Quintessential Inflation with a Trap

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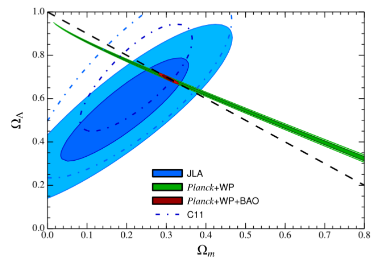
Dimopoulos, MK, Owen (2019)

Gonzalvo, MK, Rusak

Introduction

- Introduction
- Tachyonic trap
- A concrete example

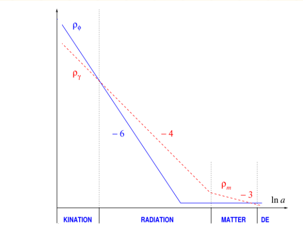
Cosmological Constant



Betoule+ (2014)

- Cosmological Constant Λ
  - ρ_λ is $\sim$ 120 orders of magnitude smaller than $m_{\rm Pl}$
  - The coincidence: $\Omega_\Lambda \simeq \Omega_m$

Quintessence

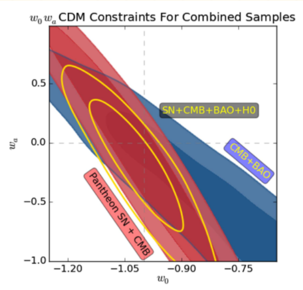


- Assume $\Lambda = 0$
- A dynamical mechanism: quintessence
  - Slowly rolling scalar field ϕ

$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi} = 0$$

  - Reminiscent of inflation, but matter and radiation cannot be neglected

Quintessence



Scolnic+ (2018)

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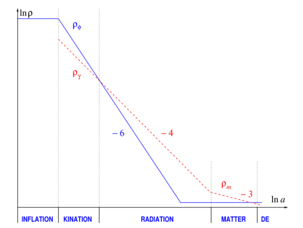

Borrowed from: Dimopoulos & Owen (2017)

- Inflaton and quintessence are the same field
  - Economy: no new degrees of freedom
  - Quitessence initial conditions given by inflation
- Difficulty: a huge range of energies between ρ_{inf} and ρ_{Λ}
  - The potential has to have a huge gradient

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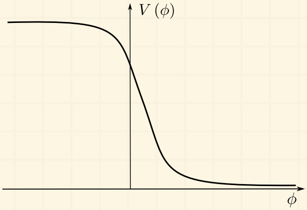

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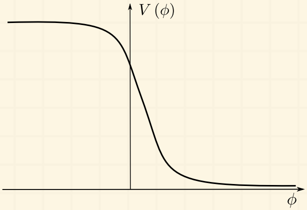

- Reheating
  - Non-oscillating part
- Other options
  - gravitational reheating, but it is very inefficient
  - instant preheating
  - curvaton preheating

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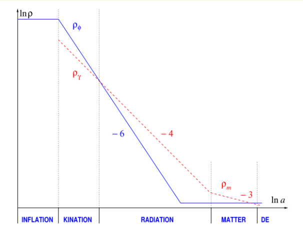

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Other Problems

- The mass of the quintessence field $m_\phi \ll H_0$ very light, also [Carroll (1998)]

$$\beta_i \left(\frac{\phi}{M} \right) \mathcal{L}_i$$

  - 5th force: Eötvös-type experiments constraint violations of equivalence principle
  - Varying fundamental constants: e.g. fine structure constant α from $\beta_{F^2} \left(\frac{\phi}{M} \right) F_{\mu\nu} F^{\mu\nu}$
- The excursion of the scalar field $\Delta\phi > m_{\rm Pl}$
  - Radiative corrections
  - Non-renormalisable terms

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The Trapping Mechanism

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$$\mathcal{L} = -\partial_\mu \phi \partial^\mu \phi - \partial_\mu \chi \partial^\mu \chi - \frac{1}{2} g^2 \chi^2 \left(\phi - \phi_{\mathrm{ESP}}\right)^2$$

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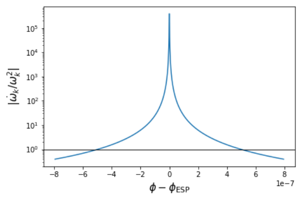

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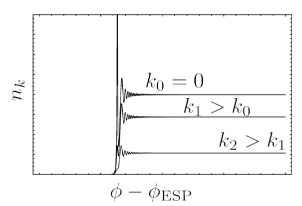

