Dynamic AdS/QCD and the spectra of gauge theories

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New understanding of holographic descriptions of mesons

A stab at predicting the spectra of arbitrary AF gauge theories

Oxford October 2014

Back track to 2005

Top down models of chiral symmetry breaking

Bottom up AdS/QCD

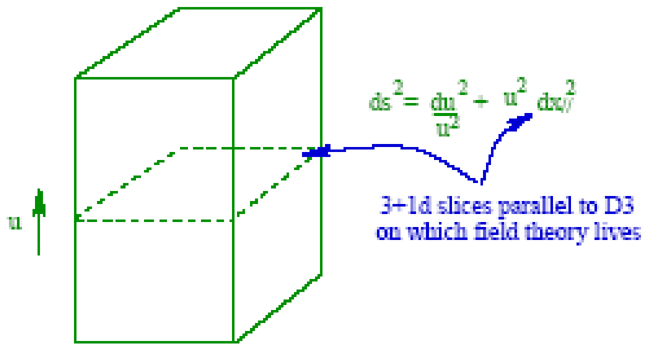
Building Holographic QCD

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

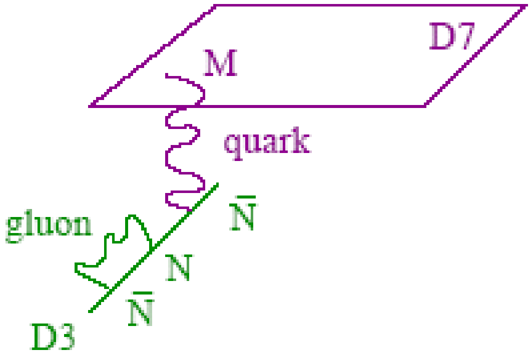
$$\int d^4x\ \Phi_{SUGRA}(u_0)\lambda\lambda$$

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

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

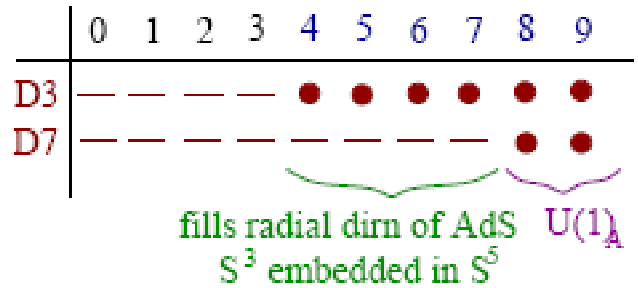
Adding Quarks

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



Quarks can be introduced via D7 branes in AdS

The brane set up is



We will treat D7 as a probe - quenching in the gauge theory.

Minimize D7 world volume with DBI action

$$S_{D7} = -T_7 \int d\xi^8 \sqrt{P[G_{ab}]}, \qquad P[G_{ab}] = G_{MN} \frac{dx^M}{d\xi^a}\frac{dx^N}{d\xi^b}$$

Mesons in AdS$_5$

Kruczenski, Myers, Mateos, Winters

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

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

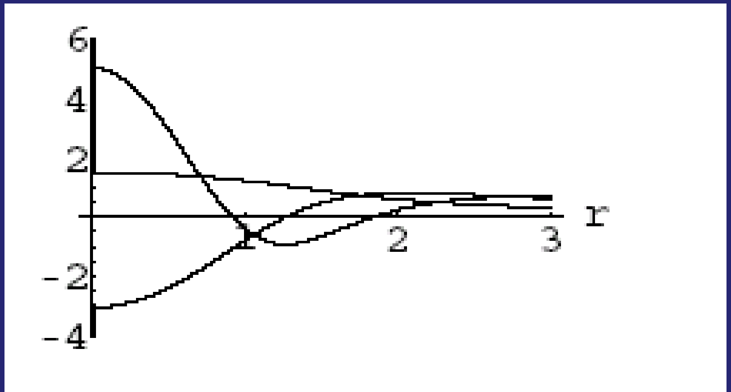
δ satisfies a linearized EoM

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

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



Orthonormal wave functions

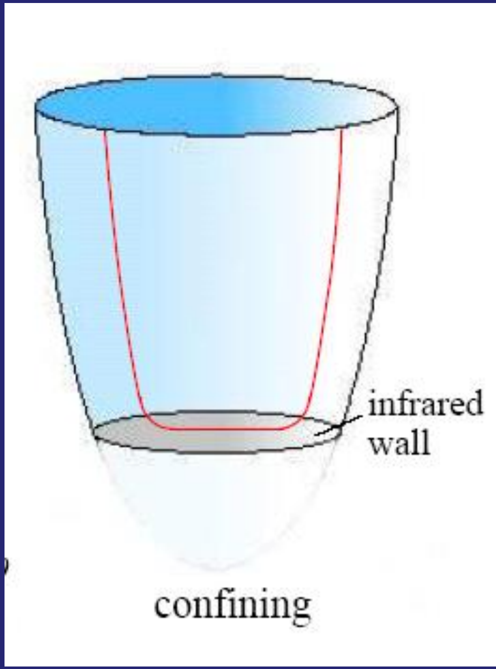
Add Confinement and Chiral Symmetry Breaking

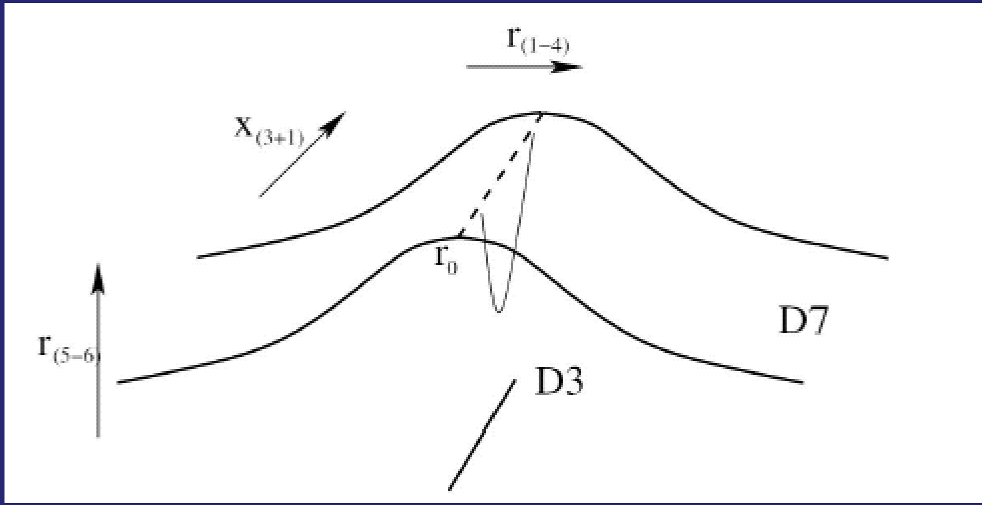
$$ds^2 = \frac{r^2}{R^2} A^2(r) dx_{3+1}^2 + \frac{R^2}{r^2} dr_6^2,$$

$$A(r) = \left(1 - \left(\frac{r_w}{r}\right)^8\right)^{1/4}, \qquad e^{\phi} = \left(\frac{1 + (r_w/r)^4}{1 - (r_w/r)^4}\right)^{\sqrt{3/2}}$$

Dilaton Flow Geometry: Gubser, Sfetsos

Here, this is just a simple, back reacted, repulsive, hard wall….





Babington et al, Ghoroku..

Erdmenger,
NE,Kirsch,
Threlfall
0711.4467

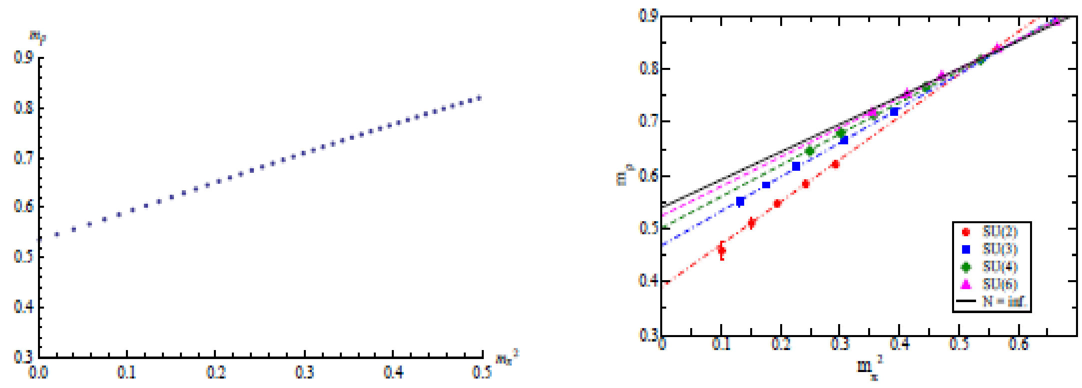


Figure 6.5: A plot of m_ρ vs m_π^2 in the Constable-Myers background on the left (we thank Andrew Tedder for generating this plot). Lattice data [20] (preliminary, quenched and at finite spacing) for the same quantity is also shown on the right.

