

MAKING DARK MATTER COOL AGAIN: DYNAMICS OF SELF-INTERACTING DARK SECTORS

Andrzej Hryczuk



based on:

- { **E. Cervantes, AH [2407.12104](#)**
- { **N. Bernal, E. Cervantes, K. Deka, AH [2506.09155](#)**
- { work in progress **E. Cervantes, AH, S. Lederer**

MOTIVATION & OBJECTIVES

New mechanism for **cooling DM**
& significantly weakening the
Lyman- α bound

Freeze-in of **cannibal**
dark sectors

Cautionary tale about
adopted **cosmology**

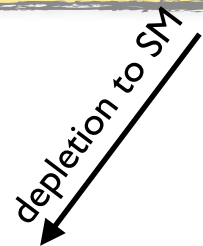
Does DM interact (somewhat)
with any particle of the SM?

Yes

At high temperature
DM thermalises, has
very high abundance



An **efficient**
depletion is needed
(freeze-out)

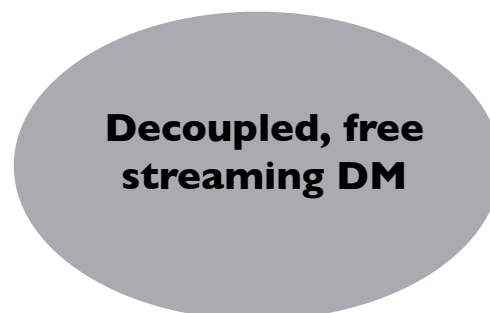
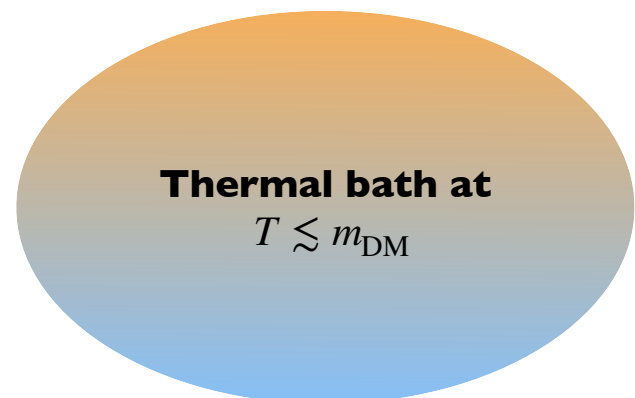
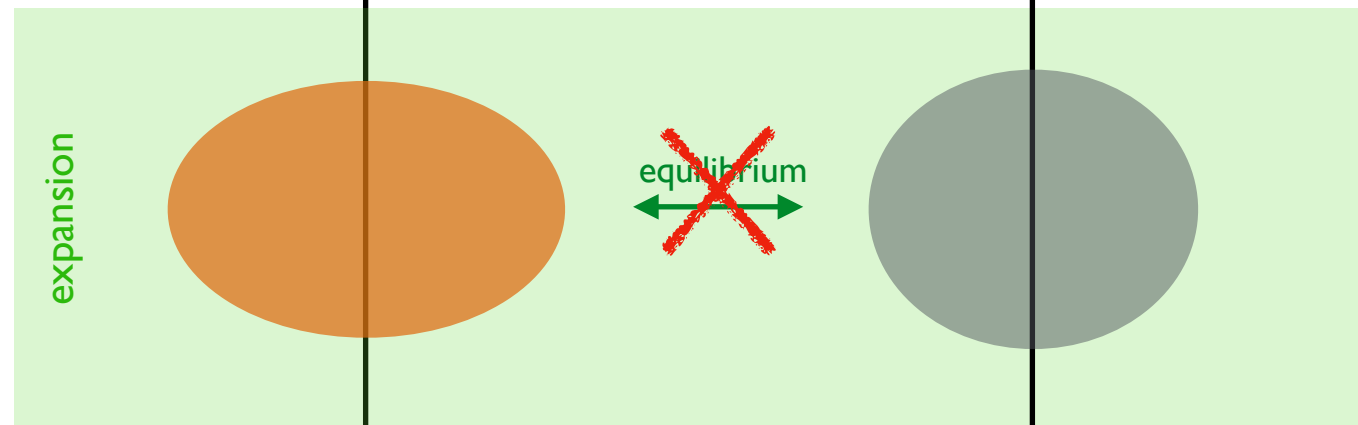
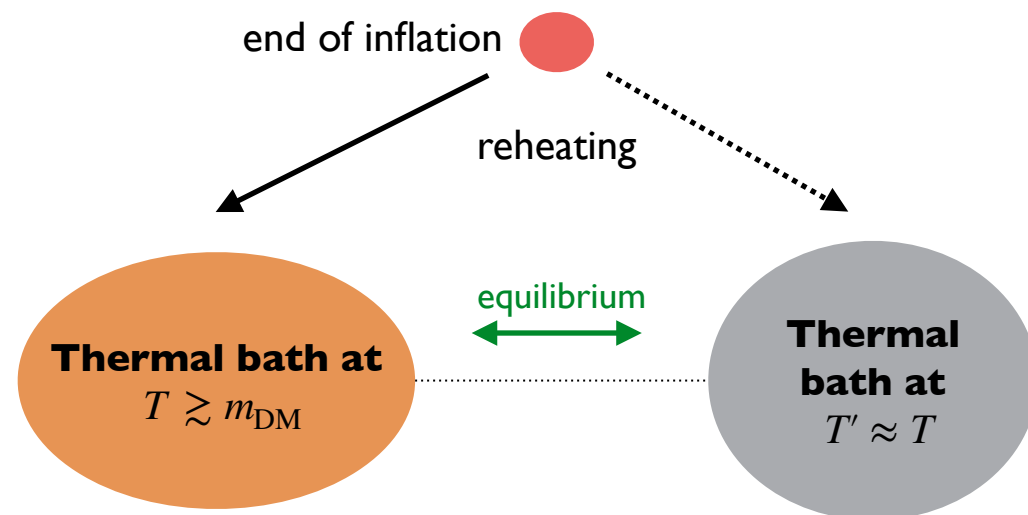


„WIMP”

FREEZE-OUT

Visible Sector

Dark Sector



I. Natural

Comes out **automatically** from the expansion of the Universe

Naturally leads to **cold DM**

II. Predictive

No dependence on **initial conditions**

Fixes **coupling(s)** $\Rightarrow$ signal in DD, ID & LHC

III. It is not optional

Overabundance constraint

To avoid it one needs **quite significant deviations** from standard cosmology

time

Does DM interact (somewhat)
with any particle of the SM?

Yes

At high temperature
DM thermalises, has
very high abundance



An **efficient
depletion** is needed
(freeze-out)

depletion to SM

„WIMP”

depletion
to other states
to kinetic energy

Secluded
dark sector

(e.g. cannibal dark sector)

CANNIBAL DM

Explains depletion of DM solely
through **self number changing**
reactions!

SELF-INTERACTING DARK MATTER

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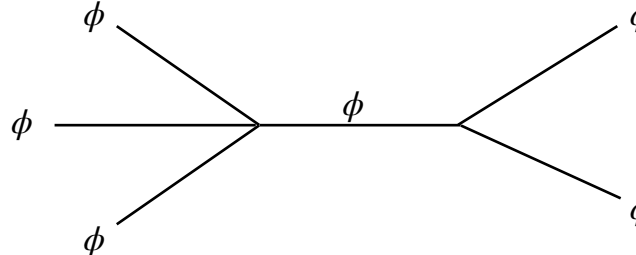
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Simplest example, scalar ϕ with interactions (no coupling to SM!):

$$\frac{g}{3!}\phi^3 + \frac{\lambda}{4!}\phi^4 \Rightarrow$$


To obtain correct relic abundance: $m_\phi \sim \mathcal{O}(10 - 100 \text{ MeV})$

..., Hochberg et al. '14; ...

cannibalisation: mass $\rightarrow$ kinetic energy

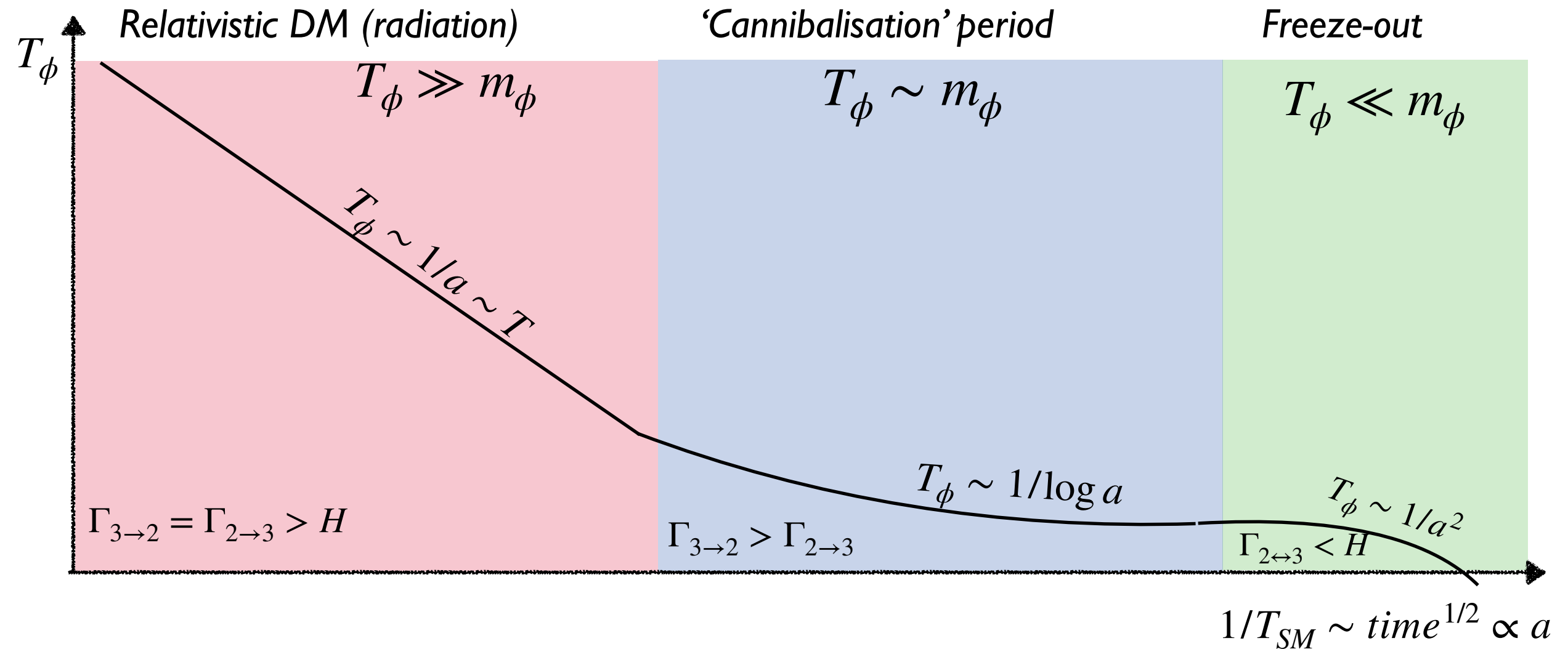
expansion: kinetic energy redshifts $\rightarrow$ depletion of E of the dark sector

Problem: structure formation...

de Laix et al. '95

CANNIBAL FREEZE-OUT

Self-heating of DM makes it warmer, **erasing the formation of structures!**
Tracking its temperature evolution is essential!



- Initially DM is *relativistic* ($T_{DM} \gg m_{DM}$);
- During freeze-out the dark sector uses its rest mass as *fuel* to keep itself warm;
- The system decouples and behaves as a non-relativistic gas.

Does DM interact (somewhat)
with any particle of the SM?

Yes

No (or nearly no)

At high temperature
DM thermalises, has
very high abundance

Is initial population (e.g.
from reheating) small?

Yes

No

An **efficient
depletion** is needed
(freeze-out)

A **slow production**
is needed
(freeze-in)

„Initial condition”
dependence

„WIMP”

depletion to SM

to kinetic energy

depletion to other states

**Secluded
dark sector**
(e.g. cannibal dark sector)

WHAT IS FREEZE-IN?

Visible Sector

Dark Sector

end of
inflation

reheating

~empty

$$T \gg m_X$$

UV freeze-in

Thermal bath at
 $T \gtrsim m_\chi$

production
 X

Dark Sector:
 $\chi, \dots$

expansion

IR freeze-in

$$T \sim m_X$$

Thermal bath at
 $T \lesssim m_\chi$

Dark Sector:
 $\chi, \dots$

time

Freeze-in defined like this
is a (very) old idea:

