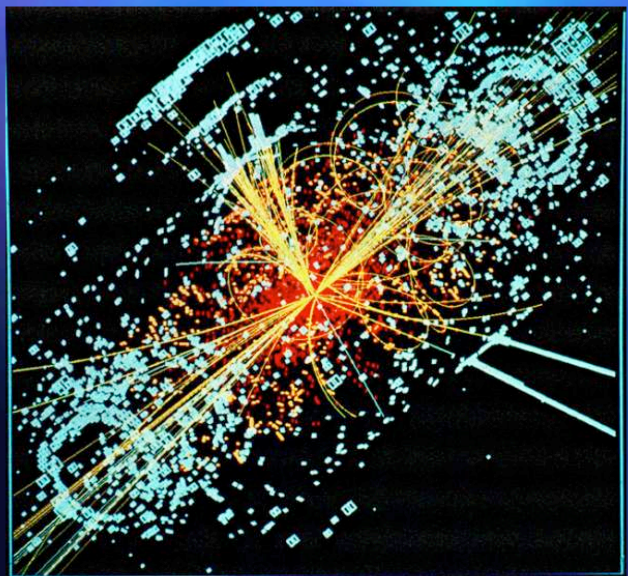
Quarks in AdS - lessons for QCD & beyond



Prof Nick Evans

UNIVERSITY OF Southampton

Mesons in Gauge/Gravity Duals - A Review.
Johanna Erdmenger, Nick Evans, Ingo Kirsch, Ed Threlfall
Eur.Phys.J.A35:81-133,2008, **arXiv:0711.4467** [hep-th]

Introduction

- String theory was originally an attempt to describe mesons
- QCD took over…
- String Theory became a quantum theory of gravity – a TOE

- The AdS/CFT Correspondence has re-united them
- & there are now positive links back to QCD

  * new pictures of confinement, mesons
  * new understanding of mass generation
  * new ideas on hadronization
  * novel descriptions of heavy ion physics

Smolin & Woit are wrong!

QCD

An SU(3) gauge theory of quark color

$$D^\mu = \partial^\mu + igC^{a\mu}T^a$$

$$\mathcal{L} = -\frac{1}{4}G^{\mu\nu}G_{\mu\nu} + i\bar{\psi}_L \not{D}\psi_L + i\bar{\psi}_R \not{D}\psi_R + m\bar{\psi}_L\psi_R$$

$$\psi \rightarrow e^{ig\theta^a(x)T^a}\psi$$

$$C^{a\mu} \rightarrow C^{a\mu} - \partial^\mu\theta^a(x)$$

Quarks come in 3 colours

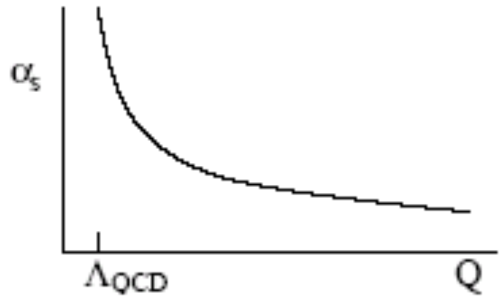
8 gluons mediate the force

$$G^{\mu\nu} = \partial^\mu C^{a\nu}T^a - \partial^\nu C^{a\mu}T^a + g[C^{a\mu}T^a, C^{b\nu}T^b]$$

Strong Dynamics

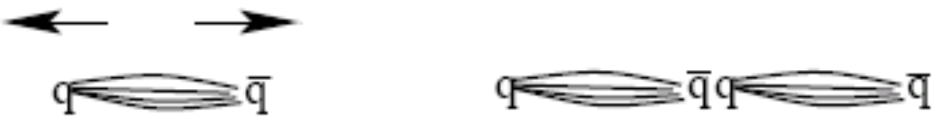
$$\beta = -\frac{11}{3}N_c + \frac{2C(R)}{3}N_f^{\mathrm{chiral}} \left(+\frac{C(R)}{6}N_{\mathrm{scalar}}^{\mathrm{real}}\right)$$

The force is asymptotically free (Wilczek, Gross, Politzer)



Confinement:

Quarks can not be liberated from hadrons.



Hadronization in even electron positron collisions is very messy and uncomputable from first principles… as for heavy ion collisions….

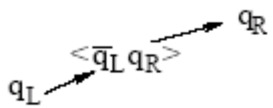
Strong Dynamics

Chiral Symmetry Breaking:

Quark masses $\ll \Lambda_{QCD}$ - so effectively massless

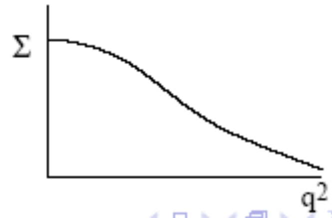
Left handed and right handed spinning quarks become distinct when they travel at the speed of light - quark number is preserved in each sector (chiral symmetry)

Strong interactions make it energetically favourable to fill space with pairs



A dynamical quark mass is generated (1/3 the proton mass)

The pseudo-Goldstone bosons of the symmetry breaking are the pions



$$m_u, m_d, m_s \ll \Lambda_{QCD}$$

$$SU(3)_L \otimes SU(3)_R$$

$$SU(3)_V$$

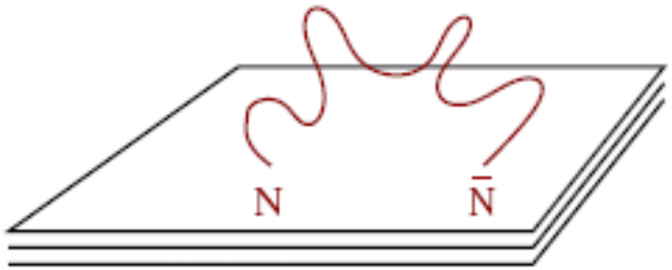
Chiral Lagrangian description of pions

$$\mathcal{L} = \frac{f_\pi^2}{4} Tr \partial^\mu U \partial_\mu U + \nu^3 Tr M_q U$$

$$U = e^{\frac{2 i \pi^a T^a}{f_\pi}}$$

Strings, Branes & Fields

Open strings described gauge fields in 10d... their ends can be restricted to D-branes though

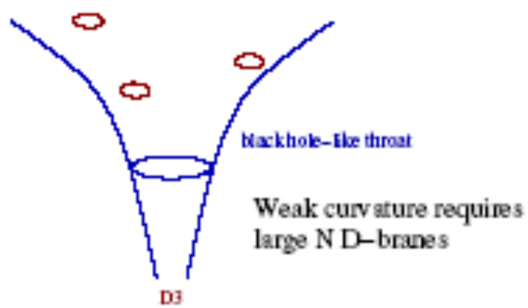


EG D3 branes generate
3+1d N=4 gauge theory

A^{μ} 6ϕ 4Ψ

SO(1,9) -> SO(1,3) x SO(6)

Alternative description of branes via the supergravity geometry they create (closed strings in 10d)



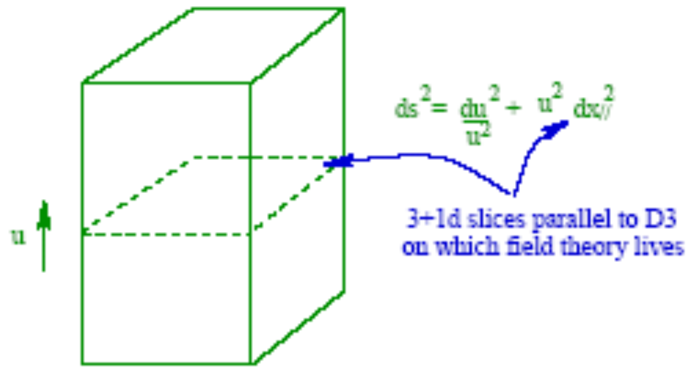
Now believe these are two dual descriptions

AdS/CFT Correspondence

Maldacena, Witten...

4d strongly coupled $\mathcal{N}$=4 SYM = IIB strings on $AdS_5 \times S^5$

Pretty well established by this point!



u corresponds to energy (RG) scale in field theory

The SUGRA fields act as sources

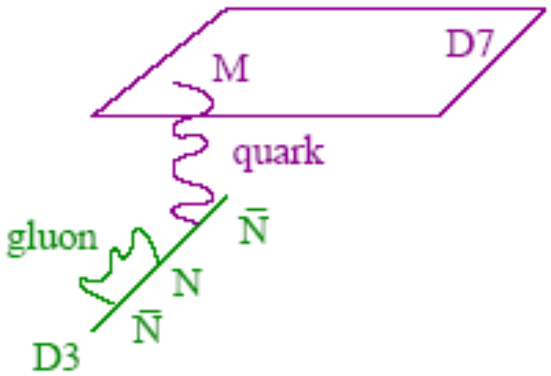
$$\int d^4x \ \Phi_{SUGRA}(u_0)\lambda\lambda$$

eg asymptotic solution ($u \to \infty$) of scalar

$$\varphi \simeq \frac{m}{u} + \frac{\langle\lambda\lambda\rangle}{u^3}$$

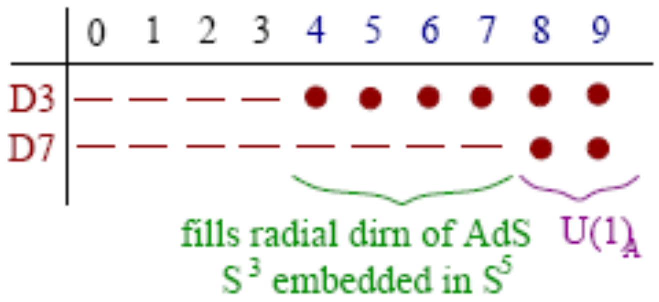
Adding Quarks

Bertolini, DiVecchia...; Polchinski, Grana; Karch, Katz...



