2006: The Year in Strings

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Outline

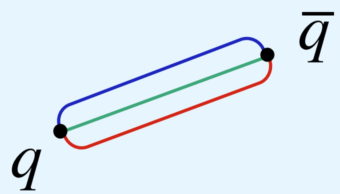
- Gauge/string (AdS/CFT) duality: applications and extensions
- Some interesting spots in the landscape

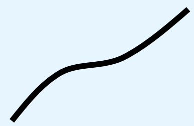
… plus a few general remarks.

Gauge/string duality

A brief history:

1968-72: String theory of the strong interaction.

Meson: 

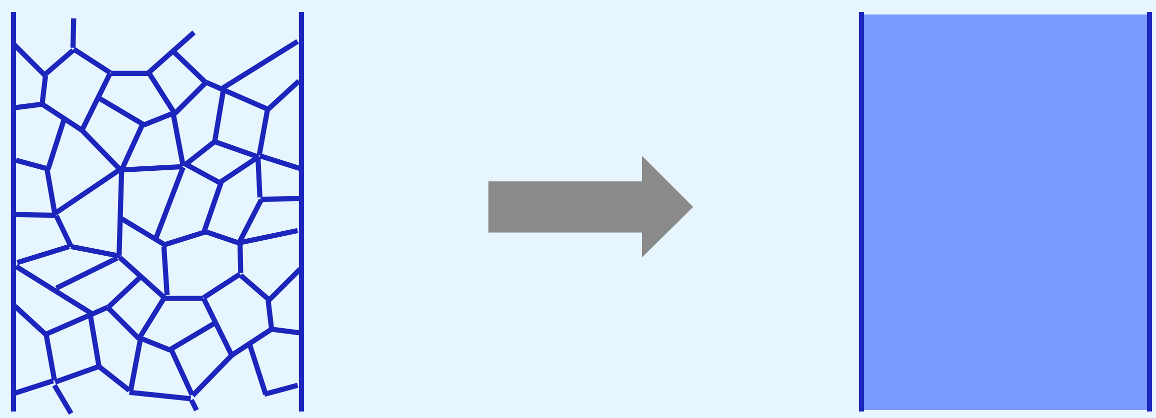
vs. 

String model worked for some things, but had wrong short-distance behavior. Even worse: consistent quantization required D > 4, and led to massless spin-1 and spin-2 particles.

1972: Asymptotic freedom: correct theory is QCD.

1974: Strings as a theory of gravity (Scherk-Schwarz, Yoneya)

1974: ’t Hooft shows that QCD becomes simpler in the limit of large N_c with g^2N_c held fixed: only planar graphs survive. Still too hard to solve, but he also proposed that in the strong-coupling limit Feynman graphs become dense



and that the theory can then be rewritten as a string theory! (Similar argument from lattice gauge theory).

1997: Maldacena finds exact realization of 't Hooft's idea, not for QCD but for $\mathcal{N}$=4 supersymmetric Yang-Mills.

Surprise: it is the same string theory that describes gravity, but in an unusual spacetime, $AdS_5 \times S^5$

$$ds^2 = \frac{r^2}{R^2}\eta_{\mu\nu}dx^\mu dx^\nu + \frac{R^2}{r^2}dr^2, \quad R^4 = g^2 N_c l^4_{\mathrm{string}}$$

Warping removes massless spin-1 and spin-2, and gives effectively four-dimensional kinematics.

Maldacena's `derivation': assume that the following diagram commutes:

	Weak coupling:		*Strong coupling*:
High energy:	D3-branes	$\overset{\text{Strominger-Vafa}}{\leftrightarrow}$	Black 3-branes
	$\updownarrow$		$\updownarrow$
Low energy:	$\mathcal{N} = 4$ SYM	$\leftrightarrow$	$AdS_5 \times S^5$

Explained unexpected agreements between gravitational and Feynman graph calculations.

Maldacena's duality is remarkable for many reasons. First, it allows one to solve some *four dimensional strongly coupled quantum field theories*. $\mathcal{N}$=4 SYM is much more symmetric than QCD, but by deforming the duality one can get to more QCD-like theories.

- Confinement
- χSB
- Numerical tests
- Quark-gluon plasma
- Integrability

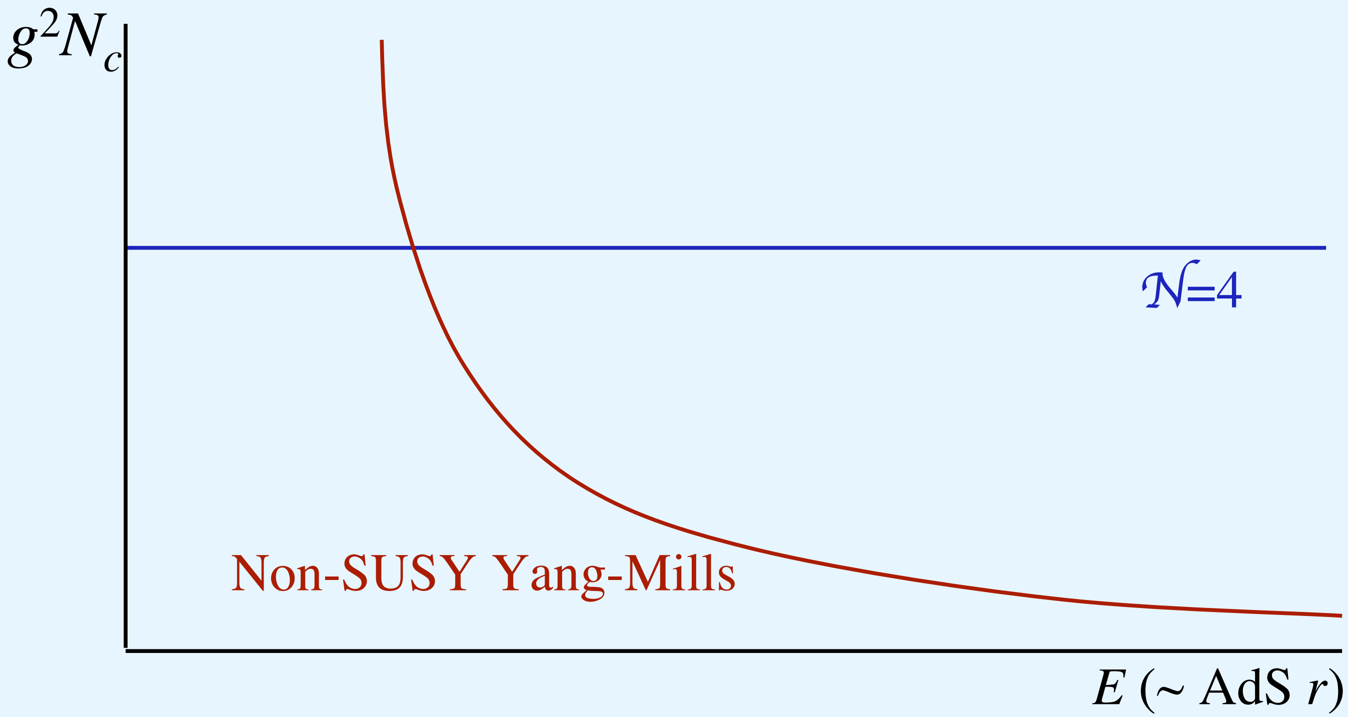
From CFT toward QCD - confinement:

