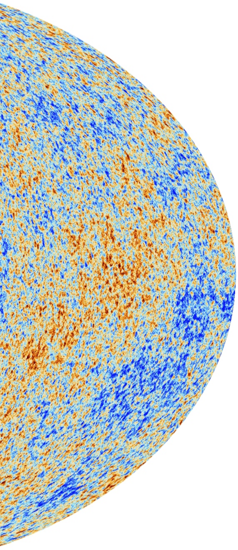

Holographic inflation

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Introduction

- Over the last two decades, striking new observations have transformed cosmology from a *qualitative* to a *quantitative* science.
- A minimal set of just six parameters characterizes the observed universe, all of which are now known to within a few percent.
- This presents a unique window to Planck-scale physics and as such it could provide important clues/constrains about the fundamental theory.

The Planck results

From the Planck Press Release:

> *Planck reveals an almost perfect Universe*
>
> Overall, the information extracted from Planck's new map provides an excellent confirmation of the standard model of cosmology at an unprecedented accuracy.

The Planck data is compatible with the simplest single scalar slow-roll inflationary models but appears to give no further clues about quantum gravity.

Introduction

In this talk, I will present a holographic description of the very early universe, the period usually associated with inflation.

- This holographic description includes:
- Conventional inflation.
- New models for the very early universe that have a weakly coupled holographic dual QFT. Such universe would be non-geometric at early times.

Main questions

There are two main questions we would like to address:

- Which of the inflationary predictions are fixed by symmetries and which are a property of the specific fundamental theory that governs the universe at early times?
- Can we use the data to constraint/falsify the new non-geometric theories for the early universe?

Holographic framework [McFadden, KS]

The underlying framework for this work is gravity coupled to a scalar field Φ with a potential $V(\Phi)$.

$$S = \frac{1}{2\kappa^2} \int d^4x \sqrt{-g}(R - (\partial\Phi)^2 - 2\kappa^2 V(\Phi))$$

The holographic framework was obtained by using the fact that

- inflationary FRW solutions of the theory with potential V are in correspondence with holographic RG flows of the theory with potential $-V$ [KS, Townsend (2006)] .
- Arbitrary fluctuations around the backgrounds are also in correspondence [McFadden, KS (2009-2012)].

Related work: (E-branes) [Hull (1998)] (dS/CFT correspondence) [Witten (2001)] [Strominger (2001)],

...(wavefunction of the universe) [Maldacena (2002)] ... (quantum cosmology) [Hartle, Hawking, Hertog (2012)] ...

Holographic inflation

- There are two classes of inflationary backgrounds that can be described holographically:

➢ spacetimes that become de Sitter at late times,

$$ds^2 \to ds^2 = -dt^2 + e^{2t} dx^i dx^i, \qquad \text{as} \quad t \to \infty$$

➢ spacetimes that become power-law at late times ,

$$ds^2 \to ds^2 = -dt^2 + t^{2n} dx^i dx^i, \quad (n > 1) \qquad \text{as} \quad t \to \infty$$

- These backgrounds are in 1-1 correspondence with holographic RG flows, either asymptotically AdS or asymptotically power-law (non-conformal Dp branes).

Dual QFT

The two classes of asymptotic behaviors correspond to two classes of dual QFT's.

- asymptotically de Sitter $\rightarrow$ QFT is a deformation of a CFT
- asymptotically power-law $\rightarrow$ QFT is super-renormalizable

We will discuss both cases.

Cosmological observables

- In cosmology we are interested in computing cosmological observables, like the power spectra and non-Gausianities.
- These can be obtained from the late-time behavior of in-in correlators.
- The power-spectra are obtained from 2-point functions, $\langle \zeta\zeta \rangle$ (scalars) $\langle \gamma^{(s_1)}\gamma^{(s_2)} \rangle$ (tensors).
- Non-Gaussianities are obtained from 3-point functions, $\langle \zeta\zeta\zeta \rangle, \langle \zeta\zeta\gamma^{(s)} \rangle, \langle \zeta\gamma^{(s_1)}\gamma^{(s_2)} \rangle, \langle \gamma^{(s_1)}\gamma^{(s_2)}\gamma^{(s_3)} \rangle$.

Holographic formulae for cosmology

- The cosmological 2-point functions are given by

$$\langle\zeta(q)\zeta(-q)\rangle = \frac{-1}{8\mathrm{Im}[B(\bar{q})]}, \qquad \langle\hat{\gamma}^{(s)}(q)\hat{\gamma}^{(s')}(-q)\rangle = \frac{-\delta^{ss'}}{\mathrm{Im}[A(\bar{q})]},$$

where $\langle T_{ij}(\bar{q})T_{kl}(-\bar{q})\rangle = A(\bar{q})\Pi_{ijkl} + B(\bar{q})\pi_{ij}\pi_{kl}$, $\bar{q} = -iq$ and we also need to take $N^2 \to -N^2$.

