Shedding light onto the dark freeze-out with FIMPs

Esau Cervantes

Physics Graduate Seminar

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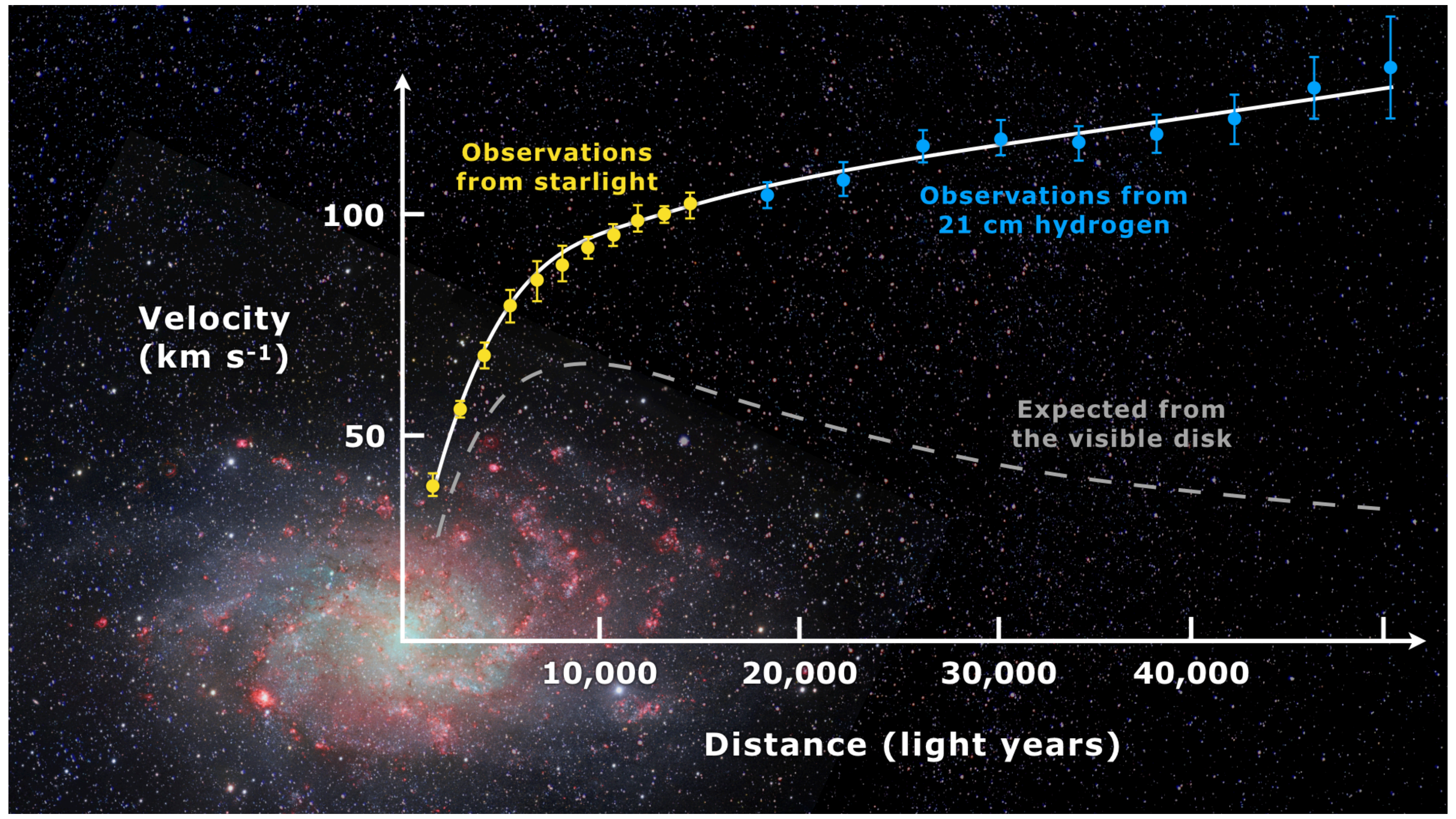
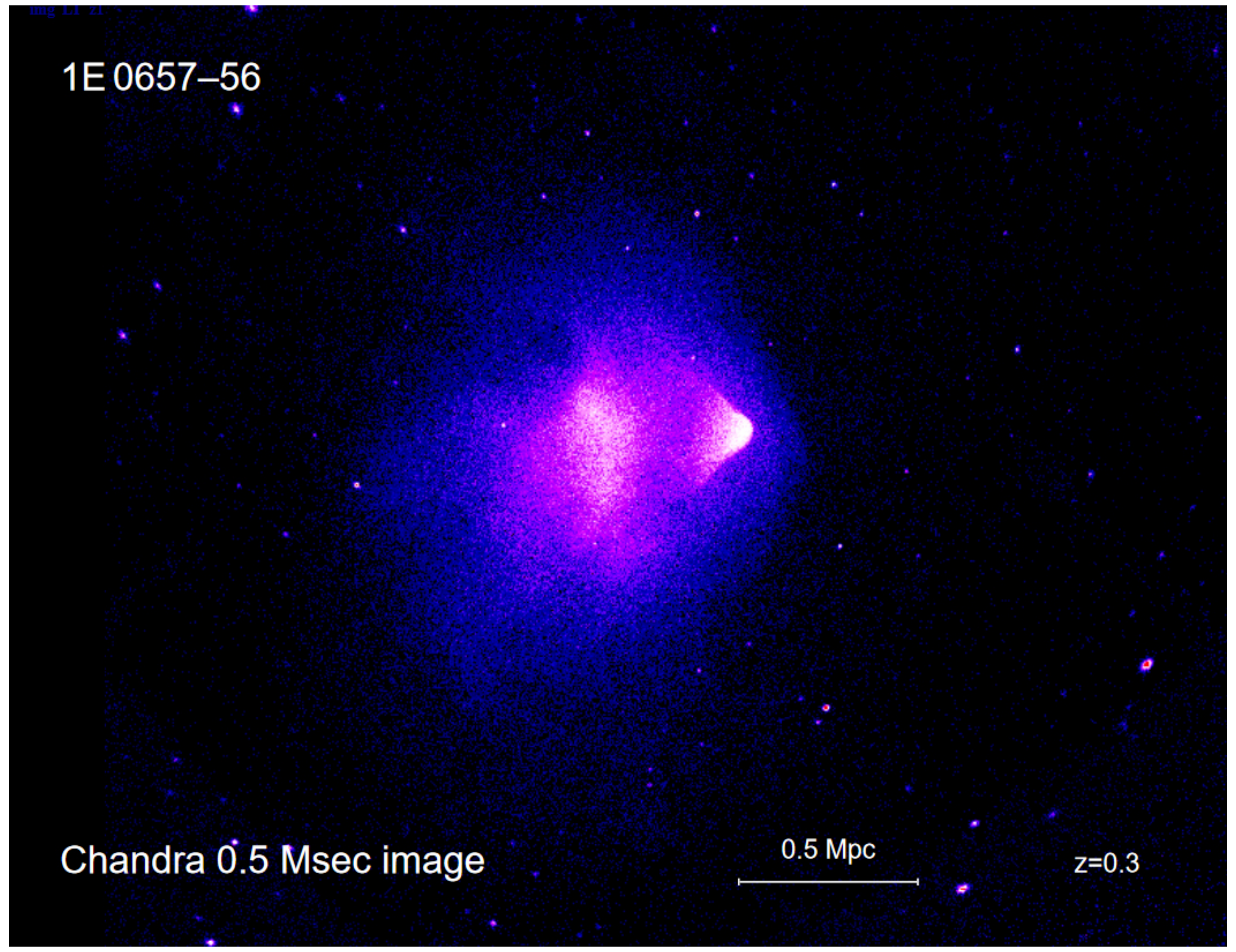
Evidence for Dark Matter

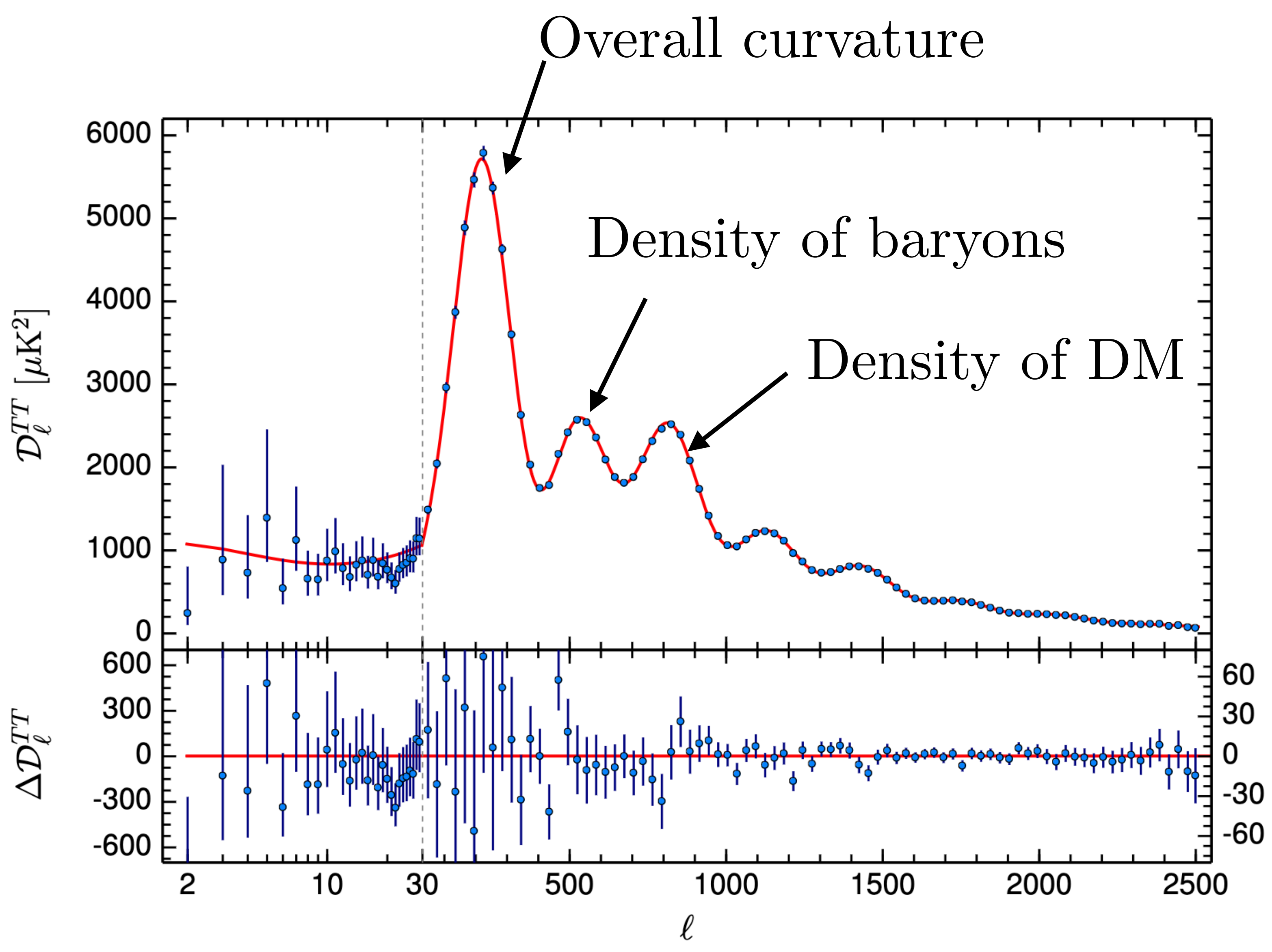
Galaxy rotation curves



Bullet Cluster



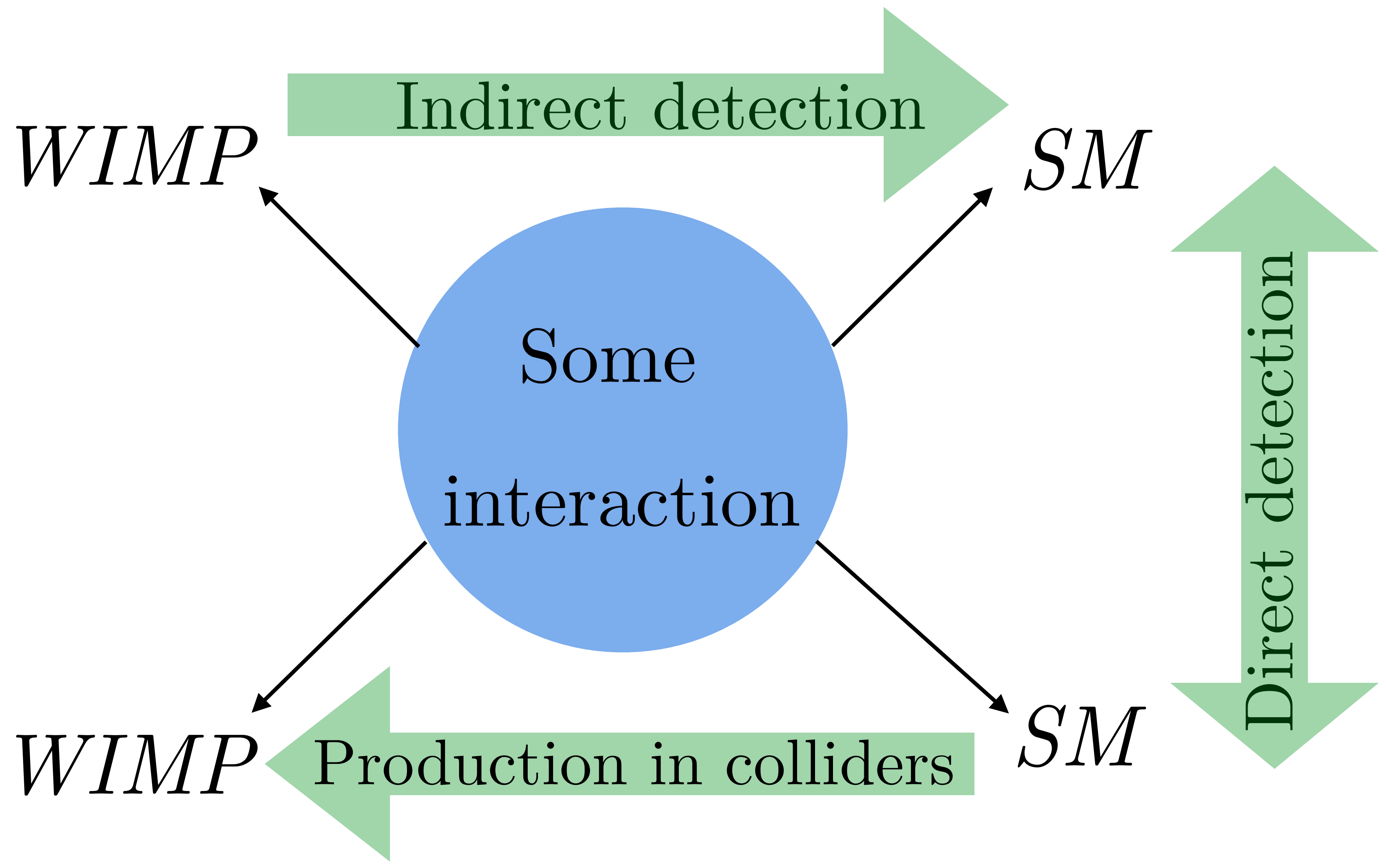
CMB



Planck 1807.06209

Credits: Wikipedia

DM models on the market



Bertone et.al 1810.01668

How does DM look like?

