Cosmic Singularities and String Theory

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Plan

- What is a spacetime singularity?
- What is string theory?
- Two examples of stringy resolution of static singularities
- Cosmic singularities and string theory
- Lessons and implications

What is a spacetime singularity

- A spacetime is singular if there exists at least one freely falling particle or photon which ends (or has begun) its existence within a finite “time”.

- Intuitively, a spacetime singularity is a “place” where some “pathological behavior” of the metric takes place, e.g. the curvature “blows up” or …

Some Examples

- **Big Bang/Big Crunch**
  beginning or end of time?

- **Collapse of a star**
  black holes

- **Infinitely thin cosmic strings**
  Conical singularities

Singularities in general relativity

- In the late sixties, Hawking and Penrose showed that "generic" classes of spacetimes in general relativity are singular.

- Standard notion of spacetime breaks down at the singularities.

- General relativity and other known physics laws such as quantum field theory also break down.

Greatest crisis in physics of all time

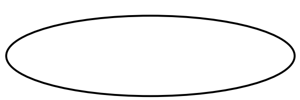
-- "Gravitation" by Misner, Thorne and Wheeler

To understand singularities, one must go beyond the general relativity, e.g.

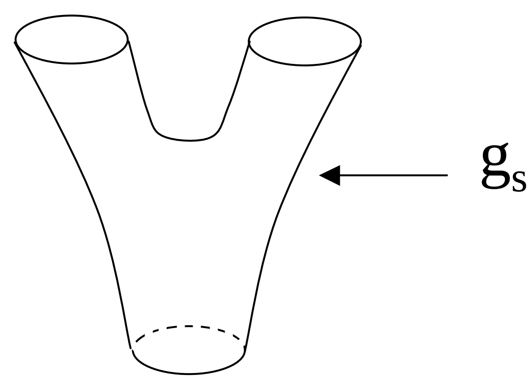
- Modify it at the classical level
- Quantum gravity

String Theory I

- Quantum field theory : particles are point-like objects propagating in space time.
- String theory: gravitons, photons and all other elementary particles are one-dimensional objects, strings.
- Interactions are described by splitting or joining of strings in spacetime.
- Point-particle description arises only in a low energy limit.



Tension = $\dfrac{1}{2\pi\alpha'}$



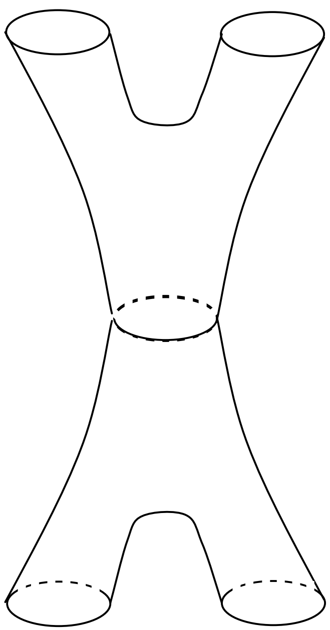
String theory II

- Presently, string theory is mostly formulated in terms of perturbation theory.
  - Perturbative degrees of freedom: graviton, Yang-Mills fields, …
  - Their masses have a well-defined limit as $g_s \to 0$.
- Much progress has been made toward a non-perturbative formulation.
  - Non-perturbative degrees of freedom: solitons, D-branes, black holes …
  - Their masses depend on inverse powers of g_s, and thus are not visible in perturbation theory.
  - M(atrix) theory, AdS/CFT …..

Example:

Graviton + Graviton $\longrightarrow$ *Graviton + Graviton*

$$A = \lambda_2 \, g_s^2 + O(g_s^4) + \cdots$$



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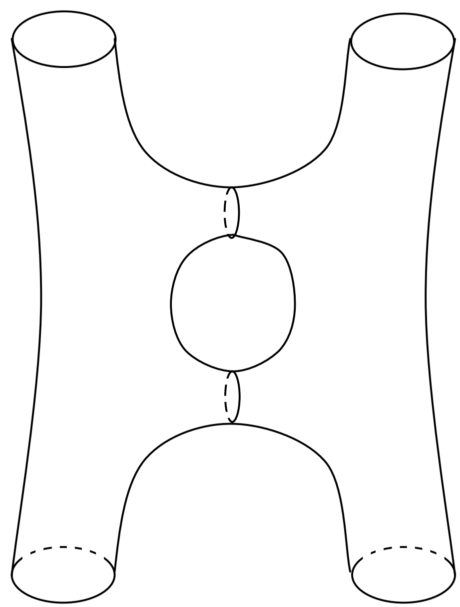

