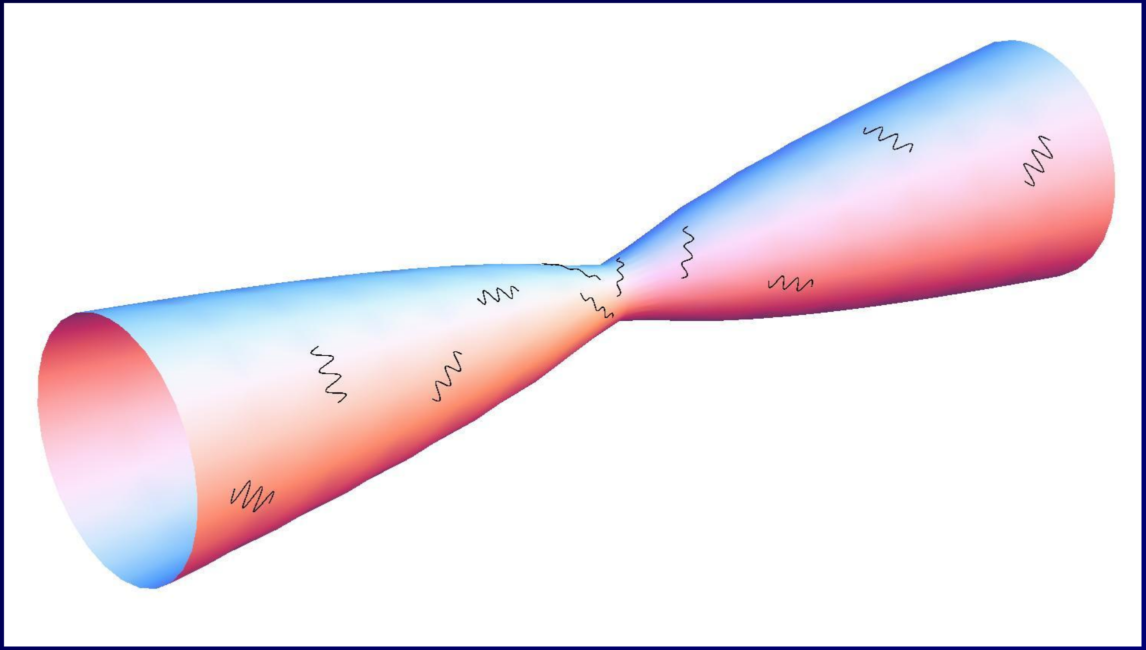
The String and The Cosmic Bounce



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Summary

- The Inflation and The String
- The String and The Bounce
- The Bounce and The Perturbations
- The Bounce and The Inflation

Standard Inflation

Why is the universe so flat?
Why is the universe so homogeneous on large scales?

These puzzles can be solved by invoking a period of accelerated expansion, called inflation, in the very early universe.

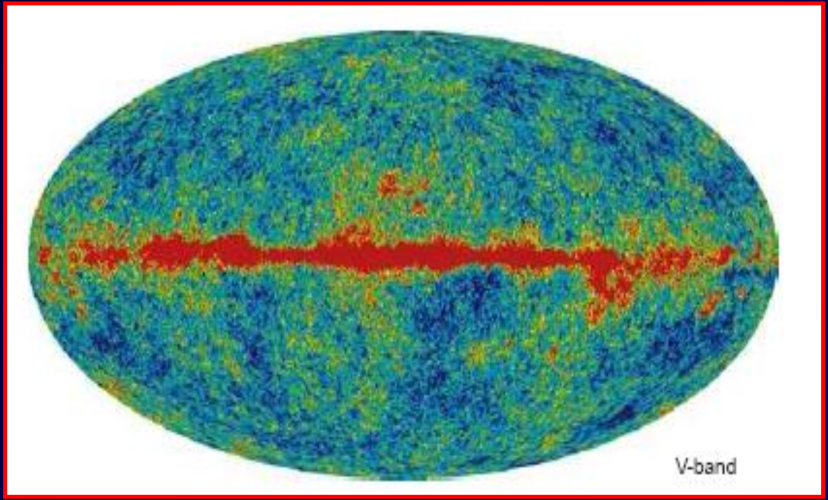
The radius of curvature becomes much larger than the horizon $\left|\frac{K}{aH}\right| << 1$

Any inhomogeneities are washed away far beyond the horizon. $\left|\frac{k}{aH}\right| << 1$

Inflation can be easily realized using a scalar field dominated by its potential energy.

