PASCOS 2021

26th International Symposium on Particles, Strings & Cosmology

IBS, Center for Theoretical Physics of the Universe

Dark Matter Production During Reheating
(by example)

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17/06/2021

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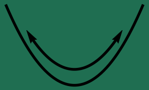
UAM Universidad Autónoma de Madrid

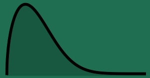
CSIC Consejo Superior de Investigaciones Científicas

1. DM model

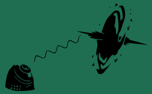
2. Reheating



3. Freeze-in



4. Constraints



Is a spin-$\frac{3}{2}$ dark matter particle the missing piece in the puzzle?

Described by Rarita-Schwinger Lagrangian

$$\mathcal{L}^0_{3/2} = -\frac{1}{2}\bar{\Psi}_\mu \left(i\gamma^{\mu\rho\nu}\partial_\rho + m_{3/2}\gamma^{\mu\nu} \right) \Psi_\nu$$

with $\gamma^{\mu\nu} = \gamma^{[\mu}\gamma^{\nu]}$ and $\gamma^{\mu\nu\rho} = \gamma^{[\mu}\gamma^{\nu}\gamma^{\rho]}$.

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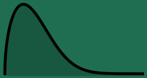

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Instead of highly symmetric WIMP/gravitino-like scenario, consider a minimal embedding,

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{\rm SM} + \mathcal{L}^0_{3/2} + \mathcal{L}^0_{\nu_R} + yH\bar{\nu}_L\nu_R + \frac{M_R}{2}\bar{\nu}^c_R\nu_R \\ &+ i\frac{\alpha_1}{2M_P}\bar{\nu}_R\gamma^\mu[\gamma^\rho,\gamma^\sigma]\Psi_\mu F_{\rho\sigma} + i\frac{\alpha_2}{2M_P}i\sigma_2(D^\mu H)^*\bar{L}\Psi_\mu + \text{h.c.}\end{aligned}$$

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

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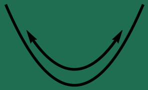
2. Reheating



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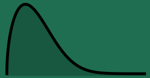

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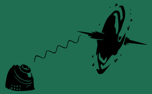
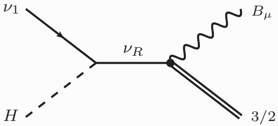
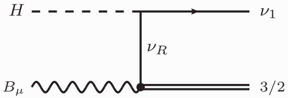
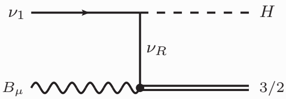


Scatterings and decays

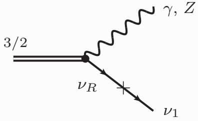
$$\mathcal{L}_{3/2} = \boxed{i\frac{\alpha_1}{2M_P}\bar{\nu}_R\gamma^\mu[\gamma^\rho,\gamma^\sigma]\Psi_\mu F_{\rho\sigma}} + i\frac{\alpha_2}{2M_P} i\sigma_2 (D^\mu H)^* \bar{L}\Psi_\mu + \text{h.c.}$$

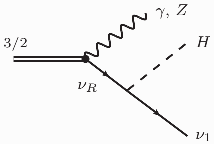






$$\sigma(s) = \frac{11\alpha_1^2 y^2 s^2}{72\pi m_{3/2}^2 M_R^2 M_P^2}, \qquad s = E_{\text{CM}}^2$$





$$\tau^{2b}_{3/2} \simeq 1.6\times 10^{29}\left(\frac{10^{-2}}{y\,\alpha_1}\right)^2\left(\frac{M_R}{10^{14}\,\text{GeV}}\right)^2\left(\frac{10^4\,\text{GeV}}{m_{3/2}}\right)^3 \text{s}$$

$$\tau^{3b}_{3/2} \simeq 5.6\times 10^{28}\left(\frac{10^{-2}}{y\,\alpha_1}\right)^2\left(\frac{M_R}{10^{14}\,\text{GeV}}\right)^2\left(\frac{10^4\,\text{GeV}}{m_{3/2}}\right)^5 \text{s}$$

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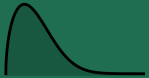
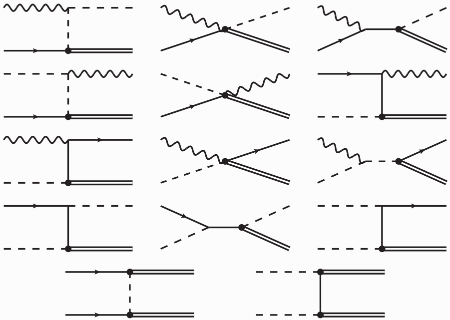
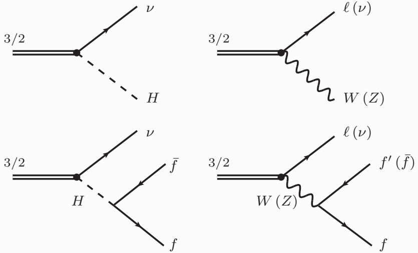


