NATIONAL SCIENCE CENTRE
POLAND

# MAKING DARK MATTER COOL AGAIN:

## DYNAMICS OF SELF-INTERACTING DARK SECTORS

Andrzej Hryczuk

NATIONAL
CENTRE
FOR NUCLEAR
RESEARCH
ŚWIERK

based on:

$\Big\{$ **E. Cervantes, AH** 2407.12104
**N. Bernal, E. Cervantes, K. Deka, AH** 2506.09155

$\{$ work in progress **E. Cervantes, AH, S. Lederer**

Seminar @ FUW, University of Warsaw

28th May 2026

# MOTIVATION & OBJECTIVES

New mechanism for cooling DM
& significantly weakening the
Lyman-$\alpha$ 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

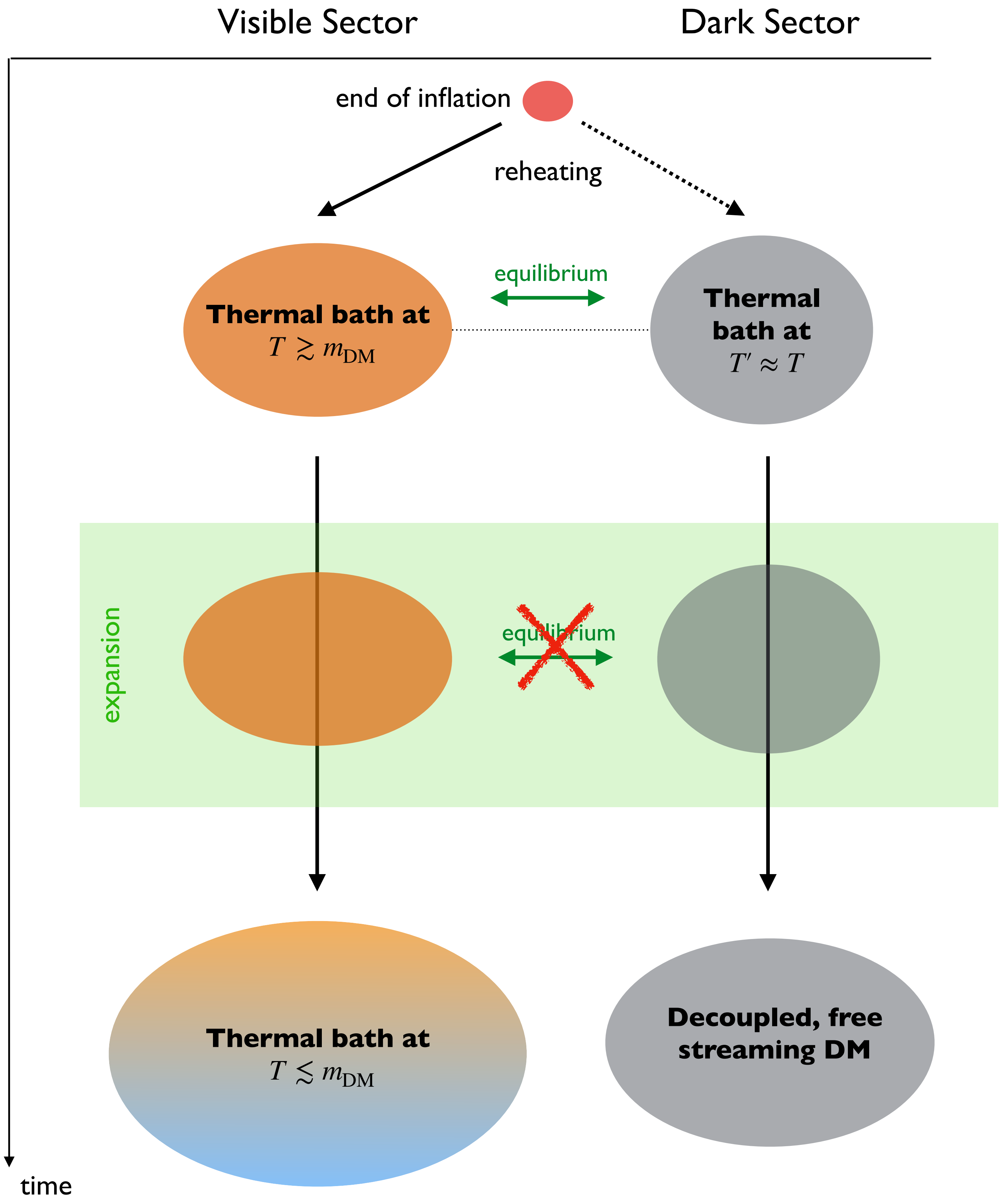
⇓

An efficient depletion is needed (freeze-out)

depletion to SM

„WIMP”

# FREEZE-OUT



## I. Natural

Comes out automatically from the expansion of the Universe

Naturally leads to cold DM

## II. Predictive

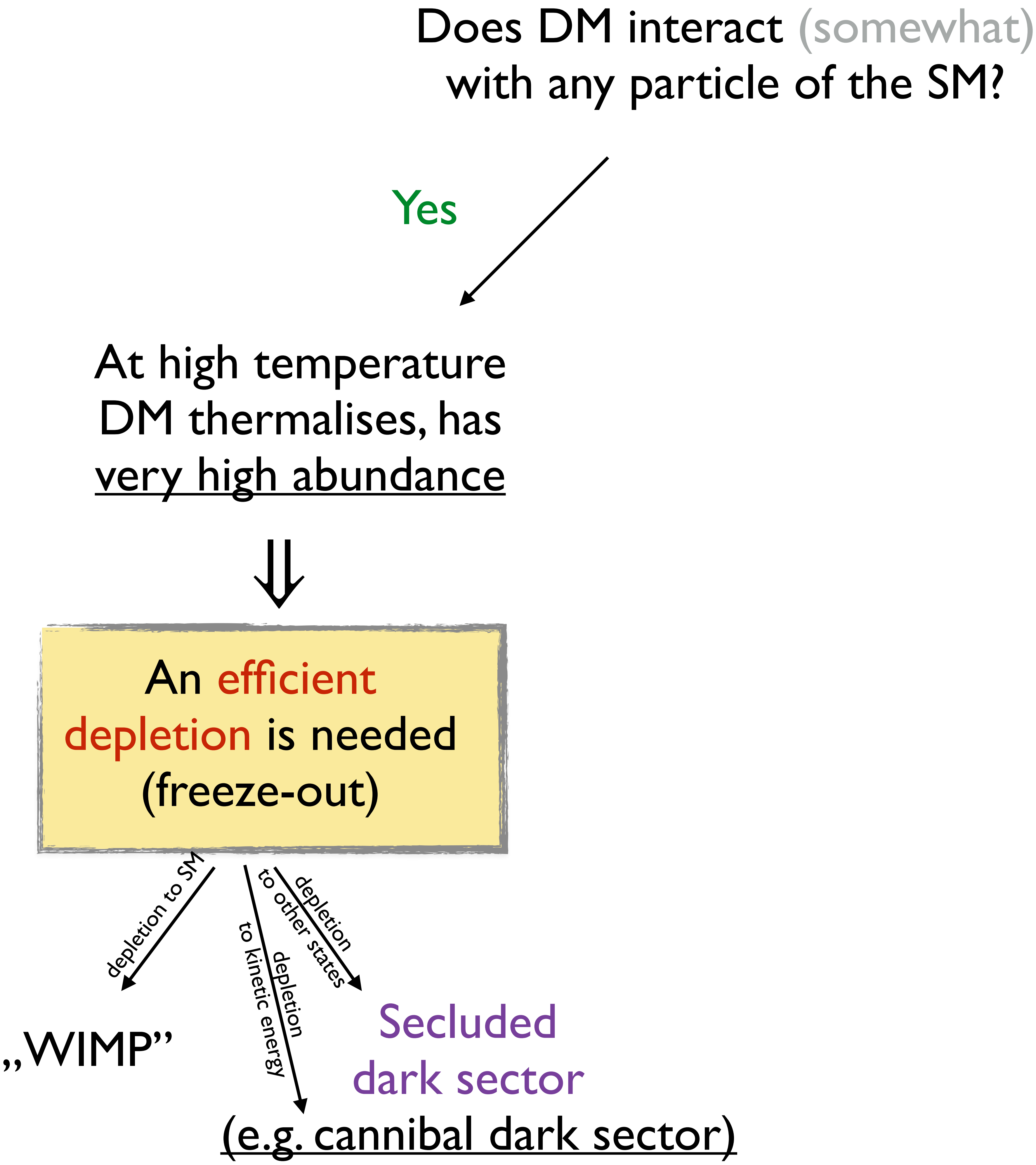
No dependence on initial conditions

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



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

Yes

At high temperature DM thermalises, has <u>very high abundance</u>

⇓

An efficient depletion is needed (freeze-out)

depletion to SM

„WIMP"

depletion to kinetic energy

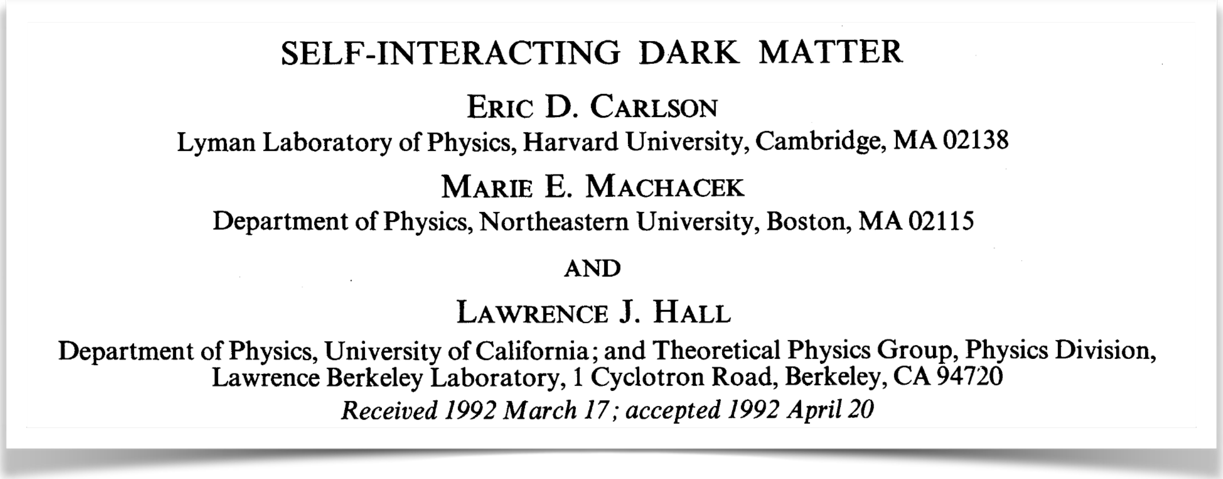
<u>(e.g. cannibal dark sector)</u>

depletion to other states

Secluded dark sector

# CANNIBAL DM

Explains depletion of DM solely through self number changing reactions!



SELF-INTERACTING DARK MATTER

ERIC D. CARLSON
Lyman Laboratory of Physics, Harvard University, Cambridge, MA 02138

MARIE E. MACHACEK
Department of Physics, Northeastern University, Boston, MA 02115

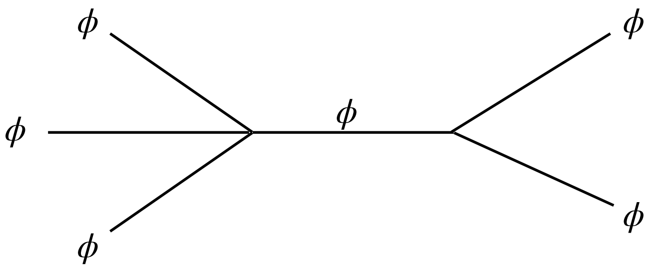
AND

LAWRENCE J. HALL
Department of Physics, University of California; and Theoretical Physics Group, Physics Division, Lawrence Berkeley Laboratory, 1 Cyclotron Road, Berkeley, CA 94720

*Received 1992 March 17; accepted 1992 April 20*

Simplest example, scalar $\phi$ with interactions (no coupling to SM!):

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



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

…, Hochberg et al. '14; …

cannibalisation: mass → kinetic energy

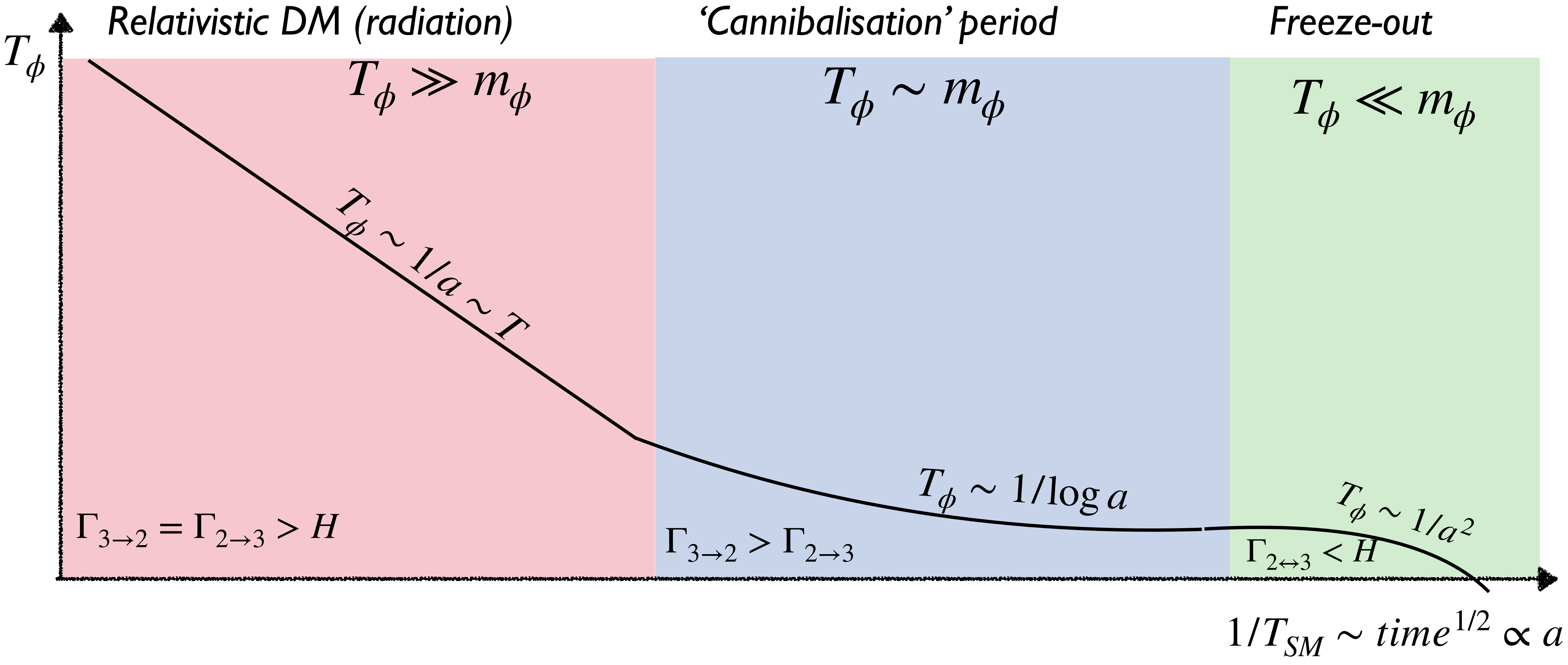
expansion: kinetic energy redshifts → depletion of $E$ of the dark sector