1. The Inflation and The String

CMB and Primordial perturbations



$$\Omega_b = 0.0456^{+0.0016}_{-0.0016}$$

$$\Omega_m = 0.272^{+0.016}_{-0.015}$$

$$H_0 = 70.4^{+1.3}_{-1.4}$$

$$\Delta_R^2 = \left(2.441^{+0.088}_{-0.092}\right)\times 10^{-9}$$

$$n_s = 0.963^{+0.012}_{-0.012}$$

$$\tau = 0.087^{+0.014}_{-0.014}$$

CMB anisotropies today are the outcome of primordial perturbations

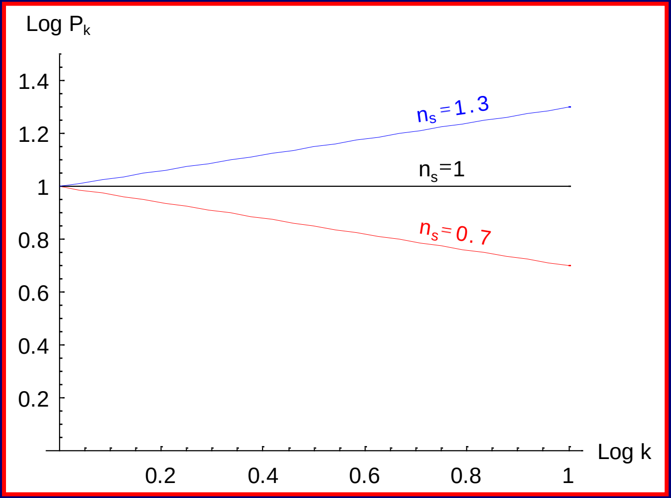
$$P_k = k^3 |\Phi|^2 = A\, k^{n_s - 1}$$

k = wave number

Φ = Newtonian potential

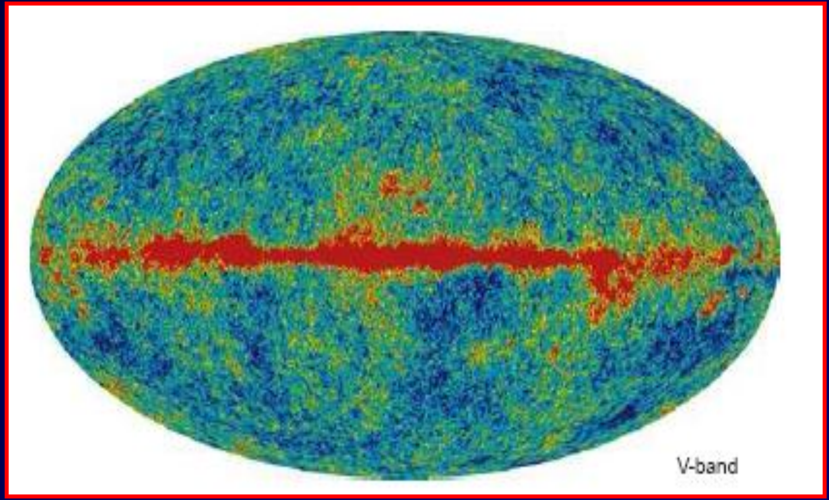
A = amplitude

n_s = spectral index



1. The Inflation and The String

CMB and Primordial perturbations



"Unobserved" observables in CMB are

The tensor-to-scalar ratio $r < 0.36$

The tensor spectral index $n_T = ?$

Non-gaussianities $-10 < f_{NL} < 74$

Running spectral index, oscillations, isocurvature, …

Inflation and primordial spectrum

Whatever the initial conditions, the universe is cleaned out by inflation and all that remains are quantum fluctuations.

The spectrum of quantum fluctuations of the vacuum determines the spectrum of primordial perturbations.

$$P_k = k^3 |\Phi|^2 = A\, k^{n_s - 1} \qquad n_s = 1 - 4\varepsilon - 2\delta$$

A similar spectrum, but with different amplitude, is predicted for primordial gravitational waves.

$$P_k = k^3 |h|^2 = A_T\, k^{n_T} \qquad n_T = -2\varepsilon$$

Why look for alternatives to inflation?

Issues in inflation

(Brandenberger hep-th/0701111)

Standard inflation provides a remarkable solution to the problems of Big Bang cosmology. Moreover, it yields a prediction for the spectrum of cosmological perturbations in agreement with experimental data.

Yet it leaves some questions unsolved:

- It has no roots within any fundamental theory.
- It does not answer the initial singularity problem.
- Initial conditions for perturbations in a Transplanckian regime.
- Potential very flat (fine tuning?).

String Theory

- String theory unifies all interactions including gravity in a very appealing quantum picture.
- Particles are replaced by strings. There is only one parameter: the string length L_s.
- String theory can be consistently formulated only in 10 (or 11) dimensions.
- Extra-dimensions must be kept at bay by some compactification mechanism.
- There is a huge number of possible low energy limits, depending on the details of the compactification.
- The extra-degrees of freedom survive in the effective 4-D theory in the form of scalar fields (moduli).

String Cosmology

Cosmology can help String Theory to find experimental signatures

String Theory can help cosmology to find a solid foundation for inflation and early universe cosmology.

