History of a hidden sector

From production to thermalisation

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Based on

R. Coy, JK, M. Tytgat, *JCAP* 02 (2025) 077 (arXiv:2405.10792)
S. Cléry, JK, M. Tytgat, arXiv:25XX.XXXXX

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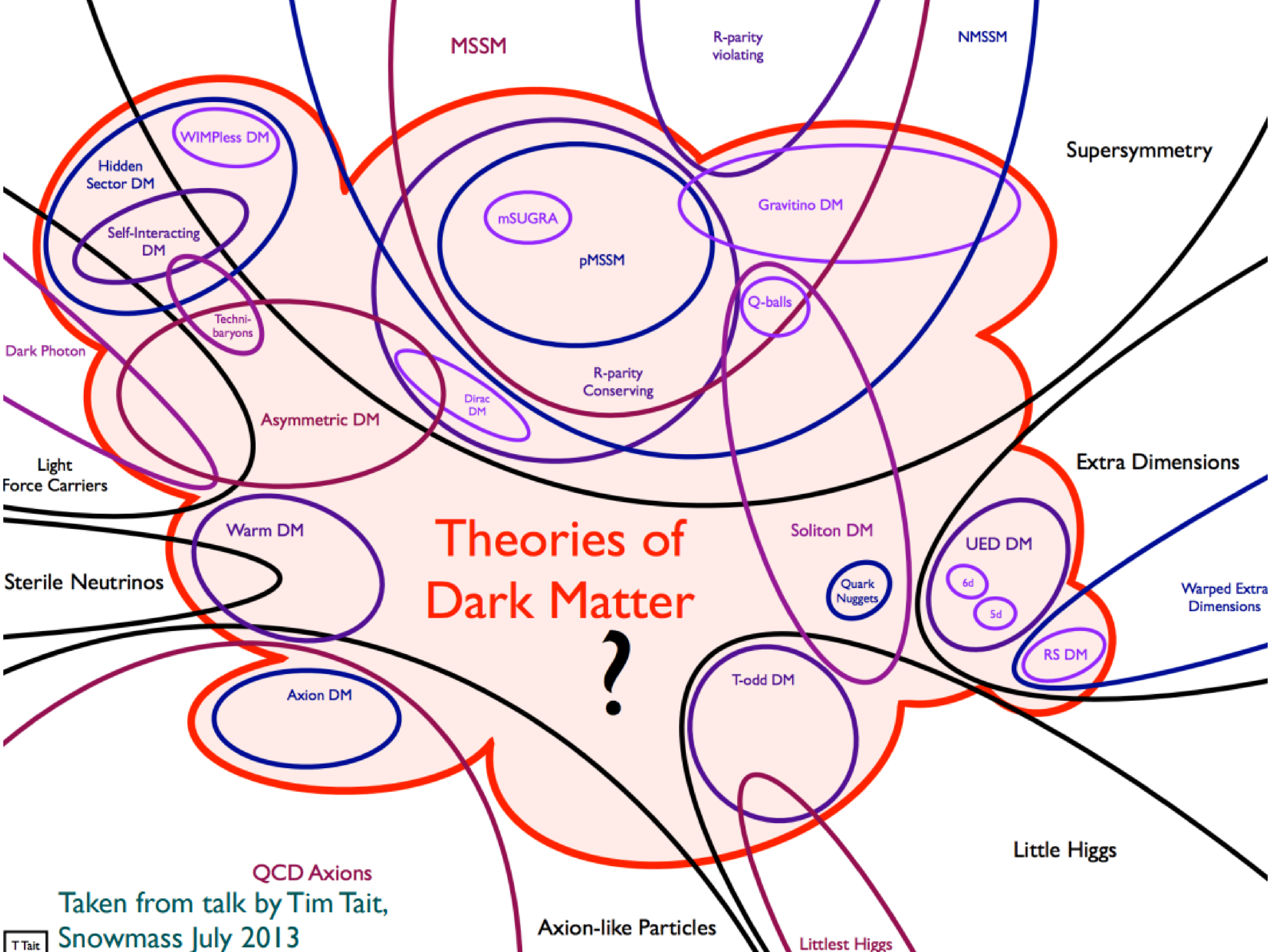
Outline

- **Hidden sectors (HS)**
- **Unitarity limit on DM mass**
- **Impact of entropy dilution**

- **How to produce hidden sectors: asymmetric reheating**
- **HS thermalisation** (in progress)



Taken from talk by Tim Tait, Snowmass July 2013

Hidden sector (HS) dark matter

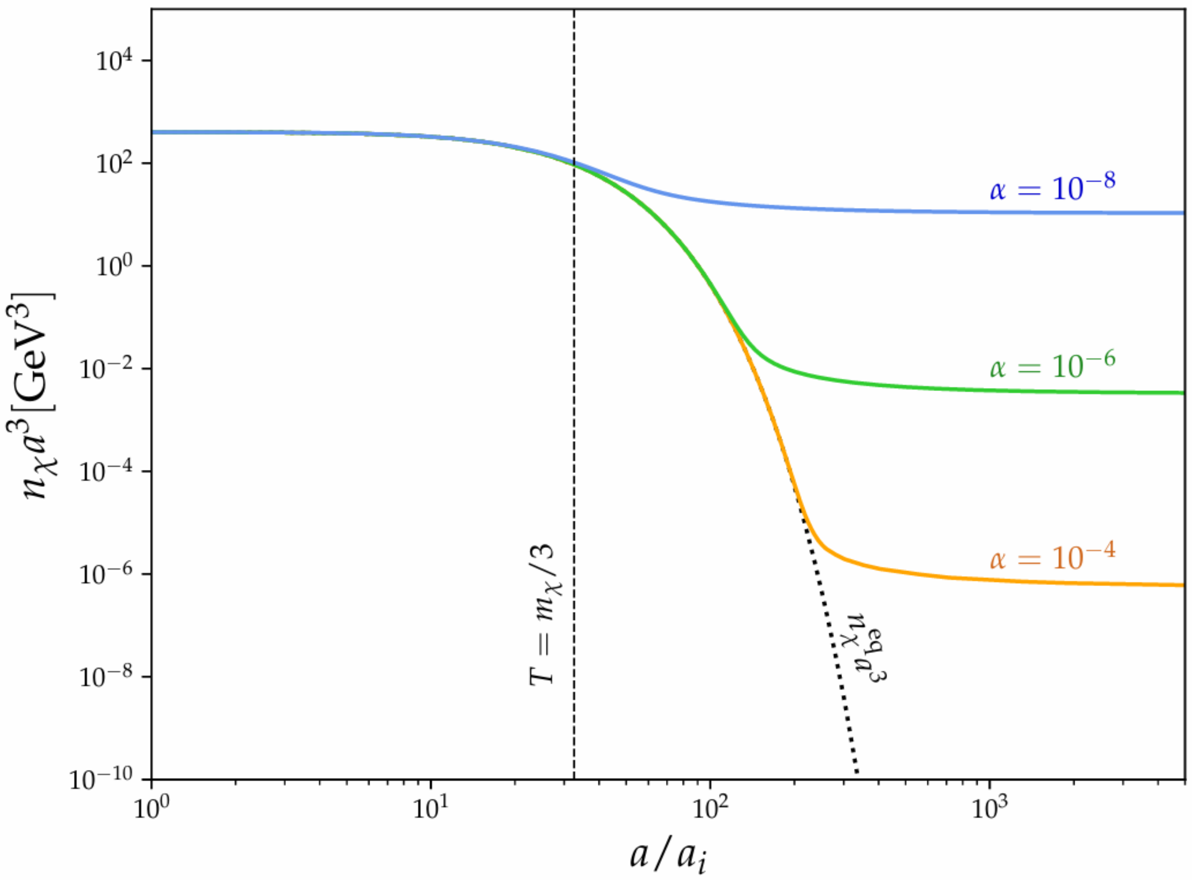
- « Visible sector » dark matter : **fully thermalised** Universe
- Standard WIMP scenario : DM freeze-out at $T \sim m_\chi$

→ Relic abundance:

$$\Omega_\chi h^2 \simeq \frac{10^9}{\langle \sigma v \rangle m_{\rm Pl} \text{GeV}} = 0.12$$

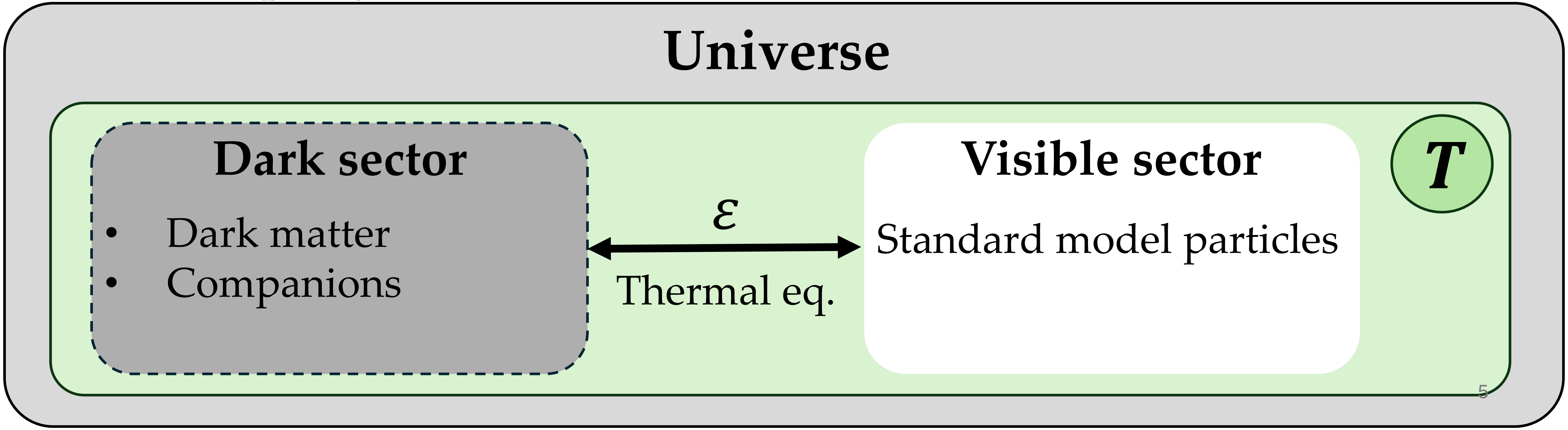
→$\langle \sigma v \rangle \sim 10^{-9} \text{GeV}^{-2} \sim 10^{-27} \text{cm}^3 \text{s}^{-1}$

