

# Collective effects in dark matter production

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## Focus points:

- direct renormalizable inflaton couplings
- preheating , reheating
- non-thermal dark matter production
- collective effects (resonances, rescattering,...)
- inflaton = dark matter ?

Based on

2105.05860 (Lebedev, Yoon)

2107.06292 (Lebedev, Smirnov, Solomko, Yoon)

+ review **2104.03342**

# Framework

General statement :

The **only** renormalizable coupling of the inflaton to the SM is

$$V_{\phi h} = \frac{1}{2} \lambda_{\phi h} \phi^2 H^\dagger H + \sigma_{\phi h} \phi H^\dagger H$$



On general grounds, expected to drive **reheating**

Scalar dark matter  $s$  :

$$V_{\phi s} = \frac{1}{4} \lambda_{\phi s} \phi^2 s^2 + \frac{1}{2} \sigma_{\phi s} \phi s^2$$

**NB:** neglect Higgs-DM coupling

Simplified cases:

$$(a) \quad V_{\phi s} = \frac{\lambda_{\phi s}}{4} \phi^2 s^2 \quad , \quad V_{\phi h} = \frac{\sigma_{\phi h}}{2} \phi h^2 \quad ,$$
$$(b) \quad V_{\phi s} = \frac{\sigma_{\phi s}}{2} \phi s^2 \quad , \quad V_{\phi h} = \frac{\sigma_{\phi h}}{2} \phi h^2 \quad ,$$
$$(c) \quad V_{\phi s} = \frac{\sigma_{\phi s}}{2} \phi s^2 \quad , \quad V_{\phi h} = \frac{\lambda_{\phi h}}{4} \phi^2 h^2 \quad .$$

Inflaton potential **after** inflation :

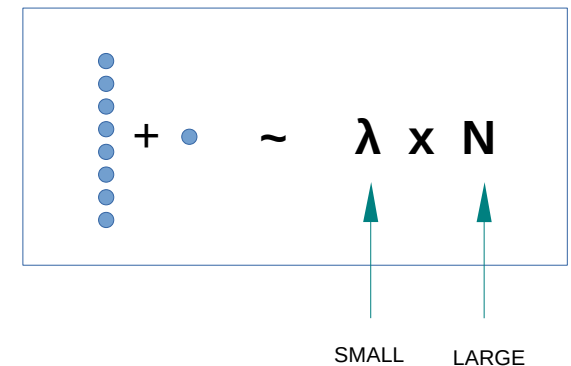
$$V_{\phi} = \frac{m_{\phi}^2}{2} \phi^2 \quad \text{or} \quad V_{\phi} = \frac{1}{4} \lambda_{\phi} \phi^4$$

Main challenge:

**complicated collective effects**

*(often invalidate perturbative description)*

Khlebnikov, Tkachev '96



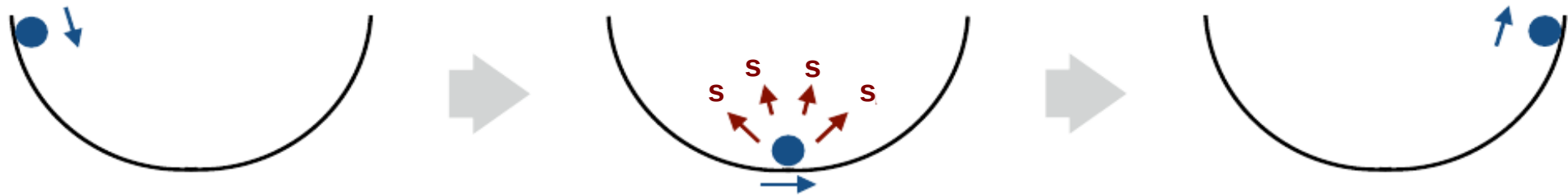
# Reheating + DM production in $\phi^2$

$$V_{\phi s} = \frac{\lambda_{\phi s}}{4} \phi^2 s^2, \quad V_{\phi h} = \frac{\sigma_{\phi h}}{2} \phi h^2$$

early (resonant) production

late time perturbative decay

inflaton



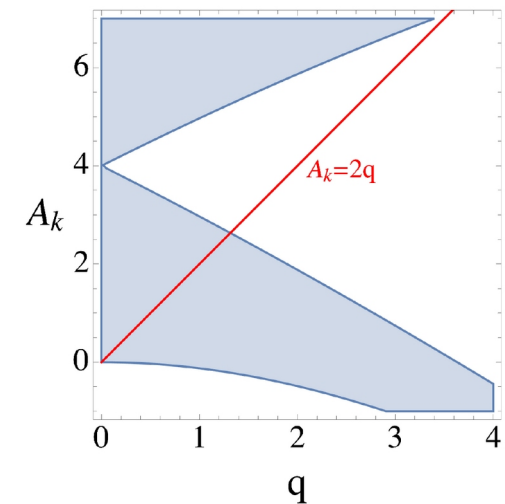
Linde, Kofman, Starobinsky '94

Equation of motion for the s-Fourier modes  $X_k$  (Mathieu eq.) :

