A taxonomy of hidden sector dark matter

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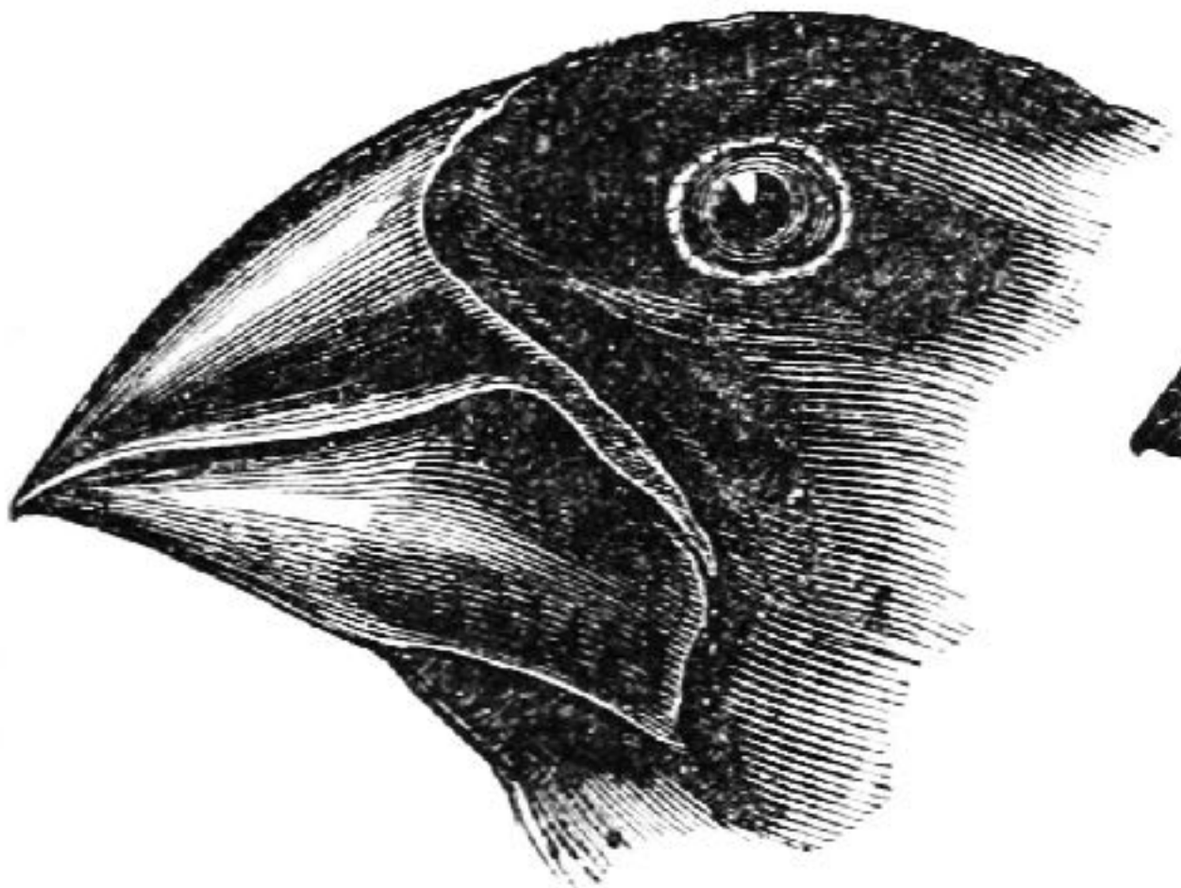
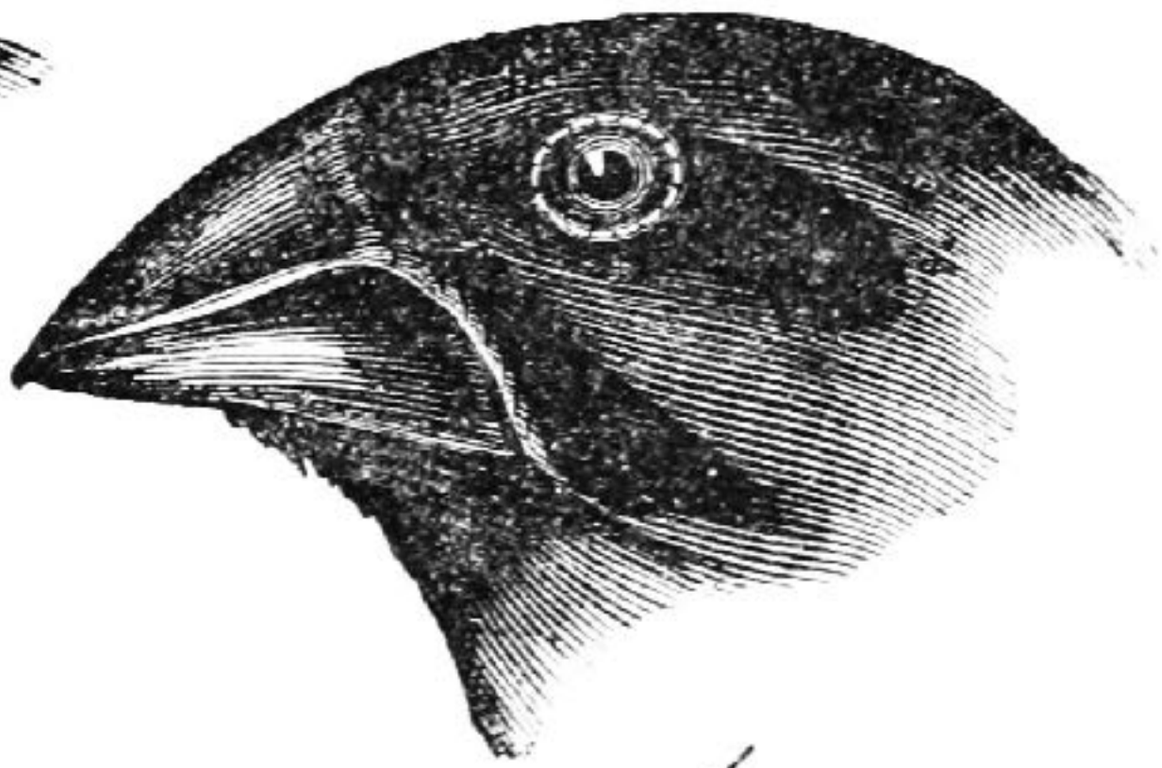
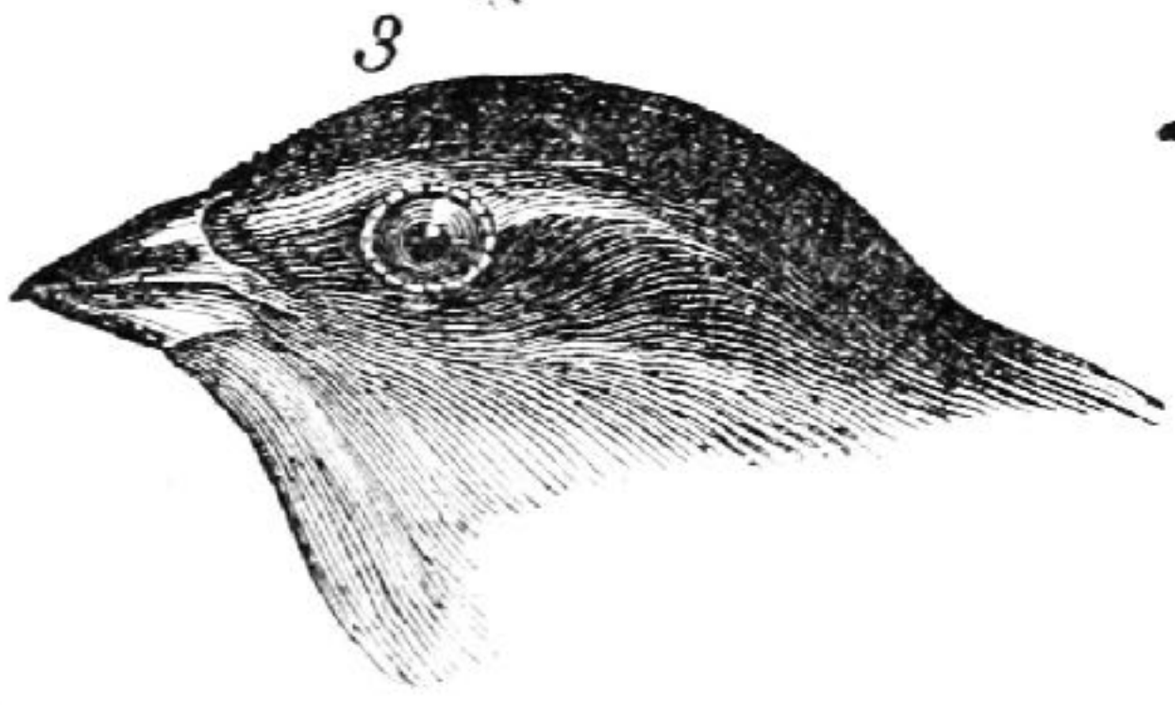
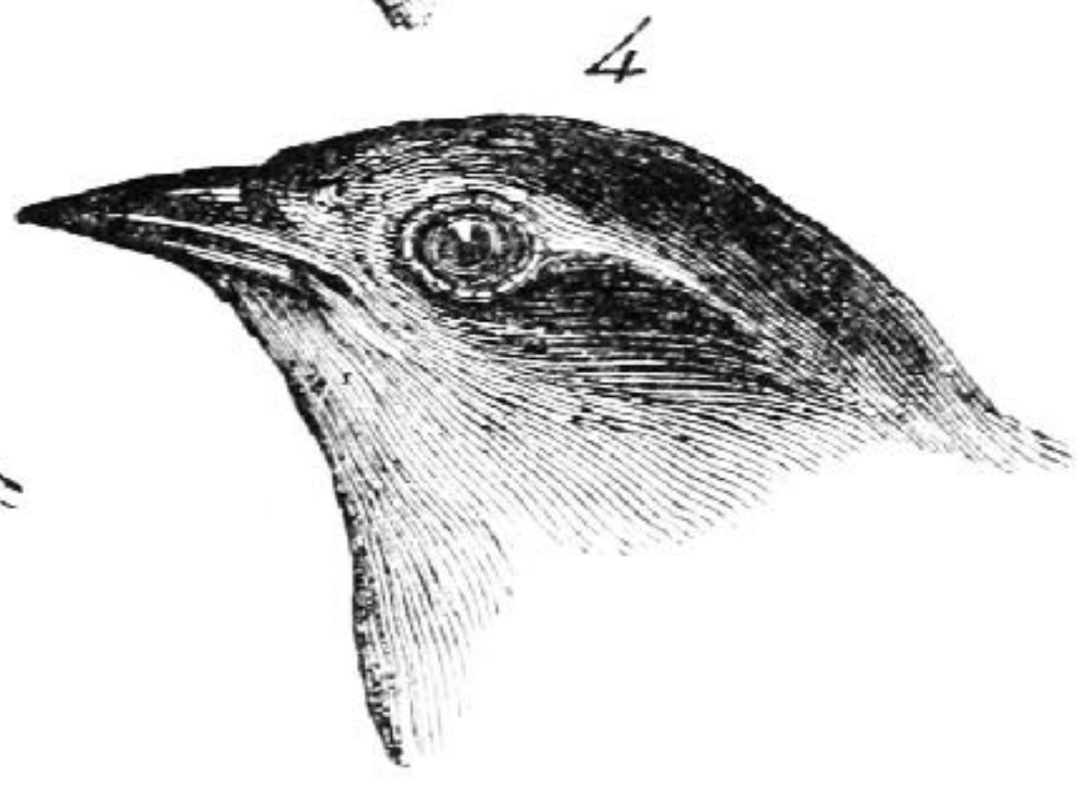
Université Libre de Bruxelles
Belgium

DESY THEORY WORKSHOP
Bright ideas for a dark universe
DESY Hamburg, Germany
21-24 september 2021

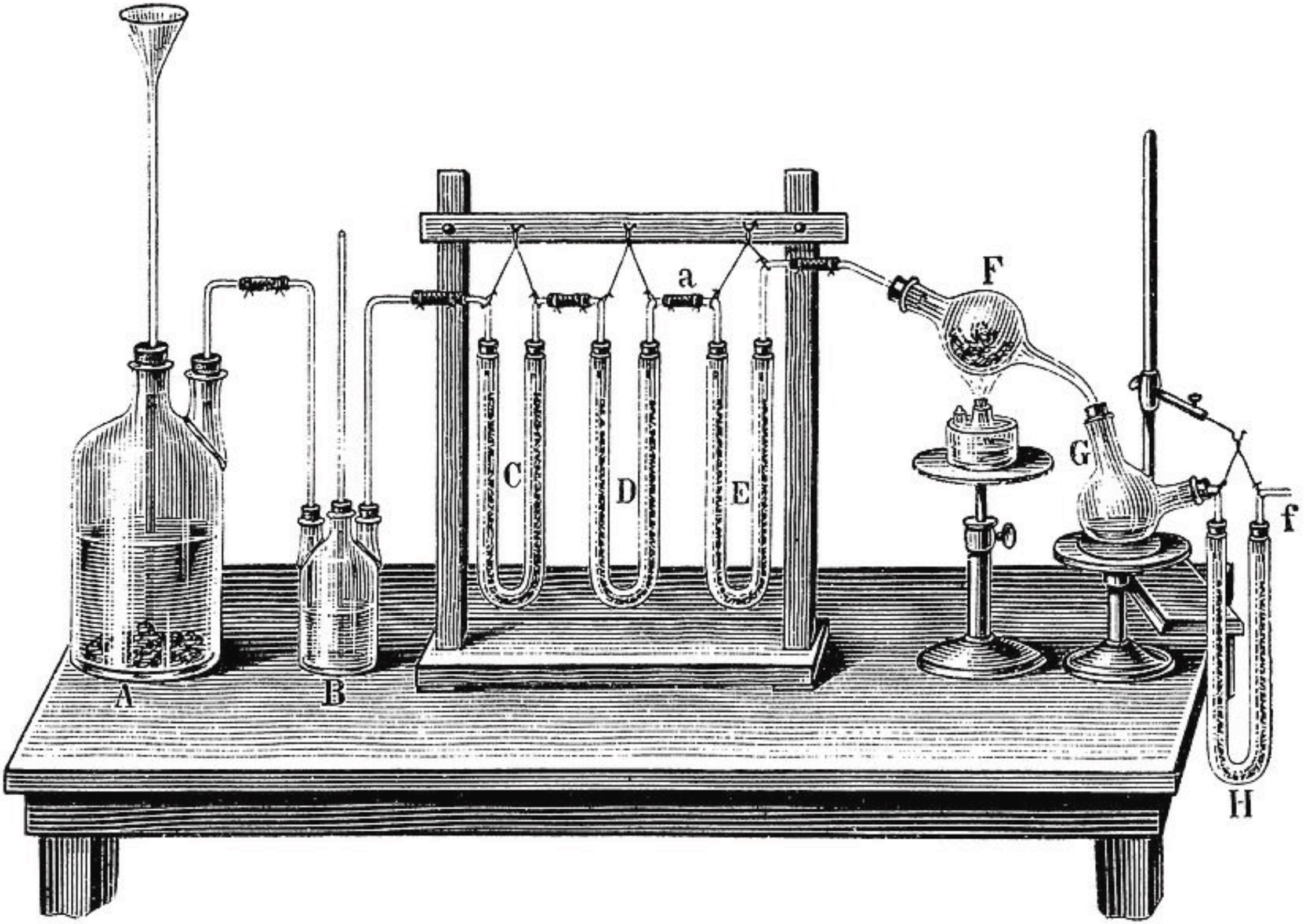






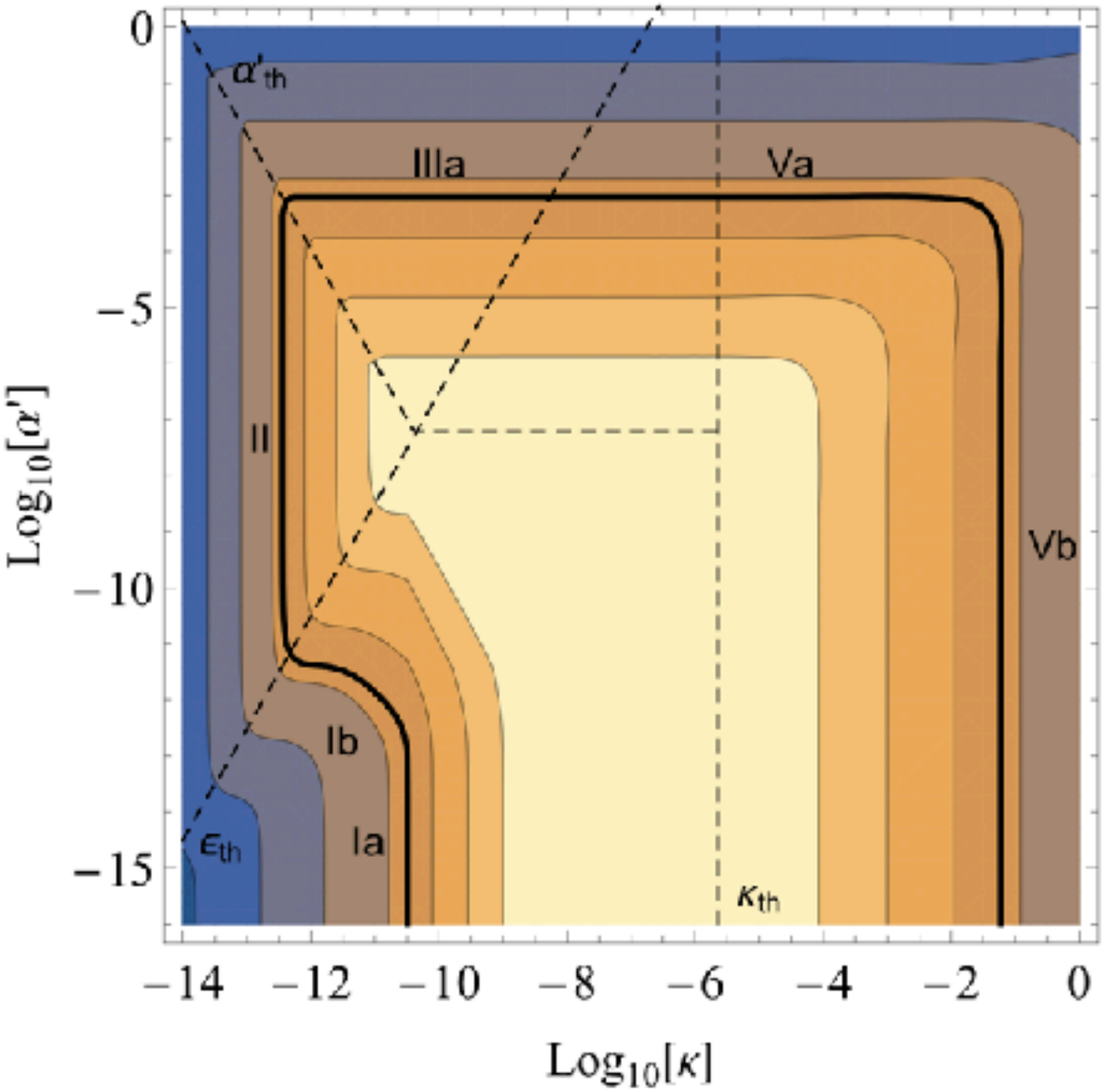


1. Geospiza magnirostris.
2. Geospiza fortis.
3. Geospiza parvula.
4. Certhidea olivacea.

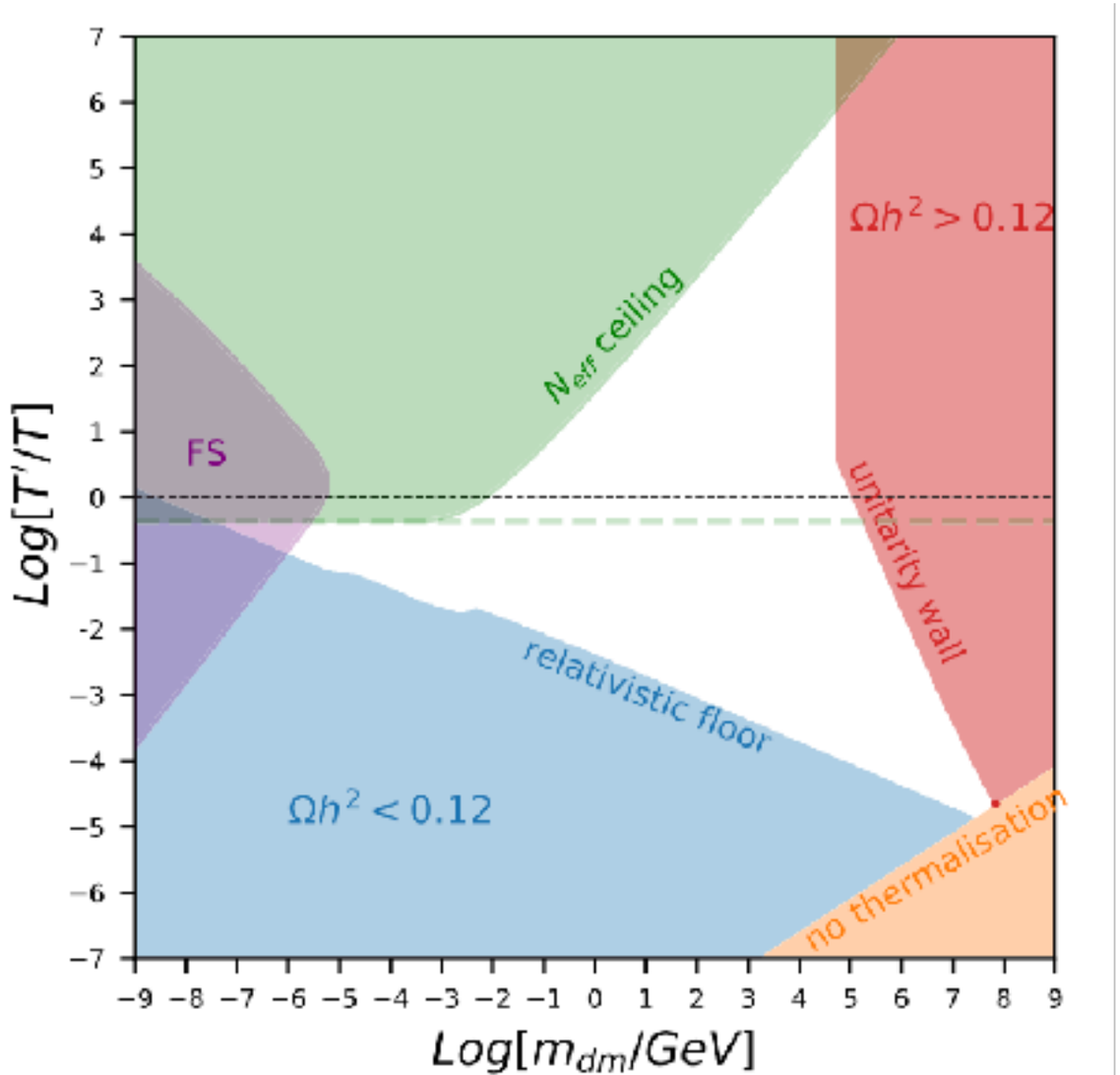

A
B
C
D
E
a
F
G
H
f

Hunt-Lenox globe, circa 1510

KEY RESULTS



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



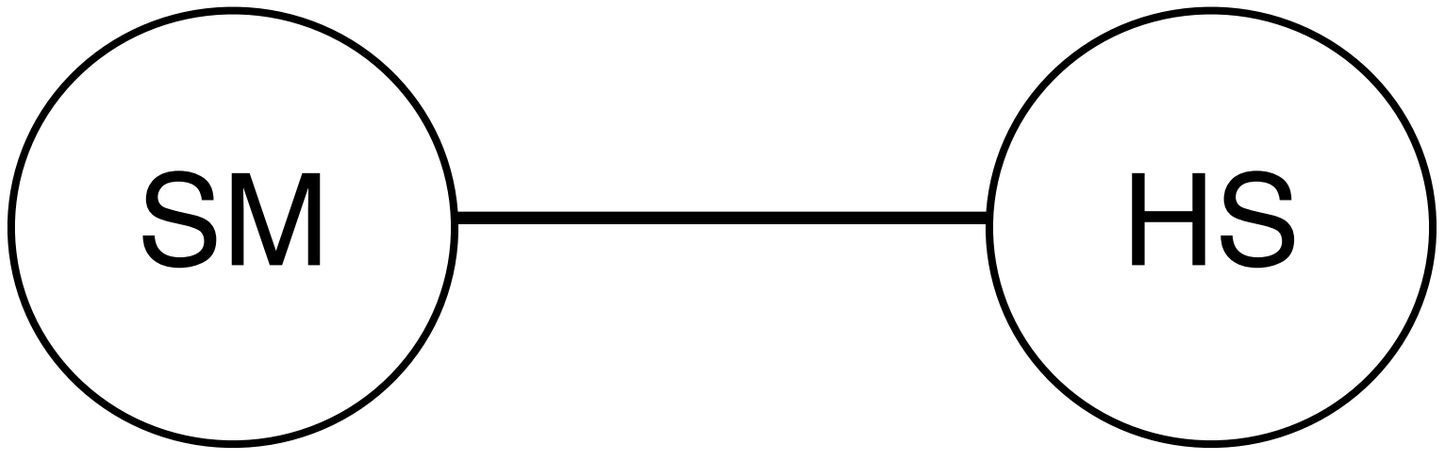
The domain of thermal dark matter candidates
R. Coy, Th. Hambye, M.H.G.T., L. Vanderheyden
arXiv:2105.01263

HIDDEN SECTOR

SM

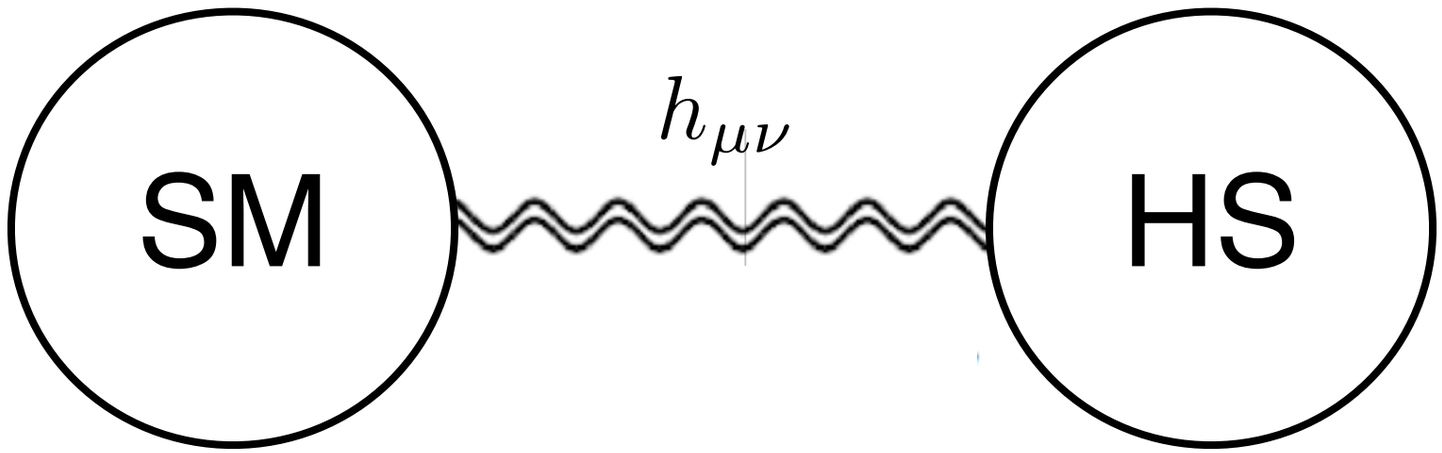
HS

HIDDEN SECTOR



- several particles
- T’ ≠ T
- portal

HIDDEN SECTOR



- several particles
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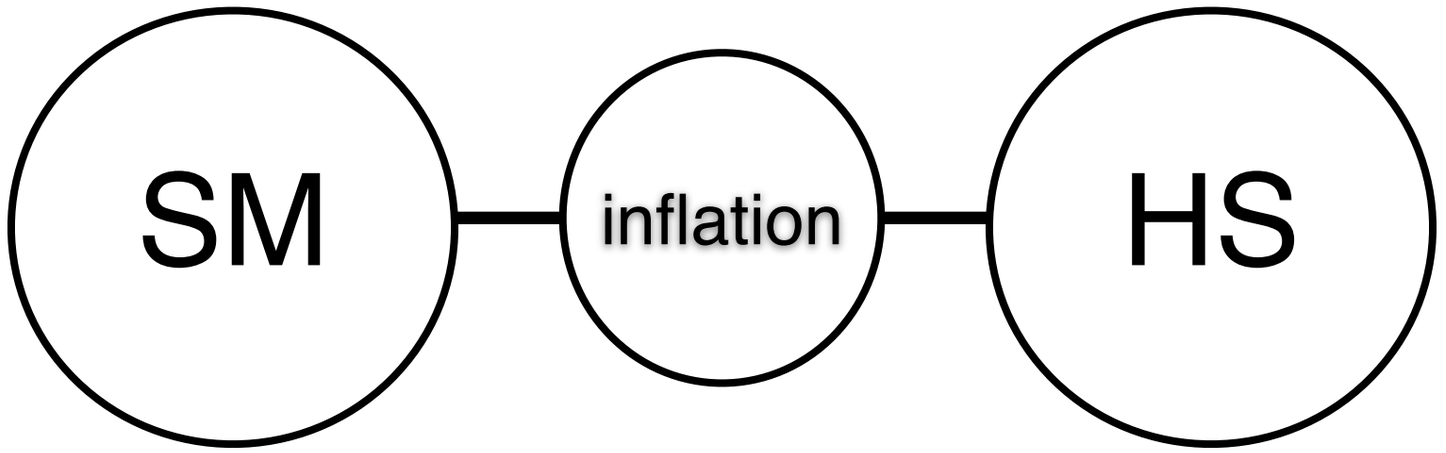
- portal

