Pre-thermalization Production of Dark Matter

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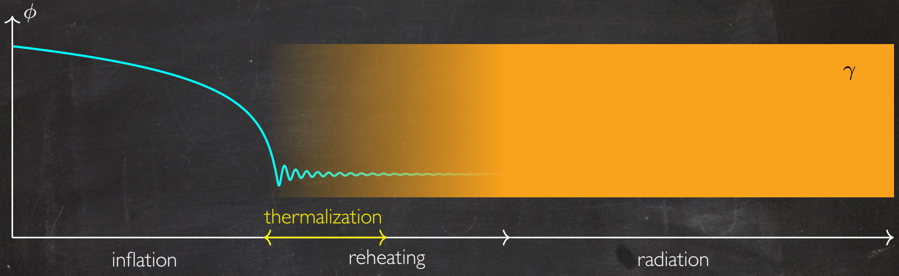
1709.01549, MG, Y. Mambrini, K. Olive, M. Peloso
1806.01865, MG, M. Amin (today)

RICE

Freeze-in vs. Freeze-out

The reheating and thermalization processes after inflation have a finite duration



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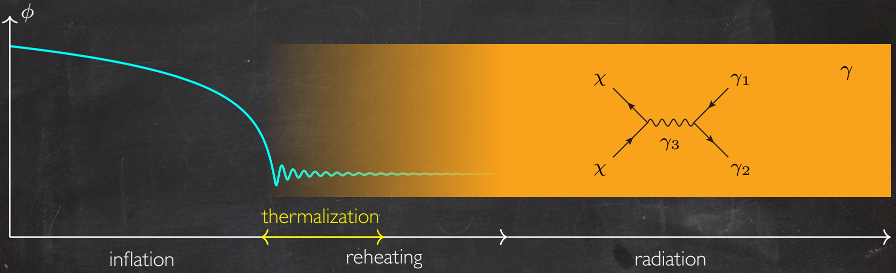
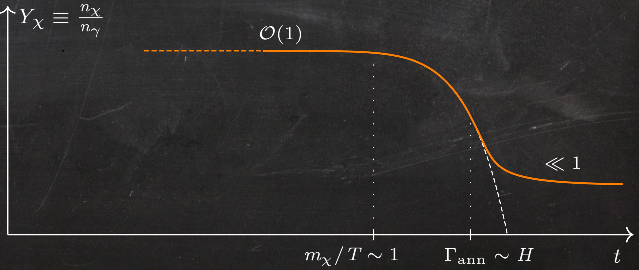


Freeze-out:

- Thermal equilibrium
- Thermal production
- $Y_\chi \longleftrightarrow \langle\sigma v\rangle_{\rm ann}$
- IR dominated



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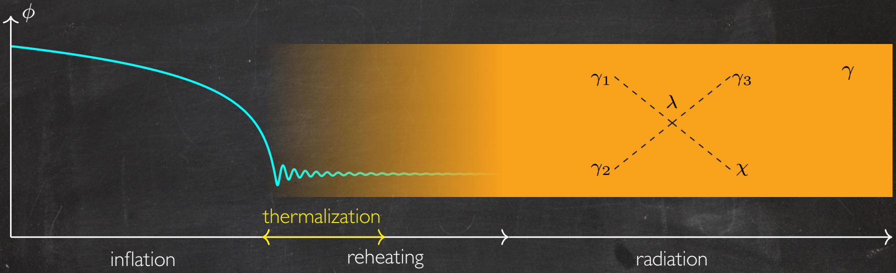
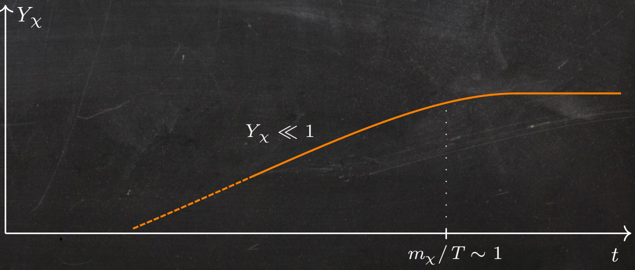


