19/11/21

Ending Inflation and the Hot Big Bang

SimonsCenter for Geometry and Physics

Freeze-in from Preheating

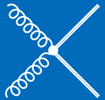
Marcos A. G. García

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

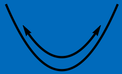
Universidad Nacional Autónoma de México

Instituto de Física

1. UV freeze-in



2. Perturbative reheating

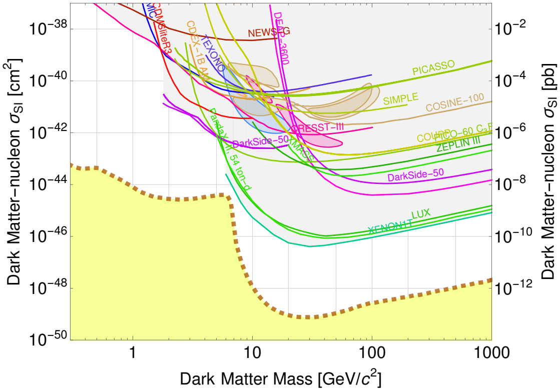


3. Preheating

4. Relic abundances

The case for FIMP dark matter

No detection of WIMPs yet!

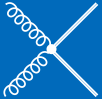


SuperCDMS Dark Matter Limit Plotter

Consider FIMPs:

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

1. UV freeze-in



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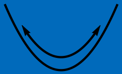


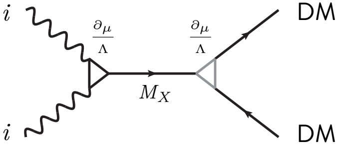
3. Preheating

4. Relic abundances

Freeze-in

$$\frac{\partial f_{\rm DM}}{\partial t} - Hp\frac{\partial f_{\rm DM}}{\partial p} = \frac{1}{16p}\int \frac{d^3\boldsymbol{p}'}{(2\pi)^3 p_0'}\,\frac{d^3\boldsymbol{k}}{(2\pi)^3 k_0}\,\frac{d^3\boldsymbol{k}'}{(2\pi)^3 k_0'}\,(2\pi)^4\delta(\boldsymbol{p}+\boldsymbol{p}'-\boldsymbol{k}-\boldsymbol{k}')\,|\mathcal{M}|^2_{\to}\, f_i(k) f_i(k')$$

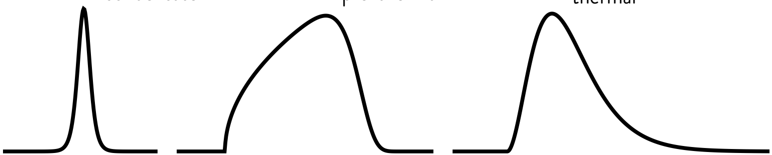
$$\frac{dn_{\rm DM}}{dt} + 3Hn_{\rm DM} = \int \frac{d^3\boldsymbol{k}}{(2\pi)^3 k_0}\,\frac{d^3\boldsymbol{k}'}{(2\pi)^3 k_0'}\,(k\cdot k')\,\sigma(s)\, f_i(k) f_i(k')$$



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

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

$k^2 f_i(k)$:



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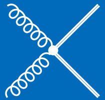
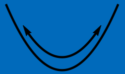
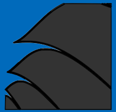


2. Perturbative reheating



3. Preheating

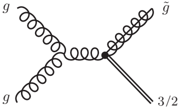


4. Relic abundances

The spin-3/2 family

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

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



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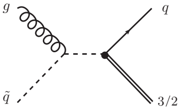

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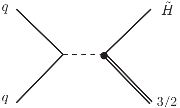
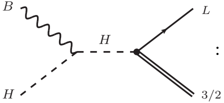


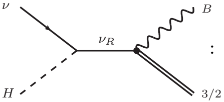
$+ \ldots \; : \quad |\mathcal{M}|^2 \sim \dfrac{s}{M_P^2}$

No susy, SM + ν_R + 3/2

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



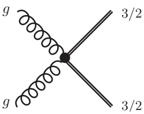
$: \quad |\mathcal{M}|^2 \sim \dfrac{s^2}{m_{3/2}^2 M_P^2}$



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

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

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



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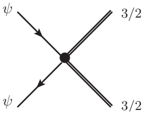

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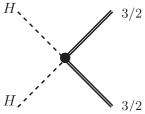
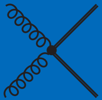


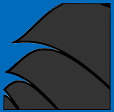
$: \quad |\mathcal{M}|^2 \sim \dfrac{s^4}{m_{3/2}^4 M_P^4}$

1. UV freeze-in



2. Perturbative reheating

3. Preheating



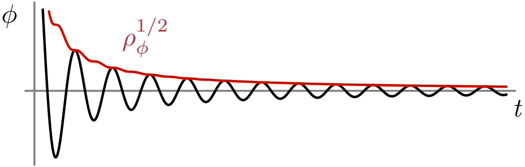
4. Relic abundances

The inflaton and its decay products

$$\mathcal{S} \;=\; \int d^4x\sqrt{-g}\left[\frac{1}{2}(\partial_\mu\phi)^2 - 6\lambda M_P^4 \tanh^2\left(\frac{\phi}{\sqrt{6}M_P}\right)\right.$$ inflaton

$$+\frac{1}{2}(\partial_\mu\chi)^2 - \frac{1}{2}\sigma\phi^2\chi^2$$ scalar $(m_\chi^2 = \sigma\phi^2)$

