The curvaton scenario in bouncing cosmologies

A multi-component de Broglie-Bohm bouncing cosmology

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Overview

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Motivation - Current Status

The most recent Planck results [1] show that the cosmological perturbations in the CMB have

- almost scale-invariant spectral index $n_s = 0.9649 \pm 0.0042$
- low tensor-to-scalar ratio $r < 0.064$
- low local non-Gaussianity $f_{\mathrm{NL}}^{\mathrm{local}} = -0.9 \pm 5.1$

Many early-universe models respect those constraints. In special, **inflationary** and **matter bounce** cosmologies.

[1] Planck 2018 results. X. Constraints on inflation - A&A, 641 (2020) A10

Motivation - Duality at 1st Order

A **de Sitter** expansion and a **matter contraction** are dual to each other with respect to **scalar** perturbations, thanks to a symmetry in the Mukhanov-Sasaki equations.

$$v_k^{''} + \left(k^2 + \frac{z^{''}}{z} \right) v_k = 0 \tag{1}$$

The **horizon term** $\frac{z^{''}}{z}$ is the same for both scenarios, $2/\eta^2$, which leads to **scale invariance**.

Motivation - Gravitational Waves

The amount of **primordial gravitational waves** in both scenarios, depending on the models, respects the Planck constraints on r.

That is particularly the case for the **curvaton** scenario of inflation and for **matter bounce** models in general.

Motivation - Non-Gaussianity

However, it is uncertain if bouncing cosmologies can predict a **similar behavior** for non-Gaussianities;

Bouncing scenarios with **multiple fields** present new challenges, may not be degenerate with inflation;

Multi-component bouncing cosmologies shall be analyzed in the search of scale-dependent non-Gaussianities.

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Motivation

- We previously analyzed degeneracies between inflationary and bouncing modelss [2] ;
- We constructed a curvaton inflationary model with the desired behavior of scale-dependent non-Gaussianities [3] ;
- Now, we must analyze non-Gaussianities in curvaton-like bouncing cosmologies.

[2] Guimarães et al. - PRD 99, 103515 (2019)
[3] Guimarães et al. - PRD 103, 063530 (2021)

Motivation

We refer to

- *'Mixed matter-curvaton scenario in de Broglie-Bohm quantum cosmology* ', in preparation.

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Curvaton Scenario

In the **curvaton scenario** [4], the inflaton dominates the background, while the **curvaton** is responsible for the **curvature perturbations.**

That allows for the **energy scale** of inflation to reduce, which **lowers** the predicted value of the **tensor-to-scalar ratio**.

[4] **Generating the curvature perturbation without an inflaton** - David Lyth, David Wands, Physics Letters B, 524, Issues 1–2, 2002.

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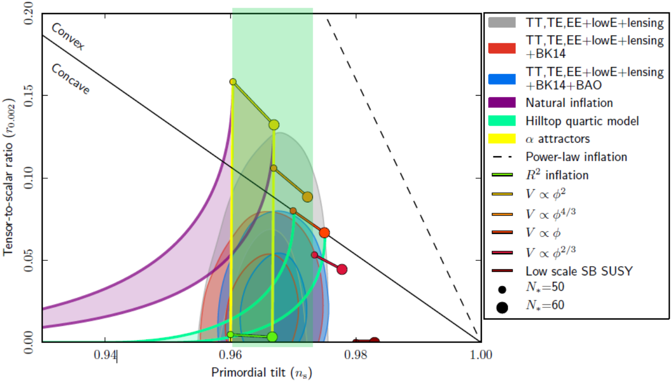
Curvaton Scenario

Every inflaton potential that previously predicted larger r in SFI respects the Planck constraints for the curvaton scenario.



Curvaton scenario for Bouncing Cosmologies?

In the matter bounce scenario, a field/fluid with **negative** equation of state is necessary to achieve a red-tilted spectra and to be dual to an inflationary model.

However, baryonic and dark matter result in **positive** equation of state and a **blue-tilt**.

Could a curvaton-like field save those types of more realistic models?

Curvaton scenario for Bouncing Cosmologies?

Multi-component scenarios might result in non-Gaussianities.

