Asymmetric Reheating : Thermalization and Relics of an abelian Hidden Sector

Simon Cléry, TUM
Astroparticle Symposium 2025

* *Asymmetric Reheating: Thermalization and relics of an Abelian Hidden Sector,* SC, Kimus, Tytgat, **2512.XXXXX**

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

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…)

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

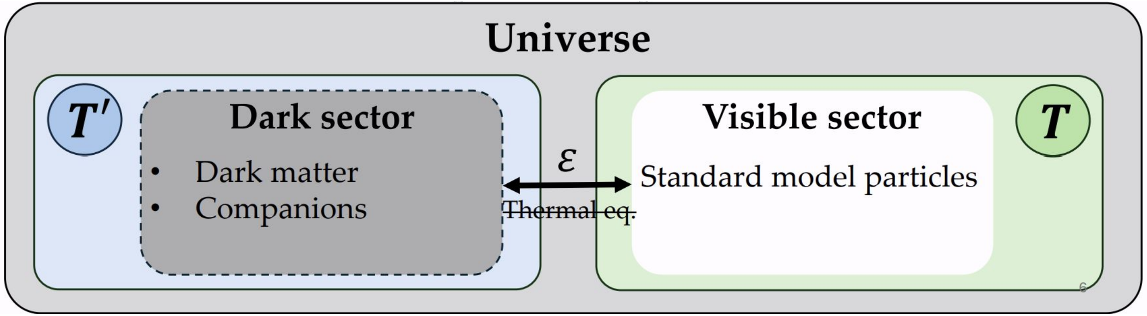
HS thermalised at $T' \neq T$ secluded from Visible Sector (VS) or with small HS-VS coupling **ε ≪ 1**

DM relic from Freeze-out of the HS

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

Berlin, Hooper, Krnjaic, **1602.08490**

➜ **Broader parameter space**



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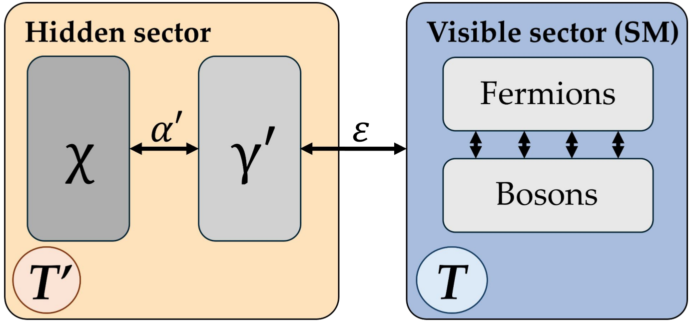
Dark QED



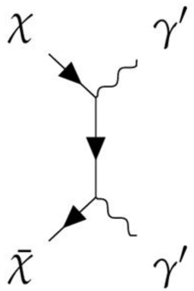
Dark QED

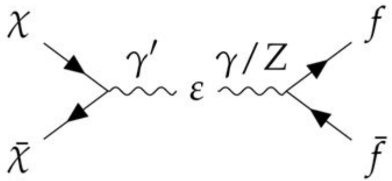
Benchmark model for the Hidden Sector $\mathcal{L} \supset \overline{\chi}\,(i\not{D} - m_\chi)\,\chi - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m^2_{\gamma'}A'_\mu A'^\mu - \frac{\varepsilon}{2}B_{\mu\nu}F'^{\mu\nu}$

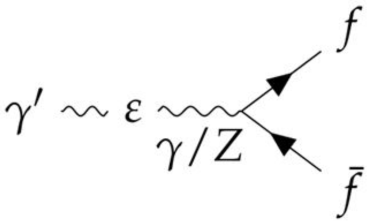
➜ Two BSM fields:

- ***Dark electron χ*** □ DM
- ***Dark photon γ′*** □ abelian gauge boson companion

➜ Small kinetic mixing **ε ≪ 1** between HS-VS







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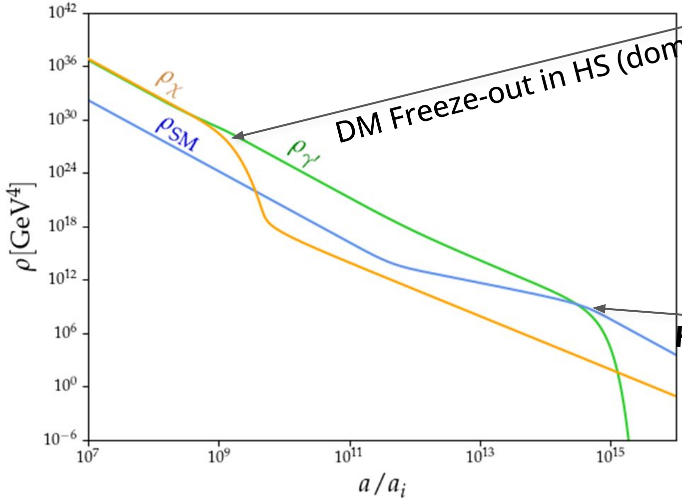
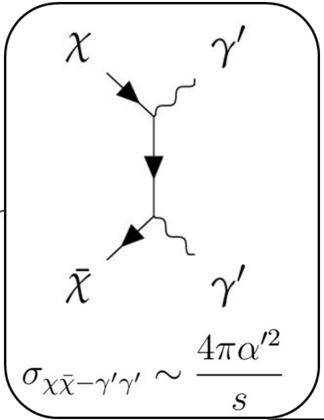
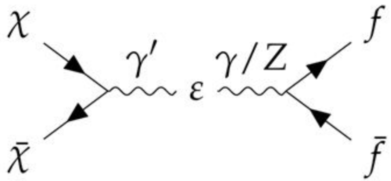


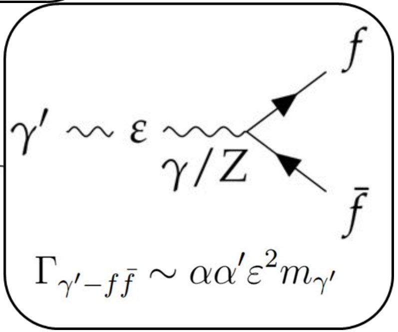
DM Freeze-out in HS (dominant process)





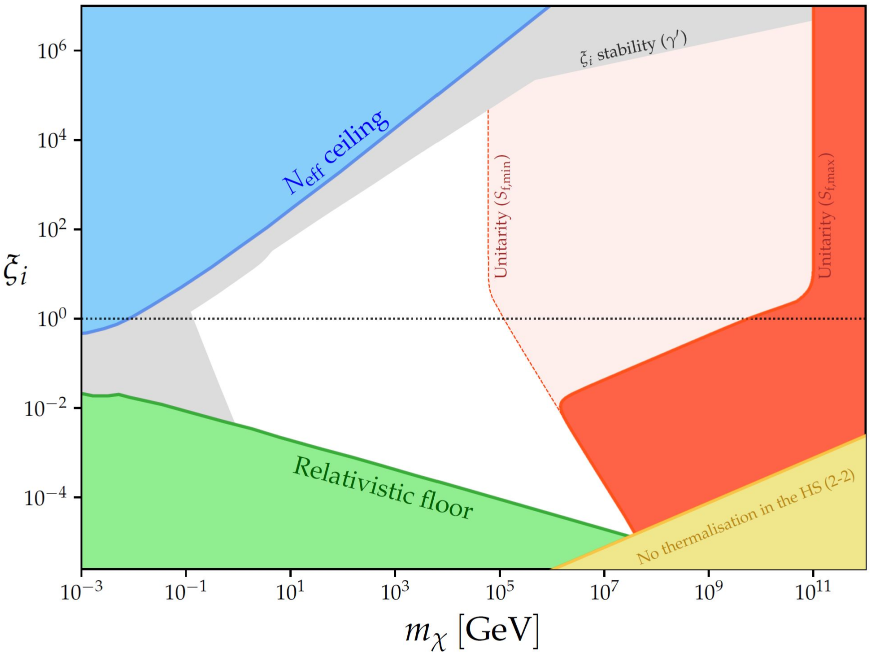
Dark photon decay

Heating SM (entropy dilution)



Freeze-out in a thermal HS : DM domain

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

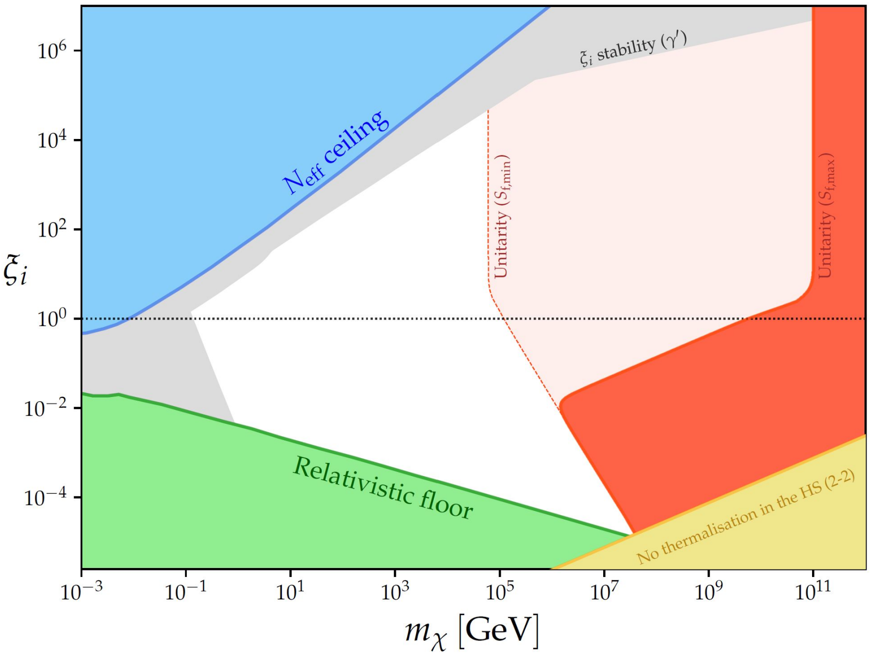


Light from darkness: History of a hot Dark Sector, Coy, Kimus, Tytgat, **2405.10792**

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

Freeze-out in a thermal HS : DM domain

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



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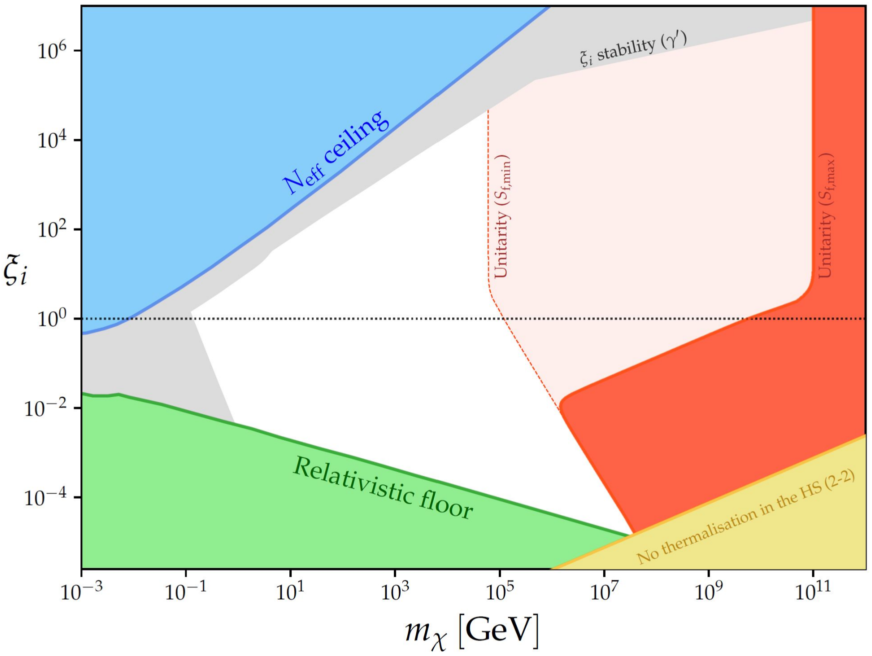

