Lecture 3

1. Introduction. The classical theory of strings. Application: physics of cosmic strings.

2. Quantum string theory. Applications:

   i) Systematics of hadronic spectra

   ii) Quark-antiquark potential (lattice simulations)

   iii) AdS/CFT correspondence.

   iv) AdS/CFT and the quark-gluon plasma.

3. String models of particle physics. The string theory landscape. Alternatives: Loop quantum gravity?
   Formulations of string theory.

Quark-gluon plasma

Experiments at RHIC (Relativistic Heavy Ion Collider) at Brookhaven National Laboratory (New York) started around 2000.

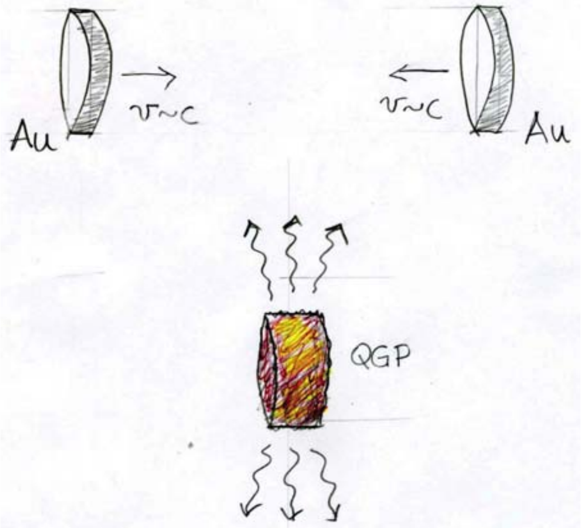
Colliding gold nuclei (Au, 197 nucleons) with CM energy of 200 GeV per nucleon.

RHIC temperatures are $T \sim 2T_c$, with $T_c \sim 175 MeV$, the QCD deconfinement temperature.

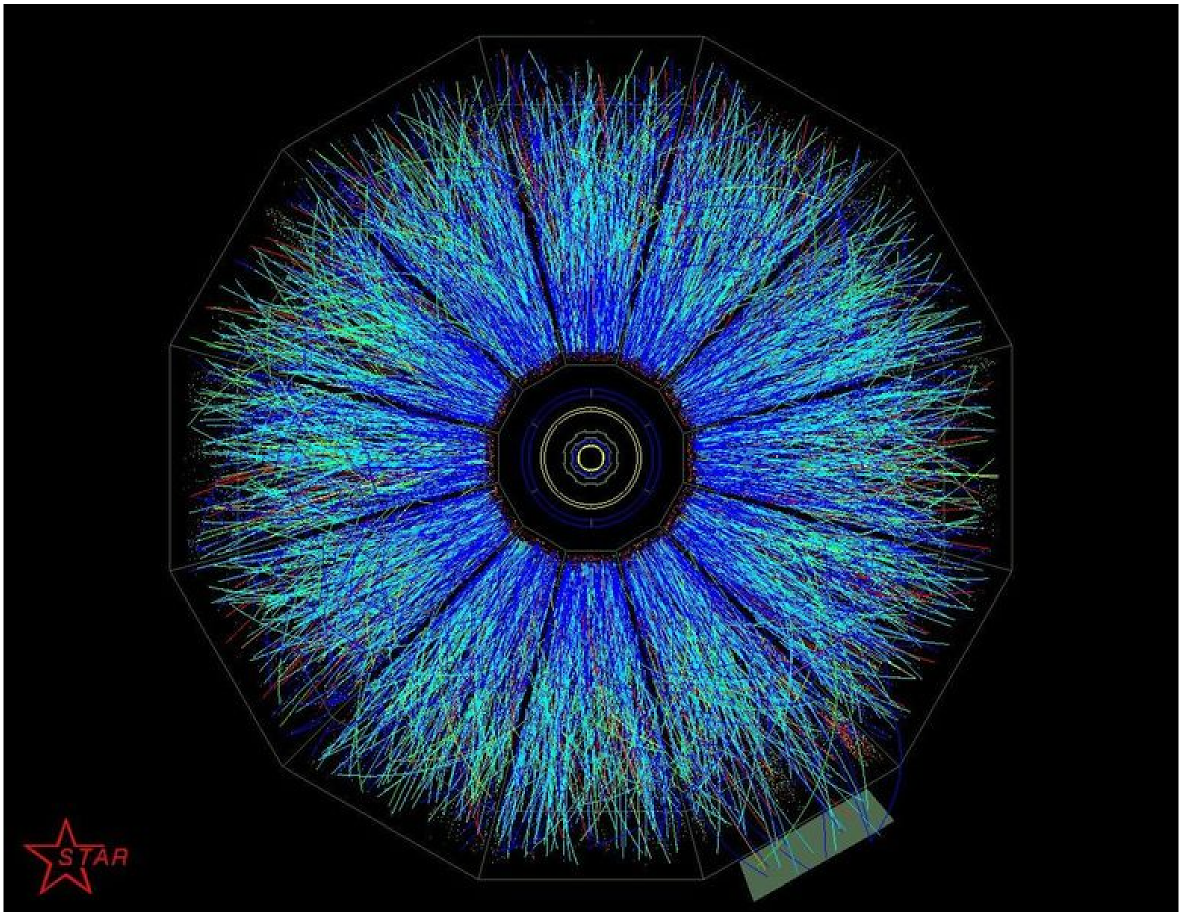
The collision appears to create a strongly coupled quark-gluon plasma (QGP) that represents a deconfined state of QCD.

