Emergent Spacetime

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Legal disclaimers

- I'll outline my points of confusion.

- There will be many elementary and well known points.

- There will be overlap with other speakers.

- Not all issues and all points of view will be presented.

- The presentation will be biased by my views and my own work.

- There will be no references.

Outline

- Ambiguous space
- Comments about locality
- Nonstandard theories without gravity from string theory
- Derived general covariance
- Examples of emergent space
  - Without gravity
  - With gravity
- Emergent time
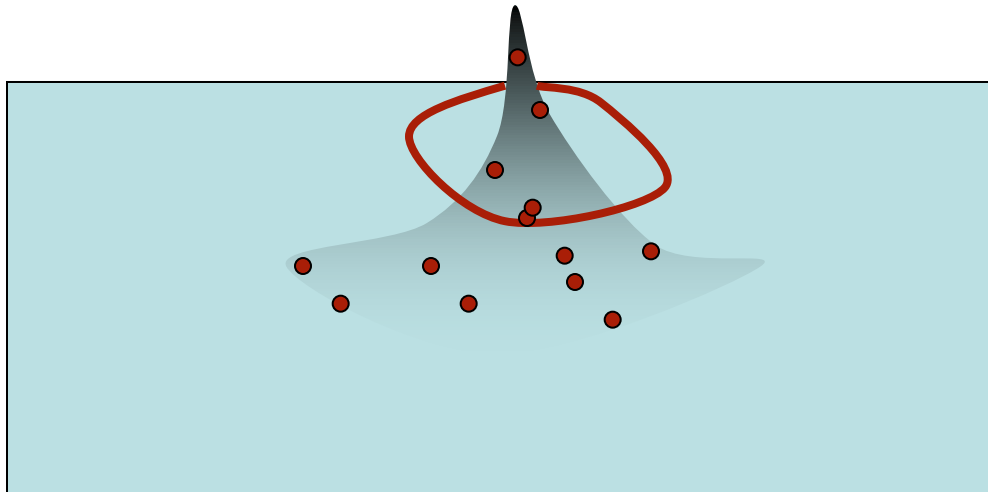- End of standard reductionism?
- Conclusions

Ambiguous space

- Ambiguous geometry/topology in classical string theory – T-duality
- Peculiarities at the string length
- Ambiguous space due to quantum mechanics
- Ambiguous noncompact dimensions
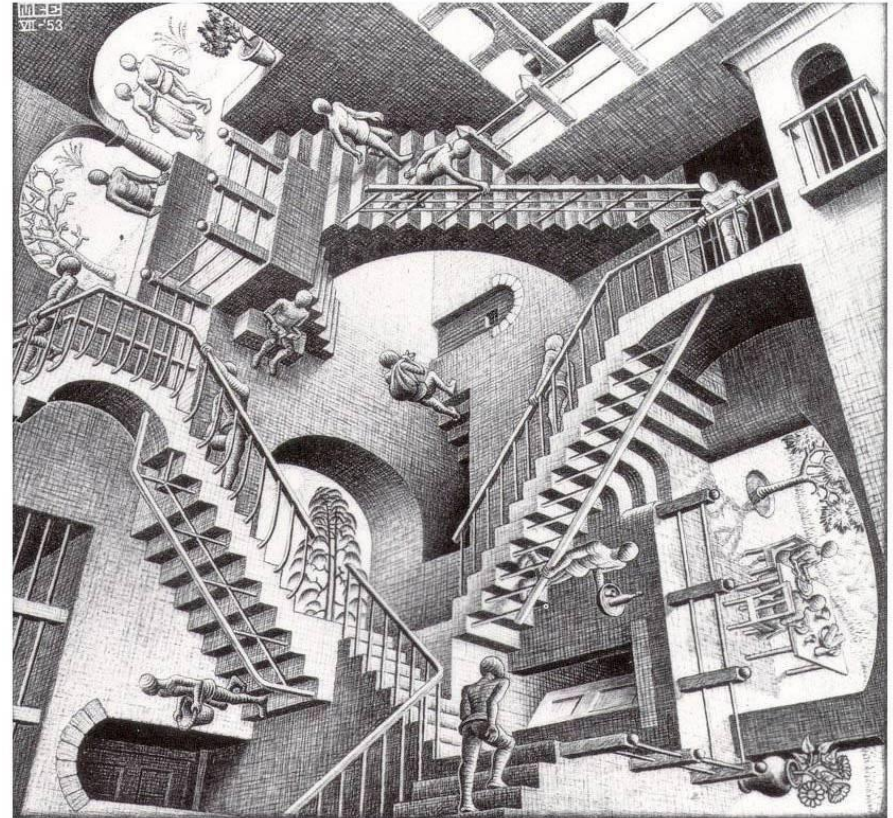
Ambiguous space in classical string theory