4. Constraints

Scatterings and decays

$$\mathcal{L}_{3/2} = i\frac{\alpha_1}{2M_P}\bar{\nu}_R\gamma^\mu[\gamma^\rho,\gamma^\sigma]\Psi_\mu F_{\rho\sigma} + \boxed{i\frac{\alpha_2}{2M_P}i\sigma_2(D^\mu H)^*\bar{L}\Psi_\mu} + \text{h.c.}$$



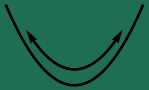


$$\sigma(s) = \frac{\alpha_2^2 s}{9216\pi m_{3/2}^2 M_P^2}(639g^2 + 87g'^2 + 144h_t^2 + 32h_\tau^2)$$

$$\frac{\tau_{3/2}}{10^{28}\text{s}} \simeq \begin{cases} 14.8\left(\frac{10^{-7}}{\alpha_2}\right)^2\left(\frac{1\,\text{GeV}}{m_{3/2}}\right)^3, & m_{3/2} > m_H \\ 0.6\left(\frac{10^{-3}}{\alpha_2}\right)^2\left(\frac{1\,\text{GeV}}{m_{3/2}}\right)^{5.28}, & m_e < m_{3/2} < m_W \\ 4.8\left(\frac{10^{-3}}{\alpha_2}\right)^2\left(\frac{1\,\text{GeV}}{m_{3/2}}\right)^5, & m_{3/2} < m_e \end{cases}$$

1. DM model

2. Reheating



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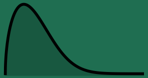

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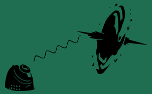
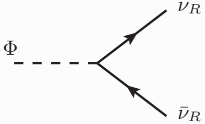
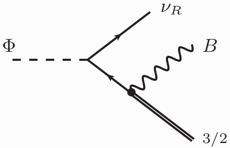


Production (via inflaton decay)

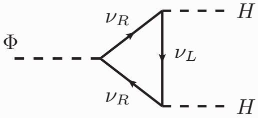
Assume $\mathcal{L}_\Phi \supset y_\nu \Phi \bar{\nu}_R \nu_R$. Via α_1,

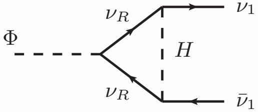
$M_R \ll m_\Phi$:

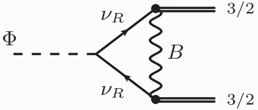




$M_R \gg m_\Phi$:

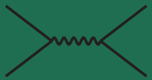






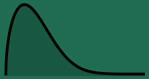
(via α_2 are 2-loop suppressed)

1. DM model



2. Reheating

3. Freeze-in



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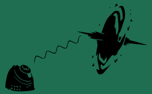
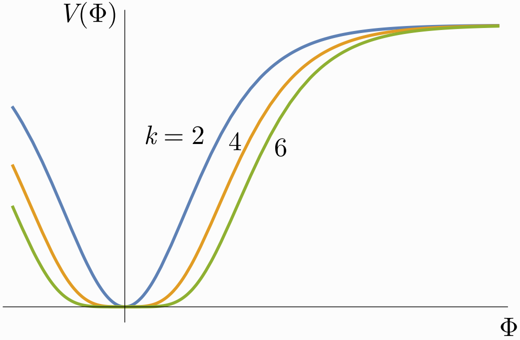


Reheating

After inflation, the Universe is reheated through the decay of the inflaton Φ



$$V(\Phi) = \lambda M_P^4 \left[\sqrt{6}\tanh\left(\frac{\Phi}{\sqrt{6}M_P}\right)\right]^k \xrightarrow{\Phi \ll M_P} \lambda \frac{\Phi^k}{M_P^{k-4}}$$

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

$$\begin{aligned} \dot{\rho}_\Phi + 3H(\rho_\Phi + P_\Phi) &= 0 \\ 3H^2 M_P^2 &= \rho_\Phi \end{aligned}$$

where

$$\begin{aligned} \rho_\Phi &= \frac{1}{2}\dot{\Phi}^2 + V(\Phi) \\ P_\Phi &= \frac{1}{2}\dot{\Phi}^2 - V(\Phi) \end{aligned}$$

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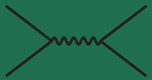

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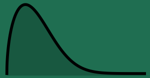

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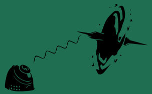
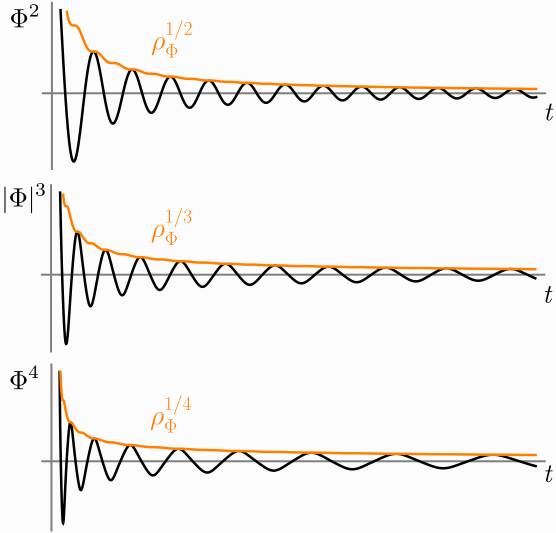