Two directions

Incorporate inflation in string theory

Alternative “stringy” mechanisms

String Inflation

(Mulryne & Ward 2011)

Inflation can be found in many realizations of string theory

- Modular inflation *(KKLT , Racetrack, LVS, Kahler, Roulette, …)*
- Brane inflation *(DBI , D3/D7, D-term, …)*
- Axion *(Silverstein & Westpahl '08, …)*
- Tachyon *(Sen' 05, …)*
- Higher-derivative *(P-adic, CSFT)*
- Assisted inflation *(Liddle et al. '98, Dimopoulos et al. '08, …)*
- M-theory *(Becker et al. '05, Buchbinder '05, …)*

These models can be already tested or will soon be with PLANCK!

String Gas Cosmology

(Brandenberger et al.)

Low energy effective theories are not stringy enough.

The very early universe was very different from our low energy world.

Are we missing real string theory?

The Universe might have emerged from a gas of strings.

Thermal equilibrium leads here to a scale-invariant spectrum. *(Nayeri, et al. '06)*

The existence of winding modes can explain why we only see 3 spatial dimensions. *(Brandenberger & Vafa '89)*

But… no explicit field theory describing the model!

Supercritical string cosmology

(Ellis, Mavromatos, Nanopoulos 1993; Gravanis &Mavromatos 2002)

With the “wrong” number of dimensions, a central charge remains

Conformal invariance restored by a “Liouville mode”

Modifications of Boltzmann equations: dark matter spectrum

… more in tomorrow’s talk by Mavromatos

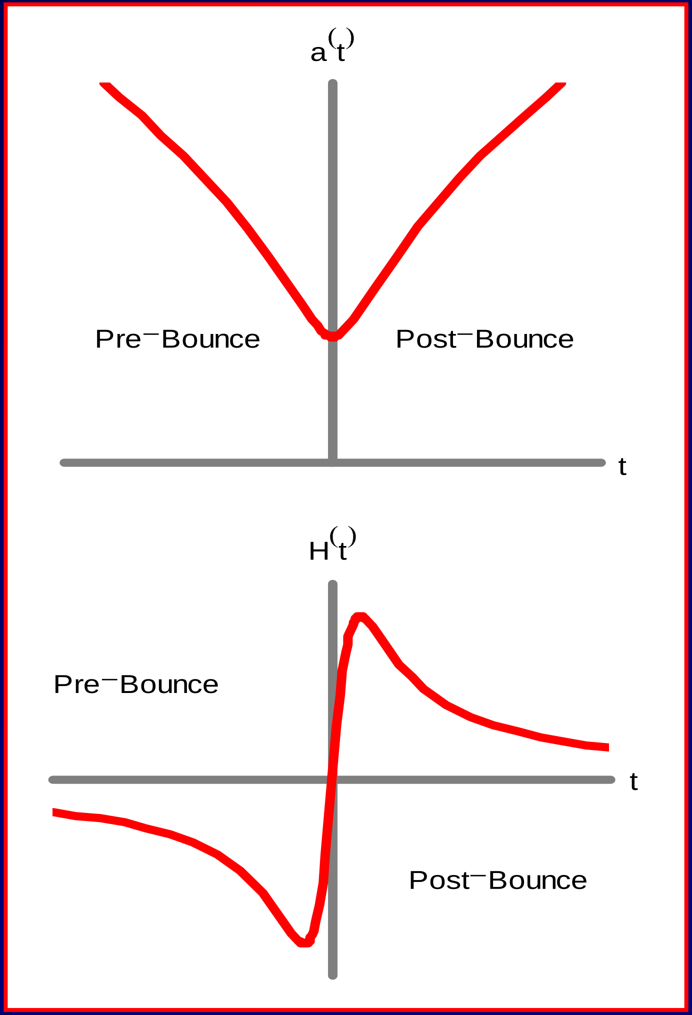
The Bounce

The string length provides a fundamental cut-off for quantum gravity.

The Big Bang singularity should be cured by string theory.

If there is no singularity, what happened before the big bang?

The present expansion was perhaps preceded by a contraction phase ending with a cosmic bounce.



Horizon and Flatness

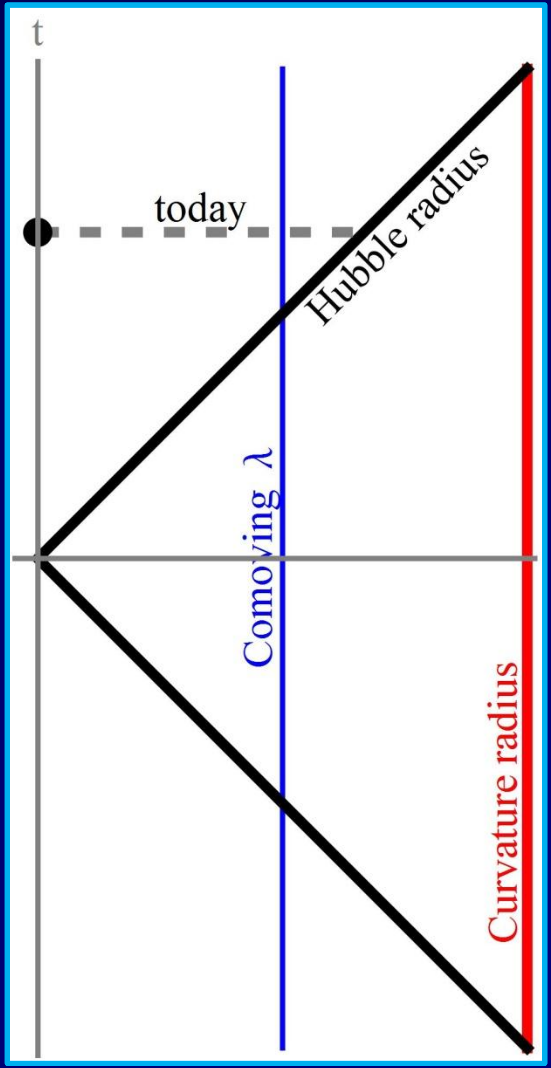
Since there is no singularity in the past, there is no particle horizon:

$$\int_{-\infty}^{t} \frac{dt}{a(t)} = \infty \quad \text{if} \quad \lim_{t\to-\infty} \frac{a(t)}{t} < \infty$$

The spatial curvature becomes negligible as we approach the bounce:

$$\frac{d}{dt}\left|\frac{K}{aH}\right| = -\frac{d}{dt}\frac{|K|}{\dot{a}} = |K|\frac{\ddot{a}}{\dot{a}^2} < 0$$

Perturbations never become Trans-Planckian!



Challenges for bouncing cosmologies

- A cosmic bounce requires violation of the Null-Energy-Condition.
  Ghosts? Instabilities?
- Anisotropies grow during contraction.
  Super-stiff source required ($w>1$)
- The correct perturbation spectra must be generated.
- Calculating the evolution of perturbations across the bounce is absolutely non-trivial!

Pre – Big Bang scenario

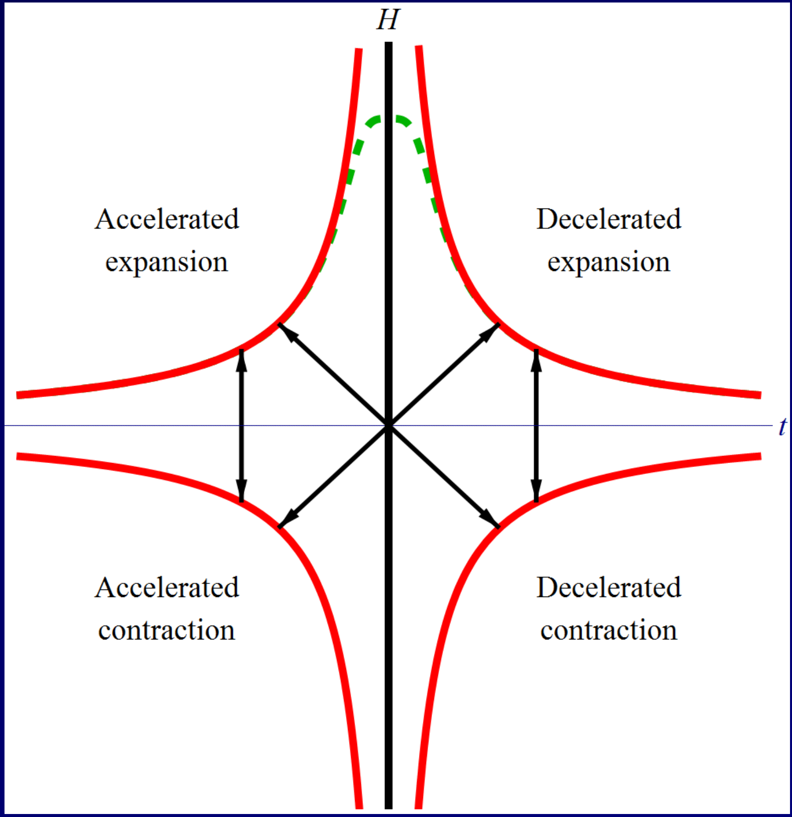
(Veneziano, Gasperini 1991)

The Pre-Big Bang scenario is based on considerations about the T-duality of string theory.

$$a \rightarrow \frac{1}{a}$$

The spectrum of the Bardeen potential after the bounce is steeply blue (n_s=4).

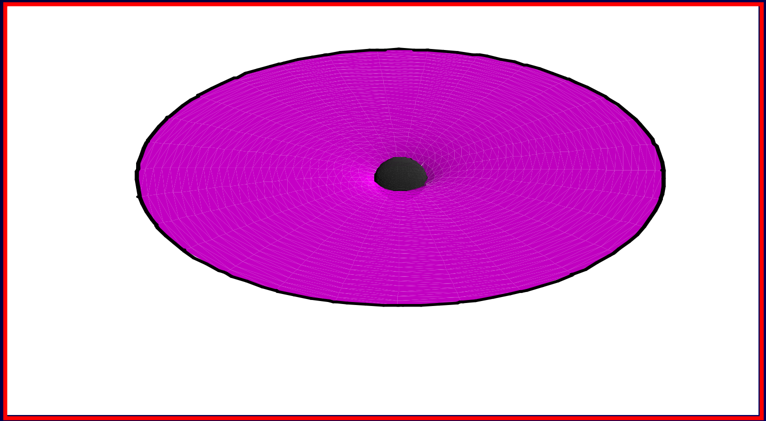
The spectrum of the axion is scale-invariant $\rightarrow$ curvaton mechanism



(VB, Gasperini, Giovannini & Veneziano 2002).

