Quintessential Inflation with α-attractors

Konstantinos Dimopoulos

Lancaster University

Work done with: Charlotte Owen

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Accelerated Expansion

- Observations suggest that expansion is accelerated at early and late times
- **Primordial:** **Horizon & Flatness, Scale invariant perturbations**
- **Current:** **SN-Ia, Age problem, Planck 2015:** $w = -1.006 \pm 0.045$
- Accelerated expansion → Universe dominated by **Dark Energy** $w < -\frac{1}{3}$
- Accelerated expansion = **quasi-de Sitter** $w \approx -1$
- **Inftationary Paradigm:** **Early Universe dominated by potential density of scalar field (inflaton field)**
- **Current Dark Energy:** **Non-zero vacuum density** $\Lambda \neq 0$
  - But Λ = fine-tuned as vacuum density $\sim 10^{-120}$ of Planck density

    "worse fine-tuning in Physics" Laurence Krauss
- **Quintessence:** **Universe dominated by potential density of another scalar field; the 5th element after baryons, CDM, photons & neutrinos**
  - Does not resolve Λ - problem: vacuum density assumed zero

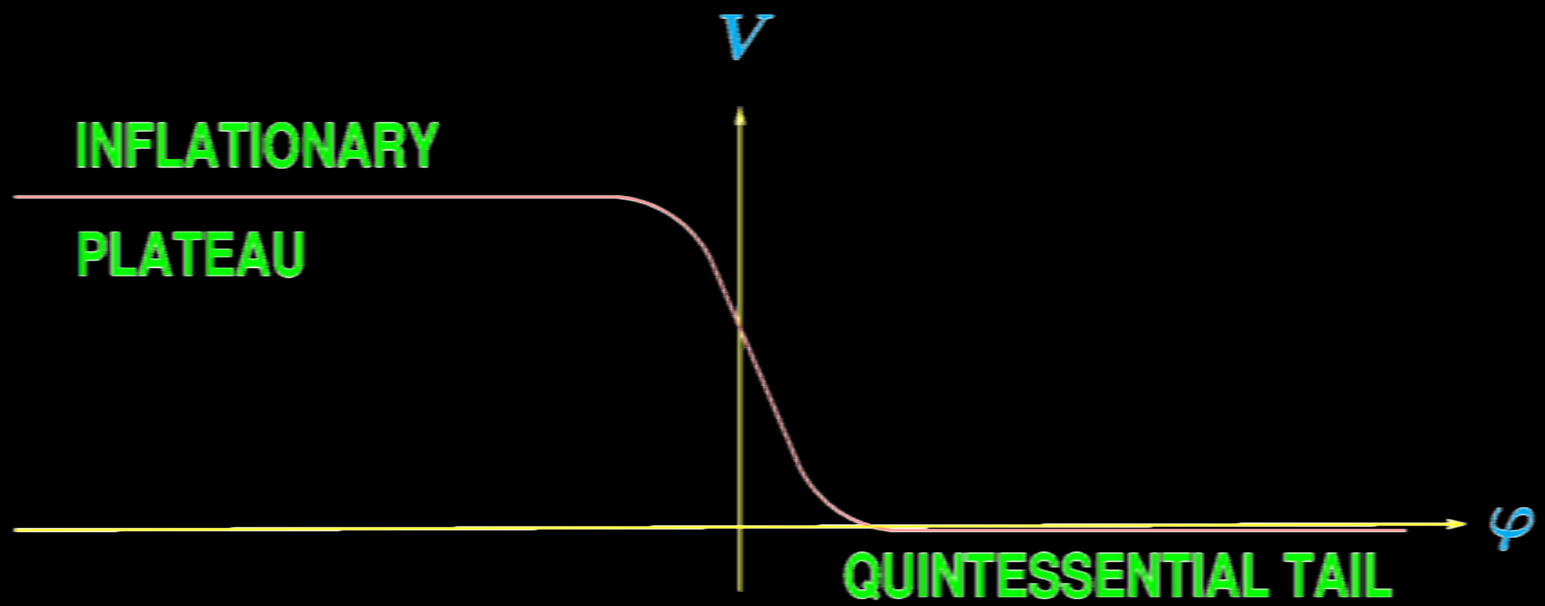
Quintessential Inflation

- Quintessence problems:
  - Initial conditions
  - Coincidence

  } ameliorated by **tracker quintessence**
  - Potential flatness against radiative corrections $\sim \exp(\beta_i \, \phi / m_P) \, \mathcal{L}_i$
  - 5^{th} force problem: violation of the Principle of Equivalence
- **Quintessential Inflation: Both inflation and current acceleration due to the same field (cosmon)**