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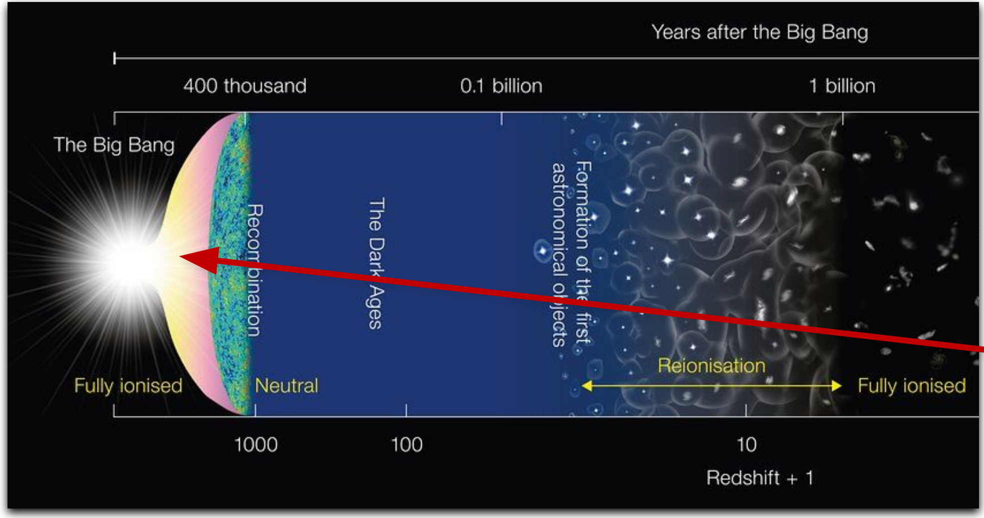
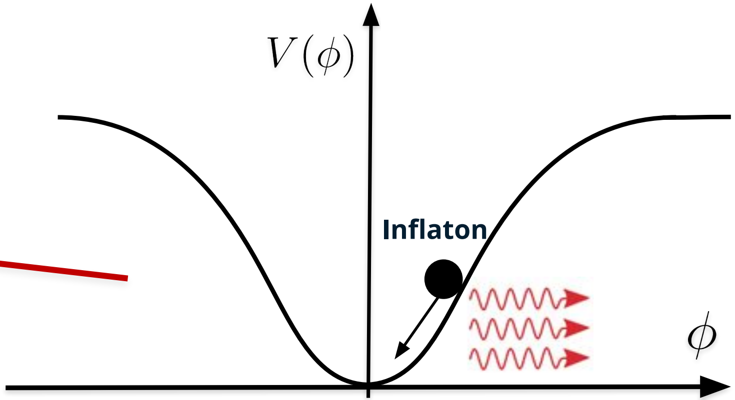
Production of a Hidden Sector : Asymmetric Reheating





Transition from cold inflaton condensate to a hot thermal plasma : **Reheating**

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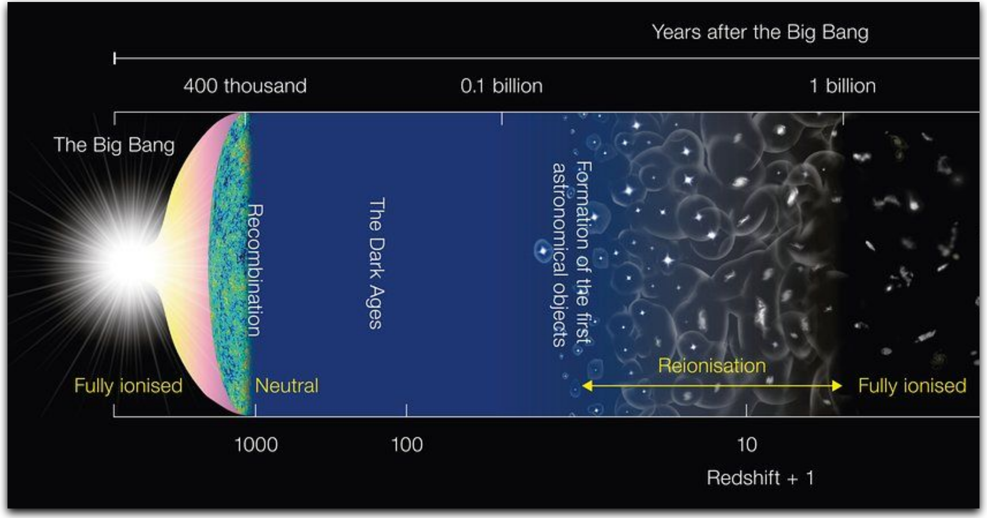
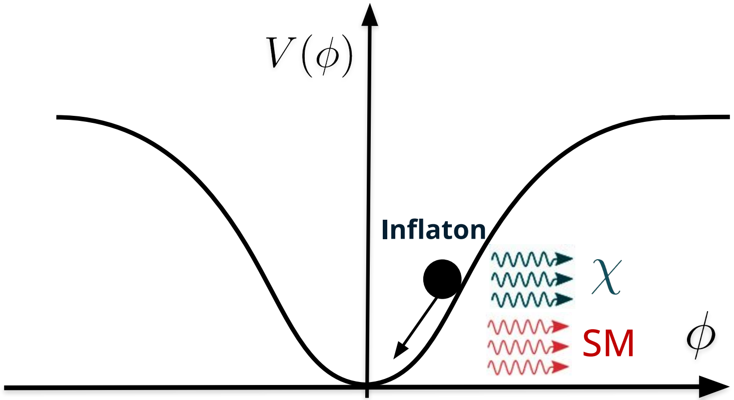
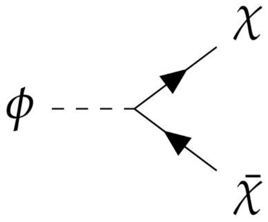
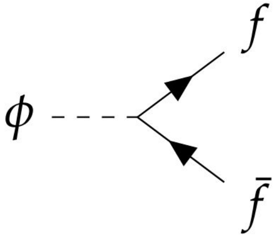








Γ_ϕ^χ $\Gamma_\phi^{\mathrm{SM}}$

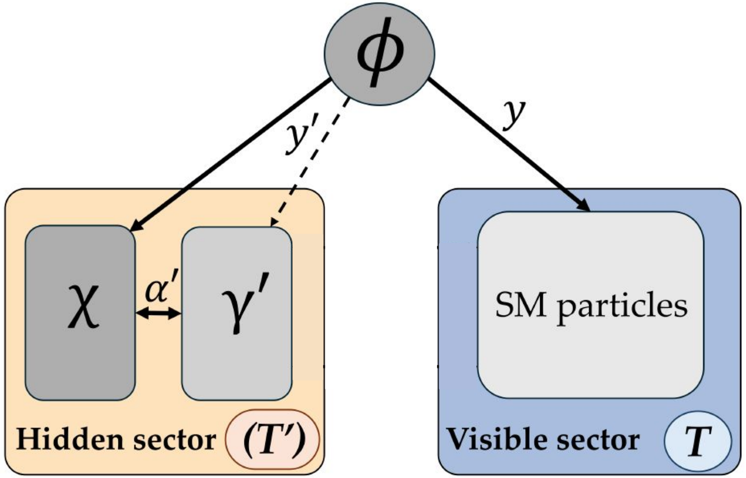
What if inflaton is also coupled to a Hidden Sector ?

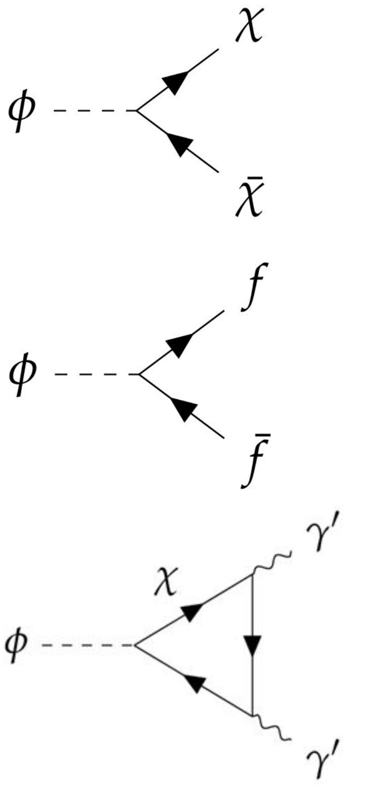
➜ Can lead to an **Asymmetric Reheating**

Production of a Hidden Sector : Asymmetric Reheating

A way to produce DM in a HS, via asymmetric energy transfer from inflaton to HS and VS

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





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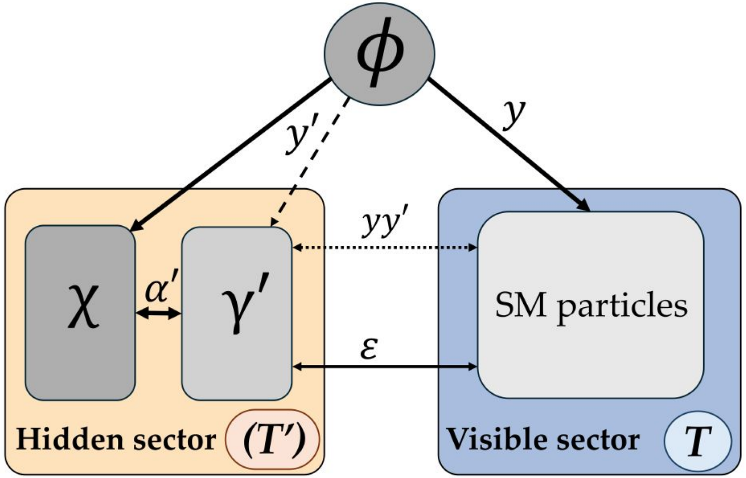
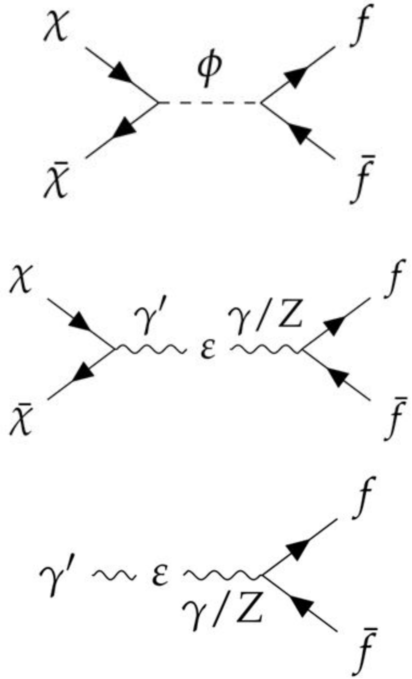
$$+ \bar{\chi}\left(i\not{D} - m_\chi\right)\chi - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{\gamma'}A'_\mu A'^\mu - \frac{\epsilon}{2}B_{\mu\nu}F^{\mu\nu}$$





Contact between SM and HS

Production of a Hidden Sector : Asymmetric Reheating

Numerical solutions to the 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...)

