# Asymmetric Reheating of Dark QED
## Thermalization and Relics of a Hidden Sector

**Simon Cléry**, TUM

GGI Workshop: Exploring New Frontiers in Cosmology

***Based on***

- ✦ *Asymmetric Reheating of Dark QED,* SC, Kimus, Tytgat, **2605.09686**

***See also***

- ✦ *Light from darkness: History of a hot Dark Sector,* Coy, Kimus, Tytgat, **2405.10792**
- ✦ *The Domain of Thermal Dark Matter candidates,* Coy, Hambye, Tytgat, Vanderheyden, **2105.01263**
- ✦ *Thermalization after/during Reheating,* Harigaya, Mukaida, **1312.3097**

Technische Universität München

SFB 1258 Neutrinos Dark Matter Messengers

UNTERSTÜTZT VON / SUPPORTED BY Alexander von HUMBOLDT STIFTUNG

# Hidden Sector Dark Matter

Standard thermal scenario: DM thermalized with SM bath and relic from non-relativistic Freeze-out

$$\Omega_\chi h^2 \simeq \frac{10^9}{\langle\sigma v\rangle m_{\rm Pl}{\rm GeV}} \to \langle\sigma v\rangle \sim 10^{-9}{\rm GeV}^{-2}$$

➜ WIMP miracle. But no WIMP detected so far…

Several ways to relax this constraint (Freeze-in, SIMP, Light and ULDM, etc…)

➜ One alternative: DM part of a broader **Hidden Sector (HS)**

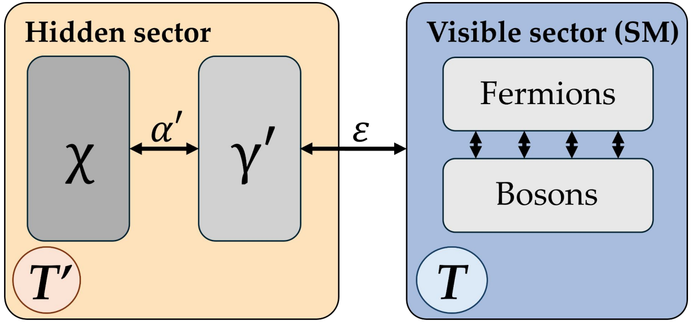
HS thermalized at $T' \neq T$ secluded from Visible Sector (VS) or with small HS-VS coupling **ε ≪ 1**

DM relic from freeze-out of the HS

➜ **Broader parameter space**

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

Berlin, Hooper, Krnjaic, **1602.08490**




$$\xi \equiv \frac{T'}{T}$$

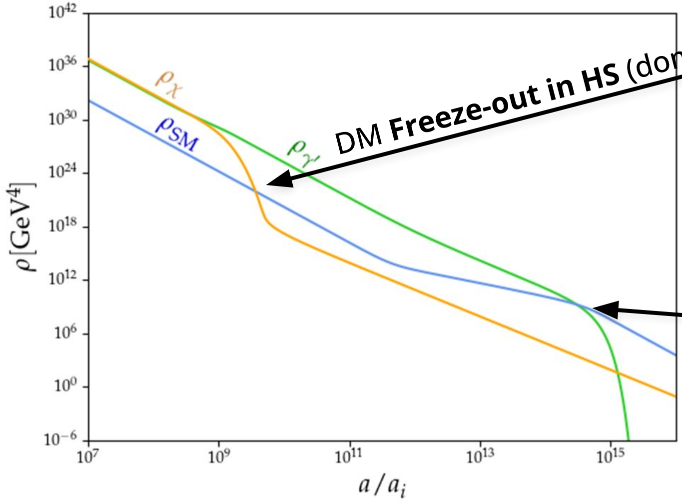
# Dark QED

Benchmark model for the Hidden Sector $\mathcal{L} \supset \overline{\chi}\,(i\not{D} - m_\chi)\,\chi - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{\gamma'}^2 A'_\mu A'^\mu - \frac{\varepsilon}{2}B_{\mu\nu}F'^{\mu\nu}$

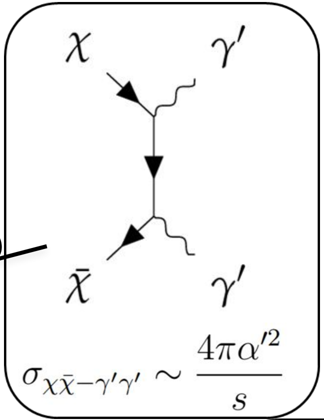
➜ Two Beyond SM fields:

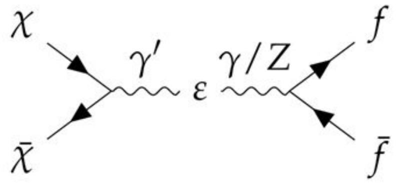
- ✦ ***Dark electron χ*** : DM
- ✦ ***Dark photon γ'*** : abelian gauge boson companion

➜ a mechanism to give a mass $m_{\gamma'}$ to dark photons
➜ small kinetic mixing **ε ≪ 1** between HS-VS

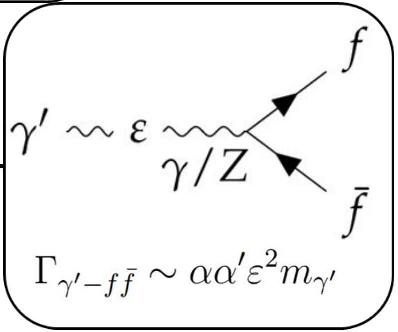



DM **Freeze-out in HS** (dominant process)

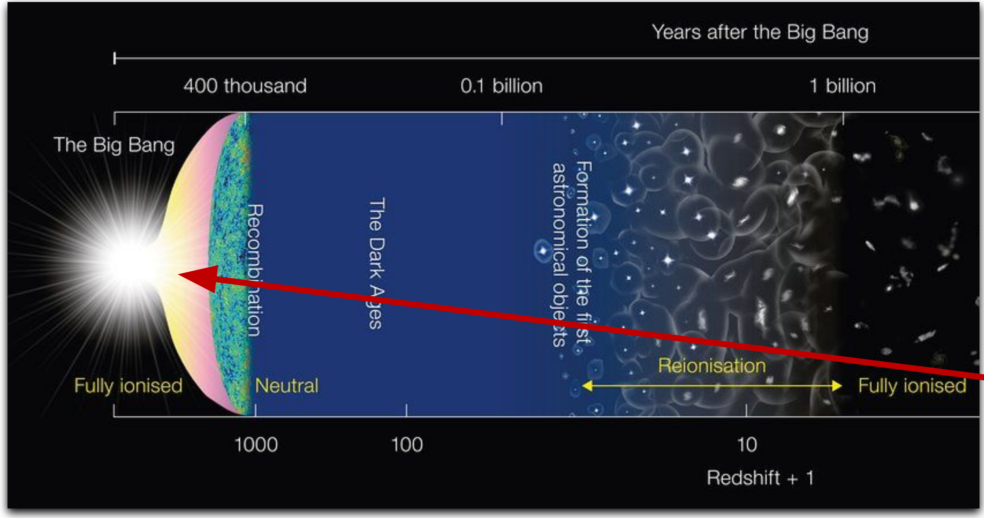


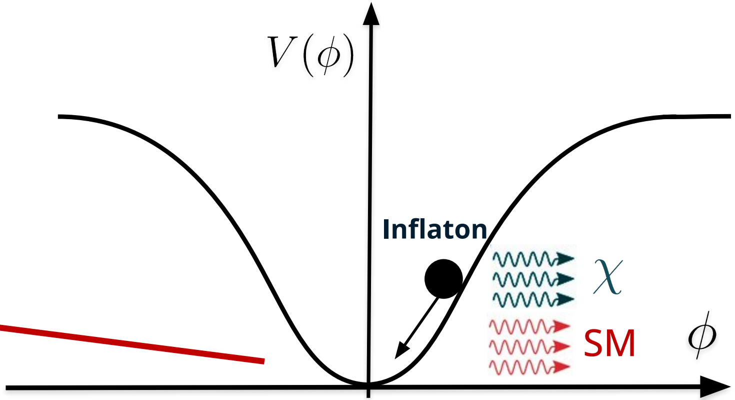



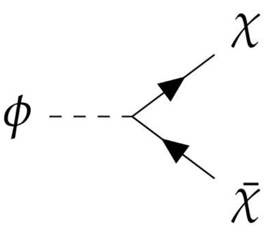

Dark photon decay
**"Heating" SM**



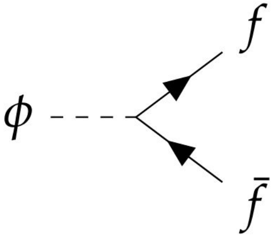
# Asymmetric Reheating




$\Gamma_\phi^\chi$




$\Gamma_\phi^{\mathrm{SM}}$

What if inflaton is also coupled to the Hidden Sector ?

➜ **Asymmetric Reheating**

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - V(\phi) - y\phi \bar{f} f - y' \phi \bar{\chi}\chi$$

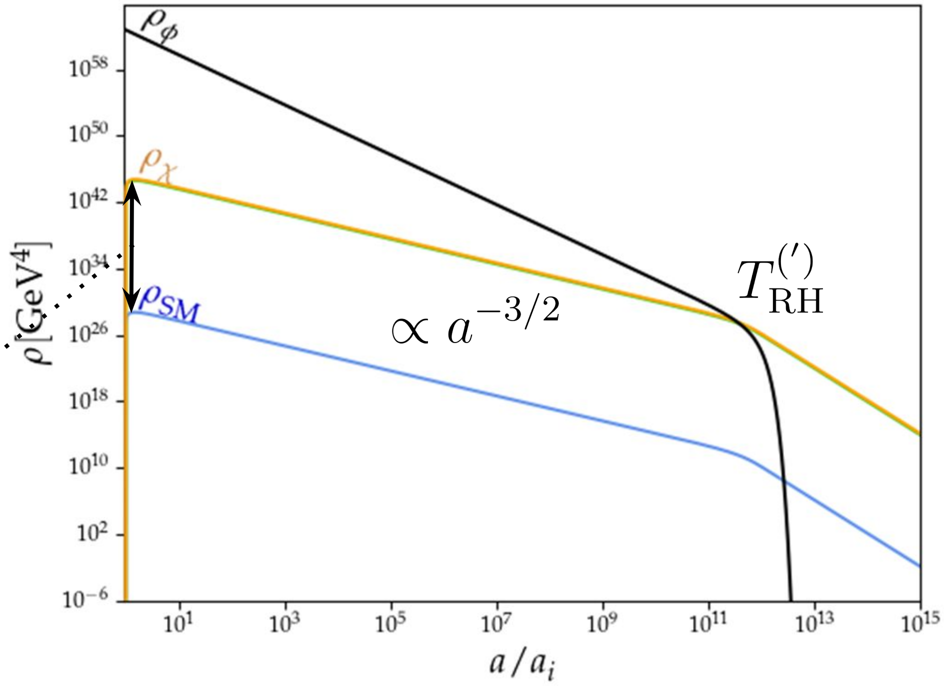
# Asymmetric Reheating

Boltzmann equations:

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

Assume rapid thermalization in the SM sector
(large non-abelian gauge couplings, many degrees of freedom)

$$\xi \equiv \frac{T'}{T} \sim \sqrt{\frac{y'}{y}}$$



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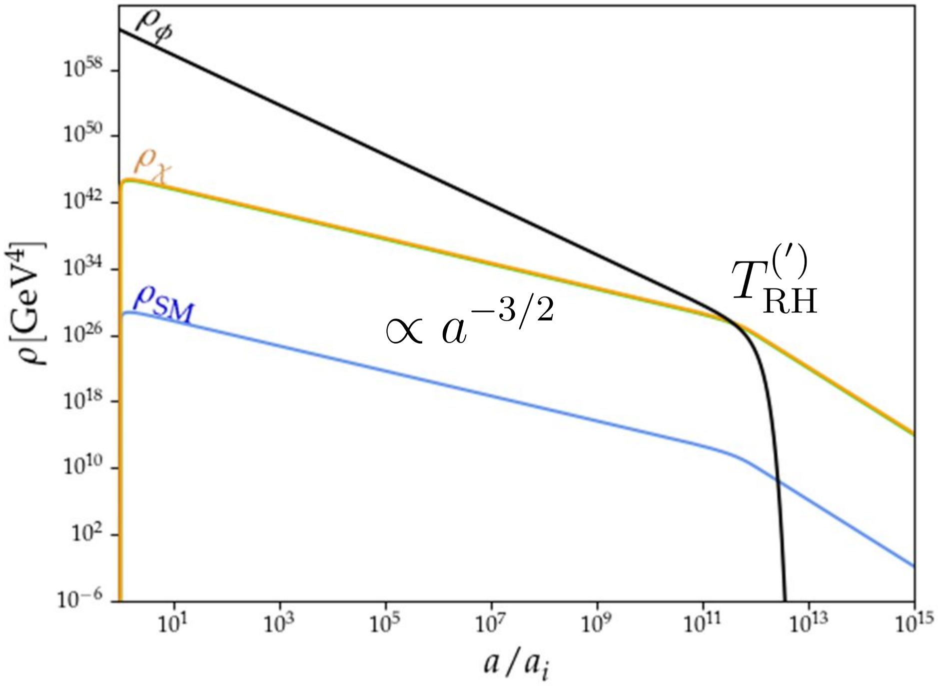
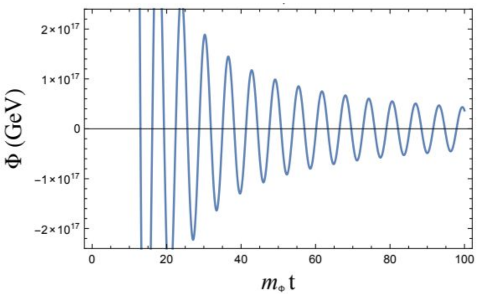
Assume rapid thermalization in the SM sector
(large non-abelian gauge couplings, many degrees of freedom)

- ✦ **Thermalization of the HS ?**
- ✦ Interaction between the two sectors?
  **Evolution of the temperature ratio ?**



# Non-thermal production from the inflaton



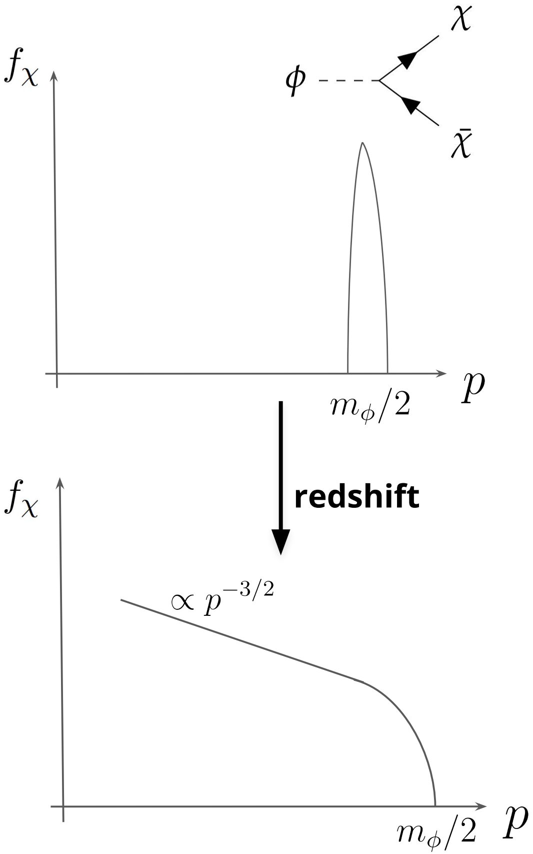

$$f_\phi = (2\pi)^3 n_\phi \delta^{(3)}(p)$$

$$\frac{\partial f_\chi}{\partial t} - Hp\frac{\partial f_\chi}{\partial p} = \frac{2\pi^2}{p^2} n_\phi \Gamma_\phi \delta(p - m_\phi/2)$$

$$f_\chi \simeq 24\pi^2 \frac{n_\chi}{m_\phi^3}\left(\frac{m_\phi}{2p}\right)^{3/2} \Theta(m_\phi/2 - p)$$

