Inflation
x
Dark Matter
x
Dark Energy

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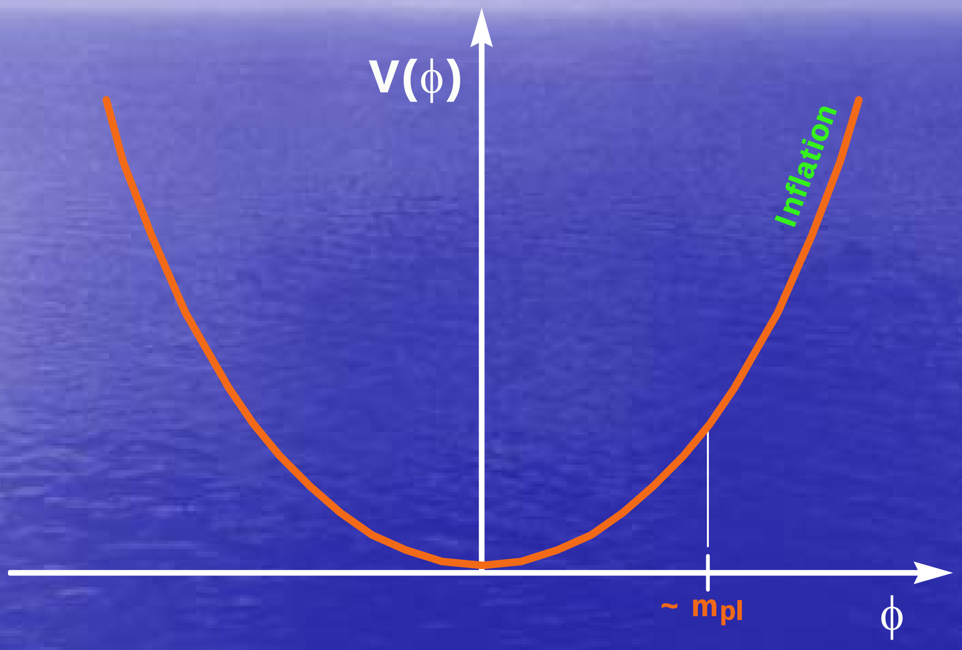
Based on astro-ph/0605205 and ongoing work

Unification scenario

Inflation



Unification scenario

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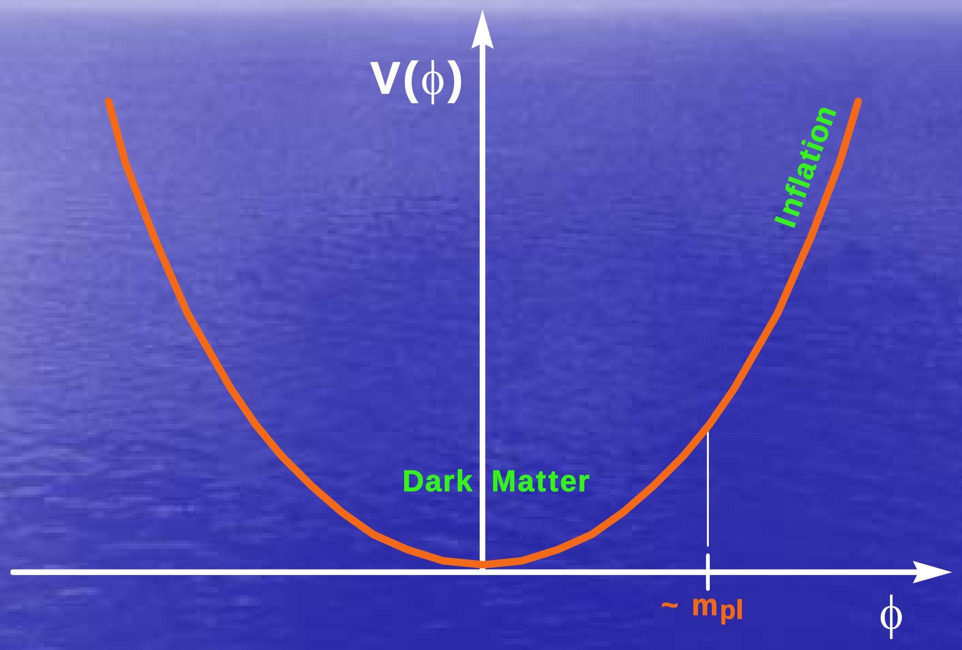
Dark Matter