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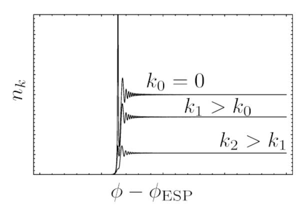

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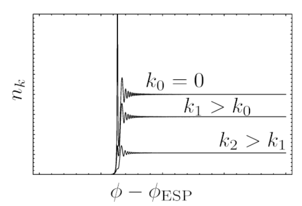

- The expectation value

$$\left\langle \chi^2 \right\rangle \equiv \int \mathrm{d}k \left|\chi_k\right|^2 \simeq \frac{n_\chi}{g \left|\phi\right|}$$

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- Linear potential

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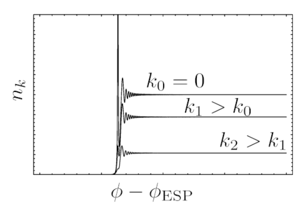

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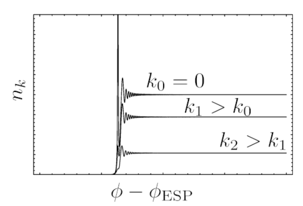

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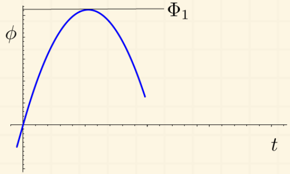

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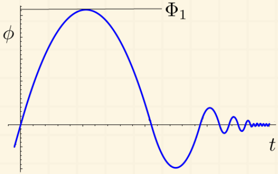

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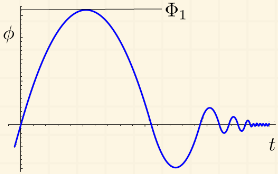

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- End of resonance

$$|\Delta\phi| < \sqrt{v/g} \;\Rightarrow\; \rho_\chi \simeq \rho_{\mathrm{kin}}$$

Tachyonic Trap

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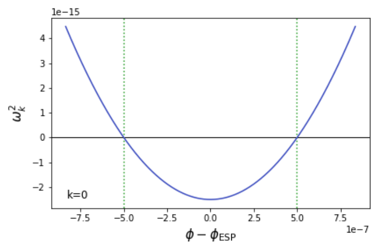

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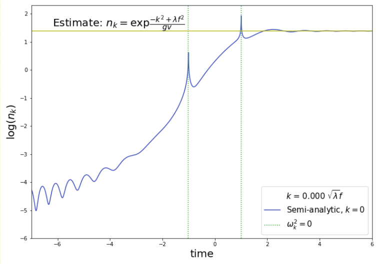

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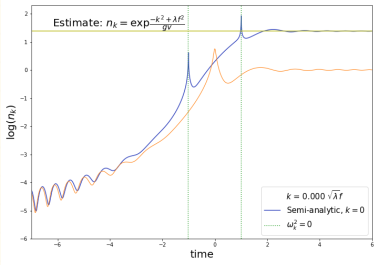

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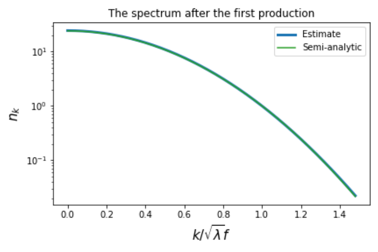

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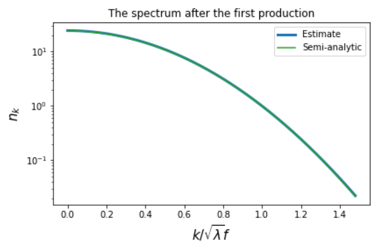
- Particle production stops when either
  - $|\Delta\phi| <$ non-adiabitc region; or
  - χ becomes heavy



Prompt Trapping

- Field excursion $\phi \ll m_{\mathrm{Pl}} \Rightarrow \phi_{\mathrm{ESP}} \ll m_{\mathrm{Pl}}$ and $\Phi_1 \ll m_{\mathrm{Pl}}$
  1. Trapping is prompt

$$H_{\mathrm{ESP}} \simeq v \quad \Rightarrow \quad t_1 H_{\mathrm{ESP}} \ll 1$$

  2. Radiative corrections small
  3. Non-renormalisable terms in the perturbative potential are small

- In the vacuum ϕ is heavy and fixed

$$m_\phi^2 \;=\; g^2 f^2 \gg H^2$$

  1. No 5th force
  2. No variation of fundamental constants

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Non-Perturbative Part

- Non-perturbative + perturbative part

$$\mathcal{L} = \mathcal{L}_{\mathrm{kin}} + \mathcal{L}_{V} + \mathcal{L}_{\mathrm{prtb}}$$

