History of a hot hidden dark sector

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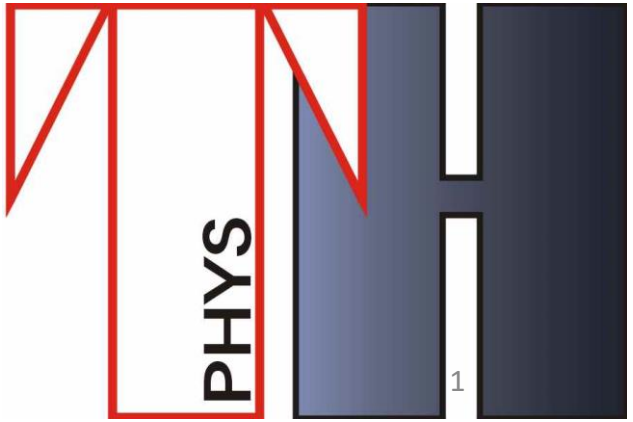
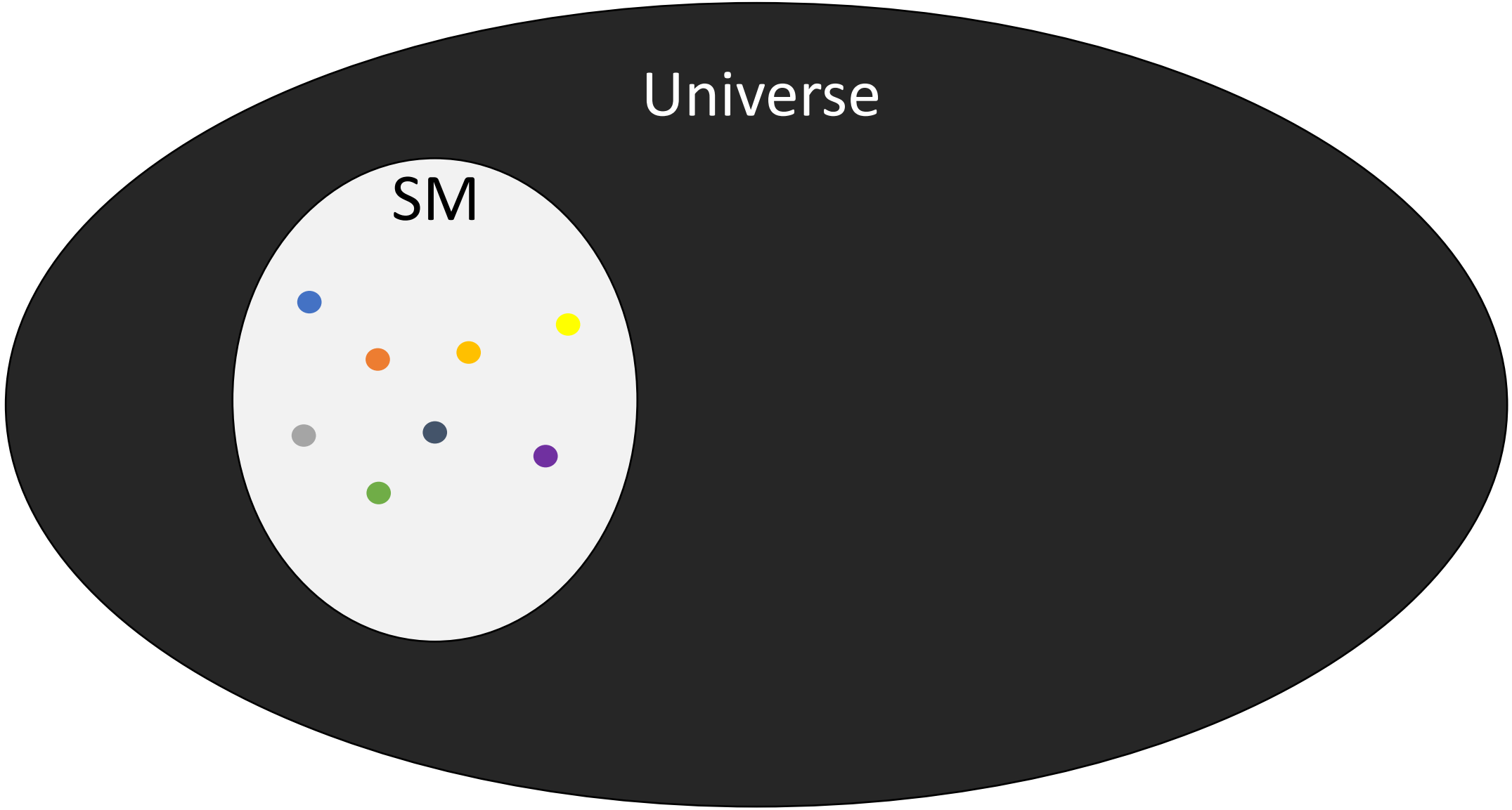


Introduction



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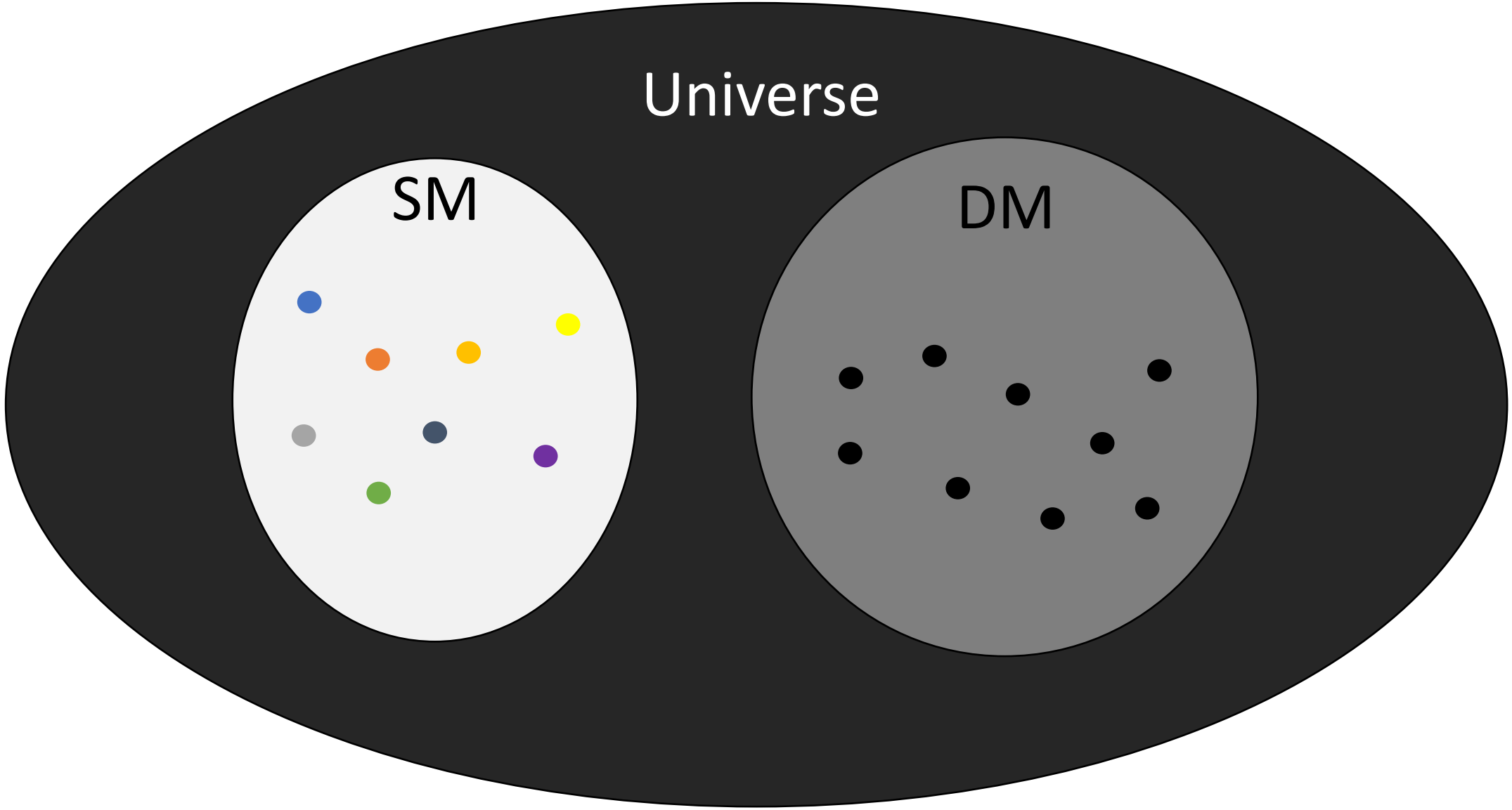

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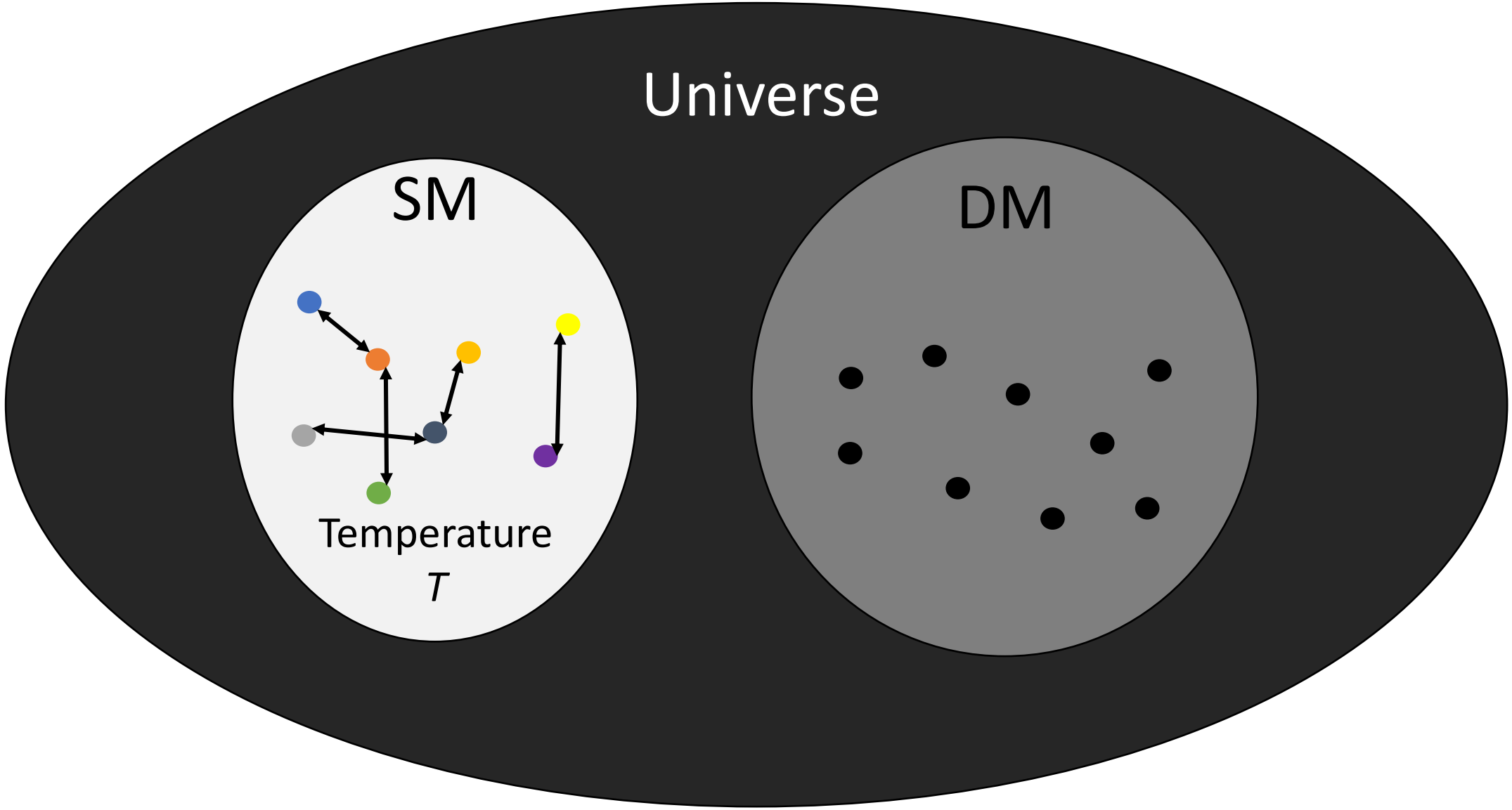

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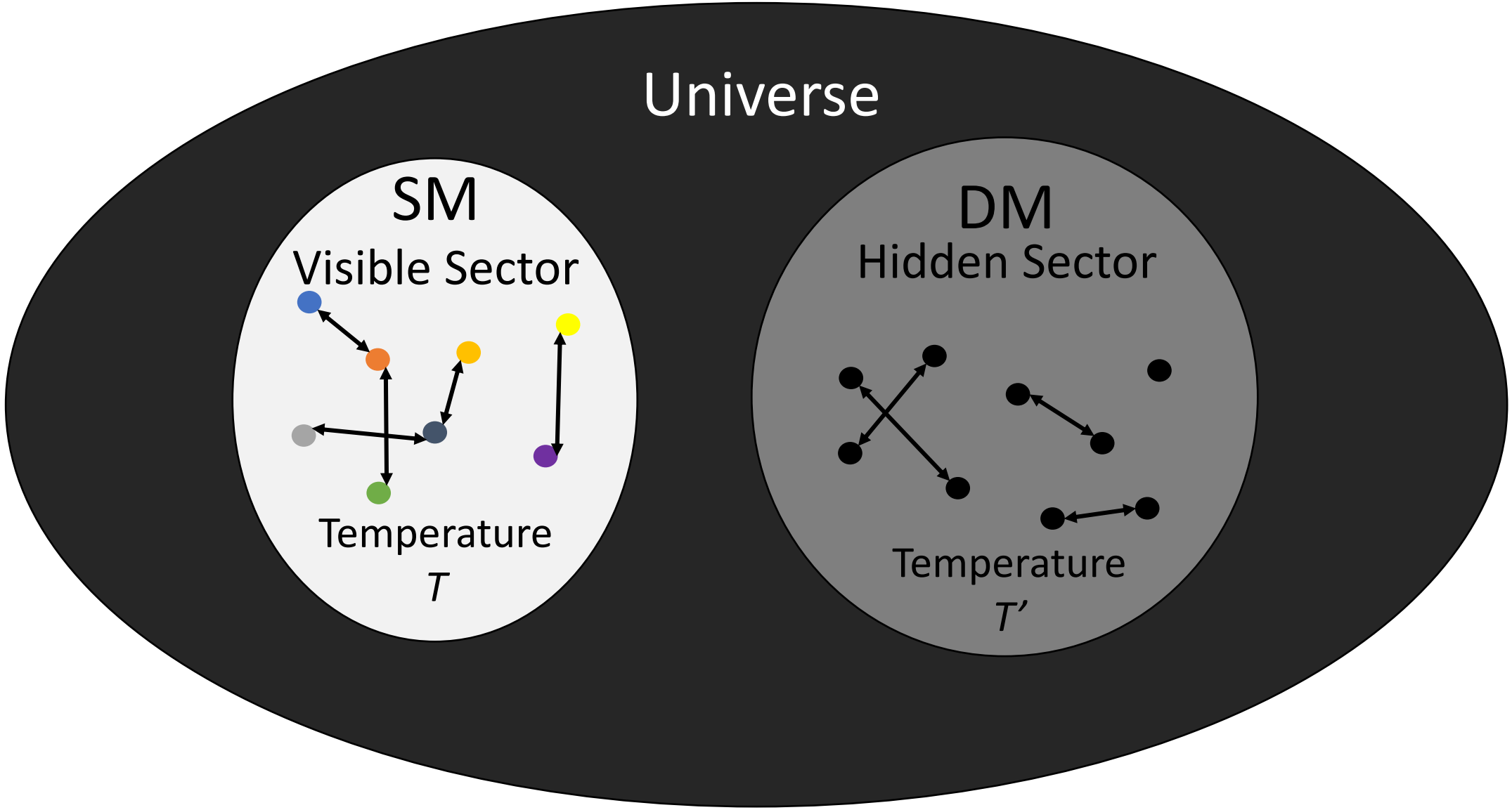
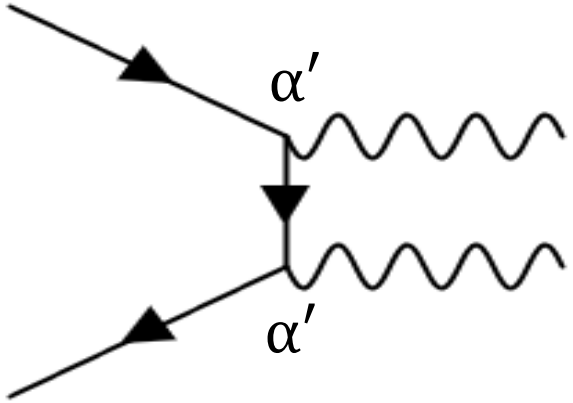