The plasma seems to be thermalized, because particle abundances and ratios are reproduced by statistical models.

At LHC, ALICE (A Large Ion Collider Experiment) ATLAS (A Toroidal LHC ApparatuS), and CMS (Compact Muon Solenoid – including my MIT friends) will study lead-lead (Pb-Pb) collisions at much higher energies, reaching $T \sim 5T_c$.



Pancake like nuclei collide and create the QGP, which expands and radiates all kinds of particles, mostly transversely.

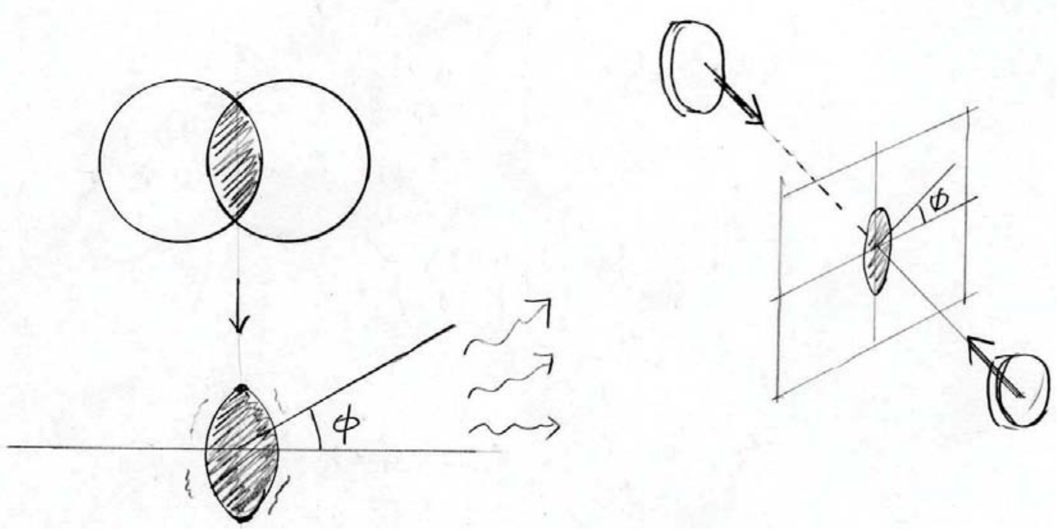


First gold Beam-Beam Collision events at RHIC.

