AdS/CFT and The Axial Sector of large-N Yang-Mills theory

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Work with U. Gursoy, I. Iatrakis, E. Kiritsis, L. Mazzanti, A. O'Bannon, 0707.1349, 0903.2859, 1212.3894

Work in progress with some of the above plus Regensburg Lattice group

A case study in AdS/CFT phenomenology

- The AdS/CFT correspondence translates the strongly coupled regime of four dimensional Large-N gauge theories into the language of classical gravity.

- In this talk I will discuss a *bottom up* AdS/CFT description of the CP-odd sector of YM theory, controlled by the operator $TrF\tilde{F}$.

- This is a simple and hopefully useful case study in how to use ideas from holography in associacion with other techniques to have quantitative results and (possibly) predictions.

Topological charge at large-N

$$\mathcal{L}_{YM} = \frac{1}{4g^2} Tr F_{\mu\nu} F^{\mu\nu} + \frac{\theta}{32\pi^2} Tr F_{\mu\nu} \tilde{F}^{\mu\nu}, \qquad \tilde{F}^{\mu\nu} = \frac{1}{2} \epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma}$$

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- Quantities computed from $L[\lambda, \theta/N]$ have a well-defined large-N limit

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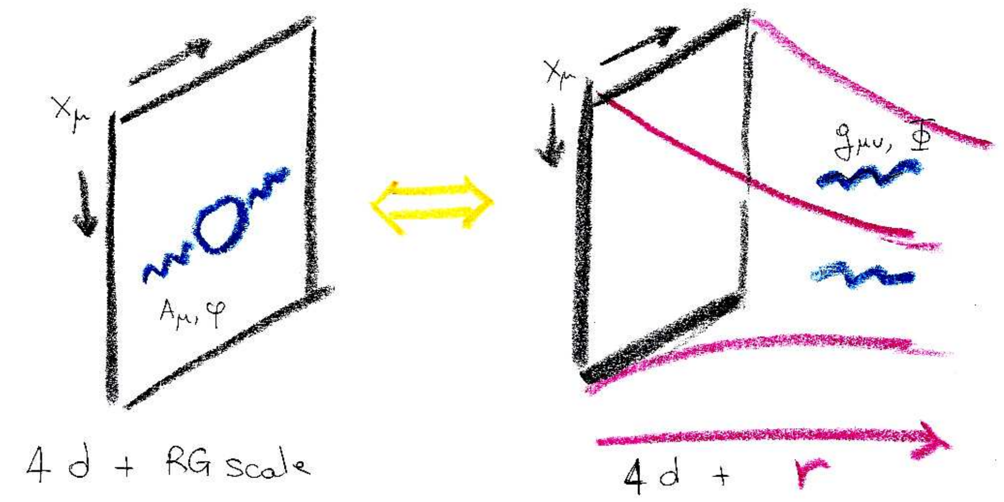
- Quantities computed from $L[\lambda, \theta/N]$ have a well-defined large-N limit
- $\theta \in [0, 2\pi] \Rightarrow$ the contribution of the topological term to glue dynamics is suppressed at large N. For example (Witten):

$$\mathcal{E}(\lambda, \theta) \approx N^2 \mathcal{E}(\lambda, 0) + \frac{1}{2}\chi\,\theta^2, \qquad \chi = \mathcal{E}''(\lambda, 0)$$

AdS/CFT

The AdS/CFT duality: conjecture that certain quantum field theories are equivalent to theories of gravity in higher dimensions.



