A BRIEF TOUR OF STRING THEORY

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TIFR.

In the beginning...

The 20th century revolutions:

•Special relativity (1905)

•General Relativity (1915)

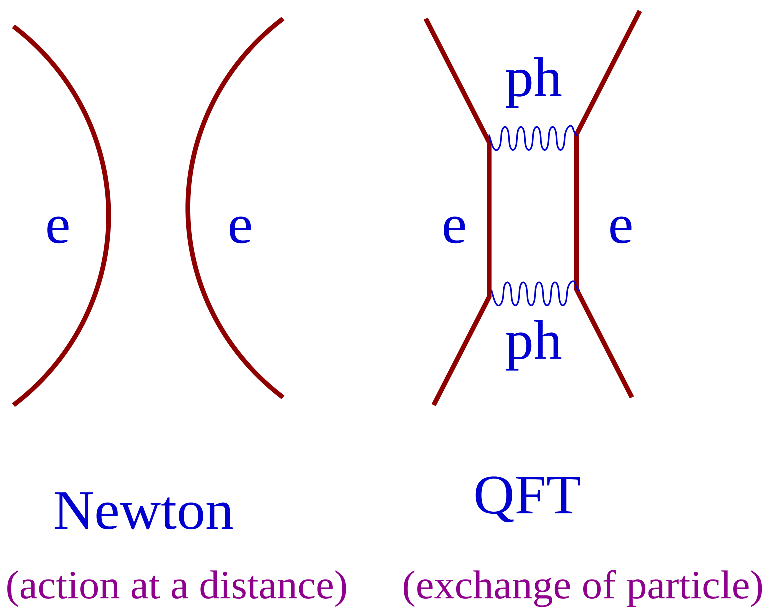
•Quantum Mechanics (1926)

metamorphosed our concepts of space and time and structure of matter.

By 1950's they appeared invincible:

The atom was stable. We had a picture of what happened inside stars. We understood the atomic structure of thermodynamics. We had a model of the universe......

Quantum mechanics plus Special Relativity gave Quantum Field Theory (QFT) which taught us how forces are meant to work

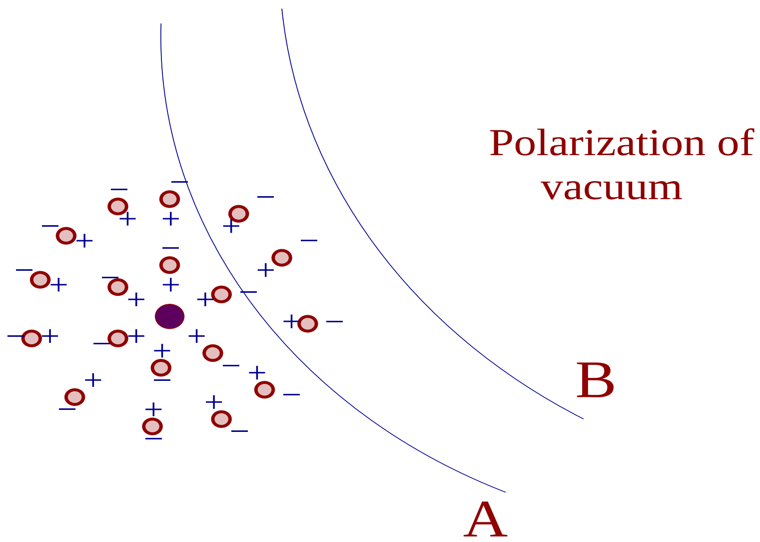


QFT worked beautifully for the electromagnetic force (called QED in that case). But soon enough it faced serious challenges from strong interactions and gravity...

Chinks in the armour...

Strong interactions (nuclear binding force):

QED experience: "charge" $e(r)$ grows at higher energies or short distances: $V = e(r)/r$



Wrong for strong interactions: "charge" $e(r)$ decreases at short distances!

At energies > 1 Gev, protons and neutrons, and mesons, appear to be composed of nearly free quarks. On the other hand, at low energies i.e. large distances quarks appear strongly bound (confinement).

