A taxonomy of dark matter production through dark photons

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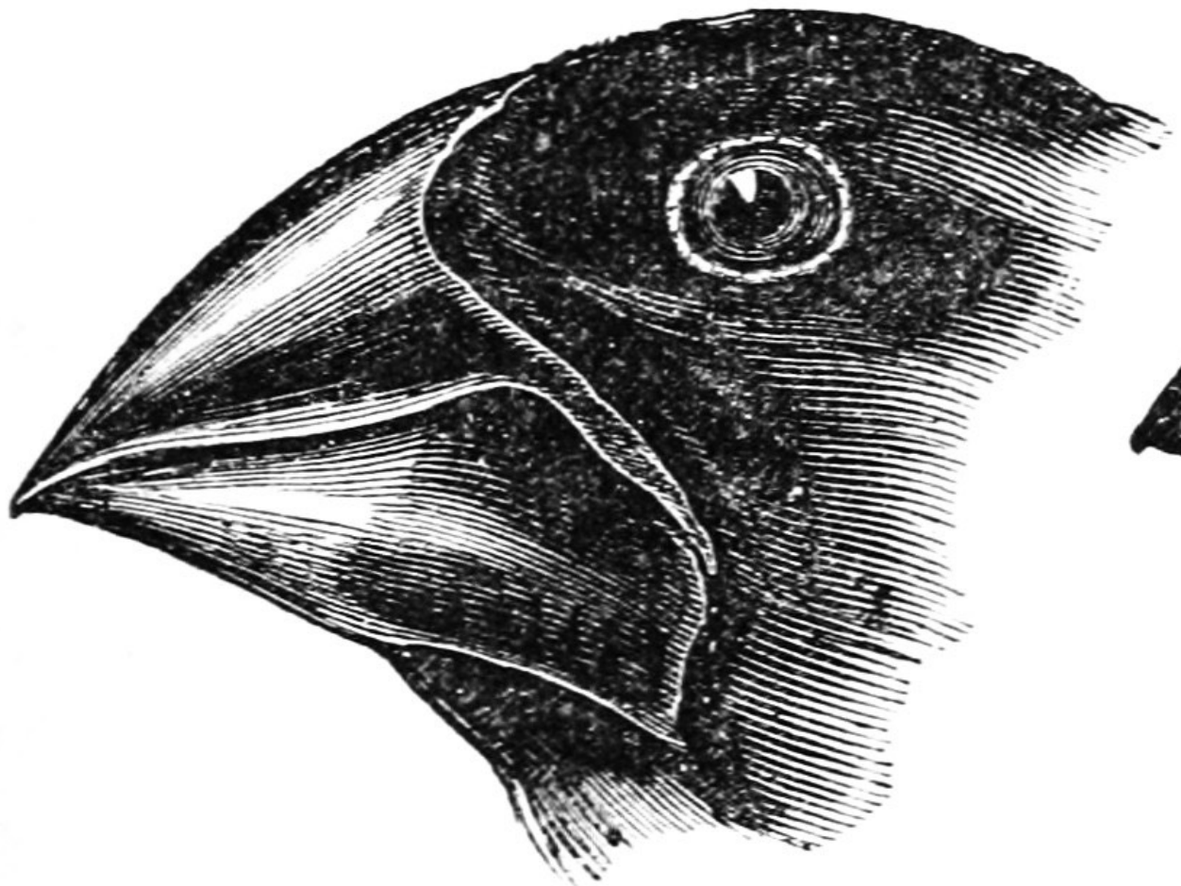
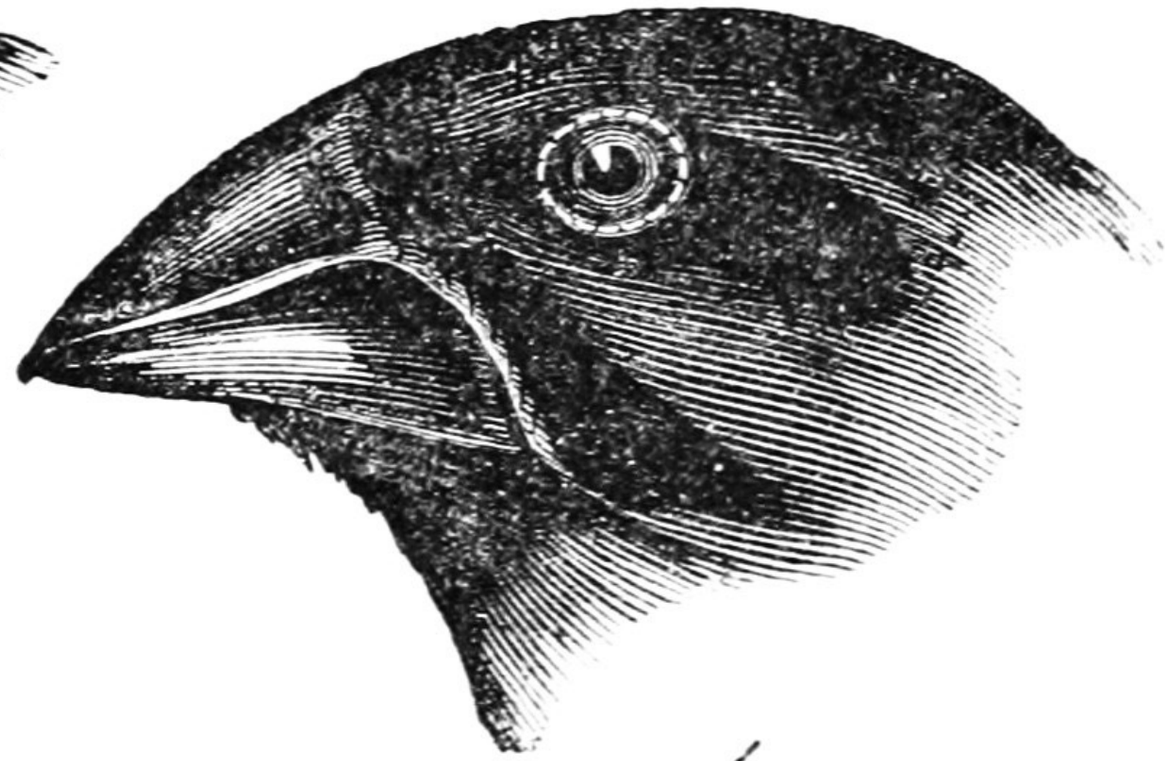
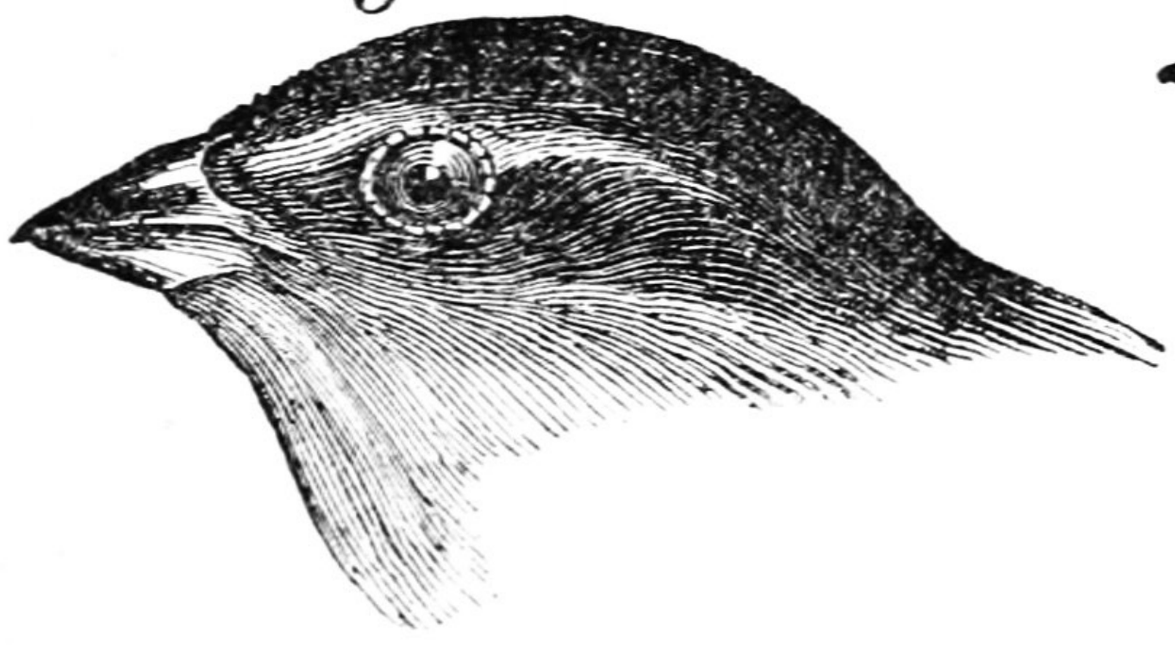
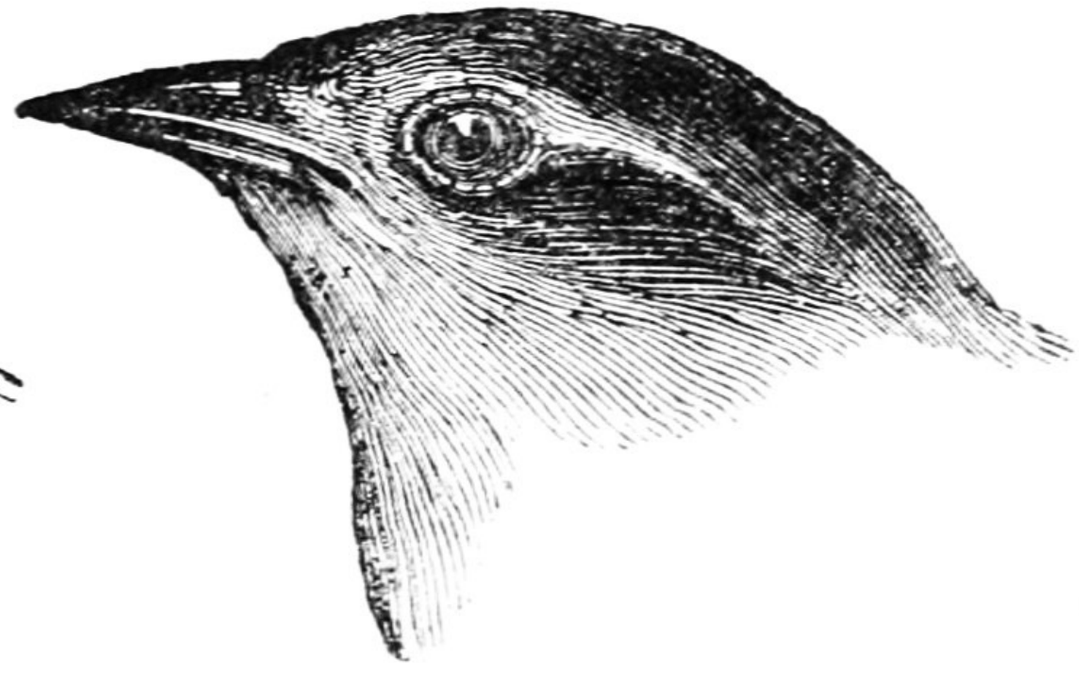
Hong Kong - January 20-22 2020



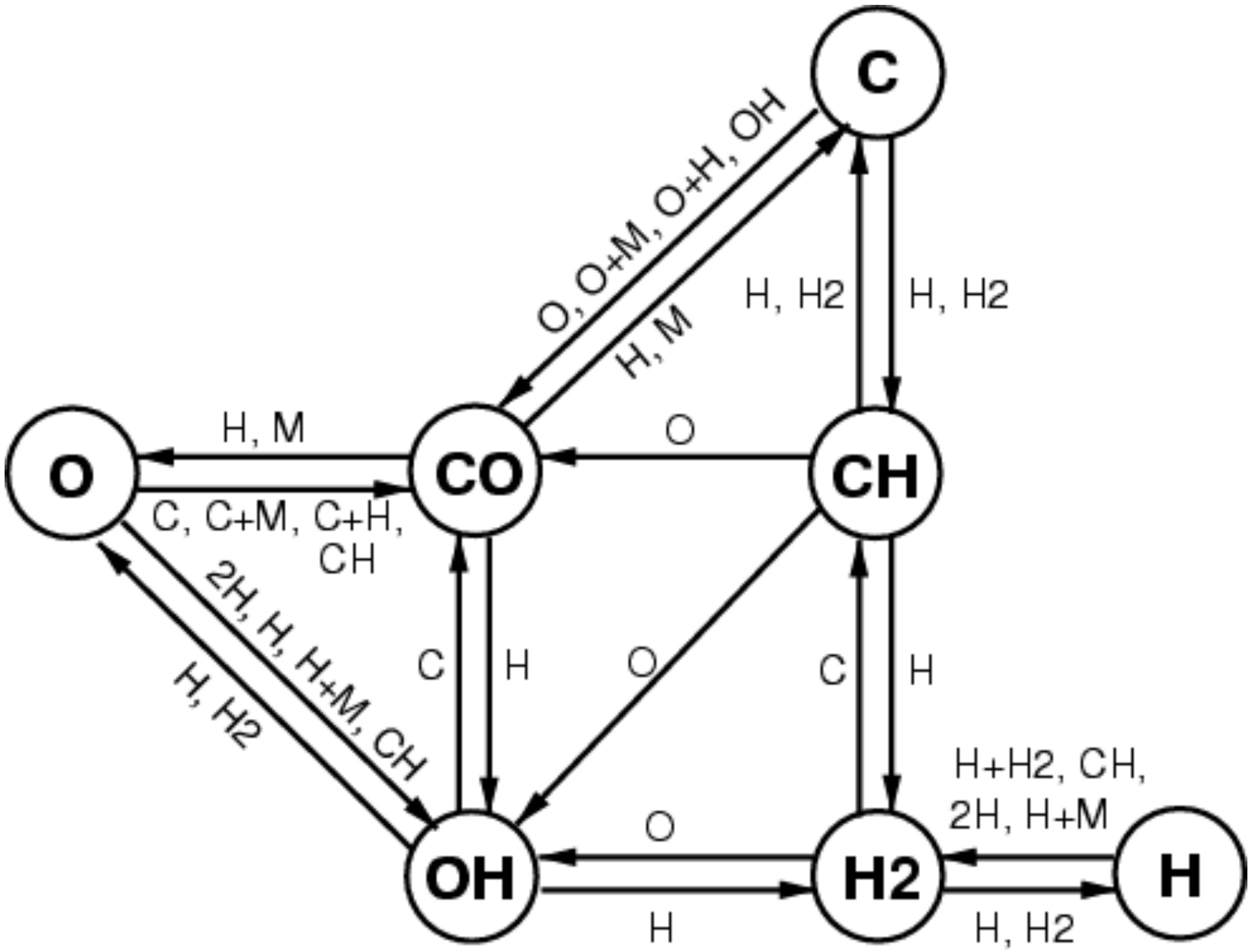






1. Geospiza magnirostris.
3. Geospiza parvula.

2. Geospiza fortis.
4. Certhidea olivasea.


C
O, O+M, O+H, OH
H, M
H, H2
H, H2
H, M
O
O
CO
CH
C, C+M, C+H,
CH
2H, H, H+M, CH
H, H2
C
H
O
C
H
H+H2, CH,
2H, H+M
O
OH
H2
H
H
H, H2

Based on

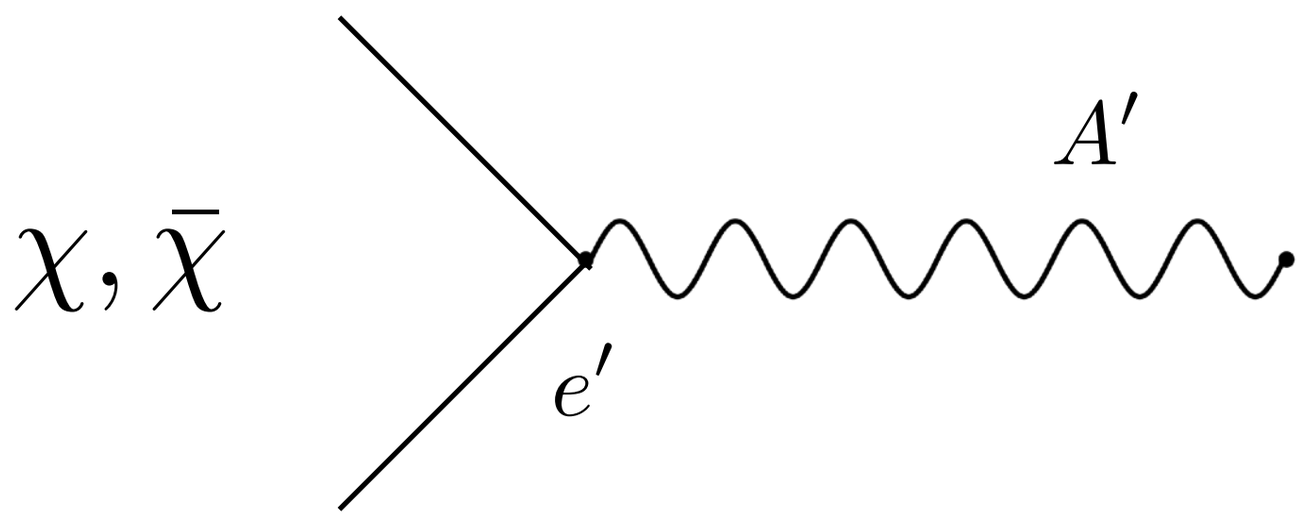
The 4 basic ways of producing dark matter through a portal
X. Chu, Th. Hambye, M.H.G.T.
arXiv:1112.0493

Dark matter from dark photons : a taxonomy of production mechanisms
Th. Hambye, M.H.G.T., J. Vandecasteele, L. Vanderheyden
arXiv:1908.09864

Dark matter detection is testing freeze-in
Th. Hambye, M.H.G.T., J. Vandecasteele, L. Vanderheyden
arXiv:1807.05022

KINETIC MIXING PORTAL

$$\mathcal{L} \supset \bar{\chi}(i\not{D}' - m_\chi)\chi - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{\gamma'}A'_\mu A'^\mu - \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}$$



e' or α'

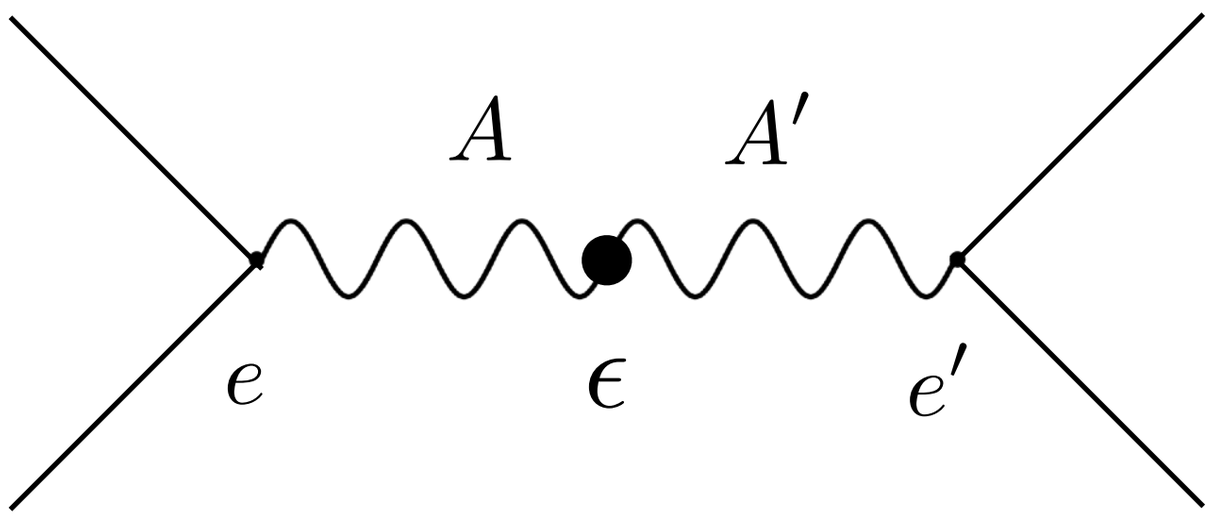
« dark fine structure constant »

Ackerman, Buckley, Carroll and Kamionkowski

KINETIC MIXING PORTAL

$$\mathcal{L} \supset \bar{\chi}(i\not{D}' - m_\chi)\chi - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{\gamma'}A'_\mu A'^\mu \; - \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}$$

SM



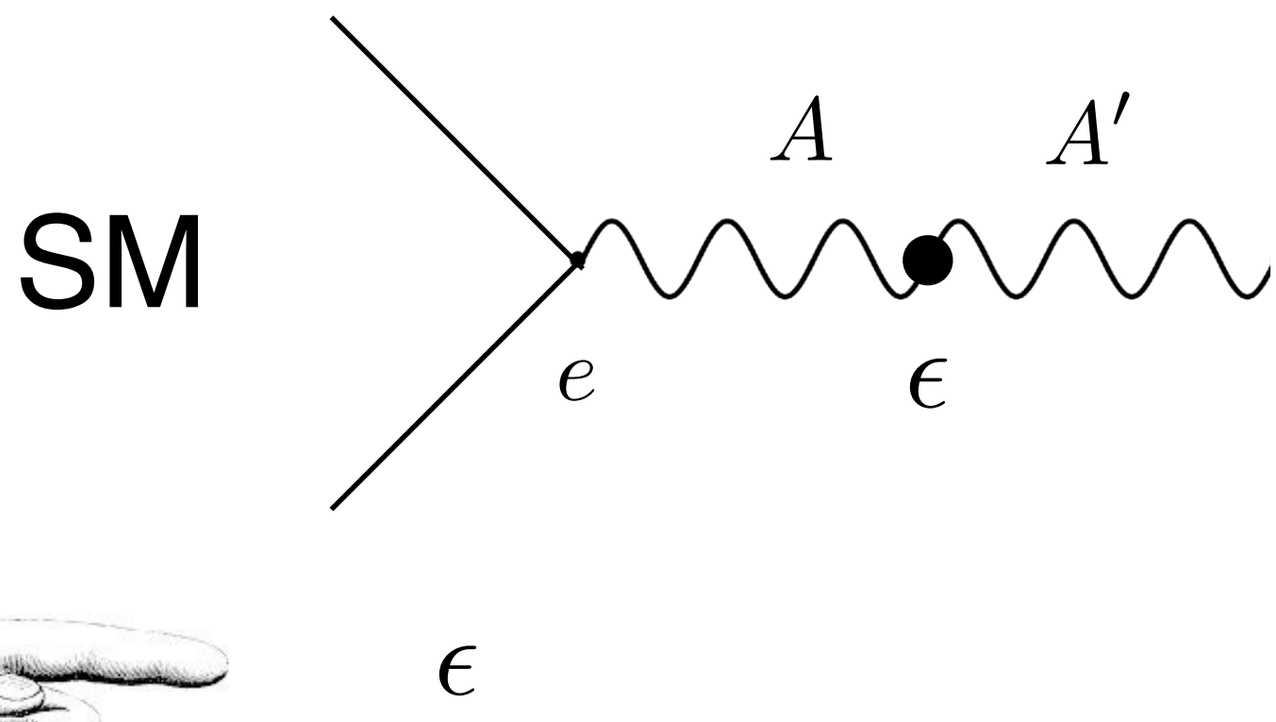
$\chi, \bar{\chi}$

$\kappa = \epsilon\, e'/e$ « millicharge »

Feldman, Kors, Nath;
Pospelov, Ritz, Voloshin;

