Summary of Lecture 1:

- String theory is very promising as a theory of quantum gravity (and particle physics) at the Planck length, but we need a better understanding of systems with many strings interacting strongly.
- Since 1994, there are new methods based on supersymmetry for understanding strongly coupled quantum systems.

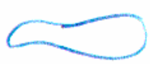
Discoveries in <u>field theory</u> include weak/strong (electric/magnetic) duality and many new nonperturbative phenomena — e.g. massless composite particles.

- String Duality:

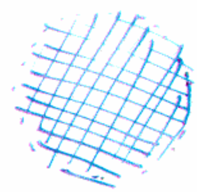
pre-1995: many conjectures

1994/95 Hull, Townsend, Witten find a unique candidate for the dual of almost every string theory (with maximal supersymmetry) in every dimension. Evidence rapidly mounted.

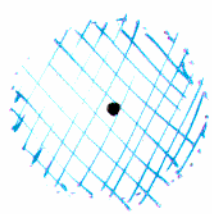
Multiplets include



strings



magnetic monopoles + other solitons

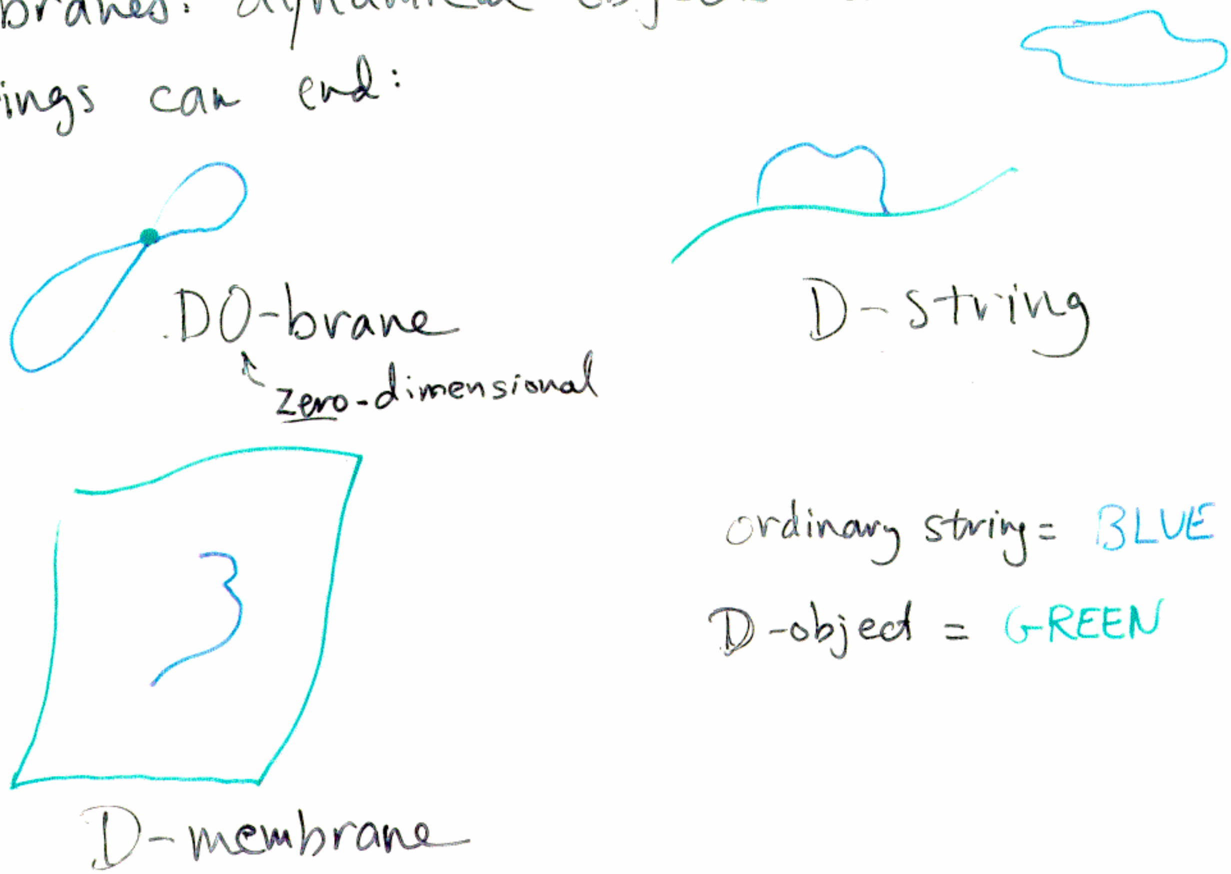


black holes

D-branes

(note: > 2)

