Inflaton Dark Matter

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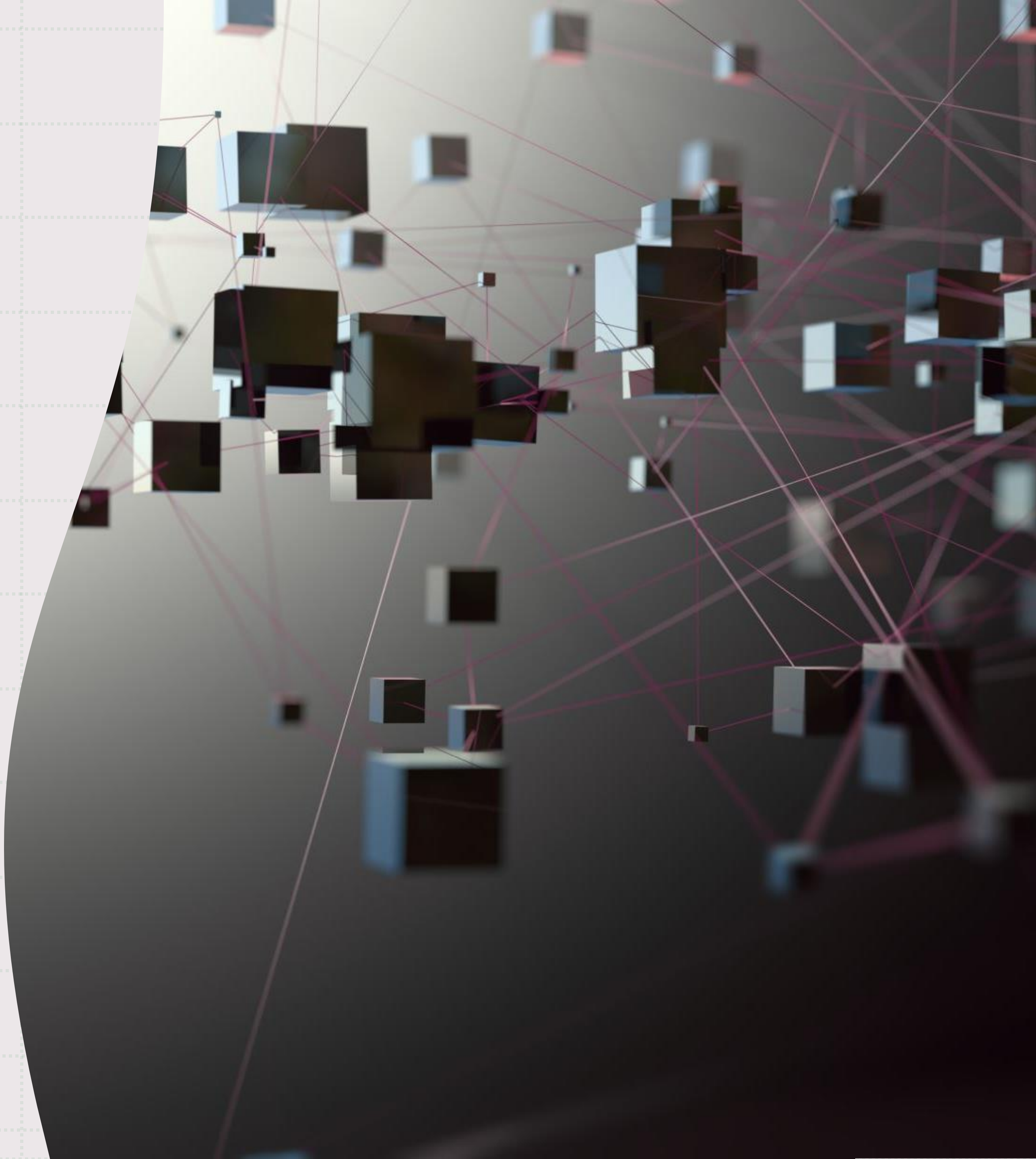
This talk is based on:

O. Lebedev and J.-H. Yoon, “Challenges for Inflaton Dark Matter”, 2105.05860



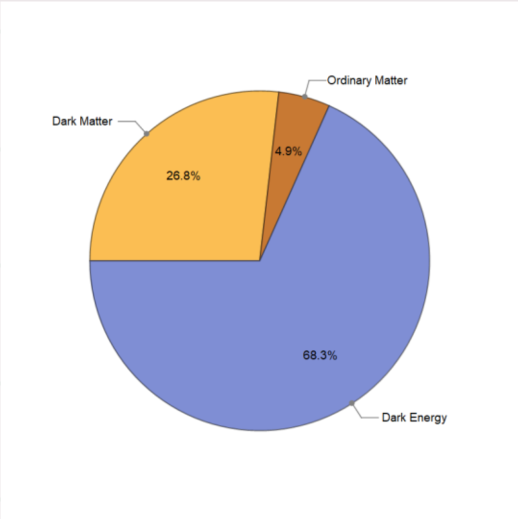
Introduction

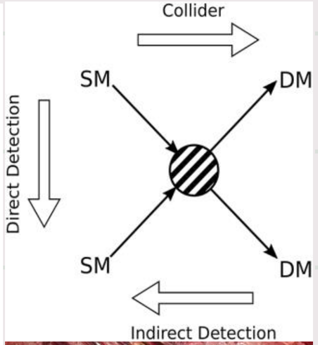
Dark Matter (Zwicky, 1933)

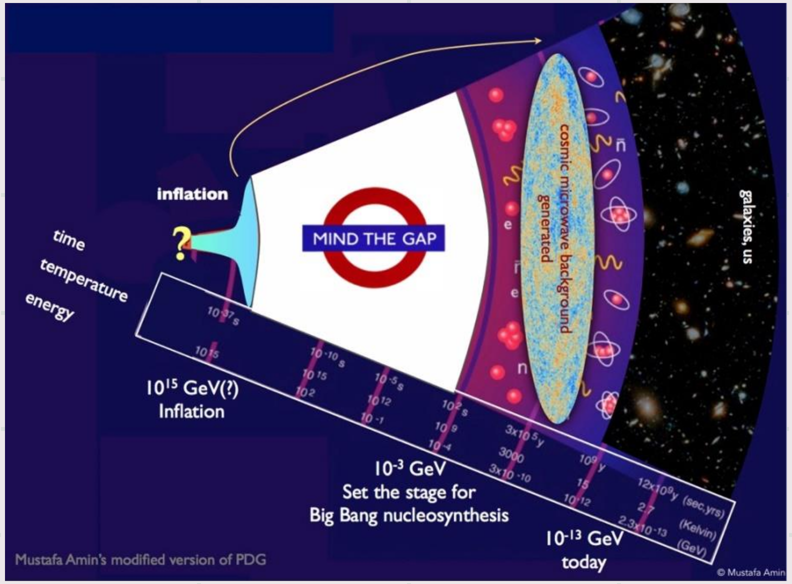
Cosmic Inflation (Guth, 1979)

- New Inflation, Slow-roll, Chaotic, etc.
 (Linde, etc., 1982~)

- A real scalar field, "Inflaton"







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Introduction

Inflaton and Dark Matter

- What if Inflaton is dark matter?