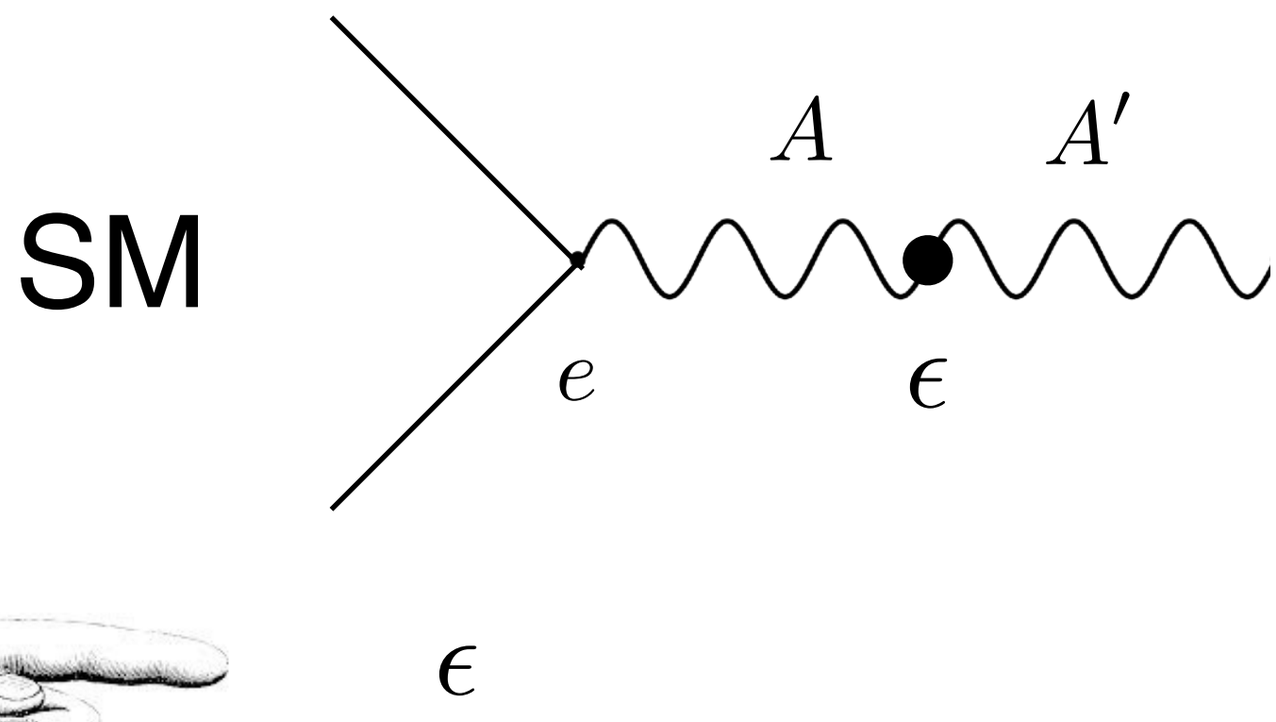
KINETIC MIXING PORTAL

$$\mathcal{L} \supset \bar{\chi}(i\not{D}' - m_\chi)\chi - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{\gamma'}A'_\mu A'^\mu - \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}$$



KINETIC MIXING PORTAL

$$\mathcal{L} \supset \bar{\chi}(i\not{D}' - m_\chi)\chi - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{\gamma'}A'_\mu A'^\mu - \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}$$



actually $\epsilon_{\text{eff}} = \epsilon \dfrac{m_{\gamma'}^2}{m_{\gamma'}^2 - m_\gamma^2(T)}$

BOLTZMANN EQUATIONS

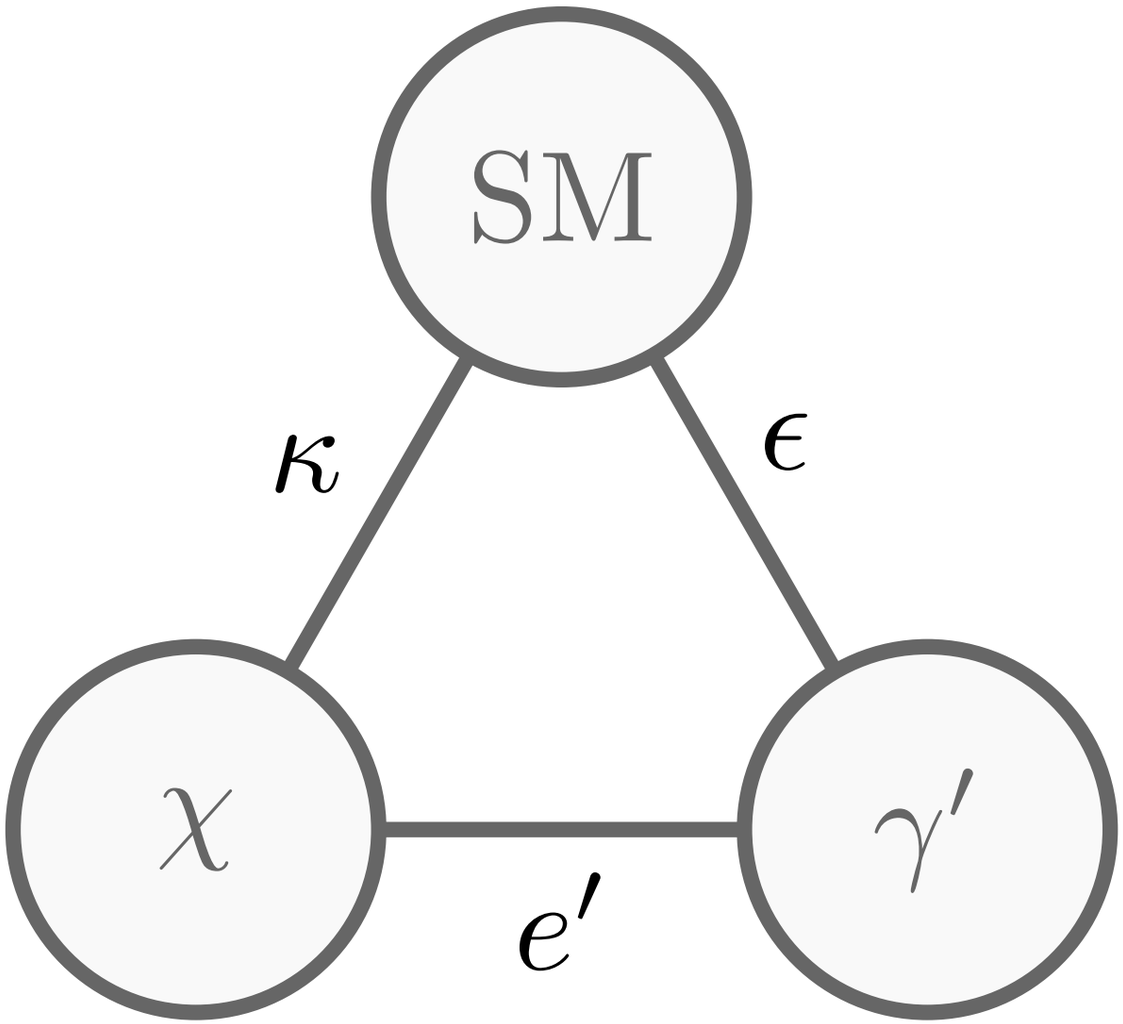
$$
\begin{aligned}
zHs\frac{dY_{\rm DM}}{dz} &= \langle\sigma_{\rm DM\to SM}\, v\rangle\, \left[(n_{\rm DM}^{\rm eq})^2 - n_{\rm DM}^2\right] \\
&\quad + \langle\Gamma^D_{\rm DM\to SM}\rangle \frac{n_Z^{\rm eq}}{(n_{\rm DM}^{\rm eq})^2}\left[(n_{\rm DM}^{\rm eq})^2 - n_{\rm DM}^2\right] \\
&\quad + \langle\sigma_{\gamma'\to\rm DM} v\rangle n_{\gamma'}^2 - \langle\sigma_{\rm DM\to\gamma'} v\rangle n_{\rm DM}^2
\end{aligned}
$$

$$
\begin{aligned}
zHs\frac{dY_{\gamma'}}{dz} &= \langle\sigma_{\gamma'\to\rm SM}\, v\rangle\, n_{\rm SM}^{\rm eq}\left[n_{\gamma'}^{\rm eq} - n_{\gamma'}\right] \\
&\quad + \langle\sigma_{\rm DM\to\gamma'} v\rangle n_{\rm DM}^2 - \langle\sigma_{\gamma'\to\rm DM} v\rangle n_{\gamma'}^2
\end{aligned}
$$

$$
\begin{aligned}
zH\frac{d\rho'}{dz} + 4H(\rho' + p') &= (n_{\rm SM}^{\rm eq}(z))^2\langle\sigma_{\rm SM\to DM}\, v\, \Delta E\rangle \\
&\quad + (n_{\rm SM}^{\rm eq}(z))^2\langle\sigma_{\rm SM\to\gamma'}\, v\, \Delta E\rangle
\end{aligned}
$$

Hambye, M.T., Vandecasteele, Vanderheyden ’19

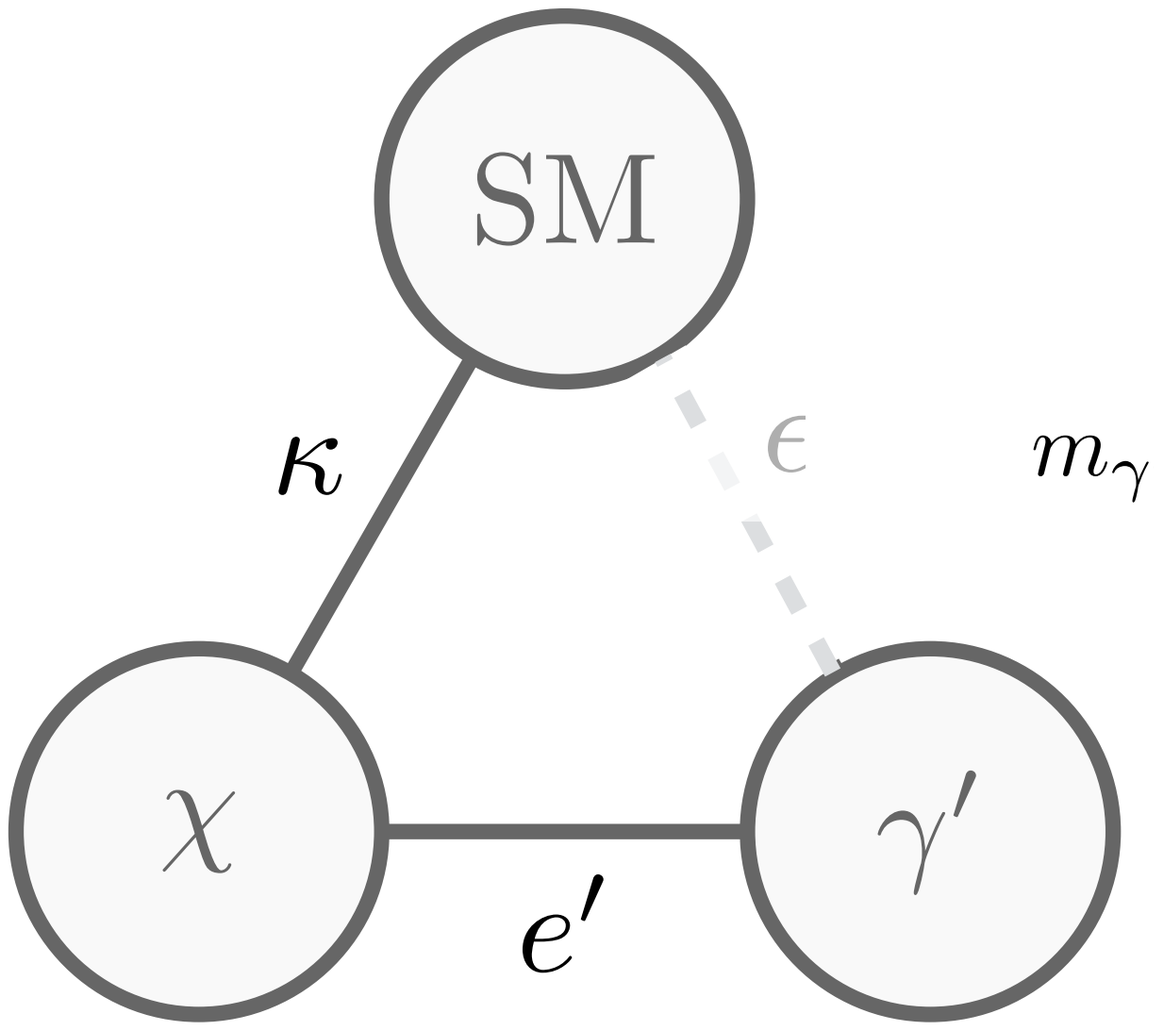
GRAPHICAL REPRESENTATION



$$\kappa = \epsilon\, e'/e$$

OLD

MASSLESS DARK PHOTON LIMIT



$m_{\gamma'} \to 0$

$\kappa = \epsilon\, e'/e$

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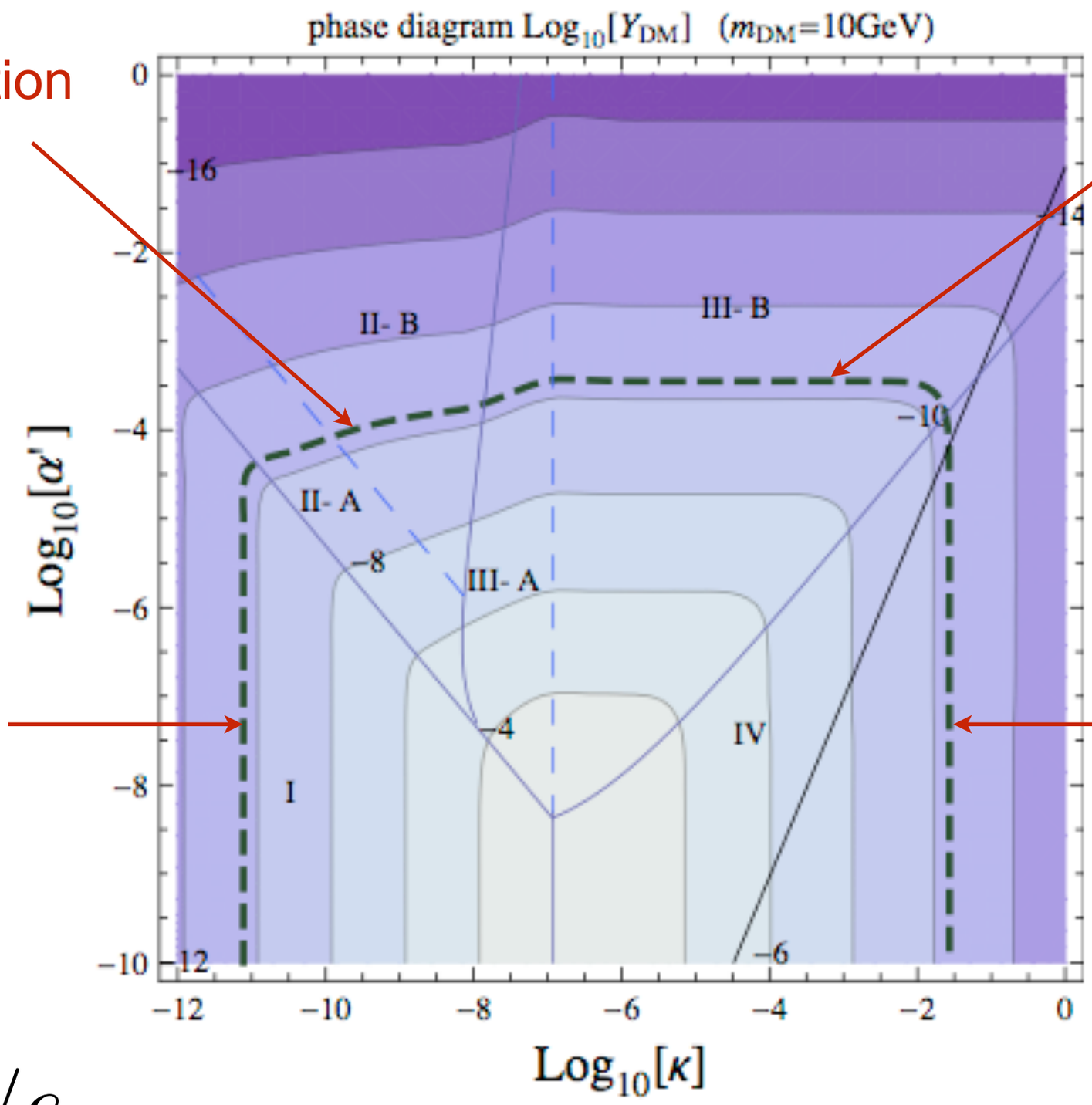
OLD THE 4 BASIC WAYS TO PRODUCE DM

$$m_{\gamma'} \to 0$$

II : reannihilation

III : freeze-out in hidden sector



I : freeze-in

IV : standard freeze-out

$$\kappa = \epsilon\, e'/e$$

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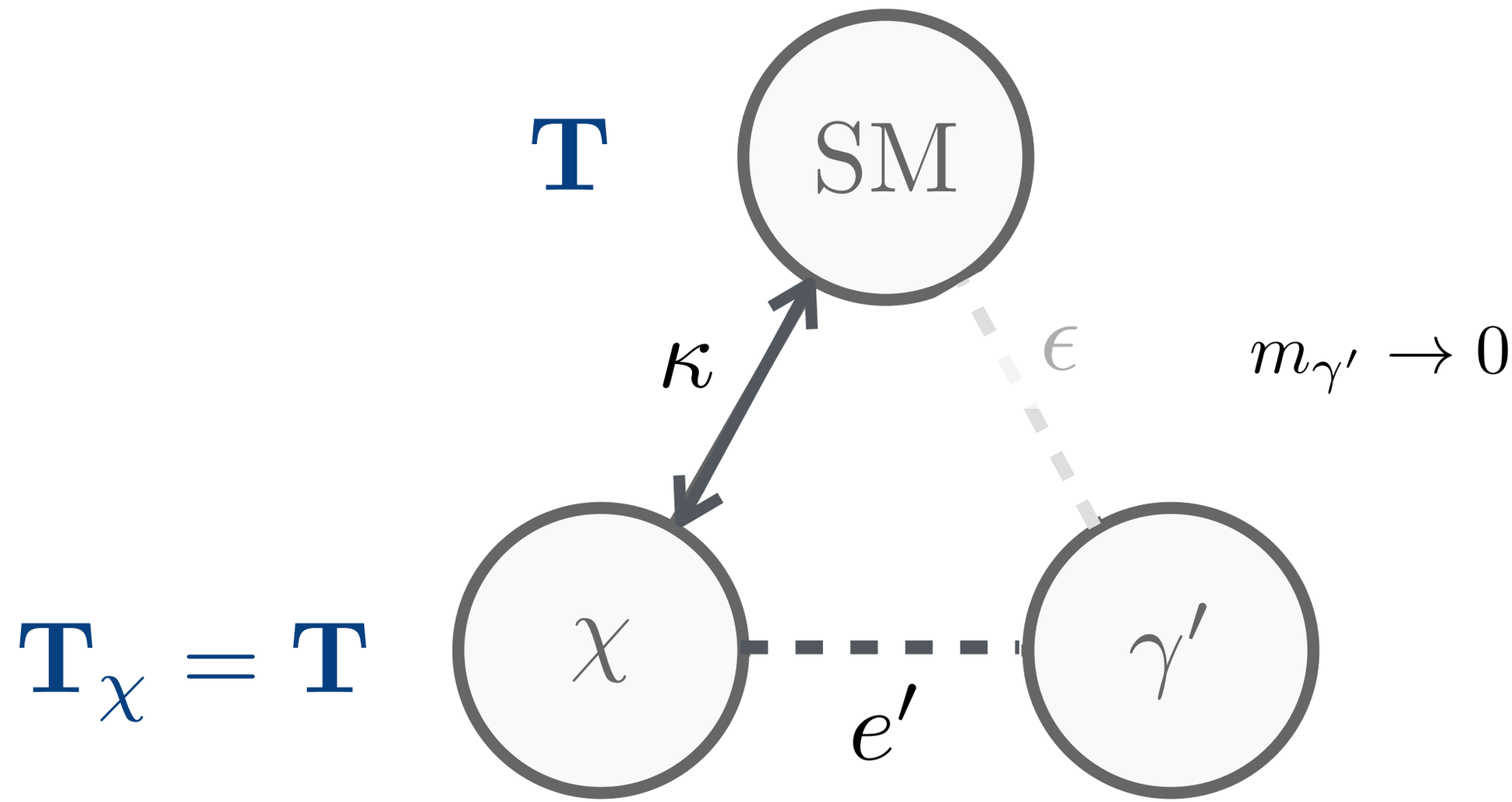
STANDARD FREEZE-OUT



$$\kappa = \epsilon\, e'/e$$

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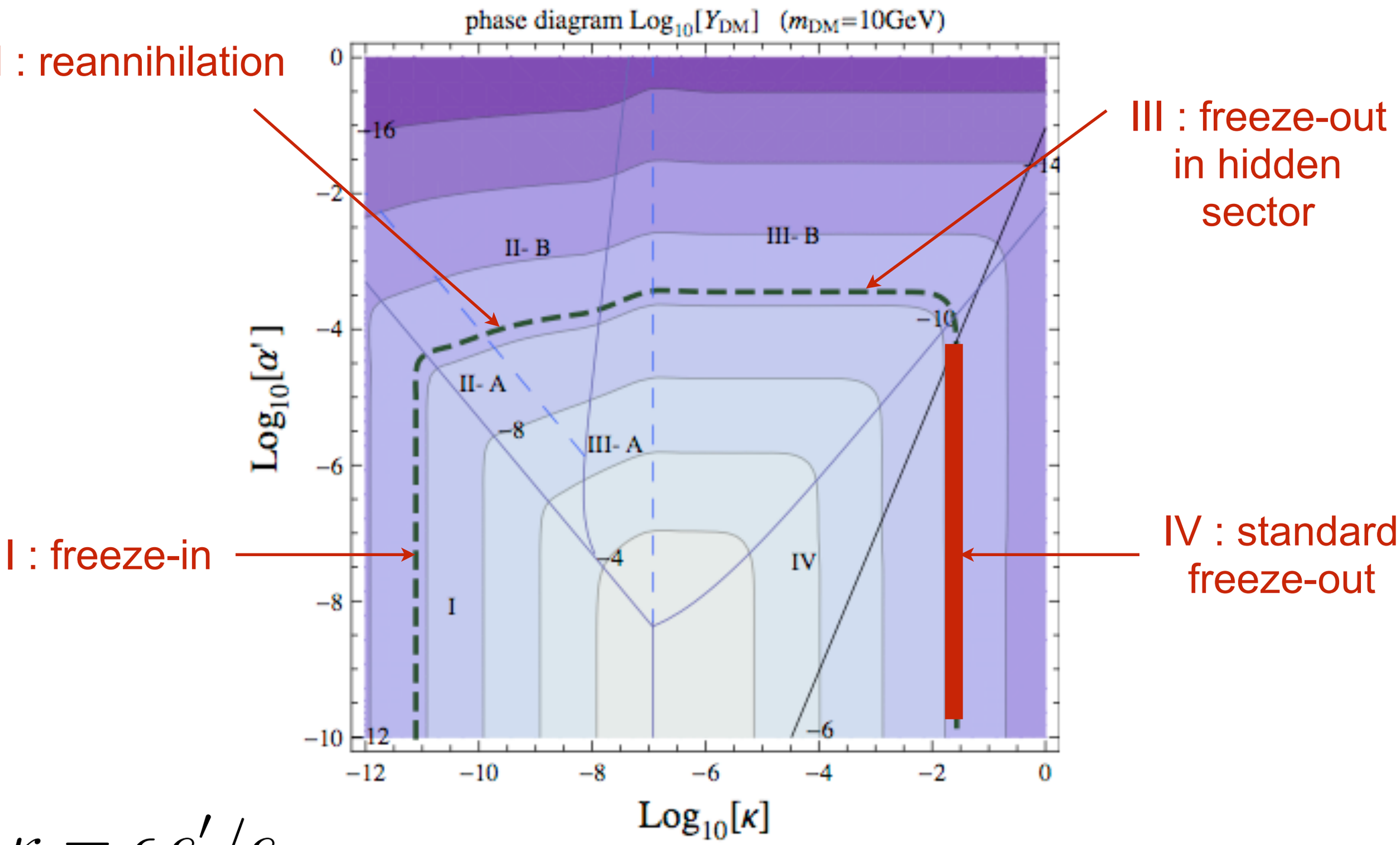
OLD STANDARD FREEZE-OUT

