QCD FROM STRING THEORY

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Analogy: Lattice QCD

I. 1974-79. Analytic strong coupling expansion → cartoon of real QCD. Confinement, etc., but not quantitative

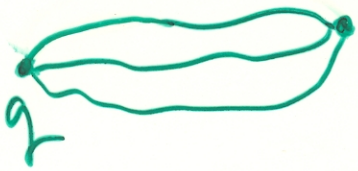
II. 1980- Numerical, quantitative.

In string QCD we have I and are working towards II. Advantages vs. lattice: dynamics, finite density, nonequilibrium ...

Some history:

1968-73: string theory of the strong interaction —

meson = 

(cf. QCD: 

)

This works in some regimes, but there were problems —

- massless spin-1 and spin-2 states.
- quantization requires $D > 4$.
- experiment revealed pointlike constituents (partons), whereas string is soft at high energy.

1973: Asymptotic freedom + QCD

1974: String theory of quantum gravity (Scherk, Schwarz; Yonega)

...

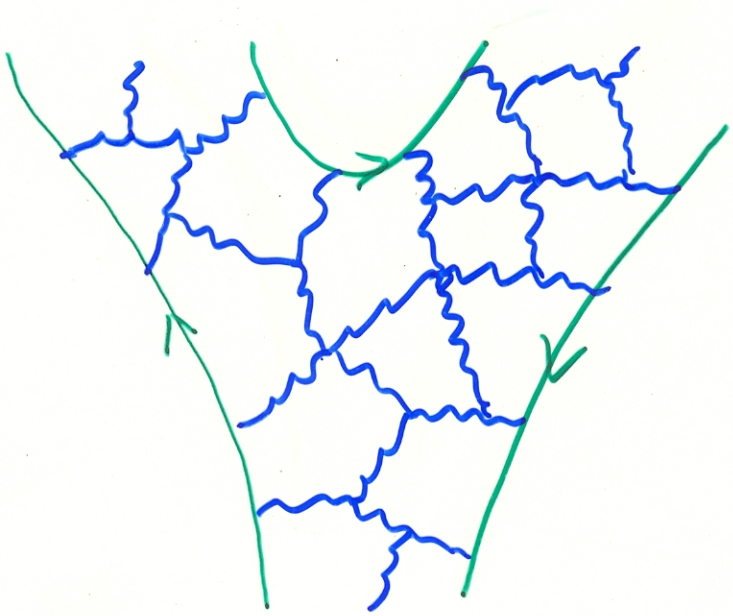
1974: Lattice gauge theory. (Wilson)

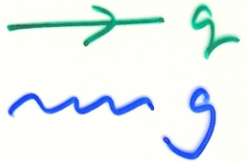
- Analytic strong coupling approx.
- Numerical method.

1974: Large-N_c approx. ('t Hooft)

1974: Black hole evaporation. (Hawking)

't Hooft: taking $N_c \to \infty$ with $g^2 N_c$ fixed gives a smooth limit. Only planar graphs without quark loops survive:



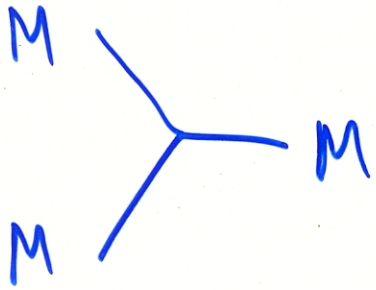


Many aspects of strong interaction phenomenology (e.g. Zweig's rule) suggest that $N_c = 3$ is 'large'.