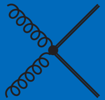
$$\left. + \bar{\psi}i\bar{\gamma}^\mu\nabla_\mu\psi - y\phi\bar{\psi}\psi + \cdots\right]$$ fermion $(m_\psi^2 = y^2\phi^2)$



$$\langle p_\phi\rangle = \tfrac{1}{2}\langle\dot{\phi}^2 + m_\phi^2\phi^2\rangle \simeq 0$$

(matter)

1. UV freeze-in



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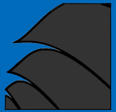


4. Relic abundances

The fluid picture

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

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

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

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

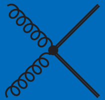
$$E_n \;=\; n\, m_\phi$$

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

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

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

1. UV freeze-in



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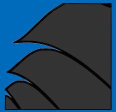
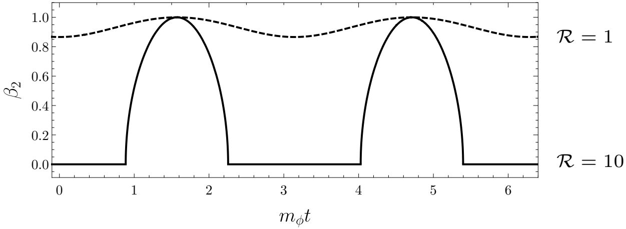


4. Relic abundances

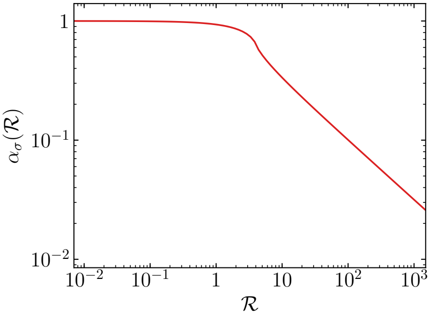
Kinematic blocking: scalars

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

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



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



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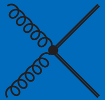


2. Perturbative reheating

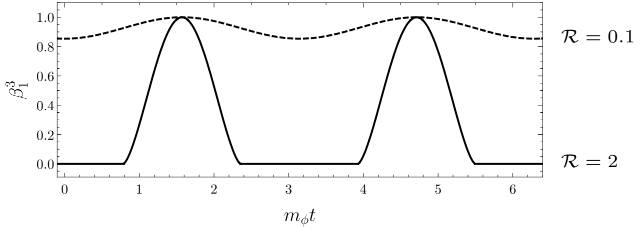
3. Preheating

4. Relic abundances

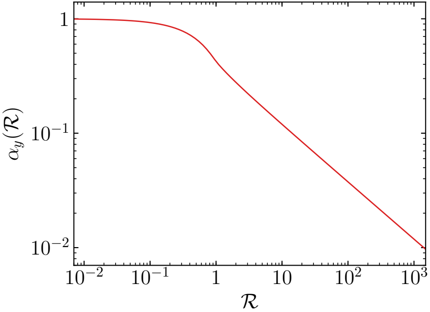
Kinematic blocking: fermions

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

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



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



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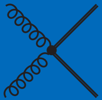

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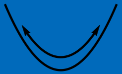


3. Preheating

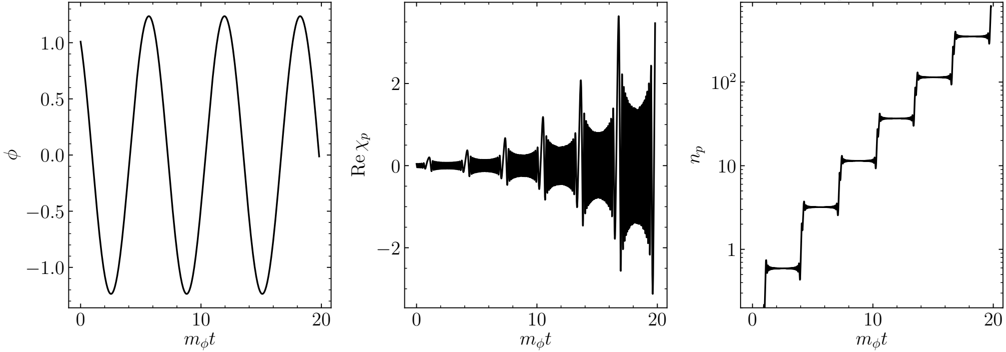
4. Relic abundances

Scalar preheating

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

Neglecting expansion,

$$n_p = \frac{1}{2\omega_p}|\omega_p\chi_p - i\dot{\chi}_p|^2$$



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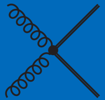

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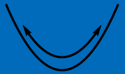


