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

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Introduction

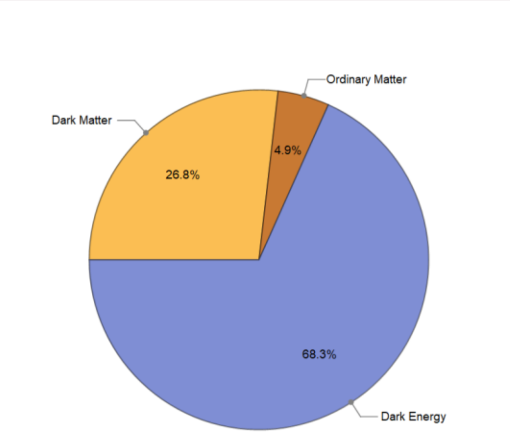
Dark Matter (Zwicky, 1933)

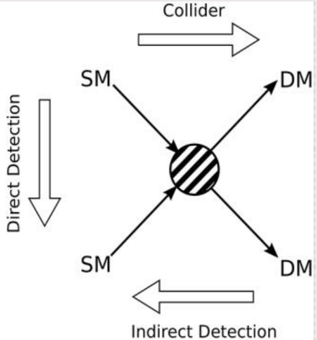
Cosmic Inflation (Guth, 1979)

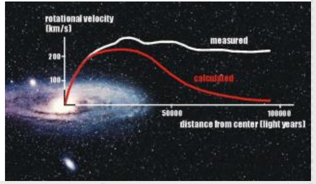
- New Inflation, Slow-roll, Chaotic, etc.

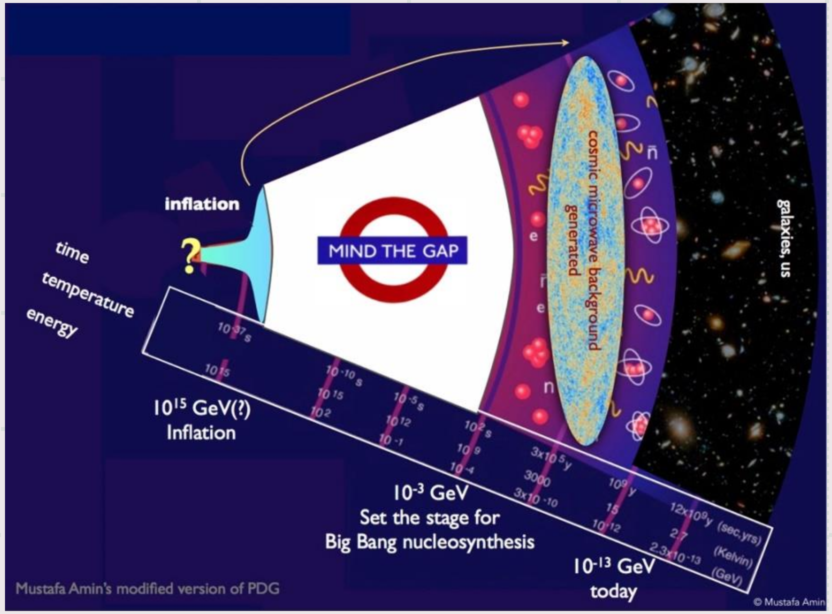
(Linde, etc., 1982~)

- A real scalar field, "Inflaton"