$$m_{\gamma'} \to 0$$



$$\kappa = \epsilon\, e'/e$$

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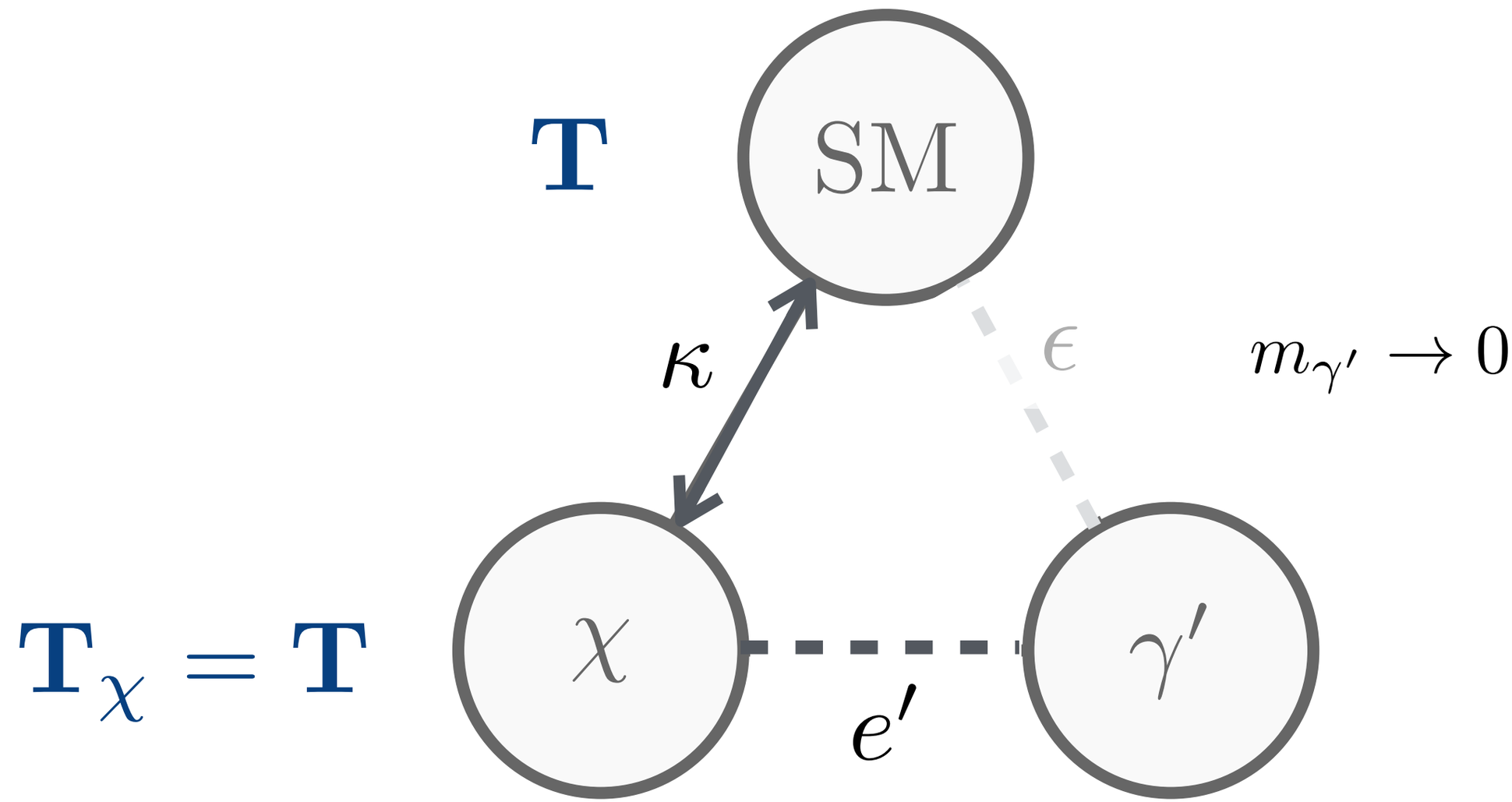
STANDARD FREEZE-OUT



$$\kappa = \epsilon\, e'/e$$

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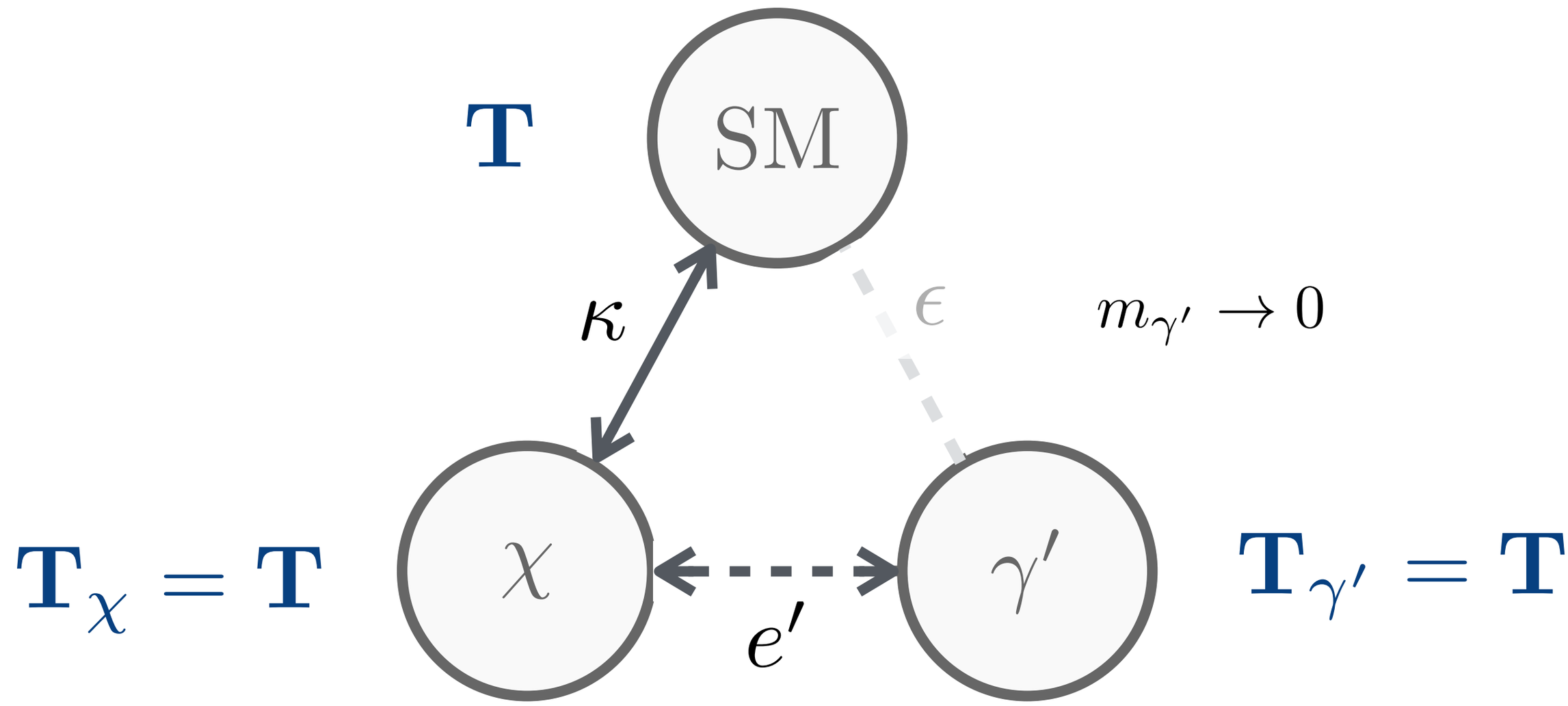
FREEZE-OUT INTO DARK PHOTONS



$$\kappa = \epsilon\, e'/e$$

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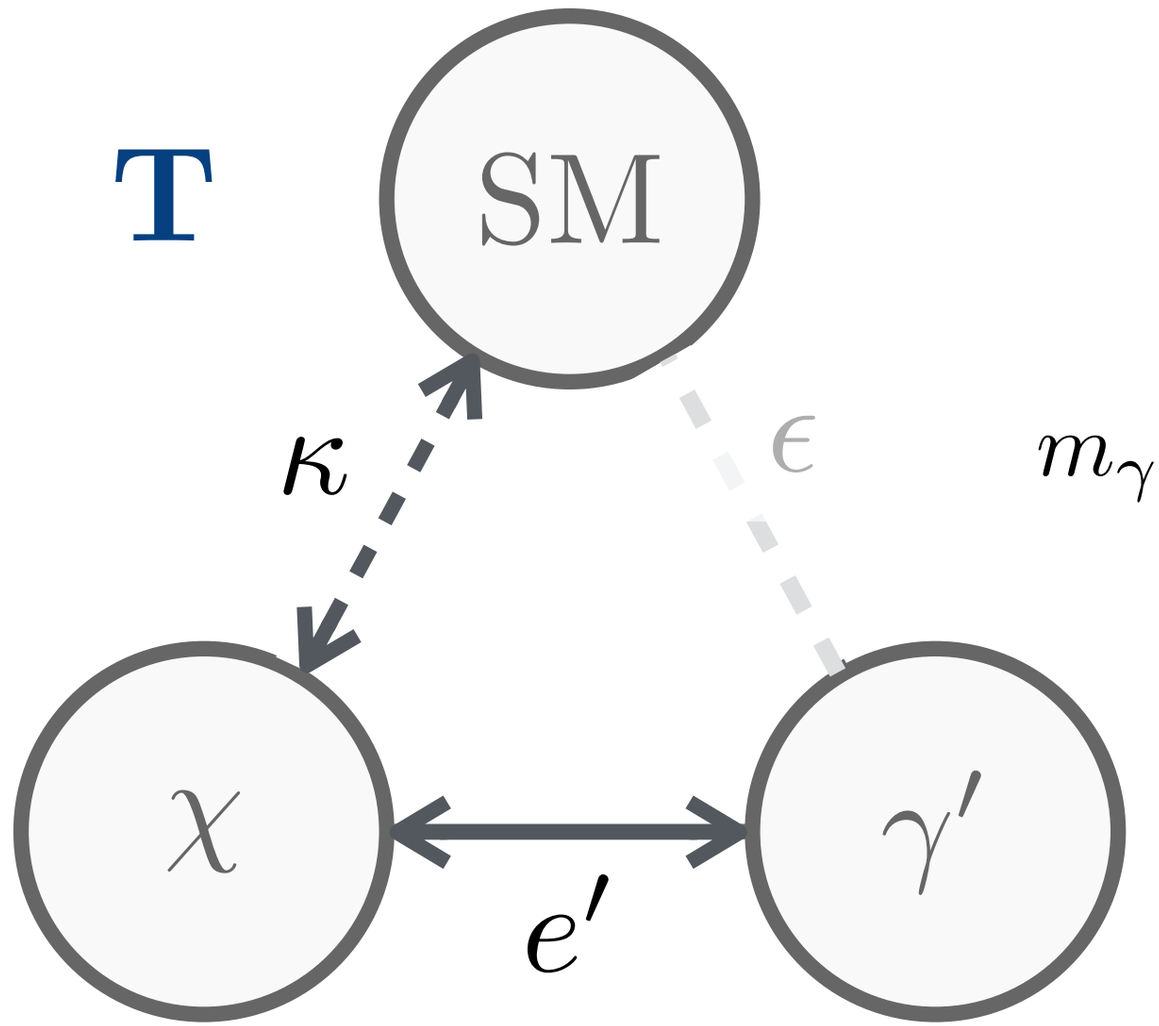
FREEZE-OUT INTO DARK PHOTONS

$\mathbf{T}$



$m_{\gamma'} \to 0$

$\mathbf{T}_\chi = \mathbf{T}$

$\mathbf{T}_{\gamma'} = \mathbf{T}$

$\kappa = \epsilon\, e'/e$

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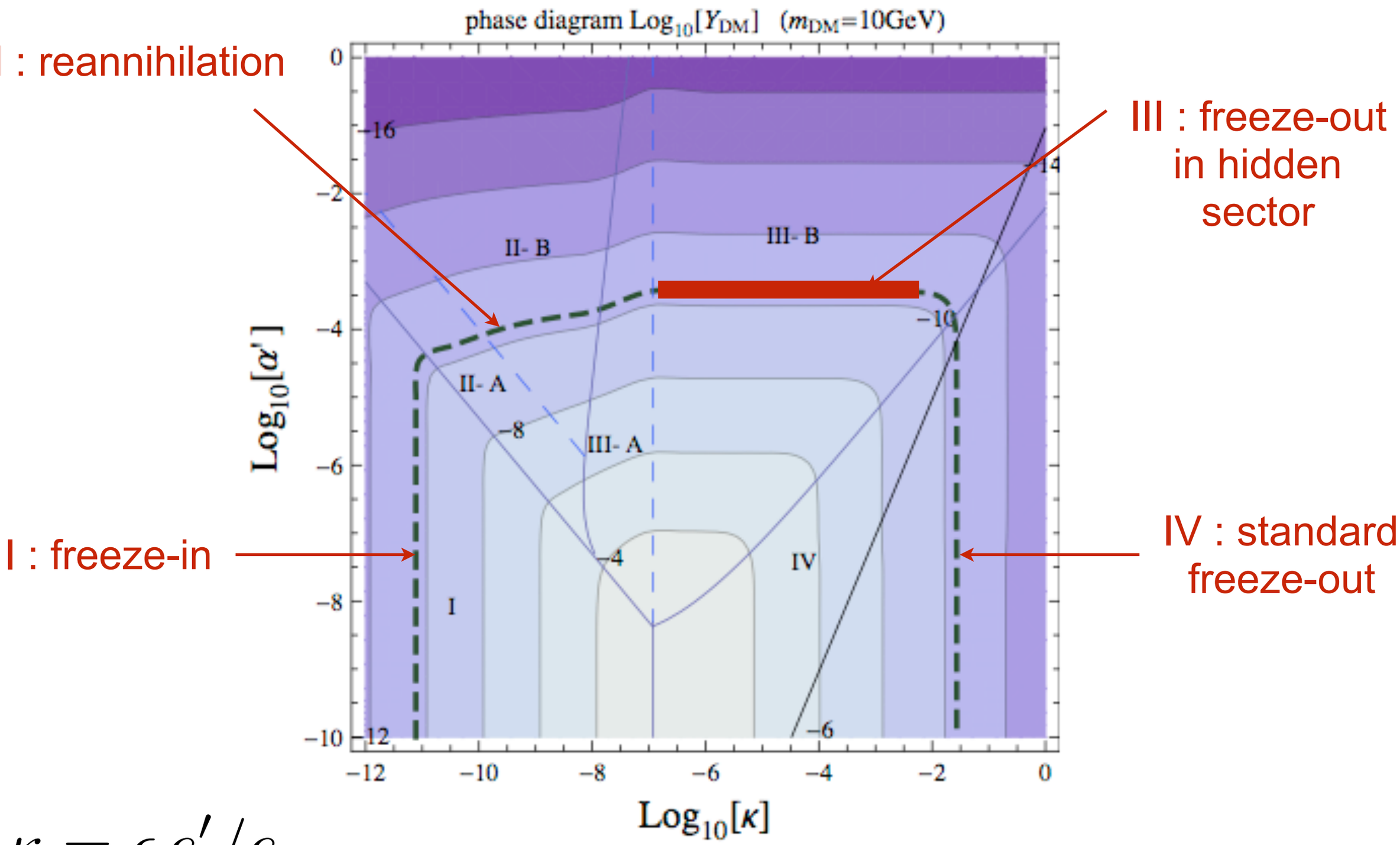
OLD FREEZE-OUT INTO DARK PHOTONS

$m_{\gamma'} \to 0$



$\kappa = \epsilon\, e'/e$

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OLD FREEZE-IN

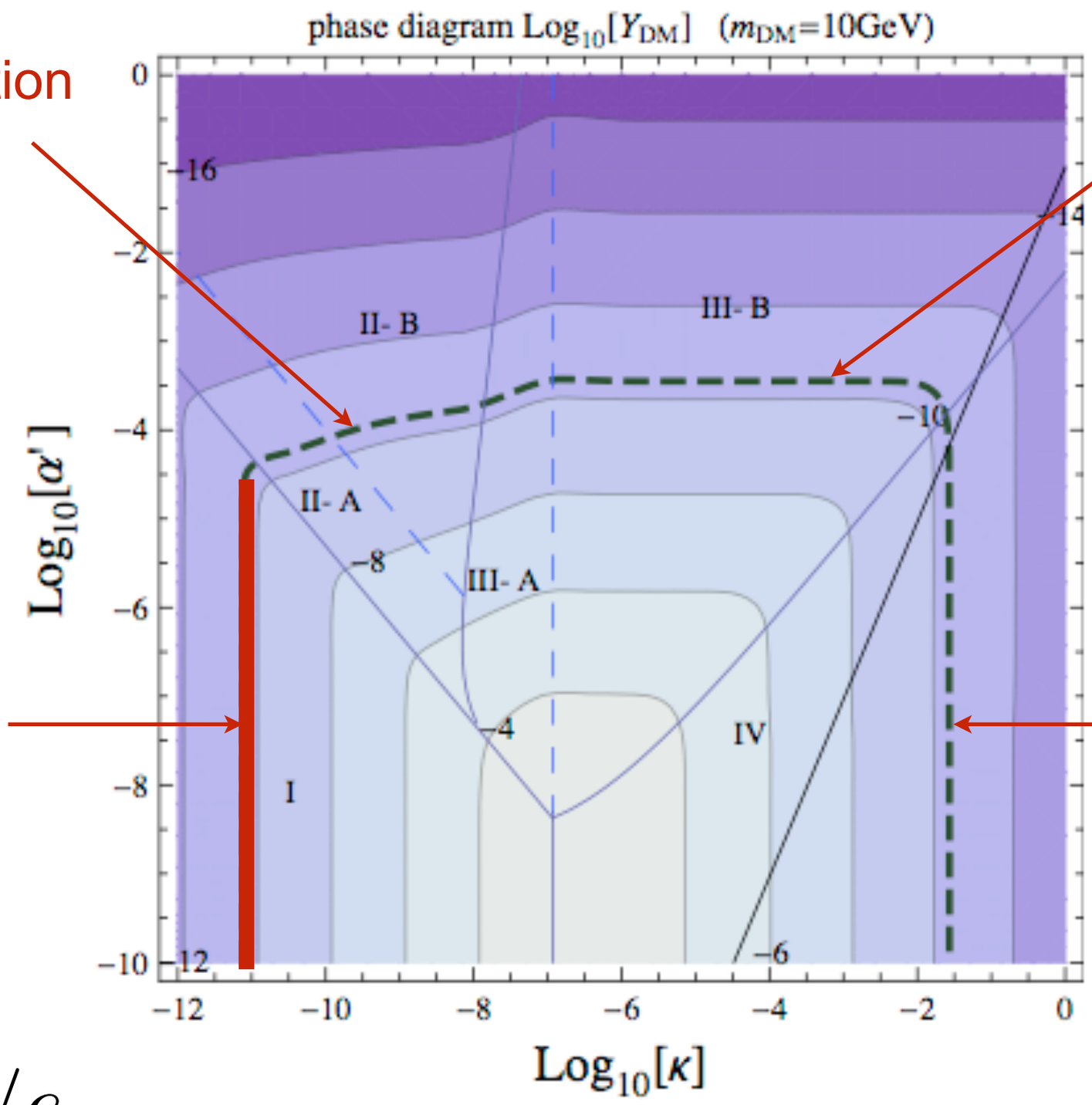
$m_{\gamma'} \to 0$

II : reannihilation

III : freeze-out in hidden sector

I : freeze-in

IV : standard freeze-out



$\kappa = \epsilon\, e'/e$

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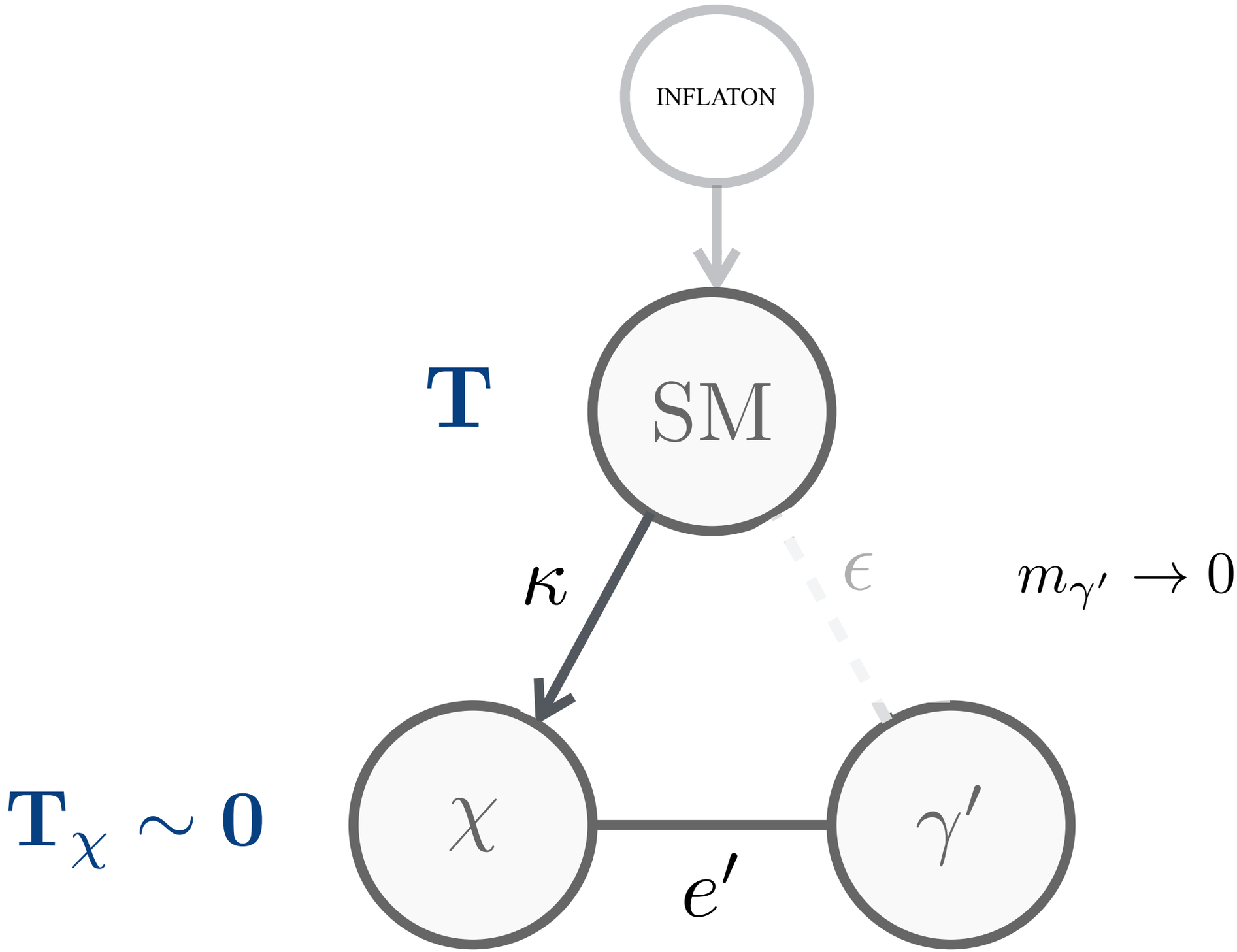
FREEZE-IN