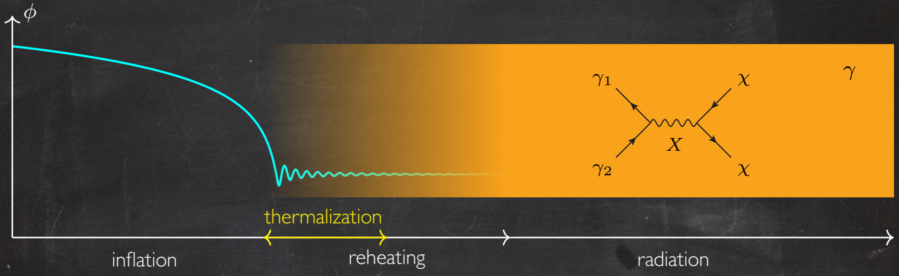
Freeze-in:

- Not in equilibrium
- Thermal production
- $Y_\chi \longleftrightarrow \langle \sigma v \rangle_{\rm prod}$
- IR dominated



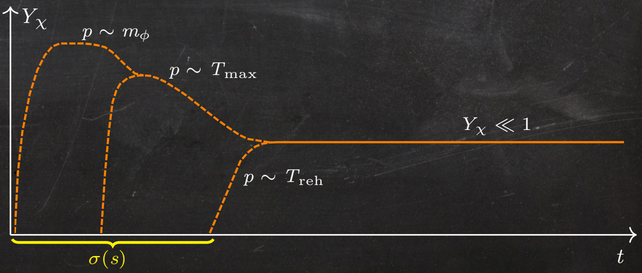
Freeze-in vs. Freeze-out

The reheating and thermalization processes after inflation have a finite duration

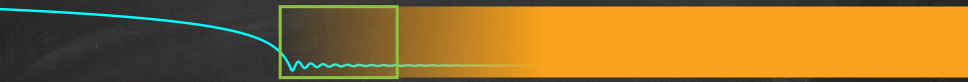


Freeze-in:

- Not in equilibrium
- Non-thermal and thermal production
- $Y_\chi \longleftrightarrow \langle \sigma v \rangle_{\text{prod}}$
- UV dominated



Pre-thermalization



$$\dot{\rho}_\phi + 3H\rho_\phi + \Gamma_\phi \rho_\phi = 0$$
$$\dot{\rho}_\gamma + 4H\rho_\gamma - \Gamma_\phi \rho_\phi = 0$$
$$\rho_\phi + \rho_\gamma = 3M_P^2 H^2$$

$$\downarrow$$

$$n_\gamma \simeq \frac{\rho_{\rm end}}{m_\phi}\left(\frac{a}{a_{\rm end}}\right)^{-3}\left(1-e^{-\Gamma_\phi t}\right)$$
$$< g\, n_\gamma^T \sim g\, \rho_\gamma^{3/4}$$

If $\Gamma_\phi / m_\phi \lesssim 10^{-10}$ (Planck suppressed)

Pre-thermalization

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If $\Gamma_\phi / m_\phi \lesssim 10^{-10}$ (Planck suppressed)

$$f_\phi = (2\pi)^3 n_\phi \delta^3(\mathbf{p})$$

$$\downarrow$$

$$\frac{\partial f_\gamma}{\partial t} - Hk\frac{\partial f_\gamma}{\partial k} = \frac{2\pi^2}{k^2} n_\phi \Gamma_\phi \delta(k - m_\phi/2)$$

$$\downarrow$$

$$f_\gamma(k) \simeq 24\pi^2 \frac{n_\gamma}{m_\phi^3}\left(\frac{m_\phi}{2k}\right)^{3/2} \theta(m_\phi/2 - k)$$

$$\downarrow$$

$$\langle k \rangle \sim m_\phi$$

Pre-thermalization

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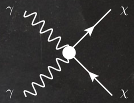


$$\frac{\partial f_\chi}{\partial t} - p_1 \frac{\partial f_\chi}{\partial p_1} = -\frac{1}{2p_1}\int \frac{g_\chi\, d^3\mathbf{p}_2}{(2\pi)^3 2p_2}\frac{g_\gamma\, d^3\mathbf{k}_1}{(2\pi)^3 2k_1}\frac{g_\gamma\, d^3\mathbf{k}_2}{(2\pi)^3 2k_2}(2\pi)^4\delta^{(4)}(k_1+k_2-p_1-p_2)$$