Mustafa Amin's modified version of PDG

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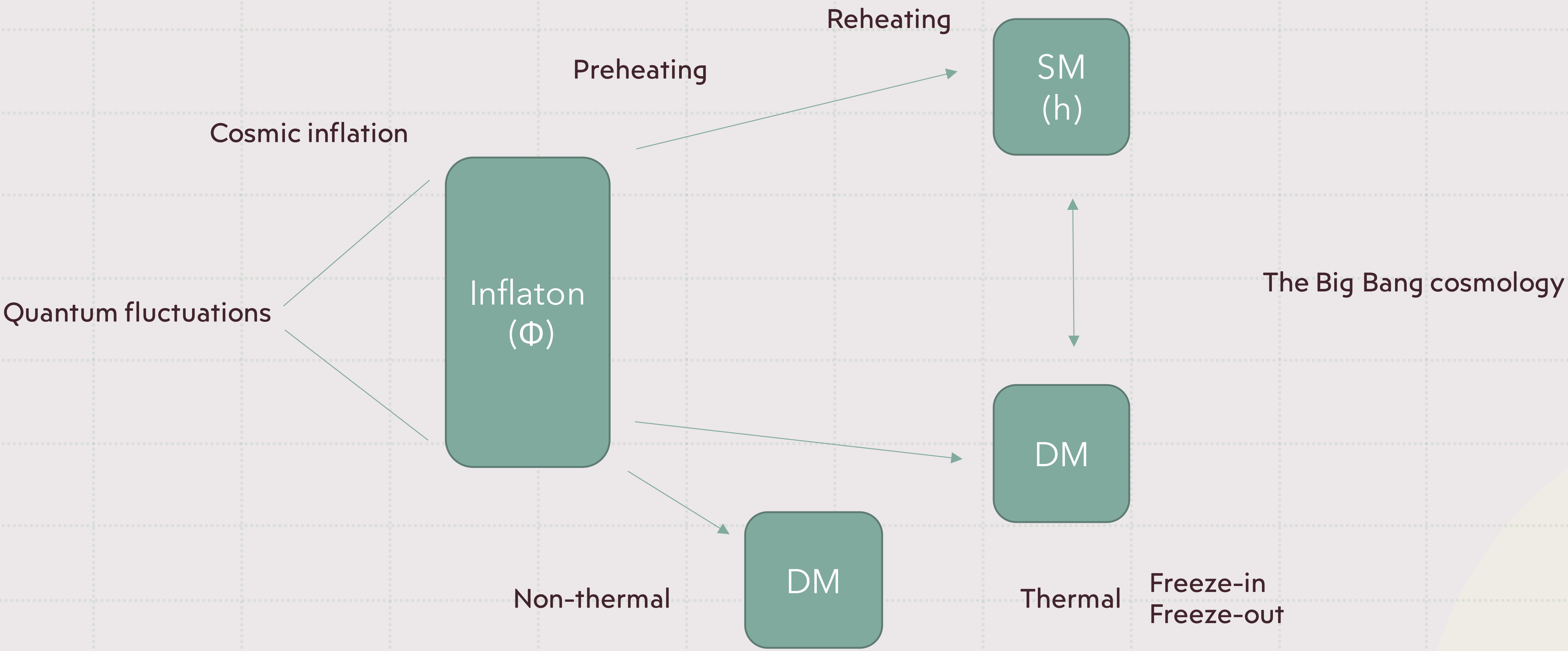
Introduction



Reheating

Preheating

Cosmic inflation

SM
(h)

Inflaton
(Φ)

