SEQUENTIAL FREEZE-IN
A TALE OF TWO SCALARS

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Based on:

work in progress with **S. Chatterjee**

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

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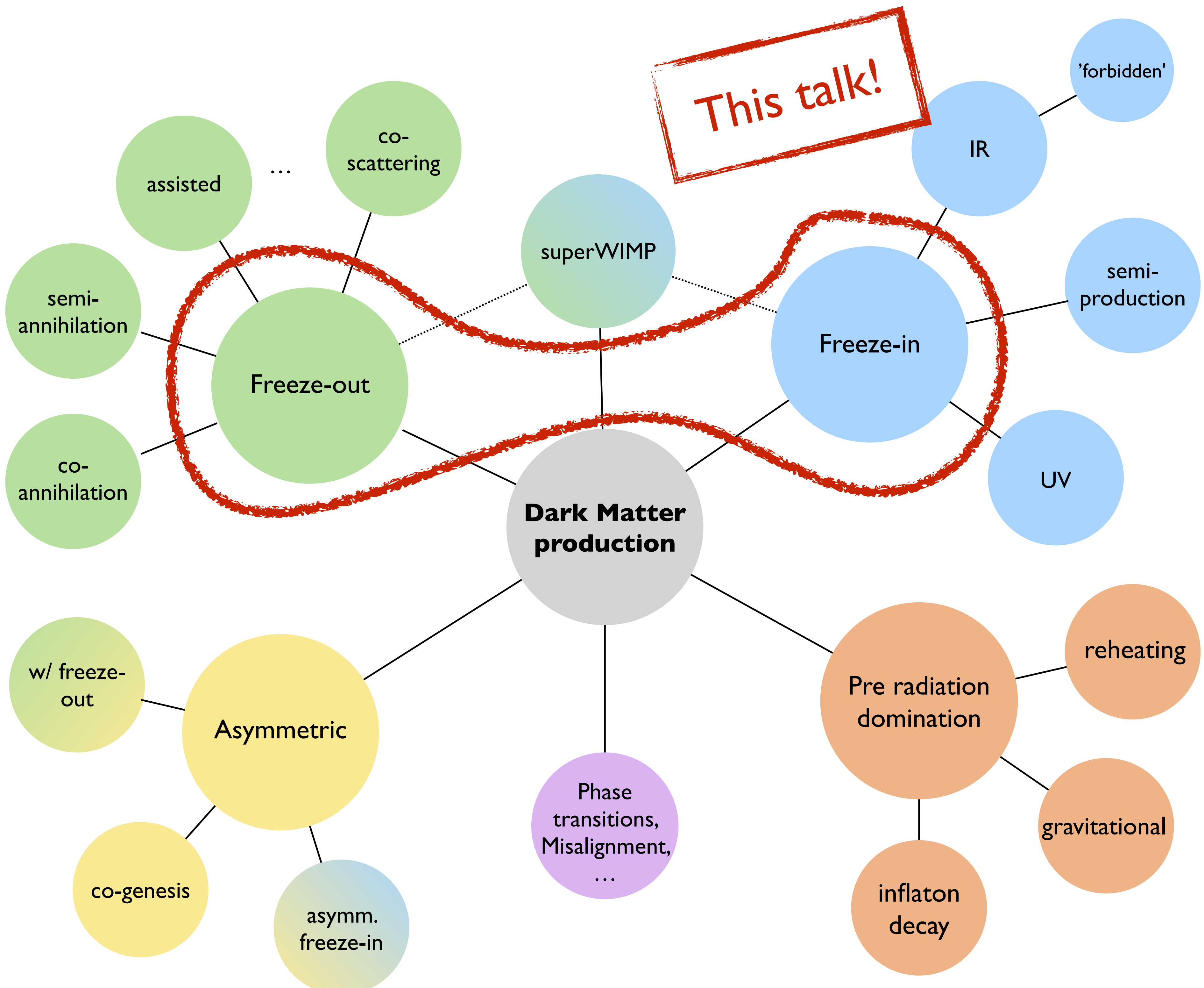
Motivation & Objectives

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

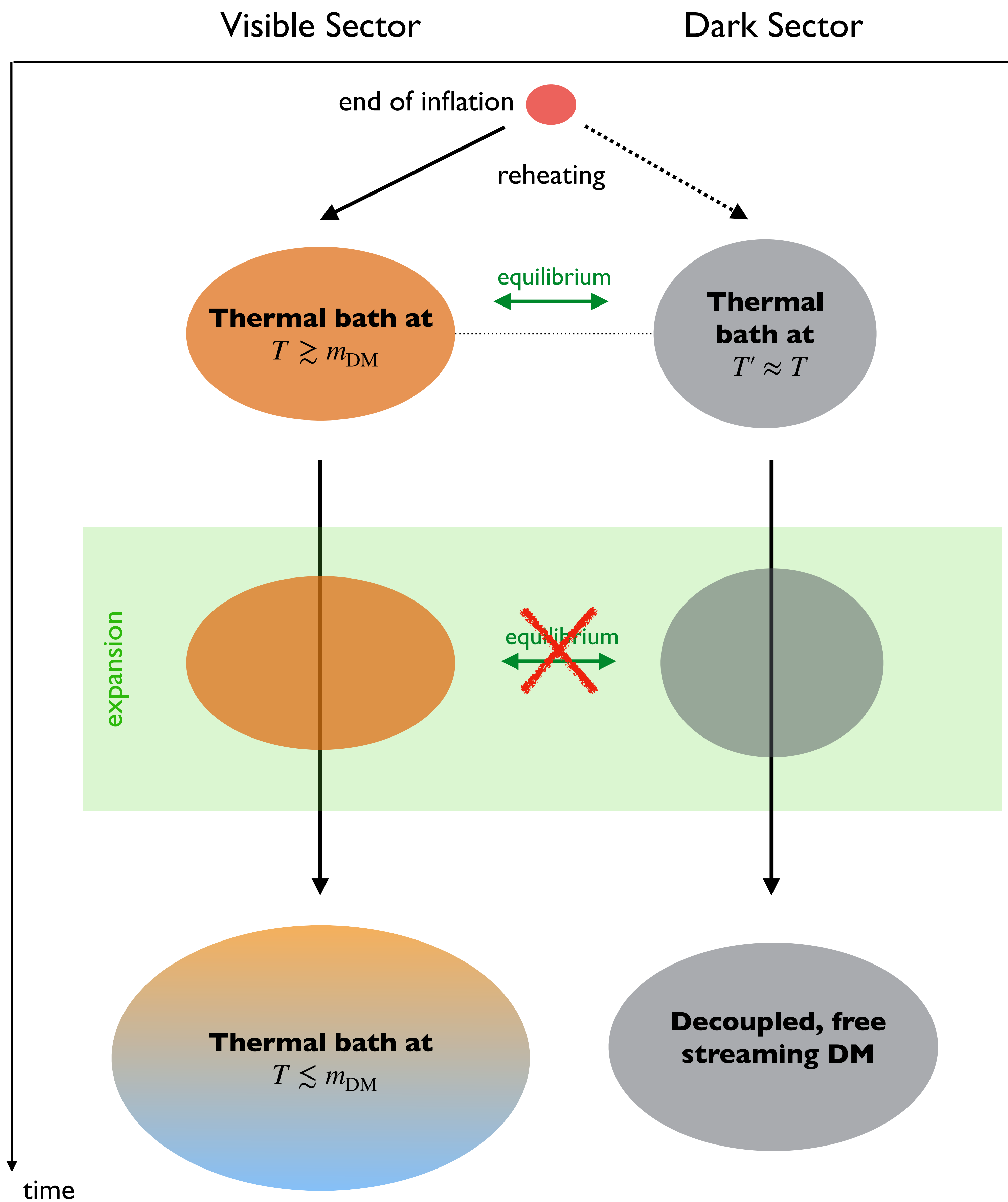
Study of a SM+2 scalars theory with detectable, frozen-in DM

Implementation of freeze-in production in DRAKE2 code

DARK MATTER ORIGIN



What is 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

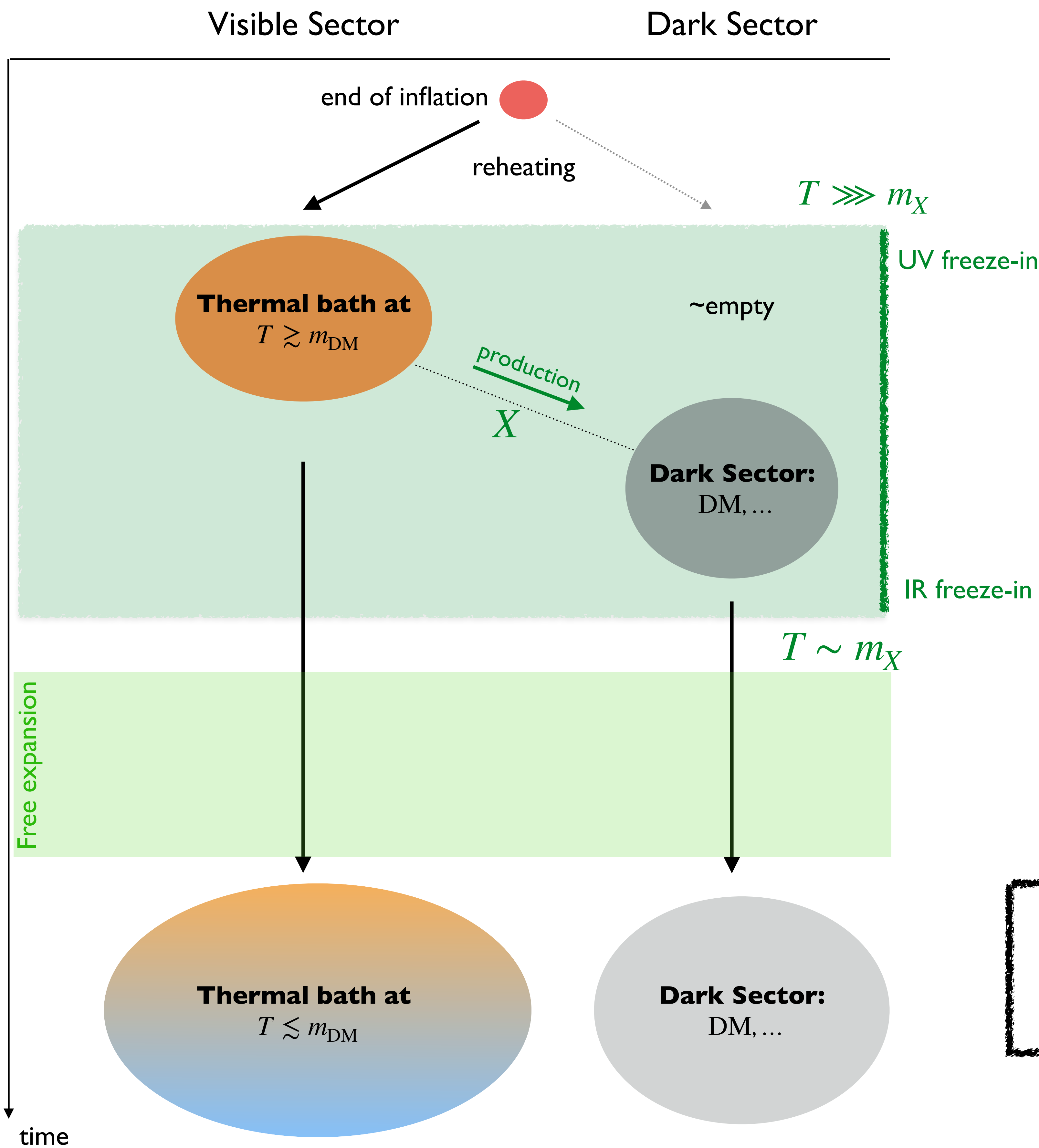
Fixes coupling(s) $\Rightarrow$ signal in DD, ID & LHC