$$X_k'' + (A_k + 2q \cos 4z) X_k = 0$$

$$q \equiv \frac{\lambda_{\phi s} \Phi^2}{2m_\phi^2}$$

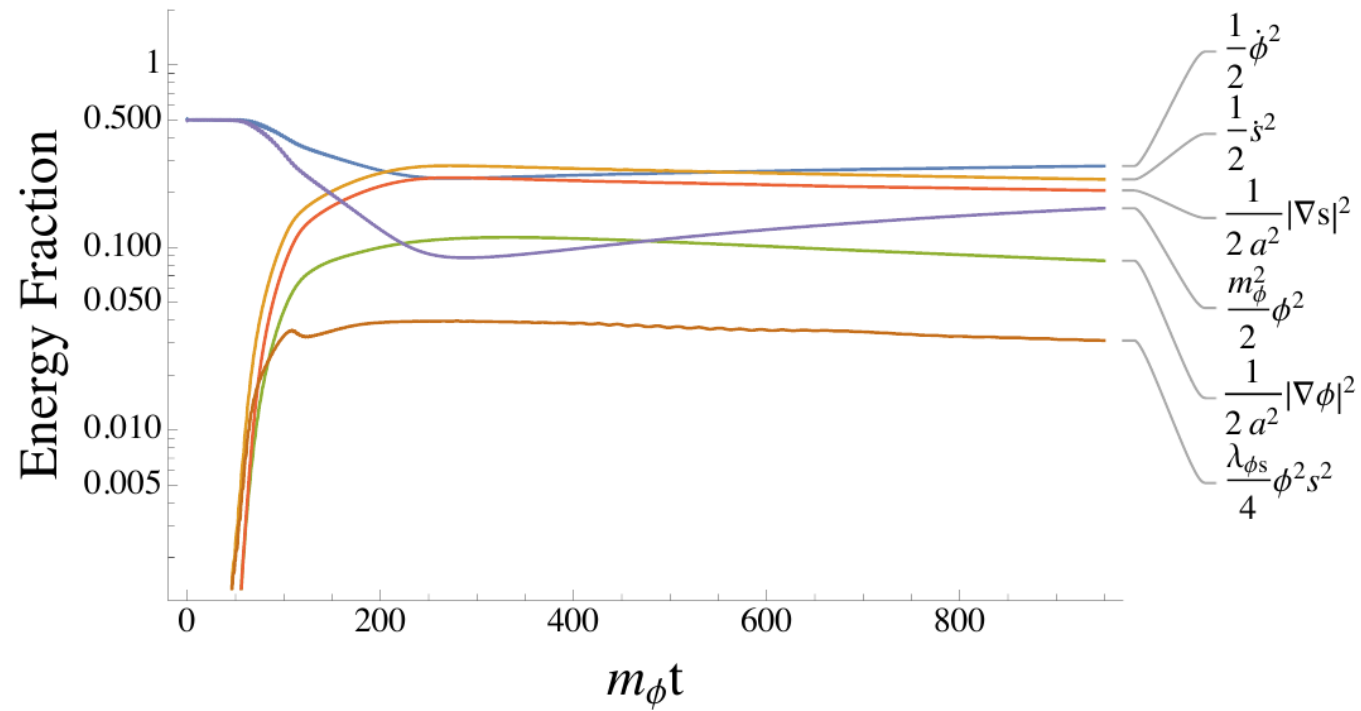
$$A_k \equiv \frac{4k^2}{m_\phi^2 a^2} + 2q$$