Gravity:

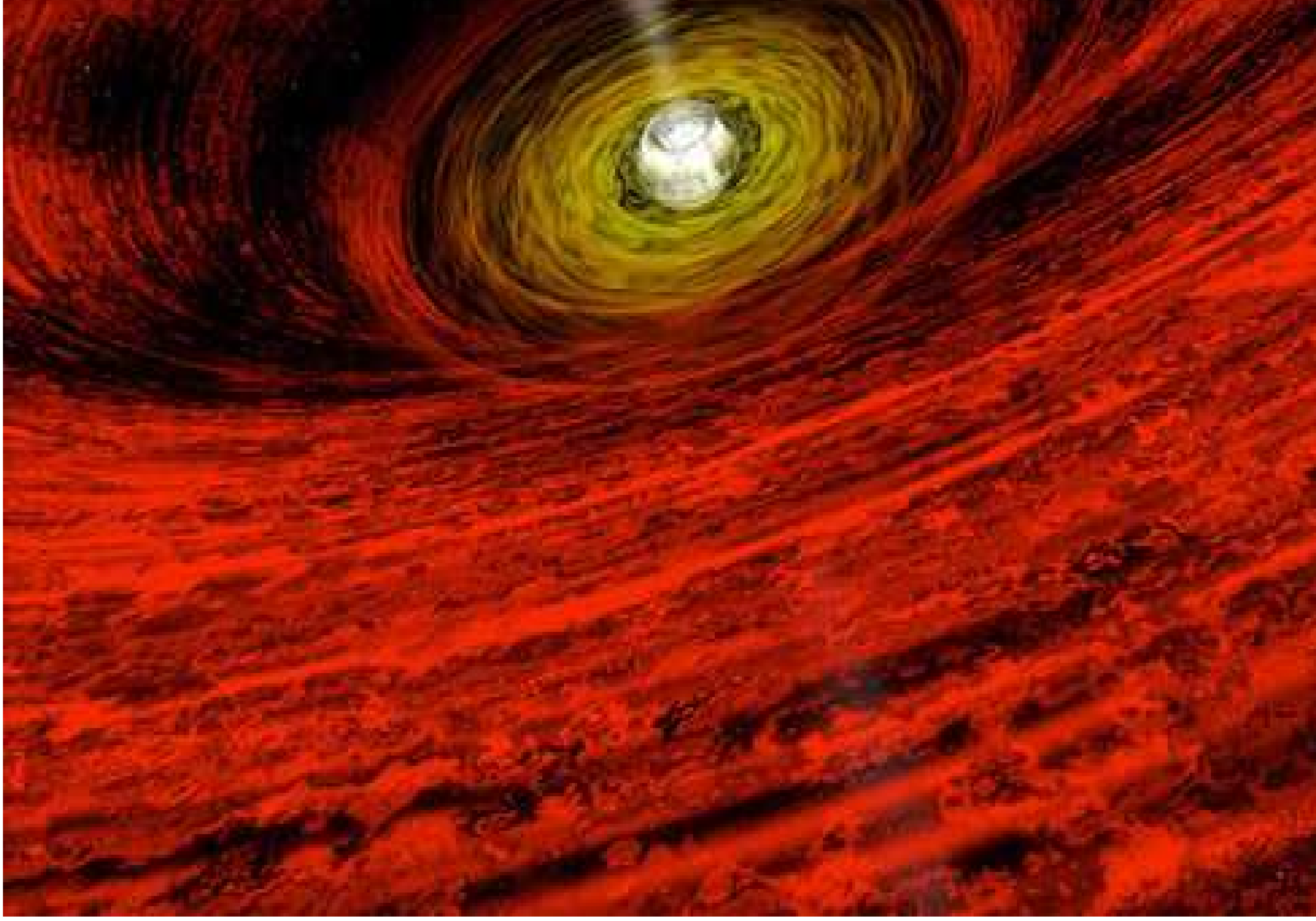
The ulitra-violet divergence problem:

Gravitational force between two electrons receives infinite quantum corrections.

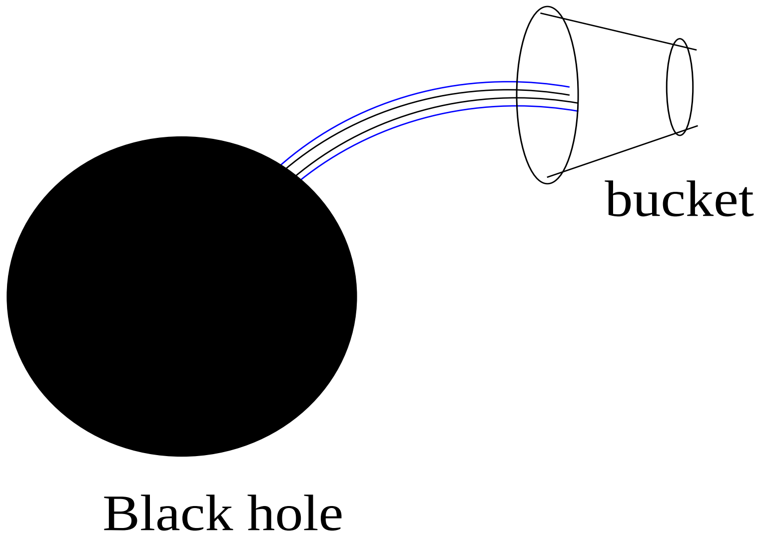
$$V = -G\,\frac{M_1 M_2}{r}$$

Charge=mass (energy). To see the uv behaviour, let $r = r'/b$, $M_i = M_i'\ b, V = V'\ b$ (b large),

$$V' = -b^2\,G\,\frac{M_1' M_2'}{r'} \quad \stackrel{b\to\infty}{\to} \quad \infty$$



Black holes:



A black hole must have entropy.