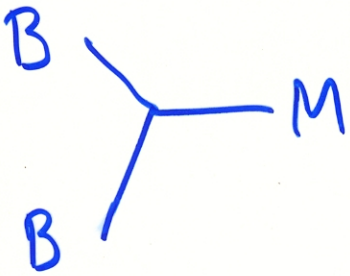
M = meson

B = baryon

G = glueball



$$\propto \frac{1}{\sqrt{N_c}}$$



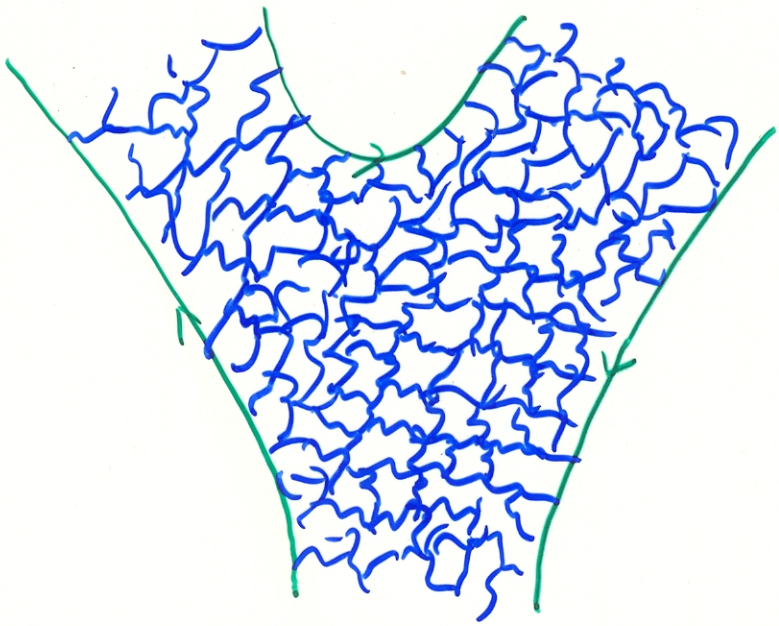
$$\propto \frac{1}{\sqrt{N_c}}$$

$$\propto \frac{1}{N_c}$$

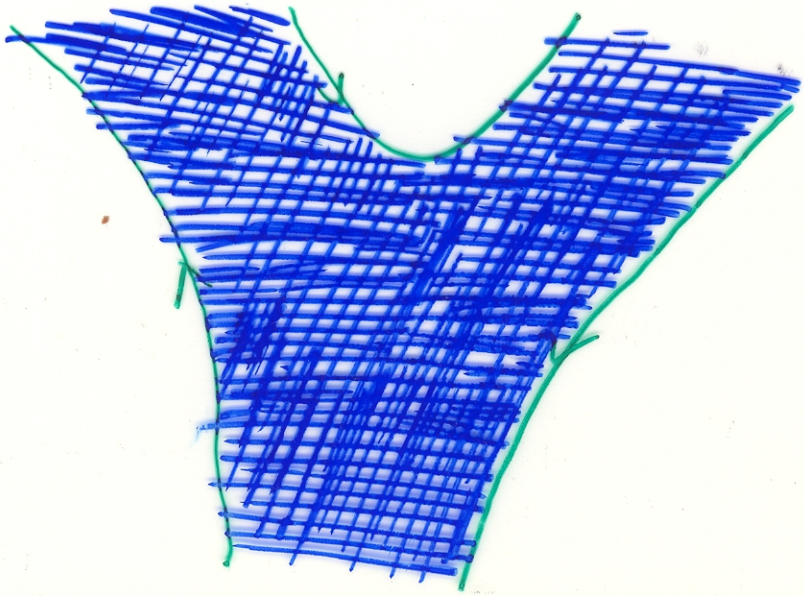
Hadron interactions $\to 0$ in $N_c \to \infty$ limit.

But can we <u>solve</u> QCD in this limit?

At strong coupling gluons might form a fine mesh



or even a continuous surface



= string theory ... ?!

23 years go by...

1997: $\mathcal{N}=4$ supersymmetric Yang-Mills

$=$ IIB string in $AdS_5 \times S^5$

(Maldacena)

Duality:

$$H = H_0 + g H_{int}$$

$$= H_0' + g' H_{int}'$$

$$g' = 1/g$$

Since 1994, many dualities discovered in supersymmetric field and string theories. Maldacena's duality discovered by taking low energy limit of black hole – D-brane duality.

