Warm Little Inflaton becomes Cold Dark Matter

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Goal

Use the inflaton field to account for the present dark matter density.

The inflaton as dark matter: Why though?

Although scalar fields are galore in unification theories, they are hard to come by in well established physical models.

So, when doing model building, if you have to add something to a model that works, you try to check if it can solve other open problems...

Not easy in (cold) inflation

→ The early Universe is composed of two parts (inflaton, radiation) which do not interact with one another:

$$\frac{d^2\phi}{dt^2} + 3H\frac{d\phi}{dt} + \partial_\phi V = 0 \quad , \quad \frac{d\rho_r}{dt} + 4H\rho_r = 0 \quad , \qquad (1)$$

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- → The extra mechanisms ((p)reheating) required to generate the Hot Big Bang universe usually imply the decay of the inflaton.
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Can reheating be avoided?

And thus, **avoid** the **decay** of the **inflaton** (after inflation occurs)?

Warm Inflation

Revisit the assumption that the inflaton does not interact with other particles during inflation. What happens if it does?

→ Interactions generate an extra dissipation term in the inflaton equation of motion, affecting the dynamics;

→ Interactions sustain a non-negligible radiation density during inflation (Warm inflation);

→ Interactions can lead to a smooth transition from warm inflation to a radiation-dominated era (no reheating is necessary);

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There are several difficulties with doing this, but recently [Bastero-Gil et al., 2016] managed to develop a consistent particle physics model of inflation, where the inflaton interacts with only two fields and sustains a non-negligible radiation bath, by imposing symmetries.

Field content

- **Inflaton** ϕ. Generated by the collective spontaneous breaking of a U(1) gauge symmetry by two complex fields $\phi_{1,2}$ with identical charges [Bastero-Gil et al., 2016, Rosa and Ventura, 2018]:

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

$\phi_{1,2}$ have Yukawa interactions with:

- **Fermions** $\psi_{1,2}$ of mass gM, which remain light during inflation if $gM < T < M$. These have Yukawa interactions with:
- **Massless scalar** σ and **fermion** ψ_σ.

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Two-stage mechanism

As a result, there is a two-stage mechanism: out-of-equilibrium decay of the inflaton into $\psi_{1,2}$, followed by decays and scatterings of these fields into $\sigma,\ \psi_\sigma$:

$$\phi \to \psi_{1,2} \leftrightarrow \sigma,\ \psi_\sigma \ \ ,$$

which causes dissipation of the inflaton energy.

Symmetries and interaction Lagrangians

Interchange symmetry $\phi_1 \leftrightarrow \phi_2$ composed with $\psi_1 \leftrightarrow \psi_2$

$$-\mathcal{L}_{\phi\psi} = \frac{1}{\sqrt{2}} g\phi_1 \overline{\psi}_{1L}\psi_{1R} + \frac{1}{\sqrt{2}} g\phi_2 \overline{\psi}_{2L}\psi_{2R} + \text{H.c.} = $$
$$= gM\overline{\psi}_1 e^{i\gamma_5\phi/M}\psi_1 + gM\overline{\psi}_2 e^{-i\gamma_5\phi/M}\psi_2 \ , \qquad (3)$$

implies $\phi \leftrightarrow -\phi$ with $\psi_1 \leftrightarrow \psi_2$: ϕ can only decay directly to $\psi_{1,2}$. The latter decay/scatter through

$$-\mathcal{L}_{\psi\sigma} = h\sigma \sum_{i=1,2} \overline{\psi}_{iL}\psi_{\sigma R} + \overline{\psi}_{\sigma L}\psi_{iR} + \text{H.c.} \ , \qquad (4)$$

Inflaton potential

The inflaton potential is given by the simplest renormalizable terms, $V(\phi) = \lambda\phi^4 + (m_\phi^2/2)\phi^2$, with $\lambda \sim 10^{-15}$ fixed by the amplitude of the CMB fluctuations [Akrami et al., 2018] and $m_\phi \sim 10^{-4} - 10^{-1}$ eV by requiring that ϕ accounts for all the dark matter in the Universe.

Equations of motion

$$\frac{d^2\phi}{dt^2} + (3H + \Upsilon)\frac{d\phi}{dt} + \partial_\phi V = 0 \quad ,$$
$$\frac{d\rho_r}{dt} + 4H\rho_r = \Upsilon\dot{\phi}^2 \quad , \tag{5}$$

where H is the Hubble parameter $H^2 = (\rho_\phi + \rho_r)/3M_{\mathrm{P}}^2$, ρ_ϕ (ρ_r) the inflaton (radiation) density and Υ is the dissipation coefficient created by the interaction of the inflaton with the mediators $\psi_{1,2}$ (check Υ in [Rosa and Ventura, 2018]).

