Higgs-boson reheating and frozen-in DM

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based on:

- Aqeel Ahmed, BG, Anna Socha, Phys.Lett.B 831 (2022) 137201, e-Print: 2111.06065
- Aqeel Ahmed, BG, Anna Socha, e-Print: 2207.11218

Workshop on the Standard Model and Beyond, September 6, 2022, Corfu

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Motivations

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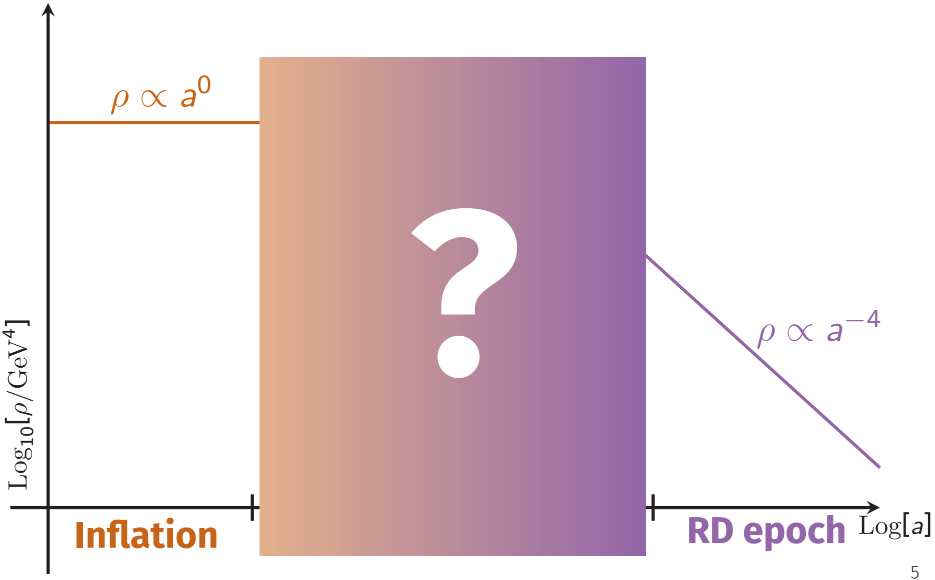
- It is usually assumed that the inflaton decay rate, Γ_ϕ, is constant.
- Hereafter we are going to discuss relations between inflation and reheating dynamics focusing on possible interactions between the Higgs boson and inflaton.
- Dynamics of reheating influences the dark matter sector, especially in the context of the freeze-in DM production.

Non-instantaneous reheating



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The α-attractor T-model

$$\mathcal{L}_\phi = \frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - V(\phi)$$

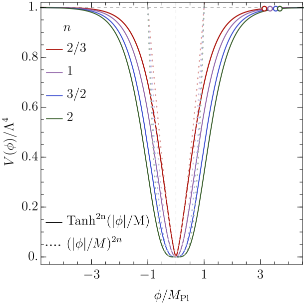
$$V(\phi) = \Lambda^4 \tanh^{2n}\left(\frac{|\phi|}{\sqrt{6\alpha}\,M_{\rm Pl}}\right)$$

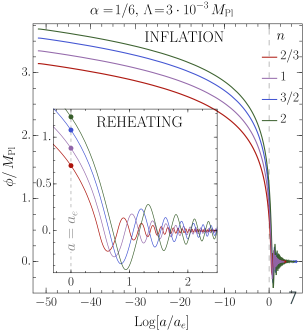
$$\simeq \begin{cases} \Lambda^4 & |\phi| \gg M_{\rm Pl} \\ \boxed{\Lambda^4 \left|\dfrac{\phi}{M_{\rm Pl}}\right|^{2n}} & |\phi| \ll M_{\rm Pl} \end{cases},$$

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

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

$H \equiv \dot{a}/a$ is the Hubble rate.