The latest Planck results requite it to be small or **scale-dependent**.
It might also explain the existence of the **CMB anomalies**.

What are the consequences of a curvaton-like bouncing scenario?

Multi-component Cosmology - Fields and Fluids

In the inflationary scenario, dealing with multiple fields result in **isocurvature perturbations**.

In the curvaton scenario, it leads to the **entropic mechanism**.

In a background where only one **field** is present, alongside one **matter fluid**, we **avoid** isocurvature perturbations. That is not the usual scenario for a curvaton-like model.

Multi-component Cosmology - Two Fields

The first preposition of a **curvaton-like** model in boucing cosmologies has been developed before [5] devised a contrived way to guarantee the **scale invariance** of perturbations.

But all the other more realistic models use **two fields** and the **entropic mechanism** to exchange entropy perturbations for curvature perturbations as well.

Ubiquitous to most is an Ekpyrotic phase of contraction [6].

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[5] The matter bounce curvaton scenario - Yi-Fu Cai et al JCAP03(2011)003

[6] Ekpyrotic collapse with multiple fields - Kazuya Koyama and David Wands JCAP04(2007)008

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Multi-component Cosmology - Ekpyrotic Models

However, because of vacuum inicial conditions for the background field, a **strong blue-tilt** at small scales is inevitable [7]. Even for models which use a LQC bounce [8].

That is why we first choose to use one field and one fluid.

[7] Two field matter bounce cosmology - Yi-Fu Cai et al JCAP10(2013)024

[8] Ekpyrotic loop quantum cosmology - Edward Wilson-Ewing JCAP08(2013)015

de Broglie-Bohm Quantum Cosmology

In the **dBB interpretation** of quantum mechanics, a non-singular **bounce** takes place thanks to **quantum effects.** The background evolution of a universe dominated by a perfect fluid with equation of state ω is

$$a(T) = a_b \left[1 + \left(\frac{T}{T_b}\right)^2\right]^{\frac{1}{3(1-\omega)}} \tag{2}$$

In the dBB scenario, entropy perturbations can be analyzed, in opposition to the LQC scenario.

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Fluid perturbations in dBB Cosmology

The fluid is chosen to be dust-like, i.e. $\omega \approx 0$. Therefore, the spectral index of the fluid perturbations in the dBB setting is

$$n_F - 1 = \frac{12\omega}{(1 + 3\omega)} \tag{3}$$

For a **positive** equation of state parameter, $\omega > 0$, eq. (3) results in a **blue-tilted** spectra.

Field perturbations in dBB Cosmology

We need the field fluctuations to be **red-tilted** in such a way that the **total curvature perturbation** is red-tilted as well.
For a scalar field in our setting, we get

$$n_\sigma - 1 = 3 - 2\sqrt{\nu_F^2 - \frac{12\eta_\sigma}{(3\omega + 1)^2}} \tag{4}$$

At first, we consider a model where η_σ is constant.

Field perturbations - Red-Tilted Fluctuations

We can analyze when the field fluctuations are red-tilted. As a function of the background equation of state parameter, we obtain that

$$n_\sigma - 1 < 0 \Rightarrow \eta_\sigma < -\frac{3}{2}\left(\omega + \omega^2\right) \tag{5}$$

Therefore, for models in which η_σ is (almost-)constant and $\omega \gtrapprox 0$, the spectral index can be made red-tilted if η_σ is negative.

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Field perturbations - Vacuum Initial Conditions

The case of scalar fields in this background, one needs to pay attention to the **vacuum initial conditions** in the far past.

If η_σ grows to the far past, this term dominates over k^2. In such a case, the vacuum **is not** the Minkowski vacuum.

As mentioned, in our models we **do** have a Minkowski vacuum. The mass term is **subdominant** to the past.

Mixed Field-Fluid perturbations

To sum up our assumptions:

- Minkowski vacuum initial conditions for the field;
- η_σ parameter to be approximately constant.

We **add** that we want the η_σ parameter to be **small**, so that we can compute an effective spectral index.