III. It is not optional

Overabundance constraint

To avoid it one needs quite significant deviations from standard cosmology

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, …

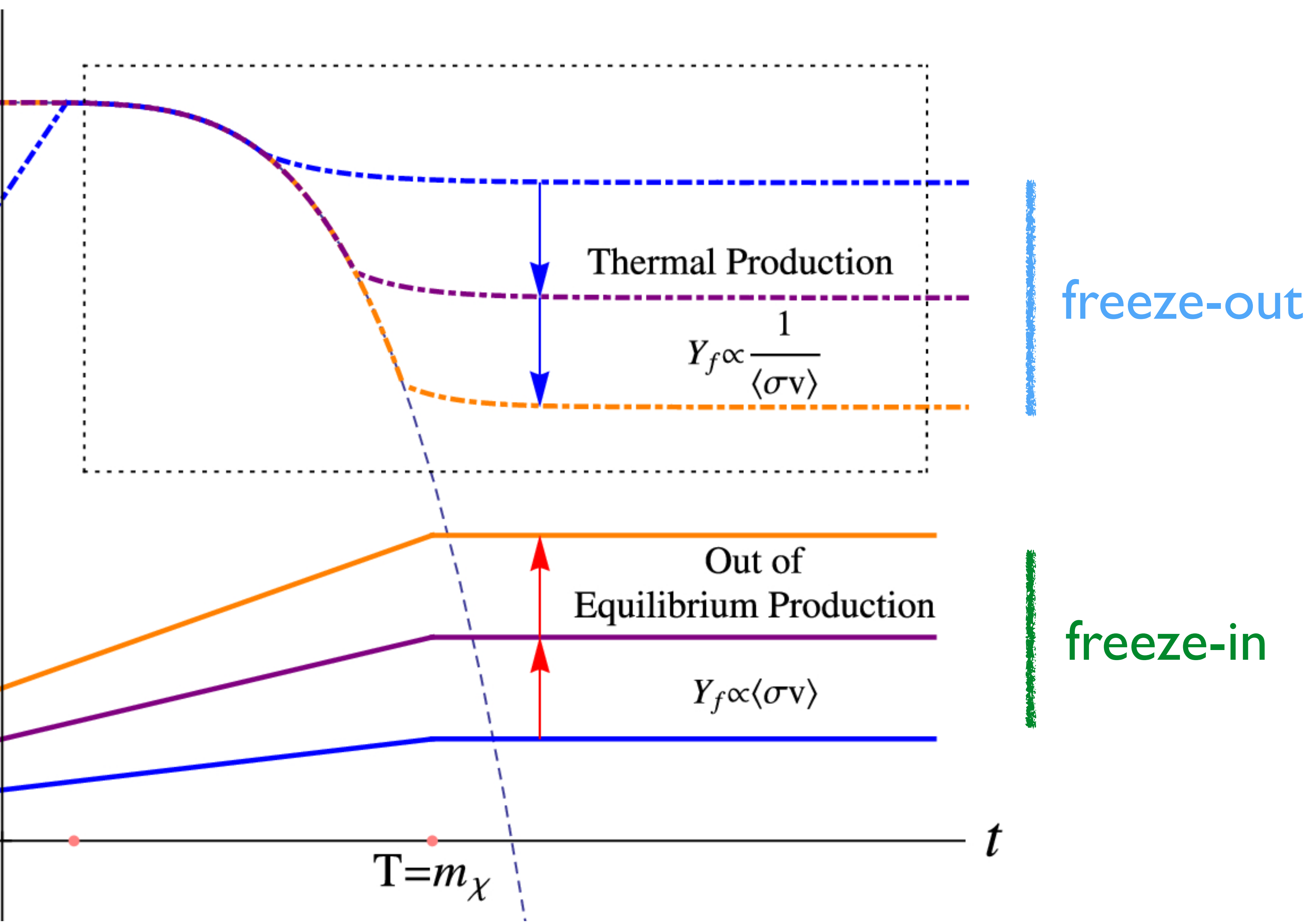
however, old works focused on what now people call UV freeze-in

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

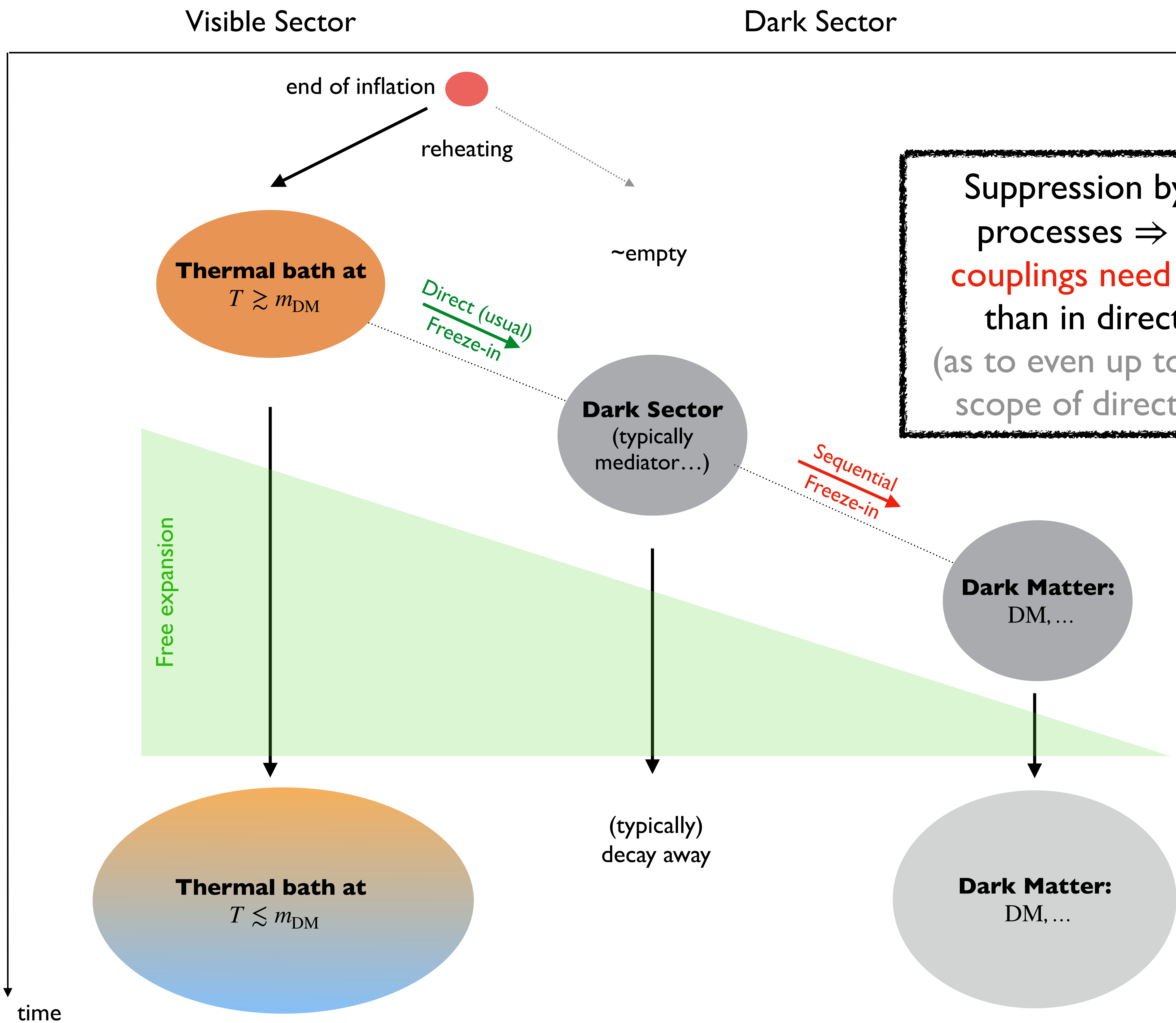
Freeze-in = the above mechanism through renormalizable operators (IR freeze-in)

FREEZE-IN *VS.* FREEZE-OUT

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



What is <u>Sequential</u> Freeze-in?



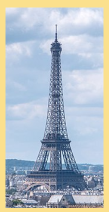
Suppression by <u>two</u> weak processes ⇒ respective couplings need to be larger than in direct freeze-in (as to even up to being within scope of direct detection!)

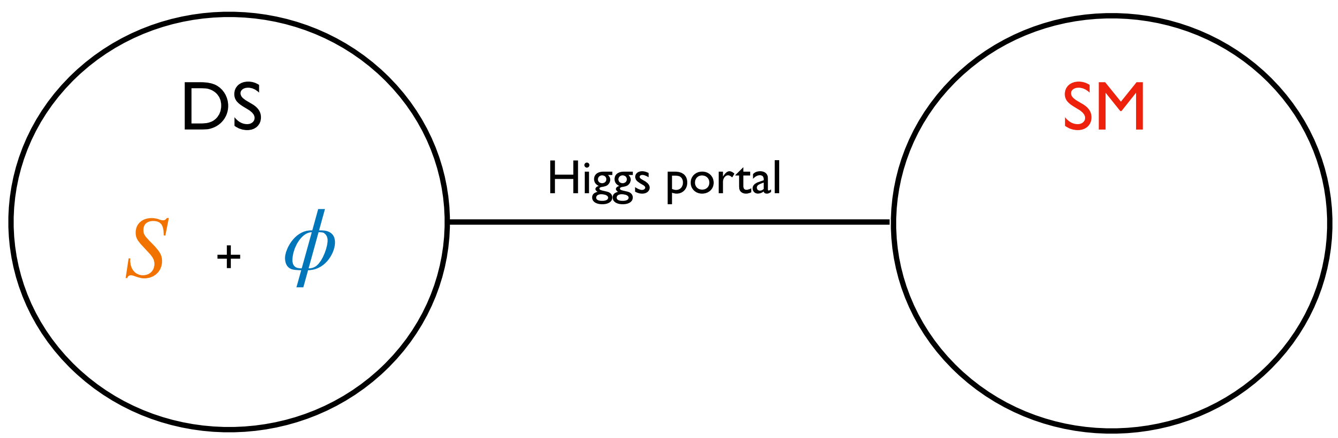
Hambye *et al.* 1908.09864
Belanger *et al.* 2005.06294

…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

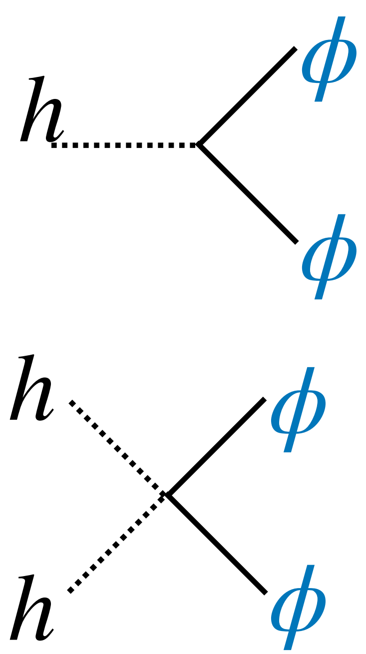
$$\sin\theta = \frac{Av}{m_h^2 - m_\phi^2}\left(1 - \frac{\lambda_{h\phi} v^2}{2m_\phi^2}\right)$$

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

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

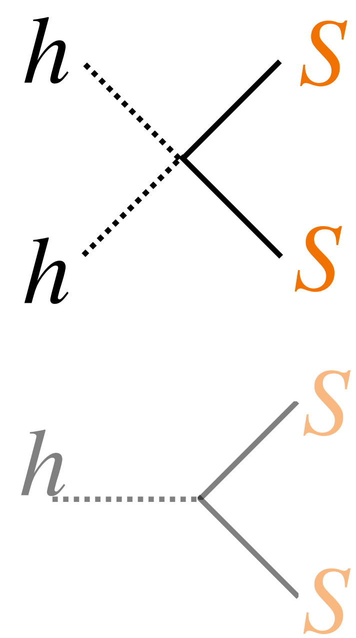
A Tale of Two Scalars

mediator freeze-in:



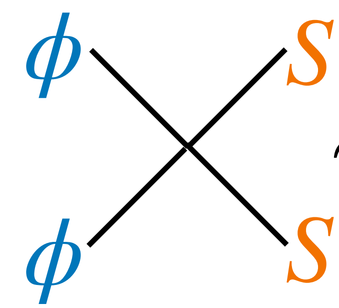
$\sim \lambda_{h\phi}$

DM freeze-in:



$\sim \lambda_{Sh}$

sequential freeze-in:



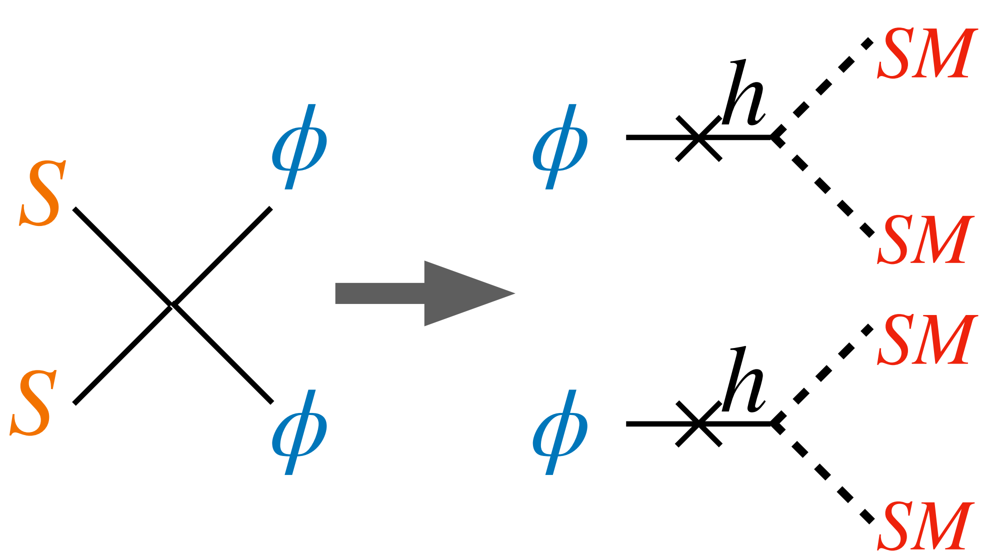
$\sim \lambda_{S\phi}$

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 $m_S > m_\phi$):



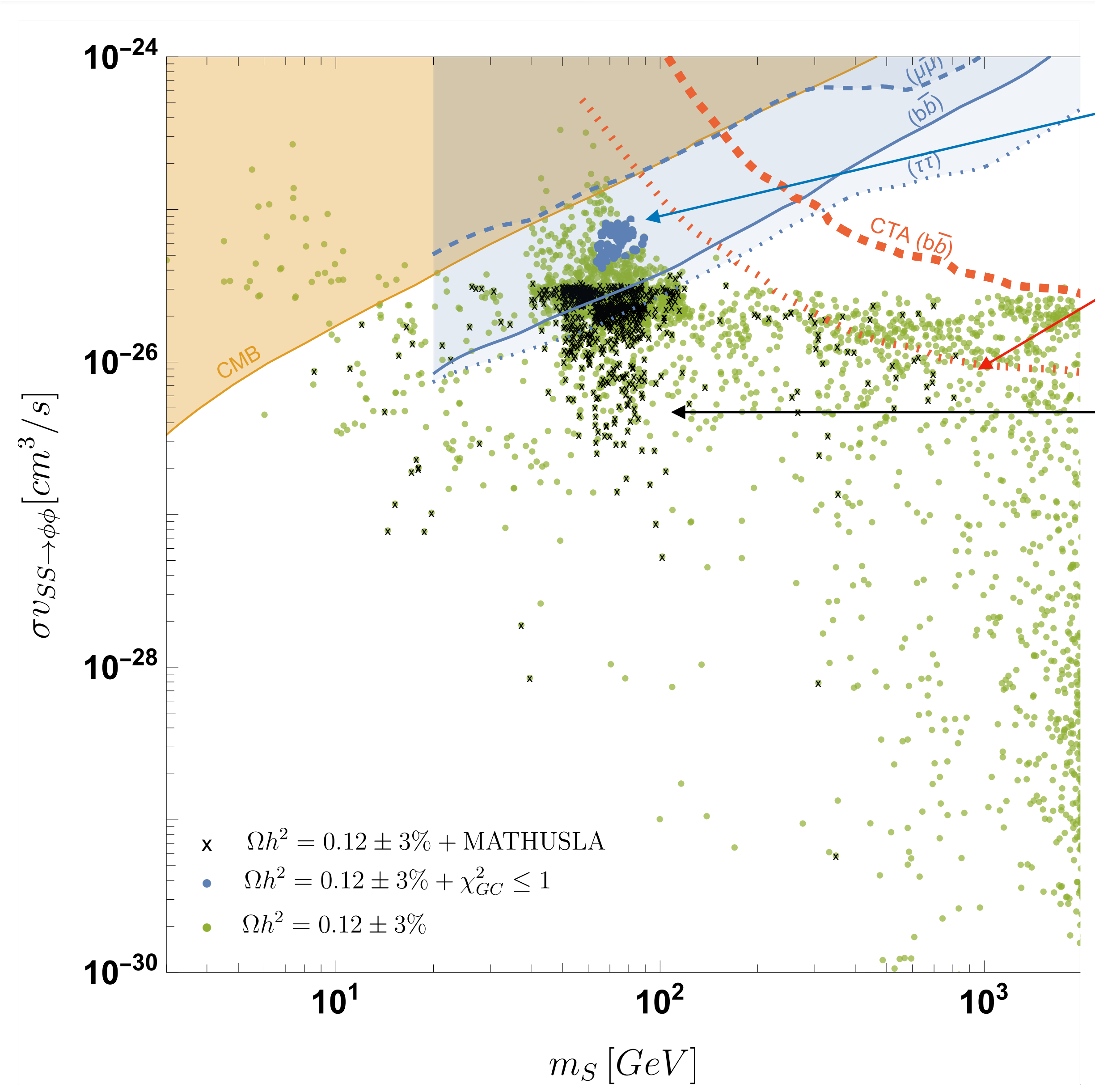
ID signal = requirement of sub-threshold sequential freeze-in

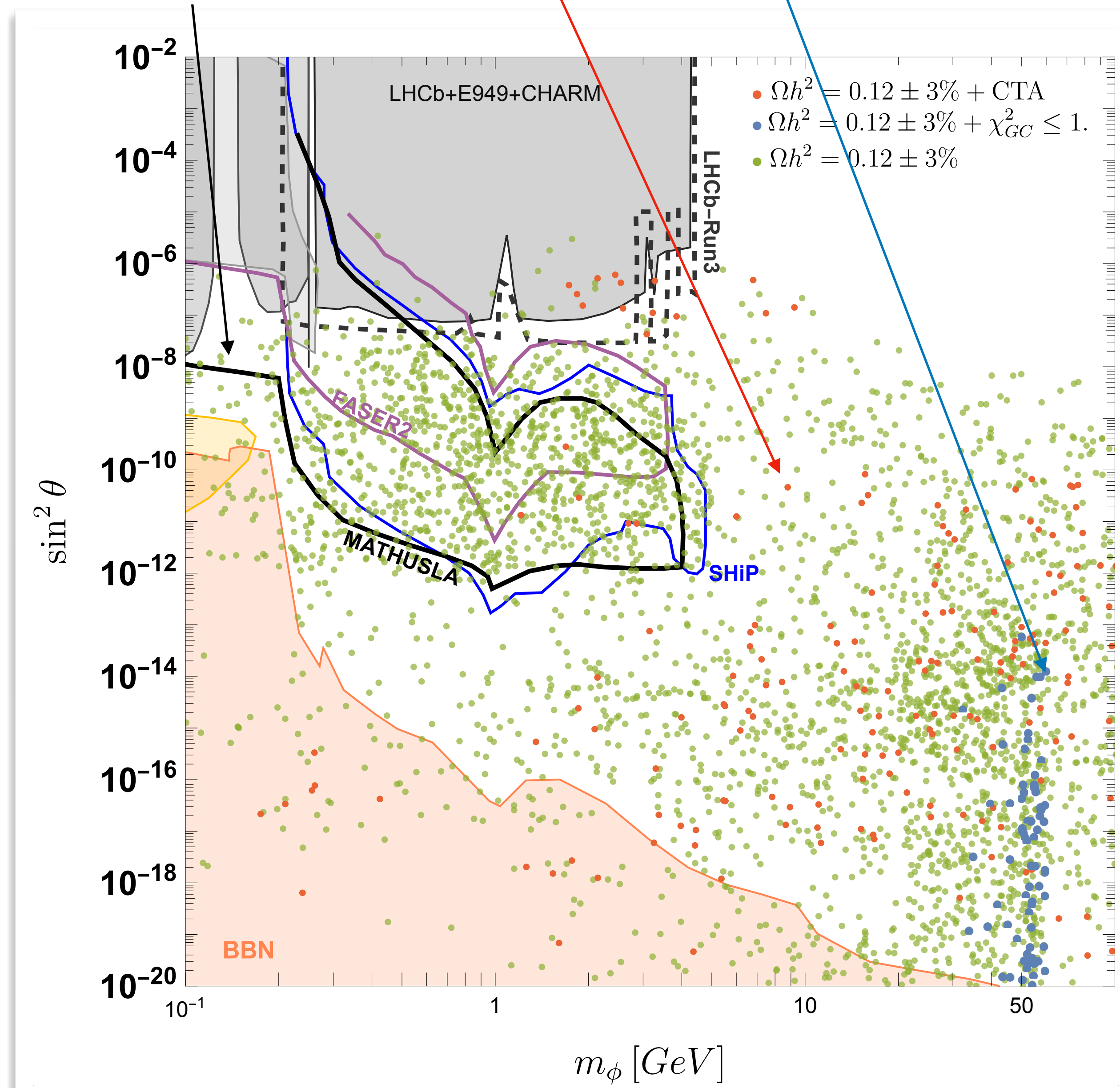
SCAN RESULTS: ID AND FORWARD PHYSICS

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

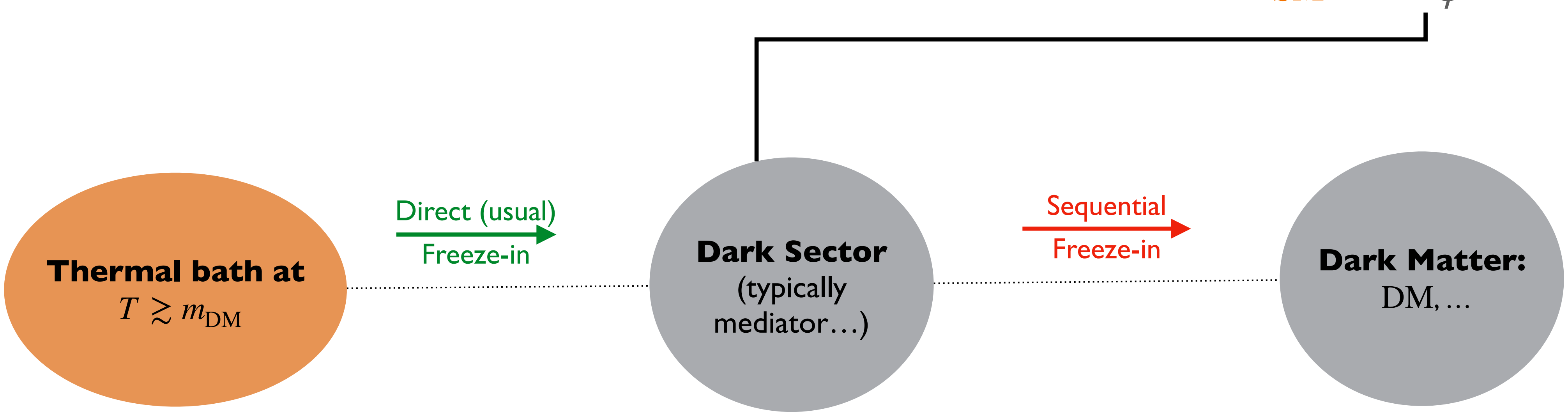
A SECOND LOOK ON Ωh^2

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 we need to 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:

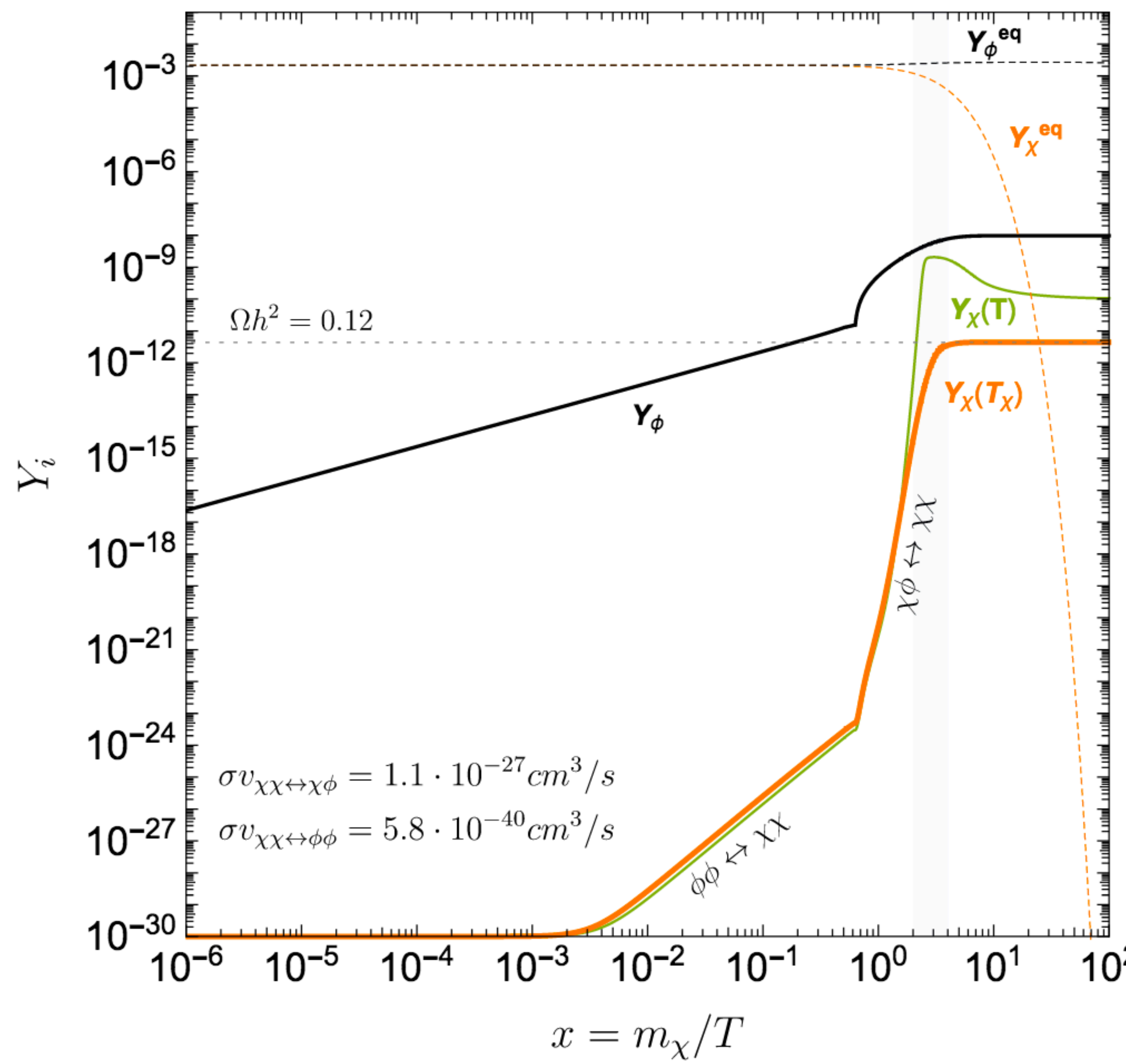
$$\chi\phi \to \chi\chi$$

DM　　　mediator or a SM state

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



THERMAL RELIC DENSITY
STANDARD APPROACH

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

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

$\Downarrow$

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

$\Downarrow$

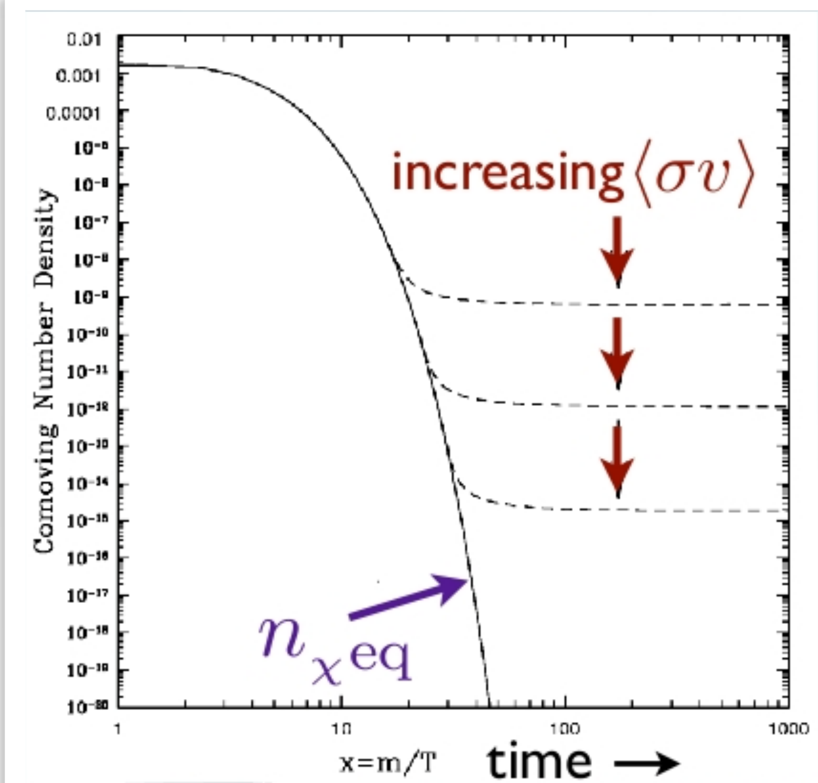


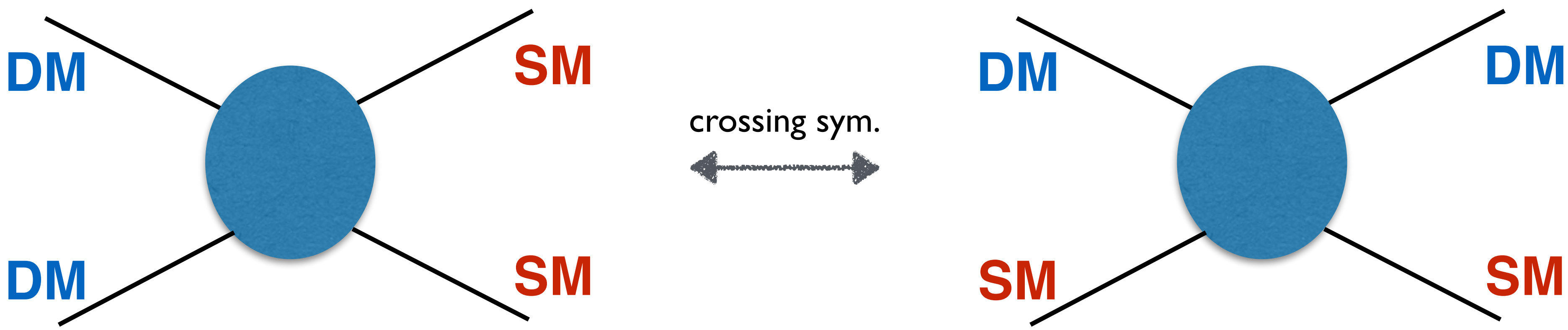
Fig.: Jungman, Kamionkowski & Griest, PR'96

Critical assumption:
kinetic equilibrium at chemical decoupling

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

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

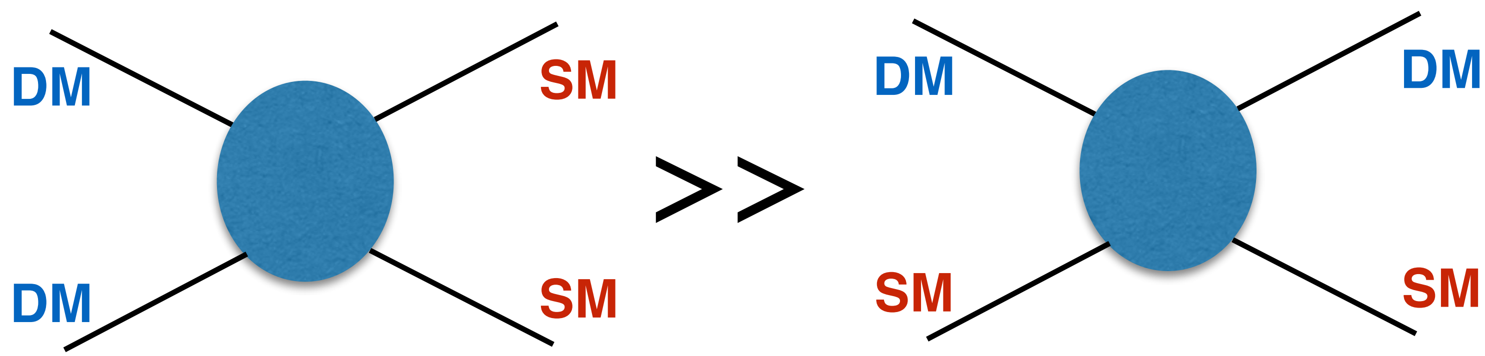
see e.g., Bringmann, Ihle, Karsten, Walia '16

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

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

have insight on the distribution

no constraining assumptions

numerically challenging

often an overkill

cBE

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

0-th moment: n_χ

2-nd moment: T_χ

…

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!

System of cBE for Y_i and T_i

This we obtain through equations for the 0th and 2nd moment of the BE:

$$\frac{Y_i'}{Y_i} = \frac{m_i}{x\tilde{H}} C_i^0\,,$$

$$\frac{y_i'}{y_i} = \frac{m_i}{x\tilde{H}} C_i^2 - \frac{Y_i'}{Y_i} + \frac{H}{x\tilde{H}} \frac{\langle p^4/E_i^3 \rangle}{3T_i}$$

where $y \equiv \frac{m_\chi T_\chi}{s^{2/3}}$ is a parameter that describes the 'temperature' $T_\chi \equiv \frac{g_\chi}{3 n_\chi} \int \frac{\mathrm{d}^3 p}{(2\pi)^3} \frac{p^2}{E} f_\chi(p)$

The collision term is also given by its moments:

$$C_i^0 \equiv \frac{g_i}{m_i n_i} \int \frac{d^3 p}{(2\pi)^3 E_i} C[f_i]\,, \qquad C_i^2 \equiv \frac{g_i}{3 m_i n_i T_i} \int \frac{d^3 p}{(2\pi)^3 E_i} \frac{p^2}{E_i} C[f_i]$$

$C[f_i]$ contains all scatterings and production/annihilation processes

In our model we got 4 equations for: Y_S, T_S, Y_ϕ, T_ϕ

Implementation of such capability [together with fBE system, giving also evolution of the $f(p)$] is a part of update in the new version of DRAKE2

DRAKE2

coming this winter*…

New features:

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

Freeze-out & Freeze-in

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

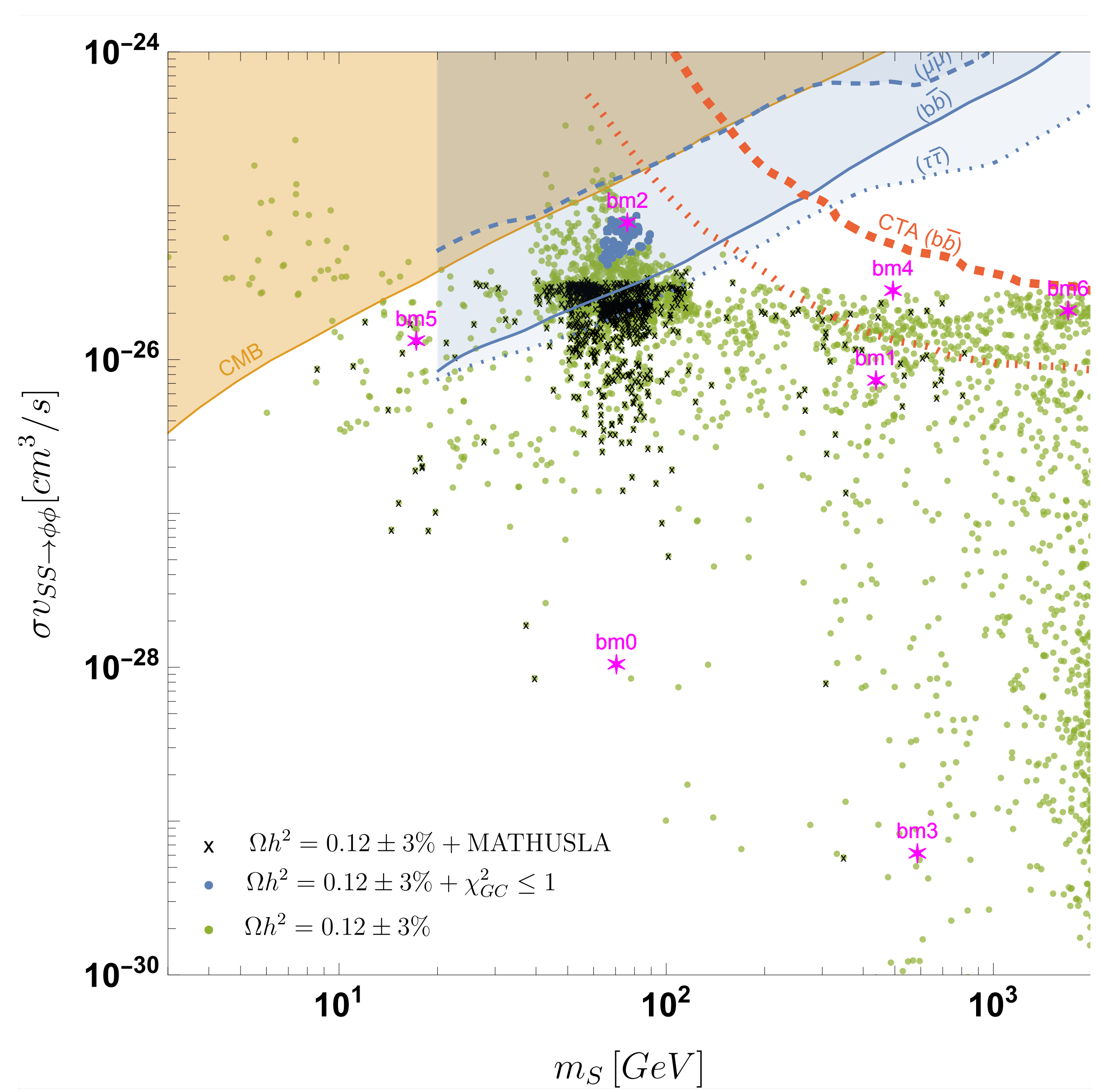
Improvements:

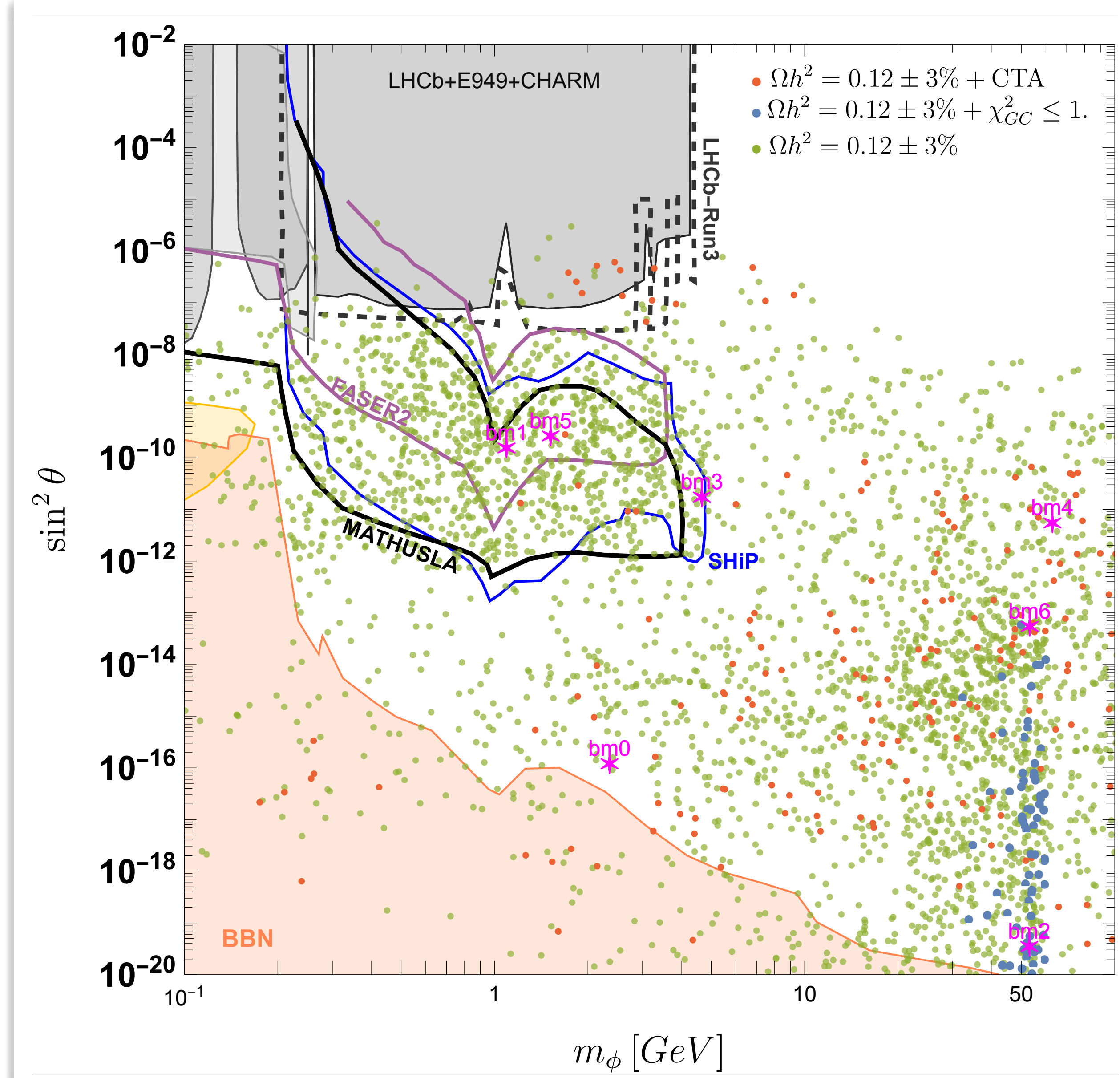
Increased efficiency
[e.g. more extended use of compiled functions, parallelisation, matrix formulation]

Updated *user interface*

*hopefully… but already essentially available for sharing, just talk or DM me

BENCHMARKS





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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
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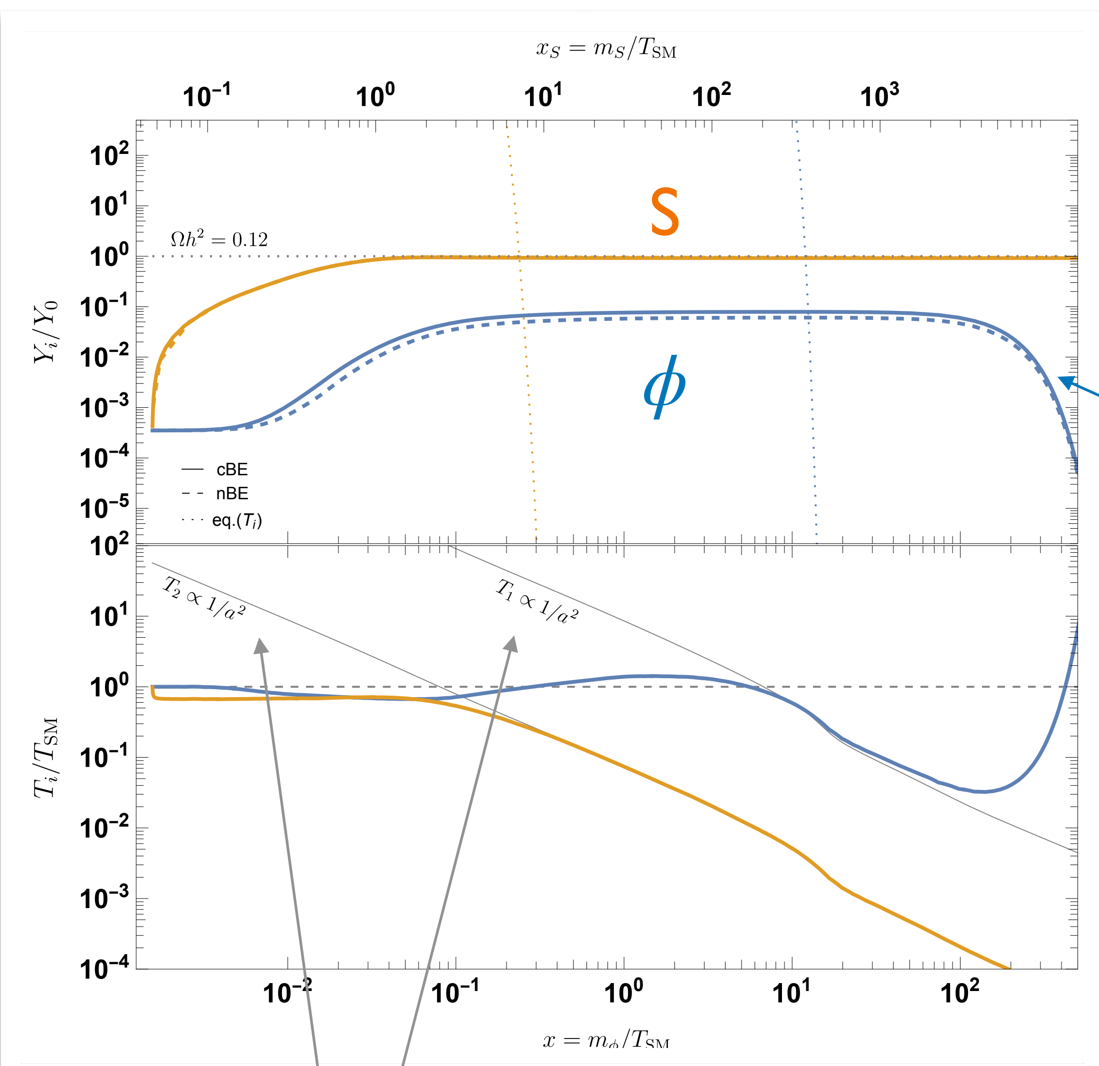

yield (abundance)

Ratio of S and ϕ temperatures to the SM plasma one

Free scaling after departure from LTE

Simple point to keep in mind as a baseline

Relatively small $\lambda_{S\phi}$ means both S and ϕ evolve separately

In the end ϕ decays

Very mild cBE effect

BENCHMARKS

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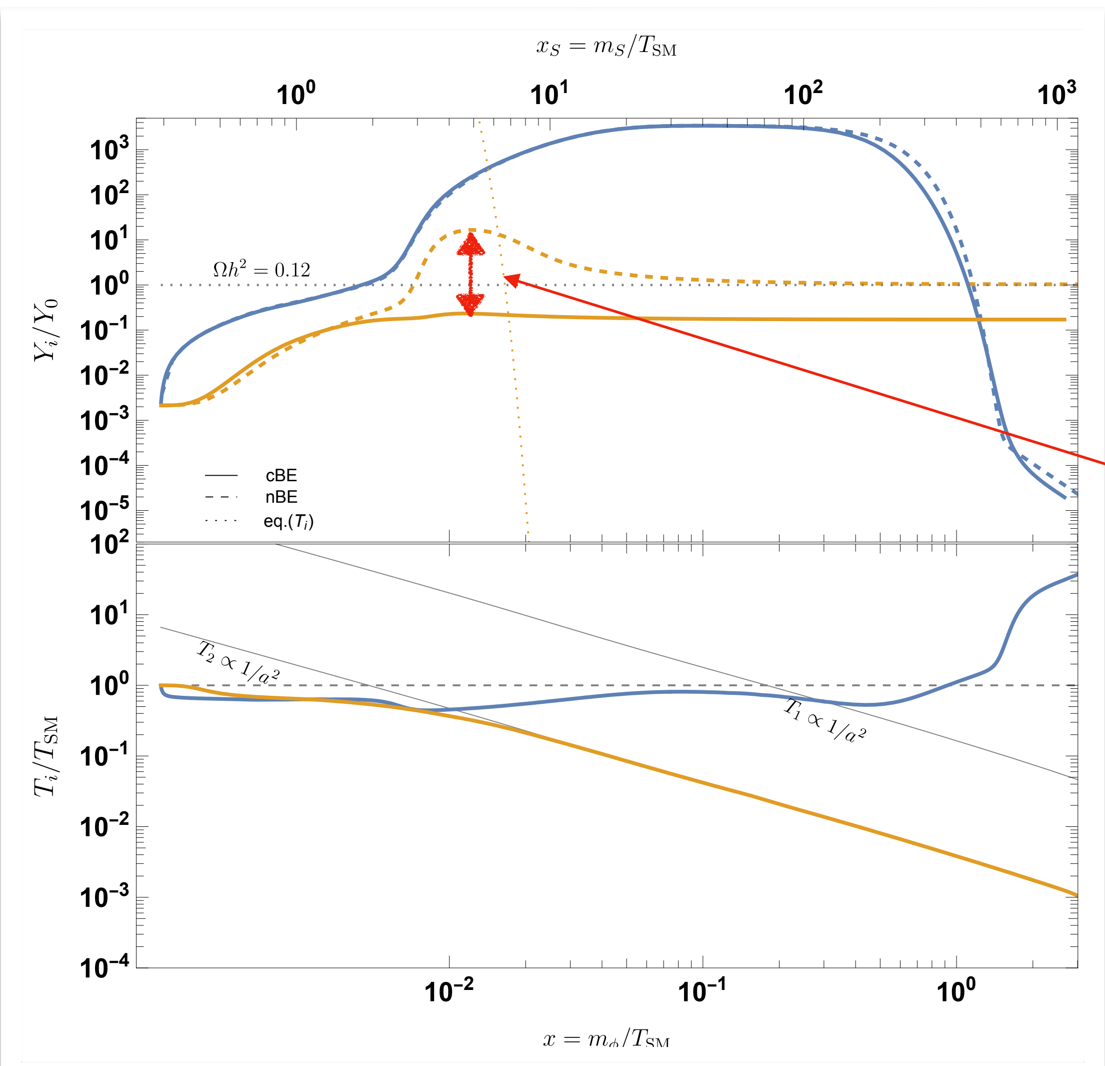