Kofman, Linde and Starobinsky (1994 & 1997)

Unification scenario

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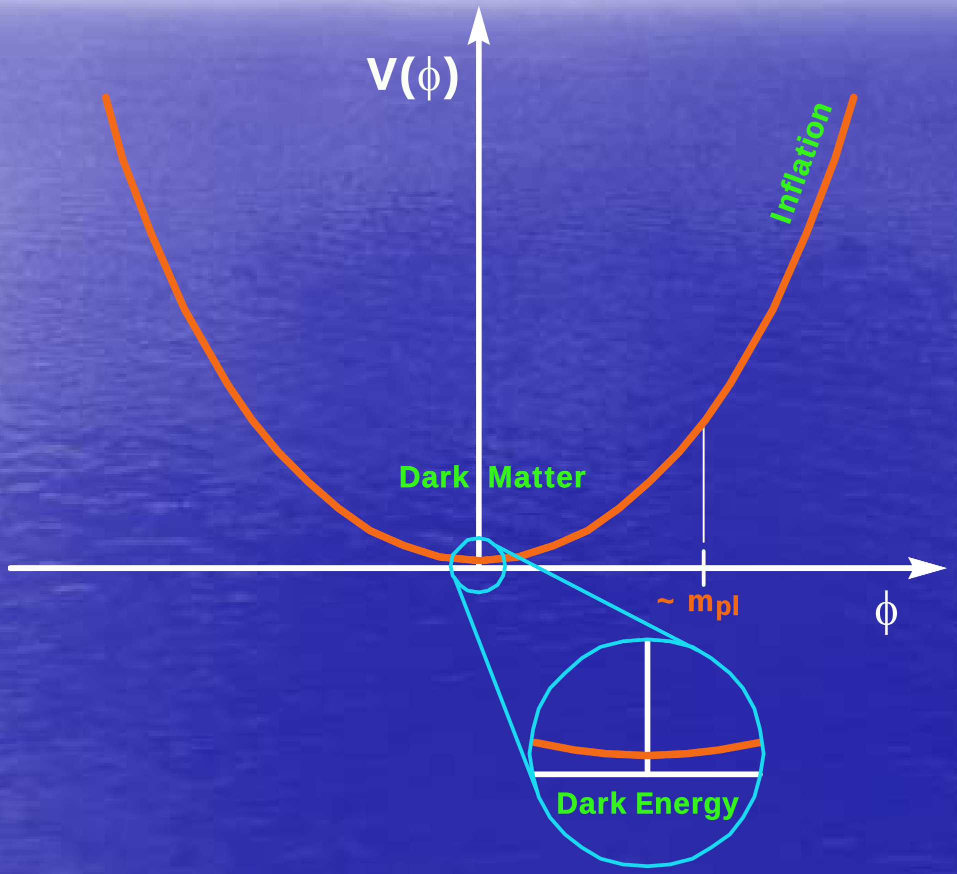