Because of its extended nature, the string cannot explore short distances.
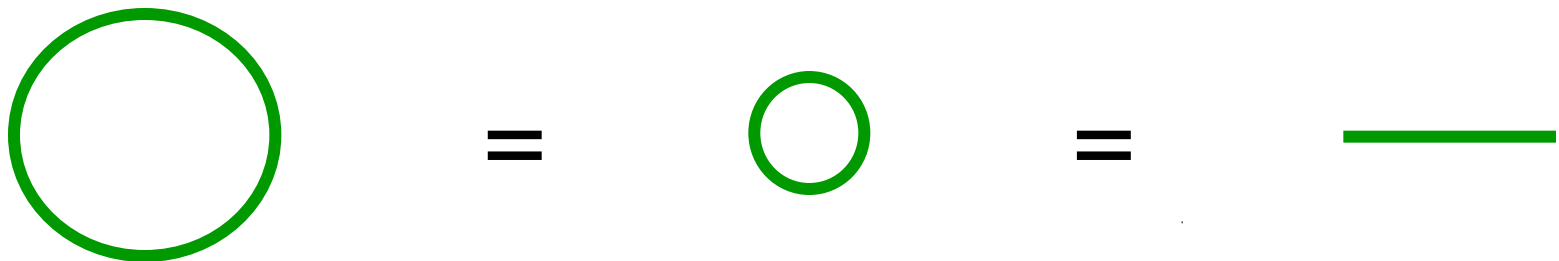

String length $l_s = \sqrt{\alpha'}$

T-duality

T-duality: geometry and topology are ambiguous at the string length $l_s = \sqrt{\alpha'}$.

T-duality is a gauge symmetry. Hence, it is exact.

Simple examples:

- A circle with radius R is the same as a circle with radius $\frac{\alpha'}{R}$.

- A circle with $R = 2\sqrt{\alpha'}$ is the same as its orbifold with $R = \sqrt{\alpha'}$.

# Examples of T-duality (cont.)

More complicated and richer examples: mirror symmetry and topology change in Calabi-Yau spaces.

Related phenomenon: the "cigar geometry" is the same as an infinite cylinder with a nonzero condensate of wound strings.
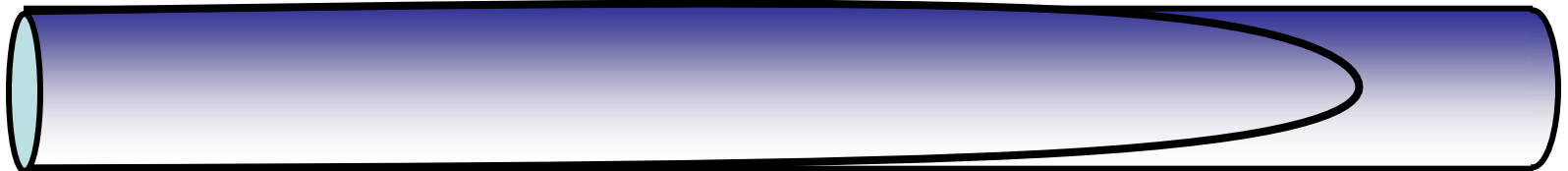
Peculiarities at the string length