● Entropy = Area/4G,

According to GR, the BH absorbs the hot water and settles back to a unique geometry. Where does the entropy come from?

•**Hawking radiation:**

Hawking (1974): Black holes emit thermal radiation, and eventually disappear.

What happens to the entropy?

If, at every stage of evaporation, the emitted radiation is thermal, the final product of black hole evaporation is unique, irrespective of the initial wavefunction.

Such many-to-one evolution is impossible in Schrodinger equation.

"Black holes violate Schrodinger equation, hence Quantum Mechanics." Information loss paradox.

Enter Strings...

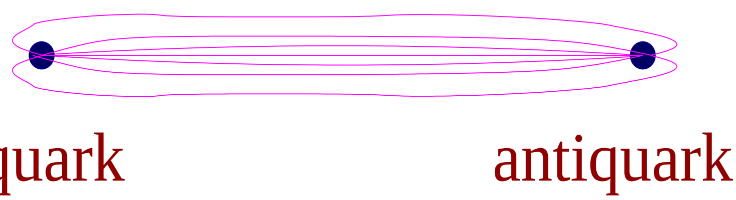
to solve the problem of strong interactions..

Philosophy: Try a theory not of the point-like quarks, but of the extended objects, nucleons and mesons, as the basic entities.

String model: Mesons are open strings, end-points represent quark and antiquark.

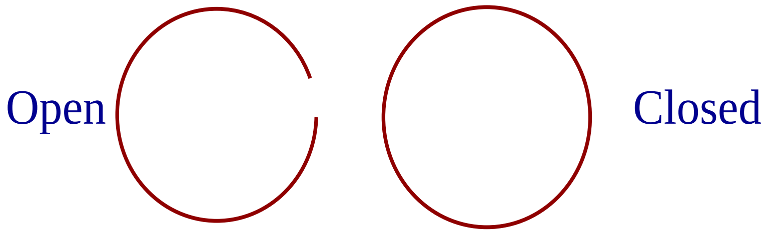
Why linear model?

Mesons are like flux tubes

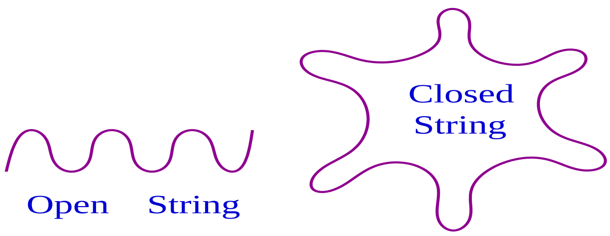


The string model worked initially, but...

Problem 1: Open strings cannot live without closed strings, even as one tries.



Closed strings could not be interpreted, e.g. closed string spectrum invariably has a massless, spin two particle.



The only such particle known is way outside the world of strong interactions: it is the graviton: the exchange "photon" of gravitational force!

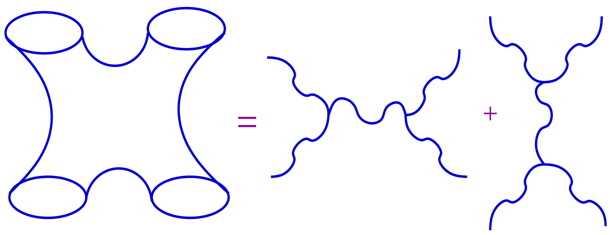
Problem 2: The required dimension for consistent string theories turned out to be 10.

"Strings can't be a model of strong interactions?!" (more later)

...Ends up giving quantum gravity

•It has the graviton-like state in the spectrum: mass=0, spin=2

•It IS the graviton.



•For this agreement strings must have tiny size = Planck length = $\sqrt{(\hbar c/G)} \sim 10^{-33}$ cm. Looks point-like even to the smallest microscopes today.

•Quantum corrections are finite $\Rightarrow$ finite Quantum Gravity.

•Indeed we get other interactions too from the second piece of bad news, namely 6 extra dimensions!

Summary so far

- Strong interaction problem: quarks behaved in a funny fashion.

- Open Strings invented to directly describe mesons.

- Closed strings appeared, which invariably had gravitons.