(also Gubser, Klebanov, Polyakov, Witten)

The duality is between:

- $\mathcal{N}=4$ SUSY QCD, 3+1 dim.

massless gluons + 4 Weyl fermions + 6 scalars
all in adjoint representation of $SU(N_c)$

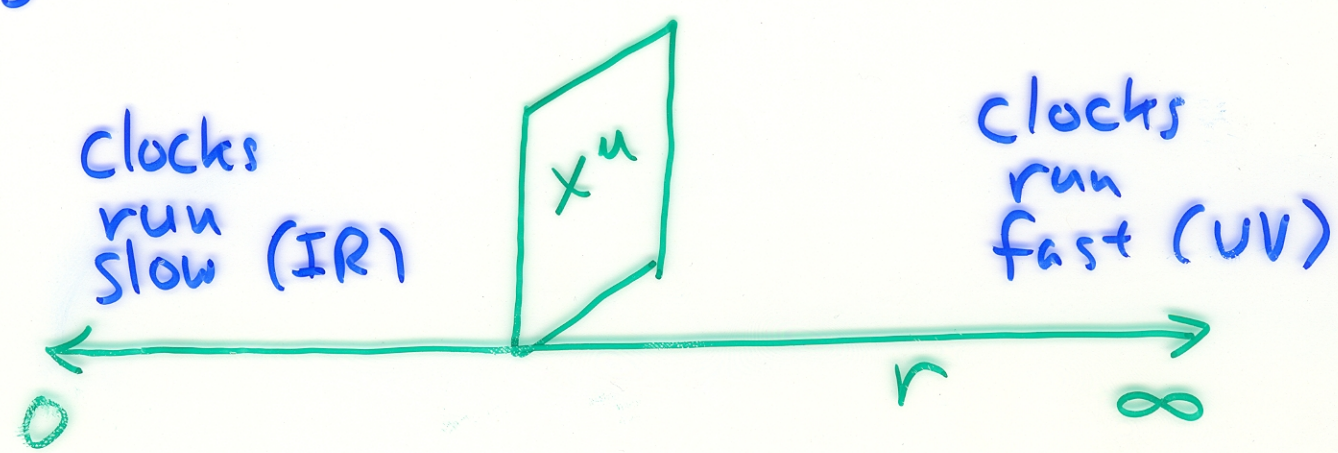
- IIB string in $AdS_5 \times S^5$: same string as for quantum gravity, but in unusual 9+1-dim spacetime:

coordinates x^μ, $\underbrace{r, 5 \text{ angles}}_{\text{6-d cavity}}$

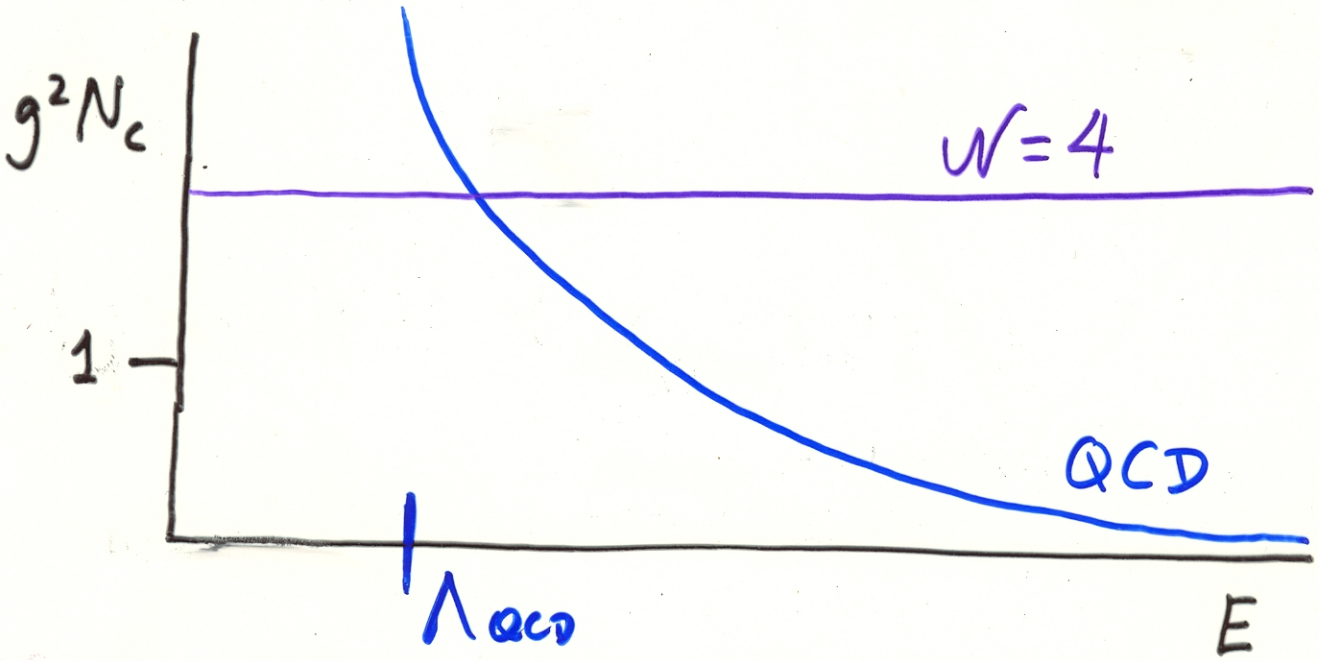
$$ds^2 = \frac{r^2}{R^2}\underbrace{\eta_{\mu\nu}dx^\mu dx^\nu}_{\text{flat}} + \frac{R^2}{r^2}dr^2 + R^2 d\Omega_5^2$$