Quantum fluctuations

The Big Bang cosmology

DM

DM

Non-thermal

Thermal

Freeze-in
Freeze-out

Introduction

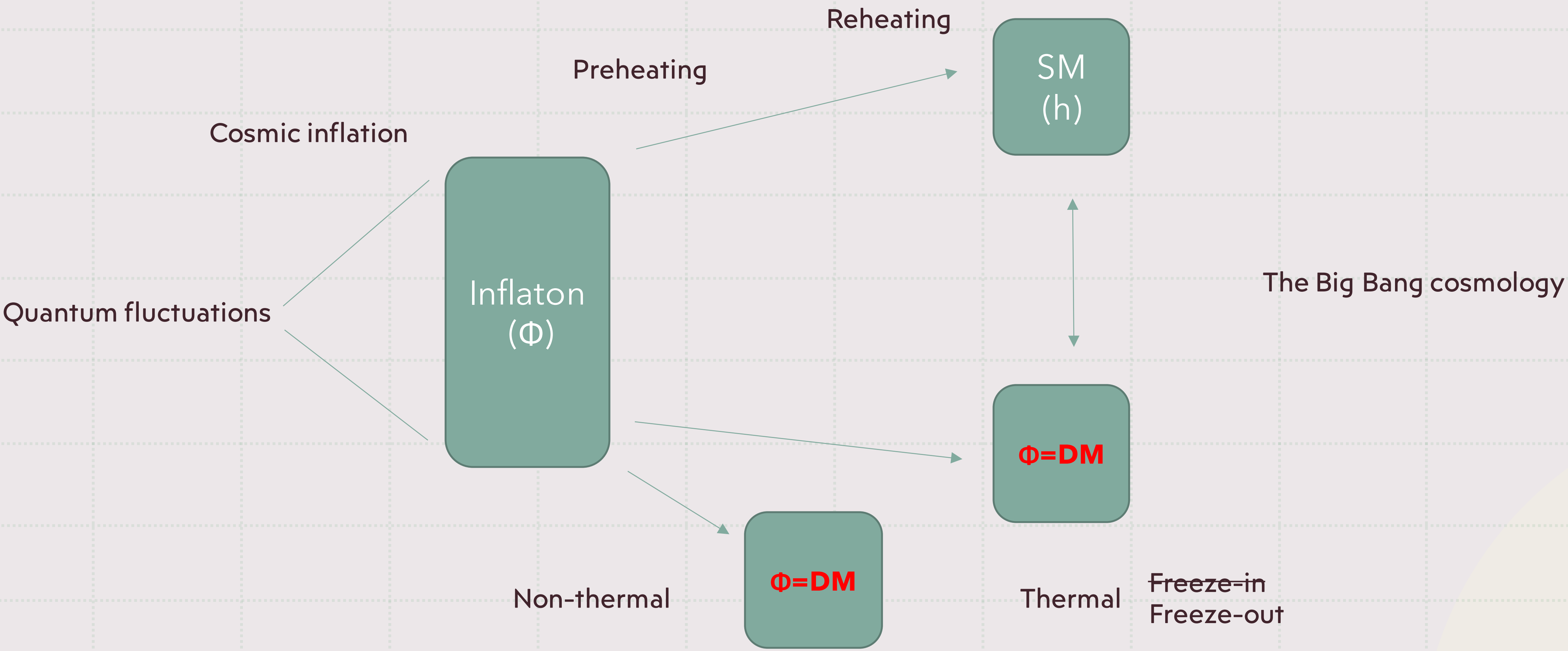
Inflaton and Dark Matter

- **'Inflaton = Dark Matter'**

- 'Inflaton ≠ Dark Matter'

- 'Inflaton → Dark Matter'

'Inflaton = Dark Matter' model



Reheating

Preheating

Cosmic inflation

Quantum fluctuations

SM
(h)

Inflaton
(Φ)

The Big Bang cosmology

Φ=DM

Φ=DM

Non-thermal

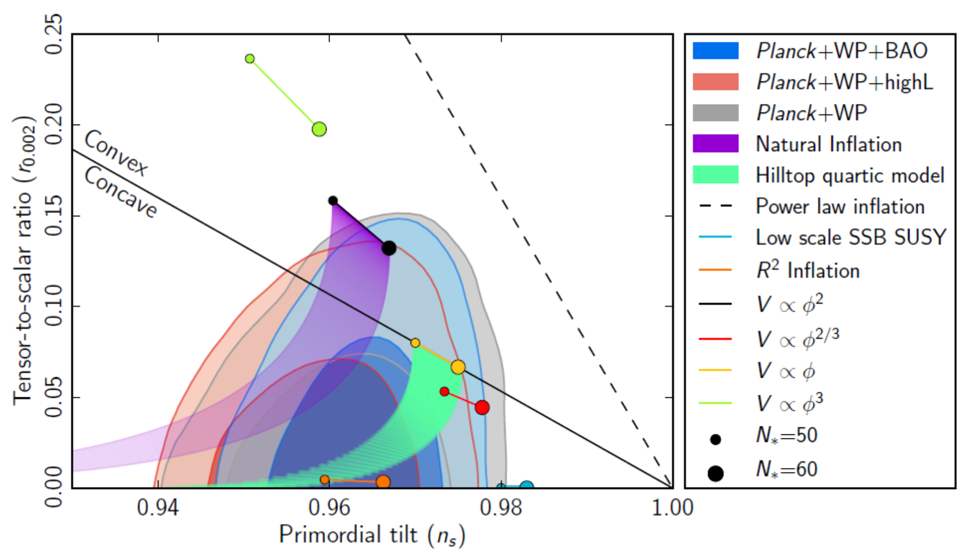
Thermal

~~Freeze-in~~
Freeze-out

Exp. constraints

Monomial potentials were ruled out (Planck, 2013)