Inflaton oscillation



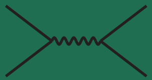
$\sim$ matter

$$\rho_\Phi = \rho_{\rm end}\left(\frac{a}{a_{\rm end}}\right)^{-\frac{6k}{k+2}}$$

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

$\sim$ radiation

1. DM model



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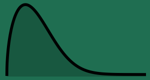

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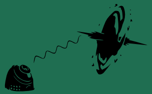
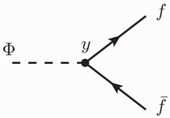
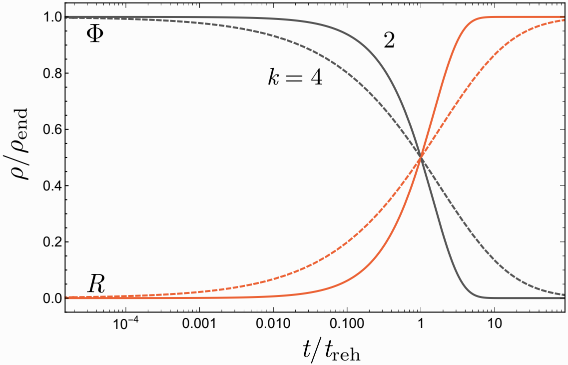


Decay of the inflaton

$$\begin{aligned}\dot{\rho}_\Phi + 3\left(\frac{2k}{k+2}\right) H\rho_\Phi &= -\Gamma_\Phi(t)\rho_\Phi \\ \dot{\rho}_R + 4H\rho_R &= \Gamma_\Phi(t)\rho_\Phi \\ 3M_P^2H^2 &= \rho_\Phi + \rho_R\end{aligned}$$



$$\begin{aligned}\Gamma_\Phi &= \frac{y^2}{8\pi} m_\Phi(t)\,, \\ m_\Phi^2 &\equiv \partial_\Phi^2 V(\Phi) \propto \rho_\Phi^{\frac{k-2}{k}}\end{aligned}$$



MG, K. Kaneta, Y. Mambrini and K. A. Olive, PRD 101 (2020), 123507

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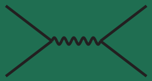

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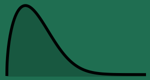

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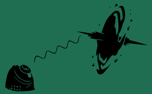

Decay of the inflaton

$$\dot{\rho}_\Phi + 3\left(\frac{2k}{k+2}\right) H\rho_\Phi = -\Gamma_\Phi(t)\rho_\Phi$$
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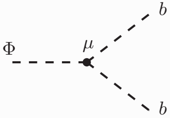
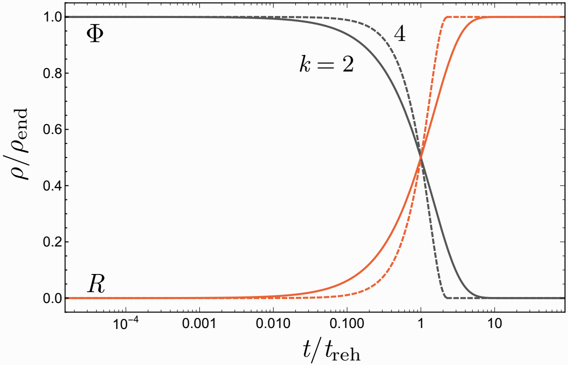
$$3M_P^2 H^2 = \rho_\Phi + \rho_R$$



$$\Gamma_\Phi = \frac{\mu^2}{8\pi m_\Phi(t)},$$
$$m_\Phi^2 \equiv \partial_\Phi^2 V(\Phi) \propto \rho_\Phi^{\frac{k-2}{k}}$$



MG, K. Kaneta, Y. Mambrini and K. A. Olive, JCAP 04 (2021), 012

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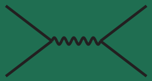

2. Reheating

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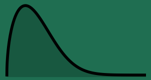

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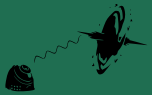

Decay of the inflaton

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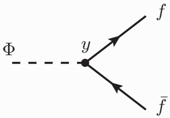
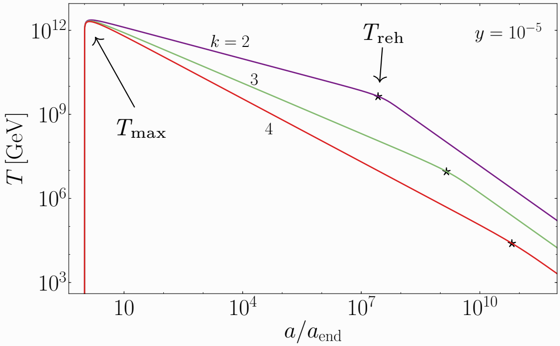


$$\Gamma_\Phi = \frac{y^2}{8\pi} m_\Phi(t)\,,$$

$$m_\Phi^2 \equiv \partial_\Phi^2 V(\Phi) \propto \rho_\Phi^{\frac{k-2}{k}}$$

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

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



MG, K. Kaneta, Y. Mambrini and K. A. Olive, PRD 101 (2020), 123507

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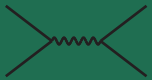

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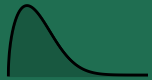

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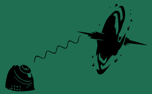
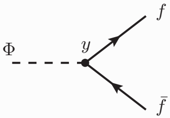


