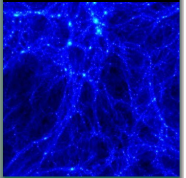
Dark Matter Production During Reheating
(by example)

MultiDark
Multimessenger Approach
for Dark Matter Detection



XVII
MultiDark
Consolider
Workshop

27/01/2021

Marcos A. G. García
IFT-UAM

2011.13458	with G. Ballesteros and M. Pierre
2012.10756	with K. Kaneta, Y. Mambrini and K. Olive
2006.03325	with Y. Mambrini, K. Olive and S. Verner
2004.08404	with K. Kaneta, Y. Mambrini and K. Olive
1806.01865	with M. Amin

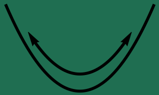
Instituto de Física Teórica UAM-CSIC

Universidad Autónoma de Madrid

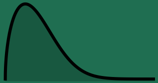
CSIC Consejo Superior de Investigaciones Científicas

1. Model Building

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

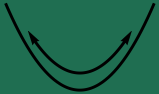
Not a new idea: the gravitino in supergravity is a well-known non-thermal relic. For WIMP-like models see

- Z. H. Yu et al., Nucl. Phys. B **860** (2012), 115
- R. Ding et al., JCAP **05** (2013), 028
- N. D. Christensen et al., Eur. Phys. J. C **73** (2013) no.10, 2580
- K. G. Savvidy and J. D. Vergados, Phys. Rev. D **87** (2013) 075013

For these there's a Z_2 symmetry to make it stable.

1. Model Building

2. Reheating



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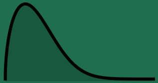

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with $\gamma^{\mu\nu} = \gamma^{[\mu}\gamma^{\nu]}$ and $\gamma^{\mu\nu\rho} = \gamma^{[\mu}\gamma^{\nu}\gamma^{\rho]}$

Consider instead a minimal set-up,

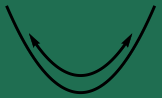
$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{\rm SM} + \mathcal{L}^0_{3/2} + \mathcal{L}^0_{\nu_R} + yH\bar{\nu}_L\nu_R + \frac{M_R}{2}\bar{\nu}^c_R\nu_R \\ &\quad + i\frac{\alpha_1}{2M_P}\bar{\nu}_R\gamma^\mu[\gamma^\rho,\gamma^\sigma]\Psi_\mu F_{\rho\sigma} + i\frac{\alpha_2}{2M_P}i\sigma_2(D^\mu H)^*\bar{L}\Psi_\mu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

with usual mixing relations

$$m_1 \simeq \frac{y^2v^2}{2M_R}, \quad m_2 \simeq M_R, \quad \tan\theta \simeq \frac{yv}{\sqrt{2}M_R}$$

1. Model Building

2. Reheating



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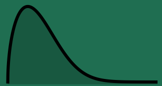
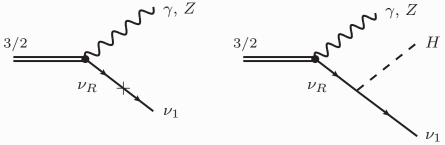


4. Constraints

Decays

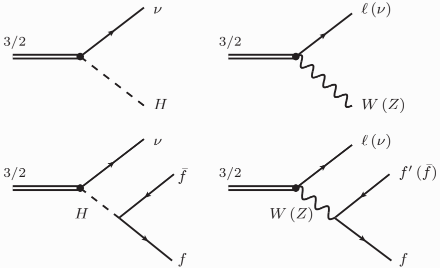
α_1 dominates



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

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

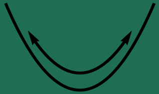
α_2 dominates



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

1. Model Building

2. Reheating



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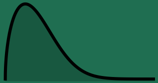