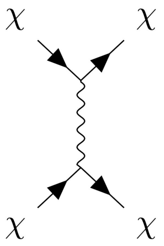
$$\langle p \rangle \sim O(m_\phi)$$

Harigaya, Mukaida, **1312.3097**
Garcia, Amin, **1806.01865**



# Kinetic vs Chemical equilibrium

**Kinetic equilibrium** may be reached through 2 ↔ 2 processes $\frac{\Gamma^h_{2-2}}{H} \approx 10^2 \alpha'^2 \frac{M_P^2 \Gamma^\chi_\phi}{m_\phi^3} \gtrsim 1$

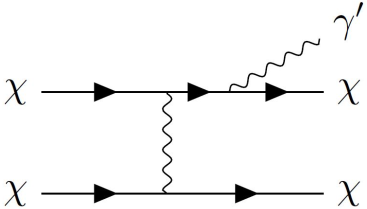



$$\dot{n}_\chi + 3Hn_\chi = \Gamma^\chi_\phi n_\phi \longrightarrow n_\chi \sim \frac{\Gamma^\chi_\phi}{H}\frac{\rho_\phi}{m_\phi} \sim \frac{\Gamma_\phi H M_P^2}{m_\phi}$$

$$\dot{\rho}_\chi + 4H\rho_\chi = \Gamma^\chi_\phi \rho_\phi \longrightarrow n^{\rm th}_\chi \sim T'^3 \sim \left(\frac{\Gamma_\phi \rho_\phi}{H}\right)^{3/4} \sim (\Gamma_\phi H M_P^2)^{3/4}$$

$$\frac{n_\chi}{n^{\rm th}_\chi} \sim \frac{(\Gamma^\chi_\phi H M_P^2)^{1/4}}{m_\phi} \sim \frac{T'}{m_\phi} \lesssim 1$$

But for **under-abundant initial population,** chemical equilibrium is not guaranteed
➜ Thermalization must usually involve **particle number changing processes** as **Bremsstrahlung**

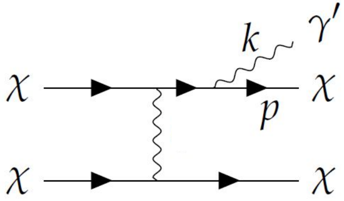



expected to be suppressed for small gauge coupling $\alpha'$
➜ can take a **finite time** before being efficient

# Thermalization in an Abelian plasma

In an **abelian plasma** daughter **boson does not interact** efficiently after being emitted.
➜ **Separation** of mother hard fermion via transverse momentum diffusion such that $k_\perp = \frac{k}{\boxed{p}}\sqrt{\alpha' n_h t}$

$$t_{\rm form} \sim k/k_\perp^2 \sim \sqrt{\frac{\boxed{p^2}}{\alpha'^2 n_h\, k}}$$




$$\Gamma^A_{2-3} \sim \begin{cases} \alpha'\,\Gamma^s_{2-2}\sqrt{\frac{k}{k^A_{\rm LPM}}} & \boxed{k \lesssim k^A_{\rm LPM}} \\ \alpha'\,\Gamma^s_{2-2} & k \gtrsim k^A_{\rm LPM} > m_\phi \end{cases}$$

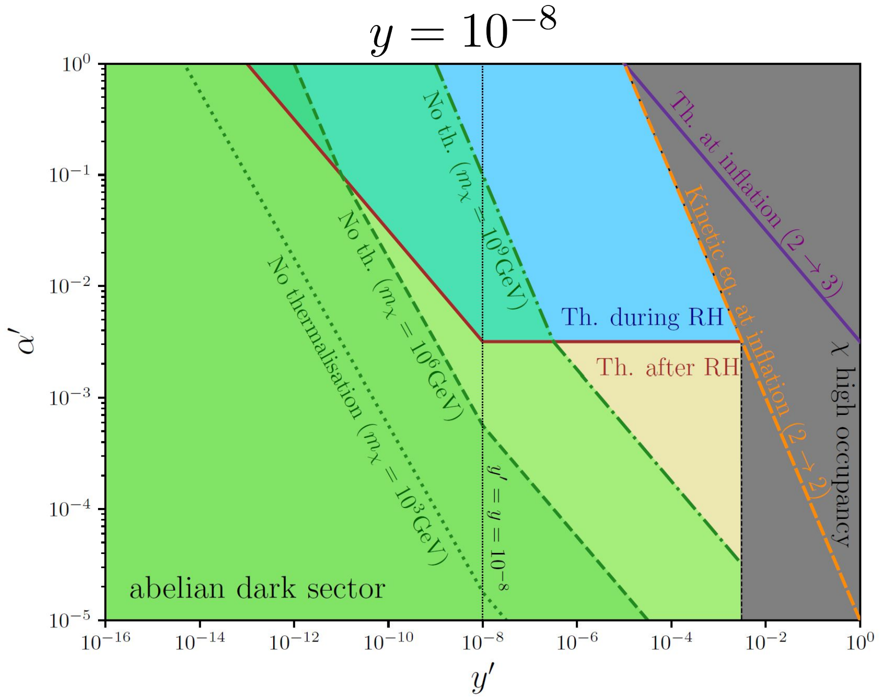
**Landau-Pomeranchuk-Migdal**

➜ Relatively **"hard" gauge boson are first produced**, then cascade in fermion–antifermion pairs, degrading gradually energy towards low momentum : **top-bottom thermalization**
➜ **Bottleneck** of thermalization is the **LPM suppressed gauge boson emission**

$$\boxed{t^{\rm A}_{\rm th} \sim 1/\Gamma_{2\to 3} \sim \frac{1}{\alpha'^2 m_\phi}\left(\frac{m_\phi^3}{n_h}\right)^{1/2}}$$

SC, Kimus, Tytgat, **2605.09686**

# Constraints from Thermalization of the Hidden Sector




Domain of thermalization during/after reheating
**Abelian plasma**

**grey region** : initially abundant and/or strongly coupled HS

**purple line**: perturbative splitting processes are fast at the end of inflation

**orange line**: perturbative 2-2 scattering processes bring to kinetic equilibrium

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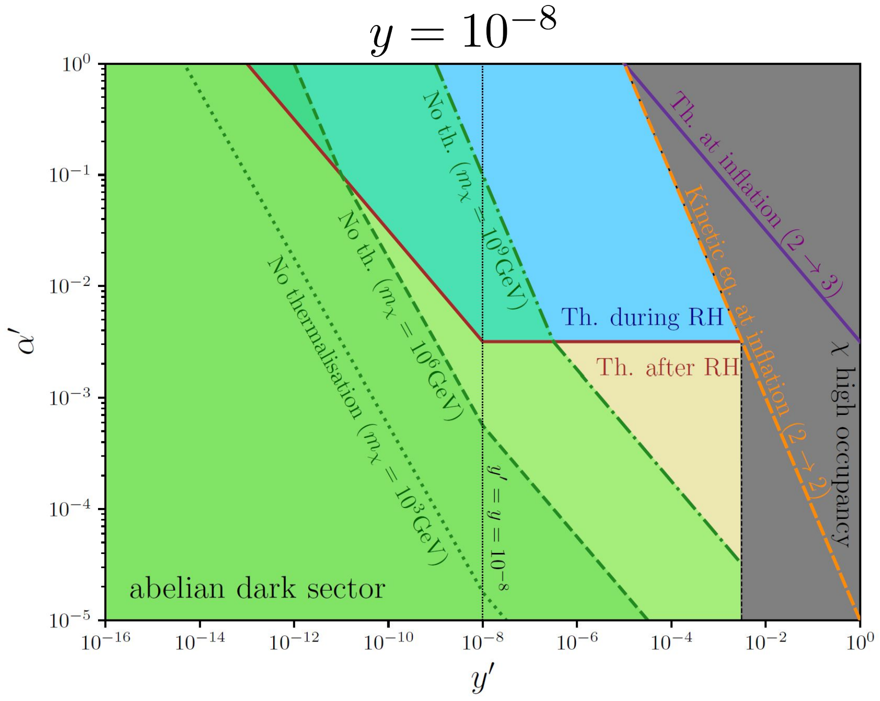
# Constraints from Thermalization of the Hidden Sector




Domain of thermalization
during/after reheating
**Abelian plasma**

**blue region** : thermalization via fast splitting processes before reheating ends

**yellow region** : thermalization via fast splitting processes only after reheating ends

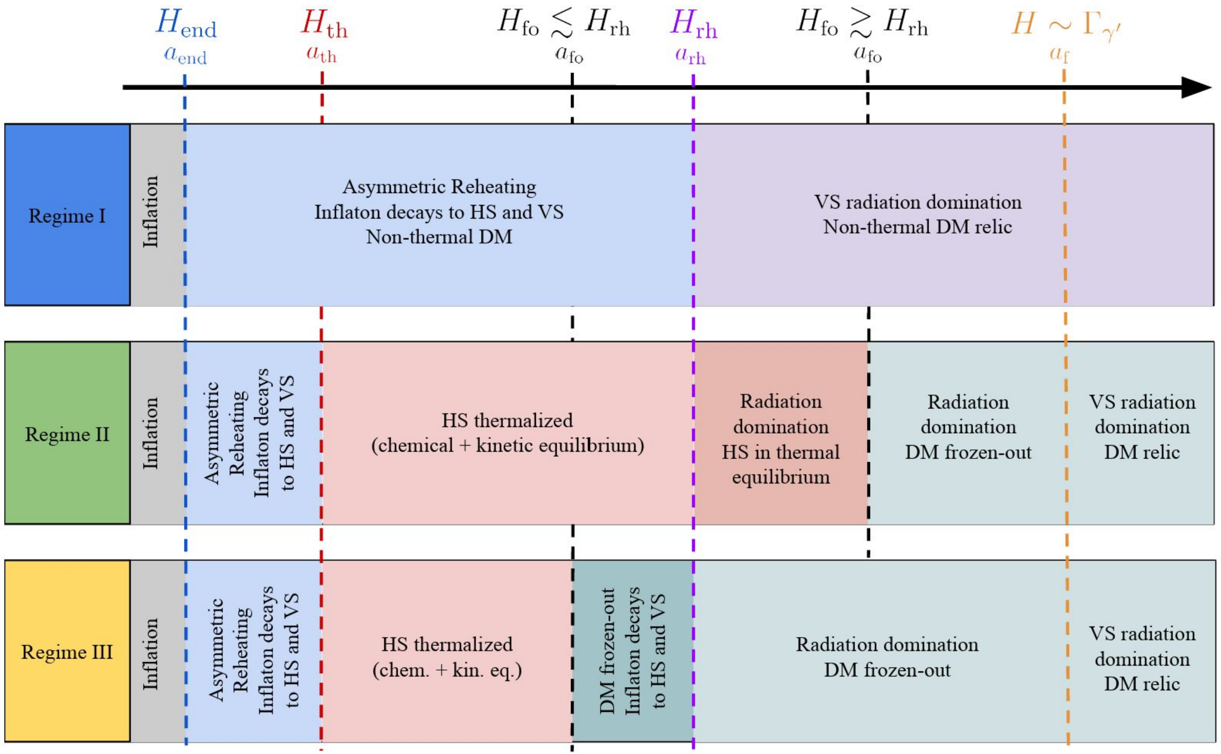
**green regions** : no thermalization; dark electrons become non-relativistic too early

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

**vertical limit** : dominant **(y' > y)** or subdominant **(y' < y)** HS during reheating

SC, Kimus, Tytgat, **2605.09686**

# Reheating and Freeze-in/Freeze-out scenarios




**3 Regimes** with different cosmological histories :

● **Non-thermal** DM produced from "Freeze-in" **(Regime I)**

■ Thermalization + **Freeze-out after reheating (Regime II)**

▲ Thermalization + **Freeze-out during reheating (Regime III)**

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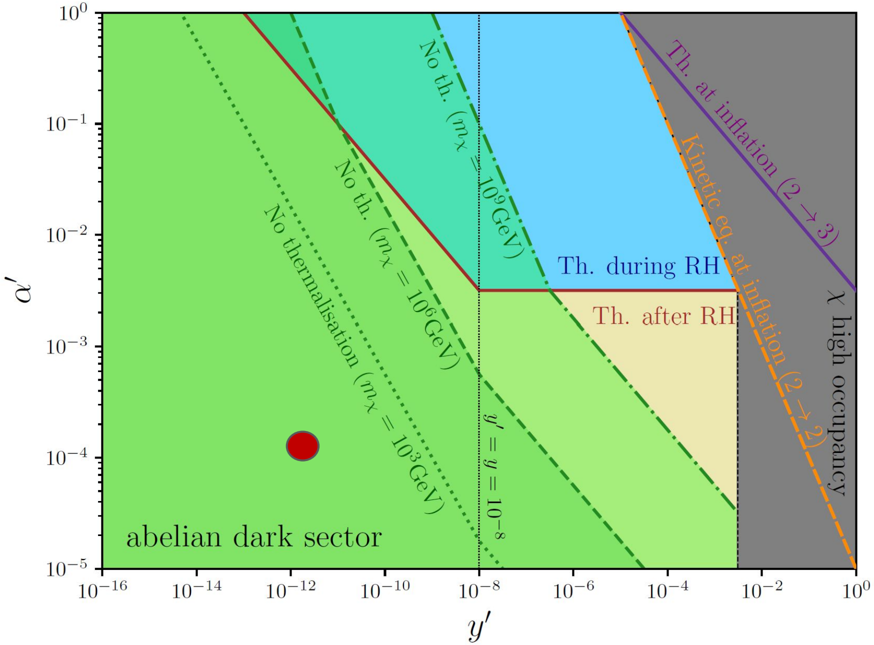
# Freeze-in from inflaton decays




● **Thermalization** is **not reached** during reheating and HS is **subdominant (y' < y)**

