Inflaton Dark Matter

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

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HELSINKI INSTITUTE OF PHYSICS
UNIVERSITY OF HELSINKI

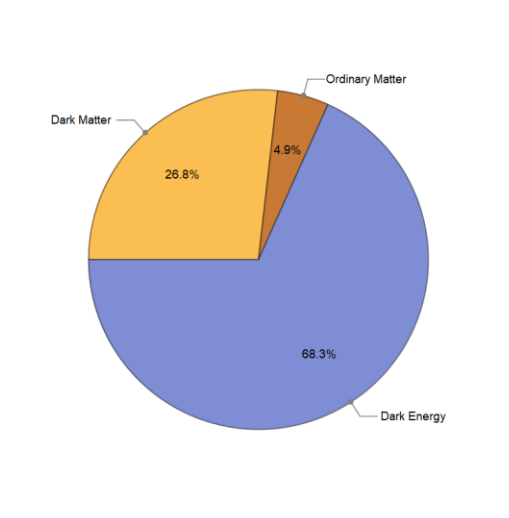
Introduction

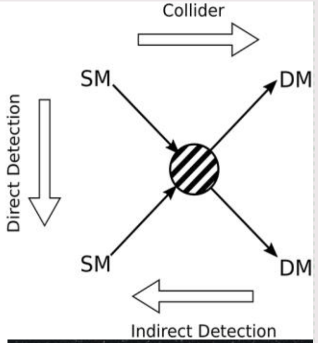
Dark Matter (1933~)

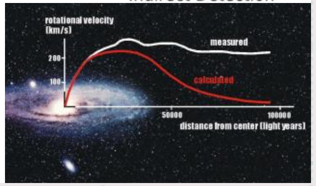
Cosmic Inflation (1979~)

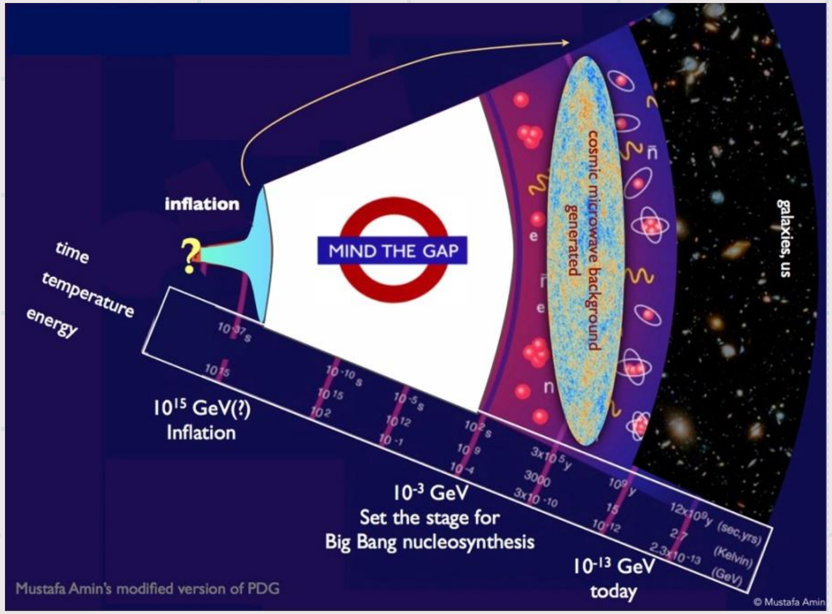
- New Inflation (1982~)

- A real scalar field "Inflaton"

