INFLATION AT TEV SCALE WITH A PNGB CURVATON

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Origin of Curvature Perturbations

Observations ⇒ structure formation and CMB anisotropy = due to superhorizon perturbations

Perturbations = Gaussian + scale-invariant ⇒

Inflation: Period of superluminal accelerated expansion of spacetime

Superhorizon perturbations: from amplification of quantum fluctuations of light scalar field

Horizon crossing: $\delta\phi = H_{\rm inf}/2\pi$
Superhorizon evolution: $\delta\phi \simeq$ const.

Inflaton Hypothesis: ϕ = Inflaton
Curvaton Hypothesis: ϕ = Curvaton

"Light" Field: $m \ll H_{\rm inf}$ ⇒ ϕ = PNGB

Flatness of PNGB = protected by global U(1)

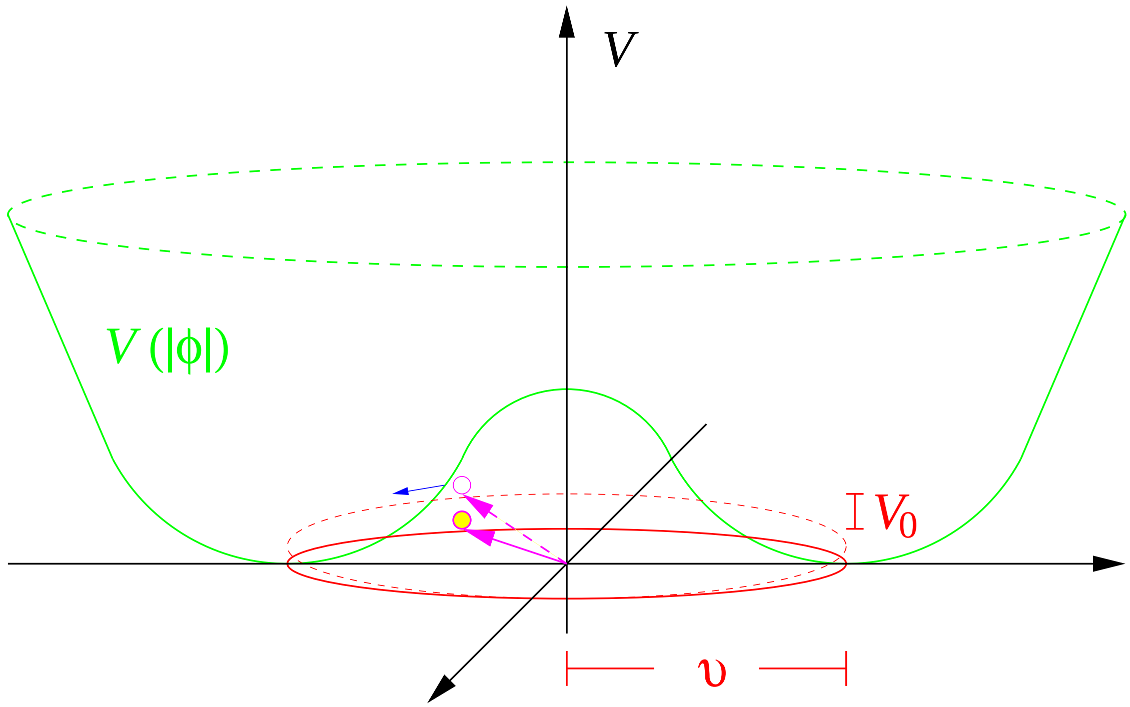
SUSY breaking ⇒ soft mass: $m < H_{\rm inf}$ ✓

