

# UV Freeze-in and Non-standard Cosmologies

Based on:

NB, Maíra Dutra, Yann Mambrini, Keith Olive, Marco Peloso and Mathias Pierre - arXiv:1803.01866

NB, Fatemeh Elahi, Carlos Maldonado and James Unwin - arXiv:1909.07992

NB and Hardi Veermäe - arXiv:2001.soon

**Nicolás BERNAL**

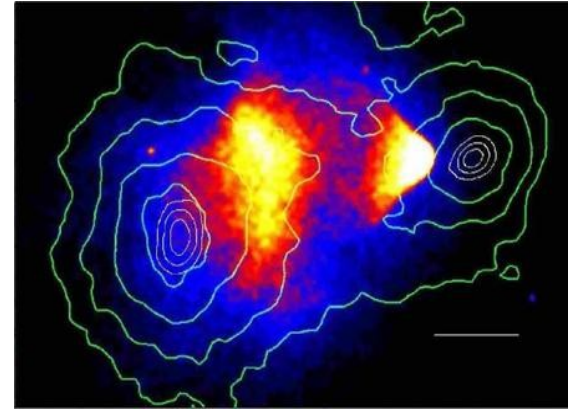


COMHEP 2019  
December 6<sup>th</sup>, 2019

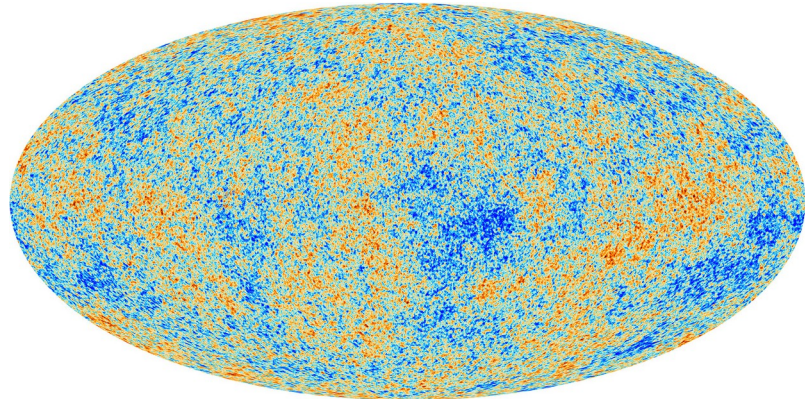
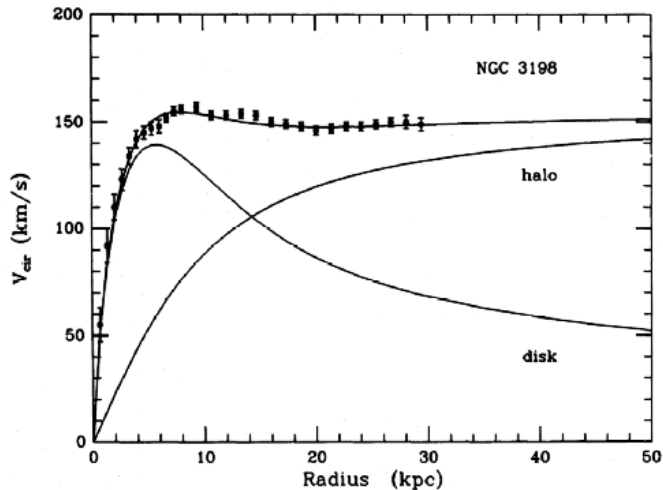
# Evidences for Dark Matter

Several observations indicate the existence of non-luminous Dark Matter (missing force) at very different scales!

- \* Galactic rotation curves
- \* RC in Clusters of galaxies
- \* Clusters of galaxies
- \* CMB anisotropies



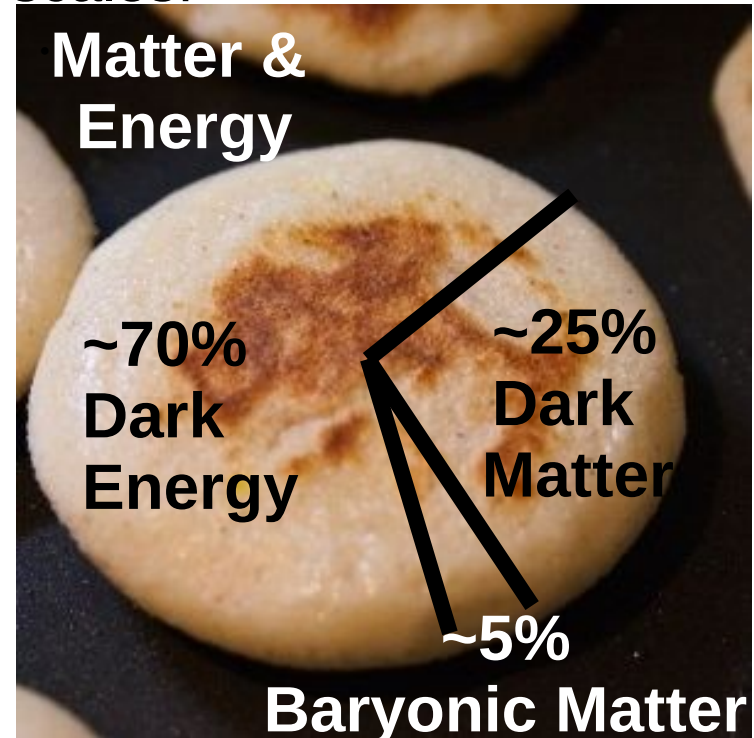
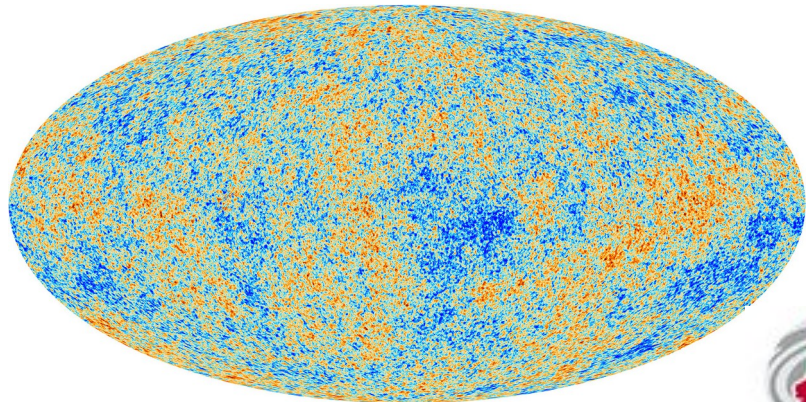
DISTRIBUTION OF DARK MATTER IN NGC 3198



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**Dark Matter is there! :-)**

But what is it? :-/

- \* Neutral
- \* Massive
- \* 'Weak' interactions with the SM
- \* Stable or long-lived

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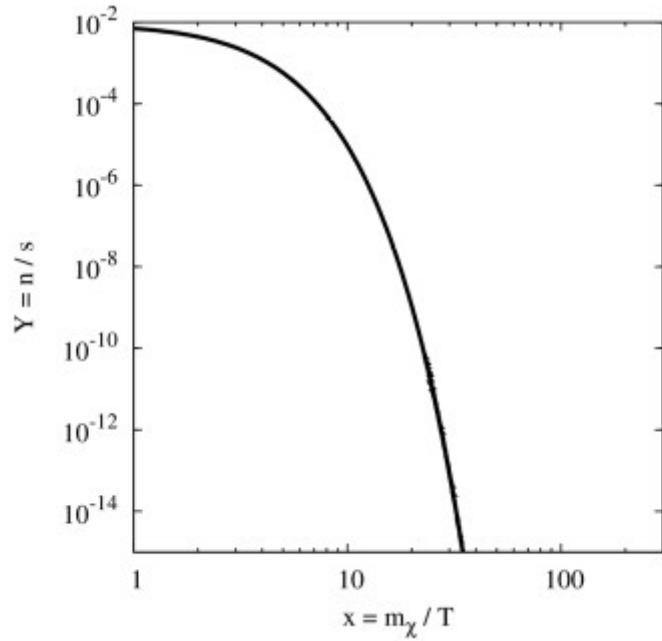
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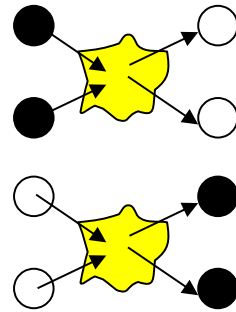
Talk by Roberto!

# How was Dark Matter produced in the Early Universe?

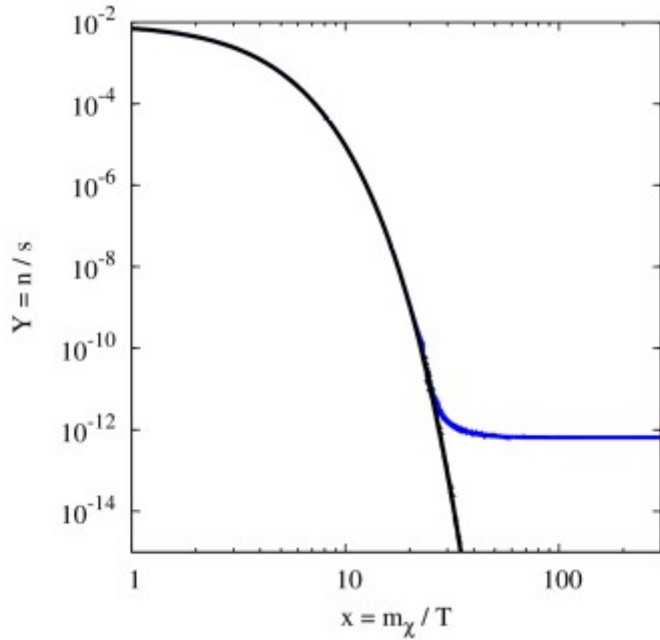
# WIMP Dark Matter



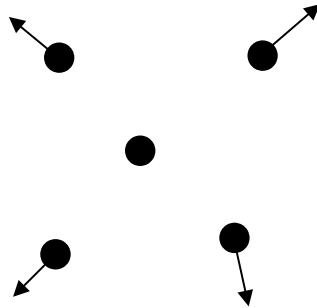
Early Universe:  
DM in full **thermal equilibrium**  
with the Standard Model.



