Boosting Ultraviolet Freeze-in

Based on:
NB, Maíra Dutra, Yann Mambrini, Keith Olive, Marco Peloso and Mathias Pierre - arXiv:1803.01866
NB, Javier Rubio and Hardi Veermäe - arXiv:2004.13706 & arXiv:2006.02442
NB - arXiv:2005.08988

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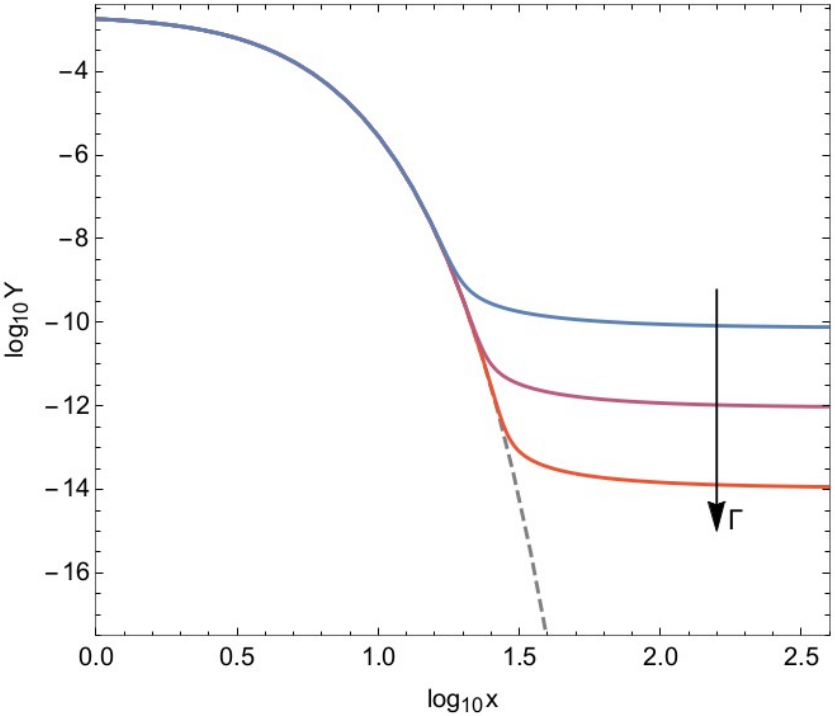
October 7th, 2020

WIMP paradigm



$$\frac{dn}{dt} + 3\,H\,n = -\langle\sigma v\rangle\left(n^2 - n_{\rm eq}^2\right)$$

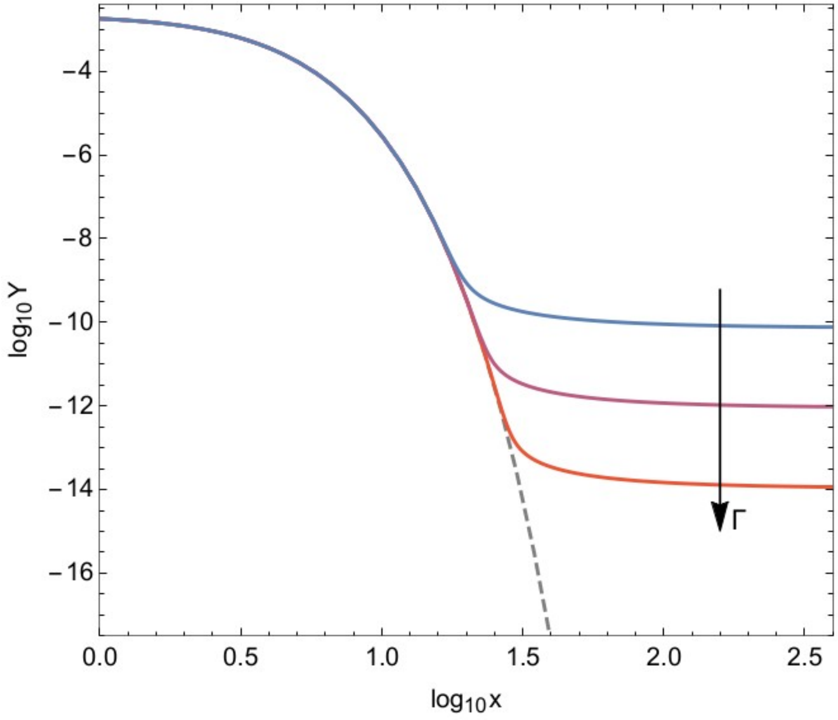
$$Y \equiv n/s \text{ and } x \equiv m/T$$

$$\frac{dY}{dx} = -\frac{\langle\sigma v\rangle\, s}{H\,x}\left(Y^2 - Y_{\rm eq}^2\right)$$

* chemical equilibrium
* <σv> ~ few 10^{-26} cm^3/s
* T_{fo} ~ m / 20

→ independent from initial conditions

WIMP paradigm



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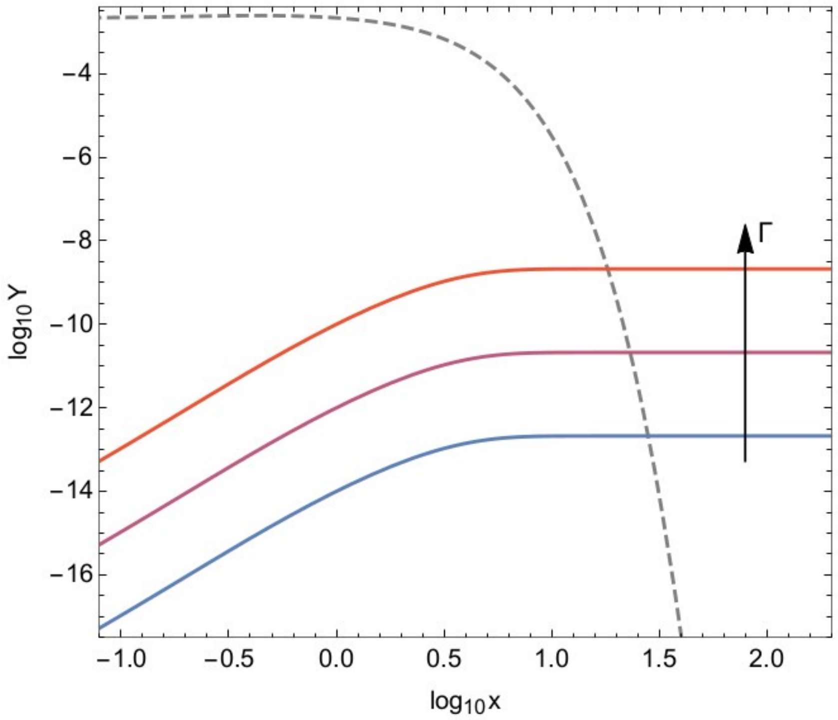
Over the last decades a huge worldwide effort to detect WIMP DM using a multi-channel and multi-messenger approach…

but no compelling detection so far! :-(

IR FIMP paradigm



$$\frac{dn}{dt} + 3\,H\,n = -\langle\sigma v\rangle\,\left(\cancel{n^2} - n_{\rm eq}^2\right)$$