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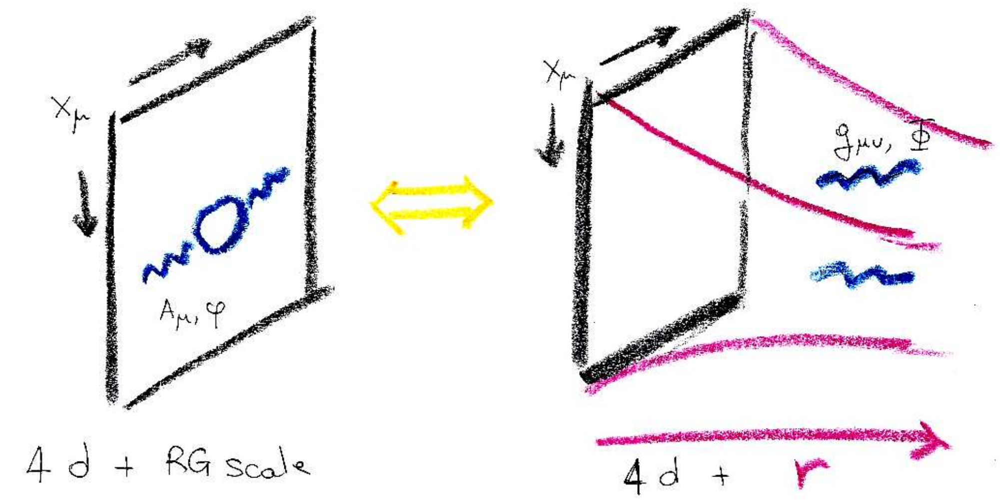
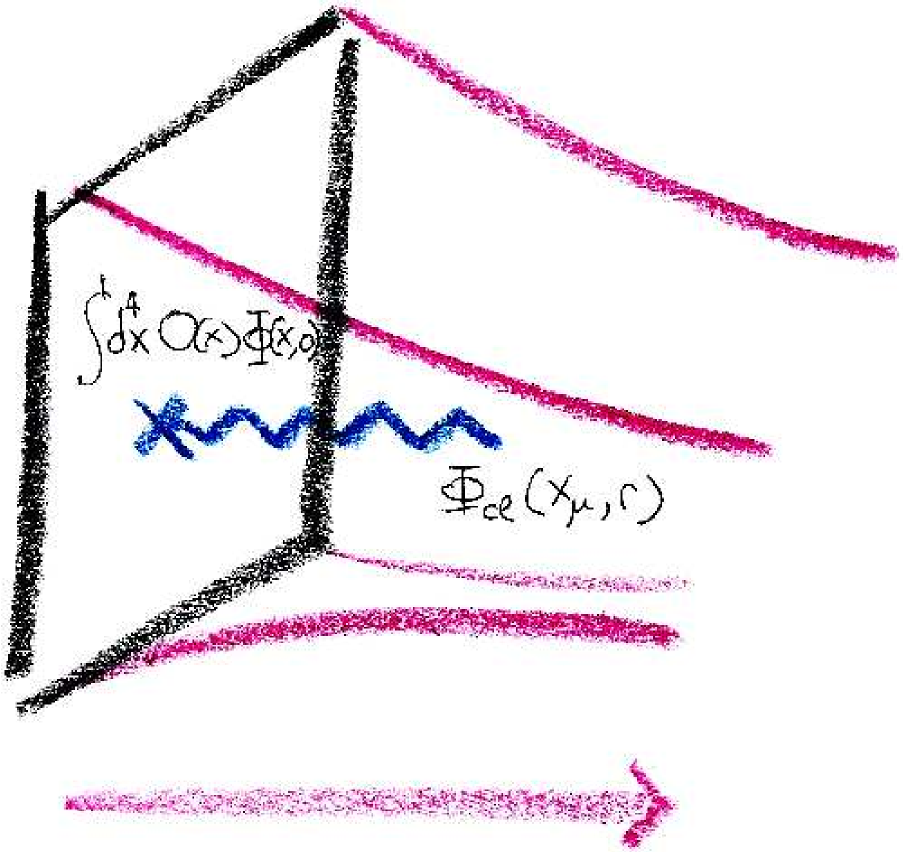


- Conformally invariant theory ⇔ bulk AdS spacetime $ds^2 = r^{-2}(dr^2 + dx_\mu^2)$
- RG scale ⇔ radial coordinate of the extra dimension;
- Field theory UV ⇔ large volume region $(r \to 0)$;
- Deformation of AdS ⇔ breaking of conformal invariance;