➜ **Freeze-in** sourced by the inflaton decays

$$Y_\chi = \frac{n_\chi}{s} \sim \frac{\Gamma_\phi^\chi M_P^{1/2}}{m_\phi H_{\rm rh}^{1/2}} \sim y'^2 y^{-1} \left(\frac{M_P}{m_\phi}\right)^{1/2}$$

$$m_\chi \sim \xi_i^{-4} \left(\frac{10^{-11}}{y}\right) \text{GeV}$$

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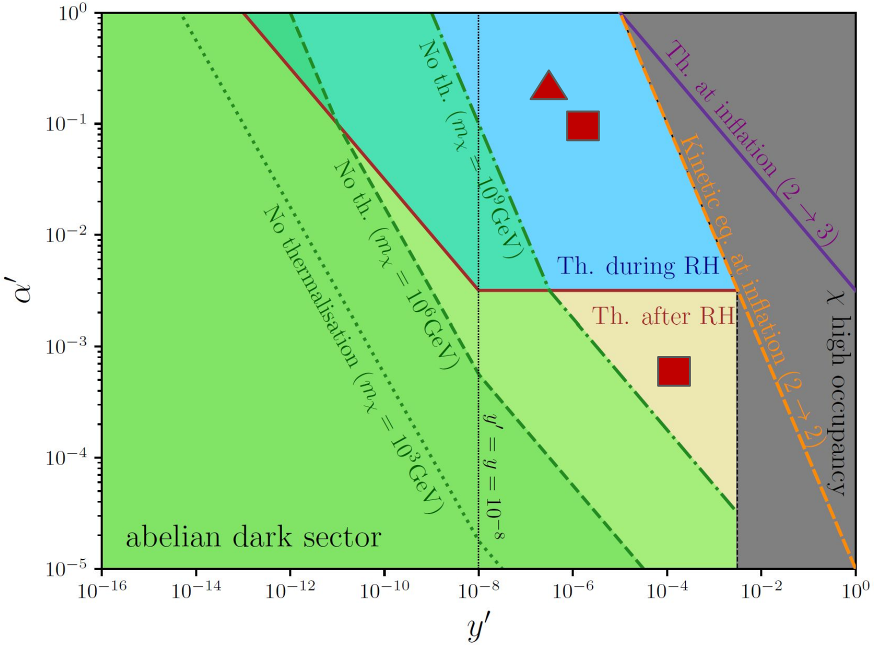
# Freeze-out scenarios




■ Thermalization + **freeze-out after reheating (Regime II)**

▲ Thermalization + **freeze-out during reheating (Regime III)**

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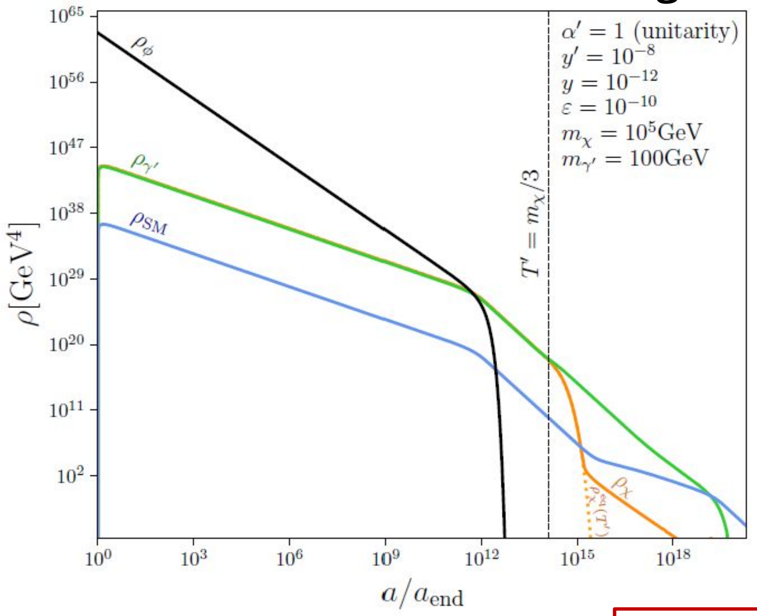
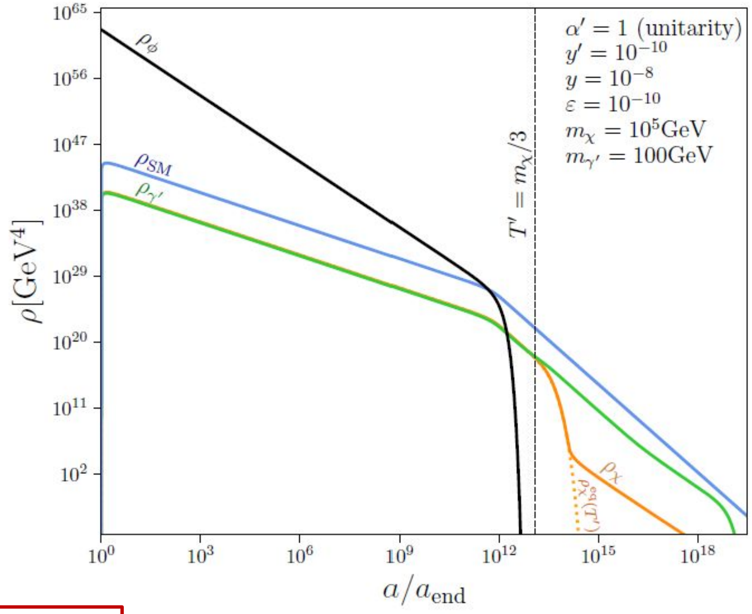
# Freeze-out after Reheating (Regime II)

**Dominant HS (hot T' > T)**
**Freeze-out after Reheating**




**Sub-dominant HS (cold T' < T)**
**Freeze-out after Reheating**




$$T'(a_{\rm RH}) \gg m_\chi$$

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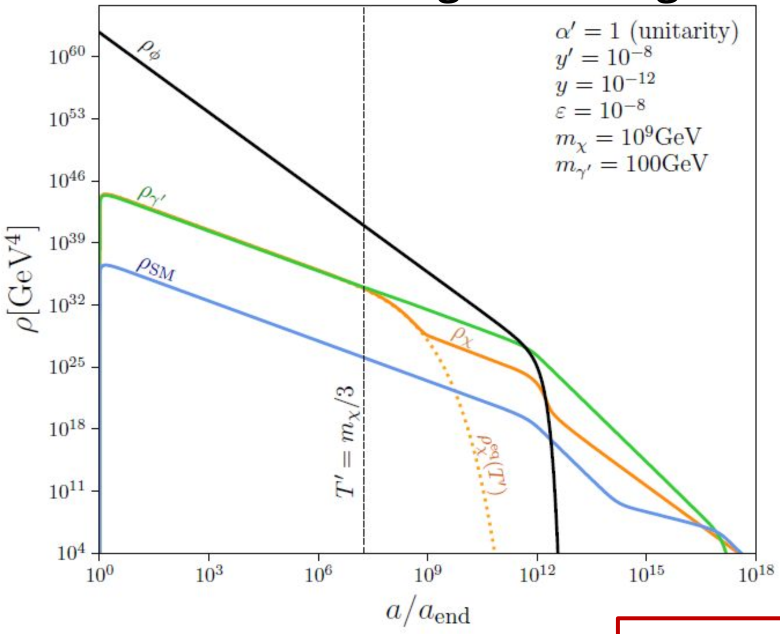
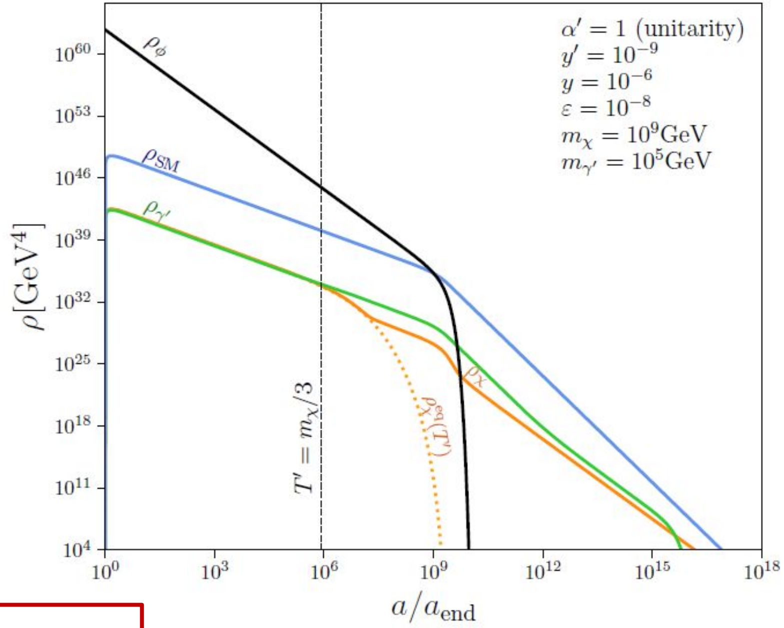
# Freeze-out during Reheating (Regime III)

**Dominant HS (hot T' > T)**
**Freeze-out during Reheating**




**Sub-dominant HS (cold T' < T)**
**Freeze-out during Reheating**




$$T'(a_{\mathrm{RH}}) \ll m_\chi$$

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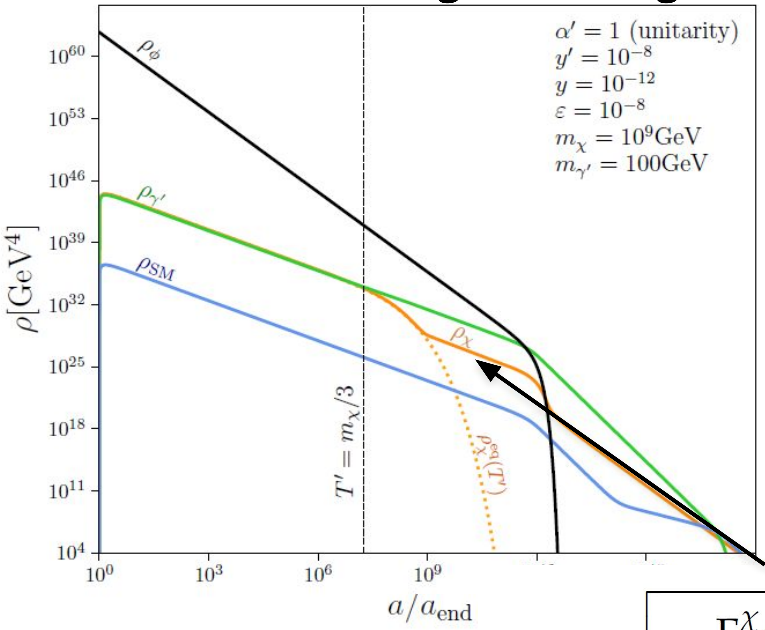
# Freeze-out during Reheating (Regime III)

**Dominant HS (hot T' > T)**
**Freeze-out during Reheating**




**Sub-dominant HS (cold T' < T)**
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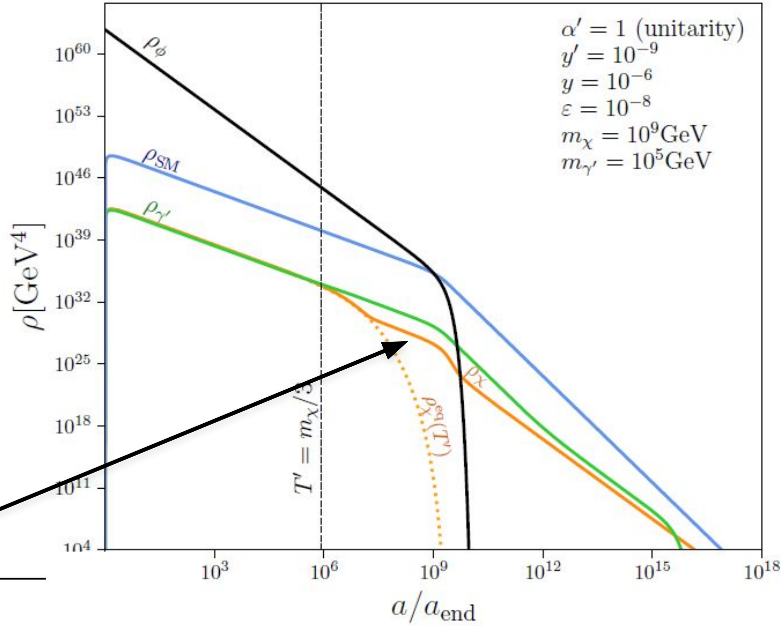
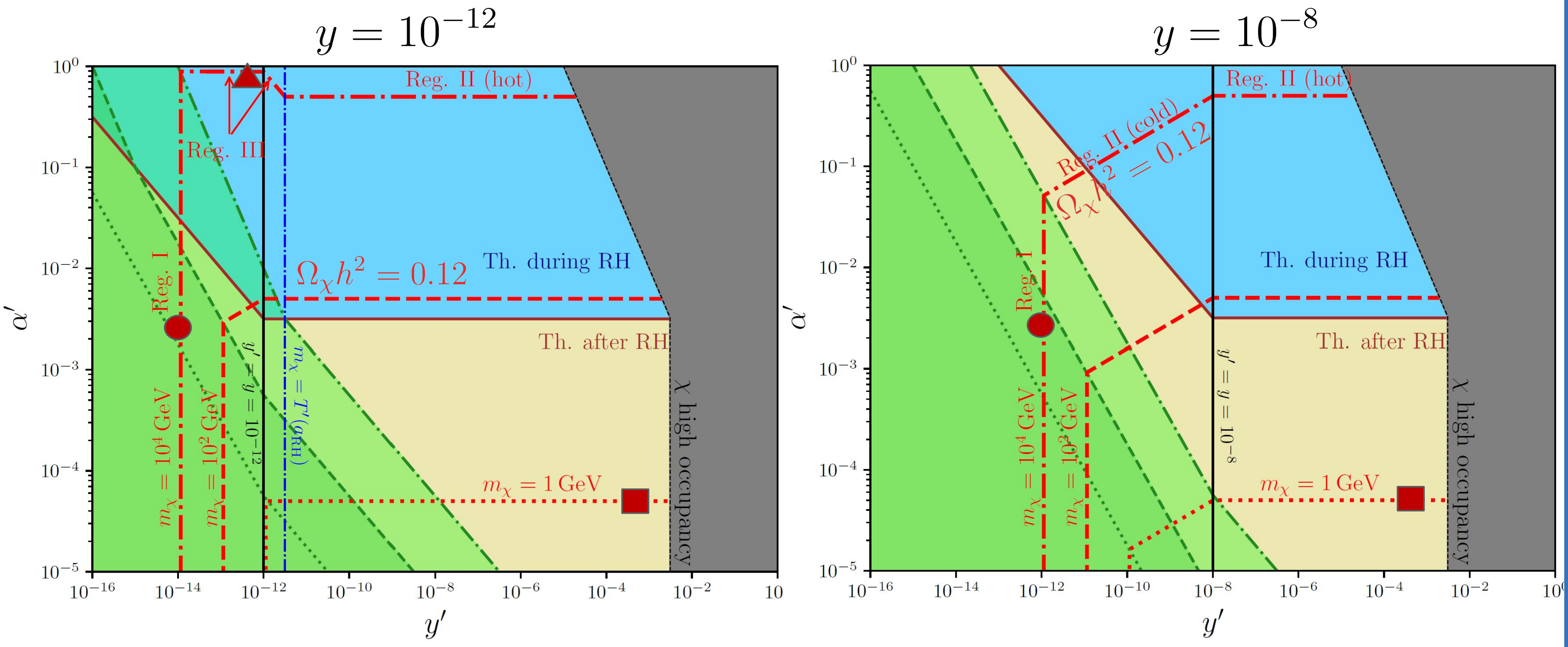



$$\rho_\chi \sim \sqrt{\frac{\Gamma_\phi^\chi m_\chi^2}{\langle \sigma_{\chi-\gamma'} v E\rangle_0}\rho_\phi} \propto a^{-3/2}$$