- EW scale → **WIMP miracle**
- But no WIMP detected so far…



Hidden sector (HS) dark matter

- **Standard WIMP scenario**: dark sector particles thermalised with SM ones (fully thermalised Universe)
- **Visible sector** : SM particles, always thermalised
- **Dark sector**: DM particles + companion(s)
- **Thermal equilibrium** between the two (sufficiently large HS-VS coupling, ε)

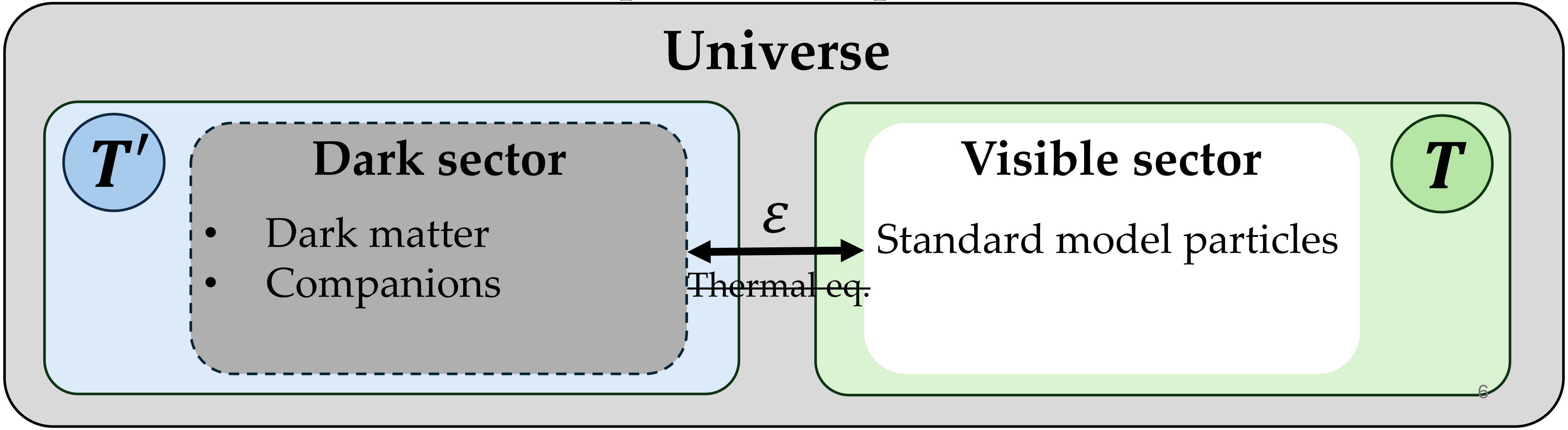


Hidden sector (HS) dark matter

- **Hidden sector** dark matter : thermalised at temperature $T' \neq T$, secluded from SM (small HS-VS coupling, ε ≪ 1)
- Freeze-out within this secluded sector
- Relic abundance

$$\Omega_\chi h^2 \simeq \frac{10^9 \times (T'/T)}{\langle \sigma v \rangle m_{\rm Pl} \mathrm{GeV}} \frac{s_{fo} a_{\rm fo}^3}{s_{\rm f} a_{\rm f}^3} \quad (T' \ll T)$$

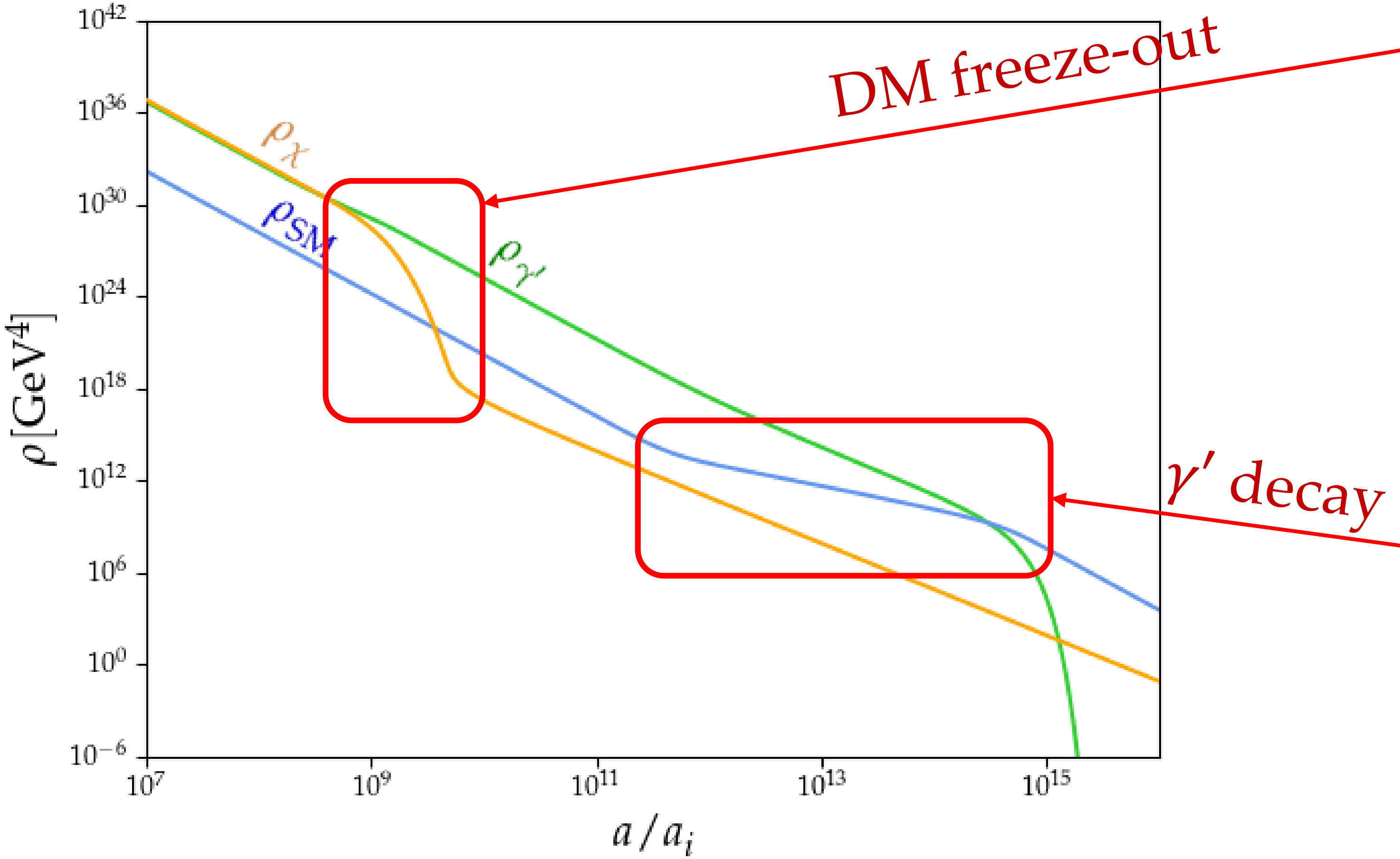
→ Additional factors, broader parameter space

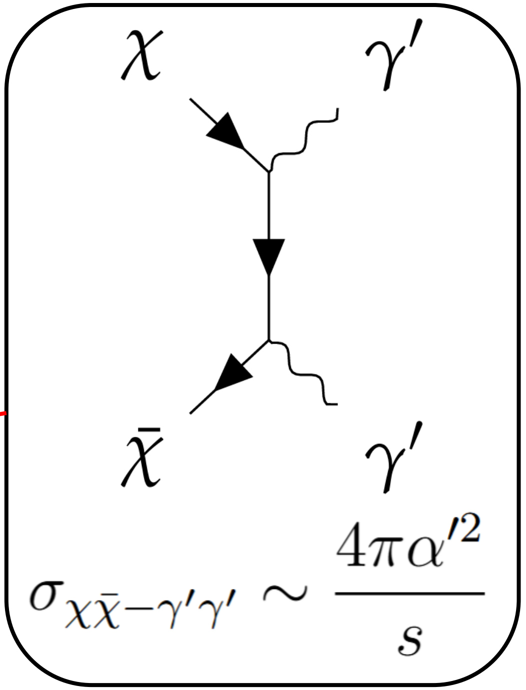


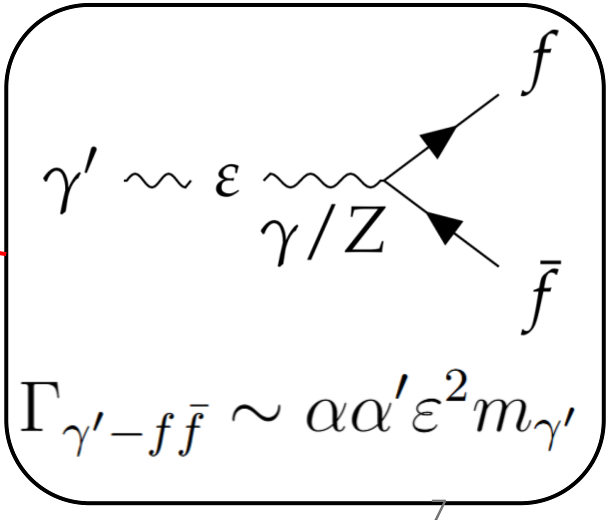
Hidden sector (HS) dark matter – dark QED

- Model for the HS:

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







Unitarity limit

- Unitarity limit on $\chi\bar{\chi} \to \gamma'\gamma'$ process:

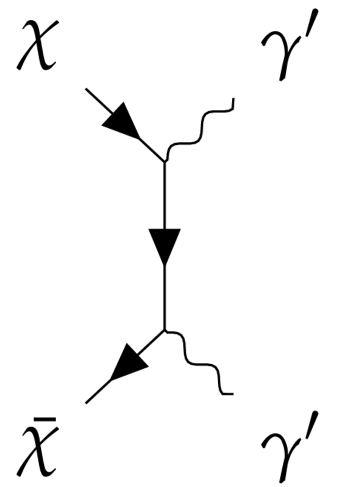
$$\sigma_{\chi\bar{\chi}-\gamma'\gamma'} \leq \frac{4\pi}{\mathbf{p}_i^2} \Rightarrow \langle \sigma_{\chi\bar{\chi}-\gamma'\gamma'} v \rangle_{\text{fo}} \lesssim \frac{4\pi}{m_\chi^2}$$