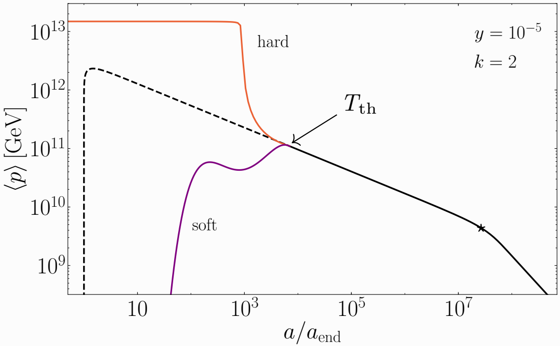
Decay of the inflaton

$$
\begin{aligned}
\dot\rho_\Phi + 3\left(\frac{2k}{k+2}\right) H\rho_\Phi &= -\Gamma_\Phi(t)\rho_\Phi \\
\dot\rho_R + 4H\rho_R &= \Gamma_\Phi(t)\rho_\Phi \\
3M_P^2 H^2 &= \rho_\Phi + \rho_R
\end{aligned}
$$



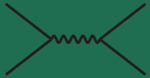
$$
\begin{aligned}
\Gamma_\Phi &= \frac{y^2}{8\pi} m_\Phi(t)\,, \\
m_\Phi^2 &\equiv \partial_\Phi^2 V(\Phi) \propto \rho_\Phi^{\frac{k-2}{k}}
\end{aligned}
$$

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



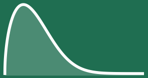
K. Harigaya, K. Mukaida, JHEP 05 (2014), 006

1. DM model

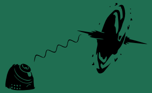


2. Reheating

3. Freeze-in



4. Constraints



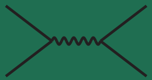
Freeze-in during reheating

For the out-of-equilibrium process $i + j + \cdots \to \Psi + a + b + \cdots$,

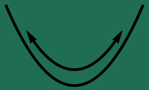
$$\frac{\partial f_{3/2}}{\partial t} - H|\boldsymbol{p}|\frac{\partial f_{3/2}}{\partial|\boldsymbol{p}|} \simeq \frac{1}{2p_0}\int \frac{g_a d^3\boldsymbol{p}_a}{(2\pi)^3 2p_{a0}}\frac{g_b d^3\boldsymbol{p}_b}{(2\pi)^3 2p_{b0}}\cdots\frac{g_i d^3\boldsymbol{p}_i}{(2\pi)^3 2p_{i0}}\frac{g_j d^3\boldsymbol{p}_j}{(2\pi)^3 2p_{j0}}\cdots$$
$$\times (2\pi)^4\delta^{(4)}(p + p_a + p_b + \cdots - p_i - p_j - \cdots)$$
$$\times |\mathcal{M}|^2_{i+j+\cdots\to\Psi+a+b+\cdots} f_i f_j \cdots$$

(*freeze-in*)

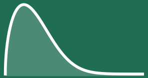
1. DM model



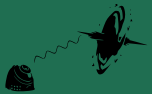
2. Reheating



3. Freeze-in



4. Constraints

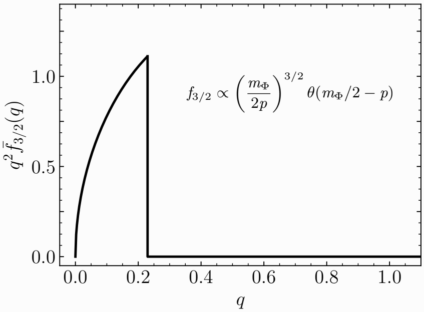


Inflaton decay $\Phi \to \Psi + \Psi$

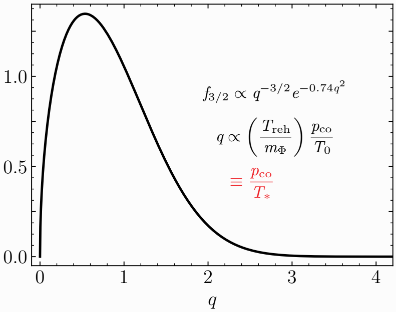
$$\frac{\partial f_{3/2}}{\partial t} - H|\boldsymbol{p}|\frac{\partial f_{3/2}}{\partial |\boldsymbol{p}|} \simeq \frac{1}{2p_0}\int \frac{g_{3/2}\, d^3\boldsymbol{k}}{(2\pi)^3 2k_0}\frac{d^3\boldsymbol{P}}{(2\pi)^3 2P_0}(2\pi)^4\delta^{(4)}(P-p-k)$$

$$\times \frac{2{\alpha_1}^4 y_\nu^2 m_\Phi^2}{9\pi^4 M_p^4 m_{3/2}^4}\left[5 - 6\ln\left(\frac{M_R^2}{m_\Phi^2}\right)\right]^2 (2\pi)^3 n_\Phi(t)\delta^{(3)}(\boldsymbol{P})$$