These models live at very large coupling – QCD is at intermediate coupling strength…

The running coupling is rather different (UV strong fixed point)

Success beyond caricature seems surprising… how does one improve towards QCD?

Back track to 2005

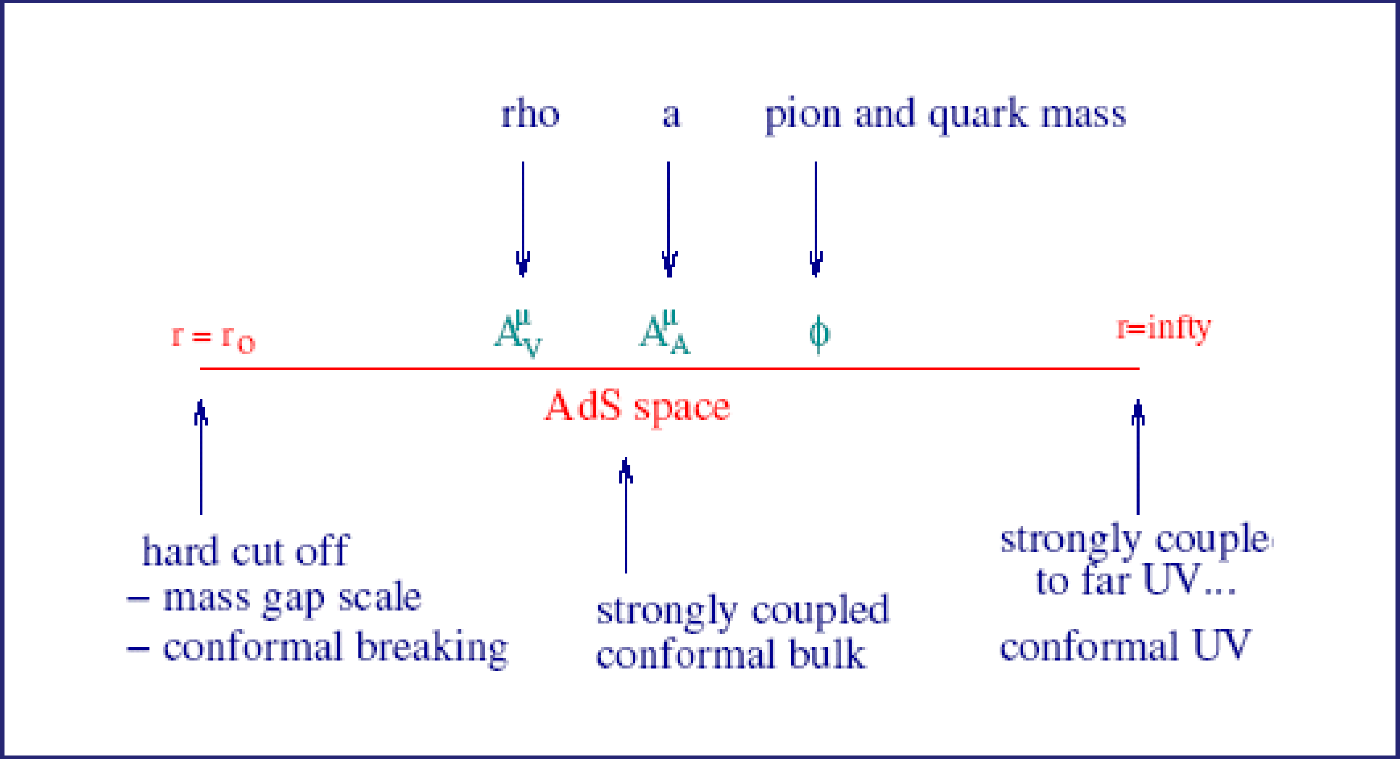
Top down models of chiral symmetry breaking

Bottom up AdS/QCD

Traditional AdS/QCD

Son, Stephanov,
Erlich, Katz

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



Parameter count

r_0

c = qq

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

The basic ideas are remarkably good… but… to systematically move to QCD we would need to:

IR improve – include all operators that are non-zero in the vacuum and back react them on each other

UV perfect – need to match the running of operators to the true perturbative QCD values in the UV….

No dynamics – inputing condensate and hard wall and fitting is only dynamics….

Of course as in any effective description of QCD this is overwhelming and you end up just re-parameterizing the data…. In QCD the regime of validity of the gravity description is very tight…

A New Insight in 2012

It had been quite hard to understand how to put in the dynamics of an individual gauge theory…

Holographic Models for QCD in the Veneziano Limit
Matti Jarvinen, Elias Kiritsis
1112.1261

We model the qq condensate by a scalar in "AdS"…

Breitenlohner-Freedman Bound

A scalar in AdS is stable until

msq < - 4

ie Δ < 2

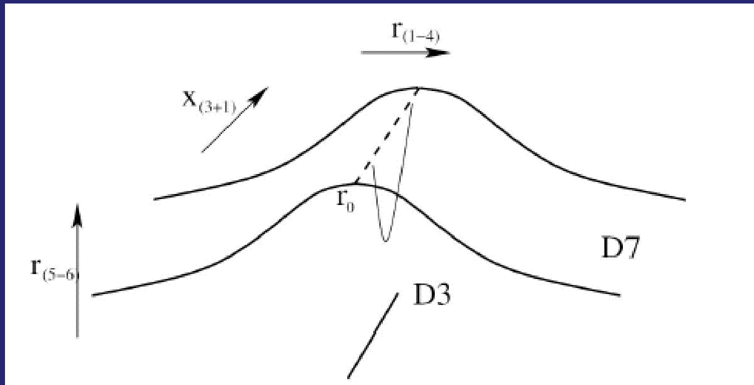
$$m^2 = \Delta(\Delta - 4)$$

A hard prediction that matches gap equation-ology for the on-set of chiral symmetry breaking…

Holographic models work for QCD mesons because they are describing the running of the anomalous dimension of qq rather than the running of the coupling…

D3/ Probe D7 Model

Alvares, NE, Kim,
1204.2474



λ

$$S_{D7} = -T \int d^4x d\rho\, \rho^3 e^{\phi} \sqrt{1 + (\partial_\rho L)^2}$$

$$S = \int \mathrm{d}\rho \lambda(r) \rho^3 \sqrt{1 + L'^2}$$

We expand for small L

$$S = \int \mathrm{d}\rho \left(\frac{1}{2} \lambda(r)\Big|_{L=0} \rho^3 L'^2 + \rho^3 \frac{d\lambda}{dL^2}\Big|_{L=0} L^2 \right)$$

we can now make a coordinate transformation

$$\lambda(\rho)\rho^3 \frac{d}{d\rho} = \tilde{\rho}^3 \frac{d}{d\tilde{\rho}}, \qquad \tilde{\rho} = \sqrt{\frac{1}{2} \frac{1}{\int_\rho^\infty \frac{d\rho}{\lambda \rho^3}}}$$

$$L = \tilde{\rho}\phi$$

$$S = \int \mathrm{d}\tilde{\rho} \frac{1}{2} \left(\tilde{\rho}^5 \phi'^2 - 3\tilde{\rho}^3 \phi^2 \right) + \int \mathrm{d}\tilde{\rho} \frac{1}{2} \lambda \frac{\rho^5}{\tilde{\rho}} \frac{d\lambda}{d\rho} \phi^2$$

This is the action of a scalar in AdS with a mass squared of -3 + ρ dependent correction from the gradient of λ

For example if we try to (very naively) input the two loop QCD running of the coupling…

