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:1908.soon

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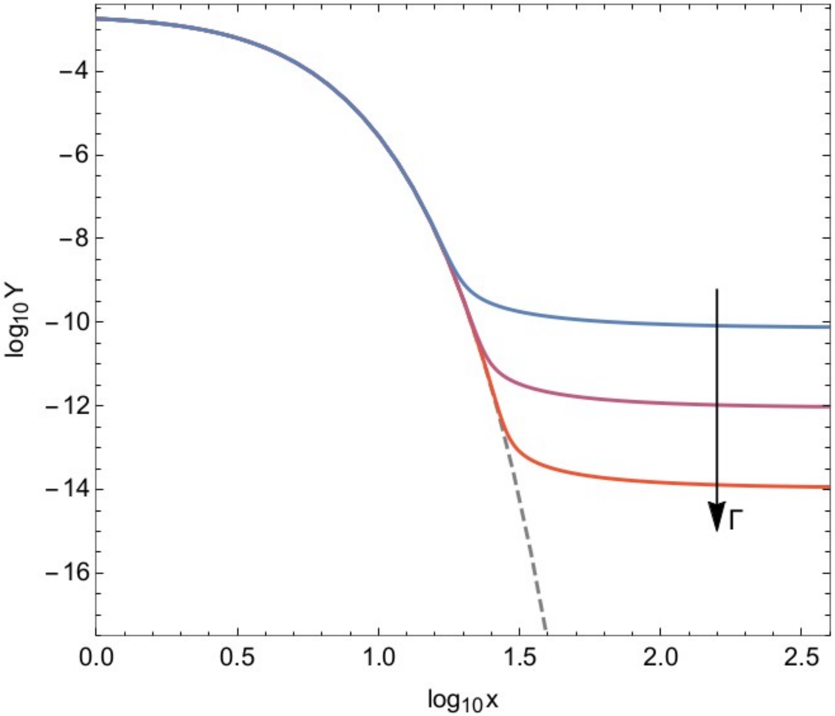
UNIVERSIDAD ANTONIO NARIÑO

Light Dark World 2019
August 12th, 2019

WIMP paradigm



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

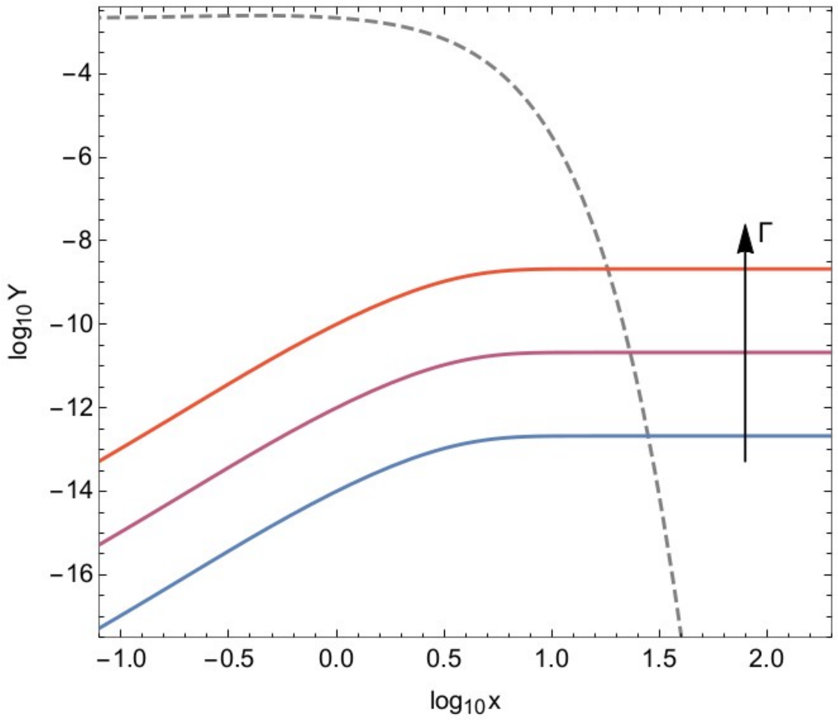
$$Y \equiv n/s \text{ and } x \equiv m/T$$

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

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

→ independent on initial conditions

IR FIMP paradigm



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

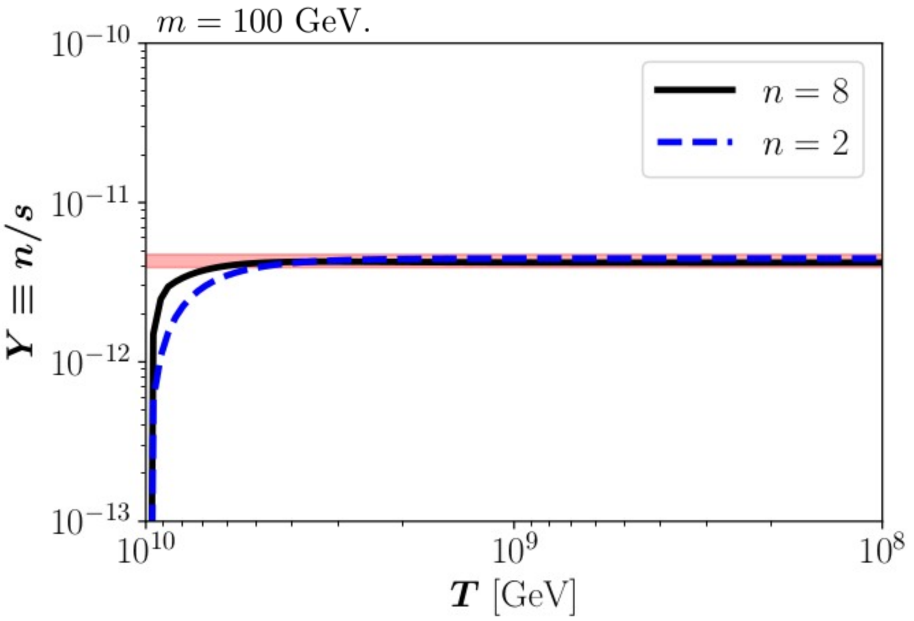
$$Y \equiv n/s \text{ and } x \equiv m/T$$