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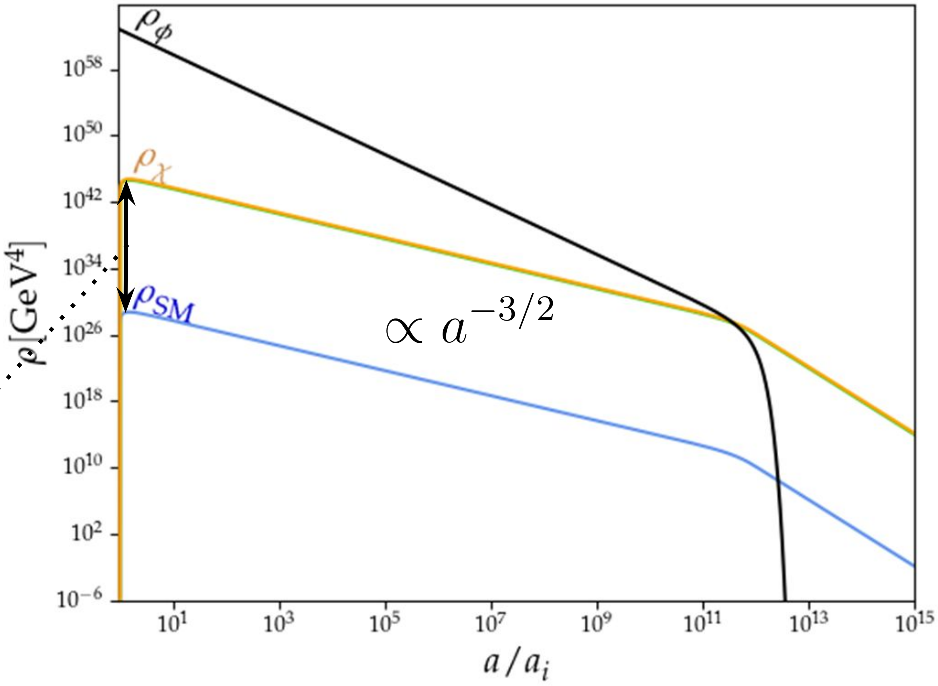

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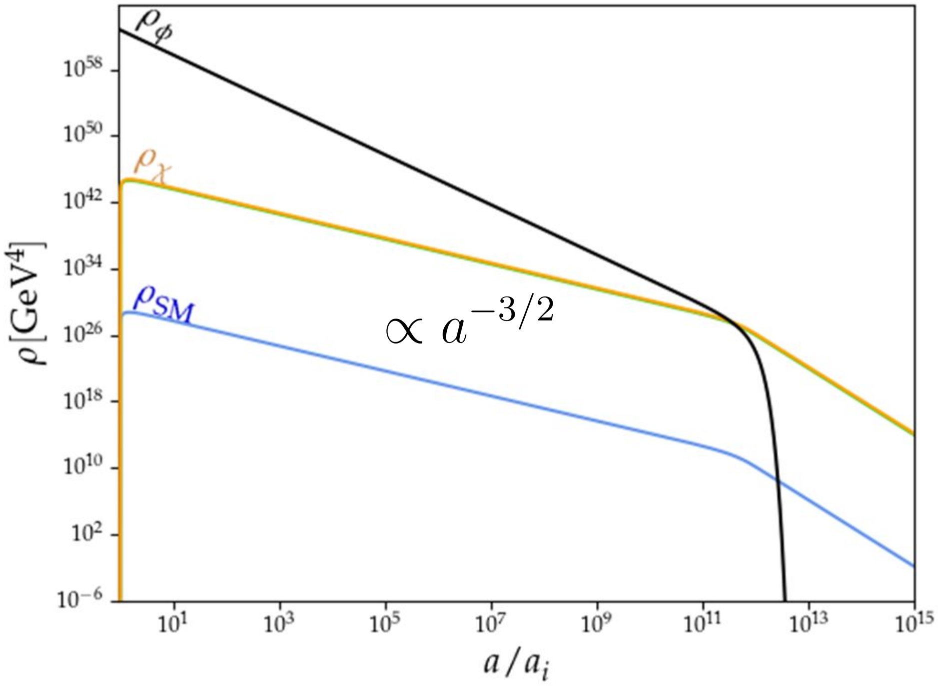
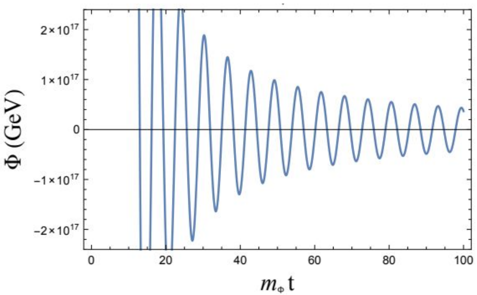


Assume rapid thermalization in the SM sector
(large non-abelian gauge couplings, many degrees of freedom)

Still some questions:

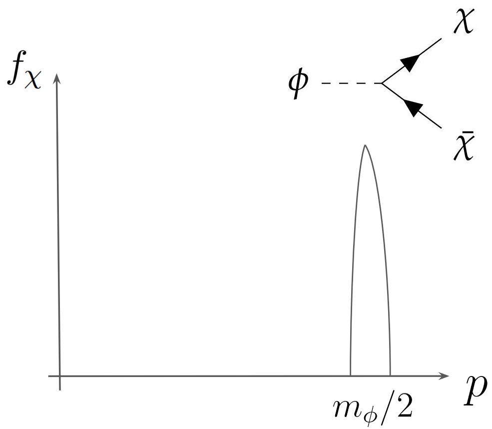
- **Thermalisation of the HS ?**
- Interaction between the two sectors?
  Evolution of the temperature ratio ?

Thermalization of a Hidden Sector : Non-thermal phase



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

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



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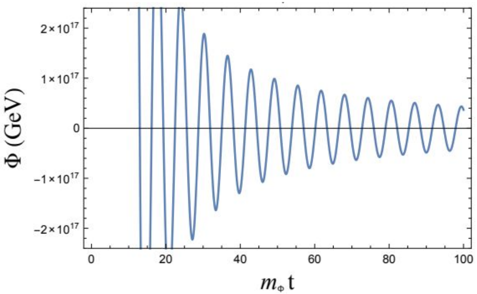

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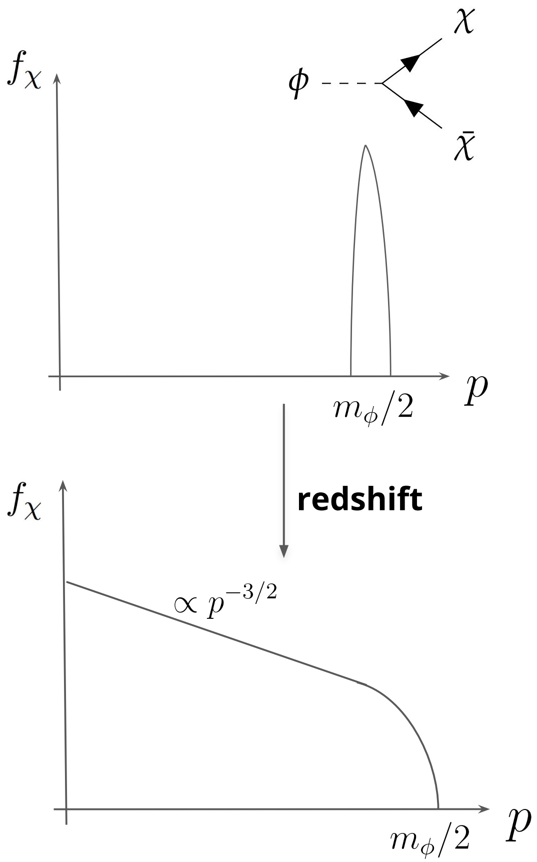
$$f_\chi \simeq 24\pi^2 \frac{n_\chi}{m_\phi^3} \left(\frac{m_\phi}{2p}\right)^{3/2} \Theta(m_\phi/2 - p)$$

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

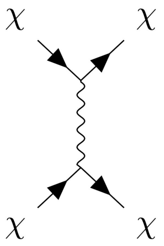
$$\langle p \rangle \sim m_\phi$$



Thermalization of a Hidden Sector : Kinetic vs Chemical equilibrium

Kinetic equilibrium may be reached through 2 ↔ 2 processes

$$\frac{\Gamma^h_{2-2}}{H} \approx 10^2 \alpha'^2 \frac{M_P^2 \Gamma_\phi^\chi}{m_\phi^3} \gtrsim 1$$



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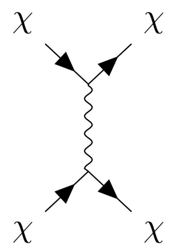

$$\left.\begin{aligned} \dot{n}_\chi + 3Hn_\chi = \Gamma^\chi_\phi n_\phi \longrightarrow n_\chi^{\text{kin}} \sim \frac{\Gamma^\chi_\phi}{H}\frac{\rho_\phi}{m_\phi} \sim \frac{\Gamma_\phi H M_P^2}{m_\phi} \sim T'^3_{\text{kin}} e^{\mu_\chi / T'\text{kin}} \\ \dot{\rho}_\chi + 4H\rho_\chi = \Gamma^\chi_\phi \rho_\phi \longrightarrow n_\chi^{\text{th}} \sim T'^3 \sim \left(\frac{\Gamma_\phi \rho_\phi}{H}\right)^{3/4} \sim (\Gamma_\phi H M_P^2)^{3/4} \end{aligned}\right\} \quad \frac{n_\chi^{\text{kin}}}{n_\chi^{\text{th}}} \sim \frac{(\Gamma^\chi_\phi H M_P^2)^{1/4}}{m_\phi} \ll 1$$

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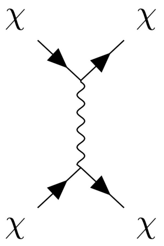
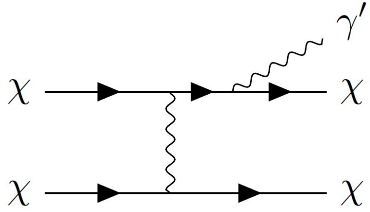


$$\dot{n}_\chi + 3Hn_\chi = \Gamma^\chi_\phi n_\phi \longrightarrow n_\chi^{\rm kin} \sim \frac{\Gamma^\chi_\phi}{H}\frac{\rho_\phi}{m_\phi} \sim \frac{\Gamma_\phi H M_P^2}{m_\phi} \sim T'^3_{\rm kin} e^{\mu_\chi/T'{\rm kin}}$$

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

$$\frac{n_\chi^{\rm kin}}{n_\chi^{\rm th}} \sim \frac{(\Gamma^\chi_\phi H M_P^2)^{1/4}}{m_\phi} \ll 1$$