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



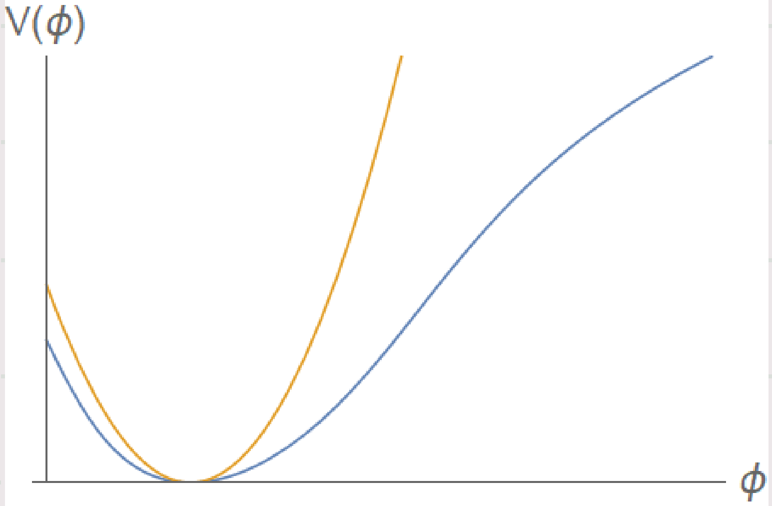
→ Non-minimal coupling to gravity

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

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

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

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



How to light up the Dark Universe

The universe was full of Inflaton in the beginning

If Inflaton-DM fails to transfer its energy to SM enough, we would end up with DM-dominated universe

※ Force ourselves to fragment Inflaton as much as possible through its Higgs coupling

Non-thermal v.s. Thermal DM production

Non-thermal Dark Matter

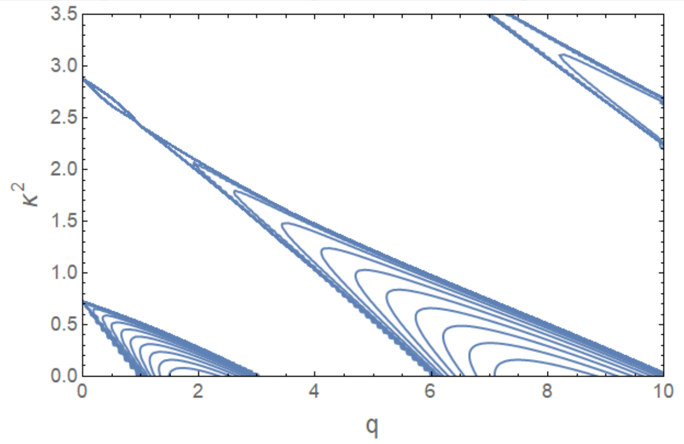
Inflaton field oscillates coherently (homogeneous) → Parametric resonance

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

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

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

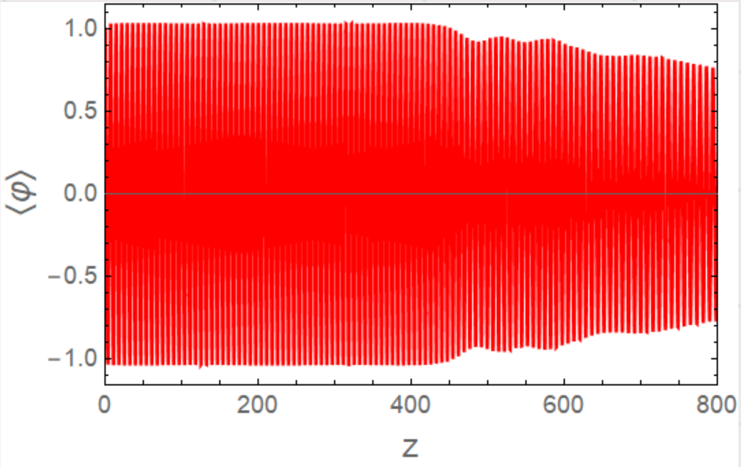
q parameter



Modes inside bands grow exponentially

Non-thermal Dark Matter

Fast Higgs decay → No B.E. condensation → Perturbative computation



Inflaton bck. decays alone
and produces its quanta

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

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 → B.E. condensation → Resonance

