

DRAKE2

Andrzej Hryczuk



Based on:

work in progress with **S. Chatterjee**

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

MOTIVATION & OBJECTIVES

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

Two-component systems

Implementation of
freeze-in production

PUBLIC TOOL!

Binder, Bringmann, Gustafsson, AH 2103.01944

GOING BEYOND THE STANDARD APPROACH

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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, a 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

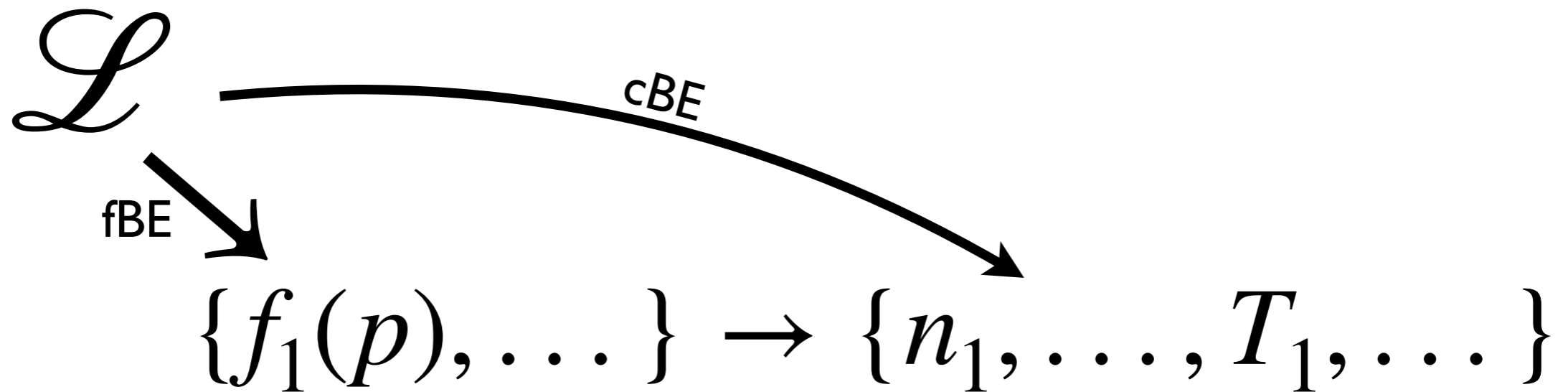
see e.g., [1202.5456](#)

...

(only) prerequisite:
Wolfram Language (or Mathematica)

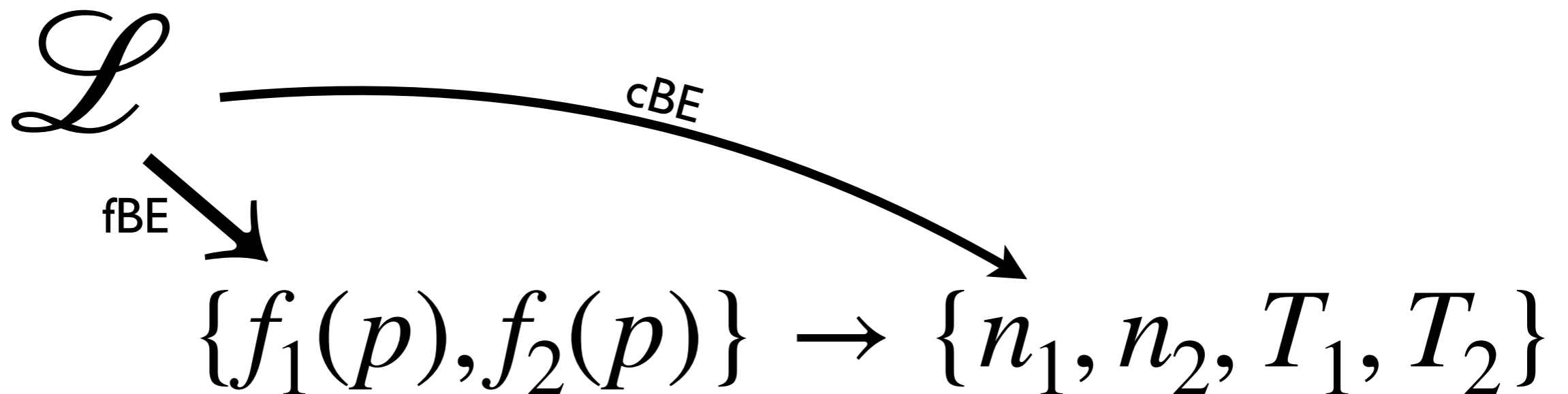
*at the moment for a single DM species and w/o
co-annihilations... but stay tuned for extensions!

DRAKEN_N



For $N=2$

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.**]

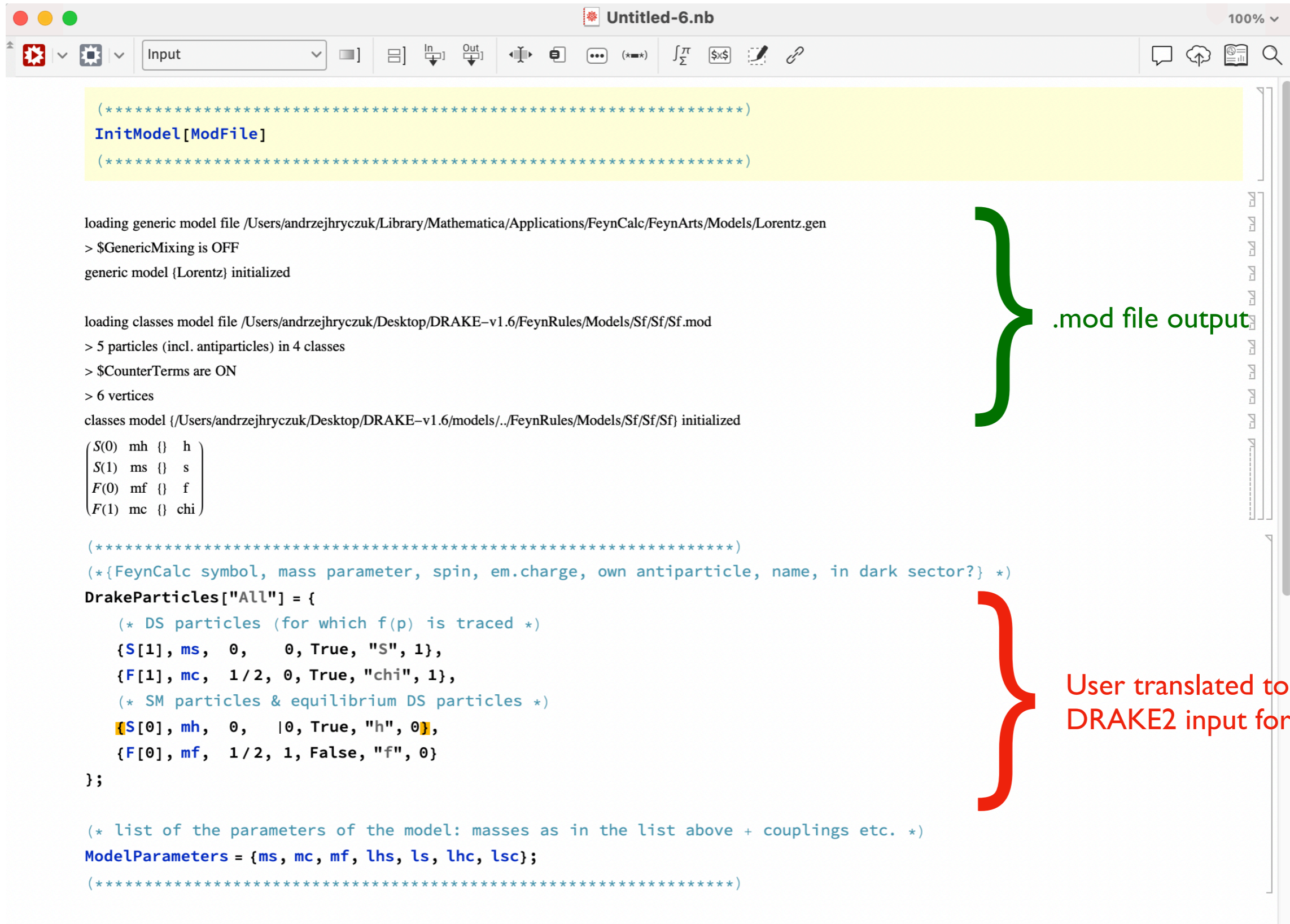
Improvements:

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

Updated *user interface*

AUTOMATIC MODEL GENERATION

When you have a *.mod* file, e.g. from *FeynRules*, then you need only...



```
(*****)  
InitModel[ModFile]  
(*****)  
  
loading generic model file /Users/andrzejhryczuk/Library/Mathematica/Applications/FeynCalc/FeynArts/Models/Lorentz.gen  
> $GenericMixing is OFF  
generic model {Lorentz} initialized  
  
loading classes model file /Users/andrzejhryczuk/Desktop/DRAKE-v1.6/FeynRules/Models/Sf/Sf/Sf.mod  
> 5 particles (incl. antiparticles) in 4 classes  
> $CounterTerms are ON  
> 6 vertices  
classes model {/Users/andrzejhryczuk/Desktop/DRAKE-v1.6/models/./FeynRules/Models/Sf/Sf/Sf} initialized  

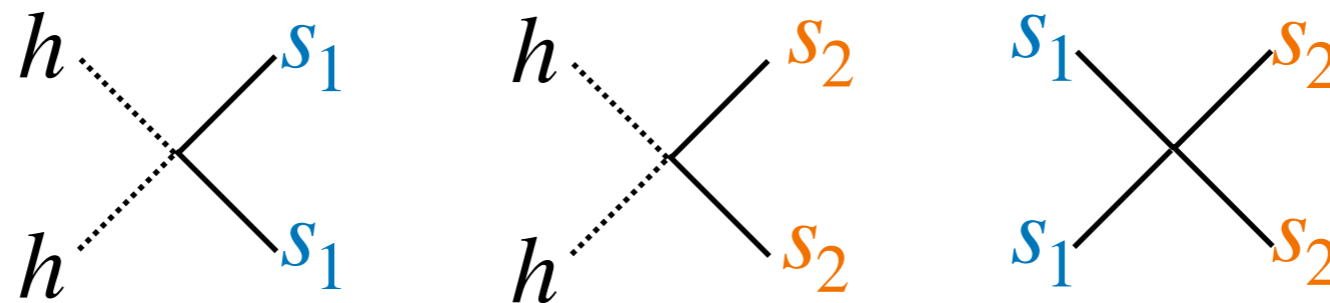
$$\begin{pmatrix} S(0) & mh & \{ & h \\ S(1) & ms & \{ & s \\ F(0) & mf & \{ & f \\ F(1) & mc & \{ & chi \end{pmatrix}$$
  
  
(*****)  
(*{FeynCalc symbol, mass parameter, spin, em.charge, own antiparticle, name, in dark sector?} *)  
DrakeParticles["All"] = {  
  (* DS particles (for which f(p) is traced *)  
  {S[1], ms, 0, 0, True, "S", 1},  
  {F[1], mc, 1/2, 0, True, "chi", 1},  
  (* SM particles & equilibrium DS particles *)  
  {S[0], mh, 0, 0, True, "h", 0},  
  {F[0], mf, 1/2, 1, False, "f", 0}  
};  
  
(* list of the parameters of the model: masses as in the list above + couplings etc. *)  
ModelParameters = {ms, mc, mf, lhs, ls, lhc, lsc};  
(*****)
```

.mod file output

User translated to
DRAKE2 input format

EXAMPLE: RUN EXAMPLE NOTEBOOK

(Toy model of 2 real scalars coupled to the Higgs)





UNDER THE HOOD

In its essence:

DRAKE \Leftrightarrow BE solvers + UI

Compiled into C (as much as possible)

Parallelisation of rate computations

Vectorisation

$$\frac{d\vec{f}}{dx} = \text{FM} \cdot \vec{f} + \text{EM} \cdot \vec{f} + \vec{f}^{eq} (\text{AM} \cdot \vec{f}^{eq}) - \vec{f} (\text{AM} \cdot \vec{f}) \\ + \alpha \left[\left((\hat{A} \vec{f}) \cdot (\vec{V} \vec{f}) \right) \cdot \vec{V} - \left((\hat{A} \vec{f}) \cdot \vec{V} \right) \cdot (\vec{V} \vec{f}) \right],$$

e.g. Annihilation matrix:

$$(\text{AM}_i)_{i,k} \equiv \frac{g_{\chi_i}}{(2\pi^2)x\tilde{H}} dP dQ_k^{\chi_i} dq W_k (p_k^{\chi_i})^2 \langle \sigma v_{\text{mol}} \rangle_{\theta}(p_i^{\chi_i}, p_k^{\chi_i}),$$

e.g. Conversion matrix:

$$(\hat{A}_{\chi_1})_{ikj} \equiv \hat{\Theta}_{ikj}^{\chi_1} \hat{\Pi}_{ikj}^{\chi_1} / (E_{\chi_1} | \vec{p}_{\chi_1} |)_i,$$