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

* 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



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

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

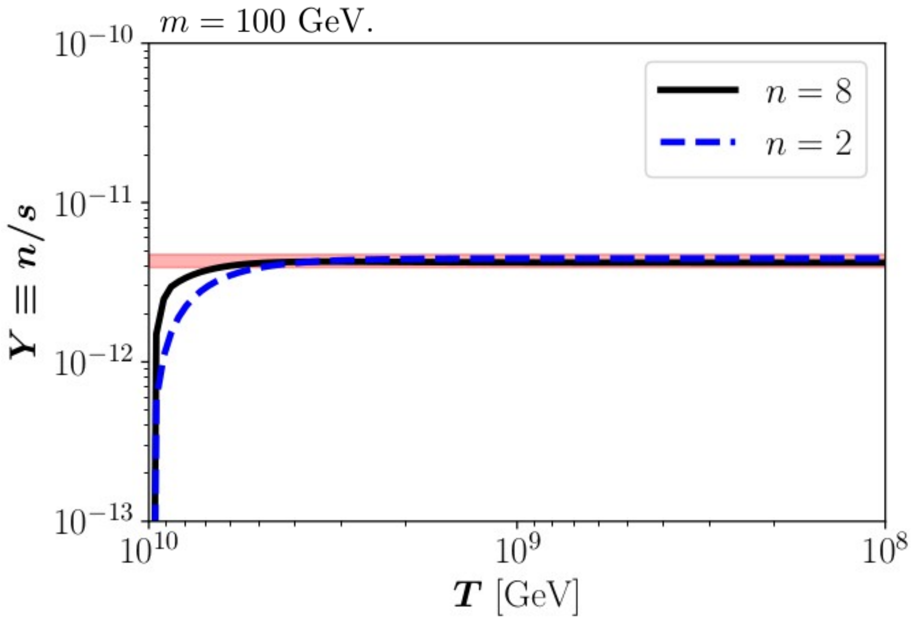
$$\frac{dY}{dx} = -\frac{\langle\sigma v\rangle\,s}{H\,x}\,\left(\cancel{Y}^2 - Y_{\rm eq}^2\right)$$

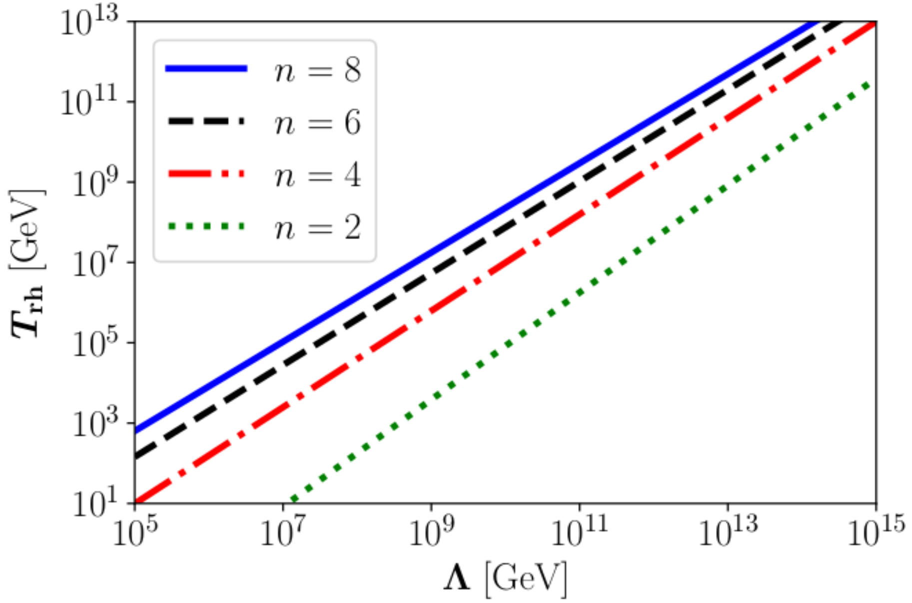
$$\langle\sigma v\rangle = \frac{T^n}{\Lambda^{2+n}}$$