$$\kappa = \epsilon\, e'/e$$

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OLD FREEZE-IN

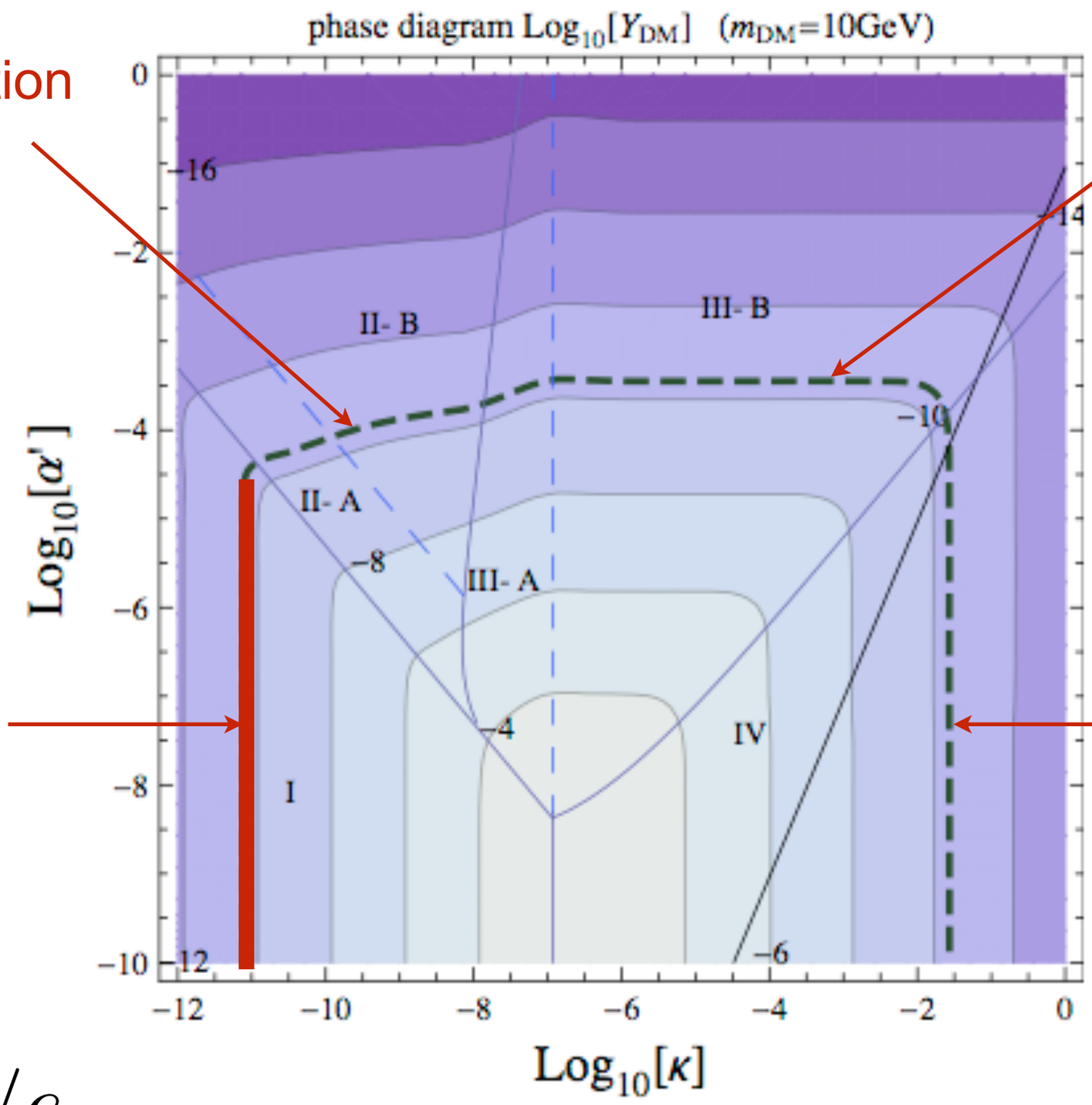
$m_{\gamma'} \to 0$

II : reannihilation

III : freeze-out in hidden sector

I : freeze-in

IV : standard freeze-out



$\kappa = \epsilon\, e'/e$

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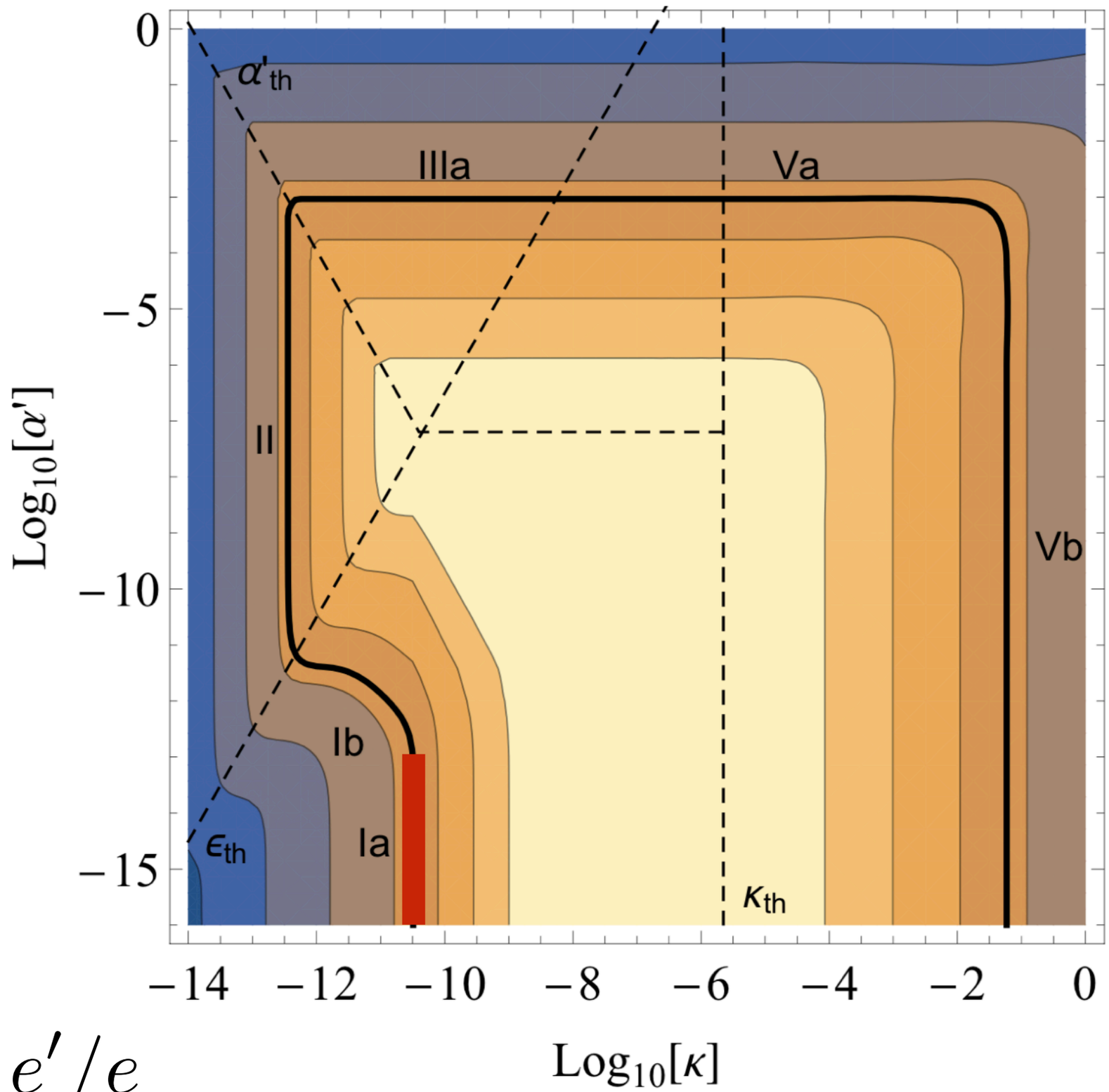
NEW

FREEZE-IN REVISITED

$m_{\gamma'} \neq 0$



$\kappa = \epsilon\, e'/e$

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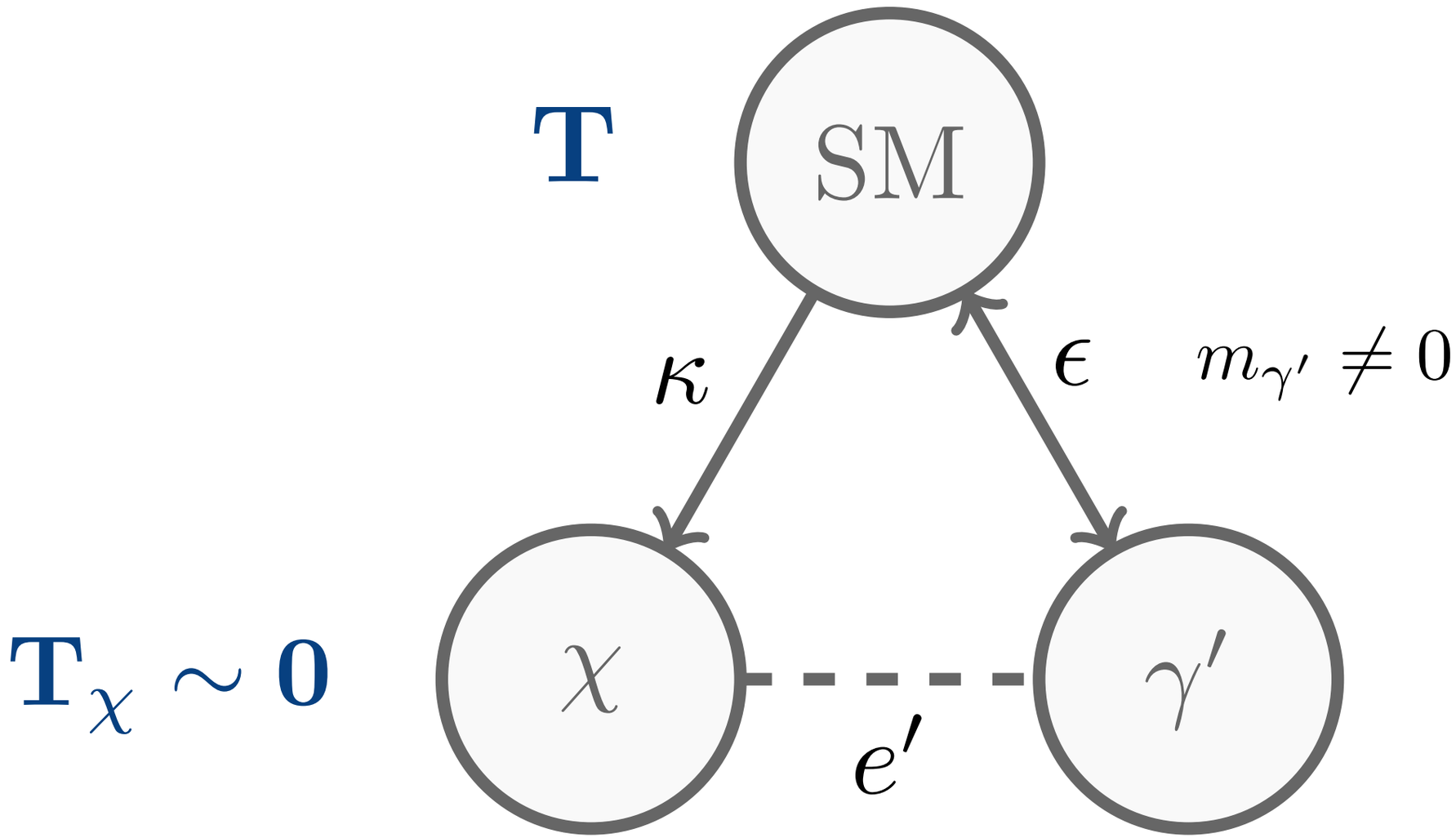
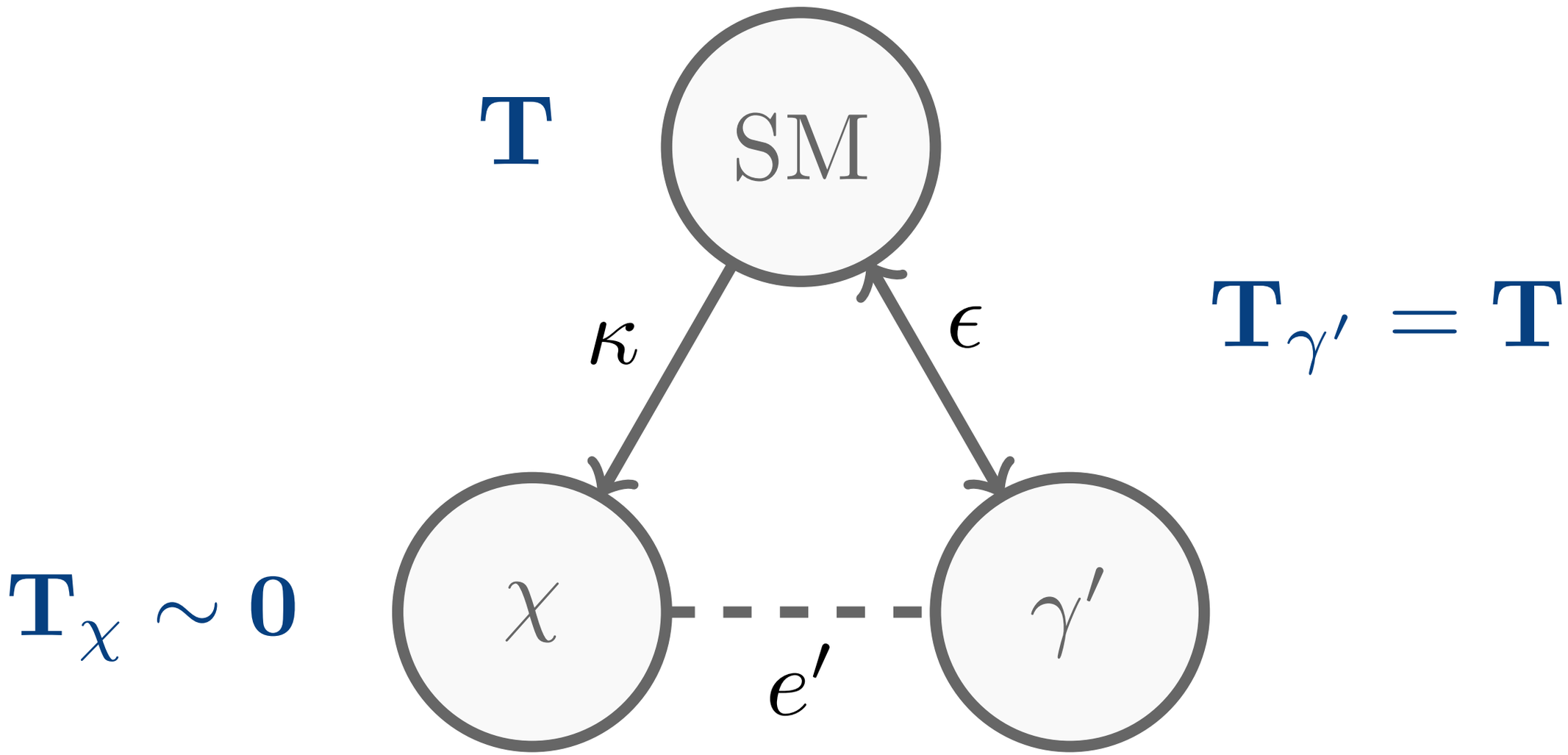
FREEZE-IN REVISITED