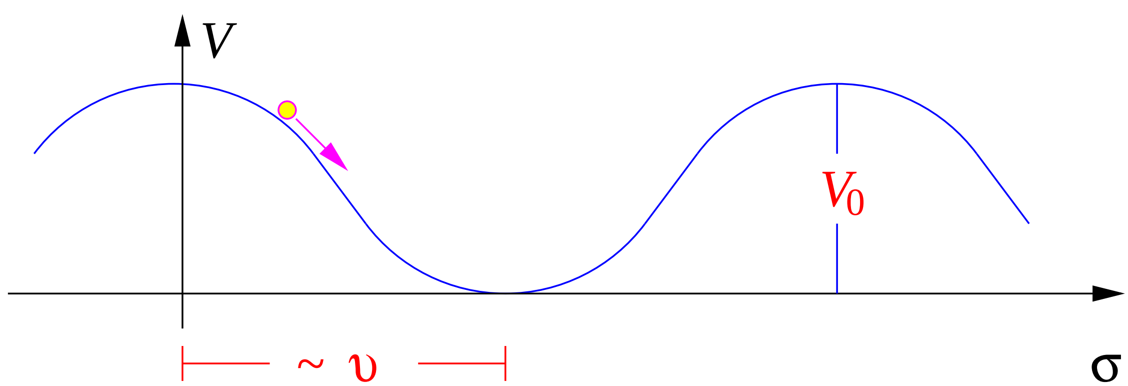
Inflaton Hypothesis: $V_{\rm inf}^{1/4} = 0.03\,\epsilon^{1/4} m_P$ ⇒ $V_{\rm inf}^{1/4} \sim$ GUT COBE

Tight constraint ⇒ fine tuning

Curvaton Hypothesis: Allows $V_{\rm inf}^{1/4} \ll$ GUT

The curvaton liberates inflation model-building


V
V (|ϕ|)
V0
υ


V
V0
~ υ
σ

The Curvaton scenario ($\phi \rightarrow \sigma$)

How the scenario works

- During Inflation σ = frozen (overdamped)
- After Inflation σ unfreezes when $m \sim H(t)$
- After unfreezing σ oscillates around its VEV
- σ dominates (or nearly dominates) the Universe imposing its curvature perturbation $\zeta_\sigma \rightarrow \zeta$
- σ decays into thermal bath of standard model particles (Hot Big Bang begins)