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

→ dependent on initial conditions ← **Tommi**

UV FIMP paradigm

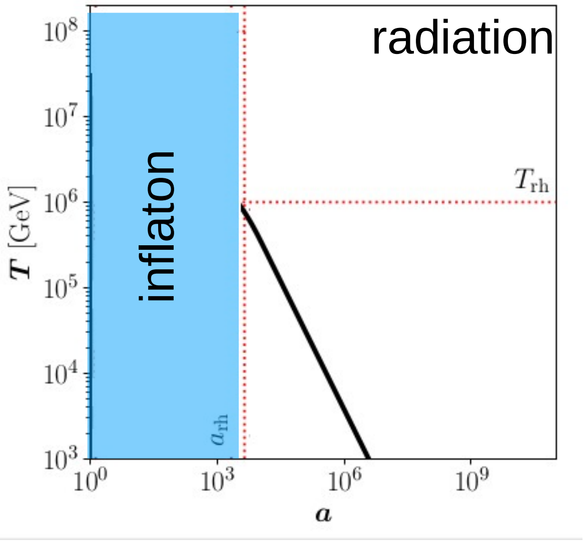


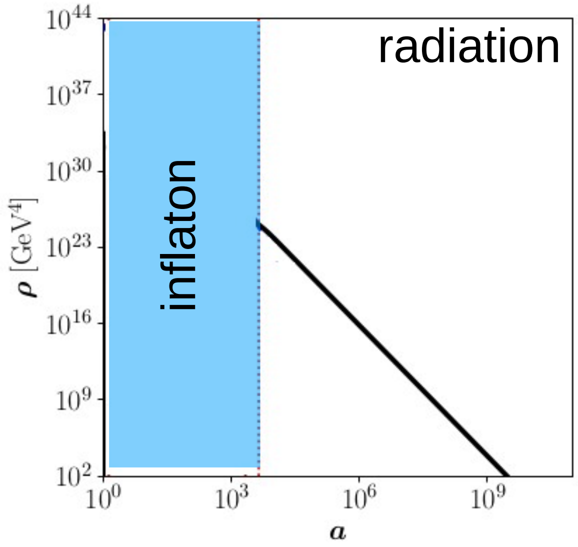


$$\langle \sigma v \rangle = \frac{T^n}{\Lambda^{2+n}}$$

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

Instantaneous Reheating





$T \sim 1/a$

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

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

Non-instantaneous Reheating

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

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

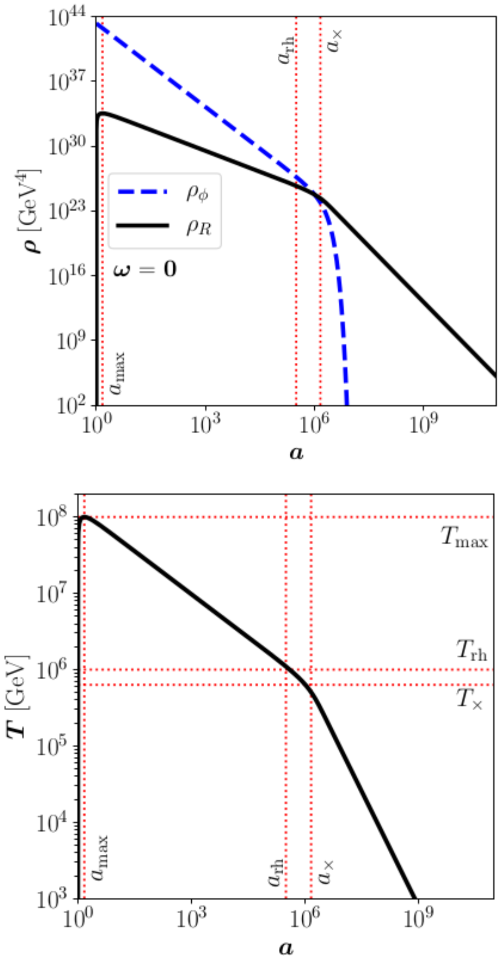
$$\frac{d\rho_R}{dt} + 4\, H\, \rho_R = +\Gamma_\phi\, \rho_\phi$$

3 free parameters:
$\boldsymbol{H_{\text{ini}}}$, $\boldsymbol{\Gamma_\phi}$ 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



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

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

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

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

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

→ Chung, Kolb & Riotto ‘98

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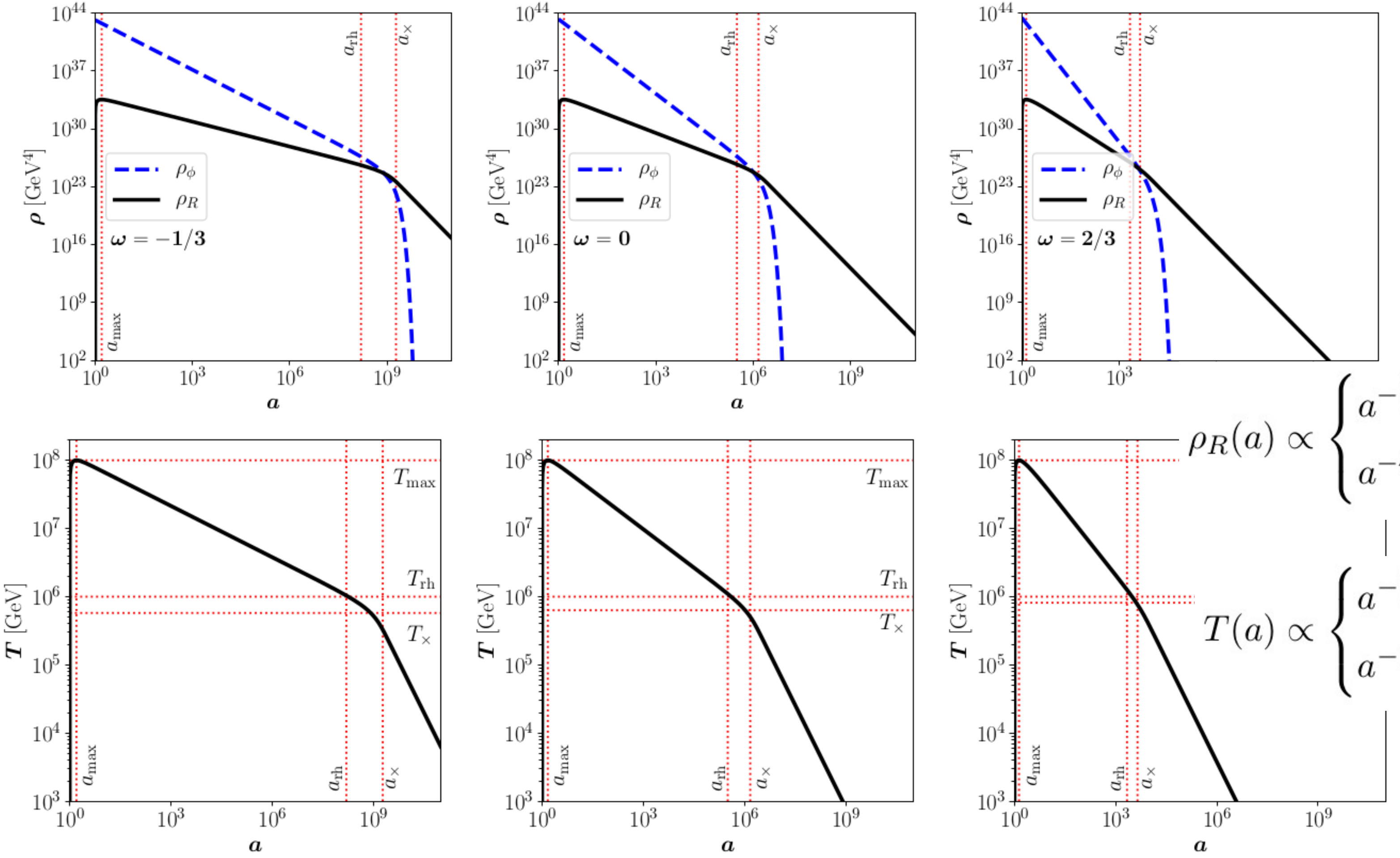
Non-instantaneous Reheating



