# Reconstructing Non-standard Cosmologies with Dark Matter

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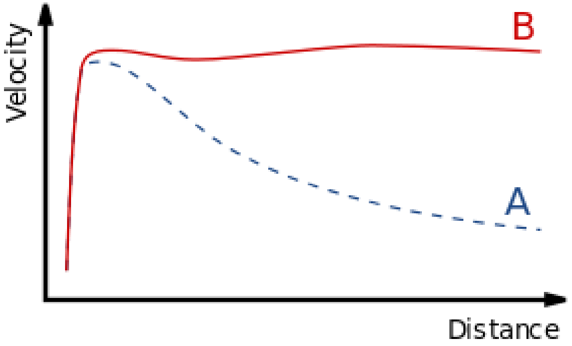
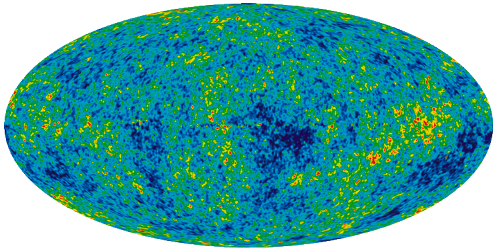
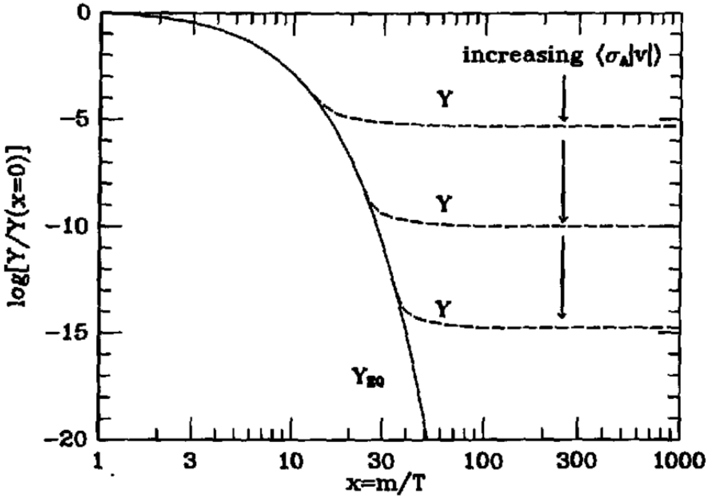
# Introduction: WIMPs

Galaxy rotation curves
CMB Anisotropies
Gravitational lensing






WIMP Dark matter

Early universe → SM+DM in thermal eq.

Universe expanded and cooled → Freeze-out

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

$$\langle \sigma v \rangle \sim 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s} \sim 3 \times 10^{-9} \mathrm{GeV}^{-2}$$

# Non-Standard Cosmologies

For some period of the early Universe, assume total energy density dominated by a component $\phi$ with a decay rate $\Gamma_\phi$.

The evolution of the energy densities $\rho_\phi$ and $\rho_R$ as well as the DM number density $n$ are governed by the system of coupled Boltzmann equations:

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

$$\frac{ds}{dt} + 3\, H\, s = +\frac{\Gamma_\phi\, \rho_\phi}{T}\left(1 - \frac{E_\chi\, b}{m_\phi}\right) + 2\frac{E_\chi}{T}\langle\sigma v\rangle\left(n^2 - n_{\rm eq}^2\right)$$

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

# Non-Standard Cosmologies

For some period of the early Universe, assume total energy density dominated by a component $\phi$ with a decay rate $\Gamma_\phi$.

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

$$\frac{ds}{dt} + 3\, H\, s = +\frac{\Gamma_\phi\, \rho_\phi}{T}$$

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

Fully parametrized with

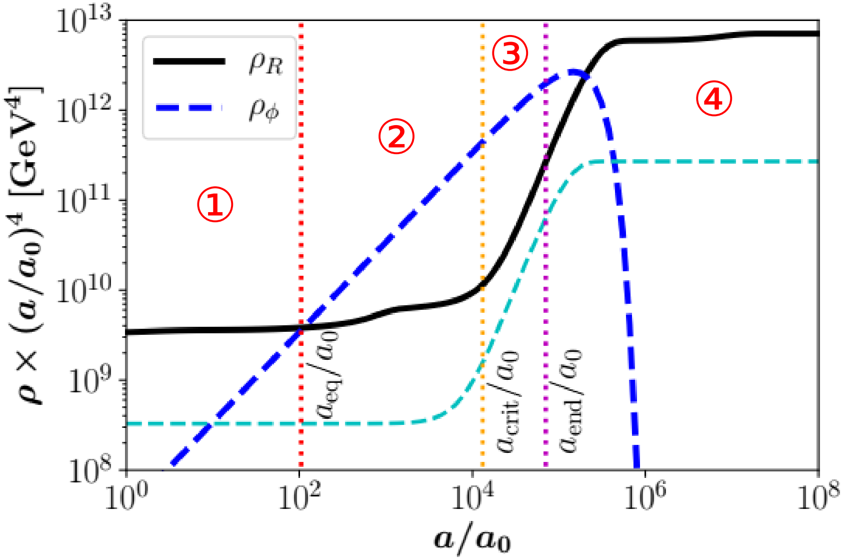
$$\omega$$

$$T_{\rm end}$$

$$\kappa \equiv \left.\frac{\rho_\phi}{\rho_R}\right|_{T=m}$$

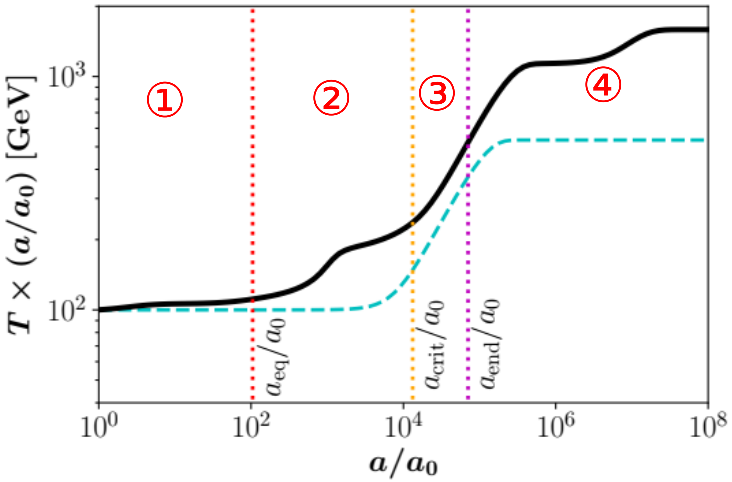
For having a successful BBN → $T_{\rm end} > 4$ MeV.