Dark QED

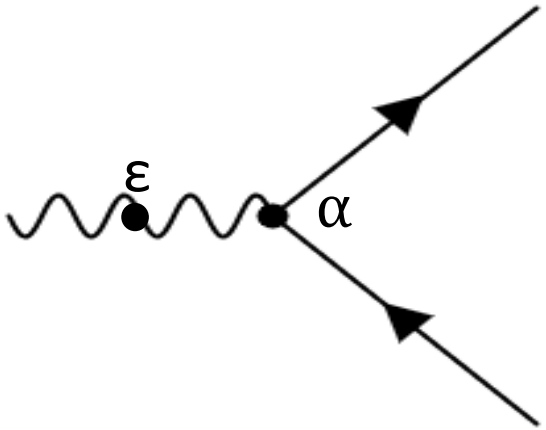
$$\mathcal{L} \supset \overline{\chi}(i\not{D} - m_{\mathrm{dm}})\chi - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m'^{2}A'_{\mu}A'^{\mu} - \frac{\varepsilon}{2}B_{\mu\nu}F'^{\mu\nu}$$

DM annihilation into DP:



Leading process for **dark matter Freeze-out**
(1112.0493, Chu et al.)

DP decay into SM fermions



Leading process for **dark photon evolution** after DM freeze-out **(1605.07195, Berger et al.)**

Boltzmann equations

3 parameters : (T, T', μ) → 3 equations:

- ρ_t: Total energy density
- ρ': Dark photon energy density
- n': Dark photon number density

Γ' = Dark photon decay width

H = Hubble parameter

ω = state parameter

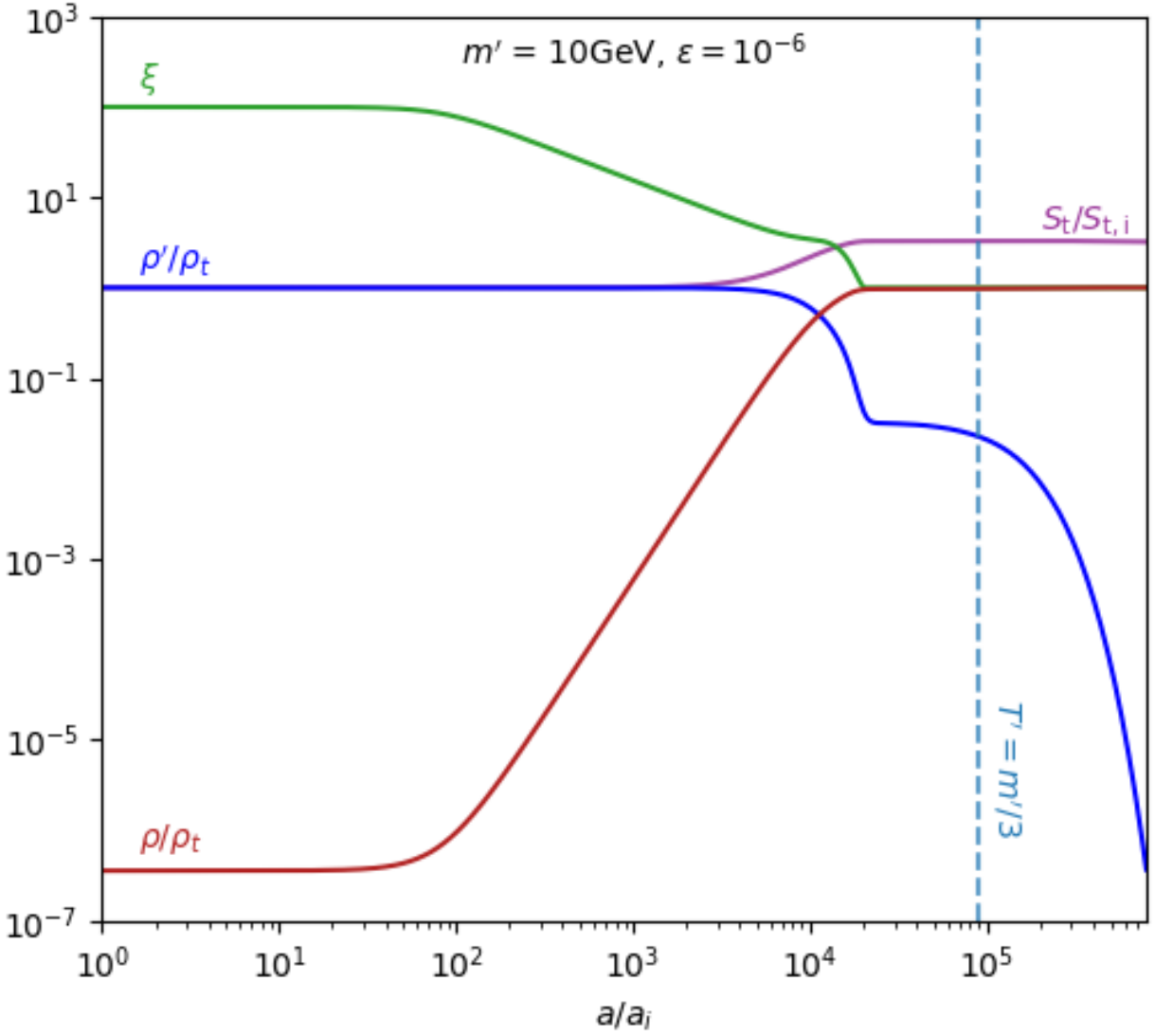
$$\frac{d\rho_t}{dt} + 3(1+\omega_t)H\rho_t = 0$$ → Total energy density

$$\frac{dn'}{dt} + 3Hn' = \langle\Gamma'\rangle_T n'_{eq}(T) - \langle\Gamma'\rangle_{T'} n'$$ → Dark Photon number density

$$\frac{d\rho'}{dt} + 3(1+\omega')H\rho' = m'\Gamma'\left[n'_{eq}(T) - n'\right]$$ → Dark Photon energy density

Numerical solutions (dominant hidden sector)

Decay of a relativistic dark photon



<u>Important parameters to track</u>

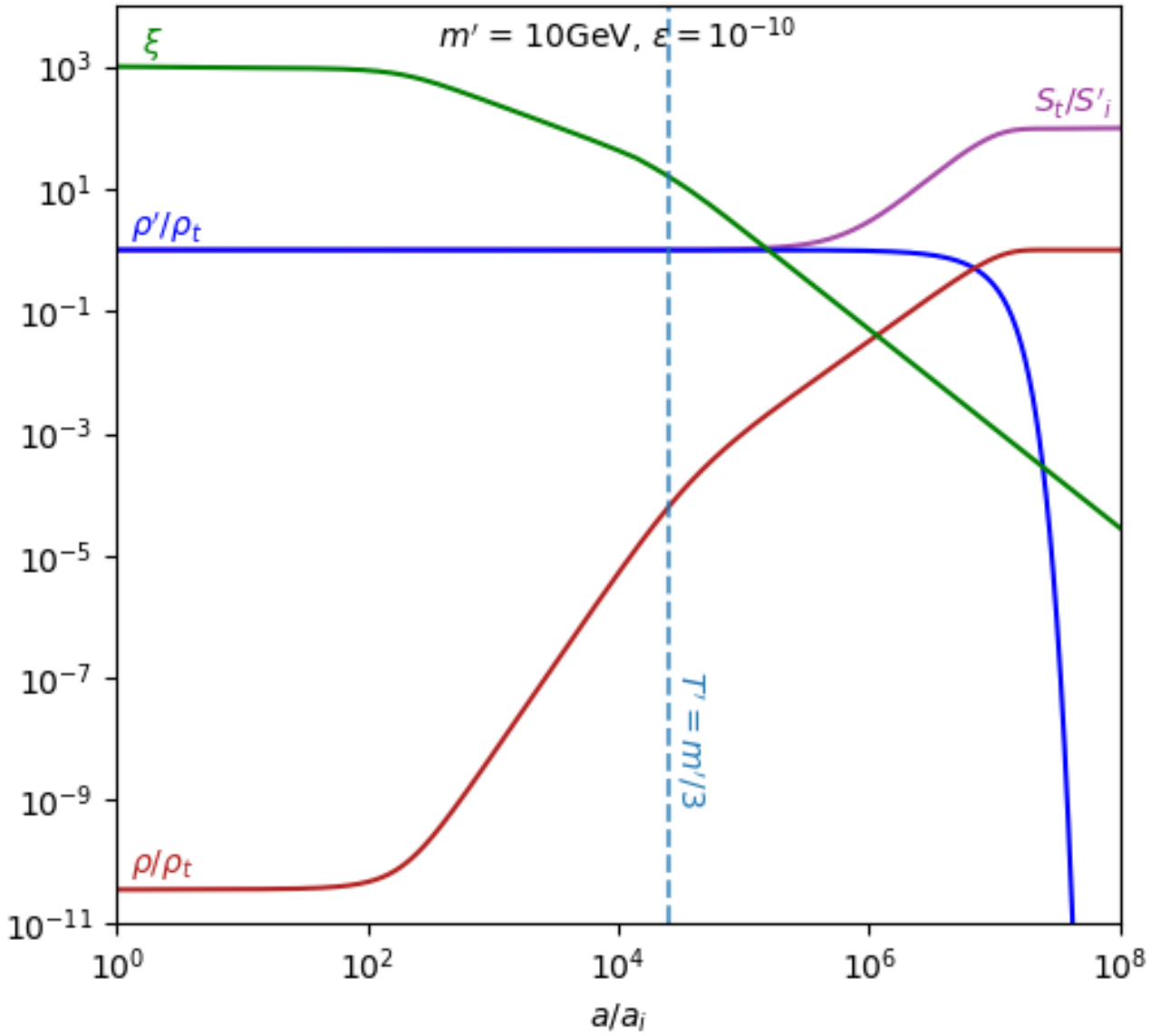
- Temperature ratio $\boldsymbol{\xi = T'/T}$
- Energy density fractions $\boldsymbol{\rho'/\rho_t}$ and $\boldsymbol{\rho/\rho_t}$
- Total entropy production factor $\boldsymbol{S_t/S_{t,i}}$

Relativistic decay:

$$\frac{S_{t,f}}{S_{t,i}} \approx \frac{S_f}{S_i'} \approx \left(\frac{g_*}{g_*'}\right)^{1/4}$$

Numerical solutions (dominant hidden sector)

Decay of a non-relativistic dark photon



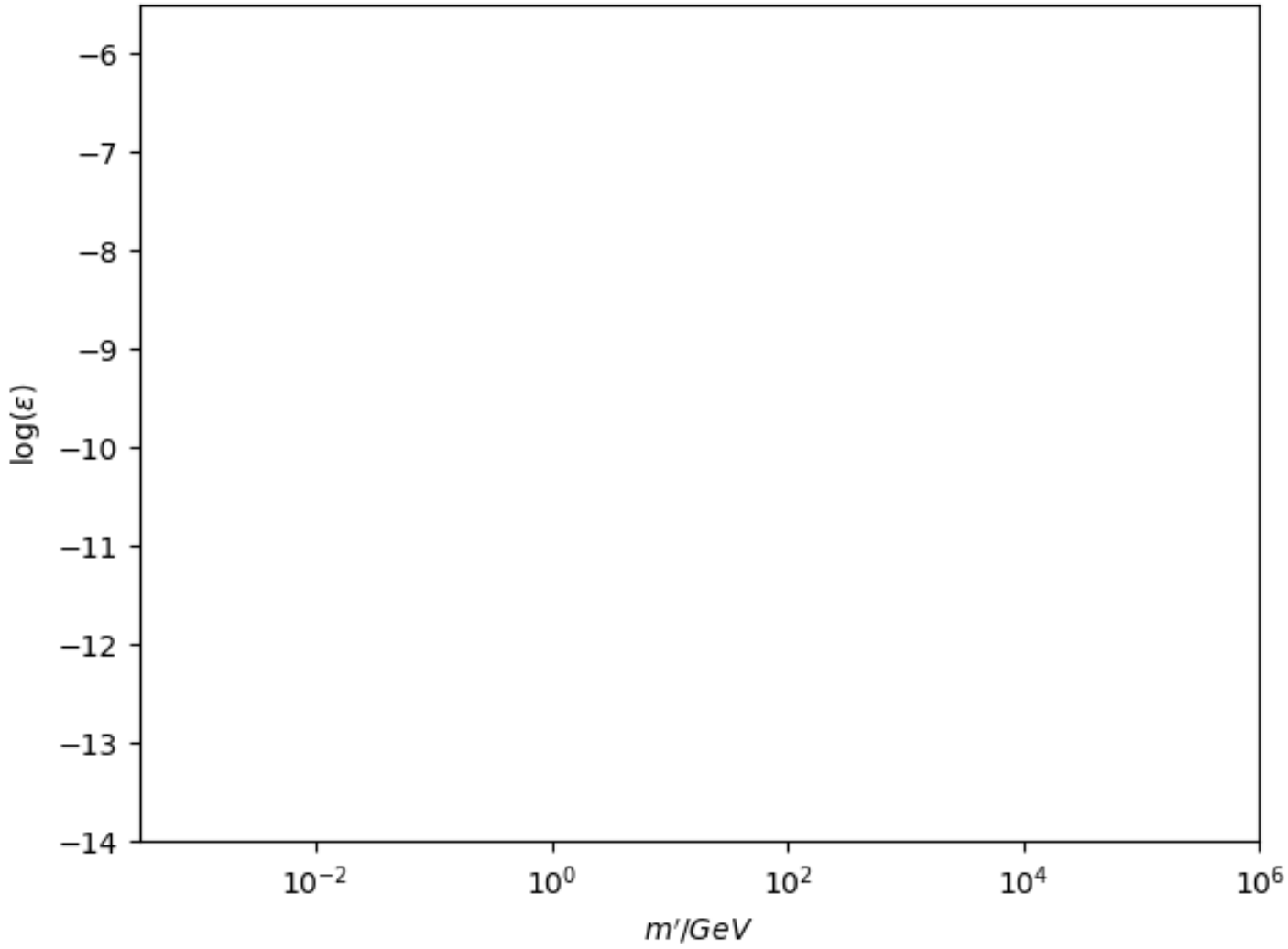
Important parameters to track

- Temperature ratio $\boldsymbol{\xi = T'/T}$
- Energy density fractions $\boldsymbol{\rho'/\rho_t}$ and $\boldsymbol{\rho/\rho_t}$
- Total entropy production factor $\boldsymbol{S_t/S_{t,i}}$

