Higgs-boson induced reheating and ultraviolet freeze-in dark matter

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University of Warsaw

based on: A. Ahmed, B. Grządkowski, AS 2111.06065 and 2206.XXXXX

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- The relevance of the reheating dynamics is typically ignored with a minimal assumption, such as instantaneous reheating.
- Even in the case of non-instantaneous reheating models, it is usually assumed that the inflaton decay rate, Γ_ϕ, is constant.
- However, this widely used assumption of constant can be violated in generic models of perturbative reheating, e.g., when the inflaton has a non-trivial potential.
- The understanding of the reheating era is essential for the dark matter sector, especially in the context of the freeze-in DM production.

Reheating dynamics

The dynamics of the early Universe is captured by the following time-averaged Boltzmann equations for the inflaton field and the SM radiation $\mathcal{R}$

$$\dot{\rho}_\phi + 3(1+w)H\rho_\phi = -\Gamma_\phi \rho_\phi,$$
$$\dot{\rho}_\mathcal{R} + 4H\rho_\mathcal{R} = +\Gamma_\phi \rho_\phi,$$

where the Hubble rate is given by

$$H^2 = \frac{1}{3M_{pl}^2}\left(\rho_\phi + \rho_\mathcal{R}\right),$$

whereas the time-dependence of the averaged inflaton decay width can be parametrized as

$$\boxed{\Gamma_\phi = \Gamma_\phi^e \left(\frac{a_e}{a}\right)^\beta}.$$

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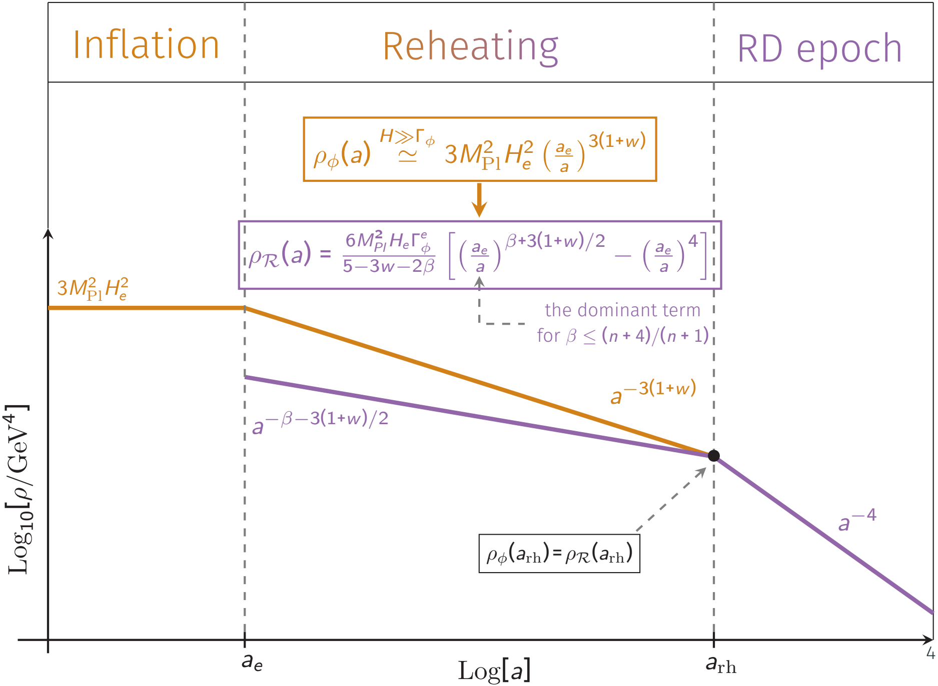
initial value of a scale factor