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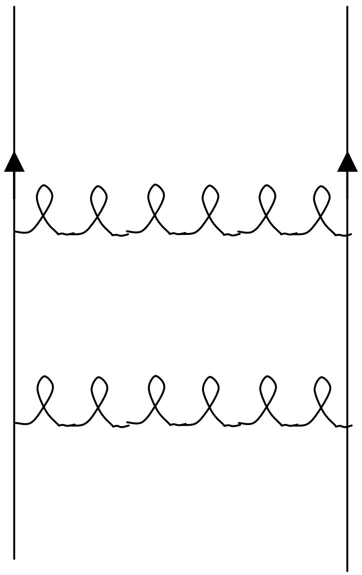
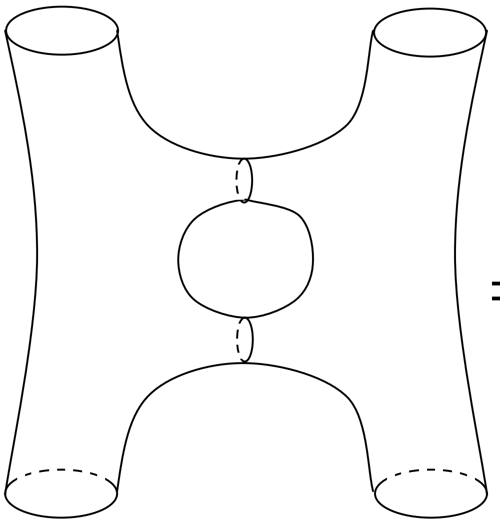
A consistent theory of gravity



= infinite



= finite

In string theory, interactions no longer occur at points.

It eliminates the UV problem in general relativity.

Thus it is a promising candidate for a consistent theory of gravity.

Low energy expansions

$$L_{eff} = \frac{1}{g_s^2 \alpha'} \left(R + \alpha' R^2 + \cdots \right) + \cdots$$

A double expansion in:

$$Energy^2 \alpha' \quad \text{and} \quad g_s^2$$

$$M_{pl}^2 = \frac{1}{g_s^2 \alpha'}$$

At low energy it reduces to Einstein relativity.

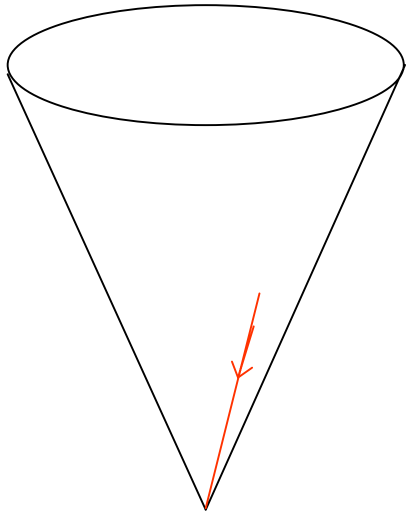
String theory and singularities

Can singularities in general relativity be resolved in string theory?

- in perturbative string theory (due to extended nature of strings) ?
- Or does one need a non-perturbative formulation?

Conical Singularities

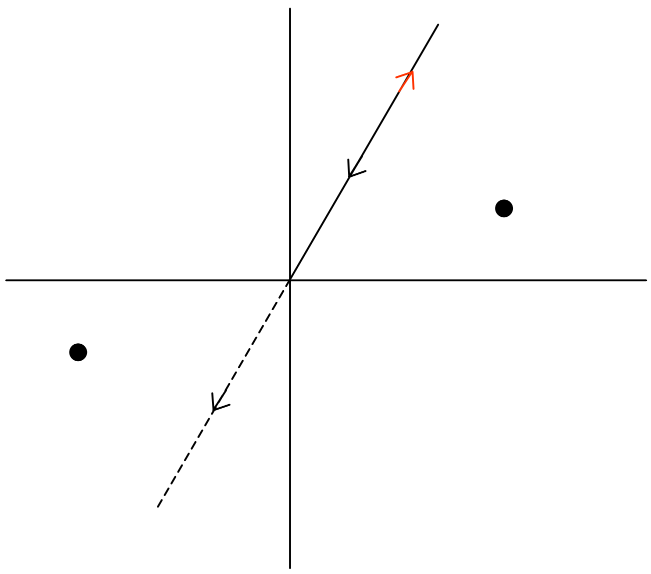
- Einstein gravity breaks down at a generic conical singularity. Those time- or null-like geodesics which hit the singularity cannot be continued beyond.