Quarks can be introduced via D7 branes in AdS

The brane set up is



An N=2 theory with

$$\mathcal{L} = \mathcal{L}_{\mathcal{N}=4} + \tilde{Q} A_{89} Q|_F + m\tilde{Q}Q$$

SO(6) broken to SO(4) on A4-A7 plus….

SO(2) on A8,A9 now acts on quarks too… the quark mass term breaks it…

Probe D7 Branes (Quenching)

$$S_{Dp} = - \mu_p \int d^{(p+1)}\xi \ e^{-\phi} \sqrt{- \det \left(P[G + 2\pi\alpha' B]_{ab} + 2\pi\alpha' F_{ab}\right)}$$

$$ds^2 = \frac{r^2}{R^2} dx_{3+1}^2 + \frac{R^2}{r^2}\left(d\rho^2 + \rho^2 d\Omega_3^2 + dw_5^2 + dw_6^2\right)$$

$$P[G] = \begin{pmatrix} -\frac{r^2}{R^2} & & & & & & & \\ & \frac{r^2}{R^2} & & & & & & \\ & & \frac{r^2}{R^2} & & & & & \\ & & & \frac{r^2}{R^2} & & & & \\ & & & & \frac{R^2}{r^2}\left(1 + (\partial_\rho w_6)^2\right) & & & \\ & & & & & \frac{R^2}{r^2}\rho^2 & & \\ & & & & & & \frac{R^2}{r^2}\rho^2 .. & \\ & & & & & & & \frac{R^2}{r^2} .. \end{pmatrix}$$

$$\mathcal{L} = \rho^3 \sqrt{1 + (\partial_\rho w_6)^2}$$

Quarks In AdS

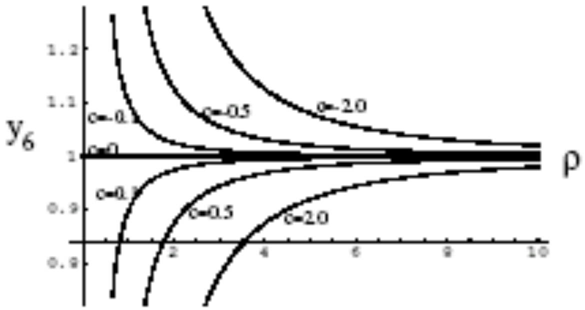
Myers et al

$$S_{D7} = -T_7 \int d^8\xi \, \epsilon_3 \, \rho^3 \sqrt{1 + \frac{g^{ab}}{\rho^2 + u_5^2 + u_6^2}(\partial_a u_5 \partial_b u_5 + \partial_a u_6 \partial_b u_6)}$$

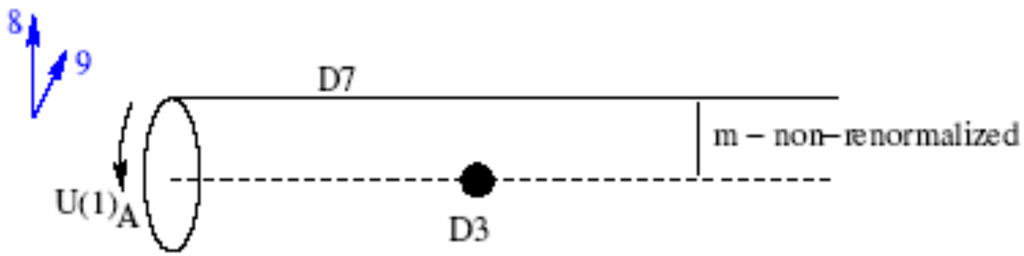
EoM is: $$\frac{d}{d\rho}\left[\frac{\rho^3}{\sqrt{1+\left(\frac{du_6}{d\rho}\right)^2}}\frac{du_6}{d\rho}\right] = 0$$

UV asymptotic solution is
$$u_6 = m + \frac{c}{\rho^2} + \ldots$$

m is the quark mass, c the $\langle \bar{q} q \rangle$ condensate



In AdS regular D7 solution is flat brane



Mesons in AdS_5

Kruczenski, Myers, Mateos, Winters

The D7 lie flat in AdS. We can consider fluctuations that describe R-chargeless mesons

$$w_6 + i w_5 = d + \delta(\rho) e^{ik.x}$$

δ satisfies a linearized EoM

$$\partial_\rho^2 \delta + \frac{3}{\rho} \partial_\rho \delta + \frac{M^2}{(\rho^2+1)^2} \delta = 0$$

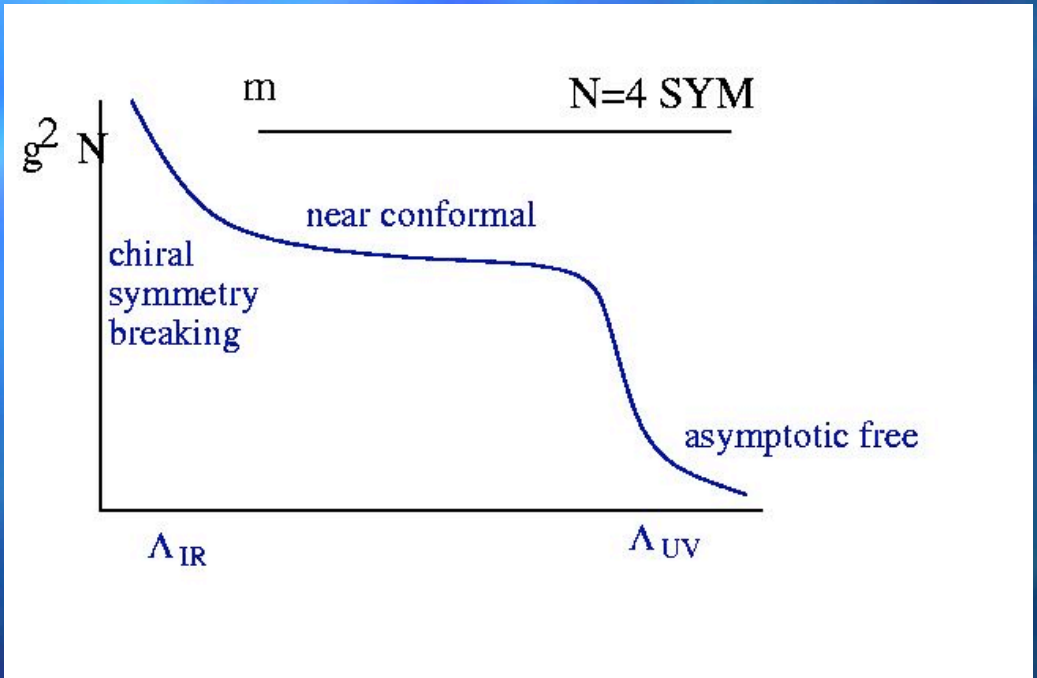
and the mass spectrum is

$$M = \frac{2d}{R^2} \sqrt{(n+1)(n+2)} \sim \frac{2m}{\sqrt{\lambda_{YM}}}$$

Tightly bound - meson masses suppressed relative to quark mass

Lesson for Walking Theories?

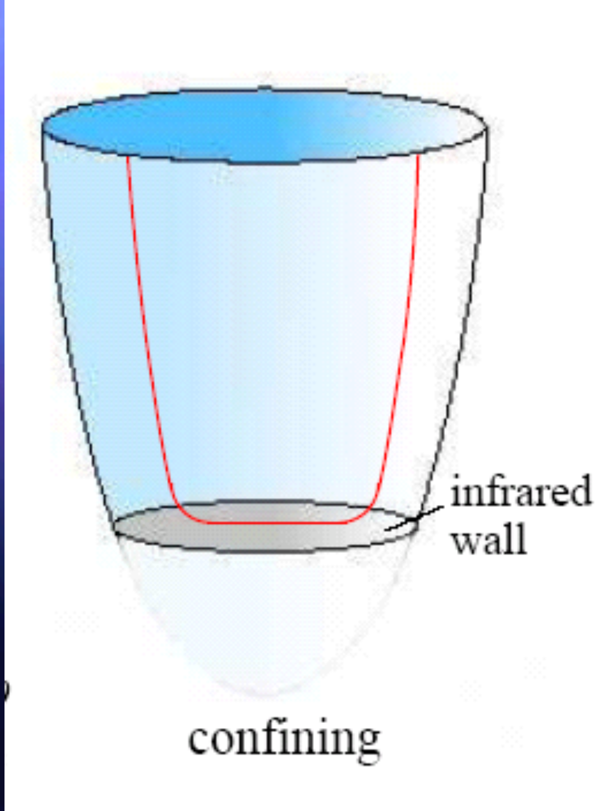
Strong coupling over a long RG range induces deeply bound mesons whose masses are << constituents mass…