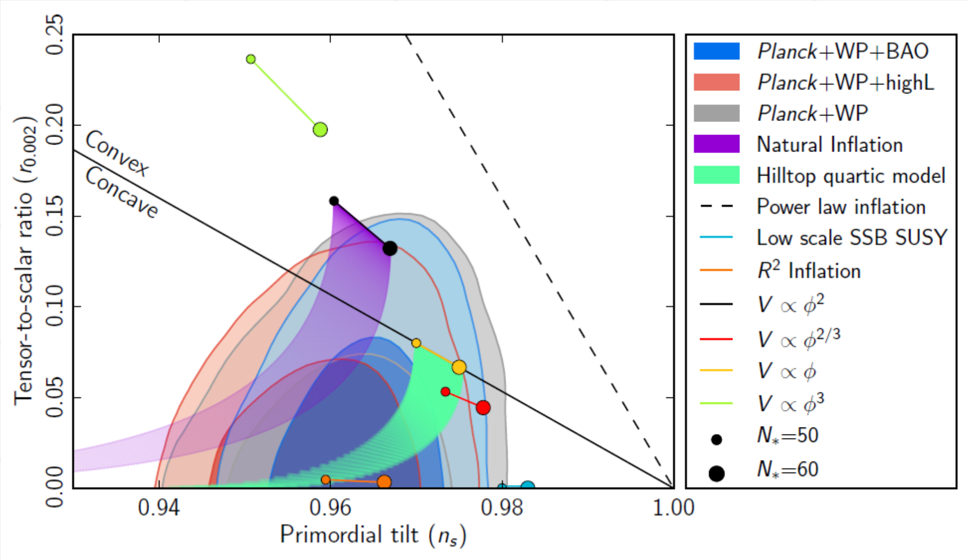
- Inflaton decaying into dark matter?

- Inflaton freezes out first then decays into dark matter

What would be the most minimalistic model?

Exp. constraints

Monomial potentials were ruled out (Planck, 2013)



→ Non-minimal coupling to gravity

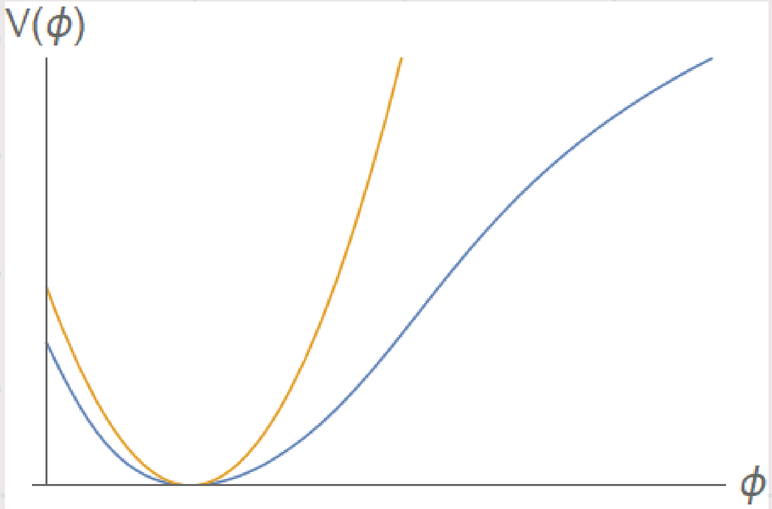
$$\mathcal{L}_J = \sqrt{-\hat{g}}\left(-\frac{1}{2}\Omega\hat{R} + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + (D_\mu H)^\dagger D^\mu H - V(\phi, H)\right)$$

$$V(\phi, h) = \frac{1}{4}\lambda_h h^4 + \frac{1}{4}\lambda_{\phi h}h^2\phi^2 + \frac{1}{4}\lambda_\phi\phi^4 + \frac{1}{2}m_h^2 h^2 + \frac{1}{2}m_\phi^2\phi^2$$

$$\Omega = 1 + \xi_h h^2 + \xi_\phi\phi^2$$

$$g_{\mu\nu} = \Omega\,\hat{g}_{\mu\nu}$$

$$V_E = \frac{\lambda_\phi}{4\xi_\phi^2}\left(1 + \exp\left(-\frac{2\gamma\chi'}{\sqrt{6}}\right)\right)^{-2}$$



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'Inflaton = Dark Matter' model

Framework

- Renormalizable & Minimal

$$\mathcal{L}_J = \sqrt{-\hat{g}}\left(-\frac{1}{2}\Omega\hat{R} + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + (D_\mu H)^\dagger D^\mu H - V(\phi, H)\right)$$

$$V(\phi, h) = \frac{1}{4}\lambda_h h^4 + \frac{1}{4}\lambda_{\phi h} h^2\phi^2 + \frac{1}{4}\lambda_\phi\phi^4 + \frac{1}{2}m_h^2 h^2 + \frac{1}{2}m_\phi^2\phi^2$$

