

Freeze-in from Preheating



Marcos A. G. García

+ K. Kaneta, Y. Mambrini, K. Olive, S. Verner, arXiv:2109.13280 [hep-ph]

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Istituto Nazionale di Fisica Nucleare
Sezione di Padova

1. UV freeze-in



2. Perturbative reheating



3. Preheating

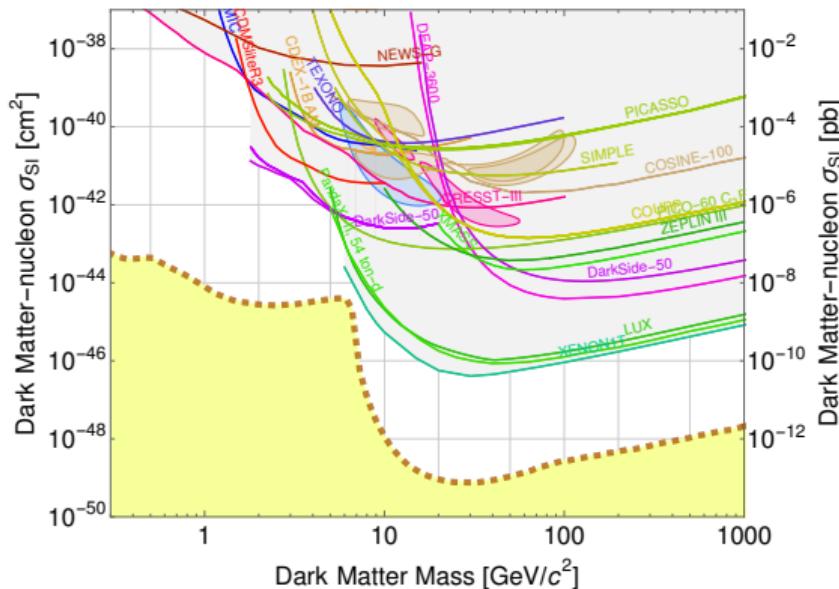


4. Relic abundances



The case for FIMP dark matter

No detection of WIMPs yet!



SuperCDMS Dark Matter Limit Plotter

Consider FIMPs:

- Never in thermal equilibrium
- Produced via freeze-in
- Elusive (in)direct detection
- Dependence on initial conditions (inflation, reheating)

1. UV freeze-in



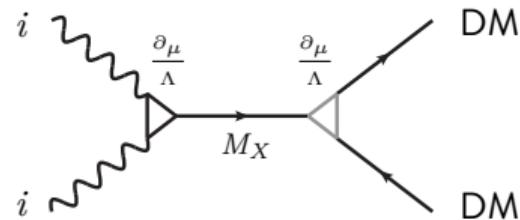
Freeze-in

$$\frac{\partial f_{\text{DM}}}{\partial t} - H p \frac{\partial f_{\text{DM}}}{\partial p} = \frac{1}{16p} \int \frac{d^3 p'}{(2\pi)^3 p'_0} \frac{d^3 k}{(2\pi)^3 k_0} \frac{d^3 k'}{(2\pi)^3 k'_0} (2\pi)^4 \delta(\mathbf{p} + \mathbf{p}' - \mathbf{k} - \mathbf{k}') |\mathcal{M}|^2 f_i(k) f_i(k')$$

2. Perturbative reheating

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

3. Preheating



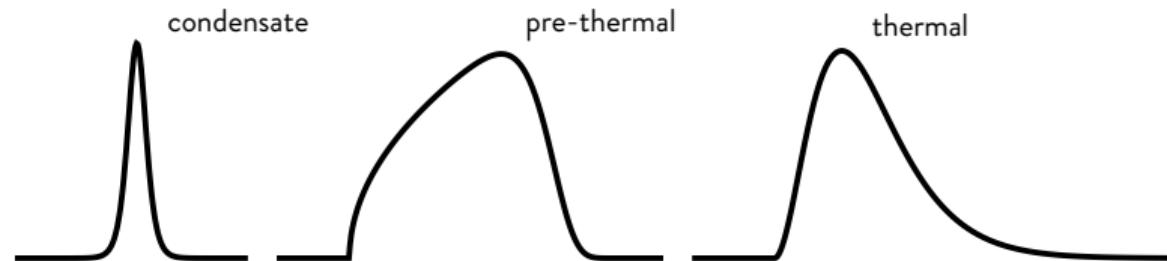
$$|\mathcal{M}|^2 = 16\pi \frac{s^{\frac{n}{2}+1}}{\Lambda^{n+2}}$$

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

4. Relic abundances



$$k^2 f_i(k) :$$



1. UV freeze-in



2. Perturbative reheating



3. Preheating

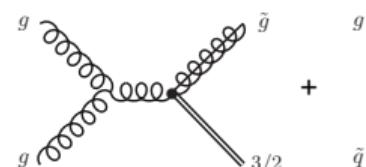


4. Relic abundances

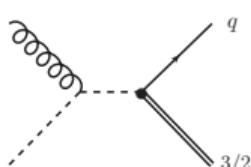


The spin-3/2 family

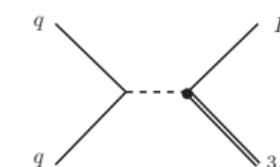
Low scale susy breaking, $m_{\text{susy}} \ll m_\phi$



+



+

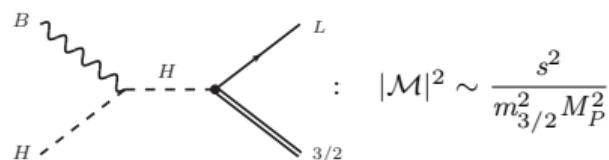


+ ...

$$: |\mathcal{M}|^2 \sim \frac{s}{M_P^2}$$

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

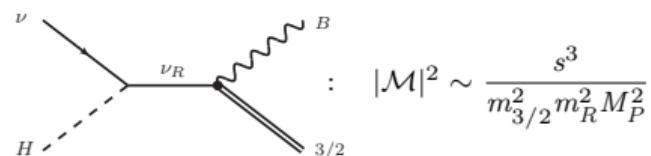
No susy, SM + ν_R + 3/2



:

$$|\mathcal{M}|^2 \sim \frac{s^2}{m_{3/2}^2 M_P^2}$$

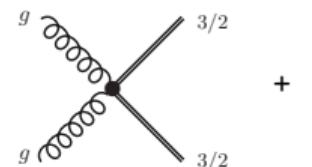
MG, Y. Mambrini, K. Olive, S. Verner, PRD 102 (2020), 083533



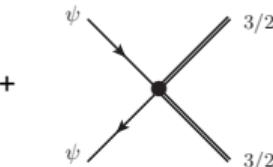
:

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

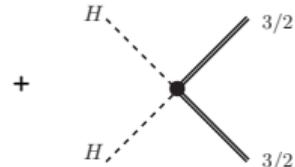
High scale susy breaking, $m_{\text{susy}} \gg m_\phi$



+



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



:

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

1. UV freeze-in



2. Perturbative reheating



3. Preheating

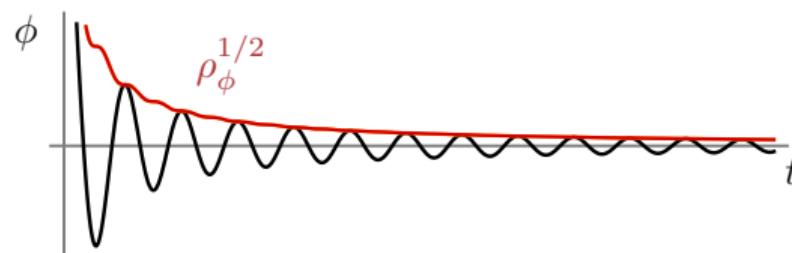


4. Relic abundances



The inflaton and its decay products

$$\begin{aligned} \mathcal{S} = & \int d^4x \sqrt{-g} \left[\frac{1}{2}(\partial_\mu \phi)^2 - 6\lambda M_P^4 \tanh^2 \left(\frac{\phi}{\sqrt{6}M_P} \right) \right. & \text{inflaton} \\ & + \frac{1}{2}(\partial_\mu \chi)^2 - \frac{1}{2}\sigma \phi^2 \chi^2 & \text{scalar } (m_\chi^2 = \sigma \phi^2) \\ & \left. + \bar{\psi} i \gamma^\mu \nabla_\mu \psi - y \phi \bar{\psi} \psi + \dots \right] & \text{fermion } (m_\psi^2 = y^2 \phi^2) \end{aligned}$$



$$\langle p_\phi \rangle = \frac{1}{2} \langle \dot{\phi}^2 + m_\phi^2 \phi^2 \rangle \simeq 0 \quad (\text{matter})$$

1. UV freeze-in



The fluid picture

$$T^{\mu\nu} = \rho_\phi \text{diag}(1, 0, 0, 0) + \frac{\rho_R}{3} \text{diag}(3, 1, 1, 1)$$

2. Perturbative reheating



$$\nabla_\mu T^{\mu\nu} = 0 \quad \Rightarrow \quad \dot{\rho}_R + 4H\rho_R = -(\dot{\rho}_\phi + 3H\rho_\phi) \equiv \Gamma_\phi \rho_\phi$$

3. Preheating



Decay rate of an oscillating inflaton condensate: $\phi(t) \simeq \phi_0(t)\mathcal{P}(t) = \phi_0(t) \sum_n \mathcal{P}_n e^{-in\omega t}$

$$\Gamma_\phi = \frac{1}{8\pi\rho_\phi} \sum_{n=1}^{\infty} E_n \left\langle |\mathcal{M}_n|^2 \beta_n \right\rangle$$

