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Recent progress in holographic QCD

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Outline

This talk: model construction

1. Introduction to holographic QCD
   - Top-down approach
   - Bottom-up approach
2. Improved holographic QCD
   - Holographic model for Yang-Mills
3. V-QCD
   - Holographic model for QCD with backreacted quarks

AdS/CFT

Generic structure

- Conformal field theory on the boundary
  $\leftrightarrow$ String theory in the bulk
- Field theory at large N_c and λ
  $\leftrightarrow$ Classical limit of string theory (supergravity)

Dictionary

- Operator $\mathcal{O}_i(x)$ on the bdry $\leftrightarrow$ field ϕ_i in the bulk

$$Z_{\text{CFT}}[J_i(x)] = Z_{\text{sugra}}[\phi_i]\Big|_{\phi_i(x)=J_i(x) \text{ @ bdry}}$$

- Here $J_i(x)$ is the source for $\mathcal{O}_i(x)$

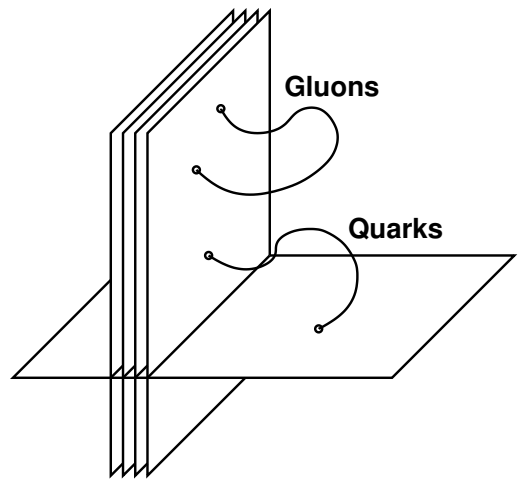
Apply to QCD?

- Supported by QCD string picture ('t Hooft)?
- Could shed light on the strongly coupled IR
- Duality however works only for certain field theories (typically conformal and SUSY) $\Rightarrow$ QCD difficult!

Holographic QCD: Top-down approach

Constructions directly motivated by the original AdS/CFT duality

- Concrete, fixed string models in 10/11 d
- Specific brane intersections
- Typically probe quarks in glue background
- Control on what dual field theory is



However..

- Field theory not QCD (Light Kaluza-Klein modes..)
  - Still works quite well!

E.g., Sakai-Sugimoto model: $D4$-$D8$-$\overline{D8}$

Holographic QCD: Bottom-up approach

Holographic models constructed "by hand"

- Follow generic principles of holography
- Lots of freedom $\rightarrow$ effective 5d description, no link to specific dual theory
- (Surprisingly?) good description of QCD data
- Difficult to improve systematically
- Results often depend on the choice of boundary conditions

Examples

- Hard-wall and soft-wall models
- Light-front holography

Improved holographic QCD

IHQCD: bottom up model for pure Yang-Mills inspired by string theory

[Gursoy, Kiritsis, Nitti]
[Gubser, Nellore]

Idea:

- Follow generic structure predicted by string theory as closely as possible
  $\rightarrow$ Ansatz for Lagrangian, better control on the model
- Explore all remaining degrees of freedom

Implementation:

- Five-dimensional noncritical string theory
- Brane construction, N_c $D3$ branes

Result:

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

Issue:

- V_g has wrong UV behavior, "bad dictionary" ($\lambda \to 0$, no surprise!)
- Fix by hand: map V_g to QCD beta function instead in the UV