- The resulting theory of gravitons was finite, thus solving the divergence problem of quantum gravity.

- Thus, quantum gravity requires us to move from particles to strings.

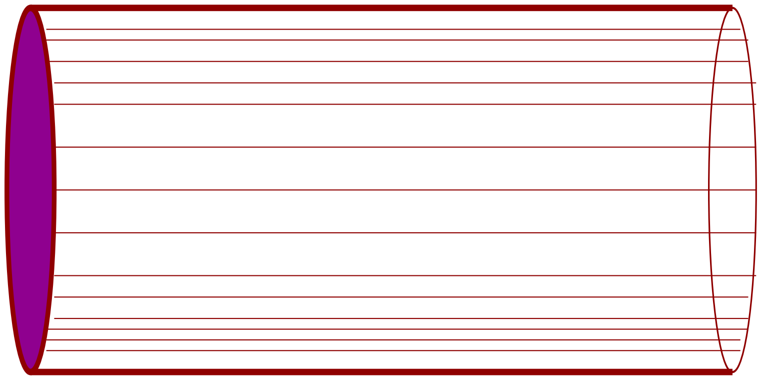
- Strong interaction found the right theory, QCD; but more on meson strings later...

- Need to still address the issue of black holes...

Extra dimensions

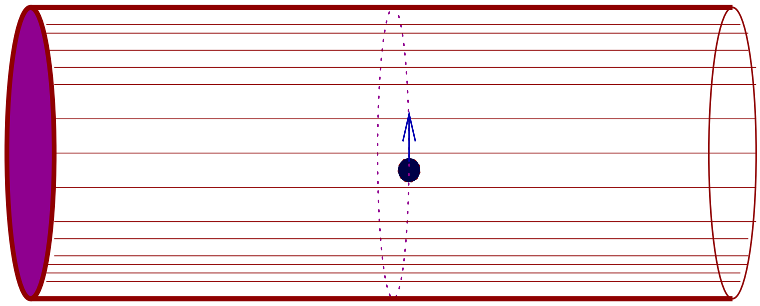
How does one handle 6 extra dimensions?

The idea (due to Kaluza and Klein): consider 2 space, 1 time, where space is a cylinder



If the circle is small, it looks like 1+1 dimensional.

However, the "hidden dimension" gives...



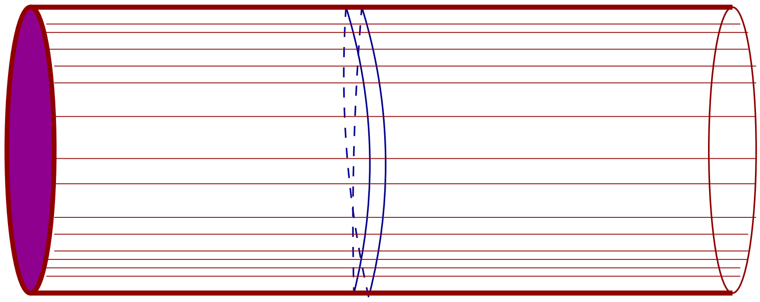
New particles: Consider a massless particle ($E = p$) moving along the circle, with momentum $p = n/R = E, c = \hbar = 1$. If the radius is small, the motion will be invisible.

In 1+1 dim it will appear as a static particle, with rest mass:

$$m = n/R$$

New force: Gravitational field vibrates in 2 directions. If one of those is the "hidden" direction, the field will appear to vibrate in only the other direction: but that is an electromagnetic field: $G_{\theta x} = A_x$!

The "hidden" momentum $n = p_\theta$ becomes charge under this new electromagnetic field.
$G_{\theta x}\ p_\theta\ p_x \propto n\ p_x\ A_x$.



For strings: A string can wrap the circle, with energy $E = n'R/\alpha'$ (if it wraps n' times). $1/(2\pi\alpha')$ represents the mass per unit length of the string.

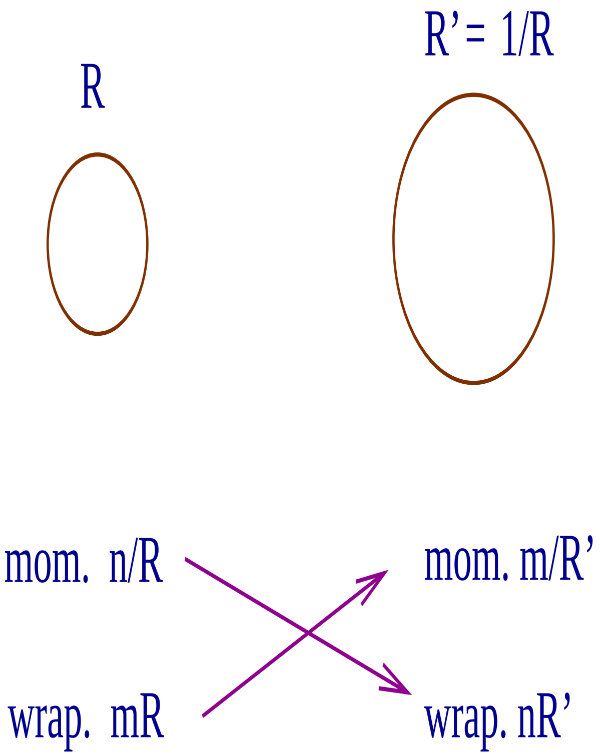
For small radius, this too will appear as a particle in 1+1 dim, of mass