3. Preheating

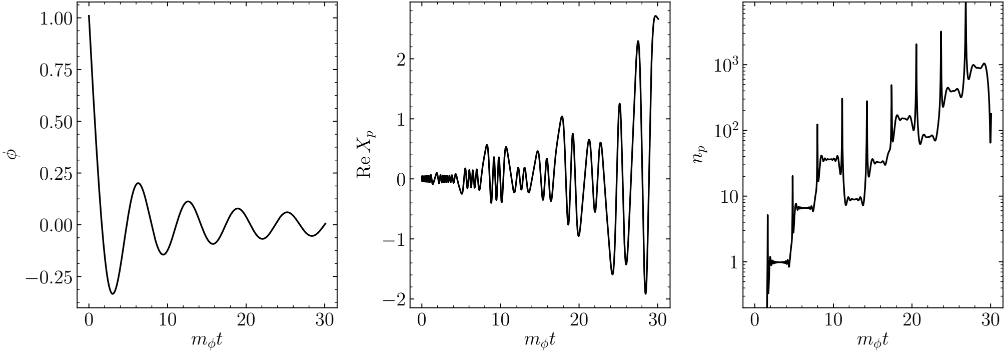
4. Relic abundances

Scalar preheating

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

With expansion,

$$X = a\chi \qquad n_p = \frac{1}{2\omega_p}|\omega_p X_p - iX_p'|^2$$



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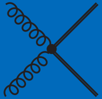

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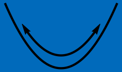


3. Preheating

4. Relic abundances

Unstable-scalar preheating

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

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

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

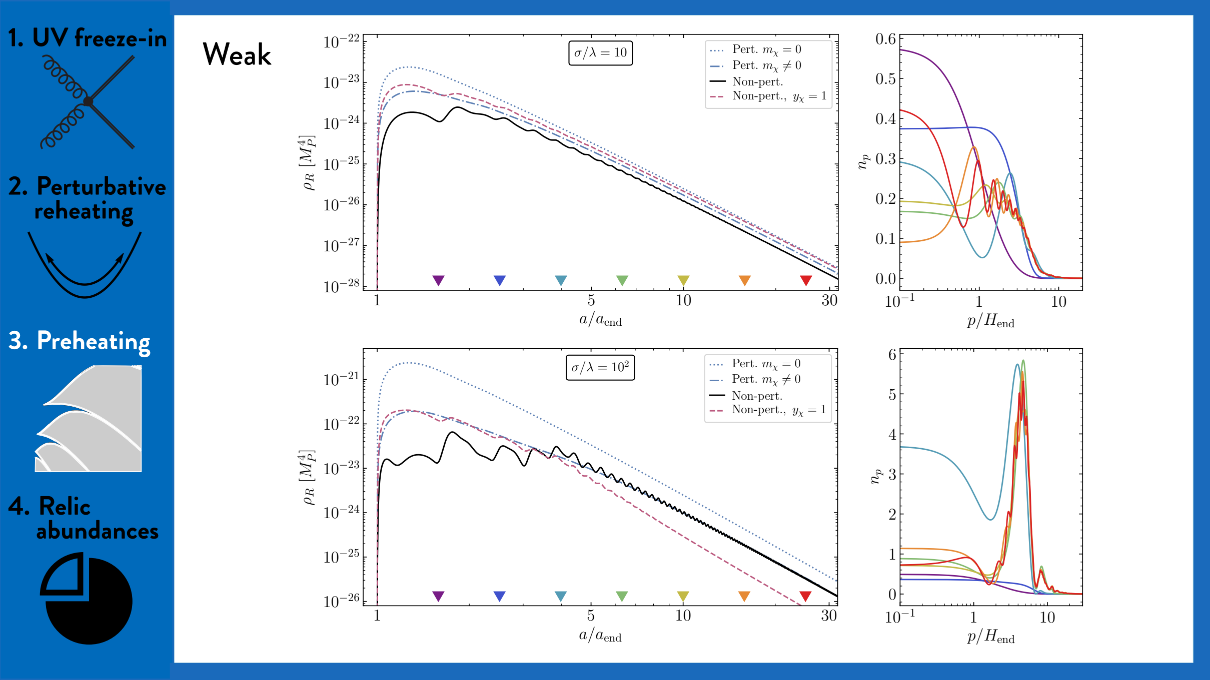
$$Y_p'' + \omega_p^2 Y_p = 0$$

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

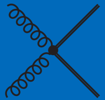
where

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

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


1. UV freeze-in
2. Perturbative reheating
3. Preheating
4. Relic abundances
Weak
$\sigma/\lambda = 10$
Pert. $m_\chi = 0$
Pert. $m_\chi \neq 0$
Non-pert.
Non-pert., $y_\chi = 1$
$\rho_R\ [M_P^4]$
$a/a_{\rm end}$
n_p
$p/H_{\rm end}$
$\sigma/\lambda = 10^2$
Pert. $m_\chi = 0$
Pert. $m_\chi \neq 0$
Non-pert.
Non-pert., $y_\chi = 1$
$\rho_R\ [M_P^4]$
$a/a_{\rm end}$
n_p
$p/H_{\rm end}$