It must satisfy the following criteria:

- No interactions with the electromagnetic field (or extremely weakly).
- Couplings with quarks and leptons should be significantly suppressed as well.
- It must facilitate the formation of large structures.
- It must account for the observed quantity of DM ($\sim 80\%$ of the ***total*** matter).
- It must be stable.

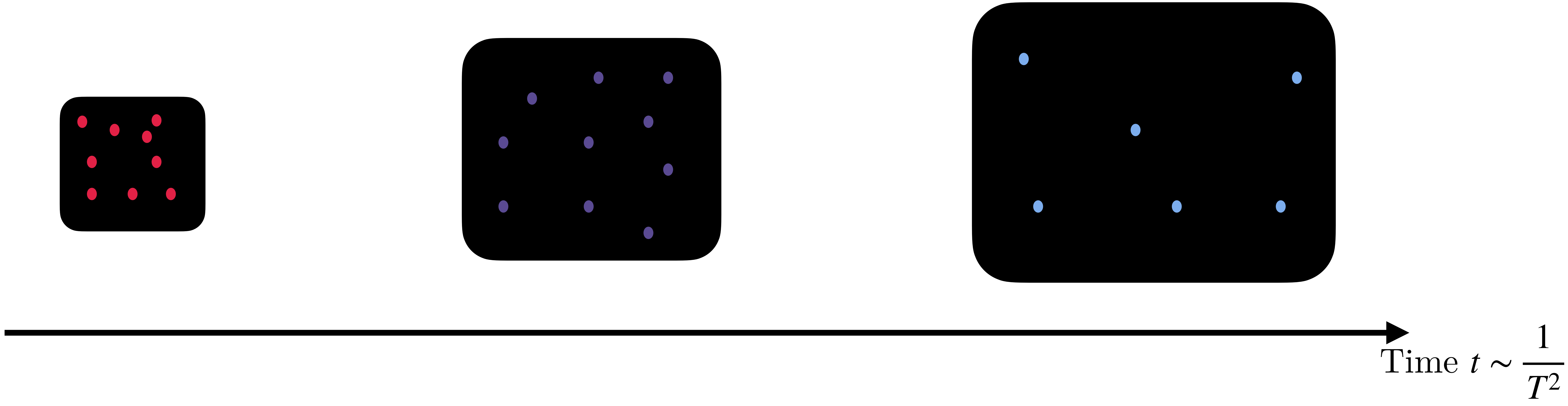
Up until now, our understanding of DM is largely shaped by what it is ***not***, rather than a clear grasp of what it truly is.

Standard freeze-out

Universe expands with rate: $H = \dfrac{\dot{a}(t)}{a(t)}$; a: how the size changes over time.

The early universe is dominated by radiation $\Longrightarrow$ $a(t) \propto t^{1/2} \sim \dfrac{1}{T}$ and $H \simeq 1.66 g_* \dfrac{T^2}{m_{Pl}}$.

As time progresses, the universe expands, cools down and particles dilute:

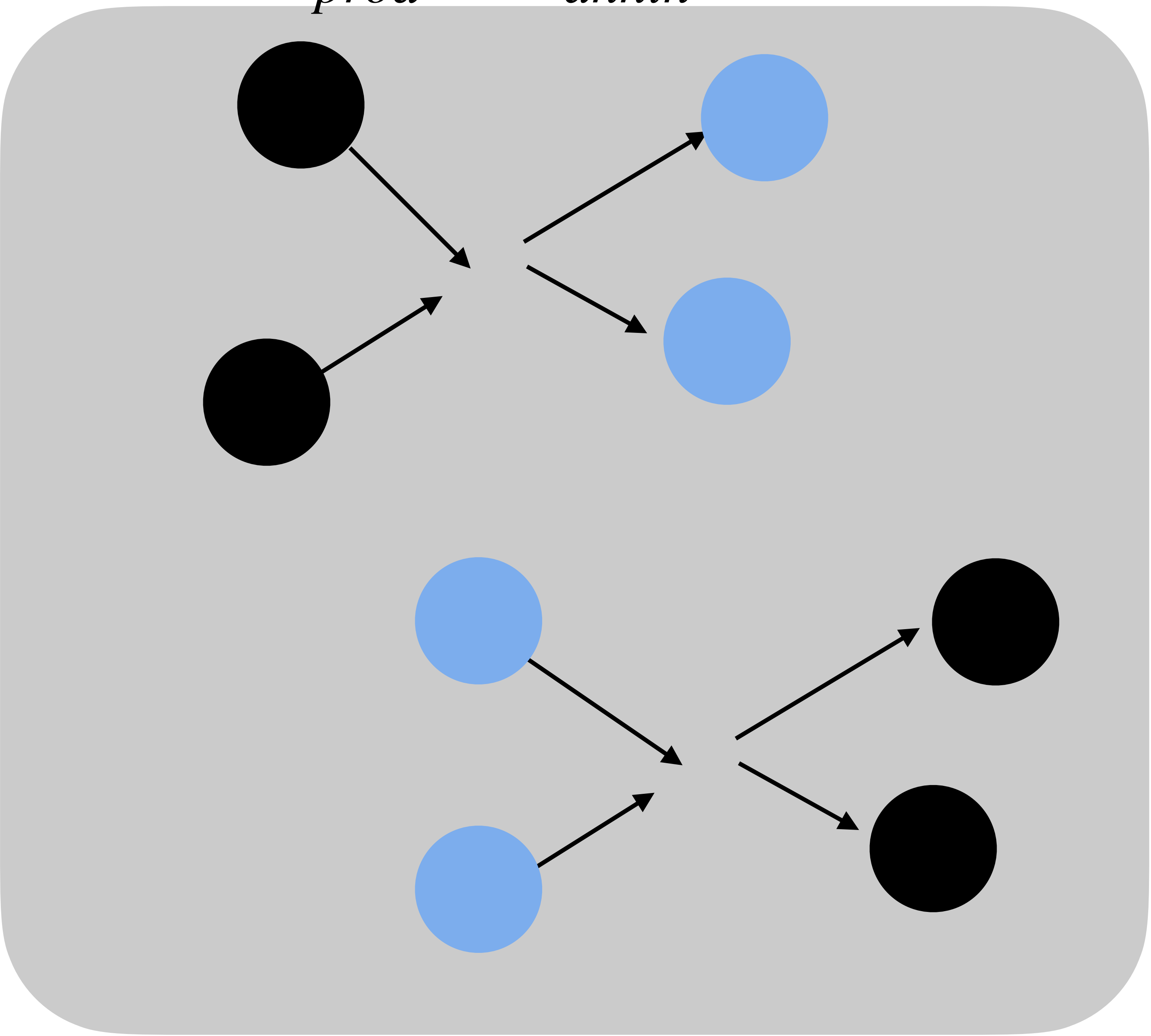


Standard freeze-out

What if DM interacts with Standard Model particles?

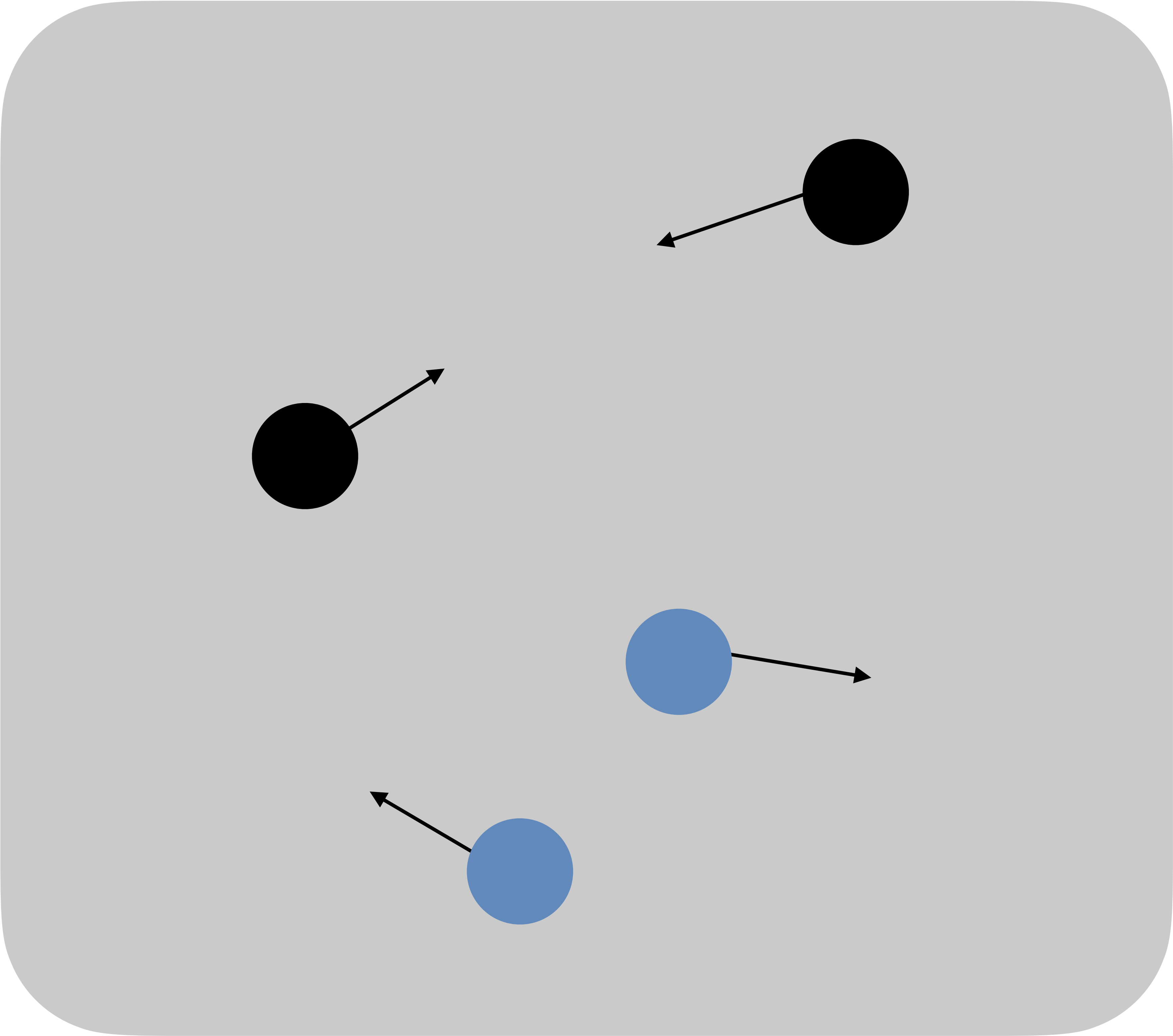
Particles find each other easily. No net change in the # of particles.

$$\Gamma_{prod} = \Gamma_{annih} > H$$



Particles diluted and unable to interact. Remains net amount of DM.

$$\Gamma_{interaction} < H$$



How much DM remains?

QFT reactions
(model dependent)

Key entity $f_{DM}(p,t) \rightarrow n_{DM}(t) = \frac{1}{(2\pi)^3}\int d^3p\, f_{DM}(p,t)\,.$

$$\frac{df}{dt} = \hat{C}[f] \xrightarrow{\text{FLRW}} \frac{\partial f}{\partial t} - H p\frac{\partial f}{\partial p} = \hat{C}[f]/E\,, \qquad \hat{C}[f_{DM}] := \int d\Pi_a\, d\Pi_b\, d\Pi_c\, |\mathcal{M}_{DM,a\leftrightarrow bc}|^2 (f_b f_c - f_{DM} f_a)$$