**"Re-sourcing "**

SC, Kimus, Tytgat, **2605.09686**

# Mapping the Regimes

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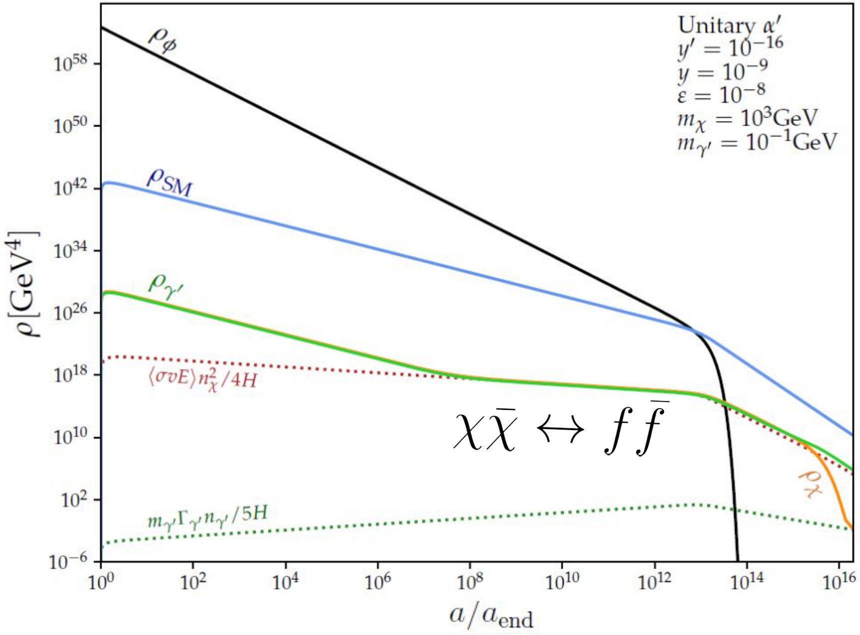
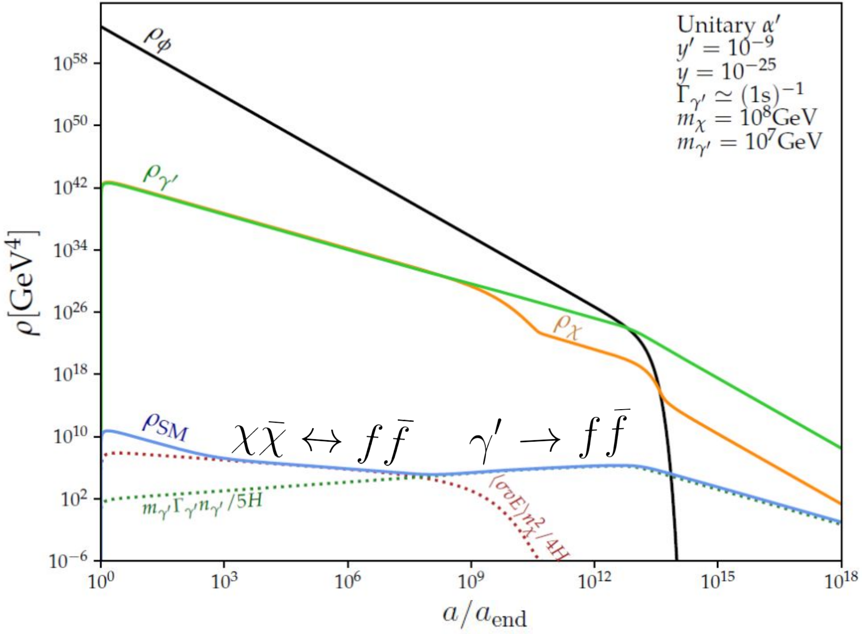
# Evolution of the temperature ratio $\xi$

**HS-VS interactions can affect the temperature ratio** by sourcing one sector from the other

Sub-dominant HS (cold T' < T)

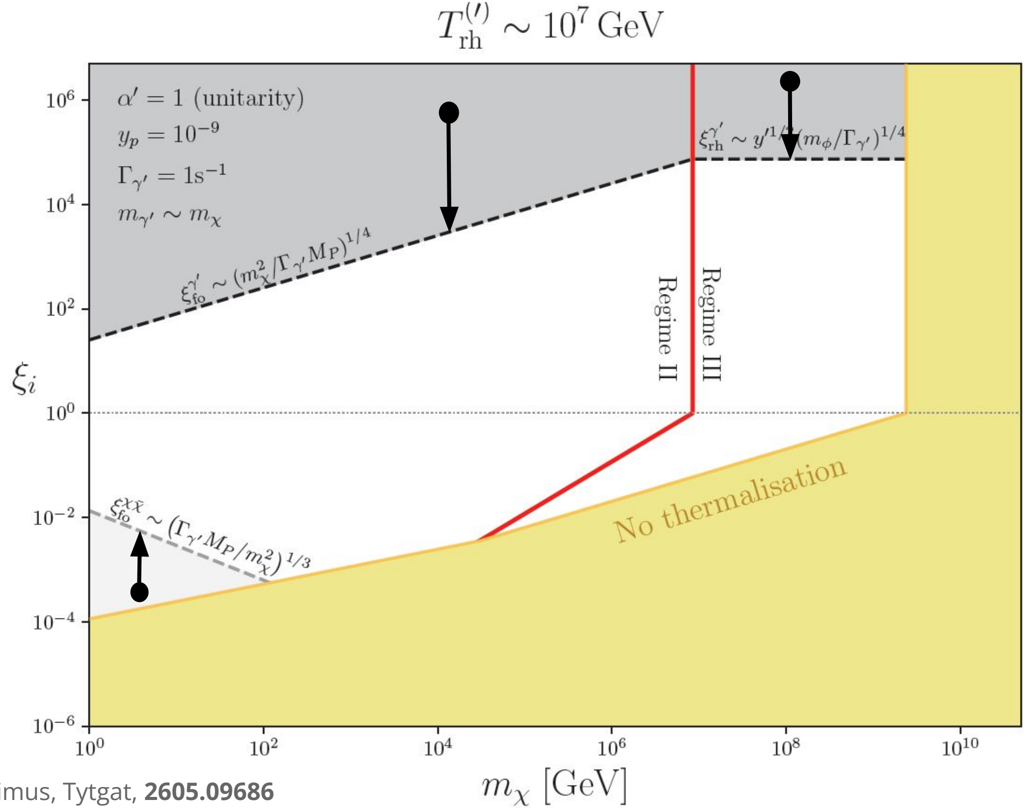



Dominant HS (hot T' > T)



# Evolution of the temperature ratio $\xi$

**Domain of stability of the temperature ratio $\xi$**

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- A **too large** ($\xi \gg 1$) or **too low** ($\xi \ll 1$) is **driven closer to 1**
- $\xi$ reaches **at DM decoupling** the values on dashed line boundaries
- Depends on **which process drives equilibration** of the two sectors and **whether freeze-out occurs during or after reheating (red frontier)**
- Strict **upper bound on $\xi$ for hot HS from dark photons decay before BBN**

# Thermal Dark Matter domains

**Unitarity limit** $\langle \sigma_{\chi\bar{\chi}-\gamma'\gamma'} v \rangle_{\text{fo}} \lesssim \frac{4\pi}{m_\chi^2}$

Upper bounds on DM mass
**Here : Freeze-out after reheating**

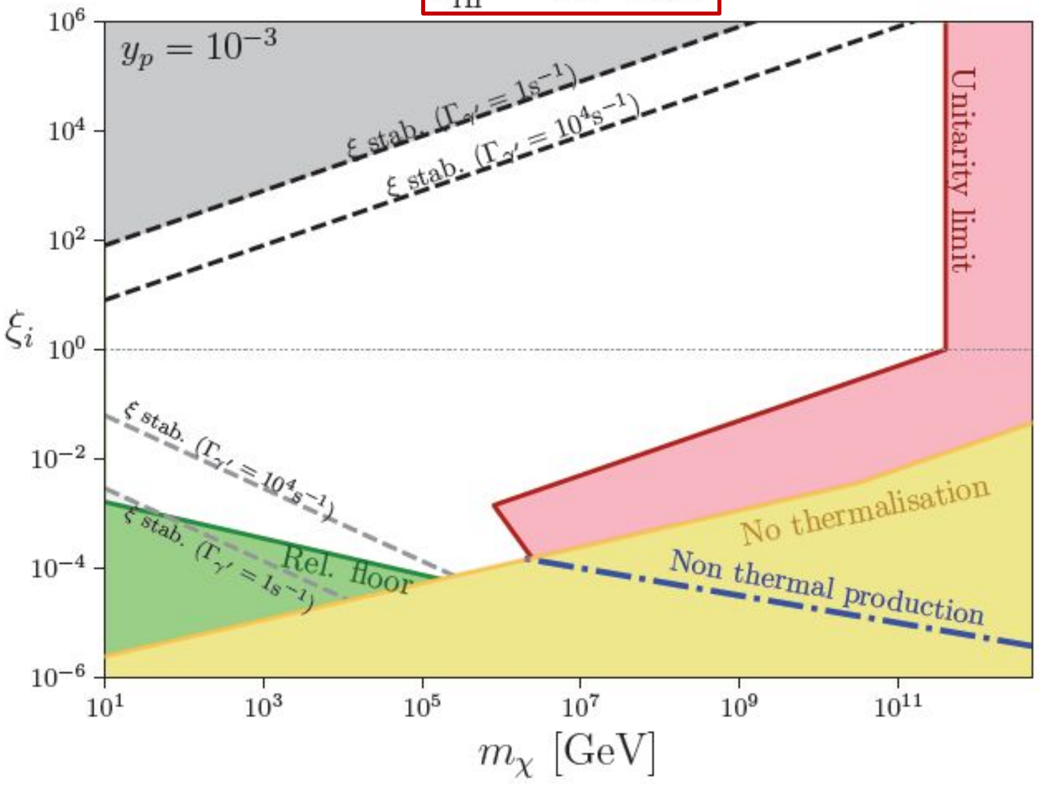
$\xi$ driven to the edge of the region
**Maximum** $\xi$ imposed by **minimal dark photon decay width (BBN)**

Constraint from **thermalization** timescale **after reheating** $m_\chi > T'_{\text{th}}$

**Right relic** from inflaton decays via **freeze-in**

Maximal relic from **relativistic freeze-out**; below **relativistic floor** DM is under abundant

$T_{\text{rh}}^{(\prime)} \sim 10^{12}\text{GeV}$

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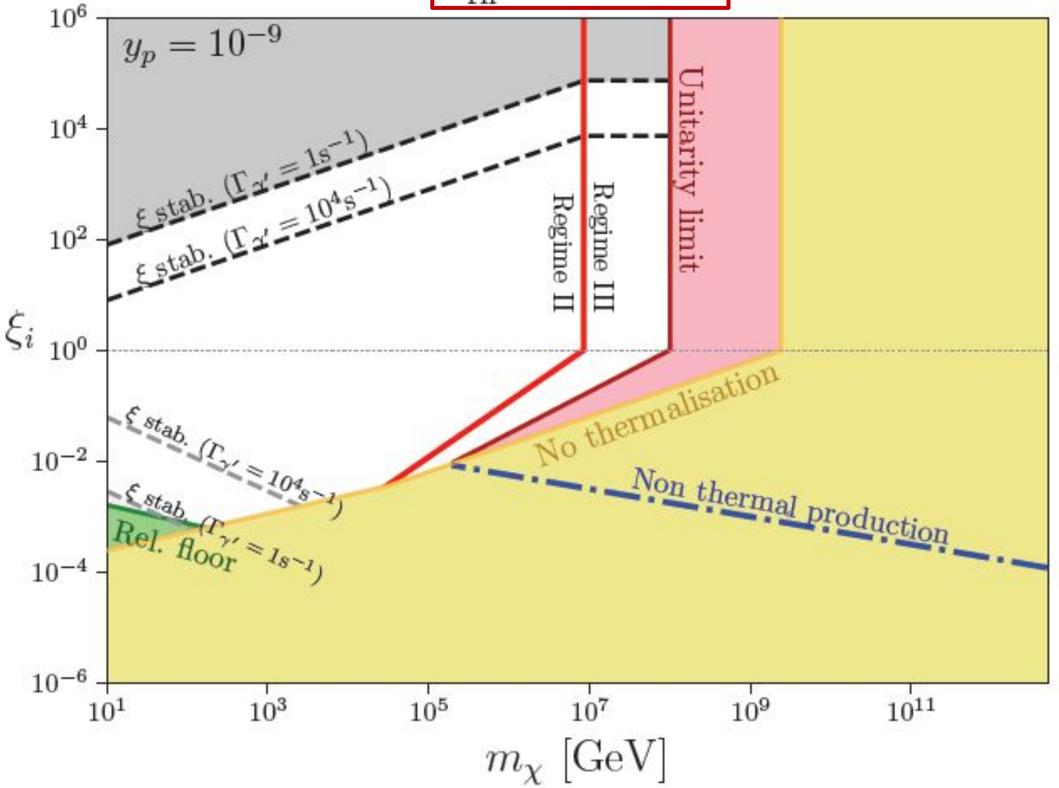
# Thermal Dark Matter domains

$T_{\rm rh}^{(\prime)} \sim 10^7 \mathrm{GeV}$




SC, Kimus, Tytgat, **2605.09686**

Limit between **Freeze-out after/during reheating (Regimes II/III)**

**Maximum** $\xi$ depends on the regime of **freeze-out after/during reheating**

**Freeze-out during reheating:** relic abundance and upper bounds from unitarity affected by reheating

Constraint from **thermalization** time scale **during reheating** $m_\chi > T'_{\rm th}$

# Summary

- Hidden Sector thermalized at a temperature **T' ≠ T broadens viable thermal DM candidates**
- **Reheating sets the initial non-thermal HS,** which can take **finite time to reach chemical equilibrium for a dilute, weakly coupled HS**
- **DM relic from different cosmological histories** during/after reheating**, depending on initial abundance and HS couplings**
- **Reheating and thermalization modify generic bounds** on the HS-VS **temperature ratio at Freeze-out** and on the **viable DM mass range**

**Outlook :**

- Non-perturbative/high abundance regime during (p)reheating
- Connection to SIDM phenomenology
- Late energy injection for subdominant dark photons ?