  Peebles & Vilenkin 1999
  - Natural: inflation & quintessence based on the same idea
  - Economic: fewer parameters / mass scales & couplings
  - Common theoretical framework
  - Initial conditions for quintessence determined by inflationary attractor
  - Coincidence resolved by mass scales & couplings only

Quintessential Inflation



- **Potential for Quintessential Inflation features two flat regions: Inflationary Plateau & Quintessential Tail. Differ by $\sim 10^{108}$**
  - Form of Potential = artificial + Physics at extreme scales
- **Inflaton does not decay; must survive until the present**
  - Non-oscillatory inflation
  - Reheating achieved by means other than inflaton decay
- **Radiative corrections and 5th force problems unresolved**

α- attractors to the rescue

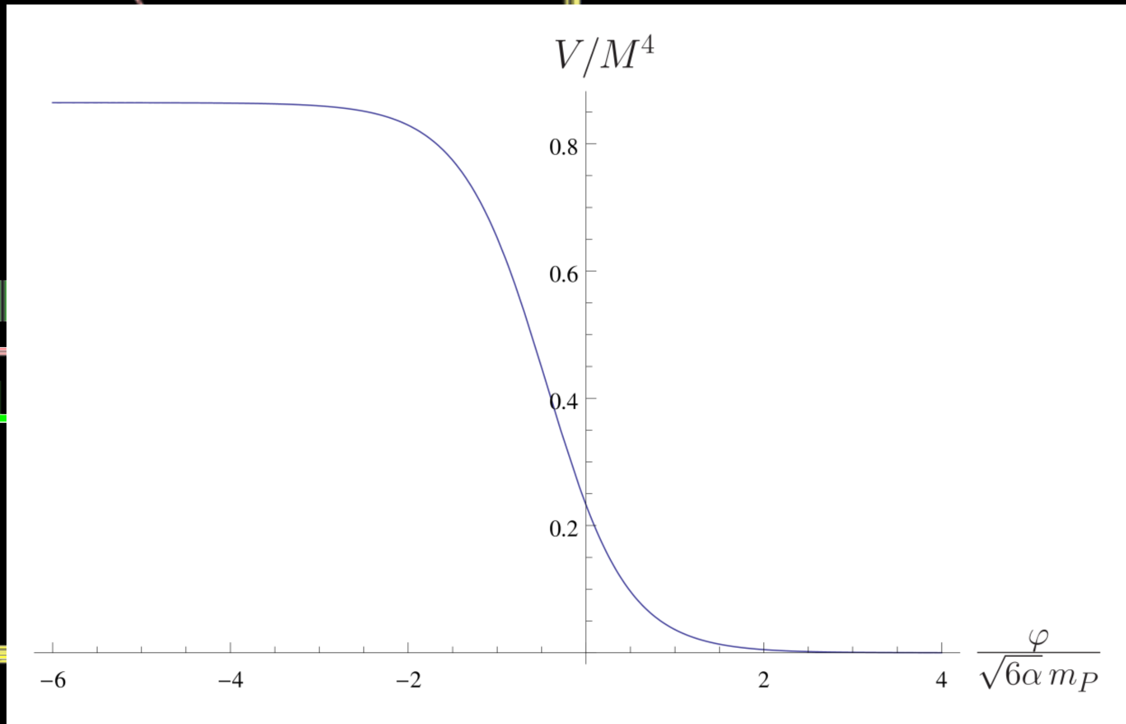
- **Scalar kinetic term features poles due to non-trivial Kãhler manifold**
- Switching to canonically normalised field transposes poles to infinity generating plateaus in the scalar potential (poles are never reached)
  - ► Can explain form of Quintessential Inflation potential (not artificial)
- Variation of canonically normalised field can be super-Planckian while variation of the non-canonically normalised field remains sub-Planckian
- **Sub-Planckian excursion avoids radiative corrections and 5$^{\rm th}$ force**
  - ► Strongly super-Planckian variation for canonical field can bridge difference between inflationary plateau and quintessential tail

$$\mathcal{L}_{\rm kin} = \frac{\frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi}{(1-\frac{\phi^2}{6\alpha})^2}\,m_P^2$$

$$\phi = \sqrt{6\alpha}\,\tanh\frac{\varphi}{\sqrt{6\alpha}m_P}$$

$$|\phi| < \sqrt{6\alpha}$$

The model



- Exponential potential
- Poles from α - attractors
- No vacuum density
- **Switch to canonical field**

$$\mathcal{L} = \frac{\frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi}{\left(1-\frac{\phi^2}{6\alpha}\right)^2} - V(\phi), \qquad V(\phi) = V_0\, e^{-\kappa\phi}$$

$$V(\varphi) = e^{-2n} M^4 \left\{\exp\left[n\left(1-\tanh\frac{\varphi}{\sqrt{6\alpha}\, m_P}\right)\right] - 1\right\}$$

$$M^4 \equiv e^n V_0 \qquad \Lambda = e^{-2n} M \qquad n \equiv \kappa\sqrt{6\alpha}$$

