Mixed inflaton and curvaton perturbations

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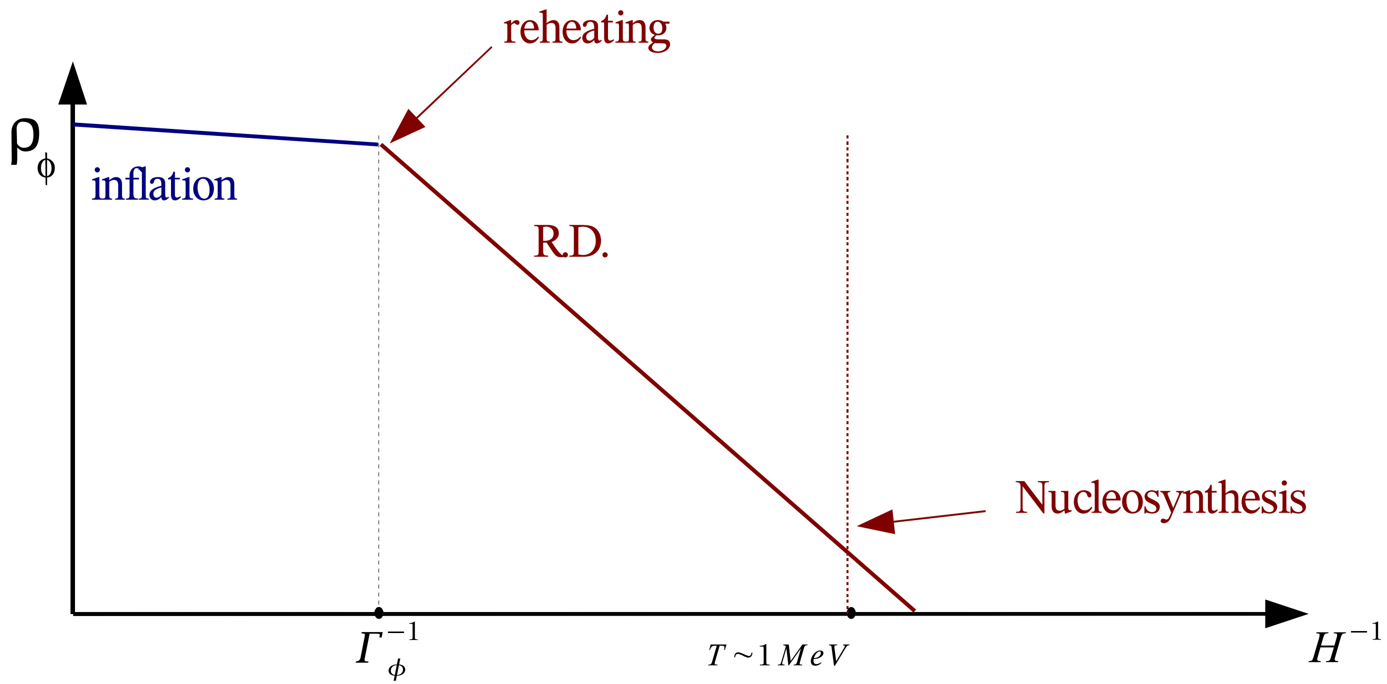
and in prep.

Concise Oxford dictionary:
Curvaton / 'ku:vaton/ *noun*
Light scalar field partially or totally responsible for the primordial density perturbations