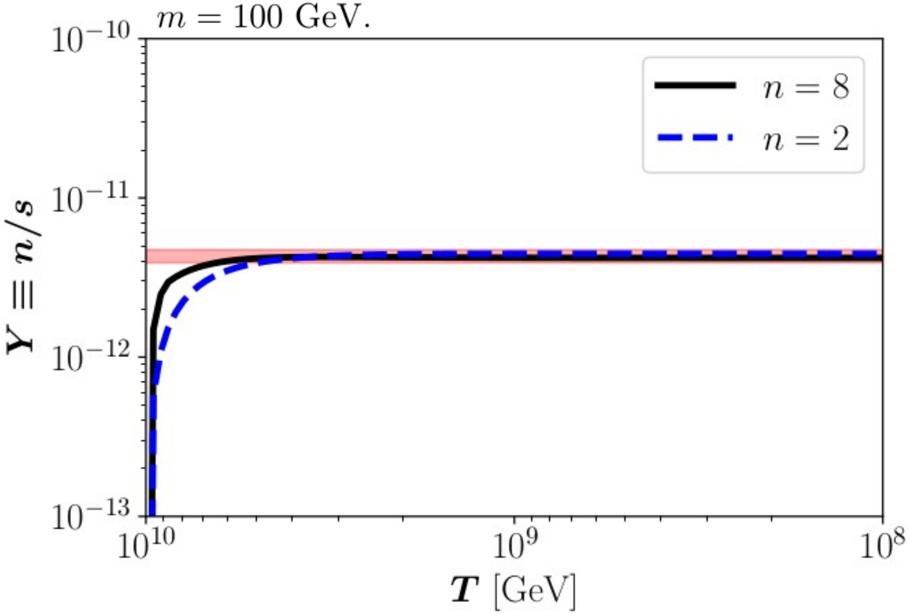
$$Y \equiv n/s \text{ and } x \equiv m/T$$

$$\frac{dY}{dx} = -\frac{\langle\sigma v\rangle\,s}{H\,x}\,\left(\cancel{Y^2} - Y_{\rm eq}^2\right)$$

* chemical equilibrium never reached
* renormalizable operators
* $\lambda_{DM\text{-}SM} \sim 10^{-11}$
* $T_{fi} \sim m$

→ (mild) dependence from initial conditions

UV FIMP paradigm



$$\frac{dn}{dt} + 3\,H\,n = -\langle\sigma v\rangle\,\left(\cancel{n}^2 - n_{\rm eq}^2\right)$$

$$Y \equiv n/s \text{ and } x \equiv m/T$$

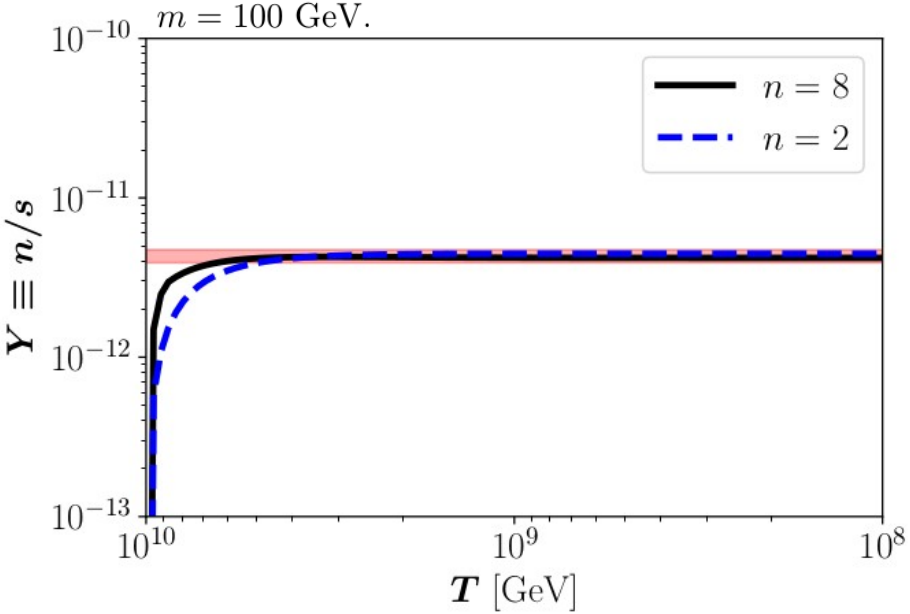
$$\frac{dY}{dx} = -\frac{\langle\sigma v\rangle\,s}{H\,x}\,\left(\cancel{Y}^2 - Y_{\rm eq}^2\right)$$

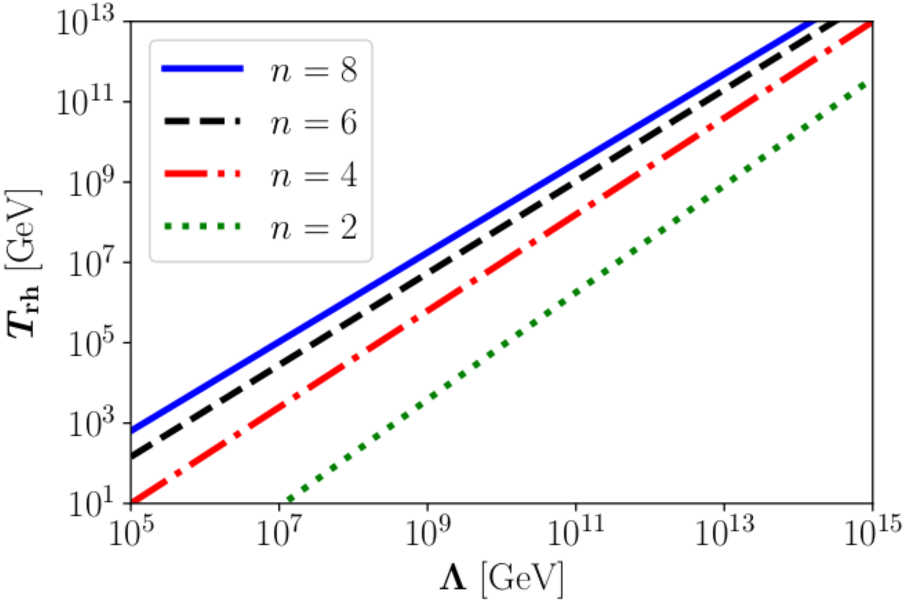
$$\langle\sigma v\rangle = \frac{T^n}{\Lambda^{2+n}}$$

