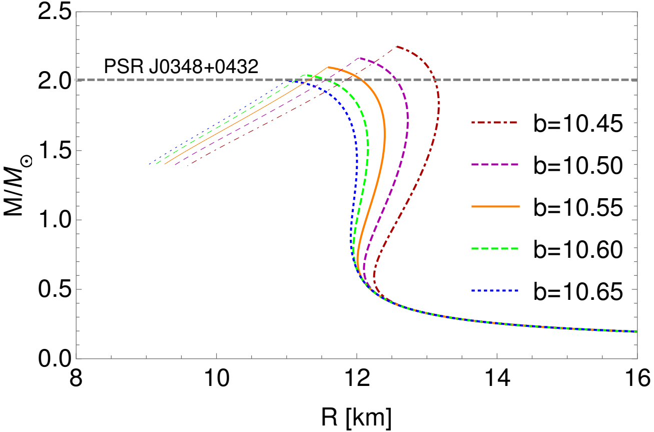
Fitting: glue sector



- Determine precise form of $V_g(\lambda)$ with UV and IR asymptotics fixed (at $N_f = 0$)
- Follow roughly the strategy in [Gürsoy, Kiritsis, Mazzanti, Nitti arXiv:0903.2859]
- Stiff fit to large N_c YM lattice data [Panero, arXiv:0907.3719]

Neutron star mass-radius relation

Values allowed by the experimental constraints: $10.45 \lessapprox b \lessapprox 10.65$



- No stable quark matter cores