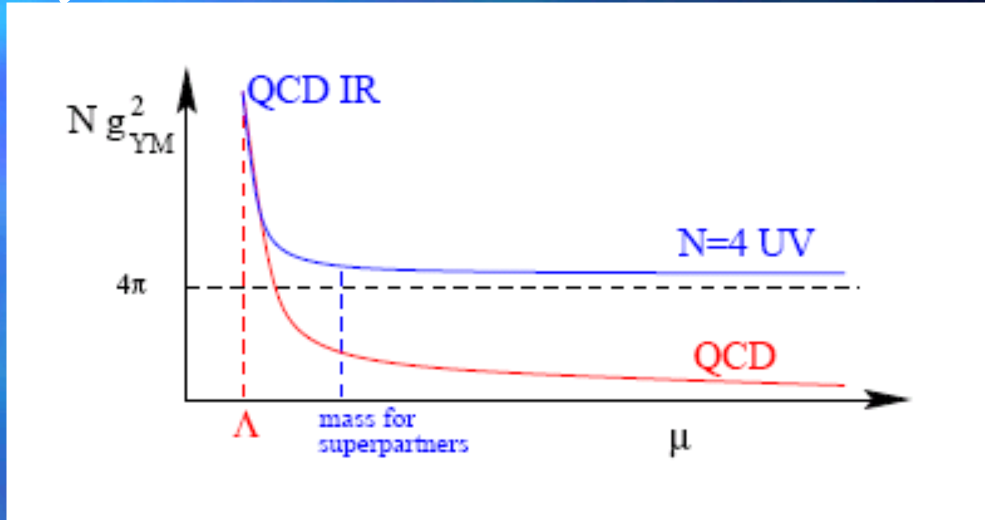


In walking theories higgs mass << Lambda_TC ????

Deforming to Less Symmetry

We now have many examples of deformed N=4 SYM – the UV is the susy theory.. the IR has eg masses for particles breaking supersymmetry and conformality…





Confining theories develop a wall – a block to small RG scales…

A linear potential grows between the quarks…

Example: YangMills*

Babington, Crooks, NE

N=4 SYM + mass for 4 gauginos + equal mass for 6 scalars

$$ds^2_{10} = (\xi_+\xi_-)^{\frac{1}{4}} ds^2_{1,4} + (\xi_+\xi_-)^{-\frac{3}{4}} ds^2_5$$

$$ds^2_5 = \xi_- \cos^2\alpha \; d\Omega^2_+ + \xi_+ \sin^2\alpha \; d\Omega^2_- + \xi_+\xi_- d\alpha^2$$

$$ds^2_{(1,4)} = e^{2A(r)} dx^\mu dx_\mu + dr^2$$

$$\xi_\pm = c^2 \pm s^2 \cos 2\alpha, \quad c = \cosh\lambda, \quad s = \sinh\lambda$$

$$A_{(2)} = iA_+ \cos^3\alpha \, \cos\theta_+ d\theta_+ \wedge d\phi_+ - A_- \sin^3\alpha \, \cos\theta_- d\theta_- \wedge d\phi_-$$

$$A_\pm = \sinh 2\lambda / \xi_\pm$$

$$F_{(4)} = F + \star F, \quad F = dx^0 \wedge dx^1 \wedge dx^2 \wedge dx^3 \wedge d\omega$$

$$\omega(r) = e^{4A(r)} A'(r)$$

$$B = \frac{\sinh^2\lambda \cos 2\alpha}{\cosh^2\lambda + (\xi_+\xi_-)^{1/2}}$$

$$C + ie^{-\Phi} = i\frac{(1-B)}{(1+B)}$$

$$\lambda'' + 4A'\lambda' = \frac{\partial V}{\partial \lambda}, \qquad -3A'' - 6A'^2 = \lambda'^2 + 2V$$

$$V = -\frac{3}{2}\left[1 + \cosh^2\lambda\right]$$

Example: an insightful toy

Note – in the above we never decouple superpartners…

- the physics is really in the running coupling…

- lets simplify to allow computation & insight…

$$ds^2 = \frac{r^2}{R^2} dx_{3+1}^2 + \frac{R^2}{r^2} dr^2 + R^2 d\Omega_5^2$$

$$e^{\phi} = g_s = \text{constant}$$

$$C_{(4)} = \frac{r^4}{R^4} g_s^{-1} dx^0 \wedge .. \wedge x^3$$

$$R^4 = 4\pi g_s N \alpha'^2$$

Give the dilaton a profile of your choice….

hard wall

soft wall

$$ds^2 = \frac{r^2}{R^2} dx_{3+1}^2 + \frac{R^2}{r^2}\left(d\rho^2 + \rho^2 d\Omega_3^2 + dw_5^2 + dw_6^2\right)$$

$$e^{\phi} = g_{YM}^2(r^2)$$

A probe D7 brane

$$\begin{aligned} S_{D7} &= \int d^8\xi\, e^{\phi} \sqrt{-\det P[G]_{ab}} \\ &= \int d^4x\; d\rho\; \rho^3 g_{YM}^2 \sqrt{1 + (\partial_\rho w_5)^2} \end{aligned}$$

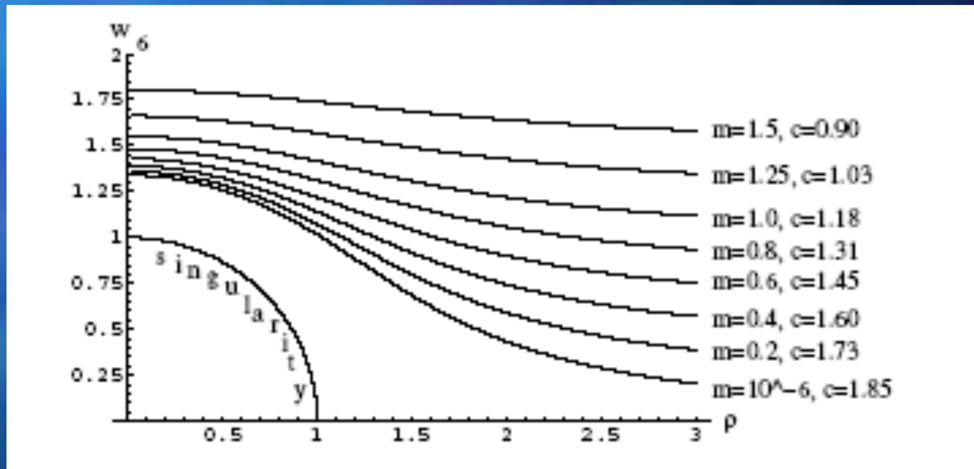
Embedding eqn

$$\partial_\rho \left[\frac{g_{YM}^2 \rho^3 \partial_\rho w_5}{\sqrt{1+(\partial_\rho w_5)^2}} \right] - 2 w_5 \rho^3 \sqrt{1+(\partial_\rho w_5)^2}\, \frac{\partial g_{YM}^2}{\partial r^2} = 0$$

$$w_5 = m + \frac{c}{\rho^2} + \ldots$$

Any r dependence in g leads to c…. eg

$$g_{YM}^2 = a + \frac{1}{\ln(\rho^2/\Lambda^2)}$$

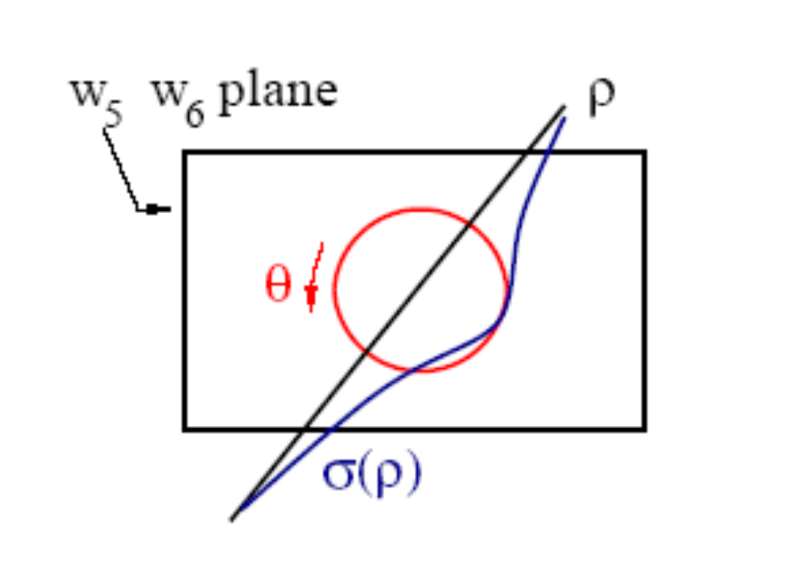


This is a plot of the quark self energy Σ(k)

Pions

We look at small fluctuations in the w6 direction….

