MODULAR INFLATION WITHOUT FLAT DIRECTIONS AND THE CURVATON

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Inflation and the Hot Big Bang

The Standard Hot Big Bang

The Cosmological Principle: On large scales the Universe is Homogeneous and Isotropic

CMB Observations: Spatial Flatness & $n_s \approx 1$

flat FRW : $$ds^2 = dt^2 - a^2(t)\left(dr^2 + r^2 d\Omega^2\right)$$

- **Successes:** Hubble expansion, t_0, BBN, CMB
- **Problems:** Baryons, Horizon & Flatness, LSS & CMB-Anisotropy

Inflation

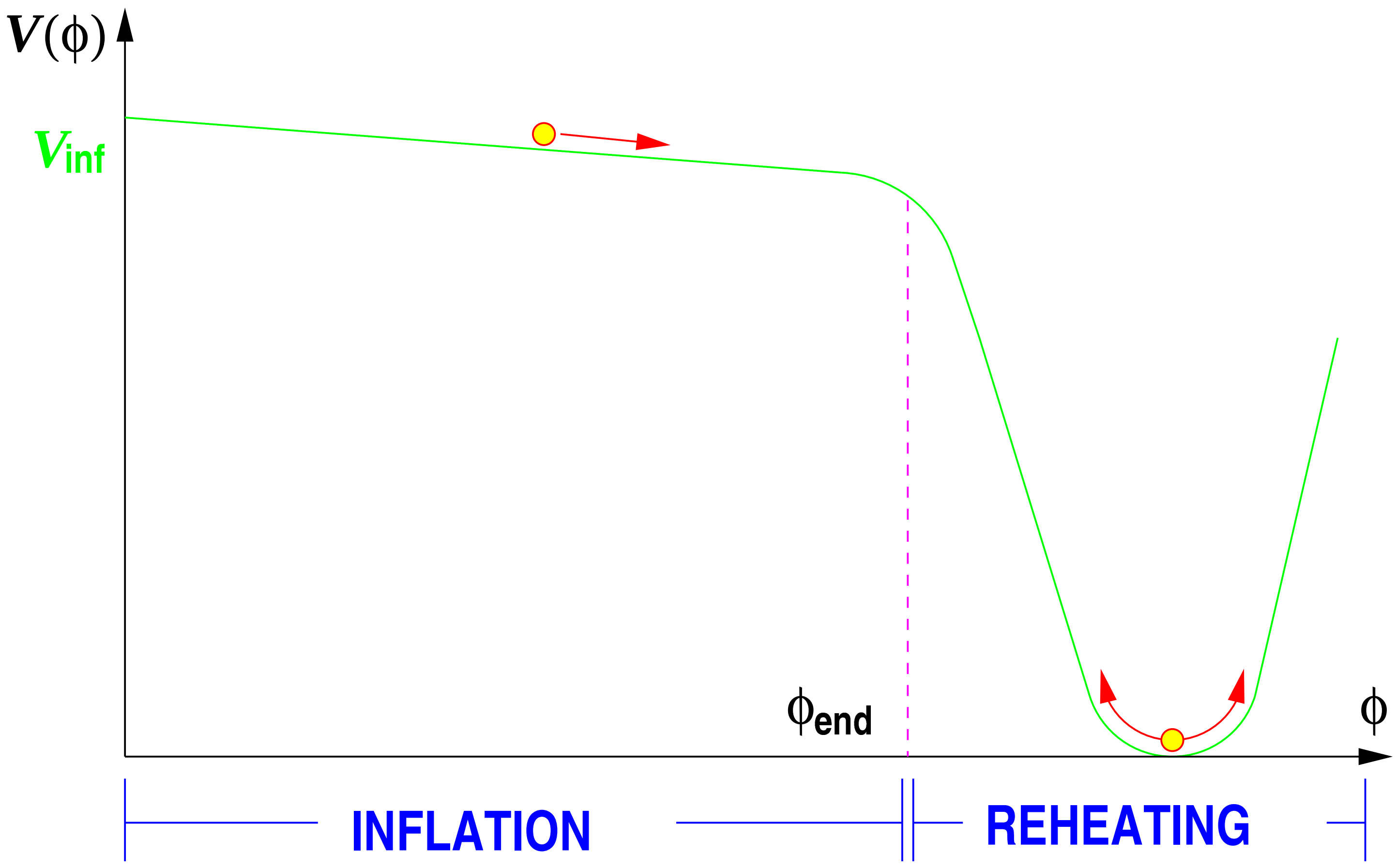
Inflation: A period of accelerated expansion in the Early Universe