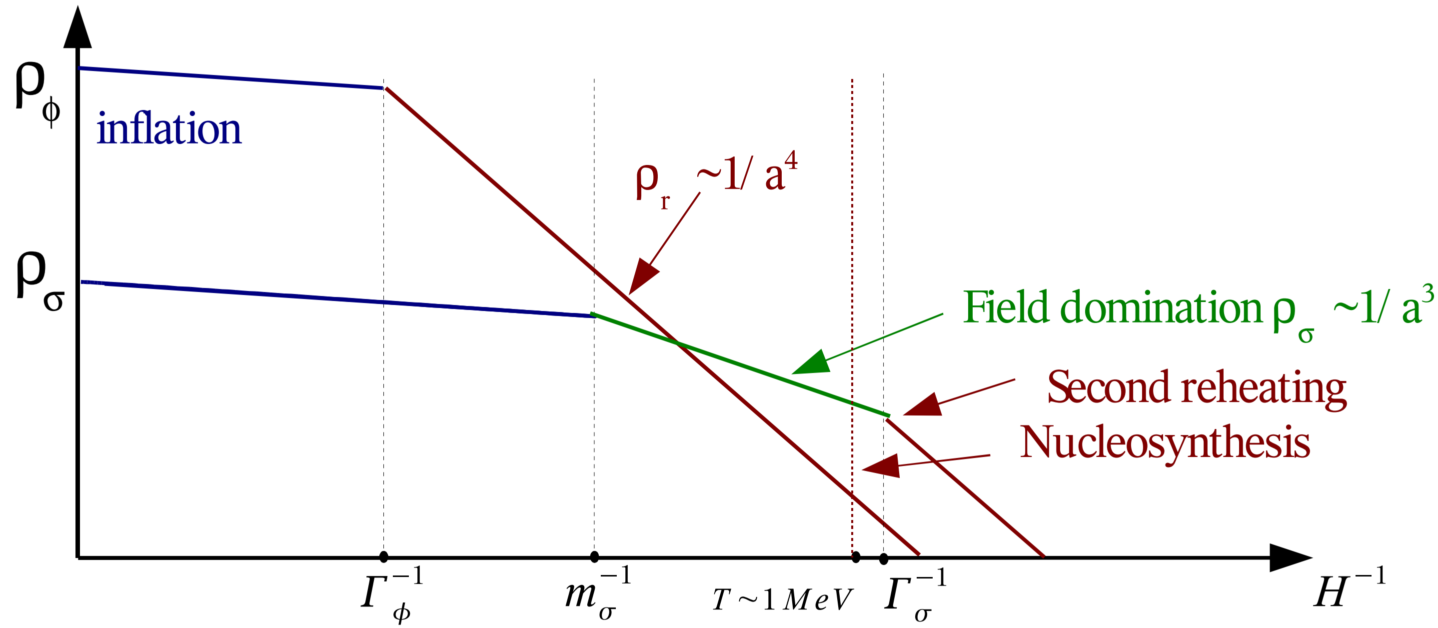
LIGHT FIELDS



Moduli problem: [Coughlan et al., '83]

Weakly coupled light scalar fields (m<<H) are not diluted during inflation and can dominate the universe and decay during or after nucleosynthesis

LIGHT FIELDS



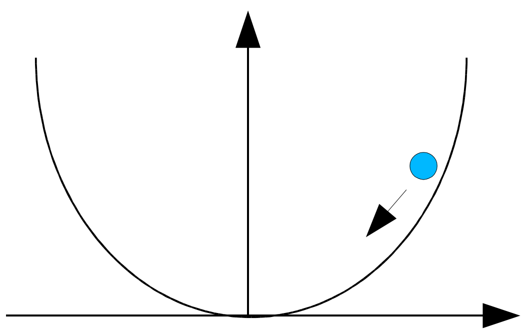
- Scalar field σ negligible during inflation, $\rho_\sigma << \rho_\phi$
- Light field, $L = \frac{1}{2}\dot{\sigma} - \frac{1}{2} m_\sigma^2 \sigma^2$, $m_\sigma << H$

$$\ddot{\sigma} + 3H\dot{\sigma} + m_\sigma^2 = 0$$

$$m_\sigma < H \;\Rightarrow\; \sigma \simeq const$$

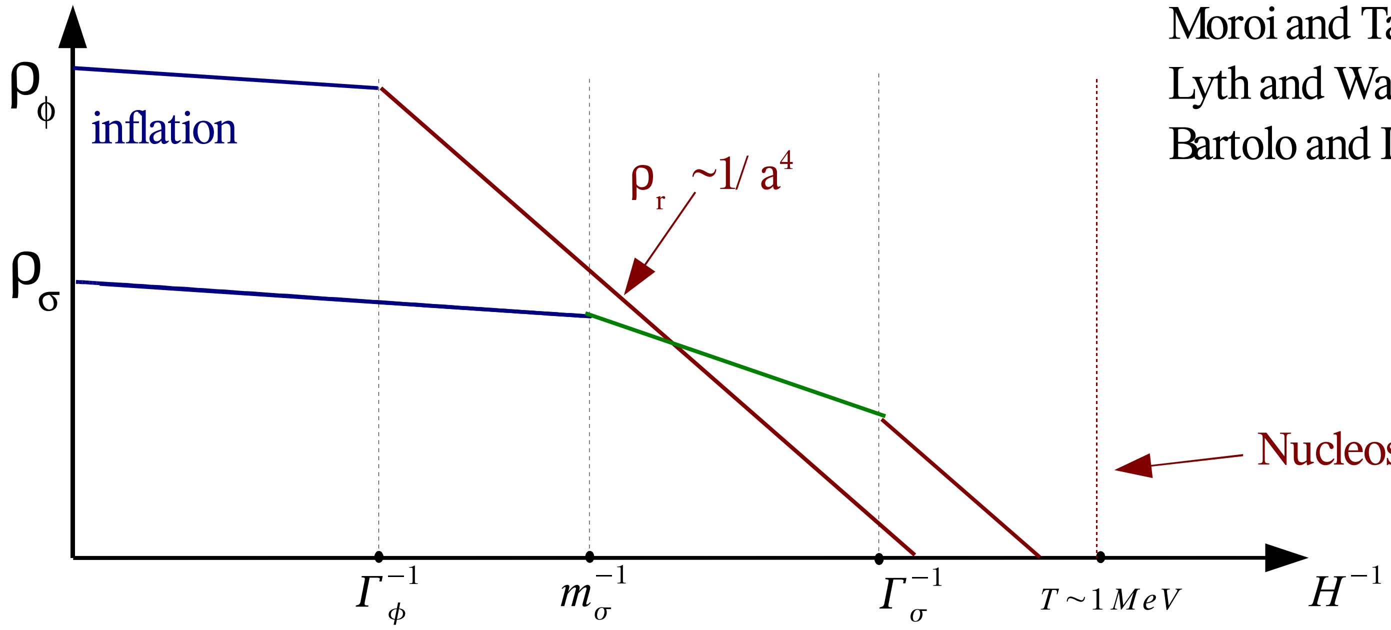
$$m_\sigma \geqslant H \;\Rightarrow\; \sigma \simeq a^{3/2} \sin(m_\sigma t)$$

Non-relativistic fluid, $\rho_\sigma \sim 1/a^3$



CURVATON

[Mollerach, '90;
Enqvist and Sloth, '02;
Moroi and Takahashi, '01;
Lyth and Wands, '02;
Bartolo and Liddle, 03]



QUESTION: WHY???

