Dilaton and IR-Driven Inflation

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Outline

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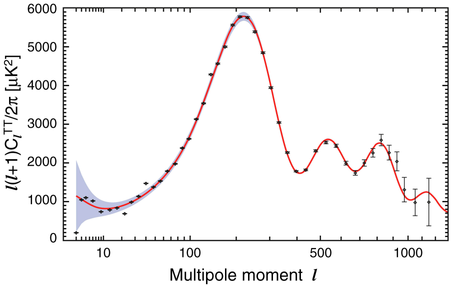
Inflationary Paradigm

- Inflation paradigm: our universe has undergone a period of accelerated expansion in the early time described by a de Sitter spacetime:

$$ds^2 = -dt^2 + e^{2Ht}dx^2,$$

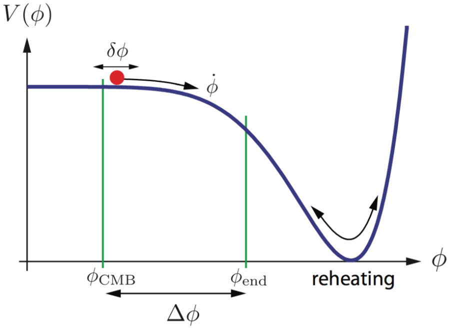
- Excellent agreement with observational results of CMB



- However it has been proven very difficult to bring together the inflationary paradigm with fundamental particle physics.

Motivation 1: eta problem

- The canonical model of inflation relies on a slow roll potential.



with slow roll parameters:

$$\varepsilon = \ll 1, \quad \eta = \frac{m_\phi^2}{3H^2} \ll 1.$$

- However it is difficult to maintain $m_\phi^2 \ll H_E^2$ due to large quantum corrections on m_ϕ^2.
- Like Higgs hierarchy problem, generically

$$m_\phi^2 \sim \Lambda_{\rm UV}^2 \gg H_E^2, \quad \Longrightarrow \eta \gg 1$$

- SUSY improves it a little but it must be SSB during inflation, leading to to

$$m_\phi^2 \sim H_E^2, \quad \Longrightarrow \eta \sim 1$$

In this talk, I will discuss a new mechanism to drive inflation:

a. Slow roll inflation without slow roll potential !

Motivation 2: Screening of Cosmological Constant

1. It has been conjectured that IR effect of gravitons in de Sitter space may "screen" the cosmological constant and explain the "smallness of the cosmological constant":
   - IR quantum instability for massless minimally coupled scalar field in dS was first pointed out by Ford (85). It was also conjectured that quantum gravitational effects may diminish the cosmological constant.
   - Polyakov (88) conjectured that the cosmological constant is "screened" by the infrared fluctuation of the metric.
   - *Question: concrete mechanism? is it sufficient?*
2. In answer this question, we realized that instead of trying to use the IR effects of graviton to explain the small magnitude of V (screening), we may also try to use it to provide an explanation of the slope of the potential, explaining the "slow-rollness of V", with the advantage that the eta problem is avoided completely.

Kea Idea

We consider a dilaton-gravity theory with a non-minimal coupling of a Brans-Dicke scalar

- $$S = \int \sqrt{-g} d^4x \left[\frac{M^2}{2} e^{-2\phi/\eta} R - \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right],$$

  where M is a fundamental mass scale, η is a mass scale which determines the strength of the non-minimal coupling of ϕ to R. $V(\phi)$ is a potential for the dilaton.
- Allowing classical vev of scalar $\phi = v$ and incoorperates the IR quantum effects of graviton loop, we find

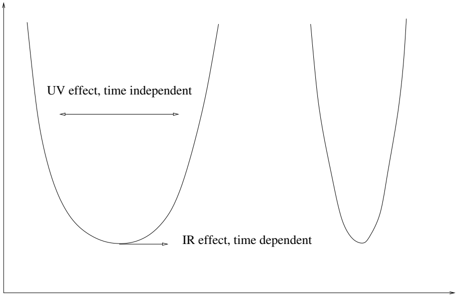
  $$v_{\rm eff} = v + \delta v(\tau)$$

- In Einstein frame, this time dependent vev modifies the cosmological constant,

  $$S_E \sim \int d^4x \sqrt{-g_E}\, V(v) e^{4v_{\rm eff}/\eta}.$$

  This brings in a time dependence (screening) in the cosmological constant.