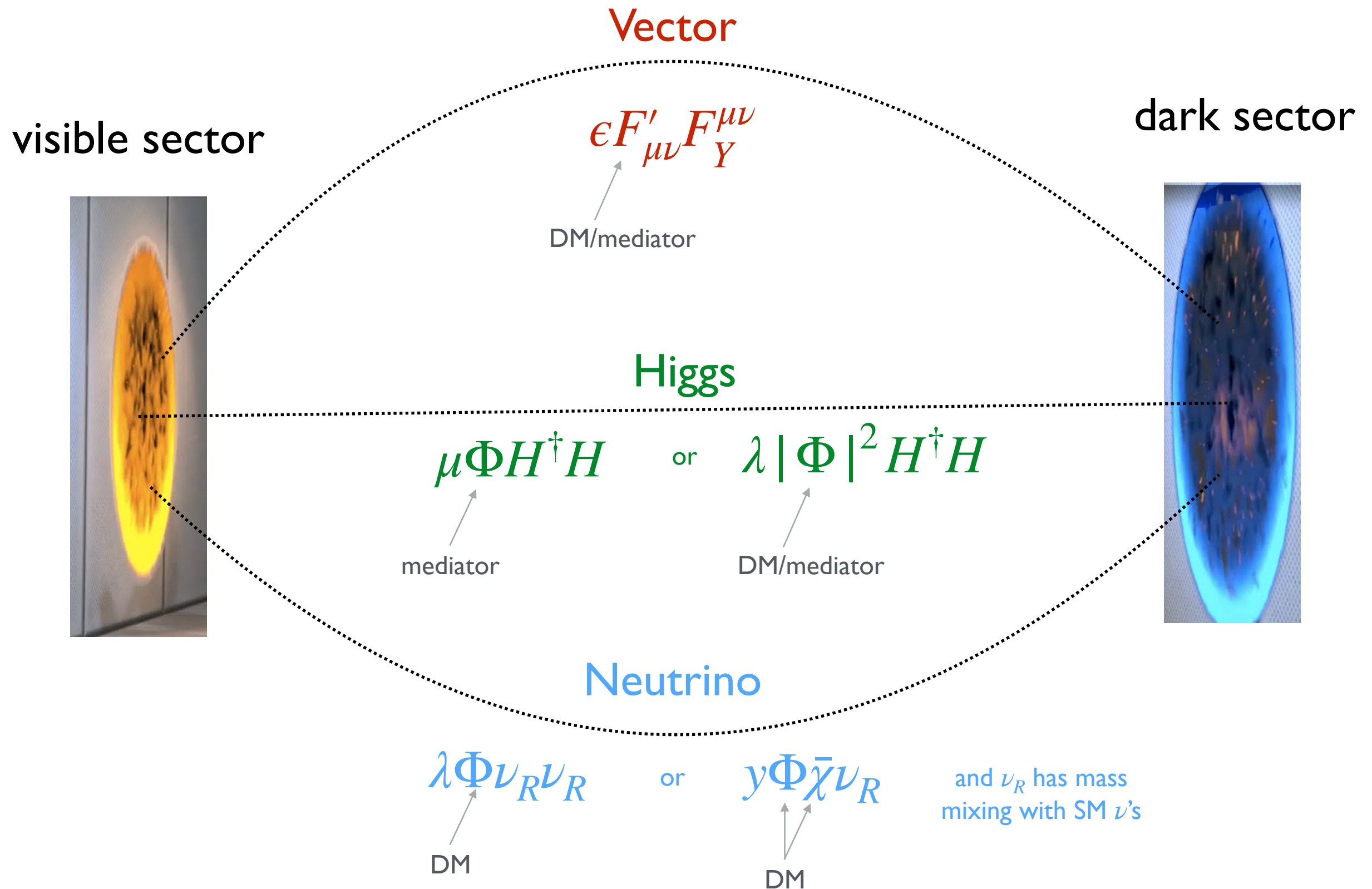
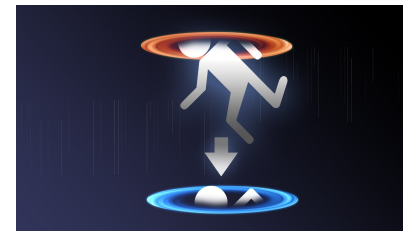
this is a standard production
mechanism for e.g. **sterile
neutrino, gravitino, axino,...**

however, old works
focused on what now
people call **UV freeze-in**

i.e. dominated by **non-renormalizable
operators** and dependent on T_{RH}

Freeze-in = the above mechanism
through renormalizable operators
(**IR freeze-in**)

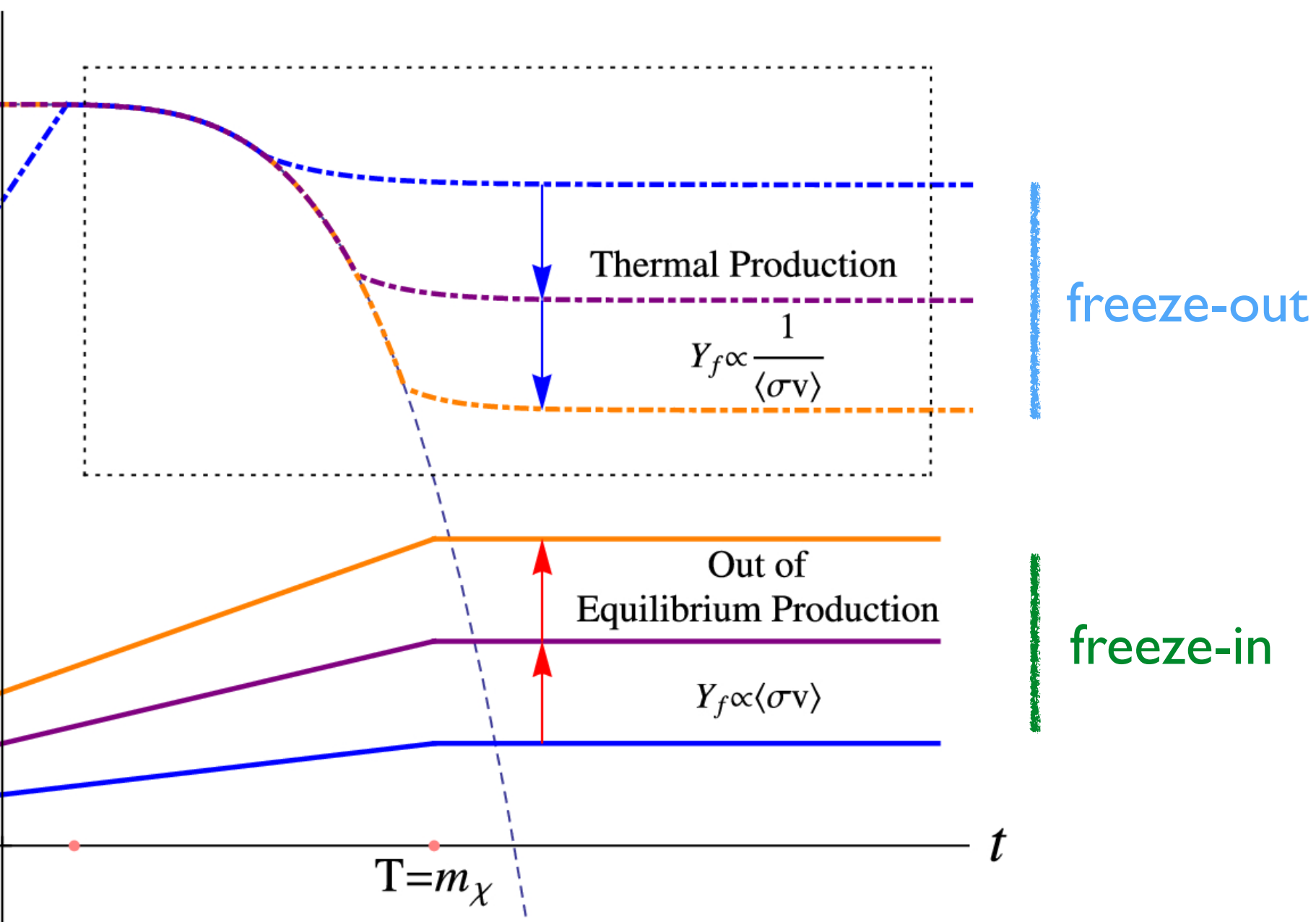
PORTALS



*portal mediator can also be non-reonoramlizable or composite (for more complex dark sector)

FREEZE-IN vs. FREEZE-OUT

Freeze-in is in a sense the 'opposite' of freeze-out



FREEZE-IN CALCULATION

Boltzmann equation for $f_\chi(p)$:

$$E (\partial_t - H \vec{p} \cdot \nabla_{\vec{p}}) f_\chi = \mathcal{C}[f_\chi]$$

with initial condition:

$$f_\chi(p, t = 0) = 0$$

The collision term:

$$C[f_\chi] \sim \int d\Pi_{ij \dots \rightarrow ab} (2\pi)^4 \delta^4(\dots) |M|^2 \left[f_i f_j \dots (1 \pm f_\chi) (1 \pm f_a) (1 \pm f_b) \dots - f_\chi f_a f_b \dots (1 \pm f_i) (1 \pm f_j) \dots \right]$$

„gain” term

(the simple one, describes production)

„loss” term

(the difficult one, usually neglected in freeze-in!)

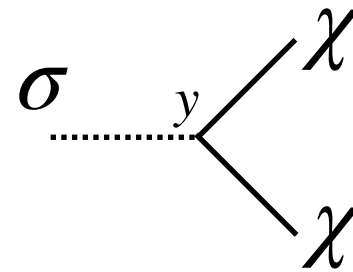
The collision term can also contain:

decays, annihilations, cannibalizations, ...

Note: to first approximation freeze-in production is much easier to determine than freeze-out!

FREEZE-IN CALCULATION

Example: freeze-in from decay of σ in equilibrium



$$\frac{x}{Y_{\sigma}^{\text{eq}}} \frac{dY}{dx} = 2 \frac{\Gamma_{\sigma \rightarrow \chi\chi}}{H} \frac{K_1(x)}{K_2(x)} \Rightarrow \Omega_{\chi} h^2 \simeq 4.48 \times 10^8 \frac{g_{\sigma}}{g_{*s} \sqrt{g_*}} \frac{m_{\chi}}{\text{GeV}} \frac{M_P}{m_{\sigma}^2} \Gamma_{\sigma \rightarrow \chi\chi}$$

$Y = n/s$ independent!

$$\Rightarrow y \simeq 10^{-12} \left(\frac{\Omega_{\chi} h^2}{0.12} \right)^{1/2} \left(\frac{g_*}{100} \right)^{3/4} \left(\frac{m_{\sigma}}{m_{\chi}} \right)^{1/2}$$

Why is this IR dominated?

time vs. temperature: $t \sim M_P / T^2$

$$\Rightarrow \frac{t(T = 0.1 \text{ GeV}) - t(T = 1 \text{ GeV})}{t(T = 1 \text{ GeV}) - t(T = T_{\text{RH}})} \sim 100$$

and produced DM $\propto$ time $\times$ rate: $\frac{n_{\chi}}{T^3} \simeq t \Gamma_{\sigma \rightarrow \chi\chi}$

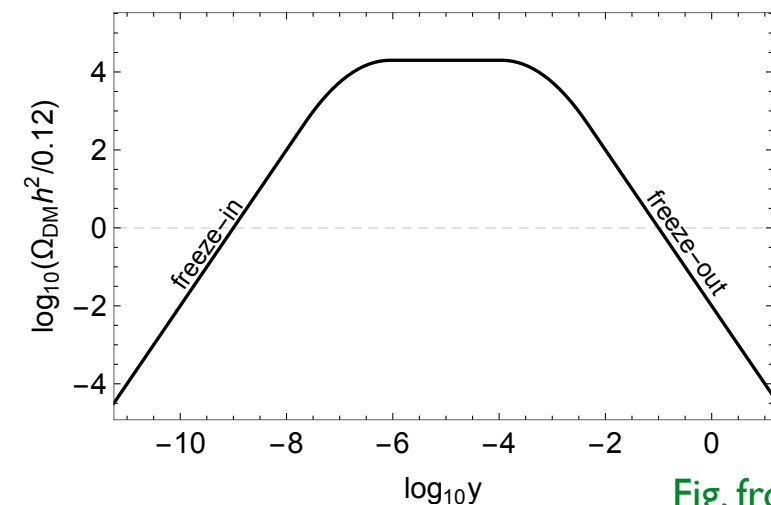


Fig. from I706.07442

CANNIBAL FREEZE-IN

EXAMPLE: SCALAR SINGLET DM

The simplest DM model: $\mathcal{L}_{SM} \supset -\frac{m^2}{2}\varphi^2 - \frac{\lambda}{4!}\varphi^4 - \frac{1}{2}\lambda_{h\varphi}\varphi^2|H|^2$

$\langle\varphi\rangle = 0$ & $\lambda_{h\varphi} \gtrsim 10^{-4}$ „WIMP” (thermalizes, undergoes freeze-out)

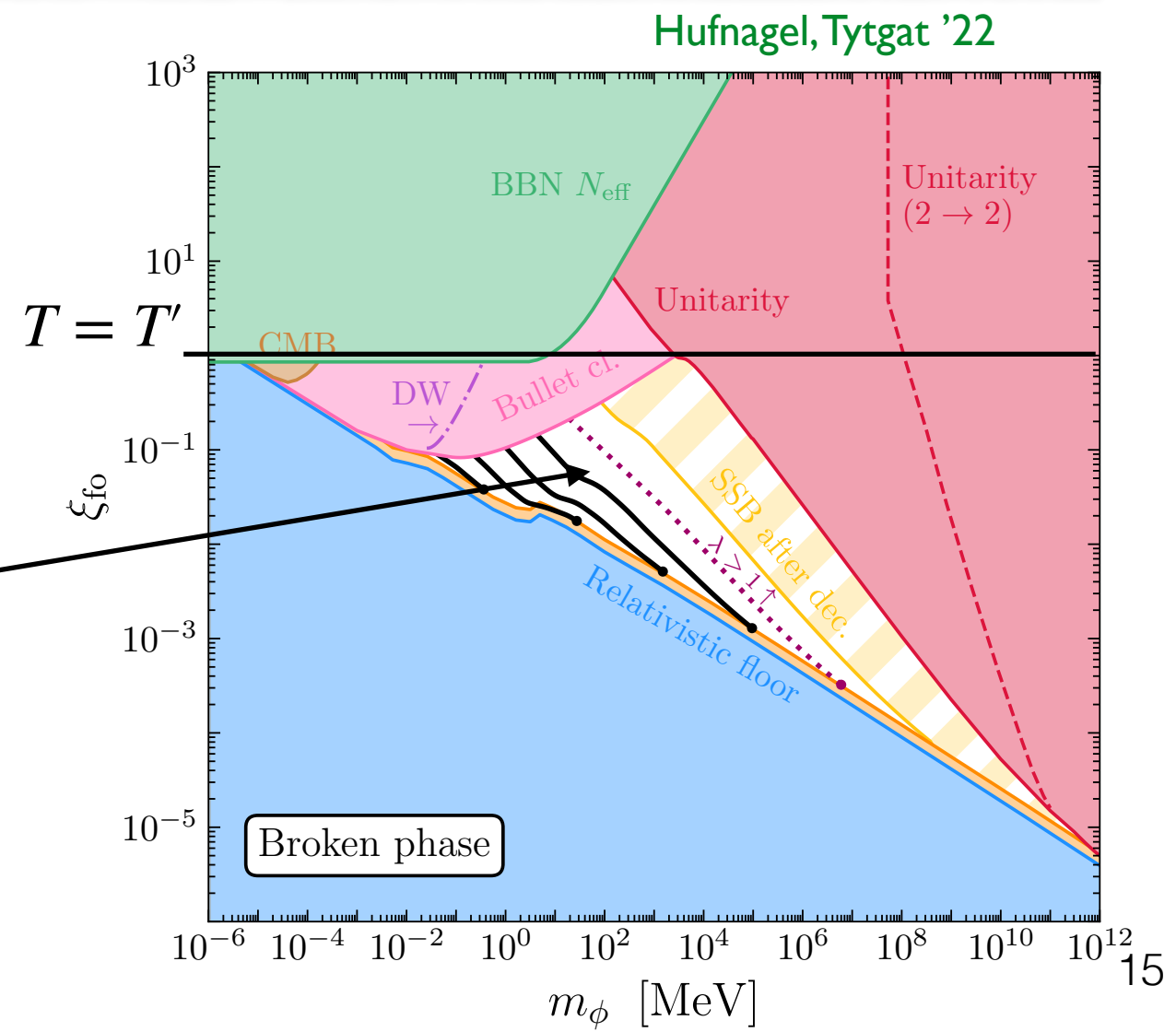
$\langle\varphi\rangle = 0$ & $\lambda_{h\varphi} \lesssim 10^{-9}$ FIMP (feebly-interacting, undergoes freeze-in)