4. Relic abundances



$$E_n = n m_\phi$$

$$\beta_n = \sqrt{1 - \frac{4m_{\chi,\psi}^2}{E_n^2}}$$

(For $V \propto \phi^k$ see
MG, K. Kaneta, Y. Mambrini, K. Olive,
JCAP 04 (2021), 012)

$$\langle f | i \int d^4x \mathcal{L}_I | 0 \rangle = i(2\pi)^4 \sum_{n=-\infty}^{\infty} \mathcal{M}_n \delta^{(4)}(p_n - p_1 - p_2)$$

1. UV freeze-in



2. Perturbative reheating



3. Preheating



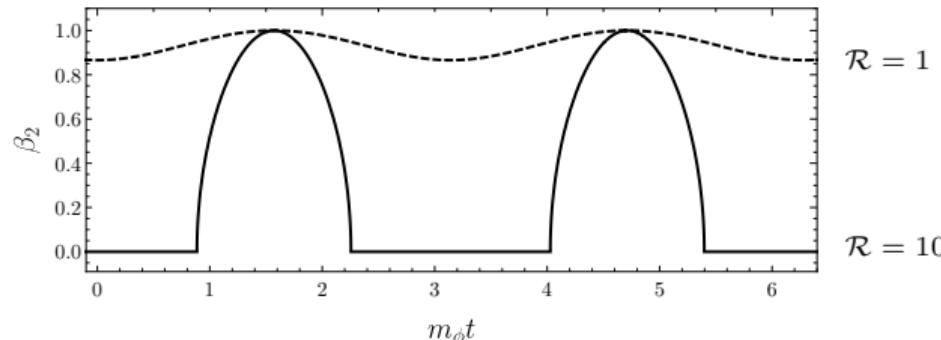
4. Relic abundances



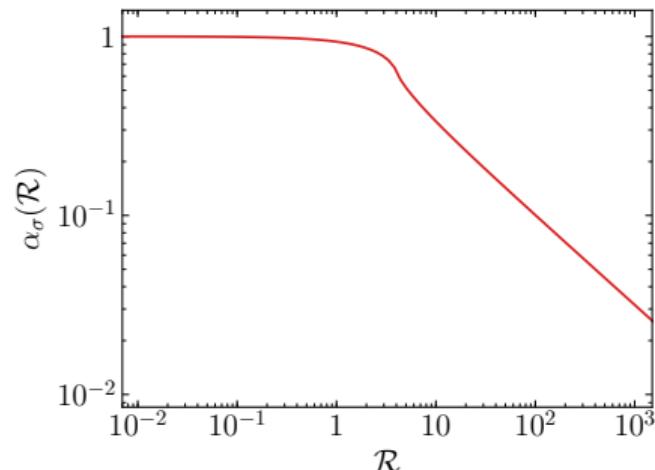
Kinematic blocking: scalars

$$\beta_n = \left(1 - \frac{\mathcal{R}}{n^2} \mathcal{P}^2\right)^{1/2}$$

$$\mathcal{R} = 2 \left(\frac{\sigma}{\lambda}\right) \left(\frac{\phi_0}{M_P}\right)^2$$



$$\Gamma_{\phi\phi \rightarrow \chi\chi} = \frac{\sigma^2 \rho_\phi(t)}{32\pi m_\phi^3} \alpha_\sigma(\mathcal{R})$$



1. UV freeze-in



2. Perturbative reheating



3. Preheating



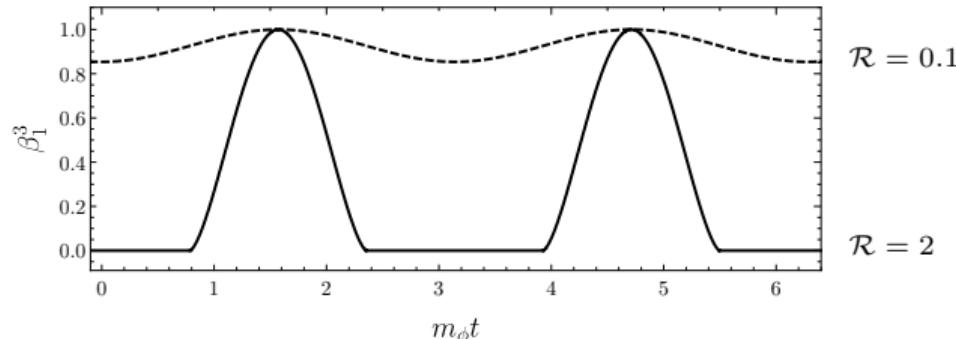
4. Relic abundances



Kinematic blocking: fermions

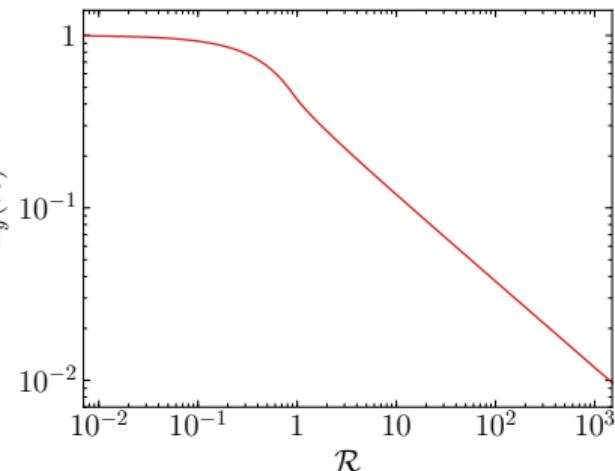
$$\beta_n = \left(1 - \frac{\mathcal{R}}{n^2} \mathcal{P}^2\right)^{1/2}$$

$$\mathcal{R} = 2 \frac{y^2}{\lambda} \left(\frac{\phi_0}{M_P}\right)^2$$



$$\Gamma_{\phi \rightarrow \bar{\psi} \psi} = \frac{y^2}{8\pi} m_\phi \alpha_y(\mathcal{R})$$

$$\alpha_y(\mathcal{R})$$



1. UV freeze-in



2. Perturbative reheating



3. Preheating



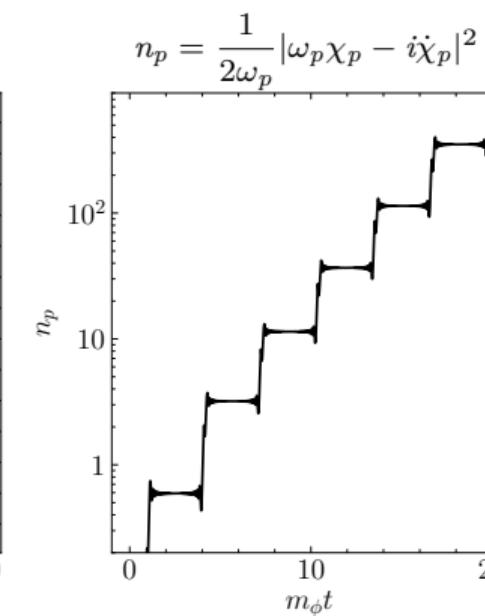
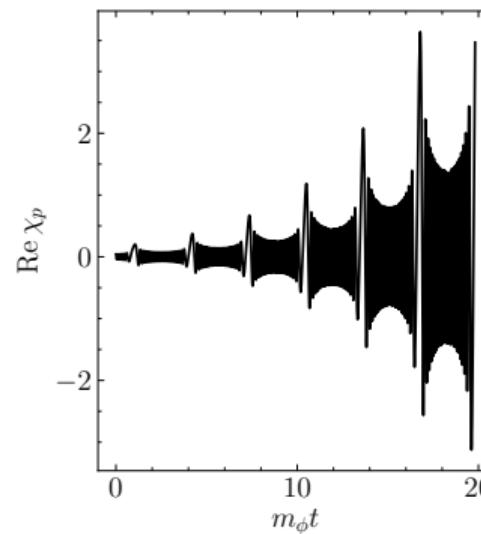
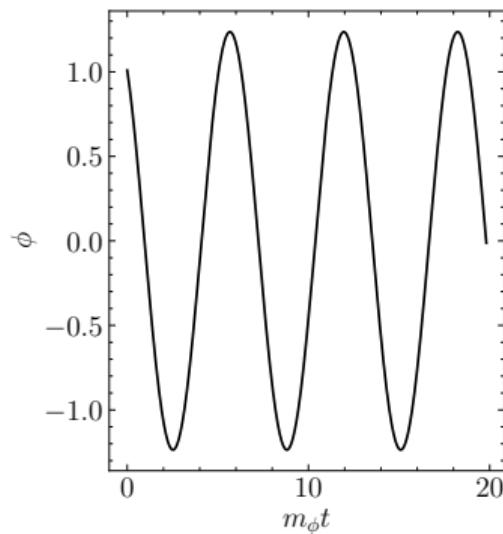
4. Relic abundances



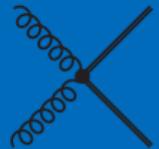
Scalar preheating

$$\ddot{\chi}_p + 3H\dot{\chi}_p + \left[\frac{p^2}{a^2} + m_\chi^2(t) \right] \chi_p = 0, \quad m_\chi^2(t) = \frac{1}{2}\sigma\phi^2$$