Problem: structure formation…

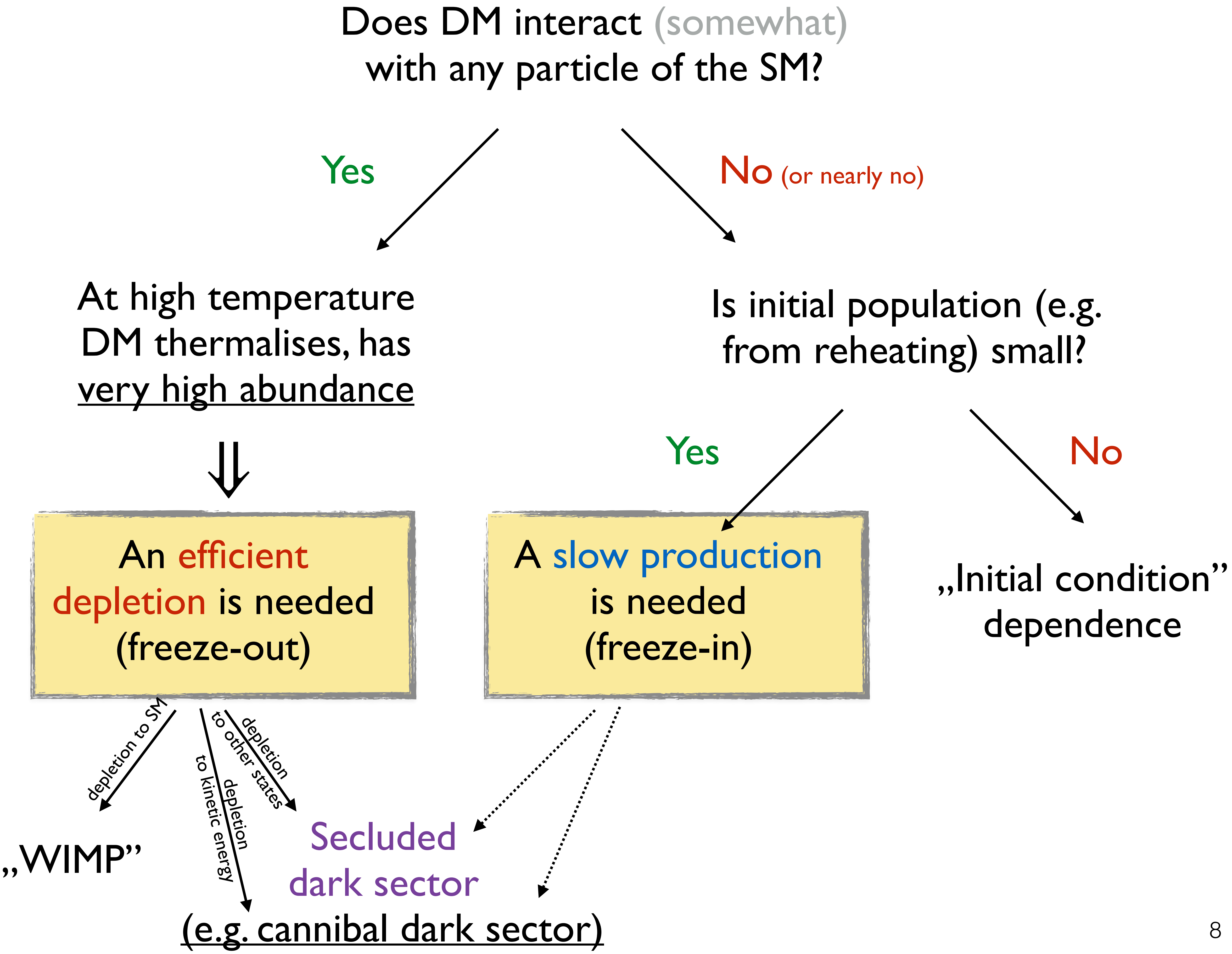
de Laix et al. '95

# 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

⇓

An efficient depletion is needed (freeze-out)

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

Yes

No

A slow production is needed (freeze-in)

„Initial condition" dependence

depletion to SM

depletion to kinetic energy

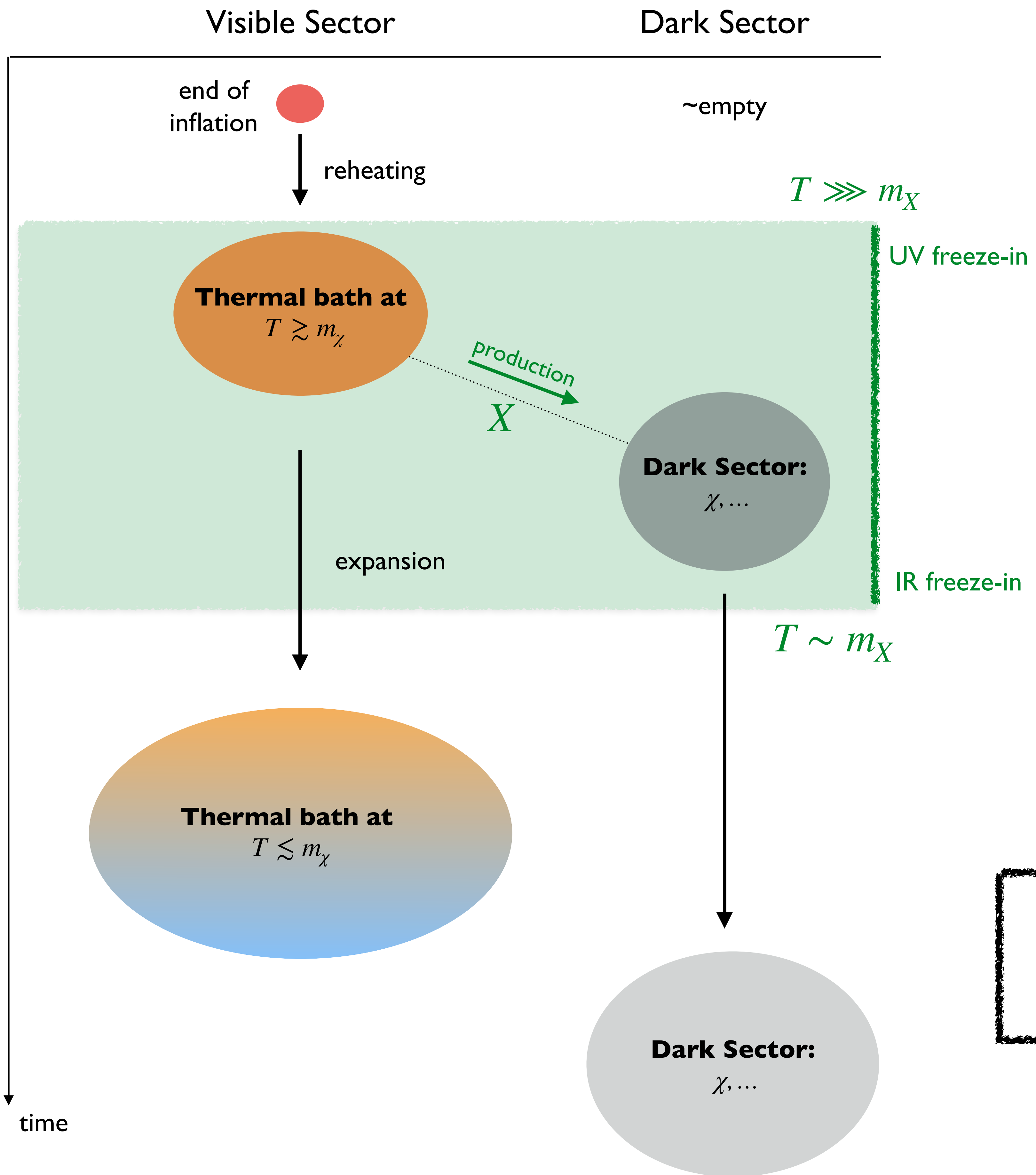
depletion to other states

„WIMP"

Secluded dark sector

(e.g. cannibal dark sector)

# WHAT IS FREEZE-IN?



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

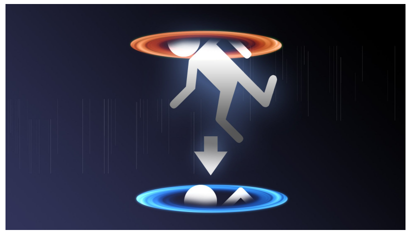
this is a standard production mechanism for e.g. sterile neutrino, gravitino, axino,…

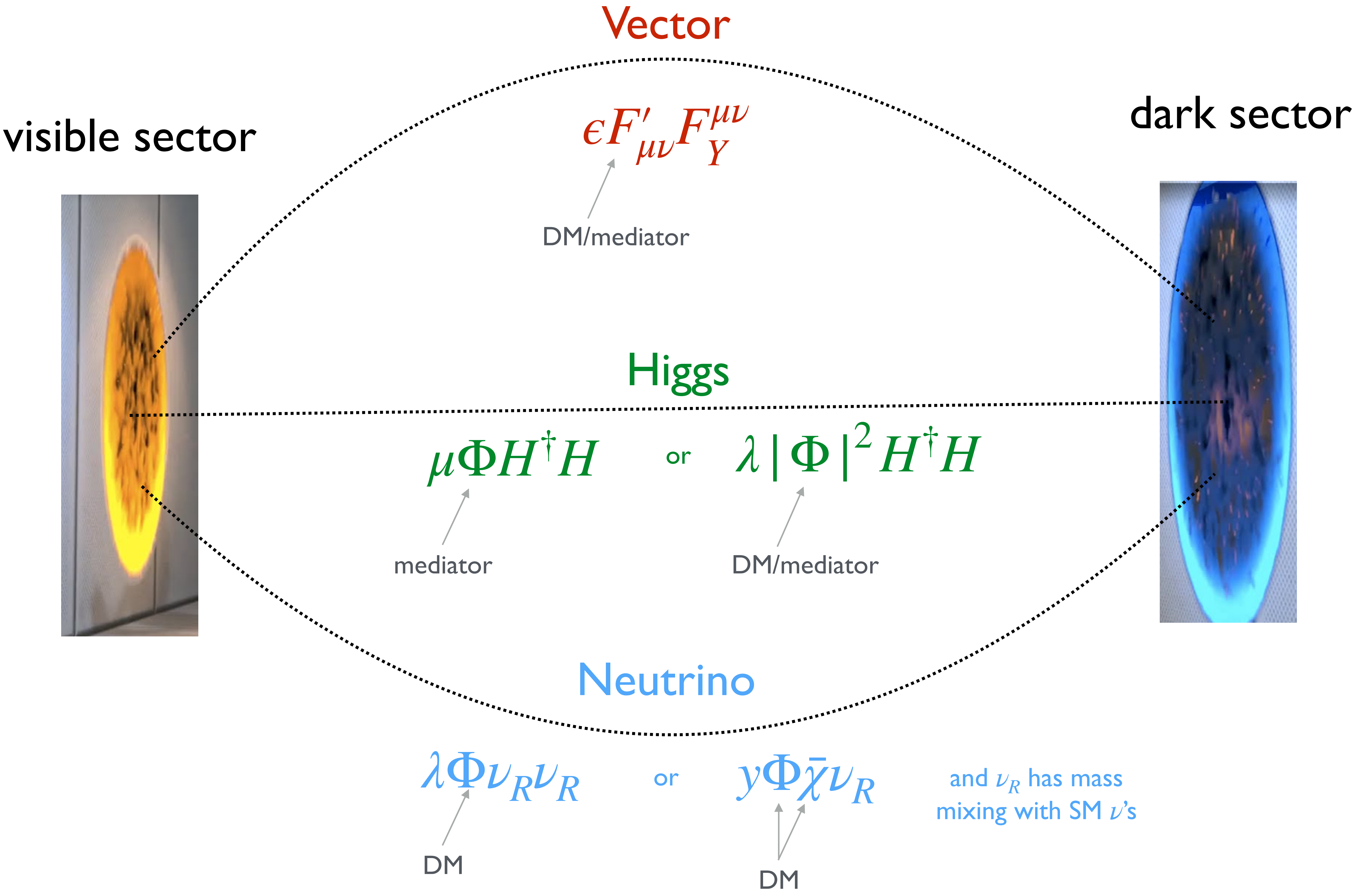
however, old works focused on what now people call UV freeze-in

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

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

# PORTALS





visible sector

dark sector

## Vector

$$\epsilon F'_{\mu\nu}F^{\mu\nu}_{Y}$$

DM/mediator

## Higgs

$$\mu\Phi H^{\dagger}H \quad \text{or} \quad \lambda|\Phi|^{2}H^{\dagger}H$$

mediator

DM/mediator

## Neutrino

$$\lambda\Phi\nu_{R}\nu_{R} \quad \text{or} \quad y\Phi\bar{\chi}\nu_{R}$$

DM

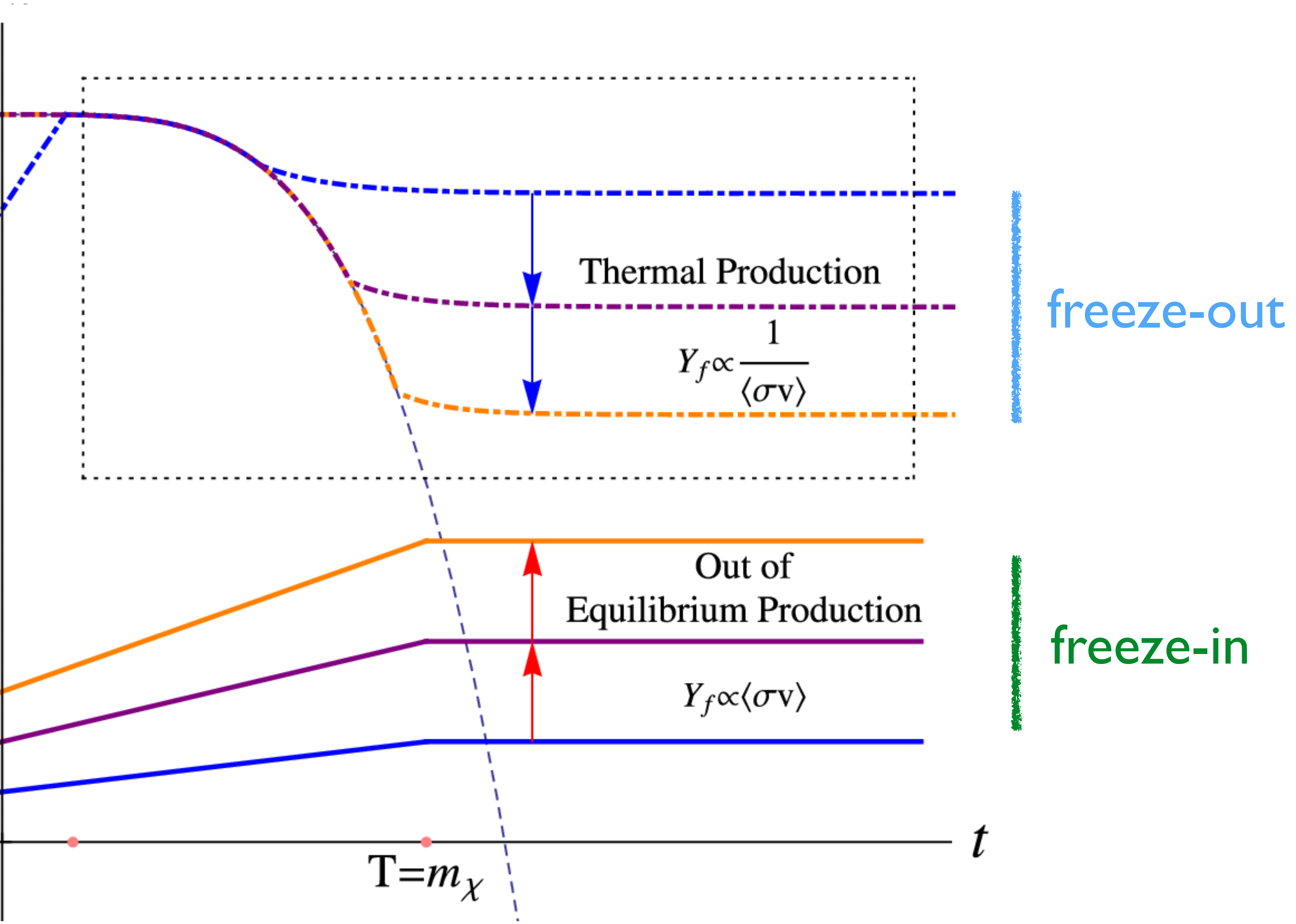
DM

and $\nu_R$ has mass mixing with SM $\nu$'s

*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 $f_\chi(p)$:

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

with initial condition:

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

The collision term:

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

„gain” term

(the simple one, describes production)

„loss” term

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

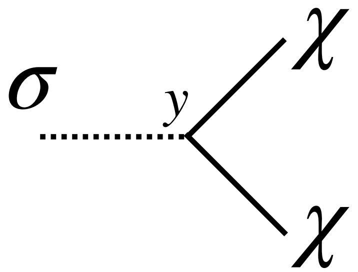
The collision term can also contain:

decays, annihilations, cannibalizations, …

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

# FREEZE-IN CALCULATION

<u>Example</u>: freeze-in from decay of $\sigma$ in equilibrium



$$\frac{x}{Y_\sigma^{\mathrm{eq}}}\frac{\mathrm{d}Y}{\mathrm{d}x} = \underline{2\,\frac{\Gamma_{\sigma\to\chi\chi}}{H}\frac{K_1(x)}{K_2(x)}} \quad \Rightarrow \quad \Omega_\chi h^2 \simeq 4.48\times 10^8 \frac{g_\sigma}{g_{*s}\sqrt{g_*}}\frac{m_\chi}{\mathrm{GeV}}\frac{M_{\mathrm{P}}\,\Gamma_{\sigma\to\chi\chi}}{m_\sigma^2}$$

$Y = n/s$ independent!