- Z_2 symmetry → Stable DM

$$\Omega = 1 + \xi_h h^2 + \xi_\phi\phi^2$$

$$g_{\mu\nu} = \Omega\,\hat{g}_{\mu\nu}$$

$$V_E = \frac{\lambda_\phi}{4\xi_\phi^2}\left(1 + \exp\left(-\frac{2\gamma\chi'}{\sqrt{6}}\right)\right)^{-2}$$

- Non-minimal coupling to gravity

Couplings to Higgs → Reheating (the hot dense plasma)

Non-thermal v.s. Thermal DM production



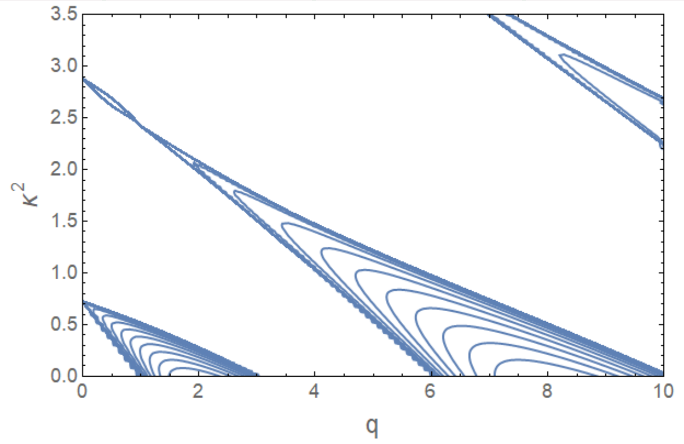

Non-thermal Dark Matter

Inflaton field oscillates coherently (homogeneous) → Parametric resonance

EOM: $\ddot{\phi} + 3H\dot{\phi} + \lambda_\phi \phi^3 = 0$

$$\phi(t) = \frac{\Phi_0}{a(t)} \,\mathrm{cn}\left(x, \frac{1}{\sqrt{2}}\right)$$

$$X_k'' + \left[\kappa^2 + \frac{\lambda_{\phi h}}{2\lambda_\phi}\,\mathrm{cn}^2\left(x, \frac{1}{\sqrt{2}}\right)\right] X_k = 0$$

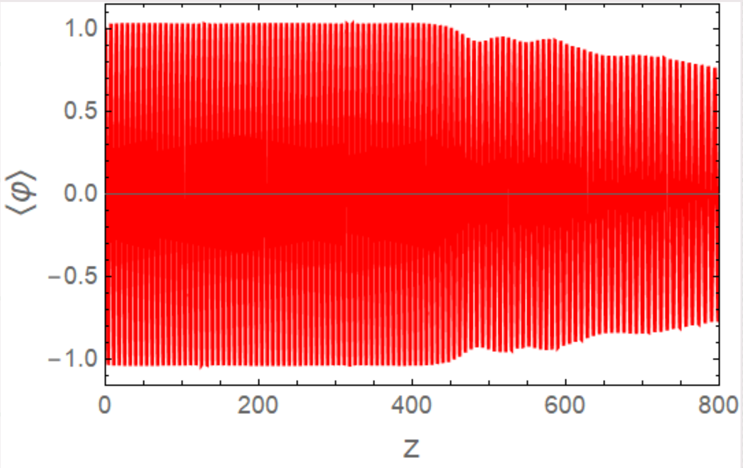


Modes inside bands grow exponentially

Non-thermal Dark Matter

Fast Higgs decay → No resonance → Perturbative computation

$$\Gamma_\phi^{\rm pert} = C\,\frac{\lambda_{\phi h}^2}{16\pi}\,\frac{\Phi_0}{a(t)\sqrt{\lambda_\phi}}$$



Inflaton bck. decays alone
and produces its quanta

Decay into Higgs is much slower than decay into inflaton quanta

→ We are left with too much inflaton DM

Non-thermal Dark Matter

Slow Higgs decay

- Parametric resonance

- When does it end?