The Mathieu eq. neglects backreaction and rescattering

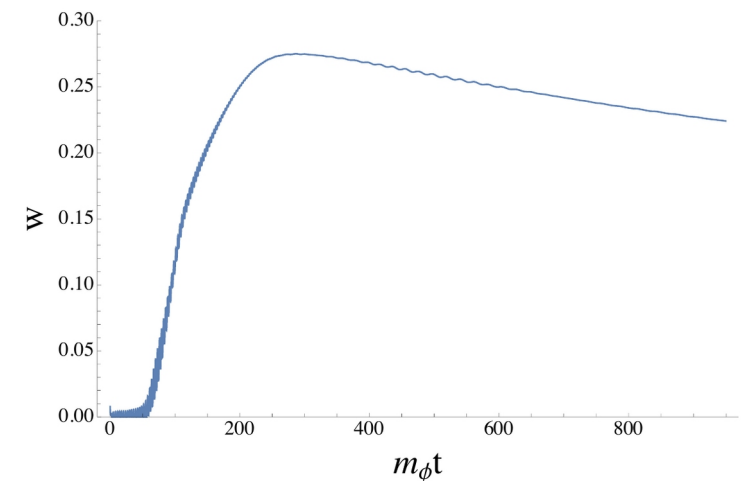


**lattice simulations**



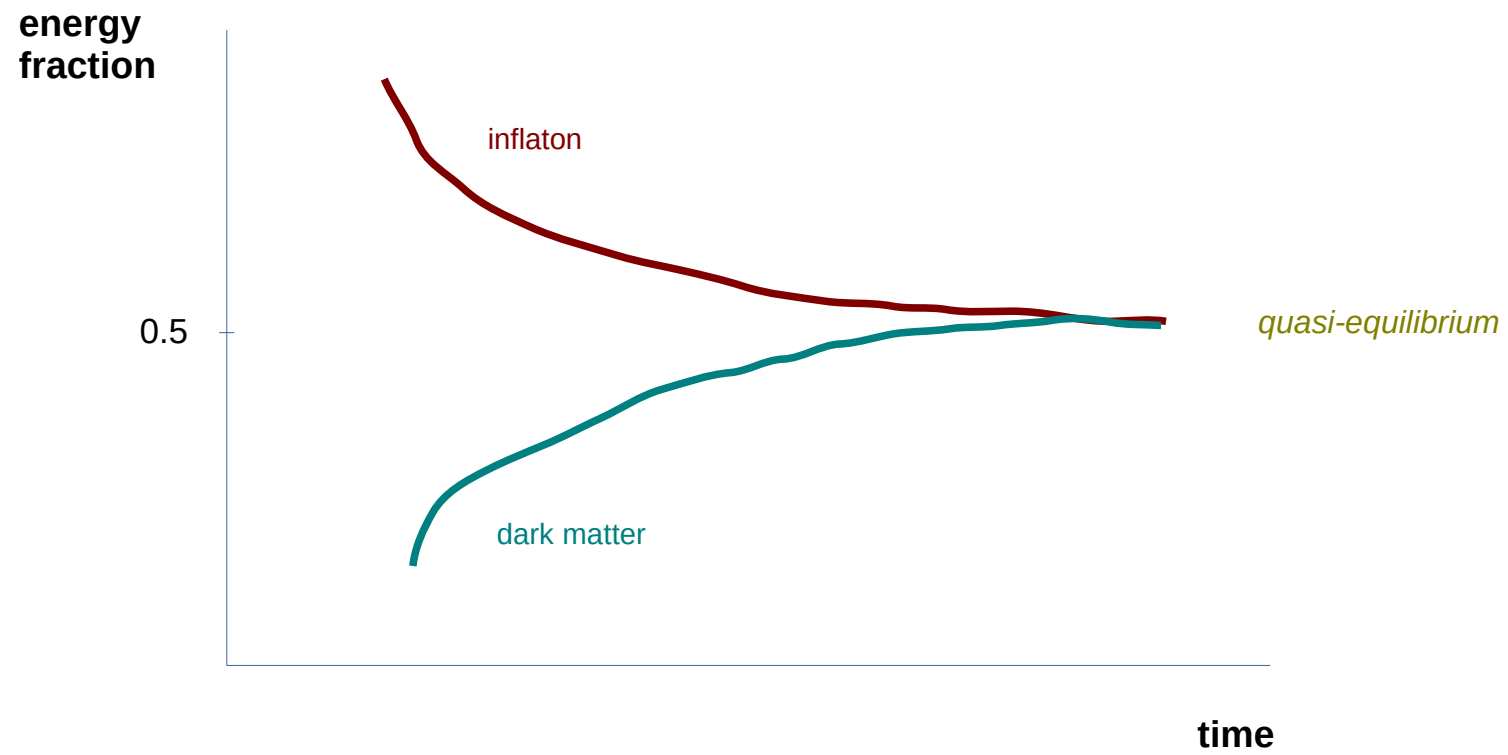
OL, Smirnov, Solomko, Yoon '21

- the inflaton background gets destroyed by DM rescattering
- the system becomes relativistic ( $w \sim 1/3$ )
- it reaches *quasi-equilibrium* during preheating



Schematically:

$\phi^2 s^2$  coupling



**Cannot transfer more than 50% of the inflaton energy at any coupling!**

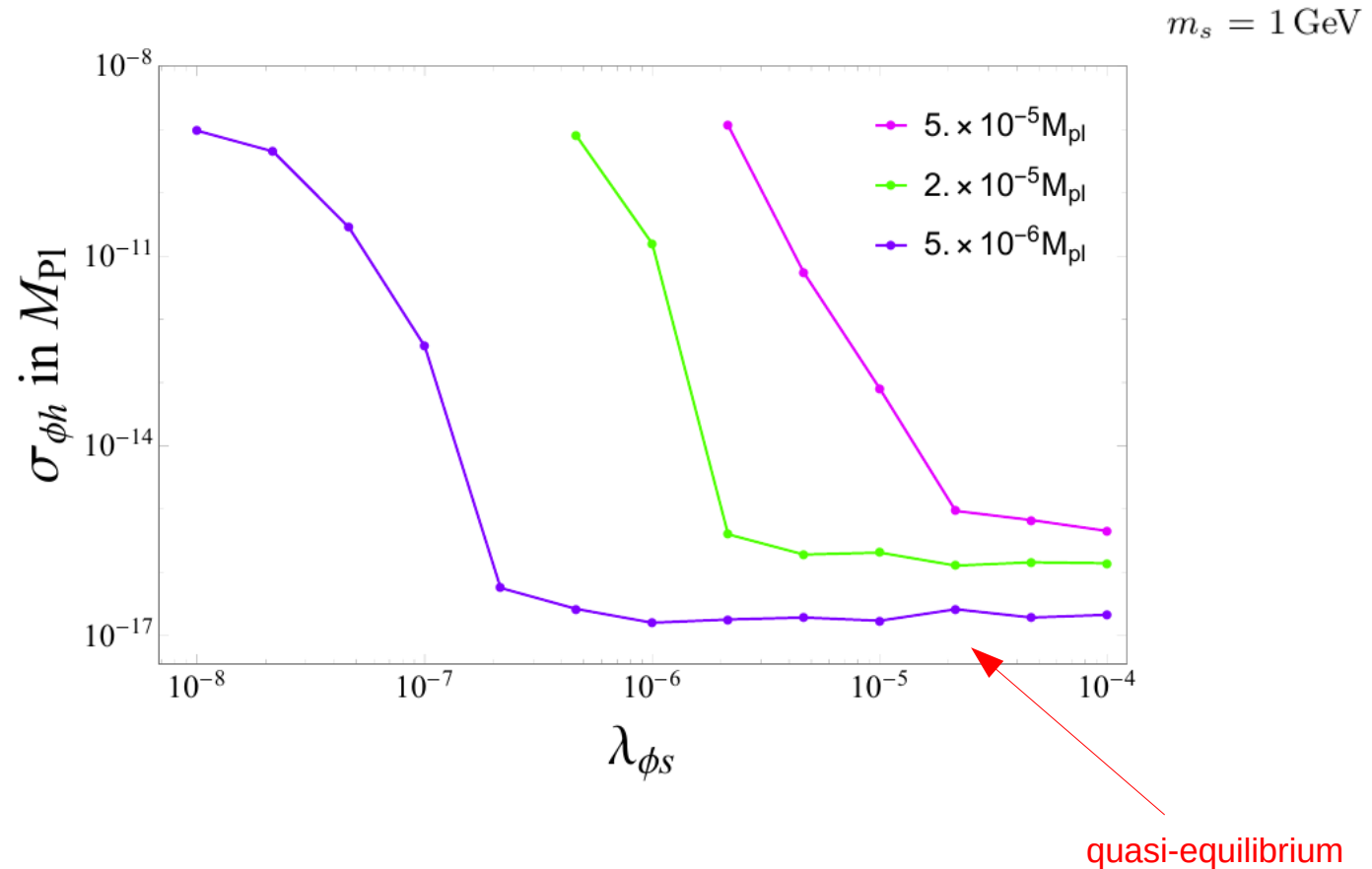
Reheating:

late time perturbative inflaton decay into **hh**

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

Correct relic DM abundance:

simulations  
+  
perturbative  
calculations



“Strong coupling” (still very weak):