The idea:



a. Inflaton is slow rolled by the IR effects of gravitons
b. IR effect is orthogonal to the UV corrections. Hence η problem is resolved in our model.

Outline

IR divergence and dS symmetry breaking

- dS space in Poincare coordinates:

$$\begin{aligned} ds^2 &= -dt^2 + a^2(t)dx_3^2, \quad a(t) = e^{Ht} \\ &= a^2(\tau)(-d\tau^2 + dx_3^2), \qquad \tau = -\frac{1}{H}e^{-Ht}, \quad -\infty < \tau < 0. \end{aligned}$$

- dS symmetry is $SO(D,1)$ and it is necessary that $\Lambda = \text{const.}$ in time.
- If one want $\Lambda = \Lambda(t)$, the desired quantum effect must be time dependent and break the de Sitter symmetry.

Quantum field in dS space

Massive scalar

- Massive scalar field in dS space admits dS invariant vacuum states: Bunch-Davies + α-vac (non-Hadamard) Allen 85, Mottola 85

Massless scalar

- Due to IR divergent effects, massless minimally coupled (mmc) scalar field does not admit dS invariant vacuum Allen, Folacci 87
- In fact, the two point function

$$\langle\phi(x)\phi(x')\rangle \sim \int_{P>H} \frac{d^3P}{(2\pi)^3}\frac{1}{2P} + \underbrace{\int_{P<H} \frac{d^3P}{(2\pi)^3}\frac{1}{2P^3}}_{\text{superhorizon modes. IR divergence}}$$

where $P = p/a$ is the physical momentum.

- If IR cutoff p_0 is introduced, the two point function is

$$\langle\phi(x)\phi(x')\rangle = \frac{H^2}{4\pi^2}\left(\frac{1}{y} - \frac{1}{2}\log y + \underline{\frac{1}{2}\log a(\tau)a(\tau')} + \frac{1}{2}\log(\frac{H^2}{p_0^2}) + 1 - \gamma\right)$$

Graviton in dS space

- Graviton in TTS gauge: $\partial_\mu h^{\mu\nu} = 0, \quad h^\mu_\mu = 0, \quad h_{\mu 0} = 0.$
- TTS graviton satisfies the same EOM as mmc scalar field and so acquires the same time-dependent dS breaking IR logarithm.

Woodard, Tsamis 94

Outline

Our model

- Consider the action

$$S = \int \sqrt{-g} d^4x \left[\frac{M^2}{2} e^{-2\phi/\eta} R - \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right],$$

- The potential admits a vacuum at $\phi = v$ and defines a dS bkgd:

$$g_{\mu\nu} = a_0^2(t)\eta_{\mu\nu}, \quad a_0 = e^{H_0 t}$$

with

$$H_0^2 = \frac{e^{2v/\eta} V(v)}{3M^2}$$

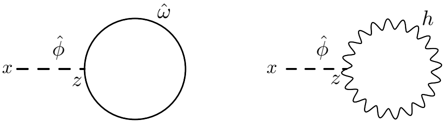
- With some mild conditions on V, the background is classically stable

Effective vev from one-loop graviton effect

- We consider the one-loop correction to the v.e.v of the dilaton scalar

$$\delta v = \langle \Omega | \phi(x) | \Omega \rangle .$$

- We are interested in the time dependent part of the correction. For this we need only to consider the propagation of mmc mode of the graviton in the loop, which generates time dependent IR logarithm. This is given by the one loop tadpole diagram



(a) (b)

- Note: Graviton perturbations can be categorized into massless minimally coupled (mmc) modes and conformally coupled (cc) modes. Only mmc graviton mode give rises to time dependent IR logaritm.