* chemical equilibrium never reached
* non-renormalizable operators
* $\Lambda > T_{rh}$
* $T_{fi} \sim T_{rh}$

→ (strong) dependence from initial conditions

UV FIMP paradigm





$$\langle \sigma v \rangle = \frac{T^n}{\Lambda^{2+n}}$$

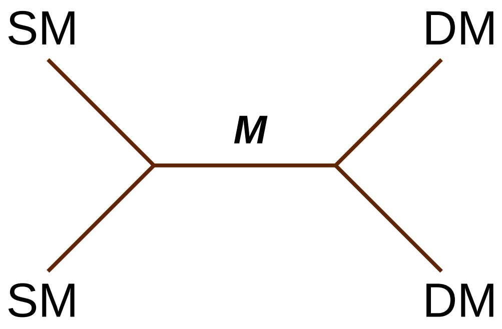
$$Y \sim \int_0^{T_{\rm RH}} \frac{M_{\rm Pl}\, T^n}{\Lambda^{n+2}} \sim \frac{M_{\rm Pl}\, T_{\rm RH}^{n+1}}{\Lambda^{n+2}}$$

UV FIMP paradigm

$$\langle \sigma v \rangle = \frac{T^n}{\Lambda^{2+n}}$$

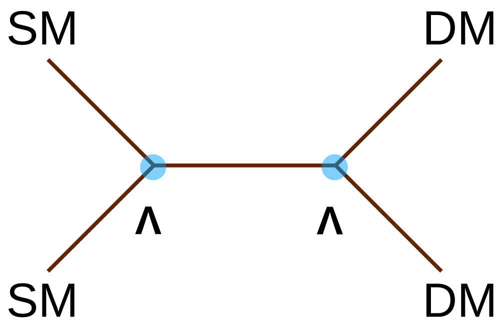
- **Heavy mediator** ($M >> T_{rh}$)

$$\langle \sigma v \rangle \propto g^4 \frac{T^2}{M^4}$$



UV FIMP paradigm

$$\langle \sigma v \rangle = \frac{T^n}{\Lambda^{2+n}}$$



- **Heavy mediator** ($M >> T_{rh}$)

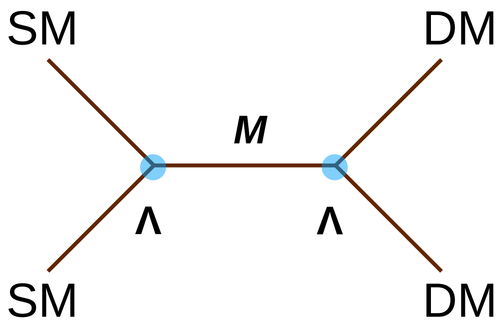
$$\langle \sigma v \rangle \propto g^4 \frac{T^2}{M^4}$$

- **Suppressed couplings** ($\Lambda >> T_{rh}$)

$$\langle \sigma v \rangle \propto \frac{T^2}{\Lambda^4}$$

UV FIMP paradigm

$$\langle \sigma v \rangle = \frac{T^n}{\Lambda^{2+n}}$$



- **Heavy mediator** ($M \gg T_{rh}$)

$$\langle \sigma v \rangle \propto g^4 \frac{T^2}{M^4}$$

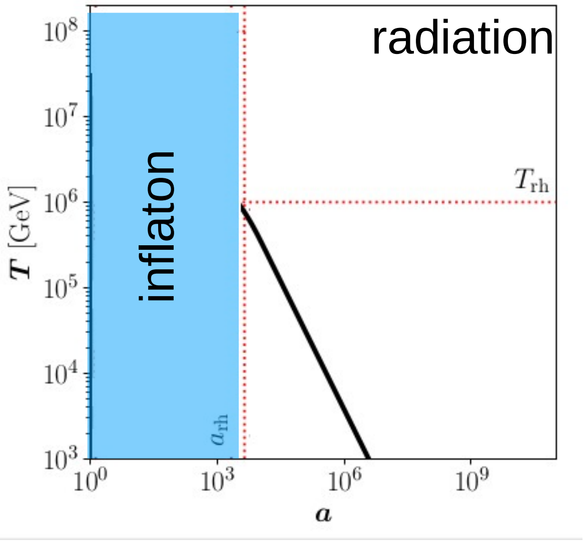
- **Suppressed couplings** ($\Lambda \gg T_{rh}$)

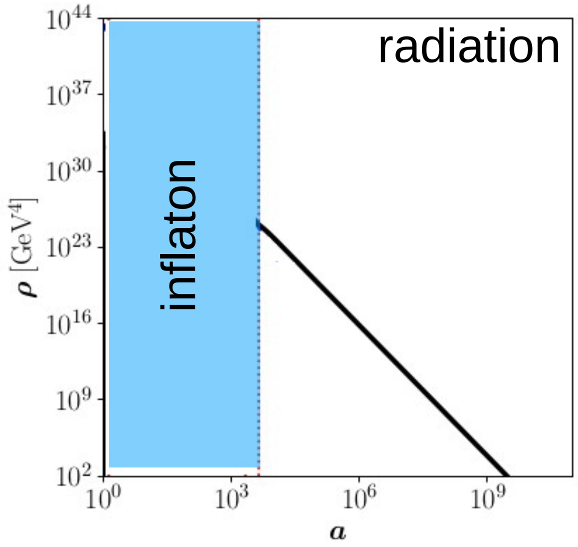
$$\langle \sigma v \rangle \propto \frac{T^2}{\Lambda^4}$$

