From darkness to light

A history of a Hot Dark Sector

A history of a Hot Dark Sector

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Essentially based on

From darkness to light:
a history of a hot dark sector
with R. Coy & J. Kimus
2405.XXXXX

building upon

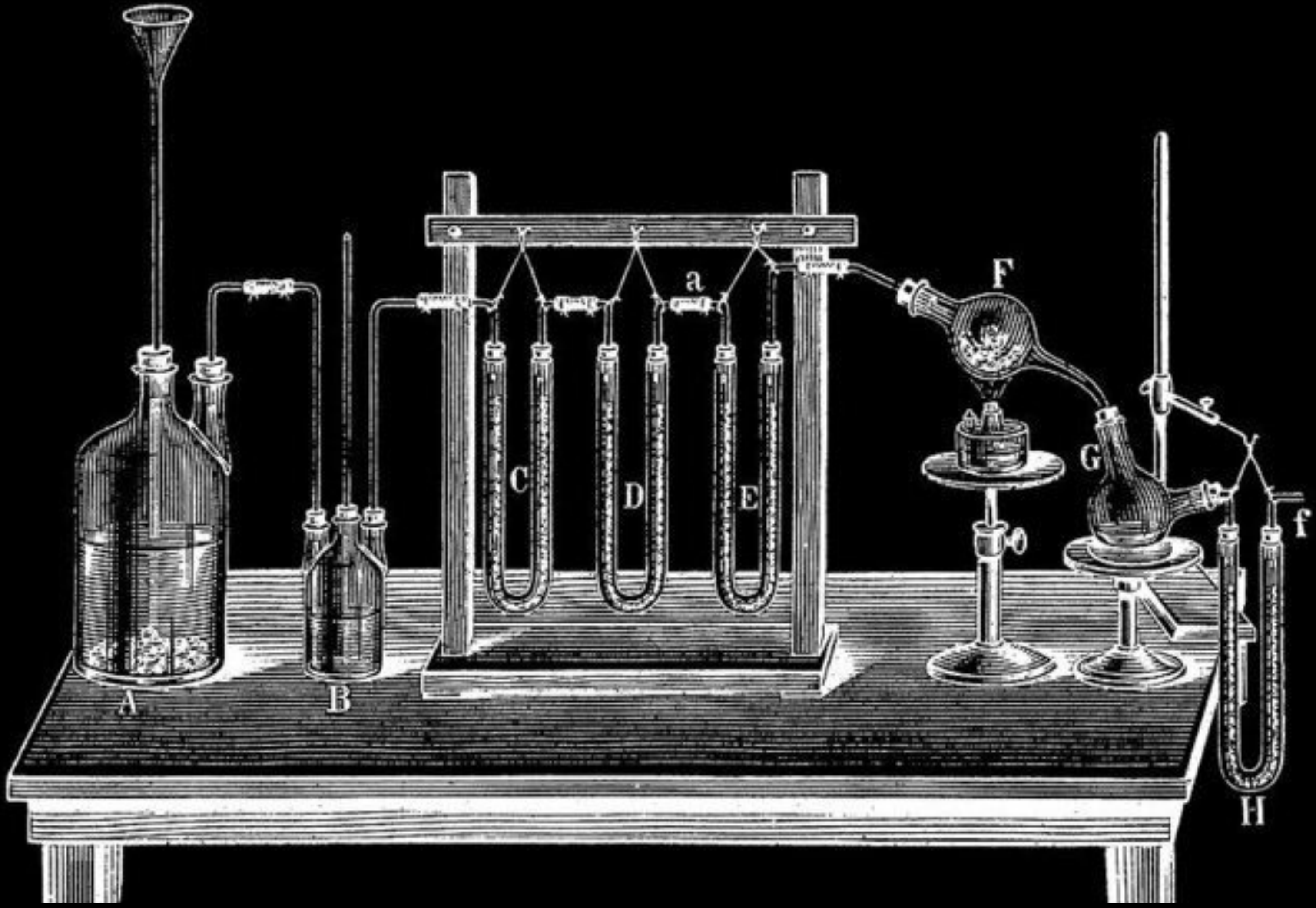
Domain of thermal dark matter candidates
Coy, Hambye, MHGT, Vanderheyden
2105.01263

see also

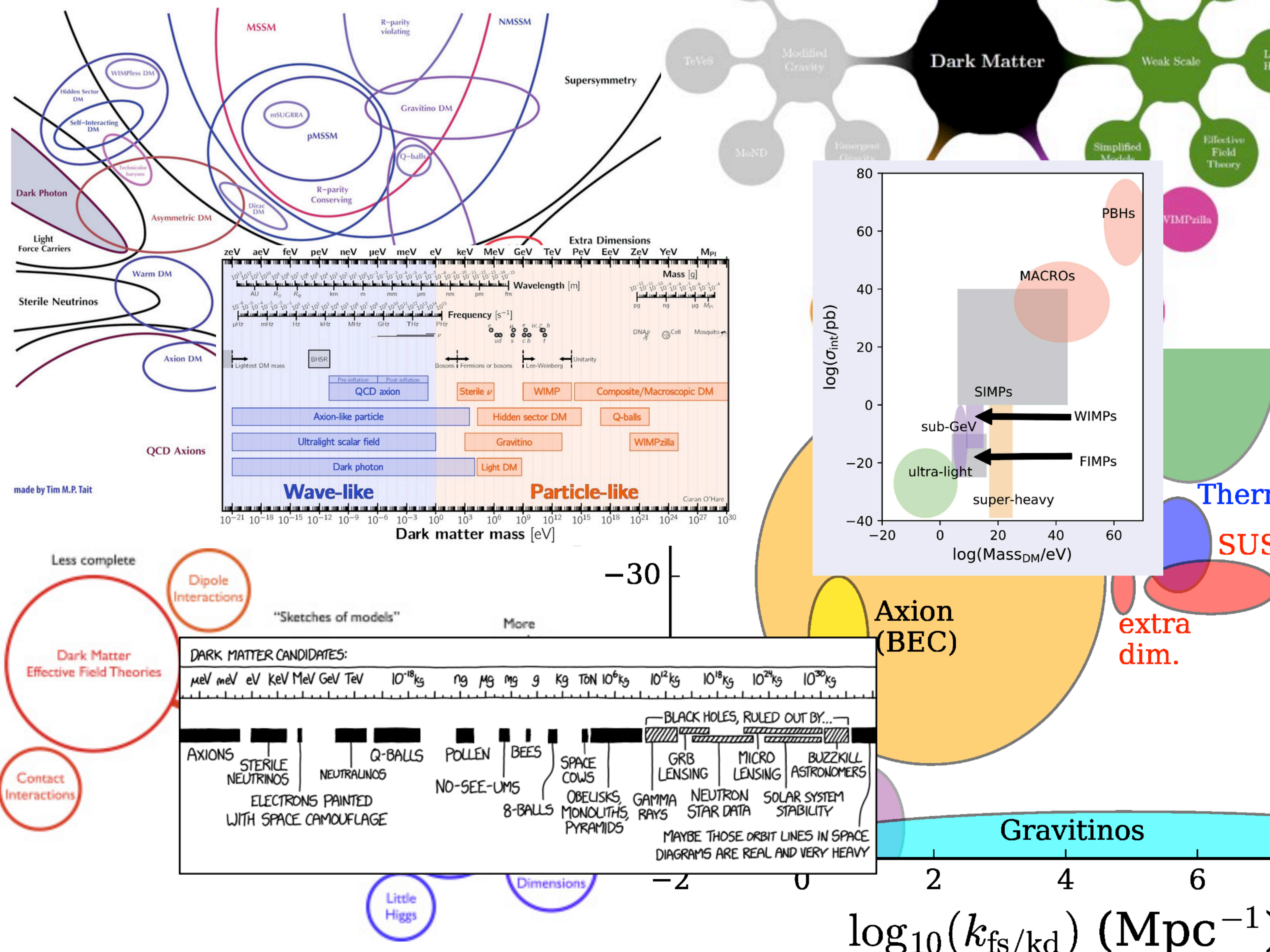
Revisiting the domain of a cannibal DM
Hufnagel, MHGT
2212.09759

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

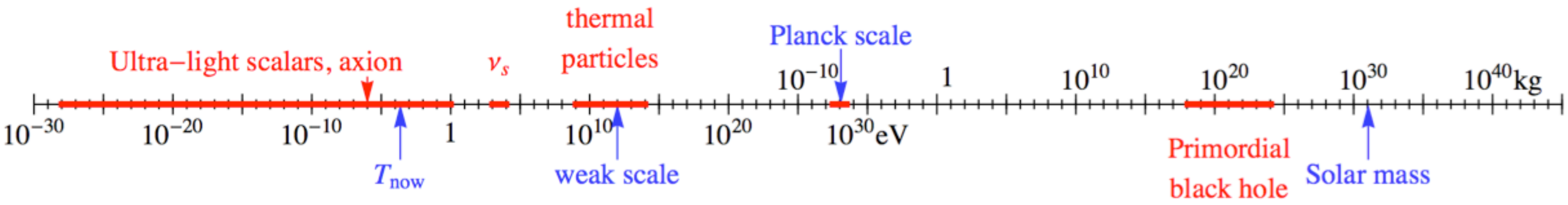
dark matter abundance ~ chemistry (albeit in an expanding universe)



mapping matter candidates


MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
mSUGRRA
pMSSM
Gravitino DM
Q-balls
Technicolor baryons
Dark Photon
Asymmetric DM
Dirac DM
R-parity Conserving
Light Force Carriers
Warm DM
Sterile Neutrinos
Axion DM
QCD Axions
made by Tim M.P. Tait
Extra Dimensions
zeV aeV feV peV neV µeV meV eV keV MeV GeV TeV PeV EeV ZeV YeV M_{Pl}
Wavelength [m]
Frequency [s^{-1}]
Mass [g]
Lightest DM mass
BHSR
Bosons | Fermions or bosons
Lee-Weinberg
Unitarity
Pre-inflation
Post-inflation
QCD axion
Sterile ν
WIMP
Composite/Macroscopic DM
Axion-like particle
Hidden sector DM
Q-balls
Ultralight scalar field
Gravitino
WIMPzilla
Dark photon
Light DM
Wave-like
Particle-like
Ciaran O'Hare
10^{-21} 10^{-18} 10^{-15} 10^{-12} 10^{-9} 10^{-6} 10^{-3} 10^{0} 10^{3} 10^{6} 10^{9} 10^{12} 10^{15} 10^{18} 10^{21} 10^{24} 10^{27} 10^{30}
Dark matter mass [eV]
TeVeS
Modified Gravity
Dark Matter
Weak Scale
MoND
Emergent Gravity
Simplified Models
Effective Field Theory
WIMPzilla
$\log(\sigma_{int}/pb)$
$\log(Mass_{DM}/eV)$
80 60 40 20 0 −20 −40
−20 0 20 40 60
PBHs
MACROs
SIMPs
WIMPs
sub-GeV
FIMPs
ultra-light
super-heavy
Therm
SUS
extra dim.
Axion (BEC)
Gravitinos
−30
−2 0 2 4 6
$\log_{10}(k_{fs/kd})$ (Mpc^{-1})
Less complete
Dipole Interactions
"Sketches of models"
More
Dark Matter Effective Field Theories
Contact Interactions
Little Higgs
Dimensions
DARK MATTER CANDIDATES:
µeV meV eV KeV MeV GeV TeV 10^{-18}kg ng µg mg g kg TON 10^{6}kg 10^{12}kg 10^{18}kg 10^{24}kg 10^{30}kg
BLACK HOLES, RULED OUT BY...
AXIONS
STERILE NEUTRINOS
NEUTRALINOS
Q-BALLS
POLLEN
BEES
ELECTRONS PAINTED WITH SPACE CAMOUFLAGE
NO-SEE-UMS
8-BALLS
SPACE COWS
OBELISKS, MONOLITHS, PYRAMIDS
GRB LENSING
GAMMA RAYS
MICRO LENSING
NEUTRON STAR DATA
BUZZKILL ASTRONOMERS
SOLAR SYSTEM STABILITY
MAYBE THOSE ORBIT LINES IN SPACE DIAGRAMS ARE REAL AND VERY HEAVY

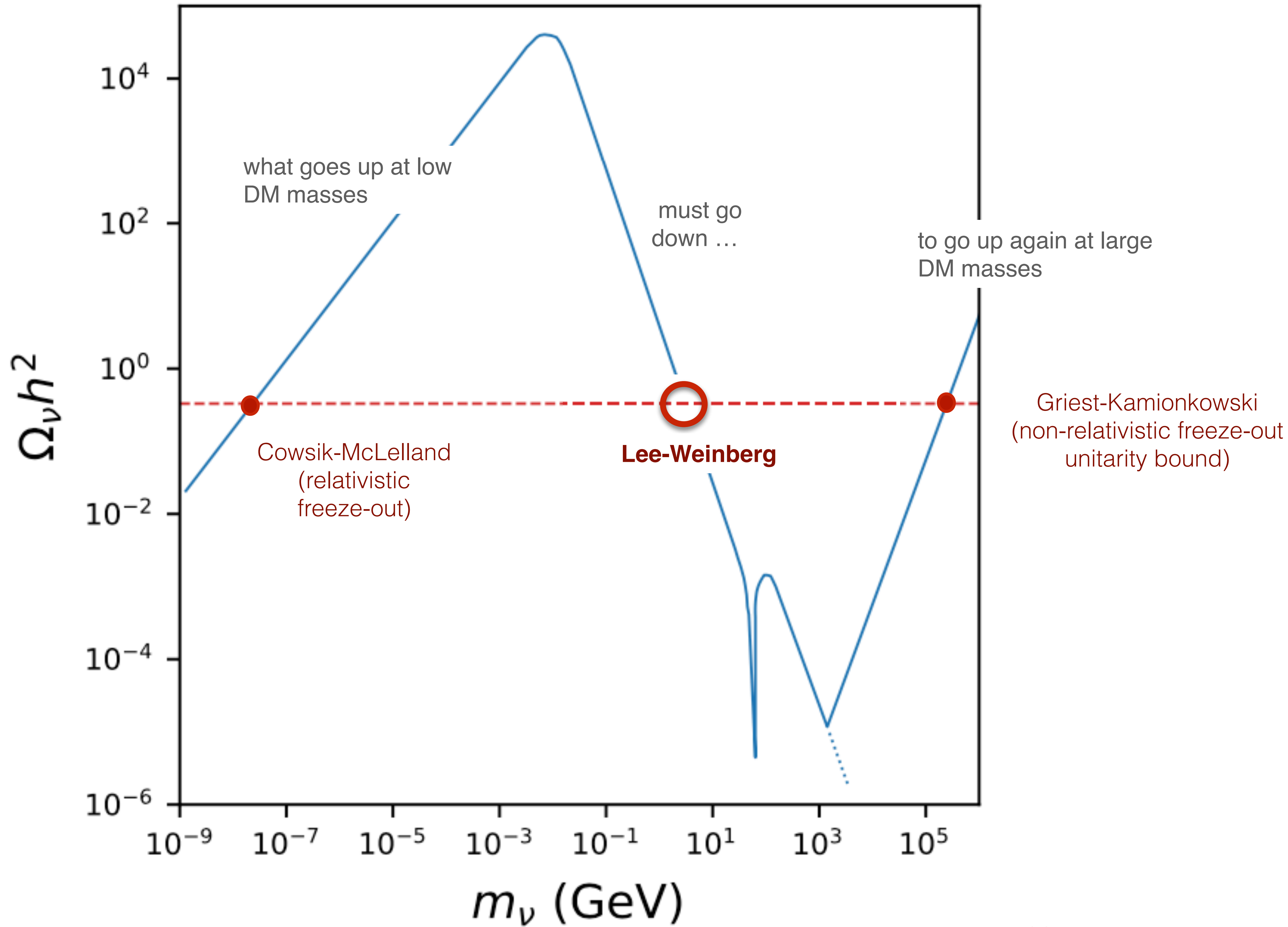
Domain of thermal Dark Matter candidates?



thermal particles
(aka WIMP)

Courtesy M.Cirelli

a classic example ~ massive neutrino DM



what goes up at low DM masses

must go down …

to go up again at large DM masses

Cowsik-McLelland (relativistic freeze-out)

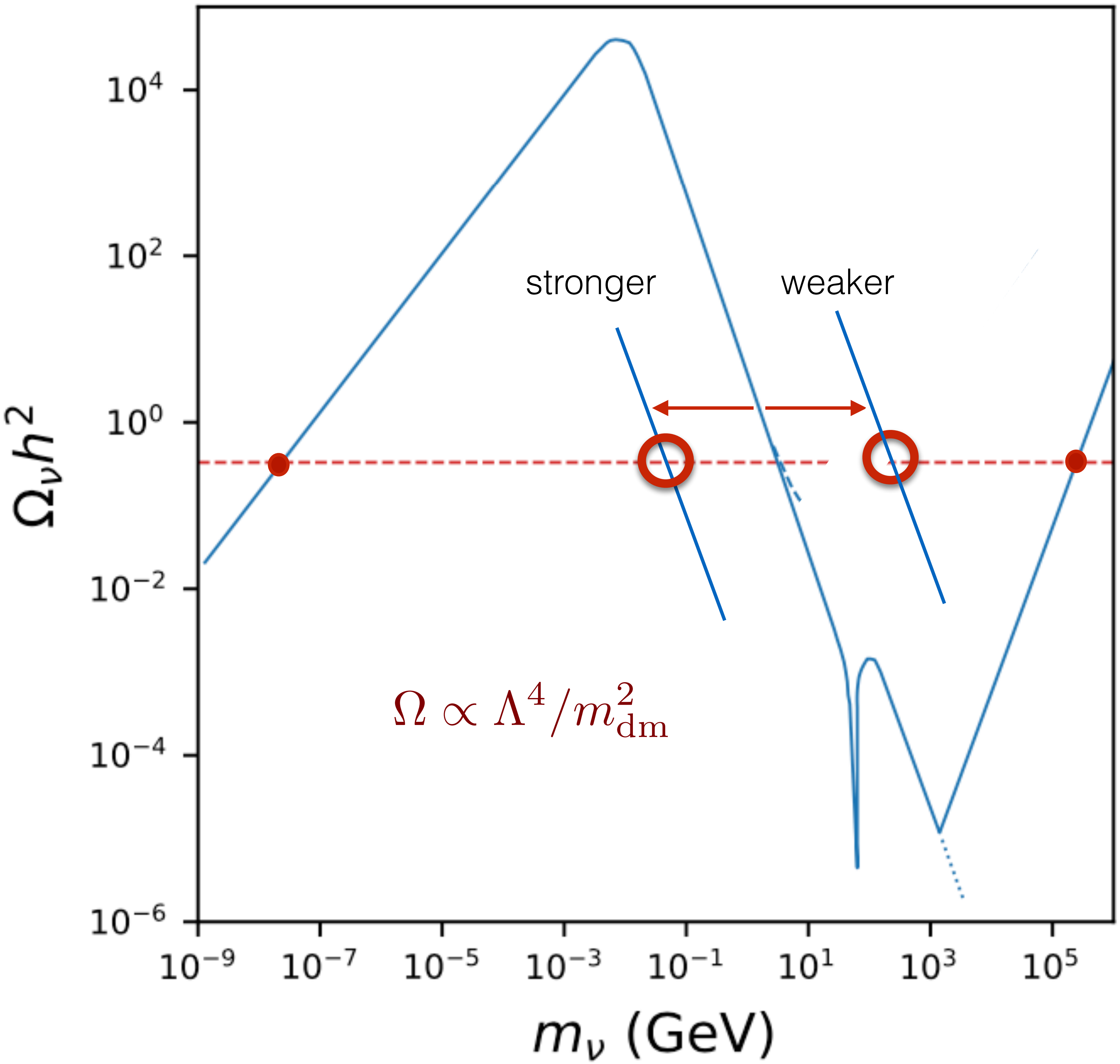
Lee-Weinberg

Griest-Kamionkowski (non-relativistic freeze-out unitarity bound)

I ❤ your plot Kimmo !

