NATIONAL SCIENCE CENTRE
POLAND

FREEZEING-IN CANNIBAL DARK SECTORS

Andrzej Hryczuk

NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

based on:

E. Cervantes and AH 2407.12104 (to appear in JHEP)

COSMO-24, Kyoto University

Kyoto, 24th October 2024

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

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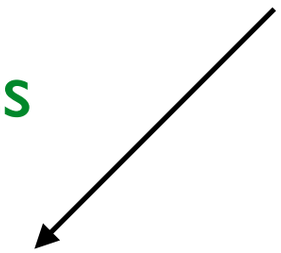
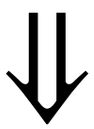
Yes



At high temperature
DM thermalises, has
very high abundance



An efficient
depletion is needed
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A slow production is needed (freeze-in)

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„Initial condition" dependence

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depletion to SM

„WIMP”

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Secluded dark sector

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depletion to kinetic energy

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(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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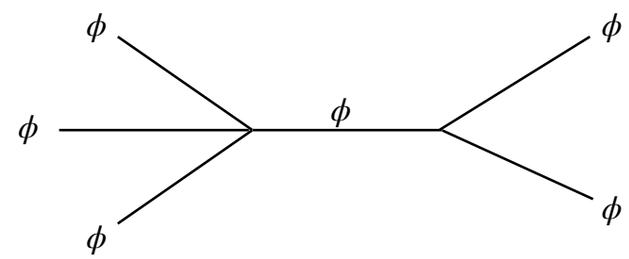
Received 1992 March 17; accepted 1992 April 20

…, Hochberg et al. '14; …

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

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



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

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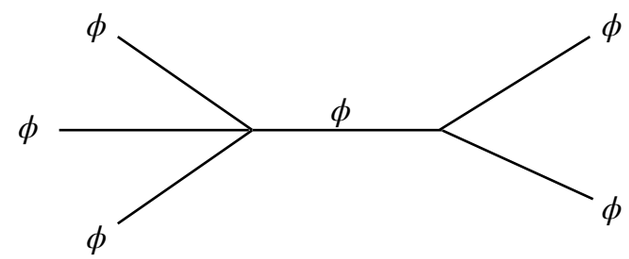


To obtain correct relic abundance: $m_\phi \sim \mathcal{O}(10 - 100\,\mathrm{MeV})$

cannibalisation: mass → kinetic energy

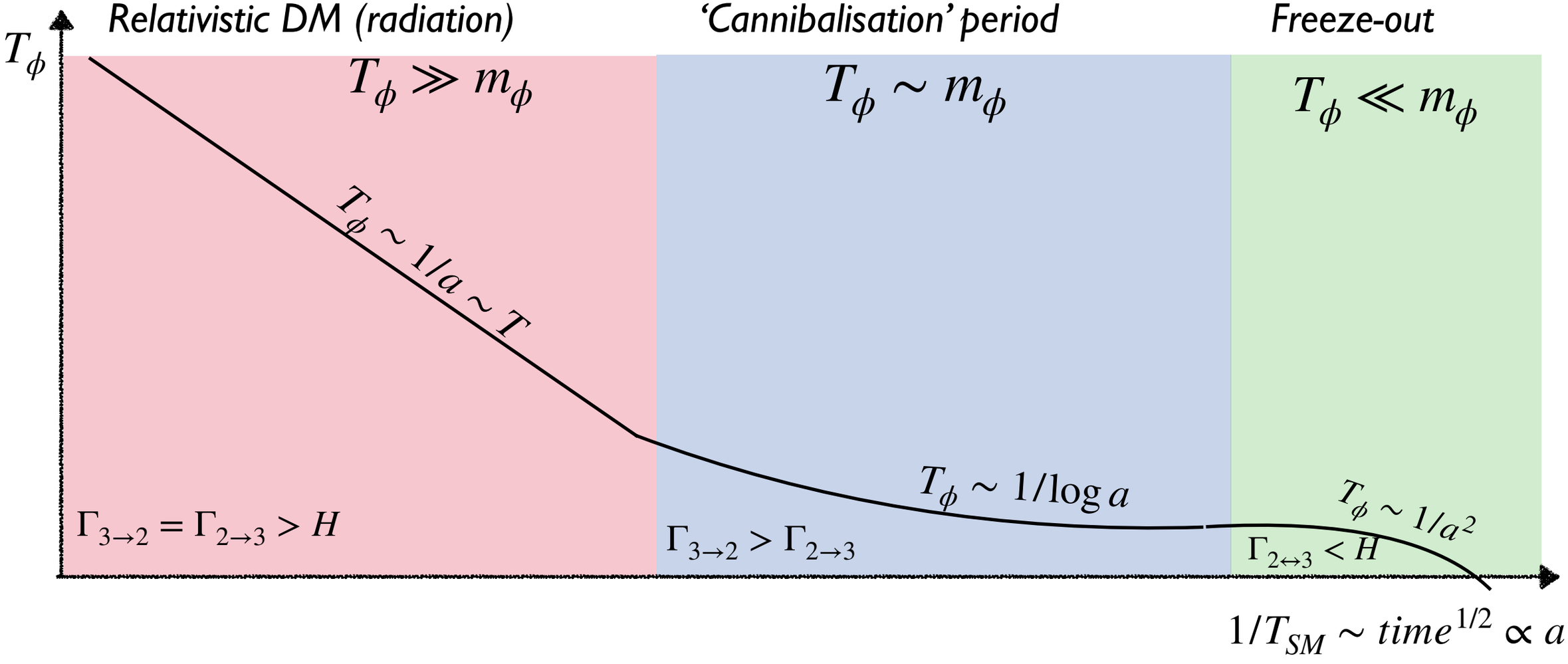
expansion: kinetic energy redshifts → depletion of E of the dark sector

Problem: structure formation…

de Laix et al. '95

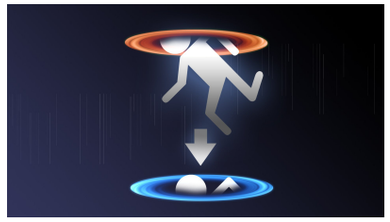
CANNIBAL FREEZE-OUT

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.

