A Taxonomy of Dark Matter Production

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Based on arXiv:1908.09864 (PRD)
with T. Hambye, M. H. G. Tytgat et L. Vanderheyden

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Dark Matter : A quick introduction

On very different time (and length) scales, we have evidences for the existence of matter which isn't SM particles :

- Distribution of velocities in cluster of galaxies
- Galaxy rotation curves
- CMB and large scale structure formation

We even know how much there is :

$$\Omega_{\mathrm{DM},0} = 0.268$$

$$\Omega h^2 = 0.123$$

$$Y_{\mathrm{DM}} = \frac{n_{\mathrm{DM}}}{s} = 4.09 \times 10^{-10} \left(\frac{\mathrm{GeV}}{m_{\mathrm{DM}}} \right)$$

An Incomplete Dark Matter Panorama

$\neq$ models (*i.e.* fixed gauge groups, matter)

- Super Heavy
- WIMP
- Ultra light
- Colored
- Composite
- ...

$\neq$ experimental searches

- Gravitational lensing
- Indirect Detection
- Direct Detection
- Light shining through wall
- ...

Exploring further

lowering coupling

$\neq$ production mechanism

- ...
- Freeze-out
- Co-annihilations
- Conversion driven freeze out
- ...
- Freeze-in (UV/IR)
- Sequential Freeze-in (**new !**)
- Secluded Dark Matter
- Non thermal production
  - Gravitationally
  - ...
- ...

$\neq$ signatures

- monojet, MET, resonance
- Long Lived Particles
  - Disappearing tracks
  - Displaced vertices
  - Delayed jets
- New targets for Direct Detection
- Gravitational Waves
- ...

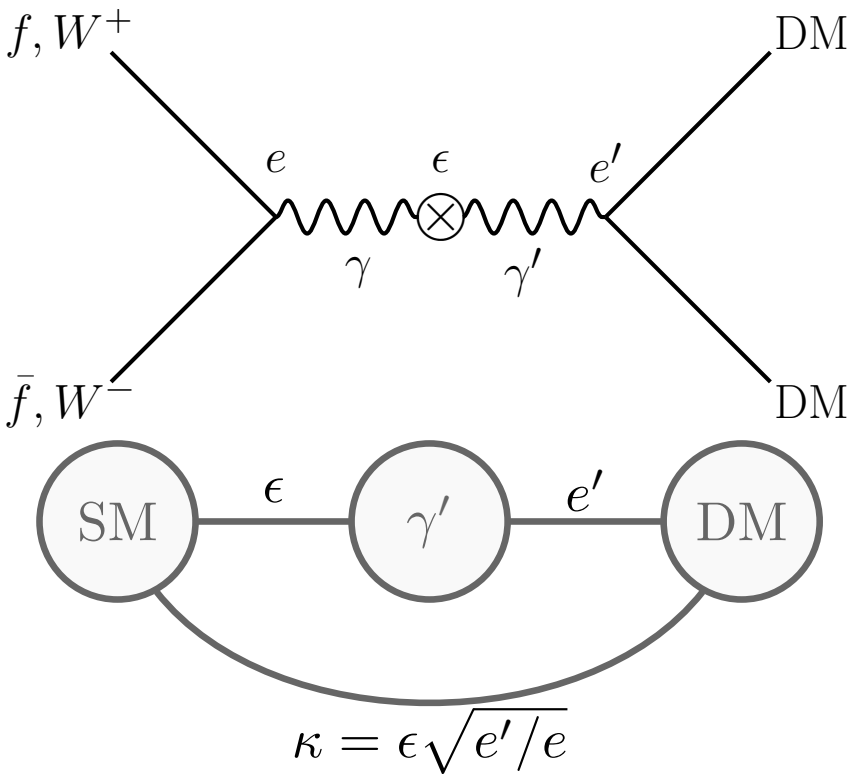
A simple model of « millicharged » dark matter

Holdom, 1986 ; Chu et al., 1112.0493 ; Patt, hep-ph/0605188

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} +$$

$$-\frac{1}{4} F_{\mathrm{D}}^{\mu\nu} F_{\mathrm{D}\ \mu\nu} + \chi \left(i \not{D} - m_{\mathrm{DM}} \right) \overline{\chi} + (\text{Dark QED, } U(1)_D)$$

$$+ \frac{\epsilon}{2} F_{\mathrm{D}}^{\mu\nu} F_{\mathrm{Y}\ \mu\nu} + \frac{1}{2} m_{\gamma'}^2 A_D^{\mu} A_{D\mu} \qquad (\text{Kinetic Mixing, massive } \gamma')$$



Boltzmann Equations for DM, γ' number evolution

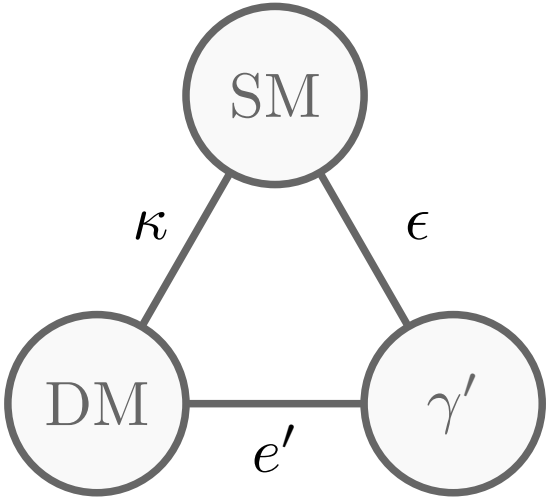
DM Production | DM Depletion

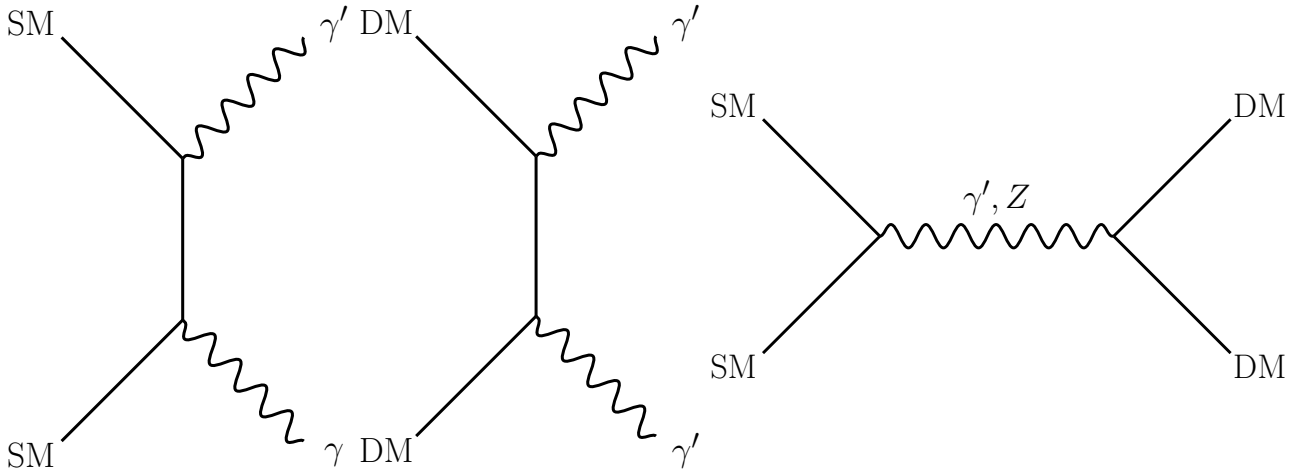
$$\frac{dn_{DM}}{dt} + 3Hn_{DM} = \langle\sigma_{SMSM\to DMDM} v\rangle\, n^2_{SM,Eq} + \langle\sigma_{\gamma'\gamma'\to DM\,DM} v\rangle\, n^2_{\gamma'} - \langle\sigma_{DMDM\to SMSM} v\rangle\, n^2_{DM} - \langle\sigma_{DM\,DM\to\gamma'\gamma'} v\rangle\, n^2_{DM}$$

Dilution

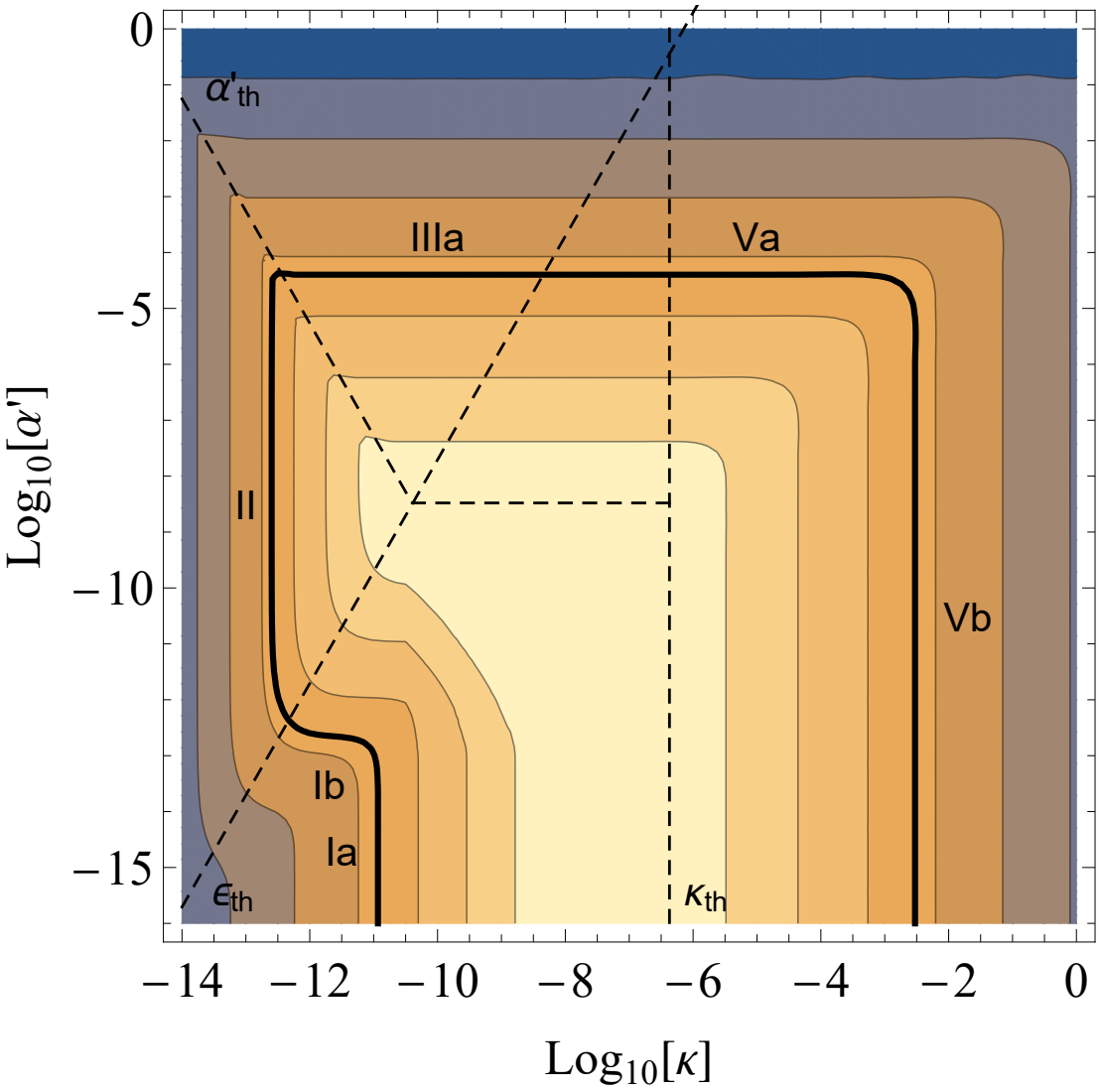
$$\frac{dn_{\gamma'}}{dt} + 3Hn_{\gamma'} = \langle\sigma_{SMSM\to\gamma' SM} v\rangle\, n^2_{SM,Eq} + \langle\sigma_{DM\,DM\to\gamma'\gamma'}\rangle\, n^2_{DM} - \langle\sigma_{\gamma' SM\to SMSM}\rangle\, n_{SM,Eq}\, n_{\gamma'} - \langle\sigma_{\gamma'\gamma'\to DM\,DM}\rangle\, n^2_{DM}$$

