Thermal DM with LTR
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Intro

• Typical BE $\quad \underbrace{\frac{dn}{dt} + \underbrace{3Hn}_{\text{cosmo}}}_{\text{Liouville}} = \underbrace{-\underbrace{\langle\sigma v\rangle}_{\text{particle physics}}(n^2 - n_{eq}^2)}_{\text{collision}}$

• Standard cosmology :

- Entropy SM conserved $\rightarrow T \sim \frac{1}{a}$
- Hubble dominated by SM radiation $\rightarrow H \sim T^2 \sim \frac{1}{a^2}$

guaranteed $T < T_{BBN}$

- Very high inflationary reheating

dangerous extrapolation

inflation — reheating — RD $\longrightarrow t$

• Reheating

$* \; H \sim \sqrt{\rho_{\text{inflaton}}}$

$\rho_{\text{inflaton}} \propto a^{-3(1+w)}$ $\quad$ w: effective EoS during reheating

$H(a) \propto a^{-\frac{3}{2}(1+w)}$

$$w \begin{cases} 0 : & MD \\ \frac{1}{3} : & RD \\ +1 : & \text{Kination} \\ \frac{n-2}{n+2} : & V(\phi) \propto \phi^n \end{cases}$$

$w \leq \frac{1}{3}$: ϕ has to decay / annihilate

$\Rightarrow$ Injection of entropy

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* SM temperature during reheating:

$$T(a) = T_{rh}\left(\frac{a_{rh}}{a}\right)^{\alpha} .$$

$$\begin{cases} a_{rh} \equiv a(T_{rh}) \\ \rho_R(T_{rh}) = \rho_\phi(T_{rh}) \end{cases}$$

- Examples:

* MD: $w = 0$ $\quad \alpha = 3/8$

  - inflation in $V \sim \phi^2$ with <u>constant</u> Γ $\quad \boxed{\text{plot}}$
  - EMD } (non-adiabatic)
  - PBH. }

→ Inflaton decay $\Gamma = \Gamma(a)$ or $\Gamma = \Gamma(\phi)$ $\quad w = 0 \quad \alpha \neq \frac{3}{8}$

→ $\phi \to$ relativistic particle $\to$ SM $\quad w = 0 \quad \alpha = 0$

* RD: $w = \frac{1}{3}$ $\quad$ mass becomes <u>field dependent</u>

$$\begin{cases} \alpha = 1/4 \\ \alpha = 3/4 \end{cases}$$ decay scalars / fermions

* $V(\phi) \sim \phi^n$, $\quad w = \frac{n-2}{n+2}$

$\alpha = \frac{3}{2}\frac{1}{2+n}$ decay scalar

$\alpha = \frac{3}{2}\frac{n-1}{n+2}$ decay fermions

$\alpha = \frac{9}{2n+4}$ annihilation | heavy | bosons

$\alpha = \frac{3(7-2n)}{2n+4}$ annihilation | light | bosons

mediator | into

$\alpha = 1$ annihilation heavy fermions

$\alpha = \frac{3(5-n)}{2n+4}$ light

* Kination a faster-than radiation $w > \frac{1}{3}$ $\alpha = T$

→ If $\alpha > 0$: $T_{max} \gg T_{rh}$.

$\alpha = 0$: T constant during reheating

$\boxed{\text{PLOT}}$

* Hubble: $H^2 = \frac{\rho_R + \rho_\phi}{3 M_p^2}$

$$H(a) = H_{rh} \times \begin{cases} \left(\frac{a_{rh}}{a}\right)^{\frac{3(1+w)}{2}} & a \leq a_{rh} \\ \left(\frac{a_{rh}}{a}\right)^2 & a_{rh} \leq a \end{cases}$$

$$H(T) = H_{rh} \times \begin{cases} \left(\frac{T}{T_{rh}}\right)^{\frac{3(1+w)}{2\alpha}} & T \geq T_{rh} \\ \left(\frac{T}{T_{rh}}\right)^2 & T_{rh} \geq T \end{cases}$$

3 free parameters: T_{rh}, w, α ← { Effective approach to reheating

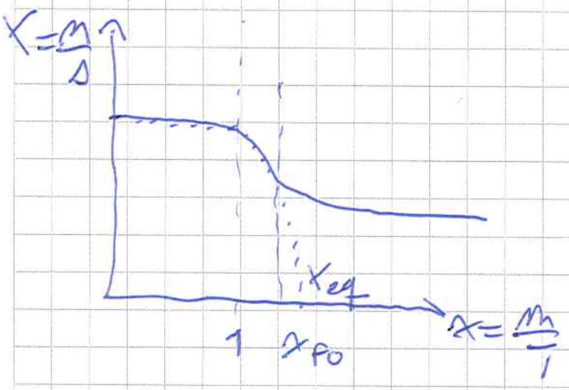
we only assume power-law scalings for H & T after decoupling