Nonrelativistic decay:

$$\frac{S_{t,f}}{S_{t,i}} \approx \frac{S_f}{S'_i} \approx \left(\frac{g_*}{g'_*}\right)^{1/4} \left(\frac{\tau'}{t_{\rm nr}}\right)^{1/2}$$

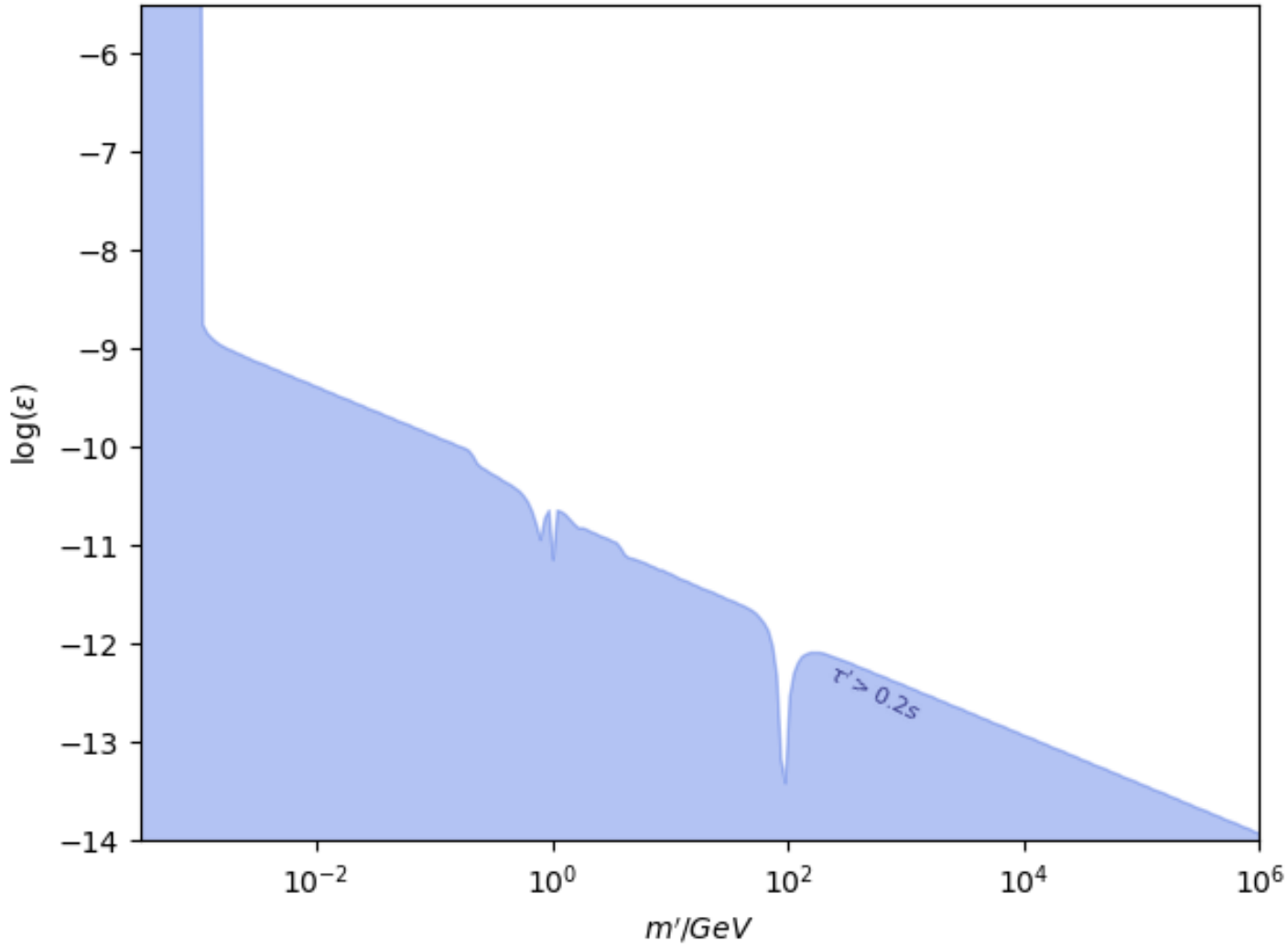
Constraints on the Dark photon characteristics In a dominant Hidden sector ($\xi \gg 1$)



Constraints on the Dark photon characteristics In a dominant Hidden sector ($\xi \gg 1$)

- Decay before BBN :

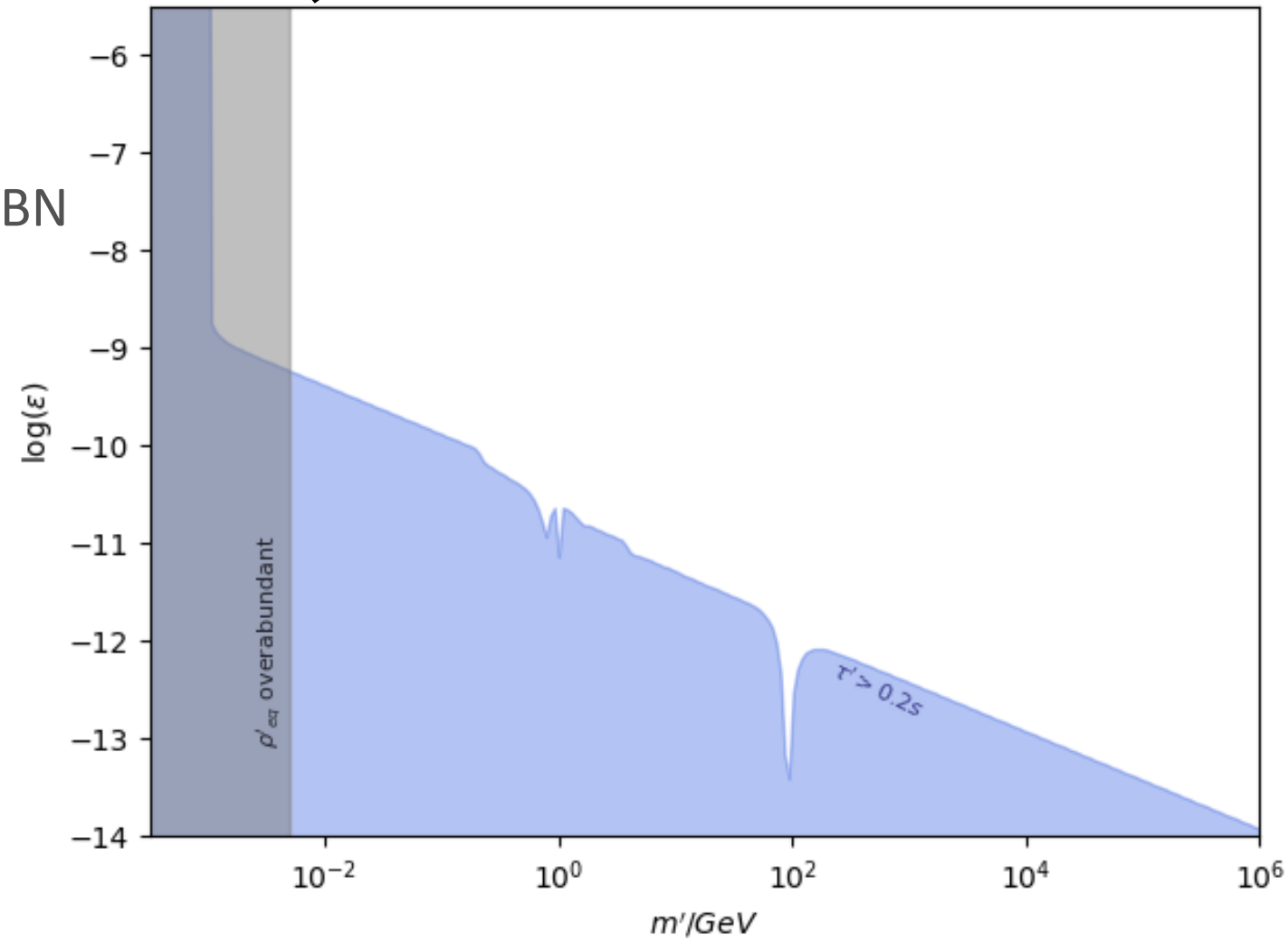
$$\Gamma' \sim \varepsilon^2 m' > \frac{1}{0.2s}$$



Constraints on the Dark photon characteristics In a dominant Hidden sector ($\xi \gg 1$)

- Decay before BBN
- Equilibrium density underabundant at BBN **(1712.03972, Hufnagel et al.)**:

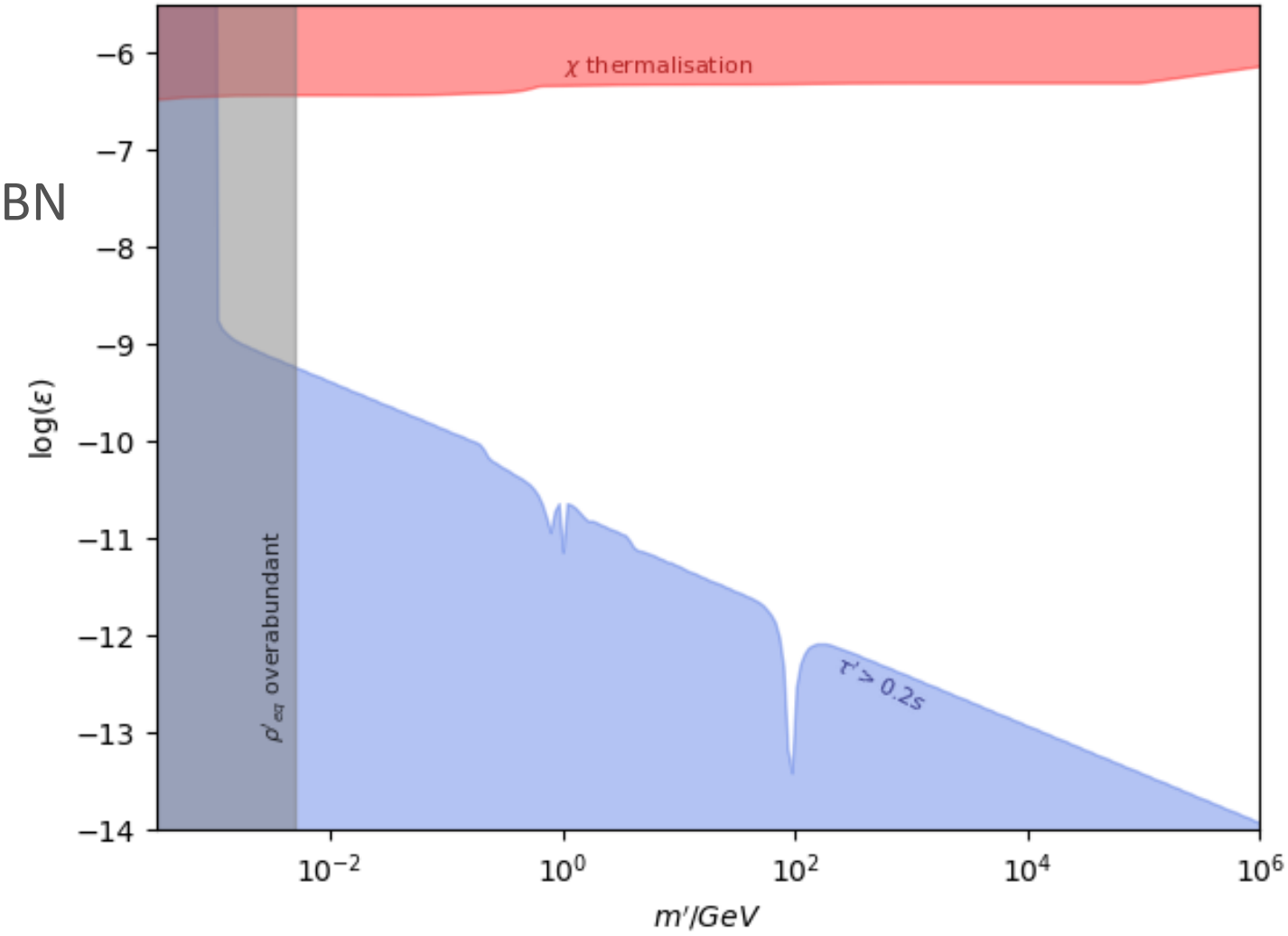
$$\rho'_{eq}(T_{BBN}) < 0.04\, \rho_{eq}(T_{BBN})$$



Constraints on the Dark photon characteristics In a dominant Hidden sector ($\xi \gg 1$)

- Decay before BBN
- Equilibrium density underabundant at BBN **(1712.03972, Hufnagel et al.)**
- Non thermalisation of DM before FO:

$$\frac{n_\chi \langle \sigma_{\chi\bar{\chi}\to f\bar{f}} v \rangle_{FO}}{H_{FO}} < 1$$