Neglecting expansion,



1. UV freeze-in



2. Perturbative reheating



3. Preheating



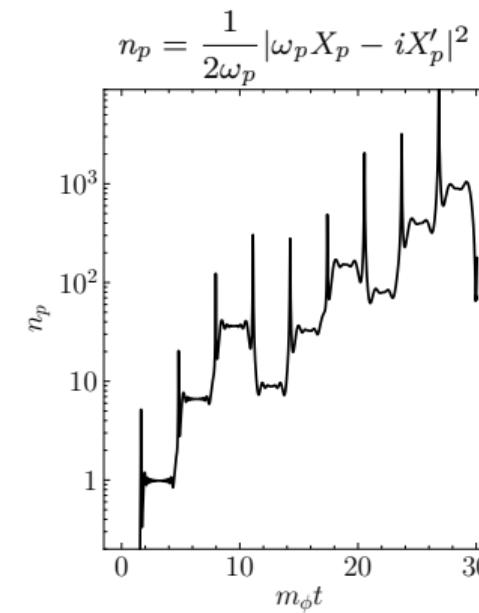
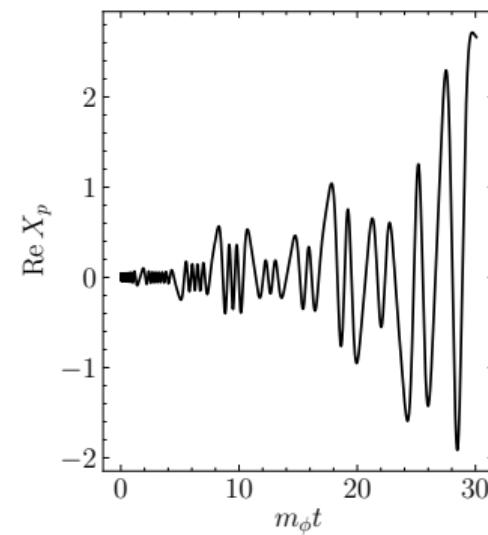
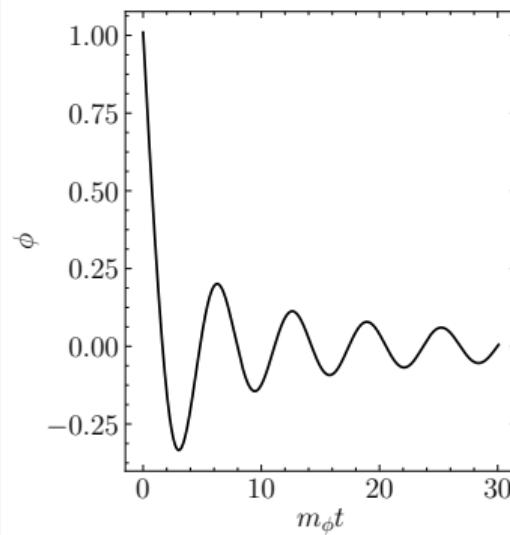
4. Relic abundances



Scalar preheating

$$\ddot{\chi}_p + 3H\dot{\chi}_p + \left[\frac{p^2}{a^2} + m_\chi^2(t) \right] \chi_p = 0, \quad m_\chi^2(t) = \frac{1}{2}\sigma\phi^2$$

With expansion,



1. UV freeze-in



2. Perturbative reheating



3. Preheating



4. Relic abundances



Unstable-scalar preheating

$$\left(\frac{d^2}{dt^2} - \frac{\nabla^2}{a^2} + (3H + \Gamma_\chi) \frac{d}{dt} + m_\chi^2(t) \right) \chi = 0 \quad \Gamma_\chi = \frac{y_\chi^2}{8\pi} m_\chi(t)$$

$$\dot{\rho}_f + 4H\rho_f = \Gamma_\chi \dot{\chi}^2$$

Or, with $Y_p \equiv a \exp\left(\frac{1}{2} \int a\Gamma_\chi d\tau\right) \chi_p$

$$Y_p'' + \omega_p^2 Y_p = 0$$

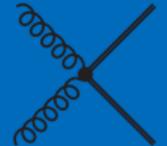
$$\dot{\rho}_f' + 4\mathcal{H}\rho_f = a\Gamma_\chi \dot{\chi}^2$$

where

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

$$\rho_\chi = \frac{e^{-\int a\Gamma_\chi d\tau}}{(2\pi)^3 a^4} \int d^3 p \omega_p n_p, \quad n_p = \frac{1}{2\omega_p} |\omega_p Y_p - i Y_p'|^2$$

1. UV freeze-in



2. Perturbative reheating



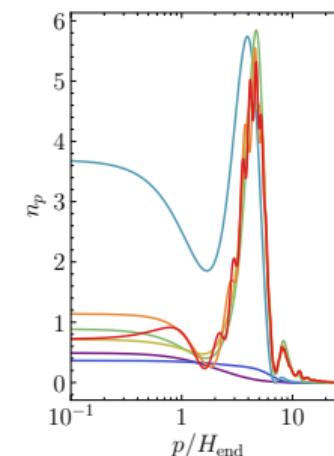
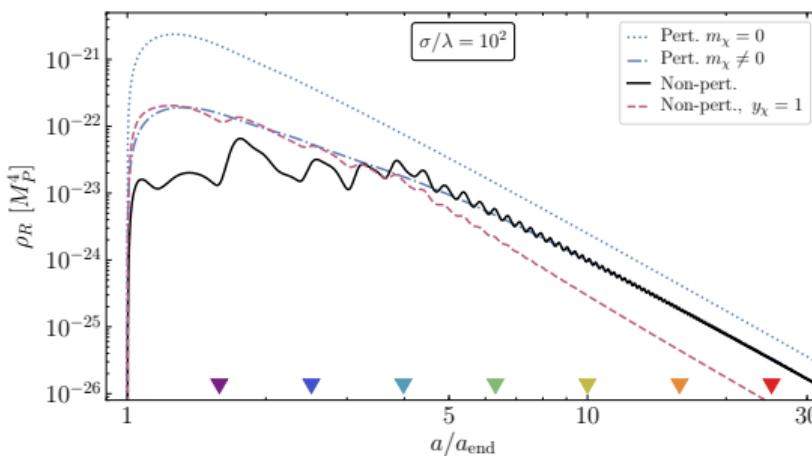
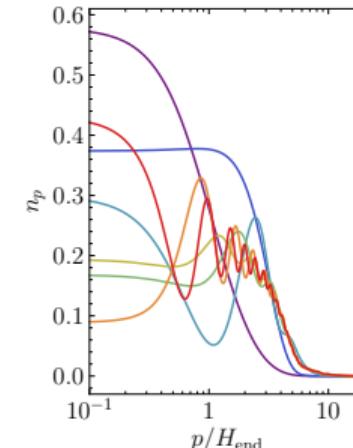
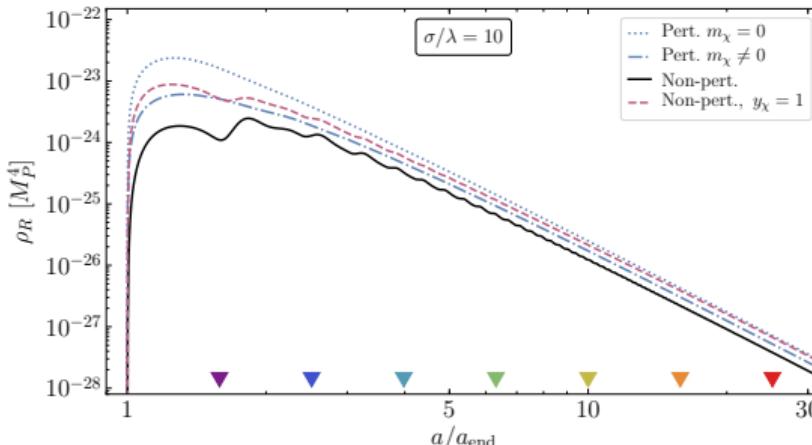
3. Preheating



4. Relic abundances



Weak



1. UV freeze-in



2. Perturbative reheating



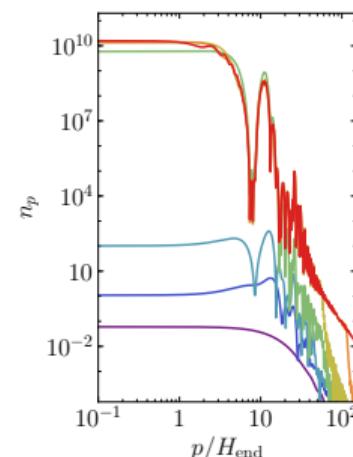
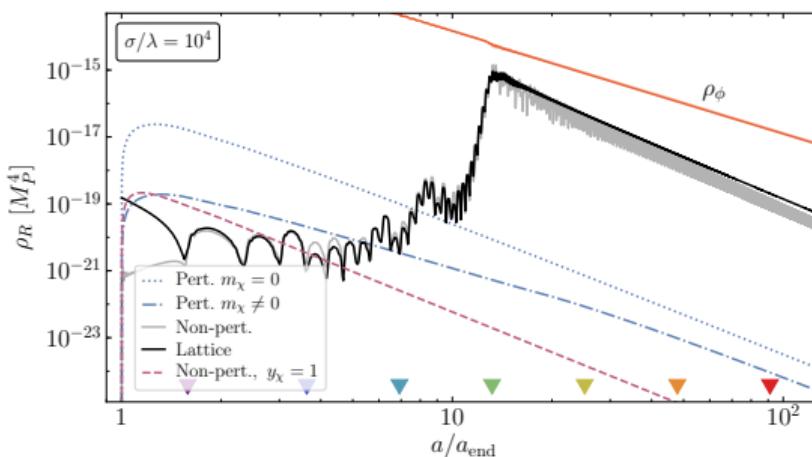
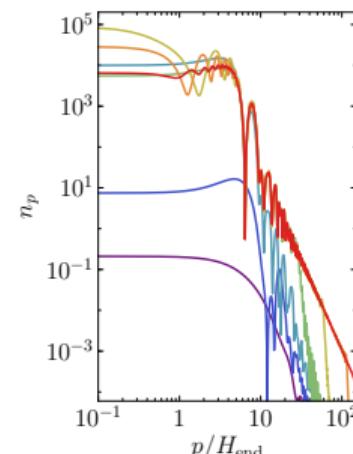
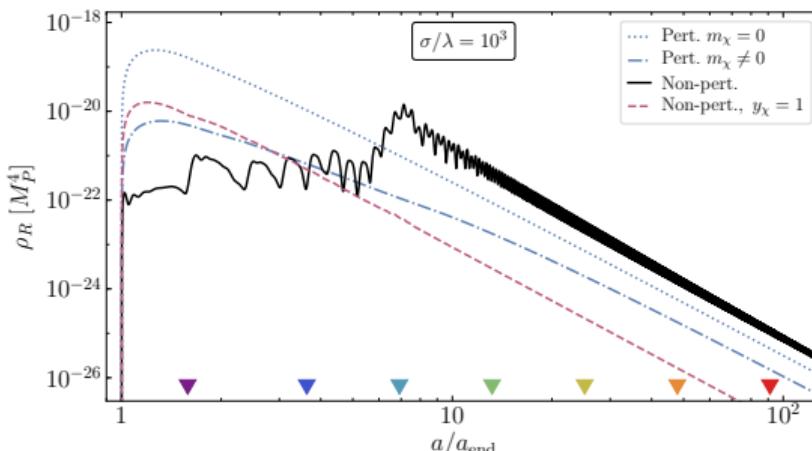
3. Preheating