- **Heavy mediator + suppressed couplings** ($M, \Lambda \gg T_{rh}$)

$$\langle \sigma v \rangle \propto \frac{T^6}{\Lambda^4 M^4}$$

Instantaneous Reheating



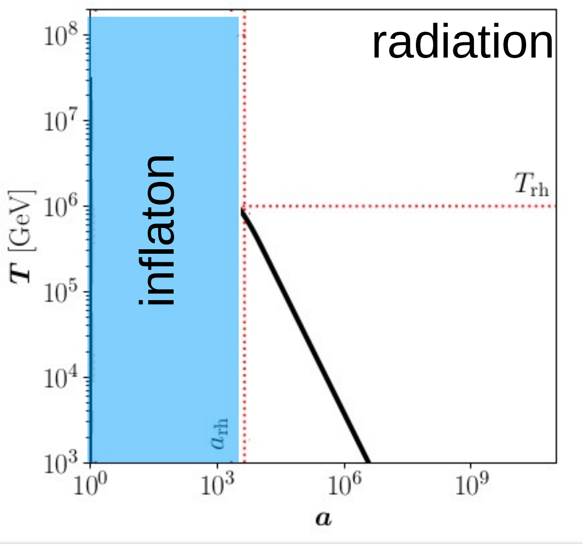


$T \sim 1/a$

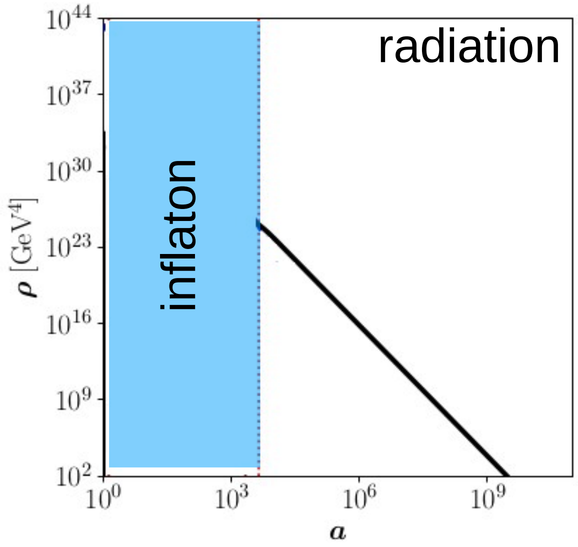
$\rho \sim T^4 \sim a^{-4}$

* SM entropy conserved
* $H \sim T^2 / M_P$

Instantaneous Reheating



$T \sim 1/a$



$\rho \sim T^4 \sim a^{-4}$

* SM entropy conserved
* $H \sim T^2 / M_P$

This is pretty much the common lore of the particle physics community! ;-)

1. Beyond the instantaneous reheating approximation...

Non-instantaneous Reheating

Decay of the inflaton into SM radiation is a *continuous process*

$$\frac{d\rho_\phi}{dt} + 3(1+\omega)\,H\,\rho_\phi = -\Gamma_\phi\,\rho_\phi$$

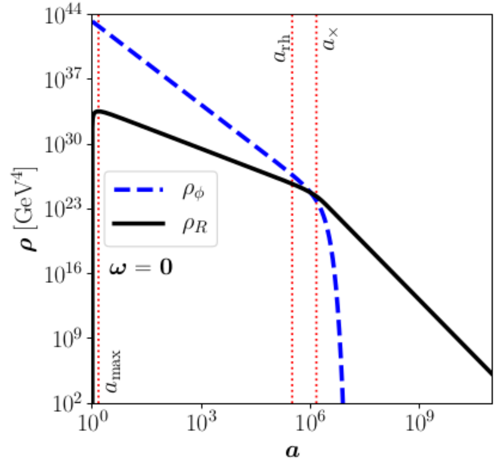
$$\frac{d\rho_R}{dt} + 4\,H\,\rho_R = +\Gamma_\phi\,\rho_\phi$$

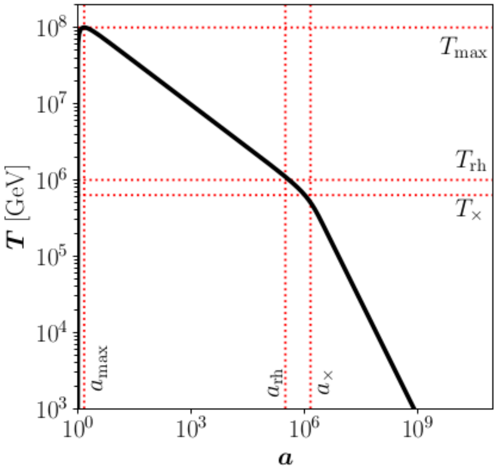
3 free parameters:
$\boldsymbol{H_{\rm ini}}$, $\boldsymbol{\Gamma_\phi}$ and $\boldsymbol{\omega}$

Inflaton decay width $$\Gamma_\phi = \frac{\pi}{3}\sqrt{\frac{g_\star(T_{\rm RH})}{10}}\,\frac{T_{\rm RH}^2}{M_{\rm Pl}}$$

Hubble expansion rate $$H^2 = (\rho_\phi + \rho_R)/(3\,{M_{\rm Pl}}^2)$$

Non-instantaneous Reheating





T_{max}: SM thermal bath reaches a temperature $T_{max} >> T_{rh}$ due to the non-sudden decay

$$\rho_\phi(a) \propto \begin{cases} a^{-3(1+\omega)} & \text{for } a_{\max} \ll a \ll a_{\rm rh} \\ 0 & \text{for } a_{\rm rh} \ll a \end{cases}$$

$$\rho_R(a) \propto \begin{cases} a^{-\frac{3}{2}(1+\omega)} & \text{for } a_{\max} \ll a \ll a_{\rm rh} \\ a^{-4} & \text{for } a_{\rm rh} \ll a \end{cases}$$

$$T(a) \propto \begin{cases} a^{-\frac{3}{8}(1+\omega)} & \text{for } a_{\max} \ll a \ll a_{\rm rh} \\ a^{-1} & \text{for } a_{\rm rh} \ll a \end{cases}$$

3 free parameters:
H_{ini}, ***Γ_ϕ*** and ***ω***
or
T_{max}, ***T_{rh}*** and ***ω***

→ Chung, Kolb & Riotto ‘98

UV Freeze-in

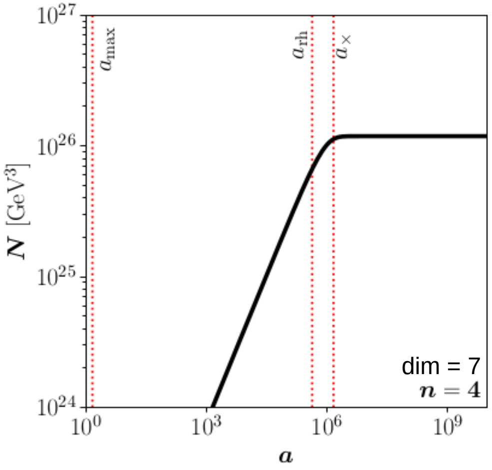
$$\left\{\begin{aligned} &\frac{dn}{dt} + 3\,H\,n = -\langle\sigma v\rangle\,\left(n^2 - n_{\rm eq}^2\right) \\ &\frac{d\rho_\phi}{dt} + 3(1+\omega)\,H\,\rho_\phi = -\Gamma_\phi\,\rho_\phi \\ &\frac{d\rho_R}{dt} + 4\,H\,\rho_R = +\Gamma_\phi\,\rho_\phi \end{aligned}\right.$$