$\mathcal{N}$=4 SYM: $SU(N_c)$ gauge field + 4 fermions + 6 scalars, all in adjoint representation. *Add mass terms* for the fermions and scalars, so the only massless fields are the gluons: at low energy the theory should confine. In the dual theory the AdS space

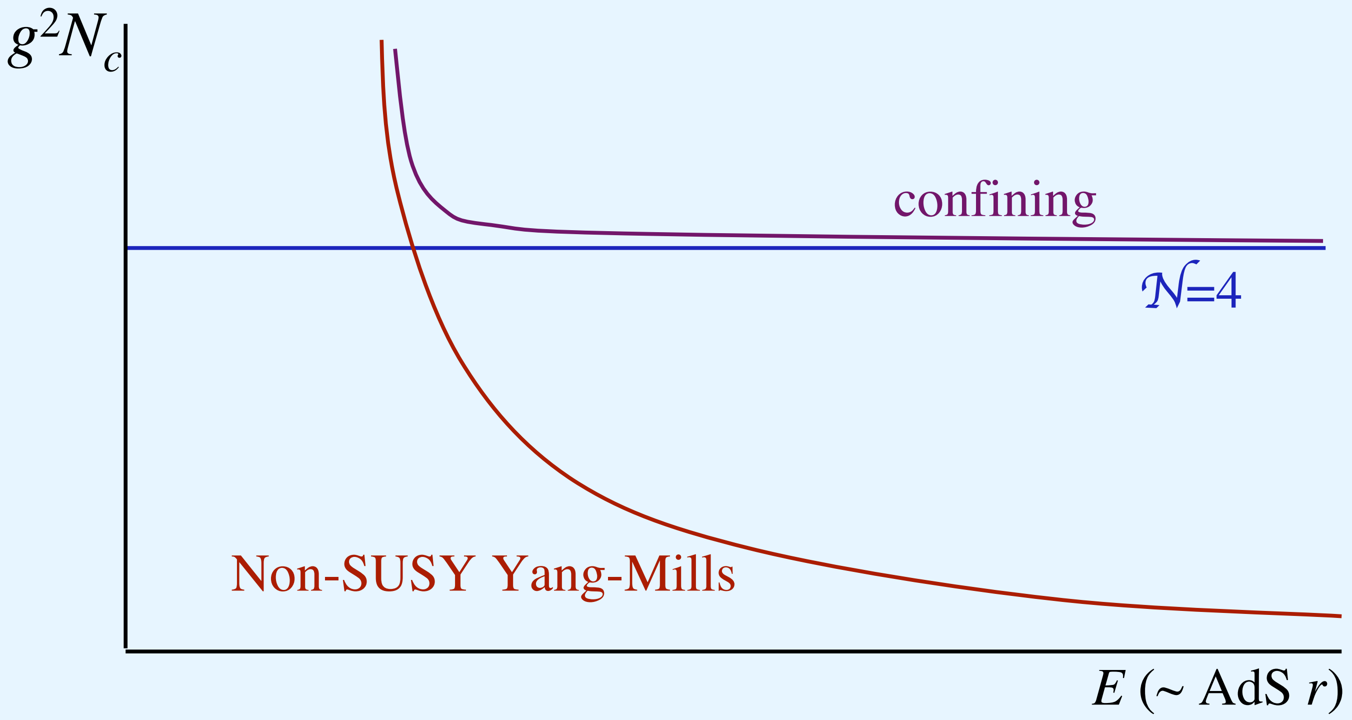
$$ds^2 = \frac{r^2}{R^2}\eta_{\mu\nu}dx^\mu dx^\nu + \frac{R^2}{r^2}dr^2$$

is cut off below some scale $r = r_0$. This gives mass to the hadrons, $m \sim r_0/R^2$, and a linear force law between external quark sources. Witten ‘98, JP & Strassler ‘00, Klebanov & Strassler ‘00.

Running couplings:



Running couplings:



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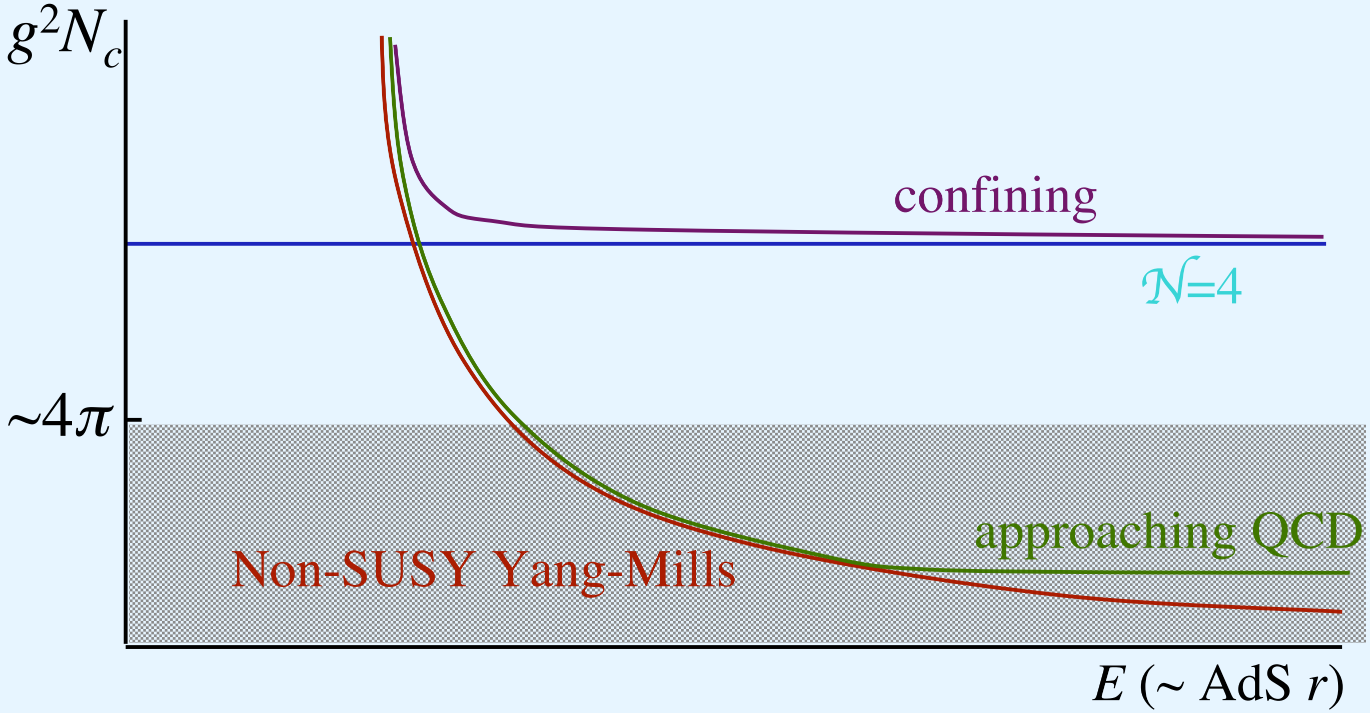
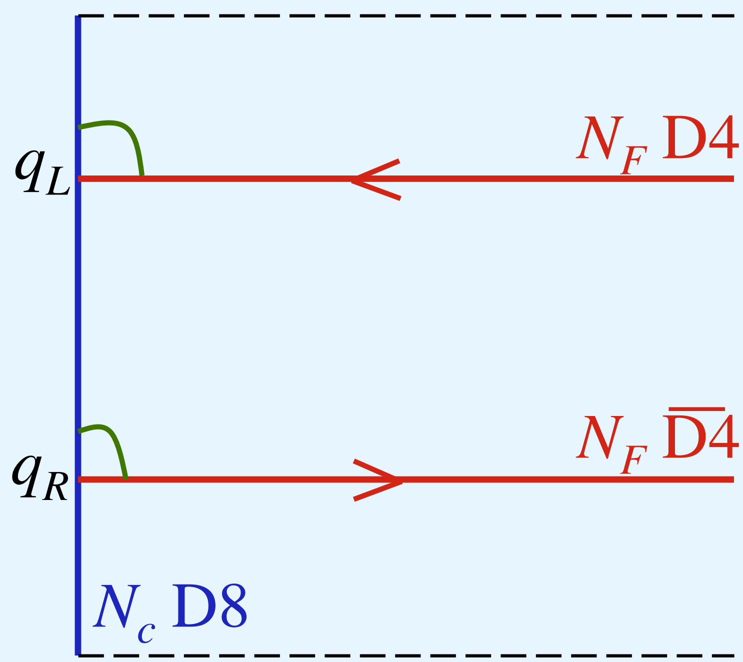