STANDARD VIEW:

INFLATION provides us with three things:

Superluminal expansion	INFLATON
Origin of matter: reheating	INFLATON
Density perturbations	INFLATON

quantum fluctuations: $\delta\,\phi \sim H$ ← Hubble parameter during inflation

INFLATON PERTURBATIONS

$$\Phi \simeq \frac{1}{\sqrt{\epsilon}} \frac{\delta \phi}{m_{Pl}} \simeq \frac{H}{\sqrt{\epsilon}\, m_{Pl}} \simeq \frac{V^{1/2}}{\sqrt{\epsilon}\, m_{Pl}^2}$$

OBSERVABLES:

$$P_\Phi , n_S , r$$

$$P_\Phi \equiv \frac{V}{\epsilon\, m_{Pl}^4}$$

Power spectrum

$$r \equiv \frac{P_T}{P_\Phi} = 16\epsilon$$

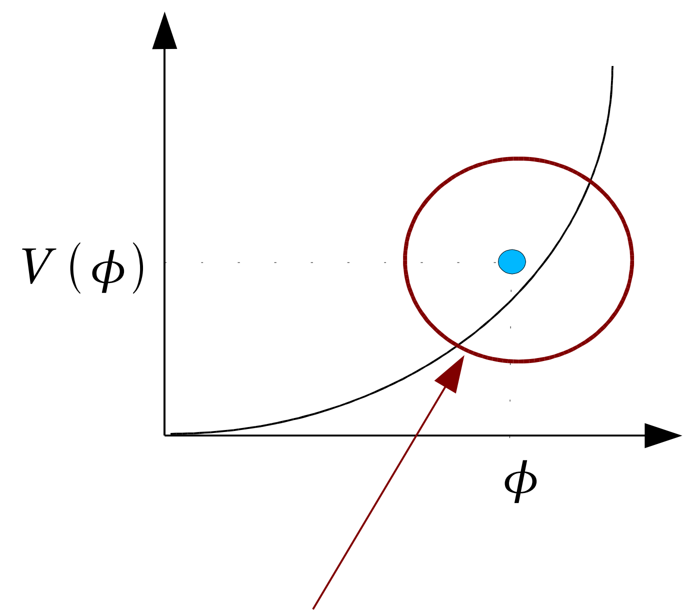
Tensor/ scalar ratio

$$n_S \equiv 1 + d\frac{ln P_\Phi}{d\, ln\, k} = 1 + 2\eta - 6\epsilon$$

Scalar spectral index

Relation between the inflaton potential and the density perturbations

Constraints on the inflaton potential



$$\epsilon \equiv \frac{m_{Pl}^2}{2}\left(\frac{V'}{V}\right)^2 \qquad \eta \equiv m_{Pl}^2 \frac{V''}{V}$$

Slow-roll parameters

INFLATON PERTURBATIONS

$$\Phi \simeq \frac{1}{\sqrt{\epsilon}} \frac{\delta \phi}{m_{Pl}} \simeq \frac{H}{\sqrt{\epsilon}\, m_{Pl}} \simeq \frac{V^{1/2}}{\sqrt{\epsilon}\, m_{Pl}^2}$$

OBSERVABLES:

$$P_\Phi, n_S, r, n_T$$

$$P_\Phi \equiv \frac{V}{\epsilon\, m_{Pl}^4}$$

Power spectrum

$$r \equiv \frac{P_T}{P_\Phi} = 16\epsilon$$

Tensor/ scalar ratio

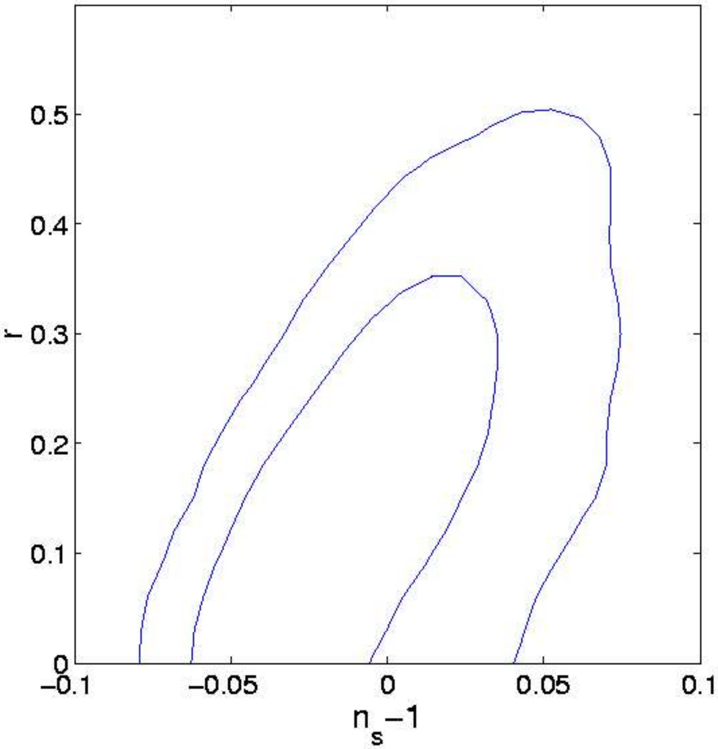
$$n_S \equiv 1 + d\frac{\ln P_\Phi}{d \ln k} = 1 + 2\eta - 6\epsilon$$

Scalar spectral index

Data constraints

[Leach and Liddle, 2002]

$$r = 16\epsilon$$



$$n_S - 1 = 2\eta - 6\epsilon$$

INFLATON CONSTRAINTS

$$\Phi \simeq \frac{1}{\sqrt{\epsilon}} \frac{\delta \phi}{m_{Pl}} \simeq \frac{H}{\sqrt{\epsilon}\, m_{Pl}} \simeq \frac{V^{1/2}}{\sqrt{\epsilon}\, m_{Pl}^2}$$