constant parameter


Inflation
Reheating
RD epoch
$\rho_\phi(a) \overset{H\gg\Gamma_\phi}{\simeq} 3M_{\rm Pl}^2 H_e^2 \left(\frac{a_e}{a}\right)^{3(1+w)}$
$\rho_{\mathcal{R}}(a) = \frac{6M_{Pl}^2 H_e \Gamma_\phi^e}{5-3w-2\beta}\left[\left(\frac{a_e}{a}\right)^{\beta+3(1+w)/2} - \left(\frac{a_e}{a}\right)^4\right]$
$3M_{\rm Pl}^2 H_e^2$
the dominant term
for $\beta \leq (n+4)/(n+1)$
$a^{-3(1+w)}$
$a^{-\beta-3(1+w)/2}$
a^{-4}
$\rho_\phi(a_{\rm rh}) = \rho_{\mathcal{R}}(a_{\rm rh})$
$\mathrm{Log}_{10}[\rho/\mathrm{GeV}^4]$
a_e
$\mathrm{Log}[a]$
$a_{\rm rh}$
4

Example model

As an illustration, we consider the α-attractor T-model:

$$V(\phi) = \Lambda^4 \tanh^{2n}\left(\frac{|\phi|}{\sqrt{6\alpha}M_{\rm Pl}}\right)$$

R. Kallosh et al. , arXiv:1306.5220
R. Kallosh et al. , arXiv:1311.0472

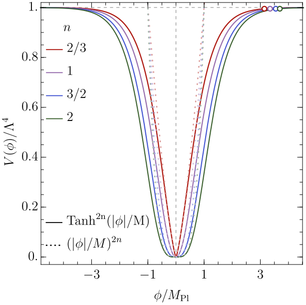
$$\simeq \begin{cases} \Lambda^4 & |\phi| \gg M_{\rm Pl} \\ \boxed{\Lambda^4 \left|\frac{\phi}{M_{\rm Pl}}\right|^{2n}} & |\phi| \ll M_{\rm Pl} \end{cases},$$

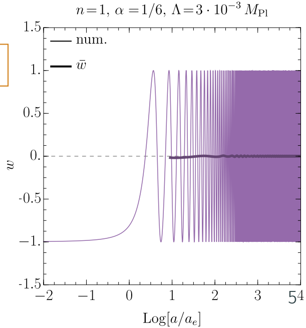
$\alpha = 1/6,\ \Lambda = 3\cdot 10^{-3}\,\mathrm{M_{Pl}}$

where $n > 0$, $\sqrt{6\alpha} \lesssim 10$, and $\Lambda \lesssim 1.6\times 10^{16}$ GeV.

N. Aghanim et al.,arXiv:1807.06209

$w = \frac{n-1}{n+1}$





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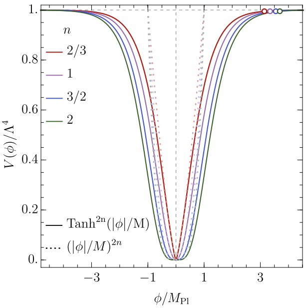
$w = \frac{n-1}{n+1}$

- $n = 2/3$ → $-1/5$
- $n = 1$ → 0 — matter-like e.o.s
- $n = 3/2$ → $1/5$
- $n = 2$ → $1/3$ — radiation-like e.o.s



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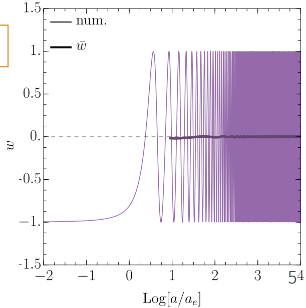

Reheating

We assume that the inflaton couples to the SM sector through the Higgs portal

$$\boxed{g_{h\phi} M_{\rm Pl} \phi(a) |\mathbf{h}|^2 = g_{h\phi} M_{\rm Pl} \varphi(a) \mathcal{P}(a) |\mathbf{h}|^2}$$

