From warm inflation to cold dark matter

The tale of the twinflaton

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Introduction

The purpose of this work is to reignite an idea first introduced in [1] that the **inflaton**, a field responsible for an accelerated phase that explains the observed isotropy and flatness of the universe, can account for the **present dark matter density** in warm inflation scenarios.

The crucial observation is that the symmetries imposed in these constructions to guarantee a consistent model of inflation naturally lead to a **long-lived inflaton relic**. We find that if the inflaton particles have masses around $0.05-20$ eV, they can account for **all the dark matter** in the Universe. Due to feeble interactions, direct and indirect searches are unlikely to find these particles. However, **isocurvature perturbations** generated during inflation provide the primary smoking gun for this scenario. Despite their amplitude, $\beta_{\rm Iso} \in [2,5]\times 10^{-4}$, being below the most constraining bounds from the Planck satellite, $\beta^{\rm Planck}_{\rm Iso} < 1\times 10^{-3}$ [2], future experiments as the CMB-S4 [3] can help shed light into this paradigm.

Cold and warm inflation

Cold inflation The overdamped motion of the inflaton field drives a phase of accelerated expansion. Its quantum fluctuations then act as seeds for structure formation and CMB anisotropies that match observations [2]. It is followed by a **reheating** phase where the inflaton oscillates about the minimum of its potential and **decays completely** to Standard Model particles.

Warm inflation Interactions between the inflaton and other fields are non-negligible during inflation, causing dissipative effects that transfer the inflaton energy into light degrees of freedom that sustain a sub-dominant radiation energy. When **dissipative effects** are strong enough, quantum fluctuations are replaced by thermal ones and the end of inflation is concomitant with the dominance of the radiation energy density. **Reheating is not necessary**, which may leave a **stable** inflaton **remnant**.

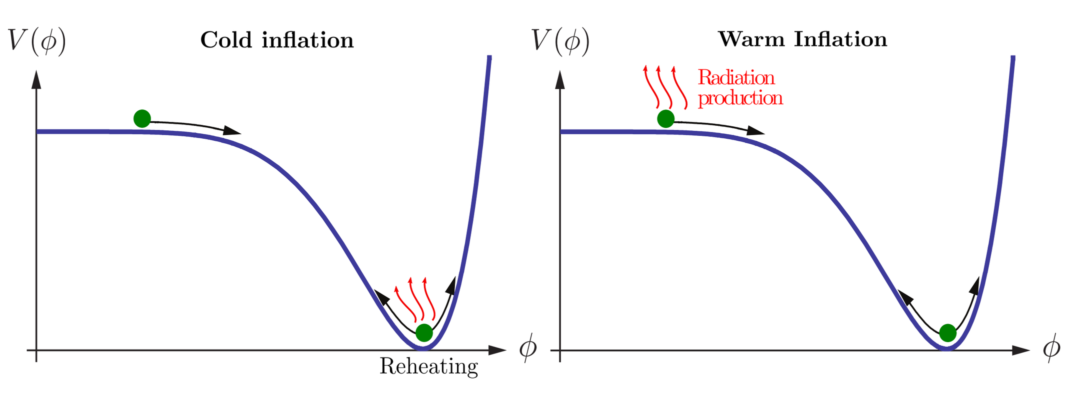

Figure 1: Cold and warm inflation.

Warm Twinflaton

The Warm Twinflaton is a particular case of a family of warm inflation models [4], drawing its name from the similarities with the Twin Higgs scenario [5]. It is composed by two complex scalar fields, ϕ_1 and ϕ_2, with identical $U(1)$ charges. Due to spontaneous breaking of the $U(1)$ at $T = M$, the remaining physical degree of freedom is the relative phase between ϕ_1 and ϕ_2, ϕ,

$$\phi_1 = \frac{M}{\sqrt{2}} e^{i\phi/M} \quad , \quad \phi_2 = \frac{M}{\sqrt{2}} e^{-i\phi/M} \quad , \qquad (1)$$

which we identify as the inflaton. Its Yukawa interactions with a pair of Dirac fermions ψ_i $(i=1,2)$ with **mass** gM

$$\begin{aligned} -\mathcal{L}_{\phi\psi} &= \sqrt{2} g \phi_1 \overline{\psi}_{1L}\psi_{1R} + \sqrt{2} g \phi_2 \overline{\psi}_{2L}\psi_{2R} + \text{h.c} \\ &= gM\overline{\psi}_1 e^{i\gamma_5\phi/M}\psi_1 + gM\overline{\psi}_2 e^{-i\gamma_5\phi/M}\psi_2 \ , \end{aligned} \qquad (2)$$

are invariant under the **interchange symmetry** $\phi \leftrightarrow -\phi$, $\psi_1 \leftrightarrow \psi_2$. This guarantees the **absence** of **local** radiative and thermal **corrections** to the inflaton potential, while **non-local corrections** generate a **dissipative** term $Q \propto T/H$ that transfers the inflaton energy to the light degrees of freedom. This also guarantees that, except for the coupling to the ψ_i fermions, interactions between the inflaton and other fields obey a $\mathbb{Z}_2$ symmetry.

