31/10/22

AstroParticle Symposium

INSTITUT PASCAL

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Inflation, preheating, reheating: signatures and codes

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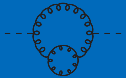
Instituto de Física UNAM

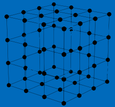
1. **Perturbative reheating**

2. **Thermalization**



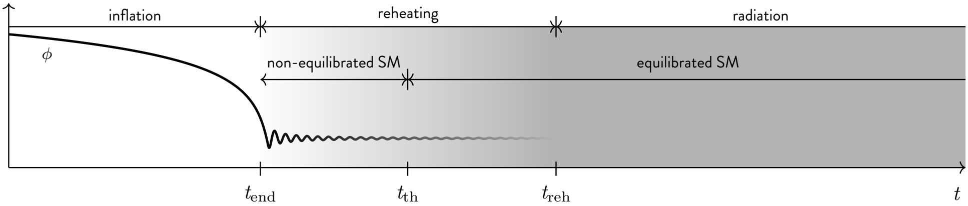
3. **Preheating**

4. **Backreaction**



5. **Signals**

Introducing reheating



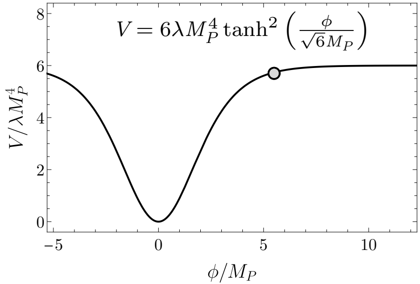
Inflation: a slowly-rolling scalar in FRW, $ds^2 = dt^2 - a(t)^2\, d\mathbf{x}^2$

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

$$H \equiv \frac{\dot{a}}{a} = \left(\frac{\rho_\phi}{3M_P^2}\right)^{1/2}$$

$$\frac{1}{2}\dot{\phi}^2 + V(\phi) = \rho_\phi$$

$$\frac{1}{2}\dot{\phi}^2 - V(\phi) = p_\phi$$



R. Kallosh and A. Linde, JCAP 10 (2013), 033

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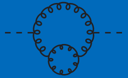

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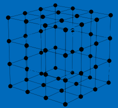

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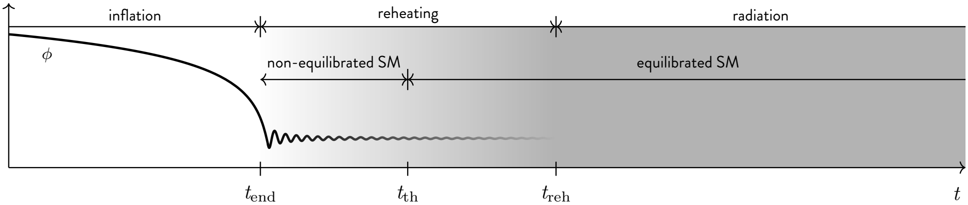
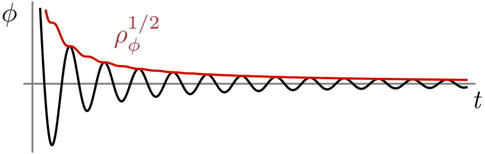


The end of inflation: $\ddot{a} = 0 \quad \Leftrightarrow \quad w = -1/3 \quad \Leftrightarrow \quad \dot{\phi}^2 = V(\phi)$



quadratic minimum ≈ matter

$$\phi(t) \simeq \phi_0(t)\mathcal{P}(t) = \phi_0(t)\sum_n \mathcal{P}_n e^{-in\omega t}$$

$$\langle \dot{\phi}^2 \rangle \simeq \langle \phi V'(\phi) \rangle$$

$$\rho_\phi \simeq 2\langle V(\phi) \rangle = V(\phi_0)$$

$$p_\phi \simeq 0$$

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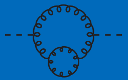

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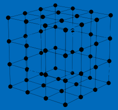

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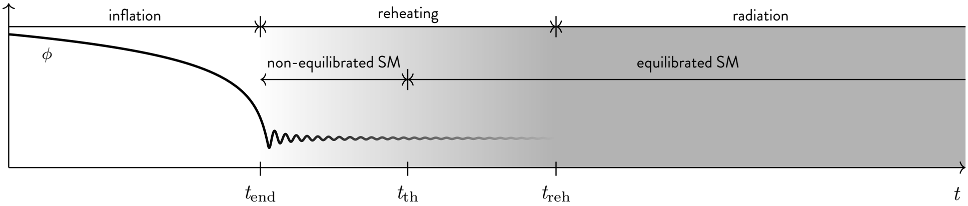

Perturbative reheating: energy exchange between ideal fluids

$$\ddot{\phi} + (3H + \Gamma_\phi)\dot{\phi} + V'(\phi) = 0 \quad \Rightarrow \quad \dot{\rho}_\phi + 3H\rho_\phi = -\Gamma_\phi \rho_\phi$$

$$\begin{aligned} T^{\mu\nu} &= T^{\mu\nu}_\phi + T^{\mu\nu}_R \\ &= \rho_\phi \,\mathrm{diag}(1,0,0,0) + \rho_R \,\mathrm{diag}(1, \tfrac{1}{3}, \tfrac{1}{3}, \tfrac{1}{3}) \end{aligned}$$

$$\nabla_\mu T^{\mu\nu} = 0 \quad \Rightarrow \quad \dot{\rho}_R + 4H\rho_R = \Gamma_\phi \rho_\phi$$

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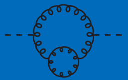

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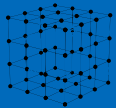

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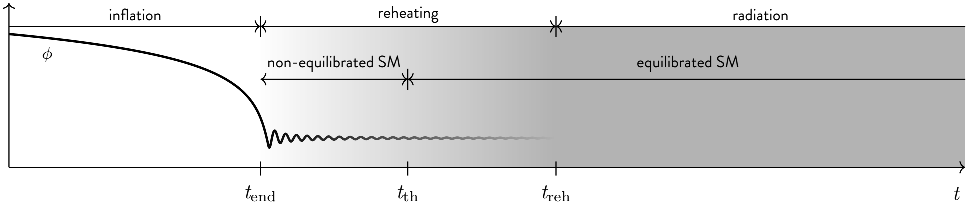
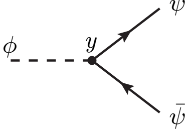
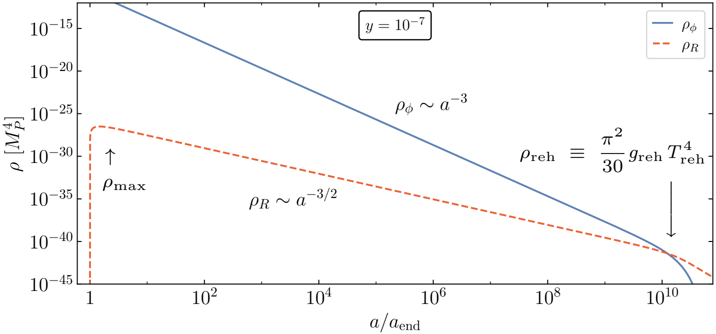




$$\Gamma_\phi = \frac{y^2}{8\pi} m_\phi$$



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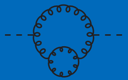

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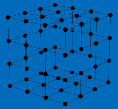
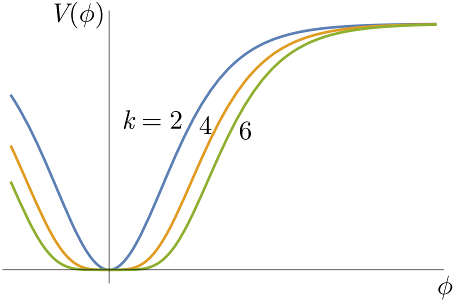


5. Signals

Non-quadratic minimum



$$V(\phi) \;=\; \lambda M_P^4 \left[\sqrt{6}\tanh\left(\frac{\phi}{\sqrt{6}M_P}\right)\right]^k$$

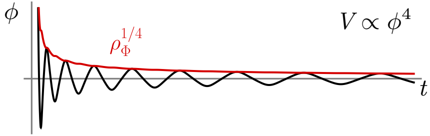
$$\xrightarrow{\phi \ll M_P} \quad \lambda \frac{\phi^k}{M_P^{k-4}}$$

R. Kallosh and A. Linde, JCAP 07 (2013), 002

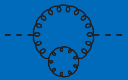
$$\begin{aligned} \phi(t) &\simeq \phi_0(t)\mathcal{P}(t) \\ &= \phi_0(t)\sum_n \mathcal{P}_n e^{-in\omega t} \end{aligned}$$