$$\times \Big[|\mathcal{M}|^2_{\chi\chi\to\gamma\gamma} \; \cancel{f_\chi(p_1)\, f_\chi(p_2)}\, [1+f_\gamma(k_1)]\,[1+f_\gamma(k_2)]$$

$$- |\mathcal{M}|^2_{\gamma\gamma\to\chi\chi} \; f_\gamma(k_1)\, f_\gamma(k_2)\, [1-\cancel{f_\chi(p_1)}]\,[1-\cancel{f_\chi(p_2)}]\Big]$$

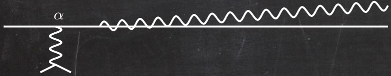
$$\downarrow$$

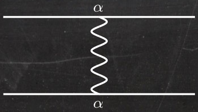
$$\dot{n}_\chi + 3Hn_\chi = 18 g_\chi^2 g_\gamma^2 \frac{n_\gamma^2}{m_\phi^3}\int_0^{m_\phi^2} ds\,\sqrt{s}\,\sigma(s)\left[\ln\left(\frac{m_\phi+\sqrt{m_\phi^2-s}}{\sqrt{s}}\right) - \frac{\sqrt{m_\phi^2-s}}{m_\phi}\right]$$

Thermalization

$$\dot{n}_\chi + 3Hn_\chi = 18 g_\chi^2 g_\gamma^2 \frac{n_\gamma^2}{m_\phi^3} \int_0^{m_\phi^2} ds\, \sqrt{s}\, \sigma(s) \left[\ln\left(\frac{m_\phi + \sqrt{m_\phi^2 - s}}{\sqrt{s}} \right) - \frac{\sqrt{m_\phi^2 - s}}{m_\phi} \right]$$

Gauge-interacting γ equilibrate through small angle scattering





Including LPM suppression

$$t_\gamma \sim \sqrt{\frac{\tau E}{q_\perp^2}}$$

Elastic screening scale

$$m_s^2 \sim \alpha \int d^3k \; f_\gamma(k)/k$$

(P. Arnold, G. Moore, L. Yaffe, hep-ph/0111107; hep-ph/0204343; hep-ph/0209353)

Thermalization

$$\dot{n}_\chi + 3Hn_\chi \;=\; 18 g_\chi^2 g_\gamma^2 \frac{n_\gamma^2}{m_\phi^3} \int_0^{m_\phi^2} ds\, \sqrt{s}\, \sigma(s) \left[\ln\left(\frac{m_\phi + \sqrt{m_\phi^2 - s}}{\sqrt{s}} \right) - \frac{\sqrt{m_\phi^2 - s}}{m_\phi} \right]$$

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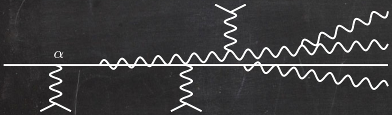

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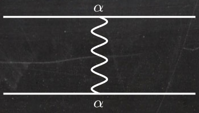

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Gauge-interacting γ equilibrate through small angle scattering

$$\Gamma_\phi t_{\rm th} \;\simeq\; \alpha^{-16/5} \left(\frac{\Gamma_\phi m_\phi^2}{M_P^3} \right)^{2/5} \;\sim\; 10^{-6,-7}$$

$$\downarrow$$

$$T_{\rm max} \;\simeq\; \alpha^{4/5} m_\phi \left(\frac{24}{\pi^2 g_{\rm reh}} \right)^{1/4} \left(\frac{\Gamma_\phi M_P^2}{m_\phi^3} \right)^{2/5}$$

(K. Harigaya, K. Mukaida, 1312.3097; K. Mukaida, M. Yamada, 1312.3097)

Post-thermalization

$$\dot{n}_\chi + 3Hn_\chi = 18 g_\chi^2 g_\gamma^2 \frac{n_\gamma^2}{m_\phi^3} \int_0^{m_\phi^2} ds\, \sqrt{s}\,\sigma(s) \left[\ln\left(\frac{m_\phi + \sqrt{m_\phi^2 - s}}{\sqrt{s}} \right) - \frac{\sqrt{m_\phi^2 - s}}{m_\phi} \right]$$

$$\Gamma_\phi t_{\rm th} \simeq \alpha^{-16/5} \left(\frac{\Gamma_\phi m_\phi^2}{M_P^3} \right)^{2/5} \ll 1$$