- Locality of string interactions is not obvious (centers of mass are not at the same point).
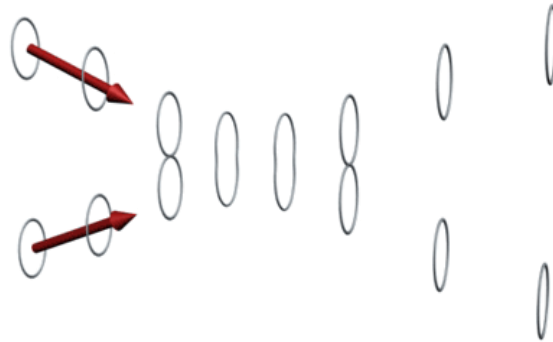
- Do we expect locality in the space or in its T-dual (importance of winding modes)?

- Is $l_s = \sqrt{\alpha'}$ a minimum length?

Peculiarities at the string length (cont.)

- Hagedorn temperature

  Is it a maximal temperature or a signal of a phase transition?

  It is associated with the large high-energy density of states, long strings, winding modes around Euclidean time.
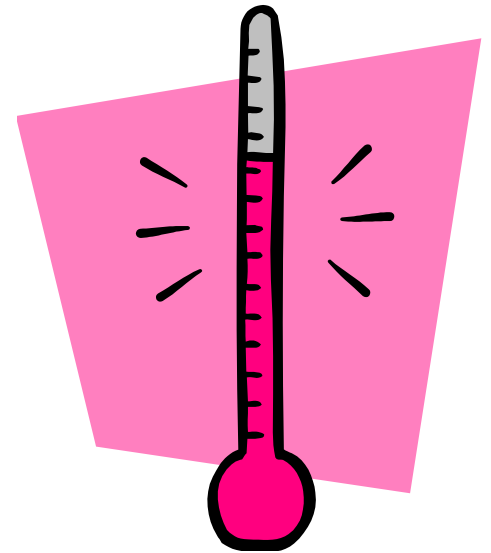
- Maximal acceleration
- Maximal electric field due to long strings

Ambiguous space in quantum string theory

Space is ambiguous at the Planck length $l_p \ll l_s$.

For resolution r we need to concentrate energy
$E > 1/r$, in a region of size r, but this creates
a black hole unless $r > l_p$.

This leads to new ambiguities – other dualities change
the string coupling, exchange branes, etc.

In all these ambiguities: higher energy does not lead
to better resolution; it makes the probe bigger.

Ambiguous noncompact dimensions: locality in AdS

- Obvious at the boundary

- Subtle in the bulk

- Because of the infinite warp factor, possible violation of locality in the bulk (with distances of order l_s) could be consistent with locality at the boundary.

- What exactly do we mean by locality, if all we can measure are observables at infinity?

Ambiguous noncompact dimensions: linear dilaton backgrounds

Linear dilaton backgrounds (*e.g. c ≤ 1* string theories):

$$\xrightarrow{\hspace{8cm}} \phi$$

Weak coupling   Strong coupling
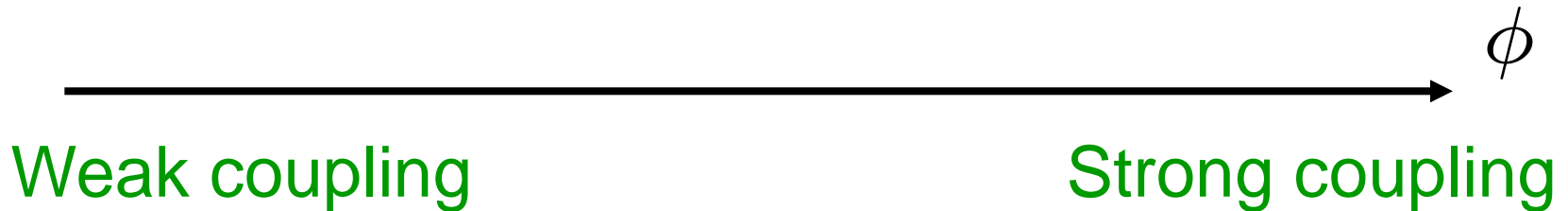
- Liouville direction ϕ
- Other nonlocal coordinates (*e.g.* Backlund field in Liouville theory – it is "T-dual" of ϕ)
- Eigenvalue space in the matrix model

In which of them do we expect locality?