The cold inflaton equations of motions are modified to:

$$\begin{aligned} &\ddot{\phi} + 3H(1+Q)\dot{\phi} + V_{,\phi} = 0 \quad , \\ &\dot{\rho}_r + 4H\rho_r = 3HQ\dot{\phi}^2 \quad , \\ &H^2 = \frac{\rho_\phi + \rho_r}{3M_{\rm P}^2} \quad , \end{aligned} \qquad (3)$$

where $\dot{} = \partial_t$, $H = \dot{a}/a > 0$ is the Hubble expansion rate, $\rho_\phi = (\dot{\phi}^2/2) + V(\phi)$, $\rho_r = (\pi^2/30)g_* T^4$ are the inflaton and radiation energy densities, T is the temperature, g_* is the total number of relativistic degrees of freedom, and $M_{\rm P} = 2.4\times 10^{18}$ GeV$/c^2$ is the reduced Planck mass.

Cosmology

How can this model for inflation have built-in dark matter? Let us take a look into Fig. 2.:

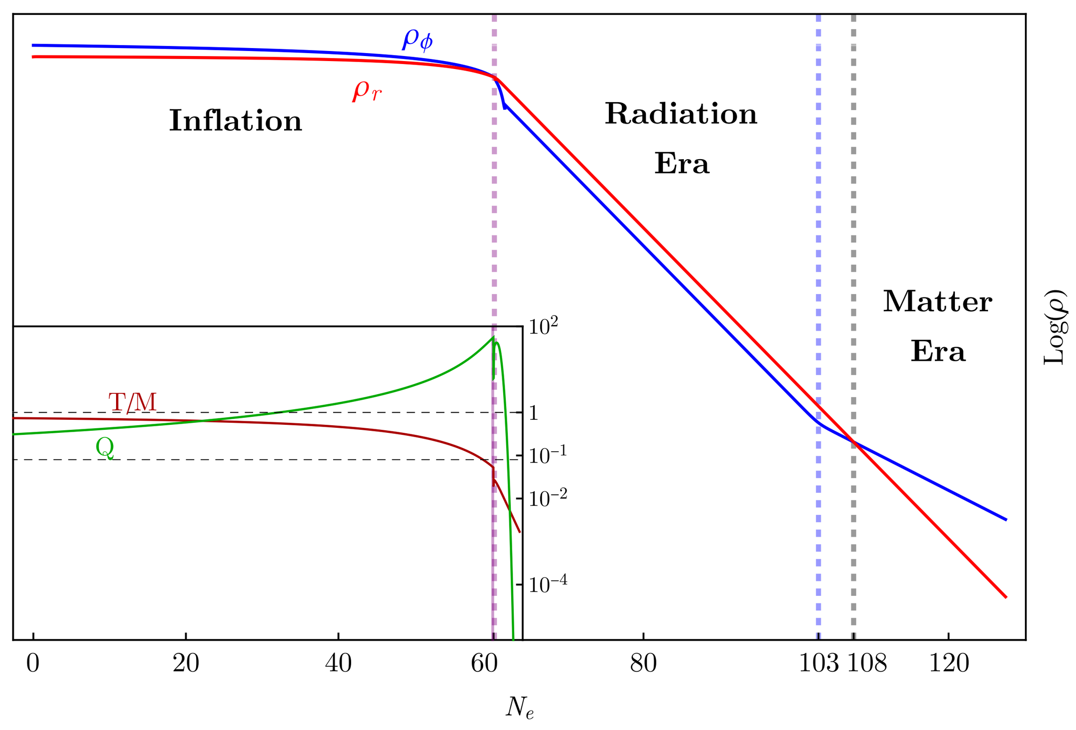

Figure 2: Cosmological dynamics of the warm twinflaton.

The cosmological evolution starts with a period where the inflaton potential energy $V(\phi)$ dominates the energy content of the Universe, leading to a period of accelerated expansion lasting around 60 e-folds. Simultaneously, the kinetic energy is being transformed into radiation ($\rho_\phi \to \rho_r$) by means of the dissipative term Q.

When $\rho_\phi \approx \rho_r$, the accelerated expansion can **no longer** be sustained and inflation **ends** (purple line above). As a result, this phase is followed by an era where the energy density of the relativistic degrees of freedom, $\rho_r \propto a^{-4}$, dominates the energy content of the Universe.