Flores, Petraki, arXiv:2405.02222

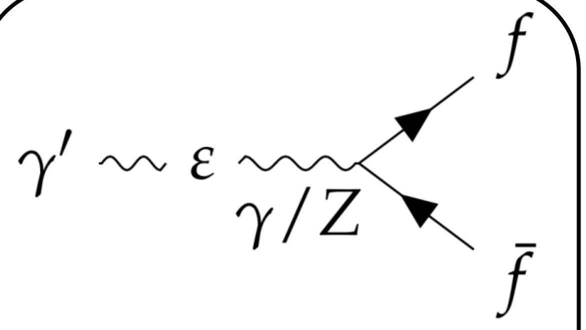
→ **Minimal** relic abundance:

$$\Omega_\chi h^2 \simeq \begin{cases} \dfrac{10^9}{\langle \sigma v \rangle m_{\text{Pl}} \text{GeV}} \dfrac{s_{\text{fo}} a_{\text{fo}}^3}{s_{\text{f}} a_{\text{f}}^3} \\ \dfrac{10^9 \times (T'/T)}{\langle \sigma v \rangle m_{\text{Pl}} \text{GeV}} \dfrac{s_{\text{fo}} a_{\text{fo}}^3}{s_{\text{f}} a_{\text{f}}^3} \end{cases} \gtrsim \begin{cases} \dfrac{10^8 \times m_\chi^2}{m_{\text{Pl}} \text{GeV}} \dfrac{s_{\text{fo}} a_{\text{fo}}^3}{s_{\text{f}} a_{\text{f}}^3} & (T' \gg T) \\ \dfrac{10^8 (T'/T) \times m_\chi^2}{m_{\text{Pl}} \text{GeV}} \dfrac{s_{\text{fo}} a_{\text{fo}}^3}{s_{\text{f}} a_{\text{f}}^3} & (T' \ll T) \end{cases}$$

→ Upper bound on the DM mass, dubbed **Unitarity wall**



$$\sigma_{\chi\bar{\chi}-\gamma'\gamma'} \sim \frac{4\pi\alpha'^2}{s}$$



$$\Gamma_{\gamma'-f\bar{f}} \sim \alpha\alpha'\varepsilon^2 m_{\gamma'}$$

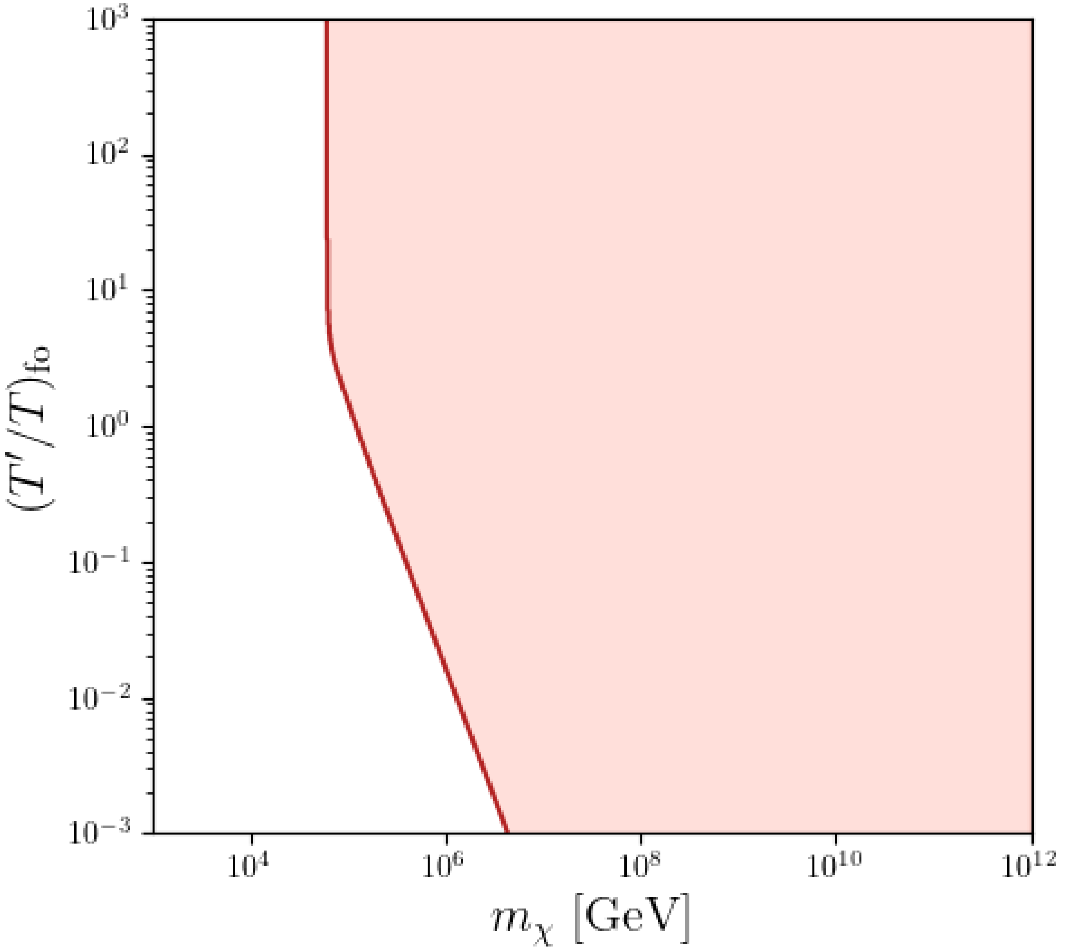
Unitarity limit (without entropy dilution)

- Neglecting entropy dilution at first:

$$m_\chi \lesssim \begin{cases} 10^5\text{GeV} & (T' \gg T) \\ 10^5\text{GeV}\,(T'/T)|_{\text{fo}} & (T' \ll T) \end{cases}$$

→ **Upper bound** on the mass of a DM candidate decoupling in a secluded HS

- More massive candidates are **overabundant**, even with the very minimal possible relic abundance



Coy, Hambye, Tytgat, Vanderheyden, arXiv:2105.01263

Entropy dilution

- Decaying massive particles may produce important amounts of entropy, thereby **diluting** DM abundance
- Relic abundance Ω_χ expressed via the **yield** $Y_\chi \equiv n_\chi / s_{\mathrm{t}}$:

$$\Omega_\chi \equiv \frac{\rho_\chi}{\rho_{\mathrm{t}}} = \frac{m_\chi s_{\mathrm{t}} Y_\chi}{\rho_{\mathrm{t}}} \quad \text{(cold DM)}$$

- Yield Y_χ is reduced if the total comoving entropy is increased:

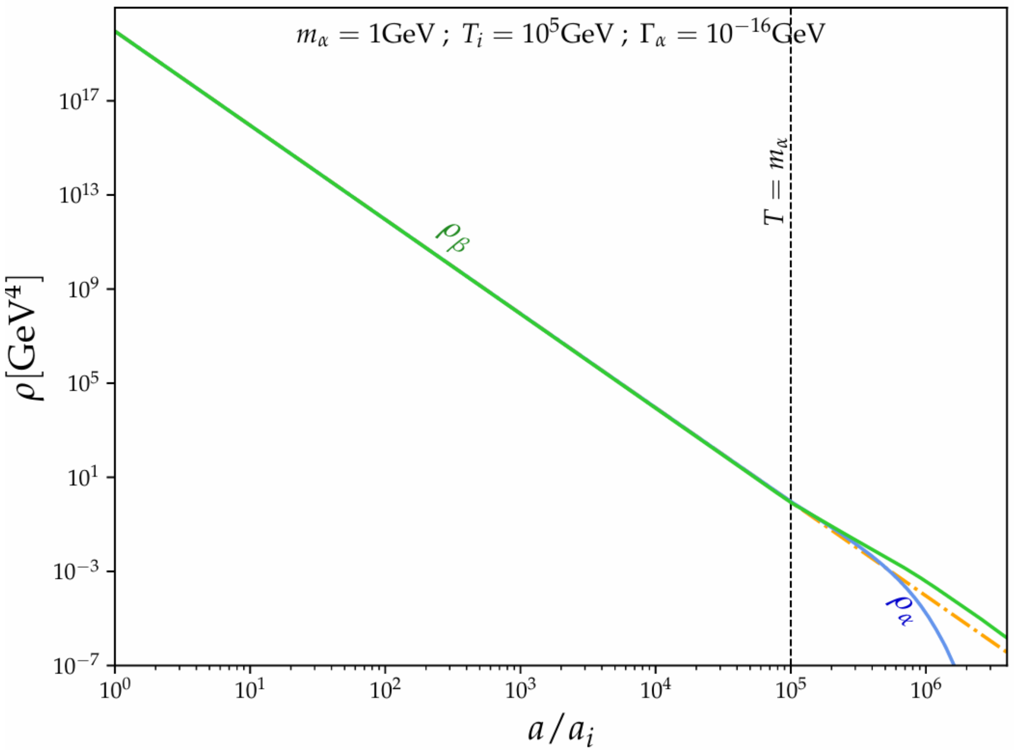
$$Y_\chi(a) = \frac{n_\chi^{\mathrm{fo}} (a_{\mathrm{fo}}/a)^3}{s_{\mathrm{t}}(a)} \Rightarrow Y_\chi^0 = Y_\chi^{\mathrm{fo}} \frac{s_{\mathrm{t,fo}} a_{\mathrm{fo}}^3}{s_{\mathrm{t},0} a_0^3}$$

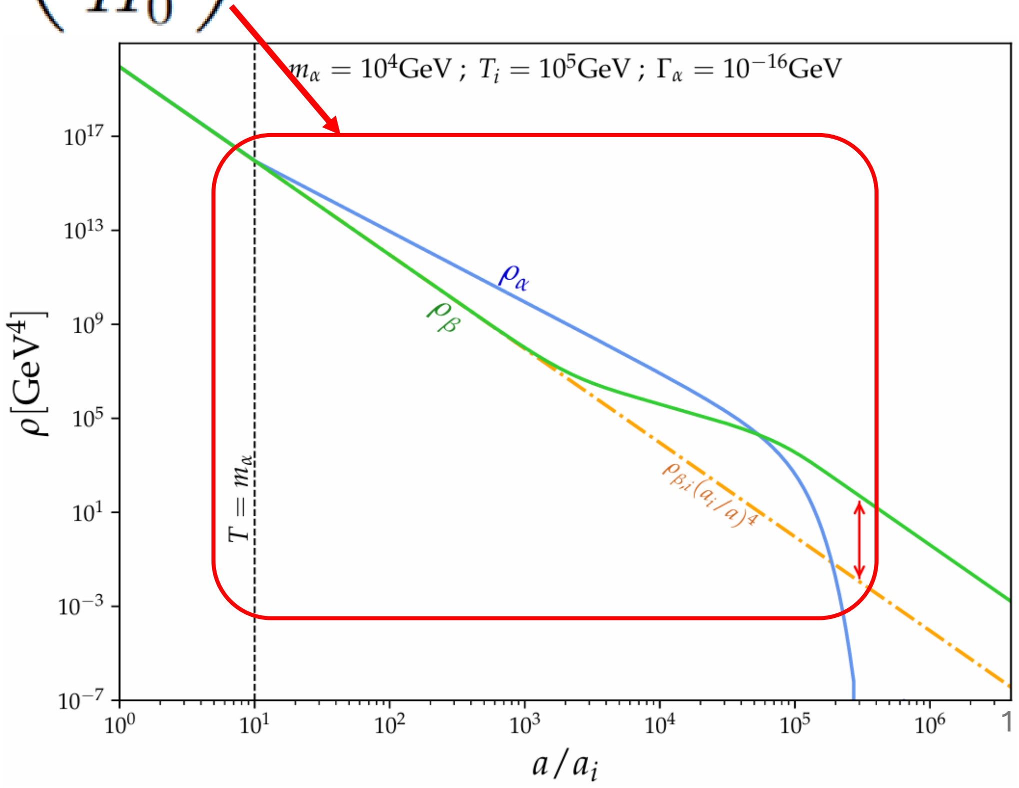
→ Dilution of the final relic abundance: $\boxed{\Omega_\chi^0 = \Omega_\chi^{\mathrm{fo}} \frac{s_{\mathrm{t}}^{\mathrm{fo}} a_{\mathrm{fo}}^3}{s_{\mathrm{t}}^0 a_0^3}}$