$\langle\varphi\rangle \neq 0$ Cannibal DM: spontaneous $\mathbb{Z}_2$ breaking $\rightarrow$ Higgs mixing terms

The case with $\lambda_{h\varphi} = 0$ was studied here:

Conclusion:

allowed (white region) only if the DS temperature T' is smaller than the SM plasma one T



EXAMPLE: SCALAR SINGLET DM

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Hufnagel, Tytgat '22

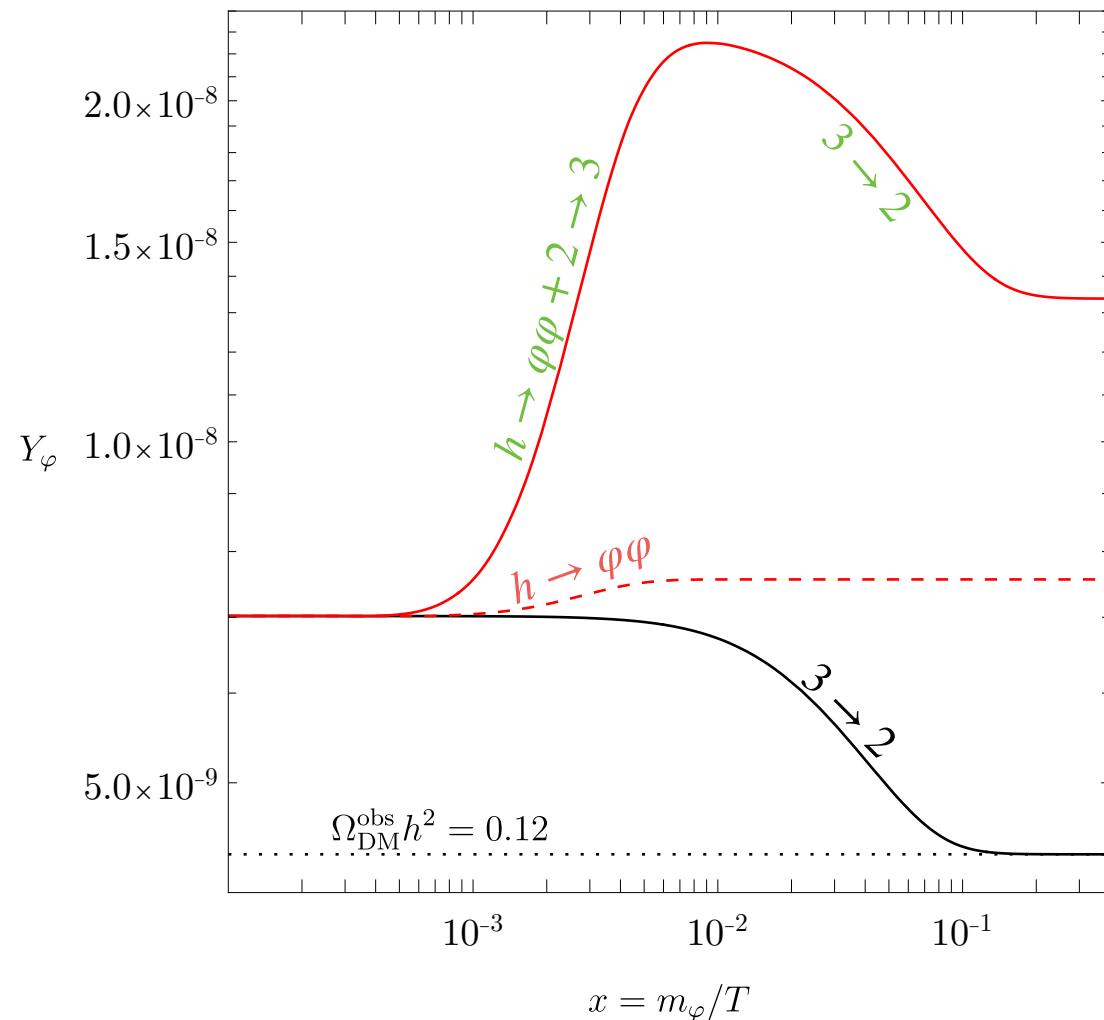
Evolution of number density $Y_\varphi := n_\varphi/s$ and 'temperature' $x_\varphi := m_\varphi/T_\varphi$ governed by set of Boltzmann equations:

$$\begin{aligned} \frac{Y'_\varphi}{Y_\varphi} &= \frac{1}{x\tilde{H}} \left(\langle C_{h\rightarrow\varphi\varphi} \rangle + \langle C_{hh\rightarrow\varphi\varphi} \rangle + \langle C_{3\leftrightarrow 2} \rangle \right) \\ -\frac{x'_\varphi}{x_\varphi} &= \frac{1}{x\tilde{H}} \left(\langle C_{h\rightarrow\varphi\varphi} \rangle_2 + \langle C_{hh\rightarrow\varphi\varphi} \rangle_2 + \langle C_{\phi h\leftrightarrow\phi h} \rangle_2 + \langle C_{3\leftrightarrow 2} \rangle_2 \right) - \frac{Y'_\varphi}{Y_\varphi} + \frac{H}{x\tilde{H}} \frac{\langle p^4/E^3 \rangle}{3T_\varphi} + \frac{2s'}{3s} \end{aligned}$$

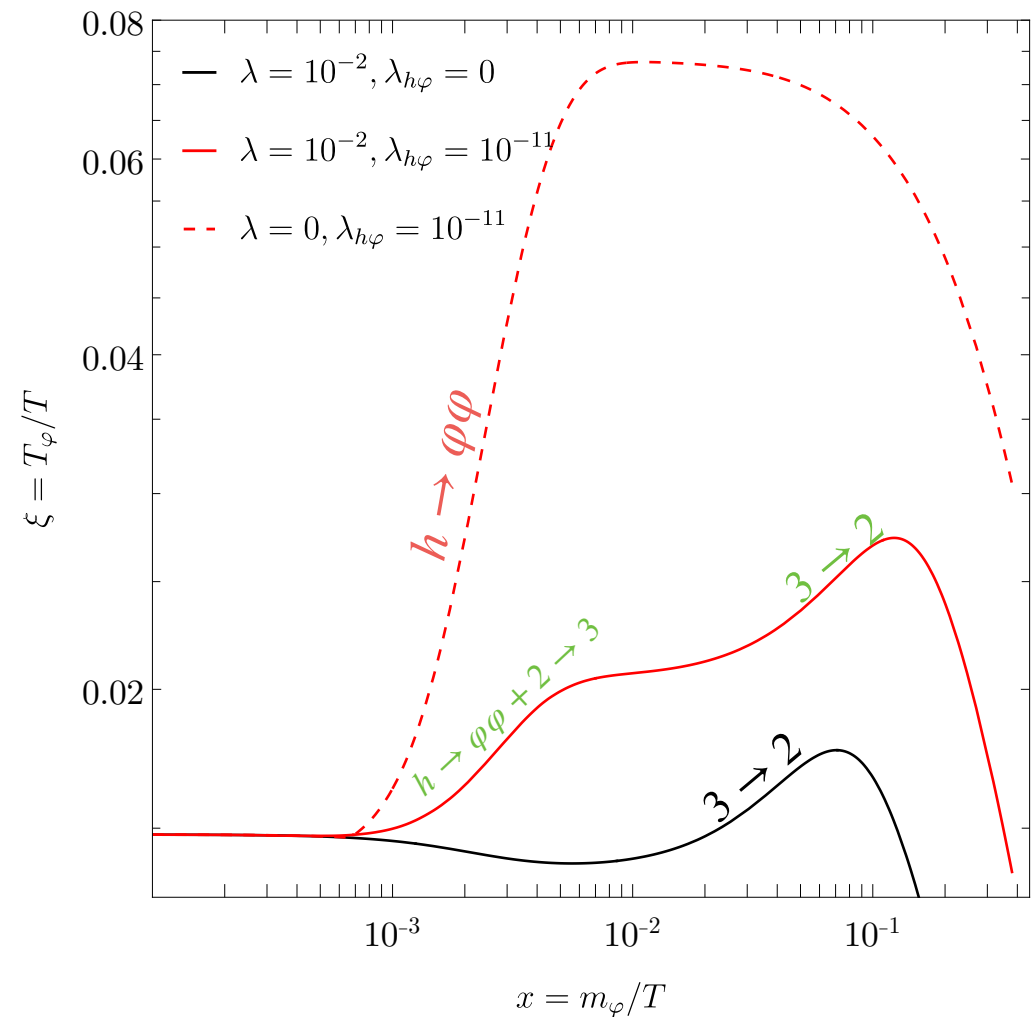
Freeze-in Freeze-in/out El. scattering Cannibal

BOOSTING FREEZE-IN

Consider an initial cold, low populated dark sector: $T_{DM}^i = 10^{-2} T_{SM}^i$



only cannibalization

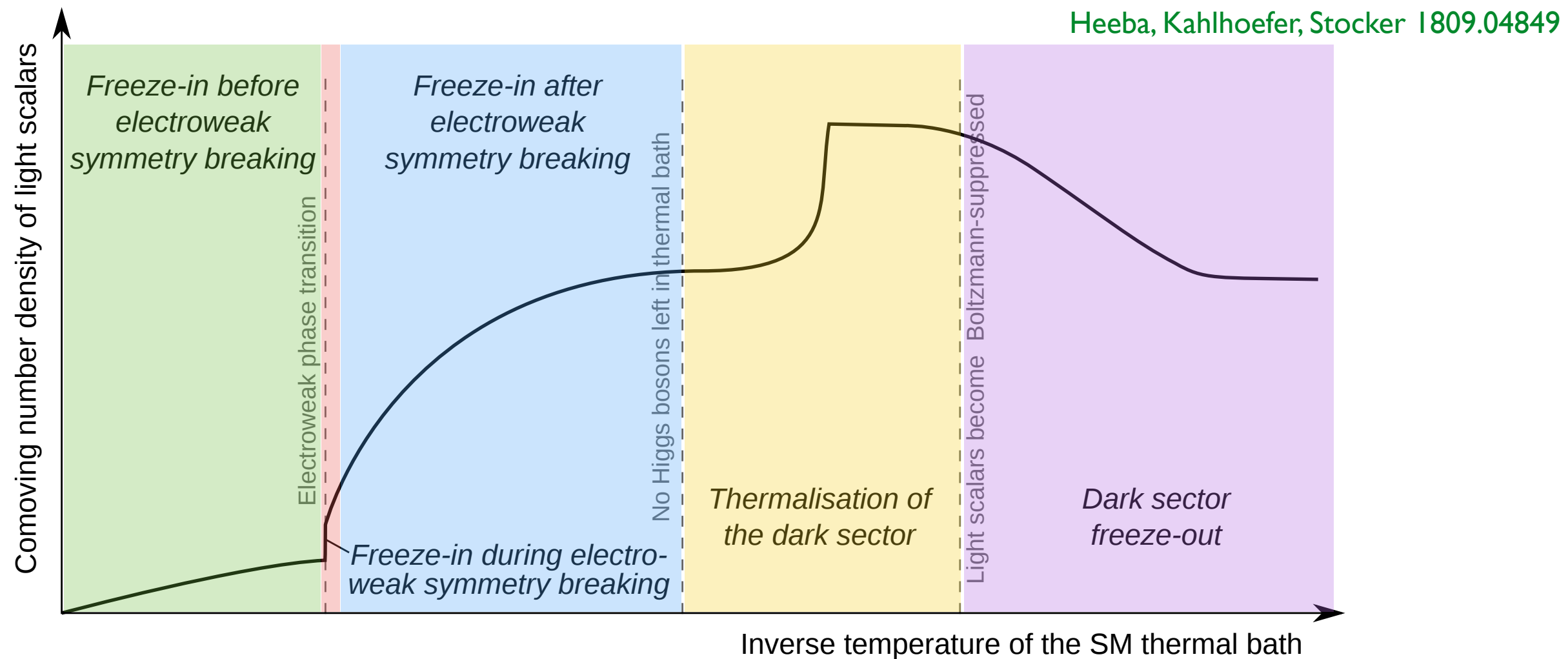


only freeze-in

cannibal+freeze-in

MORE COMPLETE PICTURE

Illustration for production through Higgs portal:



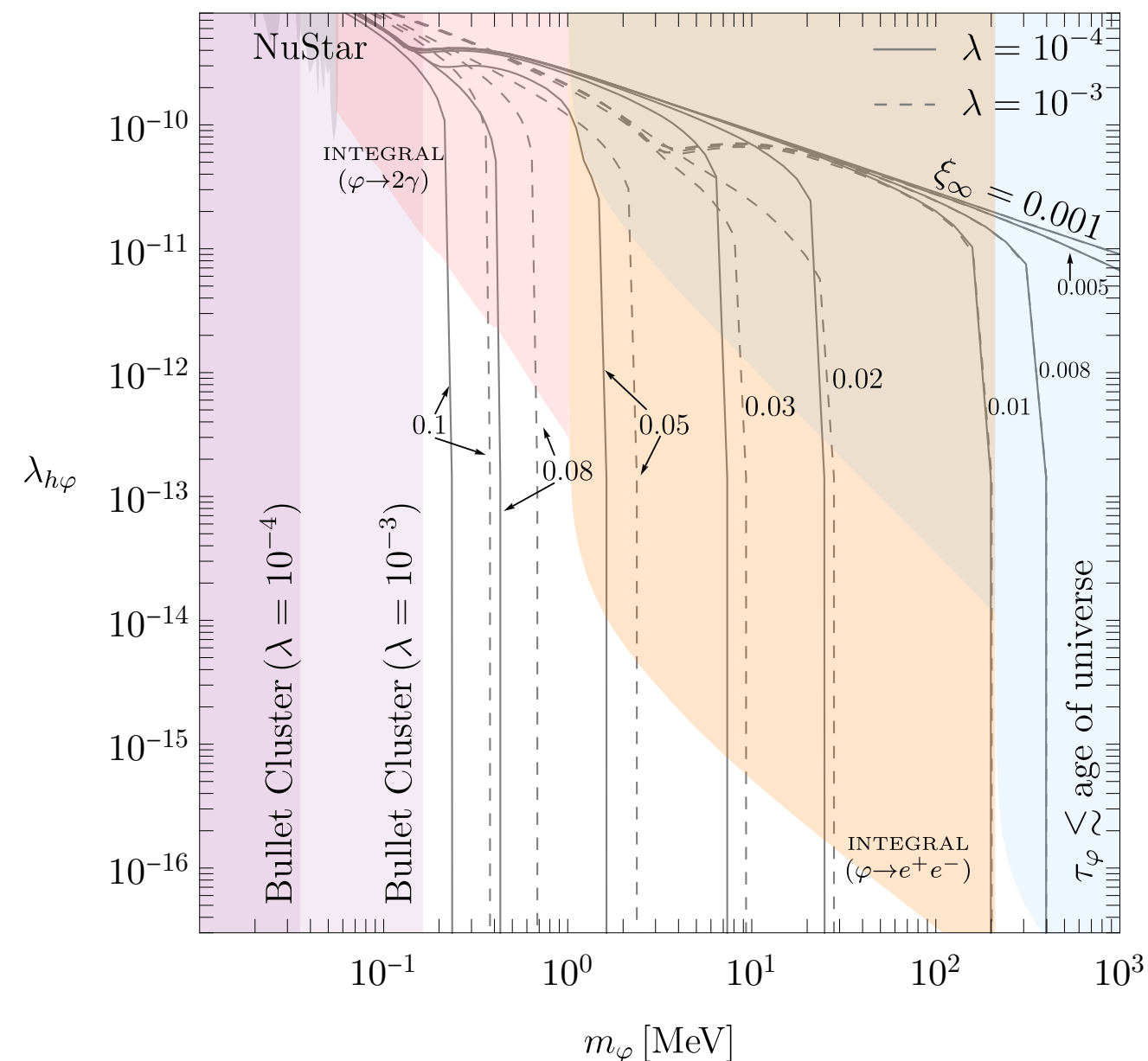
One should be careful to include such (potentially relevant) effects!

THIS MODEL HAS DECAYING DM

$$\mathbb{Z}_2 \text{ breaking} \Rightarrow \varphi \text{ unstable with } \tau_\varphi \propto 1/\lambda_{h\varphi}^2$$

Gray lines match
observed relic density

Colored areas are
excluded



For decaying DM only very
long lifetimes are allowed
 $\Rightarrow \lambda_{h\varphi}$ **needs to be very small**

The impact of our improved
treatment **small in the allowed
region**

... but still it is a viable model
(in the asymmetric reheating scenario)

goes to the scenario of Hufnagel, Tytgat '22

EXTENDED MODEL

Natural extension:

a complex ($\mathbb{Z}_3$ stabilised) **DM candidate** S with a **real singlet mediator** ϕ

$$\mathcal{L} \supset -\frac{1}{3!}g_s(S^3 + (S^*)^3) - \frac{\lambda_s}{4}|S|^4 - A_{\phi s}\phi|S|^2 - \frac{\lambda_{\phi s}}{2}\phi^2|S|^2 - B_{\phi h}\phi|H|^2$$

DM self interactions

thermalisation between ϕ
and S

Portal

Portal to the visible sector $B_{\phi h}\phi|H|^2$ **induces mixing** between ϕ and the Higgs post-EWPT:

$$\phi \rightarrow \phi + \theta h$$

$$h \rightarrow h - \theta \phi$$



ϕ couples to matter in a Higgs-like way

Such a model exhibits new dynamics + detection signals

BOLTZMANN EQUATIONS

DM evolution

Freeze-in

DM-mediator interactions

DM self-interactions

$$\frac{Y'_S}{Y_S} = \frac{1}{x \tilde{H}} \left(\langle C_{h \rightarrow \phi SS^*} \rangle + \langle C_{h \rightarrow SS^*} \rangle + \langle C_{\phi \phi \leftrightarrow SS^*} \rangle + \langle C_{3 \leftrightarrow 2} \rangle \right),$$

$$-\frac{x'_S}{x_S} = \frac{1}{x \tilde{H}} \left(\langle C_{h \rightarrow \phi SS^*} \rangle_2 + \langle C_{h \rightarrow SS^*} \rangle_2 + \langle C_{\phi S \leftrightarrow \phi S} \rangle_2 + \langle C_{3 \leftrightarrow 2} \rangle_2 \right) - \frac{Y'_S}{Y_S} + \frac{H}{x \tilde{H}} \frac{\langle p^4/E^3 \rangle}{3T_S} + \frac{2s'}{3s}$$

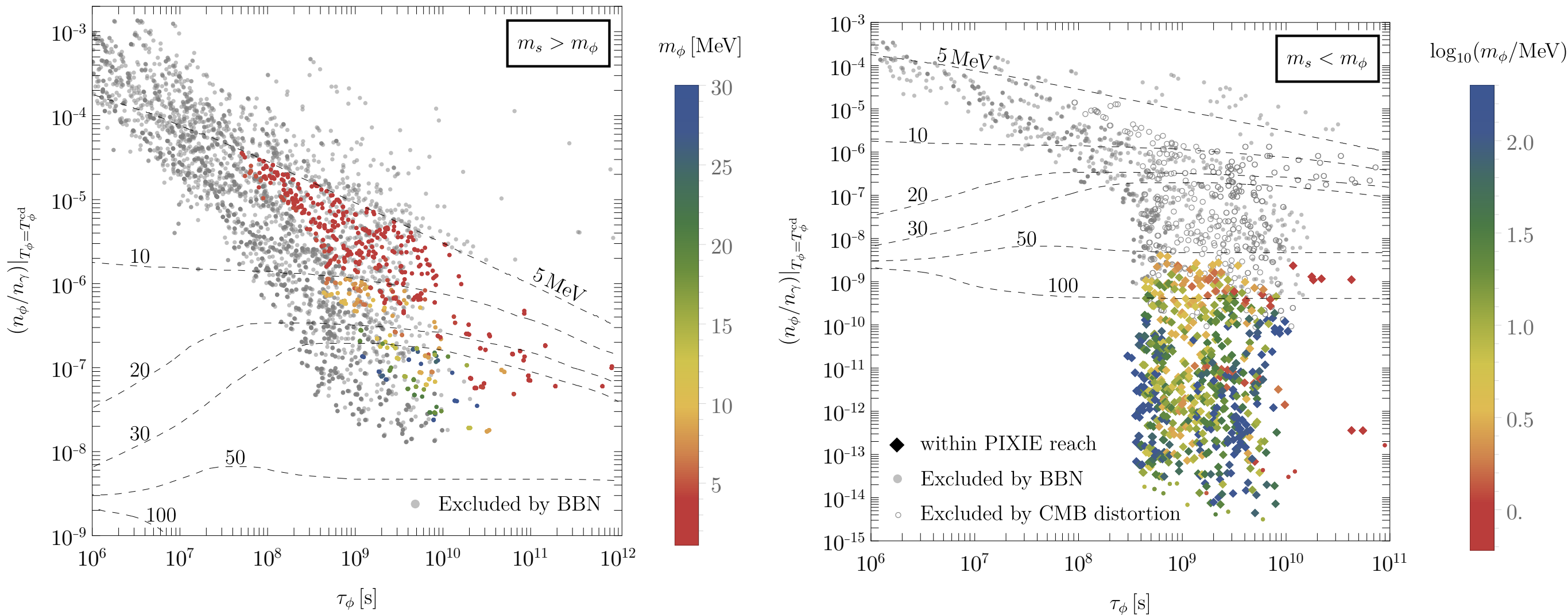
Mediator evolution

$$\frac{Y'_\phi}{Y_\phi} = \frac{1}{x \tilde{H}} \left(\langle C_{h \rightarrow \phi SS^*} \rangle + \langle C_{\text{sm sm} \rightarrow \text{sm } \phi} \rangle + \langle C_{\phi \phi \leftrightarrow SS^*} \rangle \right),$$

$$-\frac{x'_\phi}{x_\phi} = \frac{1}{x \tilde{H}} \left(\langle C_{h \rightarrow \phi SS^*} \rangle_2 + \langle C_{\text{sm sm} \rightarrow \text{sm } \phi} \rangle_2 + \langle C_{\phi S \leftrightarrow \phi S} \rangle_2 \right) - \frac{Y'_\phi}{Y_\phi} + \frac{H}{x \tilde{H}} \frac{\langle p^4/E^3 \rangle}{3T_\phi} + \frac{2s'}{3s}.$$

BBN & CMB CONSTRAINTS

Mediator is decaying to SM:
different phenomenology for two mass hierarchies between S (the DM) and ϕ

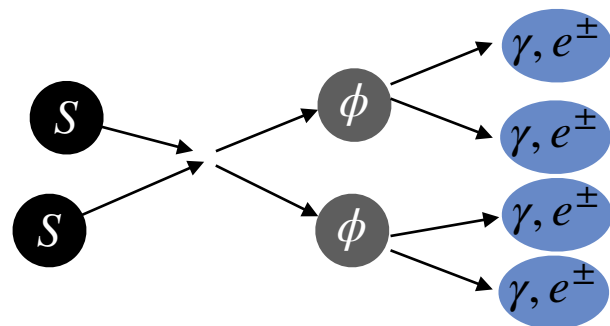


Resulting constraints are significant, but many viable points found in a scan & some with prospects of CMB distortion in reach of PIXIE

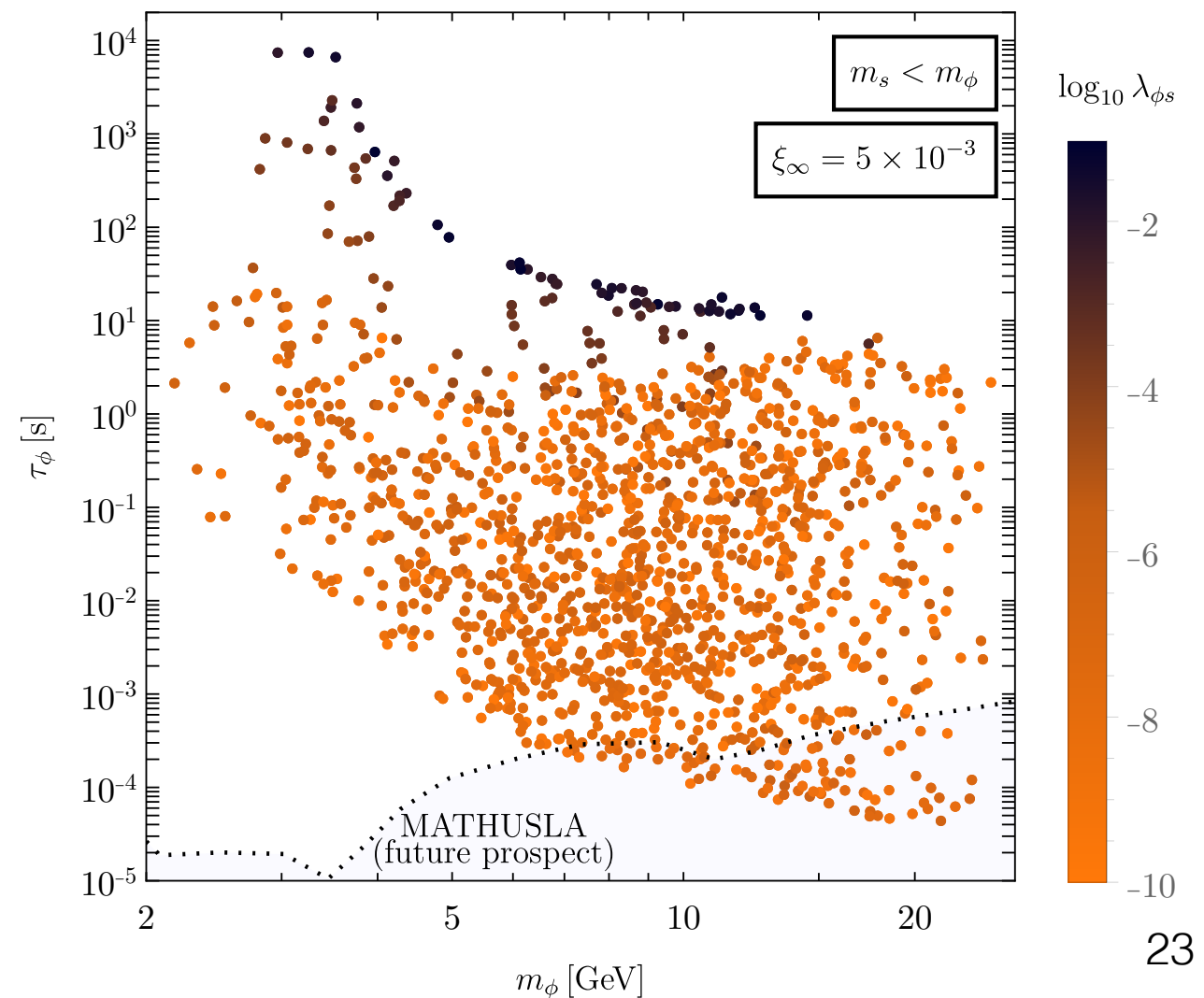
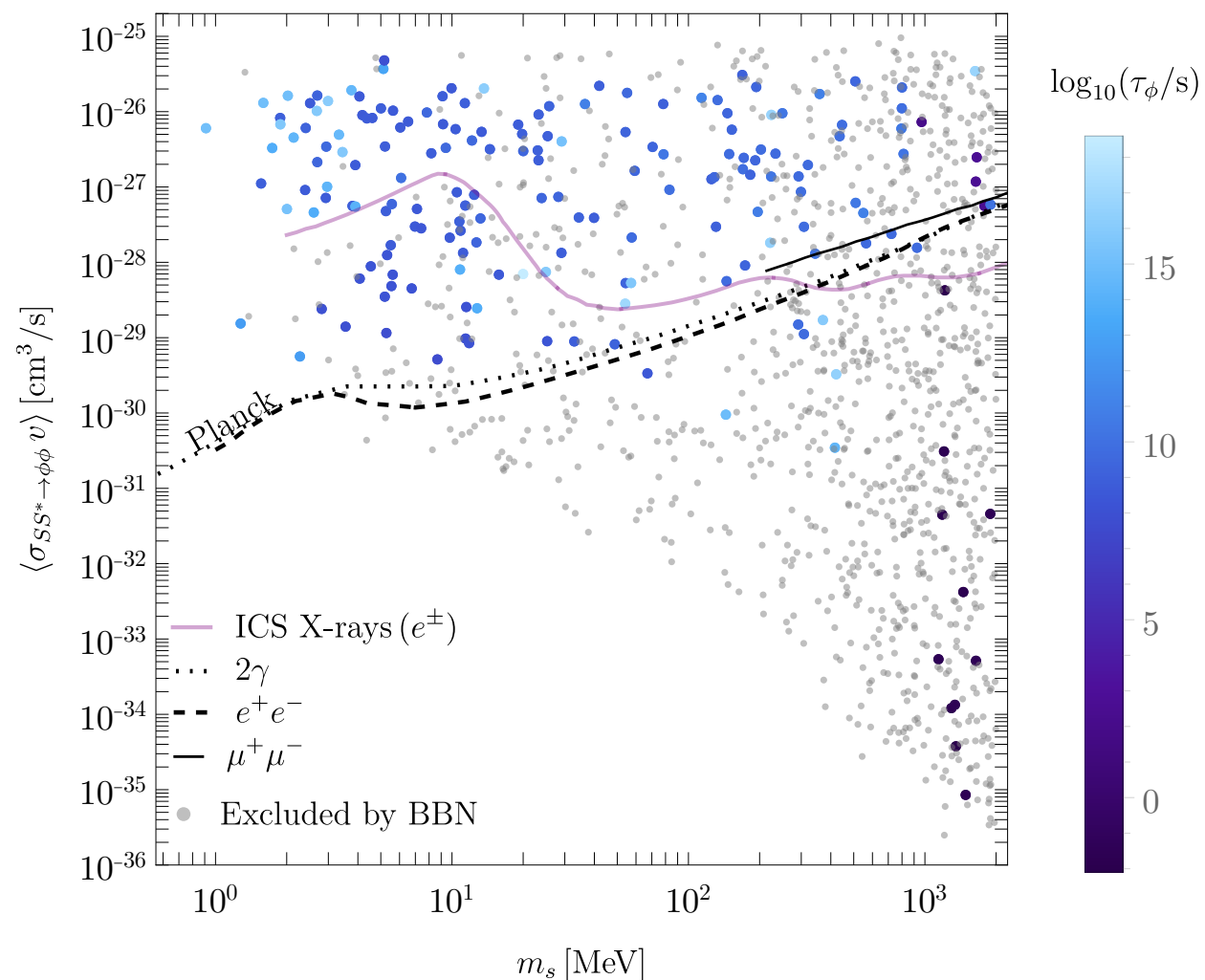
(The Primordial Inflation Explorer)