# WIMP Dark Matter



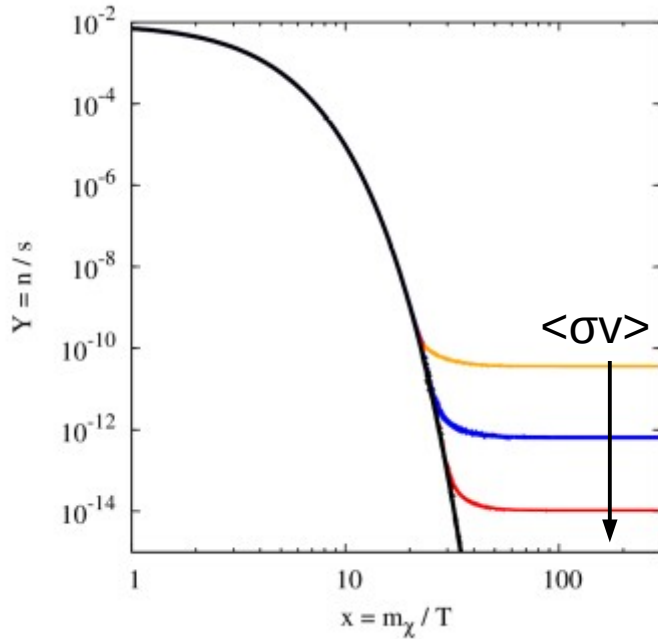
Due to the expansion of the Universe DM particles fall **out of chemical equilibrium** and cannot annihilate anymore.



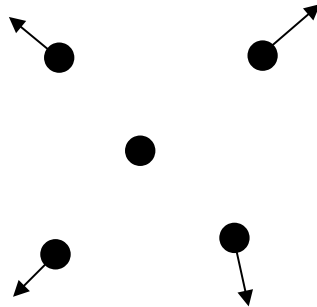
A relic density of DM is obtained which remains constant.



# WIMP Dark Matter



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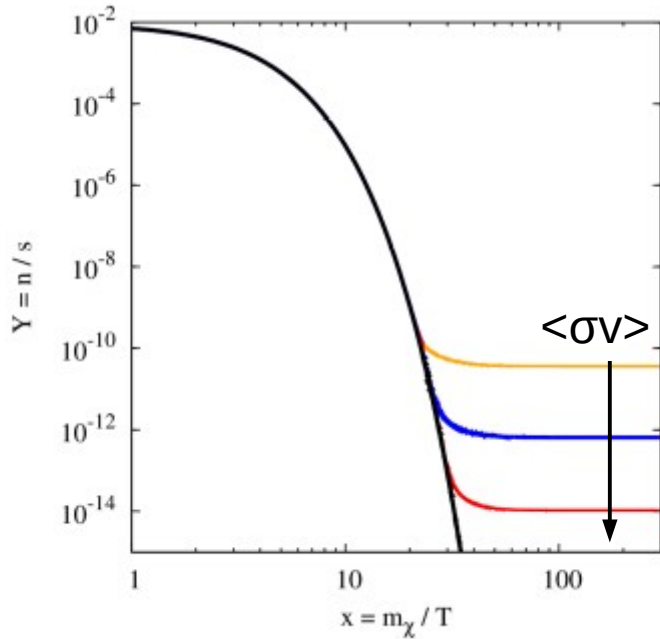


A particle with very weak interactions decouples earlier, having a larger relic density.

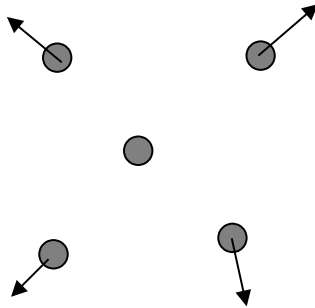
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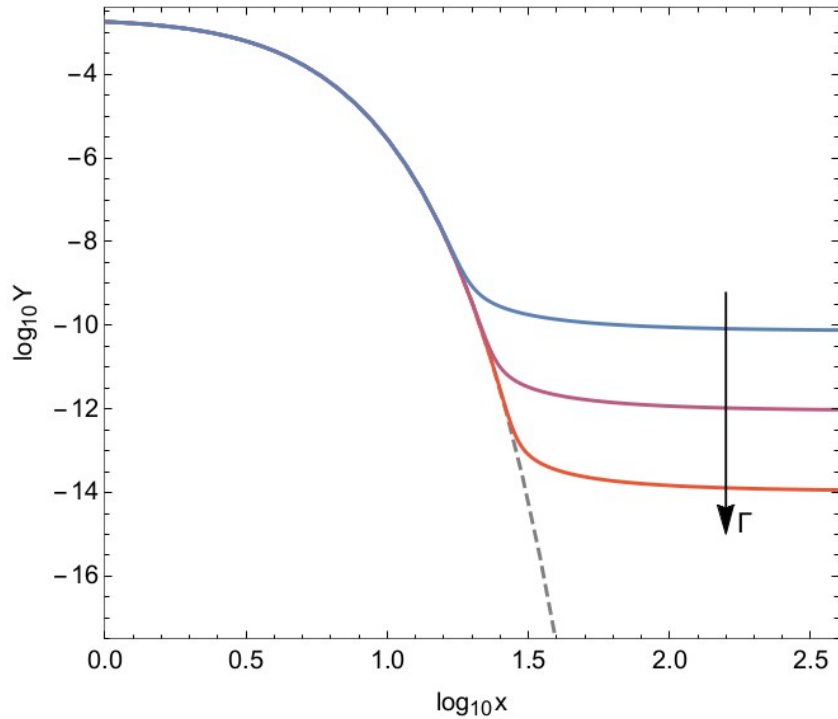


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# WIMP paradigm



$$\frac{dn}{dt} + 3Hn = -\langle\sigma v\rangle (n^2 - n_{\text{eq}}^2)$$

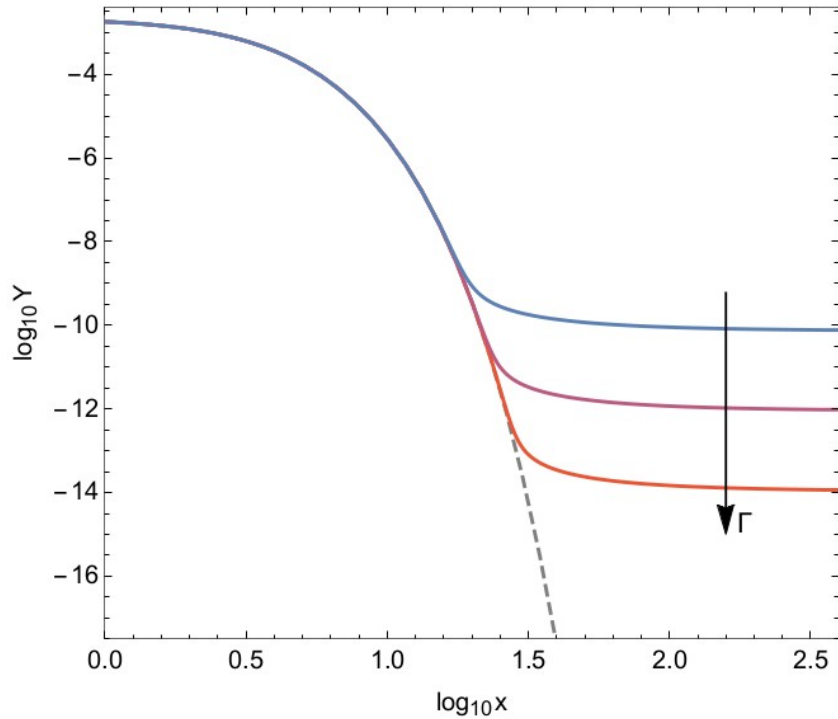
$$Y \equiv n/s \text{ and } x \equiv m/T$$

$$\frac{dY}{dx} = -\frac{\langle\sigma v\rangle s}{Hx} (Y^2 - Y_{\text{eq}}^2)$$

- \* chemical equilibrium
- \*  $\langle\sigma v\rangle \sim \text{few } 10^{-26} \text{ cm}^3/\text{s}$
- \*  $T_{\text{fo}} \sim m / 20$