- Parametric resonance

- How long? 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

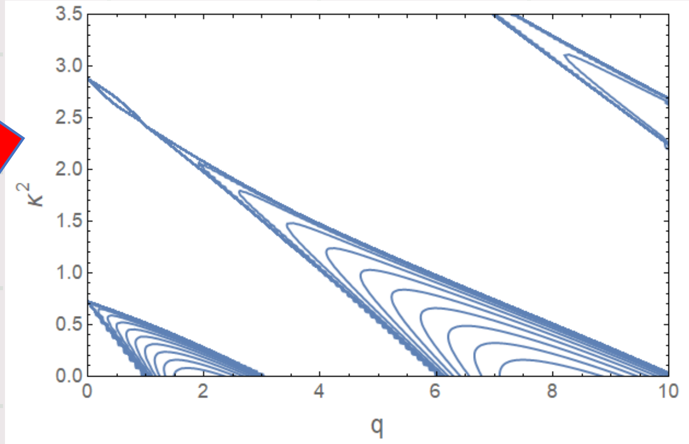
Non-thermal Dark Matter

Inflaton field oscillates coherently (homogeneous) → Parametric resonance

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

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

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



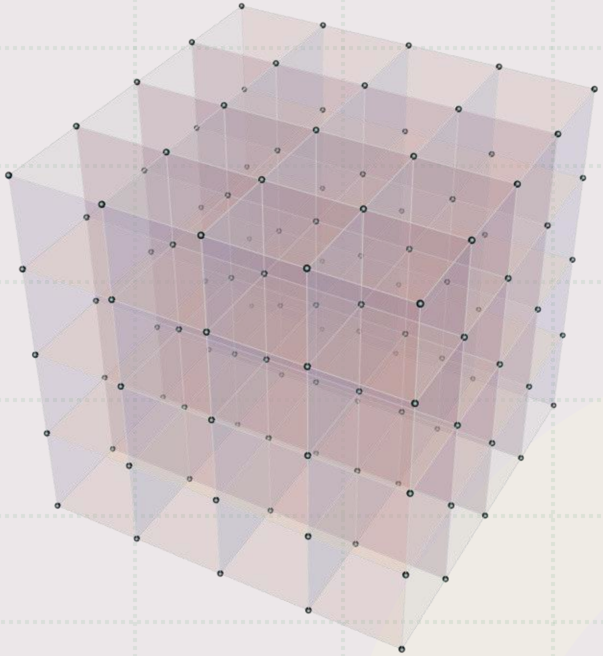
Modes inside bands grow exponentially

Non-thermal Dark Matter

Backreaction and Rescattering → Non-perturbative description

Lattice simulations

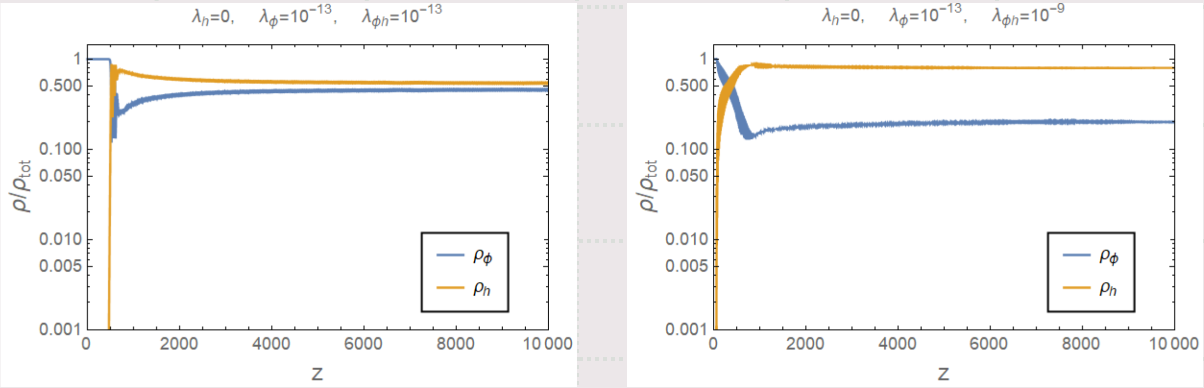
- solve equations of motion at each space point
- LATTICEEASY, CosmoLattice, etc.
- Parallel computation on cluster computers



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 $\frac{\rho_\phi}{\rho_{\rm tot}} \sim \frac{1}{\#\,\mathrm{d.o.f.}}$