$$m = n'R/\alpha'$$

n' appears as charge under a new force which appears because of the stringy nature of the compactification.

T-duality:

$R \to R' = \alpha'/R$: **the set of particles is unchanged, only relabelled.**



Suggests the existence of a minimum length in string theory: $R = R' = \sqrt{\alpha'} \approx 10^{-33}$**cm.**

Unification

So, extra dimensions give us new forces and new particles.

When the extra dimensions are described by more complicated spaces, the particles can carry charges of the kind seen in weak and strong interactions ("non-abelian" gauge charges).

For some choices of compactifications, the spectrum of light particles in string theory is close to what we expect in the supersymmetric standard model, coupled to supergravity.

This theory is finite in perturbation theory. That is, quantum corrections are finite for any number of particle exchanges. So is this the TOE?

Not quite...

- There are more than one (five) such string theories.
- What happens beyond perturbation theory?
- How about black holes?

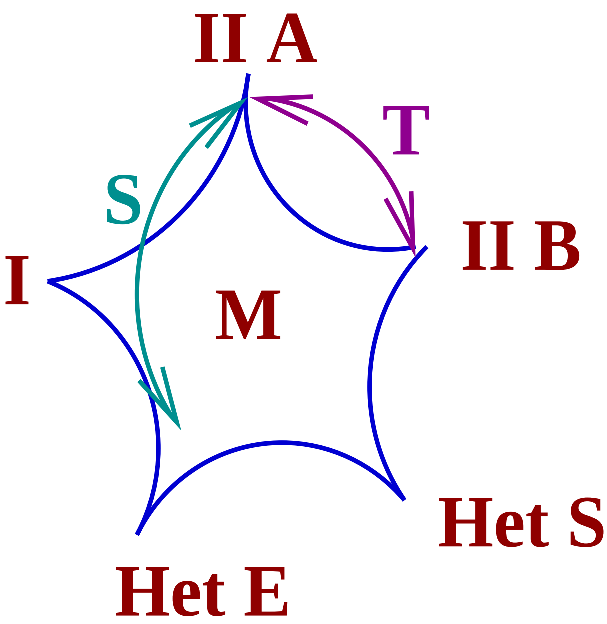
S-duality & nonperturbative Strings

The charge of a magnetic monopole, when they exist, satisfies (Dirac)

$$\text{magnetic charge} \propto \frac{1}{\text{electric charge}}$$

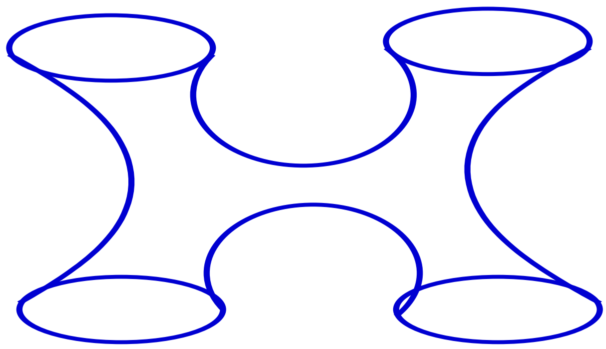
S-duality: Strongly quantum phenomena with high electric charge become classical phenomena, when described in terms of magnetic charges.