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

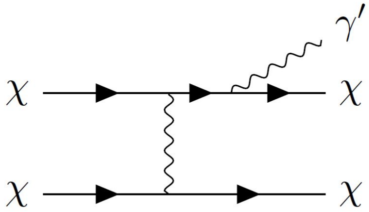


expected to be suppressed for small gauge coupling α'
➜ can take a **finite time** before being efficient

Thermalization of a Hidden Sector : Bremsstrahlung

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 $m_D^2 \sim \alpha' \int d^3k \frac{f(k)}{k}$



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

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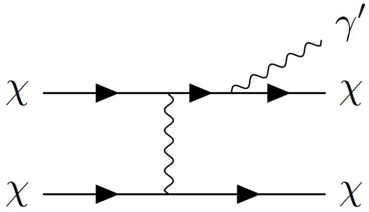

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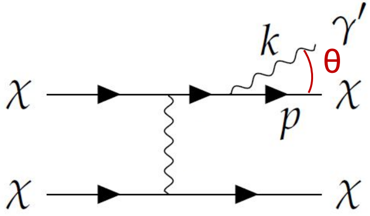
Emitted soft gauge bosons are **collinear** with their parent particle
➜ a certain time before the particles are **"separated"**

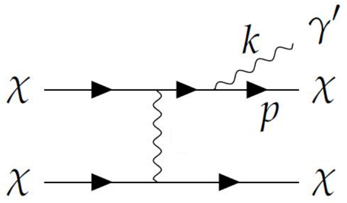


Several amplitudes interfering destructively can **suppress the splitting rate ➜ Landau–Pomeranchuk–Migdal (LPM) effect**

Thermalization of a Hidden Sector : Non-Abelian plasma

In a non-abelian plasma daughter boson are charged, and can itself undergo soft t-channel scatterings in the medium diffusing its transverse momentum $k_\perp = \sqrt{\alpha'^2 n_h\, t}$

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



$$t_{\rm form} \sim \begin{cases} \frac{1}{\Gamma^s_{2-2}}\sqrt{\frac{k}{k^{\rm NA}_{\rm LPM}}} & k \gtrsim k^{\rm NA}_{\rm LPM} \\ 1/\Gamma^s_{2-2} & k \lesssim k^{\rm NA}_{\rm LPM} \end{cases}$$

LPM suppression

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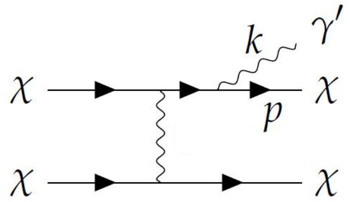
In a non-abelian plasma daughter boson are charged, and can itself undergo soft t-channel scatterings in the medium diffusing its transverse momentum $k_\perp = \sqrt{\alpha'^2 n_h\, t}$

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



$$t_{\rm form} \sim \begin{cases} \frac{1}{\Gamma^s_{2-2}}\sqrt{\frac{k}{k^{\rm NA}_{\rm LPM}}} & k \gtrsim k^{\rm NA}_{\rm LPM} \\ 1/\Gamma^s_{2-2} & k \lesssim k^{\rm NA}_{\rm LPM} \end{cases}$$

LPM suppression

➜ Soft gauge bosons are emitted, further self-interact in cascade and finally slow down hard fermions, filling momentum from low momenta upward: **bottom-up thermalization**
➜ **Bottleneck is the cooling of hard fermions** by soft gauge bosons

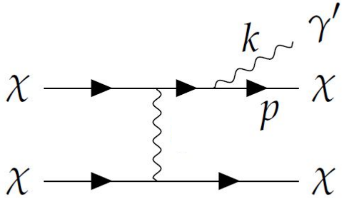
$$t^{\rm NA}_{\rm th} \sim \frac{1}{\alpha'^2 m_\phi}\left(\frac{m_\phi^3}{n_h}\right)^{3/8}$$

Harigaya, Mukaida, **1312.3097**

Thermalization of a Hidden Sector : Abelian plasma

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

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



$$t_{\rm form} \sim \begin{cases} \sqrt{\frac{k^A_{\rm LPM}}{k}}/\Gamma^s_{2-2} & k \lesssim k^A_{\rm LPM} \\ 1/\Gamma^s_{2-2} & k \gtrsim k^A_{\rm LPM} \end{cases}$$

LPM suppression

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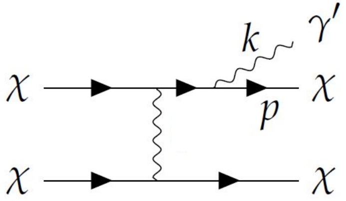

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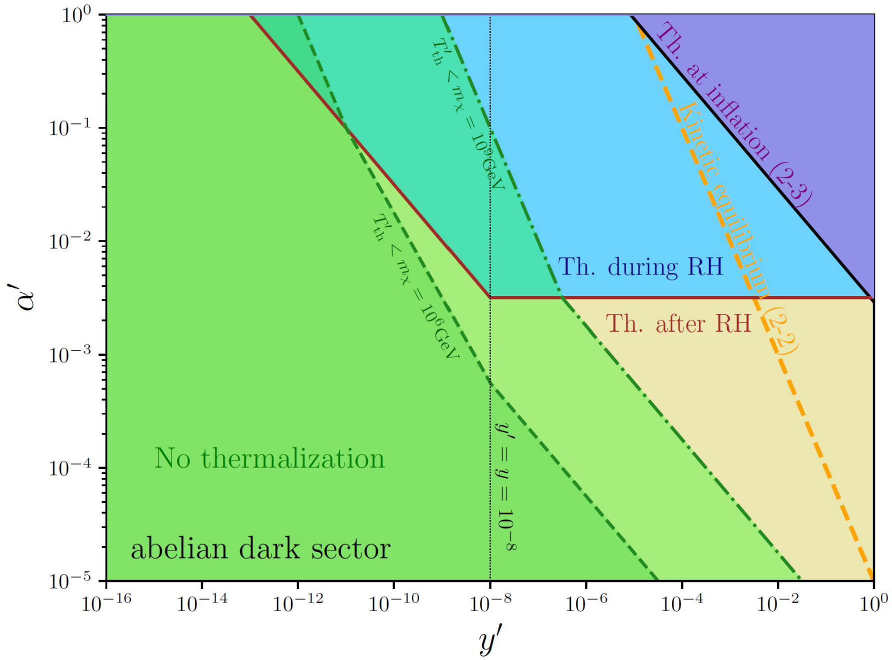
LPM suppression

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

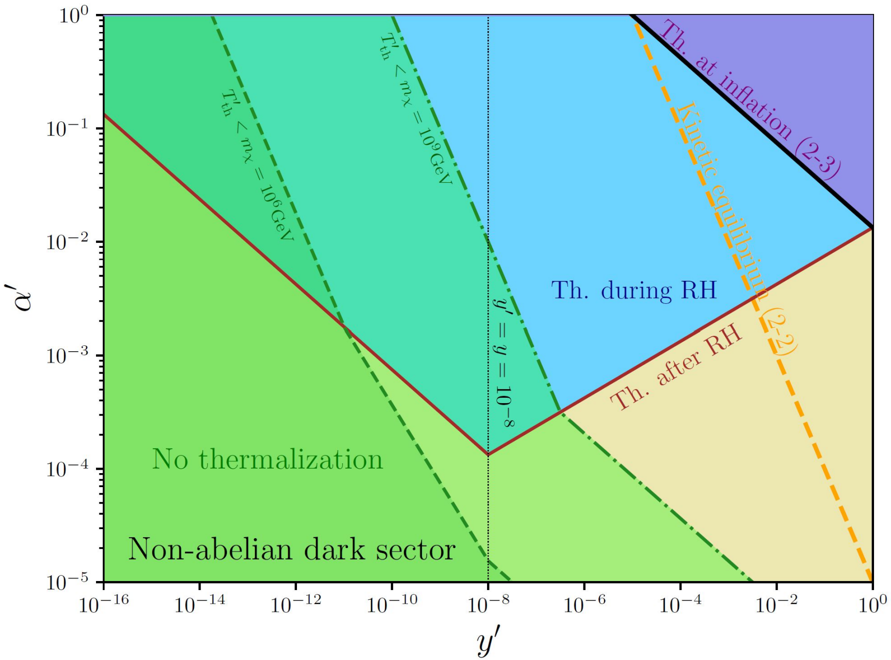
$$t^{\rm A}_{\rm th} \sim 1/\Gamma_{2\to 3} \sim \frac{1}{\alpha'^2 m_\phi}\left(\frac{m_\phi^3}{n_h}\right)^{1/2}$$

SC, Kimus, Tytgat, **2512.XXXXX**

Thermalization of a Hidden Sector



Domain of thermalization
during/after reheating
Abelian plasma



Domain of thermalization
during/after reheating
non-Abelian plasma

SC, Kimus, Tytgat, **2512.XXXXX**

Reheating and Freeze-out scenarios

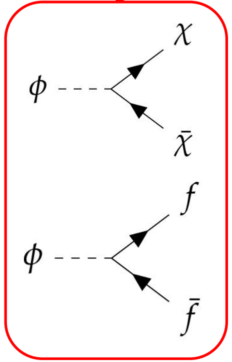
Boltzmann equations for **thermal HS and SM solved numerically**

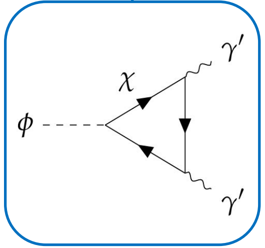
$$\dot{\rho}_\phi + 3H\rho_\phi = -\Gamma_\phi\rho_\phi$$

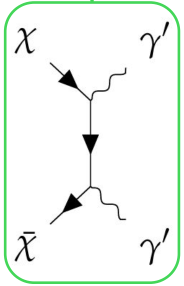
$$\dot{\rho}_\chi + 3(1+w_\chi)H\rho_\chi = \Gamma_\phi^\chi\rho_\phi - \langle\sigma_{\chi-\gamma'}vE\rangle_{T'}\left(n_\chi^2 - (n_\chi^{\mathrm{eq}}(T'))^2\right) - \langle\sigma_{\chi-f}vE\rangle_{T'}n_\chi^2 + \langle\sigma_{\chi-f}vE\rangle_T\left(n_\chi^{\mathrm{eq}}(T)\right)^2$$

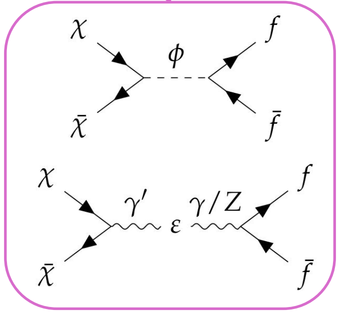
$$\dot{\rho}_{\gamma'} + 3(1+w_{\gamma'})H\rho_{\gamma'} = \Gamma_\phi^{\gamma'-\mathrm{loop}}\rho_\phi - \langle\sigma_{\chi-\gamma'}vE\rangle_{T'}\left(n_\chi^2 - (n_\chi^{\mathrm{eq}}(T'))^2\right) - m_{\gamma'}\Gamma_{\gamma'}\left(n_{\gamma'} - n_{\gamma'}^{\mathrm{eq}}(T)\right)$$