DM & MEDIATOR DETECTION

$m_S > m_\phi$: indirect DM
detection feasible



$m_S < m_\phi$: weaker BBN
limits allow for points
that are potentially
testable in LLP searches

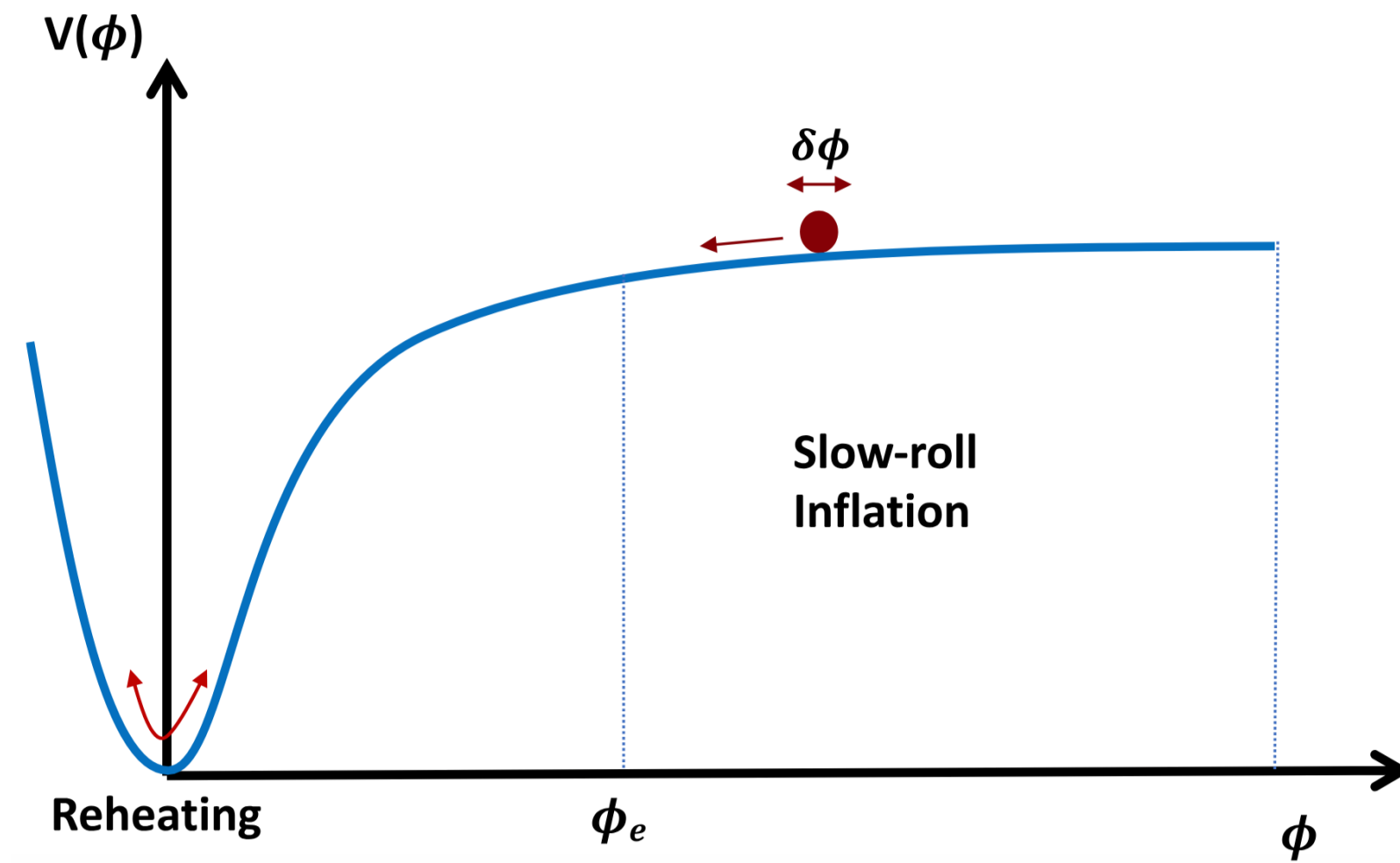


CANNIBAL FREEZE-IN

NON-STANDARD COSMOLOGY

HOW DOES THE INFLATION END?

The field ϕ that drives inflation ($a \propto e^{Ht}$) needs to stop slow-rolling, enter a phase of oscillations around its potential minimum, and finally decay



reheating

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = -\Gamma\rho_\phi$$
$$\frac{d\rho_R}{dt} + 4H\rho_R = +\Gamma\rho_\phi$$

How and when exactly it happens may have a huge impact on cosmology



form of the potential

T_{RH}

WHAT DO WE KNOW ABOUT T_{RH} ?

In **standard** (Λ CDM or not) cosmology: $10^9 \text{ GeV} \lesssim T_{\text{RH}} \lesssim 10^{15} \text{ GeV}$
(If reheating is instantaneous;
good for leptogenesis, bad for gravitino production...)

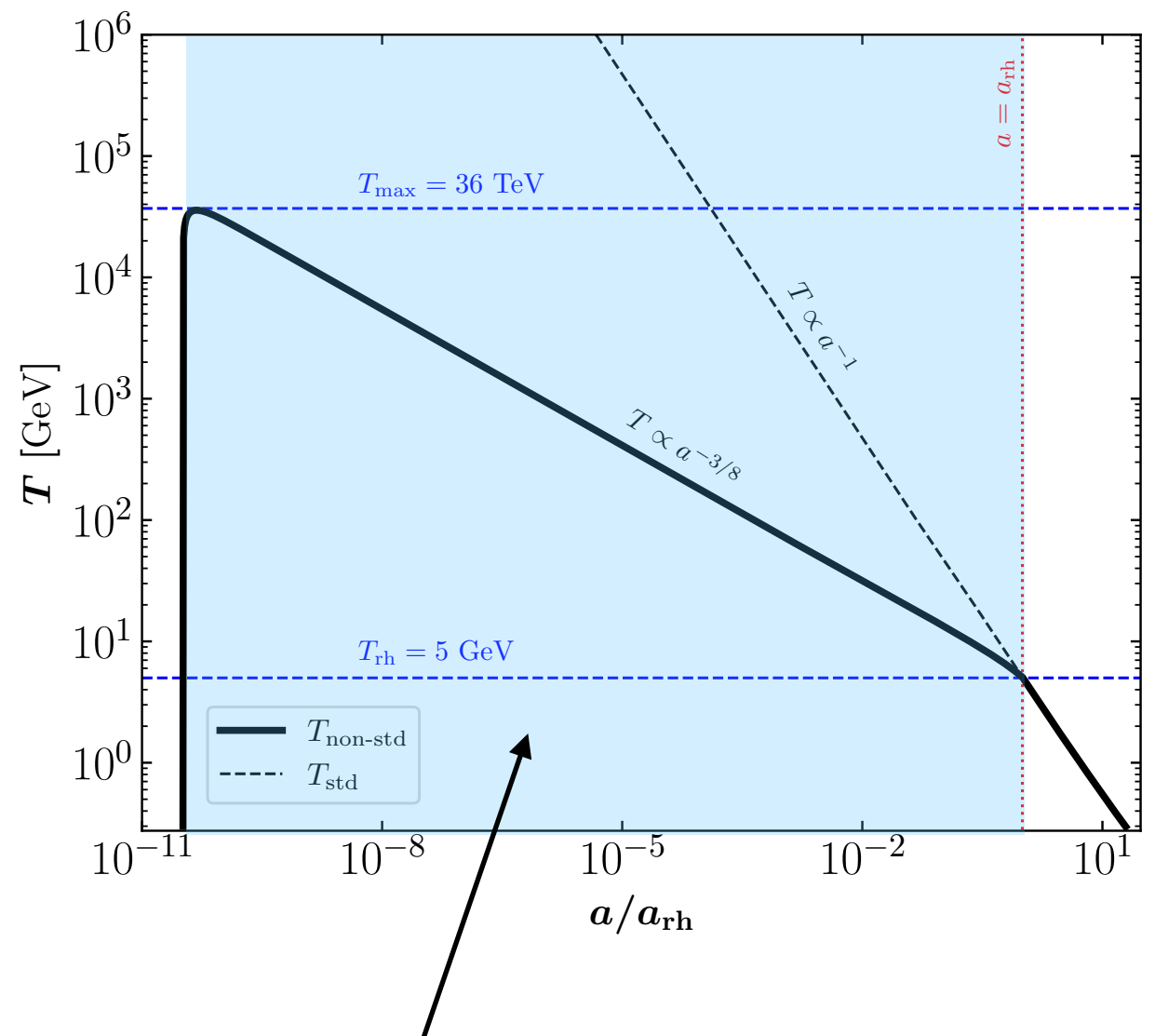
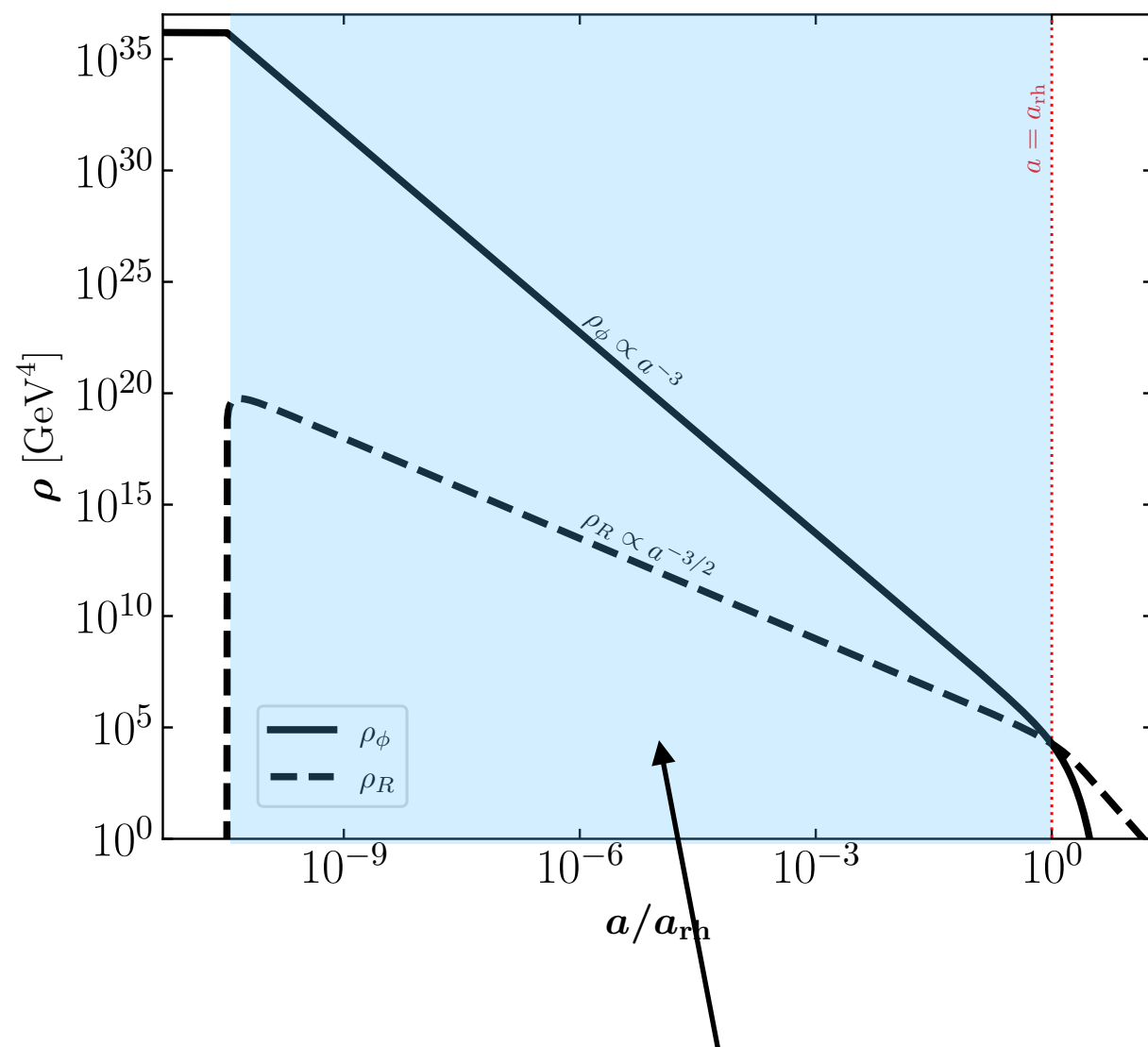
From **observations we know** only that: $T_{\text{RH}} \gtrsim \mathcal{O}(\text{few}) \text{ MeV}$