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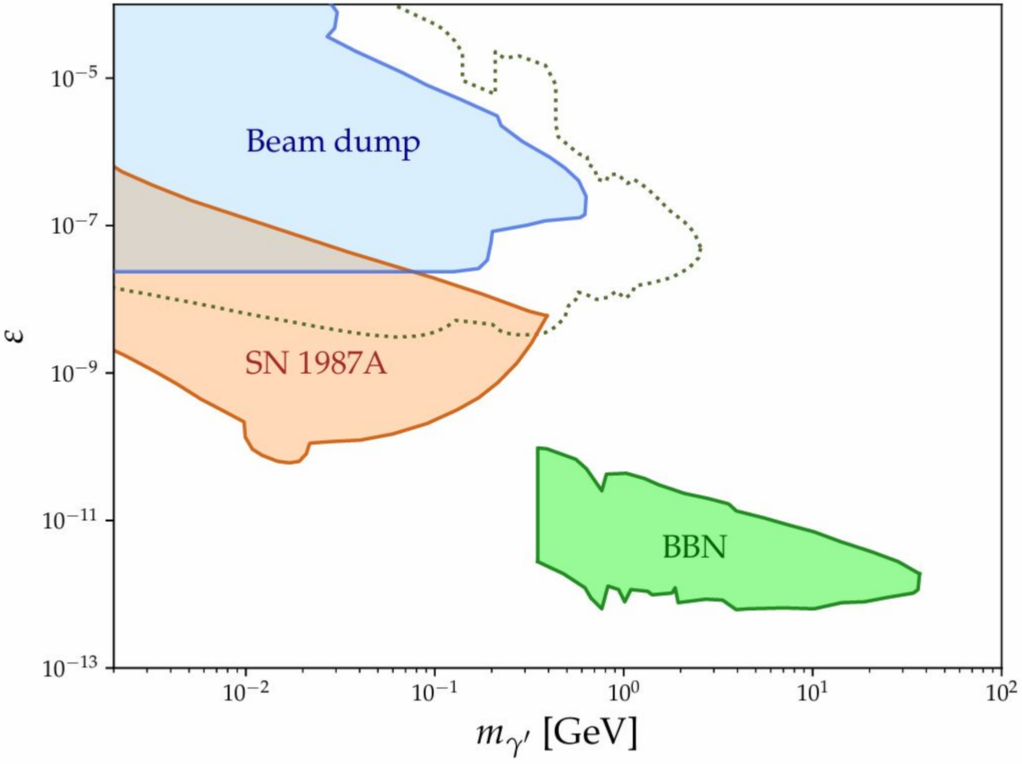
# Thank you for your attention !

# Backup

# Observational/Experimental constraints on massive Dark Photons

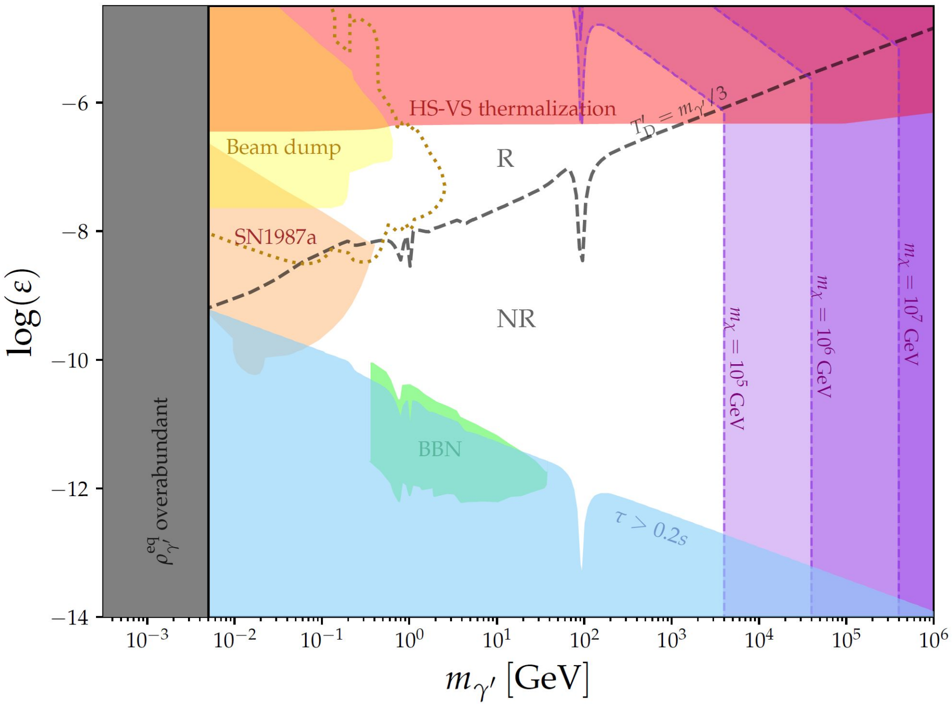
- Beam dump : absence of additional feeble interaction channels for fixed target experiments (E137, LSND, CHARM, NuCal, and projected as SHiP)
- SN 1987 A : absence of additional energy loss processes in observed ν flux from Supernovae
- BBN : Nucleosynthesis abundances not disrupted by frozen-in Dark Photons




For more see *The Heavy Dark Photon Handbook: Cosmological and Astrophysical Bounds*, Caputo, Park, Yun **2511.15785**

# Domain of (dominant) Dark Photons

- ✦ Experimental and observational constraints
- ✦ Decay before BBN (and subdominant freeze-in abundance)
- ✦ Too abundant relativistic dark photons at BBN
- ✦ DM freeze-out in the HS and stays secluded ($\chi\bar{\chi} \to f\bar{f}$, do not lead to T=T')
- ✦ DM freeze-out in the HS $m_{\gamma'} < m_\chi / x'_{\rm fo}$ and stays secluded ($\gamma' \to f\bar{f}$, do not lead to T = T')
- ✦ Separation between Relativistic (R) and Non Relativistic (NR) dark photon decay scenarios




*Light from darkness: History of a hot Dark Sector,* Coy, Kimus, Tytgat, **2405.10792**

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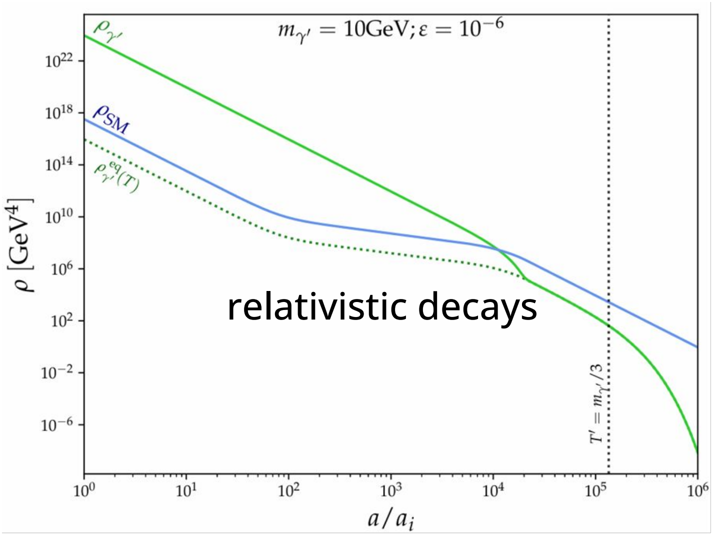
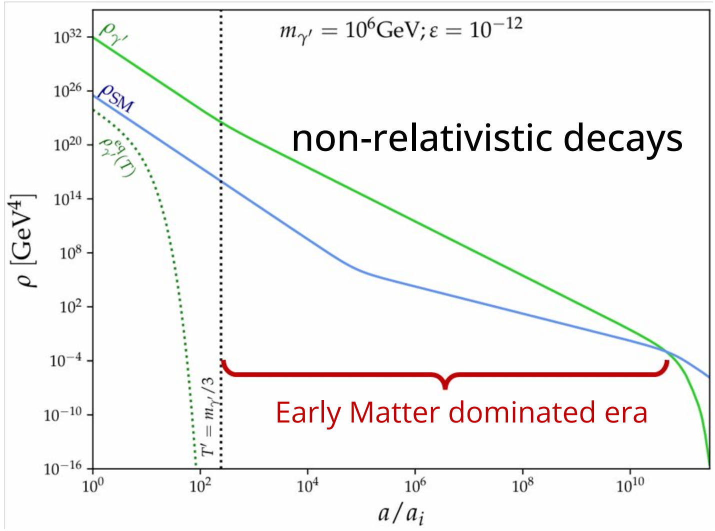
# Dark Photons decay and entropy dilution

Basic assumptions:

- ✦ DM particles **freeze-out before dark photons decay** $m_{\gamma'} \lesssim m_\chi$
- ✦ Dark photons at kinetic equilibrium after DM freeze-out
- ✦ Dark photons **decay before BBN** $\Gamma_{\gamma'} \gtrsim 1\,\mathrm{s}^{-1}$

➜ Massive particles decay may **increase the total comoving entropy if they are dominant**

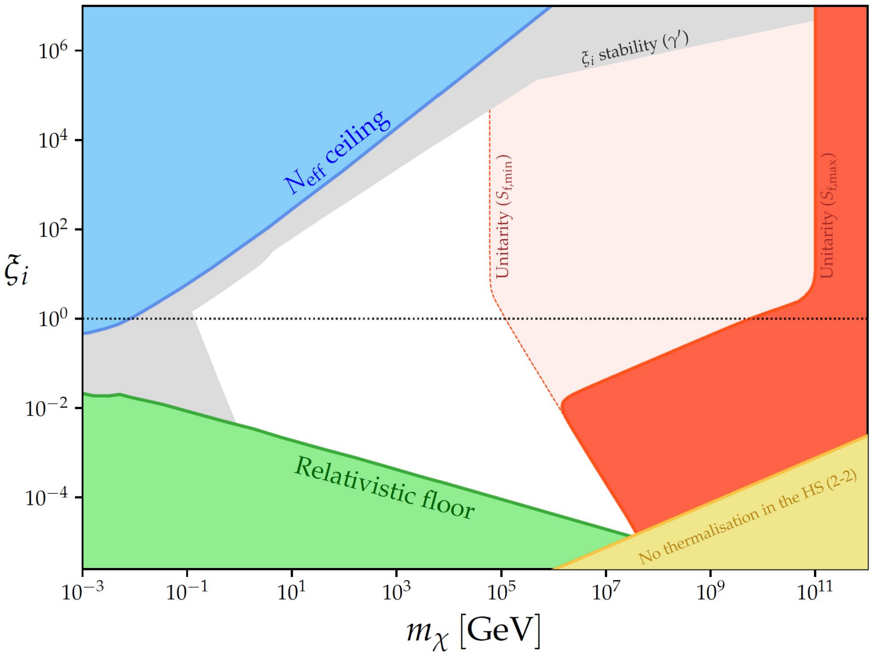



➜ Large entropy injection

# Freeze-out in a thermal HS : Dark Matter domain

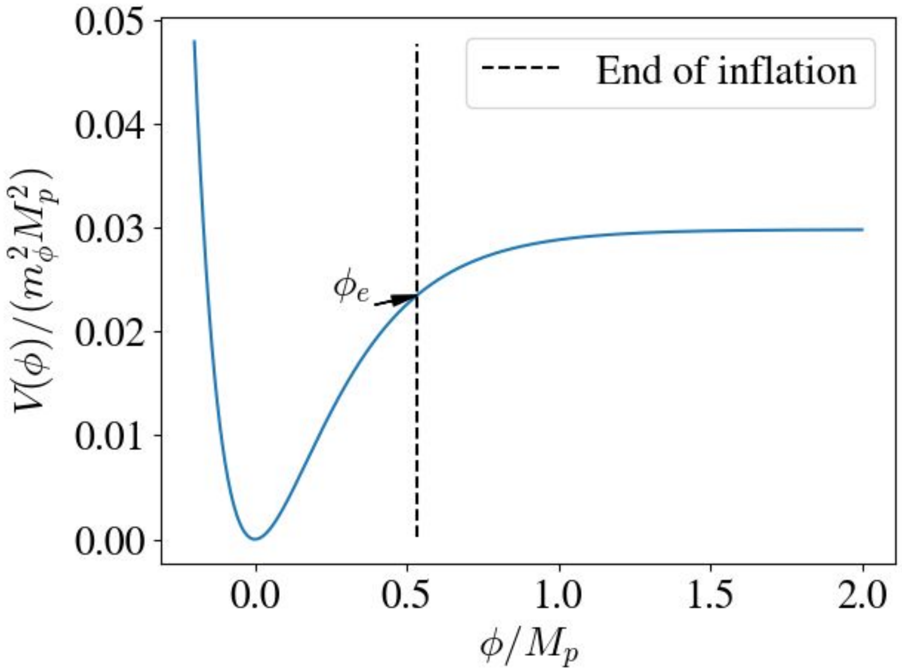
- **Relativistic floor :** relativistic freeze-out yields the maximal relic abundance at fixed $\xi$ = **T'/T**
  ➜ DM is under abundant
- **Neff ceiling :** DM particles are relativistic at BBN
  ➜ Lower bound on DM mass depending on ratio $\xi$ = **T'/T** at freeze-out
- **ξ stability :** DM freeze-out in a secluded HS, with constant ξ
- **HS thermalization :** Efficient HS thermalization for maximal $\alpha'$
- **Unitarity wall :** maximal cross section allowed by unitarity $\chi\bar{\chi} \to \gamma'\gamma'$
  ➜ DM is over abundant




*Light from darkness: History of a hot Dark Sector,* Coy, Kimus, Tytgat, **2405.10792**

*The Domain of Thermal Dark Matter candidates,* Coy, Hambye, Tytgat, Vanderheyden, **2105.01263**

# Starobinsky inflation




$$V(\phi) = \frac{3}{4} m_\phi^2 M_P^2 \left(1 - e^{-\sqrt{\frac{2}{3}}\frac{\phi}{M_P}}\right)^2$$

$$m_\phi \simeq 3 \times 10^{13}\ \text{GeV}$$

$\phi \ll M_P$

$$V(\phi) \approx \tfrac{1}{2} m_\phi^2 \phi^2$$

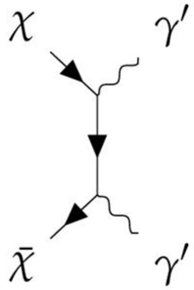
$$w_\phi = P_\phi / \rho_\phi \simeq 0$$

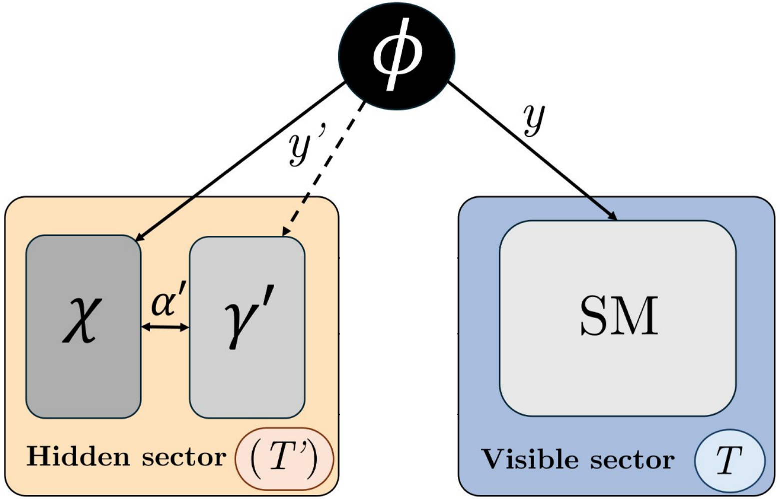
**Quadratic potential near the minimum**

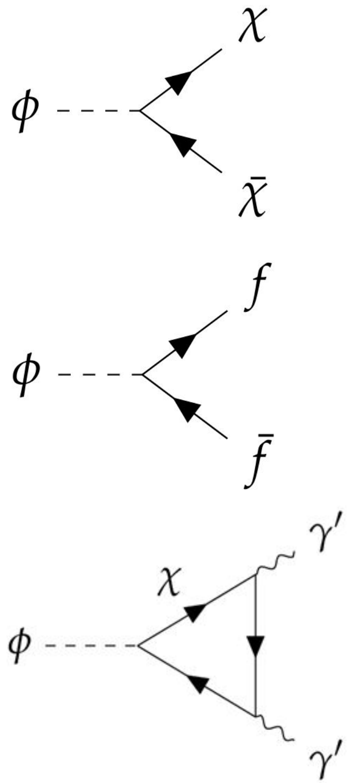
# Asymmetric Reheating

A way to produce the HS, via **asymmetric energy transfer** from inflaton to both HS and VS

