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:

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

Inflaton potential **after** inflation :

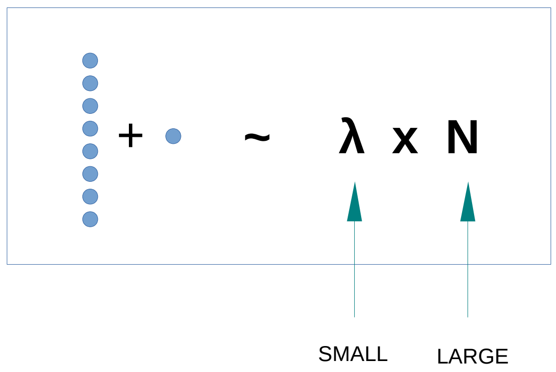
$$V_\phi = \frac{m_\phi^2}{2}\phi^2$$ or $$V_\phi = \frac{1}{4}\lambda_\phi \phi^4$$

Main challenge:

complicated collective effects

(*often invalidate perturbative description*)

Khlebnikov,Tkachev '96

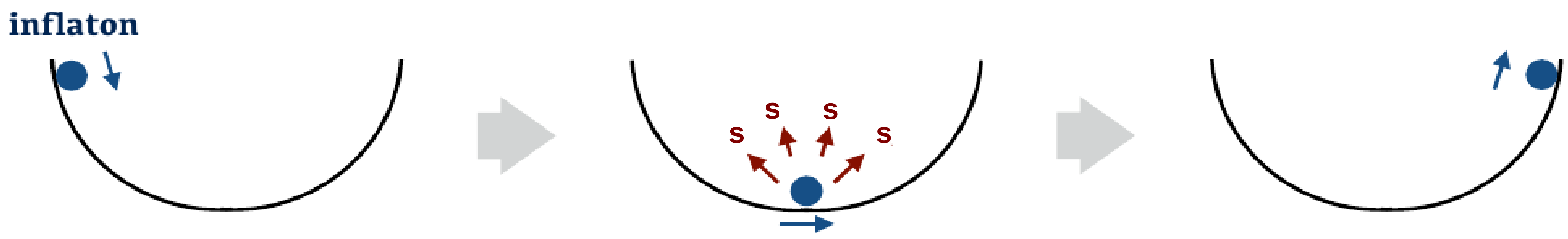


Reheating + DM production in ϕ^2

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

early (resonant) production

late time perturbative decay

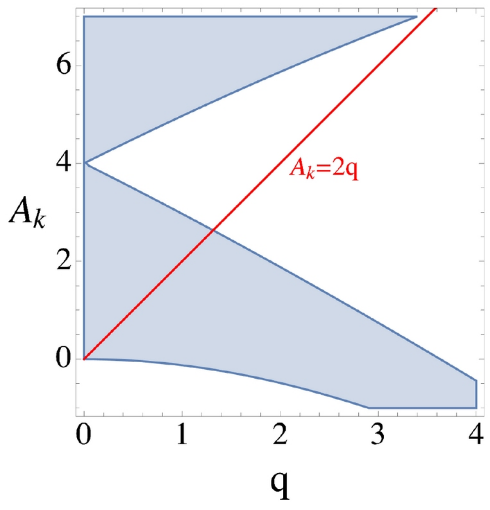


Linde,Kofman,Starobinsky '94

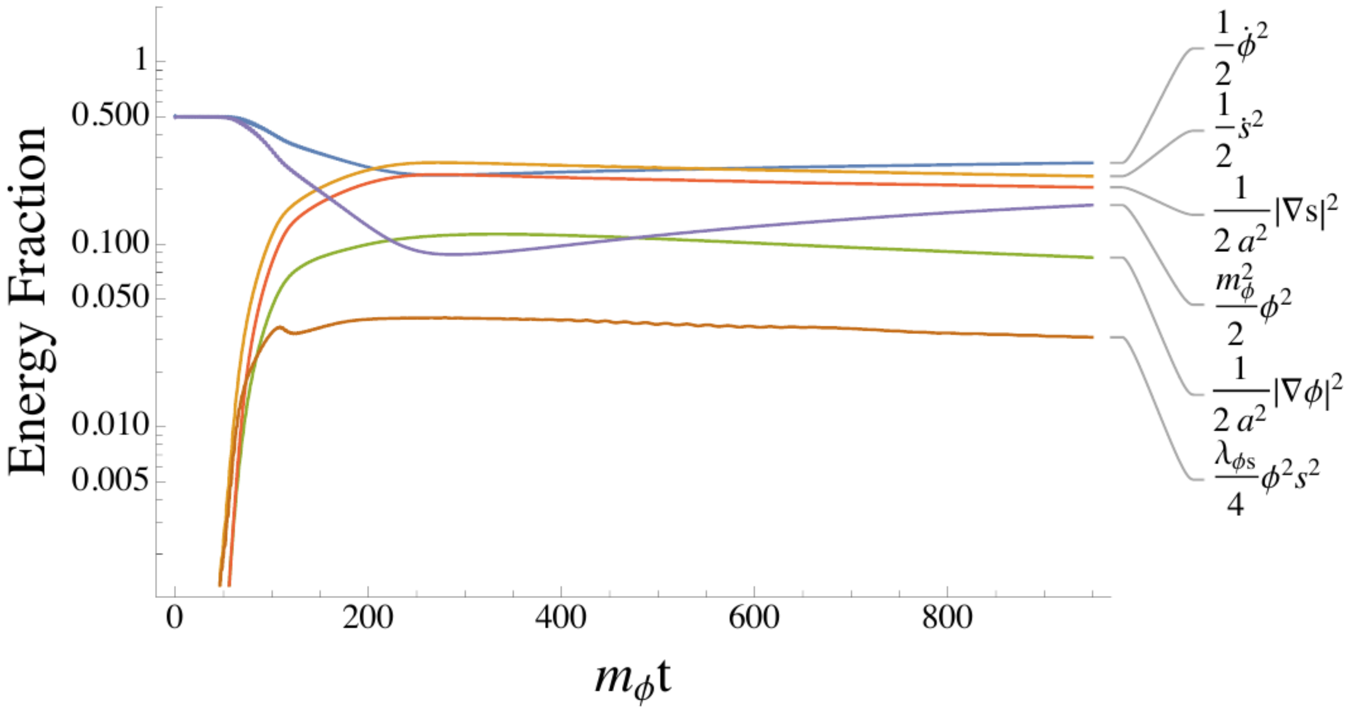
Equation of motion for the s-Fourier modes X_k (Mathieu eq.) :