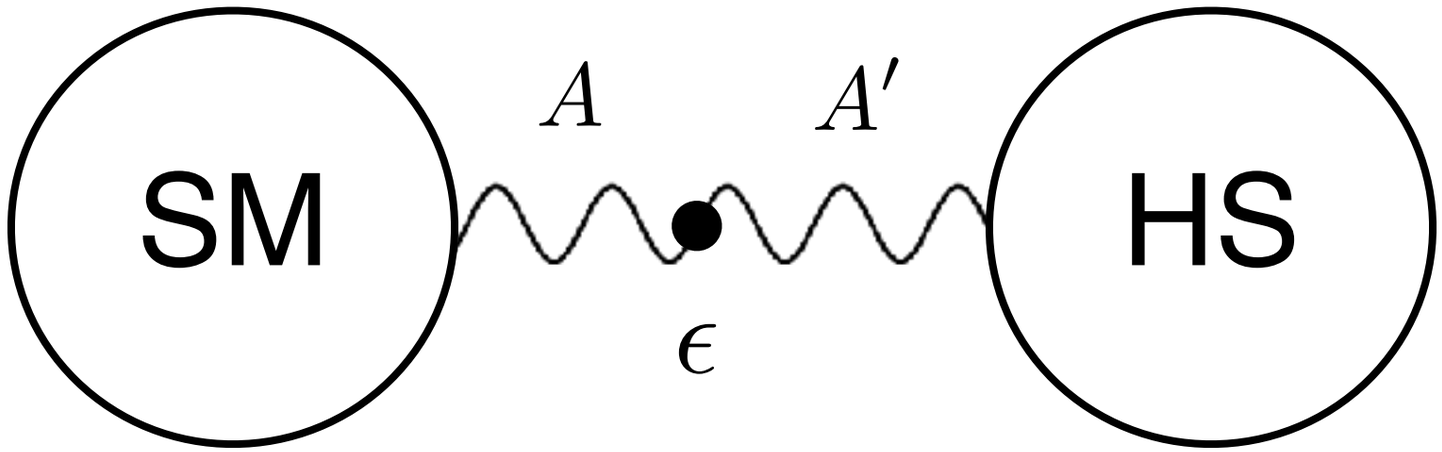
HIDDEN SECTOR



- several particles
- T’ ≠ T
- portal

e.g. Arvanitaki et al ‘21

KINETIC MIXING



- several particles
- T’ ≠ T
- portal

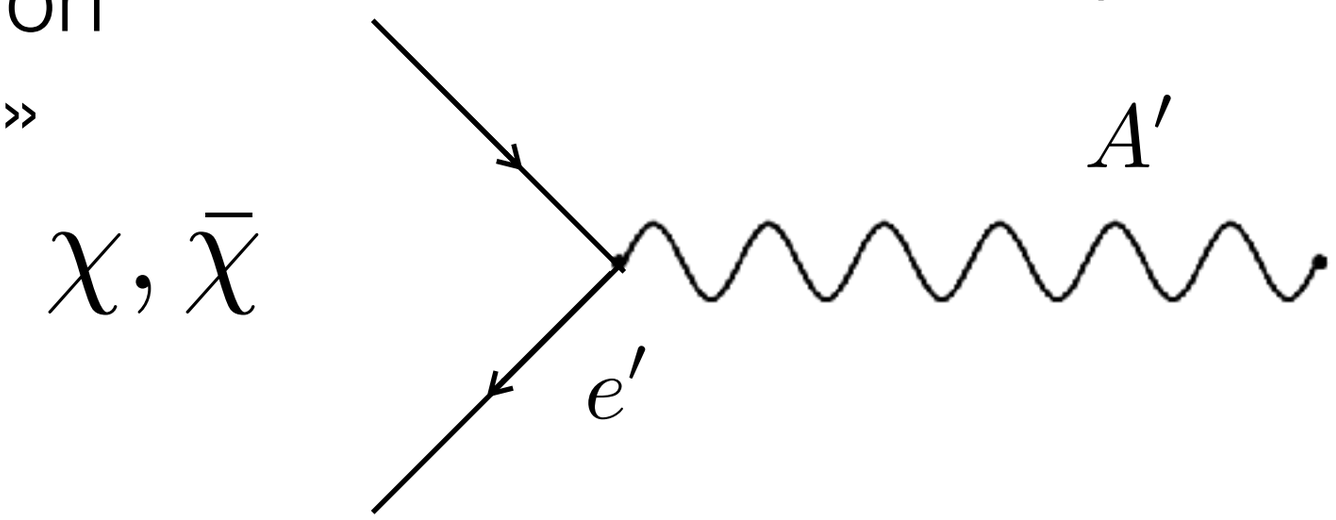
Chu, Hambye, M.T. ‘12

DARK QED with KINETIC MIXING

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

« dark electron & positron »

« dark photon »



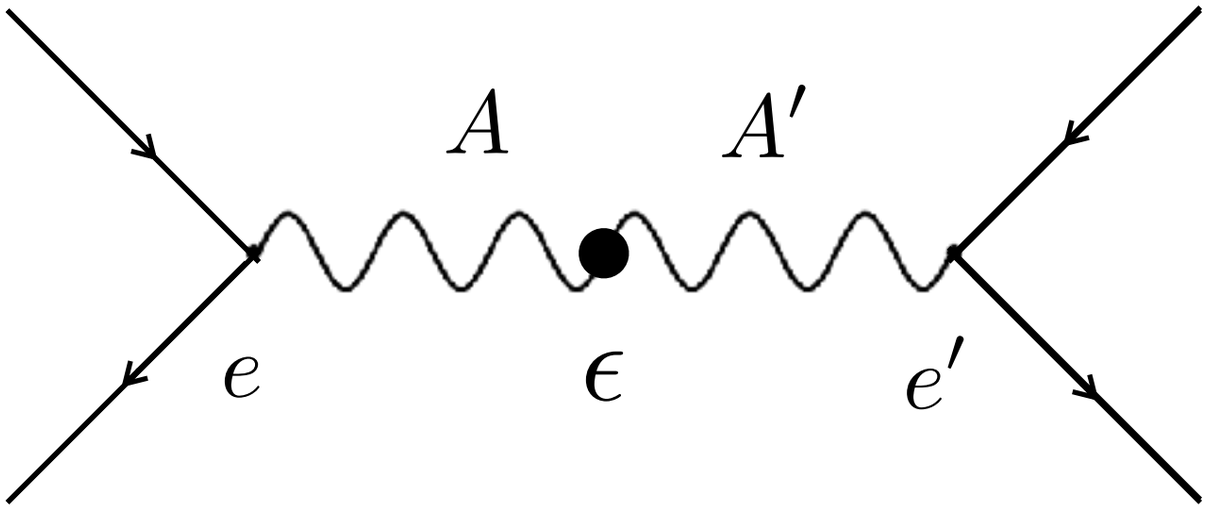
e' or α'

« dark fine structure constant »

DARK QED with KINETIC MIXING

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

SM



$\chi, \bar{\chi}$

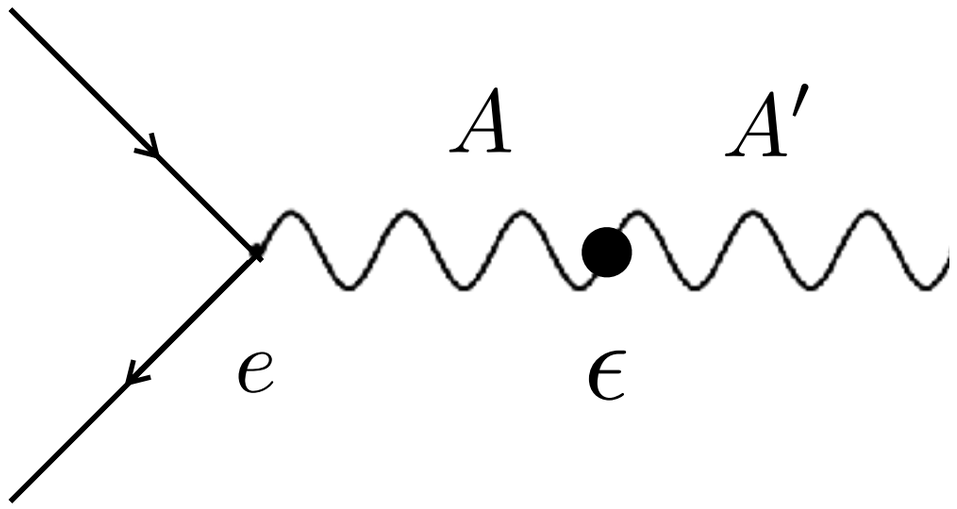
$$\kappa = \epsilon e'/e = \epsilon\sqrt{\alpha'/\alpha}$$ « millicharge »

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

DARK QED with KINETIC MIXING

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

SM

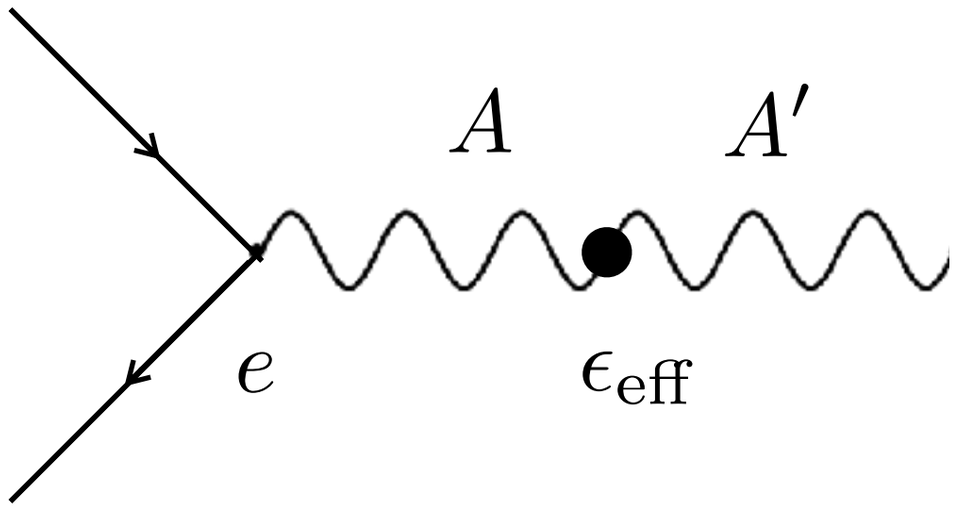


ϵ

DARK QED with KINETIC MIXING

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

SM



$$\epsilon_{\text{eff}} = \epsilon \frac{m^2_{\gamma'}}{m^2_{\gamma'} - m^2_\gamma(T)}$$

actually

An, Pospelov, Pradler ‘13

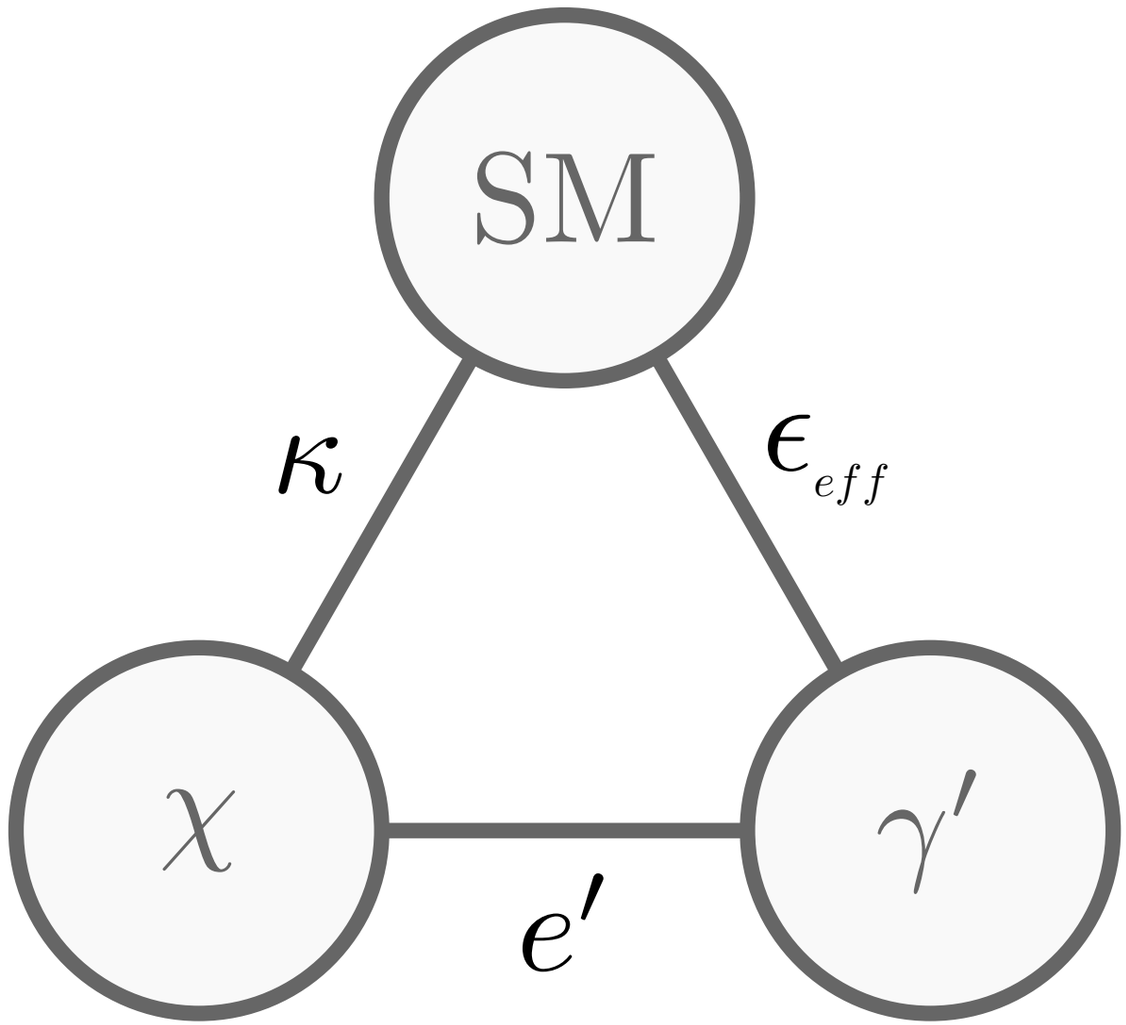
BOLTZMANN EQUATIONS

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

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

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

BOLTZMANN EQUATIONS GRAPHICALLY



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

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

OLD

MASSLESS DARK PHOTON LIMIT

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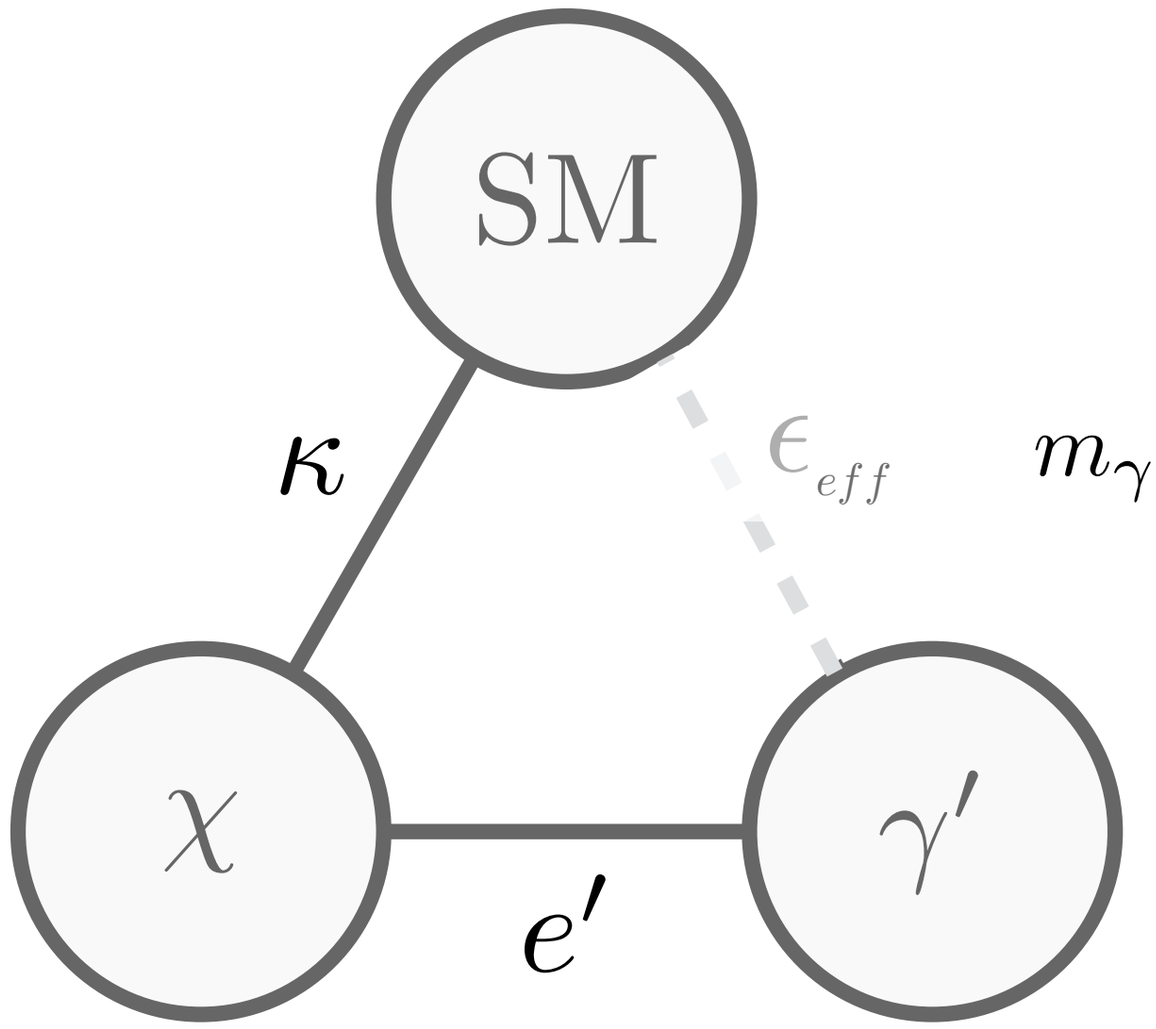


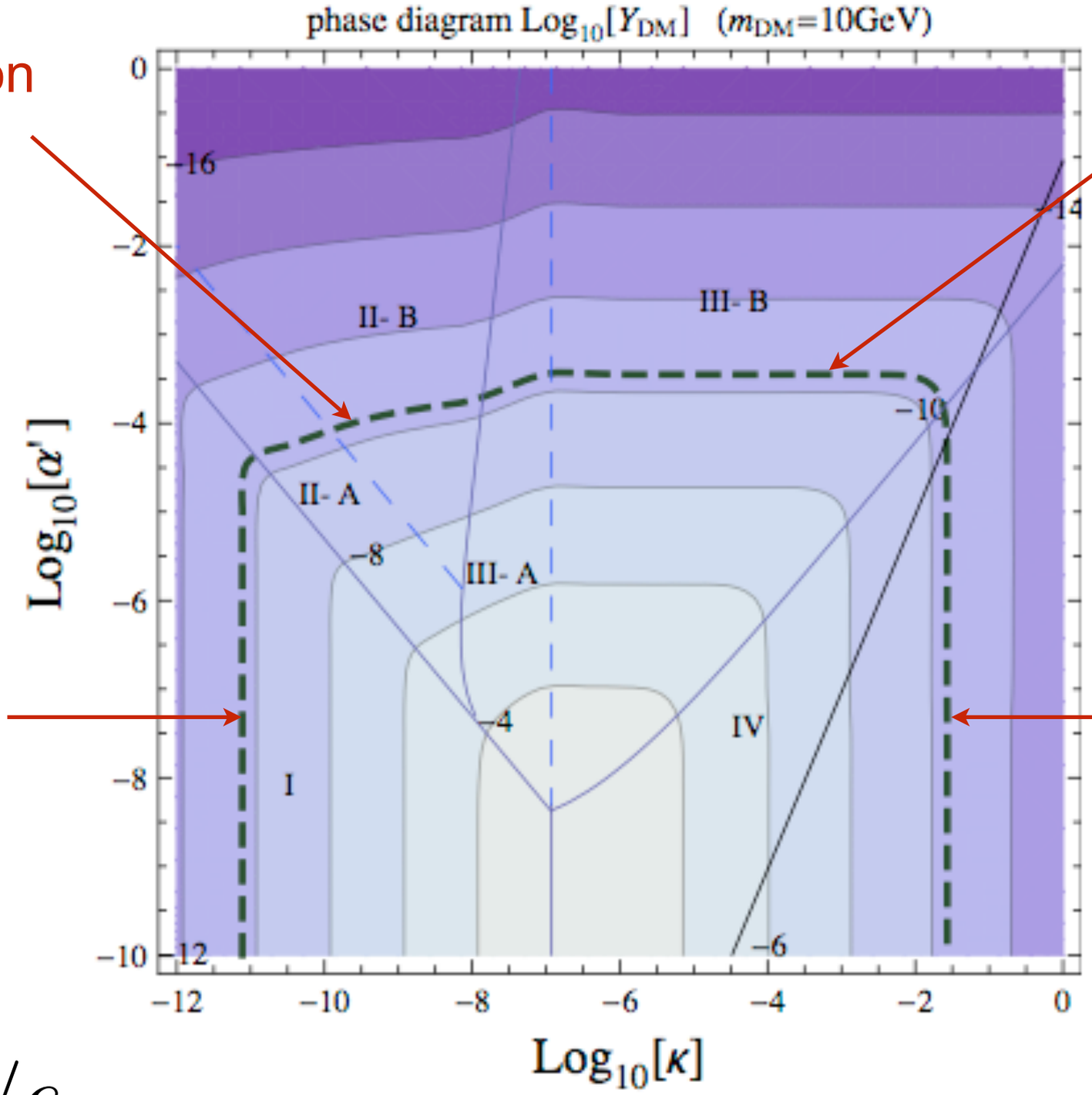
$$\kappa = \epsilon\, e'/e$$

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

OLD THE 4 BASIC WAYS TO PRODUCE DM

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

reannihilation



secluded freeze-out

freeze-in

standard freeze-out

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

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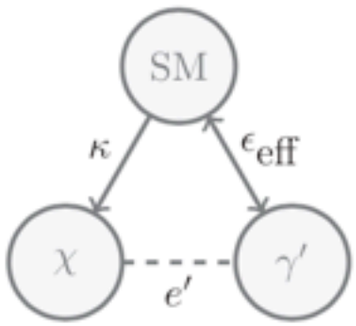
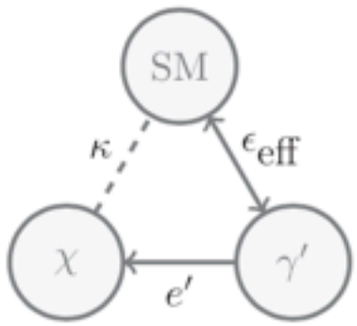
NEW 9 WAYS (5 REGIMES) TO PRODUCE DM

$m_{\gamma'} \neq 0$

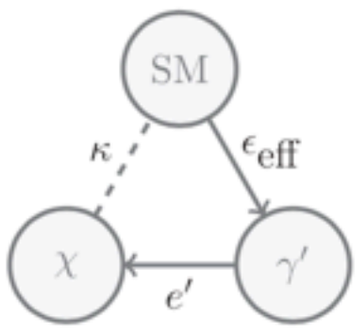


(a) Ia



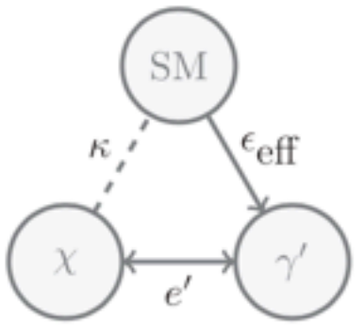
(b) Ib

freeze-in (Ia & Ib)

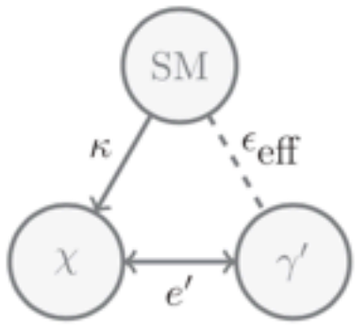


(c) II

sequential freeze-in (II)

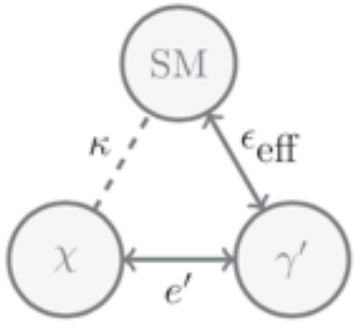


(d) IIIa & IVa

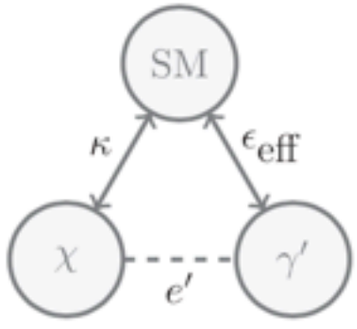


(e) IIIb & IVb

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



(f) Va



(g) Vb

freeze-out (Va & Vb)

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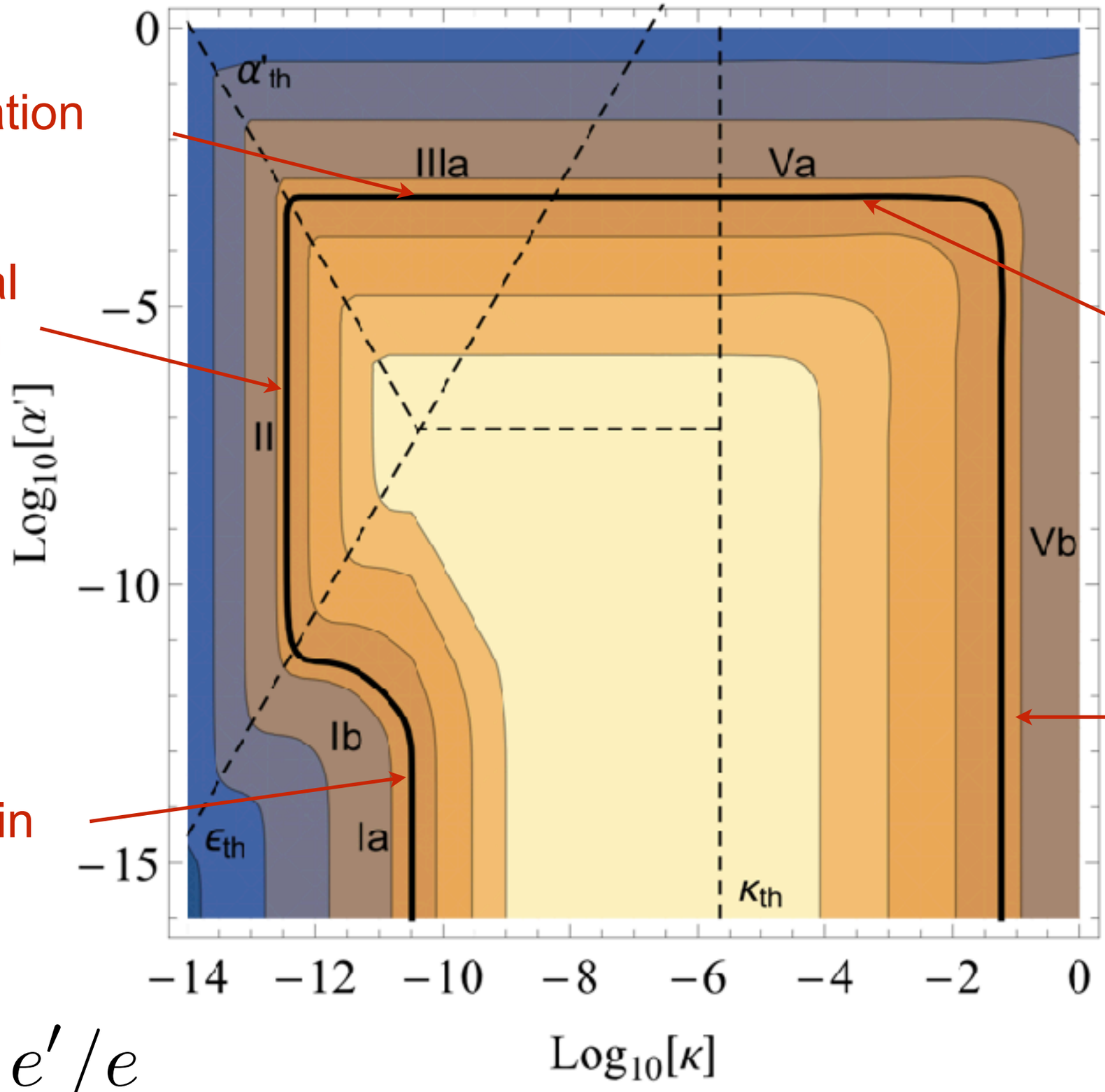
NEW PRODUCTION REVISITED