$$\delta_{\omega_6}(\rho, x) = f^n(\rho)\Pi^n(x)$$



$$S_7 = -\overline{T_7}\int d\rho dx^4 \rho^3 g_{YM}^2 \sqrt{1+\Sigma_q'(\rho)^2}(1 + \frac{1}{2}\frac{f'^n(\rho)^2\Pi^n(x)^2}{1+\Sigma_q'(\rho)^2} + \frac{1}{2}\frac{R^4}{r^4} f^n(\rho)^2(\partial_x \Pi^n(x))^2 + \frac{1}{4}\frac{R^4}{r^4} f^n(\rho)^2(\partial_x \Pi^n(x))^2 f'^n(\rho)^2 \Pi^n(x)$$

$$\Pi(x) = e^{-ik.x}, \qquad k^2 = 0$$

$$\partial_\rho\left[\frac{g_{YM}^2\rho^3\partial_\rho f^0}{\sqrt{1+(\partial_\rho\Sigma)^2}}\right] - 2f^0\rho^3\sqrt{1+(\partial_\rho\Sigma)^2}\frac{\partial g_{YM}^2}{\partial r^2} = 0$$

There is a regular solution with $f^0 = \Sigma$

Connecting the UV & IR

We can now substitute back into the action and obtain integral expressions for chiral Lagrangian parameters… eg

$$\langle \bar{q} q \rangle \sim \int d\rho \; \rho^3 \Sigma \sqrt{1 + (\partial_\rho \Sigma)^2} \frac{d g^2_{YM}}{d r^2}$$

This is essentially an integral over Σ dominated around the points of maximum derivative in the running…

As with constituent quark model estimates the UV behaviour of Σ is important…

Eg Walking enhances the tail of Σ and hence the condensate…

Fπ

$$\frac{1}{f_\Pi^2} = \frac{\overline{T_7}}{I_0^2}\int d\rho\rho^3 g_{YM}^2\sqrt{1+\Sigma'(\rho)^2}\frac{1}{4}\frac{R^4}{r^4}\Sigma(\rho)^2\Sigma'(\rho)^2$$

$$I_0 = \overline{T_7}\int d\rho\rho^3 g_{YM}^2\sqrt{1+\Sigma_q'(\rho)^2}\frac{R^4}{r^4}\Sigma(\rho)^2$$

The $1/r^4$ terms in all integrals mean Fπ is dominated by low energy behaviour in S…

Agrees with Pagel Stokar formula….

Magnetic Field Induced Chiral Symmetry Breaking

Clifford Johnson

$$S_{Dp} = -\mu_p \int d^{(p+1)}\xi \; e^{-\phi} \sqrt{-\det\left(P[G+2\pi\alpha' B]_{ab} + 2\pi\alpha' F_{ab}\right)}$$

The F ^{ab} term is a gauge field living on the surface of the D7 brane…

A^{m} is dual to the operators $\bar{q}\ \gamma^{m} q$ …. and a baryon number background gauge field…

So we can include a background magnetic field

$$P[G]+F = \begin{pmatrix} -\frac{r^2}{R^2} & & & & & & & \\ & \frac{r^2}{R^2} & B^z & & & & & \\ & -B^z & \frac{r^2}{R^2} & & & & & \\ & & & \frac{r^2}{R^2} & & & & \\ & & & & \frac{R^2}{r^2}\left(1+(\partial_\rho w_6)^2\right) & & & \\ & & & & & \frac{R^2}{r^2}\rho^2 & & \\ & & & & & & \frac{R^2}{r^2}\rho^2 .. & \\ & & & & & & & \frac{R^2}{r^2} .. \end{pmatrix}$$

$$\mathcal{L} = \rho^3 \sqrt{1+(\partial_\rho w_6)^2} \sqrt{1+\frac{B^z R^4}{r^4}}$$

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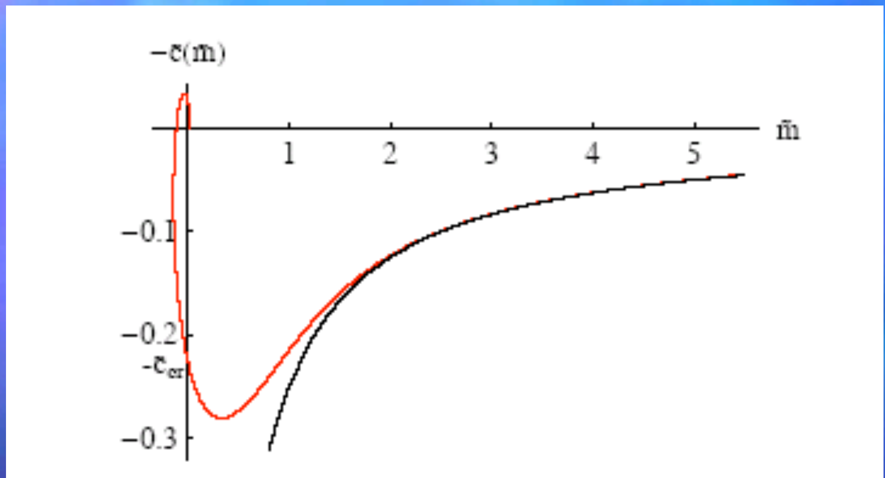
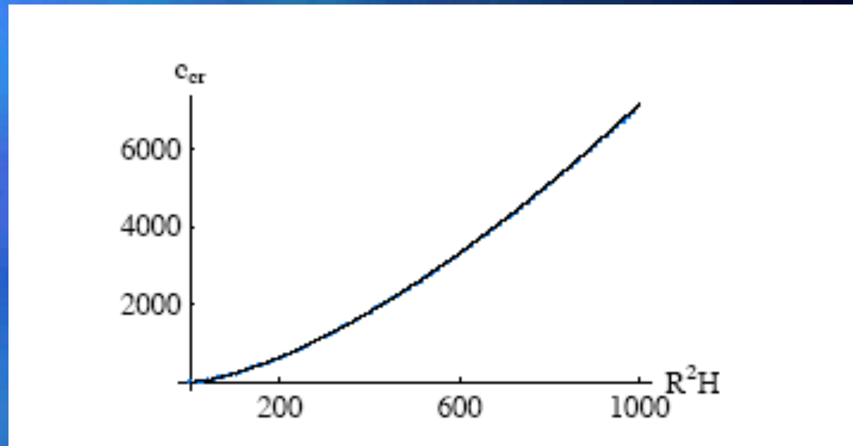
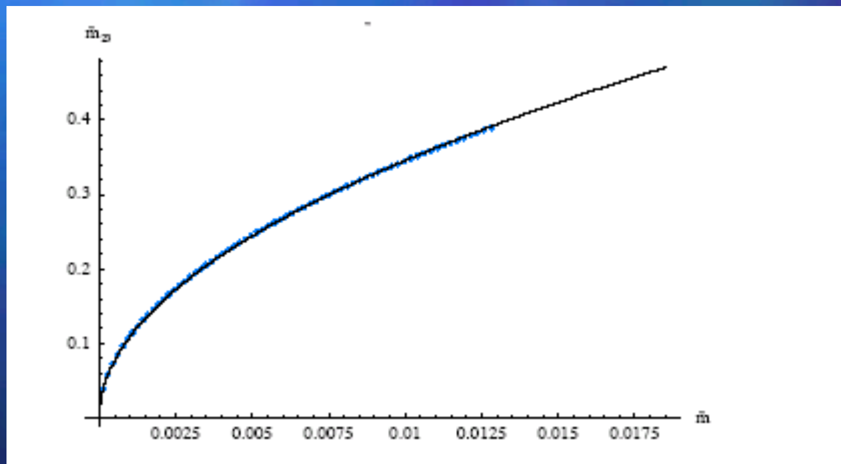






AdS-Schwarzschild

$$ds^2 = \frac{K(r)}{R^2}d\tau^2 + R^2\frac{dr^2}{K(r)} + \frac{r^2}{R^2}d\vec{x}^2 + R^2 d\Omega_5^2\,,$$