PORTALS



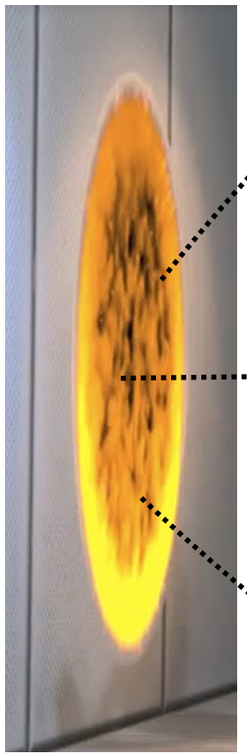
Vector

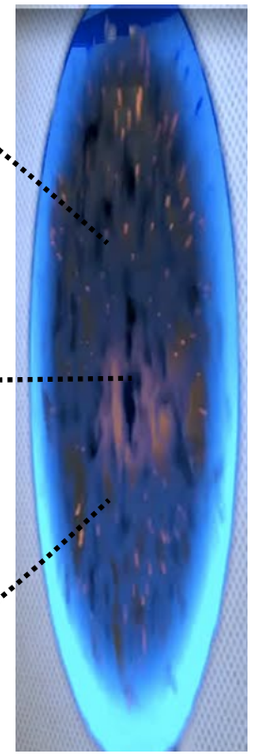
$$\epsilon F'_{\mu\nu} F_Y^{\mu\nu}$$

DM/mediator

visible sector

dark sector





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 ν_R has mass mixing with SM ν's

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

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

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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:

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

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

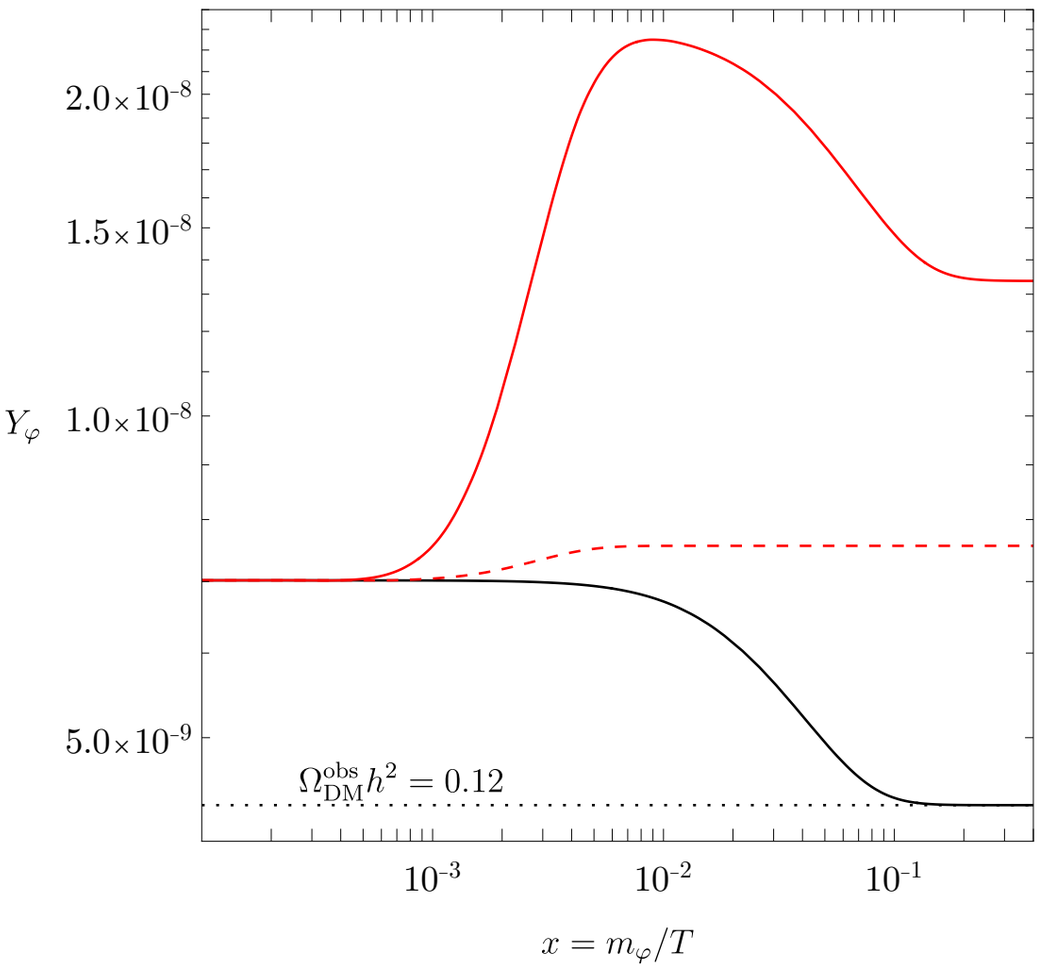
Freeze-in Freeze-in/out El. scattering

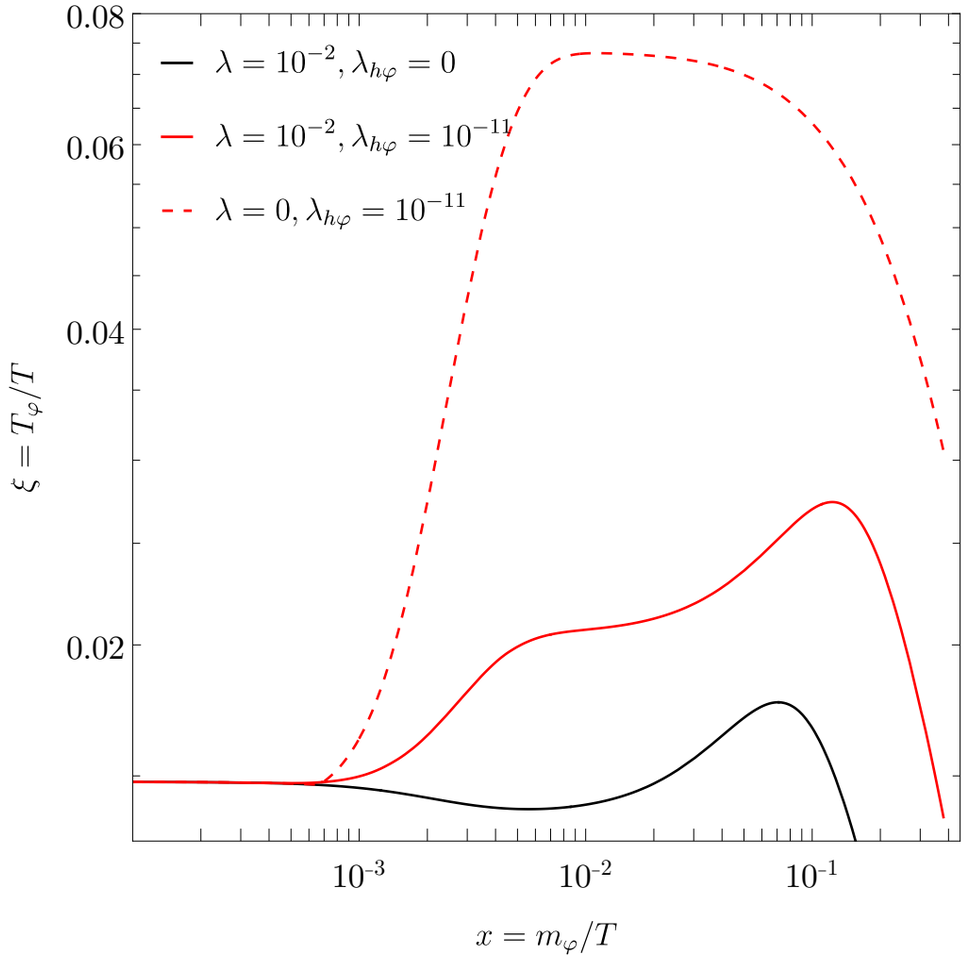
see also Ghosh et al. '22

BOOSTING FREEZE-IN

see also Bernal '05

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





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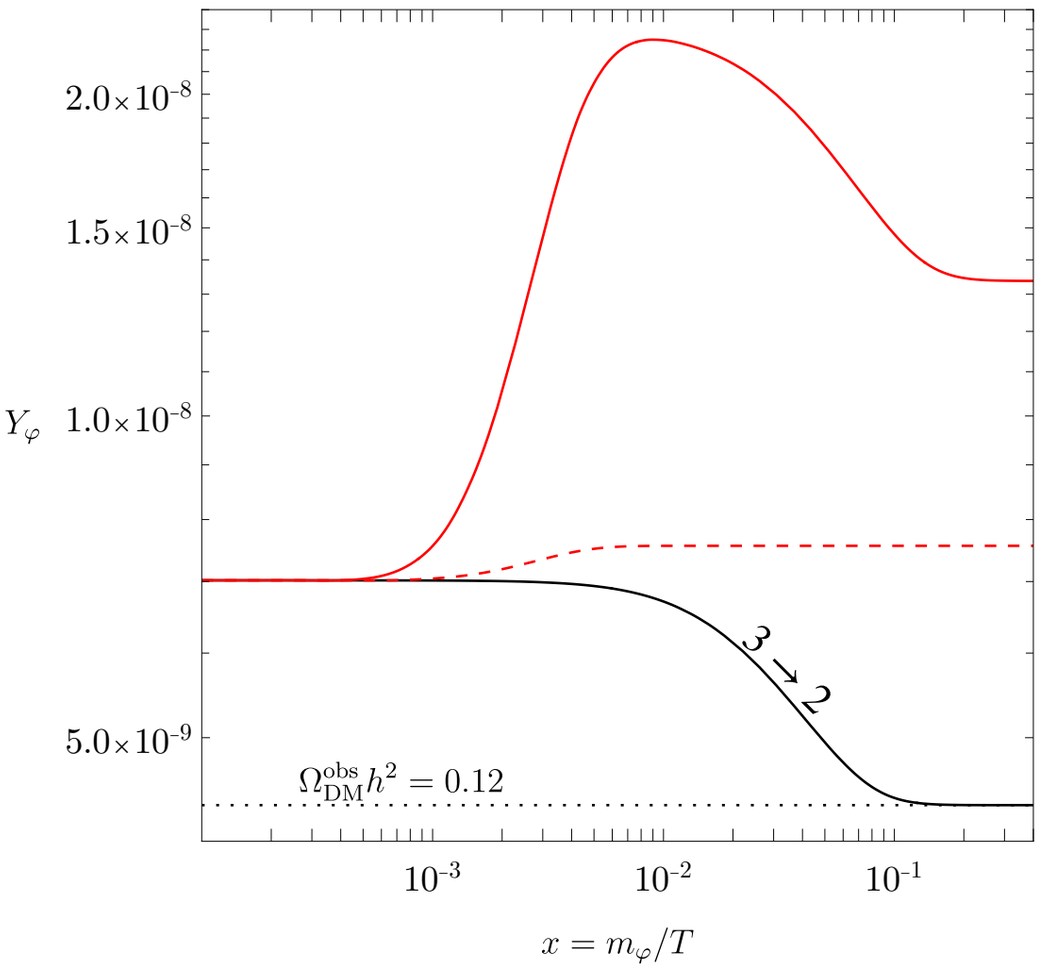

