Title: Holographic Cosmology

Speakers: Paul McFadden

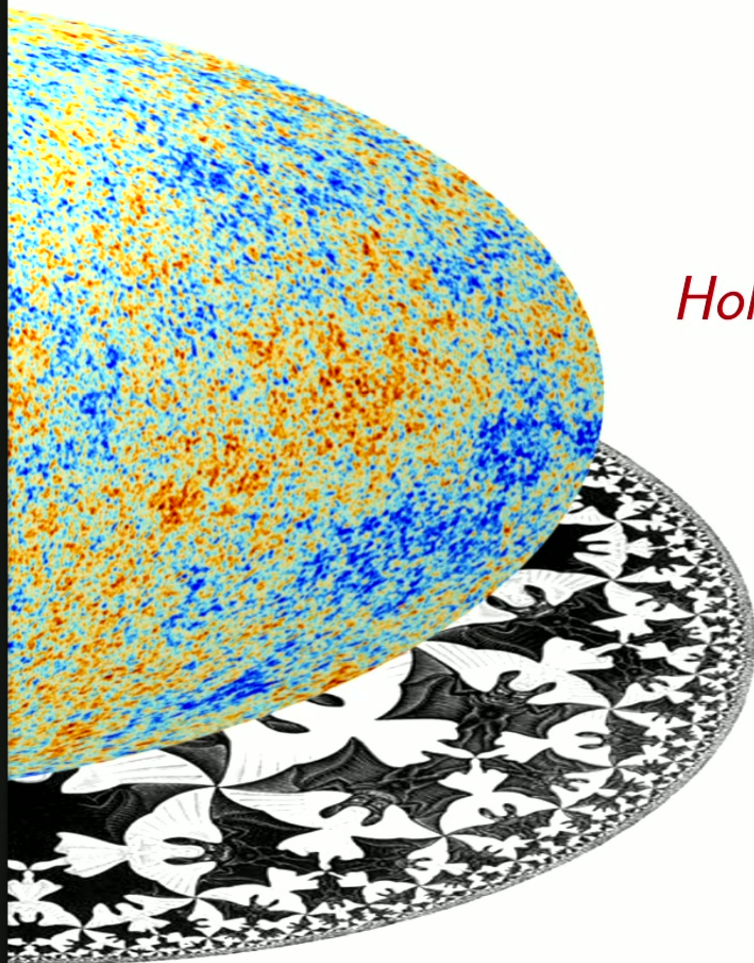
Collection: Quantum Spacetime in the Cosmos: From Conception to Reality

Date: May 10, 2023 - 3:30 PM

URL: https://pirsa.org/23050124

Abstract: Holography has profoundly transformed our understanding of quantum gravity in spacetimes with asymptotic negative curvature. Its implications for cosmology are equally profound, suggesting that time is emergent and that our universe has a dual description in terms of a three-dimensional quantum field theory. This talk will outline key features of holographic cosmology, from the perspective it offers for the cosmic singularity to the strategies it presents for computing cosmological observables. Recent results for the de Sitter wavefunction will be discussed and their interpretation in the language of three-dimensional conformal field theory.

Zoom Link: https://pitp.zoom.us/j/98277900018?pwd=SW92OWYrRFpkWC9QOS9NeTlQWkY5dz09



Holographic Cosmology

Paul McFadden

Newcastle University

Quantum Spacetime in the Cosmos:
From Conception to Reality

Perimeter Institute 2023

Plan

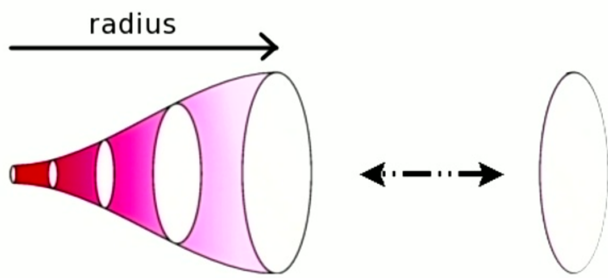
This talk has two parts:

1. Holographic cosmology: the big picture
2. de Sitter correlators from the boundary perspective

Holography

String theory and black hole physics have taught us that gravity is holographic:

Gravitational physics has a completely equivalent *dual description* in terms of a quantum field theory, without gravity, *living in one dimension fewer.*



$(d+1)$-dimensional spacetime

(the 'bulk')

d-dimensional QFT

(the 'boundary')