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

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UV Freeze-in

$$\frac{dn}{dt} + 3\,H\,n = -\langle\sigma v\rangle\,\left(n^2 - n_{\rm eq}^2\right) \qquad \rightarrow \qquad \frac{dN}{da} = -\frac{\langle\sigma v\rangle}{a^4\,H}\,\left(N^2 - N_{\rm eq}^2\right)$$

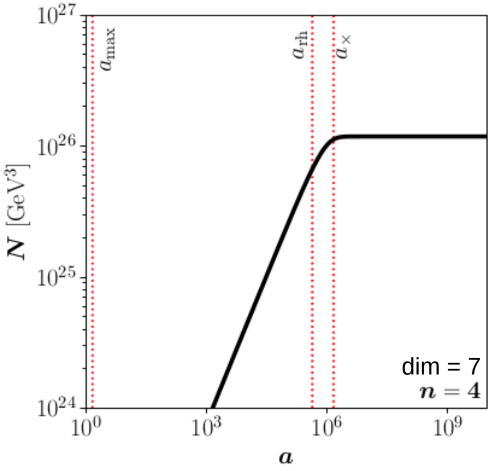
$$\frac{d\rho_\phi}{dt} + 3(1+\omega)\,H\,\rho_\phi = -\Gamma_\phi\,\rho_\phi$$