→ independent on initial conditions

# WIMP paradigm



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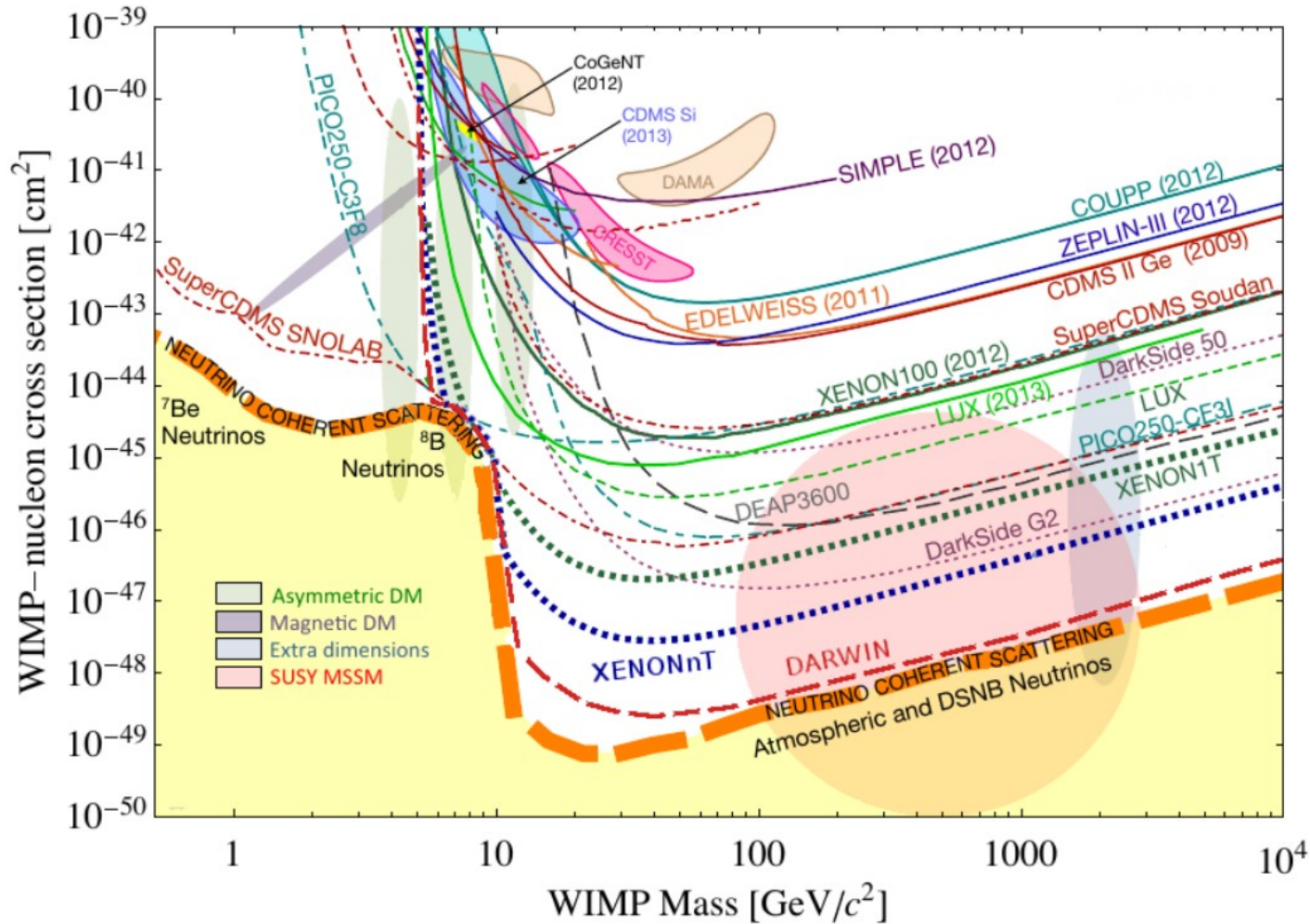
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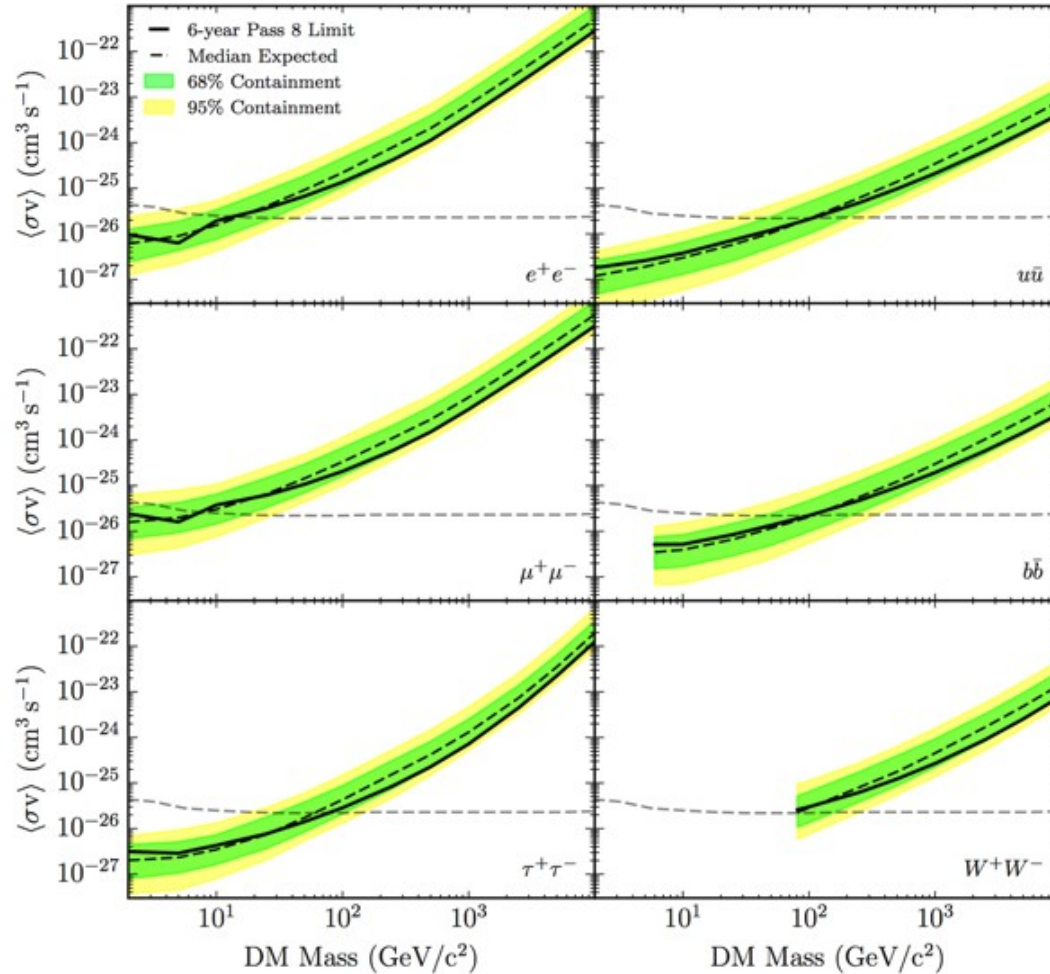
Over the last decades a huge worldwide effort to detect WIMP DM using a multi-channel and multi-messenger approach...

but no compelling detection so far! :-)

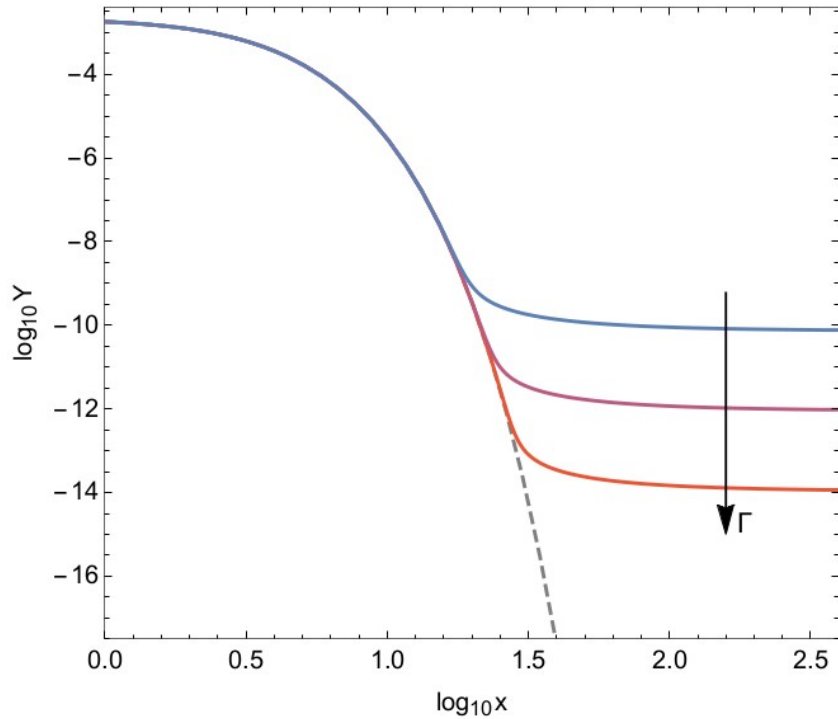
# WIMP Dark Matter under Tension



# WIMP Dark Matter under Tension



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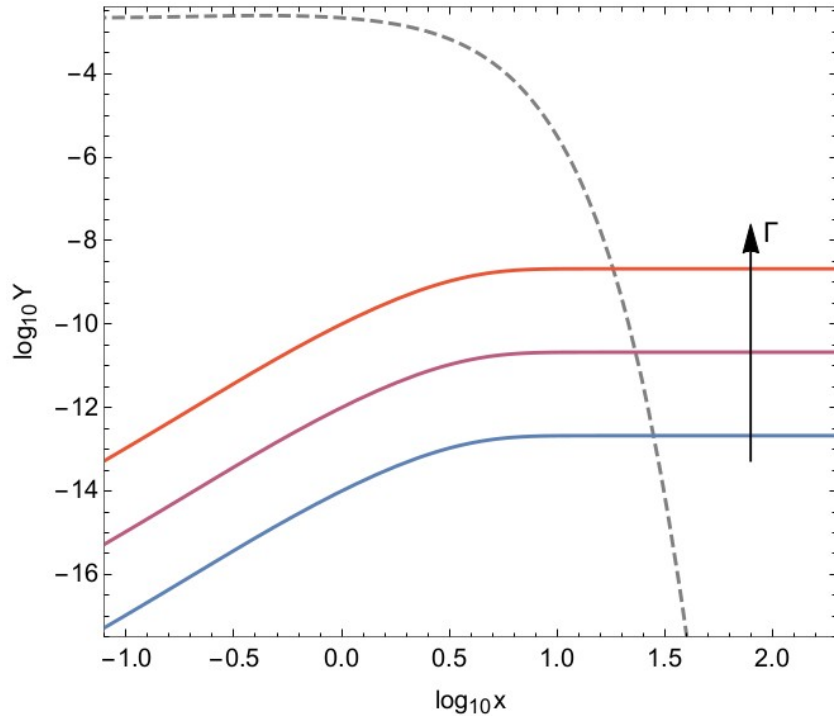
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→ independent on initial conditions

# IR FIMP paradigm



$$\frac{dn}{dt} + 3Hn = -\langle\sigma v\rangle (n - n_{\text{eq}}^2)$$

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

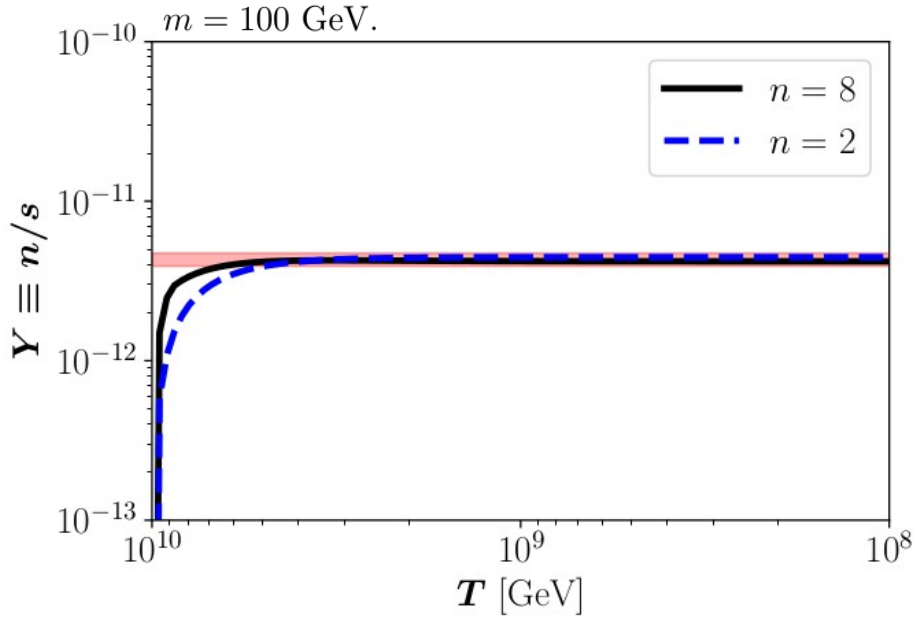
$$\frac{dY}{dx} = -\frac{\langle\sigma v\rangle s}{Hx} (Y - Y_{\text{eq}}^2)$$