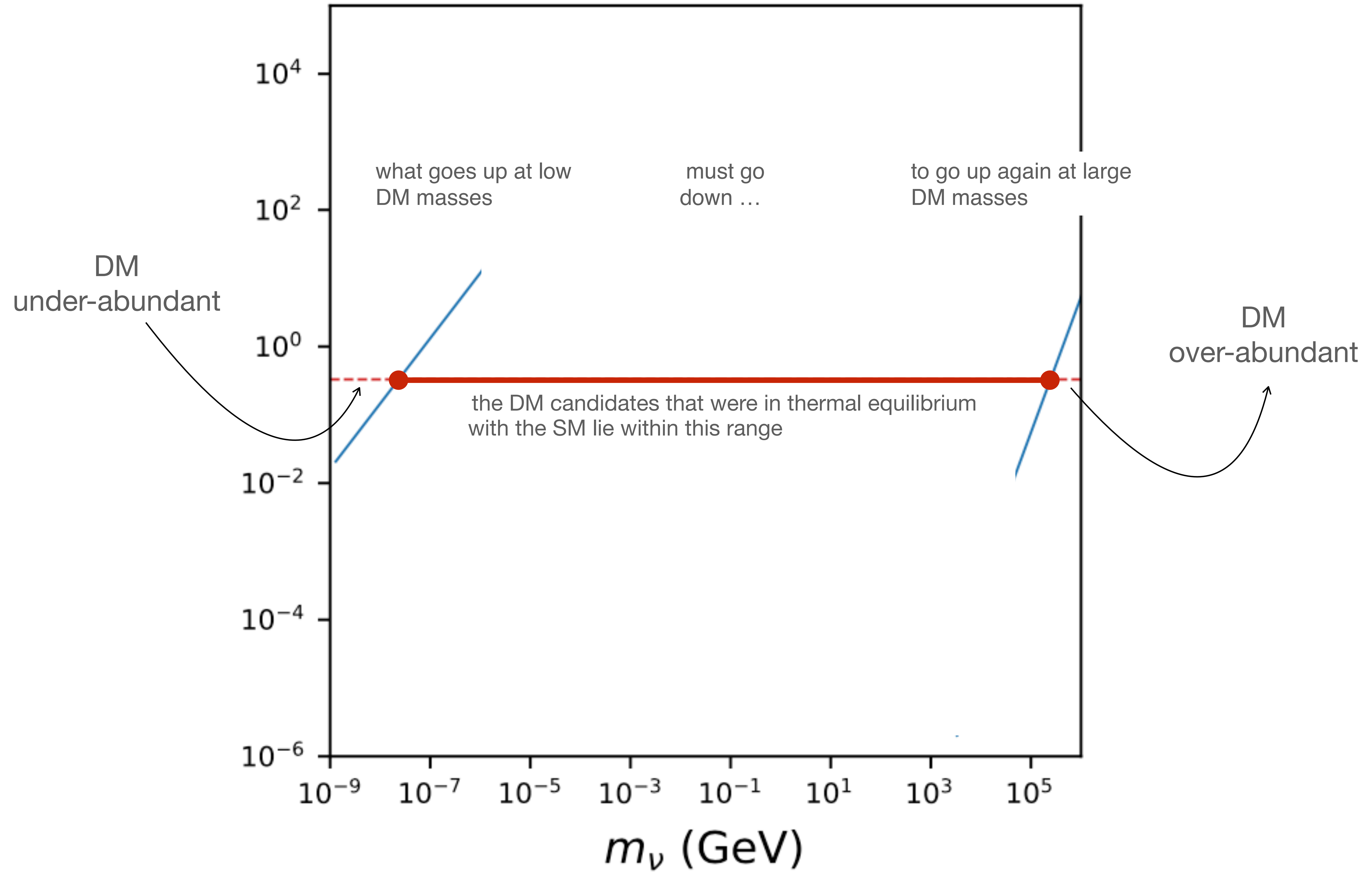
Plot from Kainulainen & K. Olive ‘03

changing interaction strength



$\Omega \propto \Lambda^4/m_{\rm dm}^2$

range of thermal DM candidates



what goes up at low DM masses

must go down …

to go up again at large DM masses

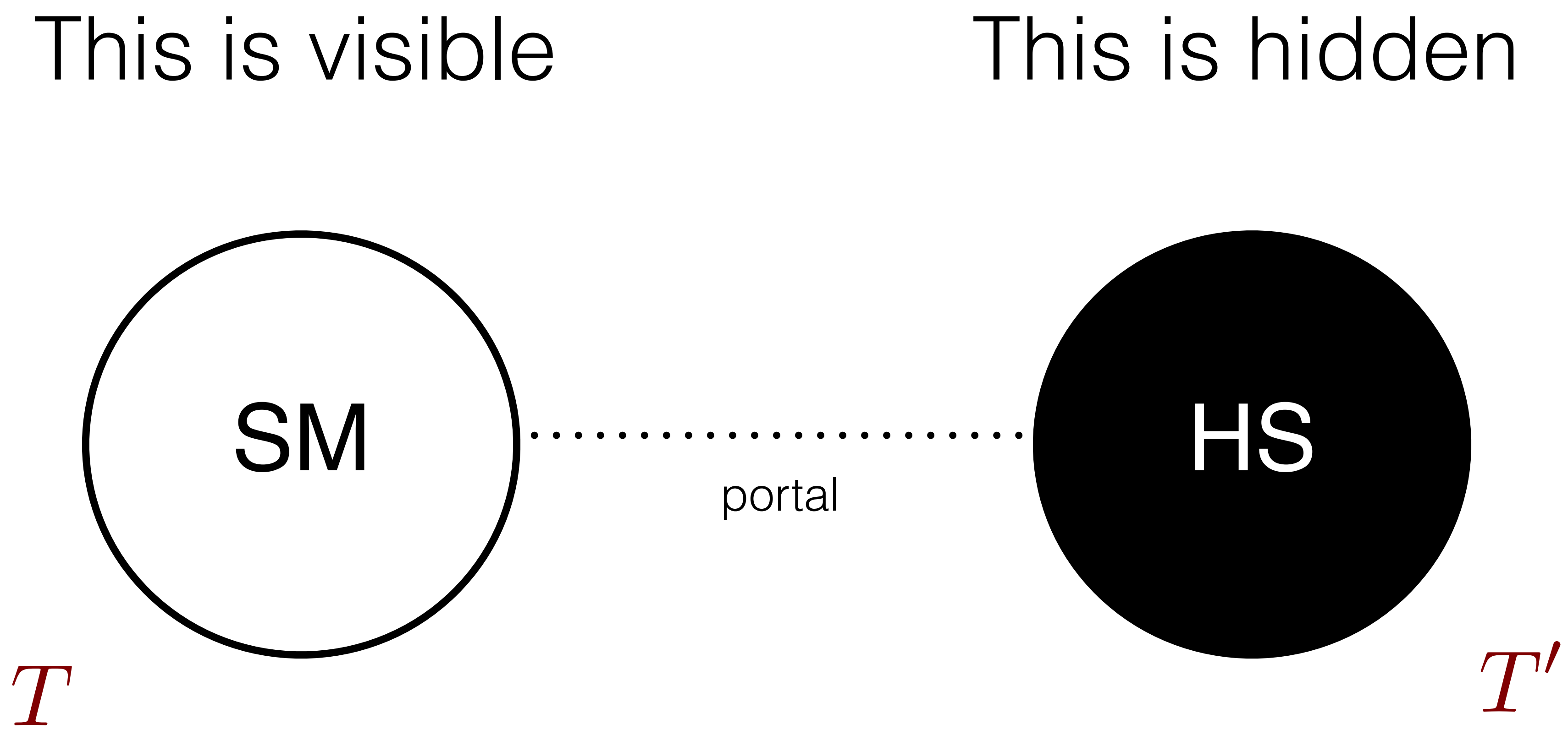
DM under-abundant

DM over-abundant

the DM candidates that were in thermal equilibrium with the SM lie within this range

Plot from Kainulainen & Olives ‘03

HIDDEN SECTOR (HS)



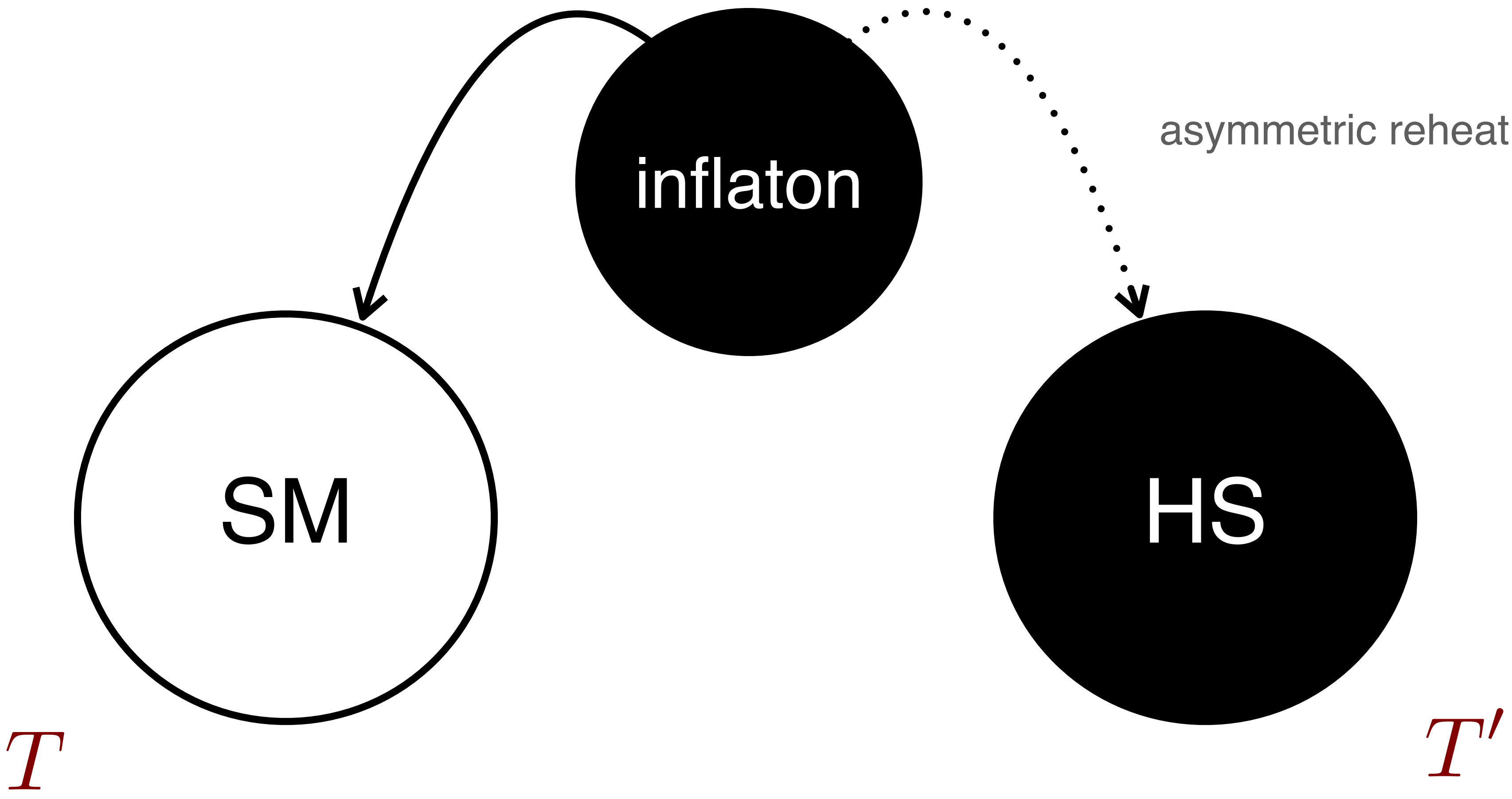
hidden sector :

possibly many SM singlet particles, possibly with their own interactions

possibly in thermal equilibrium, but temperatures (T & T’) may be different

possibly interacting with SM through a portal

asymmetric reheating & secluded DM freeze-out

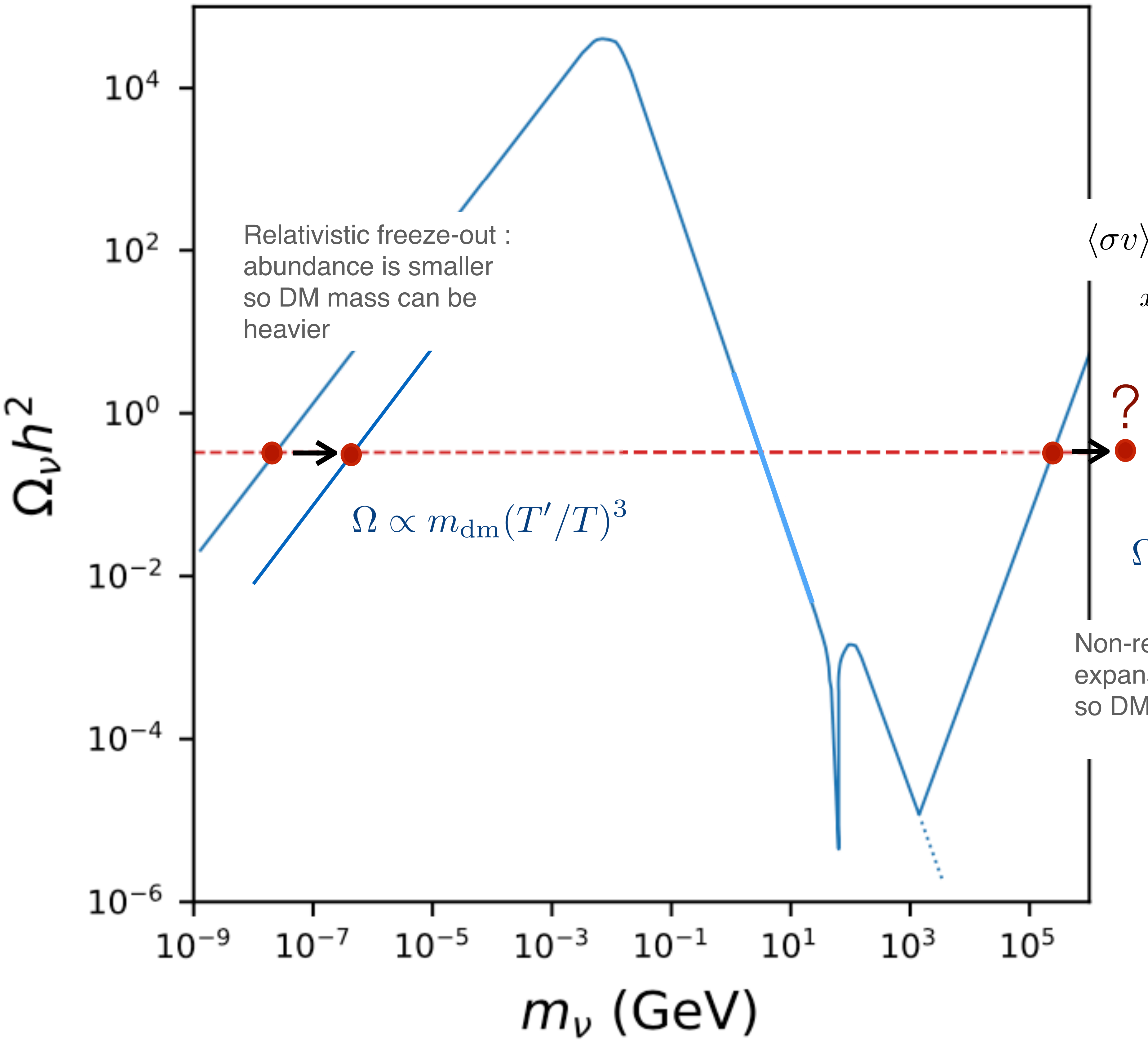


asymmetric reheating

dark matter abundance through
secluded freeze-out

Foot; Feng, Tu & Hai-Bo; Pospelov, Ritz, Voloshin;…

cold hidden sector ?