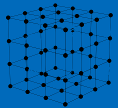
$$\rho_\phi \simeq \frac{k+2}{2}\langle V(\phi)\rangle = V(\phi_0)$$

$$p_\phi \simeq \frac{k-2}{k+2} V(\phi_0)$$



quartic minimum ≈ radiation





Non-quadratic minimum

More careful Boltzmann treatment:

$$\frac{\partial f_R}{\partial t} - H|\boldsymbol{P}|\frac{\partial f_R}{\partial |\boldsymbol{P}|} = \frac{1}{P^0}\sum_{n=1}^{\infty}\int \frac{d^3\boldsymbol{K}}{(2\pi)^3 n_\phi}\frac{d^3\boldsymbol{P}'}{(2\pi)^3 2P'^0}(2\pi)^4\delta^{(4)}(K_n - P - P')|\overline{\mathcal{M}_n}|^2$$
$$\times\Big[f_\phi(K)(1\pm f_R(P))(1\pm f_R(P')) - f_R(P)f_R(P')(1+f_\phi(K))\Big]$$

condensate PSD

$$f_\phi(P,t) = (2\pi)^3 n_\phi(t)\delta^{(3)}(\boldsymbol{P})$$

oscillation mode energy

$$K_n = (E_n, \boldsymbol{0}) = (n\omega_\phi(t), \boldsymbol{0})$$

↓

$$\dot\rho_\phi + 3H(1+w_\phi)\rho_\phi = -\Gamma_\phi(1+w_\phi)\rho_\phi$$
$$\dot\rho_R + 4H\rho_R = \Gamma_\phi(1+w_\phi)\rho_\phi$$

$$\Gamma_\phi = \frac{1}{8\pi(1+w_\phi)\rho_\phi}\sum_{n=1}^{\infty}\left\langle |\mathcal{M}_n|^2 E_n\beta_n\right\rangle, \quad \beta_n = \sqrt{\left(1-\frac{(m_1+m_2)^2}{E_n^2}\right)\left(1-\frac{(m_1-m_2)^2}{E_n^2}\right)}$$

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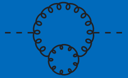

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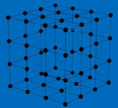
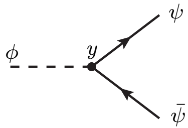


5. **Signals**

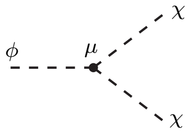
Nature of final state matters!

$$\mathcal{L} \supset y\,\phi\bar{\psi}\psi$$



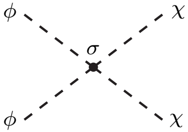
$$\Gamma_\phi = \frac{y(k)^2}{8\pi} m_\phi(t)$$

$$\mathcal{L} \supset \mu\,\phi\chi\chi$$



$$\Gamma_\phi = \frac{\mu(k)^2}{8\pi m_\phi(t)}$$

$$\mathcal{L} \supset \frac{1}{2}\sigma\,\phi^2\chi^2$$



$$\Gamma_\phi = \frac{\sigma(k)^2 \rho_\phi(t)}{32\pi m_\phi(t)^3}$$

$$\Gamma_\phi(t) \propto \left(\frac{\rho_\phi}{M_P^4}\right)^\ell$$

MG, K. Kaneta, Y. Mambrini, K. A. Olive, PRD 101 (2020), 123507
MG, K. Kaneta, Y. Mambrini, K. A. Olive, JCAP 04 (2021), 012
MG, M. Pierre, S. Verner, arXiv:2206.08940 [hep-ph]

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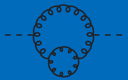

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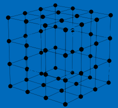

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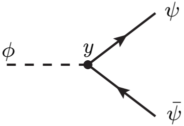

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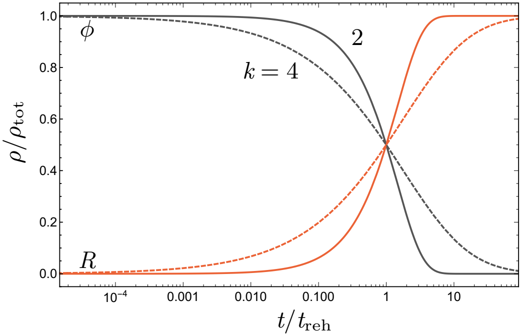

$$\rho_\phi \propto \begin{cases} e^{-\Gamma_\phi t}, & k = 2 \\ t^{\frac{2k}{2-k}}, & k \neq 2 \end{cases}$$

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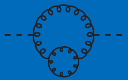

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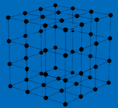

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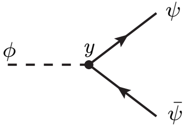
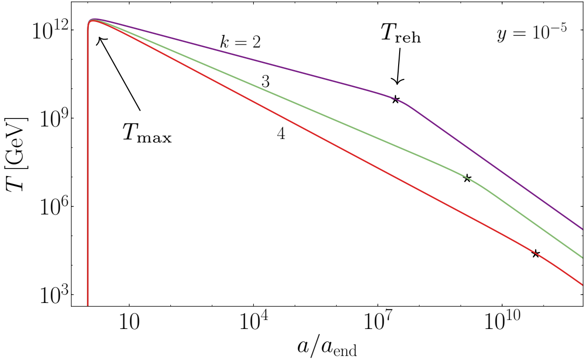
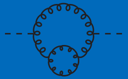


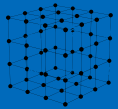
$$\Gamma_\phi = \frac{y(k)^2}{8\pi} m_\phi(t)$$

$$T = \left(\frac{30\rho_R}{\pi^2 g_*}\right)^{1/4}$$

$$\propto a^{-\frac{3}{2}\frac{k-3}{k+4}}$$







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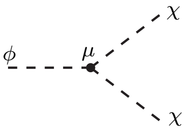

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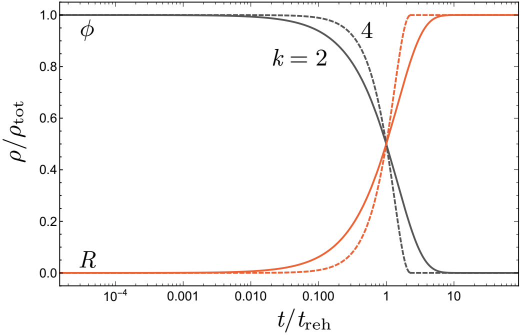

$$\rho_\phi \propto \begin{cases} e^{-\Gamma_\phi t}, & k=2 \\ ??\,, & k\neq 2 \end{cases}$$

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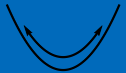

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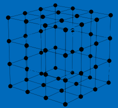

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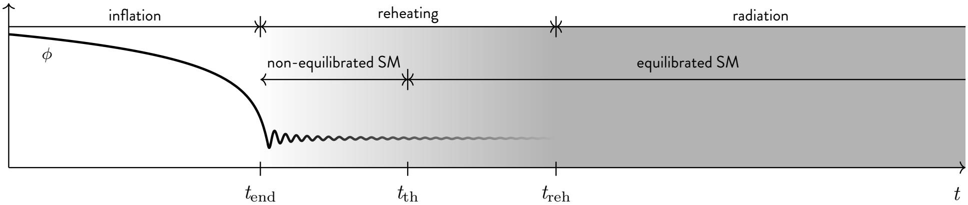
The path to thermal equilibrium

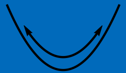


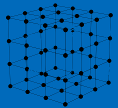
Low occupation number, direct decay: $\mathcal{C}[f_R(p,t)] \;=\; \dfrac{8\pi^2}{m_\phi^2} n_\phi \Gamma_\phi \delta(p - m_\phi/2)$

$$f_R(p,t) \;=\; \frac{16\pi^2\Gamma_\phi}{m_\phi^3}\int_{t_{\rm end}}^{t} dt'\,\frac{n_\phi(t')}{H(t')}\,\delta(t'-t_0)\,, \qquad \frac{a(t)}{a(t_0)} = \frac{m_\phi}{2p}$$

$$\simeq\; \frac{24\pi^2 n_R(t)}{m_\phi^3}\left(\frac{m_\phi}{2p}\right)^{3/2}\theta(m_\phi/2 - p)\,, \qquad (t \ll t_{\rm reh})$$

$$n_R(t) \;\simeq\; \frac{\rho_{\rm end}}{m_\phi}\left(1 - e^{-\Gamma_\phi(t - t_{\rm end})}\right)\left(\frac{a(t)}{a_{\rm end}}\right)^{-3}$$ (count produced quanta)





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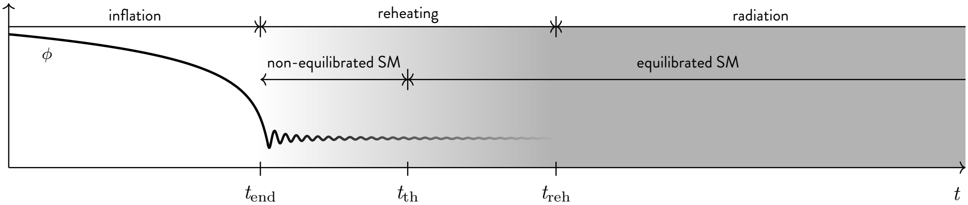
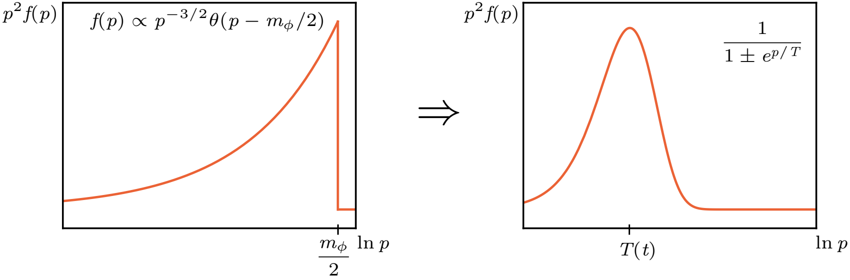