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

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



The Mathieu eq. neglects backreaction and rescattering → **lattice simulations**

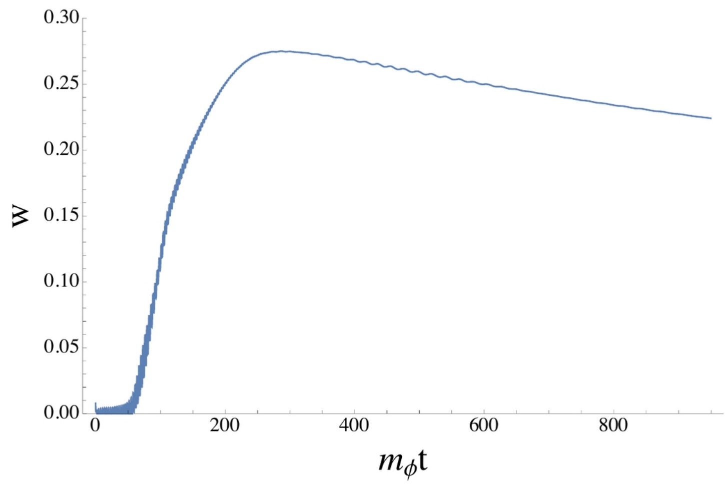


OL, Smirnov, Solomko,Yoon ' 21

– the inflaton background gets destroyed by DM rescattering

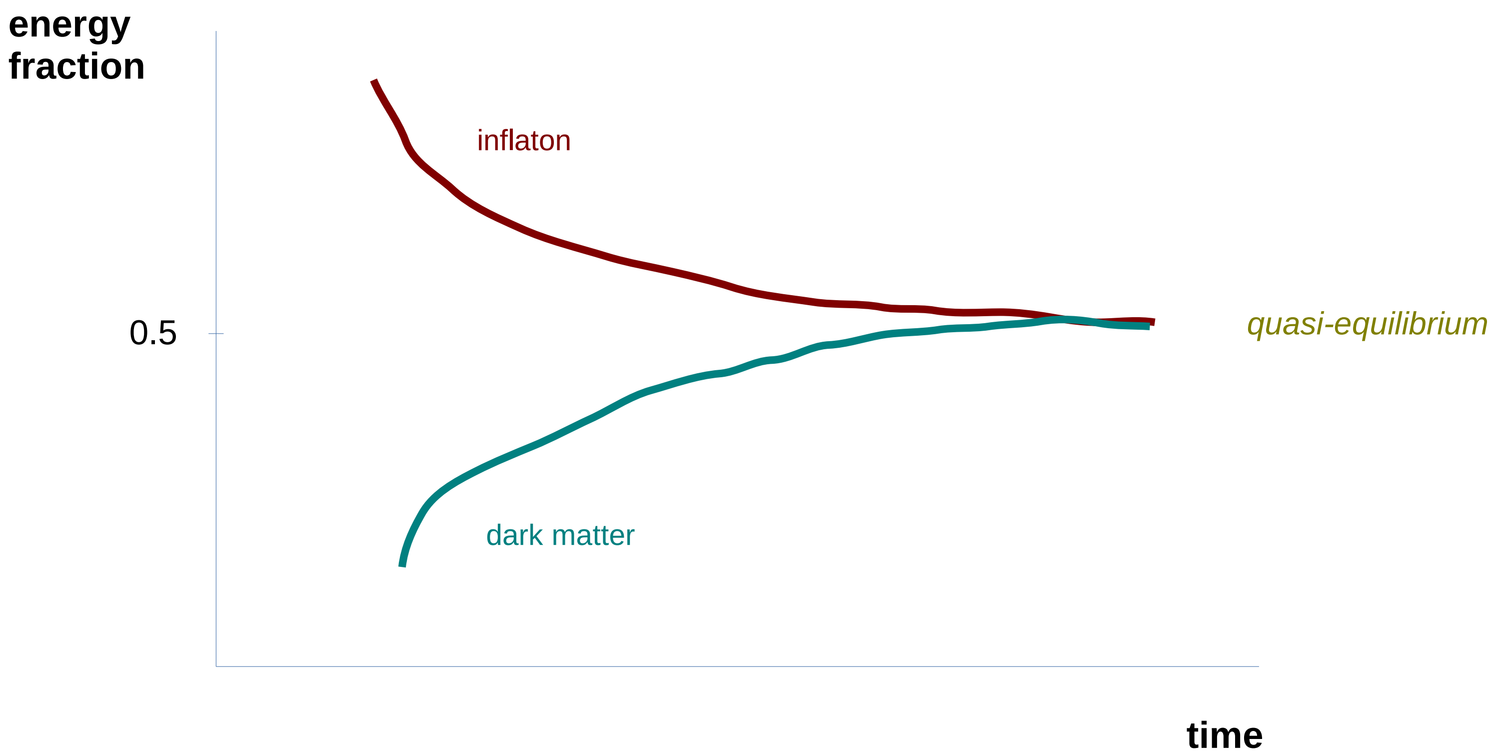
– the system becomes relativistic (w ~ 1/3)

– it reaches *quasi-equilibrium* during preheating



Schematically:

$\phi^2 s^2$ coupling



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

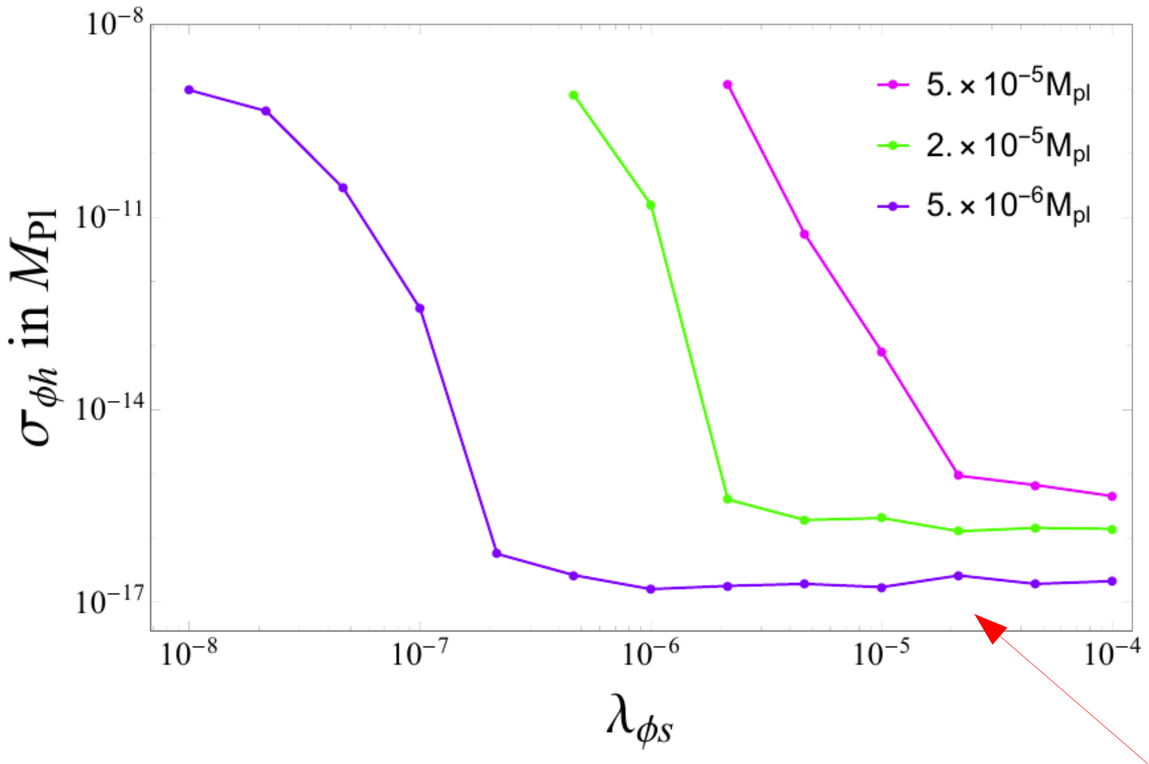
<u>Reheating</u>: late time perturbative inflaton decay into **hh**

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

Correct relic DM abundance:

simulations
+
perturbative
calculations

$m_s = 1\,\mathrm{GeV}$



quasi-equilibrium

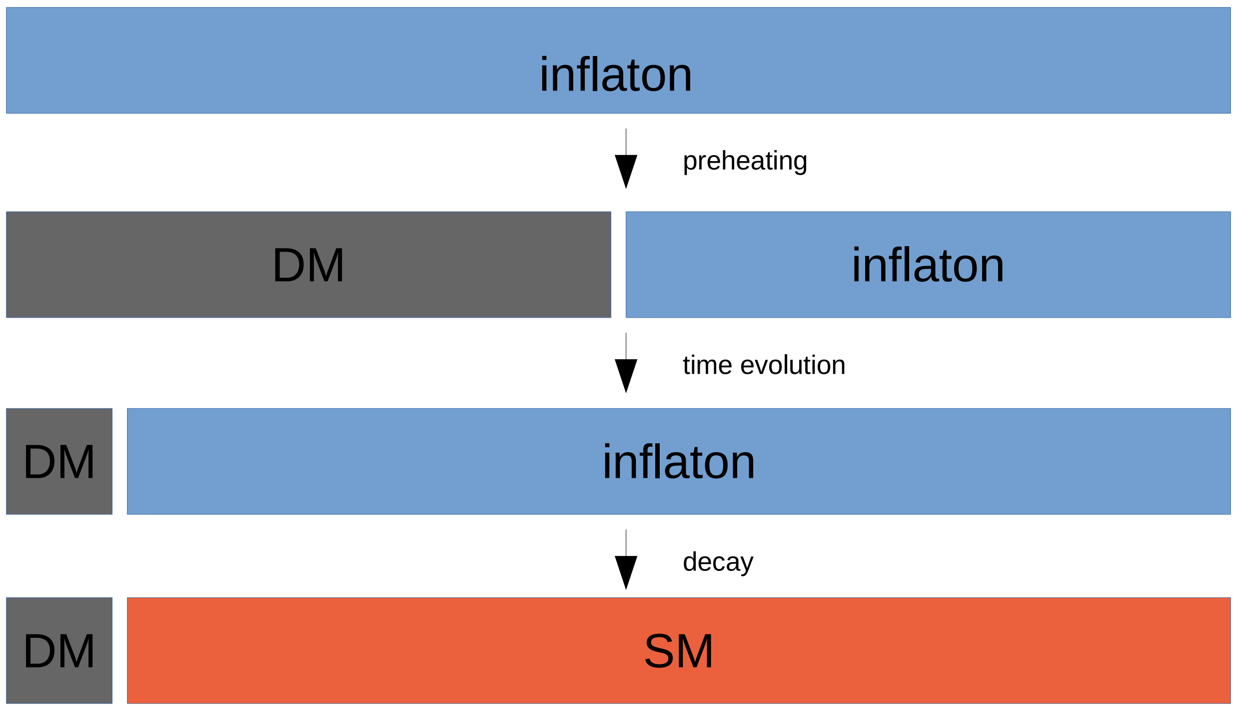
“Strong coupling” (*still very weak*):