Standard cosmology is standard-by-convention
(unlike the Standard Model of particle physics)

A low reheating temperature scenario: universe where the inflaton decays very slowly, continuously dumping entropy and keeping the radiation temperature low until just before BBN

INFLATION DECAY & REHEATING

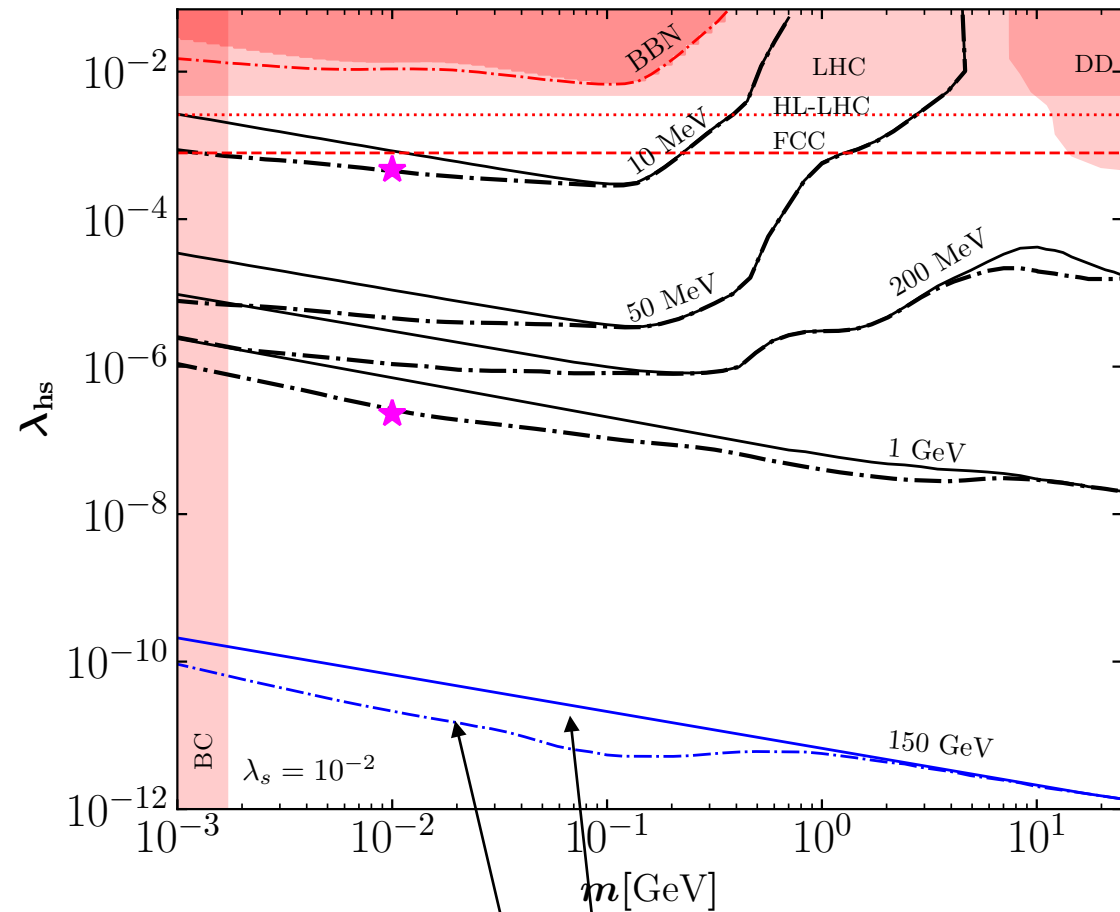
During reheating $T \propto a^{-3/8}$ (matter domination), and $H \propto T^4$, i.e., rapid expansion of the universe



Strongly affects DM produced during this period

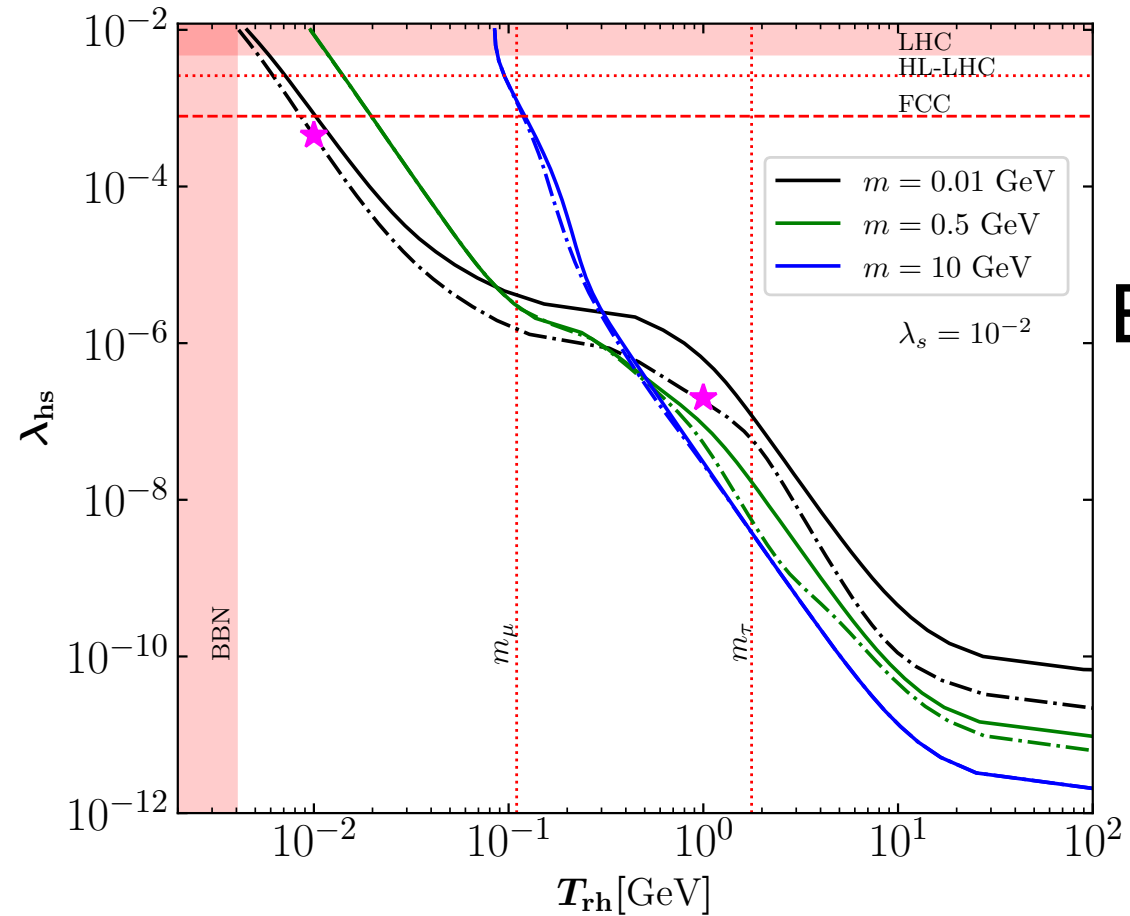
IMPACT ON PHENOMENOLOGY

Example of a change of the model parameters giving correct relic abundance:

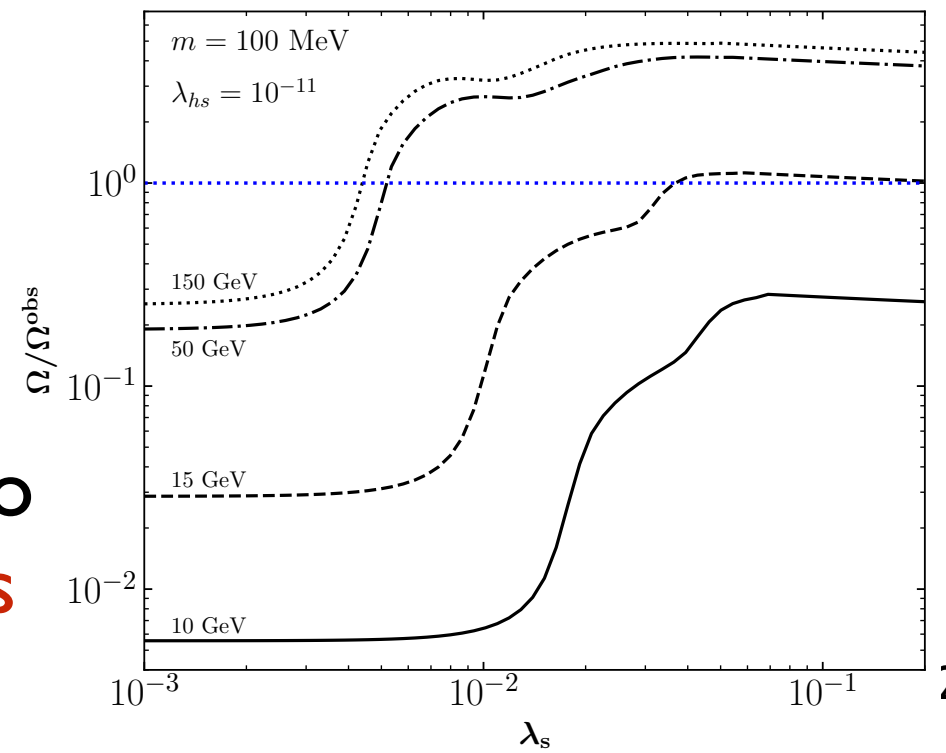


on/off **cannibal**
interactions

change in Ωh^2 due to
cannibal interactions



Effect of **low**
reheating T



IDEA:
MAKE DM COOL AGAIN

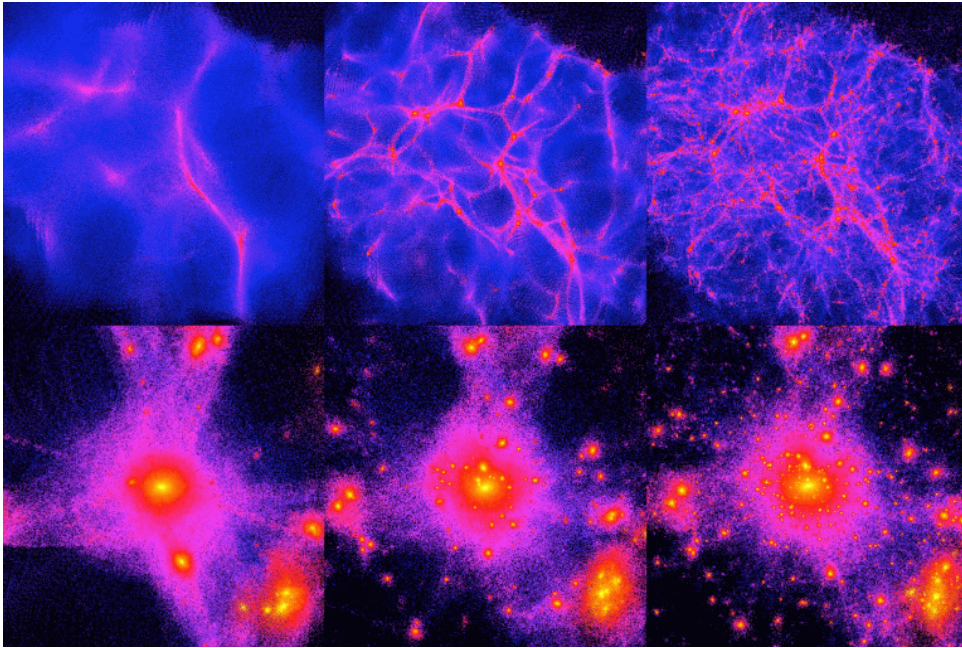
DM & LSS

Hot

Warm

Cold

ITC @ University of Zurich



Comoving free-streaming length.

integrated distance a DM particle travels from its production until matter-radiation equality:

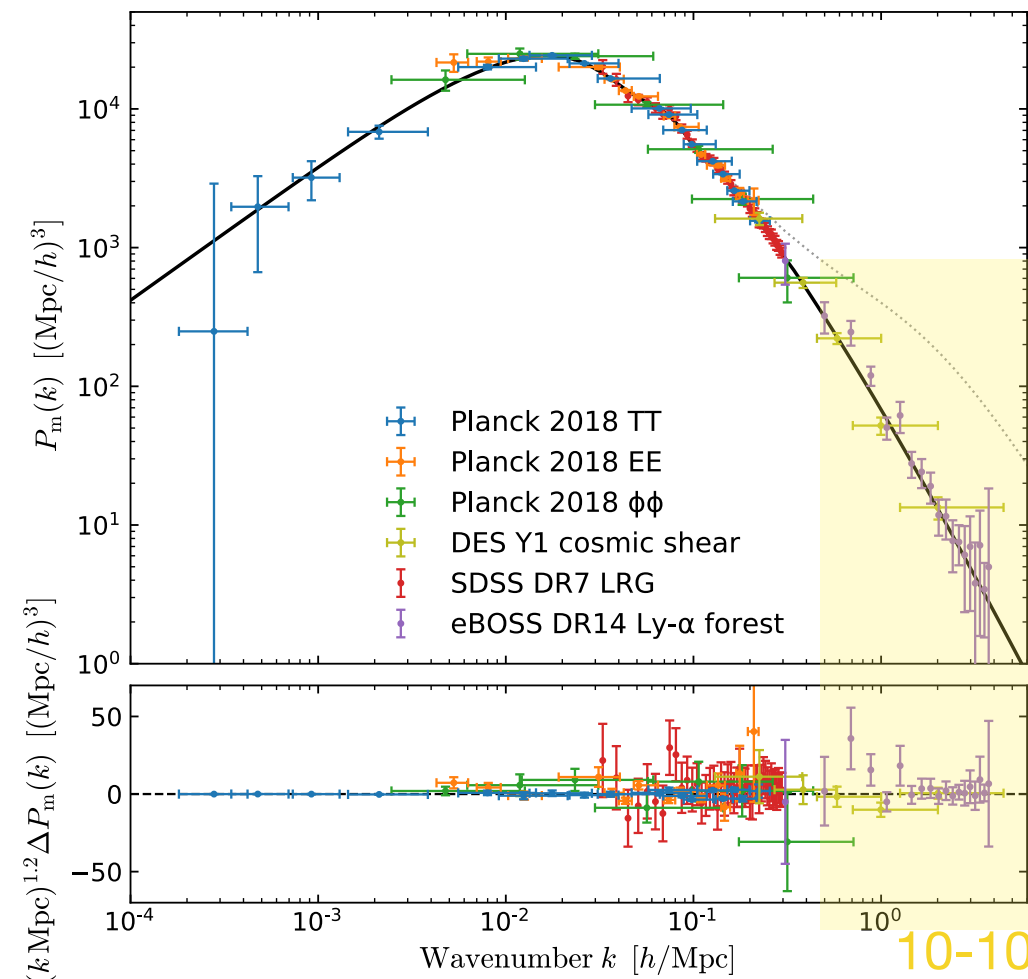
$$\lambda_{\text{fs}} = \int_0^{t_{\text{eq}}} \frac{v(t)}{a(t)} dt$$

- **Hot Dark Matter:** $\lambda_{\text{fs}} \sim$ tens of Mpc (smooths out fluctuations $\sim$ galaxy cluster scales).
- **Warm Dark Matter:** $\lambda_{\text{fs}} \sim$ sub-Mpc (smooths out small dwarf galaxy scales).
- **Cold Dark Matter:** $\lambda_{\text{fs}} \rightarrow 0$ (negligible free-streaming; collapses at all observable scales).