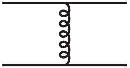
Thermal equilibrium: decay products need to *slow-down* and *multiply*



The path to thermal equilibrium

A. Kurkela, G. Moore, 1107.5050

$$\frac{\partial f_\chi}{\partial t} - Hp\frac{\partial f_\chi}{\partial p} = \left| \quad \right|^2 + \left| \quad \right|^2 + \cdots$$



$$\equiv -\mathcal{C}^{2\leftrightarrow 2}[f_\chi] - \mathcal{C}^{\text{“}1\leftrightarrow 2\text{”}}[f_\chi] + \cdots\,,$$

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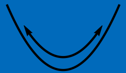

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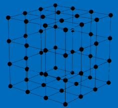

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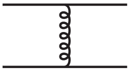
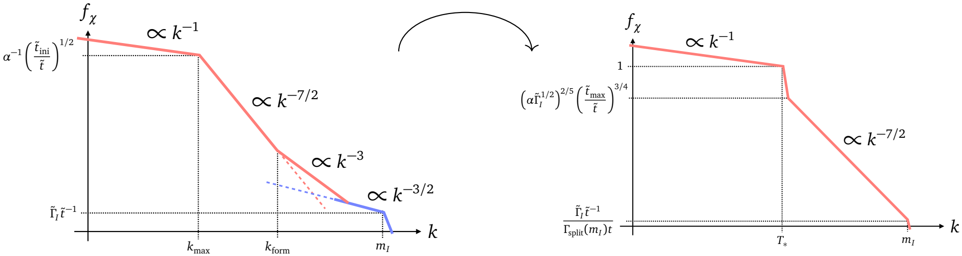
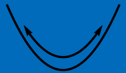


$$\equiv -\mathcal{C}^{2\leftrightarrow 2}[f_\chi] - \mathcal{C}^{\text{“}1\leftrightarrow 2\text{”}}[f_\chi] + \cdots ,$$

K. Harigaya, K. Mukaida, 1312.3097; K. Mukaida, M. Yamada, 1506.07661



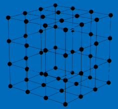
1. **Perturbative reheating**



2. **Thermalization**

3. **Preheating**

4. **Backreaction**

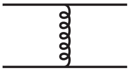


5. **Signals**

The path to thermal equilibrium

A. Kurkela, G. Moore, 1107.5050

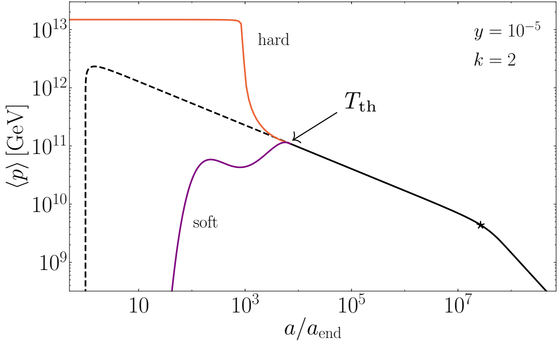
$$\frac{\partial f_\chi}{\partial t} - Hp\frac{\partial f_\chi}{\partial p} =$$

$\Big|$  $\Big|^2 +$ $\Big|$  $\Big|^2 + \cdots$

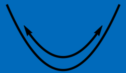
$$\equiv -\mathcal{C}^{2\leftrightarrow 2}[f_\chi] - \mathcal{C}^{\text{``}1\leftrightarrow 2\text{''}}[f_\chi] + \cdots\,,$$

$$\Gamma_\phi t_{\rm th} \simeq \alpha_{\rm SM}^{-16/5}\left(\frac{\Gamma_\phi m_\phi^2}{M_P^3}\right)^{2/5}$$

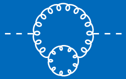
$$T_{\rm th} \simeq \alpha_{\rm SM}^{4/5} m_\phi \left(\frac{24}{\pi^2 g_{\rm reh}}\right)^{1/4} \times \left(\frac{\Gamma_\phi M_P^2}{m_\phi^3}\right)^{2/5}$$



1. Perturbative reheating



2. Thermalization



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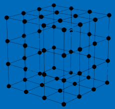
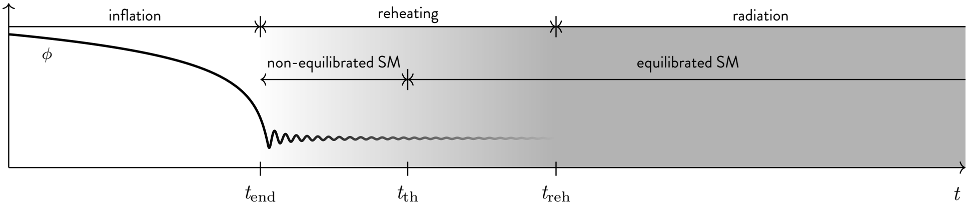
4. Backreaction

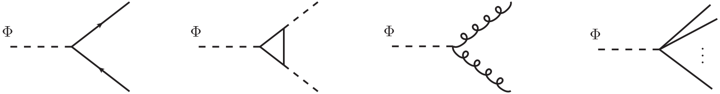


5. Signals

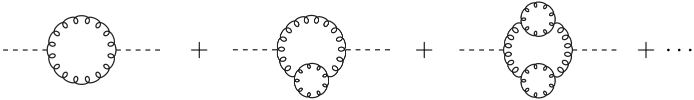
Thermalization for generic potential



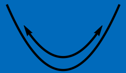
The nature of the final state matters a lot



Condensate *and* pre-thermal in-medium effects cannot be neglected



If you know the answer let me know ☺

1. Perturbative reheating

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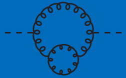
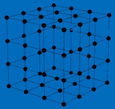
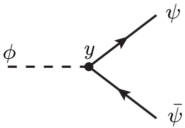

3. Preheating

4. Backreaction

5. Signals

Beyond perturbation theory: fermions

$$\mathcal{L} \supset y\phi\bar{\psi}\psi$$



$$(i\gamma^\mu \partial_\mu - a m_\psi(t))\Psi = 0$$

Introducing $\Psi \equiv a^{3/2}\psi$,

$$\Psi(\tau, \mathbf{x}) = \sum_{r=\pm} \int \frac{d^3\mathbf{p}}{(2\pi)^{3/2}} e^{-i\mathbf{p}\cdot\mathbf{x}} \left[u_p^{(r)}(\tau)\hat{a}_{\mathbf{p}}^{(r)} + v_p^{(r)}(\tau)\hat{b}_{-\mathbf{p}}^{(r)\dagger} \right]$$

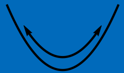
with

$$u_p^{(r)}(\tau) = \frac{1}{\sqrt{2}} \begin{pmatrix} U_1(\tau)\xi_r(\mathbf{p}) \\ U_2(\tau)\frac{\boldsymbol{\sigma}\cdot\mathbf{p}}{p}\xi_r(\mathbf{p}) \end{pmatrix}$$

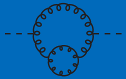
and

$$U_1'(\tau) = -ip\,U_2(\tau) - iam_\psi\,U_1(\tau)$$
$$U_2'(\tau) = -ip\,U_1(\tau) + iam_\psi\,U_2(\tau)$$

1. Perturbative reheating



2. Thermalization



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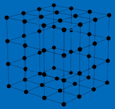

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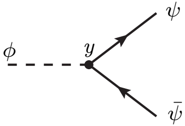
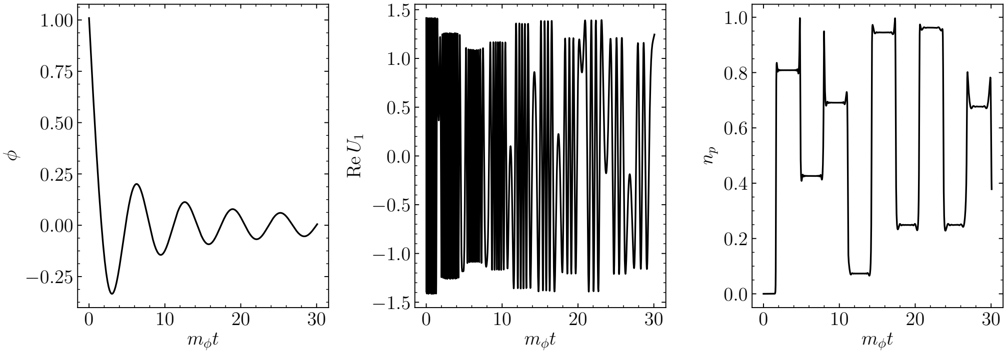
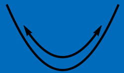
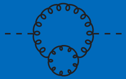
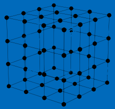


$$(i\gamma^{\mu}\partial_{\mu} - am_{\psi}(t))\Psi = 0$$









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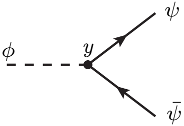


$$(i\gamma^\mu \partial_\mu - a m_\psi(t))\Psi = 0$$

The UV-convergent energy density is

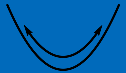
$$\rho_\psi = \frac{1}{(2\pi)^3 a^4} \int d^3\boldsymbol{p}\,\omega_p n_p$$

with the occupation number (PSD)

$$n_p = \frac{1}{2}\left|\left(1+\frac{a m_\psi}{\omega_p}\right)^{1/2} U_2 - \left(1-\frac{a m_\psi}{\omega_p}\right)^{1/2} U_1\right|^2 = f_\psi(p,t)$$