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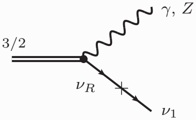
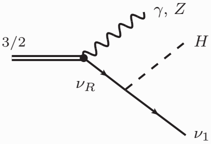
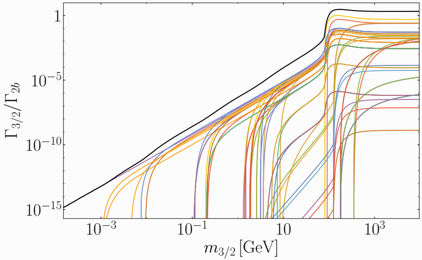




$$\tau_{3/2}^{2b} \simeq 1.6 \times 10^{29} \left(\frac{10^{-2}}{y\,\alpha_1}\right)^2 \left(\frac{M_R}{10^{14}\,\mathrm{GeV}}\right)^2 \left(\frac{10^4\,\mathrm{GeV}}{m_{3/2}}\right)^3 \mathrm{s}$$

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

α_2 dominates



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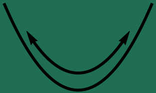
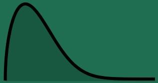
2. Reheating



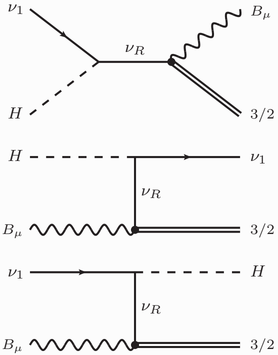
3. Freeze-in



4. Constraints

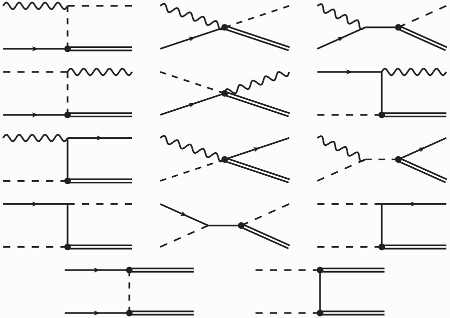
Production (via scatterings)

α_1 dominates



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

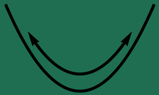
α_2 dominates



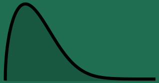
$$\sigma(s) = \frac{\alpha_2^2 s}{9216\pi m_{3/2}^2 M_P^2} \times \left(639 g^2 + 87 g'^2 + 144 h_t^2 + 32 h_\tau^2\right)$$

1. Model Building

2. Reheating



3. Freeze-in

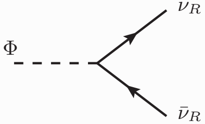


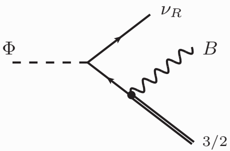
4. Constraints

Production (via inflaton decay)

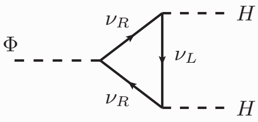
Assume $\mathcal{L}_\Phi \supset y_\nu \Phi \bar{\nu}_R \nu_R$. Via α_1,

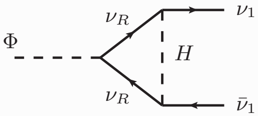
$M_R \ll m_\Phi$:

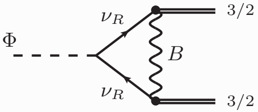




$M_R \gg m_\Phi$:

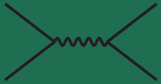






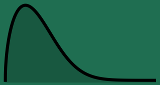
(via α_2 are 2-loop suppressed)

1. Model Building



2. Reheating

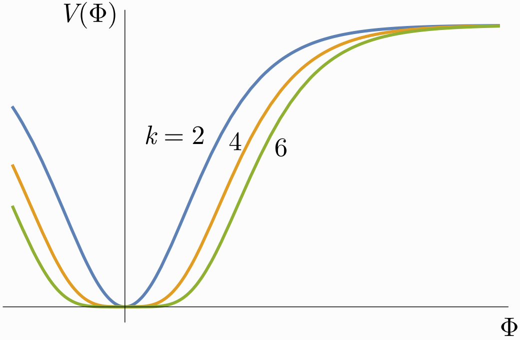
3. Freeze-in



4. Constraints

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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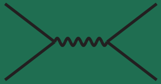