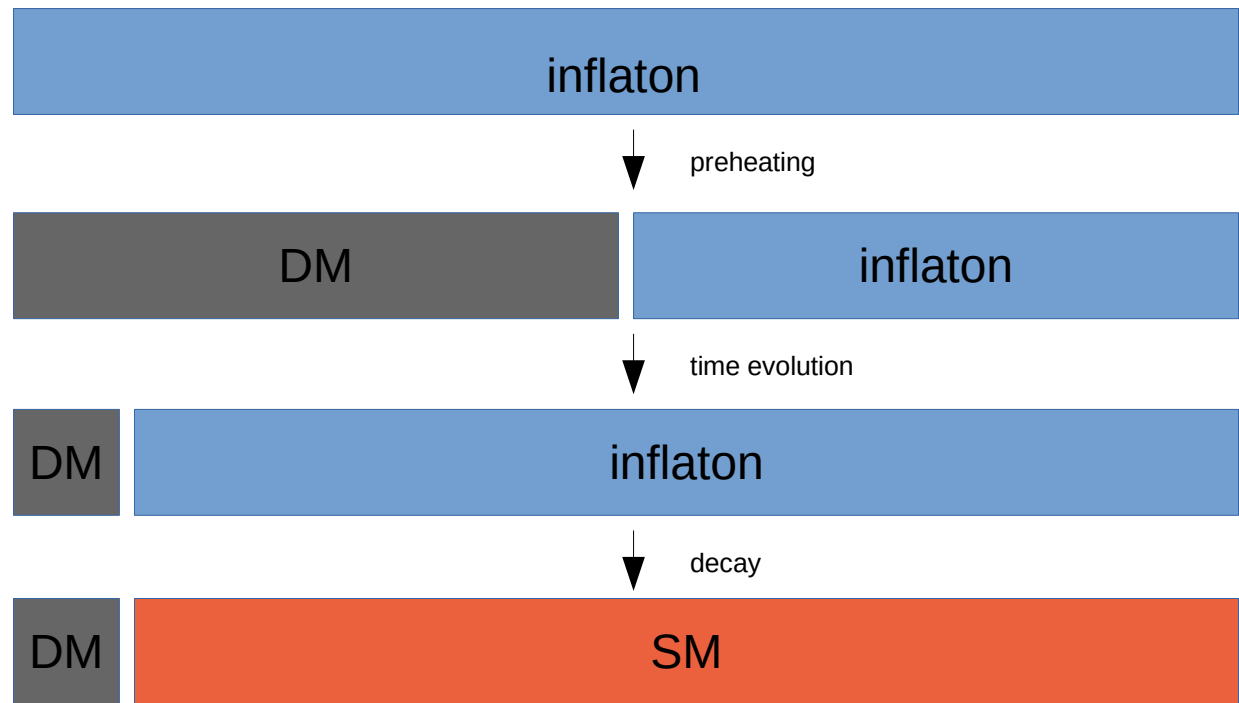
$$Y \simeq 0.4 \frac{\Gamma_{\phi \rightarrow hh}^{1/2}}{m_\phi}$$

Universal !

(no coupling dependence,  
no initial condition dependence)



Schematically:



# Reheating + DM production in $\phi^4$

Inflaton EOM :

$$\ddot{\phi} + 3H\dot{\phi} + \lambda_{\phi}\phi^3 = 0 \quad \rightarrow \quad \phi(t) = \frac{\Phi_0}{a(t)} \text{cn}\left(x, \frac{1}{\sqrt{2}}\right), \quad x \equiv (48\lambda_{\phi})^{1/4}\sqrt{t}$$

DM momentum mode EOM (Lame eq.) :

$$X_k'' + \left( \kappa^2 + \frac{\lambda_{\phi s}}{2\lambda_{\phi}} \text{cn}^2\left(x, \frac{1}{\sqrt{2}}\right) \right) X_k = 0, \quad \kappa^2 \equiv \frac{k^2}{\lambda_{\phi}\Phi_0^2}$$

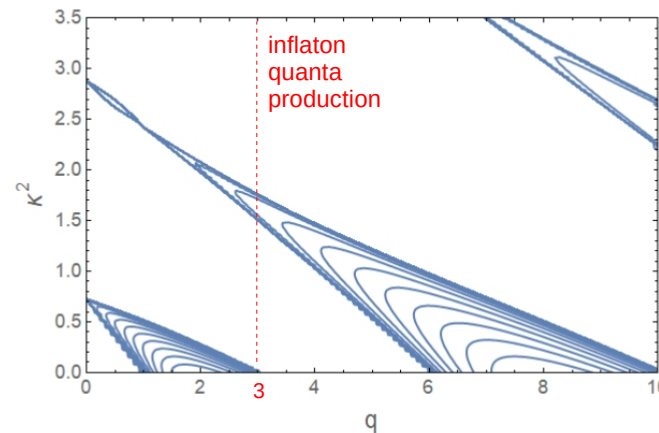
Greene, Linde, Kofman, Starobinsky '97

Inflaton fluctuation EOM (Lame eq. with  $q=3$ ) :

$$\varphi_k'' + \left[ \kappa^2 + 3 \text{cn}^2\left(x, \frac{1}{\sqrt{2}}\right) \right] \varphi_k = 0$$

**New feature !**

Stability chart:



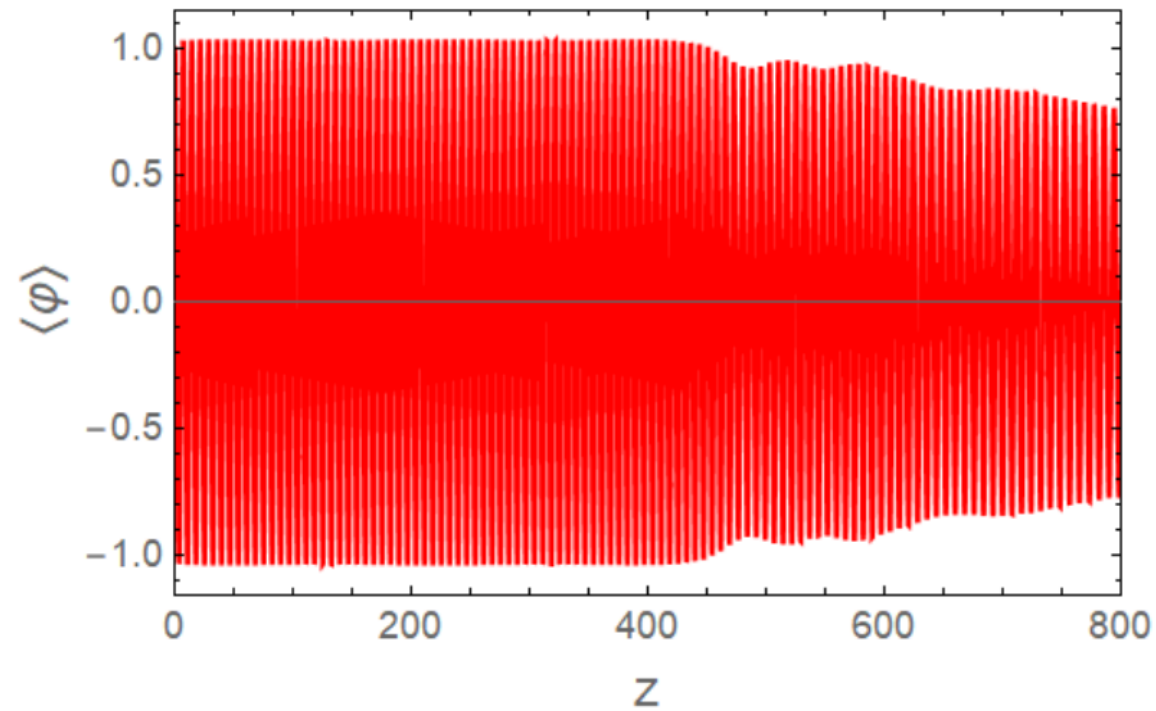
Resonant DM production at tiny couplings

as long as

$$\lambda_{\phi s} \gtrsim \lambda_{\phi}$$

New feature:

*inflaton fluctuation production in **pure**  $\phi^4$*



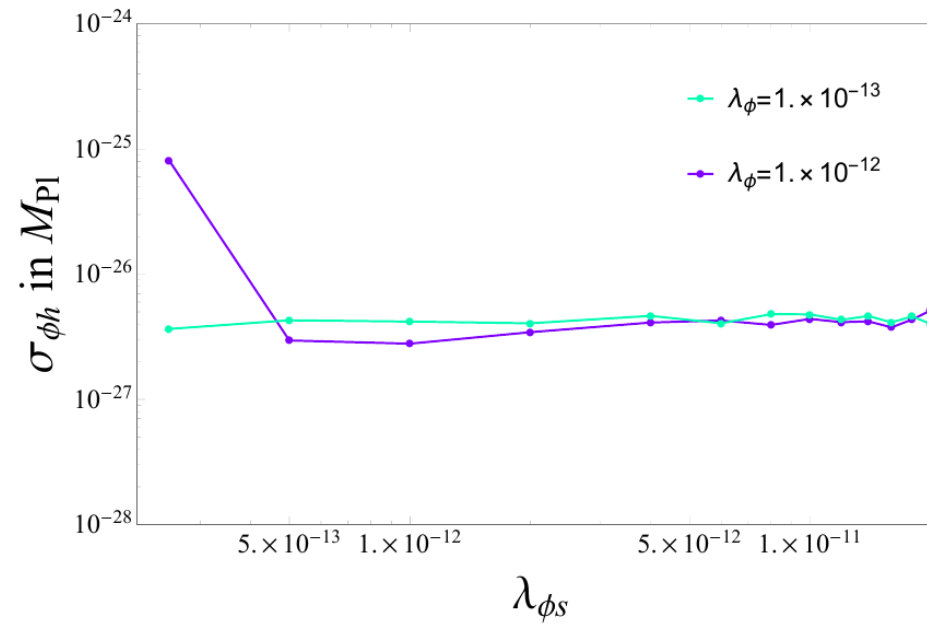
conformal time  $z$ :

$$dz = \sqrt{\lambda_\phi} \Phi_0 dt / a(t)$$

The inflaton background decays quickly!

Correct relic DM abundance:

1 eV (!) →



$m_{\phi} = 1 \text{ TeV}$   
 $m_s = 10 \text{ keV}$

Quasi—equilibrium sets in at

$$\lambda_{\phi s} \gtrsim \lambda_{\phi}$$



$$Y \simeq 0.4 \frac{\Gamma_{\phi \rightarrow hh}^{1/2}}{m_{\phi}}$$

(no coupling dependence,  
no initial condition dependence)

**Tiny couplings are sufficient!**

# Inflaton = DM ?

Lerner, McDonald '09

Minimal model :