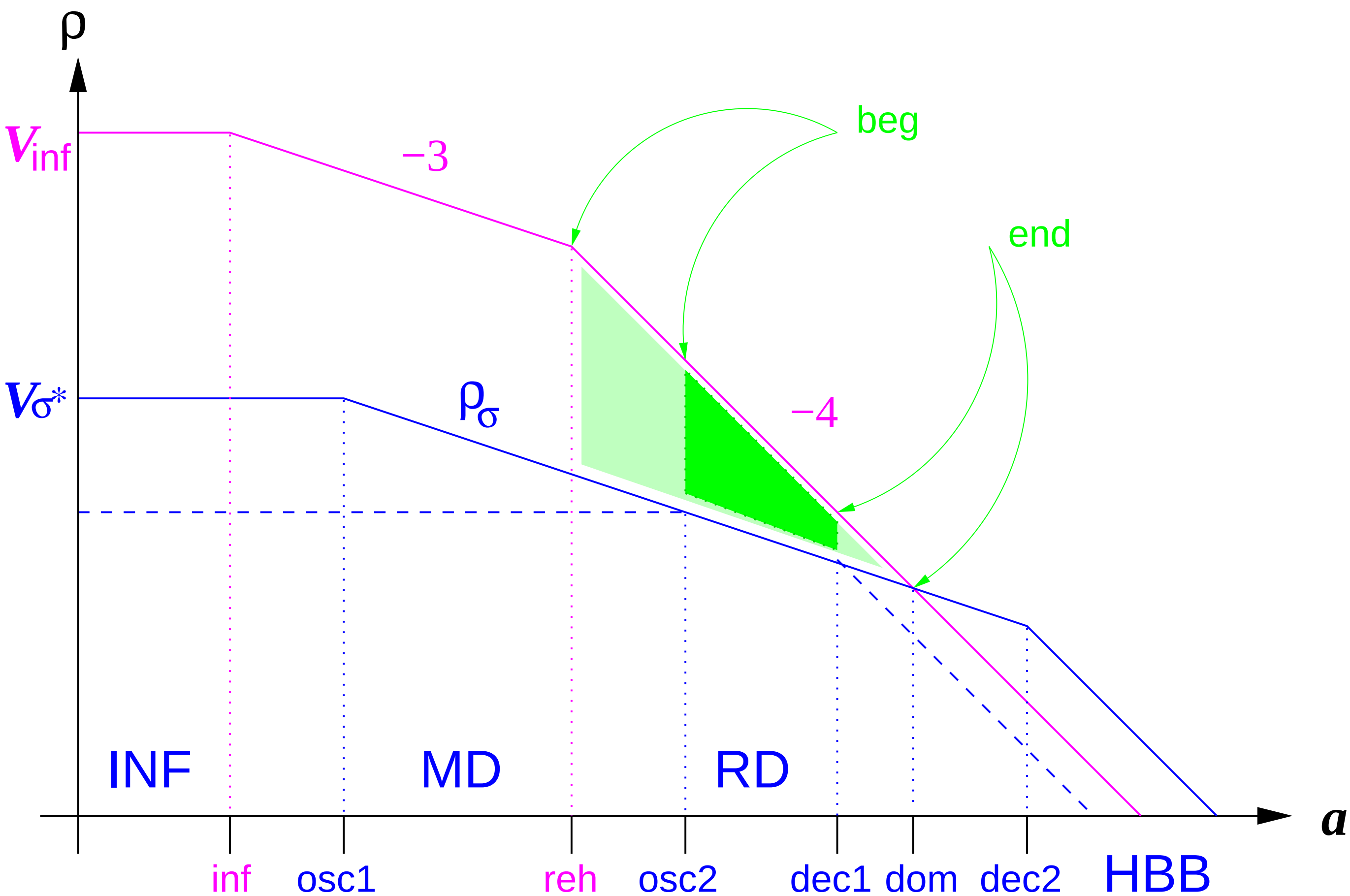
The merits of the Curvaton

Inflation is liberated by the Curvaton Hypothesis

- COBE relaxes to upper bound: $V_{\rm inf}^{1/4} <$ GUT
- No problem with $m_{\rm inf} \sim H_{\rm inf}$ (i.e. $\eta_{\rm inf} \sim 1$)
- No problem with $V(\sigma) \rightarrow 0$ during inflation

The curvaton can be associated with low energy (TeV) physics $\Rightarrow$ accommodated in simple extensions of standard model

The curvaton can link cosmological observations with collider experiments



ρ
V_inf
−3
beg
end
V_σ*
ρ_σ
−4
INF
MD
RD
a
inf
osc1
reh
osc2
dec1
dom
dec2
HBB

Curvaton bound on the inflation scale

In general, there is a lower bound on the inflation scale even in the curvaton scenario

Observed curvature perturbation:
$\zeta = 5 \times 10^{-5}$ (COBE)

In curvaton scenario: $\boxed{\zeta \sim \Omega_\sigma \zeta_\sigma}$

$$\zeta_\sigma(t) \equiv -H\frac{\delta\rho_\sigma}{\dot\rho_\sigma} = \frac{\delta\rho_\sigma}{3(\rho_\sigma+p_\sigma)} = \frac{1}{3(1+w_\sigma)}\frac{\delta\rho_\sigma}{\rho_\sigma} \Rightarrow \zeta_\sigma \sim \left.\frac{\delta\rho_\sigma}{\rho_\sigma}\right|_{\rm dec}$$

$$\rho_\sigma \simeq \frac{1}{2}m_\sigma^2\sigma^2 \Rightarrow \left.\frac{\delta\rho_\sigma}{\rho_\sigma}\right|_{\rm dec} = 2\left.\frac{\delta\sigma}{\sigma}\right|_{\rm dec} \simeq 2\left.\frac{\delta\sigma}{\sigma}\right|_{*} \Rightarrow \left.\frac{\delta\rho_\sigma}{\rho_\sigma}\right|_{\rm dec} \simeq \frac{H_*}{\pi\sigma_*}$$

$$\boxed{\zeta \sim \Omega_\sigma H_*/\sigma_*}$$

$$\Omega_\sigma \equiv \left.\frac{\rho_\sigma}{\rho}\right|_{\rm dec} = \left(\frac{a_{\rm end}}{a_{\rm beg}}\right)\left.\frac{\rho_\sigma}{\rho}\right|_{\rm osc} \sim \sqrt{\frac{t_{\rm end}}{t_{\rm beg}}}\left(\frac{m_\sigma^2\sigma_*^2}{m_\sigma^2 m_P^2}\right) \Rightarrow$$