Solving without DM for $T_{end} = 7\times10^{-3}\,\mathrm{GeV}$, $\kappa = 10^{-2}$, $\omega = 0.$

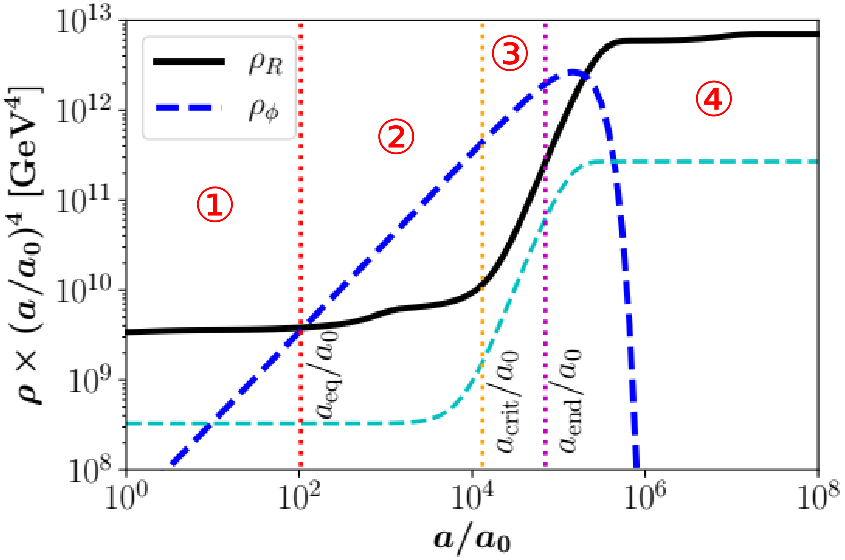



| $T(a) \propto$ \ $H^2 \propto$ | $\rho_R$ | $\rho_\phi$ |
|---|---|---|
| $a^{-1}$ | Case 1, 4 | Case 2 |
| $a^{-\frac{3}{8}(1+\omega)}$ | None | Case 3 |

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



Solving without DM for $T_{end} = 7 \times 10^{-3}\,\mathrm{GeV}$, $\kappa = 10^{-2}$, $\omega = 0$.




| $H^2 \propto$ / $T(a) \propto$ | $\rho_R$ | $\rho_\phi$ |
|---|---|---|
| $a^{-1}$ | Case 1, 4 | Case 2 |
| $a^{-\frac{3}{8}(1+\omega)}$ | None | Case 3 |

**Case 4: $T_{fo} \ll T_{end}$**

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

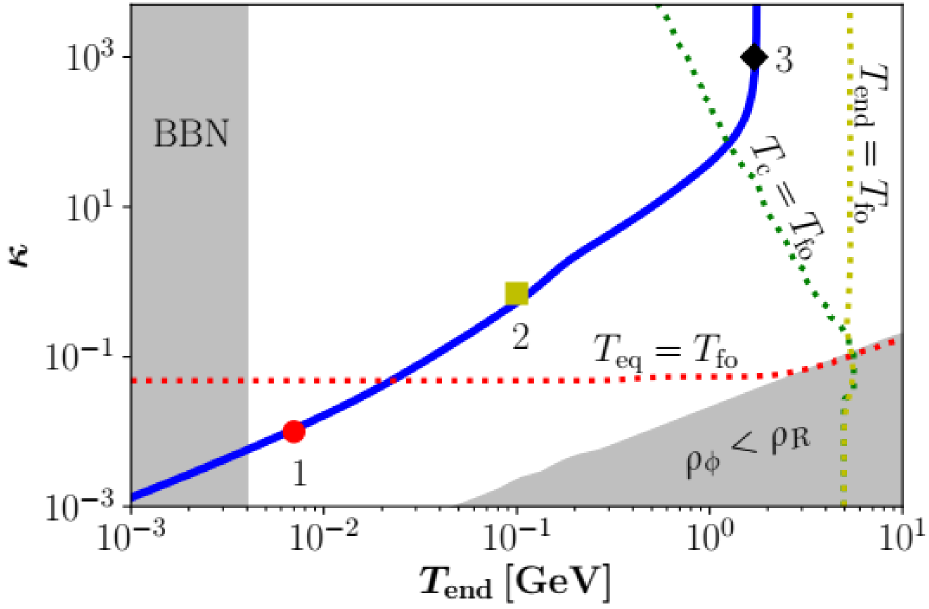
No effect on the final DM relic abundance
$\phi$ decays at a very high temperature
while DM is still in chemical eq. with the
SM thermal bath.

# Reconstructing Cosmological parameters

We assume that both the DM mass *m* and its thermally averaged annihilation cross section <*σv*> are known after a discovery, and we try to reconstruct the non-standard cosmological parameters that make the DM compatible with the WIMP paradigm.

Parameters:

$$m = 100 \text{ GeV}$$
$$\langle \sigma v \rangle = 10^{-11} \text{ GeV}^{-2}$$
$$\omega = 0$$

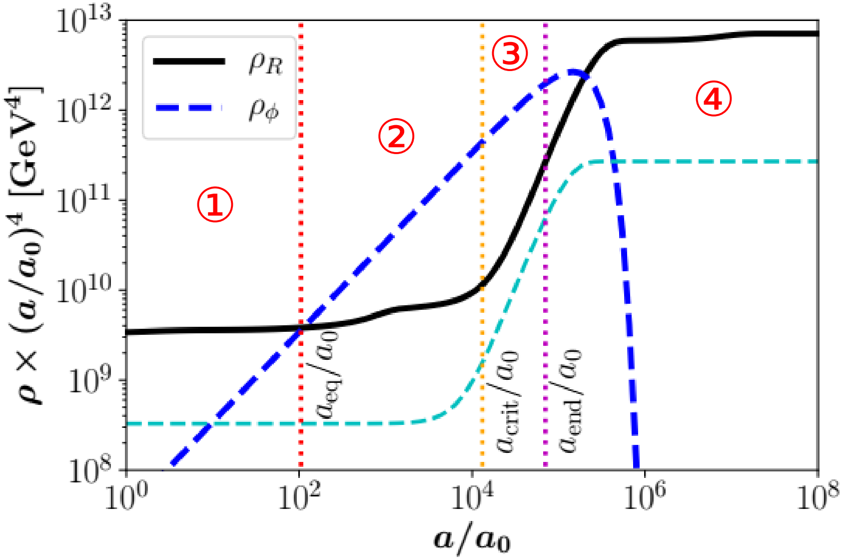


# Classification

$Case\,1:\ T_{eq} \ll T_{fo}$

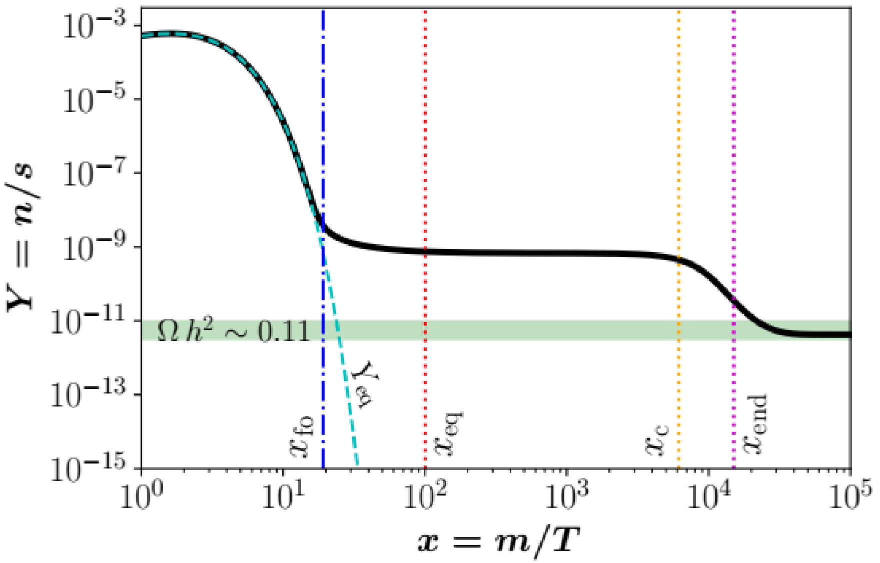
$Case\,2:\ T_{crit} \ll T_{fo} \ll T_{eq}$