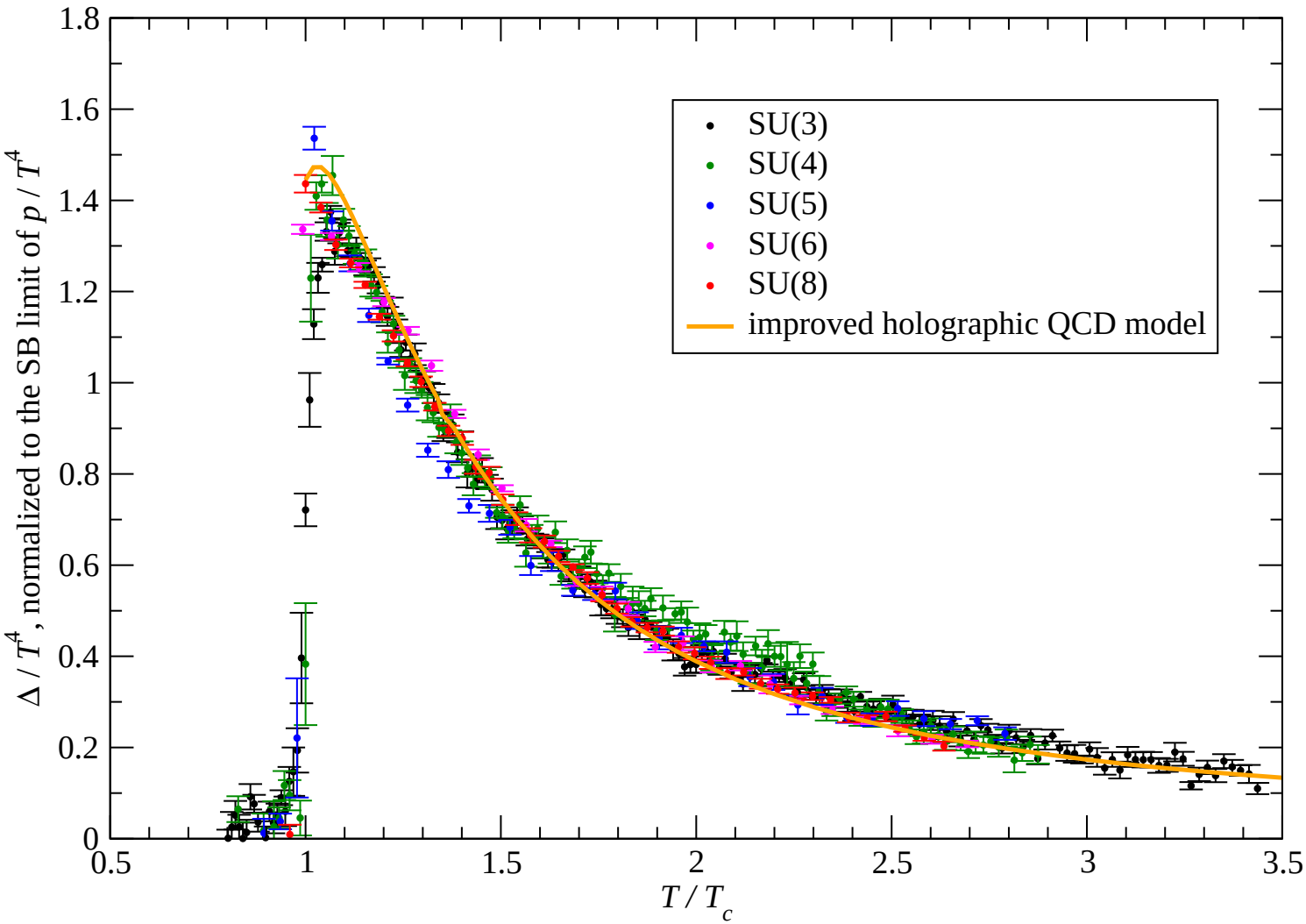
Exploration of all choices of V_g in the IR
$\Rightarrow$ String theory prediction (power-law) + minor corrections (logarithmic) works

- "Good" IR singularity: all IR boundary conditions uniquely fixed

Good agreement with pure YM lattice data, both at zero and finite temperature

[Gursoy, Kiritsis, Mazzanti, Nitti; Panero; . . .]

Trace of the energy-momentum tensor



Adding (probe) flavor in IHQCD

Framework: $D4$-$\overline{D4}$ (space-filling) probe branes
$\Rightarrow$ Sen like brane action (Tachyonic Dirac-Born-Infeld)

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

Results in the probe limit (fundamental quarks):

- Confining asymptotics of the geometry triggers chiral symmetry breaking
- Gell-Mann-Oakes-Renner relation
- Linear Regge trajectories for mesons
- A very good fit of the light meson masses

[Gursoy,Kiritsis,Nitti; Iatrakis,Kiritsis,Paredes]

V-QCD: motivation

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

Backreaction $\Rightarrow$ better modeling of (ordinary) QCD?