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

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

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

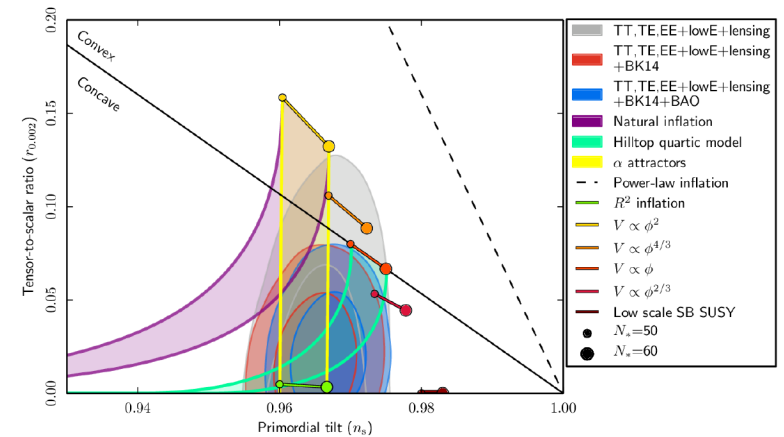
Inflation :

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

canonically normalized inflaton

Preheating :

$$V_E = \frac{1}{4} \lambda_{\phi h} h^2 \phi^2 + \frac{1}{4} \lambda_\phi \phi^4$$



Excellent fit!

Results:

(1) non—thermal: *too much DM*

Initially the Universe is totally DARK



need efficient SM production



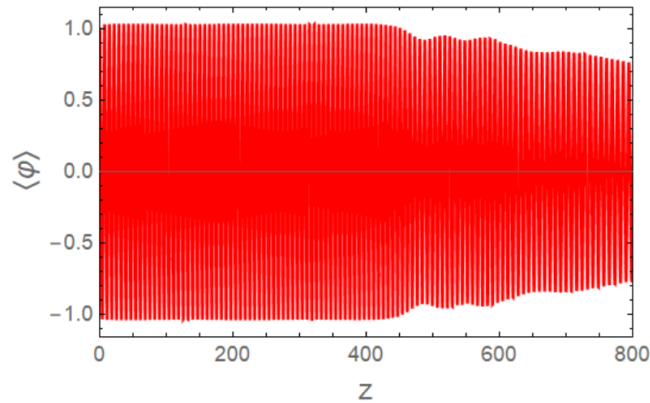
$$\lambda_{\phi h} \gtrsim \lambda_{\phi}$$

no resonant Higgs production



inflaton fluctuation production

$$\varphi_k'' + \left[ \kappa^2 + 3 \operatorname{cn}^2 \left( x, \frac{1}{\sqrt{2}} \right) \right] \varphi_k = 0$$



zero mode  
converts into  
fluctuations

suppressed SM matter production



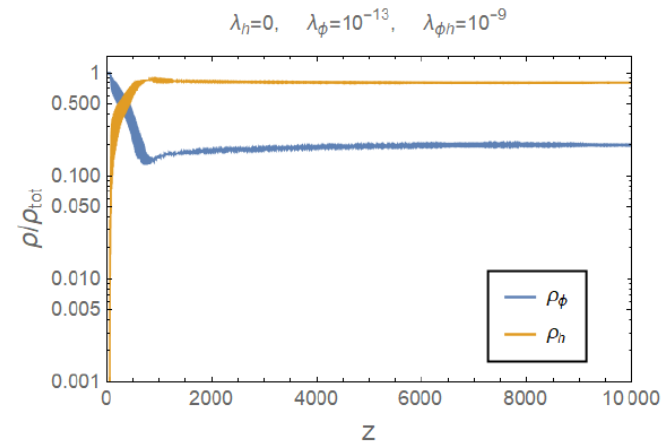
**Dark Universe**

resonant Higgs production



quasi—equilibrium

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



Higgs—inflaton  
quasi—equilibrium

$$Y_{\text{DM}} > 10^{-3}$$



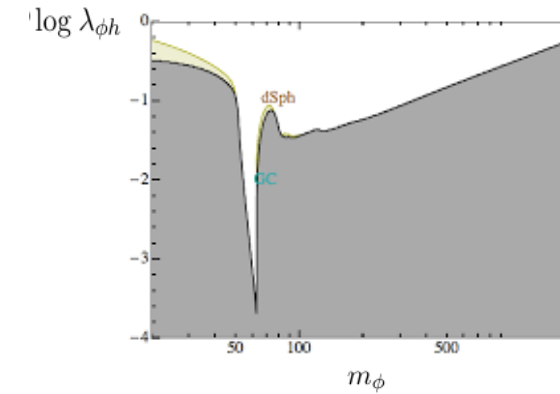
(2) thermal DM: **possible**

“singlet scalar DM” freeze-out

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



large loop correction to inflaton potential  
(loss of unitarity)



Exception:

**Higgs resonance**

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

$$\lambda_{\phi h} \gtrsim 10^{-4}$$



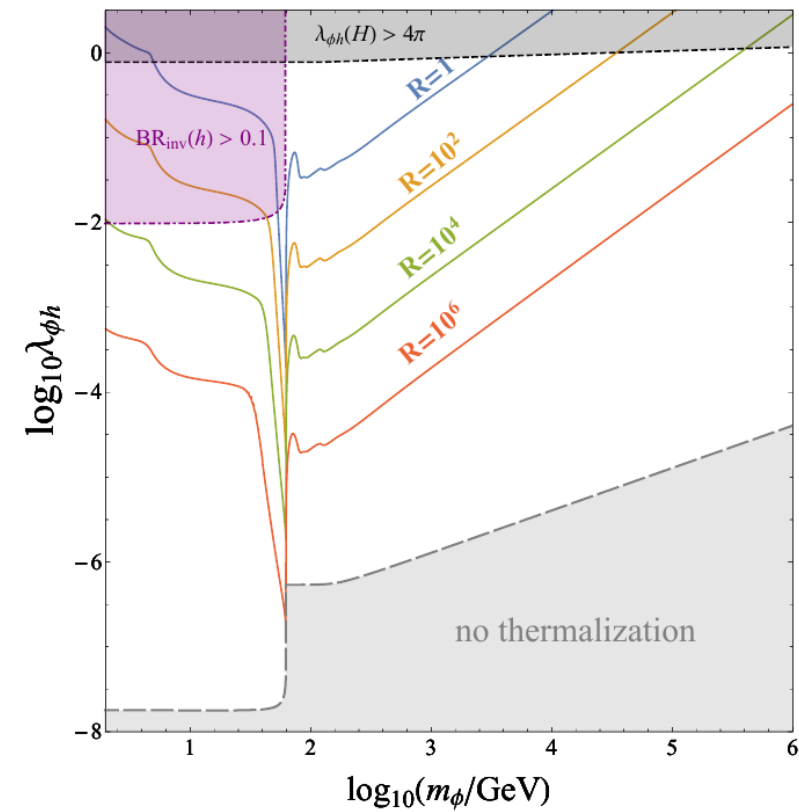
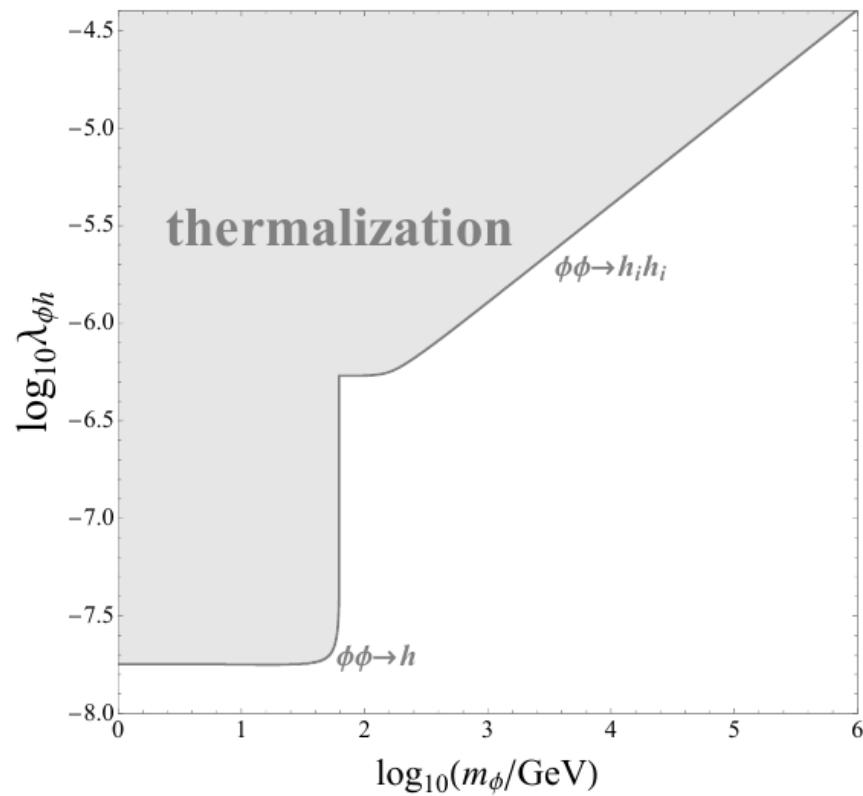
thermal inflaton DM

(in a very narrow mass range)

*NB: non-minimal models viable*

## Inflaton freeze-out

An inflaton can *thermalize* via  $\phi\phi \leftrightarrow h_i h_i$ , *freeze-out* and *decay* into DM  $\phi \rightarrow ss$



DM relic abundance is automatically suppressed



## CONCLUSION

- *collective effects are essential*
- *quasi-equilibrium in the inflaton-DM system*
- *breakdown of perturbative approach*
- *minimal inflaton DM model: thermal DM, tuned inflaton mass*