What matters is the typical velocity dispersion $\sqrt{\langle v^2 \rangle}$:

- A particle can be light (e.g. axion), but if produced via a non-thermal mechanism, it can be **cold** with $p \approx 0$
- Conversely, a sterile ν of a few keV mass produced via the Dodelson-Widrow mechanism is **warm**

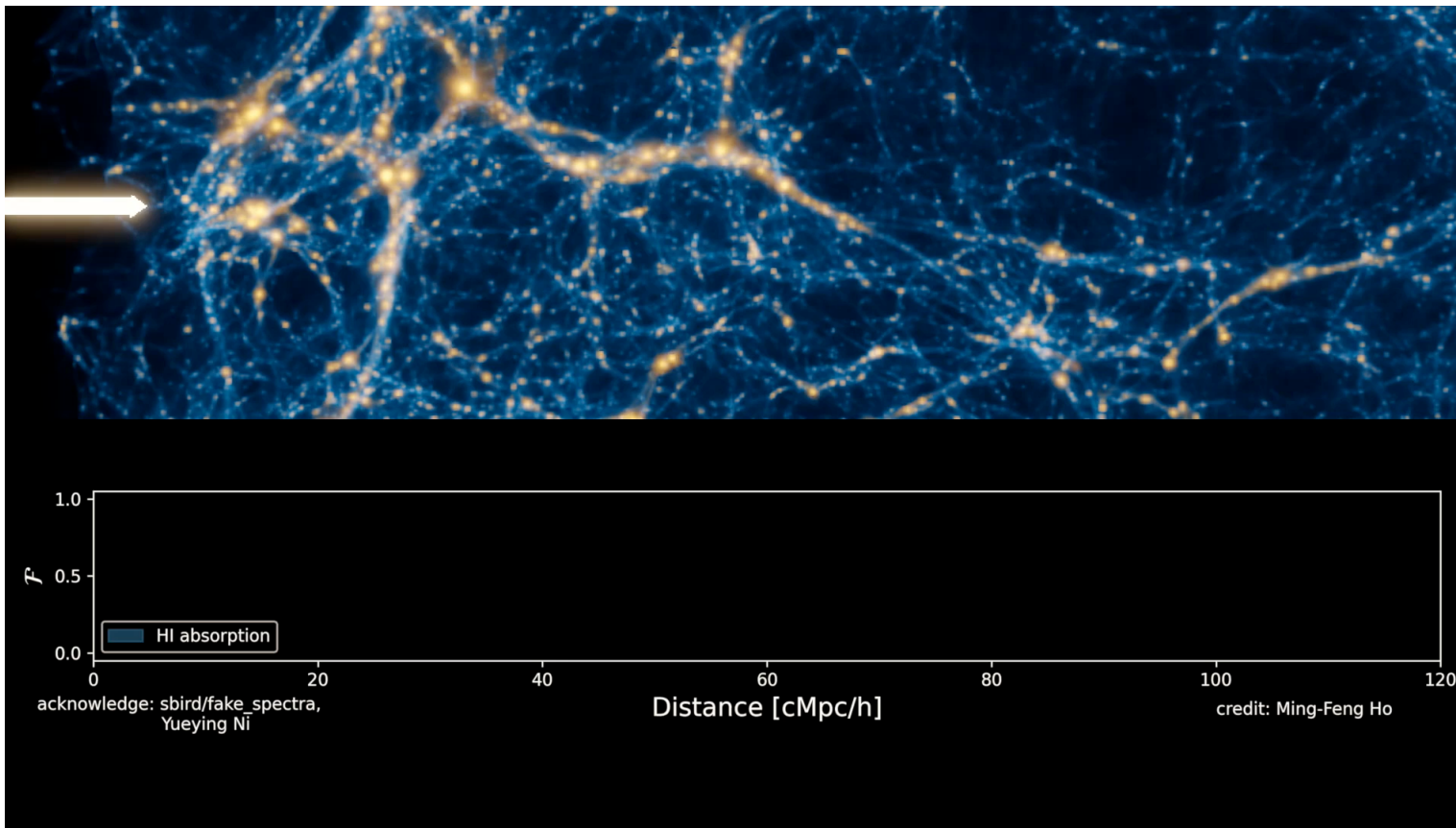
Observationally: matter power spectrum



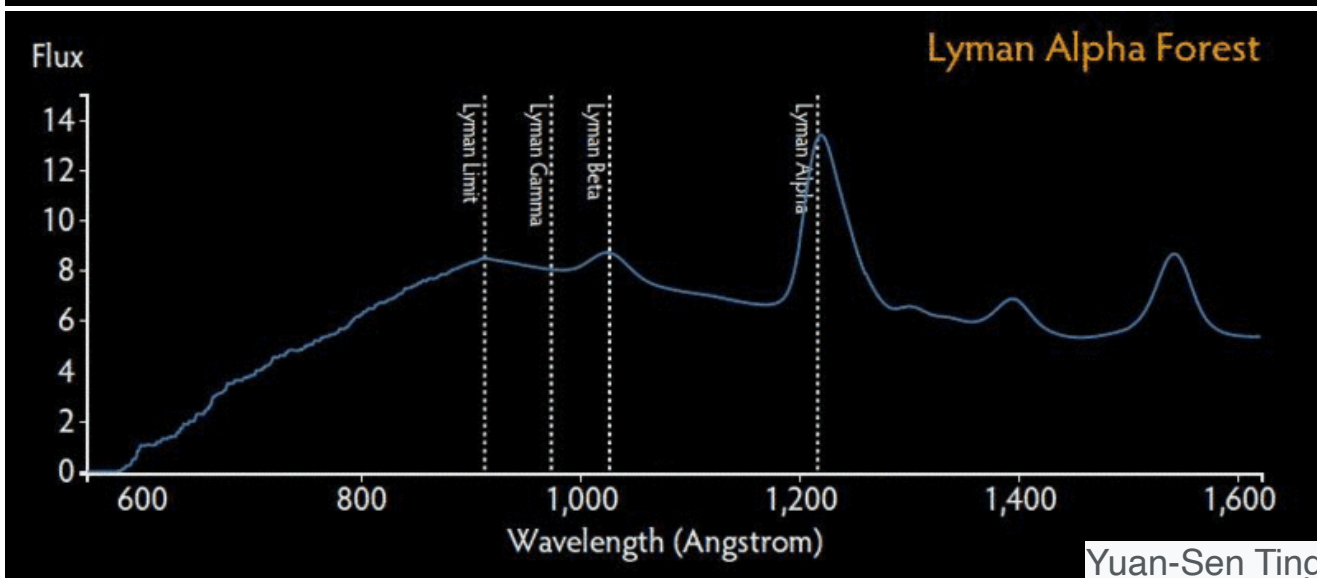
10-100 kpc

WARM DM & LYMAN- α

In particular, **large wavenumber k (i.e. small scales)** are well measured through the Lyman- α transitions in H gas in the IGM at redshifts ($z \sim 2 - 5$)
i.e. before non-linear collapse erases early structures



Light for a distant quasar features absorption lines at $1215.67 \text{ \AA}$ that is **redshifted depending on the distance**



(Other lines are also present & the redshift makes it a „forest”)

LYMAN- α LIMITS ON FI AND FO

If λ_{fs} sizeable, sub-Mpc density fluctuations are washed out by its kinetic movement
 $\Rightarrow$ sharp, characteristic ***small-scale cutoff*** in the linear matter power spectrum

Often the limits are quoted as lower limit on the DM mass

$$m_{\text{WDM}}^{\text{Ly}-\alpha} \gtrsim 2 \div 6 \text{ keV}$$

Depending on astro uncertainties, e.g. reionization history and T of the IGM

What is meant here by the WDM model:

- a generic fermion in **equilibrium at early times**
- **decoupled when relativistic** with Fermi-Dirac distribution
- interaction fit to give **correct relic abundance**

For any other model the limit needs to be „translated”, e.g.:

Probe	NCDM test	$m_{\text{FI}}^{\text{lim}}$ [keV]	$m_{\text{SW}}^{\text{lim}}$ [keV]
Lyman- α	Velocity dispersion, Sec. 3.1.1	16	3.8
	Fits to transfer function, see Sec. 3.1.2	15	3.9
	Area criterion, see Sec. 3.1.3	15	3.8
ΔN_{eff}	see Sec. 3.2	1.3×10^{-2}	3.4×10^{-3}

SECLUDED DARK SECTOR WITH $T' < T$?

The Lyman- α limits „warmness” $\Rightarrow$ if dark sector is secluded, maybe it is simply **colder** and bounds **are weakened**?

Temperature Asymmetry: Origin

1 Asymmetric Reheating

Inflaton couples more strongly to SM $\rightarrow$ visible sector reheated preferentially

2 Entropy Injection & #DOF

QCD & EW transitions heat the SM bath post-decoupling; dark sector can have huge number of states

Bottom line: viable —
but in rather unnatural &
tightly constrained scenarios

Main Cosmological Constraints

A Inflaton-Mediated Thermalization (“Washout”)

- Off-shell inflaton $SM+SM \rightarrow DM+DM$ re-couples sectors
- If $\Gamma > H$, asymmetry is erased ($T'/T \rightarrow 1$)
- Avoided only with low reheating T or heavy inflaton

B N_{eff} & BBN Constraints

- Dark radiation shifts N_{eff} , altering He & D abundances
- Constrains residual entropy in the dark sector

C Detectability Problem

- Portal couplings must satisfy $\varepsilon \lesssim 10^{-7}-10^{-9}$
- Direct detection and collider tests become inaccessible

WHAT IF CANNIBAL ϕ IS THE MEDIATOR?

A mediator field does not need a stabilising symmetry $\Rightarrow$ cubic interactions exist generically and generate $2 \leftrightarrow 3$ interactions

...example: a scalar field with ϕ^3 or a non-abelian vector e.g. SU(N)

In the following we take the case:

$$\mathcal{L}_s \ni \frac{g_h}{2} |H|^2 \phi^2 + \frac{\sqrt{3}\lambda}{3!} m_\phi \phi^3 + \frac{\lambda}{4!} \phi^4 + \kappa \phi \bar{\chi} \chi$$