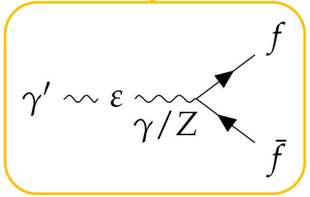
$$\dot{\rho}_{\mathrm{SM}} + 4H\rho_{\mathrm{SM}} = \Gamma_\phi^{\mathrm{SM}}\rho_\phi + \langle\sigma_{\chi-f}vE\rangle_{T'}n_\chi^2 - \langle\sigma_{\chi-f}vE\rangle_T\left(n_\chi^{\mathrm{eq}}(T)\right)^2 + m_{\gamma'}\Gamma_{\gamma'}\left(n_{\gamma'} - n_{\gamma'}^{\mathrm{eq}}(T)\right)$$





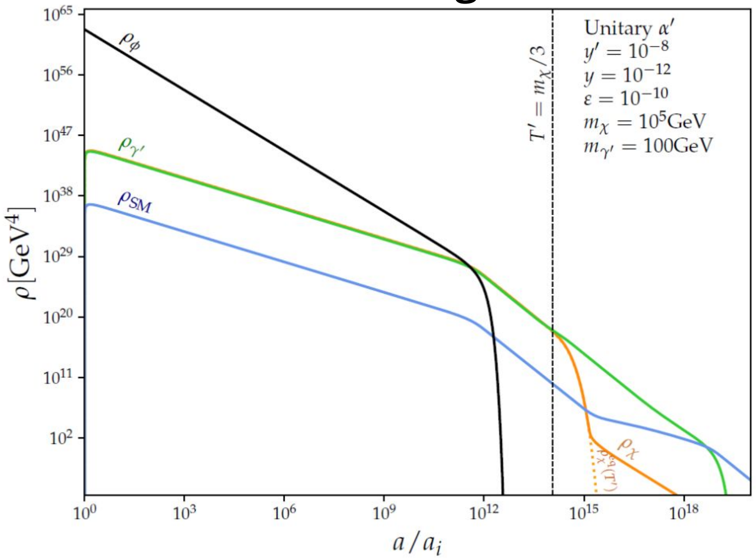




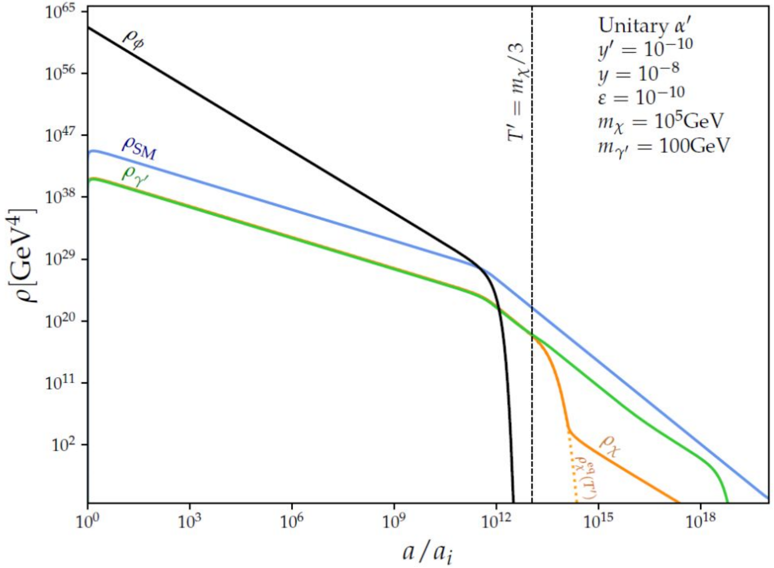


Reheating and Freeze-out scenarios

Dominant HS
Post Reheating Freeze-out



Sub-dominant HS
Post Reheating Freeze-out

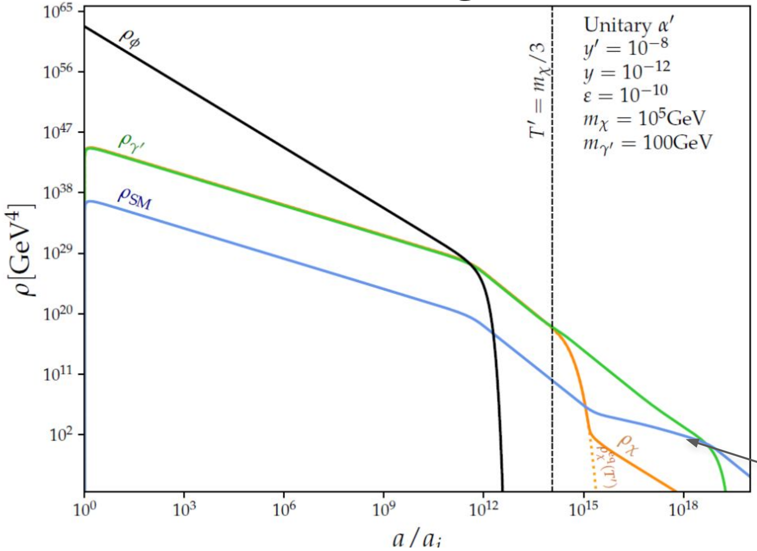


$$T'(a_{\rm RH}) \gg m_\chi$$

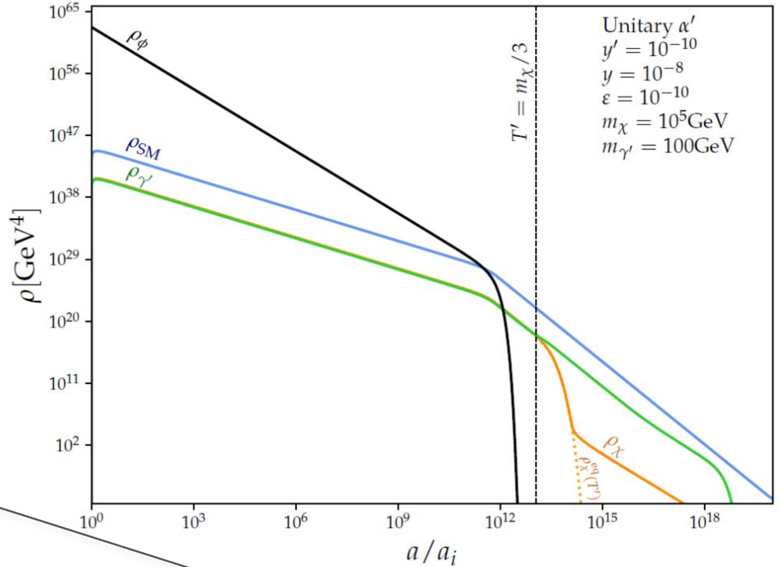
SC, Kimus, Tytgat, **2512.XXXXX**

Reheating and Freeze-out scenarios

Dominant HS
Post Reheating Freeze-out



Sub-dominant HS
Post Reheating Freeze-out



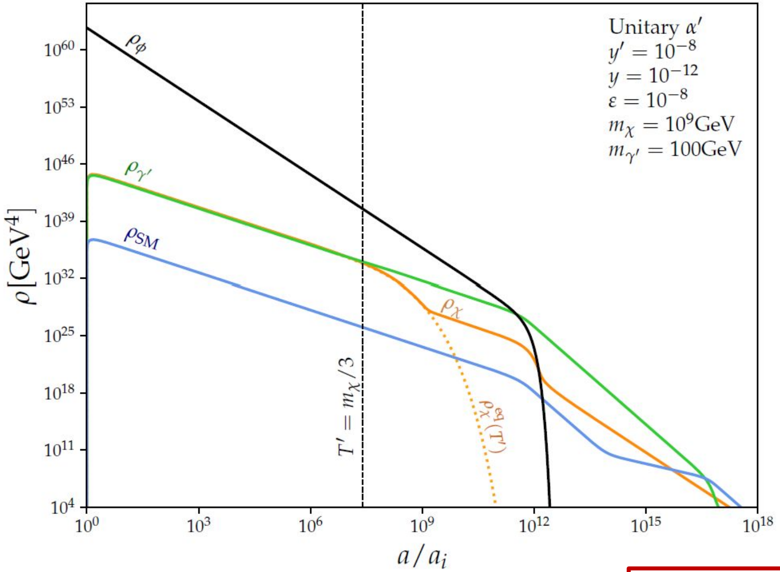
$$Y_\chi^{\rm fo} \equiv \frac{n_{\chi,\rm fo}}{s_{\rm t,\,fo}} \sim \frac{H_{\rm fo}}{\langle\sigma_{\chi-\gamma'}v\rangle_{T'_{\rm fo}} \left(H_{\rm fo} m_{\rm Pl}\right)^{3/2}} \rightarrow \begin{cases} \dfrac{1}{\langle\sigma_{\chi-\gamma'}v\rangle_{T'_{\rm fo}} m_{\rm Pl} m_\chi} & (y' \gg y) \\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