4. Relic abundances



Strong



1. UV freeze-in



2. Perturbative reheating



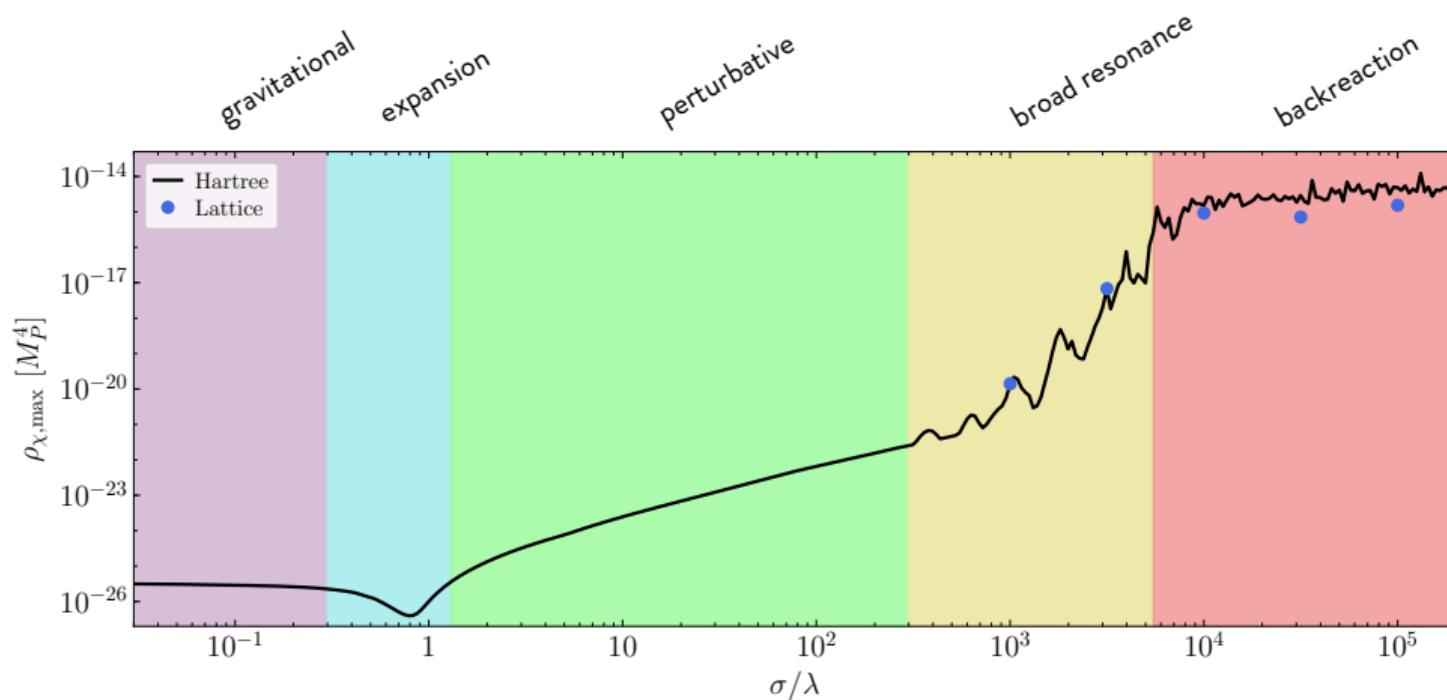
3. Preheating



4. Relic abundances



The maximum energy density



1. UV freeze-in



2. Perturbative reheating



3. Preheating



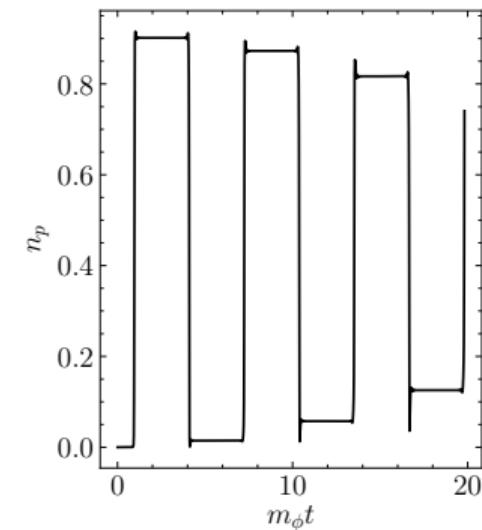
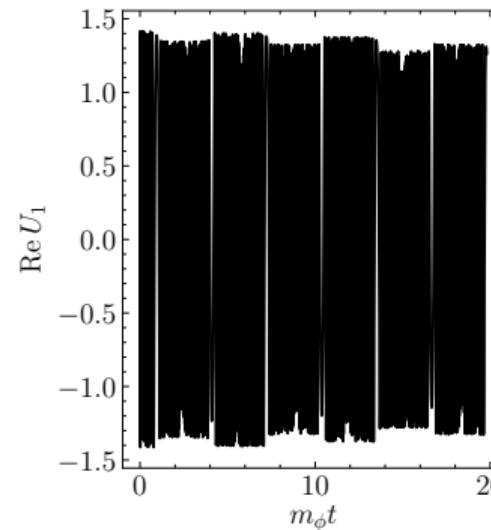
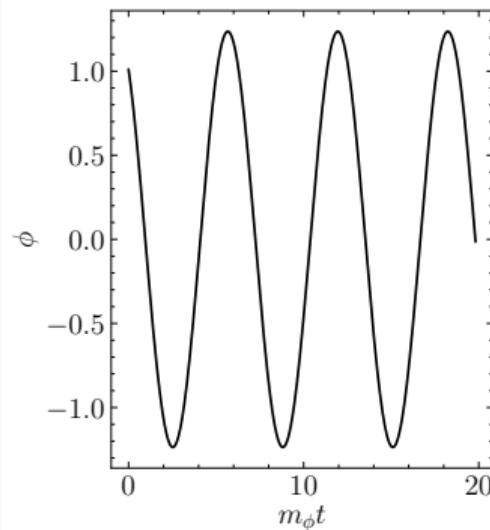
4. Relic abundances

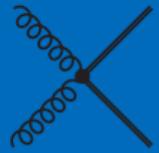


Fermion preheating

$$\left[i\gamma^\mu \partial_\mu + i\frac{3a'}{2a} \gamma^0 - am_\psi(\tau) \right] \psi = 0, \quad m_\psi^2(\tau) = y^2 \phi^2$$

Neglecting expansion,*



1. UV freeze-in**2. Perturbative reheating****3. Preheating****4. Relic abundances**

Fermion preheating

$$\left[i\gamma^\mu \partial_\mu + i\frac{3a'}{2a}\gamma^0 - am_\psi(\tau) \right] \psi = 0, \quad m_\psi^2(\tau) = y^2\phi^2$$

Neglecting expansion,*

* $dt/d\tau = a$ and

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

with

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

1. UV freeze-in



2. Perturbative reheating



3. Preheating



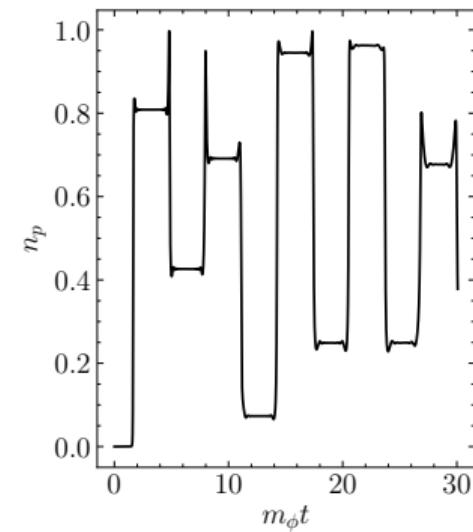
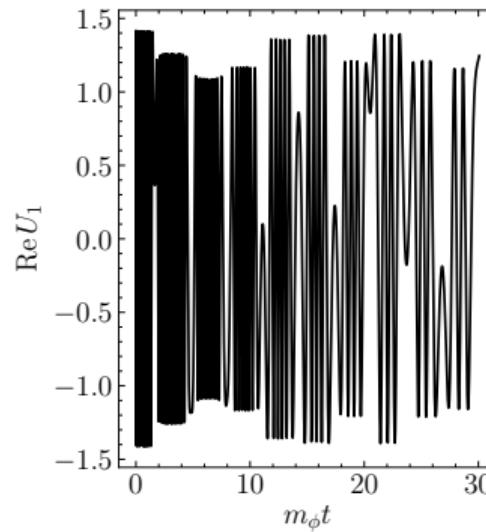
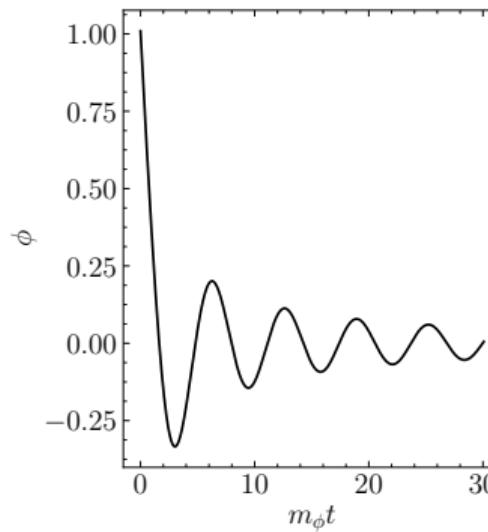
4. Relic abundances



