A CASE FOR CALCULATING $f_{\mathrm{DM}}(p)$
(AND HOW TO… MAKE DM COOL AGAIN)

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Based on:

work (in progress) with **E. Cervantes & S. Lederer**

work with **S. Chatterjee** 2604.14688

+ some earlier works with **T. Binder, T. Bringmann, M. Gustafsson, M. Laletin**

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8th May 2026

Be Careful what you Average over

Dynamics of particle production is often governed by various rates:

$$n\langle \sigma v \rangle \quad \text{or} \quad \langle \Gamma \rangle$$

where the average is done over the (momentum) distribution $f(p)$:

$$\langle \ldots \rangle \equiv \langle \ldots \rangle_f$$

The question is: what is $f(p)$? Is it thermal? Does it matter if not?…

(often it is… but in many cases it is not) it depends…

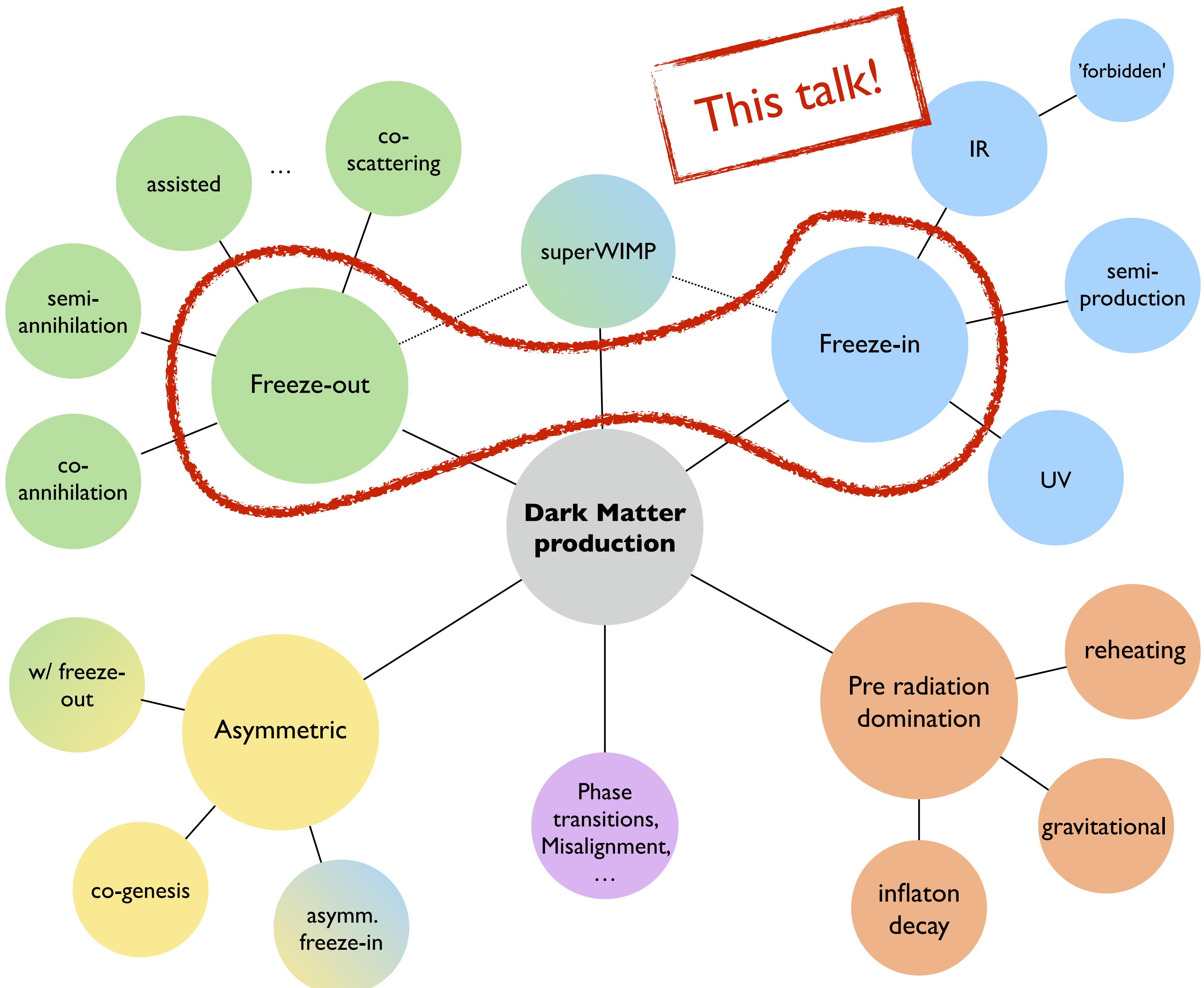
MOTIVATION & OBJECTIVES

A (step in a) program of describing
Dark Matter production
in systems
departing from local thermal equilibrium

Implementation of freeze-in production & two-component systems in DRAKE2

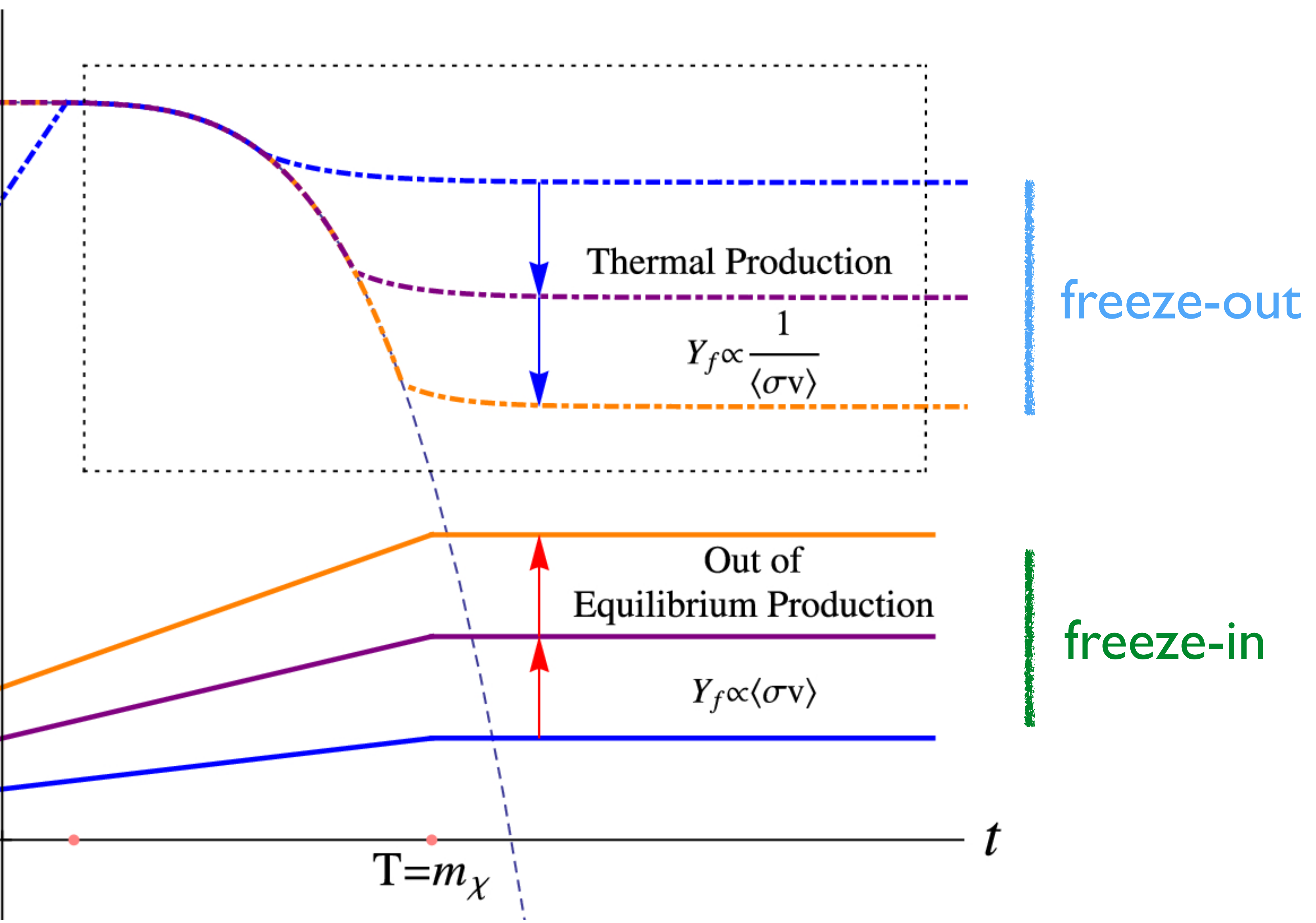
New mechanism for cooling DM & loosening Lyman-α bound

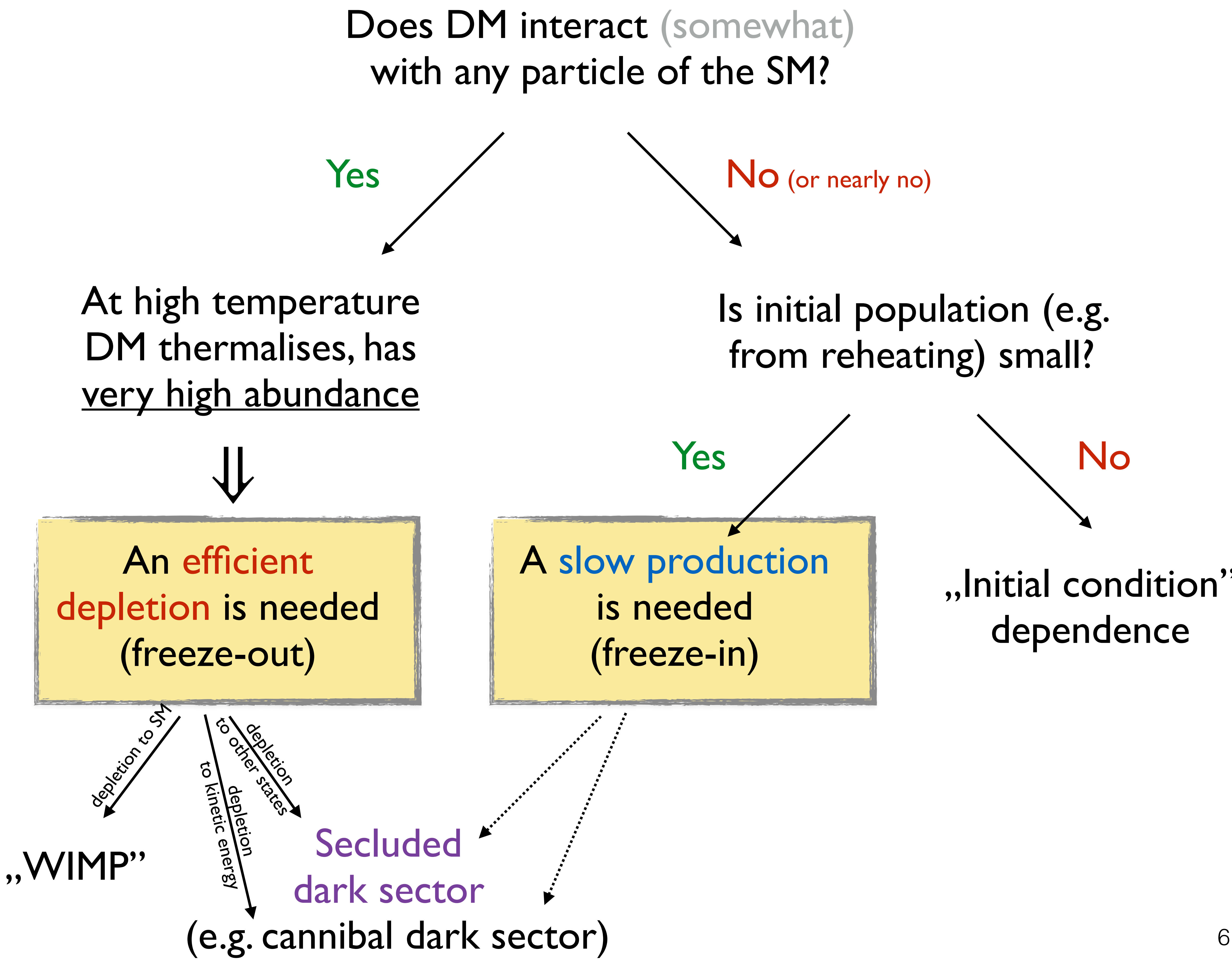
Dark Matter Origin



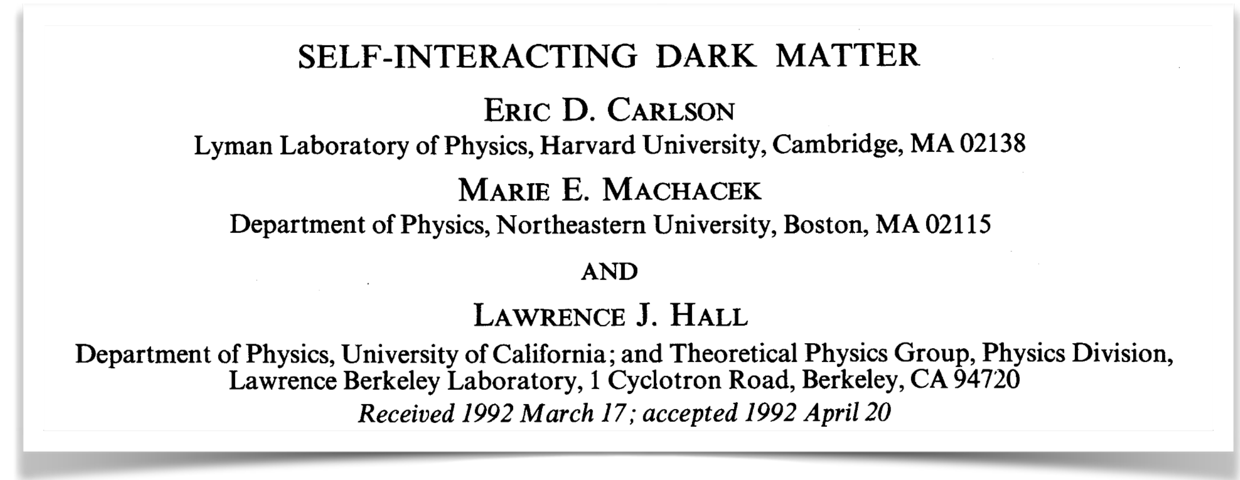
FREEZE-IN *VS.* FREEZE-OUT

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




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
to kinetic energy
depletion
to other states
depletion
„WIMP"
Secluded
dark sector
(e.g. cannibal dark sector)

Cannibal DM


SELF-INTERACTING DARK MATTER

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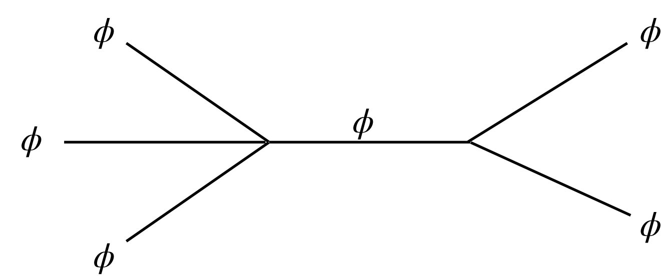
Received 1992 March 17; accepted 1992 April 20

Explains depletion of DM solely through self number changing reactions!

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: $m_\phi \sim \mathcal{O}(10 - 100\,\mathrm{MeV})$

…, Hochberg et al. '14; …

cannibalisation: mass → kinetic energy

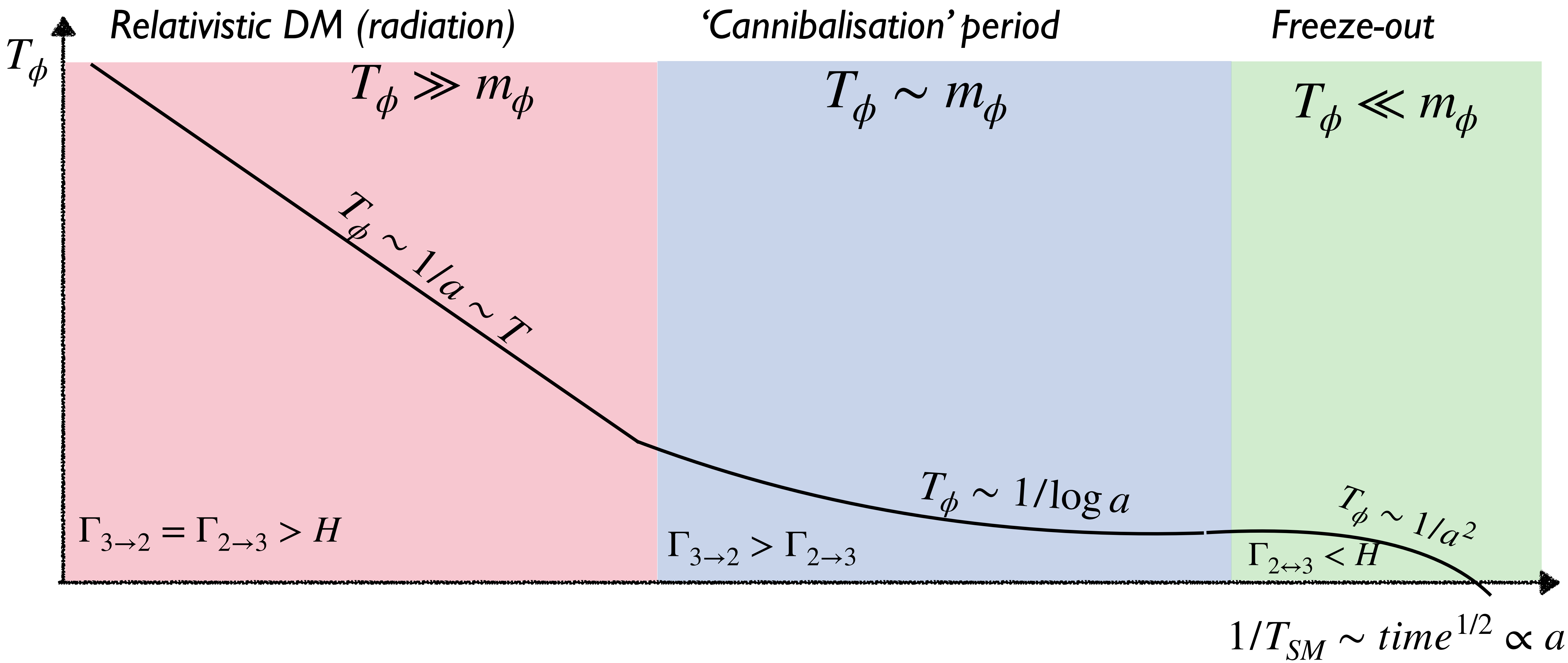
expansion: kinetic energy redshifts → depletion of E of the dark sector

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 <u>temperature evolution</u> 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.