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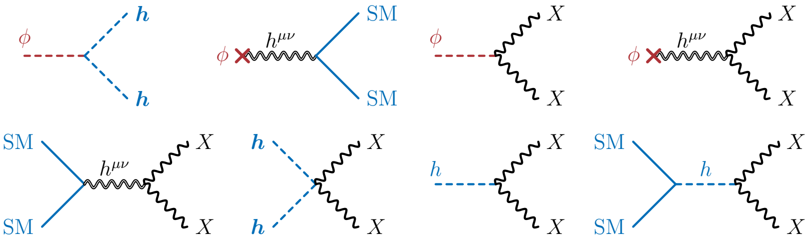
Interactions

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

$$\mathcal{L}_{\rm int} = -\left\{\boxed{g_{h\phi}M_{\rm Pl}\,\phi|\mathsf{h}|^2} + \frac{h^{\mu\nu}}{M_{\rm Pl}}\left[T^{\phi}_{\mu\nu} + T^{\rm DM}_{\mu\nu} + T^{\rm SM}_{\mu\nu}\right]\right.$$
$$\left. + \frac{\mathcal{C}_X^{\phi}\,m_X^2}{2M_{\rm Pl}}\phi X_\mu X^\mu + \frac{\mathcal{C}_X^{\mathsf{h}}\,m_X^2}{2M_{\rm Pl}^2}|\mathsf{h}|^2 X_\mu X^\mu\right\},$$



Limits on $g_{h\phi}$

- Perturbativity ($h_i\phi \to h_i\phi$)

$$g_{h\phi} \lesssim \left(\frac{\Lambda^2}{\phi M_{\rm Pl}}\right),$$

- The inflationary dynamics is dominated by the cosmological constant term $\sim \Lambda^4$ therefore

$$g_{h\phi} \lesssim \sqrt{\lambda_h}\left(\frac{\Lambda^2}{\phi M_{\rm Pl}}\right),$$

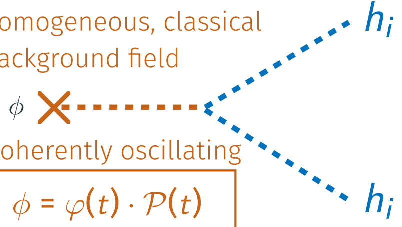
- If $m_{h_0} > 3H_I/2$ the Higgs field fluctuations during inflation are strongly suppressed ensuring stability (J. R. Espinosa, et al. , [arXiv:1505.04825]), therefore

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

$$\boxed{6\cdot 10^{-11} \lesssim g_{h\phi} \lesssim 3\cdot 10^{-6}}$$

The Higgs portal

$$\mathcal{L}_{int} = g_{h\phi} M_{\rm Pl}\, \phi |\mathrm{h}|^2$$



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

rapidly-oscillating

slowly-varying envelope, $\rho_\phi \equiv V(\varphi)$

⇨ **Reheating** i.e., energy transfer between the inflaton and the SM sector

$$\frac{1}{V}\frac{dE_g}{dt} \equiv \rho_\phi \Gamma_\phi = g_{h\phi}^2 M_{\rm Pl}^2 \frac{\varphi^2(t)}{8\pi} \sum_{i=0}^{3} \sum_{k=1}^{\infty} k\omega |\mathcal{P}_k|^2 \sqrt{1 - \left(\frac{2m_{h_i}}{k\omega}\right)^2}\,, \quad \mathcal{P}(t) = \sum_{k=-\infty}^{\infty} \mathcal{P}_k e^{-ik\omega t}$$

⇨ **Higgs mass** induced by the oscillating inflaton background

$$m_{h_0}^2 = g_{h\phi} M_{\rm Pl} \varphi \begin{cases} |\mathcal{P}|\,, & \mathcal{P}(t) > 0 \\ 2|\mathcal{P}|\,, & \mathcal{P}(t) < 0 \end{cases} \qquad v_h = \begin{cases} 0\,, & \mathcal{P}(t) > 0 \\ \sqrt{|m_{h_0}^2|/(2\lambda_h)}\,, & \mathcal{P}(t) < 0 \end{cases}$$