$\boxed{\text{Plot}}$

production

• Thermal DM AFTER reheating

* WIMPs & SIMPs ($T_{rh} \gg T_{FO} \gg T_k$)

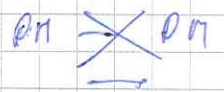


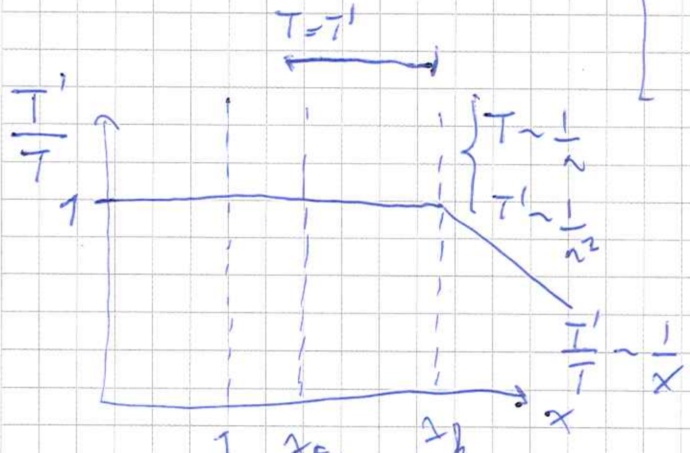
$\cancel{x}_{FO} \sim 20$ chemical FO

(number-changing interactions)

WIMP: annihilation, semi-annihilation, coannihilation

SIMP: 3-to-2, 4-to-2



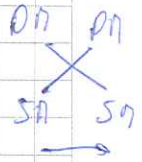


$x_k \sim 10^2 - 10^4$ WIMP

$x_k \gtrsim x_{FO}$ SIMP

kinetic FO

(elastic interactions)



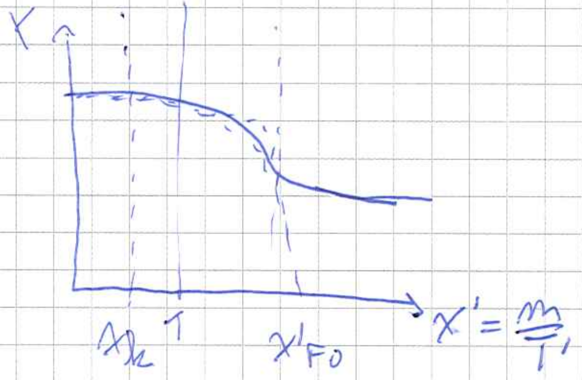
→ Instantaneous decoupling

$$Y_0 \simeq Y_{FO} = \frac{n_{eq}(T_{FO})}{s(T_{FO})} \qquad \left\{ \begin{array}{l} n_{eq} \sim (mT)^{\frac{3}{2}} e^{-\frac{m}{T}} \\ s \sim T^3 \end{array} \right.$$

$$Y_0 \simeq x_{FO}^{3/2} e^{-x_{FO}}$$

* ELDERs & cannibals $(T_{sh} \gg \underline{T_k \gg T_{FO}})$

$T_{FO} \neq T'_{FO}$



$$Y_0 \simeq Y_{FO} = \frac{n_{eq}(T'_{FO})}{s(T_{FO})}$$

S and S' <u>independently</u> conserved: $s(T_{FO}) = s(T_k)\left(\frac{a_k}{a_{FO}}\right)^3$

$$= s(T_k)\,\frac{s'(T_k)}{s'(T'_{FO})}$$

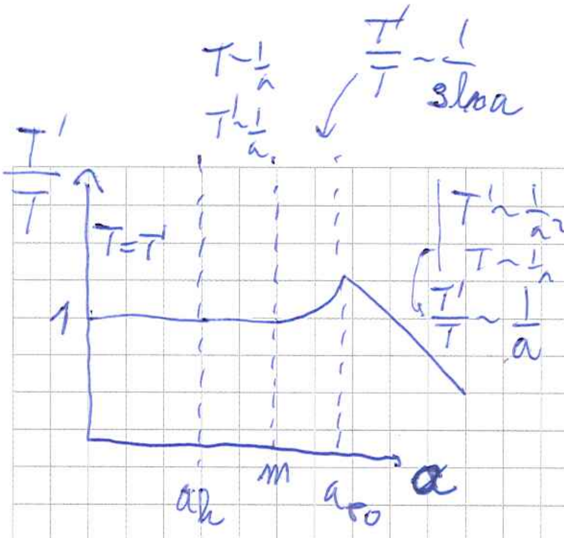
$$Y_0 \simeq \frac{n_{eq}(T'_{FO})}{s(T_k)}\,\frac{s'(T_k)}{s'(T'_{FO})}$$