$$Y \simeq 0.4\, \frac{\Gamma^{1/2}_{\phi\to hh}}{m_\phi}$$

Universal !

(no coupling dependence,
no initial condition dependence)

Schematically:



Reheating + DM production in ϕ^4

Inflaton EOM :

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

DM momentum mode EOM (Lame eq.) :

Greene,Linde,Kofman,Starobinsky '97

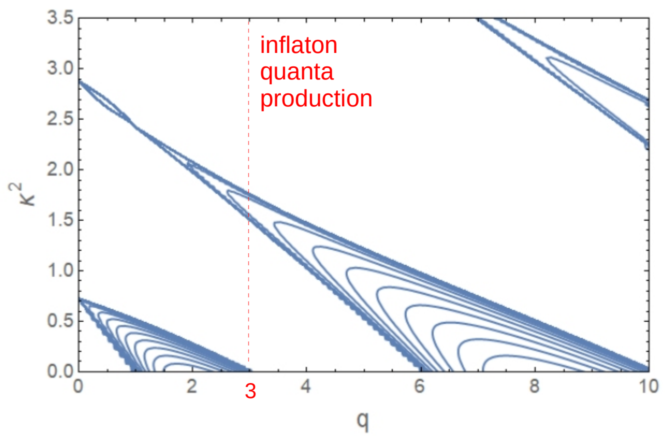
$$X_k'' + \left(\kappa^2 + \underbrace{\frac{\lambda_{\phi s}}{2\lambda_\phi}}_{q} \mathrm{cn}^2\left(x, \frac{1}{\sqrt{2}}\right)\right) X_k = 0, \quad \kappa^2 \equiv \frac{k^2}{\lambda_\phi \Phi_0^2}$$

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

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

New feature !

Stability chart:



Resonant DM production at tiny couplings

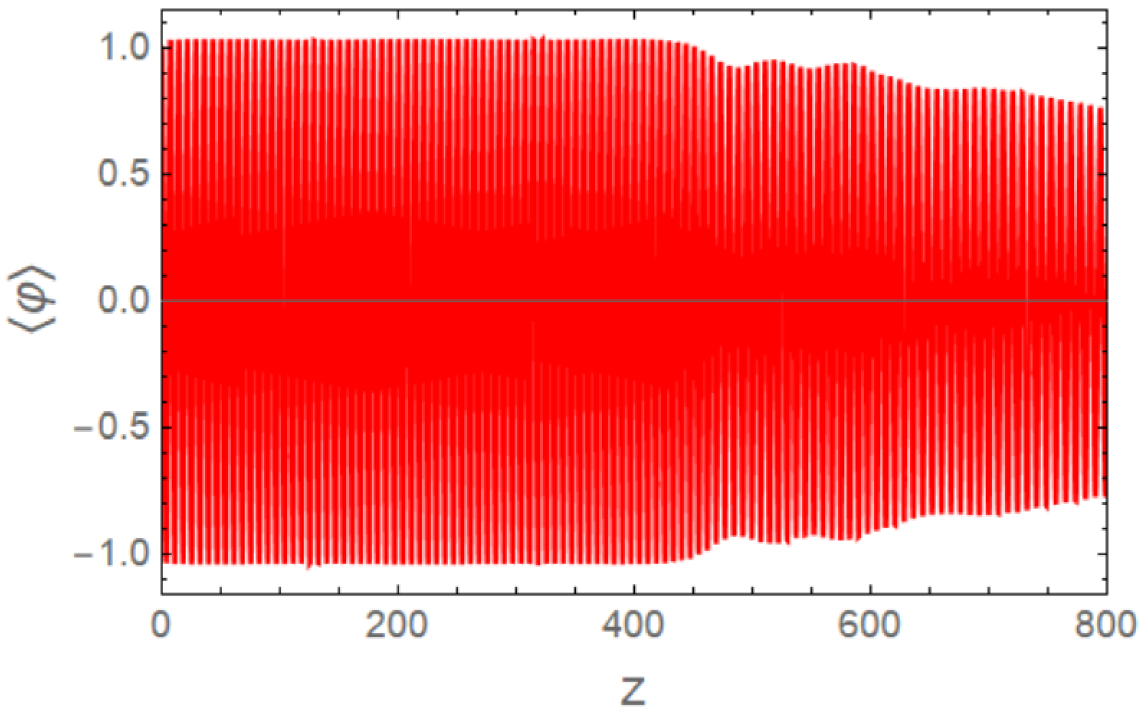
as long as

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

Khlebnikov,Tkachev ‘96

New feature:

*inflaton fluctuation production in **pure*** ϕ^4



conformal time z:

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

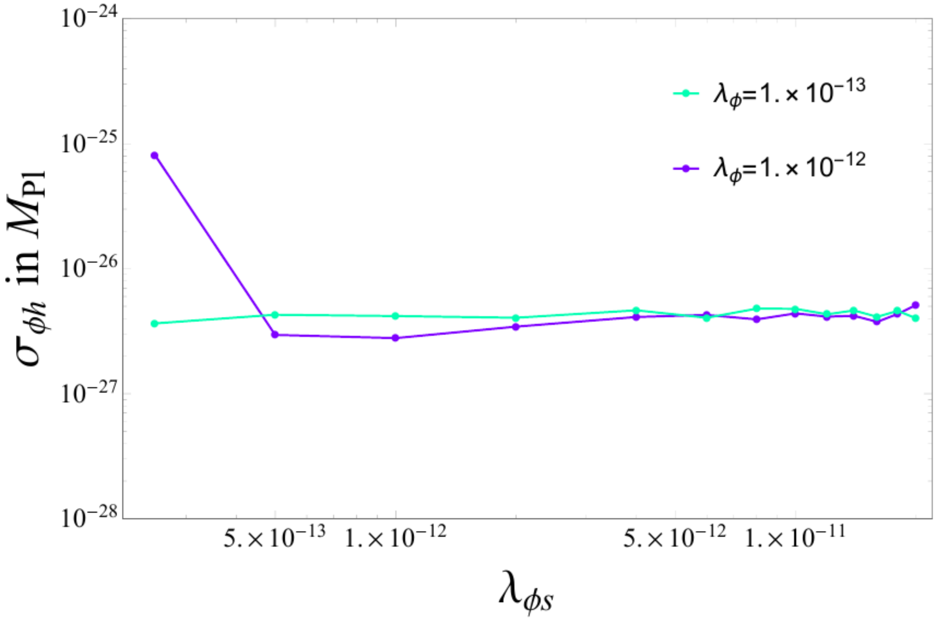
The inflaton background decays quickly!

Correct relic DM abundance:

$$m_\phi = 1\,\mathrm{TeV}$$

$$m_s = 10\,\mathrm{keV}$$

1 eV (!)



Quasi—equilibrium sets in at