Non-thermal Dark Matter

Produced particles can re-scatter off background field

→ Inflaton is no longer dominant

→ Linear regime breaks down

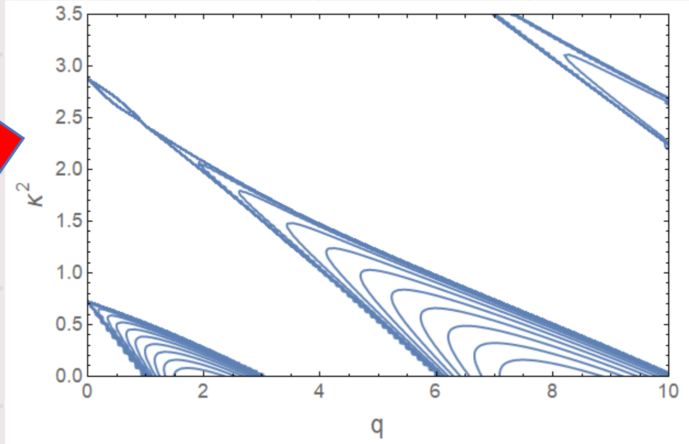
Non-thermal Dark Matter

Inflaton field oscillates coherently (homogeneous) → Parametric resonance

EOM: $\ddot{\phi} + 3H\dot{\phi} + \lambda_\phi \, \phi^3 = 0$

$$\phi(t) = \frac{\Phi_0}{a(t)} \, \mathrm{cn}\left(x, \frac{1}{\sqrt{2}}\right)$$

$$X_k'' + \left[\kappa^2 + \frac{\lambda_{\phi h}}{2\lambda_\phi} \, \mathrm{cn}^2\left(x, \frac{1}{\sqrt{2}}\right)\right] X_k = 0$$



Modes inside bands grow exponentially

Non-thermal Dark Matter

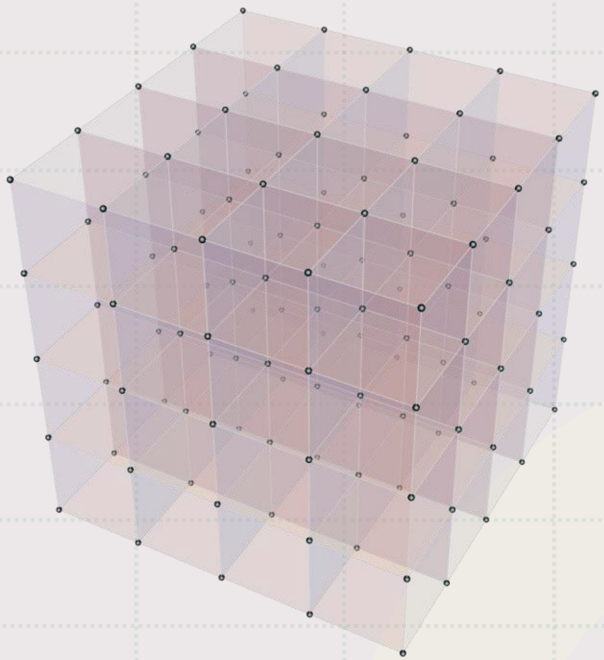
Backreaction and Rescattering → Non-perturbative description

Lattice simulations

- solve coupled equations of motion at each space point

- LATTICEEASY, CosmoLattice, etc.

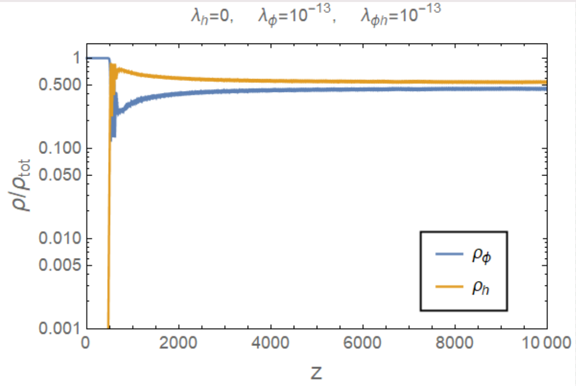
- Parallel computation on cluster computers