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rapidly-oscillating function

slowly-varying envelope

Y. Shtanov, et al., arXiv:9407247

$$\frac{3}{4}\sqrt{6\alpha}\left(\frac{\Lambda^2}{\phi M_{\rm Pl}}\right)^2\left(\frac{\phi}{M}\right) < g_{h\phi} < \frac{\Lambda^2}{\phi M_{\rm Pl}}$$

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Reheating

The energy gain of the radiation sector per volume and time is

$$\frac{1}{V}\frac{dE_g}{dt} = \rho_\phi \Gamma_\phi$$

with

$$\frac{1}{V}\frac{dE_g}{dt} = \frac{\varphi^2(t)}{8\pi} \sum_{i=0}^{3} \sum_{k=1}^{\infty} k\omega |\mathcal{P}_k|^2 \times \sqrt{1 - \left(\frac{2m_{h_i}}{k\omega}\right)^2} |\mathcal{M}_{0\to h_i h_i}(k)|^2$$

Inflaton-induced Higgs mass

$$m_{h_i}^2 = g_{h\phi} M_{\rm Pl} \varphi \begin{cases} |\mathcal{P}|\,, & \mathcal{P}(a) > 0,\ i = 0, 1, 2, 3 \\ 2|\mathcal{P}|\,, & \mathcal{P}(a) < 0,\ i = 0 \\ \infty\,, & \mathcal{P}(t) < 0,\ i = 1, 2, 3 \end{cases}$$

Due to the inflaton oscillations, the Higgs field goes through rapid phase transitions with ϕ-dependent vev:

$$v_h = \begin{cases} 0\,, & \mathcal{P}(a) > 0 \\ \sqrt{\frac{|m_{h_0}^2|}{2\lambda_h}}\,, & \mathcal{P}(a) < 0 \end{cases}$$

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K. Ichikawa et al., arXiv:0807.3988

$$\frac{1}{V}\frac{dE_g}{dt} = \rho_\phi \Gamma_\phi$$

with $\mathcal{P} = \sum_k \mathcal{P}_k e^{-ik\omega t}$

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Reheating

The inflaton decay rate can be written as

$$\Gamma_\phi = \frac{g_{h\phi}^2}{32\pi}\frac{M_{\rm Pl}^2}{m_\phi(a)}\gamma_h(a),$$

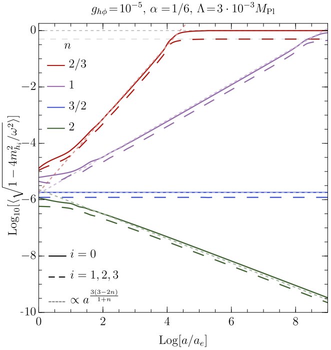
$$\boxed{\gamma_h(a) \simeq \sum_{i=0}^{3}\sum_{k=1}^{\infty} k|\mathcal{P}_k|^2\left\langle\sqrt{1-\left(\frac{2m_{h_i}(a)}{k\omega(a)}\right)^2}\right\rangle}$$

It turns out that

$$\gamma_h \propto \begin{cases} a^0\,, & m_{h_i}=0 \\ a^{\frac{3(3-2n)}{1+n}}\,, & m_{h_i}\neq 0 \end{cases}$$

which, in turn, implies

$$\Gamma_\phi \propto \begin{cases} a^{\frac{3(n-1)}{n+1}}\,, & m_{h_i}=0 \\ a^{\frac{6-3n}{1+n}}\,, & m_{h_i}\neq 0 \end{cases}$$



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$$\Gamma_\phi = \frac{g_{h\phi}^2}{32\pi}\frac{M_{\rm Pl}^2}{m_\phi(a)}\gamma_h(a),$$

effective mass

$m_\phi(a) = V_{,\phi\phi}|_{\phi=\varphi}$

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$\omega \propto m_\phi$

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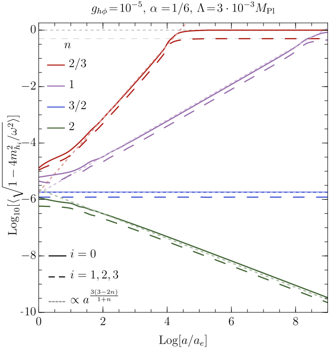
$-\beta$