$m_\chi = 100\,\mathrm{GeV},\ m_{\gamma'} = 10\,\mathrm{GeV}$



reannihilation

sequential freeze-in

freeze-out into dark photons

standard freeze-out

freeze-in

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

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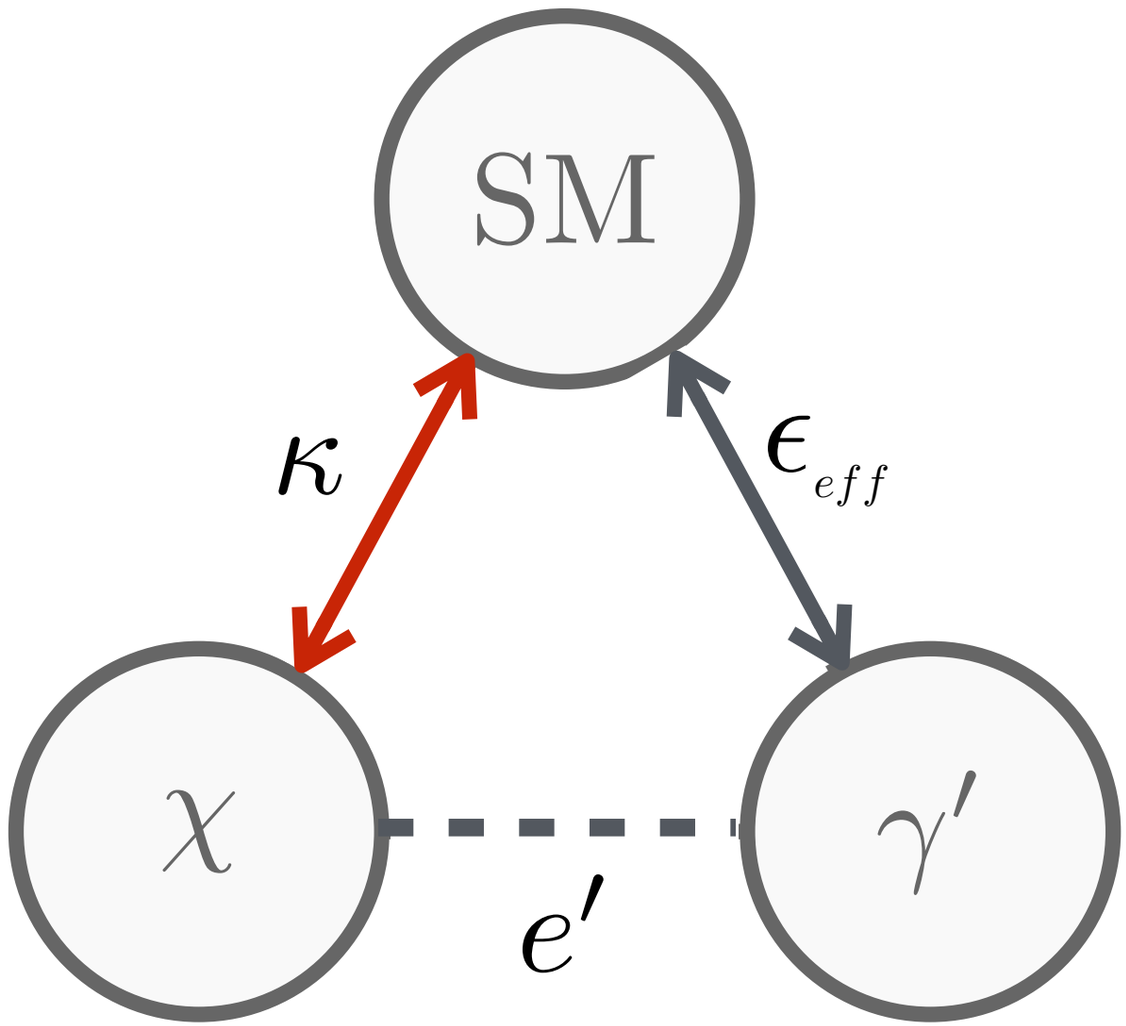
STANDARD FREEZE-IN



$$T' = T$$

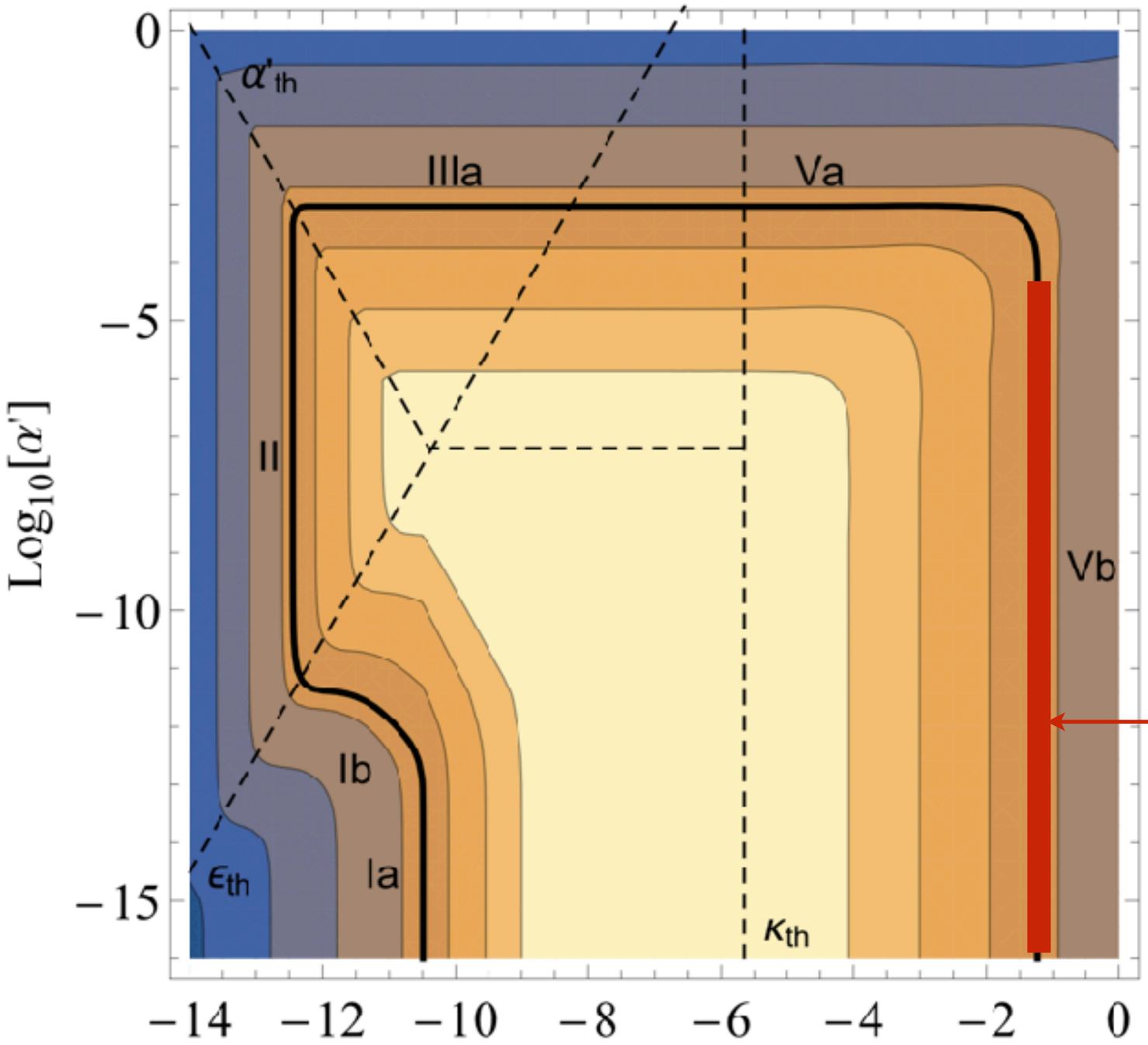
$$\kappa = \epsilon\, e'/e$$

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

STANDARD FREEZE-OUT

$m_{\gamma'} \neq 0$

$m_\chi = 100\,\mathrm{GeV},\ m_{\gamma'} = 10\,\mathrm{GeV}$

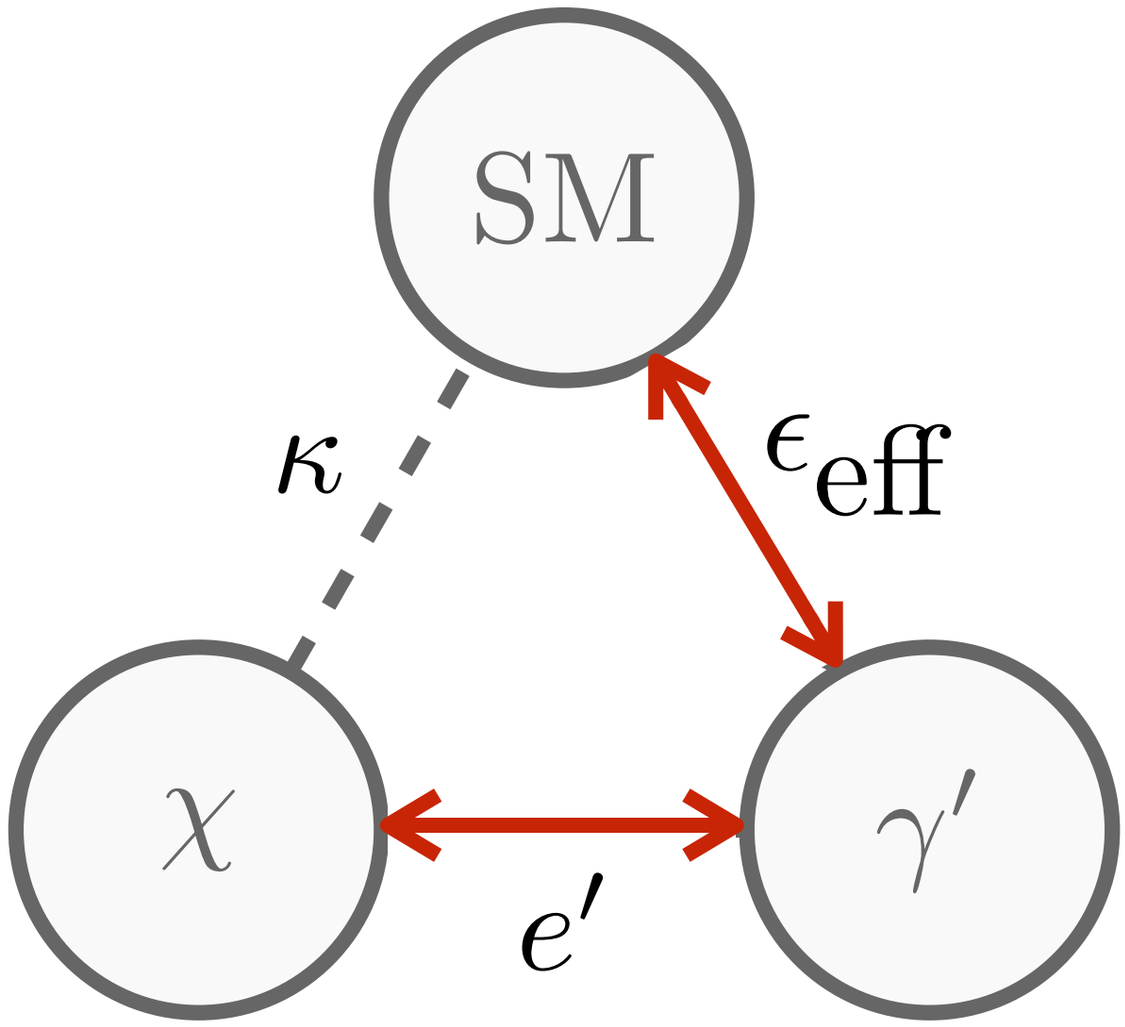


standard freeze-out

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

Chu, Hambye, M.T. ‘12

FREEZE-OUT INTO DARK PHOTONS



$T' = T$

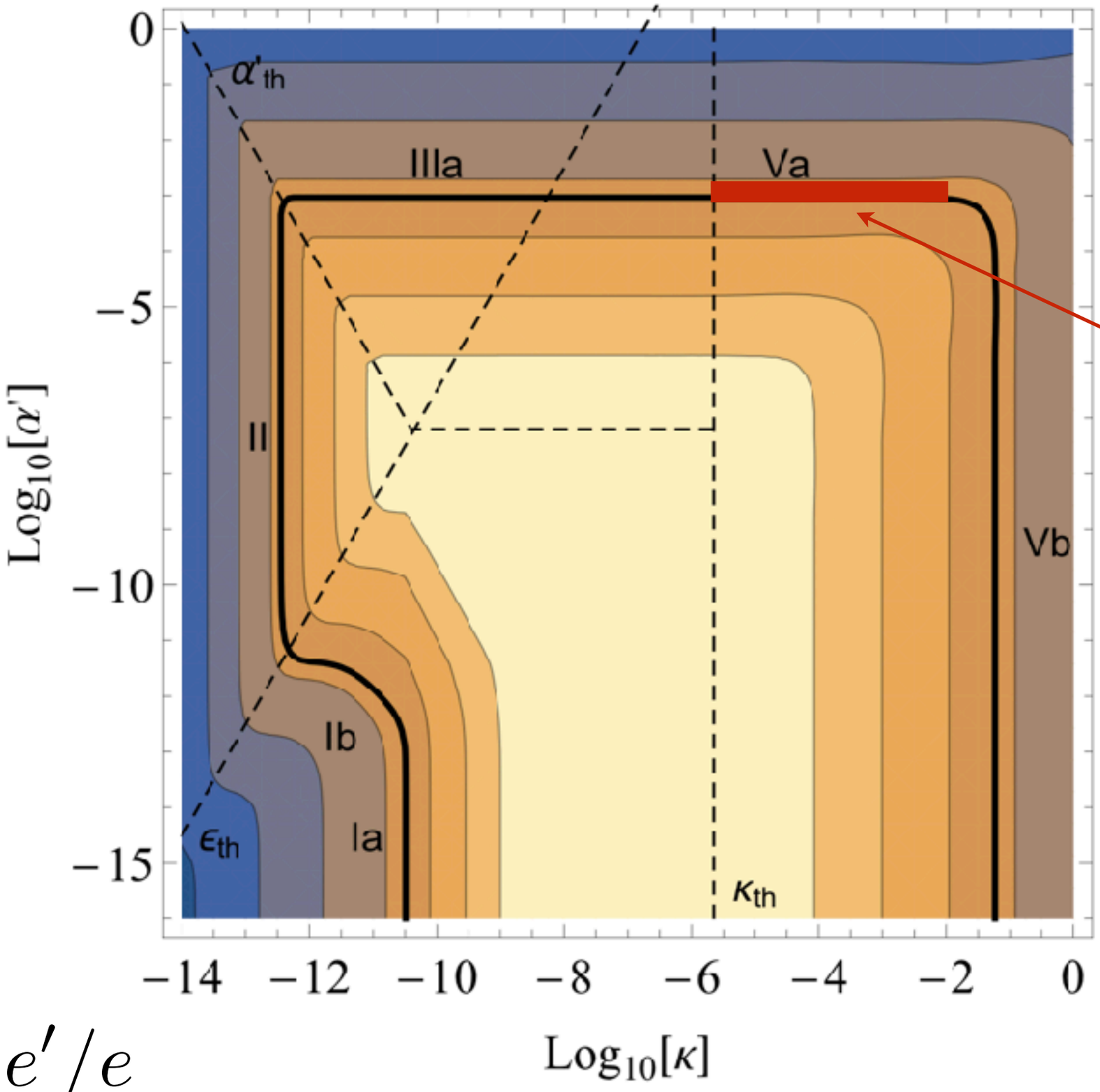
$\kappa = \epsilon\, e'/e$

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

FREEZE-OUT INTO DARK PHOTONS

$m_\chi = 100\,\mathrm{GeV},\ m_{\gamma'} = 10\,\mathrm{GeV}$

$m_{\gamma'} \neq 0$



freeze-out into dark photons

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

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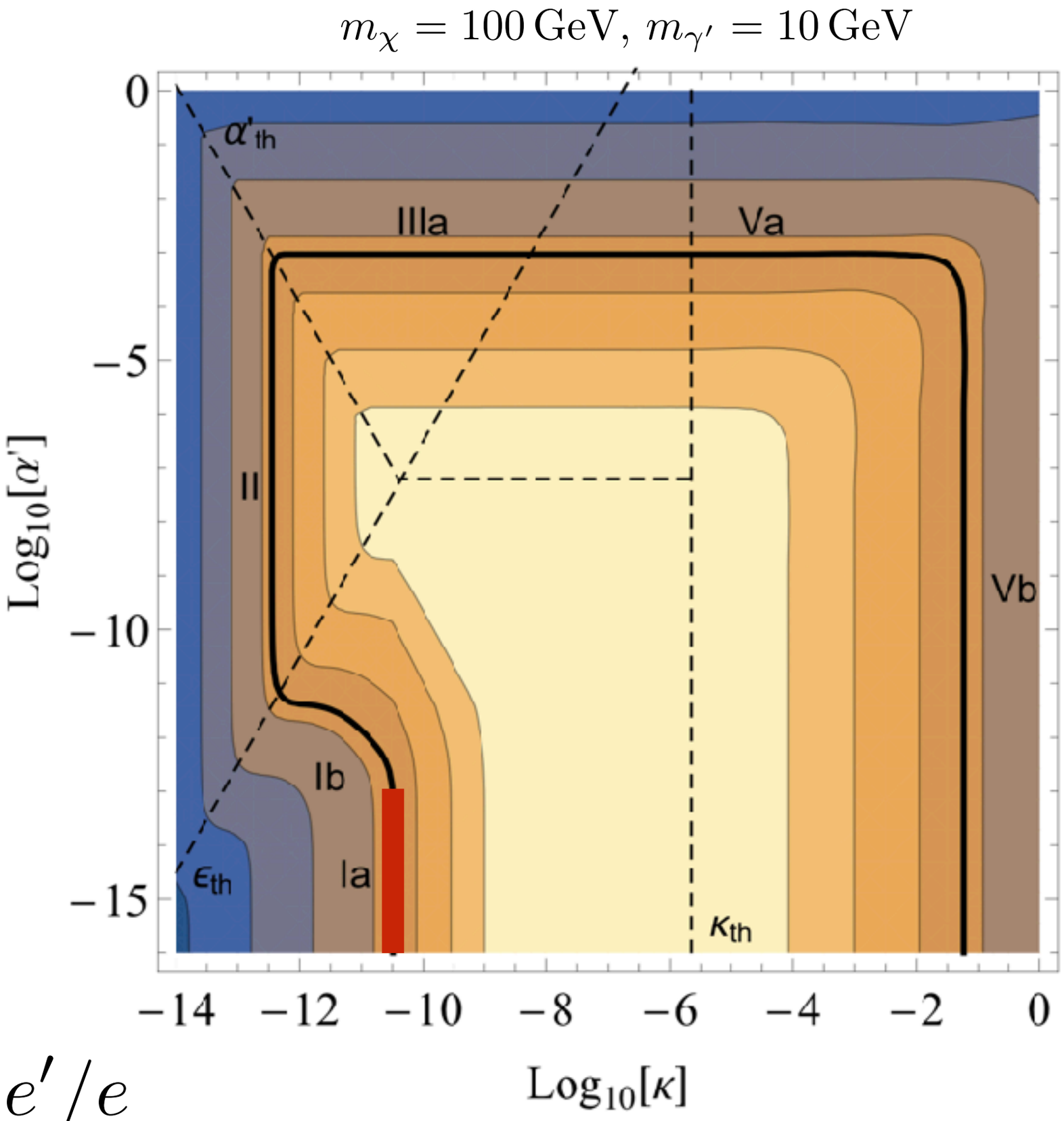
FREEZE-IN REVISITED

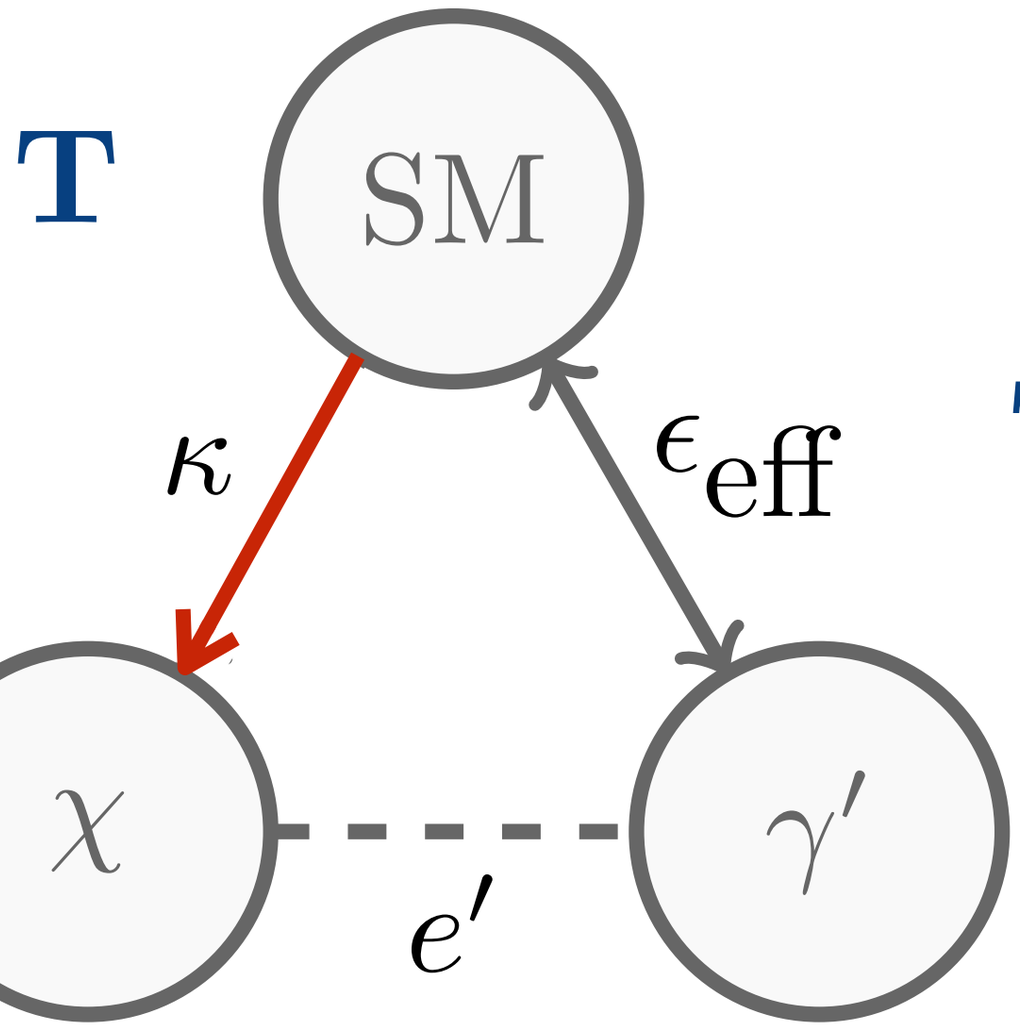
$m_{\gamma'} \neq 0$



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

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

FREEZE-IN REVISITED



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

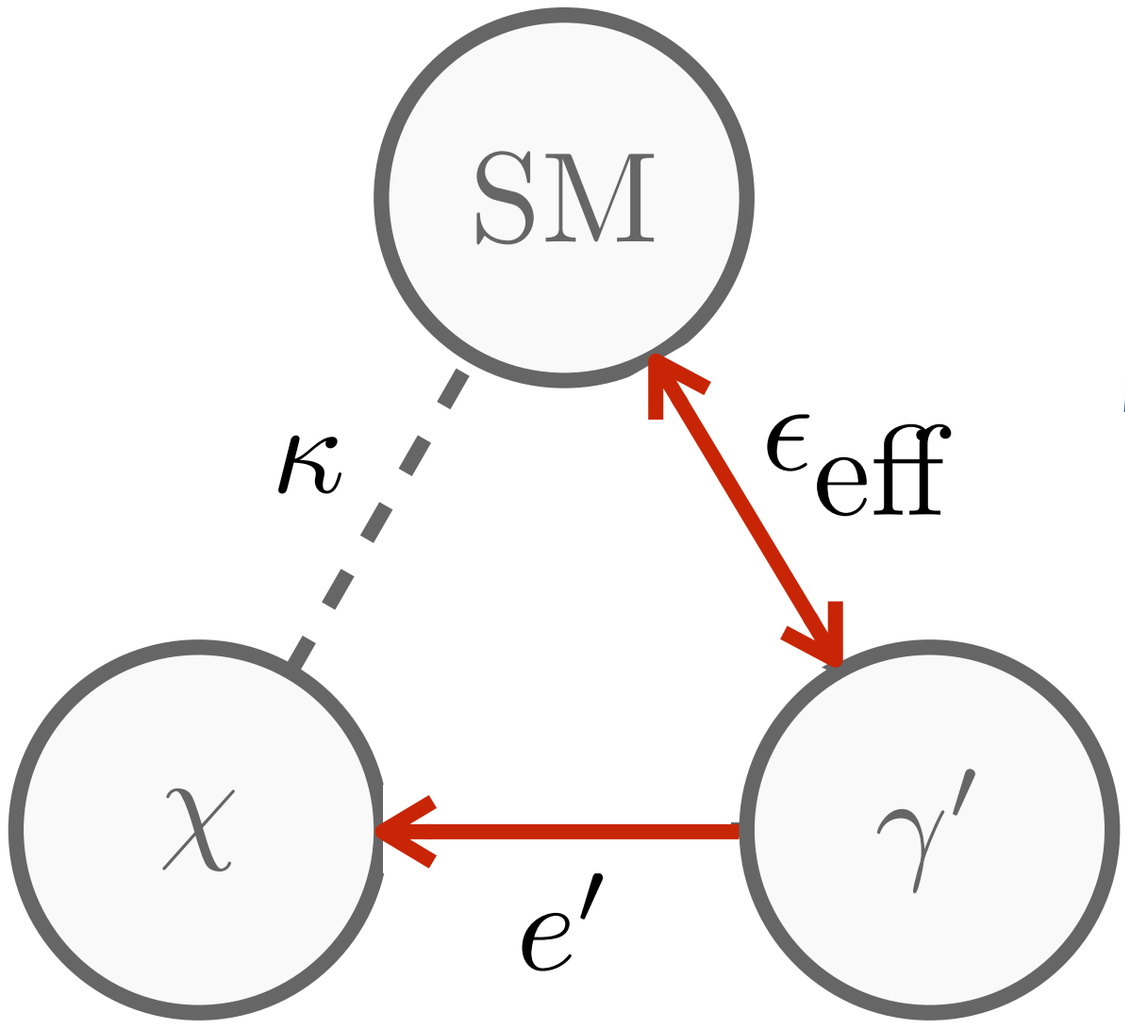
$\mathbf{T}_{\chi} \sim \mathbf{0}$

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

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

FREEZE-IN FROM THERMAL DARK PHOTONS

$m_{\gamma'} \neq 0$



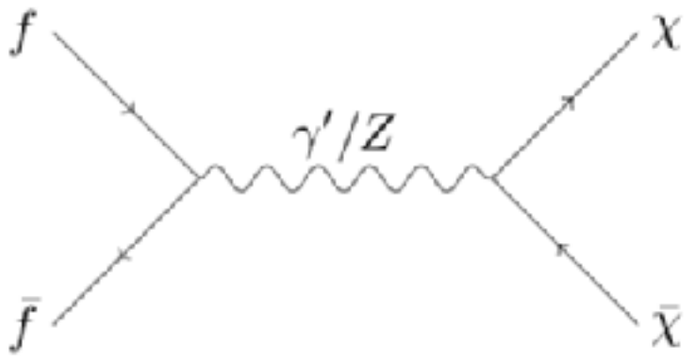
$\mathbf{T}_{\gamma'} = \mathbf{T}$

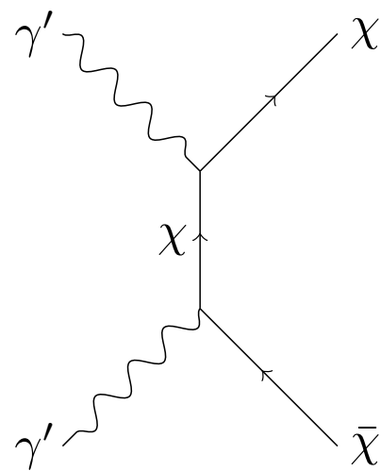
$\mathbf{T}_{\chi} \sim \mathbf{0}$

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

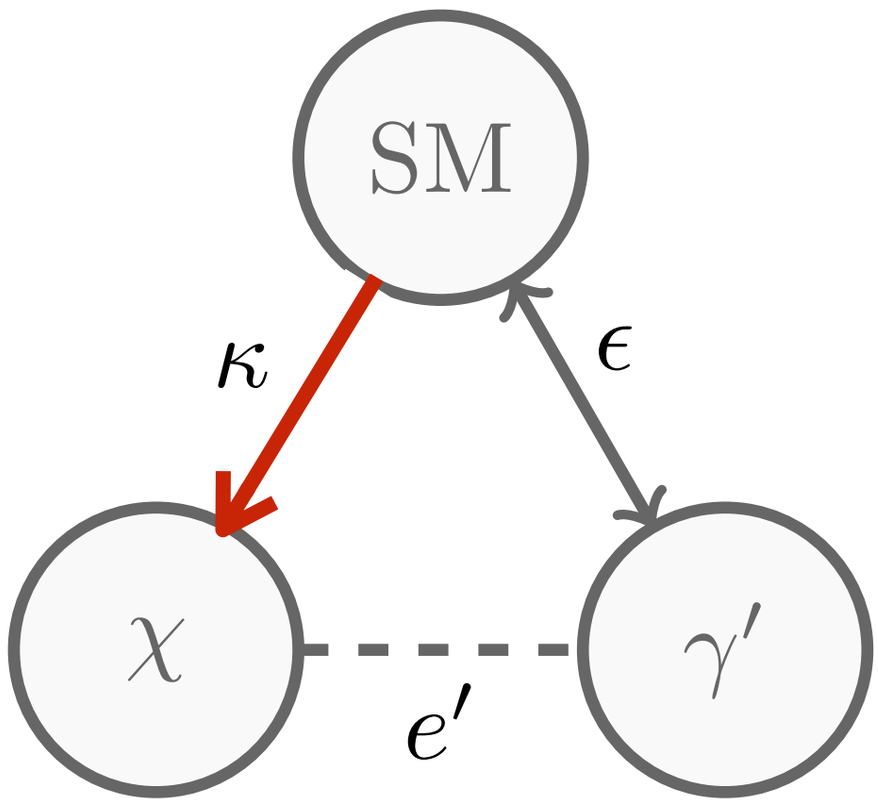
$$\epsilon_{\rm eff} = \epsilon \frac{m_{\gamma'}^2}{m_{\gamma'}^2 - m_{\gamma}^2(T)}$$