MG, K. Kaneta, Y. Mambrini, K. A. Olive, S. Verner, JCAP 03 (2022), 016

1. Perturbative reheating



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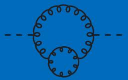

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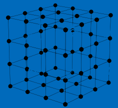

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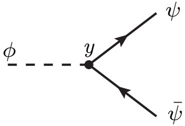
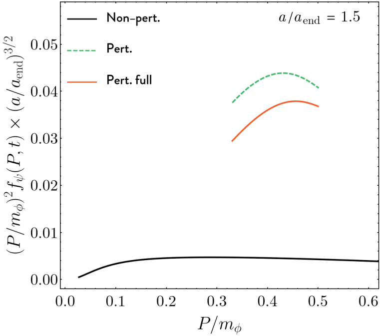
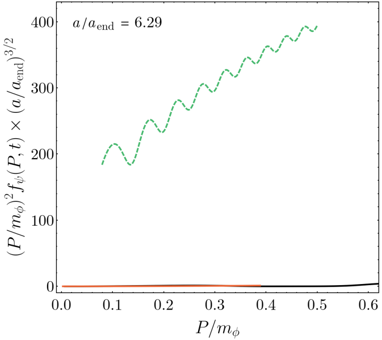


$$(i\gamma^\mu\partial_\mu - a m_\psi(t))\Psi = 0$$





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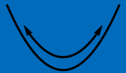

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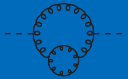

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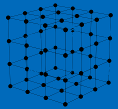

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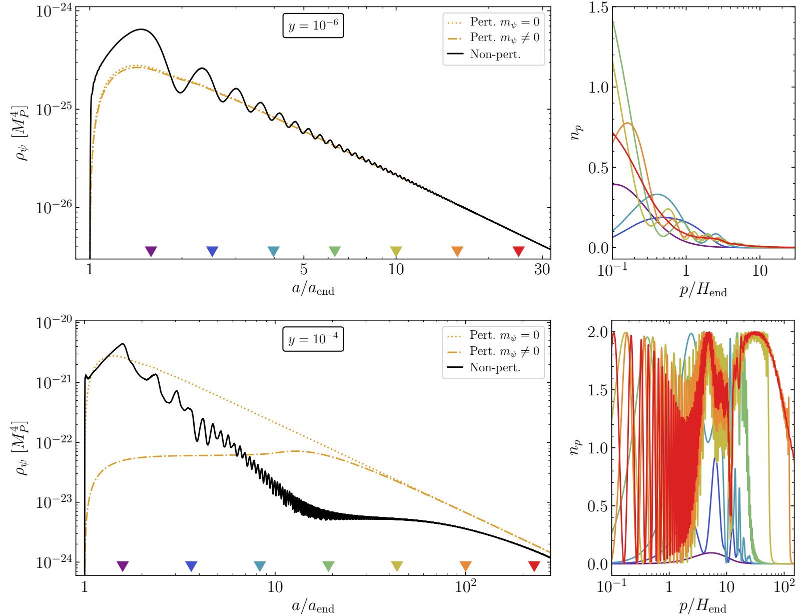

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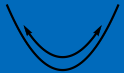

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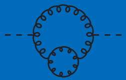

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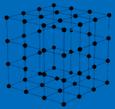
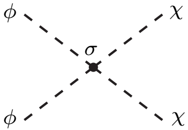


5. Signals

Beyond perturbation theory: scalars

$$\mathcal{L} \supset \tfrac{1}{2}\sigma\,\phi^2\chi^2$$



$$\ddot{\chi} + (3H + \Gamma_\chi)\dot{\chi} - a^{-2}\nabla^2\chi + m_\chi^2(t)\chi \;=\; 0$$

Using the quantization-friendly variable $X_p \;\equiv\; a\exp\left(\tfrac{1}{2}\int a\Gamma_\chi\, d\tau\right)\chi_p$

$$X_p'' + \omega_p^2 X_p \;=\; 0$$

$$\rho_f' + 4\mathcal{H}\rho_f \;=\; a\Gamma_\chi\dot{\chi}^2$$

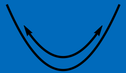
where

$$\omega_p^2 \;\equiv\; p^2 + a^2 m_\chi^2 - \frac{a''}{a} - \frac{1}{4}(a\Gamma_\chi)^2 - \frac{3}{2}a\mathcal{H}\Gamma_\chi$$

and the UV-convergent energy density (and occupation number) are

$$\rho_\chi \;=\; \frac{e^{-\int a\Gamma_\chi\, d\tau}}{(2\pi)^3 a^4}\int d^3\mathbf{p}\,\omega_p n_p\,, \qquad n_p \;=\; \frac{1}{2\omega_p}|\omega_p X_p - iX_p'|^2$$

1. Perturbative reheating



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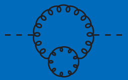

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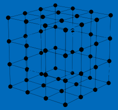

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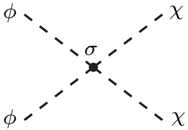

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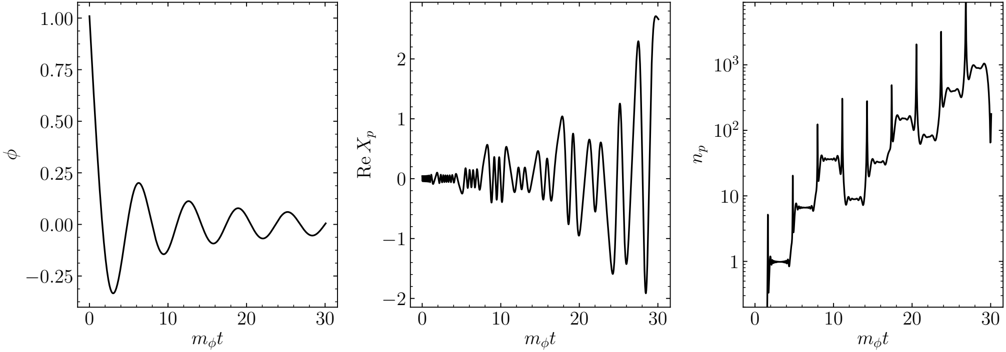

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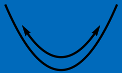

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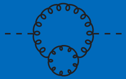

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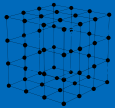

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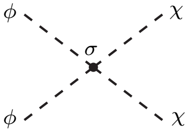

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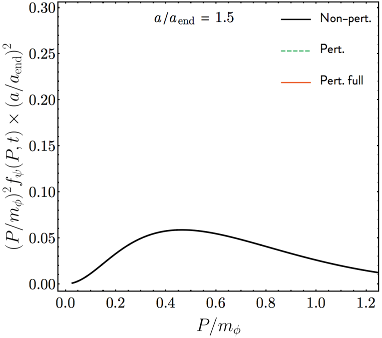

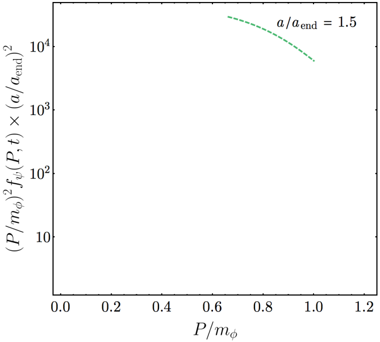

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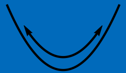

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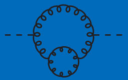

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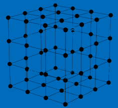