One string theory is the magnetic dual of another (tifr)

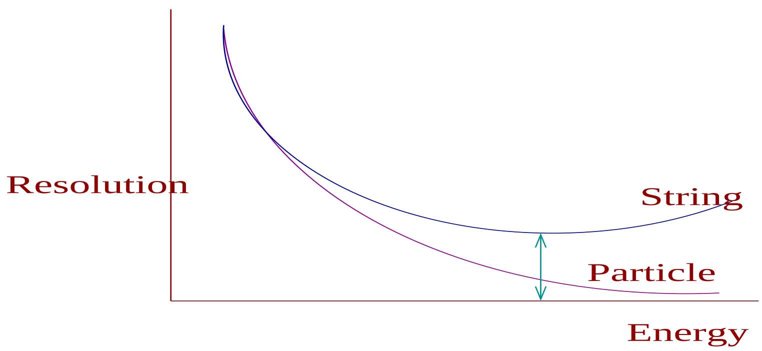


Minimum length scale in String theory

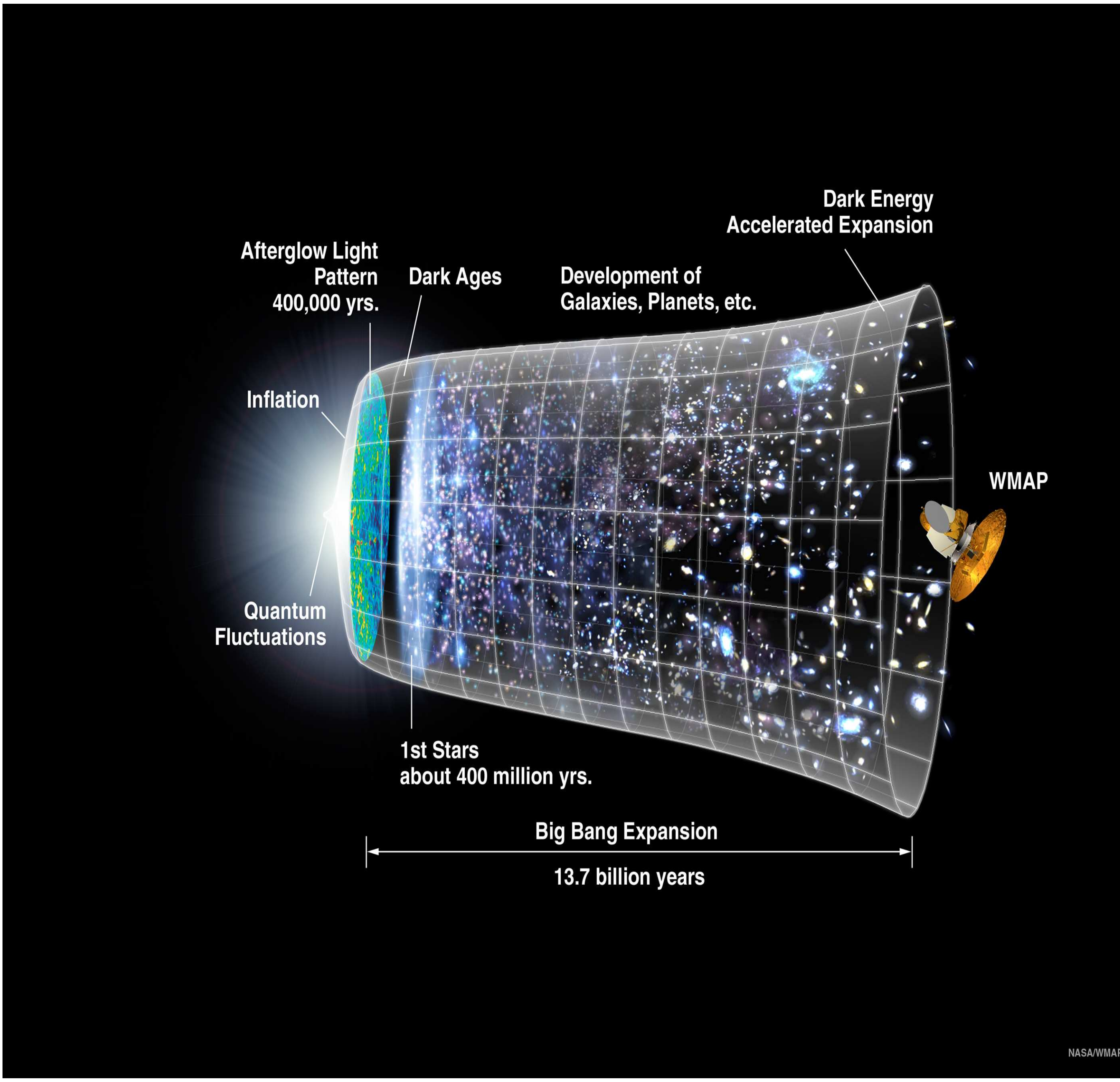
In string theory, all sizes and shapes of diagrams are summed. At high energies, the dominant diagrams do not pinch.



String length grows with energy and leads to a minimum resolution.



Minimum length is related to absence of ultraviolet divergence. This is a major difference from particles.


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WMAP

Spacetimes and string theory

The simplest example of propagation of strings is in flat space. But the graviton-strings can condense, and give rise to curved spacetimes.