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:

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

Cannibal

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

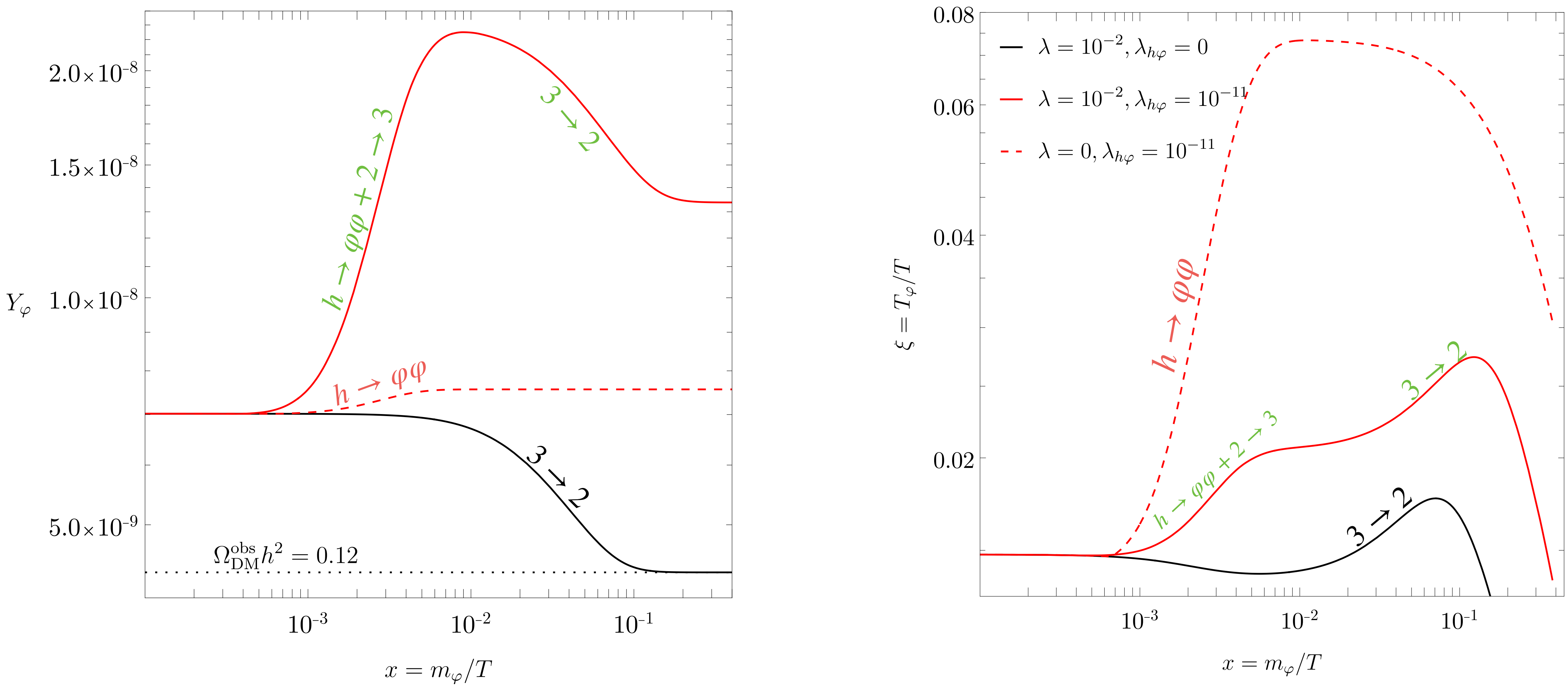
Freeze-in Freeze-in/out El. scattering

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

Idea:

Make DM Cool Again

What if ϕ is the mediator?

A mediator field does not need a stabilising symmetry $\Rightarrow$ cubic interactions exist <u>generically</u> 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:

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

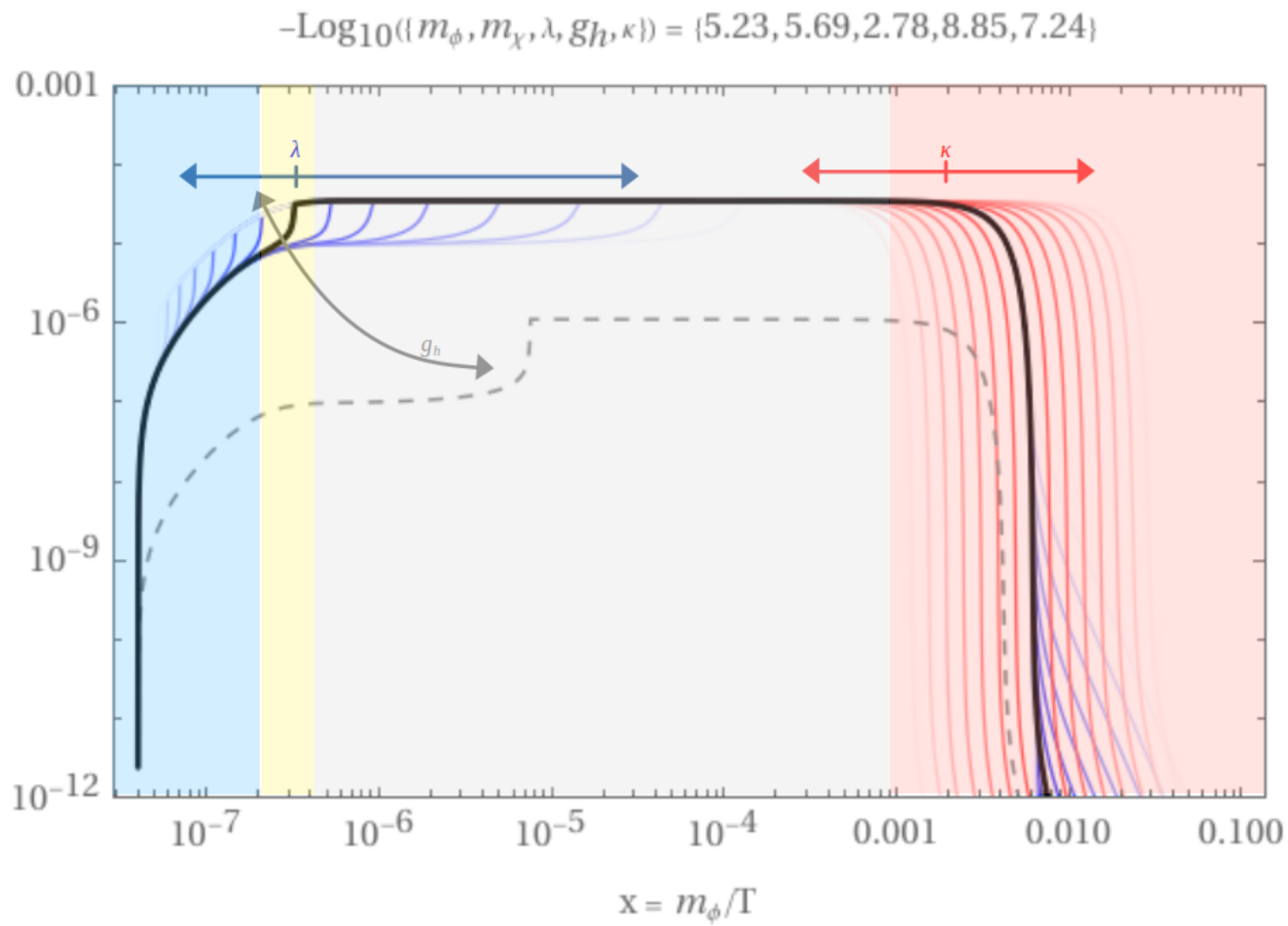
Higgs portal → ϕ freeze-in

cubic + quartic → FI boost & self-cooling

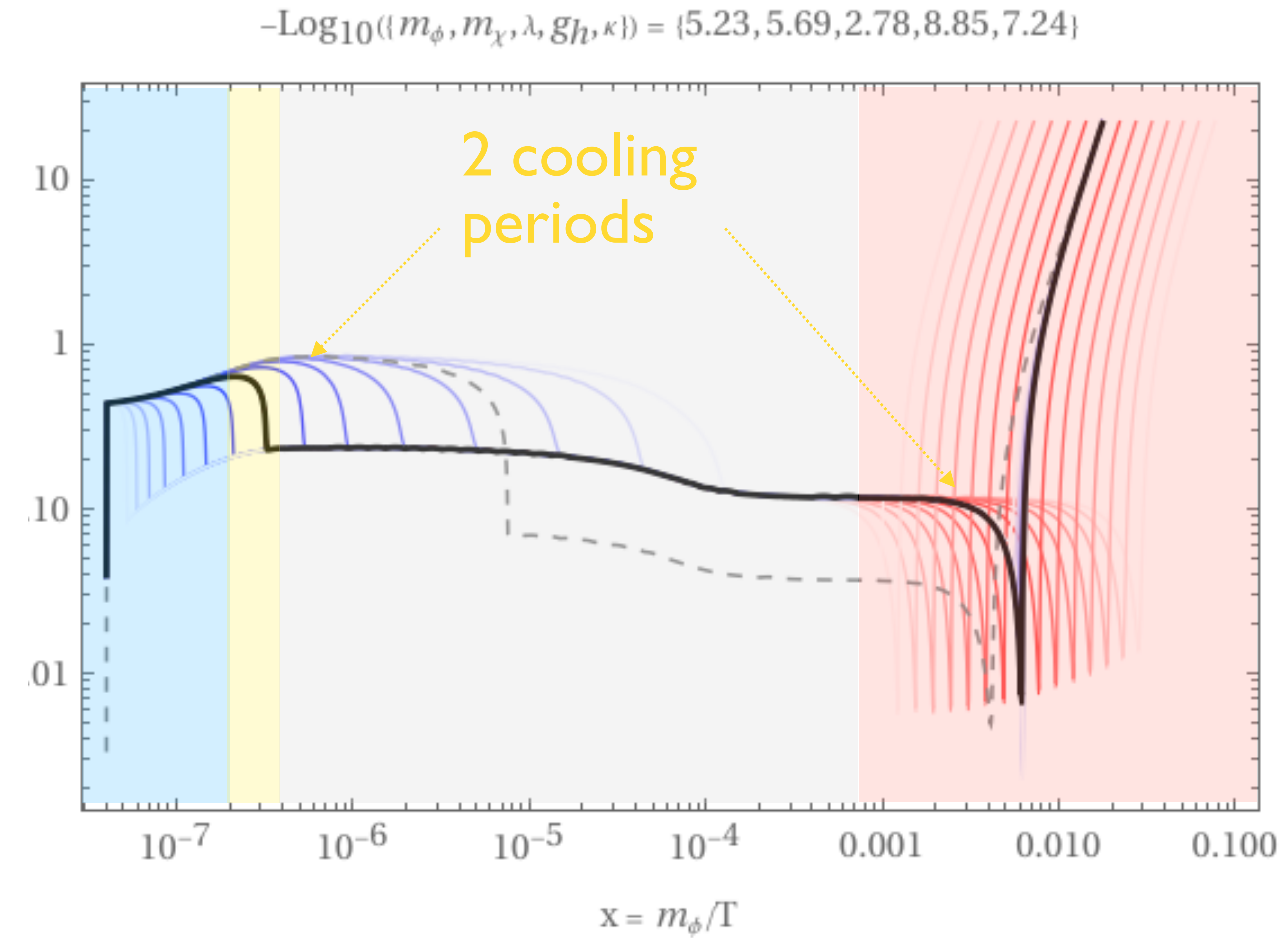
decay to χ → DM freeze-in

SELF-COOLING: HOW DOES IT WORK?

ϕ yield evolution:



T_ϕ evolution:



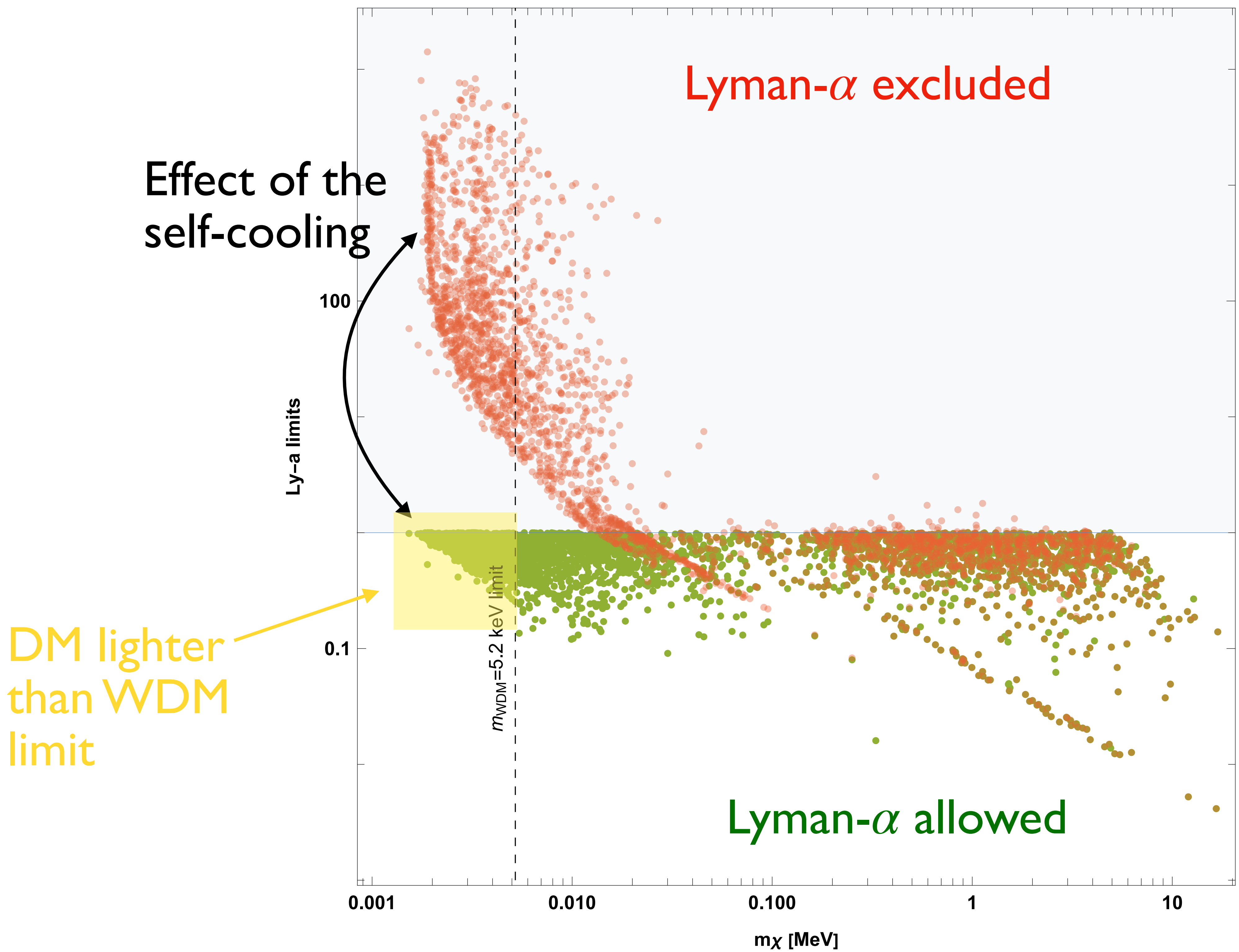
1. Higgs decay provides ϕ freeze-in → 1. Temperature $\sim T/2$

2. Expansion rate drops, yield grows $\Rightarrow 2 \to 3$ efficiency grows → 2. Self-cooling drop

3. Self-thermalization $\Rightarrow$ plateau → 3. Equilibrium expansion

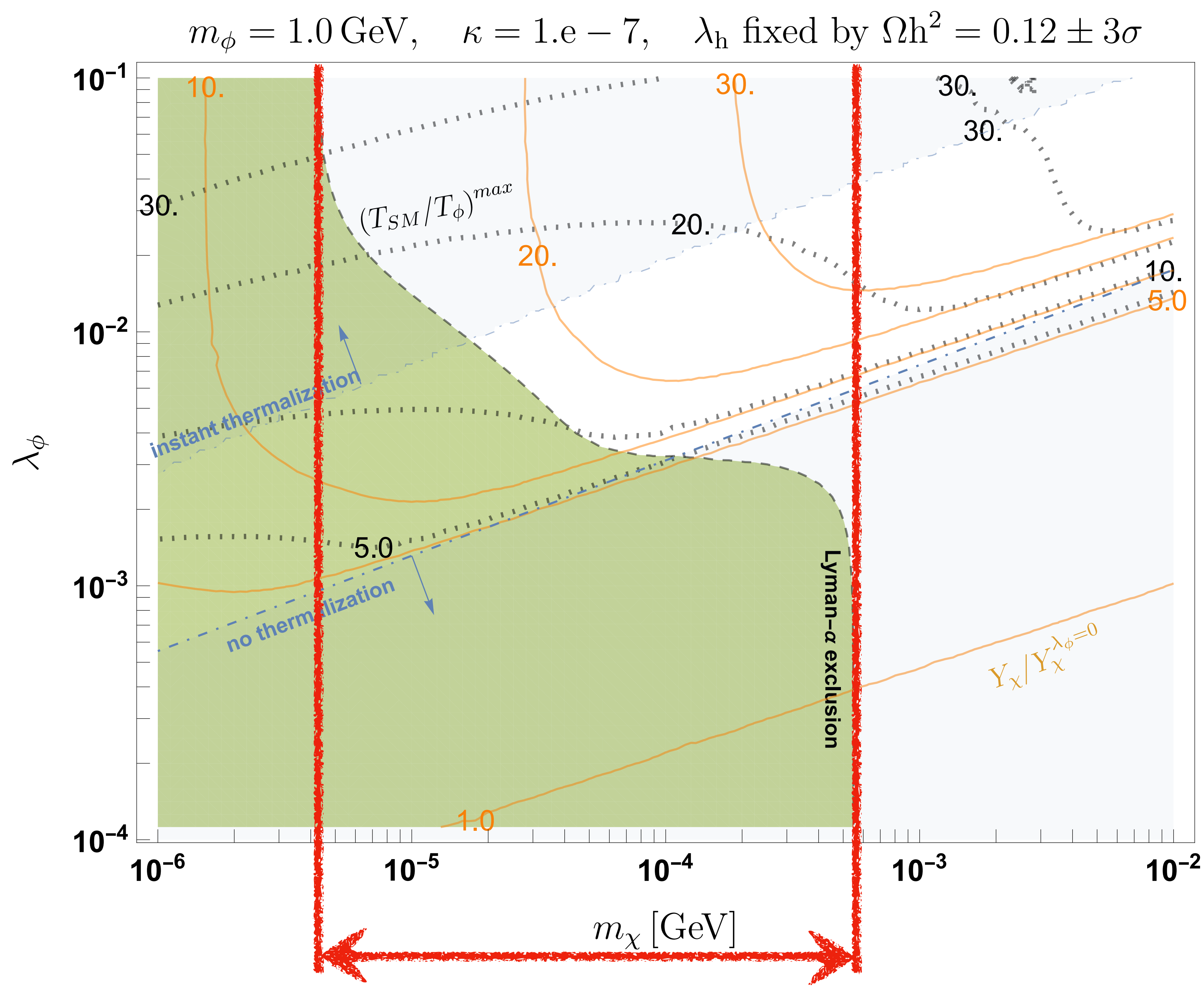
4. Decay to DM → 4. Apparent heating: skewing due to time dilatation

MCMC scan for Lyman-α



MODEL PARAMETER SPACE

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



Loosening limits due to self-cooling!

