Cosmological implications of light fields during inflation

extending some standard inflationary predictions

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Predictions from (single) field inflation

Inflation makes a series of predictions: see A. Liddle talk

1- universe is flat: $\Omega=1$
2- classical inhomogeneities are erased
3- metric perturbations are Gaussian, almost scale invariant
4- no vector perturbation
5- tensor perturbations are almost scale invariant

6- there exists a consistency relation between *T/S*, n_t et n_s

7- all light scalar fields develop almost scale invariant Gaussian fluctuations on large scales

To which extent are these predictions robust:

A- effect of scalar fields on the predicted fluctuations

F. Bernardeau, L. Kofman and JPU, astro-ph/0403

B- can we generate some non-Gaussianities

F. Bernardeau and JPU, PRD **66** (2002) 103506,
PRD **67** (2003) 121301(R)
astro-ph/0311421, astro-ph/0311422

Light fields during de Sitter inflation

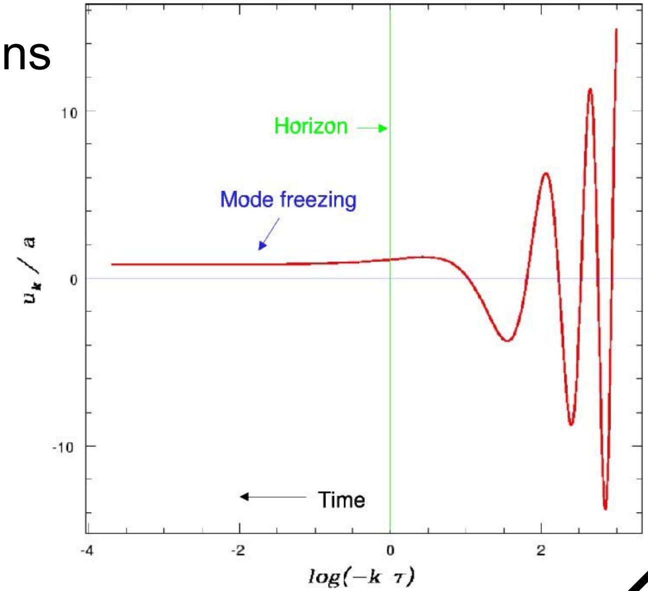
This equation can be rewritten as

$$v_k'' + \left(k^2 - (\nu^2 - 1/4)/\eta^2\right) v_k = 0 \quad \text{with} \quad \nu^2 = 9/4 - m^2/H^2$$

Frozen super-Hubble fluctuations

$$\chi_k \sim \frac{H}{\sqrt{2k^3}}(-k\eta)^{3/2-\nu}$$

10^{-28} cm
amplitude $\sim 10^{-5} M_4$



Plane wave en small scales

$$\chi_k \xrightarrow[k\eta \gg 1]{} \frac{e^{-ik\eta}}{\sqrt{2k}}$$

10^{-33} cm

$$\chi_k \sim \frac{\sqrt{\pi}}{2}\sqrt{-\eta}\, H_\nu^{(2)}(-k\eta)$$

Scalar fields during inflation

If $m/H \ll 1$, the field is said to be light

it develops super-Huble fluctuations of amplitude $\sim H/(2k^3)^{1/2}$

If $m/H \gg 1$, the field is heavy

it is exponentially damped on large scales

Exact power spectrum of the field depends on:

1- the mass of the field

2- the expansion rate during inflation

Light fields: origin and effects

Theories with extra-dimensions (e.g. superstring)

dimensional reduction leaves us with scalar fields

* moduli fields
* dilaton

If light, they will be excited during inflation

Coupling constants depend on these moduli fields

they can become spacetime dependent

Effects to be expected:

1- spacetime variation of fundamental constants (JPU, Rev. Mod. Phys. **75** (2003) 403)

2- modulation of cosmological perturbations (Kofman 03, Dvali et al.,03)

3- may seed some non-Gaussianity

Moduli may pose some problems in cosmology

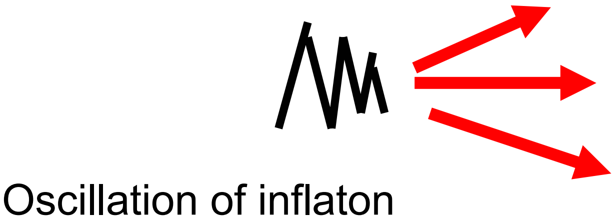
BBN (dominantion before BBN/ TeV mass scale moduli decay may destroy BBN)