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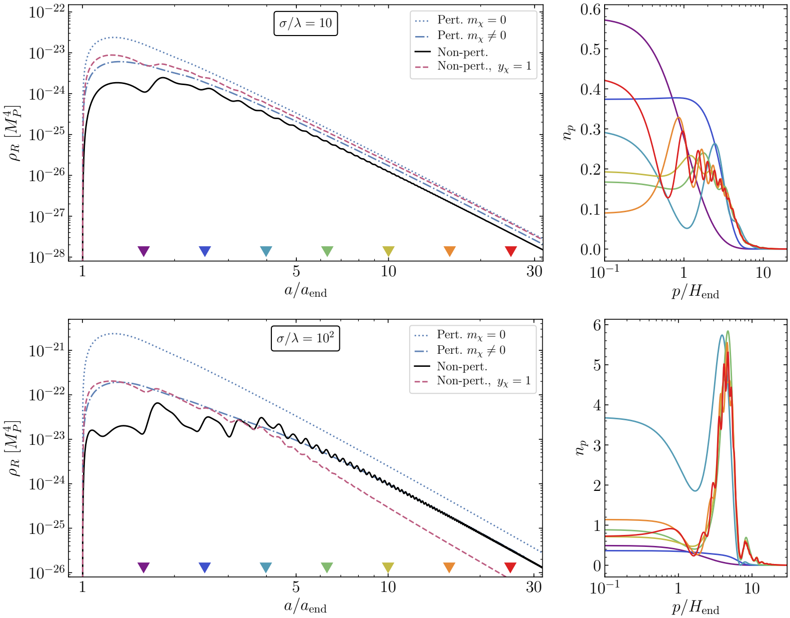

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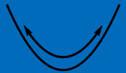

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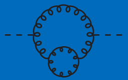

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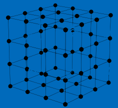

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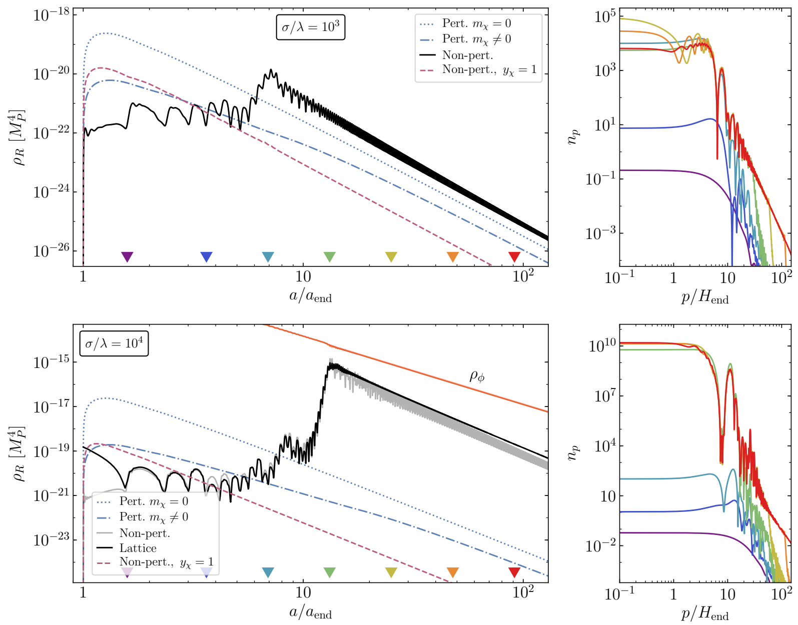

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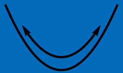

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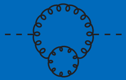

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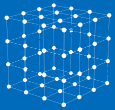


5. Signals

Backreaction

For $\rho_\chi \lesssim 0.1\rho_\phi$, the Hartree approximation is sufficient

$$\ddot{\phi} + 3H\dot{\phi} + V_\phi + \sigma\langle\chi^2\rangle\phi = 0\,, \qquad \langle\chi^2\rangle = \frac{1}{(2\pi)^3 a^2}\int d^3\mathbf{p}\left(|X_p|^2 - \frac{1}{2\omega_p}\right)$$

L. Kofman, A. Linde, A. Starobinsky, PRD 56 (1997) 3258

For $\rho_\chi \gtrsim 0.1\rho_\phi$ re-scattering of χ in ϕ fragments the inflationary condensate.

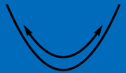
Spectral methods are insufficient and lattice codes in configuration space are necessary

$$\ddot{\phi} + 3H\dot{\phi} - \frac{\nabla^2\phi}{a^2} + V_{,\phi} = 0$$
$$\ddot{\chi} + 3H\dot{\chi} - \frac{\nabla^2\chi}{a^2} + V_{,\chi} = 0$$

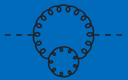
Software of choice: `CosmoLattice (v1.0)`

D. Figueroa, et al., arXiv:2102.01031 [astro-ph.CO]

1. **Perturbative reheating**

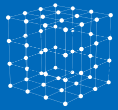


2. **Thermalization**



3. **Preheating**

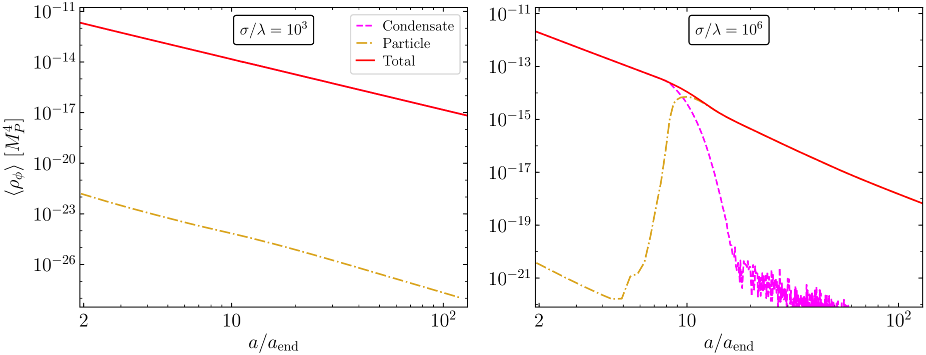
4. **Backreaction**



5. **Signals**

Backreaction

For $\rho_\chi \gtrsim 0.1\rho_\phi$ re-scattering of χ in ϕ fragments the inflationary condensate



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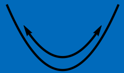

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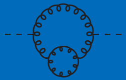

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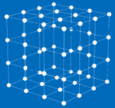
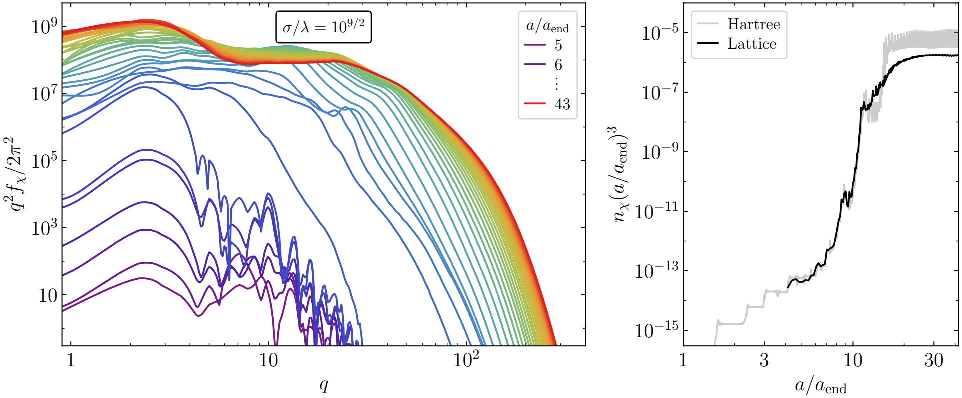


5. **Signals**

Backreaction

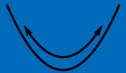
For $\rho_\chi \gtrsim 0.1\rho_\phi$ re-scattering of χ in ϕ fragments the inflationary condensate

$$f_\chi \sim e^{-\alpha(\sigma/\lambda;t)\,q} \quad \text{in the UV}$$

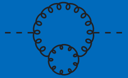


MG, M. Pierre, S. Verner, arXiv:2206.08940 [hep-ph]

1. Perturbative reheating

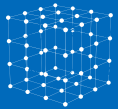


2. Thermalization

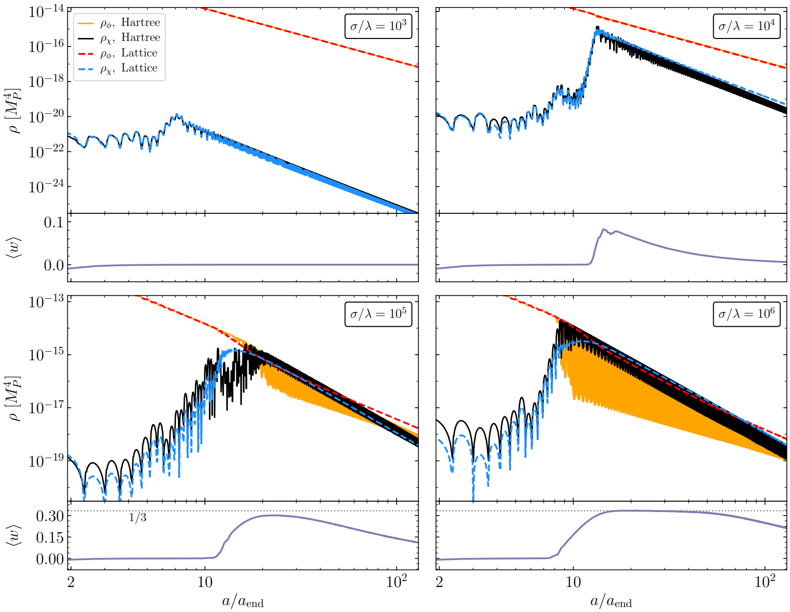


3. Preheating

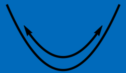
4. Backreaction



5. Signals



1. Perturbative reheating



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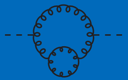
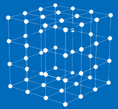


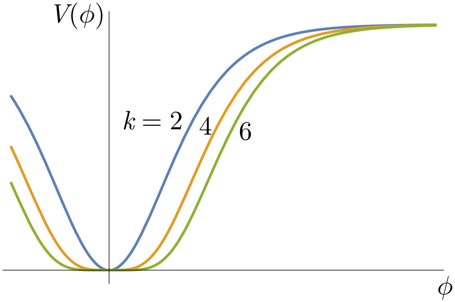
3. Preheating

4. Backreaction



5. Signals

Inflaton self-resonance



$$V(\phi) \;=\; \lambda M_P^4 \left[\sqrt{6}\tanh\left(\frac{\phi}{\sqrt{6}M_P}\right)\right]^k$$

$$\xrightarrow{\phi \ll M_P} \;\; \lambda \frac{\phi^k}{M_P^{k-4}}$$

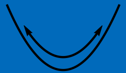
R. Kallosh and A. Linde, JCAP 07 (2013), 002

Non-adiabaticity is encountered for most of the parameter space
$\Rightarrow$ preheating cannot be ignored!