$$K(r) = r^2 - \frac{r_H^4}{r^2}\,.$$

Compact time direction

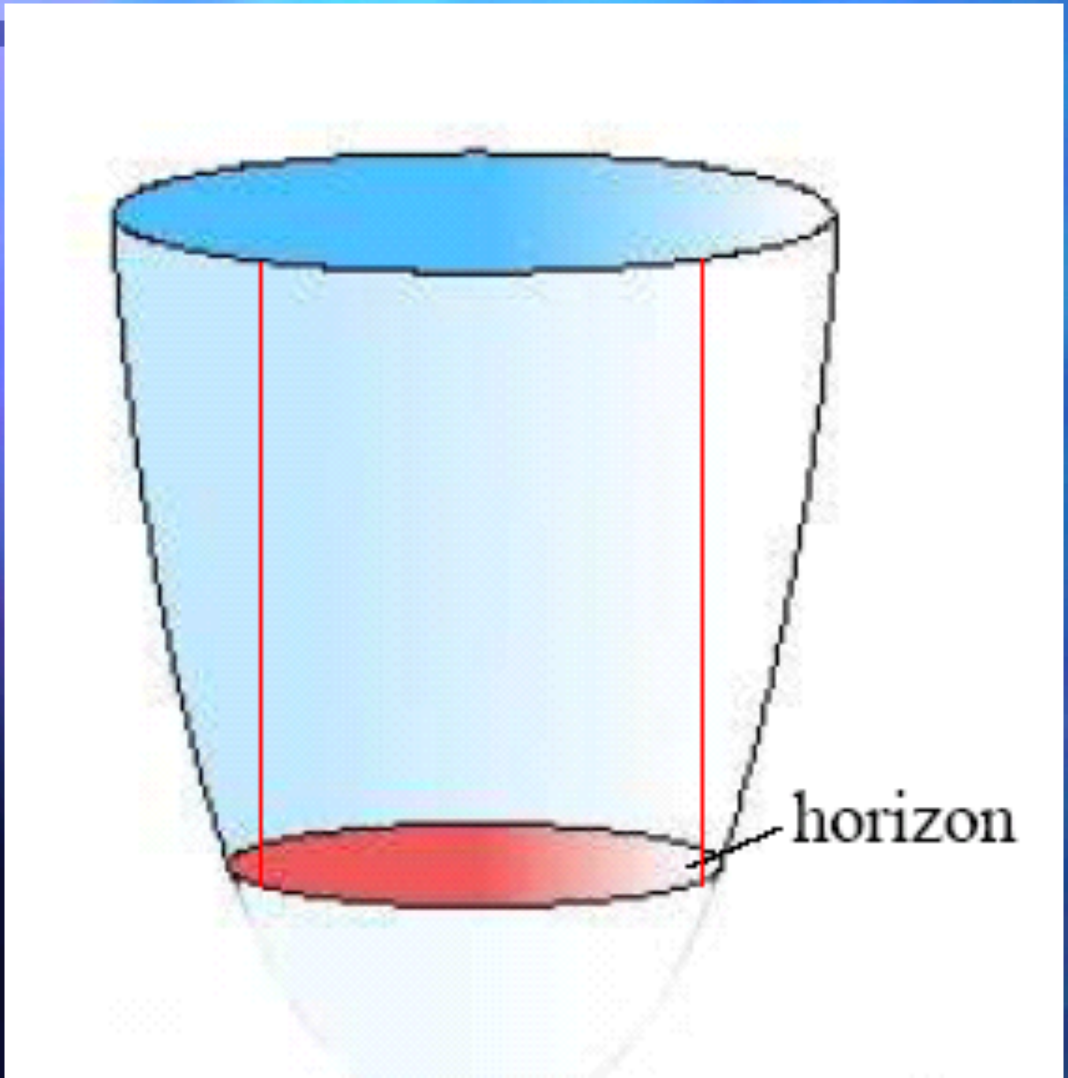
$$T = r_H/(R^2\pi)$$

Asymptotically AdS, SO(6) invariant at all scales… but has a horizon that swallows information at r_H …. Witten interpreted this as the gauge theory at finite temperature… black hole has right thermodynamic properties…

$$2w^2 = r^2 + \sqrt{r^4 - r_H^4}\,.$$

$$ds^2 = \left(w^2 + \frac{w_H^4}{w^2}\right)d\vec{x}^2 + \frac{(w^4 - w_H^4)^2}{w^2(w^4 + w_H^4)}dt^2 + \frac{1}{w^2}\left(\sum_{i=1}^{6} dw_i^2\right),$$

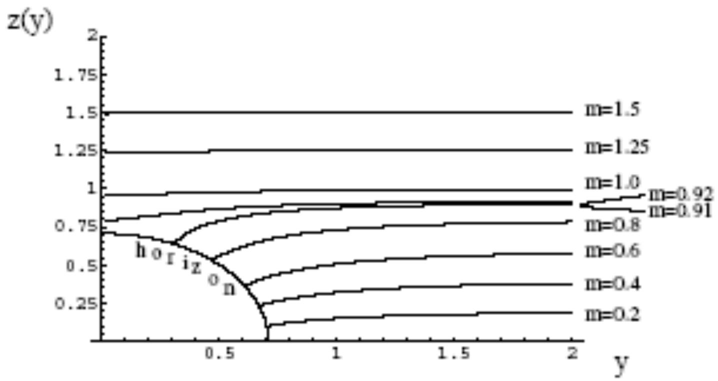
Screening

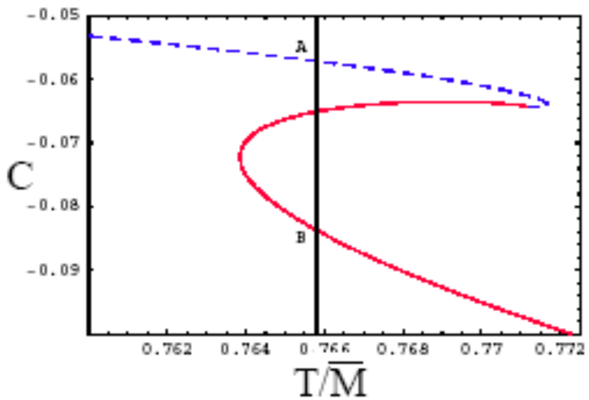


The string between the quarks breaks and they are screened by the plasma

Novel Transition when $T > m_q$

(BEEKG, Kirsch, Myers et al)





$$S_{D7} = -\mu_7 \int d^8\xi \; \epsilon_3 \; \mathcal{G}(\rho, w_5, w_6)$$
$$\times \left(1 + \frac{g^{ab}}{(\rho^2 + w_5^2 + w_6^2)} \partial_a w_5 \partial_b w_5 + \frac{g^{ab}}{(\rho^2 + w_5^2 + w_6^2)} \partial_a w_6 \partial_b w_6 \right)^{1/2},$$

where the determinant of the metric is given by

$$\mathcal{G}(\rho, w_5, w_6) = \sqrt{\frac{g_{tt} g_{xx}^3 \rho^6}{(\rho^2 + w_5^2 + w_6^2)^4}}$$
$$= \rho^3 \frac{((\rho^2 + w_5^2 + w_6^2)^2 + w_H^4)((\rho^2 + w_5^2 + w_6^2)^2 - w_H^4)}{(\rho^2 + w_5^2 + w_6^2)^4}. \quad (7.7)$$

With the ansatz $w_5 = 0$ and $w_6 = w_6(\rho)$, the equation of motion becomes

$$\frac{d}{d\rho}\left[\mathcal{G}(\rho, w_6) \sqrt{\frac{1}{1 + \left(\frac{dw_6}{d\rho}\right)^2}} \frac{dw_6}{d\rho}\right] - \sqrt{1 + \left(\frac{dw_6}{d\rho}\right)^2} \frac{8 w_H^8 \rho^3 w_6}{(\rho^2 + w_6^2)^5} = 0. \quad (7.8)$$

Quasi-normal modes & meson melting

Linearized fluctuations in eg the scalars on the D7 brane must now enter the black hole horizon…

Quasi-normal modes are those modes that near the horizon have only in-falling pieces…

The mass of the bound states become complex – they decay into the thermal bath…

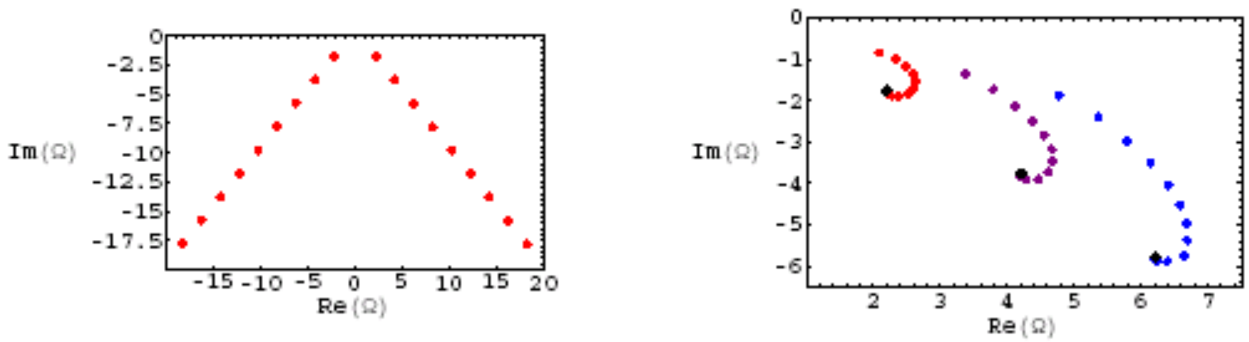


Figure 7.4: The lowest quasi-normal modes for $m_q = 0$ on the left and the three lowest quasi-normal modes for increasing m_q on the right. The black points on the right show the limiting values for $m_q = 0$.

Electric Field

$$P[G]+F = \begin{pmatrix} -\frac{r^2}{R^2} & E^z & & & & & & \\ -E^z & \frac{r^2}{R^2} & & & & & & \\ & & \frac{r^2}{R^2} & & & & & \\ & & & \frac{r^2}{R^2} & & & & \\ & & & & \frac{R^2}{r^2}\left(1+(\partial_\rho w_6)^2\right) & & & \\ & & & & & \frac{R^2}{r^2}\rho^2 & & \\ & & & & & & \frac{R^2}{r^2}\rho^2.. & \\ & & & & & & & \frac{R^2}{r^2}.. \end{pmatrix}$$

$$\mathcal{L} = \rho^3\sqrt{1+(\partial_\rho w_6)^2}\sqrt{1-\frac{E^z R^4}{r^4}}$$

There is now an horizon-like surface at

$r^4 = E^z R^4$

It behaves like a black hole horizon with the embeddings falling into the surface..