Inflation

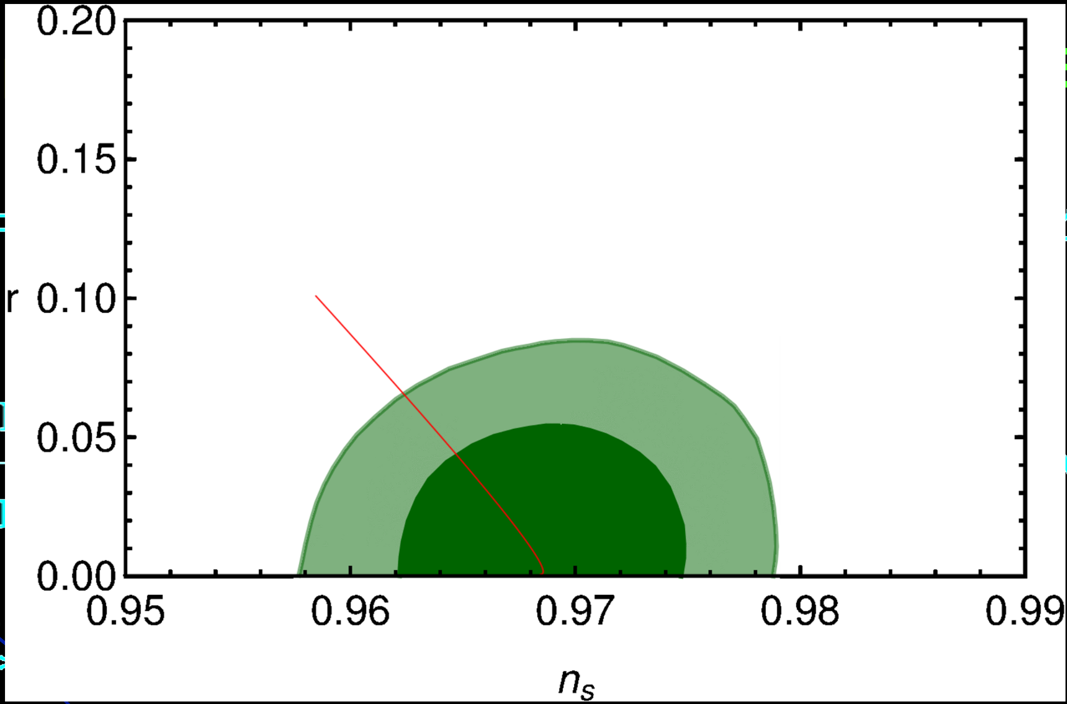
- In the limit: $\varphi \to -\infty$ $(\phi \to -\sqrt{6\alpha})$ $V(\varphi) \simeq M^4 \exp\left(-2n e^{\frac{2\varphi}{\sqrt{6\alpha} m_P}}\right)$

- **Inflationary** ... **B observations**

$n_s =$ ... $1 - \frac{2}{N_*}$

$n_s' \equiv \frac{d \ln}{d \ln}$ ... $N_* + \frac{\sqrt{3\alpha}}{2}\Big)^{-2}$

N ... $10^{15}\,\mathrm{GeV}$



With: $\alpha \to 0 \quad \Rightarrow \quad n_s \simeq 0.9685 \quad n_s' \simeq -5.11 \times 10^4$ √