Relativistic freeze-out :
abundance is smaller
so DM mass can be
heavier

$$\Omega \propto m_{\rm dm}(T'/T)^3$$

$$\langle \sigma v\rangle n_{\rm dm}(T'_{\rm fo}) \sim H(T_{\rm fo})$$

$$x'_{\rm fo} = m_{\rm dm}/T'_{\rm fo} = \mathcal{O}(20)$$

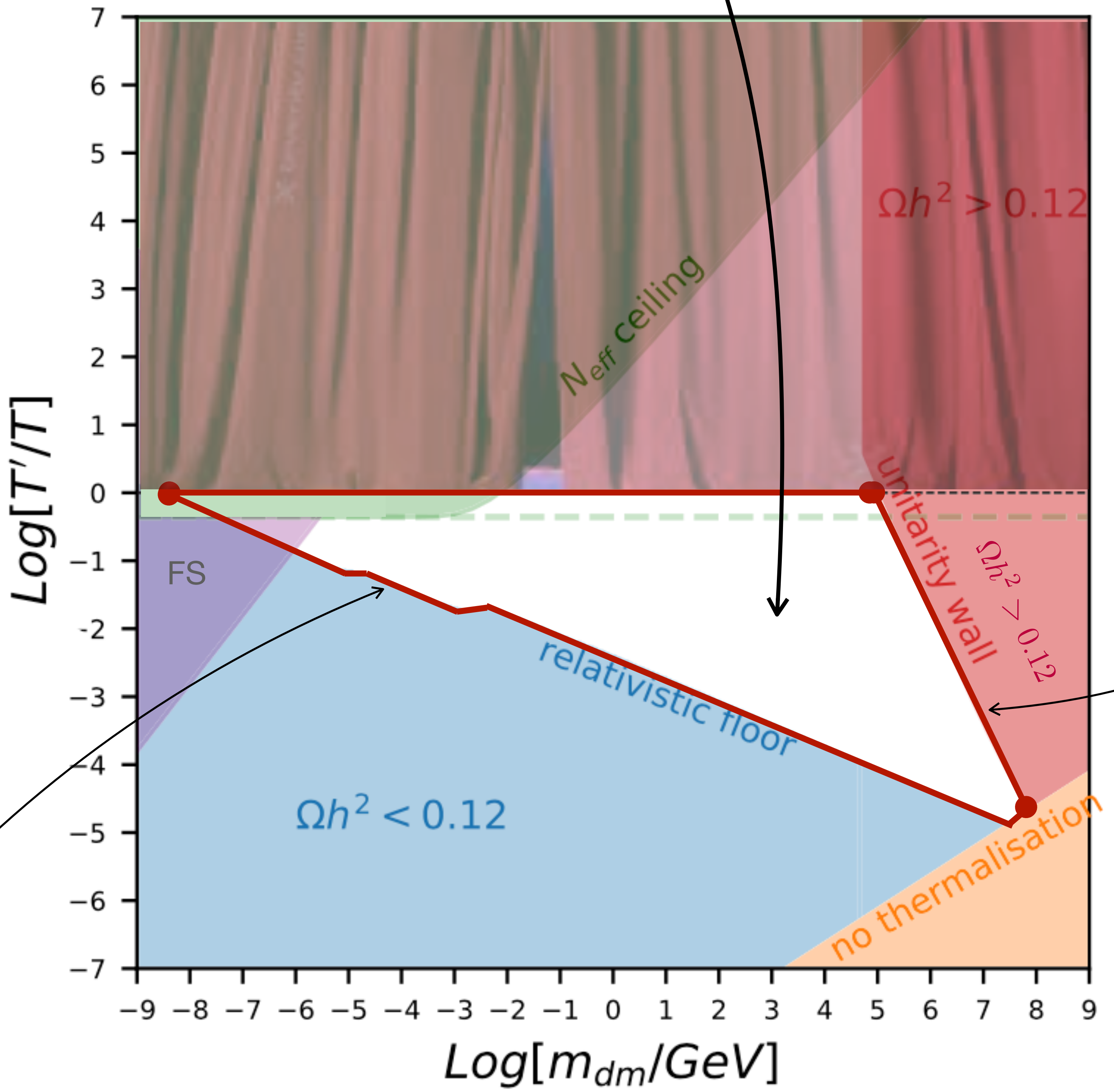
$$\Omega \propto m^2_{\rm dm}(T'/T)$$

Non-relativistic freeze-out :
expansion faster if T’/T < 1
so DM mass can be heavier

domain of thermal DM

thermal : candidates that were once in thermal equilibrium

cold & dark sector $T' \leq T$



this boundary scale like

$T'/T \propto 1/m_{\rm dm}^2$

call it the 'unitarity wall'

this boundary scale like

$T'/T \propto m_{\rm dm}^{-1/3}$

call it the 'relativistic floor'

Coy, Hambye, MHGT, Vanderheyden '21

domain of thermal DM

merely asking not too much stuff at BBN ($\Delta N_{\rm eff}$)

(OK for non-thermal candidates)

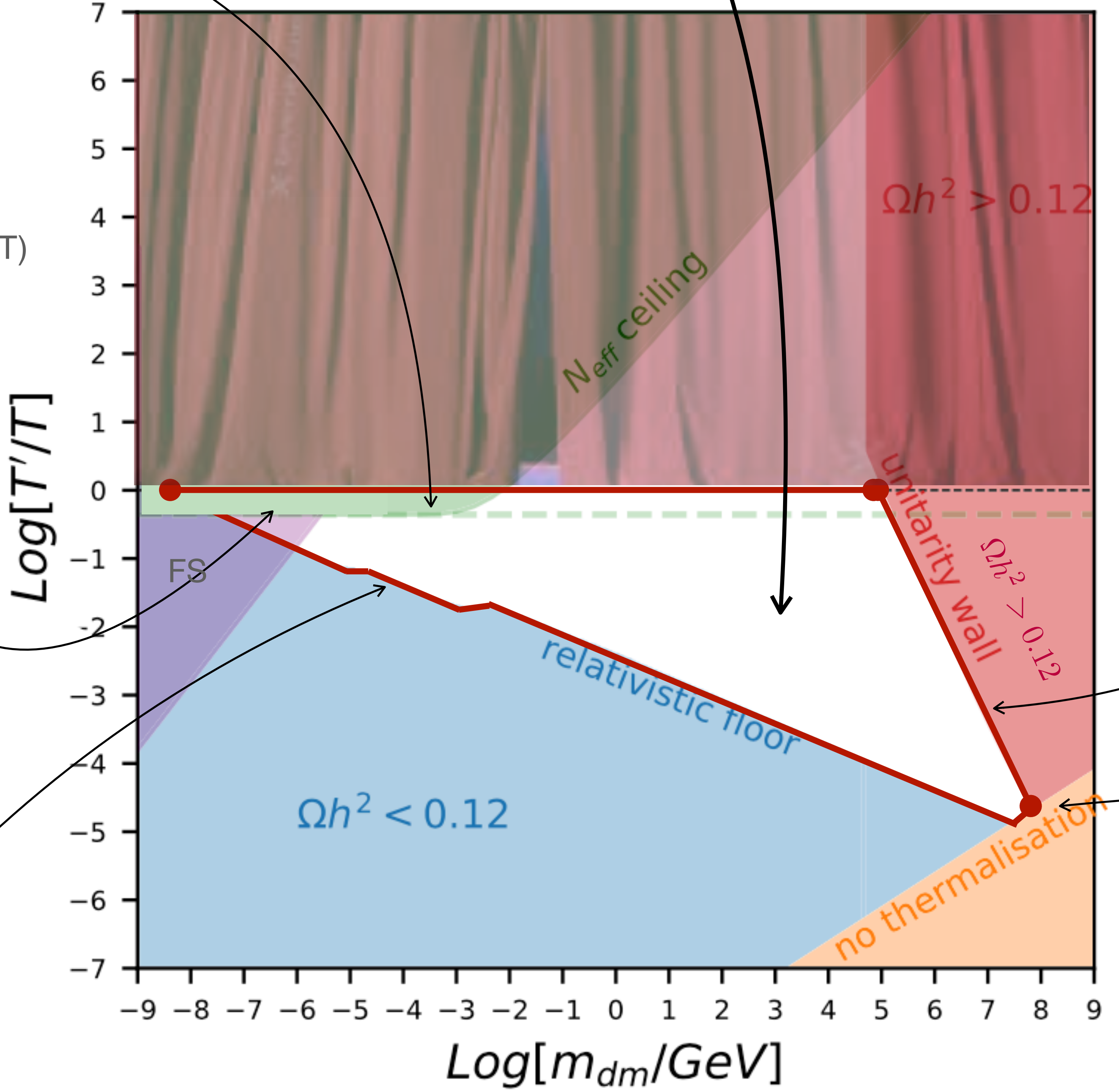
free streaming excludes too hot DM candidates (Lyman-α, $m_{\rm dm} \gtrsim {\rm keV}$ for T'=T)

cold & dark sector

this boundary scale like

$$T'/T \propto 1/m^2_{\rm dm}$$

call it the 'unitarity wall'



this boundary scale like

$$T'/T \propto m_{\rm dm}^{-1/3}$$

call it the 'relativistic floor'

if HS too cold ~ expansion too fast, DM may never reach thermal equilibrium

$$m_{\rm dm} \sim 50\,{\rm PeV}$$

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

Coy, Hambye, MHGT, Vanderheyden '21

example dark qed

dark fine structure constant (α')

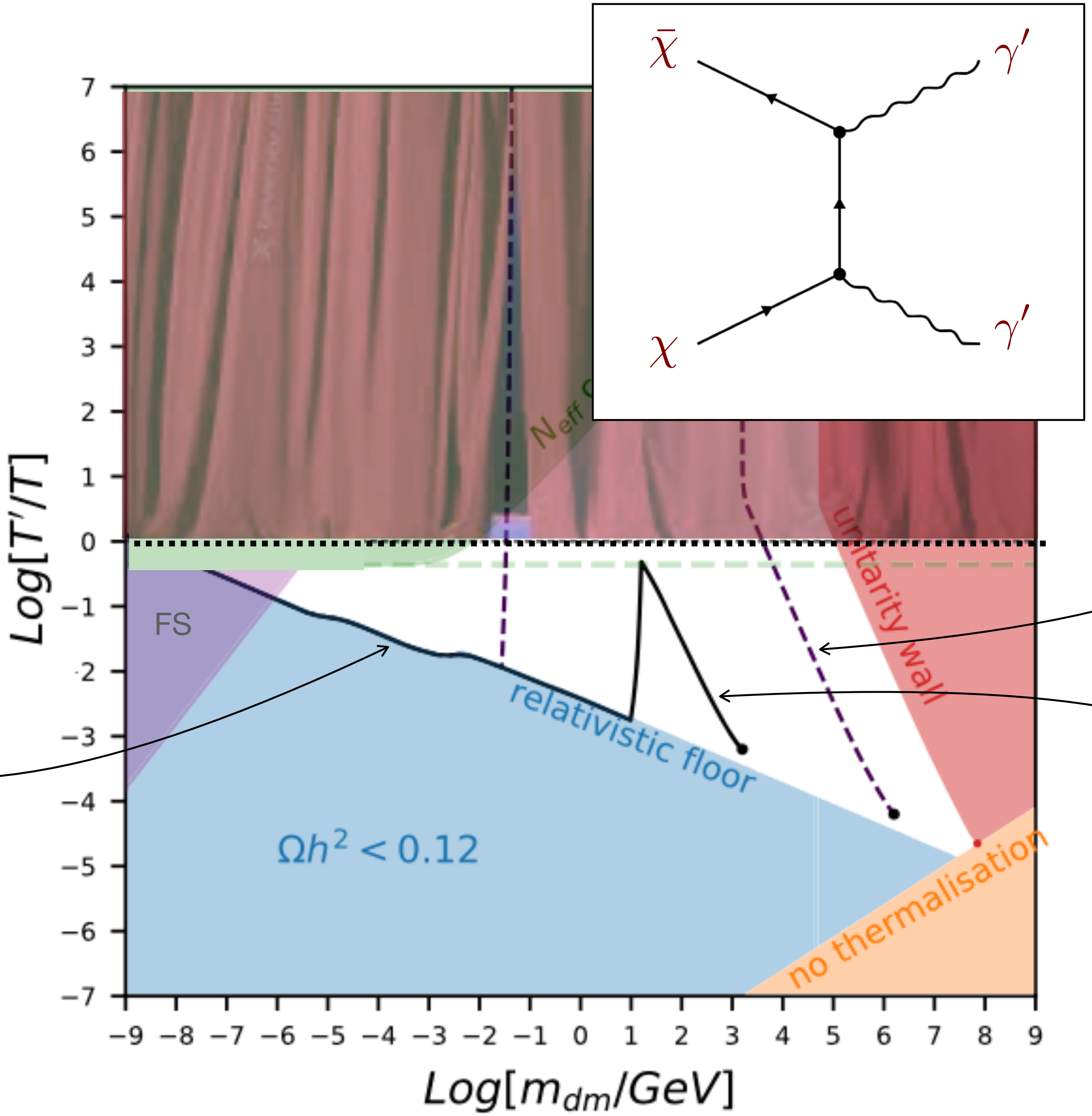
$$\mathcal{L} \supset \bar{\chi}(i\not{D}' - m_\chi)\chi - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{\gamma'}A'_\mu A'^\mu$$

dark electrons & positrons (DM)

(massive) dark photons

3 parameters + T'/T

example : dark qed



larger α'