The cosmological constant

$$\Lambda$$
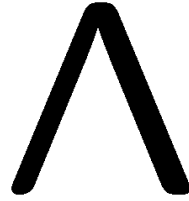
Old fashioned point of view:

The issue of the cosmological constant might be related to UV/IR mixing and to violation of naive locality.

More modern point of view:

Λ is set anthropically.

Comments about locality

- Ambiguities in space and UV/IR mixing – increasing the energy does not lead to better resolution, but rather makes the probe bigger.

- Should we expect locality in the space, or in its dual space, or in both, or in neither?

- We would like to have causality (or maybe not?).

- Locality leads to causality.

- Analyticity of the S-matrix is consistent with locality/causality, but is this the only way to guarantee it?

- There are no obvious diagnostics of locality.

Non-standard theories without gravity

- Local field theories without Lagrangians (*e.g.* six-dimensional (2,0) theory)

- Field theories on noncommutative spaces – UV/IR mixing (objects get bigger with energy)

- Little string theory
  - It has T-duality
  - Does it have an energy momentum tensor?
  - Is it local?
  - Does it exist above a thermal phase transition?

Derived general covariance

General covariance is a gauge symmetry

- Not a symmetry of the Hilbert space

- Redundancy in the description

- Experience from duality in field theory shows that gauge symmetries are not fundamental – a theory with a gauge symmetry is often dual to a theory with a different gauge symmetry, or no gauge symmetry at all.

- This suggests that general covariance is not fundamental.

Derived general covariance (cont.)

- Global symmetries cannot become local gauge symmetries. This follows from the fact that the latter are not symmetries, or more formally, by a theorem (Weinberg and Witten).

- In the context of general covariance, this shows that if general covariance is not fundamental, the theory does not have an energy momentum tensor.

- Spacetime itself might not be fundamental.

Derived general covariance (cont.)

General relativity has no local observables and perhaps no local degrees of freedom.

- What do we mean by locality, if there are no local observables?

- There is no need for an underlying spacetime.

Examples of emergent space
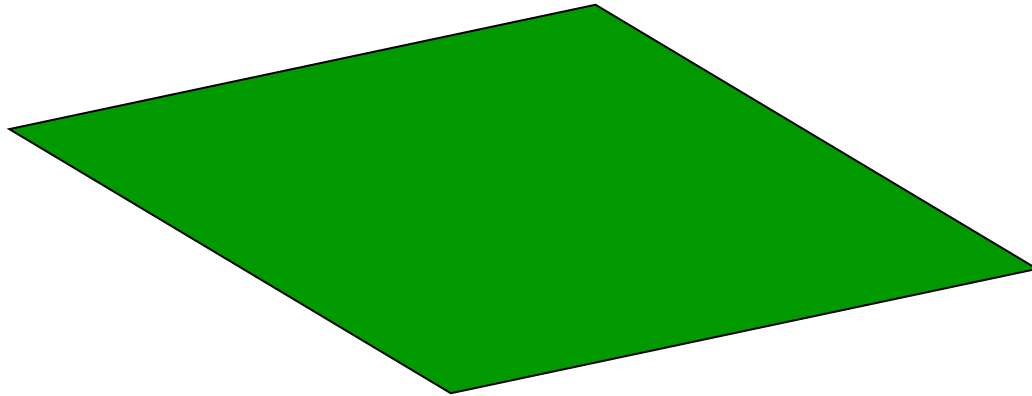
Without gravity

- Eguchi-Kawai
- Noncommutative geometry
- Myers effect
- Fuzzy spaces
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-

With gravity

- $c \leq 1$ matrix models
- BFSS matrix model
- AdS/CFT
- Near AdS/CFT
- Linear dilaton
-
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# Emergent space without gravity

In all these examples a collection of branes in background flux makes a higher dimensional object.