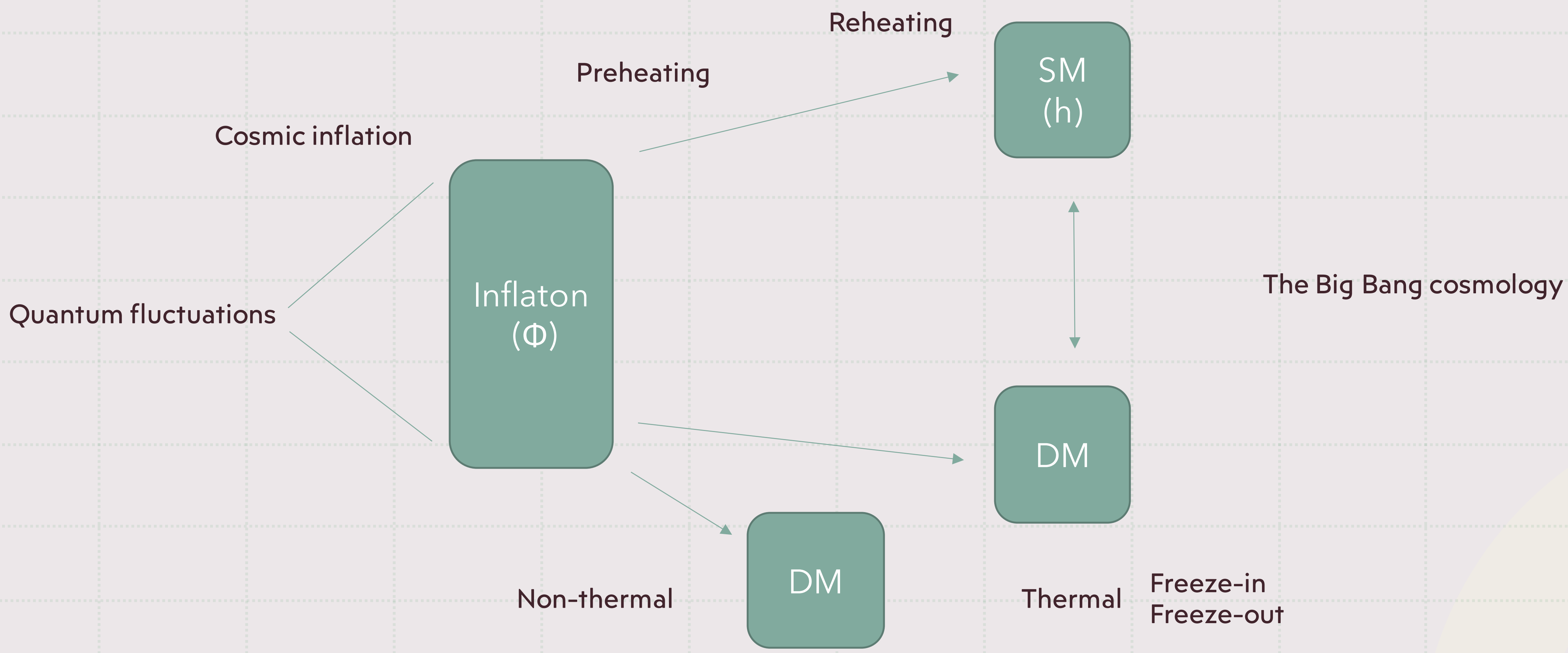








Introduction



Introduction

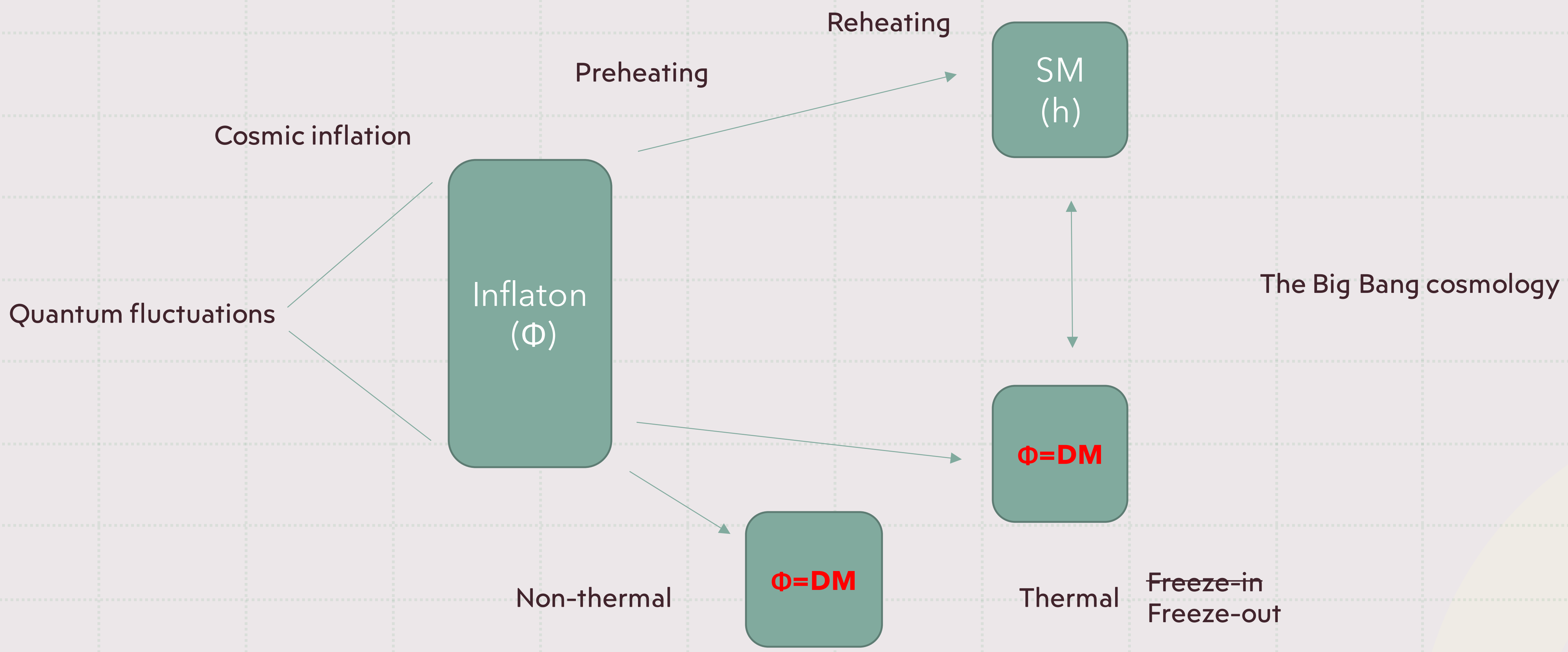
Inflaton and Dark Matter

- **'Inflaton = Dark Matter'**

- 'Inflaton ≠ Dark Matter'

- 'Inflaton → Dark Matter'

'Inflaton = Dark Matter' model



How to light up the Dark Universe

The very-early universe is full of Inflaton