Inflationary dynamics

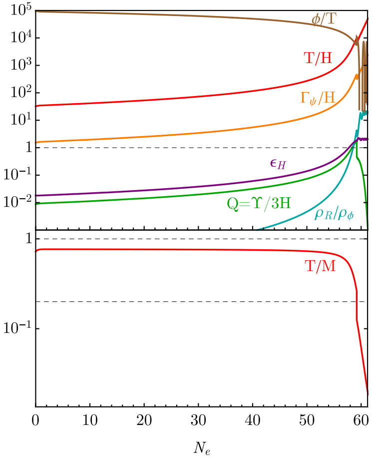

Figure 1: Evolution of ϕ/T (brown), T/H (red), Γ_ψ/H (orange), $Q \equiv \Upsilon/3H$ (green), $\epsilon_H \equiv -\dot{H}/H^2$ (purple), ρ_r/ρ_ϕ (cyan) and T/M (red, bottom plot) during inflation. Check details in Fig. 2 of [Rosa and Ventura, 2018].

Cosmological evolution

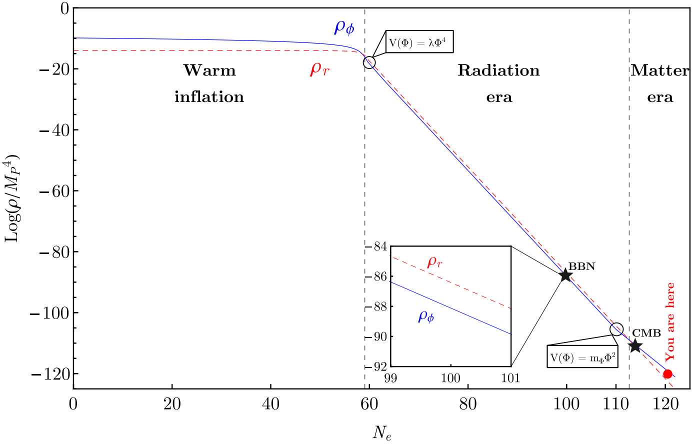

Figure 2: Cosmological evolution of the inflaton (solid blue line) and radiation (dashed red line) energy densities for a representative choice of parameters. The vertical dashed black lines mark the inflaton-radiation equality times at the end of inflation and of the radiation era. Check details Fig. 1 of [Rosa and Ventura, 2018].

Observables

- → Inflationary constraints;
- → CDM isocurvature perturbations;
- → Inflaton mass;
- → Extra relativistic degrees of freedom during BBN but not during recombination;

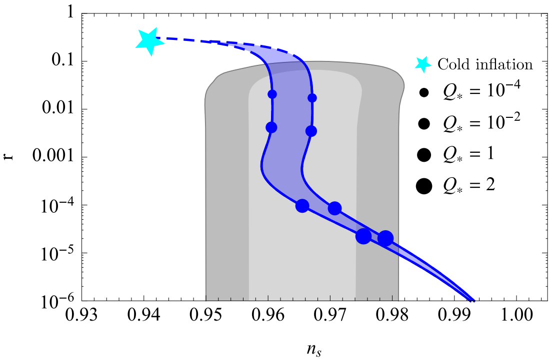

Figure 3: Observables for the quartic model. The star marks the $\lambda\phi^4$ in cold inflation ($Q_* = 0$). The Planck 2015 68% and 95% C.L. contours are shown in gray. Modified from [Bastero-Gil et al., 2016].

CDM isocurvature perturbations

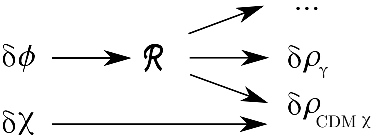

Figure 4: Adiabatic and isocurvature perturbations generated during inflation.

$\beta_{\mathrm{Iso}}^{\mathrm{Planck}} < 2 \times 10^{-3}$ [Akrami et al., 2018]

$\beta_{\mathrm{Iso}} = [3, 4] \times 10^{-4}$,

For Figs. 1 and 2 ,
$\beta_{\mathrm{Iso}} = 3.15 \times 10^{-4}$.

Inflaton mass

Determined from the correct dark matter abundance today, $\Omega_{\mathrm{DM}} \approx 0.25$ [Aghanim et al., 2018]

$$m_\phi = 10^{-4} - 10^{-1}\ \text{eV} \quad , \tag{6}$$

For Figs. 1 and 2 , $m_\phi = 2.7 \times 10^{-3}$ eV. Due to this mass, the inflaton behaves as dark radiation during BBN.

Extra relativistic DOF (Dark radiation)

BSM radiation affects the synthesis of light elements (BBN), so that ΔN_{eff} is constrained [Cyburt et al., 2016]

$$\Delta N_{\text{eff}} < 0.20 \quad , \tag{7}$$

For Figs. 1 and 2, $\Delta N_{\text{eff}} = 0.13$.

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Conclusions

- → Dissipation modifies the inflationary dynamics. It maintains a non-negligible ρ_r during inflation and causes a smooth transition to a radiation-dominated era;
- → The model's symmetries (imposed for inflationary consistency) combined with the particular dynamics of warm inflation naturally lead to inflaton dark matter;
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