→ Over-abundance

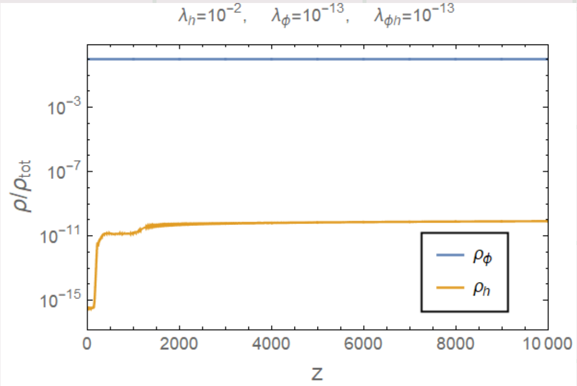
$$Y = n_\phi / s_{\rm SM} \gtrsim 10^{-3}$$

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

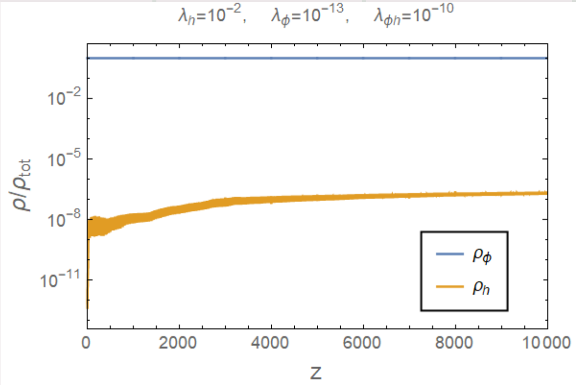
Non-thermal Dark Matter

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

$\lambda_h = 0.01$



λ=10^-13



Stronger interaction

Higgs production is hindered by backreaction (large effective mass)

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

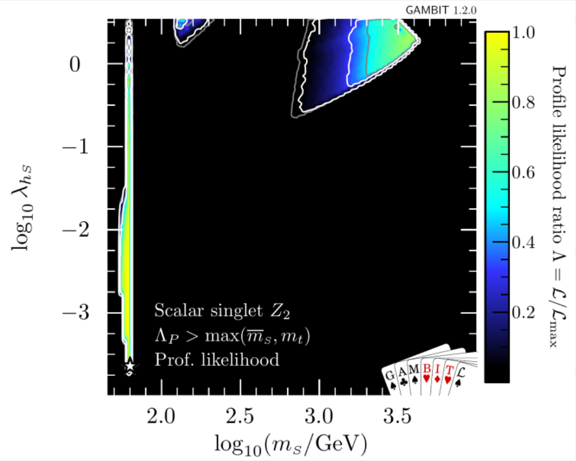
$$\rho_\phi \gg \rho_{\rm SM}$$

for the same reason in Fast Higgs decay scenario

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 $\Lambda \sim 1/\xi_\phi$

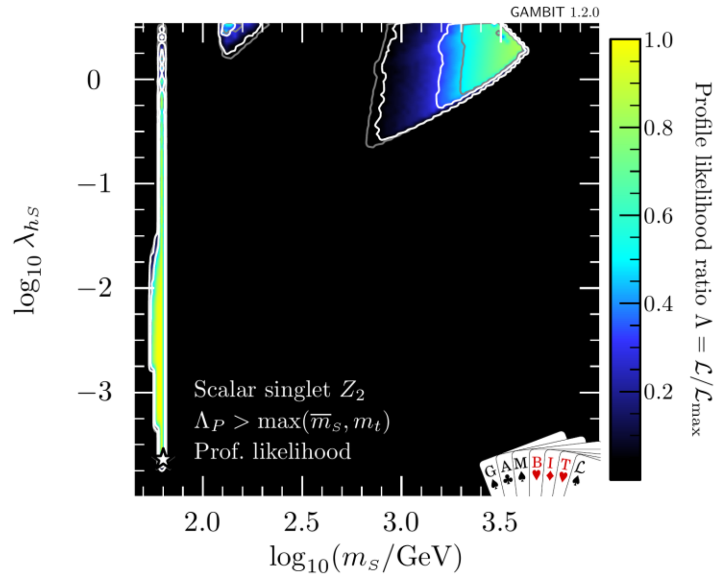
Inflationary energy scale can't be larger than the cut-off scale