Theoretical constraints

- In absence of decays, for quadratic potentials, the scalar field behaves as

$$\rho_\phi \cong \text{const} \quad m << H$$

$$\rho_\phi \propto 1/a^3 \quad m >> H$$

- Within the context of the string landscape, a non-zero vacuum energy of the inflaton field explains Dark Energy

$$V(\phi) = V_0 + \frac{1}{2} m^2 \phi^2$$

Observational constraints

- The scalar field dark matter mass per photon $\xi_{dm} \equiv \rho_\phi / n_\gamma$ is observed to be

$$\xi_{dm,0} = 2.4 \times 10^{-28}\, m_{Pl}$$

- The quantity ξ_{dm}/g_S is constant for $t > t_*$, corresponding to $m = H_*$. This implies

$$\left(\frac{m}{m_{Pl}}\right)^{1/2} \frac{\phi_*^2}{m_{Pl}^2} \simeq 4 \times 10^{-29}$$

- Obtaining the correct amplitude of scalar perturbations requires $m/m_{Pl} \cong 10^{-6}$, and so

$$\phi_* \cong 10^{-13}\, m_{Pl}$$

Between Inflation and Hot BB

- In the usual belief, the inflaton decays away completely after inflation ends, during the first oscillations, through preheating and reheating, which may happen in sequence.

- Preheating offers a rapid but incomplete decay, with a *quadratic* interaction $g^2\phi^2\chi^2$, which ends once

$$\phi \sim m/g \overset{g\sim 1}{\sim} 10^{-6}\, m_{\mathrm{Pl}}$$

- So preheating usually comprises a *trilinear* interaction as well, or is followed by a reheating period, allowing a complete decay:

$$\dot{\rho}_\phi + 3H\dot{\phi}^2 = -\Gamma_\phi \dot{\phi}^2$$

Can a residual oscillation survive as Dark Matter?

- Suppose we have a preheating period only, with a quadratic interaction, this must satisfy

$$\phi_{\rm th} \sim m/g \overset{g\sim 1}{\sim} 10^{-6} m_{\rm Pl} \quad \rightarrow \quad \phi_{\rm obs} \sim 10^{-13} m_{\rm Pl}$$

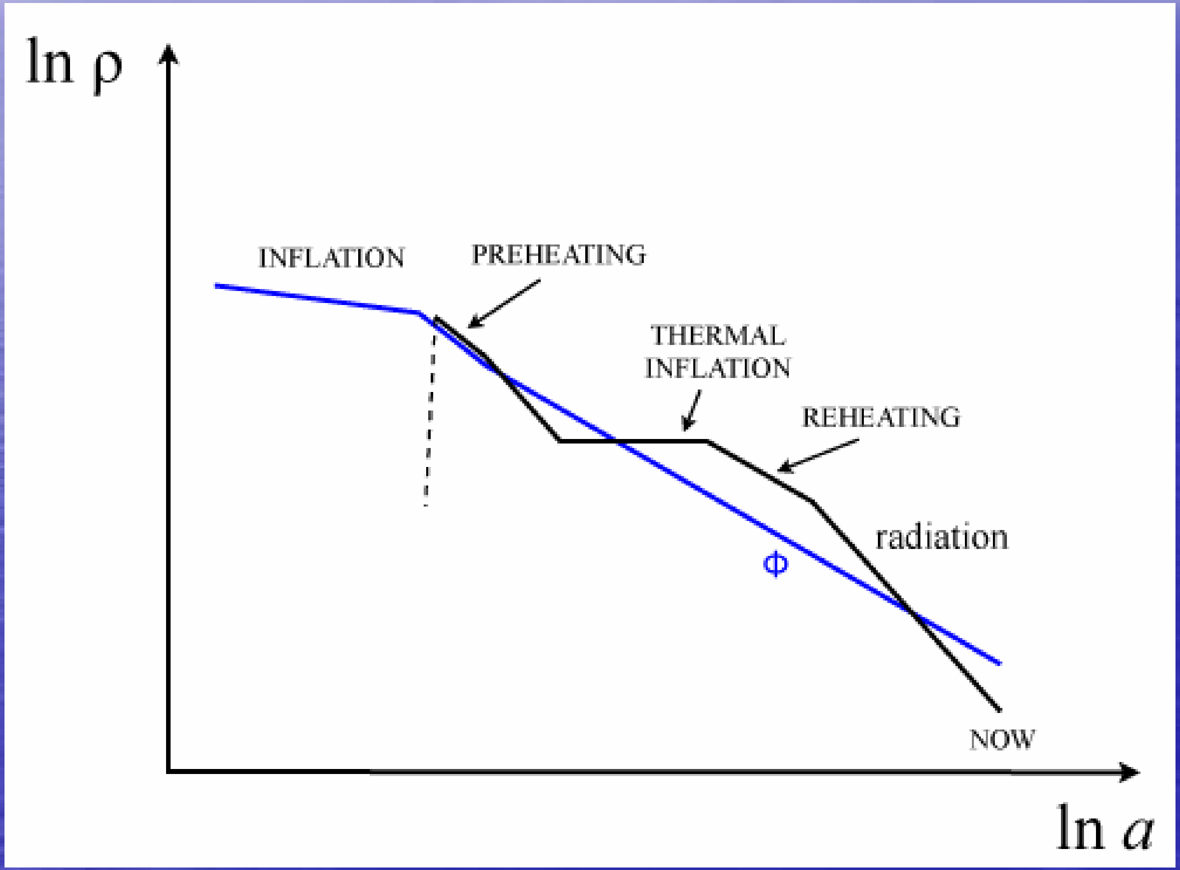
- An alternative is to exploit annihilations via perturbative interactions during the reheating process, instead of the usual decay (AL & LUL):