Elliptic flow. The viscosity of the QGP.

Collisions are non-central, so the QGP is initially created in the shape of an approximate ellipse.

The radiation is ϕ-dependent (larger for $\phi = 0$).



$$\text{Number of particles} \simeq C\Big(1 + 2v_2(p_T)\cos(2\phi) + \ldots\Big)$$

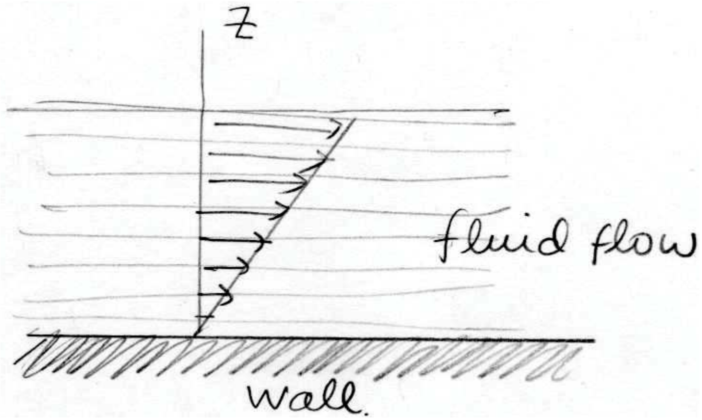
The existence of a large v_2 is a characteristic of elliptic flow.

Simulations of the evolution of the plasma consistent with the observed elliptic flow, indicate that, most likely,

The QGP has extremely low viscosity

A primer on (shear) viscosity

Layers flowing at different velocities experience friction.



The force F transmitted across layers of area A

$$\frac{F}{A} = \eta \frac{dv}{dz} \qquad \eta \text{ is the viscosity,} \qquad [\eta] = \frac{M}{LT}\,.$$

Consider entropy density:

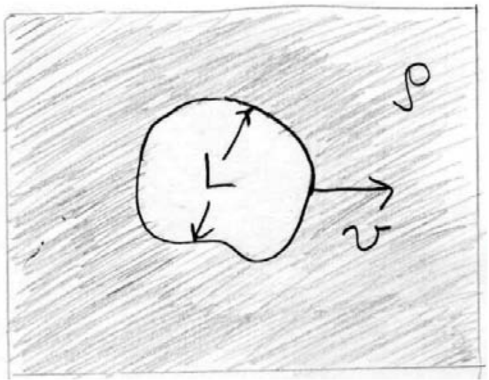
$$s = \frac{S}{V} = \frac{k}{V} \ln \Omega\,, \qquad [s] = \frac{[k]}{L^3}\,.$$

Then

$$\left[\frac{\eta}{s}\right] = \frac{1}{[k]} \frac{ML^2}{T} = \frac{1}{[k]}\,[\hbar]$$

New uncertainty principle ?

Kovtun, Son, Starinets: $\frac{\eta}{s} \gtrsim \frac{\hbar}{4\pi k}$



Shear viscosity enters into the definition of the Reynolds number which is used to study the motion of an object in a viscous fluid:

$$\text{Reynolds\#} = \frac{\text{Inertial pressure}}{\text{viscous pressure}} = \frac{\rho v^2}{\eta \frac{v}{L}} = \frac{L\rho v}{\eta}$$

Large viscosity is low Reynolds number.

Small viscosity is high Reynolds number.

