Quintessential Inflation at low reheating temperatures,

based on:
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Historic summary

1. GR and FLRW metric $\longrightarrow$ Big Bang model, which leads to some problems:
   - Horizon problem.
   - Flatness problem.
   - Magnetic monopole problem.
2. Birth of cosmic inflation (Alan Guth, 1981).

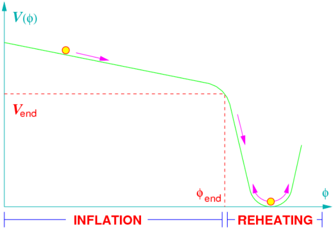

Figure: The inflaton slow-rolls and, after inflation, oscillates in a deep well creating matter.

Historic summary

3. Discovery of the current accelerated expansion of the universe (1998).
4. Quintessence inflation: unifies early and late acceleration of the universe (see e.g. Zlatev, Wang and Steinhardt, 1992)

   EoS: $P = P(\rho)$ EoS Parameter: $w = \frac{P(\rho)}{\rho} = \frac{\frac{\dot{\varphi}^2}{2} - V(\varphi)}{\frac{\dot{\varphi}^2}{2} + V(\varphi)}$

   The potential has no deep well but a phase transition where matter is created and a small cosmological constant after the phase transition to ensure the current acceleration of the universe.

Introduction

Our aim is to build viable quintessential models with

1. Smooth transition between inflation $w < -\frac{1}{3}$ and kination $(w = 1)$.
2. Accordance with recent observational data provided by BICEP and Planck's teams.
3. Fulfilling constraints for the reheating temperature:
   - Successful BBN: 1 MeV$\leq T_R \leq 10^9$ GeV.
   - Gravitino overproduction problem: $T_R \leq 10^2$ GeV.
   - Moduli field production problem: $T_R \leq 1$ GeV.

A simple Quintessential Inflation model

Dynamical system

$$\dot{H} = \begin{cases} -k(M_{pl} - H)^2 & \text{for} \quad H \geq H_E \\ -3(H - H_f)^2 & \text{for} \quad H \leq H_E, \end{cases}$$

where $M_{pl} \gg H_E \gg H_f \sim H_0$ and $k = \frac{3(H_E - H_f)^2}{(M_{pl} - H_E)^2} \cong \frac{3H_E^2}{M_{pl}^2}$ for continuity of $\dot{H}$.

$$w_{eff} = \begin{cases} -1 + \frac{2k}{3}\left(\frac{M_{pl}}{H} - 1\right)^2 & \text{when} \quad H \geq H_E \\ -1 + 2\left(1 - \frac{H_f}{H}\right)^2 & \text{when} \quad H \leq H_E \end{cases}$$

Cosmological perturbations

1. Slow roll parameters $\longrightarrow \begin{cases} \epsilon = -\frac{\dot{H}}{H^2} \\ \eta = 2\epsilon - \frac{\dot{\epsilon}}{2H\epsilon} \end{cases}$
2. Inflationary parameters $\longrightarrow$
   - Spectral index: $n_s = 1 - 6\epsilon_* + 2\eta_*$
   - Running: $\alpha_s = \frac{H_* \dot{n}_s}{H_*^2 + \dot{H}_*}$
   - Tensor to scalar perturbations: $r = 16\epsilon_*$
3. BICEP and Planck's observational constraints $\longrightarrow \begin{cases} n_s = 0.968 \pm 0.006 \\ \alpha = -0.003 \pm 0.007 \\ r < 0.12 \end{cases}$
4. Power spectrum: $P \cong \frac{H_*^2}{8\pi^2 \epsilon_* M_{pl}^2} \sim 2 \times 10^{-9}$
5. Number of e-folds: $\begin{cases} N = -\int_{H_{end}}^{H_*} \frac{H}{\dot{H}} dH \\ N \cong 52 - \frac{1}{3} \ln \left(\frac{g_R^{1/4} T_R H_E}{M_{pl}^2} \right) : 63 < N < 73 \end{cases}$

with degrees of freedom $g_R = \begin{cases} 107, & T_R > 175 \text{ GeV} \\ 90, & 175 \text{ GeV} > T_R > 200 \text{ MeV} \\ 11, & T_R < 200 \text{ MeV}. \end{cases}$

Reheating constraints

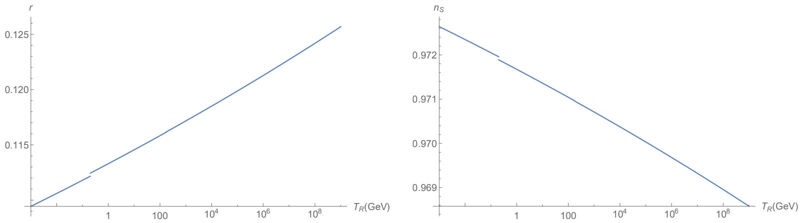

Figure: Evolution of the tensor/scalar ratio r (left) and the spectral index n_s (right) versus the reheating temperature T_R.

All constraints fulfilled for 1 MeV $\leq T_R \leq 10^5$ GeV.

Reheating constraints

Mechanisms of reheating:

1. Particle creation due to the oscillations of the inflation field.
2. Particle production via instant preheating (Felder, Kofman and Linde, 1999).
3. Gravitational particle production via
   - Production of heavy massive particles conformally coupled with gravity: $T_R \sim 10$ GeV.
   - Production of massless particles nearly conformally coupled with gravity: 1 MeV $\leq T_R \leq 10^5$ GeV for $3 \times 10^{-7} \lesssim \left|\xi - \frac{1}{6}\right| \lesssim 6 \times 10^{-2}$.
   - Production of massless particles far from the conformal coupling: $T_R \sim 10^5$ GeV.