$$f_{DM}(E) = \frac{Y}{Y^{eq}} e^{-E/T_{DM}}$$

$$Y := \frac{n_{DM}}{s}$$

Entropy density: $s = \frac{2\pi^2}{45} g_* T^3$

$$\frac{Y'}{Y} = \frac{1}{x\tilde{H}}\langle\hat{C}\rangle\,,$$

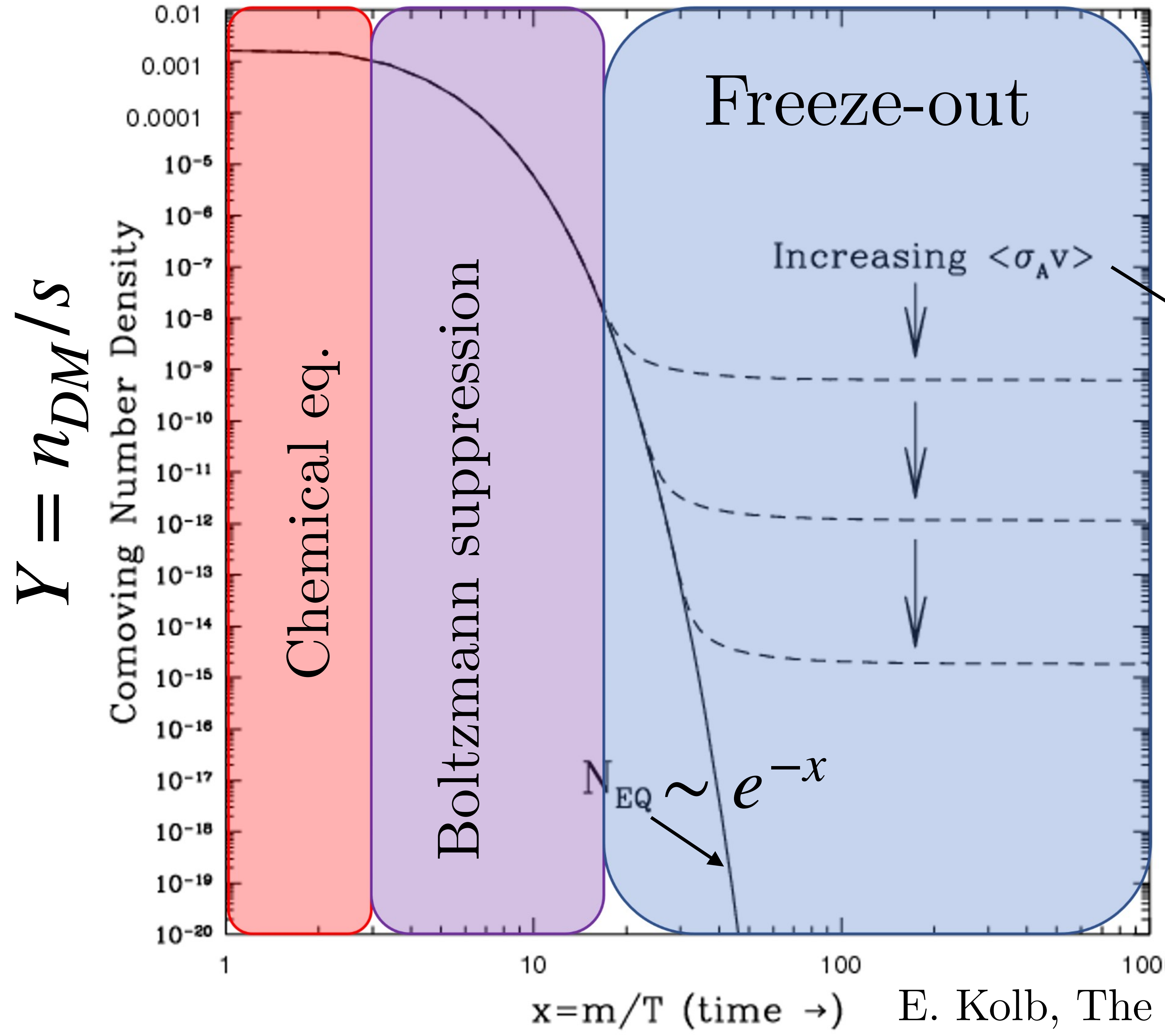
Information of $\Gamma_{interaction}$

$$\frac{T'_{DM}}{T_{DM}} = \frac{1}{x\tilde{H}}\langle\hat{C}\rangle_2 - \frac{Y'}{Y} + \ldots\,, \langle\hat{C}\rangle_2 = \frac{1}{3T_{DM}n_{DM}}\int \frac{d^3p}{(2\pi)^3 2E}\frac{p^2}{E}\hat{C}$$

Code to solve the eqs. : Binder et.al 2103.01944

How much DM remains?

$$\text{DM-SM interactions} \xrightarrow[\text{probability of int.}]{\text{QFT}} |\mathscr{M}_{DM\leftrightarrow SM}|^2 \xrightarrow[\text{thermal av.}]{\text{collisions}} \langle \sigma_{DM\to SM} v \rangle \xrightarrow[\#\text{ density}]{\text{change in}} \frac{Y'}{Y} = \frac{1}{x\tilde{H}} \langle \sigma_{DM\to SM} \rangle \left(1 - \frac{Y^2}{Y_{eq}^2}\right)$$



E. Kolb, The Early Universe

Couplings with visible matter

Stronger cross sec./couplings lead to *fewer* DM

What cross section/couplings lead to the *observed* amount of DM ($\sim 80\,\%$)?

The WIMP miracle

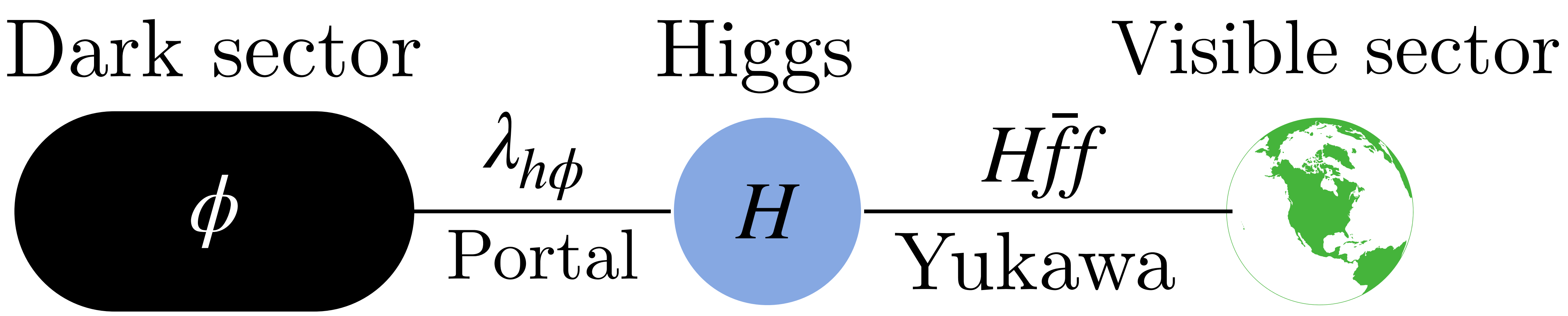
$\Omega_{DM}^{obs} h^2 = 0.12$ if $\sigma_{\phi\phi \to sm,sm} v \simeq 3 \times 10^{-26} \mathrm{cm}^3\, \mathrm{s}^{-1} \implies$ electroweak cross section!

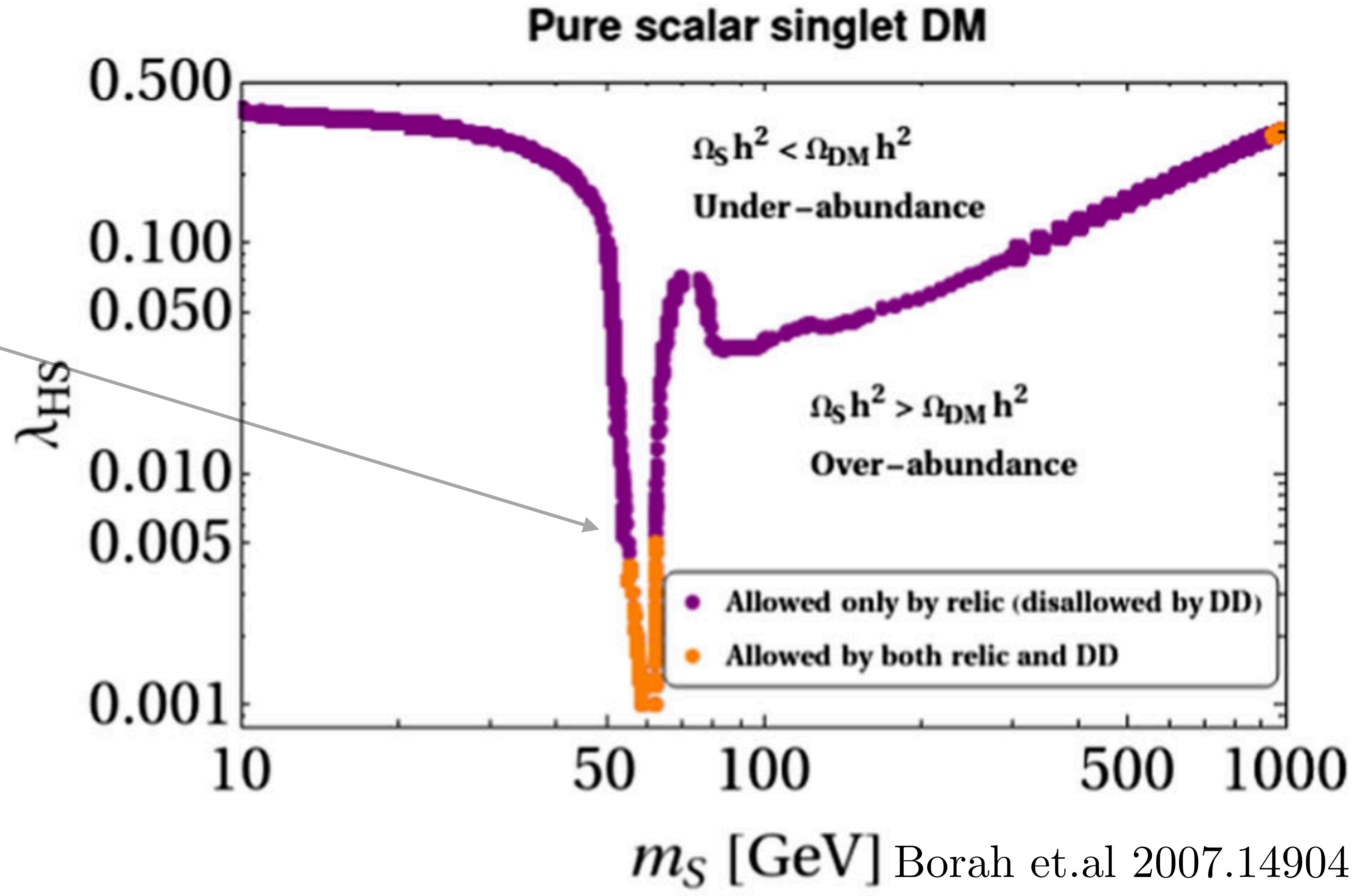
Weakly Interacting Massive Particles: DM candidates with couplings in the electroweak scale (~100 GeV→LHC!).

$$\mathscr{L}_{Higgs\,Portal} \supset -\frac{m^2}{2}\phi^2 - \frac{\lambda}{24}\phi^4 - \frac{1}{2}\lambda_{h\phi} H^\dagger H \phi^2$$

Simplest WIMP model: $\mathbb{Z}_2$ singlet scalar DM

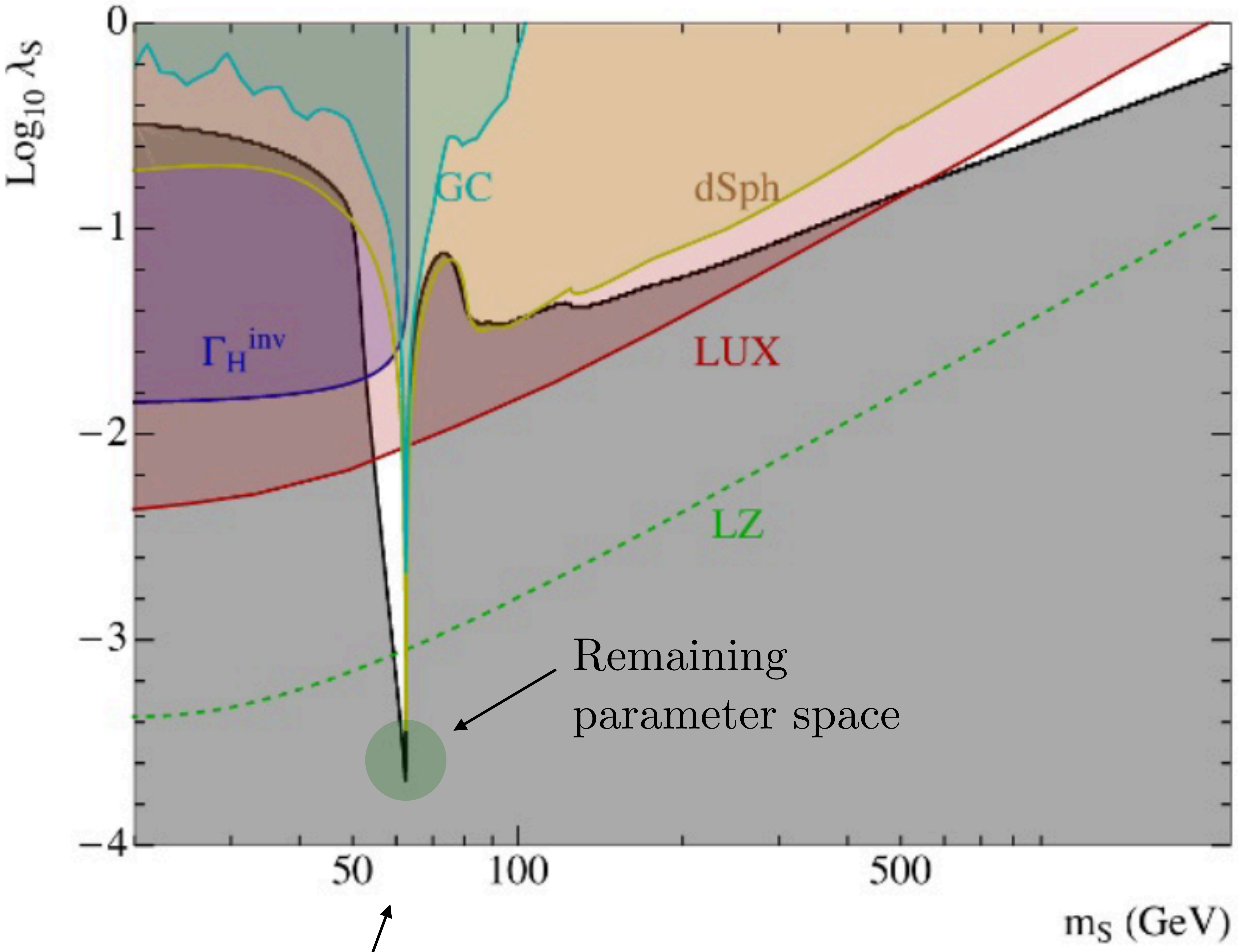
$\Omega_{DM}^{obs} h^2 = 0.12 \leftrightarrow$ DM is 80% of *total* matter