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

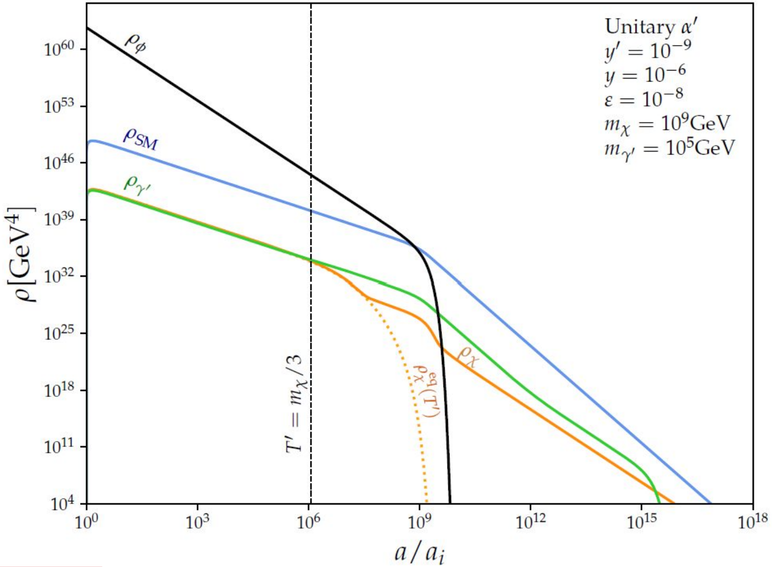
SC, Kimus, Tytgat, **2512.XXXXX**

Reheating and Freeze-out scenarios

Dominant HS
Pre Reheating Freeze-out



Sub-dominant HS
Pre Reheating Freeze-out

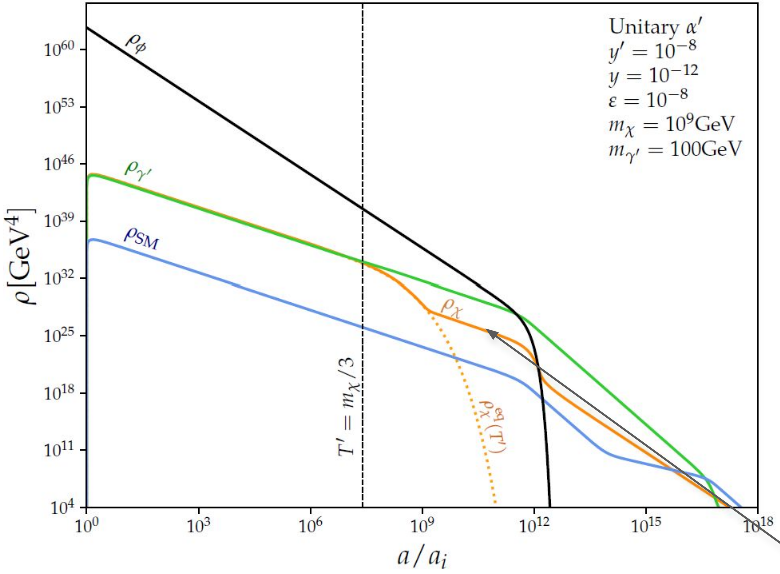


$$T'(a_{\rm RH}) \ll m_\chi$$

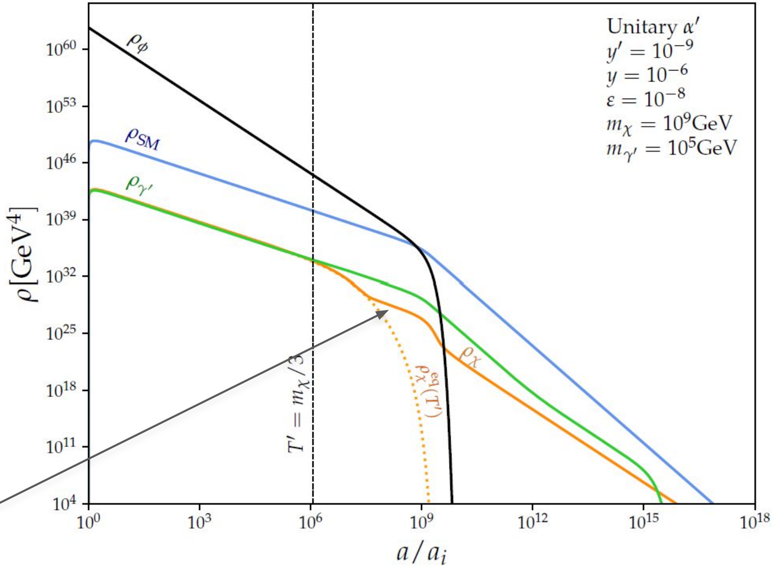
SC, Kimus, Tytgat, **2512.XXXXX**

Reheating and Freeze-out scenarios

Dominant HS
Pre Reheating Freeze-out



Sub-dominant HS
Pre Reheating Freeze-out



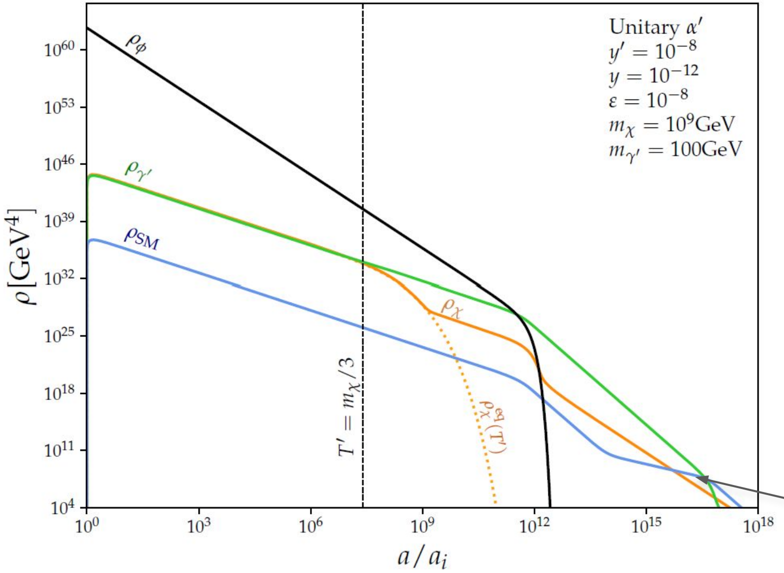
$$\rho_\chi \sim \sqrt{\frac{\Gamma_\phi^\chi m_\chi^2}{\langle \sigma_{\chi-\gamma'} v E\rangle_0}\rho_\phi} \propto a^{-3/2}$$

"Resourcing"

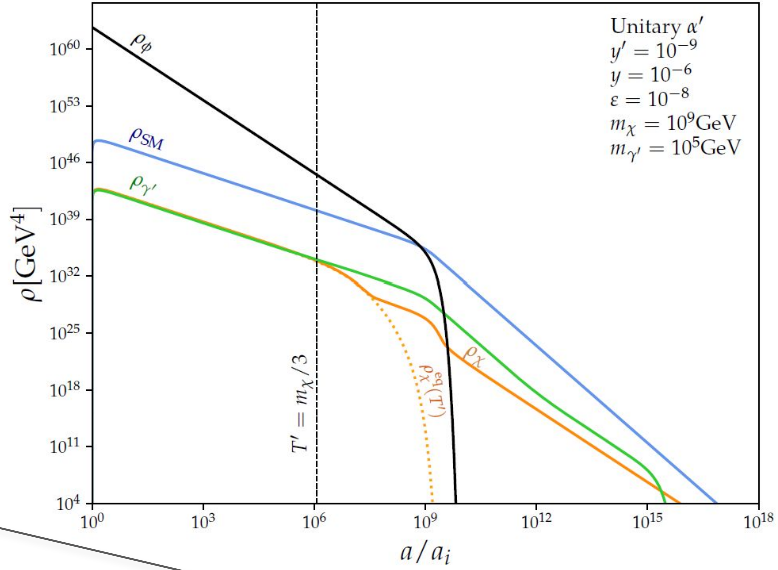
SC, Kimus, Tytgat, **2512.XXXXX**

Reheating and Freeze-out scenarios

Dominant HS
Pre Reheating Freeze-out



Sub-dominant HS
Pre Reheating Freeze-out



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

✖

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

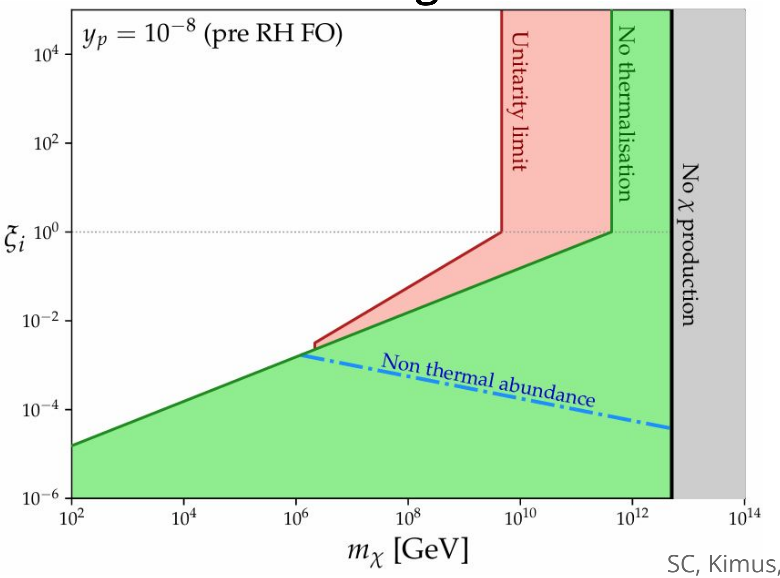
SC, Kimus, Tytgat, **2512.XXXXX**

Impact on the domain of thermal Dark Matter

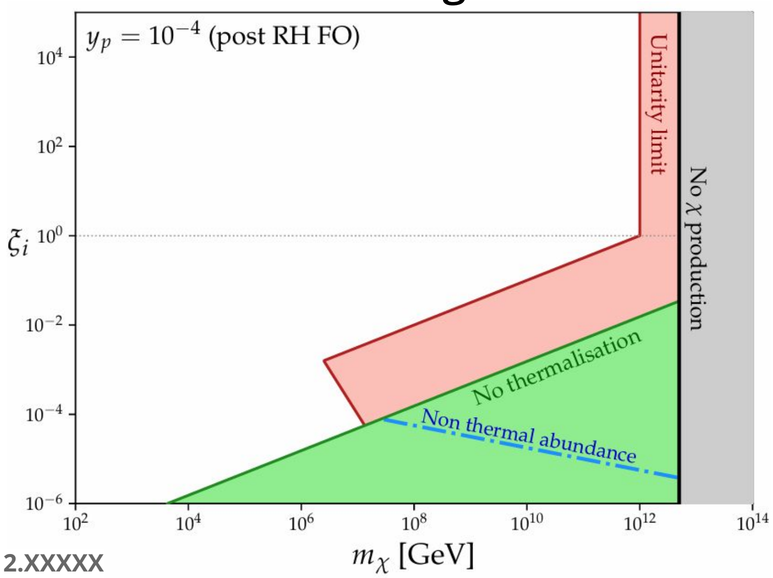
Unitarity limit $\sigma_{\chi\bar{\chi}-\gamma'\gamma'} \leq \frac{4\pi}{\mathbf{p}_i^2} \Rightarrow \langle \sigma_{\chi\bar{\chi}-\gamma'\gamma'} v \rangle_{\rm fo} \lesssim \frac{4\pi}{m_\chi^2}$

Post-reheating FO: similar upper bounds on DM mass as already obtained in Coy, Kimus, Tytgat, **2405.10792**
Pre-reheating FO: relic abundance and upper bounds affected by reheating as depicted below