↑ gravitational redshift

$R^2 = \sqrt{g^2 N_c}\, \ell_{\text{string}}^2$



Physics is different from QCD:



$\beta = 0$ for $\mathcal{N}=4$ theory – coupling doesn't run.

IR- no confinement/chiral symmetry breaking; strongly coupled gluons + colored fields

UV- no asymptotic freedom.

In string dual, IR is $r \to 0$, UV is $r \to \infty$.

Quark-gluon plasma = black hole in AdS (Witten)

Hydrodynamics modes of plasma = "quasinormal modes" of fields near black hole ... "membrane paradigm"

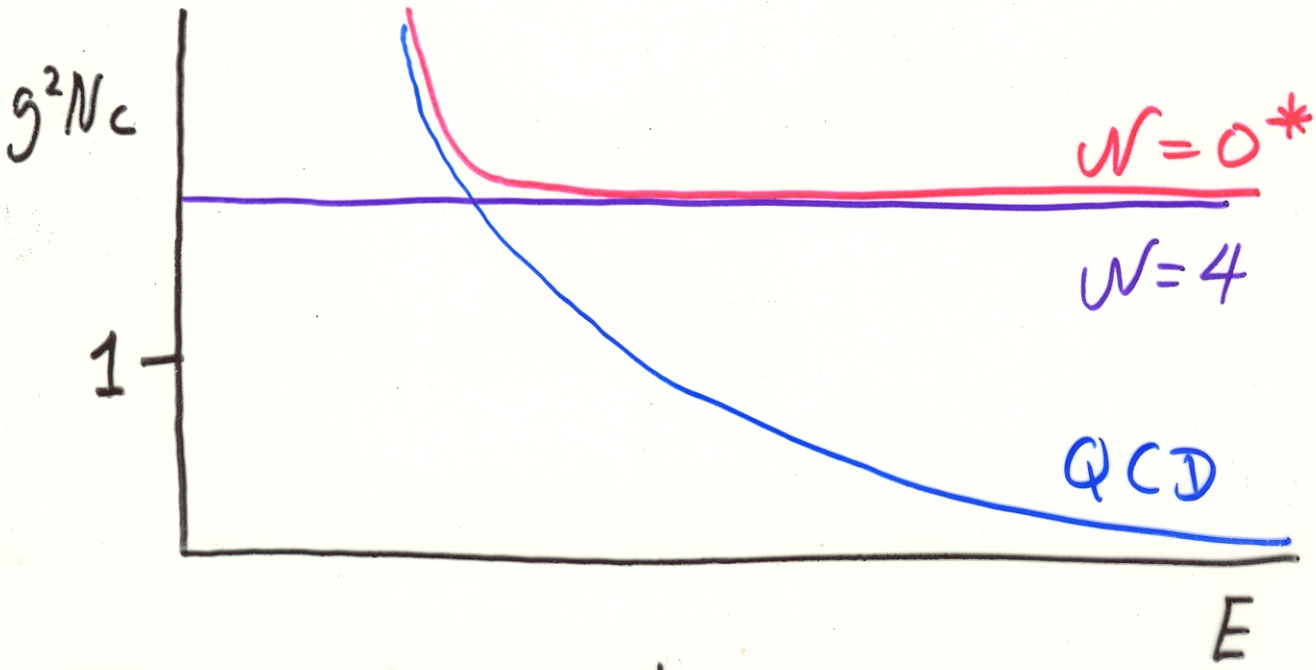
(Son, Herzog, Starinets, Policastro ...)