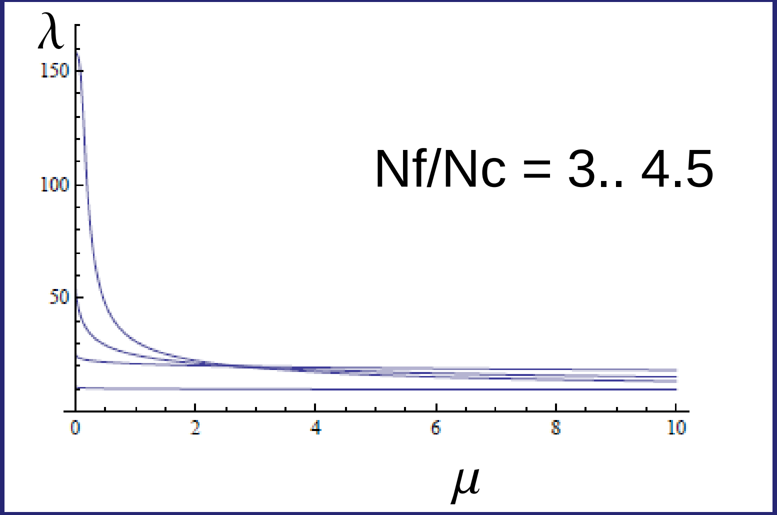
$$\beta(g) = -\frac{g^3}{(4\pi)^2}\left\{\frac{11}{3}N_c - \frac{2}{3}N_f\right\} - \frac{g^5}{(4\pi)^4}\left\{\frac{34}{3}N_c^2 - \frac{N_f}{N_c}\left[\frac{13}{3}N_c^2 - 1\right]\right\} + \cdots$$

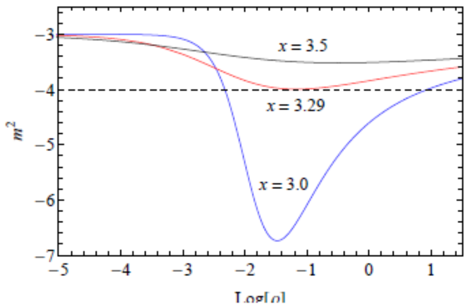
Using the 't Hooft coupling, and setting $\frac{N_f}{N_c} \to x$ we obtain

$$\lambda \equiv g^2 N_c \quad , \quad \dot{\lambda} = -b_0\lambda^2 + b_1\lambda^3 + \mathcal{O}(\lambda^4)$$

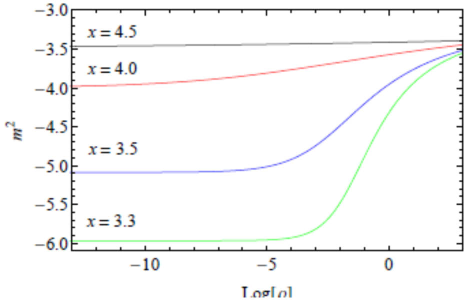
with

$$b_0 = \frac{2}{3}\frac{(11-2x)}{(4\pi)^2} \quad , \quad \frac{b_1}{b_0^2} = -\frac{3}{2}\frac{(34-13x)}{(11-2x)^2}$$





(a)The model with the QCD running imposed in section III ($x = 3.5, 3.29, 3.0$).

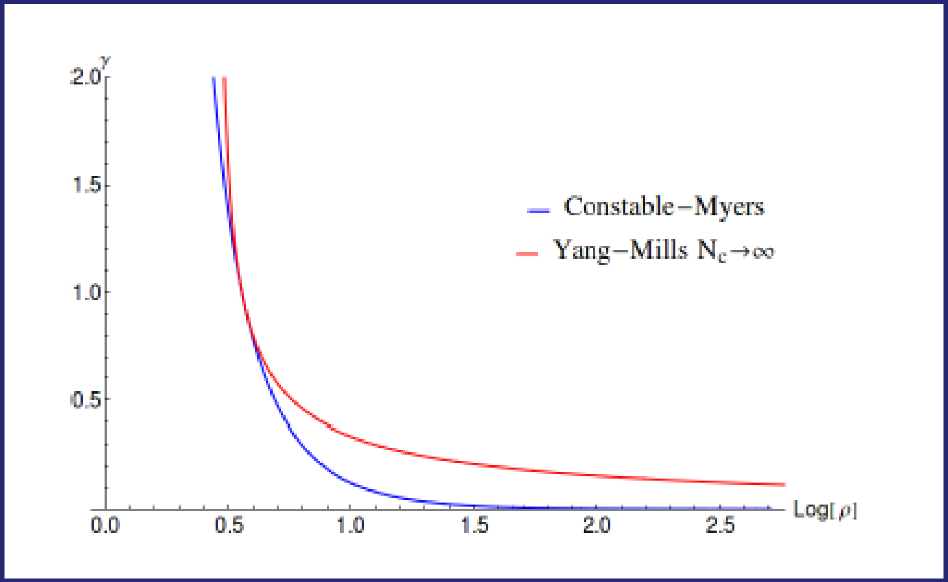


(b)The model of section IVa where the QCD anomalous dimension is imposed in the IR ($x = 4.5, 4, 3.5, 3.3$).

We output these running masses… to be compared with the perturbative expectation below…

$$\gamma_m^{(1)} = \mu\frac{d\ln m_q}{d\mu} = \frac{3(N_c^2-1)}{4N_c\pi}\alpha$$

$$m^2 = \Delta(\Delta - 4)$$



Top-down probe-brane models of QCD are just AdS/QCD with the background providing a running γ…

Dynamic AdS/QCD

Timo Alho, NE, KimmoTuominen
1307.4896

$$S = \int d^4x \, d\rho \, \mathrm{Tr} \, \rho^3 \left[\frac{1}{\rho^2 + |X|^2} |DX|^2 + \frac{\Delta m^2}{\rho^2} |X|^2 + \frac{1}{2\kappa^2} (F_V^2 + F_A^2) \right]$$

$$X = L(\rho) \, e^{2i\pi^a T^a}.$$

$$ds^2 = \frac{d\rho^2}{(\rho^2 + |X|^2)} + (\rho^2 + |X|^2) dx^2,$$

D7 probe action in AdS expanded to quadratic order

X is now a dynamical field whose solution will determine the condensate as a function of m

We use the top-down IR boundary condition on mass-shell: $X'(\rho=X) = 0$

X enters into the AdS metric to cut off the radial scale at the value of m or the condensate – no hard wall