Fermion preheating

$$\left[i\gamma^\mu \partial_\mu + i\frac{3a'}{2a} \gamma^0 - am_\psi(\tau) \right] \psi = 0, \quad m_\psi^2(\tau) = y^2 \phi^2$$

With expansion,



1. UV freeze-in



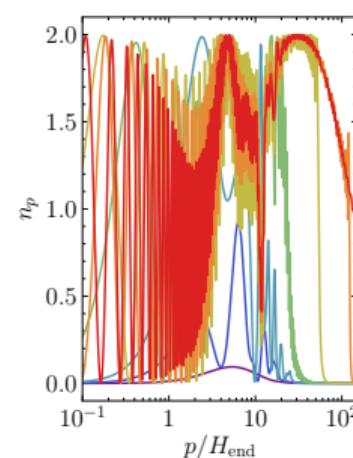
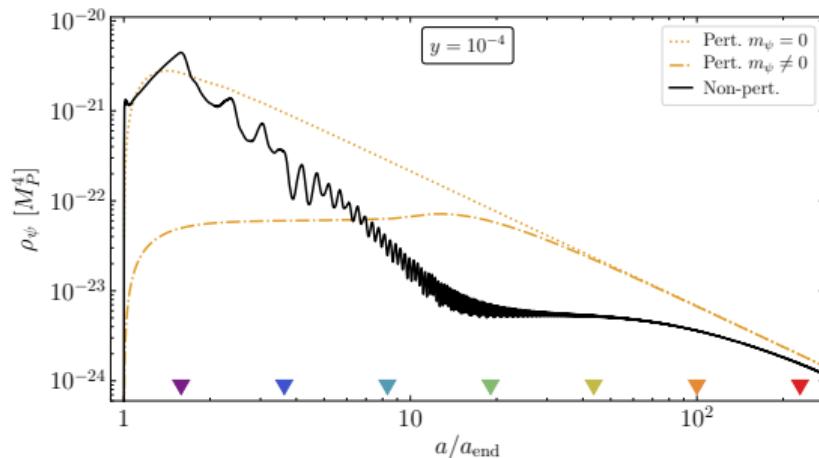
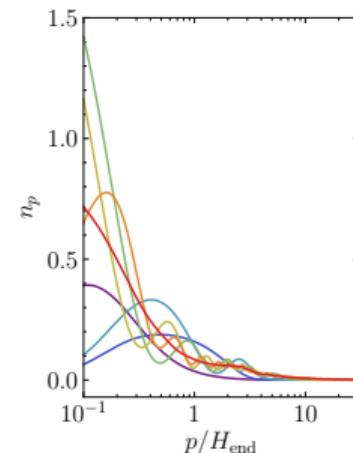
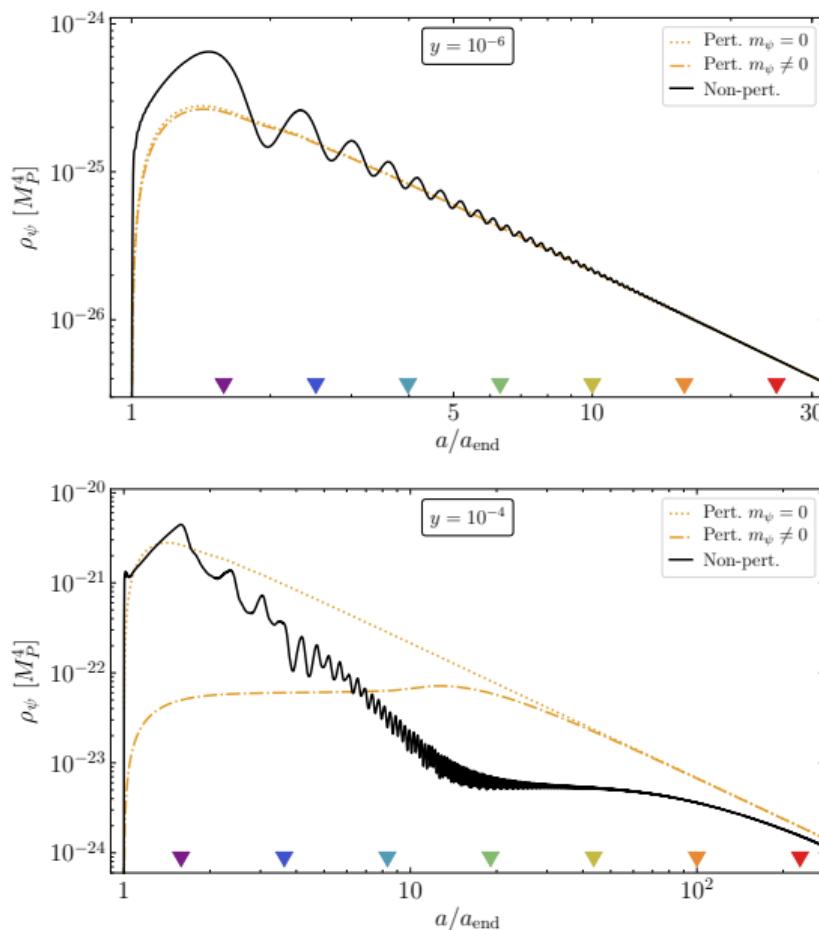
2. Perturbative reheating



3. Preheating



4. Relic abundances



1. UV freeze-in**2. Perturbative reheating****3. Preheating****4. Relic abundances**

Freeze-in from scalar preheating

Reminder:

$$\frac{dn_{\text{DM}}}{dt} + 3Hn_{\text{DM}} = \int \frac{d^3k}{(2\pi)^3 k_0} \frac{d^3k'}{(2\pi)^3 k'_0} \sqrt{(k \cdot k')^2 - m_\chi^2} \sigma(s) f_\chi(k) f_\chi(k')$$

with

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

Parent distributions

Perturbative: $\frac{\partial f_\chi}{\partial t} - HP \frac{\partial f_\chi}{\partial P} = \frac{\pi^2}{\beta^2 m_\phi^3} \rho_\phi \Gamma_{\phi\phi \rightarrow \chi\chi} (1 + 2f_\chi) \delta(P - \beta m_\phi)$

Non-perturbative: $f_\chi(P, t) = \frac{1}{2\omega_p} |\omega_p X_p - iX'_p|_{p \rightarrow aP}^2$

1. UV freeze-in



2. Perturbative reheating



3. Preheating

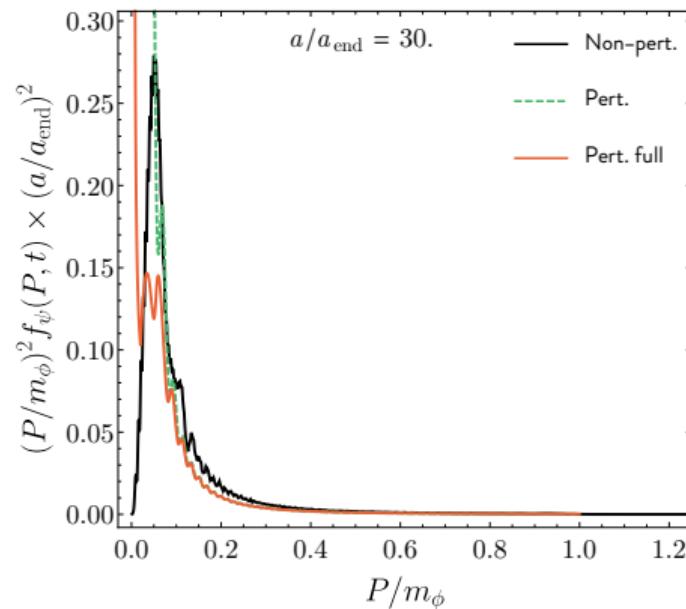


4. Relic abundances

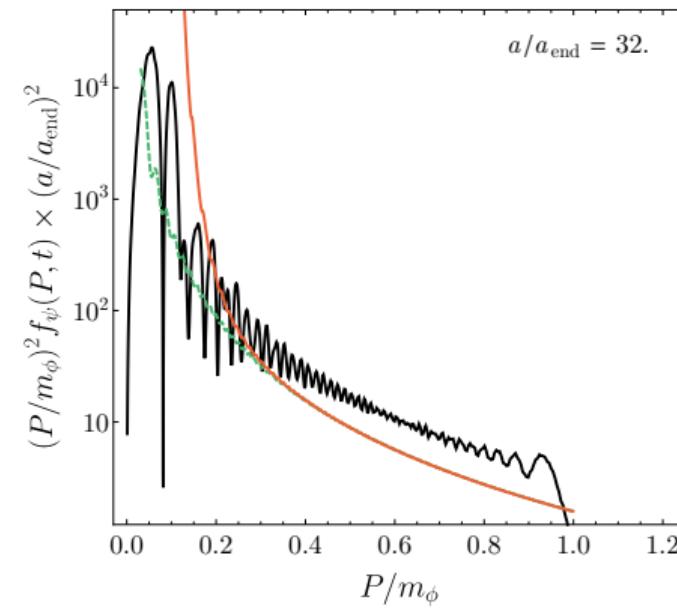


Scalar PSD

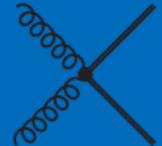
weak ($\sigma/\lambda = 10$)



strong ($\sigma/\lambda = 10^3$)