Non-Perturbative Part

- Kinetic term

$$\mathcal{L} = \frac{\alpha}{2}\left(\frac{m_{\mathrm{Pl}}}{\phi}\right)^2 \partial_\mu\phi\partial^\mu\phi + \mathcal{L}_V + \mathcal{L}_{\mathrm{prtb}}$$

Non-Perturbative Part

- The potential (e.g. gaugino condensation)

$$\mathcal{L} = \frac{\alpha}{2}\left(\frac{m_{\mathrm{Pl}}}{\phi}\right)^2 \partial_\mu\phi\partial^\mu\phi + V_0 \mathrm{e}^{-\kappa\phi/m_{\mathrm{Pl}}} + \mathcal{L}_{\mathrm{prtb}}$$

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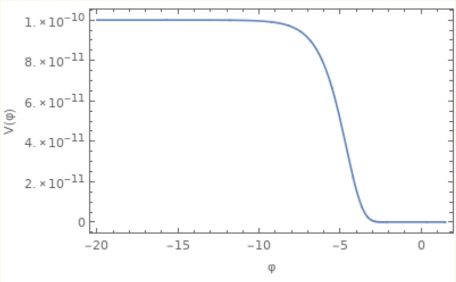
$$\frac{\varphi}{m_{\rm Pl}} \equiv \sqrt{\alpha}\ln\left(\frac{\phi}{m_{\rm Pl}}\right)$$

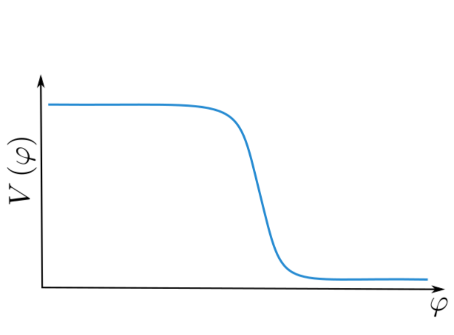
The pole is sent to $-\infty$



Perturbative Lagrangian

- Perturbative part

$$\mathcal{L} = \frac{\alpha}{2}\left(\frac{m_{\mathrm{Pl}}}{\phi}\right)^2 \partial_\mu\phi\partial^\mu\phi + V_0 \mathrm{e}^{-\kappa\phi/m_{\mathrm{Pl}}} + \mathcal{L}_{\mathrm{pert}}$$



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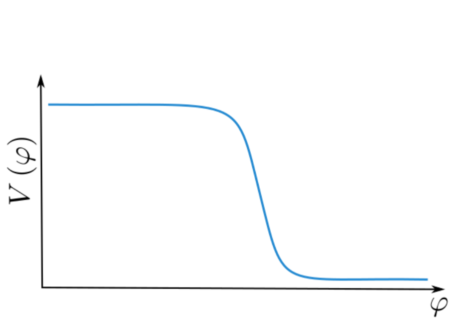

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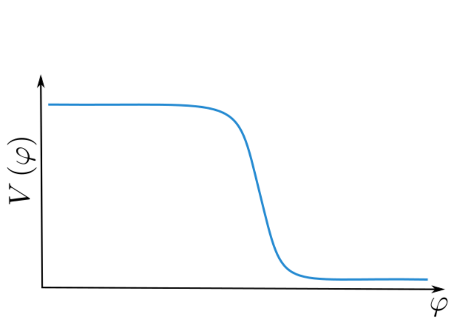

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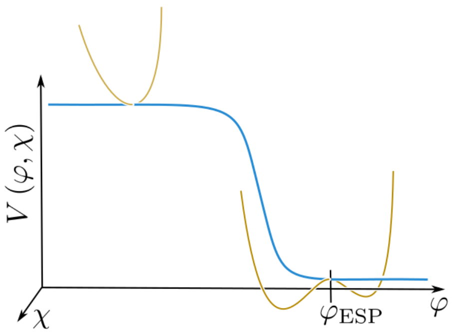
- Perturbative part

$$\mathcal{L} = \frac{\alpha}{2}\left(\frac{m_{\rm Pl}}{\phi}\right)^2 \partial_\mu\phi\partial^\mu\phi + V_0 \mathrm{e}^{-\kappa\phi/m_{\rm Pl}}$$
$$+\partial_\mu\chi\partial^\mu\chi + \frac{1}{2}g^2\chi^2\left(\phi-\phi_{\rm ESP}\right)^2 + \frac{1}{4}\lambda\left(\chi^2-f^2\right)^2$$