The electric field shreds the mesons into a quark gluon plasma…

Karch, O'Bannon

Sakai Sugimoto Model

$$\mathcal{L} = \mathcal{L}_{\mathcal{N}=4} \;+\; \tilde{Q} A_{89} Q|_F + m\tilde{Q}Q$$

A standard complaint about the D3-D7 system is that it does not have non-abelian chiral symmetries… and there's no well understood hard wall…

(Although the condensate formation is controlled by the strong dynamics not the global symmetries….)

Sakai & Sugimoto proposed a model that does have non-abelian chiral symmetries… but at the expense of being intrinsically 5 dimensional…

Type IIA

D4s wrapped on a circle

	0	1	2	3	(4)	5	6	7	8	9
D4	X	X	X	X	X					
D8 - $\overline{\text{D8}}$	X	X	X	X		X	X	X	X	X

$$ds^2 = \left(\frac{u}{R}\right)^{\frac{3}{2}} (dx_4^2 + f(u)d\tau^2) + \left(\frac{R}{u}\right)^{\frac{3}{2}} \left(\frac{du^2}{f(u)} + u^2 d\Omega_4^2\right)$$

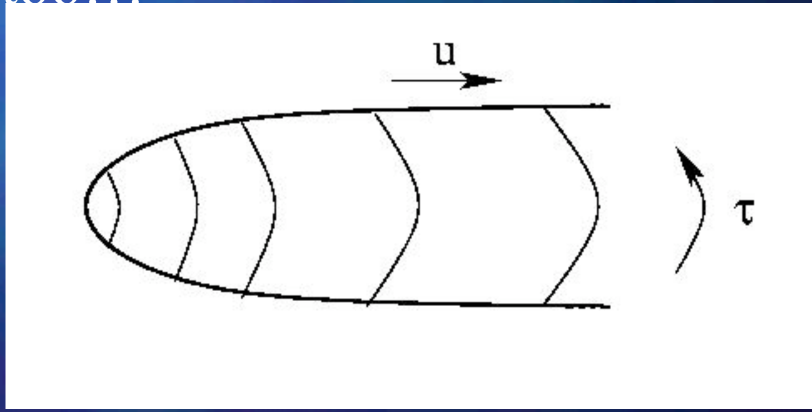
$$e^{-\phi} = g_s \left(\frac{u}{R}\right)^{-\frac{3}{4}}$$

$$f(u) \equiv 1 - \left(\frac{u_{KK}}{u}\right)^3$$

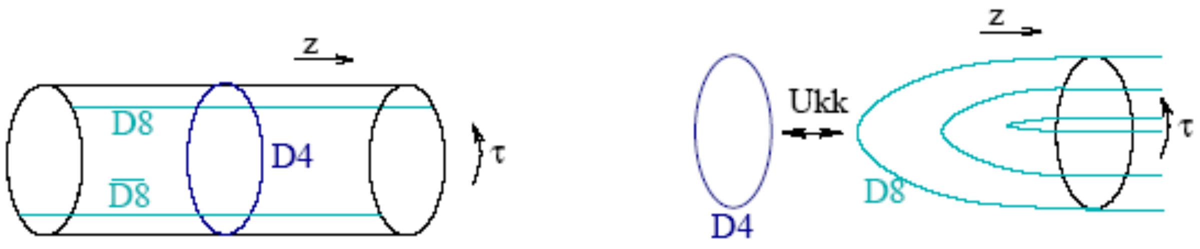
The τ period is $\frac{4\pi}{3} \frac{R^{\frac{3}{2}}}{u_{KK}^{\frac{1}{2}}}$ & can not be small relative to the string length….

The 5d SYMs theory becomes a non-supersymmetric YMs theory in 4d... but the compactification scale controls the strong coupling scale… the UV is strongly coupled too…

The geometry is singular at u_{KK} when the τ direction degenerates… there's a cone like structure



Flavour is provided by a D8 brane



	0	1	2	3	(4)	5	6	7	8	9
D4	X	X	X	X	X					
D8 - $\overline{D8}$	X	X	X	X		X	X	X	X	X

$$S_{DBI} = \int_{D8} d^8\zeta \, e^{-\phi} \sqrt{- \det[\mathcal{P}\,(g_{ab})]} \, .$$

The solutions wrap round the end of the cone and head back to infinity… SS interpreted this as the non-perturbative version of a weakly coupled D8 – D8 system… dynamical mass generation…

At large u SU(N) ^{2} but broken in the IR to sub-group SU(N)

Chiral symmetry breaking for chiral quarks…

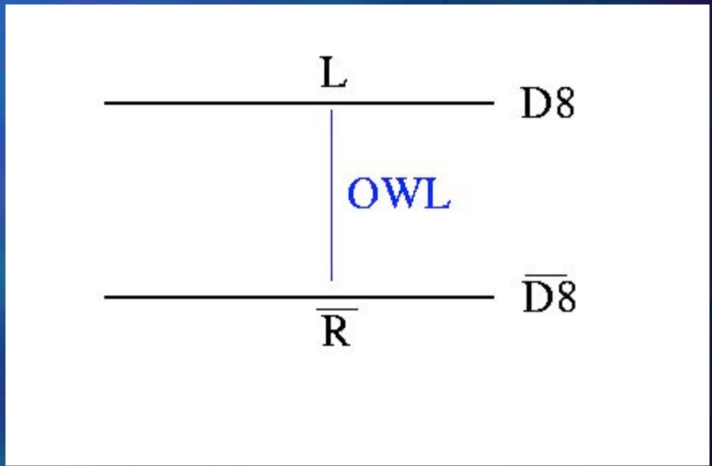
Vacuum Manifold & Pions

The SU(N) gauge field living on the D8 world volume is naturally dual to $\bar{q}\ \gamma^{\mu}\ q$

But there is also the A^u component… the Lagrangian is independent of the u dependence of this field if its only u dependent… the vacuum manifold… hence massless pions…

Its generally agreed that the condensate is described by a string between the branes that transforms under both L & R symmetries… Aharony's OWLS or Kiritsis' tachyon

Its phase is the pion but can be moved by a gauge transform into $A^u(u)$…



There remains debate about how you include mass…

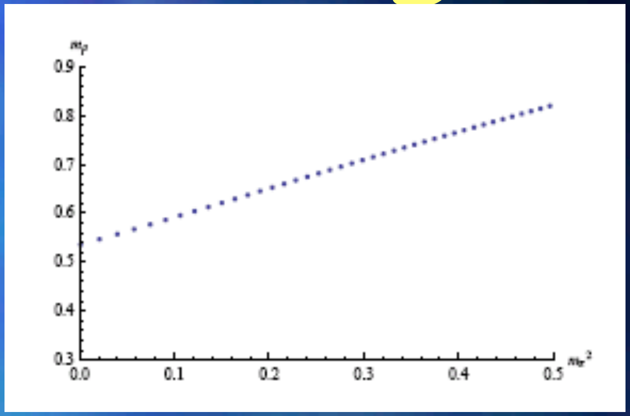
Lets get phenomenological

YET

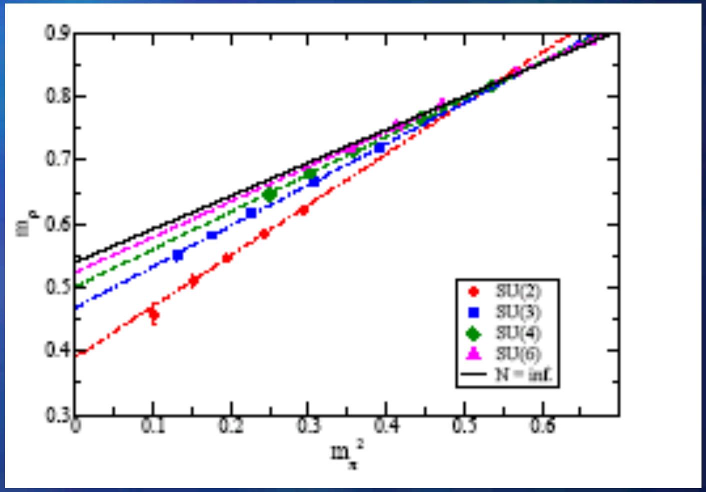
Of course these theories are NOT QCD

* large N
* extra undecoupled super-partners
* mesons masses << quark masses

So of course they will only describe QCD quantitatively upto corrections of order 100% (right?!!)