$t \ll t_{\rm reh}$

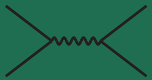


$t \gg t_{\rm reh}$

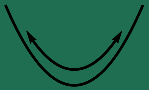


G. Ballesteros, MG and M. Pierre, JCAP 03 (2021), 101

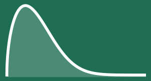
1. DM model



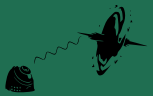
2. Reheating



3. Freeze-in



4. Constraints



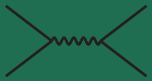
Inflaton decay $\Phi \to \Psi + \Psi$

$$\frac{\partial f_{3/2}}{\partial t} - H|\boldsymbol{p}|\frac{\partial f_{3/2}}{\partial|\boldsymbol{p}|} \simeq \frac{1}{2p_0}\int \frac{g_{3/2}\, d^3\boldsymbol{k}}{(2\pi)^3 2k_0}\frac{d^3\boldsymbol{P}}{(2\pi)^3 2P_0}(2\pi)^4\delta^{(4)}(P-p-k)$$
$$\times \frac{2{\alpha_1}^4 y_\nu^2 m_\Phi^2}{9\pi^4 M_p^4 m_{3/2}^4}\left[5-6\ln\left(\frac{M_R^2}{m_\Phi^2}\right)\right]^2 (2\pi)^3 n_\Phi(t)\,\delta^{(3)}(\boldsymbol{P})$$

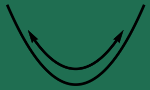
$$\Omega_{3/2}h^2 \simeq 0.1\left(\frac{\alpha_1}{1.1\times 10^{-8}}\right)^4\left(\frac{m_\Phi}{3\times 10^{13}\,\mathrm{GeV}}\right)^5\left(\frac{0.15\,\mathrm{eV}}{m_1}\right)^2$$
$$\times\left(\frac{10^4\,\mathrm{GeV}}{m_{3/2}}\right)^3\left(\frac{T_{\mathrm{reh}}}{10^{10}\,\mathrm{GeV}}\right)\times\frac{(\ln(M_R^2/m_\phi^2)-5/6)^2}{\ln^2(M_R^2/m_\phi^2)}\,.$$

Light DM production from non-quadratic inflaton decay / preheating $\to$ work in progress!

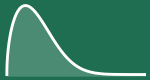
1. DM model



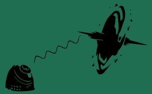
2. Reheating



3. Freeze-in

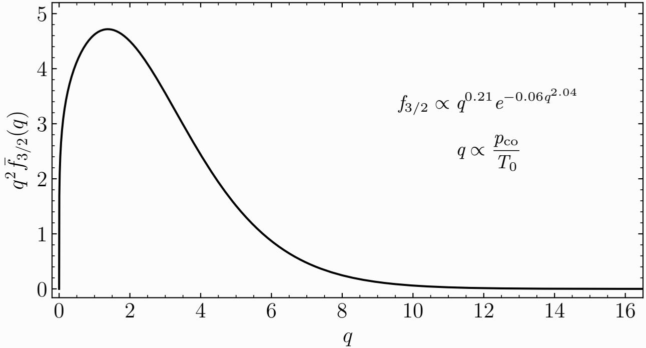


4. Constraints



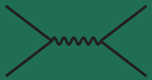
Scatterings $H + \nu \to \Psi + B$

$$\frac{\partial f_{3/2}}{\partial t} - H|\boldsymbol{p}|\frac{\partial f_{3/2}}{\partial |\boldsymbol{p}|} \simeq \frac{1}{2p_0}\int \frac{2d^3\boldsymbol{p}'}{(2\pi)^3 2p_0'}\frac{d^3\boldsymbol{k}_1}{(2\pi)^3 2k_1^0}\frac{2d^3\boldsymbol{k}_2}{(2\pi)^3 2k_2^0}(2\pi)^4\delta^{(4)}(p+p'-k_1-k_2)$$
$$\times\left(-\frac{8}{3}\frac{{\alpha_1}^2 y^2}{m_{3/2}^2 M_R^2 M_P^2}s^2 t\right)\frac{1}{e^{k_1/T}+1}\frac{1}{e^{k_2/T}-1}$$

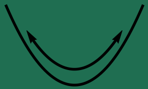


G. Ballesteros, MG and M. Pierre, JCAP 03 (2021), 101

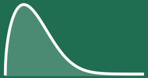
1. DM model



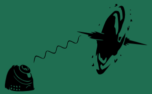
2. Reheating



3. Freeze-in



4. Constraints



Scatterings $H + \nu \to \Psi + B$

$$\frac{\partial f_{3/2}}{\partial t} - H|\boldsymbol{p}|\frac{\partial f_{3/2}}{\partial|\boldsymbol{p}|} \simeq \frac{1}{2p_0}\int \frac{2d^3\boldsymbol{p}'}{(2\pi)^3 2p_0'}\frac{d^3\boldsymbol{k}_1}{(2\pi)^3 2k_1^0}\frac{2d^3\boldsymbol{k}_2}{(2\pi)^3 2k_2^0}(2\pi)^4\delta^{(4)}(p+p'-k_1-k_2)$$