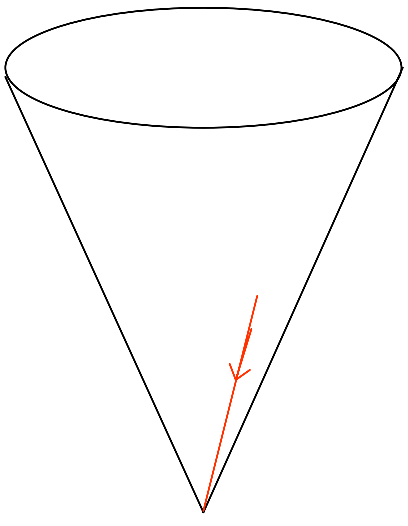
Orbifolds

- For those obtainable from 2-dimensional flat space by discrete identifications, one can still make sense the classical theory, e.g.

$$(x_1, x_2) \sim (-x_1, -x_2)$$

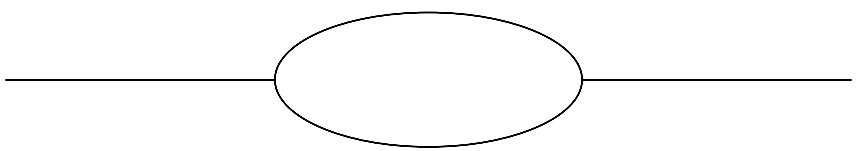


R^2/Z_2



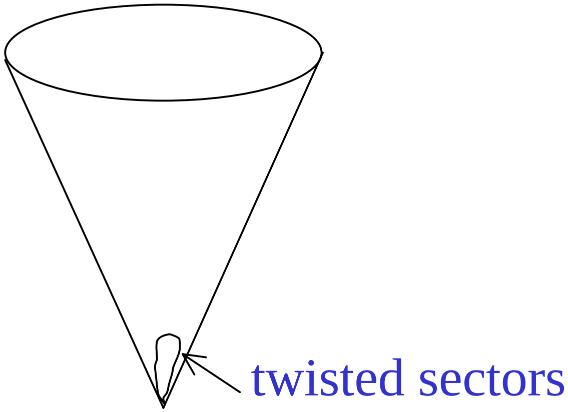
Orbifolds II

- Similarly, one can try to define a quantum field theory in the cone by projecting onto the subspace of the Hilbert space in R^2 which are invariant under the identifications.
- However, a field theory defined this way is not unitary at the quantum level.



String theory on orbifolds

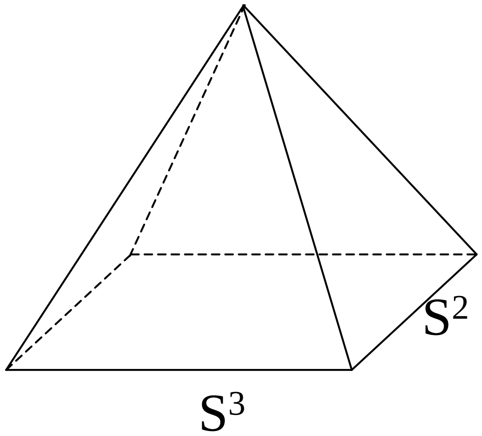
- The extended nature of string theory introduces additional degrees of freedom localized at the tip of the cone: twisted sectors.



- Including the twisted sectors, string amplitudes are unitary and physics is completely smooth.
- This is an example where string theory resolves the singularity at the perturbative level.

Conifold

- General relativity is singular.
- Classical string theory is singular.
- By including the non-perturbative degrees of freedom at the tip of the cone, the physics is again smooth.