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

→ (mild) dependence on initial conditions



# UV FIMP paradigm



$$\frac{dn}{dt} + 3Hn = -\langle\sigma v\rangle (n^2 - n_{\text{eq}}^2)$$

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

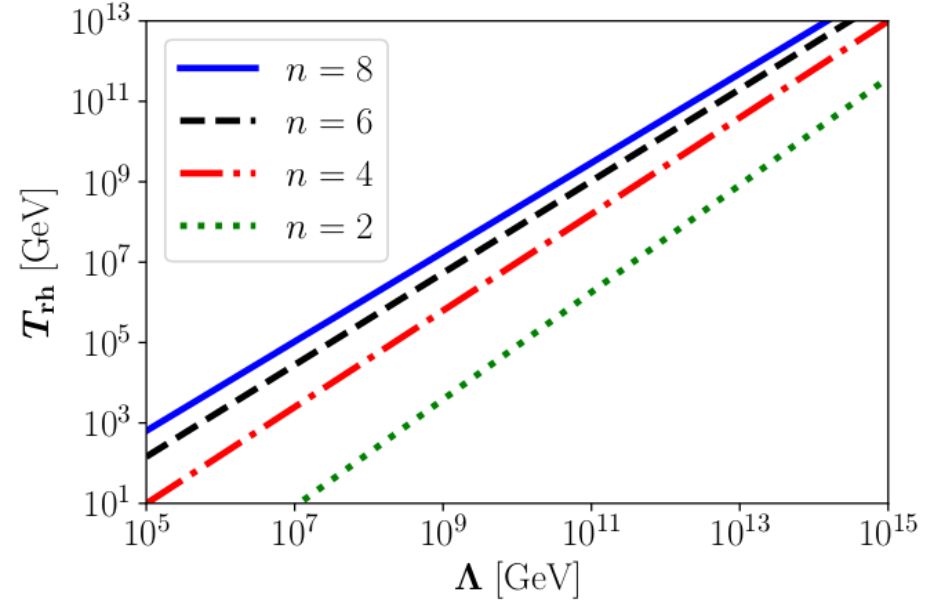
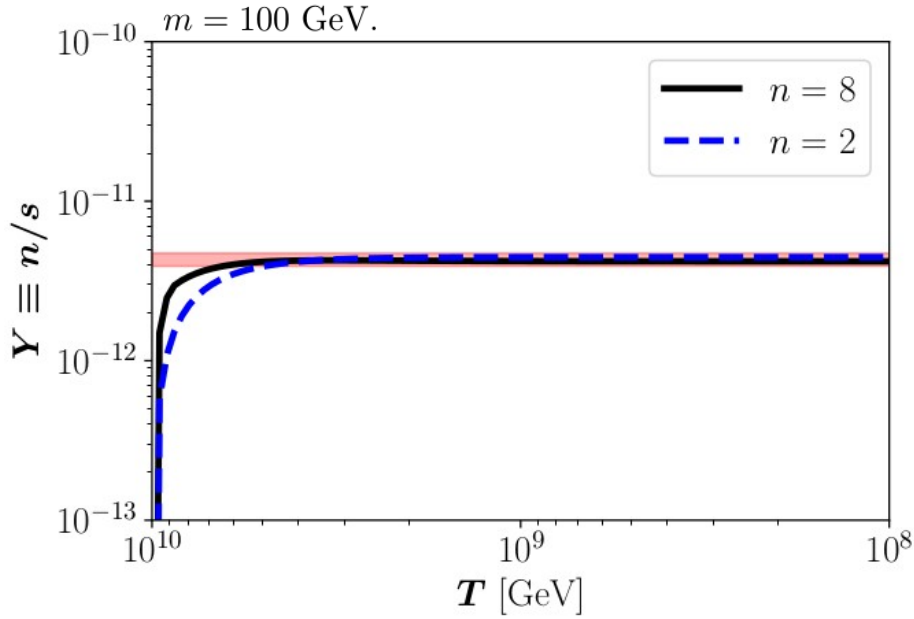
$$\frac{dY}{dx} = -\frac{\langle\sigma v\rangle s}{Hx} (Y^2 - Y_{\text{eq}}^2)$$

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

→ strong dependence on initial conditions

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

# UV FIMP paradigm

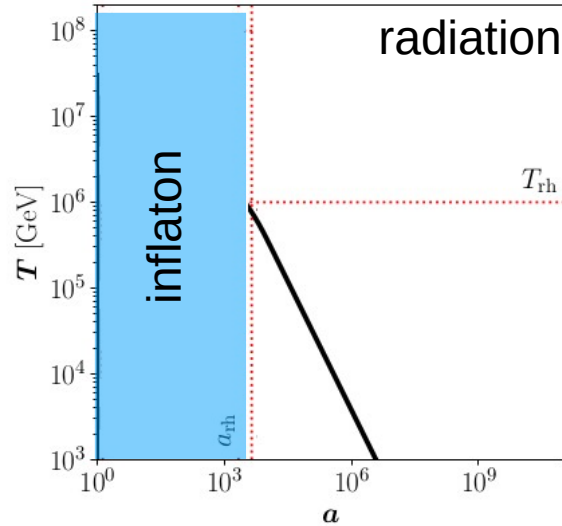


$$\langle \sigma v \rangle = \frac{T^n}{\Lambda^{2+n}}$$

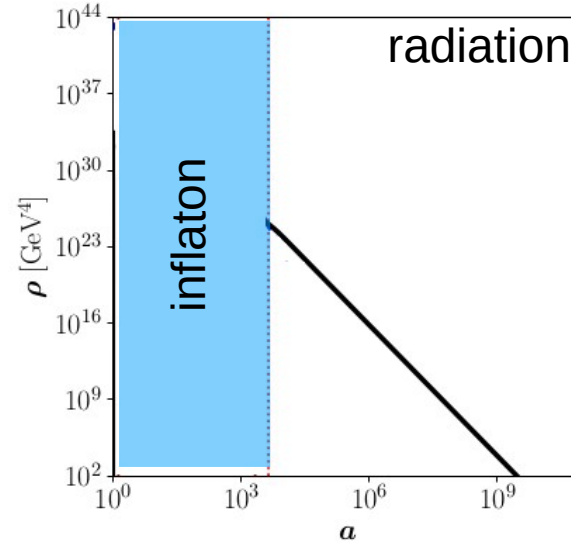
$$Y \sim \int_0^{T_{\text{RH}}} \frac{M_{\text{Pl}} T^n}{\Lambda^{n+2}} \sim \frac{M_{\text{Pl}} T_{\text{RH}}^{n+1}}{\Lambda^{n+2}}$$

# Instantaneous Reheating?

# Instantaneous Reheating approximation



$$T \sim 1/a$$

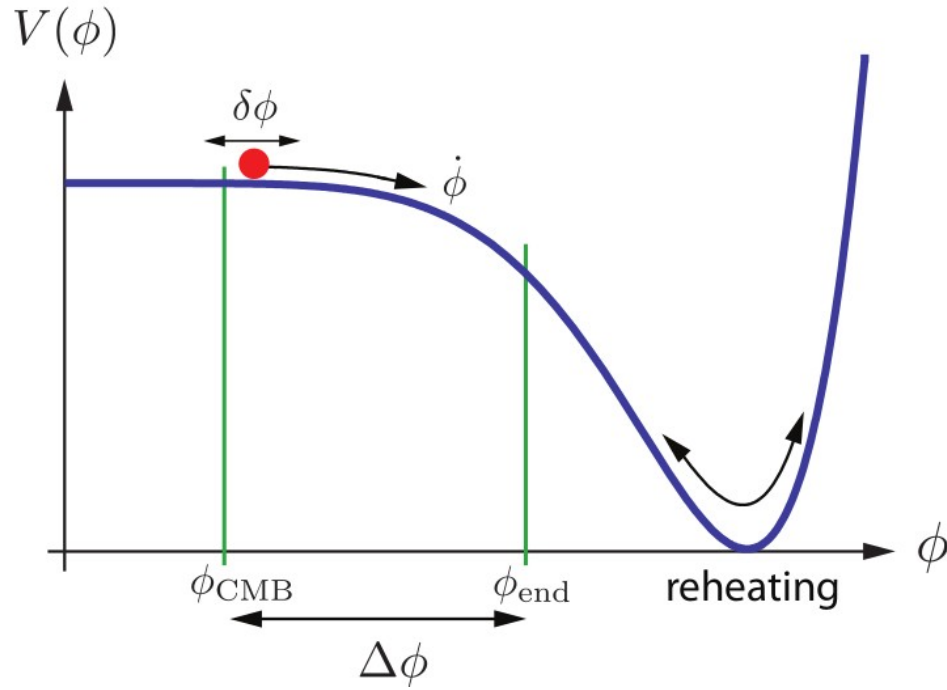


$$\rho \sim T^4 \sim a^{-4}$$

- \* SM entropy conserved
- \*  $H \sim T^2 / M_{\text{p}}$

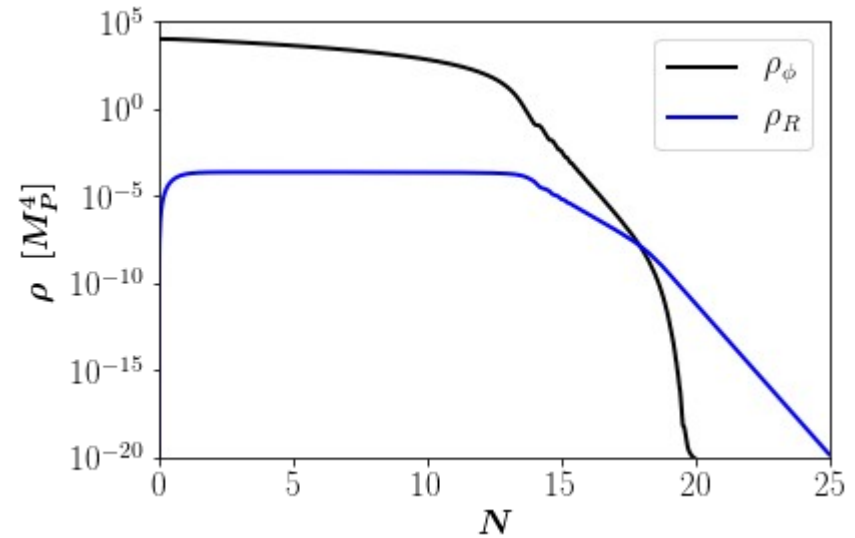
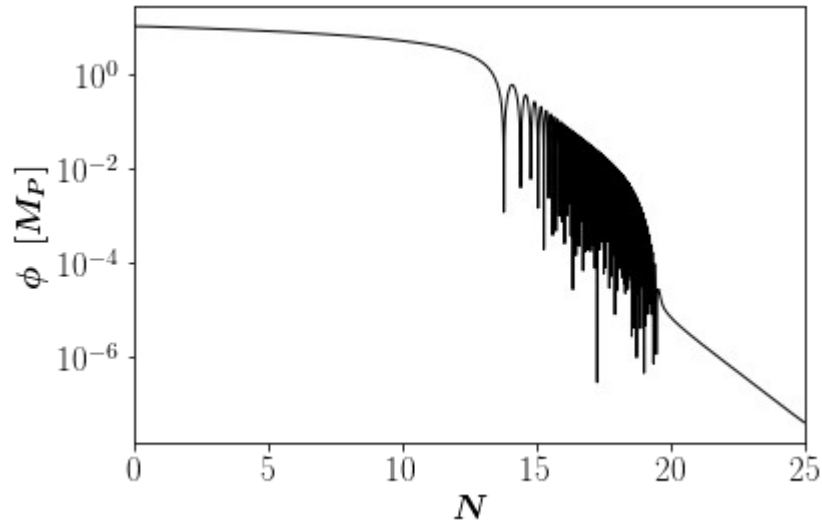
# ***Instantaneous Reheating???***

# Reheating the universe is a *continuous* process



# Equation of state of the inflaton after inflation

# Equation of state of the inflaton



- \* During inflation  $\omega = -1$
- \* After inflation ( $\epsilon > 1$ ), its EoS depends on the shape of the potential where the inflaton oscillates.