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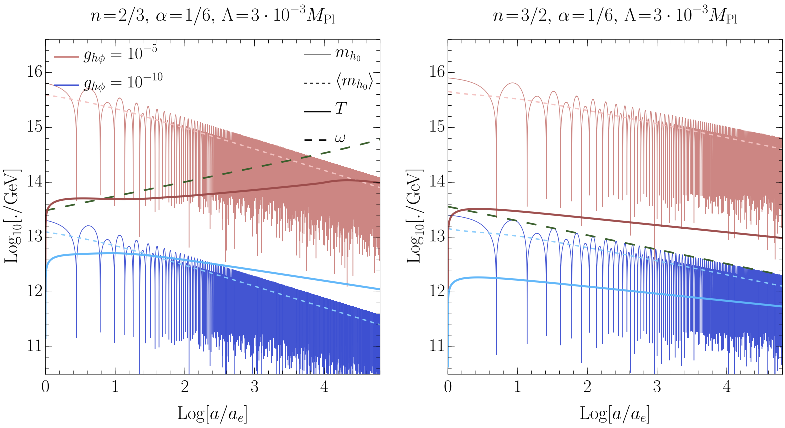


Kinematic suppression

The inflaton decay rate can be written as

effective mass

$$m_\phi^2(a) = V_{,\phi\phi}|_{\phi=\varphi}$$

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

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

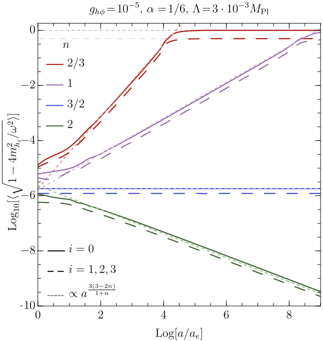
$$\omega \propto m_\phi$$

It turns out that

$$\gamma_h \propto a^{\frac{3(3-2n)}{1+n}}$$

which implies

$$\langle \Gamma_\phi \rangle \propto a^{\frac{6-3n}{1+n}} \equiv a^{-\beta}$$



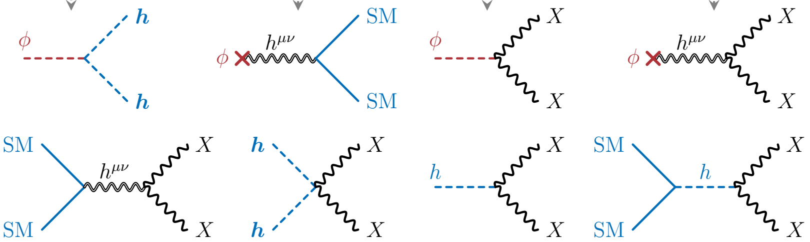
The time-averaged Boltzmann equations

$$\dot{\rho}_\phi + \frac{6n}{n+1} H\rho_\phi = -\boxed{\langle \Gamma_\phi \rangle}\rho_\phi$$

$$\dot{\rho}_{\rm SM} + 4H\rho_{\rm SM} = \langle \Gamma_{\phi\to{\rm SM\,SM}}\rangle \rho_\phi - 2\langle E_X\rangle \mathcal{S}_{\rm SM} - \langle E_{h_0}\rangle \mathcal{D}_{h_0}$$

$$\dot{n}_X + 3Hn_X = \mathcal{D}_\phi + \mathcal{S}_\phi + \mathcal{S}_{\rm SM} + \mathcal{D}_{h_0}$$

with the Hubble rate $H^2 = \frac{1}{3M_{\rm Pl}^2}\left(\rho_\phi + \rho_{\rm SM} + \rho_X\right)$