γ' Production | γ' Depletion





The Mesa - Visualisation of DM production regimes



[Thomas Hambye, Michel H.G. Tytgat, JV, Laurent Vanderheyden, 2019]

Contour plot of

$$Y_{\mathrm{DM}} = \frac{n_{\mathrm{DM}}}{s}$$

in the (κ, α') plane with $(m_{\mathrm{DM}}, m_{\gamma'}) = (3, 1)$ GeV

$$\kappa = \epsilon\sqrt{e'/e}$$

« millicharge »

$$\alpha' = e'^2/4\pi$$

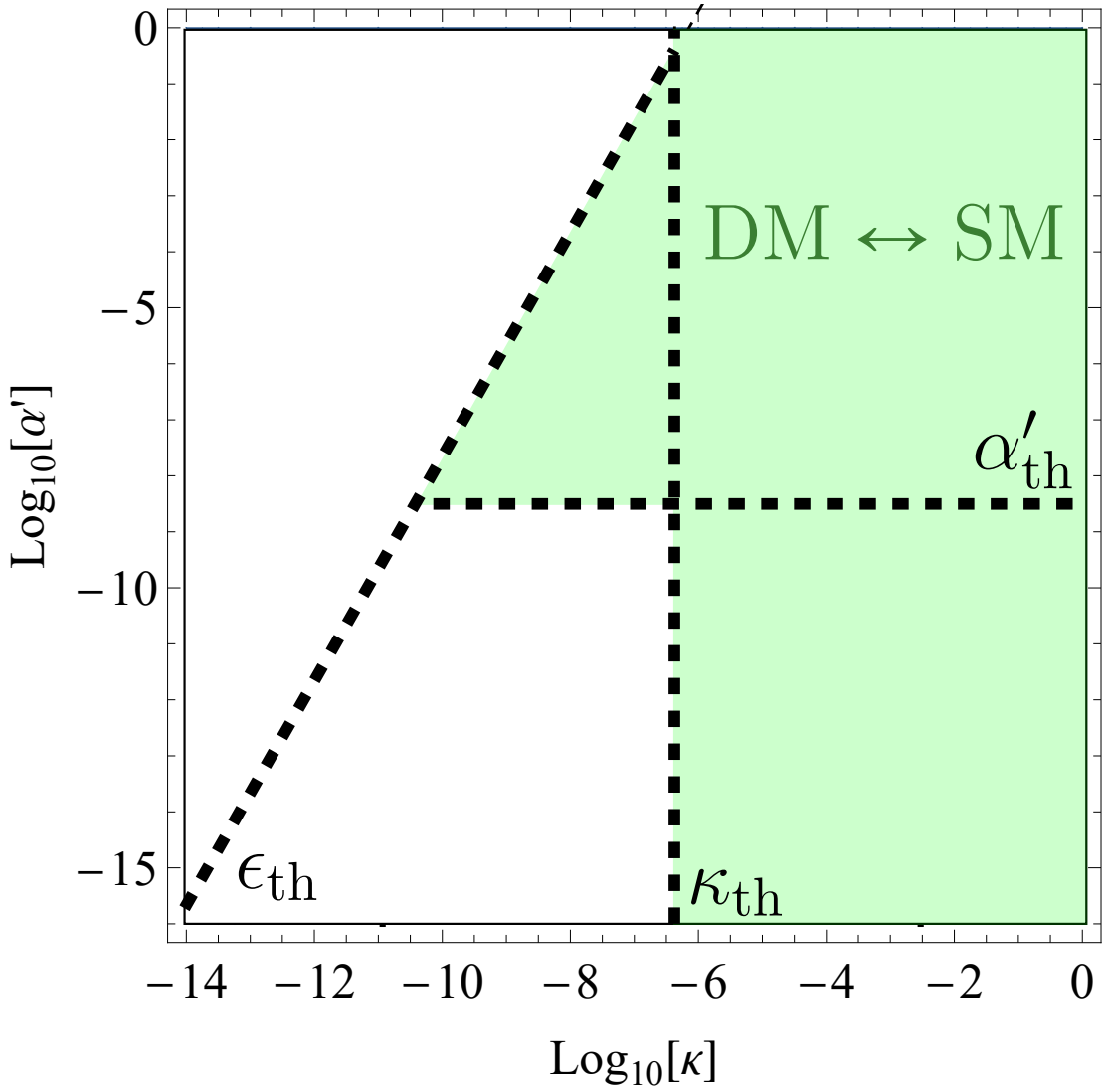
« dark fine structure constant »

Blue : $Y_{\mathrm{DM}} < Y_{\mathrm{relic}}$

Yellow : $Y_{\mathrm{DM}} > Y_{\mathrm{relic}}$

Black line : $Y_{\mathrm{DM}} = Y_{\mathrm{relic}}$

The Mesa Diagram : Thermalisation conditions



$$\frac{\Gamma_{\rm DM\leftrightarrow SM}}{H} > 1 \Rightarrow \kappa > \kappa_{\rm th}$$

$$\frac{\Gamma_{\gamma'\leftrightarrow \rm SM}}{H} > 1 \Rightarrow \epsilon > \epsilon_{\rm th}$$