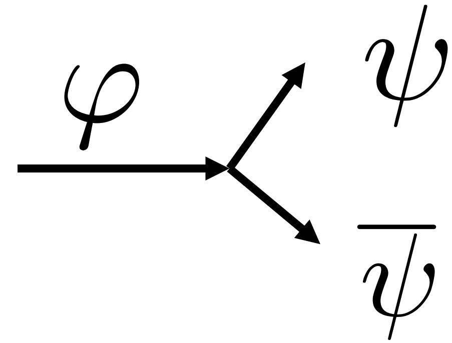
must decouple from matter or stabilize

Modulated cosmological perturbations

(Kofman 03, Dvali et al. 03)

Inflaton decays at the end of inflation





If the coupling depends on some moduli, then the decay rate will be space dependent

$$\mathcal{L} \sim f(\chi/M)\,\varphi\overline{\psi}\psi \longrightarrow \Gamma \sim f(\chi/M)\, m_\varphi/8\pi$$

$$\rho_{\rm r} \sim T_{\rm r}^4 \sim \Gamma^2 M_4^2 \sim f^4 m_\varphi^2 M_4^2$$

$$\delta\rho_r/\rho_r \sim 4\,\frac{f'}{f}\frac{\delta\chi}{M} \sim \frac{H}{M} k^{-3/2}$$

Modulated fluctuations in hybrid inflation

We consider a 2-field model with potential

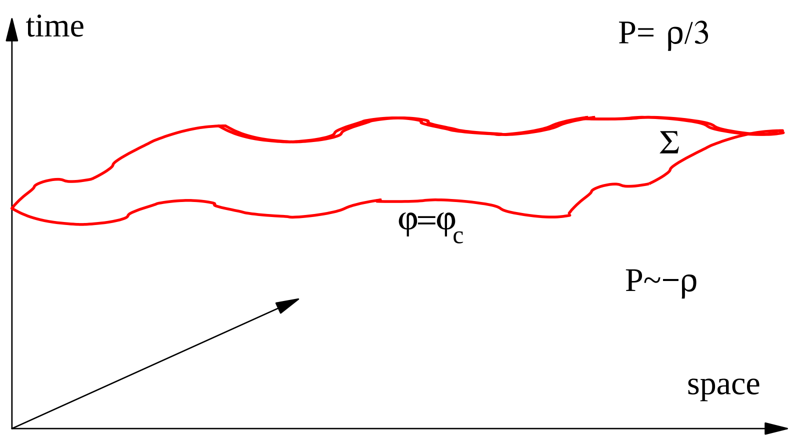
$$V = \frac{\lambda}{4}(\sigma^2 - v^2)^2 + \frac{g^2}{2}\varphi^2\sigma^2 + V(\varphi)$$

Spinodal instability at $\varphi_c = \frac{\sqrt{\lambda}\, v}{g}$

If moduli fields are light then φ_c will fluctuate and inflation will not end at the same « time » everywhere.

In the case of <u>hybrid inflation</u>: tachionic preheating very fast (Felder et al, 00)
transition inflation-RDU can be considered as instantaneous

One can use matching conditions to relate pre- and post- inflationary eras.



Restrictions on the model

The dependence of the potential on moduli fields have different status

$$V = \frac{\lambda(\chi)}{4}(\sigma^2 - v^2)^2 + \frac{g^2(\chi)}{2}\varphi^2\sigma^2 + V(\varphi)$$

Mass of the fluctuation $\delta\chi$ are of order

$$m_\chi^2 \sim (v^4/4) d^2\lambda/d^2\chi \sim H^2 M_4^2/M^2$$

$\delta\chi$ is heavy unless λ has no dependence on moduli

There is no restriction on g

It has 2 consequences:

1- the field stabilizes rapidly

2- it decouples from the metric perturbation

So that we have 2 sectors: inflaton+gravity (generate primordial metric fluct.

moduli (test field triggering end of inflation)

An explicit model can be constructed from Sugra D-term inflation.

The case of modulated hybrid inflation

The end of the inflation is triggered by the phase transition on a hypersurface defined by

$$q(\varphi, \chi) = \varphi - \varphi_c(\chi) = 0$$

We expect the perturbations deep in the RDU to be a mixture of the inflationary perturbations (seeded by φ) modulated by the fluctuation of the transition surface (induced by χ).

The curvature perturbation during inflation and deep in the RDU are related by

$$\mathcal{R}_+ = \mathcal{R}_- + \left(1 - \frac{\varepsilon}{2}\right) \frac{H}{\dot{\varphi}}\Big|_* \sum_a \gamma_a \delta\chi_a(-\eta_*)$$

With

$$\gamma_a \equiv \frac{\mathrm{d}\varphi_c}{\mathrm{d}\chi_a}(-\eta_*)$$

In our Sugra model, we have $\Sigma\gamma^2_a$**=2**.