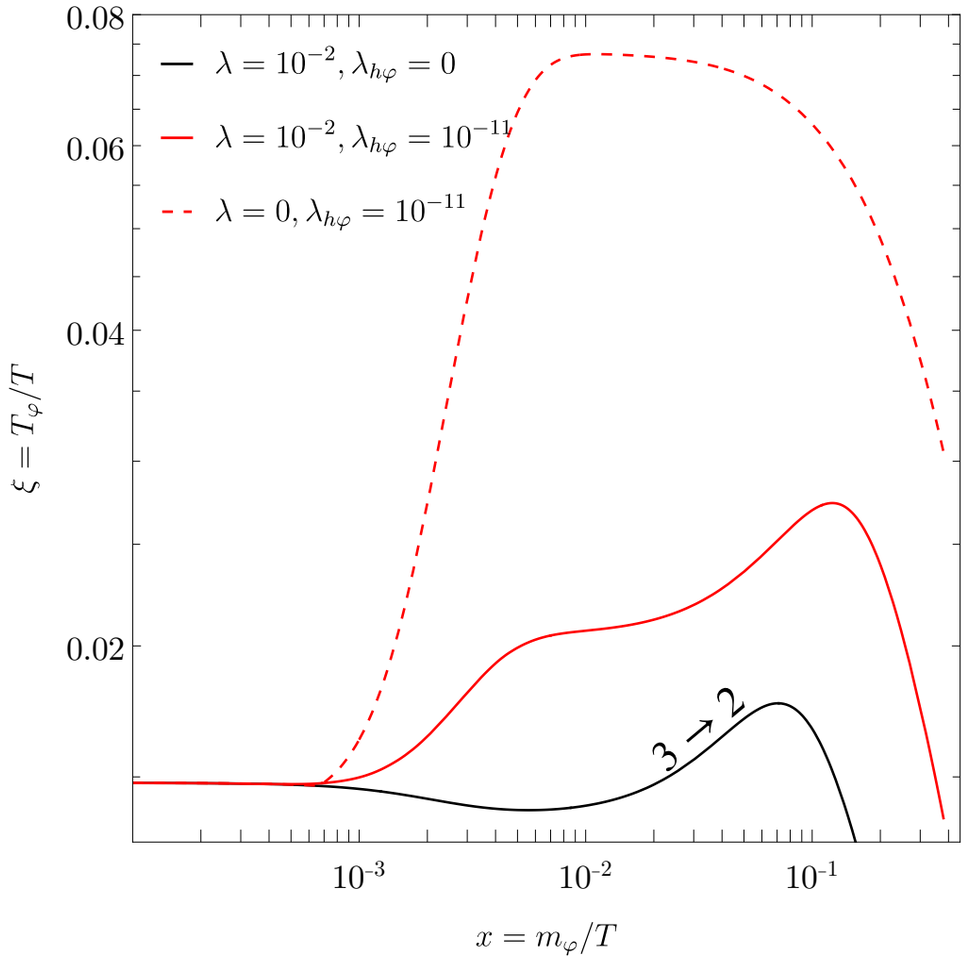

only cannibalization

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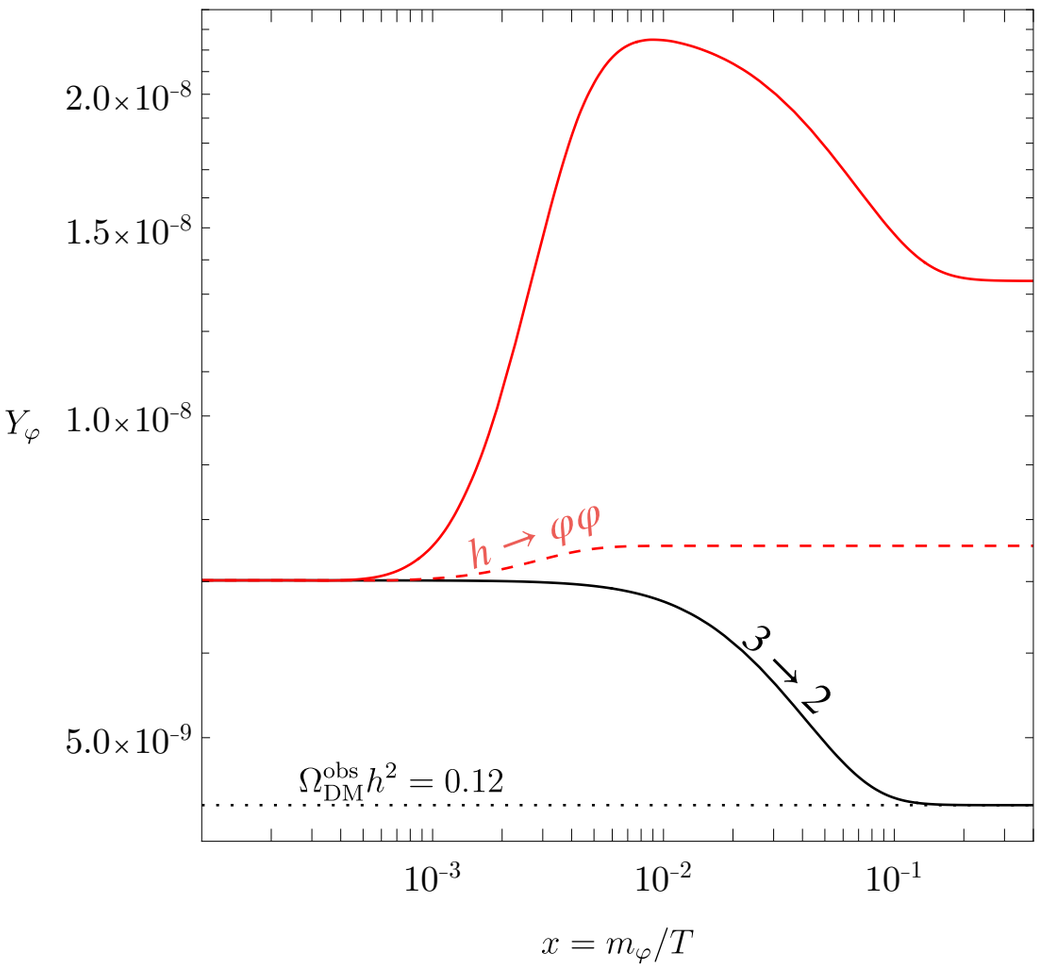