Entropy dilution

- To estimate entropy dilution factor:

$$\frac{s_{\rm fo}a_{\rm fo}^3}{s_0 a_0^3} \simeq \left(\frac{\rho_{\rm fo}a_{\rm fo}^4}{\rho_0 a_0^4}\right)^{3/4} \simeq \begin{cases} 1 & \text{(RD era)} \\ \left(\dfrac{H_{\rm fo}}{H_0}\right)^{1/2} & \text{(MD era)} \end{cases}$$





Entropy dilution from dark photon decay

- Remaining dark photons can inject substantial amounts of entropy when decaying into SM particles
- Assumptions:
  - SM at **kinetic** and **chemical** equilibrium → temperature T
  - HS at **kinetic** equilibrium → temperature T' + chemical potential $\mu_{\gamma'}$

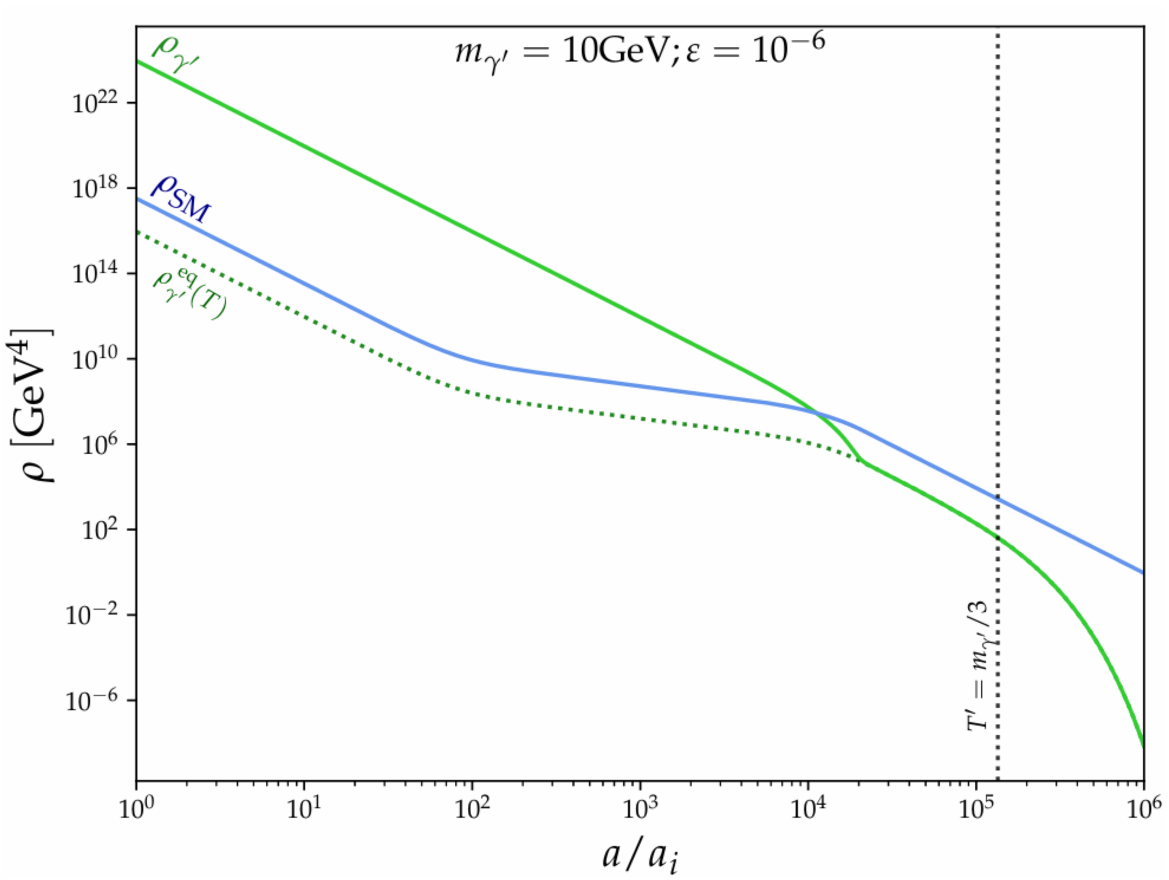
→ 3 Boltzmann equations:

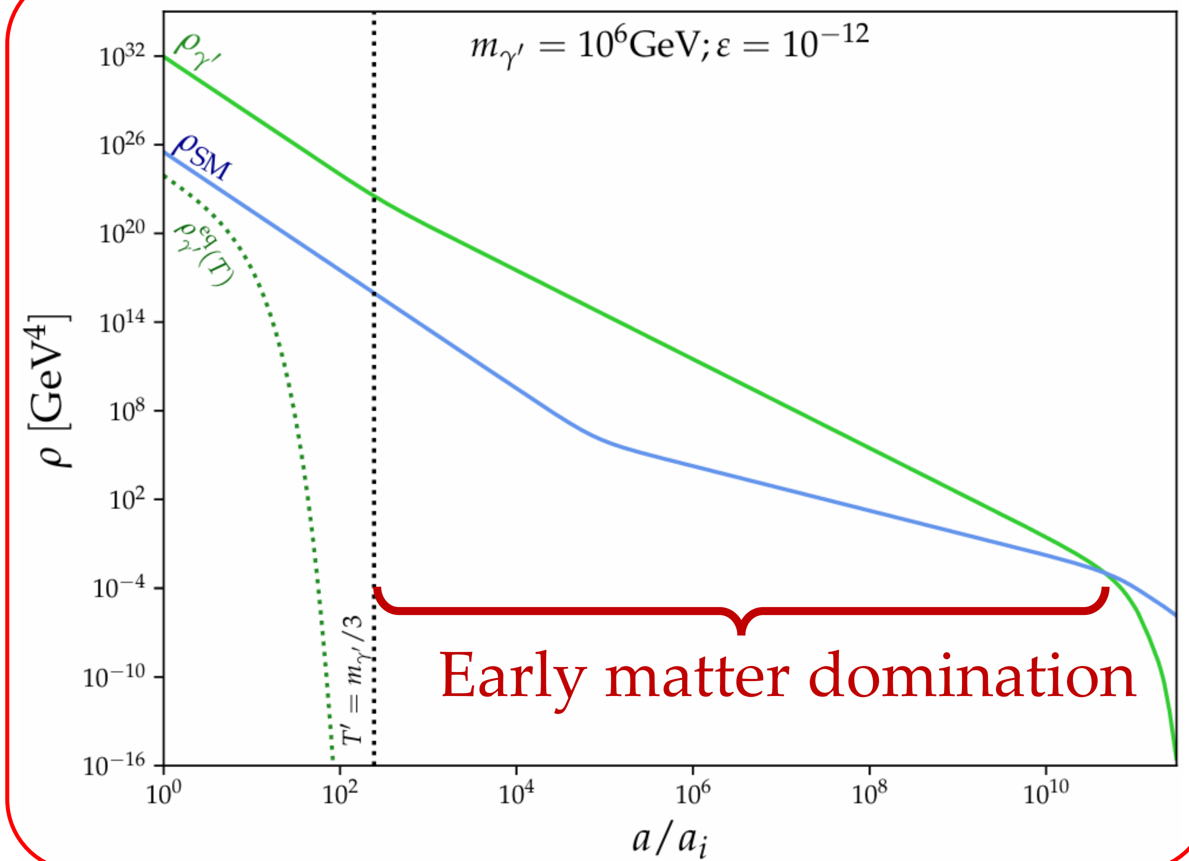
$$\begin{cases} \dot{n}_{\gamma'} + 3Hn_{\gamma'} & = -\langle\Gamma_{\gamma'}\rangle_{T'} n_{\gamma'} + \langle\Gamma_{\gamma'}\rangle_{T} n_{\gamma'}^{\mathrm{eq}}(T) \\ \dot{\rho}_{\gamma'} + 3(1+w_{\gamma'})H\rho_{\gamma'} & = -m_{\gamma'}\Gamma_{\gamma'}\left(n_{\gamma'} - n_{\gamma'}^{\mathrm{eq}}(T)\right) \\ \dot{\rho}_{\mathrm{SM}} + 4H\rho_{\mathrm{SM}} & = m_{\gamma'}\Gamma_{\gamma'}\left(n_{\gamma'} - n_{\gamma'}^{\mathrm{eq}}(T)\right) \end{cases}$$

Entropy dilution from dark photon decay

- Numerical solutions:

$$\begin{cases} \dot{n}_{\gamma'} + 3Hn_{\gamma'} & = -\langle\Gamma_{\gamma'}\rangle_{T'}n_{\gamma'} + \langle\Gamma_{\gamma'}\rangle_T n^{\rm eq}_{\gamma'}(T) \\ \dot{\rho}_{\gamma'} + 3(1+w_{\gamma'})H\rho_{\gamma'} & = -m_{\gamma'}\Gamma_{\gamma'}\left(n_{\gamma'} - n^{\rm eq}_{\gamma'}(T)\right) \\ \dot{\rho}_{\rm SM} + 4H\rho_{\rm SM} & = m_{\gamma'}\Gamma_{\gamma'}\left(n_{\gamma'} - n^{\rm eq}_{\gamma'}(T)\right) \end{cases}$$