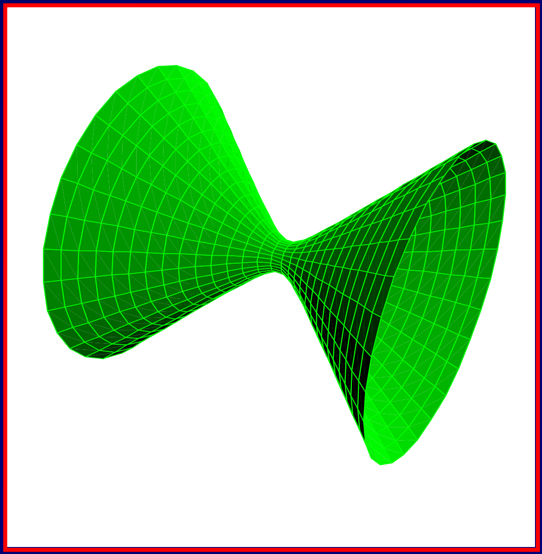
Bounces with extra-dimensions

Bounce with time-like extra-dimension *(Shtanov & Sahni 2003)*



Bounce of a boundary brane
(Mukherji & Peloso 2002; Burgess et al. 2003)

Bounce of a probe brane
(Brax & Steer 2002; Burgess et al. 2003; Kachru & Mcallister 2002; Germani et al. 2006; Easson et al. 2007)



High-energy Bounces

Quantum cosmology bounces

- Loop Quantum Cosmology *(Bojowald, Maartens & Singh 2004; …)*
- Wheeler – de Witt approach *(Peter, Pinho & Pinto-Neto 2006)*
- Quantum backreaction *(Srivastava 2007)*

Higher derivative bounces

- α' corrections of string theory *(Tsujikawa, Brandenberger & Finelli 2002)*
- Non-perturbative corrections (e.g. exp($\Box$)): no ghosts arise *(Biswas, Mazumdar & Siegel 2005)*

Low-energy Bounces

Non-minimal coupled Vector Fields*(Novello & Salim 1979)*

Weyl Integrable Spacetime duality *(Novello et al. 1993)*

Non-local dilaton potential *(Gasperini, Giovannini & Veneziano 2003)*

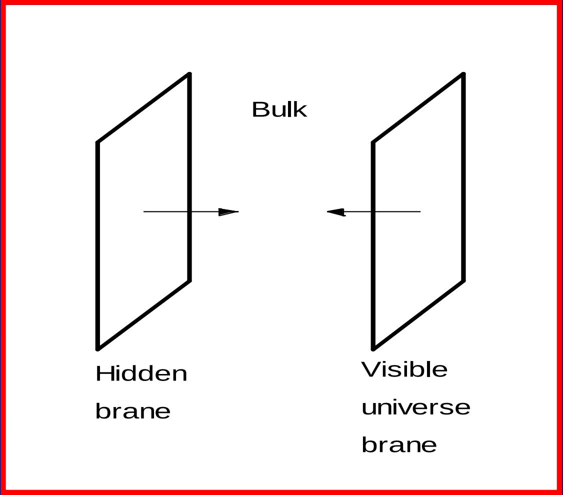
Ghost condensate *(Creminelli, Luty, Nicolis & Senatore 2006)*

2. The String and The Bounce

Ekpyrotic/Cyclic Universe

(Steinhardt, Turok et al. 2001)

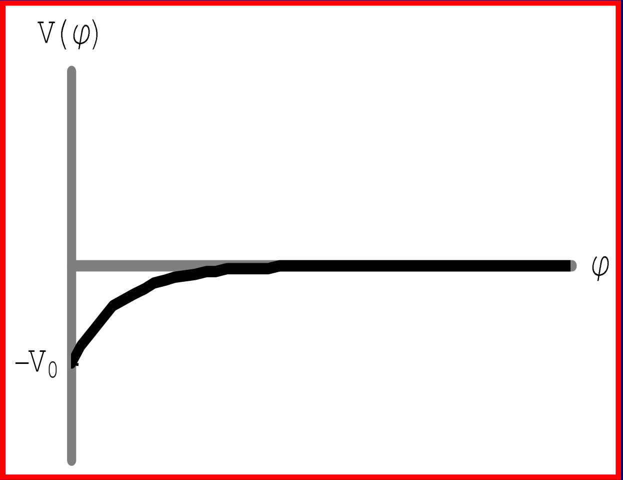
In the Ekpyrotic scenario, the visible universe is a brane embedded in an 11-dimensional space-time.