Friedmann : $$H^2 \equiv (\dot{a}/a)^2 = \frac{1}{3}\rho/M_P^2$$

$$\rho \simeq M_P^2 \Lambda_{\text{eff}} \simeq \text{const.} \Rightarrow \underline{a \propto e^{Ht}}$$

- **Horizon:** superluminal expansion rate $\Rightarrow$ superhorizon causal correlations
- **Flatness:** Curvature = inflated away
- **LSS & CMB-A:** Particle Production

Inflationary Paradigm: The Universe inflates due to being dominated by the potential density $V(\phi)$ of a scalar field ϕ (inflaton)



V(ϕ)
V_inf
ϕ_end
ϕ
INFLATION
REHEATING

The unbearable lightness of the inflaton

Light Inflaton: $m_{\rm eff} \equiv \sqrt{V''} \ll H_{\rm inf}$

A: Inflationary period long enough

There need to be at least $\Delta N_{\rm inf} \lesssim 70$
e-foldings of Inflation for Horizon & Flatness

B: Particle Production of inflaton perturbations

$m < H \Leftrightarrow$ Compton wavelength > Horizon ($\sim H^{-1}$)

Quantum fluctuations reach and exit Horizon

$$\Delta\mathcal{E} \cdot \Delta t \sim 1 \;\Rightarrow\; \delta\phi = H/2\pi \quad ({\rm Hawking} - T)$$

Particle Horizon during Inflation	$\Leftrightarrow$	Event Horizon of inverted Black Hole

After Horizon exit: fluctuation → classical object

$$\text{Klein} - \text{Gordon}: \quad (\ddot{\delta\phi}) + 3H(\dot{\delta\phi}) + m^2(\delta\phi) = 0$$

$$\Rightarrow \delta\phi \simeq \frac{H}{2\pi}\left[e^{-\frac{1}{3}(\frac{m}{H})^2 H\Delta t} - \frac{1}{9}\left(\frac{m}{H}\right)^2 e^{-3H\Delta t}\right] \approx H/2\pi$$

perturbation freezes ⇒ scale-invariant spectrum

C: Flatness of curvature perturbation spectrum

$$n_s(k) - 1 \equiv \frac{d\ln\mathcal{P}_{\mathcal{R}}}{d\ln k}$$ spectral index of power spectrum

$$n_s = 1 + 2\eta - 6\epsilon \;:\; \epsilon = -\dot{H}/H^2 \ll 1 \;\;\&\;\; \eta \equiv M_P^2 V''/V = \frac{1}{3}(m/H)^2$$

WMAP: $n_s = 0.99 \pm 0.04$

The η-Problem of Inflation

$$V_F(W,K) \simeq e^{K/M_P^2}\,|W|^2 \times$$
$$\times \left[\Sigma_{nm}(\frac{K_n}{M_P^2}+\frac{W_n}{W})K^{n\bar{m}}(\frac{K_m}{M_P^2}+\frac{W_m}{W})^* - 3M_P^{-2}\right]$$

W = Superpotential $\quad$ K = Kähler potential

$\mathcal{L}_{\rm kin} = \Sigma_{nm} K_{nm}\, \partial_\mu \phi_n \partial^\mu \bar{\phi}_m$ $\Rightarrow$ Canonical: $K_{nm} = \delta_{nm}$

SUGRA corrections lift flatness of V

$$V_F'' = \frac{K''}{M_P^2} V_F + \cdots \;\Rightarrow\; \eta = K'' + \cdots$$

K : Canonical $\Rightarrow$ $\eta \sim 1 \Rightarrow m \sim H_{\rm inf}$

Famous η-Problem of Inflation

Curvaton to the Rescue

Curvaton: Field responsible for curvature perturbation is other than the inflaton

Curvaton = not associated with physics of inflation
$\Rightarrow$ can be accommodated in simple extensions of SM

The curvaton can link cosmological observations with collider experiments

e.g. PNGB curvaton = protected by Global U(1)

$m_\sigma \ll H \;\Rightarrow$ $\delta\sigma = H/2\pi$ $\quad$ (B)

$n_s - 1 = 2(\eta_\sigma - \epsilon) \ll 1$ $\quad$ (C)

Only requirement : Length of Inflation $\quad$ (A)

Modular Hybrid Inflation

$$V(\Phi,\phi) = \frac{1}{2}m_\Phi^2\Phi^2 + \frac{1}{2}\lambda\Phi^2\phi^2 + \frac{1}{4}\alpha(\phi^2 - M^2)^2$$

Φ & ϕ : Flat Directions of Supersymmetry lifted by Supergravity corrections

$$m_\Phi \sim \frac{M_S^2}{m_P} \qquad M \sim m_P \qquad \alpha \sim \left(\frac{M_S}{m_P}\right)^4$$