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

Why is this IR dominated?

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

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

and produced DM ∝ time × rate: $\frac{n_\chi}{T^3} \simeq t\,\Gamma_{\sigma\to\chi\chi}$

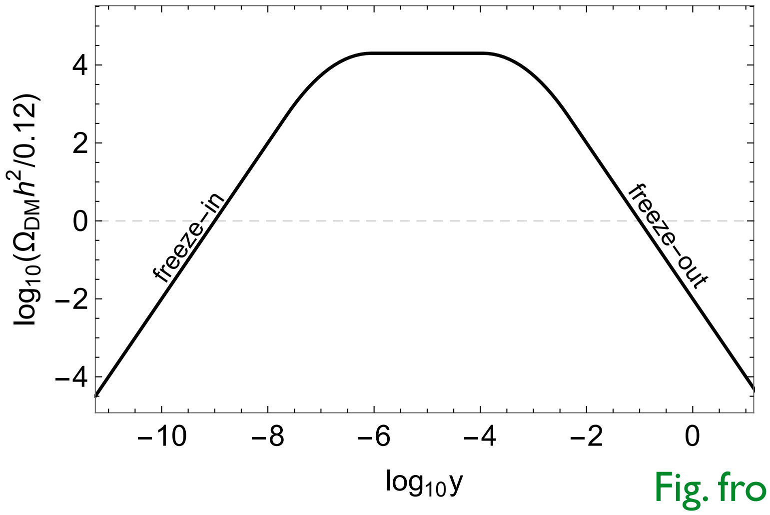


Fig. from 1706.07442

# CANNIBAL FREEZE-IN

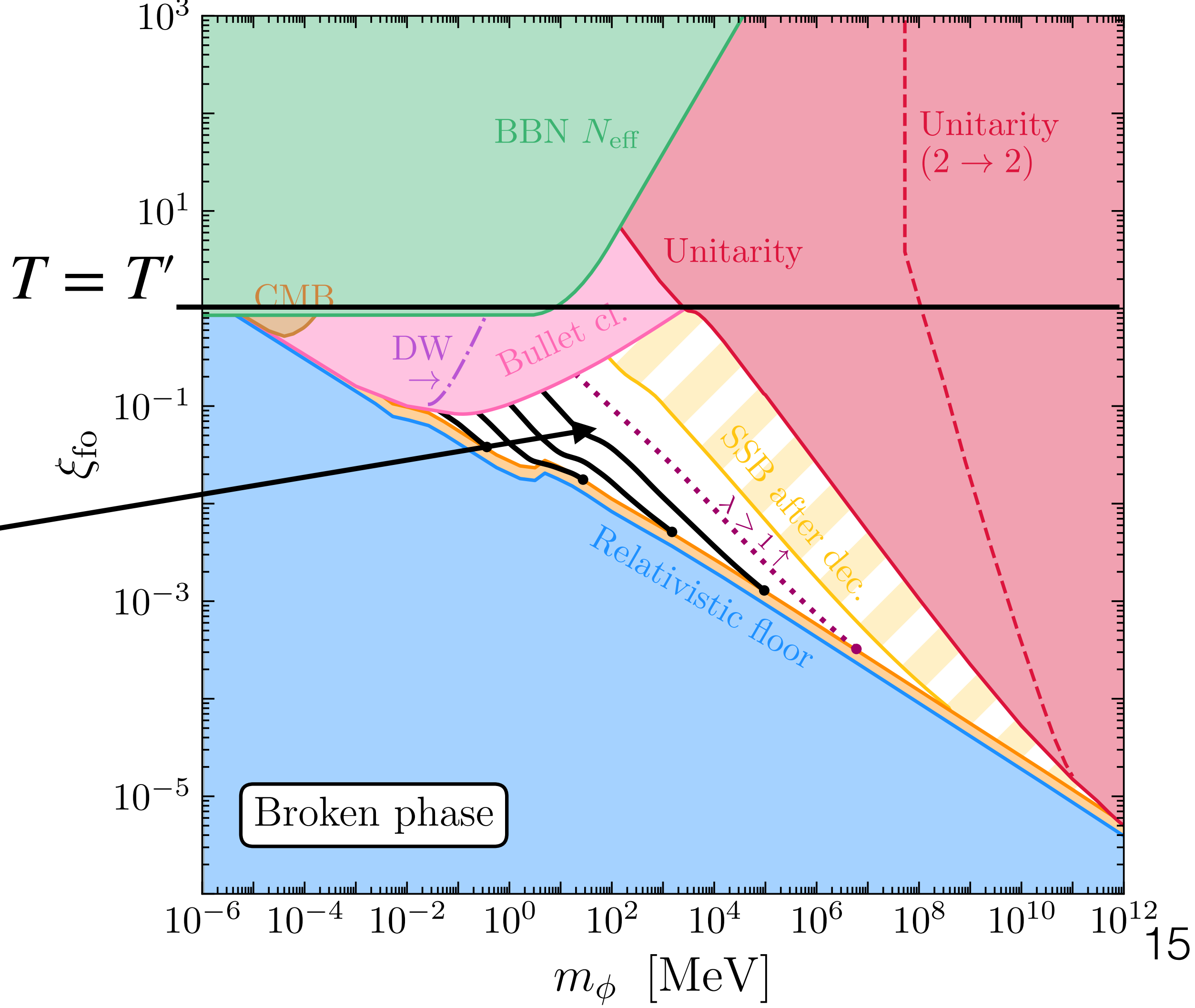
# EXAMPLE: SCALAR SINGLET DM

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

| | |
|---|---|
| $\langle\varphi\rangle = 0$ & $\lambda_{h\varphi} \gtrsim 10^{-4}$ | „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 → Higgs mixing terms |

Hufnagel, Tytgat '22

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

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

| | |
|---|---|
| $\langle\varphi\rangle = 0 \ \& \ \lambda_{h\varphi} \gtrsim 10^{-4}$ | „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 → Higgs mixing terms |

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:

$$\frac{Y'_\varphi}{Y_\varphi} = \frac{1}{x\tilde{H}}\Big(\langle C_{h\to\varphi\varphi}\rangle + \langle C_{hh\to\varphi\varphi}\rangle + \langle C_{3\leftrightarrow 2}\rangle\Big)$$

Cannibal

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

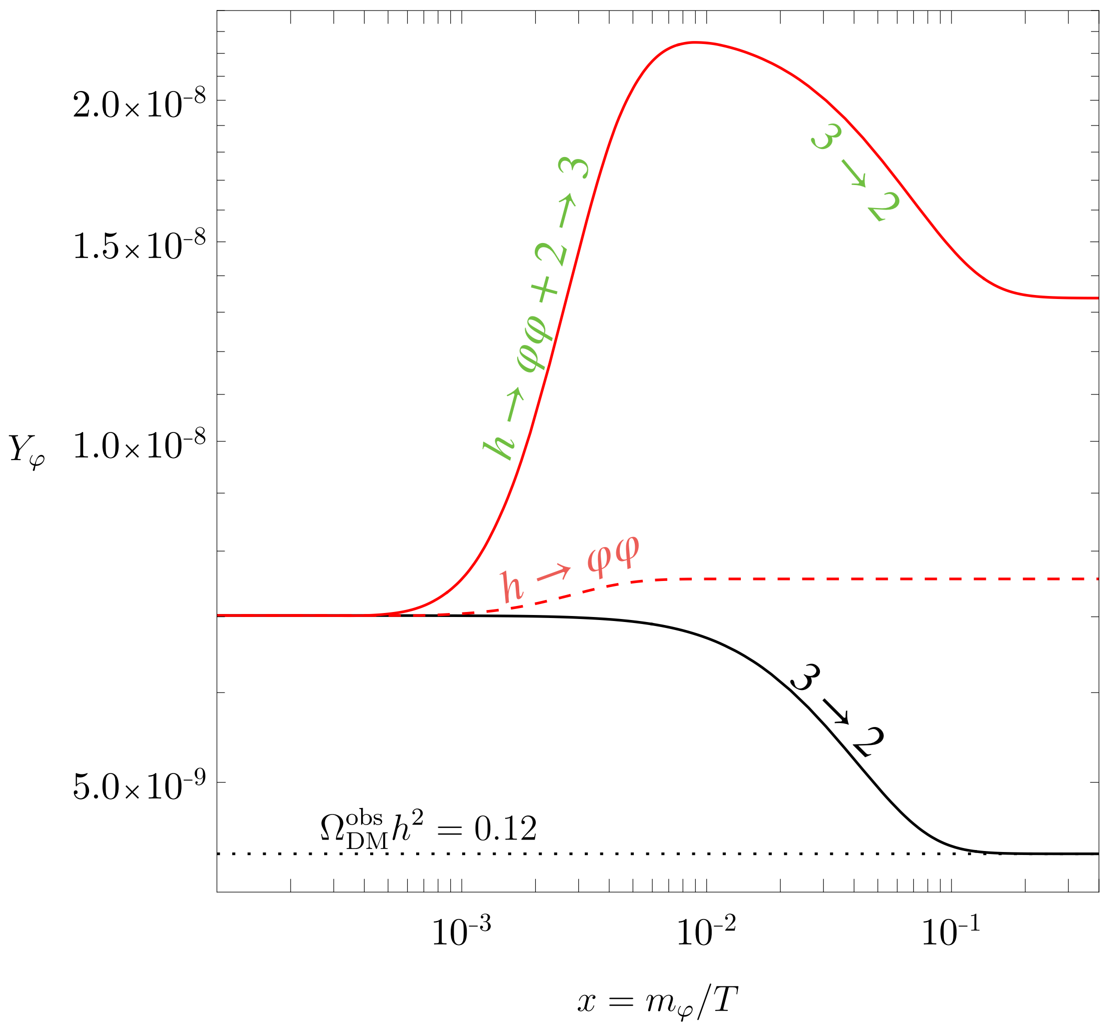
Freeze-in Freeze-in/out El. scattering

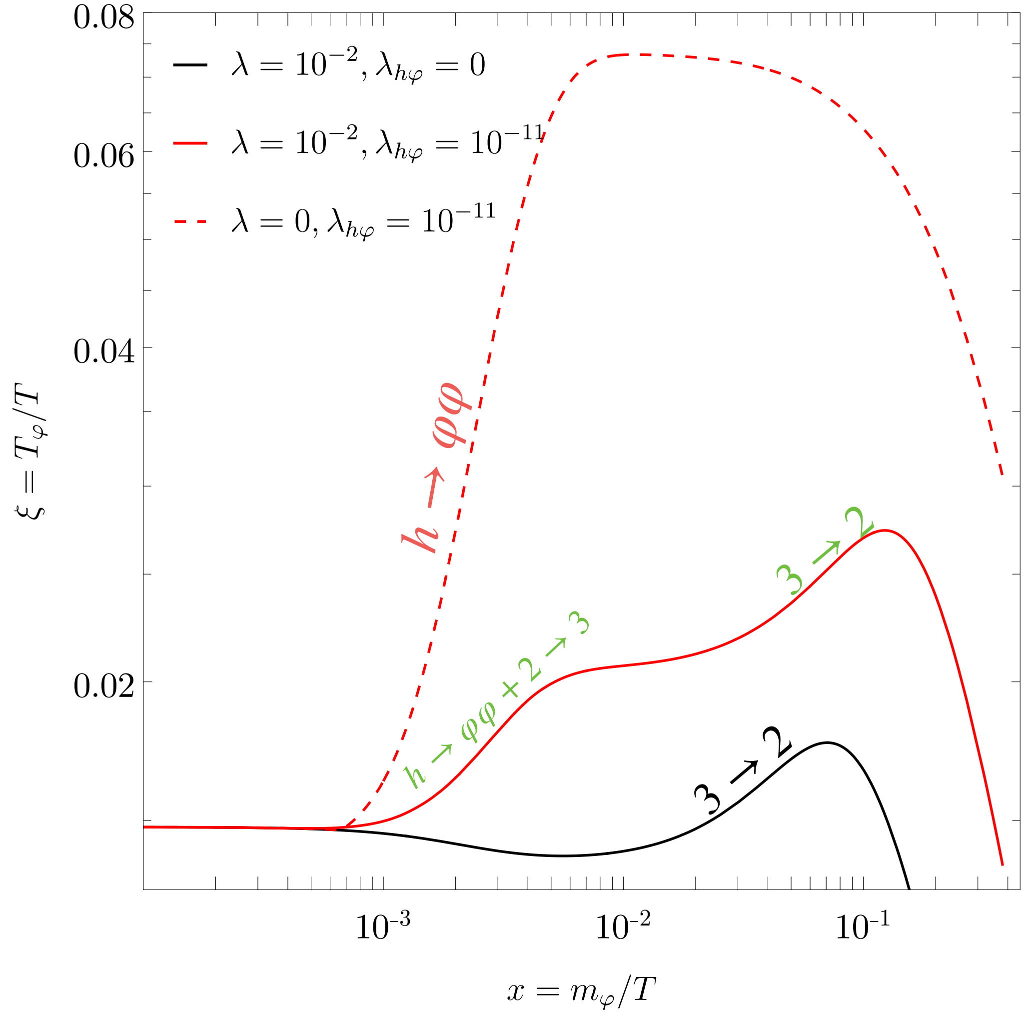
**E. Cervantes** and **AH** 2407.12104

see also Ghosh et al. '22

# BOOSTING FREEZE-IN

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





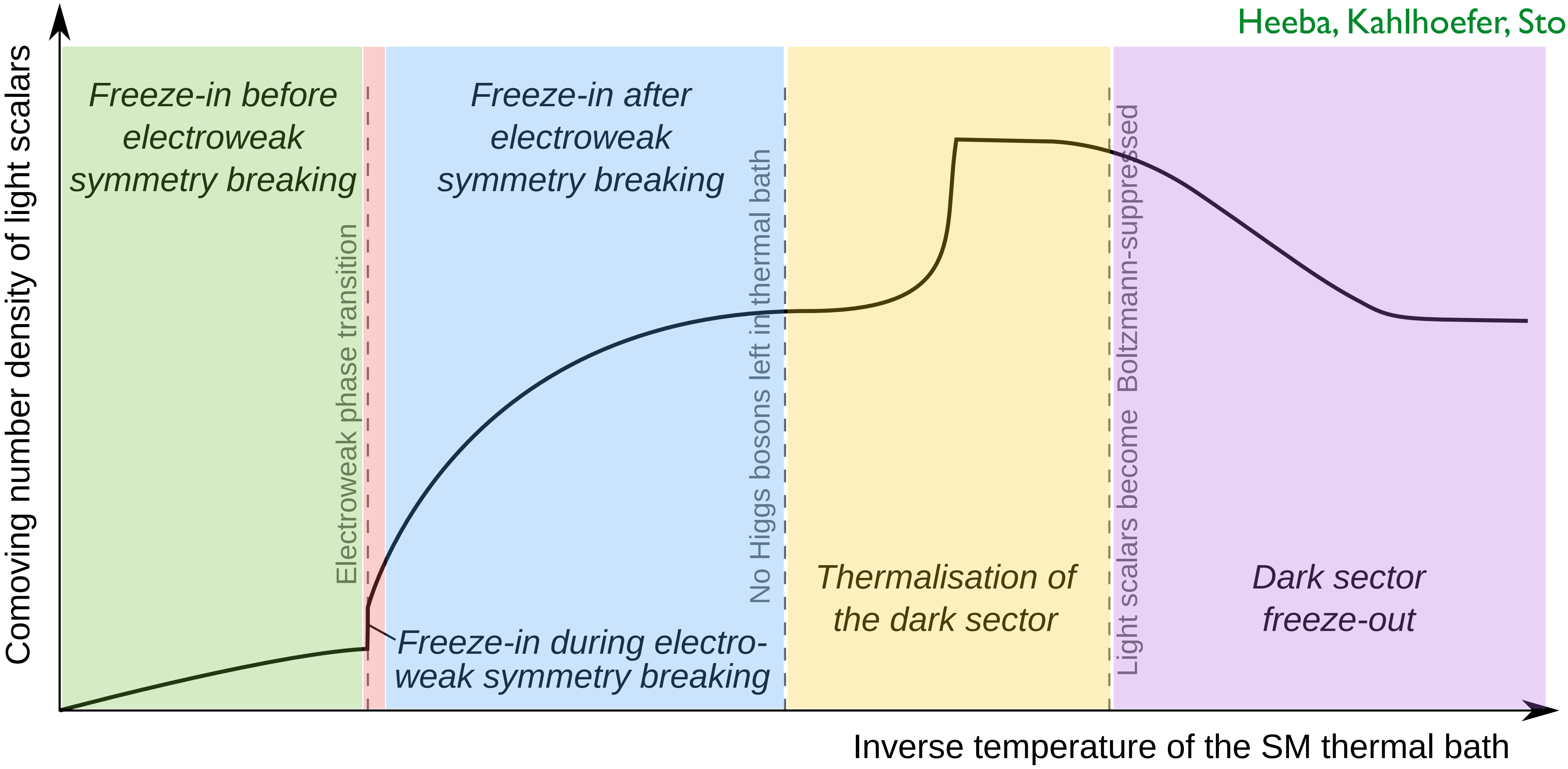
only cannibalization only freeze-in cannibal+freeze-in