Field/Operator correspondence

An operator $O(x)$ with dimension Δ corresponds to a bulk field $\Phi(x, r)$ with mass $m^2 = \Delta(4 - \Delta)$. Φ represents a source for O:



Setup

Consider a 5-dimensional model

$$S_{bulk} = N^2 S_{bkg}[g_{\mu\nu}, \Phi_I]$$

$$\Downarrow$$

Background geometry

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$\Downarrow$ Background geometry

$\Downarrow$ probe pseudoscalar $a(x,r)$

- $a(x,r) \Leftrightarrow \tilde{O} = TrF\tilde{F}$ $\qquad \Delta = 4 \Rightarrow m_a^2 = 0$

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- $a(x, r) \Leftrightarrow \tilde{O} = TrF\tilde{F}$ $\qquad \Delta = 4 \Rightarrow m_a^2 = 0$
- Shift symmetry in the large-N limit $\Rightarrow$ No potential for a.
- Neglect backreaction of a on the geometry.
- $Z(\Phi_I)$ to be fixed phenomenologically.

Action and Field Equation

A vacuum background is specified by a solution of Einsetin field equations for $(g_{\mu\nu}, \Phi_I)$, in the form:

$$g_{\mu\nu} = b^2(r)\left[dr^2 + \eta_{\mu\nu}dx^\mu dx^\nu\right], \quad \Phi_I = \Phi_I(r)$$

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Once this is specified, the axion action takes the universal form:

$$S_a = \int d^4x\, dr\, \frac{A(r)}{2}\left[(\partial_r a)^2 + \eta^{\mu\nu}\partial_\mu a \partial_\nu a\right], \qquad A(r) = b^3(r) Z(\Phi_I(r))$$

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The field equations are linear:

$$\partial_r\left[A(r)\,\partial_r a(x,r)\right] + A(r)\,\partial_\mu\partial^\mu a(x,r) = 0$$

Vacuum Topological Susceptibility

Homogeneous solutions ($\partial_\mu a = 0$)

$$\left(A(r)a'\right)' = 0 \quad \Rightarrow \quad a(r) = a_0 + a_1 \int_0^r \frac{dr'}{A(r')}$$

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- One can compute χ on the lattice $\Rightarrow$ fix normalization by matching lattice result.

Axial Glueball Spectrum

- In AdS/CFT, normalizable modes in the bulk correspond to gauge-invariant states in the Hilbert space of the field theory.
- the spectum of normalizable modes of the axion field is identified with the spectrum of composite states associated to $TrF\tilde{F}$, i.e. 0^{-+} glueballs.
- This can be recast in searching the spectrum of bound states in a 1-d Schrödinger equation.

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- Define: $\psi(r) = \sqrt{A(r)} a_k(r)$. This eliminates the first derivative term and one is left with:

$$\psi'' - \left[\frac{1}{2}\frac{A''}{A} - \frac{1}{4}\left(\frac{A'}{A}\right)^2\right]\psi - k^2 \psi = 0$$

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- 0^{-+} spectrum $\Leftrightarrow$ spectrum of normalizable solutions. If the background $A(r)$ comes from a confining geometry $\Rightarrow$ infinite tower of discrete eigenvalues m_n

Field theory correlators from the gravity side

The boundary value of $a(x,r)$ represents a source for $TrF\tilde{F}(x)$:

$$a(x,r) \simeq_{r\to 0} \alpha(x) + \ldots \quad \Leftrightarrow \quad S_{QFT} = S_0 + \int d^4x\, \alpha(x) TrF\tilde{F}(x)$$

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- Compute correlators as in QFT:

$$\langle TrF\tilde{F}(x_1)\ldots TrF\tilde{F}(x_n)\rangle = \frac{\delta}{\delta\alpha(x_1)}\cdots\frac{\delta}{\delta\alpha(x_n)} Z_{QFT}[\alpha]$$

Two-point function and decay constants

Beyond the spectrum: full two-point function from AdS/CFT. one can show that:

$$\left\langle \tilde{O}(k)\tilde{O}(-k) \right\rangle = \lim_{r \to 0} \left[A(r) a_{-k}(r) a'_{k}(r) \right] /2$$