Rho vs pi mass in a backreacted dilaton flow… slope 0.57



Lattice large N data.. Slope 0.52.. little N dependence

AdS/QCD – Son et al, Pomarol et al

$$ds^2 = r^2 dx_4^2 + \frac{dr^2}{r^2}$$

AdS5, no S5 since no SO(6) in QCD

To include confinement & a mass gap we simply impose a hard wall at $r = r_0$ - crude but simple…

Include the "D7 embedding field" simply as an N_f x N_f scalar of $m^2 = -3$

$$X = X_0 e^{2i\pi^a t^a}$$

$$X_0 = \frac{1}{2}\frac{m}{r} + \frac{1}{2}\frac{\Sigma}{r^3}$$

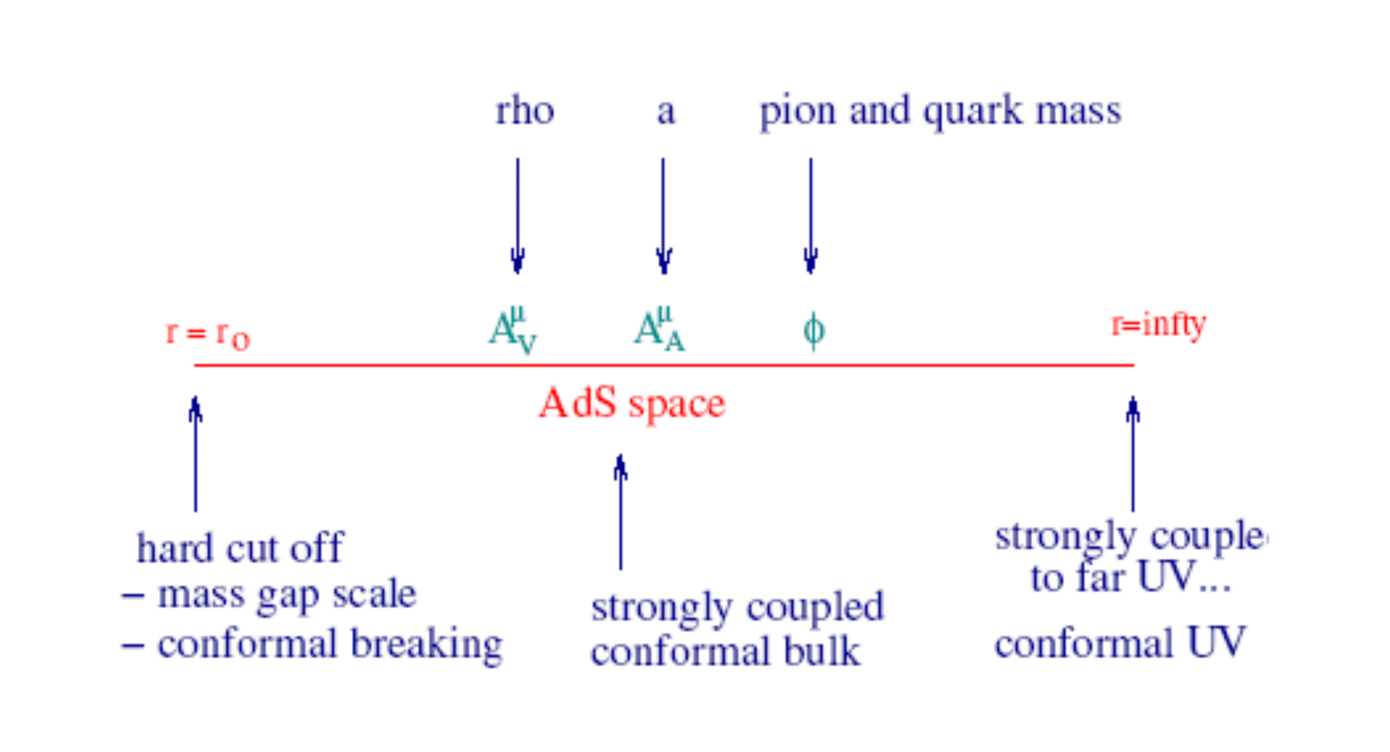
We can describe mass and condensate (but no dynamics – fit them)

$\bar{q}_L \gamma^\mu q_L$

Gauge fields to be dual to vector and axial-vector currents…

$\bar{q}_R \gamma^\mu q_R$

$$S = \int_{r_0}^{\infty} d^5x \sqrt{-g}\, Tr \left\{ |DX|^2 + 3|X|^2 - \frac{1}{4g_5^2}(F_L^2 + F_R^2) \right\}$$



Parameter count

r_o

c

m

g_5

Observable	Measured (MeV)	AdS A (MeV)	AdS B (MeV)
m_π	139.6 ± 0.0004	139.6*	141
m_ρ	775.8 ± 0.5	775.8*	832
m_{a_1}	1230 ± 40	1363	1220
f_π	92.4 ± 0.35	92.4*	84.0
$F_\rho^{1/2}$	345 ± 8	329	353
$F_{a_1}^{1/2}$	433 ± 13	486	440

3 parameter fit

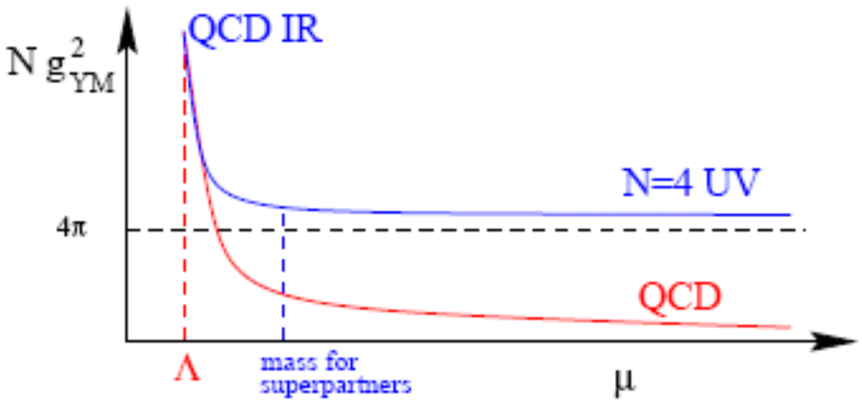
$$\begin{aligned}\mathcal{L}_4 &= L_1 \mathrm{Tr}^2[D_\mu U^\dagger D^\mu U] + L_2 \mathrm{Tr}[D_\mu U^\dagger D_\nu U]\mathrm{Tr}[D^\mu U^\dagger D^\nu U] + L_3 \mathrm{Tr}[D_\mu U^\dagger D^\mu U D_\nu U^\dagger D^\nu U] \\ &+ L_4 \mathrm{Tr}[D_\mu U^\dagger D^\mu U]\mathrm{Tr}[U^\dagger \chi + \chi^\dagger U] + L_5 \mathrm{Tr}[D_\mu U^\dagger D^\mu U (U^\dagger \chi + \chi^\dagger U)] \\ &+ L_6 \mathrm{Tr}^2[U^\dagger \chi + \chi^\dagger U] + L_7 \mathrm{Tr}^2[U^\dagger \chi - \chi^\dagger U] + L_8 \mathrm{Tr}[\chi^\dagger U \chi^\dagger U + U^\dagger \chi U^\dagger \chi] \\ &- iL_9 \mathrm{Tr}[F_R^{\mu\nu} D_\mu U D_\nu U^\dagger + F_L^{\mu\nu} D_\mu U^\dagger D_\nu U] + L_{10} \mathrm{Tr}[U^\dagger F_R^{\mu\nu} U F_{L\mu\nu}] \,.\end{aligned}$$

Pomarol computed Gasser Leutwyler coeffs too…

	Experiment	AdS_5
L_1	0.4 ± 0.3	0.4
L_2	1.4 ± 0.3	0.9
L_3	-3.5 ± 1.1	-2.6
L_4	-0.3 ± 0.5	0.0
L_5	1.4 ± 0.5	1.7
L_6	-0.2 ± 0.3	0.0
L_9	6.9 ± 0.7	5.4
L_{10}	-5.5 ± 0.7	-5.5

Improving IR, Perfecting the UV

These theories are not QCD in UV...



Need strong coupling for gravity description!

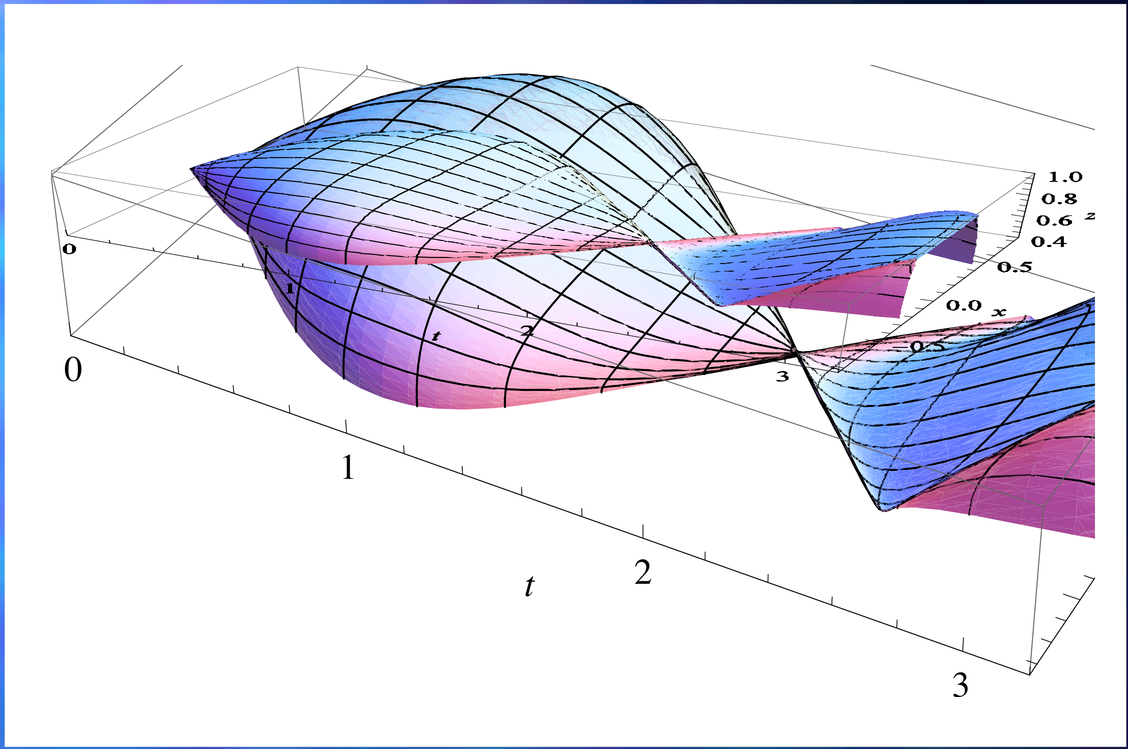
How can we cure for phenomenology?