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

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

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

UV Freeze-in

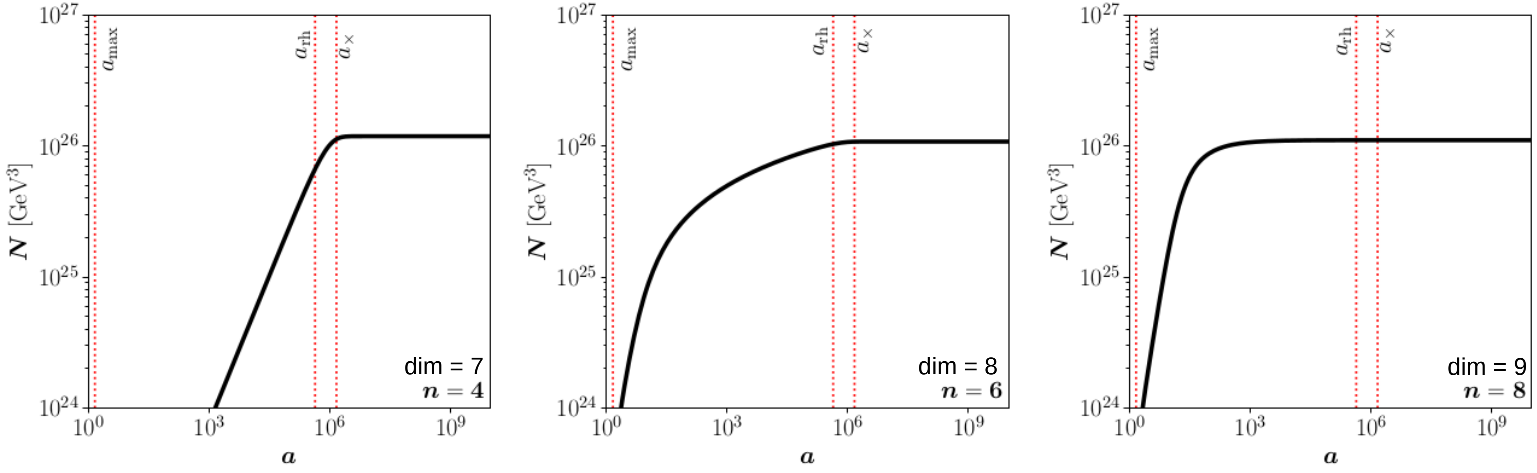


m = 100 GeV

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

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

UV Freeze-in

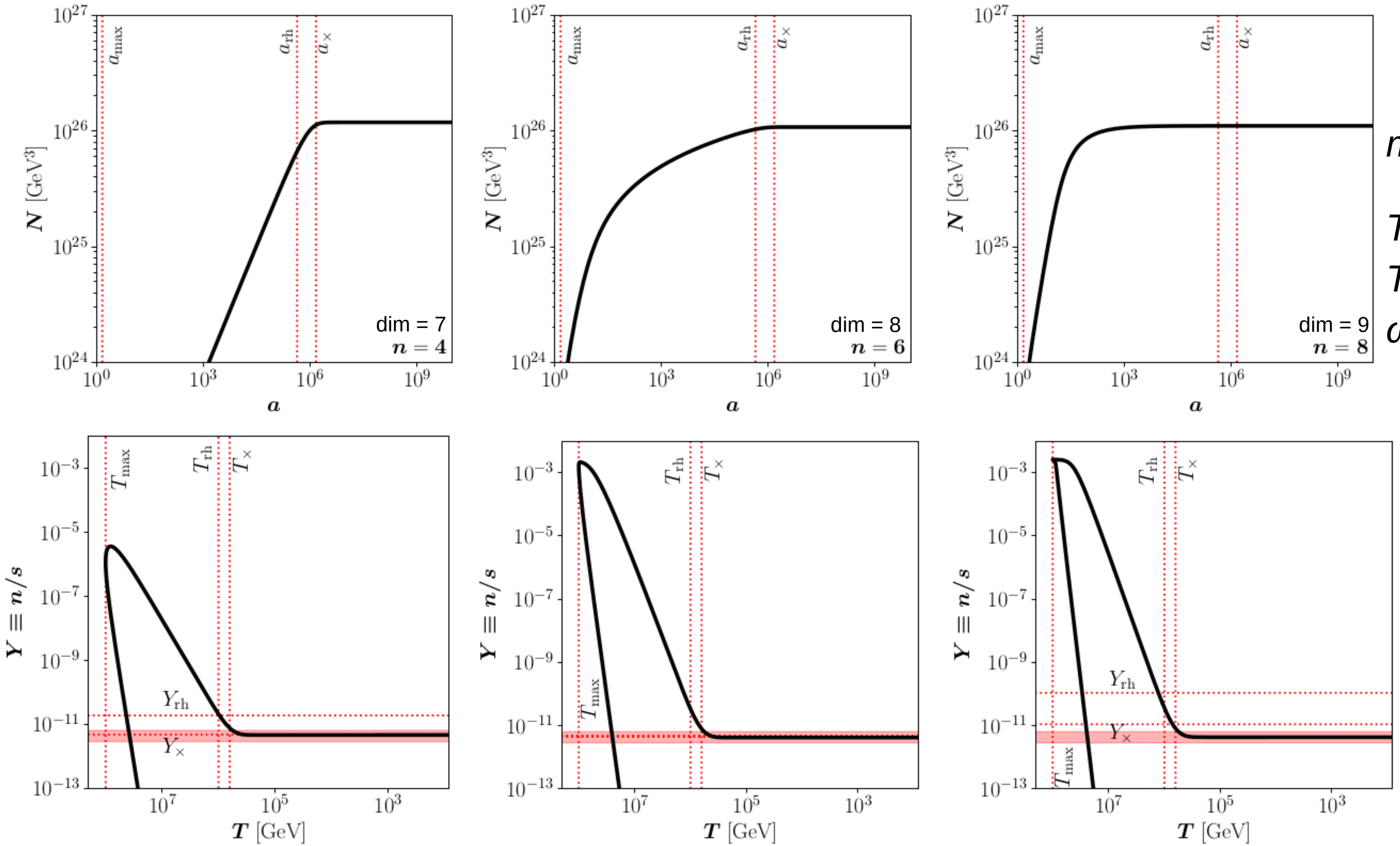


m = 100 GeV

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

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

UV Freeze-in



m = 100 GeV

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UV Freeze-in

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

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

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

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

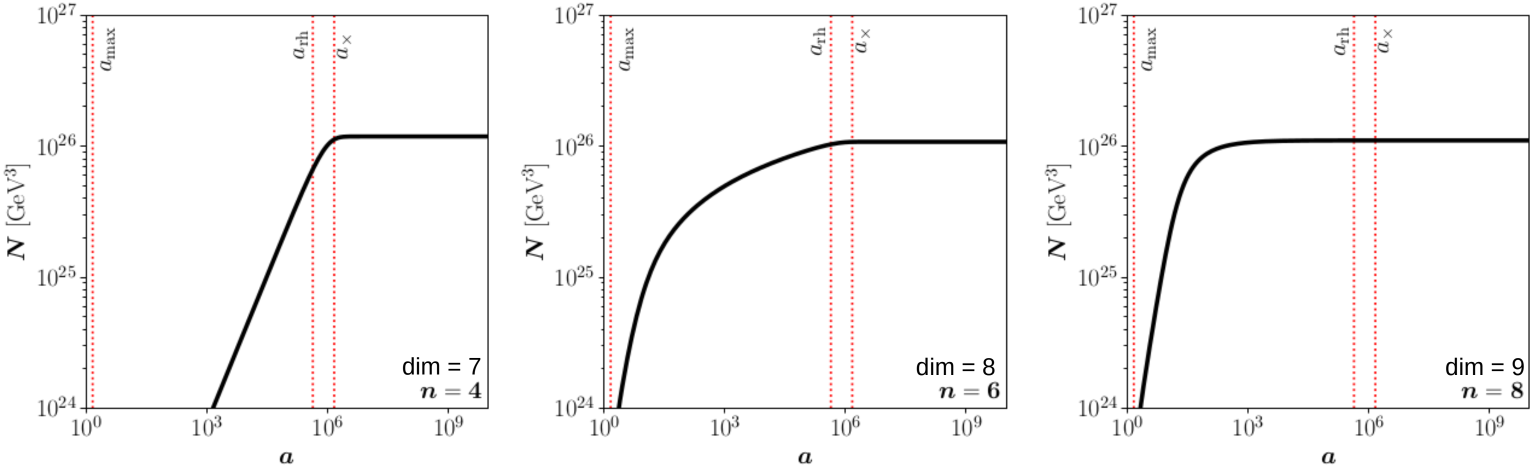
$$Y_\infty = \frac{45\,\zeta(3)^2\,(n+2)\,g^2}{2\pi^7\,g_{\star s}}\sqrt{\frac{10}{g_\star}}\,\frac{M_{\rm Pl}\,T_{\rm rh}^{1+n}}{\Lambda^{2+n}}\,\ln\frac{T_{\rm max}}{T_{\rm rh}} \quad \text{for } n = n_c$$