Viscosity of a dilute gas

With $n = N/V$, ℓ the mean free path, $\bar{v}$ the average velocity and m the mass of the particles,

$$\eta \simeq \frac{1}{3} n \bar{v} m \ell = \frac{2}{3} \frac{N}{V} \left(\frac{1}{2} m \bar{v}^2 \right) \frac{\ell}{\bar{v}} = \frac{2}{3} \frac{N}{V} u \tau \,.$$

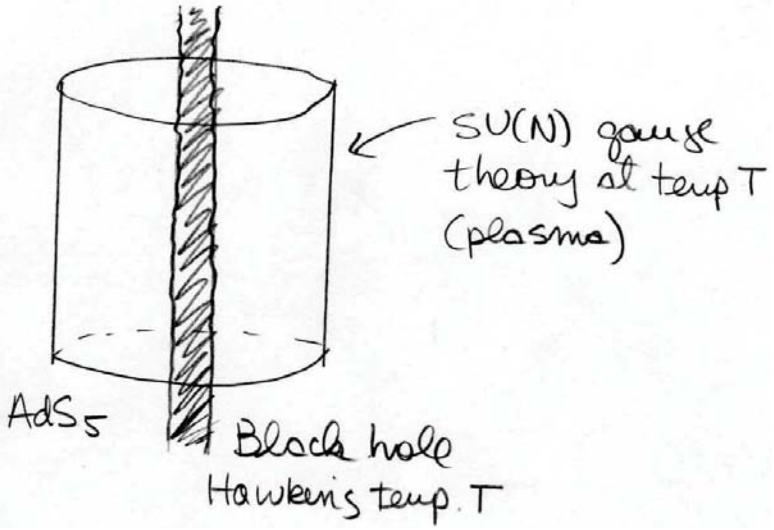
Here u is the energy of the particle. Moreover we know that $s = S/V \sim kN/V$, so

$$\boxed{\frac{\eta}{s} = \frac{1}{k} u \, \tau \gtrsim \frac{\hbar}{k} \,.}$$

What can AdS/CFT tell us ?

$SU(N)$ gauge theory at finite temperature T is equivalent superstrings with a Black Hole of Hawking temperature T on the AdS$_5$ part of the spacetime.

The gauge theory is strongly coupled, so its gravity dual is workable.



The AdS/CFT dictionary:

η → related to the horizon area

s → related to the black hole entropy

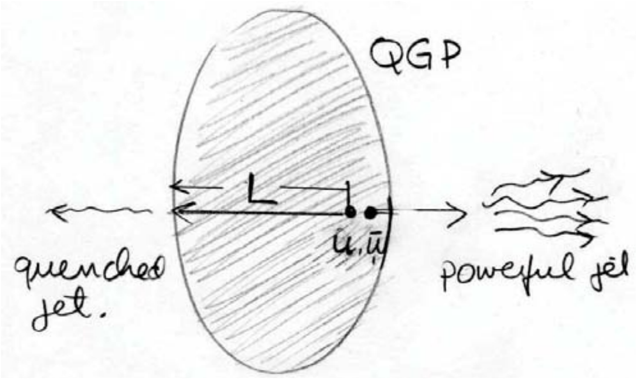
Kovtun, Son, Starinets (hep-th/0405231) find that

$$\boxed{\frac{\eta}{s} = \frac{\hbar}{4\pi k}\left(1 + \frac{c_1}{\lambda^{3/2}} + \dots\right)}$$

They conjectured that $\frac{\eta}{s} \geq \frac{\hbar}{4\pi k}$ and that $\mathcal{N} = 4$ Yang Mills saturates the bound.

Jet quenching

In the QGP if a meson breaks we get two quarks flying away in opposite directions. The parton that travels a longer distance in the QGP will be quenched:



The energy loss ΔE is given by

$$\Delta E \sim g_{YM}^2 \, \hat{q} \, L^2$$

The "quenching" parameter $\hat{q}$ measures the rate of change of transverse momentum per unit length.

It is calculated using AdS/CFT (Liu, Rajagopal, Wiedemann, [hep-ph] 0612168):

$$\hat{q} \simeq \# \sqrt{g_{YM}^2 N} \, T^3 \, .$$

The result provides a plausible fit to the data.

A Standard Model ?