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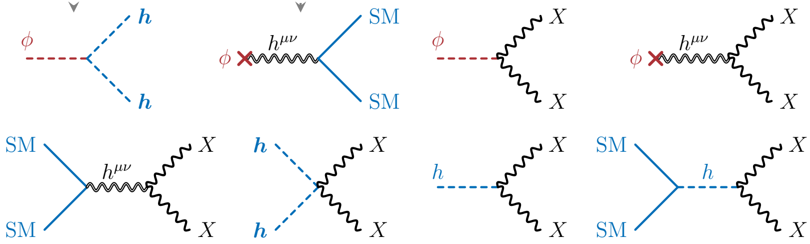

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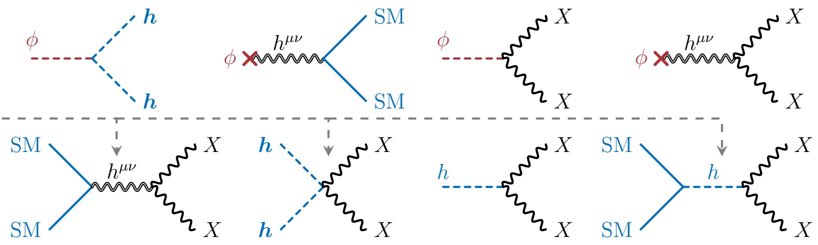

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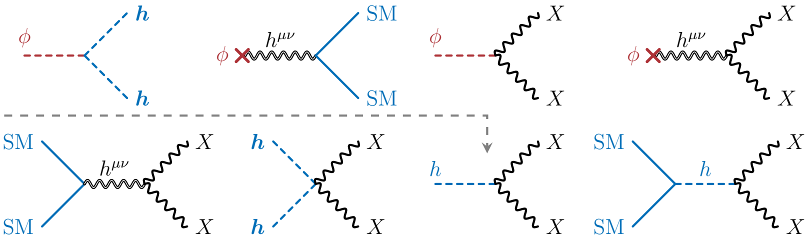

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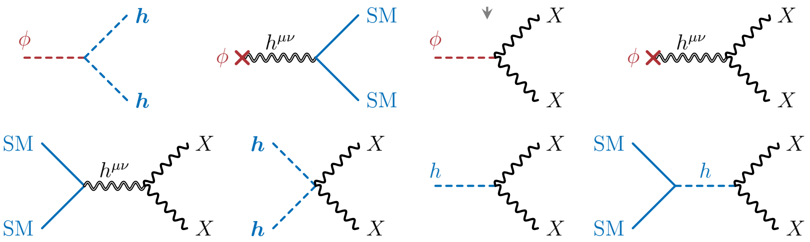

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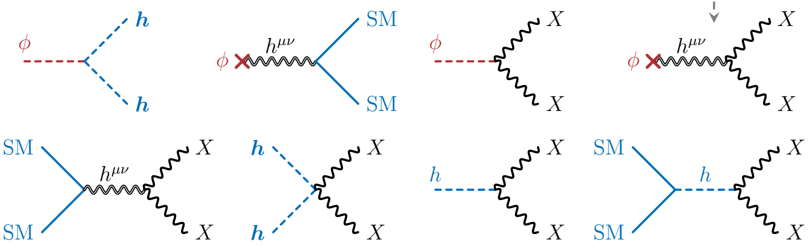