$m_\chi < m_{\gamma'}$

relativistic freeze-out

$T'/T \propto m_{\rm dm}^{-1/3}$

$m_\chi > m_{\gamma'}$

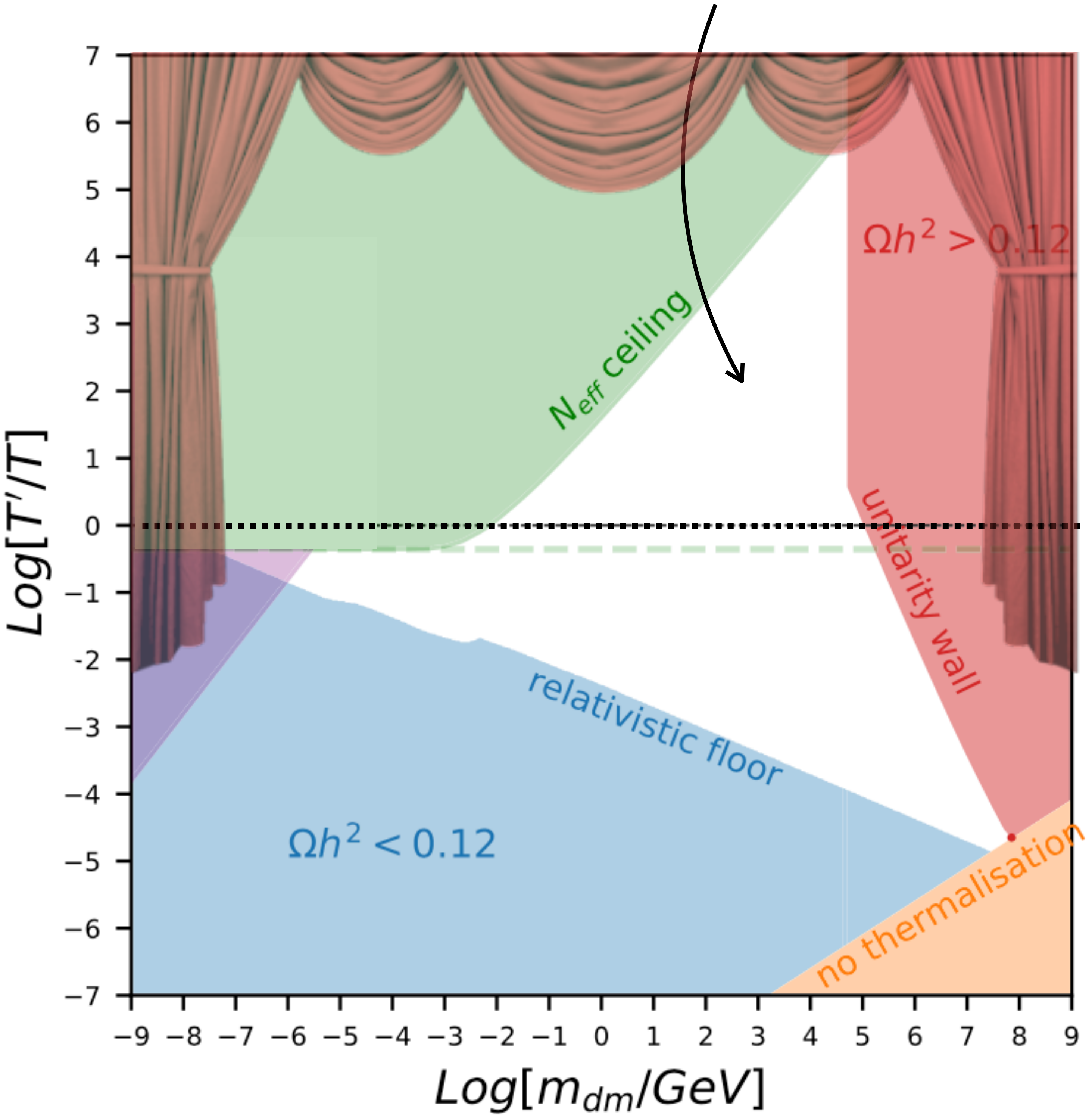
non-relativistic freeze-out

$T'/T \propto 1/m_{\rm dm}^2$

Coy, Hambye, MHGT, Vanderheyden ’21

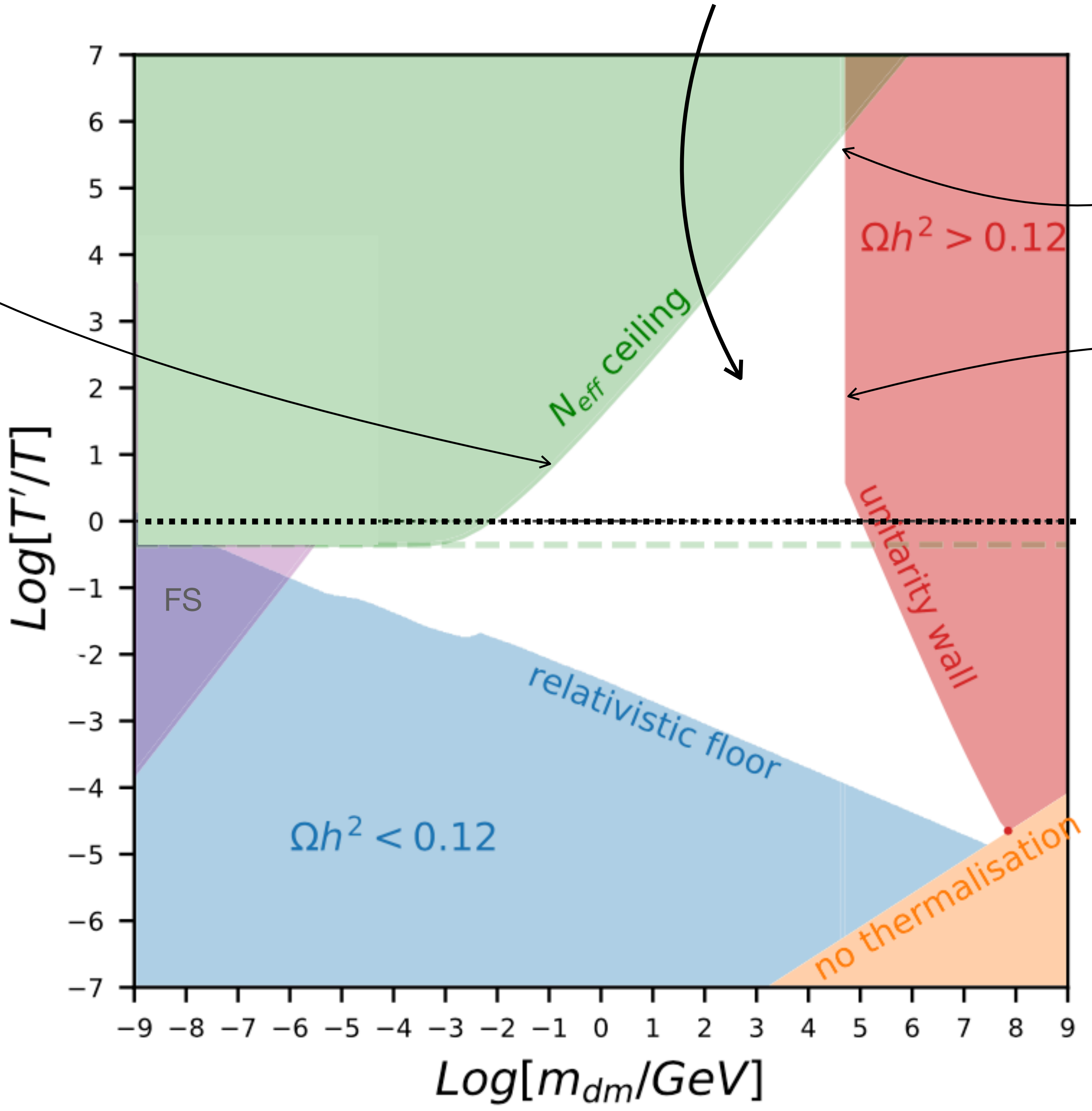
domain of thermal DM

hot dark sector $T' \gtrsim T$



Coy, Hambye, MHGT, Vanderheyden ’21

domain of thermal DM



hot hidden sector $T' \gtrsim T$

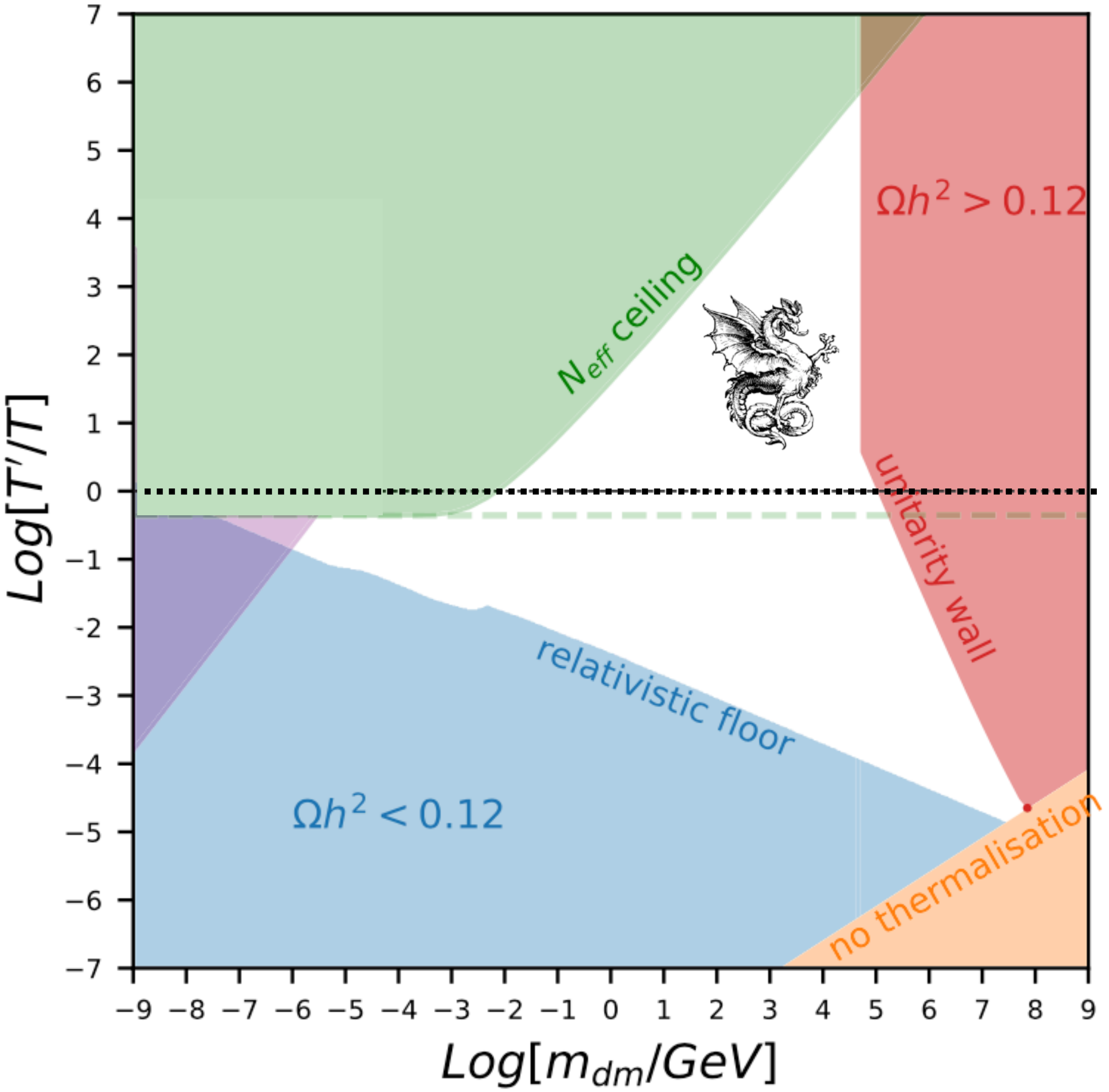
merely asking not too much stuff at BBN ($\Delta N_{\rm eff}$)

freeze-out ~ @BBN

expansion driven by hidden sector ~ SM irrelevant

Coy, Hambye, MHGT, Vanderheyden ’21

hic sunt dracones

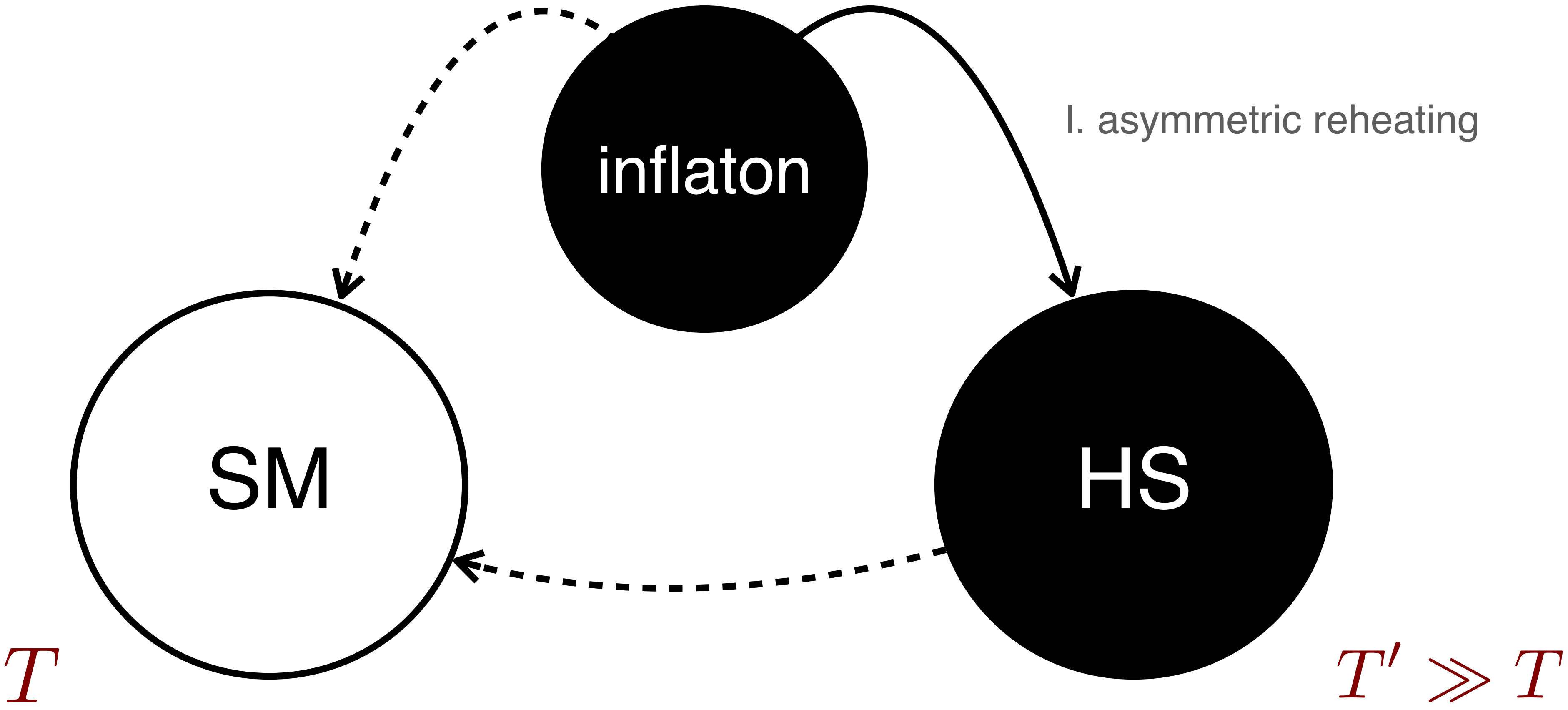


"Here be dragons" means dangerous territories, a medieval practice of putting mythological creatures on uncharted maps where potential dangers were thought to exist (abbreviated from Wikipedia)

here 'dragons' are the DM companion particle(s) (eg a dark photon)

Coy, Hambye, MHGT, Vanderheyden '21

history of a hot dark sector



I. asymmetric reheating

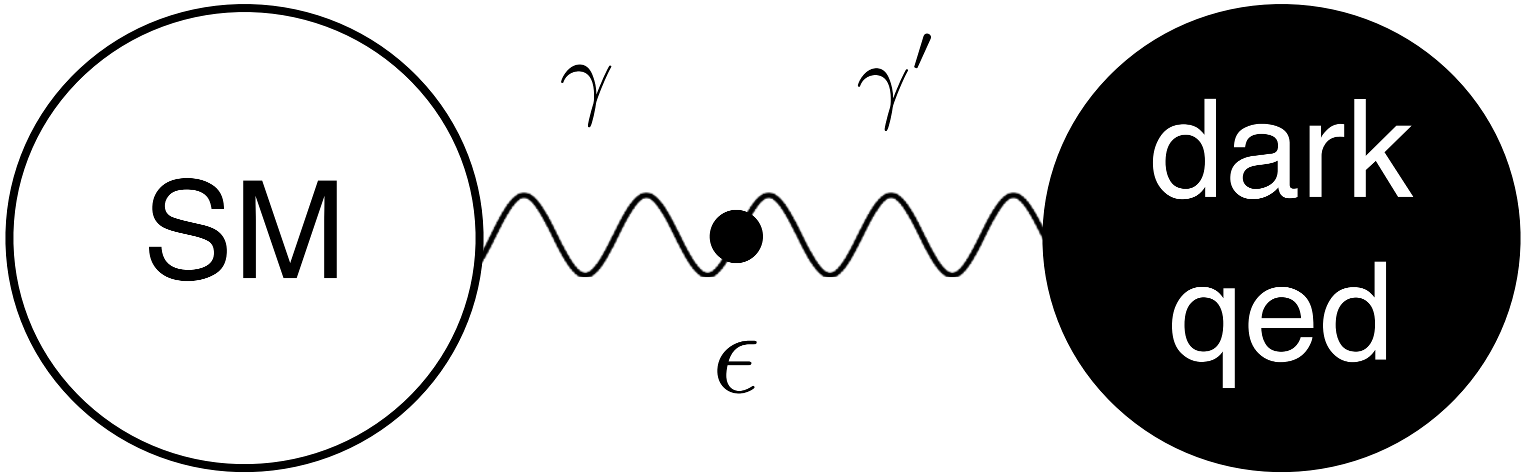
III. companion decays through
a portal ~ entropy transfer

II. dark matter abundance through
secluded freeze-out

In brief, a weird, indirect reheating of the SM sector

kinetic mixing

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

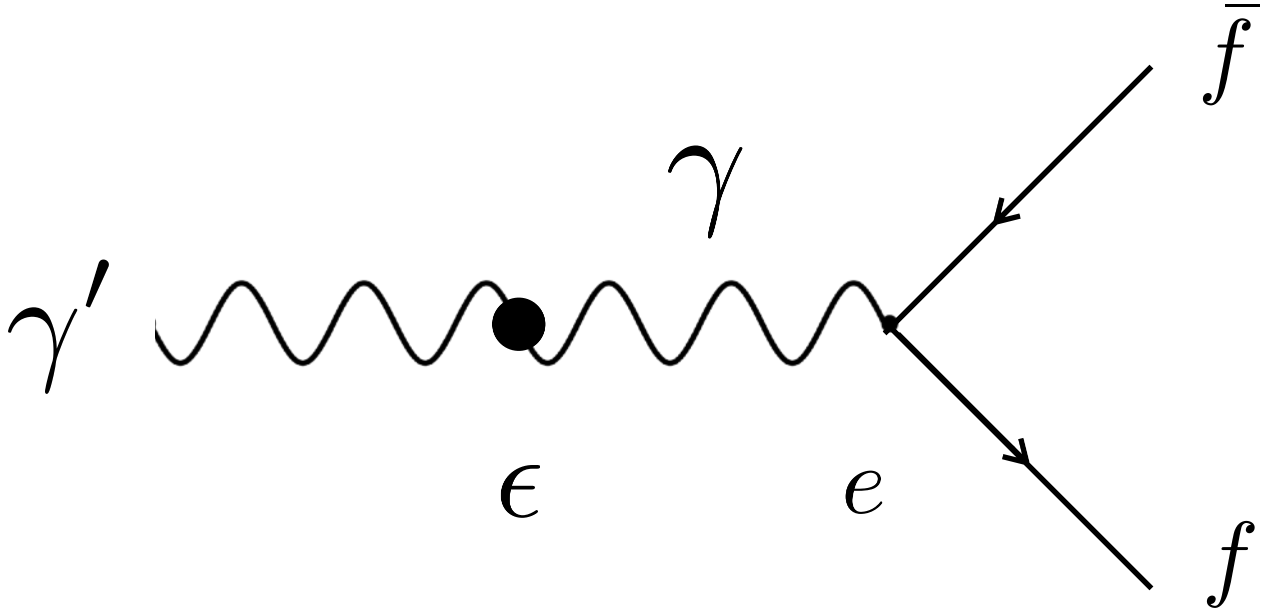


dark electrons & positrons (DM)