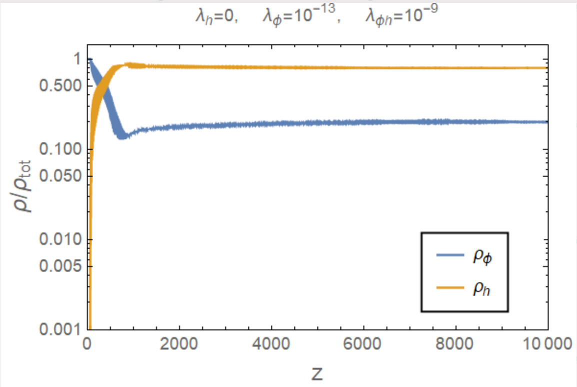
Non-thermal Dark Matter

Zero v.s. Non-zero for the Higgs self-interaction coupling

$\lambda_h = 0$



λ=10^-13



Stronger interaction

Democratic energy distribution

→ Quasi-equilibirum $\dfrac{\rho_\phi}{\rho_{\rm tot}} \sim \dfrac{1}{\#\,\mathrm{d.o.f.}}$

→ Over-abundance

$$Y = n_\phi / s_{\rm SM} \gtrsim 10^{-3}$$

$$Y_{\rm obs} = 4 \times 10^{-10}\ \mathrm{GeV}/m_\phi$$

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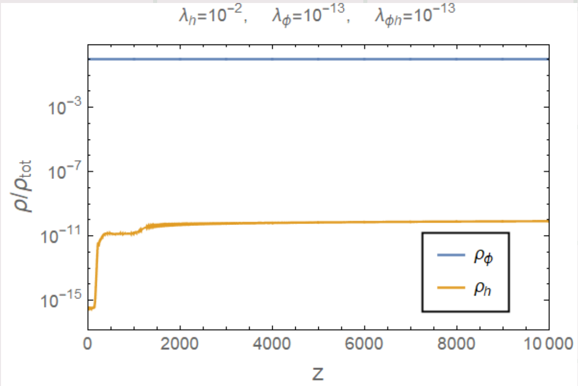
Non-thermal Dark Matter

Zero v.s. Non-zero for the Higgs self-interaction coupling

$\lambda_h = 0.01$



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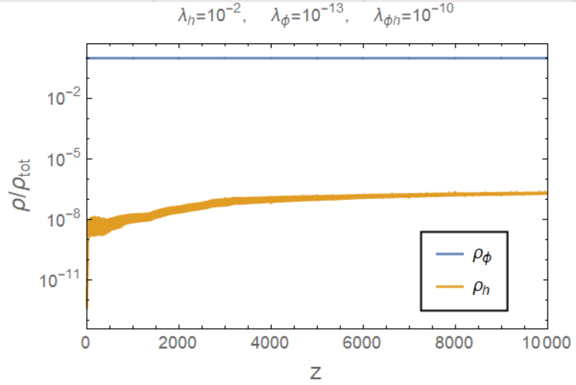

Stronger interaction

Higgs production is hindered by backreaction (large effective mass)

$$\lambda_\phi \phi^2 \sim \lambda_h \langle h^2 \rangle$$

$$\rho_\phi \gg \rho_{\rm SM}$$

for the same reason in Fast Higgs decay scenario

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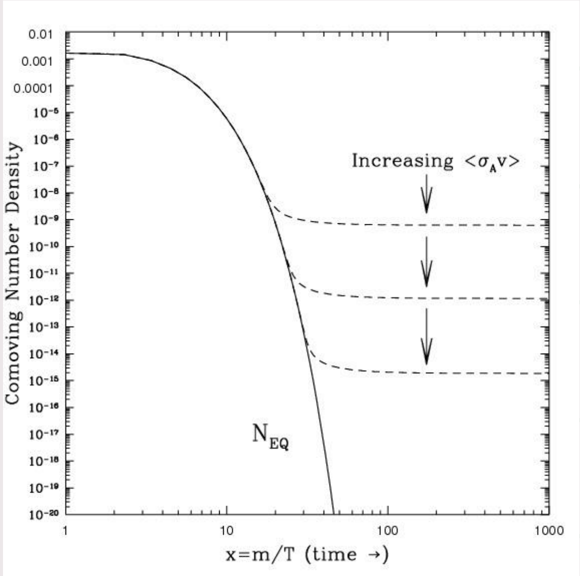
Thermal Dark Matter