Mathematica (or WL script) w/ full benefits

Pre-tabulation of rates

User friendly workflow

Functions for all physical quantities

Easily adjustable settings

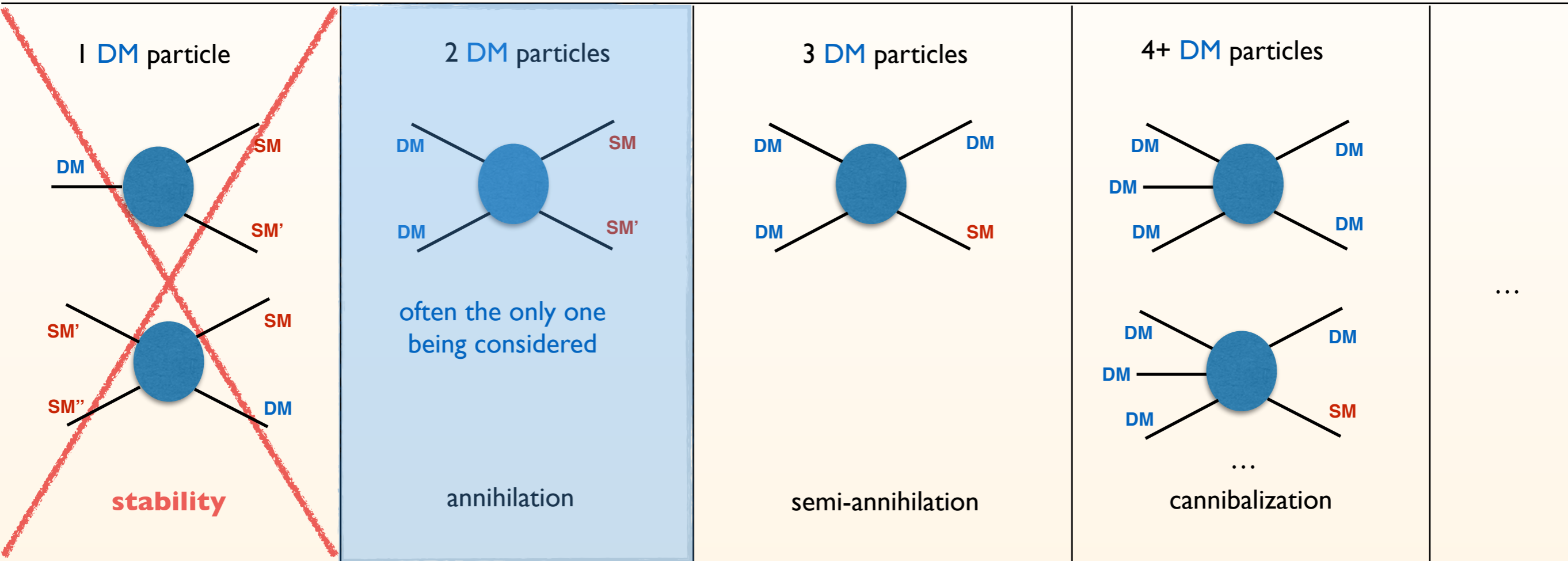
Modularity & easy modding

EXAMPLE A:
EFFECT OF CONVERSION PROCESSES

WHAT GOES INTO C IN GENERAL?

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

changing processes \Rightarrow number density

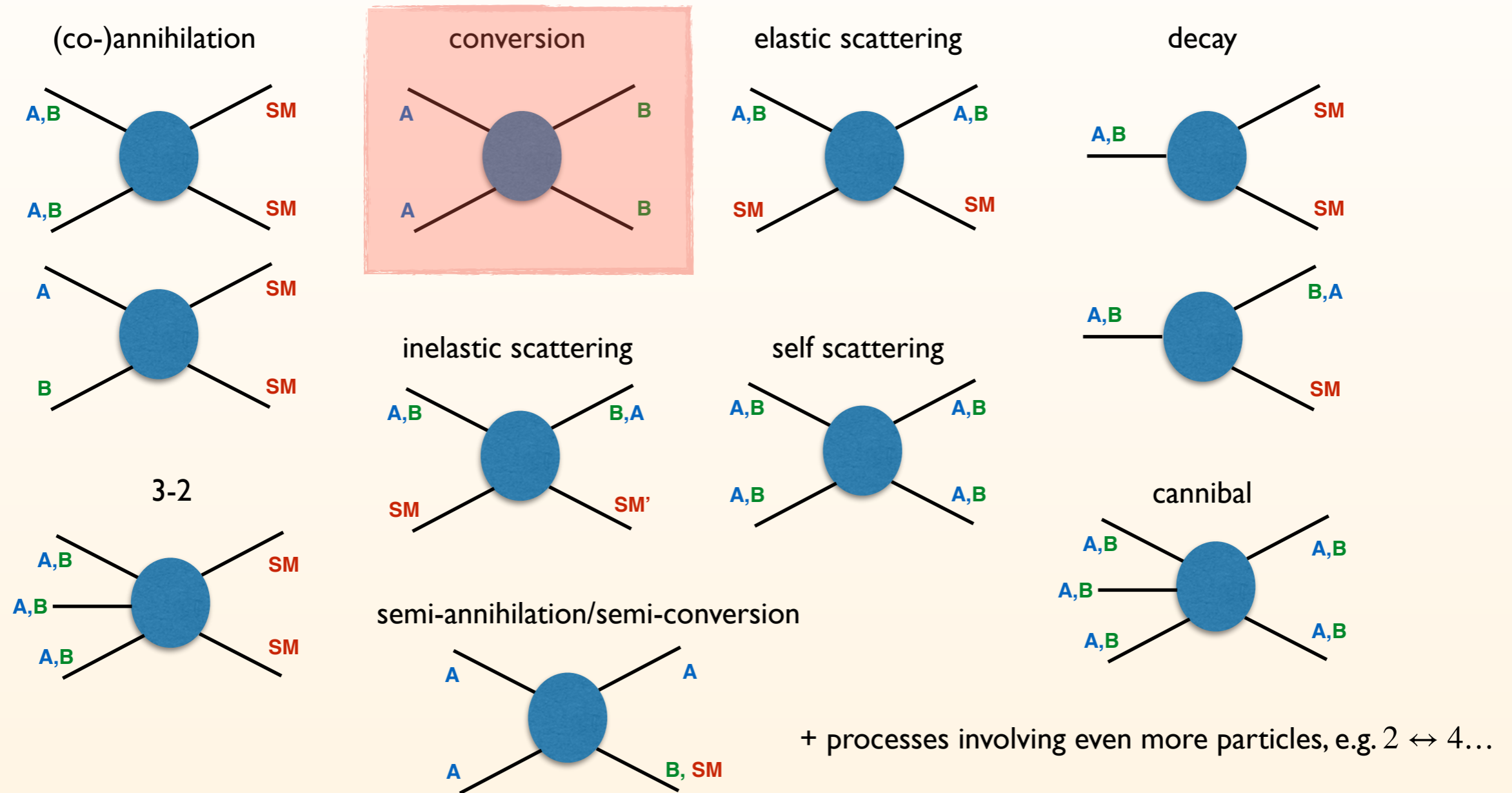


conserving processes \Rightarrow energy density



WHAT IF A NON-MINIMAL SCENARIO?

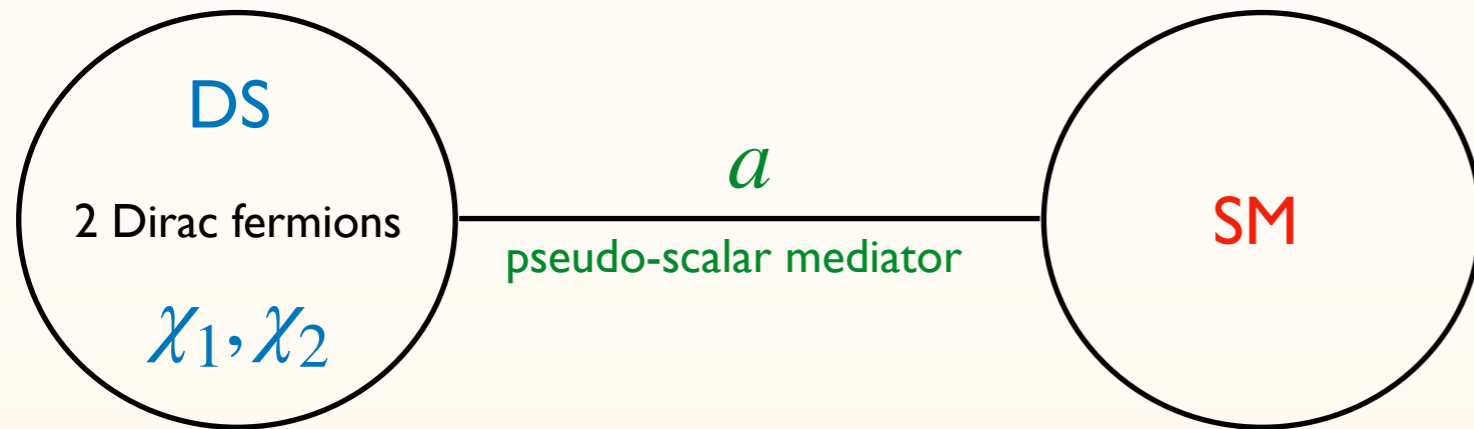
A,B — two different dark sector states (at least one needs to be stable)



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:



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

coupled directly to SM fermions in a MFV way

New fields: χ_1, χ_2, a New params: m_1, m_2, m_a
 $\lambda_1, \lambda_2, \lambda_y$

Parametrically:

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

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

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



Varying:

$$\lambda_1 \rightarrow c \lambda_1$$

$$\lambda_2 \rightarrow c \lambda_2$$

$$\lambda_y \rightarrow \lambda_y / c$$

Keeps everything fixed, except 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”)

MOTIVATIONAL RESULT

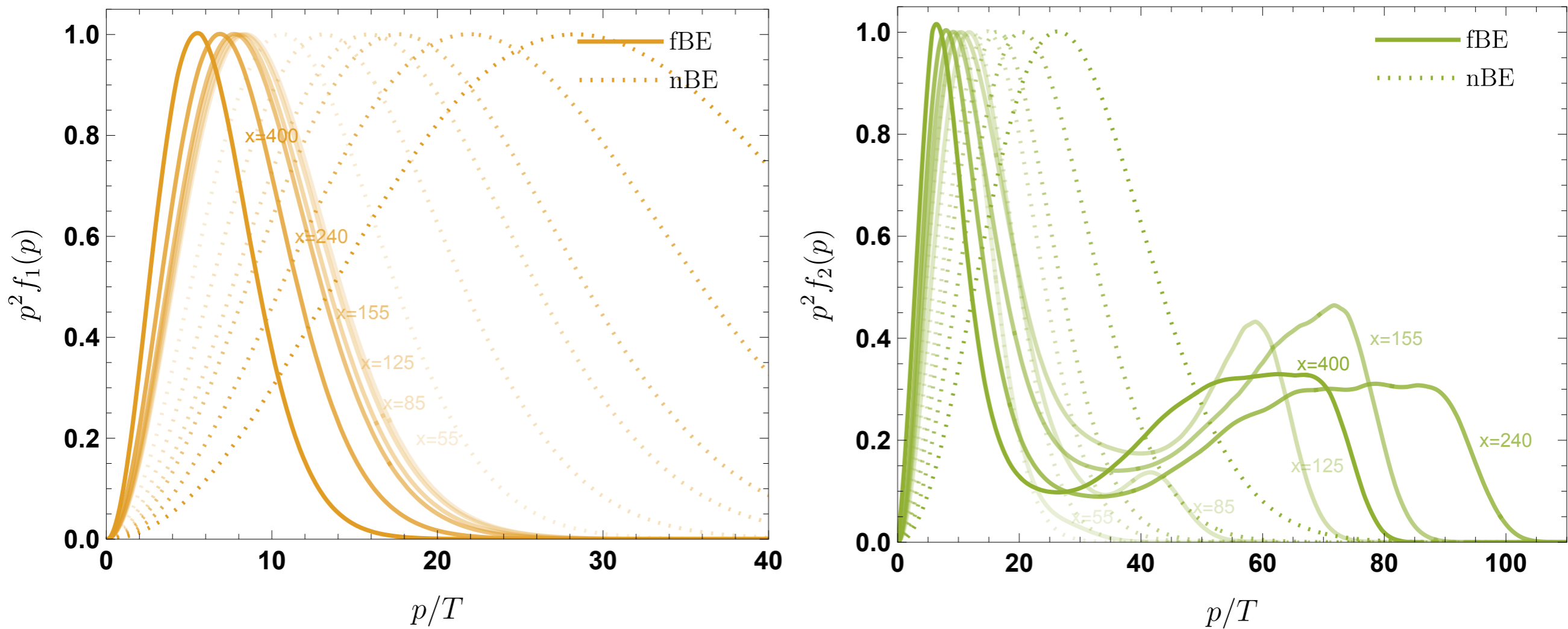
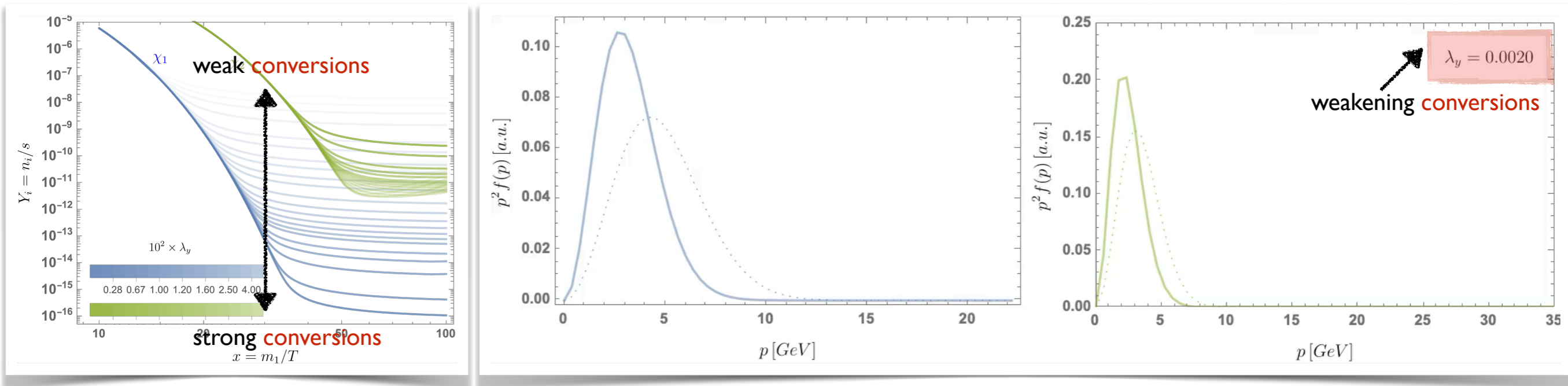