Natural questions:

1. Does the Standard Model of Particle Physics arise as a solution of string theory ?
2. Can one embed this solution in a consistent cosmology ?
3. Is the solution natural, or selected by some symmetry principles ?

Answers: (1) Possibly, (2) Possibly, (3) Not clear.

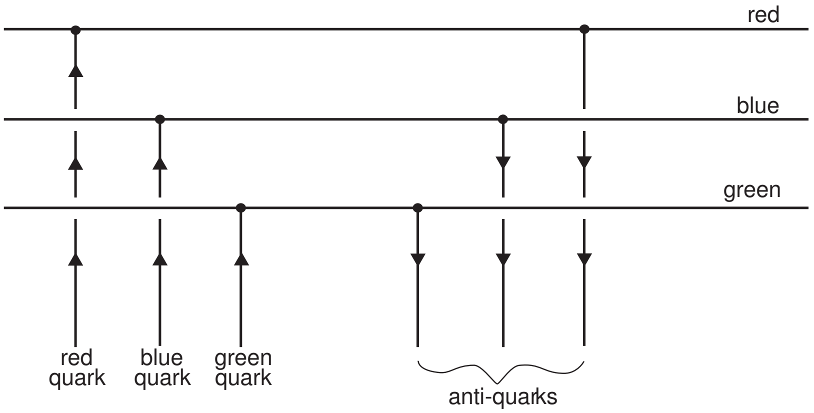
- 1986-1987 First models with $N = 1$ SUSY from Heterotic Strings
- 2001-2003 First models that get the precise particle spectrum of the Standard Model (but with zero mass).
- 2003- .... Incorporation of cosmology – fixing moduli

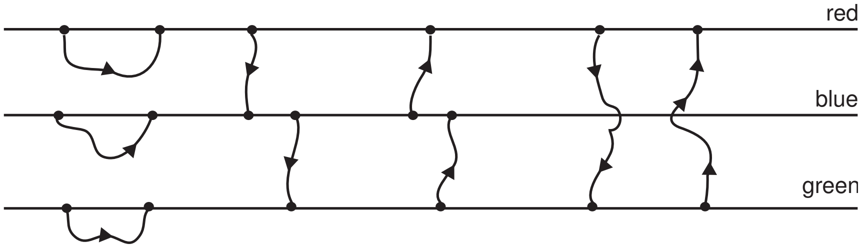
Fully realistic models (maybe 10 years away ?) with the help of data (LHC, cosmology, etc).

How do models look like?

How to get quarks using D-branes and strings?

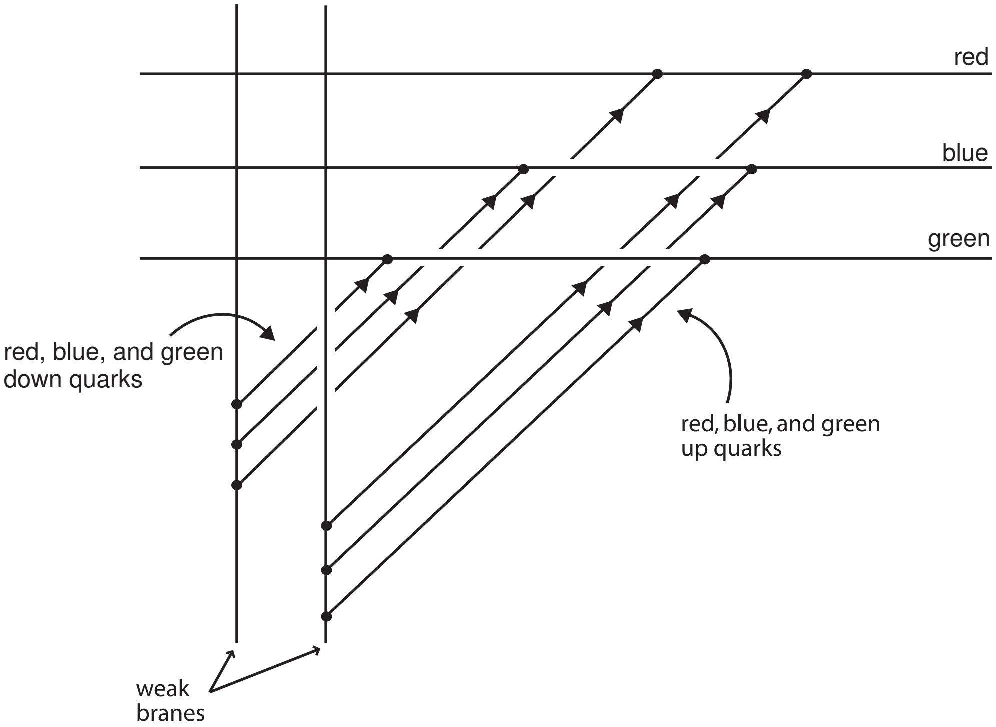
Use three D-branes: a red, a blue, and a green brane.