→ Large entropy dilution

Entropy dilution from dark photon decay

- Relic abundance:

$$\Omega_\chi h^2 \gtrsim \begin{cases} \dfrac{10^8 \times m_\chi^2}{m_{\rm Pl}\text{GeV}} \dfrac{s_{\rm fo} a_{\rm fo}^3}{s_{\rm f} a_{\rm f}^3} & (T' \gg T) \\ \dfrac{10^8 \times m_\chi^2}{m_{\rm Pl}\text{GeV}} (T'/T) \dfrac{s_{\rm fo} a_{\rm fo}^3}{s_{\rm f} a_{\rm f}^3} & (T' \ll T) \end{cases}$$

- Dilution factor largest for **very massive** ($m_{\gamma'} \to m_\chi$) and **long lived** (small $\Gamma_{\gamma'}$) dark photons:

$$\frac{s_{\rm fo} a_{\rm fo}^3}{s_{\rm f} a_{\rm f}^3} \simeq \begin{cases} \left(\dfrac{\Gamma_{\gamma'}}{H_{\rm nr}}\right)^{1/2} & (T' \gg T) \\ \left(\dfrac{T'}{T}\right)^4 \left(\dfrac{\Gamma_{\gamma'}}{H_{\rm nr}}\right)^{1/2} & (T' \ll T) \end{cases}$$

- Freeze-out via $\chi\bar{\chi} \to \gamma'\gamma'$ annihilation → $m_{\gamma'} \leq m_\chi$
- Dark photon decay before BBN → $\Gamma_{\gamma'} \geq 1\text{s}^{-1}$

Unitarity limit (with entropy dilution)

- Relic abundance:

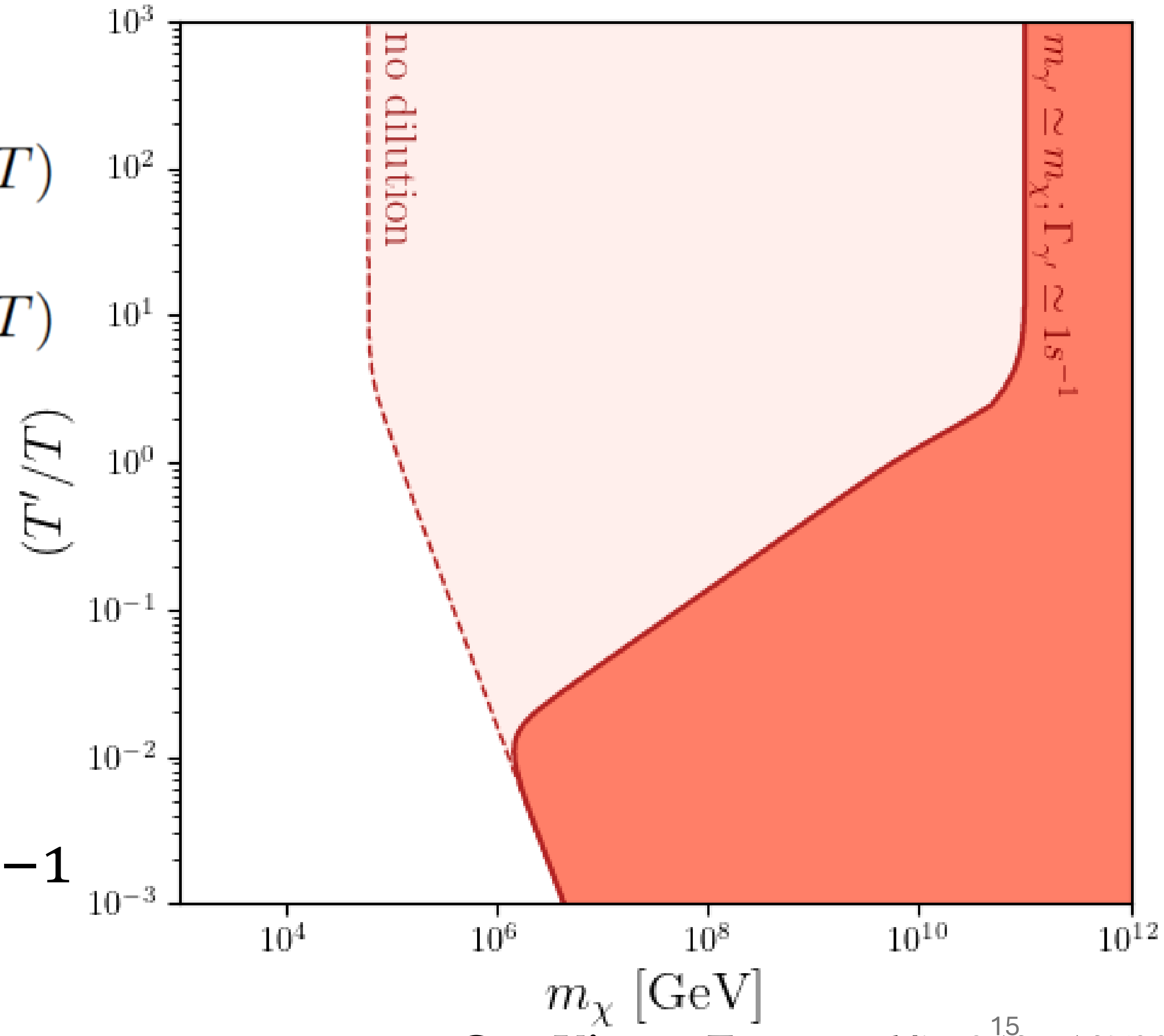
$$\Omega_\chi h^2 \gtrsim \begin{cases} \frac{10^8 \times m_\chi^2}{m_{\rm Pl}\mathrm{GeV}} \frac{s_{\rm fo} a_{\rm fo}^3}{s_{\rm f} a_{\rm f}^3} & (T' \gg T) \\ \frac{10^8 \times m_\chi^2}{m_{\rm Pl}\mathrm{GeV}} (T'/T) \frac{s_{\rm fo} a_{\rm fo}^3}{s_{\rm f} a_{\rm f}^3} & (T' \ll T) \end{cases}$$

- Entropy dilution:

$$\frac{s_{\rm fo} a_{\rm fo}^3}{s_{\rm f} a_{\rm f}^3} \propto \left(\frac{\Gamma_{\gamma'}}{H_{\rm nr}}\right)^{1/2}$$

- DM freeze-out: $m_{\gamma'} \leq m_\chi$
- γ' decay before BBN: $\Gamma_{\gamma'} \geq 1\mathrm{s}^{-1}$