Figure 1: Time snapshots of the evolution of the normalised momentum distributions for χ_1 (left) and χ_2 (right) in p/T , for the benchmark point showcasing the interplay of conversions and resonant annihilations with early kinetic decoupling. The solid lines show the particle distribution functions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

RESULTS: CONVERSION IMPACT

weaker conversions \Rightarrow less depletion of $\chi_1 \Rightarrow$ around χ_2 freeze-out more χ_1 in the plasma
 \Rightarrow 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
- inelastic scatterings
- semi-annihilations
- cannibal ($3 \leftrightarrow 2$)

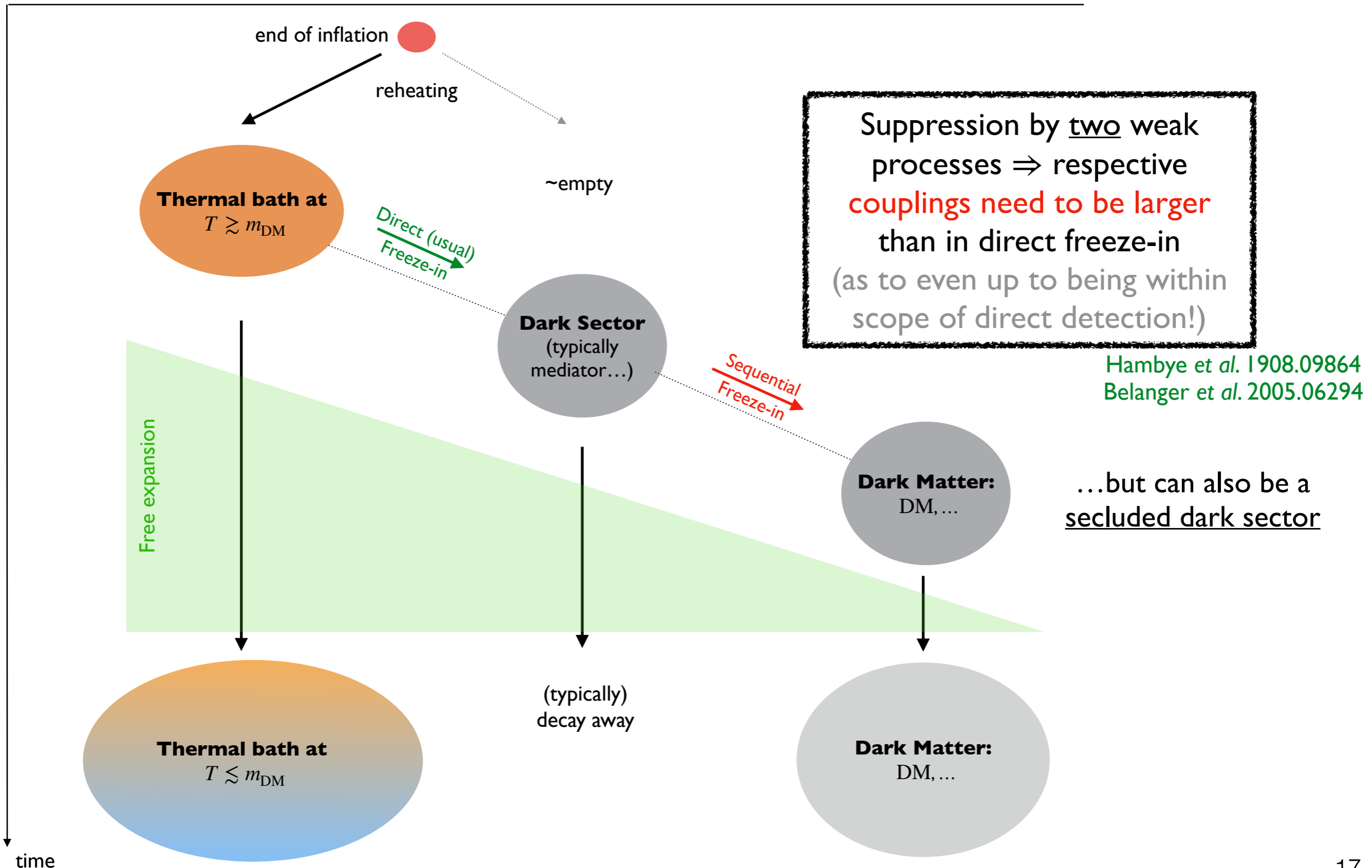
A.H. & Laletin 2204.07078 (see also Beauchesne & Chiang 2401.03657)
 A.H. & Laletin 2104.05684
 Cervantes & A.H. 2407.12104

EXAMPLE B:
(SEQUENTIAL) FREEZE-IN

WHAT IS SEQUENTIAL FREEZE-IN?



Visible Sector

Dark Sector

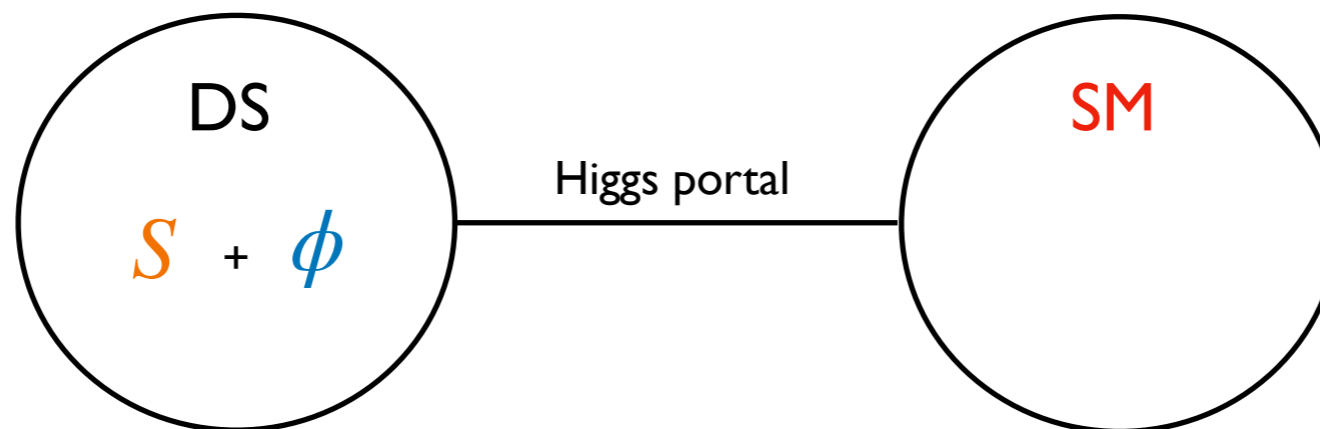


A TALE OF TWO SCALARS

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

	S	\mathbb{Z}_2 -symmetric	stable	dark matter	feeble int. with SM
	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

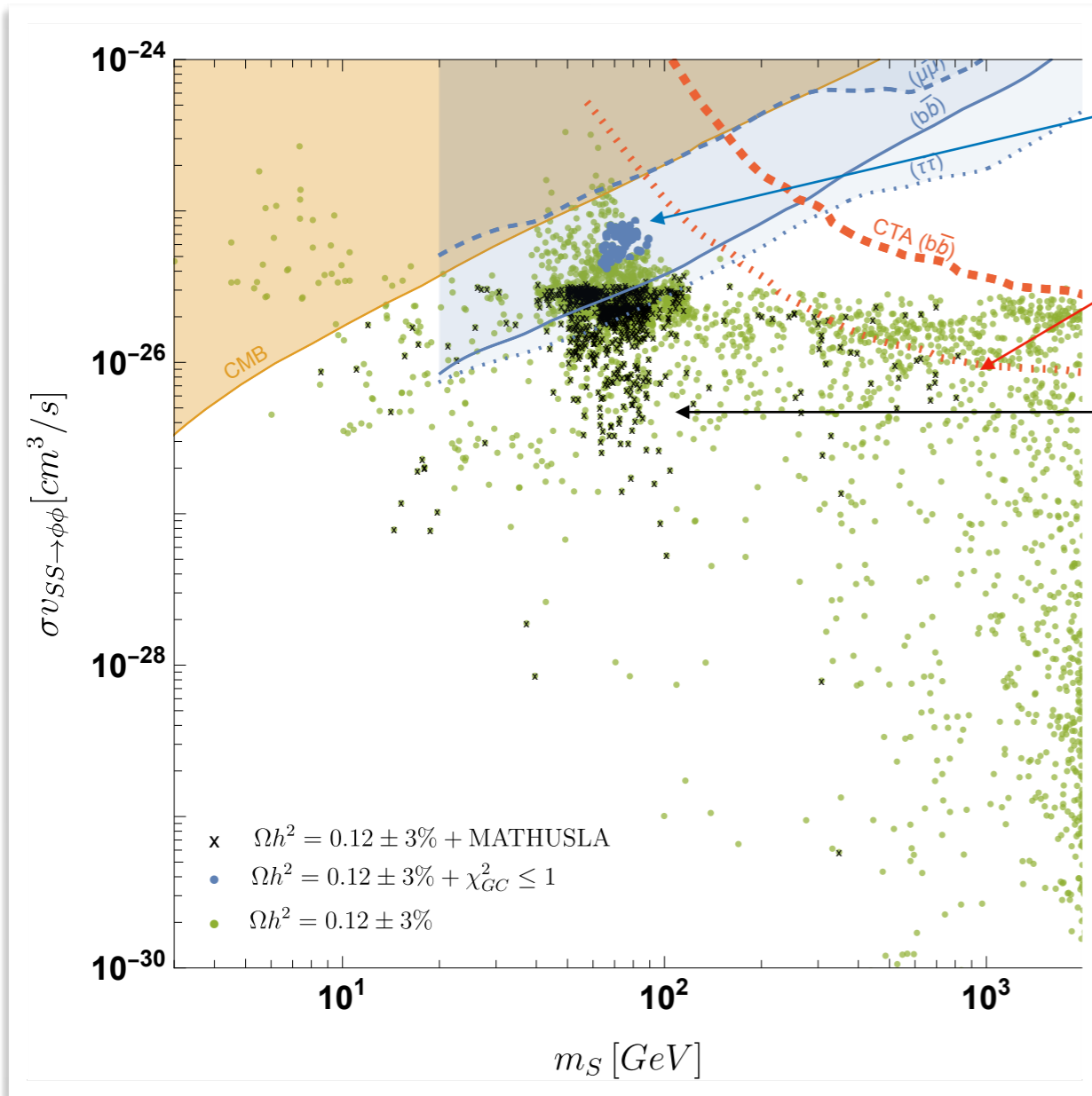
mediator-Higgs mixing

$$\sin \theta = \frac{Av}{m_h^2 - m_\phi^2} \left(1 - \frac{\lambda_{h\phi} v^2}{2m_\phi^2} \right) \quad 18$$