D-branes*: dynamical objects where strings can end:

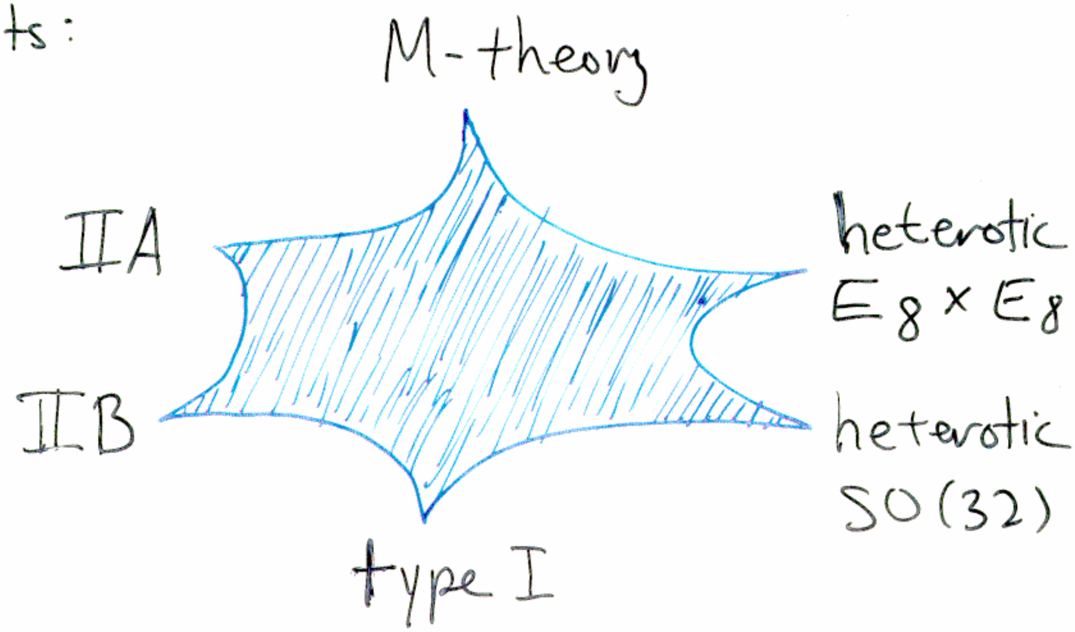


- must be included in string theory: can be produced from ordinary strings
- fill out duality multiplets
- "smaller" than strings (form factors).

* Dirichlet membranes

Old picture: 5 different string theories (different superspaces).

New picture: one theory with many limits:



The parameter space of string couplings.*

Five limits are weakly coupled string theories. New limit, M-theory, has SO(10, 1) Lorentz symmetry = <u>new dimension</u>

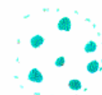
* "couplings" are not parameters but <u>radii</u> of compact dimensions + dilaton field.

How does one discover a new dimension?

D0-brane  mass $= \dfrac{M_{string}}{g}$

(exact: BPS)

Heavy when g is small, light when g is large.

Bound state of N D0-branes 

mass $= N\,\dfrac{M_{string}}{g}$ (exact: BPS).

Q: What kind of spectrum behaves this way? A: Threshold of new dimension.

Radius $= g/M_{string}$: small g = small R, large g = large R.

An alternative to string theory: "noncommutative geometry":

QM has a momentum/position uncertainty principle. Perhaps there is also a position/position uncertainty principle,

$$(\delta X)^2 \geq L^2_{\text{Planck}} .$$

Let us try to implement this as follows: In N-particle QM, coordinates are

$$\vec{X}_i , \qquad i = 1, \ldots, N$$

Let us try to make these into matrices:

$$\vec{X}_{ij} , \qquad i,j = 1, \ldots, N .$$

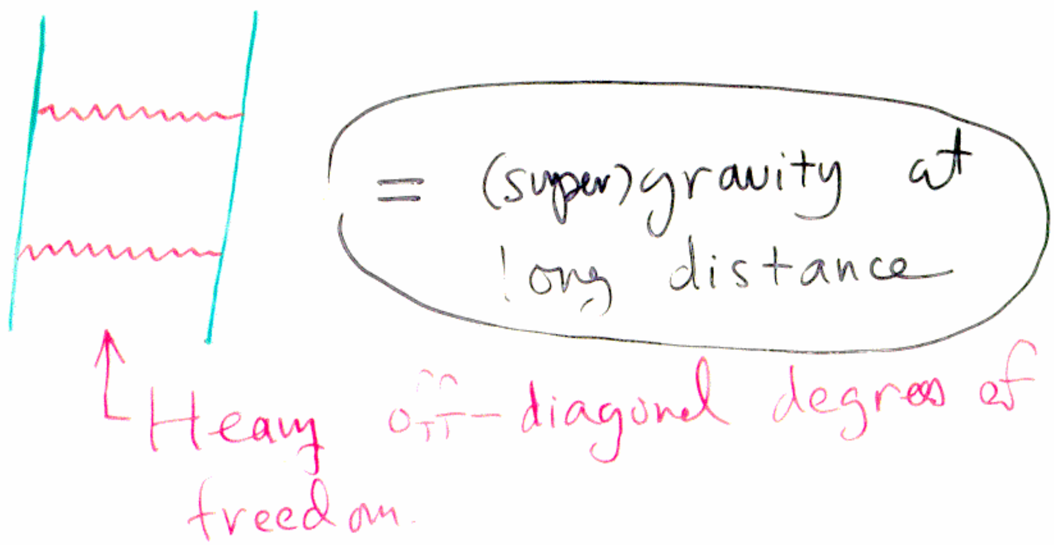
Hamiltonian:

$$H = \frac{1}{2M_p} \sum_{ijk} (p^k_{ij})^2 + \sum_{ijkl} \frac{M_p^3}{4} \left([X^k, X^l]_{ij}\right)^2$$

We want to recover ordinary geometry at low energy. The potential is large unless all the X^k_{ij} commute for different k (spatial direction). When they do commute, they can all be diagonalized, and diagonal elements $\vec{X}_{ii}$ can be interpreted as particle positions $\Rightarrow$ ordinary Q.M.

More:

- QM with 16 supersymmetry charges (maximum number) takes this precise form. (with extra fermionic bits)
- Supersymmetry is actually <u>necessary</u> to prevent destabilizing quantum corrections.
- Long-distance interaction:

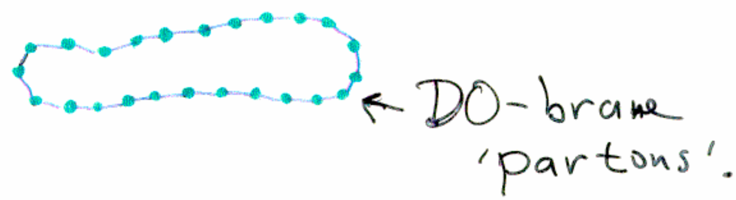


alternative to string theory?

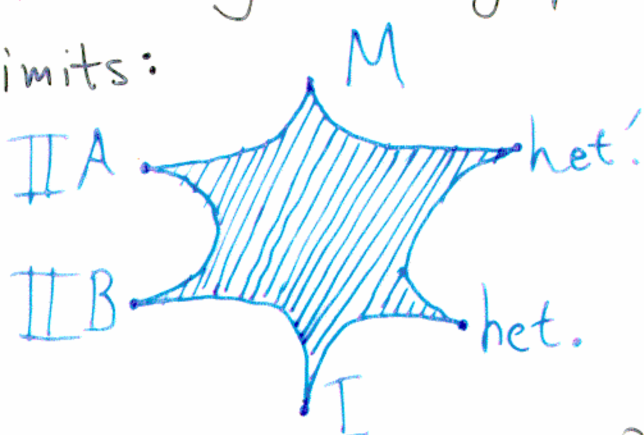
No: this *is* string theory.

- It is the Hamiltonian describing N D0-branes at low energy.

- It is conjectured to be a complete description of string theory when viewed at large boost (Matrix Theory; Banks, (Thorn) Fischler, Shenker, Susskind) For example, a string becomes



* It is now believed that the 'string' description is only an asymptotic expansion in the limits:



We seek the true degrees of freedom and Hamiltonian

- Black Hole Quantum Mechanics

There is a close analogy between the laws of black hole dynamics and thermodynamics. In particular, the <u>event-horizon</u> <u>area</u> (in Planck units) is like the entropy (nondecreasing), and black holes Hawking-radiate at the corresponding temperature.

