Emergent Quantum Gravity

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One of the big successes of string theory:

In certain simple situations (like flat space) —

An algorithmically complete, consistent description of quantum gravity

The only ones known...

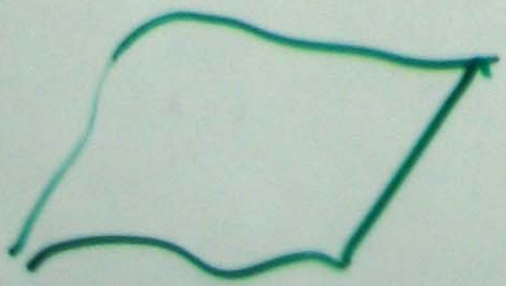
A basic lesson:

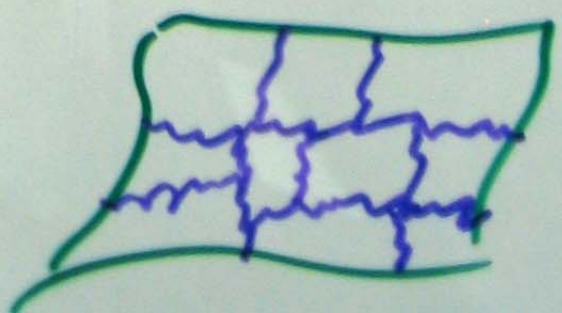
Quantum Gravity is Emergent

Strings are Collective Phenomena

These descriptions flow from one of the oldest ideas about string theory

QCD strings are made out of gluons

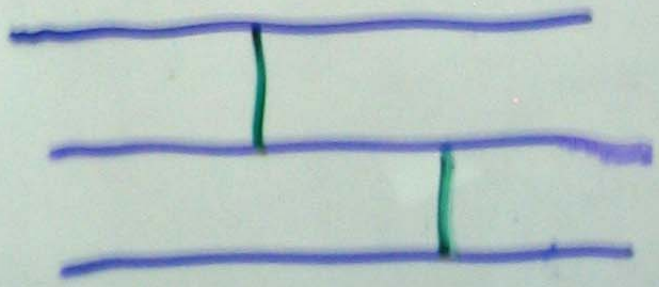




Things were unclear for a long time

QCD strings and "fundamental" strings seemed qualitatively different; we now know that they differ only quantitatively.

We now think of gluons as D-branes (and the straight strings that join them.)



In these descriptions, the basic degrees of freedom are D-branes.

The first precise description of "fundamental" strings was formulated in $D=2$, where string dynamics is exceptionally simple (varying coupling const.)