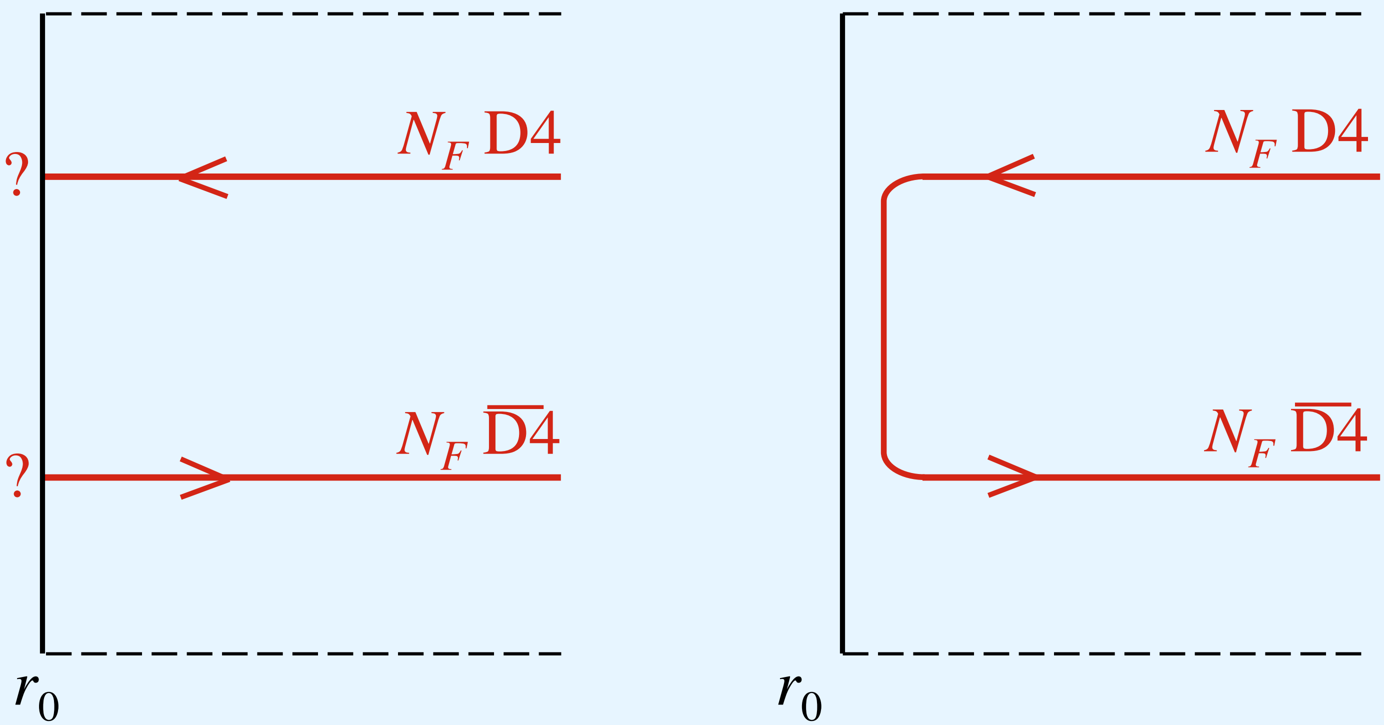
In principle, we can decouple the extra $\mathcal{N}$=4 matter at higher energy (green) and get a string dual to the pure glue theory. However, once the coupling drops below ~4π the spacetime curvature gets large and the string worldsheet is strongly coupled.

Chiral Symmetry:

It is relatively straightforward to add matter in the fundamental representation by introducing branes (e.g. Karch & Katz, ‘02), but until recently, there was no way to realize $SU(N_F)_L$ x $SU(N_F)_R$ chiral symmtetry of QCD. Solved by Sakai and Sugimoto, hep-th/0412141, 0507073:



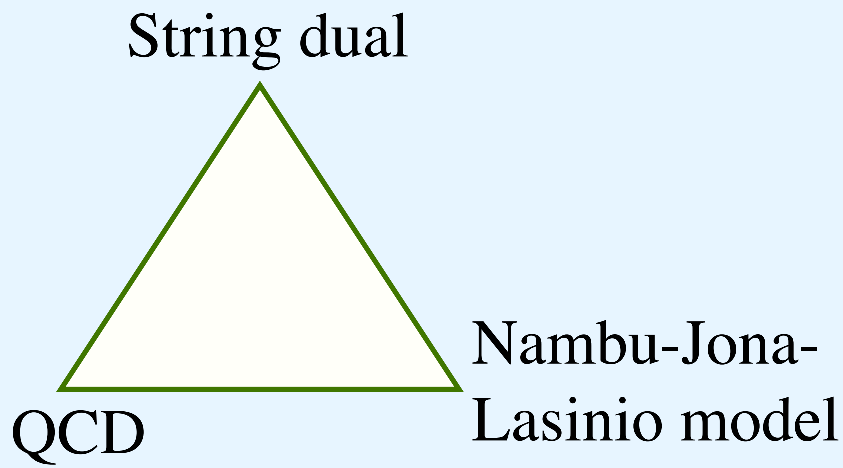
Confinement forces chiral symmetry breaking:



Right and left branes pair up, breaking $SU(N_F)_L$ x $SU(N_F)_R$ to $SU(N_F)$. Reproduces much of the low energy phenomenology of QCD. (Baryons: talk by Sugimoto).