The gauge DYNAMICS is input through Δm

$$m^2 = \Delta(\Delta - 4)$$

$$\Delta m^2 = -2\gamma = -\frac{3(N_c^2 - 1)}{2N_c \pi} \alpha$$

The only free parameters are Nc, Nf, m, Λ

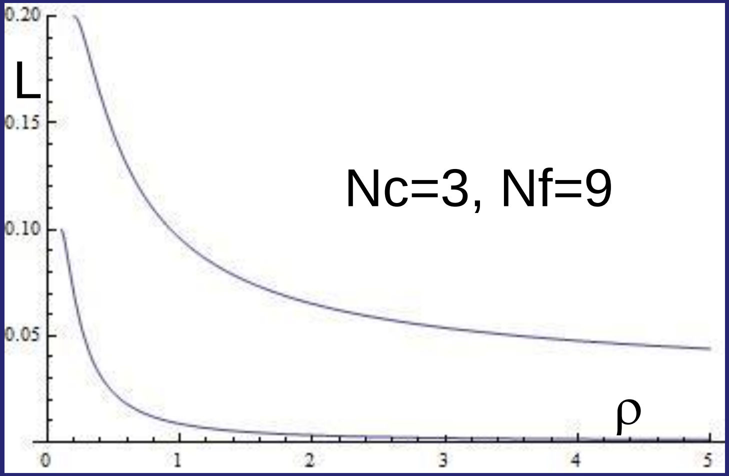
Formation of the Chiral Condensate

We solve for the vacuum configuration of L

$$\partial_\rho[\rho^3 \partial_\rho L] - \rho \Delta m^2 L = 0\,.$$

Shoot out with

L'(ρ=L) = 0



Read off m and qq in the UV…

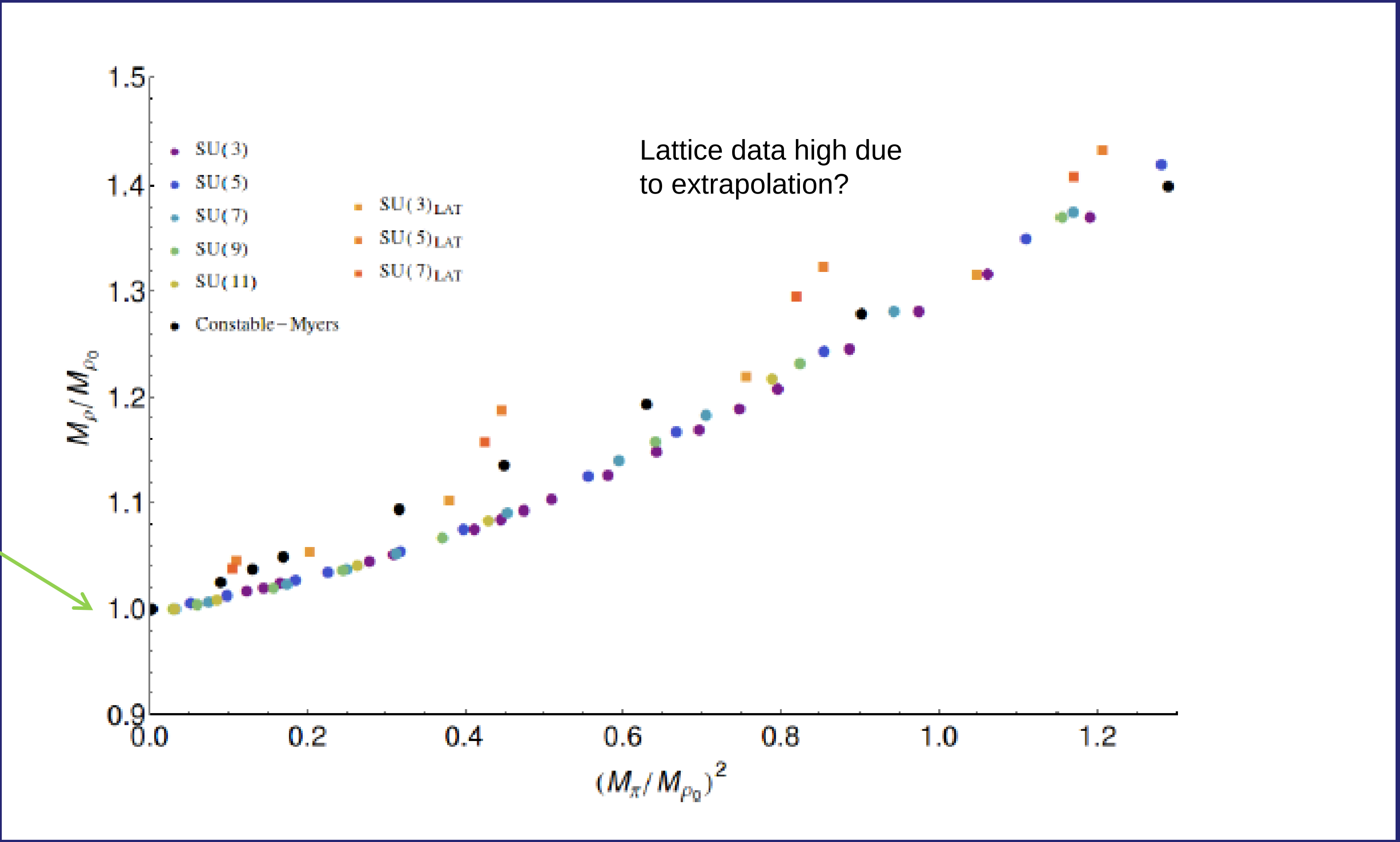
Now solve for meson masses by looking at linearized fluctuations about this vacuum…

Quenched SU(Nc) gauge

NE, Erdmenger & Mark Scott

M_rho = 1 defines Λ

Real QCD lies here

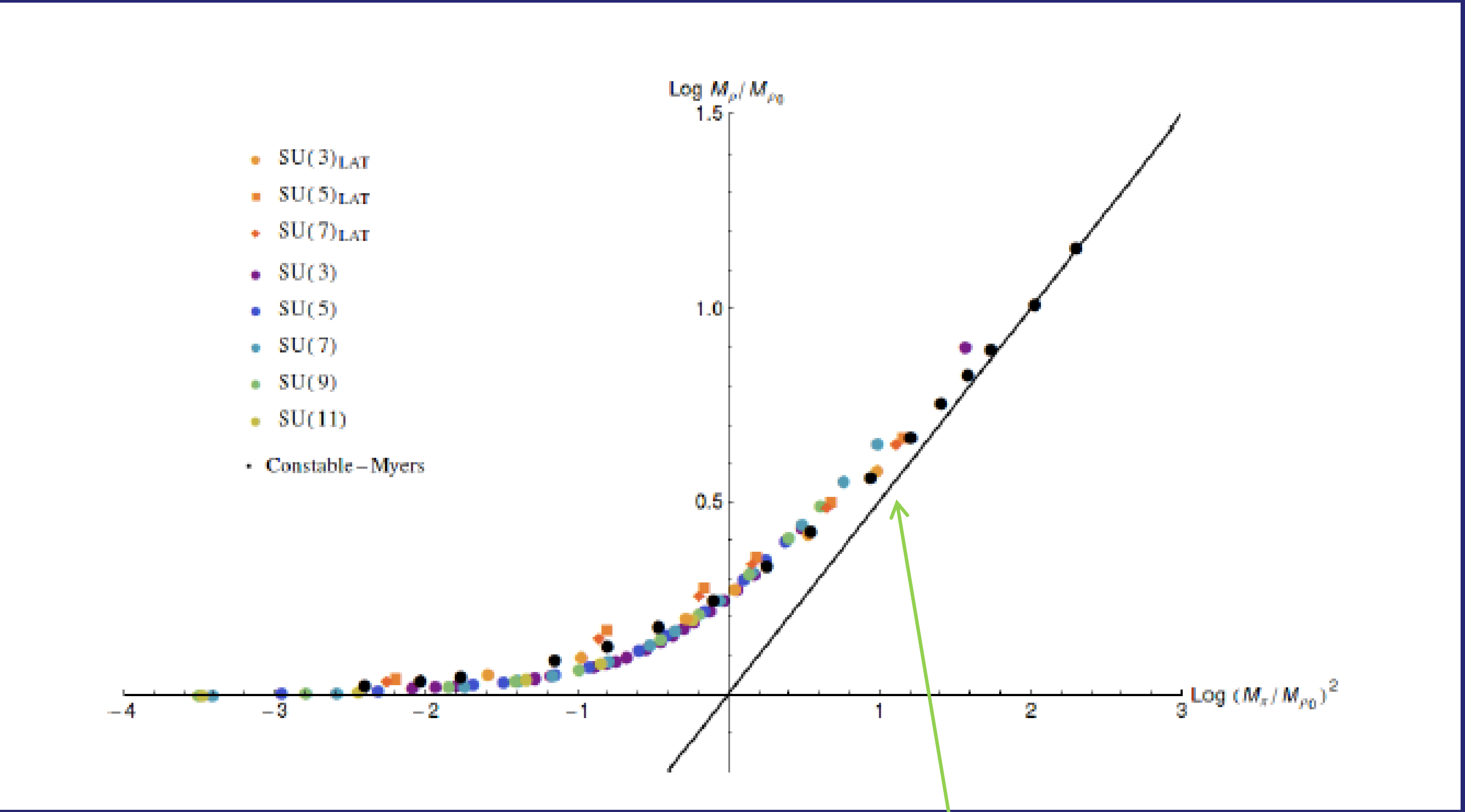


There is very little Nc dependence

Comparison to quenched lattice data (Bali et al… arXiv1304.4437)

All of these models lie within 10% on any point....