Deconfinement and chiral symmetry transitions (Buchel, Klebanov, Tseytlin ...)

Add matter in fundamental rep. (quarks)

(Karch, Katz, ...)

Once we have one duality we can find more. Adding mass terms for the scalar and fermi fields leads to the red curve:



QCD-like at low energy. J.P. + Strassler
Klebanov + "

Dual string theory has less symmetric spacetime: $\sim AdS_5 \times S^5$ at large r, but cut off smoothly at $r = r_{min}$

In $\mathcal{N}=0^*$ (and other models*),
can calculate

- hadron masses
- parton distribution functions
- thermodynamic properties of quark-gluon plasma

Like strongly coupled lattice theory,
but better...

Deep inelastic scattering in $\mathcal{N}=0^*$

(JP + Strassler)

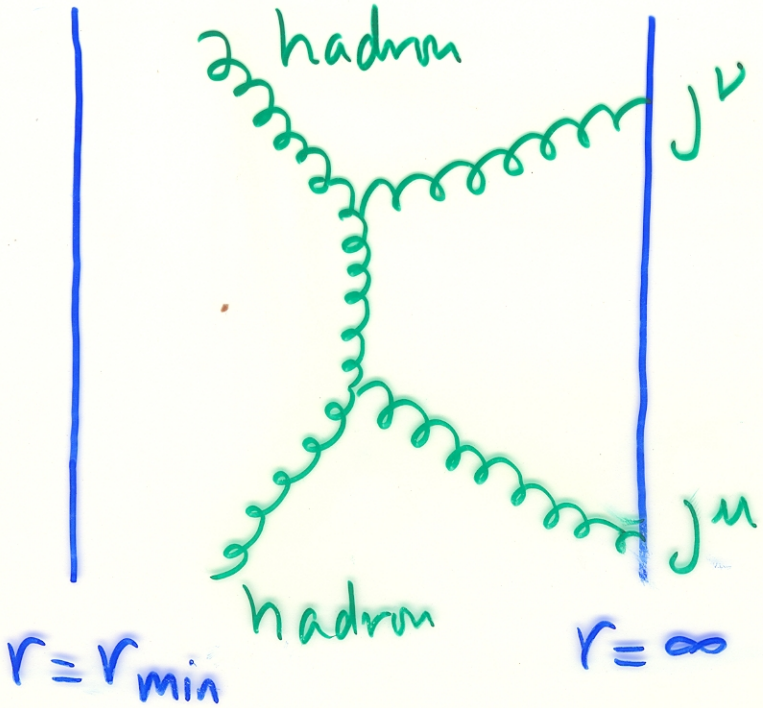
Total cross section for

$$\text{hadron} + e^- \to X$$

$\Rightarrow$ need matrix element

$$\langle \text{hadron} | j^\mu(q) j^\nu(0) | \text{hadron} \rangle$$

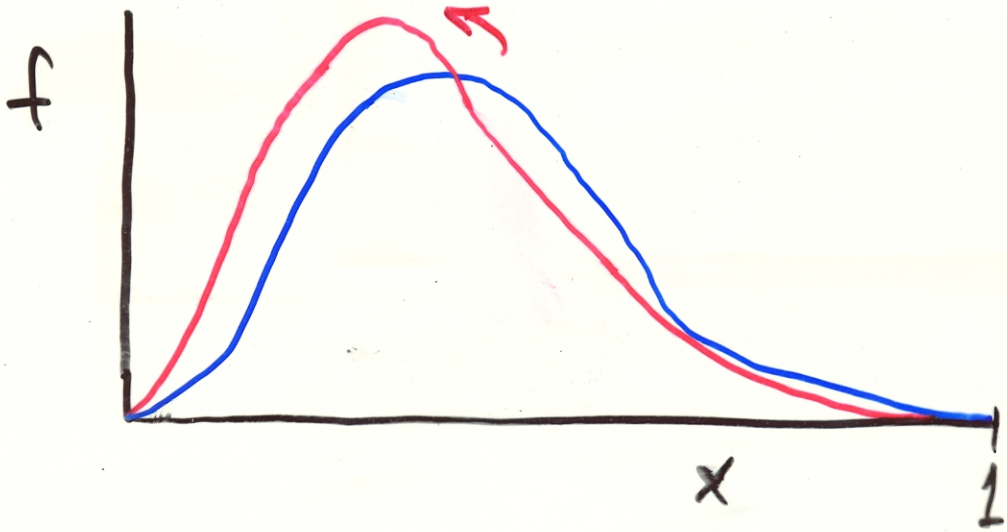
String calculation:



~~~ = string (e.g. graviton)
~~~

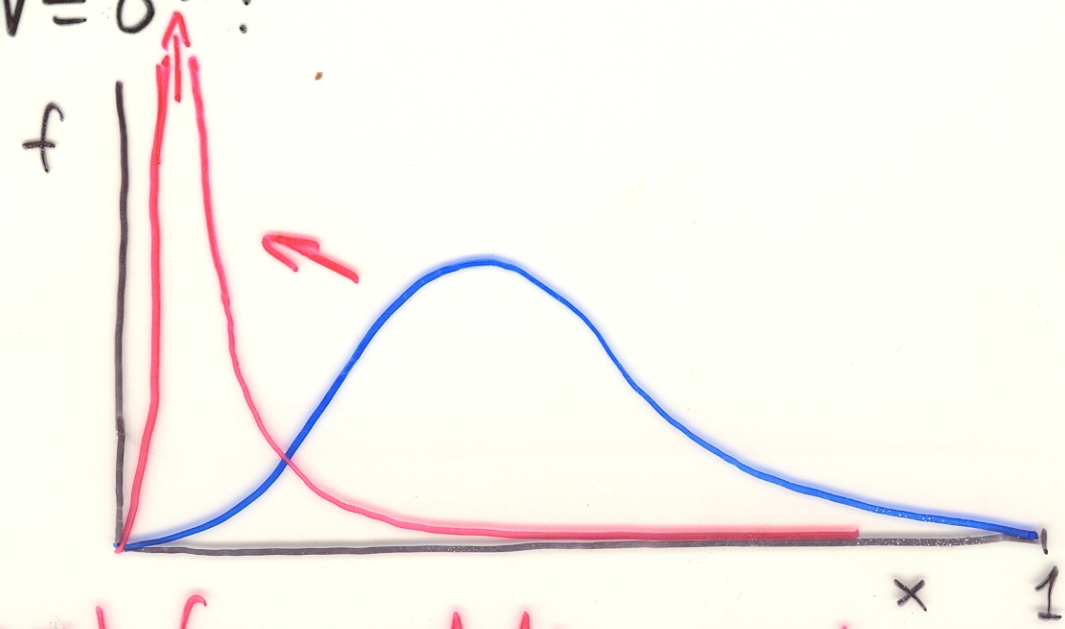
Can parameterize the result in terms of parton distribution functions -

QCD:



slow evolution in q^2 due to parton fragmentation.

$N=0$:



rapid fragmentation, rapid evolution

Quark-gluon plasma = black hole in AdS (Witten)

Hydrodynamic modes of plasma = "quasinormal modes" of fields near black hole (Son, Herzog, Starinets, Policastro) "Membrane paradigm"