OBSERVABLES:

P_Φ, n_S, r, n_T

CONSTRAINTS:

V, V', V''

$P_\Phi \equiv \dfrac{V}{\epsilon\, m_{Pl}^4}$ Power spectrum	→	$V = 10^{-7} \epsilon^2 m_{Pl}^4$ COBE normalization
$r \equiv \dfrac{P_T}{P_\Phi} = 16\epsilon$ Tensor/ scalar ratio	→	$\epsilon \ll 1 \;\Rightarrow\; m_{Pl} V'/V \ll 1$ No gravity waves observed
$n_S \equiv 1 + d\dfrac{\ln P_\Phi}{d \ln k} = 1 + 2\eta - 6\epsilon$ Scalar spectral index	→	$\eta \ll 1 \;\Rightarrow\; m_{Pl}^2 V''/V \ll 1$ Scale invariance

INFLATON CONSTRAINTS

- Inflation is very economical but tightly constrained:
severe constraints on inflaton potential

- Some inflationary models motivated by particle physics (supersymmetry) require the violation of some of these constraints

[Dimopoulos and Lyth, 2002] [Dvali and Kachru, 2003]

$$V(\phi) \ll (10^{16}\, GeV)^4 \quad and \quad m_\phi \sim H$$

CONSTRAINTS:

$$V,\, V',\, V''$$

$V = 10^{-7}\epsilon^2 m_{Pl}^4$ COBE normalization
$\epsilon \ll 1 \;\Rightarrow\; m_{Pl} V'/V \ll 1$ No gravity waves observed
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Superluminal expansion	INFLATON
Origin of matter: reheating	INFLATON
Density perturbations	CURVATON

• The curvaton can generate perturbations and liberate the inflaton relaxing the constraints on inflaton potential: **division of labours**

Drawback:

• more difficult to directly test inflation

CONSTRAINTS:

$$V, V', V''$$

$V < 10^{-7} \epsilon^2 m_{Pl}^4 \sim (10^{16} GeV)^4$ COBE bound
$\epsilon \ll 1 \quad \Rightarrow \quad m_{Pl} V'/V \ll 1$
$\eta \sim 1 \quad \Rightarrow \quad \cancel{m_\phi \ll H}$ $m_\phi \sim H$

CURVATON GENERATED PERTURBATIONS

• Any light field (overdamped during inflation, m<<H) inherits the same quantum fluctuation (flat spectrum) as the inflaton

Curvaton σ : $\qquad \delta\sigma \simeq H \qquad \delta\phi \simeq H$

• By dominating the universe and decaying before nucleosynthesis the curvaton imprints its perturbations: generation of curvature perturbations

$$\boxed{\Phi \simeq -\frac{1}{2}\frac{\rho_r\delta_r+\rho_\sigma\delta_\sigma}{\rho} \simeq -\Omega_{\sigma,dec.}\frac{\delta\sigma}{\sigma} \simeq -\Omega_{\sigma,dec.}\frac{H}{\sigma}}$$

$$if\ \rho_\sigma \gg \rho_r$$

• These may be much larger than the inflaton perturbations

$$\delta_r = \delta_\phi \simeq \frac{H}{\sqrt{\epsilon}\, m_{Pl}} \ll \delta_\sigma \simeq \Omega_{\sigma,dec.}\frac{H}{\sigma} \qquad if\ \sigma \ll \sqrt{\epsilon}\, m_{Pl},\quad and\quad \Omega_{\sigma,dec.} \simeq 1$$

New extra parameter: σ expectation value during inflation

PURE CURVATON PERTURBATIONS

$$\Phi \simeq \Omega_{\sigma,dec} \frac{\delta\sigma}{\sigma} \simeq \Omega_{\sigma,dec} \frac{H}{\sigma} \qquad \sigma \ll m_{Pl}$$

OBSERVABLES: P_Φ, n_S, r		CONSTRAINTS with $\sigma \ll m_{Pl}$: V, V', V''
$P_\Phi \simeq \Omega_{\sigma,dec} \frac{V}{\sigma^2 m_{Pl}^2}$	→	$V \ll 10^{-7} \epsilon^2 m_{Pl}^4$ COBE bounds
$r \equiv \frac{P_T}{P_\Phi} \simeq \frac{16}{\Omega_{\sigma,dec}} \left(\frac{\sigma}{m_{Pl}}\right)^2 \ll 1$	→	No gravity waves observable
$n_S \simeq 1 - 2\epsilon$	→	$\epsilon \ll 1 \qquad \eta \sim 1$