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- Peccei-Quinn field
  - Economy: axion DM $f \sim 10^{12}$ GeV

- χ heavy during inflation $\Rightarrow$ no isocurvature perturbations
- κ: the vacuum energy

$$\kappa\frac{\phi_{\mathrm{ESP}}}{m_{\mathrm{Pl}}} = \ln\frac{V_0}{V_{\mathrm{vac}}} \sim 10^2$$

Constraints

- Inflation
- Kination
- ESP
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$m_{\mathrm{Pl}} = 1$

$$\varphi \equiv \sqrt{\alpha}\ln\phi$$

Inflation

- Double exponential potential $V(\varphi) = V_0 \exp\left[-\kappa \exp\left(\varphi/\sqrt{\alpha}\right)\right]$
- Observables

$$n_\mathrm{s} \simeq 1 - \frac{2}{N_*} - \frac{\alpha}{N_*^2}; \qquad r \simeq \frac{8\alpha}{N_*^2}; \qquad A_\mathrm{s} = \frac{1}{24\pi^2}\frac{V}{\epsilon};$$

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- Observational (Planck) constraints

$$\begin{aligned} n_s &= 0.968 \pm 0.006 & & 53 \leq N_* < 70 \\ r &< 0.06 & \Rightarrow \quad & 1 \leq \alpha < 37 \\ \ln\left(10^{10} A_s\right) &= 3.094 \pm 0.034 & & \kappa\phi_{\mathrm{ESP}} < 236 \end{aligned}$$

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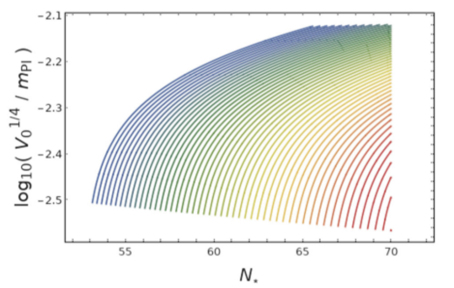
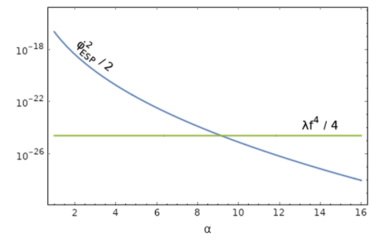
- Inflationary energy scale (within 2σ of n_s)



Kination

- Potential is irrelevant

$$\ddot{\varphi} + 3H\dot{\varphi} \simeq 0$$
$$\Downarrow$$
$$\dot{\varphi}^2 \propto a^{-6}$$



$$\alpha < 10$$

- Velocity at ESP

$$\dot{\varphi}_{\mathrm{ESP}} = \frac{\sqrt{2V_0(\alpha)/3}}{\exp\left(\sqrt{\alpha/2}\right)} \left(\frac{\sqrt{2\alpha}}{\kappa(\alpha)\,\phi_{\mathrm{ESP}}}\right)^{\sqrt{3\alpha/2}} < \sqrt{V(\varphi)}$$

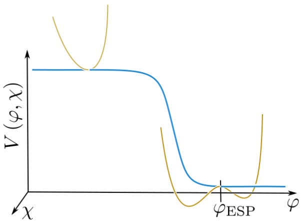
At the enhanced symmetry point

- With $|\varphi - \varphi_{\rm ESP}| \ll 1$

$$V \simeq V_{\rm vac}\left(\frac{V_{\rm vac}}{V_0}\right)^{(\varphi-\varphi_{\rm ESP})/\sqrt{\alpha}} + \frac{1}{2}\gamma^2\left(\varphi - \varphi_{\rm ESP}\right)^2\chi^2 + V\left(\chi\right)$$

where

$$\gamma \equiv \frac{g\phi_{\rm ESP}}{\sqrt{\alpha}}$$



- Dispersion relation of χ_k

$$\omega_k^2 = k^2 + \gamma^2\left(\varphi - \varphi_{\rm ESP}\right)^2 + \lambda\left(3\left\langle\chi^2\right\rangle - f^2\right)$$