(massive) dark photons

dark photon decay into SM

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



$$\Gamma' \sim \alpha\,\epsilon^2\,m'$$

set of simplified Boltzmann equations

total energy

eos

simplify…

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

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

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

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

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

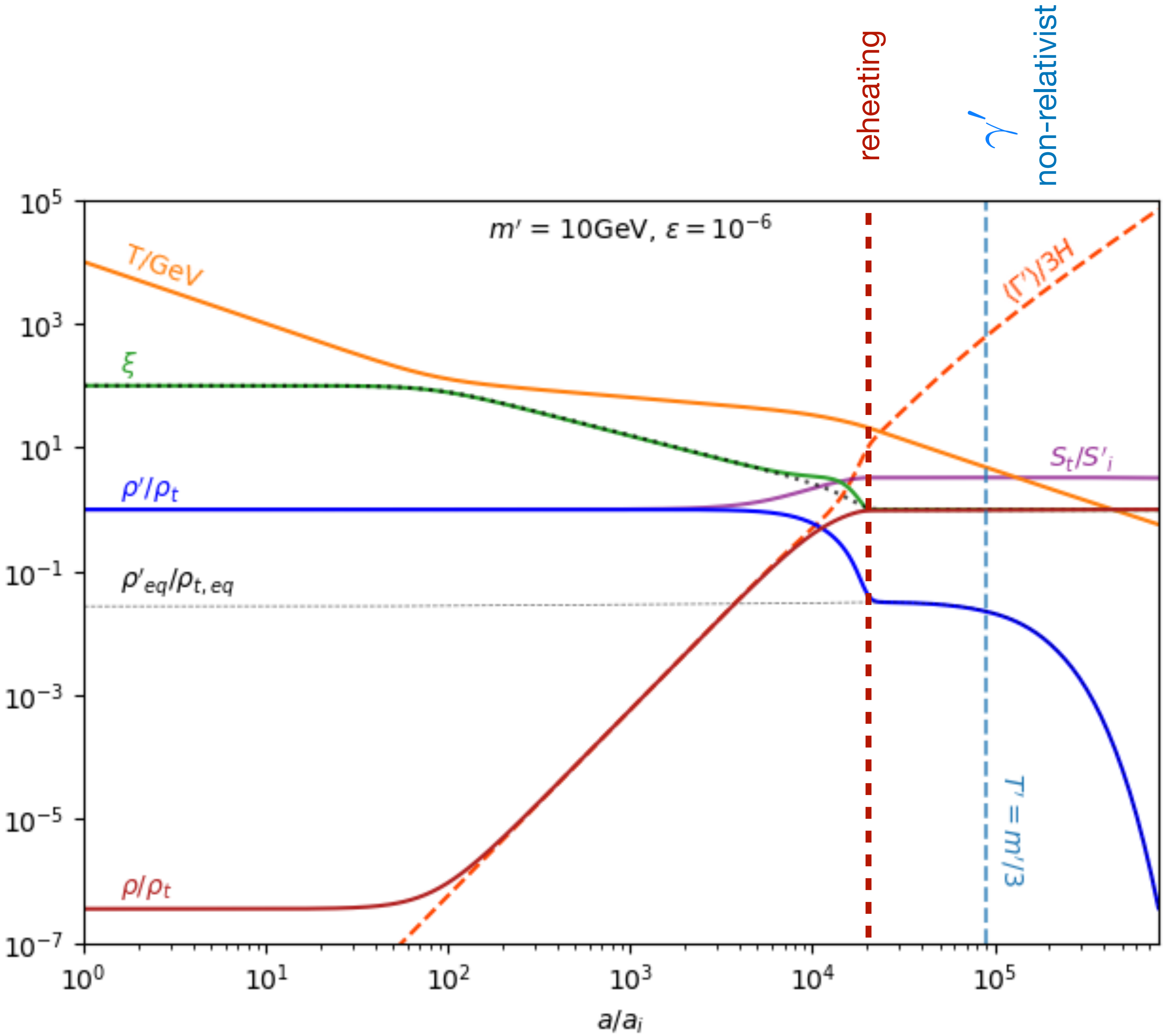
simplify…

Coy, Kimus, MHGT ‘23

1st scenario : relativistic reheating

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

hot DS



scale factor

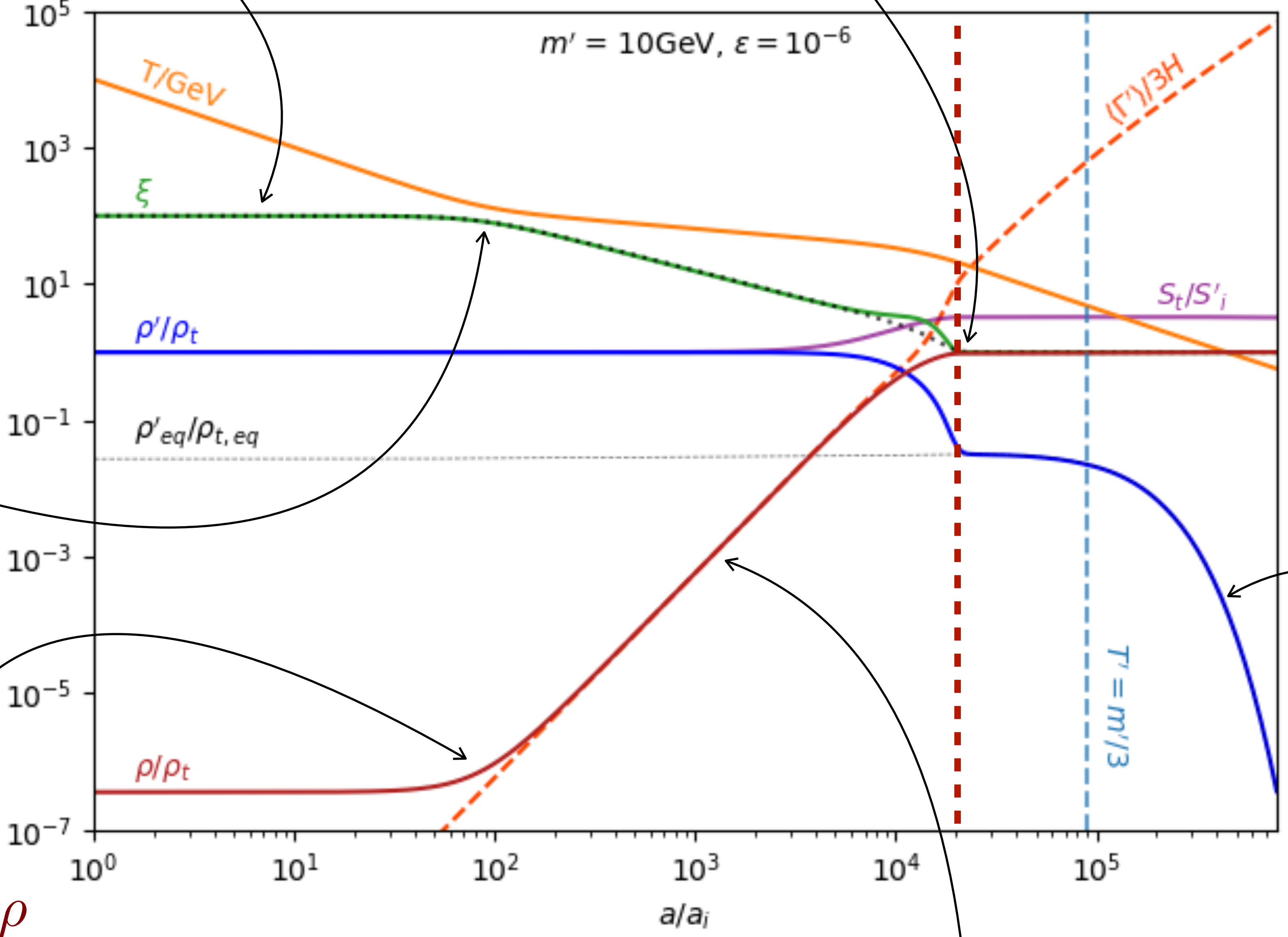
Coy, Kimus, MHGT ‘24

1st scenario : relativistic reheating

$\xi = \frac{T'}{T}$ I. constant initially (plateau)

III. reheating : γ' are still relativistic

both sectors reach thermal equilibrium $T' = T$



O(1) entropy production

$S_f/S_i \approx (g/g')^{1/4}$

II. heat transfer effectively begins

this happens when

$\rho/\rho' \sim \langle\Gamma'\rangle/H$

meaning when

(energy from decay) $\gtrsim \rho$

scale factor

IV. γ' non-relativistic

Boltzmann suppressed

$\rho/\rho' \sim \langle\Gamma'\rangle/H$ throughout heating

Coy, Kimus, MHGT ‘24

2nd scenario : non-relativistic reheating

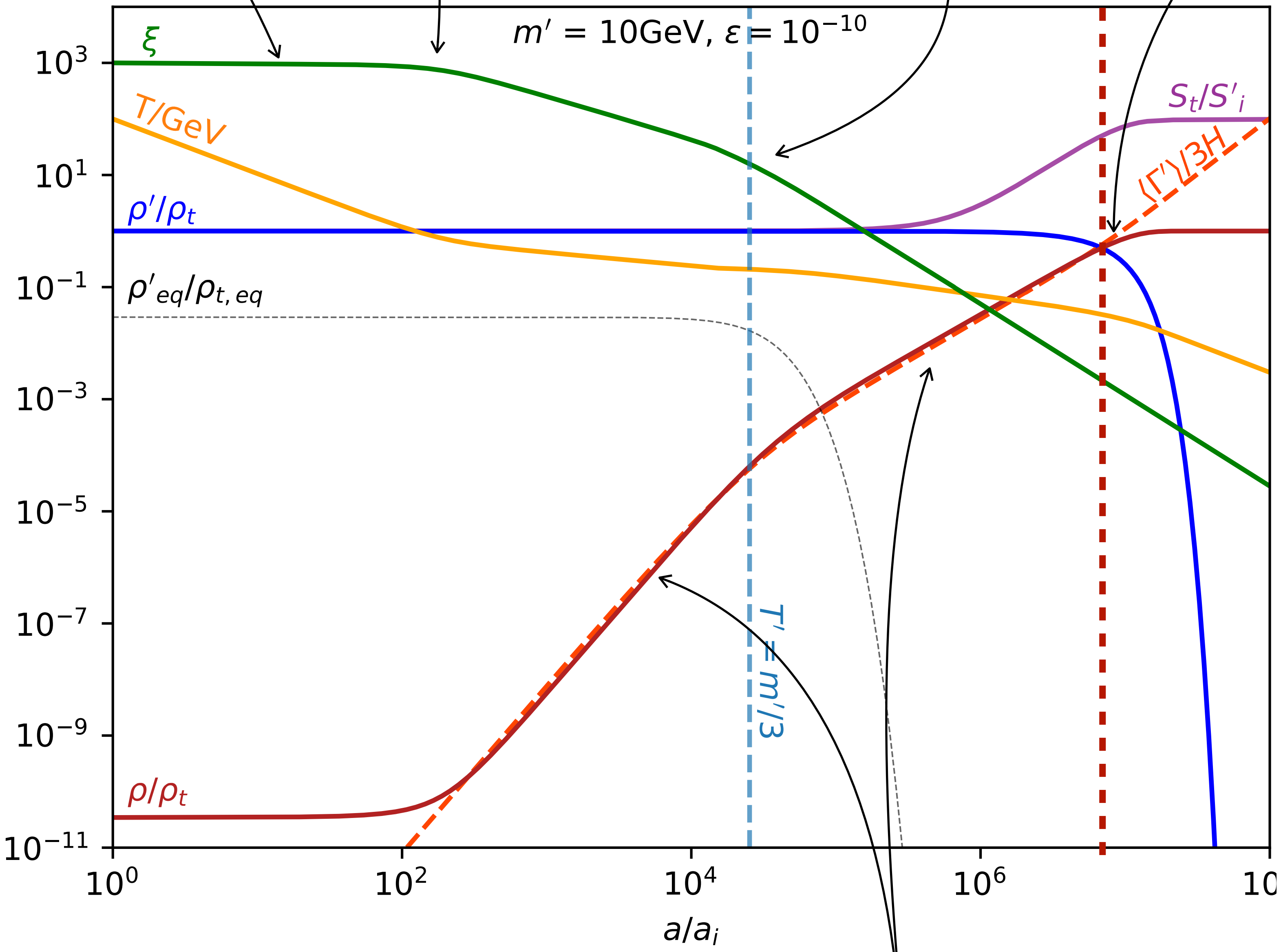
$$\xi = \frac{T'}{T}$$

I. plateau

II. onset of heating

III. γ' non-relativistic ($t_{\rm nr}$)

IV. reheating



scale factor

entropy production

$$\frac{S_f}{S_i} \approx \left(\frac{g}{g'}\right)^{1/4} \left(\frac{\tau'}{t_{\rm nr}}\right)^{1/2}$$

τ'

dark photon lifetime
(cf Scherrer & Turner)

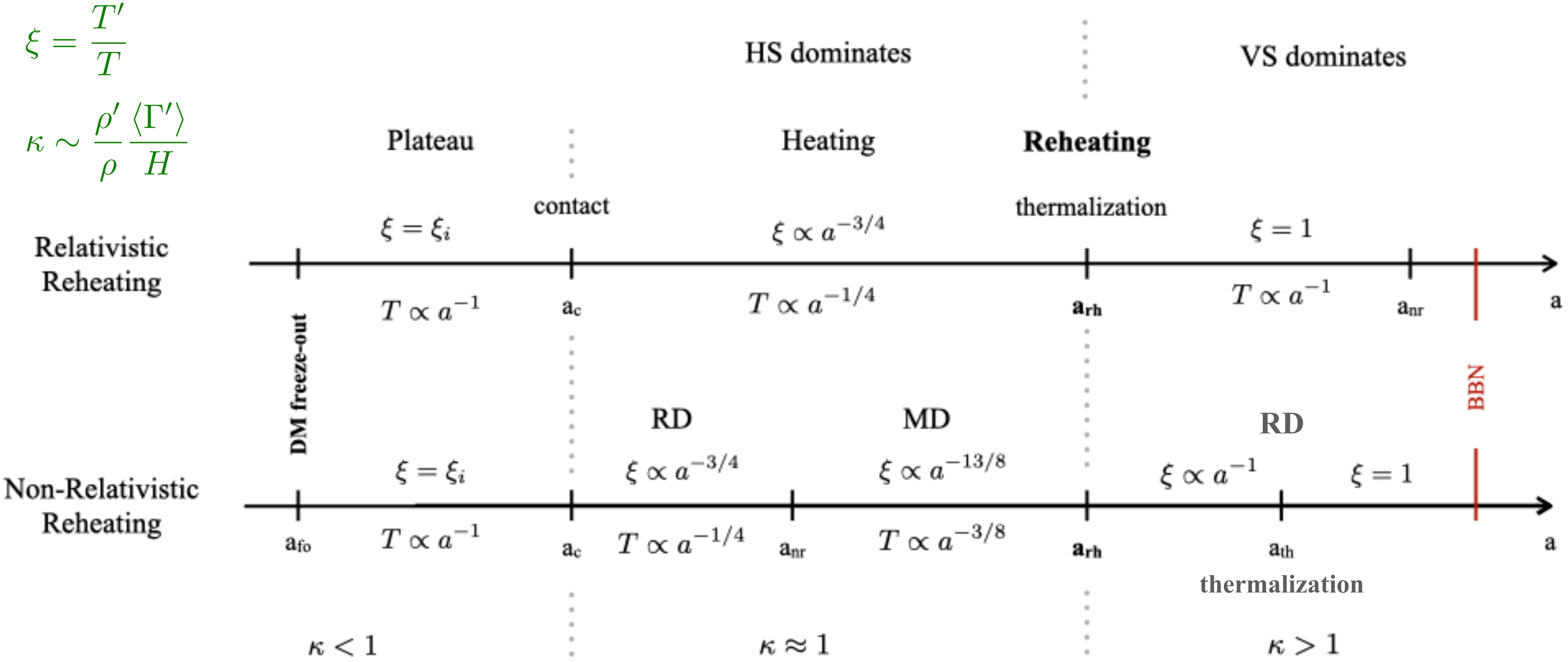
$\rho/\rho' \sim \langle\Gamma'\rangle/H$ throughout heating

Coy, Kimus, MHGT ‘24

relativistic vs non-relativistic reheating

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

$$\kappa \sim \frac{\rho'}{\rho}\frac{\langle\Gamma'\rangle}{H}$$



- after asymmetric reheating, initial phase with T’/T ~ constant

- DM initial abundance from secluded FO

- early phase of heating from relativistic and/or non-relativistic decay of dark photons

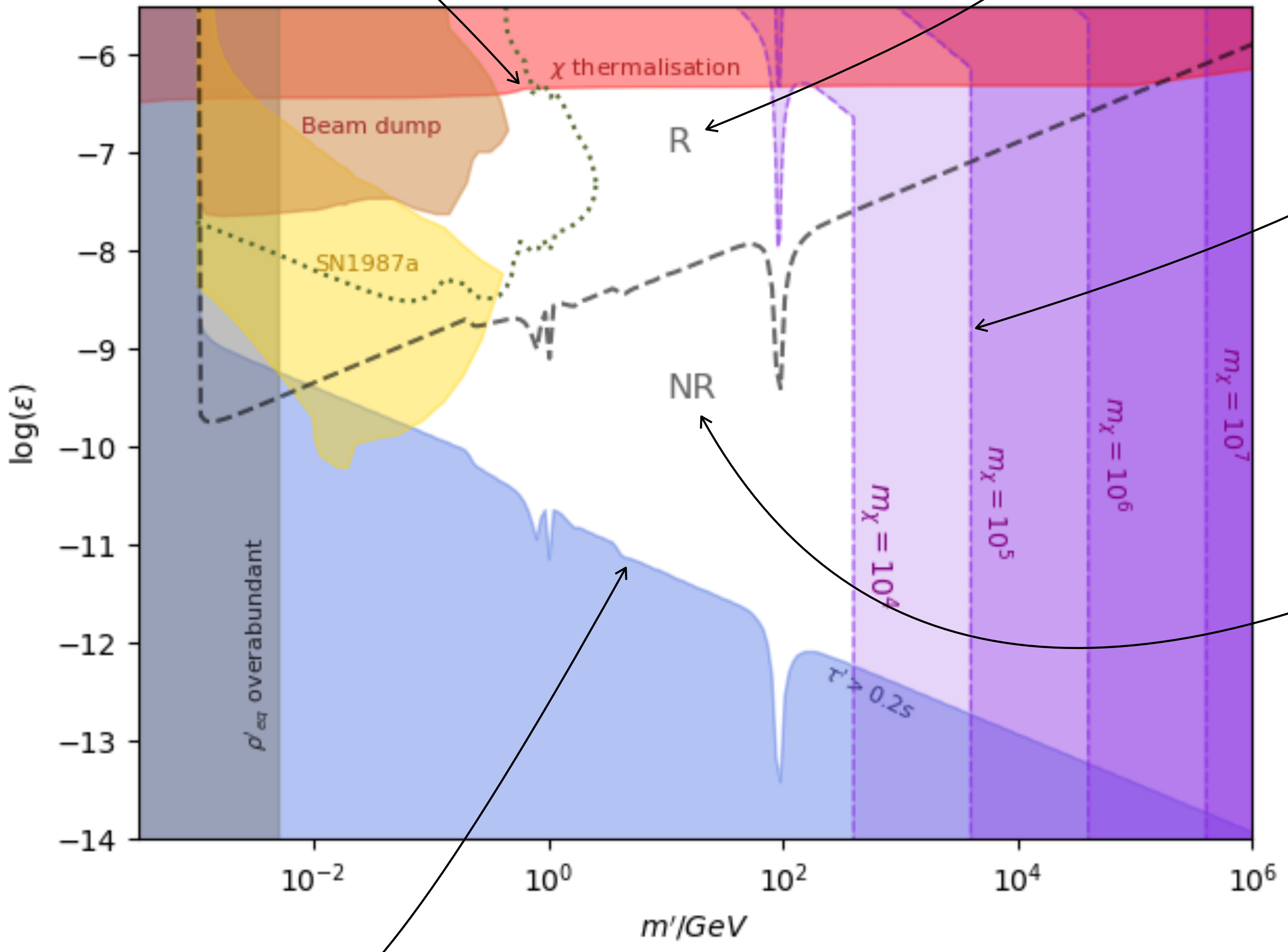
- VS reheated, dark photon thermalised or simply gone

- large entropy production possible if MD phase

$$\Omega_{\rm dm} = \Omega_{\rm dm}\big|_{\rm fo}\frac{S_{t,i}}{S_{t,f}}$$

Coy, Kimus, MHGT ‘24

constraints on dark photons



DS & HS do not thermalise from the onset

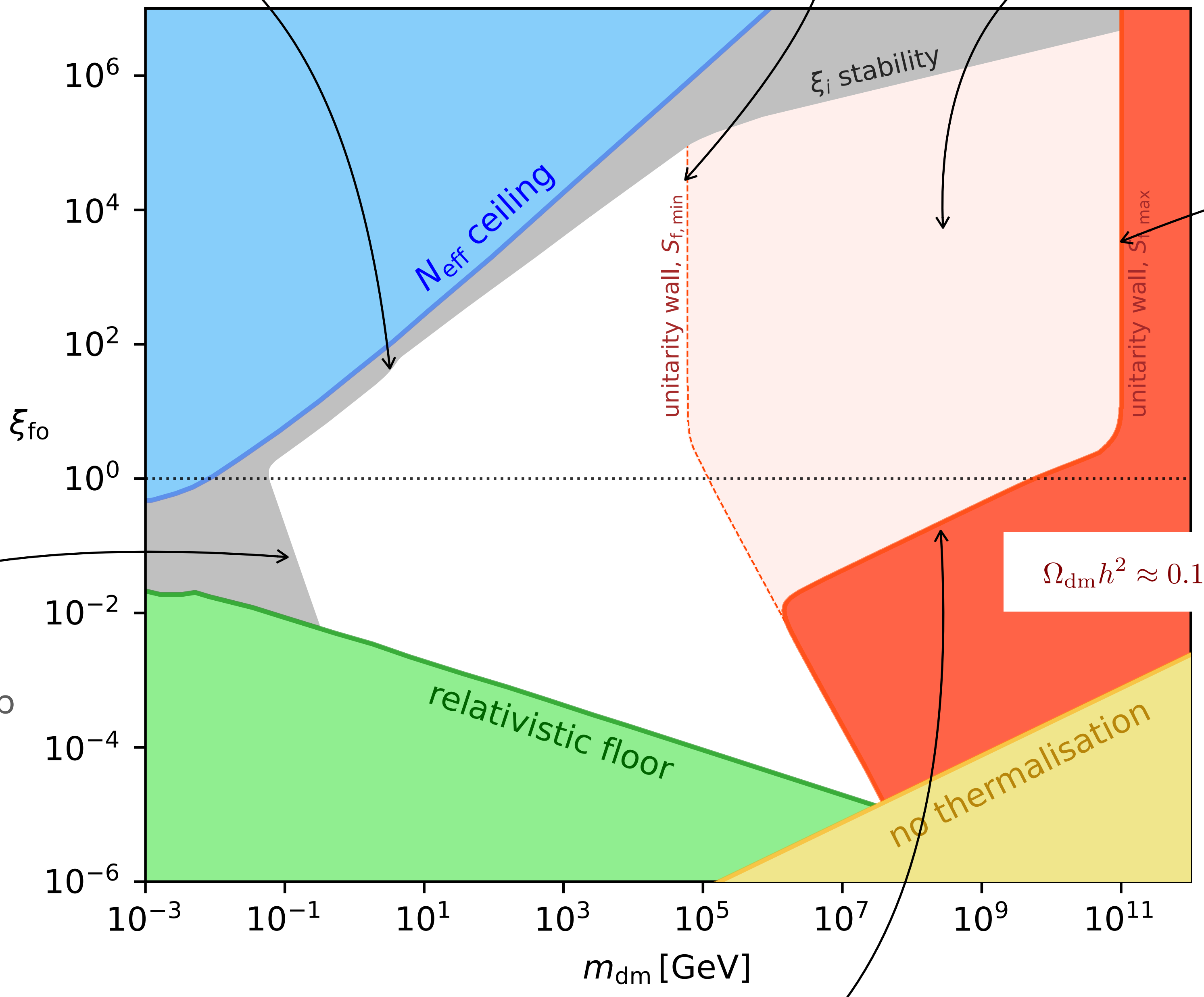
relativistic reheating

$m_{\gamma'} \lesssim T'_{\rm fo}$

non-relativistic reheating

dark photon decays before BBN

implications for domain of thermal DM



ask that DS does not heat up
the VS from the onset

relativistic reheating

non-relativistic reheating

entropy production
dilutes DM abundance

larger DM mass !