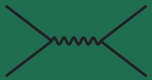
$$\times\left(-\frac{8}{3}\frac{{\alpha_1}^2 y^2}{m_{3/2}^2 M_R^2 M_P^2}s^2 t\right)\frac{1}{e^{k_1/T}+1}\frac{1}{e^{k_2/T}-1}$$

$$\Omega_{3/2}h^2 \simeq 0.1\left(\frac{\alpha_1}{1.1\times10^{-3}}\right)^2\left(\frac{427/4}{g_{\mathrm{reh}}}\right)^{3/2}\left(\frac{T_{\mathrm{reh}}}{10^{10}\,\mathrm{GeV}}\right)^5$$

$$\times\left(\frac{m_1}{0.15\,\mathrm{eV}}\right)\left(\frac{10^{14}\,\mathrm{GeV}}{M_R}\right)\left(\frac{10^4\,\mathrm{GeV}}{m_{3/2}}\right)$$

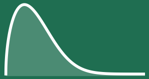
(quadratic inflaton potential)

1. DM model

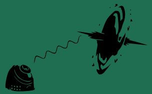


2. Reheating

3. Freeze-in



4. Constraints



Scatterings $H+\nu \to \Psi + B$

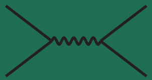
$$\frac{\partial f_{3/2}}{\partial t} - H|\boldsymbol{p}|\frac{\partial f_{3/2}}{\partial |\boldsymbol{p}|} \simeq \frac{1}{2p_0}\int \frac{2\,d^3\boldsymbol{p}'}{(2\pi)^3 2p'_0}\,\frac{d^3\boldsymbol{k}_1}{(2\pi)^3 2k_1^0}\,\frac{2\,d^3\boldsymbol{k}_2}{(2\pi)^3 2k_2^0}(2\pi)^4\delta^{(4)}(p+p'-k_1-k_2)$$
$$\times\left(-\frac{8}{3}\frac{{\alpha_1}^2 y^2}{m_{3/2}^2 M_R^2 M_P^2}s^2 t\right)\frac{1}{e^{k_1/T}+1}\,\frac{1}{e^{k_2/T}-1}$$

$$\Omega_{3/2}h^2 \simeq 0.1\left(\frac{\alpha_1}{2\times 10^{-3}}\right)^2\left(\frac{427/4}{g_{\rm reh}}\right)^{3/2}\left(\frac{T_{\rm reh}}{10^{10}\,{\rm GeV}}\right)^5$$
$$\times\left(\frac{m_1}{0.15\,{\rm eV}}\right)\left(\frac{10^{14}\,{\rm GeV}}{M_R}\right)\left(\frac{10^4\,{\rm GeV}}{m_{3/2}}\right)\left(\frac{T_{\rm max}}{T_{\rm reh}}\right)^{10/3}$$

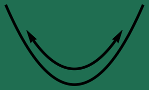
(quartic inflaton potential, $\phi \to \bar{f}f$)

MG, K. Kaneta, Y. Mambrini and K. A. Olive, JCAP 04 (2021), 012

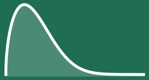
1. DM model



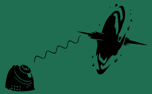
2. Reheating



3. Freeze-in



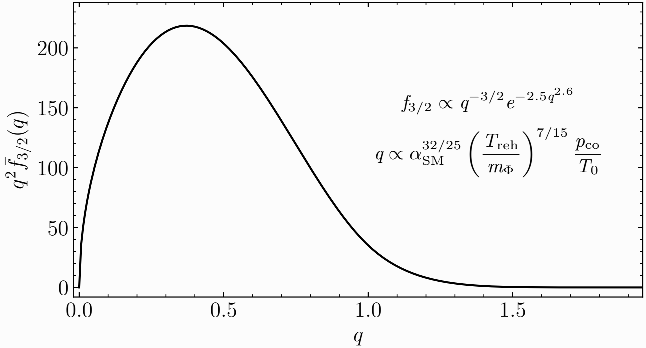
4. Constraints



Scatterings $H + \nu \to \Psi + B$

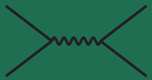
$$\frac{\partial f_{3/2}}{\partial t} - H|\boldsymbol{p}|\frac{\partial f_{3/2}}{\partial|\boldsymbol{p}|} \simeq \frac{1}{2p_0}\int \frac{2\,d^3\boldsymbol{p}'}{(2\pi)^3 2p_0'}\,\frac{d^3\boldsymbol{k}_1}{(2\pi)^3 2k_1^0}\,\frac{2\,d^3\boldsymbol{k}_2}{(2\pi)^3 2k_2^0}(2\pi)^4\delta^{(4)}(p+p'-k_1-k_2)$$

$$\times\left(-\frac{8}{3}\,\frac{\alpha_1{}^2 y^2}{m_{3/2}^2 M_R^2 M_P^2}\,s^2\,t\right)\mathrm{Br}_\nu\left(\frac{24\pi^2\Gamma_\Phi\, t\, n_\Phi}{m_\Phi^3}\right)^2\left(\frac{m_\Phi^2}{4k_1k_2}\right)^{3/2}\theta\Big(\frac{m_\Phi}{2}-k_1\Big)\theta\Big(\frac{m_\Phi}{2}-k_2\Big)$$



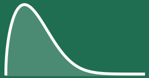
G. Ballesteros, MG and M. Pierre, JCAP 03 (2021), 101