- We work with the in-in formalism

$$\langle\Omega|\phi(x)|\Omega\rangle = \langle 0|\,\tilde{T}\{e^{i\int_{\tau_i}^{\tau} H_{\rm int-}d\tau'}\}\phi(x)\,T\{e^{-i\int_{\tau_i}^{\tau} H_{\rm int+}d\tau''}\}|0\rangle$$

- One loop result gives the leading IR logarithm

$$\langle\Omega|\phi(x)|\Omega\rangle = -\frac{\zeta}{\eta}\frac{3H^2}{4\pi^2}\log^2 a(\tau) + \text{sub-leading}$$

and the effective vev is obtained as

$$v_{\rm eff}(\tau) = v - \frac{\zeta^2}{\eta}\frac{3H^2}{4\pi^2}\log^2 a(\tau) + \text{sub-leading},$$

where

$$\zeta(v) = \frac{1}{\sqrt{1+\frac{6M^2}{\eta^2}e^{-2v/\eta}}}$$

- Subleading terms include $\log a, 1/a, \cdots$ etc.

- Perturbation breaks down at late time when $\log a$ becomes large. However DRG (Dynamical RG) method allows to resum the leading IR logarithm effectively

  Boyanovsky, Vega 03; Burgess, Leblond, Holmanm, Shandera 10

  The idea is similar to that in QFT where resummation of large logarithm can be obtained by the RG equation.

- We obtain

$$v_{\mathrm{eff}}(\tau) = r + \frac{1}{q} W(pqe^{-qr})$$

where

$$p := \frac{3M^2}{\eta}, \qquad q := \frac{2}{\eta}, \qquad r := v - \frac{3M^2}{\eta} e^{-2v/\eta} - \frac{3H_0^2 \log^2 a_0(\tau)}{4\pi^2 \eta}$$

and $W(z)$ is the Lambert-W function

$$z = W(z) e^{W(z)}.$$

The result is valid for all time as long as $\epsilon \ll 1$.

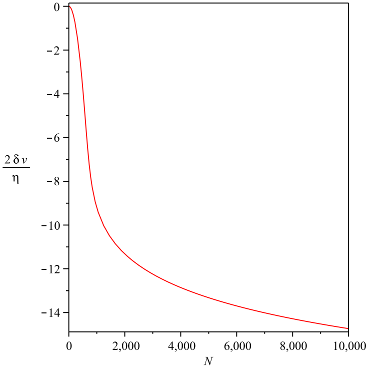


Figure: Plot of $\frac{2\delta v}{\eta}$ against N for $x = 1, y = 0.01$

- $$x := \frac{Me^{-v/\eta}}{H_0}, \quad y := \frac{Me^{-v/\eta}}{\eta}$$

  parameterize the model

Validity of approximation

- At the tree level, the Hubble parameter is given by

$$H_0^2 = \frac{1}{3M^2} e^{\frac{2v}{\eta}} V(v).$$

- The one loop Hubble constant in the string frame is given by

$$H^2 = \frac{1}{3M^2} e^{2v_{\rm eff}/\eta} V(v) = H_0^2 e^{2\delta v/\eta}$$

- We can compute the "slow rolll" parameters

$$\varepsilon = \frac{d\ln H}{d\mathcal{N}}, \quad \eta := \frac{d\ln\varepsilon}{d\mathcal{N}},$$

to measure the size of the backreaction. Need

$$\varepsilon, \eta \ll 1$$

in order to trust the quantum field theory computation.

- Given x and y, ε and η stay very small for a large range of N from the initial time, and then increase rapidly at around N of the order of $N \sim xy^{-1}\ln y^{-1}$.