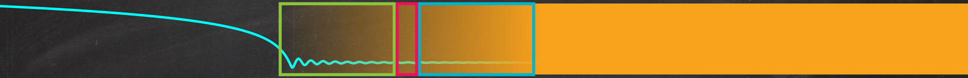
$$\dot{n}_\chi + 3Hn_\chi = \frac{g_\chi^2 g_\gamma^2}{8\pi^4} \int dk_1\, dk_2\, d\cos\theta_{12} \frac{(k_1 k_2)^2 (1 - \cos\theta_{12})}{(e^{k_1/T} \pm 1)(e^{k_2/T} \pm 1)} \sigma(s)$$

$$\Big\downarrow \text{ M.B.}$$

$$\simeq \frac{g_\chi^2 g_\gamma^2 T}{2(2\pi)^4} \int_0^\infty ds\, s^{3/2} \sigma(s) K_1(\sqrt{s}/T)$$

(P. Gondolo, G. Gelmini, Nucl. Phys. B360 (1991) 145)

Non-thermal vs. thermal production



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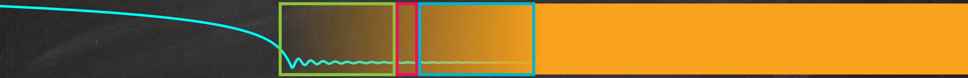

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Thermal:

$$Y_\chi^{\rm T}(T_{\rm reh}) \propto \frac{M_P T_{\rm reh}^7}{g_{\rm reh}^{1/2} M^{n+2}} \times \begin{cases} \dfrac{1}{n-6}\left(T_{\rm max}^{n-6} - T_{\rm reh}^{n-6}\right), & n > -1,\ n \neq 6 \\ \ln\left(\dfrac{T_{\rm max}}{T_{\rm reh}}\right), & n = 6 \end{cases}$$

Non-thermal vs. thermal production

$$\dot{n}_\chi + 3Hn_\chi = 18 g_\chi^2 g_\gamma^2 \frac{n_\gamma^2}{m_\phi^3} \int_0^{m_\phi^2} ds\, \sqrt{s}\, \sigma(s) \left[\ln\left(\frac{m_\phi + \sqrt{m_\phi^2 - s}}{\sqrt{s}} \right) - \frac{\sqrt{m_\phi^2 - s}}{m_\phi} \right]$$

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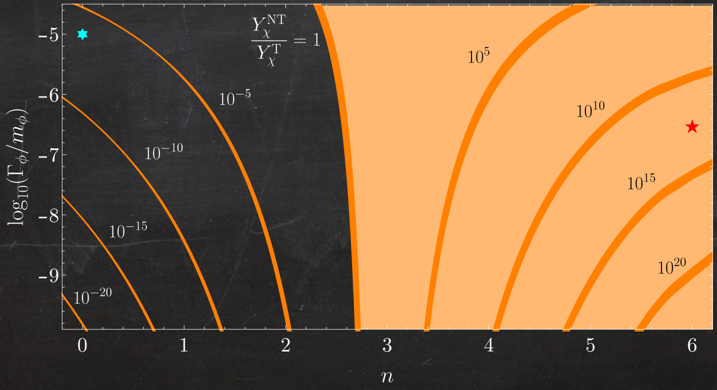
$$\sigma(s) \propto \frac{s^{n/2}}{M^{n+2}}$$

Non-thermal:

$$Y_\chi^{\rm NT}(T_{\rm reh}) \propto g_{\rm reh}^{3/2} \frac{T_{\rm reh}^3 M_P m_\phi^{n-2}}{M^{n+2}} (\Gamma_\phi t_{\rm th})$$