1. DM model

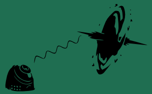


2. Reheating

3. Freeze-in



4. Constraints



Scatterings $H + \nu \to \Psi + B$

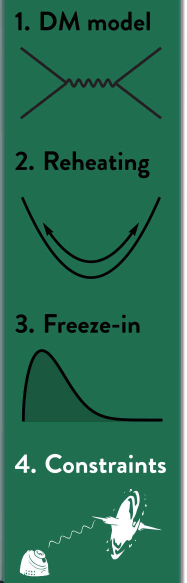
$$\frac{\partial f_{3/2}}{\partial t} - H|\boldsymbol{p}|\frac{\partial f_{3/2}}{\partial |\boldsymbol{p}|} \simeq \frac{1}{2p_0}\int \frac{2d^3\boldsymbol{p}'}{(2\pi)^3 2p'_0}\frac{d^3\boldsymbol{k}_1}{(2\pi)^3 2k_1^0}\frac{2d^3\boldsymbol{k}_2}{(2\pi)^3 2k_2^0}(2\pi)^4\delta^{(4)}(p+p'-k_1-k_2)$$
$$\times\left(-\frac{8}{3}\frac{{\alpha_1}^2 y^2}{m_{3/2}^2 M_R^2 M_P^2}s^2 t\right)\mathrm{Br}_\nu\left(\frac{24\pi^2\Gamma_\Phi\, t n_\Phi}{m_\Phi^3}\right)^2\left(\frac{m_\Phi^2}{4k_1k_2}\right)^{3/2}\theta\left(\frac{m_\Phi}{2}-k_1\right)\theta\left(\frac{m_\Phi}{2}-k_2\right)$$

$$\Omega_{3/2}h^2 \simeq 0.1\left(\frac{\alpha_1}{1.1\times 10^{-3}}\right)^2\left(\frac{0.030}{\alpha_{\rm SM}}\right)^{16/5}\left(\frac{m_1}{0.15\,\mathrm{eV}}\right)\left(\frac{g_{\rm reh}}{427/4}\right)^{7/10}\left(\frac{10^4\,\mathrm{GeV}}{m_{3/2}}\right)$$
$$\times\left(\frac{10^{14}\,\mathrm{GeV}}{M_R}\right)\left(\frac{m_\Phi}{3\times 10^{13}\,\mathrm{GeV}}\right)^{14/5}\left(\frac{T_{\rm reh}}{10^{10}\,\mathrm{GeV}}\right)^{19/5}\left(\frac{\mathcal{B}_1}{7\times 10^{-4}}\right)$$

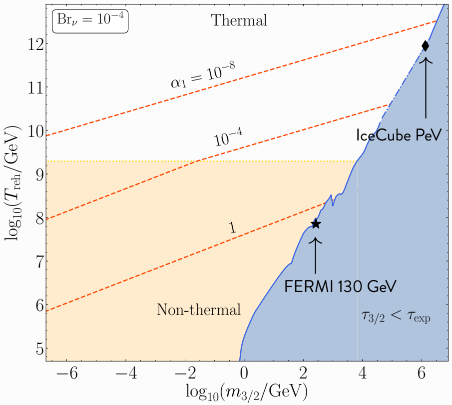
Thermalization in non-quadratic reheating to be determined

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

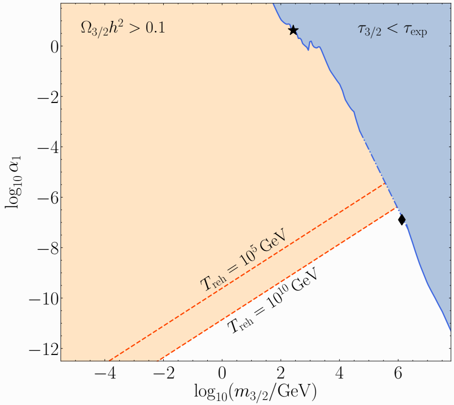
Constraints: $\Omega_{DM} + \gamma + \nu$



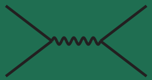
Scattering



Inflaton decay

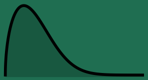


1. DM model

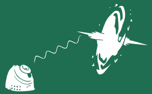


2. Reheating

3. Freeze-in

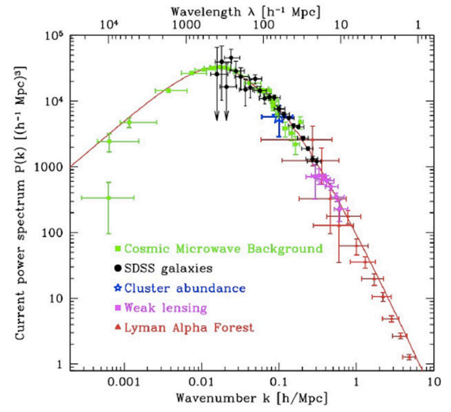


4. Constraints

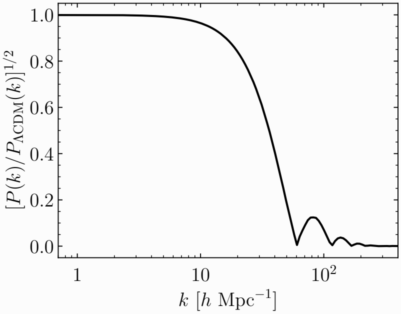


How warm is out-of-equilibrium dark matter?