$D=2$ String Theory

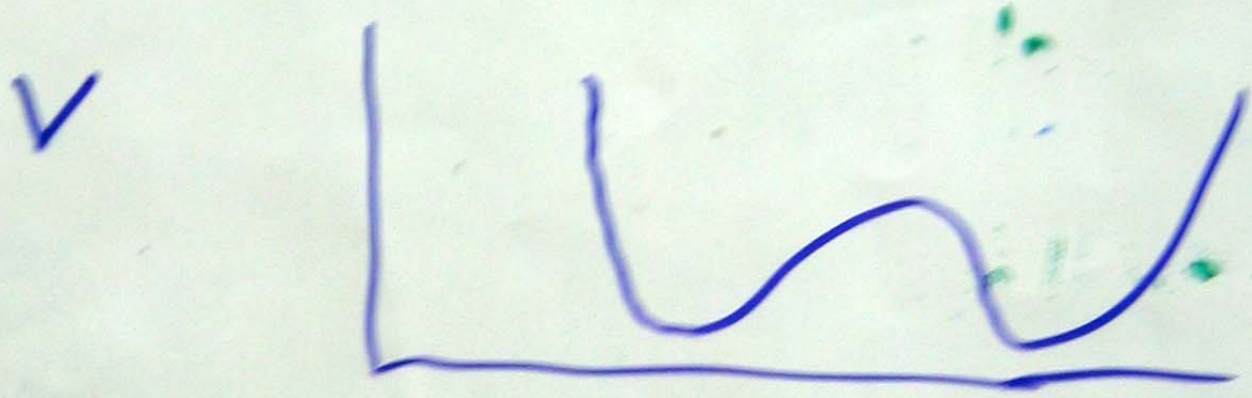
$\longleftrightarrow$

QM of a $N \times N$ Matrix

$N \to \infty$

"Old Matrix Models" $M_{ab}(\tau)$ $a,b=1,\dots,N$

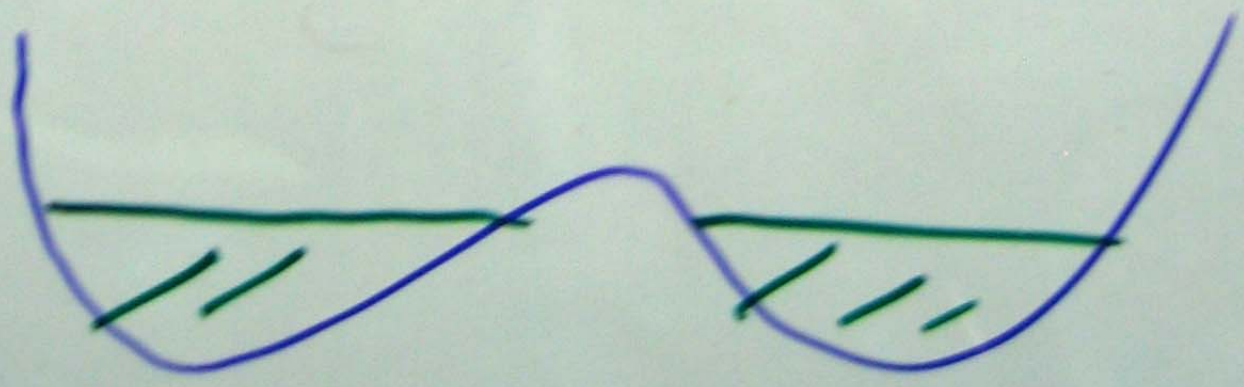
$$L = \mathrm{tr}\int d\tau \left(\frac{dM_{ab}}{d\tau}\right)^2 - V(M)$$



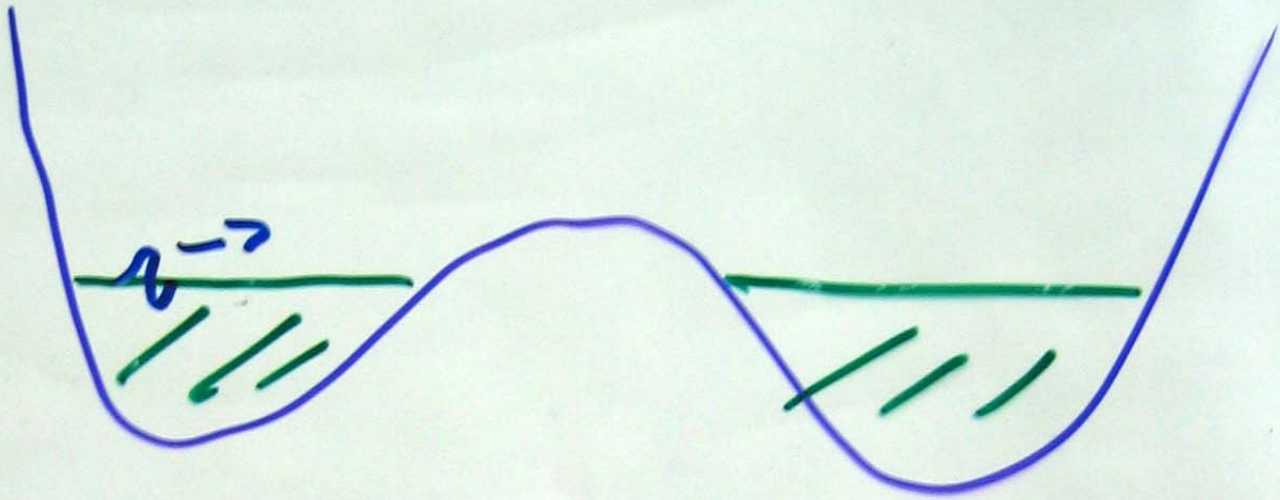
$$M_{ab} = \mathrm{diag}(\lambda_1 \dots \lambda_N)$$

λ repel $\longrightarrow$ free fermions

(D0-branes)



term: surface



Strings are ripples on fermi surface Collective

No more fundamental than water waves are

as a description of water

strings are a collective phenomenon.