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

$$Y \simeq 0.4\,\frac{\Gamma^{1/2}_{\phi\to hh}}{m_\phi}$$

(no coupling dependence,
no initial condition dependence)

Tiny couplings are sufficient!

Inflaton = DM ?

Minimal model :

Lerner, McDonald '09

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

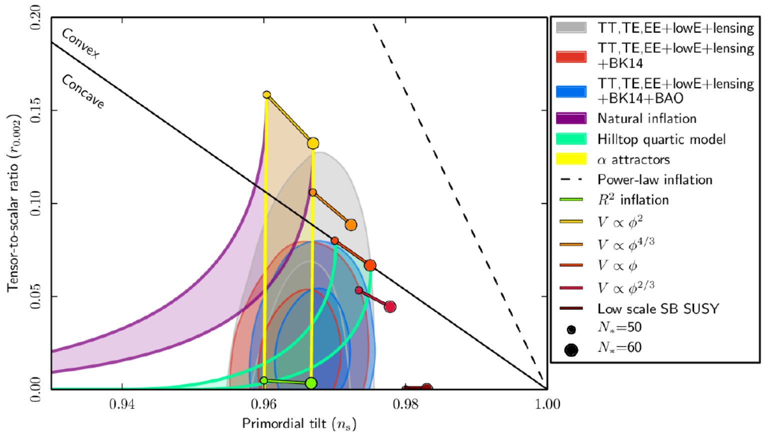
$$\Omega = 1 + \xi_h h^2 + \xi_\phi \phi^2$$

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

Inflation :

canonically normalized inflaton

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



Excellent fit!