Inflaton DM must be converted enough to the SM thermal bath

Reheating depends on Inflaton-Higgs couplings and the rest of Inflaton remains DM

SM + Φ

Renormalizable interactions with Higgs (essential for reheating)

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

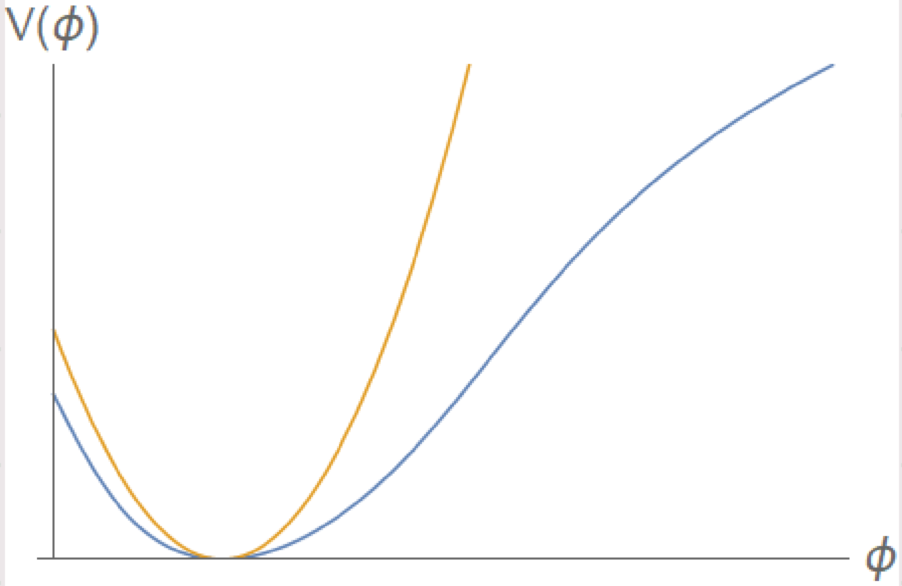
+ Non-minimal coupling to gravity in the Jordan frame