Borah et.al 2007.14904

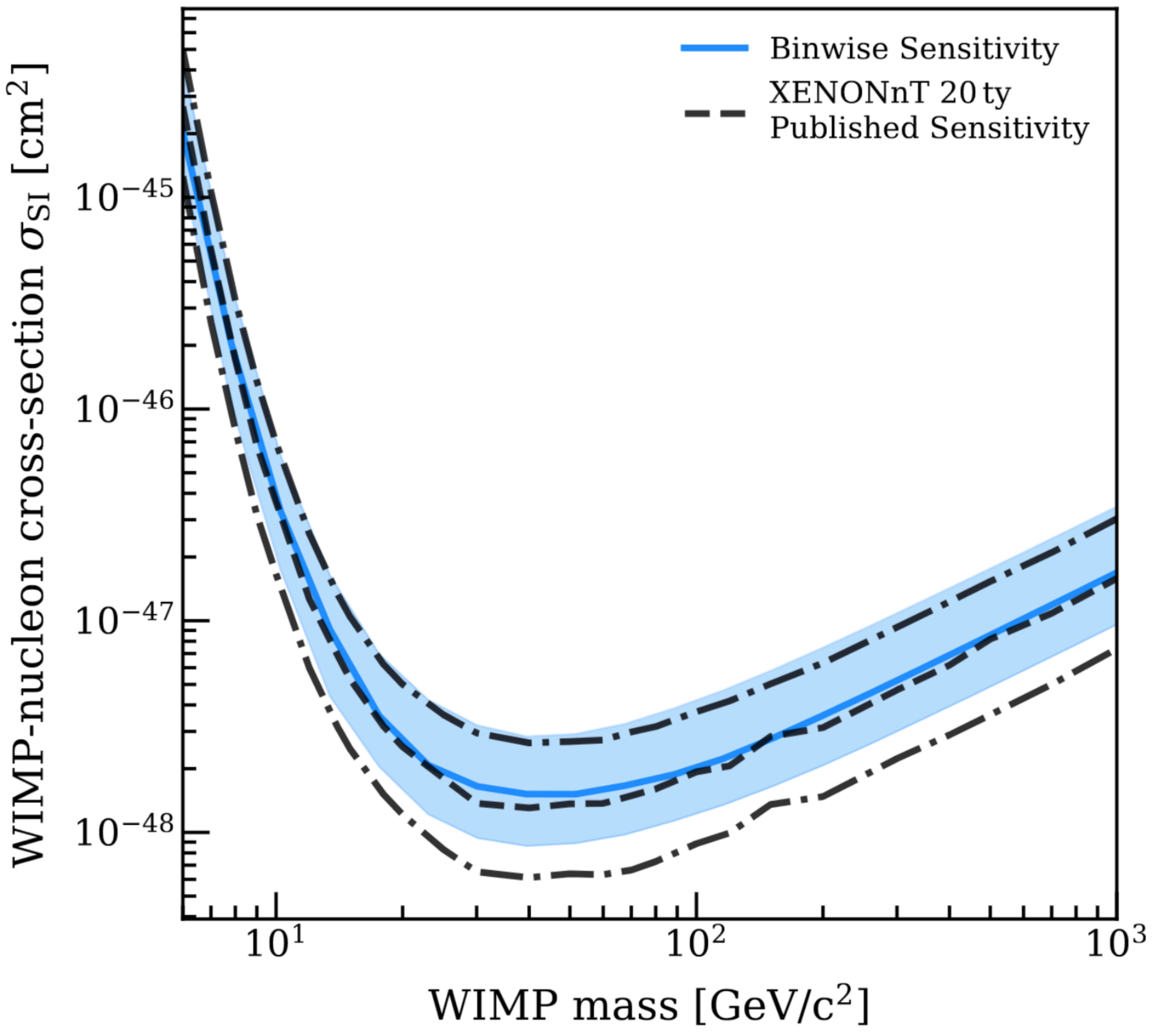
Are WIMPs just a fairy tale?



Remaining parameter space

Higgs resonance $m_{DM} = m_h/2$

Casas et.al 1701.08134



XENON1T 2210.07231

What alternatives do we have?

Self interacting DM

SELF-INTERACTING DARK MATTER

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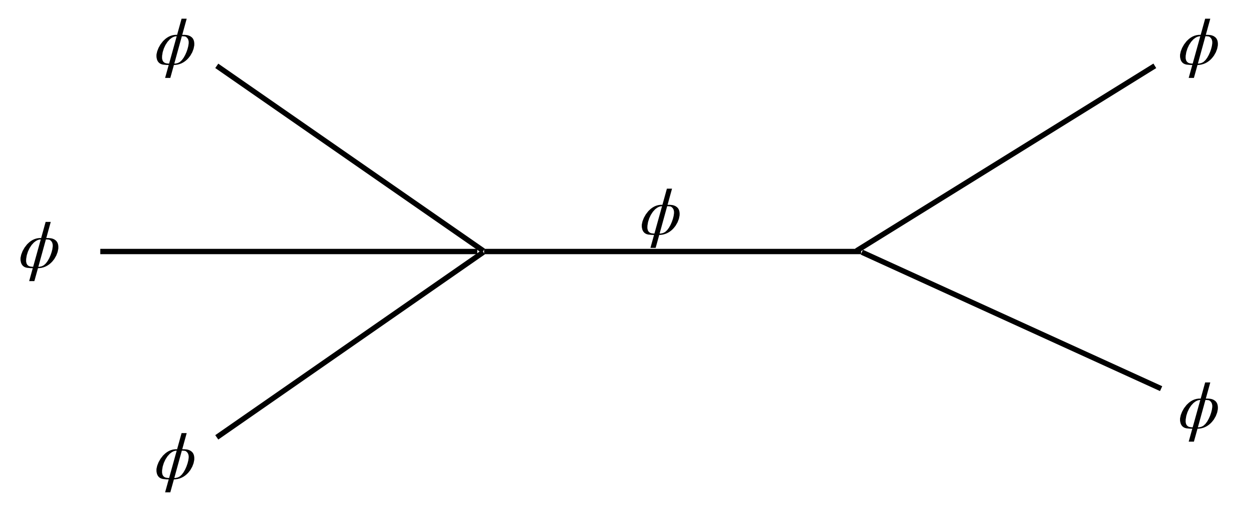
$\longrightarrow$ Ω_{DM}^{obs} solely through self number changing reactions

$\downarrow$

For a scalar field $\frac{g}{3!}\phi^3 + \frac{\lambda}{4!}\phi^4$ leads to self interactions, e.g. $3 \leftrightarrow 2$



$\#$ changing reactions

WIMPs	SIDM
$\phi\phi \leftrightarrow$ SM,SM	$\phi\phi\phi(\phi) \leftrightarrow \phi\phi$

No portals $\Longrightarrow$ challenging to falsify!

Solving the cBE for $3 \leftrightarrow 2$ reactions

Collision operator:

$$\begin{aligned}
C_{self} = \int \Big(& -f_\phi(p)\,|\tilde{\mathcal{M}}_{\underline{\phi}2\to345}|^2 f_2\, d\Pi_2 \left(\frac{1}{3!} d\Pi_3 d\Pi_4 d\Pi_5\,(1+f_3)(1+f_4)(1+f_5)\right) \\
& +(1+f_\phi(p))\,|\tilde{\mathcal{M}}_{12\to\underline{\phi}45}|^2 \left(\frac{1}{2!} d\Pi_1 d\Pi_2\, f_1 f_2\right)\left(\frac{1}{2!} d\Pi_4 d\Pi_5\,(1+f_4)(1+f_5)\right) \\
& -f_\phi(p)\,|\tilde{\mathcal{M}}_{12\leftarrow\underline{\phi}45}|^2 \left(\frac{1}{2!} d\Pi_4 d\Pi_5\, f_4 f_5\right)\left(\frac{1}{2!} d\Pi_1 d\Pi_2\,(1+f_1)(1+f_2)\right) \\
& +(1+f_\phi(p))\,|\tilde{\mathcal{M}}_{\underline{\phi}2\leftarrow345}|^2 \left(\frac{1}{3!} d\Pi_3 d\Pi_4 d\Pi_5\, f_3 f_4 f_5\right) d\Pi_2 (1+f_2)\Big),
\end{aligned}$$

The system of cBE:

$$C_{self} \xrightarrow[\langle C_{self}\rangle_0]{\frac{1}{n_\phi}\int d\Pi_\phi C_{self}} \quad \frac{Y'}{Y} = \frac{s^2}{x\tilde{H}}\langle \sigma_{3\to2} v^2\rangle Y(Y^{eq}-Y)$$

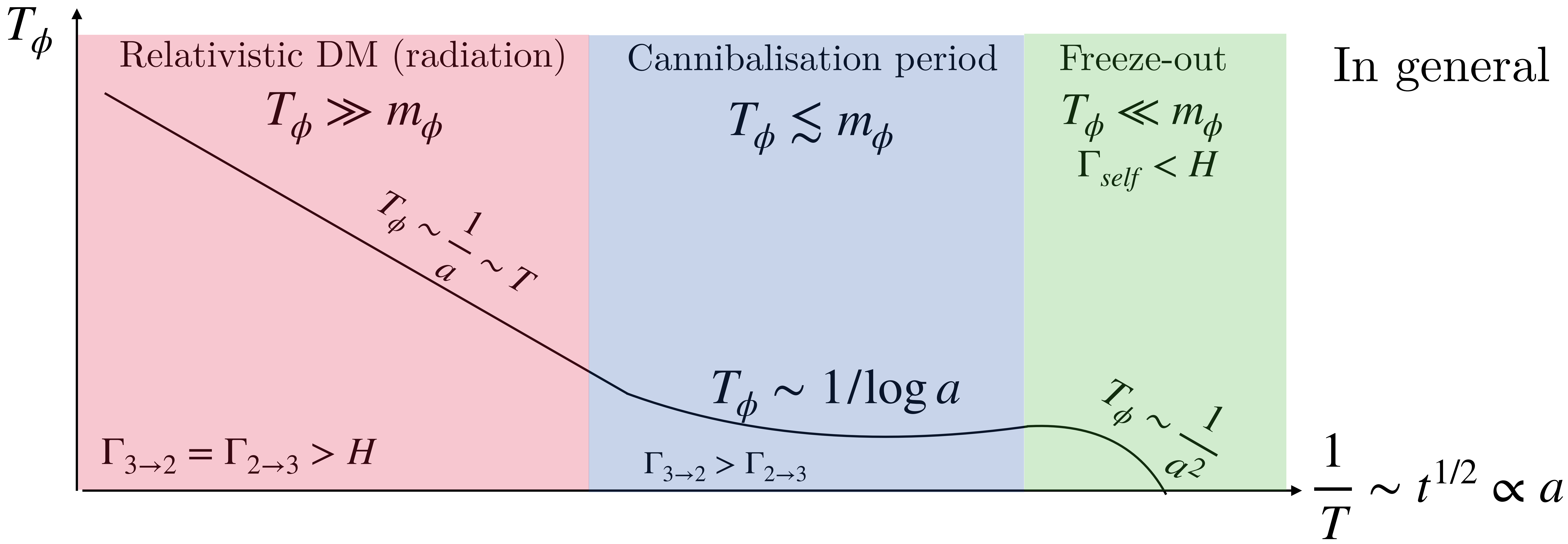
$$Y := \frac{n_\phi}{s}$$

$$C_{self} \xrightarrow[\langle C_{self}\rangle_2]{\frac{1}{3n_\phi T_\phi}\int d\Pi_\phi \frac{p_\phi^2}{E_\phi} C_{self}} \quad \frac{x'_\phi}{x_\phi} = -\frac{1}{x\tilde{H}}\langle \hat{C}\rangle_2 + \frac{Y'}{Y} + \ldots$$

$$x_\phi := \frac{m_\phi}{T_\phi}$$

Self interacting DM

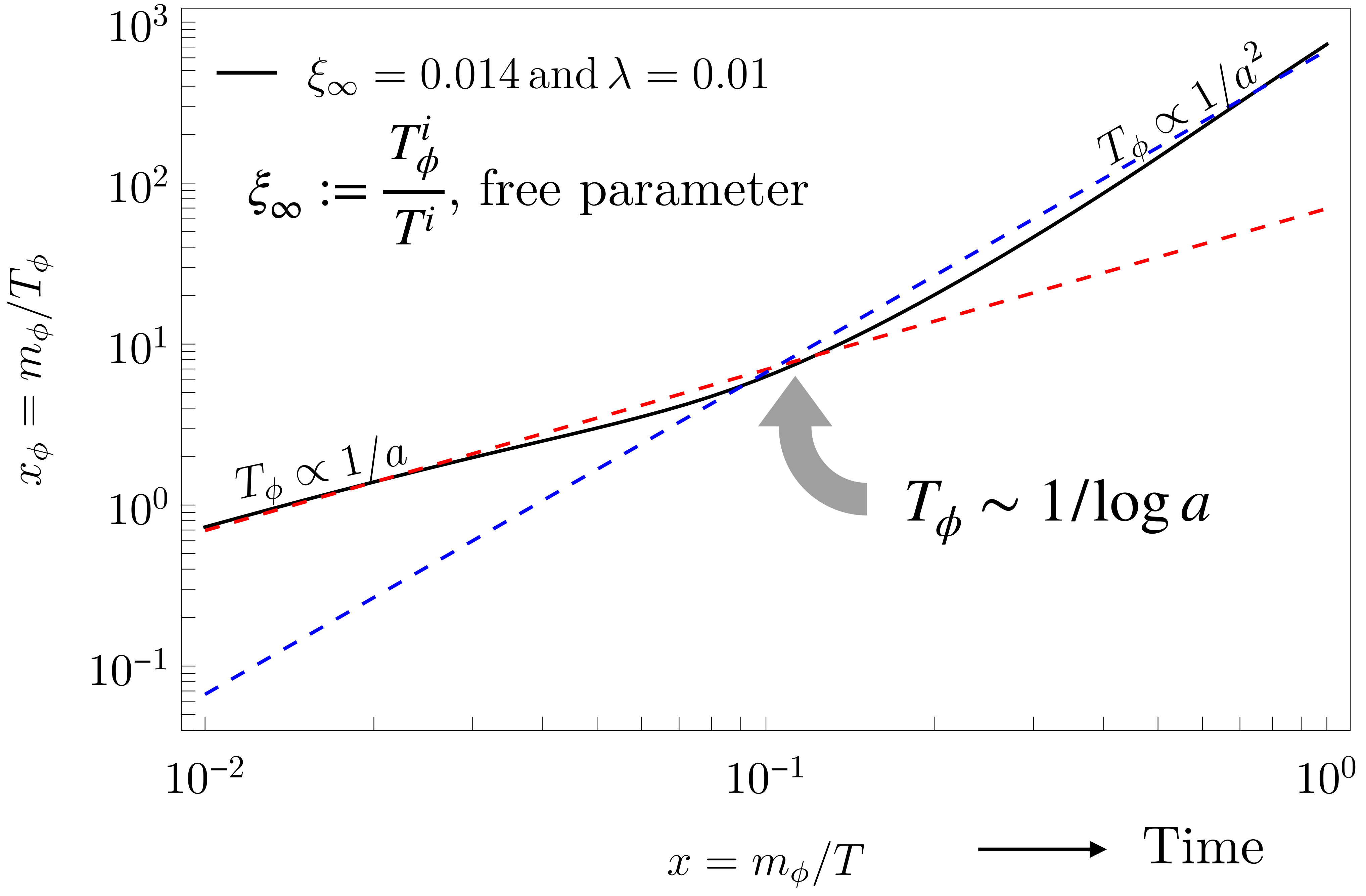
- When DM is relativistic ($T_{DM} \gg m_{DM}$), $\Gamma_{3\leftrightarrow 2} > H$ (chemical eq.);
- During freeze-out the dark sector uses its rest mass as *fuel* to keep itself warm;
- $\implies T_\phi \sim 1/\log a$ (conservation of dark entropy during freeze-out).