Planck: $n_s = 0.968 \pm 0.006 \quad n_s' = -0.003 \pm 0.007$

Kination

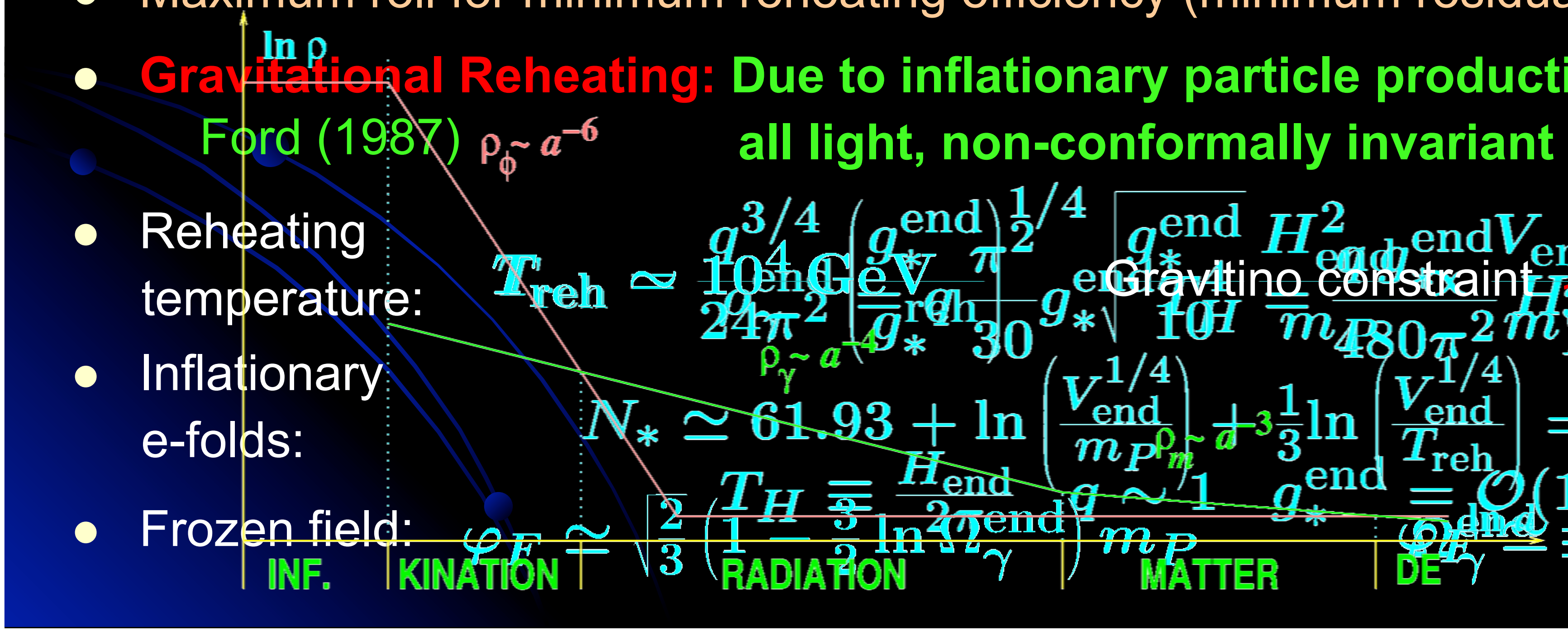
- **Kination: After inflation kinetic density dominates**
  - ► Inflaton oblivious of potential $\ddot{\varphi} + 3H\dot{\varphi} \simeq 0$
  - ► Field rolls to quintessential tail
- **Reheating: Radiation eventually dominates** $\rho_{\rm kin} \equiv \frac{1}{2}\dot{\varphi}^2 \propto a^{-6}$
  - ► Field rolls for a while but eventually freezes $\rho_\gamma \propto a^{-4}$
  - ► Residual density = Dark Energy today
- Maximum roll for minimum reheating efficiency (minimum residual density)
- **Gravitational Reheating: Due to inflationary particle production of all light, non-conformally invariant fields**

Ford (1987)

- Reheating temperature: $T_{\rm reh} \simeq \frac{q^{3/4}}{24\pi^2}\left(\frac{g_*^{\rm end}}{g_*^{\rm reh}}\right)^{1/4}\sqrt{\frac{\pi^2}{30}g_*}\,\frac{H^2_{\rm end}}{m_P}$, $T_{\rm reh} \simeq 10^4\,{\rm GeV}$, $\Omega_\gamma^{\rm end} = \frac{g_*^{\rm end}}{480\pi^2}\frac{H^2_{\rm end}}{m_P^2}$, $T_H = \frac{H_{\rm end}}{2\pi}$