One To Bind It All:

DRAKE2

Thermal Relic Density
standard approach

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

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

$\Downarrow$

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma_{\chi\bar{\chi}\to ij}\sigma_{\rm rel}\rangle^{\rm eq}\left(n_\chi n_{\bar\chi} - n_\chi^{\rm eq} n_{\bar\chi}^{\rm eq}\right)$$

$\Downarrow$

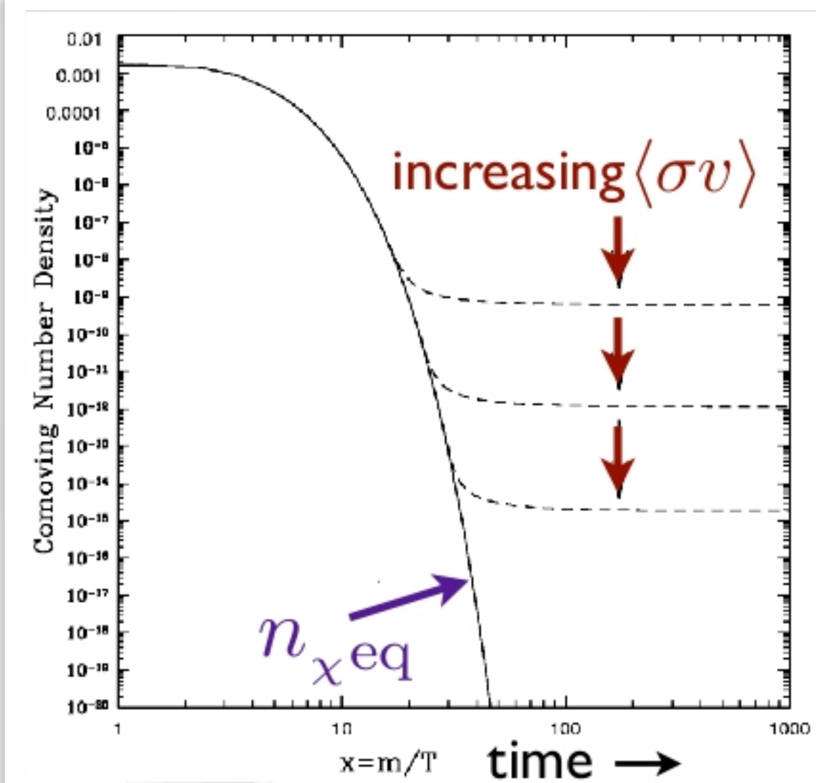


Fig.: Jungman, Kamionkowski & Griest, PR'96

Critical assumption:
kinetic equilibrium at chemical decoupling

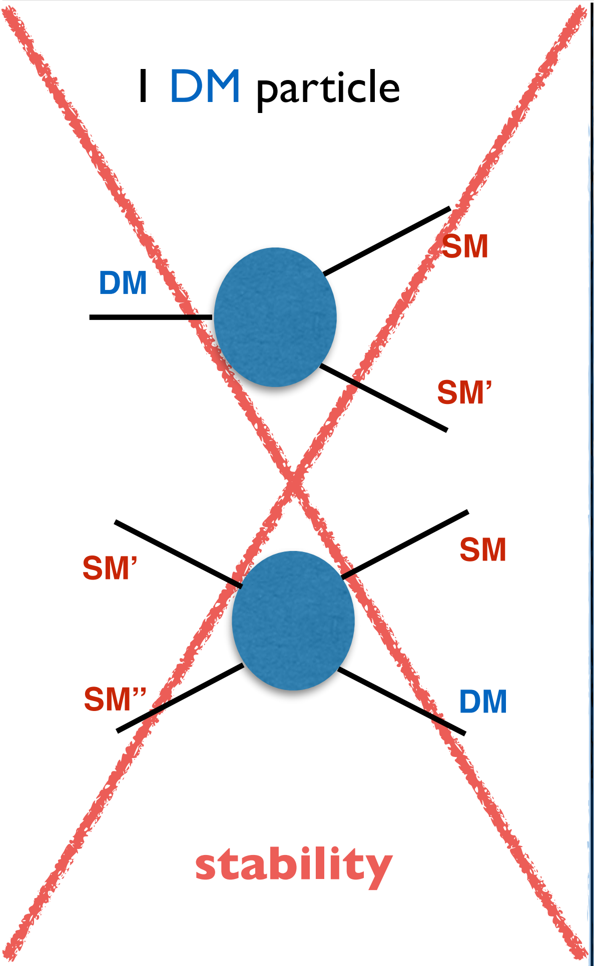
$$f_\chi \sim a(T) f_\chi^{\rm eq}$$

What goes into C in general?

For now assume a minimal theory of SM + one DM field

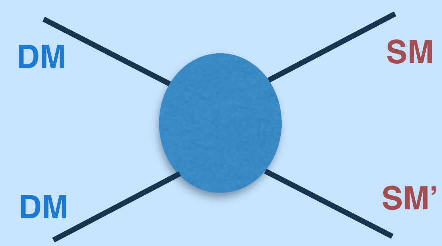
changing processes ⇒ number density

1 DM particle



stability

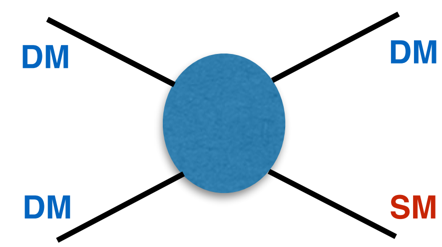
2 DM particles



often the only one being considered

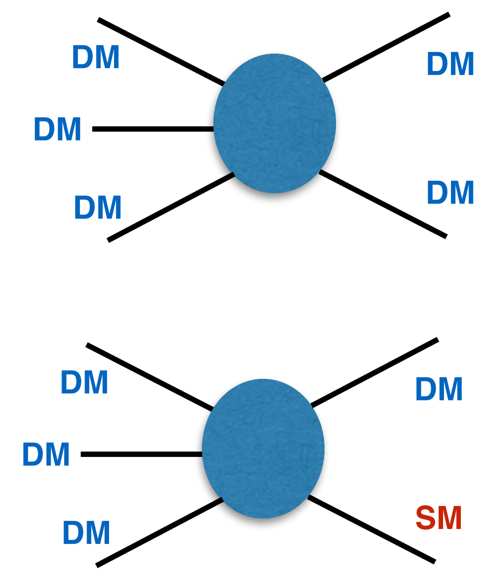
annihilation

3 DM particles



semi-annihilation

4+ DM particles



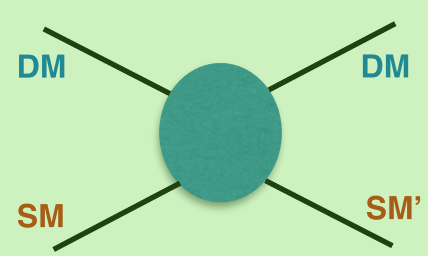
…

cannibalization

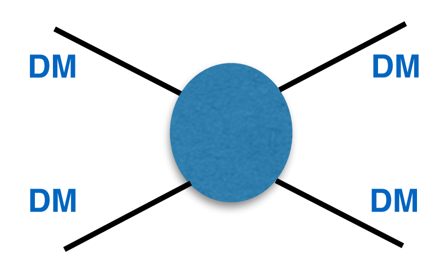
…

conserving processes ⇒ energy density

often assumed to be "∞"



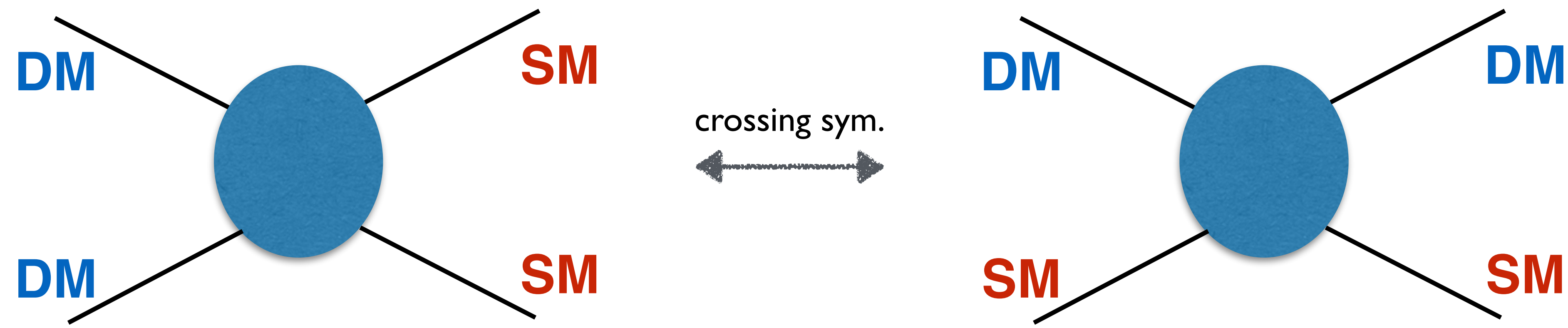
elastic scattering



self scattering

FREEZE-OUT *VS.* DECOUPLING

annihilation | (elastic) scattering



$$\sum_{\text{spins}} \left|\mathcal{M}^{\text{pair}}\right|^2 = F(p_1, p_2, p_1', p_2') \quad \sim \quad \sum_{\text{spins}} \left|\mathcal{M}^{\text{scatt}}\right|^2 = F(k, -k', p', -p)$$

Boltzmann suppression of DM vs. SM $\Rightarrow$ scatterings <u>typically</u> more frequent

dark matter frozen-out but <u>typically</u>
still kinetically coupled to the plasma

$$\tau_r(T_{kd}) \equiv N_{coll}/\Gamma_{el} \sim H^{-1}(T_{kd})$$

Schmid, Schwarz, Widern '99; Green, Hofmann, Schwarz '05

Two consequences:

1. During freeze-out (chemical decoupling) <u>typically</u>: $f_\chi \sim a(\mu) f_\chi^{eq}$
2. If kinetic decoupling much, much later: possible impact on the matter power spectrum

i.e. kinetic decoupling can have observable consequences and affect e.g. missing satellites problem

see e.g., Bringmann, Ihle, Karsten, Walia '16

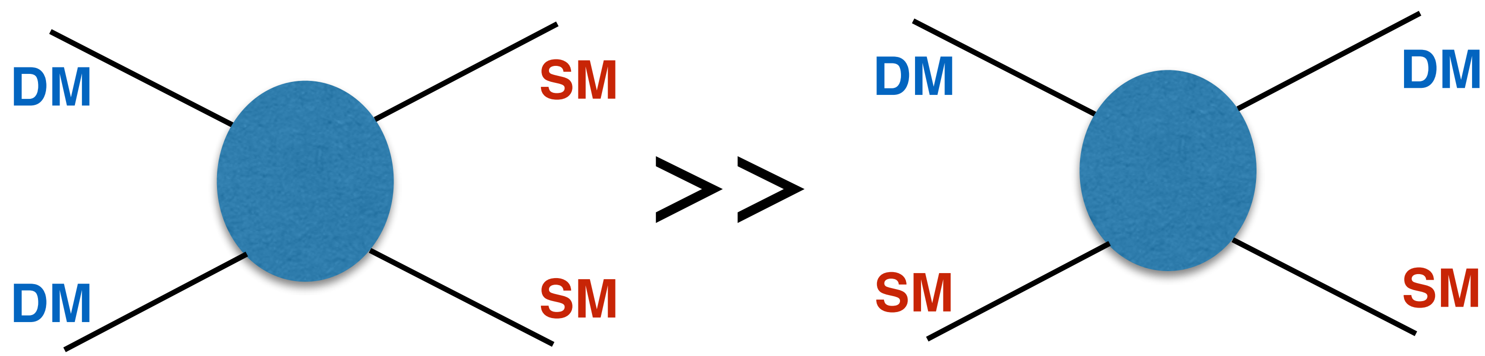
DEPARTURE FROM KINETIC EQUILIBRIUM?

A necessary and sufficient condition: <u>scatterings weaker than annihilation</u>

i.e. rates around freeze-out: $H \sim \Gamma_{\rm ann} \gtrsim \Gamma_{\rm el}$

Possibilities:

A)



e.g., resonant annihilation

B) Boltzmann suppression of SM as strong as for DM

e.g., below threshold annihilation (forbidden-like DM)

C) Scatterings and annihilation have different structure

e.g., semi-annihilation, 3 to 2 models,…

D) Multi-component dark sectors

e.g., additional sources of DM from late decays, …

How to go beyond kinetic equilibrium?

All information is in the full BE:

both about chemical ("normalization") and kinetic ("shape") equilibrium/decoupling

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

→ contains both scatterings and annihilations

Two possible approaches:

fBE

cBE

0-th moment: n_χ
2-nd moment: T_χ
…

solve numerically for full $f_\chi(p)$

have insight on the distribution
no constraining assumptions

numerically challenging
often an overkill

consider system of equations for moments of $f_\chi(p)$

partially analytic/much easier numerically
manifestly captures all of the relevant physics

finite range of validity
no insight on the distribution

PUBLIC TOOL!

Binder, Bringmann, Gustafsson, AH 2103.01944

GOING BEYOND THE STANDARD APPROACH

- Home
- Downloads
- Contact

DRAKE

Dark matter Relic Abundance beyond Kinetic Equilibrium

Authors: Tobias Binder, Torsten Bringmann, Michael Gustafsson and Andrzej Hryczuk

DRAKE is a numerical precision tool for predicting the dark matter relic abundance also in situations where the standard assumption of kinetic equilibrium during the freeze-out process may not be satisfied. The code comes with a set of three dedicated Boltzmann equation solvers that implement, respectively, the traditionally adopted equation for the dark matter number density, fluid-like equations that couple the evolution of number density and velocity dispersion, and a full numerical evolution of the phase-space distribution. The code is written in Wolfram Language and includes a Mathematica notebook example program, a template script for terminal usage with the free Wolfram Engine, as well as several concrete example models.
DRAKE is a free software licensed under GPL3.

If you use DRAKE for your scientific publications, please cite

- **DRAKE: Dark matter Relic Abundance beyond Kinetic Equilibrium,**
  Tobias Binder, Torsten Bringmann, Michael Gustafsson and Andrzej Hryczuk, [arXiv:2103.01944]

Currently, an user guide can be found in the Appendix A of this reference.
Please cite also quoted other works applying for specific cases.

v1.0 « Click here to download DRAKE

(March 3, 2021)

https://drake.hepforge.org

Applications:

DM relic density for
any (user defined) model*

Interplay between chemical and kinetic decoupling

Prediction for the DM
phase space distribution

Late kinetic decoupling
and impact on cosmology

see e.g., 1202.5456

…

(only) prerequisite:
Wolfram Language (or *Mathematica*)

*at the moment for a single DM species and w/o co-annihlations… but stay tuned for extensions!