- Constraint

$$\Phi_1\left(\alpha, \gamma, \phi_{\rm ESP}\right) < 1$$

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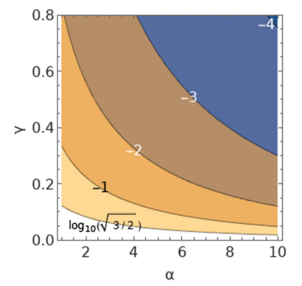


$\phi_{\rm ESP} = 1$

Trapping

- Particle production ends when

  1. $|\Delta\varphi| <$ non-adiabtic window $\quad \Rightarrow \quad \rho_r \simeq \frac{1}{2}\dot{\varphi}^2_{\mathrm{ESP}}$

  2. $m_\chi^2 \simeq \lambda\left(3\left\langle\chi^2\right\rangle - f^2\right)$ becomes large $\quad \Rightarrow \quad \rho_r < \frac{1}{2}\dot{\varphi}^2_{\mathrm{ESP}}$

- 1st case if

$$\frac{\lambda}{\gamma^2} < \frac{1}{7}$$

- Stronger χ's self-coupling less effective trapping.

Reheating

- If $\frac{\lambda}{\gamma^2} < \frac{1}{7}$ is satisfied
- Reheating temperature (instant thermalisation)

$$\frac{1}{2}\dot{\varphi}^2_{\rm ESP} \quad \simeq \quad \frac{\pi^2}{30} g_* T^4_{\rm reh}$$

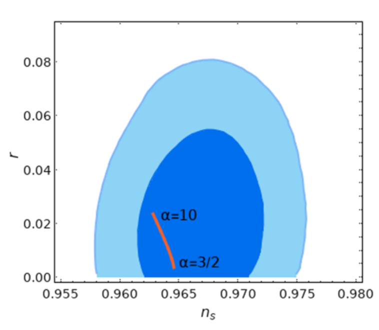
- An estimate

$$\begin{aligned} \phi_{\rm ESP} &\simeq 1 \\ V^{1/4}_{\rm end} &\sim 10^{-2} \\ \kappa &\sim 10^2 \\ &\Downarrow \\ T_{\rm reh} &\sim 10^{11-13}\ \text{GeV} \end{aligned}$$

Planck Constraints

- Number of e-folds of observable inflation

$$N_* \simeq 56.3 + \sqrt{\frac{\alpha}{24}} \ln\left(\frac{244}{\sqrt{2\alpha}}\phi^2_{\mathrm{ESP}}\right)$$



Conclusions

- Quintessential inflation
- Trapping mechanism helps solving several traditional problems
- A concrete example

Kinetic Term

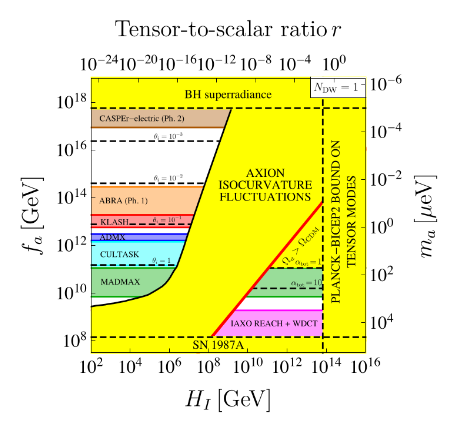
- Kähler Potential for a string modulus $T = \frac{\phi + \mathrm{i}\sigma}{\sqrt{2} m_{\mathrm{Pl}}}$

$$\frac{K}{m_{\mathrm{Pl}}^2} = -3 \ln \left(T + \bar{T} \right) = -3 \ln \left(\sqrt{2} \frac{\phi}{m_{\mathrm{Pl}}} \right)$$

This gives the kinetic term

$$\mathcal{L}_{\mathrm{kin}} = K_{T\bar{T}} \partial_\mu T \partial^\mu \bar{T} = \underbrace{\frac{3}{2}}_{\alpha} \left(\frac{m_{\mathrm{Pl}}}{\phi} \right)^2 \left[\frac{1}{2} (\partial\phi)^2 + \frac{1}{2} (\partial\sigma)^2 \right]$$

Axion DM Constraints



Di Luzio+ (2020)