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

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

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

UV Freeze-in



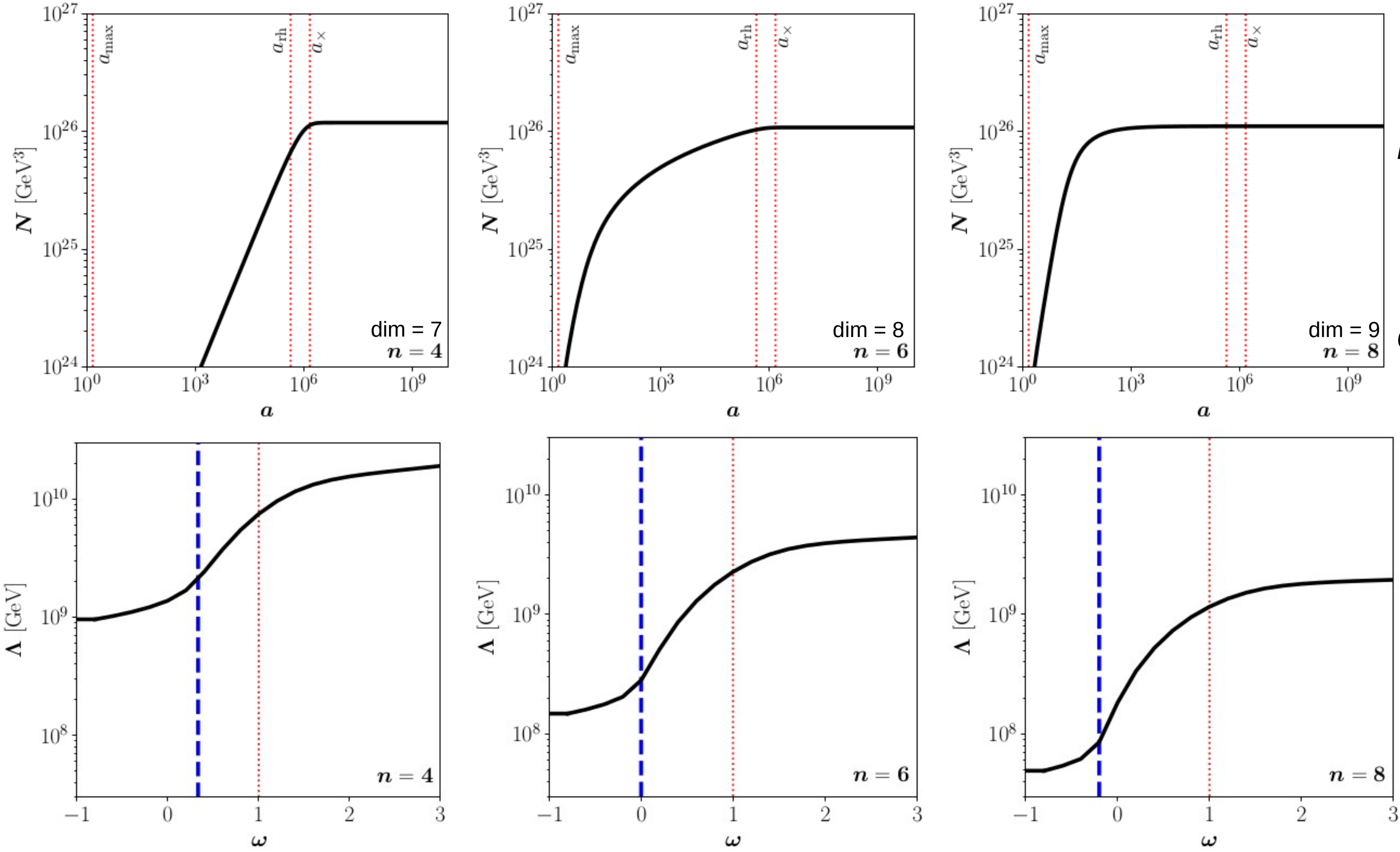
m = 100 GeV

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

DM production:

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

UV Freeze-in



m = 100 GeV

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

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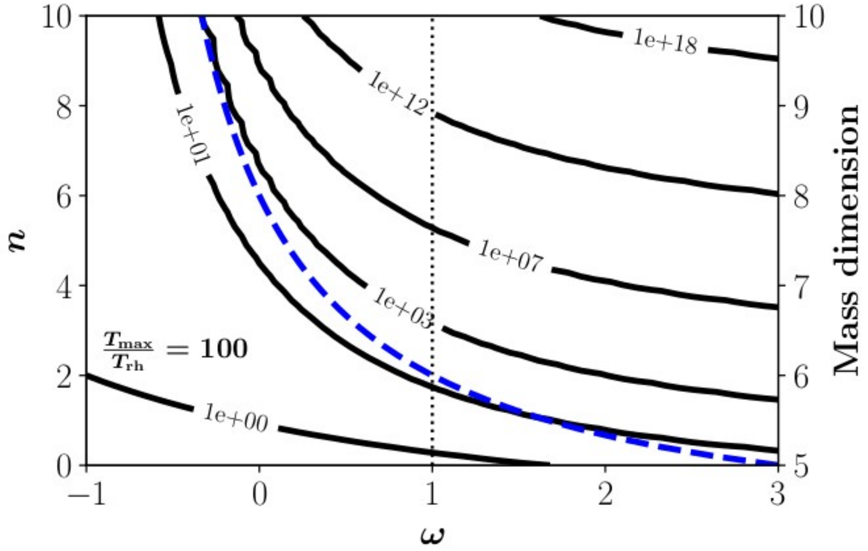
Boost Factors