DRAKE2

coming soon*…

New features:

Two-component dark sectors
(also with potentially unstable states)

Freeze-out & Freeze-in

Automatic model generation
[linking to ***FeynRules etc.***]

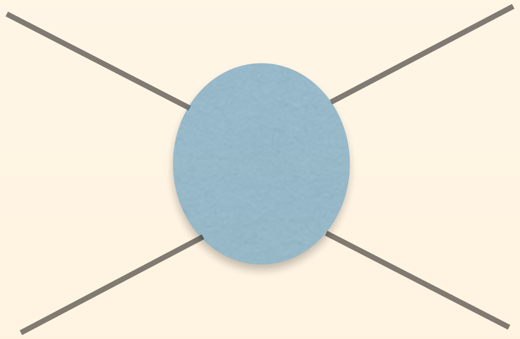
Improvements:

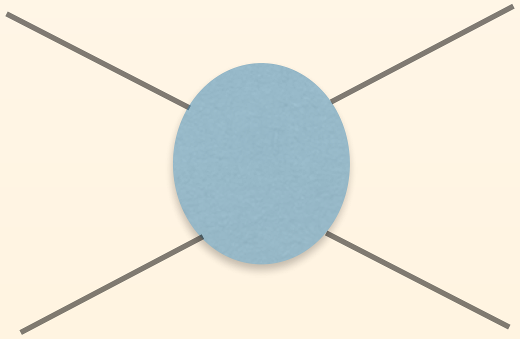
Increased efficiency
[e.g. more extended use of compiled functions, parallelisation, matrix formulation]

Updated *user interface*

* already alfa-version available for sharing, just talk or DM me

EXAMPLE A:
SCALAR SINGLET DM



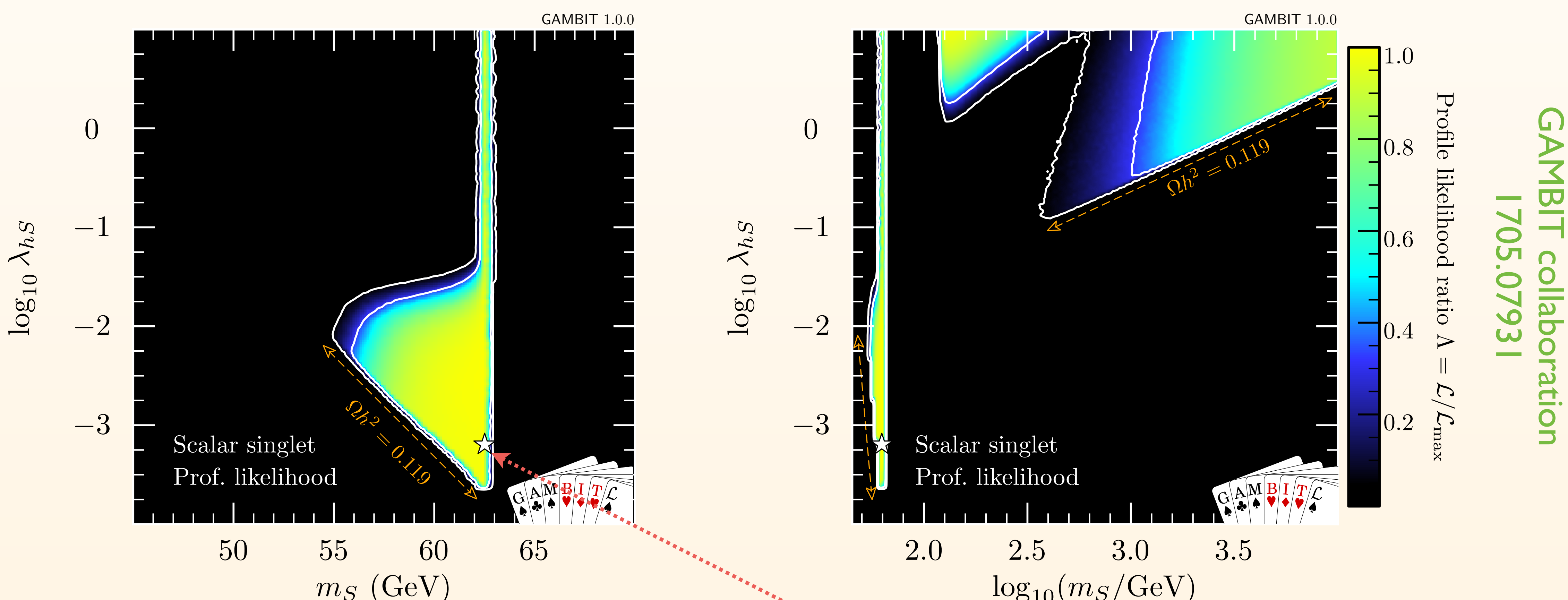


EXAMPLE A
SCALAR SINGLET DM

To the SM Lagrangian add one singlet scalar field S with interactions with the Higgs:

$$\mathcal{L}_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}\mu_S^2 S^2 - \frac{1}{2}\lambda_s S^2 |H|^2$$

$$m_s = \sqrt{\mu_S^2 + \frac{1}{2}\lambda_s v_0^2}$$



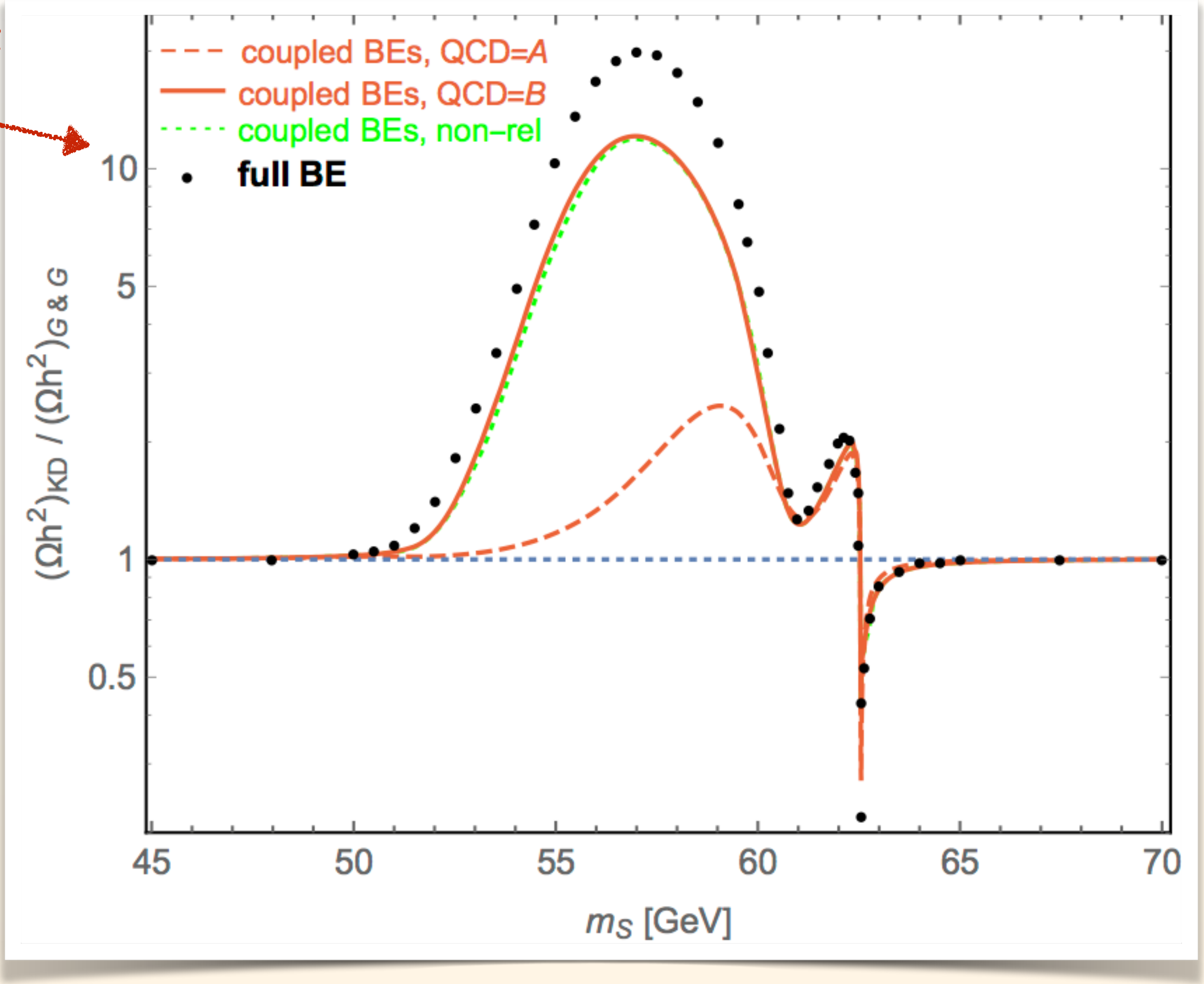
Most of the parameter space excluded, but… even such a simple model is hard to kill

→ best fit point hides in the resonance region!

RESULTS

EFFECT ON THE Ωh^2

effect on relic density: up to O(~10)

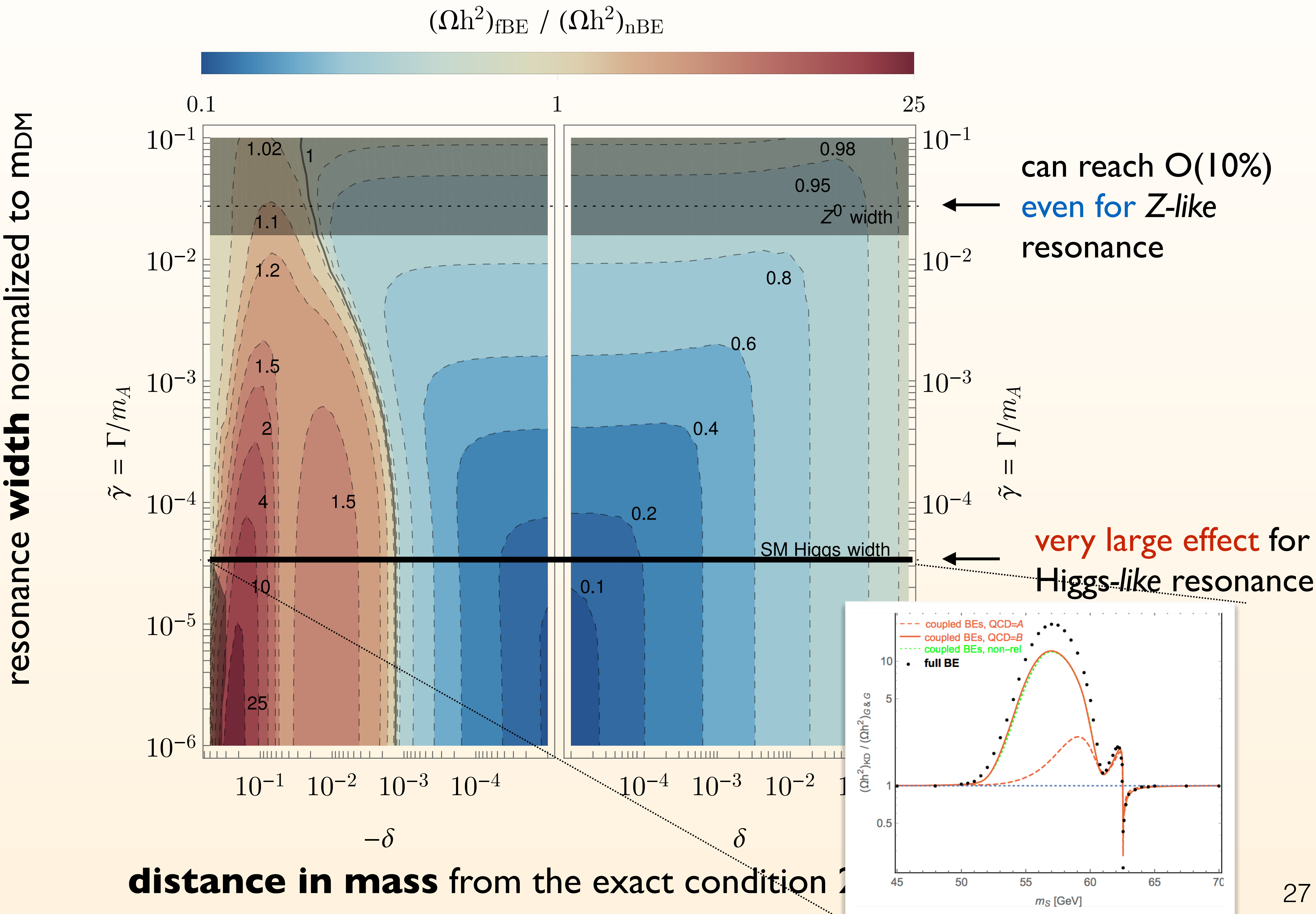


[… Freeze-out at few GeV ⟶ what is the abundance of heavy quarks in QCD plasma?

two scenarios: QCD = A - all quarks are free and present in the plasma down to T_c =154 MeV
QCD = B - only light quarks contribute to scattering and only down to $4T_c$ …]

Generic Resonant Annihilation

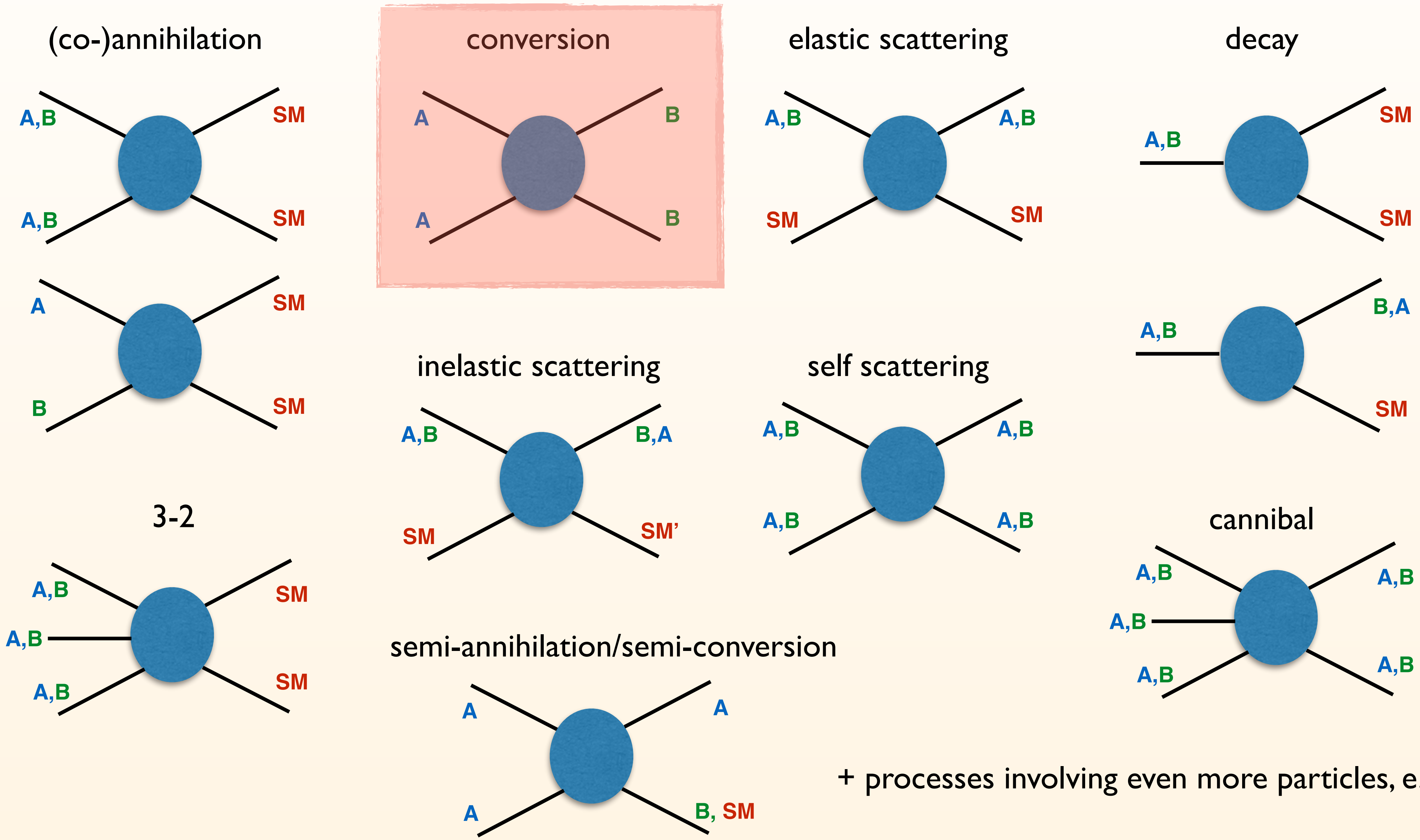
Example effect of early KD on relic density



Example B:
Effect of conversion processes

WHAT IF A NON-MINIMAL SCENARIO?

A,B — two different dark sector states (at least one needs to be stable)

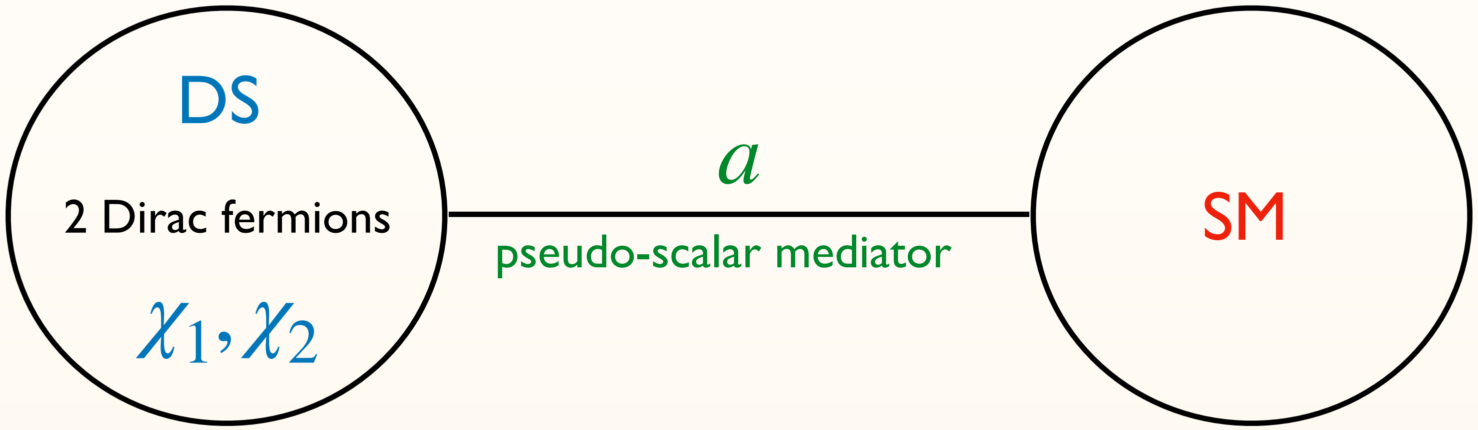


+ processes involving even more particles, e.g. $2 \leftrightarrow 4\ldots$

Note: some of these processes affect not only # density, but also strongly modify the energy distribution of DM particles!