Pre-reheating freeze-out



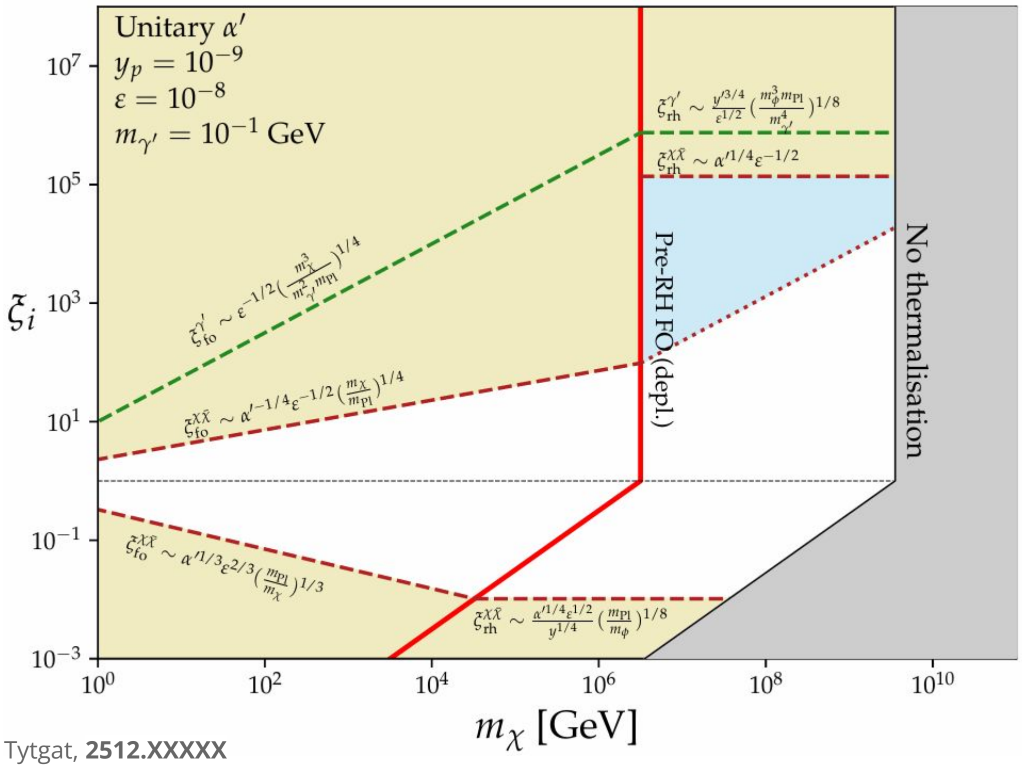
Post-reheating freeze-out

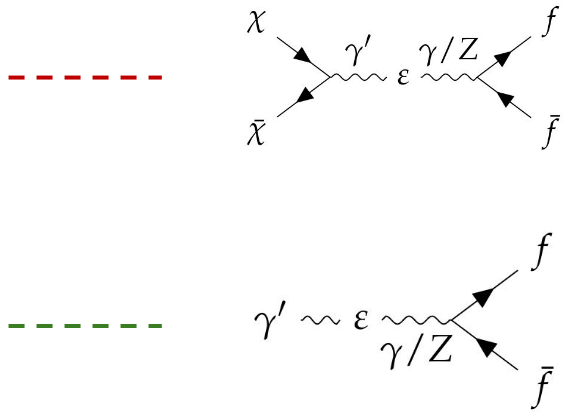


SC, Kimus, Tytgat, **2512.XXXXX**

Evolution of the temperature ratio ξ

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

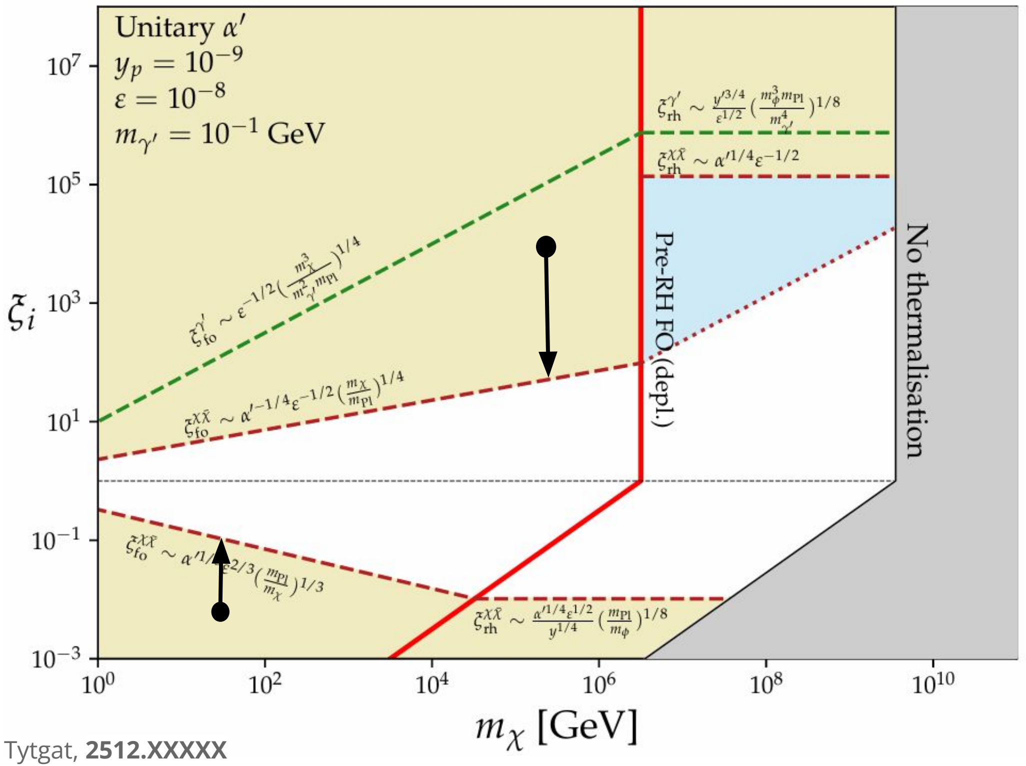


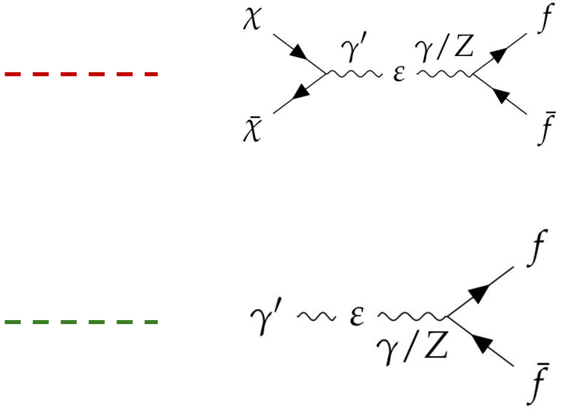


SC, Kimus, Tytgat, **2512.XXXXX**

Evolution of the temperature ratio ξ

Domain of stability of the initial temperature ratio ξ





SC, Kimus, Tytgat, **2512.XXXXX**

Conclusions

What has been done ?

- Obtain (conservative) **conditions for thermalization in such abelian plasma during/after reheating**

- Coherent history from **asymmetric reheating** until DM freeze-out and late time dark photons decay ➜ **bounds on the temperature ratio** when DM decouples

- New scenarios of **pre-reheating freeze-out with resourcing identified and constrained**

Under investigation:

- Numerics for unintegrated Boltzmann equations to confirm thermalization time scale ?
- How **BBN, ΔNeff** bounds are modified for **pre-reheating freeze-out** ?

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Thank you !

Backup

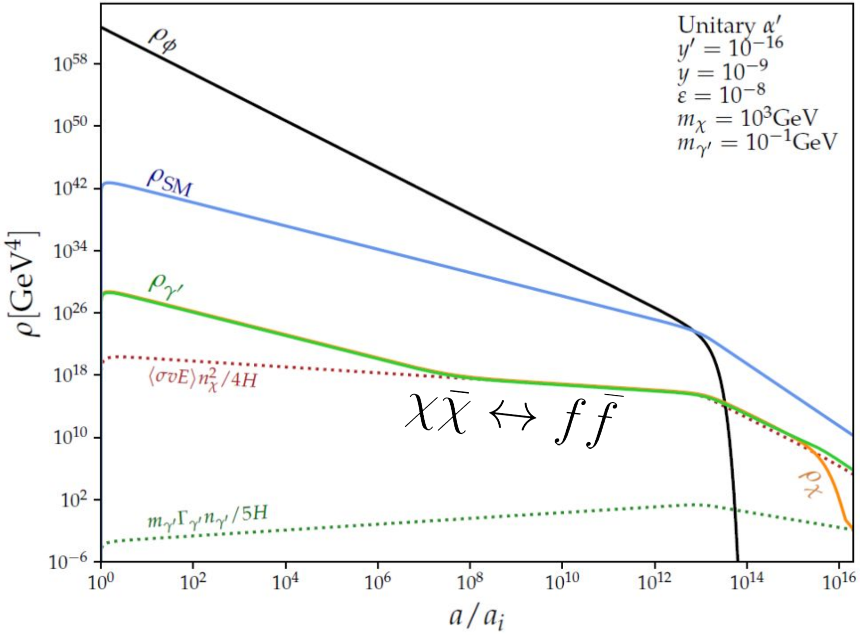
Thermalization timescales : abelian vs non-abelian

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

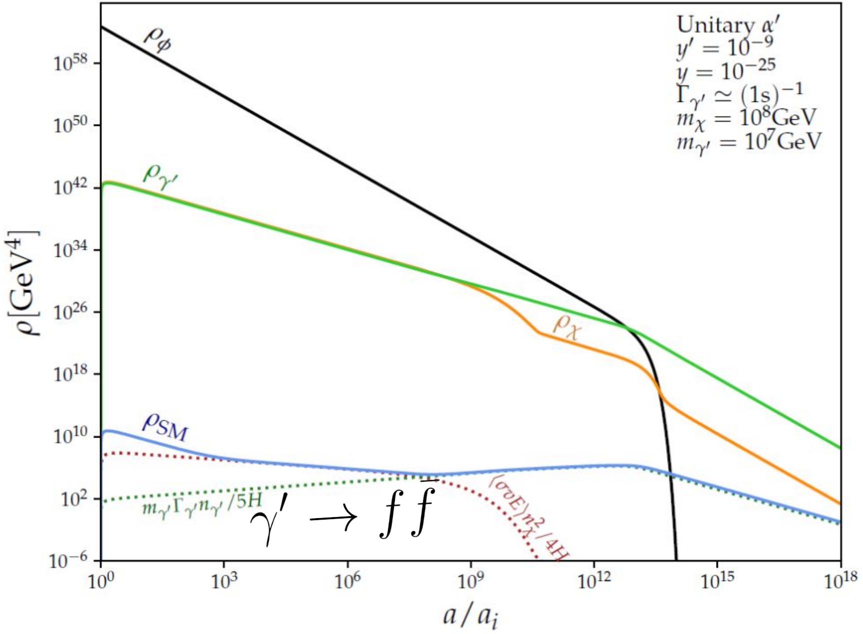
Evolution of the temperature ratio ξ

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

Sub-dominant HS



Dominant HS



SC, Kimus, Tytgat, **2512.XXXXX**

Freeze-out in a thermal HS (after Reheating) : DM domain

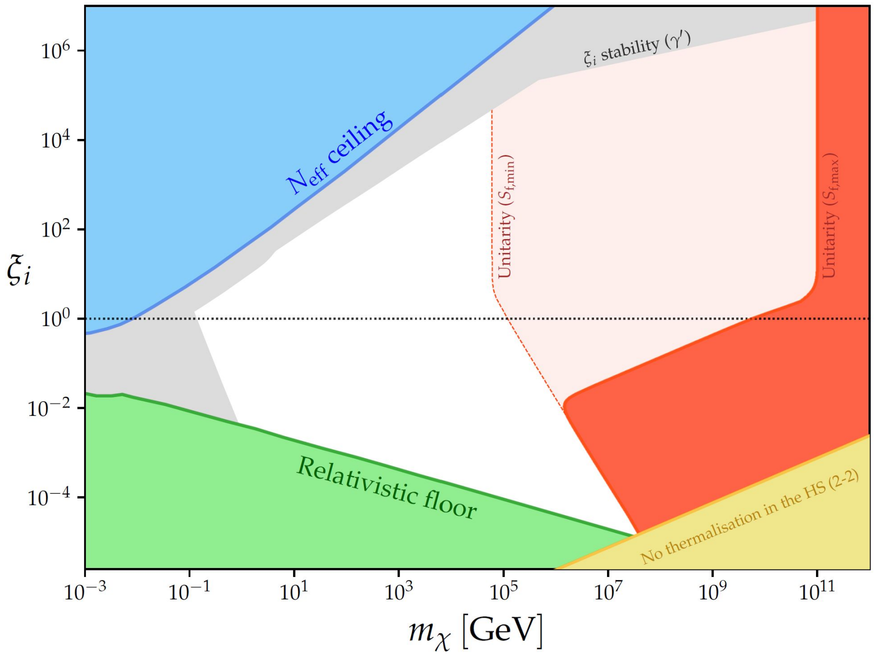
- **Relativistic floor :** relativistic freeze-out yields the maximal relic abundance
  ➜ DM candidates are under abundant

- **Neff ceiling :** DM particles are relativistic at BBN
  ➜ Lower bound on DM mass depending on ratio ξ = **T'/T** at freeze-out

- **HS thermalisation :** Efficient 2-2 processes before DM freeze-out, maximal α'
  (More on this next slides!)