$$\Omega_\sigma \sim \sqrt{\frac{H_{\rm beg}}{H_{\rm end}}}\left(\frac{\sigma_*}{m_P}\right)^2 \Rightarrow$$ Ω_σ grows during radiation domination

$$\left.\begin{array}{l} H_{\rm end} = \max\{H_{\rm dom}, \Gamma_\sigma\} \geq H_{\rm BBN} \\ H_{\rm beg} = \min\{m_\sigma, \Gamma_{\rm inf}\} \leq H_* \end{array}\right\} \Rightarrow \frac{H_{\rm beg}}{H_{\rm end}} \leq \frac{H_* m_P}{T_{\rm BBN}^2}$$

$$\boxed{V_*^{1/4} \sim \sqrt{H_* m_P} \geq \left(\frac{\zeta}{\sqrt{\Omega_\sigma}}\right)^{2/5}(T_{\rm BBN} m_P^4)^{1/5} \geq 10^{12}\,{\rm GeV}}$$

where, from WMAP: $10^{-2} \leq \Omega_\sigma \leq 1$

Further reduction of $V_*^{1/4}$ is possible using a PNGB curvaton with varying order parameter

Relaxing the bound further

PNGB Curvaton : $V(\sigma) = V_0[1 - \cos(\sigma/v)]$

$V_0 \equiv (v m_\sigma)^2 \;\Rightarrow\; V(\sigma \ll v) \simeq \frac{1}{2} m_\sigma^2 \sigma^2$

Curvaton = Phase field: $\sigma = \sqrt{2}\theta v$

$$\left.\frac{\delta\sigma}{\sigma}\right|_{osc} = \left.\frac{\delta\theta}{\theta}\right|_* = \left.\frac{\delta\sigma}{\sigma}\right|_* = \frac{H_*}{2\pi\sigma_*} \Rightarrow \delta\sigma_{osc} = \frac{H_*}{2\pi}\frac{\sigma_{osc}}{\sigma_*} = \frac{H_*}{2\pi}\frac{v_0}{v_*}$$