RESULTS: THE MODEL

Let's take one of the simplest two-component DM models:



Parametrically:

$$\sigma_{11\to SM} \sim \sigma_{1SM\to 1SM} \sim \lambda_1^2 \lambda_y^2$$

$$\sigma_{22\to SM} \sim \sigma_{2SM\to 2SM} \sim \lambda_2^2 \lambda_y^2$$

$$\sigma_{11\to 22} \sim \lambda_1^2 \lambda_2^2$$

$$\Downarrow$$

$$\mathscr{L}_{int} = -\sum_{i=1,2} i\lambda_i \, a \, \bar{\chi}_i \gamma^5 \chi_i - i\lambda_y \frac{m_f}{v} a \, \bar{f}\gamma^5 f$$

coupled directly to SM fermions in a MFV way

Varying:

$\lambda_1 \to c\,\lambda_1$

$\lambda_2 \to c\,\lambda_2$

$\lambda_y \to \lambda_y / c$

Keeps everything fixed, except conversions

New fields: χ_1, χ_2, a

New params: m_1, m_2, m_a, $\lambda_1, \lambda_2, \lambda_y$

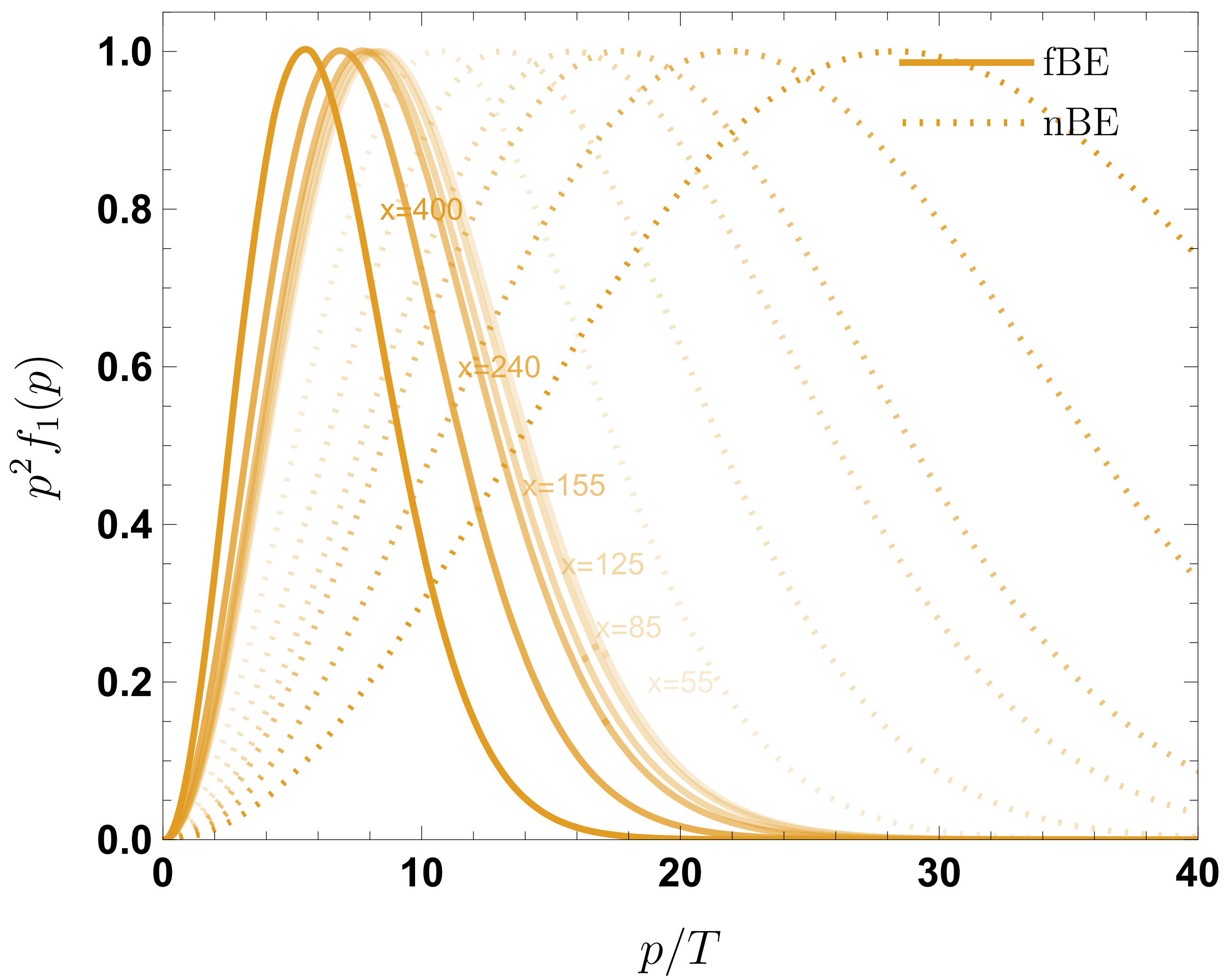
Main motivation (for models in the literature with pseudo-scalar mediator):

Evasion of the direct detection bounds… while giving strong signal in indirect detection, in particular for explaining the Galactic Centre excess

(see e.g. „Coy DM")

C. Boehm et al. 1401.6485,

Motivational Plot



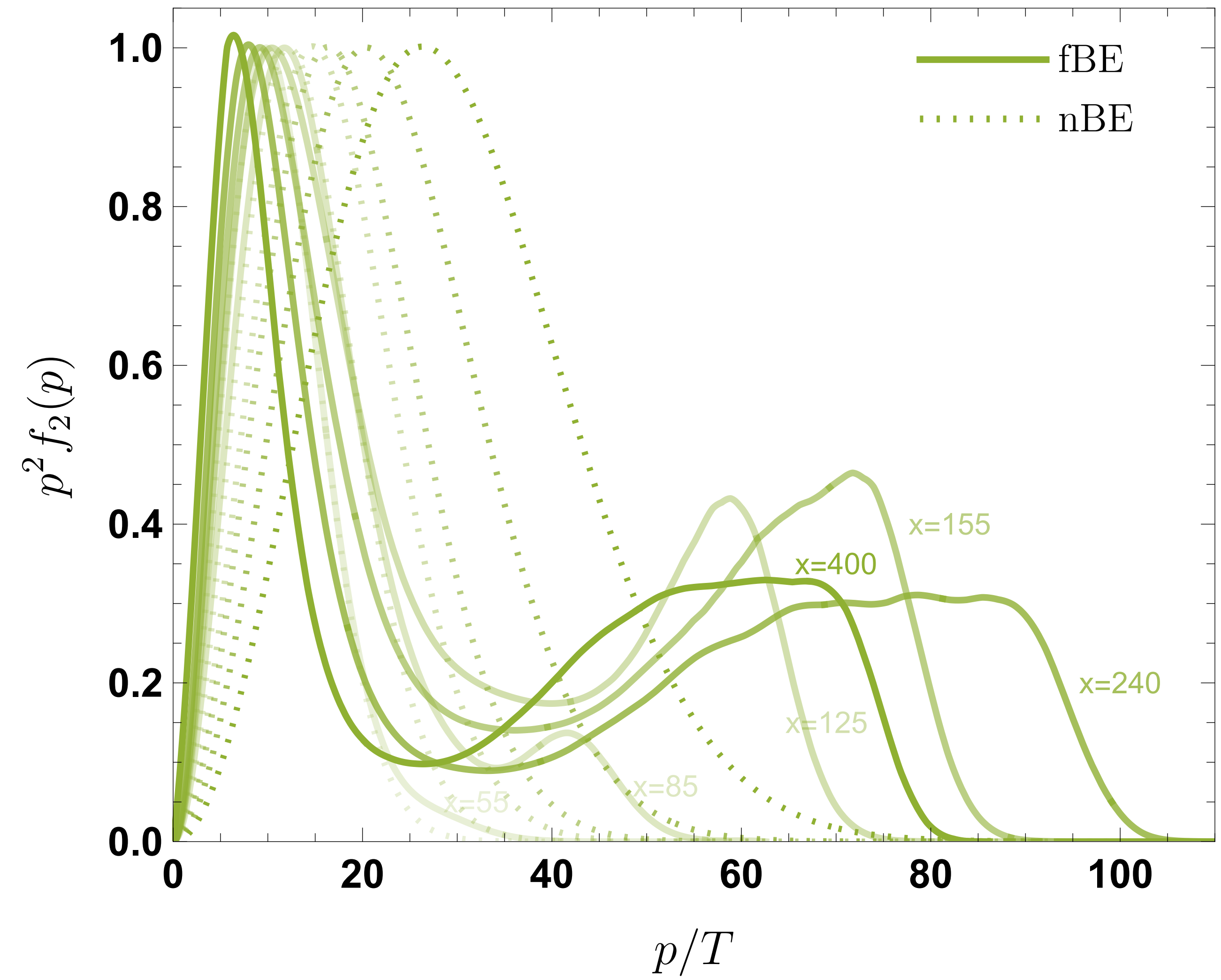
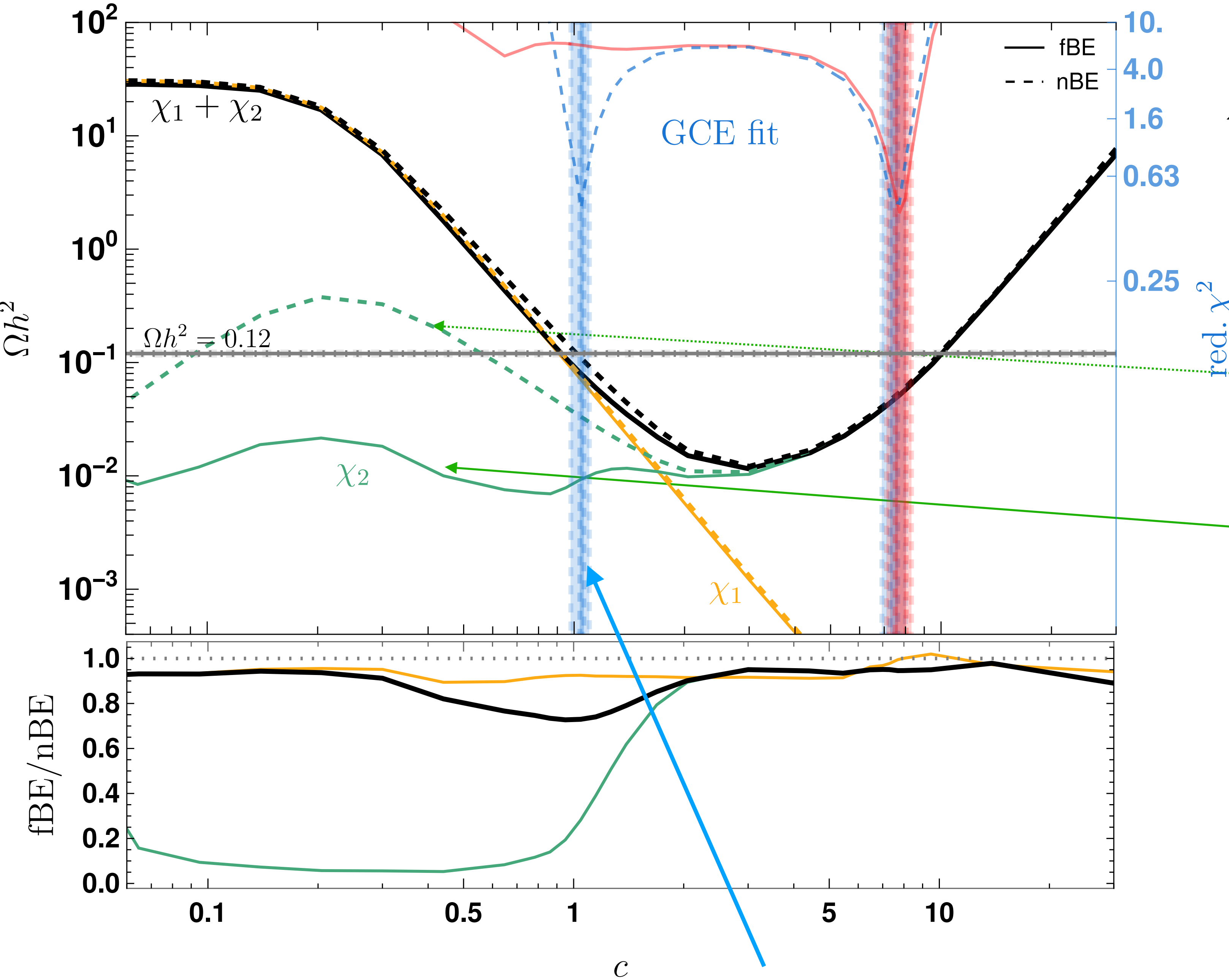


Figure 1: Time snapshots of the evolution of the normalised momentum distributions for χ_1 (left) and χ_2 (right) in p/T, for the benchmark point showcasing the interplay of conversions and resonant annihilations with early kinetic decoupling. The solid lines show the particle distribution functions f_{χ_i} while the dotted lines show the corresponding equilibrium distributions.

Results: conversion impact

Varying: $\lambda_1 \to c\,\lambda_1$ $\lambda_2 \to c\,\lambda_2$ $\lambda_y \to \lambda_y/c$ Only conversions change!

weak conversions ⟷ strong conversions



total relic abundance

only number density (nBE) — *as in micrOMEGAs*

phase space calculation (fBE)

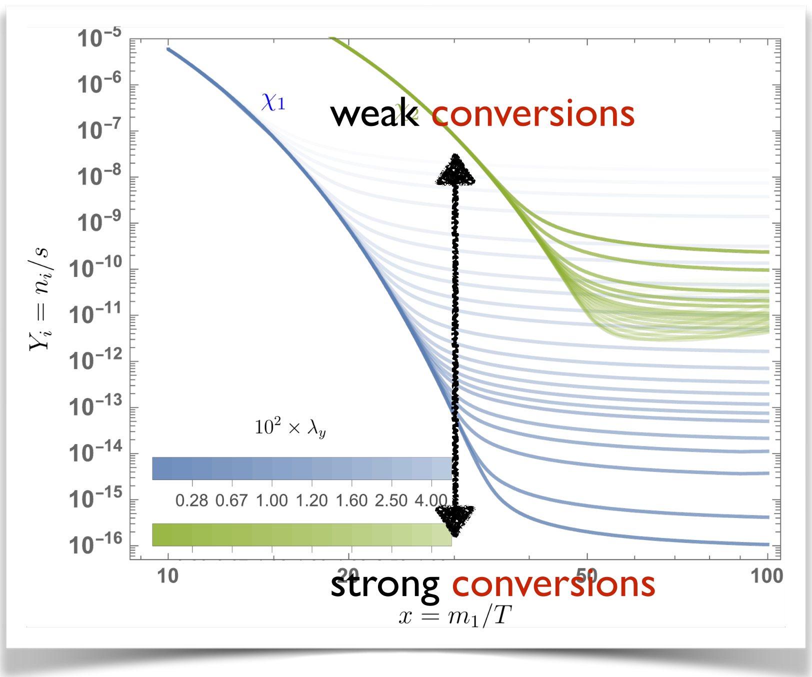
This region for GCE disappears!

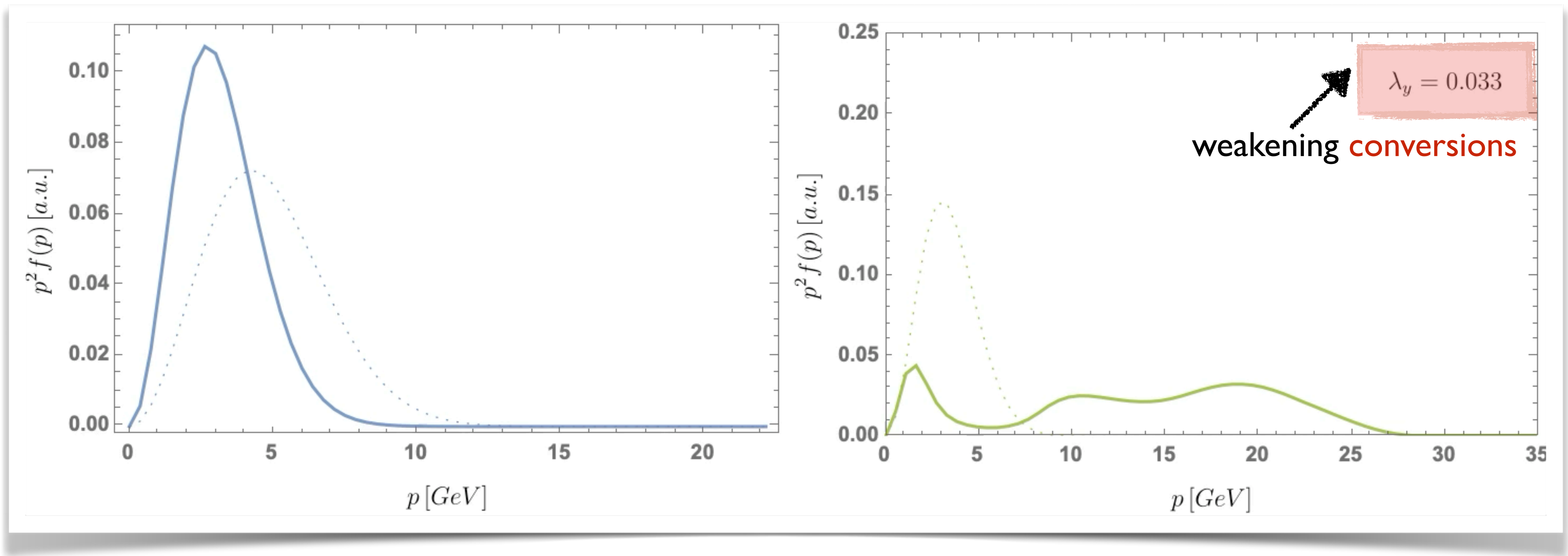
Weak conversions lead to larger discrepancy between nBE and fBE calculations!

cf. Kamada et al. 2111.06808

RESULTS: CONVERSION IMPACT

weaker conversions ⇒ less depletion of χ_1 ⇒ around χ_2 freeze-out more χ_1 in the plasma
⇒ larger distortion of thermal shape