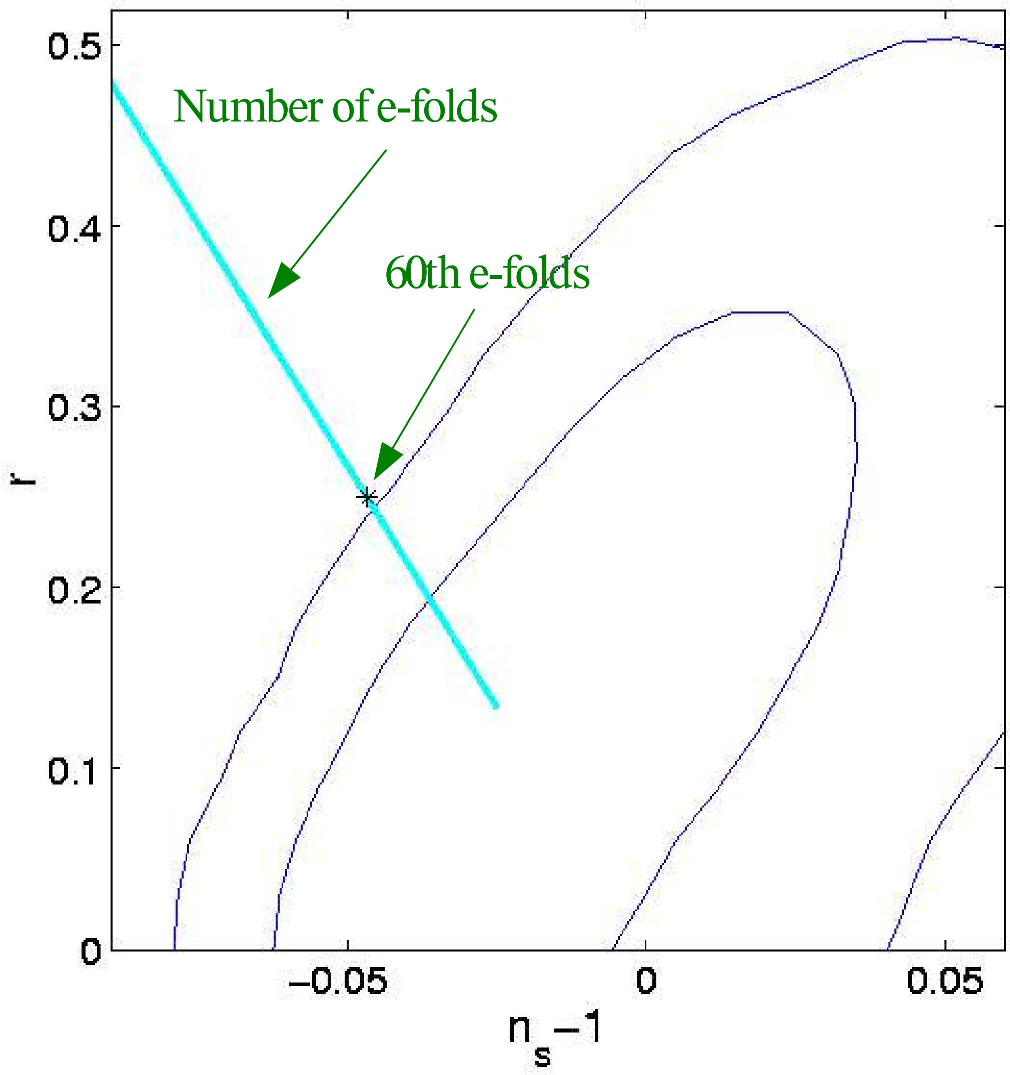
QUARTIC INFLATION

$$V(\phi) = \lambda \phi^4$$

Quartic inflation is excluded at 95% C.L. by combined WMAP data

[Peiris et al., '03]

[Leach and Liddle, '03]