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

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

Constraints (CMB)

CMB favors a flat inflaton potential at large field value



Non-minimal coupling to gravity

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

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

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

↓

$$\mathcal{L} = \frac{3}{4}\left(\partial_\mu \ln(\xi_h h^2 + \xi_\phi\phi^2)\right)^2 + \frac{1}{2}\frac{1}{\xi_h h^2 + \xi_\phi\phi^2}\left((\partial_\mu h)^2 + (\partial_\mu\phi)^2\right) - \frac{V}{(\xi_h h^2 + \xi_\phi\phi^2)^2}$$

Potential in the Einstein frame

Constraints (CMB)

Field redefinition

$$\chi = \sqrt{\frac{3}{2}} \ln(\xi_h h^2 + \xi_\phi \phi^2)$$
$$\tau = \frac{h}{\phi},$$

$$\chi' = \chi \sqrt{1 + \frac{1}{6\xi_\phi}} \quad , \quad \tau' = \frac{\tau}{\sqrt{\xi_\phi}}$$

Flat at large field values

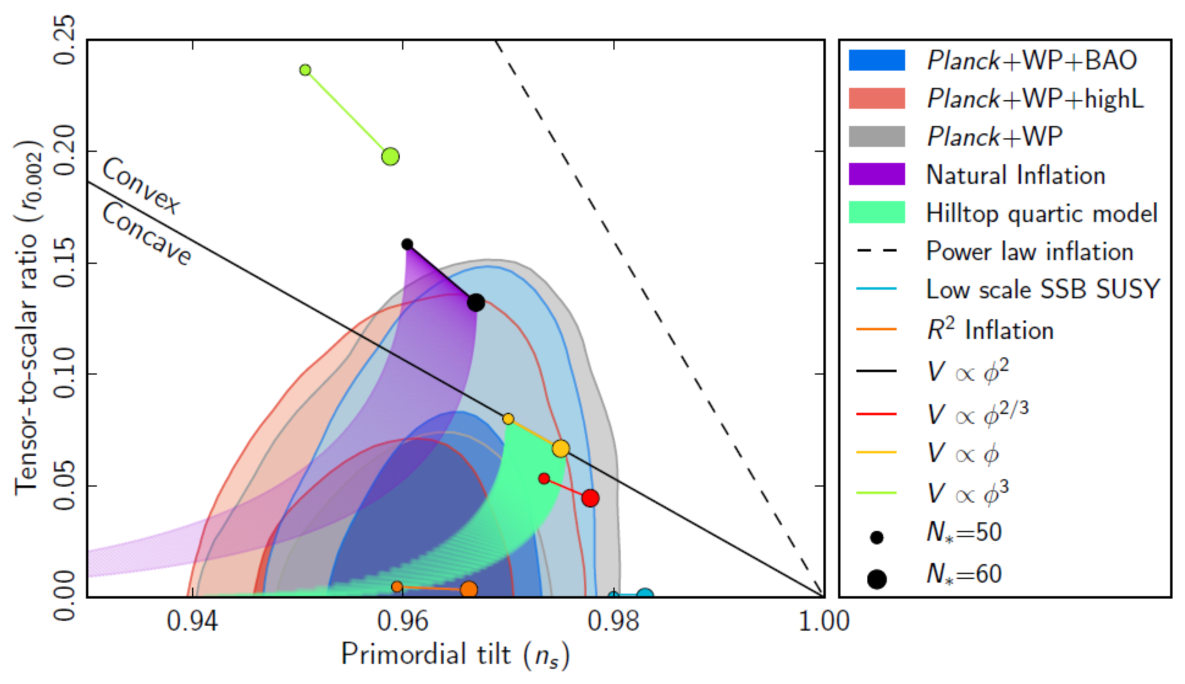
$$V_E = \frac{\lambda_\phi}{4\xi_\phi^2}\left(1 + \exp\left(-\frac{2\gamma\chi'}{\sqrt{6}}\right)\right)^{-2}$$