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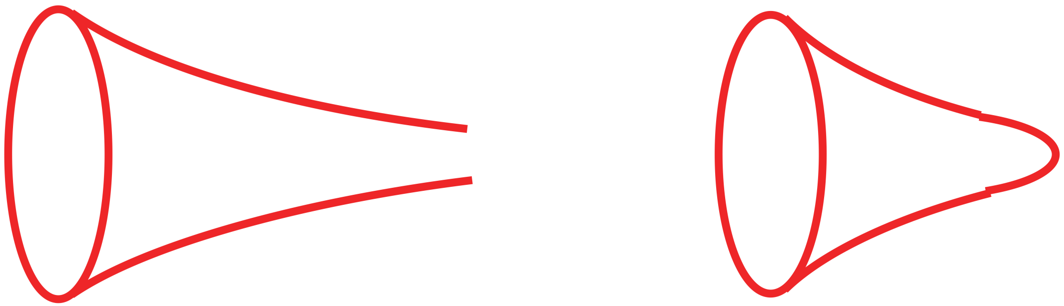
- The residues (glueball decay constants) f_n are given by:

$$f_n = \sqrt{A(0)} \left| \psi'_n(0) - \frac{1}{2}\frac{A'(0)}{A(0)}\psi_n(0) \right|$$

Deconfined phase

- Above the deconfinement transition, the relevant gravity solution is a 5d black hole.



$T < T_c$ $\qquad$ $T > T_c$

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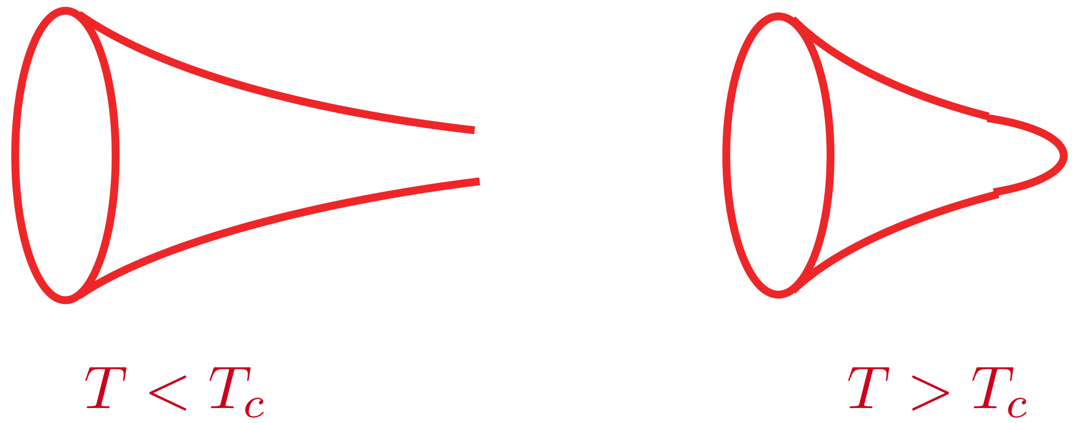

- The only solution $a(r)$ regular at the BH horizon is $a(r) = const$.

$$\Rightarrow \ \chi_{top} = 0 \qquad T > T_c$$

This agrees with what is found numerically (Vicari,Panagopoulos, '08) and with large N arguments.

Chern-Simons diffusion

The low frequency limit of the correlator gives a *diffusion constant*

$$\Gamma_{CS} = \lim_{\omega \to 0} \frac{2T}{\omega} \mathrm{Im} G_{ret}(\omega, \vec{k} = 0) \quad G_{ret}(t) = i\theta(t) \left\langle \left[\tilde{O}(t), \tilde{O}(0) \right] \right\rangle$$

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- This quantity plays an important role in the chiral magnetic effect Kharzaeev,Pisarsky,Tytgat '00
- AdS/CFT can easily compute real-time correlators: they are obtained by the mode solutions $a_\omega(r)$ which are infalling at the black hole horizon.