**E. Cervantes** and **AH** 2407.12104 , see also Bernal ’05

# MORE COMPLETE PICTURE

Illustration for production through Higgs portal:

Heeba, Kahlhoefer, Stocker 1809.04849



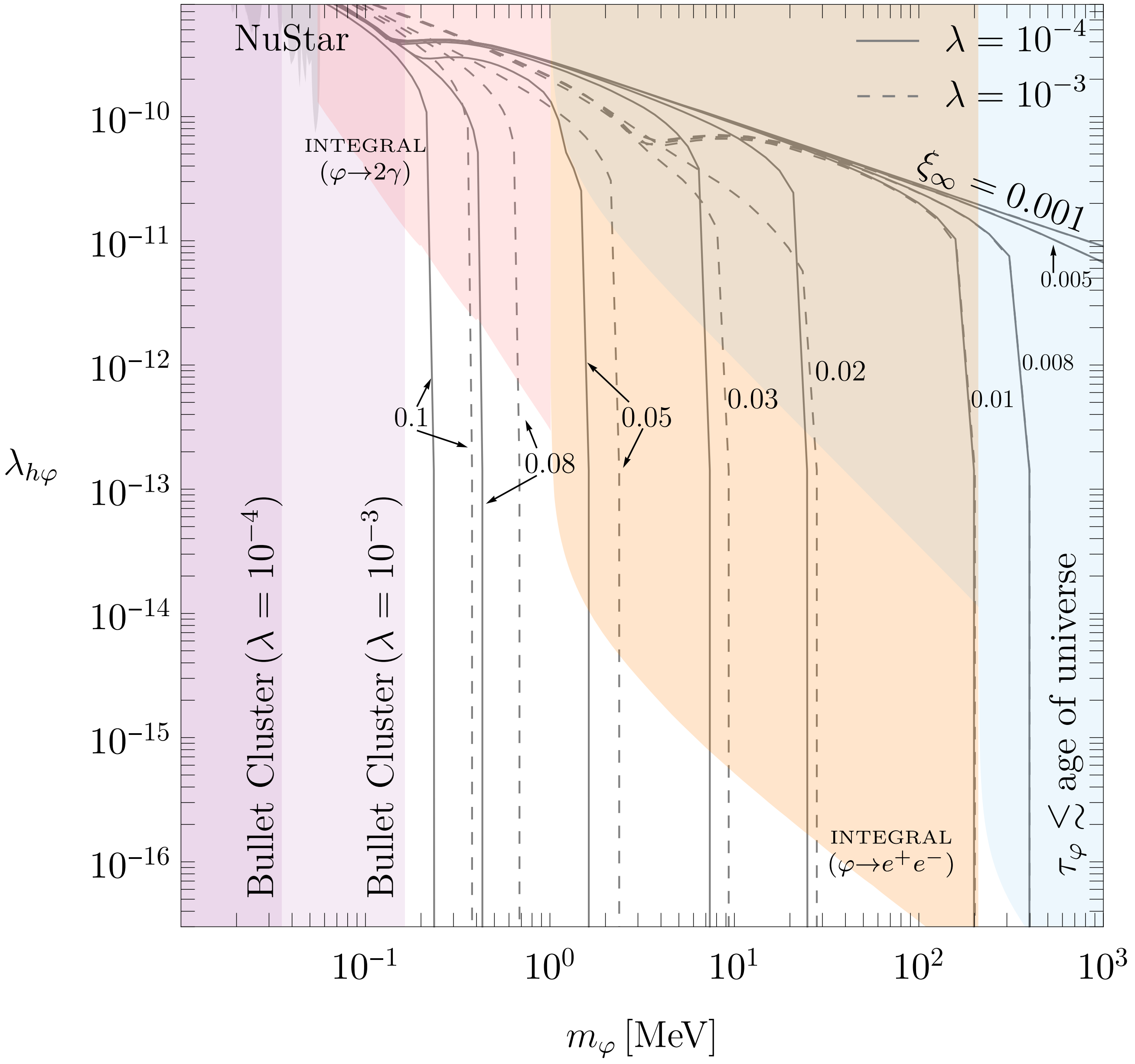
One should be careful to include such (potentially relevant) effects!

# THIS MODEL HAS DECAYING DM

$\mathbb{Z}_2$ breaking $\Rightarrow$ $\varphi$ 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 $\phi$

$$\mathscr{L} \supset \underbrace{-\frac{1}{3!}g_s(S^3+(S^*)^3)-\frac{\lambda_s}{4}|S|^4}_{\text{DM self interactions}} \underbrace{-A_{\phi s}\phi|S|^2-\frac{\lambda_{\phi s}}{2}\phi^2|S|^2}_{\text{thermalisation between } \phi \text{ and } S} - \underbrace{B_{\phi h}\phi|H|^2}_{\text{Portal}}$$

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

$$\begin{aligned} \phi &\to \phi + \theta h \\ h &\to h - \theta \phi \end{aligned}$$

→ $\phi$ couples to matter in a Higgs-like way

Such a model exhibits new dynamics + detection signals

# BOLTZMANN EQUATIONS

Freeze-in
DM-mediator interactions
DM self-interactions

**DM** evolution

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

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

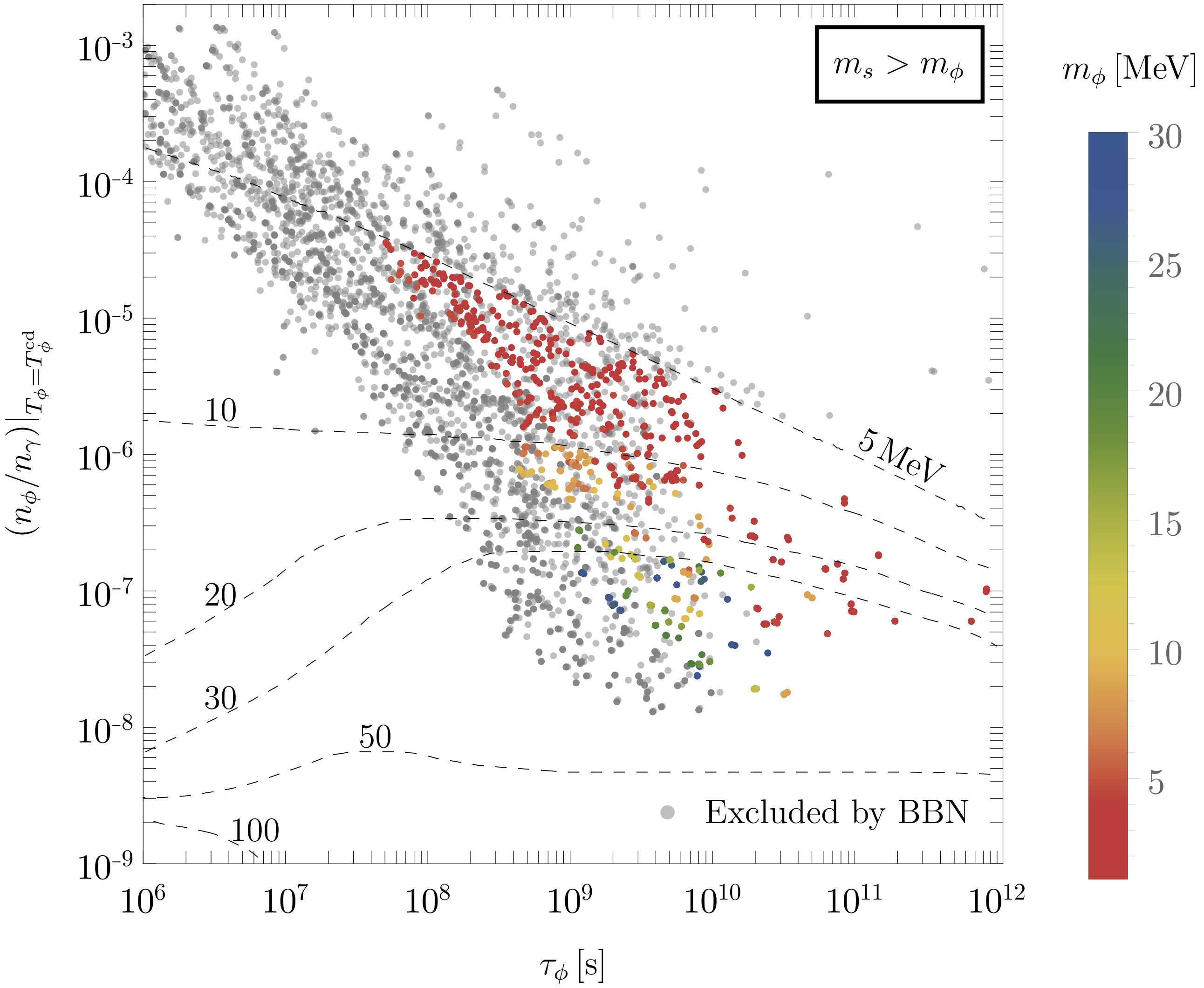
**Mediator** evolution

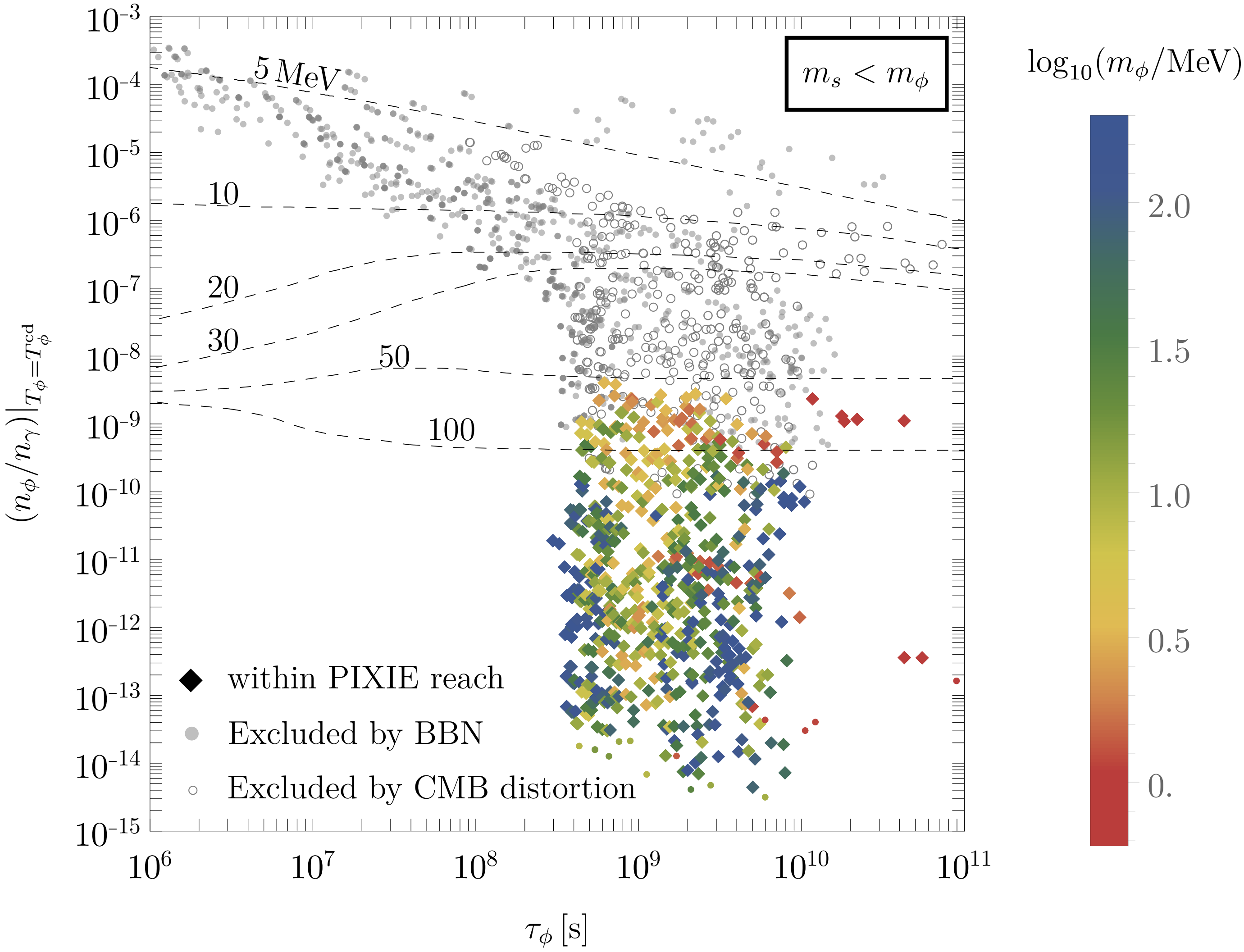
$$\frac{Y_\phi'}{Y_\phi} = \frac{1}{x\,\tilde{H}}\left(\langle C_{h\to\phi SS^*}\rangle + \langle C_{\mathrm{sm\ sm}\to\mathrm{sm}\,\phi}\rangle + \langle C_{\phi\phi\leftrightarrow SS^*}\rangle\right)\,,$$

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

# BBN & CMB CONSTRAINTS

**Mediator** is decaying to SM:
different phenomenology for two mass hierarchies between $S$ (the DM) and $\phi$





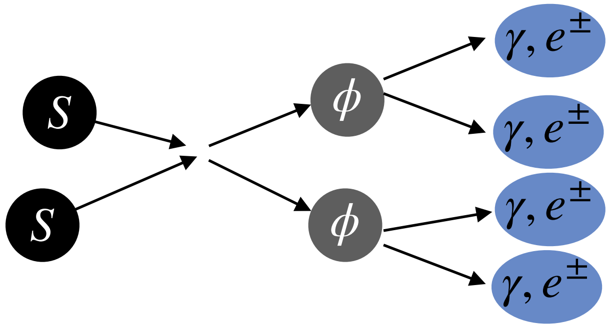
Resulting constraints are significant, but many viable points found in a scan & some with prospects of CMB distortion in reach of PIXIE