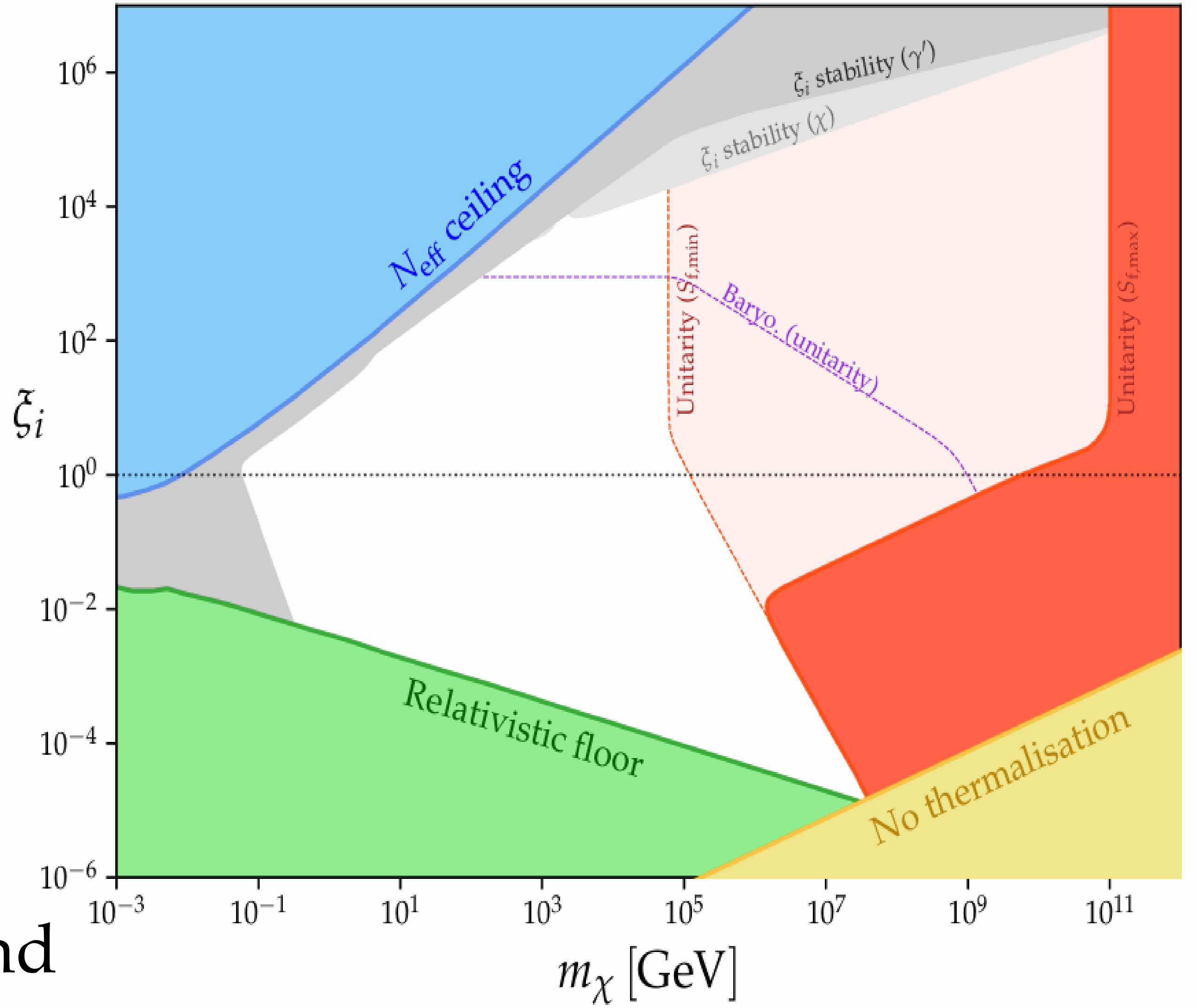
→ Much higher unitarity limit



Coy, **Kimus**, Tytgat, arXiv:2405.10792

The domain of dark matter in a thermal HS

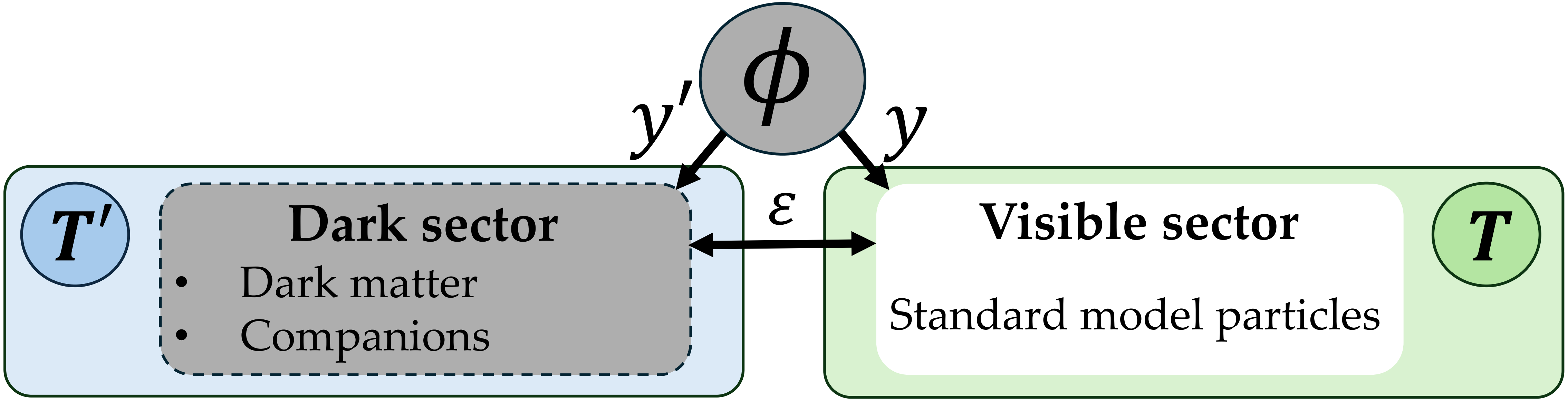
- Unitarity wall (with and without entropy dilution)
- Relativistic floor (underabundant DM, even for a relativistic decoupling scenario)
- $N_{\rm eff}$ ceiling (nonrelativistic DM during BBN)
- $\xi_i = T'_i/T_i$ stability and no thermalisation (DM freeze-out in a secluded HS)
- **Question** : how can we produce such initial conditions (secluded and thermalised HS) ?



Coy, **Kimus**, Tytgat, arXiv:2405.10792

Post-inflationary asymmetric reheating

- Starting point so far: after DM decoupling in a **secluded** and **thermalised** hidden sector
- **Arbitrary** initial temperature T'_i
- **Asymmetric reheating** is a way to produce such initial conditions (Hardy, Unwin, arXiv:1703.07642)



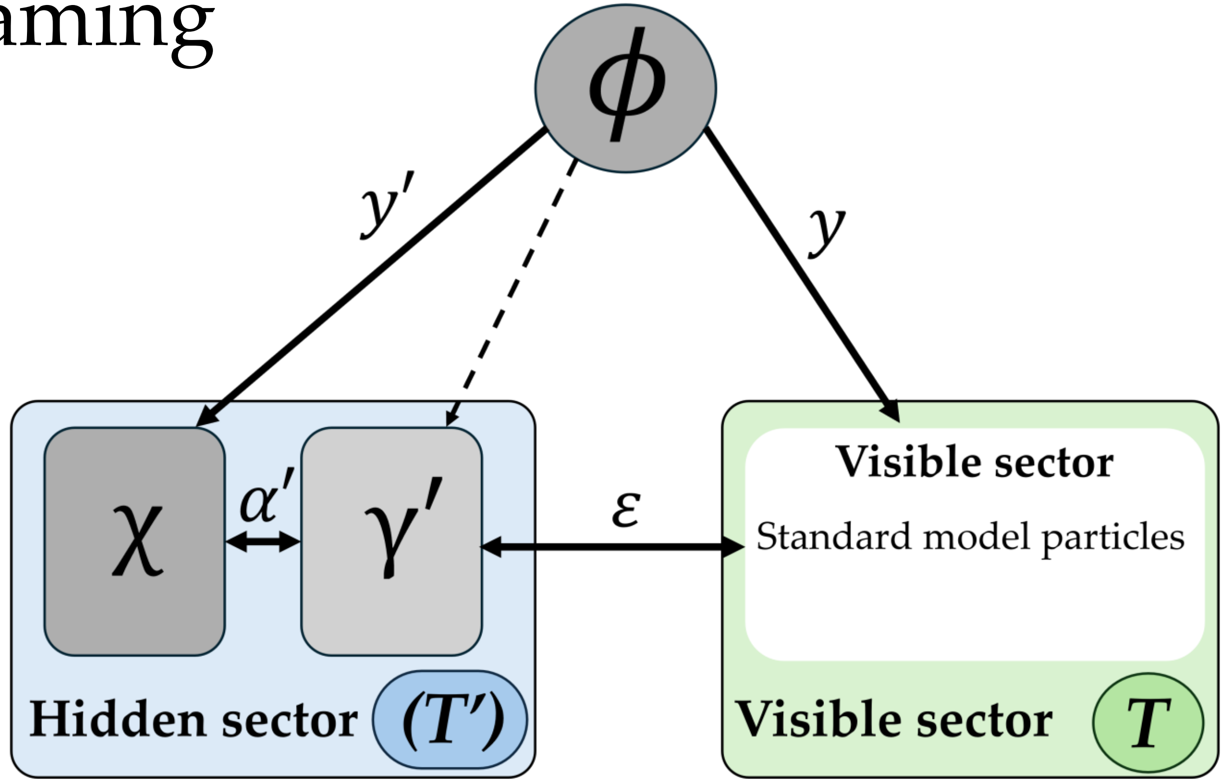
Post-inflationary asymmetric reheating

- Adding the inflatons

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 - y'\phi\chi\bar{\chi} - y\phi f\bar{f} + \bar{\chi}\left(i\not{D} - m_\chi\right)\chi - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{\gamma'}^2 A'_\mu A'^\mu - \frac{\varepsilon}{2}B_{\mu\nu}F'^{\mu\nu}$$

→ Boltzmann equations (free streaming decay products):

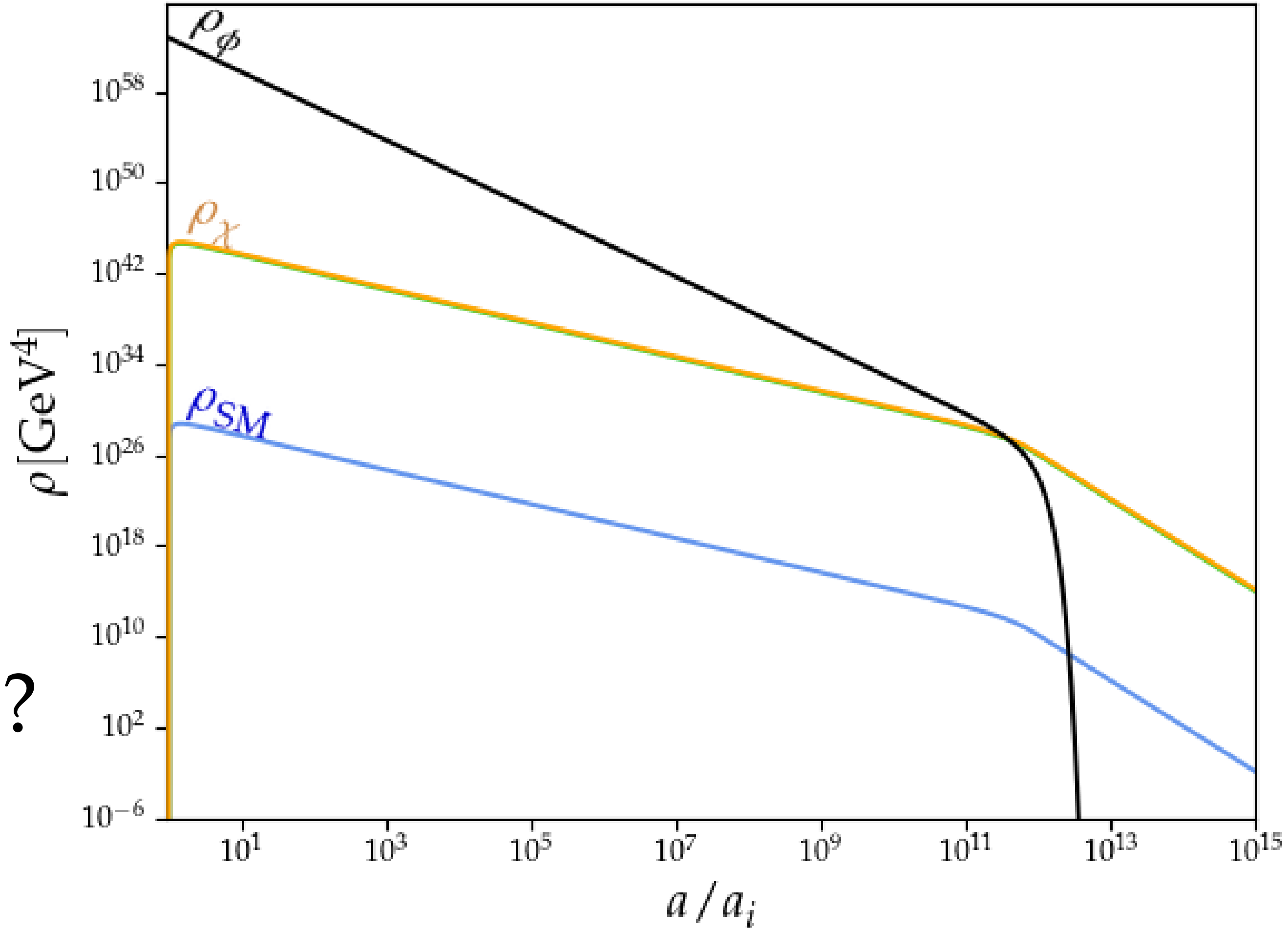
$$\begin{cases} \dot{\rho}_\phi + 3H\rho_\phi & = -\Gamma_\phi\rho_\phi \\ \dot{\rho}_\chi + 4H\rho_\chi & = \Gamma_\phi^\chi\rho_\phi \\ \dot{\rho}_{\rm SM} + 4H\rho_{\rm SM} & = \Gamma_\phi^{\rm SM}\rho_\phi \end{cases}$$



Post-inflationary asymmetric reheating

- Numerical solutions

$$\begin{cases} \dot{\rho}_\phi + 3H\rho_\phi & = -\Gamma_\phi \rho_\phi \\ \dot{\rho}_\chi + 4H\rho_\chi & = \Gamma_\phi^\chi \rho_\phi \\ \dot{\rho}_{\rm SM} + 4H\rho_{\rm SM} & = \Gamma_\phi^{\rm SM} \rho_\phi \end{cases}$$