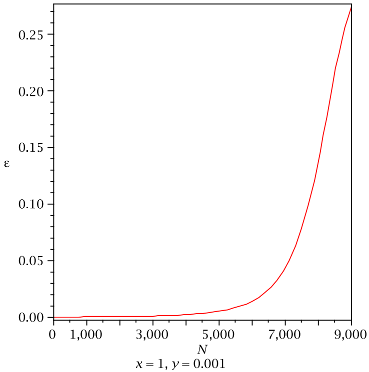


Figure: Plot of ε against N

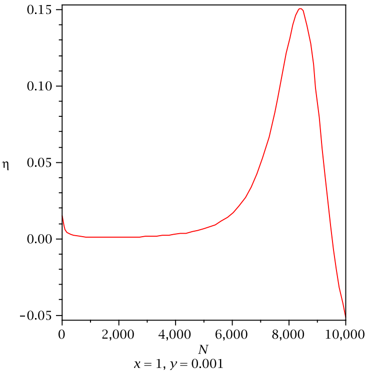


Figure: Plot of η against N

Outline

Hubble constant in Einstein frame

- To examine the physical effects of the time dependent vev, we need to go back to the Einstein frame by performing a Weyl scaling of the string frame metric
$$g_{\mu\nu} = g^{E}_{\mu\nu} e^{2(\frac{\varphi}{\eta}+\beta)},$$
where φ denote the dynamical part of ϕ above the vev,
$$\phi = v_{\text{eff}} + \varphi$$
and $\beta = \delta v/\eta$.
- We obtain the Planck mass
$$M_P = Me^{-\frac{v}{\eta}}.$$
and the Hubble parameter
$$H_E = e^{\frac{2\delta v}{\eta}} H_0.$$
- As δv is always negative, we get a screening of the Hubble constant and the CC.

Slow roll inflation

- The slow roll parameters,

$$\varepsilon_E := \frac{d}{dt_E} H_E^{-1}, \quad \eta_E := \frac{1}{H_E \varepsilon_E} \frac{d\varepsilon_E}{dt_E}$$

  are given by

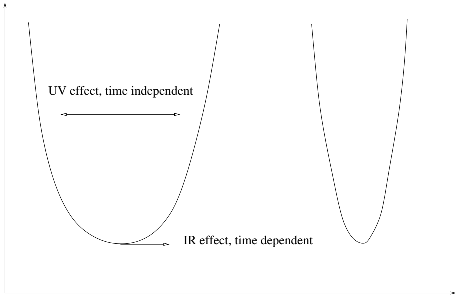
$$\varepsilon_E = 2e^{\frac{\delta v}{\eta}} \varepsilon, \quad \eta_E = e^{\frac{\delta v}{\eta}} (\eta - \varepsilon)$$

- It is clear that as long as we can trust the quantum field theory computations, the corresponding cosmology in the Einstein frame describes a slow roll inflation with

$$\varepsilon_E, \eta_E \ll 1.$$

Remarks

1. Slow roll inflation is achieved without a slow roll potential: In contrast to the simplest slow roll inflation, where expansion is driven by the slow rolling of an inflaton field down an almost flat potential, here inflation is driven by the IR effects of the gravitons themselves.
2. No eta problem in our model:



Inflaton moved slowly by IR effects of graviton and the IR effect is orthogonal to the UV corrections. η problem is resolved in our model.

Outline

In this talk, IR effect of graviton is studied. We found that IR divergence of graviton in the loop induces a time dependence on the vev of the dilaton field

As applications, we provide an alternative mechanism to achieve inflation, but without the need of an adhoc inflationary potential as in slow roll inflation.

Further studies:

- We have two free parameters (dilaton coupling η and vev v) in our model. We have used it to fit with observations (spectral index, scalar amplitude, and r).
  Other observables?
  UV sensitivity? e.g before the last 60-efolding.
- Time dependent effects of reheating is important.