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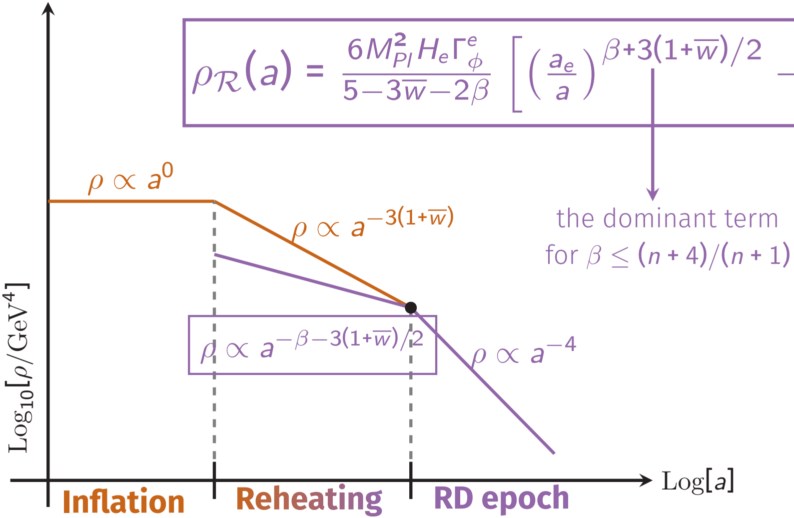
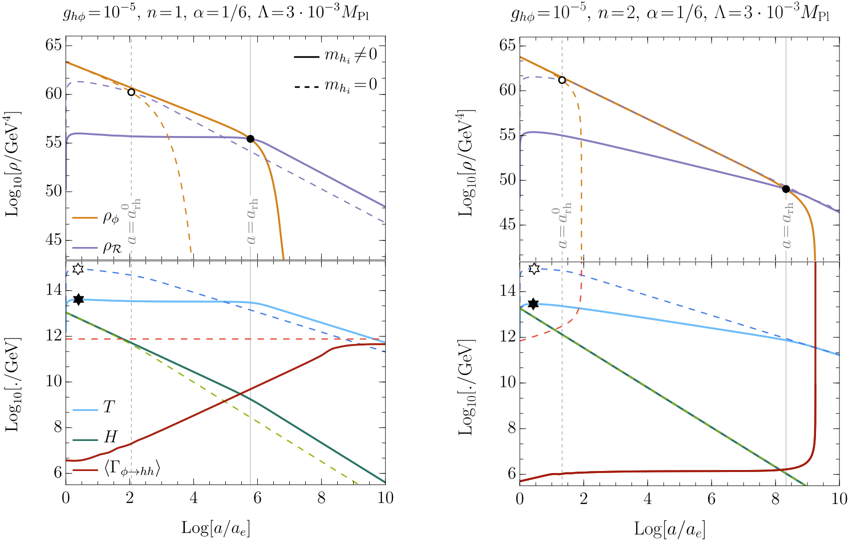
Non-instantaneous reheating

$$\boxed{\rho_\phi(a) \overset{H\gg\Gamma_\phi}{\simeq} 3M_{\rm Pl}^2 H_e^2 \left(\frac{a_e}{a}\right)^{3(1+\overline{w})}}$$

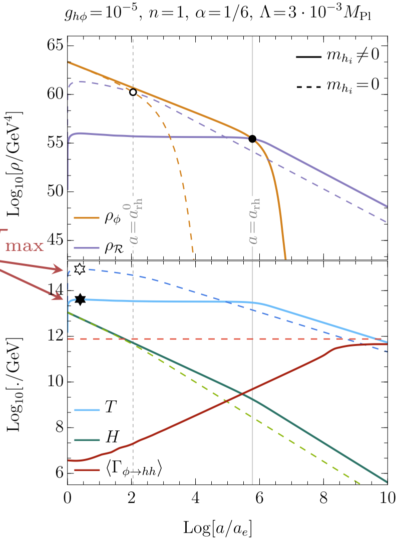
$$\boxed{\rho_{\mathcal{R}}(a) = \frac{6M_{Pl}^2 H_e \Gamma_\phi^e}{5-3\overline{w}-2\beta}\left[\left(\frac{a_e}{a}\right)^{\beta+3(1+\overline{w})/2} - \left(\frac{a_e}{a}\right)^4\right]}$$