$$\rightarrow \qquad \frac{dN}{da} = -\frac{\langle\sigma v\rangle}{a^4\,H}\,\left(N^2 - N_{\rm eq}^2\right)$$

$$N \equiv n \times a^3$$

$$\langle\sigma v\rangle = \frac{T^n}{\Lambda^{2+n}}$$

UV Freeze-in

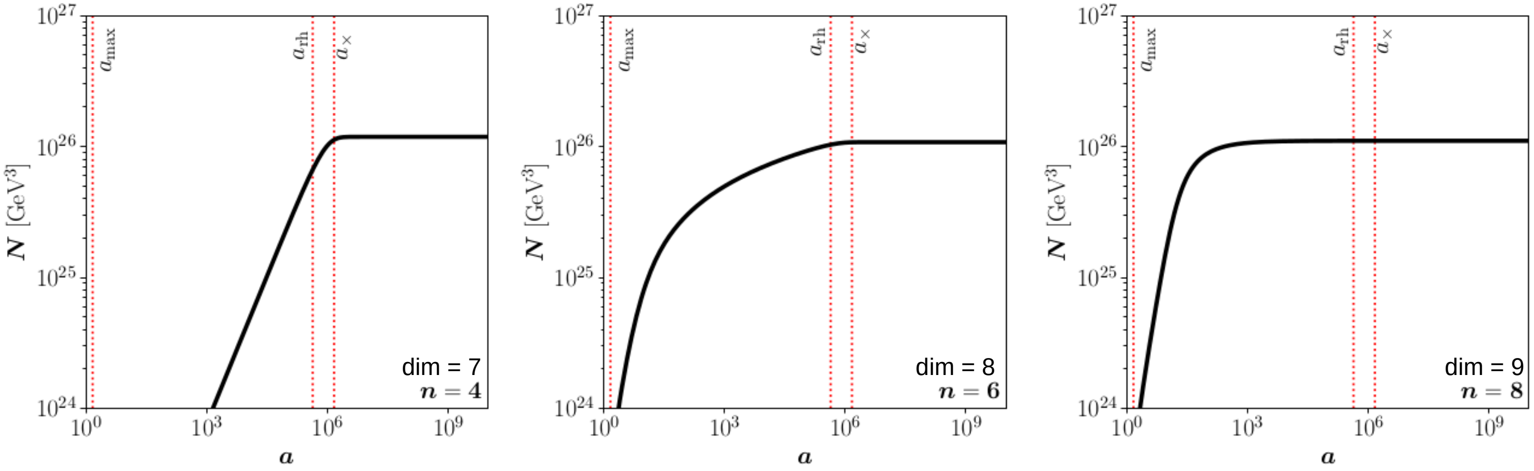


m = 100 GeV

T_{max} = 10^8 GeV
T_{rh} = 10^6 GeV
ω = 0

DM production: $T = T_{rh}$

UV Freeze-in



m = 100 GeV

T_{max} = 10^8 GeV
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ω = 0

DM production: $T = T_{rh}$ $T \sim T_{rh}$ $T >> T_{rh}$

UV Freeze-in

$$\frac{dn}{dt} + 3\,H\,n = -\langle\sigma v\rangle\left(n^2 - n_{\rm eq}^2\right)$$

$$\frac{d\rho_\phi}{dt} + 3(1+\omega)\,H\,\rho_\phi = -\Gamma_\phi\,\rho_\phi$$

$$\frac{d\rho_R}{dt} + 4\,H\,\rho_R = +\Gamma_\phi\,\rho_\phi$$

$$Y_\infty = \frac{180\,\zeta(3)^2\,g^2}{\pi^7\,g_{\star s}}\sqrt{\frac{10}{g_\star}}\,\frac{1}{(n-n_c)(1+\omega)}\,\frac{M_{\rm Pl}\,T_{\rm rh}^{\frac{7-\omega}{1+\omega}}}{\Lambda^{n+2}}\left[T_{\rm max}^{n-n_c} - T_{\rm rh}^{n-n_c}\right] \qquad \text{for } n \neq n_c.$$

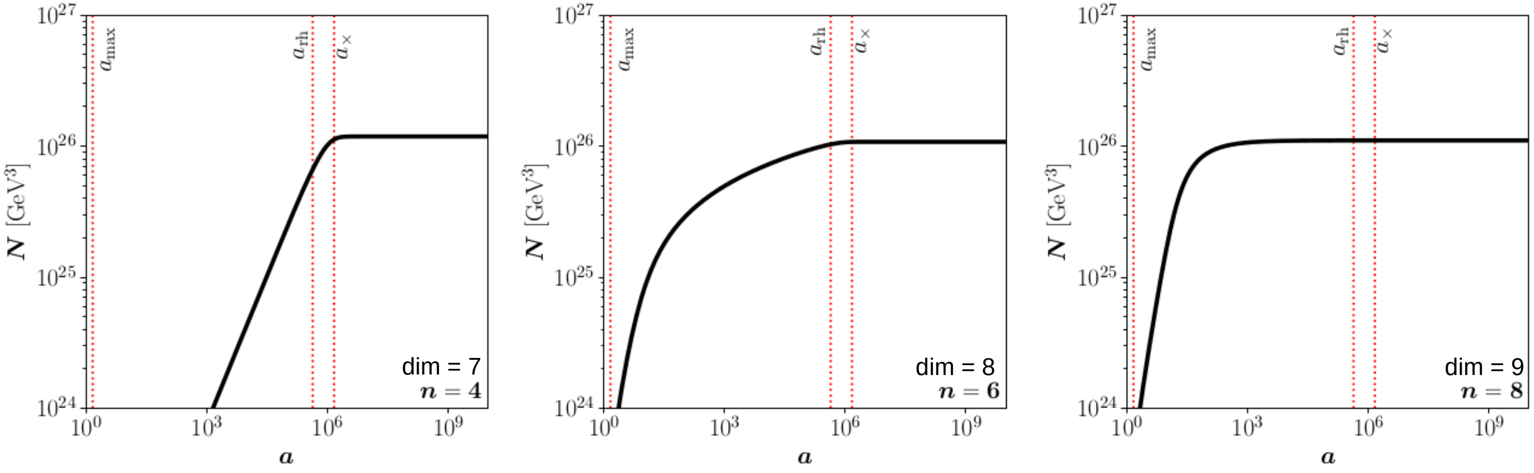
$$Y_\infty = \frac{45\,\zeta(3)^2\,(n+2)\,g^2}{2\pi^7\,g_{\star s}}\sqrt{\frac{10}{g_\star}}\,\frac{M_{\rm Pl}\,T_{\rm rh}^{1+n}}{\Lambda^{2+n}}\ln\frac{T_{\rm max}}{T_{\rm rh}} \qquad \text{for } n = n_c$$

$$\langle\sigma v\rangle = \frac{T^n}{\Lambda^{2+n}}$$

$$n_c \equiv 2 \times \left(\frac{3-\omega}{1+\omega}\right)$$

$\boldsymbol{\omega}$	$\boldsymbol{n_c}$
-1/3	10
-1/5	8
0 (dust)	6
1/3 (radiation)	4
1 (kination)	2