$$\Gamma_{CS} = \frac{sT}{N^2} \frac{Z(r_h)}{2\pi}$$

Towards the real world

Take a background generated by a single scalar λ, dual to TrF^2, and representing the running t'Hooft coupling Gursoy, Kiritsis, Mazzanti, FN 08-09

$$S_{bkg} = N^2 \int d^5x \sqrt{-g} \left[R - \frac{4}{3} \frac{(\partial\lambda)^2}{\lambda^2} + V(\lambda) \right]$$

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- UV asymptotic freedom, confinement, 0^{++} and 2^{++} glueball spectrum and thermodynamics in agreement with lattice, can be achieved by an appropriate choice of $V(\lambda)$.
- The solution has asymptotics:

$$g_{ab} \simeq \eta_{ab} \begin{cases} \dfrac{\ell^2}{\ell^2} \\ e^{-2\Lambda^2 r^2} \end{cases} \qquad \lambda(r) \simeq \begin{cases} \dfrac{1}{\beta_0 \ln r} & r \to 0 \\ r e^{3\Lambda^2 r^2/2} & r \to \infty \end{cases}$$

Parametrizing the axion Lagrangian

$$S_a = \frac{1}{2}\int \sqrt{-g}Z(\lambda)(\partial a)^2$$

$$Z(\lambda) = Z_0\left(1 + c_1\lambda + c_4\lambda^4\right)$$

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Finite χ_{top} Universal Regge slopes

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Free parameters to fix by matching lattice/experiment

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Discrete 0^{-+} spectrum with asymptotics (from WKB method)

$$m_n^2 \sim n, \qquad f_n \sim n$$

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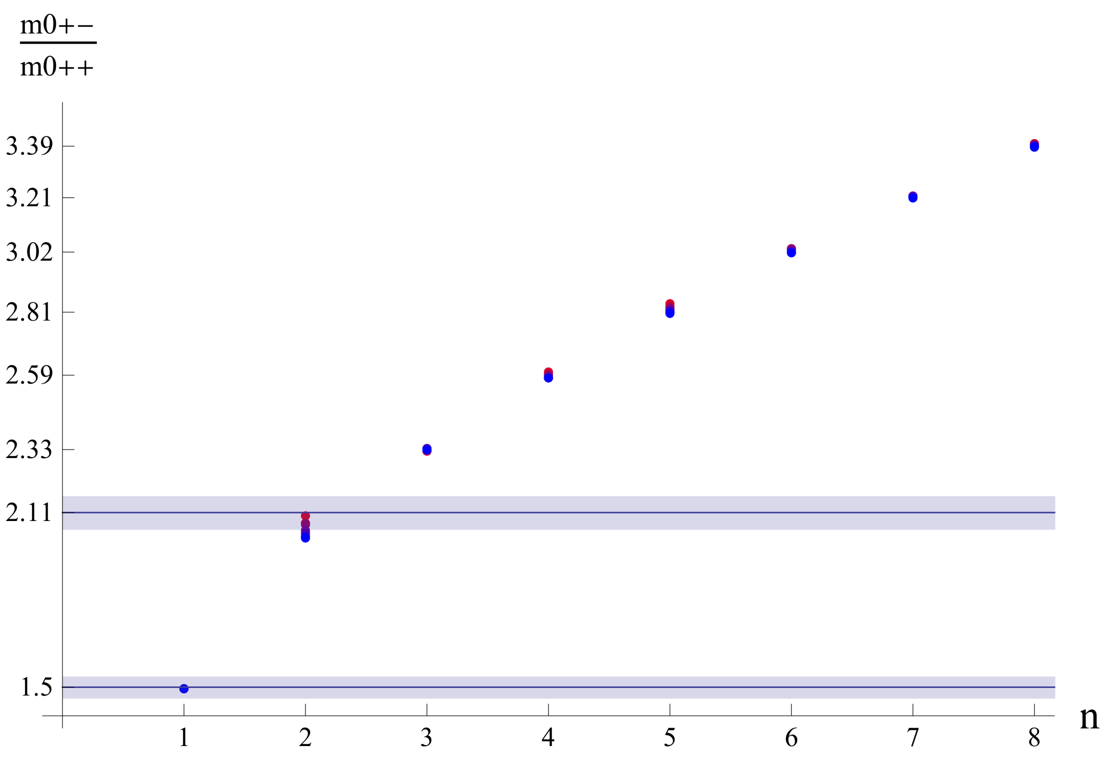
For $c_1 = 0$, $c_4 = 0.26$ one finds a good match with Lattice result for the lowest lying 0^{-+} states.