1. UV freeze-in



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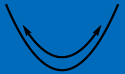
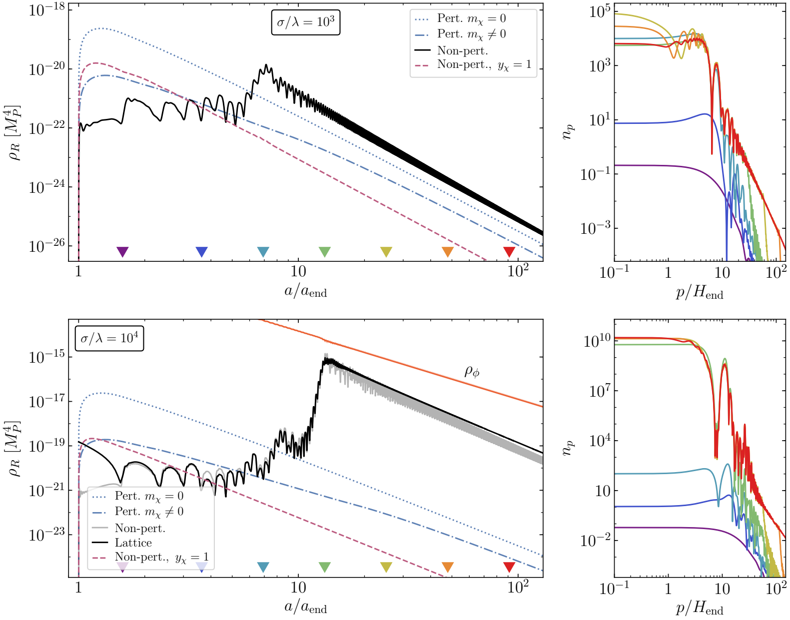


3. Preheating

4. Relic abundances

Strong



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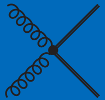

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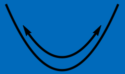
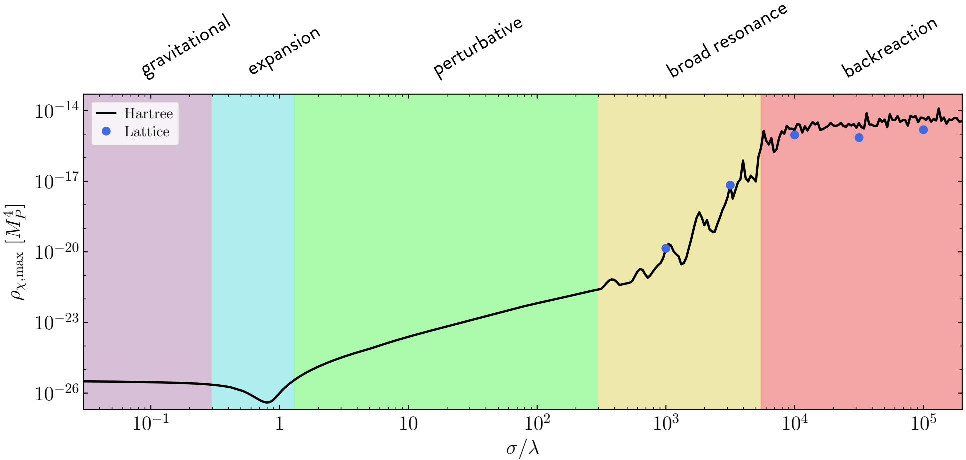


3. Preheating

4. Relic abundances

The maximum energy density



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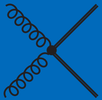

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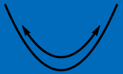