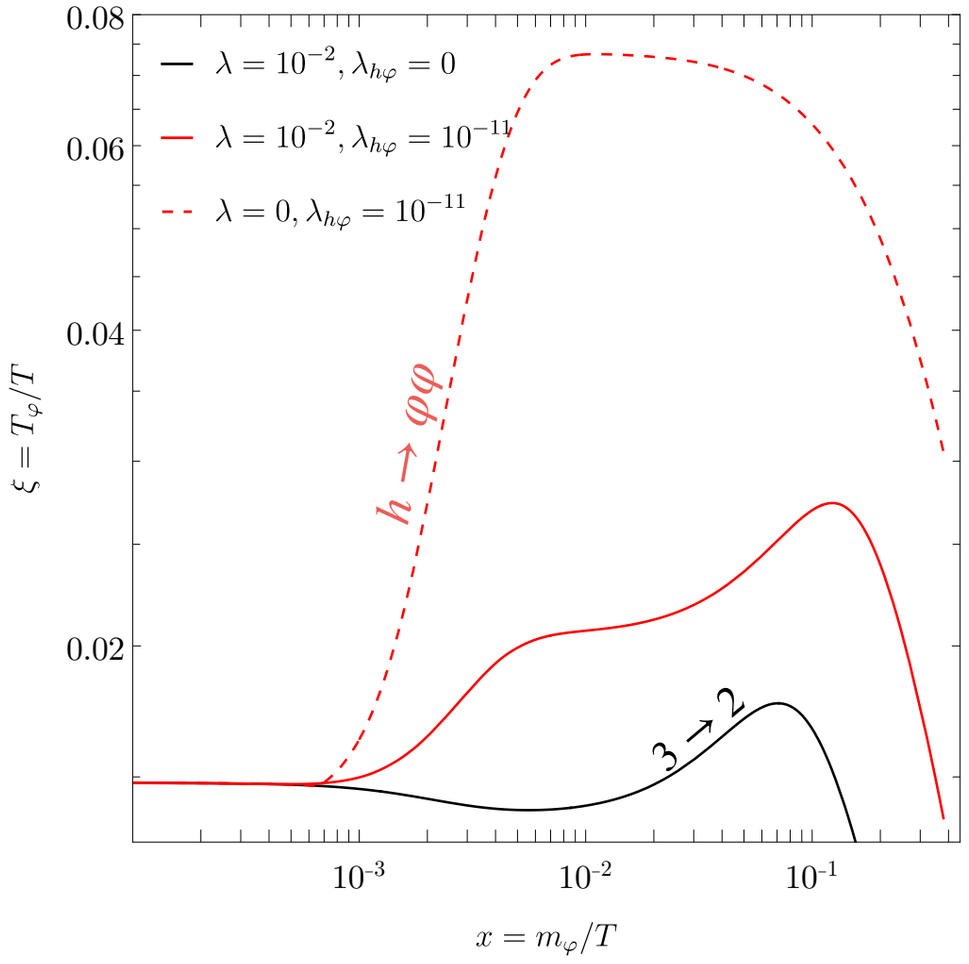

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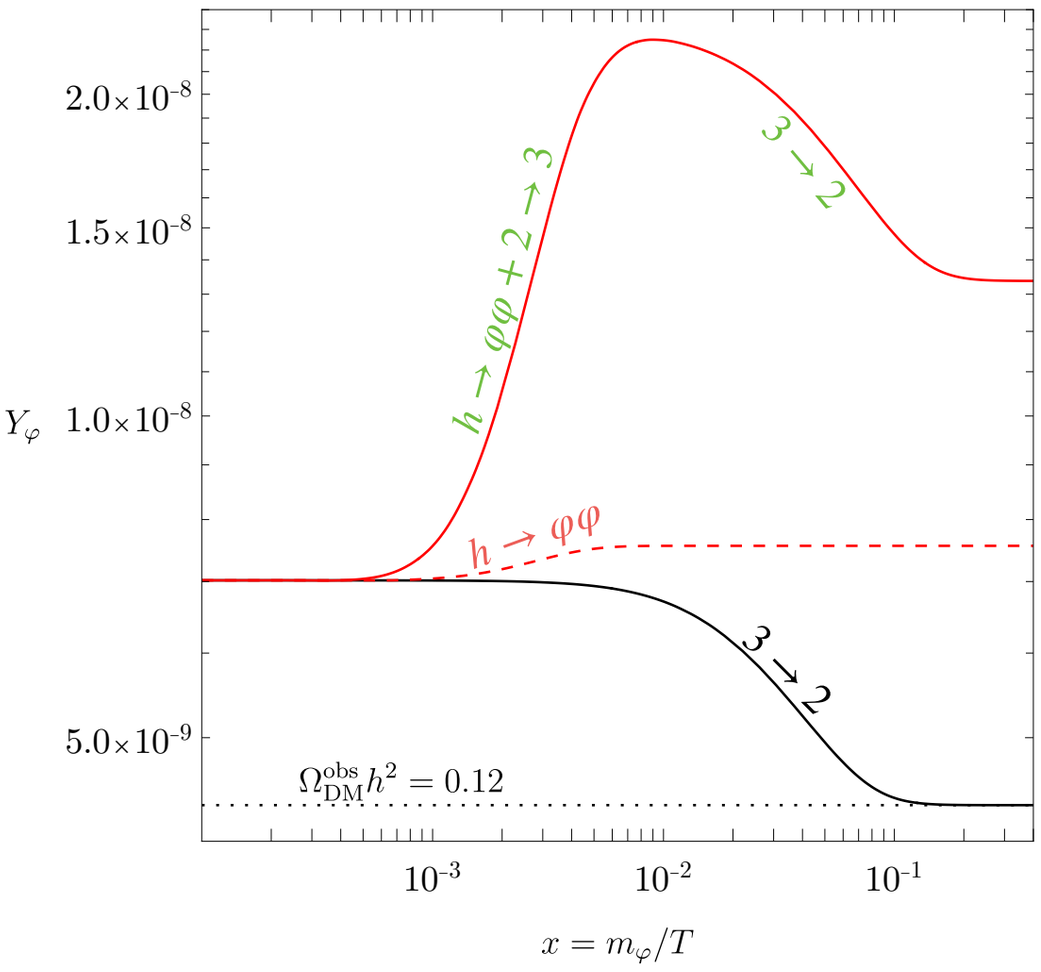
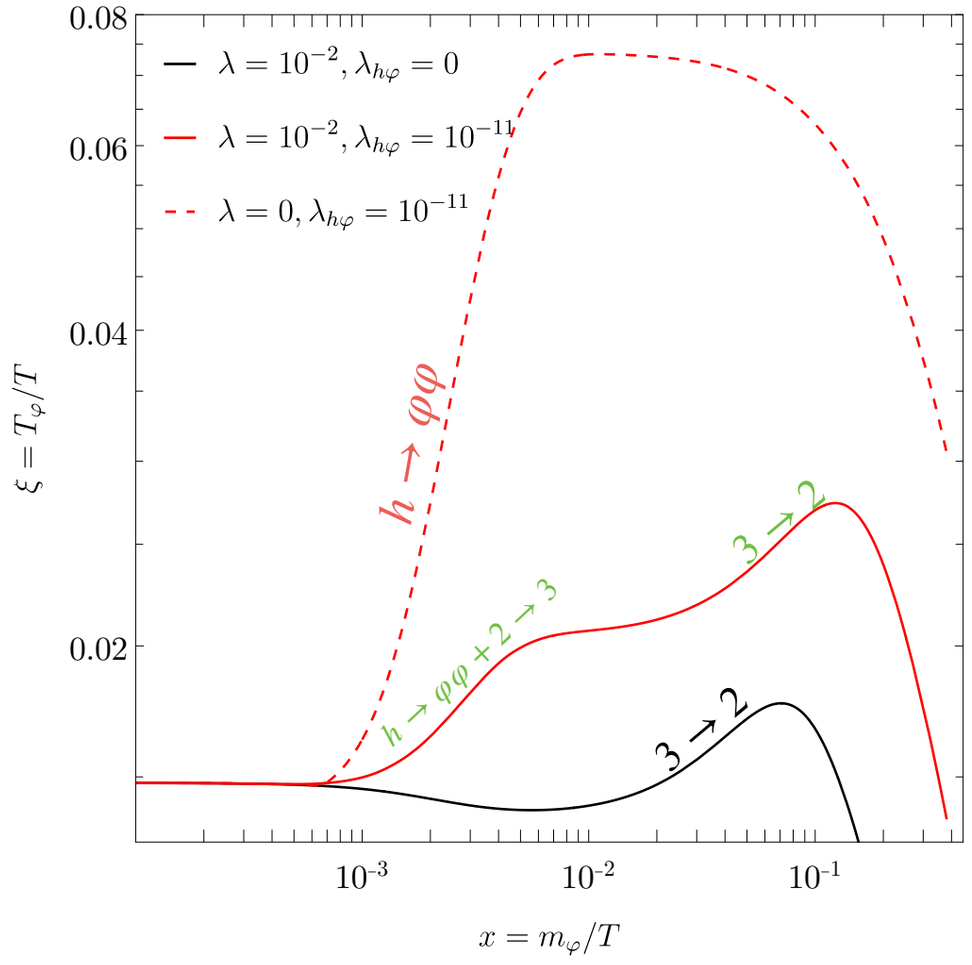