Recent work:

Antonyan, Harvey, Jensen, Kutasov hep-th/0604017:



Antonyan, Harvey, Kutasov hep-th/0608019: String dual to Gross-Neveu model

Talk by Sahakyan: Quarks at finite chemical potential

Condensed matter applications?

New tests of the dualities

We now know of many weak/strong dualities,

$$\text{Field theory} \leftrightarrow \text{Field theory}$$
$$\text{String theory} \leftrightarrow \text{String theory}$$
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These are remarkable statements: that the degrees of freedom of a strongly coupled theory can rearrange themselves in a new and simple form. However, we have no direct derivation, e.g. from the path integral. This is one of the big open questions!

We do have a very large number of successful tests. For the most part, the precise quantitative tests involve supersymmetry, while the nonsupersymmetric tests are more qualitative.

In principle, predictions of the behavior of strongly coupled field theories can be tested by numerical simulation. In practice, this is very difficult because of large-N_c and supersymmetry.

Hiller, Pinsky, Selwan & Trittmann, hep-th/0506225*, avoid these via Discrete Light-Cone Quantization; also, they consider the 1+1 dimensional version of AdS/CFT. Simplest observable to consider: the 2-point function

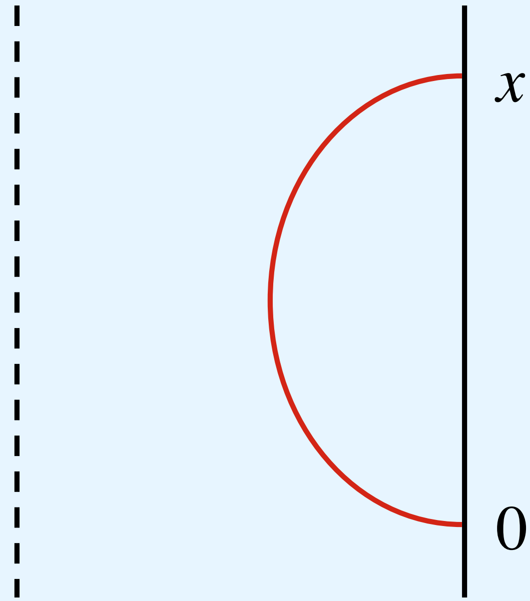
$$\langle 0|T_{\mu\nu}(x)T_{\mu\nu}(0)|0\rangle \propto x^{-\gamma}$$

Weak coupling (Feynman graph): $\gamma = 4$.
Strong coupling prediction: $\gamma = 5$ at long distance.

*Following idea of Antonuccio, A. Hashimoto, Lunin & Pinsky, hep-th/9906087.

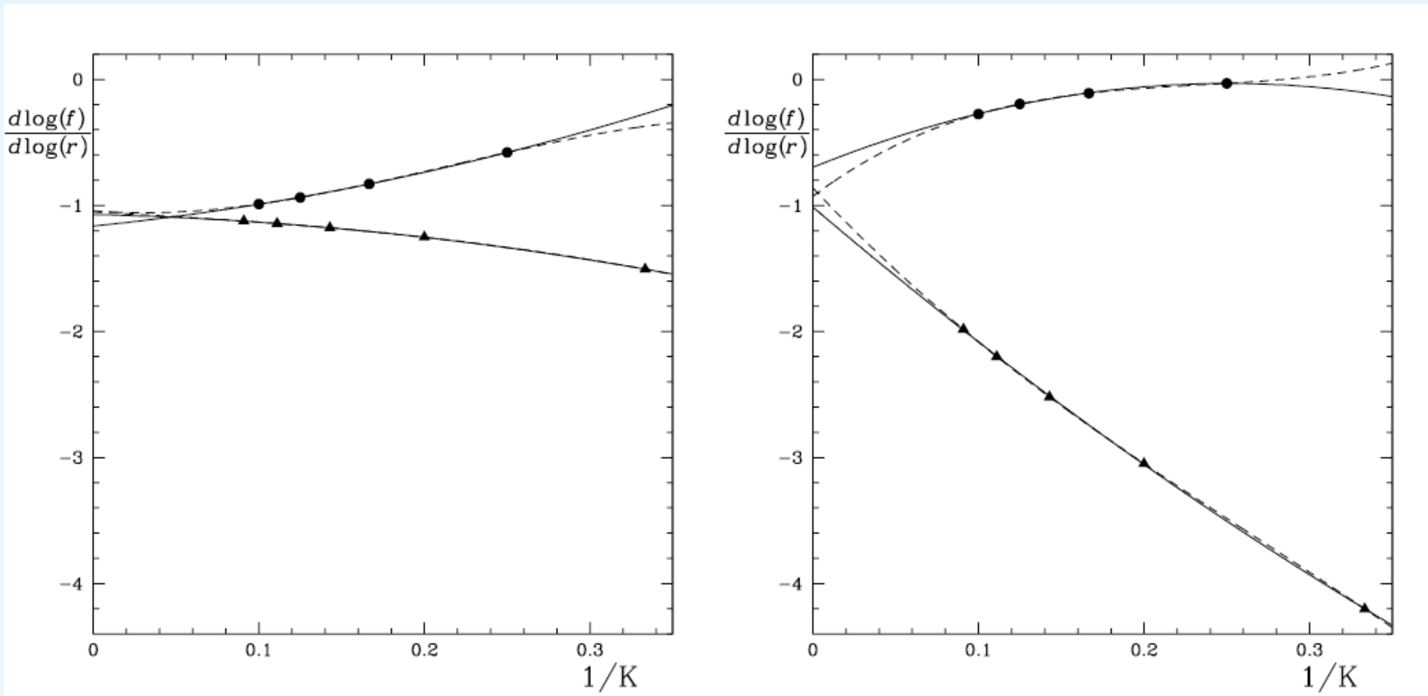
$$\langle 0|T_{\mu\nu}(x)T_{\mu\nu}(0)|0\rangle \propto x^{-\gamma}$$

Strong coupling calculation: graviton propagator in D1-brane background



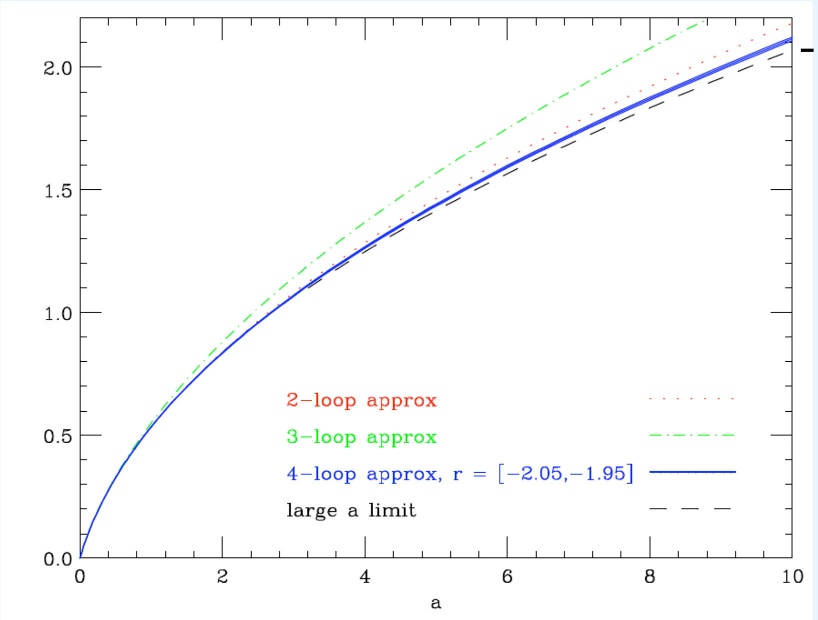
DLCQ calculation: truncate Hilbert space, diagonalize the Hamiltonian, and insert a complete set of states.