Such spacetimes, even when they are far from flat space, are self-consistently determined by string theory itself ("Strings make the spacetime they move in") (tifr)

Examples of spacetimes occurring in string theory:

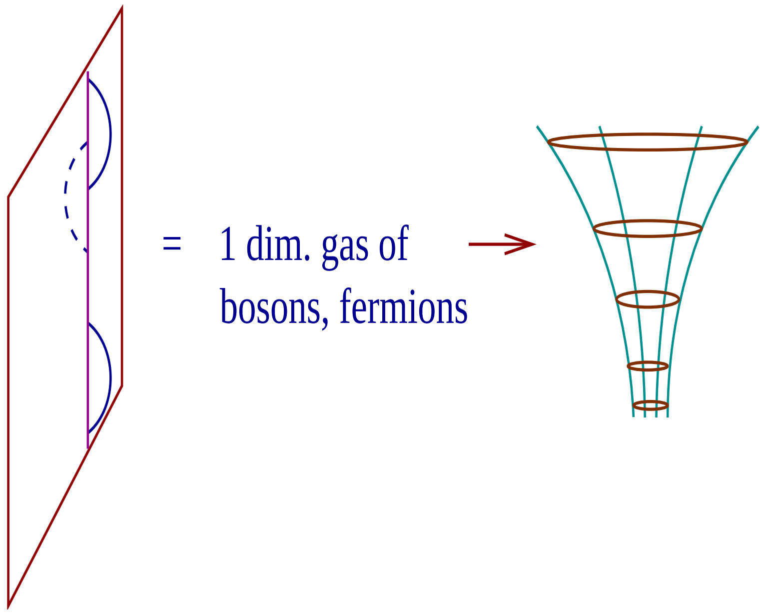
•Black holes (tifr)

•Cosmological solutions: e.g. solutions which explain the recent astrophysical observations that suggest that the universe is presently going through an accelerating phase. (tifr)

Black hole: the entropy problem...

Several years back a special black hole solution was discovered in string theory. It is in five dimensions, is charged and "extremal" (doesn't decay) and quantum fluctuations around it are supersymmetrically paired.

The special thing is that the measurable properties, i.e. the mass and charges of this black hole, occur in some explicitly constructed quantum states in string theory!



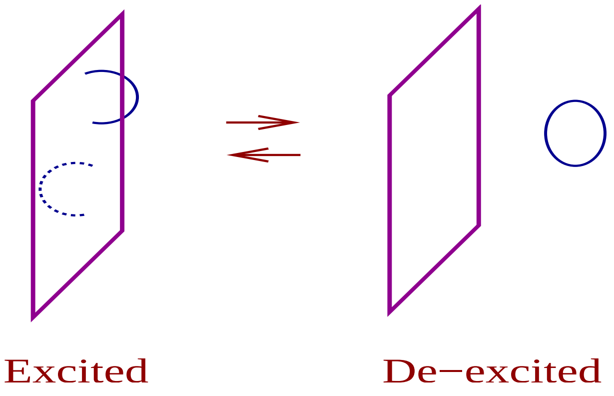
There are many such states, N of them, which can all be counted. The black hole entropy turns out to be exactly explained by this number:

$$\boldsymbol{S = \frac{\text{Area}}{4G} = k \log \mathrm{N}}$$

Thus, the uniqueness of the black hole is only classical. Quantum mechanically there are many "microstates" each of which corresponds to the same macroscopic black hole. The number N of the microstates explains the entropy.

Resolution of information loss...

The microstates described above can be excited which can decay. It happens as follows:



One can compute the decay amplitude from string theory by using standard quantum mechanical methods.

If we don't care about the specific microstates, the excited object appears to be a non-extremal black hole and the decay process turns to exactly describe Hawking radiation of the non-extremal black hole to the extremal one.

In other words, if we average the microscopic decay probability over the initial and final microstates, then the rate exactly matches with the rate of Hawking decay. (tifr)

Thus, radiation coming out of the black hole is thermal only in the same sense that radiation coming out of a furnace is thermal. Dependence of the radiation only on the temperature and not on the specific contents is an approximation. The information about the contents comes out with the stream of photons in a subtle fashion.

$$\psi_1 \to \psi'_1 \approx \rho,$$
$$\psi_2 \to \psi'_2 \approx \rho,$$
$$\ldots$$
$$\psi_N \to \psi'_N \approx \rho$$

In a similar way, the stream of massless particles that comes out of the non-extremal black hole does carry information about the specific microstate.

The construction of Hawking radiation from a unitary QM resolves the information loss paradox. (tifr)

Resolution came from string theory since it had quantum gravity and the nonperturbative tools to construct the black hole microstates.