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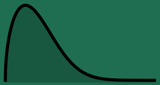
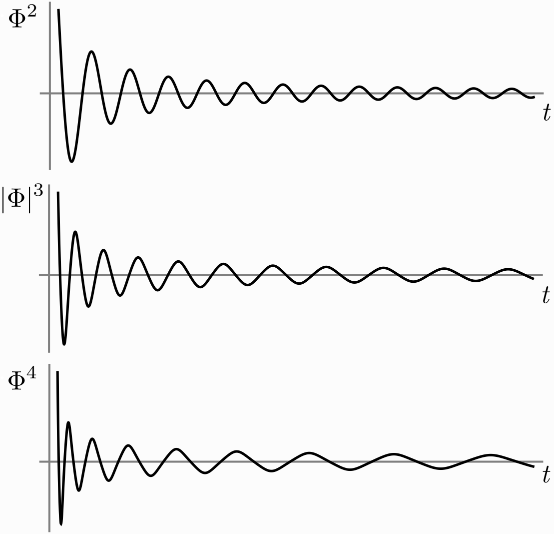


4. Constraints

Inflaton oscillation



Over one oscillation

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

$$\downarrow$$

$$\langle P_\Phi \rangle = \frac{k-2}{k+2} \langle \rho_\Phi \rangle$$

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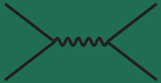

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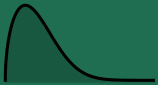
3. Freeze-in



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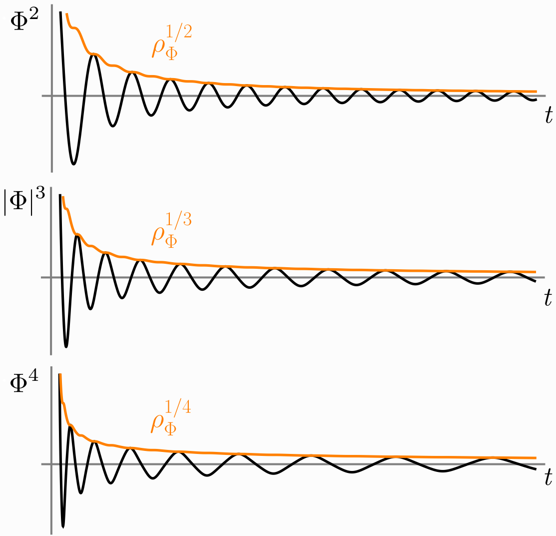


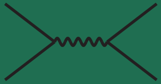
~ matter

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

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

~ radiation

1. Model Building



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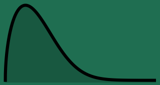


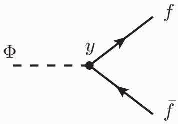
4. Constraints

Decay of the inflaton

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

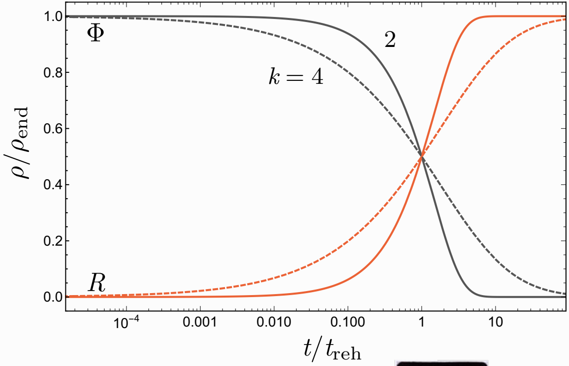
$$\dot{\rho}_R + 4H\rho_R = \Gamma_\Phi(t)\rho_\Phi$$

$$3M_P^2 H^2 = \rho_\Phi + \rho_R$$



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

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



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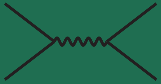

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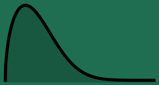

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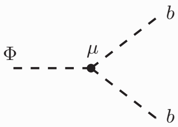

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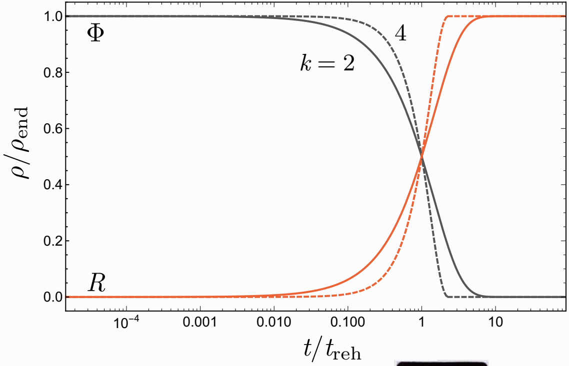