Increase of order parameter: $\varepsilon \equiv v_*/v_0 \ll 1$

$$\Rightarrow \delta\sigma_{osc} = \frac{H_*}{2\pi\varepsilon}$$

the curvaton perturbation is amplified for a given H_*

The observed curvature perturbation can be achieved with a smaller H_*

New bound: $V_*^{1/4} \geq \varepsilon^{2/5} \times 10^{12}\text{GeV}$

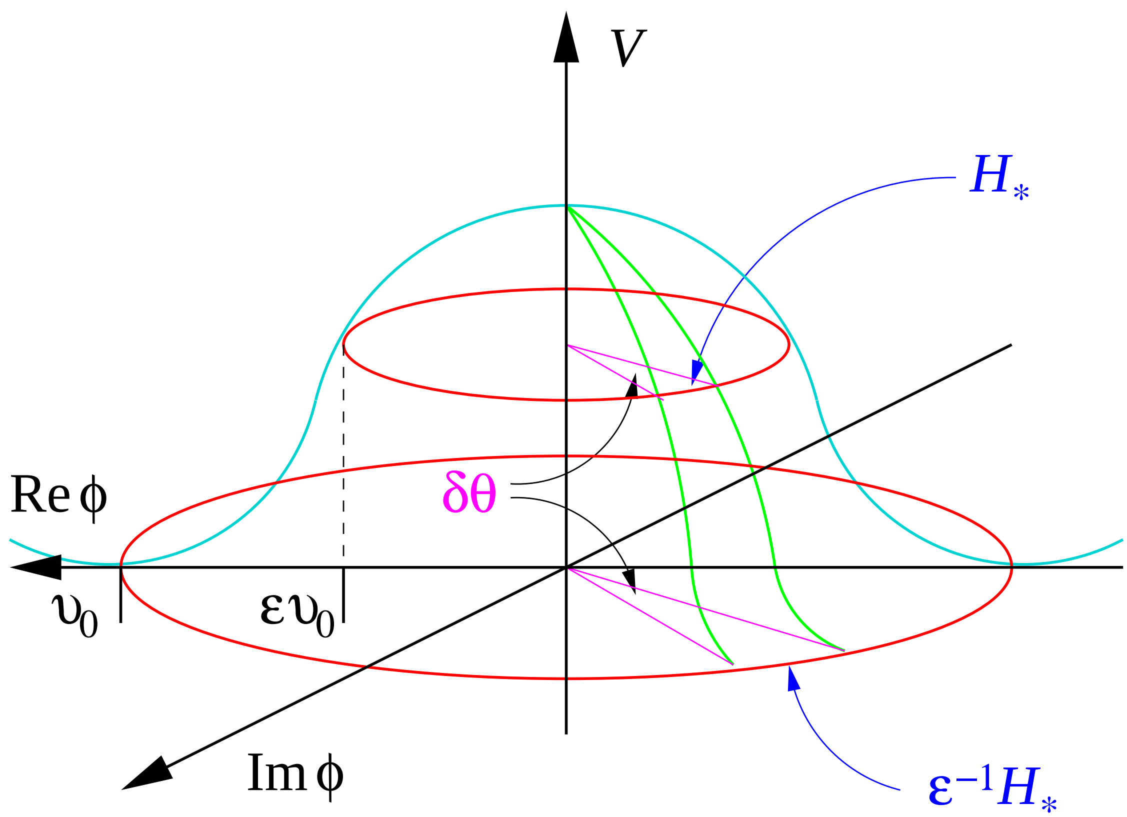
Spectral index constraint

Time dependence of order parameter $v(t) \Rightarrow$
scale dependence of perturbation $\delta\sigma_{osc} \propto 1/\varepsilon(k)$

$$\delta(n_s - 1) = -\frac{2}{H_*}(\dot{v}/v)_*$$

WMAP: $\delta(n_s - 1) = -0.06 \pm 0.04$ 95% cl

the variation of the order parameter must be at most slow when the cosmological scales exit the horizon



V
H_*
Re ϕ
δθ
υ_0
$\varepsilon\upsilon_0$
Im ϕ
$\varepsilon^{-1}H_*$

A supersymmetric toy-model

$$W = \frac{\lambda}{n+3}\frac{\phi^{n+3}}{m_P^n} \qquad \phi = |\phi|e^{i\theta},\ n \geq 0$$

$$V = (C_\phi H^2 - m_\phi^2)|\phi|^2 + \lambda^2 \frac{|\phi|^{2n+4}}{m_P^{2n}} + (C_A H + A)\frac{2\lambda}{n+3}\frac{|\phi|^{n+3}}{m_P^n}\cos[(n+3)\theta]$$

Soft mass: $m_\phi \sim m_{3/2} \sim \text{TeV} =$ negative to break the symmetry

(Also: $A \sim m_{3/2} \sim \text{TeV}$)

Supergravity corrections: $C_\phi \sim C_A \sim +1$

Curvaton scalar potential:

$$V(\sigma) \approx \lambda(C_A H + A)v^3\left(\frac{v}{m_P}\right)^n\left[1 - \cos\left(\frac{\sigma}{v}\right)\right]$$

Order parameter determined by radial field: $v \approx |\phi|$

To achieve a rolling $|\phi|$: $\varepsilon \equiv \frac{v_*}{v_0} \approx \frac{|\phi|_*}{|\phi|_0} \ll 1$ we need:

Phase transition during Inflation

$$H_* \sim m_\phi \sim \text{TeV} \Rightarrow V_*^{1/4} \sim 10^{10.5}\text{GeV} \ll \text{GUT}$$

$$(m_\sigma v)^2 = V_0 \sim \lambda m_{3/2} v^3\left(\frac{v}{m_P}\right)^n \Rightarrow m_\sigma^2 \propto v^{n+1} \Rightarrow$$

$$m_\sigma(v_*) \sim \varepsilon^{\frac{n+1}{2}} m_{3/2} \Rightarrow \text{during inflation: } m_\sigma \ll H_*$$