Consistency relation

Gravitational waves are insensitive to the shape of the transition surface
It follows that we obtain the standard results:

1- GW are generated by the fluctuations of the inflaton
2- their spectrum is given by

$$P_h = \frac{1}{4\pi^2}\frac{H^2}{M_4^2}(k\eta_*)^{-2\varepsilon}$$

Scalar modes receive both contributions. Performing the matching leads to

$$P_R = \frac{1}{4\pi^2}\frac{H^2}{M_4^2}\frac{(k\eta_*)^{-2\varepsilon}}{\varepsilon}\left[(k\eta_*)^{2\eta-4\varepsilon} + 4\pi\gamma^2(1-\varepsilon)(k\eta_*)^{2m^2/3H^2}\right]$$

Consistency relation becomes

$$\frac{T}{S} = \frac{\varepsilon}{1+4\pi(1-\varepsilon)\gamma^2}$$

Light fields and non-Gaussianity

In single field inflation

1- initial state is Gaussian (vacuum state)

2- non linearities can not be large if we are in slow roll

$$\delta\ddot{\phi} + 3H\delta\dot{\phi} - \Delta\delta\phi/a^2 \simeq -V''\delta\phi \boxed{-3V'''\delta\phi^2} + \dots$$

Indeed, they are other possibilities: (see. S Matarrese talk)

1- Topological defects formed at the end of inflation

2- Change in the initial state

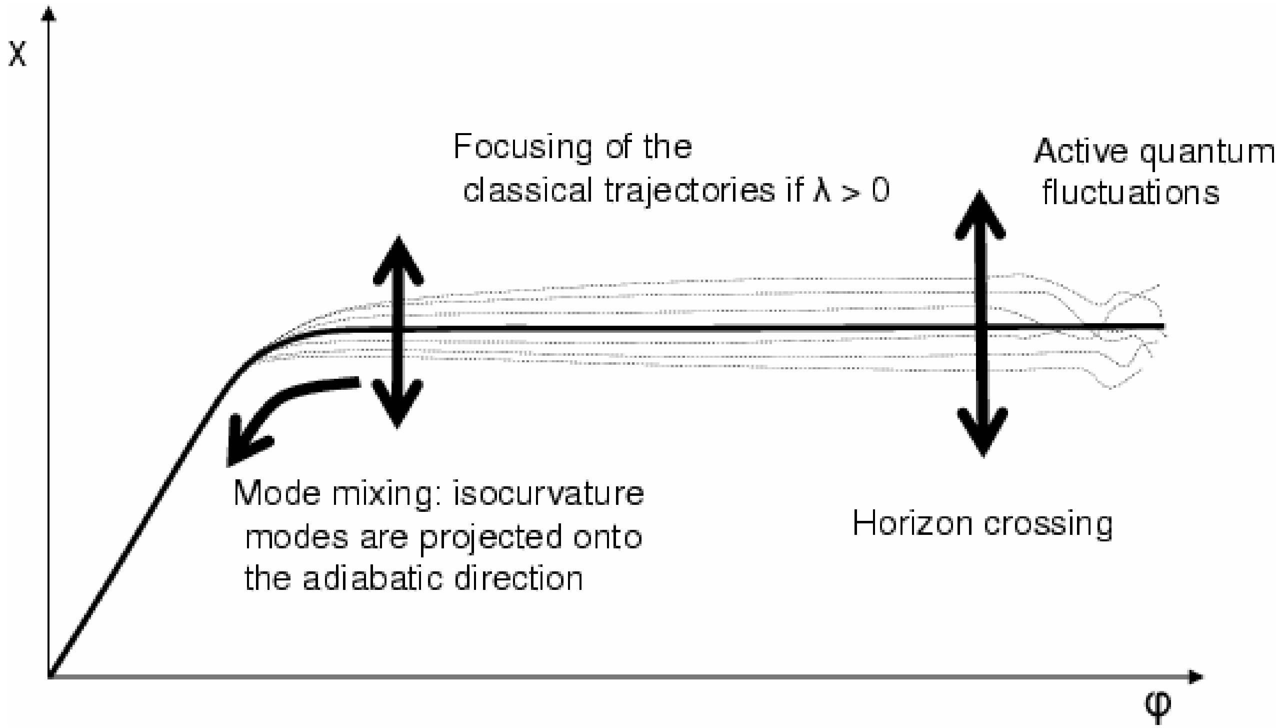
3- Features in the potential

4- Multifield model (isocurvature modes)

Is it possible to seed non-Gaussianity on a large band of *k* and still have adiabatic fluctuations?