$Case\,3:\ T_{end} \ll T_{fo} \ll T_{crit}$



# $Case\,1:\ T_{eq} \ll T_{fo}$

$T_{end} = 7\times 10^{-3}\,\text{GeV}\,,\ \kappa = 10^{-2}.$

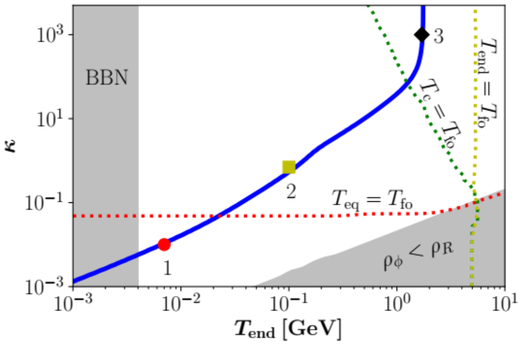



$$H \sim \sqrt{\frac{\rho_R}{3M_p^2}}$$

$$T(a) \propto a^{-1}$$

The decay of $\phi$ dilutes the DM by injecting entropy to the SM bath.

$$Y_{obs} = \frac{Y_0}{D} \sim \left(\frac{15}{2\pi\sqrt{10\,g_\star}}\frac{x_{fo}}{m\,M_P\,\langle\sigma v\rangle}\right)\left[\frac{1}{\kappa}\left(\frac{T_{end}}{m}\right)^{1-3\omega}\right]^{\frac{1}{1+\omega}}$$




In order to reproduce the DM abundance:

$\kappa \propto T_{end}^{1-3\omega}$, and for $\omega = 0,\ \kappa \propto T_{end}$.

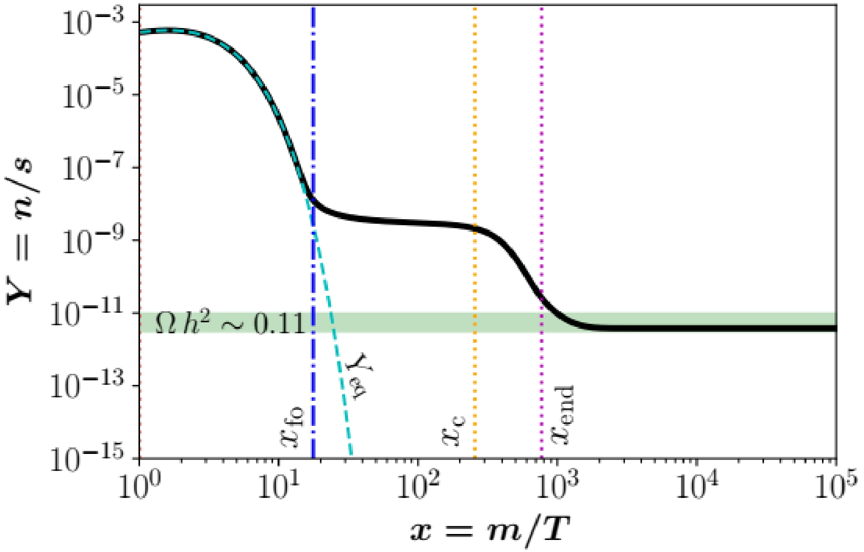
# $Case\, 2:\ T_{crit} \ll T_{fo} \ll T_{eq}$

$$H \sim \sqrt{\frac{\rho_\phi}{3M_p^2}}$$

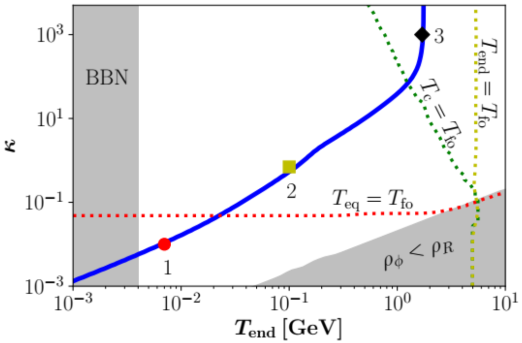
$$T(a) \propto a^{-1}$$

The decay of $\phi$ dilutes the DM by injecting entropy to the SM bath.

$T_{end} = 10^{-1}\,\text{GeV}\,,\ \kappa = 1.$




$$Y_{\rm obs} = \frac{Y_0}{D} \sim \left(\frac{45(1-\omega)}{4\pi\sqrt{10 g_\star}}\,\frac{\sqrt{\kappa}}{m\, M_P\, \langle\sigma v\rangle}\, x_{\rm fo}^{\frac{3}{2}(1-\omega)}\right)\left[\frac{1}{\kappa}\left(\frac{T_{\rm end}}{m}\right)^{1-3\omega}\right]^{\frac{1}{1+\omega}}$$




In order to reproduce the DM abundance:

$\kappa \propto T_{\rm end}^{2\frac{1-3\omega}{1-\omega}}$, and for $\omega = 0,\ \kappa \propto T_{\rm end}^2$

# $Case\,3:\ T_{end} \ll T_{fo} \ll T_{crit}$

$$H \sim \sqrt{\frac{\rho_\phi}{3M_p^2}}$$

$$T(a) \propto a^{-\frac{3}{8}(1+\omega)}$$

Freeze-out when $\phi$ is decaying → SM entropy not conserved.

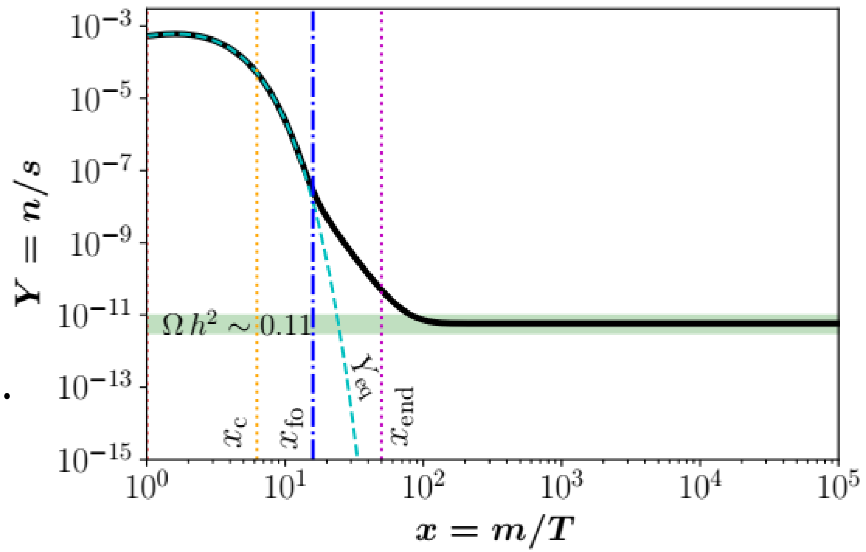
$$\frac{dN}{da} = -\frac{\langle\sigma v\rangle}{H\,a^4}\left(N^2 - N_{\rm eq}^2\right)$$