In the case where $V(\phi) = \lambda\phi^4 + m_\phi^2\phi^2/2$, the inflaton field starts oscillating about a quartic potential shortly after inflation ends, acting as dark radiation. This occurs **until** the quadratic term dominates over the quartic one, $\phi_{\rm dm} = \sqrt{2/\lambda}\, m_\phi$ (dark blue line above), after which the inflaton behaves as cold dark matter, $\rho_\phi \propto a^{-3}$.

Main points:

- Dissipation guarantees a smooth transition from inflation to a radiation-dominated era, leading to a **non-negligible** ρ_ϕ after inflation;
- The imposed symmetries only allow the inflaton to decay to ψ_i fermions. When this process becomes suppressed ($T \ll gM$), the inflaton becomes stable;
- The **present** dark matter density, Ω_c, is then determined by the ratio $\rho_\phi/\rho_r \propto (\phi/T)^4$ defined after the **end** of **inflation**.

Mass estimates

One can now use n_ϕ/s, which remains constant throughout the post-inflationary cosmological history

$$\frac{n_\phi}{s} = \frac{\rho_\phi/m_\phi}{(2\pi^2/45)g_{*,{\rm dm}}T^3_{\rm dm}} = \sqrt{\frac{\lambda}{2}}\frac{45}{2\pi^2}\frac{1}{g_*}\left(\frac{\phi}{T}\right)^3 \quad , \qquad (4)$$

where $\rho_\phi = m_\phi^2\phi^2_{\rm dm}/2$ and the present dark matter abundance $\Omega_c = (n/s)(s_0 m_\phi/\rho_{\rm crit.}) \approx 0.25$, to estimate the inflaton mass m_ϕ and the temperature at which the inflaton starts behaving as dark matter, $T_{\rm dm}$

$$\begin{aligned} m_\phi &\approx 5\left(\frac{\lambda}{10^{-16}}\right)\left(\frac{10^{-2}}{g}\right)^3\left(\frac{10^{-3}}{M}\right)^3 \ \text{eV} \, , \\ T_{\rm dm} &\approx 2.5\times 10^{-3}\left(\frac{\lambda}{10^{-16}}\right)\left(\frac{10^{-2}}{g}\right)^4\left(\frac{10^{-3}}{M}\right)^4 \ \text{keV} \, , \end{aligned} \qquad (5)$$

where $g_* = 106.75$. For $g \in [0.01, 0.1]$, $\lambda \in [5,10]\times 10^{-16}$ and $M \in [3,10]\times 10^{-4} M_{\rm P}$, the **inflaton mass** ranges from about 0.05 to 20 eV and the temperature at which the inflaton changes its behavior from dark radiation to dark matter, $T_{\rm dm}$, is between 5 and 2.5×10^3 keV, well above matter-radiation equality ($T \sim 0.8$ eV).

Observables

The **inflationary origin** of this **dark matter** candidate can provide singular **smoking guns** for its detection. The first, and most important, is the presence of **isocurvature perturbations** in the cold dark matter distribution generated by thermal fluctuations of the inflaton:

$$S_c = -3H\left(\frac{\delta\rho_c}{\dot{\rho}_c} - \frac{\delta\rho_r}{\dot{\rho}_r}\right) \quad . \qquad (6)$$

These are fully anti-correlated with the adiabatic perturbations $\mathcal{R} \equiv \delta\phi/(H\dot{\phi})$ and their spectrum is given by $\beta_{\rm Iso} = \Delta_I^2/(\Delta_I^2 + \Delta_R^2)$ where $\Delta_I^2 = \langle S_c S_c\rangle$ and $\Delta_R^2 = \langle\mathcal{R}\mathcal{R}\rangle$.

In this model, $\beta_{\rm Iso} \in [2,5]\times 10^{-4}$, below the most constraining data of the Planck Collaboration for fully anti-correlated isocurvature perturbations, $\beta^{\rm Planck}_{\rm Iso} < 1\times 10^{-3}$.

Apart from the the inflaton condensate, there is a sub dominant DM density under the form of thermalized inflaton particles. These decouple at $T \sim gM$, making them the first to break away from the thermal bath. Their contribution to the **effective degrees of freedom**, $N_{\rm eff}$, is then

$$\Delta N_{\rm eff} = \frac{4}{7}\left(\frac{43}{4g_*}\right)^{4/3} \approx 0.027 \quad , \qquad (7)$$

for $g_* = 106.75$, well within $N_{\rm eff} = 3.27 \pm 0.15$ [2]. It is expected that future CMB experiments (as CMB-S4) and observations of the large scale structure of the universe (as (e)BOSS, DES(I)) can already constrain $\beta_{\rm Iso}$ and $\Delta N_{\rm eff}$ considerably [6].

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