$$\gamma = \sqrt{\frac{6\xi_\phi}{6\xi_\phi + 1}}$$

$$\epsilon = \frac{1}{2}\left(\frac{\partial V_E/\partial\chi'}{V_E}\right)^2$$
$$\eta = \frac{\partial^2 V_E/\partial\chi'^2}{V_E}.$$

$$n = 1 - 6\epsilon + 2\eta$$

$$r = 16\epsilon \simeq \frac{12}{\gamma^2 N^2}$$



Constraints (Unitarity)

Cut off scale Λ in EFT **>** Energy scale

Dim-5 operator ($\xi\Phi^2 R$)

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

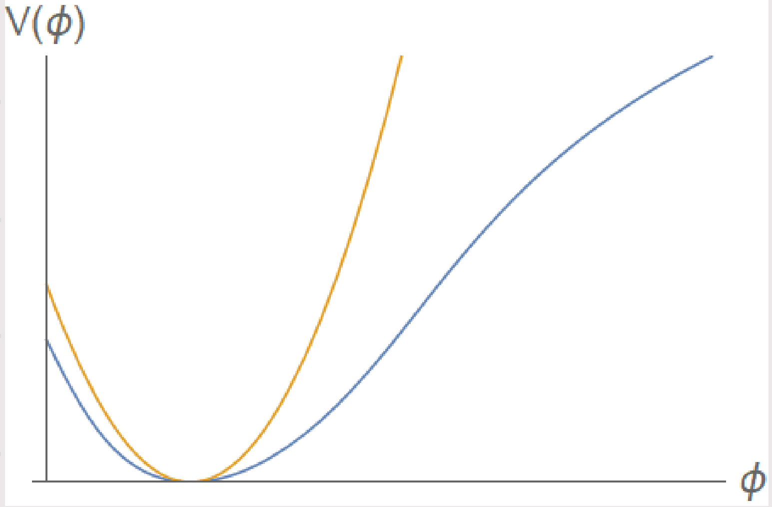
→ $\Lambda \sim 1/\xi_\phi$ **>** $(\lambda_\phi/4\xi_\phi^2)^{1/4}$

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

$\xi_\phi(H) < 300$

Non-thermal Dark Matter

Inflaton field oscillates coherently (homogeneous)



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

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

Non-thermal Dark Matter

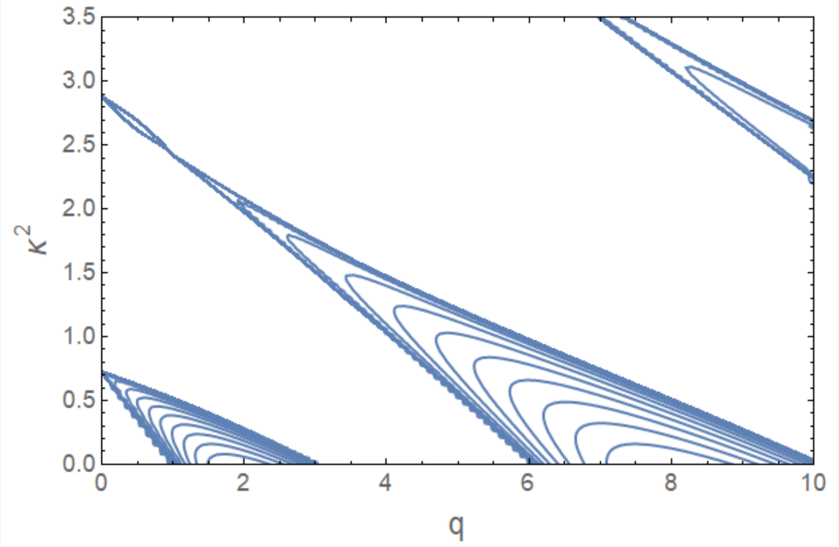
Lamé equation and instability charts → Parametric Resonance