For >20 years it has been a goal to find the corresponding "statistical mechanical" ("atomic") picture — to count the states of a black hole.

In at least some cases, D-branes are the "atoms" from which black holes are made.

A thought experiment: follow a black hole as G_N is reduced; what does it become? For certain charged black holes, the answer is a gas of weakly coupled D-branes

Count BPS states at weak coupling; but this is an adiabatic invariant, so it also gives the number for the black hole — result agrees with Bekenstein-Hawking entropy. (for BPS - supersymmetric - black holes).

cf. UV problem

This also works for some non-supersymmetric black holes, and for dynamical properties.

It suggests a duality:

Strongly coupled (highly quantum) gas of D-branes = classical black hole.

(Also for black p-branes, which are like black holes but are extended in some directions).

Black Hole Information Problem:

Hawking radiation is incoherent and independent of formation of black hole ⇒

black hole evaporation turns pure quantum state into mixed state — a violation of ordinary QM.

Sharp paradox: QM vs. locality.

D-brane picture indicates that black holes are described by ordinary quantum mechanics, but a precise resolution of the paradox has not yet been given (22 years and counting).

Note: nonlocality / non-commutative geometry / holographic principle
↳ fundamental degrees of freedom live on boundary, not in bulk

Large-N_c Gauge Theory.

An old idea ('t Hooft, 1974): $SU(N_c)$ gauge theory becomes simple when $N_c \to \infty$; possibly some sort of string theory (based on QCD flux tube).

But until recently, nothing quantitative...

Now:

N D3-branes at strong coupling, large N = classical black 3-brane

Also:

Low energy dynamics of N D3-branes = SU(N) gauge theory (with $\mathcal{N}=4$ supersymmetry).

Low energy black-3brane limit = Anti-de-Sitter space ($AdS_5 \times S_5$)

"Maldacena conjecture"

Running the duality backwards, classical gravity (or string) calculations determine spectrum + interactions of gauge theory at large N_c and $g^2 N_c$. For nonsupersymmetric gauge theories, it agrees with qualitative expectations.

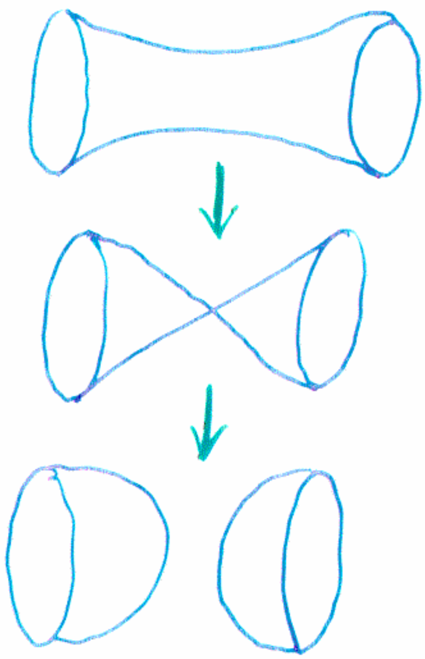
- Still a conjecture, but the evidence is strong.

Summary: We have remarkable new tools for understanding strongly coupled systems.

An Aside –

Spacetime can **bend**, but can it also **break**? Does topology change?