$$\kappa = \epsilon\, e'/e$$

FREEZE-IN REVISITED

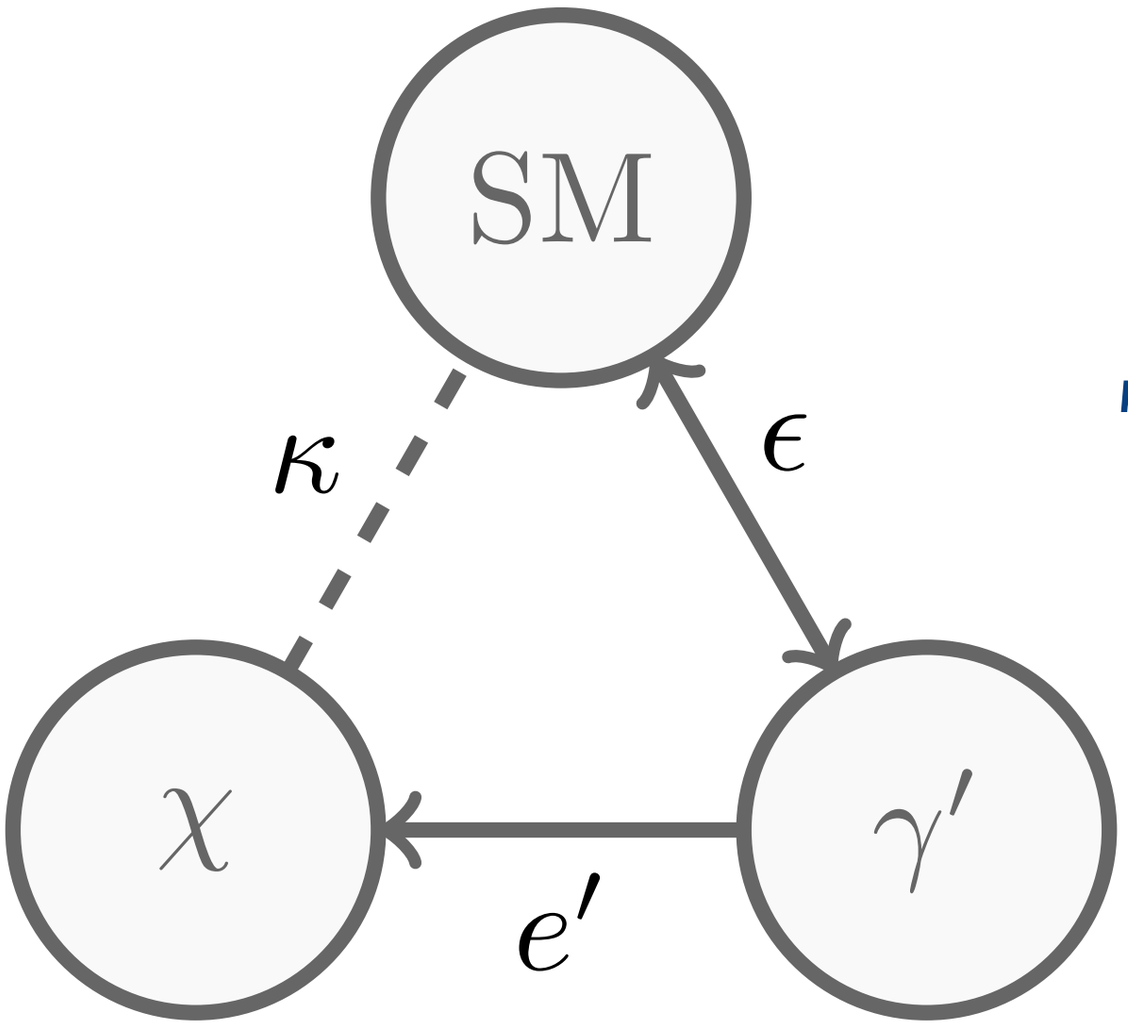
$m_{\gamma'} \neq 0$



$\kappa = \epsilon\, e'/e$

FREEZE-IN FROM THERMAL DARK PHOTONS

$m_{\gamma'} \neq 0$

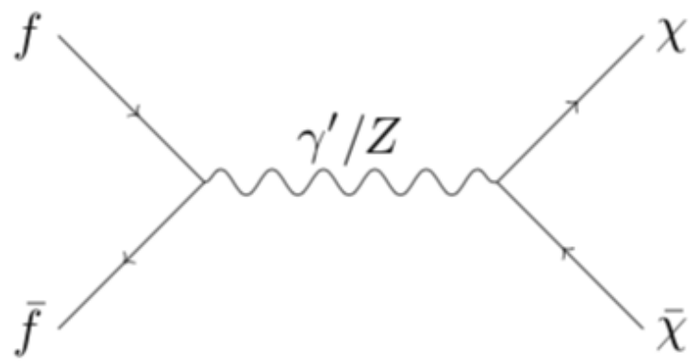


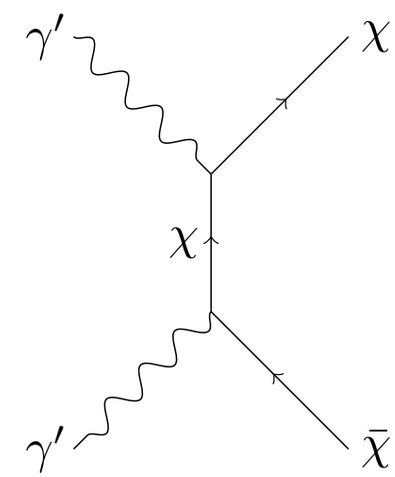
$\mathbf{T}_{\gamma'} = \mathbf{T}$

$\mathbf{T}_{\chi} \sim \mathbf{0}$

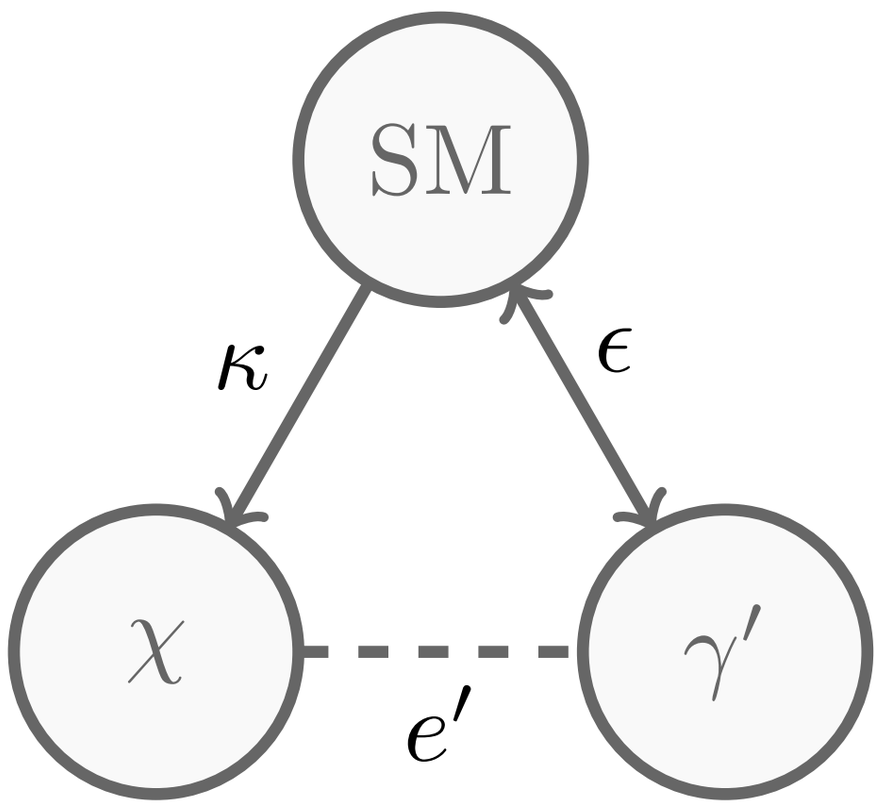
$\kappa = \epsilon\, e'/e$

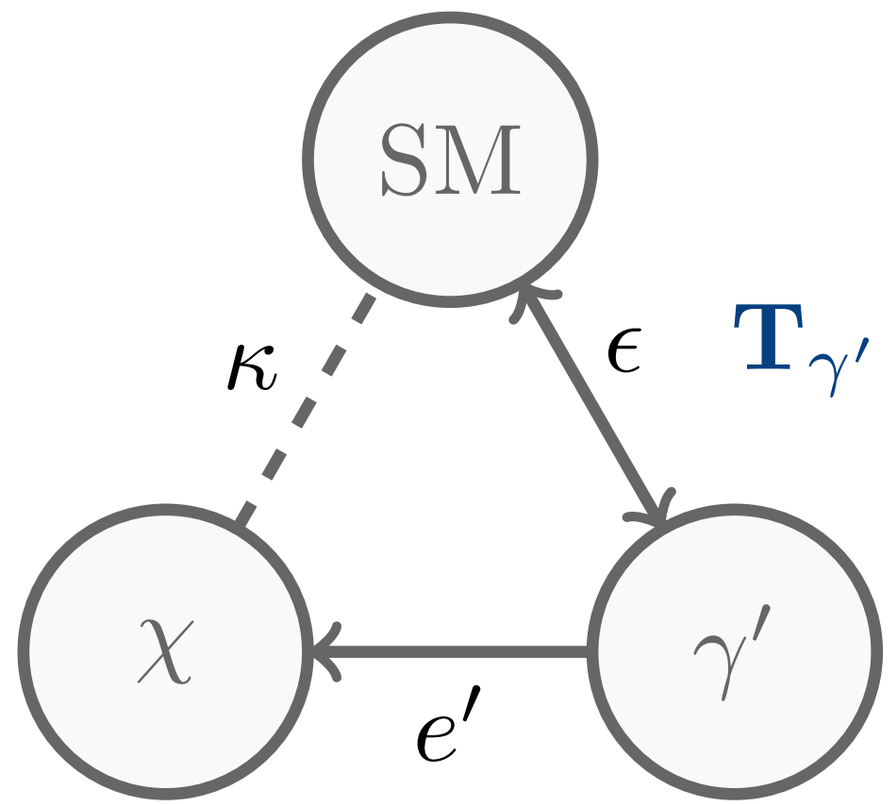
FREEZE-IN Ia & Ib





$m_{\gamma'} \neq 0$





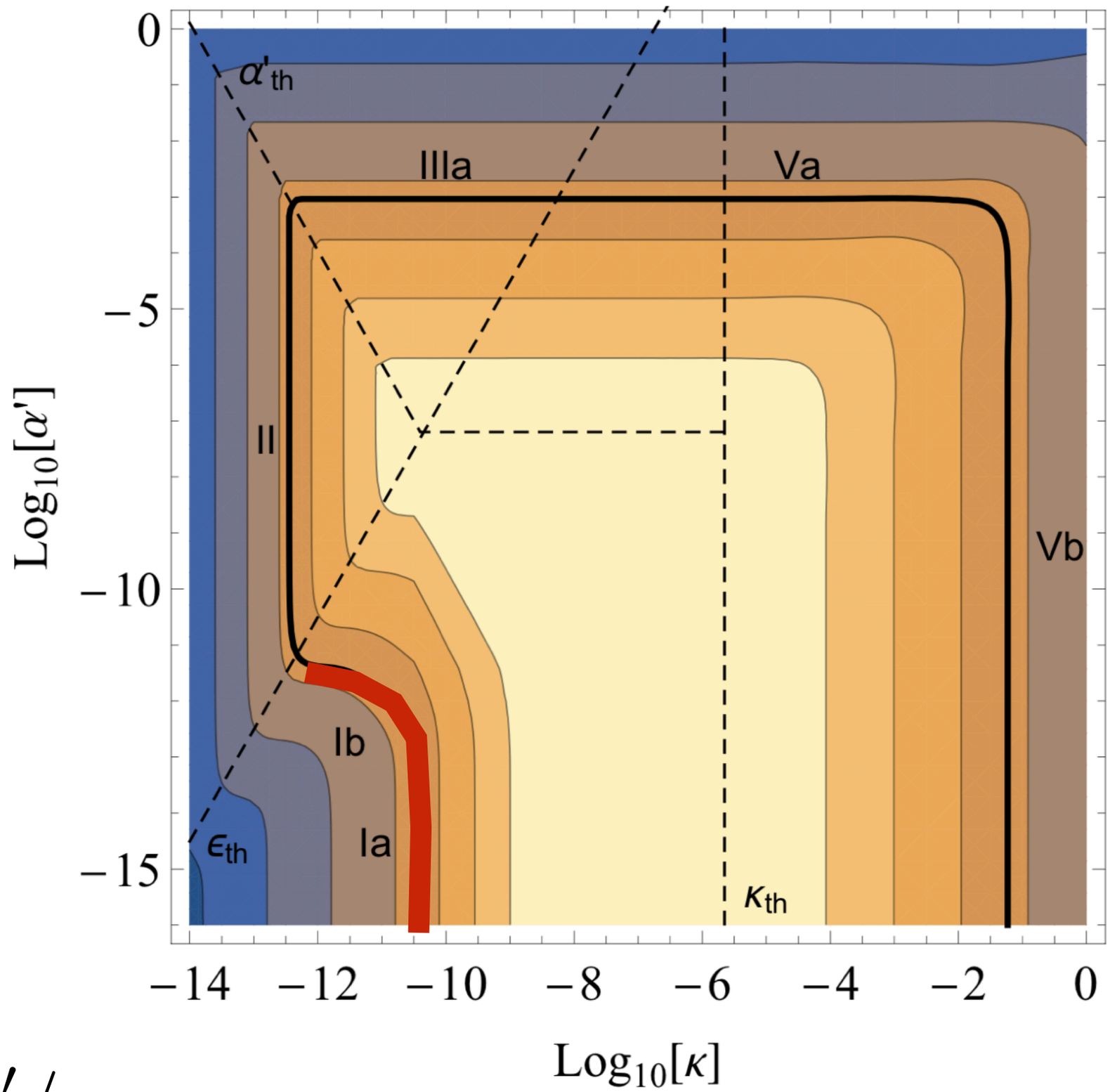
$\mathbf{T}_{\gamma'} = \mathbf{T}$

Type Ia

Type Ib

FREEZE-IN Ia & Ib

$m_{\gamma'} \neq 0$



$\kappa = \epsilon\, e'/e$

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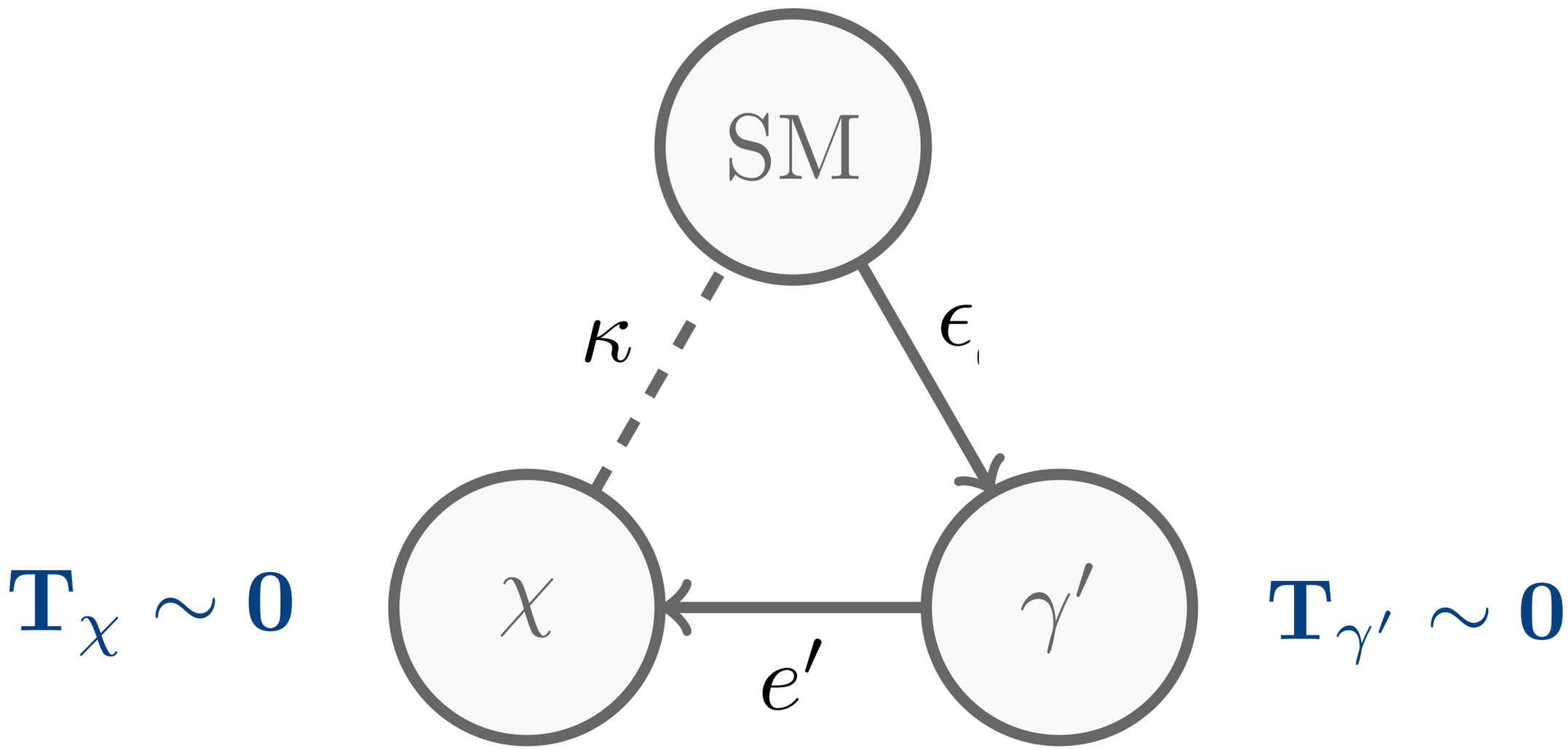
NEW REGIME!

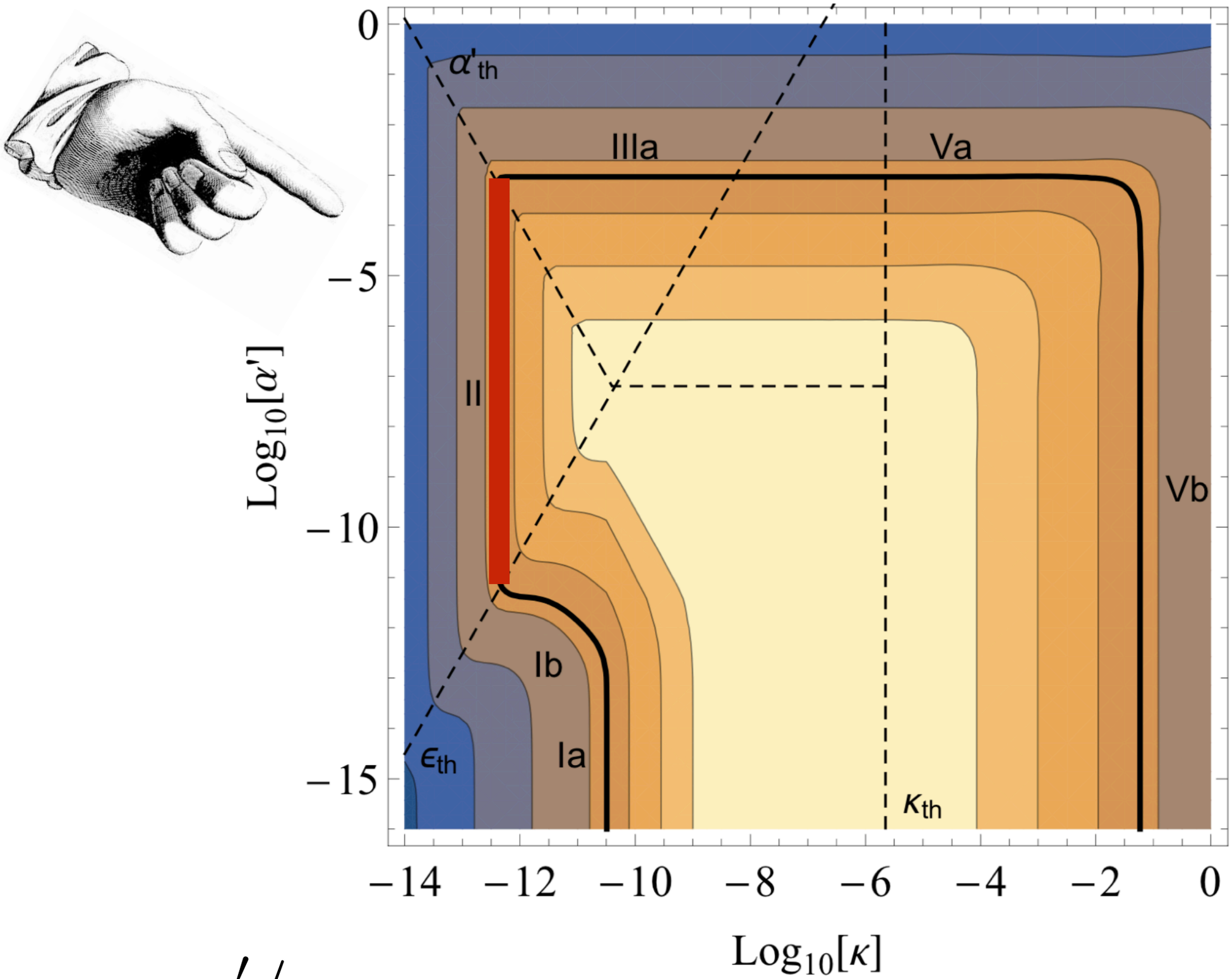
SEQUENTIAL FREEZE-IN

$m_{\gamma'} \neq 0$



Type II

NEW REGIME! SEQUENTIAL FREEZE-IN



$$\kappa = \epsilon\, e'/e$$

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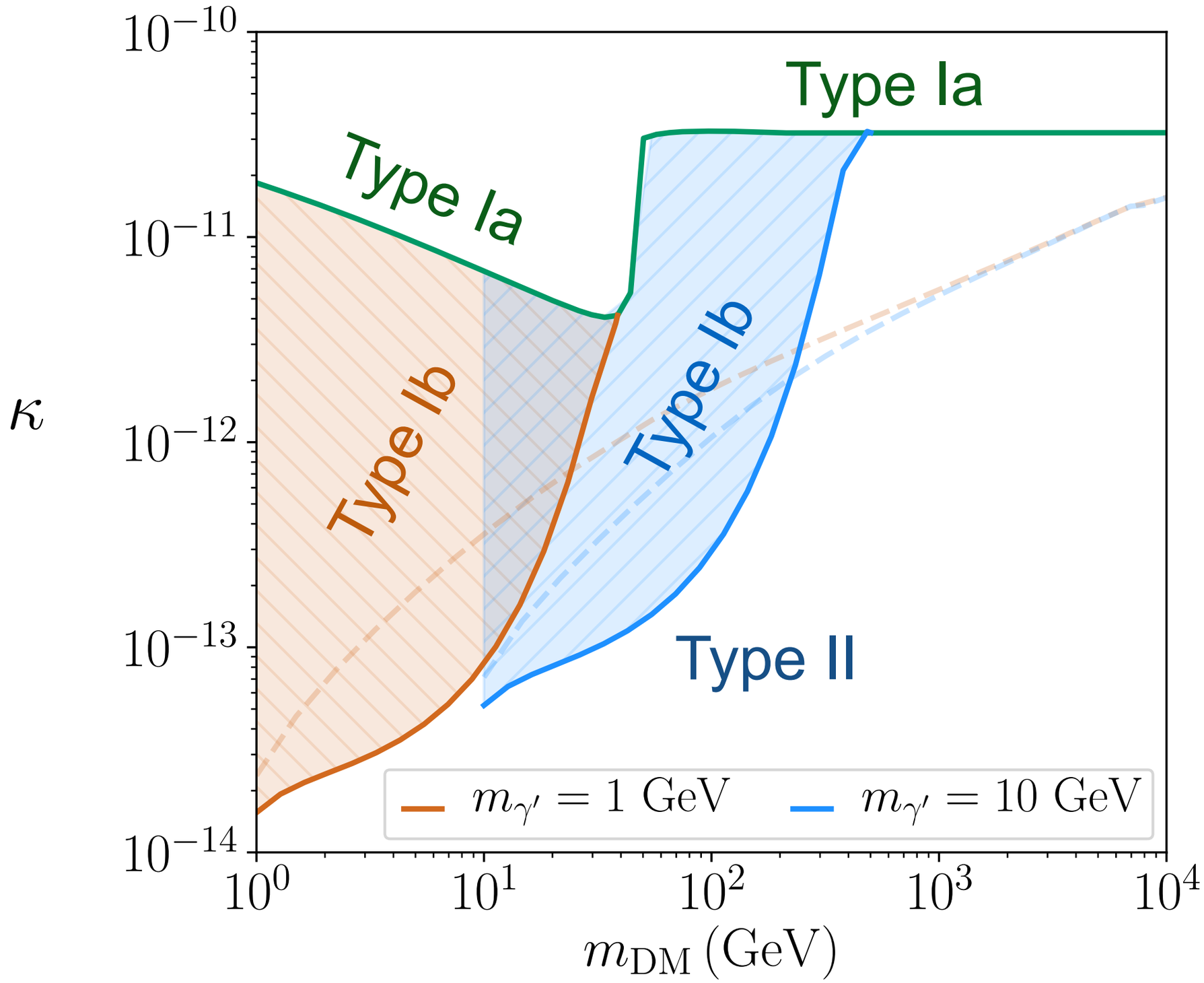
NEW REGIME!

SEQUENTIAL FREEZE-IN



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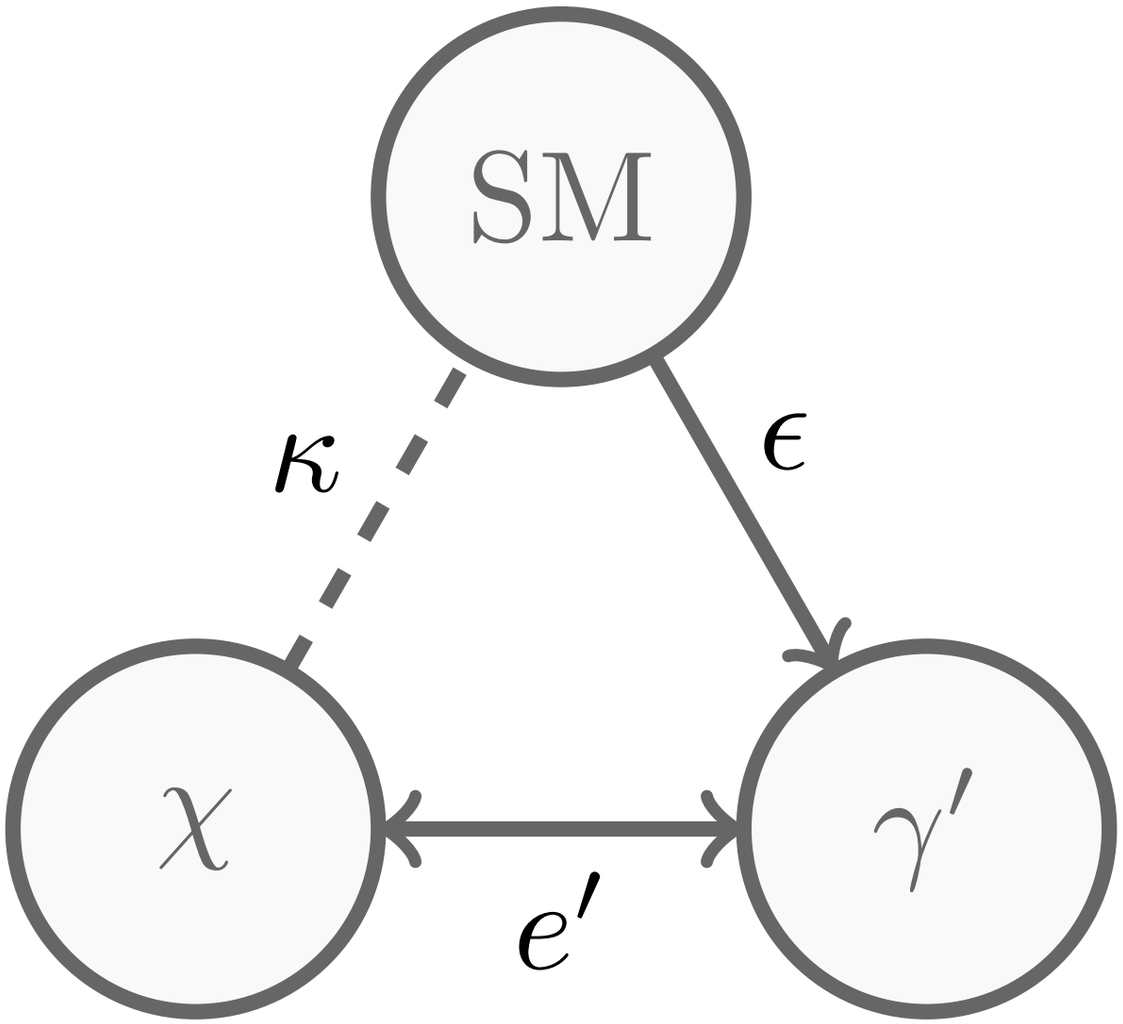
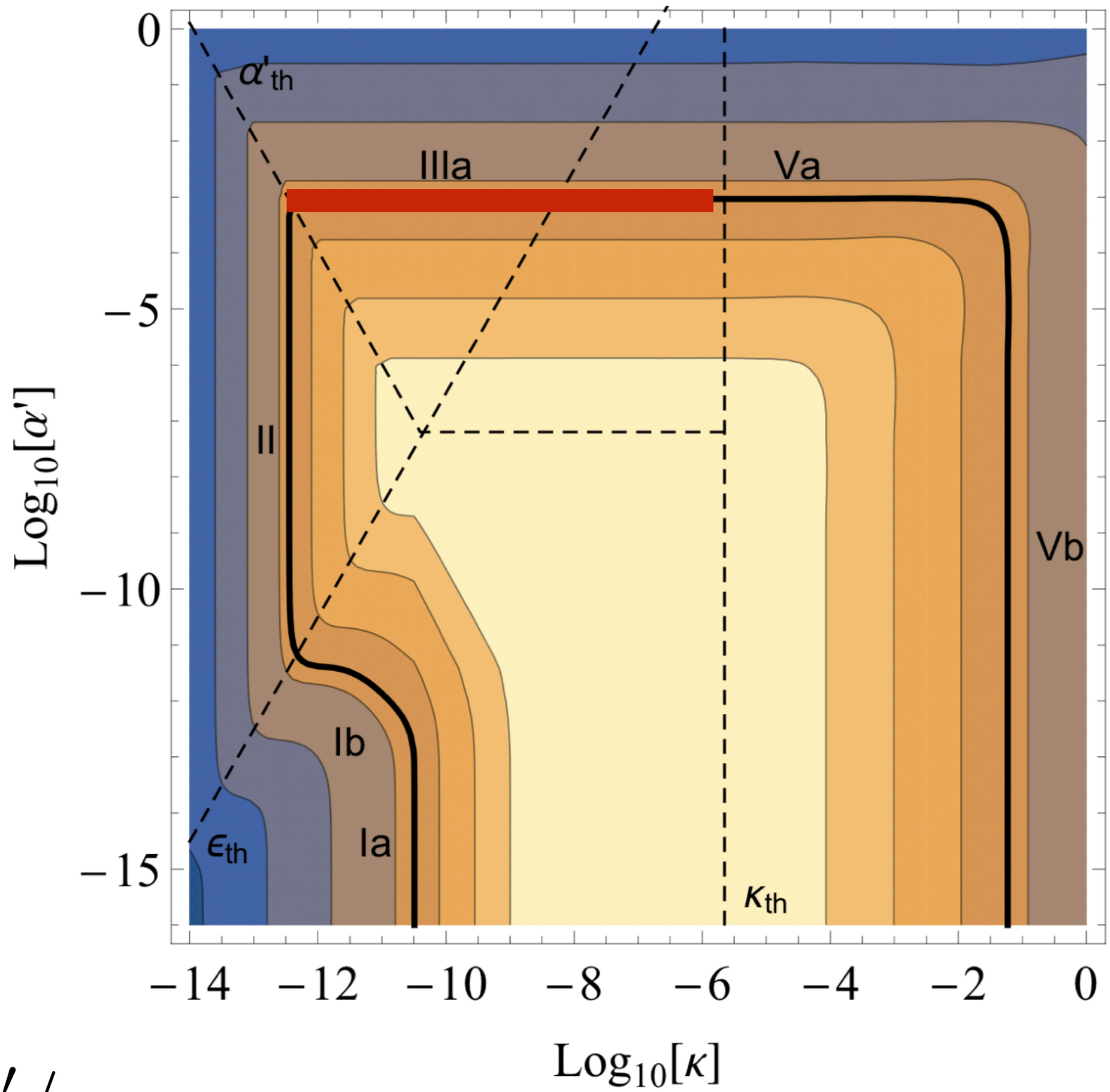
REANNIHILATION, ETC.