Quenched SU(Nc) gauge

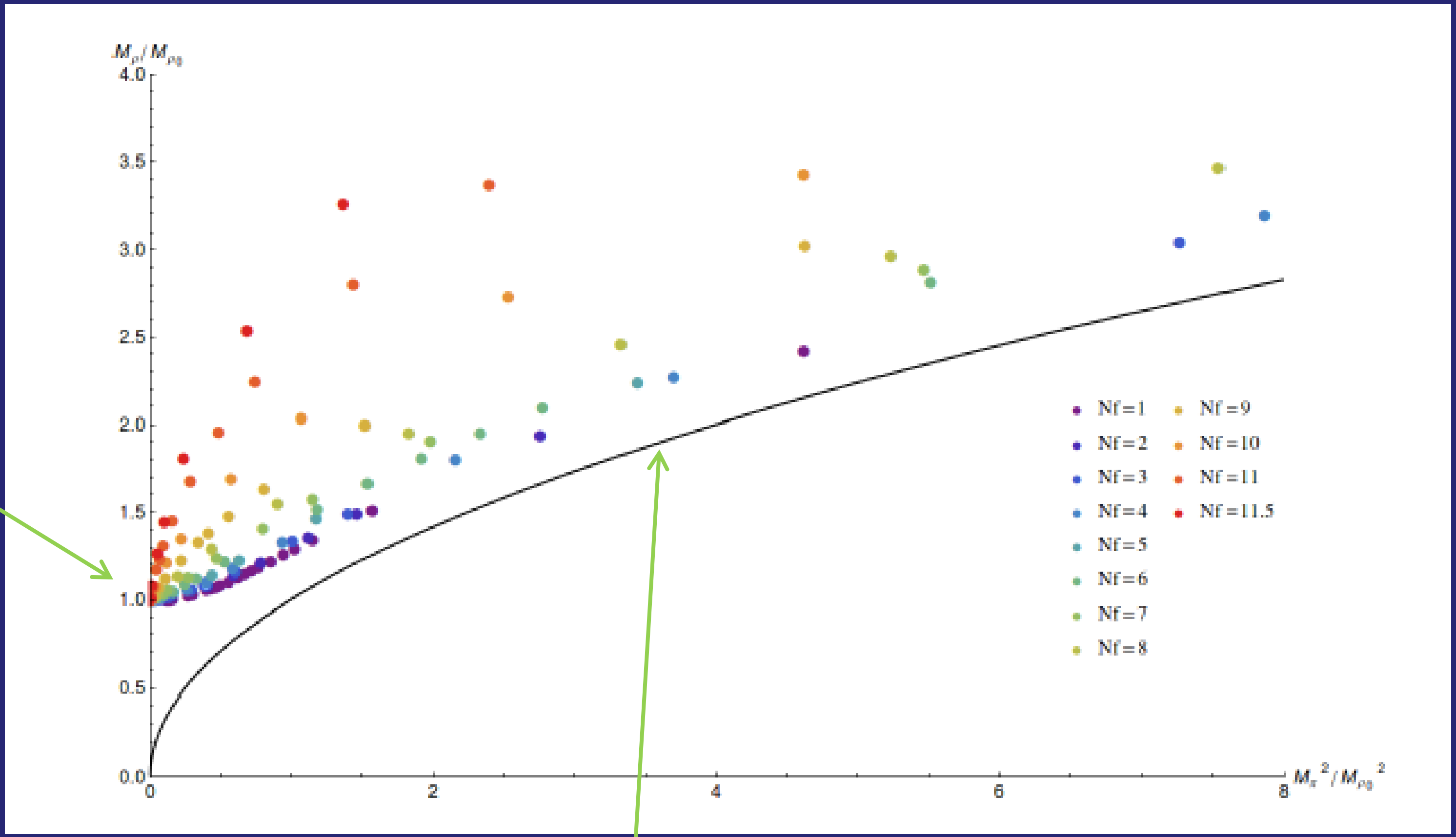


M_rho = M_pi

SU(3) gauge theory + Nf quarks

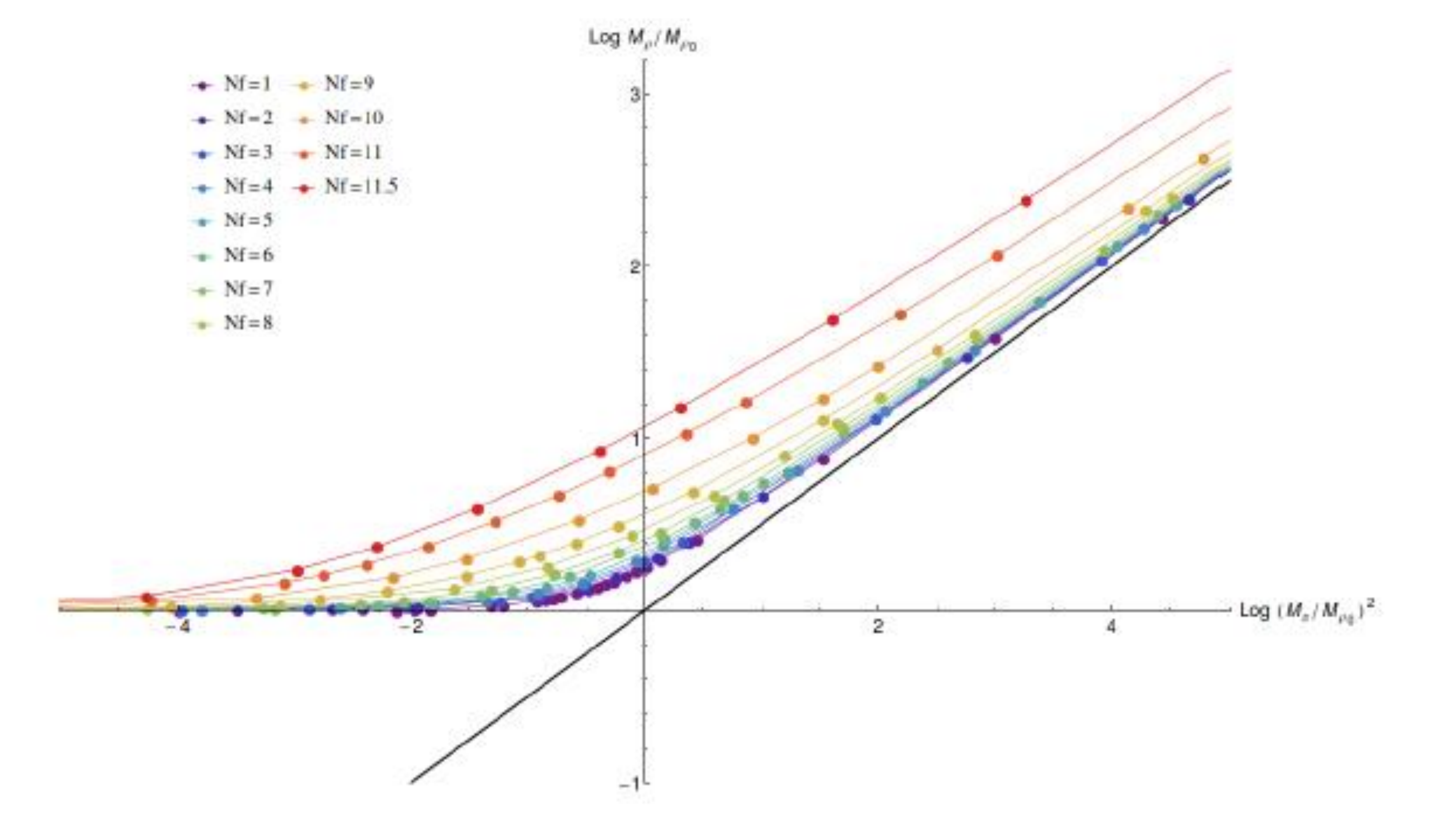
M_rho = 1
defines Λ

Real QCD
lies here



M_rho = M_pi

SU(3) gauge theory + Nf quarks



We do see new behaviour as Nf heads towards 12….

The Conformal Window

SU(Nc) gauge theory with Nf fundamental quarks

No AF

Nf=11/2 Nc

CFT

Nf = 4 Nc

χ SB

$$\beta(g) = -\frac{g^3}{(4\pi)^2}\left\{\frac{11}{3}N_c - \frac{2}{3}N_f\right\} - \frac{g^5}{(4\pi)^4}\left\{\frac{34}{3}N_c^2 - \frac{N_f}{N_c}\left[\frac{13}{3}N_c^2 - 1\right]\right\} + \cdots$$