which means respectively

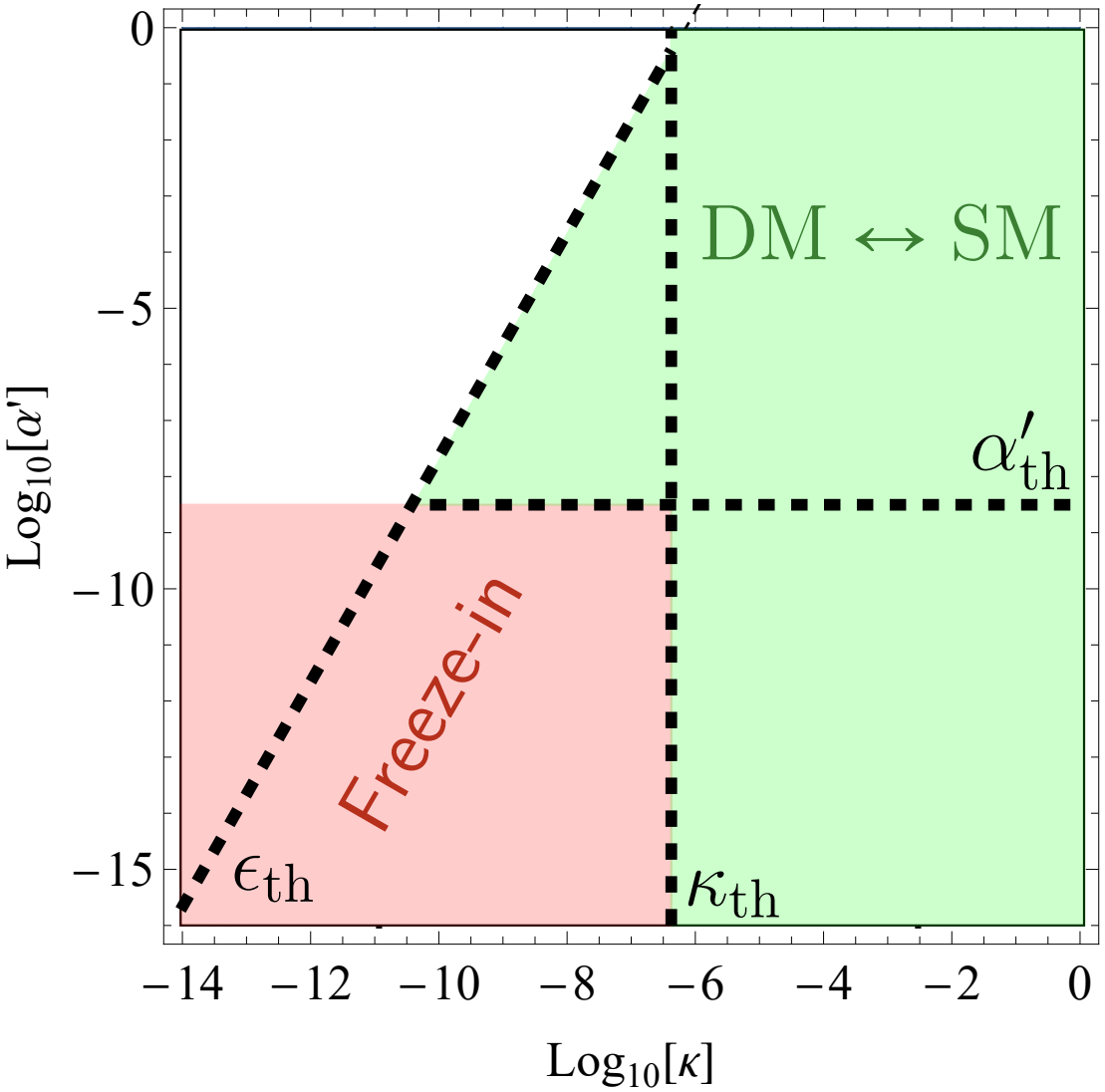
$$n_{\rm DM} = n_{\rm DM,Eq}$$

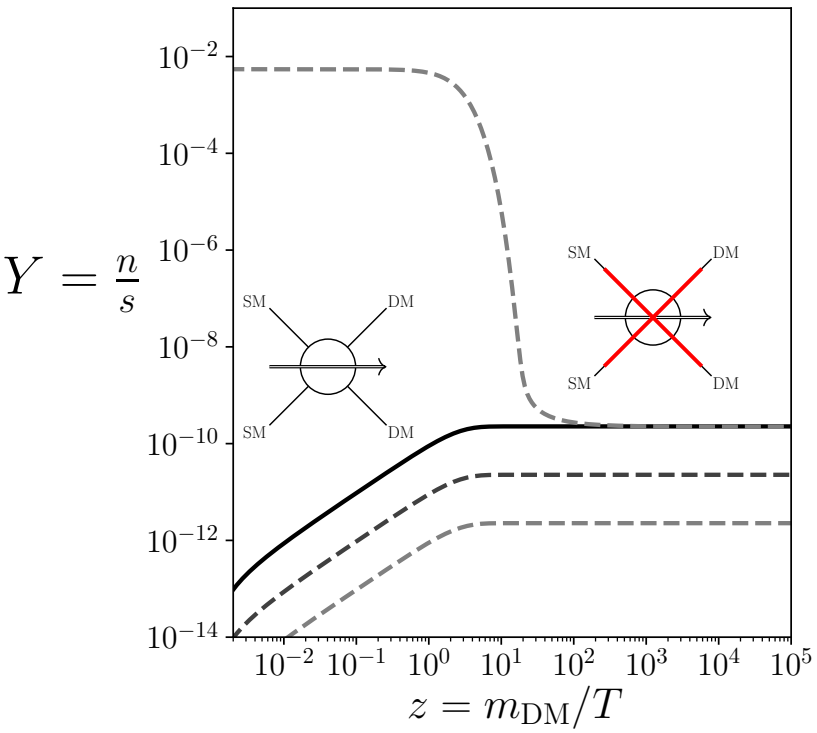
$$n_{\gamma'} = n_{\gamma',\rm Eq}$$

And assuming $n_{\gamma',\rm Eq}$

$$\frac{\Gamma_{\gamma'\leftrightarrow \rm DM}}{H} > 1 \Rightarrow \alpha' > \alpha'_{\rm th}$$

The Mesa Diagram : Freeze-in Regimes



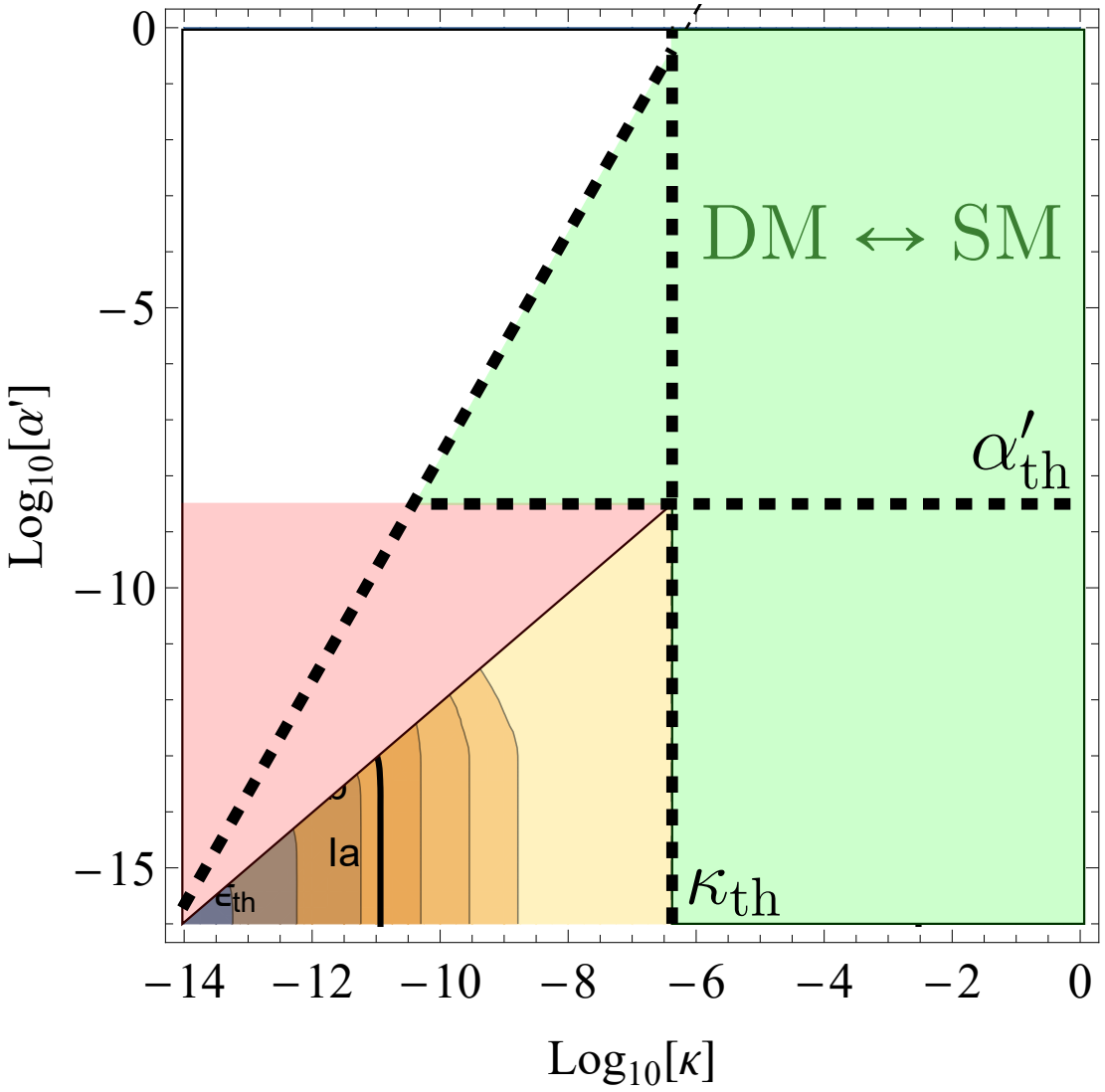


$$Y_{\rm DM,0} = 0 = Y_{\gamma',0}$$

$$\kappa < \kappa_{\rm th}$$

$$\alpha' < \alpha'_{\rm th}$$

The Mesa Diagram : Regime Ia (standard freeze-in)



Still a thermal production mechanism !

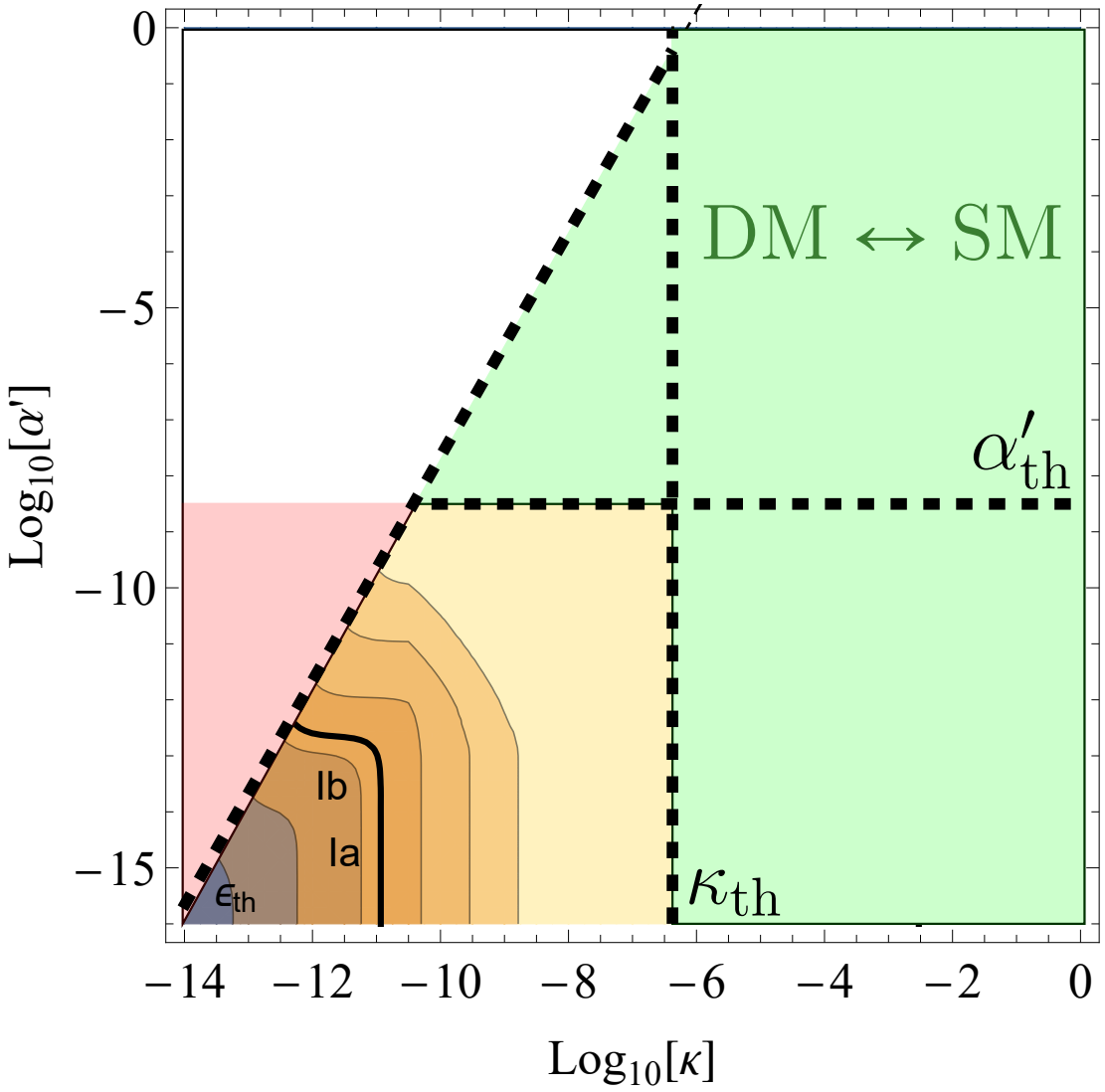
$\epsilon > \epsilon_{\rm th}$, α' irrelevant