Probably not by solving strongly coupled string theory...

Need to start doing effective field theory with a cut off in the UV…

Hadronization

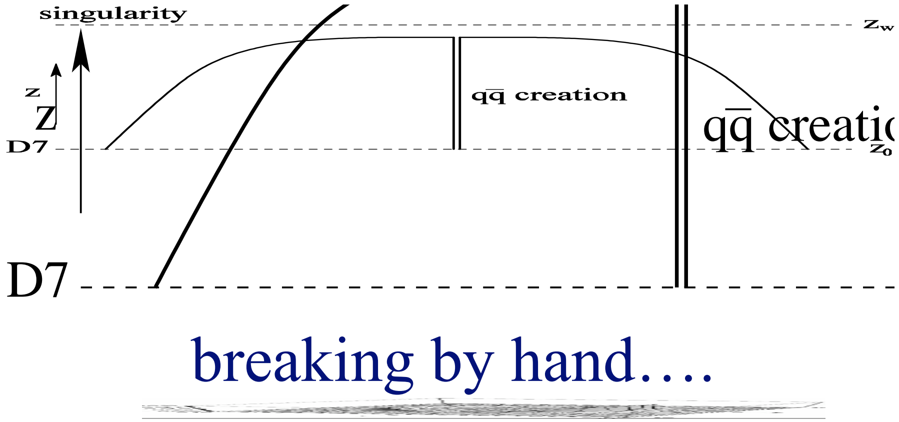
NE, French, Threlfall



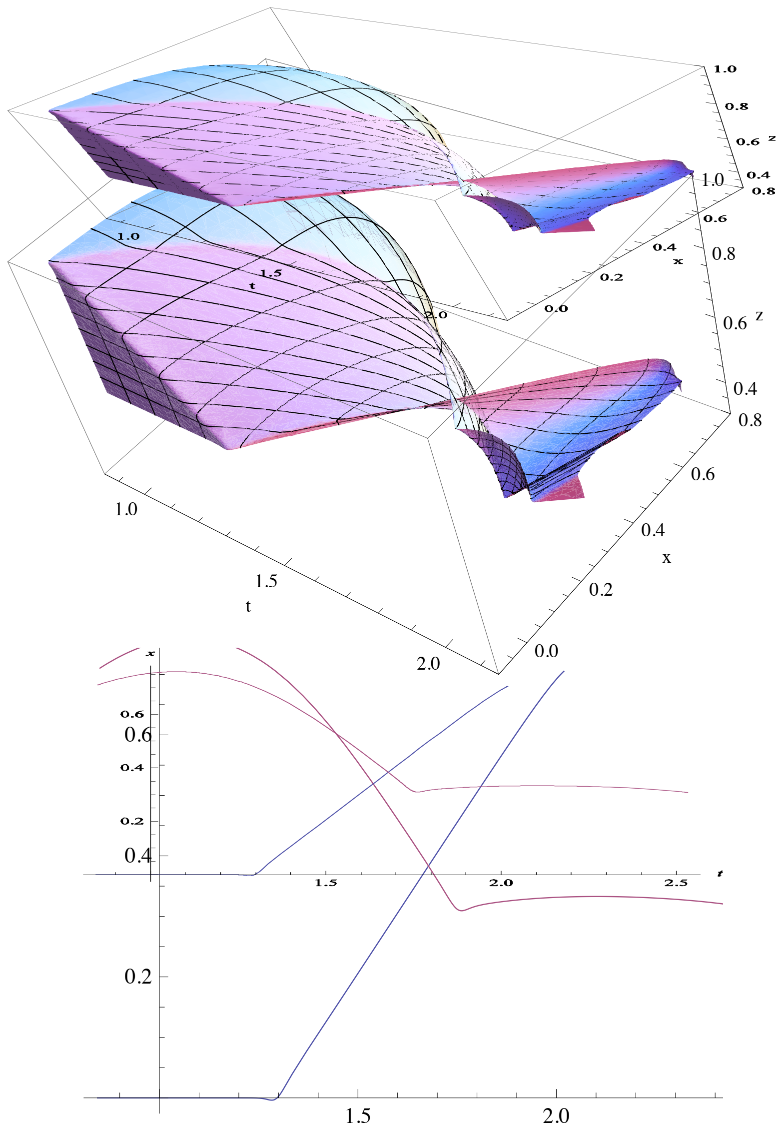
We can follow the evolution of a point like string as the ends separate… the string falls first in a 1/r potential then hits a hard wall forming a QCD string…

The quarks, in the absence of string breaking, bounce about the centre of mass due to the string tension…

Hadronization – string breaking and rho emission

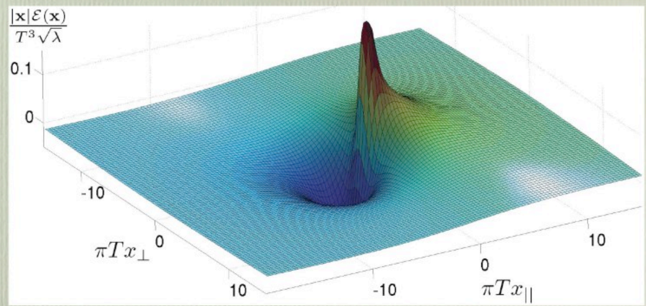


breaking by hand….

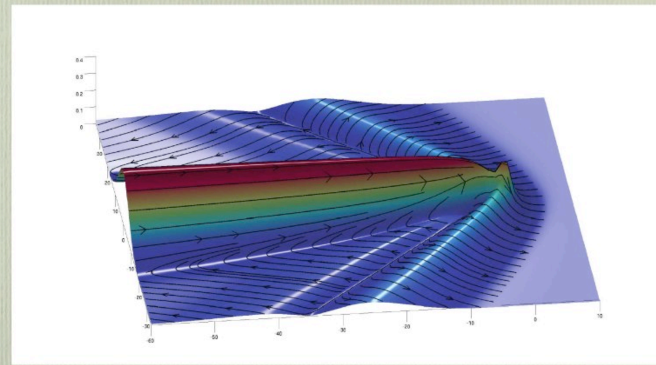


Quarks in a Dense QCD Plasma

Similar computations have been done in a black hole background to describe jet quenching in RHIC fireballs



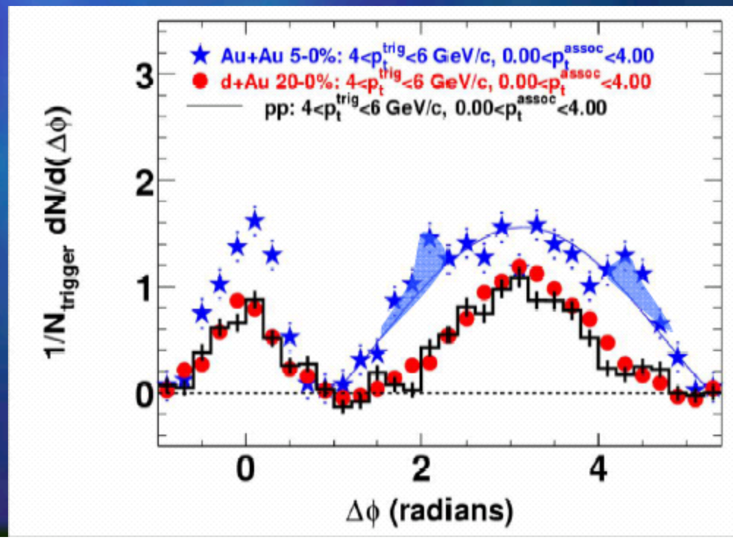
Energy density (× r) for v = 0.25
(minus leading short distance contributions)



Energy flux for v = 0.75

Larry Yaffe’s calculations of the shock wave produced by a moving quark

RHIC seeing a mach cone in away side jet data (??!!)



Conclusions

Qualitative vs quantitative

We now know that some strongly coupled gauge theories have a weakly coupled gravitational description

Some of these theories display confinement, chiral symmetry breaking and a thermal transition to a deconfined phase…

They are NOT QCD but they provide new insights into QCDs behaviour and provide novel starting points for models of QCD

AdS/QCD; Hadronization; Transport properties of gauge plasmas

BSM – unparticles, technicolour & susy breaking