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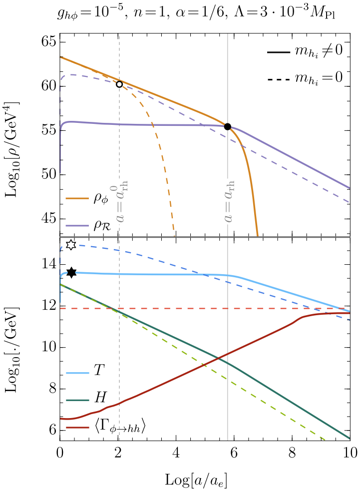
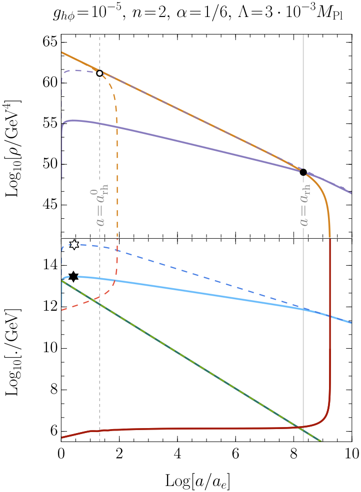
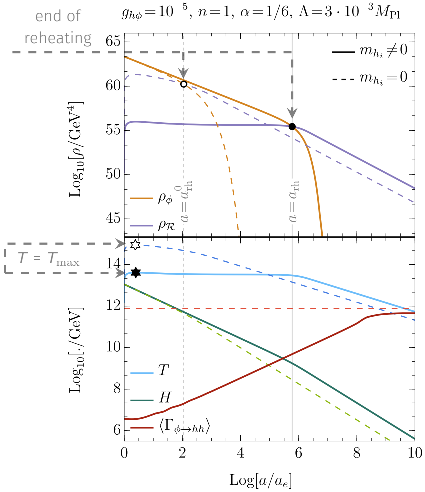


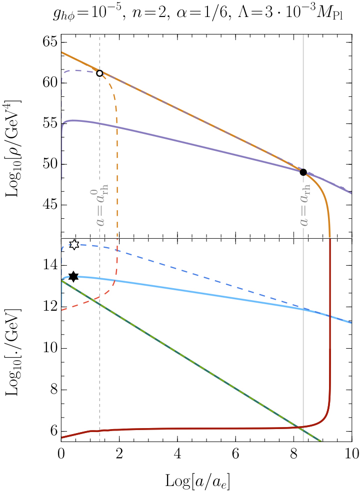
$g_{h\phi}=10^{-5},\ n=1,\ \alpha=1/6,\ \Lambda=3\cdot10^{-3}M_{\rm Pl}$
$m_{h_i}\neq0$
$m_{h_i}=0$
ρ_ϕ
$\rho_{\mathcal{R}}$
$a=a^0_{\rm rh}$
$a=a_{\rm rh}$
$\mathrm{Log}_{10}[\rho/\mathrm{GeV}^4]$
T
H
$\langle\Gamma_{\phi\to hh}\rangle$
$\mathrm{Log}_{10}[\cdot/\mathrm{GeV}]$
$\mathrm{Log}[a/a_e]$



$g_{h\phi}=10^{-5},\ n=2,\ \alpha=1/6,\ \Lambda=3\cdot10^{-3}M_{\rm Pl}$
$a=a^0_{\rm rh}$
$a=a_{\rm rh}$
$\mathrm{Log}_{10}[\rho/\mathrm{GeV}^4]$
$\mathrm{Log}_{10}[\cdot/\mathrm{GeV}]$
$\mathrm{Log}[a/a_e]$