Top: Three parallel D-branes (shown as horizontal lines) are needed to produce the color interactions. The branes can be labeled by colors: red, blue, and green. The left-handed quarks are open strings that end on the colored branes. A red quark, for example, is a string that ends on the red brane. The left-handed antiquarks are open strings that begin on the colored branes.

Bottom: The open strings that begin *and* end on the brane configuration are gauge bosons. This brane configuration supports nine gauge bosons, eight of which are the gluons of QCD.



The color branes intersect two weak branes

Open strings near the intersection that stretch from the weak branes to the color branes are left-handed quarks.

The two flavors of quarks, u and d, arise because there are two weak branes.

In order to get left-handed quarks with flavors c and s we need a second intersection of the weak and the color branes.

In order to get left-handed quarks with flavors t and b we need a third intersection of the weak and the color branes.

What particles have we left out ?

Well, we are missing the leptons. In the first generation,

$$\begin{pmatrix} \nu_{eL} \\ e^-_L \end{pmatrix}, \quad e^-_R, \quad \nu_{eR}\,.$$

The left-handed states in the doublet feel the weak interactions, while the right-handed electron and the right-handed neutrino states do not.

We need a leptonic brane that intersects the weak branes to produce the doublet. Two more intersections are needed for the doublets in the second and third generation.

The right-handed states can be produced if we introduce a right brane that intersects the leptonic brane.

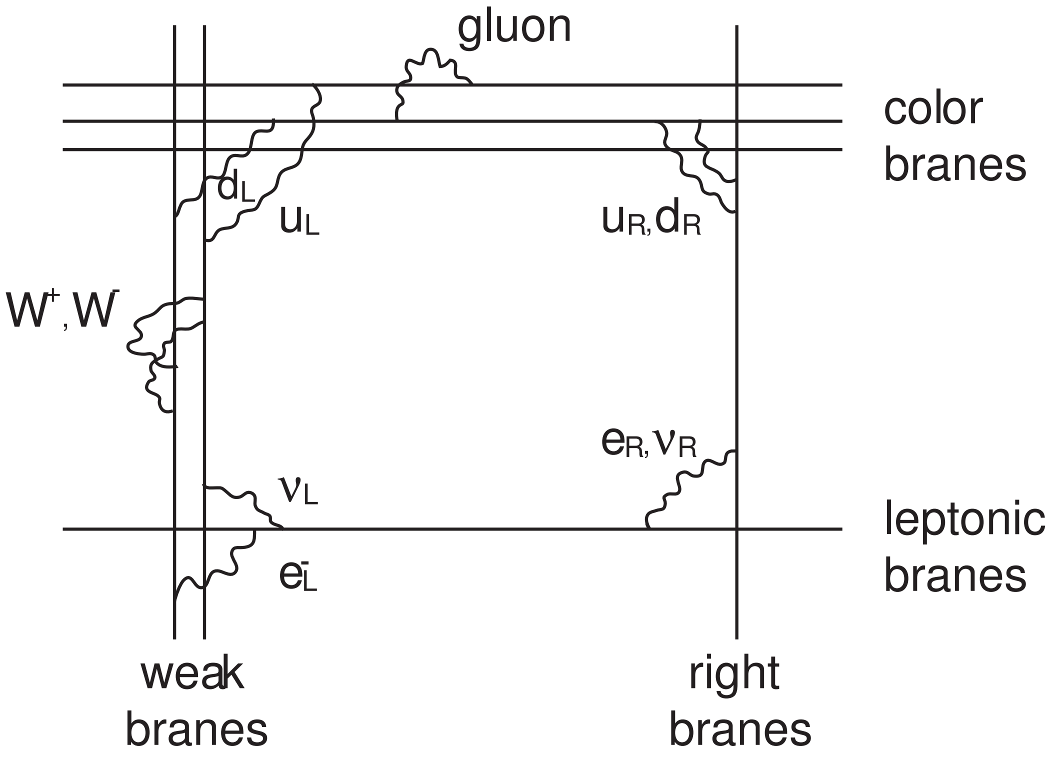
We are also missing the right-handed quarks, which do not feel the weak interactions