- Cosmological 3-point functions

$$\langle\zeta(q_1)\zeta(q_2)\zeta(q_3)\rangle = -\frac{\mathrm{Im}\left[\langle T(\bar{q}_1)T(\bar{q}_2)T(\bar{q}_3)\rangle + (\mathrm{semi-local\ terms})\right]}{256\prod_i \mathrm{Im}[B(\bar{q}_i)]}$$

- Similar formulae for all other 3-point functions.

Outline

1 Holographic slow-roll models

2 New holographic models

3 Conclusions

Holographic slow-roll inflation

We will now discuss an example [Bzowski, McFadden, KS (2012)] with the following properties

- The QFT correlation functions can be computed at strong coupling using QFT methods alone.
- It is a slow-roll model so that the cosmological results can be obtained by standard analysis.

Related work: [K.Schalm, G. Shiu, T. van der Aalst (2012)] [I. Mata, S. Raju, S. Trivedi (2012)] [Garriga, Urakawa (2013)]

QFT at strong coupling

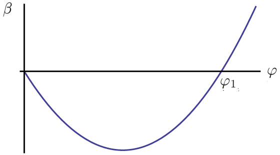
- We will use conformal perturbation theory.
- We consider a QFT specified by the action

$$S_{UV} = S_{CFT}^{UV} + \int d^3x \varphi O$$

where O is a relevant operator, which we take to have dimension $(3 - \lambda)$ and consider $\lambda \ll 1$.
- The UV CFT need not be perturbative.

Conformal perturbation theory

- The relevant deformation induces at RG-flow, whose beta function is $\beta = -\lambda\varphi + c\varphi^2 + O(\varphi^3)$.



- The flow is controlled by the OPE of O:

$$O(x_1)O(x_2) = \frac{\alpha}{|x_{12}|^{6-2\lambda}} + \frac{c}{|x_{12}|^{3-\lambda}} O(x_2) + \ldots$$

- When $c > 0$ and of order unity the β-function has a UV fixed point at the origin and a nearby IR fixed point at $\varphi = \varphi_1 = \lambda/c \ll 1$.

- Without loss of generality, we can consider a beta function that is exactly quadratic, $\beta = -\lambda\varphi + c\varphi^2$.

From QFT to gravity

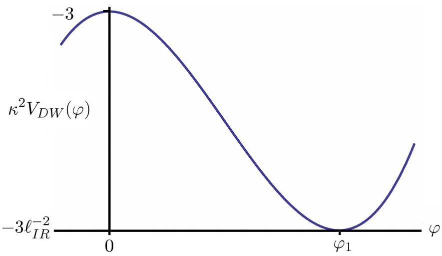
- In holography: the RG scale becomes the radial direction (time direction in the context of cosmology).
- The beta function is linked with the fake superpotential [Townsend, KS (1999)] (Hubble function in the context of cosmology [Bond, Salopek (1990)]),

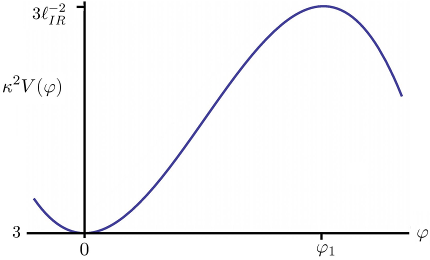
$$\beta = \partial_\varphi W(\varphi) \quad \Rightarrow \quad W(\Phi) = -2 - \frac{1}{2}\lambda\Phi^2 + \frac{1}{3}c\Phi^3,$$

- The potential is then given by [Townsend (1984)]

$$V = \frac{1}{2\kappa^2}\left((W')^2 - \frac{3}{2}W^2\right)$$

Holographic RG vs Cosmology





Holographic RG flow. The CFT is deformed by a relevant operator in the UV and flows to a nearby IR fixed.

Hilltop inflation. The inflaton field starts at the maximun of the potential at $t = -\infty$ and ends up at the minimun at $t = +\infty$.