Emergent space with gravity from a local quantum field theory: Gauge/Gravity duality

String theory in AdS and nearly AdS backgrounds is dual to a local quantum field theory on the boundary.

This QFT is holographic to the bulk string theory.
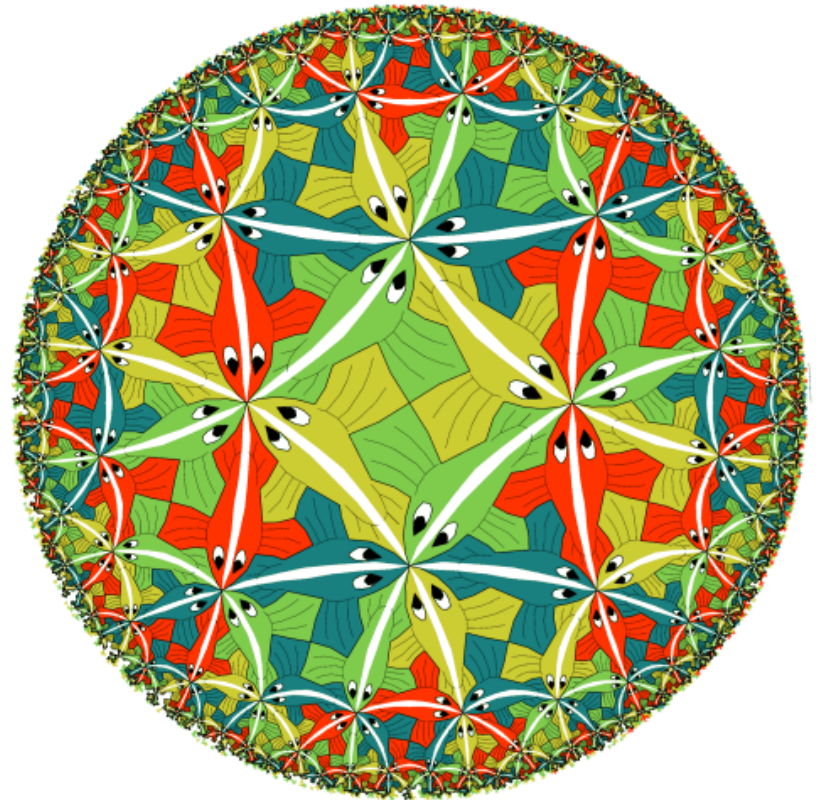
Gauge/Gravity duality (cont.)

Correlations functions in the boundary field theory are string amplitudes with appropriate boundary conditions in the bulk theory.

The radial direction emerges out of the boundary field theory. It is related to the energy (renormalization) scale.

This has led to many new insights about gauge theories, about gravity, and about the relation between them.

Gauge/Gravity duality (cont.)

Finite distances in the field theory correspond to infinite distances in the bulk – the warp factor diverges at the boundary.

For example, finite temperature in the boundary theory corresponds to very low temperature in most of the bulk (except a finite region of size R_{AdS}).

Possible violation of locality on distances of order l_s in the bulk might be consistent with locality at the boundary.

Emergent space with gravity: linear dilaton backgrounds

Most linear dilaton theories are holographic to a nonstandard (likely to be nonlocal) theory, *e.g.* little string theory.

The linear dilaton direction is noncompact, but the interactions take place in an effectively compact region (the strong coupling end). The boundary theory is at the weak coupling end.

$\longrightarrow$

Weak coupling   Strong coupling

Linear dilaton backgrounds (cont.)

Finite distances in the boundary theory are finite distances (in string units) in the bulk.

For example, finite T in the boundary theory is dual to finite T in the entire bulk.

The boundary theory has nonzero α' and is stringy.

- It has T-duality.
- It does not appear to be a local field theory.
- It might have maximal temperature.

Special linear dilaton backgrounds: d =1, 2 string theory

- *c < 1* string theories describe one dimensional backgrounds with a linear dilaton. The holographic theories are matrix integrals.