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

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

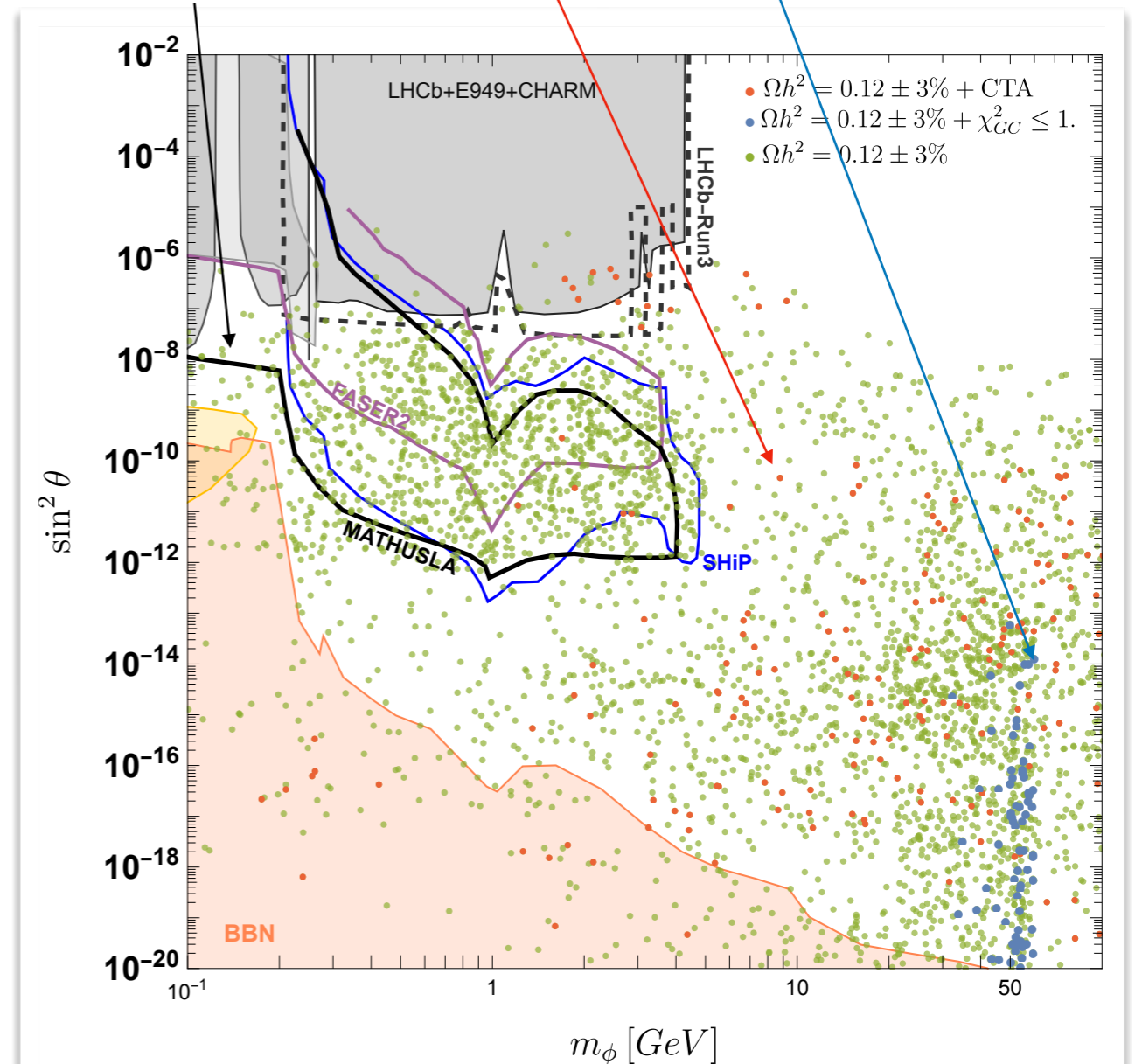
SCAN RESULTS: ID AND FORWARD PHYSICS



Points giving good fit to GCE

Points within (optimistic) reach of CTA

within reach of MATHUSLA



All points satisfy relic density constraint

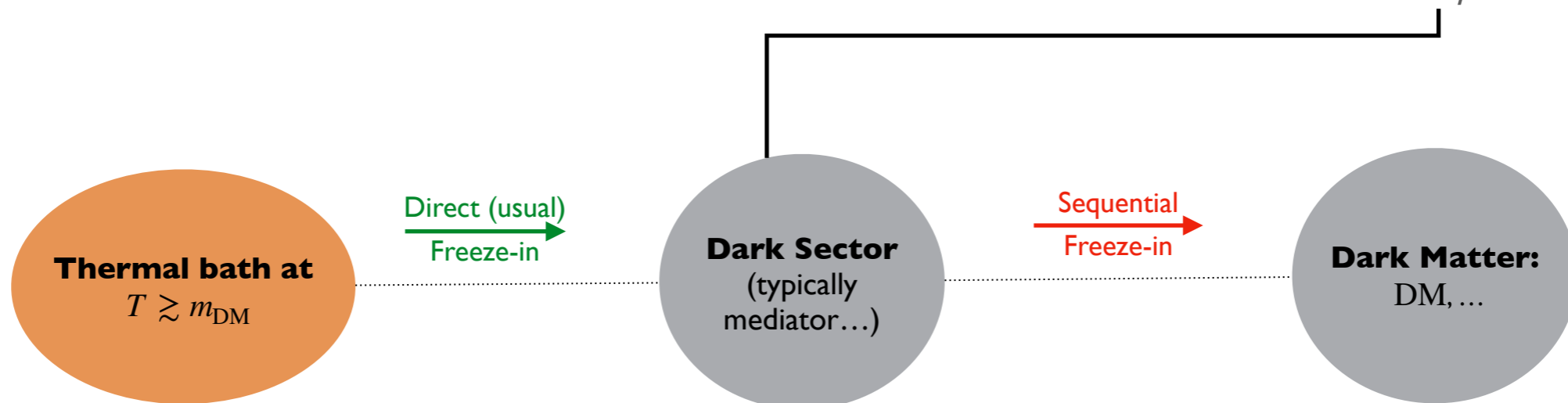
Scan driven towards regions that are covered by any of the experiments

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?

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

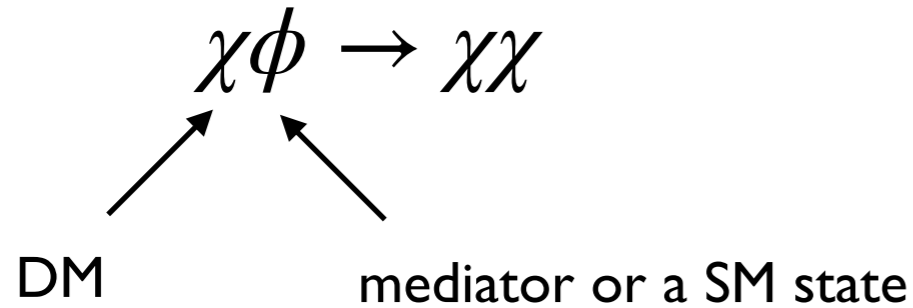


...OK, so it looks like we need to trace T_ϕ as well!

THIS IS REMINISCENT OF...

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

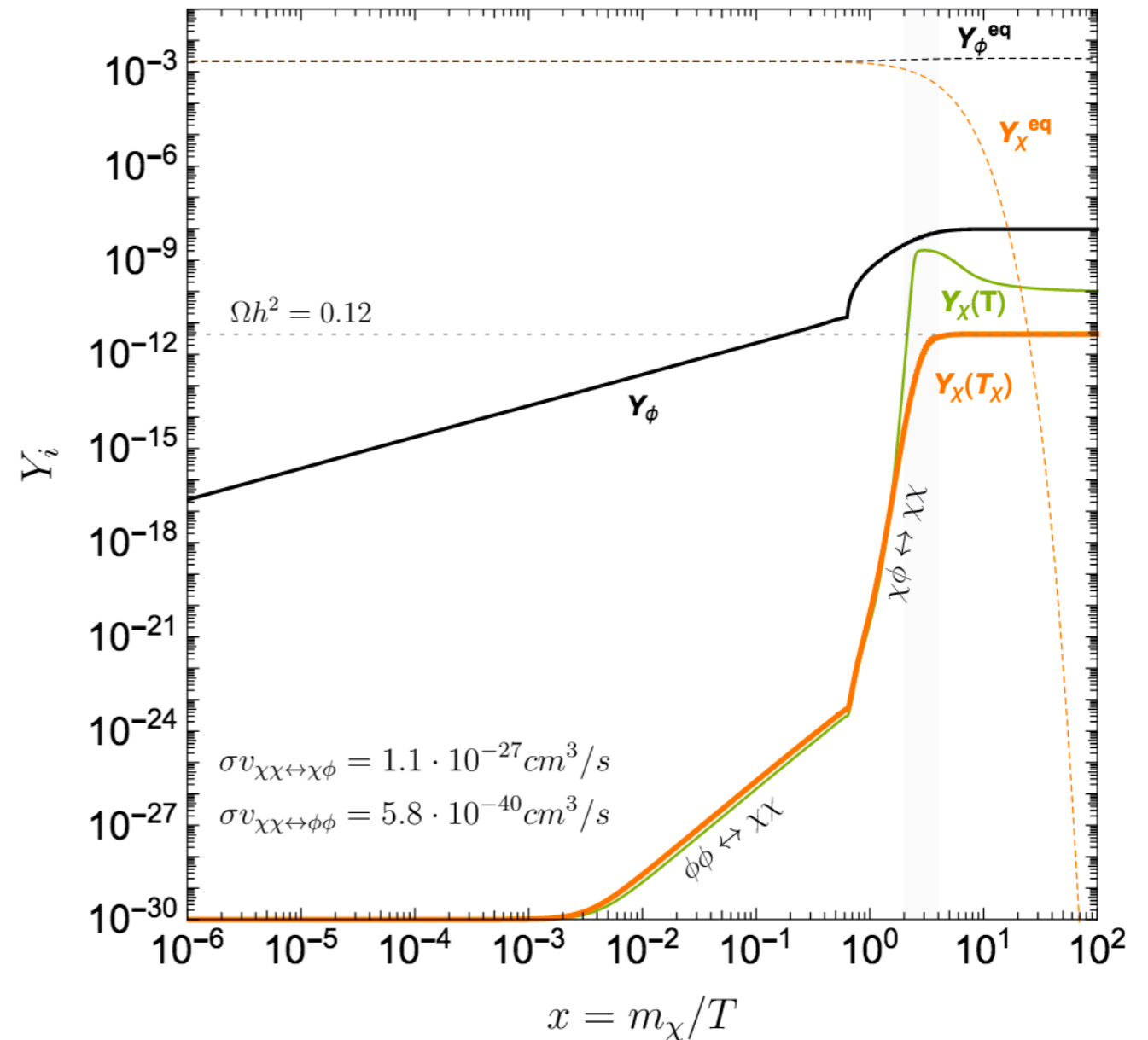
Consider process of production that is the **inverse of semi-annihilation**:



What is different?