HPST diagonalize *H* in successively larger Hilbert spaces (largest is 3 x 10^{12}, reduced to 3 x 10^{7} by symmetries).



Exponent shift (prediction -1) at two different separations.

Another result of similar flavor: Bern, Czakon, Dixon, Kosower & Smirnov, hep-th/0610248, calculate cusp anomalous dimension to *four loops* in $\mathcal{N} = 4$ theory. Using Pade or Kotikov-Lipatov-Velizhanin extrapolation to strong coupling gives ~2% agreement:

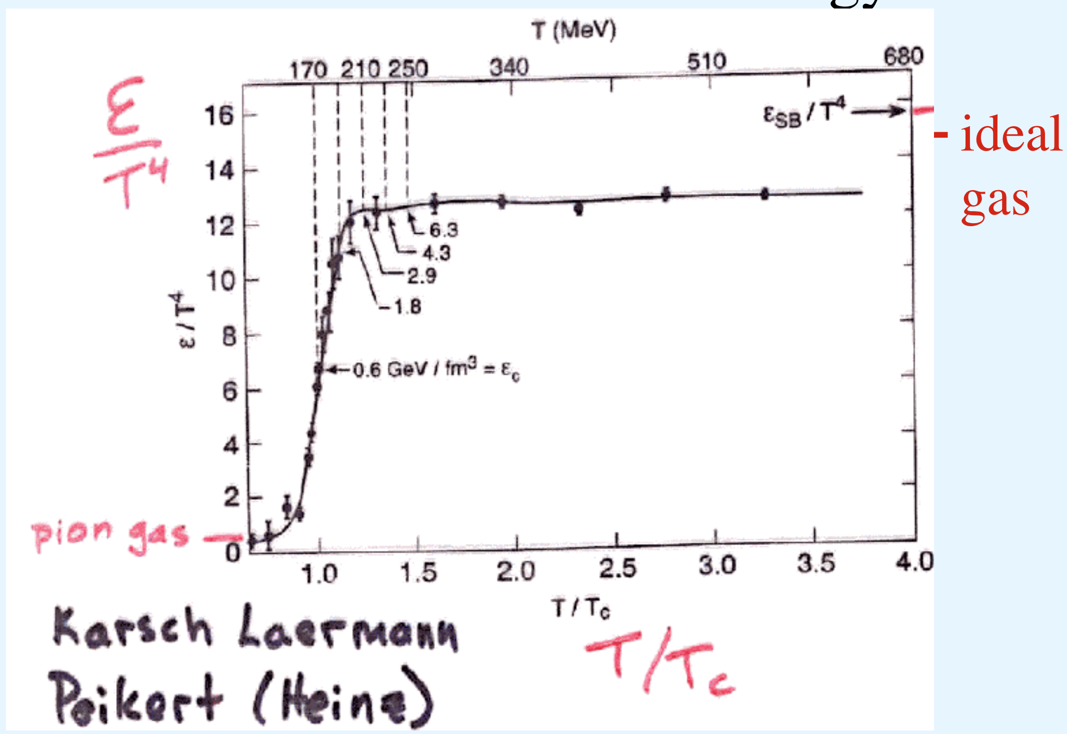


String result from energy of spinning string in AdS space.

Also, resolves discrepancy between AdS/CFT and 'BMN scaling': BMN scaling breaks down at four loops.

Standard Monte-Carlo simulation: talk by Nishimura (with Hotta, Tsuchiya) on 0+1 theory (BFSS) … work in progress.

A curious result: Monte Carlo simulation of free energy of the quark-gluon plasma:



Approach to the ideal gas result is very slow. Ratio stays constant near 0.81. In the $\mathcal{N} = 4$ theory it is 0.75 at strong coupling.* This suggests that the QGP is closer to strong coupling than weak: $g^2 N_c \sim 6\pi > 4\pi$. Universal strong coupling behavior? (From Rajagopal, KITP Superstring Cosmology conference).

*Bekenstein-Hawking entropy

The result for the free energy suggests that the QGP is closer to the strong-coupling limit than the weak one. This is also consistent with the fact that at RHIC it appears to be more liquid-like than gas-like (low shear viscosity η). String black holes have universal $\eta/s = 1/4\pi$.* For the QGP Teaney (2003) estimates $\eta/s = 0.1$, but the uncertainties are large.

Moral? In a situation where the interactions are strong, an exact solution to the wrong theory (interpreted cautiously) may be the best approximation one has. Other applications:

Jet quenching:

Liu - Rajagopal - Wiedemann, hep-ph/0605178
Herzog et al., 0605158
Casalderrey-Solana - Teaney, hep-ph/0605199
Gubser, 0605182

J/ψ suppression:

Liu - Rajagopal - Wiedemann, hep-ph/0607062
Chernicoft - Garcia - Guijosa, 0607089
Caceres - Natsuume - Okamura, 0607233; 06mmnnn

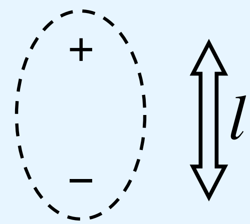
*See talk by Natsuume.

Any application to LHC QCD physics? Difficulty: the strongly coupled $\mathcal{N} = 4$ theory gets partonic behavior wrong (rapid fragmentation).

One small particle physics application: small-x physics. String dual produces same qualitative behavior as BFKL resummation (Brower, JP, Strassler, Tan, hep-th/0603115)

Q: In what sense is QCD a five-dimensional theory?

A: For a color singlet dipole, interactions are approximately local in the dipole *size*. E.g. color transparency, BFKL.

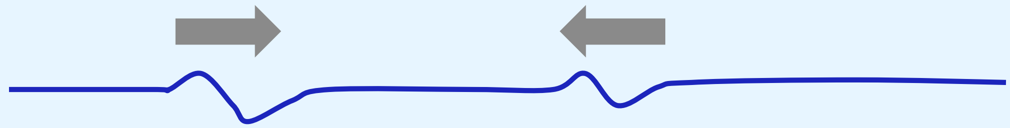


5-d models: de Teramond & Brodsky, hep-th/0501022; Erlich, Katz, Son & Stephanov, hep-ph/0501128.