$$T_\chi = T_{\gamma'} \ll T$$

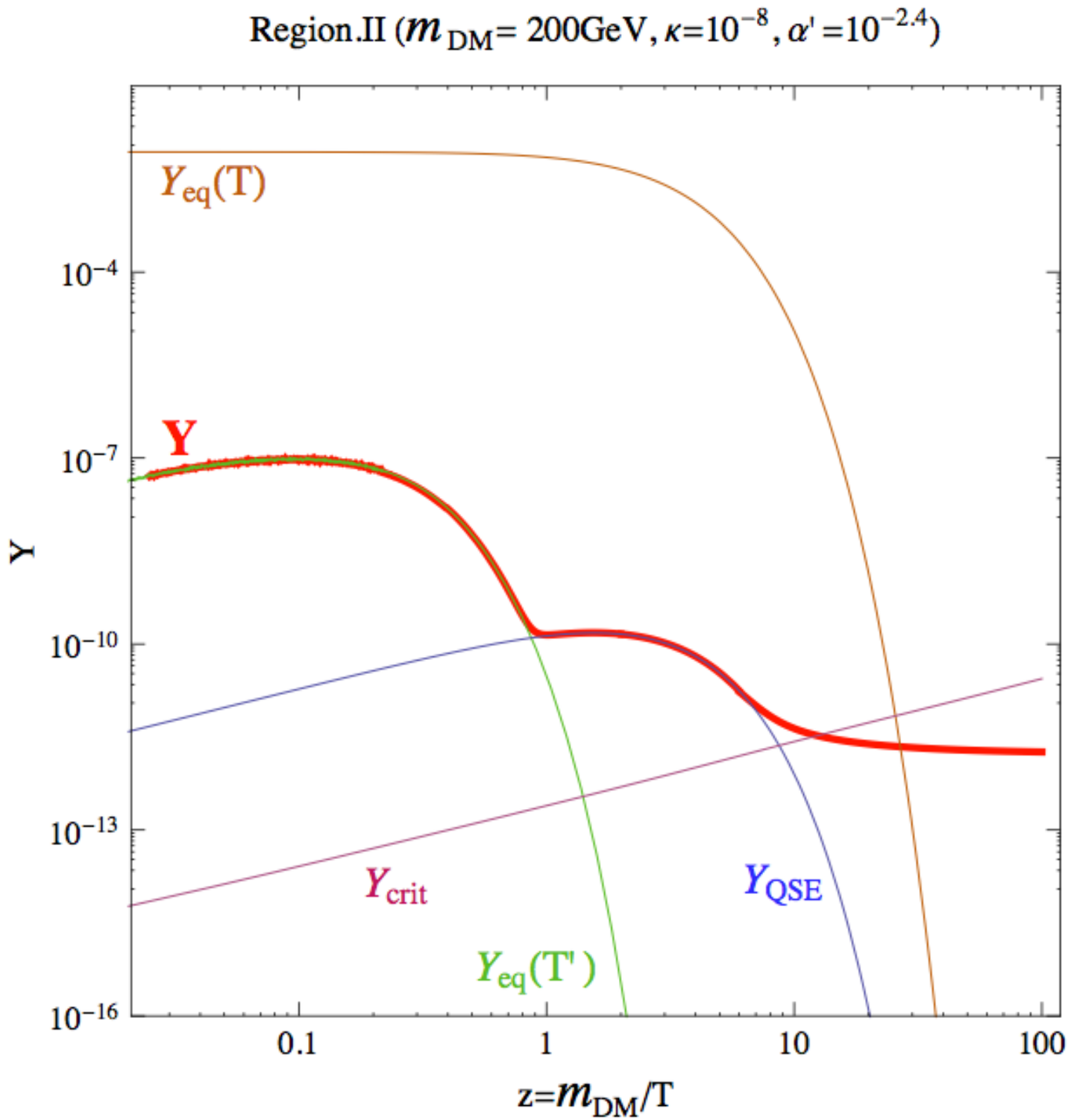
REANNIHILATION, ETC.



$$\kappa = \epsilon\, e'/e$$

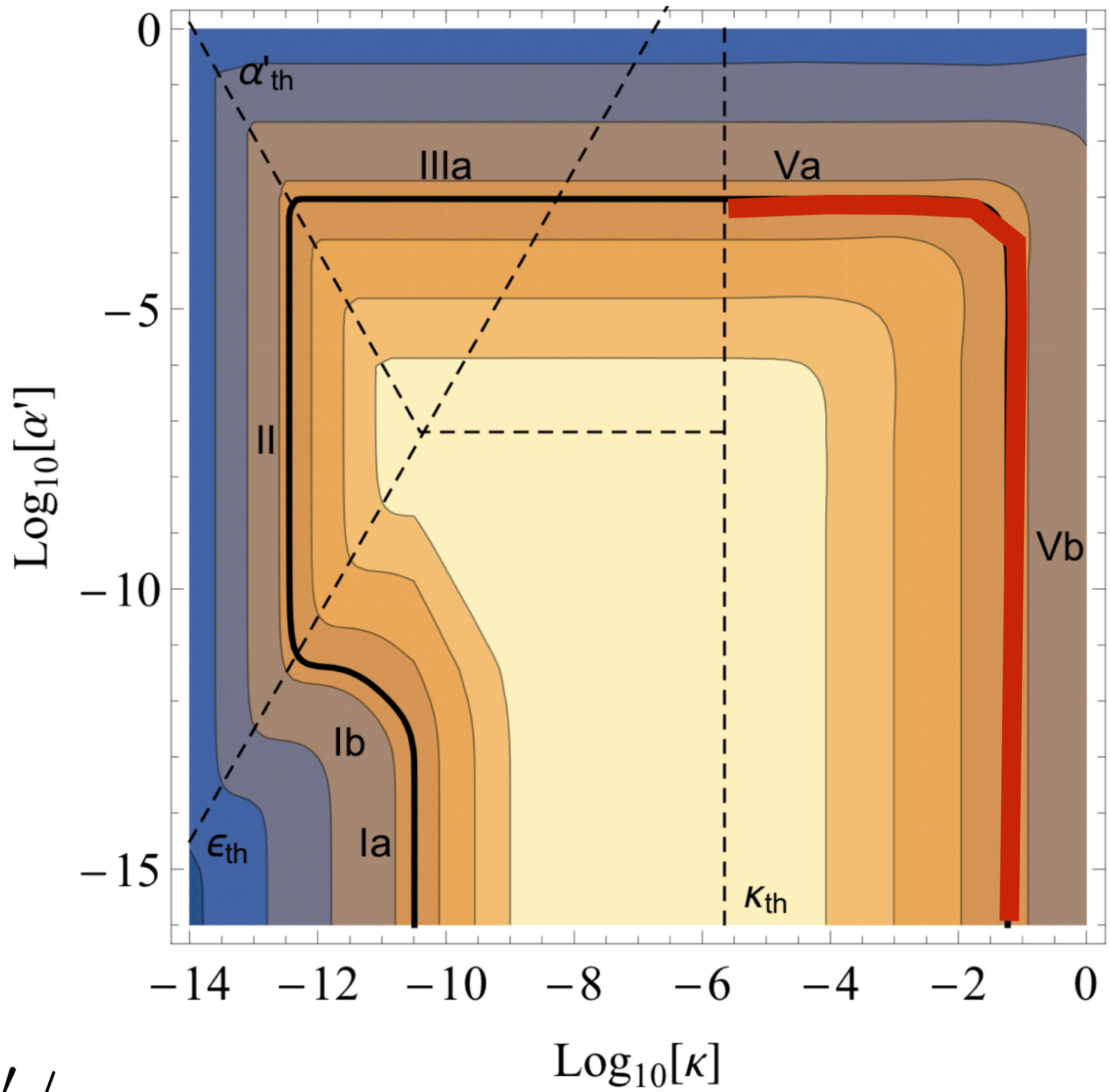
Hambye, M.T., Vandecasteele, Vanderheyden ’19

REANNIHILATION, ETC.



Chu, Hambye, M.T. '12

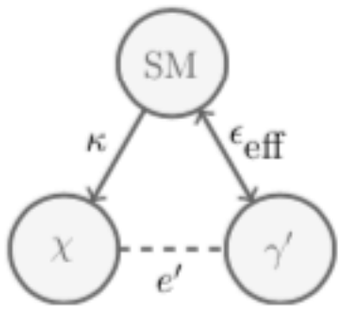
BACK TO FREEZE-OUT REGIMES



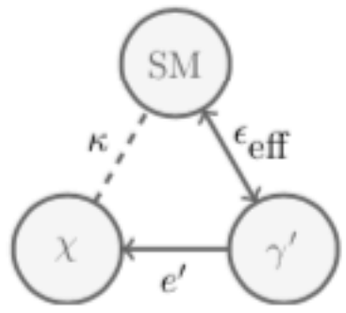
$$\kappa = \epsilon\, e'/e$$

Hambye, M.T., Vandecasteele, Vanderheyden ’19

9 WAYS, 5 REGIMES TO PRODUCE DM

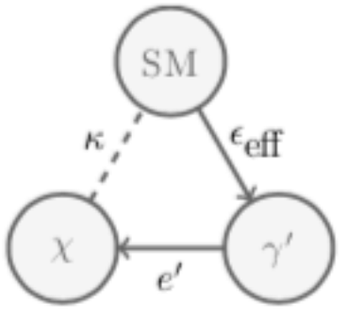


(a) Ia



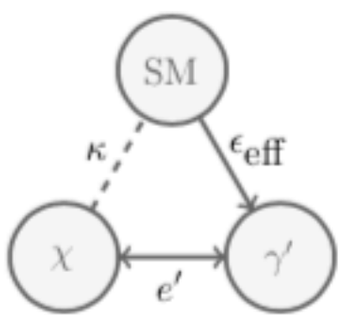
(b) Ib

freeze-in (Ia & Ib)

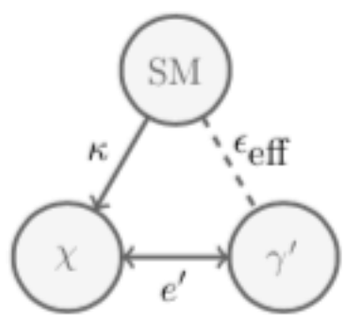


(c) II

sequential freeze-in (II)

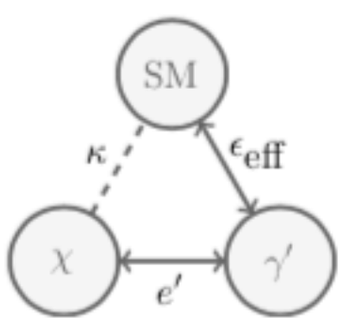


(d) IIIa & IVa

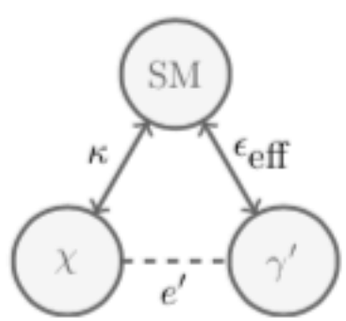


(e) IIIb & IVb

reannihilation (IIIa & IIIb)
secluded freeze-out (IVa & IVb)



(f) Va

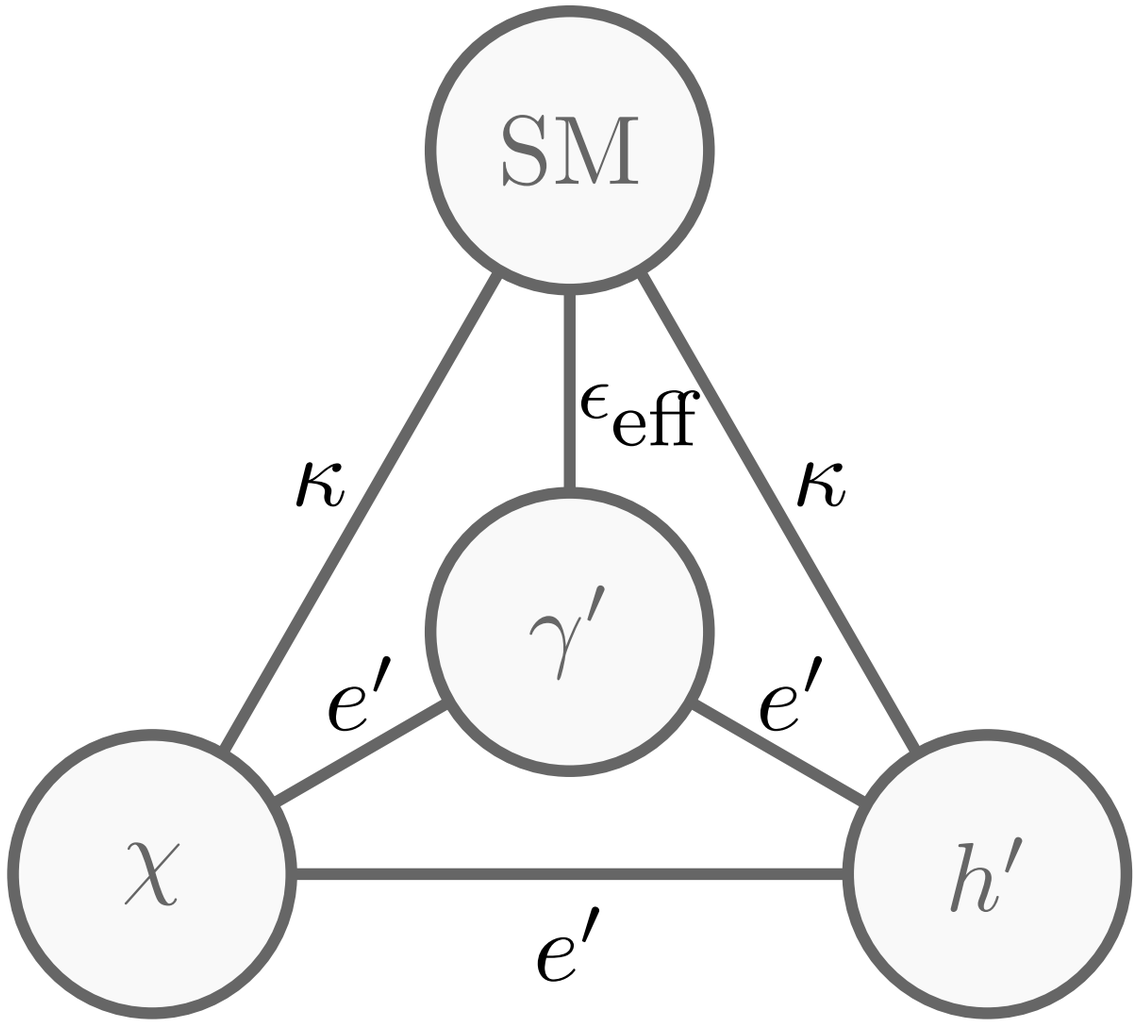


(g) Vb

freeze-out (Va & Vb)

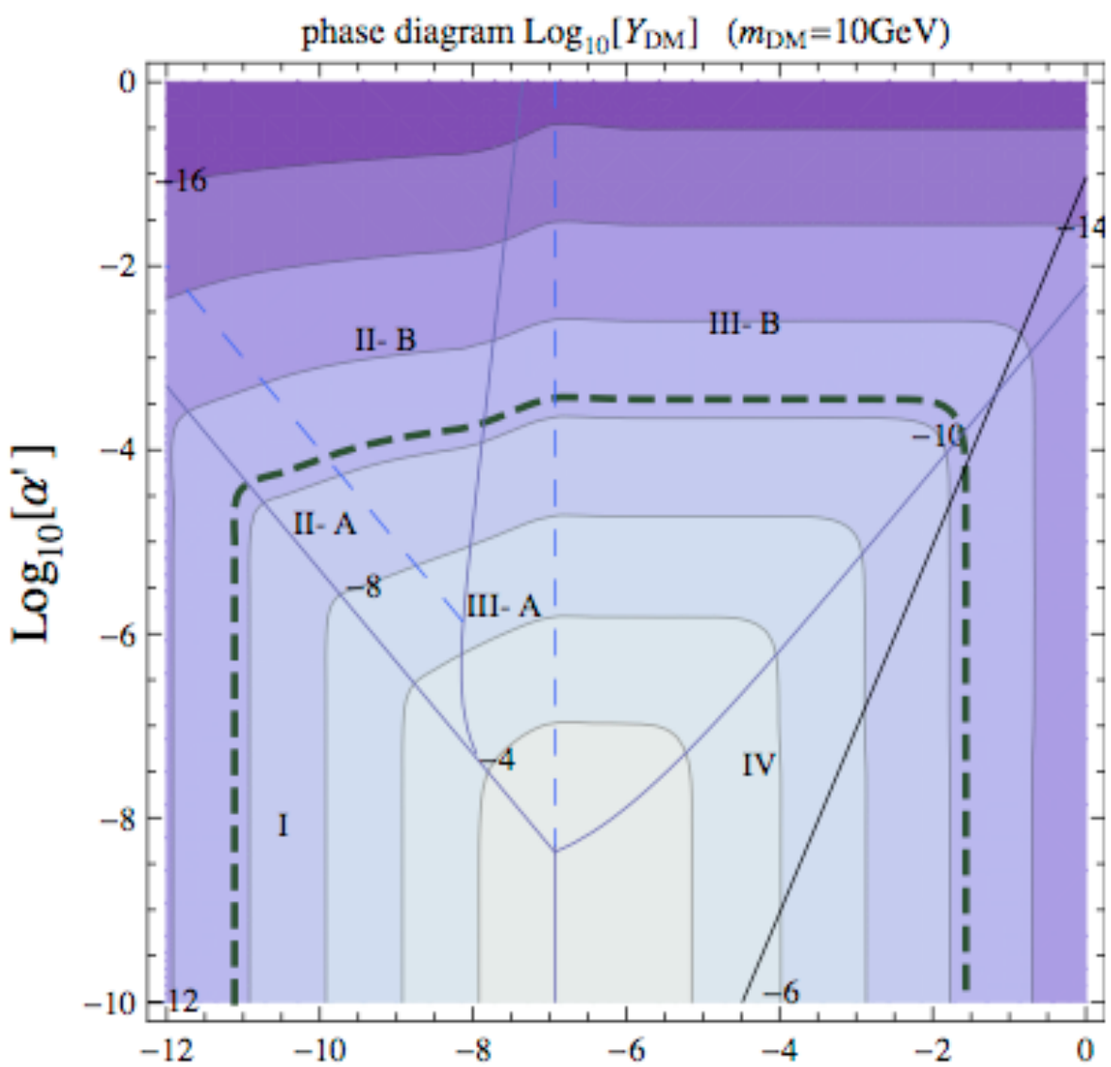
Chu, Hambye, M.T. ‘12
Hambye, M.T., Vandecasteele, Vanderheyden ’19

GENERALIZATIONS?