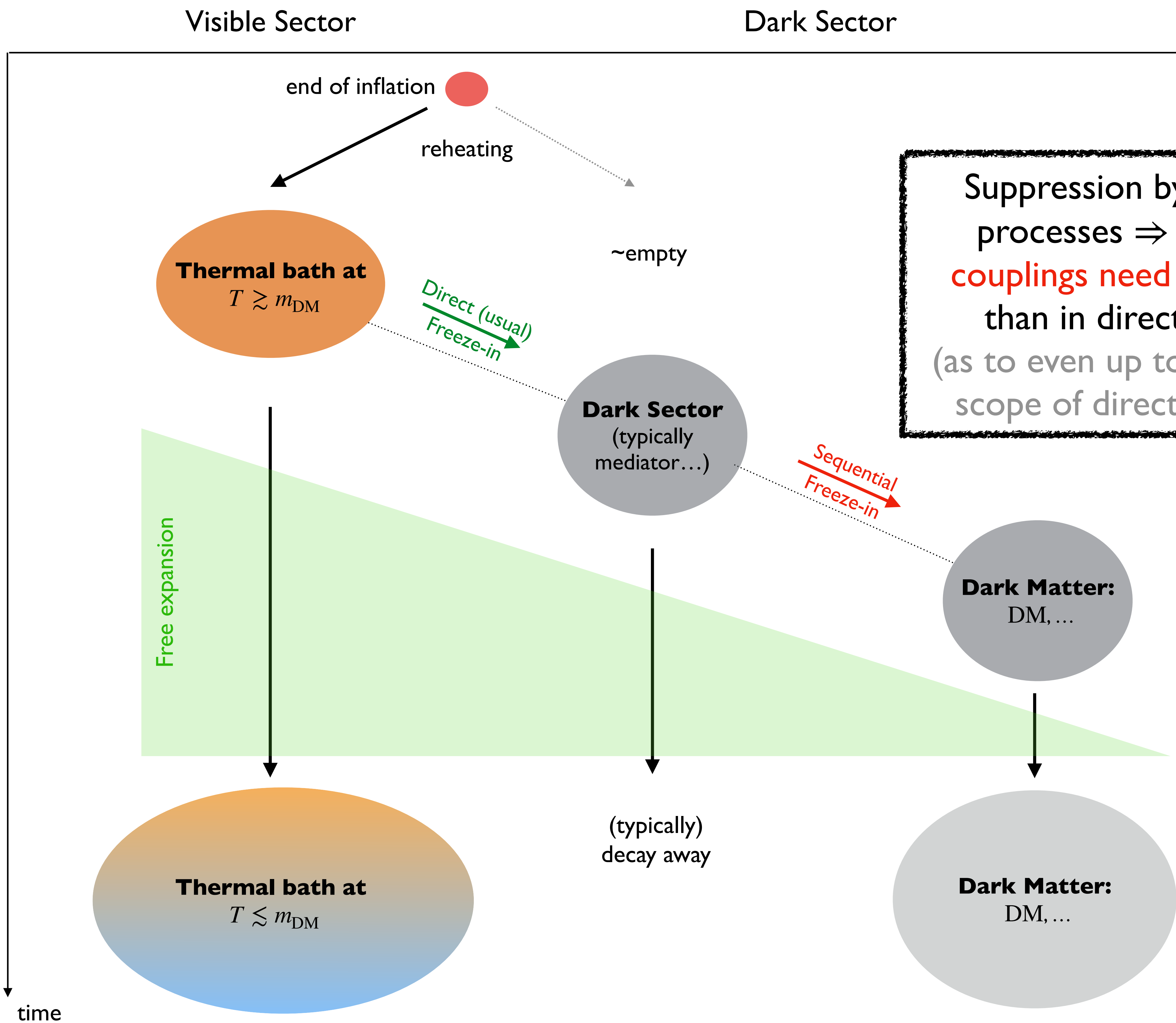
Conversions are ubiquitous in multicomponent models… but not the only processes affecting the distributions:

- decays of heavier to lighter dark sector states — A.H. & Laletin 2204.07078 (see also Beauchesne & Chiang 2401.03657)
- inelastic scatterings
- semi-annihilations — A.H. & Laletin 2104.05684
- cannibal $(3 \leftrightarrow 2)$ — Cervantes & A.H. 2407.12104

bits useful for next DRAKE release

EXAMPLE C:
(SEQUENTIAL) FREEZE-IN

WHAT IS SEQUENTIAL FREEZE-IN?



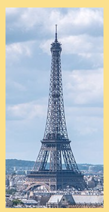
Suppression by <u>two</u> weak processes ⇒ respective couplings need to be larger than in direct freeze-in (as to even up to being within scope of direct detection!)

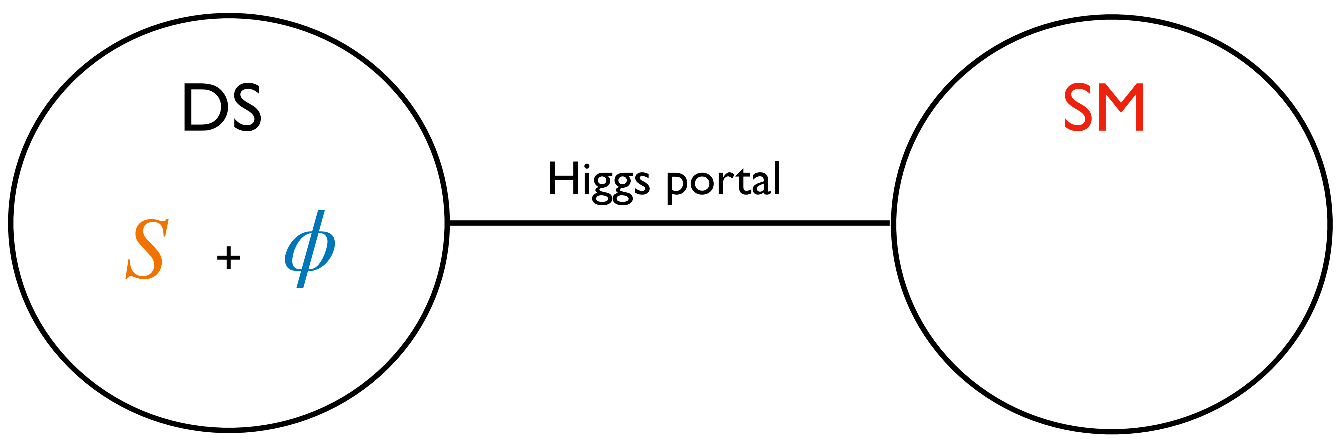
Hambye *et al.* 1908.09864
Belanger *et al.* 2005.06294

…but can also be a <u>secluded dark sector</u>

A Tale of Two Scalars

Postulate two new scalars (singlets w.r.t SM gauge group):

||	S	$\mathbb{Z}_2$-symmetric	stable	dark matter	feeble int. with SM
					$\wedge$
||	ϕ	~~$\mathbb{Z}_2$~~ explicitly broken	unstable	"mediator"	feeble int. with SM



$$V \supset -A\phi H^\dagger H - \frac{\lambda_{h\phi}}{2}\phi^2 H^\dagger H - \frac{\lambda_{Sh}}{2} S^2 H^\dagger H - \frac{1}{4}\lambda_{S\phi} S^2 \phi^2$$

mediator-Higgs DM-Higgs DM-mediator

mediator-Higgs mixing

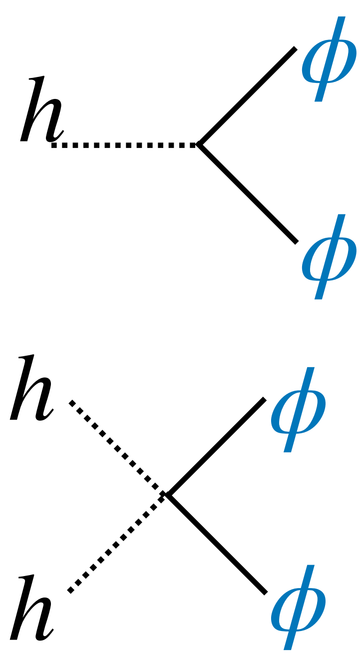
$$\sin\theta = \frac{Av}{m_h^2 - m_\phi^2}\left(1 - \frac{\lambda_{h\phi} v^2}{2m_\phi^2}\right)$$

Such models are not unheard of. Most similar in the literature:

…; Wang, Han '14; Claude, Godfrey '21; …

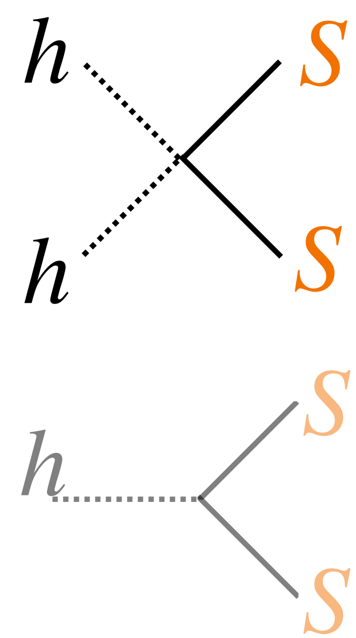
A Tale of Two Scalars

mediator freeze-in:



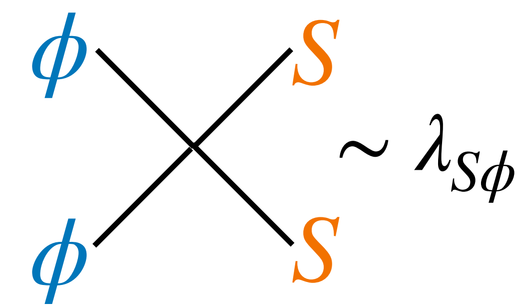
$\sim \lambda_{h\phi}$

DM freeze-in:



$\sim \lambda_{Sh}$

sequential freeze-in:

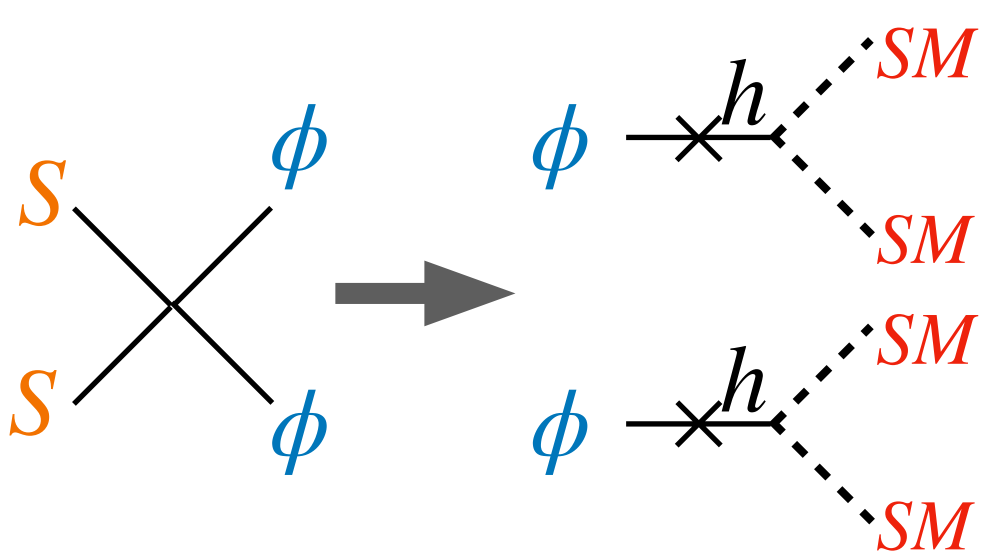


Typical hierarchy:

$\lambda_{S\phi} \ggg \lambda_{h\phi} \gg \lambda_{Sh}$

Freeze-out-like Freeze-in-like

Indirect detection through a cascade decay (iff $m_S > m_\phi$):



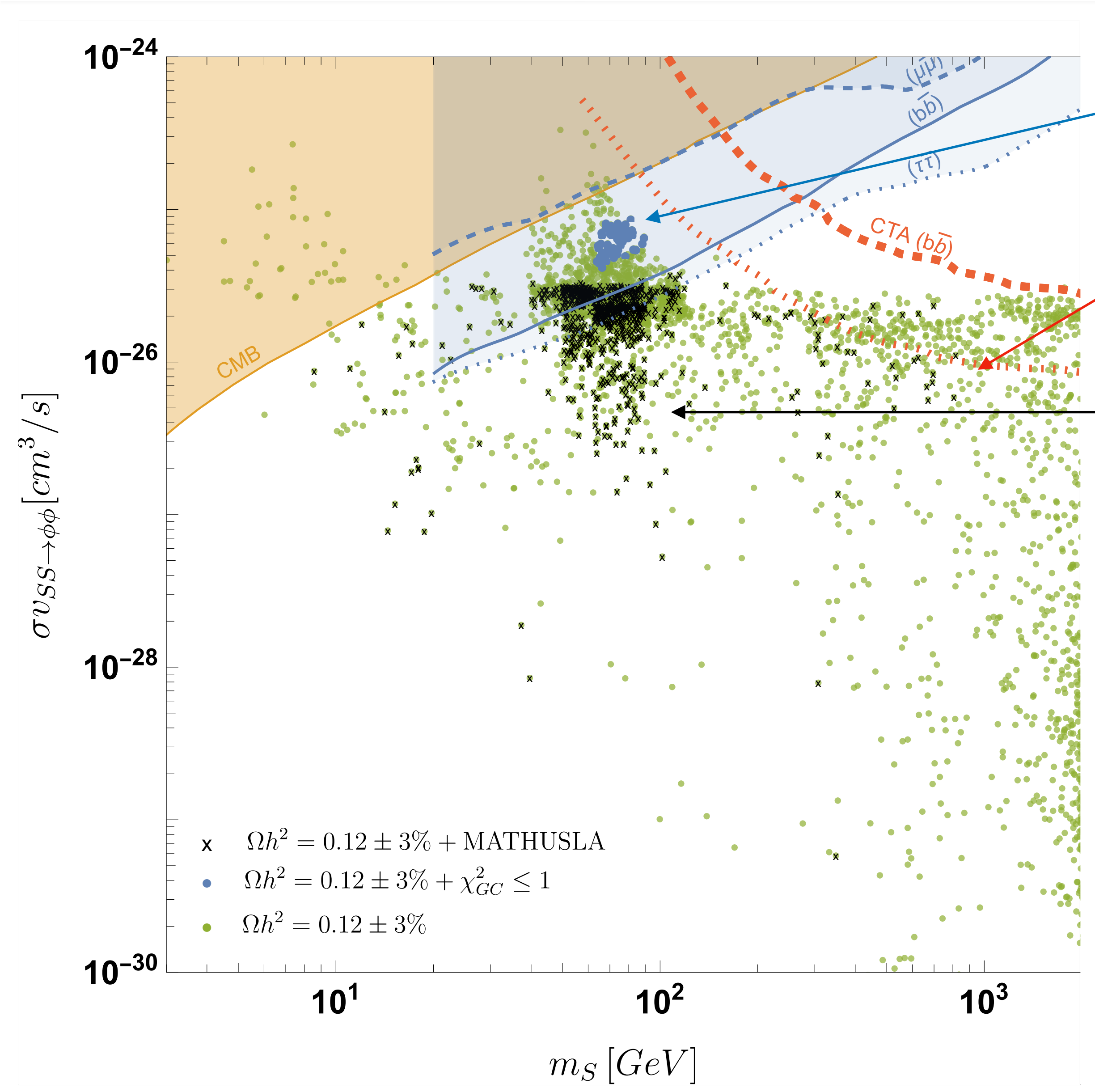
ID signal = requirement of sub-threshold sequential freeze-in