Reheating





	$n=1$	$n=2$
$m_{h_i}=0$	$\beta=0,\ \rho_{\mathcal{R}}\propto a^{-3/2}$	$\beta=-1,\ \rho_{\mathcal{R}}\propto a^{-1}$
$m_{h_i}\neq0$	$\beta=-\frac{3}{2},\ \rho_{\mathcal{R}}\propto a^{0}$	$\beta=0,\ \rho_{\mathcal{R}}\propto a^{-2}$

Let there be darkness

Let us assume that the dark sector is composed of spin-1, massive particles X_μ, charged under a dark, abelian $U(1)_X$ symmetry, with the following Lagrangian density

$$\mathcal{L}_{\rm DM} = -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} + \frac{1}{2} m_X^2 X_\mu X^\mu + \mathcal{L}_{\rm int}.$$

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$$\mathcal{L}_{\rm int} \supset \frac{h^{\mu\nu}}{M_{\rm Pl}}\left(T_\phi^{\mu\nu} + T_X^{\mu\nu} + T_{\rm SM}^{\mu\nu}\right) + \frac{\mathcal{C}_X^{\mathbf{h}}}{2}\frac{m_X^2}{M_{\rm Pl}^2}|\mathbf{h}|^2 X_\mu X^\mu$$

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$$\mathcal{C}_X^{\mathbf{h}} \lesssim \min\{\left(\frac{M_{\rm Pl}}{m_X}\right)^2, \left(\frac{M_{\rm Pl}}{T_{\rm max}}\right)^2\}$$

M. Garny et al., arXiv:1511.03278
Y. Tang et al., arXiv:1708.05138
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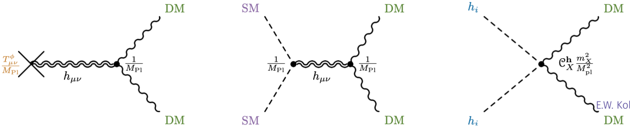

E.W. Kolb et al., arXiv:1708.04293

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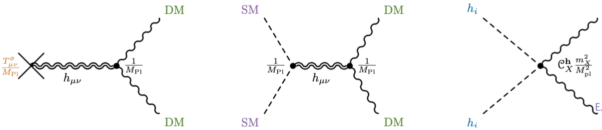

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The evolution of the dark sector is governed by the following equation:

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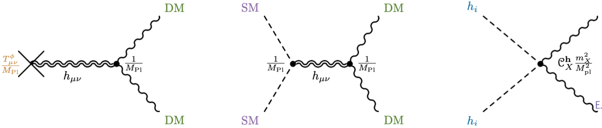

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$$N_X \equiv n_X a^3$$

Gravitational production

The source terms are

$$\mathcal{S}_\phi = \frac{1}{8\pi}\left(\frac{\rho_\phi}{M_{\rm Pl}^2}\right)^2 \sum_{k=1}^{\infty}|\mathcal{P}_k^{2n}|^2\left[\left(1-\frac{2m_X^2}{(k\omega)^2}\right)^2 + \frac{8m_X^4}{(k\omega)^4}\right] \times \sqrt{1-\frac{4m_X^2}{(k\omega)^2}}$$

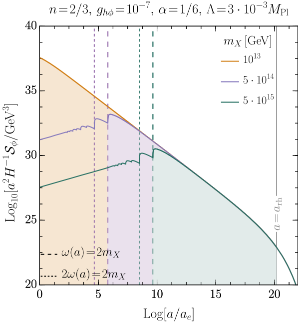
$$\mathcal{S}_{\rm SM} = n_0\langle\sigma|v|\rangle_0 + n_{1/2}\langle\sigma|v|\rangle_{1/2} + n_1\langle\sigma|v|\rangle_1$$

