Dark Matter from dark QED

Michel HG Tytgat

Université Libre de Bruxelles
Belgium

8th International Conference on High Energy Physics in the LHC era
Universidad Técnica Federico Santa María
Valparaiso, Chile, 9-13 January 2023

Essentially based on

Dark matter from dark photons: a taxonomy of dark matter production
Hambye, MHGT, Vandecasteele, Venderheyden
1908.09864

Domain of thermal dark matter candidates
Coy, Hambye, MHGT, Venderheyden
2105.01263

Revisiting the domain of a cannibal DM
Hufnagel, MHGT
2212.09759

A history of a hot dark sector
with Coy & Kimus
2301.XXXXX

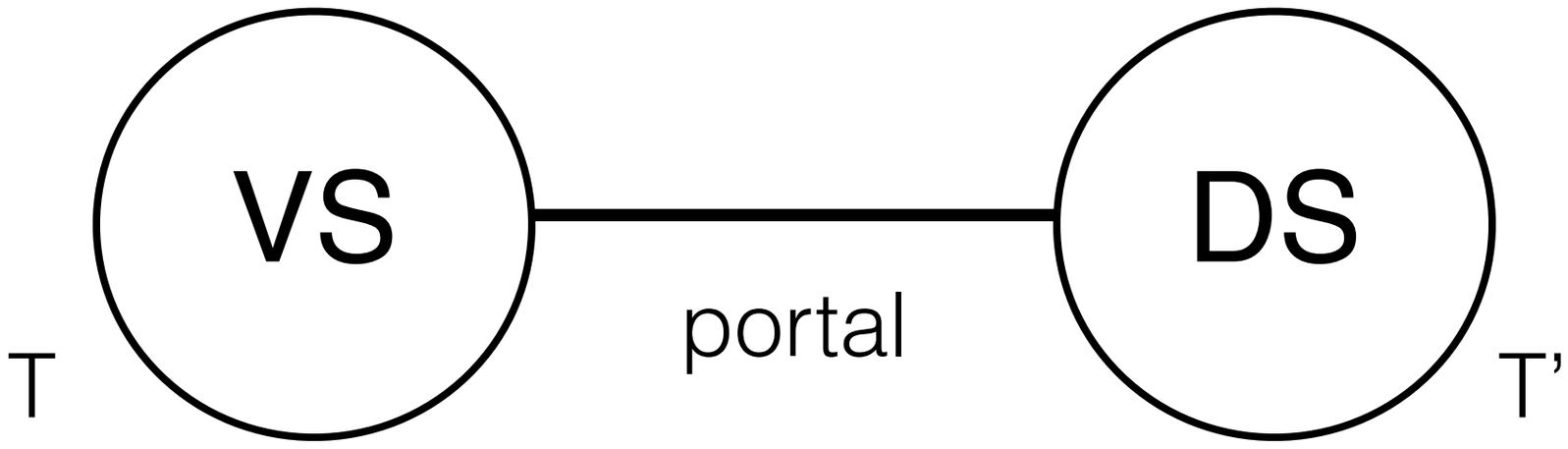
1.
DARK MATTER

DARK SECTOR (DS)

Visible sector

Dark sector

DARK SECTOR (DS)

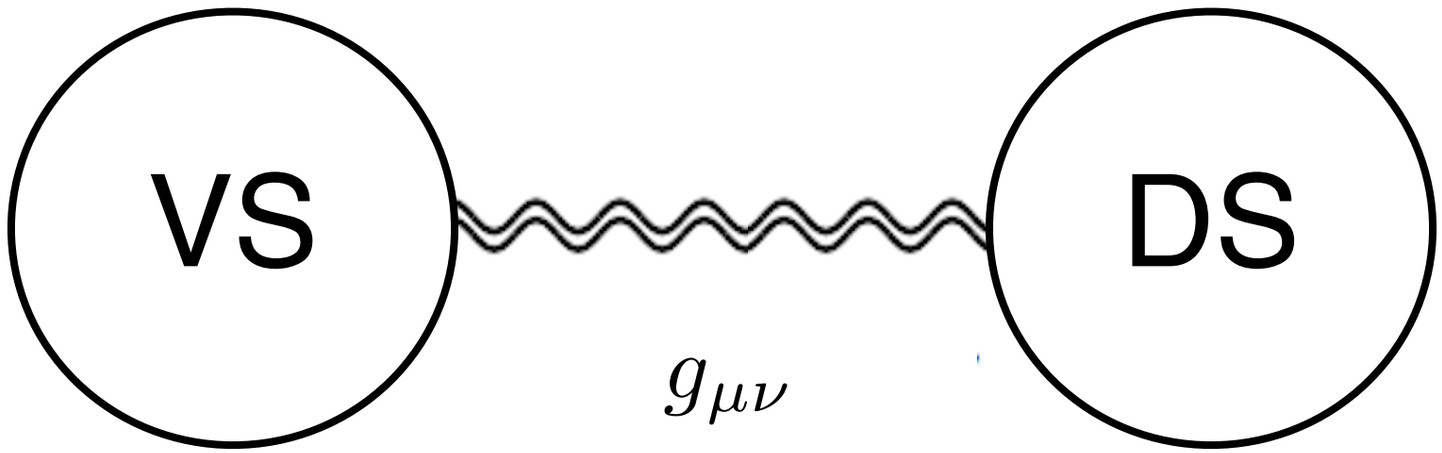


SM singlets, possibly with interactions

Possibly in thermal equilibrium with T’ ≠ T

Interacts (albeit feebly) with SM through a ‘portal’

DARK SECTOR (DS)



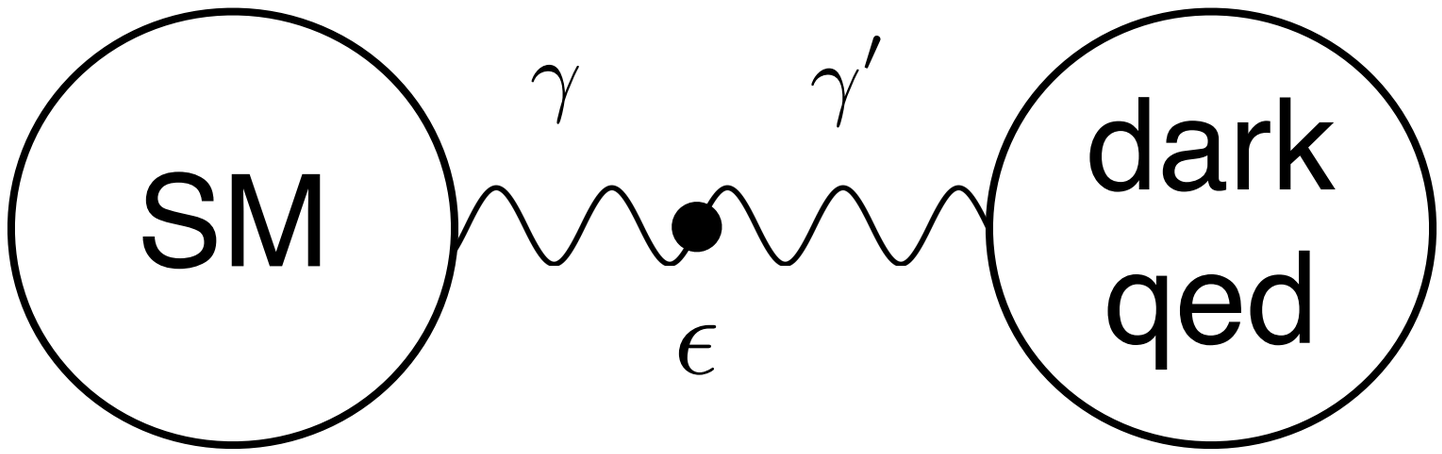
SPECIAL SM PORTALS

$\bar{L}\tilde{H}$ $\quad\quad$ $\Delta\mathcal{L} \supset y\,\bar{L}\tilde{H}N$ $\quad\quad$ 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)
Patt & Wilczek (2006)

DARK QED



dark electrons and positrons (DM)

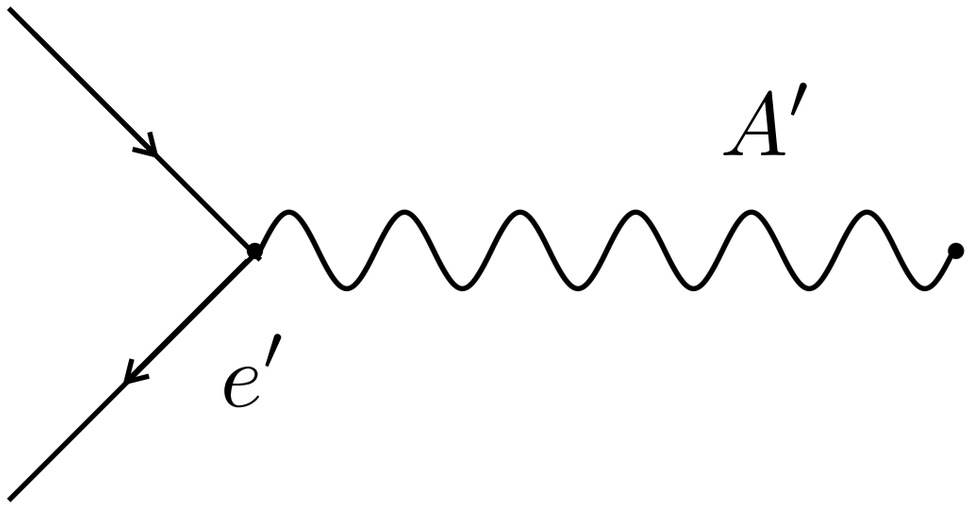
dark photons

KINETIC MIXING with DARK QED

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

dark electron & positron (here the DM)

$\chi, \bar{\chi}$



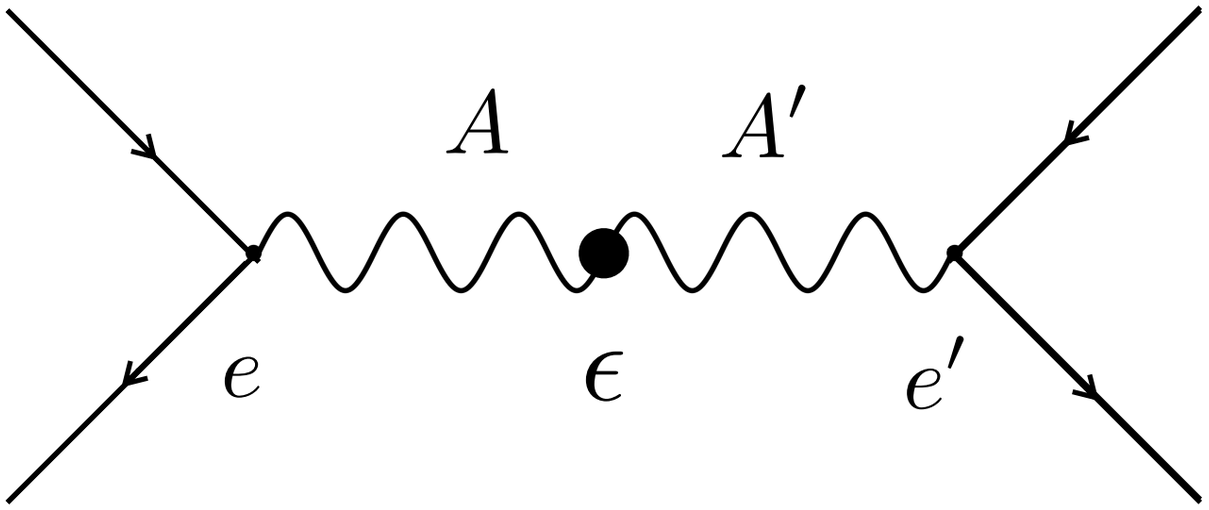
e' or α'

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

KINETIC MIXING with DARK QED

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

SM



$\chi, \bar{\chi}$

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

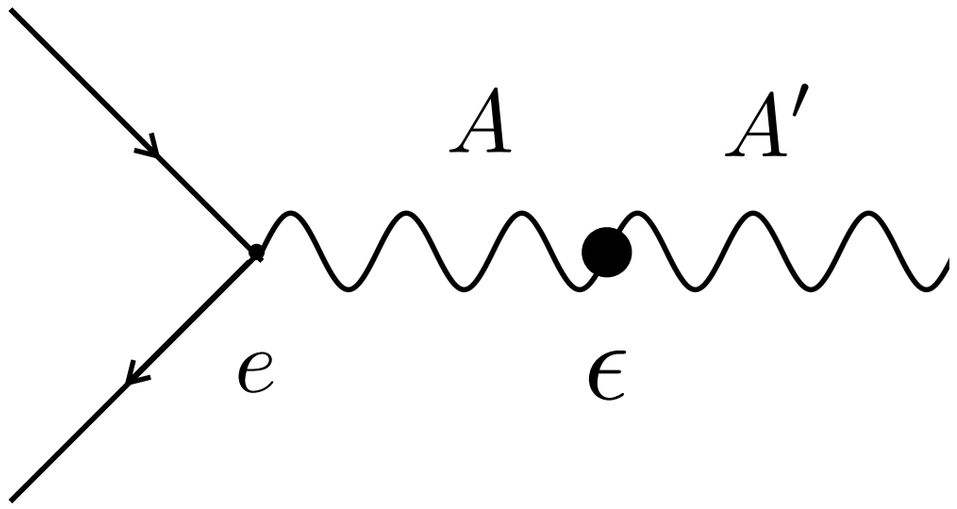
'millicharge'

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

EMISSION OF DARK PHOTON BY SM

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

SM

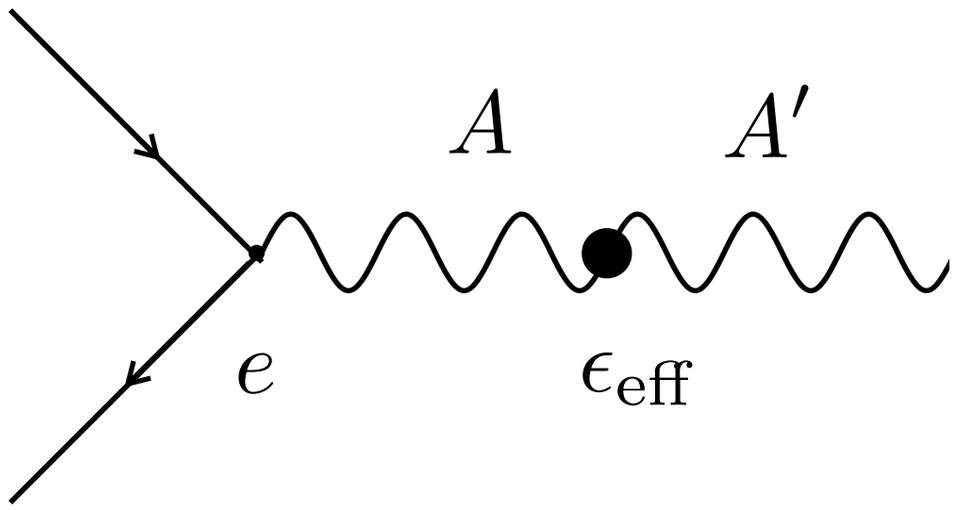


ϵ

EMISSION OF DARK PHOTON BY SM

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

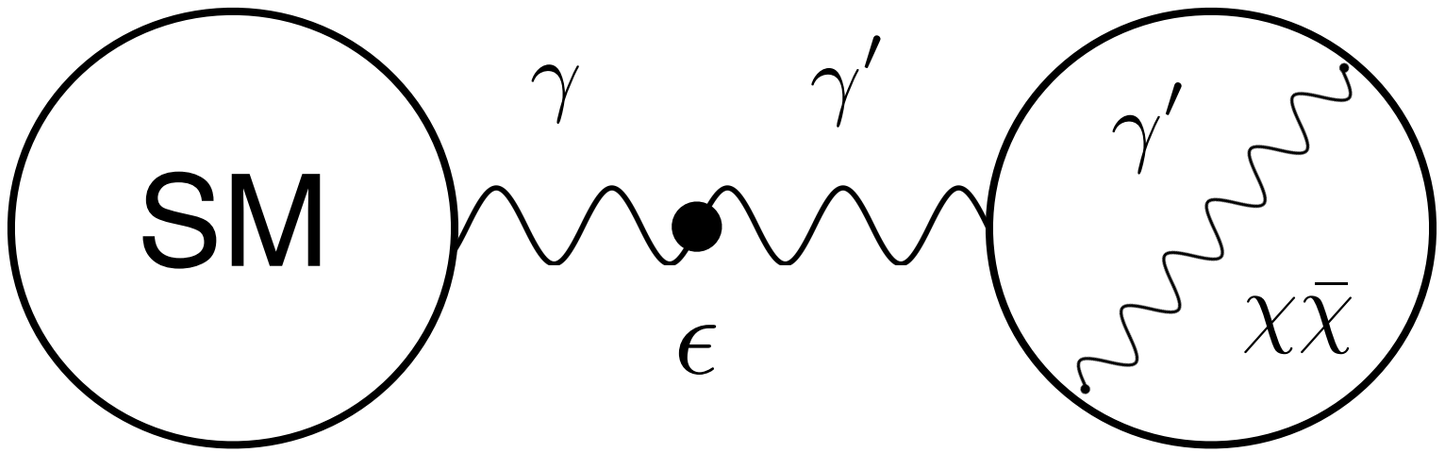
SM

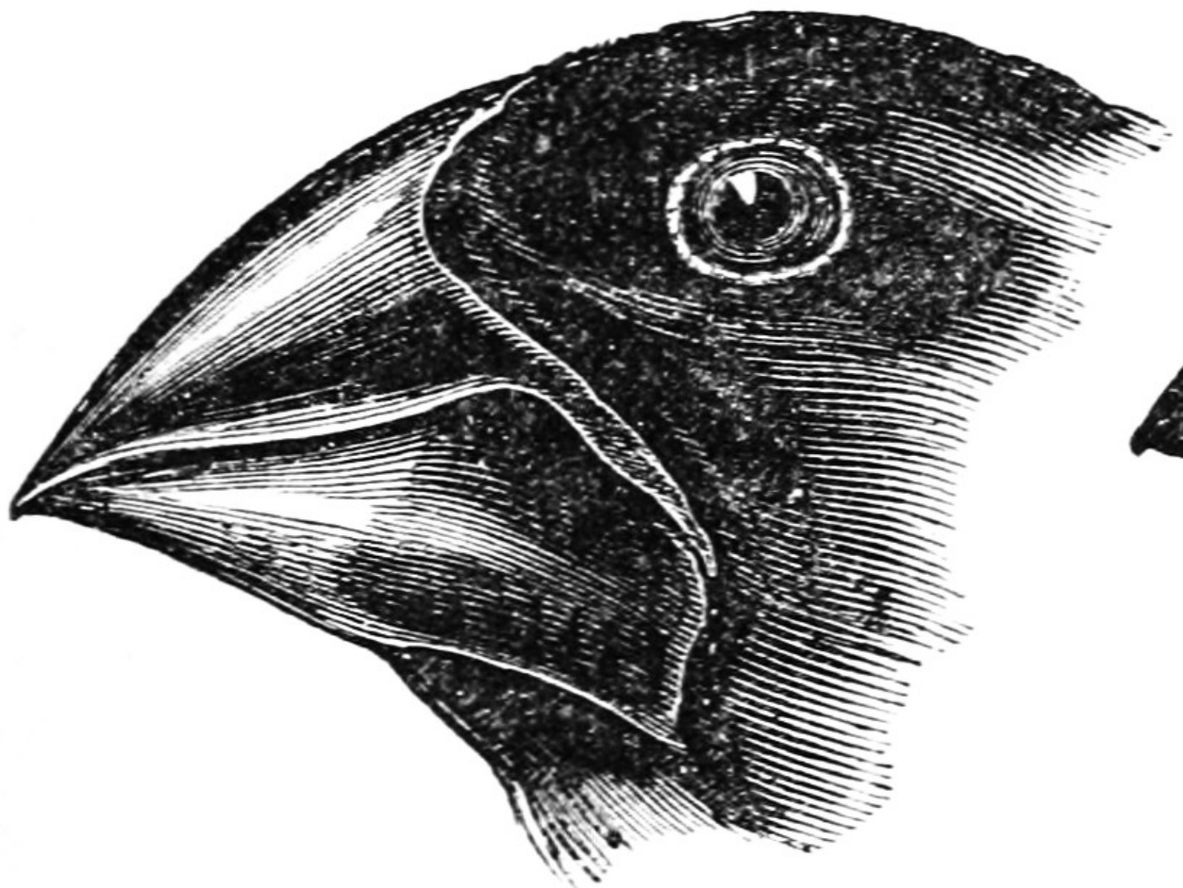


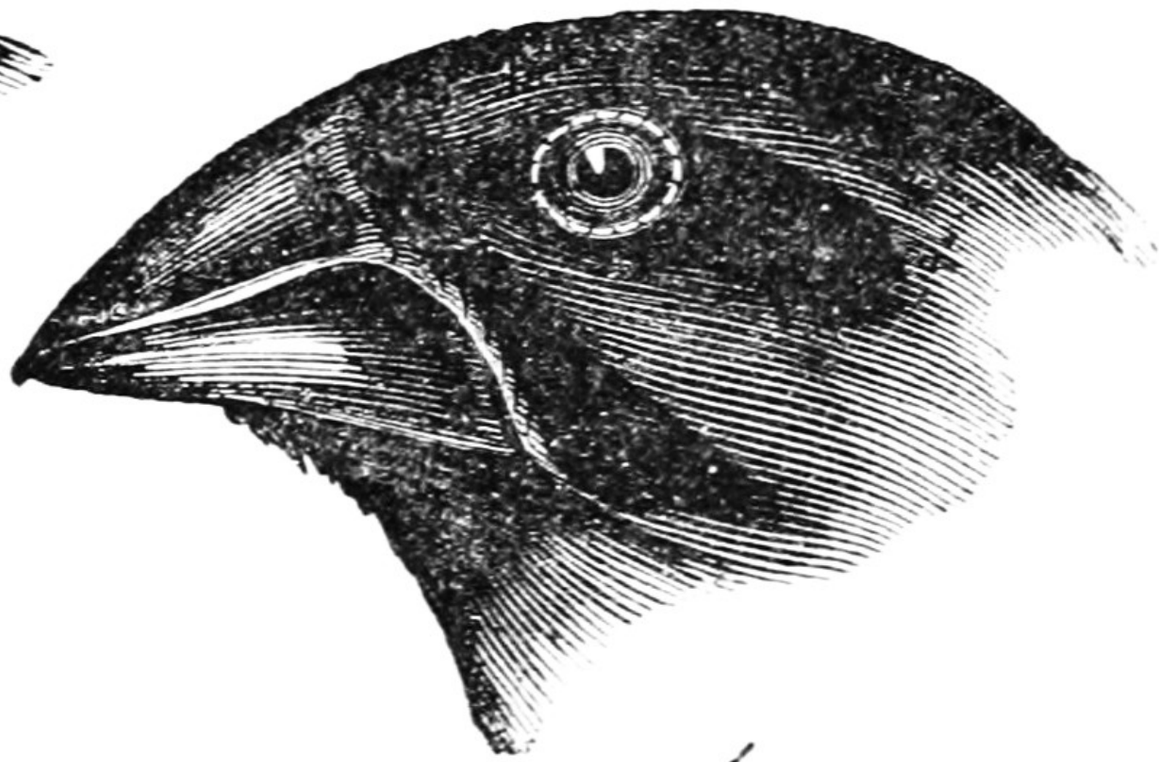
$$\epsilon_{\rm eff} = \frac{\epsilon\, m^2_{\gamma'}}{m^2_{\gamma'} - m^2_\gamma(T) + i m_\gamma \Gamma_\gamma}$$

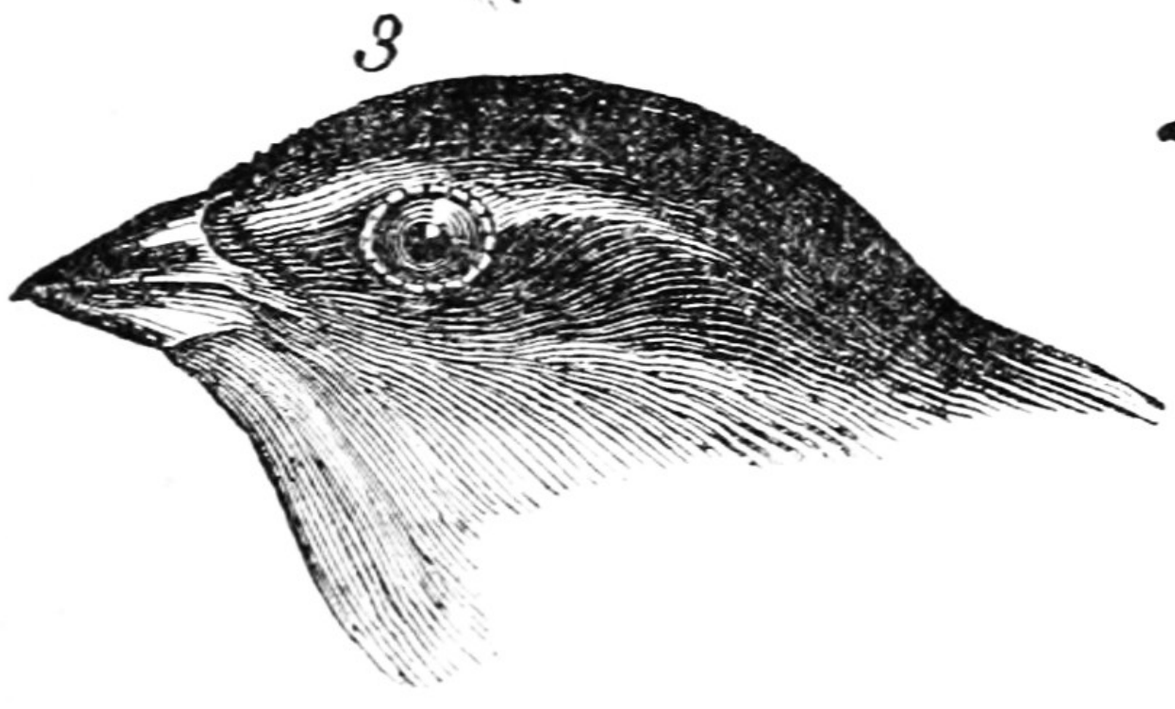
for emission
(but ϵ for exchange)

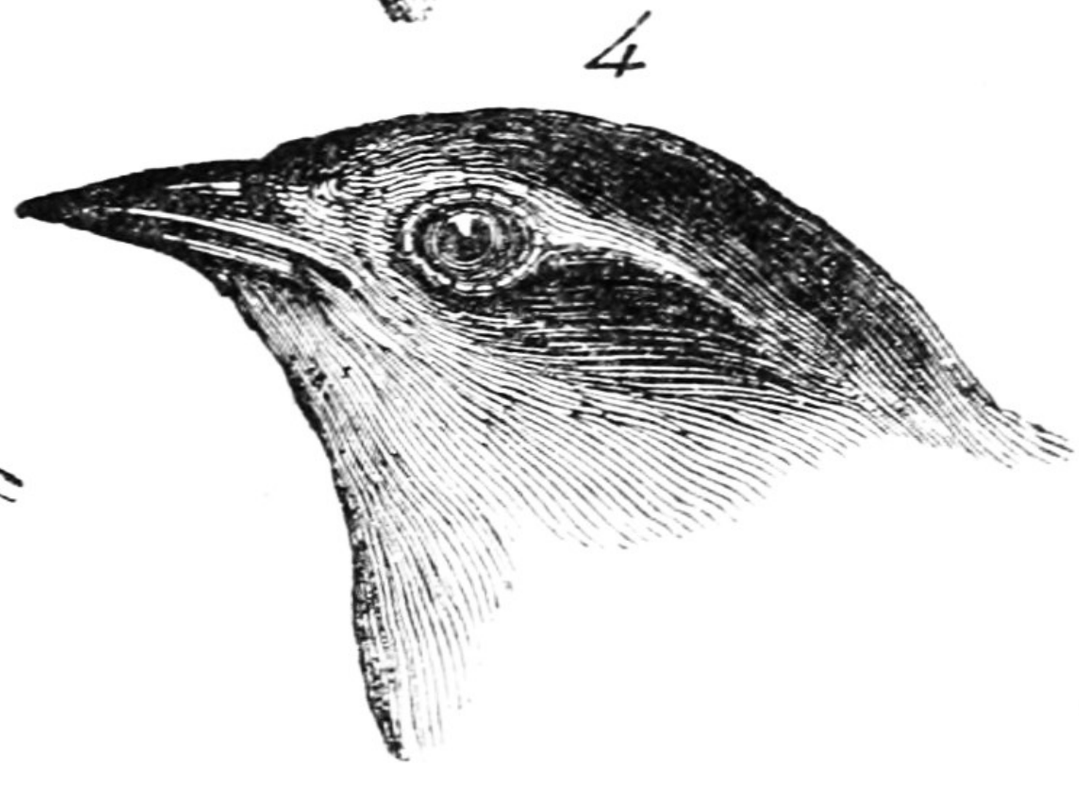
2
TAXONOMY OF DM PRODUCTION



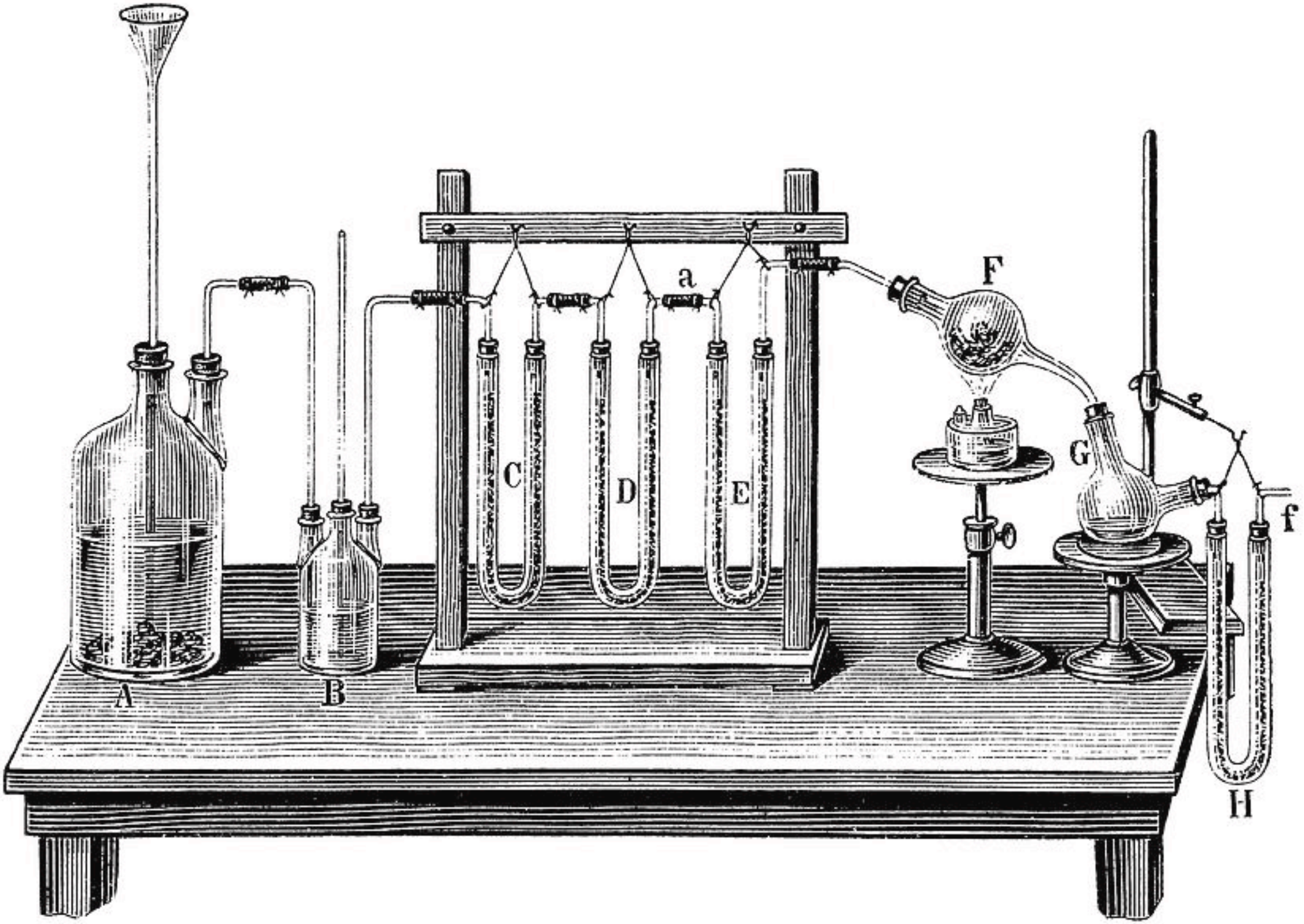








1. Geospiza magnirostris.
2. Geospiza fortis.
3. Geospiza parvula.
4. Certhidea olivasea.


A
B
C
D
E
a
F
G
H
f

BOLTZMANN EQUATIONS

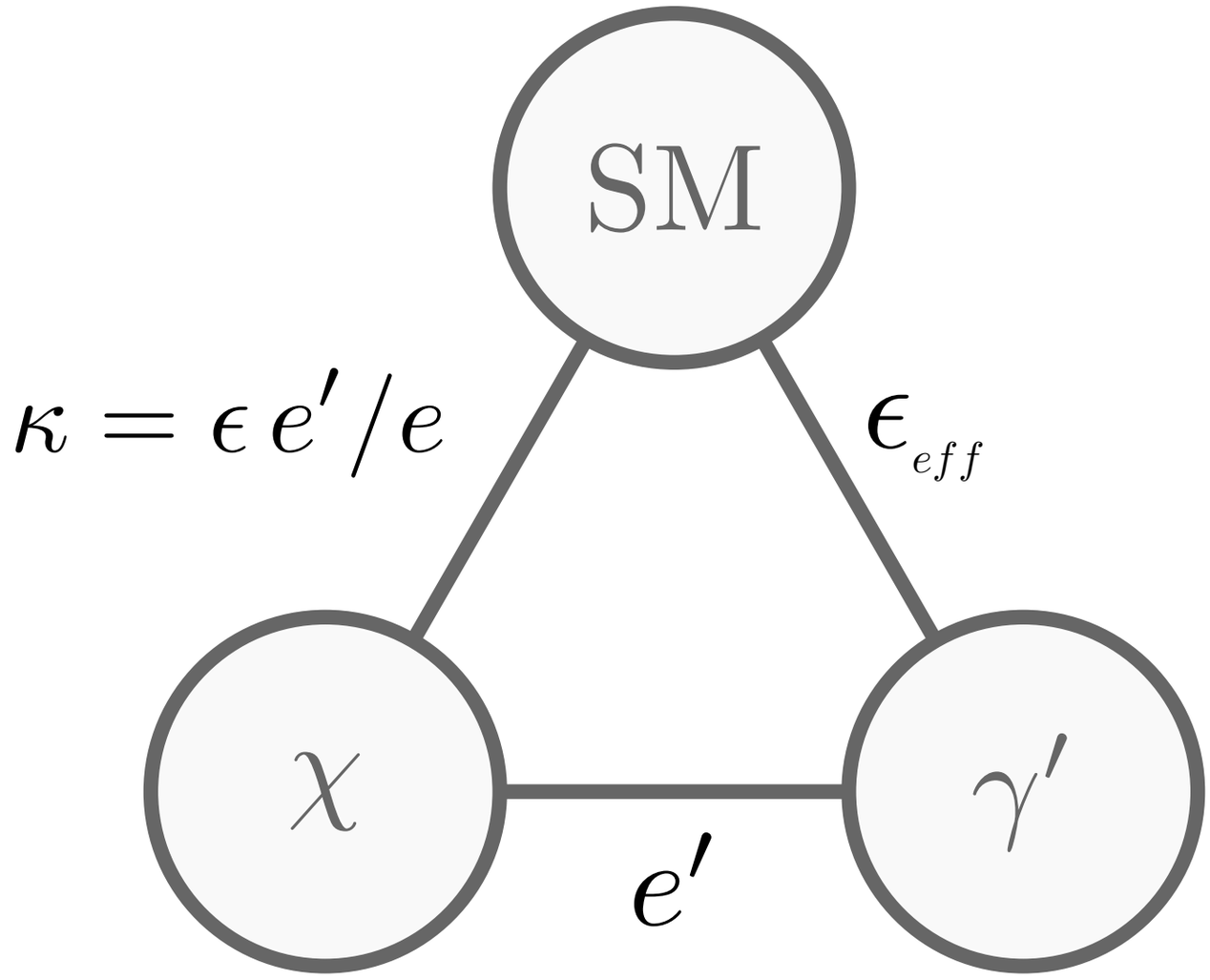
$$
\begin{aligned}
zHs\frac{dY_{\rm DM}}{dz} = & \ \langle\sigma_{\rm DM\to SM}\, v\rangle \ \left[(n^{\rm eq}_{\rm DM})^2 - n^2_{\rm DM}\right] \\
& + \langle\Gamma^{D}_{\rm DM\to SM}\rangle \frac{n^{\rm eq}_{Z}}{(n^{\rm eq}_{\rm DM})^2} \left[(n^{\rm eq}_{\rm DM})^2 - n^2_{\rm DM}\right] \\
& + \langle\sigma_{\gamma'\to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