Using the 't Hooft coupling, and setting $\frac{N_f}{N_c} \to x$ we obtain

$$\lambda \equiv g^2 N_c \quad , \quad \dot{\lambda} = -b_0\lambda^2 + b_1\lambda^3 + \mathcal{O}(\lambda^4)$$

with

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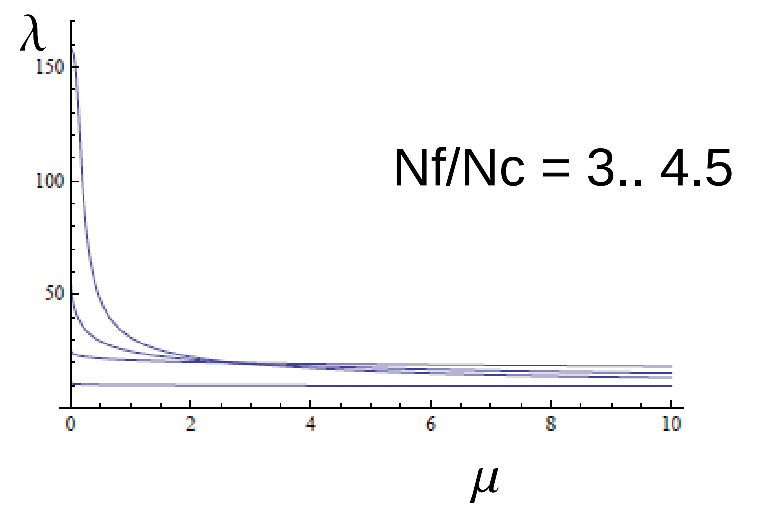
$m\ \bar{q}q$

$$\gamma_m^{(1)} = \mu\frac{d\ln m_q}{d\mu} = \frac{3(N_c^2-1)}{4N_c\pi}\alpha$$



If critical γ = 1…. Nf/Nc ~ 4

Yamawaki,Appelquist, Terning, Sannino,…

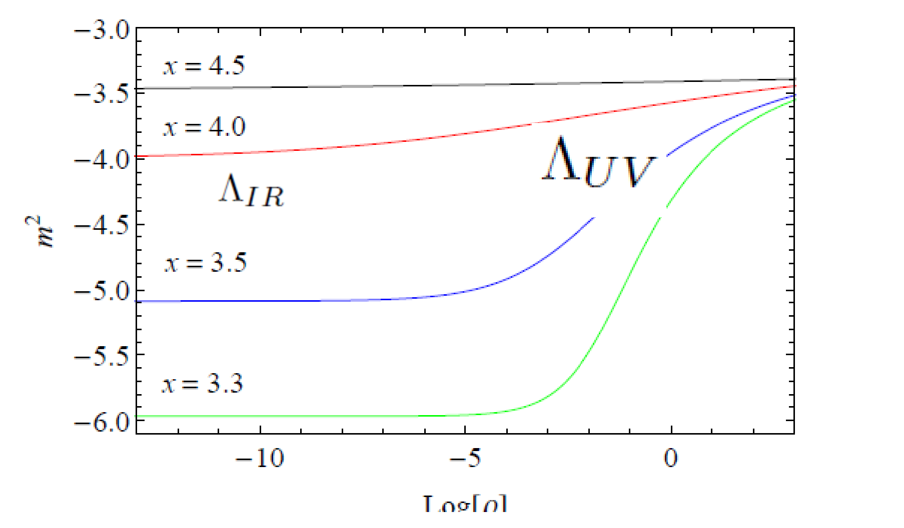
Walking Dynamics

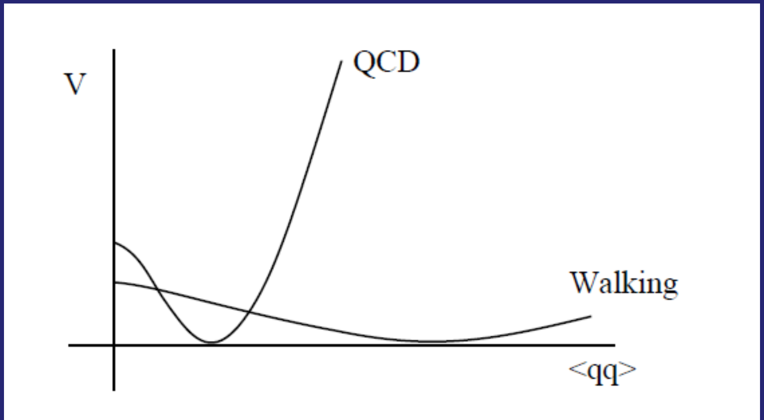
Holdom

Just above the CW regime theories have an enhanced UV quark condensate

$$\langle \bar{q} q \rangle_{UV} \sim \Lambda_{UV} \langle \bar{q} q \rangle_{IR} \sim \Lambda_{UV} \Lambda_{IR}^2$$

$$f_\pi \sim \Lambda_{IR}$$

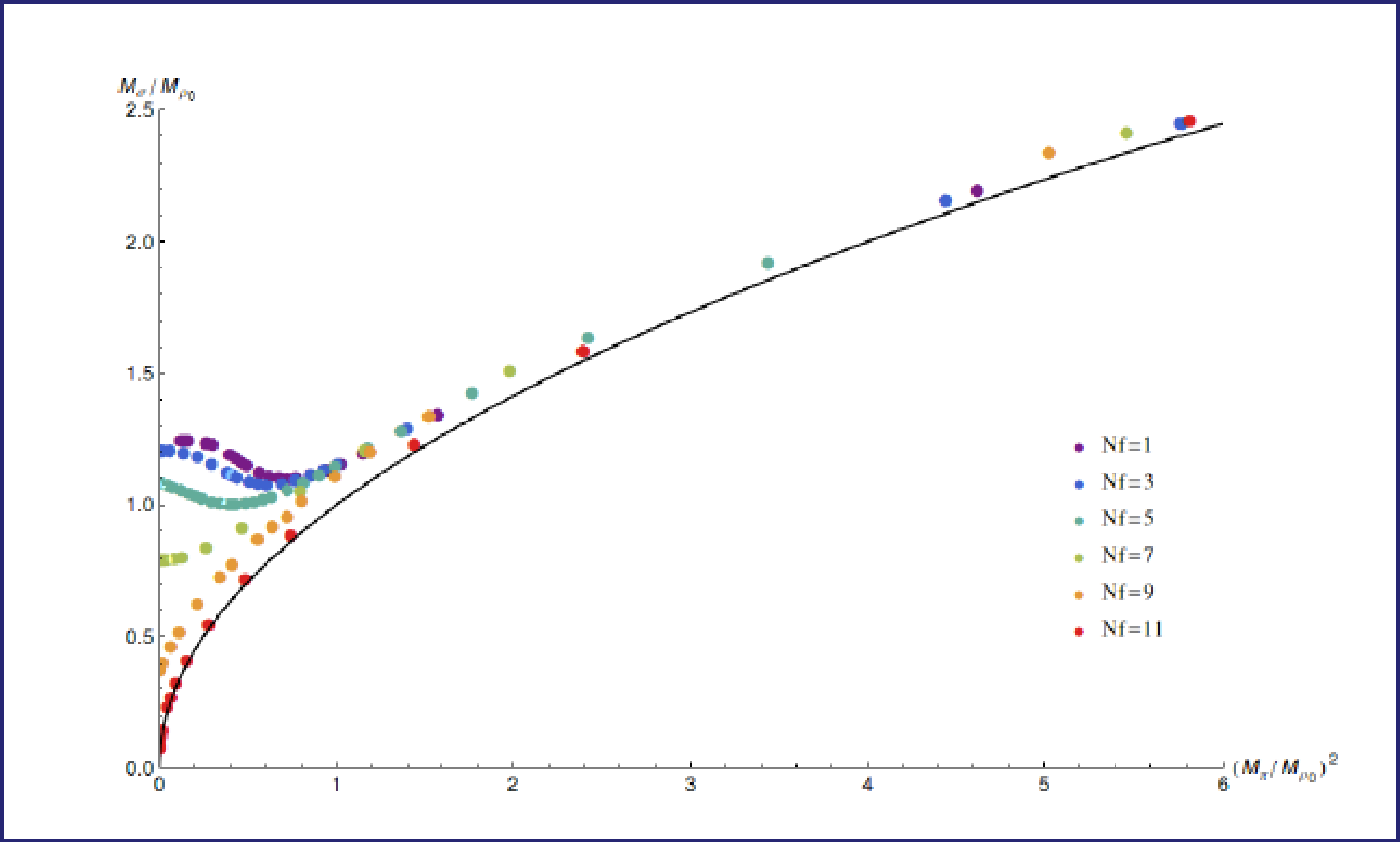




- Is the sigma particle light – a techni-dilaton?
- Is the higgs such a technicolor state?

SU(3) gauge theory + Nf quarks

The QCD point is not right for the f0(500) but about right for the f0(980) – is the f0(500) odd eg a molecule ???