The bounce occurs when our brane collides with a hidden brane (singularity!).

The observer on the visible brane sees a scalar field with a negative exponential potential

$$S = -\frac{1}{\lambda_P^2}\int d^4x\sqrt{|g|}\left[R - \tfrac{1}{2}(\partial\varphi)^2 - V_0 e^{-\varphi\sqrt{2/p}}\right]$$



We have w>>1 and the scale factor is then $a(t) \sim |t|^p$ where *p* can be chosen arbitrarily small and positive.

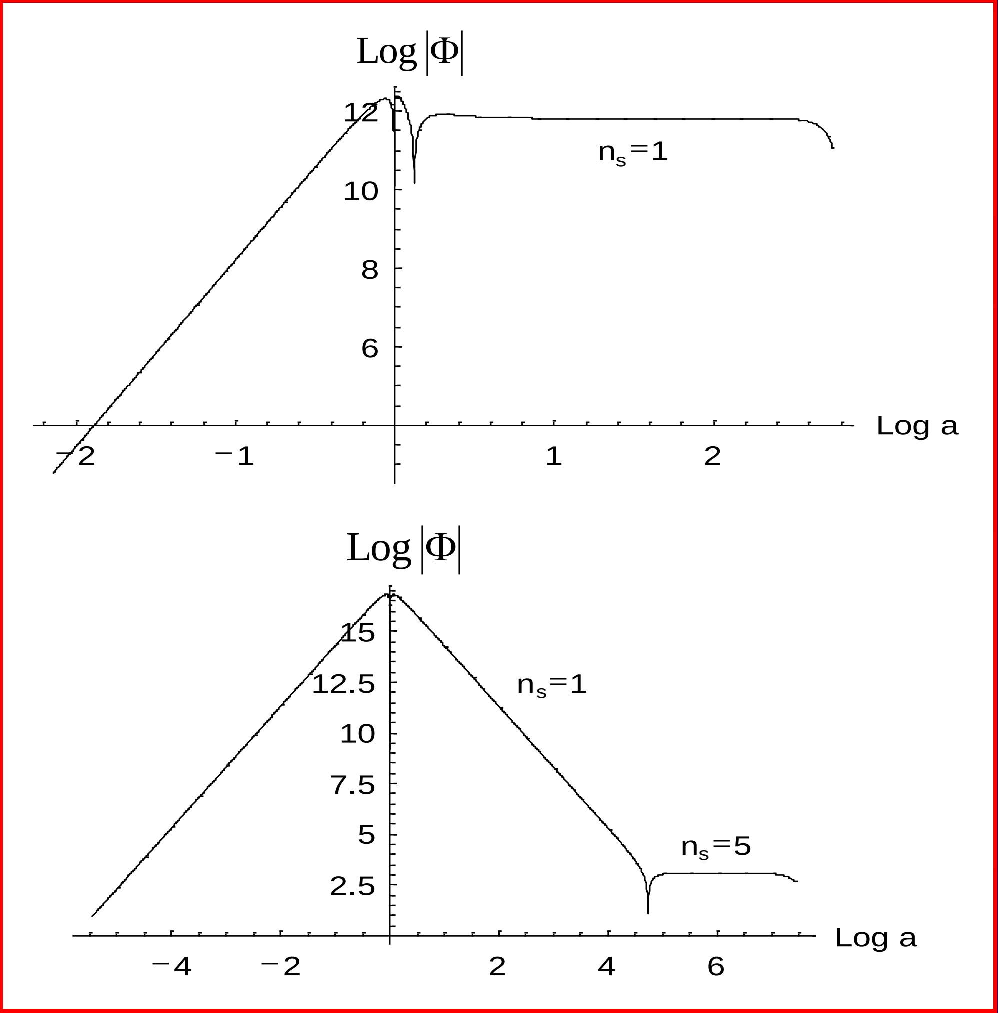
3. The Bounce and The Perturbations

Ekpyrotic/Cyclic Universe

During a slow contraction, scalar perturbations grow with a scale-invariant spectrum.

After the bounce we have two possibilities:

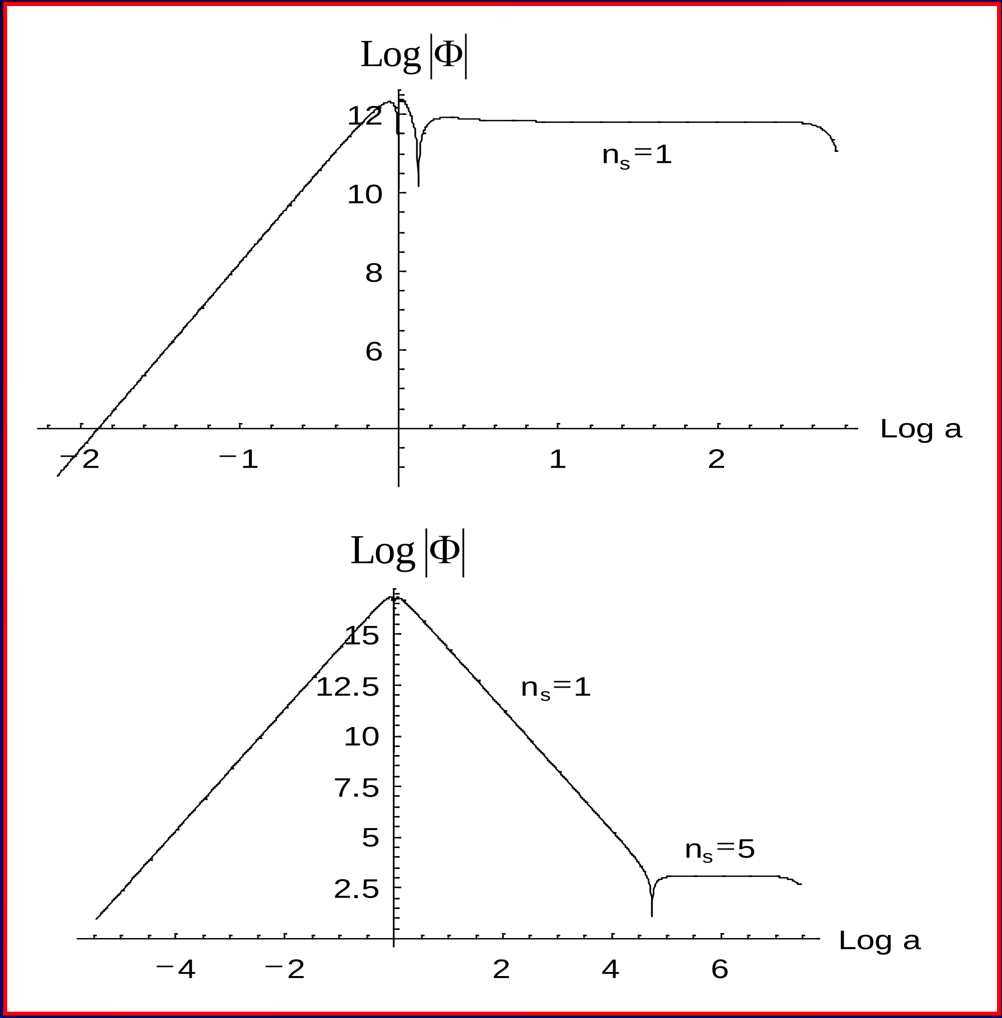
- The growing mode delivers its spectrum to a constant mode.
- The growing mode turns into a decaying mode, leaving place to a blue constant mode.



3. The Bounce and The Perturbations

Perturbations through the bounce

What decides whether the growing mode survives or not?



General solution for scalar perturbations

(VB and Veneziano 2005; VB 2006)

We base our general analysis on four minimal assumptions:

1) It makes sense to define a 4-dimensional metric tensor at all times. Then we can always write effective Einstein equations $G_\mu^{\ \nu} = T_\mu^{\ \nu}$.

2) The universe is homogeneous and isotropic; thus the background metric is FRW.

3) The bounce is entirely determined by a unique physical scale.

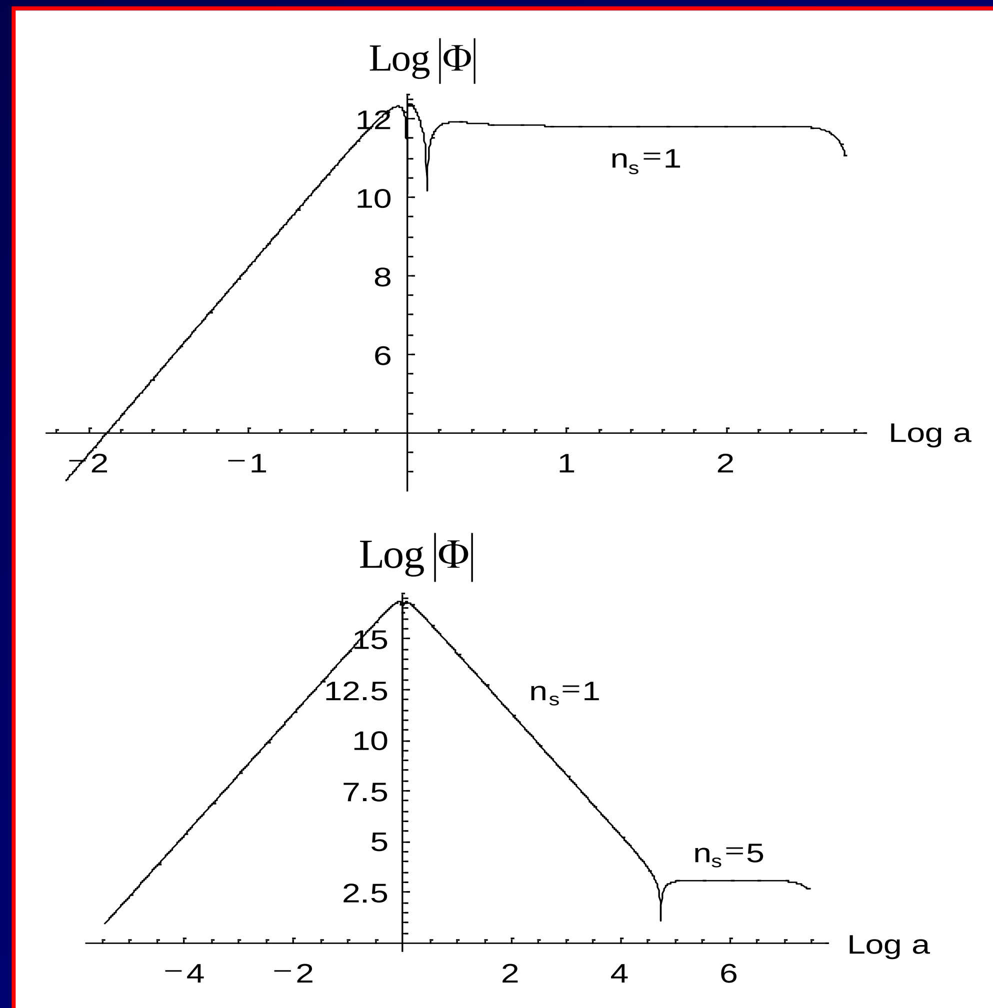
4) Before and after the bounce, the universe is characterized by constant w and c_s^2, with $w > -1/3$ (no inflation, no deflation).