Integrability:

We can calculate in the $\mathcal{N} = 4$ theory at large $g^2 N_c$ using string theory and at small $g^2 N_c$ using ordinary perturbation theory. There is some indication (beginning with Lipatov in 1993) of a higher symmetry (integrability) that would make it possible to solve the theory for *all* values of the coupling.*

Thus far, slow but tantalizing progress: much guesswork, what is needed is a clearer set of principles! Recent result (Beisert, Eden, Stuadacher, hep-th/0610251): exact (?) S-matrix for ripples on the string/spin chain.



*Talks by Hatsuda, Yoshida

The Landscape

Only since around 2003, with the work of Kachru, Kallosh, Linde, and Trivedi (KKLT), have we had tools to study realistic (e.g. SUSY-breaking) string vacua. Apparently there are a lot of them (the landscape). This raises some serious issues, which I will return to at the end, but first I want to look at a few features that may be common to large classes of vacua:

- Inflation in a KS throat
- Modulus + anomaly (mirage) mediation
- MQSM
- MBSSM

KS Throats

Randall & Sundrum introduced the idea that a gravitational redshift (warping) in the higher dimensions could be the source of hierarchies of scales in four dimensions. Most phenomenology has been five-dimensional,

$$ds^2 = \frac{r^2}{R^2}\eta_{\mu\nu}dx^\mu dx^\nu + \frac{R^2}{r^2}dr^2$$

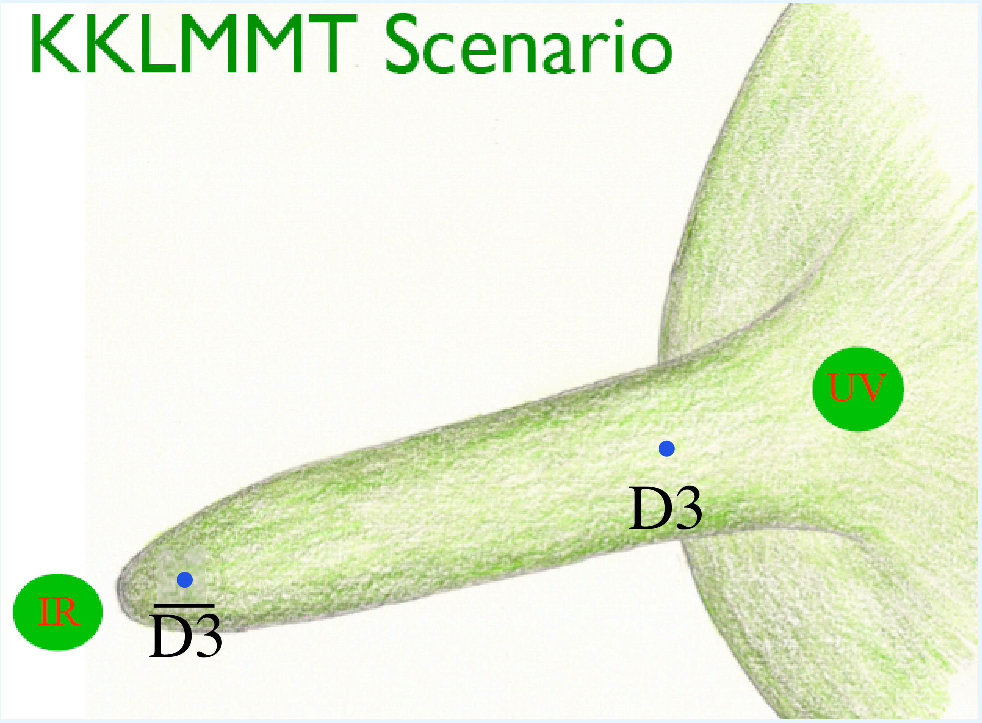
(AdS_5 again!) The simplest lift of RS I to string compactifications is the *Klebanov-Strassler throat* (aka warped deformed conifold). These are actually very common in IIB compactifications, and the physics in them will be largely independent of the details outside the throat.

Calabi-Yau manifold with two throats (thanks to Clifford Johnson). The main part should actually have many handles. The throats are places where the gravitational redshift is large (~IR brane), and the physics there is largely independent of the rest of the geometry.

One important hierarchy in nature is

$$\frac{\text{inflation scale}}{\text{Planck scale}} \lesssim 10^{-4}$$

A natural source of the vacuum energy to drive inflation is a brane-antibrane pair, and the Coulombic force between them gives a slow-role potential. This is the KKLMMT model, D3/anti-D3 in a KS throat:



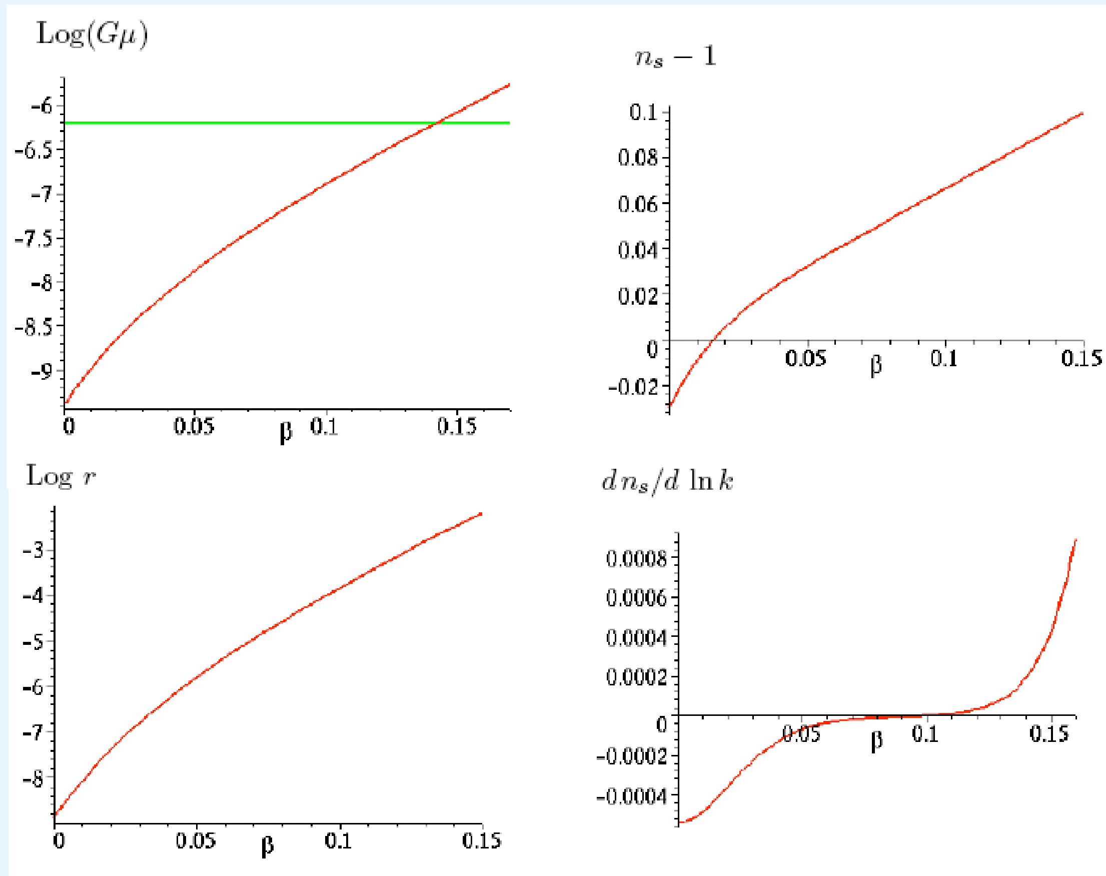
Inflationary potential is highly constrained in form,

$$V \approx V_0 - \frac{V_0^2}{\phi^4} + \frac{V_0}{2M_{\rm P}}\beta\phi^2$$ Observed $\delta T/T$ fixes V_0, then