Cosmological observables

- One can compute the slow-roll parameters at horizon exit,

$$\epsilon_* = \frac{\lambda^4}{2c^2} \frac{q^{2\lambda}}{(1+q^\lambda)^4} + O(\lambda^7), \qquad \eta_* = -\lambda + \frac{2\lambda}{1+q^\lambda} + O(\lambda^4),$$

- Cosmological observables can now be computed by applying standard formulas. For example, [Steward, Lyth (1993)]

$$\Delta_S^2 = \frac{q^3}{2\pi^2}\langle\zeta(q)\zeta(-q)\rangle = \frac{H_*^2}{8\pi^2\epsilon_*}\left(1 + 2b\eta_* + O(\lambda^2)\right)$$

Holography for slow-roll inflation

- The holographic formulas express the cosmological observables in terms of correlation functions of the dual QFT.
- Using conformal perturbation theory we can express the correlation functions of the dual QFT in terms of CFT correlation functions.
- These CFT correlation functions are uniquely fixed by conformal invariance up to a few constants.
- In this way we recover exactly the slow-roll results both for the power spectra and the non-gaussianities!
- ⇒ This includes both scalar and tensor modes.

Scalar Non-gaussianity

- The scalar non-gaussianity for slow-roll models has been worked by [Maldacena (2002)]. For the model at hand and to leading order in λ the answer is

$$\langle \zeta(q_1)\zeta(q_2)\zeta(q_3)\rangle = \frac{H_*^4 \eta_*}{16\epsilon_*^2}\left(\frac{1}{q_1^3 q_2^3} + \frac{1}{q_2^3 q_3^3} + \frac{1}{q_1^3 q_3^3}\right)$$

- In this limit the non-Gaussianity is purely of a local type with $f_{NL} = 5\eta^*/6$.
- Note that $(H_*^4 \eta_*)/(16\epsilon_*^2)$ has a complicated momentum dependence,

$$\frac{H_*^4 \eta_*}{16\epsilon_*^2} = \frac{576\, c^4}{\alpha^2 \lambda^7}\left(-1 + 2\left[1 + q^\lambda\right]^{-1}\right) q^{-4\lambda}\left[1 + q^\lambda\right]^8$$

- We would like to reproduce $\langle \zeta\zeta\zeta\rangle$ holographically.

Sketch of holographic computation

- The holographic formula relates $\langle\zeta(q_1)\zeta(q_2)\zeta(q_3)\rangle$ with $\langle T(q_1)T(q_2)T(q_3)\rangle$ and $\langle T(q)T(-q)\rangle$, where T is the trace of the stress energy tensor.
- Using Ward identities of the 3d theory the holographic formula simplifies to

$$\langle\zeta(q_1)\zeta(q_2)\zeta(q_3)\rangle = \frac{\phi\langle O(q_1)O(q_2)O(q_3)\rangle - \sum_{j=1}^{3}\langle O(q_j)O(-q_j)}{4\lambda^3\phi^4\prod_{j=1}^{3}\langle O(q_j)O(-q_j)\rangle}$$

- Thus we need to compute $\langle O(q_1)O(q_2)O(q_3)\rangle$, $\langle O(q_j)O(-q_j)\rangle$ in the theory specified by the action

$$S = S_{CFT} + \lambda\int d^3xO.$$

Conformal perturbation theory

- Let's discuss first the 2-point function

$$\langle O(x_1)O(x_2)\rangle = \langle O(x_1)O(x_2)e^{-\lambda \int O}\rangle_{CFT}$$
$$= \langle O(x_1)O(x_2)\rangle_{CFT} - \lambda \int d^3x \langle O(x_1)O(x_2)O(x)\rangle_{CFT} + \cdots$$

- Naively: only the terms displayed are universal and all higher order terms are negligible as $\lambda \to 0$.
- This turn out to be incorrect: *all higher order terms contribute and their leading order contribution as* $\lambda \to 0$ *is universal*.

Conformal perturbation theory

- One can show that

$$I_n = \int d^3z_1 \ldots d^3z_n \langle O(x_1)O(x_2)O(z_1)\ldots(z_n)\rangle_{CFT}.$$

in the limit $\lambda \to 0$ equals to

$$I_n \sim \frac{1}{\lambda^n}|x_{12}|^{(n+2)\lambda-6}$$

- This behavior is a manifestation of a (new?) conformal anomaly of correlators of dimension 3.

Resummed correlators

One can resum these corrections to obtain:

- 2-point function

$$\langle O(x_1) O(x_2) \rangle = \alpha |x_{12}|^{2\lambda - 6} \left[1 + |x_{12}|^{\lambda} \right]^{-4} + \ldots$$

  where α is related with the normalization of the operator at the conformal point.

- 3-point function

$$\langle O(x_1) O(x_2) O(x_3) \rangle = c \prod_{i<j} |x_{ij}|^{-(3-\lambda)} \left[1 + |x_{ij}|^{\lambda} \right]^{-2} + \ldots$$

  where c is the constant characterizing the conformal 3-point function.