only cannibalization

only freeze-in

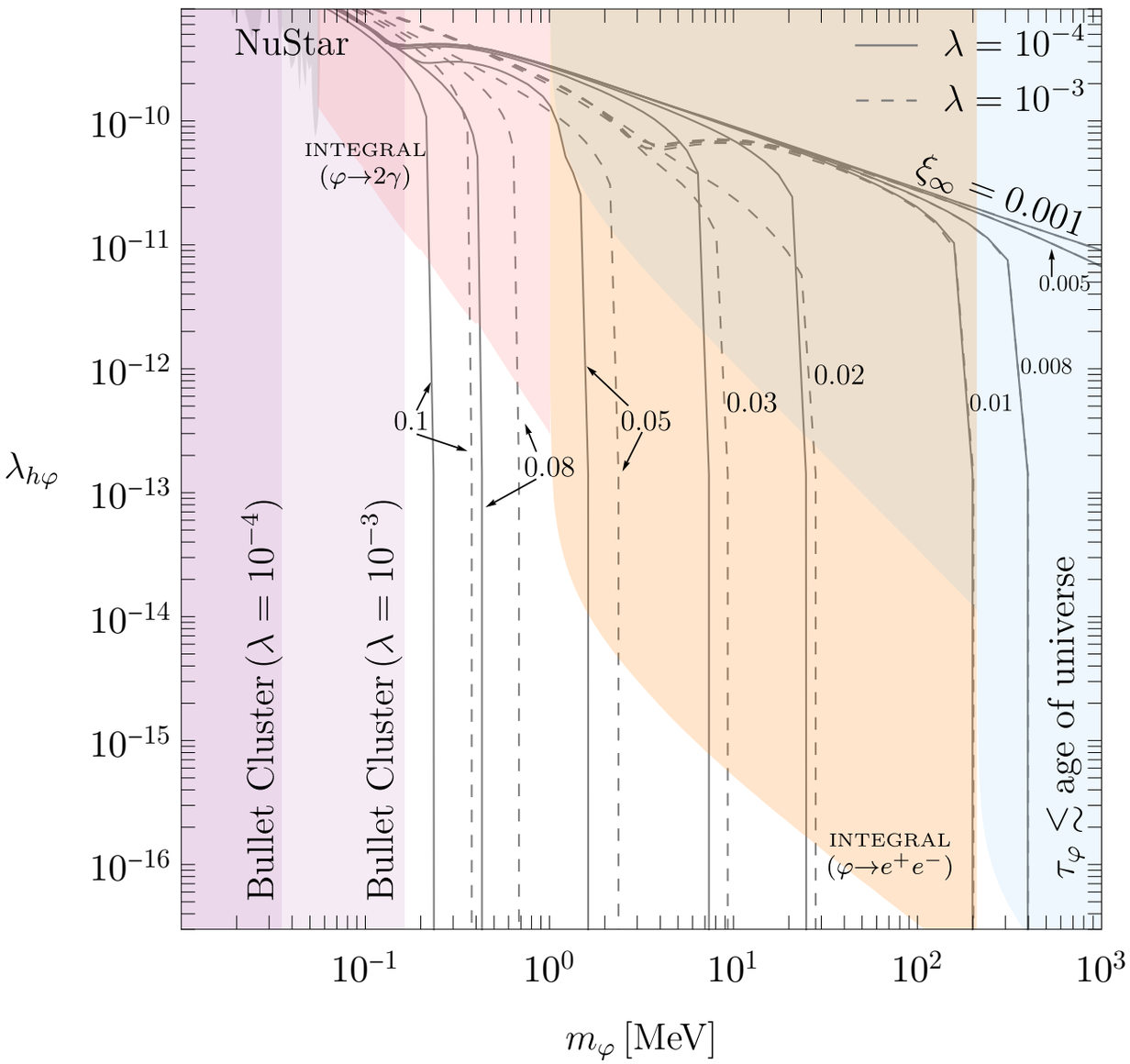
cannibal+freeze-in

THIS MODEL HAS AN ISSUE…

$\mathbb{Z}_2$ breaking $\Rightarrow$ φ 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 negligible in the allowed region

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

goes to the scenario of Hufnagel, Tytgat '22

Modified Model

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

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

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:

$$\phi \to \phi + \theta h$$
$$h \to h - \theta\phi$$

→ ϕ couples to matter in a Higgs-like way

Such a model exhibits new dynamics + provides chance of detection

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

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

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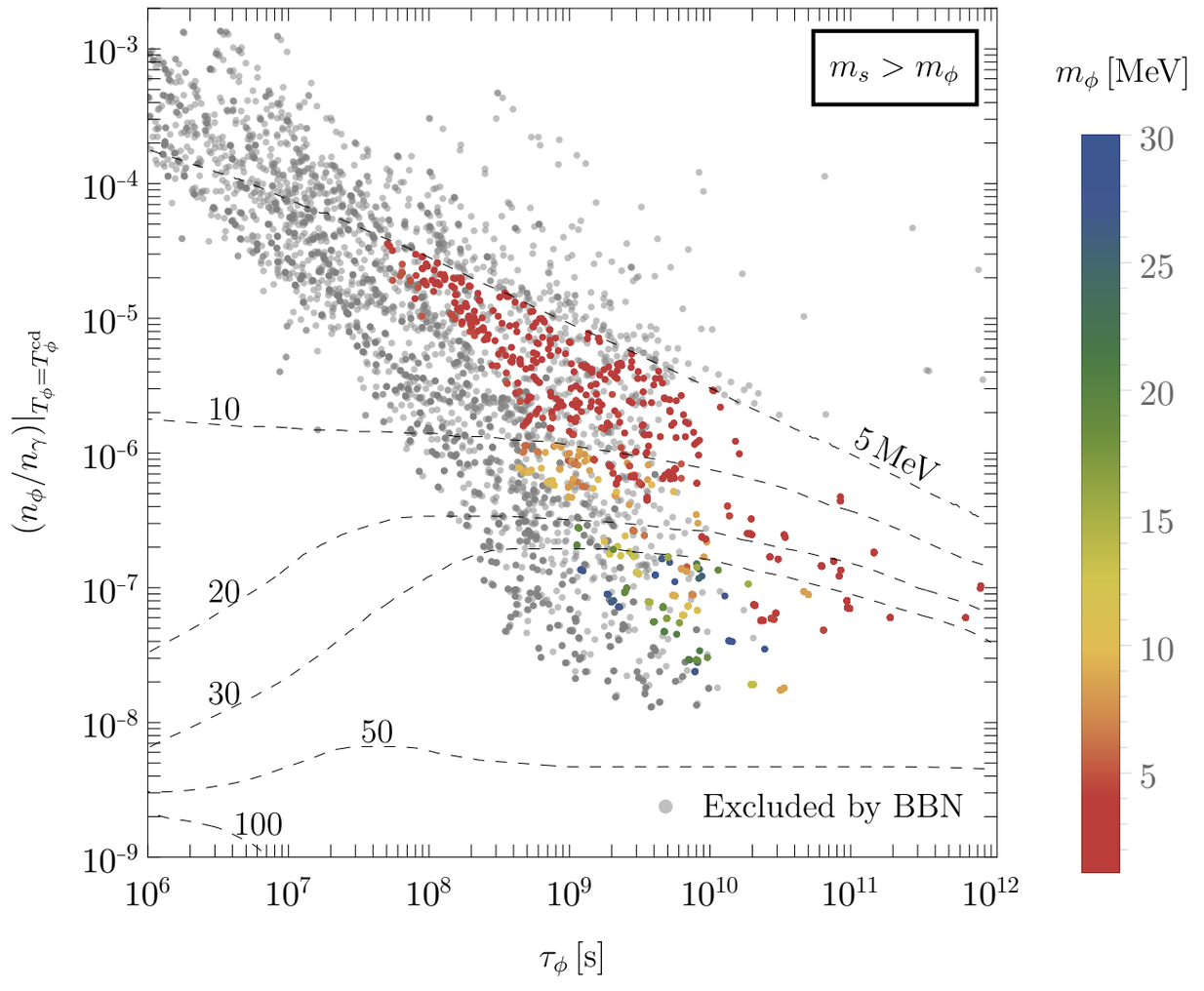
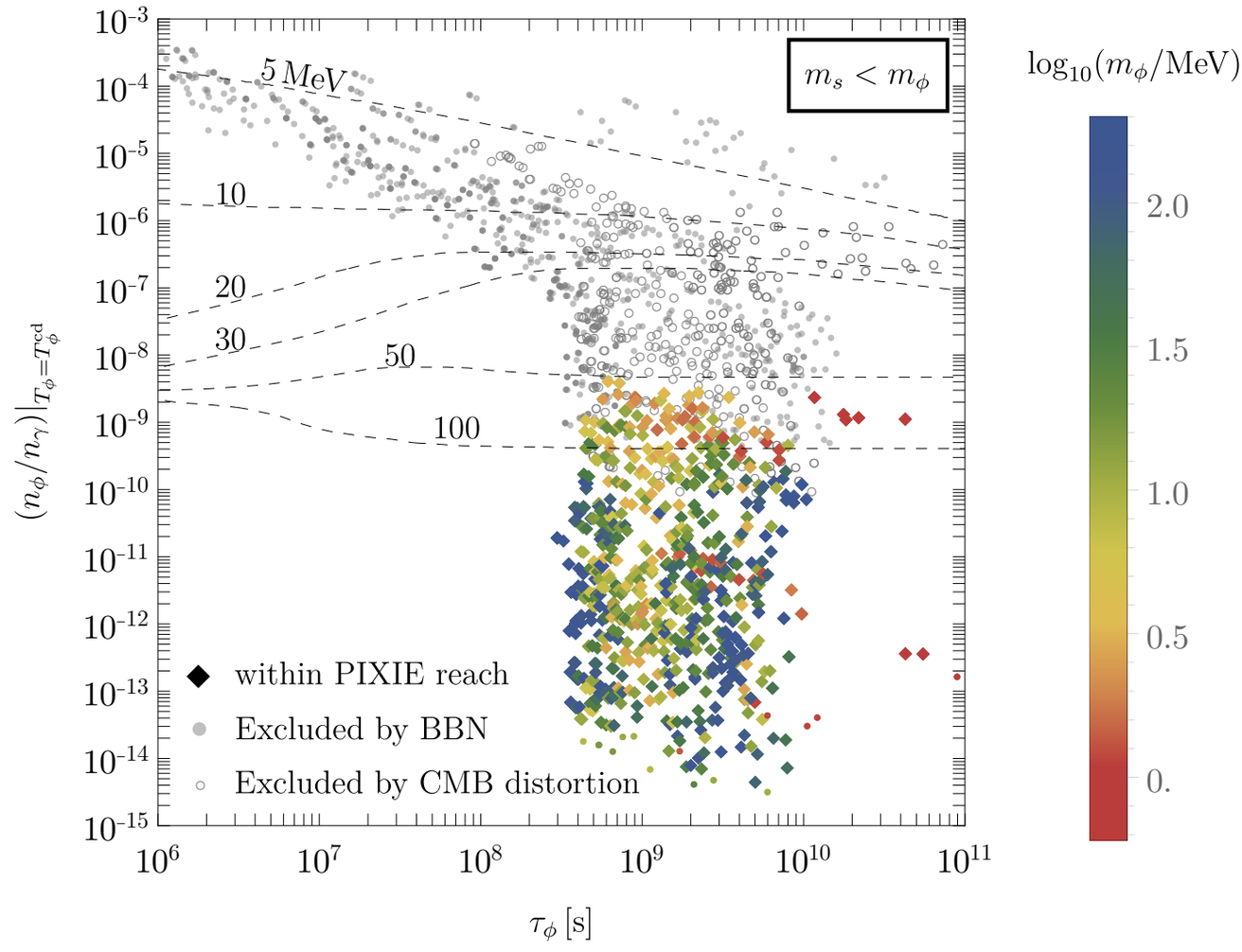
BBN & CMB CONSTRAINTS

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



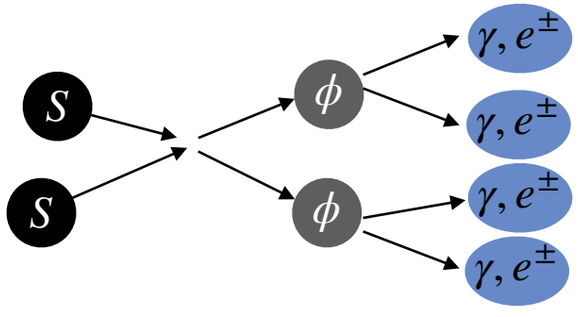


Resulting constraints are significant, but many viable points found in a scan & some with prospects of CMB distortion in reach of PIXIE