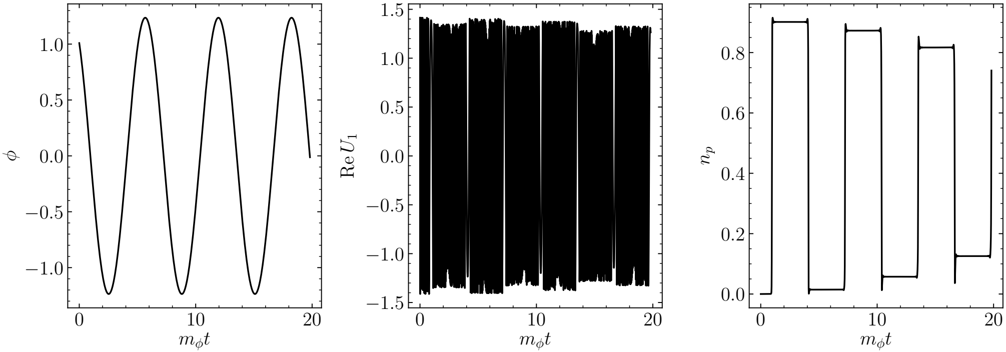
3. Preheating

4. Relic abundances

Fermion preheating

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

Neglecting expansion,*



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Neglecting expansion,*

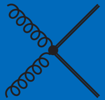
*$dt/d\tau = a$ and

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

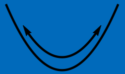
with

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

1. UV freeze-in



2. Perturbative reheating



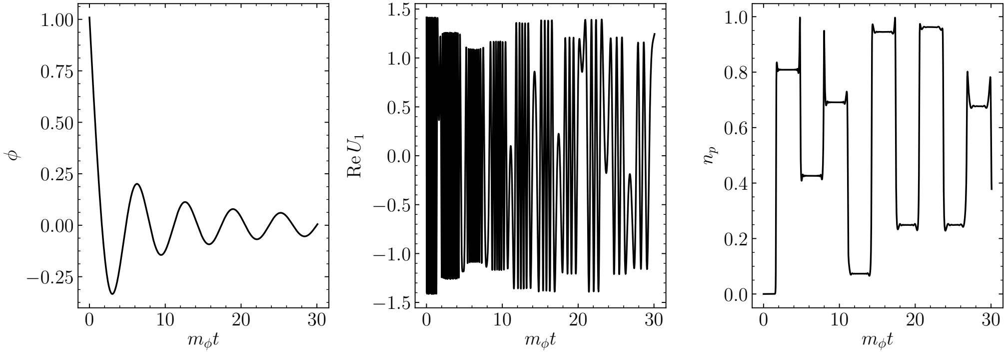
3. Preheating

4. Relic abundances

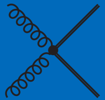
Fermion preheating

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

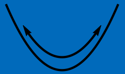
With expansion,



1. UV freeze-in

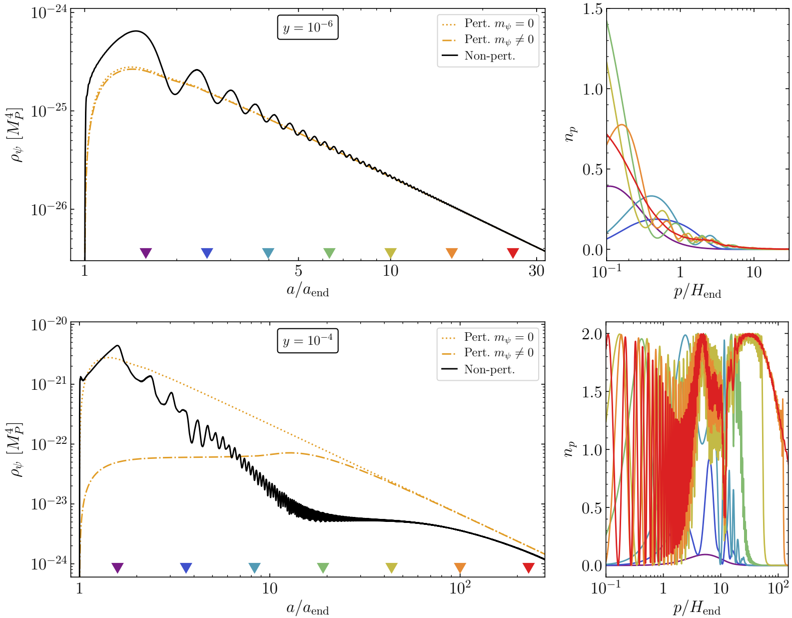


2. Perturbative reheating

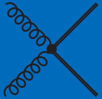


3. Preheating

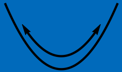
4. Relic abundances



1. UV freeze-in



2. Perturbative reheating



3. Preheating

4. Relic abundances

Freeze-in from scalar preheating

Reminder:

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

with

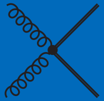
$$|\mathcal{M}|^2 = 16\pi\frac{s^{\frac{n}{2}+1}}{\Lambda^{n+2}}$$

Parent distributions

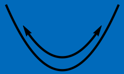
Perturbative: $$\frac{\partial f_\chi}{\partial t} - HP\frac{\partial f_\chi}{\partial P} = \frac{\pi^2}{\beta^2 m_\phi^3}\rho_\phi \Gamma_{\phi\phi\to\chi\chi}(1+2f_\chi)\delta\left(P - \beta m_\phi\right)$$

Non-perturbative: $$f_\chi(P,t) = \frac{1}{2\omega_p}\left|\omega_p X_p - iX_p'\right|^2_{p\to aP}$$