Vacuum: $v_0 \approx |\phi|_0 \Rightarrow$ $v_0 \sim \left(\lambda^{-1} m_P^n m_{3/2}\right)^{\frac{1}{n+1}}$

Curvaton physics

$$\left.\begin{array}{r}\varepsilon\sigma_{\rm osc} \simeq \sigma_* \sim \Omega_\sigma H_*/\zeta \\ \sigma_{\rm osc} \sim \theta v_0 \;\&\; H_* \sim m_{3/2}\end{array}\right\} \Rightarrow \boxed{\varepsilon \sim \frac{\Omega_\sigma}{\theta\zeta}\left(\frac{m_{3/2}}{m_P}\right)^{\frac{n}{n+1}}}$$

Bound: $\varepsilon < \frac{\sqrt{\Omega_\sigma}}{\zeta}(\frac{m_P}{T_{\rm BBN}})^{1/2}(\frac{m_{3/2}}{m_P})^{5/4} \sim 10^{-4}\sqrt{\Omega_\sigma}$

$\Rightarrow \boxed{n \geq 1}$: $\phi =$ flaton

The radial field is stabilized
by non-renormalizable terms

Curvaton decay

solving the μ-problem : $\boxed{\Delta W = \lambda_h \frac{\phi^{n+1}}{m_P^n} h^2} \Rightarrow \boxed{\Gamma_\sigma \simeq \frac{(n+1)^2}{4\pi}\frac{m_\sigma^3}{v_0^2}}$

BBN: $\Gamma_\sigma > T^2_{\rm BBN}/m_P \Rightarrow m_\sigma > 10^{\frac{n-9}{n+1}}$ TeV $\Rightarrow \boxed{n \leq 9}$

Curvaton evolution

Inflaton decay : $\Gamma_{\rm inf} = g^2 m_{\rm inf}$ with $10\frac{m_{\rm inf}}{m_P} \leq g \leq 1$

Evolution : $\boxed{g \geq \frac{\Omega_\sigma}{\theta^2}\left(\frac{m_{3/2}}{m_P}\right)^{\frac{n-2}{n+1}}} \Rightarrow \boxed{n \geq 2}$

$n -$ range : $2 \leq n \leq 9$

The roll of the radial field

A: Following $|\phi|_{\min}$

Temporal minimum : $$|\phi|_{\min} = \left(\lambda^{-1} m_P^n \sqrt{m_\phi^2 - C_\phi H^2}\right)^{\frac{1}{n+1}}$$

$$\varepsilon = \frac{(|\phi|_{\min})_*}{v_0} = \left[1 - C_\phi \left(\frac{H_*}{m_\phi}\right)^2\right]^{\frac{1}{2(n+1)}}$$

$$\frac{\dot{v}}{v} = \frac{|\dot{\phi}|_{\min}}{|\phi|_{\min}} = \frac{\epsilon}{n+1} \left(\frac{m_\phi^2}{C_\phi H^2} - 1\right)^{-1} H$$

$$\Rightarrow \boxed{(\dot{v}/v)_* \sim \epsilon_* \, \varepsilon^{-2(n+1)} H_*} \quad \text{with } \epsilon \equiv -\frac{\dot{H}}{H^2}$$