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

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

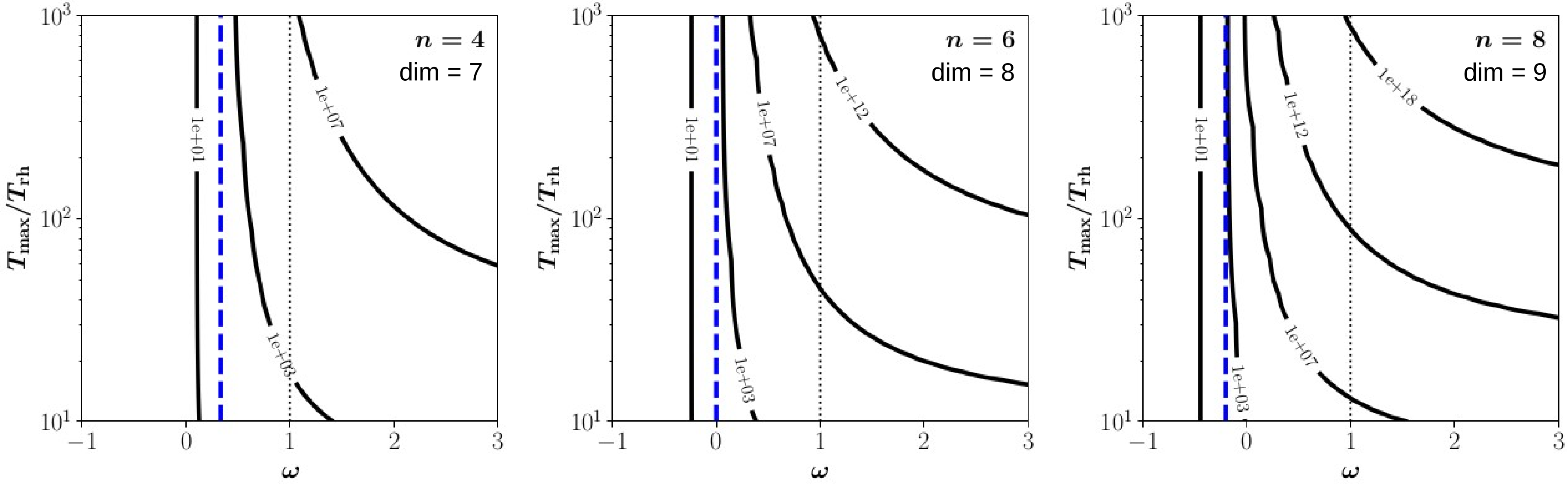


* Depends on ***n***, ***ω*** and the ratio T_{max} / T_{rh}

* Independent on ***m***, ***Λ***

→ Garcia, Mambrini, Olive & Peloso ‘17

Boost Factors



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

Example:
Spin-2 Portal DM

Spin-2 Portal DM

DM interacts with the SM via the spin-2 portal

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

$$\mathcal{L}^1_{\rm int} = \frac{1}{2M_P} h_{\mu\nu} \left(T^{\mu\nu}_{\rm SM} + T^{\mu\nu}_{\rm X}\right)$$

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

Spin-2 Portal DM

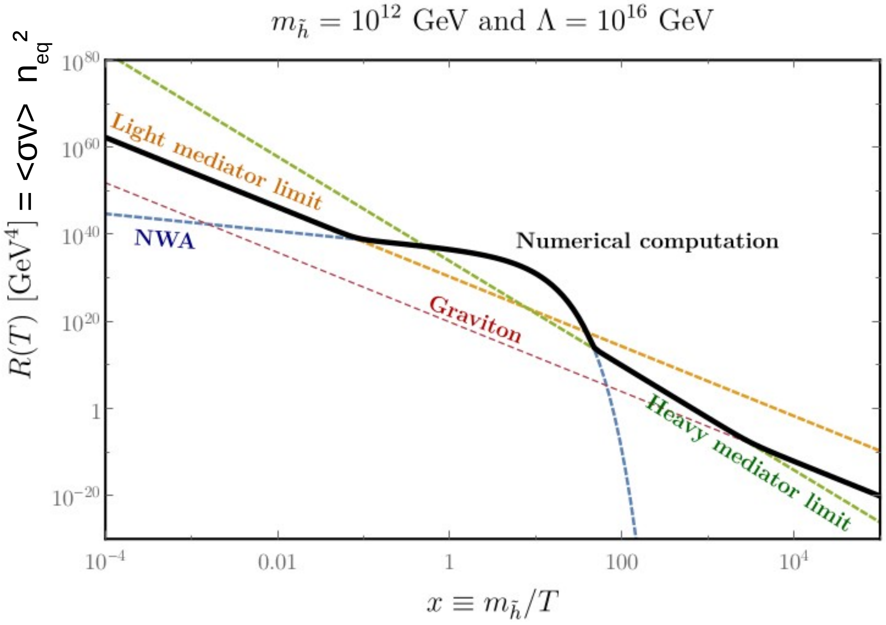
DM interacts with the SM via the spin-2 portal

* Super heavy regime (decoupling) $\langle\sigma v\rangle \sim \frac{T^2}{M_P^4}$

* **Heavy mediator** $\langle\sigma v\rangle \sim \frac{T^6}{\Lambda^4\, m_{\tilde{h}}^4}$

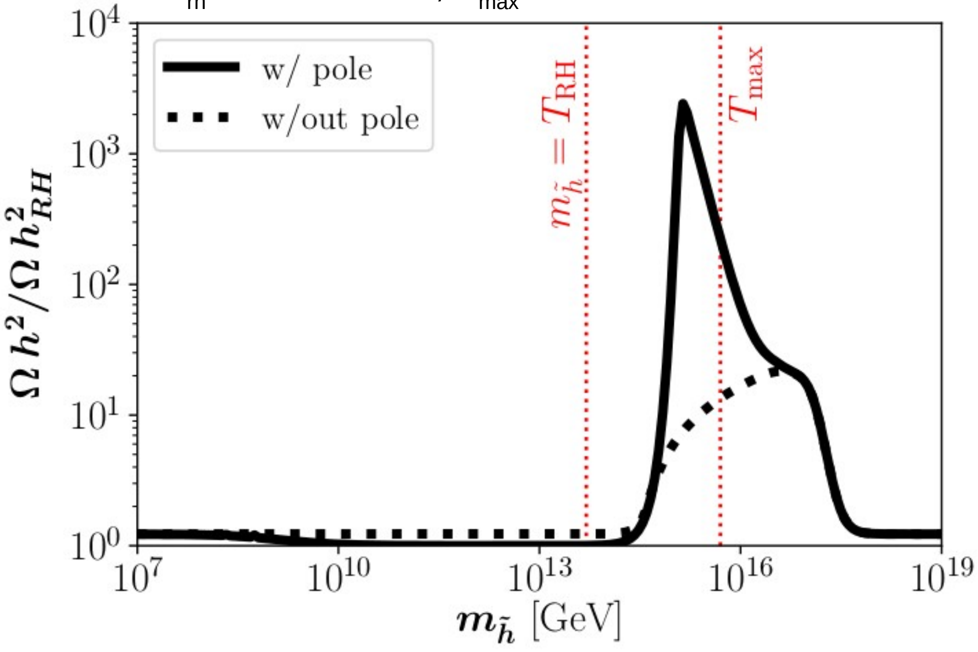
* **Resonance** $\langle\sigma v\rangle \sim \frac{m_{\tilde{h}}^3}{\Lambda^4\,\Gamma_{\tilde{h}}}\frac{T}{m_{\tilde{h}}}K_1\left(\frac{m_{\tilde{h}}}{T}\right)$