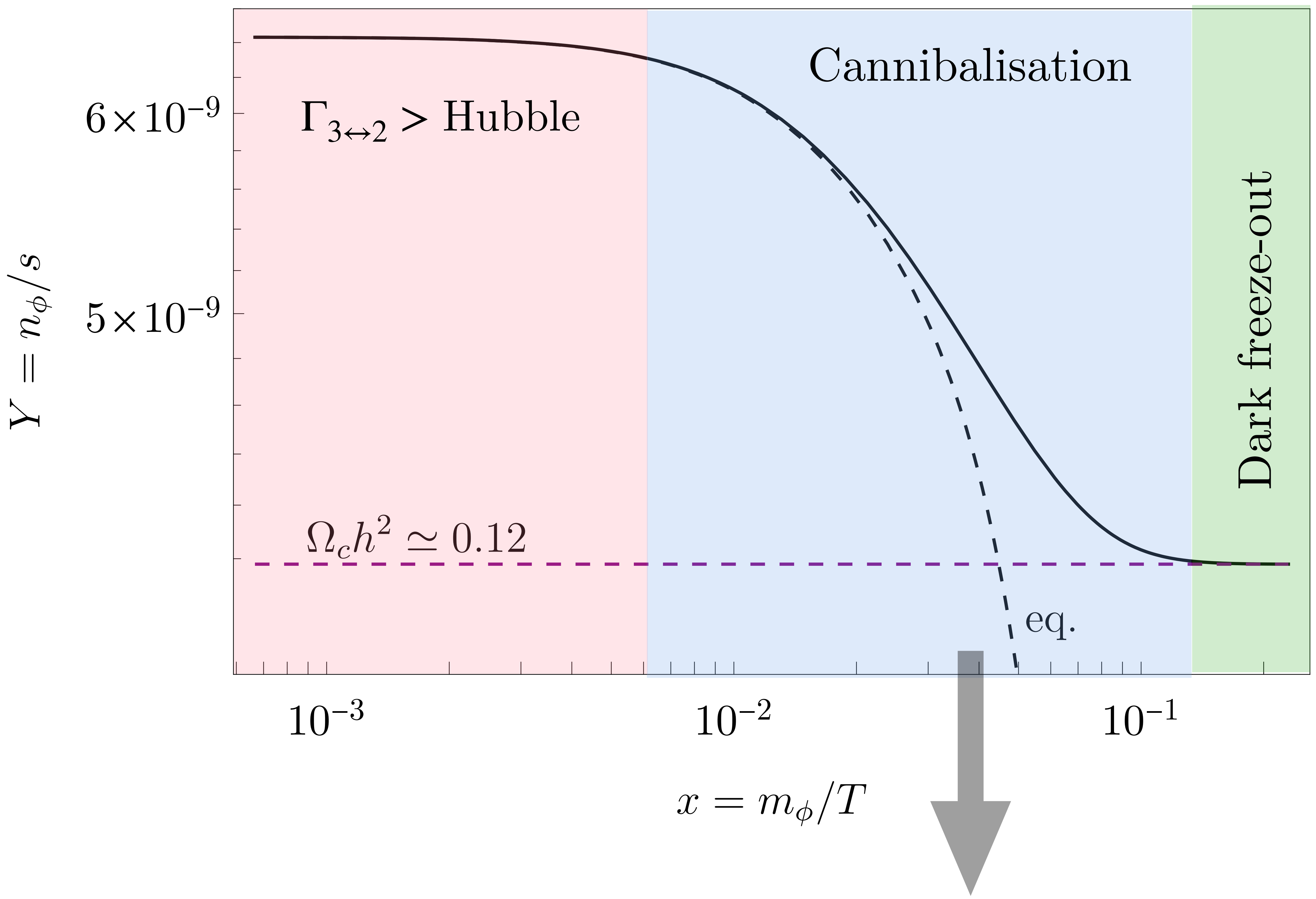


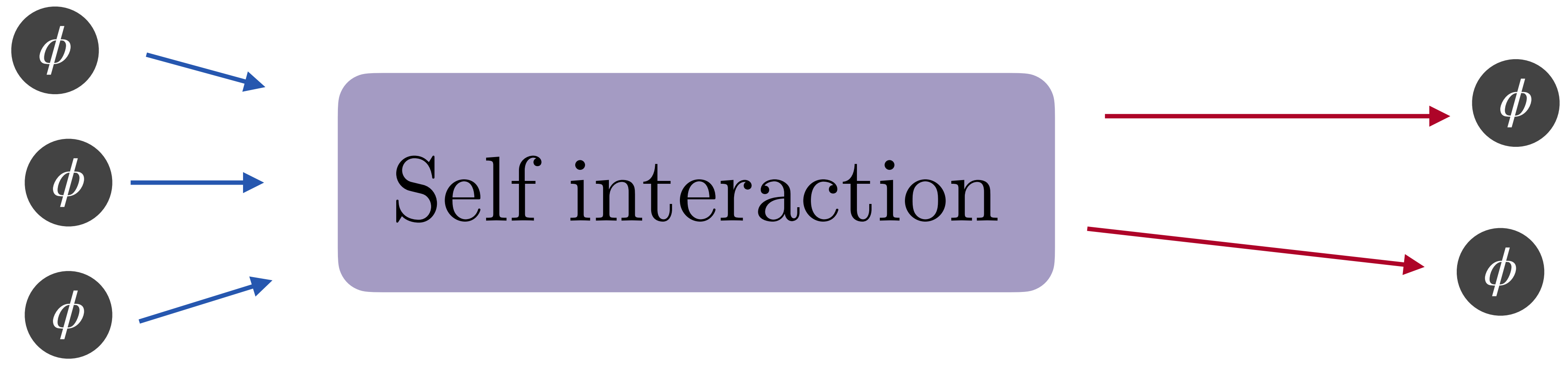
In general $T_\phi \neq T$

Dark freeze-out

Evolution for $m = 100$ MeV





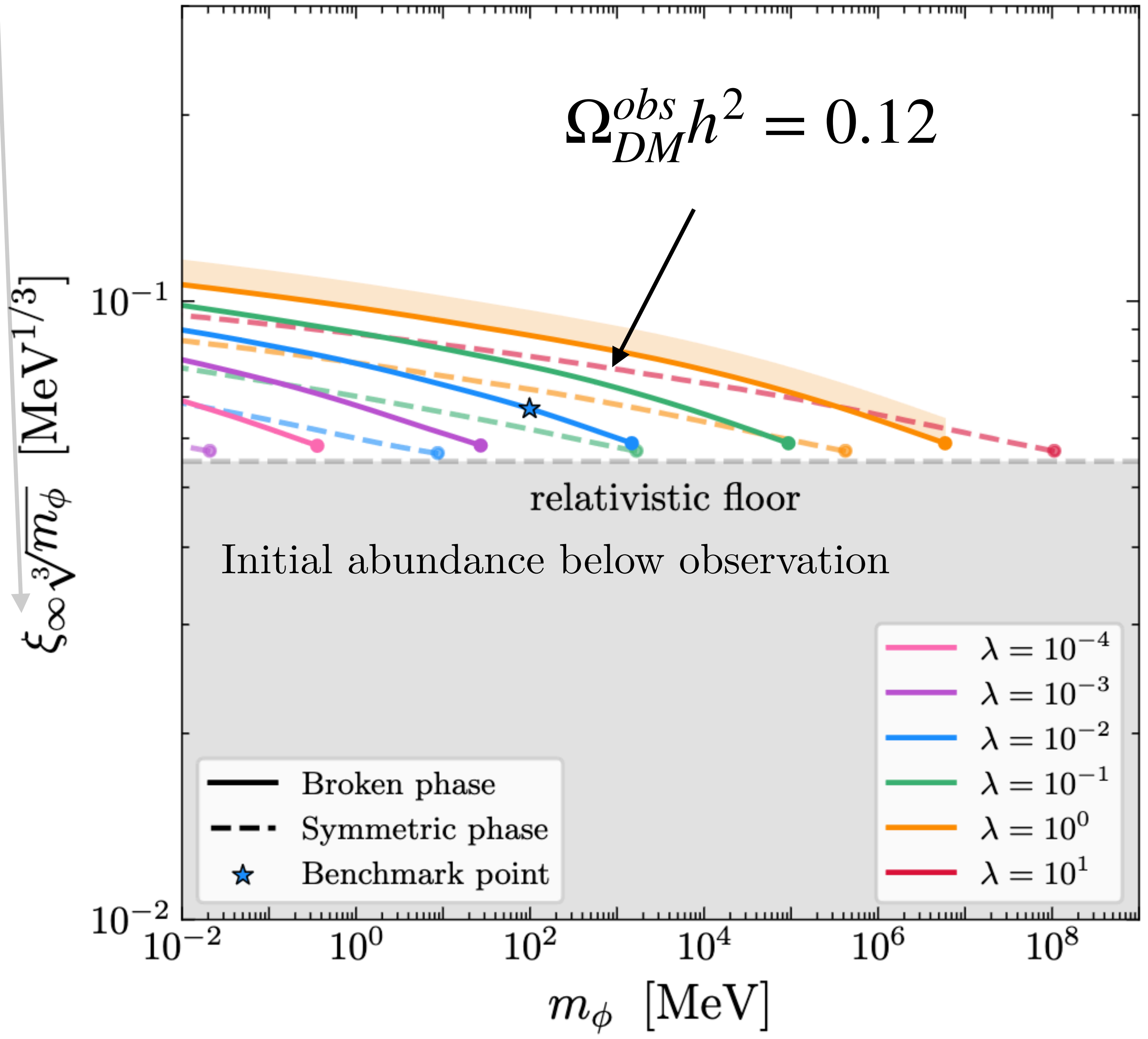


During the cannibalisation period $\Gamma_{3\to2} > \Gamma_{2\to3}$, leading to self-annihilation.

Dark entropy conservation leads to *faster moving* (hotter) DM states during freeze-out

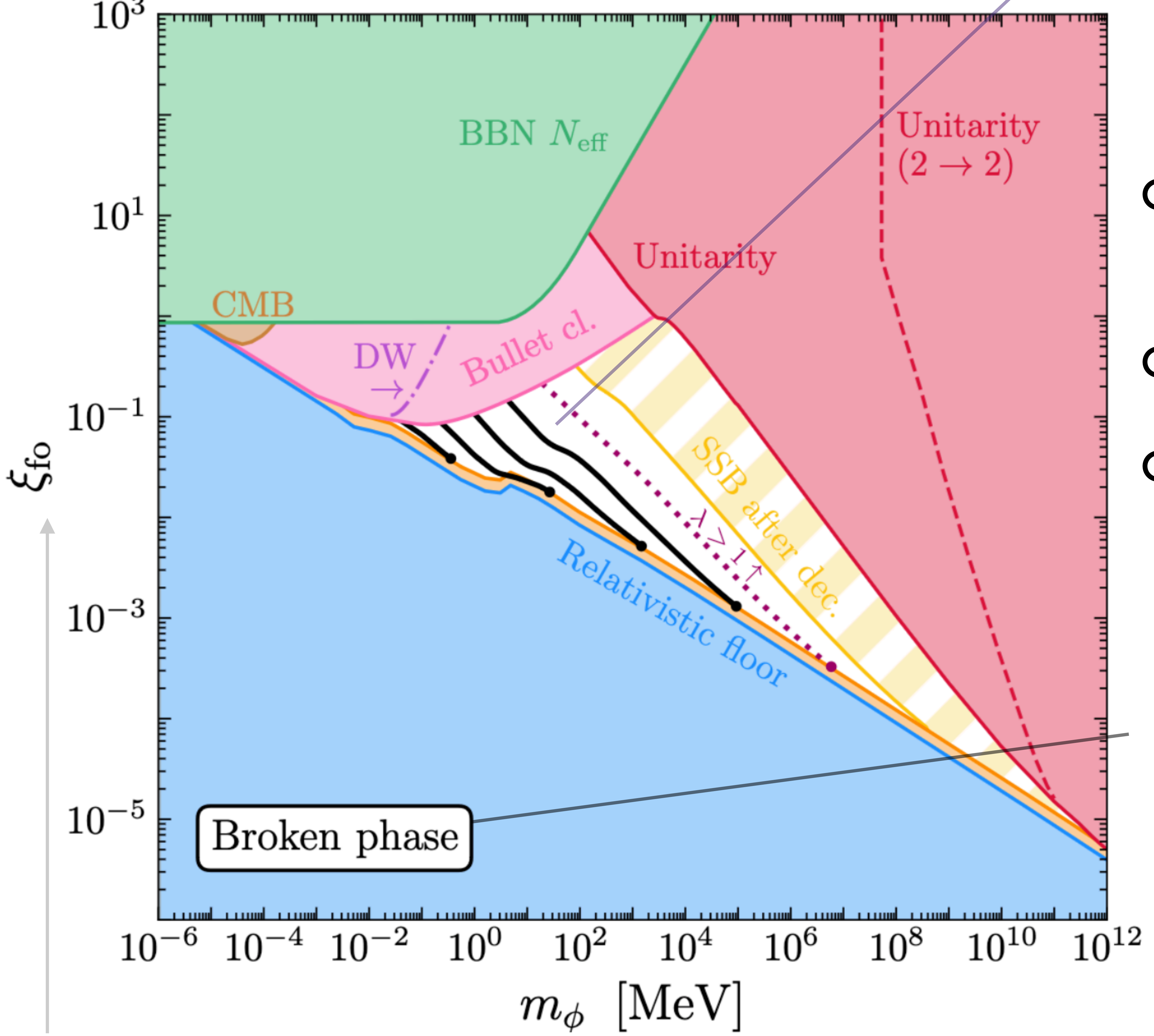
Dark freeze-out

$\xi_\infty = T^i_\phi / T^i$, initial ratio of temperatures (initial condition) after inflation



Hufnagel et.al 2212.09759

Parameter space: $(\xi_\infty, \lambda_{self}, m_{DM})$



Ratio of temperatures (T_ϕ/T) at freeze-out $(\Gamma_{3\leftrightarrow 2} = H)$

Parameter space within reach

- Preferably mass in the 100 MeV range;
- T_ϕ freeze-out temperature below T_{SM};
- λ coupling in the range $10^{-4} - 10^{-1}$.