(from the decay/annihilation freeze-in)

- The production rate is **proportional to the DM density**. (Smaller initial abundance \rightarrow 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**



SYSTEM OF CBE FOR Y_i AND T_i

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

$$\frac{Y'_i}{Y_i} = \frac{m_i}{x\tilde{H}} C_i^0, \quad \text{where } y \equiv \frac{m_\chi T_\chi}{s^{2/3}} \text{ is a parameter that describes}$$

$$\frac{y'_i}{y_i} = \frac{m_i}{x\tilde{H}} C_i^2 - \frac{Y'_i}{Y_i} + \frac{H}{x\tilde{H}} \frac{\langle p^4/E_i^3 \rangle}{3T_i} \quad \text{the 'temperature' } T_\chi \equiv \frac{g_\chi}{3n_\chi} \int \frac{d^3p}{(2\pi)^3} \frac{p^2}{E} f_\chi(p)$$

The collision term is also given by its moments:

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

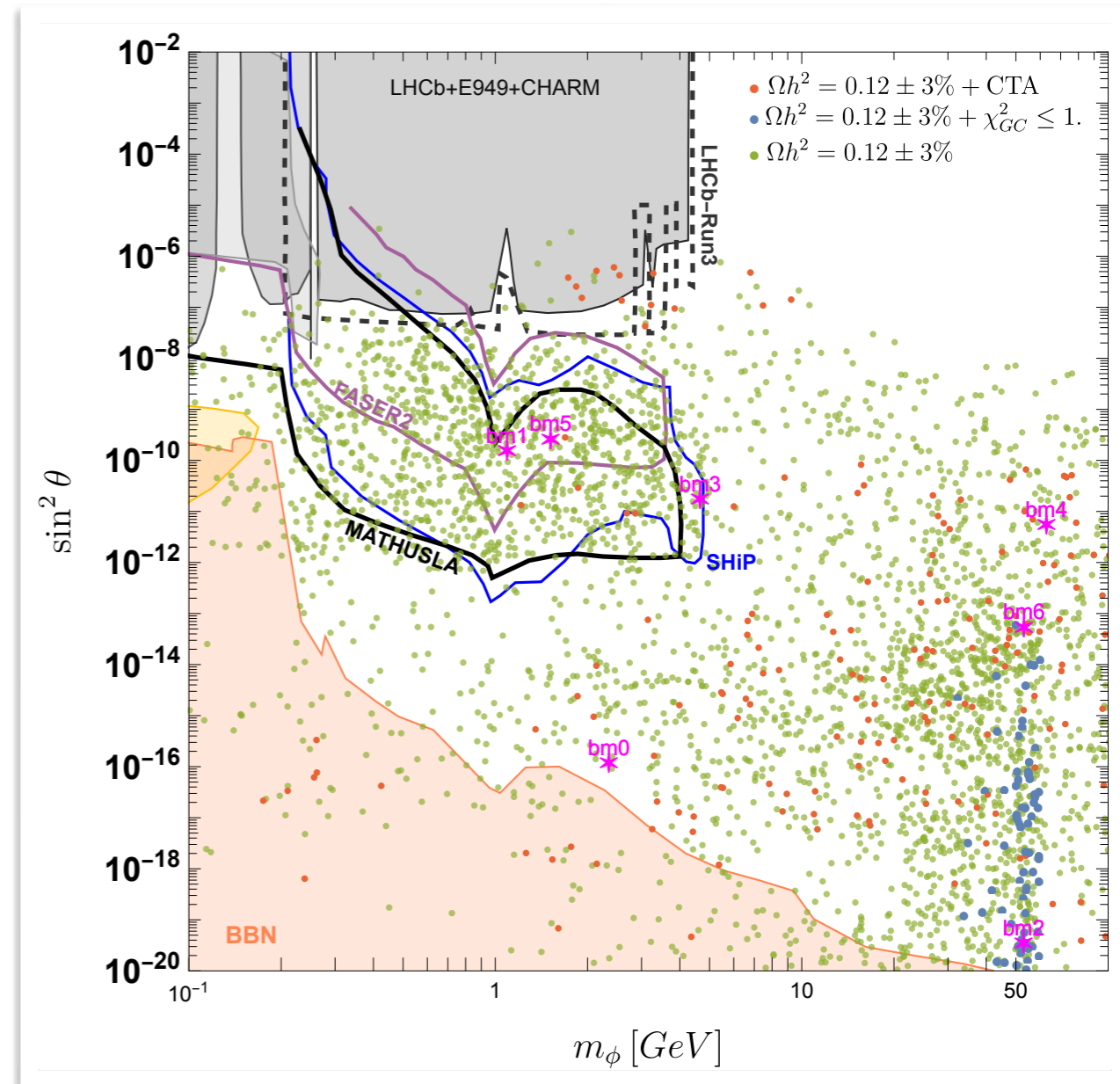
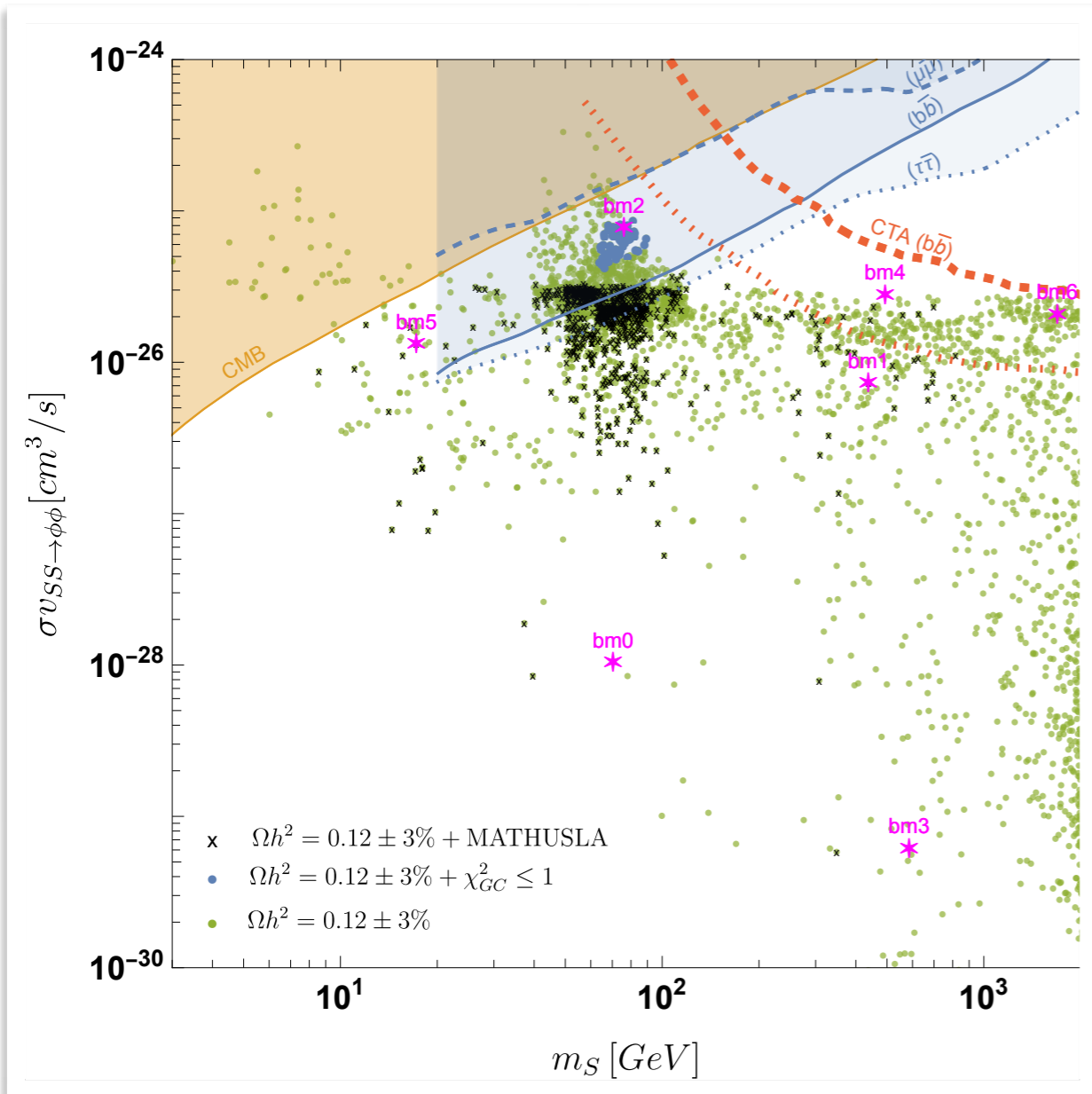
contains all scatterings and production/annihilation processes

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** 

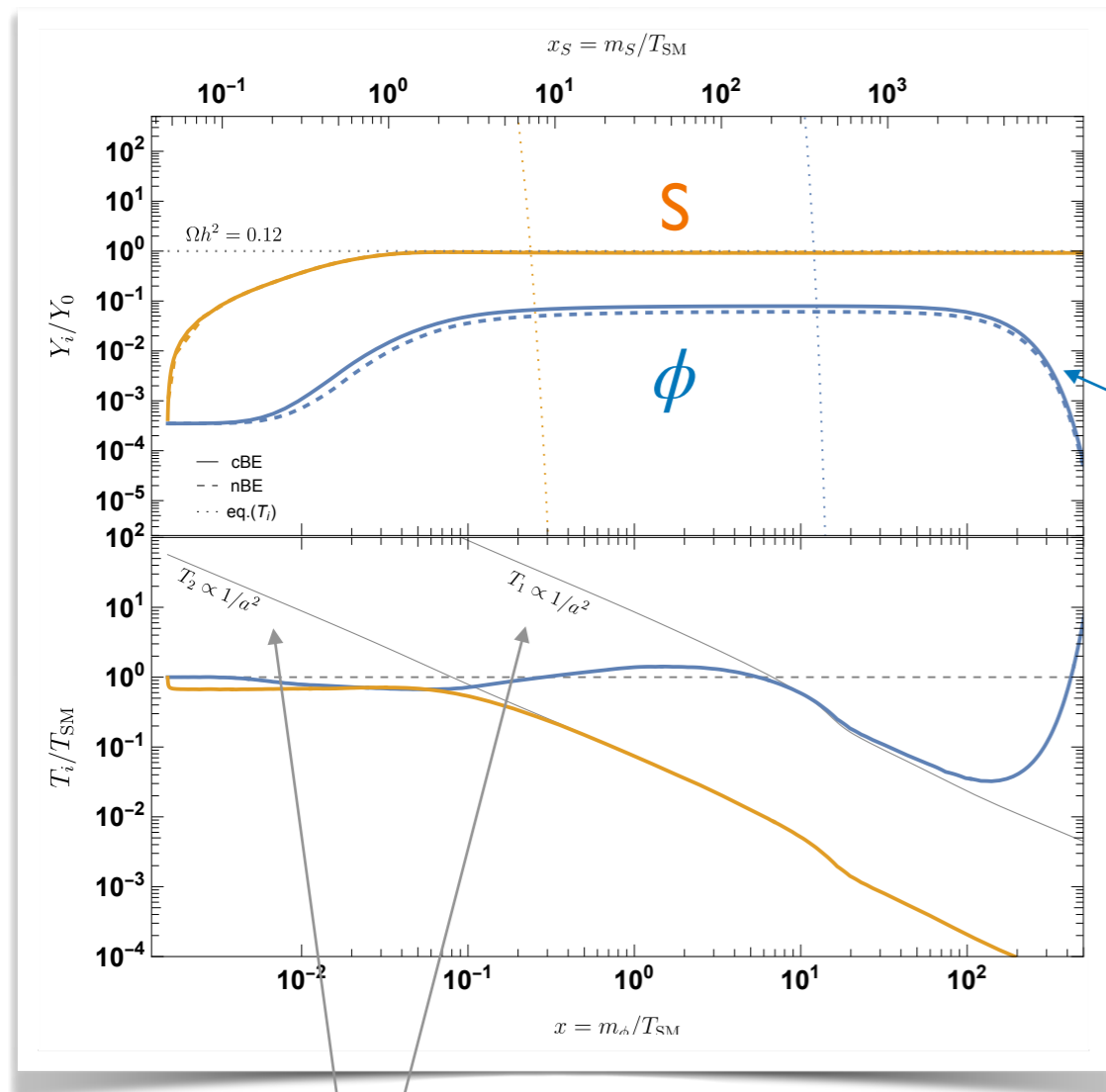
BENCHMARKS



Name	m_ϕ	m_S	θ	$\lambda_{h\phi}$	λ_{hS}	$\lambda_{S\phi}$	$(\Omega h^2)_{\text{nBE}}$	$(\Omega h^2)_{\text{cBE}}$	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

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yield (abundance)

