

The Quantum Space-Time

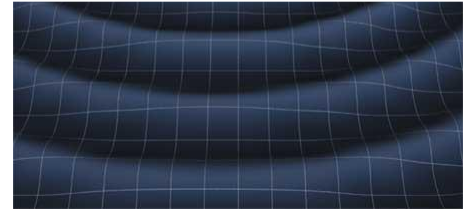
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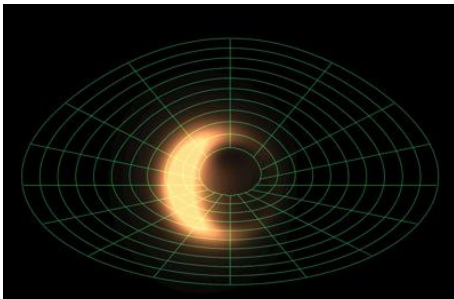
Institute for Advanced Study

Classical Spacetime

- General Relativity \rightarrow dynamical spacetime
(vibrations \rightarrow gravity waves)



- Two surprises:
 - The expanding universe
 - Black holes



Einstein to Lemaitre: "Your math is correct,
but your physics is abominable."

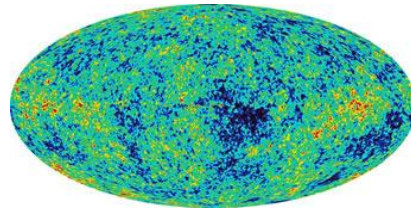
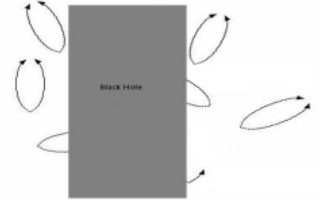


Quantum spacetime

- Nature is Quantum mechanical \rightarrow must quantize spacetime.
- Quantizing gravity waves \rightarrow easy (like the electromagnetic field) (collection of harmonic oscillators).
- Low energy interactions of these waves uniquely fixed by consistency of the theory
(GR as the unique theory of interacting spin 2 massless particles).
- Quantum fields on a fixed background

Two surprising predictions

- Black holes are hot. They have an entropy
- Inflation produces primordial density fluctuations.
- Almost scale invariant.



Both change dramatically the physics of the system. The latter has been experimentally seen.

(Inflationary gravity waves would be a more direct experimental test of quantum gravity).

Quantization at low energies

- Effective interaction strength

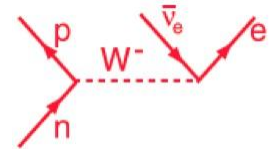
$$g_{eff}^2 \approx G_N E^2 \approx \frac{E^2}{M_{pl}^2}$$

Size of quantum
gravity corrections

- Tree and loop diagrams treated as a low energy effective field theory.
- Like Fermi's theory
- Fails at Planckian energies
- Fails for non perturbative precision.

UV completion in quantum field theory

- For the Fermi theory we have the electroweak theory that defines the theory at high energies.



- In field theory: The theory is defined at short distances, where the “fundamental” description lies.

In Gravity

- Naively local lagrangian
- But cannot prove short distances due to black holes.

- Information bound:

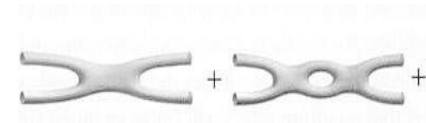
$$S \leq \frac{Area}{l_{pl}^2}$$

Perturbative string theory

- New length scale and coupling

$$l_s \quad g l_s = l_{pl}$$

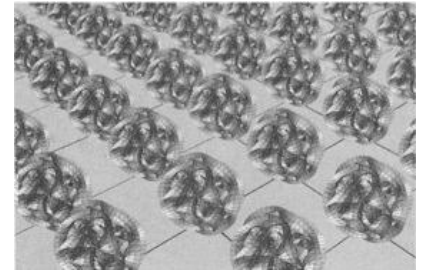
- Finite perturbation series for computing the S-matrix