Important new features can be captured in the Veneziano limit:

- Phase diagram of QCD (at zero temperature, baryon density, and quark mass), varying $x = N_f/N_c$
- The QCD thermodynamics as a function of x
- Phase diagram as a function of baryon density
- Effect of turning on a finite quark mass at finite x

V-QCD: the fusion

The fusion:

1. IHQCD: model for glue by using dilaton gravity
2. Adding flavor and chiral symmetry breaking via tachyon brane actions

Consider 1. + 2. in the Veneziano limit with full backreaction
$\Rightarrow$ V-QCD models

[MJ, Kiritsis]

Defining V-QCD

Degrees of freedom

- The tachyon $\tau \leftrightarrow \bar{q}q$, and the dilaton $\lambda \leftrightarrow \mathrm{Tr}F^2$
- $\lambda = e^{\phi}$ is identified as the 't Hooft coupling $g^2 N_c$

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

$$V_f(\lambda,\tau) = V_{f0}(\lambda)\exp(-a(\lambda)\tau^2)\,; \qquad ds^2 = e^{2A(r)}(dr^2 + \eta_{\mu\nu}x^\mu x^\nu)$$

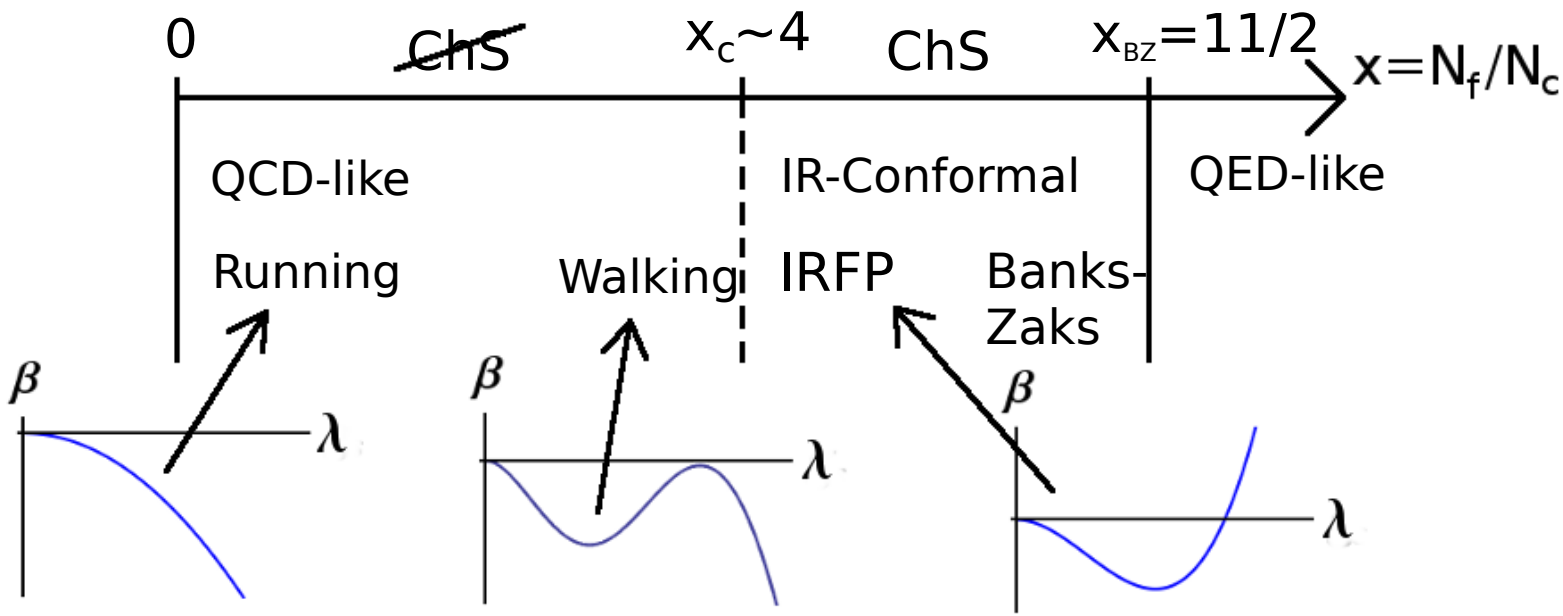
Need to choose V_{f0}, a, and κ ...