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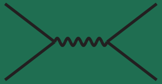

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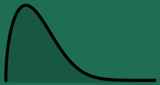

4. Constraints

Decay of the inflaton

$$
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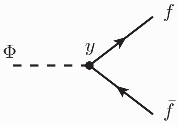
\end{aligned}
$$

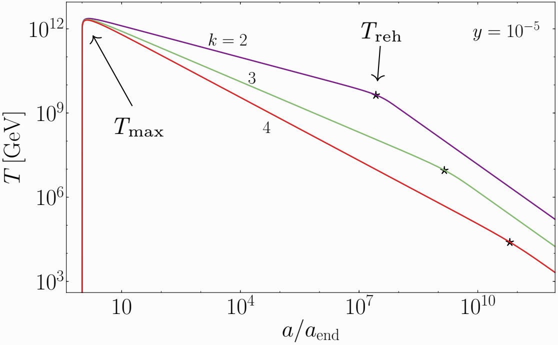


$$
\Gamma_\Phi = \frac{y^2}{8\pi} m_\Phi(t)\,,
$$

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

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

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



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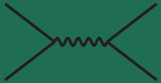

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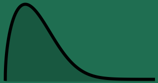

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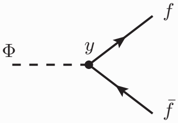
Decay of the inflaton

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

$$\dot{\rho}_R + 4H\rho_R = \Gamma_\Phi(t)\rho_\Phi$$

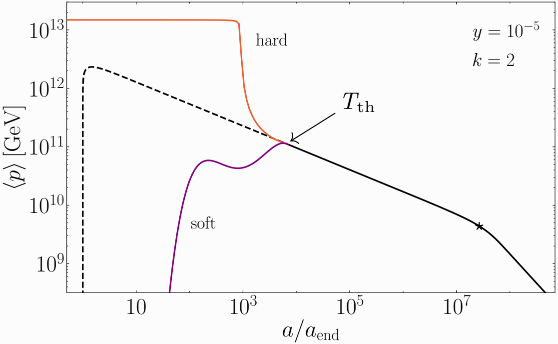
$$3M_P^2 H^2 = \rho_\Phi + \rho_R$$



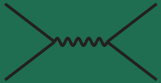
$$\Gamma_\Phi = \frac{y^2}{8\pi} m_\Phi(t)\,,$$

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

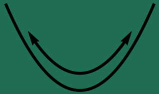
$$\Gamma_\Phi t_{\rm th} \simeq \alpha_{\rm SM}^{-16/5}\left(\frac{\Gamma_\Phi m_\Phi^2}{M_P^3}\right)^{2/5}$$



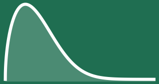
1. Model Building



2. Reheating



3. Freeze-in



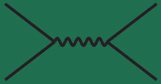
4. Constraints

Freeze-in during reheating

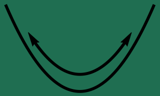
For the out-of-equilibrium process $i + j + \cdots \to \Psi + a + b + \cdots,$