Hierarchy of $\lambda_{h\phi} \gg \lambda_{hS}$ and $m_S \gg m_\phi$ means freeze-in is sequential, followed by (mild) annihilation due to large $\lambda_{S\phi}$

Large change due to cBE:
lower T_ϕ + large threshold from ϕ to S suppresses sequential freeze-in!

This point lies within reach of MATHUSLA, SHiP and FASER2

BENCHMARKS

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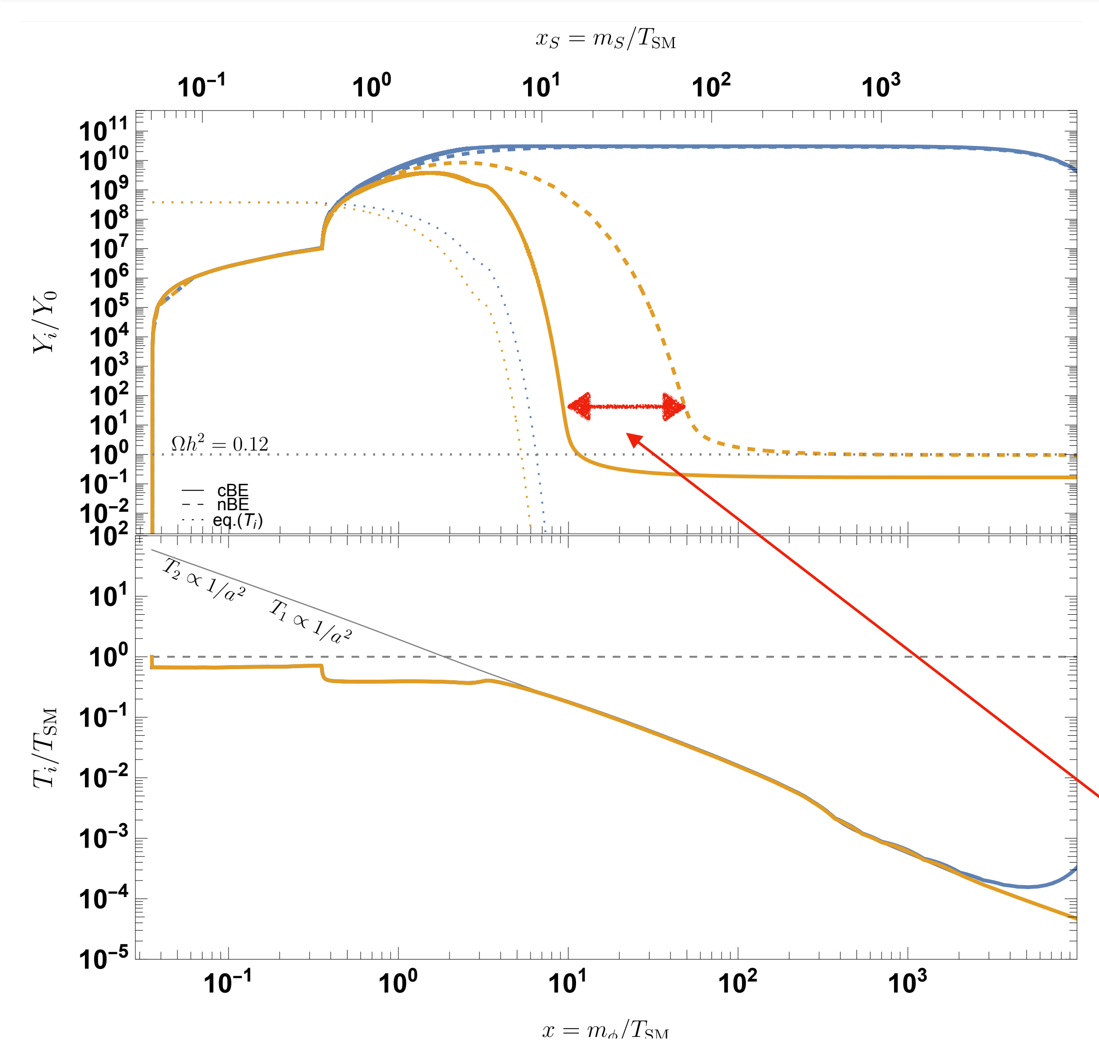
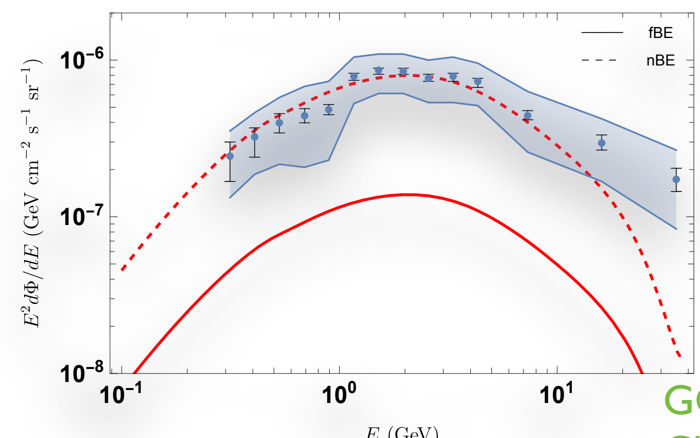


Best fit point to the GCE found in the scan:



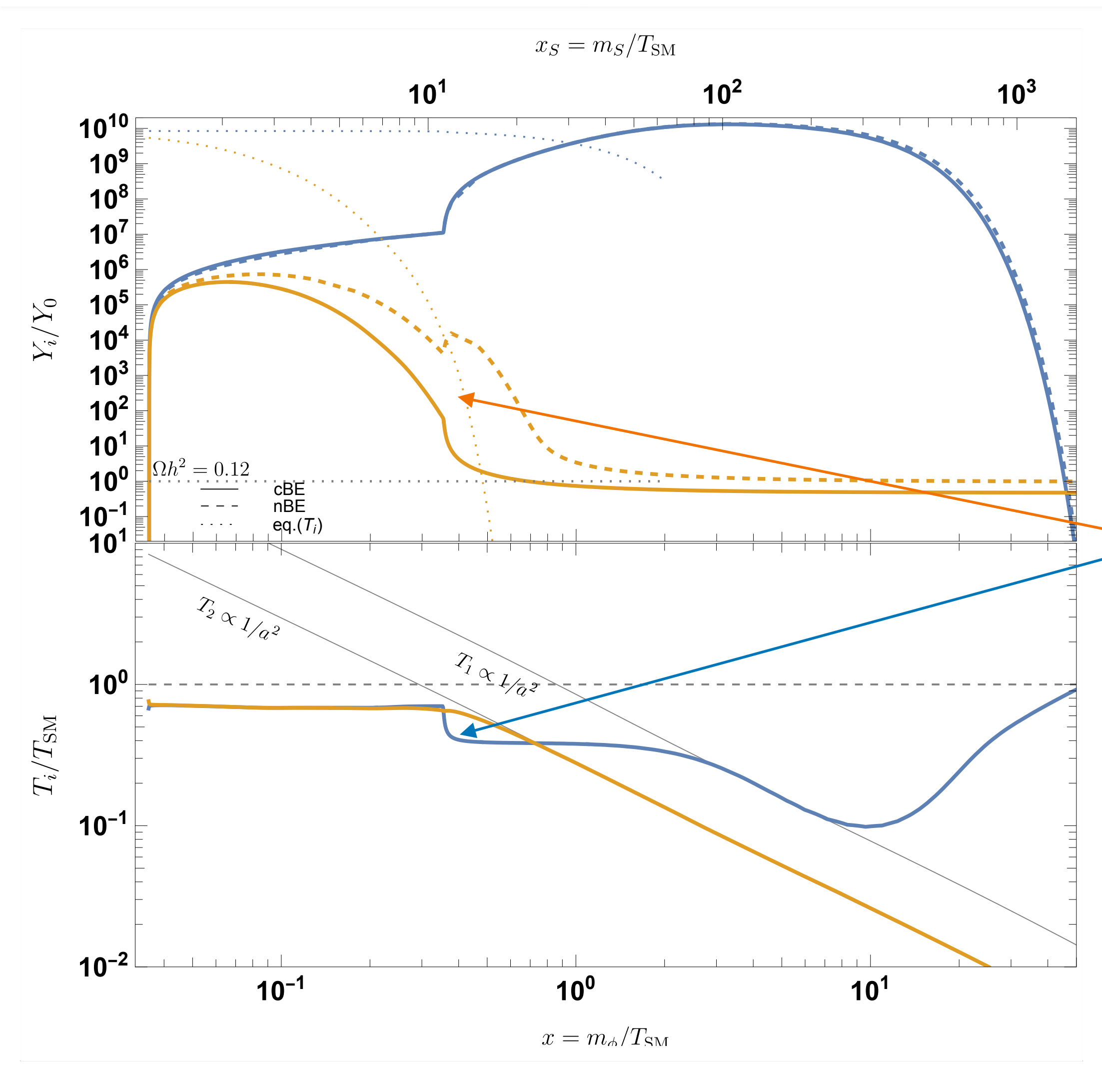
GCE analysis from Cholis et al. ’22

Mostly dark freeze-out from a thermal bath with $T_S \approx T_\phi < T_{SM}$

change in Ωh^2 due sooner freeze-out

BENCHMARKS

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



Finally, a point within reach of CTA

Notice impact of h decay after EPWT:

(as $m_\phi \sim m_h/2$ it lowers T_ϕ)

this cooling suppresses $\phi\phi \rightarrow SS$ while annihilation $SS \rightarrow \phi\phi$ can proceed