The same strategy as for IHQCD works (!):

- Match to perturbative QCD in the UV
- Logarithmically modified string theory predictions in the IR

Phase diagram of V-QCD

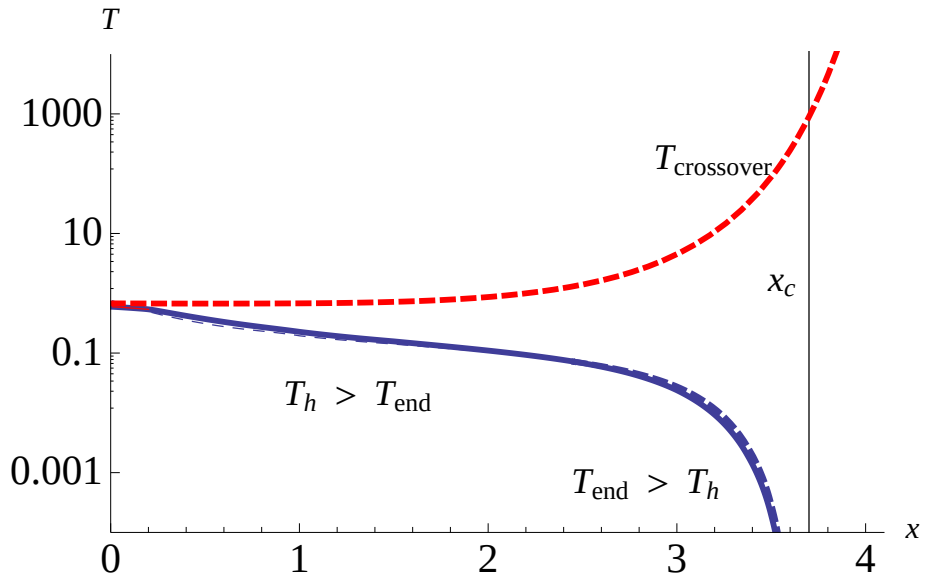
At zero quark mass and temperature,
constructing numerically all vacua,
QCD phase diagram reproduced:



- Conformal transition (BKT) at $x = x_c \simeq 4$
  [Kaplan,Son,Stephanov;Kutasov,Lin,Parnachev]
- Miransky scaling, $\langle \bar{q} q \rangle \sim \exp\left[-\frac{2K}{\sqrt{x_c - x}}\right]$, in walking regime

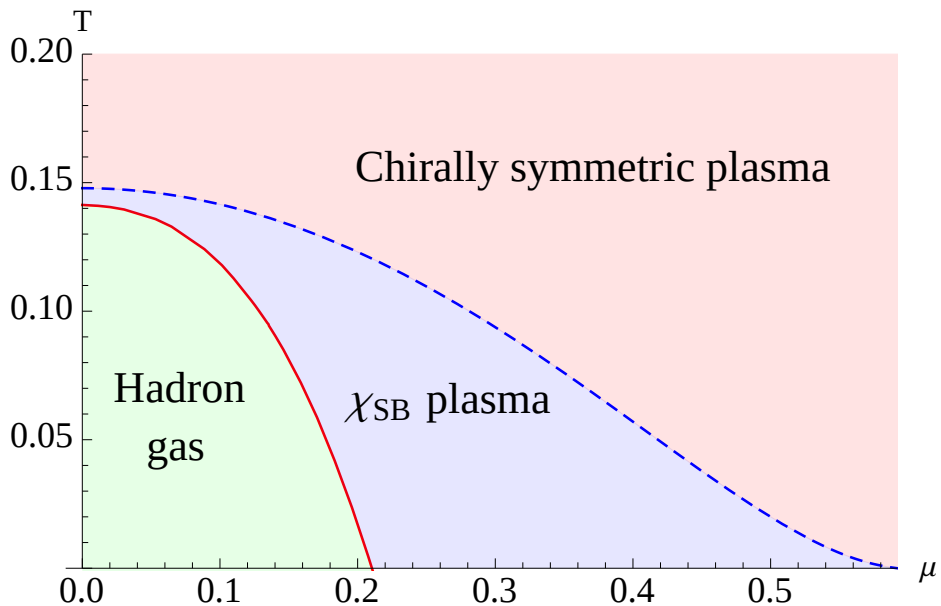
Phase diagram at finite T

[Alho,MJ,Kajantie,Kiritsis,Tuominen]