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- Decay before BBN
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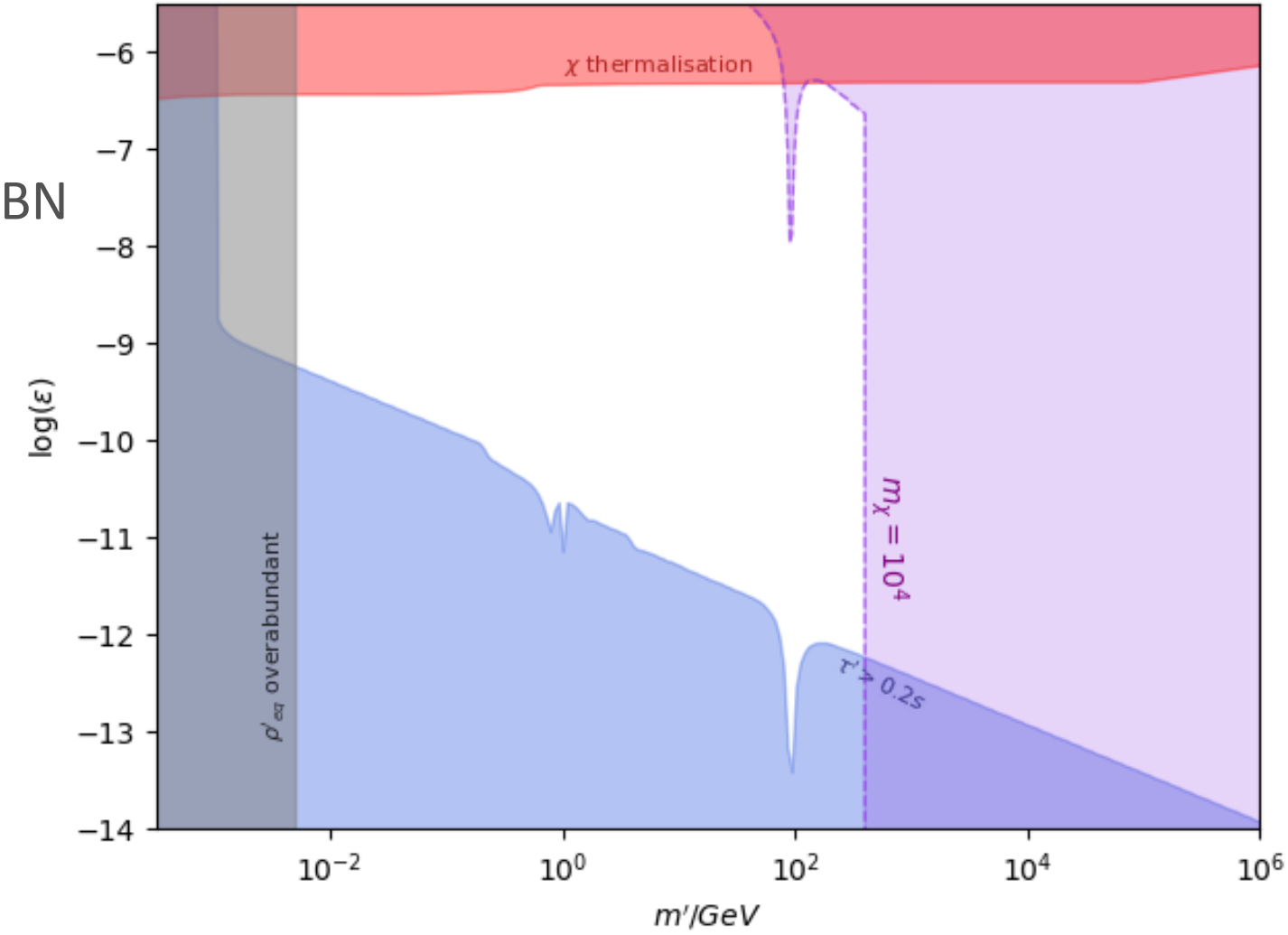
- Non thermalisation of DP before FO:

$$\frac{\langle \Gamma' \rangle_{FO}}{H_{FO}} < 1$$



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- Decay before BBN
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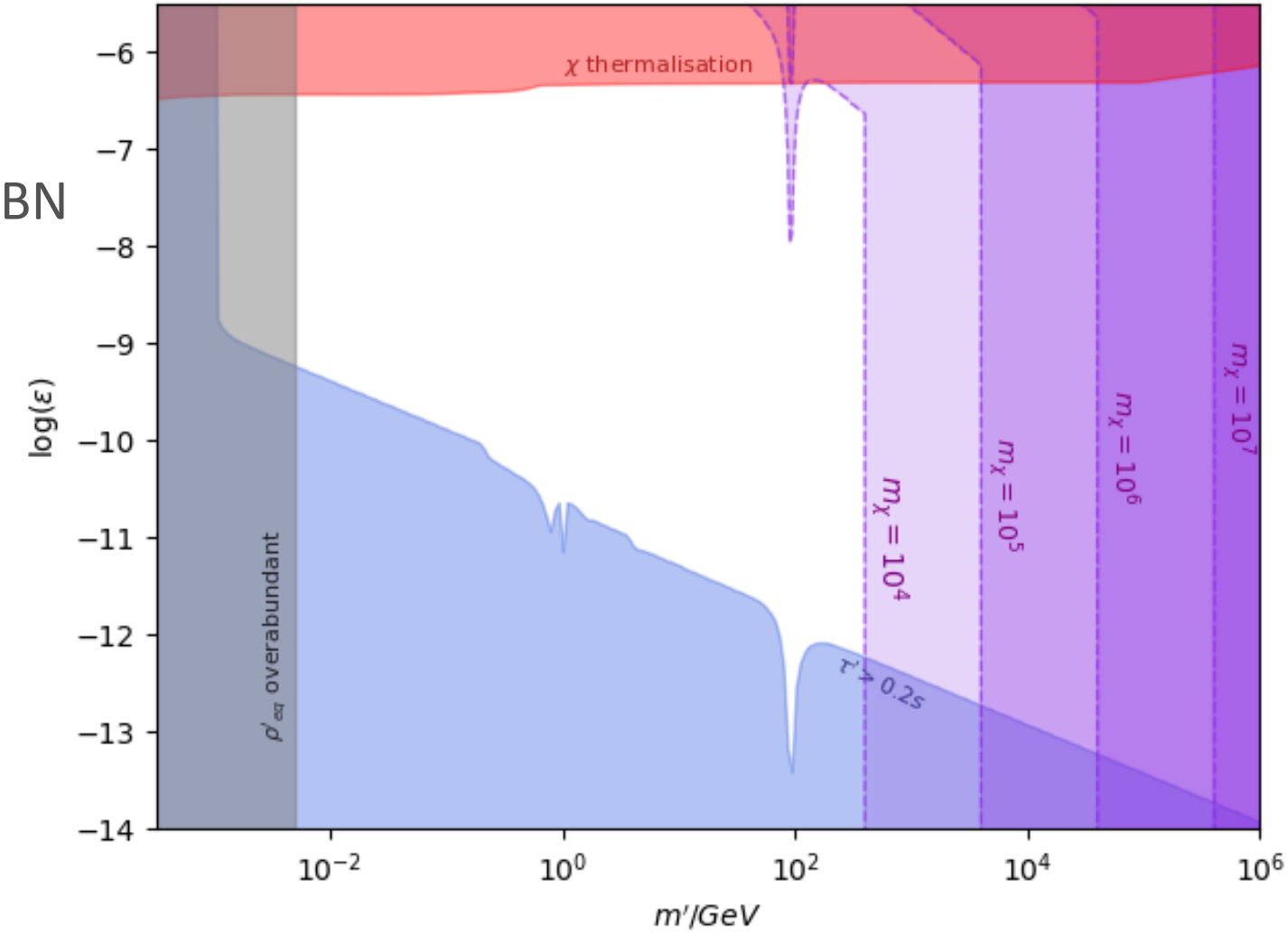
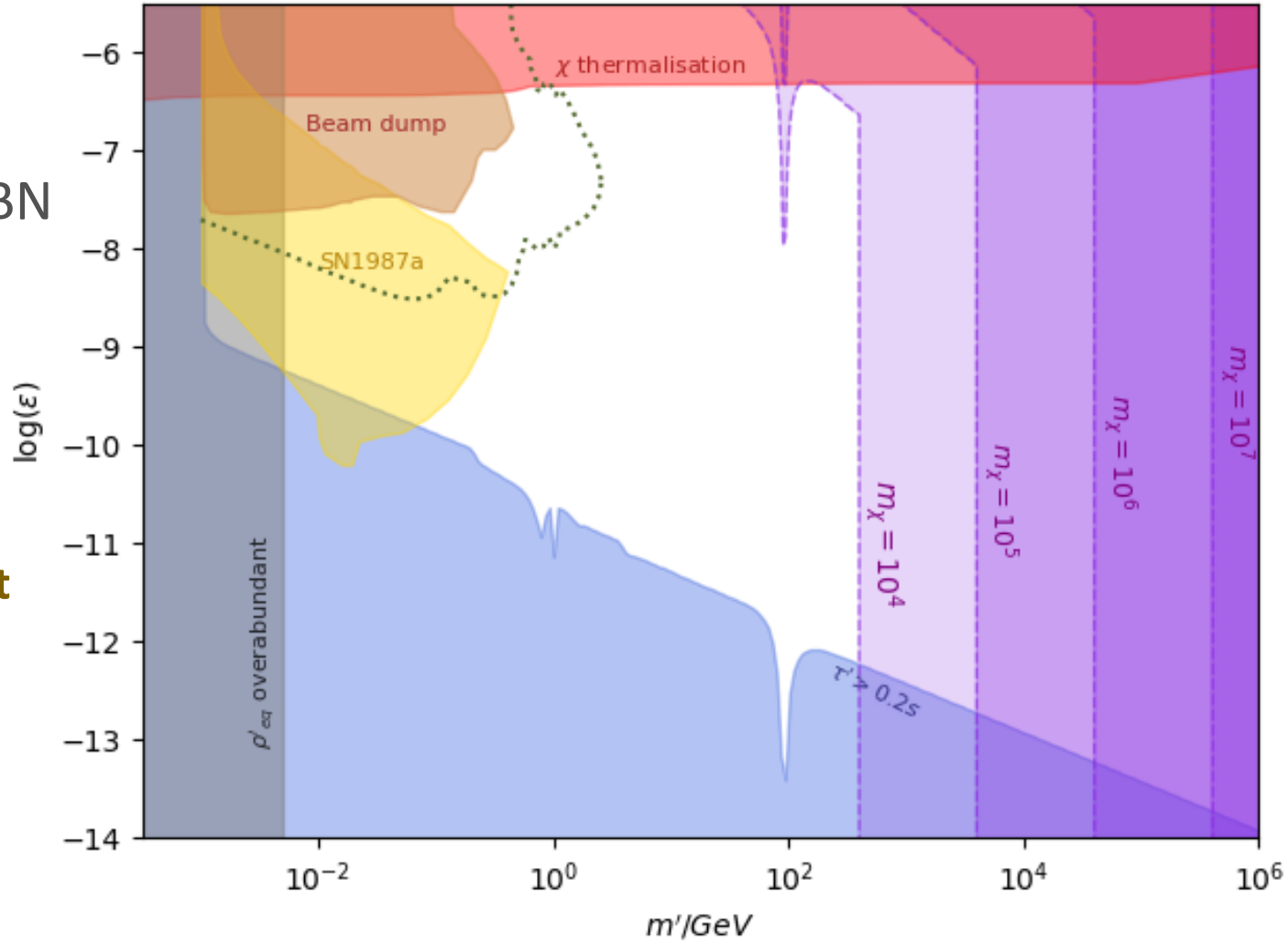
- Non thermalisation of DM before FO
- Non thermalisation of DP before FO:

$$\begin{cases} \dfrac{\langle \Gamma' \rangle_{FO}}{H_{FO}} < 1 \\ m_{\gamma'} < m_\chi / x'_{FO} \end{cases}$$



Constraints on the Dark photon characteristics In a dominant Hidden sector ($\xi \gg 1$)

- Decay before BBN
- Equilibrium density underabundant at BBN **(1712.03972, Hufnagel et al.)**
- Non thermalisation of DM before FO
- Non thermalisation of DP before FO
- Present (and future) experimental and observational bounds **(1611.05852, Hardy et al., 1803.05466, Bauer et al.)**



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- Decay before BBN
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- Non thermalisation of DP before FO
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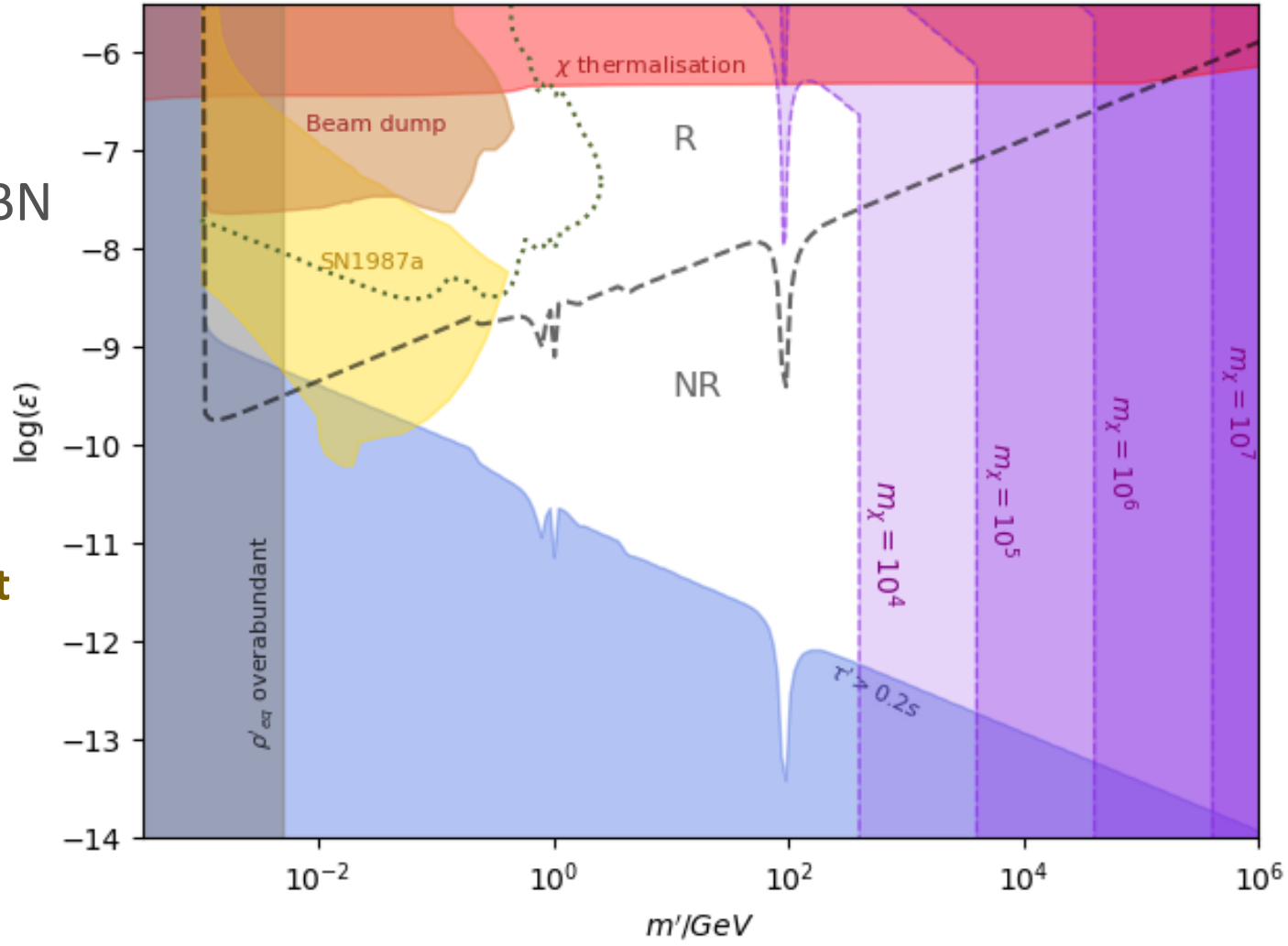
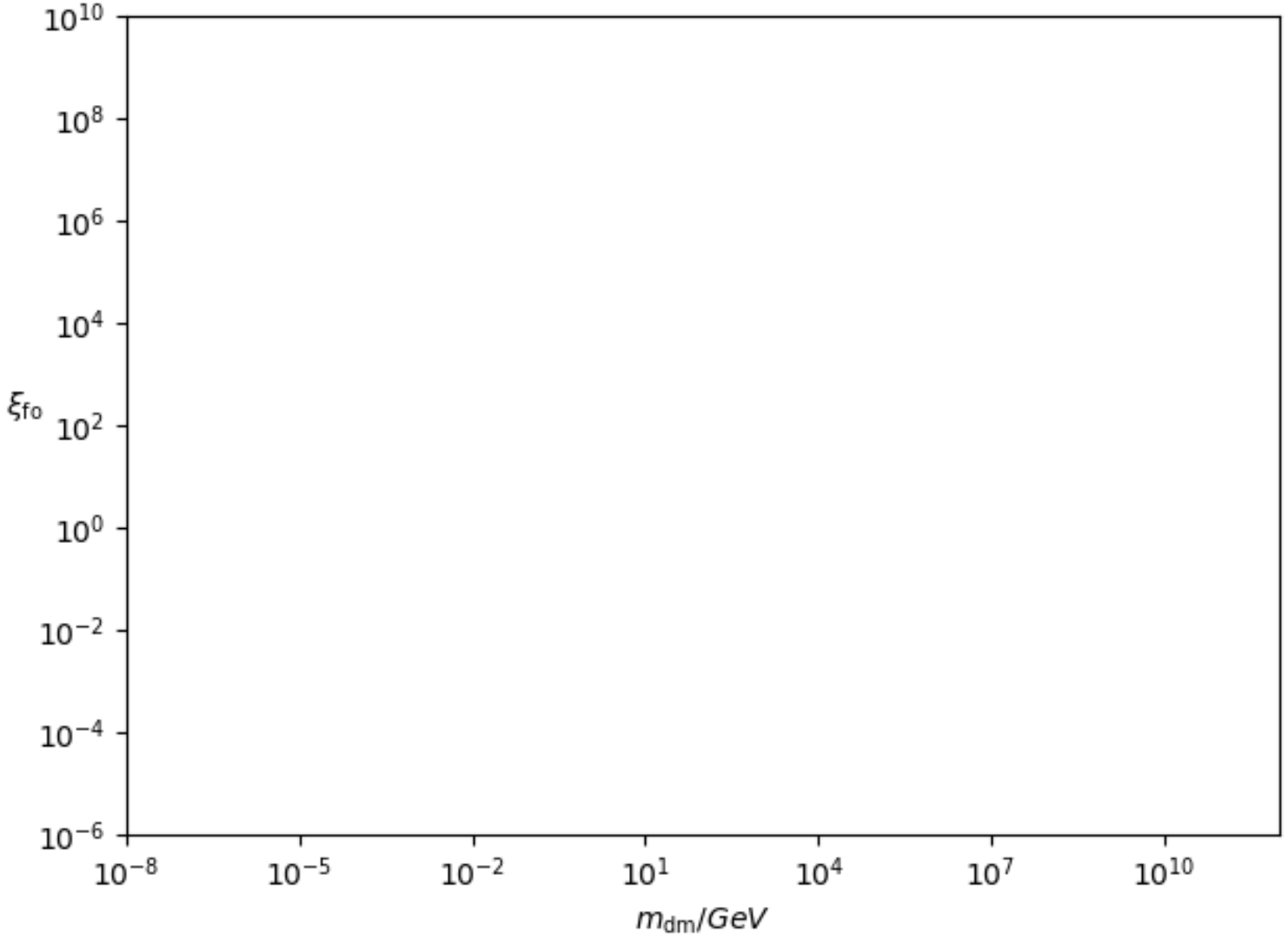
- Classification of points corresponding to Relativistic (R) and Non Relativistic (NR) decay