1. UV freeze-in



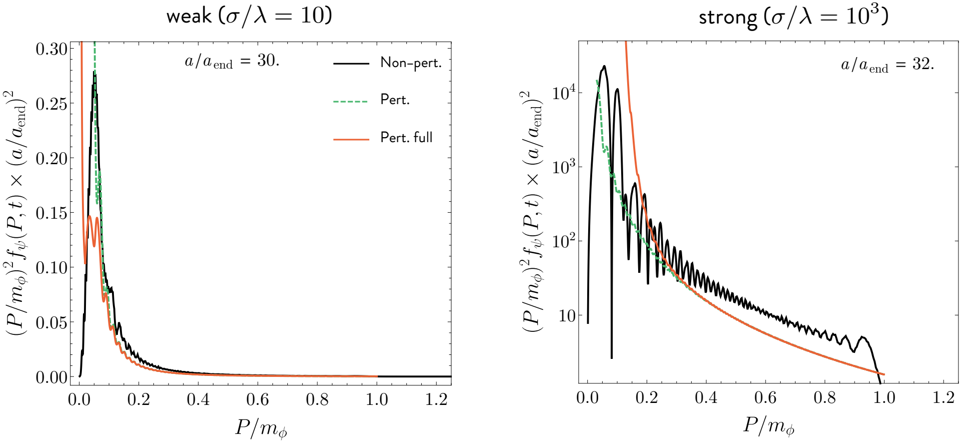
2. Perturbative reheating

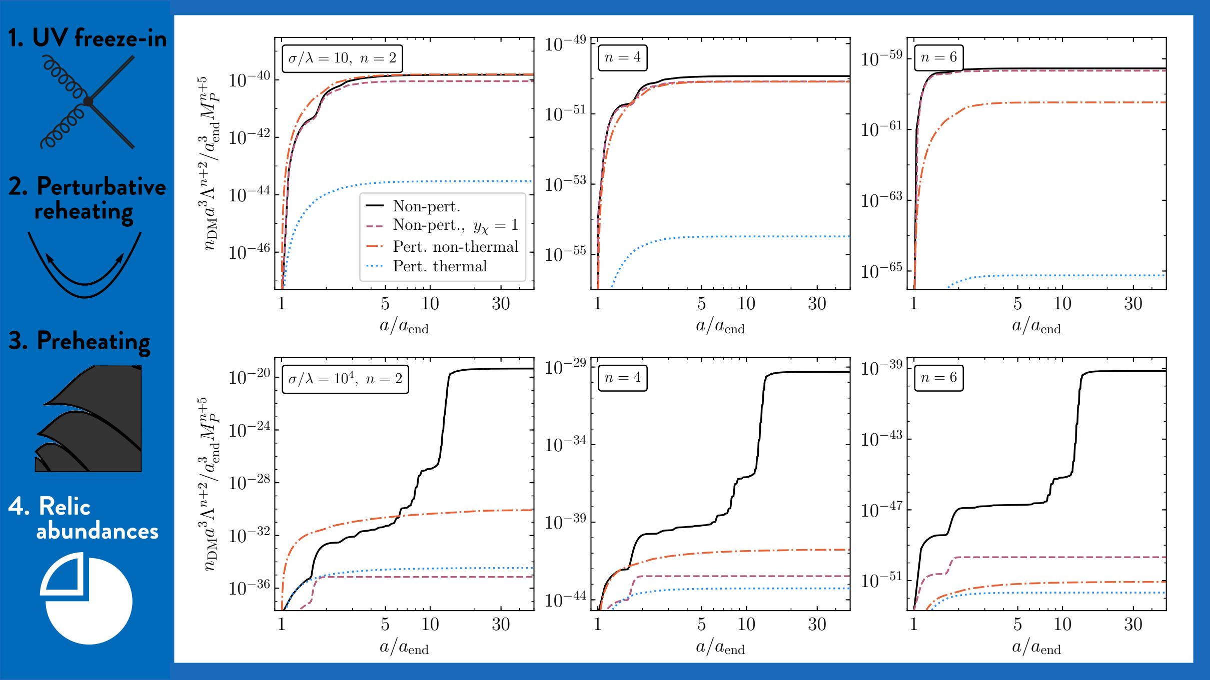


3. Preheating

4. Relic abundances

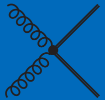
Scalar PSD



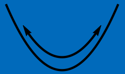


1. UV freeze-in
2. Perturbative reheating
3. Preheating
4. Relic abundances
$\sigma/\lambda = 10,\ n = 2$
$n = 4$
$n = 6$
$\sigma/\lambda = 10^4,\ n = 2$
$n = 4$
$n = 6$
$n_{\rm DM} a^3 \Lambda^{n+2} / a_{\rm end}^3 M_P^{n+5}$
$a/a_{\rm end}$
Non-pert.
Non-pert., $y_\chi = 1$
Pert. non-thermal
Pert. thermal

1. UV freeze-in



2. Perturbative reheating



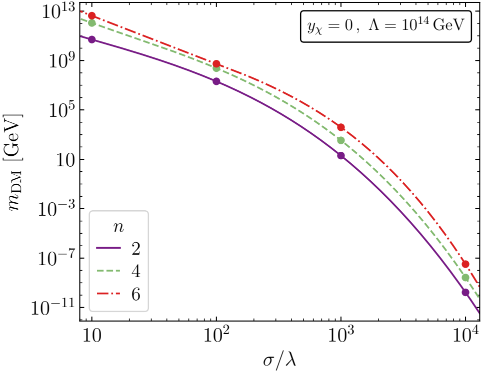
3. Preheating

4. Relic abundances

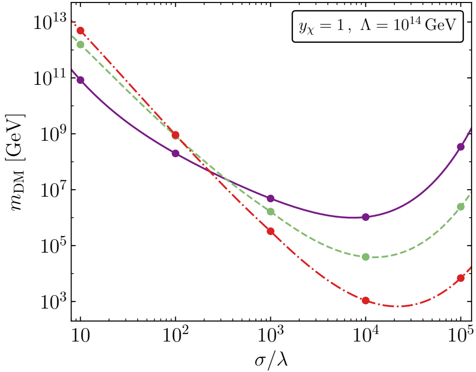
Saturating $\Omega_{\rm DM}$

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

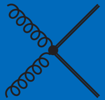
stable



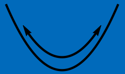
unstable



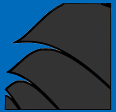
1. UV freeze-in



2. Perturbative reheating



3. Preheating



4. Relic abundances

Freeze-in from fermion preheating

Reminder:

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

with

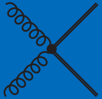
$$|\mathcal{M}|^2 = 16\pi\frac{s^{\frac{n}{2}+1}}{\Lambda^{n+2}}$$

Parent distributions

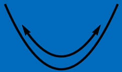
Perturbative: $$\frac{\partial f_\psi}{\partial t} - HP\frac{\partial f_\psi}{\partial P} = \frac{8\pi^2}{\beta^2 m_\phi^3}\rho_\phi \Gamma_{\phi\to\bar\psi\psi}(1-2f_\psi)\delta\left(P - \frac{1}{2}\beta m_\phi\right)$$