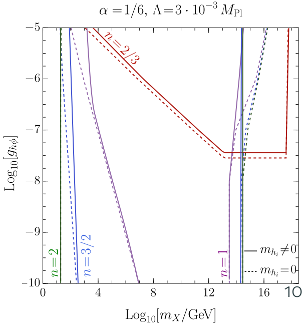
$$n_1\langle\sigma|v|\rangle_1 \simeq \begin{cases} \frac{13}{20\pi^5} T^8/M_{Pl}^4\,, & m_X \ll T\,, \\ \frac{1}{16\pi^4}\frac{m_X^5 T^3}{M_{\rm Pl}^4} e^{-2m_X/T}\,, & m_X \gg T \end{cases}$$

The DM relic abundance can be calculated as

$$\Omega_X^{\rm grav} h^2 \simeq \frac{m_X}{\rho_c}\frac{N^{\rm grav}(a_{\rm rh})}{a_{\rm rh}^3}\frac{s_0}{s(a_{\rm rh})}h^2\,.$$

Successful DM model has to predict the correct amount of DM i.e., $\Omega_X^{\rm grav} h^2 = \Omega_X^{\rm (obs)} h^2$.





Gravitational production

The source terms are

time dependent

$$\mathcal{S}_\phi = \frac{1}{8\pi}\left(\frac{\rho_\phi}{M_{\rm Pl}^2}\right)^2 \sum_{k=1}^{\infty} |\mathcal{P}_k^{2n}|^2 \left[\left(1-\frac{2m_X^2}{(k\omega)^2}\right)^2 + \frac{8m_X^4}{(k\omega)^4}\right] \times \sqrt{1-\frac{4m_X^2}{(k\omega)^2}}$$

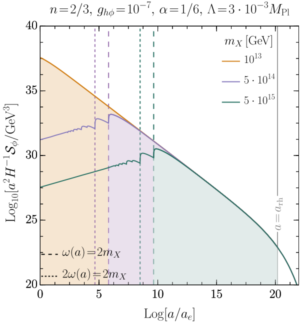
$$\mathcal{S}_{\rm SM} = n_0\langle\sigma|v|\rangle_0 + n_{1/2}\langle\sigma|v|\rangle_{1/2} + n_1\langle\sigma|v|\rangle_1$$

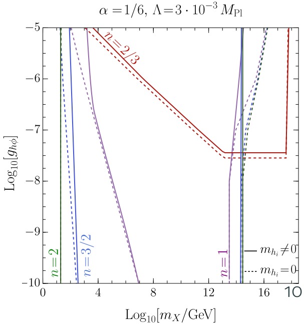
$$n_1\langle\sigma|v|\rangle_1 \simeq \begin{cases} \frac{13}{20\pi^5}\, T^8/M_{Pl}^4\,, & m_X \ll T\,, \\ \frac{1}{16\pi^4}\frac{m_X^5\, T^3}{M_{\rm Pl}^4} e^{-2m_X/T}\,, & m_X \gg T \end{cases}$$

The DM relic abundance can be calculated as

$$\Omega_X^{\rm grav} h^2 \simeq \frac{m_X}{\rho_c}\frac{N^{\rm grav}(a_{\rm rh})}{a_{\rm rh}^3}\frac{s_0}{s(a_{\rm rh})}h^2\,.$$

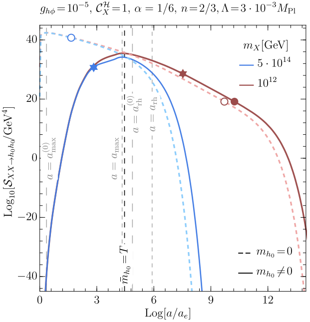
Successful DM model has to predict the correct amount of DM i.e., $\Omega_X^{\rm grav} h^2 = \Omega_X^{(\rm obs)} h^2$.