UV Freeze-in



m = 100 GeV

$T_{max} = 10^8$ GeV
$T_{rh} = 10^6$ GeV
$\omega = 0$
→ $\boldsymbol{n_c = 6}$

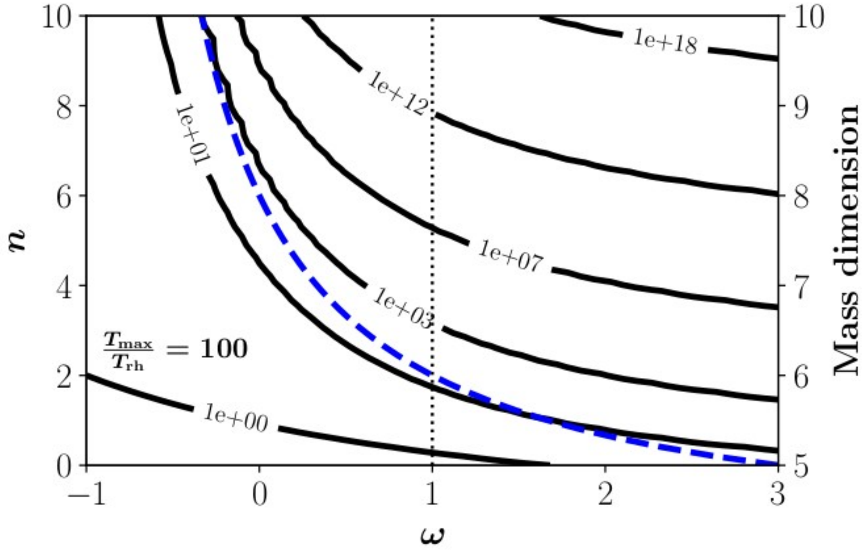
DM production:

$T = T_{rh}$	$T \sim T_{rh}$	$T >> T_{rh}$
$\boldsymbol{n < n_c}$	$\boldsymbol{n = n_c}$	$\boldsymbol{n > n_c}$

Boost Factors

$$B \equiv \frac{Y_\infty^{\text{full}}}{Y_\infty^{\text{instant.}}} \simeq \begin{cases} \frac{8}{3}\frac{(1+n)(2+n_c)}{n_c-n} & \text{for } n < n_c \\ \frac{(1+n)\,(2+n)}{3} \ln \frac{T_{\text{max}}}{T_{\text{rh}}} & \text{for } n = n_c \\ \frac{8}{3}\frac{(1+n)(2+n_c)}{n-n_c}\left[\frac{T_{\text{max}}}{T_{\text{rh}}}\right]^{n-n_c} & \text{for } n > n_c \end{cases}$$

$$n_c \equiv 2 \times \left(\frac{3-\omega}{1+\omega}\right)$$



* Depends on ***n***, ***ω*** and the ratio $\boldsymbol{T_{\text{max}} / T_{\text{rh}}}$

* Independent from ***m***, ***Λ***

2. Allowing DM self-interactions

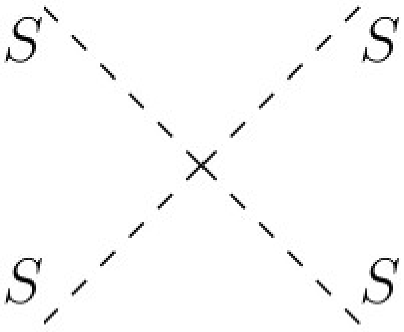
DM self-interactions

So far we have focused on the DM-SM interactions:
    WIMP, IR FIMP, IR FIMP…
ignoring possible DM self-interactions

But what about possible *DM self-interactions*?