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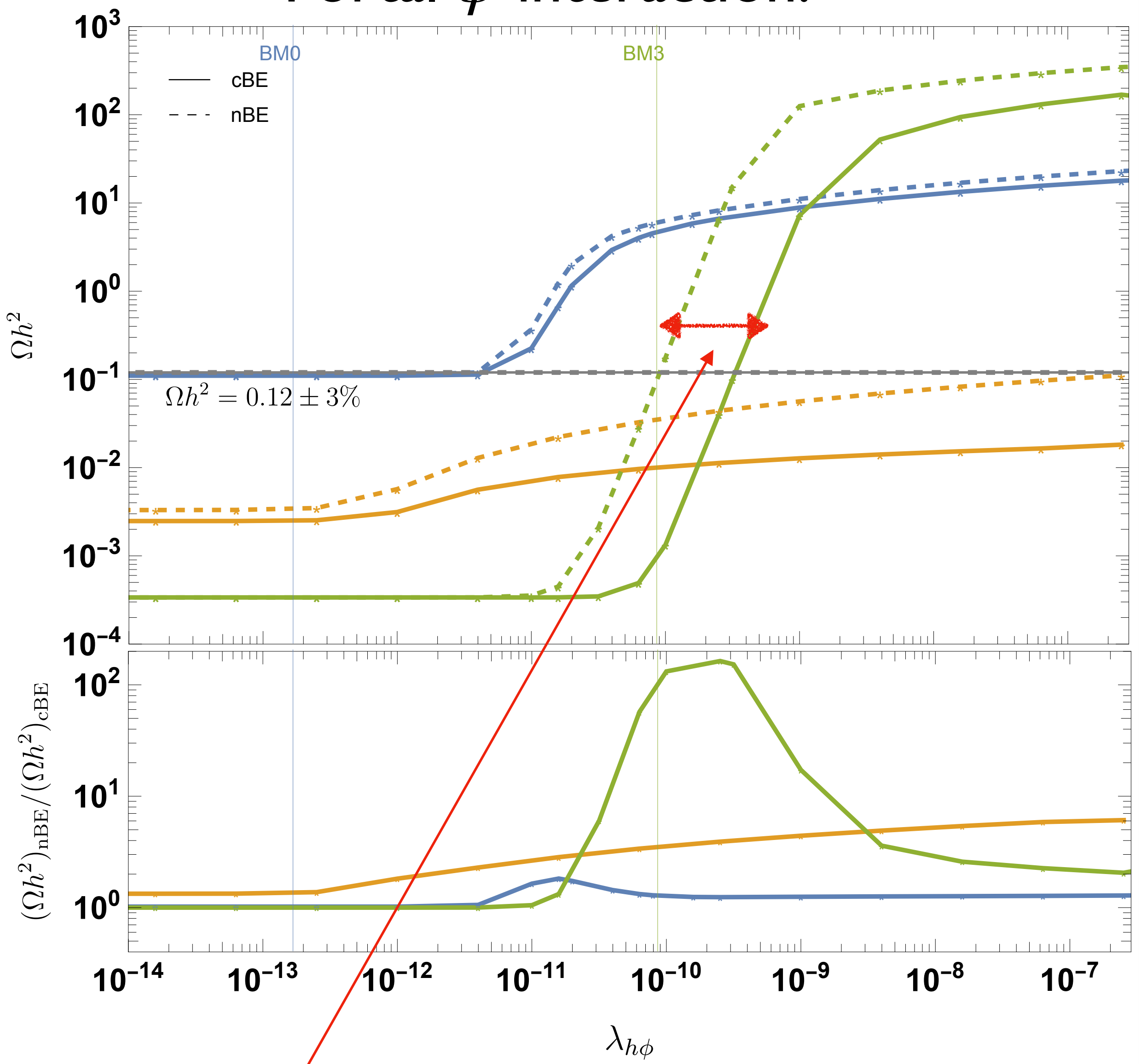
<u>The model's parameter space spans over various production modes:</u>

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

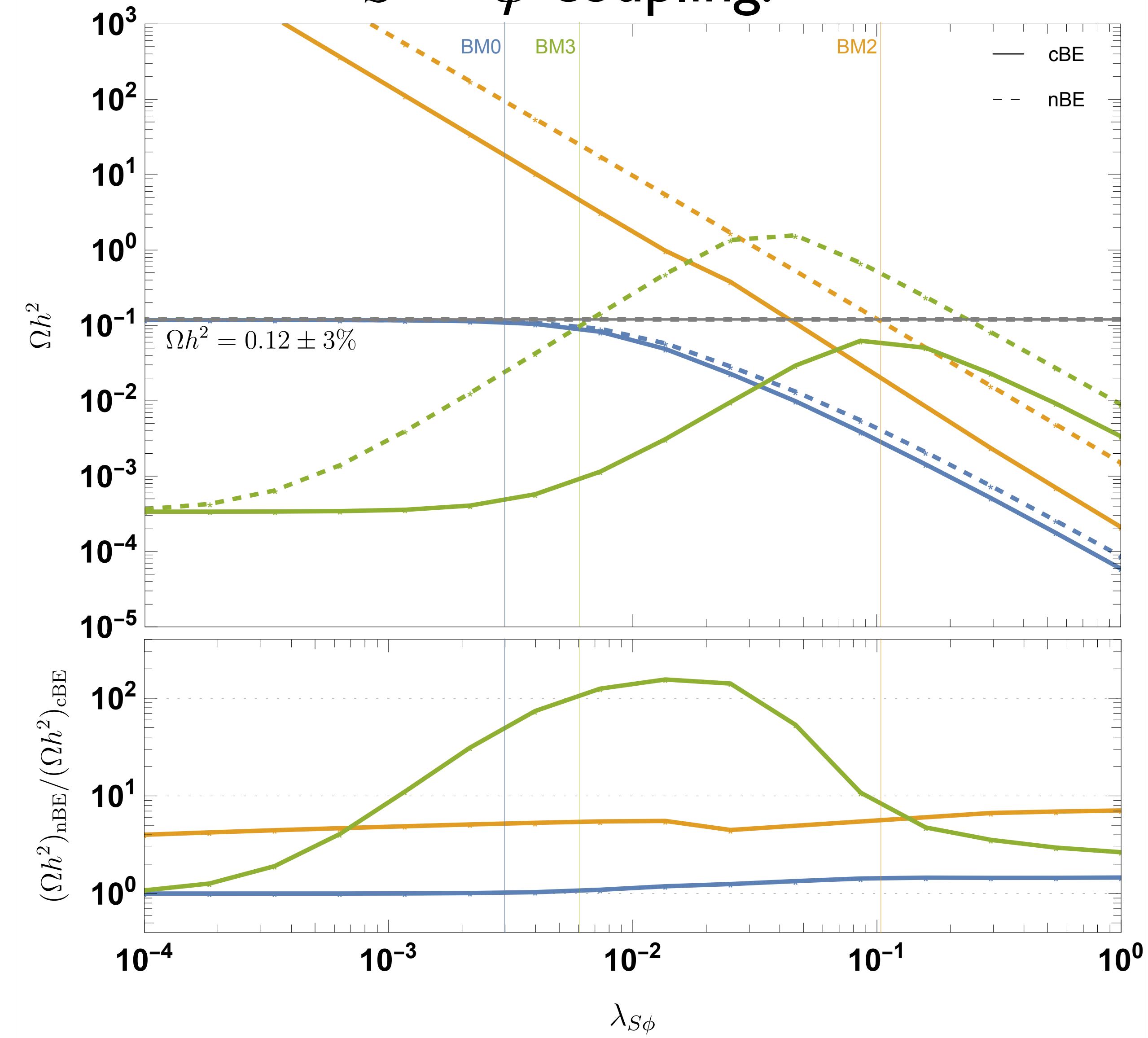
Effect of performing calculation at cBE level: from $\sim \mathcal{O}(1\%)$ to > 100

Dependence on the couplings

Portal ϕ interaction:



$S \leftrightarrow \phi$ coupling:



Increasing $\lambda_{h\phi}$ gives larger production (as expected)

Effect of cBE is the shift the required value by factor $\mathcal{O}(1)$

3 different behaviours:

BM0 - $\lambda_{S\phi}$ independent at first, then dark FO

BM2 - dark FO

BM3 - first (sequential) FI, then dark FO

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. Freeze-in in multicomponent dark sectors (like sequential freeze-in) proceeds in a $T-$dependent way. This can alter the naive predictions by more than an order of magnitude. This is another example of importance of non-equilibration in dark matter production (as seen in some freeze-out scenarios)

2. A simple two scalar model with feeble couplings to SM can provide interesting phenomenology with cross correlation of ID & forward physics experiments

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

Thank you!

BACKUP

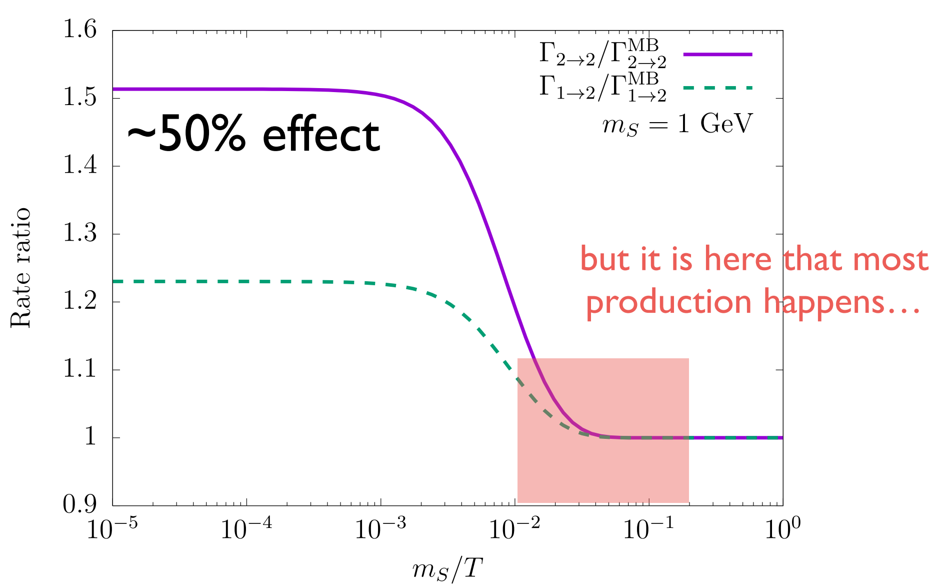
Relativistic or Not?

Relativistic reaction rate:

$$\Gamma_{a\to b} = \int \left(\prod_{i\in a} \frac{d^3\mathbf{p}_i}{(2\pi)^3 2E_i} f(p_i)\right) \left(\prod_{j\in b} \frac{d^3\mathbf{p}_j}{(2\pi)^3 2E_j}(1+f(p_j))\right) |\mathcal{M}_{a\to b}|^2 (2\pi)^4 \delta^4(p_a - p_b).$$

I) In freeze-out one (typically) takes Maxwell-Boltzmann distribution, should one use here:

$$f(p) = \frac{1}{e^{\frac{u\cdot p}{T}} - 1}$$ instead?



Lebedev, Toma 1908.05491 & subsequent works

II) when relativistic, not obvious if $(1 \pm f) \approx 1$ which poses a question of the feedback of DM distribution to the production rate

At early stages of evolution DM is very diluted allowing for such approx.

but when $T \sim m$ this is less obvious…

CBE vs. FBE

WHICH IS MORE ACCURATE?!