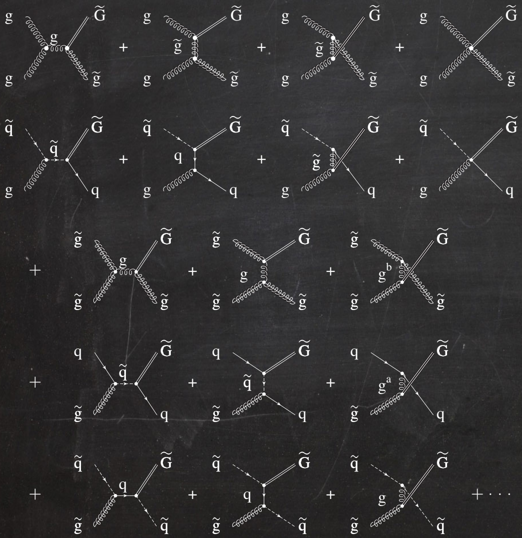
Non-thermal vs. thermal production

$$\sigma(s) \propto \frac{s^{n/2}}{M^{n+2}}$$



Light Gravitino

$\phi \to g + g$ and weak scale supersymmetry



$$\langle \sigma v \rangle_{\rm NT} = \sum_{i=1}^{3} \frac{16\pi\alpha_i}{M_P^2} |f^{abc}|^2 \left(1 + \frac{m_{\tilde{g}_i}^2}{3m_{3/2}^2}\right)$$

$$\langle \sigma v \rangle_{\rm T} = \sum_{i=1}^{3} \frac{3\pi^2 c_i \alpha_i}{4\zeta(3) M_P^2} \left(1 + \frac{m_{\tilde{g}_i}^2}{3m_{3/2}^2}\right) \ln\left(\frac{k_i}{g_i}\right)$$

(M. Bolz et. al., hep-ph/0012052)

(V. Rychkov, A. Strumia, hep-ph/0701104)

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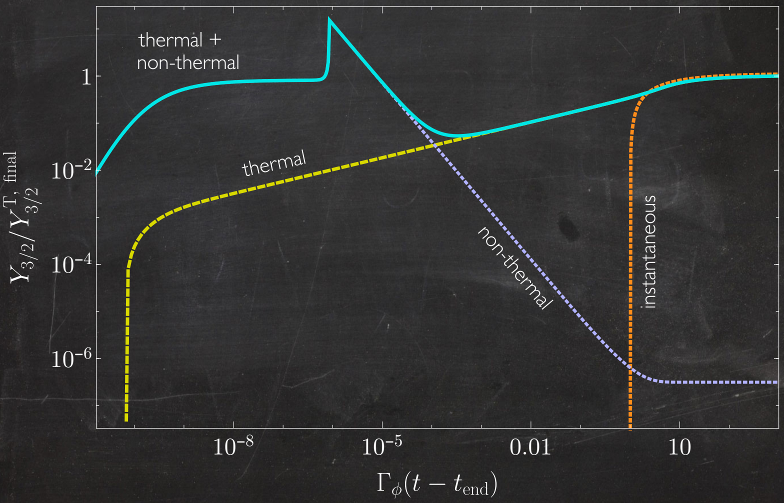
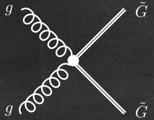


Heavy Gravitino

High scale supersymmetry. Only susy state below the inflationary scale is the gravitino

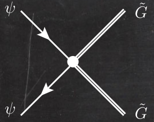
Leading-order universal Goldstino-matter interactions $(F = \sqrt{3} m_{3/2} M_P)$:

$$\mathcal{L}_{2G} = \frac{i}{2F^2}\left(G\sigma^\mu\partial^\nu\bar{G} - \partial^\nu G\sigma^\mu\bar{G}\right) T_{\mu\nu}$$



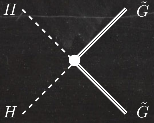
$(F^{\lambda a}_{\mu} F^{a}_{\nu\lambda})$

$$\langle\sigma v\rangle_{\rm NT} = \frac{154 m_\phi^6}{5(64)^2 F^4}$$



$(\bar{\psi}\bar{\sigma}_\mu\partial_\nu\psi + \cdots)$

$$\langle\sigma v\rangle_{\rm T} = \frac{6400\pi^{11} T^6}{(945)^2\zeta(3)^2 F^4}$$



$(\partial_\mu H \partial_\nu H^\dagger + \text{h.c.})$

(E. Dudas, Y. Mambrini, K. Olive, 1704.03008)
(K. Benakli et. al., 1701.06574)