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

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

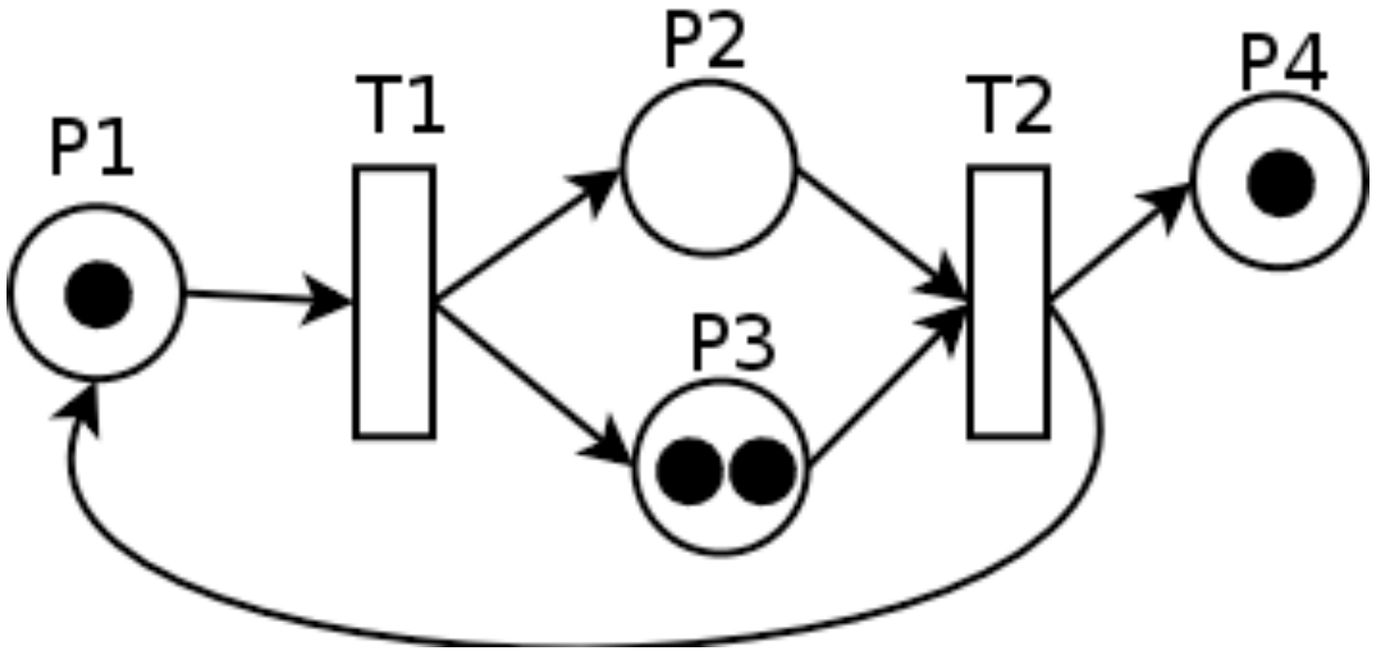
Hambye, M.T., Vandecasteele, Vanderheyden ’19

BOLTZMANN EQUATIONS



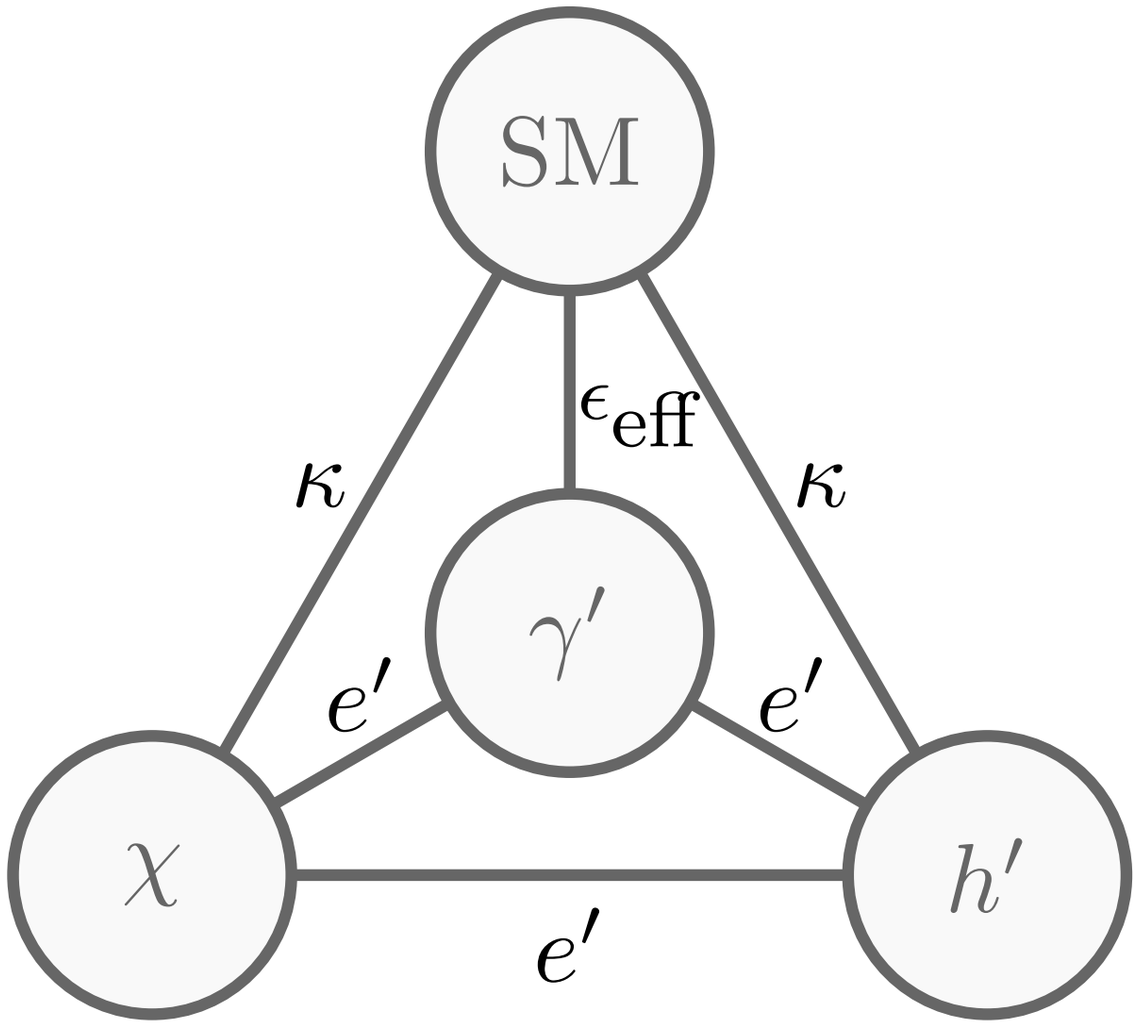
$$\epsilon_{\text{eff}} = \epsilon \frac{m_{\gamma'}^2}{m_{\gamma'}^2 - m_{\gamma}^2(T) + i\varepsilon}$$

PETRI NETS



https://en.wikipedia.org/wiki/Petri_net

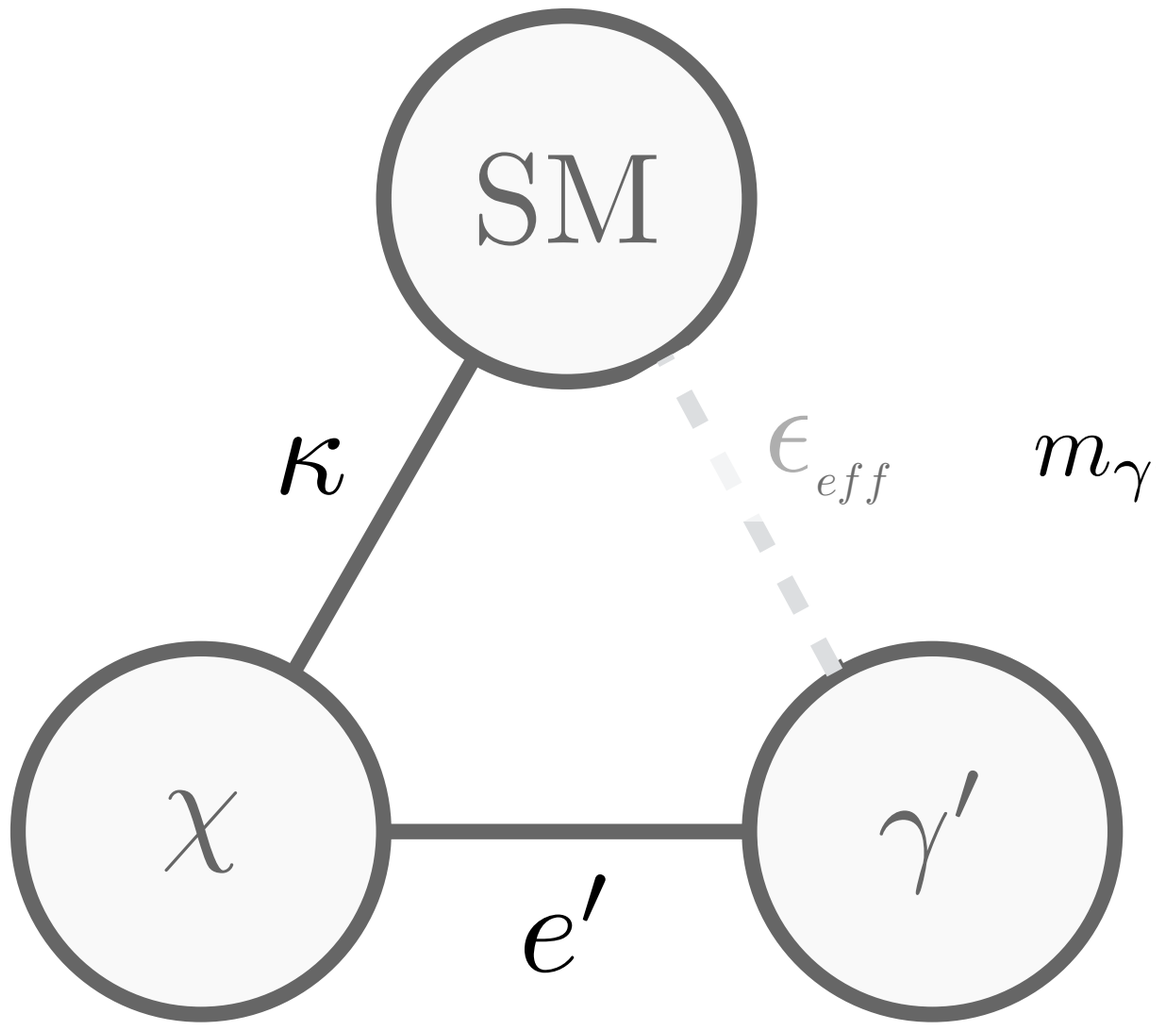
BOLTZMANN EQUATIONS



OLD

MASSLESS DARK PHOTON LIMIT

Chu, Hambye, M.T. ‘12



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

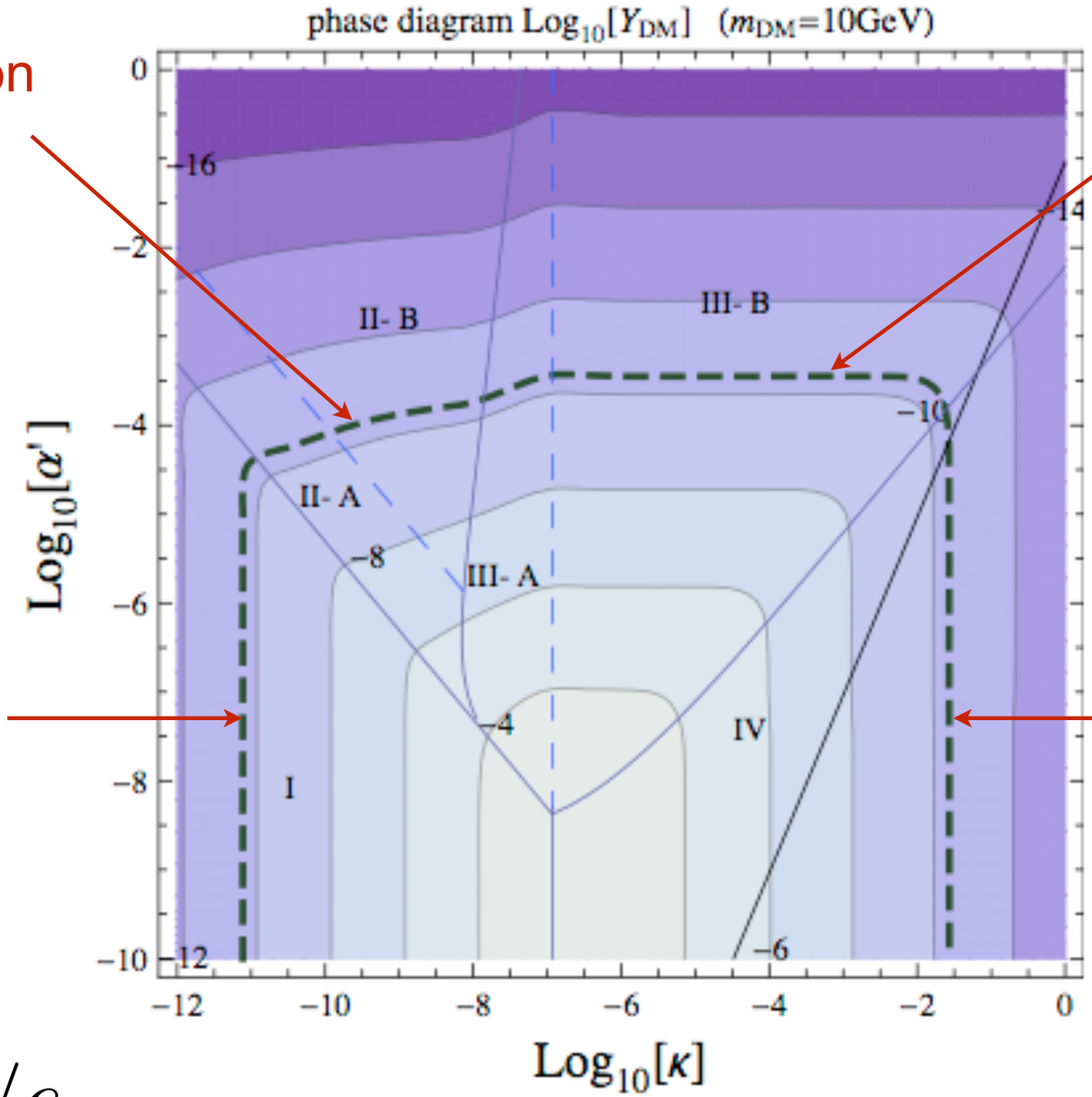
$$\epsilon_{\rm eff} = \epsilon \frac{m_{\gamma'}^2}{m_{\gamma'}^2 - m_\gamma^2(T) + i\varepsilon}$$

OLD THE 4 BASIC WAYS TO PRODUCE DM

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

reannihilation

secluded freeze-out



freeze-in

$$\Omega_{\mathrm{dm}} \propto \sigma$$

standard freeze-out

$$\Omega_{\mathrm{dm}} \propto 1/\sigma$$

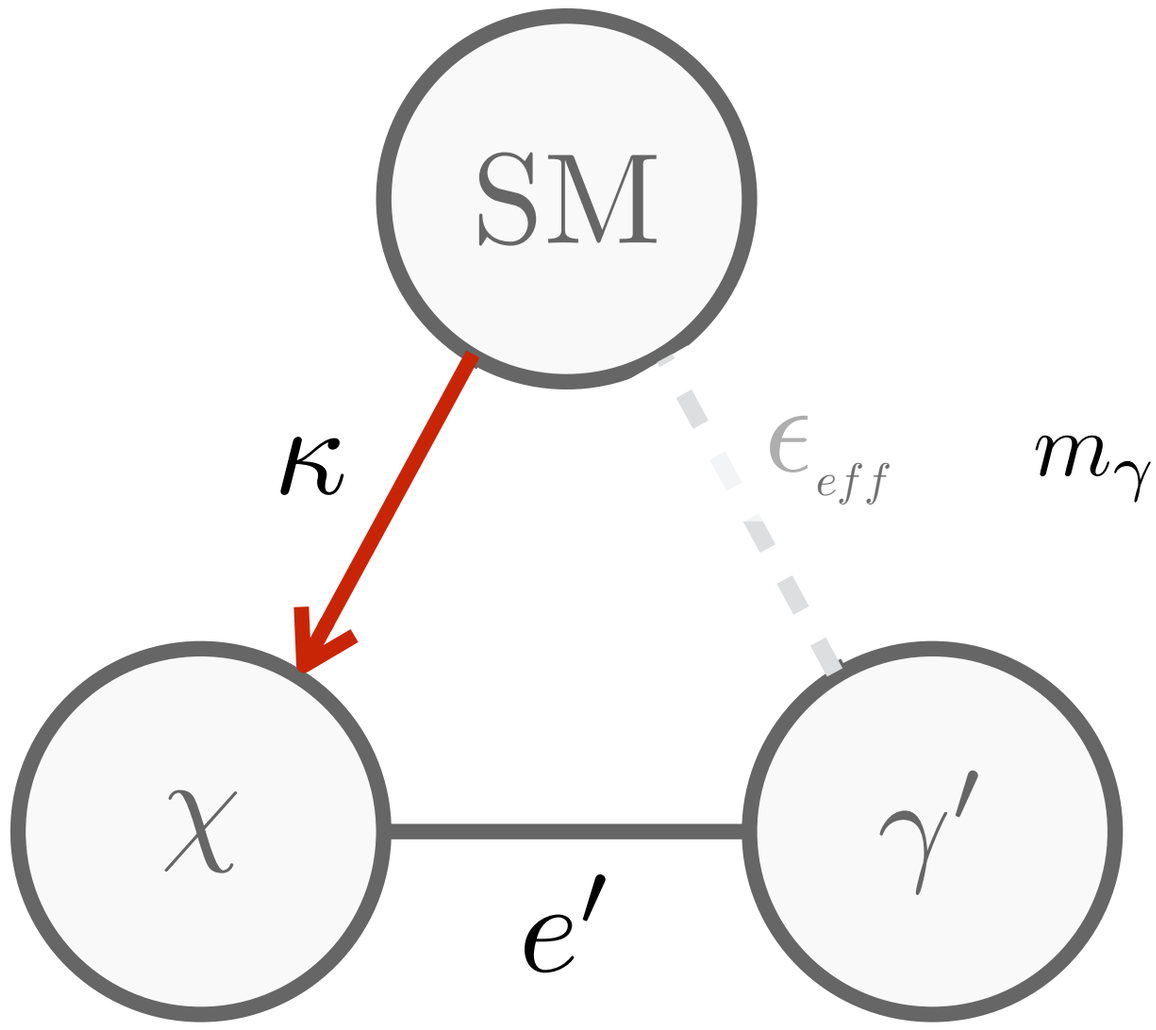
$$\kappa = \epsilon\, e'/e$$

Chu, Hambye, M.T. ‘12

OLD

MASSLESS DARK PHOTON LIMIT

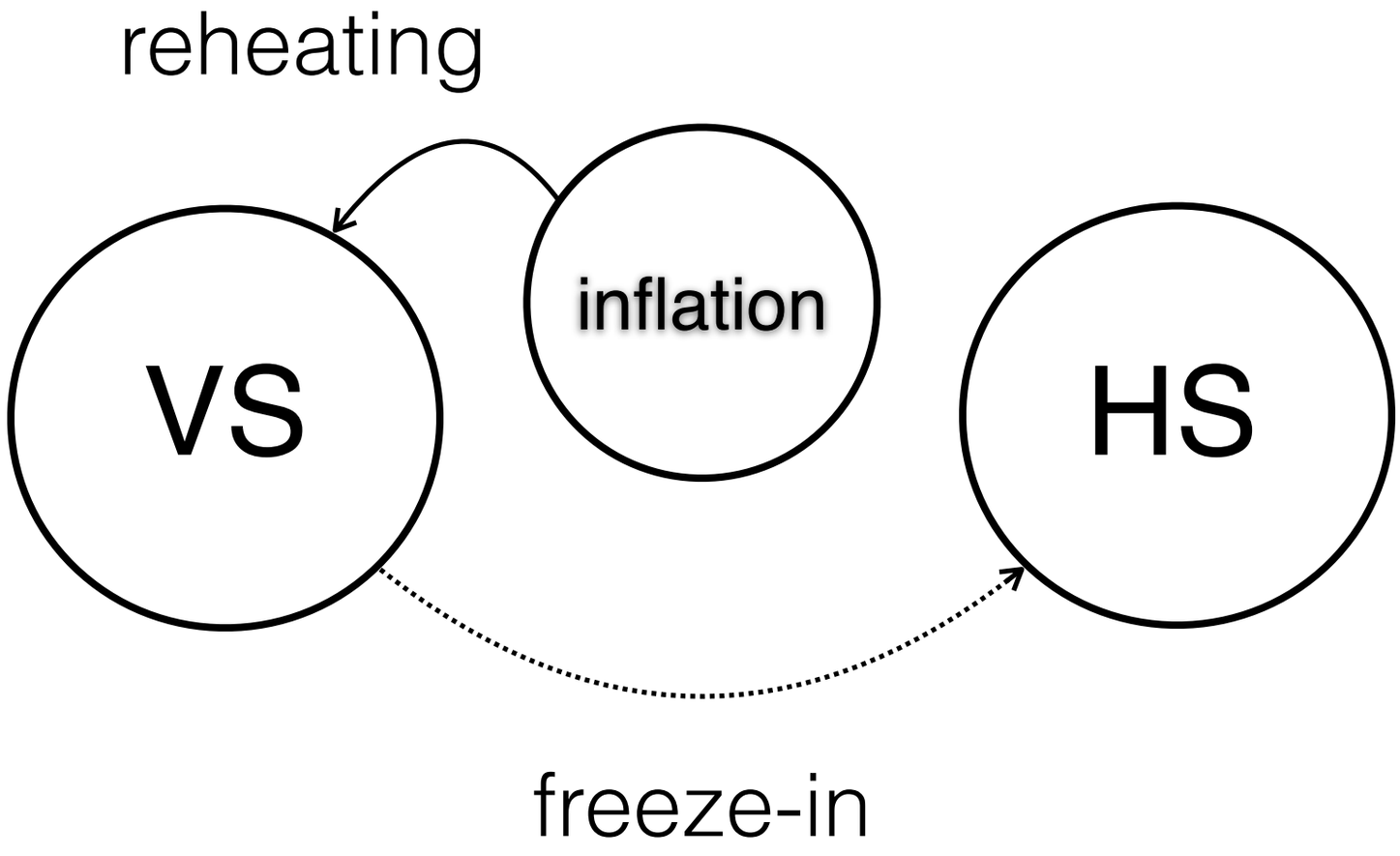
Chu, Hambye, M.T. ‘12



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

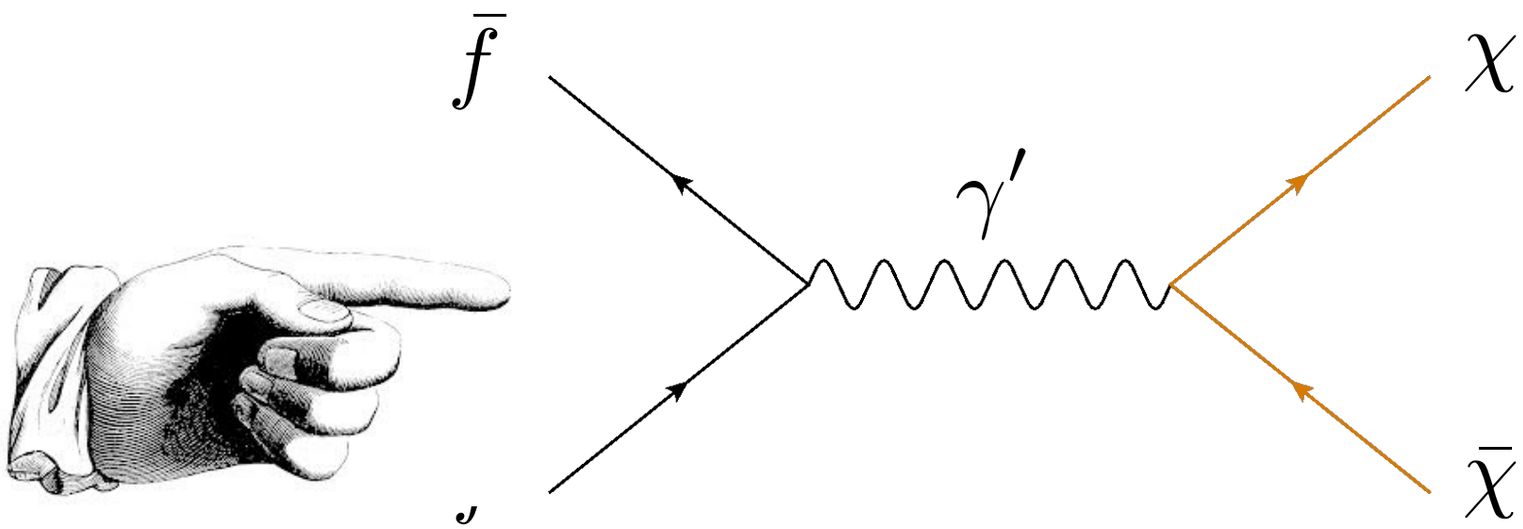
$$\epsilon_{\rm eff} = \epsilon \frac{m^2_{\gamma'}}{m^2_{\gamma'} - m^2_{\gamma}(T) + i\varepsilon}$$