DM is slowly produced by SM

$$\frac{\mathrm{dY_{DM}}}{\mathrm{dz}} = \frac{\langle \sigma_{\rm SM\to DM} v \rangle \, n^2_{\rm SM,Eq}}{zHs} + \cancel{+ \frac{\langle \sigma_{\gamma'\to \rm DM} v \rangle \, n^2_{\gamma',\rm Eq}}{zHs}}$$

$\Rightarrow Y_{\rm DM} \propto \kappa^2$

The Mesa Diagram : Regime Ib (freeze-in from mediators)



We increase α'

DM is now produced by γ'

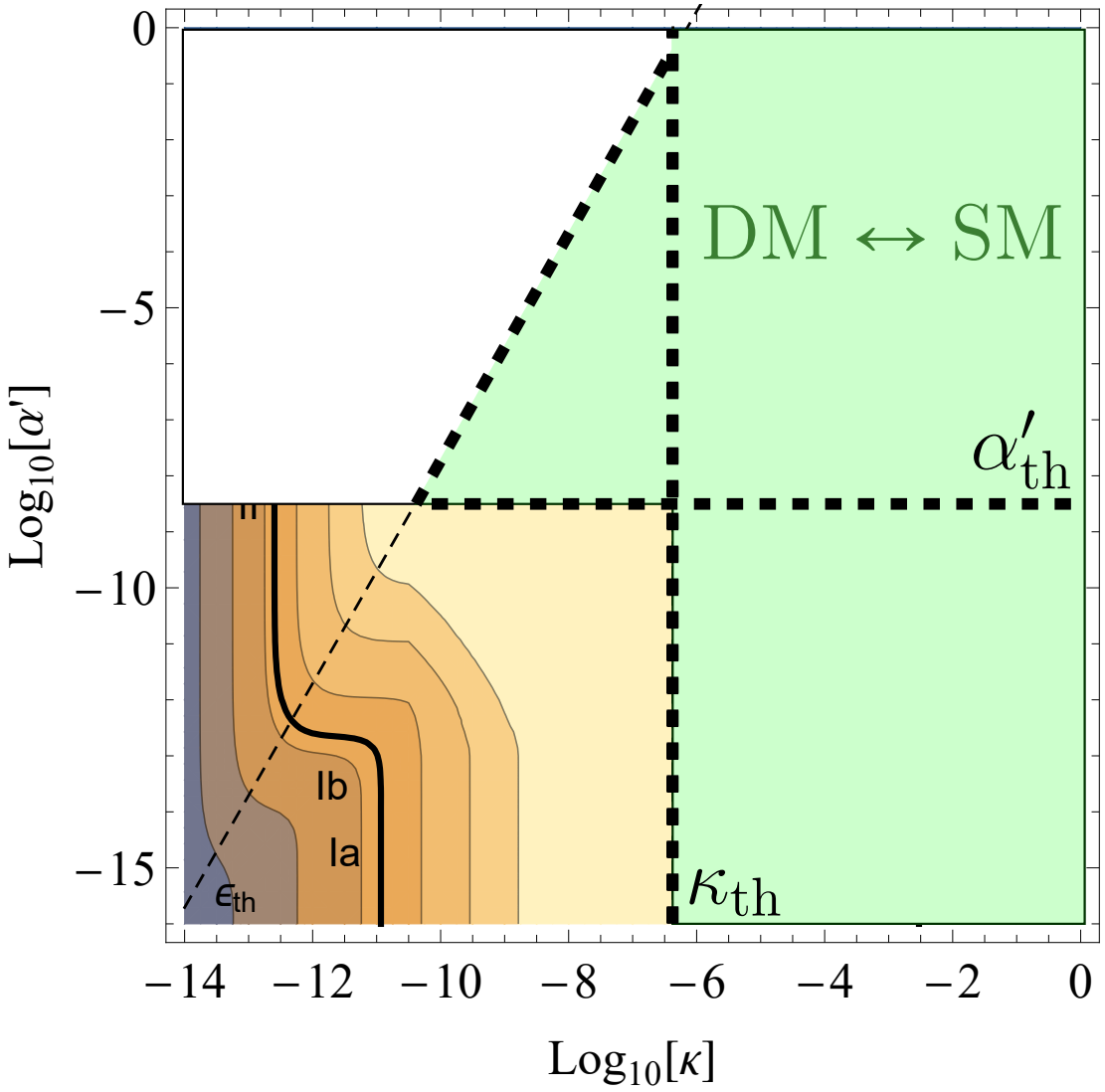
$$\frac{\mathrm{dY_{DM}}}{\mathrm{dz}} = \cancel{\frac{\langle \sigma_{\mathrm{SM}\to\mathrm{DM}} v \rangle \, n^2_{\mathrm{SM,Eq}}}{zHs}} + \frac{\langle \sigma_{\gamma'\to\mathrm{DM}} v \rangle \, n^2_{\gamma',\mathrm{Eq}}}{zHs}$$

$\Rightarrow Y_{\mathrm{DM}} \propto \alpha'^2$

Surprisingly not much studied [Heeba, Kahlhoefer, 2019]

Note that $\kappa_{\mathrm{Ib}} \ll \kappa_{\mathrm{Ia}}$

The Mesa Diagram : Regime II (sequential freeze-in)



As $\kappa \searrow$, ϵ drops below $\epsilon_{\rm th}$.

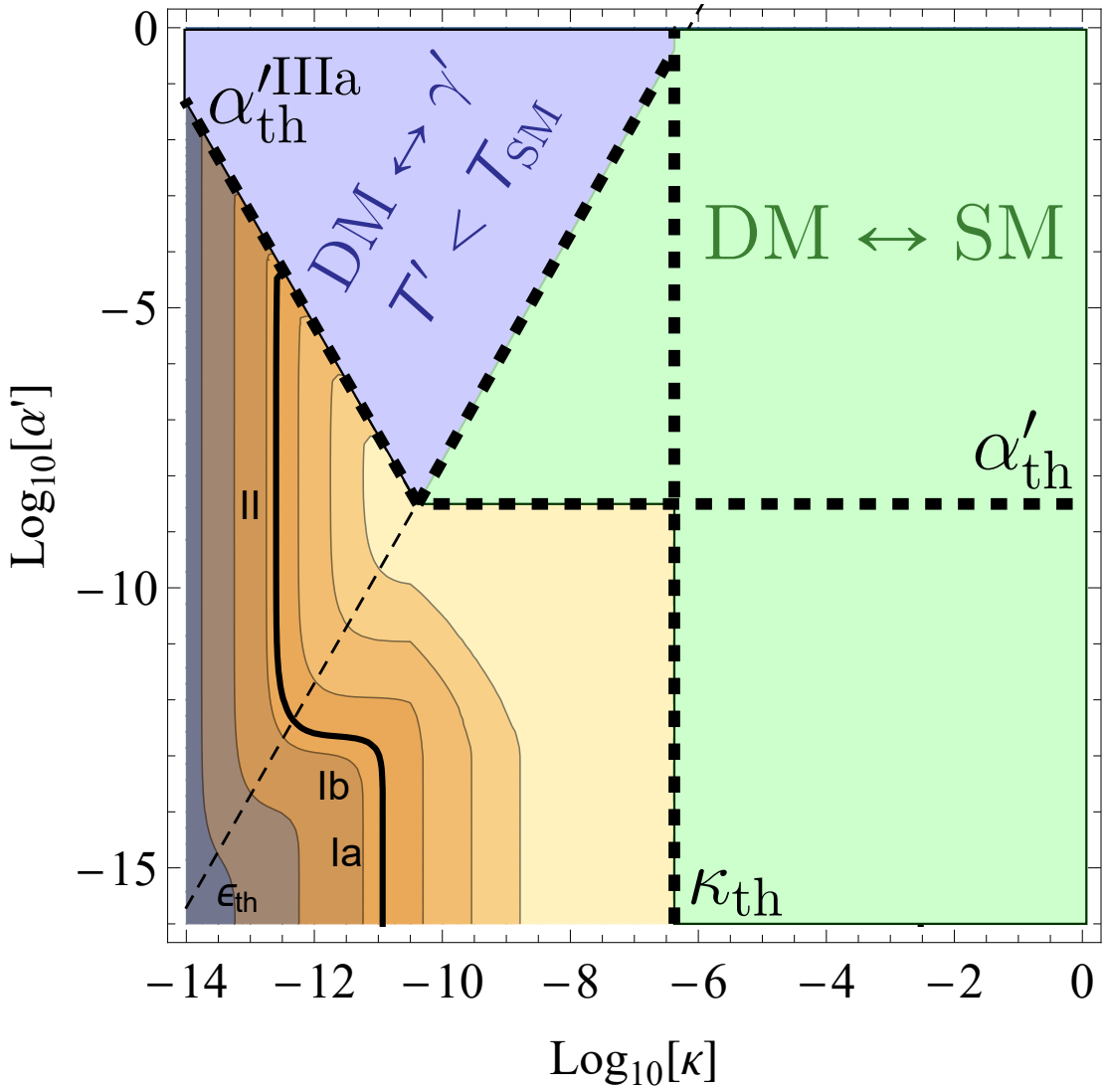
$$\frac{\mathrm{dY_{DM}}}{\mathrm{dz}} = \frac{\langle \sigma_{\gamma' \to \mathrm{DM}} v \rangle}{zHs} n^2_{\gamma'}$$

$$\frac{\mathrm{dY}_{\gamma'}}{\mathrm{dz}} = \frac{\langle \sigma_{\mathrm{SM} \to \gamma'} v \rangle \, n^2_{\mathrm{SM,Eq}}}{zHs}$$

$$\Rightarrow Y_{\rm DM} \propto \alpha'^2 \, \epsilon^4 \propto \kappa^2$$

The Dark Sector has never been in equilibrium with the Standard Model !