The homogeneous inflaton can pump energy into its own fluctuations (*self-resonance*)

$\Rightarrow$ lattice codes are indispensable

1. Perturbative reheating



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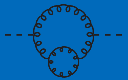
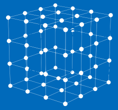


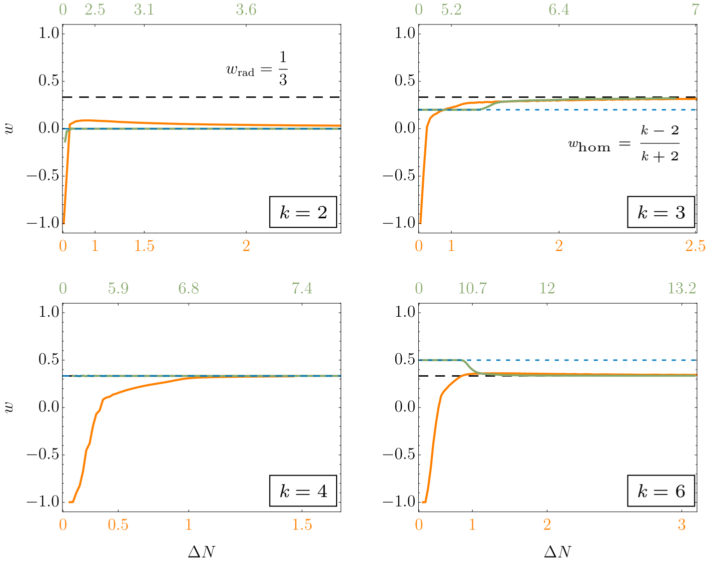
3. Preheating

4. Backreaction



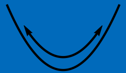
5. Signals

Inflaton self-resonance



K. Lozanov, M. Amin, PRD 97 (2018), 023533

1. Perturbative reheating



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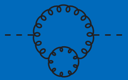
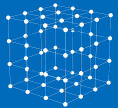


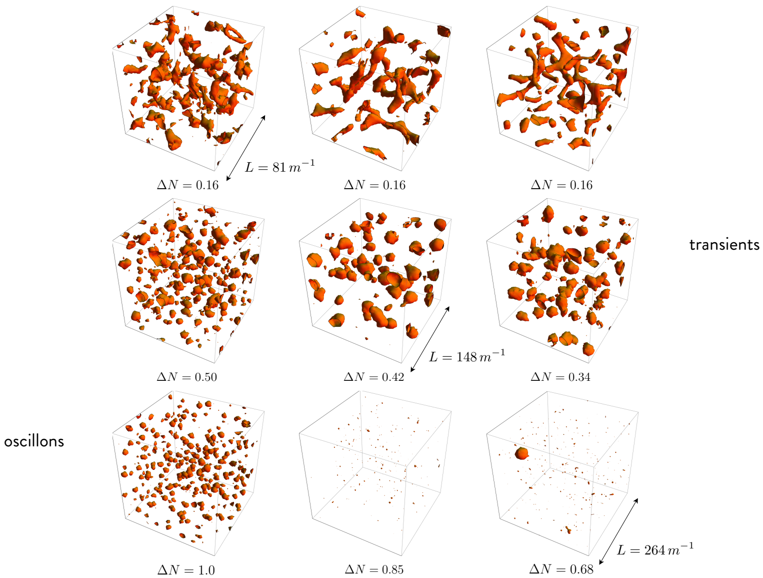
3. Preheating

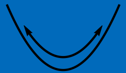
4. Backreaction

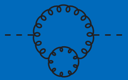


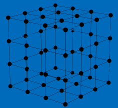
5. Signals

Fragmentation









From preheating to reheating

Perturbative pipeline:

Early times: **field picture** (limited dissipation)

↓

interactions (thermalization) ← Boltzmann

$$\frac{\partial f}{\partial t} - Hp\frac{\partial f}{\partial p} = -\mathcal{C}^{2\leftrightarrow 2}[f] - \mathcal{C}^{1\leftrightarrow 2}[f]$$

↓

Late times: **fluid picture** (no fluctuations)

From preheating to reheating

Non-perturbative pipeline:

Early times: **field picture** (limited dissipation)

↓

interactions (thermalization) ← Schwinger-Keldysh / Kadanoff-Baym

↓

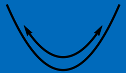
Late times: **fluid picture** (no fluctuations)

Schwinger-Keldysh / Kadanoff-Baym

$$\left(\Box_x + M^2(x)\right) G_F(x,y) = \int_0^{y_0} d^4z\, \Pi_F(x,z) G_\rho(z,y) - \int_0^{x_0} d^4z\, \Pi_\rho(x,z) G_F(z,y)$$

$$\left(\Box_x + M^2(x)\right) G_\rho(x,y) = \int_{x_0}^{y_0} d^4z\, \Pi_\rho(x,z) G_\rho(z,y)$$

1. **Perturbative reheating**



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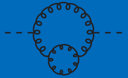
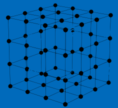


3. **Preheating**

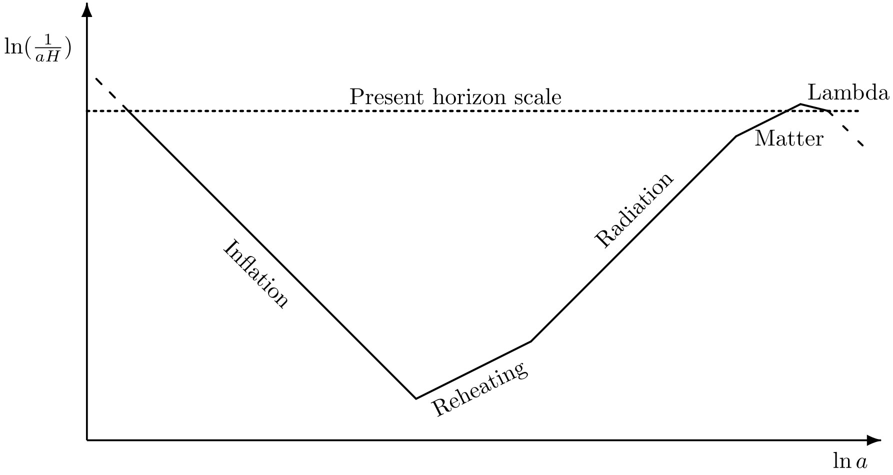
4. **Backreaction**



5. **Signals**

Signals 1: the CMB

The number of e-folds ($N \equiv \ln a$) after the comoving scale k_* crosses the horizon



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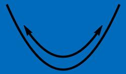
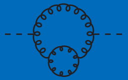
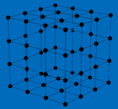


2. Thermalization



3. Preheating

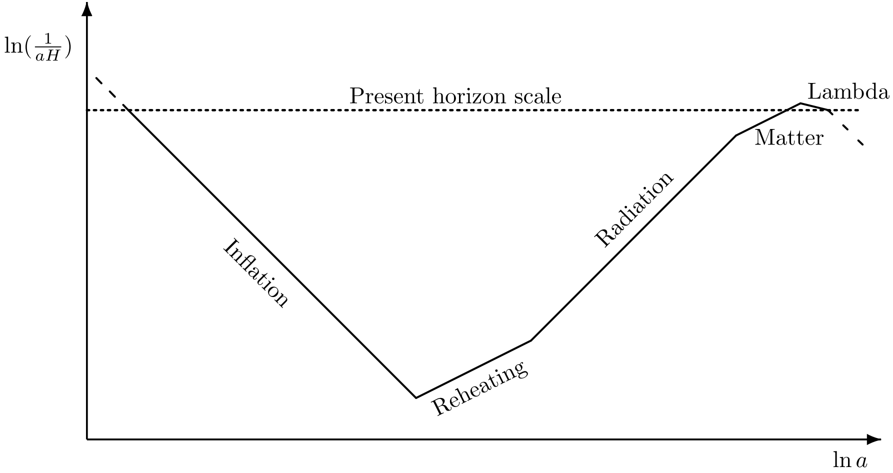
4. Backreaction



5. Signals

Signals 1: the CMB

$$N_* = 66.9 - \ln\left(\frac{k_*}{a_0 H_0}\right) + \frac{1}{4}\ln\left(\frac{V_*^2}{\rho_{\rm end} M_P^4}\right) + \ln\left[\frac{a_{\rm end}}{a_{\rm reh}}\left(\frac{\rho_{\rm end}}{\rho_{\rm reh}}\right)^{1/4}\right] - \frac{1}{12}\ln\, g_{\rm reh}$$