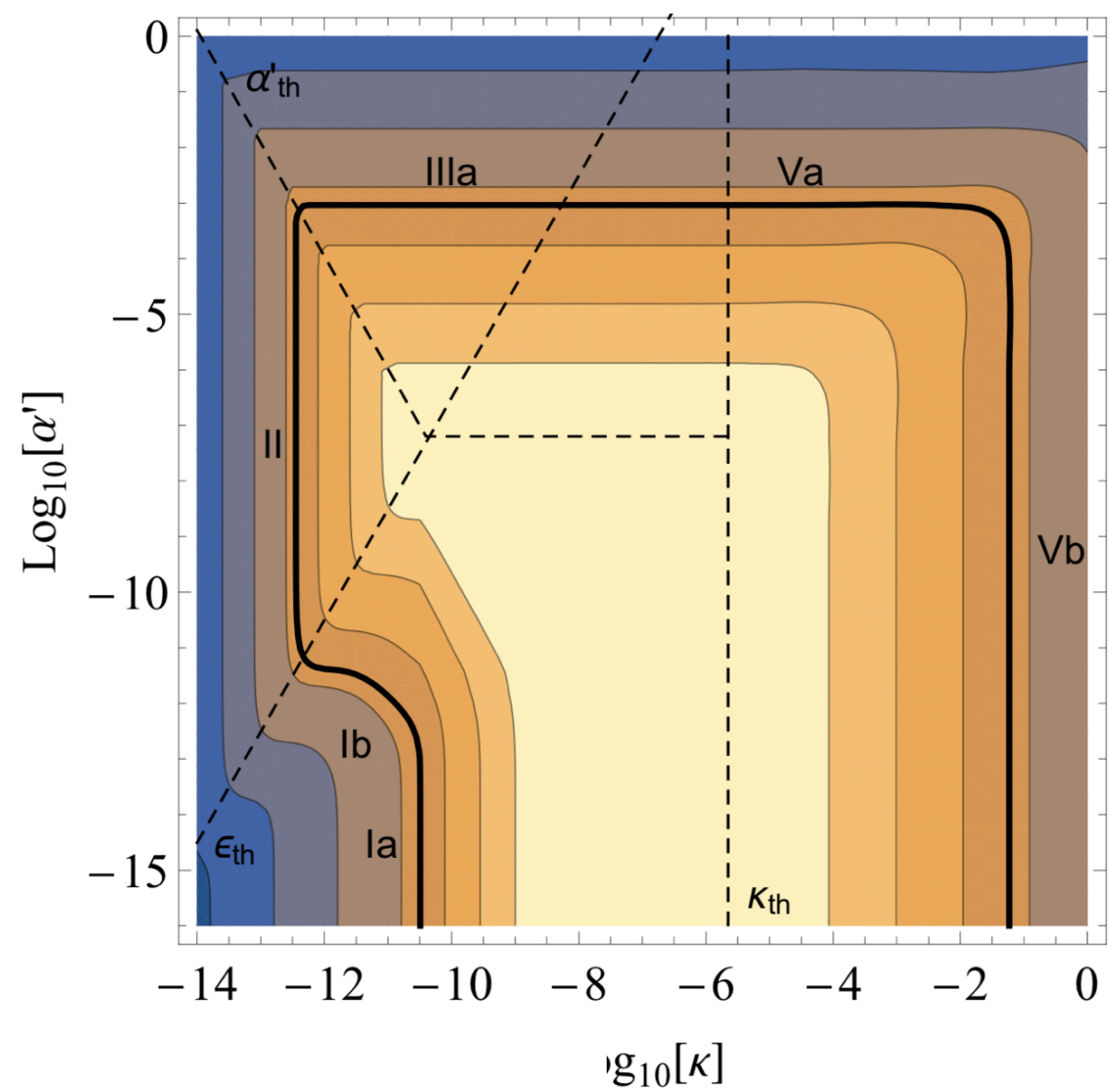


CONCLUSIONS

$m_{\gamma'} \to 0$

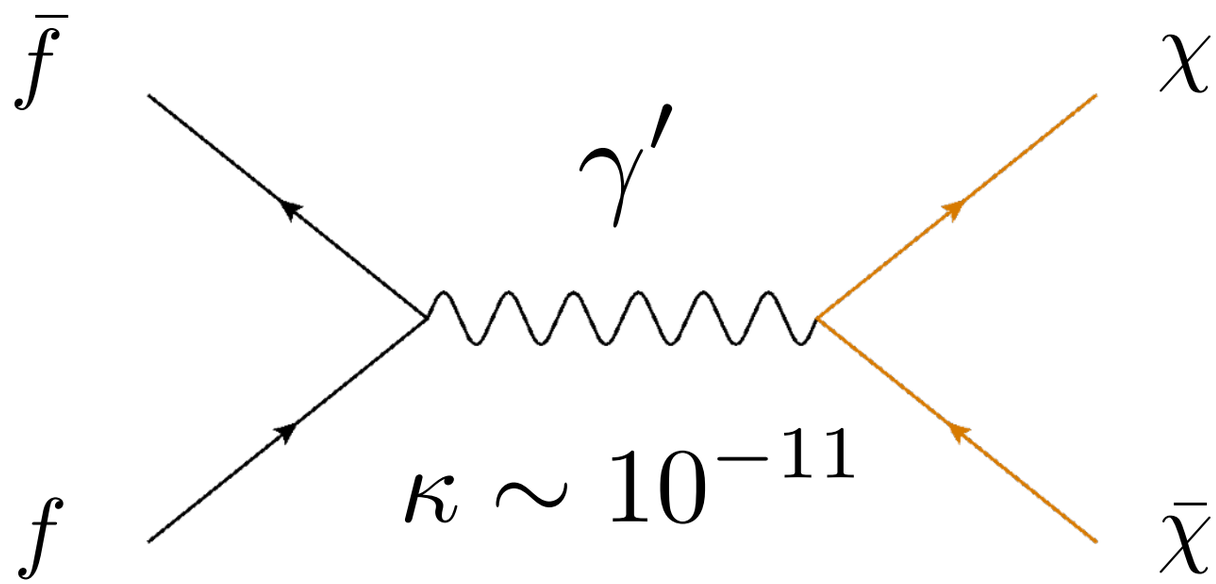


$m_{\gamma'} \neq 0$



BACKUP STORY (I)

PRODUCTION THROUGH FREEZE-IN



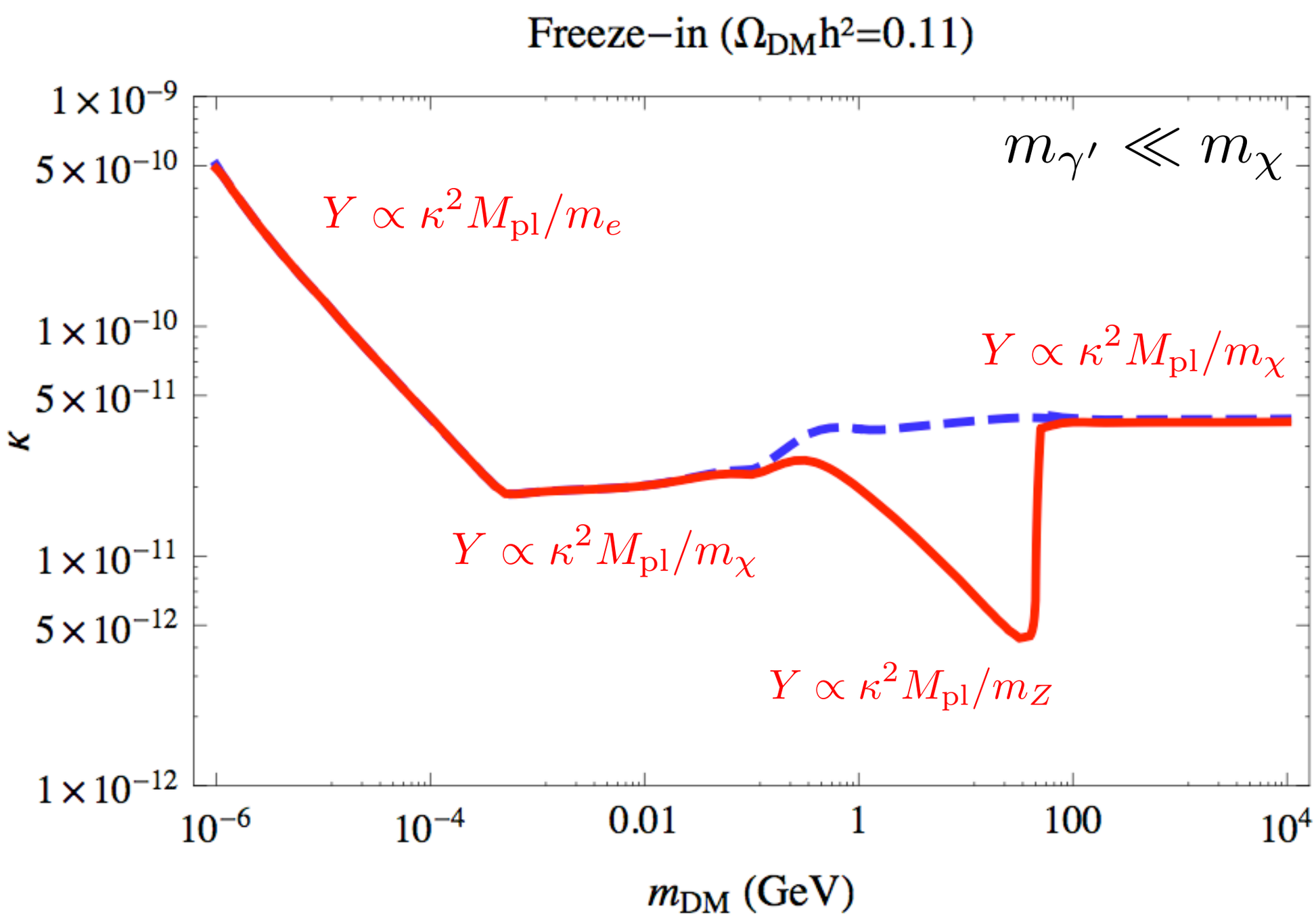
s-channel

$\longrightarrow$

determines relic abundance

very small cross section

FREEZE-IN CANDIDATES



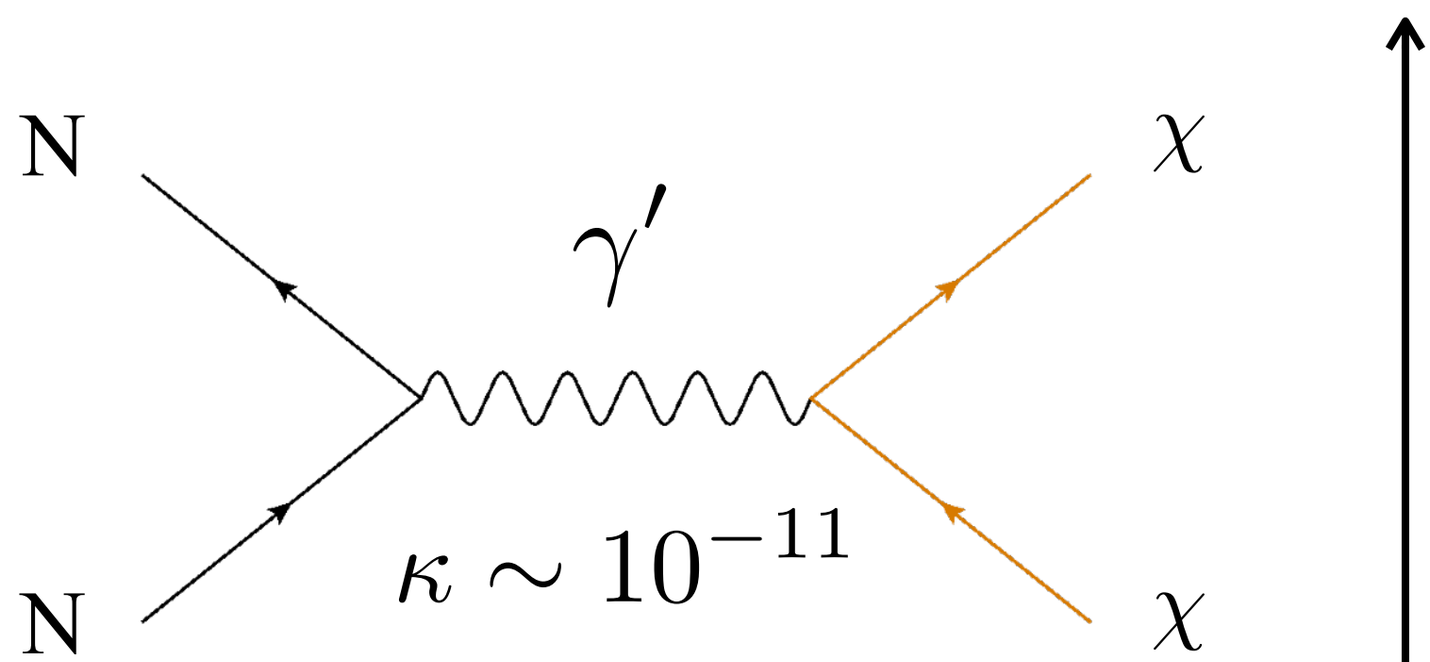
Chu, Hambye, M.T. ‘12

DIRECT DETECTION (Rutherford scattering)

recoil energy

E_R

in keV range



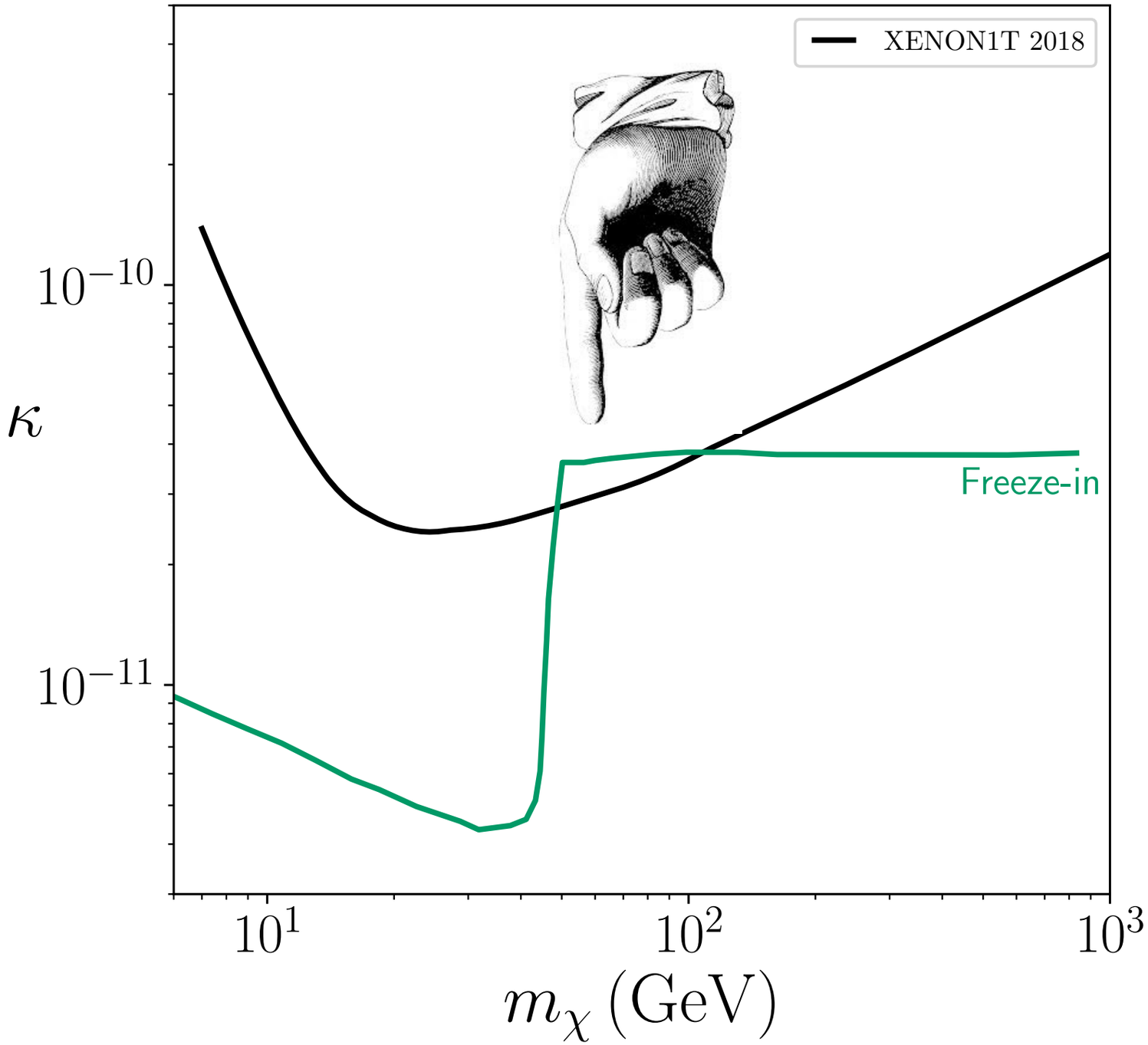
t-channel

v ~ 200 km/s (halo DM)

$$\frac{d\sigma}{dE_R} \propto \frac{m_N \kappa^2 \alpha^2 Z^2}{(2m_N E_R + m_{\gamma'}^2)^2} \sim \frac{1}{E_R^2}$$

large enhancement if $m_{\gamma'} \lesssim 40 \text{ MeV}$

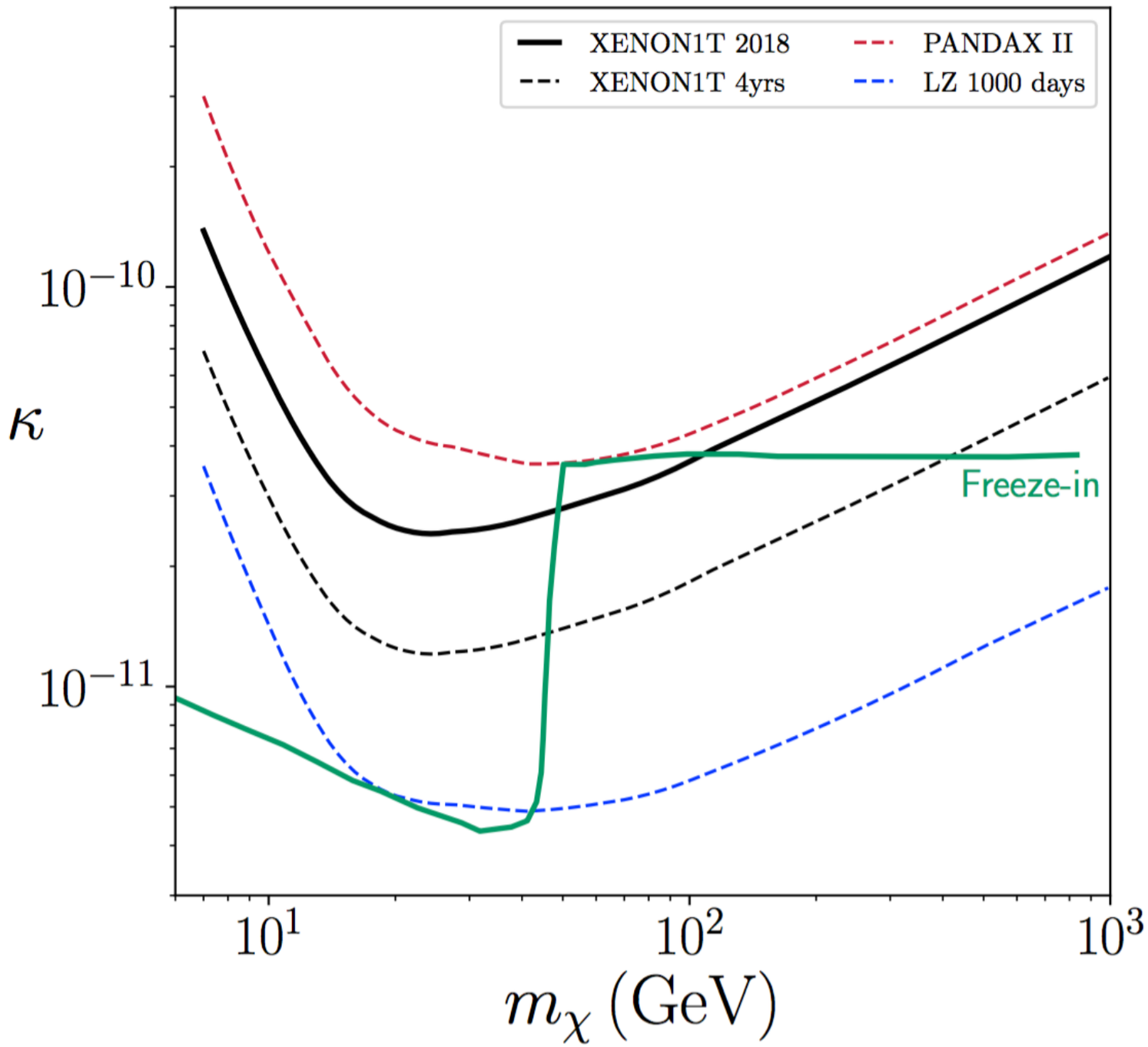
DIRECT DETECTION TEST OF FI



n.b.: not the same spectrum as a WIMP, must recast direct detection constraints

Hambye, M.T., Vandecasteele, Vanderheyden'18
Heeba, Kahlhoefer '19; Geneviève's talk

DIRECT DETECTION TEST OF FI

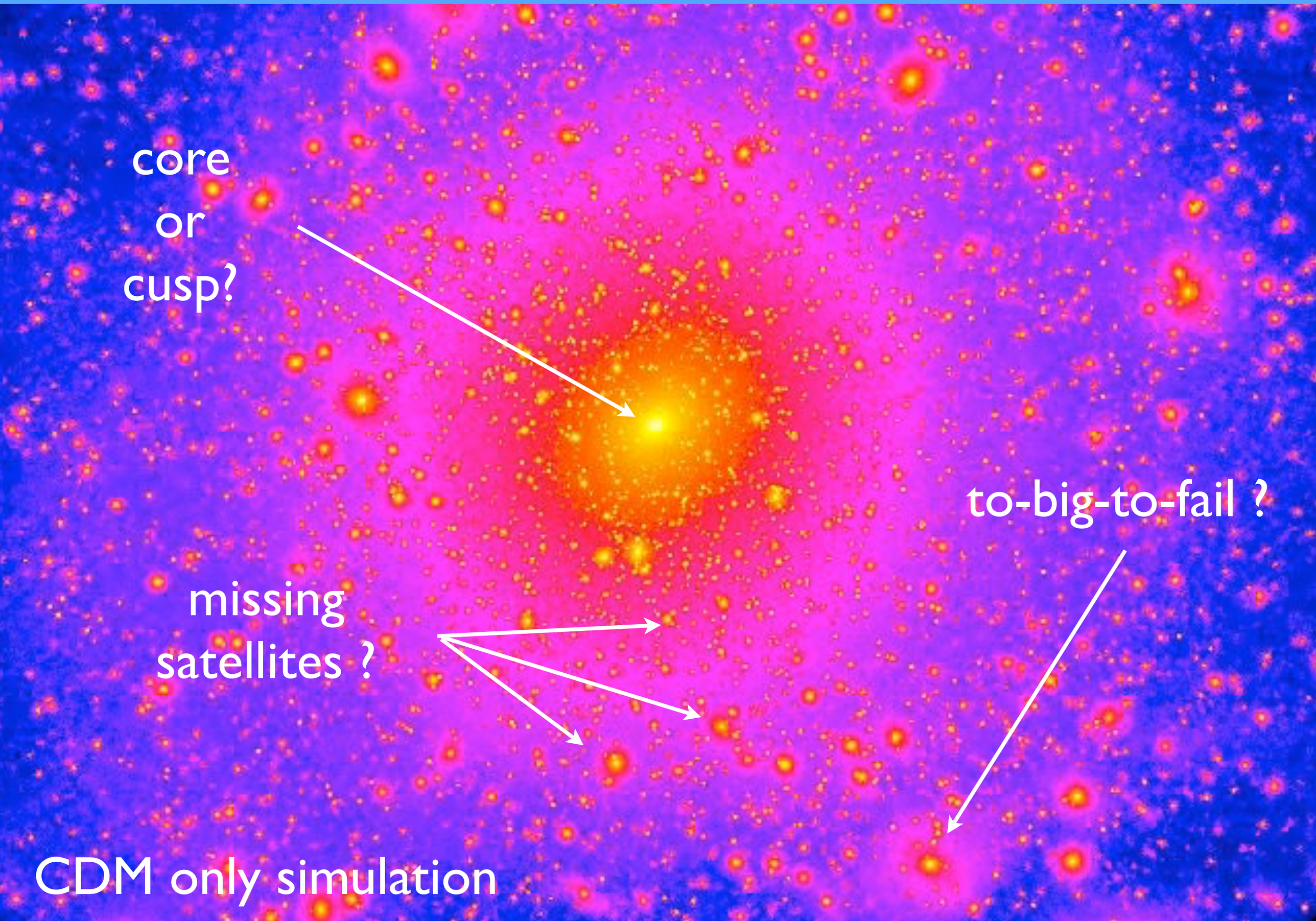


n.b.:
Not the same spectrum as a WIMP,
Must recasti the direct detection constraints