DM self-interactions

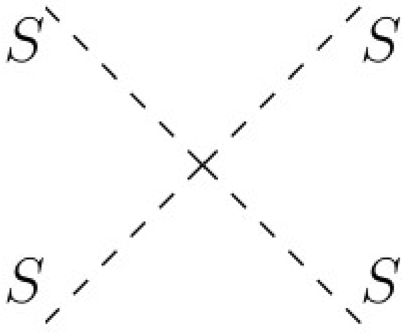
Elastic scattering



Kinetic equilibrium:
DM temperature

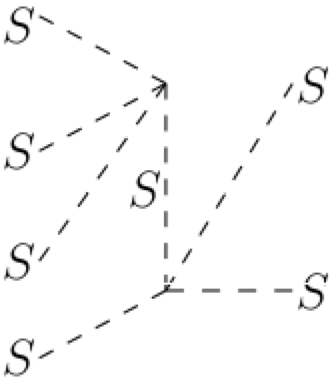
DM self-interactions

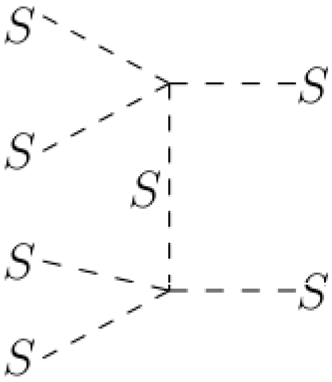
Elastic scattering



Kinetic equilibrium:
DM temperature

Number-changing interactions

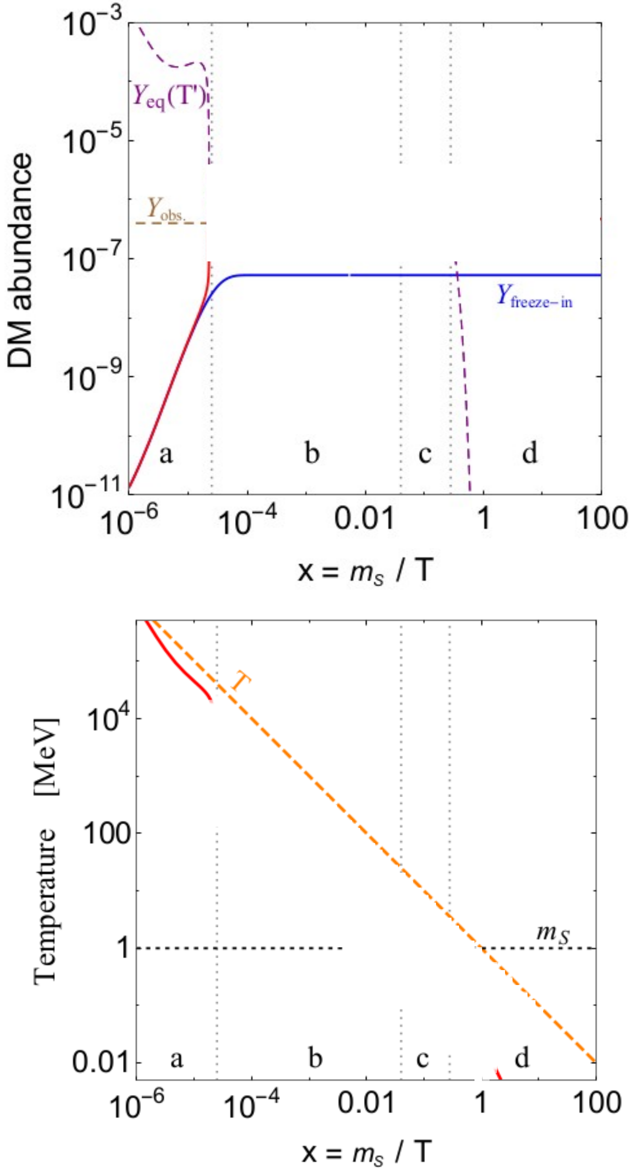




Chemical equilibrium:
4 → 2 and 2 → 4

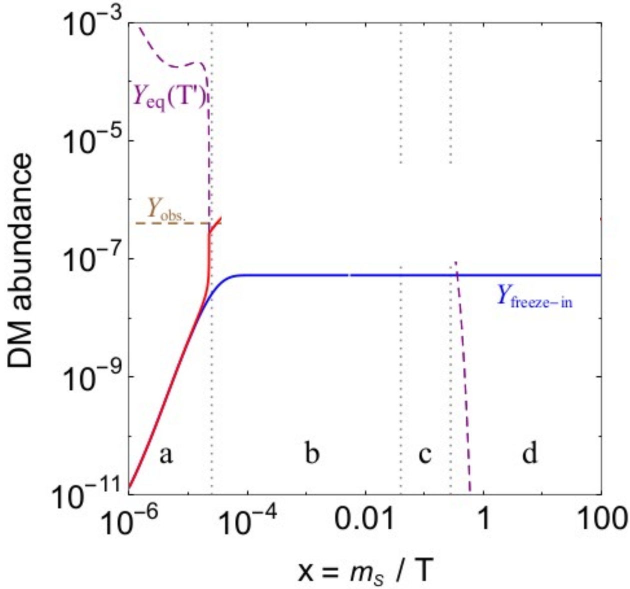
FIMP with DM self-interactions

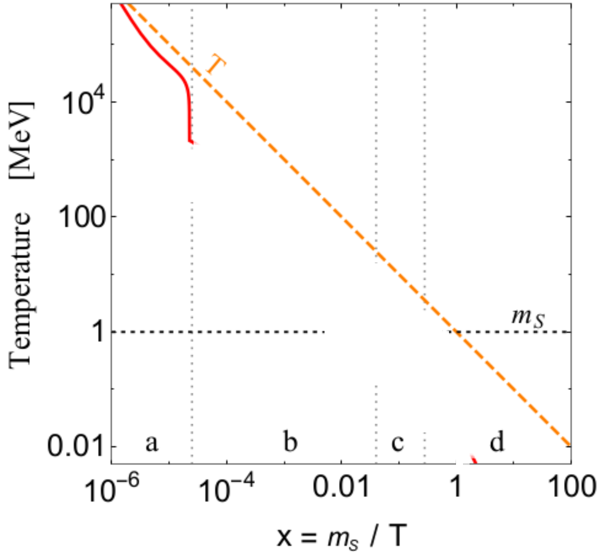
- DM under-produced (wrt equilibrium) by the FIMP mechanism with a high momentum



FIMP with DM self-interactions

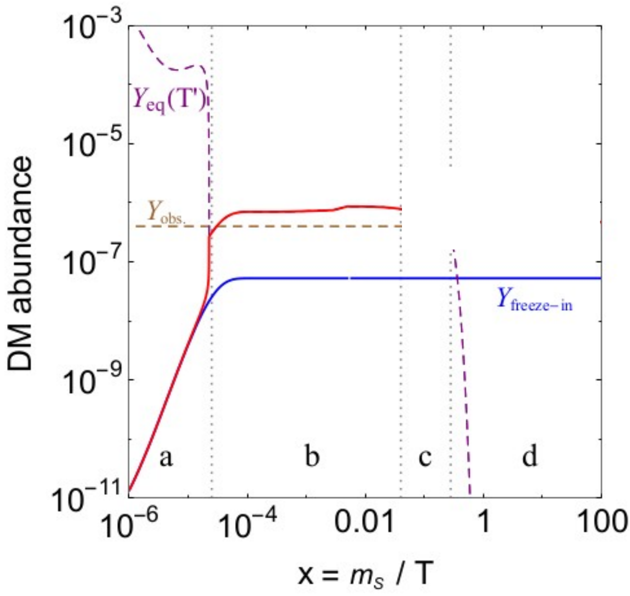
- DM under-produced (wrt equilibrium) by the FIMP mechanism with a high momentum
- **2 → 4**
  Increases DM yield
  decreases DM temperature