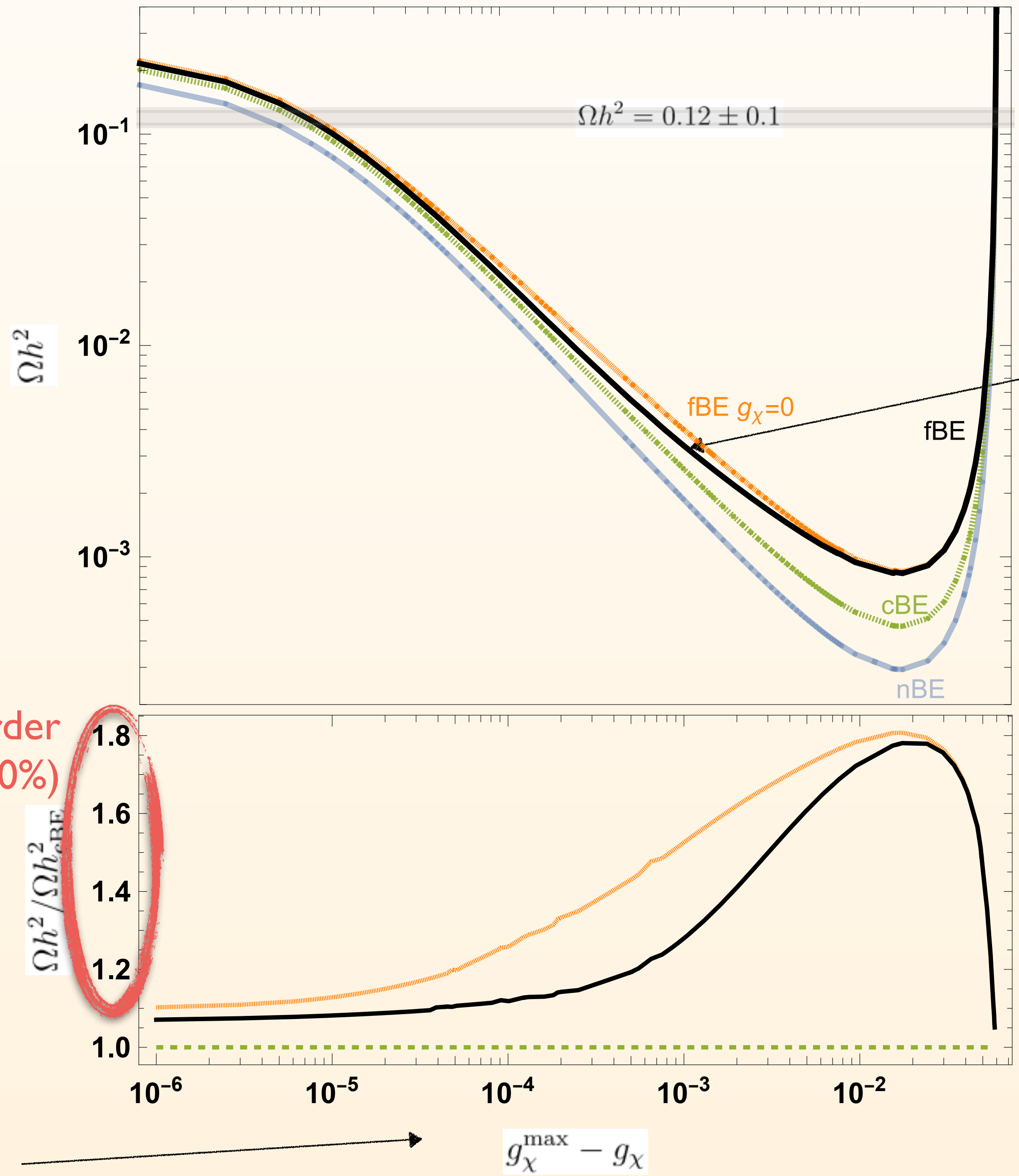
A.H. & M. Laletin 2204.07078

They correspond to the opposite limits of self-interaction strengths:

→ very efficient - **cBE**

→ inefficient - f**BE**

Which limit is closer to reality depends on the model, but it seems that fBE is typically more accurate, unless self-scattering is tuned up, e.g:



difference of order O(10%)

black line gives the result including self-scattering processes! (being between pure fBE and cBE)

coupling to the mediator; governs self-scatterings

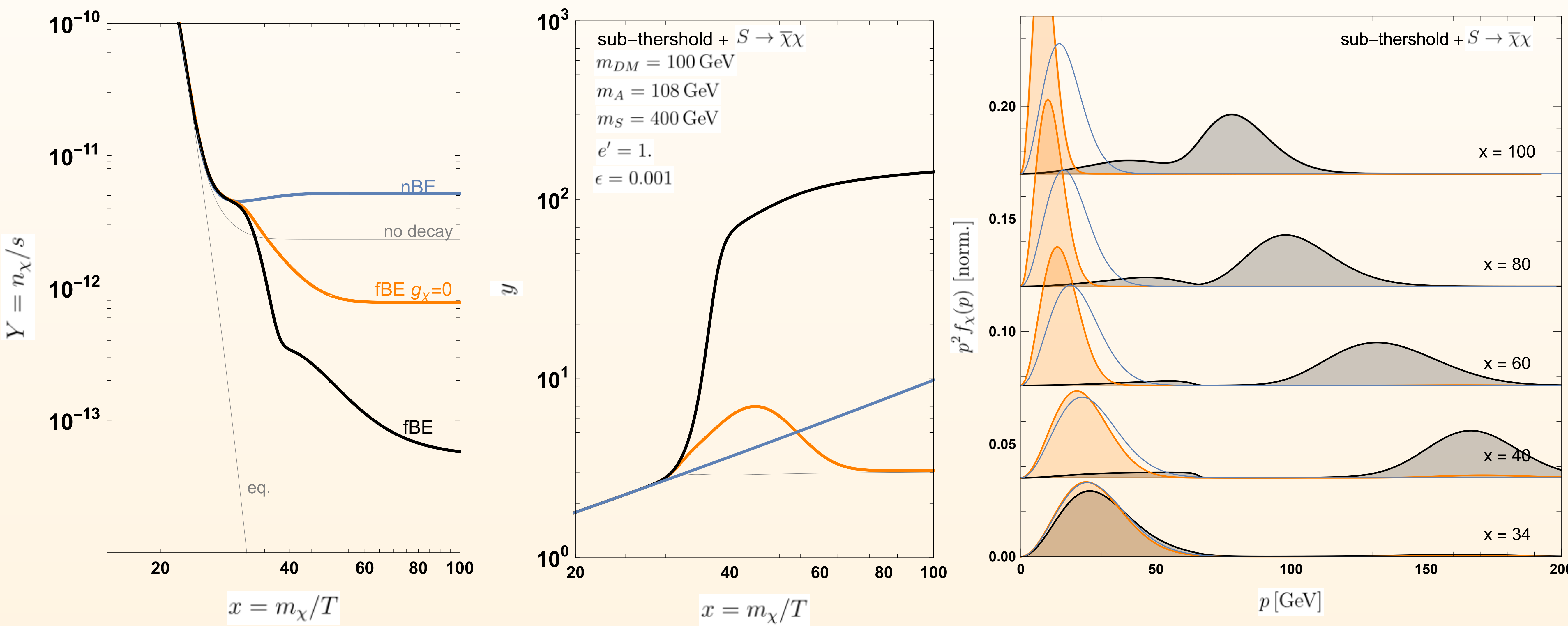
EXAMPLE EVOLUTION

AH, Laletin 2204.07078

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

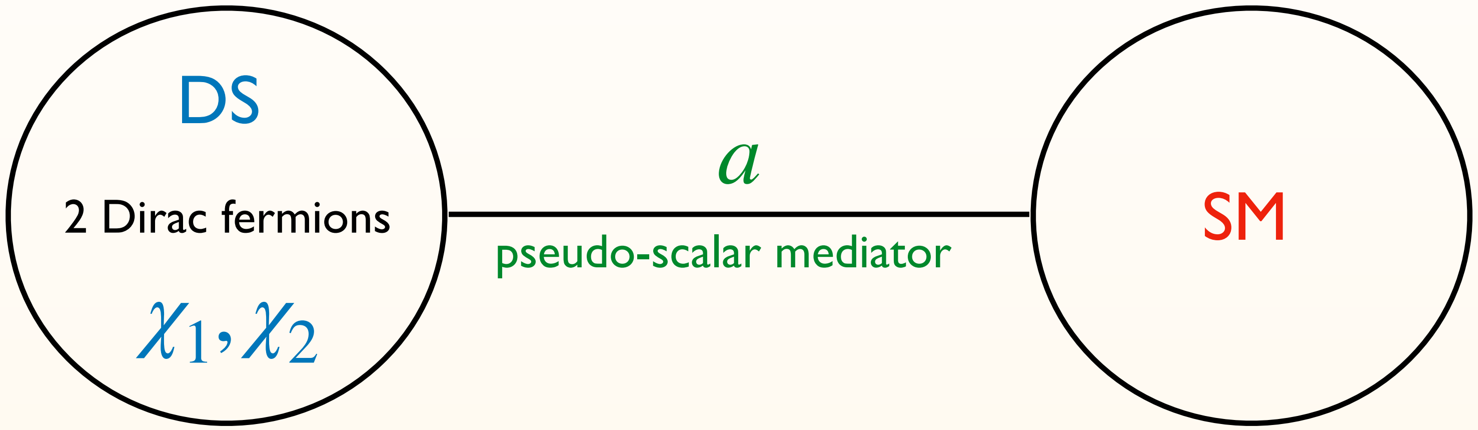
2) DM annihilation has a threshold
e.g. $\chi\bar{\chi} \to f\bar{f}$ with $m_\chi \lesssim m_f$

$Y \sim$ number density | $y \sim$ temperature | $p^2 f(p) \sim$ momentum distribution



RESULTS: THE MODEL

Let's take one <u>of the simplest</u> 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

New fields: χ_1, χ_2, a

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

Varying:

$$\lambda_1 \to \lambda_1 / c$$
$$\lambda_2 \to \lambda_2 / c$$
$$\lambda_y \to c \, \lambda_y$$

Keeps everything fixed, <u>except</u> conversions

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

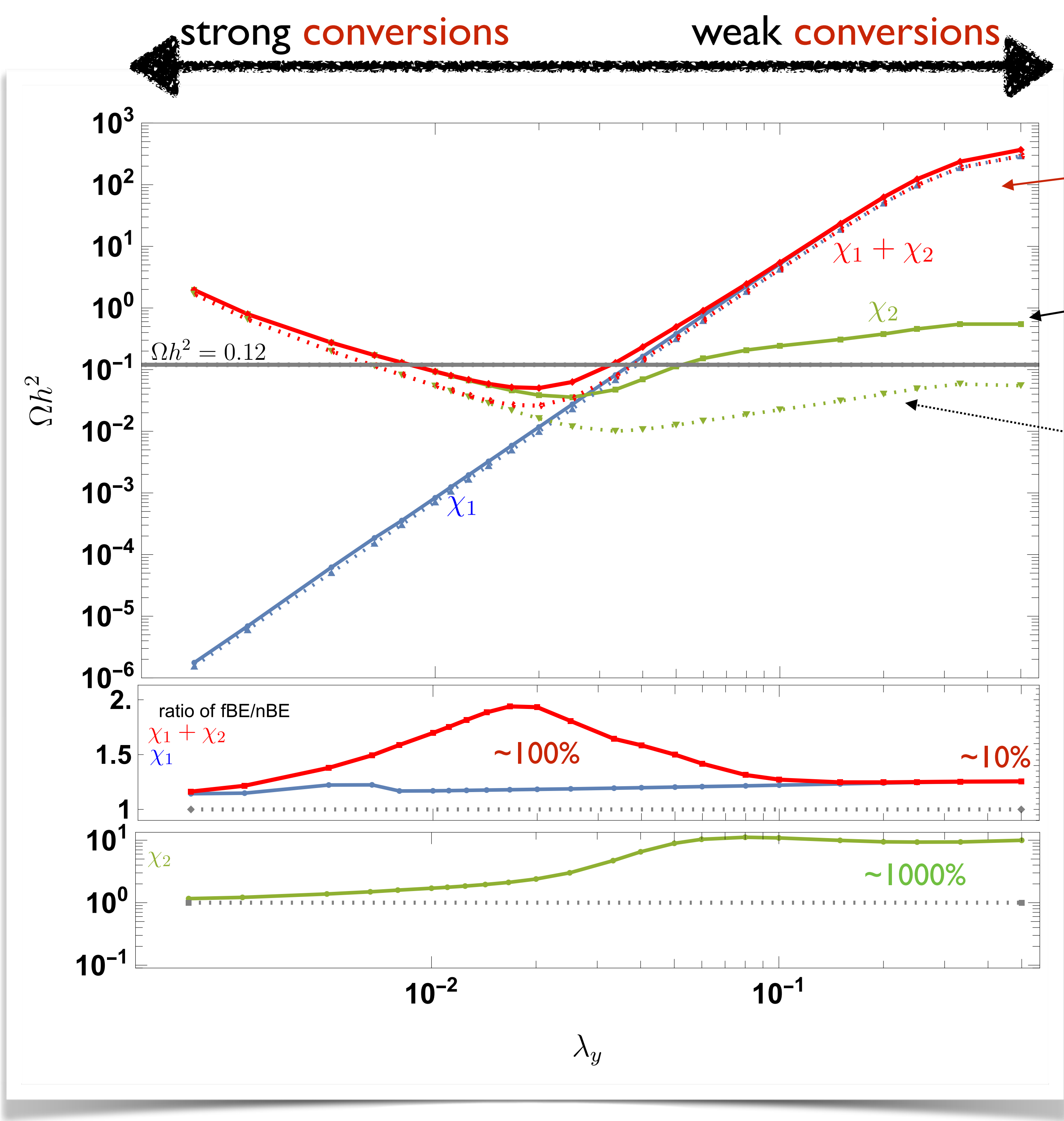
Evasion of the direct detection bounds… while giving strong signal in indirect detection, in particular for explaining the Galactic Centre excess

(see e.g. „Coy DM")

C. Boehm et al. 1401.6485,

RESULTS: CONVERSION IMPACT

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



total relic abundance

phase space calculation (fBE)

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

Ratio of the two for total and χ_1

and χ_2

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