$\mathbb{Z}_2$ broken phase:

$$\langle \phi \rangle = \sqrt{\frac{3}{\lambda}} m_\phi \implies \frac{g}{3!}\phi^3 = \frac{\sqrt{3\lambda} m_\phi}{3!}\phi^3$$

SIDM and the SM

Hochberg et.al 1402.5143

The SIMP Miracle

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[1] *Ernest Orlando Lawrence Berkeley National Laboratory, University of California, Berkeley, CA 94720, USA*
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[4] *SLAC National Accelerator Laboratory, Stanford University, Menlo Park, CA 94025 USA*

We present a new paradigm for achieving thermal relic dark matter. The mechanism arises when a nearly secluded dark sector is thermalized with the Standard Model after reheating. The freezeout process is a number-changing $3 \to 2$ annihilation of strongly-interacting-massive-particles (SIMPs) in the dark sector, and points to sub-GeV dark matter. The couplings to the visible sector, necessary for maintaining thermal equilibrium with the Standard Model, imply measurable signals that will allow coverage of a significant part of the parameter space with future indirect- and direct-detection experiments and via direct production of dark matter at colliders. Moreover, $3 \to 2$ annihilations typically predict sizable $2 \to 2$ self-interactions which naturally address the 'core vs. cusp' and 'too-big-to-fail' small structure problems.

Sizeable couplings with SM

Detectability!

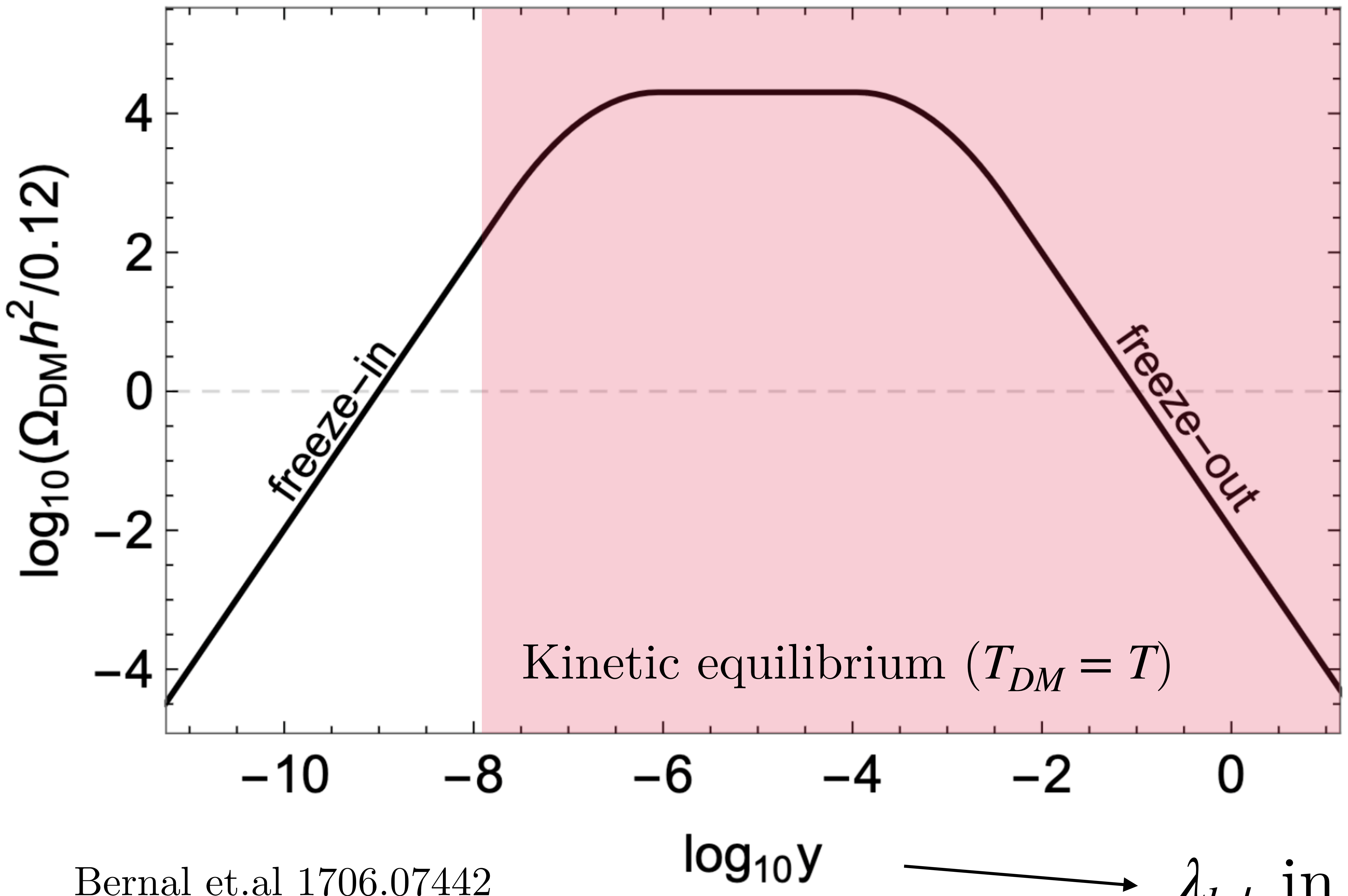
Follow up w. dark QCD: Hochberg et.al 1411.3727

What about an *almost* secluded sector?

FIMPs and freeze-in

No a priori reason to set $\lambda_{h\phi} = 0$

FIMPs: *Feebly* Interacting Massive Particles



Bernal et.al 1706.07442

→ $\lambda_{h\phi}$ in HP

Freeze-in

↓

Assume $n^{eq}_{DM} \gg n^{i}_{DM}$

↓

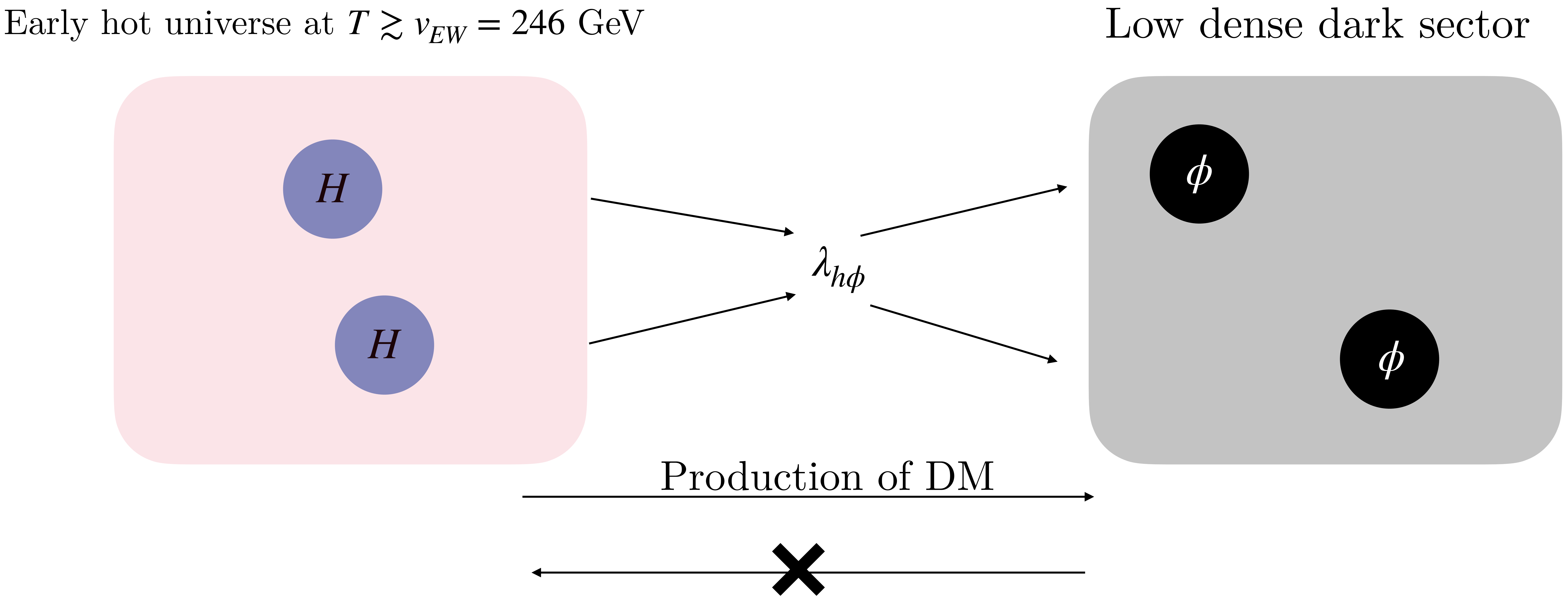
$\Gamma_{SM\to DM} \gg \Gamma_{DM\to SM}$

↓

Produce DM out of the SM plasma!

FIMPs and freeze-in

Production via: $HH^\dagger \to \phi\phi$



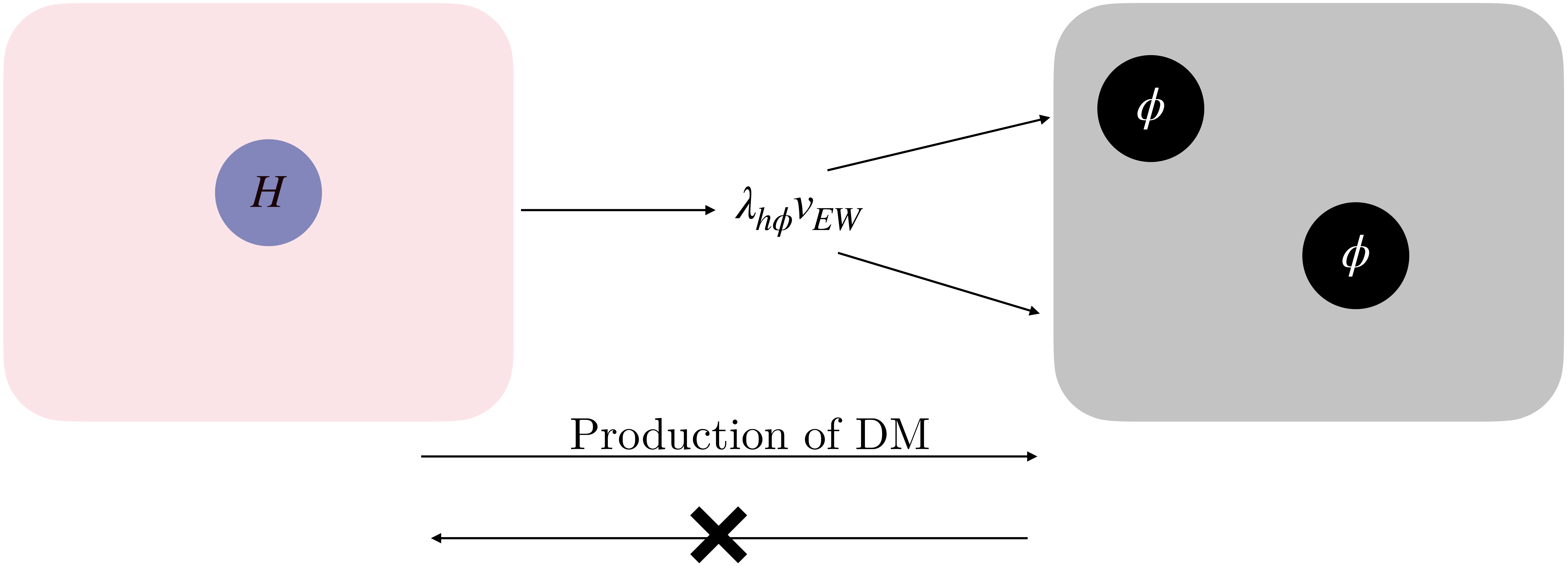
FIMPs and freeze-in

Production via: $h \to \phi\phi$

After electroweak phase transition $H^\dagger H \phi^2 \supset 2 v_{EW}\, h\phi^2$

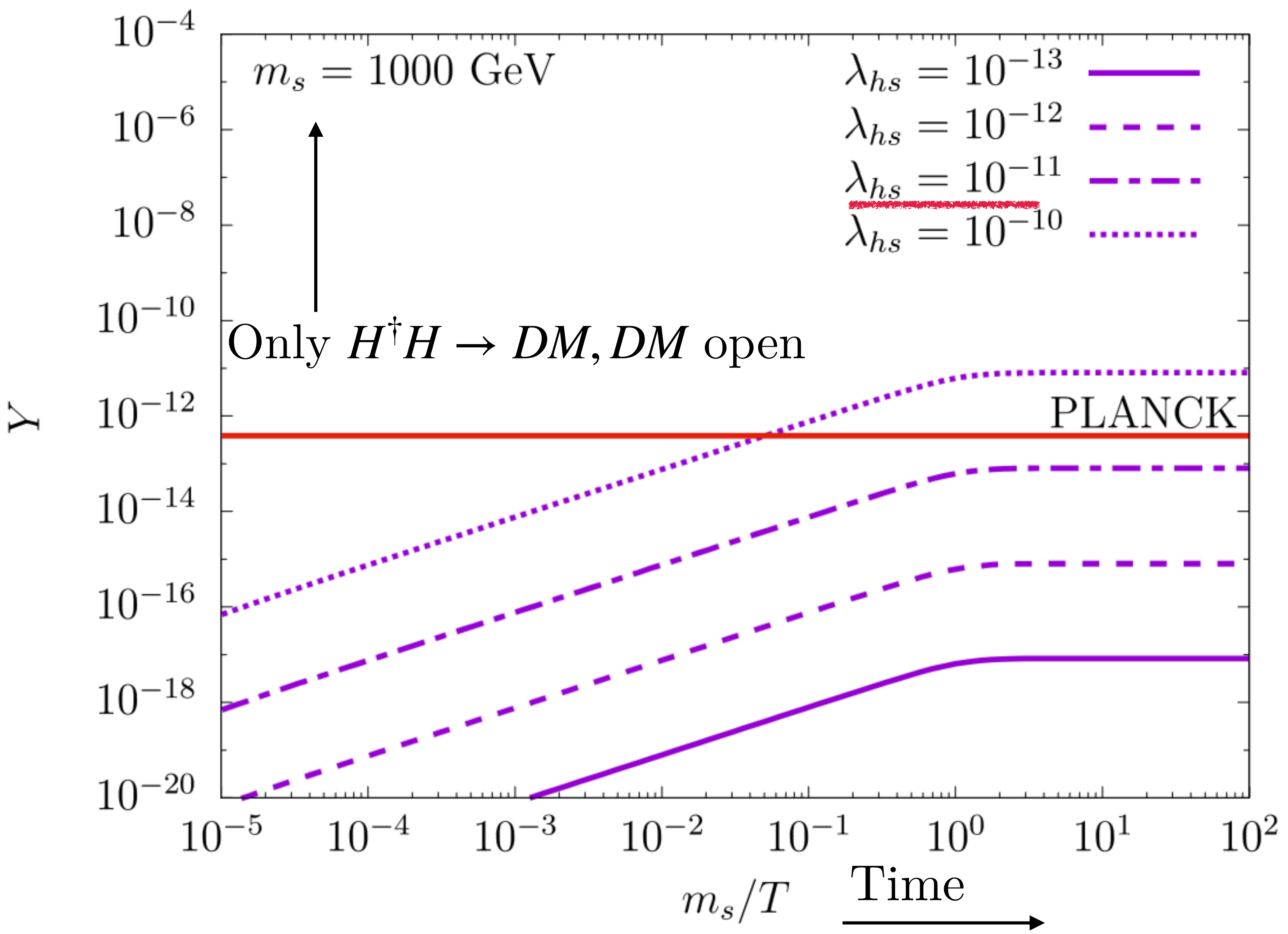
Early hot universe at $T \lesssim v_{EW} = 246$ GeV