Can also study deconfinement and chiral symmetry transitions

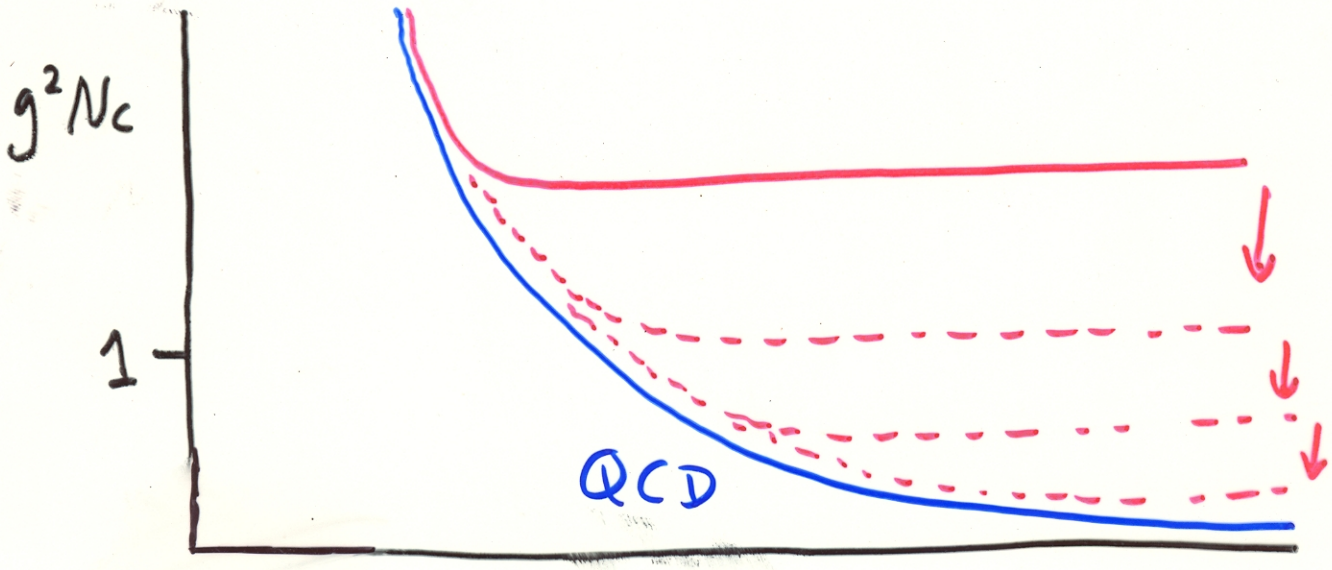
(Buchel, Klebanov, Tseytlin, ...)

Add matter in fundamental rep. (quarks)

(Karch, Katz, ...)

How about real large-N_c QCD?

In principle there is a string dual, obtained as follows:



By reducing UV value of g^2N_c, we can reach QCD as a limit.

Problem: when g^2N_c drops below 1, the string theory becomes more complicated (strongly coupled)

Curvature of AdS space (in string units) is

$$\frac{\alpha'}{R^2} = \frac{1}{\sqrt{g^2 N_c}}$$

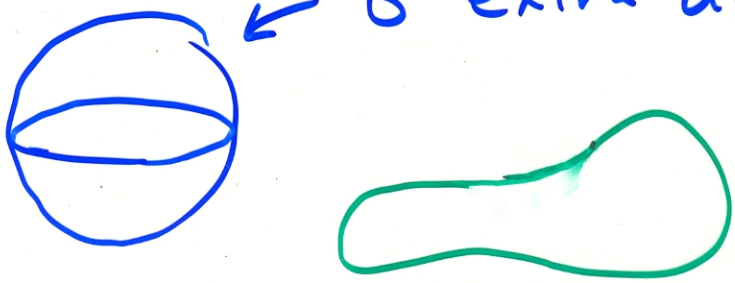
When $g^2 N_c >> 1$, curvature is small and string world-sheet theory is approximately linear (weakly coupled).

When $g^2 N_c << 1$, curvature is large → large non-linearities (strong coupling).

So we trade a strongly coupled 3+1 dimensional theory for a strongly coupled 1+1 dimensional theory.

Is this progress?

Paraphrase: in the limit of asymptotically free QCD, the 6-d cavity becomes as small as a string:



Interesting physics/mathematics - other applications, e.g. cosmology.

In addition to numerical methods, it may be possible to apply special methods of 1+1-dim. QFT (Bethe Ansatz, inverse scattering, ...)

(Bena, JP, Roiban)

cf. Lipatov

cf. Bern-Dixon-Kosower

cf. Minahan-Zarembo-Biesert-Staudacher, Witten

Conclusion + Advertisement

"Strings and Large-N_c QCD"

KITP workshop, Aug-Dec '04.