F. Bernardeau and JPU, PRD **66** (2002) 103506, PRD **67** (2003) 121301(R)
PRD **69** (2004) 063520, astro-ph/0311422

Basics of the mechanism



Bartolo et al. 01

PDF of metric fluctuation can be computed analytically

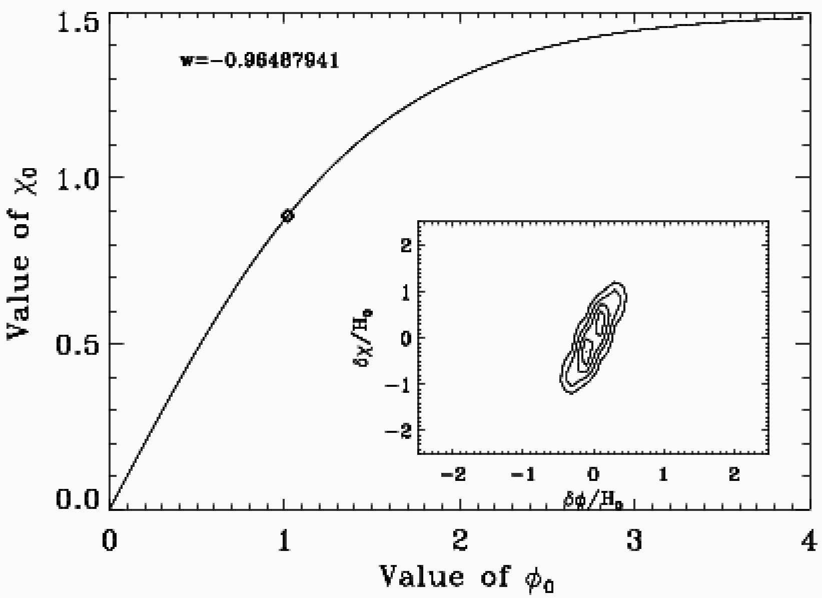
Metric fluctuation = Gaussian fluctuation of inflaton

+

non-Gaussian fluctuation of isocurvature mode

Bernardeau, JPU 02

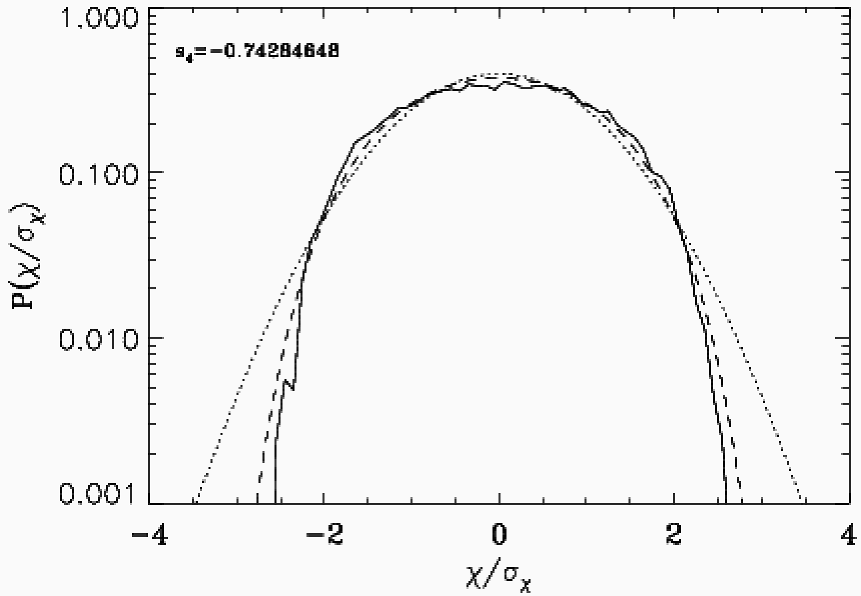
Numerical illustration (2-field model)



Evolution of the 2-field PDF

Bernardeau, JPU 03

Evolution of the PDF of the curvature



The curvature PDF is the superposition of a Gaussian and a non-Gaussian contributions with same variance

Conclusions

Modulated inflation opens the phenomenology of inflation by

1- having a consistency relation with 1 extra-parameter
2- spectral index of scalar modes may depend on *m/H*
3- gravitational waves are not affected

The consistency relation is also modified in other cases

multifield inflation: $T/S = \varepsilon \sin^2\theta$, θ isocurvature correlation angle (Wands et al, 02)

curvaton (see F. Vernizzi talk)

Possibilty produce non-Gaussianity

in a large class, an explicit expression of the PDF has been obtained

Both may leave signatures on he CMB