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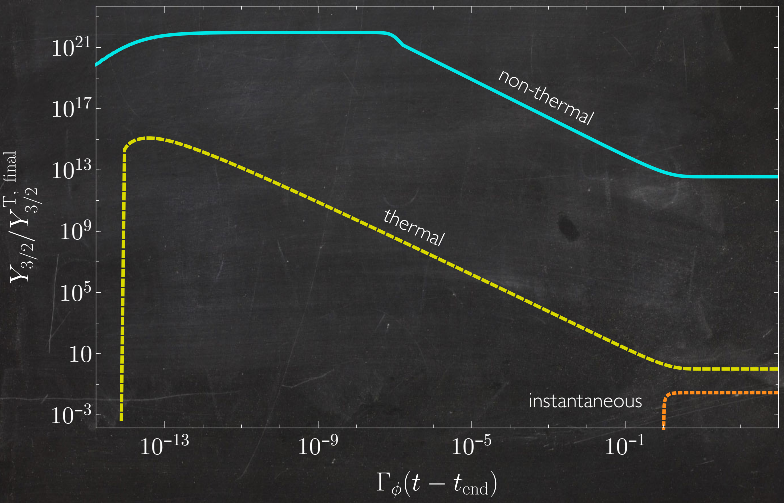

Heavy Gravitino

High scale supersymmetry. Only susy state below the inflationary scale is the gravitino

Assuming instantaneous reheating and thermalization...

$$\Omega_{3/2}^{\rm inst} h^2 \simeq 0.11 \left(\frac{0.1\,{\rm EeV}}{m_{3/2}}\right)^3 \left(\frac{T_{\rm reh}}{2.2\times 10^{10}}\right)^7$$

vs. accounting for their finite duration...

$$\Omega_{3/2} h^2 \simeq 0.11 \left(\frac{0.1\,{\rm EeV}}{m_{3/2}}\right)^3 \left(\frac{T_{\rm reh}}{2.2\times 10^{8}}\right)^{19/5} \left(\frac{m_\phi}{3\times 10^{13}\,{\rm GeV}}\right)^{24/5} \left(\frac{0.030}{\alpha_3}\right)^{16/5}$$

(similar analysis applies to DM production through heavy spin-2 mediators, N. Bernal et. al. 1803.01866)

Freezing-in dark matter through a heavy invisible Z'

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[b] *Laboratoire de Physique Théorique (UMR8627), CNRS, Univ. Paris-Sud, Université Paris-Saclay, 91405 Orsay, France*

(1806.00016 [hep-ph])

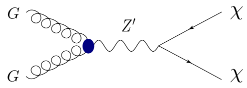

FIG. 1: *Production of dark matter through gluon fusion in the early Universe*

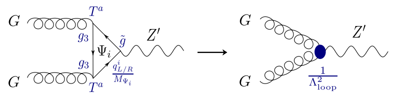

FIG. 4: *Triangle diagram generated containing heavy chiral fermions Ψ_i (left panel), and the resulting effective vertex at low energy (right panel).*

$$\langle \sigma v \rangle n_\gamma^2 = R(T) \approx \begin{cases} 2\times 10^2 \, \dfrac{\alpha^2}{\Lambda^4} \dfrac{m_\chi^2}{M_{Z'}^4} T^{10} & \text{(fermionic DM)} \\ 10^4 \, \dfrac{\beta^2}{\Lambda^4 M_{Z'}^4} T^{12} & \text{(abelian DM)} \\ 2\times 10^9 \, \dfrac{\gamma^2}{\Lambda^4 M_{Z'}^4} T^{16} & \text{(non-abelian DM)} \end{cases} \tag{14}$$

$\rightarrow n = 4$

$\rightarrow n = 6$

$\rightarrow n = 10$

Conclusion

- UV-dominated freeze-in during reheating is realized for $\sigma(s) \sim s^{n/2}$, $n > 2$
- Thermalization time-scale determines the DM abundance at late times
- Effect important for DM production in very high scale susy models, or for heavy spin-2 mediators. Other models?
- Preheating? $N_{\rm eff}$?

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Thank you