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

1. UV freeze-in



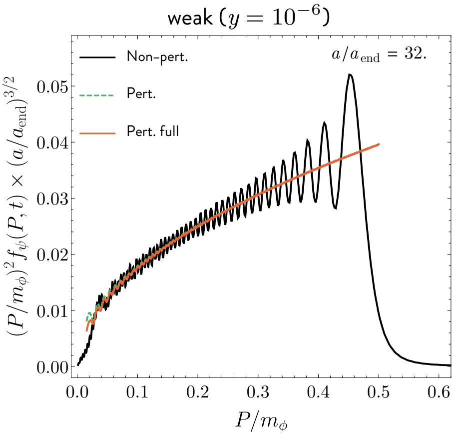
2. Perturbative reheating

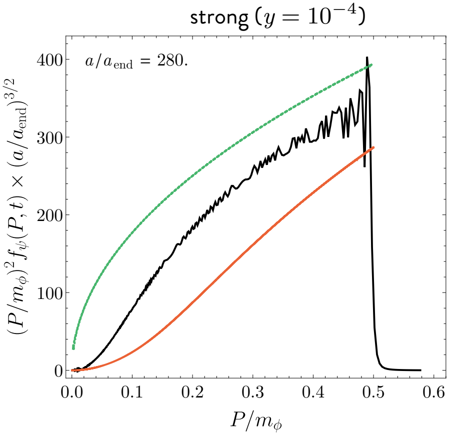


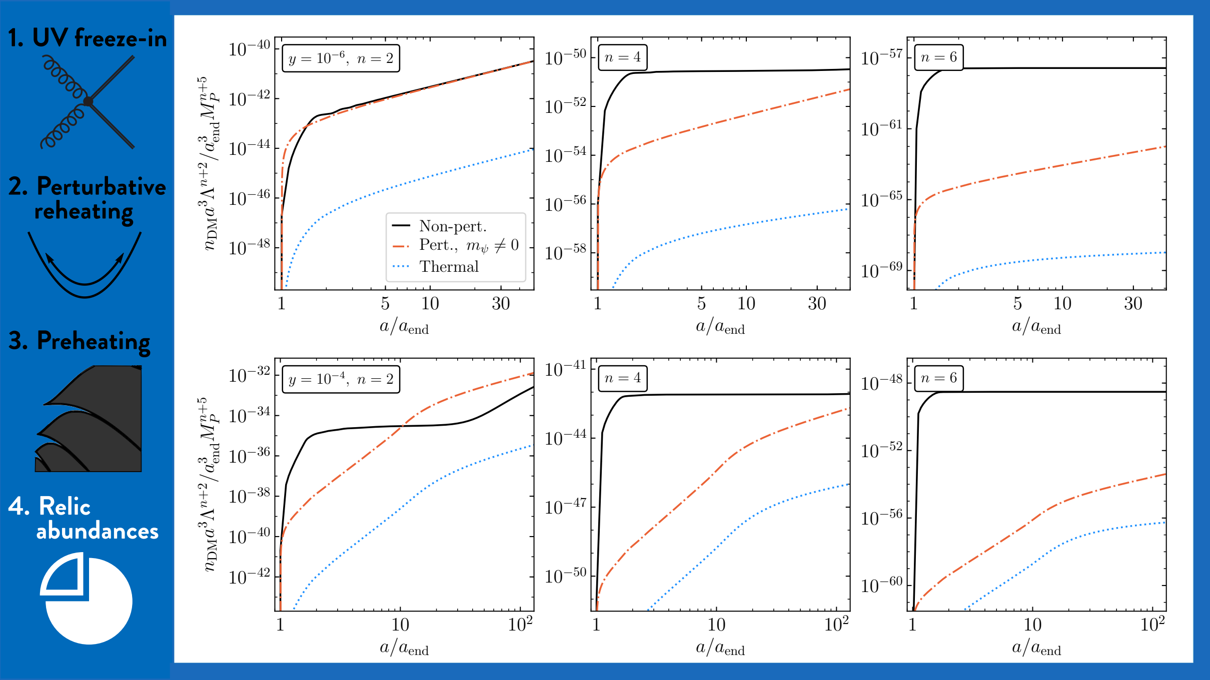
3. Preheating

4. Relic abundances

Fermion PSD

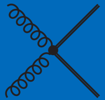




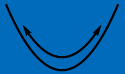


1. UV freeze-in
2. Perturbative reheating
3. Preheating
4. Relic abundances
$n_{\mathrm{DM}} a^3 \Lambda^{n+2} / a_{\mathrm{end}}^3 M_P^{n+5}$
$y = 10^{-6},\ n = 2$
$n = 4$
$n = 6$
$y = 10^{-4},\ n = 2$
Non-pert.
Pert., $m_\psi \neq 0$
Thermal
a/a_{end}

1. UV freeze-in



2. Perturbative reheating



3. Preheating

4. Relic abundances

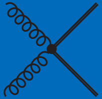
Dark matter from fermion preheating

$n_{\rm DM} a^3$:

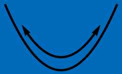
Non-perturbative $\sim$ const. $\rightarrow$ Perturbative (non-thermal) $\sim a^{3/2}$

- $n \leq 2$ $\rightarrow$ Perturbative (thermal) $\sim a^{\frac{3}{8}(6-n)}$
- $n > 2$ $\rightarrow$ Post-thermalization $\sim$ const.

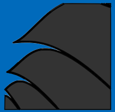
1. UV freeze-in



2. Perturbative reheating



3. Preheating



4. Relic abundances

Dark matter from fermion preheating

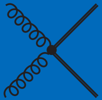
$n_{\mathrm{DM}}a^3$:

Non-perturbative $\sim$ const. $\longrightarrow$ Perturbative (non-thermal) $\sim a^{3/2}$

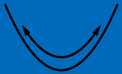
- $n \leq 2$ $\longrightarrow$ Perturbative (thermal) $\sim a^{\frac{3}{8}(6-n)}$
- $n > 2$ $\longrightarrow$ Post-thermalization $\sim$ const.