$$\Gamma_\phi = \Gamma_0 \frac{\rho_\phi/\rho_c}{1+\rho_\phi/\rho_c}$$

- More attractive and natural is to consider a brief period of inflation at lower energy densities, called thermal inflation [Lyth & Stewart (1995 & 1996) and Barreiro et al. 1996], driven by another scalar field (AL, CP & LUL):

$$\phi_{\rm start}/\phi_{\rm end} \sim 10^{\frac{2N_{\rm thermal}}{3}} \overset{N\sim 11}{\sim} 10^7$$

Universe history schematic



A detailed scenario

- End of slow-roll inflation $\phi_{end} \simeq 0.28\ m_{Pl}$
- Allowing a four-legs interaction only, preheating ends once $\phi_{pr} \simeq m / g$, where $10^{-10} < g^2 < 10^{-5}$, and $\rho_r / \rho_\phi \simeq$ a few (Podolsky et al. 2006).
- t_* being the beginning of the HBB, it is straightforward to show that for any time $t > t_*$

$$\frac{\xi_{\mathrm{dm}}}{m_{\mathrm{Pl}}} = \frac{\pi^2}{2\zeta(3)} \frac{g_{\mathrm{S}}(T)}{g_{\mathrm{S}}(T_*)} \frac{m^2}{m_{\mathrm{Pl}}^2} \frac{\phi_*^2}{m_{\mathrm{Pl}}^2} \frac{m_{\mathrm{Pl}}^3}{T_*^3}$$

From preheating to thermal inflation

- After preheating, the inflaton redshifts as CDM, $\phi \propto a^{-3/2}$

$$\phi^2_{\rm SB} = \phi^2_{\rm pr}\left(\frac{a_{\rm pr}}{a_{\rm SB}}\right)^3 = \phi^2_{\rm pr}\frac{g_{\rm S}(T_{\rm SB})}{g_{\rm S}(T_{\rm pr})}\left(\frac{\hat{m}}{T_{\rm pr}}\right)^3$$

- Once thermal equilibrium is attained at the end of preheating (Bassett et al. 2006 and Podolsky et al. 2006), $\rho_{r,\,pr} \simeq g_E(T_{pr})\, T_{pr}^4$, which gives

$$T_{pr} \simeq m\, g^{-1/2}\, g_E^{-1/4}(T_{pr})$$

- And so the dilution is mainly determined by the inflationary masses

$$\phi^2_{\rm SB} \simeq \frac{g_{\rm S}(T_{\rm SB})}{g_{\rm S}(T_{\rm pr})}\frac{g_{\rm E}^{3/4}(T_{\rm pr})}{g^{1/2}}\frac{\hat{m}^3}{m^3}m^2$$