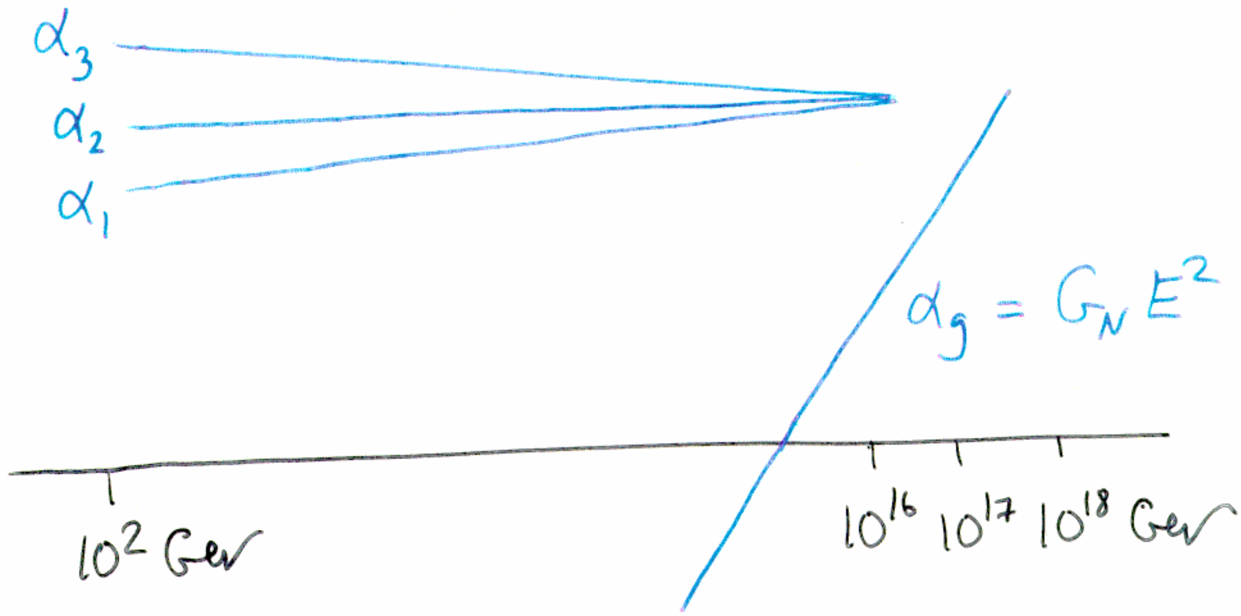
Yes. Processes like



are known to be possible.

Low energy physics ≈ phase transition.