# 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:  
 $H_{\text{ini}}$ ,  $\Gamma_\phi$  and  $\omega$

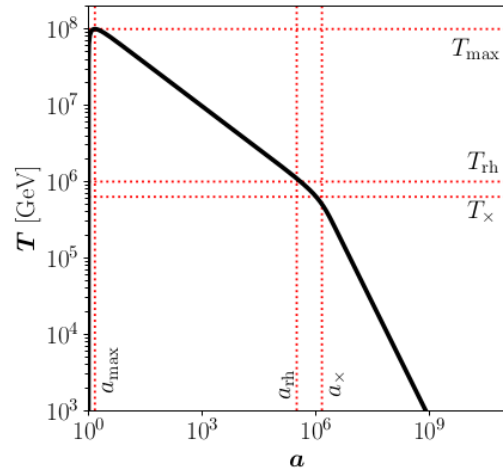
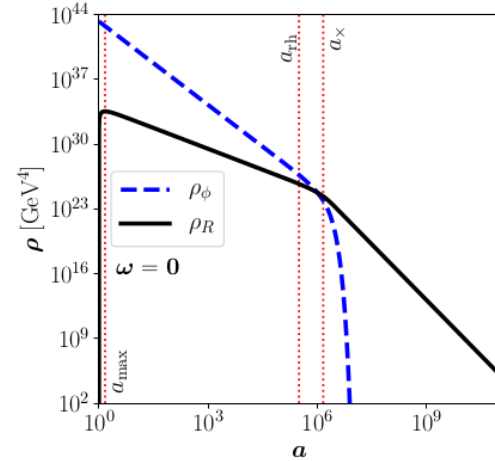
Inflaton decay width

$$\Gamma_\phi = \frac{\pi}{3} \sqrt{\frac{g_*(T_{\text{RH}})}{10}} \frac{T_{\text{RH}}^2}{M_{\text{Pl}}}$$

Hubble expansion rate

$$H^2 = (\rho_\phi + \rho_R)/(3 M_{\text{Pl}}^2)$$

# Non-instantaneous Reheating



$T_{\max}$ : SM thermal bath reaches a  $T \gg T_{\text{rh}}$  due to the non-sudden decay

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

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

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

3 free parameters:

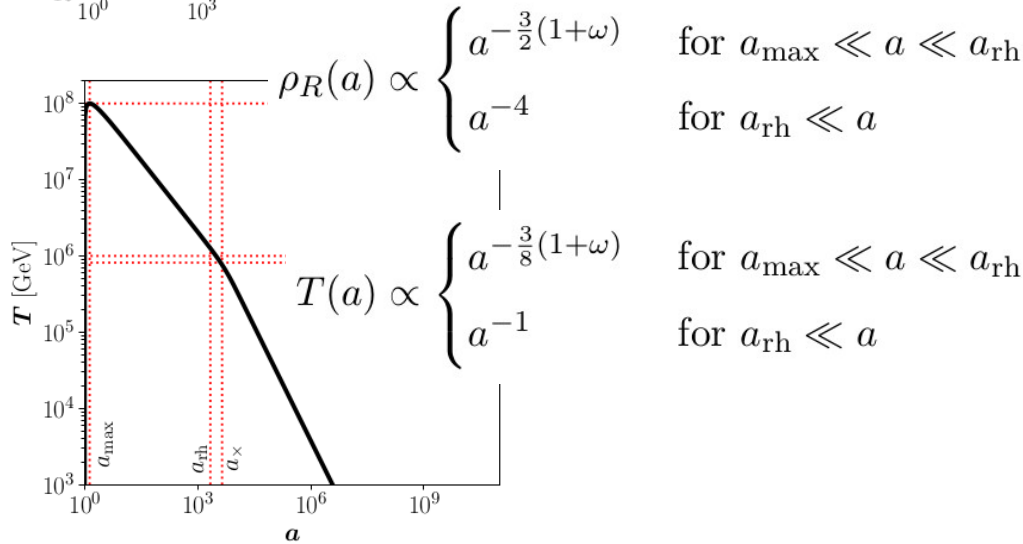
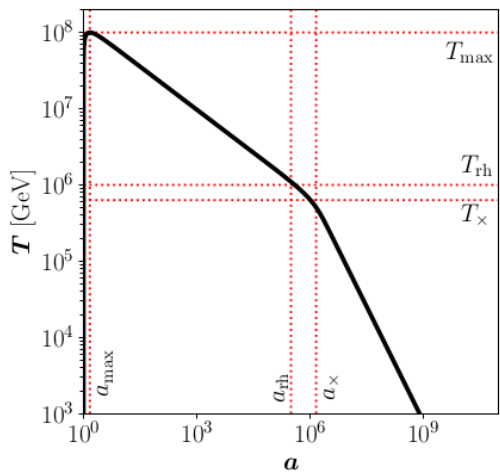
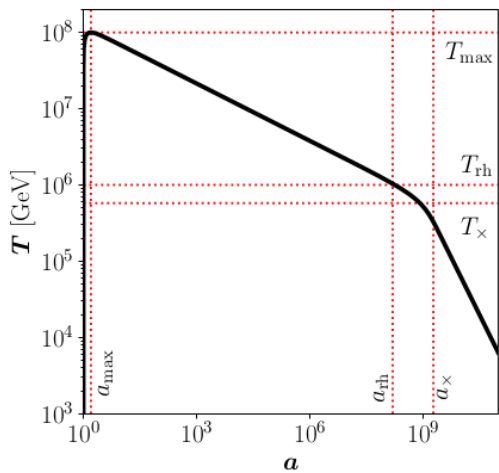
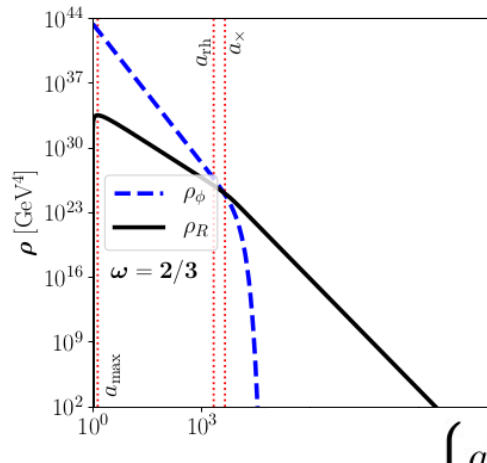
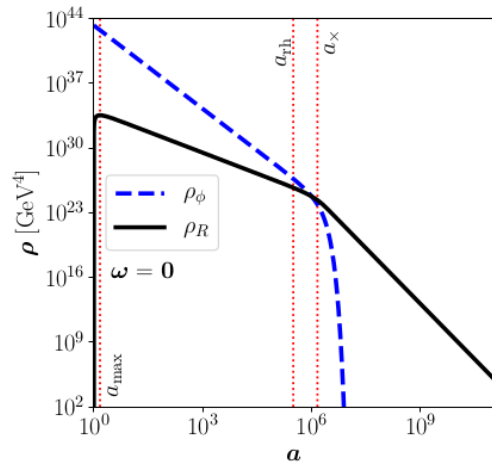
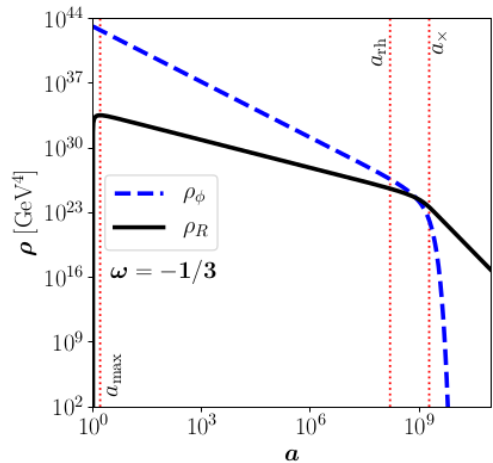
$H_{\text{ini}}$ ,  $\Gamma_{\phi}$  and  $\omega$

or

$T_{\max}$ ,  $T_{\text{rh}}$  and  $\omega$

→ Chung, Kolb & Riotto '98

# Non-instantaneous Reheating



# Ultraviolet Freeze-in

# UV Freeze-in

$$\frac{dn}{dt} + 3Hn = -\langle\sigma v\rangle (n^2 - n_{\text{eq}}^2) \quad \rightarrow \quad \frac{dN}{da} = -\frac{\langle\sigma v\rangle}{a^4 H} (N^2 - N_{\text{eq}}^2)$$

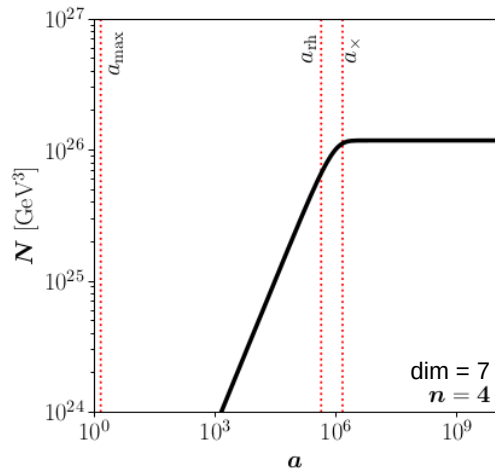
$$\frac{d\rho_\phi}{dt} + 3(1 + \omega)H\rho_\phi = -\Gamma_\phi\rho_\phi$$