Back to strong interactions

Mesons are described by flux tubes. Could the open strings perhaps describe them after all?

At first glance, no. The open strings we described above are infinitely "thin", because they are elementary strings, whereas the meson strings are "fat" (described by "form factors").

Is there any relation between the thin strings and fat strings?

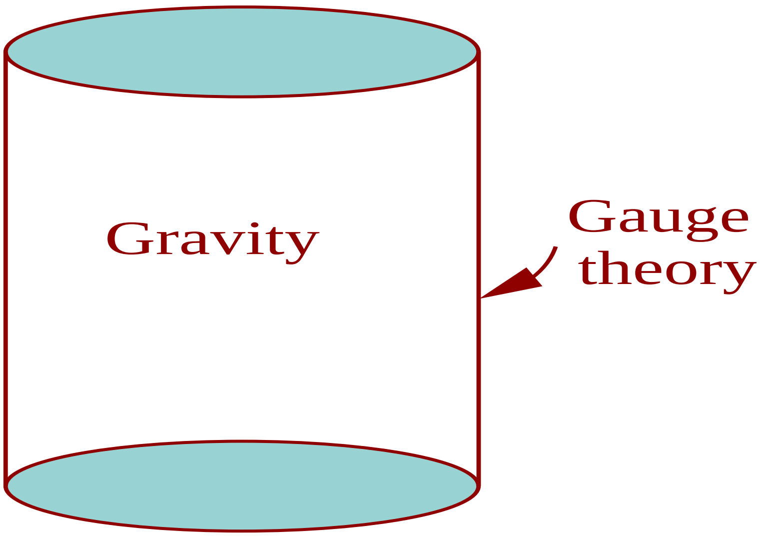
The answer comes from an unsuspected area:

Black holes!

AdS/CFT or gravity/gauge-theory duality

Black holes taught us that entropy of a 3 dim object could be proportional to a 2 dim area.

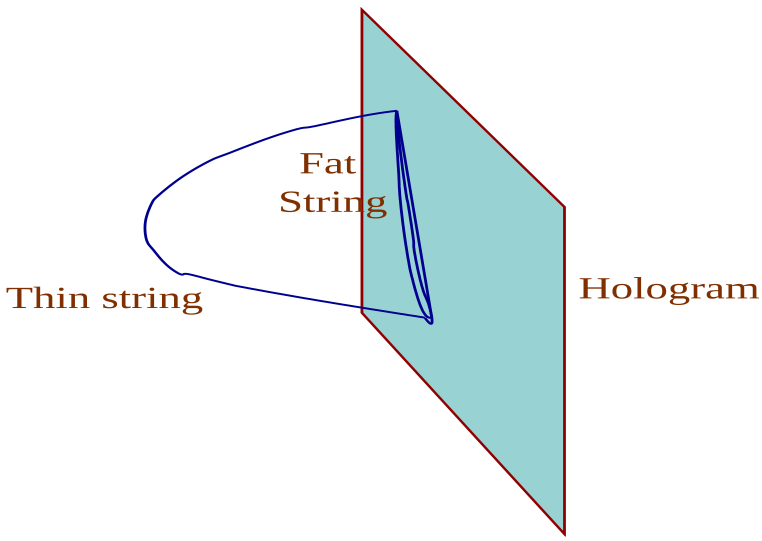
Studies of special kinds of black holes in string theory led to the surprising relation:



Strongly coupled gauge theory= weakly coupled gravity.

QCD

Holography means that the radius coordinate is mapped to “thickness”.



It has been proved that for gauge theories with a large number of colours the meson strings are indeed reproduced by the thin open strings hanging in the bulk.

Hydrodynamics

Gauge theory at finite temperature is dual to a black hole at that temperature in the dual geometry.

Black holes with slowly fluctuating horizons correspond to gauge theories at slowly varying thermodynamic parameters: hydrodynamics (tifr)

$$\frac{\eta}{\rho} = \frac{1}{4\pi}$$

Second law of thermodynamics becomes "provable" using local area theorem of black hole horizon (tifr)

Condensed Matter

Many condensed matter systems, e.g. high T_c superconductors, are believed to be described by strongly coupled field theories.

AdS/CFT duality naturally provides a weakly coupled description of such systems.

Cons: uses gravity in one higher dimension; the variables are unfamiliar.

Application of these ideas are yielding valuable insight into non-fermi liquids (tifr)

Conclusion

- We described some basic concepts in string theory, like compactification, dualities, minimum length scale and holography.

- We mentioned some applications, esp. to black hole physics and strong interactions (in QCD, hydrodynamics and condensed matter).

- Open questions: Non-supersymmetric black holes, HEP, resolution of singularities, nonperturbative string theory...