	5d model	lattice hep-lat/9901004
$m_{0^{-+}}/m_{0^{++}}$	1.50	1.50(4)
$m_{0^{*-+}}/m_{0^{++}}$	2.10	2.11(6)

Matching the lattice 0^{-+} spectrum

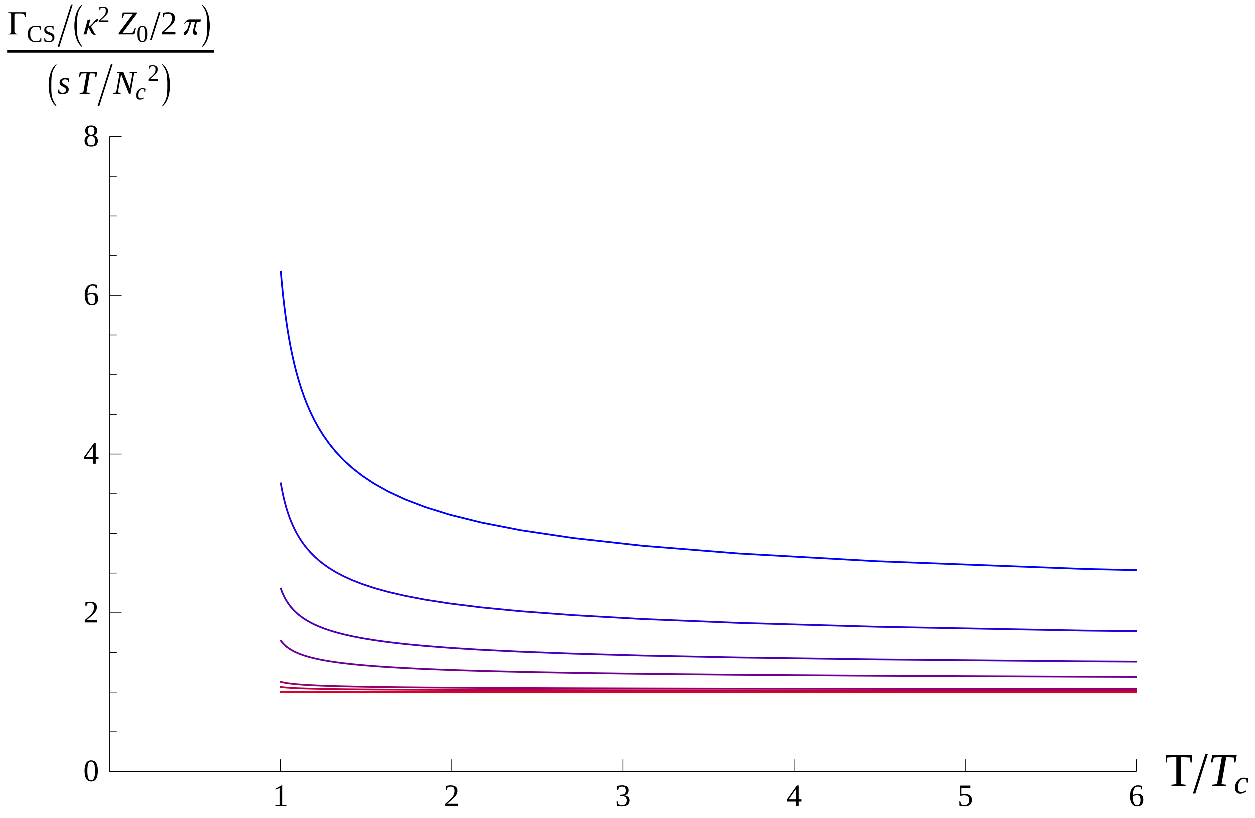
The spectrum is rather insensitive to the details of $Z(\lambda)$.