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




Asymmetric Reheating

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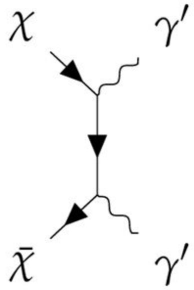
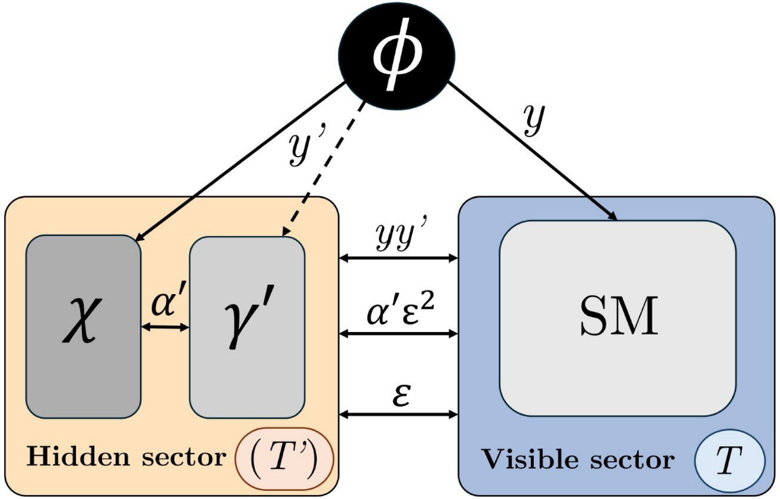
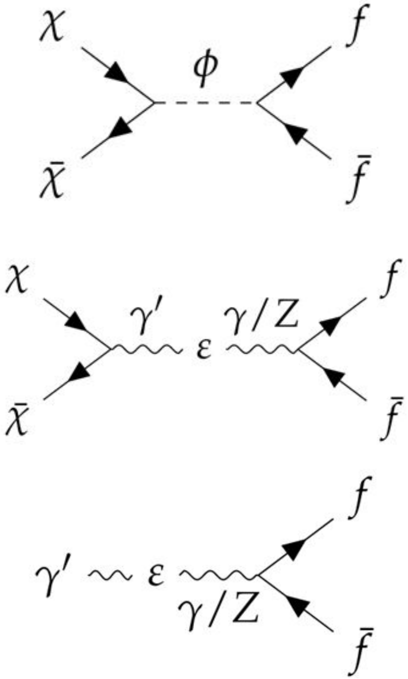


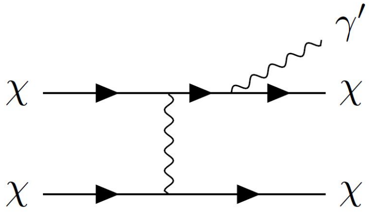




Contact between SM and HS

# Thermalization of the Hidden Sector : Splittings

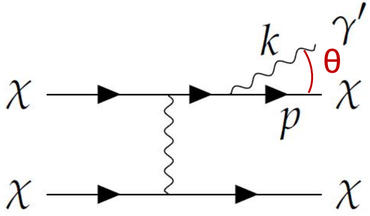
Gauge boson emission dominated by **soft t-channel collision of hard fermions** of density $n_h$

➜ slightly off-shell parent fermion radiating a gauge boson
➜ splitting rate from soft collision cut off in the medium by the Debye mass $m_D^2 \sim \alpha' \int d^3k \frac{f(k)}{k}$




$$\Gamma_{2\to3} \sim \alpha' \, \Gamma^s_{2\to2} \longleftarrow \Gamma^s_{2\to2} \sim \begin{cases} \alpha' m_\phi & m_D \gtrsim m_{\gamma'} \\ \alpha'^2 n_h / \bar{m}^2_{\gamma'}, & m_{\gamma'} \gtrsim m_D \end{cases}$$

Emitted soft gauge bosons are **collinear** with their parent particle
➜ a finite time before the particles are **"separated"**




Several amplitudes interfering destructively can **suppress the splitting rate ➜ Landau–Pomeranchuk–Migdal (LPM) effect**

# Thermalization timescales : Abelian vs Non-Abelian

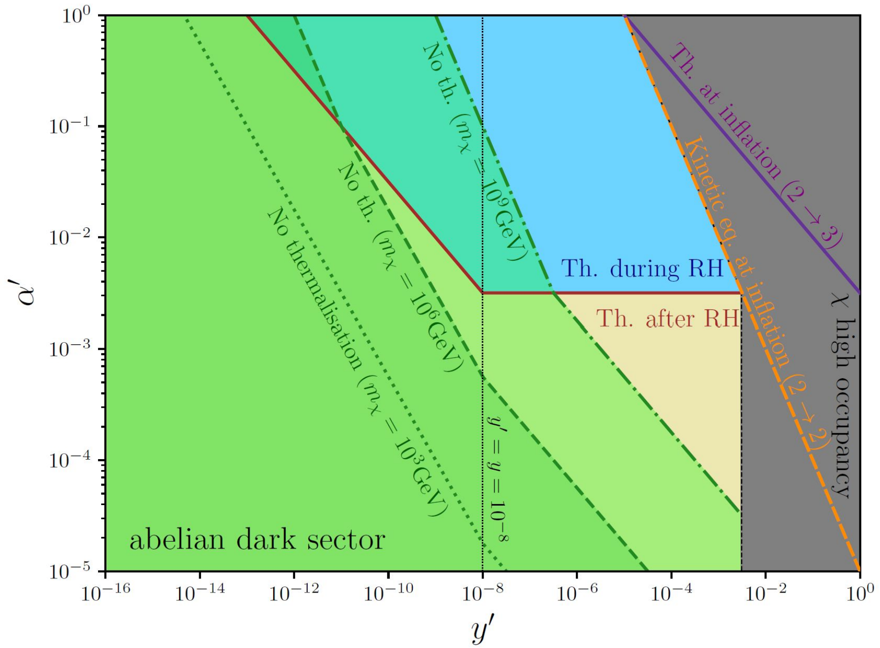
| | abelian | non-abelian |
|---|---|---|
| LPM | $k \gtrsim k_{\rm LPM}$ | $k \lesssim k_{\rm LPM}$ |
| $k_{\rm LPM}$ | $\frac{m_\phi^4}{n_h} \gg m_\phi$ | $\frac{n_h}{m_\phi^2} \ll m_\phi$ |
| $\Gamma_{2\to 3}^{\rm LPM}$ | $\alpha' \Gamma_{2-2}^s \sqrt{\frac{k}{k_{\rm LPM}}}$ | $\alpha' \Gamma_{2-2}^s \sqrt{\frac{k_{\rm LPM}}{k}}$ |
| $t_{\rm th}$ | $\frac{1}{\alpha'^2 m_\phi} \left(\frac{m_\phi^3}{n_h}\right)^{1/2}$ | $\frac{1}{\alpha'^2 m_\phi} \left(\frac{m_\phi^3}{n_h}\right)^{3/8}$ |
| $H_{\rm th}$ | $m_\phi\, \alpha'^4 \left(\frac{\Gamma_\phi^\chi M_P^2}{m_\phi^3}\right)$ | $m_\phi\, \alpha'^{16/5} \left(\frac{\Gamma_\phi^\chi M_P^2}{m_\phi^3}\right)^{3/5}$ |

**Thermalization timescales**, to compare with reheating time scale

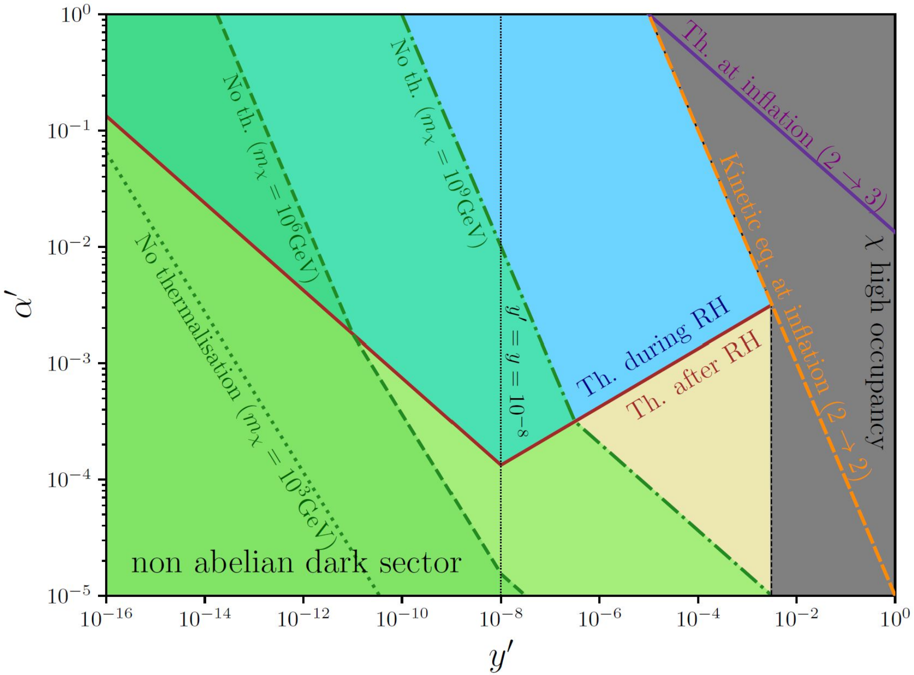
SC, Kimus, Tytgat, **2605.09686**

Harigaya, Mukaida, **1312.3097**

# Constraints on the Thermalization of the Hidden Sector




Domain of thermalization
during/after reheating
**Abelian plasma**



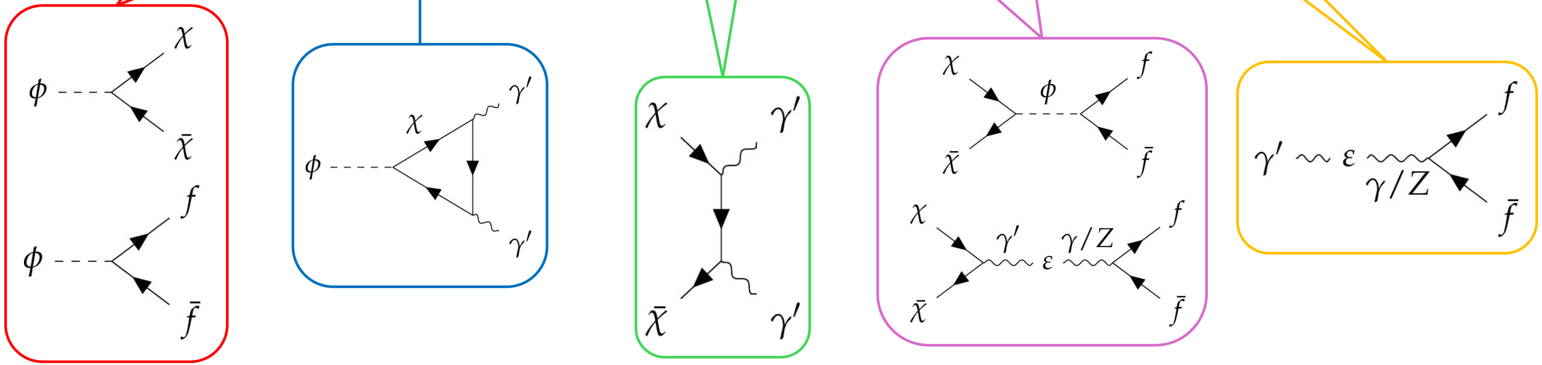

Domain of thermalization
during/after reheating
**Non-Abelian plasma**

SC, Kimus, Tytgat, **2605.09686**

# Set of Boltzmann equations

Boltzmann equations for **thermal** HS and SM solved numerically

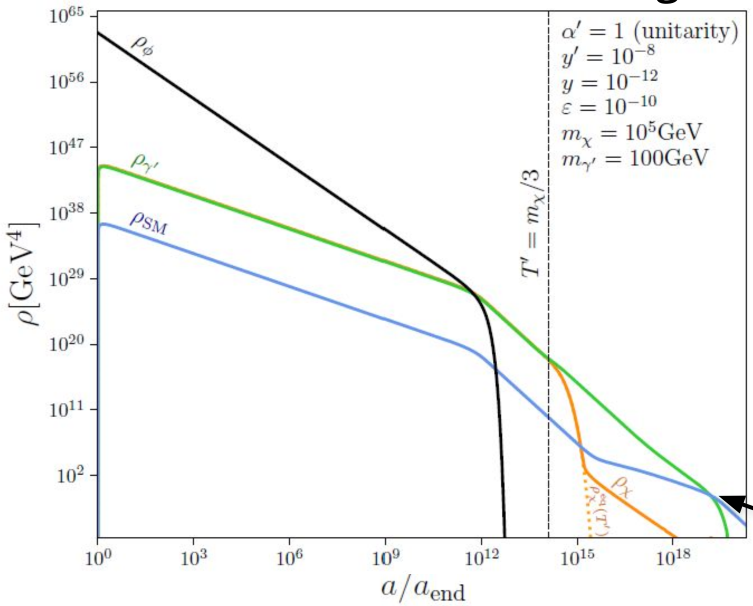
$$
\begin{aligned}
\dot{\rho}_\phi + 3H\rho_\phi &= -\Gamma_\phi \rho_\phi \\
\dot{\rho}_\chi + 3(1+w_\chi)H\rho_\chi &= \Gamma_\phi^\chi \rho_\phi - \langle \sigma_{\chi-\gamma'} v E\rangle_{T'} \left(n_\chi^2 - \left(n_\chi^{\rm eq}(T')\right)^2\right) - \langle \sigma_{\chi-f} v E\rangle_{T'} n_\chi^2 + \langle \sigma_{\chi-f} v E\rangle_{T} \left(n_\chi^{\rm eq}(T)\right)^2 \\
\dot{\rho}_{\gamma'} + 3(1+w_{\gamma'})H\rho_{\gamma'} &= \Gamma_\phi^{\gamma'-\rm loop} \rho_\phi - \langle \sigma_{\chi-\gamma'} v E\rangle_{T'} \left(n_\chi^2 - \left(n_\chi^{\rm eq}(T')\right)^2\right) - m_{\gamma'}\Gamma_{\gamma'}\left(n_{\gamma'} - n_{\gamma'}^{\rm eq}(T)\right) \\
\dot{\rho}_{\rm SM} + 4H\rho_{\rm SM} &= \Gamma_\phi^{\rm SM} \rho_\phi + \langle \sigma_{\chi-f} v E\rangle_{T'} n_\chi^2 - \langle \sigma_{\chi-f} v E\rangle_{T} \left(n_\chi^{\rm eq}(T)\right)^2 + m_{\gamma'}\Gamma_{\gamma'}\left(n_{\gamma'} - n_{\gamma'}^{\rm eq}(T)\right)
\end{aligned}
$$