We indeed see a light sigma relative to the rho…

Alho, NE, Tuominen 1307.4896

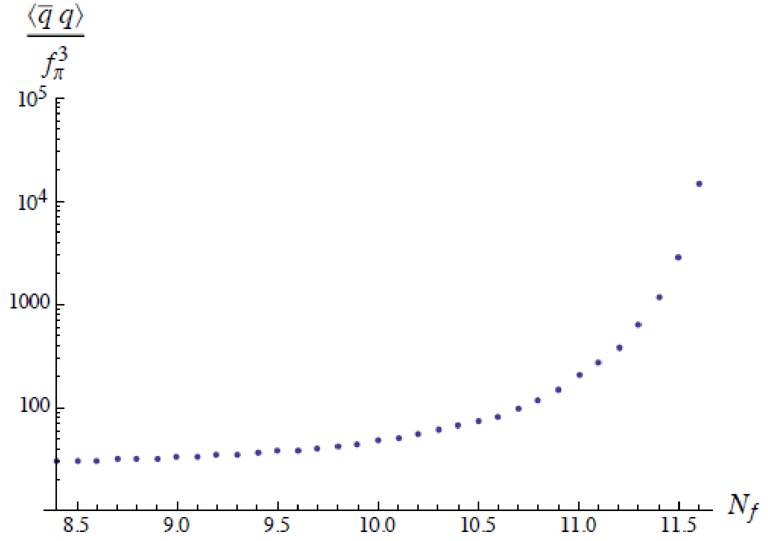


FIG. 5: The quark condensate normalized by f_π^3 vs N_f.

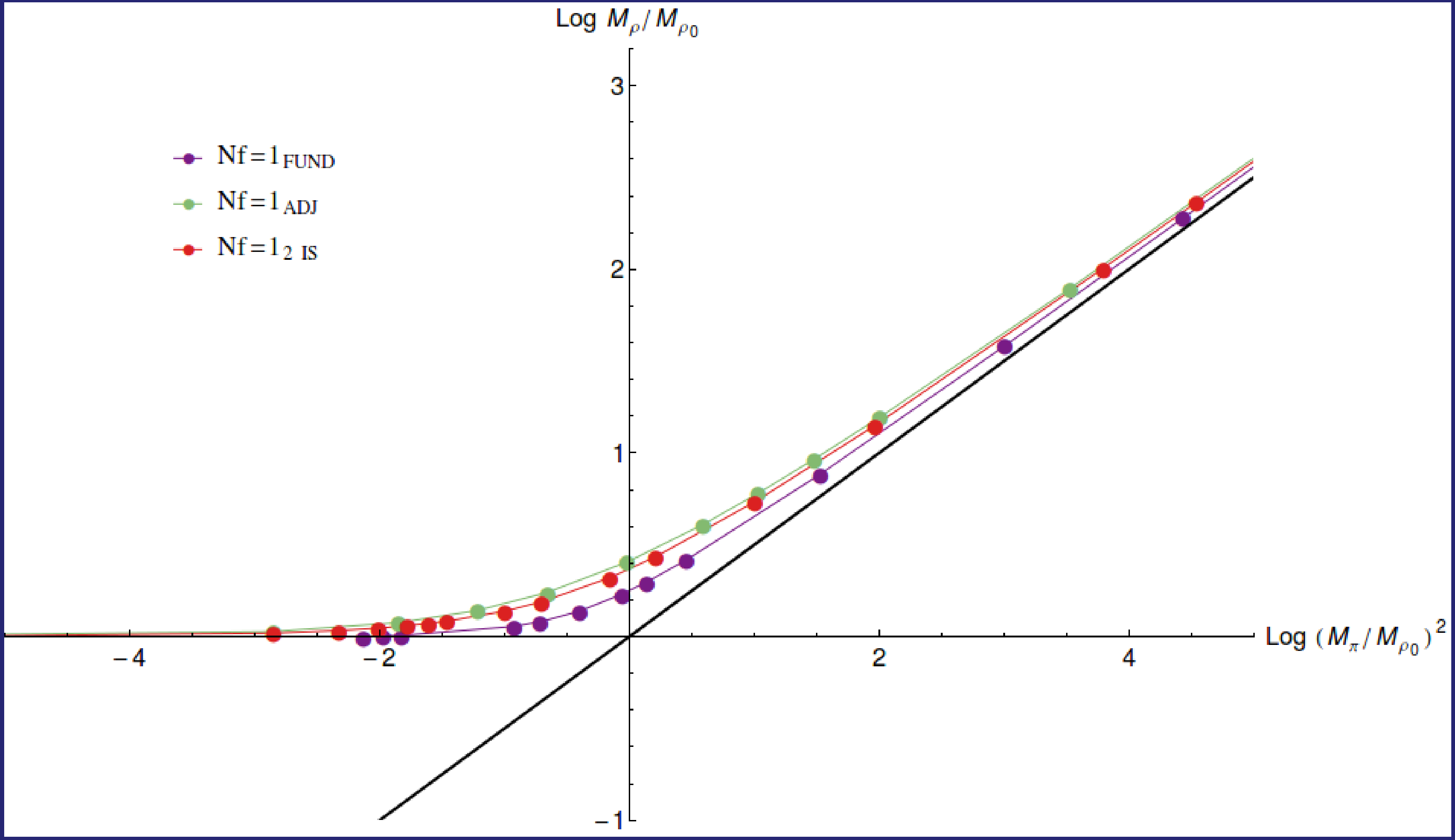
qq enhancement reproduced….