FREEZE-IN PREREQUISITE



ABUNDANCE FROM FREEZE-IN

$$Y_\chi \sim \frac{n_\chi}{n_\gamma} \sim \Gamma_\chi \times t_* \qquad t_* \sim \frac{M_{\rm pl}}{T_*^2}$$



$$\Gamma_\chi \sim \kappa^2 T$$

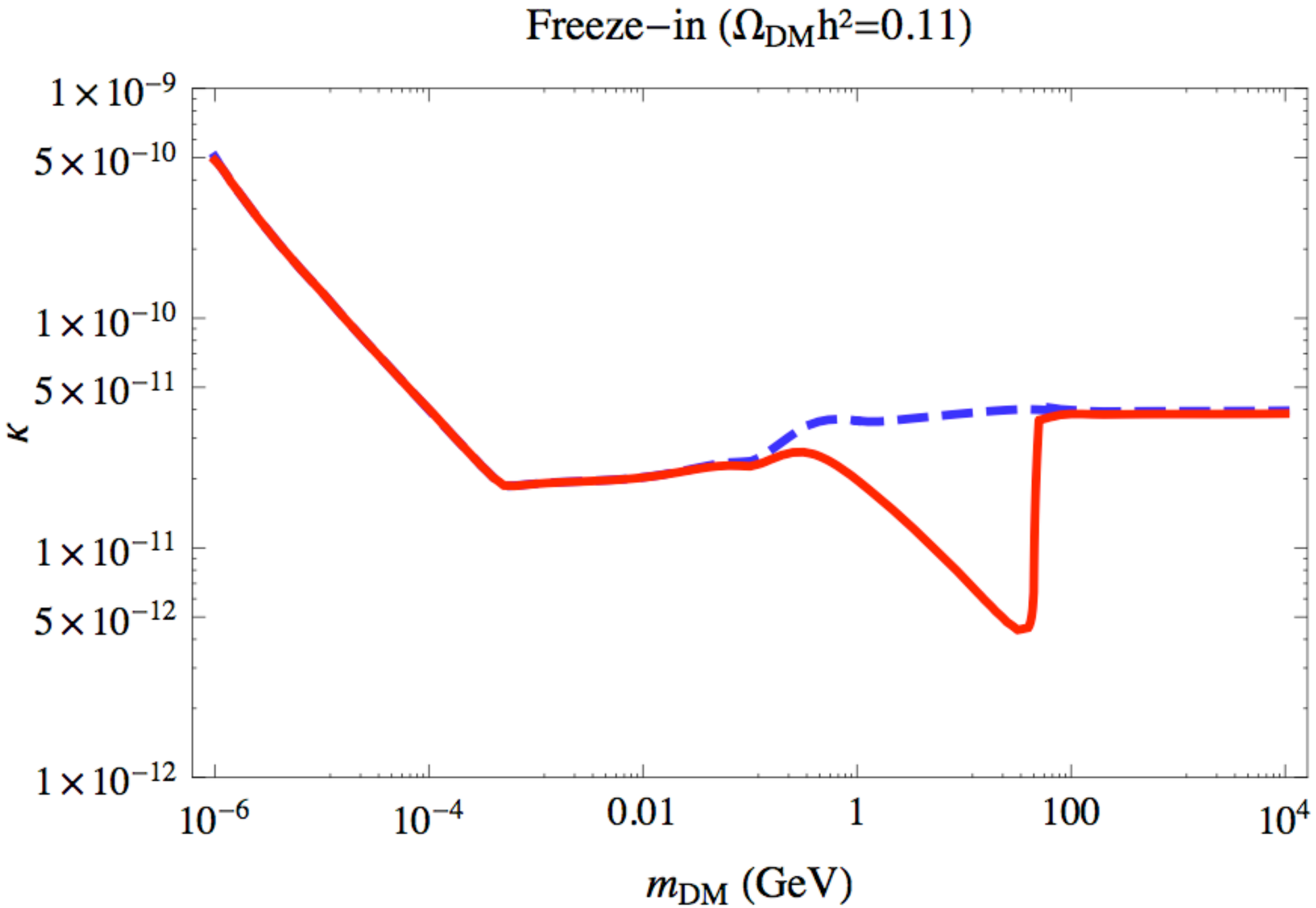
$$Y_\chi \sim \kappa^2 \frac{M_{\rm pl}}{T_*}$$

$$T_* \sim m_\chi$$

INFRARED FREEZE-IN

FREEZE-IN CANDIDATES

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

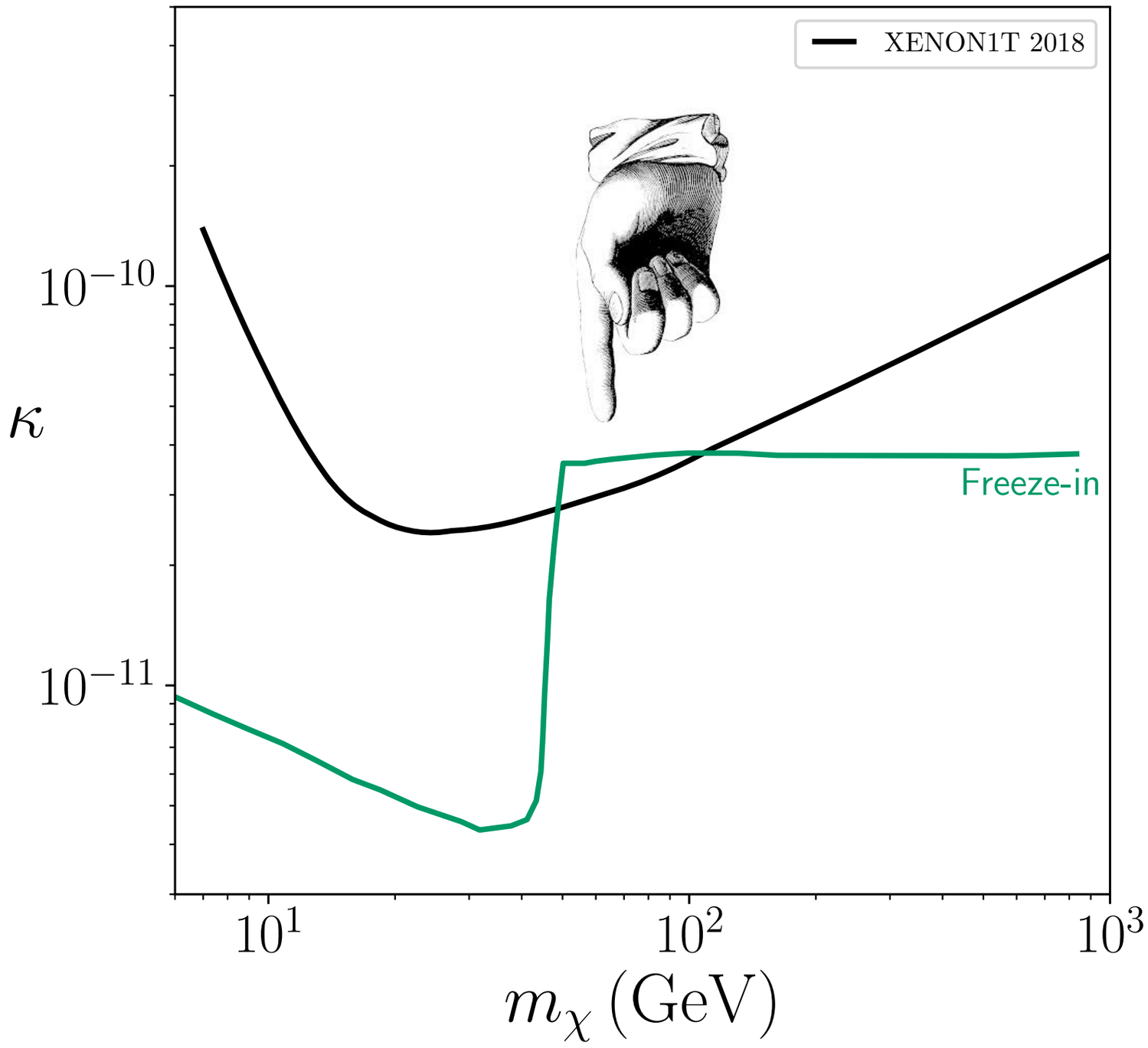


Chu, Hambye, M.T. ‘12

Essig, Mardon, Volansky ‘12

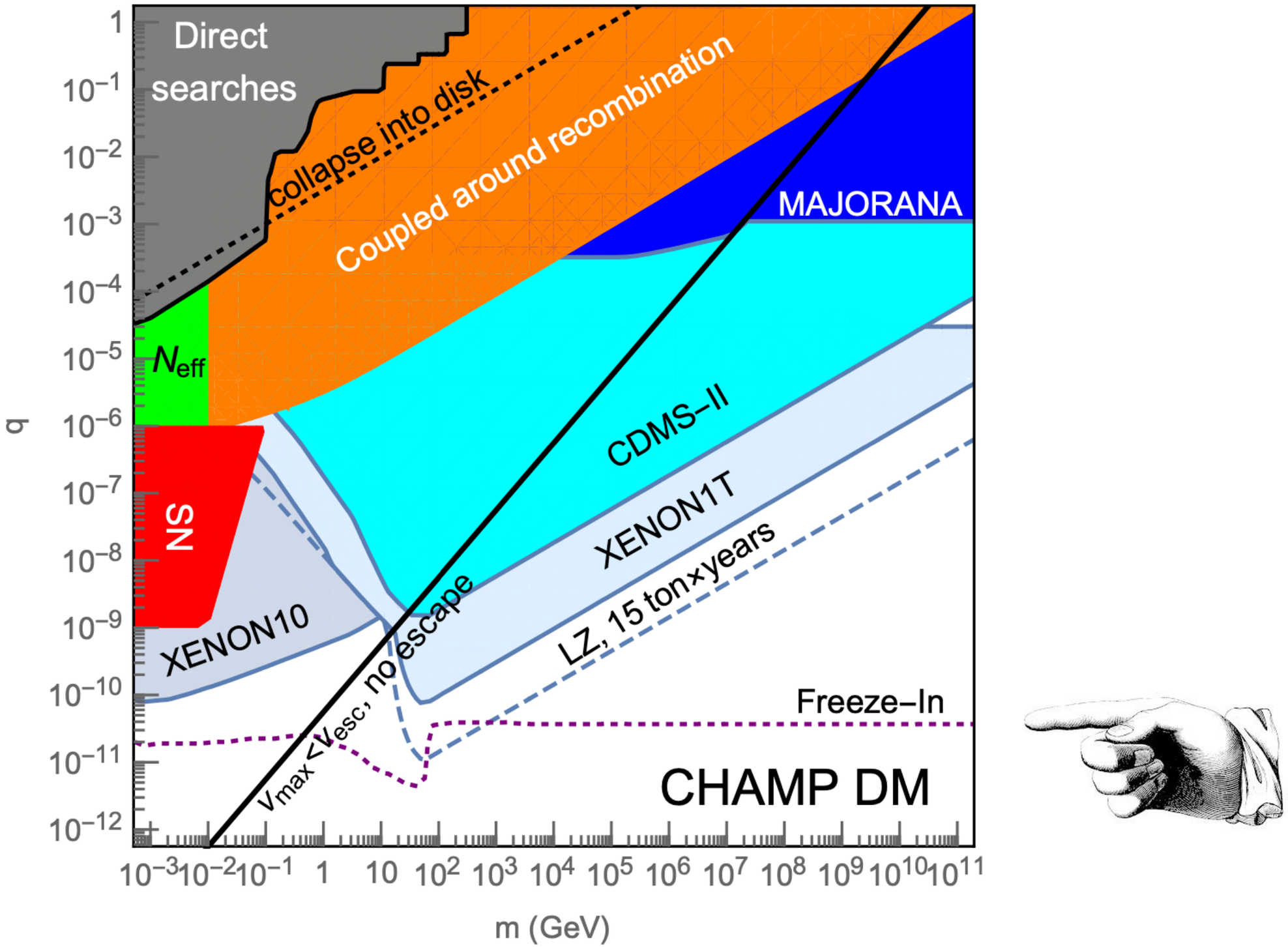
DIRECT TESTS OF DARK QED

$m_{\gamma'} \to 0$



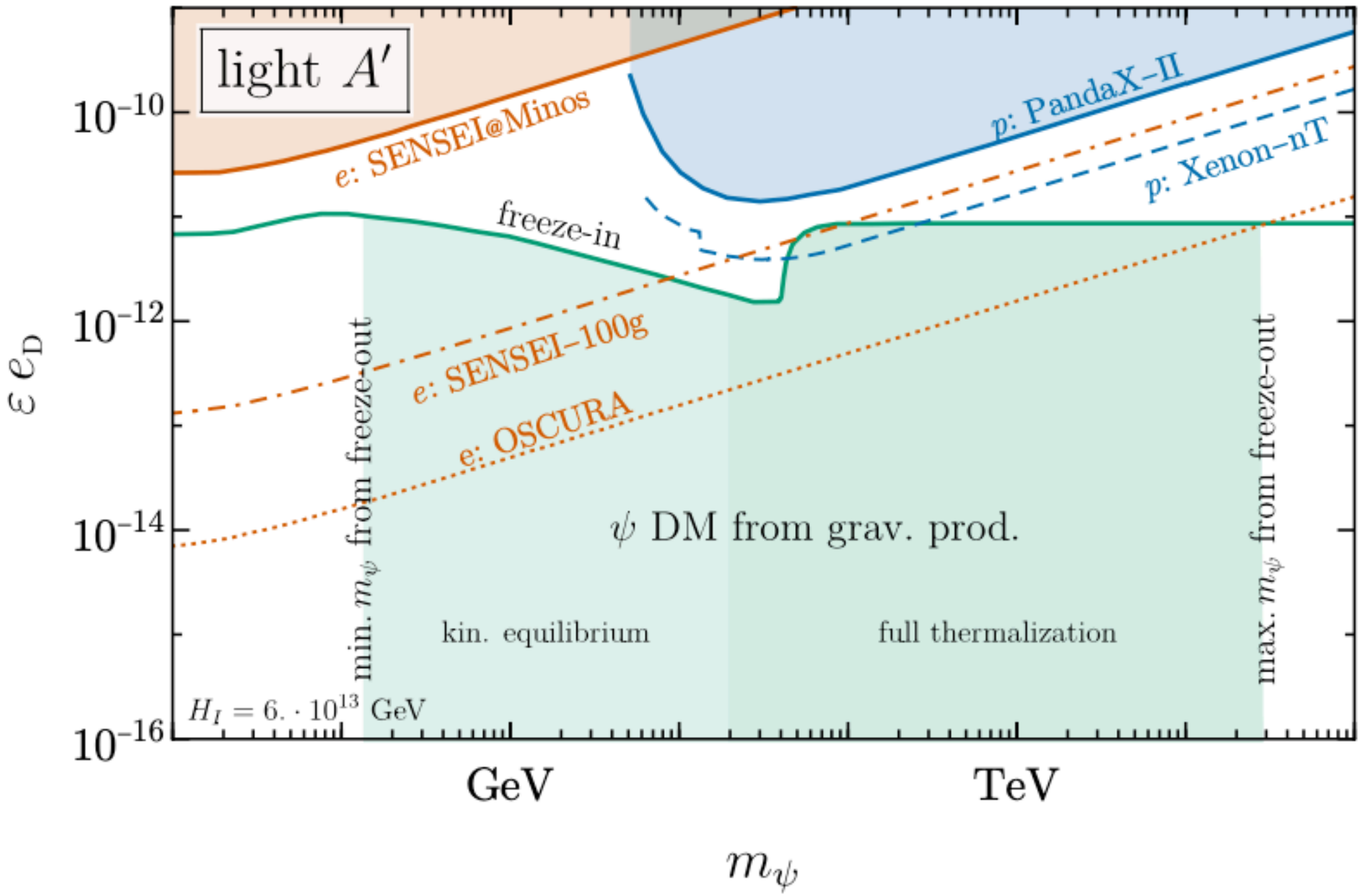
Hambye, M.T., Vandecasteele, Vanderheyden ‘18

DIRECT TESTS OF DARK QED



Dunsky, Hall, Harigaya, 2019

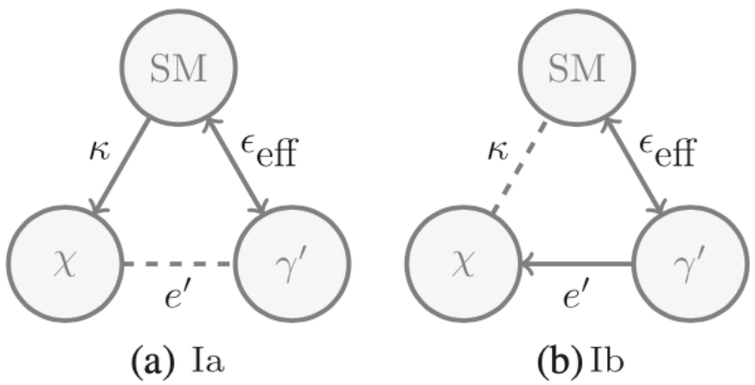
DIRECT TESTS OF DARK QED



Arvanitaki, Dimopoulos, **Ganalis,** Racci, Simon, Thompson, 2021

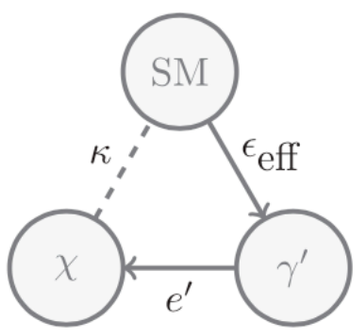
NEW 9 WAYS (5 REGIMES) TO PRODUCE DM

$m_{\gamma'} \neq 0$



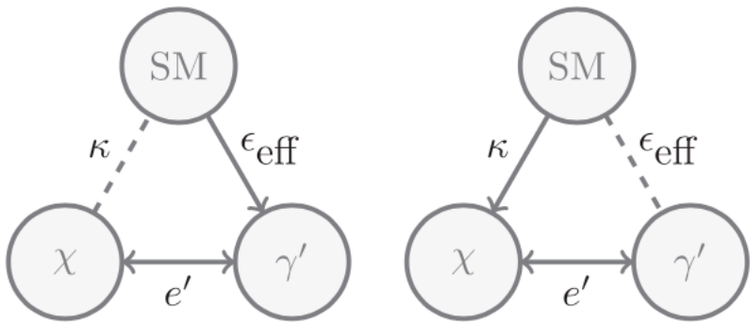
(a) Ia (b) Ib

freeze-in (Ia & Ib)



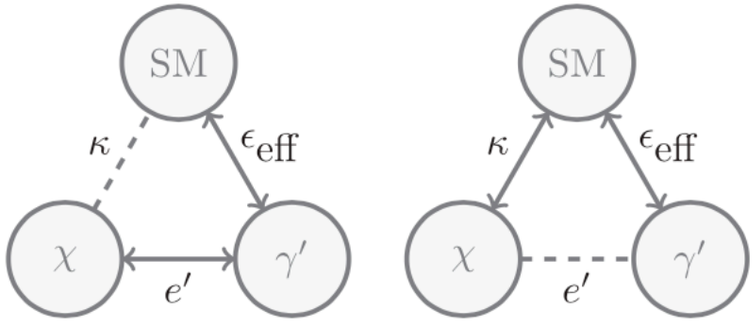
(c) II

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)

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

NEW

DM PRODUCTION REVISITED

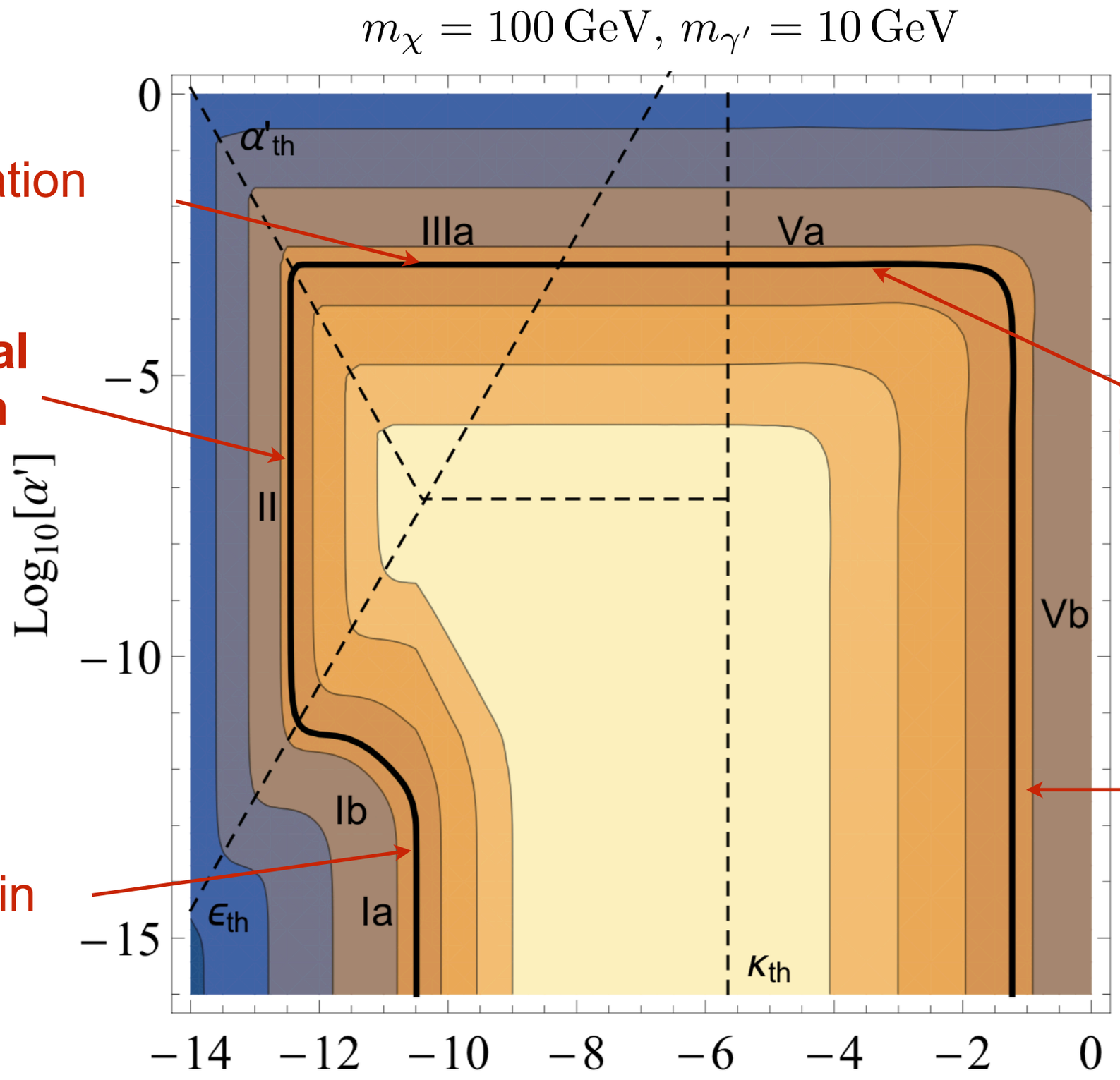
reannihilation

sequential freeze-in

freeze-out into dark photons

standard freeze-out

freeze-in

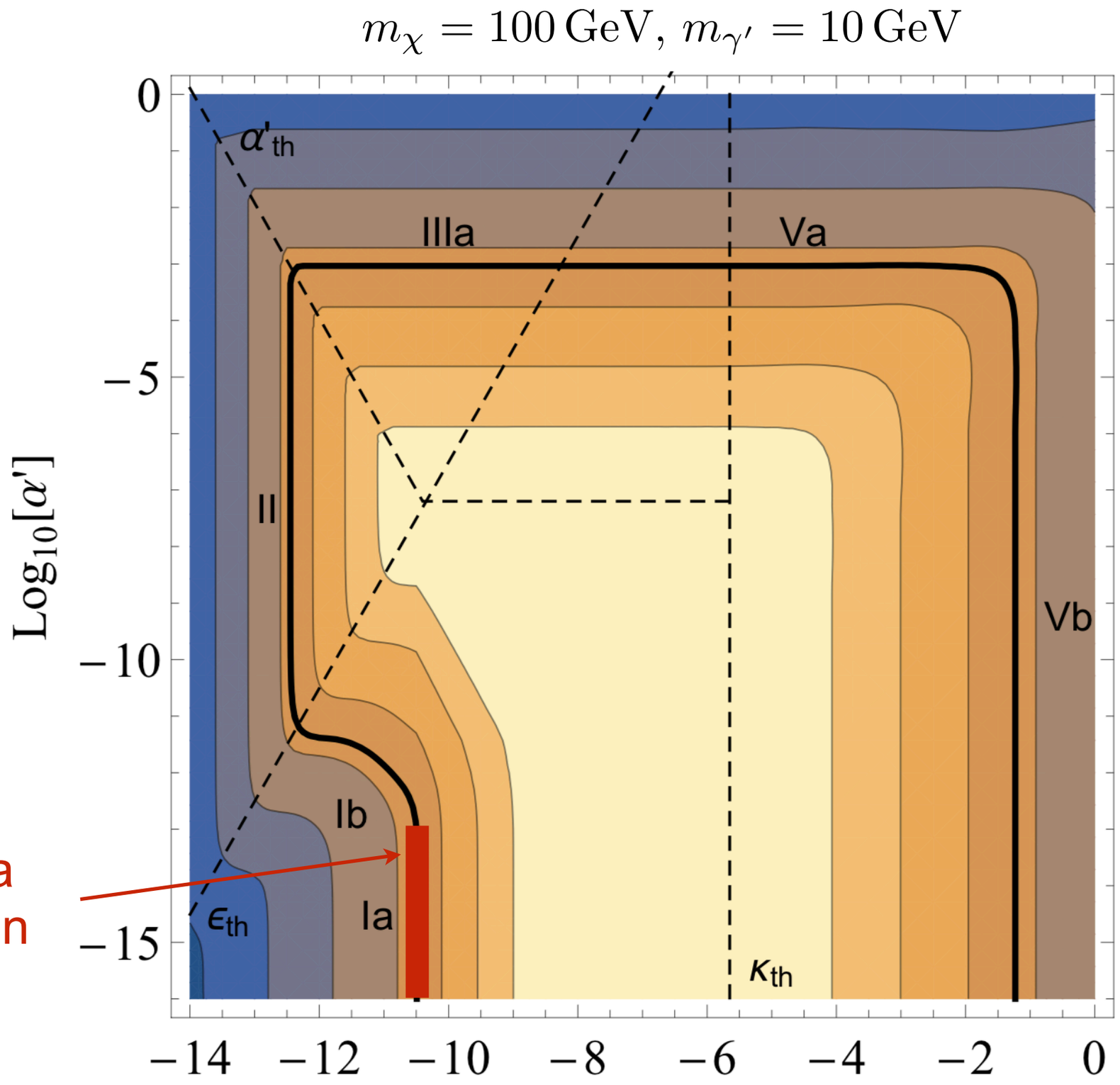


$$\kappa = \epsilon\, e'/e$$

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

FREEZE-IN REVISITED

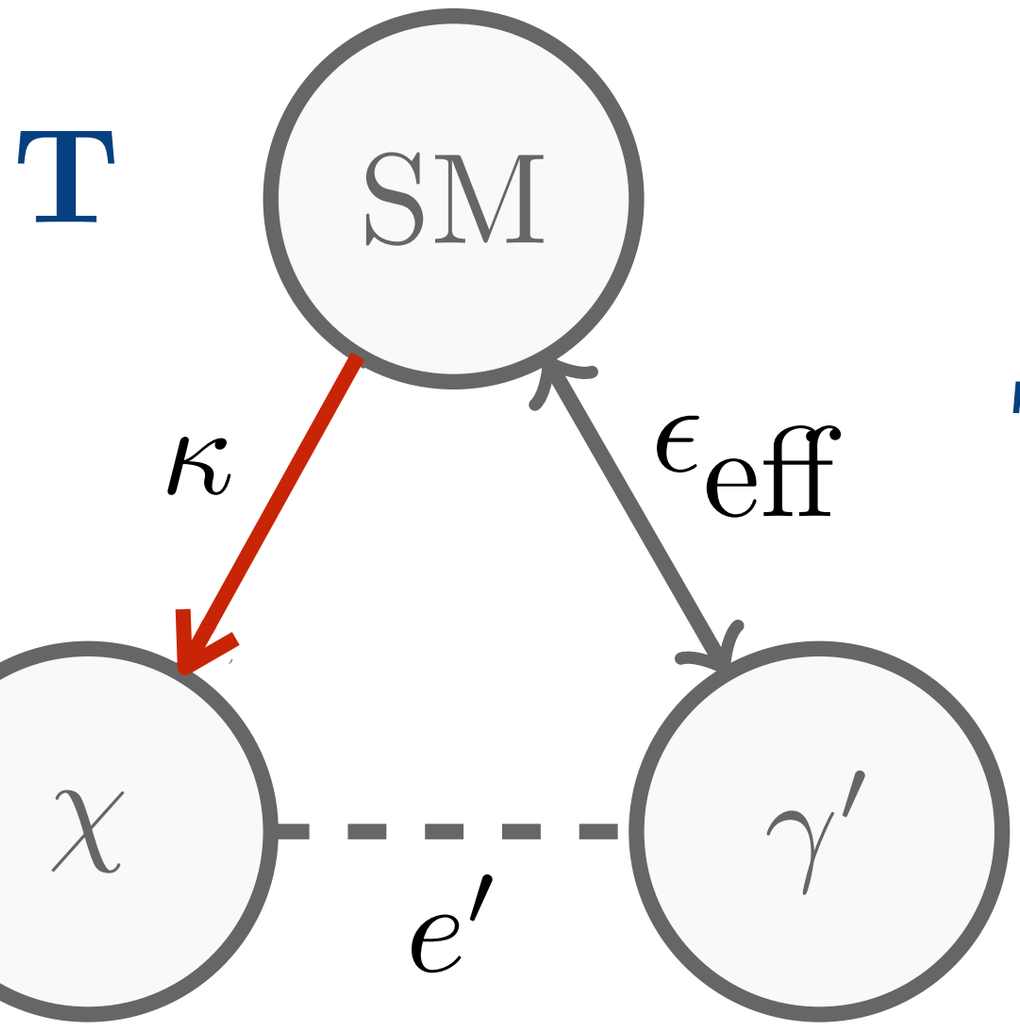
$m_{\gamma'} \neq 0$



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

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

STANDARD FREEZE-IN (type Ia)



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

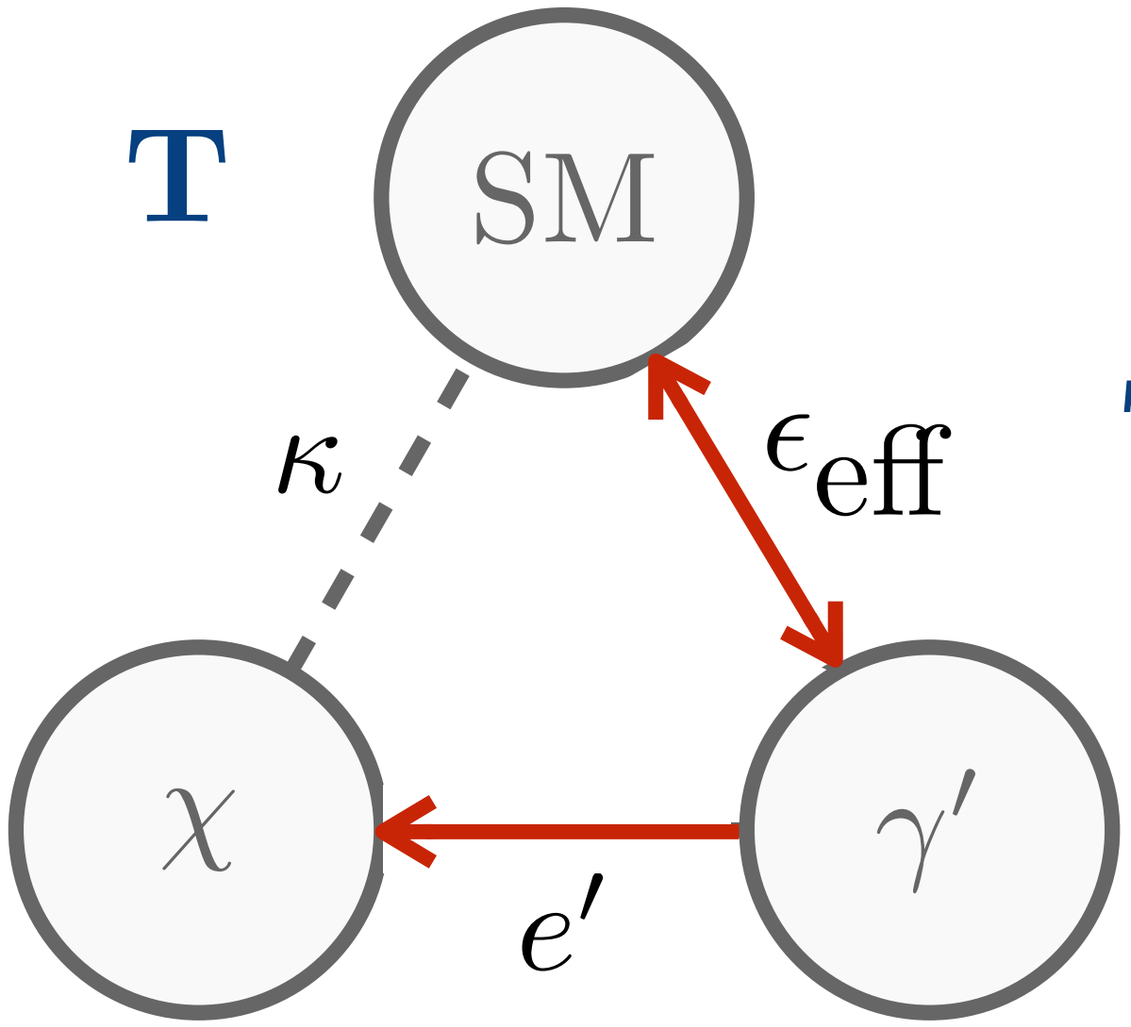
$\mathbf{T}_{\chi} \sim \mathbf{0}$

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

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

FREEZE-IN FROM DARK PHOTONS (type Ib)