Thank you

1. UV freeze-in



2. Perturbative reheating



3. Preheating

4. Relic abundances

Backreaction

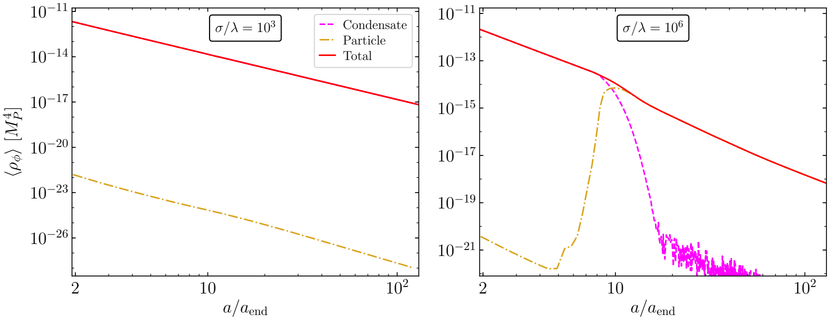
Homogeneous limit: *Hartree approximation*

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

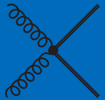
Fragmentation: classical fields in the lattice

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

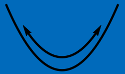
$$\Box\phi + \Gamma_\phi u^\mu \nabla_\mu \phi + V_\phi(\phi,\chi) \;=\; 0$$



1. UV freeze-in

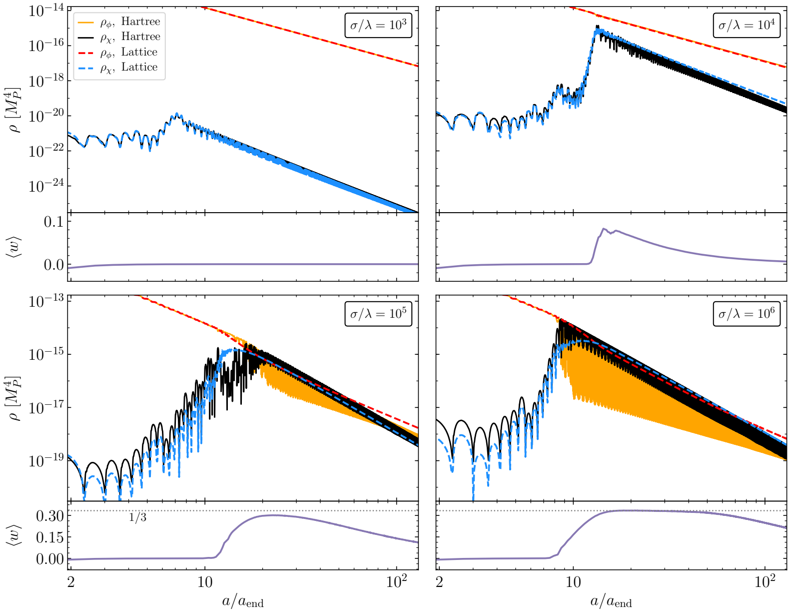


2. Perturbative reheating

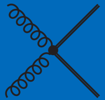


3. Preheating

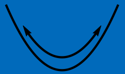
4. Relic abundances



1. UV freeze-in



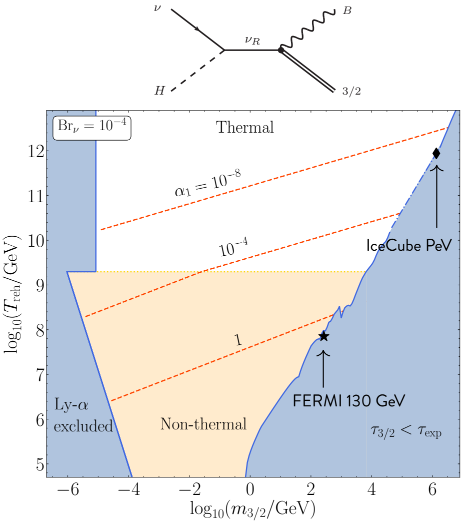
2. Perturbative reheating

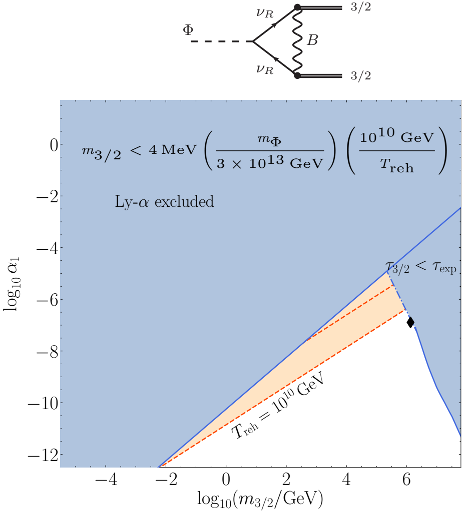


3. Preheating

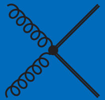
4. Relic abundances

Lyman-α constraints

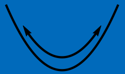




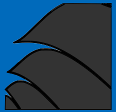
1. UV freeze-in



2. Perturbative reheating



3. Preheating



4. Relic abundances

Fermion rates