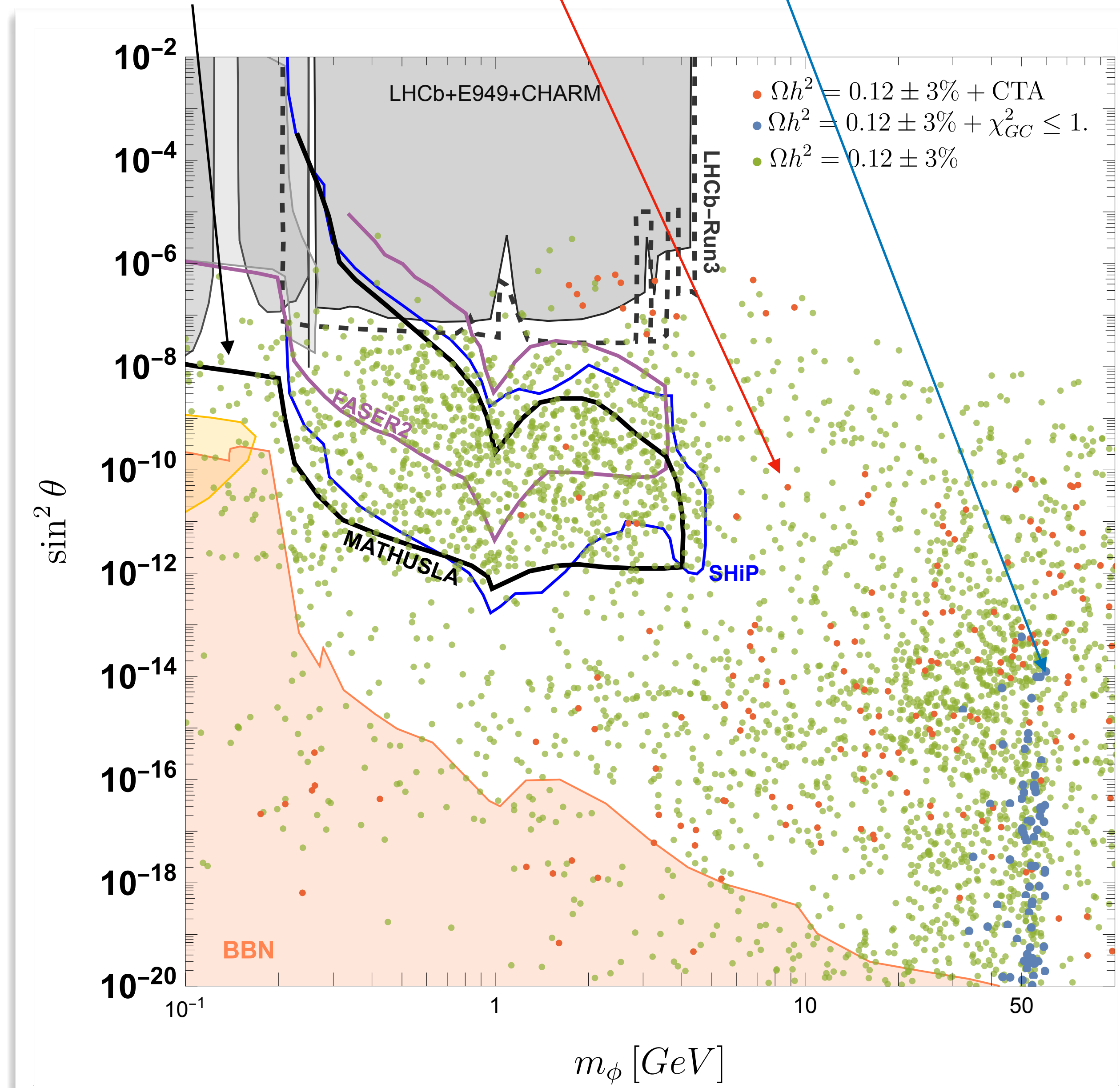
SCAN RESULTS: ID AND FORWARD PHYSICS

Points giving good fit to GCE

Points within (optimistic) reach of CTA

within reach of MATHUSLA





<u>All points satisfy relic density constraint</u>

Scan driven towards regions that are covered by any of the experiments

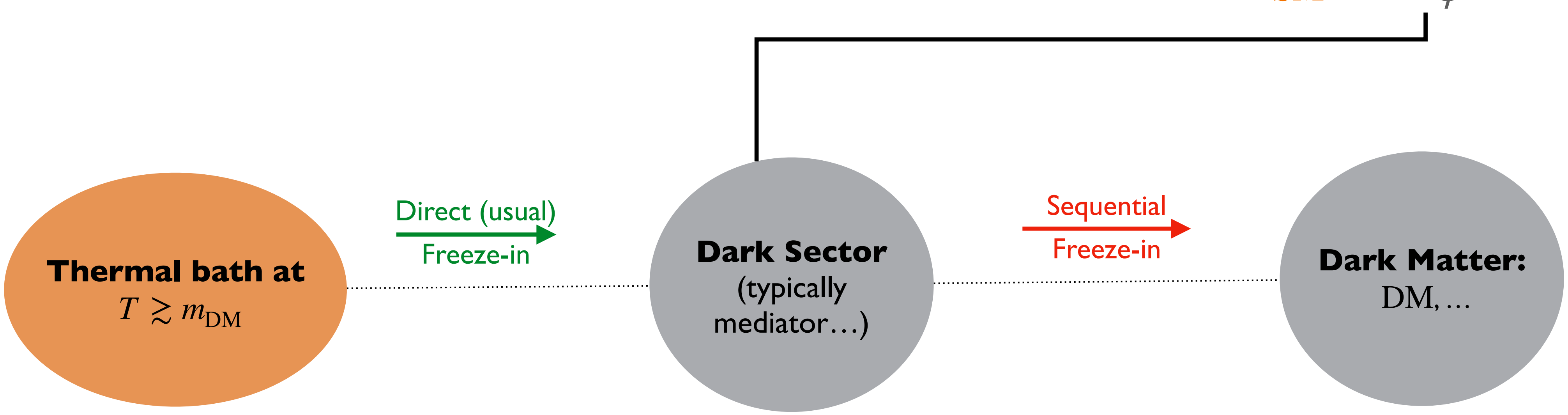
A SECOND LOOK ON Ωh^2

The relic density was the main constraint of the scan. It was obtained by solving the Boltzmann equation for number densities of ϕ and S (nBE)
(as e.g. micrOMEGAs or DarkSUSY would)

But wait… isn't relic abundance *(freeze-in or freeze-out)* dependent on the T of the thermal bath it is produced from?

$\Downarrow$

Which temperature is relevant for sequential freeze-in: T_{SM} or T_ϕ?



…OK, so it looks like <u>we need to</u> trace T_ϕ as well!

THIS IS REMINISCENT OF…

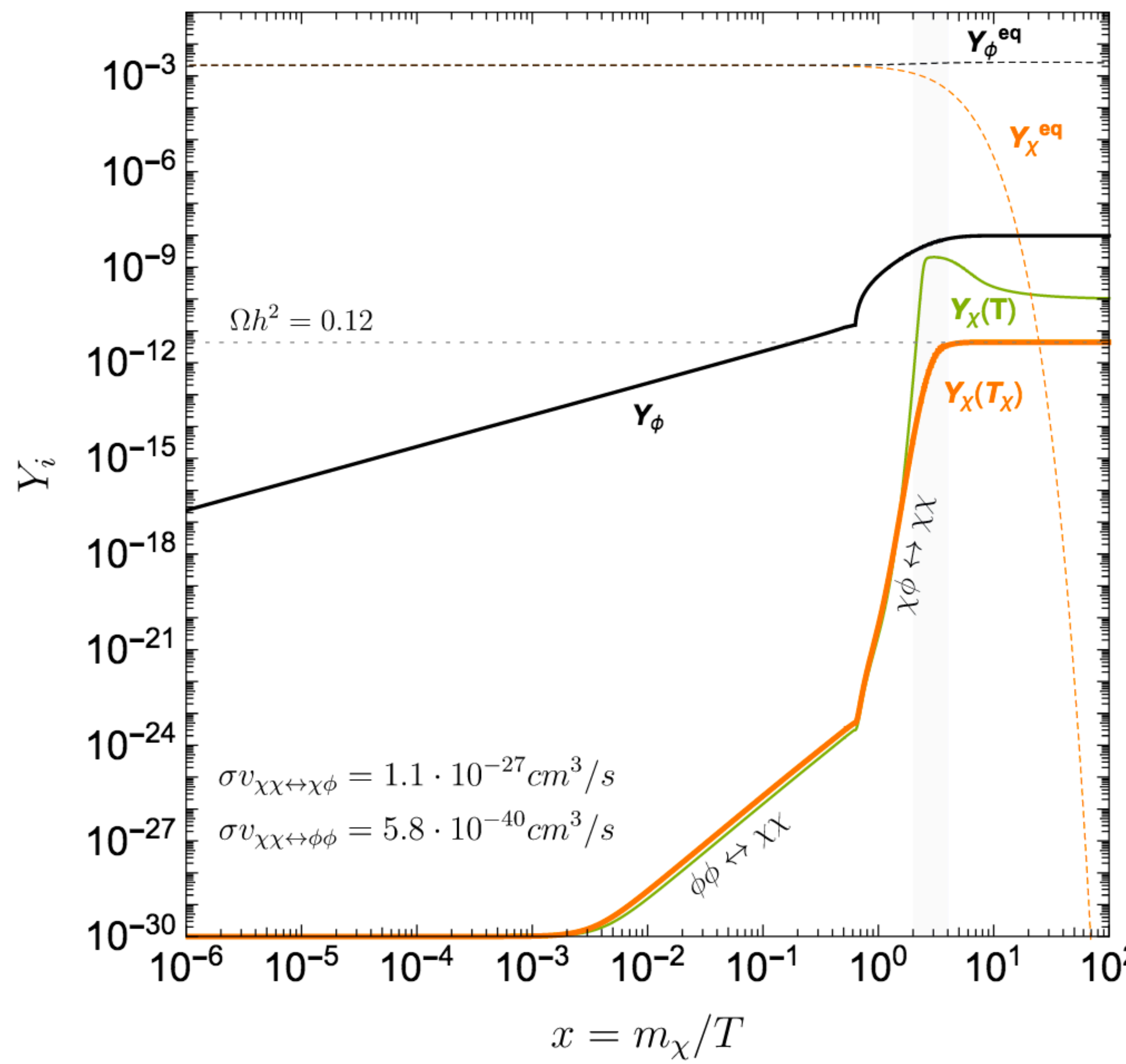
AH, Laletin 2104.05684
(see also Bringmann et al. 2103.16572)

Consider process of production that is the inverse of semi-annihilation:

$$\chi\phi \to \chi\chi$$

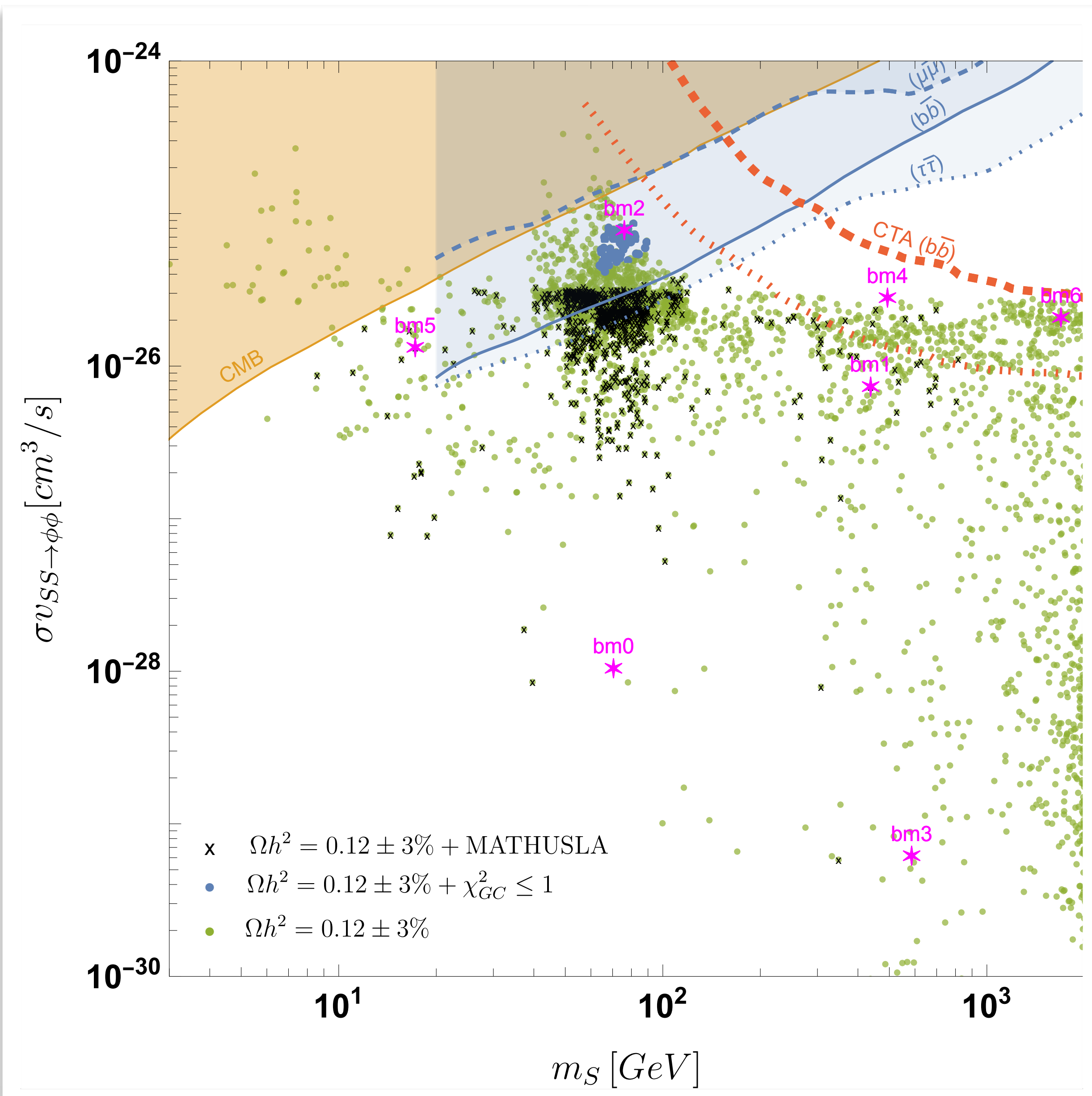
What is different?
(from the decay/annihilation freeze-in)

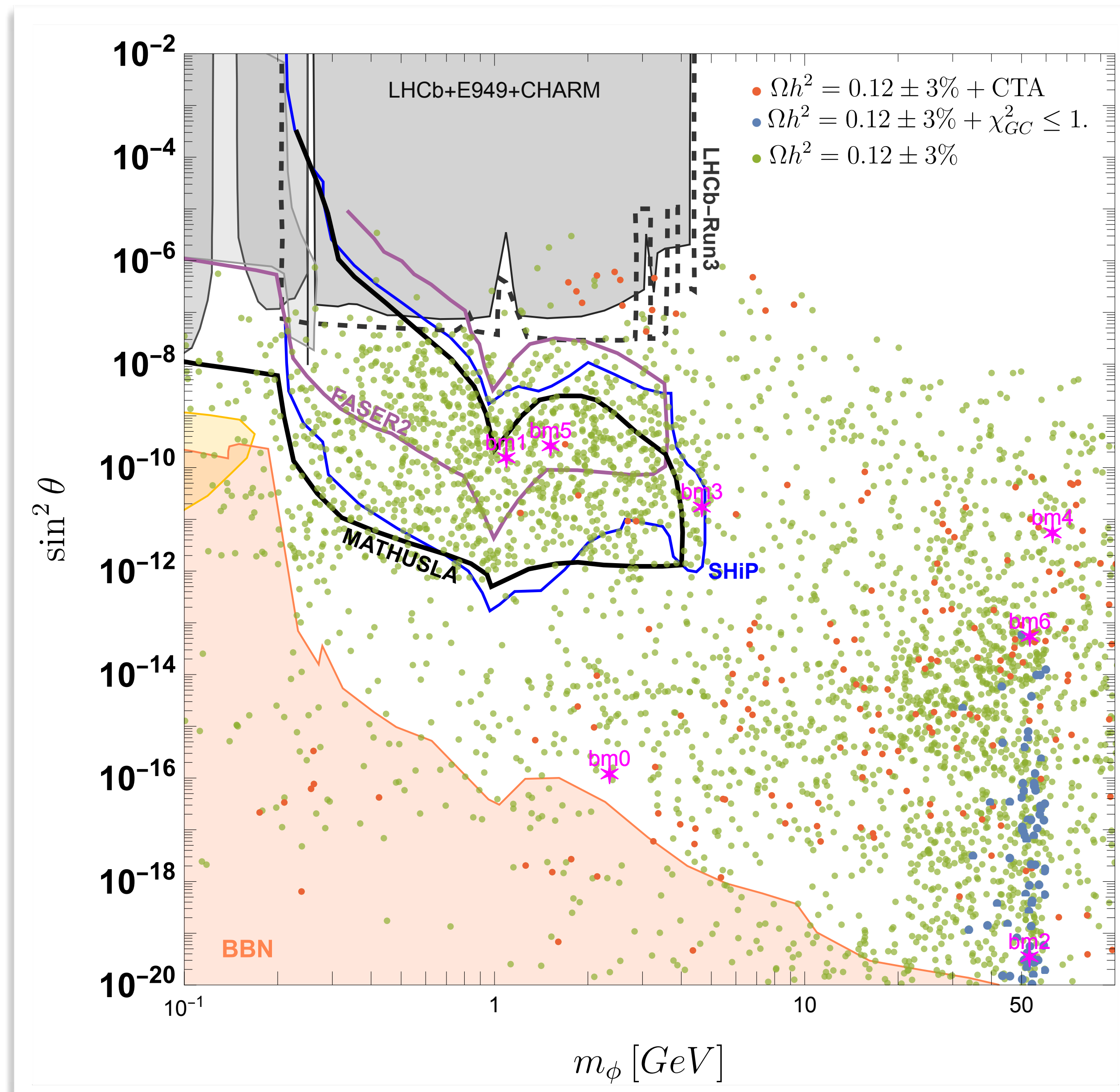
- The production rate is proportional to the DM density. (Smaller initial abundance → larger cross section…)
- Semi-production modifies the energy of DM particles in a non-trivial way, so the temperature evolution can affect the relic density



MCMC scan & Benchmarks

Points that give correct relic abundance at nBE level, projected onto indirect detection and forward physics searches planes





Benchmarks: summary

Name	m_ϕ	m_S	θ	$\lambda_{h\phi}$	λ_{hS}	$\lambda_{S\phi}$	$(\Omega h^2)_{\rm nBE}$	$(\Omega h^2)_{\rm cBE}$	change [%]	description
BM0	2.35	70.4	1.09×10^{-8}	1.67×10^{-13}	5.98×10^{-11}	0.00298	0.113	0.110	−1.96	direct FI
BM1	1.09	438.	1.24×10^{-5}	3.56×10^{-11}	3.72×10^{-13}	0.155	0.124	0.0205	−83.5	seq. FI/dark FO + MATHUSLA
BM2	53.0	76.1	1.87×10^{-10}	3.51×10^{-7}	1.96×10^{-11}	0.104	0.115	0.0199	−82.7	dark FO + best GCE fit
BM3	4.66	586.	4.15×10^{-6}	8.62×10^{-11}	4.32×10^{-15}	0.00603	0.0971	0.000883	−99.1	seq. FI
BM4	63.0	494.	2.34×10^{-6}	1.08×10^{-15}	2.70×10^{-6}	0.344	0.0902	0.0503	−44.2	dark FO/co−decay + CTA
BM5	1.52	17.2	1.62×10^{-5}	1.30×10^{-9}	4.46×10^{-9}	0.00823	0.110	0.0555	−49.5	co−decay + MATHUSLA
BM6	53.2	1.69×10^{3}	2.33×10^{-7}	5.14×10^{-8}	1.16×10^{-7}	1.01	0.119	0.0571	−51.9	dark FO + CTA