Global min: $(\Phi,\phi) = (0, \pm M)$ Saddle: $(\Phi,\phi) = (0,0)$

$M_S \sim \sqrt{m_{3/2}M_P} \sim 10^{11}\mathrm{GeV}$: Gravity mediated SUSY breaking

Tachyonic mass: $m_\phi \sim \sqrt{\alpha}\, M \Rightarrow$ $m_\phi \sim m_\Phi \sim m_{3/2}$

$(m_\phi^{\rm eff})^2 = \lambda\Phi^2 - \alpha M^2 \Rightarrow \exists$ $\Phi_c \equiv \sqrt{\alpha/\lambda}\, M \sim m_{3/2}$:

$\Phi > \Phi_c \Rightarrow \phi \to 0 \Rightarrow$ $V \simeq \frac{1}{2}m_\Phi^2\Phi^2 + M_S^4$

$\Phi < m_P \Rightarrow$ $V_{\rm inf}^{1/4} \simeq M_S$ $\Rightarrow$ $H_{\rm inf} \sim m_{3/2}$

No Flat Direction

- Fast–Roll Inflation $(m_\Phi \leq \frac{3}{2}H_{\rm inf})$

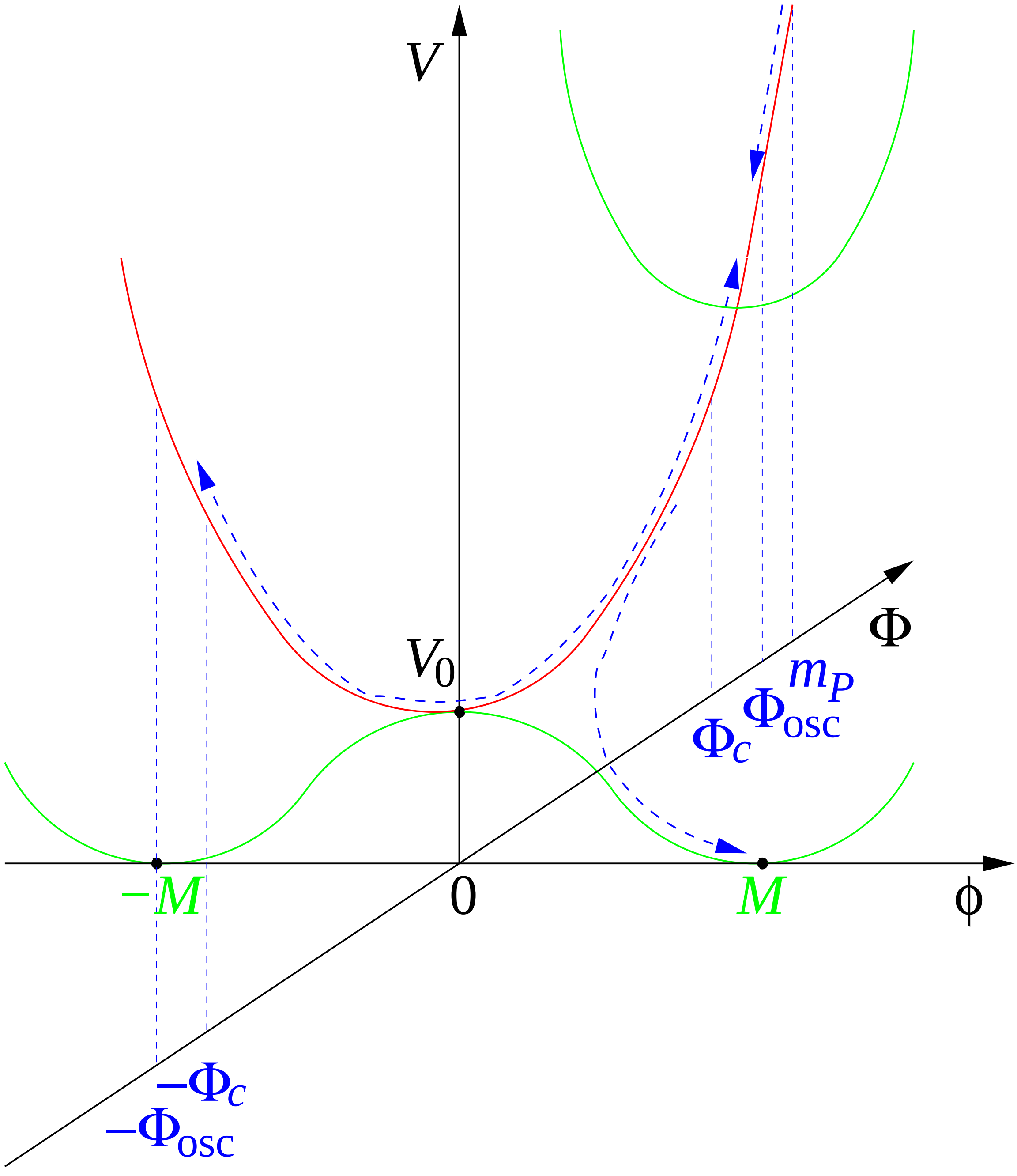
$\Phi = \Phi_0 \exp(-F_\Phi \Delta N) \;\Rightarrow$ $N_{\rm FR} \simeq F_\Phi^{-1} \ln\left(m_P/m_{3/2}\right)$