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



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

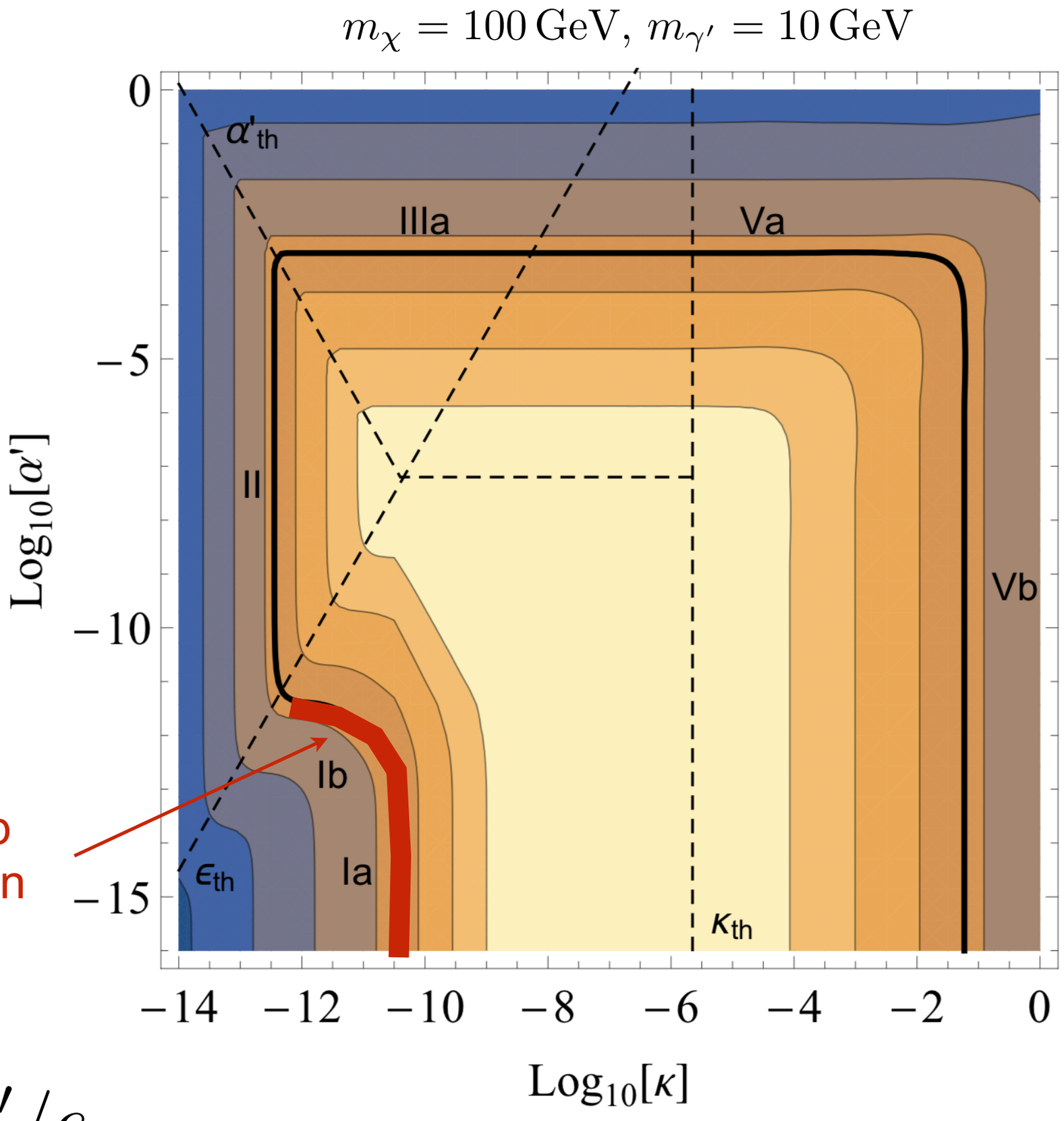
$\mathbf{T}_{\chi} \sim \mathbf{0}$

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

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

FREEZE-IN Ia & Ib

$m_{\gamma'} \neq 0$



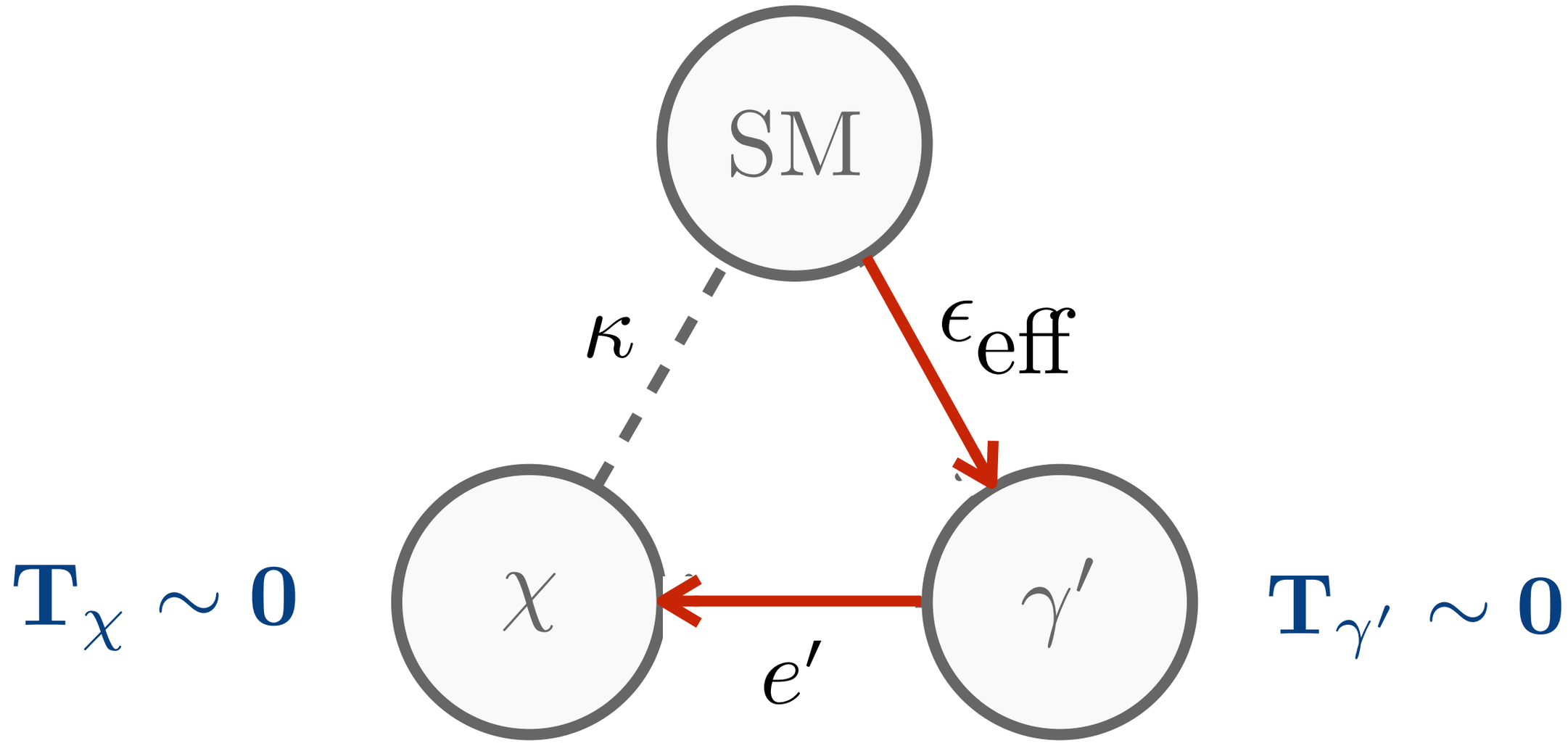
$\kappa = \epsilon\, e'/e$

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

SEQUENTIAL FREEZE-IN (type II)

NEW REGIME!

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

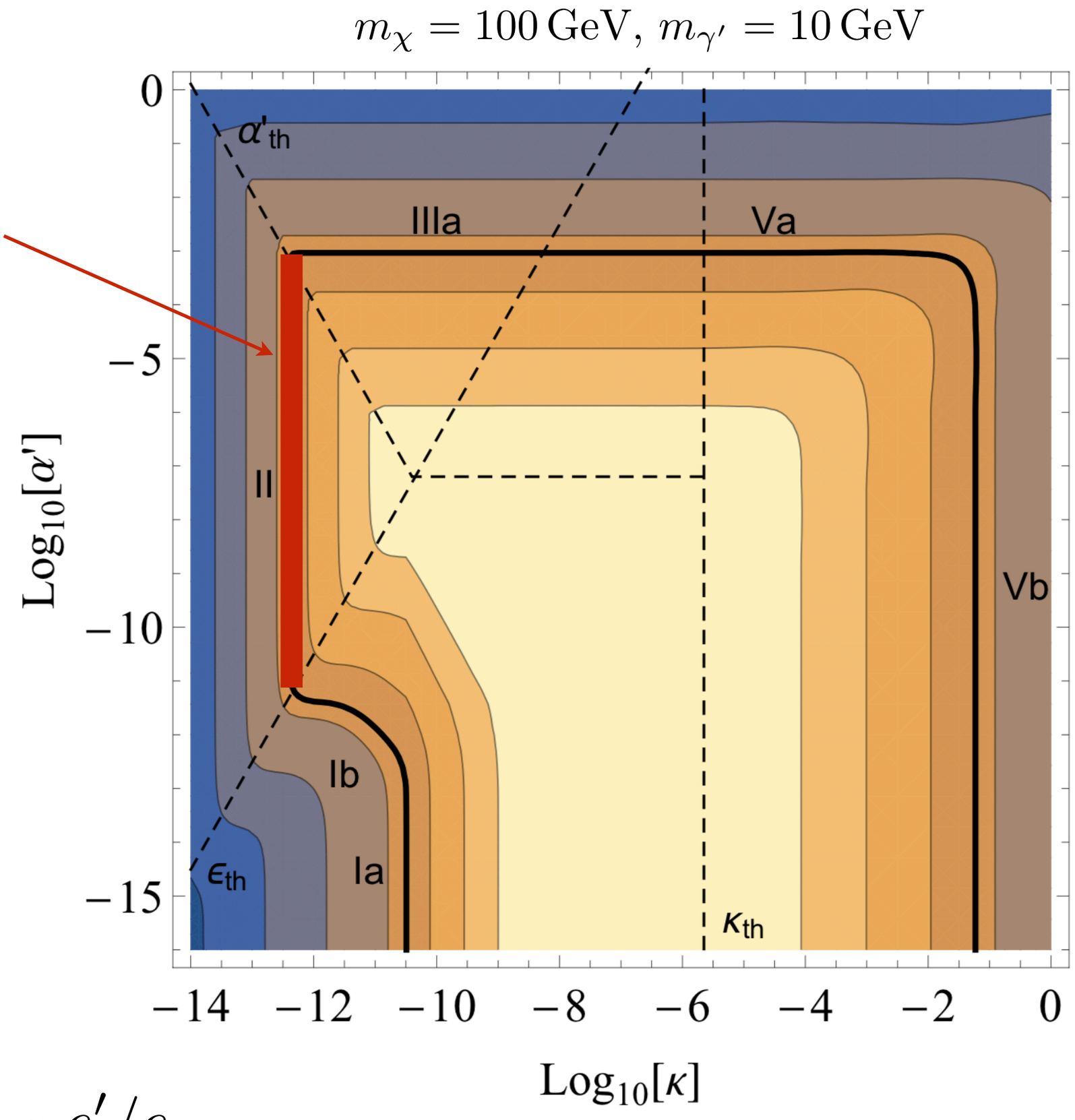


Type II

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

SEQUENTIAL FREEZE-IN (type II)

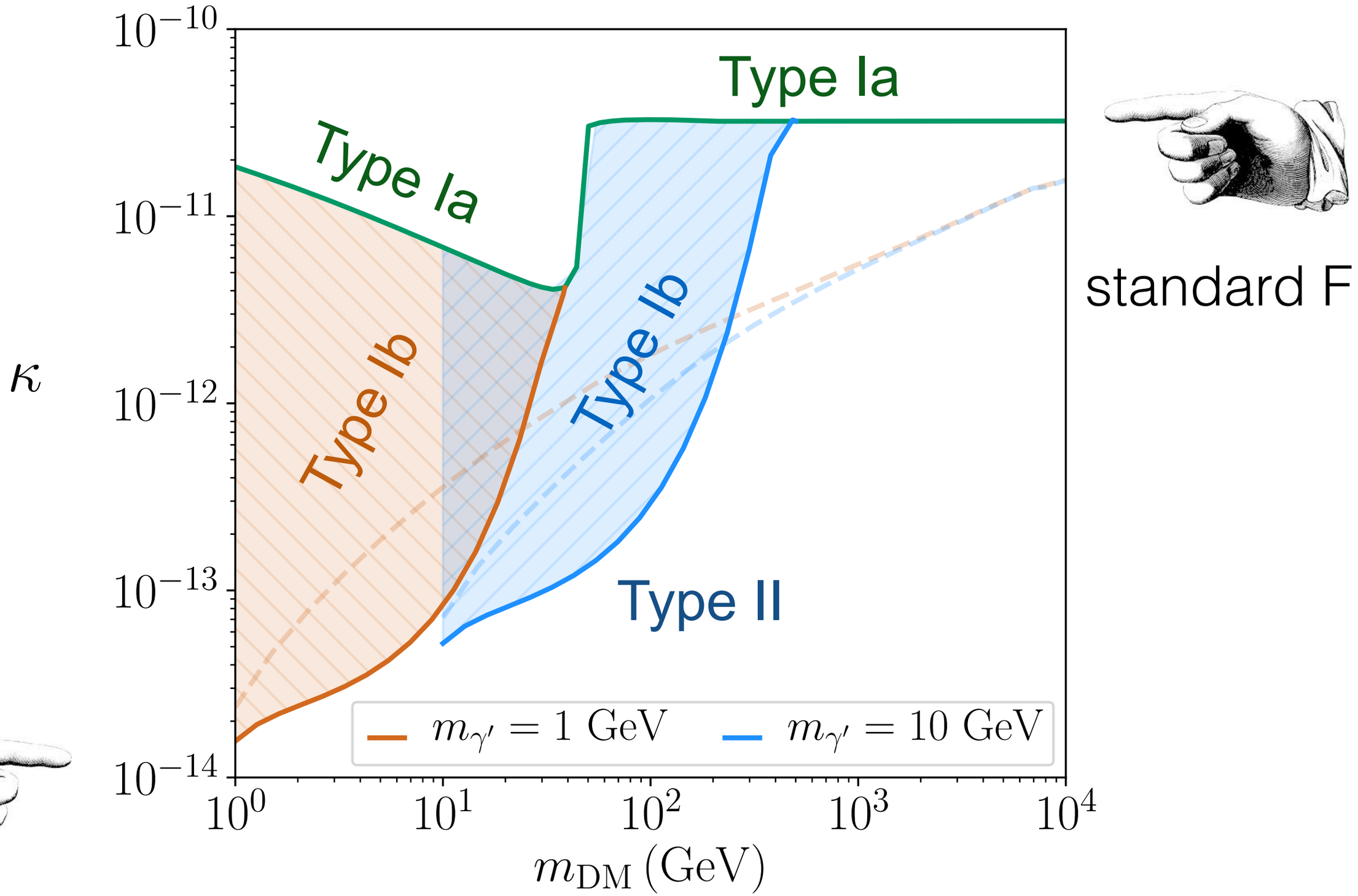
Type II freeze-in



$$\kappa_{\mathrm{eff}} = \epsilon_{\mathrm{eff}}\, e'/e$$

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

Type Ia,b and II freeze-in candidates

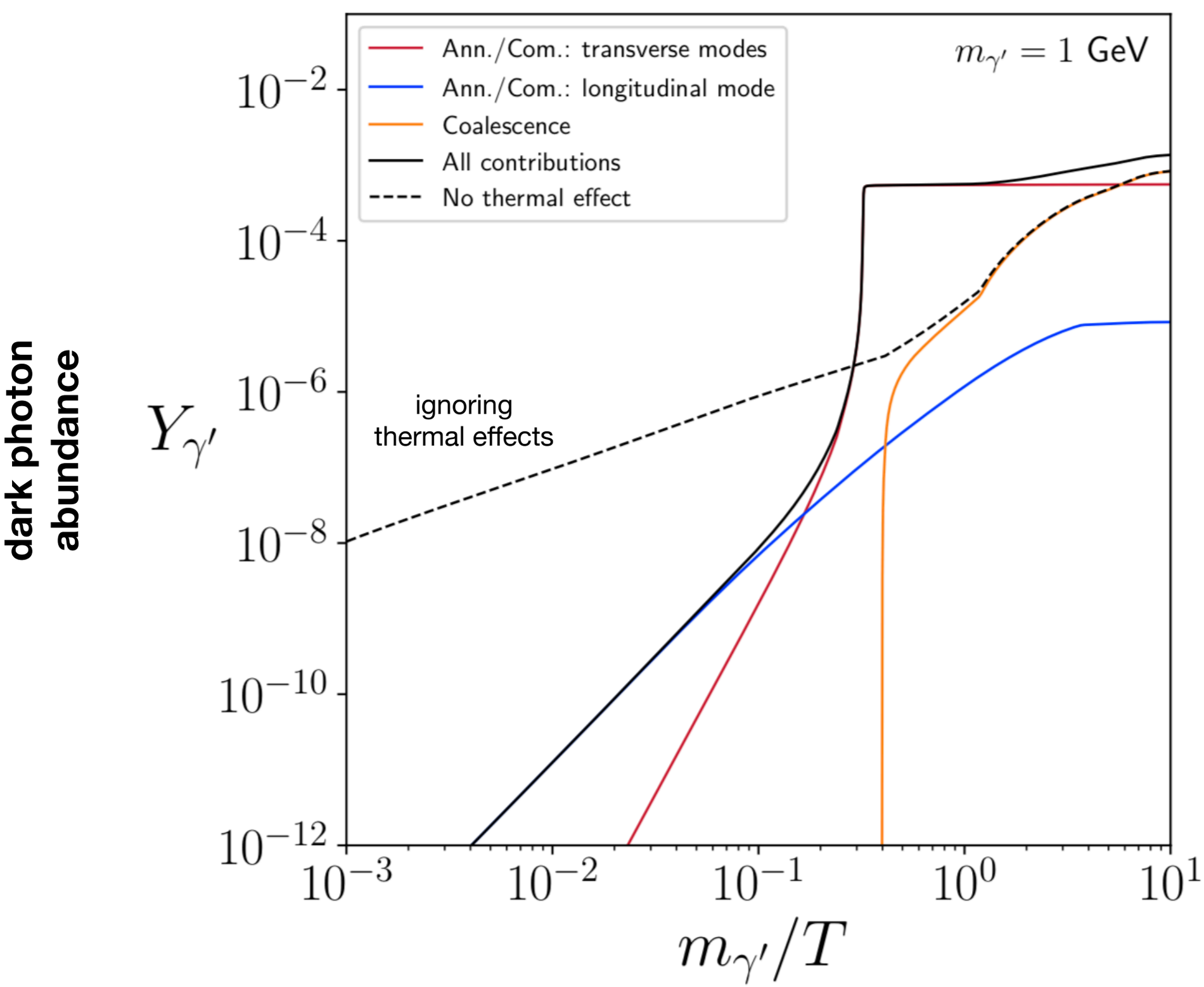


standard FI

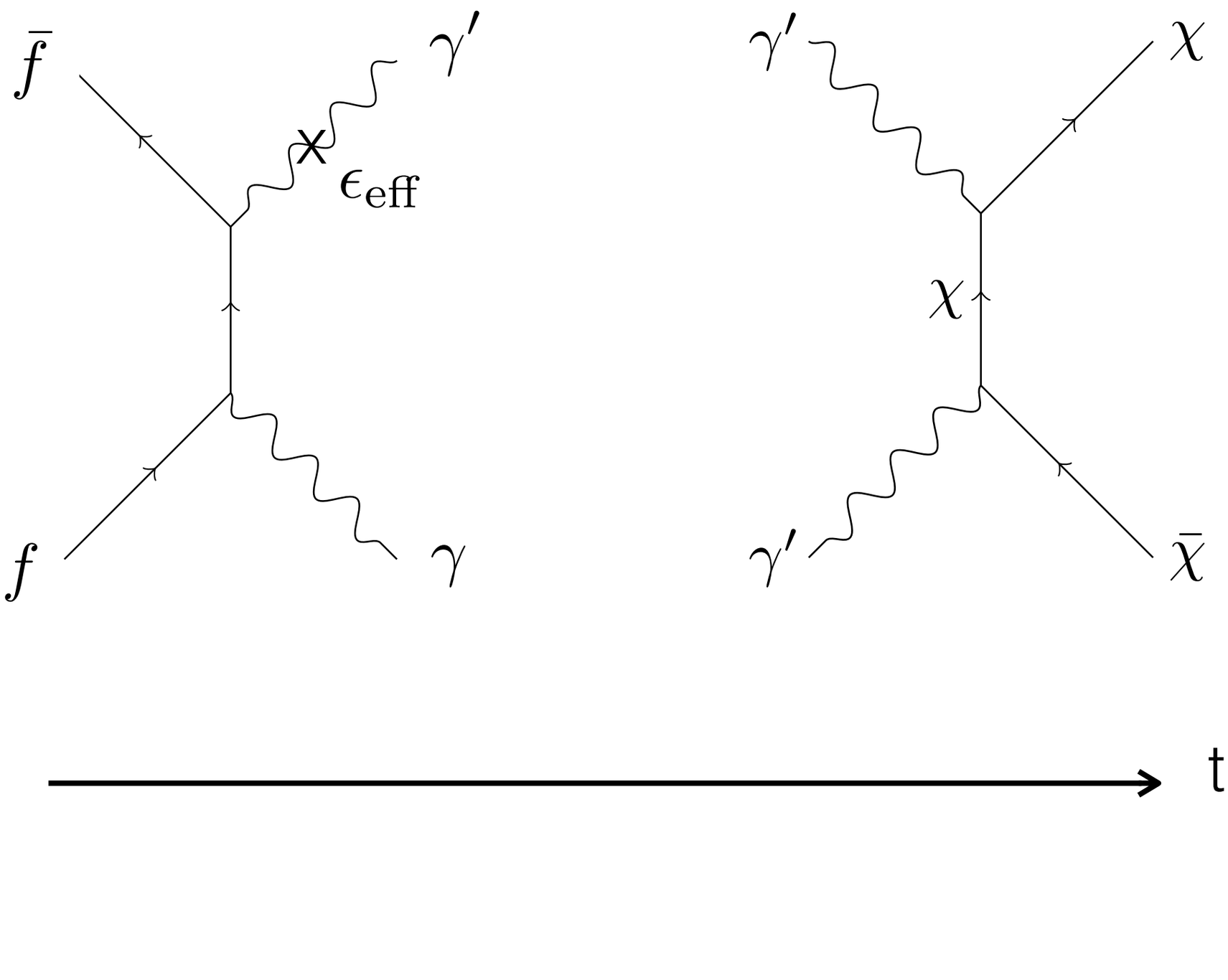
sequential FI

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

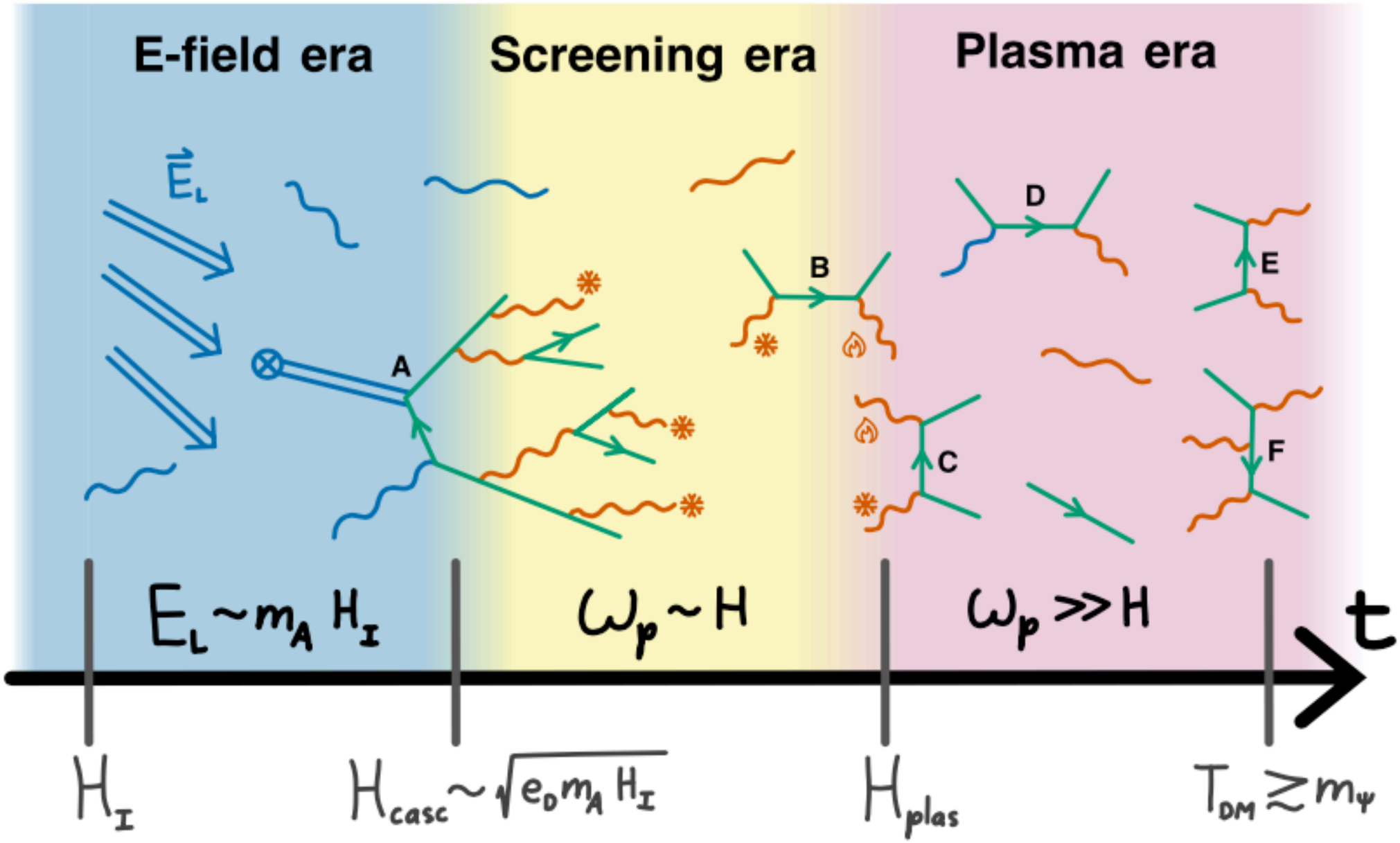
PERTURBATIVE PRODUCTION OF DARK PHOTONS



PERTURBATIVE SEQUENTIAL FREEZE-IN

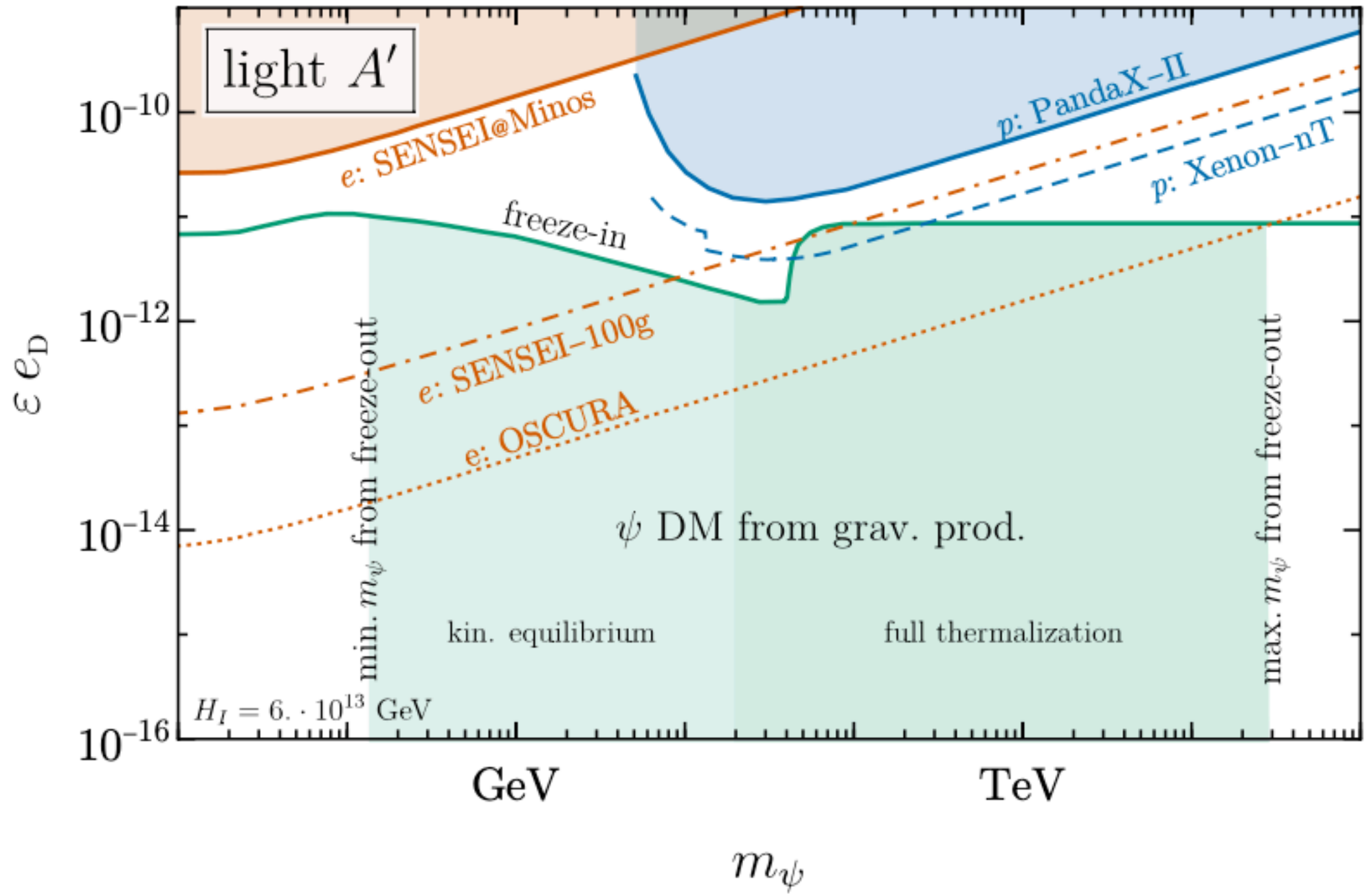


NON-PERTURBATIVE SEQUENTIAL FREEZE-IN



Arvanitaki, Dimopoulos, Ganalis, Racci, Simon, Thompson, 2021

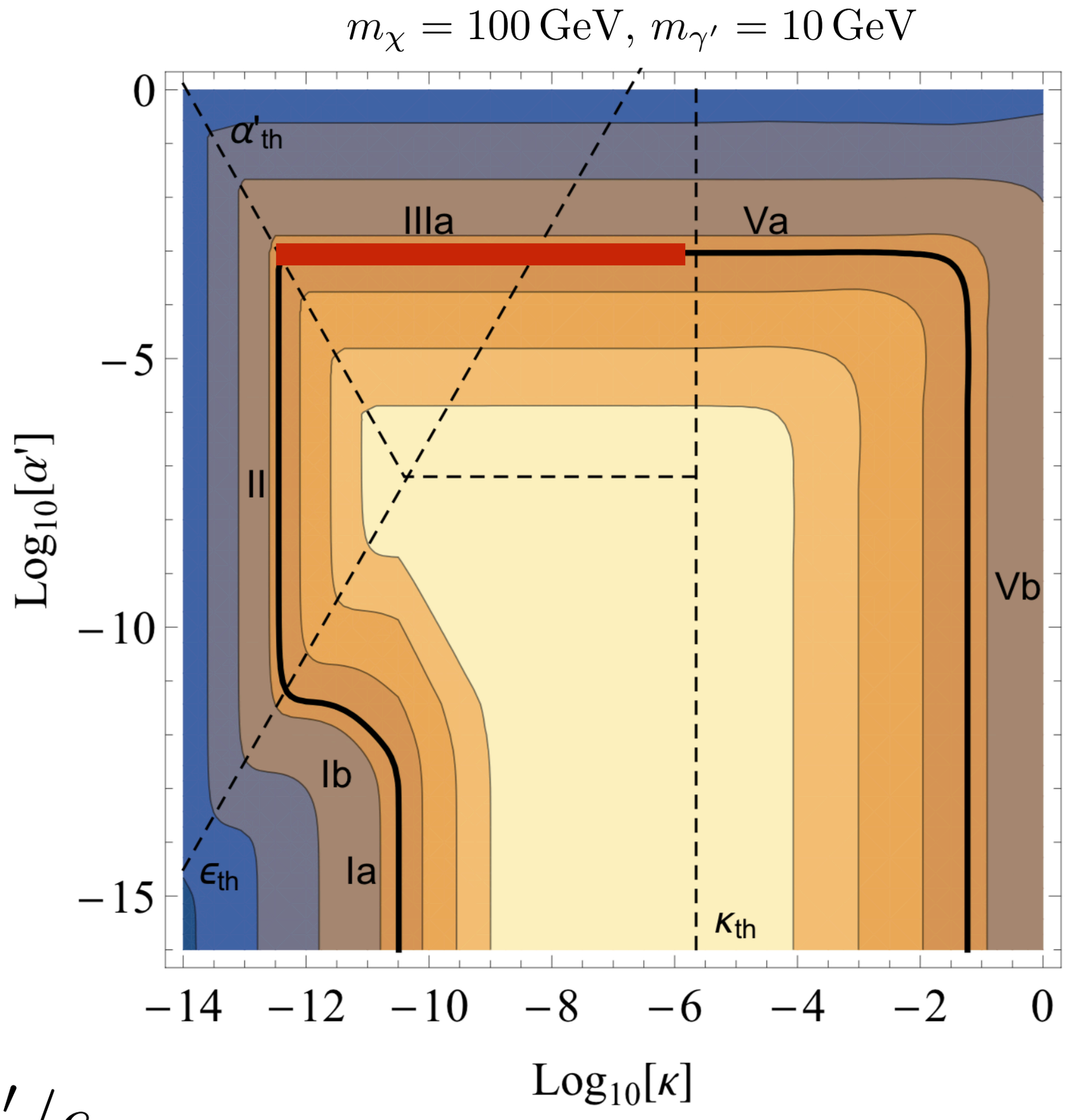
SEQUENTIAL FREEZE-IN CANDIDATES



Arvanitaki, Dimopoulos, Ganalis, Racci, Simon, Thompson, 2021

Caveat : assumes Stueckelberg mass; production changed if Higgs (Redi, Tesi, 2022)