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Mixed Field-Fluid perturbations

For this dBB setting, the **effective** spectral index is

$$n_s - 1 = G\,(n_F - 1) + (1 - G)\,(n_\sigma - 1) \tag{6}$$

$$G \equiv \frac{1}{1 + \frac{A_\sigma}{A_F} k^{-2(\nu_\sigma - \nu_F)}} \tag{7}$$

The **first term** in (6) results in a **blue-tilt**, therefore we need G and $n_\sigma - 1$ to be such that the spectrum $\mathcal{P}_\mathcal{R}$ is **red-tilted** at CMB scales.

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Working model

We have found that potentials of this type **allow for a Minkowski vacuum** for matter dominated contraction

$$V(\sigma) = -\frac{\lambda}{m}\sigma^m + \frac{\beta}{2m}\sigma^{2m} \tag{8}$$

where $4+\delta > m > 2$, $\lambda, \beta > 0$ for a red-tilted field fluctuation.

Working model

The equation of motion for the curvaton, when the background is dominated by a fluid ω, is

$$\ddot{\sigma} + \frac{2}{1+\omega}\frac{\dot{\sigma}}{t} - \lambda\sigma^{m-1} = 0 \tag{9}$$

The solution is

$$\sigma = \frac{D}{t^{\frac{2}{m-2}}}, \tag{10}$$

$$\lambda = \frac{D^{2-m}}{(m-2)^2}\left[\frac{2m(1+\omega) - 4(m-2)}{1+\omega}\right] \tag{11}$$

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Working model

The η_σ parameter is found to be **constant**,

$$\eta_\sigma = \frac{V_{\sigma\sigma}}{3H^2} = \frac{3\,(m-1)\,(1+\omega)}{4\,(m-2)^2}\left[4\,(m-2) - 2m\,(1+\omega)\right] \quad (12)$$

In case $m = 2$, this potential **breaks** one of our conditions: the η_σ parameter **diverges**. But $m \approx 4$ results in a small red-tilt!

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The relative amplitudes

The relative amplitudes between the two component's fluctuations is given by A_F and A_σ present in (7),

$$A_F = W_F^2 \left[\frac{3(1+\omega)}{2\omega^{1+\nu_F}} \right] \tag{13}$$

$$A_\sigma = W_\sigma^2 \left[\frac{\dot{\sigma}}{H^2} \right] \left[\frac{3(1+\omega)}{2\omega} \right]^2 \tag{14}$$

where W_F and W_σ are approximately equal.

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Preliminary Results

However, if we $A_F \gg A_\sigma$, then $G \approx 1$, such that at CMB scales the blue-tilted spectrum from the fluid **still dominates**.

We have two alternatives: **larger red-tilt or larger field fluctuations**.

What are the consequences for the matter content of the universe? Do we **add** a field or **replace** the fluid with one?

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Revisiting the Two Field case

Returning to the two field case, the too-blue-tilted spectrum at small k may once again troubles the modeling.

However, a complete analysis must be made, including the production of isocurvature modes. This can be done in dBB, contrary to the LQC case!

The bounce induces a mixing, guaranteeing the red-tilt for CMB scales.

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Preliminary Results

- A curvaton-like field is needed to save positive ω bouncing models;
- We found that a type of model have constant η_σ in the matter background, which guarantees a Minkowski vacuum;
- For $m \approx 4$ a **slightly red-tilted** spectrum is found;
- The ratio between amplitudes might indicate the need for a two field model.

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Conclusion

The degeneracy between observational results from inflationary and bouncing cosmologies is an everlasting challenge.

In our work, we have tackled this challenge in different manners. From a direct comparison between scenarios, to a closer look at what inflationary and bouncing cosmologies indicate.

We now summarize our results.

Conclusion

- **Curvaton models in bouncing cosmologies present their own challenges**
  It is difficult to obtain red-tilted perturbations, which indicate that such a scenario is not dual to an inflationary regime.

Conclusion

- **We may need to make use of the entropic mechanism to enhance perturbations**
  That requires that the background is dominated by another field, not a fluid
- **dBB setting allows for a simple oscillating field in the background**
  The bounce is independent of the fields, such that we can use a simple oscillating ϕ^2 to be the background, like in Brandenberger et al.

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