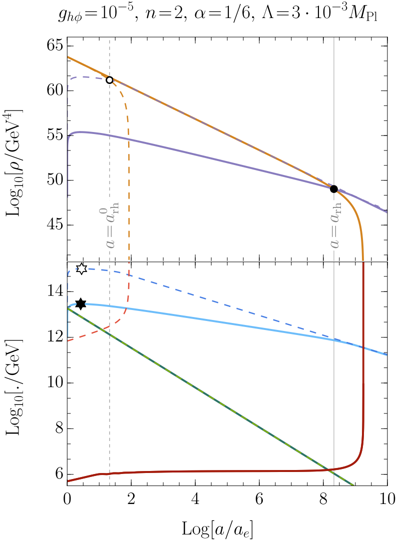




$g_{h\phi}=10^{-5}$, $n=1$, $\alpha=1/6$, $\Lambda=3\cdot10^{-3}M_{\rm Pl}$
$g_{h\phi}=10^{-5}$, $n=2$, $\alpha=1/6$, $\Lambda=3\cdot10^{-3}M_{\rm Pl}$
$m_{h_i}\neq0$
$m_{h_i}=0$
$\mathrm{Log}_{10}[\rho/\mathrm{GeV}^4]$
ρ_ϕ
$\rho_{\mathcal{R}}$
$a=a_{\rm rh}^0$
$a=a_{\rm rh}$
$\mathrm{Log}_{10}[\cdot/\mathrm{GeV}]$
T
H
$\langle\Gamma_{\phi\to hh}\rangle$
$\mathrm{Log}[a/a_e]$

T = $T_{\max}$





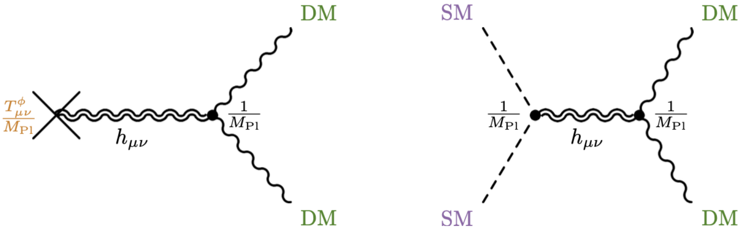
$m_{h_i} = 0$ $\quad$ $\beta = 0$, $\rho_{\mathcal{R}} \propto a^{-3/2}$ $\quad$ $\beta = -1$, $\rho_{\mathcal{R}} \propto a^{-1}$

$\boxed{m_{h_i} \neq 0}$ $\quad$ $\boxed{\beta = -\frac{3}{2},\ \rho_{\mathcal{R}} \propto a^0}$ $\quad$ $\boxed{\beta = 0,\ \rho_{\mathcal{R}} \propto a^{-2}}$

Gravitational DM production

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

$$\mathcal{L}_{\rm int} = \frac{h_{\mu\nu}}{M_{\rm Pl}} \left(T_\phi^{\mu\nu} + T_X^{\mu\nu} + T_{\rm SM}^{\mu\nu} \right)$$