From thermal inflation to reheating

- We assume that each flaton particle decays at a single-particle decay rate Γ, and so the Universe is reheated when $\Gamma \cong H_*$.
- During the reheating process, the Universe is dominated by the oscillating flaton field

$$\frac{a_{\mathrm{SB}}^3}{a_*^3} \simeq \frac{H_*^2}{H_{\mathrm{SB}}^2} \simeq \frac{3m_{\mathrm{Pl}}^2\Gamma^2}{8\pi\hat{V}}$$

- The inflaton field is further affected by this expansion

$$\frac{\phi_*^2}{m_{\mathrm{Pl}}^2} = \frac{\phi_{\mathrm{SB}}^2}{m_{\mathrm{Pl}}^2}\frac{a_{\mathrm{SB}}^3}{a_*^3} \simeq \phi_{\mathrm{SB}}^2\frac{3\Gamma^2}{8\pi\hat{V}}$$

- Finally, the reheating temperature is $T_* \cong g_E^{-1/4}(T_*)\,(m_{\mathrm{Pl}}\Gamma)^{1/2}$

From preheating to reheating

- Our dark matter constraint now looks

$$\frac{\xi_{\rm dm}}{m_{\rm Pl}} \simeq \frac{3\pi}{16\zeta(3)} \frac{g_{\rm S}(T_{\rm SB})}{g_{\rm S}(T_{\rm pr})} \frac{g_{\rm S}(T)}{g_{\rm S}(T_*)} g_{\rm E}^{3/4}(T_*) g_{\rm E}^{3/4}(T_{\rm pr}) \times g^{-1/2} \frac{m}{\hat{m}} \left(\frac{\hat{m}}{\hat{V}^{1/4}}\right)^4 \sqrt{\frac{\Gamma}{m_{\rm Pl}}}.$$

- From WMAP5 $\xi_{dm,0} = 2.4 \times 10^{-28}\, m_{Pl}$, and we assume $g_E(T) \simeq g_S(T) \simeq 100$ for $T \geq T_*$, $g_S(T_0) \simeq 3.9$, thus we obtain

$$g^{-1/2} \frac{m}{\hat{m}} \left(\frac{\hat{m}}{\hat{V}^{1/4}}\right)^4 \sqrt{\frac{\Gamma}{m_{\rm Pl}}} \simeq 10^{-29}$$