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

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

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

# UV Freeze-in



$$m = 100 \text{ GeV}$$

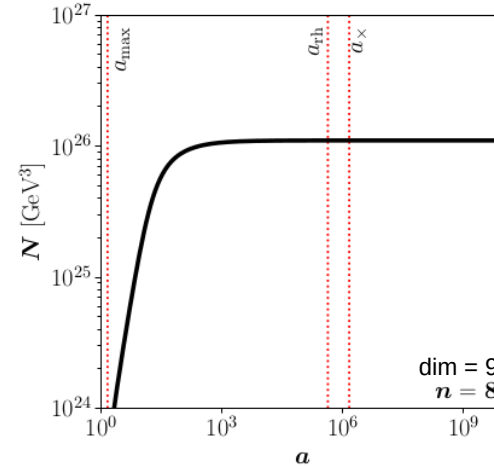
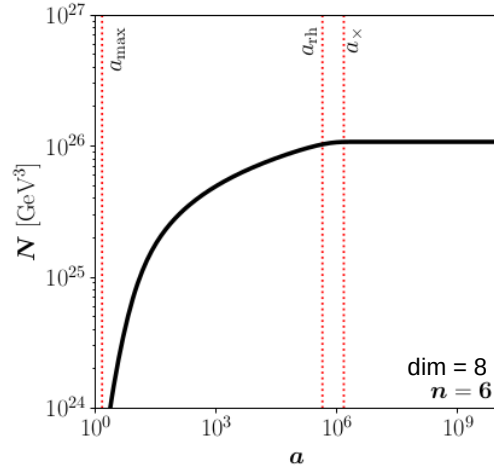
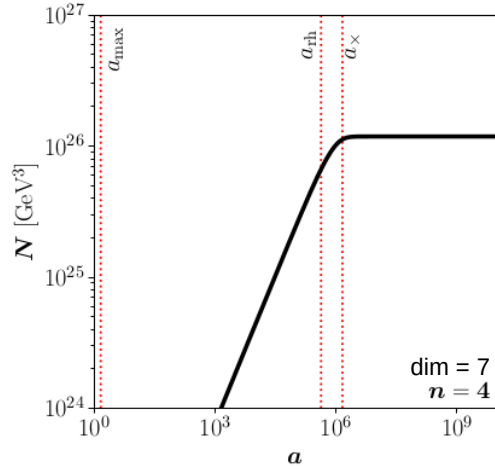
$$T_{\text{max}} = 10^8 \text{ GeV}$$

$$T_{\text{rh}} = 10^6 \text{ GeV}$$

$$\omega = 0$$

DM production:  $T = T_{\text{rh}}$

# UV Freeze-in



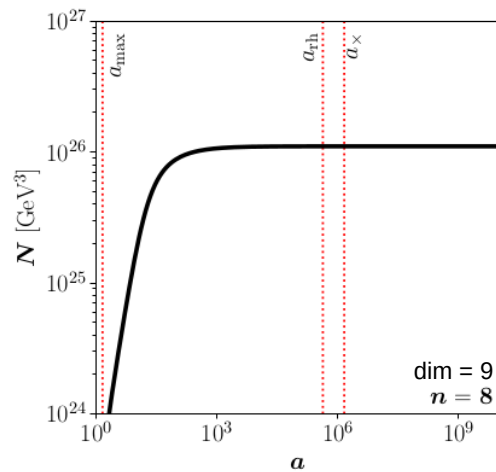
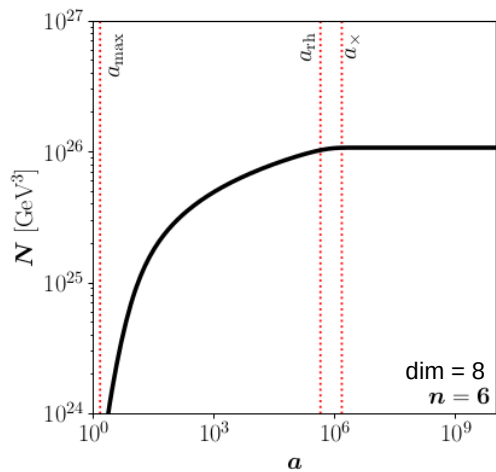
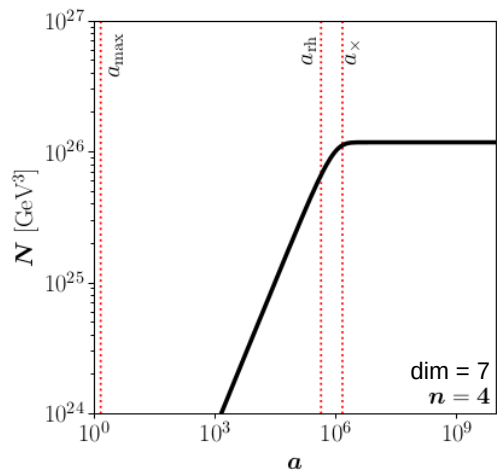
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$T \sim T_{\text{rh}}$

$T \gg T_{\text{rh}}$

# UV Freeze-in

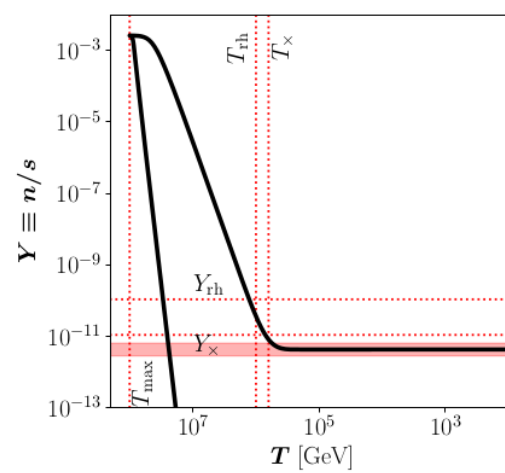
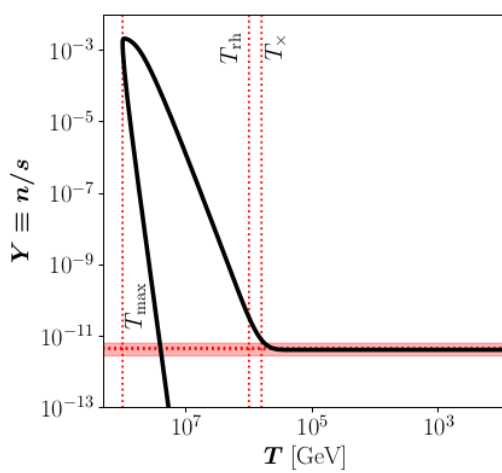
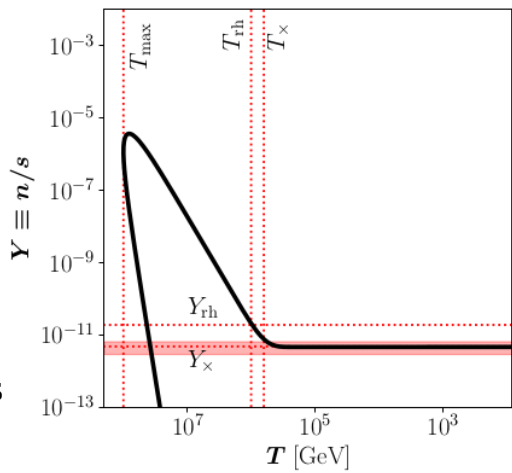


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# UV Freeze-in

$$\frac{dn}{dt} + 3Hn = -\langle\sigma v\rangle (n^2 - n_{\text{eq}}^2)$$

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

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

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

for  $n \neq n_c$ .

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

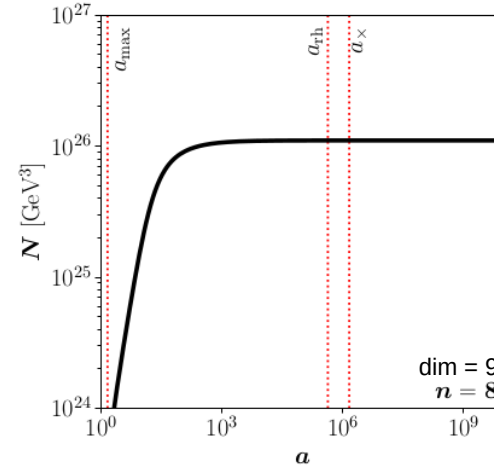
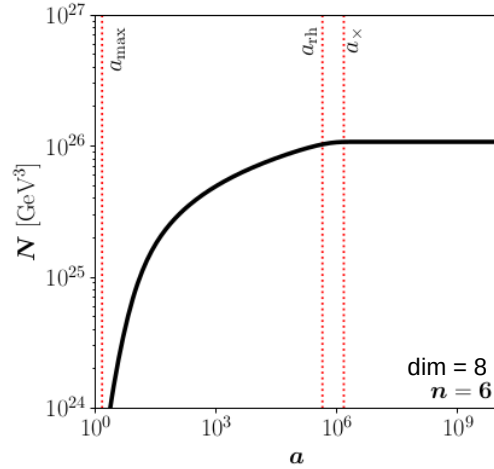
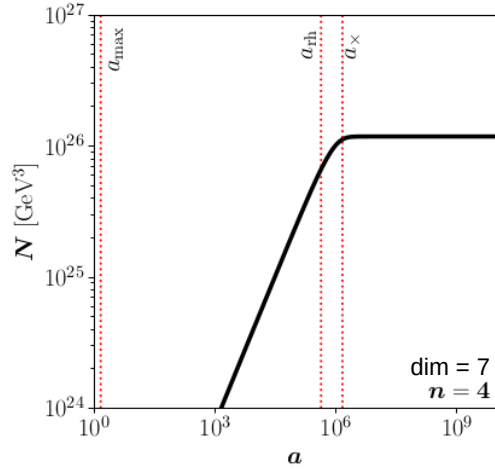
for  $n = n_c$