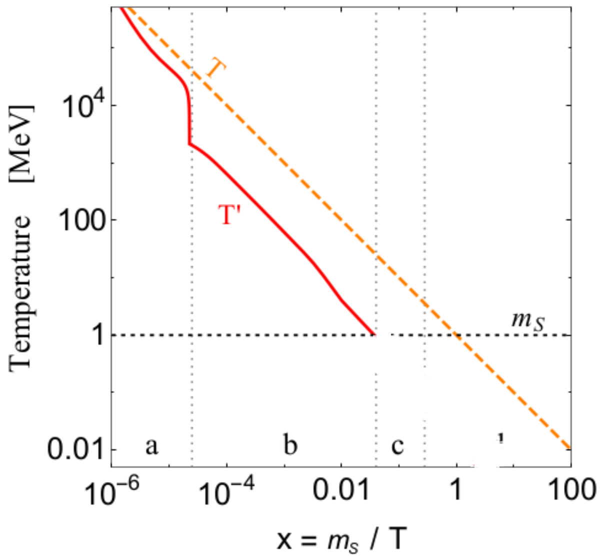




FIMP with DM self-interactions

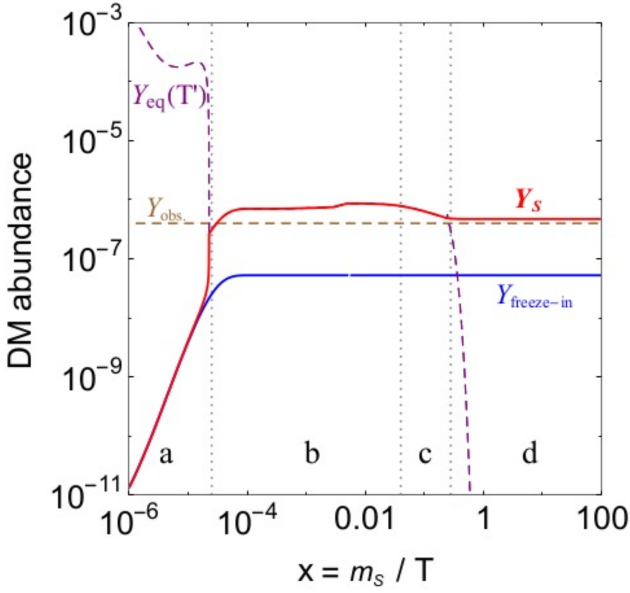
- DM under-produced (wrt equilibrium) by the FIMP mechanism with a high momentum
- **2 → 4**
  Increases DM yield
  decreases DM temperature
- **Chemical equilibirum**
  2 → 4 and 4 → 2

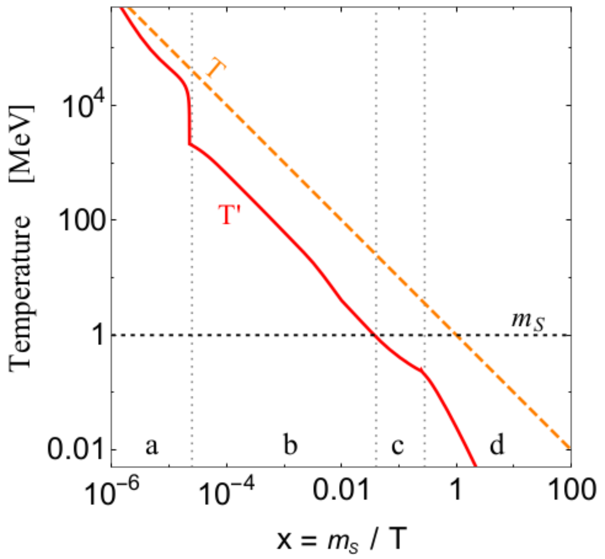




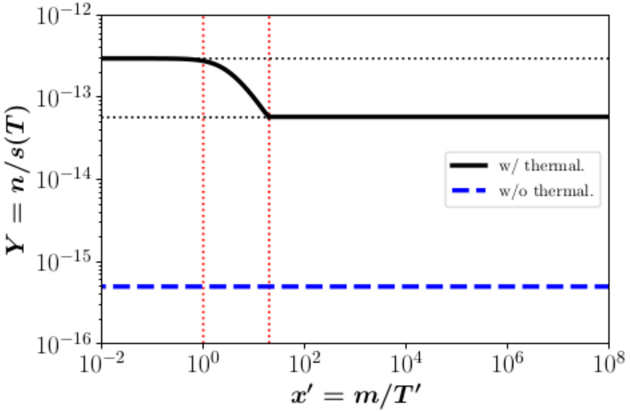
FIMP with DM self-interactions

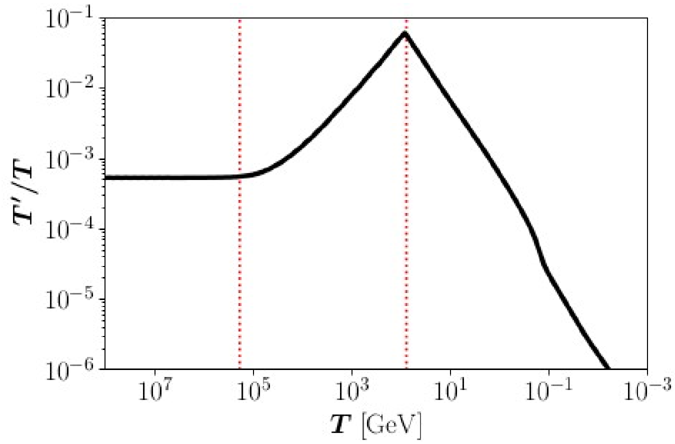
- DM under-produced (wrt equilibrium) by the FIMP mechanism with a high momentum
- **2 → 4**
  Increases DM yield
  decreases DM temperature
- **Chemical equilibirum**
  2 → 4 and 4 → 2
- **4 → 2** freeze-out:
  Decreases DM yield
  increases DM temperature





DM boost by self-interactions





The boost factors can be computed in a <u>*model-independent*</u> way!

$$B \equiv \frac{Y_0^{\mathrm{w/}}}{Y_0^{\mathrm{w/o}}} \simeq \left(\frac{8}{27} \frac{g}{g_{\star s}(T_{\mathrm{fi}})} \frac{1}{Y_0^{\mathrm{w/o}}} \right)^{\frac{1}{4}} \times \begin{cases} \frac{45\,\zeta(3)}{2^{1/4}\,\pi^4} \frac{\mathcal{C}_n}{\mathcal{C}_\rho^{3/4}} & \text{for } x'_{\mathrm{fo}} \ll 1, \\ \frac{8}{7^{3/4}} \frac{1}{x'_{\mathrm{fo}}} & \text{for } x'_{\mathrm{fo}} \gg 1. \end{cases}$$

Conclusions

- UV freeze-in is a viable DM production mechanism
- **Strongly depends on the dynamics at the highest temperatures of the Universe**: heating dynamics

$$\langle \sigma v \rangle = \frac{T^n}{\Lambda^{2+n}}$$

- Instantaneous reheating may not be a good approximation
  → miserably fails for $n > n_c$
- Boost factor B

$$B \propto \begin{cases} \mathcal{O}(1) & \text{for } n < n_c \\ \ln\left(\frac{T_{\max}}{T_{\rm rh}}\right) & \text{for } n = n_c \\ \left(\frac{T_{\max}}{T_{\rm rh}}\right)^{n-n_c} & \text{for } n > n_c \end{cases}$$

- For $n > n_c$: Bulk of DM produced near T_{max}
- Big boost factors due to the non-sudden reheating
  → $T_{max} >> T_{rh}$
  → depend on the effective equation of state of the early Universe
  → Bigger boosts for stiffer EoS
  → Bigger boosts if no entropy injection, i.e. no DM dilution
- **DM Self-interactions have a strong impact on the DM dynamics**
- Boost factors of several order of magnitude can be computed in a model independent way!

¡Muchas gracias!