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

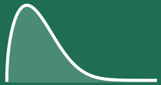
1. Model Building



2. Reheating



3. Freeze-in

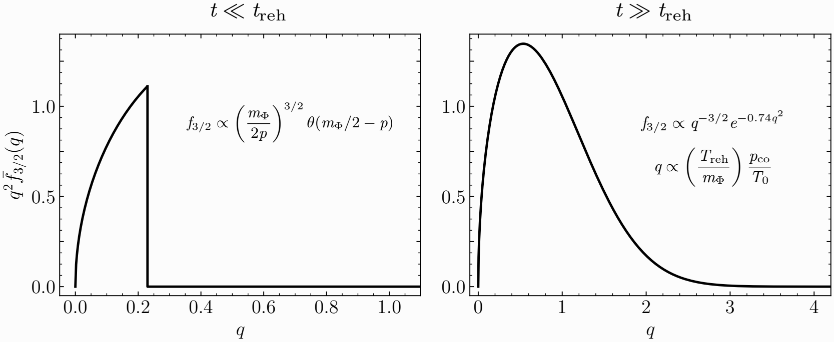


4. Constraints

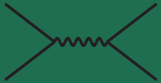
Inflaton decay $\Phi \to \Psi + \Psi$

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

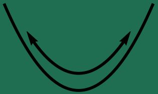
$$\times \frac{2\alpha_1{}^4 y_\nu^2 m_\Phi^2}{9\pi^4 M_p^4 m_{3/2}^4}\left[5 - 6\ln\left(\frac{M_R^2}{m_\Phi^2}\right)\right]^2 (2\pi)^3 n_\Phi(t)\delta^{(3)}(\boldsymbol{P})$$



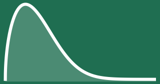
1. Model Building



2. Reheating



3. Freeze-in



4. Constraints

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

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

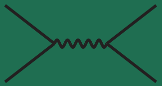
$$\times \frac{2{\color{red}\alpha_1}^4 y_\nu^2 m_\Phi^2}{9\pi^4 M_p^4 m_{3/2}^4}\left[5 - 6\ln\left(\frac{M_R^2}{m_\Phi^2}\right)\right]^2 {\color{blue}(2\pi)^3 n_\Phi(t)\delta^{(3)}(\boldsymbol{P})}$$

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

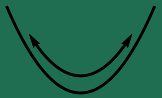
$$\times\left(\frac{10^4\,\mathrm{GeV}}{m_{3/2}}\right)^3\left(\frac{T_{\mathrm{reh}}}{10^{10}\,\mathrm{GeV}}\right)\times\frac{(\ln(M_R^2/m_\phi^2)-5/6)^2}{\ln^2(M_R^2/m_\phi^2)}\,.$$

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

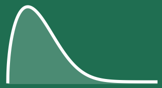
1. Model Building



2. Reheating



3. Freeze-in

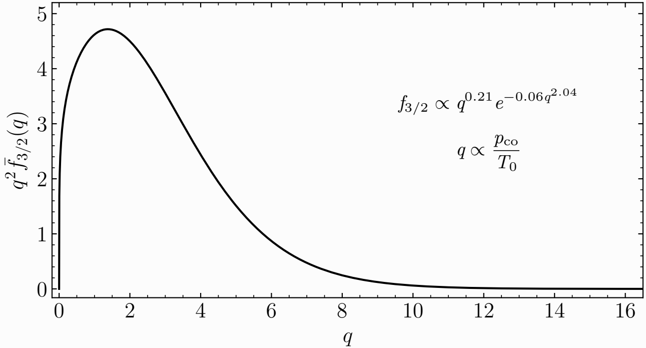


4. Constraints

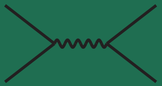
Scatterings $H + \nu \to \Psi + B$

$$\frac{\partial f_{3/2}}{\partial t} - H|\boldsymbol{p}|\frac{\partial f_{3/2}}{\partial |\boldsymbol{p}|} \simeq \frac{1}{2p_0}\int \frac{2d^3\boldsymbol{p}'}{(2\pi)^3 2p'_0}\frac{d^3\boldsymbol{k}_1}{(2\pi)^3 2k_1^0}\frac{2d^3\boldsymbol{k}_2}{(2\pi)^3 2k_2^0}(2\pi)^4\delta^{(4)}(p+p'-k_1-k_2)$$

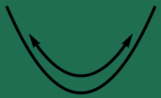
$$\times\left(-\frac{8}{3}\frac{{\alpha_1}^2 y^2}{m_{3/2}^2 M_R^2 M_P^2}s^2 t\right)\frac{1}{e^{k_1/T}+1}\frac{1}{e^{k_2/T}-1}$$



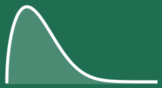
1. Model Building



2. Reheating



3. Freeze-in



4. Constraints

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

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

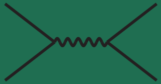
$$\times\left(-\frac{8}{3}\frac{{\alpha_1}^2 y^2}{m_{3/2}^2 M_R^2 M_P^2}s^2 t\right)\frac{1}{e^{k_1/T}+1}\,\frac{1}{e^{k_2/T}-1}$$