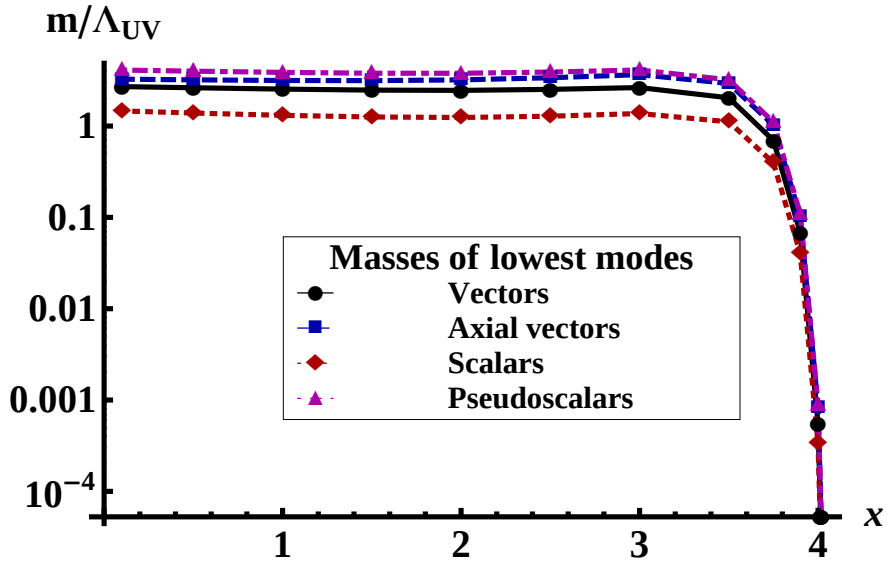
Example at finite T and μ

[Alho,MJ,Kajantie,
Kiritsis,Rosen,Tuominen]

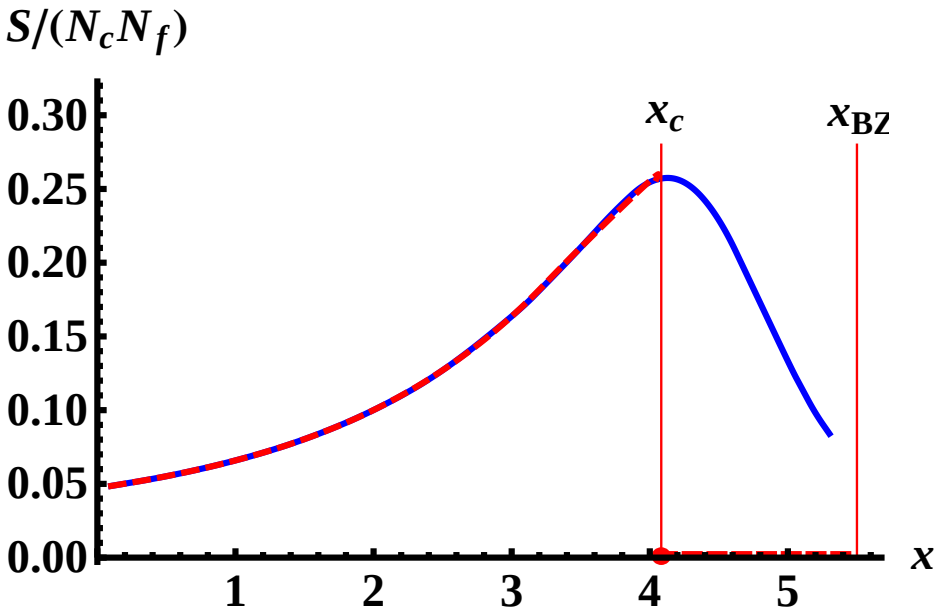


Spectra etc in V-QCD

Spectrum of light mesons
(nothing fitted to data yet)



S-parameter



Axial anomaly

[Arean,Iatrakis,MJ,Kiritsis; MJ]

Conclusion

- An ongoing program for constructing holographics duals for QCD with backreacted quarks
- Qualitative agreement with QCD data/expectations
- Next step: quantitative fit to experimental/lattice data

Extra slides

Improved holographic QCD

IHQCD: well-tested string-inspired bottom-up model for pure Yang-Mills

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

with the metric

$$ds^2 = e^{2A(r)} (dr^2 + \eta_{\mu\nu} x^\mu x^\nu)$$

- $A \to \log \mu$ energy scale
- $\lambda = e^\phi \to$ 't Hooft coupling $g^2 N_c$
- $\phi \leftrightarrow \mathrm{Tr}(F^2)$ $\qquad$ $g_{\mu\nu} \leftrightarrow T_{\mu\nu}$