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

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

Thermal Dark Matter

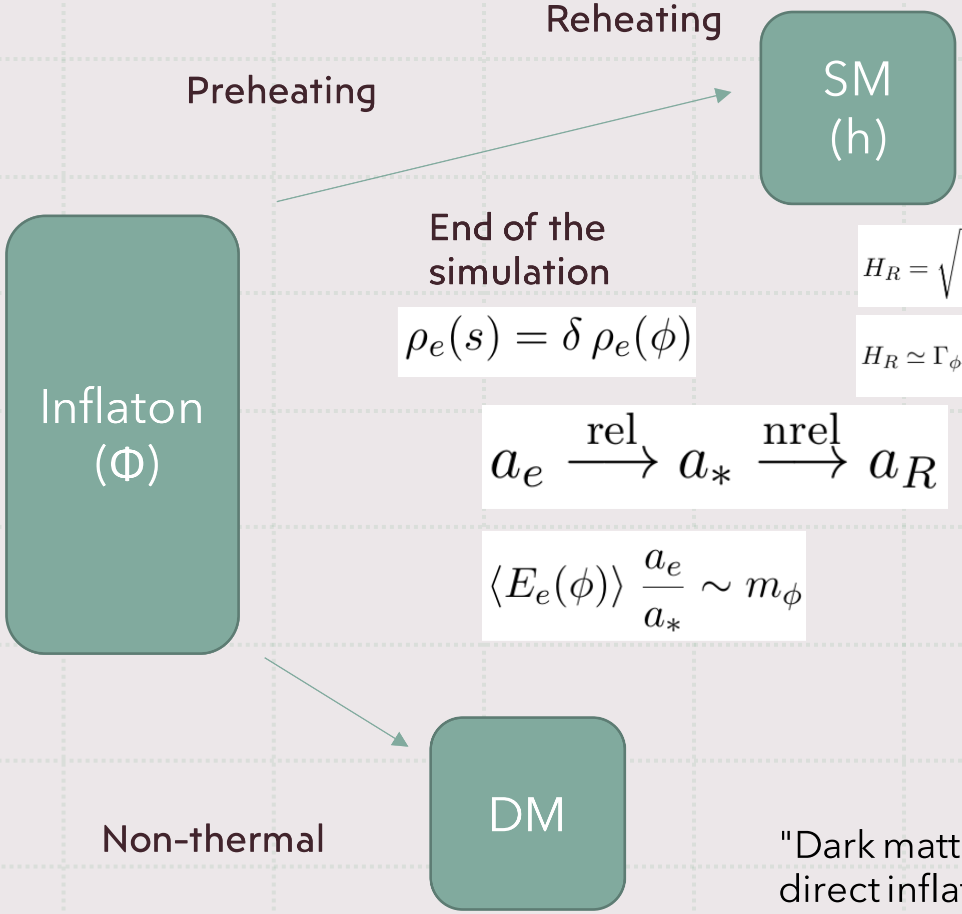
Higgs resonance $\phi\phi \to h \to \mathrm{SM}$



$$m_\phi \simeq m_{h_0}/2$$

→The mass of inflaton DM should be equal to half Higgs mass

'Inflaton ≠ Dark Matter' model



Reheating

SM (h)

Preheating

Inflaton (Φ)

DM

Non-thermal

End of the simulation

$$\rho_e(s) = \delta\, \rho_e(\phi)$$

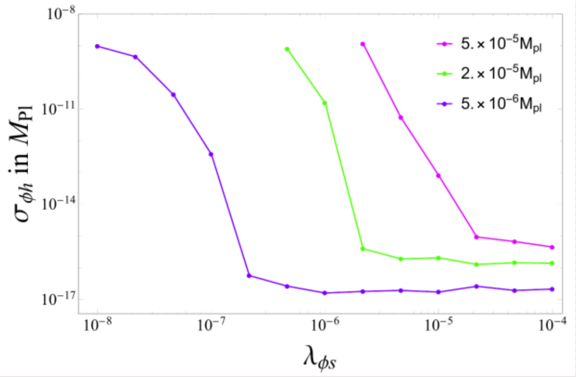
$$a_e \xrightarrow{\text{rel}} a_* \xrightarrow{\text{nrel}} a_R$$