Type IIIa : HS with T’ < T

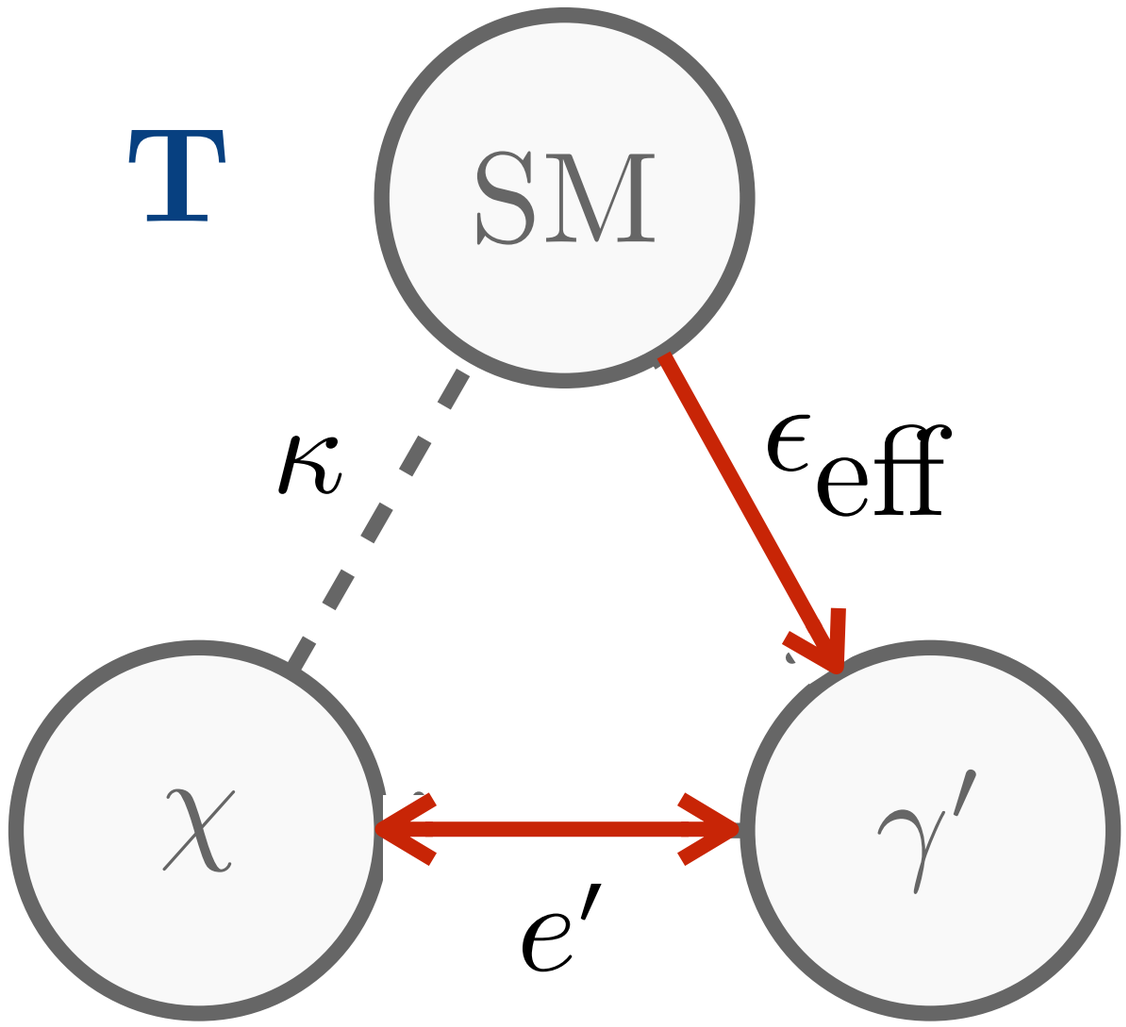


$$\kappa = \epsilon\, e'/e$$

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

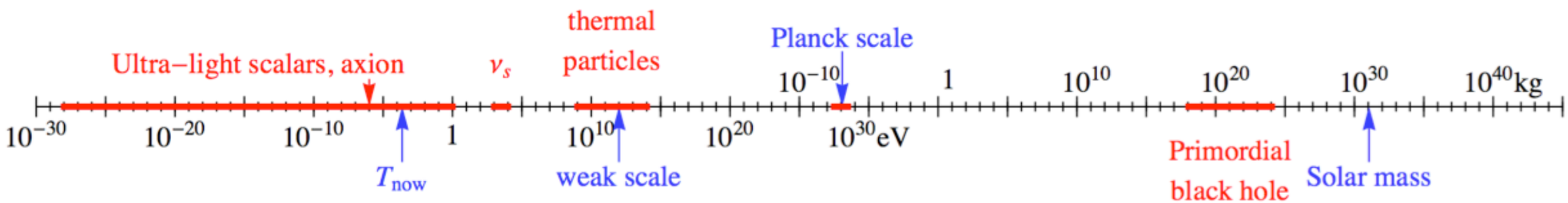
Type IIIa : HS with T' < T

$m_{\gamma'} \neq 0$



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

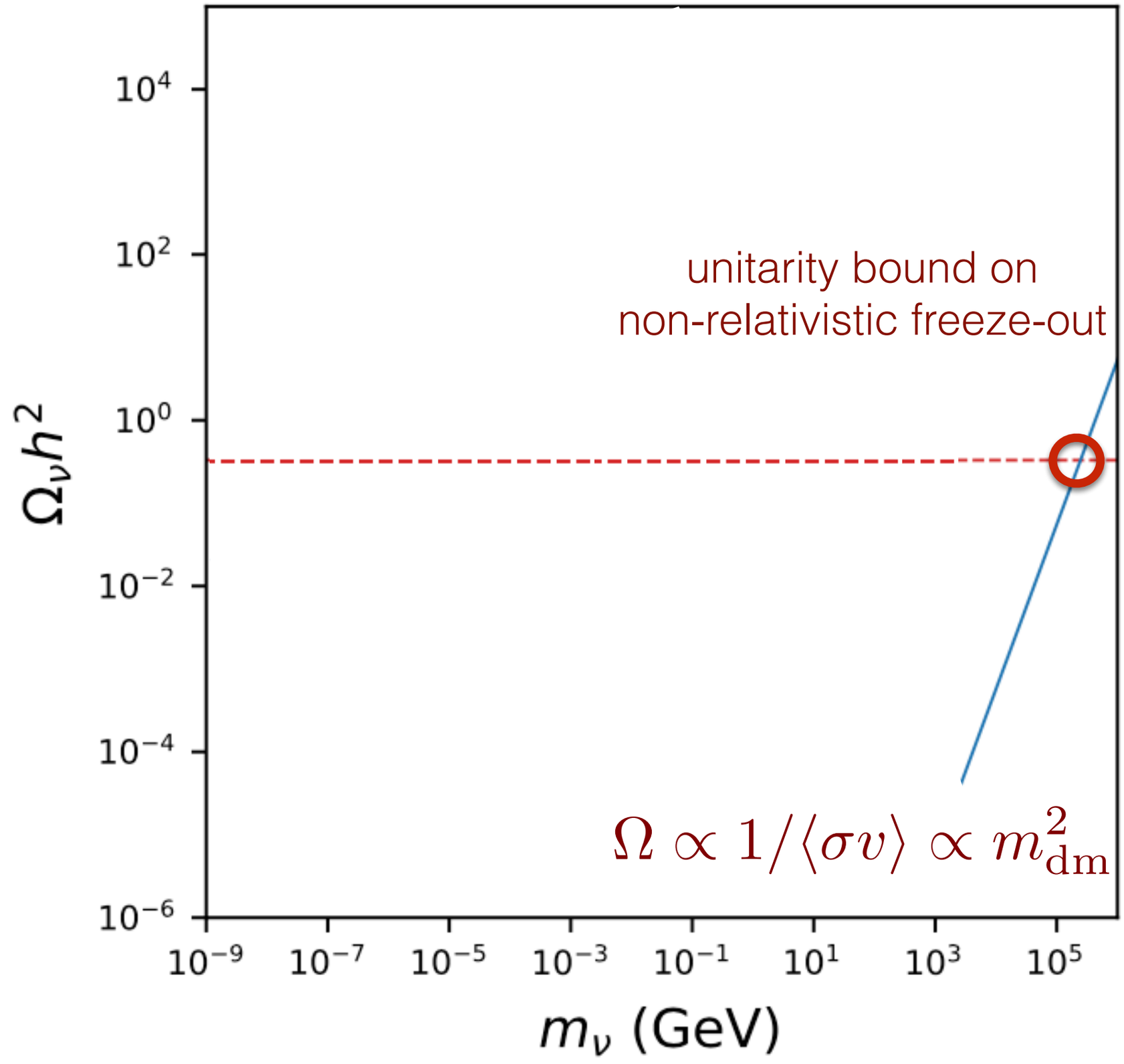
3
DOMAIN OF THERMAL DARK MATTER



WIMPs at T'=T

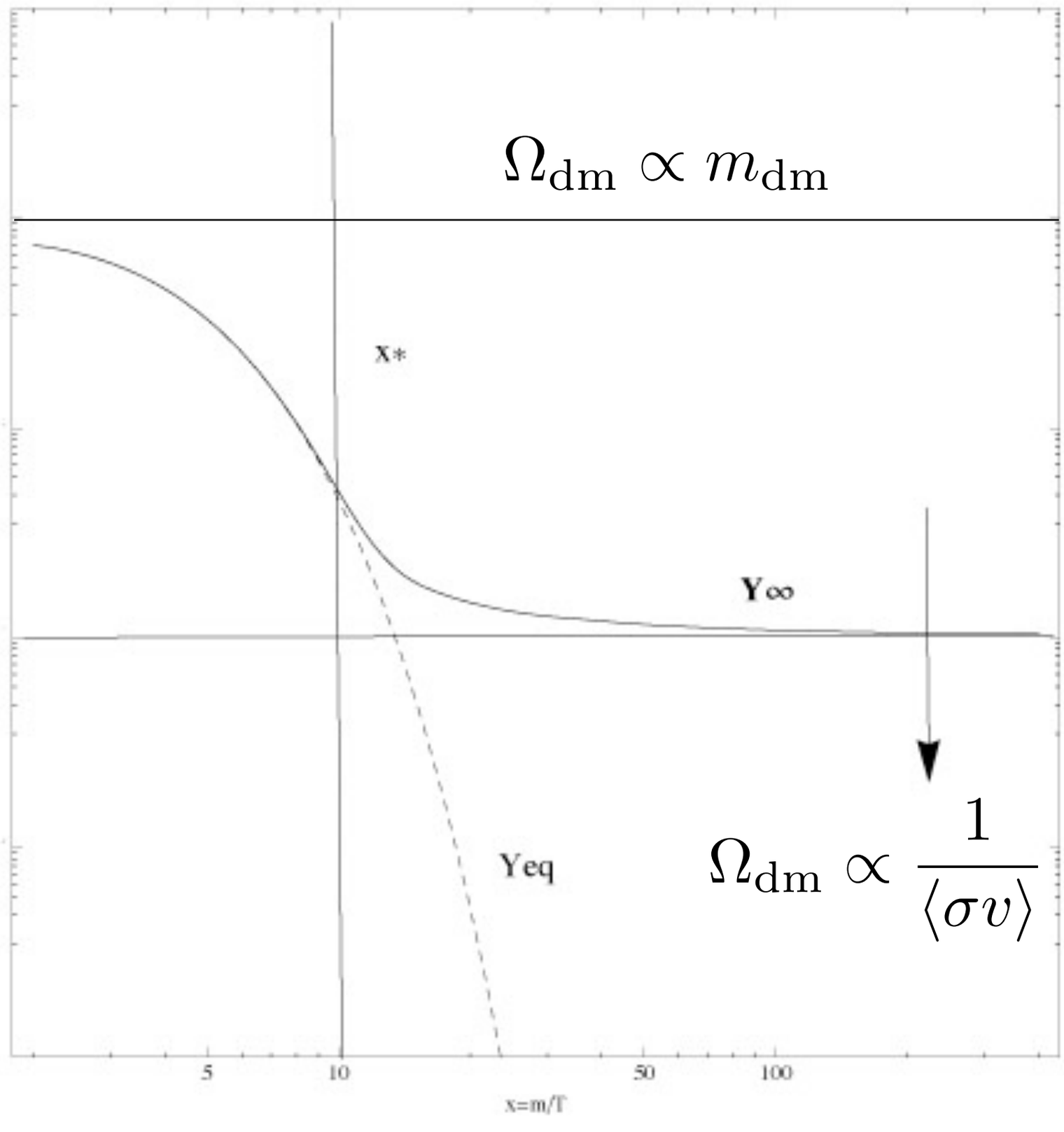
Figure from M.Cirelli

MAXIMAL DM MASS



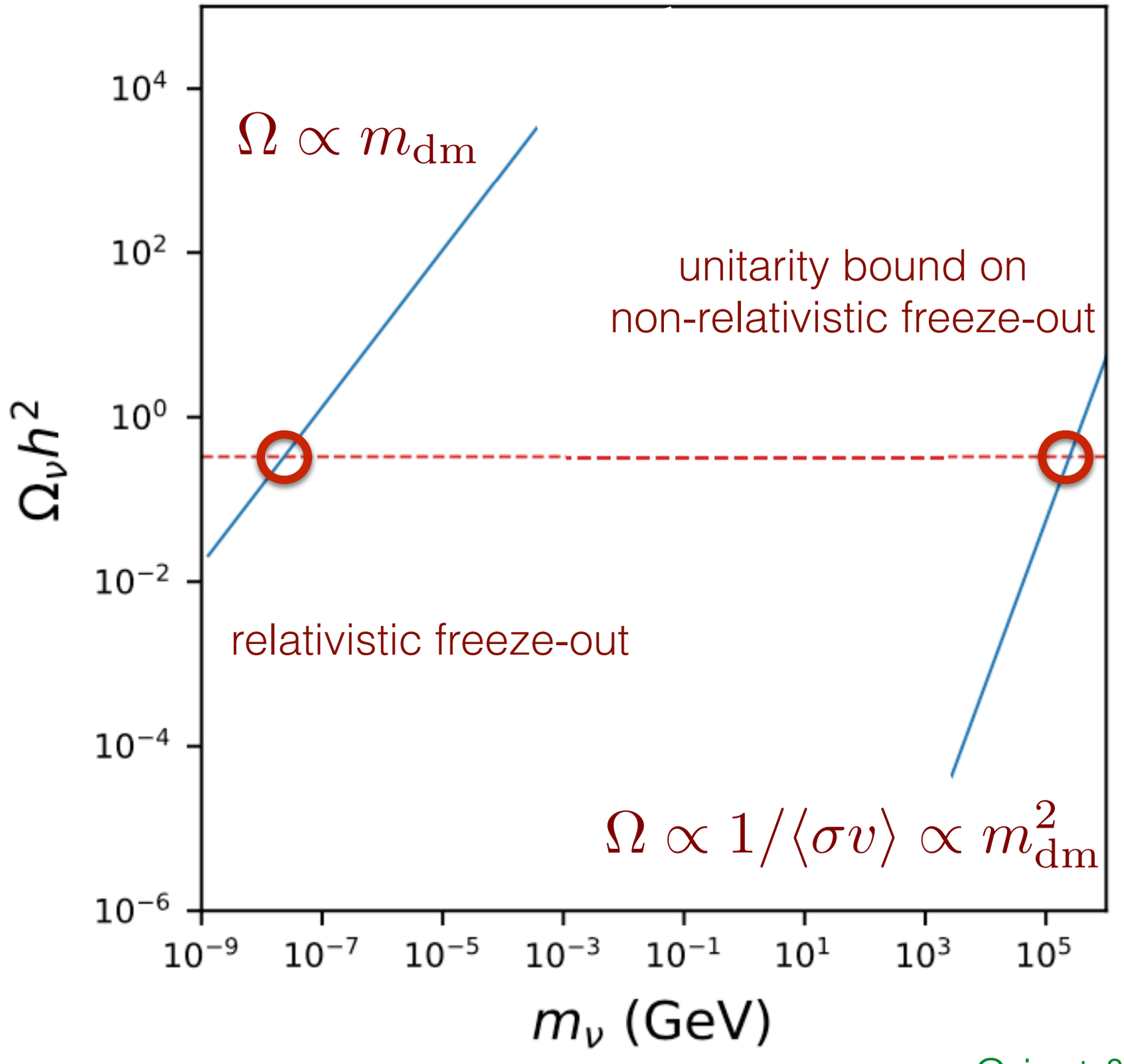
Griest & Kamionkowski

RELATIVISTIC vs NON-RELATIVISTIC FREEZE-OUT



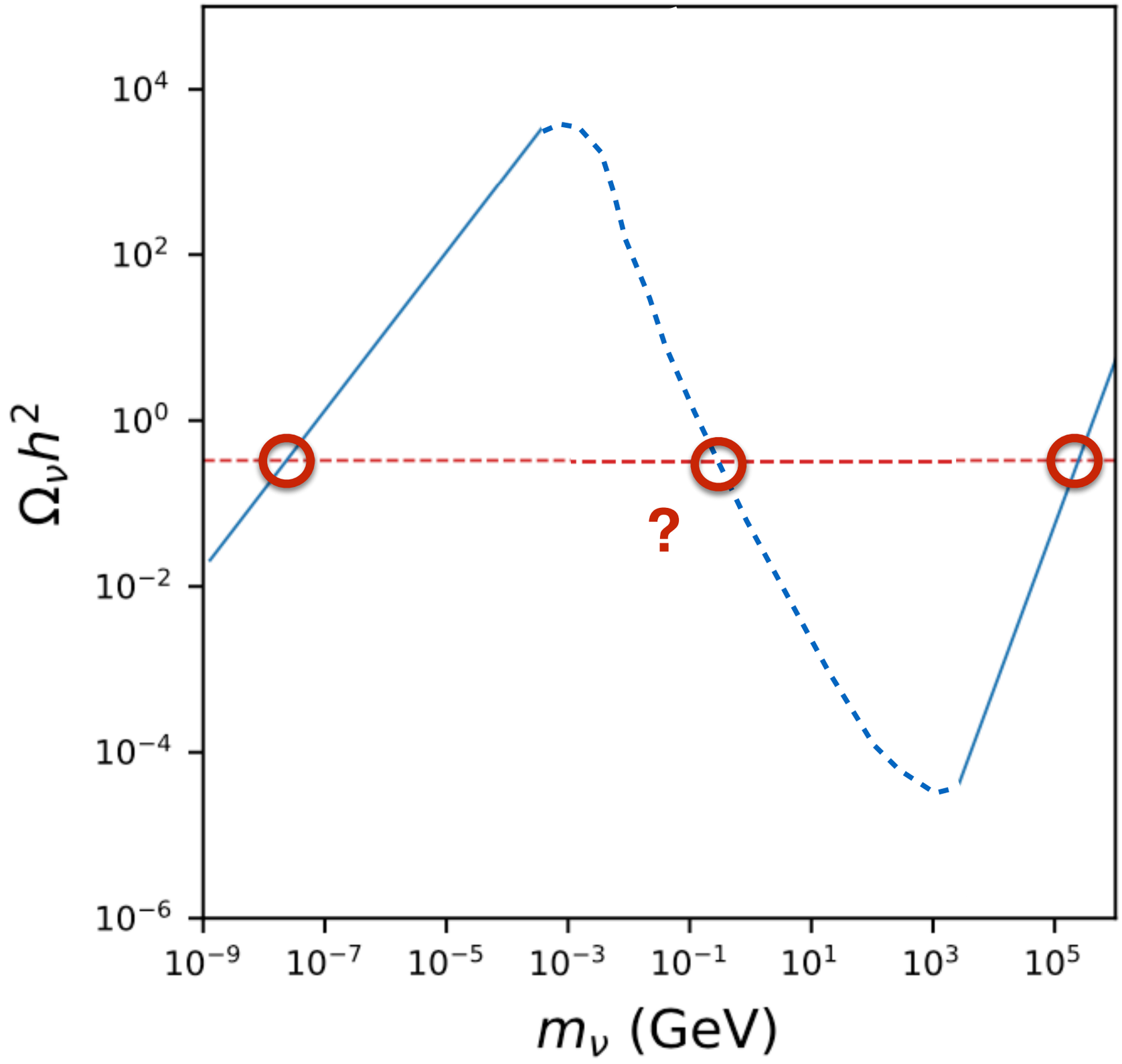
$$\Omega_{\rm dm} \propto \frac{1}{\langle \sigma v \rangle} \sim m_{\rm dm}^2$$