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

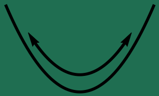
$$\times\left(\frac{m_1}{0.15\,{\rm eV}}\right)\left(\frac{10^{14}\,{\rm GeV}}{M_R}\right)\left(\frac{10^4\,{\rm GeV}}{m_{3/2}}\right)$$

(quadratic inflaton potential)

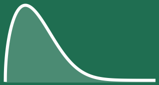
1. Model Building



2. Reheating



3. Freeze-in



4. Constraints

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

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

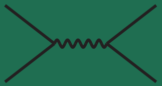
$$\times\left(-\frac{8}{3}\frac{{\alpha_1}^2 y^2}{m_{3/2}^2 M_R^2 M_P^2}s^2 t\right)\frac{1}{e^{k_1/T}+1}\,\frac{1}{e^{k_2/T}-1}$$

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

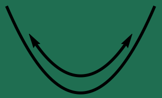
$$\times\left(\frac{m_1}{0.15\,\mathrm{eV}}\right)\left(\frac{10^{14}\,\mathrm{GeV}}{M_R}\right)\left(\frac{10^4\,\mathrm{GeV}}{m_{3/2}}\right)\left(\frac{T_{\max}}{T_{\rm reh}}\right)^{10/3}$$

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

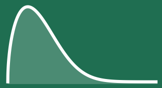
1. Model Building



2. Reheating



3. Freeze-in

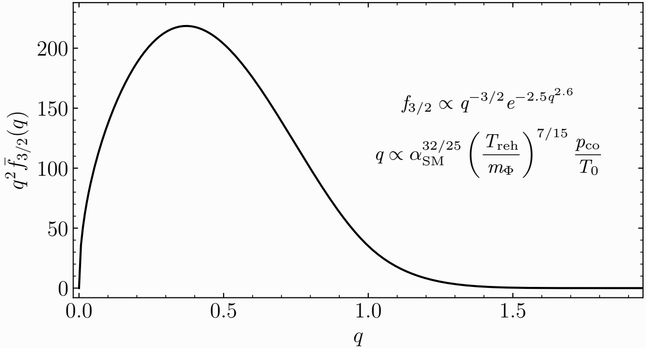


4. Constraints

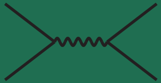
Scatterings $H + \nu \to \Psi + B$

$$\frac{\partial f_{3/2}}{\partial t} - H|\boldsymbol{p}|\frac{\partial f_{3/2}}{\partial|\boldsymbol{p}|} \simeq \frac{1}{2p_0}\int \frac{2\,d^3\boldsymbol{p}'}{(2\pi)^3 2p'_0}\frac{d^3\boldsymbol{k}_1}{(2\pi)^3 2k_1^0}\frac{2\,d^3\boldsymbol{k}_2}{(2\pi)^3 2k_2^0}(2\pi)^4\delta^{(4)}(p+p'-k_1-k_2)$$

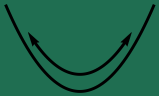
$$\times\left(-\frac{8}{3}\frac{{\alpha_1}^2 y^2}{m_{3/2}^2 M_R^2 M_P^2}s^2 t\right)\mathrm{Br}_\nu\left(\frac{24\pi^2\Gamma_\Phi t n_\Phi}{m_\Phi^3}\right)^2\left(\frac{m_\Phi^2}{4k_1 k_2}\right)^{3/2}\theta\left(\frac{m_\Phi}{2}-k_1\right)\theta\left(\frac{m_\Phi}{2}-k_2\right)$$



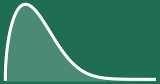
1. Model Building



2. Reheating



3. Freeze-in



4. Constraints

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

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

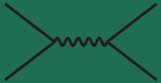
$$\times\left(-\frac{8}{3}\frac{\alpha_1{}^2 y^2}{m_{3/2}^2 M_R^2 M_P^2}s^2 t\right)\mathrm{Br}_\nu\left(\frac{24\pi^2\Gamma_\Phi t n_\Phi}{m_\Phi^3}\right)^2\left(\frac{m_\Phi^2}{4k_1 k_2}\right)^{3/2}\theta\left(\frac{m_\Phi}{2}-k_1\right)\theta\left(\frac{m_\Phi}{2}-k_2\right)$$

$$\Omega_{3/2}h^2 \simeq 0.1\left(\frac{\alpha_1}{1.1\times10^{-3}}\right)^2\left(\frac{0.030}{\alpha_{\rm SM}}\right)^{16/5}\left(\frac{m_1}{0.15\,\mathrm{eV}}\right)\left(\frac{g_{\rm reh}}{427/4}\right)^{7/10}\left(\frac{10^4\,\mathrm{GeV}}{m_{3/2}}\right)$$