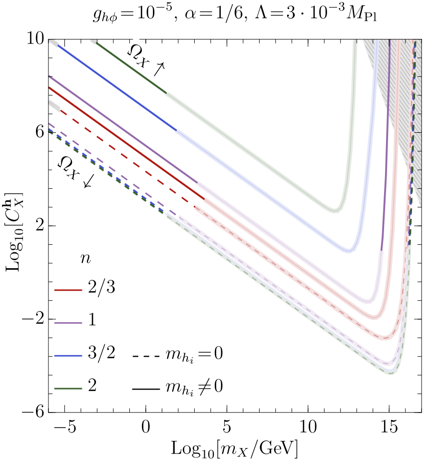




DM production through the contact operator

The DM freeze-in production is very sensitive to the dynamics of reheating.





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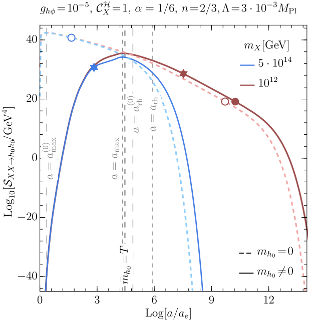
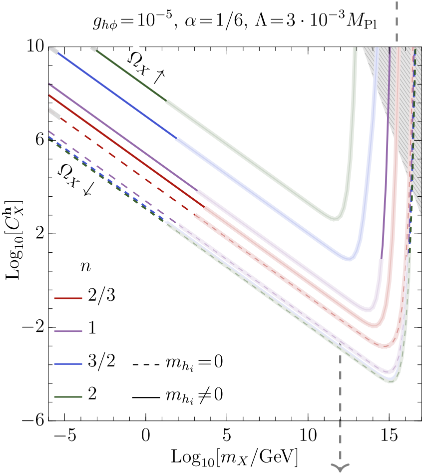


$\mathcal{C}_X^{\mathbf{h}} > (M_{\rm Pl}/m_X)^2$



Gravitational Overproduction

Summary

We have demonstrated that the non-standard $(n \neq 1)$ cosmologies and the kinematical suppression of radiation production significantly affect the thermal bath evolution and the DM production.

- In particular, we have shown that the duration of reheating and the evolution of the radiation energy density, $\rho_{\mathcal{R}}$, are sensitive to the inflaton potential shape.

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- Moreover, we have discussed the role of kinematical suppression in the reheating dynamics. We have demonstrated that the non-zero mass of the Higgs boson leads to the elongation of the reheating period, changes the $\rho_{\mathcal{R}}(a)$ and $T(a)$ evolution, and conduces to the decrease of $T_{\max}$.

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- Finally, we have pointed out that the DM freeze-in production is very sensitive to the reheating dynamics.

Thank you for your attention!

Back-up slides

EoM for the inflaton

The equation of motion (EoM) for the ϕ field is:

$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi}(\phi) = 0, \qquad H^2 = \rho_\phi/(3M_{\rm Pl}).$$

We can distinguish two types of solutions to the ϕ's EoM:

1. Slow-roll $\ddot{\phi} \simeq 0$, $\epsilon_V, \eta_V \ll 1$

$\epsilon_V = M_{\rm pl}/2(V_{,\phi}/V)^2$

$\eta_V = M_{\rm pl}^2(V_{,\phi\phi}/V)^2$

$$\phi(t) \simeq const.$$

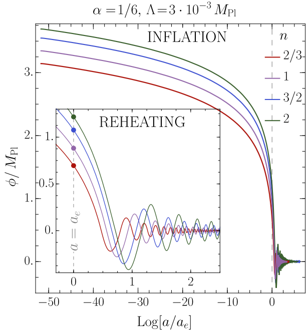
2. Oscillations

$$\phi(t) = \varphi(t) \cdot \mathcal{P}(t)$$

Slowly-varying Envelope function $\langle\rho_\phi\rangle = V(\varphi)$

Rapidly-oscillating quasi-periodic function

Y. Shtanov et al.,arXiv:9407247



value of the scale factor at the end of inflation ($\epsilon_V = 1$)