B: Free roll of $|\phi|$

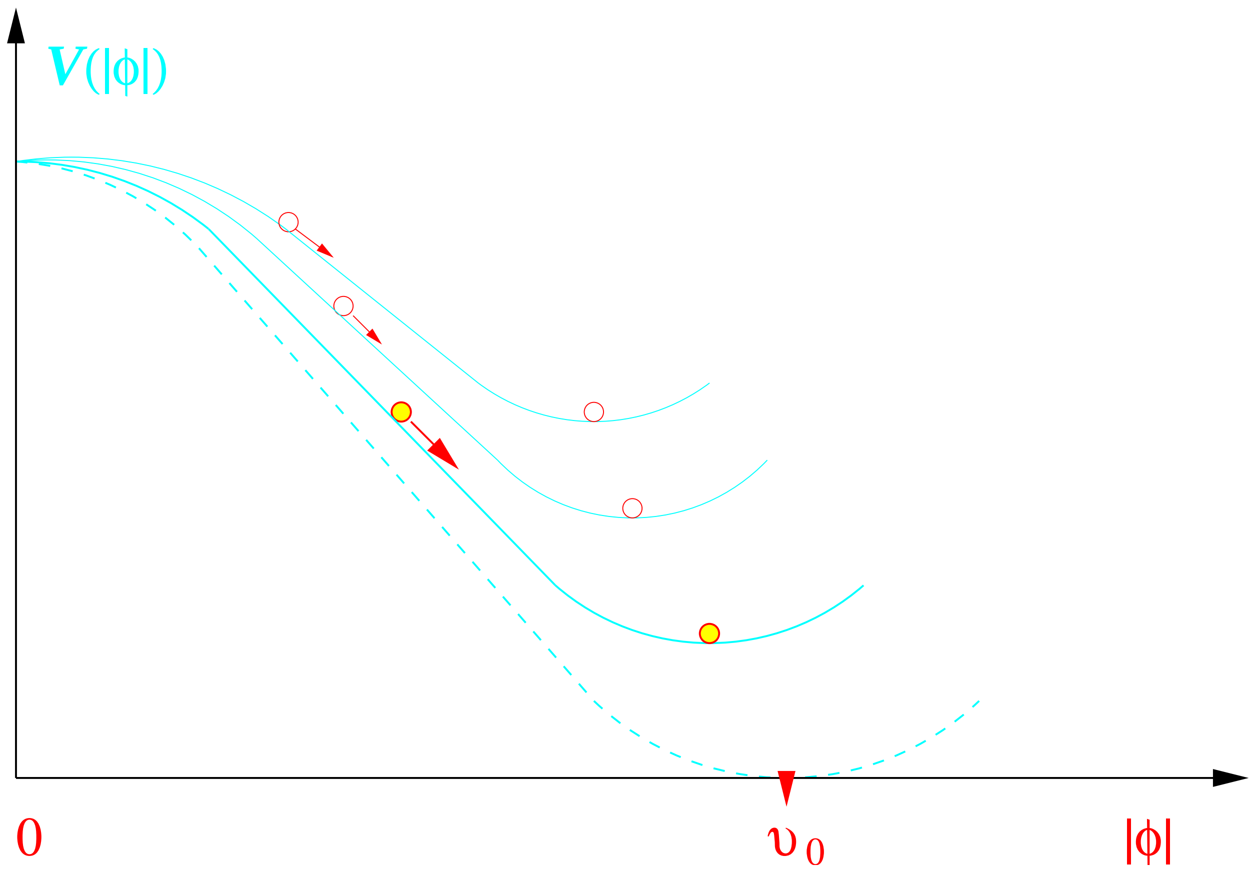
n_s-bound $\Rightarrow \dot{v}/v \ll H \Rightarrow$ $|\phi| = v$ slow rolls

Slow Roll Klein-Gordon : $$3H_* |\dot{\phi}| - (m_\phi^2 - C_\phi H^2)|\phi| \simeq 0$$

$$\varepsilon = \frac{|\phi|_*}{v_0} \quad \text{and} \quad \frac{\dot{v}}{v} = \frac{|\dot{\phi}|}{|\phi|} = \frac{1}{3} C_\phi \left(\frac{m_\phi^2}{C_\phi H^2} - 1\right) H$$

$v = |\phi|$ follows the slowest growth rate

$v = |\phi|_{\min}$ only if $\boxed{\varepsilon^{4(n+1)} > \epsilon_*}$



V(|ϕ|)
0
υ 0
|ϕ|

Concrete example

Modular Inflation

$$V(s) = V_{\rm inf} - \tfrac{1}{2}m_s^2 s^2 + \cdots \quad \text{with} \quad \begin{matrix} m_s \sim m_{3/2} \\ s_{\rm VEV} \sim m_P \end{matrix}$$

$$\Rightarrow V_{\rm inf}^{1/4} \sim \sqrt{m_{3/2} m_P} \quad \& \quad V(N) = V_{\rm inf}(1 - e^{-2F_s N})$$

$$F_s \equiv \tfrac{3}{2}\left(\sqrt{1 + \tfrac{4}{9}(\tfrac{m_s}{H_*})} - 1\right) \; : \; F_s(m_s \ll H_*) \approx \eta$$

$$\epsilon \equiv -\frac{\dot H}{H^2} = \tfrac{1}{2}F_s^2(\tfrac{s}{m_P})^2 \simeq \tfrac{1}{2}F_s^2 e^{-2F_s N} \ll 1 \Rightarrow H \simeq \text{const.}$$