1. UV freeze-in



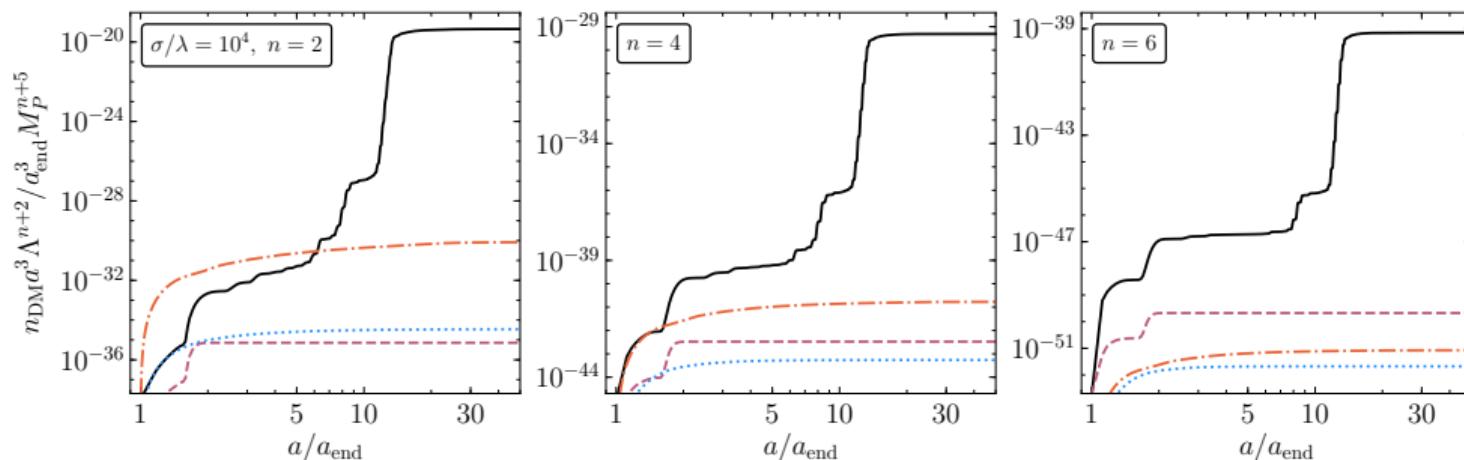
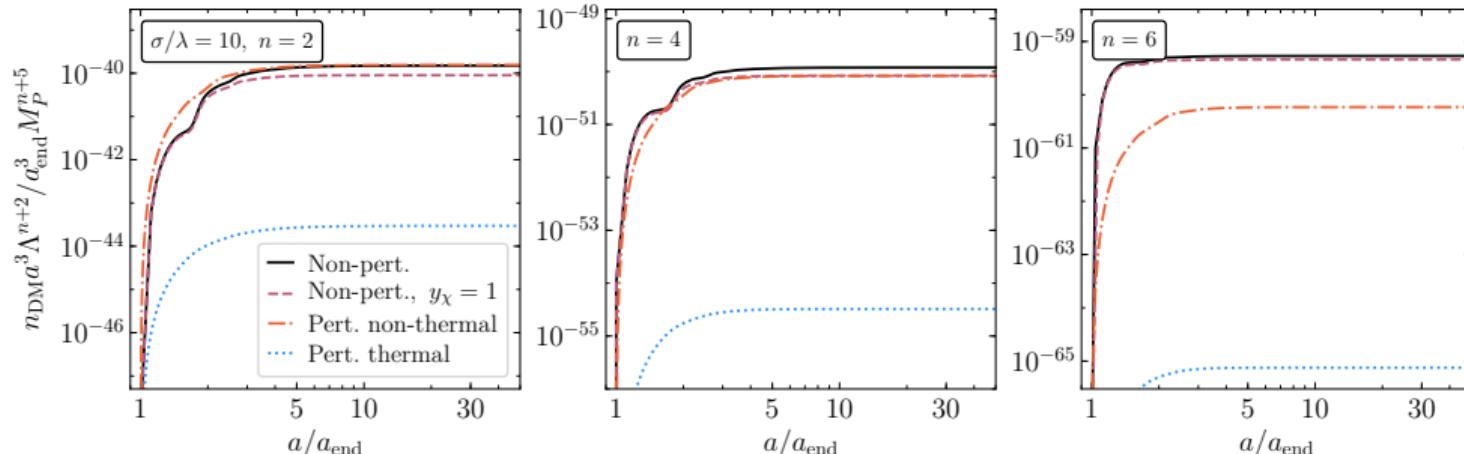
2. Perturbative reheating



3. Preheating



4. Relic abundances



1. UV freeze-in



2. Perturbative reheating



3. Preheating



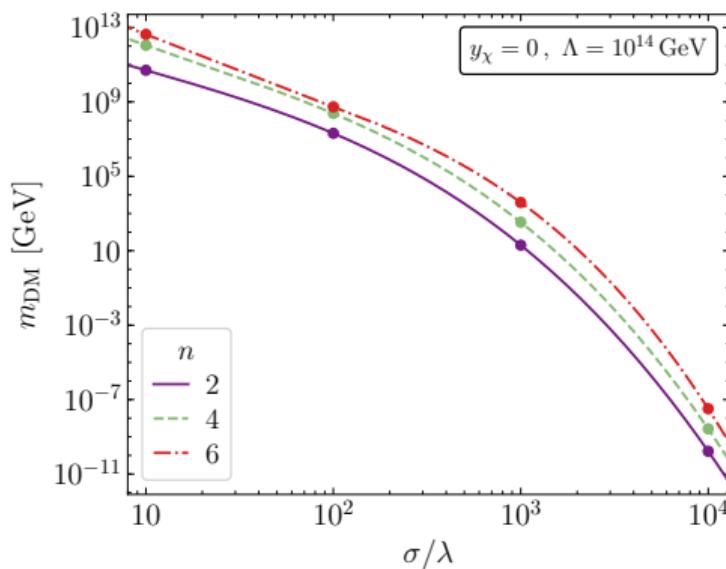
4. Relic abundances



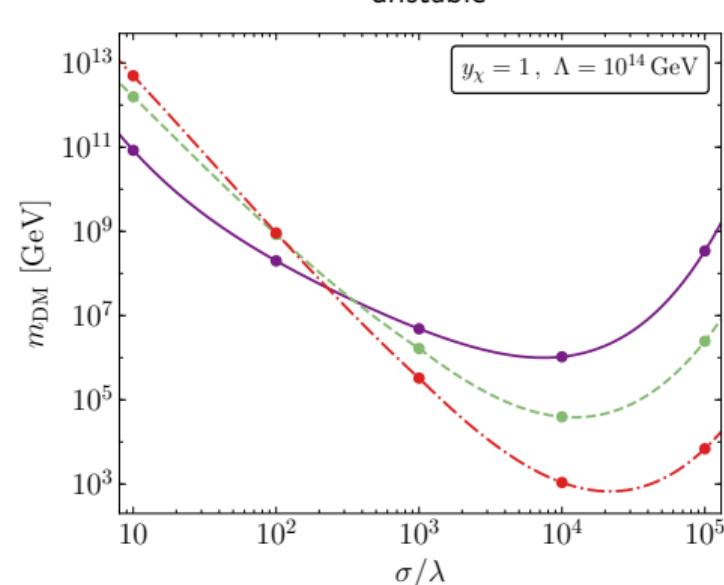
Saturating Ω_{DM}

$$\Omega_{\text{DM}} h^2 = 4 \times 10^{10} \left[n_{\text{DM}} \frac{a^3}{a_{\text{end}}^3} \frac{\Lambda^{n+2}}{M_P^{n+5}} \right] \left(\frac{M_P}{\Lambda} \right)^{n+2} \left(\frac{\rho_{\text{reh}}^{1/4}}{10^{10} \text{ GeV}} \right) \left(\frac{m_{\text{DM}}}{1 \text{ GeV}} \right)$$

stable



unstable



1. UV freeze-in**2. Perturbative reheating****3. Preheating****4. Relic abundances**

Freeze-in from fermion preheating

Reminder:

$$\frac{dn_{\text{DM}}}{dt} + 3Hn_{\text{DM}} = \int \frac{d^3k}{(2\pi)^3 k_0} \frac{d^3k'}{(2\pi)^3 k'_0} \sqrt{(k \cdot k')^2 - m_\psi^2} \sigma(s) f_\psi(k) f_\psi(k')$$

with

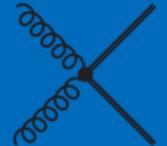
$$|\mathcal{M}|^2 = 16\pi \frac{s^{\frac{n}{2}+1}}{\Lambda^{n+2}}$$

Parent distributions

Perturbative: $\frac{\partial f_\psi}{\partial t} - HP \frac{\partial f_\psi}{\partial P} = \frac{8\pi^2}{\beta^2 m_\phi^3} \rho_\phi \Gamma_{\phi \rightarrow \bar{\psi}\psi} (1 - 2f_\psi) \delta \left(P - \frac{1}{2} \beta m_\phi \right)$

Non-perturbative: $f_\psi(P, t) = \frac{1}{2} \left| \left(1 + \frac{m_\psi}{\omega_p} \right)^{1/2} U_2 - \left(1 - \frac{m_\psi}{\omega_p} \right)^{1/2} U_1 \right|_{p \rightarrow aP}^2$