Y. Mambrini et al., arXiv:2102.06214

M.R. Haque et al., arXiv:2112.14668

S. Clery et al., arXiv:2112.15214

M. Garny et al., arXiv:1511.03278

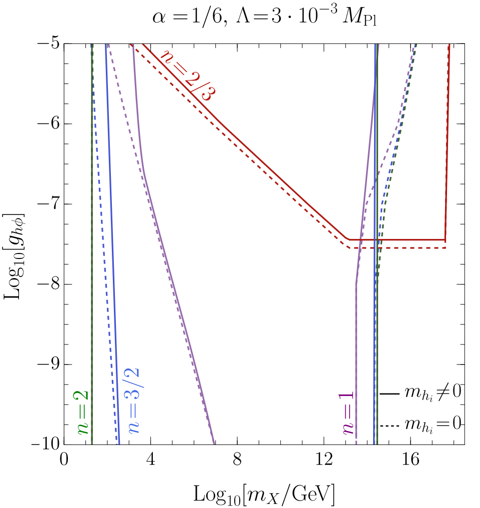
Y. Tang et al., arXiv:1708.05138

M. Garny et al., arXiv:1709.09688

Gravitational DM production

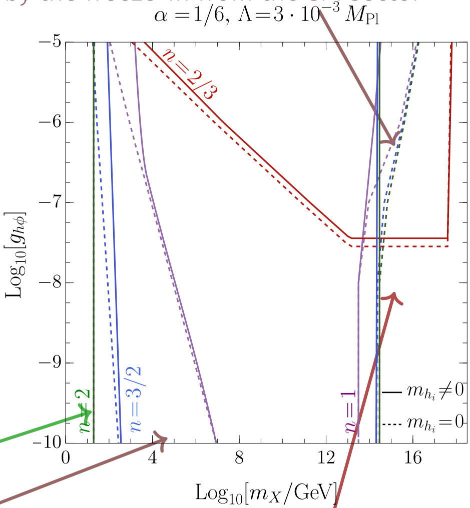
$$\Omega_X^{\mathrm{grav}} h^2 \simeq \frac{m_X}{\rho_c} \frac{N^{\mathrm{grav}}(a_{\mathrm{rh}})}{a_{\mathrm{rh}}^3} \frac{s_0}{s(a_{\mathrm{rh}})} h^2 .$$

$$\Omega_X^{\mathrm{grav}} h^2 = \Omega_X^{(\mathrm{obs})} h^2 = 0.1198 \pm 0.0012$$



Gravitational DM production

Heavy DM particles are produced
by the freeze-in from the SM sector



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

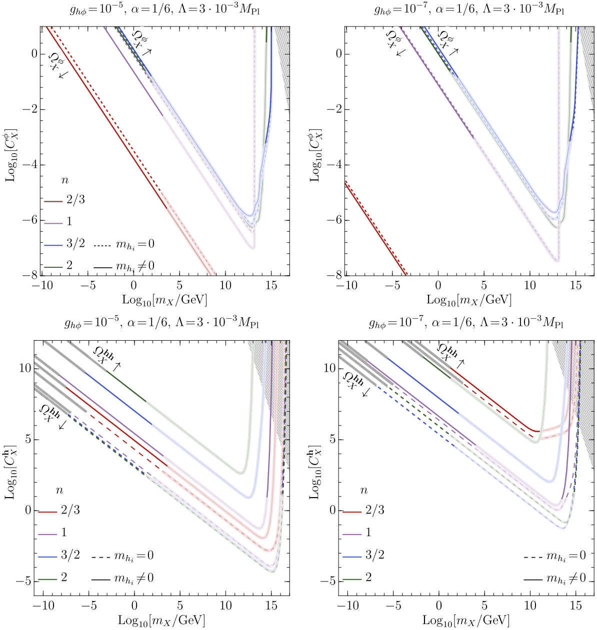
$$\Omega_X^{\rm grav} h^2 = \Omega_X^{\rm (obs)} h^2 = 0.1198 \pm 0.0012$$

For the $n=2$ case,
$\Omega_X^{\rm grav} h^2$ does not depend on $g_{h\phi}$

Light DM particles are dominantly

For the $n=2/3$ case,
$\Omega_X^{\rm grav} h^2$ does not depend on m_X

XX production



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Summary

- The α-attractor T-model potential for the inflaton field has been adopted:

$$V(\phi) = \Lambda^4 \tanh^{2n}\left(\frac{|\phi|}{\sqrt{6\alpha}M_{\rm Pl}}\right) \simeq \begin{cases} \Lambda^4 & |\phi| \gg M_{\rm Pl} \\ \boxed{\Lambda^4 \left|\dfrac{\phi}{M_{\rm Pl}}\right|^{2n}} & |\phi| \ll M_{\rm Pl} \end{cases},$$

- The reheating has been triggered by

$$\mathcal{L}_{int} = g_{h\phi} M_{\rm Pl} \phi |h|^2$$

- It has been shown that both duration of reheating and evolution of radiation energy density, $\rho_{\mathcal{R}}$, are sensitive to the shape of the inflaton potential (n).
- The role of kinematical suppression emerging from $\mathcal{L}_{int}$ has been investigated. It has been shown 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 favors reduced $T_{\rm max}$.