max for unitarity annihilation
heavy companion
decays right before BBN

$$m_{\rm dm} \lesssim 10^{11}\,{\rm GeV} \;{}^*$$

$$\Omega_{\rm dm}h^2 \approx 0.12 \left(\frac{m_{\rm dm}}{100\,{\rm TeV}}\right)^2 \left(\frac{10\,{\rm MeV}}{m'}\right) \left(\frac{0.2\,{\rm s}}{\tau'}\right)^{1/2}$$

ask that VS does not heat up
the DS from the onset
(irrelevant if DS completely
secluded)

entropy production from companion
that comes to dominate

* Bernal, Konar & Show, 2023; Coy, Kimus, MHGT ’24, see also Berlin & Hooper, 2016

examples : dark qed & kinetic mixing

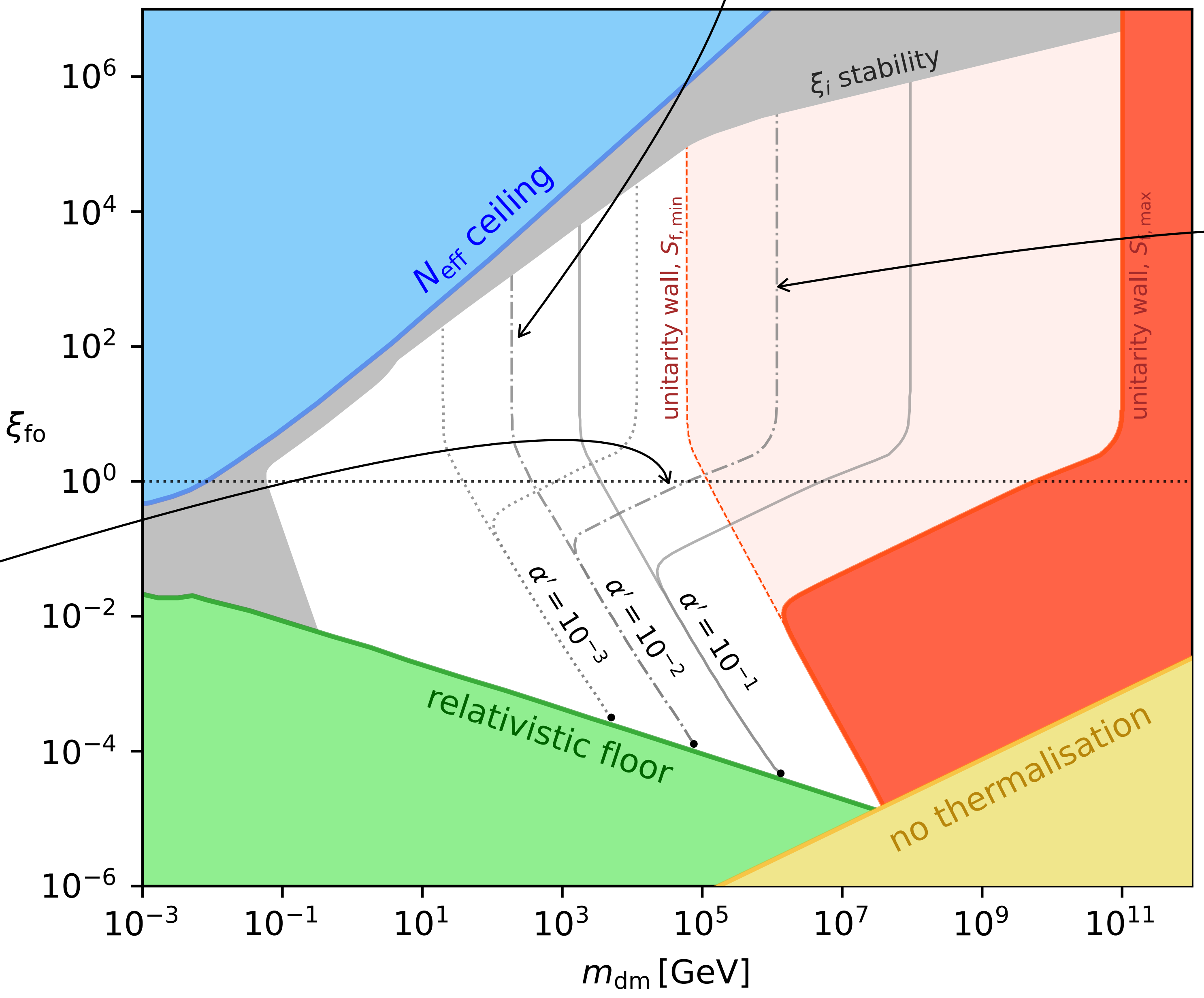
focus on $\alpha' = 10^{-2}$

relativistic reheating

non-relativistic reheating

entropy production
dilutes DM abundance

larger DM mass !



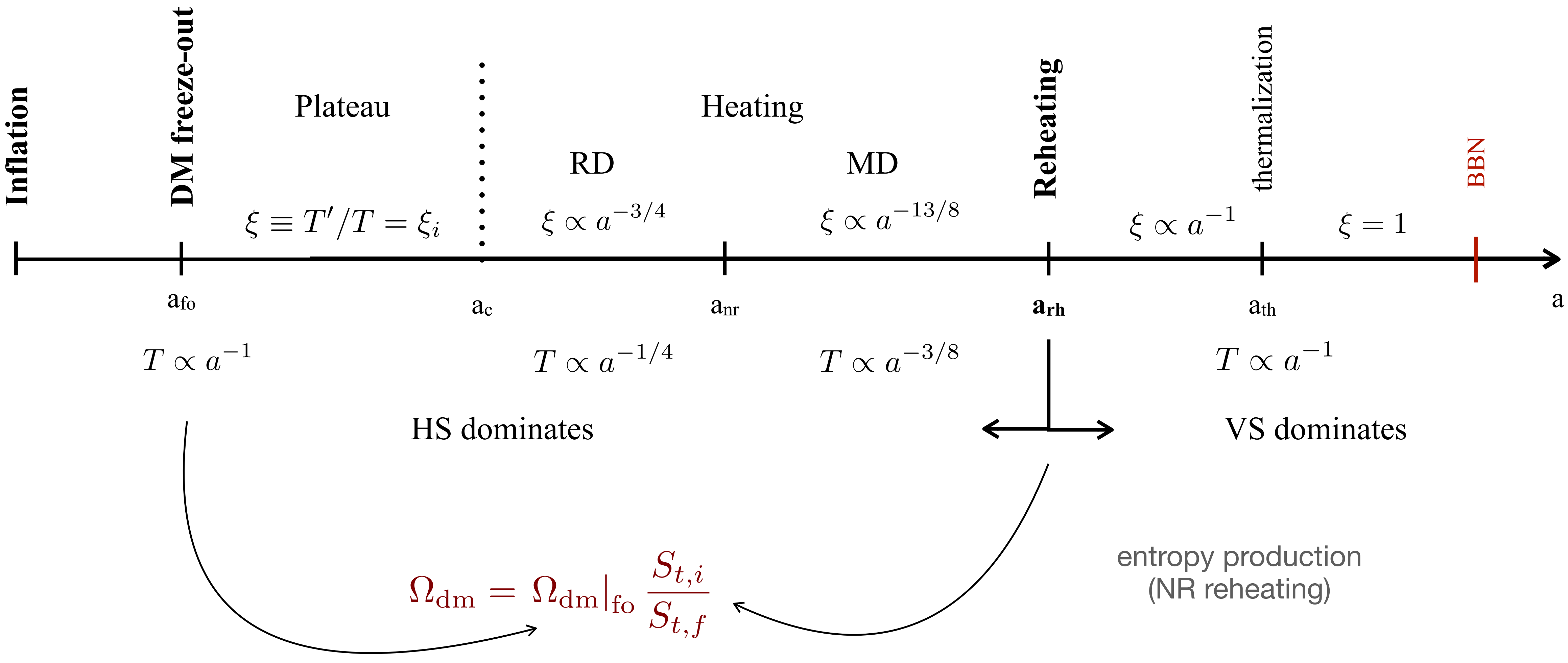
max for heavy companion
decays right before BBN

entropy production
from companion
that comes to dominate
the expansion

Coy, Kimus, MHGT ‘24

other constraints ? eg baryon asymmetry

A history of hot dark sector
(eg non-relativistic reheating)



$$\Omega_{\rm dm} = \Omega_{\rm dm}|_{\rm fo} \frac{S_{t,i}}{S_{t,f}}$$

entropy production
(NR reheating)

baryo/lepto **before** relativistic (non-relativistic) reheating

baryo/lepto **after** (or from) reheating

$$\eta_b \sim \delta_{CP} \xi_i^{-3} \left(\frac{S_{t,i}}{S_{t,f}} \right)$$

vs

$$\eta_b \sim \delta_{CP}$$

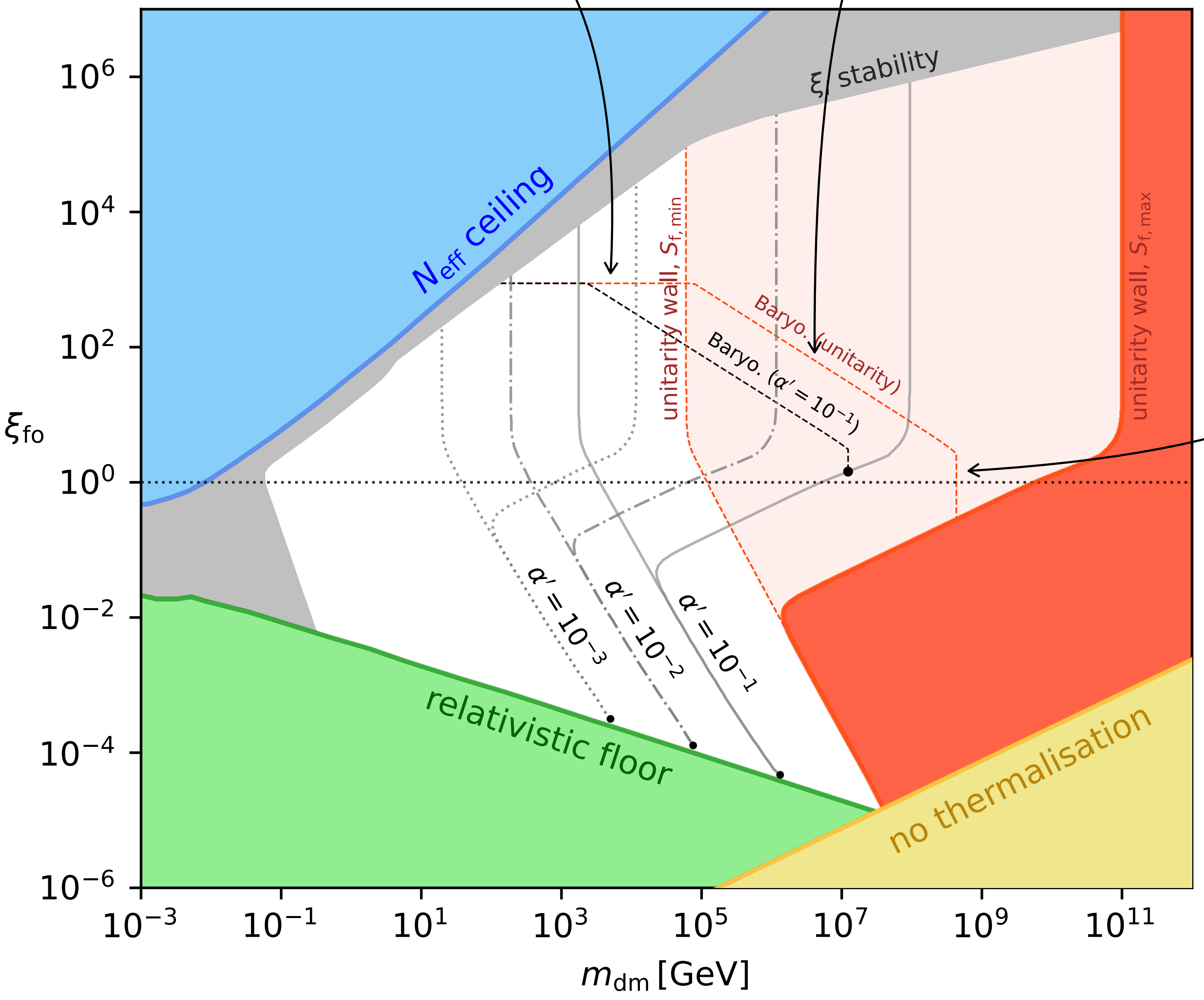
other constraints ? eg baryon asymmetry

$\eta_b \sim \xi^{-3} \sim 10^{-10}$

initial asymmetry O(1)