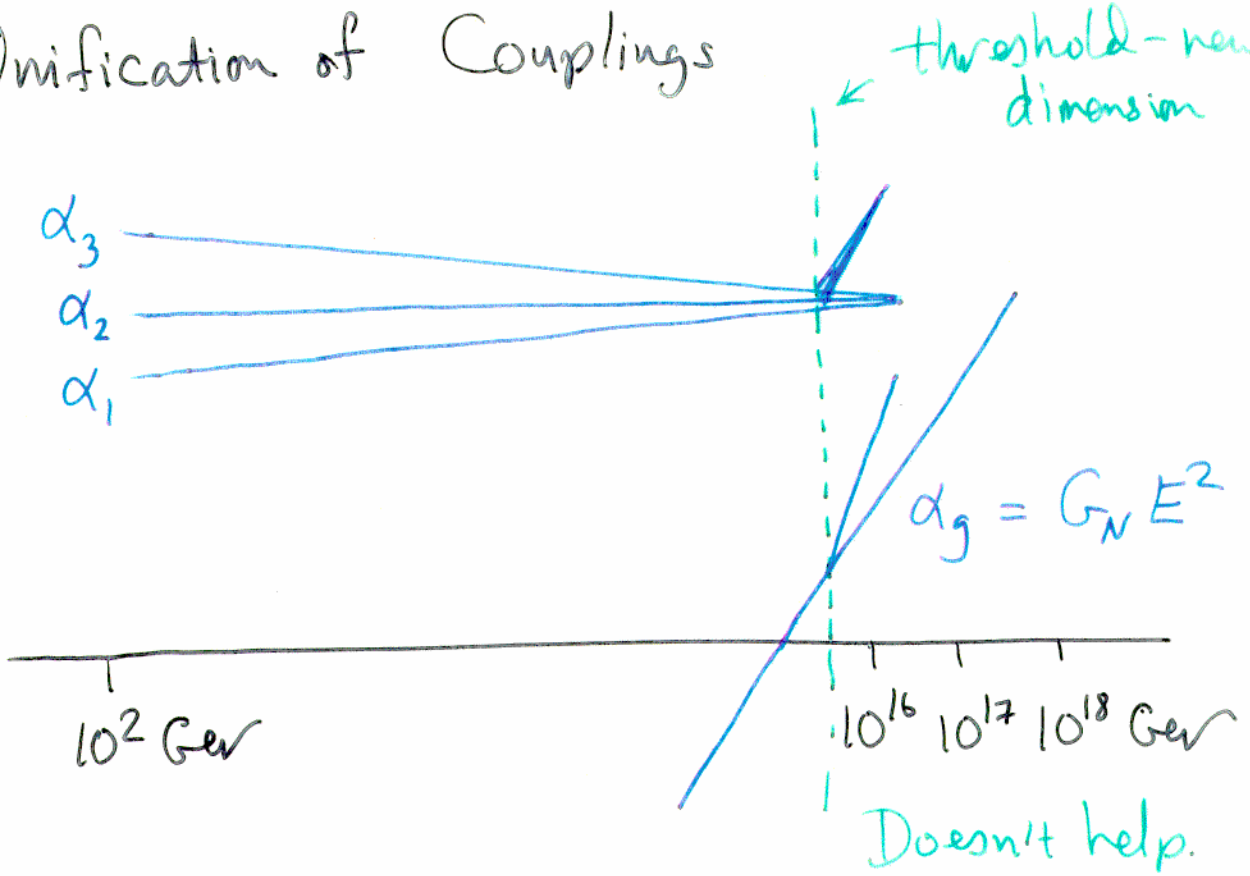
Unification of Couplings



Ideas for making 4 couplings meet — threshold corrections, intermediate scale.

· Can we change α_g? Evidently not — it's just dimensional analysis.

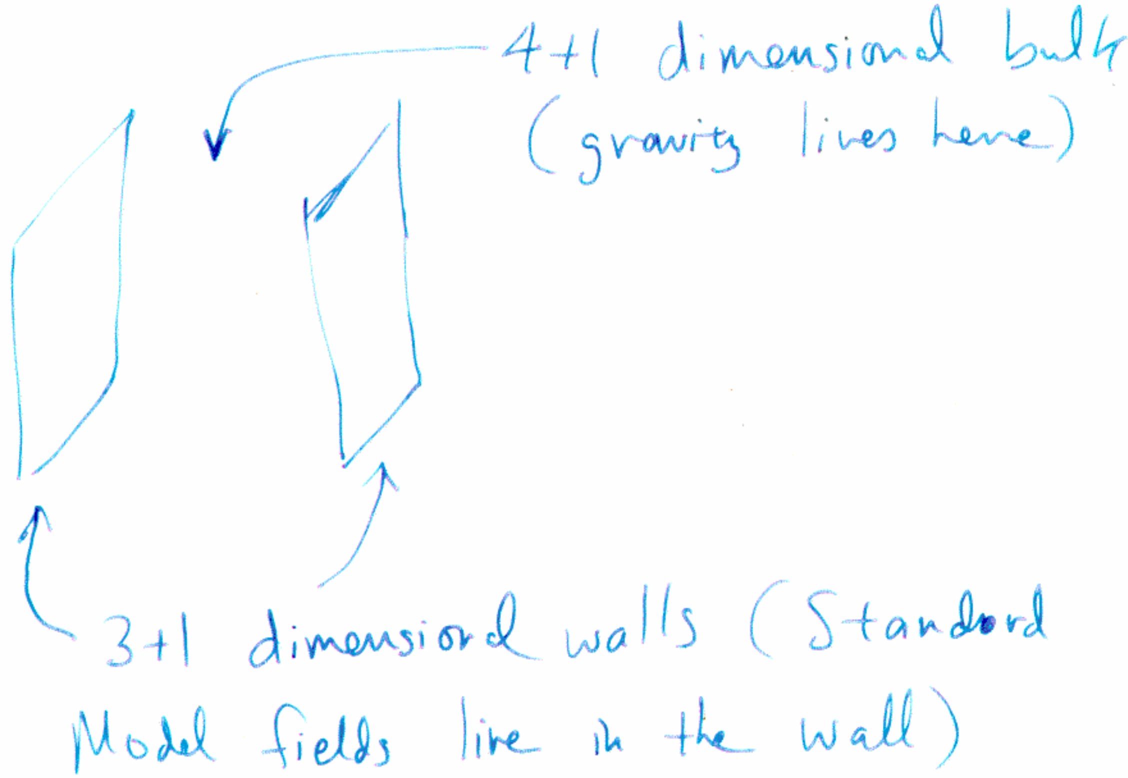
Unification of Couplings



Ideas for making 4 couplings meet — threshold corrections, intermediate scale.

- Can we change α_g? Evidently not — it's just dimensional analysis.