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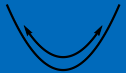

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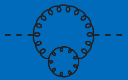

3. **Preheating**

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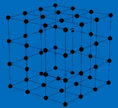
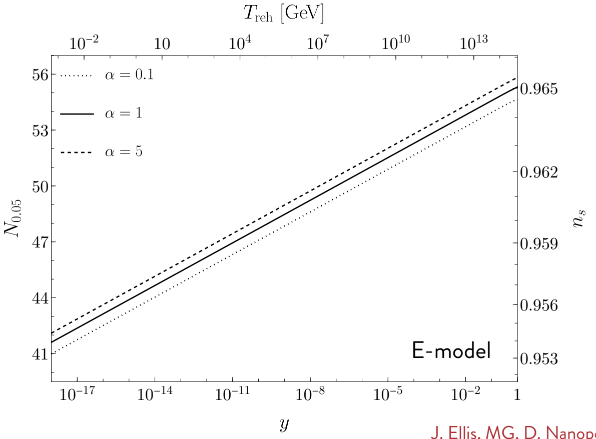


5. **Signals**

Signals 1: the CMB

Perturbative decay: $$\ln\left[\frac{a_{\rm end}}{a_{\rm reh}}\left(\frac{\rho_{\rm end}}{\rho_{\rm reh}}\right)^{1/4}\right] \simeq \frac{1}{6}\ln\left(\frac{\Gamma_\phi}{H_{\rm end}}\right)$$

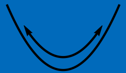


Planck pivot scale: $k_* = 0.05\,\mathrm{Mpc}^{-1}$

$$N_{0.05} \simeq 57.68 - \frac{1}{2}\ln N_{0.05} + \frac{1}{3}\ln y - \frac{1}{12}\ln g_{\rm reh}$$

J. Ellis, MG, D. Nanopoulos, K. Olive, S. Verner, PRD 105 (2022), 043504

1. Perturbative reheating



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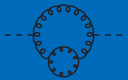

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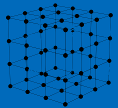
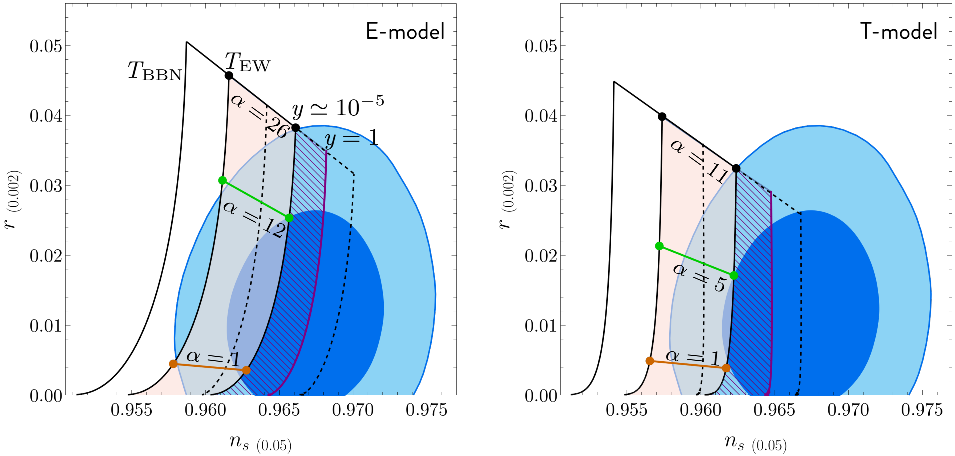
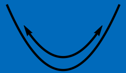


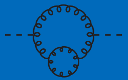
5. Signals

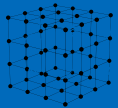
Signals 1: the CMB

Planck18+lowE+lensing+BKP18+BAO (fixed τ, no B corr., $n_T = 0$) (2110.00483)

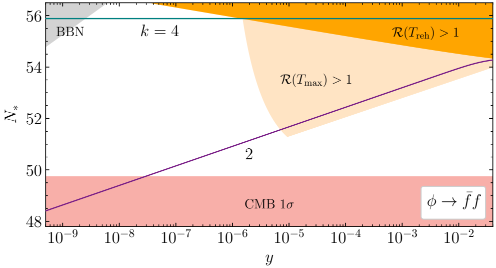


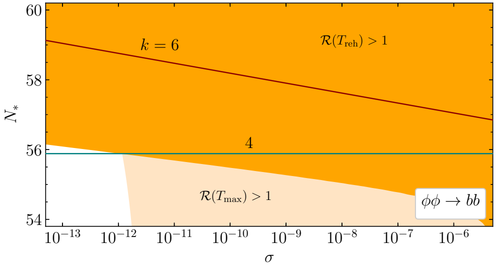






Signals 1: the CMB





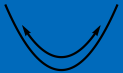
Equation of state during reheating

$$w = \frac{k-2}{k+2}$$

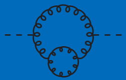
For $k = 4$, $w_{\rm int} \simeq 1/3 \Rightarrow N_* = 55.9$

For $k > 4$, $N_* \gtrsim 55.9$,
(*highly* dependent on interactions)

1. Perturbative reheating

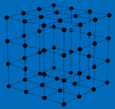


2. Thermalization



3. Preheating

4. Backreaction

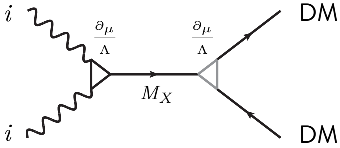


5. Signals

Signals 2: dark matter

$$\frac{\partial f_{\rm DM}}{\partial t} - Hp\frac{\partial f_{\rm DM}}{\partial p} = \frac{1}{16p}\int \frac{d^3\boldsymbol{p}'}{(2\pi)^3 p'_0}\frac{d^3\boldsymbol{k}}{(2\pi)^3 k_0}\frac{d^3\boldsymbol{k}'}{(2\pi)^3 k'_0}(2\pi)^4\delta(\boldsymbol{p}+\boldsymbol{p}'-\boldsymbol{k}-\boldsymbol{k}')\,|\mathcal{M}|^2_{\rightarrow}\, f_i(k)f_i(k')$$

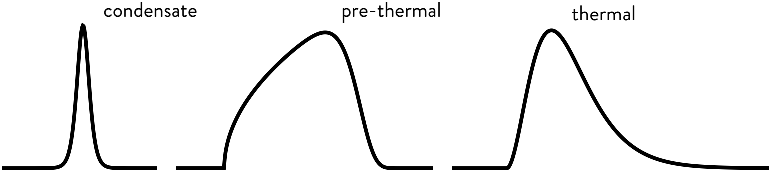
$$\frac{dn_{\rm DM}}{dt} + 3Hn_{\rm DM} = \int \frac{d^3\boldsymbol{k}}{(2\pi)^3 k_0}\frac{d^3\boldsymbol{k}'}{(2\pi)^3 k'_0}(k\cdot k')\,\sigma(s)\,f_i(k)f_i(k')$$



$$|\mathcal{M}|^2 = 16\pi\frac{s^{\frac{n}{2}+1}}{\Lambda^{n+2}}$$

$$\sigma(s) = \frac{s^{\frac{n}{2}}}{\Lambda^{n+2}}$$

$k^2 f_i(k)$:



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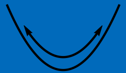

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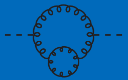

3. Preheating

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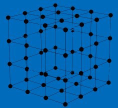
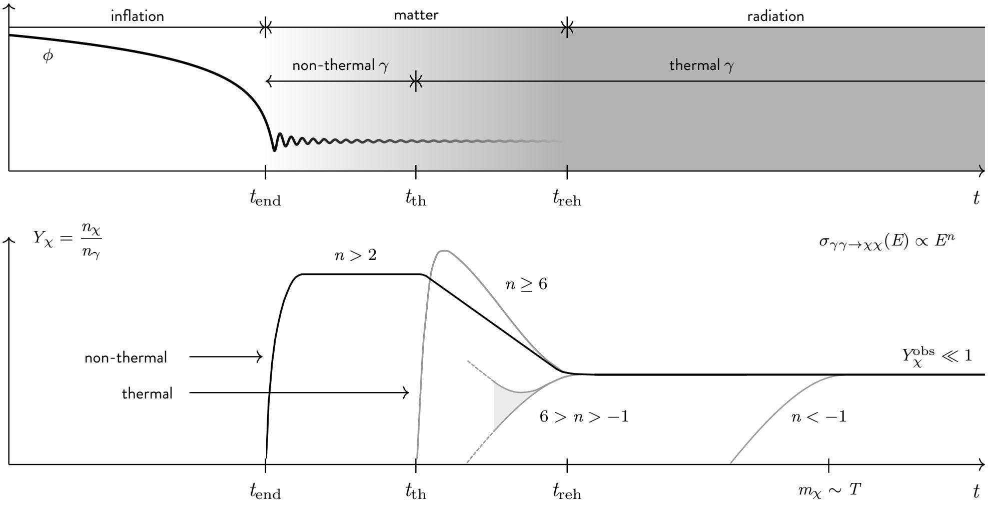
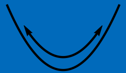