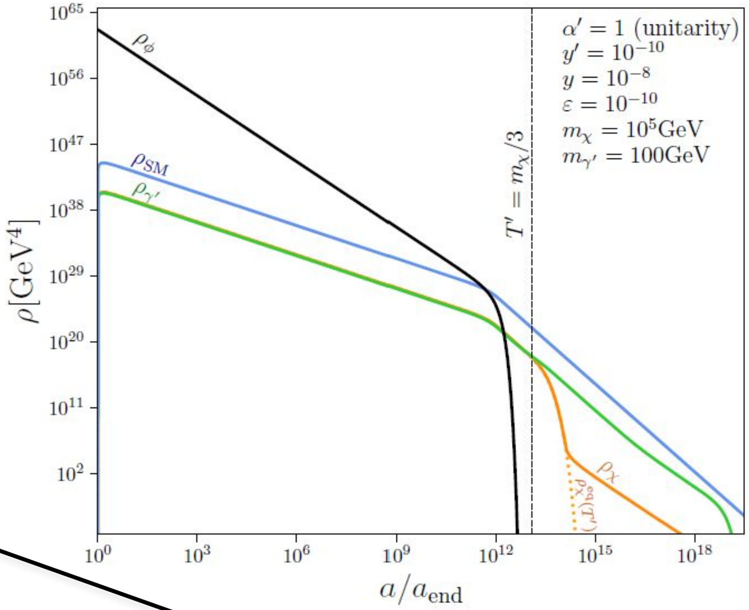

SC, Kimus, Tytgat, **2605.09686**

# Freeze-out after Reheating (Regime II)

Dominant HS (hot T' > T)
Freeze-out after Reheating




Sub-dominant HS (cold T' < T)
Freeze-out after Reheating

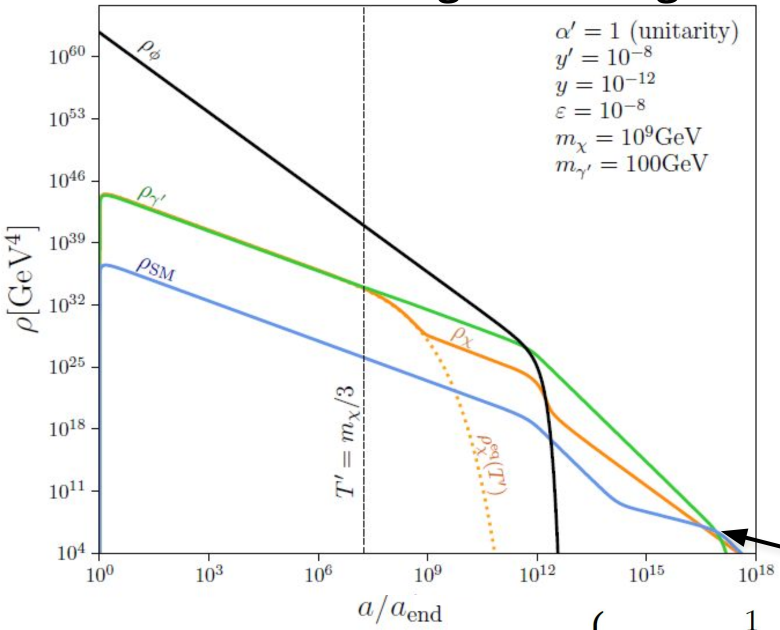



$$Y_\chi^{\mathrm{fo}} \equiv \frac{n_{\chi,\mathrm{fo}}}{s_{\mathrm{t,\,fo}}} \sim \frac{H_{\mathrm{fo}}}{\langle\sigma_{\chi-\gamma'}v\rangle_{T'_{\mathrm{fo}}}\left(H_{\mathrm{fo}}m_{\mathrm{Pl}}\right)^{3/2}} \rightarrow \begin{cases} \dfrac{1}{\langle\sigma_{\chi-\gamma'}v\rangle_{T'_{\mathrm{fo}}}m_{\mathrm{Pl}}m_\chi} & (y' \gg y) \\[2ex] \dfrac{\xi_{\mathrm{fo}}}{\langle\sigma_{\chi-\gamma'}v\rangle_{T'_{\mathrm{fo}}}m_{\mathrm{Pl}}m_\chi} & (y' \ll y) \end{cases}$$

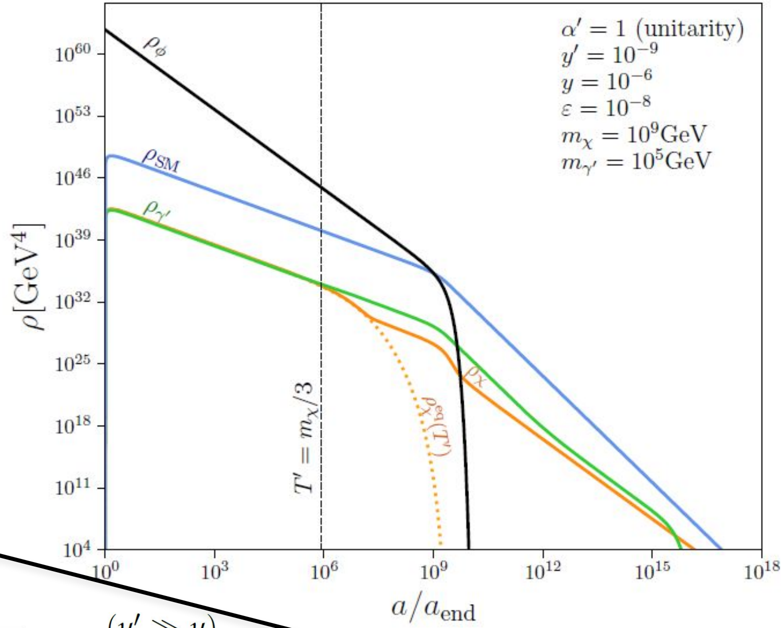
✖ $$\frac{s_{\mathrm{t,\,fo}}a_{\mathrm{fo}}^3}{s_{\mathrm{t,\,f}}a_{\mathrm{f}}^3} \sim \left(\frac{\Gamma_{\gamma'}}{H_{\mathrm{nr}}}\right)^{1/2}$$

# Freeze-out during Reheating (Regime III)

**Dominant HS (hot T' > T)**
**Freeze-out during Reheating**



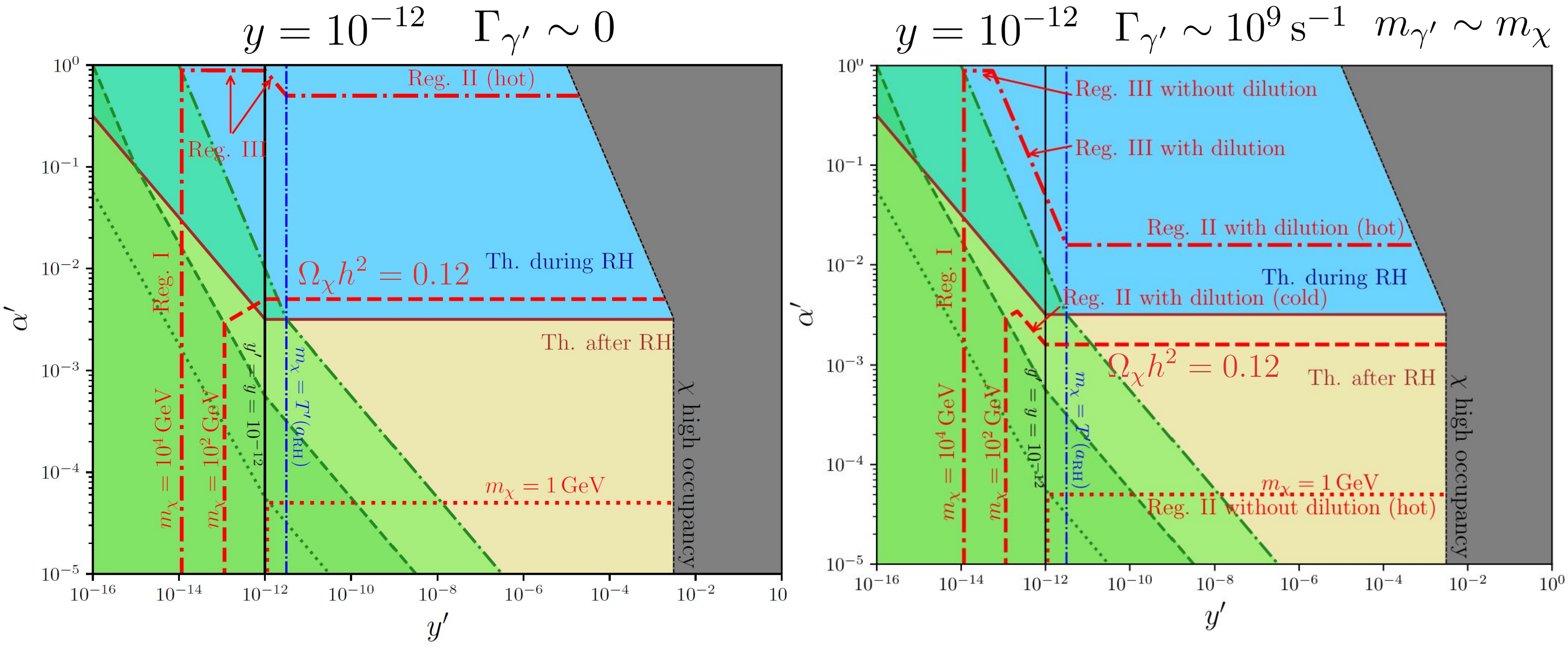

**Sub-dominant HS (cold T' < T)**
**Freeze-out during Reheating**




$$Y_\chi^{\mathrm{rh}} \equiv \frac{n_{\chi,\mathrm{rh}}}{s_{\mathrm{t,\,rh}}} \sim \frac{H_{\mathrm{rh}}}{\langle\sigma_{\chi-\gamma'}v\rangle_0\,(H_{\mathrm{rh}}m_{\mathrm{Pl}})^{3/2}} \to \begin{cases} \dfrac{1}{\langle\sigma_{\chi-\gamma'}v\rangle_0(\Gamma_\phi^\chi)^{1/2}m_{\mathrm{Pl}}^{3/2}} & (y' \gg y) \\ \dfrac{1}{\langle\sigma_{\chi-\gamma'}v\rangle_0(\Gamma_\phi^{\mathrm{SM}})^{1/2}m_{\mathrm{Pl}}^{3/2}} & (y' \ll y) \end{cases}$$

✖ $$\frac{s_{\gamma',\mathrm{rh}}a_{\mathrm{rh}}^3}{s_{\mathrm{SM,\,f}}a_{\mathrm{f}}^3} \sim \left(\frac{\Gamma_{\gamma'}}{H_{\mathrm{rh}}}\right)^{1/2}$$

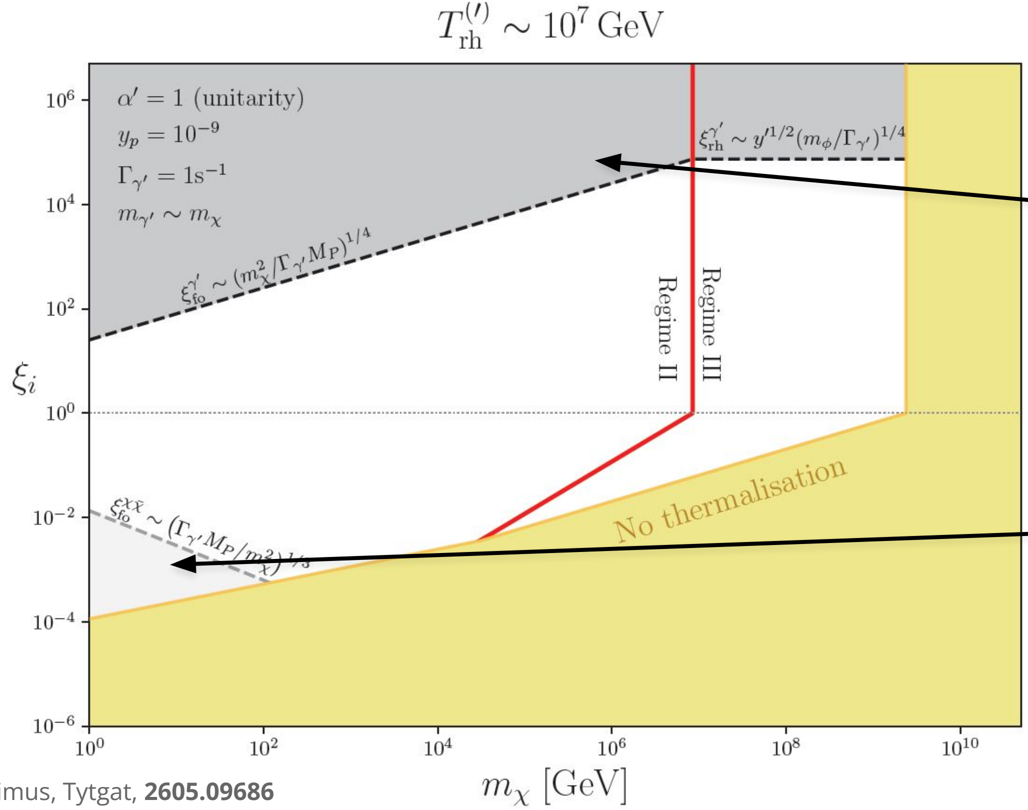
# Impact of dilution from Dark Photons decay