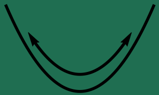
$$\times\left(\frac{10^{14}\,\mathrm{GeV}}{M_R}\right)\left(\frac{m_\Phi}{3\times10^{13}\,\mathrm{GeV}}\right)^{14/5}\left(\frac{T_{\rm reh}}{10^{10}\,\mathrm{GeV}}\right)^{19/5}\left(\frac{\mathcal{B}_1}{7\times10^{-4}}\right)$$

Thermalization in non-quadratic reheating not known yet

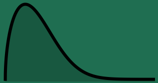
1. Model Building



2. Reheating

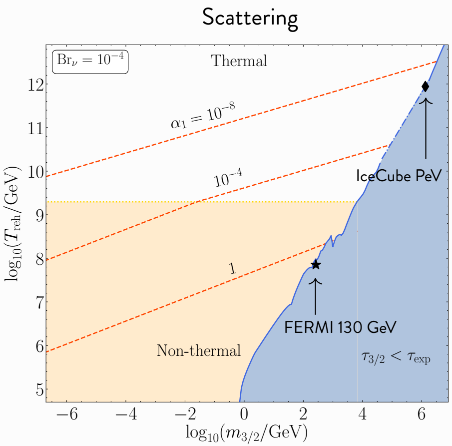


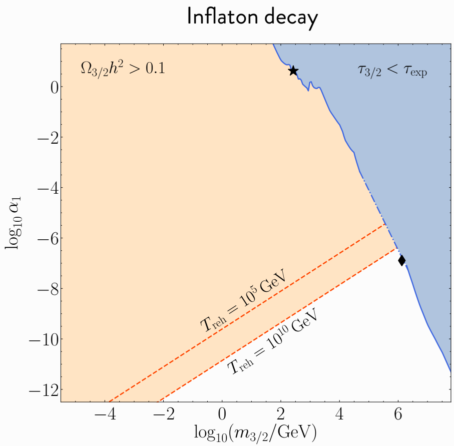
3. Freeze-in



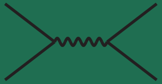
4. Constraints

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

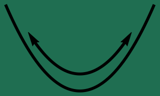




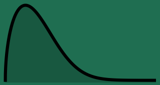
1. Model Building



2. Reheating



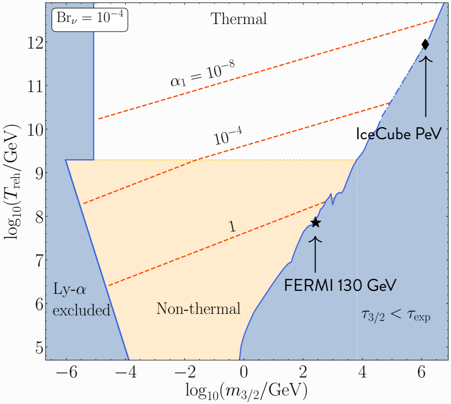
3. Freeze-in



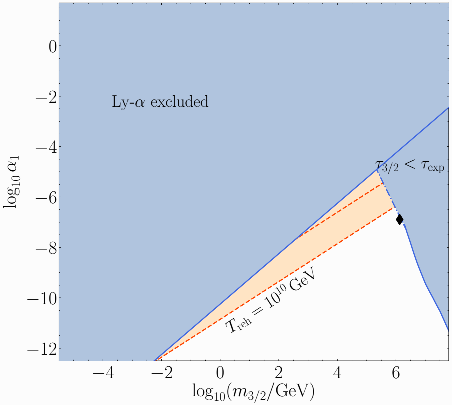
4. Constraints

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

Scattering



Inflaton decay



For further details, see Mathias' talk!