The Mesa Diagram : Regime IIIa (Reannihilation)



As $\alpha' \nearrow$, $\gamma' \leftrightarrow \mathrm{DM}$ processes can reach equilibrium.

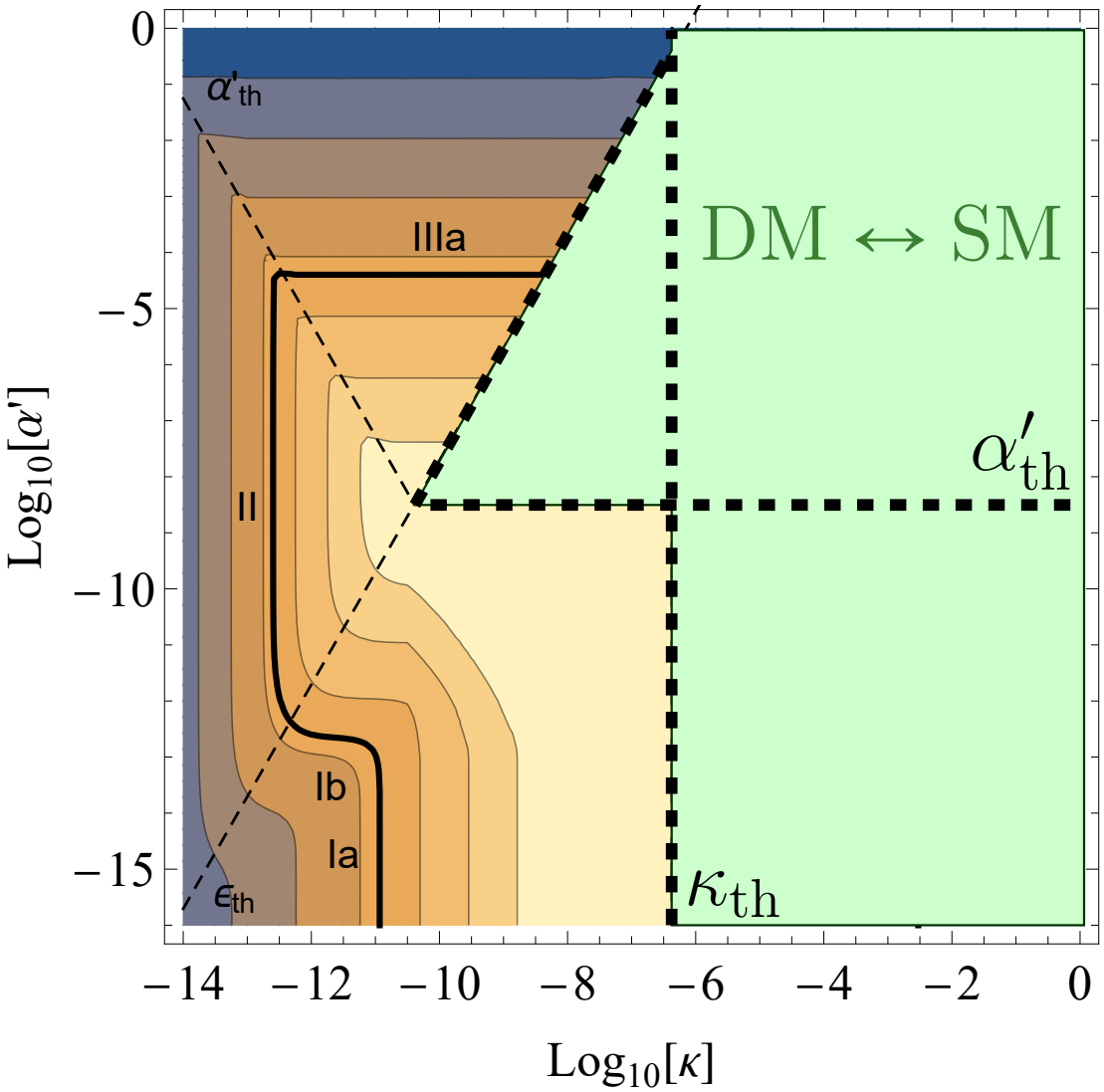
$$\alpha'^{\rm IIIa}_{\rm th} = \frac{\epsilon_{\rm th}}{\epsilon}\alpha'_{\rm th}$$

The energy transfer is

$$zH\frac{d\rho'}{dz} + 4H\left(\rho' + p'\right) = \\ = n^2_{\rm SM,Eq}\left\langle \sigma_{\rm SM\to\gamma'} v \Delta E\right\rangle$$

The Dark Sector equilibrates at $T' < T$ and is sourced.

The Mesa Diagram : Regime IIIa (Reannihilation)

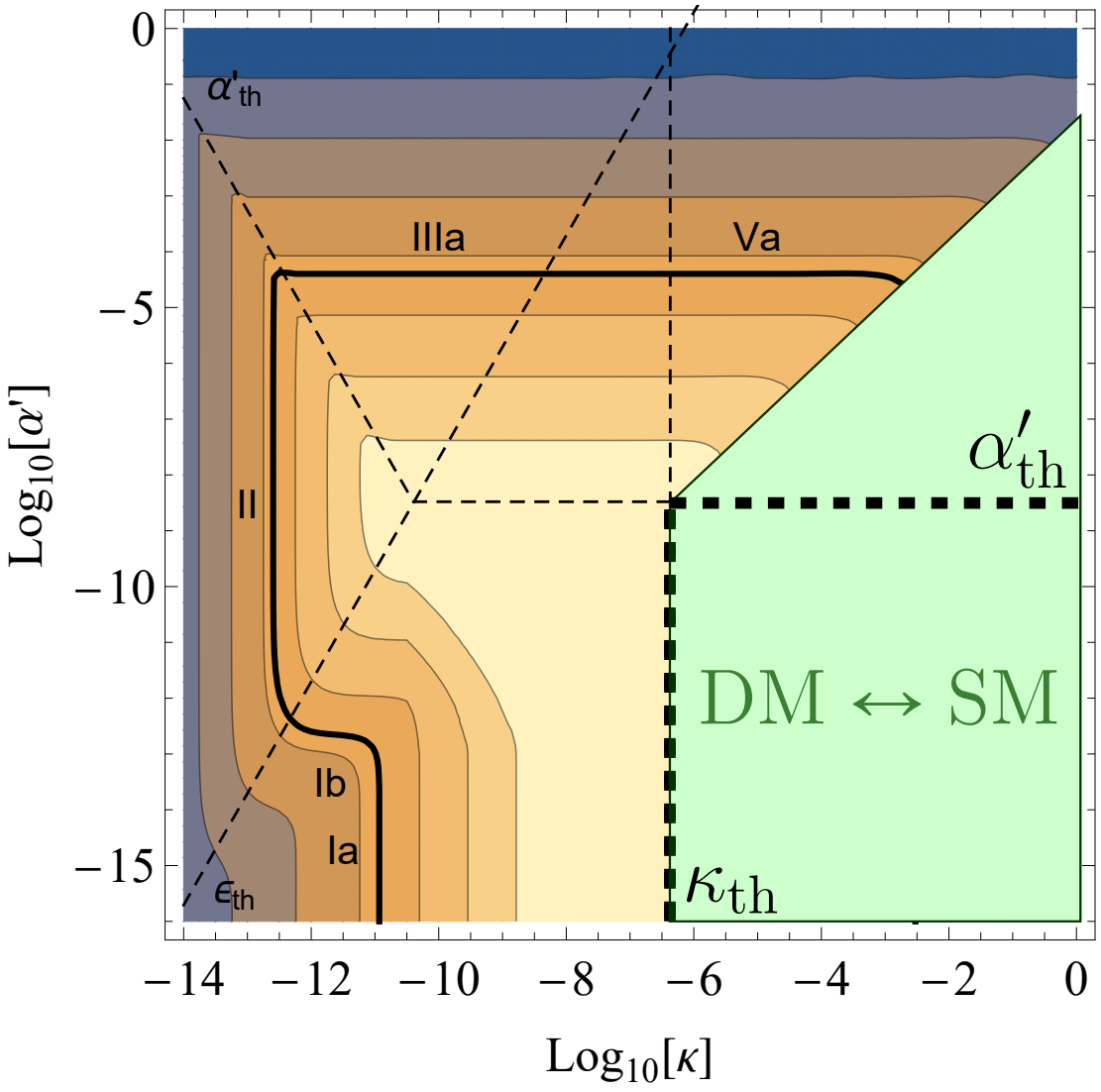


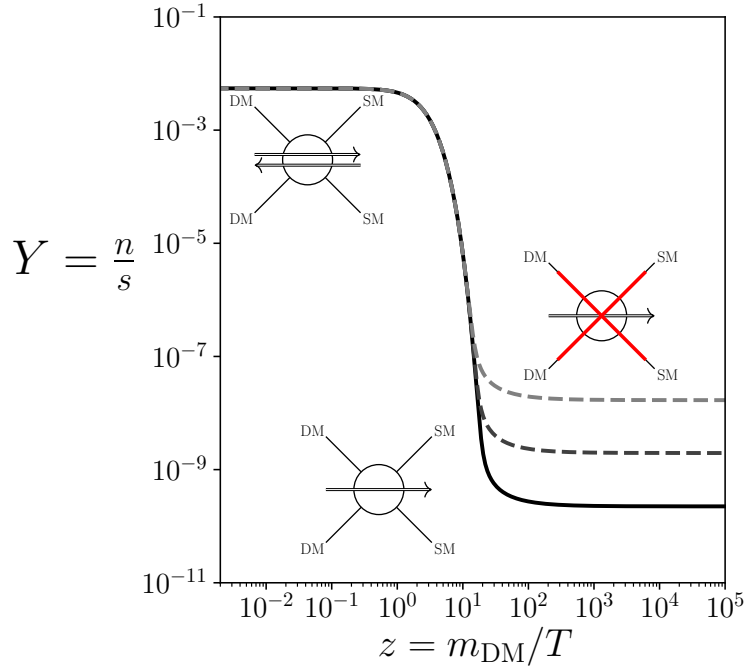
$$\frac{\mathrm{dY_{DM}}}{\mathrm{dz}} = \frac{\left\langle \sigma_{\mathrm{DM}\leftrightarrow\gamma'} v \right\rangle\big|_{T'}}{zHs} \times \left(n^2_{\mathrm{DM,Eq}}\big|_{T'} - n^2_{\mathrm{DM}} \right)$$

$$\frac{\mathrm{dY}_{\gamma'}}{\mathrm{dz}} = \frac{\left\langle \sigma_{\mathrm{SM}\to\gamma'} v \right\rangle n^2_{\mathrm{SM,Eq}}}{zHs} + \frac{\left\langle \sigma_{\mathrm{DM}\leftrightarrow\gamma'} v \right\rangle\big|_{T'}}{zHs} \times \left(n^2_{\gamma',\mathrm{Eq}}\big|_{T'} - n^2_{\gamma'} \right)$$