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

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

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

Rescaled momentum   q parameter

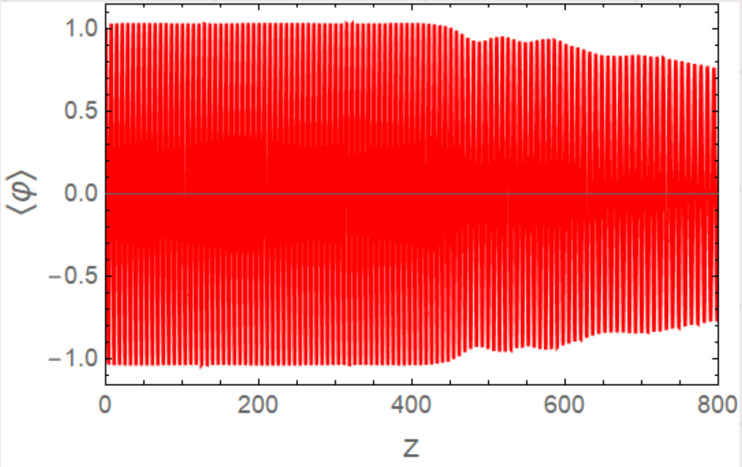


Modes inside bands grow exponentially

Non-thermal Dark Matter

Fast Higgs decay → No B.E. condensation → 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

→ Too much Inflaton DM left

Non-thermal Dark Matter

Slow Higgs decay → B.E. condensation → Resonance

- Parametric resonance

- End of resonance?