Strongly coupled limit of $E_8 \times E_8$ heterotic string gives a spacetime like



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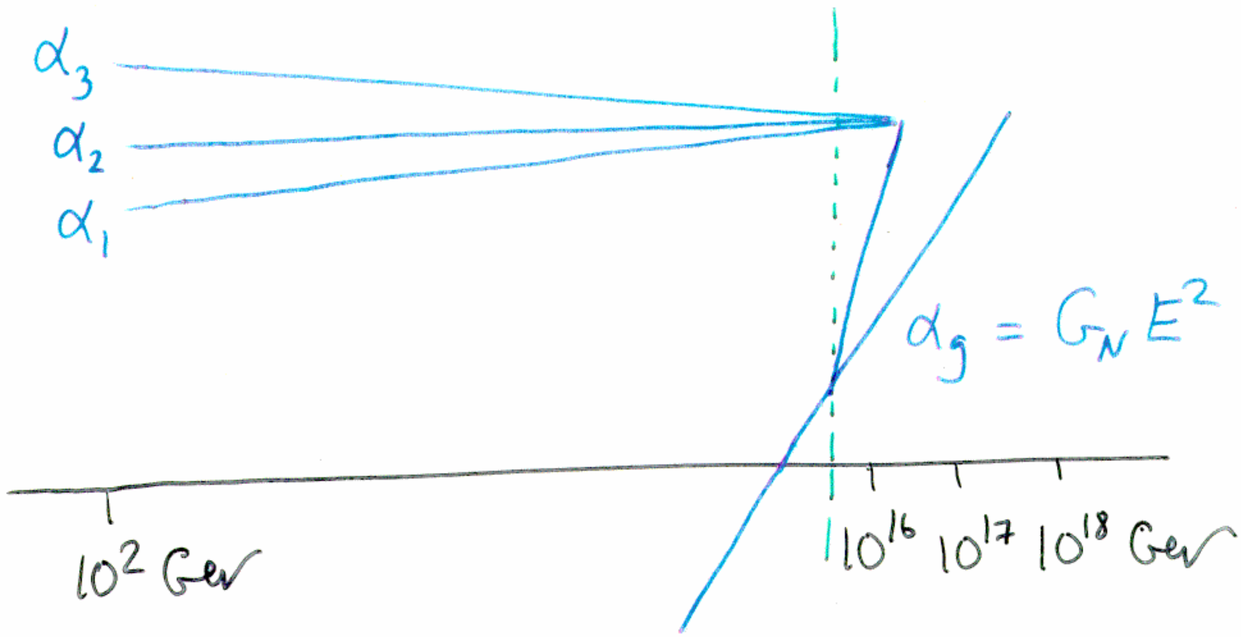
Unification of Couplings



Ideas for making 4 couplings meet —
threshold corrections, intermediate scale.

- Can we change α_g? Evidently not — it's just dimensional analysis.
- New idea (Witten): in some strongly coupled limits, gravity lives in 4+1 dimensions (or more) while gauge + matter stuck to 3+1 dimensional walls.

Outlook

- Black Hole Information Problem:

Perhaps all the ingredients for a solution are in place.

- Cosmological Constant Problem:

In any quantum theory the vacuum is a busy place, and should gravitate. Why is the cosmological constant, even if nonzero, so much smaller than particle or Planck scales.

Hard problem.

- Supersymmetry – broken/unbroken ?
- Nonlocal physics (see information problem)

- Precise predictions from string theory?

Still insufficient understanding of dynamics, especially for nonsupersymmetric vacua.

Note linkage:

Information Problem
↓ NONLOCALITY
Cosmological Constant Problem
↓ VACUUM ENERGY
Precise Predictions

- What is String Theory?

Ingredients in place? (Matrix Theory/ Maldacena Conjecture)

- ¿Distinctively Stringy Physics?
  - Fifth force from dilaton/moduli?

$$\frac{m_{\text{Planck}}}{m_{\text{weak}}^2} < \text{range} < \frac{1}{m_{\text{weak}}}$$

↖ interesting

  - TeV scale strings / millimeter scale dimensions

    Not impossible! But requires extreme values of parameters. See Arkani-Hamed's talk.

  - Something unexpected, perhaps cosmological. (Holographic principle?)

- Supersymmetry

– SUSY is very likely a symmetry at the Planck scale, but is it broken at the Planck scale or the weak scale. Arguments for weak scale:

PRO: Arguments independent of string theory (heirarchy problem, unification of couplings, heavy top)

PRO: SUSY is ubiquitous in suppressing bad quantum fluctuations at Planck scale, so probably also at weak scale.

CON: Cosmo. con. suggests new phase of SUSY, maybe different phenomenology.

– Discovery + precision measurement of SUSY parameters still best bet.

Summary: Stunning progress in past four years. Real possibility of answering hard questions.