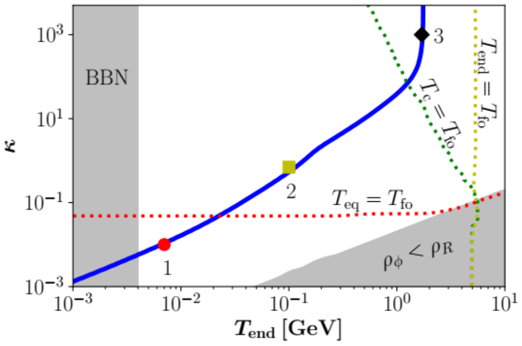
Final DM yield $Y_0$ is related to $N_0$ via the factor $s \times a^3$

$$Y_0 = \frac{N_0}{s\,a^3} = \frac{45(1-\omega)}{4\pi}\sqrt{\frac{1}{10g_\star}}\frac{1}{M_P\langle\sigma v\rangle}\left[T_{\rm fo}^{4(\omega-1)}\,T_{\rm end}^{3-5\omega}\right]^{\frac{1}{1+\omega}}$$

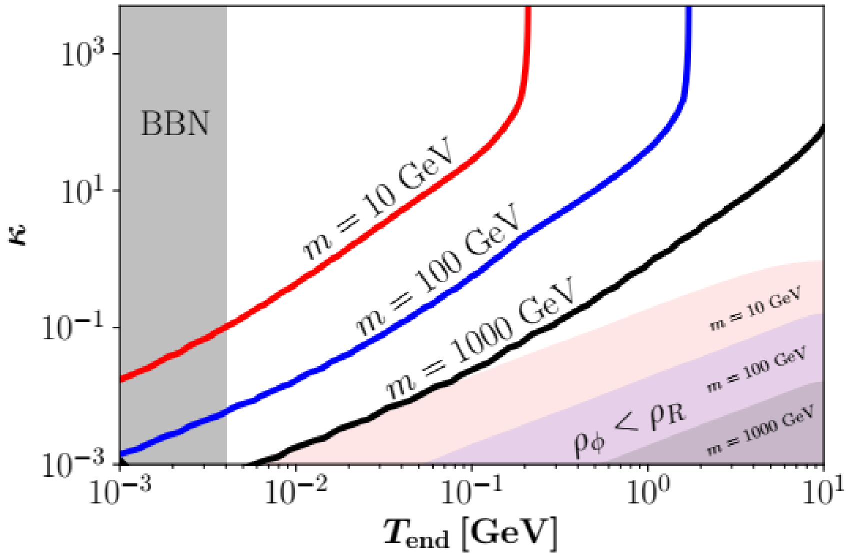
Depends only on $T_{end}$

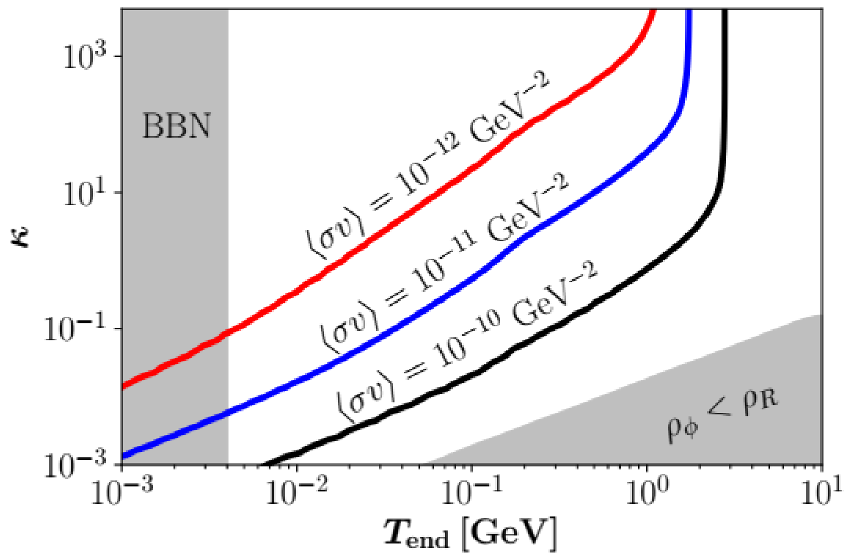
$T_{end} = 2\,\text{GeV}\,,\ \kappa = 10^3.$



# Varying the Particle Physics Parameters



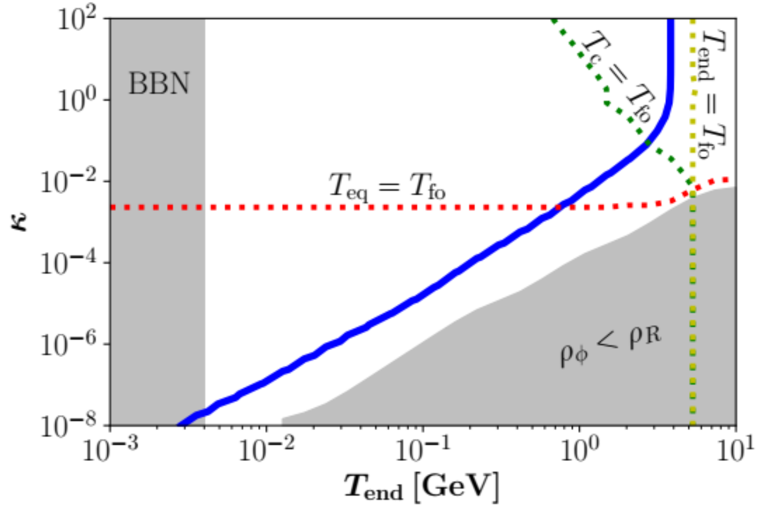

Low values of $\kappa \rightarrow$ Case 1

High values of $\kappa \rightarrow$ Case 3

$$Y_{\rm obs} \times m \sim 4 \times 10^{-10} \propto \frac{T_{\rm end}}{\langle\sigma v\rangle\, \kappa\, m}$$

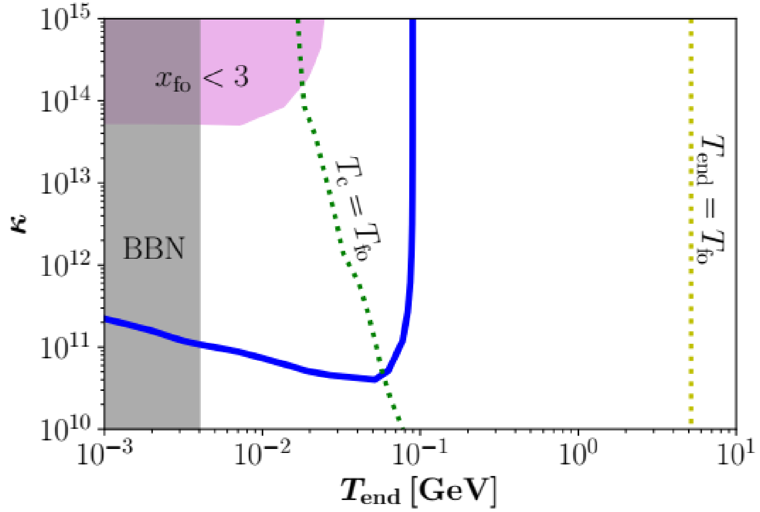
$$Y_0 \propto \frac{T_{\rm end}^3}{\langle\sigma v\rangle\, m^4}$$