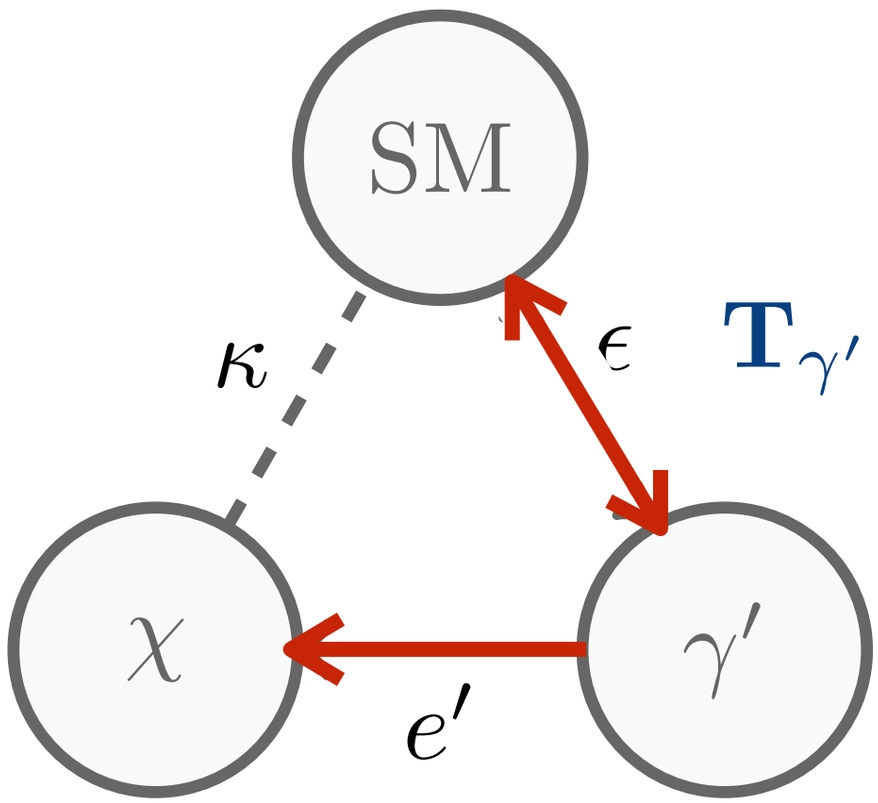
FREEZE-IN Ia & Ib





$m_{\gamma'} \neq 0$





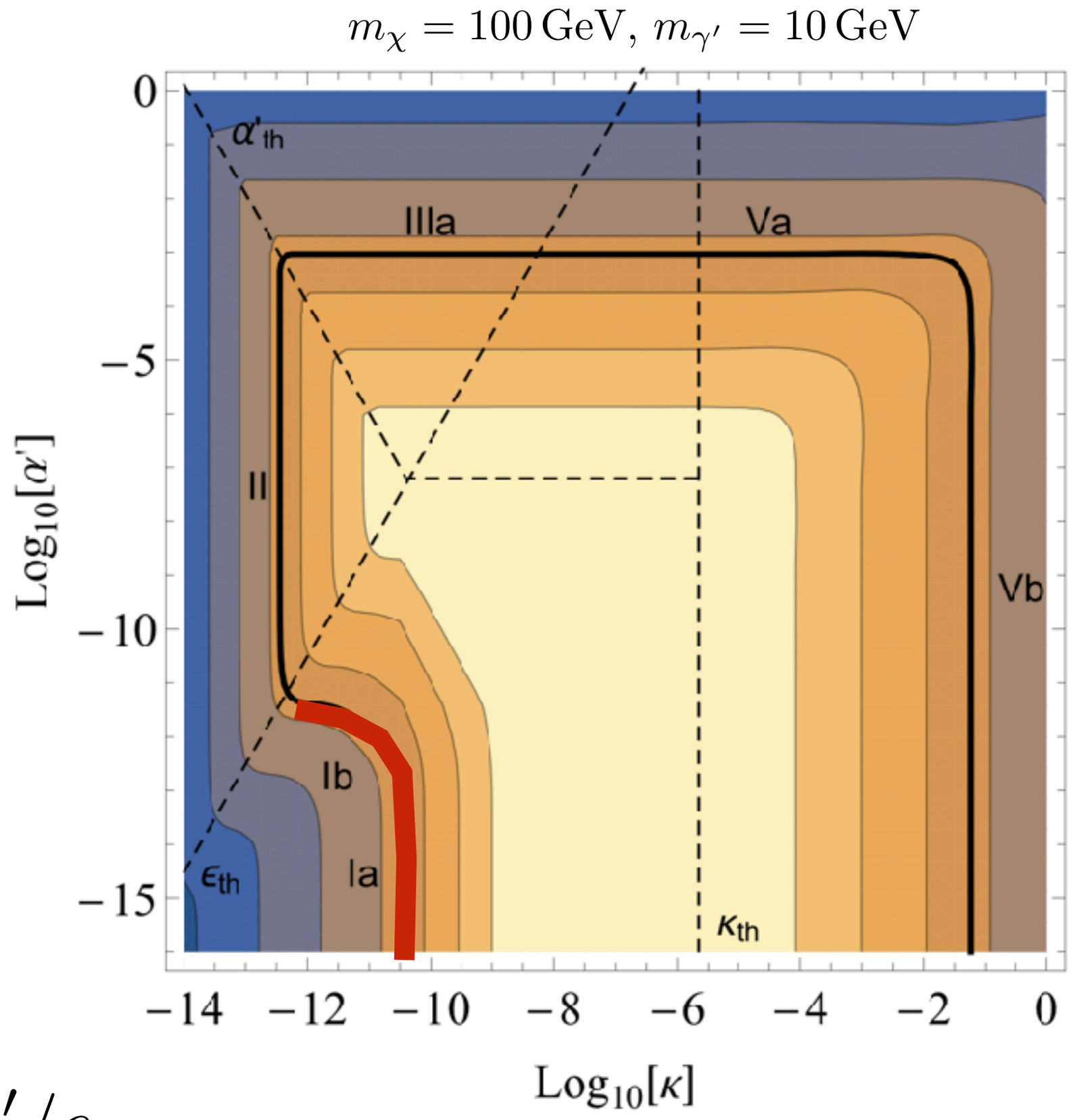
$\mathbf{T}_{\gamma'} = \mathbf{T}$

Type Ia

Type Ib

FREEZE-IN Ia & Ib

$m_{\gamma'} \neq 0$



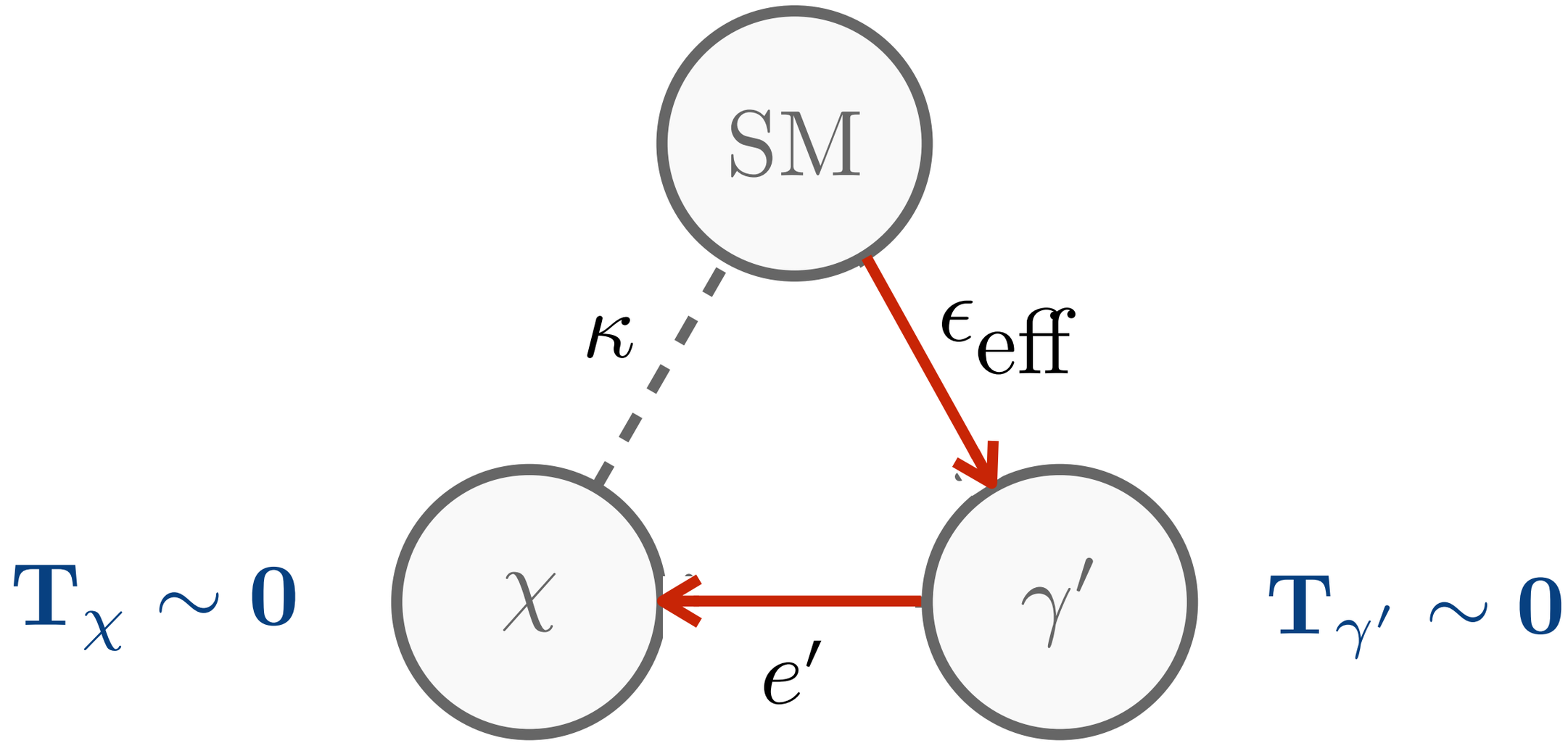
$\kappa = \epsilon\, e'/e$

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

NEW REGIME!

SEQUENTIAL FREEZE-IN

$m_{\gamma'} \neq 0$



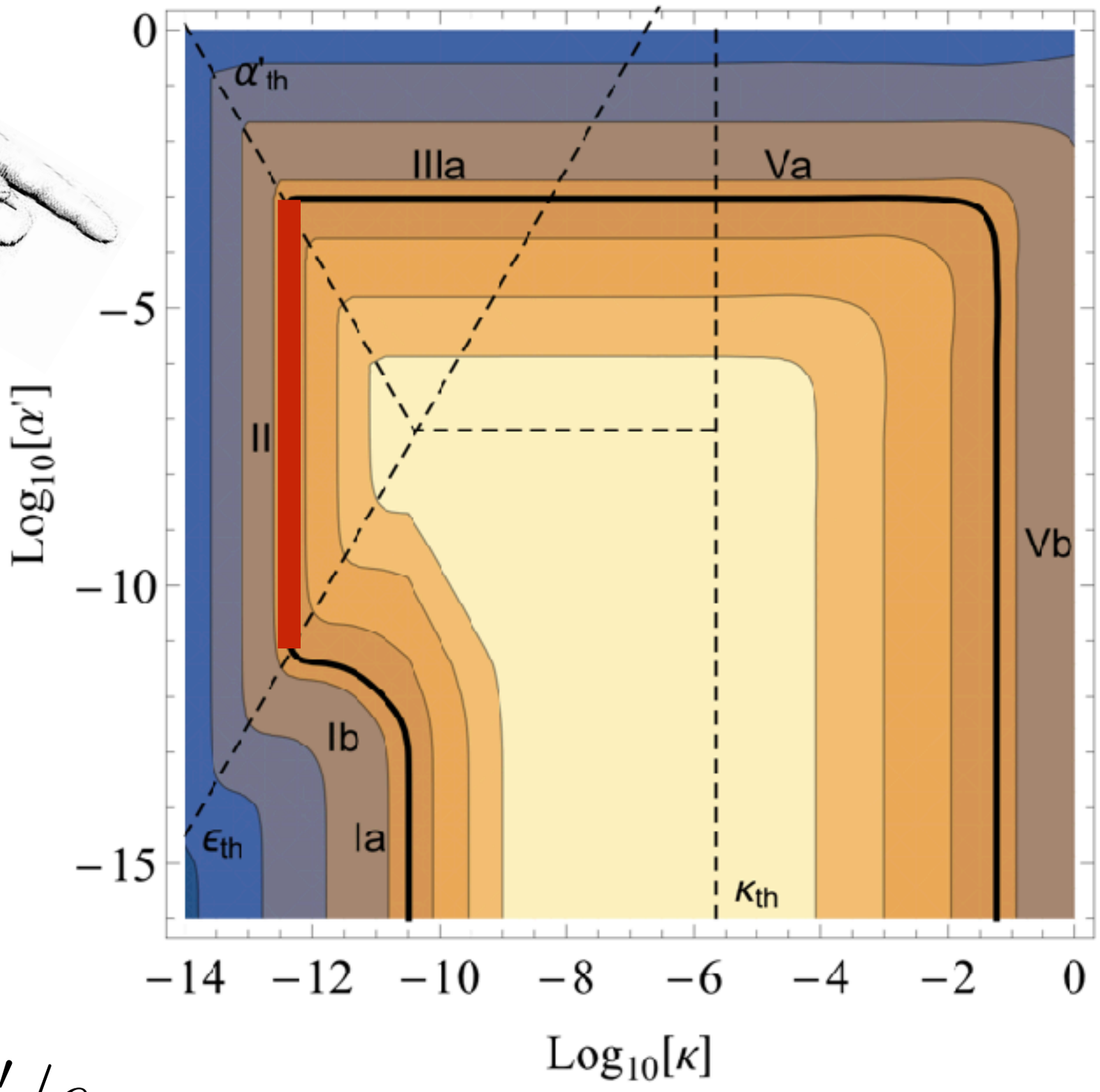
Type II

Hambye, M.T., Vandecasteele, Vanderheyden ’19
See also Bélanger et al ‘20

NEW REGIME!

SEQUENTIAL FREEZE-IN

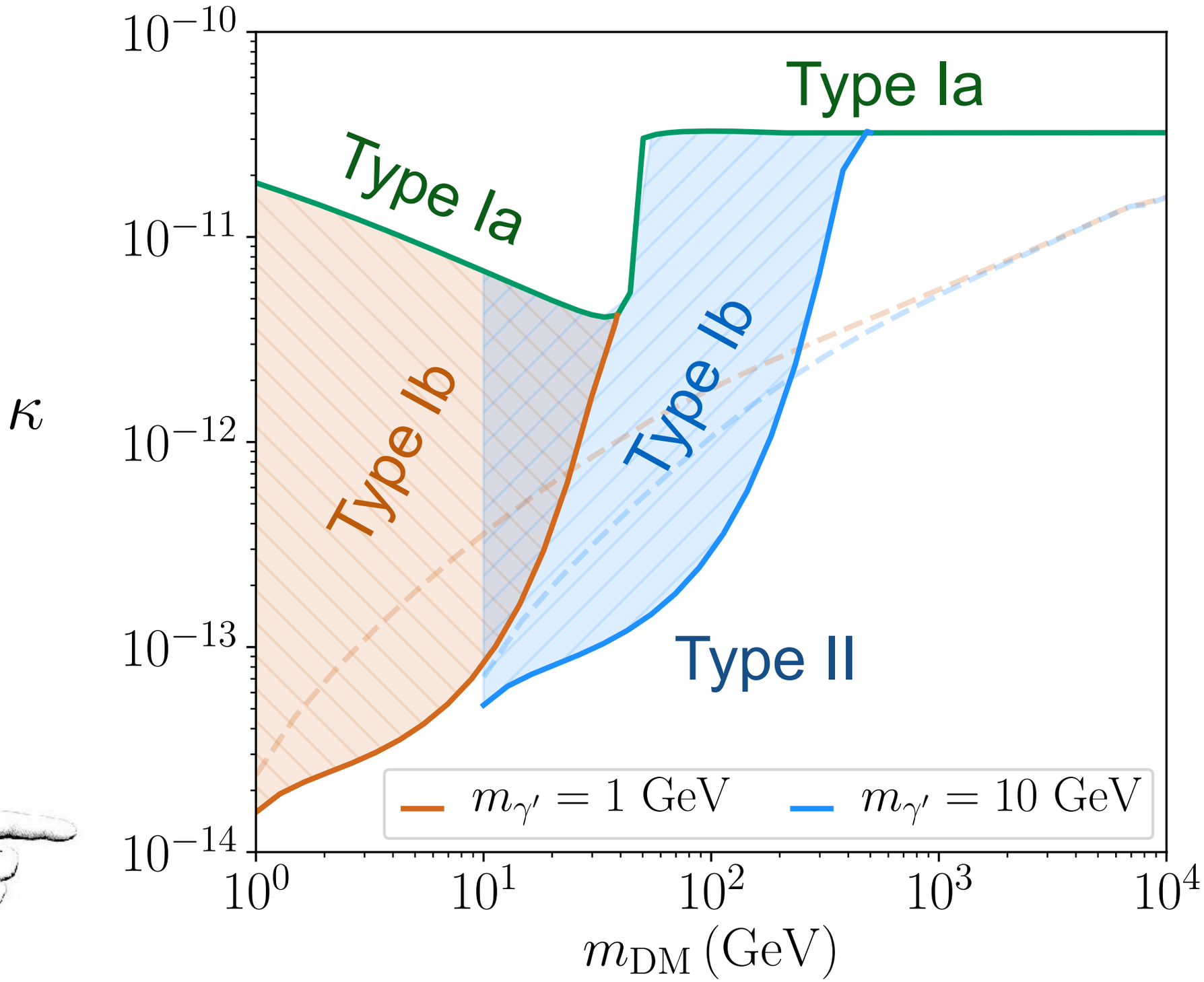
$$m_\chi = 100\,\mathrm{GeV},\ m_{\gamma'} = 10\,\mathrm{GeV}$$



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

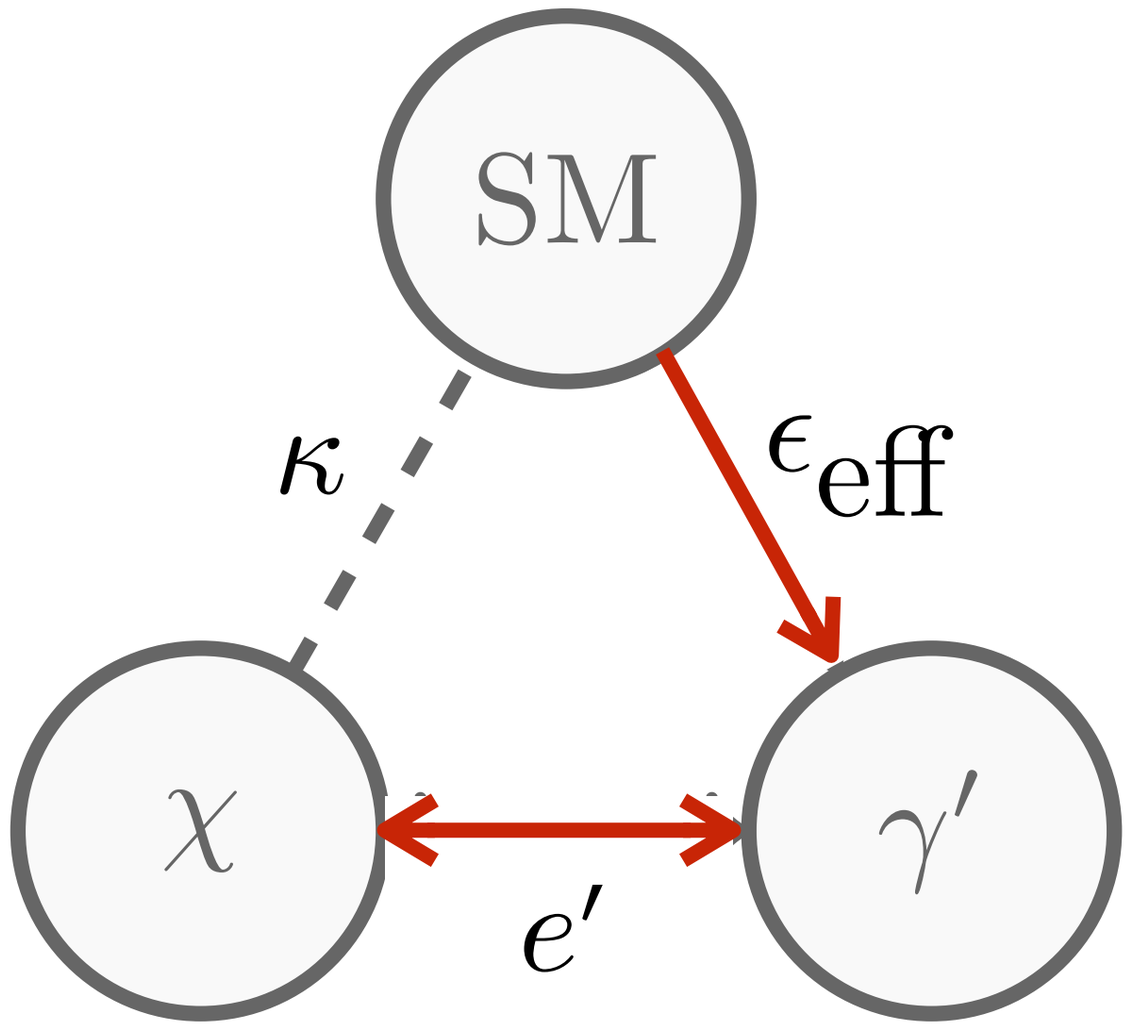
Hambye, M.T., Vandecasteele, Vanderheyden ’19

SEQUENTIAL FREEZE-IN CANDIDATES



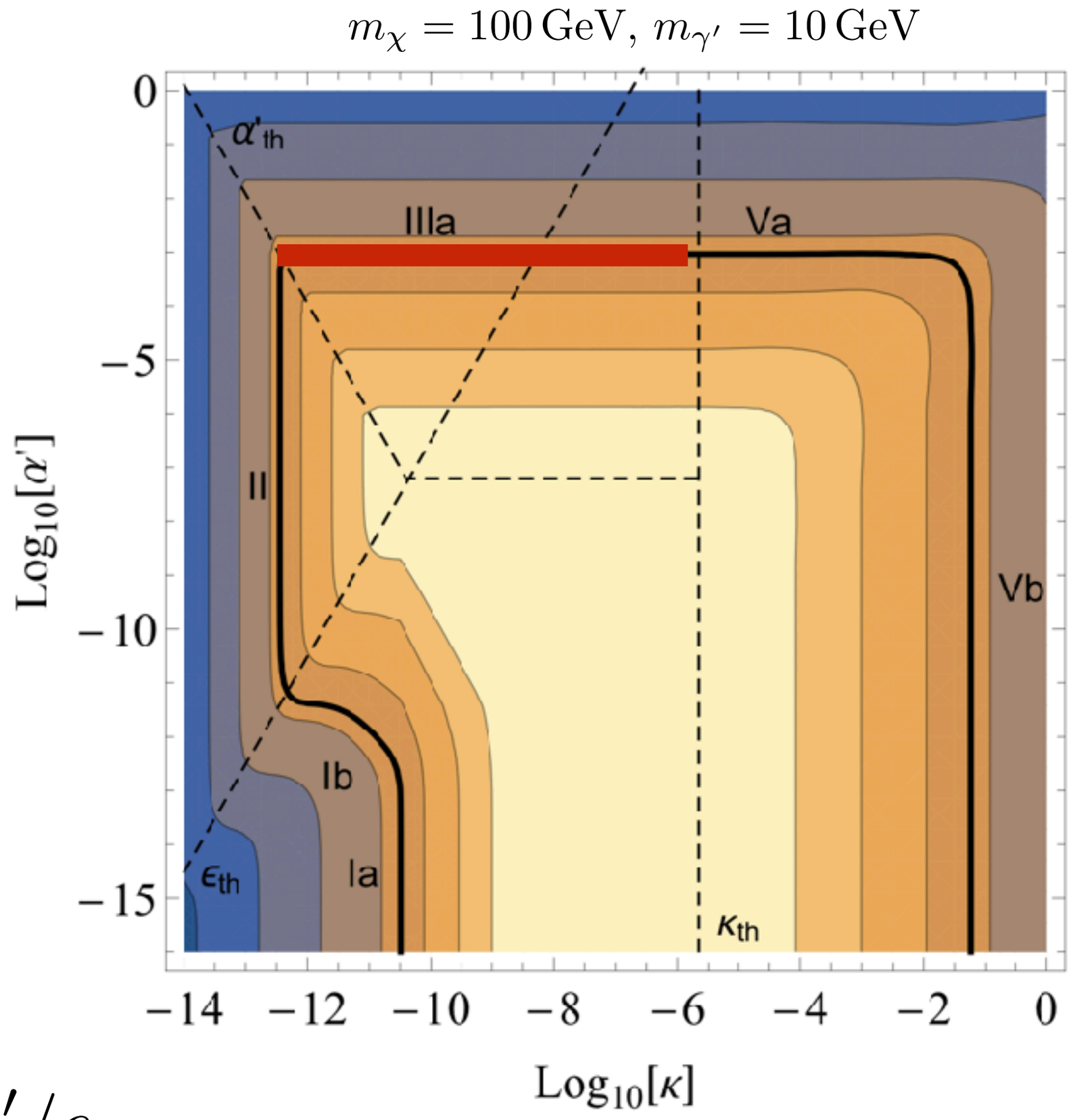
Hambye, M.T., Vandecasteele, Vanderheyden ’19

REANNIHILATION & SECLUDED FO



$$T' < T$$

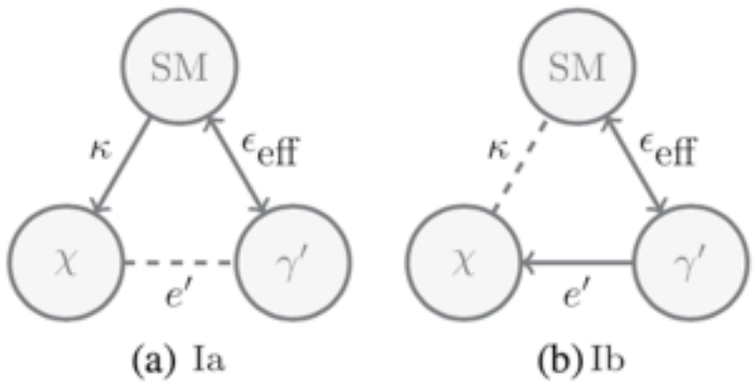
REANNIHILATION/SECLUDED FO



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

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

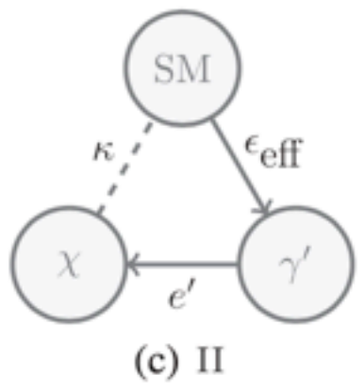
9 WAYS (5 REGIMES) TO PRODUCE DM



(a) Ia

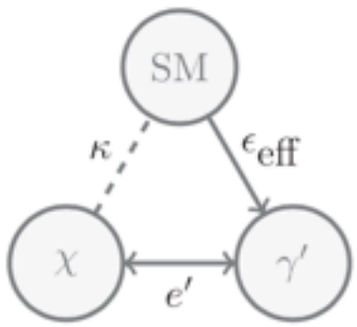
(b) Ib

freeze-in (Ia & Ib)

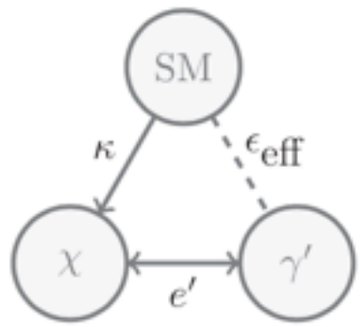


(c) II

sequential freeze-in (II)

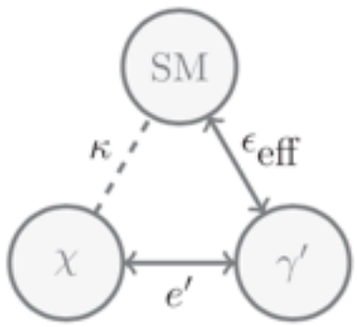


(d) IIIa & IVa

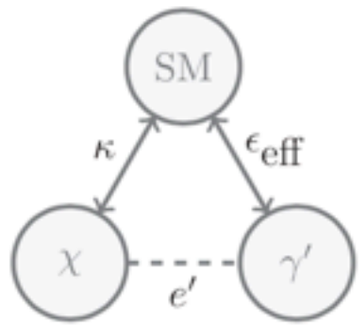


(e) IIIb & IVb

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

PRODUCTION TROUGH KINETIC MIXING

$$\mathrm{Ia} \rightarrow \mathrm{IIIb} \rightarrow \mathrm{IVb} \rightarrow \mathrm{Va} \rightarrow \mathrm{Vb} \quad (m_{\gamma'} = 0).$$

$$\mathrm{Ia} \rightarrow \mathrm{Ib} \rightarrow \mathrm{II} \rightarrow \mathrm{IIIa} \rightarrow \mathrm{Va} \rightarrow \mathrm{Vb} \quad (m_{\gamma'} \neq 0)$$

PRODUCTION TROUGH KINETIC MIXING

$$\mathrm{Ia} \rightarrow \boxed{\mathrm{IIIb} \rightarrow \mathrm{IVb}} \rightarrow \mathrm{Va} \rightarrow \mathrm{Vb} \quad (m_{\gamma'} = 0).$$

$$\mathrm{Ia} \rightarrow \mathrm{Ib} \rightarrow \mathrm{II} \rightarrow \boxed{\mathrm{IIIa}} \rightarrow \mathrm{Va} \rightarrow \mathrm{Vb} \quad (m_{\gamma'} \neq 0)$$

$$T' \leq T$$

DOMAIN OF THERMAL DM CANDIDATES?

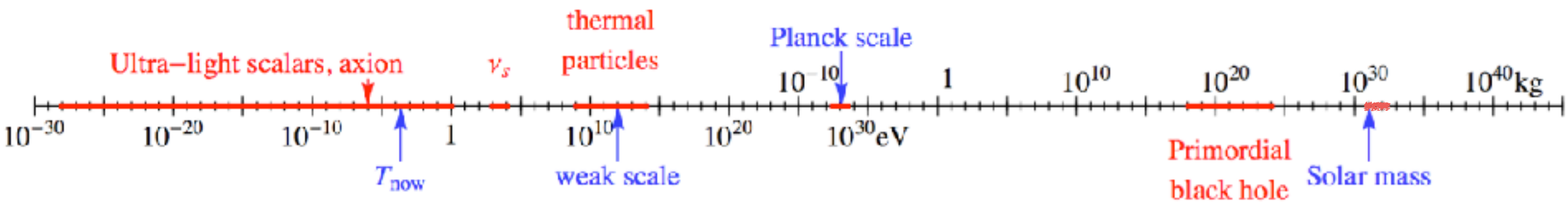
domain = DM mass range vs T’/T

WHICH DARK MATTER?