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

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

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

# UV Freeze-in



$m = 100$  GeV

$T_{\text{max}} = 10^8$  GeV

$T_{\text{rh}} = 10^6$  GeV

$\omega = 0$

$\rightarrow n_c = 6$

DM production:

$$T = T_{\text{rh}}$$

$$n < n_c$$

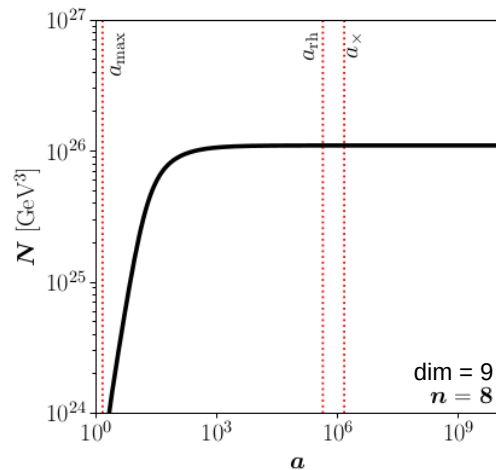
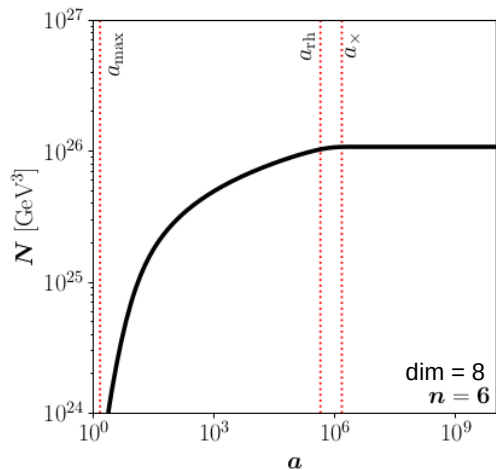
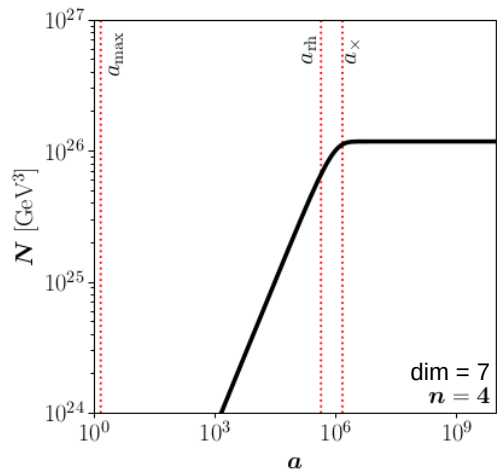
$$T \sim T_{\text{rh}}$$

$$n = n_c$$

$$T \gg T_{\text{rh}}$$

$$n > n_c$$

# UV Freeze-in



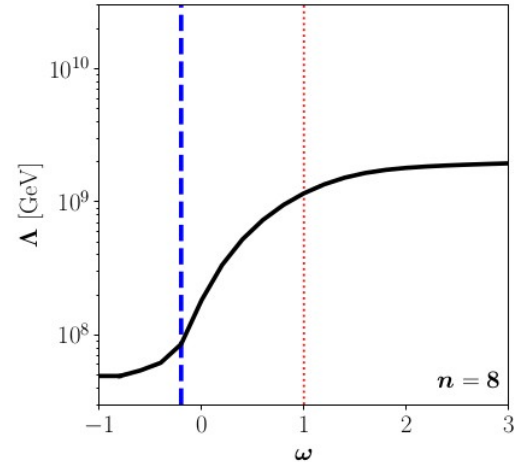
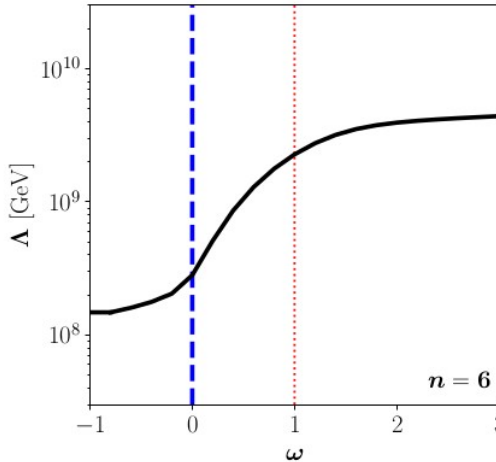
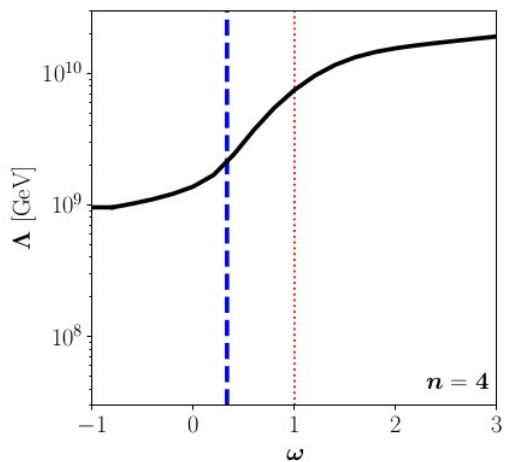
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$\rightarrow n_c = 6$



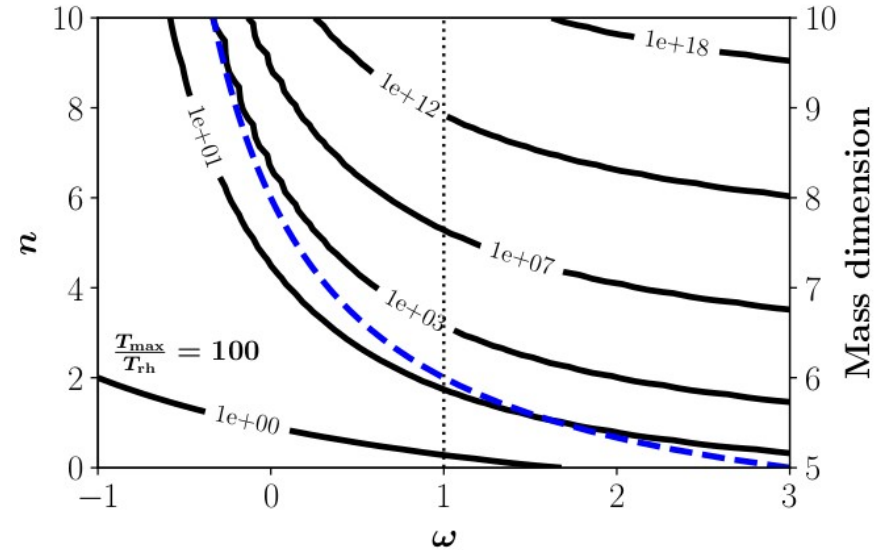
# Boost Factors

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

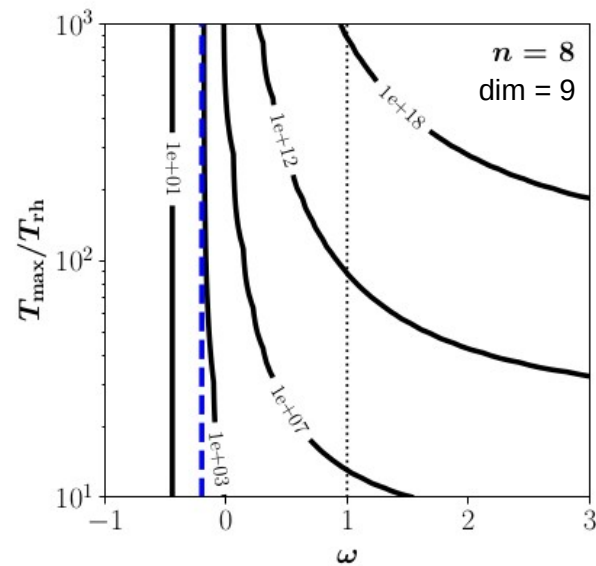
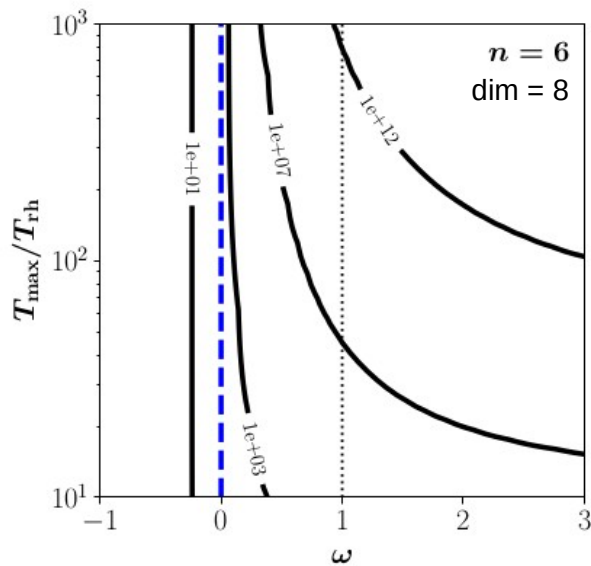
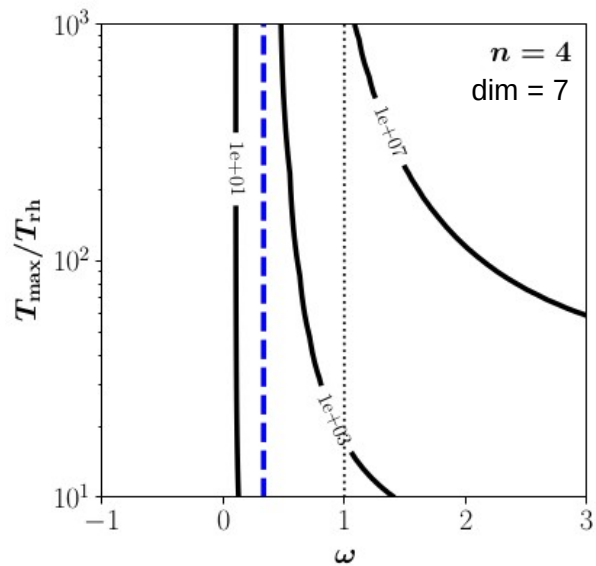
$$n_c \equiv 2 \times \left( \frac{3 - \omega}{1 + \omega} \right)$$

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

\* Independent on  $m$ ,  $\Lambda$



# Boost Factors



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

# Example: Spin-2 Portal DM

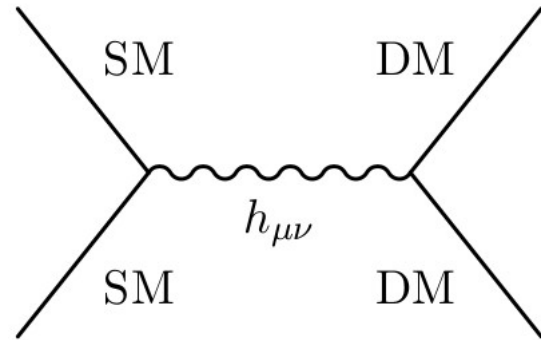
# Spin-2 Portal DM

DM interacts with the SM via the spin-2 portal

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DM}} + \mathcal{L}_{\text{EH}} + \mathcal{L}_{\tilde{h}} + \mathcal{L}_{\text{int}}^1 + \mathcal{L}_{\text{int}}^2$$

$$\mathcal{L}_{\text{int}}^1 = \frac{1}{2M_P} h_{\mu\nu} (T_{\text{SM}}^{\mu\nu} + T_{\text{X}}^{\mu\nu})$$