General solution for scalar perturbations

(VB and Veneziano 2005; VB 2006)

$$\delta p_u \propto \Phi$$

$$\delta p_u \propto \nabla^2 \Phi$$



Relation to other works

Our conclusions are in agreement with the hypersurface analysis by *Durrer & Vernizzi (2002)*: the tension of the bounce hypersurface is related to the pressure perturbation.
Is $G_0 = 0$ fine-tuning on the bounce?

Creminelli, Nicolis & Zaldarriaga (2004) study the attractor nature of the Ekpyrotic solution in the synchronous gauge.
Is $G_0 \neq 0$ fine-tuning on the bounce?

Chu, Furuta & Lin (2006) have connected the transmission of the Pre-Bounce spectrum with the presence of non-local microphysics.

Isocurvature perturbations

(Lehners, McFadden, Steinhardt & Turok 2007)

A subdominant scalar field with a negative exponential potential develops a scale-invariant spectrum.

By transferring this isocurvature spectrum to the Bardeen potential at the onset of the bounce, the spectrum after the bounce remains scale-invariant.

The isocurvature generation can be associated with a regular bounce model (for example the ghost condensate):

"New Ekpyrotic cosmology"

(Buchbinder, Khoury & Ovrut 2007 – Creminelli & Senatore 2007)

Large non-gaussianities, fine-tuning, pre-ekpyrosis!

3. The Bounce and The Perturbations

"Dust"-dominated Pre-Bounce

(Wands 1999; Finelli & Brandenberger 2002; Cai et al. 2008, 2009)

If the contraction is dominated by a source with $p = w_- \rho$, the growing mode has spectral index

$$n_s = 1 - \frac{4}{1+3w_-}$$

If the growing mode dies out in the post-bounce, the final constant mode has spectral index

$$n_s = 5 - \frac{4}{1+3w_-}$$

To get $n_s = 1$ one may choose w_=0 (anisotropy problem, unstable!)

Non-linear EoS tames anisotropy

(VB & Bruni 2009)

Suppose the EoS can be Taylor-expanded as

$$p = w\rho + \beta\rho^2 + \gamma\rho^3 + \ldots$$

In radiation-dominated contraction, anisotropies can be heavily suppressed.

Even for a dust-like contraction (w=0), we get a small suppression

$$\frac{\sigma_P^2 / \rho_P}{\sigma_i^2 / \rho_i} = 10^{-2} \left(\frac{T_c}{1\,TeV} \right)^8 \left(\frac{\rho_{\gamma,0}}{\rho_i} \right)$$

Non-linearities in EoS can help keeping anisotropy under control.

Comparing predictions

Inflation	Bounce
Solves horizon and flatness	Solves horizon and flatness
Solves anisotropies	Solves anisotropies*
$n_s = 1 - 4\varepsilon - 2\delta$	$n_s \geq 1$
$r = 9\varepsilon$	$r \leq 1$
$n_T = -2\varepsilon$	$n_T \geq 0$
	Black hole overproduction?
	Circles in the sky? *(Gurzadyan & Penrose 2011)*

Conclusions

- String theory suggests a resolution of the Big Bang singularity
- Bouncing cosmologies still face many problems (bounce details, perturbations, anisotropies)
- Even if inflation is the correct paradigm, it needs a UV completion to be fully satisfactory (singularity, Transplanckian problems)
- Predictions are however possible and testable with CMB
- String Theory may accommodate inflation and provide an answer to all these problems