Heavy quarks in a hot bath in the 't Hooft limit

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Heavy quarks and quarkonia in thermal QCD
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Outline

Based on:

- [B. Lucini and M. P., 1210.4997] (to appear in Phys. Rep.)
- [A. Mykkänen, M. P. and K. Rummukainen, JHEP 1205 (2012) 069]

Outline

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Generalities

QCD in the 't Hooft limit

Consider a QCD-like theory with SU(N) gauge group

Double limit $N \to \infty$ and $g \to 0$, with $\lambda = g^2 N$ and n_f fixed

Double-line notation:

- Quark: fundamental rep. $\Rightarrow$ single line
- Gluon: adjoint rep. $\Rightarrow$ double line

Terms proportional to different powers of $1/N$ can be arranged in a *topological series*

$$\mathcal{A} = \sum_{h,b=0}^{\infty} \left(\frac{1}{N}\right)^{2h+b-2} \sum_{n=0}^{\infty} c_{(h,b),n} \lambda^n$$

Dominance of *planar* diagrams *without dynamical quark loops*

The theory *simplifies* but does not become *integrable*

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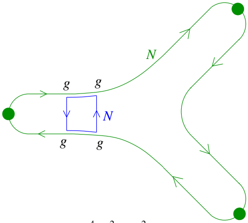
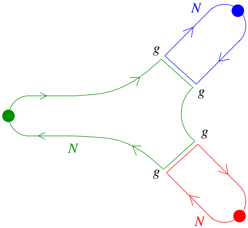
Elementary phenomenological implications

If large-N QCD is confining:

- Light spectrum: infinitely many, non-interacting glueballs and mesons, masses $O(N^0)$: large-N QCD is a theory of *weakly coupled* hadrons
- No exotica (tetraquarks, molecules, et c.)
- The OZI rule is *exact*



$g^4 N^2 = \lambda^2$



$g^4 N^3 = N\lambda^2$

- Chiral Lagrangian exact at tree level
- Axial anomaly and $m^2_{\eta'}$, are $O(1/N)$
- Baryons as "non-relativistic" ($m_B = O(N)$) solitons of the theory

The large-N limit in the holographic correspondence

Maldacena conjecture: A correspondence between gauge theories and string theories in a higher-dimensional, curved spacetime

Famous example: $\mathcal{N} = 4$ super-Yang–Mills in 4D *vs.* type IIB string theory in 10D

Arises as *open/closed string duality* in a background of D3-branes

Relations between the gauge and string parameters:

- ★ Large-N limit of the gauge theory $\longleftrightarrow$ *Classical* limit of the string theory

$$\frac{\lambda}{N} = 4\pi g_s$$

- ★ Strong-coupling limit of the gauge theory $\longleftrightarrow$ *Gravity* limit of the string theory

$$\lambda = \frac{R^4}{l_s^4}$$

From $\mathcal{N} = 4$ super-Yang–Mills to QCD (I)

Can results for $\mathcal{N} = 4$ SYM have any relevance for QCD?

At zero temperature, $\mathcal{N} = 4$ SYM and QCD are *radically qualitatively different*

- QCD is not supersymmetric; $\mathcal{N} = 4$ SYM is (*maximally*)
- QCD has fundamental quarks; $\mathcal{N} = 4$ SYM has adjoint fermions
- QCD is confining; $\mathcal{N} = 4$ SYM is not
- In QCD, the coupling runs; in $\mathcal{N} = 4$ SYM it does not
- QCD has a finite mass gap and discrete spectrum; the $\mathcal{N} = 4$ SYM spectrum is continuous
- QCD exhibits χSB; $\mathcal{N} = 4$ SYM does not

From $\mathcal{N} = 4$ super-Yang–Mills to QCD (II)

Can results for $\mathcal{N} = 4$ SYM have any relevance for QCD?

The situation is more favourable in the *deconfined phase* at finite temperature

- Finite temperature breaks supersymmetry
- QCD is not confining at high temperature
- Both QCD and $\mathcal{N} = 4$ SYM display Debye screening
- The QCD coupling runs (*logarithmically*) slowly
- Chiral symmetry restored

From $\mathcal{N} = 4$ super-Yang–Mills to QCD (III)

Is there a holographic dual for *any* gauge theory?

- ★ *Top-down* approach: Break explicitly some symmetries of $\mathcal{N} = 4$ SYM
- ★ *Bottom-up* approach: Construct "by hand" a suitable gravity dual of QCD

Essentially *all* holographic results rely on the large-N approximation $\longrightarrow$ test on the lattice

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Free energy of a heavy source in Yang–Mills

In YM, the Polyakov loop is the order parameter for deconfinement

Bare free energy is divergent $\longrightarrow$ renormalization [Dotsenko and Vergeles, 1980]

Perturbative predictions [Burnier, Laine and Vepsäläinen, 2009; Brambilla et al., 2010; Ghiglieri, 2012]

Do sources in different irreps obey Casimir scaling [Ambjørn, Olesen and Peterson, 1984]? (See [Dumitru et al., 2003; Döring et al., 2007; Gupta, Hübner and Kaczmarek, 2008; Hübner and Pica, 2008] for tests in $SU(2)$ and $SU(3)$)