* Light mediator $\langle\sigma v\rangle \sim \frac{T^2}{\Lambda^4}$



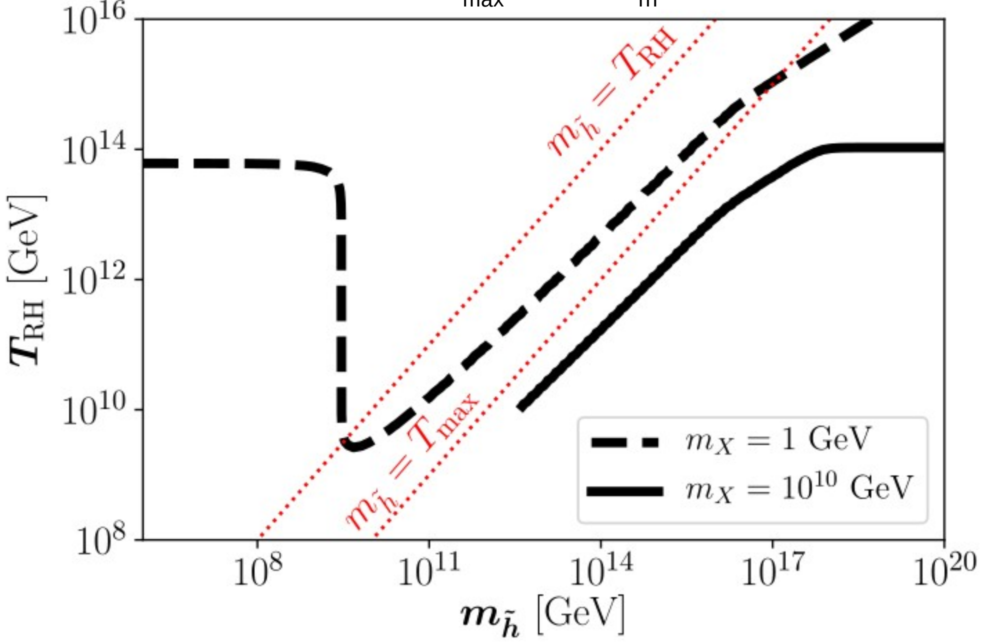
Boost Factor

$m = 10^{10}$ GeV, $\Lambda = 10^{16}$ GeV,
$T_{rh} = 5\text{x}10^{13}$ GeV, $T_{max} = 5\text{x}10^{15}$ GeV and $\omega = 0$

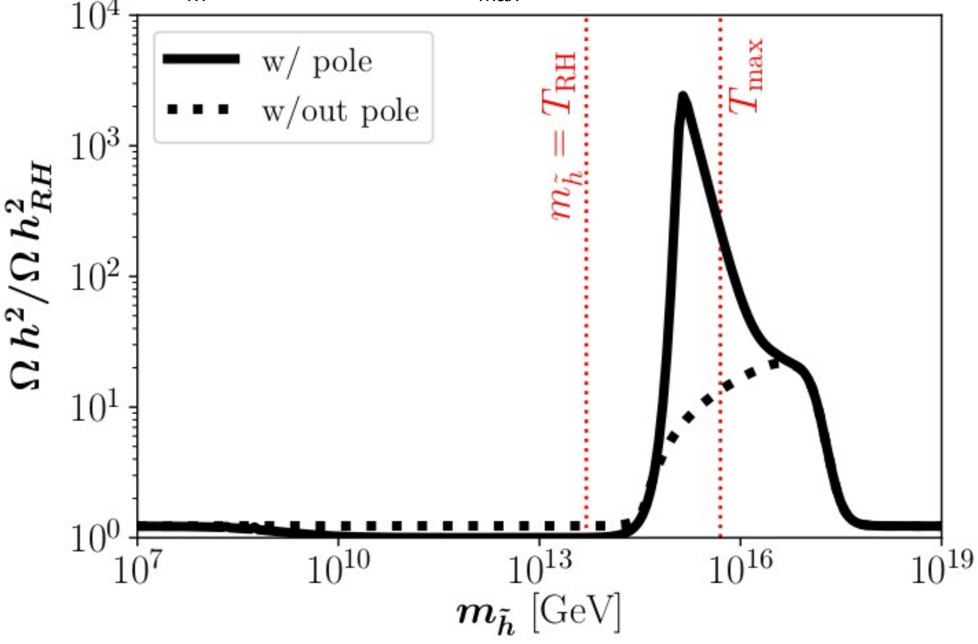


Boost Factor

$\Lambda = 10^{16}$ GeV, $T_{max} = 100\ T_{rh}$ and $\omega = 0$



$m = 10^{10}$ GeV, $\Lambda = 10^{16}$ GeV,
$T_{rh} = 5\times10^{13}$ GeV, $T_{max} = 5\times10^{15}$ GeV and $\omega = 0$



Conclusions

- UV freeze-in is a viable DM production mechanism
- Strongly depends on the dynamics near $T_{\rm rh}$
- Instantaneous reheating may not be a good approximation
  → miserably fails for $n > n_c$
- For $n > n_c$: Bulk of DM produced near $T_{\max}$
- Big boost factors due to the non-sudden reheating
  → depend on the equation of state of the early universe

- DM can be produced via the spin-2 portal
- Big boost factors when:
  → heavy mediator
  → near the resonance

Vielen Dank!