$\eta_b \sim \xi^{-3} S_f/S_i \sim 10^{-10}$

$\eta_b \sim S_f/S_i < 10^{-10}$



baryo/lepto **before** relativistic (non-relativistic) reheating

$$\eta_b \sim \delta_{CP} \xi_i^{-3} \left(\frac{S_{t,i}}{S_{t,f}} \right)$$

vs

baryo/lepto **after** (or from) reheating

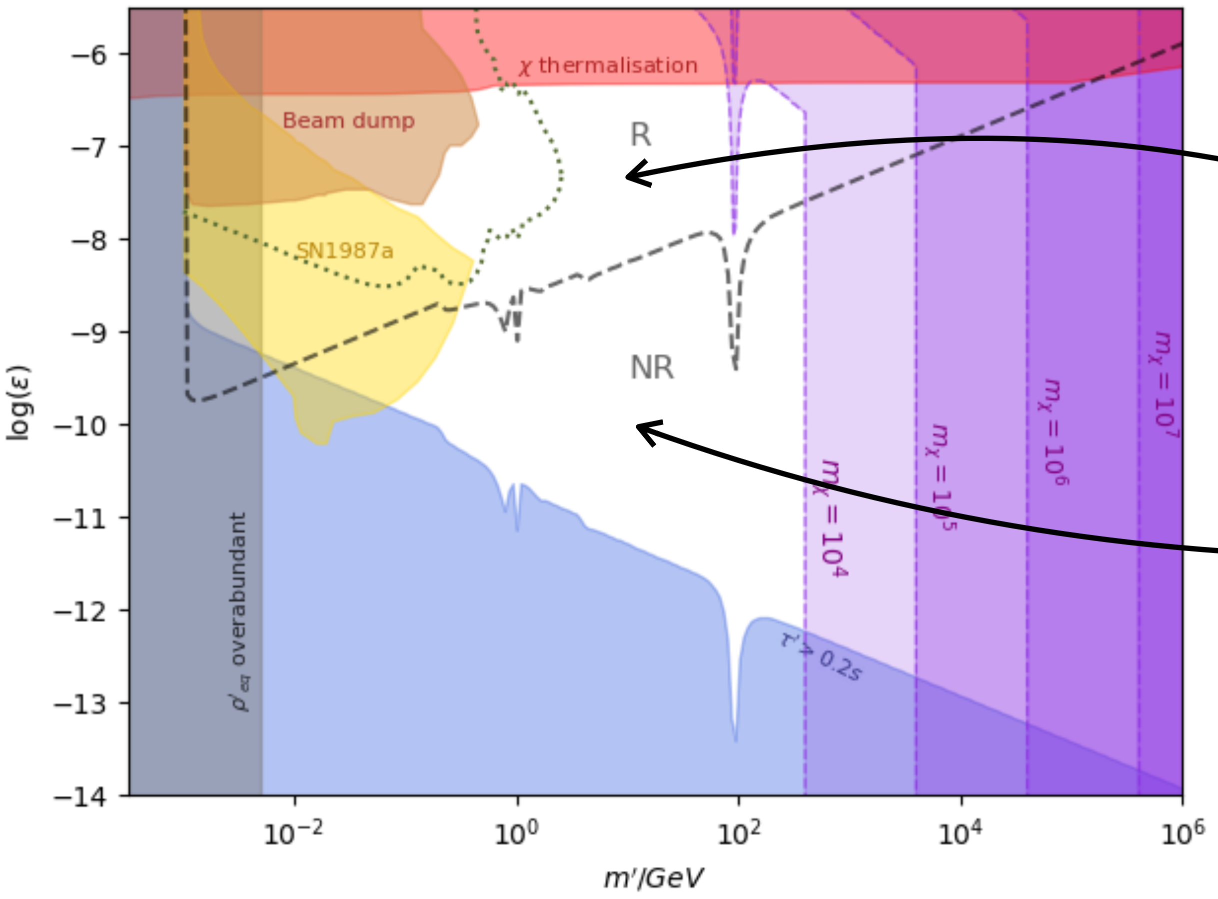
$$\eta_b \sim \delta_{CP}$$

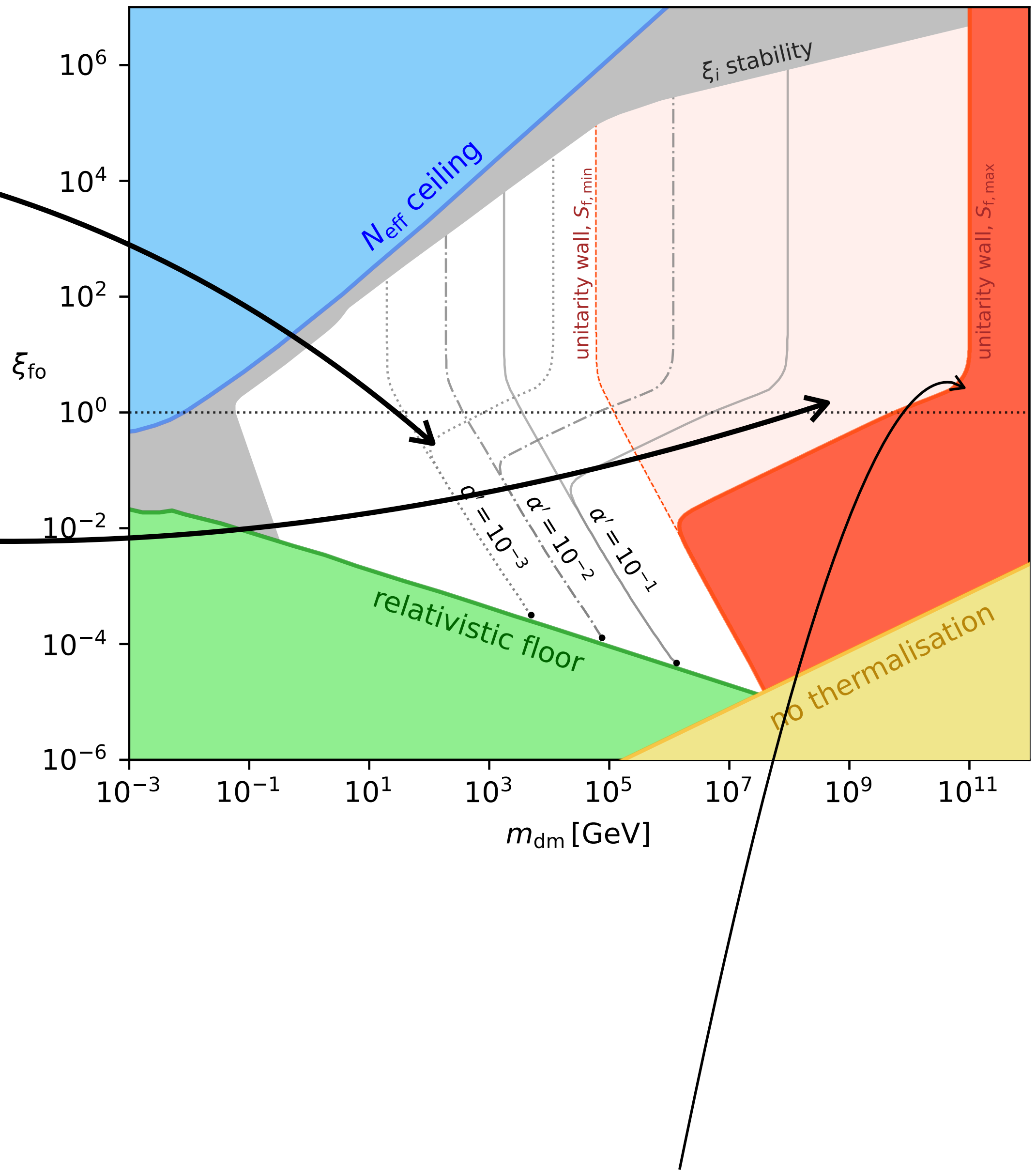
Coy, Kimus, MHGT ‘24

conclusions

dark photons

dark matter





hot dark sector = non-standard cosmological evolution

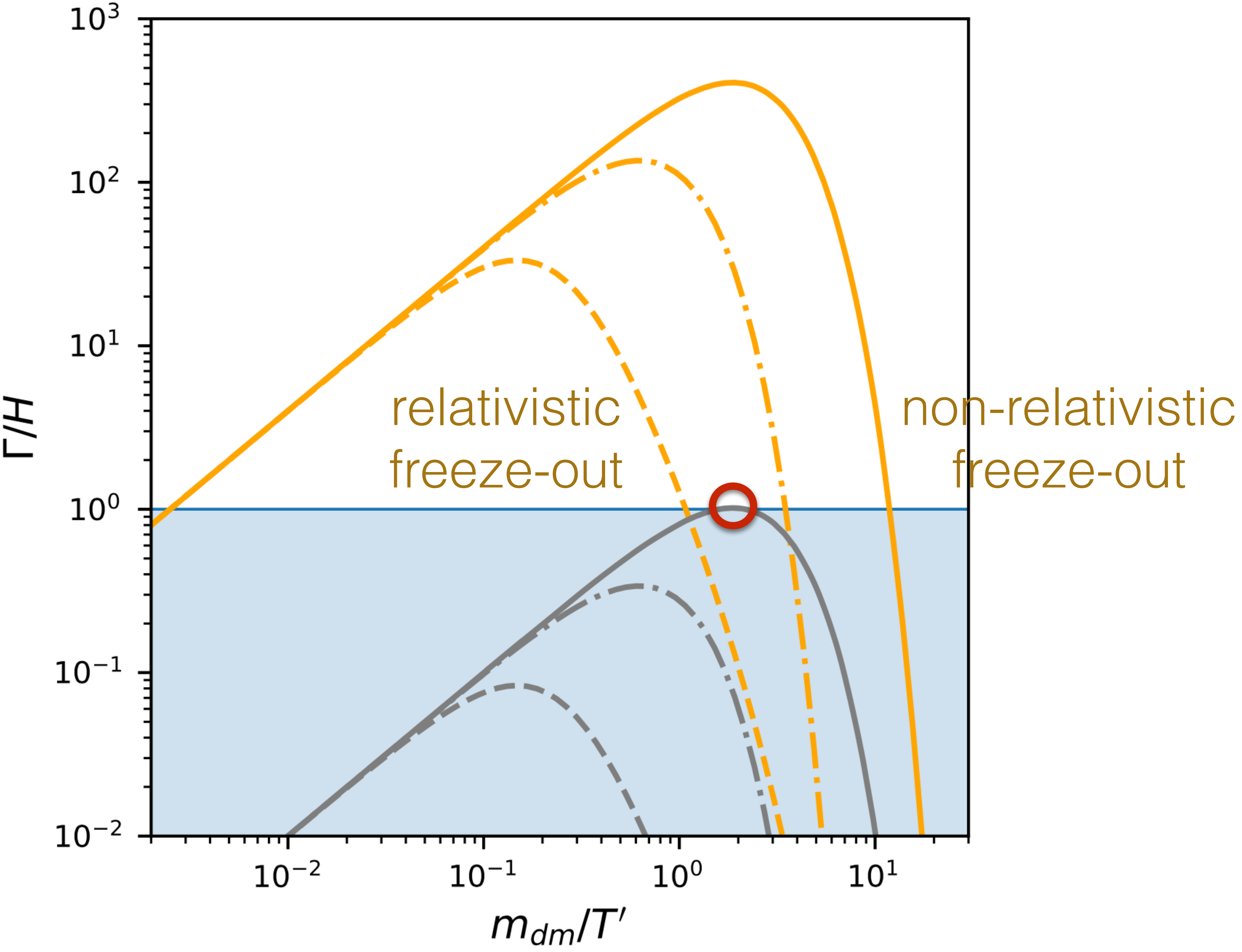
- baryogenesis/leptogenesis ?
- phase transitions (VS or DS) ?
- simple framework (more complex DS)?
- domain of dark qed vs specific cosmological constraints (eg self-interacting dm)

dark matter mass up to 10^{11} GeV

Coy, Kimus, MT 2023
Bernal, Konar, Show 2023

BACKUP SLIDES

NO THERMALIZATION



example : secluded cannibalism

$$\mathcal{L}_{\mathrm{HS}} = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}\mu^2 S^2 - \frac{\lambda}{4!}S^4$$

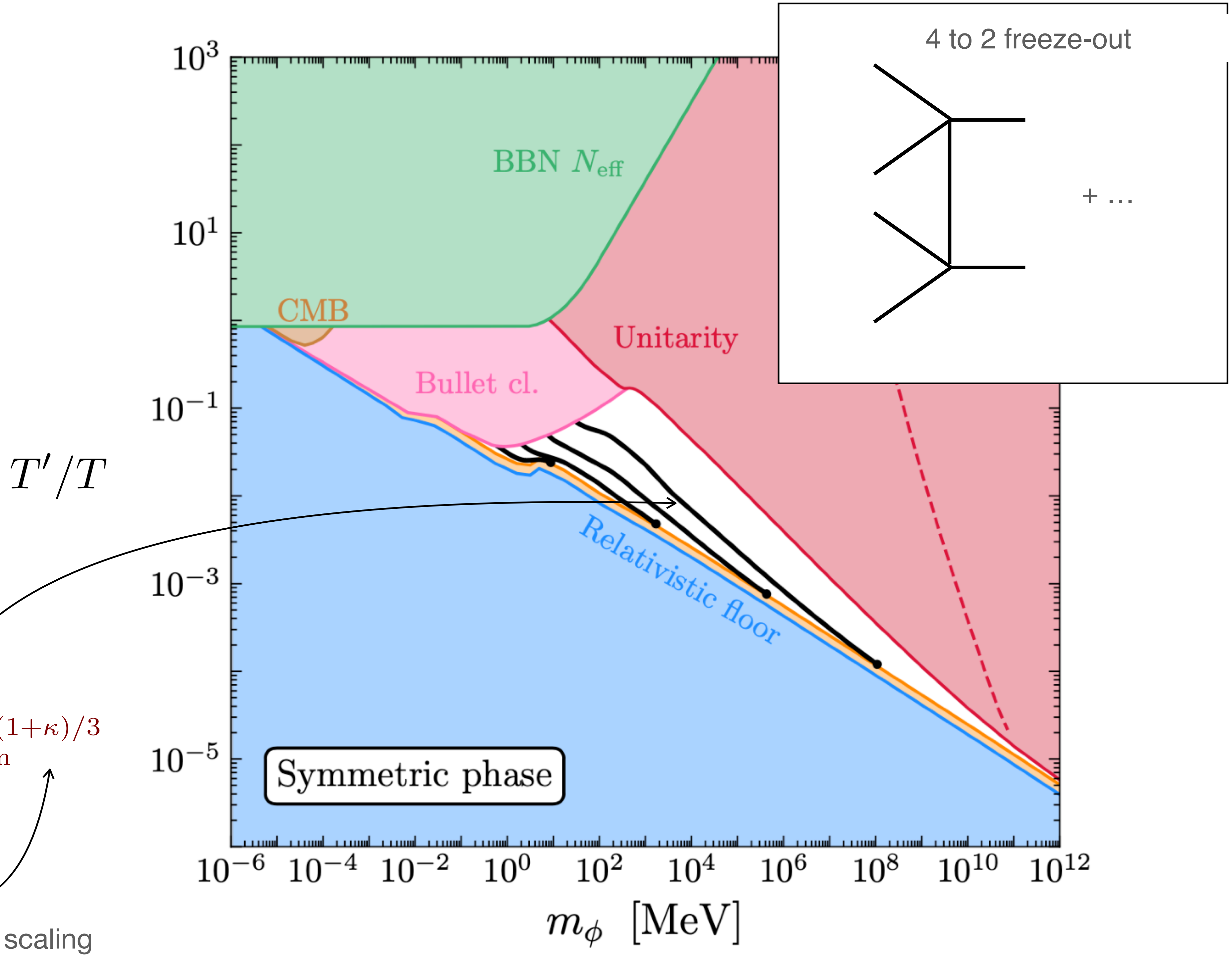
a real singlet scalar (and only that)

goes through a phase
of cannibalism cf Carlson & Hall 1992

2 parameters + T'/T

Bernal & Chu, 2016; Arcadi et al 2019; Ghosh et al 2022; Hufnagel & MHGT 2022

example : secluded cannibalism



$$T'/T \propto m_{\rm dm}^{-(1+\kappa)/3}$$

« anomalous » scaling

$$\kappa \approx \frac{5}{3k-5}\frac{T'_{\rm fo}}{m_{\rm dm}}$$

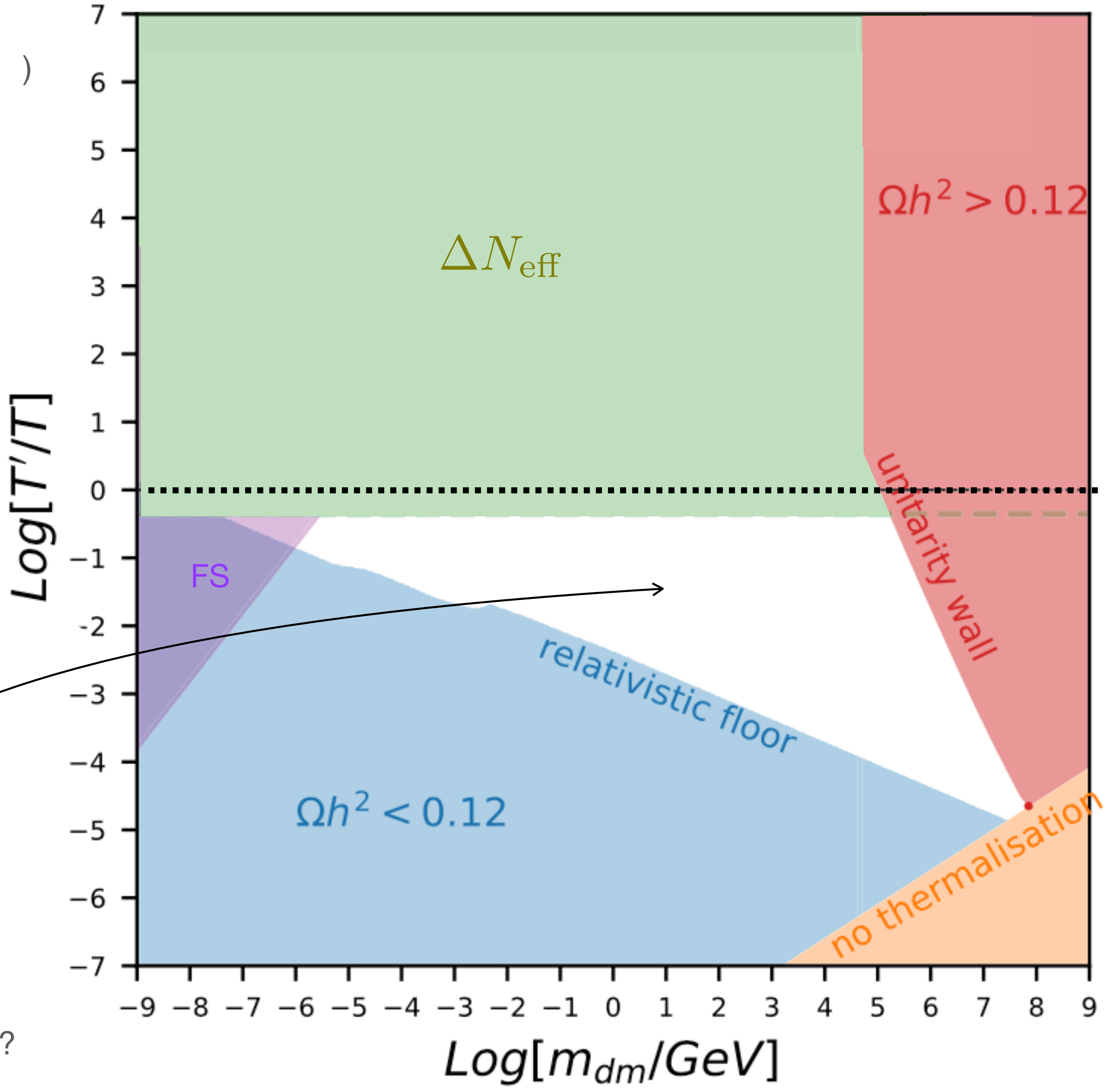
with $k = 4\ (k = 3)$ for symmetric (broken) phase

Hufnagel, MT 2022

the trouble with companions

DM comes with a lot of companion particles (eg γ')

their entropy must go away



a priori, this is (at best)
what is allowed
if the companions are still
around by BBN

what if they are both stable ?

Coy, Hambye, MHGT, Vanderheyden ’21

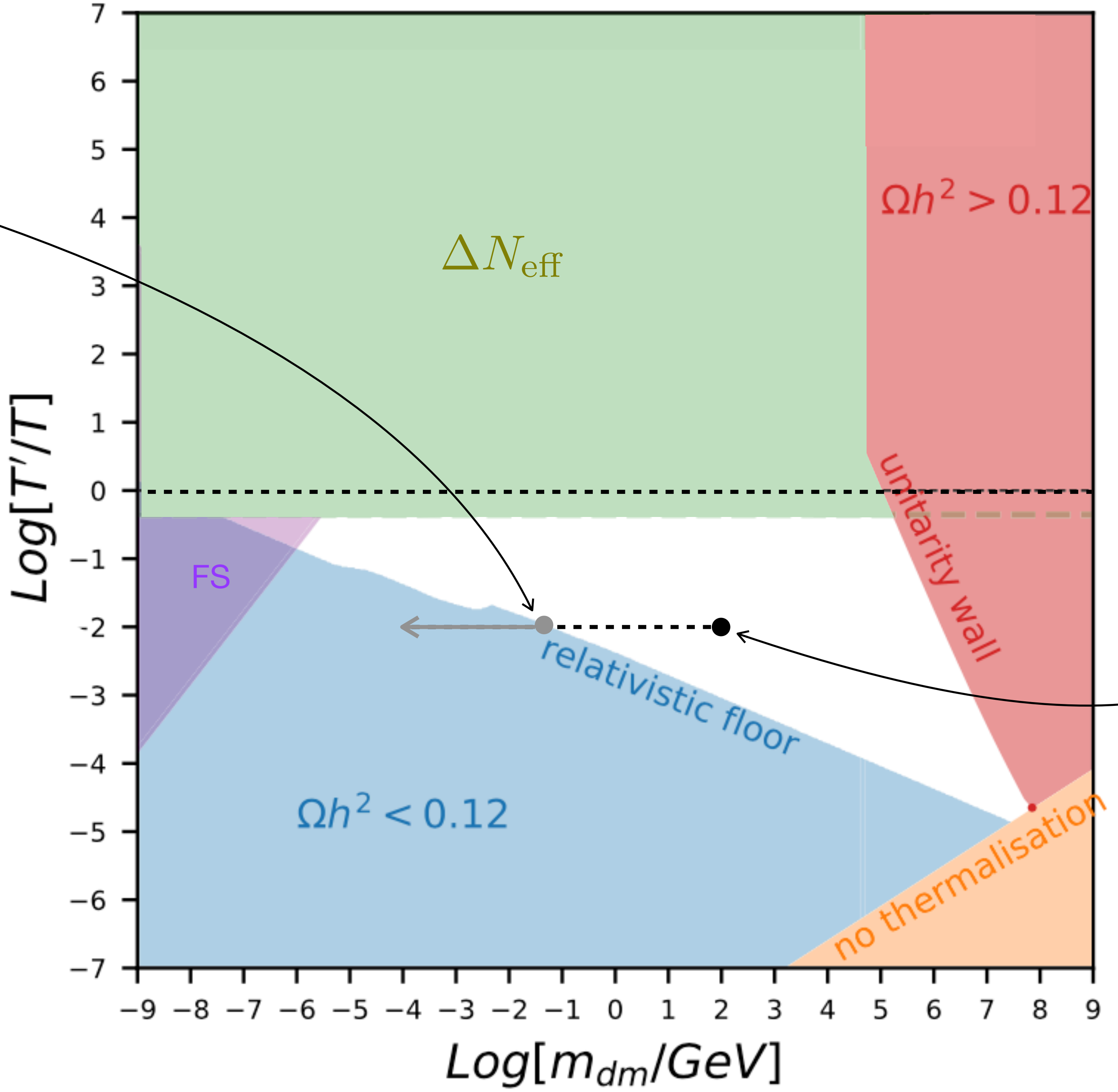
DM & companion stable ?