Light DM $\rightarrow$ free streaming $\rightarrow$ suppression of structure



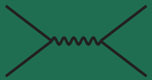
N. Palanque-Delabrouille et al., JCAP 04 (2020), 038
A. Garzilli et al., 1912.09397 [astro-ph.CO]



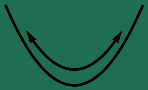
Absence of cutoff for freeze-out relic

$$\Rightarrow\ m_{\mathrm{WDM}} \gtrsim 3\,\mathrm{keV}$$

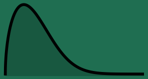
1. DM model



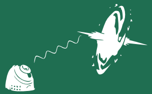
2. Reheating



3. Freeze-in



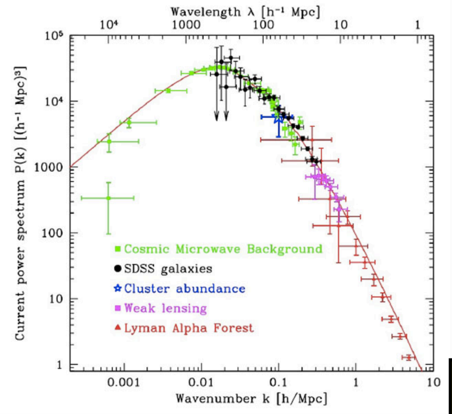
4. Constraints



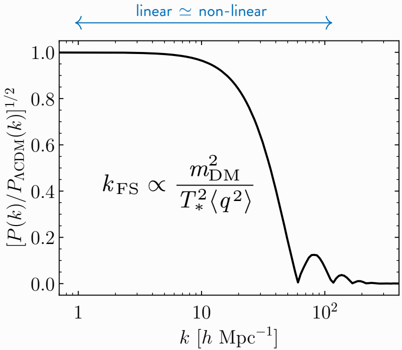
How warm is out-of-equilibrium dark matter?

For non-equilibrated DM,

R. Murgia, V. Iršič and M. Viel, PRD 98 (2018), 083540

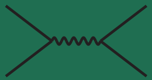


G. Ballesteros, MG and M. Pierre, JCAP 03 (2021), 101

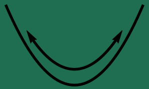


$$m_{\rm DM} = m_{\rm WDM} \left(\frac{T_*}{T_{\rm WDM}}\right) \sqrt{\frac{\langle q^2 \rangle}{\langle q^2 \rangle_{\rm WDM}}}$$

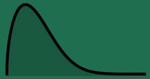
1. DM model



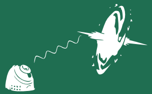
2. Reheating



3. Freeze-in



4. Constraints



How warm is out-of-equilibrium dark matter?

DM from inflaton decay:

$$m_{3/2} > 3.8\,\text{MeV}\left(\frac{m_\Phi}{3\times 10^{13}\,\text{GeV}}\right)\left(\frac{10^{10}\,\text{GeV}}{T_\text{reh}}\right)$$

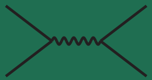
Thermal freeze-in, (α_1):

$$m_{3/2} > 8.5\,\text{keV}$$

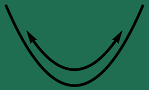
Non-thermal freeze-in, (α_1):

$$m_{3/2} > 0.4\,\text{keV}\left(\frac{\alpha_\text{SM}}{0.03}\right)^{-32/15}\left(\frac{m_\Phi}{3\times 10^{13}\,\text{GeV}}\right)^{23/15}\left(\frac{10^{10}\,\text{GeV}}{T_\text{reh}}\right)^{7/15}$$

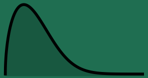
1. DM model



2. Reheating



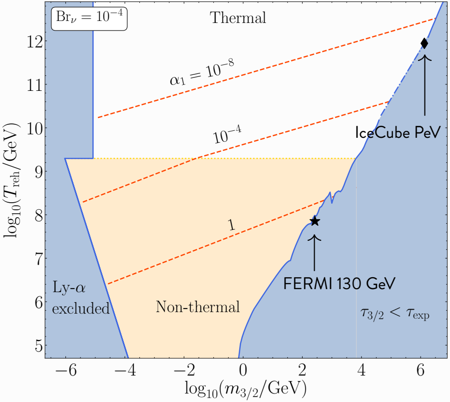
3. Freeze-in



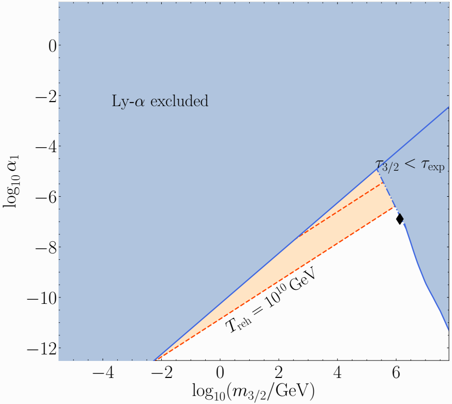
4. Constraints

Constraints: $\Omega_{\rm DM} + \gamma + \nu +$ Lyman-α

Scattering



Inflaton decay



Thank you!