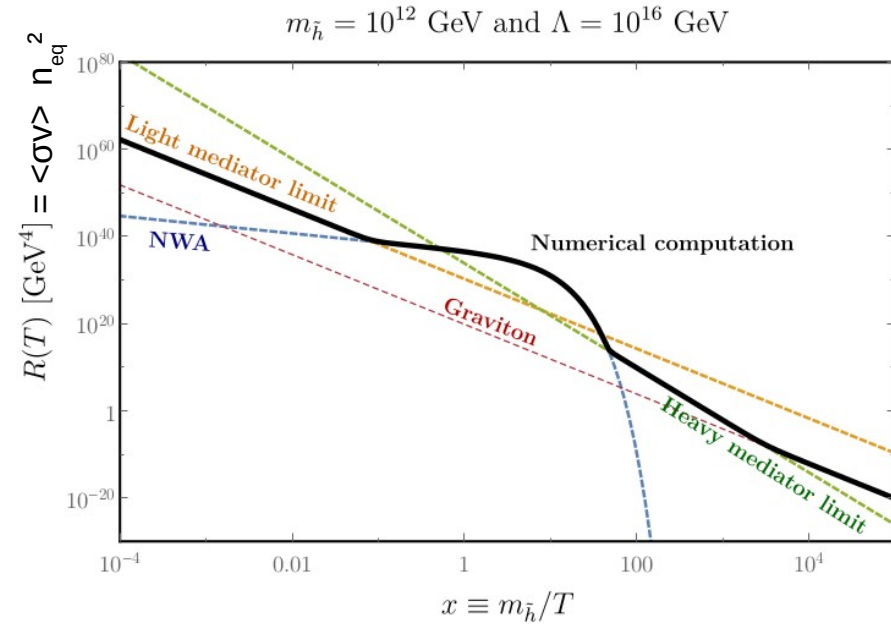
$$\mathcal{L}_{\text{int}}^2 = \frac{1}{\Lambda} \tilde{h}_{\mu\nu} (g_{\text{SM}} T_{\text{SM}}^{\mu\nu} + g_{\text{DM}} T_{\text{X}}^{\mu\nu})$$



# Spin-2 Portal DM

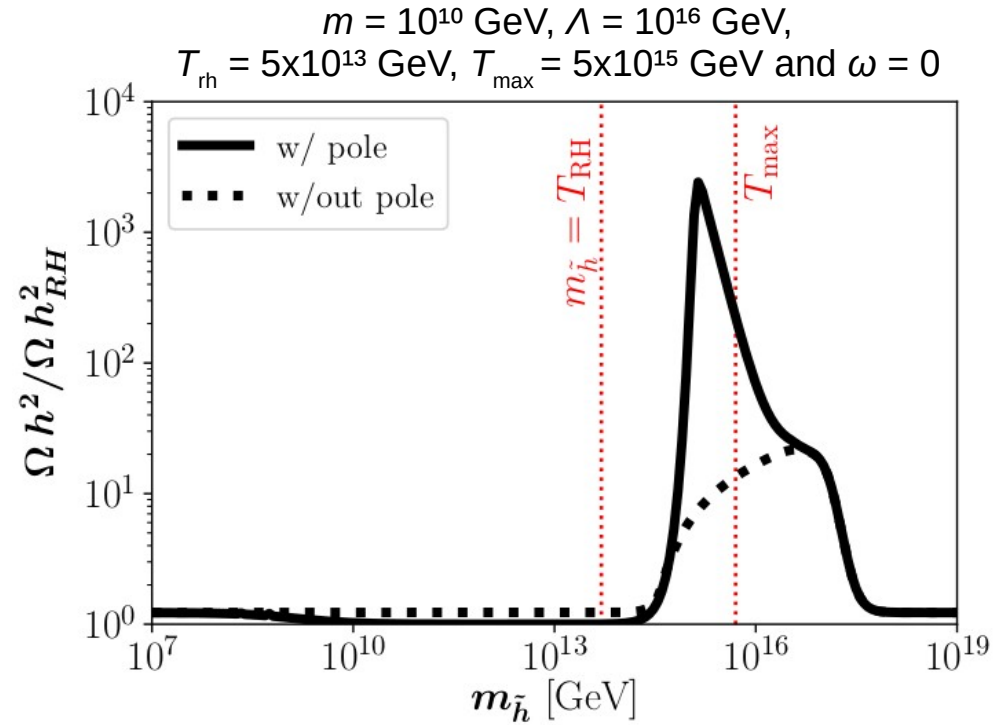
DM interacts with the SM via the spin-2 portal

- \* Super heavy regime (decoupling)  $\langle\sigma v\rangle \sim \frac{T^2}{M_P^4}$
- \* Heavy mediator  $\langle\sigma v\rangle \sim \frac{T^6}{\Lambda^4 m_{\tilde{h}}^4}$
- \* Resonance  $\langle\sigma v\rangle \sim \frac{m_{\tilde{h}}^3}{\Lambda^4 \Gamma_{\tilde{h}}} \frac{T}{m_{\tilde{h}}} K_1\left(\frac{m_{\tilde{h}}}{T}\right)$
- \* Light mediator  $\langle\sigma v\rangle \sim \frac{T^2}{\Lambda^4}$

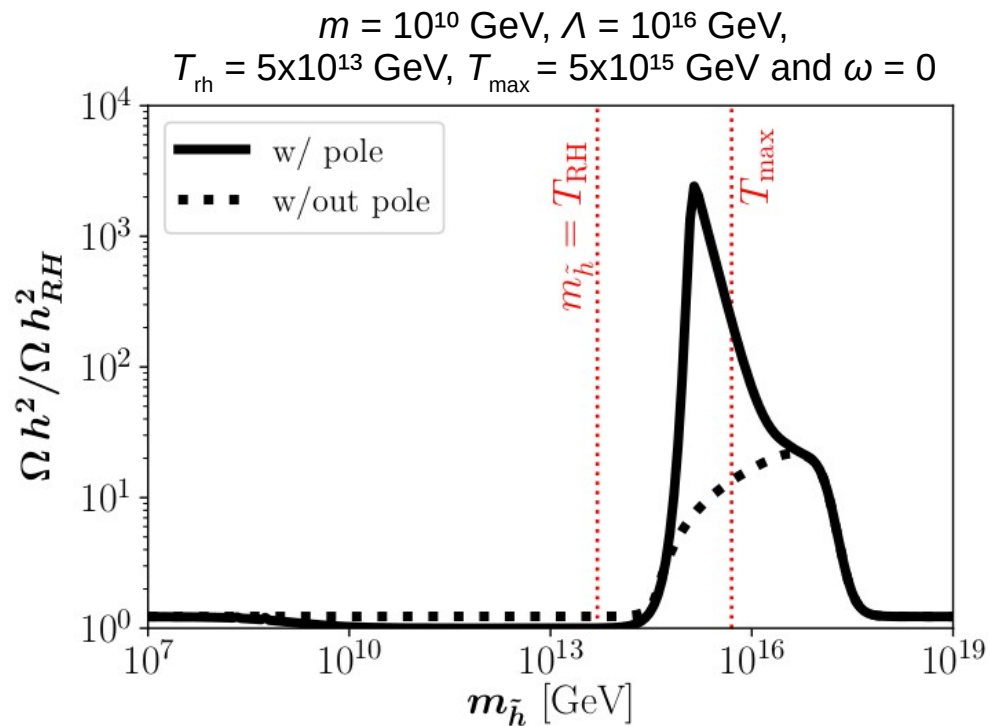
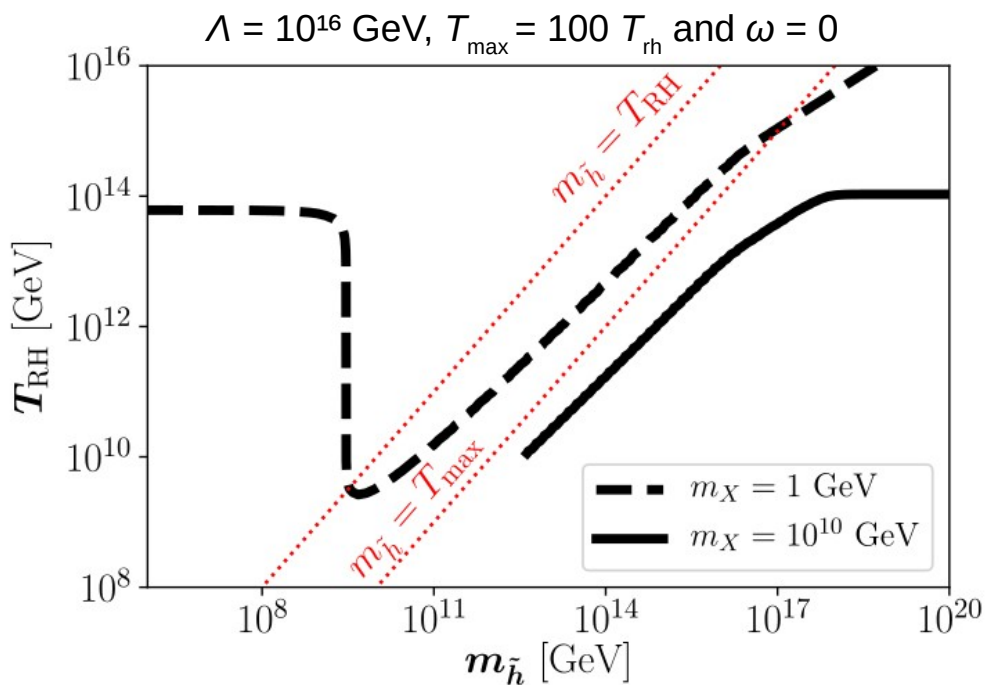




# Boost Factor



# Boost Factor



# Conclusions

- UV freeze-in is a viable DM production mechanism
- Strongly depends on the dynamics near  $T_{\text{rh}}$
- Instantaneous reheating may not be a good approximation
  - miserably fails for  $n > n_c$
- For  $n > n_c$ : Bulk of DM produced near  $T_{\text{max}}$  and not  $T_{\text{rh}}$ !
- Big boost factors due to the non-sudden reheating
  - depends on the equation of state of the early universe
  - i.e. on the *inflaton potential* during reheating!
- DM can be produced via the spin-2 portal
- Big boost factors when interaction rates are very suppressed:
  - heavy mediator
  - near the resonance

**Muchas  
gracias, ve!**

**#ElParoNoPara  
#FueraDuque**

Nicolás BERNAL @ UAN