with $F_\Phi \equiv \frac{3}{2}\left(1 - \sqrt{1 - \frac{4}{3}|\eta_\Phi|}\right) < \frac{3}{2}$ and $|\eta_\Phi| \simeq \frac{1}{3}(m_\Phi/H_{\rm inf})^2$

- Locked Inflation $(m_\Phi > \frac{3}{2}H_{\rm inf})$

$$\Phi = \Phi_0 \exp\left(-\tfrac{3}{2}\,\Delta N\right) \times \cos(m_\Phi \Delta t)$$

Oscillation $(\Delta t)_s \sim \bar{\Phi}^{-1} < m_\phi^{-1} \;\Rightarrow$ $N_{\rm lock} \simeq \frac{2}{3}\ln\left(m_P/m_{3/2}\right)$



V
V0
Φ
mP
Φosc
Φc
−M
0
M
ϕ
−Φc
−Φosc

- Tachyonic Fast-Roll Inflation

$$\Phi < \Phi_c \Rightarrow \boxed{V \simeq V_{\rm inf} - \frac{1}{2}m_\phi^2\phi^2 + \frac{1}{4}\alpha\phi^4}$$

$$\phi = \phi_0 \exp(F_\phi \Delta N) \;\Rightarrow\; \boxed{N_\phi \simeq F_\phi^{-1} \ln\left(m_P/m_{3/2}\right)}$$

with $F_\phi \equiv \frac{3}{2}\left(\sqrt{1+\frac{4}{3}|\eta_\phi|}-1\right)$ and $|\eta_\phi| \simeq \frac{1}{3}(m_\phi/H_{\rm inf})^2$

Total e-folds: $$\boxed{N_{\rm tot} = N_\Phi + N_\phi \simeq \left(\frac{1}{F_\Phi}+\frac{1}{F_\phi}\right)\ln\left(\frac{m_P}{m_{3/2}}\right)}$$

$$N_\Phi = \begin{cases} N_{\rm FR} & \text{when} \quad m_\Phi \le \frac{3}{2}H_{\rm inf} \quad (F_\Phi > 3/2) \\ N_{\rm lock} & \text{when} \quad m_\Phi > \frac{3}{2}H_{\rm inf} \quad (F_\Phi = 3/2) \end{cases}$$

Horizon & Flatness $\Rightarrow$ $$\boxed{N_{\rm cosmo} = 72 - \ln\left(\frac{m_P}{V_{\rm inf}^{1/4}}\right) - \frac{1}{3}\ln\left(\frac{V_{\rm inf}^{1/4}}{T_{\rm reh}}\right)}$$

$$T_{\rm reh} \sim \sqrt{\Gamma m_P} \;\;\&\;\; \Gamma \simeq g^2 m_\phi \;\; \text{with} \;\; \frac{m_{3/2}}{m_P} \le g \le 1$$

$$\boxed{\frac{m_\phi}{H_{\rm inf}} < \frac{3}{2}\left\{\left[\left(\frac{108+\ln\sqrt{g}}{\ln(m_P/m_{3/2})}-\frac{7}{4}\right)^{-1}+1\right]^2-1\right\}^{1/2} = (2-3)}$$

Enough inflation is achieved without flat directions

$$\boxed{m_\Phi \sim m_\phi \sim m_{3/2} \sim H_{\rm inf}}$$

Summary and Conclusions

- Inflation offers an elegant solution to most of the problems of the Hot Big Bang and, in particular, explains LSS formation and the CMB-anisotropy.
- Inflation amplifies the quantum fluctuations of light fields, generating thereby a scale-invariant superhorizon spectrum of curvature perturbations.
- However, flat directions are typically lifted by excessive supergravity corrections (η-problem).
- The curvaton ameliorates the tuning problems of inflation model-building and allows inflation to be achieved without the use of flat directions.
- The only remaining requirement is the total duration of inflation, which has to solve the horizon and flatness problems.
- Modular hybrid inflation is a concrete example that inflation without flat directions is indeed possible.