<u>The model's parameter space spans over various production modes:</u>

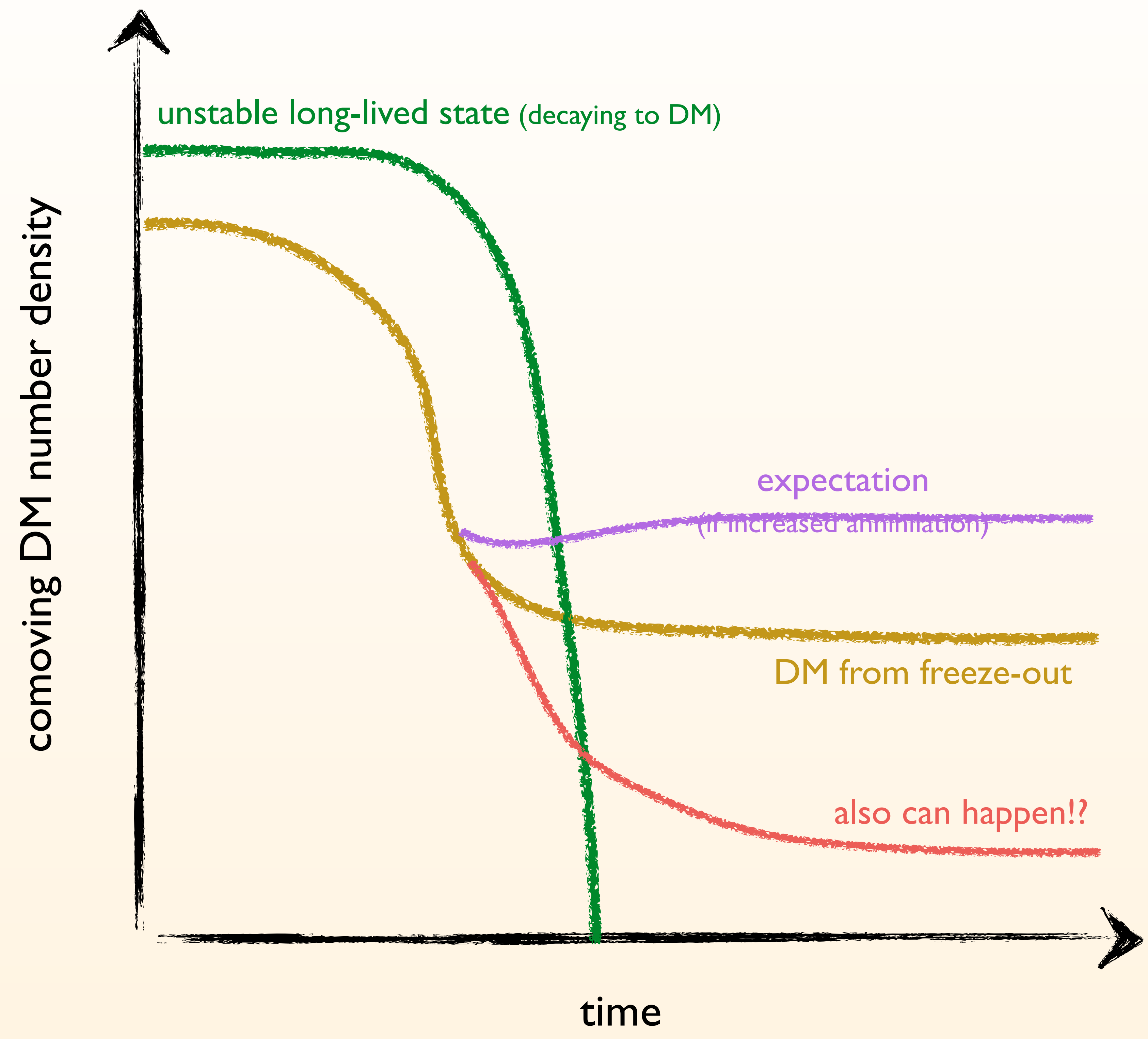
- direct & sequential freeze-in
- dark freeze-out
- co-decaying
- (and mixtures of these)

Effect of performing calculation at cBE level: from $\sim \mathcal{O}(1\%)$ to > 100

EXAMPLE D:
WHEN ADDITIONAL INFLUX OF DM ARRIVES

Sudden injection of more DM particles distorts $f_\chi(p)$
(e.g. from a decay or annihilation of other states)

- this can modify the annihilation rate (if still active)
- how does the thermalization due to elastic scatterings happen?

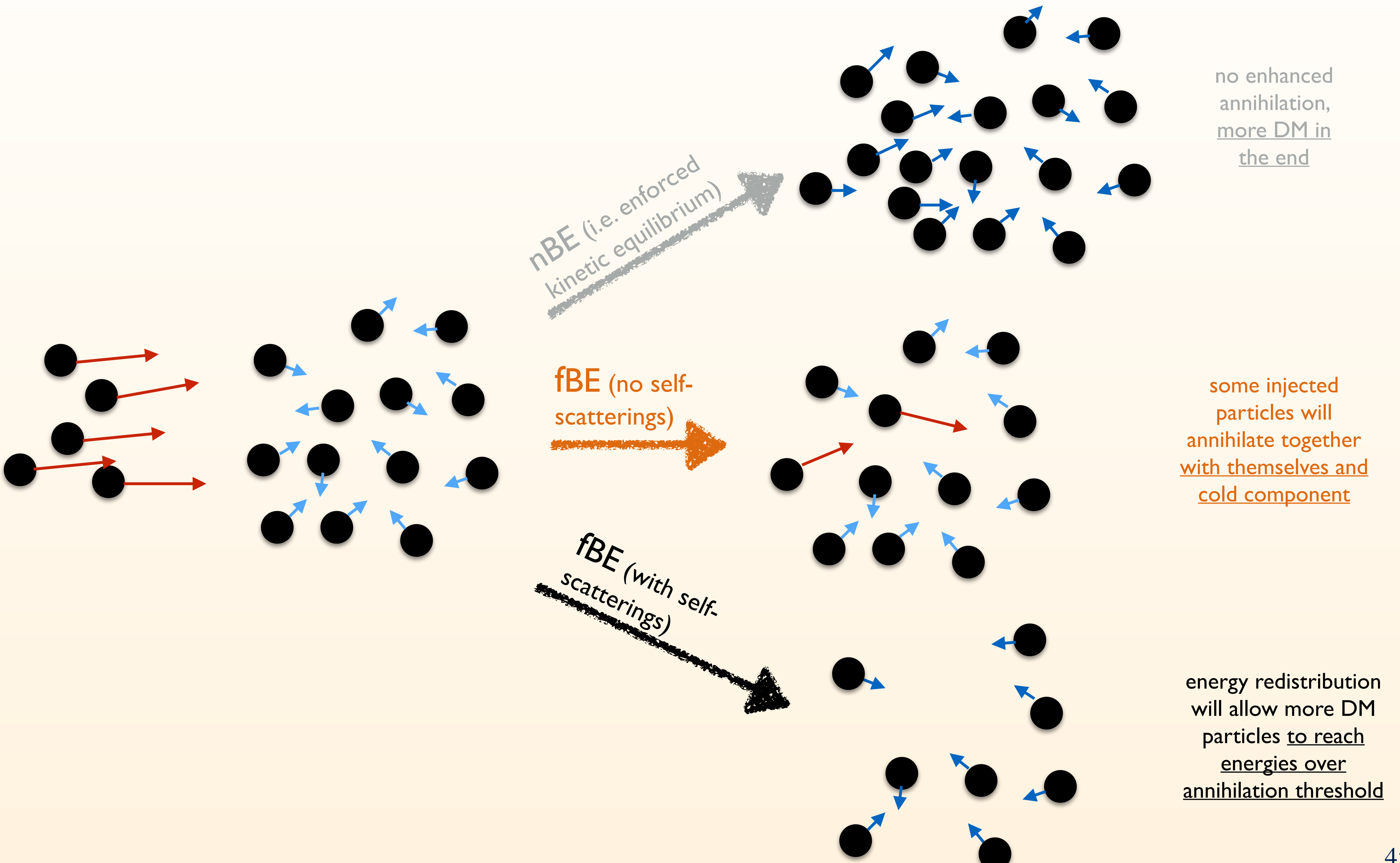

unstable long-lived state (decaying to DM)
expectation
(if increased annihilation)
DM from freeze-out
also can happen!?
comoving DM number density
time

1) DM produced via:

- 1st component from thermal freeze-out
- 2nd component from a decay $\phi \to \bar{\chi}\chi$

2) DM annihilation has a threshold

e.g. $\chi\bar{\chi} \to f\bar{f}$ with $m_\chi \lesssim m_f$



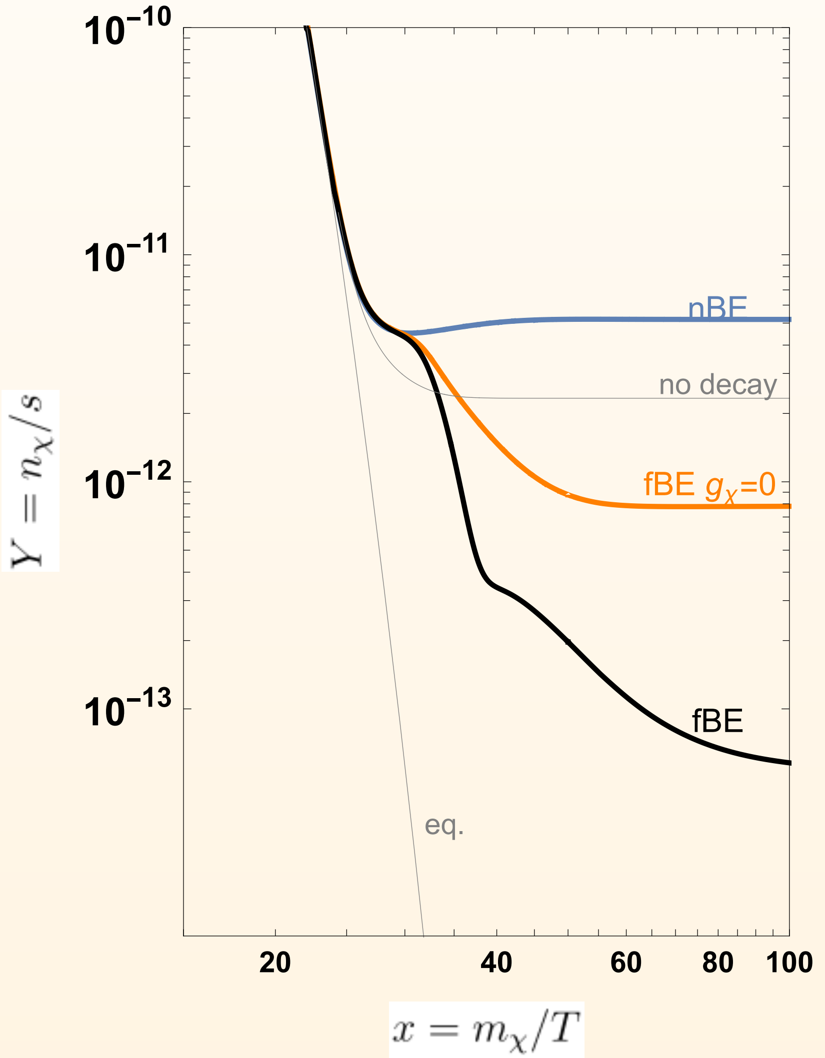
AH, Laletin 2204.07078

EXAMPLE EVOLUTION

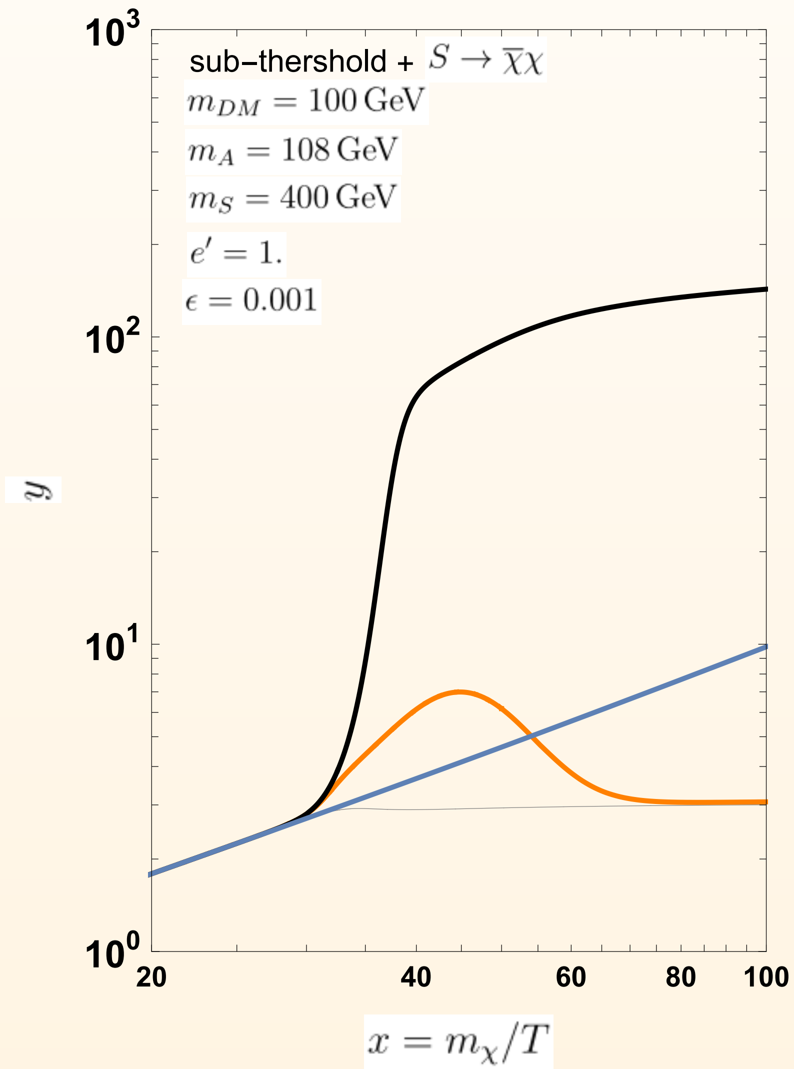
1) DM produced via:
- 1st component from thermal freeze-out
- 2nd component from a decay $\phi \to \bar{\chi}\chi$

2) DM annihilation has a threshold
e.g. $\chi\bar{\chi} \to f\bar{f}$ with $m_\chi \lesssim m_f$

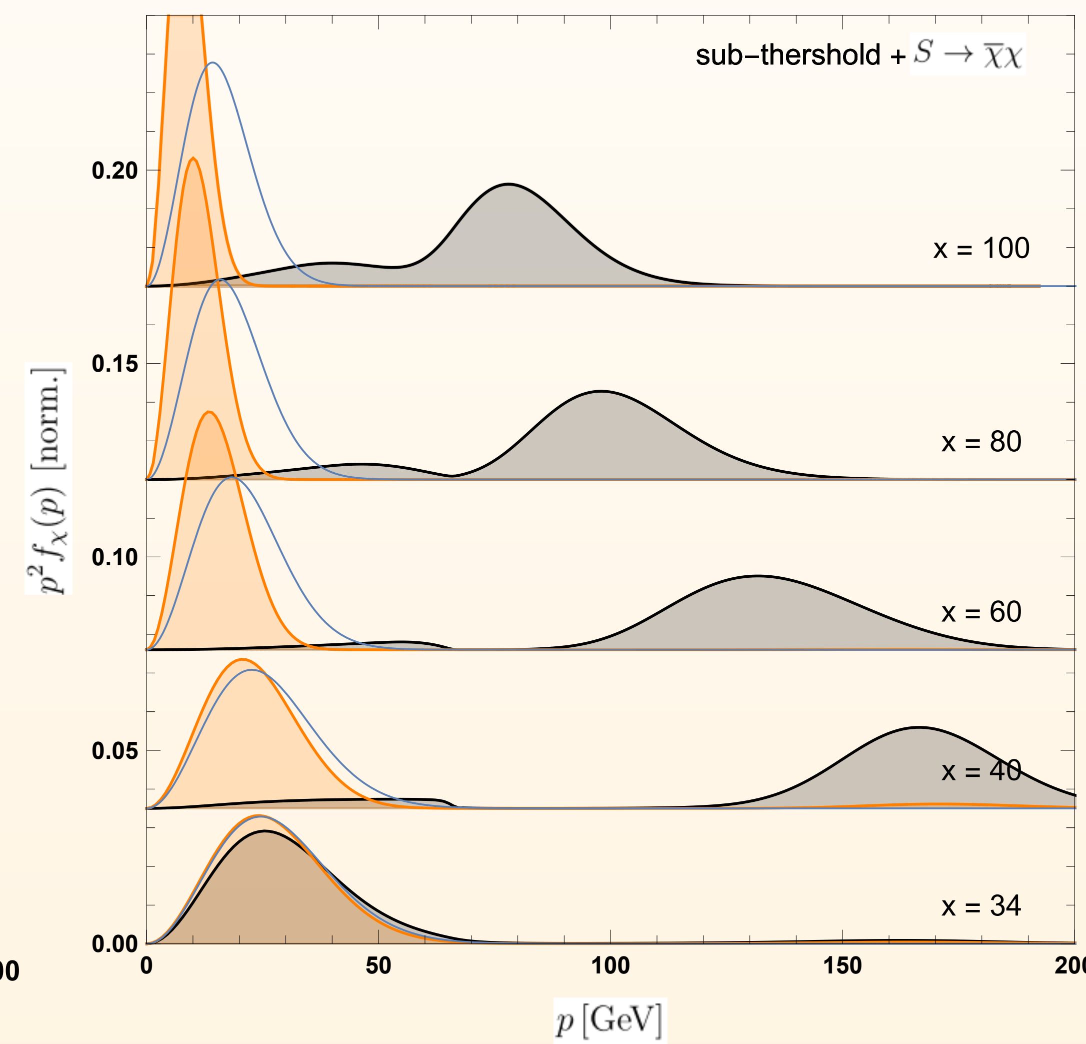
$Y \sim$ number density



$y \sim$ temperature



$p^2 f(p) \sim$ momentum distribution



OTHER EXAMPLES…

Sequential freeze-in thus adds to the list of scenarios where departure from LTE needs to be considered:

Annihilation through a (narrow) resonance

Duch, Grządkowski '17; Binder, Bringmann, Gustafsson, A.H '17; Abe '21; Ala-Mattinen et al .'22

Sub-threshold (e.g. forbidden DM)

Binder, Bringmann, Gustafsson, A.H 2103.01944; Liu et al '23; Aboubrahim et al. '23

Semi-annihilation and production

Kamada et al. '18; Cai, Spray '18; Hektor, AH & Kannike '19; AH & Laletin 2104.05684

Cannibal DM (freeze-out *or* freeze-in)

Herba et al '18; Cervantes & AH 2407.12104; Bernal, Cervantes, Deka, AH 2506.09155

Sommerfeld enhanced annihilation

Feng et al '10; Binder, Bringmann, Gustafsson, A.H 2103.01944

Two-component dark sectors (e.g. conversion-driven or co-decaying)

Beauchesne & Chiang 2401.03657; Chatterjee & AH 2502.08725

Freeze-out/freeze-in intermediate regime

Du et al. '22

SuperWIMP, WDM and Lyman-α limits

Decant et al. '22; AH & Laletin 2204.07078

…

CONCLUSIONS

1. Cannibal self-cooling can make DM lighter

2. Production in multicomponent dark sectors proceeds in a $T-$dependent way. This can alter the naive predictions by more than an order of magnitude.

3. In recent years a significant progress in refining the relic density calculations in DRAKE2 to include multicomponent case & freeze-in

Thank you!

BACKUP