MINIMAL & MAXIMAL DM MASS



Griest & Kamionkowski
Cowsik-McLelland

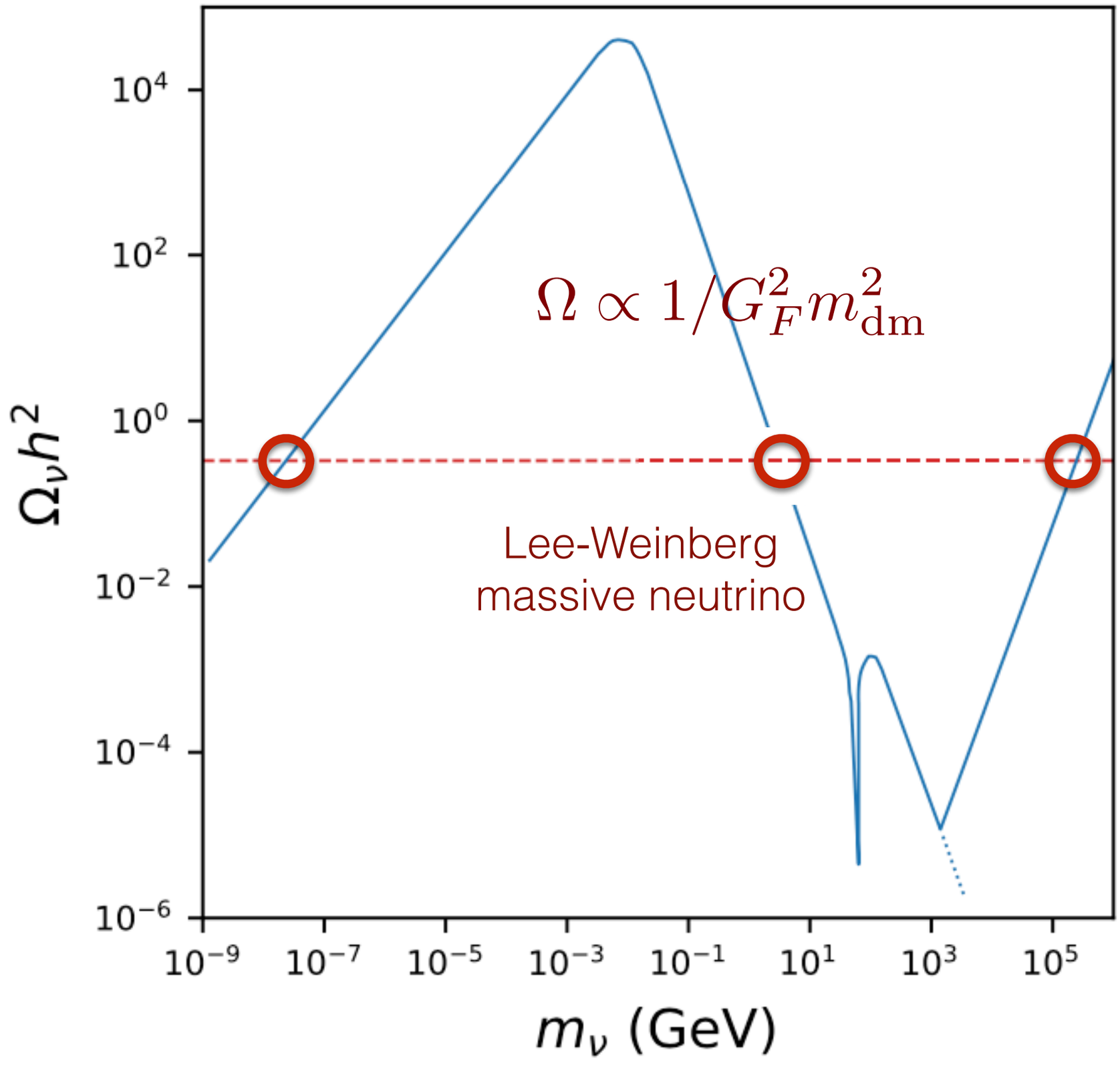
MINIMAL & MAXIMAL DM MASS



Griest & Kamionkowski

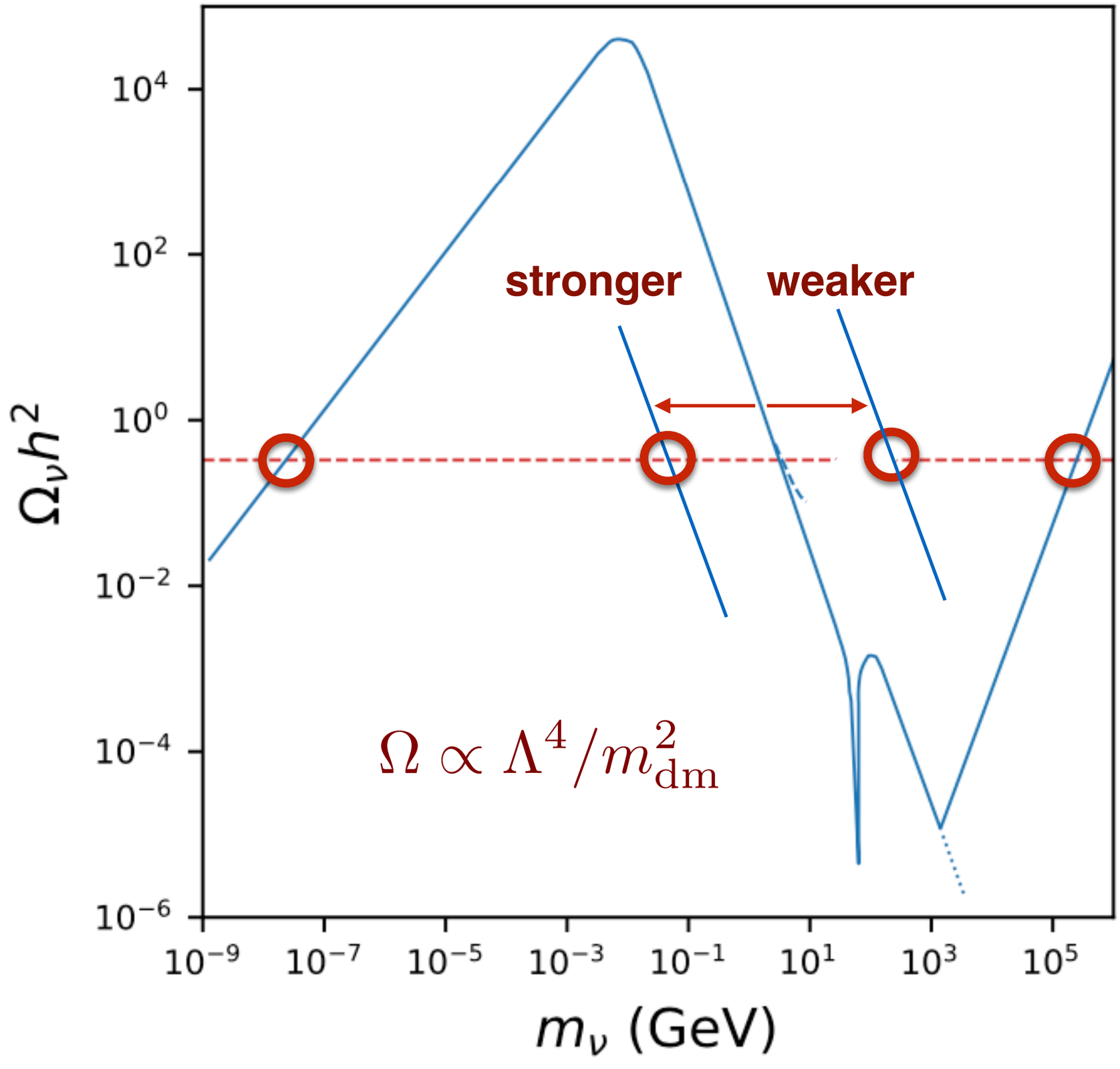
Cowsik-McLelland

A CLASSIC - DIRAC NEUTRINO DM

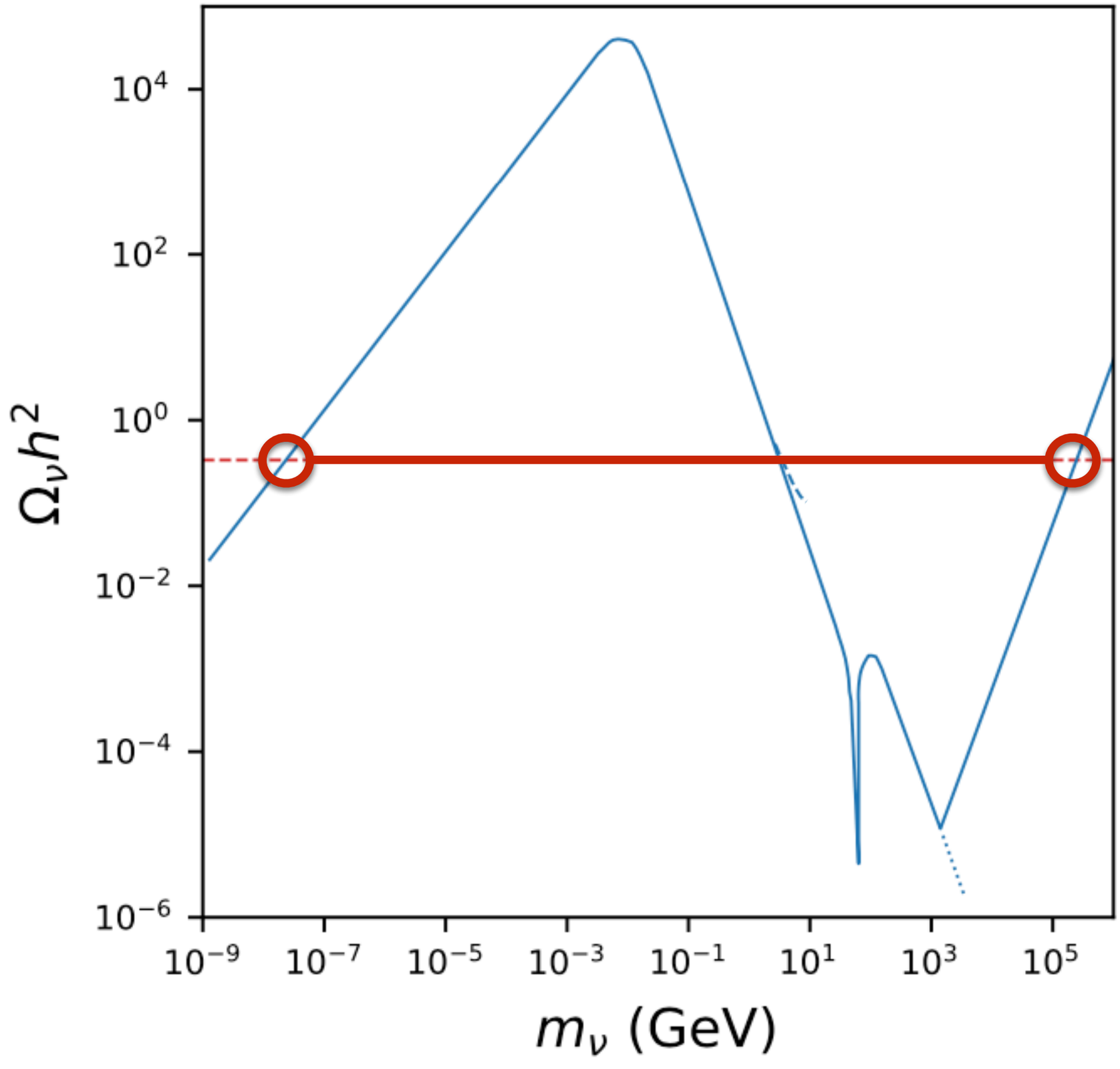


Plot from **Kainulainen** & Olives ‘03

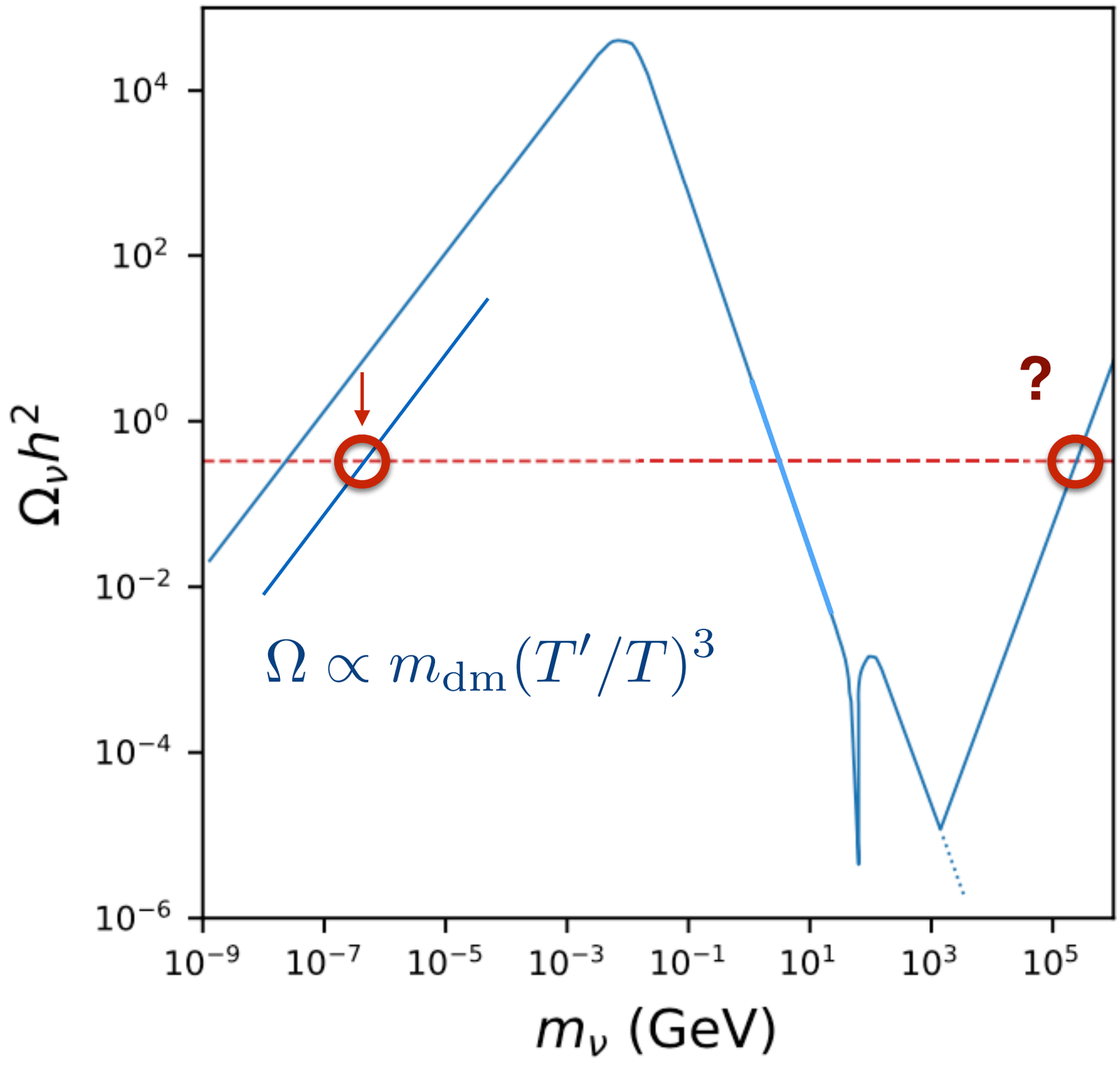
CHANGING INTERACTION STRENGTH



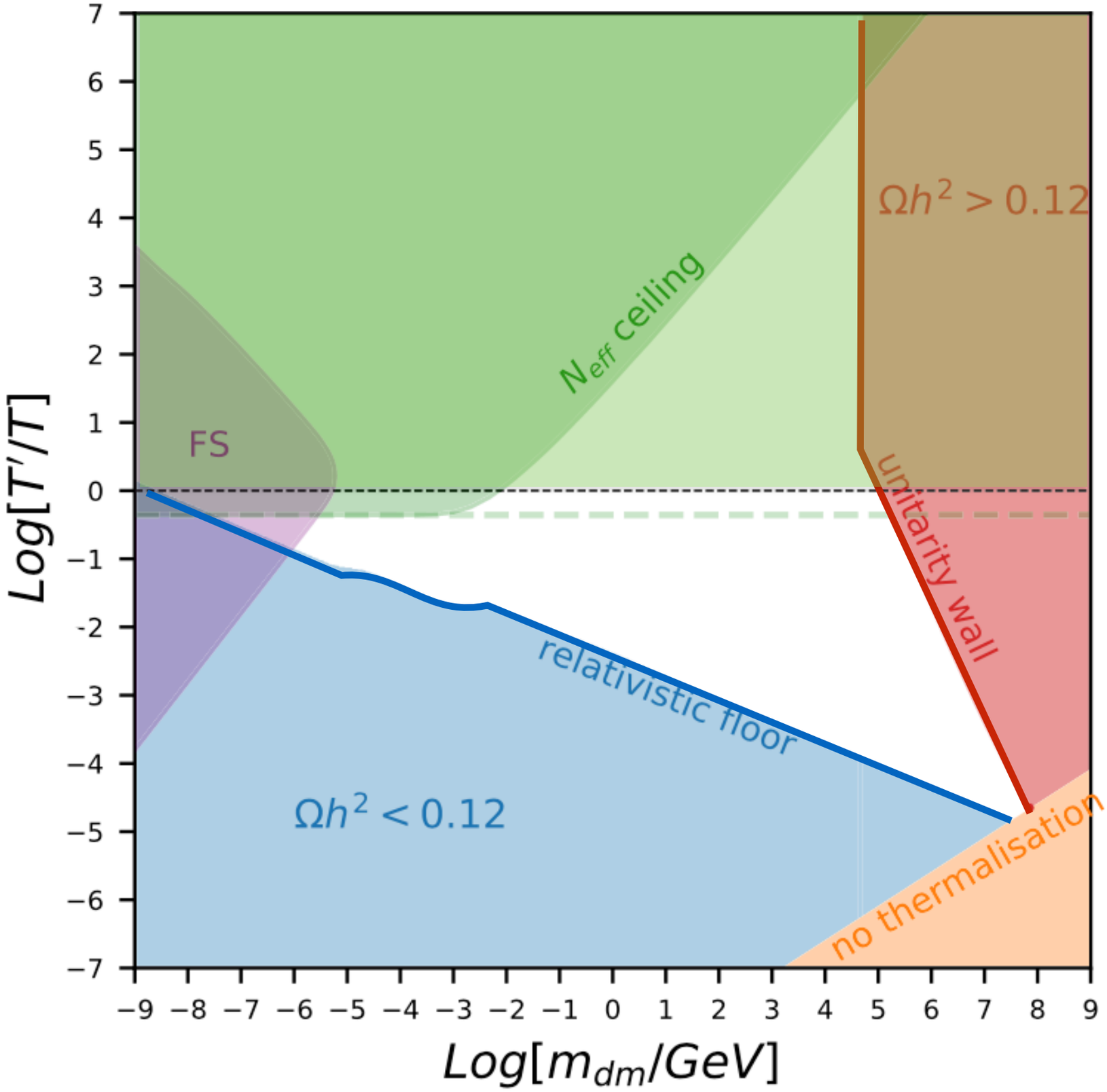
DOMAIN OF THERMAL CANDIDATES FOR T'=T



LOWERING T’/T

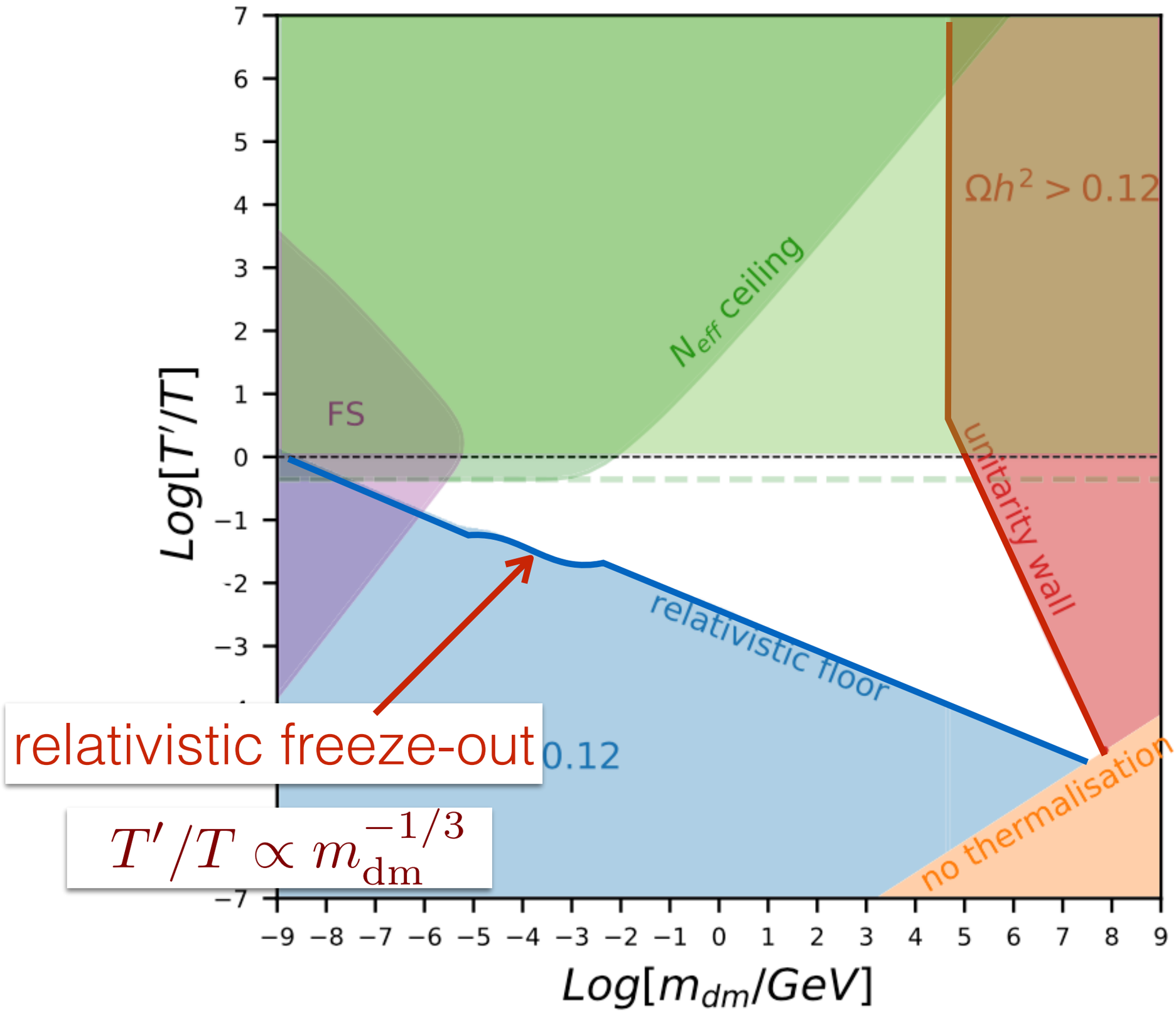

10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
$\Omega_\nu h^2$
?
$\Omega \propto m_{\rm dm}(T'/T)^3$
10^{-9} 10^{-7} 10^{-5} 10^{-3} 10^{-1} 10^{1} 10^{3} 10^{5}
m_ν (GeV)

DOMAIN OF THERMAL DM PARTICLES



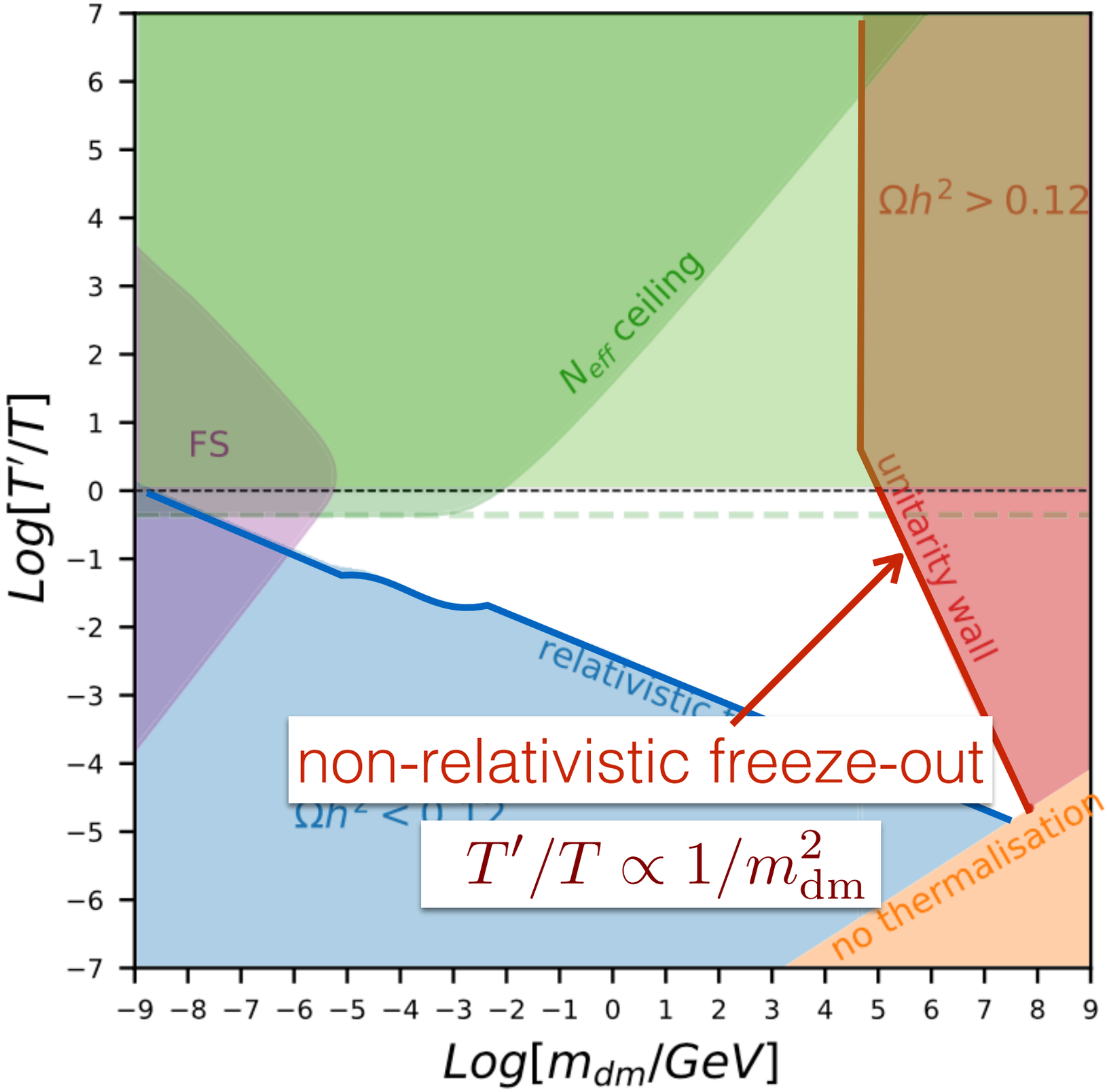
Coy, Hambye, MHGT, Vanderheyden ’21
Hambye, Lucca, Vanderheyden ‘20

DOMAIN OF THERMAL DM PARTICLES



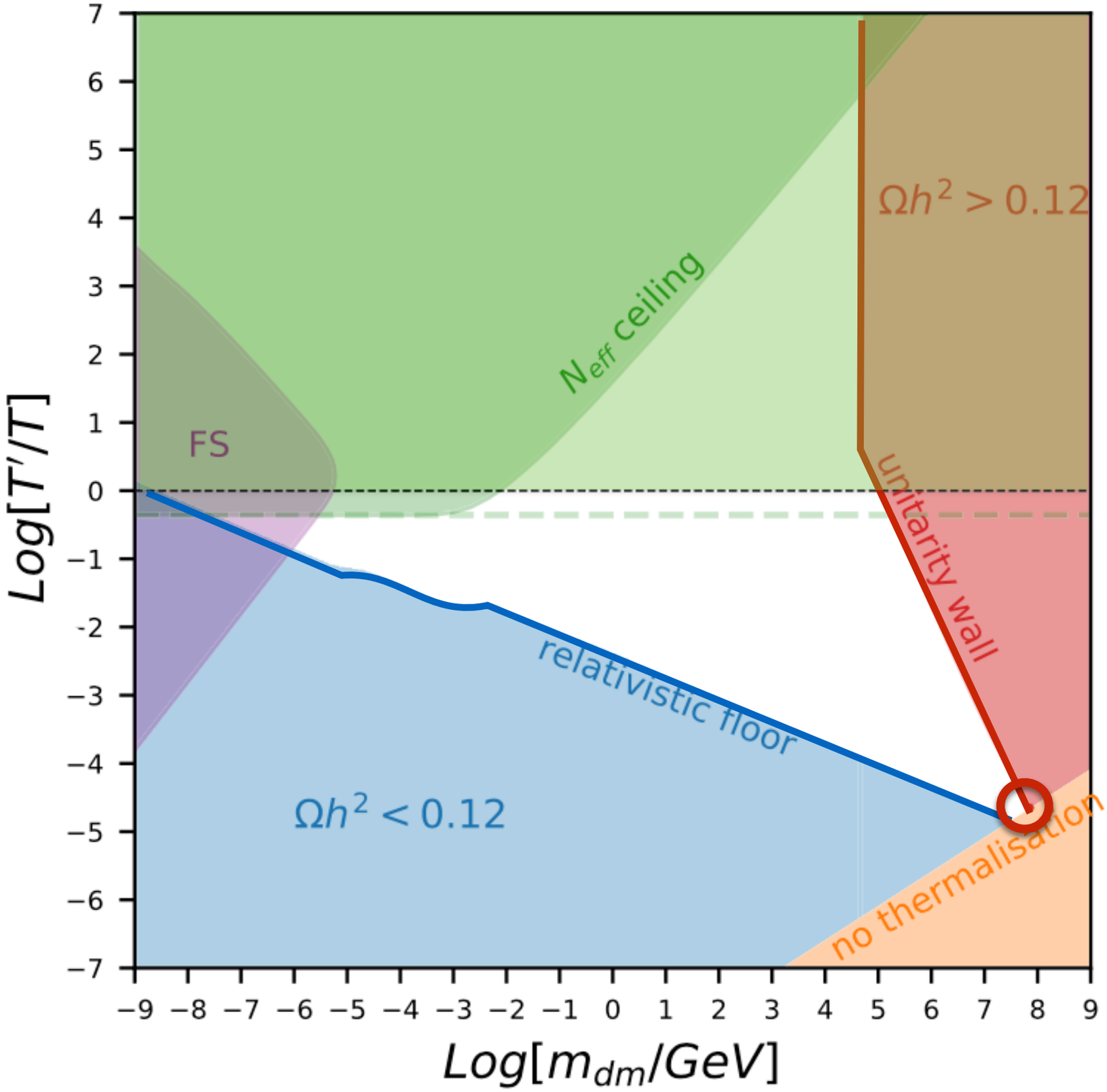
Coy, Hambye, MHGT, Vanderheyden ’21
Hambye, Lucca, Vanderheyden ‘20