Holographic non-gaussianity

- Insert these expressions in the holographic formulas.
- Normalize the operator as in AdS/CFT: this fixes α.
- Slow-roll scalar non-gaussianity.

- These results are universal and hold also beyond the regime of validity of gravity: *the CFT in conformal perturbation theory can have couplings of any strength*.
- The only freedom left is a few constants like α etc.

Summary

The QFT dual to this specific slow-roll model is a deformation of a CFT by a dimension $(3-\lambda)$ operator, which has a nearby IR fixed point.

The spectra and bispectra are fixed by symmetries and do not reflect the detailed properties of the underlying model.

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New holographic models [McFadden, KS]

- New models are obtained by considering the QFT at weak coupling. In these models the early universe is non-geometric.
- A class of models, based on superrenormalizable QFTs, correspond to power-law geometries at late times:

$$S = \frac{1}{g_{YM}^2} \int d^3x \mathrm{tr} \left[\frac{1}{2} F_{ij}^I F^{Iij} + \frac{1}{2}(D\phi^J)^2 + \frac{1}{2}(D\chi^K)^2 + \bar{\psi}^L \not{D} \psi^L + \text{interactions} \right]$$

$\Phi^M = \{\phi^I, \chi^K\}$, χ^K: conformal scalars, ϕ^I: minimally coupled scalars, ψ^L: fermions

Phenomenology

We worked out the spectra and bispectra for this class of theories.

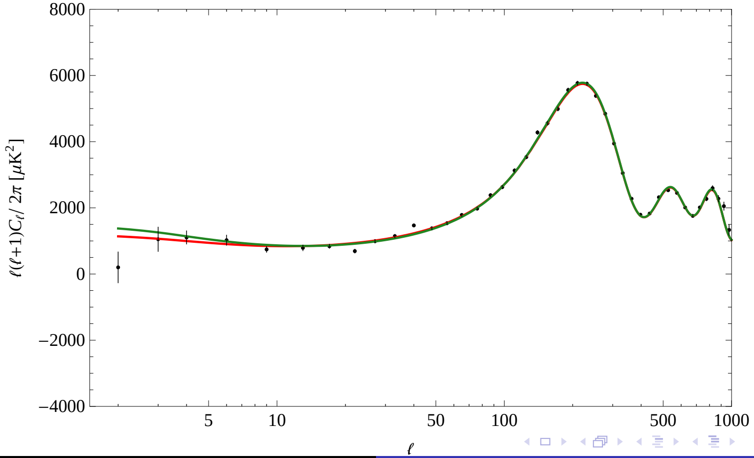
- The scalar power spectrum is given by

$$\Delta_{\mathcal{R}}^2(q) = \Delta_{\mathcal{R}}^2 \frac{1}{1 + (gq_*/q)\ln|q/gq_*|},$$

where q^* is a reference scale.

- The smallness of the amplitude $\Delta_{\mathcal{R}}^2$ is due to the fact that we are considering a large N theory.
- The small deviation from scale invariance is due to the fact that g, the coupling constant of the dual QFT, is very small!

Angular power spectrum: ΛCDM vs holographic model



Non-Gaussianities

- Scalar non-Gaussianity is exactly equal to the equilateral factorizable form with

$$f_{NL}^{\text{equil}} = \mathbf{5/36}$$

- This is independent of all details of theory.
- All other bispectra (involving tensors) exhibit similar universality!

Is this class of models consistent with data?

- The effective spectral index, $\Delta^2_{\mathcal{R}}(q) \sim q^{n_s(q)-1}$, has the property:

$$-(n_s - 1) = \frac{g q_*}{q} = \frac{d n_s}{d \ln q} = \cdots = (-1)^{n+1} \frac{d^n n_s}{d \ln q^n}.$$

- This is very different from slow-roll models where higher order running is suppressed by slow-roll parameters.
- To check this model one needs to custom-fit to data.
- A dedicated analysis to WMAP7 data [Easther, Flauger, McFadden, KS (2011) [Dias (2011)] showed that this model is competitive to ΛCDM.
- We are currently custom fit this model to Planck data [Bzowski, Easther, Flauger, McFadden, KS] to appear.

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Conclusions

- Inflation is holographic: standard observables such as power spectra and non-Gaussianities can be expressed in terms of (analytic continuation of) correlation functions of a dual QFT.
- Slow-roll results are essentially fixed by conformal invariance.
- There are new holographic models based on perturbative QFT that describe a universe that started in a non-geometric strongly coupled phase. Data from the Planck satellite should permit a definitive test of this holographic scenario.