$\Omega_{\rm comp} \lesssim \Omega_{\rm dm}$

provided

$m_{\rm comp} \lesssim 100\,{\rm MeV}$

(relativistic freeze-out)



example :

$m_{\rm dm} = 100\,{\rm GeV}$

$T'/T|_{\rm fo} = 10^{-2}$

Coy, Hambye, MHGT, Vanderheyden ’21

brief history of a hot dark sector

assume

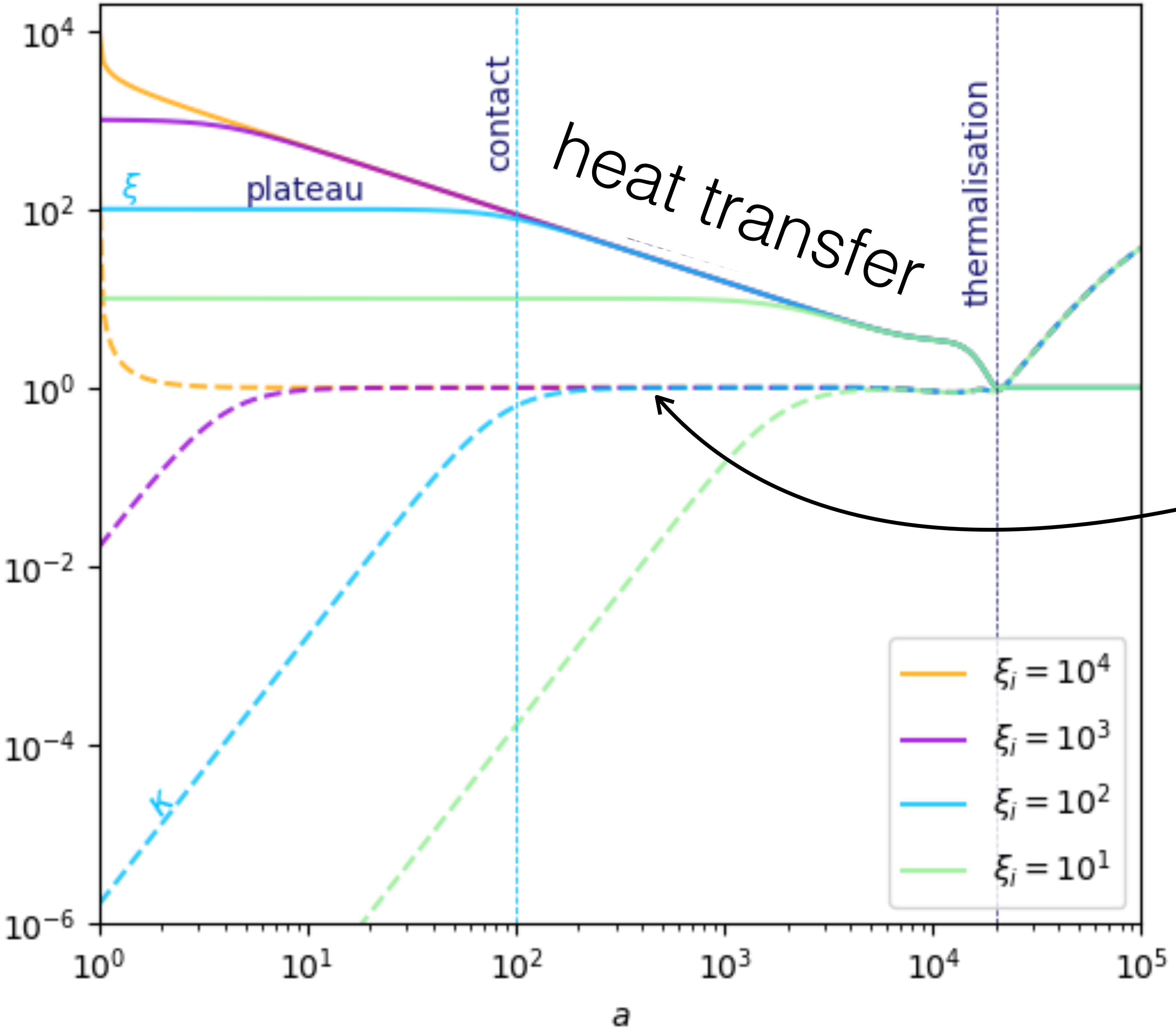
- HS with $T' \gg T$
- DM abundance from secluded freeze-out
- history starts right after DM freeze-out

we need to track

- dark photons (DP) abundance
- temperature ratio T'/T
- entropy creation

Coy, Kimus, MHGT ‘23

HEAT TRANSFER PARAMETER



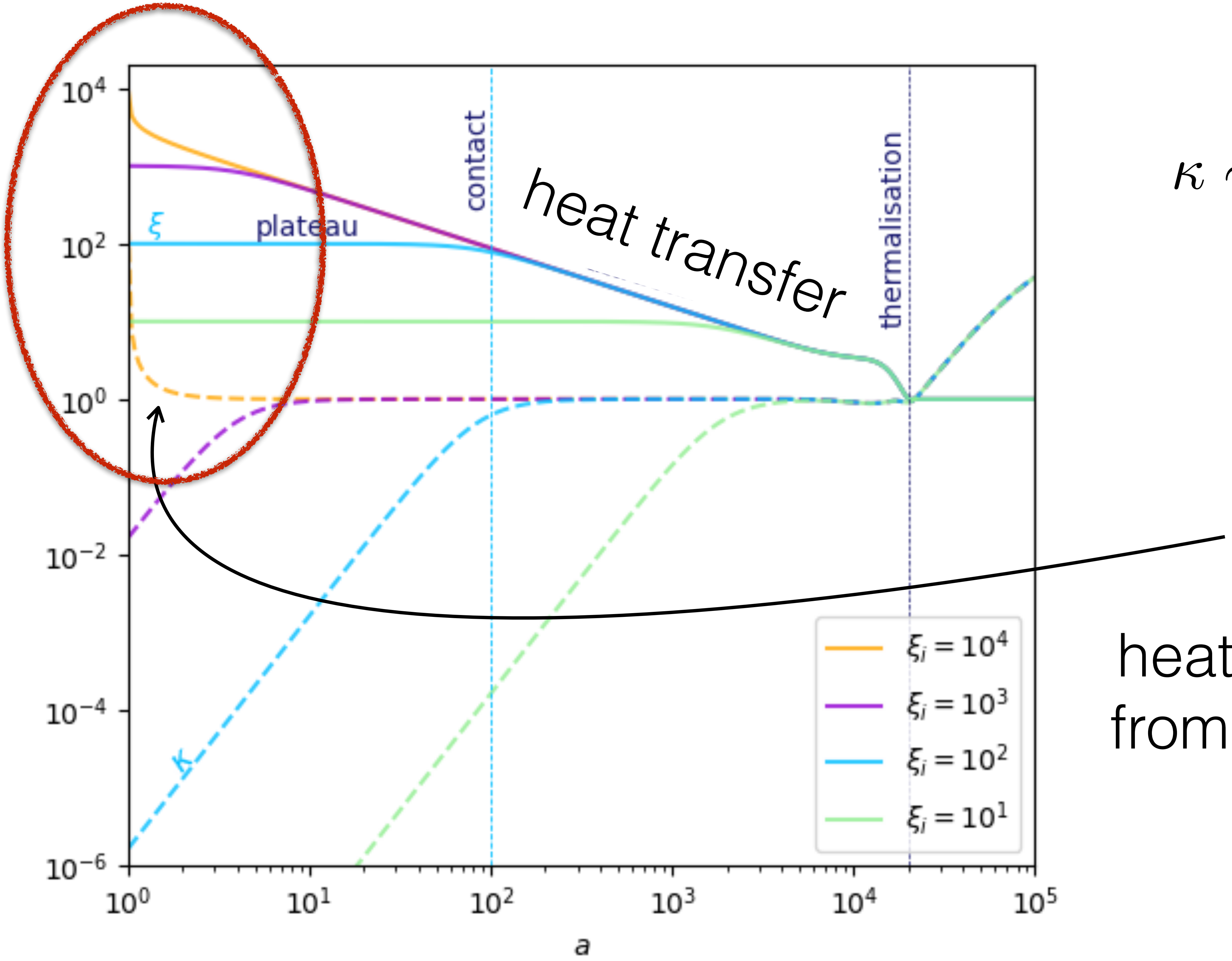
heat transfer

$$\kappa \sim \frac{\rho'}{\rho} \frac{\langle \Gamma' \rangle}{H}$$

$\kappa \sim 1$

during heat transfer

HEAT TRANSFER PARAMETER



$$\kappa \sim \frac{\rho'}{\rho} \frac{\langle \Gamma' \rangle}{H}$$

If

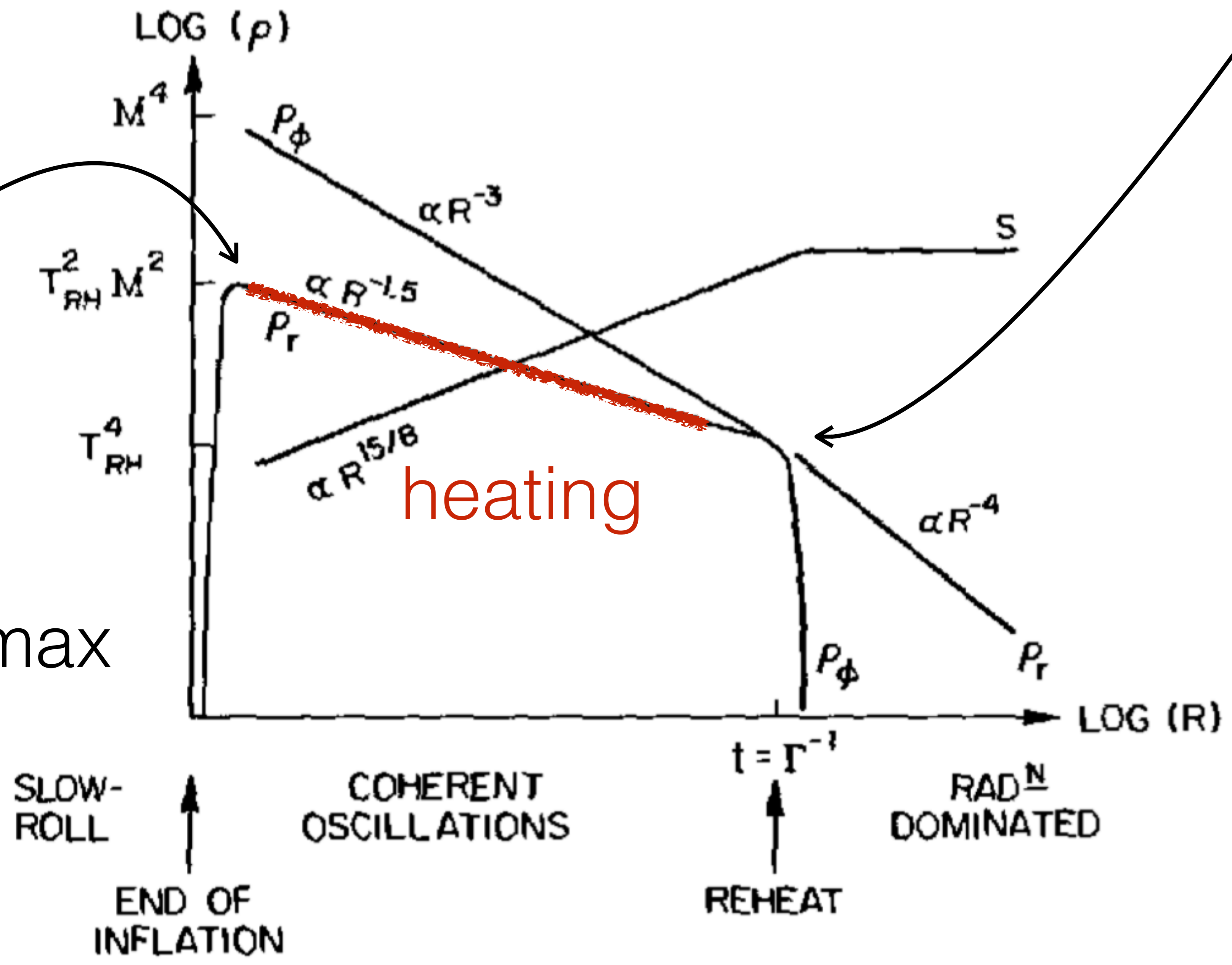
$$\kappa \gtrsim 1$$

heat tansferred from the outset!

~ REHEATING AFTER INFLATION

280 Inflation

reheating



heating

$\rho_I \gg \rho_{\rm SM}$

heating to Tmax

Fig. 8.3: Summary of the evolution of ρ_ϕ, ρ_R, and S during reheating.

From Kolb & Turner

entropy : relativistic reheating

Non-reversible process -> entropy production

ENERGY TRANSFER $\quad g' T_i'^4 a_i^4 \approx g T_f^4 a_f^4 \qquad g \gg g'$

FINAL ENTROPY $\quad S_f' \approx g T_f^3 a_f^3 = g \left(\frac{g'}{g}\right)^{3/4} a_i^3 T_i'^3$

$$= \left(\frac{g}{g'}\right)\left(\frac{g'}{g}\right)^{3/4} g' T_i'^3 a_i^3$$

$$\Rightarrow \boxed{S_f' \approx \left(\frac{g}{g'}\right)^{1/4} S_i'} > S_i$$

e.g. $g \approx 10^2$, $g' \approx 3 \Rightarrow \frac{S_f}{S_i} \approx 2$

entropy : non-relativistic reheating

Non-reversible process -> entropy production

$$\frac{dS}{dt} = \frac{1}{T}\frac{dQ}{dt} = \frac{\Gamma'}{T}\rho' a^3 \quad \Rightarrow \quad S^{4/3} = S_i^{4/3} + \# \, \Gamma' \rho'_i a_i^4 \int_{t_i}^{t} dt' \, g_*^{1/3} \frac{a}{a_i} e^{-\Gamma'(t'-t_i)}$$

Scherrer, Turner

ENTROPY PRODUCED BY γ' DECAY

MOSTLY SM

THIS FACTOR > 1

$$\frac{S_f}{S_i} \simeq \left(\frac{g}{g'}\right)^{1/4} \left(\frac{\tau'}{t_{NR}}\right)^{1/2}$$

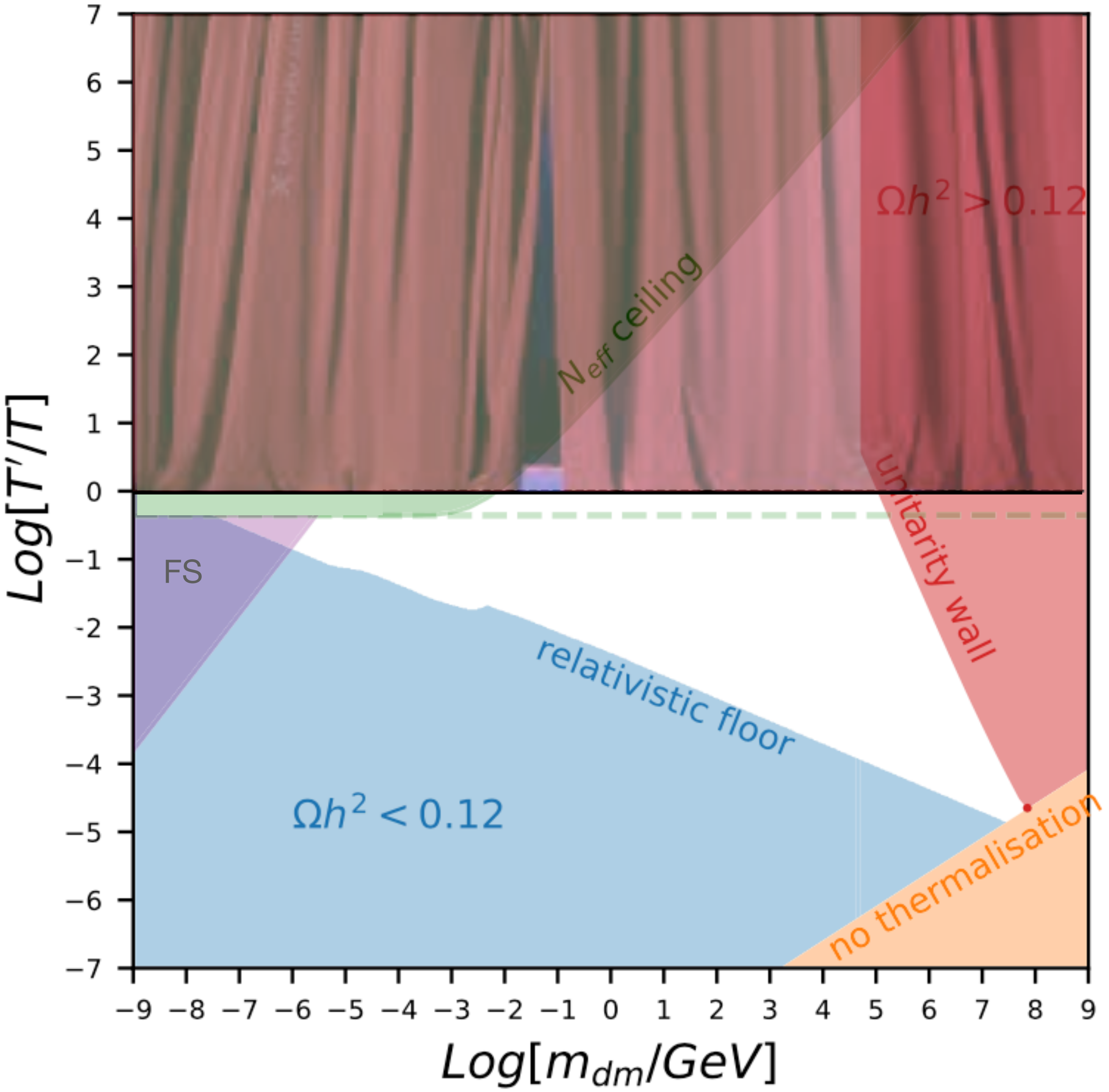
MOSTLY γ'

↳ TIME AT WHICH $T' \approx m_{\gamma'}$

the later the decay, the larger the entropy produced

Coy, Kimus, MT

domain of thermal DM



Coy, Hambye, MHGT, Vanderheyden ’21

freeze-in and then decay of dark photons