$$u_R\,, \quad d_R$$

We can get these by having the right-branes intersect the color branes!

A rough sketch of a D-brane configuration in which open strings represent the familiar particles of the Standard Model.

Cremades, Ibanez, and Marchesano, F. hep-ph/0212048.



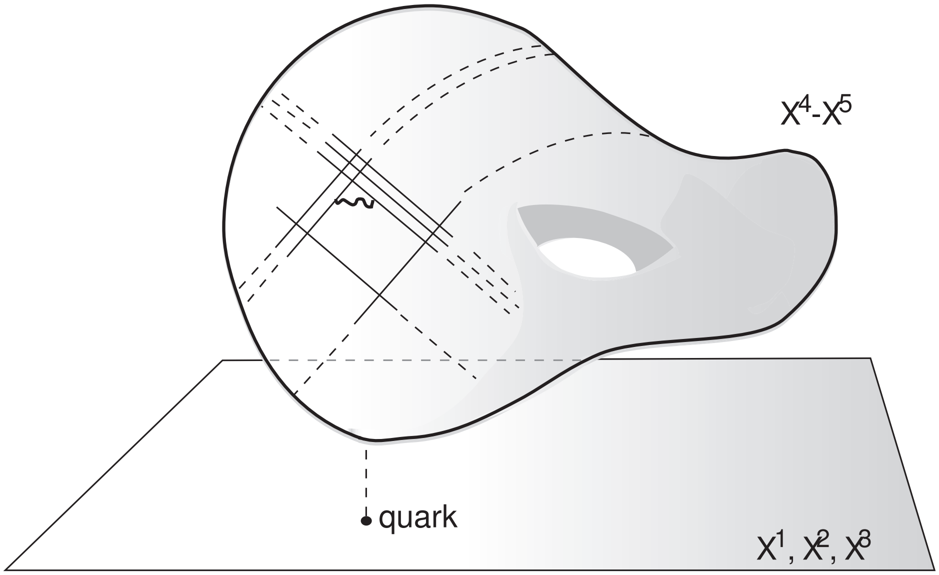
The right branes support the right-handed quarks and the right-handed leptons (both of which are weak singlets).

The leptonic branes support all leptons, the left-handed leptons (to the left) and the right-handed leptons (to the right).

What kind of branes are we using ?

What happened with the compact dimensions ?

To visualize a compactification we must imagine that a compact torus exists on top of each point of ordinary three space



The intersecting D-brane configuration.

Imagine that we have D4-branes:

3 spatial dimensions fill ordinary space

1 dimension along the torus.

The D-branes appear as lines on the torus. A left-handed quark is an open string that stretches from weak to color branes on the torus. It is perceived as a particle in three-space.