- Simplest: 10 dimensional and supersymmetric
- No parameters: g = vacuum expectation value of a field

Stringy geometry and unification

- New notion of geometry: Stringy geometry
- T-duality: $R \sim \frac{l_s^2}{R}$
- Unified description of matter and spacetime



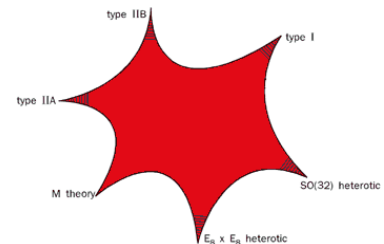
- Compactification \rightarrow Gauge fields, chiral matter, etc.

Beyond Perturbation theory?

- There is huge amount of evidence that there is an exact theory (“string theory”), whose approximation is perturbative string theory.
- Non-perturbative corrections at weak couplings \rightarrow D-branes and Instantons. (Low energy scattering of gravitons can be computed exactly)



- Strong/weak coupling dualities $g \rightarrow 1/g$.
- All string theories are connected by such dualities. Unique theory. Different classical limits.



Beyond perturbation theory

- Many important problems lie beyond perturbation theory:
 - Initial cosmological singularity
 - Graviton scattering at Planckian energies
 - Describing black hole evaporation in a unitary fashion
- Observables ? All roughly localized ones seem fundamentally approximate.
- Simple spacetimes: Asymptotically flat or AdS.
- Good observables in the asymptotic region: S-matrix.

Describing quantum spacetimes exactly

- Based on the existence of D-branes
- Matrix theory \rightarrow some flat spacetimes.
- Gauge/gravity duality \rightarrow AdS spaces.
- The spacetime physics is extracted from a well defined quantum mechanical system with no gravity.



Hyperbolic space



Simplest negatively curved space.

Spatial inflation

With time : Anti-de-Sitter space (or de Sitter)