relativistic or non-Rela.

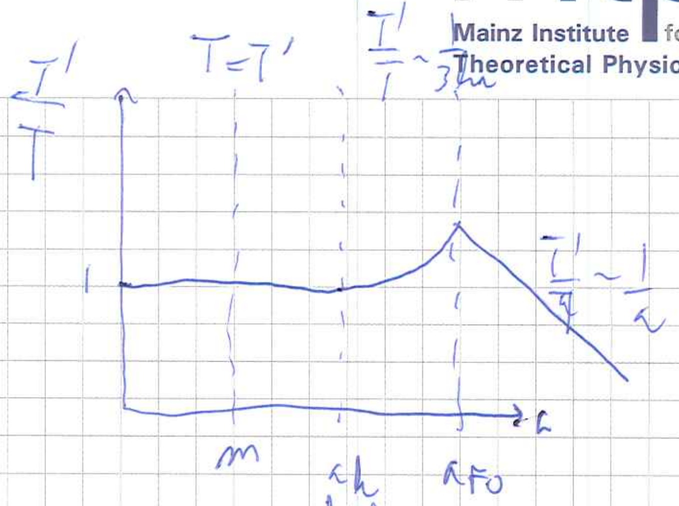
Entropy density in the dark sector: $s'(T') \sim m^3 K_3\left(\frac{m}{T'}\right)$

$$Y_0 \simeq \frac{x_k^3}{x'_{FO}}\,\frac{K_2(x'_{FO})\,K_3(x_k)}{K_3(x'_{FO})}.$$

2 limits: $Y_0 \simeq \begin{cases} \dfrac{1}{x'_{FO}} & x_k \ll 1 \quad \text{cannibal} \\[2ex] \dfrac{x_k^{5/2}\,e^{-x_k}}{x'_{FO}} & x_k \gg 1 \quad \text{ELDER} \end{cases}$



Combined
maximal "increase"



ELDER
controled "increase"

PLOTS ① T. and ② X. ③ x_h vs x_{FO}

3 Free parameters : m, x_{FO}, x_h

- Thermal DM production DURING reheating

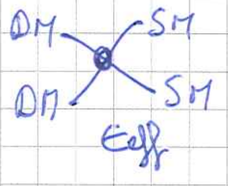
ϕ injects entropy to the SM $\rightarrow$ DM gets diluted

$$\frac{S(T)}{S(T_{rh})} = \frac{s(T)}{s(T_{rh})}\left(\frac{a}{a_{rh}}\right)^3 \sim \left(\frac{T_{rh}}{T}\right)^{\frac{3(1-\alpha)}{\alpha}}$$

PLOTS

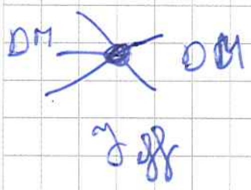
$\Rightarrow$ independent of $\underline{\underline{w}}$!

• Toy Model - contact interactions



$$\langle \sigma v \rangle_{el} \sim \langle \sigma v \rangle_{2\to 2} \sim \left[\frac{\epsilon_{eff}}{m} \frac{K_1(x)}{K_2(x)} \right]^2 \sim \begin{cases} \frac{\epsilon_{eff}^2}{4T^2} & x \ll 1 \\ \frac{\epsilon_{eff}^2}{m^2} & x \gg 1 \end{cases}$$

$3\to 2$



$$\langle \sigma v^2 \rangle_{3\to 2} \sim \frac{\gamma_{eff}^3}{m^5}$$

$$\Gamma_{el} = n_{eq}^{SM} \langle \sigma v \rangle_{el}$$

$$\Gamma_{2\to 2} = n_{eq} \langle \sigma v \rangle_{2\to 2}$$

$$\Gamma_{3\to 2} = n_{eq}^2 \langle \sigma v^2 \rangle_{3\to 2}$$