# Varying the equation of state




$$\omega = -1/3 \qquad \rho_\phi \propto a^{-2}$$

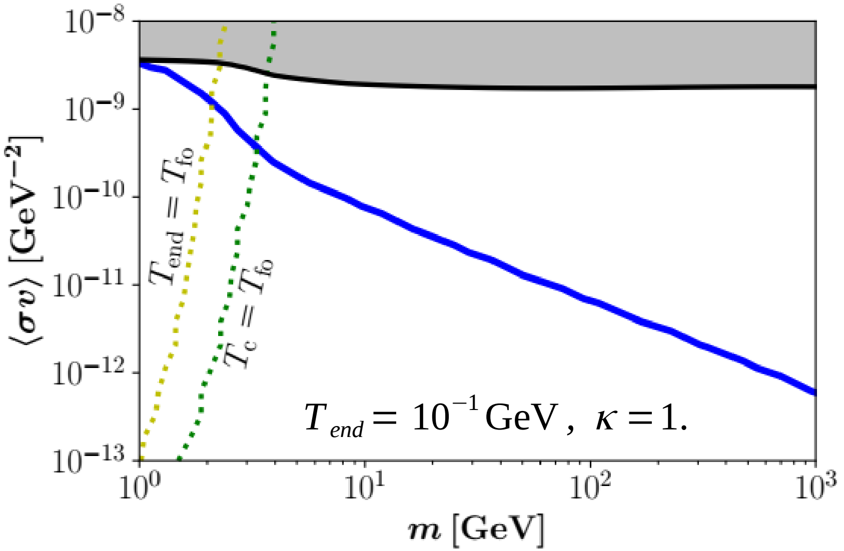
Diluted **slower** than radiation → Naturally dominates the total energy density of the universe

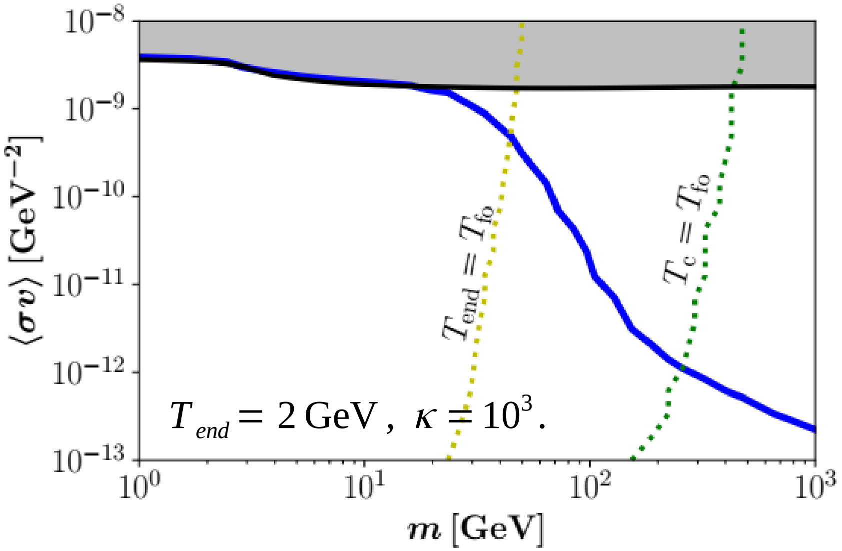



$$\omega = 2/5 \qquad \rho_\phi \propto a^{-21/5}$$

Diluted **faster** than radiation → Very large values for $\kappa$ are needed to compensate

# Varying the Non-standard Cosmological Parameters




High values of $m \rightarrow$ Case 2

$$Y_{\rm obs} \propto \frac{1}{m\langle\sigma v\rangle}\left[\frac{1}{\kappa}\left(\frac{T_{\rm end}}{m}\right)^{1-3\omega}\right]^{\frac{1}{1+\omega}}$$

$\langle\sigma v\rangle \propto m^{-1}$ for $\omega = 0$

Intermediate values of $m \rightarrow$ Case 3

$$Y_0 \propto \frac{1}{\langle\sigma v\rangle}\left[\left(\frac{x_{\rm fo}}{m}\right)^{4(\omega-1)}\right]^{\frac{1}{1+\omega}}$$

$\langle\sigma v\rangle \propto m^{-3}$ for $\omega = 0$

Low values of $m \rightarrow$ Case 4

$\langle\sigma v\rangle$ usual $few \times 10^{-9}\mathrm{GeV}^{-2}$

Standard cosmology

# Conclusions

- Despite the large amount of searches over the past decades, DM has not been found.
- A simple reason for this might be that the cosmological history was non-standard at early times.
- We considered scenarios where for some period at early times the expansion of the Universe was governed by a component $\phi$.
- If the inferred value of $\langle \sigma v \rangle$ is in the ballpark of few$\times 10^{-26}$ $cm^3/s$, the simpler freeze-out mechanism with a standard cosmology will be strongly favored
- If that turns out not to be the case, one can look for alternative cosmological scenarios.

# Thanks!

# Backup

Using the definitions

$$\rho_R(T) = \frac{\pi^2}{30}\, g_\star(T)\, T^4 \qquad H^2 = \frac{\rho_\phi + \rho_R + \rho_\chi}{3\, M_P^2} \qquad s(T) = \frac{\rho_R + p_R}{T} = \frac{2\pi^2}{45}\, g_{\star S}(T)\, T^3$$

For having a successful BBN, the temperature at the end of the $\rho_\phi$ dominated phase has to be $T_{end} > 4\ MeV$ , where $T_{end}$ is given by the total decay width $\Gamma_\phi$ as

$$T_{\rm end}^4 \equiv \frac{90}{\pi^2\, g_\star(T_{\rm end})}\, M_P^2\, \Gamma_\phi^2 \tag{4}$$

The evolution of the SM temperature follows from Eq. (2)

$$\frac{dT}{da} = \left(1 + \frac{T}{3\, g_{\star S}} \frac{dg_{\star S}}{dT}\right)^{-1} \left[-\frac{T}{a} + \frac{\Gamma_\phi\, \rho_\phi}{3\, H\, s\, a} \left(1 - \frac{E_\chi\, b}{m_\phi}\right) + \frac{2}{3} \frac{E_\chi\, \langle\sigma v\rangle}{H\, s\, a} \left(n^2 - n_{\rm eq}^2\right)\right] \tag{5}$$

# $Case\, 1: \; T_{eq} \ll T_{fo}$

Much before the decay of $\phi$, the SM entropy is conserved and therefore the Boltzmann eq. for DM can be rewritten as:

$$\frac{dY}{dx} = -\frac{\langle \sigma v \rangle \, s}{H\, x} \left(Y^2 - Y_{\rm eq}^2\right) \qquad (6)$$

where $Y \equiv n/s$ and $x \equiv m/T$, and eq. (6) admits the standard approximate solution

$$Y_0 = \frac{15}{2\pi\sqrt{10\, g_\star}} \frac{x_{\rm fo}}{m\, M_P \, \langle \sigma v \rangle} \qquad (7)$$