Ratio of S and ϕ temperatures to the SM plasma one

Simple point to keep in mind as a baseline

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

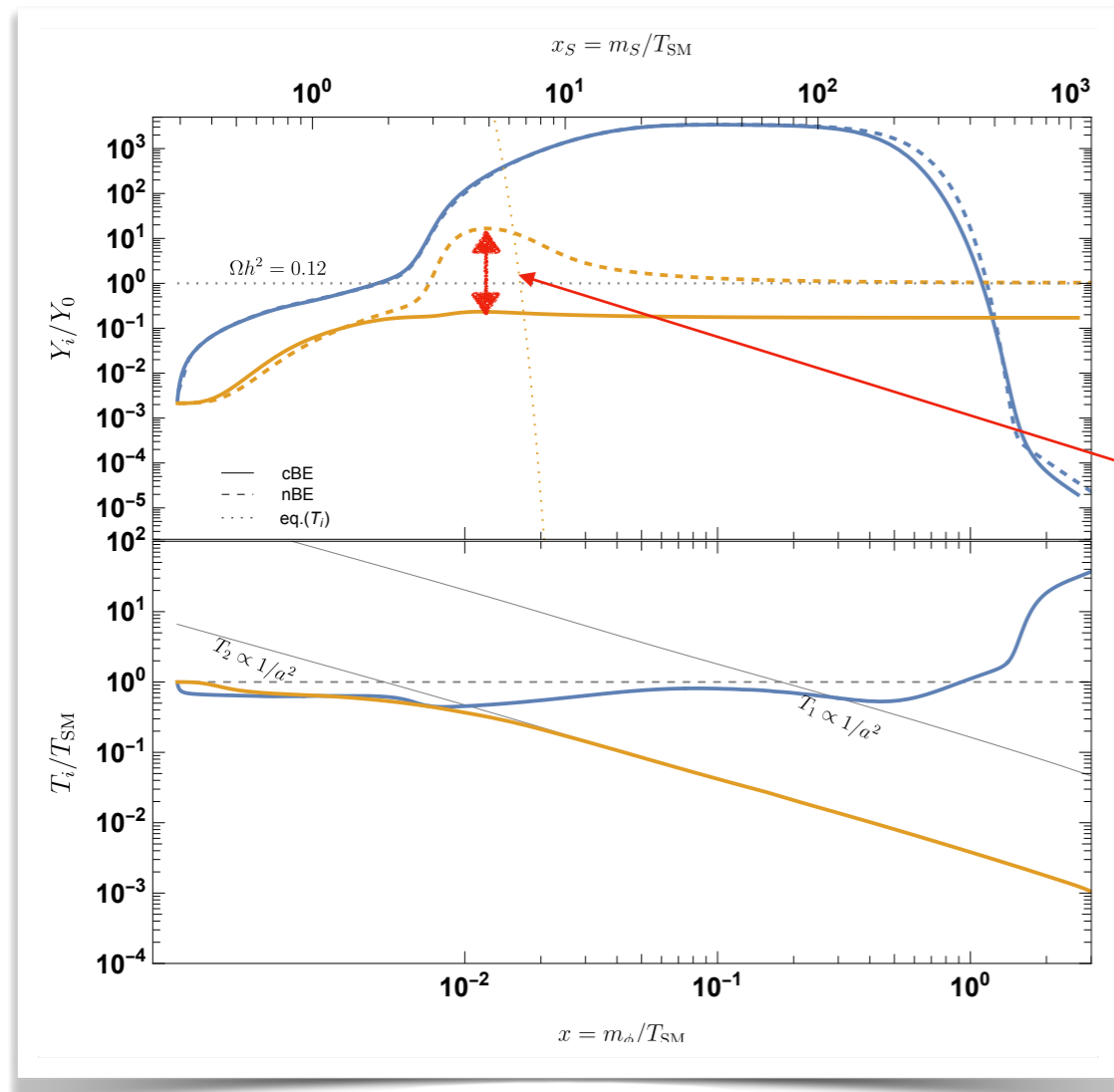
In the end ϕ decays

Very mild cBE effect

Free scaling after departure from LTE

BENCHMARKS

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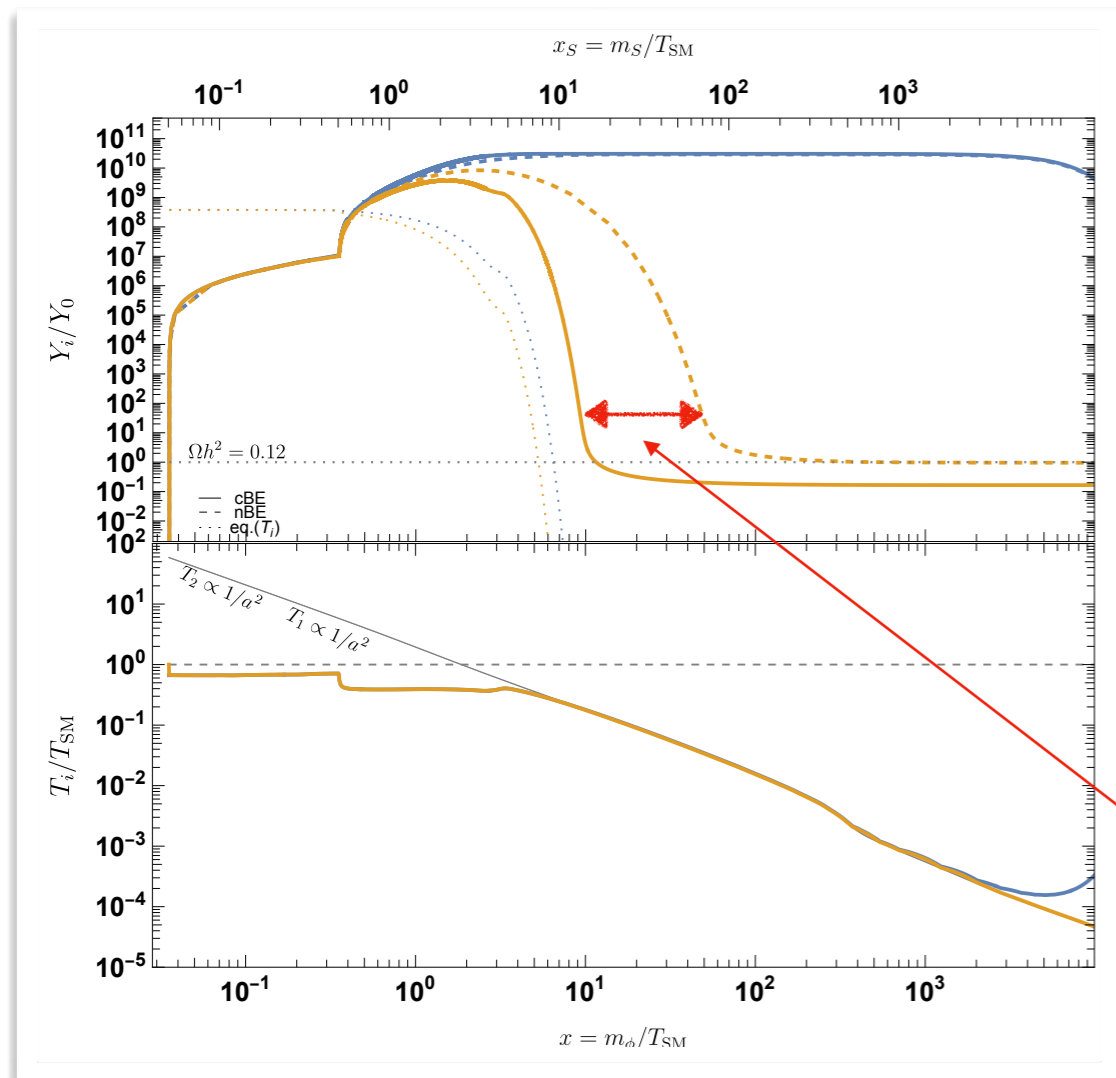
Hierarchy of $\lambda_{h\phi} \gg \lambda_{hS}$ and $m_S \gg m_\phi$ means freeze-in is sequential, followed by (mild) annihilation due to large $\lambda_{S\phi}$

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

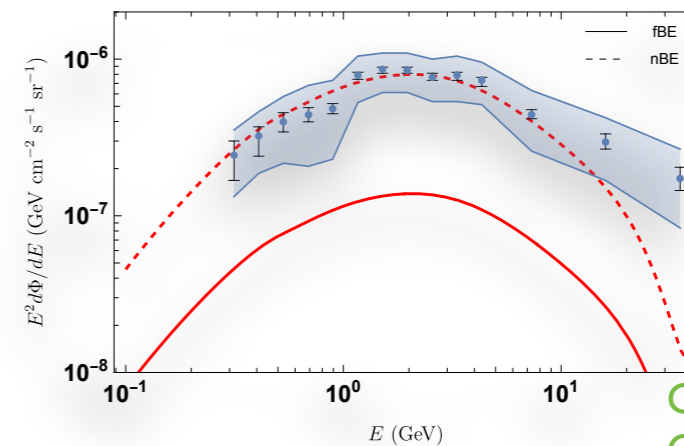
This point lies within reach of MATHUSLA, SHiP and FASER2

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Best fit point to the GCE found in the scan:



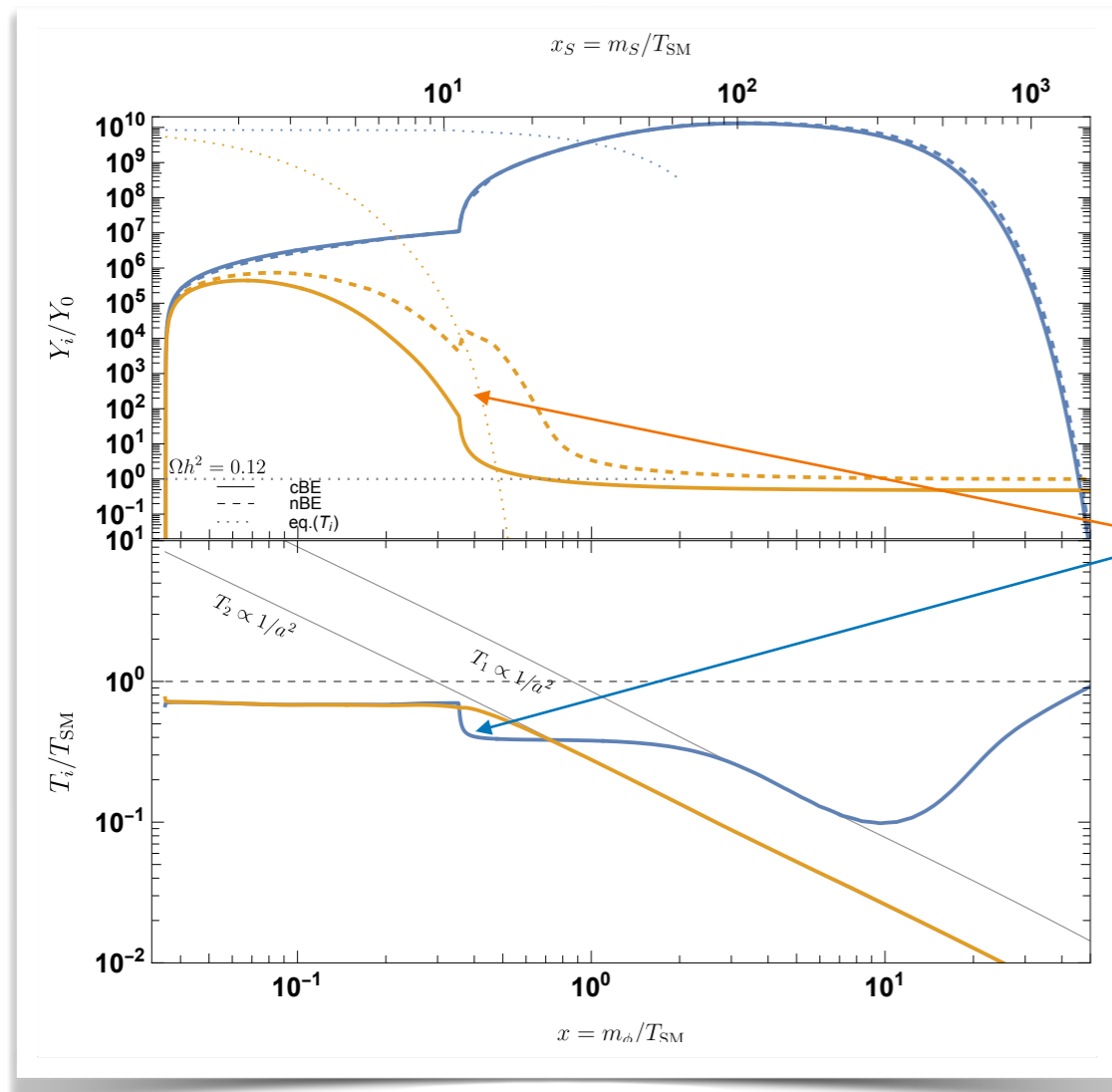
GCE analysis from Cholis et al. '22

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

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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}	$\lambda_{S\phi}$	$(\Omega h^2)_{\text{nBE}}$	$(\Omega h^2)_{\text{cBE}}$	change [%]	description
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The model's parameter space spans over various production modes:

- 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

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**

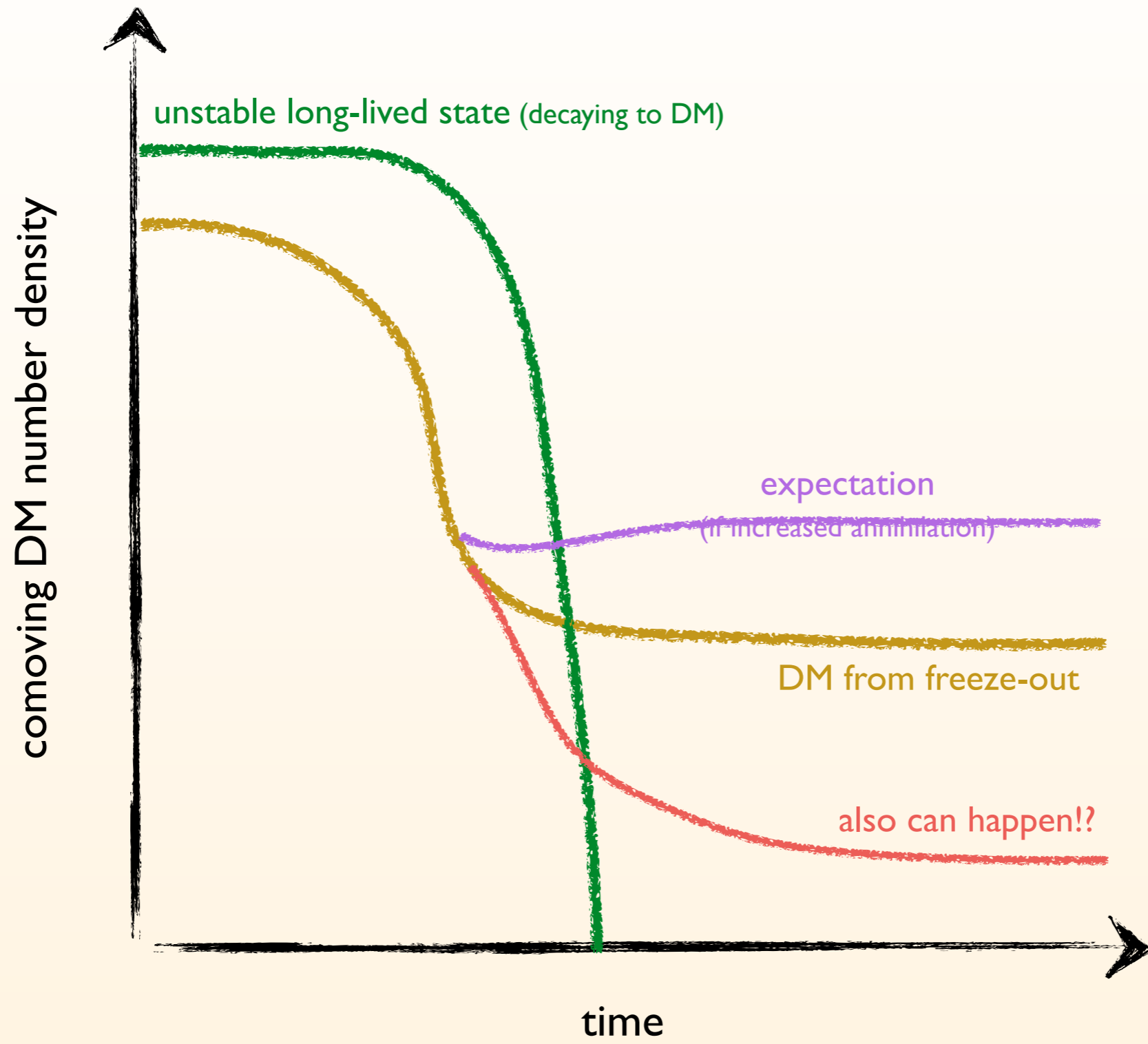
Thank you!

OTHER EXAMPLES

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)

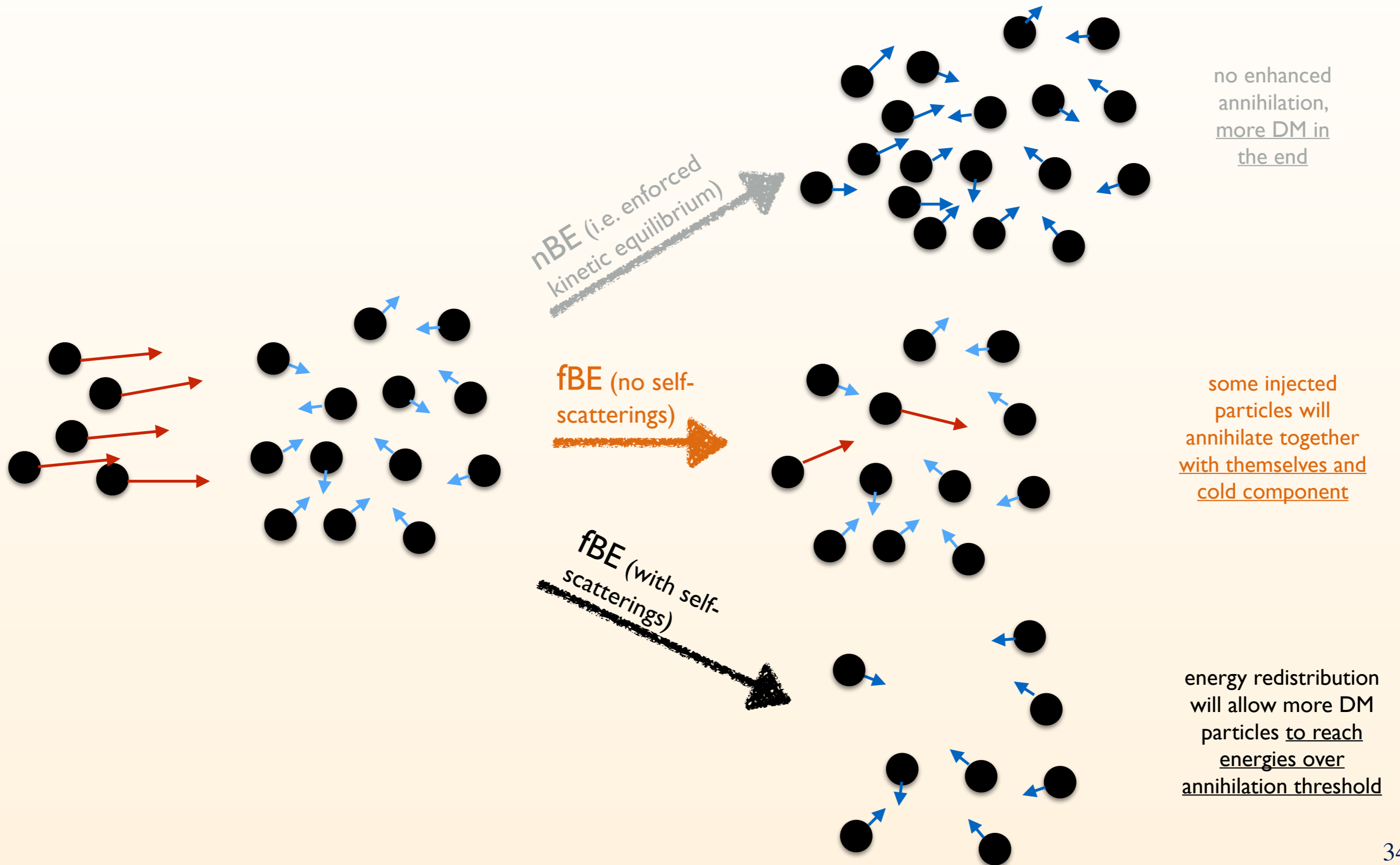
- this can **modify the annihilation rate** (if still active)
- how does the **thermalization** due to elastic scatterings happen?



1) DM produced via:

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

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



EXAMPLE EVOLUTION

1) DM produced via:

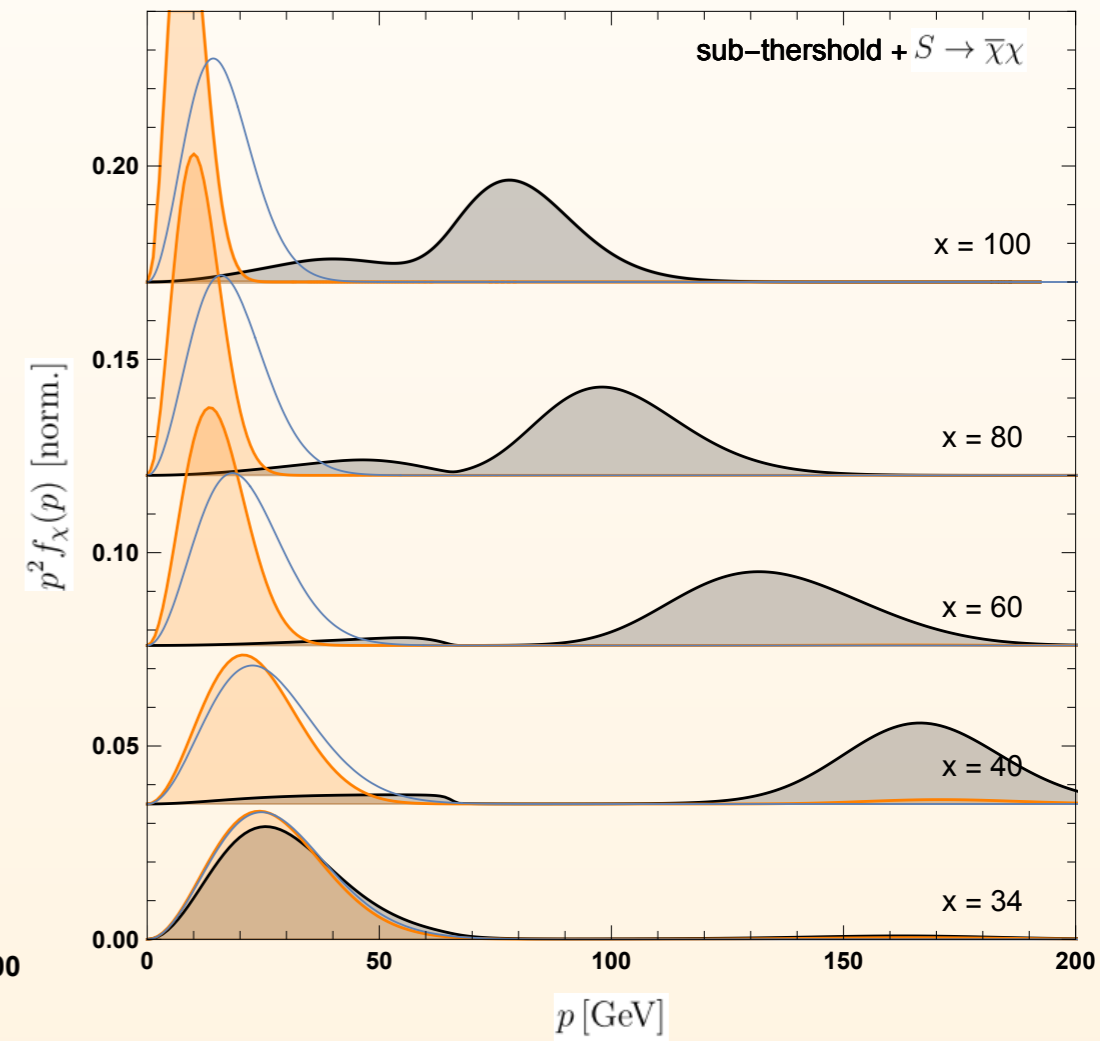
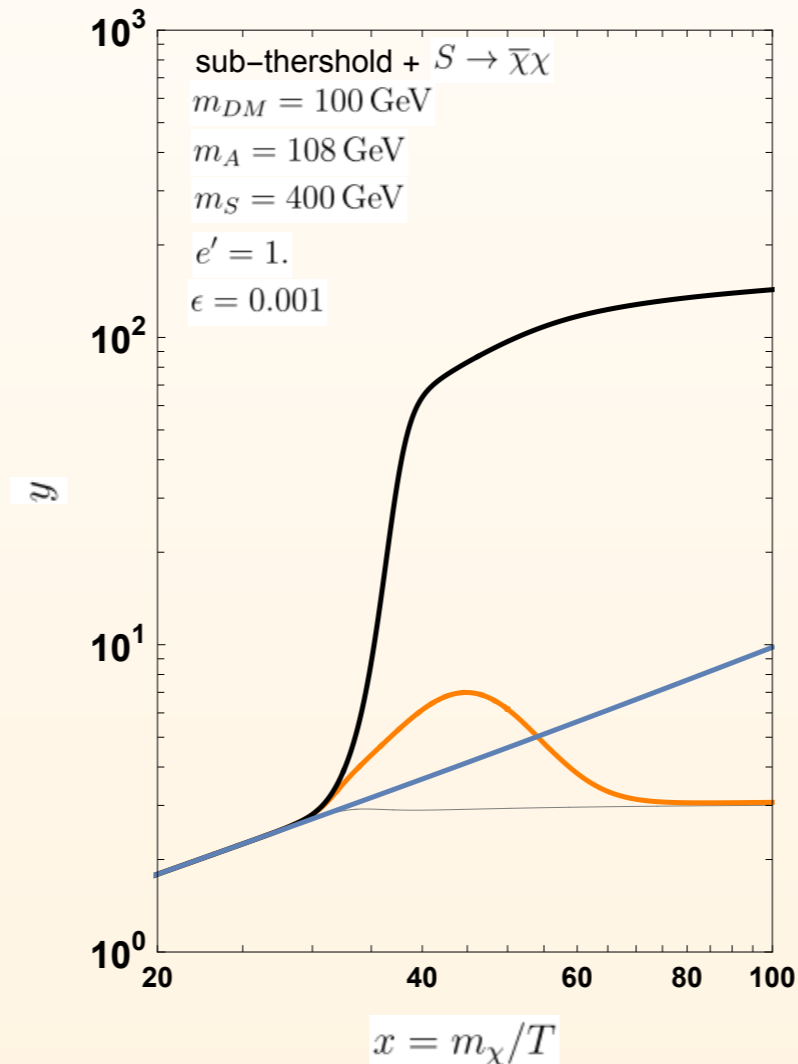
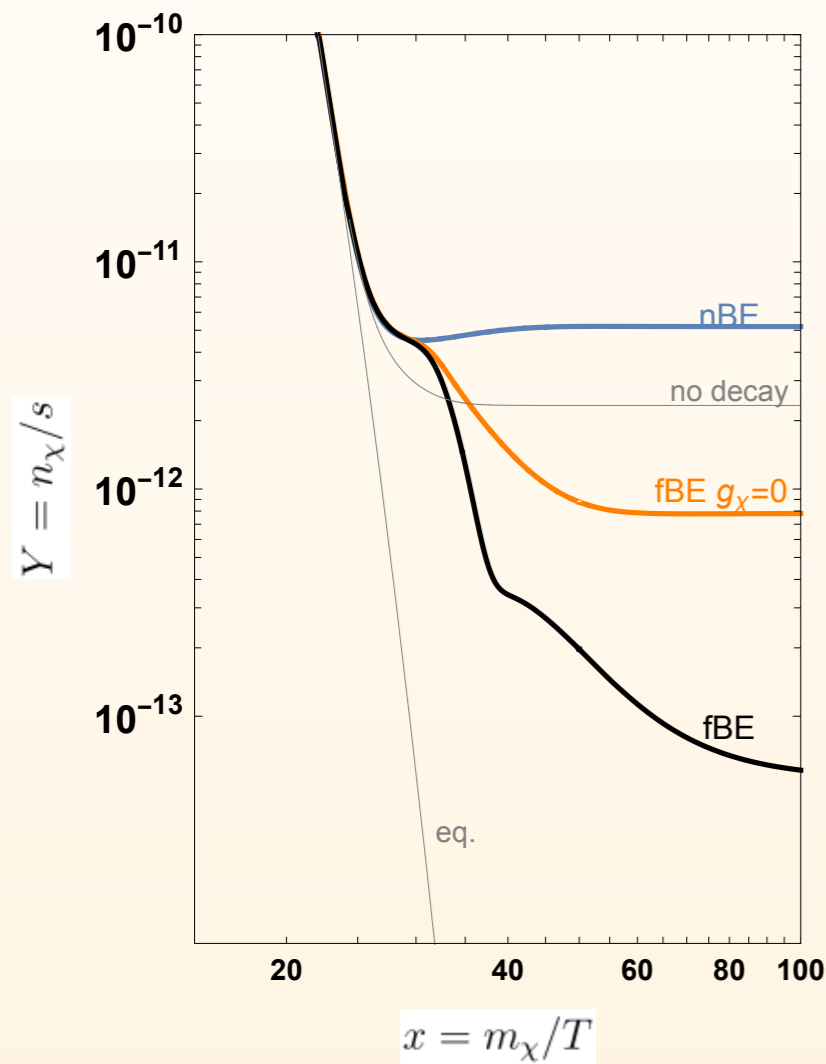
- 1st component from **thermal freeze-out**
- 2nd component from **a decay $\phi \rightarrow \bar{\chi}\chi$**