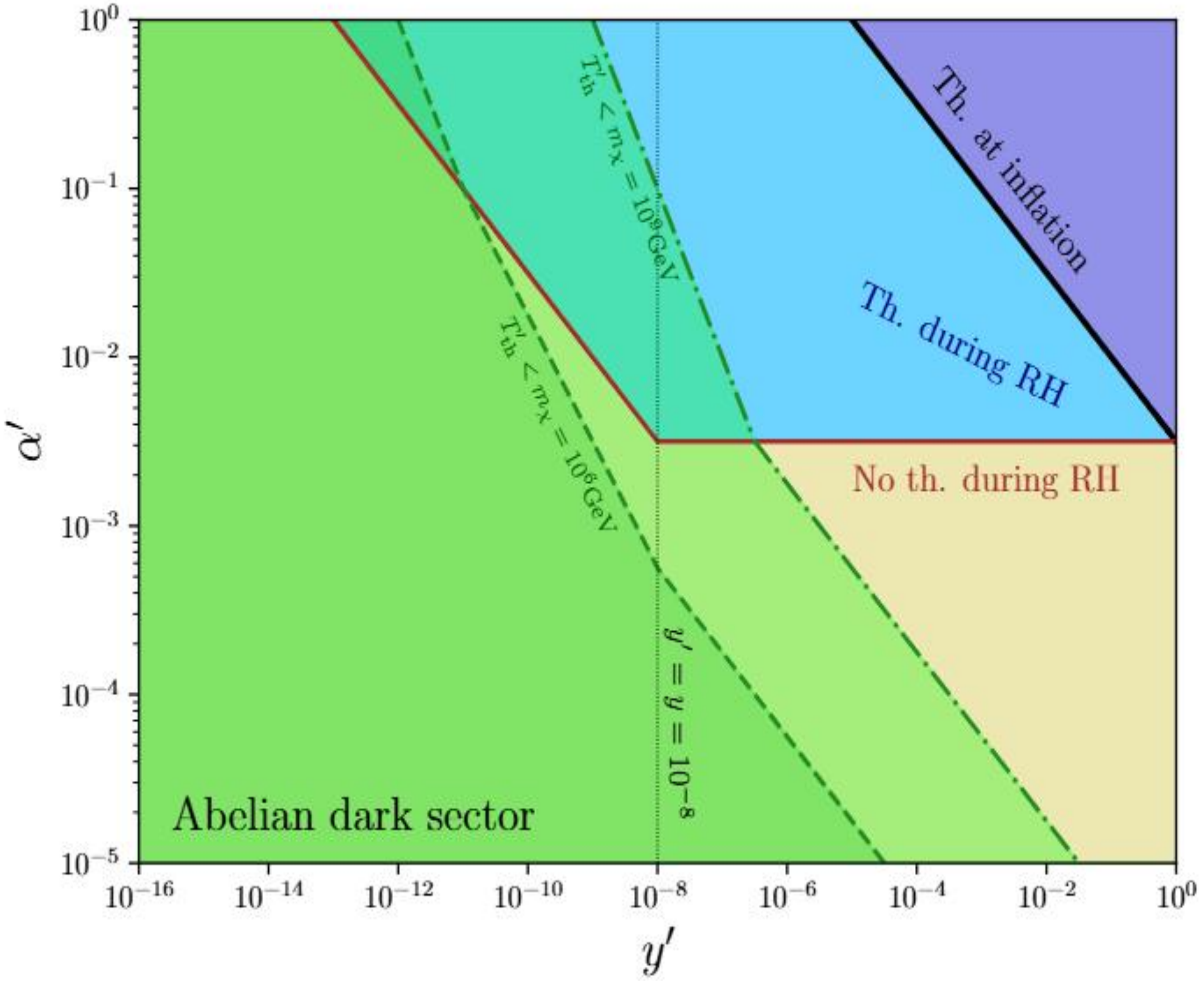
- Remaining questions:
  - Thermalisation of the HS ?
  - Other interaction channels ?

Post-inflationary asymmetric reheating HS thermalisation

- (preliminary) Thermalisation condition of an **abelian** HS

  (Non abelian case: Harigaya, Mukaida, arXiv:1312.3097)

$$m_\phi t_{\rm th} \sim \alpha'^{-4} \frac{m_\phi^3}{\Gamma_\phi^\chi m_{\rm Pl}^2}$$



- Moreover, thermalisation must happen with **relativistic** DM particles:

$$T'_{\rm th} \gtrsim m_\chi$$

Post-inflationary asymmetric reheating
Boltzmann equations

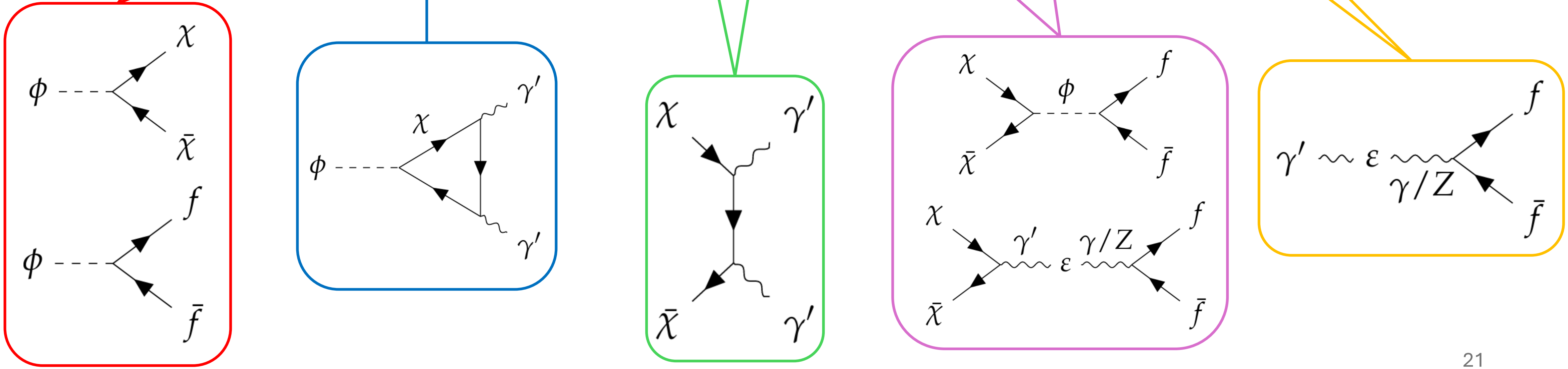
- (preliminary) Full Boltzmann equations (thermal HS):

$$\dot{\rho}_\phi + 3H\rho_\phi = -\Gamma_\phi \rho_\phi$$

$$\dot{\rho}_\chi + 3(1+w_\chi)H\rho_\chi = \Gamma_\phi^\chi \rho_\phi - \langle \sigma_{\chi-\gamma'} v E\rangle_{T'} \left(n_\chi^2 - \left(n_\chi^{\rm eq}(T')\right)^2\right) - \langle \sigma_{\chi-f} v E\rangle_{T'} n_\chi^2 + \langle \sigma_{\chi-f} v E\rangle_{T} \left(n_\chi^{\rm eq}(T)\right)^2$$

$$\dot{\rho}_{\gamma'} + 3(1+w_{\gamma'})H\rho_{\gamma'} = \Gamma_\phi^{\gamma'-\rm loop} \rho_\phi - \langle \sigma_{\chi-\gamma'} v E\rangle_{T'} \left(n_\chi^2 - \left(n_\chi^{\rm eq}(T')\right)^2\right) - m_{\gamma'}\Gamma_{\gamma'} \left(n_{\gamma'} - n_{\gamma'}^{\rm eq}(T)\right)$$

$$\dot{\rho}_{\rm SM} + 4H\rho_{\rm SM} = \Gamma_\phi^{\rm SM} \rho_\phi + \langle \sigma_{\chi-f} v E\rangle_{T'} n_\chi^2 - \langle \sigma_{\chi-f} v E\rangle_{T} \left(n_\chi^{\rm eq}(T)\right)^2 + m_{\gamma'}\Gamma_{\gamma'} \left(n_{\gamma'} - n_{\gamma'}^{\rm eq}(T)\right)$$



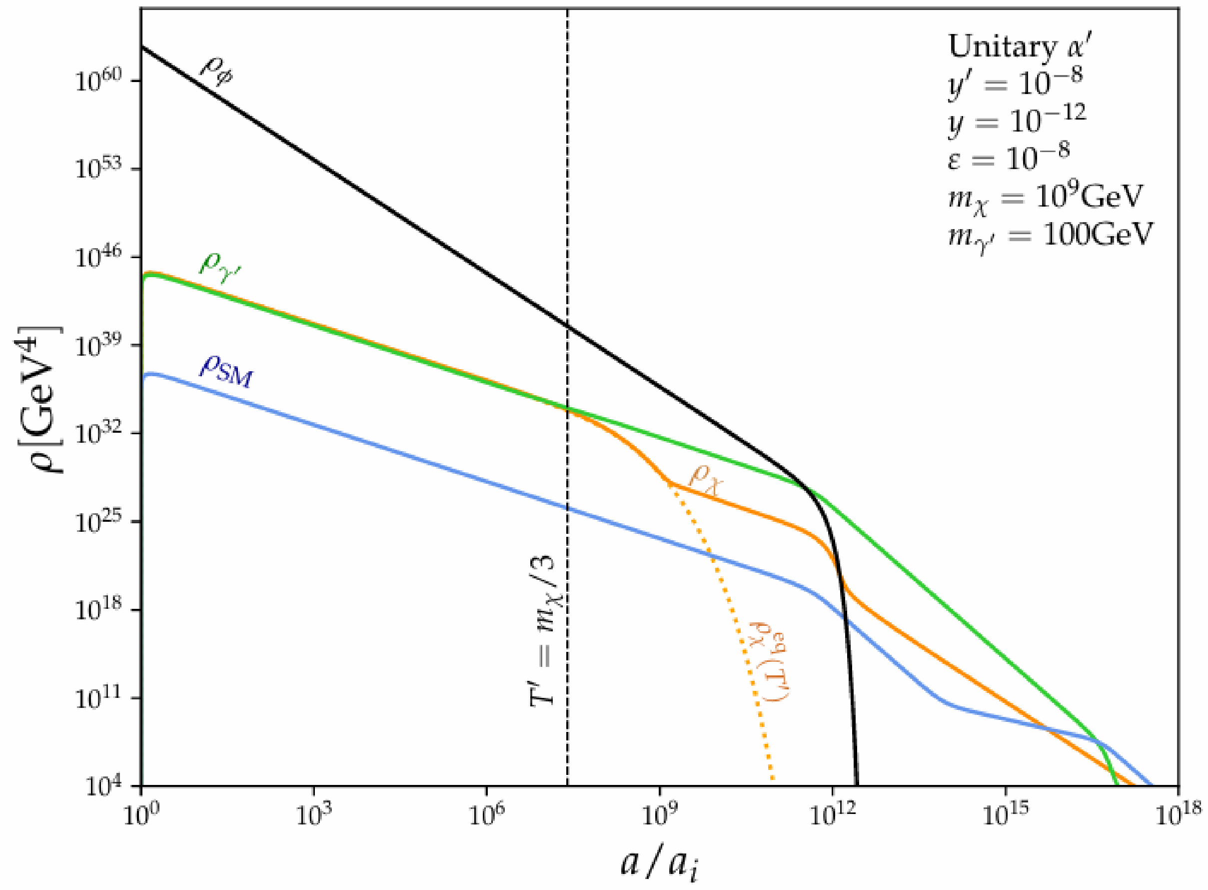
Post-inflationary asymmetric reheating – numerical solutions (preliminary)