Quantum hyperbolic space, or AdS



Quantum mechanical spacetime

Boundary

Conformal gauge theory

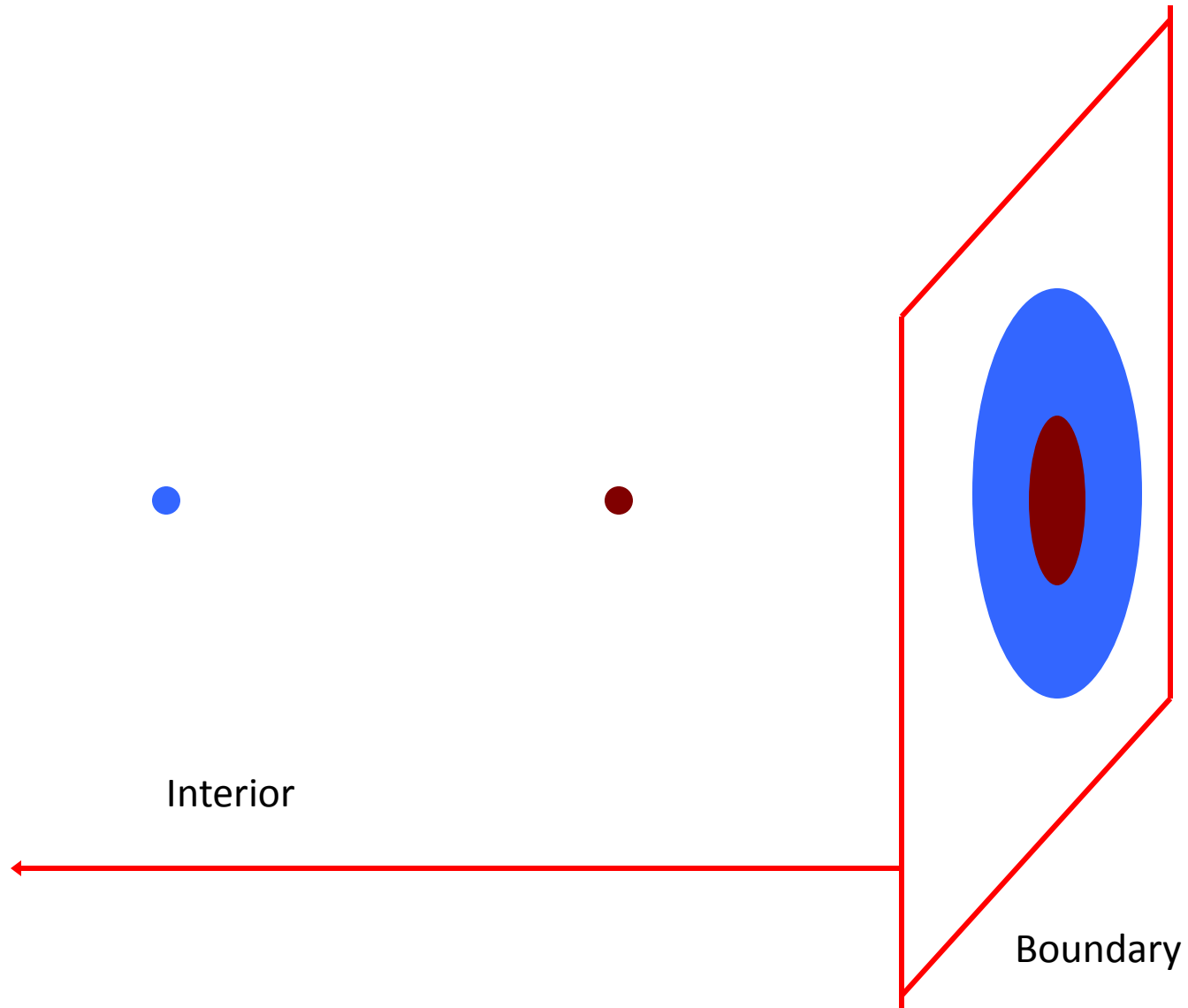
Similar to Chromodynamics

(e.g. $\mathcal{N}=4$ Super Yang Mills = maximally
Supersymmetric Chromodynamics).

Interior: quantum mechanical spacetime.

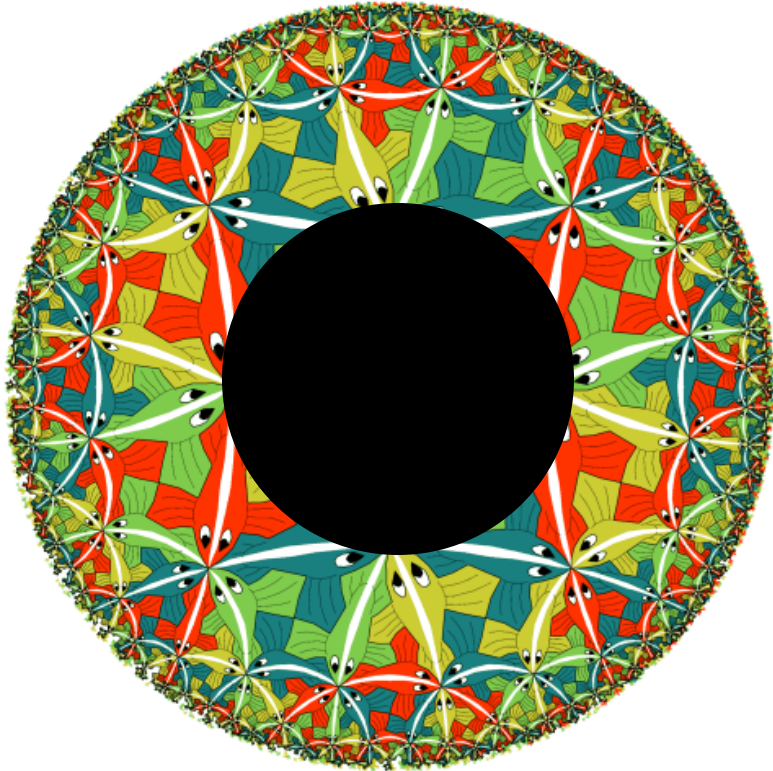
String theory on $AdS_d \times M^{10-d}$

Emergent space



Black holes in AdS

Thermal configurations in AdS and on the boundary



Entropy:

$$S_{\text{GRAVITY}} = \text{Area of the horizon} = \\ S_{\text{FIELD THEORY}} = \\ \text{Log[Number of states]}$$

Waves falling into black hole \rightarrow hydrodynamics and dissipation in the boundary theory.