First precise description of Quantum Gravity in a "full" number of dimensions (full gravitational dynamics)

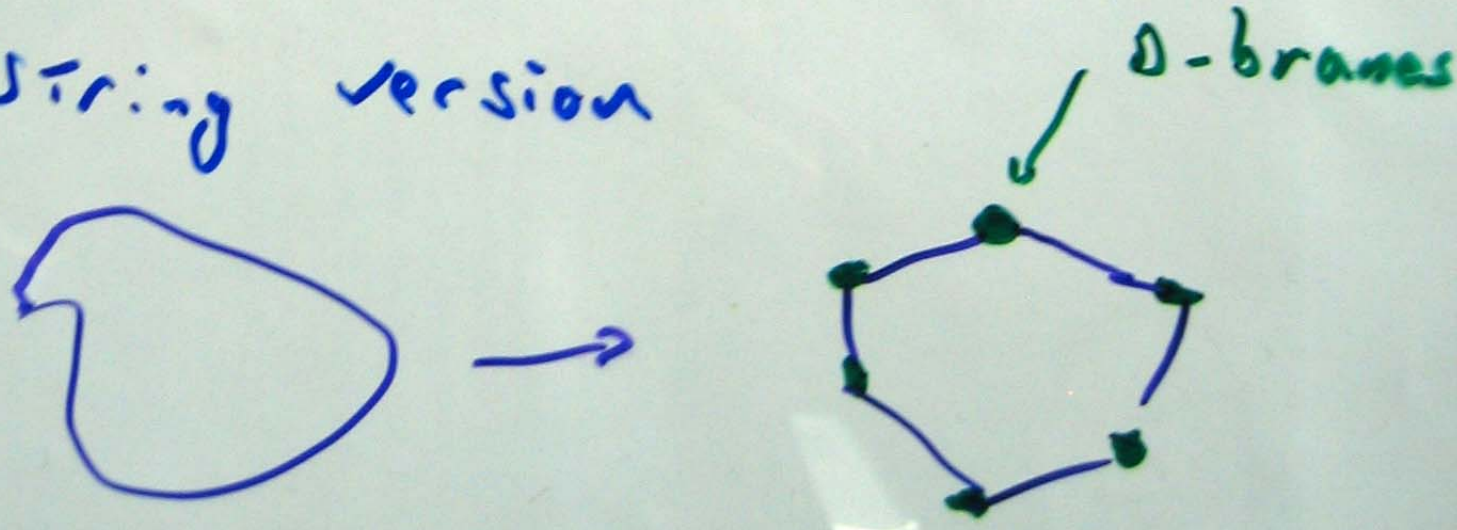
M-theory $D=11$

described by "Matrix Theory"

QM of $\underline{9}$ $N \times N$ Matrices

$N \to \infty$

String version



strings are collective

General setup AdS/CFT represents the state of the art in precise descriptions of Quantum Gravity.

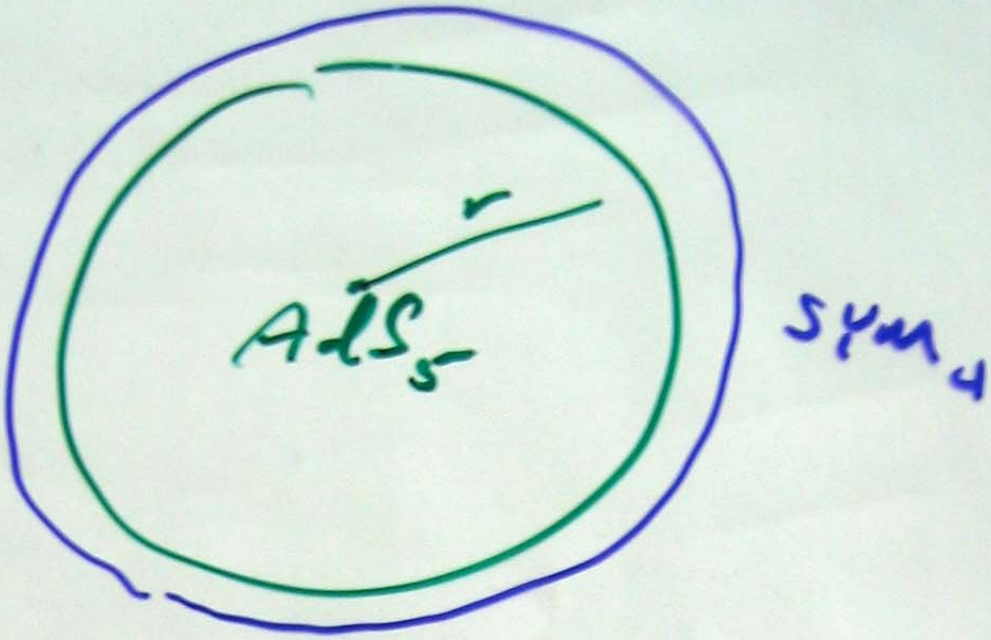
Old Matrix Models and Matrix Theory are special cases of this formalism