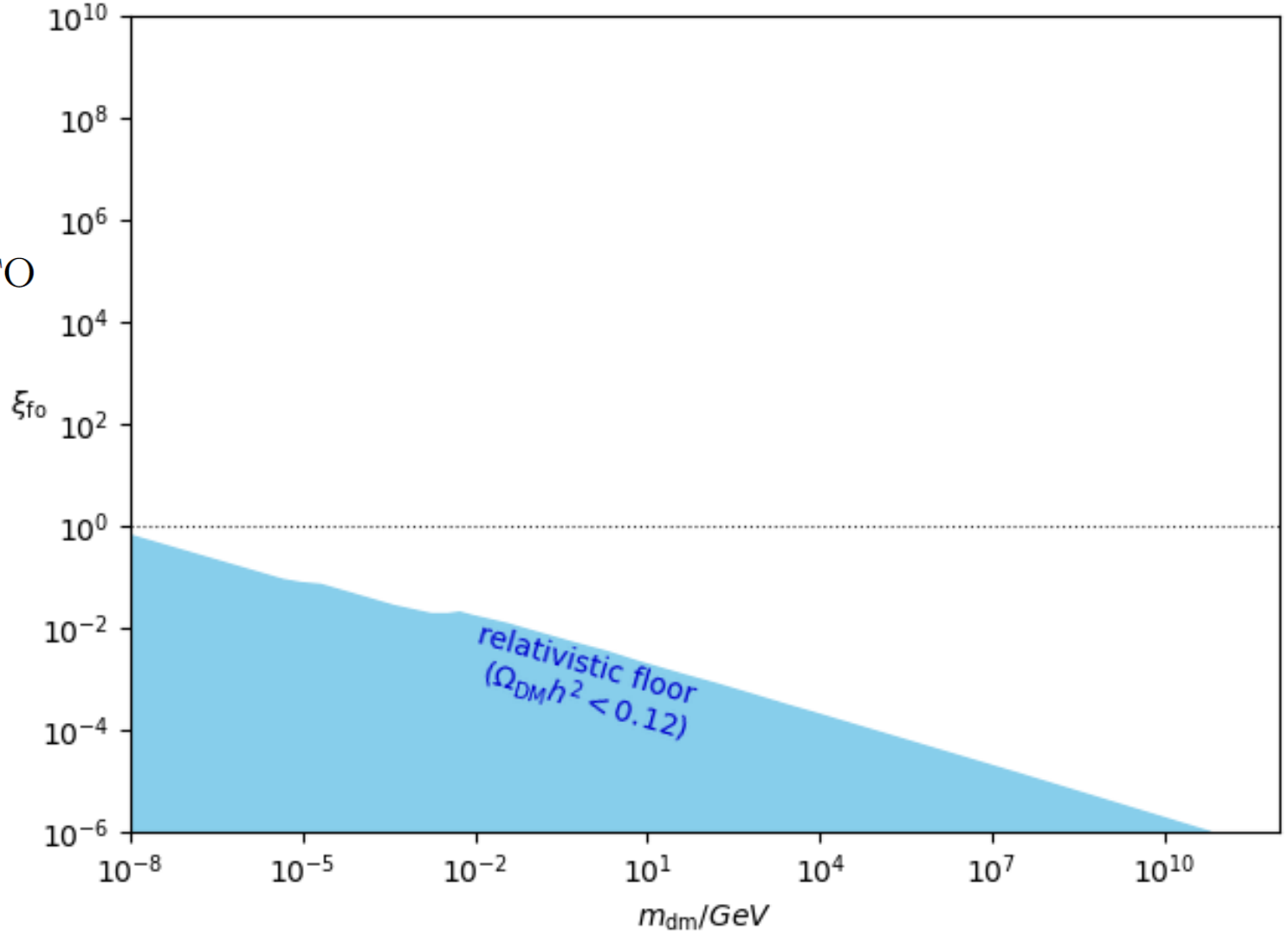
Constraints on the dark matter domain



Constraints on the dark matter domain

- Relativistic freeze-out: maximal relic density

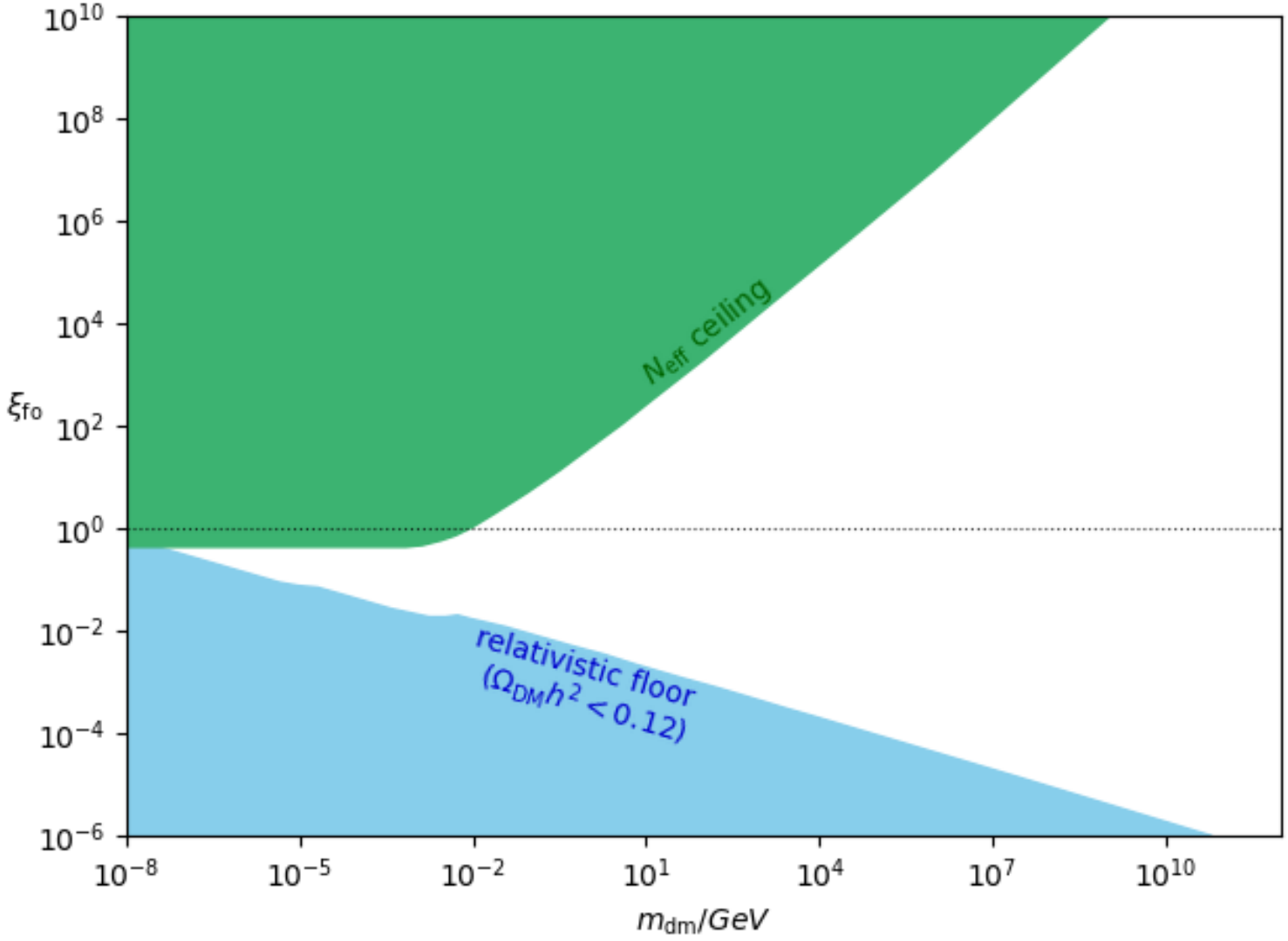
$$\Omega_\chi h^2 = 0.12 \left(\frac{g_{*s,0}}{g_{*s,\mathrm{FO}}}\right) \left(\frac{m_\chi}{6\mathrm{eV}}\right) \xi_{\mathrm{FO}}^3$$



Constraints on the dark matter domain

- Relativistic freeze-out: maximal relic density
- Non-dominating DM during BBN

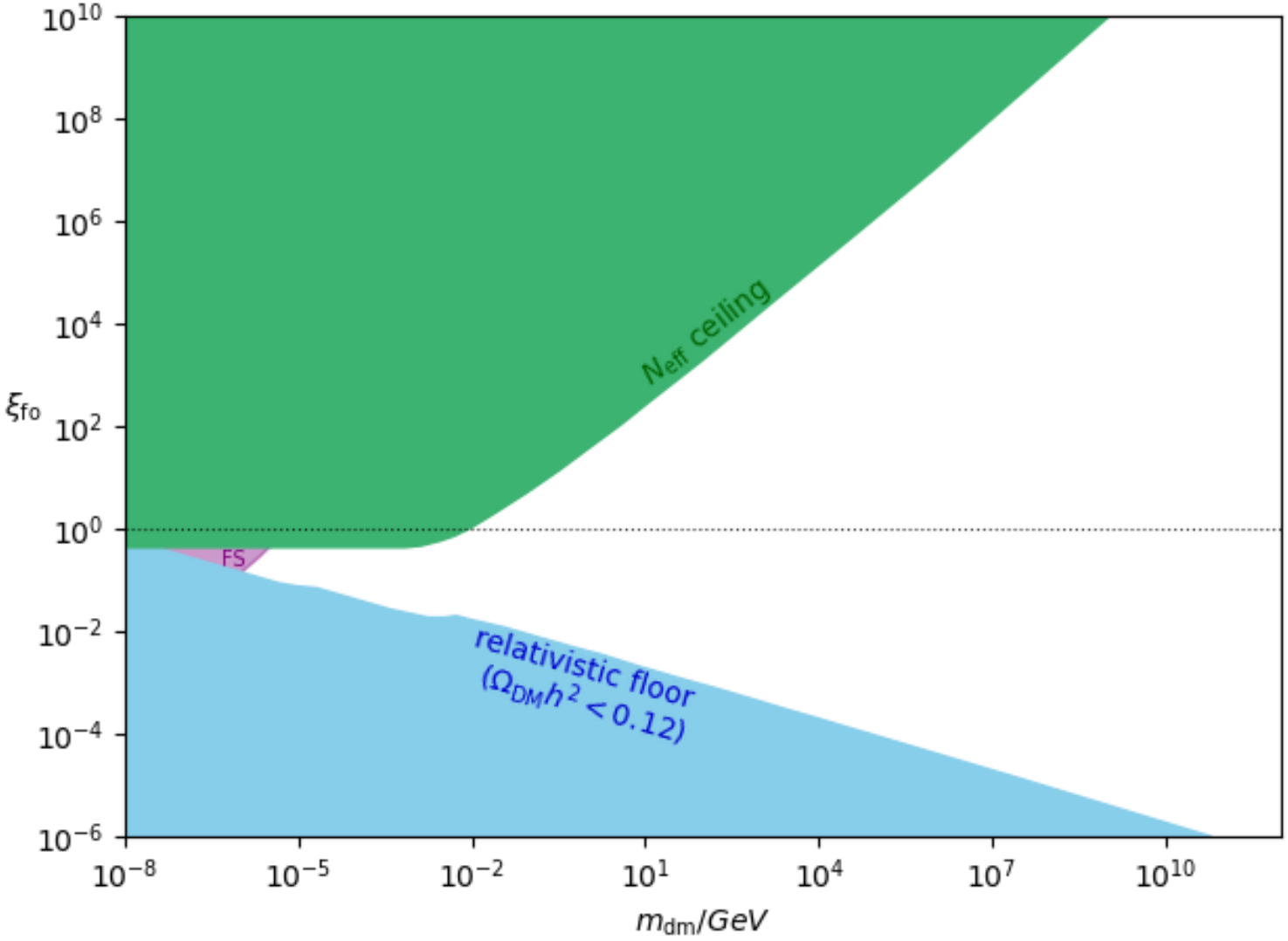
$$\xi \lesssim m_\chi/\mathrm{MeV} \quad (\mathrm{if}\ \mathrm{m}_\chi \geq \mathrm{MeV})$$