To first approximation, anything

non-baryonic, massive, neutral and long-lived

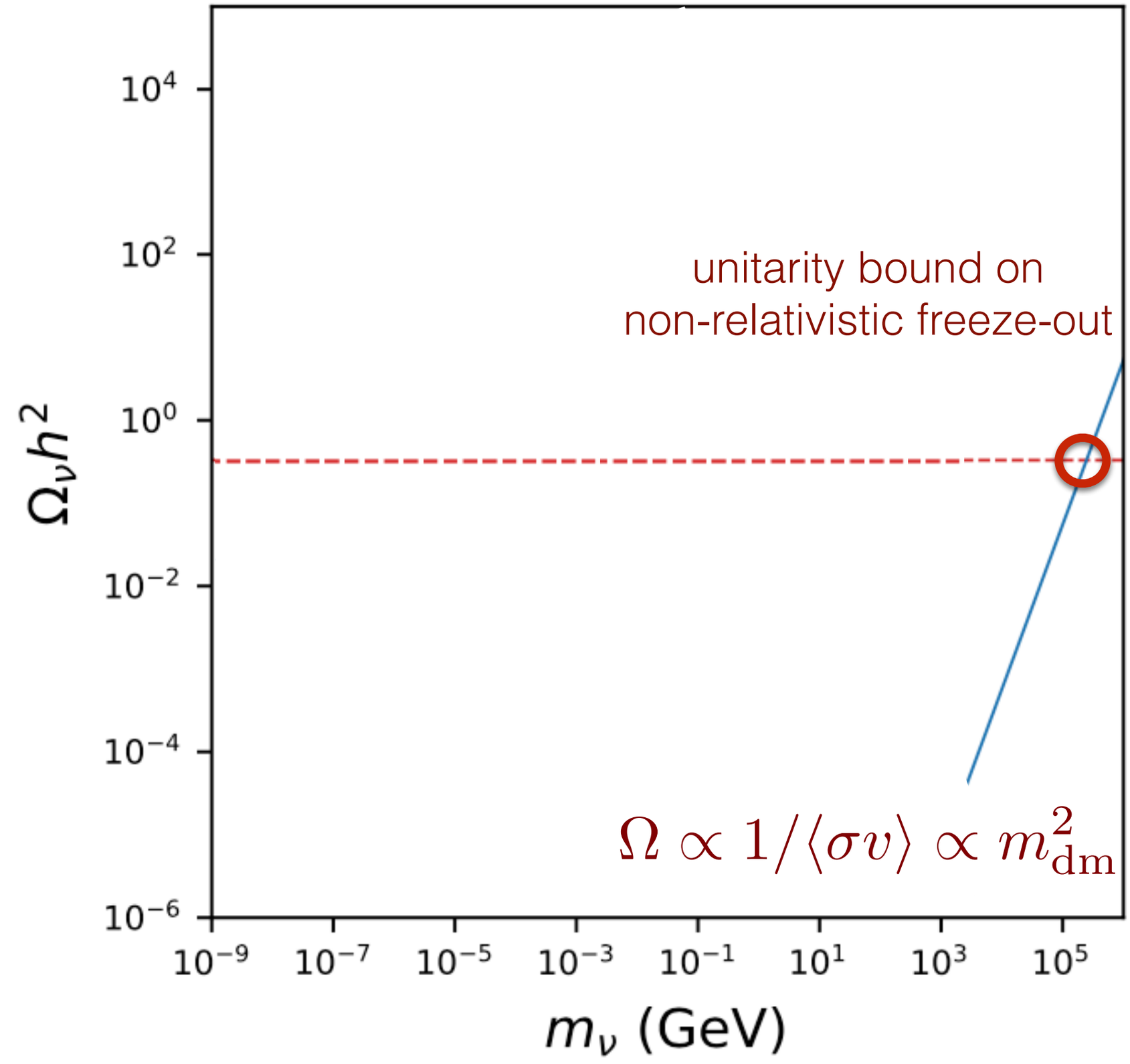
would do…



Courtesy M.Cirelli

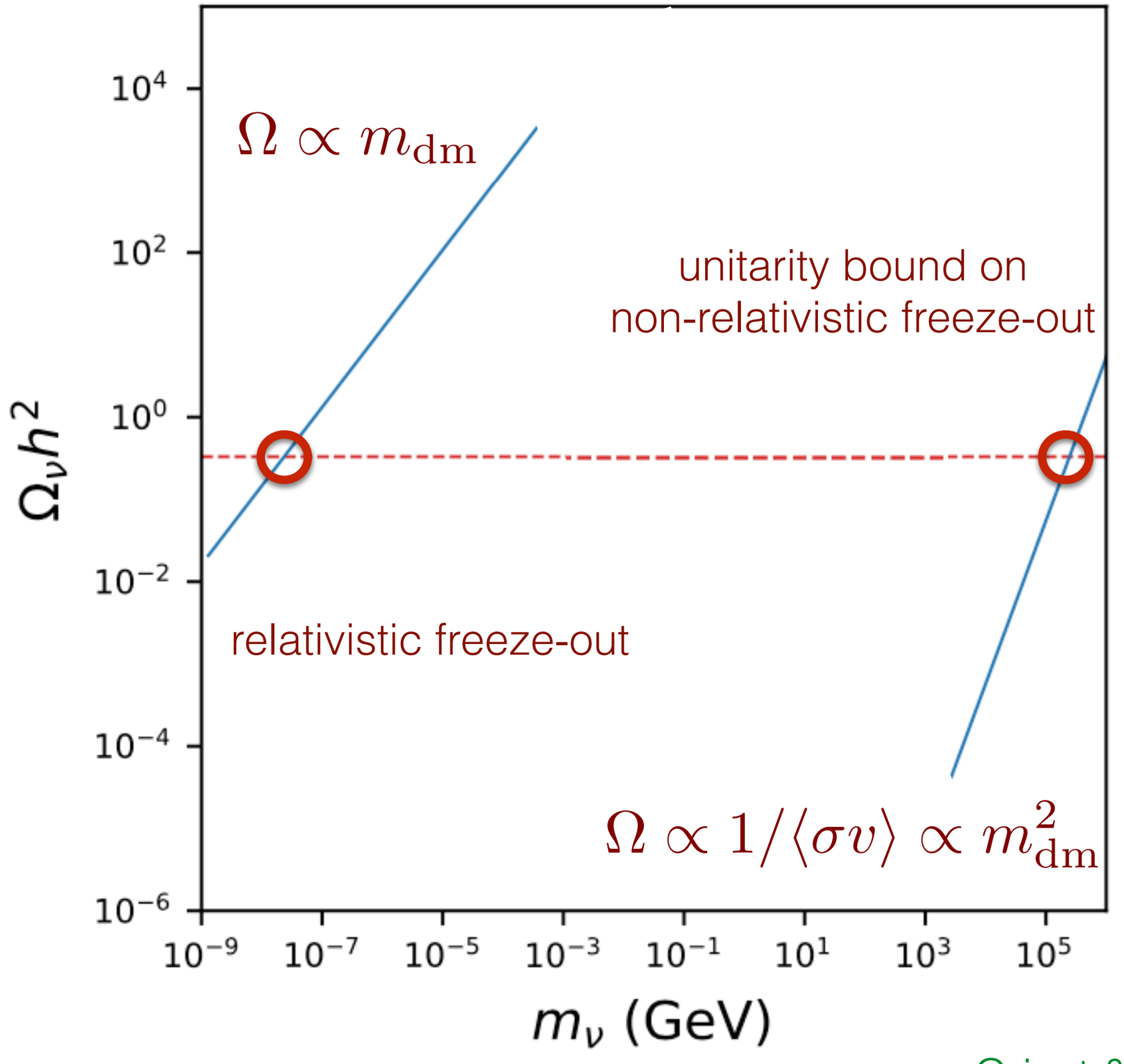
thermal particles
(aka WIMPS)