Setup of the simulations

Wilson action [Wilson, 1974] and tree-level improved action [Curci, Menotti and Paffuti, 1983; Lüscher and Weisz, 1985]

Heat-bath and overrelaxation updates on SU(2) subgroups

Non-perturbative definition of the scale (string tension and/or Sommer parameter)

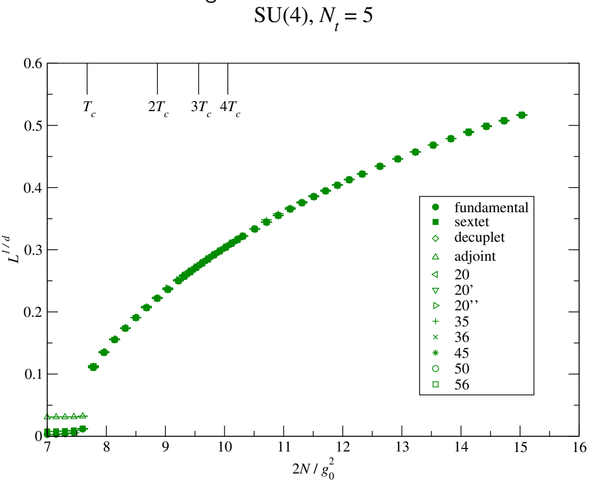
Polyakov loop renormalization from $T = 0$ static potential [Kaczmarek, Karsch, Petreczky and Zantow, 2002]

Scheme choice: Set constant term in the renormalized $T = 0$ potential to zero

(Alternative renormalization methods exist [Gupta, Hübner and Kaczmarek, 2008; Gavai, 2010])

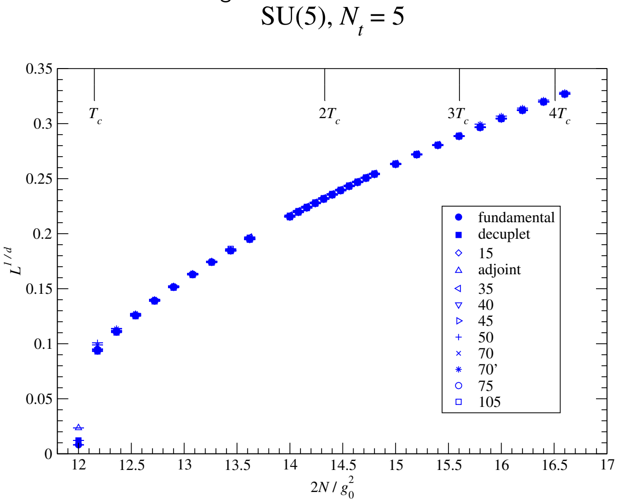
Results: Casimir scaling (I)

Strong evidence for Casimir scaling



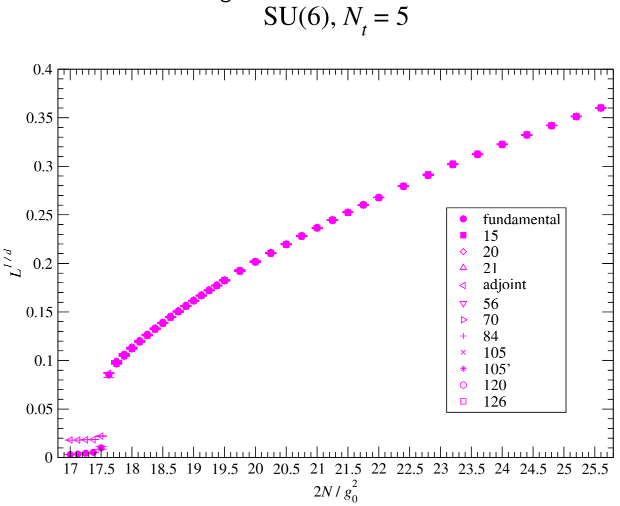
Results: Casimir scaling (II)

Strong evidence for Casimir scaling



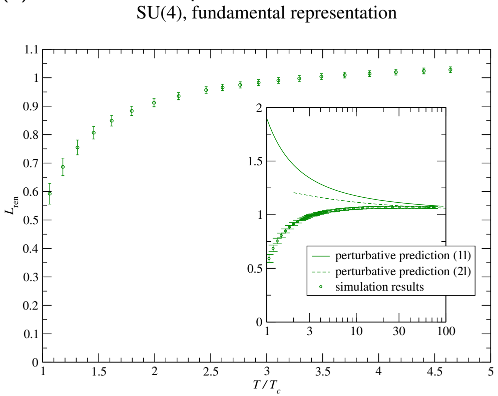
Results: Casimir scaling (III)

Strong evidence for Casimir scaling



Results: Renormalized loop

Renormalized SU(4) fundamental loop



Strong similarities with SU(3) [Gupta, Hübner and Kaczmarek, 2008]

Comparison with perturbative predictions [Burnier, Laine and Vepsäläinen, 2009; Brambilla et al., 2010]

Comparison with strong-coupling expectations from holography [Noronha, 2010]

Outline

Conclusions

- Large-N QCD as an interesting theoretical laboratory
- Interest revived by the relevance in holographic computations
- Finite-temperature setup may be suitable for comparisons with real-world QCD
- Lattice tests
- An example: Free energy of static sources in quenched QCD