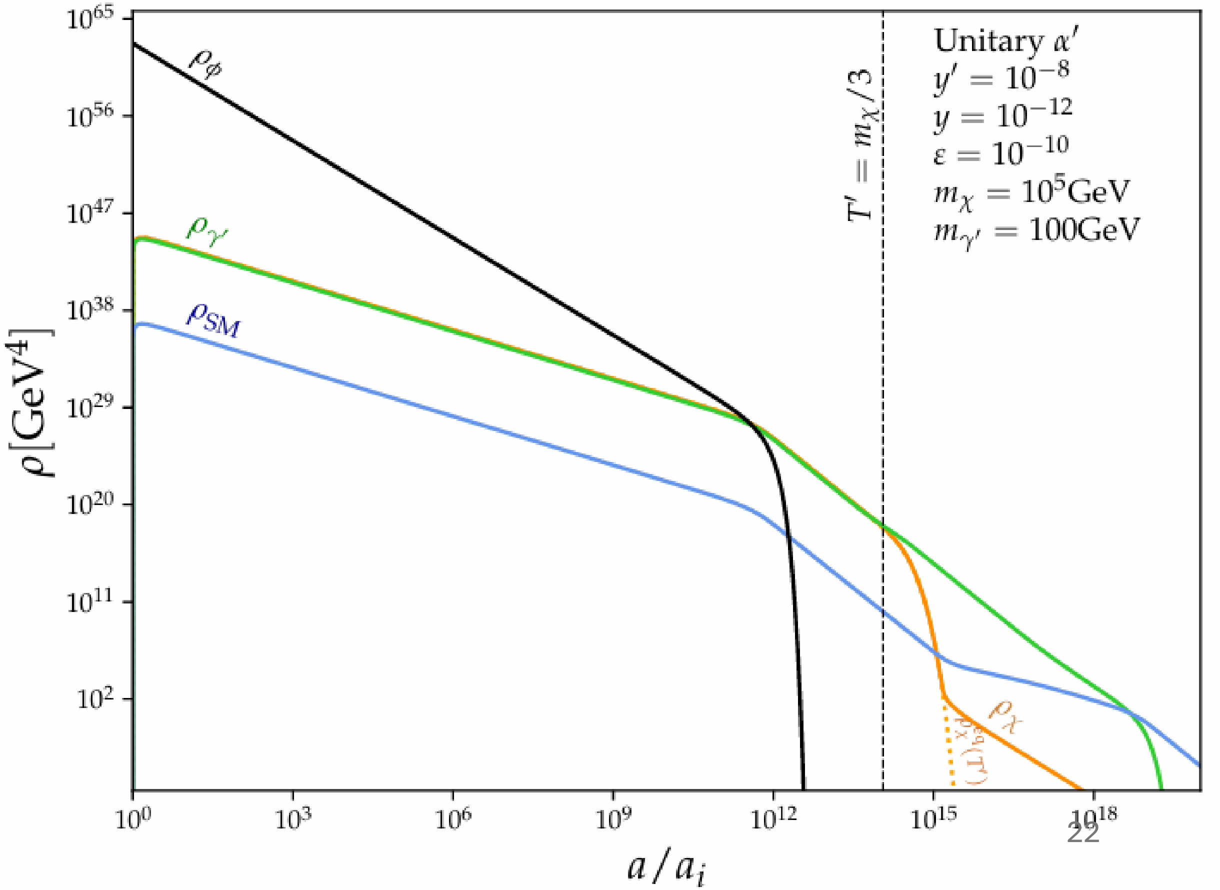
$$\dot{\rho}_\phi + 3H\rho_\phi = -\Gamma_\phi \rho_\phi$$

$$\dot{\rho}_\chi + 3(1+w_\chi)H\rho_\chi = \Gamma_\phi^\chi \rho_\phi - \langle \sigma_{\chi-\gamma'} v E\rangle_{T'} \left(n_\chi^2 - \left(n_\chi^{\rm eq}(T')\right)^2\right) - \langle \sigma_{\chi-f} v E\rangle_{T'} n_\chi^2 + \langle \sigma_{\chi-f} v E\rangle_T \left(n_\chi^{\rm eq}(T)\right)^2$$

$$\dot{\rho}_{\gamma'} + 3(1+w_{\gamma'})H\rho_{\gamma'} = \Gamma_\phi^{\gamma'-{\rm loop}} \rho_\phi - \langle \sigma_{\chi-\gamma'} v E\rangle_{T'} \left(n_\chi^2 - \left(n_\chi^{\rm eq}(T')\right)^2\right) - m_{\gamma'}\Gamma_{\gamma'} \left(n_{\gamma'} - n_{\gamma'}^{\rm eq}(T)\right)$$

$$\dot{\rho}_{\rm SM} + 4H\rho_{\rm SM} = \Gamma_\phi^{\rm SM} \rho_\phi + \langle \sigma_{\chi-f} v E\rangle_{T'} n_\chi^2 - \langle \sigma_{\chi-f} v E\rangle_T \left(n_\chi^{\rm eq}(T)\right)^2 + m_{\gamma'}\Gamma_{\gamma'} \left(n_{\gamma'} - n_{\gamma'}^{\rm eq}(T)\right)$$



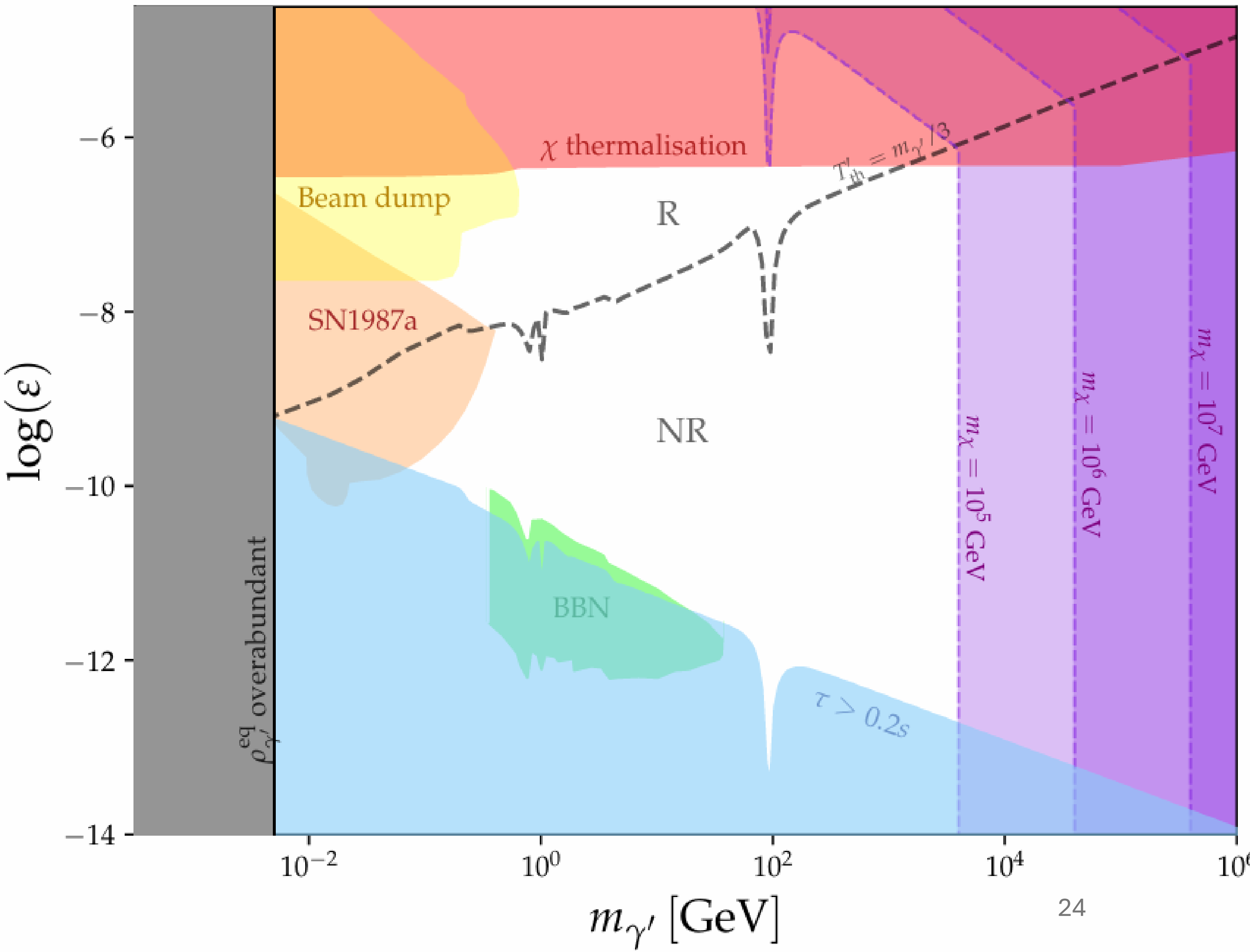


Conclusions

- **Hidden sectors** are a way to broaden the DM parameter space
- **Entropy dilution** plays a crucial role if the hidden sector (HS) is initially dominant
- **Post-inflationary asymmetric reheating** is a way to produce an initially secluded HS
- **Thermalisation** within the HS must be treated carefully, as well as $\chi - \gamma' -$ **SM interactions**

The domain of dark photons in a dominant HS

- 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.)



Thermalisation of (non-)abelian dark sectors (preliminary)