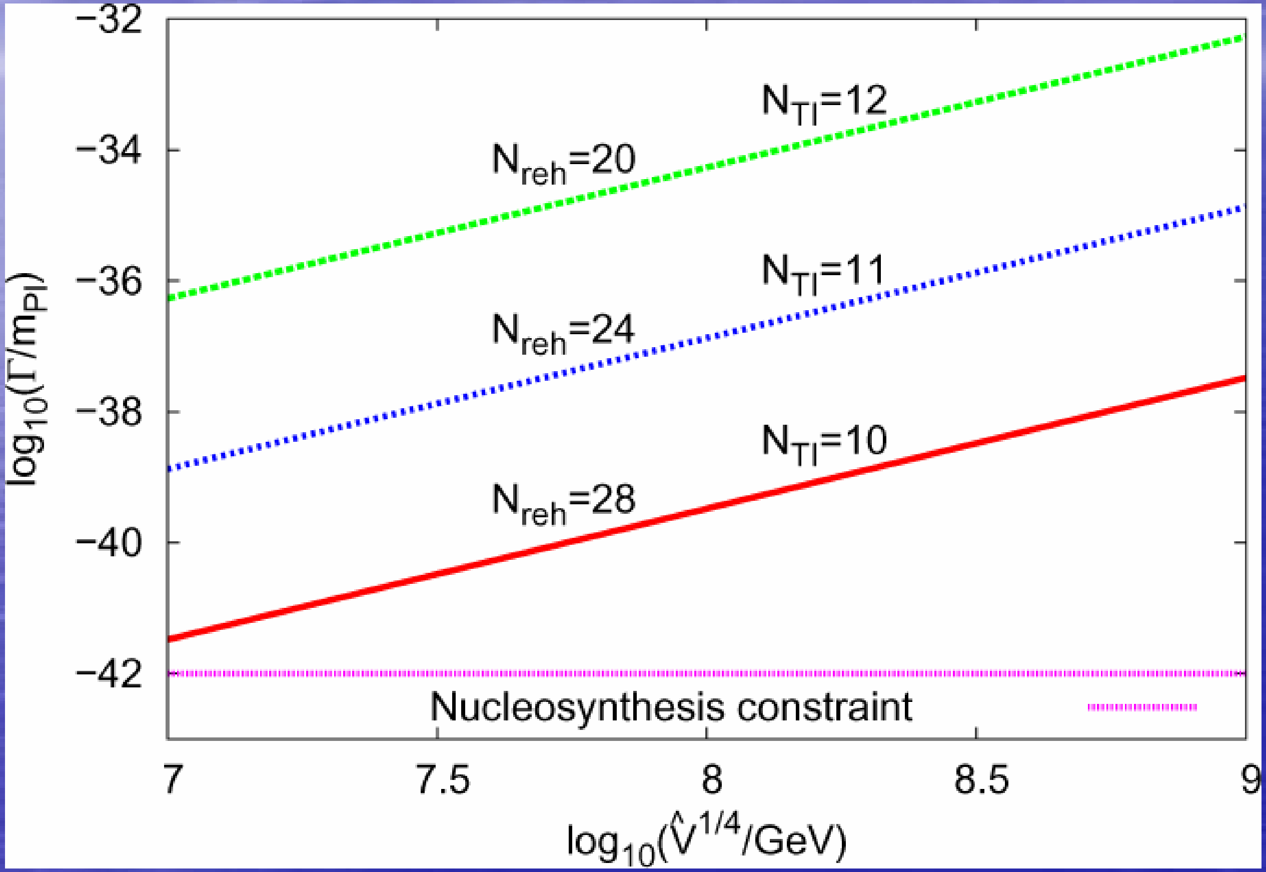
E-foldings

- Let's define $N_{\rm TI} \equiv \ln \frac{\hat{V}^{1/4}}{\hat{m}}$ and $N_{\rm reh} \equiv \frac{1}{3} \ln \frac{8\pi\hat{V}}{3m_{\rm Pl}^2\Gamma^2}$, our observational constraint thus becomes

$$N_{\rm TI} + \tfrac{1}{4} N_{\rm reh} \simeq 18 - \ln g^{1/6}$$

- Thermal inflationary theory predicts $N_{\rm TI} \simeq 11$ (Lyth & Stewart 1995), as $\hat{m} \simeq 10^2$ to 10^3 GeV, and on general grounds we expect $\hat{V}^{1/4} \simeq 10^7$ to 10^8 GeV.
- The decay width is sandwiched by two limits:
  - Reheating after TI => $\Gamma < H_{SB} \simeq 10^{-24}\ m_{Pl}$
  - Reheating before HBB => $\Gamma > 10^{-42}\ m_{Pl}$

Decay rate window



Barreiro et al. (1996) showed that $\Gamma \cong 10^{-2}\,\hat{m}^5/\hat{V}$,
and so $\hat{m} \cong 10^3$ GeV and $\hat{V}^{1/4} \cong 10^8$ GeV.

Conclusions

- The residual of an incomplete decay of the inflaton field may play the role of Dark Matter.
- Considering a second, brief, period of inflation the residual density is in good accordance with observations.
- In an anthropic string landscape sense, the inflaton field can act as Dark Energy as well.