Summary

- It has been shown that purely gravitational perturbative production of DM is possible.

- Purely gravitation perturbative reheating needs to be investigated.

Back-up slides

Particle 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

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

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

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

Planck and BICEP/Keck limits on $N_{\rm rh}$

$$r \equiv \frac{\Delta_t^2(k)}{\Delta_s^2(k)}, \qquad\qquad n_s - 1 \equiv \frac{d\ln\Delta_s^2}{d\ln k}$$

where r is the tensor-to-scalar ratio and n_s is the scalar spectral index (tilt)

- $\Lambda \lesssim 1.4 \times 10^{16}\ \mathrm{GeV}$
- $N_{\rm rh} \lesssim \frac{4}{3(1+\bar{w})}\left[6.7 + \ln\left(\frac{\Lambda}{1\ \mathrm{GeV}}\right)\right]$

α	n	$N_{\rm rh}[n_s\!:\!1\sigma]$	$N_{\rm rh}[n_s\!:\!2\sigma]$
1/6	2/3	13.8	26.1
1/6	1	22.0	41.7
1/6	3/2	48.0	47.8
1/6	3	38.4	38.4
1	2/3	15.2	27.5
1	1	23.4	43.1
1	3/2	47.8	47.7
1	3	38.2	38.0

Planck and BICEP/Keck limits on $N_{\rm rh}$

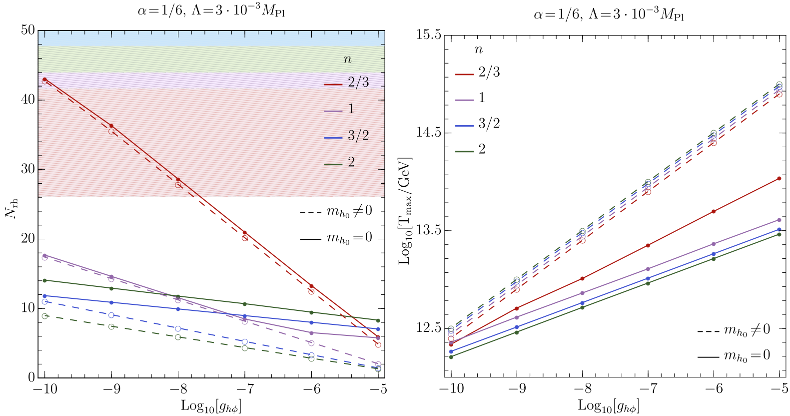

Figure 1: Left panel: Relation between reheating numbers of e-folds $N_{\rm rh}$ and the value of the inflaton-Higgs coupling $g_{h\phi}$. Right panel: Relation between the maximal temperature, $T_{\rm max}$, obtained during reheating and the value of the inflaton-Higgs coupling $g_{h\phi}$.

The α-attractor T-model

Time averaging:

$$\langle f(t)\rangle = \frac{1}{\mathcal{T}}\int_t^{t+\mathcal{T}} d\tau\ f(\tau),$$

Equation of state:

$$\bar{w} \equiv \frac{\langle p_\phi\rangle}{\langle \rho_\phi\rangle} = \frac{n-1}{n+1}$$

n	$\bar{w} \equiv \frac{\langle p_\phi\rangle}{\langle \rho_\phi\rangle}$
$\frac{2}{3}$	$-\frac{1}{5}$
1	0
$\frac{3}{2}$	$\frac{1}{5}$
2	$\frac{1}{3}$