DOMAIN OF THERMAL DM PARTICLES



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

DOMAIN OF THERMAL DM PARTICLES

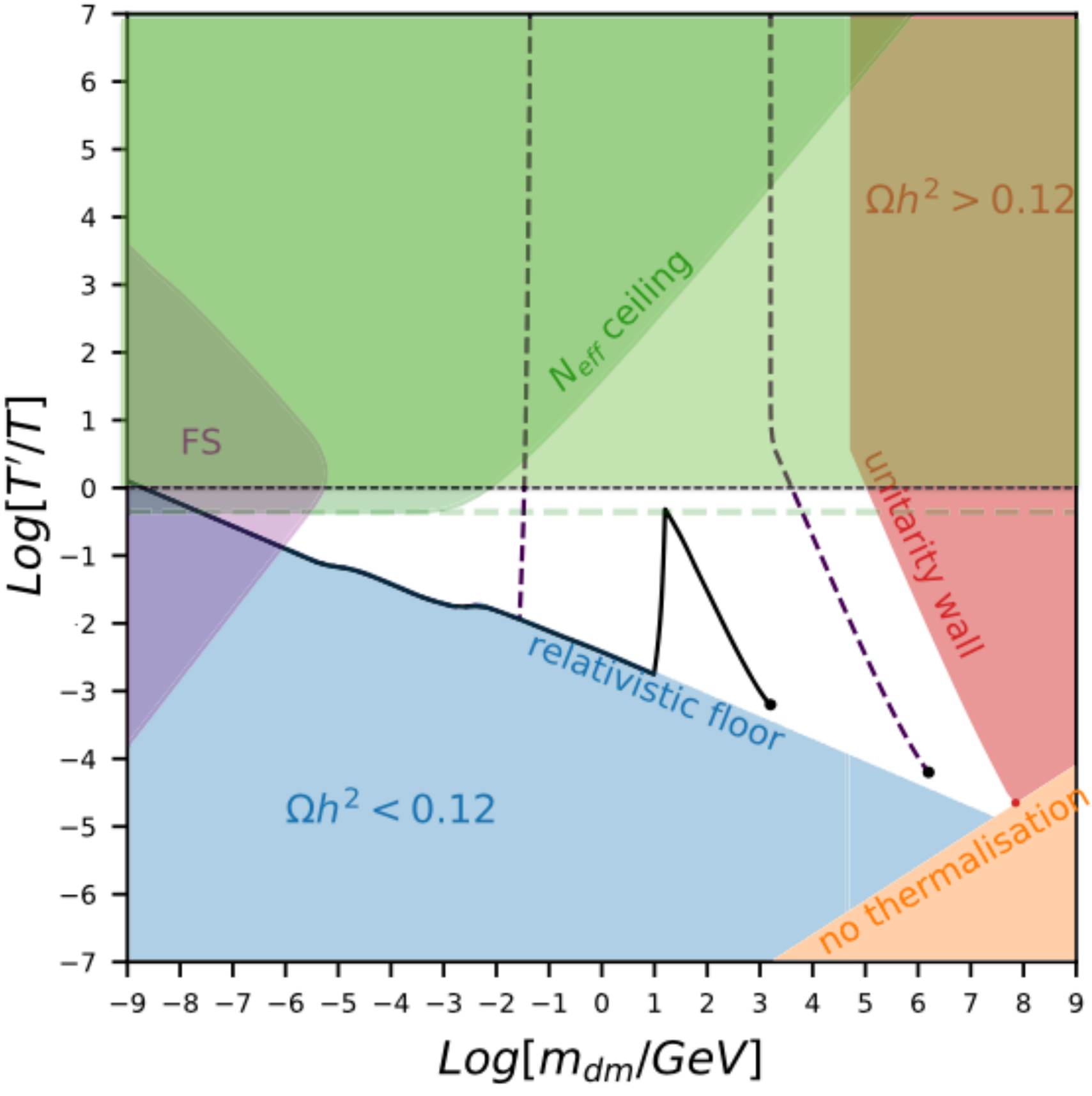


$m_{\rm dm} \approx 50$ PeV

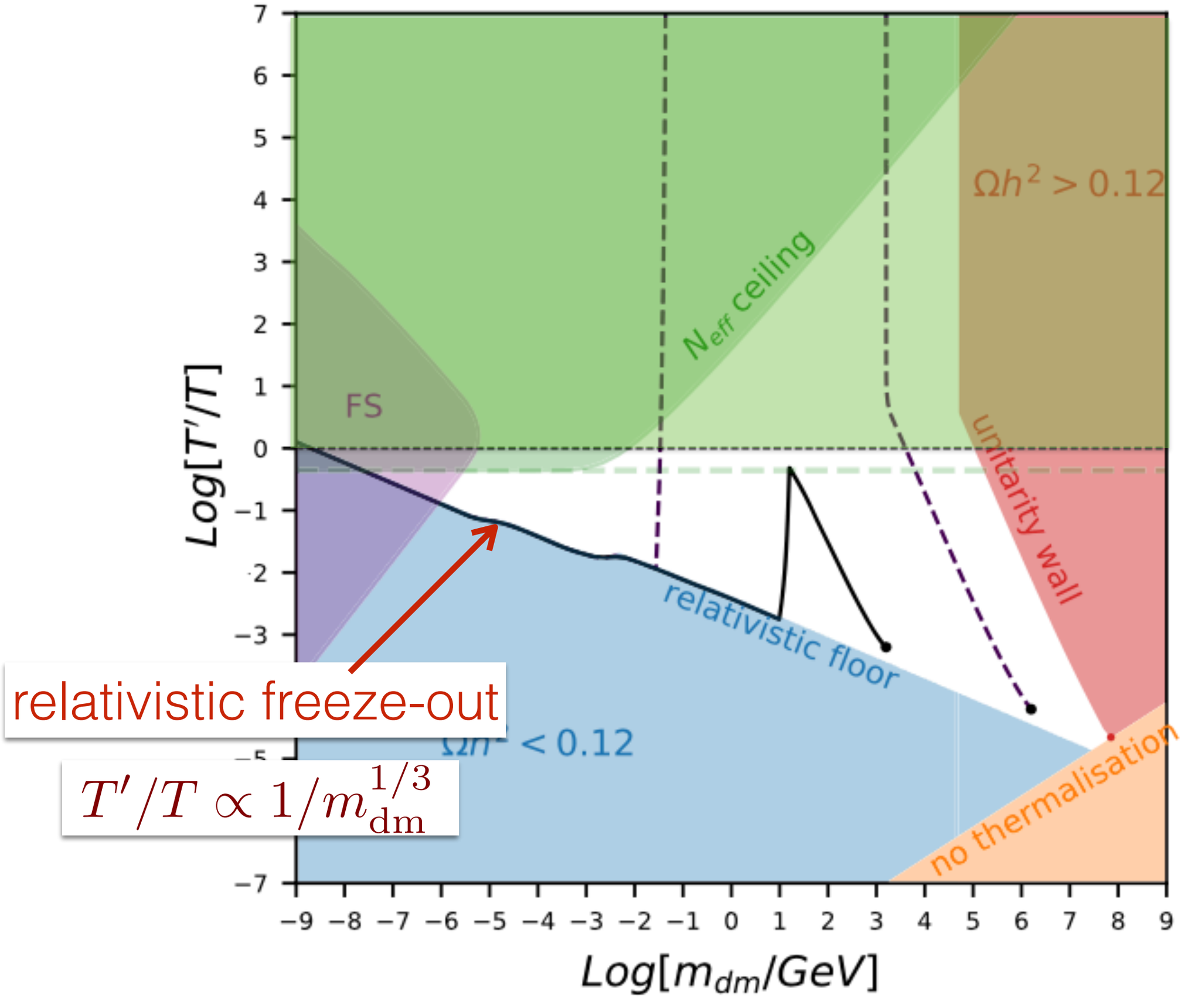
$T_{\rm fo} \approx 10^{11}$ GeV

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

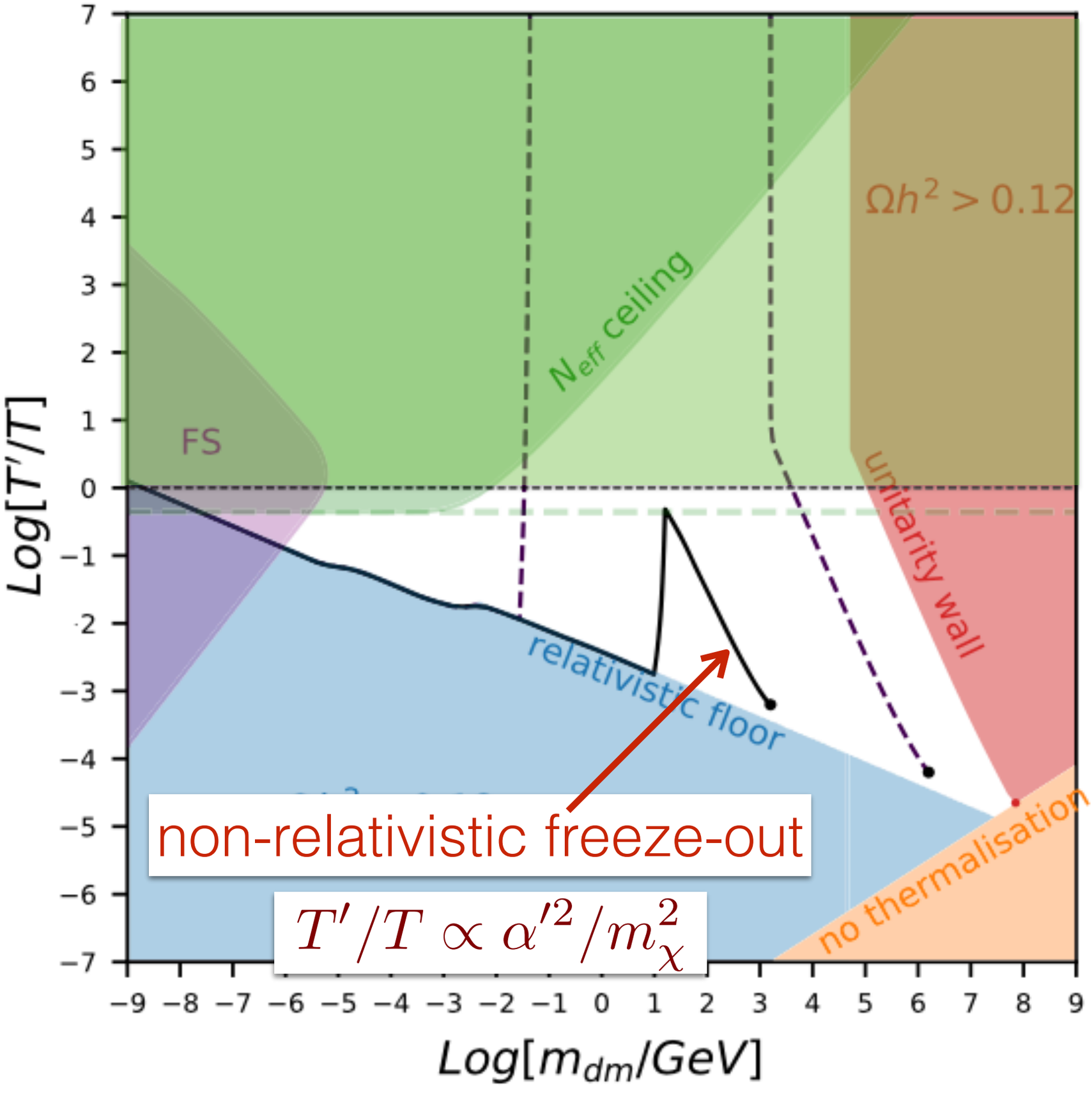
EXAMPLE : DARK QED AGAIN



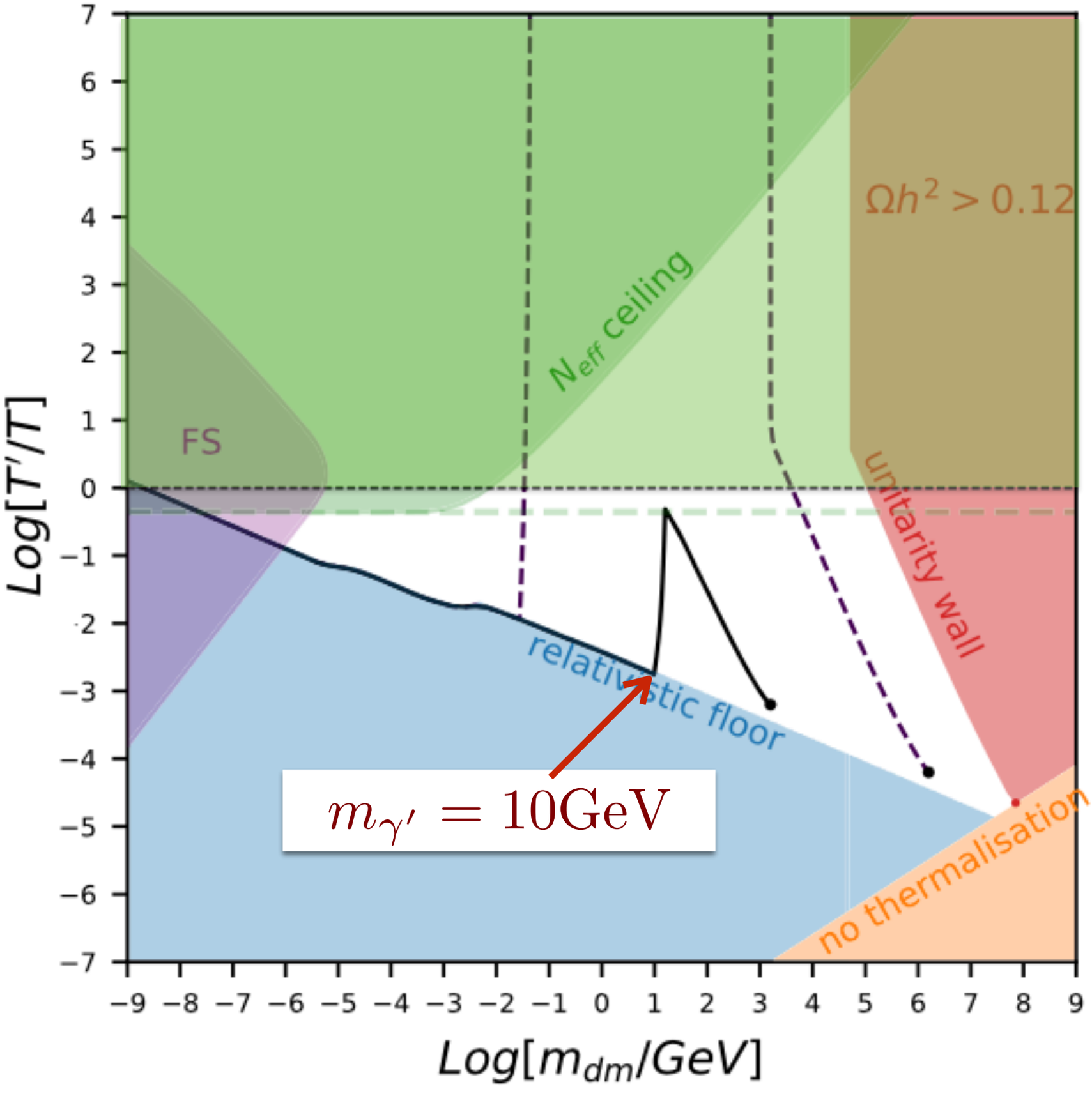
EXAMPLE : DARK QED AGAIN



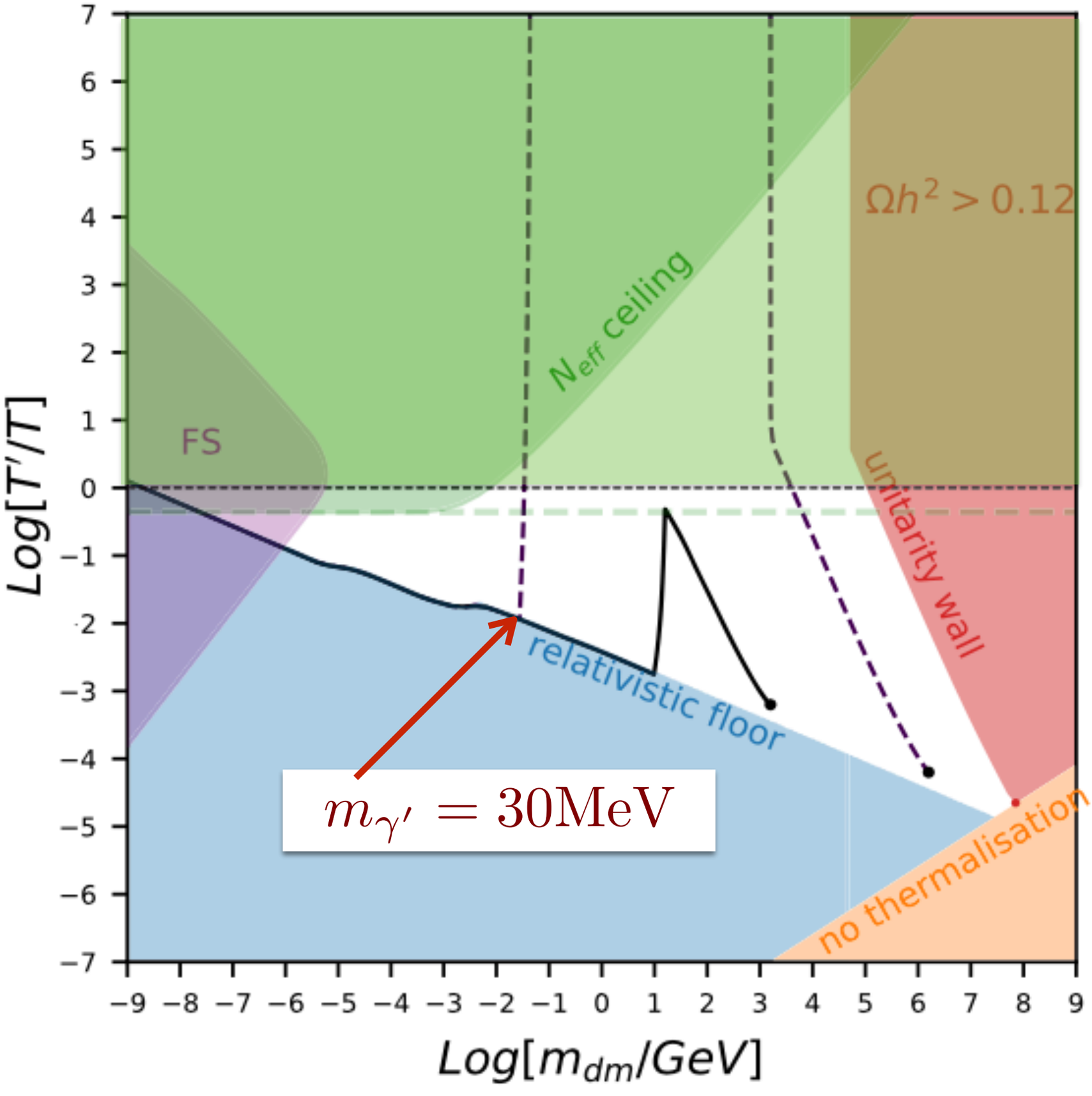
EXAMPLE : DARK QED AGAIN



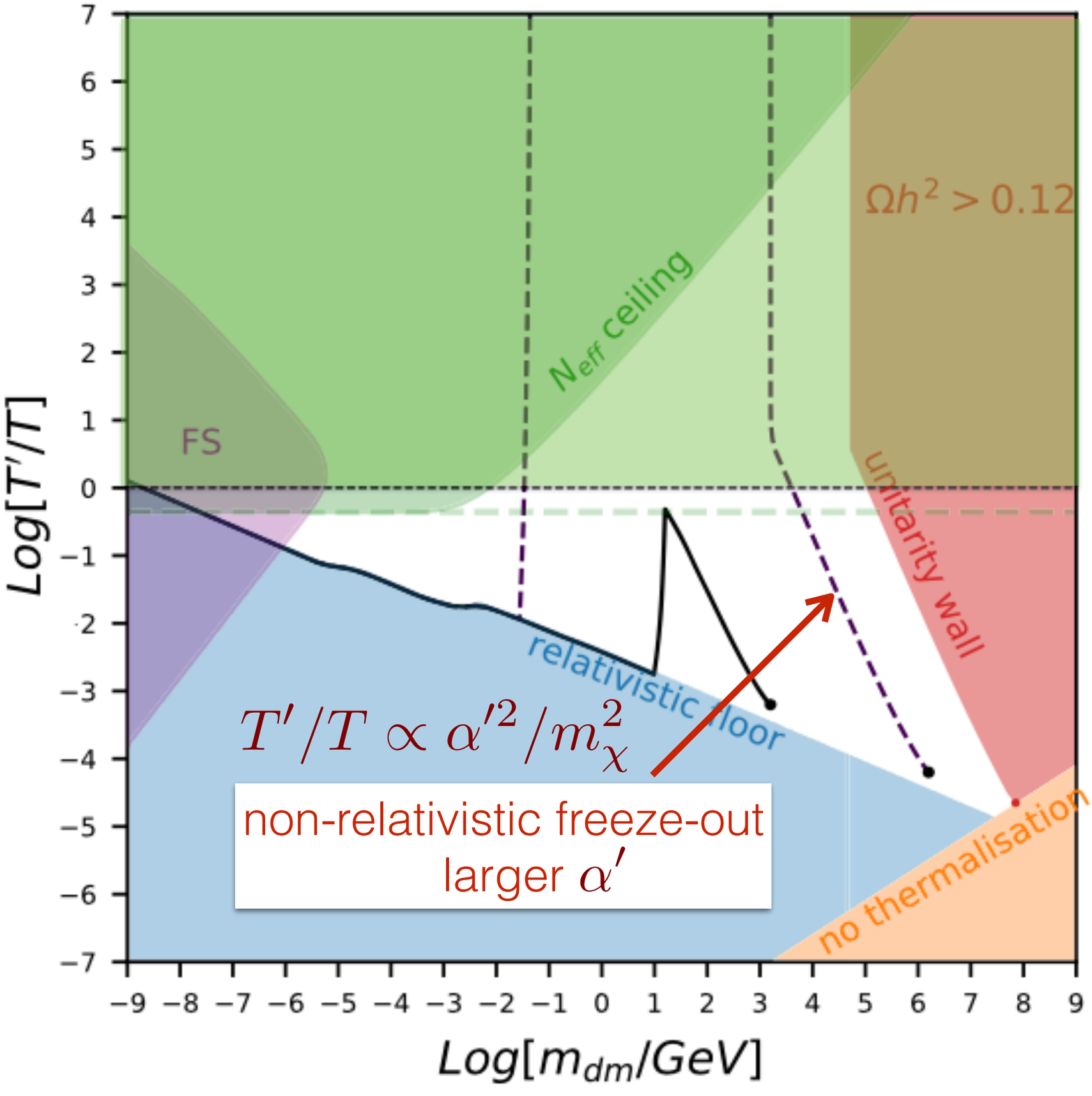
EXAMPLE : DARK QED AGAIN



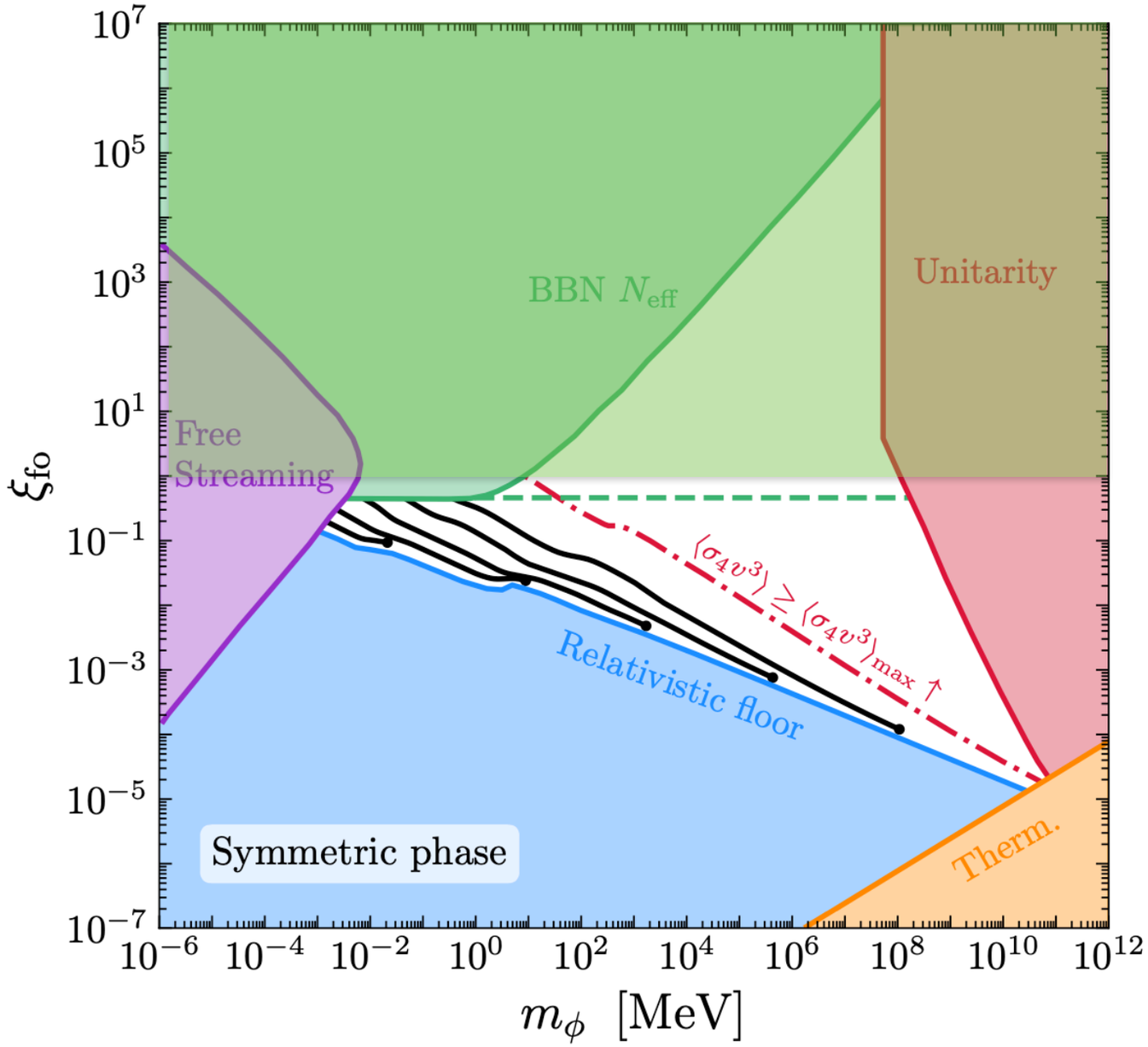
EXAMPLE : DARK QED AGAIN



EXAMPLE : DARK QED AGAIN



ANOTHER EXAMPLE : CANNIBAL DM



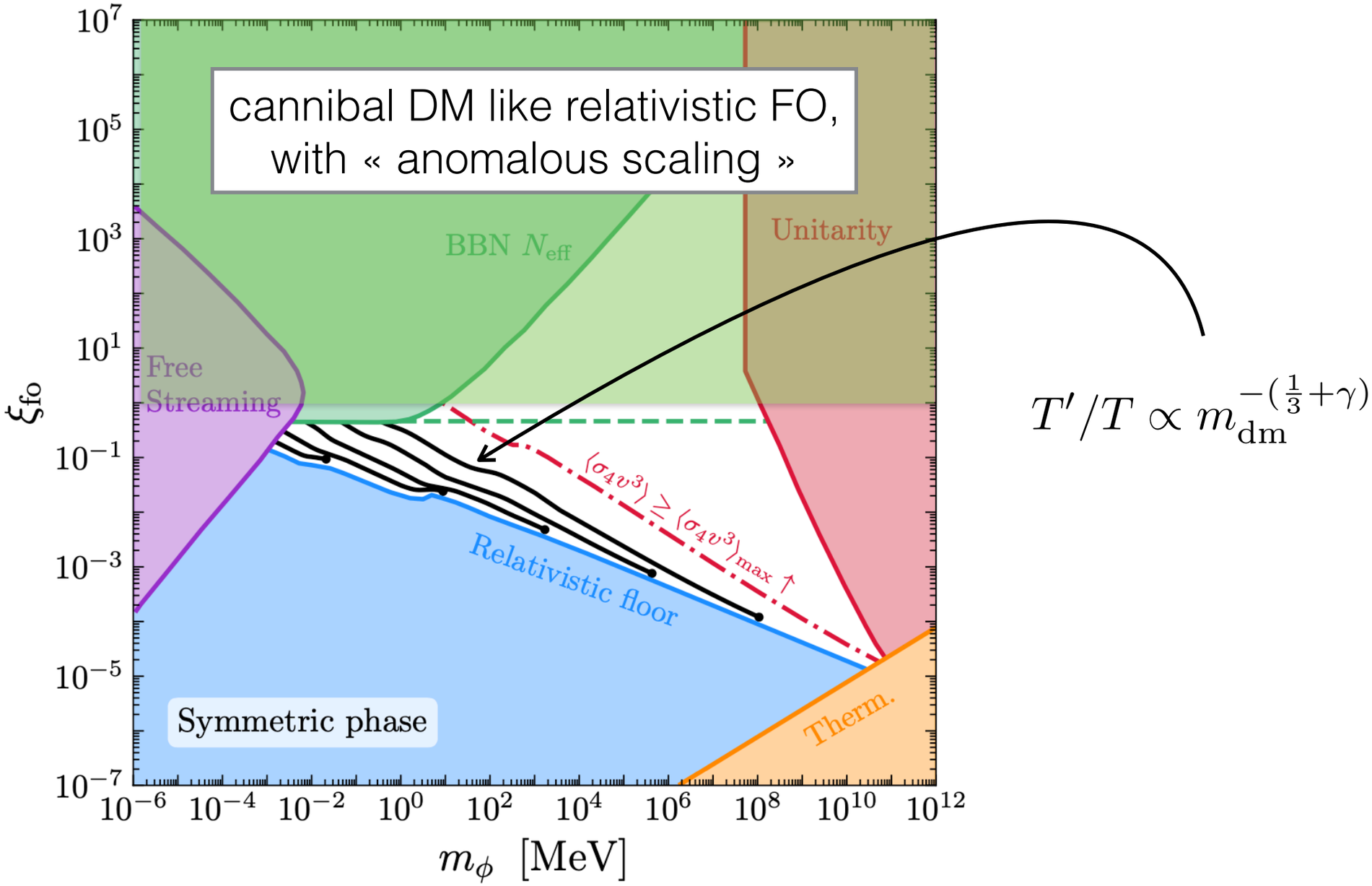
$$\mathcal{L}_{\rm hs} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}\mu^2\phi^2 - \frac{\lambda}{4!}\phi^4$$

$4\phi \to 2\phi$ symmetric phase

$3\phi \to 2\phi$ broken phase (this plot)

Hufnagel, MHGT ’22

ANOTHER EXAMPLE : CANNIBAL DM



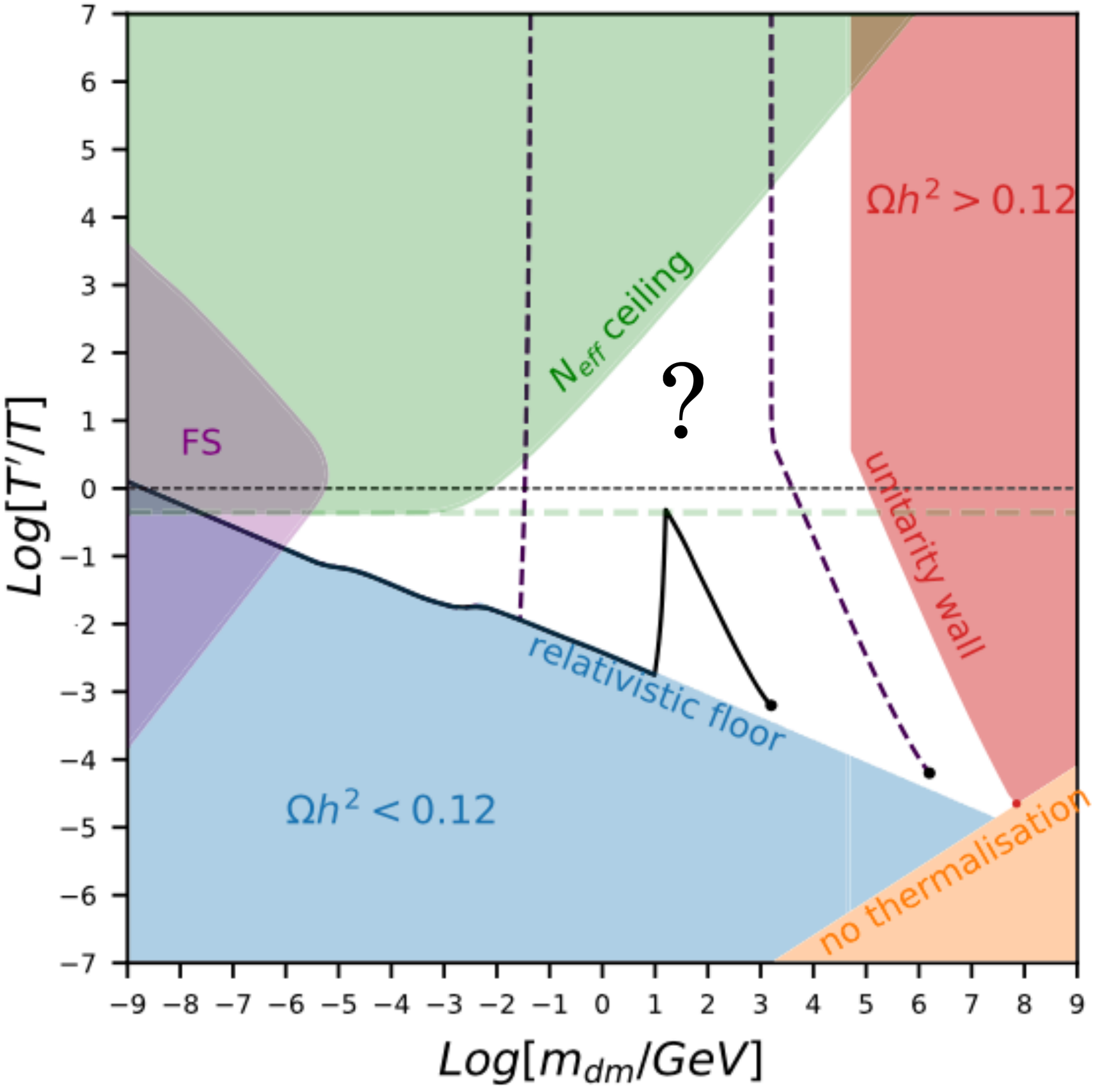
$$\mathcal{L}_{\rm hs} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}\mu^2\phi^2 - \frac{\lambda}{4!}\phi^4$$

$4\phi \to 2\phi$ symmetric phase

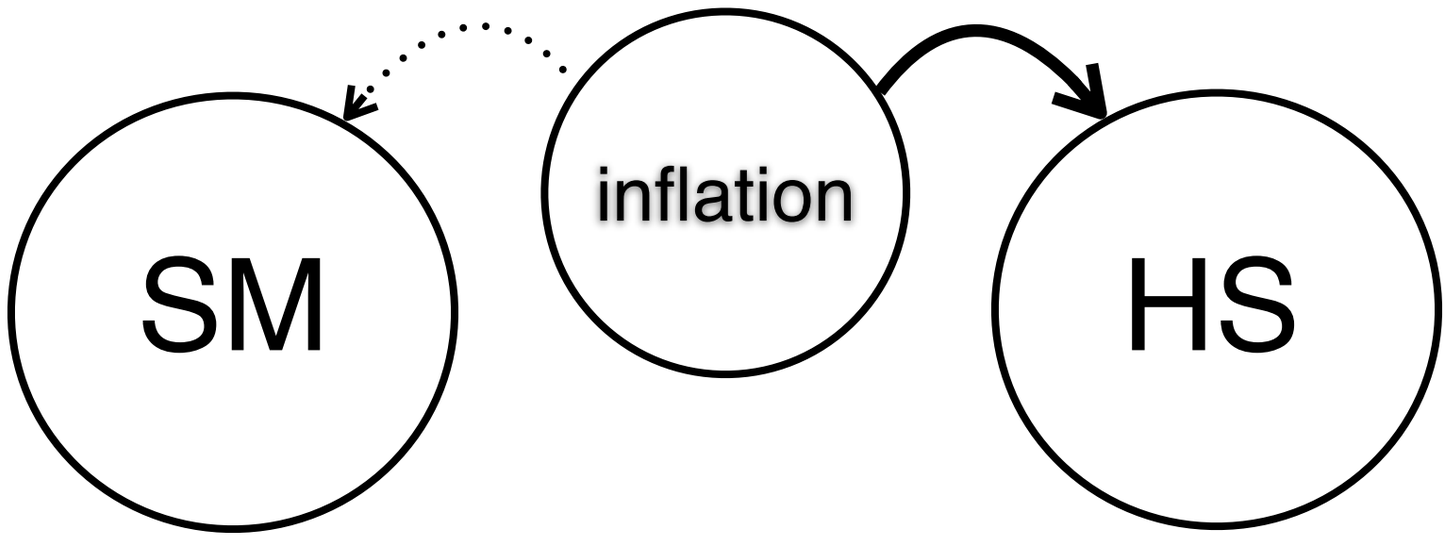
$3\phi \to 2\phi$ broken phase (this plot)

Hufnagel, MHGT, in progress but ’22

4. A HOT DARK SECTOR ?



A HOT DARK SECTOR ?



A HISTORY OF A HOT DARK SECTOR

total energy

eos

$$\left\{ \begin{array}{c} n' \\ \rho' \\ p' \\ s' \\ \vdots \end{array} \right\} \longrightarrow \{\mu', T', T\} \longrightarrow$$

simplify…

$$\frac{d\rho_{\rm t}}{dt} + 3(1+\omega_{\rm t})H\rho_{\rm t} = 0$$

$$\frac{d\rho'}{dt} + 3(1+\omega')H\rho' = m_{\gamma'}\Gamma_{\gamma'}\left[n'_{\rm eq}(T) - n'(T')\right]$$

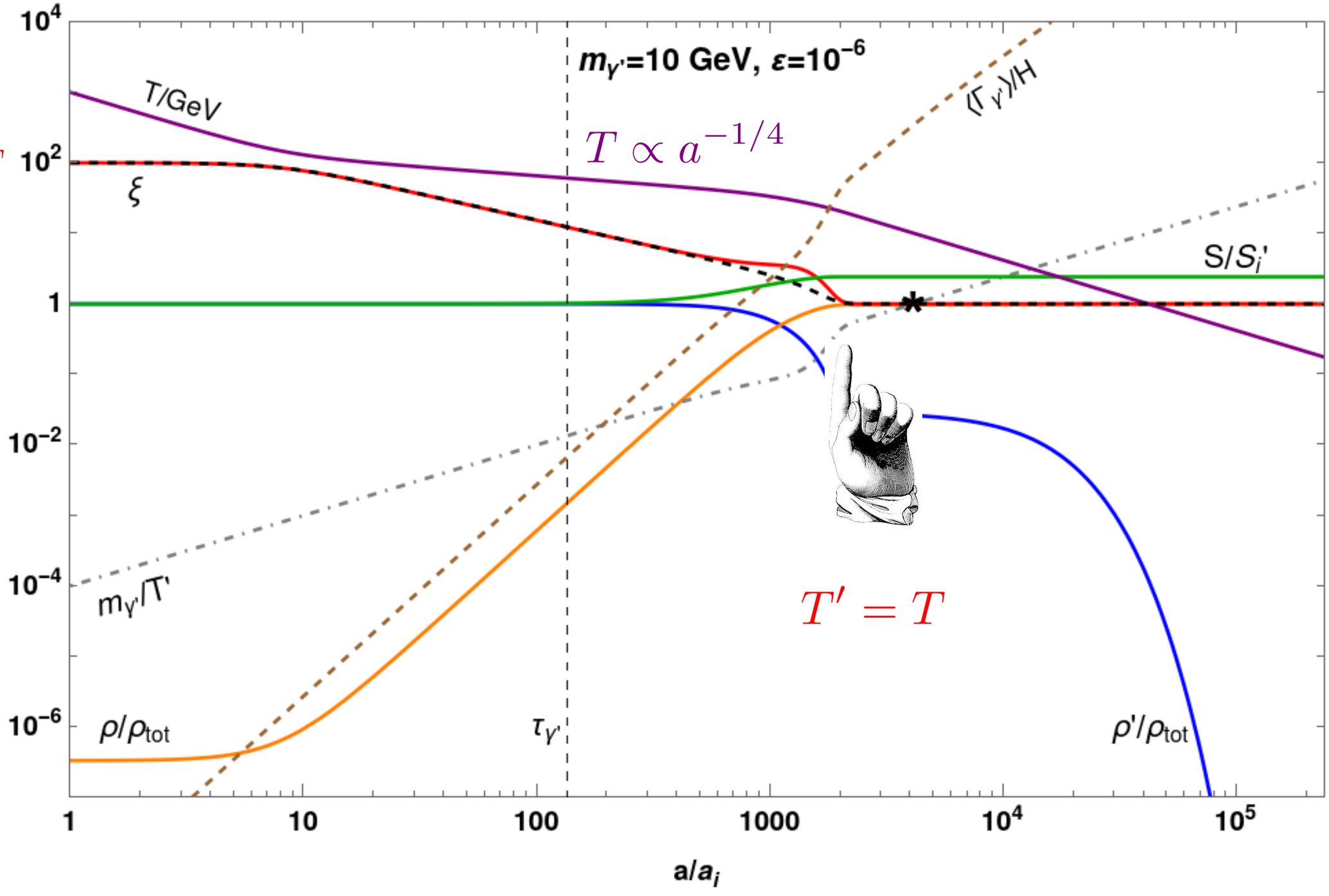
$$\frac{dn'}{dt} + 3Hn' = \Gamma_{\gamma'}\left[\frac{K_1(x)}{K_2(x)}n'_{\rm eq}(T) - \frac{K_1(x')}{K_2(x')}n'(T')\right]$$

Maxwell-Boltzmann statistics $\quad \langle \frac{m_{\gamma'}}{T'} \rangle \quad$ if $\quad T' \gtrsim m_{\gamma'}$

simplify…

EX UMBRA IN SOLEM

$T' \gg T$



$T' = T$

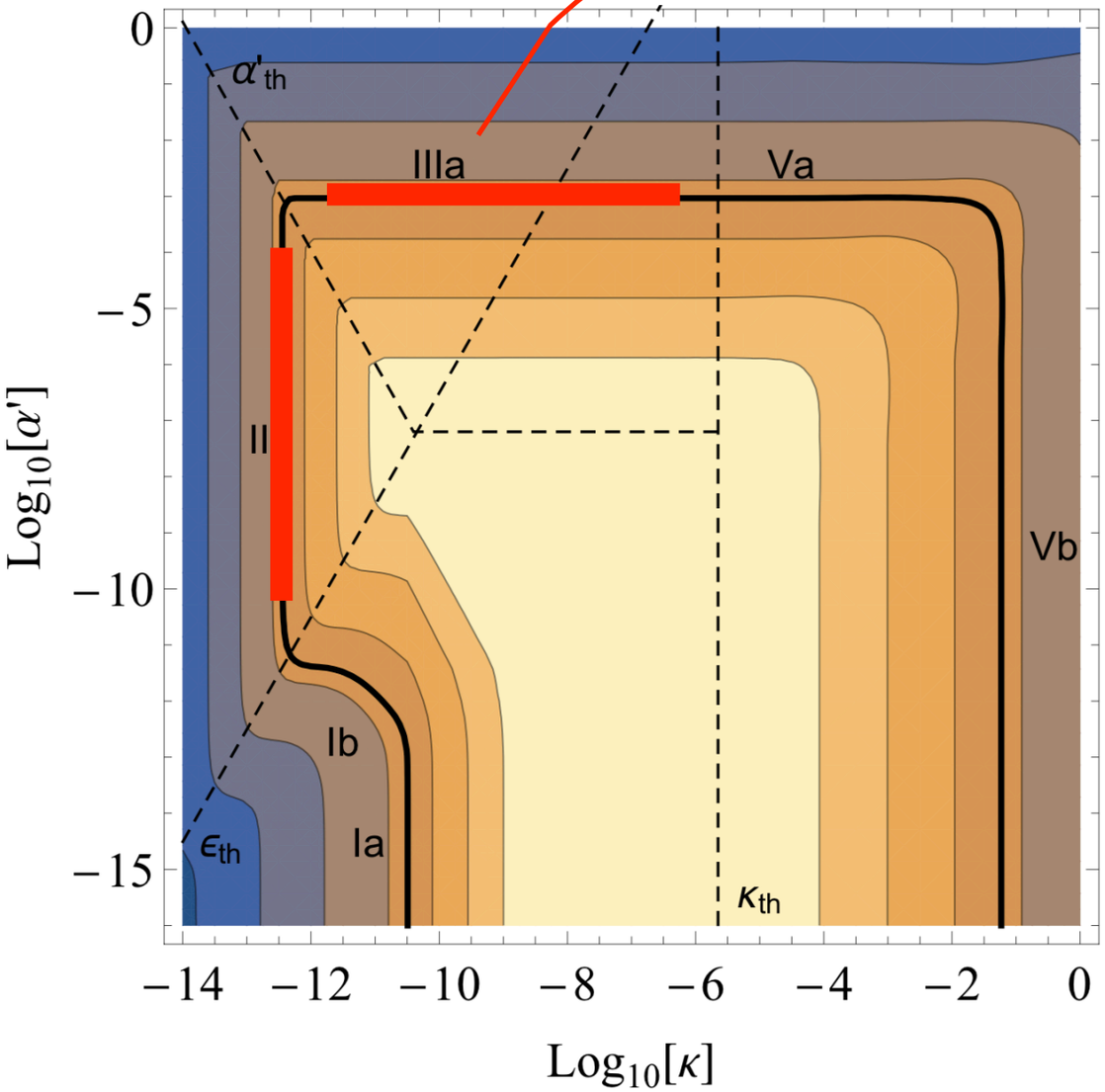
Coy et al, in progress

CONSTRAINTS, CONSEQUENCES?