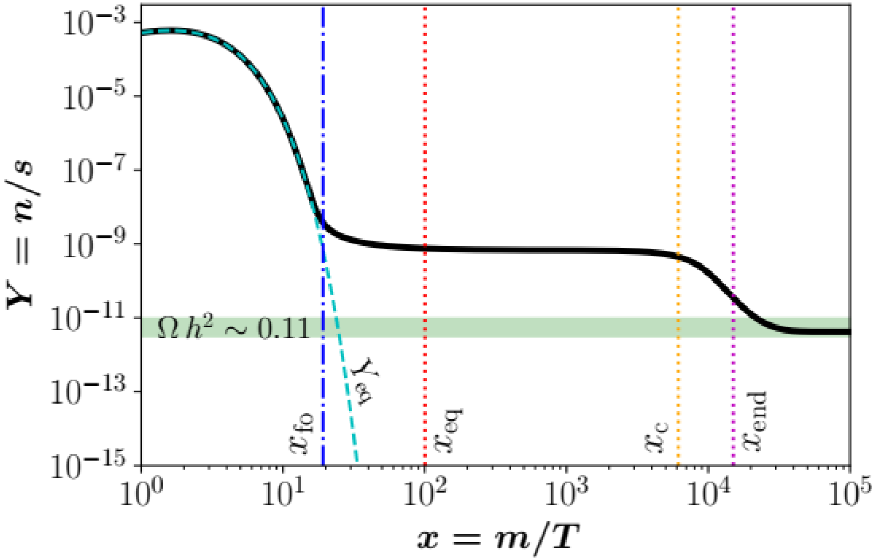
With $x_{fo}$ given by

$$x_{\rm fo} = \ln\left[\frac{3}{2}\sqrt{\frac{5}{\pi^5 g_\star}}\, g\, m\, M_P \, \langle \sigma v \rangle \sqrt{x_{\rm fo}}\right] \qquad (8)$$

Taking into account that:

$$H \sim \sqrt{\frac{\rho_R}{3M_P^2}} = \pi\sqrt{\frac{g_\star}{90}}\frac{m^2}{M_P}\frac{1}{x^2}$$

$T_{end} = 7\cdot 10^{-3}\,\mathrm{GeV}, \;\; \kappa = 10^{-2}.$



## $Case\,1:\ T_{eq} \ll T_{fo}$

The decay of $\phi$ dilutes the DM by injecting entropy to the SM bath. In the sudden decay approximation of $\phi$, the conservation of the energy density implies: $\rho_R(T_1) + \rho_\phi(T_1) = \rho_R(T_2)$

$$D = \left(\frac{T_2}{T_1}\right)^3 \sim \left[\kappa \left(\frac{m}{T_2}\right)^{1-3\omega}\right]^{\frac{1}{1+\omega}} \qquad \text{for } \omega \neq -1 \qquad D = \left(\frac{T_2}{T_1}\right)^3 = \left[1 - \kappa \left(\frac{m}{T_2}\right)^4\right]^{-\frac{3}{4}} \qquad \text{for } \omega = -1$$

The final DM abundance given by the ratio of eqs. (7) and (9) has to match the observations

$$Y_{\text{obs}} = \frac{Y_0}{D} \sim \frac{15}{2\pi\sqrt{10\,g_\star}} \frac{x_{\text{fo}}}{m\,M_P\,\langle\sigma v\rangle} \left[\frac{1}{\kappa}\left(\frac{T_{\text{end}}}{m}\right)^{1-3\omega}\right]^{\frac{1}{1+\omega}} \qquad \text{for } \omega \neq -1,$$

$$Y_{\text{obs}} = \frac{Y_0}{D} = \frac{15}{2\pi\sqrt{10\,g_\star}} \frac{x_{\text{fo}}}{m\,M_P\,\langle\sigma v\rangle} \left[1 - \kappa\left(\frac{m}{T_{\text{end}}}\right)^4\right]^{\frac{3}{4}} \qquad \text{for } \omega = -1,$$

where $Y_{\text{obs}}\, m = \frac{\rho_c\, \Omega_{\text{DM}} h^2}{s_0\, h^2} \sim 4 \times 10^{-10}\ \text{GeV}$.

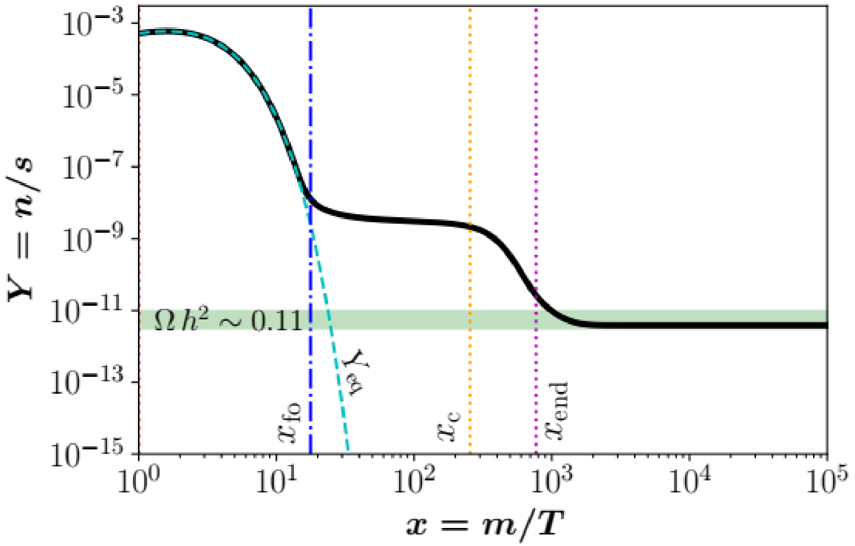
In order to reproduce the DM abundance: $\kappa \propto T_{\text{end}}^{1-3\omega}$, and for $\omega = 0,\ \kappa \propto T_{\text{end}}$.

# $Case\, 2:\ T_{crit} \ll T_{fo} \ll T_{eq}$

Compared to the previous case, the main difference here is the expansion of the Universe.

$$H = \sqrt{\frac{\rho_\phi}{3M_P^2}} = \frac{\pi}{3}\sqrt{\frac{g_\star}{10}}\frac{m^2}{M_P}\sqrt{\frac{\kappa}{x^{3(1+\omega)}}}$$

$T_{end} = 10^{-1}\,\mathrm{GeV},\ \kappa = 1.$




$$Y_0 = \frac{45}{4\pi}\frac{1-\omega}{m\,M_P\,\langle\sigma v\rangle}\sqrt{\frac{\kappa}{10 g_\star}}\,x_{fo}^{\frac{3}{2}(1-\omega)} \qquad \text{for } \omega \neq 1,$$