$Y_{\mathrm{DM}} \propto \alpha'^{-2}$
annihilations through mediators

The Mesa Diagram : Freeze-out regimes - Va

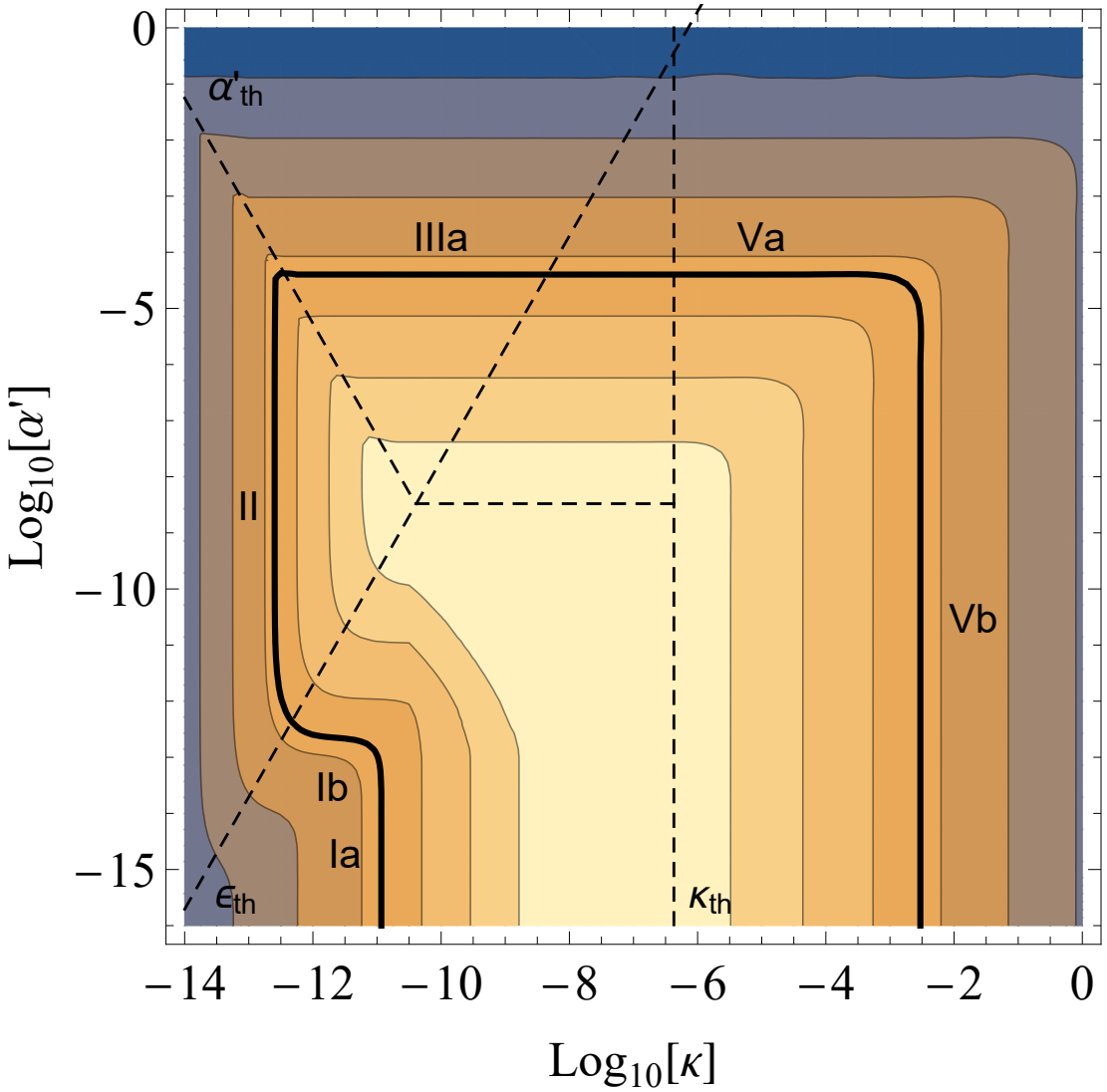


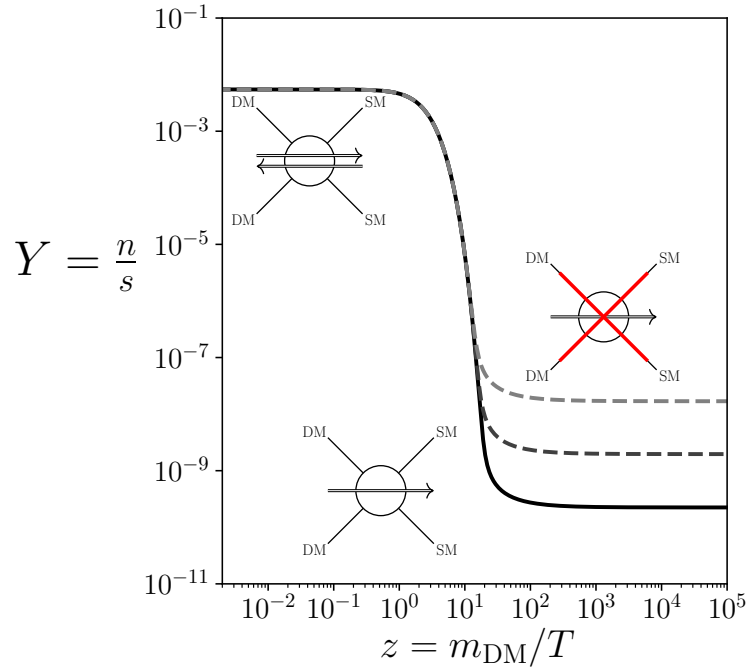


$$\frac{dY_{DM}}{dz} = \frac{\langle \sigma_{DM\to\gamma'} v \rangle}{zHs} \times \times \left(n^2_{DM,Eq} - n^2_{DM}\right)$$

$$Y_{DM} \propto \alpha'^{-2}.$$

The Mesa Diagram : Freeze-out regimes - Vb

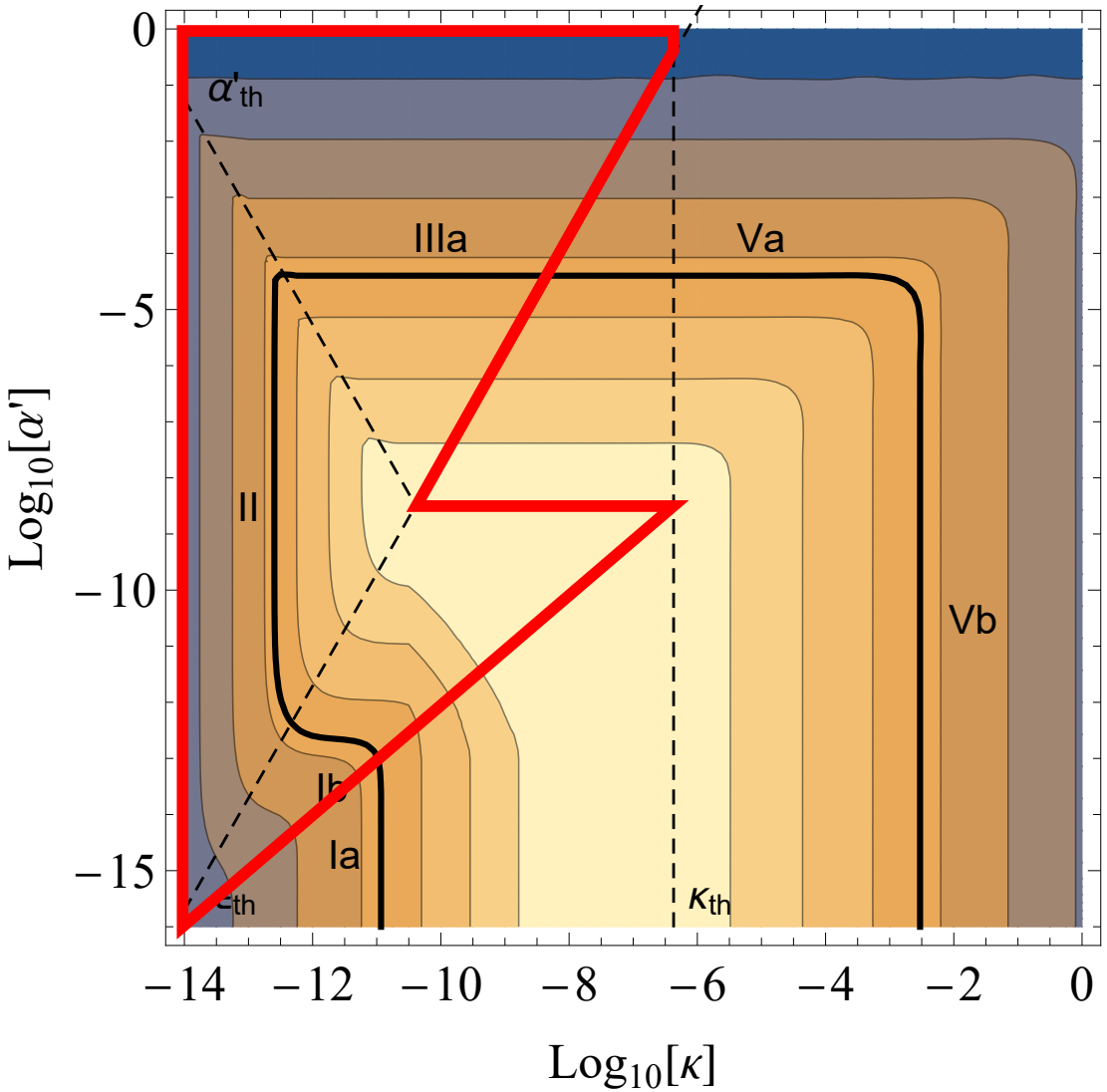




$$\frac{\mathrm{dY_{DM}}}{\mathrm{dz}} = \frac{\langle \sigma_{\mathrm{DM}\to\mathrm{SM}} v \rangle}{zHs} \times \times \left(n^2_{\mathrm{DM,Eq}} - n^2_{\mathrm{DM}} \right)$$

$$Y_{\mathrm{DM}} \propto \kappa^{-2}.$$

The Mesa Diagram of Dark Matter Production



Ia : Freeze-in from SM

$\Downarrow$

Ib : Freeze-in from γ'