Progress with main challenges

1. Realistic Spectrum.

Intersecting D-brane models (and other models) are now beginning to give the spectrum of the Standard Model and of the MSSM, at least without masses.

2. Moduli stabilization.

Moduli are parameters can take arbitrary continuous values, for example the radius of a compact circle, or the expectation value of the dilaton, a closed string field that controls the string coupling.

Associated to each moduli there is a massless scalar field. Since no massless scalar fields are observed in nature, all moduli must have been stabilized by some potential that fixes the expectation values.

This has now been achieved in with flux compactification models (see nice review by Denef, Douglas, and Kachru, hep-th/0701050).

3. Inflation and present day cosmic acceleration

Inflation seems possible (if contrived) as discussed in KKLMMT (hep-th/0308055). The basic idea is brane-antibrane inflation, in which the slow motion of a brane towards an antibrane represents the rolling inflaton. A left-over cosmological term looks plausible.

There are models that do 1 and 2, but not 3 (see, for example hep-th/0506066)

The String Theory Landscape

String theory shares with Einstein's gravity a problematic feature.

Einstein's equations of gravitation admit many cosmological solutions. Each solution represents a consistent universe, but only one of them represents *our* observable universe.

It is not easy to explain what selects the physical solution, but in cosmology this is done by the use of arguments based on initial conditions, symmetry, and simplicity.

The smaller the number of solutions a theory has, the more predictive it is.

If the set of solutions is characterized by parameters, selecting a solution is equivalent to adjusting the values of the parameters.

In this way, a theory whose formulation requires no adjustable parameters may generate adjustable parameters through its solutions!

It seems clear that in string theory the set of solutions (string models) is characterized by both discrete and continuous parameters.

For continuous parameters we do moduli stabilization. For for discrete parameters we must do choices.

Actually, with the freedom provided by flux compactification and intersecting branes, the number of string models possible are likely to be extremely large. Certainly at least 10^{500}, perhaps much more. A rich landscape.

Upside: With so many models at least one must be right !

Downside: With so many models, what about predictability ?

Possible outcomes in the search for a fully realistic string model.

1. No string model exists that is fully realistic (worst possible outcome).

2. One model works out and represents an isolated point in the space of all string solutions (best possible outcome).

3. A very large number of models agree with all known physics within present known accuracy (somewhat disappointing).

Loop Quantum Gravity

An alternative avenue to the construction of a theory of Quantum Gravity.

Claim that the perturbative infinities found in perturbative quantum Einstein theory are somehow misleading, unreliable, or irrelevant.

A true non-perturbative quantization of Einstein's theory would give no such problems.

Do not begin with spacetime: begin with some spatial 3-dimensional "substrate" which is only auxiliary: it is used for the construction of spin networks (graphs on the substrate). The Hilbert space is that of wavefunctionals (constructing using the holonomy of the Ashtekar connection) on spin networks. Hilbert space is non-separable!

LQG has a lofty, ambitious, imaginative, and abstact starting point. Unfortunately, little progress has been made to show that classical gravitation, spacetime, and Minkowski space, emerge from this theory.

Formulations of String Theory

String theory has had humble origins, but has delivered surprise after surprise!

A fundamental formulation of the theory telling us what replaces the Equivalence Principle, or what is the true nature of space-time is not yet available.

Physicists have suggested the following possibilities:

1. Holography: Given the success of AdS/CFT to provide a gauge theory description of string theory (in AdS) perhaps the result is more general and we should search for a holographic formulation string theory in any background.

2. M-theory: All 10-dimensional string theories are related by certain deformations to an 11-dimensional theory (M-theory) whose low energy limit is a supergravity theory. Formulate M-theory (perhaps with a matrix model).

3. String Field Theory: Fields now depend on loops, not points. This is the natural generalization of previous successful formulations in physics. Concrete approach with substantial progress. Final goal, however, still appears far away.

String Theory is an active and fun field of research because the major questions still remain to be answered!