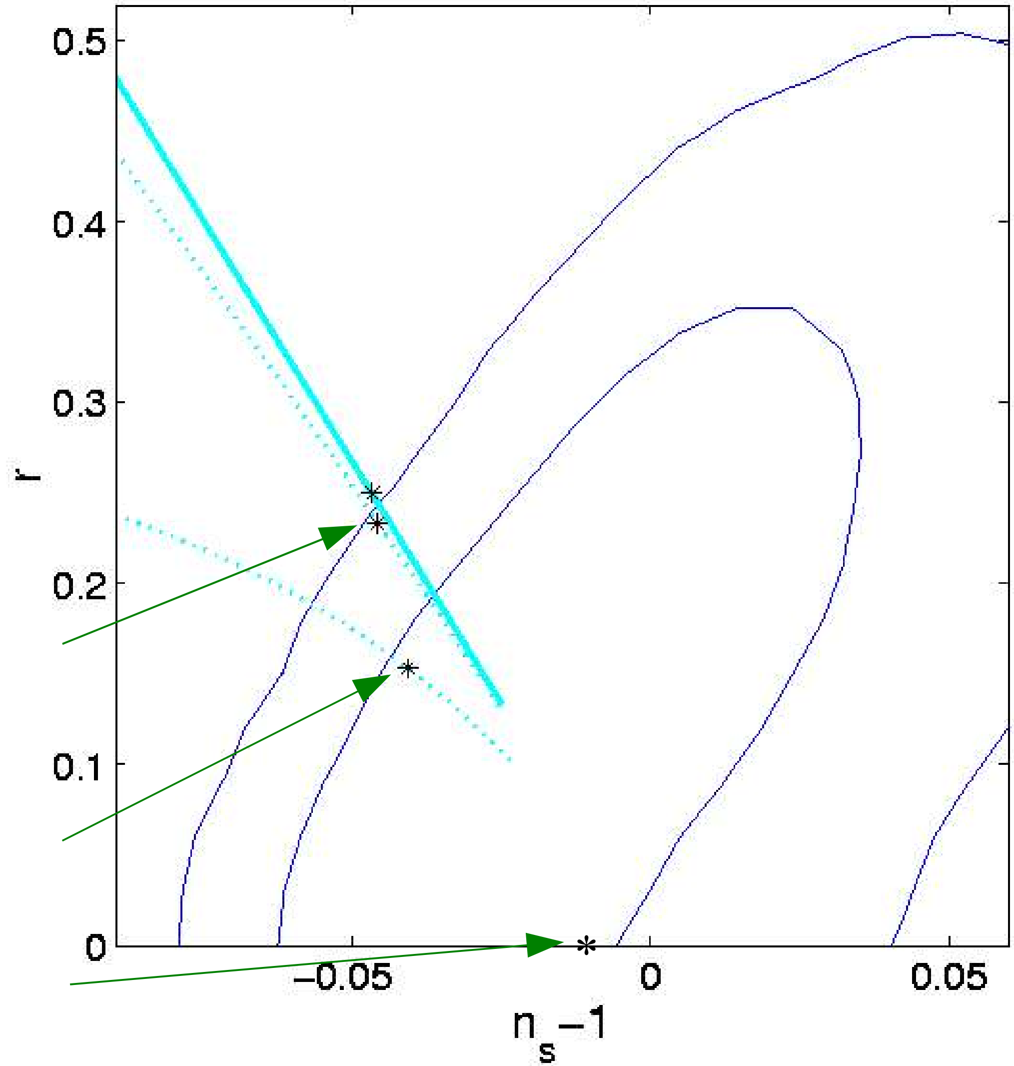


QUARTIC INFLATION + CURVATON

$$V(\phi) = \lambda \phi^4 \;+\; c$$

Assume: $\Omega_{\sigma,dec.} = 1$

[Langlois and F.V., '04]



Mixed perturbations with $\sigma \sim 0.5\, m_{Pl}$

Mixed perturbations with $\sigma \sim 0.1\, m_{Pl}$

Pure curvaton perturbations $\sigma \ll m_{Pl}$

Consistency relation

$$r = -8 \frac{n_T}{1 - f(\sigma)^2 n_T / 2}$$

It allows to measure σ and break the degeneracy

NON-GAUSSIANITIES

$$\rho_\sigma \simeq m_\sigma^2 \sigma^2 \quad \Rightarrow \quad \Phi \simeq -\frac{1}{2}\Omega_{\sigma,dec.}\frac{\delta\rho_\sigma}{\rho_\sigma} = -\Omega_{\sigma,dec.}\left[\frac{\delta\sigma}{\sigma} + \frac{1}{2}\left(\frac{\delta\sigma}{\sigma}\right)^2\right]$$

Quadratic field perturbation

Simple characterization of non-Gaussianities:

[Verde et al., '00; Komatzu and Spergel, '01]

$$\Phi = \Phi_L + f_{NL}\Phi_L^2 \quad \Rightarrow \quad f_{NL} \simeq \frac{5}{4\,\Omega_{\sigma,dec.}} \quad for \quad \Omega_{\sigma,dec.} \ll 1$$

[Lyth, Ungarelli and Wands, 03]

See Sabino Matarrese's talk

REHEATING AND THE CURVATON IN THE LAB

- The Minimal Supersymmetric Standard Model contains many flat directions (directions in the field space where V ~ 0): curvaton as flat direction of the MSSM. [Mazumdar and Enqvist, '03; Enqvist, '04]

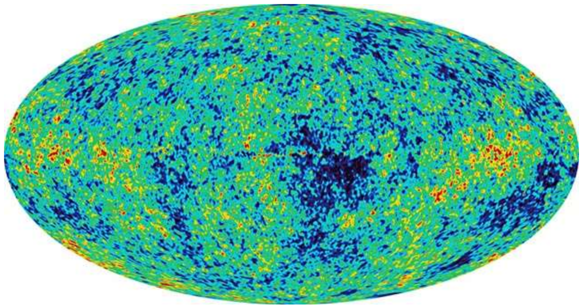
- Possibility to see the curvaton in the laboratory if LHC sees SUSY

Superluminal expansion	INFLATON
Origin of matter: reheating	CURVATON
Density perturbations	CURVATON

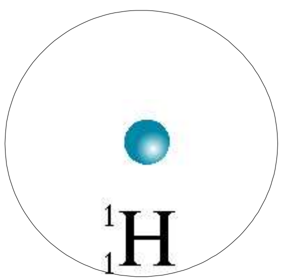
- Baryons and leptons may have been generated by the curvaton (Affleck-Dine field) [Hebecker, March-Russel, Yanagida, '02; Moroi and Murayama, '02; MacDonald, '03]

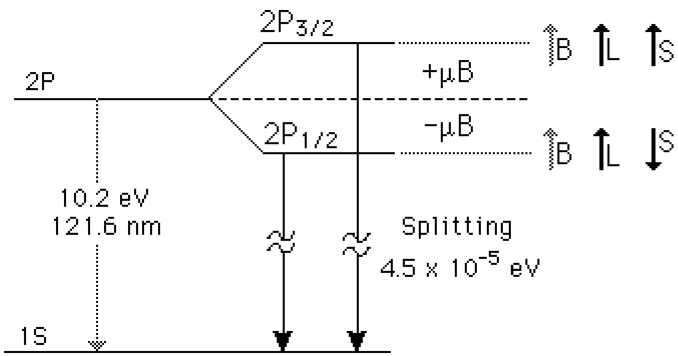
(Small) Isocurvature perturbations

FINE STRUCTURE

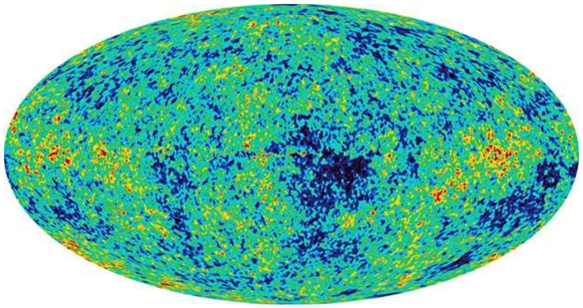


Perturbations:		Fine structure:
• Adiabatic	$\longrightarrow$	Small isocurvature perts
• Gaussian	$\longrightarrow$	Small non-Gaussianities
• Scale-invariant	$\longrightarrow$	Small deviation from scale-invariance