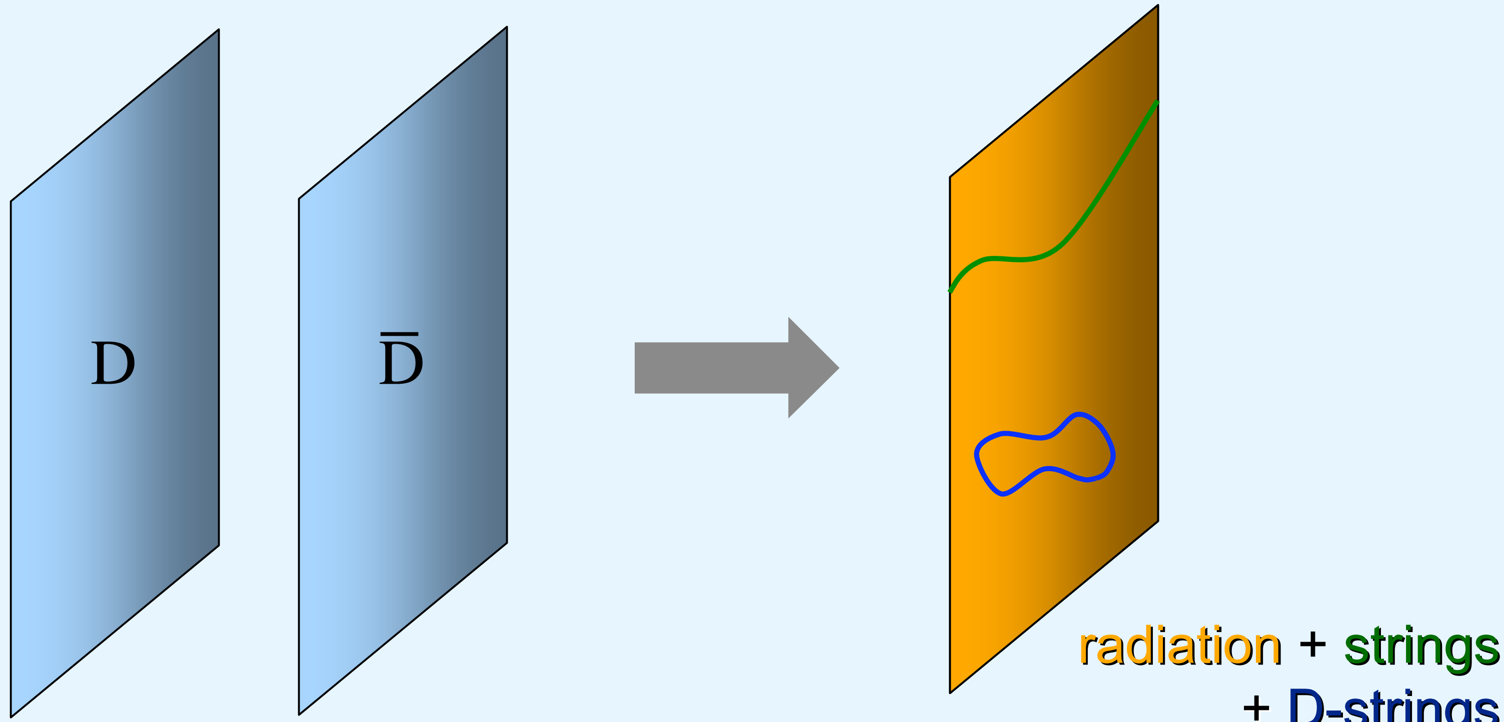
WMAP1:
$\beta < 0.15$
WMAP3:
$\beta < 0.05$

Small r

Cosmic strings (if stable)!

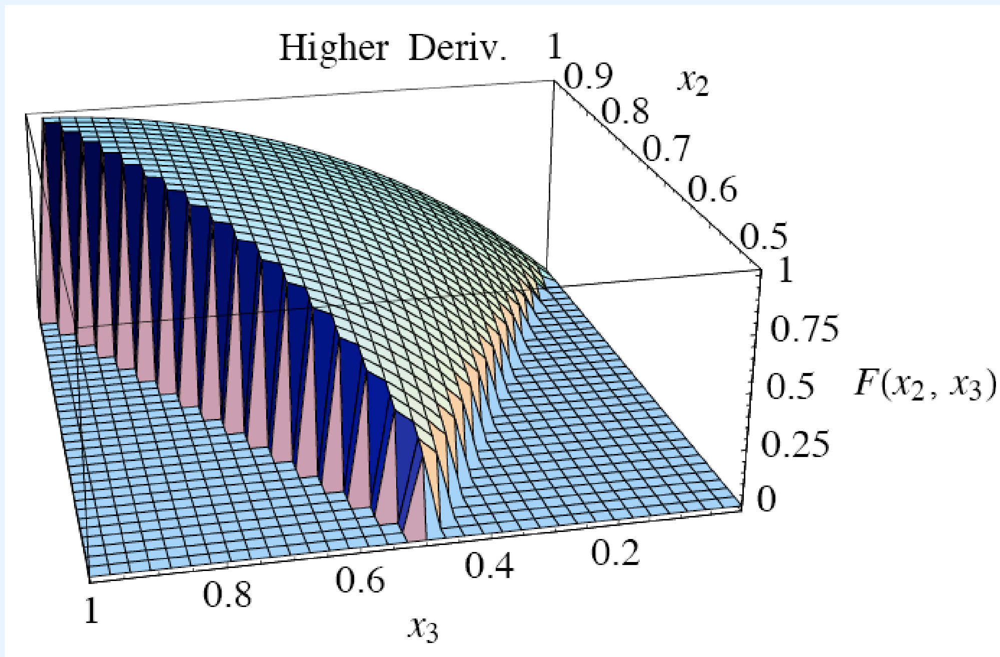


Farouzjahi & Tye, hep-th/0501099



produces cosmic strings (Tye et al, …). There are potential decays (breakage, confinement), but these are absent in many models. Likely scale of tension $G\mu \sim 10^{-9}$ is 2 orders of magnitude below CMB bounds, but gravitational waves from their decays would be seen by LISA, SKA (pulsar timing) and possibly LIGO II, PPTA.

Another part of parameter space for same model: DBI inflation (fast-roll rather than slow-roll) Alishahiha, Silverstein and Tong, hep-th/0404084, gives potentially large non-gaussianities:



Babich, Creminelli & Zaldarriaga, astro-ph/0405356

Mirage Mediation

Anomaly mediation of SUSY breaking (Randall & Sundrum) is universal in higher-dimensional models, but is often one-loop suppressed relative to other breakings. In KKLT-type stabilization, moduli and anomaly mediation are comparable and partly cancel in Higgs mass renormalization.