- *c = 1* string theories describe two dimensional backgrounds with time and a linear dilaton space.
  - The holographic theories are matrix quantum mechanics (they are local in time).
  - Finite number of particle species
  - Upon compactification of Euclidean time (finite T), there is T-duality but no Hagedorn transition.

d =1, 2 string theory (cont.)

- 2d heterotic strings also have a finite number of particles.
- Upon compactification of Euclidean time, there is T-duality with a phase transition.
- The transition has negative latent heat – it violates thermodynamical inequalities.
- Interpretation:

    Euclidean time circle ≠ finite T.

    This reflects lack of locality in Euclidean time.
- This nontrivial behavior originates from long strings.

Emergent space in the BFSS matrix model

Here we start with D0-branes, but their positions in space are not well defined. They are described by matrices.

One spacetime direction, x^-, emerges holographically. Locality in x^- is mysterious.

The transverse coordinates, x^i, emerge from the matrices. They are meaningful only when the branes are far apart, *i.e.* the matrices are diagonal.

Comment about emergent space

It seems that (almost) every theory, every field theory, every quantum mechanical system and even every ordinary integral defines a string theory.

So the question is not: What is string theory?

Instead, it is: Which string theories have macroscopic dimensions?

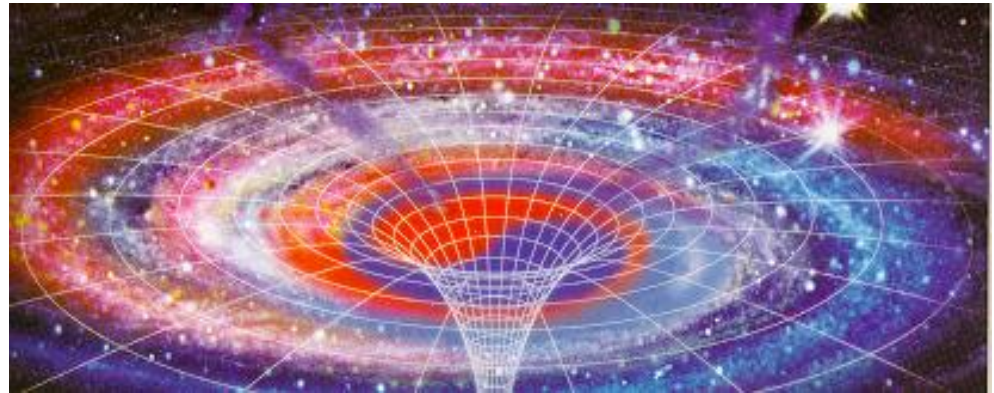Tentative answer: those with large N and almost certainly other elements.

Emergent time

- Space and time on equal footing; if space emerges, so should time.