Lessons

- String theory introduces new degrees of freedom. By including them the physics at those singularities becomes completely smooth.

- Those singularities arise in general relativity simply because the relevant degrees of freedom are not visible.

Cosmological singularities

- Beginning of time
  - Need initial conditions, wave functions of the Universe etc.

- Time has no beginning or end
  - Need to understand how to pass through the singularity. ……….

Challenges for string theory

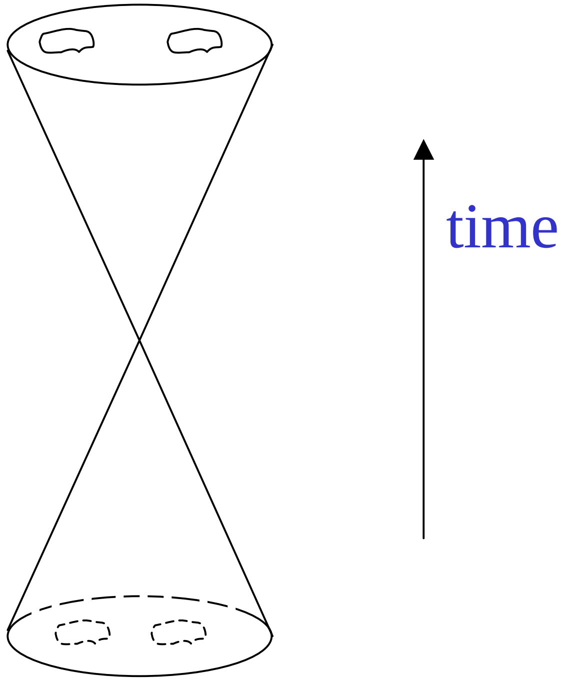
- **Hope**
  - String theory will lead to a detailed theory of the Big Bang.
  - Experimental tests of string theory.
- **Question**

Is the cosmological singularity smoothed by

classical string theory or *quantum string theory ?*

From Big Crunch to Big Bang: is it possible?

(A Toy Model)



Time-dependent orbifolds: obtainable from discrete identifications of a flat Lorentzian spacetime. (Horowitz, Steif)

Motivations

- Basis for some recently proposed cosmological scenarios: Ekpyrotic/Cyclic Model. Khoury,Ovrut,Seiberg,Steinhardt,Turok

- Simplicity: it can be subjected to an exact perturbative string analysis.

- Universality: the structure of singularity is the same as in certain black holes and certain more complicated cosmological backgrounds.

Results from string perturbation theory

Liu,Moore,Seiberg

- One can compute the S-matrix from one cone to the other.

- For generic kinematics the amplitudes in classical string theory are finite (while they diverge in GR).

  This may be attributed to the softness of strings at high energies.

- For special kinematics (near forward scattering) the string amplitudes diverge.

Origin of the divergence

Liu, Moore, Seiberg
Horowitz, Polchinski
Lawrence
Martinec, McElgin

- Since the background depends on time, energy is not conserved.
- The energy of an incoming particle is blue shifted to infinity by the contraction at the singularity.
- The infinite energy generates infinitely large gravitational field and distorts the geometry.
- String perturbative expansion breaks down as a result of large backreaction.

Lessons

- Classical string theory is singular in time dependent singular orbifolds.

- The extended nature of strings is not sufficient to resolve the singularity.

- Need to understand the full (non-perturbative) quantum theory to explain the physics at the singularity.

Implication for a non-singular bounce?

- The idea of going from a big crunch to a big bang through a non-singular bounce has a long history:

  30's Einstein, Tolman ……

- The singularity theorems of Hawking and Penrose ruled out this possibility in general relativity.
- The recent suggestions that the universe passes through the singularity is motivated by the orbifold construction of string theory.
- We now see that classical string theory is also singular and cannot be trusted.

Summary

- String theory is a promising candidate for a consistent theory of quantum gravity.
- Certain singularities in GR are resolved in perturbative string theory, while others are resolved by invoking non-perturbative degrees of freedom.
- Understanding the cosmic singularities is a big challenge for string theory. String theory has the potential to make important progress in cosmology by addressing this question.
- Our investigation indicates one needs to develop new non-perturbative tools to solve this problem.