Low dense dark sector

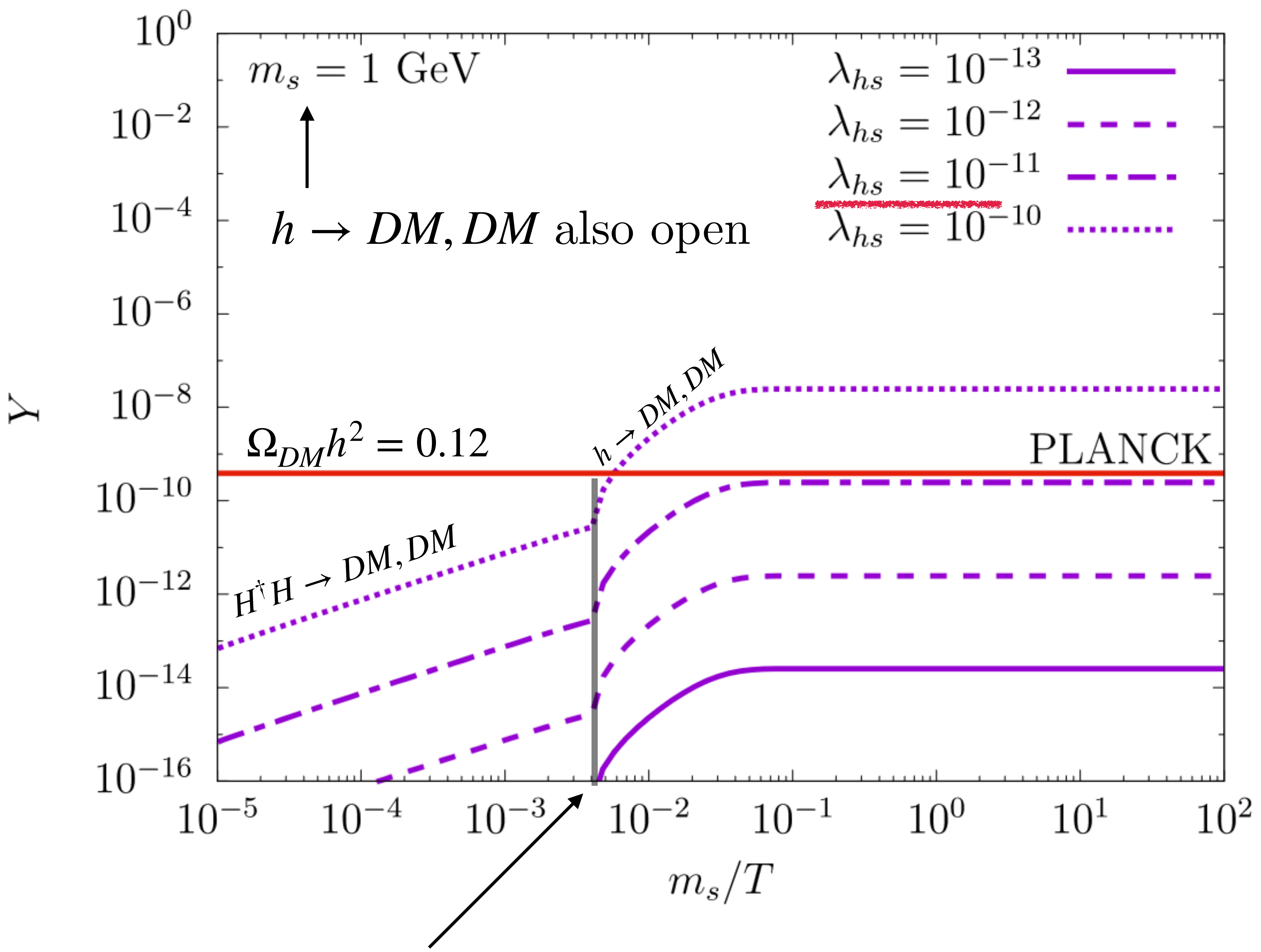


FIMPs and freeze-in

Punchline: Portal coupling $\sim 10^{-11}$



Lebedev et.al 1908.05491



$T = 150$ GeV (EW phase transition)

Consolidating both ideas

FIMPs and SIDM

No experimental signatures of standard WIMPs FO

conflict with $\lambda_{portal} \gtrsim 10^{-4}$

$\lambda_p = 0$

$\lambda_p \ll 1$

SIDM

Feebly Interacting Massive Particles

Ω^{Obs} from $3 \to 2$ self-annih.

Ω^{Obs} from Higgs

$$\mathscr{L}_{HP} \supset -\frac{m^2}{2}\phi^2 - \frac{\lambda}{24}\phi^4 - \frac{1}{2}\lambda_{h\phi} H^\dagger H \phi^2$$

Detecting FIMPs via Higgs Portals

SIDM with $\lambda_p \ll 1$

What if DM is *un*stable?

Lifetime $\overset{!}{>}$ age of universe

e.g. broken $\mathbb{Z}_2$

$\phi \to \phi + v_\phi$

$|H|^2\phi^2 \supset v_{EW} v_\phi h\phi$ (mixing)

$\phi \bar{f} f$

Detectability via $\phi \leftrightarrow SM, SM$

Stringent bounds on τ_ϕ

e.g. unbroken $\mathbb{Z}_3$

No mixing

Detectability via $\phi\phi \leftrightarrow H \leftrightarrow SM, SM$

What if DM is stable?

Signals in telescopes/colliders via

Constraints on $\sigma_{\phi\phi \leftrightarrow SM,SM}$

Detecting FIMPs via Higgs Portals

If *un*stable

Lifetime

$$\tau_{\phi\to SM,SM} = 1/\Gamma_{\phi\to SM,SM} = \frac{1}{\theta^2\,\Gamma_{h\to SM,SM}}$$

$$\theta := \frac{v_{EW}v_\phi}{m_h^2 - m_\phi^2}\lambda_{h\phi}$$

$$\Downarrow$$

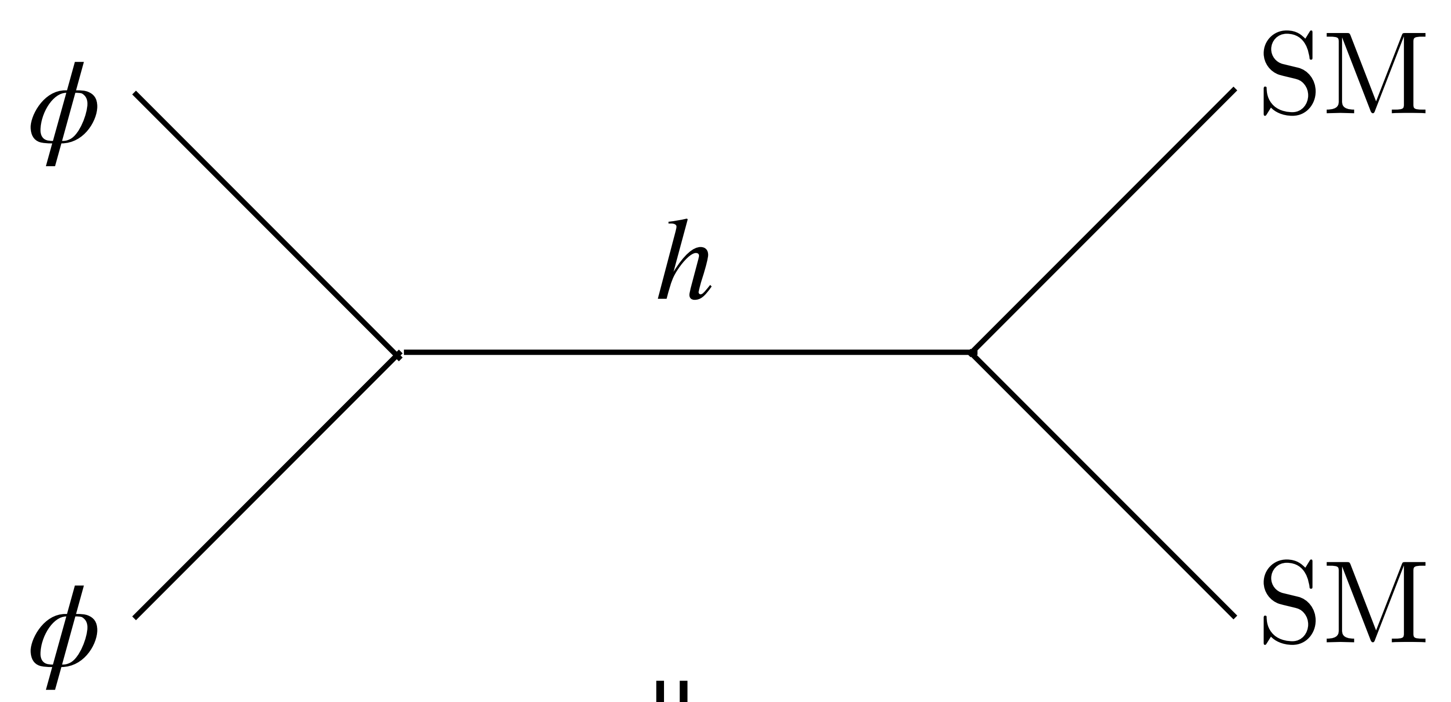
$$\tau_\phi \propto 1/\lambda_{h\phi}^2$$

$$\Downarrow$$

$\tau_\phi >$ *age of universe* naturally
for freeze-in $\lambda_{h\phi} \ll 1$

If stable

Cross section



$$\Downarrow$$

$$\sigma_{\phi\phi\to h\to ff} \propto \lambda_{h\phi}^2 \frac{Y_{hff}^2}{m_h^2}$$

$$\Downarrow$$

Additionally suppressed with Higgs mass!

SIDM produced via freeze-in

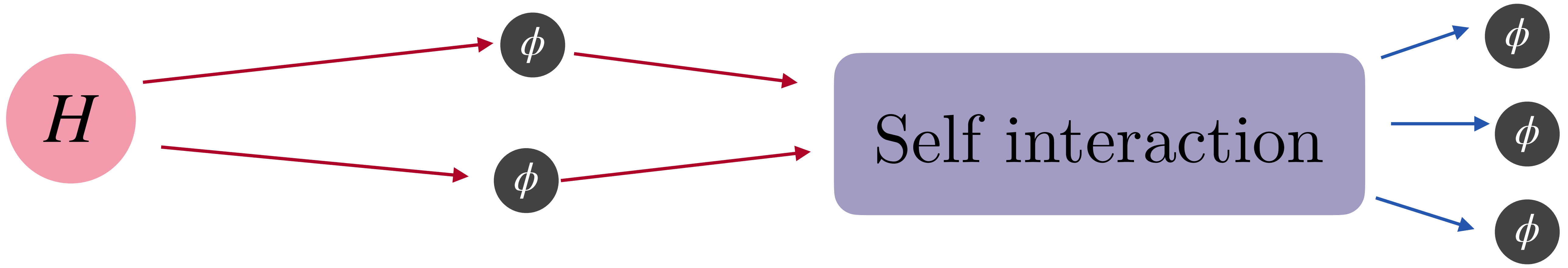
During dark freeze-out DM transforms # of particles into k. energy.

Can the reverse happen?

In principle, ***why not?***

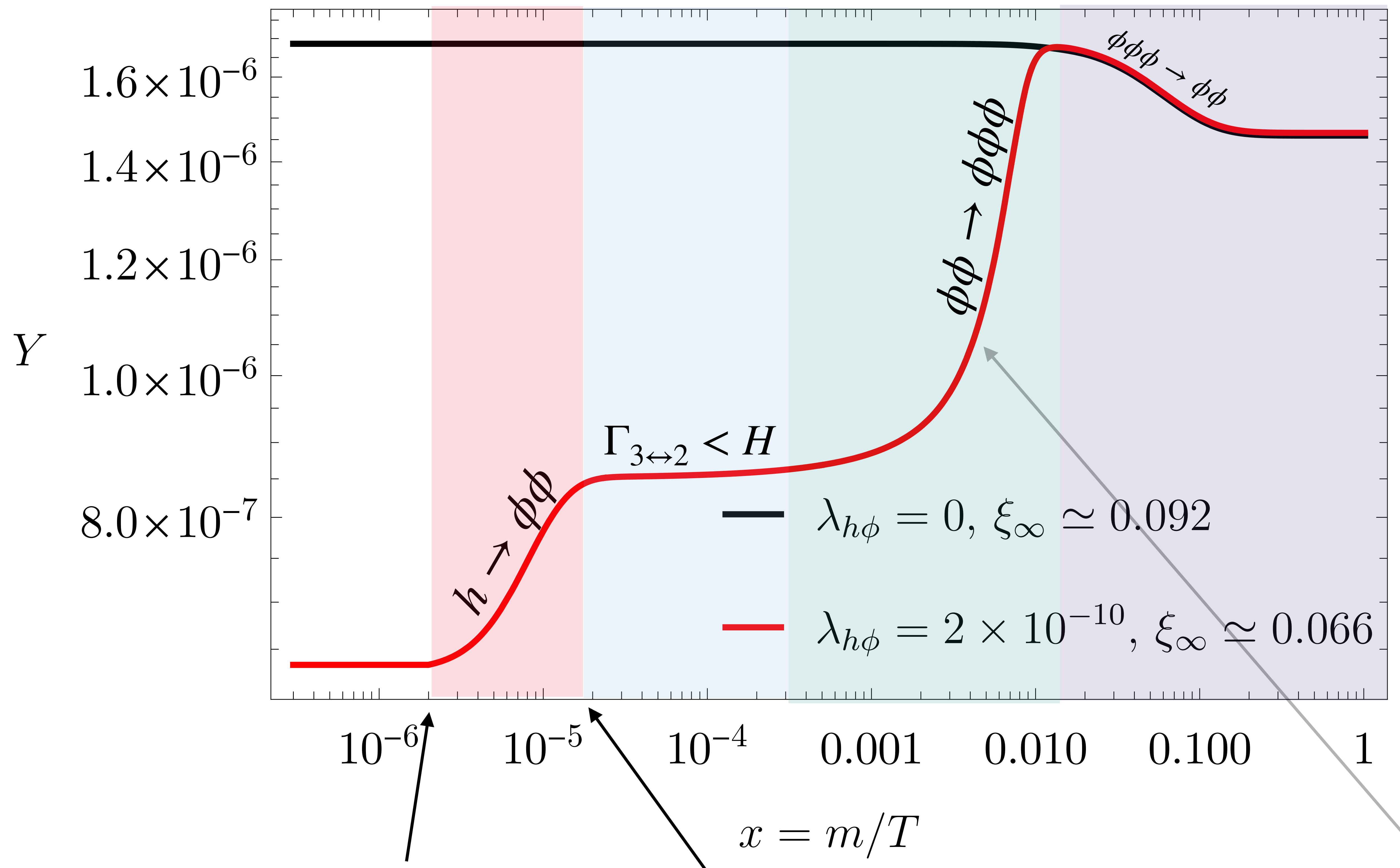
Where do we get the energy from?