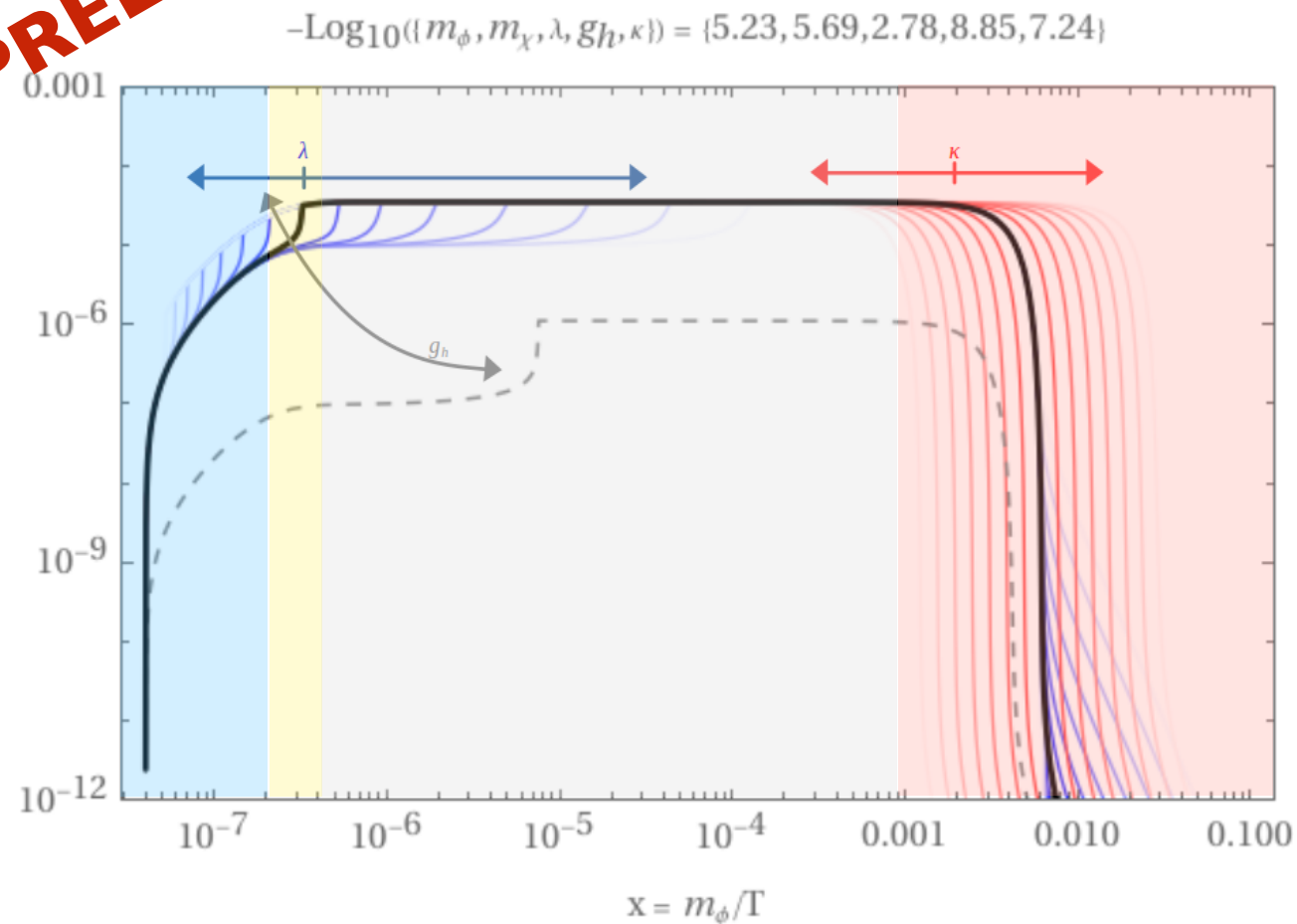
Higgs portal cubic + quartic decay to χ

ϕ freeze-in FI boost & self-cooling DM freeze-in

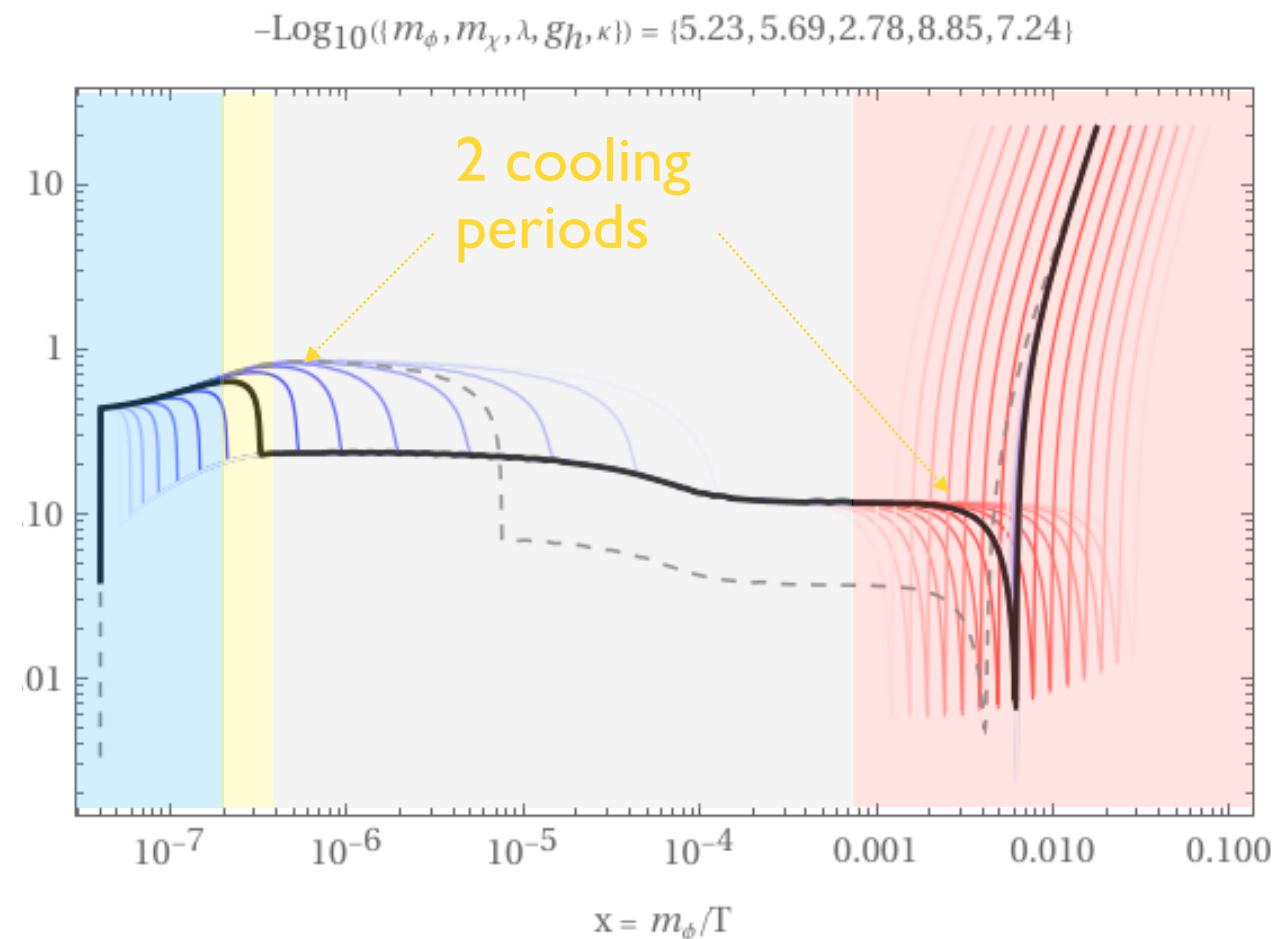
SELF-COOLING: HOW DOES IT WORK?

PRELIMINARY

ϕ yield evolution:



T_ϕ evolution:



1. Higgs decay provides ϕ freeze-in

2. Expansion rate drops, yield grows
 $\Rightarrow 2 \rightarrow 3$ efficiency grows

3. Self-thermalization $\Rightarrow$ plateau

4. Decay to DM

1. Temperature $\sim T/2$

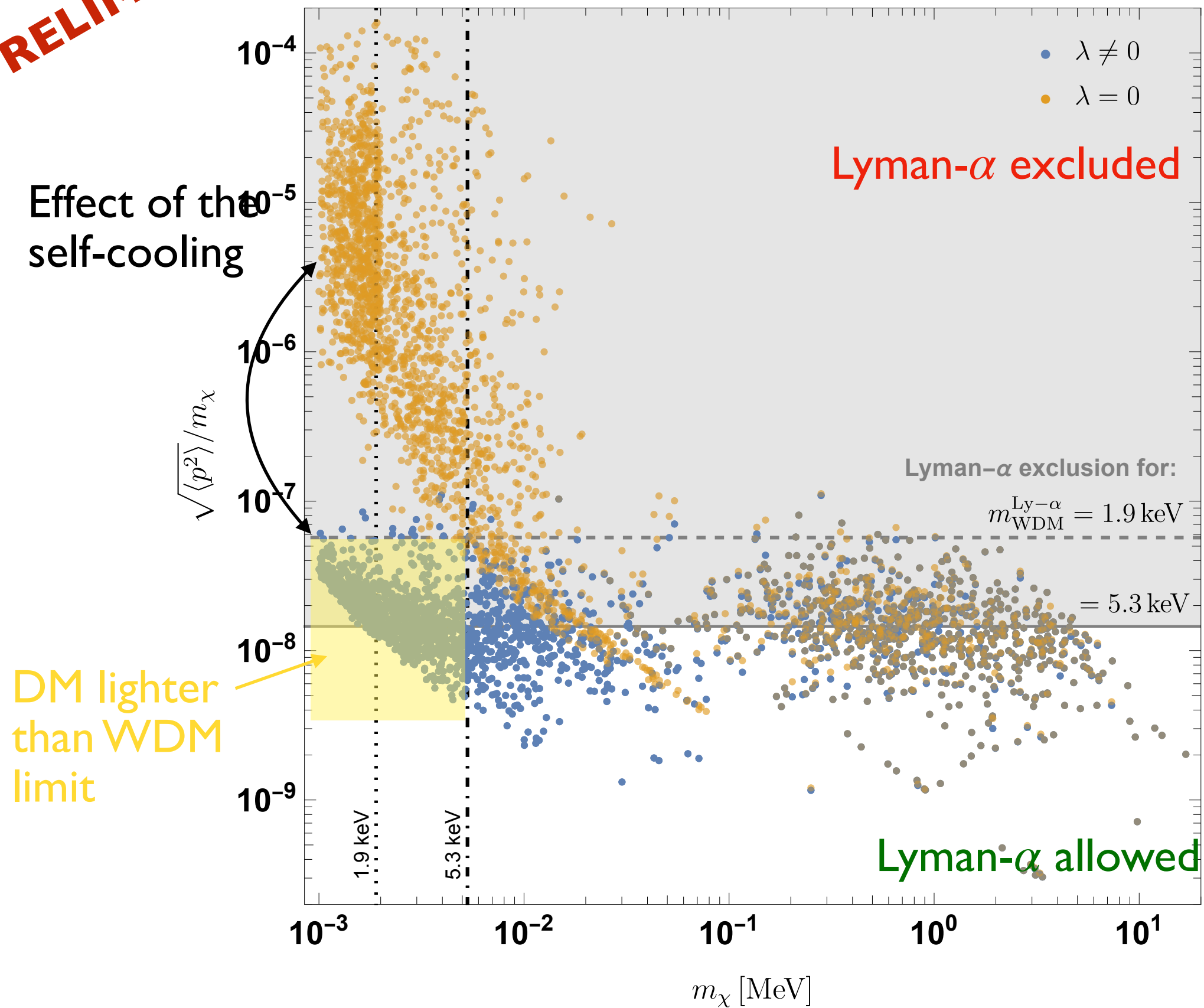
2. Self-cooling drop

3. Equilibrium expansion

4. Apparent heating: skewing due to time dilatation

PRELIMINARY

MCMC SCAN FOR LYMAN- α

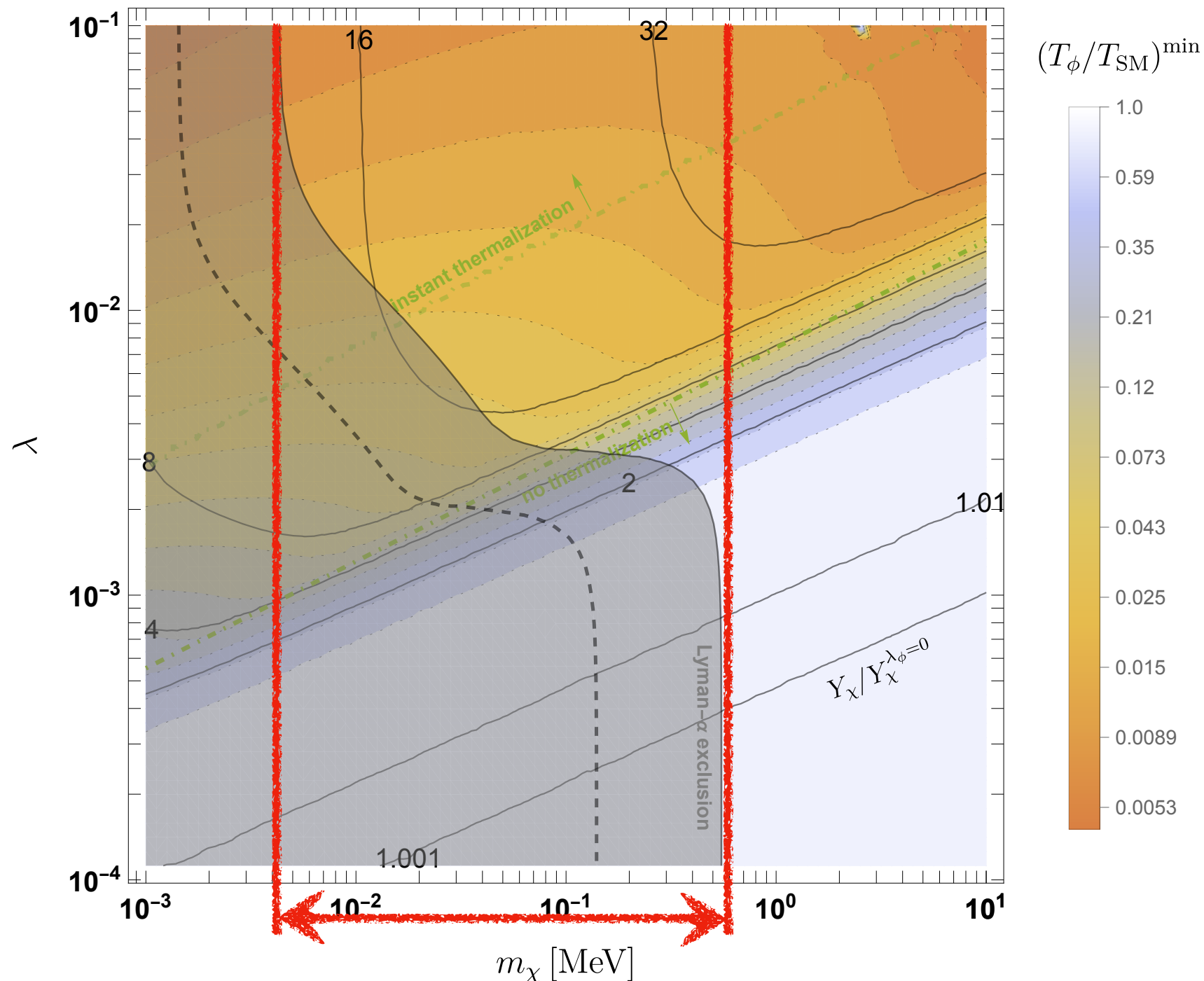


MODEL PARAMETER SPACE

Model has 5 free parameters. Fix two with smallest impact (m_ϕ, κ) and λ_h fix by relic abundance; show remaining two (m_χ - DM mass & λ_ϕ - self-interaction strength):

$$m_\phi = 1.0 \text{ GeV}, \kappa = 10^{-7}, \lambda_h \text{ fixed by } \Omega h^2 = 0.12$$

PRELIMINARY



Loosening limits due to self-cooling!

CONCLUSIONS

1. Cannibal self-cooling can make DM lighter

2. **Frozen-in** Cannibal Dark Matter is a viable scenario, naturally avoiding the large scale structure formation limits plaguing cannibalising DM.

3. It has unique evolution in the Early Universe & potentially **detectable signals in indirect searches**. Temperature (and momentum distribution) can have a **non-trivial impact** in such scenarios and **need to be studied** carefully.

Thank you!