Non-thermal Dark Matter

Produced particles can re-scatter off background field

→ Inflaton is no longer dominant

→ Linear regime breaks down

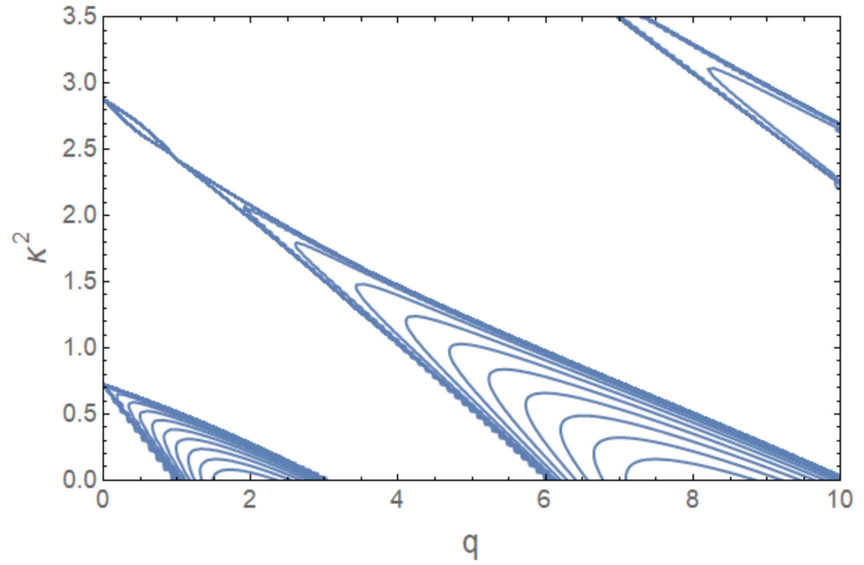
Non-thermal Dark Matter

Inflaton field oscillates ~~coherently (homogeneous)~~

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

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

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

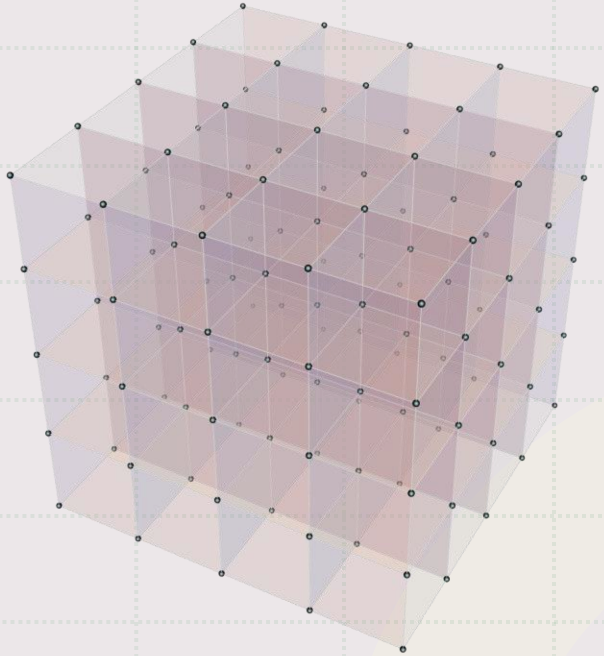


Non-thermal Dark Matter

Backreaction and Rescattering → Non-perturbative description

Lattice simulations

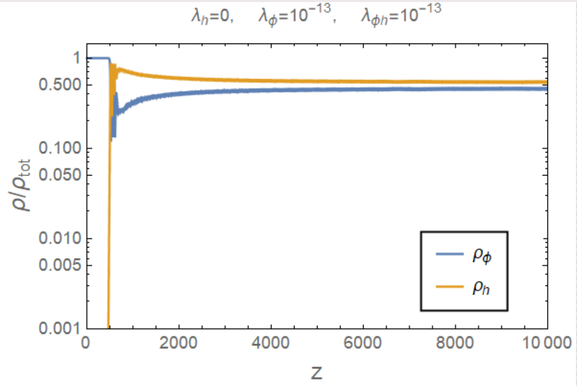
- solve equations of motion at each space point
- LATTICEEASY, CosmoLattice, etc.
- Parallel computation on cluster computers



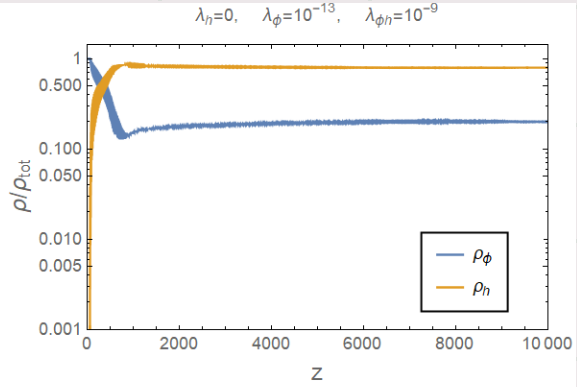
Non-thermal Dark Matter

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

$\lambda_h = 0$



λ=10^-13



Stronger interaction

Democratic energy distribution

→ Quasi-equilibirum $\frac{\rho_\phi}{\rho_{tot}} \sim \frac{1}{\#\text{d.o.f.}}$