- Expect:
  - Time is not fundamental.
  - Approximate (classical) notion of macroscopic time
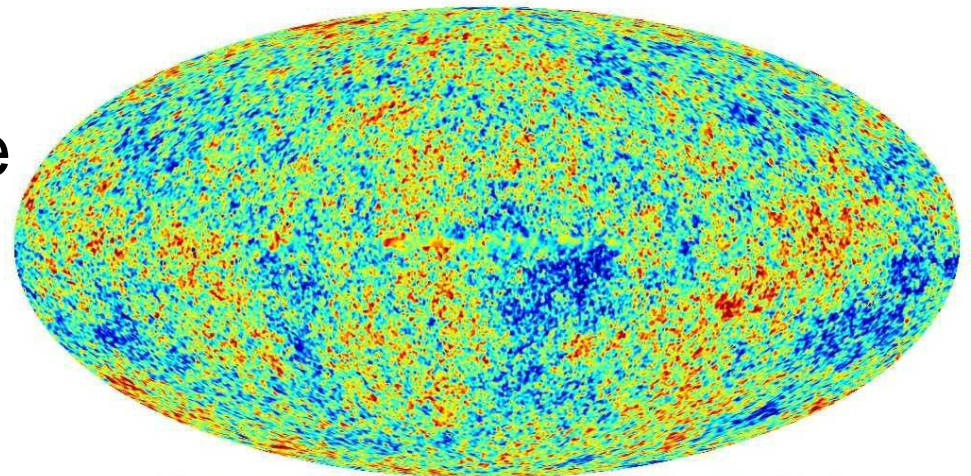 - Time is fuzzy (ill defined) near singularities.
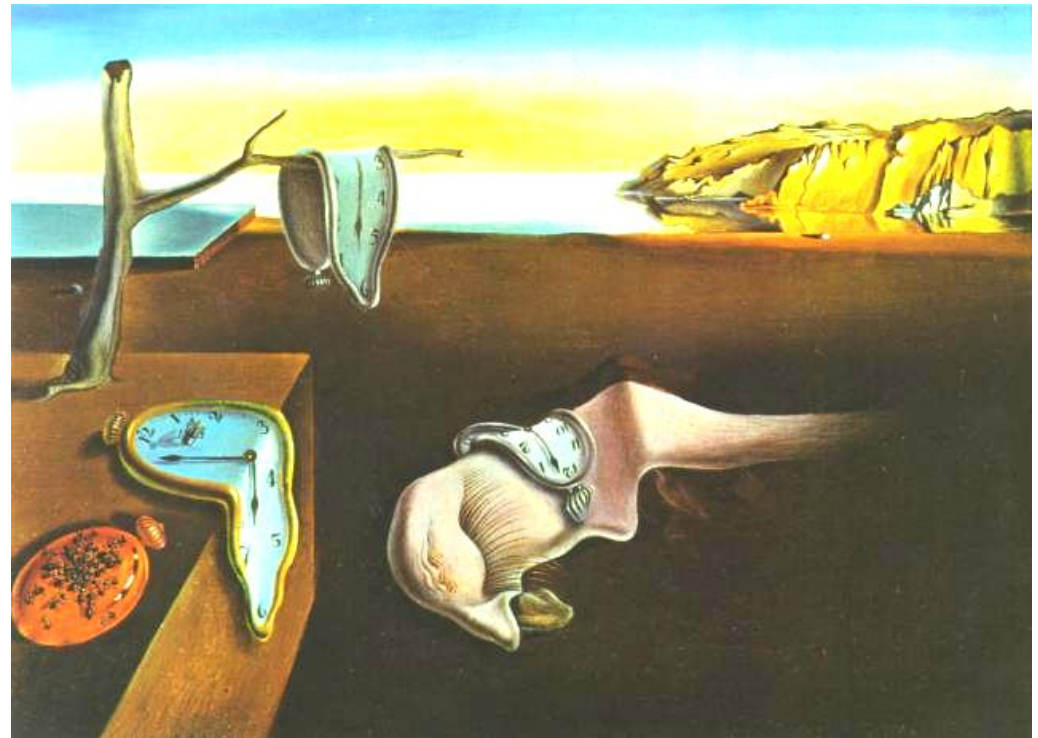
Applications of emergent time

- Black hole singularity

- Cosmological singularities
  - Early Universe
  - Wave-function of the Universe
  - Vacuum selection (landscape)

Emergent time – challenges

- We have no example of derived time.

- Locality in time is more puzzling because of the relation to causality.

- Physics is about predicting the outcome of an experiment before it is performed (causality). What do we do without time?

- How can things evolve without time?

- How is a timeless theory formulated?

Emergent time – challenges (cont.)

- What is a wave-function? What is its probabilistic interpretation?

- Is there a Hilbert space?

- What is unitarity (cannot have unitary evolution because there is no evolution)?

Prejudice: these are challenges

or clues, rather than obstacles

 to emergent time.

End of standard reductionism?

- We all like reductionism: science at one length scale is derived (at least in principle) from science at smaller scales.

- If there is a basic length scale, below which the notion of space (and time) does not make sense, we cannot derive the principles there from deeper principles at shorter distances.

Conclusions

- Spacetime is likely to be an emergent, approximate, classical concept.

- The challenge is to have emergent spacetime, while preserving some locality (macroscopic locality, causality, analyticity, etc.).

- Understanding how time emerges will shed new light on the structure of the theory.

- Understanding time will have profound implications for cosmology.