Cf FCNC problem in TC

Pick your theory…

Input (assumed) running of γ for any theory you fancy…

eg SU(3) gauge +

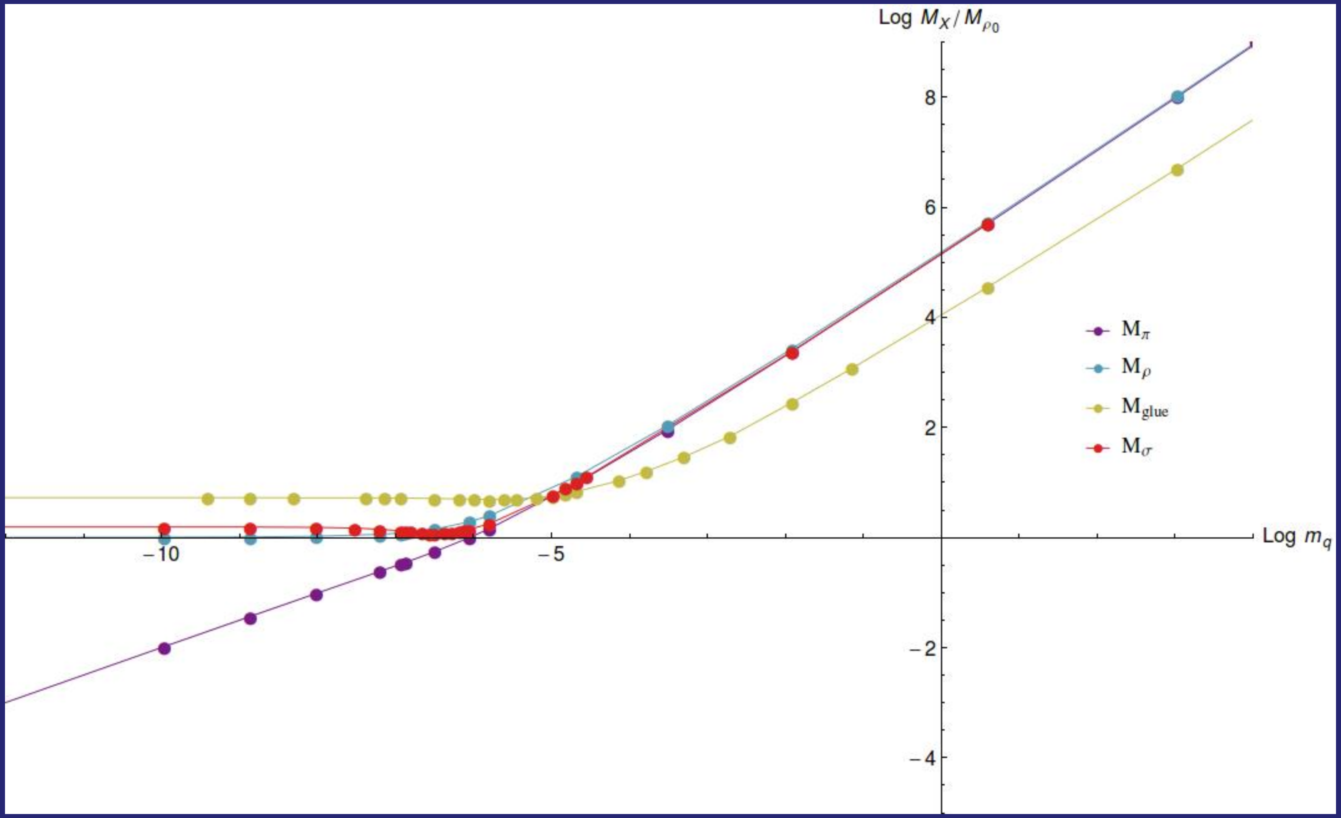


Glueballs

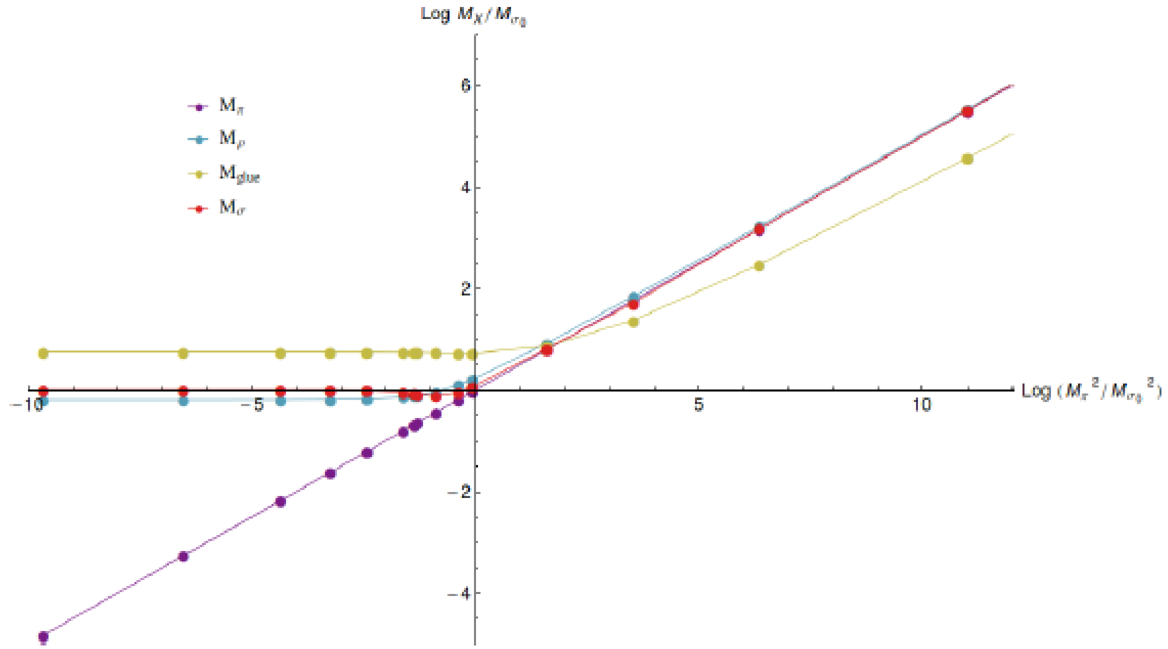
The model concentrates on the quark states… we're not trying to describe the running of the coupling or Tr F^2… however for us roughly…

Find the dynamical IR quark mass… below that scale run the coupling as pure YM.. Find the IR pole… multiply by 8 and that's the glueball mass!

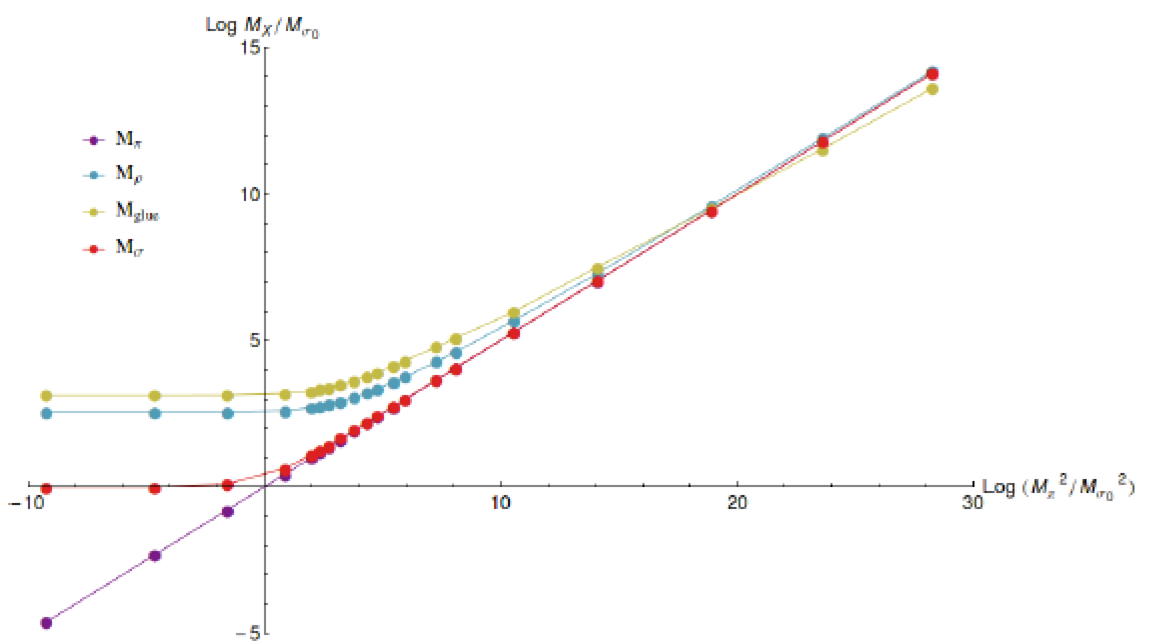
SU(3)
Nf=3



SU(3)
Nf=3



SU(3)
Nf=11

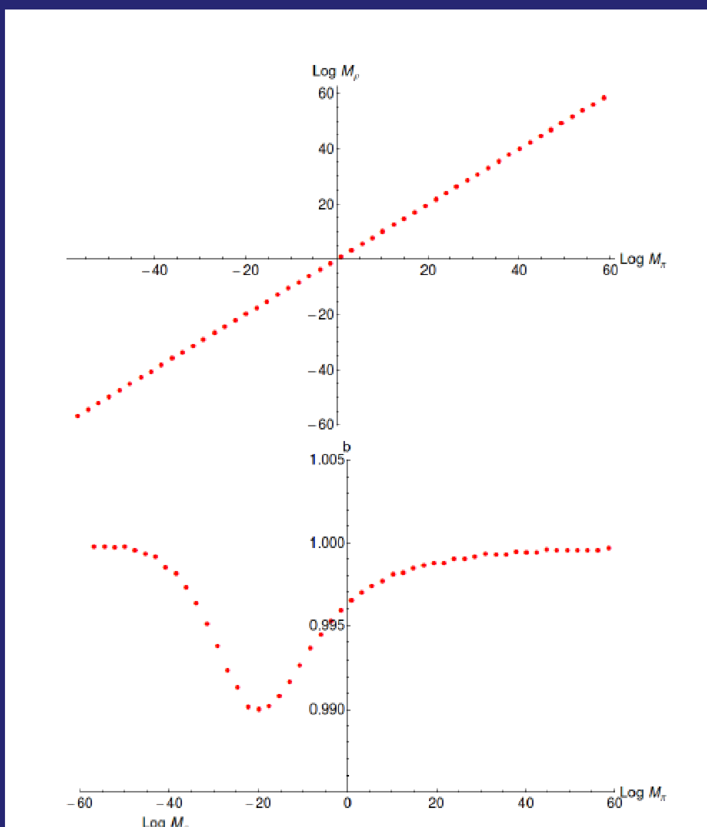


Study the Conformal Window

NE, Scott 1405.5373

For Nf > 4 Nc there is no dynamical scale so study the theory at non-zero quark mass…

eg SU(3) gauge + 13 flavours



$$M_\rho \propto M_\pi^b$$

b=1 for the conformal IR and UV regimes but deviates at the intermediate running scale…

Conclusions

Holographic models of QCD continue to improve… running of γ is crucial…one gets a good description of the lowest lying spectra at better than 10% and you can see generic behaviours with Nc Nf easily...

Holography is a remarkably simple method to get a ball park answer for behaviour… but it still can’t be systematically improved…

Hopefully Models are useful to guide lattice practitioners…

On going work: T μ phase structure… pomeron physics… enlarging to the full QCD spectra… why can I ignore other operators?