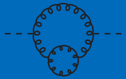
5. Signals

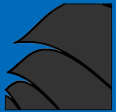
Signals 2: dark matter

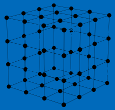


MG and M. Amin, PRD 98 (2018), 103504





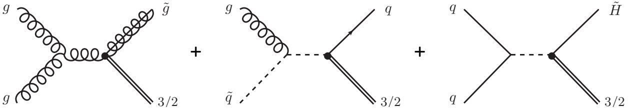




Signals 2: dark matter

Low scale susy breaking, $m_{\rm susy} \ll m_\phi$

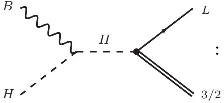
H. Eberl, I. Gialamas, V. Spanos, PRD 103 (2021), 075025



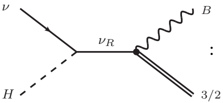
$+ \ldots \quad : \quad |\mathcal{M}|^2 \sim \dfrac{s}{M_P^2}$

No susy, SM + ν_R + 3/2

MG, Y. Mambrini, K. Olive, S. Verner, PRD 102 (2020), 083533



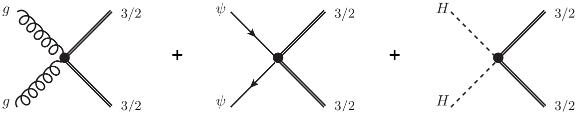
$: \quad |\mathcal{M}|^2 \sim \dfrac{s^2}{m_{3/2}^2 M_P^2}$



$: \quad |\mathcal{M}|^2 \sim \dfrac{s^3}{m_{3/2}^2 m_R^2 M_P^2}$

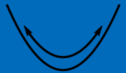
High scale susy breaking, $m_{\rm susy} \gg m_\phi$

K. Benakli, Y. Chen, E. Dudas, Y. Mambrini, PRD 95 (2017), 095002

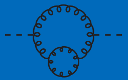


$: \quad |\mathcal{M}|^2 \sim \dfrac{s^4}{m_{3/2}^4 M_P^4}$

1. Perturbative reheating

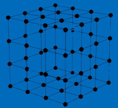


2. Thermalization



3. Preheating

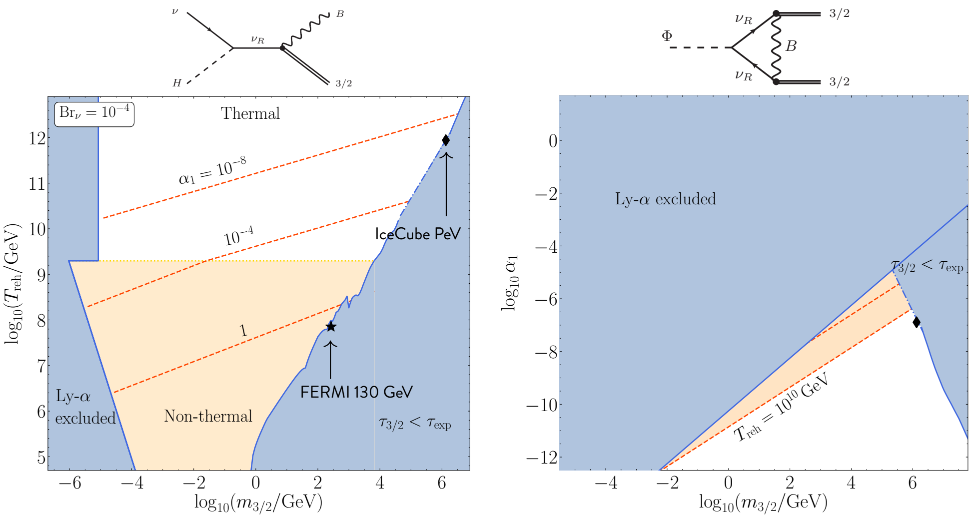
4. Backreaction



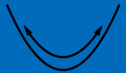
5. Signals

Signals 2: dark matter

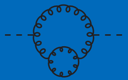
Minimal non-susy spin-3/2 dark matter



1. Perturbative reheating

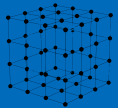


2. Thermalization



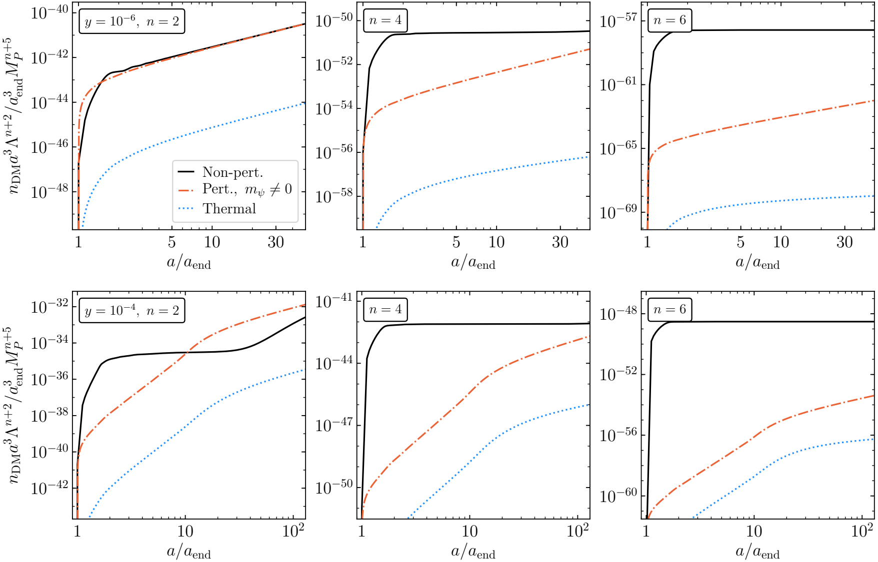
3. Preheating

4. Backreaction

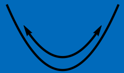


5. Signals

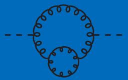
Signals 2: dark matter + $\phi \to \bar{\psi}\psi$ preheating



1. Perturbative reheating

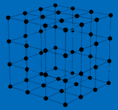


2. Thermalization



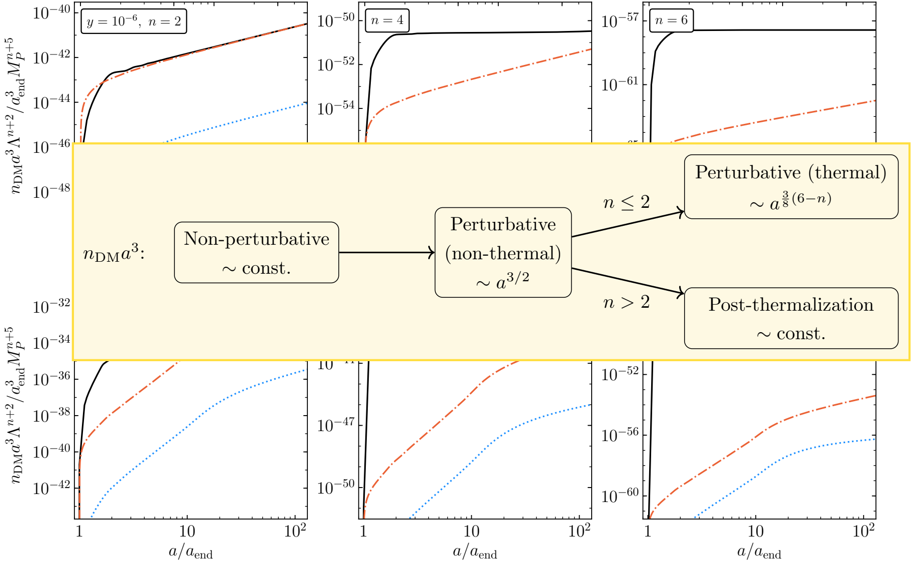
3. Preheating

4. Backreaction

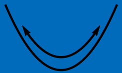


5. Signals

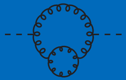
Signals 2: dark matter + $\phi \to \bar{\psi}\psi$ preheating



1. Perturbative reheating

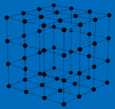


2. Thermalization



3. Preheating

4. Backreaction



5. Signals

Signals 2: dark matter + $\phi\phi \to \chi\chi$ preheating