SUMMARY



Perturbations:

- Adiabatic → Small isocurvature perts
- Gaussian → Small non-Gaussianities
- Scale-invariant → Small deviation from scale-invariance

Fine structure:

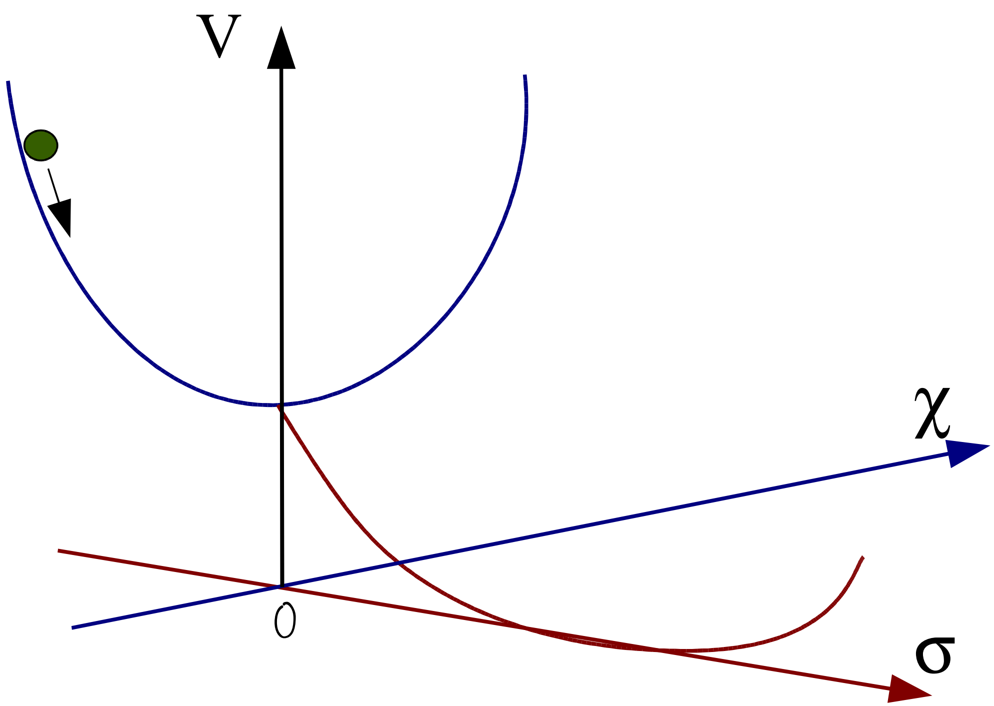
Observables	Values	INFLATION	CURVATON
P_{Φ}	$(2\times10^{-5})^2$	Y	Y
n_S	$\simeq 0$	Y	N
r	$\simeq 0$	?	N
f_{NL}	$\simeq 0$	N	Y
Isocurvature	$\simeq 0$	N	Y

PARAMETRIC RESONANCE DURING INFLATION

[Langlois and F.V., in prep.]

The curvaton cannot couple to the inflaton but can naturally couple to other fields, heavy during inflation, $m_\chi \sim H$.

$$V(\sigma,\chi) = \frac{1}{2} m_\sigma^2 \sigma^2 + \frac{1}{2} m_\chi^2 \chi^2 + \frac{1}{2} g^2 \sigma^2 \chi^2 \quad with \quad m_\sigma \ll m_\chi$$