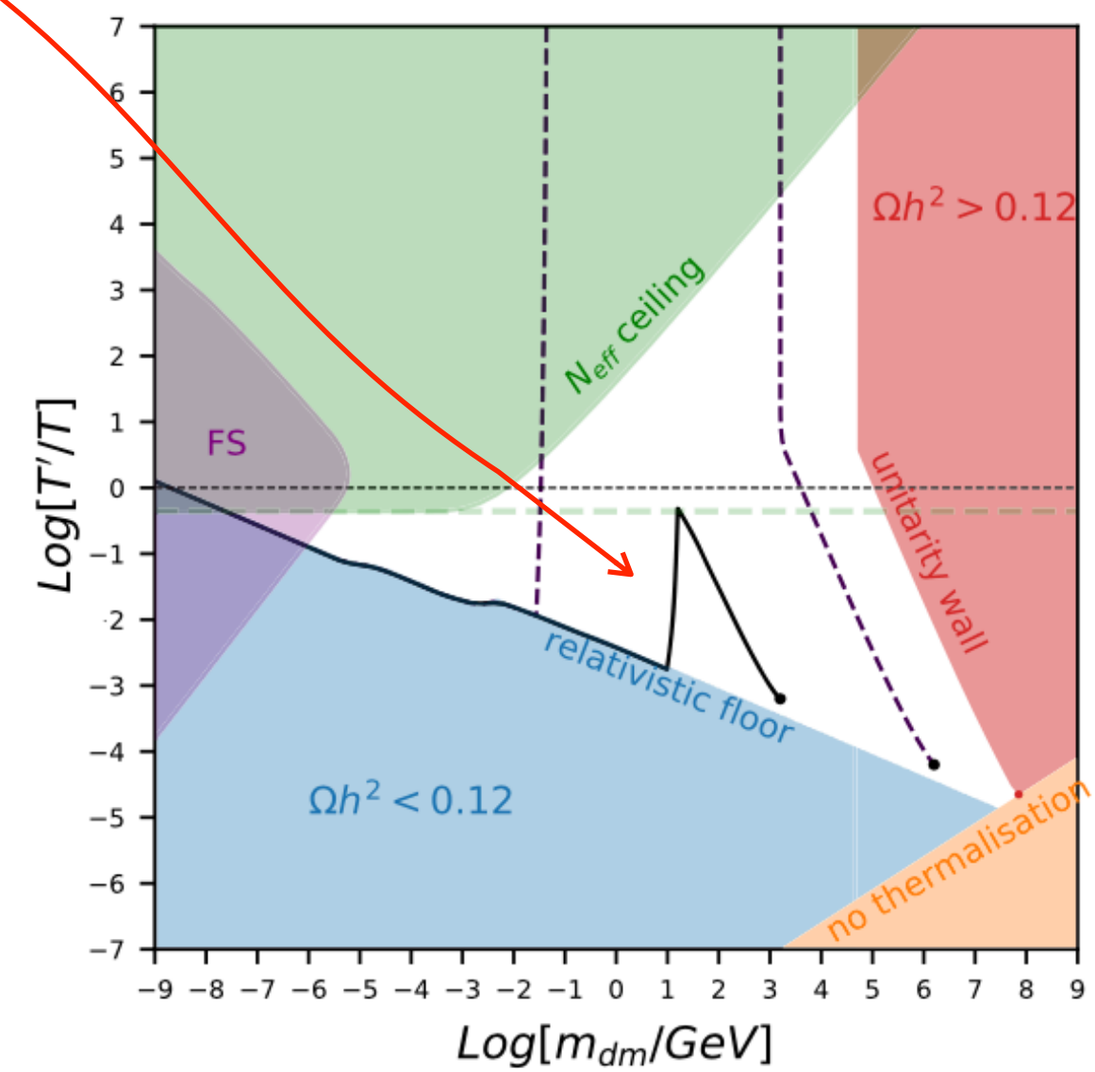
Can make sure that DP are gone
by the time of BBN (so, unfortunately, no dragons)

Work in progress
on DP parameter space, modification of domain of DM
and other consequences (ie baryo/leptogenesis,…)

SUMMARY



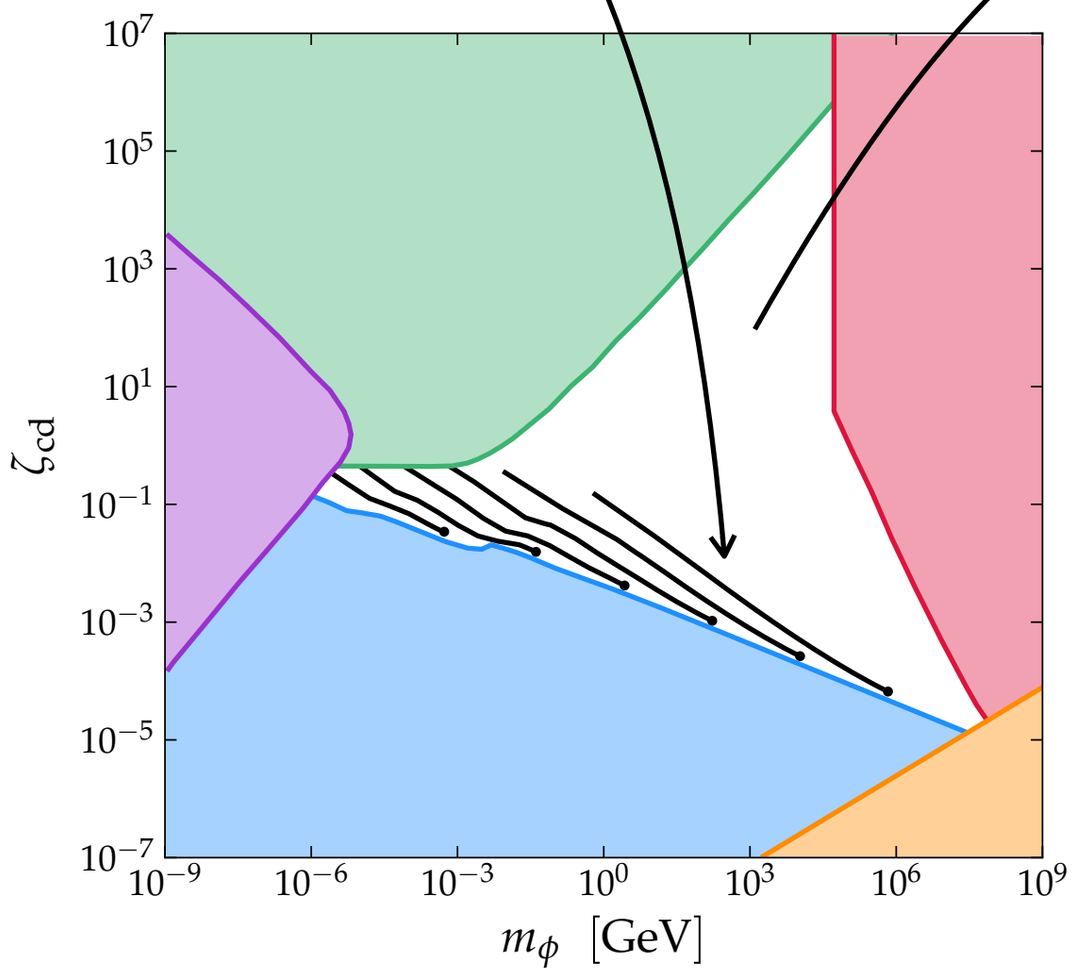
Dark matter from dark photons : a taxonomy of production mechanisms
Th. Hambye, M.H.G.T., J. Vandecasteele, L. Vanderheyden
Phys.Rev.D 100 (2019) 9, 095018



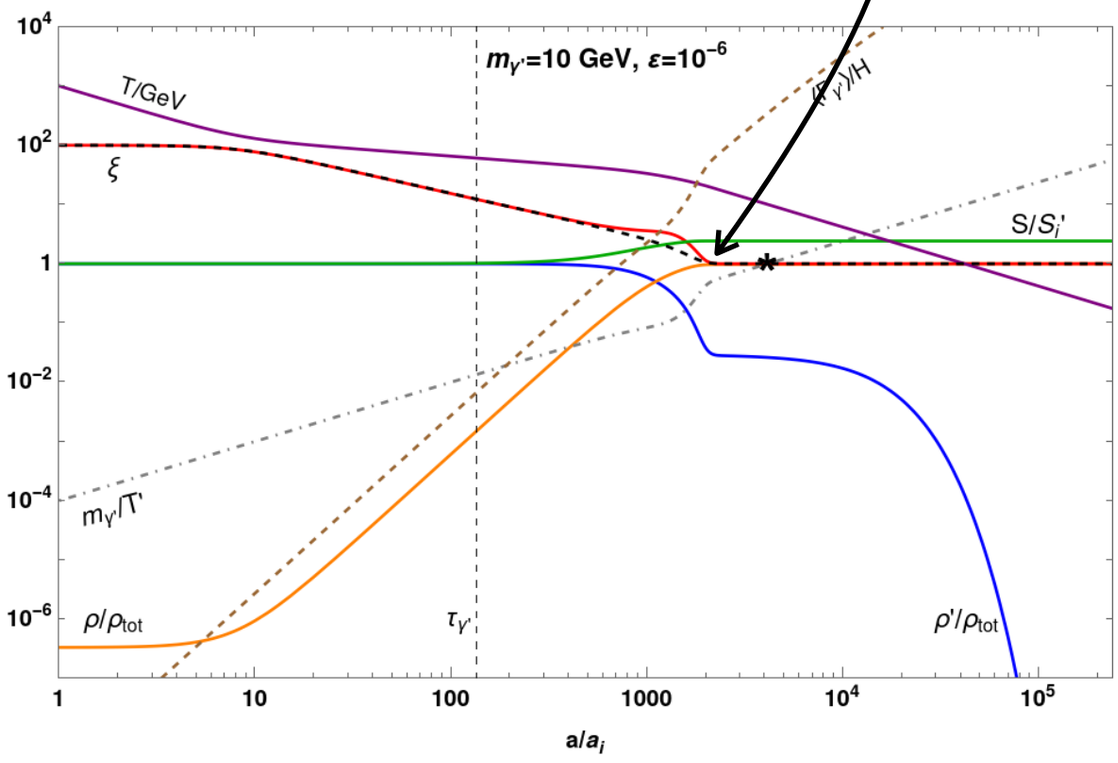
The domain of thermal dark matter candidates
R. Coy, Th. Hambye, M.H.G.T., L. Vanderheyden
Phys.Rev.D 104 (2021) 5, 055021

SUMMARY

cannibal DM almost like relativistic FO
but « anomalous scaling »



heating of VS from relativistic decay

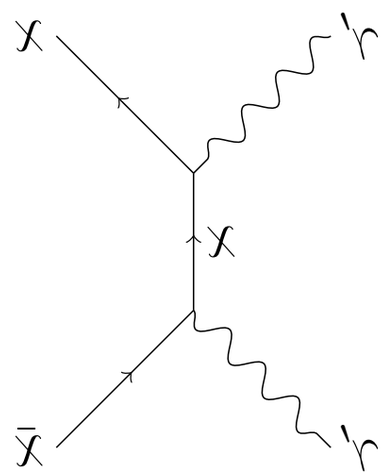


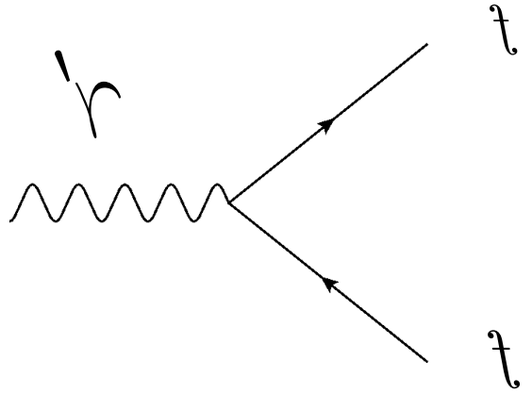
Revisiting the domain of a cannibal DMM
M. Hufnagel, M.H.G.T.
arXiv:2212.09759

Coy, Kimus, MHGT, in progress

BACKUP STORY (I)

A HOT DARK SECTOR ?

First, secluded DM FO  with $T'/T \gg 1$

then  heating the VS (hopefully before BBN)

Impact on dark QED parameter space? Other consequences?

PRODUCTION TROUGH KINETIC MIXING

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

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

PORTALS TO A DARK SECTOR

3 special gates in SM

$\bar{L}\tilde{H}$ $\quad\quad$ $\Delta\mathcal{L} \supset y\,\bar{L}\tilde{H}N$

Neutrino portal

Dodelson & Widrow (1994)
…

$B_{\mu\nu}$ $\quad\quad$ $\Delta\mathcal{L} \supset \epsilon\,B_{\mu\nu}X^{\mu\nu}$

Kinetic mixing portal

Holdom (1986)
…

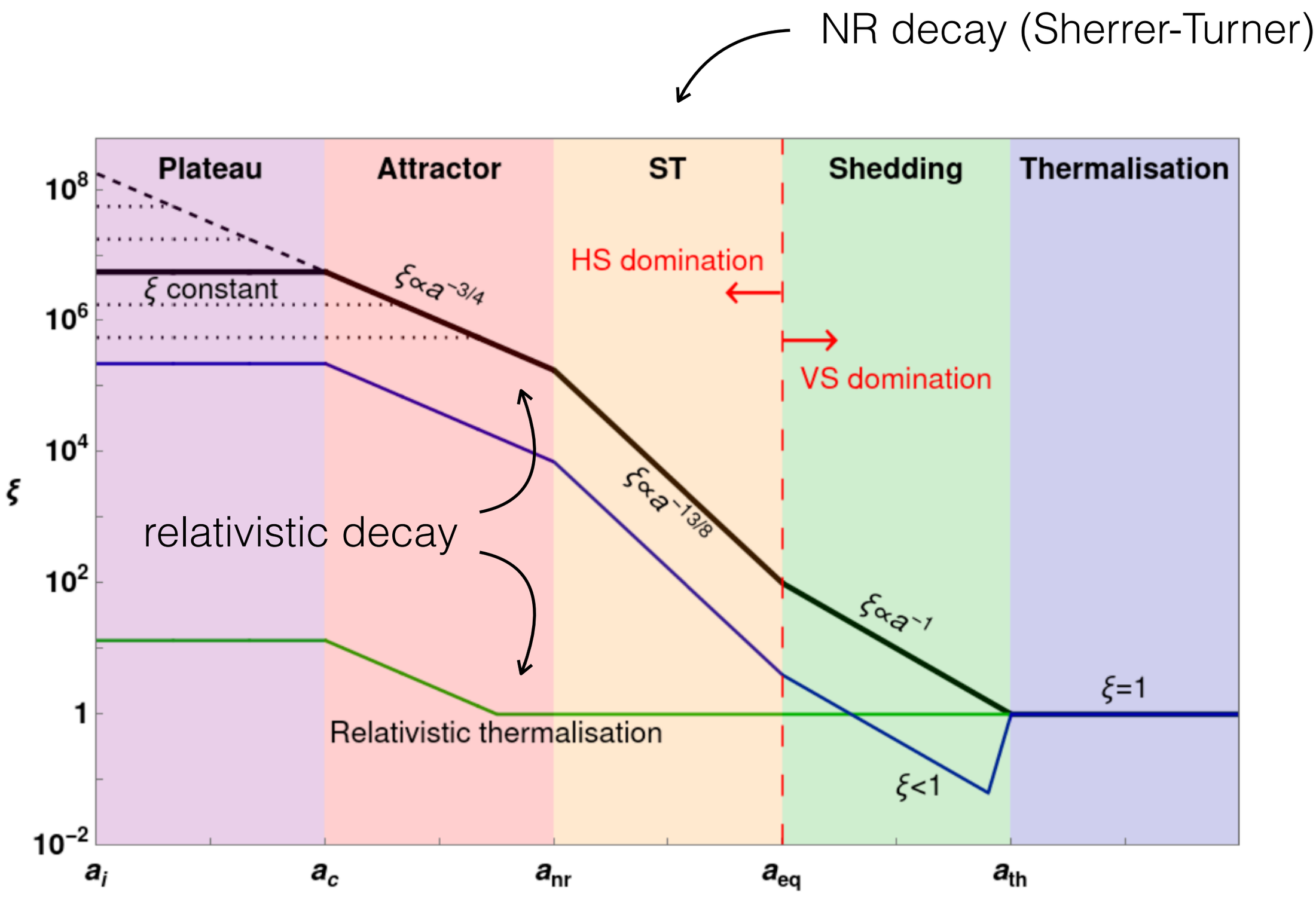
$H^\dagger H$ $\quad\quad$ $\Delta\mathcal{L} \supset \lambda\,S^2 H^\dagger H$

Higgs portal

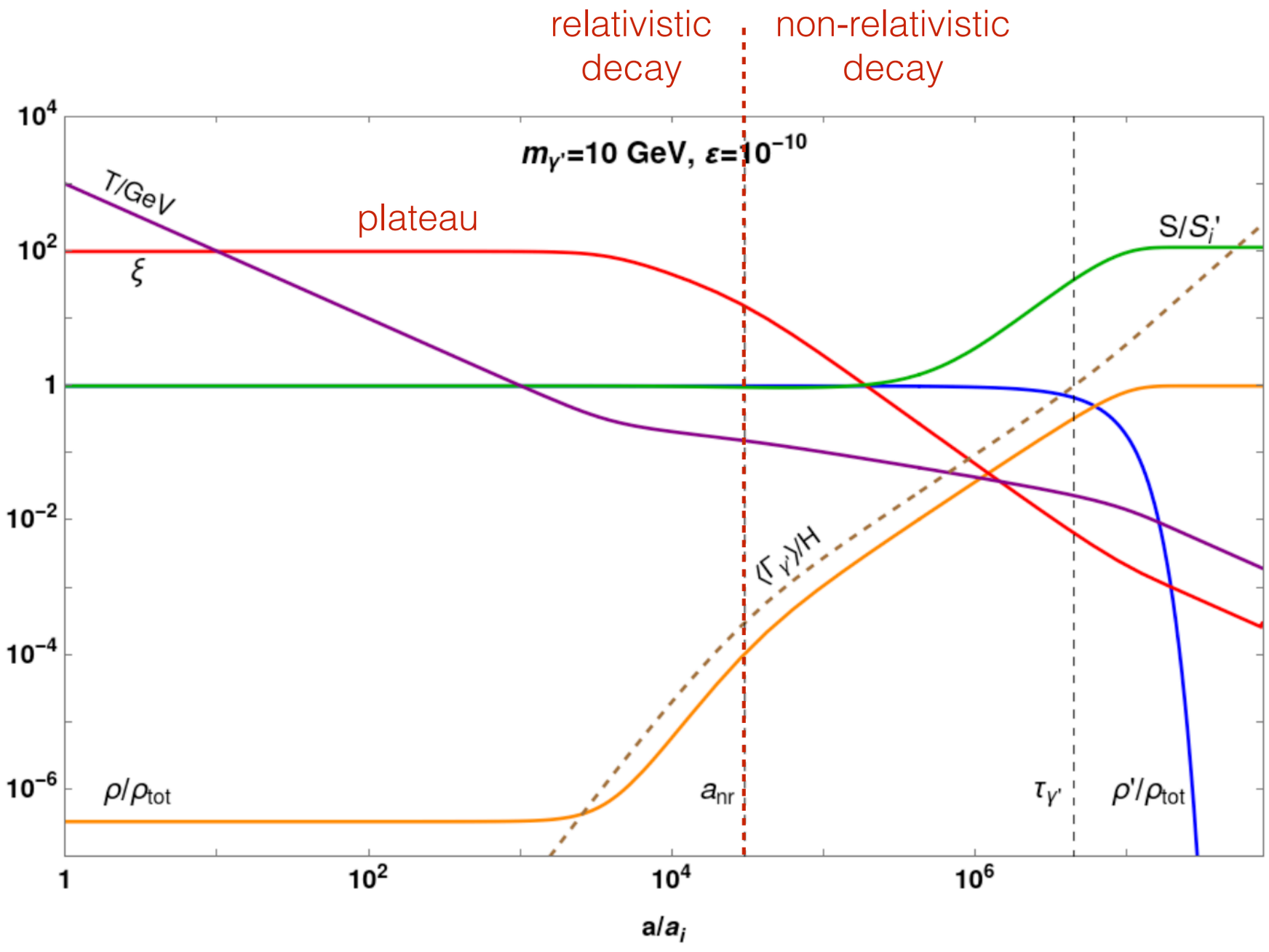
Silveira & Zee (1985)
Veltman & Ynderain (1989)
…

Patt & Wilczek (2006)

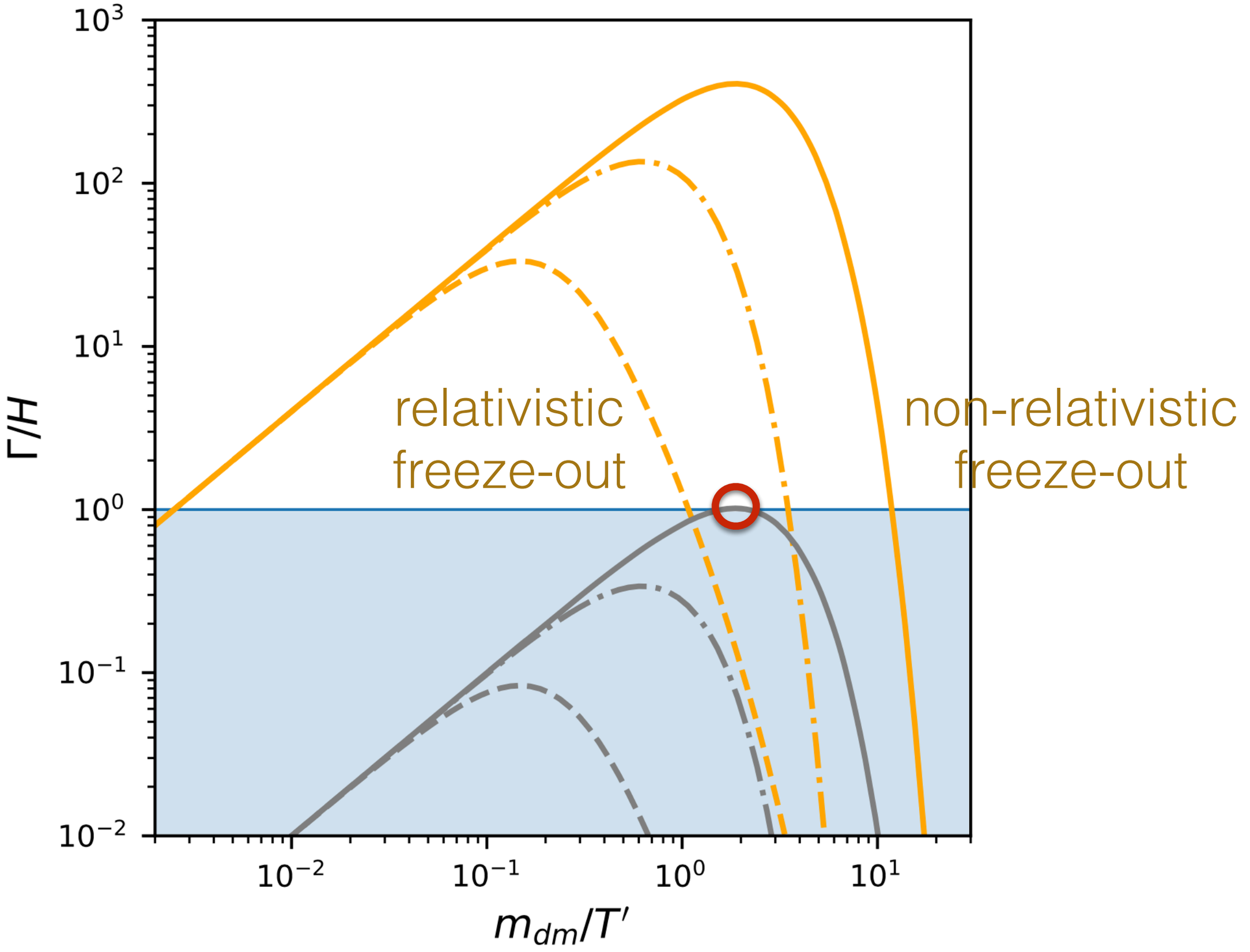
DIFFERENT REGIMES ARE POSSIBLE



SCHERRER-TURNER HEATING OF VS



NO THERMALIZATION



A DIGRESSION: WHICH BASIS ?

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

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

« SM interaction basis »

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

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

- no emission from SM fields !

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

A DIGRESSION: WHICH BASIS ?

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

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

« 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 massive dark photon (also Z)

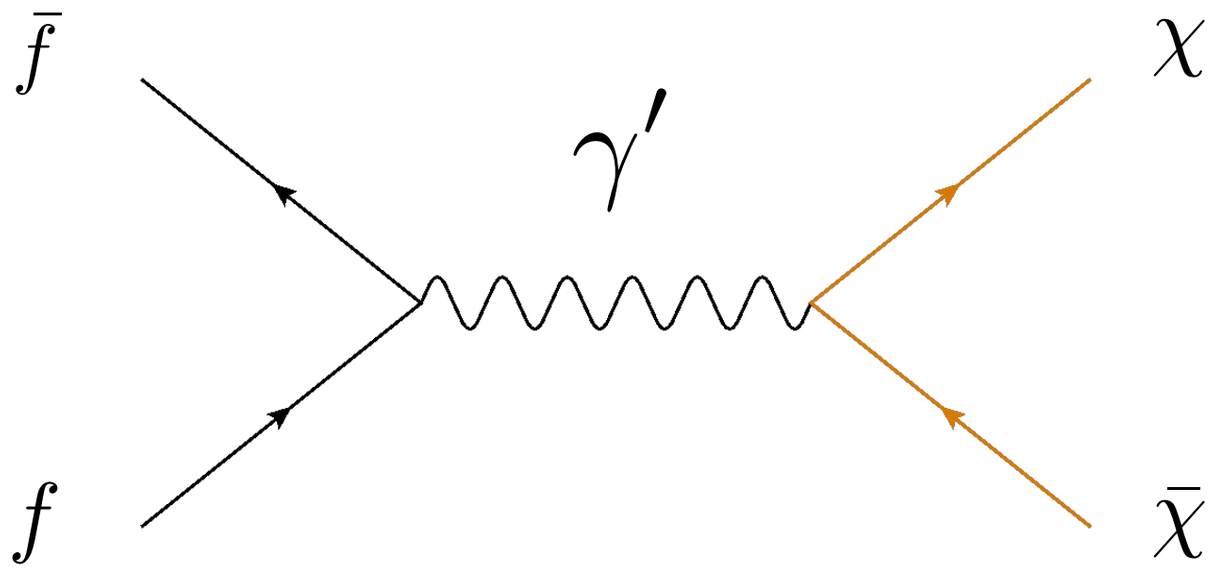
SM emission of DP with coupling ϵ

But what if

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

VIRTUAL DARK PHOTON EXCHANGE

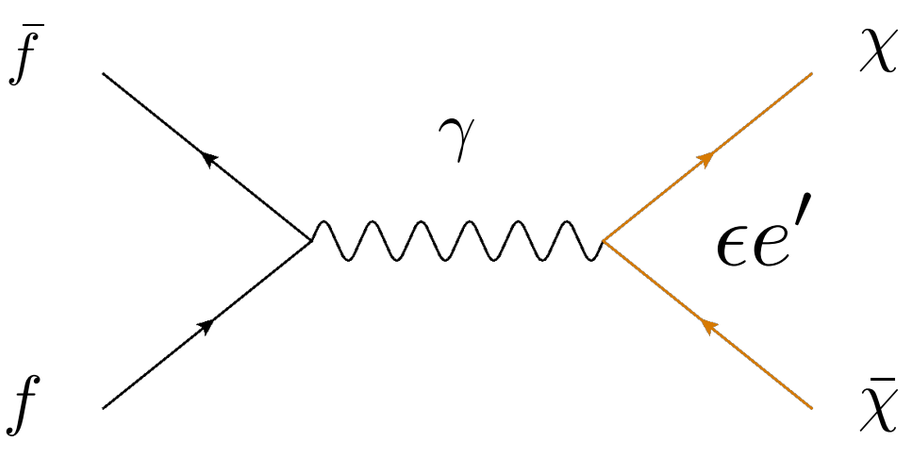
« eigenmass basis »

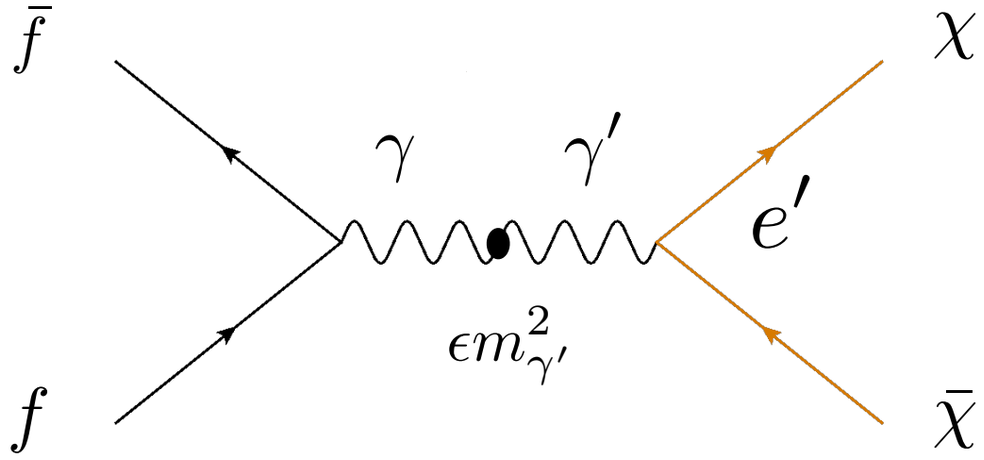


$$\mathcal{M}_{\rm vir} \sim \; e^2 \kappa \; J^{\mu}_{\rm em} \, \eta_{\mu\nu} \, J^{\nu}_{\chi} \times \frac{1}{k^2 - m^2_{\gamma'}}$$

VIRTUAL DARK PHOTON EXCHANGE

« SM interaction basis »

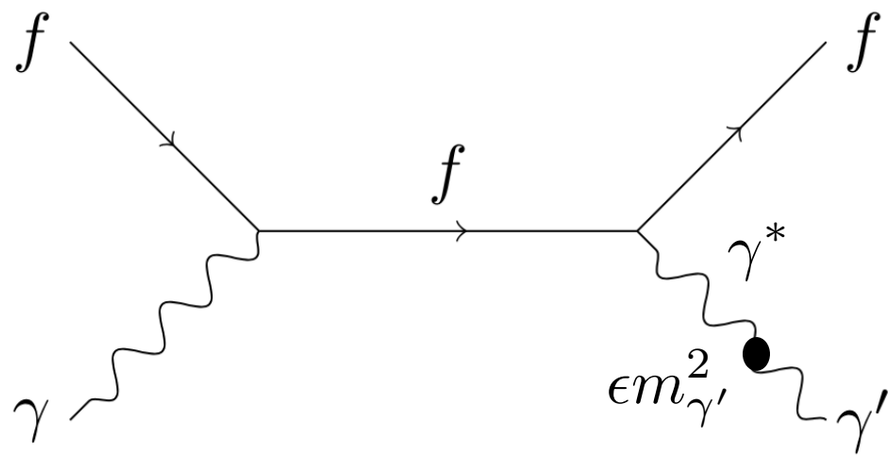




$$\mathcal{M}_{\rm vir} \sim \; e^2 \kappa \; J^{\mu}_{\rm em} \, \eta_{\mu\nu} \, J^{\nu}_{\chi} \times \frac{1}{k^2} \left(1 + \frac{m^2_{\gamma'}}{k^2 - m^2_{\gamma'}} + \dots \right)$$

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

RADIATION OF A DARK PHOTON ?

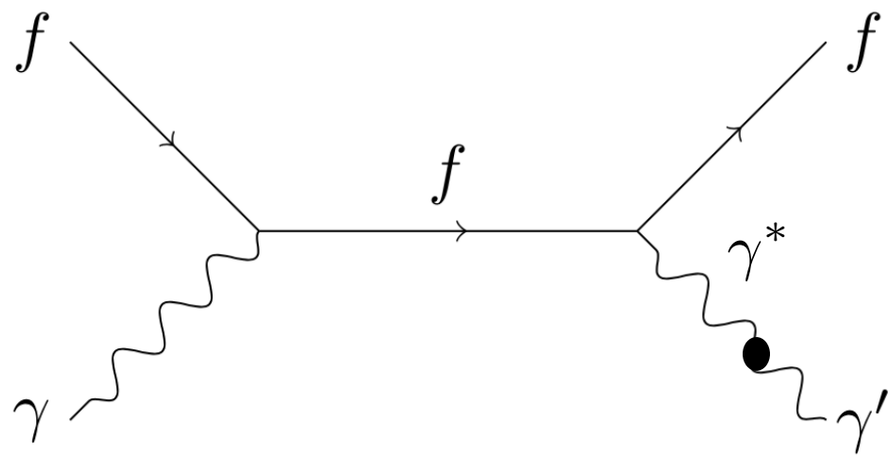


$$\mathcal{M}_{\rm rad} \propto\ e\ J^{\mu}_{\rm em}\,\eta_{\mu\nu}\,\frac{1}{k^2}\,\epsilon m^2_{\gamma'}\varepsilon'^{\nu}_{T}$$

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

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

RADIATION OF DARK PHOTON ?



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

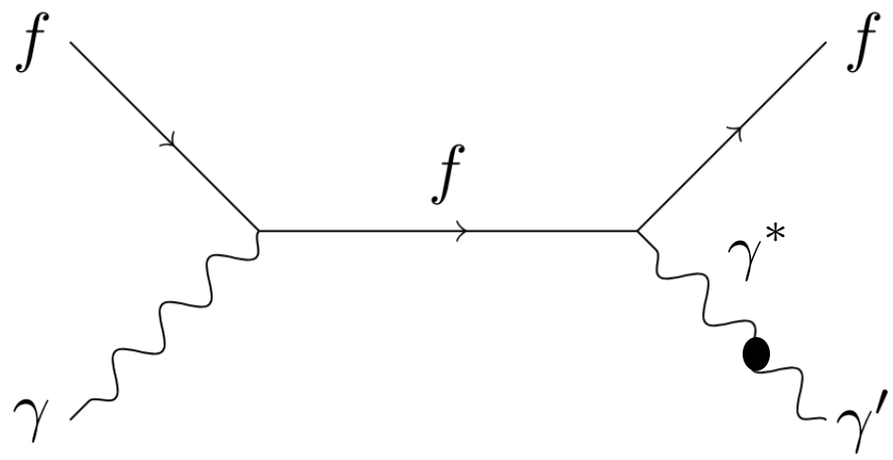
$$k^2 = m^2_{\gamma'} \quad \rightarrow \quad e\,\epsilon\, J^{\mu}_{\rm em}\, \eta_{\mu\nu} \varepsilon'^{\nu}_{T}$$

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

$$\frac{1}{k^2 + i\varepsilon}$$

asymptotic states

RADIATION OF DARK PHOTON IN 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

$$m_\gamma \sim eT$$

An, Pospelov, Pradler ‘13