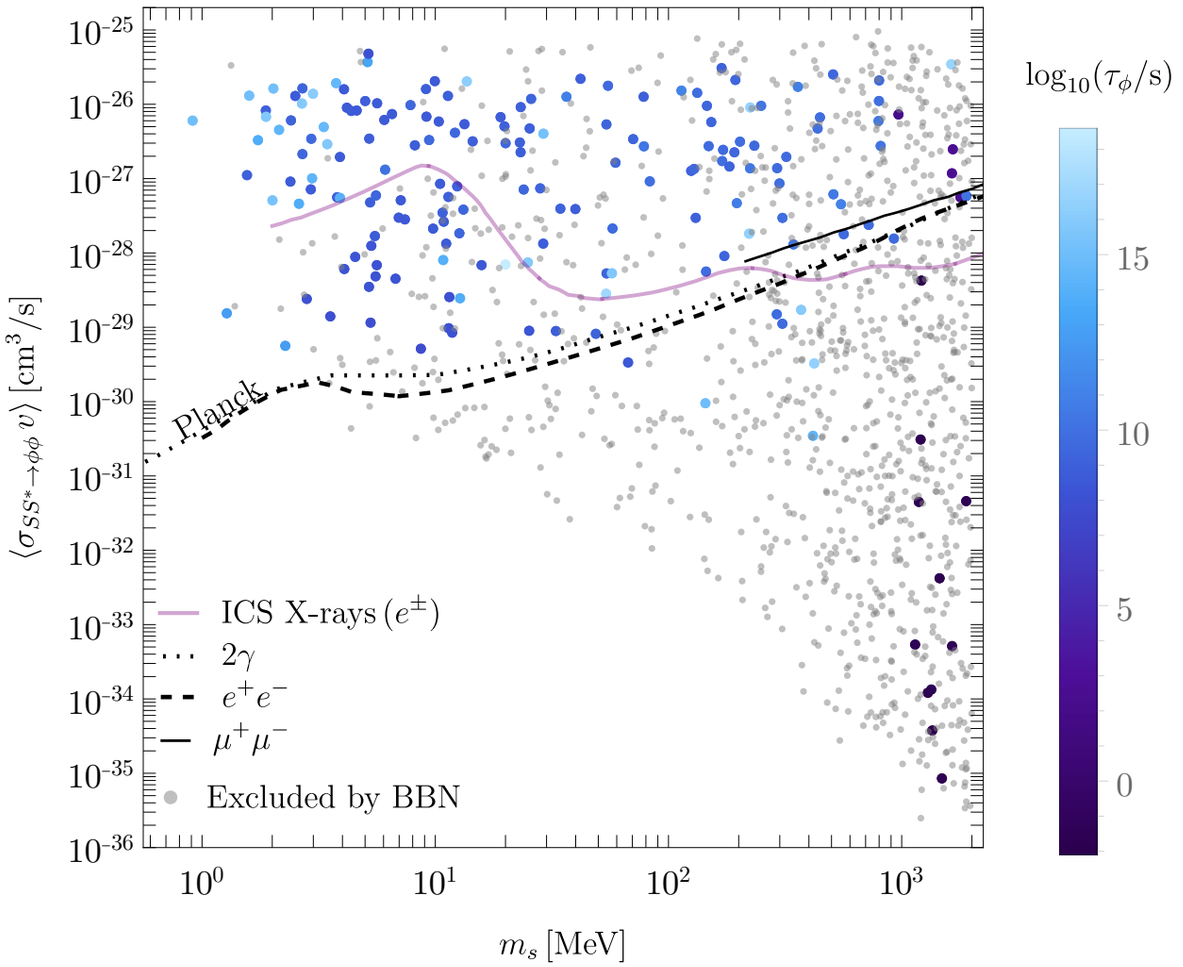
(The Primordial Inflation Explorer)

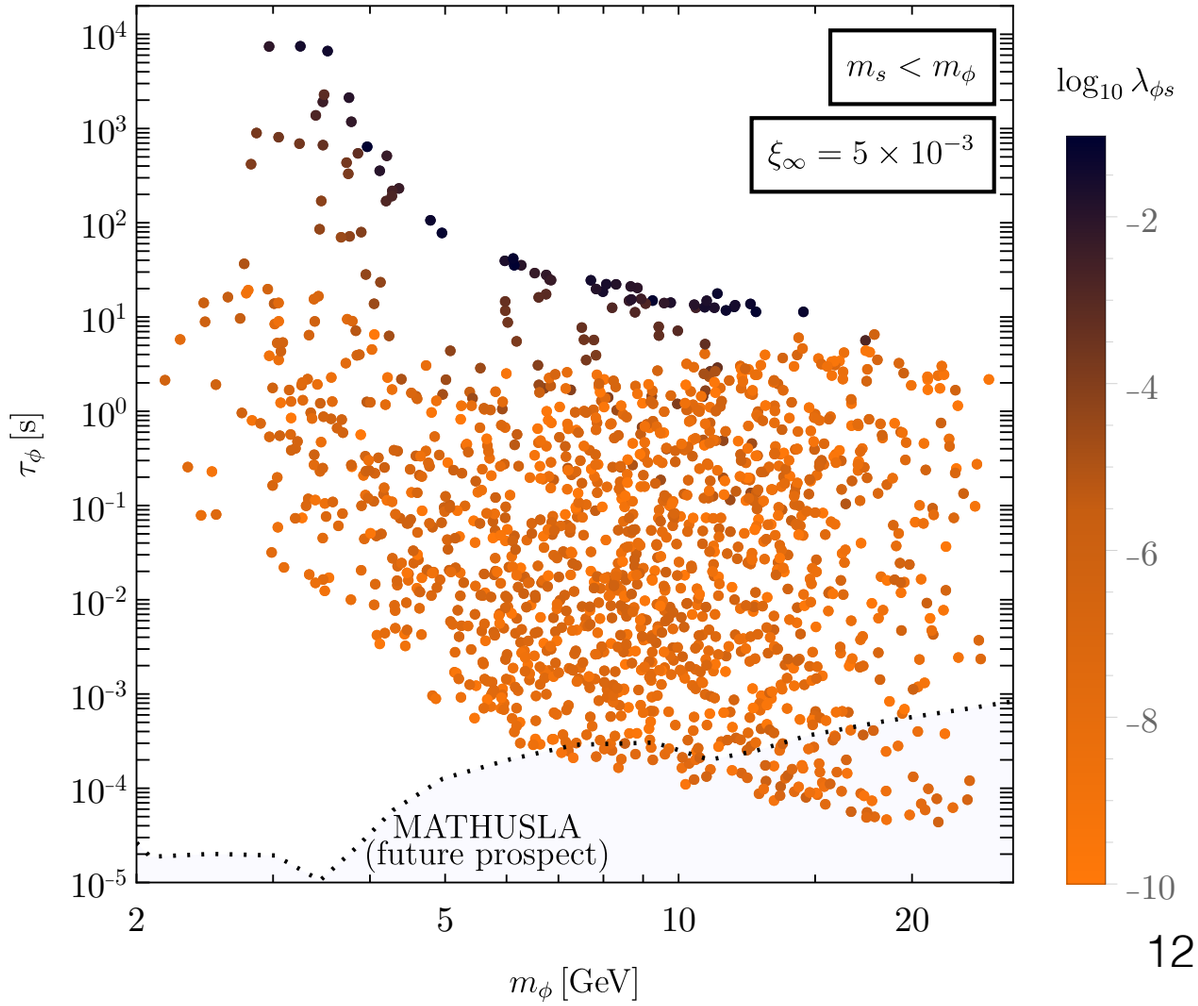
DM & MEDIATOR DETECTION

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



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





CONCLUSIONS

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

2. It has unique evolution in the Early Universe & potentially detectable signals in indirect searches.

3. Temperature (and momentum distribution) can have a non-trivial impact in such scenarios and a need to be studied carefully.

Thank you!