1. UV freeze-in



2. Perturbative reheating



3. Preheating

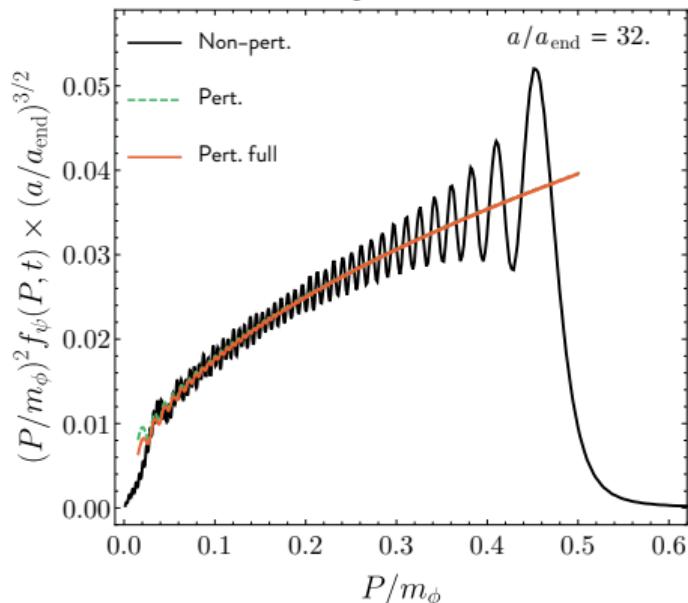


4. Relic abundances

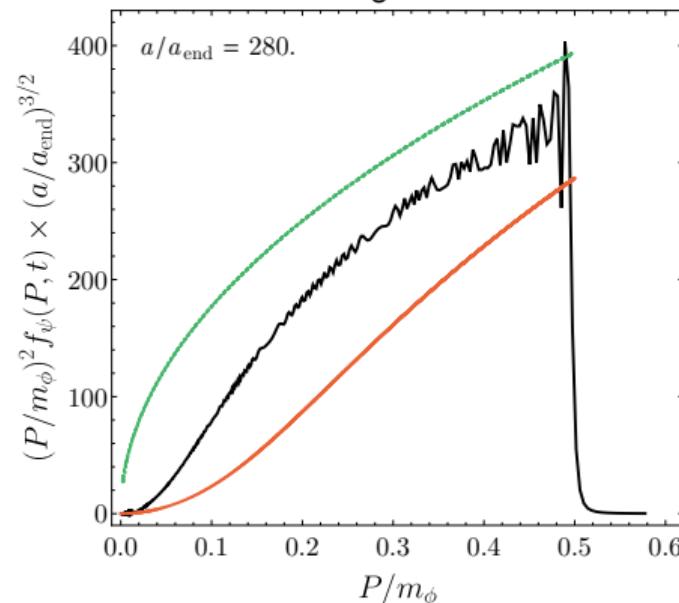


Fermion PSD

weak ($y = 10^{-6}$)



strong ($y = 10^{-4}$)