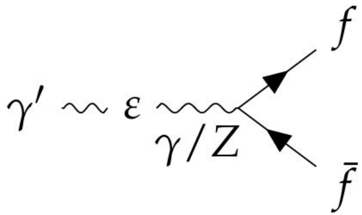


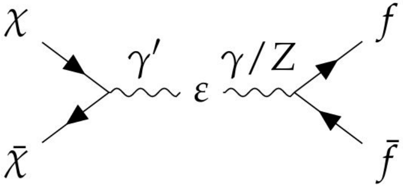

SC, Kimus, Tytgat, **2605.09686**

# Evolution of the temperature ratio $\xi$

**Domain of stability of the temperature ratio $\xi$**



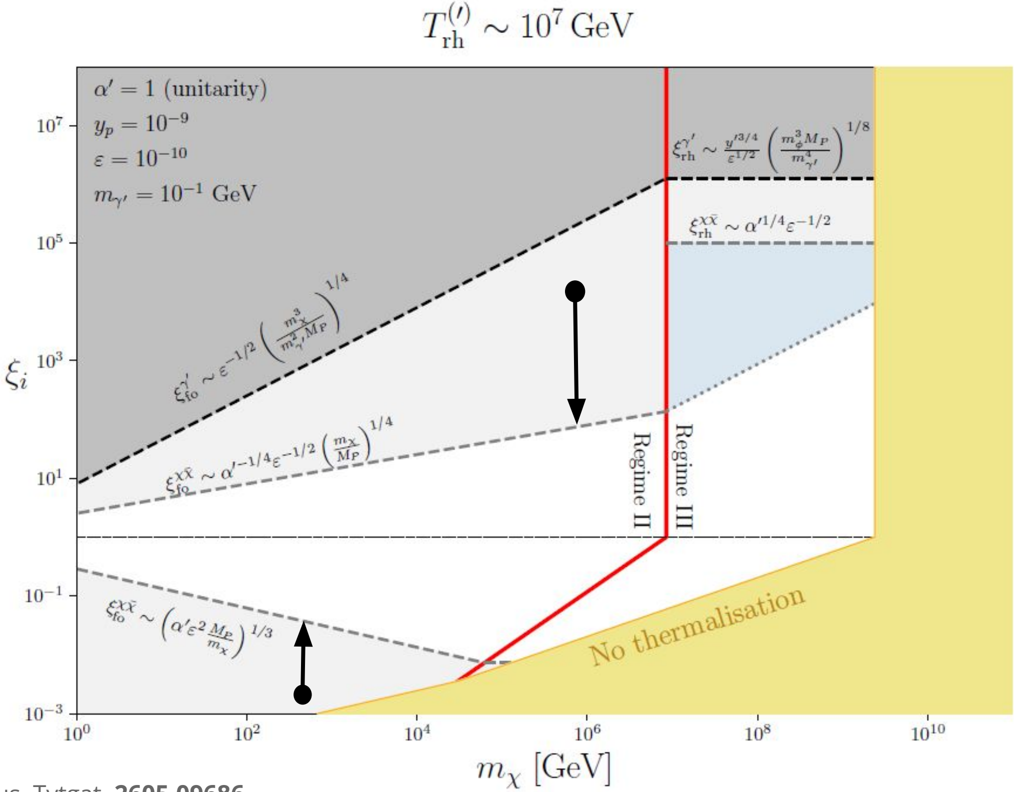



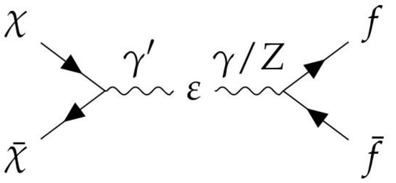



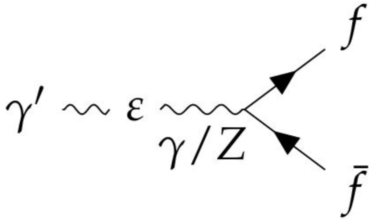

SC, Kimus, Tytgat, **2605.09686**

# Evolution of the temperature ratio $\xi$

Effect on $\xi$ stability of **large kinetic mixing at fixed dark photon mass**

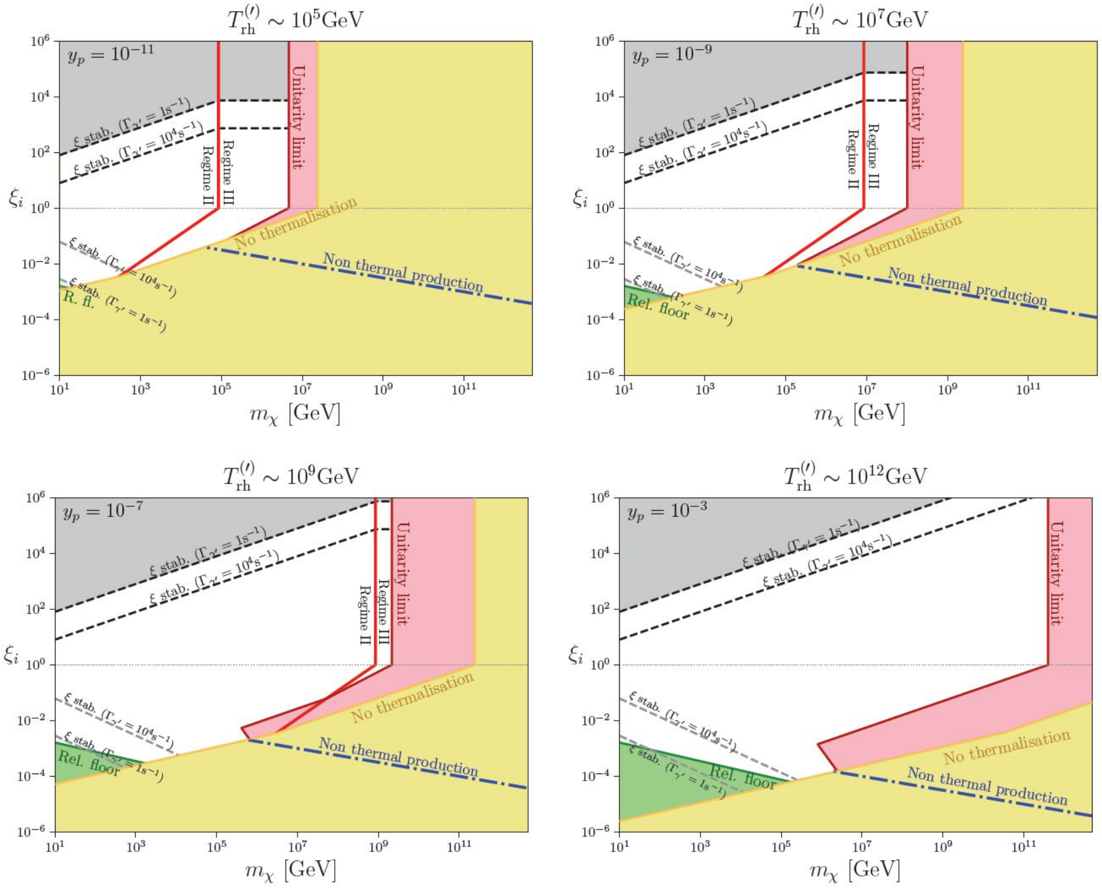


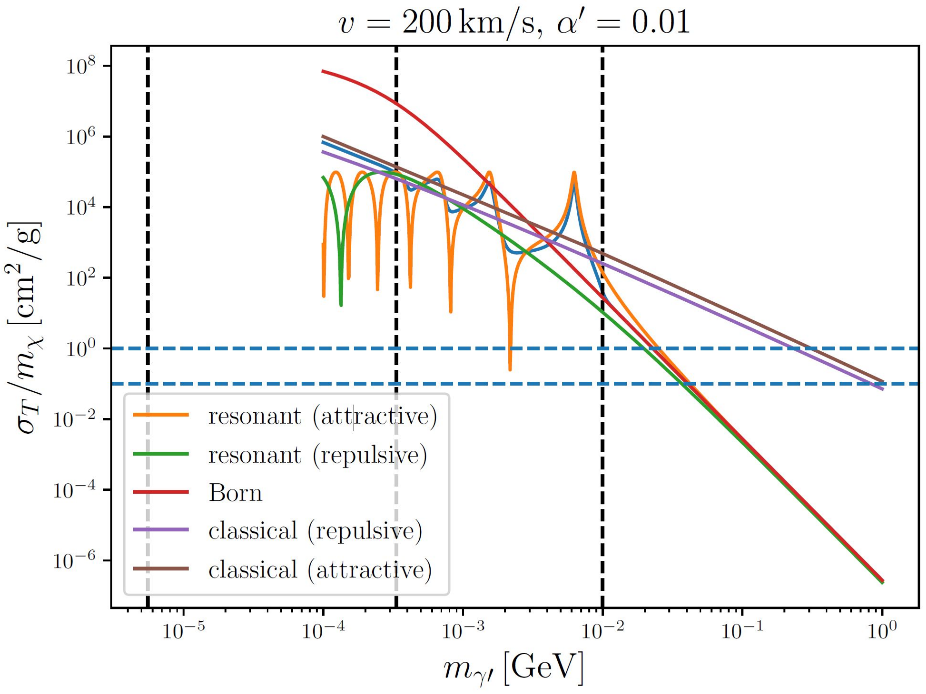

SC, Kimus, Tytgat, **2605.09686**

# Thermal Dark Matter domains




SC, Kimus, Tytgat, **2605.09686**

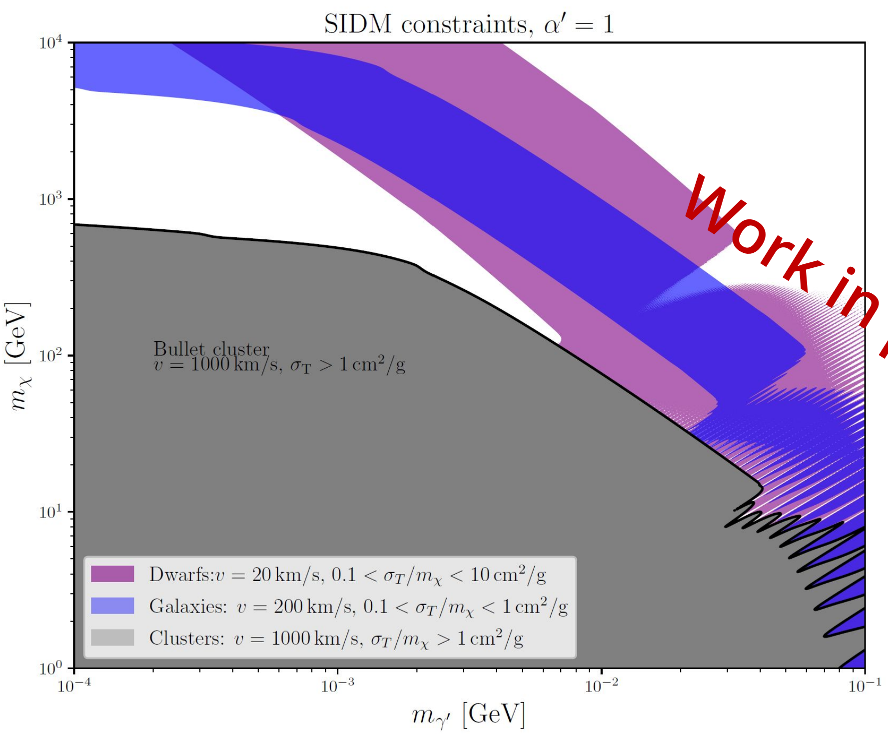
# Dark QED and SIDM

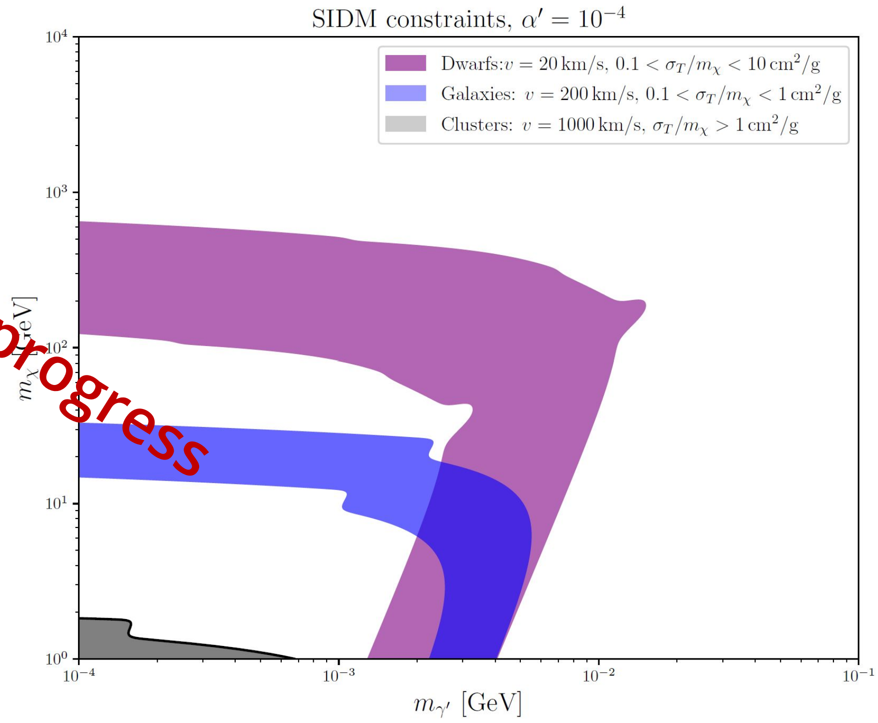



Light dark photon exchange induces DM **self-scattering cross section**

The transfer cross section is **velocity-dependent** with a **classical, resonant, and Born regime depending on the mediator mass**

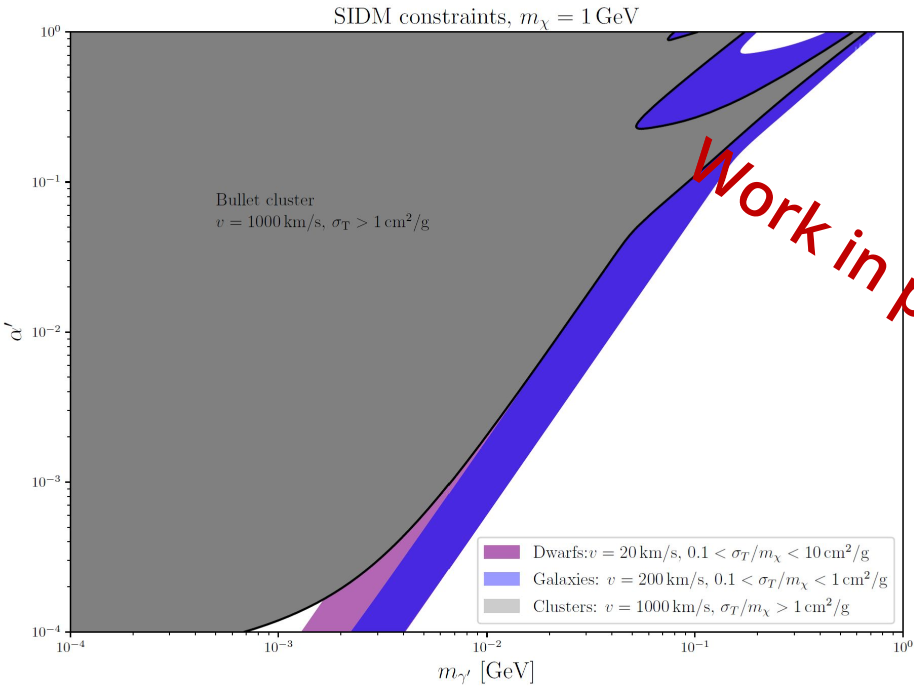
# Dark QED and SIDM

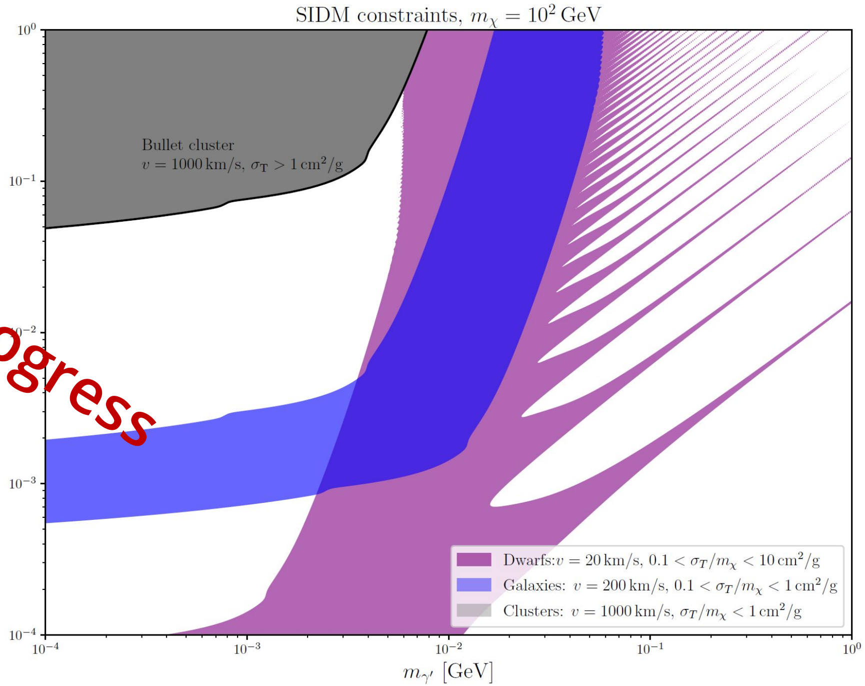



Work in progress

# Dark QED and SIDM




Work in progress