Analytical solutions to the inflaton EoM after the end of inflation

negative ($n > 0$)

The EoM for the envelope function φ is given by:

$$\dot{\varphi} = -\frac{3}{n+1} H\varphi, \quad \Rightarrow \quad \varphi(a) = \varphi(a_e)\left(\frac{a}{a_e}\right)^{-\frac{3}{n+1}},$$

while $\mathcal{P}$ satisfies the following approximate equation:

M. A. G. Garcia et al.,arXiv:2004.08404
M. A. G. Garcia et al.,arXiv:2012.10756

$$\dot{\mathcal{P}} \simeq \pm\sqrt{\frac{m_\phi^2(1-|\mathcal{P}|^{2n})}{n(2n-1)}}, \qquad m_\phi^2 = 2n(2n-1)\Lambda^2\left(\frac{\Lambda}{\sqrt{6\alpha}M_{\rm Pl}}\right)^2\left(\frac{\rho_\phi}{\Lambda^4}\right)^{\frac{n-1}{n}}.$$

The solution to the above equation can be written as

Inverse of the regularized incomplete beta function

$$\mathcal{P}(t) = \left[I_z^{-1}\left(\frac{1}{2n},\frac{1}{2}\right)\right]^{\frac{1}{2n}}, \quad z = 1 - \frac{4}{T}(t-t_0),$$

where T denotes the period of the oscillations:

$$T = \frac{\sqrt{16\pi n(2n-1)}}{m_\phi}\frac{\Gamma\left(1+\frac{1}{2n}\right)}{\Gamma\left(\frac{1}{2}+\frac{1}{2n}\right)}.$$

depend on time for $n \neq 1$

Particles production in a classical inflaton background

The inflaton field can be regarded as a homogeneous, classical field that coherently oscillates in time.
For the interactions linear in $\phi = \varphi \cdot \mathcal{P}$, the energy gain per unit volume per unit time due to the pair production of f particles with mass m can be calculated as

$$\frac{1}{V}\frac{dE_g}{dt} = \frac{\varphi^2(t)}{8\pi\,\delta_f}\sum_{k=1}^{\infty} k\omega|\mathcal{P}_k|^2\left|\mathcal{M}_{0\to f}(k)\right|^2 \mathrm{Re}\left[\sqrt{1-\frac{4m^2}{k^2\omega^2}}\right],$$

where

$$\mathcal{P}(t) = \sum_{k=-\infty}^{\infty}\mathcal{P}_k e^{-ik\omega t}, \qquad \mathcal{P}_k = \frac{1}{\mathcal{T}(t_0)}\int_{t_0}^{t_0+\mathcal{T}(t_0)} dt\,\mathcal{P}(t)e^{ik\omega t}.$$

The matrix element $\mathcal{M}_{0\to f}$ accounts for the quantum process of two particles production out of the vacuum.

Particles production in a classical inflaton background

For the interactions proportional to the $\phi = \varphi \cdot \mathcal{P}$ term, the lowest-order non-vanishing S-matrix element takes the form

$$\mathcal{S}_{if}^{(1)} = \sum_k \mathcal{P}_k \langle f| \int d^4 x \varphi(t) e^{-ik\omega t} \mathcal{L}_{\text{int}}(x) |i\rangle$$

where

$$|i\rangle \equiv |0\rangle, \qquad |f\rangle \equiv \hat{a}_f^\dagger \hat{a}_f^\dagger |0\rangle .$$

If the envelope $\varphi(t)$ varies on the time-scale much longer than the time-scale relevant for processes of particle creation, the S-matrix element can be written as

$$S_{if}^{(1)} = i\varphi(t) \sum_k \mathcal{P}_k \mathcal{M}_{0\to f}(k) \times (2\pi)^4 \delta(k\omega - 2E_f)\delta^3(p_{f_1} + p_{f_2}).$$