$\Downarrow$

II : Sequential Freeze-in

$\Downarrow$

IIIa : Reannihilation from γ'

$\Downarrow$

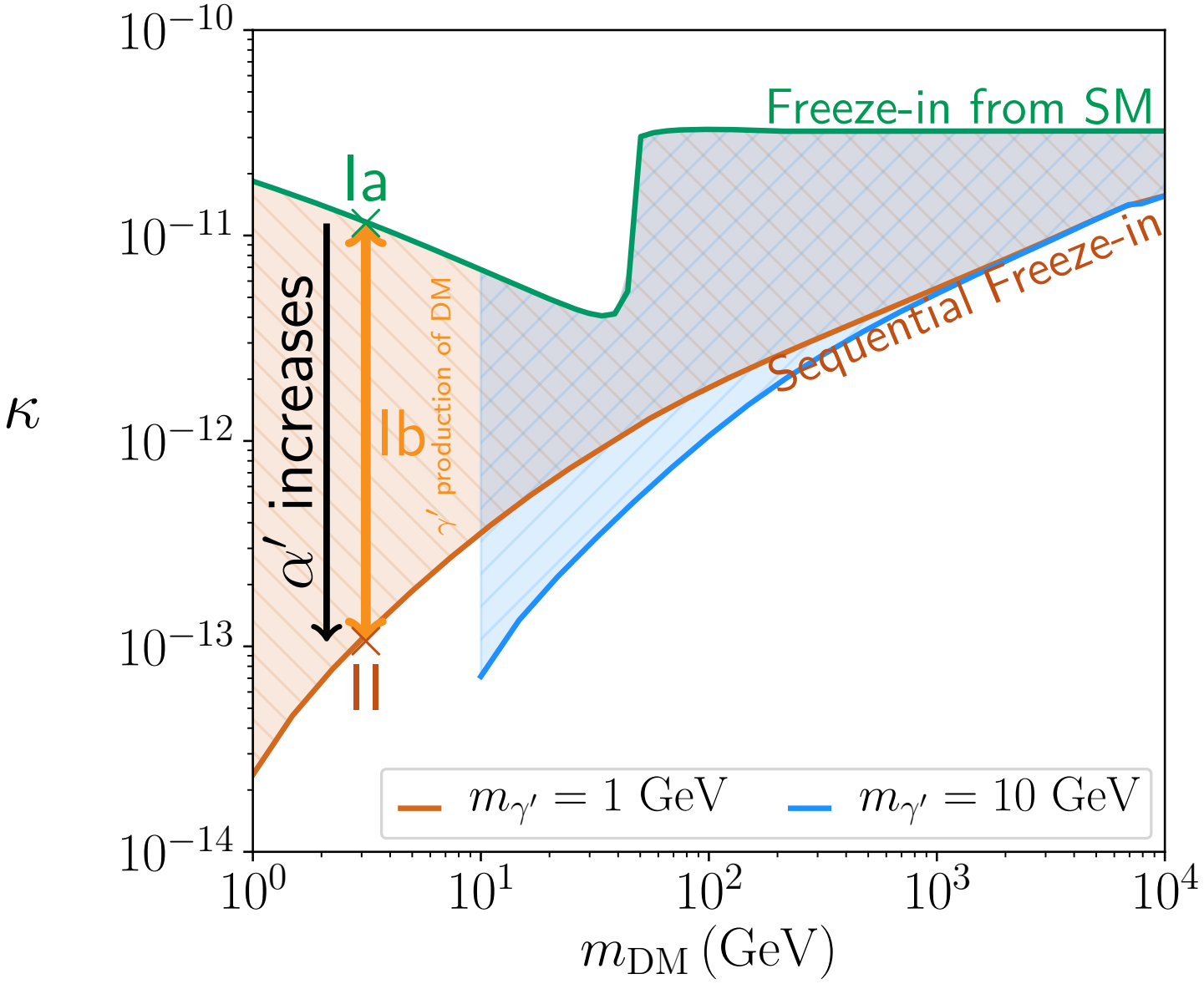
Va : Freeze-out through γ'

$\Downarrow$

Vb : Freeze-out through SM

[Thomas Hambye, Michel H.G. Tytgat, JV, Laurent Vanderheyden, 2019]

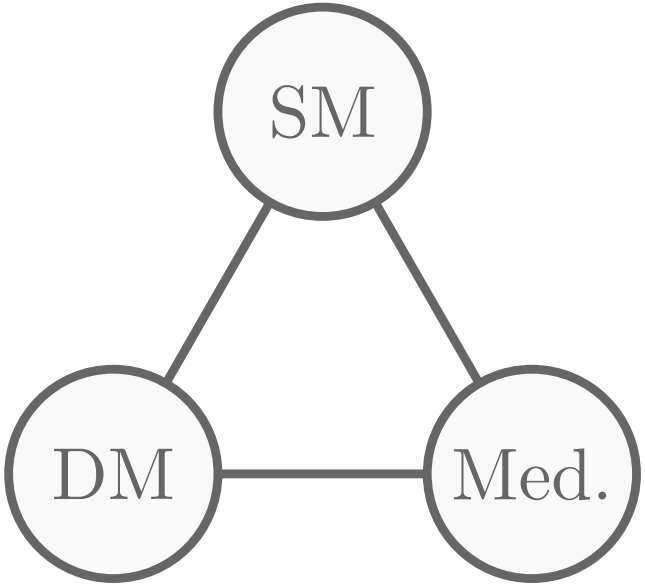
Focus on the new regimes : Large parameter space opened



[Thomas Hambye, Michel H.G. Tytgat, JV, Laurent Vanderheyden, 2019]

Conclusions

- In a simple DM model, we find that 9 regimes are potentially operative to produce the DM particles and this along 5 distinct dynamical mechanisms.
- Among these, 4 regimes are new and correspond to regimes in which the DM particles are produced by on-shell dark photons.
- One of them proceeds along a new dynamical mechanism, which we dub sequential freeze-in.
- Not discussed : Important thermal effects.
- Can be applied to other DM models, with interesting phenomenological implications.

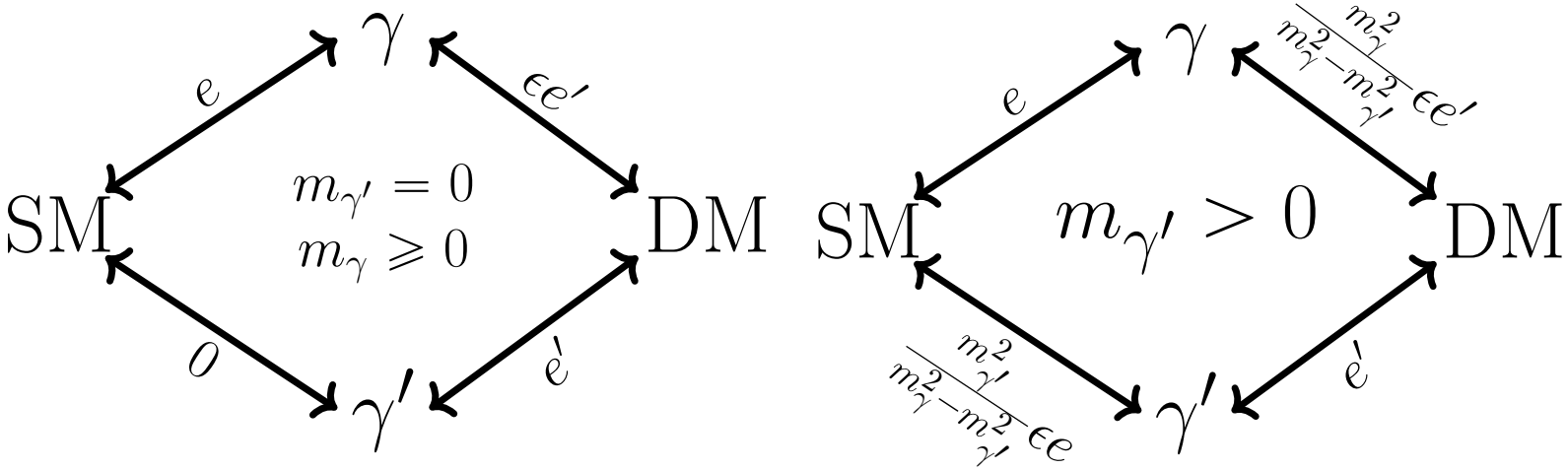


Back up slides

Eff. couplings : Longitudinal, transverse from $m_\gamma \neq 0$

For transverse modes

$$\epsilon_{\text{eff}}^{\text{DM}\leftrightarrow\gamma_T} = \frac{m_\gamma^2}{m_\gamma^2 - m_{\gamma'}^2}\epsilon \qquad \epsilon_{\text{eff}}^{\text{SM}\leftrightarrow\gamma'_T} = \frac{m_{\gamma'}^2}{m_\gamma^2 - m_{\gamma'}^2}\epsilon$$