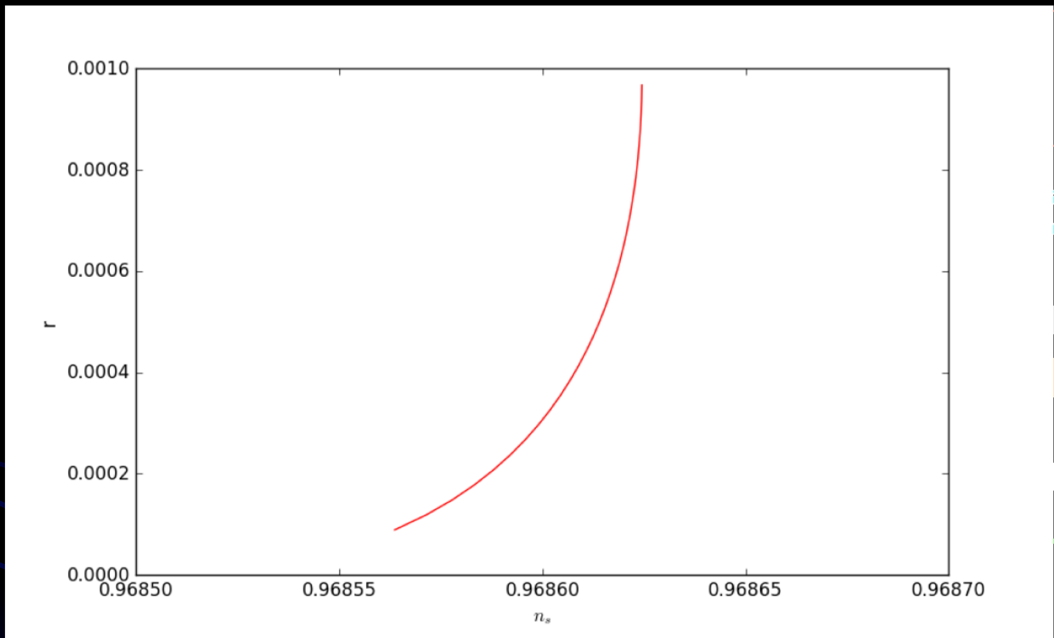
Gravitino constraint ✓

- Inflationary e-folds: $N_* \simeq 61.93 + \ln\left(\frac{V_{\rm end}^{1/4}}{m_P}\right) + \frac{1}{3}\ln\left(\frac{V_{\rm end}^{1/4}}{T_{\rm reh}}\right) = 63.49$, $q \sim 1$, $g_*^{\rm end} = \mathcal{O}(100)$
- Frozen field: $\varphi_F \simeq \sqrt{\frac{2}{3}}\left(1 - \frac{3}{2}\ln\Omega_\gamma^{\rm end}\right) m_P$, $\varphi_F = 43\, m_P$, $\Omega_\gamma^{\rm end} = \frac{\rho_\gamma}{\rho}\Big|_{\rm end}$



Quintessence

- In the limit: $\varphi \to +\infty$
  ($\phi \to \sqrt{6\alpha}$) $V \simeq 2ne^{-2n} M^4 e^{-\frac{2\varphi}{\sqrt{6\alpha} m_P}}$



- $V_Q \exp\left(-\lambda\varphi/m_P\right)$

  $2/\sqrt{6\alpha} = (2/n)\kappa$

  intessence

  l → no acceleration

  n non-canonical field

- n $0.03 \lesssim \alpha \lesssim 0.33$

  $n_s = 0.9686 \quad n_s' = -5.09\times 10^{-4}$ and $r \sim 10^{-(3-4)}$

- **Residual density comparable to present density** $\kappa \sim m_P/M$

  $\sqrt{6\alpha} \lesssim 1 \quad \frac{\rho_{\rm inf}}{\rho_0} \quad \frac{V_{\rm inf}}{V_F} \quad \Lambda^{1/4} \simeq 10^2\,{\rm GeV} \quad \frac{e^{\lambda\varphi_F/m_P}}{2ne^{-2n}} \gtrsim 10^{108}$

  $V_0^{1/4} = 10^{5-12}\,{\rm GeV}$

Conclusions

- Quintessential Inflation may well be modelled in the context of α-attractors in Supergravity
- Single field with natural mass scales & couplings
- Inflationary observables in excellent agreement with CMB
  $n_s = 0.9686 \quad n_s' = -5.09\times10^{-4}$ and $r \sim 10^{-(3-4)}$
- Quintessence avoids fine-tunings $\kappa \sim m_P/M$
  $V_0^{1/4} = 10^{5-12}\,\mathrm{GeV}$ and $\Lambda^{1/4} \gtrsim 10^2\,\mathrm{GeV}$
- Temporary acceleration avoids problem of future horizons in String Theory (unlike ΛCDM) $0.03 \lesssim \alpha \lesssim 0.33$
- **α-attractors naturally avoid radiative corrections and 5th force problems, while generate a potential with multiple plateaus, which can accommodate Quintessential Inflation**

Temporary acceleration explained

- ∃ attractor solution, which does **NOT** lead to eternal acceleration
- Field unfreezes and follows attractor, but briefly oscillates around it
- Oscillation can result in brief boost of accelerated expansion