Evolution: Unitary

Solves the information problem

The information problem

- Form a black hole with a pure state
- Let the black hole evaporate
- Pure state \rightarrow Thermal radiation. Information about the state lost.
- Not compatible with unitary evolution in quantum mechanics.

The information problem

- Information is lost to all orders in perturbation theory (2d models)
- This is no problem. Information could be preserved if we did the computation with non perturbative accuracy.
- To check whether it is lost or not one needs to do a non-perturbatively accurate computation. (Could be done using the field theory)
- What was “wrong” in Hawking’s argument?: not accurate enough.
- The gauge/gravity duality shows, via the boundary theory, that information is preserved.
- Questions: - Can we see the preservation of information from the bulk point of view?
 - How do we describe the interior ?

Some Lessons

- Spacetime is emergent and approximate.
- Holographic bounds are obeyed, and essential for the relation to work.
- Boundary conditions in AdS \rightarrow give lagrangian of theory. Physics is determined by the spacetime geometry far away (Mach's principle).

- Any quantum theory has a gravity dual (possibly strongly coupled...)
- Some field theories have a weakly coupled dual, described by ordinary geometry. (Understanding the classical limit)

Two necessary conditions:

Large number of degrees of freedom

Strong interactions.

- Could we classify all CFT's, and in particular the ones with gravity duals ?
- There is a UV/IR connection. Long distances in bulk \rightarrow short distances on the boundary. This relates ``cosmic'' scale invariance to the scale invariance we have in critical phenomena.

String theory and the real world

- String theory has four dimensional vacua that have features similar to nature: gauge fields, chiral matter, inflation, etc. Top down unification.
- It has enough vacua that one with a low value of the cosmological constant is very likely to exist.
- Physics that governs QCD is the same as the one governing spacetime! Sideways unification. (Force giving mass to the apple is the same as the one attracting it to the earth)
- Scale invariance at cosmic scales and at microscopic scales are related...

Unsolved problems

- How to describe a spacetime with a big bang singularity. Interior of black holes.
- Measure problem in cosmology (Guth).
- Getting some prediction for the spectrum of particles/inflation/dark energy from string theory.
- More surprises and unexpected predictions.

Measure problem

- Is it necessary to modify the formalism of QM? (Supplying extra ad-hoc measures).
- In ordinary physics, the microscopic description plus a choice of state is enough to give a “measure”.
- The nicely theoretically motivated “Hartle-Hawking” wavefunction seems too strongly favor universes different from ours. (This is true even when we apply it to the inflationary region only).



A falsifiable prediction of string theory

- Quantum mechanics should be valid for ordinary localized experiments we normally perform.
- It is falsifiable by any table top experiment.

Evidence for string theory

- There is great deal of evidence that there exists a full quantum theory, ``string theory'', describing the quantum mechanics of spacetime.
- It passes many physical consistency checks: Lorentz invariance, unitarity, reproduces the low energy effective field theory approximation, etc.
- Mathematical consistency checks: Physical consistency gives rise to non-trivial mathematical identities that are end up being correct.
- In many special cases it can be defined exactly, beyond perturbation theory.
- Intimate connection with field theory.
- Unification of spacetime and matter.
- Unification of gauge theory and gravity. Gauge fields giving rise to spacetime. (falling apples and the moon)
- Strings of QCD and quark gluon plasma can be interpreted as a particular corner of string theory.
- It is almost certain that string theory as a full consistent mathematical structure exists.