Experimental constraint and RG equation → Breaks Unitarity

$\lambda_{\phi h}(1\,\mathrm{TeV}) \gtrsim 0.25$

$16\pi^2 \frac{d\lambda_\phi}{dt} = 2\lambda_{\phi h}^2 + 18\lambda_\phi^2$



$\lambda_\phi(H) \gtrsim 10^{-3}$

Non-minimal coupling to gravity corresponds to Dim-5 operator

- Cut-off scale in EFT $\Lambda \sim 1/\xi_\phi$

Inflationary energy scale can't be larger than the cut-off scale

$(\lambda_\phi/4\xi_\phi^2)^{1/4}$

$\lambda_\phi(H) < 4 \times 10^{-5}$

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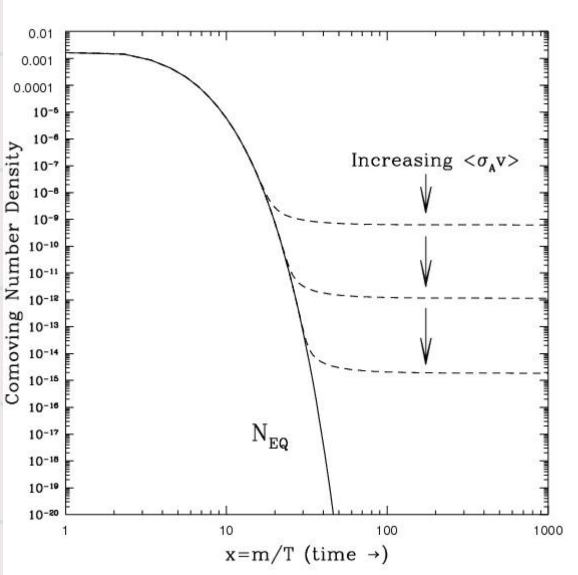
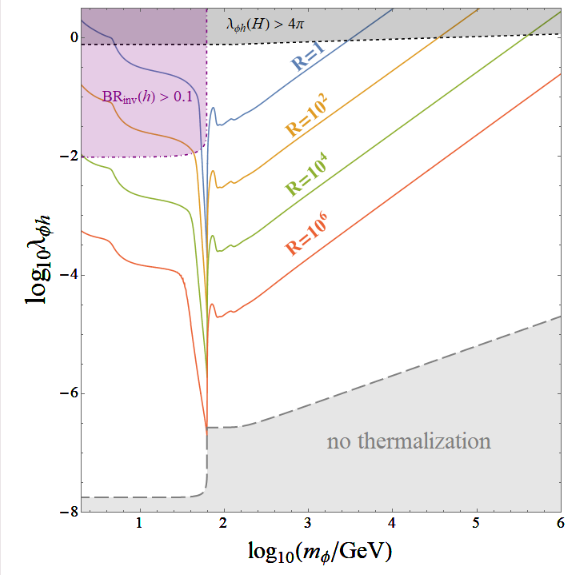
Thermal Dark Matter

Higgs resonance $m_\phi \simeq m_{h_0}/2$ $\phi\phi \to h \to \mathrm{SM}$





Resonance implies large cross section,

thus makes it easier to evade constrant

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Summary

The interplay of Inflaton and Dark matter is a fascinating area

Non-perturbative description is essential for understanding the post-inflationary physics

We have studied "Inflaton Dark Matter model" in a minimalistic framework

- Non-thermal dark matter remains too much to match current observations
- Thermal dark matter breaks unitarity condition → Mass should be fine-tuned