MAXIMAL DM MASS



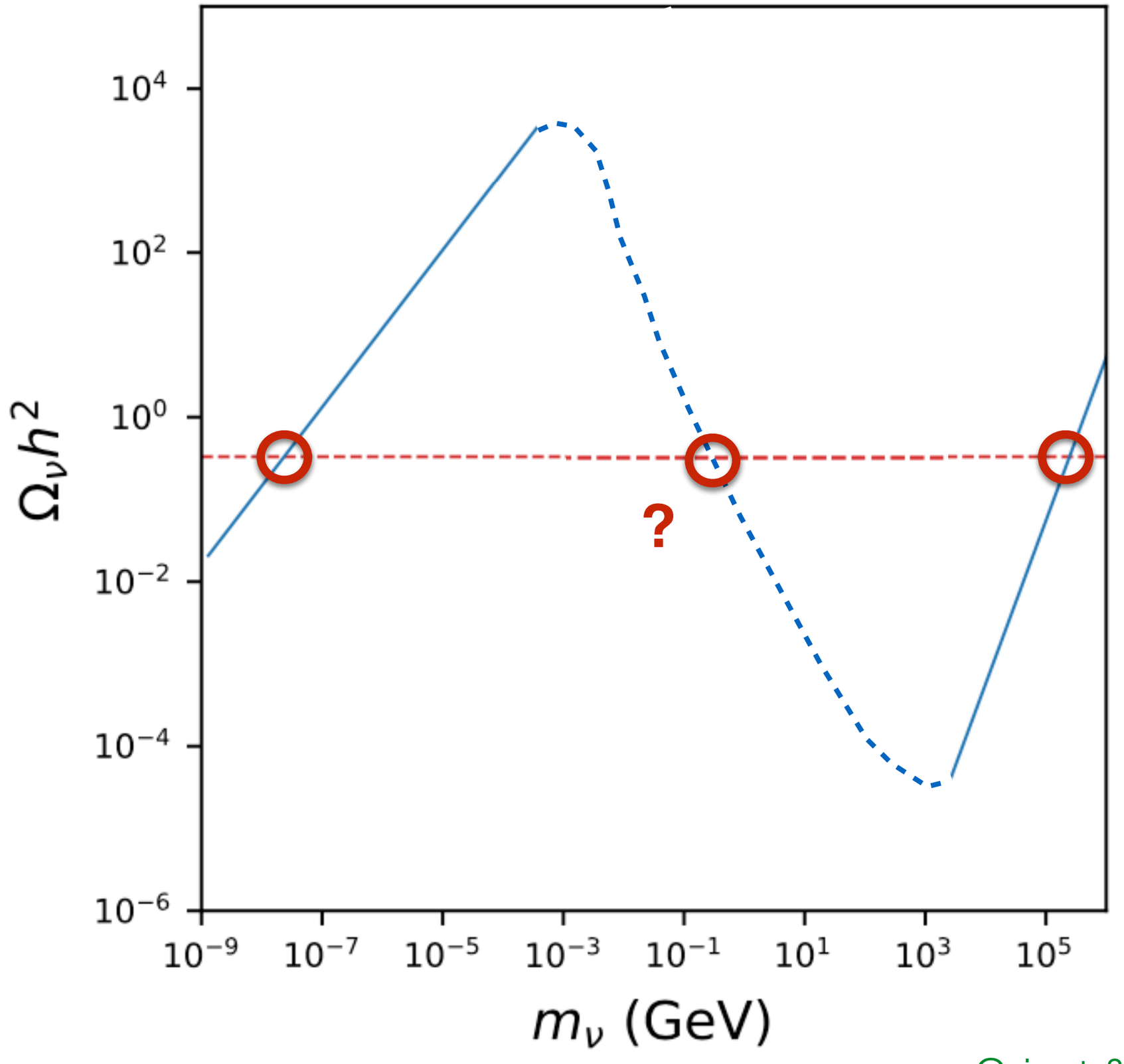
Griest & Kamionkowski

MINIMAL & MAXIMAL DM MASS



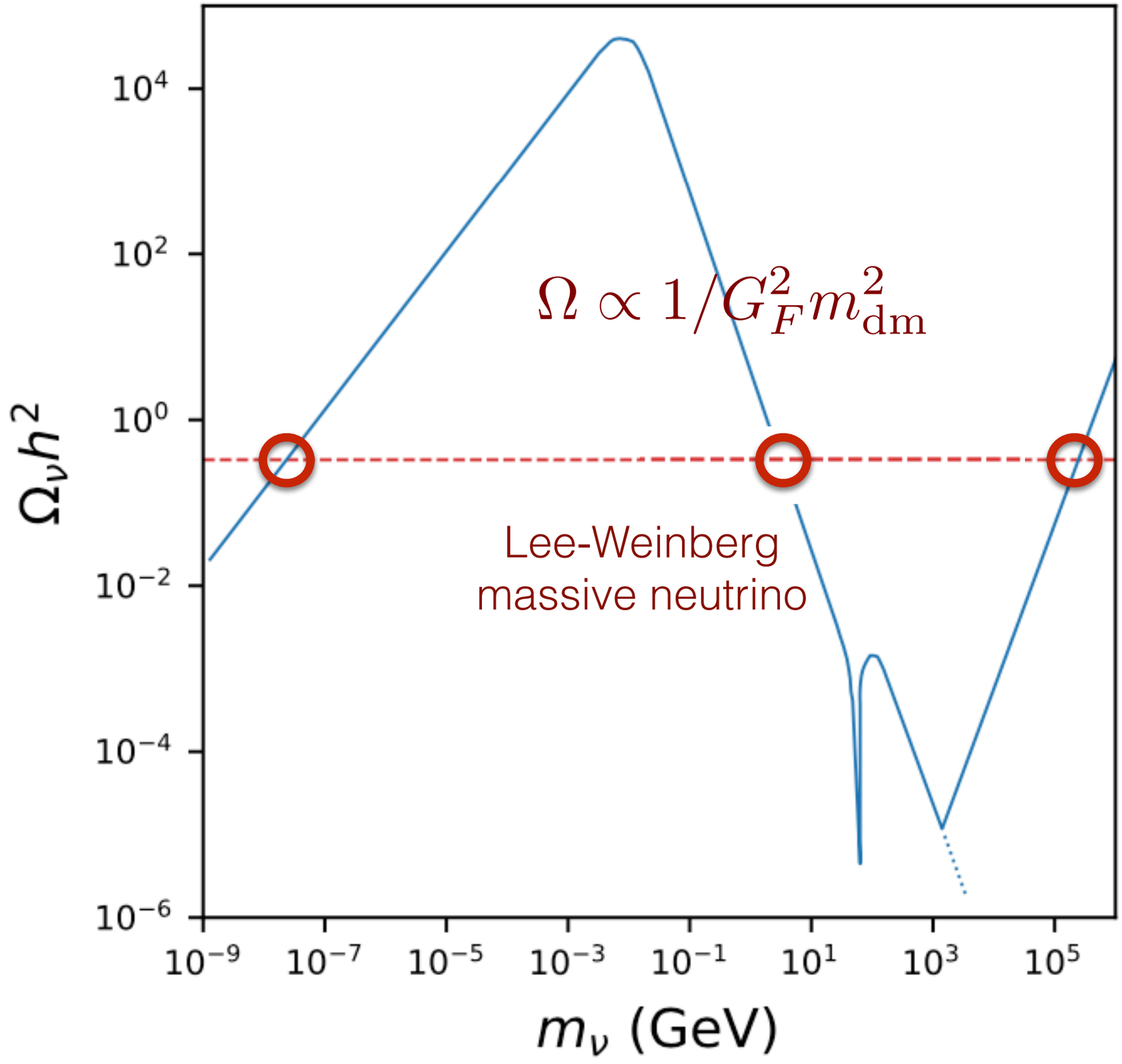
Griest & Kamionkowski
Cowsik-McLelland

MINIMAL & MAXIMAL DM MASS



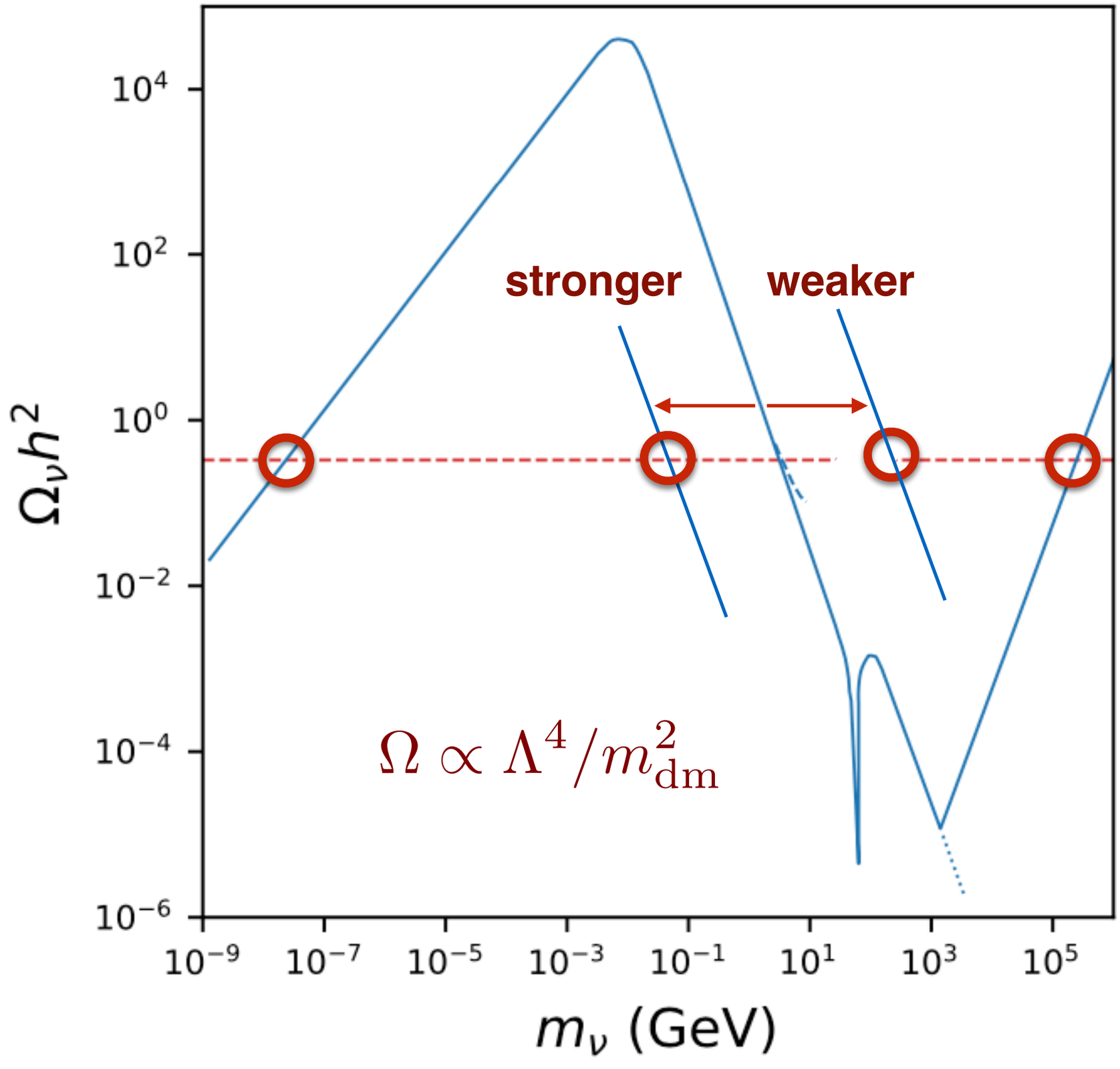
Griest & Kamionkowski
Cowsik-McLelland

AN OLD CLASSIC - DIRAC NEUTRINO DM

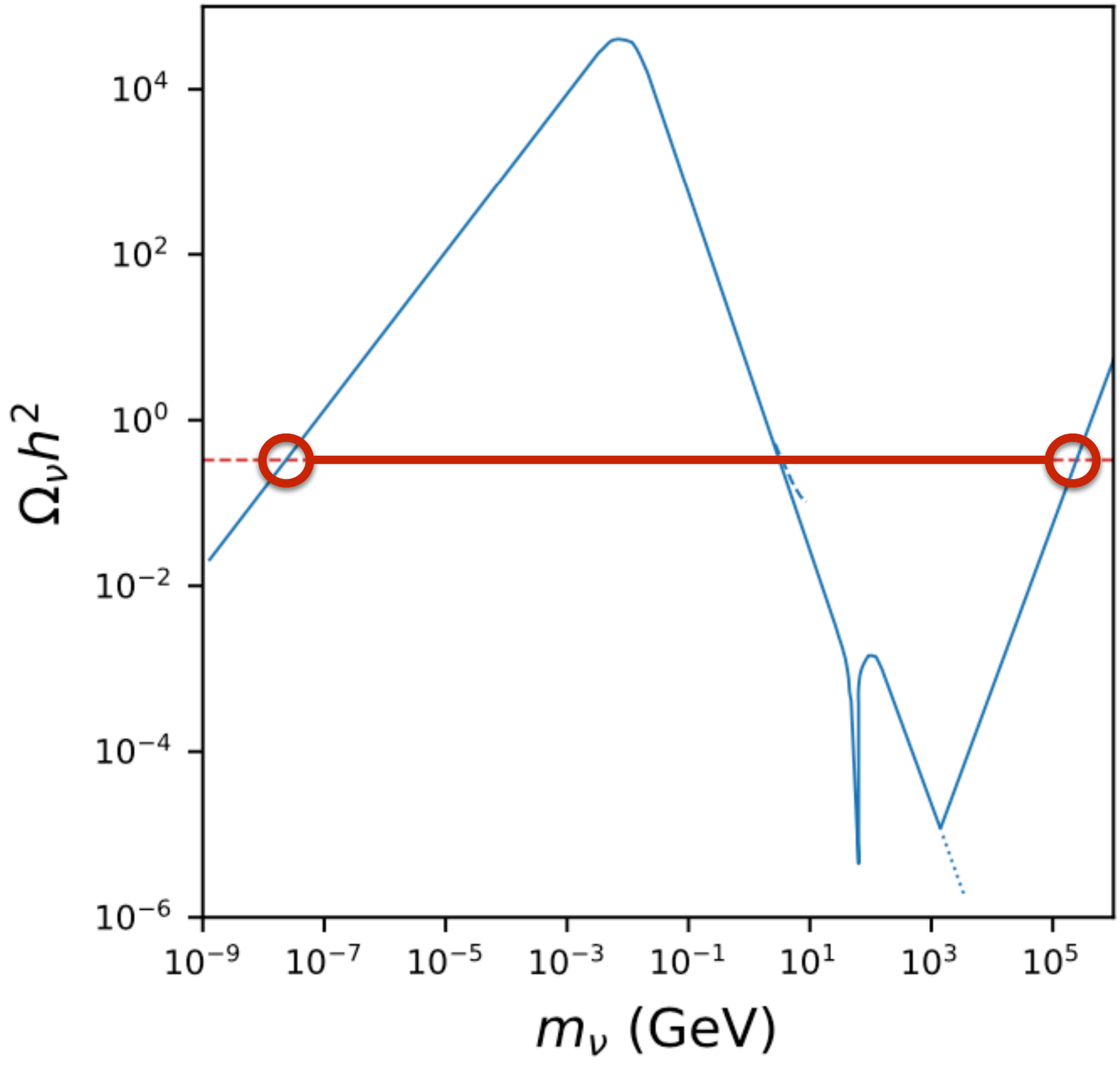


Plot from Kainulainen & Oliver ‘03

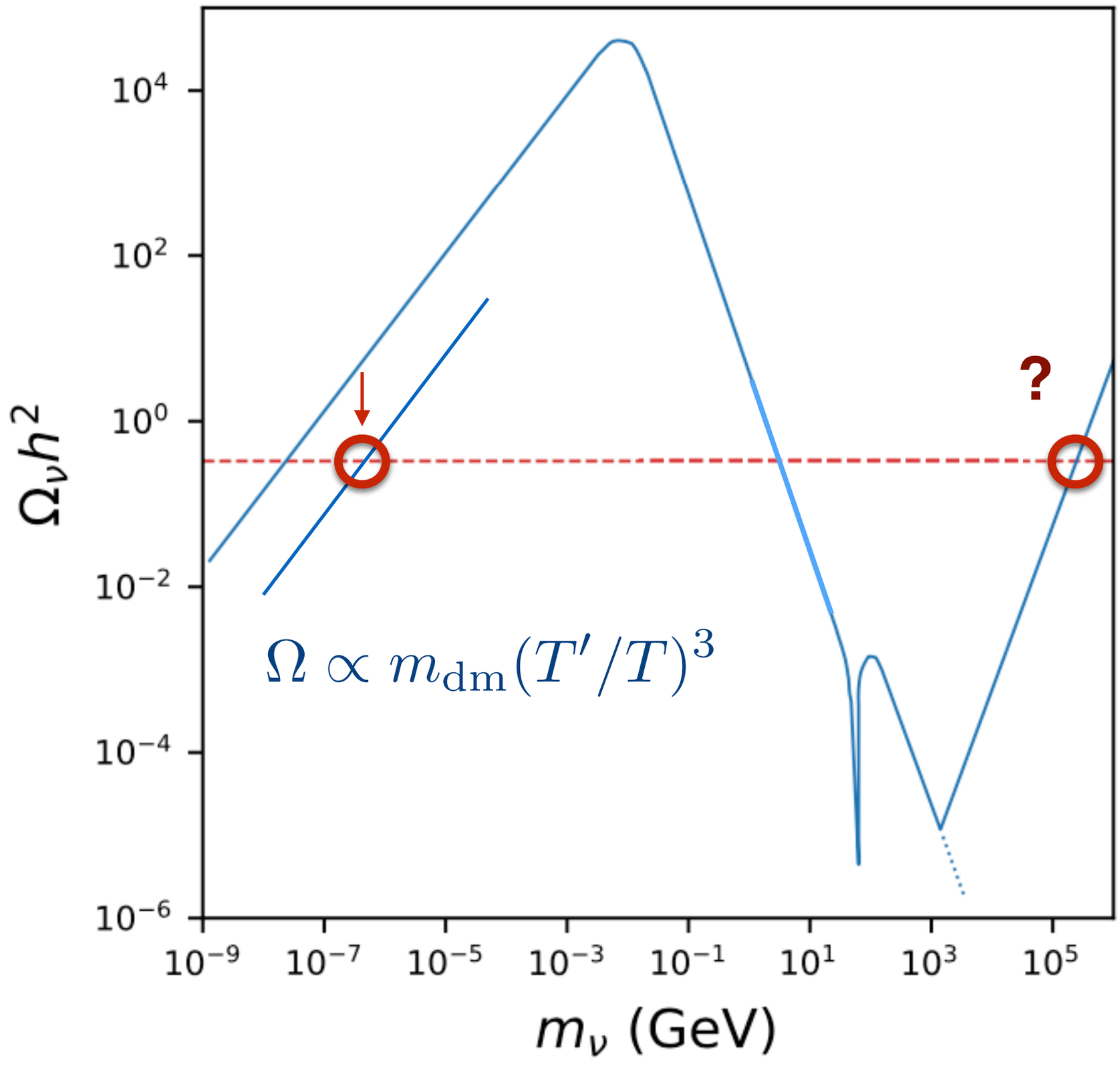
CHANGING INTERACTION STRENGTH



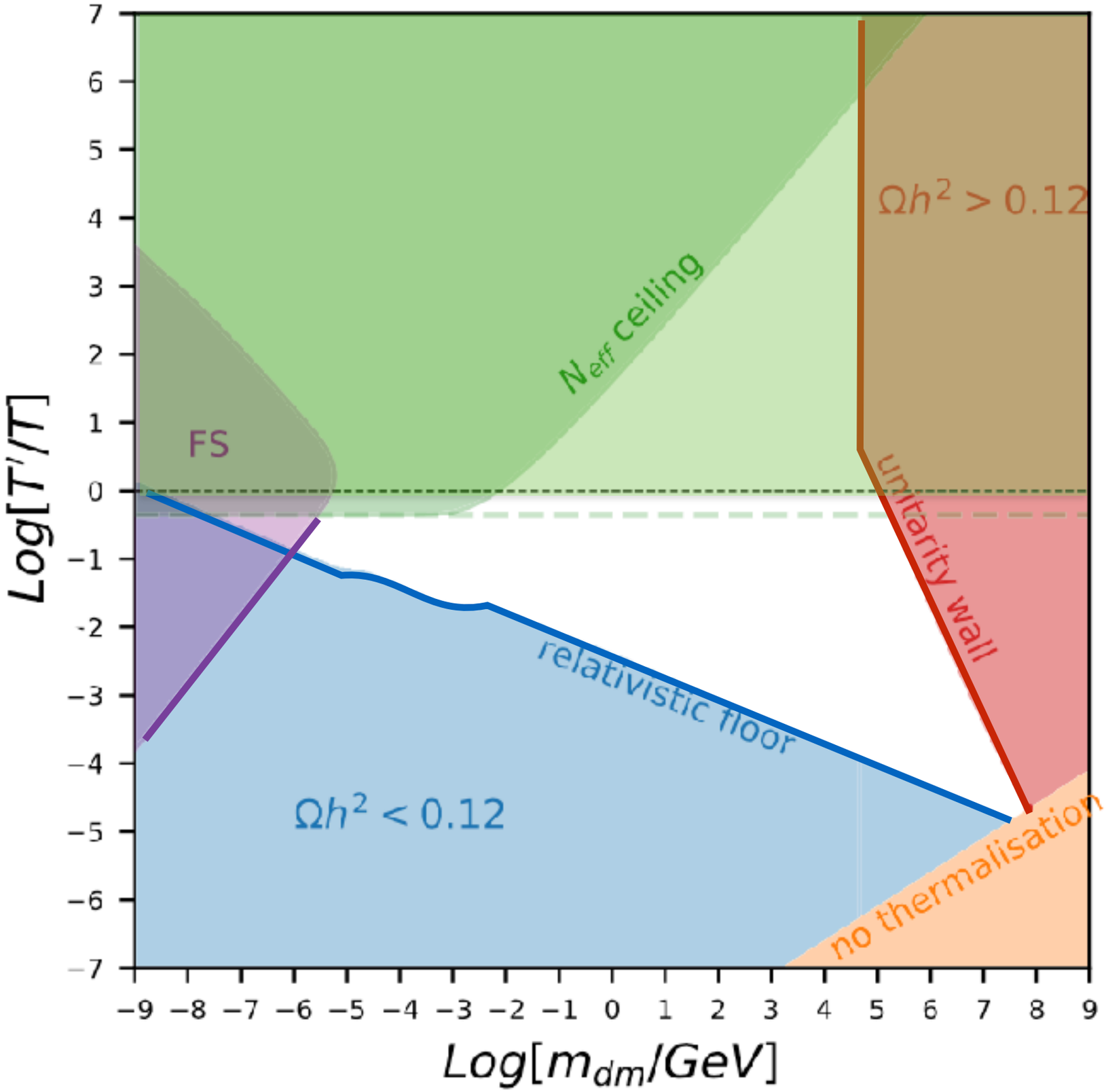
DOMAIN OF THERMAL CANDIDATES FOR T'=T



LOWERING T’/T

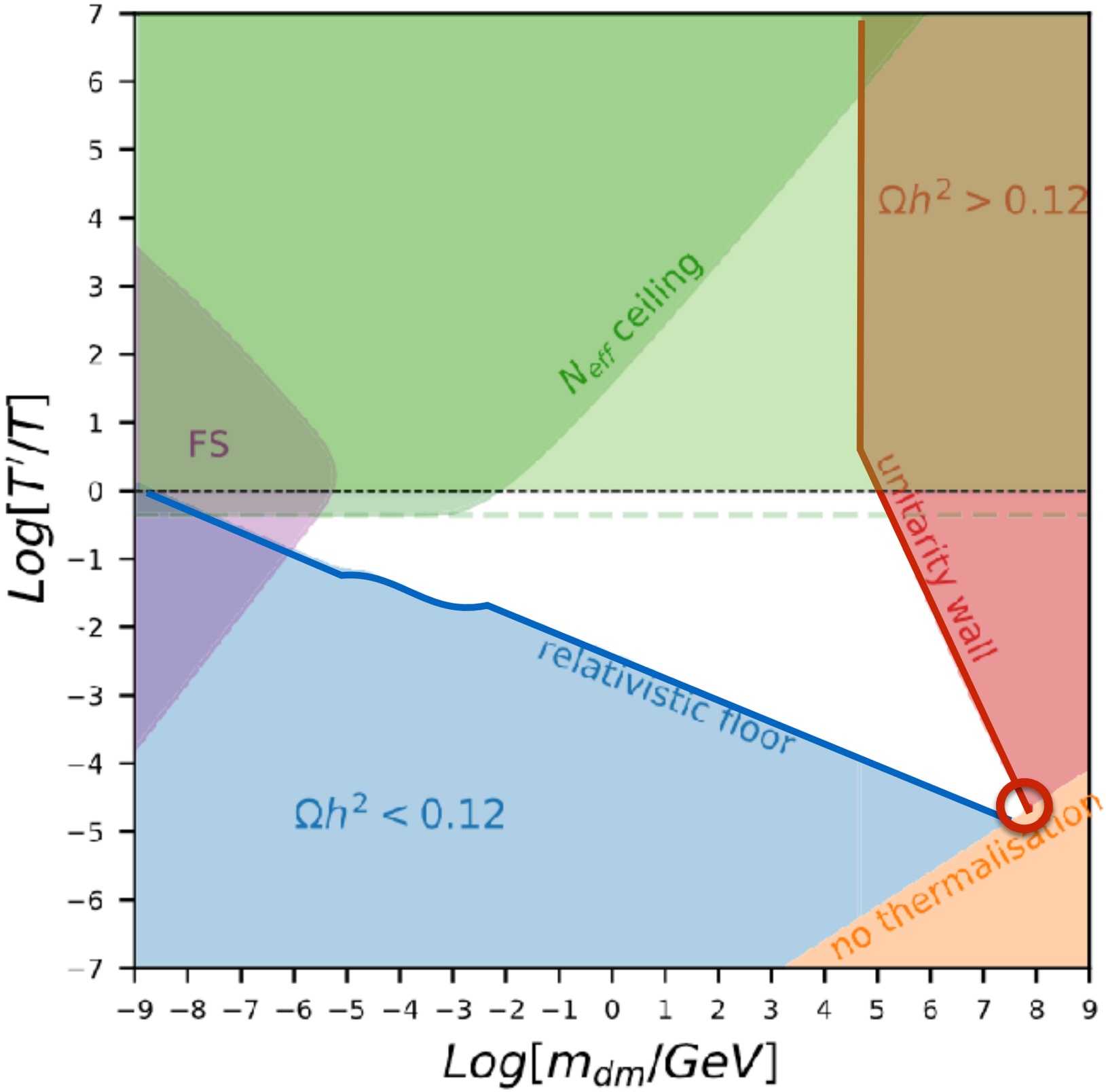

10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
$\Omega_\nu h^2$
?
$\Omega \propto m_{\rm dm}(T'/T)^3$
10^{-9} 10^{-7} 10^{-5} 10^{-3} 10^{-1} 10^{1} 10^{3} 10^{5}
m_ν (GeV)