Preheating :

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

Results:

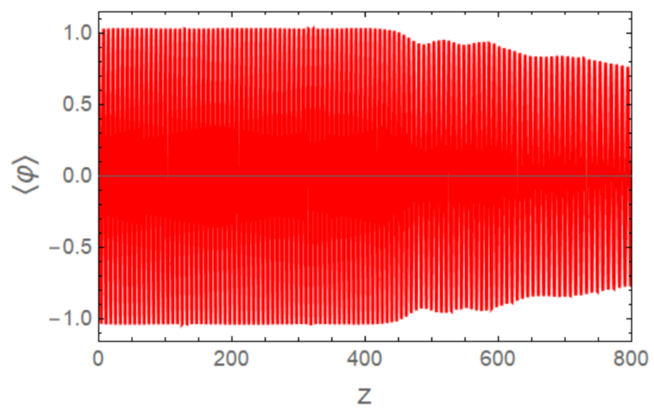
(1) non—thermal: ***too much DM***

Initially the Universe is totally DARK ➡ need efficient SM production ➡ $\lambda_{\phi h} \gtrsim \lambda_\phi$

no resonant Higgs production
⬇
inflaton fluctuation production

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

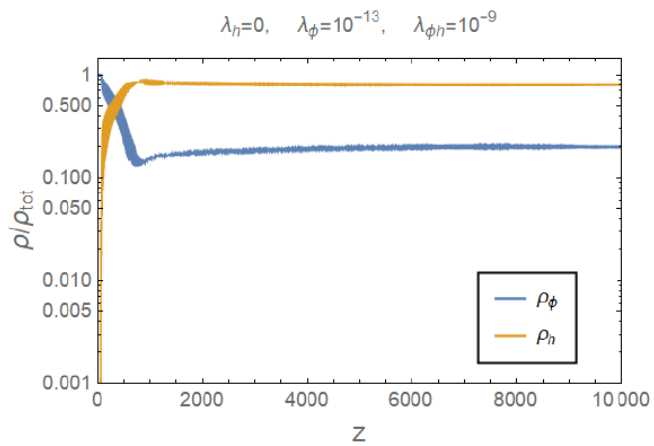
zero mode converts into fluctuations



suppressed SM matter production

resonant Higgs production
⬇
quasi--equilibrium

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



Higgs—inflaton quasi--equilibrium

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

Dark Universe

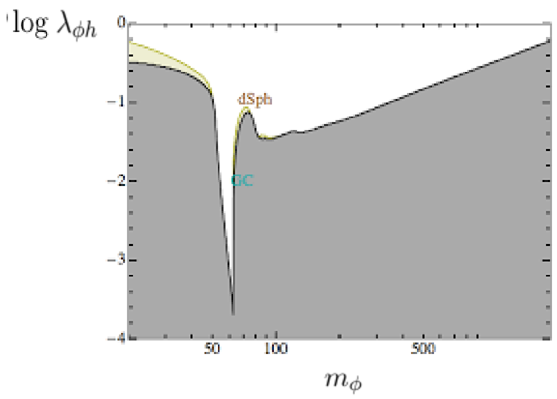
OL, Yoon ‘21

(2) thermal DM: ***possible***

“*singlet scalar DM*” freeze--out

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

large loop correction to inflaton potential
(loss of unitarity)



Exception:

Higgs resonance

$$m_\phi \simeq m_{h_0}/2$$
$$\lambda_{\phi h} \gtrsim 10^{-4}$$

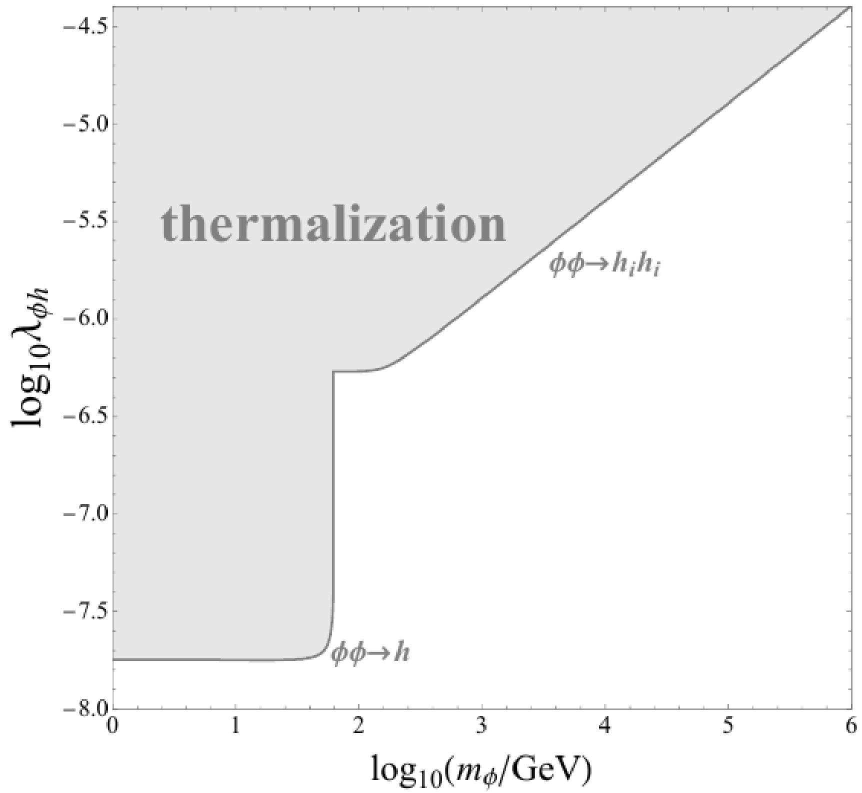
→ thermal inflaton DM

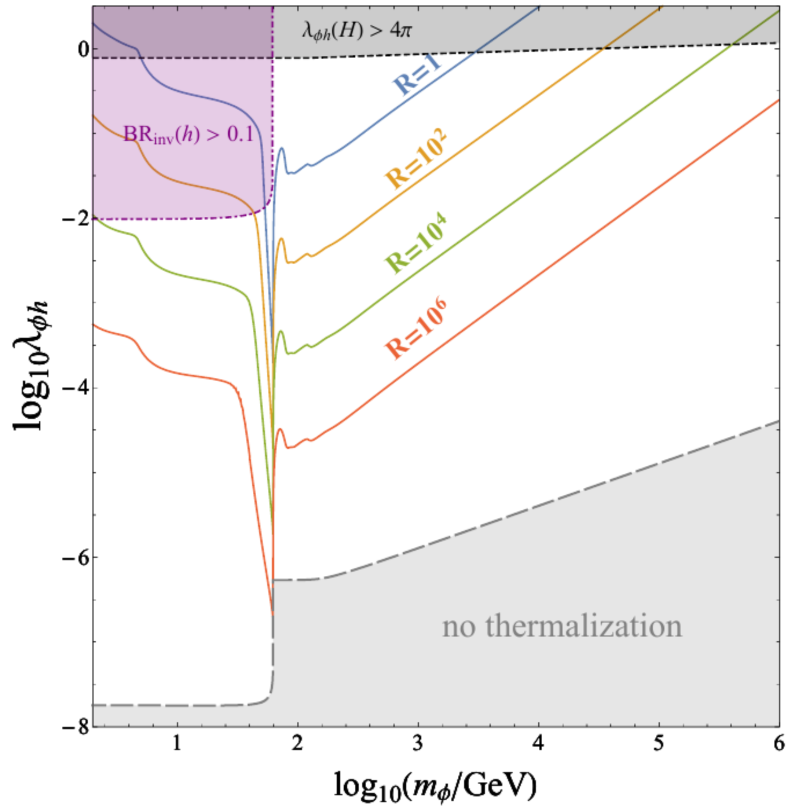
(in a very narrow mass range)

NB: non-minimal models viable Garcia, Mambrini, Olive, Verner ‘21

Inflaton freeze-out

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





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*