→ Over-abundance

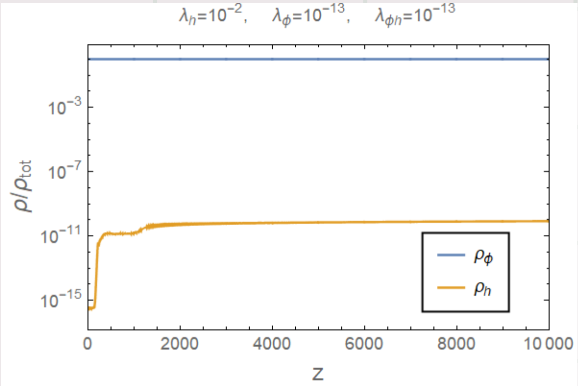
$$Y = n_\phi / s_{SM} \gtrsim 10^{-3}$$

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

Non-thermal Dark Matter

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

$$\lambda_h = 0.01$$



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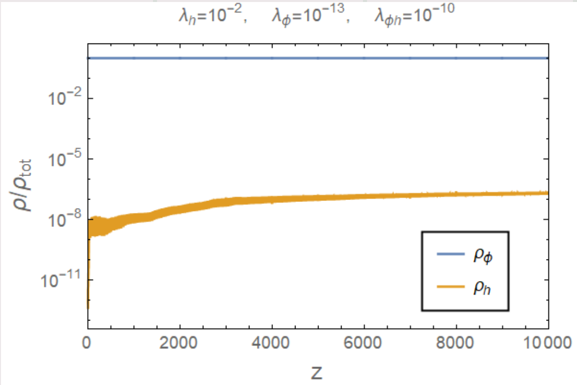


Stronger interaction

Higgs production is hindered by backreaction (large effective mass)

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

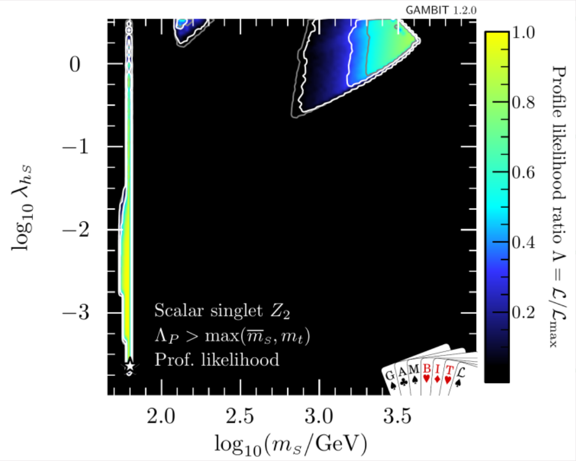
$$\rho_\phi \gg \rho_{\mathrm{SM}}$$

Too much Inflaton DM quanta would survive

Thermal F.O. Dark Matter

Experimental constraint and RG equation

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



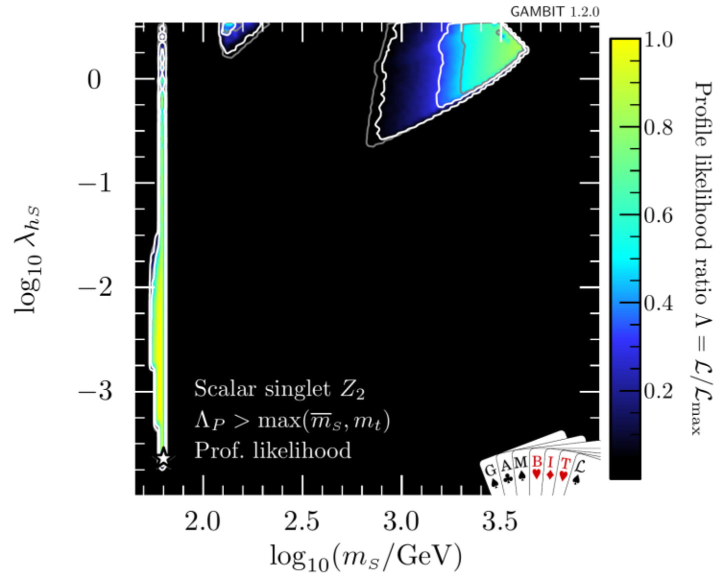
$$16\pi^2 \frac{d\lambda_\phi}{dt} = 2\lambda_{\phi h}^2 + 18\lambda_\phi^2$$

$\lambda_\phi(H) \gtrsim 10^{-3}$ ⟷ ✖ $\lambda_\phi(H) < 4 \times 10^{-5}$

→ Breaks Unitarity

Thermal F.O. Dark Matter

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



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

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

Summary

(P)reheating after inflation is a subject worthy of serious study

Large Inflaton field value + Coherent oscillation

→ Resonance, Backreaction and Rescattering

→ Lattice simulations

Inflaton Dark Matter

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