Constraints on the dark matter domain

- Relativistic freeze-out: maximal relic density
- Non-dominating DM during BBN
- Upper limit on the free-streaming (FS) length:

$$\lambda_{\rm FS} \propto \xi/m_\chi \lesssim 0.066{\rm Mpc} \quad (\xi < 1)$$

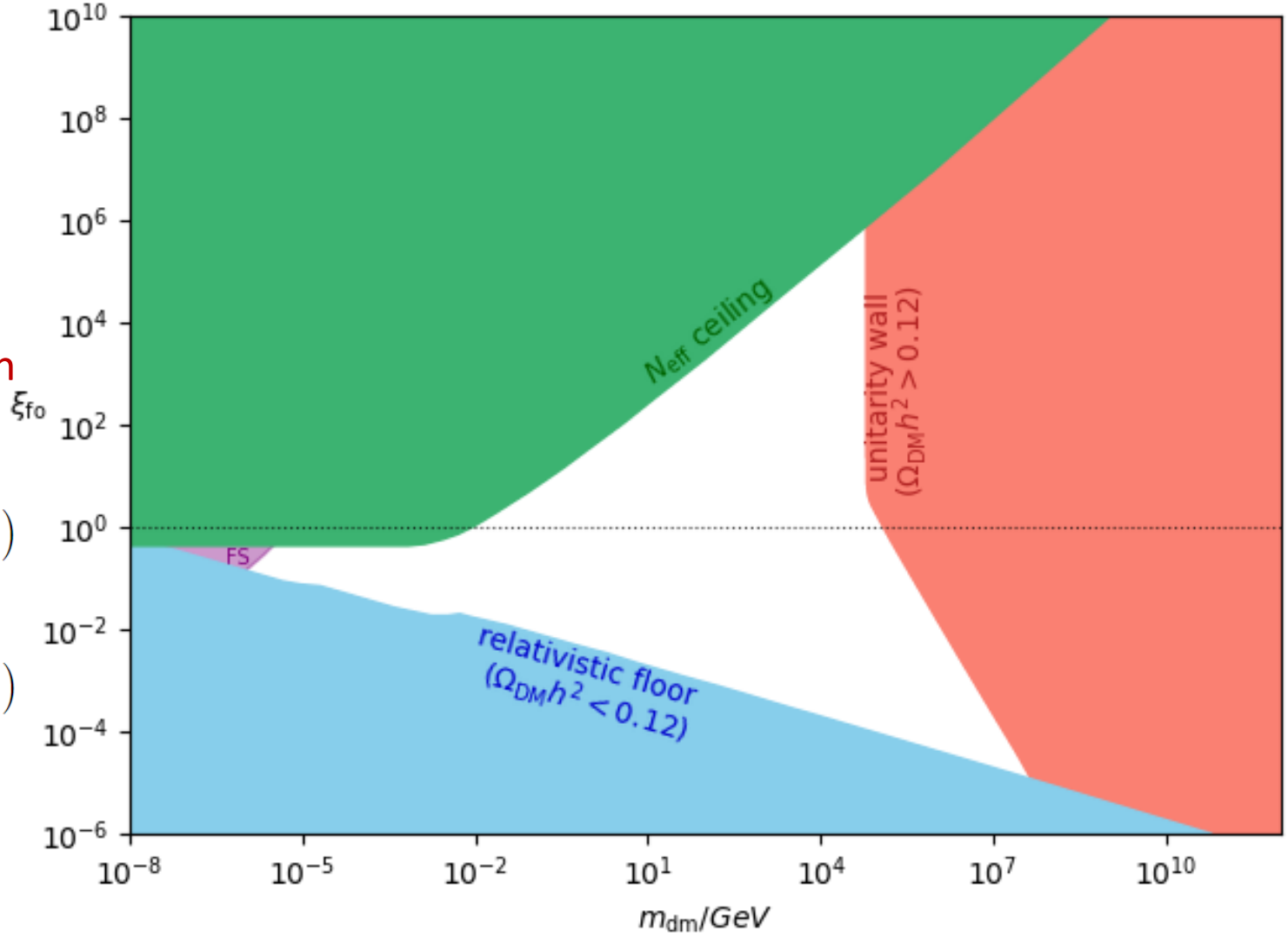


Constraints on the dark matter domain

- Relativistic freeze-out: maximal relic density
- Non-dominating DM during BBN
- Upper limit on the free-streaming (FS) length
- Non-relativistic FO with maximal cross section (unitarity): minimal relic density

$$\Omega_\chi h^2 \simeq 1.6 \times 10^8 \frac{{x'_{\rm FO}}^{1/2} m_\chi^2}{m_{\rm Pl}\sqrt{g_*}} \xi_{\rm FO} \quad (\xi_{\rm FO} \ll 1)$$

$$\Omega_\chi h^2 \simeq 1.6 \times 10^8 \frac{{x'_{\rm FO}}^{1/2} m_\chi^2}{m_{\rm Pl}\sqrt{g'_*}} \quad (\xi_{\rm FO} \gg 1)$$



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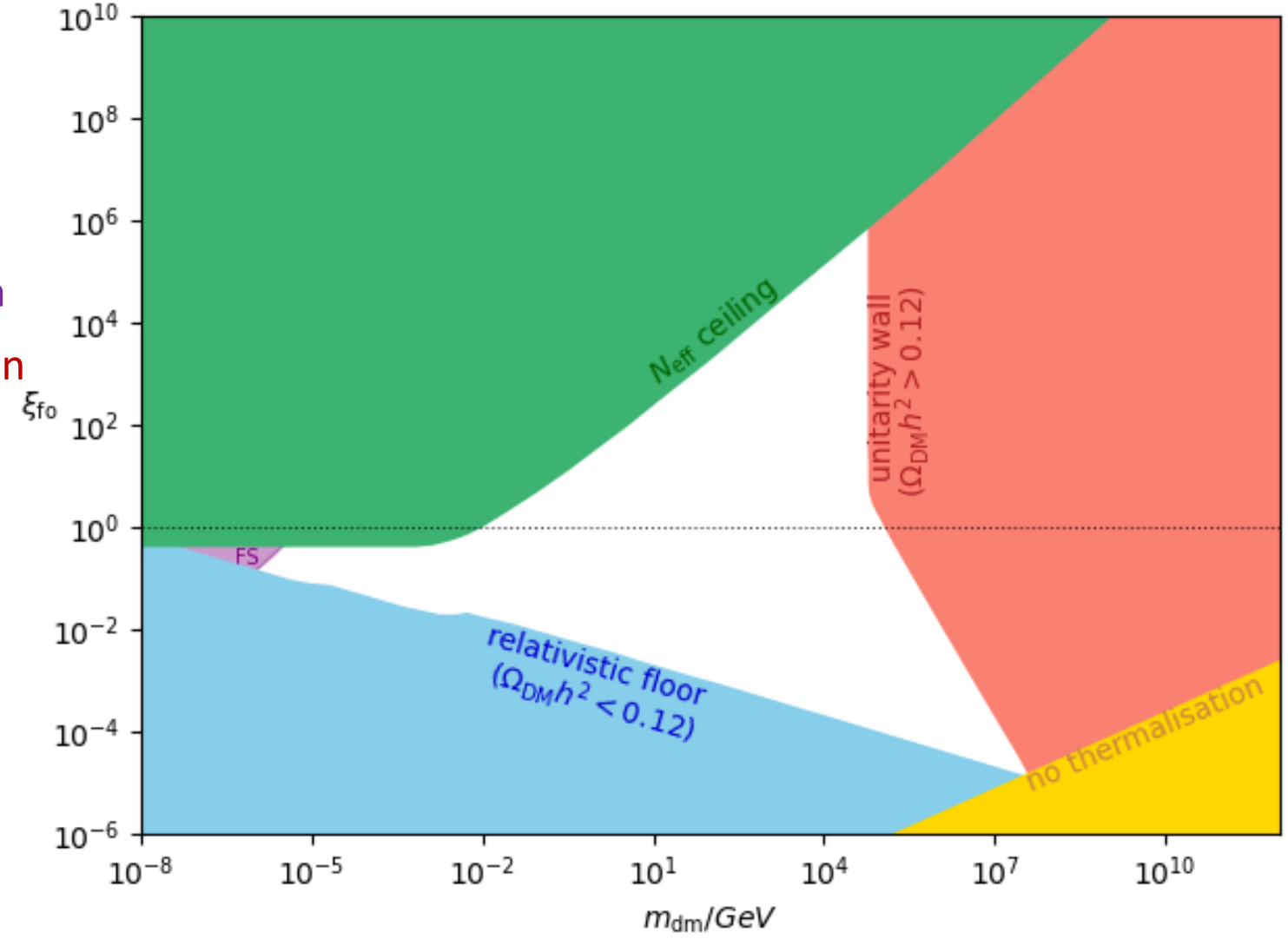
- Relativistic freeze-out: maximal relic density
- Non-dominating DM during BBN
- Upper limit on the free-streaming (FS) length
- Non-relativistic FO with maximal cross section (unitarity): minimal relic density
- Freeze-out in a subdominant secluded thermalised sector :

$$\left.\frac{n_\chi \langle \sigma v \rangle_{\chi\bar{\chi}\to\gamma'\gamma'}}{H}\right|_{T'=m_\chi} \gtrsim 1$$

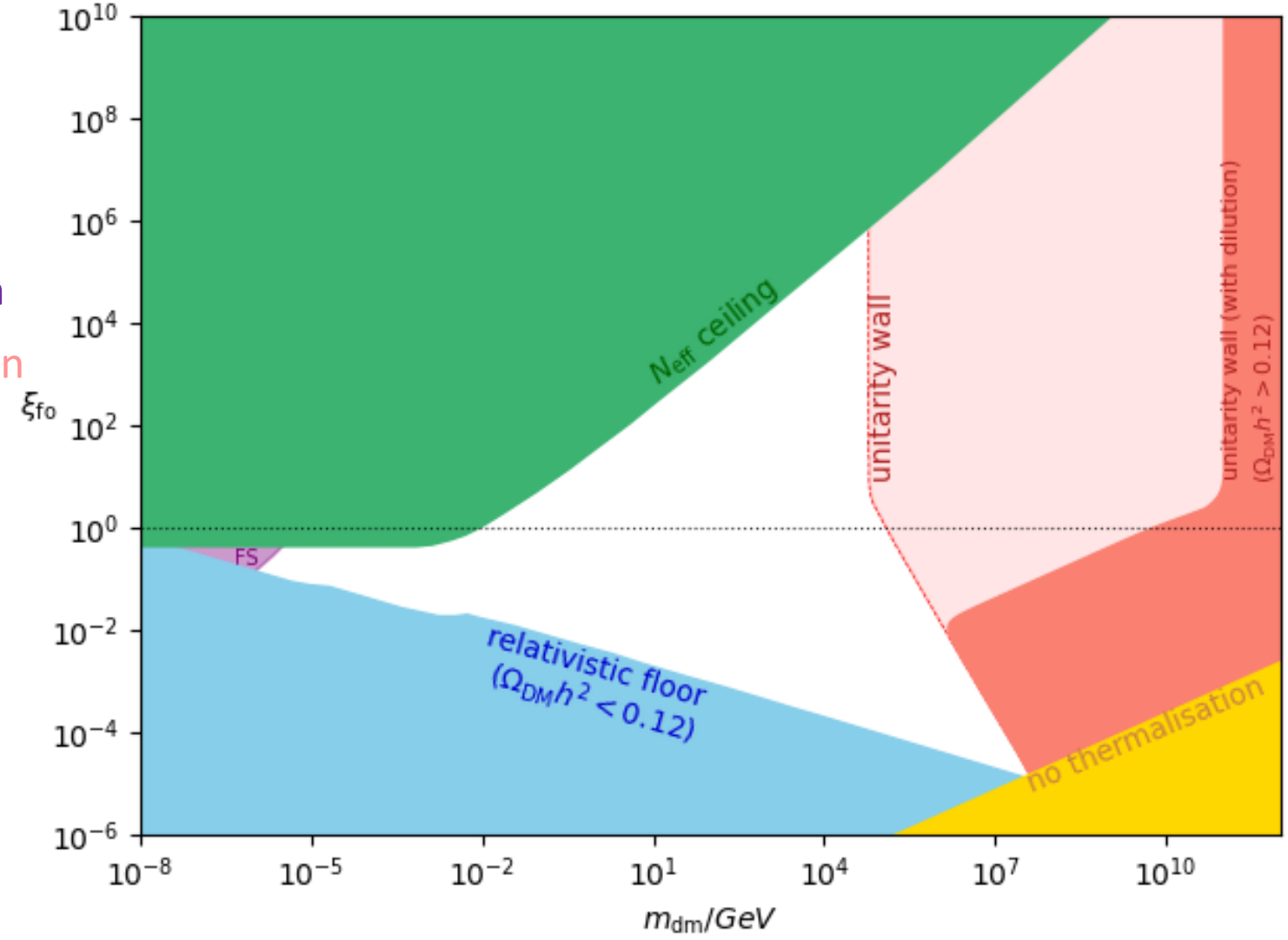
These constraints have been established previously **(2105.01263, Coy et al.)**