Dynamical study

$$V(\varphi)=\begin{cases} M_{pl}^4\left[3\left(1-e^{\frac{\varphi}{M_{pl}}\sqrt{\frac{k}{2}}}\right)^2-ke^{\frac{\varphi}{M_{pl}}\sqrt{2k}}\right] & \text{for} \quad \varphi\leq\varphi_E \\ 3M_{pl}^2H_f^2\left[1+2\left(\frac{H_E}{H_f}-1\right)e^{-\sqrt{\frac{3}{2}}\frac{\varphi-\varphi_E}{M_{pl}}}\right] & \text{for} \quad \varphi\geq\varphi_E. \end{cases}$$

$\ddot{\varphi}+3H(\varphi,\dot{\varphi})+V_\varphi=0$, where $H(\varphi,\dot{\varphi})=\sqrt{\frac{1}{3}\left(\frac{\dot{\varphi}^2}{2}+V(\varphi)\right)}$

Dynamical study

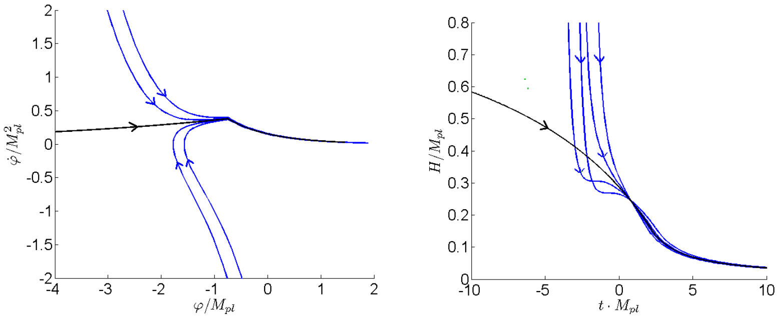

Figure: Phase portrait in the plane $(\varphi/M_{pl}, \dot{\varphi}/M_{pl}^2)$ (left) for some orbits, with the analytical one represented in black. Evolution of H/M_{pl} in function of the time $t \times M_{pl}$ (right) for the same orbits represented in the phase portrait.

Other Quintessential Inflation models

1. ESI potential: $V(\varphi) = \begin{cases} \lambda M_{pl}^4 (1 - e^{\frac{\varphi}{M_{pl}}}) & \varphi < 0 \\ 0 & \varphi \geq 0. \end{cases}$ VIABLE.
2. HI potential: $V(\varphi) = \begin{cases} \lambda M_{pl}^4 \left(1 - e^{\frac{\varphi}{M_{pl}}}\right)^2, & \varphi < 0 \\ 0, & \varphi \geq 0. \end{cases}$ NOT VIABLE.
3. PLI potential: $V(\varphi) = \begin{cases} \lambda M_{pl}^4 \left(\frac{\varphi}{M_{pl}}\right)^{2n}, & \varphi < 0 \\ 0, & \varphi \geq 0. \end{cases}$ VIABLE for $n = 1$.
4. OSTI potential: $V(\varphi) = \begin{cases} -\lambda M_{pl}^2 \varphi^2 \ln \left[\left(\frac{\varphi}{\varphi_0}\right)^2\right], & \varphi < 0 \\ 0, & \varphi \geq 0. \end{cases}$ VIABLE for $|\varphi_0| \gg M_{pl}$.
5. WRI potential: $V(\varphi) = \begin{cases} \lambda M_{pl}^4 \ln^2 \left(\frac{-\varphi}{|\varphi_E|}\right), & \varphi < -|\varphi_E| \\ 0, & \varphi \geq -|\varphi_E|. \end{cases}$ NOT VIABLE.
6. KMII potential: $V(\varphi) = \begin{cases} \lambda M_{pl}^4 \left(1 - \alpha \frac{\varphi}{M_{pl}} e^{-\varphi/M_{pl}}\right), & \varphi > \varphi_E \\ 0, & \varphi \leq \varphi_E. \end{cases}$ NOT VIABLE.
7. BI potential:
   $V(\varphi) = \begin{cases} \lambda M_{pl}^4 \left[1 - \left(\frac{-\varphi}{\mu M_{pl}}\right)^{-p}\right], & \varphi < \varphi_E \equiv -\mu M_{pl} \\ 0, & \varphi \geq \varphi_E. \end{cases}$ VIABLE for $\mu \ll 1, p > 17$.
8. LI potential:
   $V(\varphi) = \begin{cases} 0, & \varphi \leq \varphi_E \equiv M_{pl} e^{-\frac{1}{\alpha}} \\ \lambda M_{pl}^4 \left(1 + \alpha \ln\left(\frac{\varphi}{M_{pl}}\right)\right), & \varphi \geq \varphi_E \equiv M_{pl} e^{-\frac{1}{\alpha}}. \end{cases}$ NOT VIABLE.

Conclusions

We have found some quintessential inflation models that:

1. successfully explain a transition between inflation and kination.
2. are in accordance with data provided by BICEP and Planck's teams.
3. lead to a reheating temperature via the production of gravitational particles which
   - ensures a successful nucleosynthesis.
   - in some cases solves the gravitino overproduction and moduli fields problems.

THANK YOU VERY MUCH FOR YOUR ATTENTION!!!!