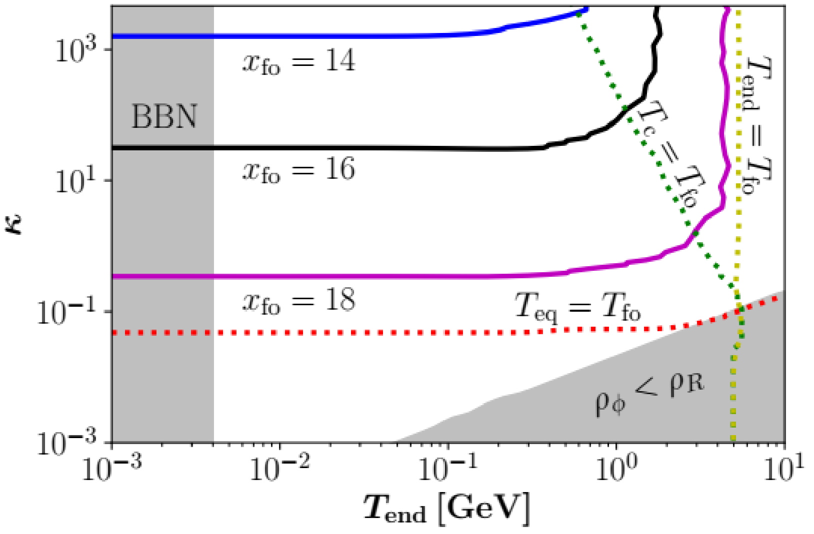
$$Y_0 = \frac{15}{2\pi}\frac{1}{m\,M_P\,\langle\sigma v\rangle}\sqrt{\frac{\kappa}{10 g_\star}}\left[\ln\frac{x_{end}}{x_{fo}}\right]^{-1} \qquad \text{for } \omega = 1.$$

The DM freeze-out happens at $x_{fo} = \ln\left[\frac{3}{2}\sqrt{\frac{5}{\pi^5 g_\star}}\, g\, \frac{m\,M_P\,\langle\sigma v\rangle}{\sqrt{\kappa}}\, x_{fo}^{\frac{3}{2}\omega}\right].$

Depends only on $\kappa$.

# $Case\,2: \; T_{crit} \ll T_{fo} \ll T_{eq}$

The final DM abundance given by the ratio of eqs. (11) and (9) has to match the observations:




for $\omega = -1$

$$Y_{\rm obs} = \frac{Y_0}{D} = \frac{45}{4\pi\sqrt{10 g_\star}} \frac{\sqrt{\kappa}}{m\, M_P \langle\sigma v\rangle} x_{\rm fo}^3 \left[1 - \kappa \left(\frac{m}{T_{\rm end}}\right)^4\right]^{\frac{3}{4}}$$

for $|\omega| \neq 1$

$$Y_{\rm obs} = \frac{Y_0}{D} \sim \frac{45(1-\omega)}{4\pi\sqrt{10 g_\star}} \frac{\sqrt{\kappa}}{m\, M_P \langle\sigma v\rangle} x_{\rm fo}^{\frac{3}{2}(1-\omega)} \left[\frac{1}{\kappa}\left(\frac{T_{\rm end}}{m}\right)^{1-3\omega}\right]^{\frac{1}{1+\omega}}$$

for $\omega = 1$

$$Y_{\rm obs} = \frac{Y_0}{D} \sim \frac{15}{2\pi}\sqrt{\frac{1}{10\, g_\star}} \frac{1}{T_{\rm end} M_P \langle\sigma v\rangle} \left[\ln \frac{T_{\rm fo}}{T_{\rm end}}\right]^{-1}$$

In order to reproduce the observed DM abundance

$\kappa \propto T_{\rm end}^{2\frac{1-3\omega}{1-\omega}}$, and for $\omega = 0,\ \kappa \propto T_{\rm end}^2$

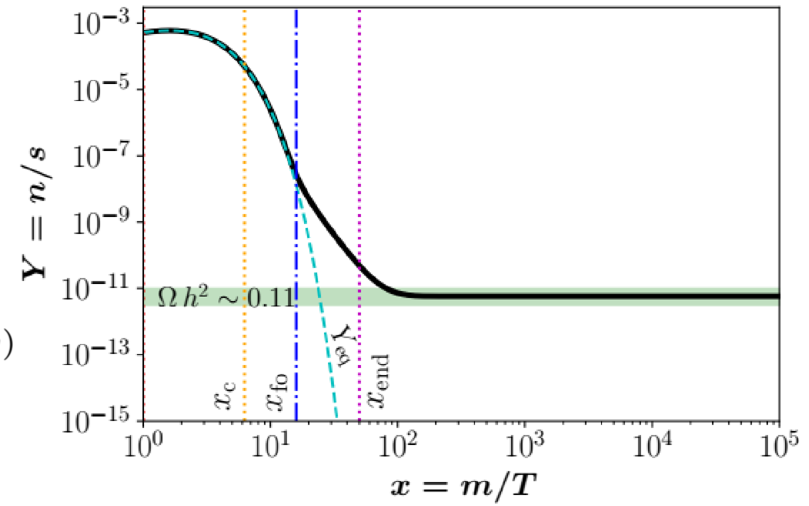
# $Case\,3:\; T_{end} \ll T_{fo} \ll T_{crit}$

Freeze-out when $\phi$ is decaying → SM entropy not conserved
→ Can not use anymore the Boltzmann eq. *dY/dx.*

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

Where $N \equiv n \times a^3$, and $H(a) \sim \sqrt{\frac{\rho_\phi(a)}{3M_P^2}} = \frac{\pi}{3}\sqrt{\kappa\,\frac{g_\star}{10}}\,\frac{m^2}{M_P}\,a^{-\frac{3}{2}(1+\omega)}$

$T_{end} = 2\,\mathrm{GeV}\,,\;\; \kappa = 10^3.$




$$N_0 = \frac{(1-\omega)\,\pi}{2}\sqrt{\kappa\,\frac{g_\star}{10}}\,\frac{m^2}{M_P\langle\sigma v\rangle}\,a_{\rm fo}^{\frac{3}{2}(1-\omega)} \qquad \text{for } \omega \neq 1$$

$$N_0 = \frac{\pi}{3}\sqrt{\kappa\,\frac{g_\star}{10}}\,\frac{m^2}{M_P\langle\sigma v\rangle}\left(\ln\frac{a_{\rm end}}{a_{\rm fo}}\right)^{-1} \qquad \text{for } \omega = 1.$$

The final DM yield is related to $N_0$ via the factor $s \times a^3$.

# $Case\,3:\ T_{end} \ll T_{fo} \ll T_{crit}$

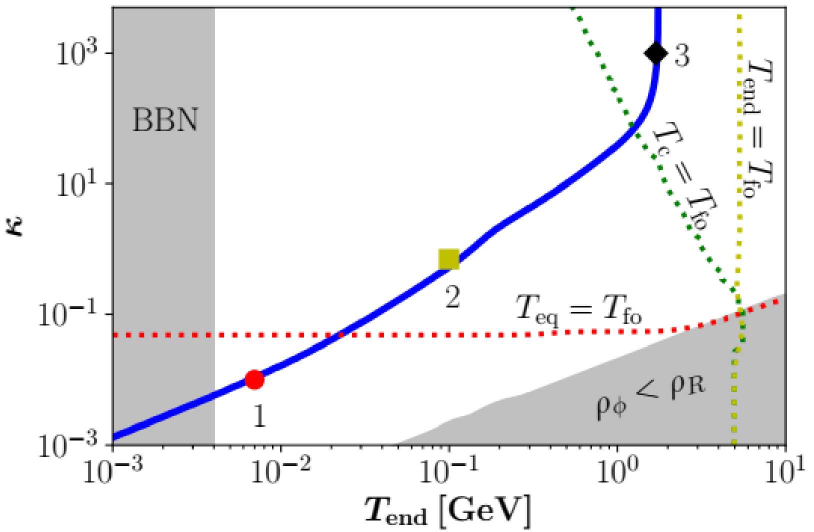
$$s\,a^3 = \frac{2\pi^2}{45} g_\star \left(T_{\rm end}\, a_{\rm end}\right)^3 = \frac{2\pi^2}{45} g_\star \left[\kappa \frac{m^4}{T_{\rm end}^{1-3\omega}}\right]^{\frac{1}{1+\omega}}$$