Simplest example of AdS/CFT

N D3-branes $\longrightarrow$ SU(N) 3+1 Super Yang Mills theory – Conformal Field Theory (CFT)

$SYM_4 \longrightarrow$ Strings in AdS_5

Remarkable



Holographic

r direction emergent scale symmetry of CFT

AdS/CFT $\rightarrow$

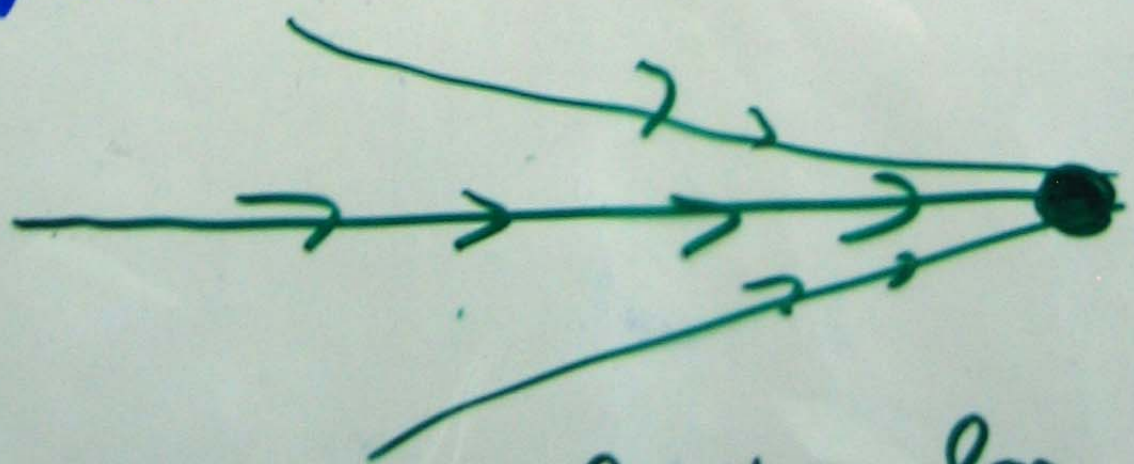
any CFT defines a consistent Quantum Gravity (any field theory) in fact

Quantum Gravities
used to be rarer than
hen's teeth,
Now they are a dime
a dozen!

Only issue is large
radius of curvature
(R_{AdS})
and weak coupling g_s.

Let's compare the notion of emergence we are seeing in Quantum Gravity with more familiar versions.

The best understood framework uses the Renormalization Group and the existence of an IR stable fixed point



large ratio of lengths $\frac{l_{IR}}{l_{UV}}$

e.g.

Many different kinds of atoms yield the same hydrodynamics (universality)

RG based on locality

Holographic theories are not local

But there is a notion of large length ratios (and of universality)

Different sequences of boundary CFTs each limiting to $R_{AdS} \to \infty$ will all describe the same flat space string theory

R_{AdS} $\longleftrightarrow$?

bulk bdary

scaling dims (critical exp)

$$\frac{R_{AdS}}{l_s} \sim \frac{\Delta_{high}}{\Delta_{low}}$$

From boundary point of view, universality is a strange correspondence between theories with large hierarchies in scaling dims.

In Bdary Theory, what are criteria for large R, small g_s
Find Them?

Natural from a bulk point of view, but we do not have a complete bulk understanding.

An important (but distant) goal

large R $\longleftrightarrow$ small c.c.
$\longleftrightarrow$ c.c. problem.

Cosmology in general is a deep open problem
what are the rules?

If Quantum Gravity is just another emergent phenomenon, why devote so much effort (and so many resources) to it?
(IR interesting)

If our most deeply held concepts, of space and time, are emergent notions then a more complete understanding will likely lead to dramatically different ways of viewing the world.