Constraints on the dark matter domain

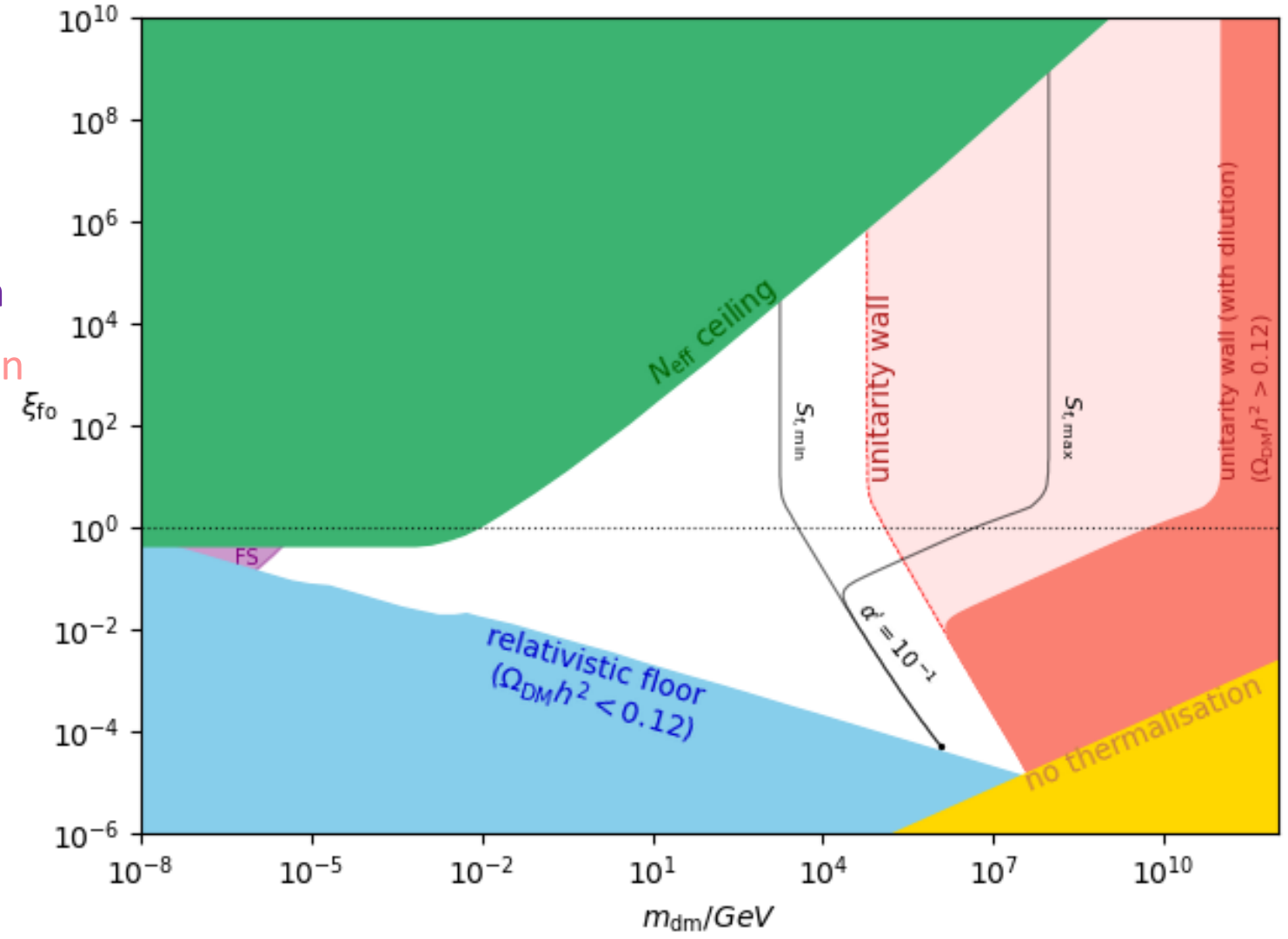
- Relativistic freeze-out: maximal relic density
- Non-dominating DM during BBN
- Upper limit on the free-streaming (FS) length
- Non-relativistic FO with maximal cross section (unitarity): minimal relic density
- Freeze-out in a secluded thermalised sector **(2105.01263, Coy et al.)**
- DM relic density entropy dilution

$$\Omega_\chi h^2 \longrightarrow \Omega_\chi h^2 \frac{S_{\mathrm{t,i}}}{S_{\mathrm{t,f}}}$$



Constraints on the dark matter domain

- Relativistic freeze-out: maximal relic density
- Non-dominating DM during BBN
- Upper limit on the free-streaming (FS) length
- Non-relativistic FO with maximal cross section (unitarity): minimal relic density
- Freeze-out in a secluded thermalised sector **(2105.01263, Coy et al.)**
- DM relic density entropy dilution
- Dark QED candidate : $\alpha' = 0.1$



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- Relativistic freeze-out: maximal relic density
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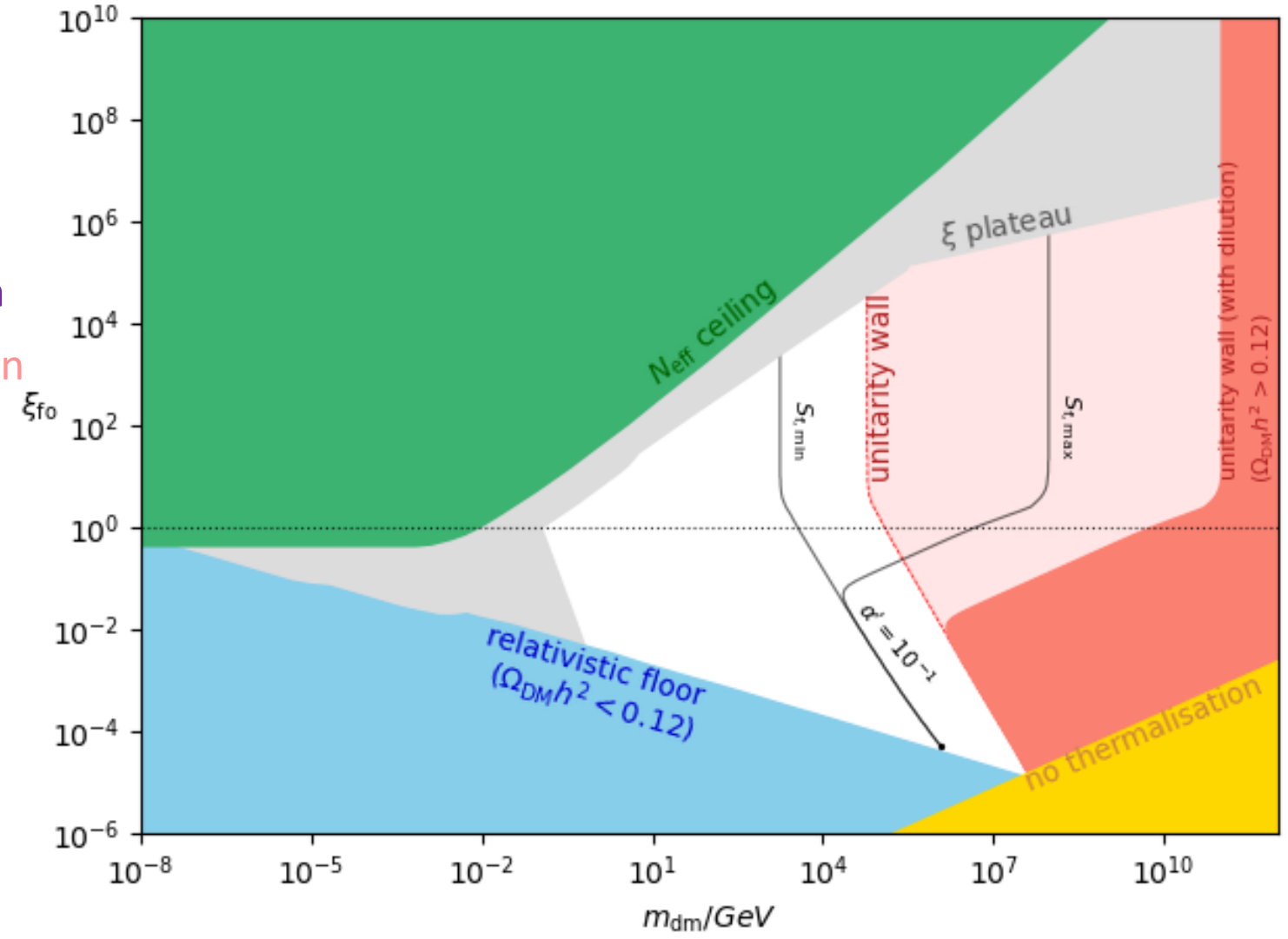
- Upper limit on the free-streaming (FS) length
- Non-relativistic FO with maximal cross section (unitarity): minimal relic density
- Freeze-out in a secluded thermalised sector **(2105.01263, Coy et al.)**
- DM relic density entropy dilution
- Dark QED candidate
- Secluded dark sector at DM freeze-out:

$$\kappa_{\rm FO} := \frac{1}{3}\xi_{\rm FO}^4 \frac{\langle \Gamma' \rangle_{T'_{\rm FO}}}{H_{\rm FO}} < 1 \quad (\xi_{\rm FO} > 1)$$



Conclusion

- Can we live with in a universe early dominated by a hot hidden sector ? Yes, but only within a given domain of parameters
- We have now an analytical model of a dark photon population's evolution, confirmed by numerical solutions
- We can thereby constrain the Dark photon characteristics (ε and $m_{\gamma'}$)
- With the Dark Photons domain, we can settle new constraints on the Dark Matter mass and temperature

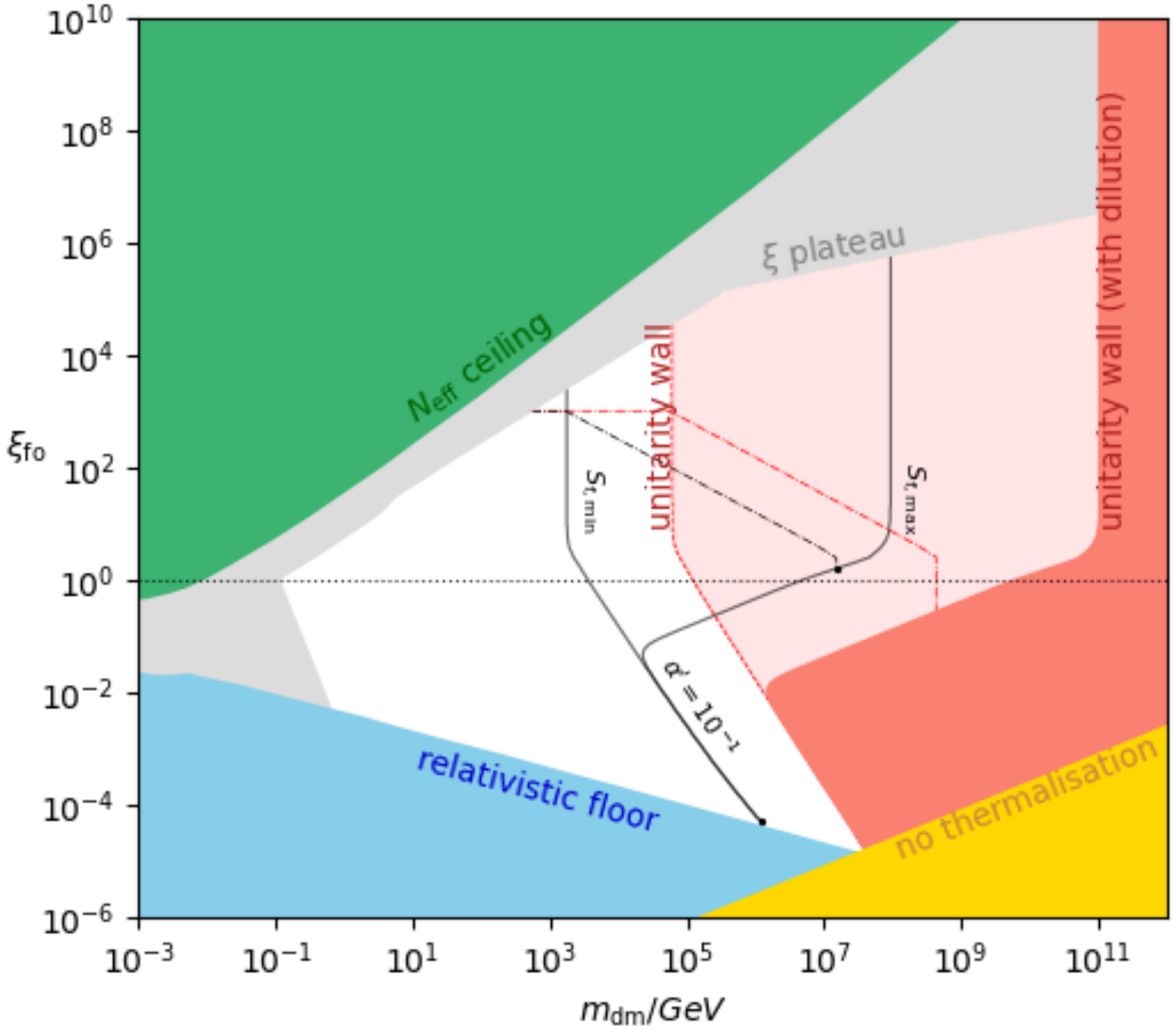
Baryogenesis constraint

The baryon number *B* in the early universe can be expressed as

$$B \sim 10^{-10} \sim \epsilon_B \left.\frac{n_\mathrm{B}}{s_\mathrm{t}}\right|_{T=T_B} \lesssim \left.\frac{n_\mathrm{B}}{s_\mathrm{t}}\right|_{T=T_B}$$

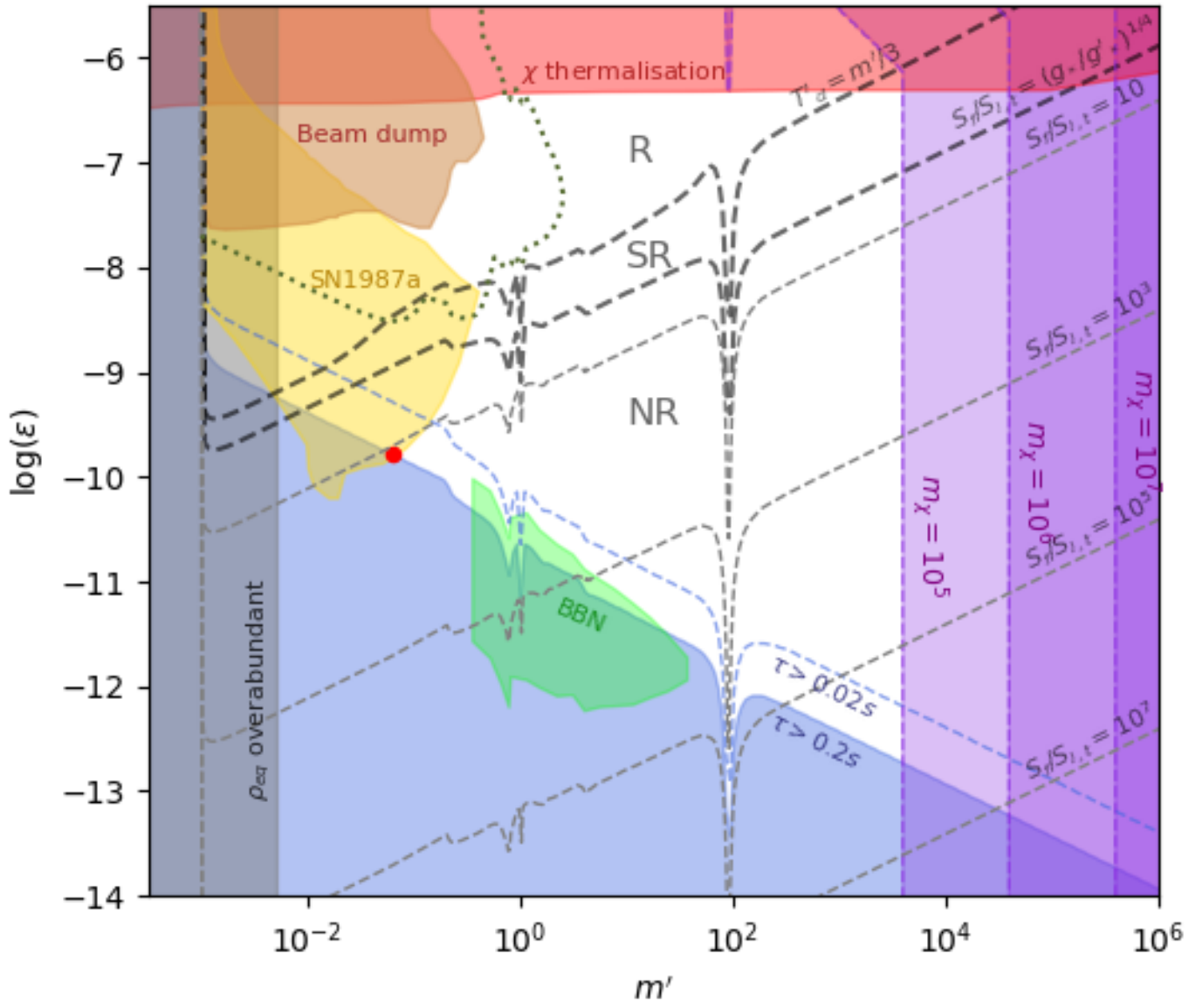
For a dominant dark sector:

$$\xi_B^3 \frac{S_{\mathrm{t,B}}}{S_{\mathrm{t,f}}} \lesssim B$$



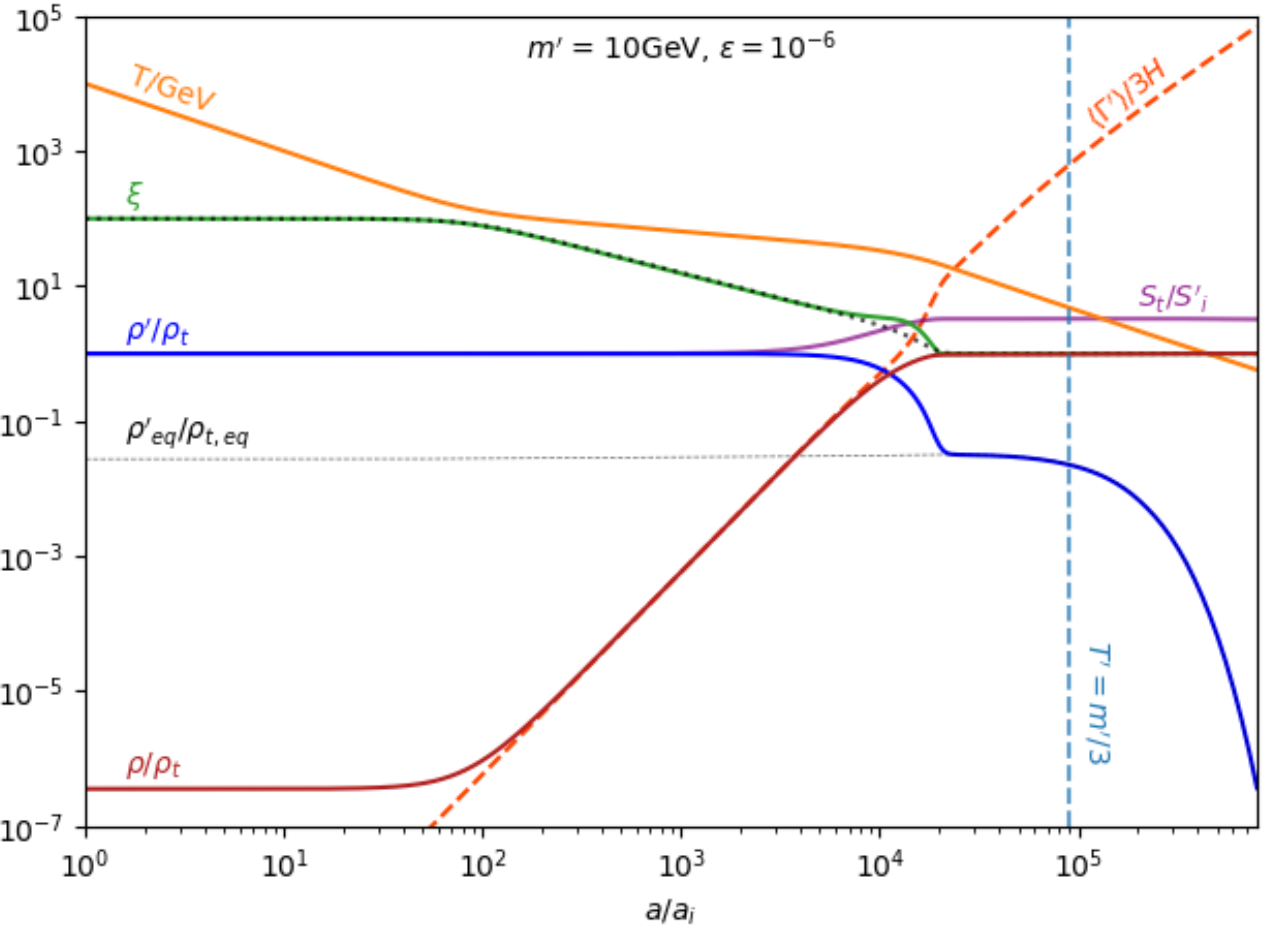
Dark photon domain

- Domains of relativistic (R) and nonrelativistic (NR) decay
- Level curves of entropy production
- Additional theoretical bound **(1605.07195, Berger et al.)**

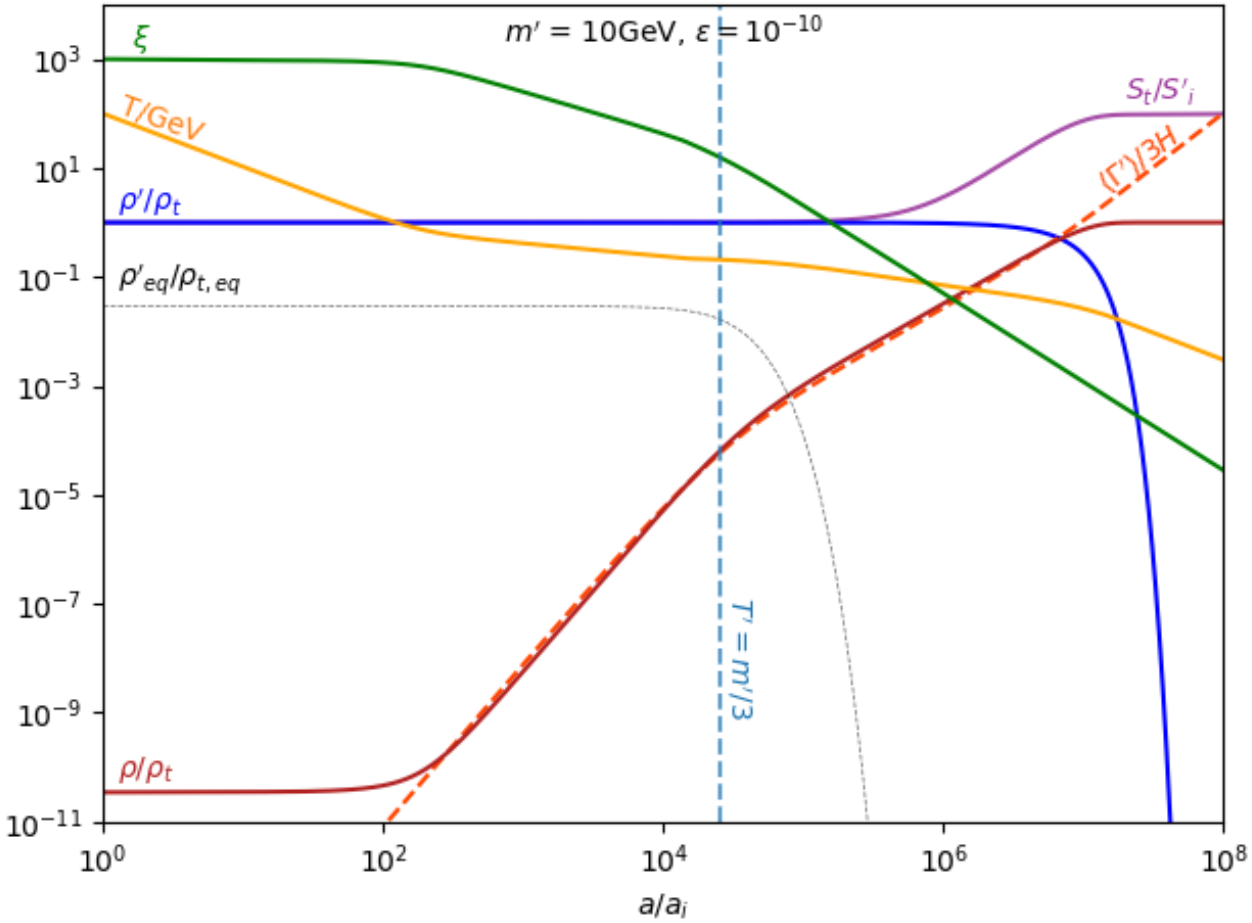


More detailed scenarios

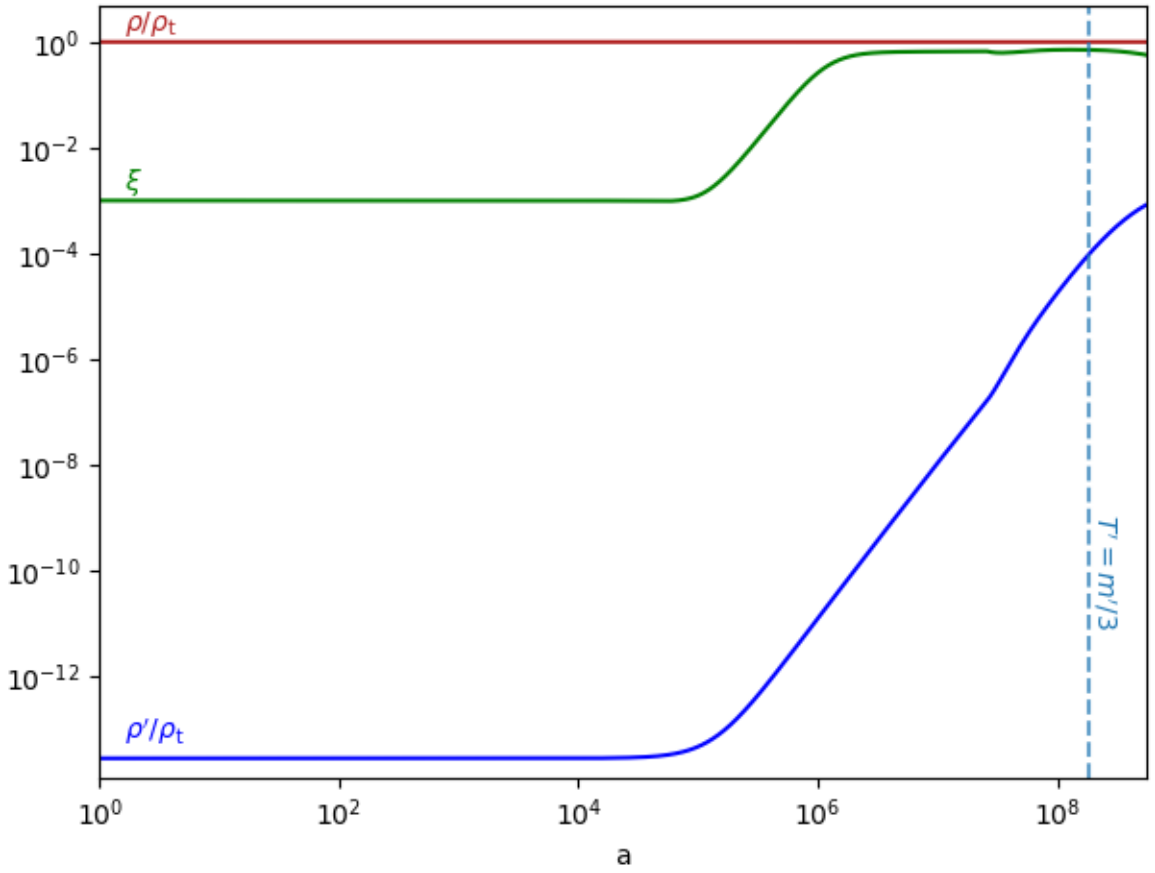
Relativistic thermalisation

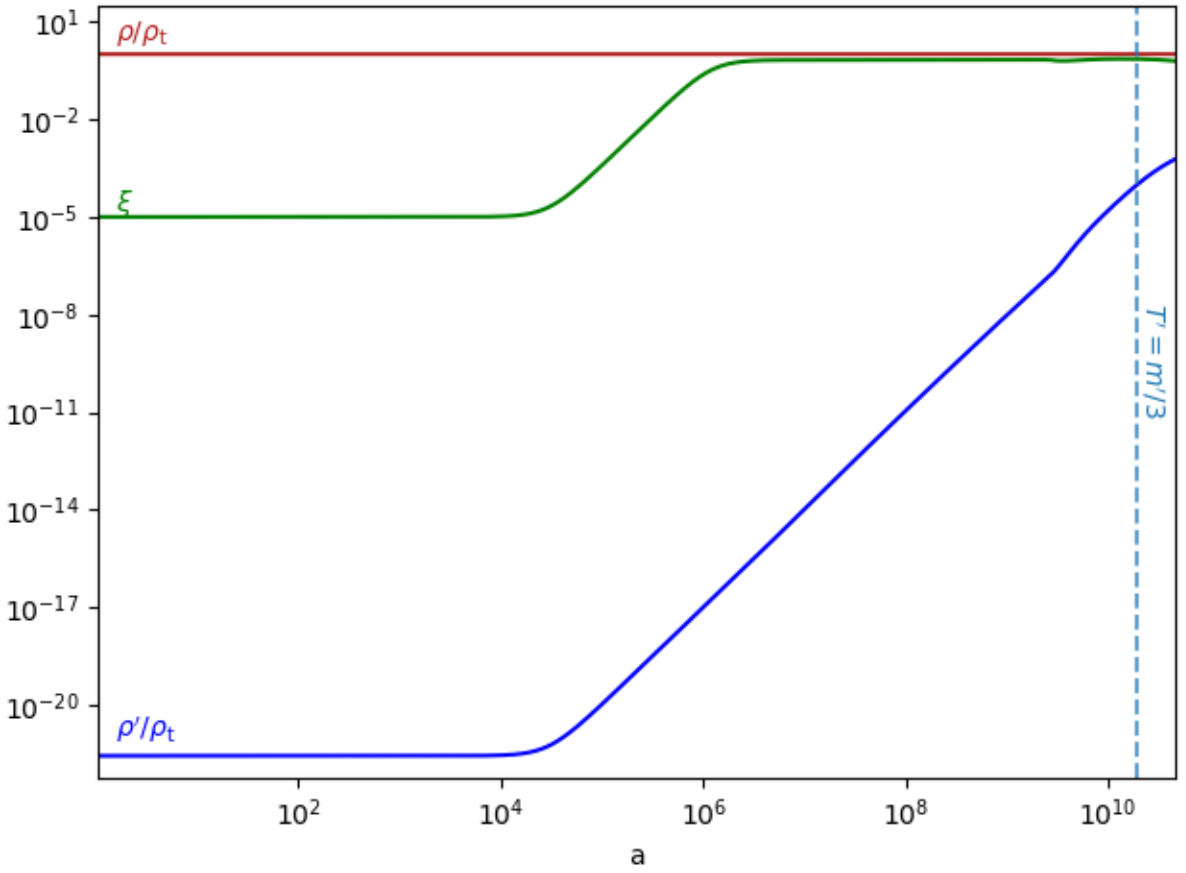


Non relativistic thermalisation



Scenarios with a subdominant Dark Photon (Freeze-in)





Parameter κ

$$\frac{d\rho'}{dt} + 3(1+\omega')H\rho' = m'\Gamma'\left[n'_{\rm eq}(T) - n'\right]$$

- **Dominant hidden sector:**

$$\kappa = \frac{1}{3}\frac{\rho'}{\rho}\frac{\langle\Gamma'\rangle}{H}$$

- **Dominant visible sector:**

$$\kappa = \frac{1}{3}\frac{\rho}{\rho'}\frac{\langle\Gamma'\rangle}{H}$$

- Plateau (decoupled sectors) → κ << 1
- Attractor (thermalisation) → κ = O(1)
- Thermalised sectors → κ > 1