Case: $n = 2$ & $\theta \sim 1$

$$g \sim \Omega_\sigma \lesssim 1 \Rightarrow T_{\rm reh} \sim g V_{\rm inf}^{1/4} \sim \Omega_\sigma \times 10^{10}\text{GeV}$$

Gravitino constraint $\Rightarrow$ $\Omega_\sigma \sim 10^{-2}$ σ=subdominant

$$\Rightarrow g \sim 10^{-2} \quad \& \quad \varepsilon \sim 10^{-7}$$

$\epsilon_* = \tfrac{1}{2}F_s^2(\tfrac{s_*}{m_P})^2 > \tfrac{1}{2}F_s^2(\tfrac{H_*}{m_P})^2 \sim 10^{30} \Rightarrow \varepsilon^{12} \not> \epsilon_* \Rightarrow$ Free roll

Klein-Gordon: $\dfrac{3}{C_\phi}\dfrac{d\ln|\phi|}{dN} = \dfrac{e^{-2F_s N_{\rm x}} - e^{-2F_s N}}{1 - e^{-2F_s N}} \Rightarrow$

$$\frac{6}{C_\phi}\ln\left(\frac{|\phi|_*}{|\phi|_{\rm x}}\right) = (1 - e^{-2F_s N_{\rm x}})\frac{1}{F_s}\ln\left|\frac{e^{2F_s N_{\rm x}} - 1}{e^{2F_s N_*} - 1}\right| - 2(N_{\rm x} - N_*)$$

$N_{\rm x}$ corresponds to phase transition: $m_\phi^2 \equiv C_\phi H^2(N_{\rm x})$

$$\delta(n_s - 1) \sim -0.04 \Rightarrow \frac{3}{C_\phi}e^{-2F_s N_*}\left(\frac{1 - e^{-2F_s(N_{\rm x} - N_*)}}{1 - e^{-2F_s N_*}}\right) \sim 0.04$$

possible to solve if transition = early: $2F_s N_{\rm x} \gg 1$

$$\begin{matrix} F_s^{-1} \simeq 1780 \\ C_\phi \sim 0.006 \end{matrix} \Rightarrow \begin{matrix} m_s \simeq 0.05\, H_* \\ m_\phi \simeq 0.08\, H_* \end{matrix}$$

Conclusions

- Recent, precise cosmological observations strongly support the case of Inflation
- If the curvature perturbations are generated by a curvaton field then inflation model-building is liberated by the COBE constraint and the energy scale of inflation can be much smaller than GUT
- However, even with a curvaton, there is a lower bound on the inflation scale, which typically demands $V_{\rm inf}^{1/4} \geq 10^{12}$GeV
- This bound can be relaxed by a factor $\varepsilon^{2/5}$ when considering a PNGB curvaton, whose order parameter v increases after the cosmological scales exit the horizon during inflation, where $\varepsilon \equiv v_*/v_0 \ll 1$
- Considering a toy-model supersymmetric realization of such a PNGB curvaton we investigated inflation with $H_* \sim$ TeV such that a phase transition occurs during inflation when the supergravity correction to the mass of the radial field reduces below the soft mass. The phase transition releases the radial field, whose slow-roll controls the growth of v

- **The scenario requires a flaton radial field (stabilized by non-renormalizable terms) to work**

- **When considering modular inflation we have shown that $H_* \sim \mathrm{TeV}$ is attainable for natural values of the model parameters: $m_{\rm inf} \sim m_\sigma \sim 0.1\, H_*$**

- **Similar results are obtained in a concrete model realization of this scenario, when the curvaton is an angular degree of freedom orthogonal to the QCD axion in a supersymmetric model of the Peccei-Quinn symmetry:**

KD & G. Lazarides, Physical Review D **73** (2006) 023525