for $\omega = 1$

$$Y_0 = \frac{N_0}{s\,a^3} = \frac{45}{8\pi}\sqrt{\frac{1}{10 g_\star}} \frac{1}{T_{\rm end}\, M_P \langle\sigma v\rangle} \left(\ln \frac{T_{\rm fo}}{T_{\rm end}}\right)^{-1}$$

for $\omega \neq 1$

$$Y_0 = \frac{N_0}{s\,a^3} = \frac{45(1-\omega)}{4\pi}\sqrt{\frac{1}{10 g_\star}} \frac{1}{M_P \langle\sigma v\rangle} \left[T_{\rm fo}^{4(\omega-1)}\, T_{\rm end}^{3-5\omega}\right]^{\frac{1}{1+\omega}}$$




Depends only on $T_{end}$

The DM freeze-out temperature can be obtained as $x_{\rm fo} = \ln\left[\frac{3}{2}\sqrt{\frac{5}{\pi^5 g_\star}}\, g\, \frac{M_P \langle\sigma v\rangle T_{\rm end}^2}{m}\, x_{\rm fo}^{\frac{5}{2}}\right]$

## $Case\,3:\ T_{end} \ll T_{fo} \ll T_{crit}$

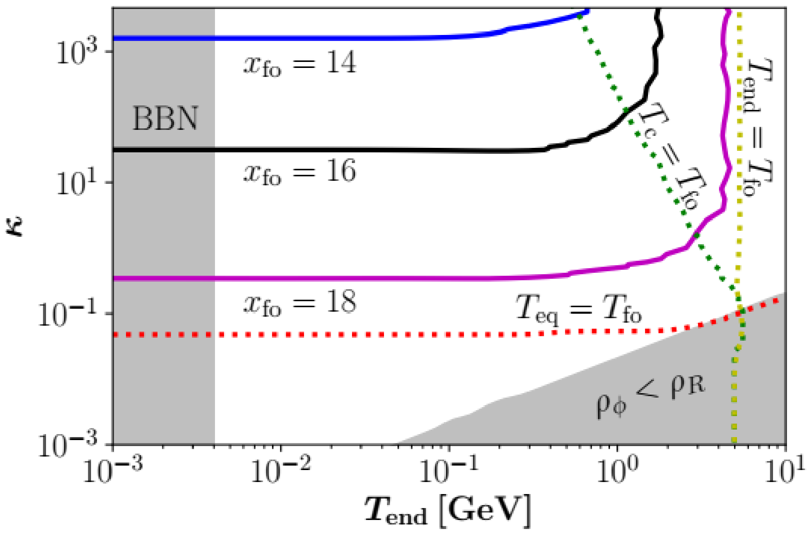
$$s\,a^3 = \frac{2\pi^2}{45} g_\star \left(T_{\rm end}\, a_{\rm end}\right)^3 = \frac{2\pi^2}{45} g_\star \left[\kappa \frac{m^4}{T_{\rm end}^{1-3\omega}}\right]^{\frac{1}{1+\omega}}$$

for $\omega = 1$

$$Y_0 = \frac{N_0}{s\,a^3} = \frac{45}{8\pi}\sqrt{\frac{1}{10 g_\star}} \frac{1}{T_{\rm end}\, M_P \langle\sigma v\rangle} \left(\ln\frac{T_{\rm fo}}{T_{\rm end}}\right)^{-1}$$

for $\omega \neq 1$

$$Y_0 = \frac{N_0}{s\,a^3} = \frac{45(1-\omega)}{4\pi}\sqrt{\frac{1}{10 g_\star}} \frac{1}{M_P \langle\sigma v\rangle} \left[T_{\rm fo}^{4(\omega-1)}\, T_{\rm end}^{3-5\omega}\right]^{\frac{1}{1+\omega}}$$

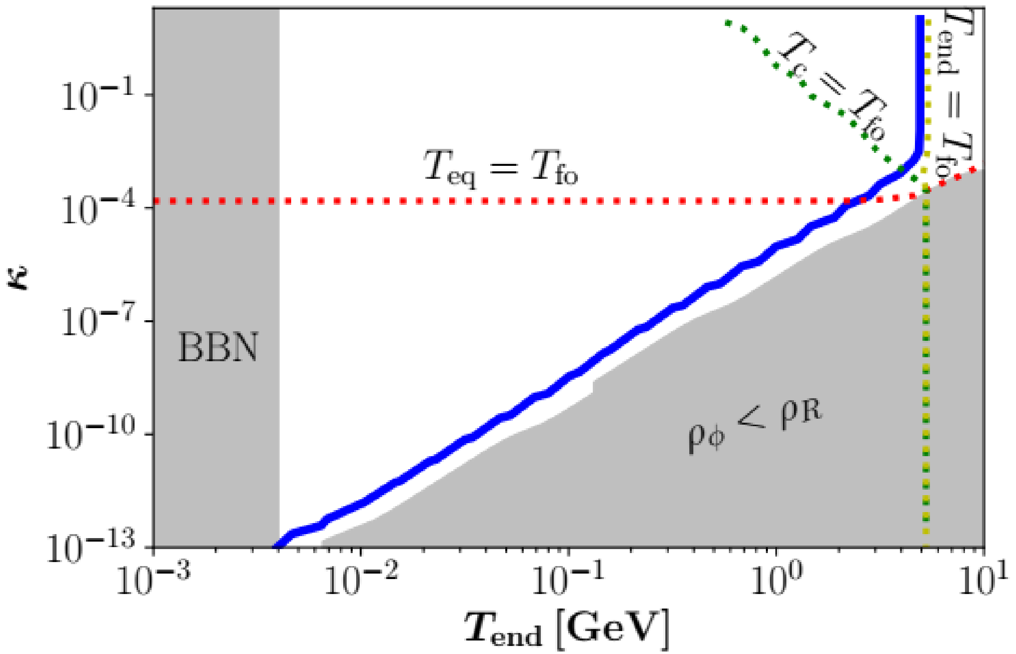



Depends only on $T_{end}$

The DM freeze-out temperature can be obtained as $x_{\rm fo} = \ln\left[\frac{3}{2}\sqrt{\frac{5}{\pi^5 g_\star}}\, g\, \frac{M_P \langle\sigma v\rangle T_{\rm end}^2}{m}\, x_{\rm fo}^{\frac{5}{2}}\right]$

Depends only on $T_{end}$

$\omega = -2/3$



$10^{-1}$
$10^{-4}$
$10^{-7}$
$10^{-10}$
$10^{-13}$
$\kappa$
BBN
$T_{eq} = T_{fo}$
$T_c = T_{fo}$
$T_{end} = T_{fo}$
$\rho_\phi < \rho_R$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^{0}$
$10^{1}$
$T_{end}$ [GeV]