Changing c_1 between zero and 100 (with c_4 conditioned to keep $m_{0^{-+}}$ fixed) only affects the first excited state in the tower.

Diffusion constant

On the other hand, the diffusion constant changes significantly if we move in (c_1, c_4) space

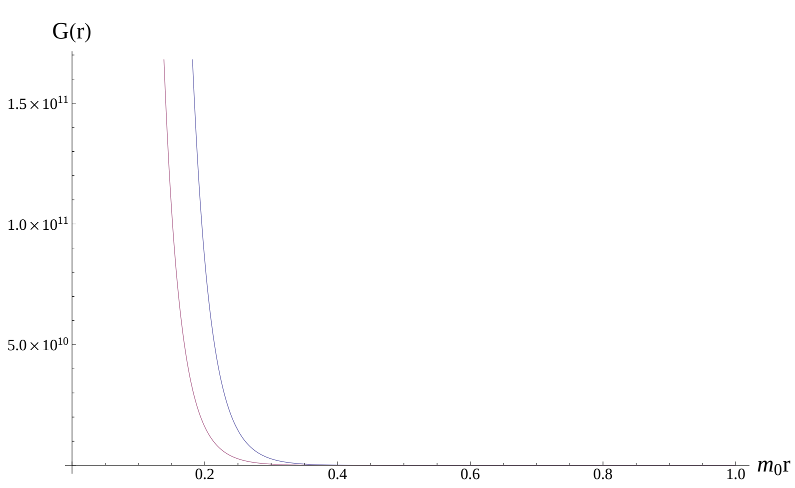


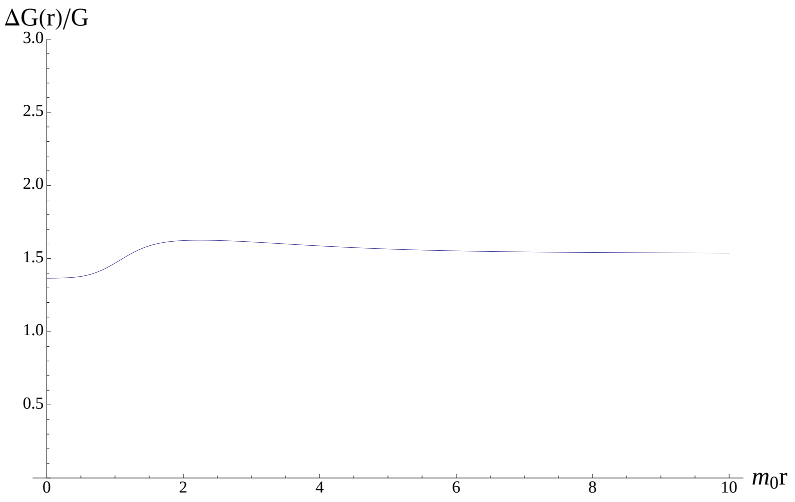
Increasing c_1 enhances the effect close to T_c

Full Correlator

The best shot at fixing $Z(\lambda)$ (and possibly predict $\Gamma_{CS}(T)$ is to compute the full correlator. We can do it in position space, and compare directly with a lattice computation (in progress)

$$\langle \tilde{O}(x)\tilde{O}(0)\rangle = \Box^3 \left(\frac{1}{|x|} \sum_{n=0}^{\infty} \frac{f_n^2}{m_n^5} K_1(m_n|x|) \right)$$





the plots correspond to the two point function with $c_1 = 0$ and $c_1 = 5$.

Conclusion

- AdS/CFT is a great tool to get qualitative picture of strongly coupled dynamics.
- To get results at a quantitative level, it is inevitable to resort to a phenomenological approach.
- The most efficient approach is to use AdS/CFT in combination with other methods, with information flowing both ways.