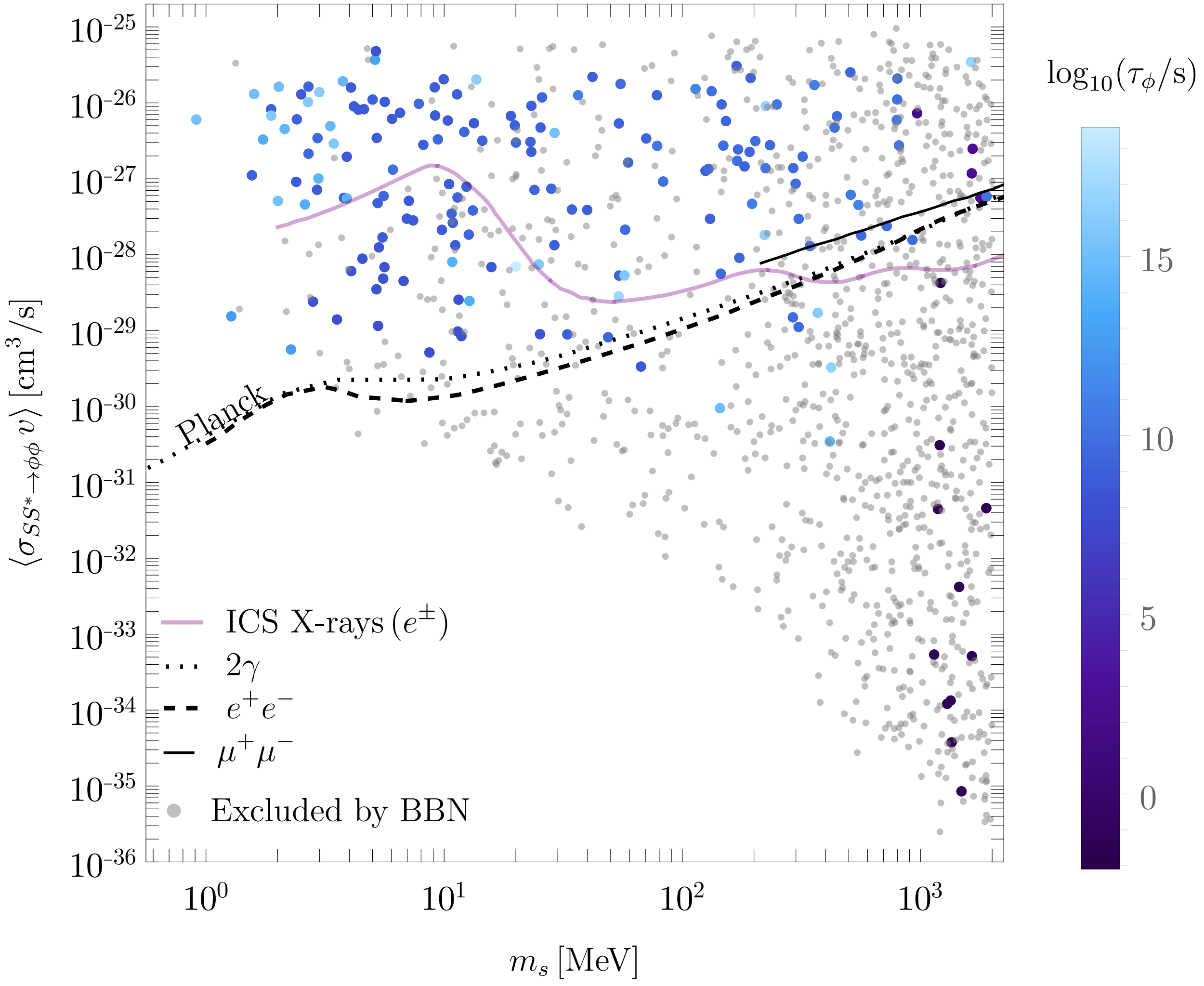
(The Primordial Inflation Explorer)

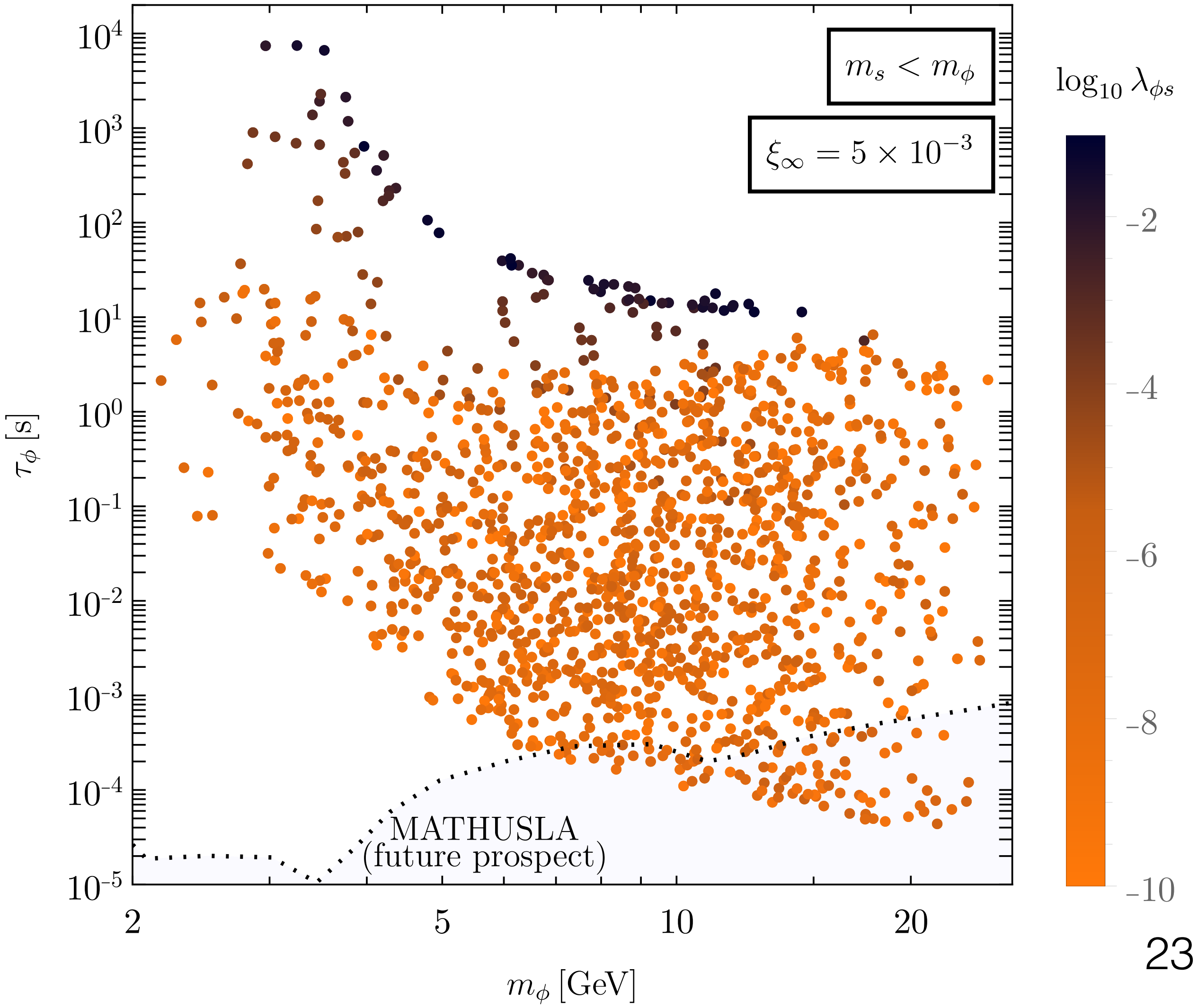
# DM & MEDIATOR DETECTION

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

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







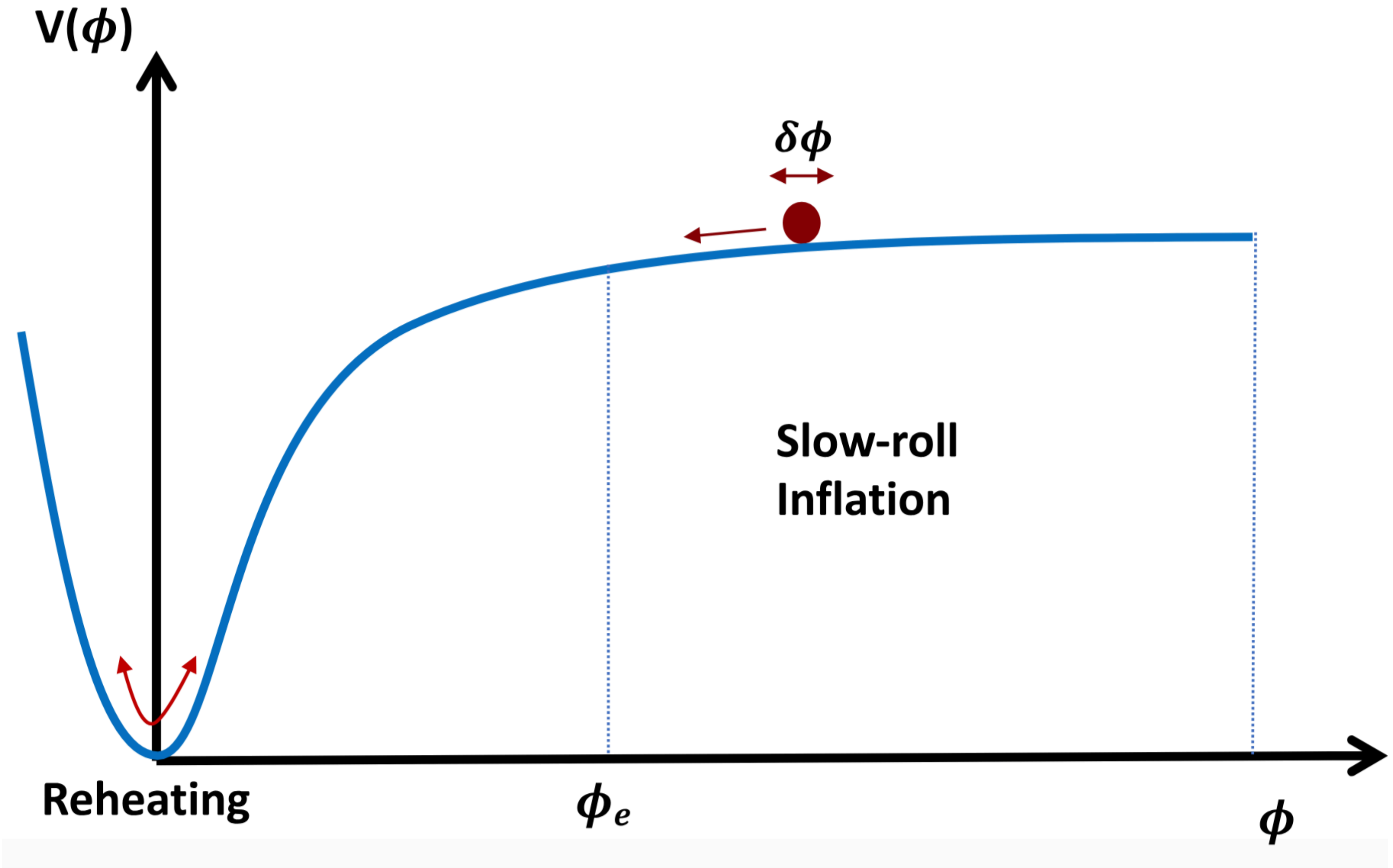
# CANNIBAL FREEZE-IN

## NON-STANDARD COSMOLOGY

# HOW DOES THE INFLATION END?

The field $\phi$ that drives inflation $\left(a \propto e^{Ht}\right)$ 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

→ $T_{\mathrm{RH}}$

# WHAT DO WE KNOW ABOUT $T_{RH}$?

In standard ($\Lambda$CDM or not) cosmology: $10^9\,\mathrm{GeV} \lesssim \mathrm{T_{RH}} \lesssim 10^{15}\,\mathrm{GeV}$

(If reheating is instantaneous;
good for leptogenesis, bad for gravitino production…)

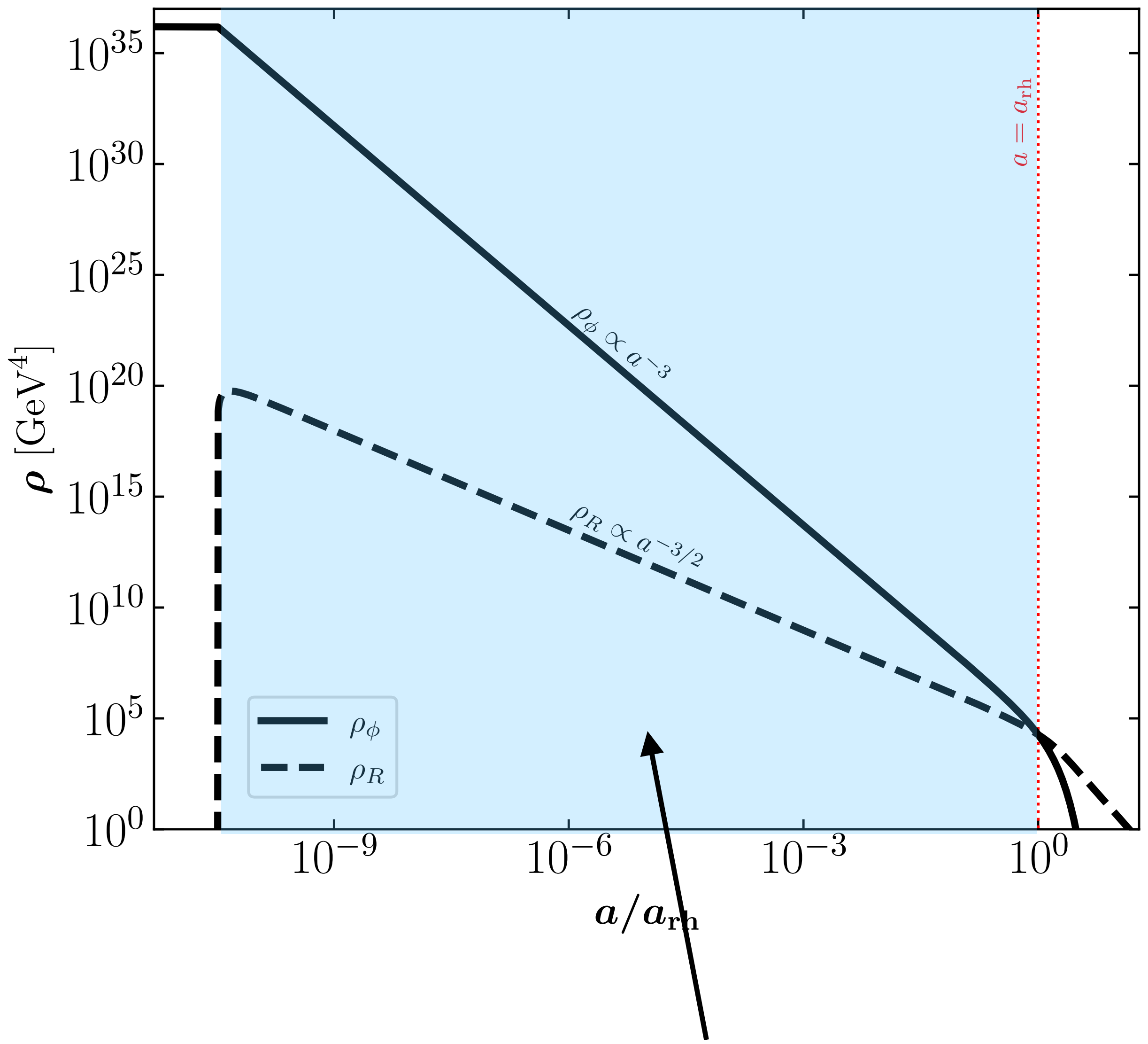
From observations we know only that: $T_{\mathrm{RH}} \gtrsim \mathcal{O}(\mathrm{few})\,\mathrm{MeV}$