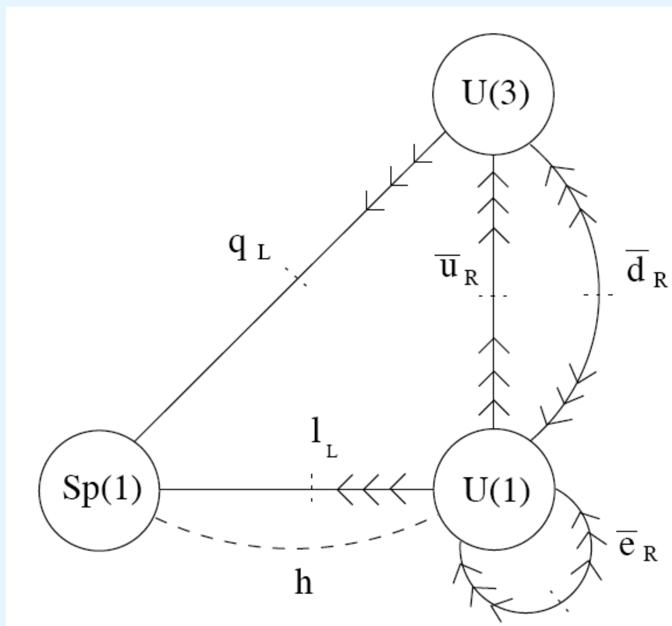
Choi, Falkowski, Nilles, Olechowski & Pokorski, hep-th/0411066;
Choi, Falkowski, Nilles & Olechowski, hep-th/0503216;
Endo, Yamaguchi and Yoshioka, hep-ph/0504036;
Choi, Jeong & Okumura, hep-ph/0504037;
Kitano & Nomura, hep-ph/0509039;
Pierce and Thaler, hep-ph/0604192 …

A bit more on SUSY breaking: metastable vacua (a key feature of the landscape) also turn out to be common in SUSY gauge theories (Intriligator, Seiberg & Shih, hep-th/0602239). Many new models.

First embedding of ISS in string theory: Ooguri & Ookouchi, hep-th/0606061.

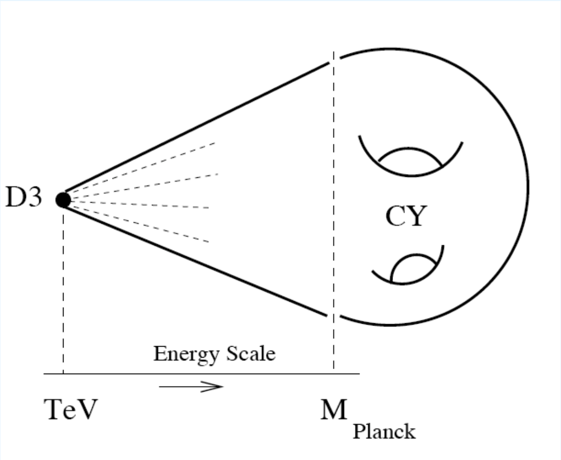
MQSM:

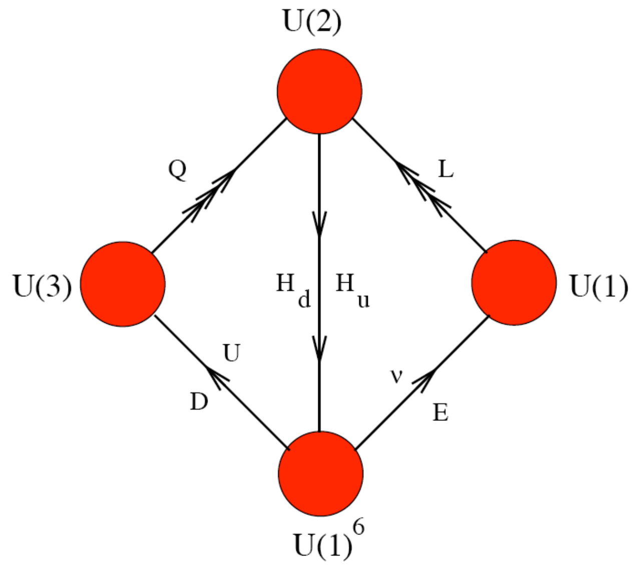
D-brane models are described by quivers: $U(N)$, $O(N)$, $Sp(N)$ gauge groups (but *not* SU(N)) with bifundamental matter. Minimal quiver containing the Standard Model has extra $U(1)$' with couplings fully determined (Berenstein & Pinansky, hep-th/0610104). $\Gamma \sim 0.15 M$.



Another `Minimal' Model

Verlinde and Wijnholt, hep-th/0508089, and Buican, Malyshev, Morrison, Wijnholt & Verlinde, hep-th/0610007 look for a geometrically minimal model, a single D3-brane at a singular point (del Pezzo 8) in the compact space. Interesting interplay between local and global properties …





Heterotic models - see talks by Ovrut, Kim, Karp, Reinbacher.

The CC, the AP, and the SL

1984 (Banks), 1987 (Weinberg): Why is the cosmological constant not weak scale or Planck scale? If it is environmental (not fixed by the underlying theory, but taking different values in different parts of spacetime or different branches of the wave-function), then anthropic selection alone will require that it be not much larger than the matter density. Corollary: if there is *only* anthropic selection, then it won't be much smaller either.

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1998: Dark energy

2006:
- Dark energy still looks like a c.c.
- No other compelling idea has emerged, either for the smallness or for the nonzero value.
- The string theory landscape appears to provide exactly the micscopic physics required.

What about the other constants? They also very over the landscape. However, not everything can be anthropic or random (Banks, Dine, Gorbatov, hep-th/0309170). In particular, θ_{QCD} and the proton lifetime would be too large. $\sin^2 q_{\mathrm{w}}$, fermion masses, … And it is clear that the landscape is not random, we need to explore it …

Maybe Weinberg got the right answer for the wrong reason:

- c.c. may be one or two orders of magnitude too large.
- If other parameters, e.g. $\delta\rho/\rho$, are varied, it seems that the prediction changes --- but in which direction?
- Weinberg's assumption that the prior on Λ is flat may be wrong (Schwartz-Perlov & Vilenkin; Steinhardt & Turok)

These questions get into issues like the cosmological initial condition … this may seem metaphysical, but so did the questions that led to inflation. Is there a probability measure on the set of vacua?

What is string theory? That may sound funny, but it took fifty+ years to sort out quantum field theory (to define the perturbation theory, and then to understand nonperturbative effects). It is clear that we do not fully understand the mathematics underlying string theory, the dualities give a tantalizing hint, and maybe when we do it will transform the questions completely.

Another approach: Freivogel, Sekino, Susskind & Yeh, hep-th/0606204: attempting to extend the framework of AdS/CFT (which gives a precise definition of string theory with AdS boundary conditions) to eternal inflation.