1. UV freeze-in



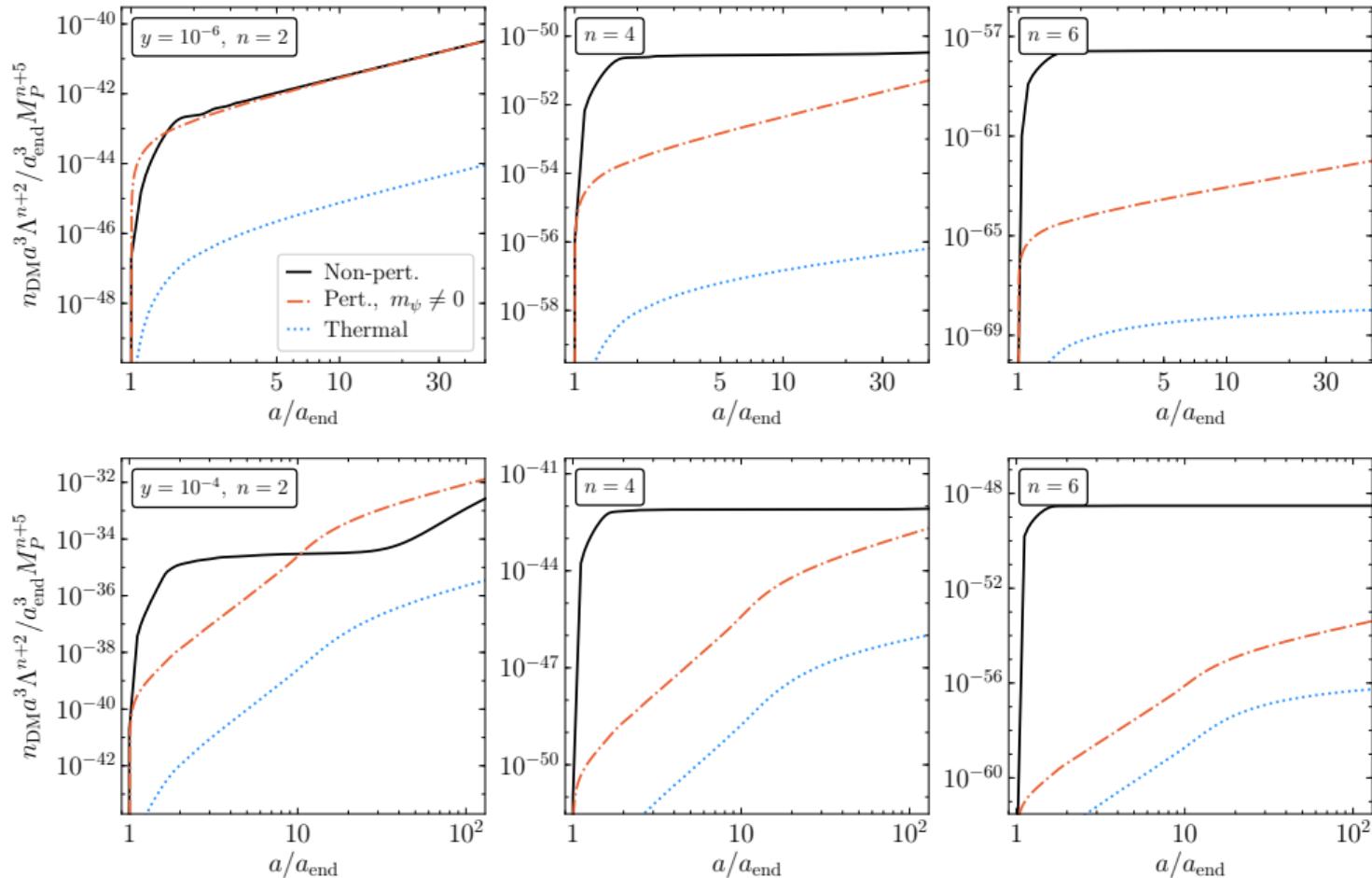
2. Perturbative reheating



3. Preheating



4. Relic abundances



1. UV freeze-in



2. Perturbative reheating



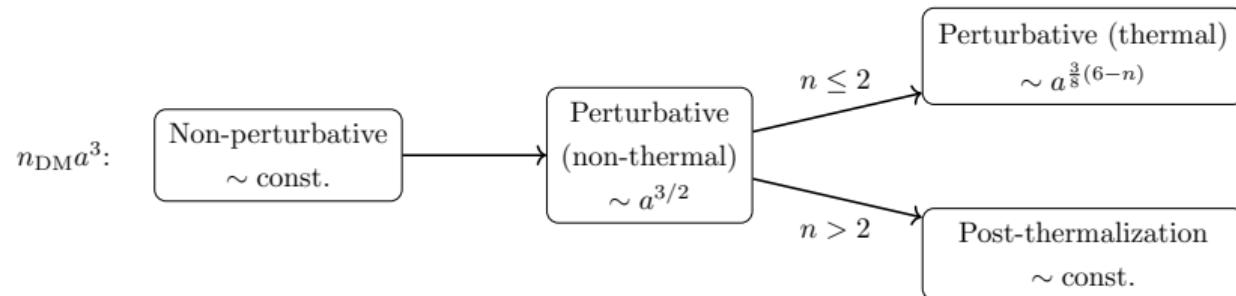
3. Preheating



4. Relic abundances



Dark matter from fermion preheating



1. UV freeze-in



2. Perturbative reheating



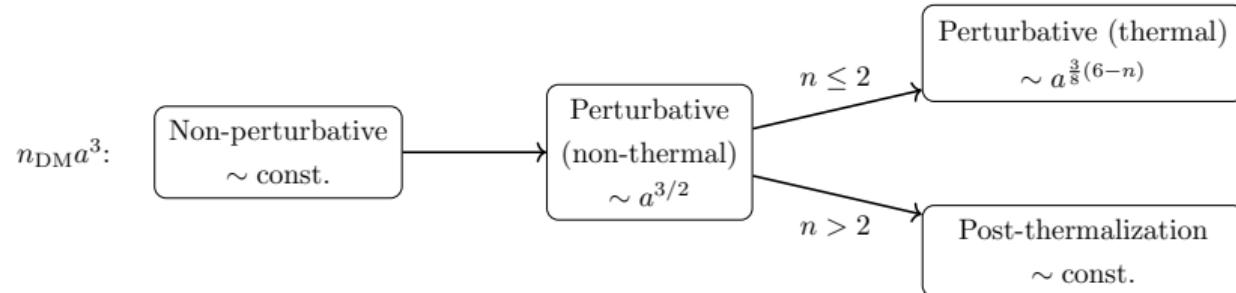
3. Preheating



4. Relic abundances



Dark matter from fermion preheating



Thank you

1. UV freeze-in



2. Perturbative reheating



3. Preheating



4. Relic abundances



Backreaction

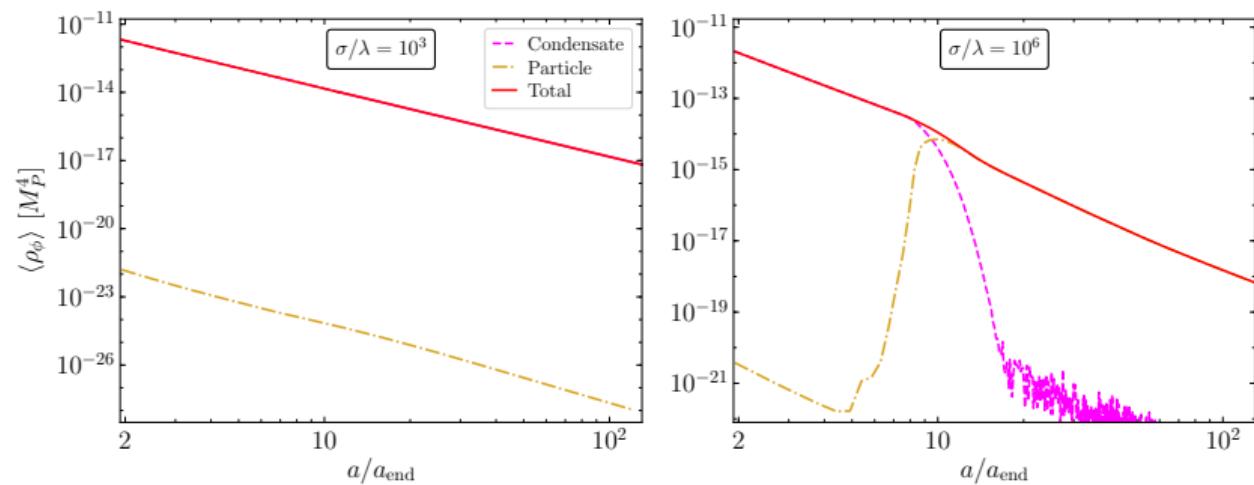
Homogeneous limit: *Hartree approximation*

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) + \sigma\langle\chi^2\rangle\phi = 0$$

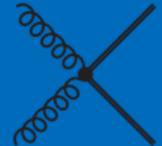
Fragmentation: classical fields in the lattice

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

$$\square\phi + \Gamma_\phi u^\mu \nabla_\mu \phi + V_\phi(\phi, \chi) = 0$$



1. UV freeze-in



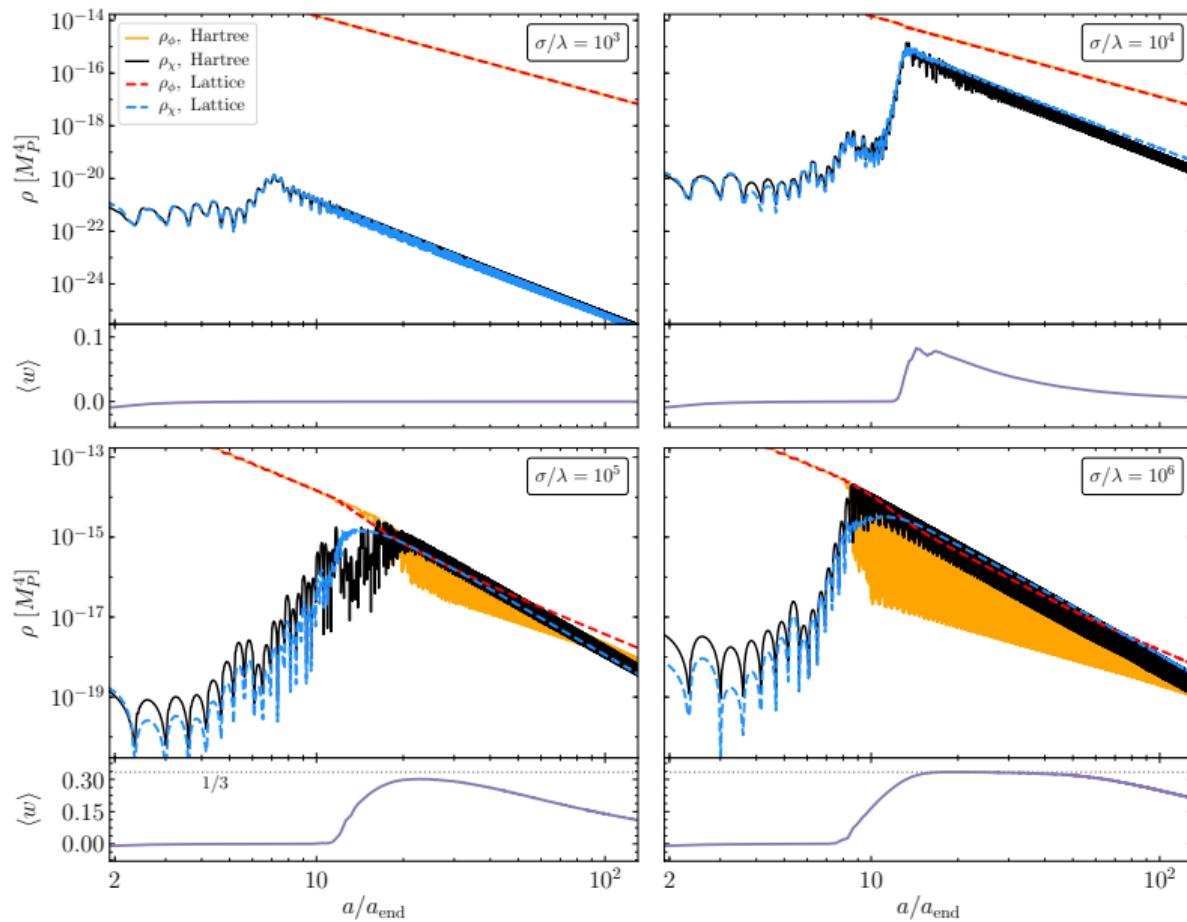
2. Perturbative reheating



3. Preheating



4. Relic abundances



1. UV freeze-in



2. Perturbative reheating



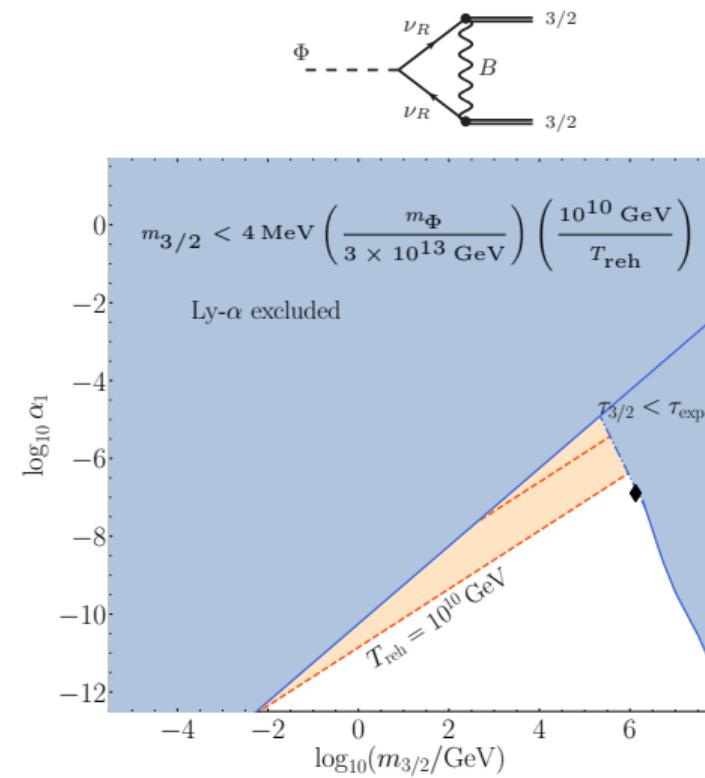
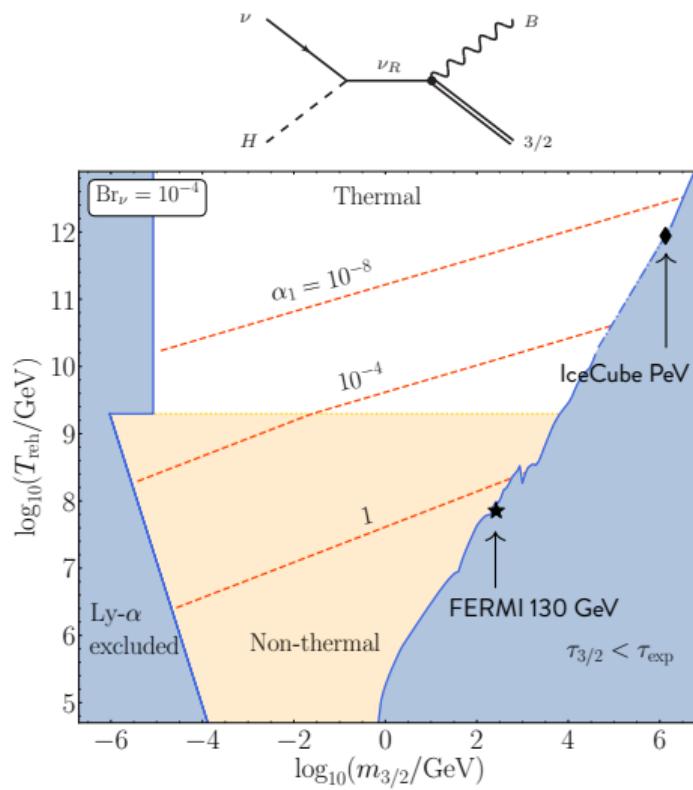
3. Preheating



4. Relic abundances



Lyman- α constraints



- 1. UV freeze-in
- 2. Perturbative reheating
- 3. Preheating
- 4. Relic abundances

Fermion rates