$$\langle E_e(\phi)\rangle \, \frac{a_e}{a_*} \sim m_\phi$$

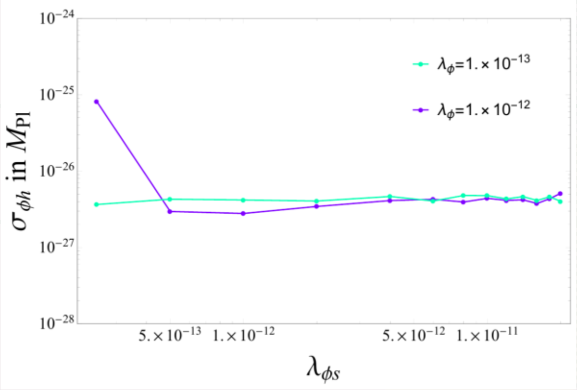
$$H_R = \sqrt{\frac{\pi^2 g_*}{90}}\, T_R^2$$

$$H_R \simeq \Gamma_{\phi\to hh}\,, \quad \Gamma_{\phi\to hh} = \frac{\sigma_{\phi h}^2}{8\pi m_\phi}$$

$$Y_\infty = 4.4\times 10^{-10}\left(\frac{\text{GeV}}{m_s}\right)$$



$$V_\phi = \frac{m_\phi^2}{2}\phi^2$$

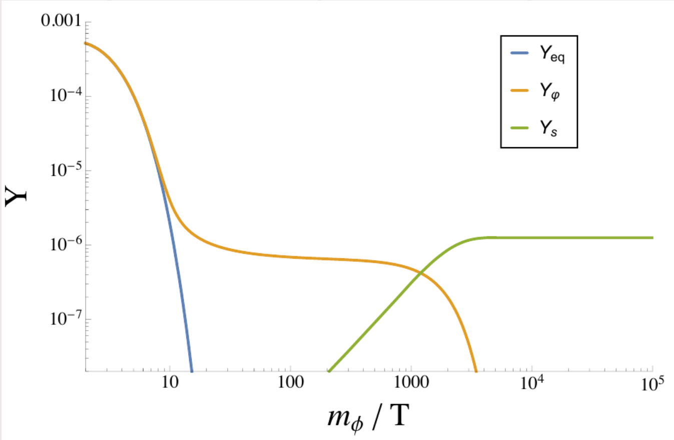


$$V_\phi = \frac{1}{4}\lambda_\phi \phi^4$$

"Dark matter production and reheating via direct inflaton couplings: collective effects", 2107.06292

'Inflaton → Dark Matter' model

Inflaton freeze-out

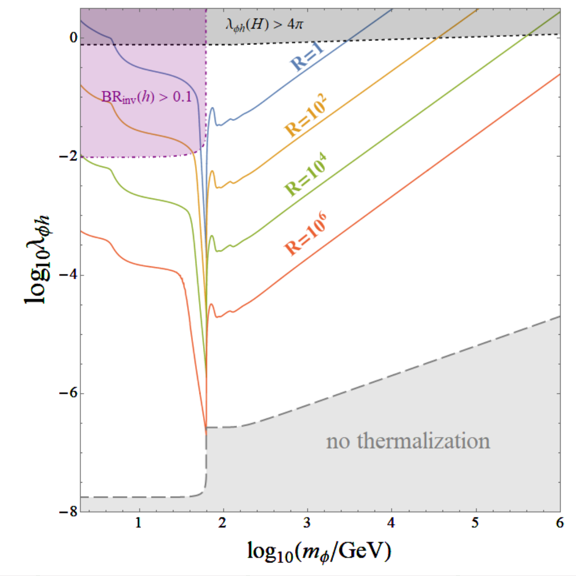


$$Y_s = Y_\phi^{\rm FO} \times 2\,{\rm BR}(\phi \to ss)$$

$$Y_s = 4.4 \times 10^{-10}\,\frac{\rm GeV}{m_s} \quad , \quad Y_\phi^{\rm FO} = 4.4 \times 10^{-10}\,\frac{\rm GeV}{m_\phi} \times R\,,$$

$$\frac{m_\phi}{R} = 2m_s\,{\rm BR}(\phi \to ss)\,.$$

Allowed parameter space →



"Inflaton freeze-out", 2110.05488

Summary

We find the interplay of Inflaton and Dark matter fun

Non-linear effects are important in the post-inflationary universe

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

- Non-thermal DM remains too much to match current observations
- Thermal DM threatens the unitarity condition → Mass should be fine-tuned