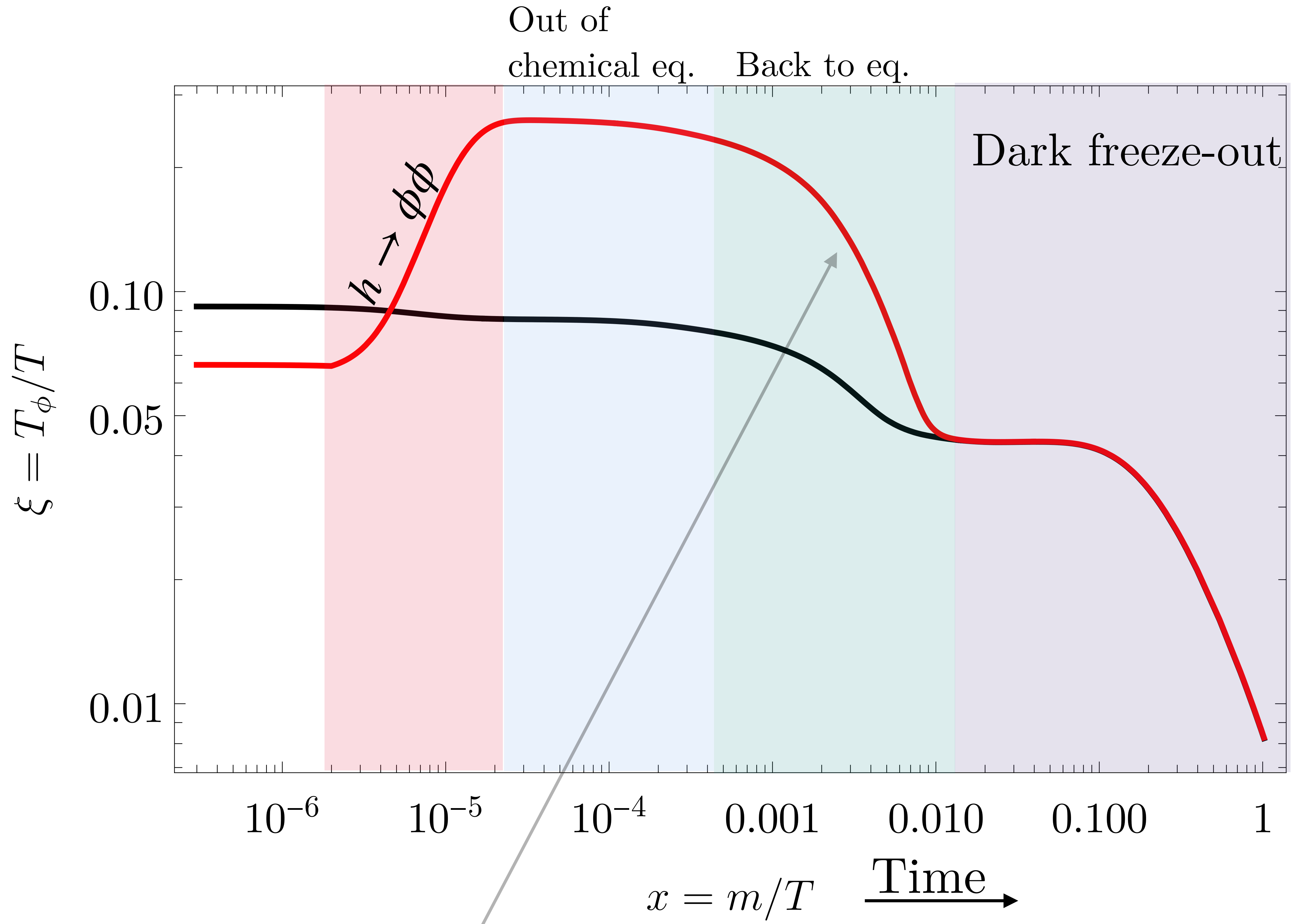
Short answer: the Higgs



Dynamics

$\mathbb{Z}_2$ broken case: real scalar with $m = 300$ KeV





Higgs decay at
$T_{EWPT} = 150$ GeV
$x = 2\times10^{-6}$

Freeze-in ends
~ 10 GeV

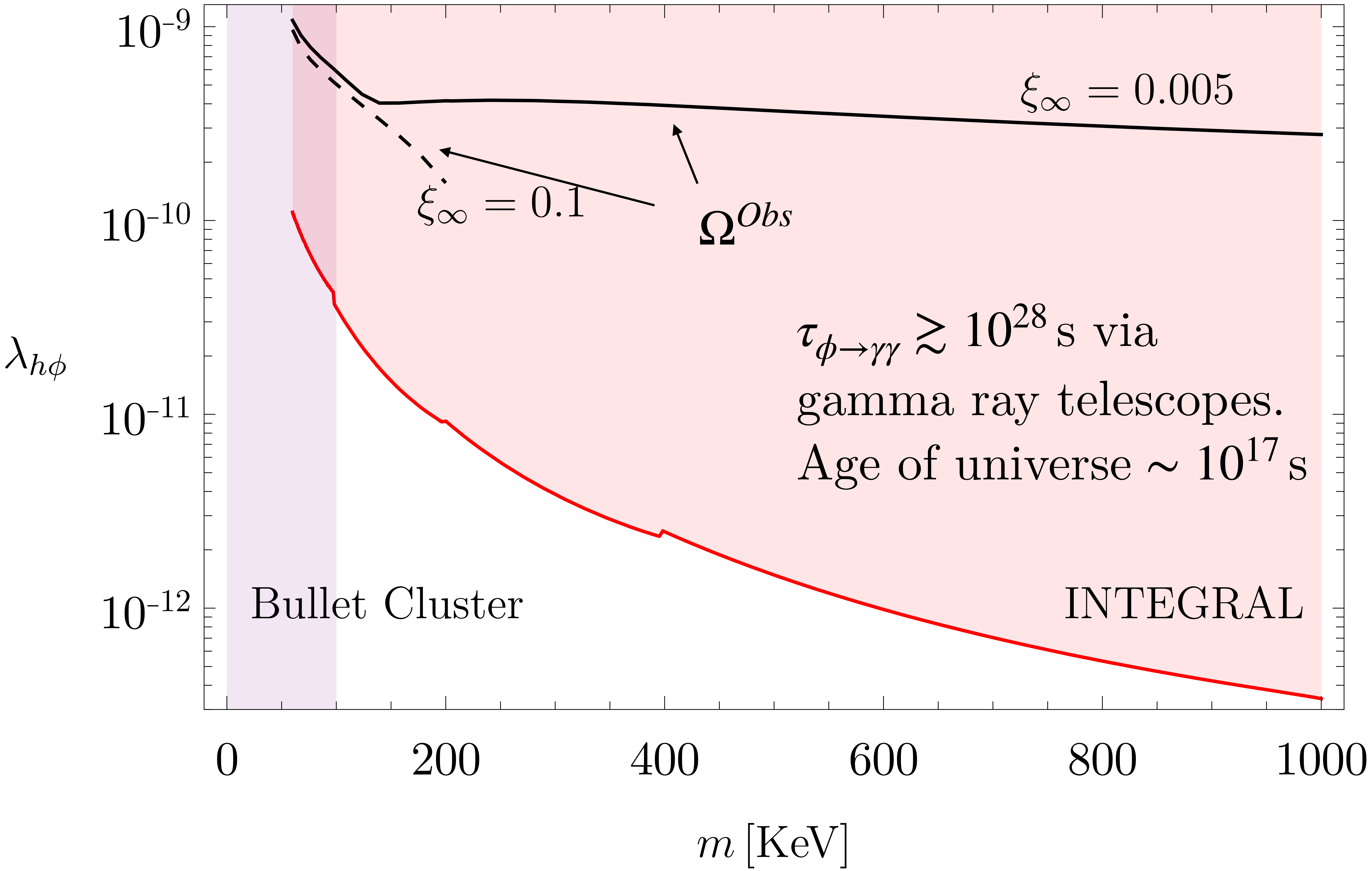
Cooling in exchange for more DM!

Any (interesting) phenomenology?

Hot dark sector
out of chemical eq.
$n_\phi(T_\phi) < n^{eq}(T_\phi)$

$2 \to 3$ self freeze-in
production

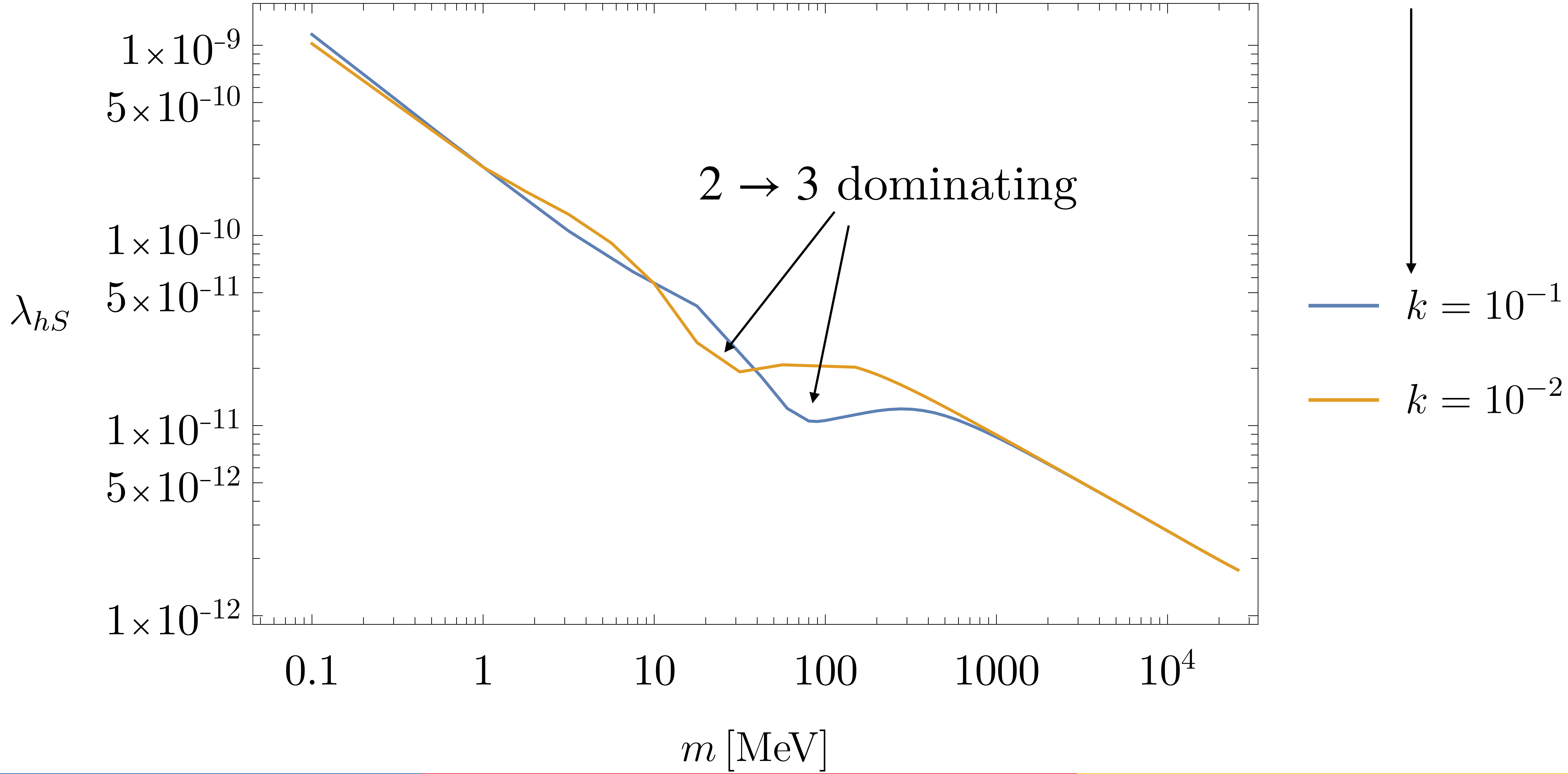
Back to chemical
equilibrium



Phenomenology

What about a stable $\mathbb{Z}_3$ complex scalar DM?

Initial cool dark sector → $\xi_\infty = 10^{-3}$, $\lambda = 10^{-2}$ ← Self interacting couplings



Conclusions

For *unstable* self interacting DM:

- considerably constrained by telescopes data: $\tau_{DM\to\gamma\gamma} \gtrsim 10^{28}\,\mathrm{s}$;
- $\Longrightarrow$ freeze-in *subdominant.*

For *stable* self interacting DM:

- No bounds from telescopes;
- Annihilation cross section suppressed due to Higgs mass (hint: light mediator);
- No falsification possible with current technology.

Thank you very much for your attention!