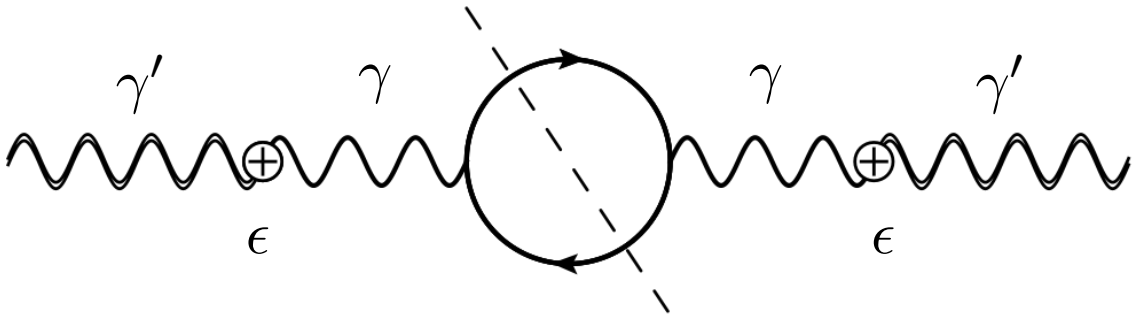


For longitudinal modes, in the relativistic limit, $T \gg m_{\gamma'}$,

$$\epsilon_{\text{eff}}^{\text{DM}\leftrightarrow\gamma_L} = -\frac{m_\gamma}{m_{\gamma'}}\epsilon \qquad \epsilon_{\text{eff}}^{\text{SM}\leftrightarrow\gamma'_L} = \frac{m_{\gamma'}}{m_\gamma}\epsilon$$

More careful treatment of the thermal effects

$$\Pi_{\gamma'} = m_{\gamma'}^2 + \frac{\epsilon^2 m_{\gamma'}^4}{(K^2 - \Pi_\gamma)}$$

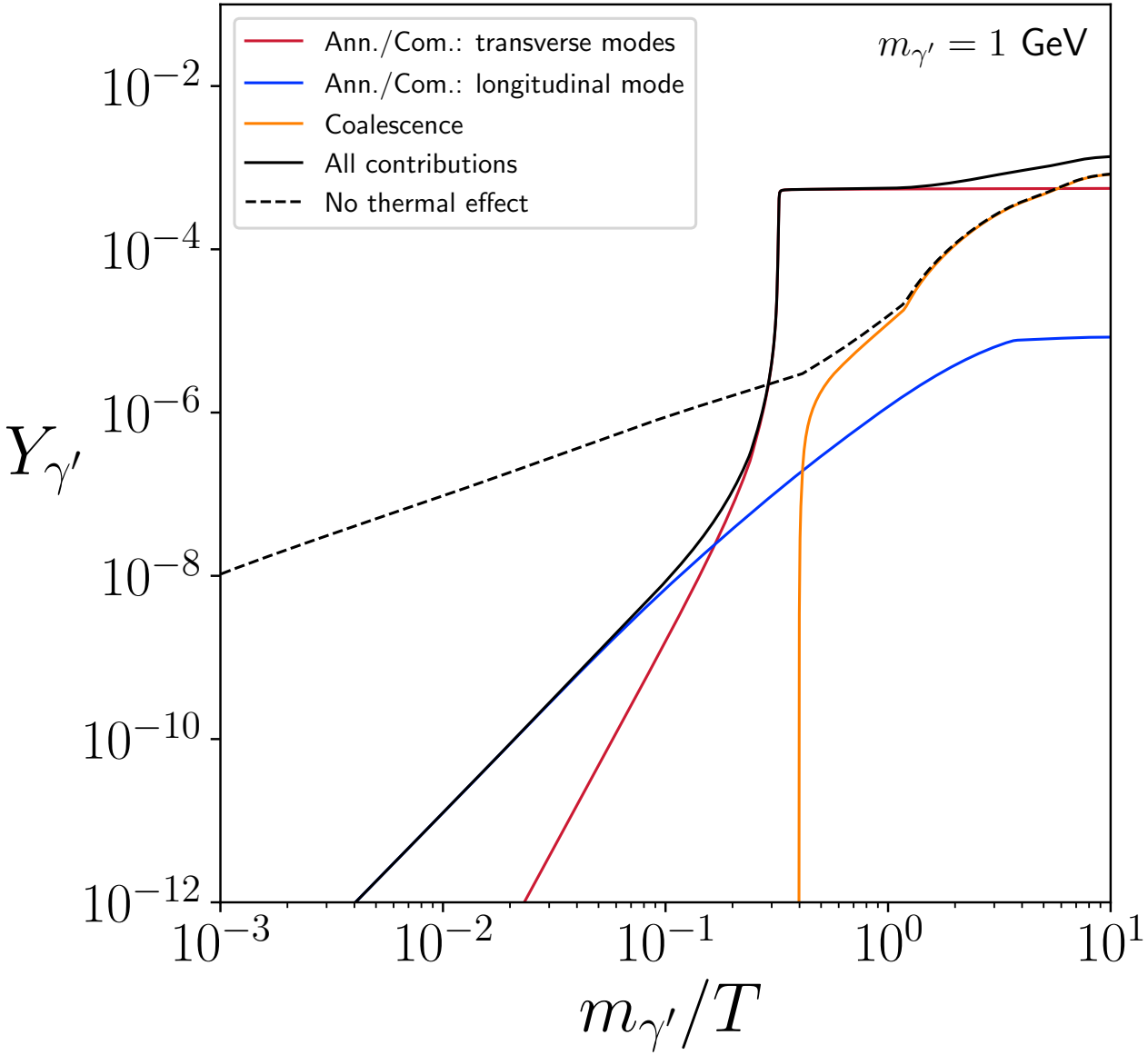


$$\mathrm{Im}\,\Pi_{\gamma'} = \frac{\epsilon^2 m_{\gamma'}^4\,\mathrm{Im}\,\Pi_\gamma}{(m_{\gamma'}^2 - \mathrm{Re}\,\Pi_\gamma)^2 + \mathrm{Im}\,\Pi_\gamma^2}$$

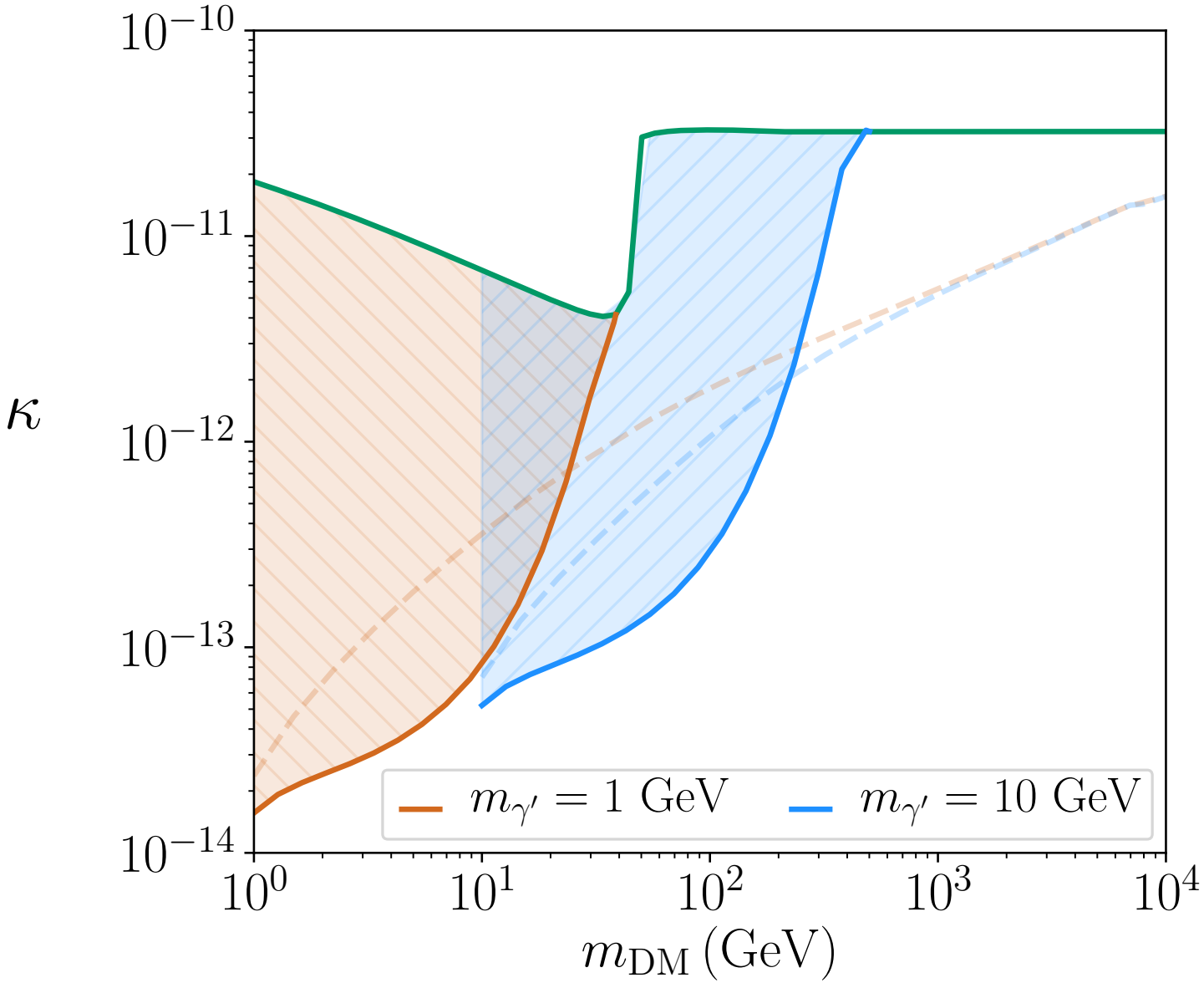
$$\mathrm{Im}\,\Pi_\gamma = -\omega\Gamma_\gamma = -\omega(\Gamma_{\gamma,\,\mathrm{em}} - \Gamma_{\gamma,\,\mathrm{abs}}).$$

$$\Gamma_{\gamma',\,\mathrm{em}} = \frac{\epsilon^2 m_{\gamma'}^4 \Gamma_{\gamma,\,\mathrm{em}}}{(m_{\gamma'}^2 - \mathrm{Re}\,\Pi_\gamma)^2 + \omega^2(e^{\omega/T} - 1)^2\Gamma_{\gamma,\,\mathrm{em}}^2} = \epsilon_{\mathrm{eff}}^2$$

Dark photon production : Channels, with(out) thermal effects



Parameter space including thermal effects



A quick phenomenological implication : Mediator searches