Holography

For a QFT living on a flat metric $\mathrm{d}s^2 = \mathrm{d}\boldsymbol{x}^2$, the bulk spacetime is

$$\mathrm{d}s^2 = \mathrm{d}r^2 + a^2(r)\mathrm{d}\boldsymbol{x}^2 \qquad \text{'domain-wall'}$$

For the following asymptotic geometries, there is a complete *top-down* microscopic description from string theory:

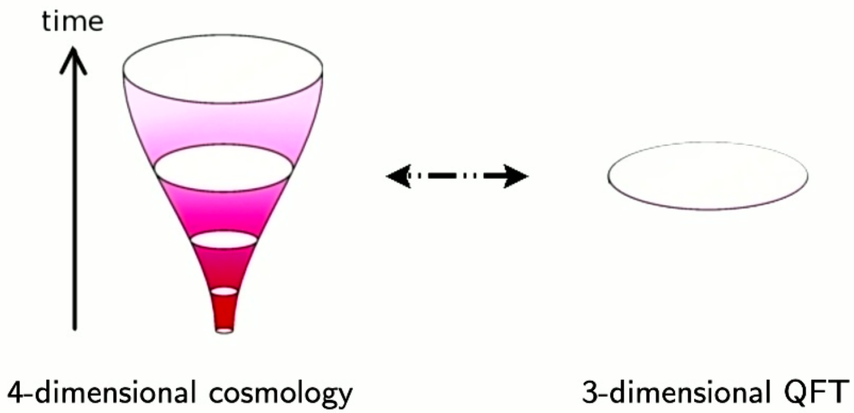
- anti-de Sitter: $a \to e^r$ as as $r \to \infty$ (the AdS/CFT correspondence)
- power-law: $a \to r^n$ for specific $n > 1$

A well-established holographic dictionary relates the asymptotic fall-off of bulk fields to observables (such as correlation functions) in the dual QFT.

Holography

However, gravity is thought to be holographic regardless of the asymptotics...

... meaning there should be a holographic description for cosmology:



The emergent direction is now time-like rather than space-like.

QFT observables are determined from the late-time fall-off of bulk fields...

... and vice versa.

Holography for cosmology

In the absence of a top-down construction from string theory, one can pursue a *bottom-up* approach via analytic continuation of domain-walls to cosmologies:

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\mathrm{d}\boldsymbol{x}^2$$

At late times $t \to \infty$, the scale factor $a(t)$ is either

- asymptotically de Sitter: $a \to e^t$
- asymptotically power-law: $a \to t^n$ where $n > 1$

As these are inflationary spacetimes, this suggests using holography to model the generation of primordial perturbations.

'Late time' $\longrightarrow$ the end of the inflationary epoch.

Modelling dark energy may also be a possibility.

Holography for cosmology

The nature of the dual QFT is *not* understood from a string theory perspective.

Nevertheless, one can set up a working holographic correspondence to all orders in perturbation theory. (i.e., in bulk loops, or $1/N$ in dual QFT)

This operates by analytically continuing metric perturbations from domain wall spacetimes to cosmologies.

- The cosmological observables relevant for the CMB are correlators of primordial perturbations ζ, γ_{ij}.
- These can be obtained from QFT correlators of T_{ij} by analytically continuing the momenta (and N) to 'unphysical' values.

Similar in spirit to map from CFT correlators $\rightarrow$ scattering amplitudes.

Holographic formulae

For example, the scalar and tensor power spectra are given by

$$\Delta_S^2(q) = \frac{-q^3}{16\pi^2 \mathrm{Im} B(-iq)}, \qquad \Delta_T^2(q) = \frac{-2q^3}{\pi^2 \mathrm{Im} A(-iq)},$$

where

$$\langle\langle T_{ij}(q) T_{kl}(-q) \rangle\rangle = A(q)\Pi_{ijkl} + B(q)\pi_{ij}\pi_{kl}$$

where π_{ij} is the transverse and Π_{ijkl} the transverse traceless projector.

Similar formulae are available for non-Gaussianities at 3-points.

[PM, Skenderis '09-'11]

Significance

What can a holographic perspective offer?

1. New ‘boundary’ approaches to computing inflationary observables.

   Based on 3d conformal field theory methods.

2. Alternatives to inflation offering a potential resolution of the big bang singularity, that are predictive, falsifiable – and fit current Planck data.

Both traditional inflation and these alternatives can be modelled in the same holographic framework.

The difference lies in the fate of the dual QFT under RG flow.