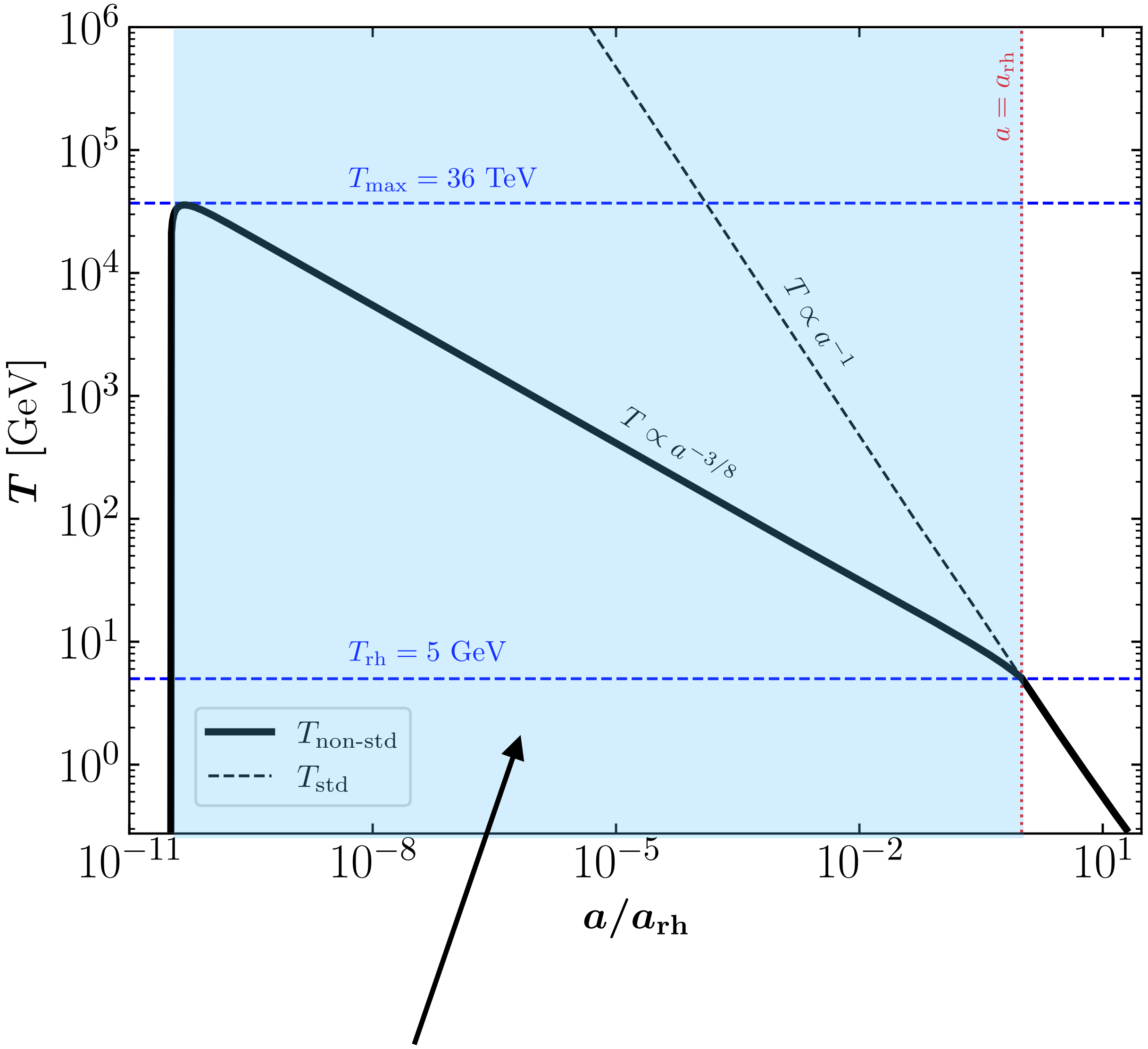
Standard cosmology is standard-by-convention
(unlike the Standard Model of particle physics)

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

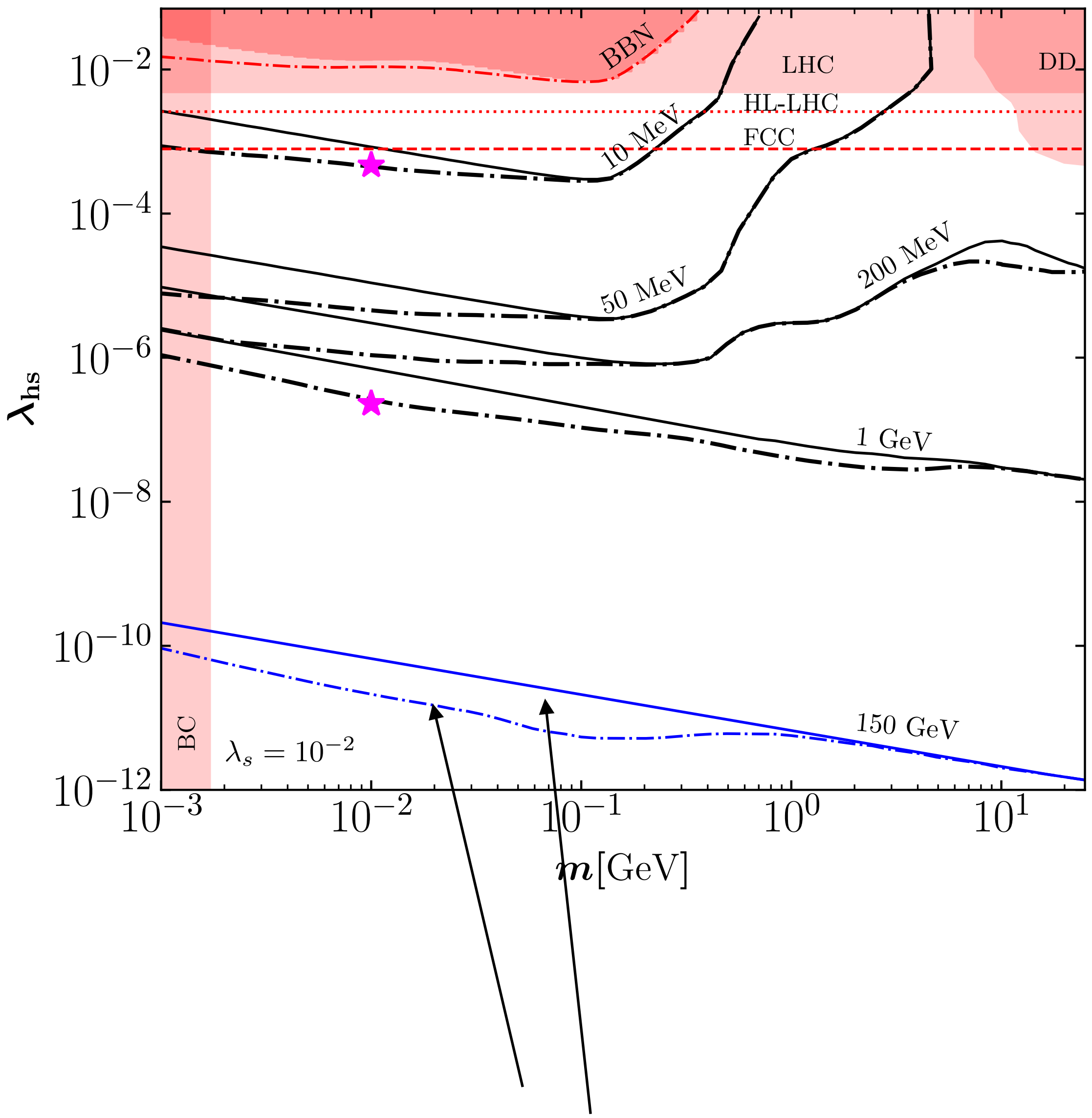




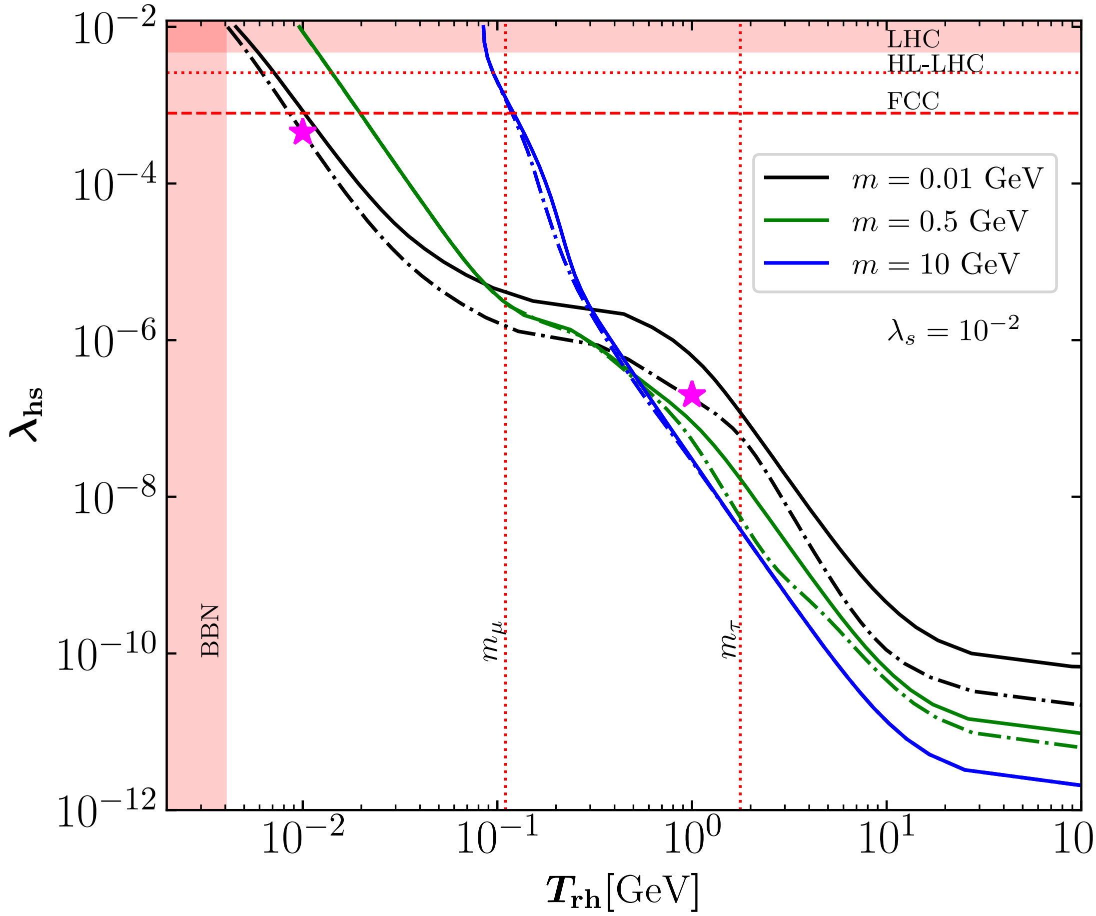
Strongly affects DM produced during this period

# IMPACT ON PHENOMENOLOGY

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

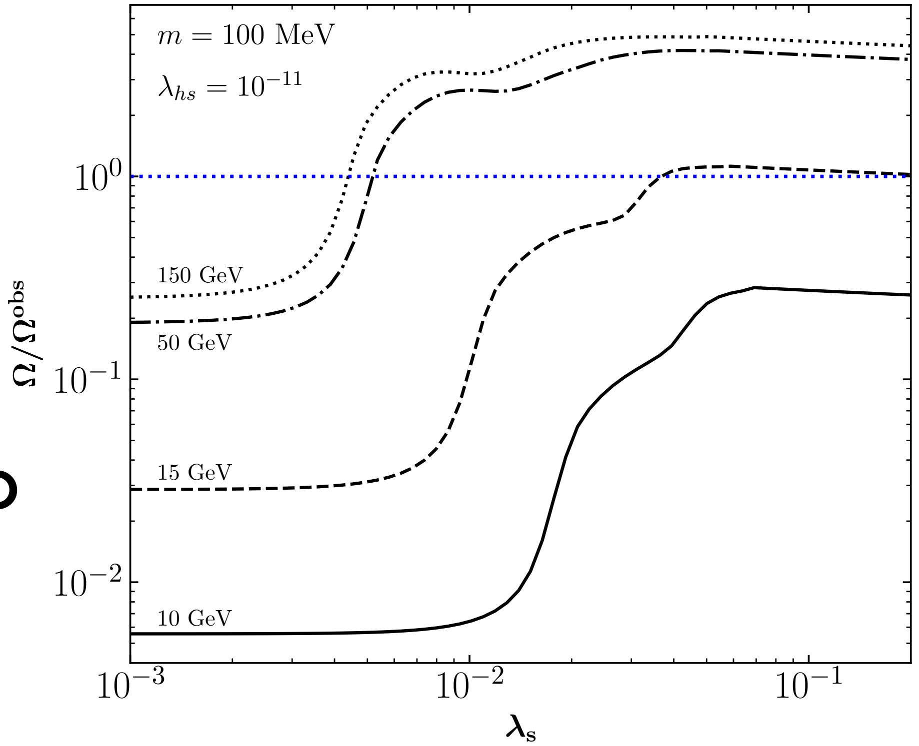


on/off cannibal interactions



Effect of low reheating T

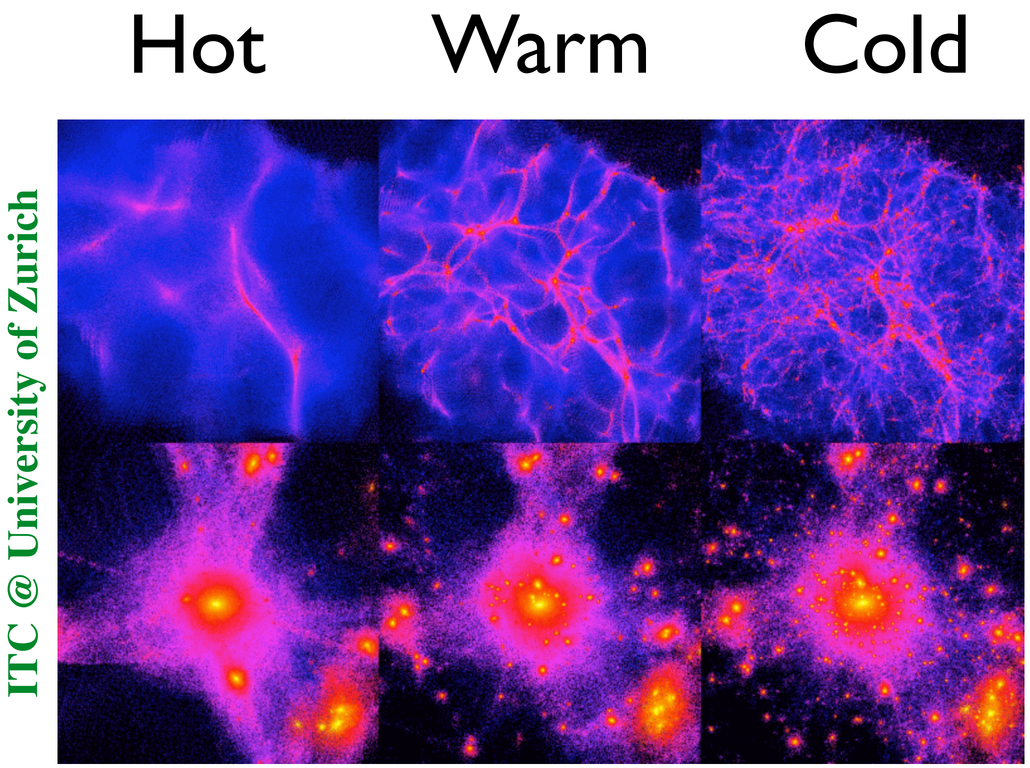
change in $\Omega h^2$ due to cannibal interactions