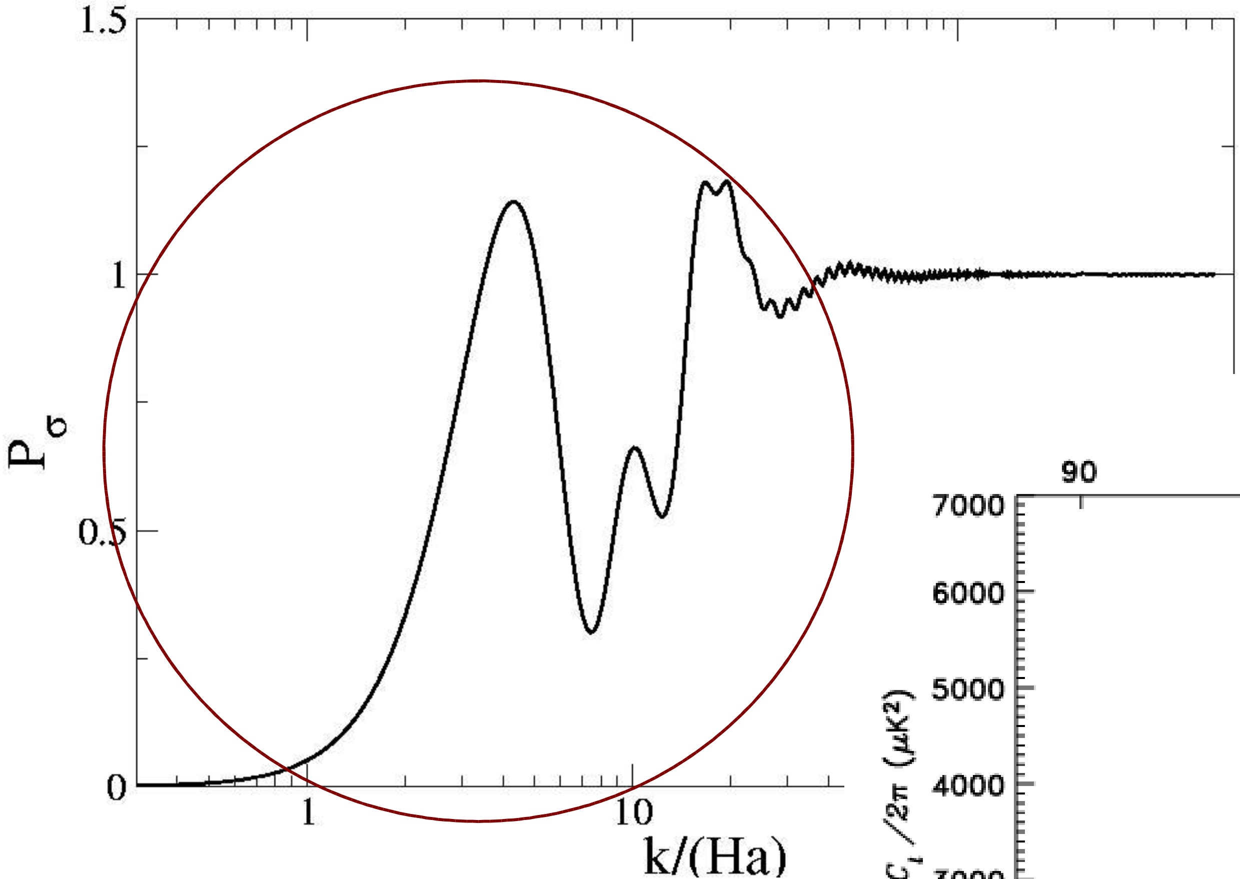
$$\chi \simeq a^{3/2} \sin(m_\chi t)$$

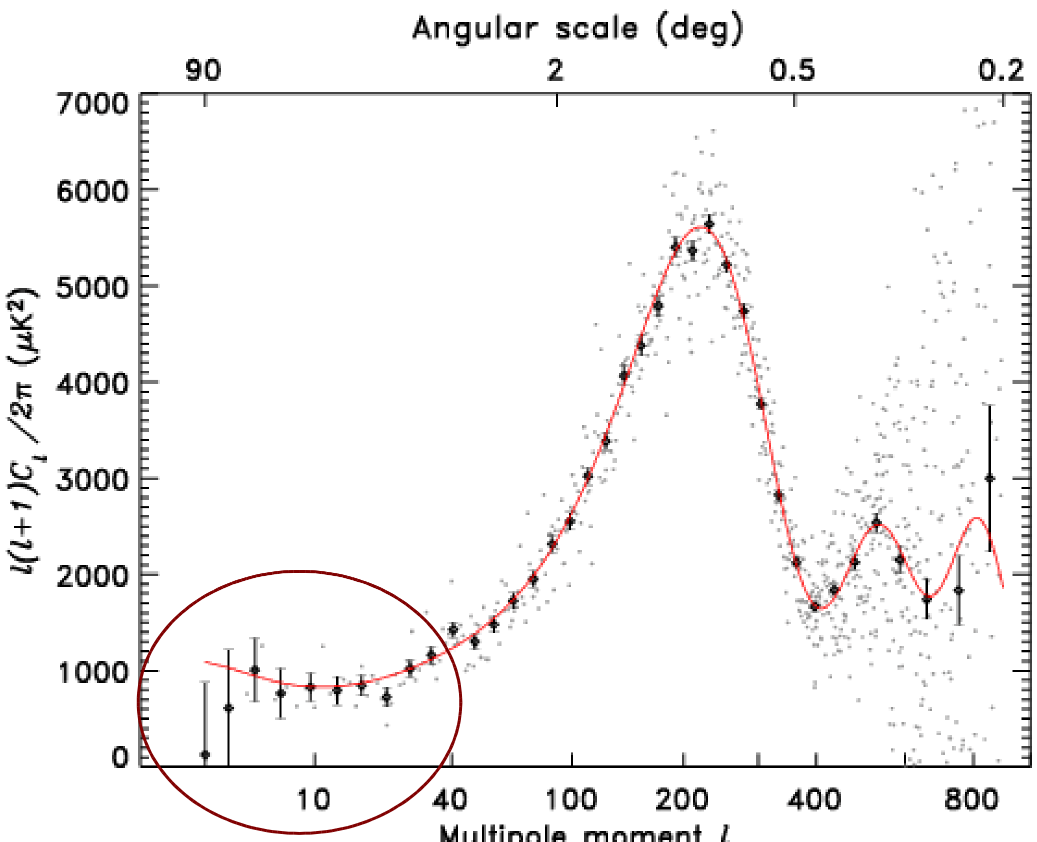
$$m_\sigma^{(eff)2} = m_\sigma^2 + g^2 X^2 e^{-3Ht} \sin^2(m_\chi t)$$

Time dependent mass breaks adiabaticity: σ -particle production

FEATURES IN THE SPECTRUM

Important only for large scales: $m_\sigma^{(eff)2} \simeq g^2\chi^2 \simeq g^2 X^2 e^{-3Ht}\sin^2(m_\chi t) > k^2/a^2$





CONCLUSIONS

Why the curvaton?

- Light fields are generically predicted by supersymmetric models
- Separating the field responsible for superluminal expansion (inflaton) from the field responsible for density perturbations (curvaton) and relax the constraints on the inflaton potential
- Contact with particle physics

Observational consequences:

- Inflation is more difficult to be tested
- The curvaton changes the predictions in the (n_s,r)-plane and introduces a new degeneracy (σ parameter)
- Features in the spectrum of perturbations may be present
- Small non-Gaussianities