First direct detection test of a FI scenario…

Hambye, M.T., Vandecasteele, Vanderheyden '18

SMALL SCALE ISSUES



SELF-INTERACTING DM

Self-interaction may alleviate the small-scale problems of collisionless dark matter

core/cusp — Spergel & Steinhardt (2000),…

too-big-to-fail — Vogelsberger, Zavala & Loeb (2012),…

diversity — Hamada, Kaplinghat, Pace & Yu (2016),…

collisions ⟶ thermalized DM ⟶ core instead of cusp

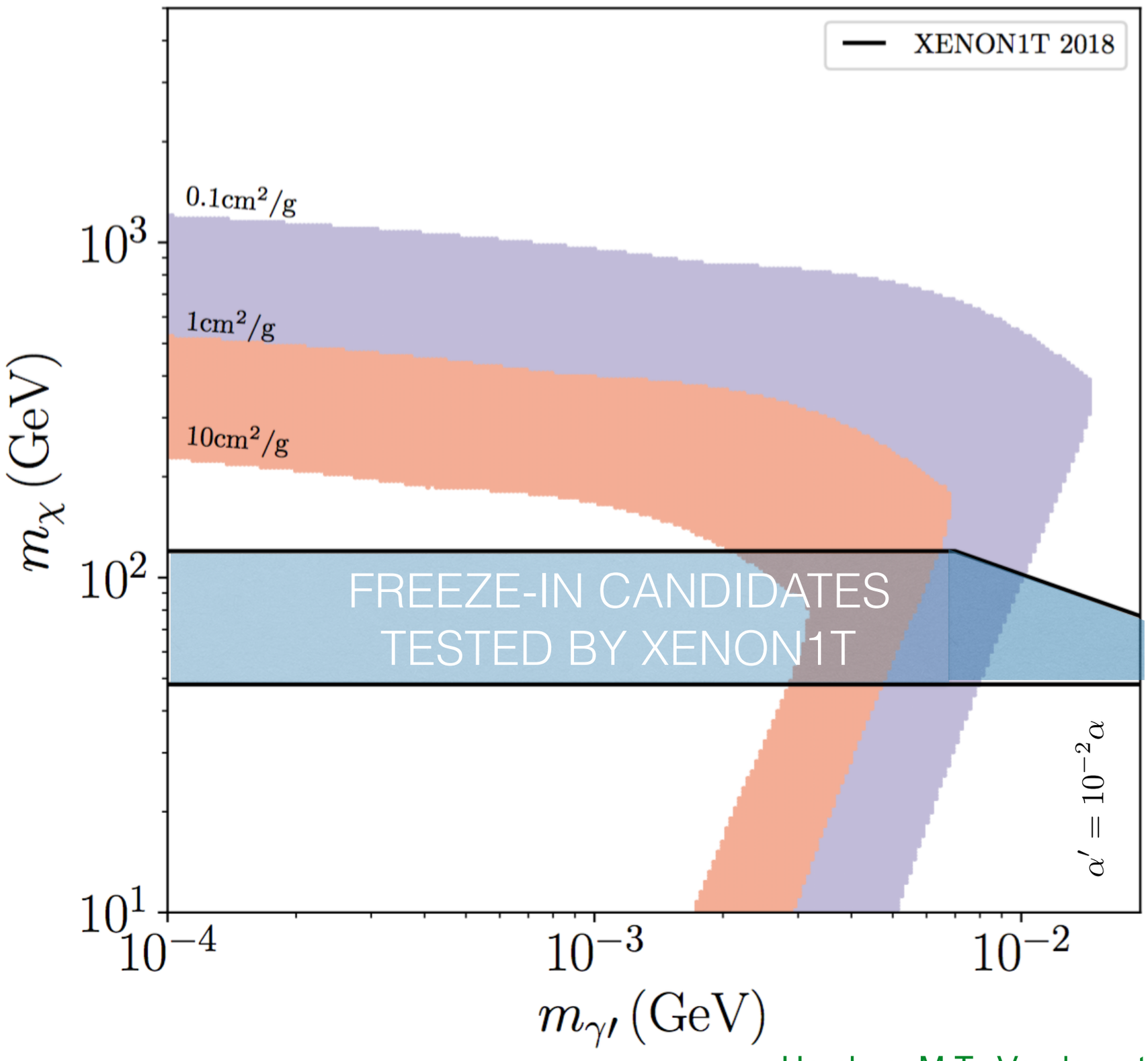
$$\frac{\sigma}{m} \sim \frac{\mathrm{cm}^2}{\mathrm{g}} \equiv \frac{\mathrm{barn}}{\mathrm{GeV}}$$

i.e. seemingly hadronic

but more generally **light mediator**

See however Jo Silk's talk !!!

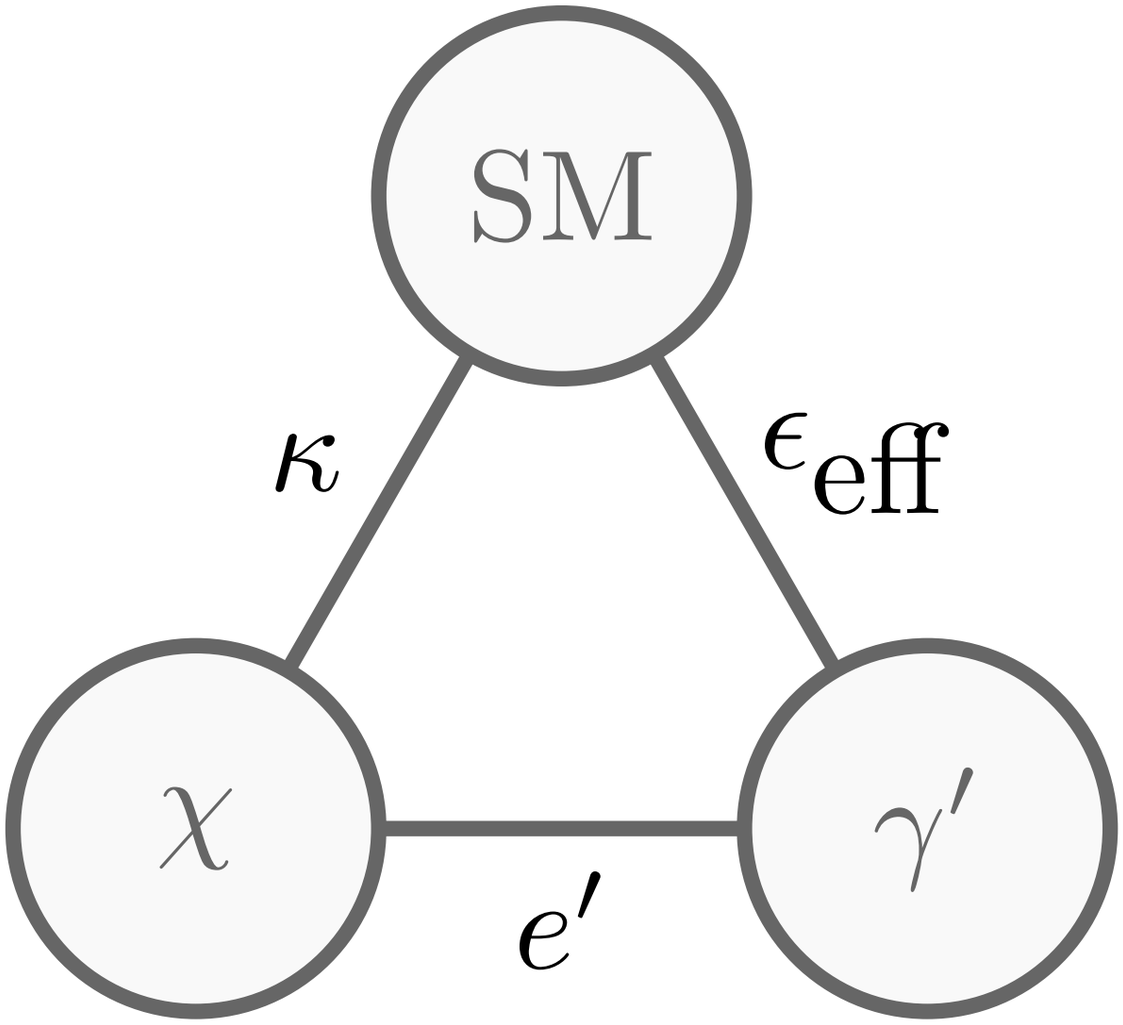
TEST OF SELF-INTERACTING FIMP



Hambye, M.T., Vandecasteele, Vanderheyden '18

BACKUP STORY (II)

EFFECTIVE MIXING PARAMETER



$$\kappa = \epsilon\, e'/e$$

$$\epsilon_{\rm eff} = \epsilon \frac{m_{\gamma'}^2}{m_{\gamma'}^2 - m_\gamma^2(T)}$$

KINETIC MIXING BASES

$$\mathcal{L} \supset -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{\gamma'}A'_\mu A'^\mu$$
$$+i\bar{\chi}\not{D}'\chi - m_\chi\bar{\chi}\chi$$

$$A'^\mu \to A'^\mu - \epsilon A^\mu$$
$$A^\mu \to A^\mu$$

« SM interaction basis »

$$\mathcal{L} \supset e\bar{\psi}\gamma^\mu\psi A_\mu - \epsilon\, m^2_{\gamma'}\, A_\mu A'^\mu$$
$$+\, e'\bar{\chi}\gamma^\mu\chi(A'_\mu - \epsilon A_\mu) + \frac{1}{2}m^2_{\gamma'}\, A'_\mu A'^\mu$$

$$m_{\gamma'} \to 0$$

no emission from SM fields

DM millicharged $\kappa = \epsilon\, e'/e$

KINETIC MIXING BASES

$$\mathcal{L} \supset -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{\gamma'}A'_\mu A'^\mu$$
$$+i\bar{\chi}\not{D}'\chi - m_\chi\bar{\chi}\chi$$

$$A'^\mu \to A'^\mu$$
$$A^\mu \to A^\mu - \epsilon A'^\mu$$

« eigenmass basis »

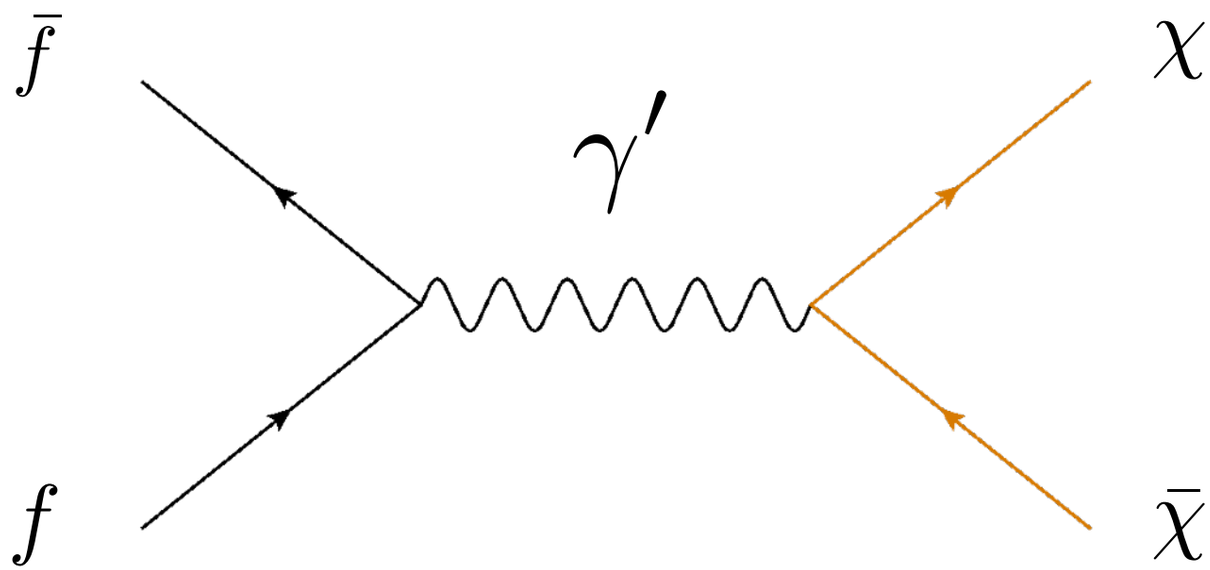
$$\mathcal{L} \supset e\bar{\psi}\gamma^\mu\psi(A_\mu - \epsilon A'_\mu)$$
$$+ e'\bar{\chi}\gamma^\mu\chi A'_\mu + \frac{1}{2}m^2_{\gamma'}\, A'_\mu A'^\mu$$

DM couples to <u>massive</u> dark photon (also Z)

$m_{\gamma'} \to 0$?

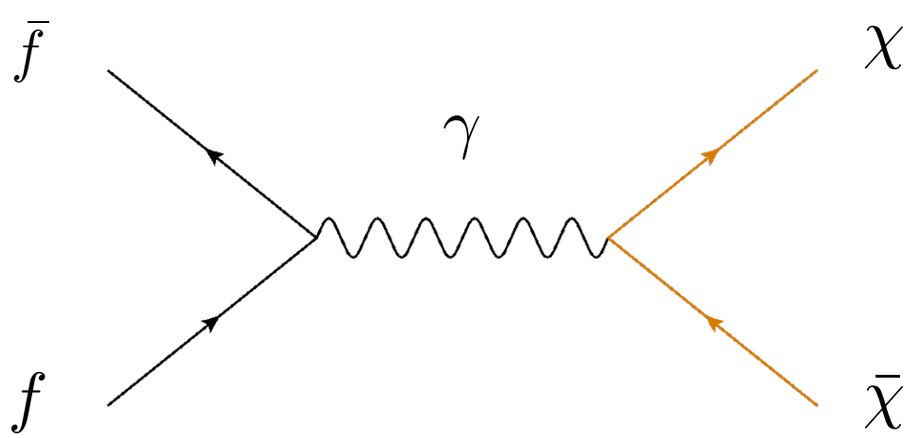
SM emission of DP with coupling ϵ

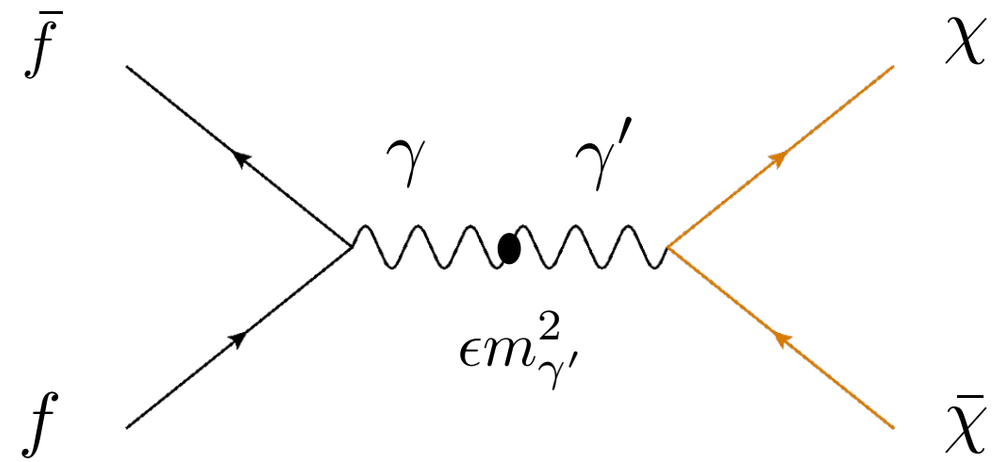
VIRTUAL DARK PHOTON EXCHANGE



$$\mathcal{M}_{\rm vir} \sim \; e^2 \kappa \; J^{\mu}_{\rm em} \, \eta_{\mu\nu} \, J^{\nu}_{\chi} \times \frac{1}{k^2 - m^2_{\gamma'}}$$

VIRTUAL DARK PHOTON EXCHANGE

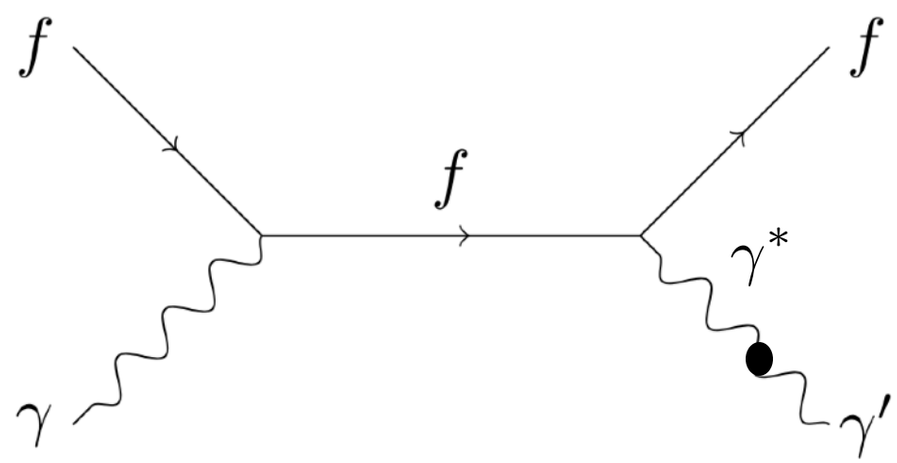




$$\mathcal{M}_{\rm vir} \sim \; e^2 \kappa \; J^{\mu}_{\rm em} \, \eta_{\mu\nu} \, J^{\nu}_{\chi} \times \frac{1}{k^2} \left(1 + \frac{m^2_{\gamma'}}{k^2 - m^2_{\gamma'}} + \ldots \right)$$

$$\rightarrow \; \mathcal{M}_{\rm vir} \sim \; e^2 \kappa \; J^{\mu}_{\rm em} \, \eta_{\mu\nu} \, J^{\nu}_{\chi} \times \frac{1}{k^2 - m^2_{\gamma'}}$$

RADIATION OF DARK PHOTONS

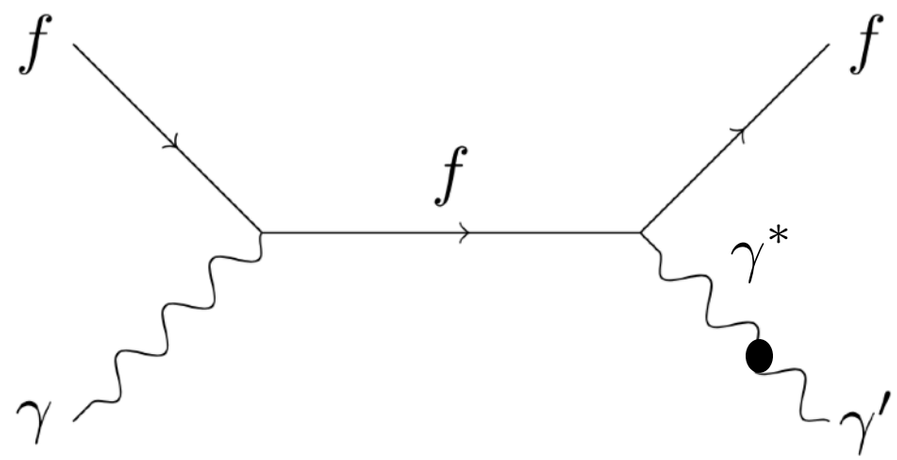


$$\mathcal{M}_{\rm rad} \propto \; e \; J^{\mu}_{\rm em} \, \eta_{\mu\nu} \, \frac{1}{k^2} \, \epsilon m^2_{\gamma'} \varepsilon'^{\nu}_{T}$$

$$\underset{k^2 = m^2_{\gamma'}}{\rightarrow} \quad e \, \epsilon \; J^{\mu}_{\rm em} \, \eta_{\mu\nu} \varepsilon'^{\nu}_{T}$$

$m_{\gamma'} \rightarrow 0$?

RADIATION OF DARK PHOTONS IN A MEDIUM

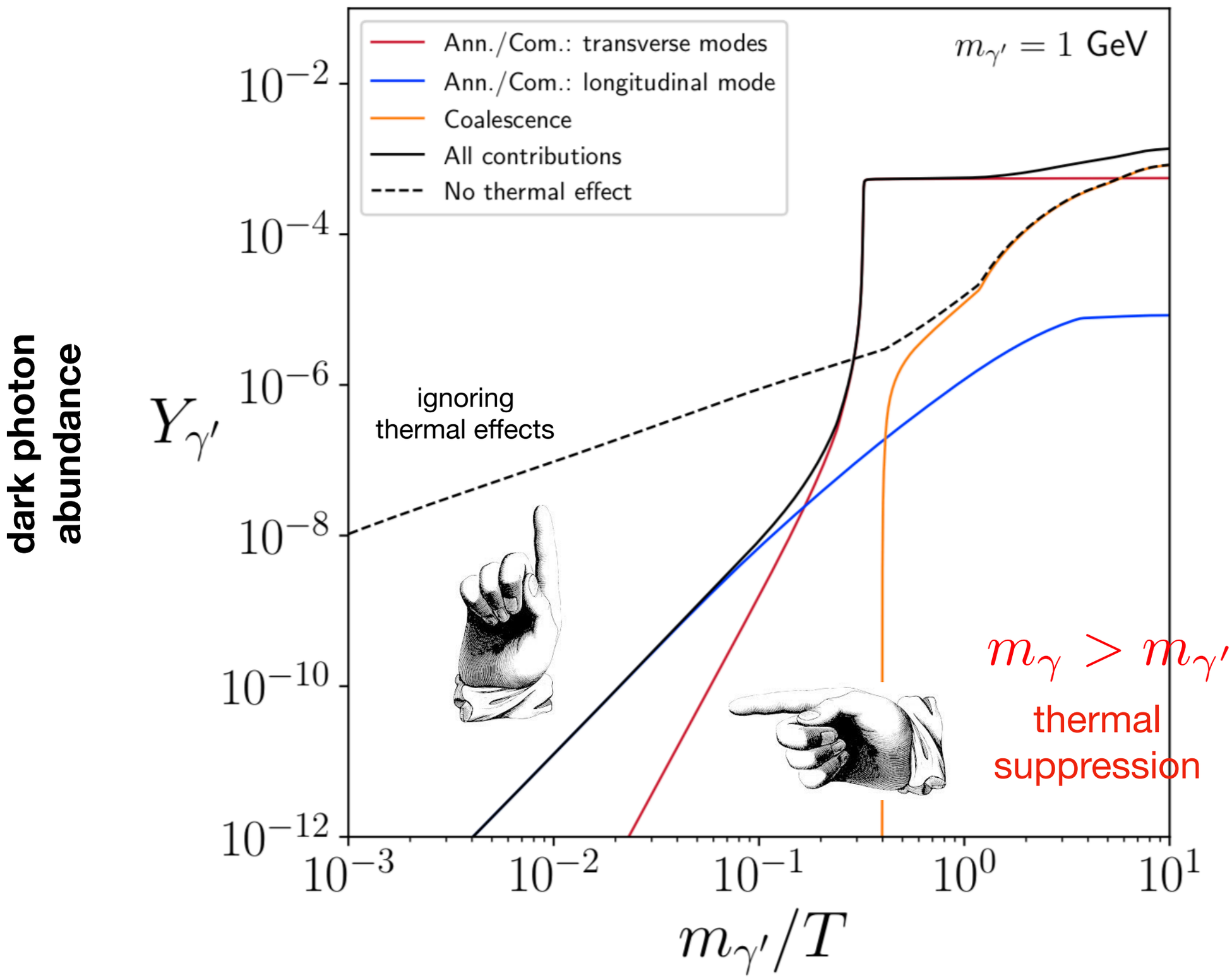


$$\mathcal{M}_{\rm rad} \propto \; e \, J^{\mu}_{\rm em} \, \eta_{\mu\nu} \, \frac{1}{k^2} \, \epsilon m^2_{\gamma'} \varepsilon'^{\nu}_{T}$$

$$\rightarrow \quad \mathcal{M}_{\rm rad} \propto \; e \, J^{\mu}_{\rm em} \, \eta_{\mu\nu} \, \frac{\epsilon m^2_{\gamma'}}{m^2_{\gamma'} - m^2_{\gamma}(T)} \, \varepsilon'^{\nu}_{T}$$

$$\boxed{\epsilon \quad \rightarrow \quad \epsilon_{\rm eff} = \epsilon \frac{m^2_{\gamma'}}{m^2_{\gamma'} - m^2_{\gamma}(T)}}$$

photon thermal mass

$$m_\gamma \sim eT$$

DARK RADIATION PRODUCTION IS SUPPRESSED AT HIGH TEMPERATURES