## IDEA:

## MAKE DM COOL AGAIN

# DM & LSS



ITC @ University of Zurich

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

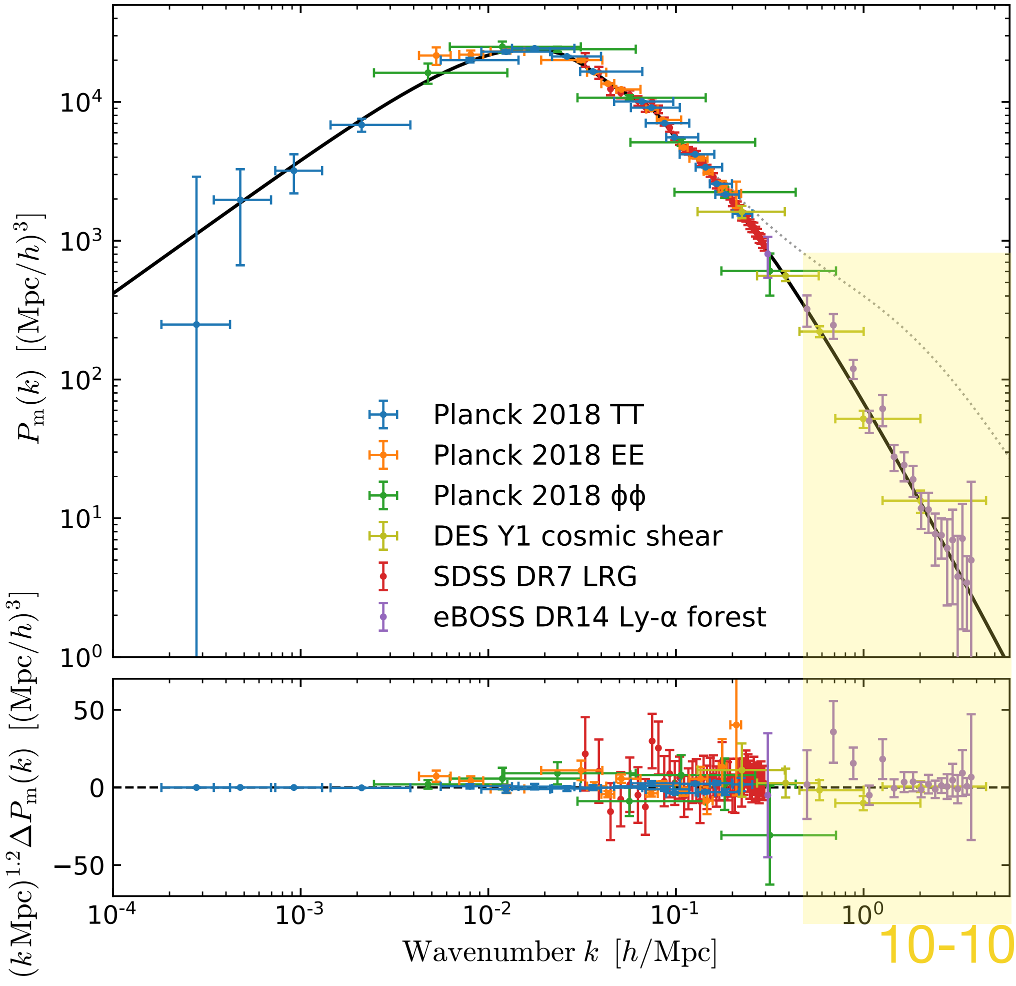
- A particle can be light (e.g. axion), but if produced via a non-thermal mechanism, it can be **cold** with $p \approx 0$
- Conversely, a sterile $\nu$ of a few keV mass produced via the Dodelson-Widrow mechanism is **warm**

## Observationally: matter power spectrum

**Comoving free-streaming length**. integrated distance a DM particle travels from its production until matter-radiation equality:

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

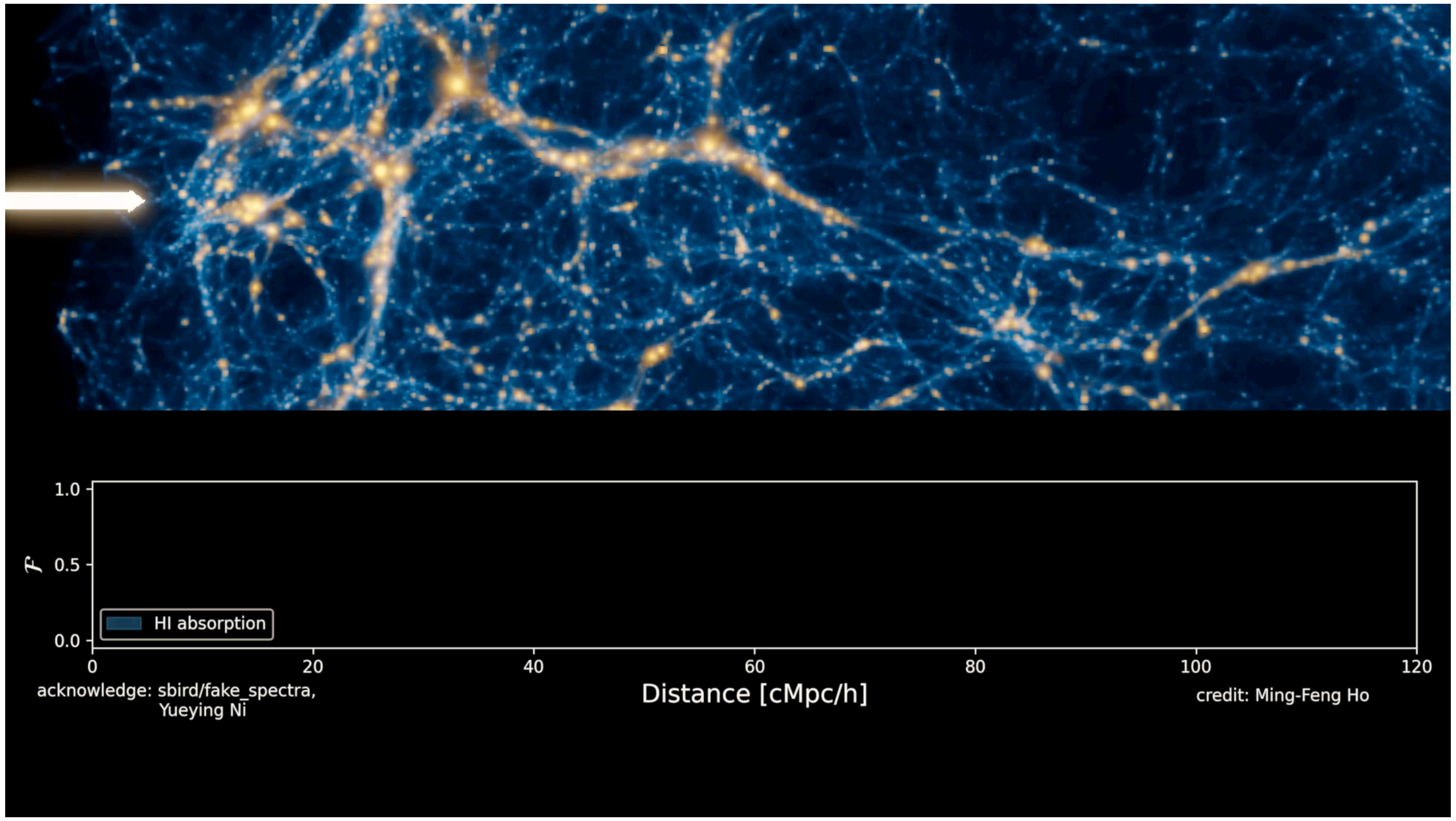
- **Hot Dark Matter:** $\lambda_{\rm fs} \sim$ tens of Mpc (smooths out fluctuations ~ galaxy cluster scales).
- **Warm Dark Matter:** $\lambda_{\rm fs} \sim$ sub-Mpc (smooths out small dwarf galaxy scales).
- **Cold Dark Matter:** $\lambda_{\rm fs} \to 0$ (negligible free-streaming; collapses at all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

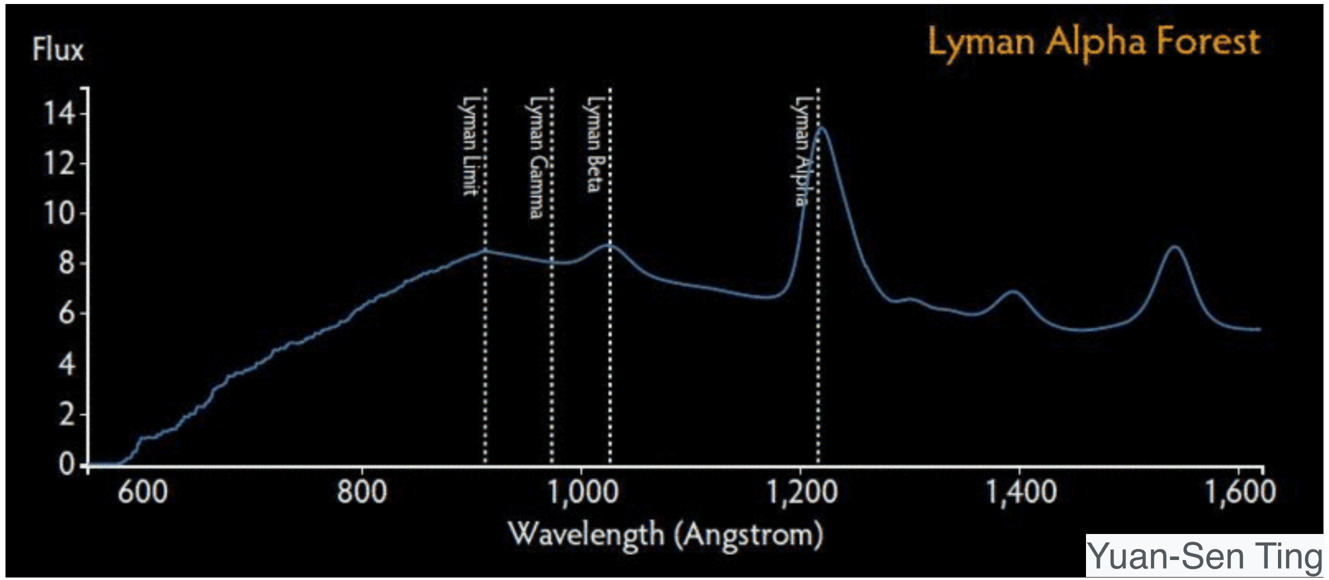


10-100 kpc

# Warm DM & Lyman-$\alpha$

In particular, large wavenumber $k$ (i.e. small scales) are well measured through the Lyman-$\alpha$ 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

$1215.67$ Å

that is redshifted depending on the distance

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

# LYMAN-$\alpha$ LIMITS ON FI AND FO

If $\lambda_{\rm fs}$ 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

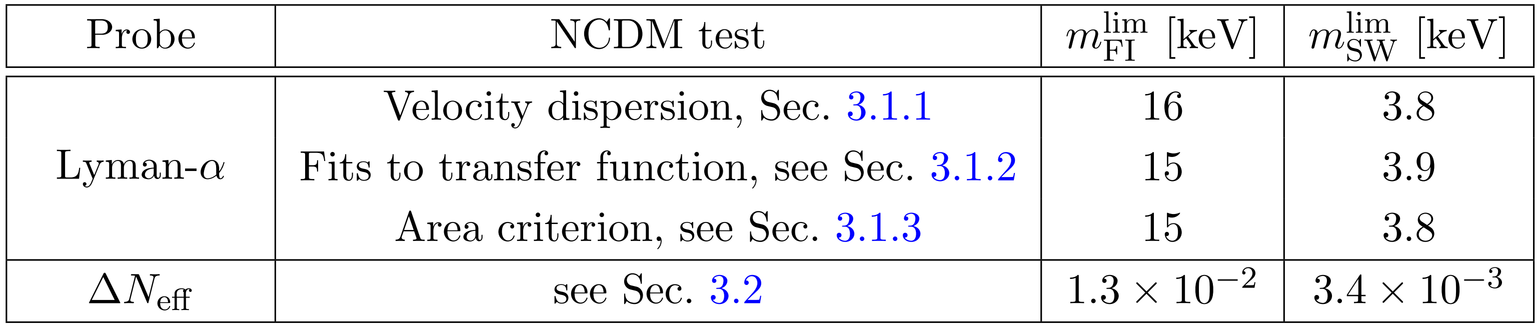
$$m_{\rm WDM}^{\rm Ly-\alpha} \gtrsim 2 \div 6\,{\rm keV}$$

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 | $m_{\rm FI}^{\rm lim}$ [keV] | $m_{\rm SW}^{\rm lim}$ [keV] |
|---|---|---|---|
| Lyman-$\alpha$ | 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 |
| $\Delta N_{\rm eff}$ | see Sec. 3.2 | $1.3 \times 10^{-2}$ | $3.4 \times 10^{-3}$ |

Decant et al. '21

# SECLUDED DARK SECTOR WITH $T' < T$ ?

The Lyman-$\alpha$ limits „warmness” ⇒ 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 → 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 → DM+DM re-couples sectors
- If Γ > H, asymmetry is erased ($T'/T \to 1$)
- 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

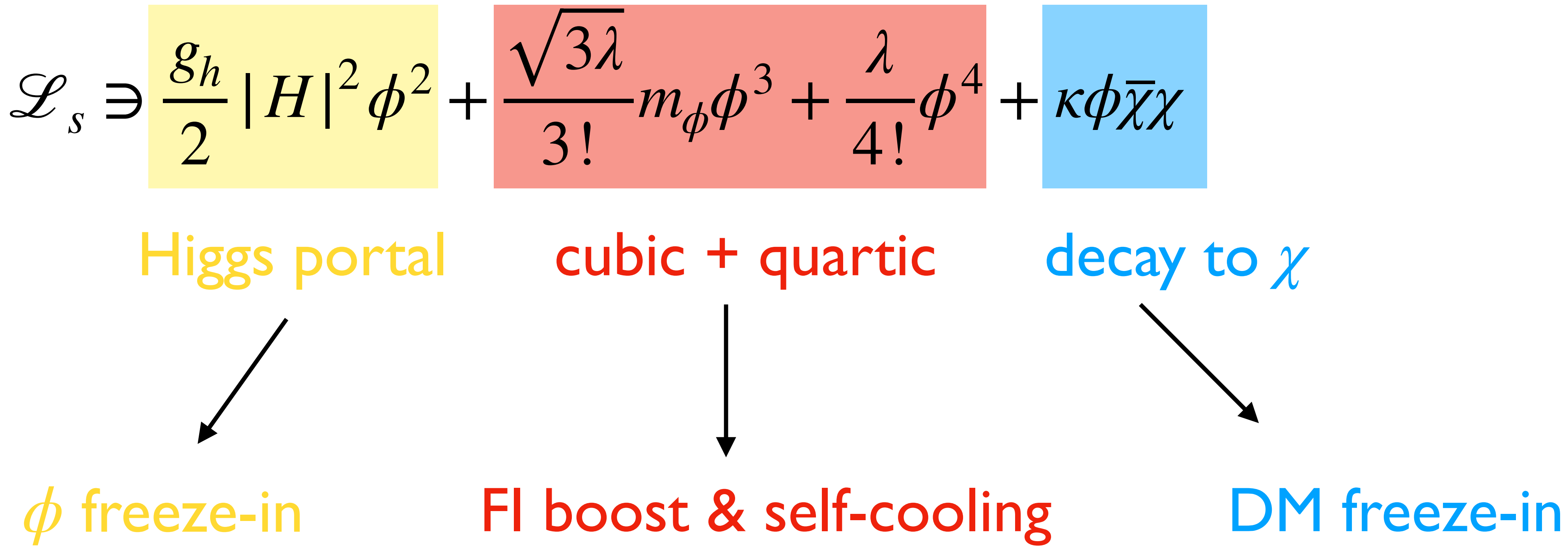
- Portal couplings must satisfy $\varepsilon \lesssim 10^{-7}–10^{-9}$
- Direct detection and collider tests become inaccessible

# WHAT IF CANNIBAL $\phi$ 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 $\phi^3$ or a non-abelian vector e.g. SU(N)

In the following we take the case:



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

Higgs portal

cubic + quartic

decay to $\chi$

$\phi$ freeze-in

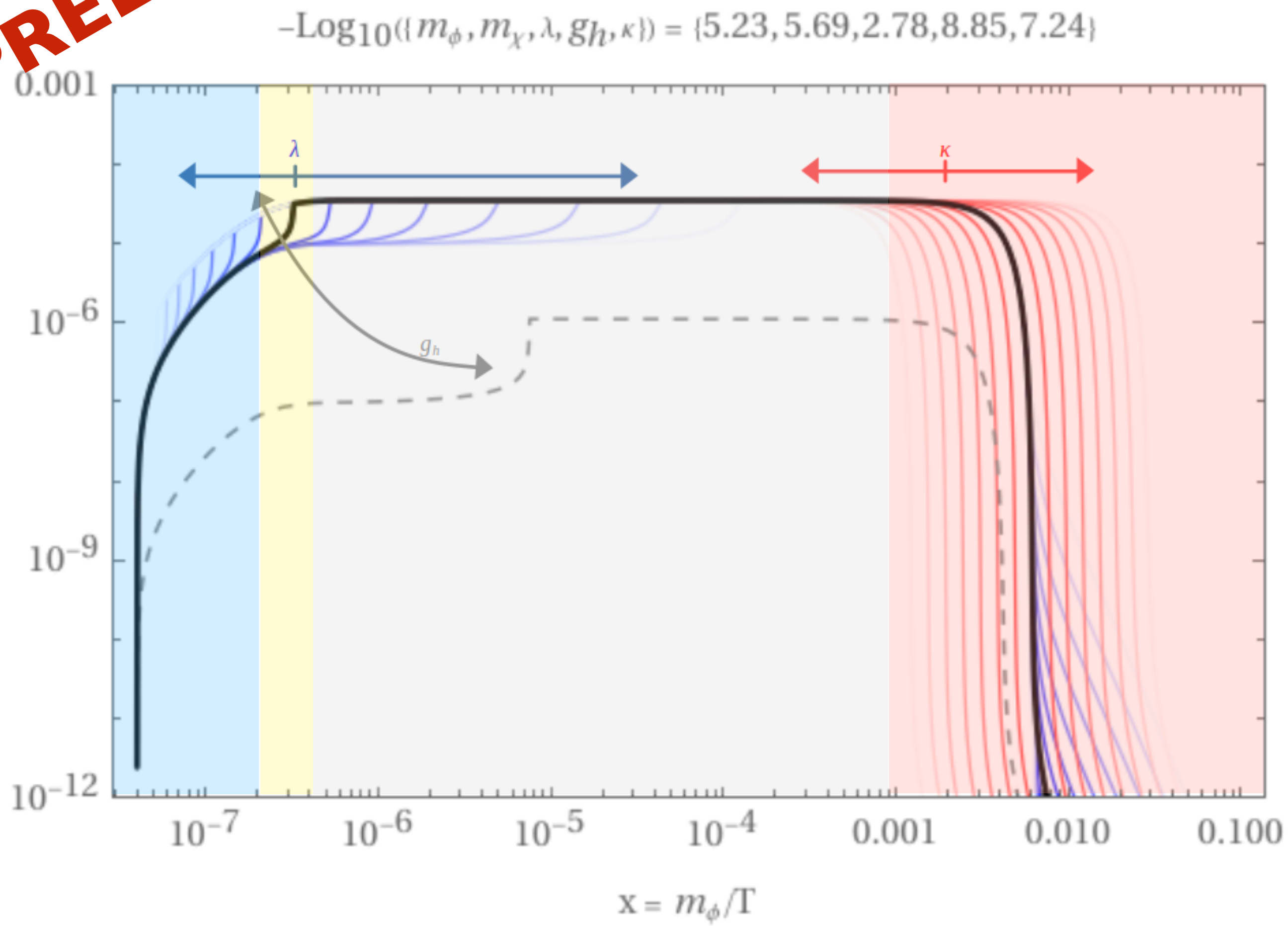
FI boost & self-cooling

DM freeze-in

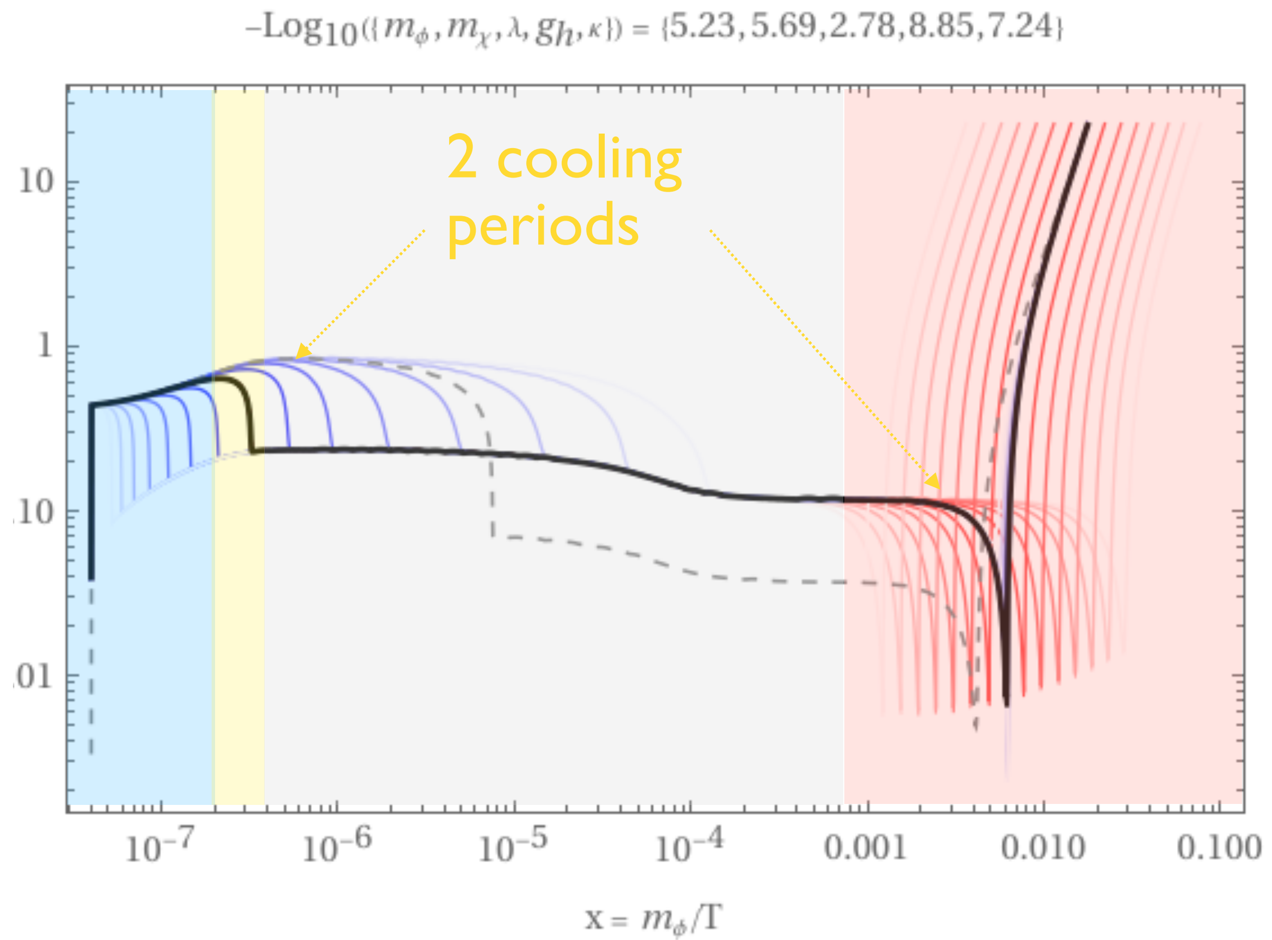
# SELF-COOLING: HOW DOES IT WORK?

**PRELIMINARY**

$\phi$ yield evolution:



$T_\phi$ evolution:



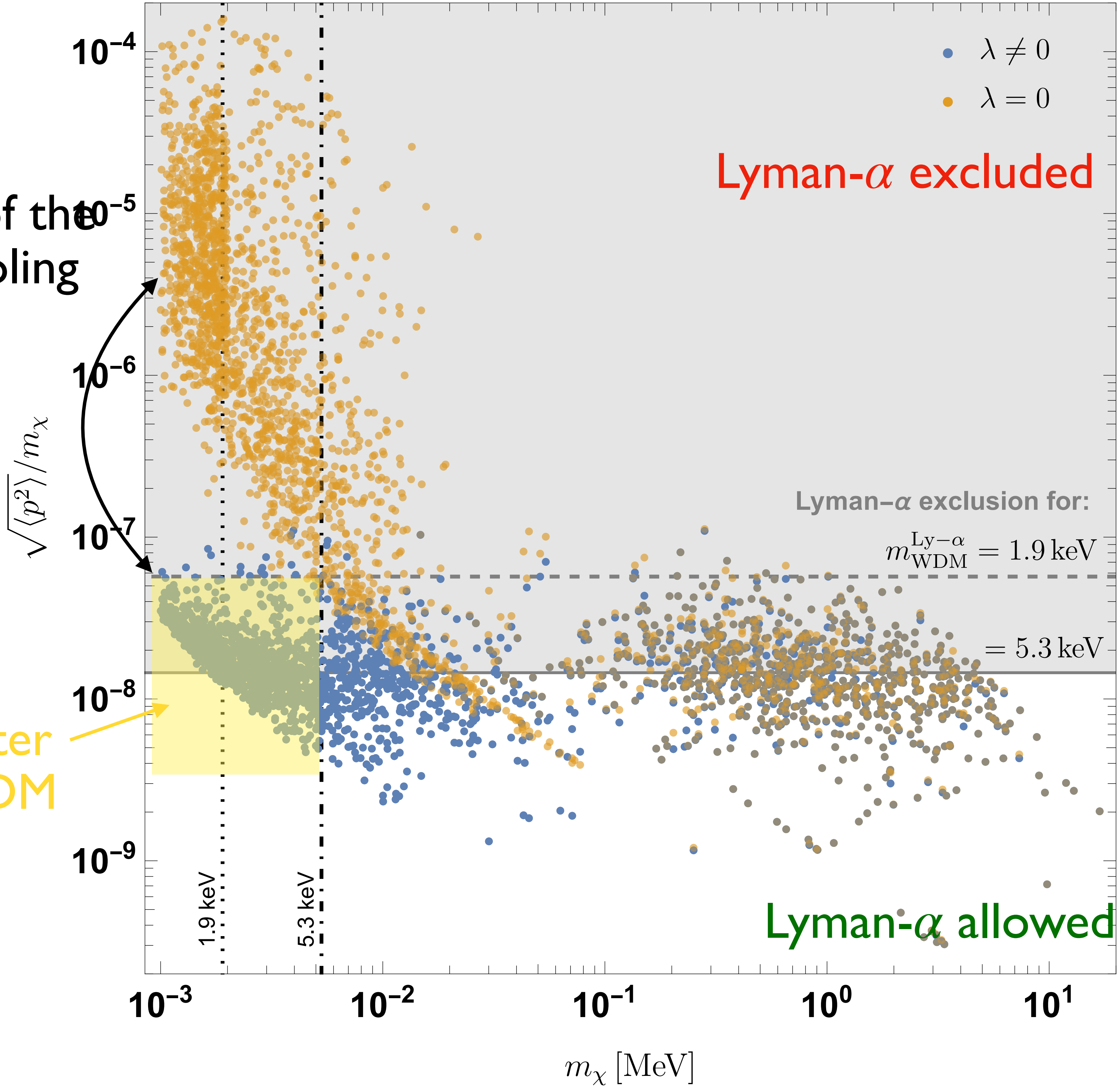
| | |
|---|---|
| 1. Higgs decay provides $\phi$ freeze-in | 1. Temperature $\sim T/2$ |
| 2. Expansion rate drops, yield grows $\Rightarrow 2 \rightarrow 3$ efficiency grows | 2. Self-cooling drop |
| 3. Self-thermalization $\Rightarrow$ plateau | 3. Equilibrium expansion |
| 4. Decay to DM | 4. Apparent heating: skewing due to time dilatation |

**PRELIMINARY**

# MCMC SCAN FOR LYMAN-$\alpha$

Effect of the self-cooling

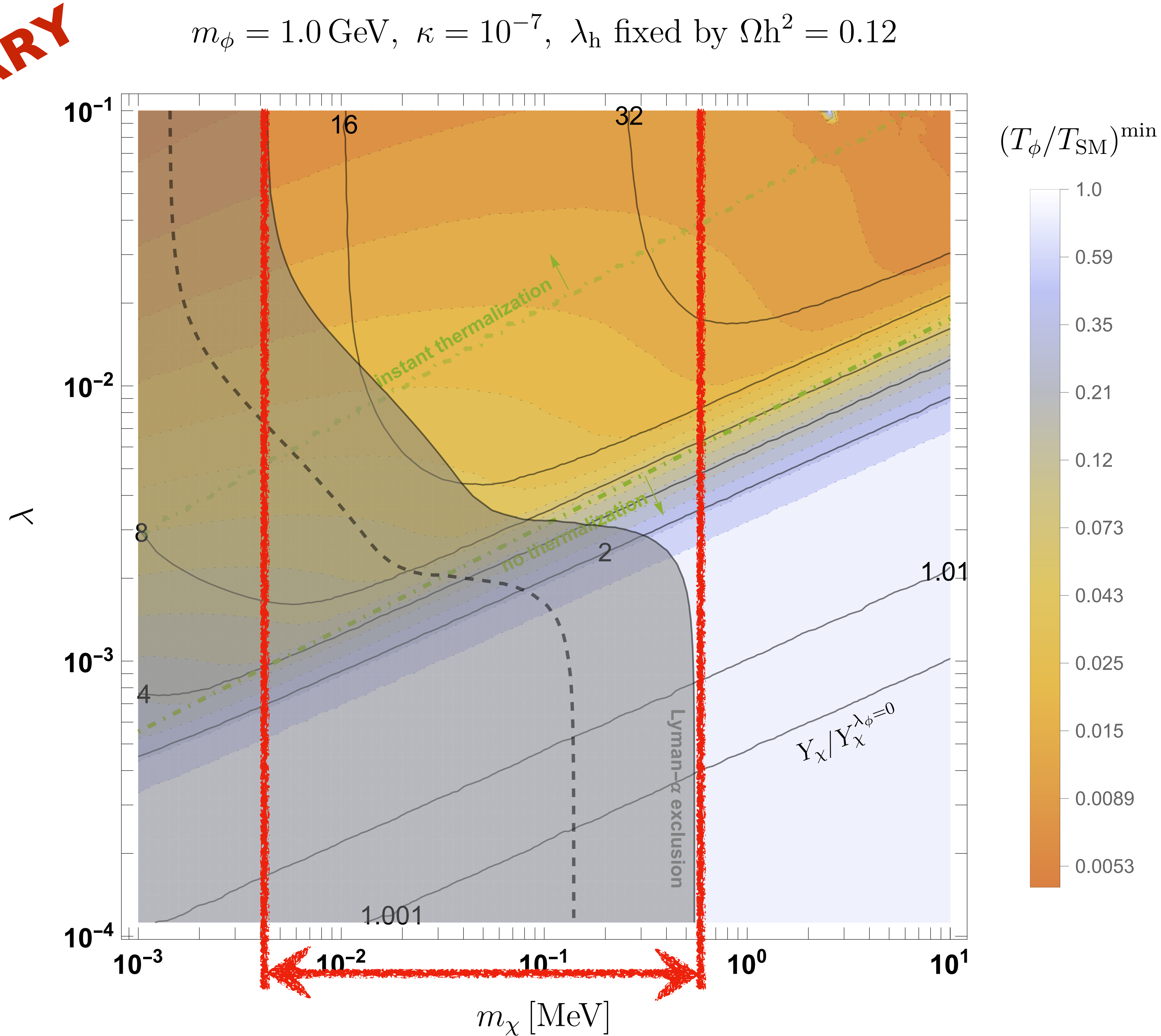
DM lighter than WDM limit



# MODEL PARAMETER SPACE

Model has 5 free parameters. Fix two with smallest impact ($m_\phi, \kappa$) and $\lambda_h$ fix by relic abundance; show remaining two ($m_\chi$ - DM mass & $\lambda_\phi$ - self-interaction strength):

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!