- **ξ stability :** DM freeze-out in a secluded HS, without thermalization between HS and SM
  (More on this next slides!)

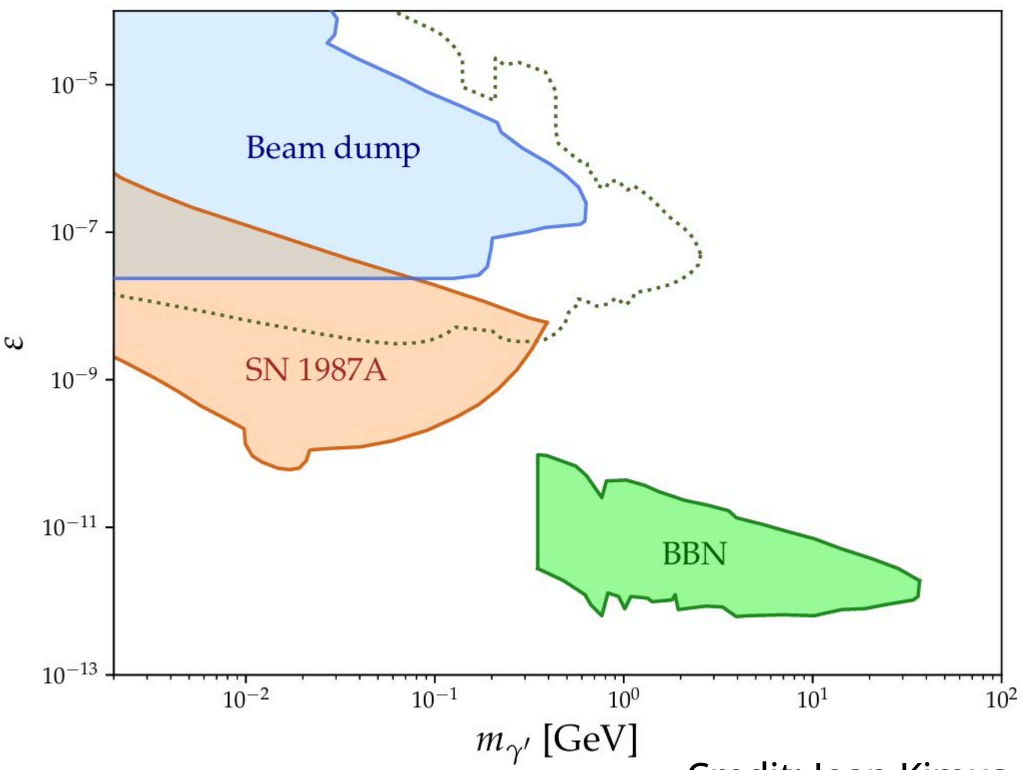
- **Unitarity wall :**
  ➜ Dashed line pale red is **without entropy injection** from γ' domination and decays
  ➜ Solid line red **including entropy injection**



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

Observational/Experimental constraints : Dark Photons domain

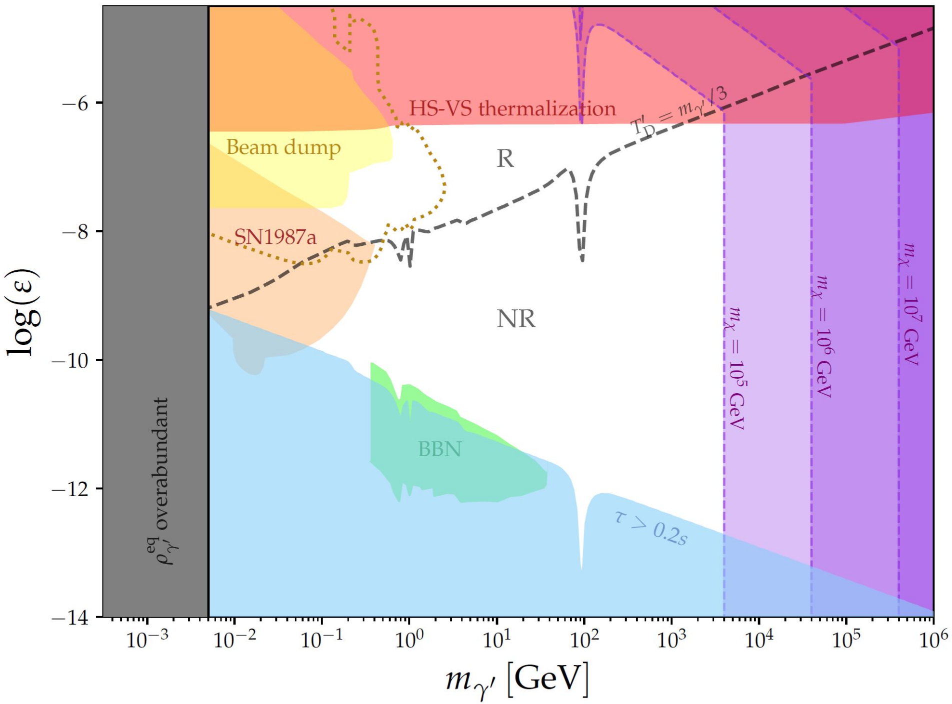
- Beam dump : absence of additional feeble interaction channels for fixed target experiments (E137, LSND, CHARM, NuCal, and projected as SHiP)
- SN 1987 A : absence of additional energy loss processes in observed ν flux from Supernovae
- BBN : Nucleosynthesis abundances not disrupted by frozen-in Dark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



Credit: Jean Kimus

Dark Photons domain (for T' > T)

- 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 that stays secluded ($\chi\bar{\chi} \to f\bar{f}$)
- DM freeze-out in the HS $m_{\gamma'} < m_\chi/x'_{\rm fo}$ and that stays secluded ($\gamma' \to f\bar{f}$)
- 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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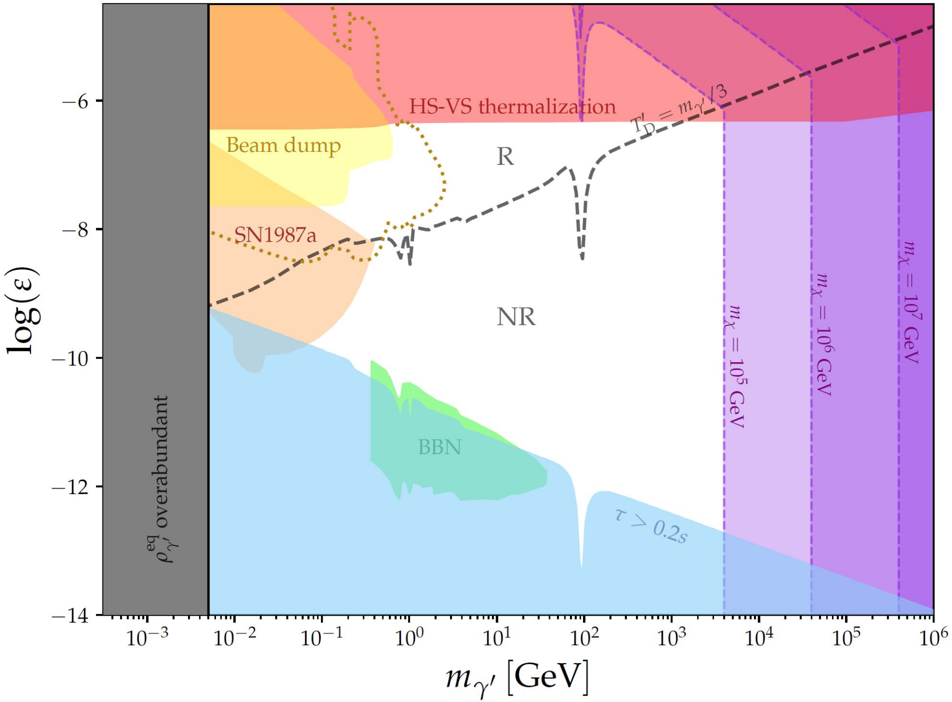
Sub-dominant (T' < T) domain under investigation



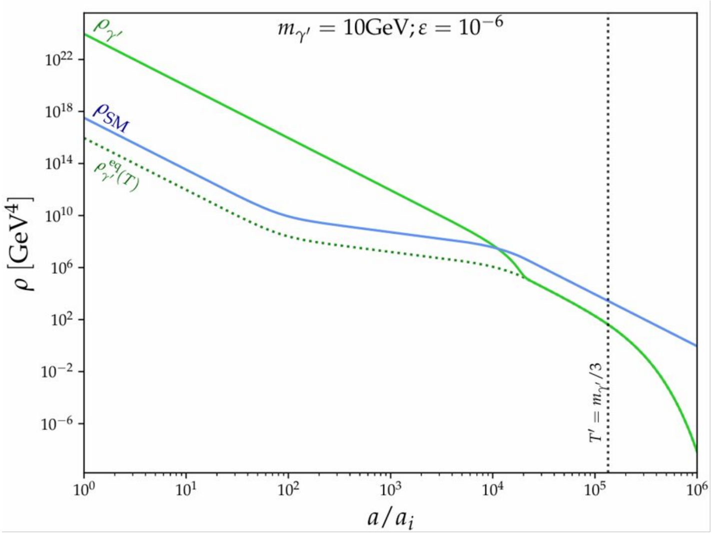
Light from darkness: History of a hot Dark Sector, Coy, Kimus, Tytgat, **2405.10792**

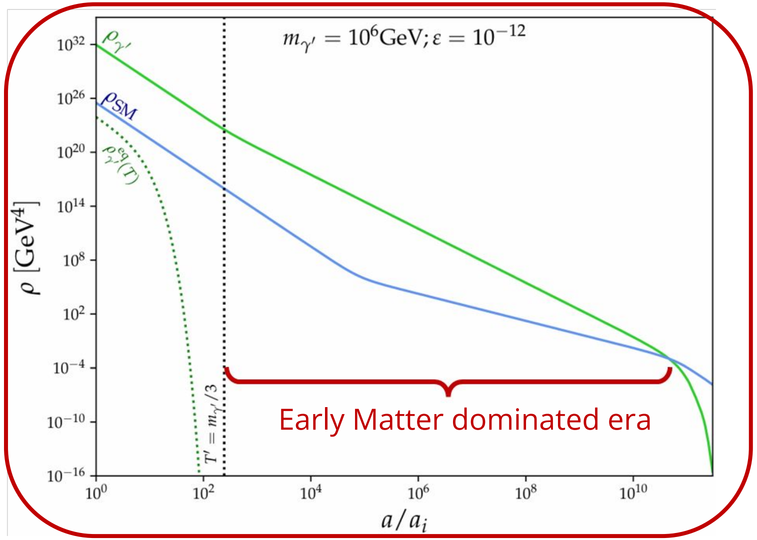
Dark Photons decay : entropy dilution

Basic assumptions:

- DM particles **freeze-out before dark photons decay**
- Dark photons at kinetic equilibrium after DM freeze-out

Credit : Jean Kimus





➜ Large entropy injection