RG flow

In holography, *inverse* radial or time evolution in the bulk corresponds to renormalisation group flow in the dual QFT:

Near boundary/late times → Deep interior/early times
= UV of QFT → = IR of QFT

RG flow integrates out degrees of freedom reducing entropy, consistent with cosmic arrow of time.

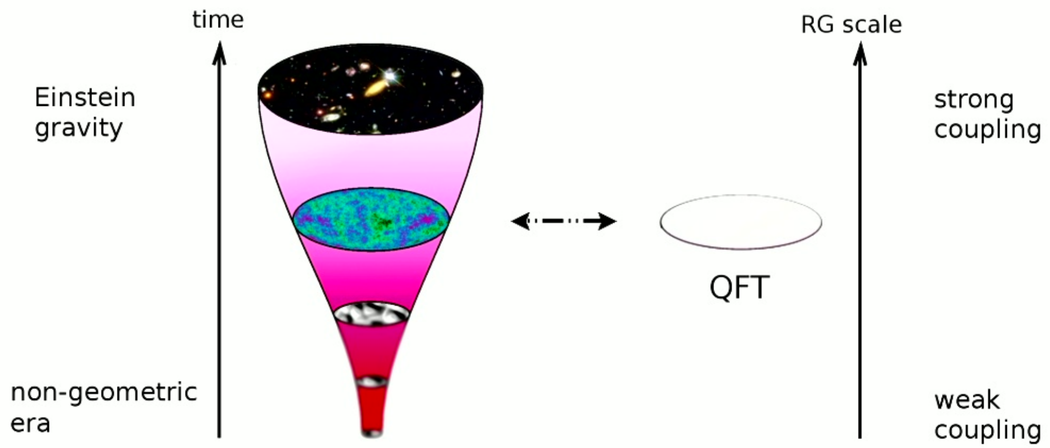
The dual QFT has a coupling that measures the strength of interactions:

- When strongly interacting, the gravitational theory is geometrical.
  (i.e., Einstein gravity)
- When weakly interacting, the gravitational theory is non-geometric.

Strong vs weak

Standard inflation corresponds to the dual QFT being strongly interacting both in the UV *and* the IR, corresponding to Einstein gravity at all times.

A new possibility arises if the dual QFT becomes weakly interacting in the IR:



Singularity resolution

The big bang singularity is a consequence of extrapolating a geometric description of spacetime back to the earliest of times.

If geometry breaks down at early times, ask instead:

$\longrightarrow$ are all observables in the dual QFT infrared finite?

A nontrivial question...

For massless super-renormalisable 3d QFTs, IR divergences arise within perturbation theory but are thought to vanish following large-N re-summation.

$[g^2_{\mathrm{YM}}] = 1$ and acts as IR regulator.

For vector matter: [Appelquist & Pisarski '81; Jackiw & Templeton '81]

For adjoint matter, currently being tested via lattice QFT simulations.

[e.g., 2009.14768, LATCos Collaboration]

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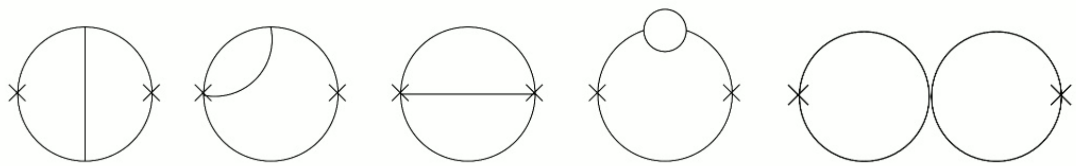
Non-geometric models

We can make *observational predictions* for the CMB via Feynman diagrams.

3d QFT $= SU(N)$ Yang-Mills + scalars + fermions + interactions

Matter content and interactions constrained by a symmetry principle but otherwise parametrised phenomenologically and fitted to data.



Full predictions for the CMB power spectra & non-Gaussianities.

- large $N \gg 1 \Rightarrow$ small amplitude of power spectrum $\Delta_S^2 \propto N^{-2}$
- weak coupling $g_{\rm eff}^2 = \dfrac{g_{\rm YM}^2 N}{q} \ll 1 \Rightarrow$ near-scale invariant $n_S - 1 \propto g_{\rm eff}^2$.

Moreover, the *shape* of the power spectrum is different to inflationary models...

[Bzowski, PM & Skenderis '09-'11]

Holographic models vs power-law ΛCDM

[Afshordi, Coriano, delle Rose, Gould, Skenderis '17]