DOMAIN OF THERMAL DM PARTICLES



Coy, Hambye, MHGT, Vanderheyden ’21
See also Hambye, Lucca, Vanderheyden ‘20

DOMAIN OF THERMAL DM PARTICLES

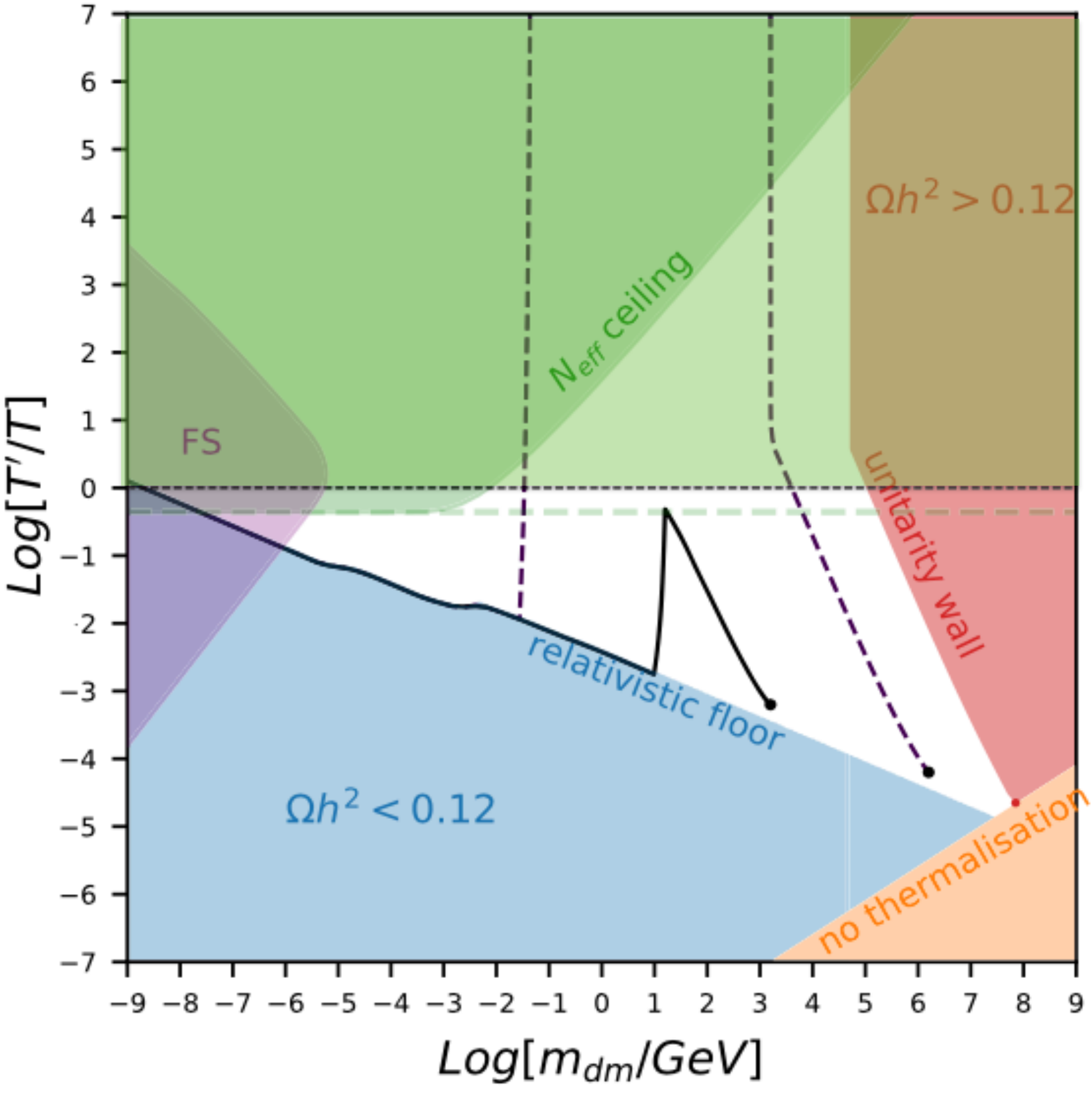


$m_{\rm dm} \approx 50$ PeV

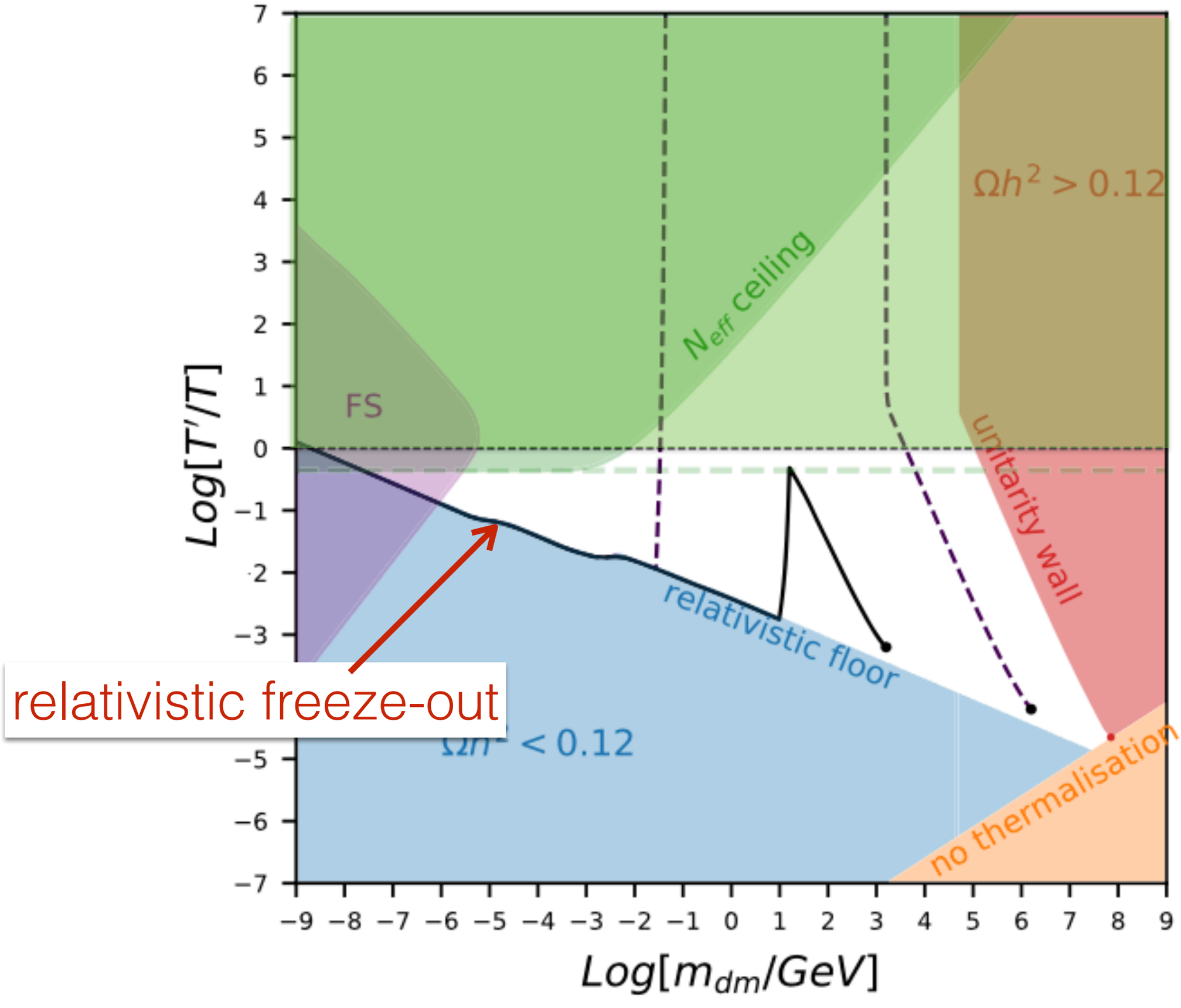
$T_{\rm fo} \approx 10^{11}$ GeV

Coy, Hambye, MHGT, Vanderheyden ’21
Hambye, Lucca, Vanderheyden ‘20

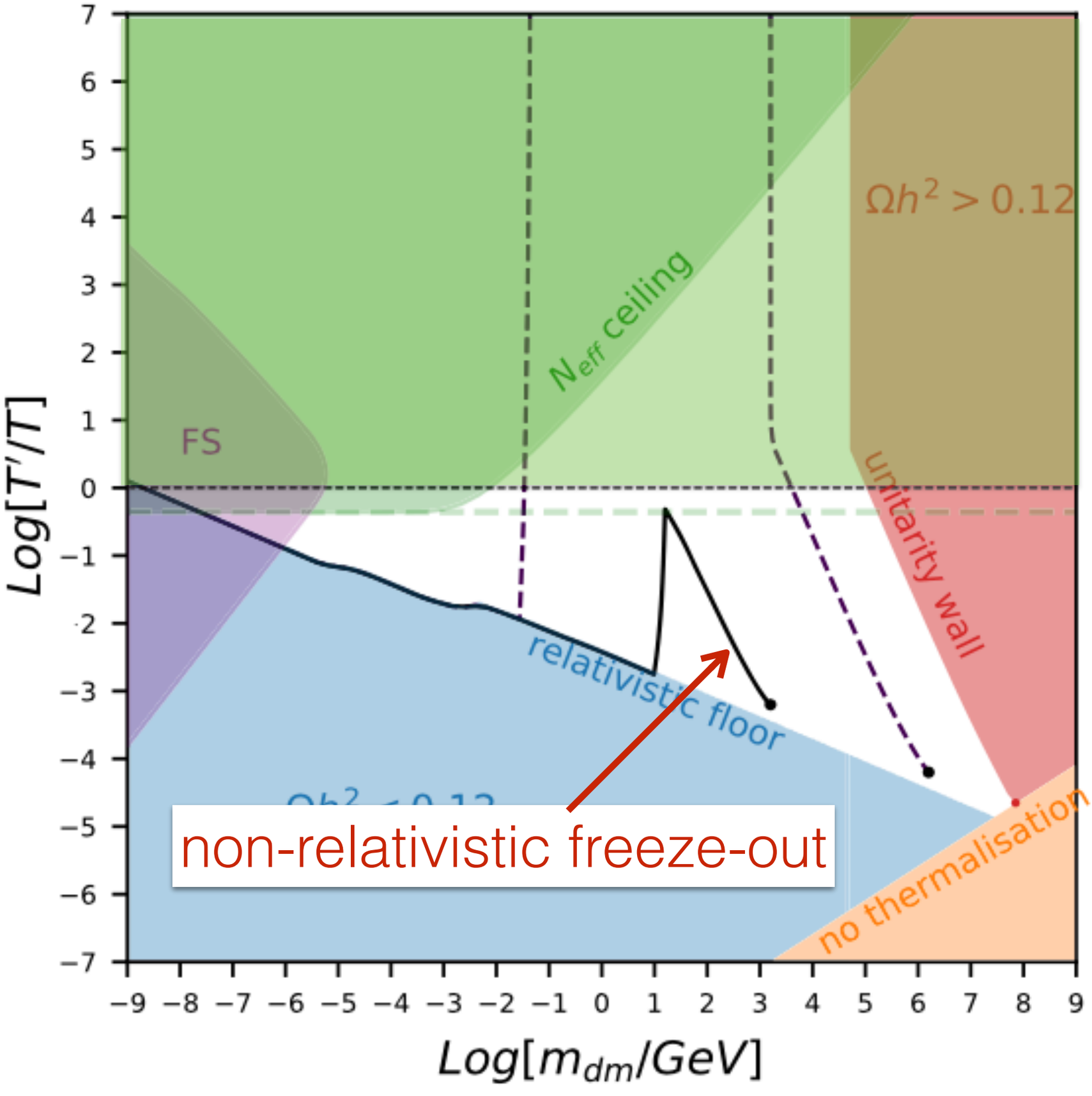
EXAMPLE : DARK QED



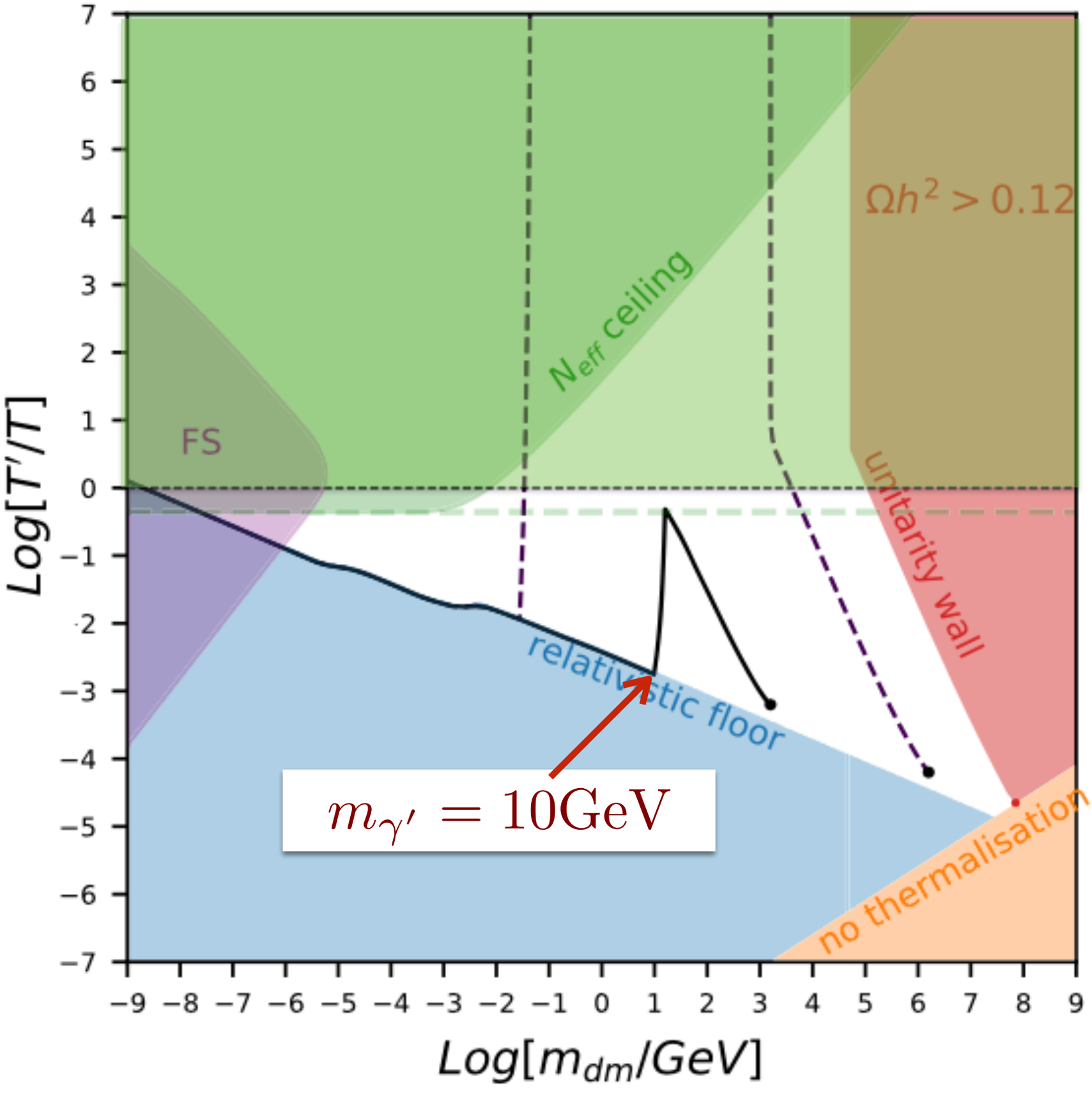
EXAMPLE : DARK QED



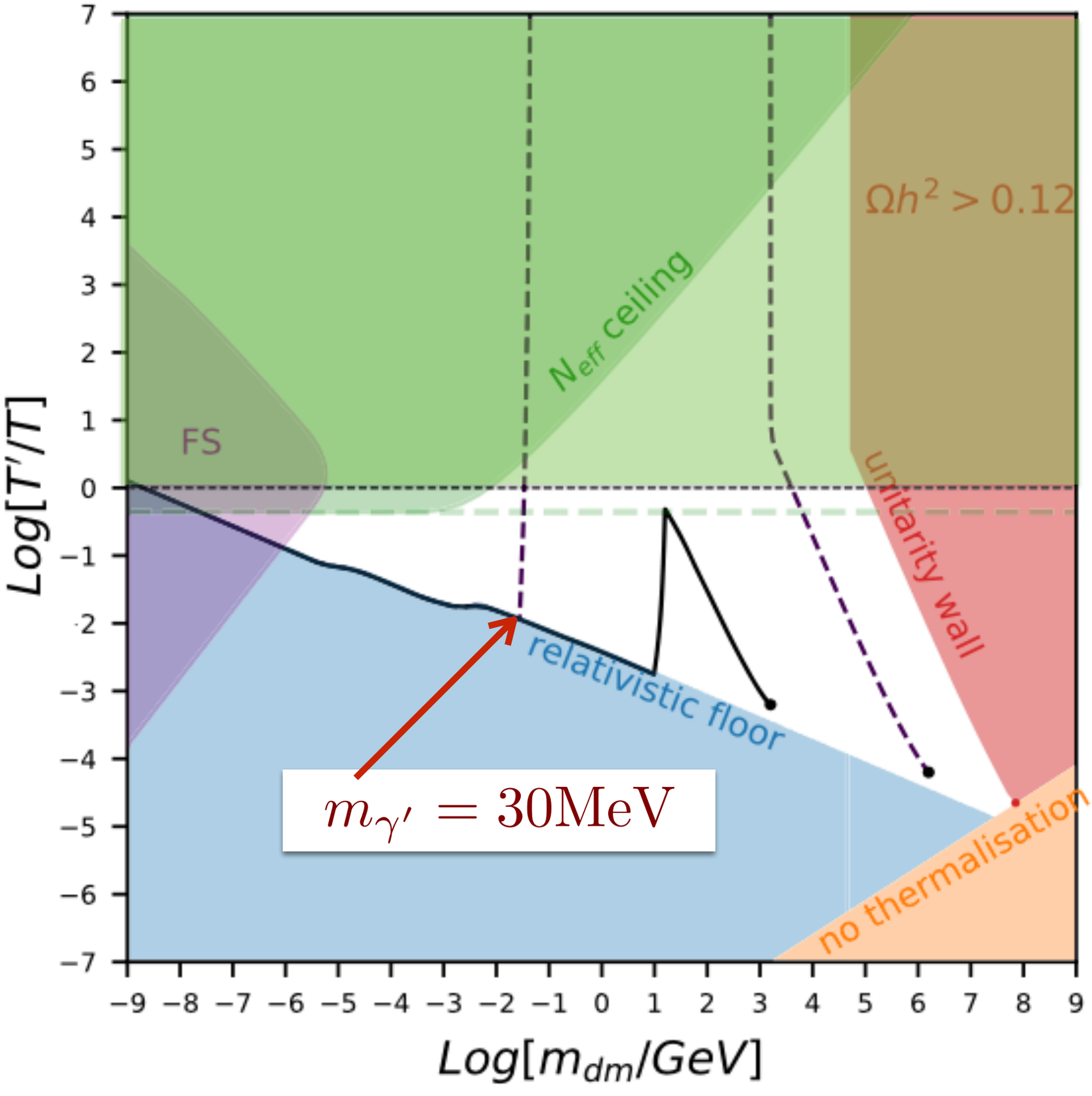
EXAMPLE : DARK QED



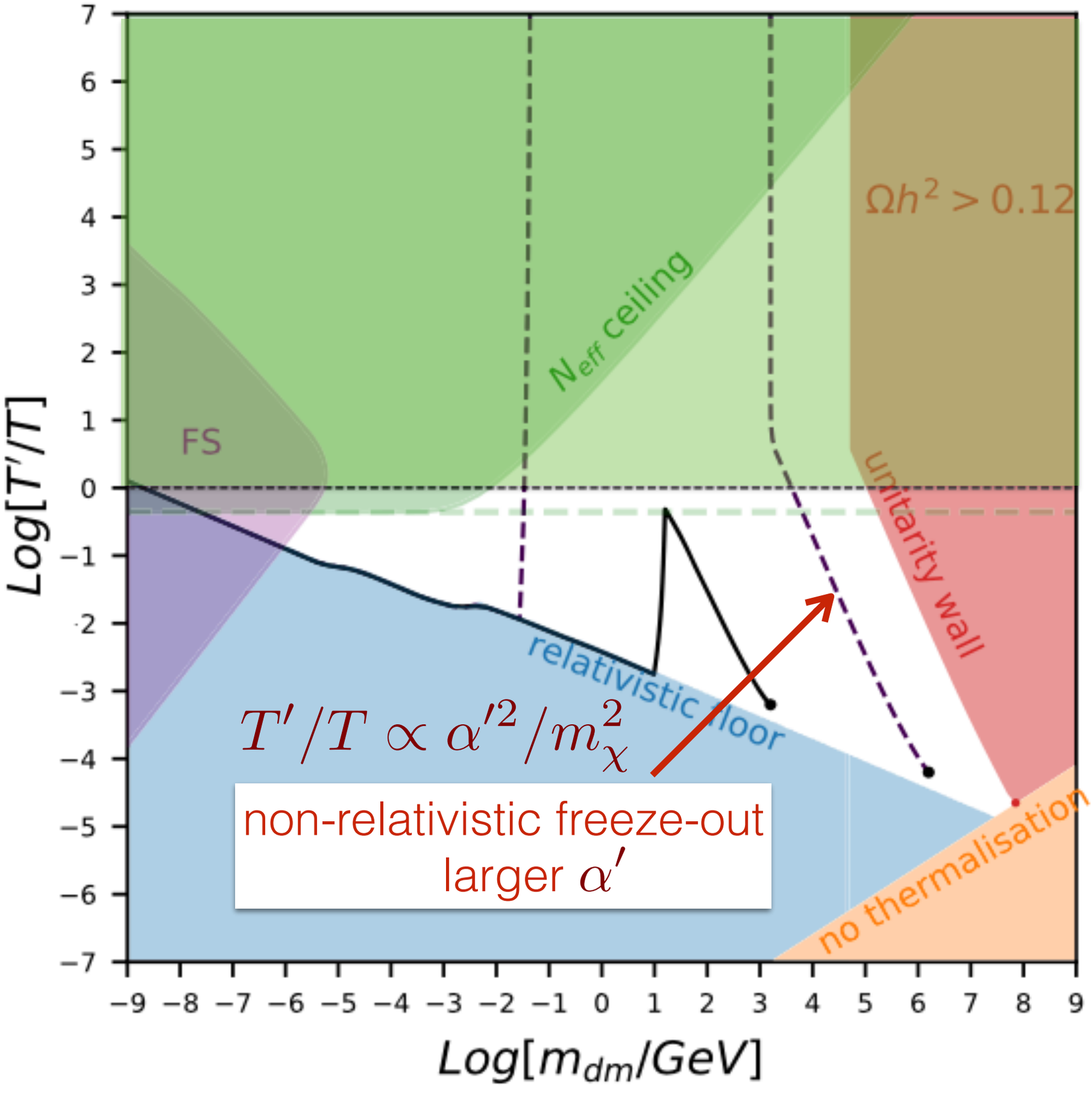
EXAMPLE : DARK QED



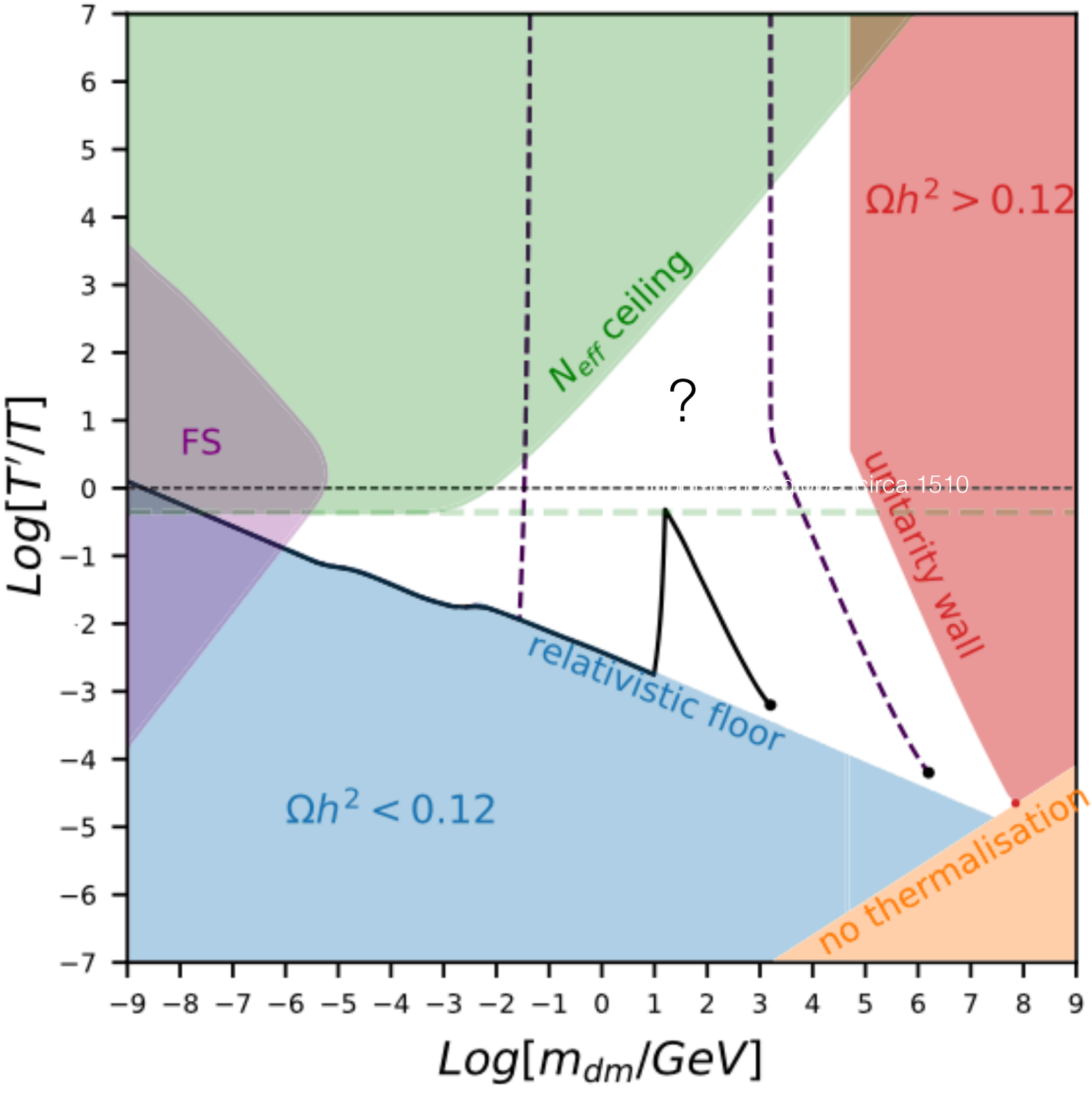
EXAMPLE : DARK QED



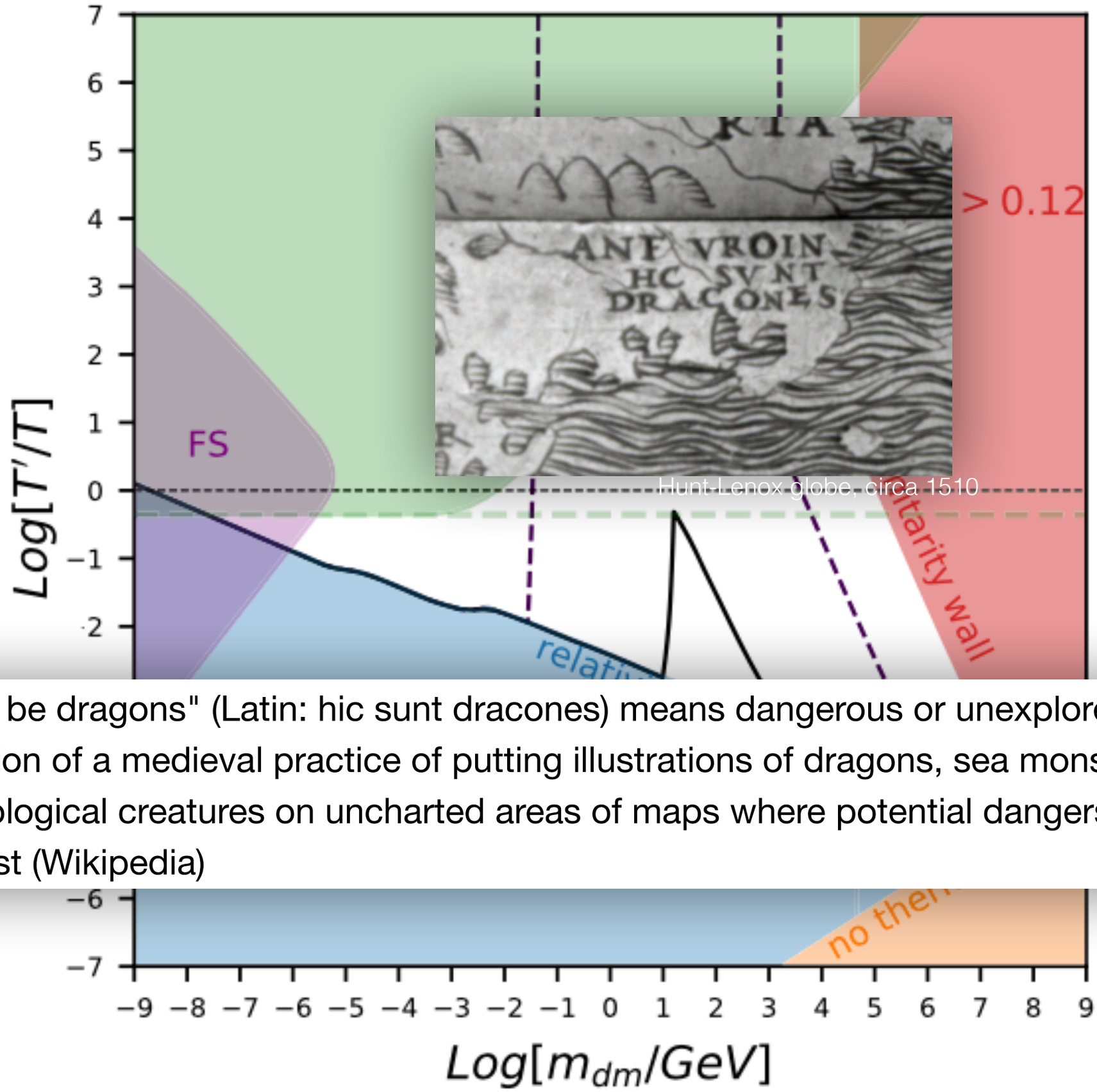
EXAMPLE : DARK QED



EXAMPLE : DARK QED



EXAMPLE : DARK QED

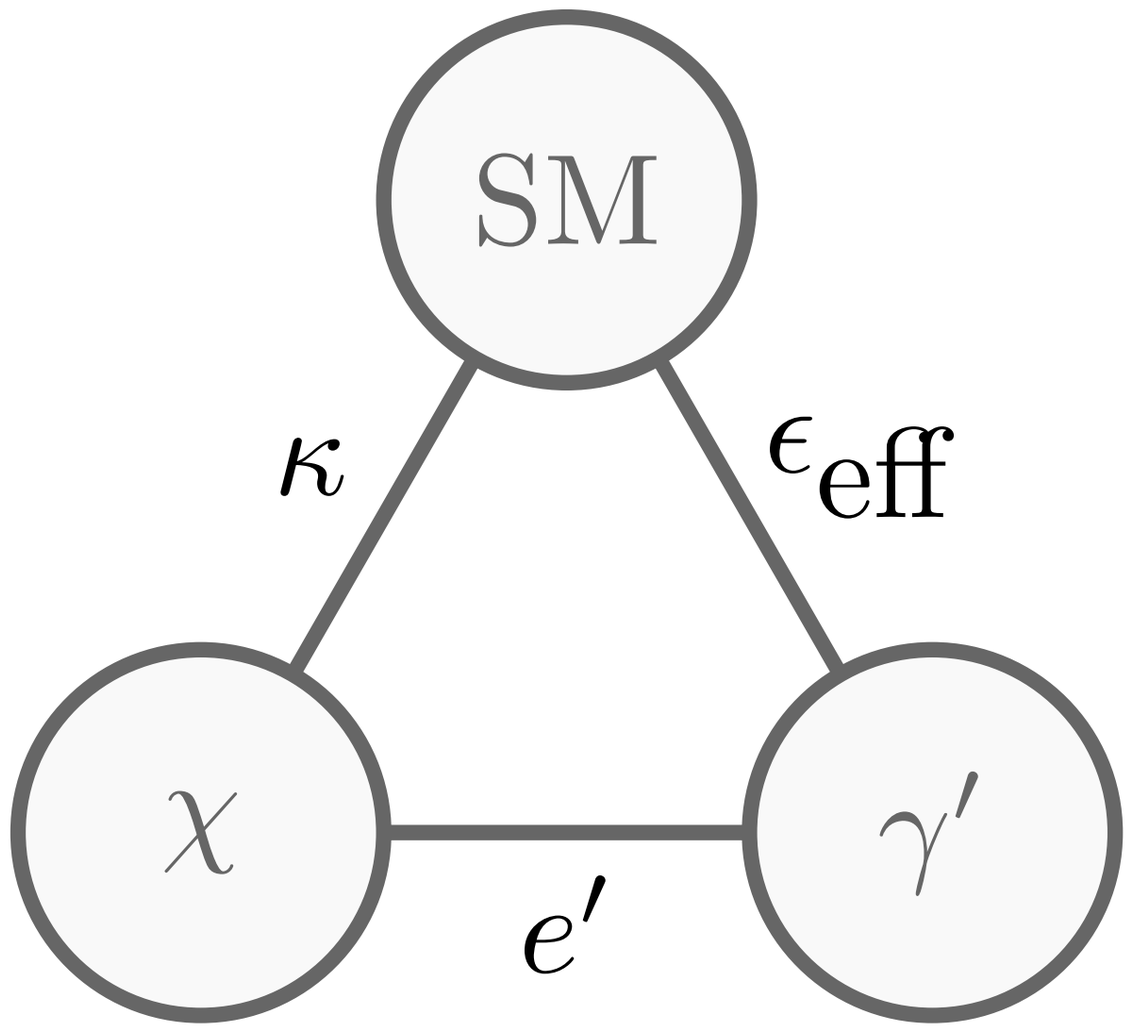


Hunt-Lenox globe, circa 1510

"Here be dragons" (Latin: hic sunt dracones) means dangerous or unexplored territories, in imitation of a medieval practice of putting illustrations of dragons, sea monsters and other mythological creatures on uncharted areas of maps where potential dangers were thought to exist (Wikipedia)

BACKUP STORY (I)

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 »

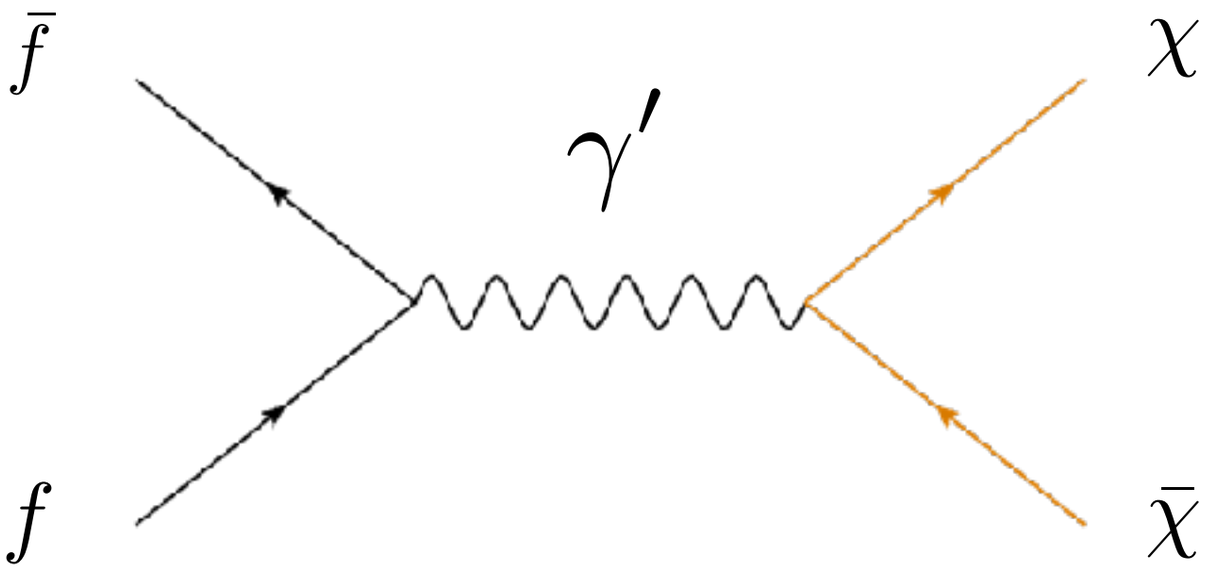
$$\mathcal{L} \supset e\bar{\psi}\gamma^\mu\psi(A_\mu - \epsilon A'_\mu)$$
$$+ e'\bar{\chi}\gamma^\mu\chi A'_\mu + \frac{1}{2}m^2_{\gamma'}\, A'_\mu A'^\mu$$

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

SM emission of DP with coupling ϵ

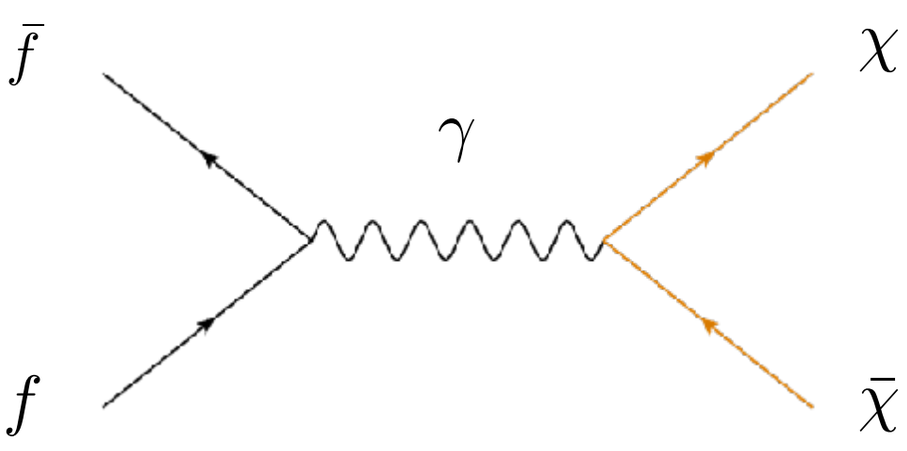
$m_{\gamma'} \to 0$?

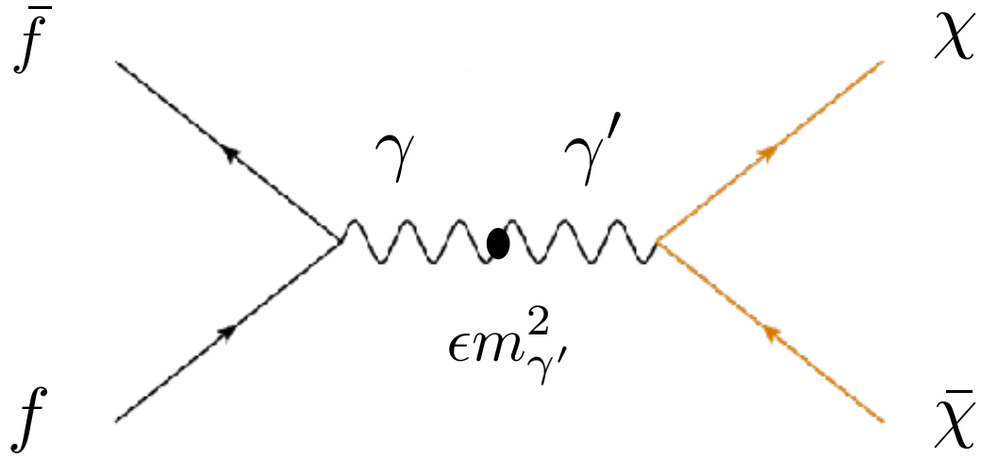
VIRTUAL DARK PHOTON EXCHANGE



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

VIRTUAL DARK PHOTON EXCHANGE

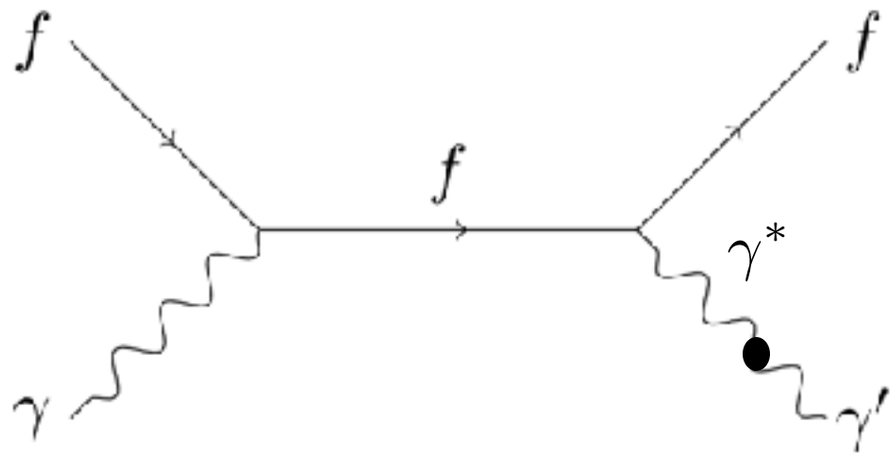




$$\mathcal{M}_{\rm vir} \sim \; e^2 \kappa \; J^{\mu}_{\rm em} \, \eta_{\mu\nu} \, J^{\nu}_{\chi} \times \frac{1}{k^2} \left(1 + \frac{m^2_{\gamma'}}{k^2 - m^2_{\gamma'}} + \dots \right)$$

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

RADIATION OF DARK PHOTONS



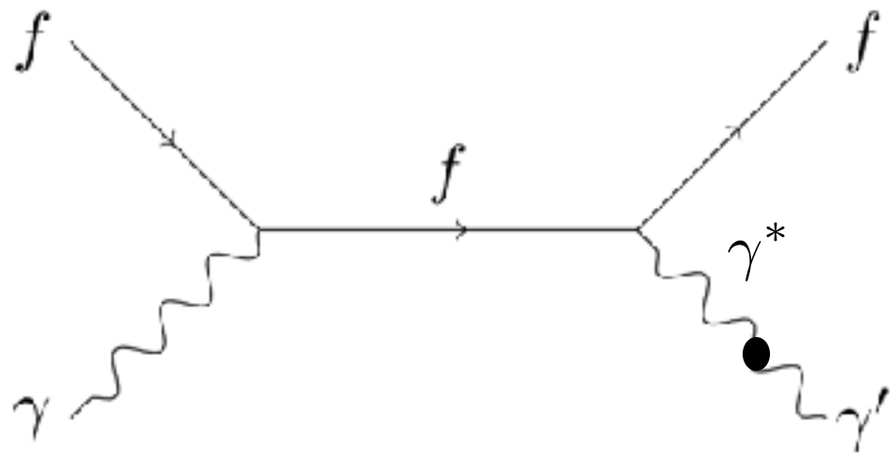
$$\mathcal{M}_{\rm rad} \propto\ e\ J^{\mu}_{\rm em}\,\eta_{\mu\nu}\,\frac{1}{k^2}\,\epsilon m^2_{\gamma'}\varepsilon'^{\nu}_{T}$$

$$\rightarrow \quad e\,\epsilon\ J^{\mu}_{\rm em}\,\eta_{\mu\nu}\varepsilon'^{\nu}_{T}$$

$k^2 = m^2_{\gamma'}$

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

RADIATION OF DARK PHOTONS IN A MEDIUM



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

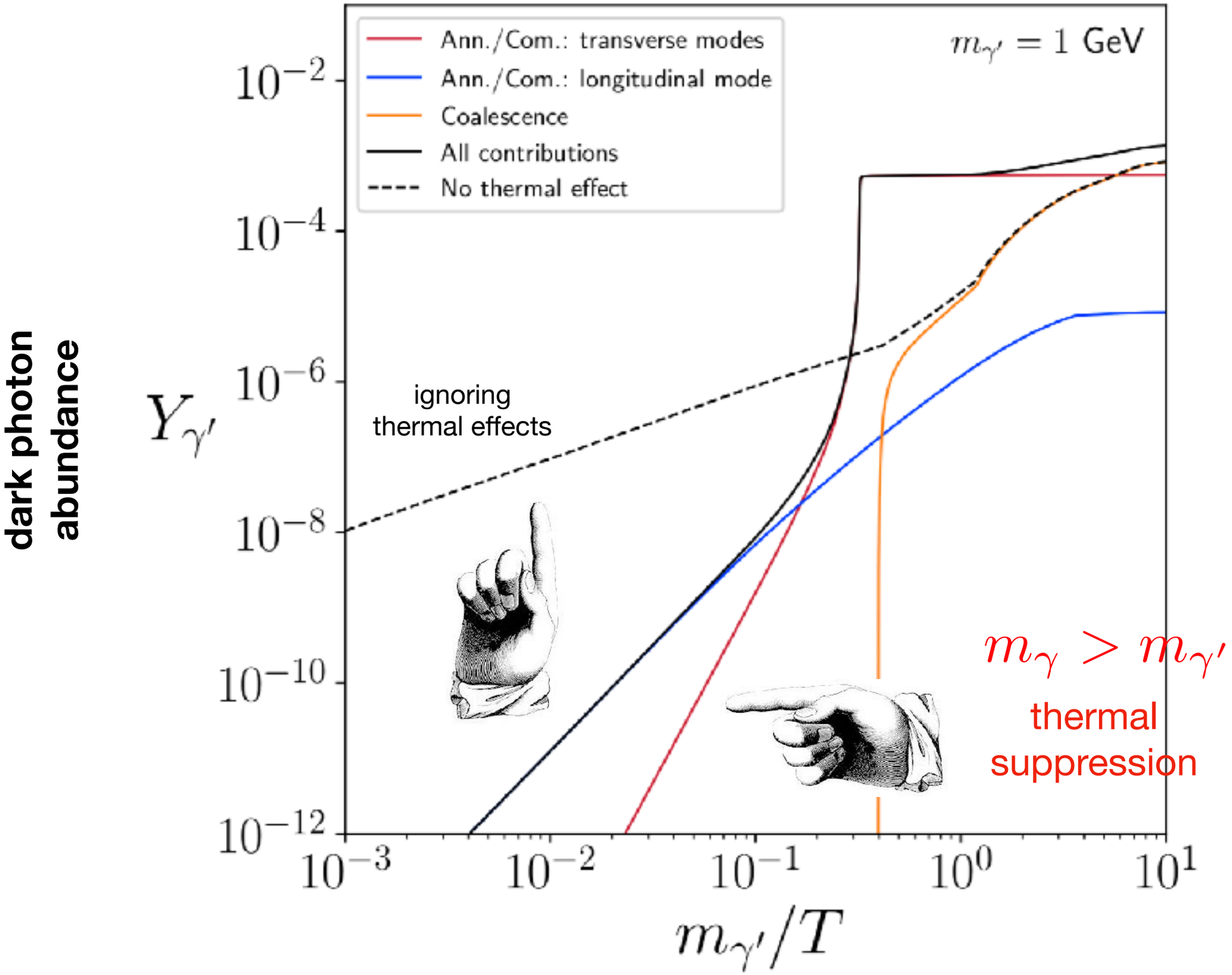
$$\rightarrow \quad \mathcal{M}_{\rm rad} \propto\ e\, J^{\mu}_{\rm em}\, \eta_{\mu\nu}\, \frac{\epsilon m^2_{\gamma'}}{m^2_{\gamma'} - m^2_{\gamma}(T)}\, \varepsilon'^{\nu}_{T}$$

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

photon thermal mass

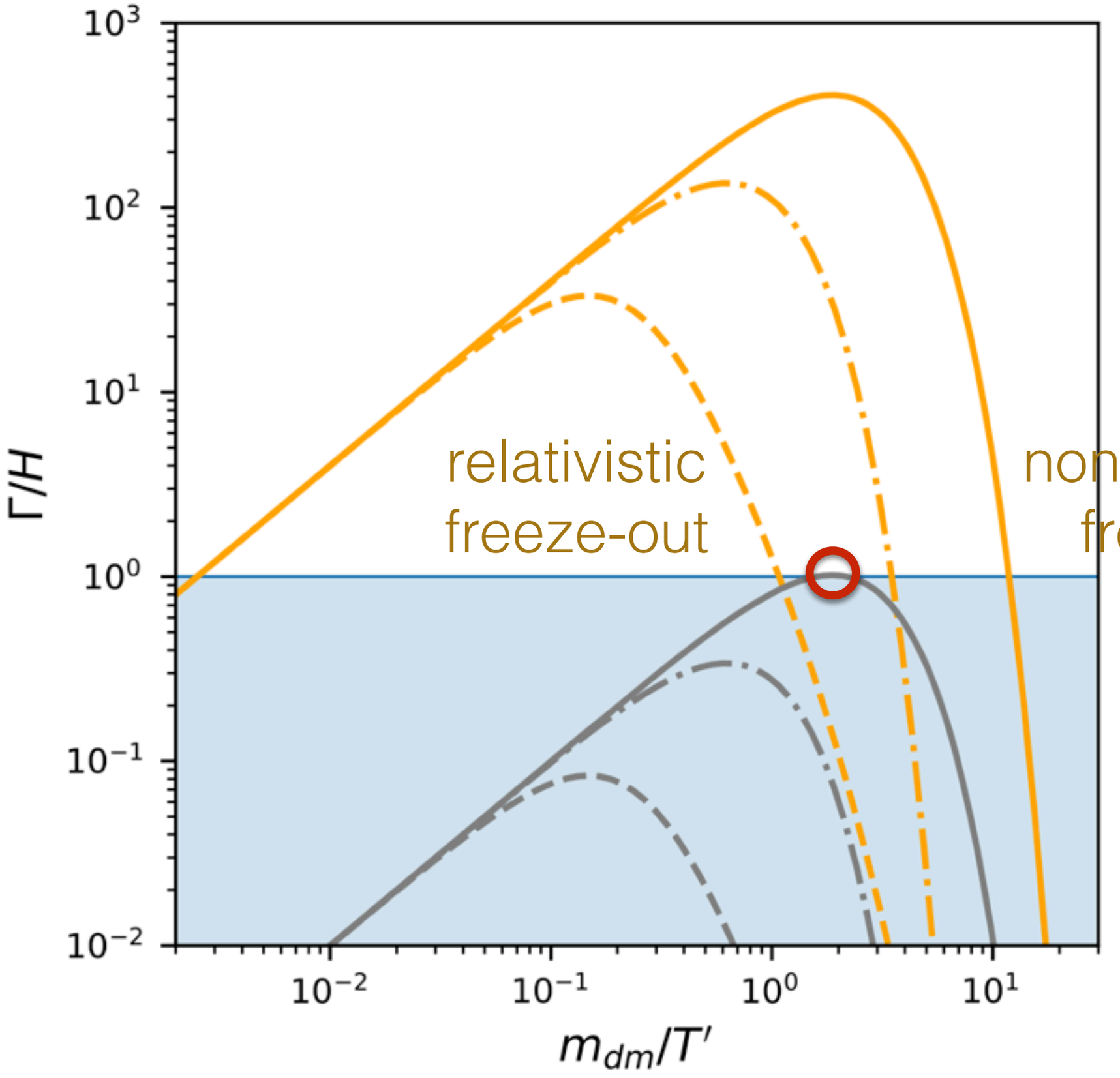
$$m_\gamma \sim eT$$

DARK RADIATION PRODUCTION IS SUPPRESSED AT HIGH TEMPERATURES

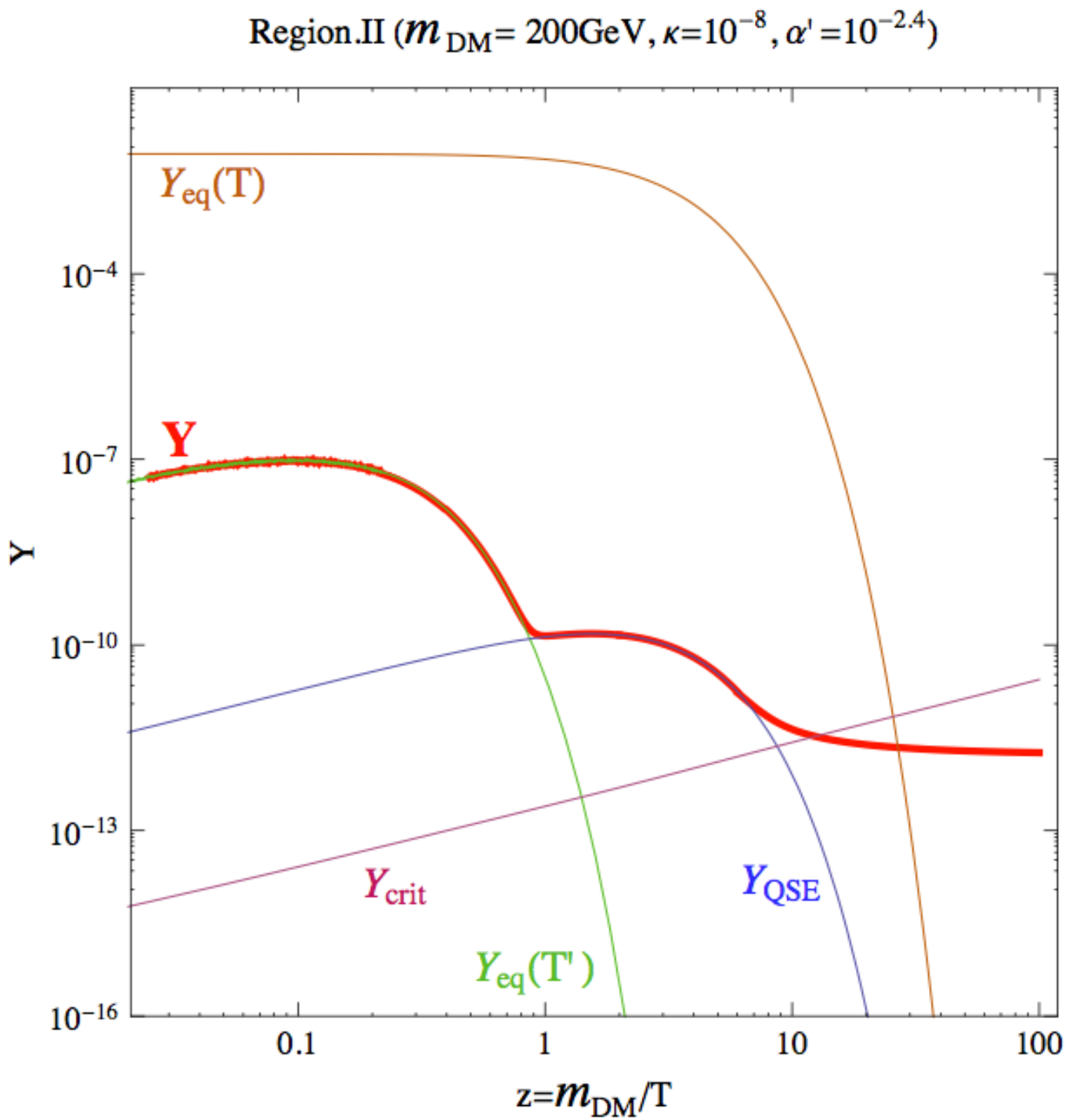


BACKUP STORY (III)

DECOUPLING OF THERMAL CANDIDATES

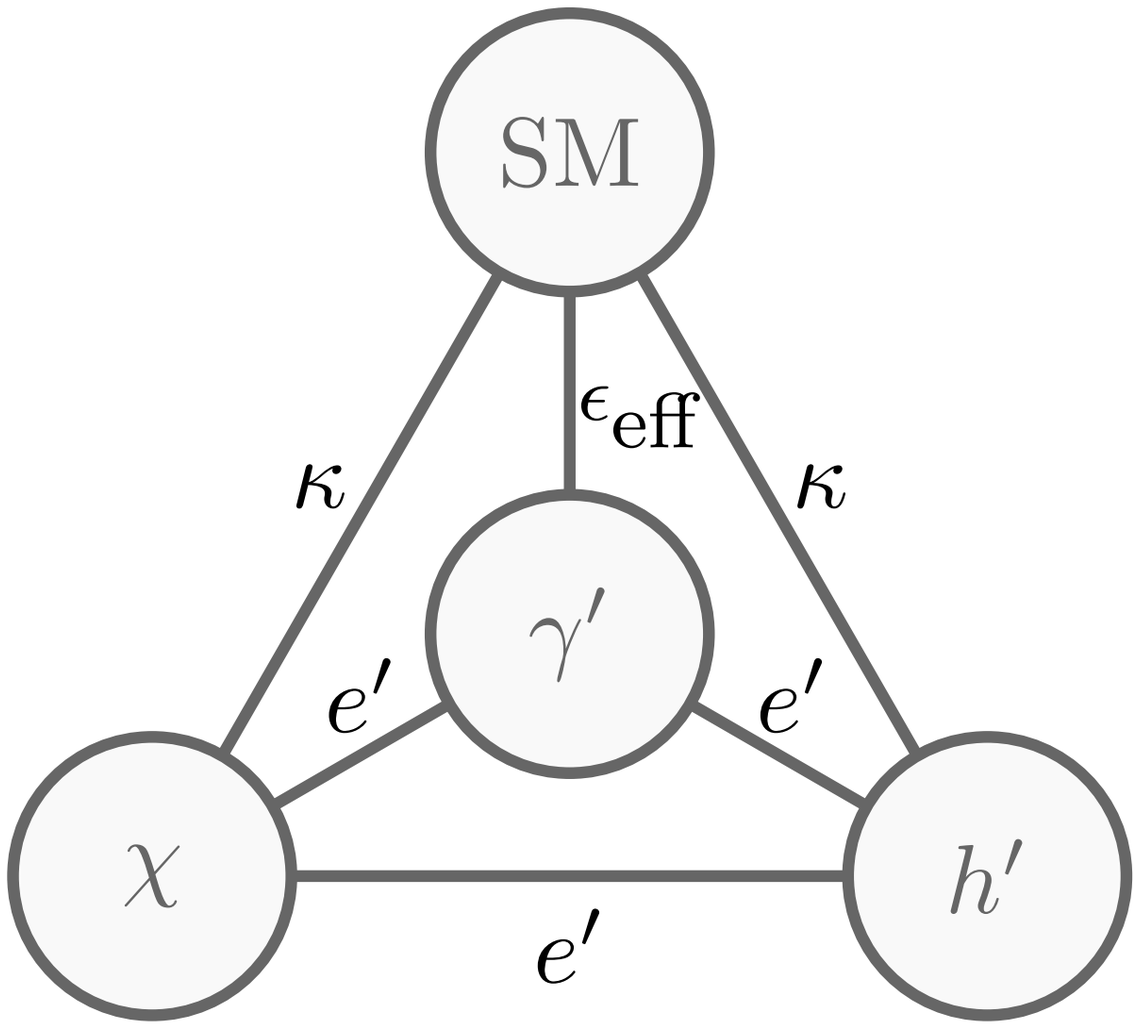


REANNIHILATION, ETC.



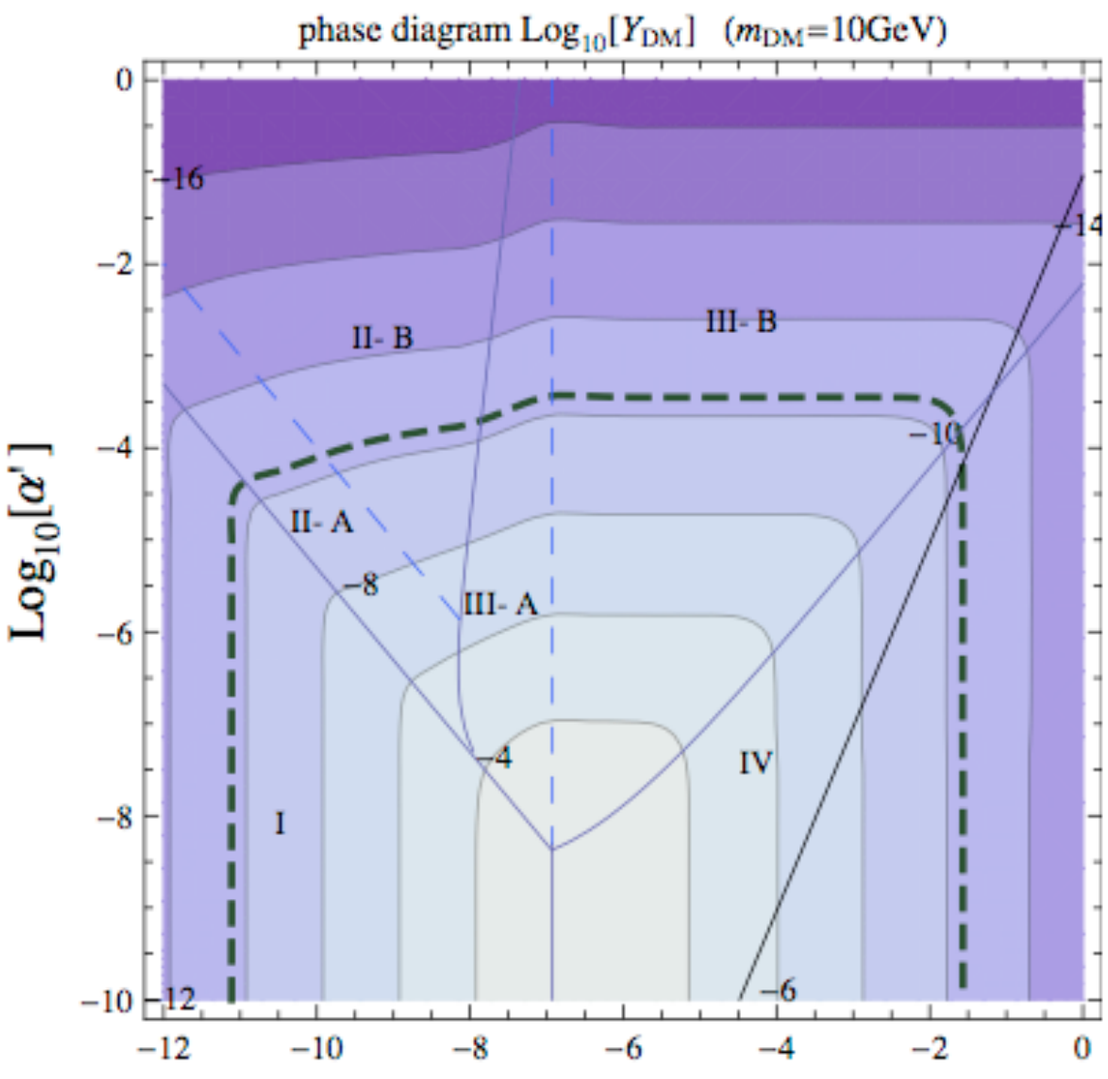
Chu, Hambye, M.T. ‘12

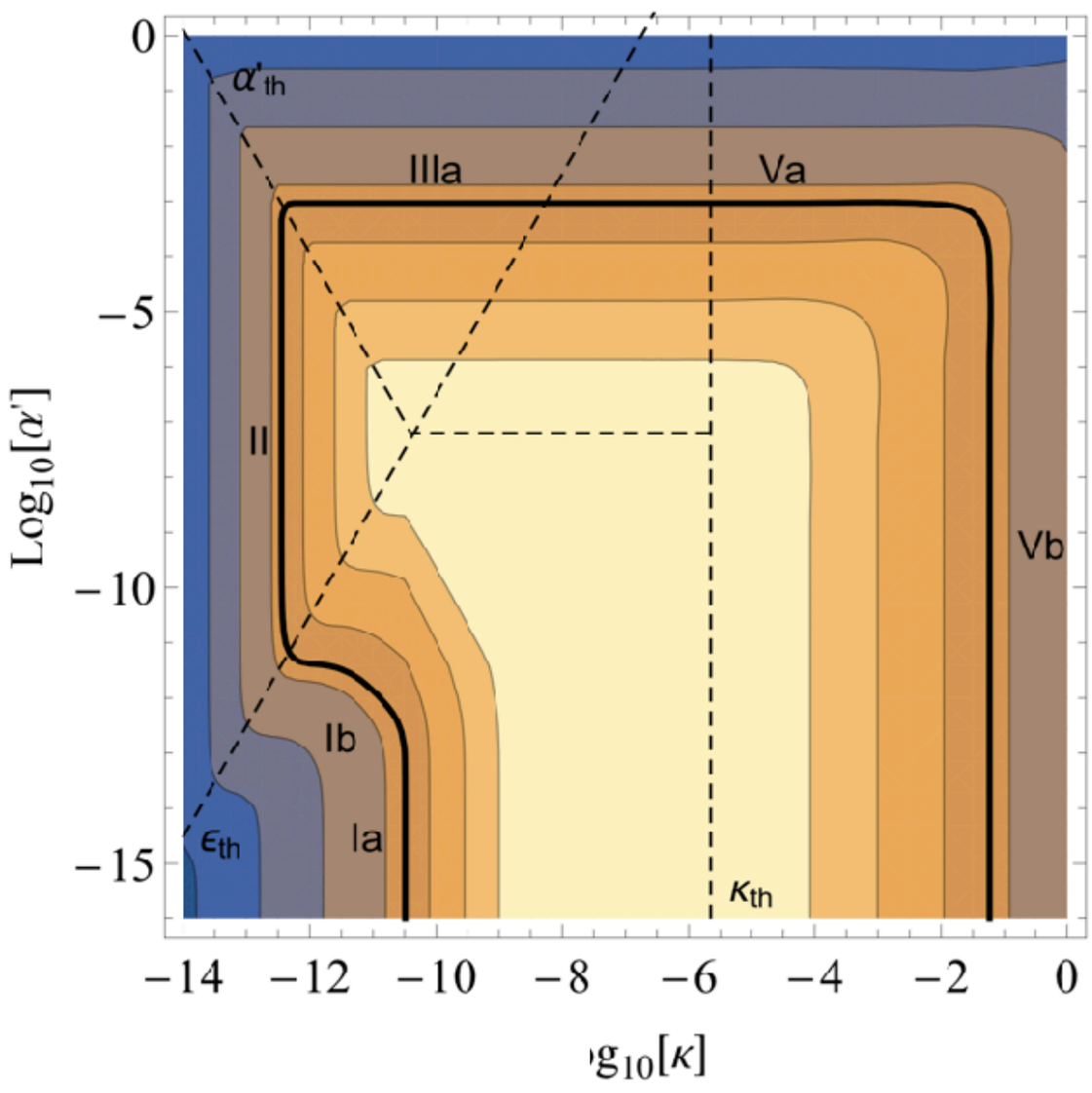
GENERALIZATIONS?

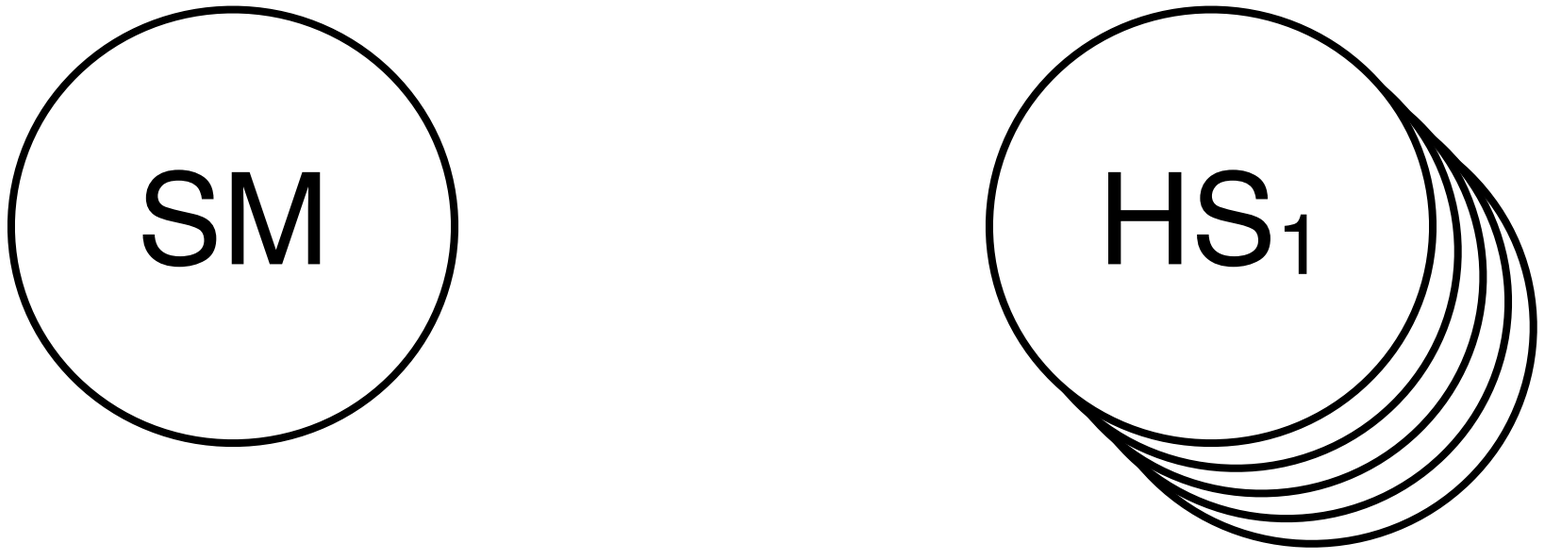


$m_{\gamma'} \to 0$

$m_{\gamma'} \neq 0$






SM
HS1

RENORMALIZABLE PORTALS

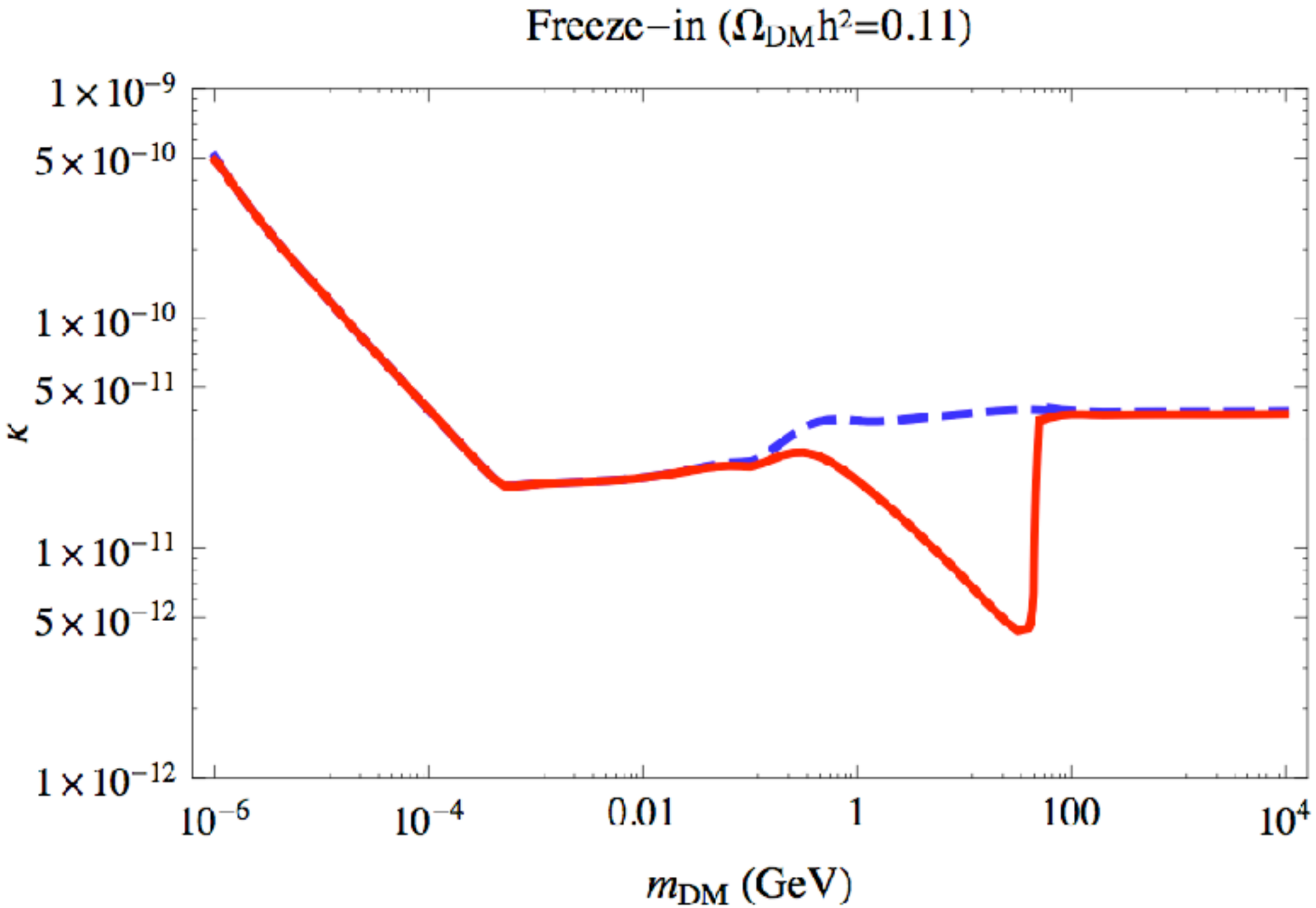
Patt & Wilczek (2006)

$\bar{L}\tilde{H}$ $\quad\quad$ $\Delta\mathcal{L} \supset y\,\bar{L}\tilde{H}N$ $\quad\quad$ Dodelson & Widrow (1994)
…

$B_{\mu\nu}$ $\quad\quad$ $\Delta\mathcal{L} \supset \epsilon B_{\mu\nu}F'^{\mu\nu}$ $\quad\quad$ Holdom (1986)
…

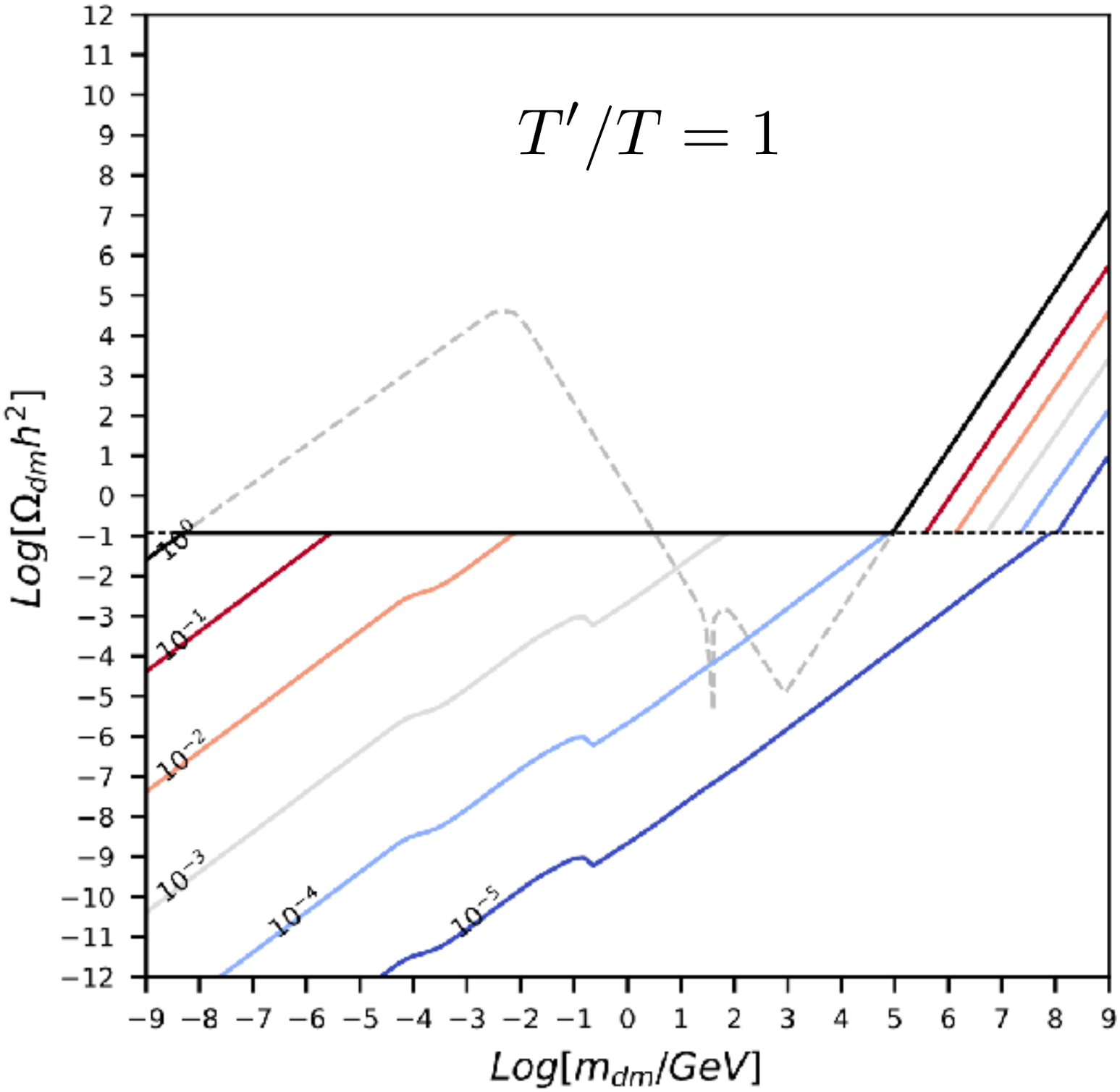
$H^\dagger H$ $\quad\quad$ $\Delta\mathcal{L} \supset \lambda\, S^2 H^\dagger H$ $\quad\quad$ Silveira & Zee (1985)
Veltman & Ynderain (1989)
…

FREEZE-IN CANDIDATES



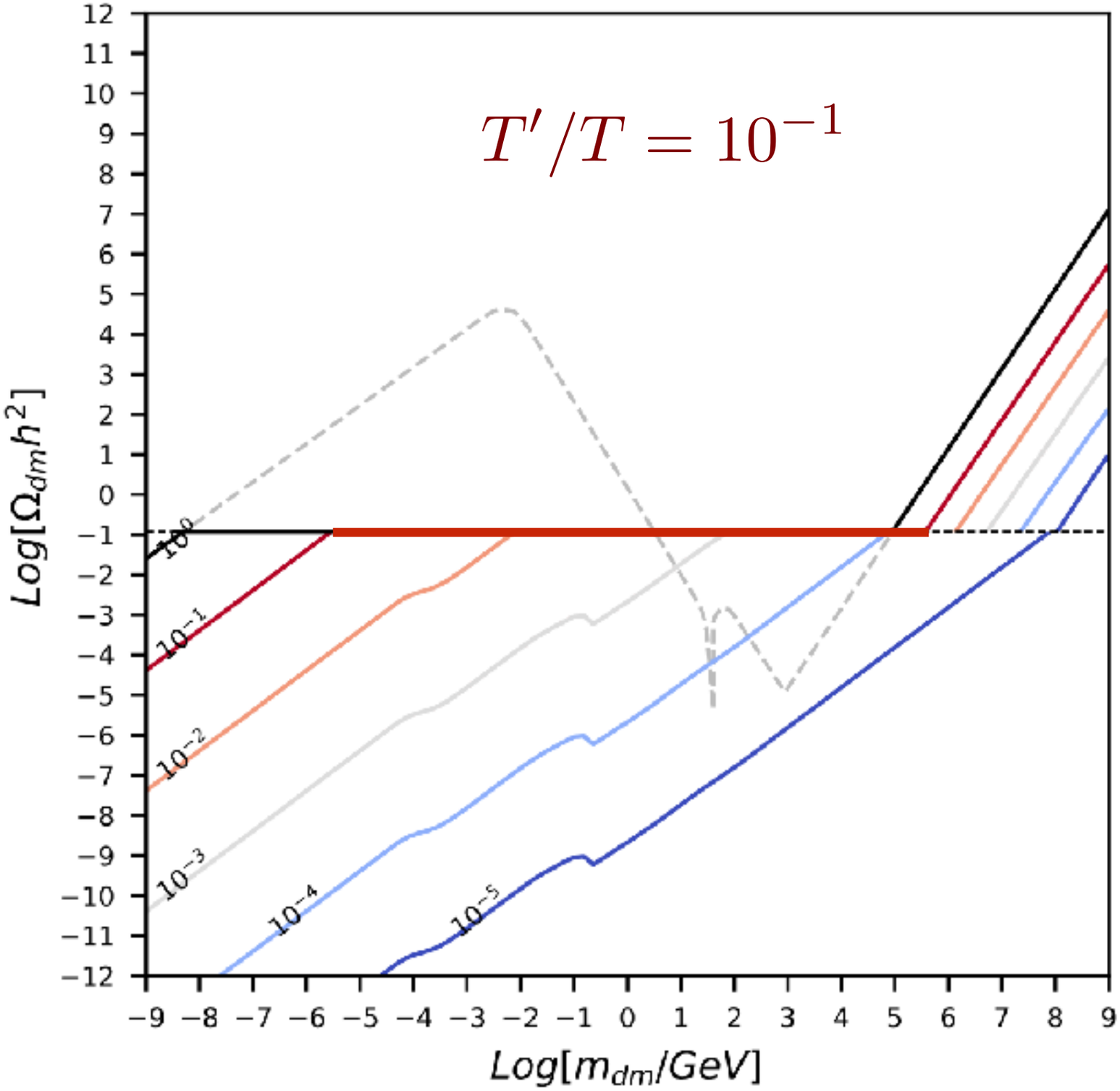
Chu, Hambye, M.T. ‘12

CHANGING T’/T



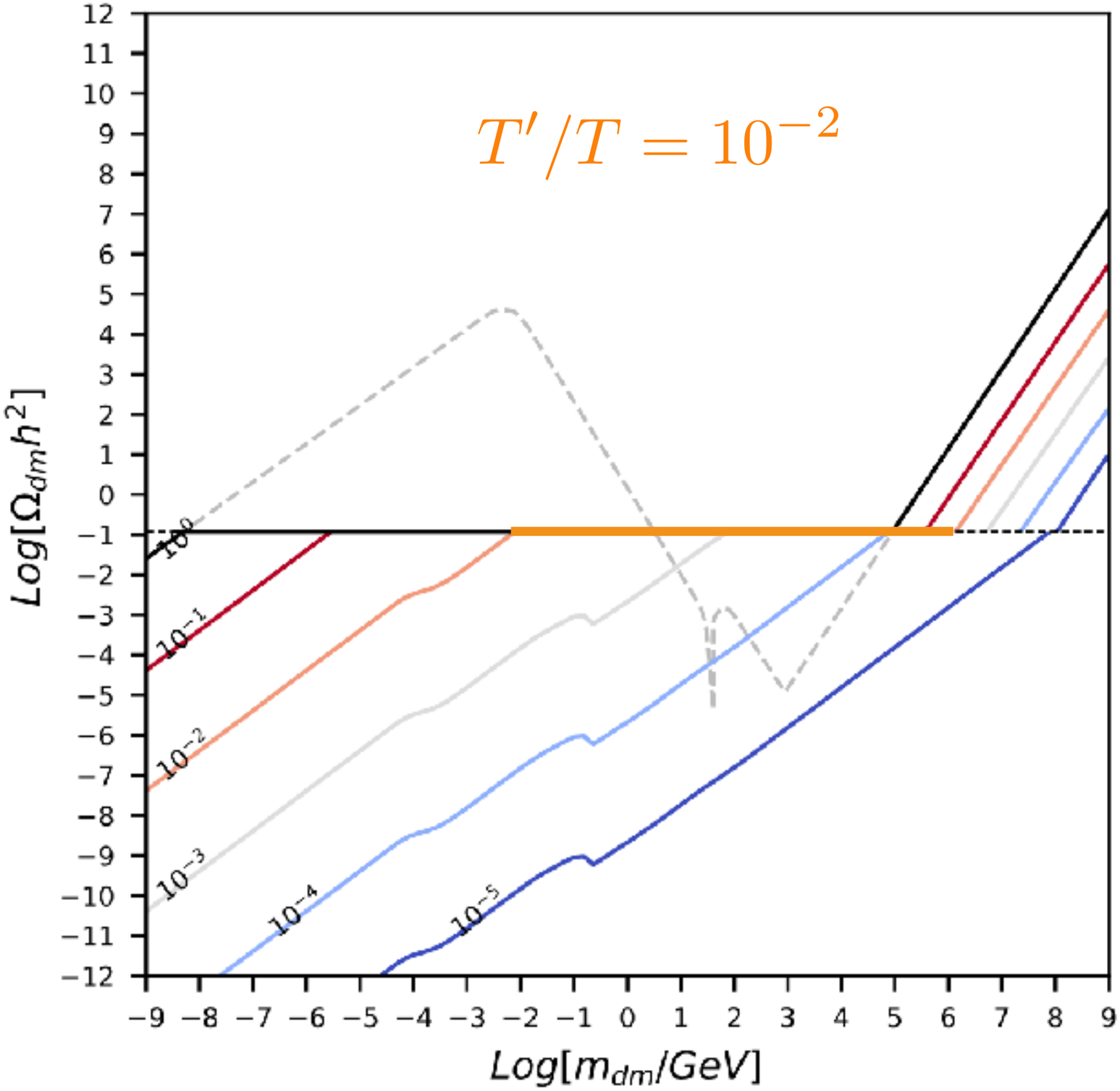
Coy, Hambye, MHGT, Vanderheyden ’21

CHANGING T’/T



Coy, Hambye, MHGT, Vanderheyden ’21

CHANGING T’/T



Coy, Hambye, MHGT, Vanderheyden ’21