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

$Y \sim$ number density

$y \sim$ temperature

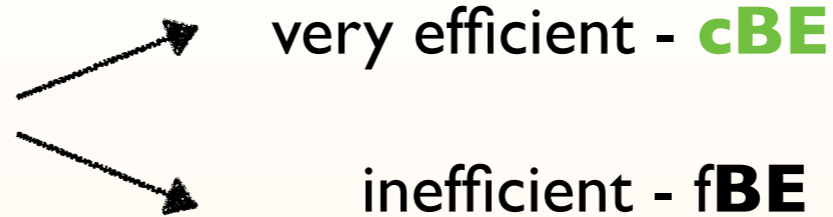
$p^2 f(p) \sim$ momentum distribution



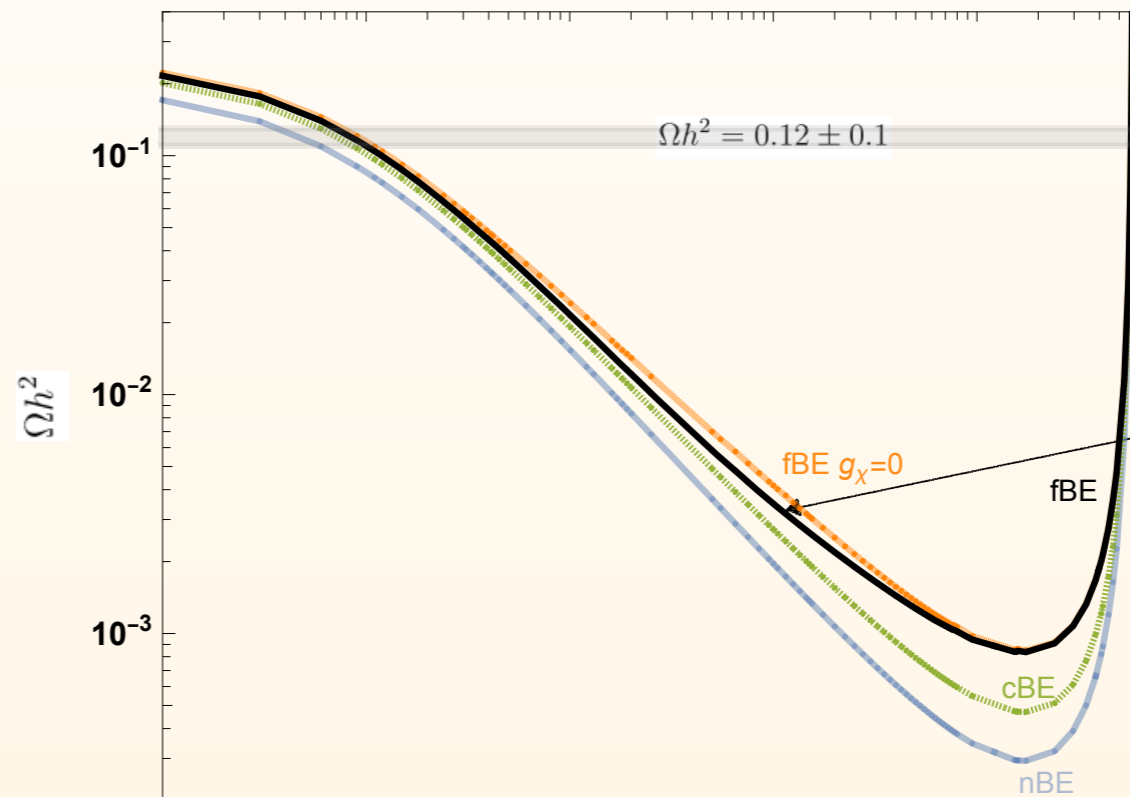
CBE vs. FBE

WHICH IS MORE ACCURATE?! **A.H. & M. Laletin** [2204.07078](#)

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

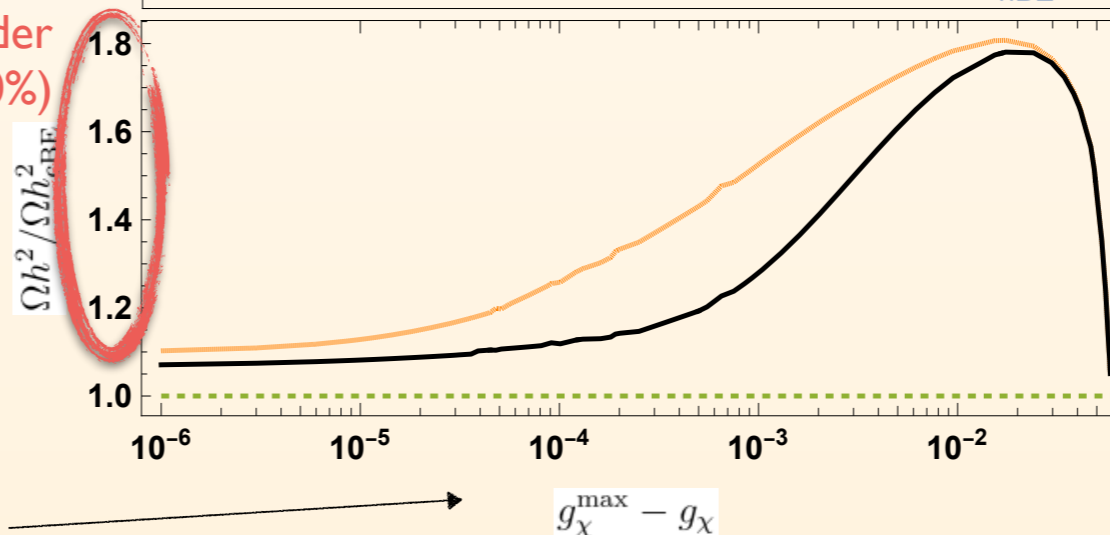


Which limit is closer to reality depends on the model, but it seems that fBE is typically more accurate, unless self-scattering is tuned up, e.g:



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

difference of order $O(10\%)$



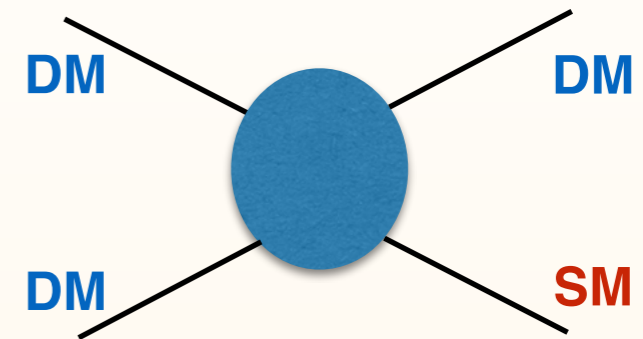
coupling to the mediator; governs self-scatterings

SEMI-ANNIHILATION

DARK MATTER SEMI-ANNIHILATION AND ITS SIMPLEST REALIZATION

DM is a thermal relic but with freeze-out governed by the semi-annihilation process

D'Eramo, Thaler '10; ...

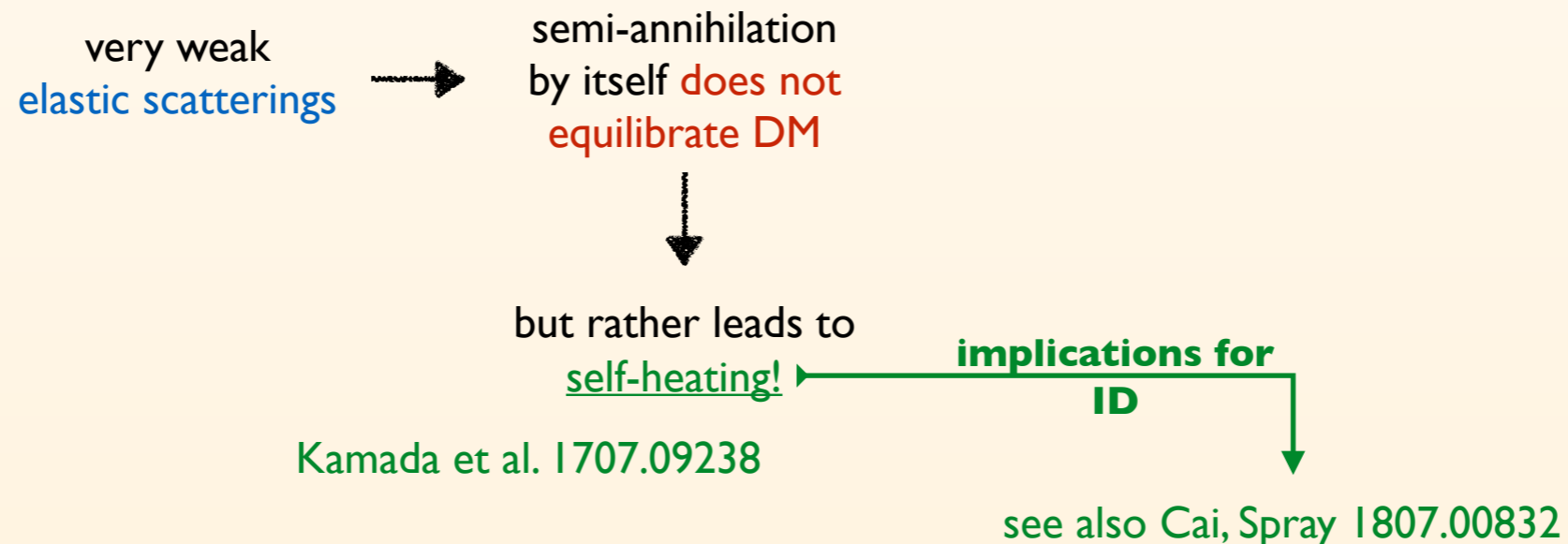


Z₃ complex scalar singlet:

$$V = \mu_H^2 |H|^2 + \lambda_H |H|^4 + \mu_S^2 |S|^2 + \lambda_S |S|^4 + \lambda_{SH} |S|^2 |H|^2 + \frac{\mu_3}{2} (S^3 + S^{\dagger 3}).$$

just above the Higgs threshold semi-annihilation dominant!

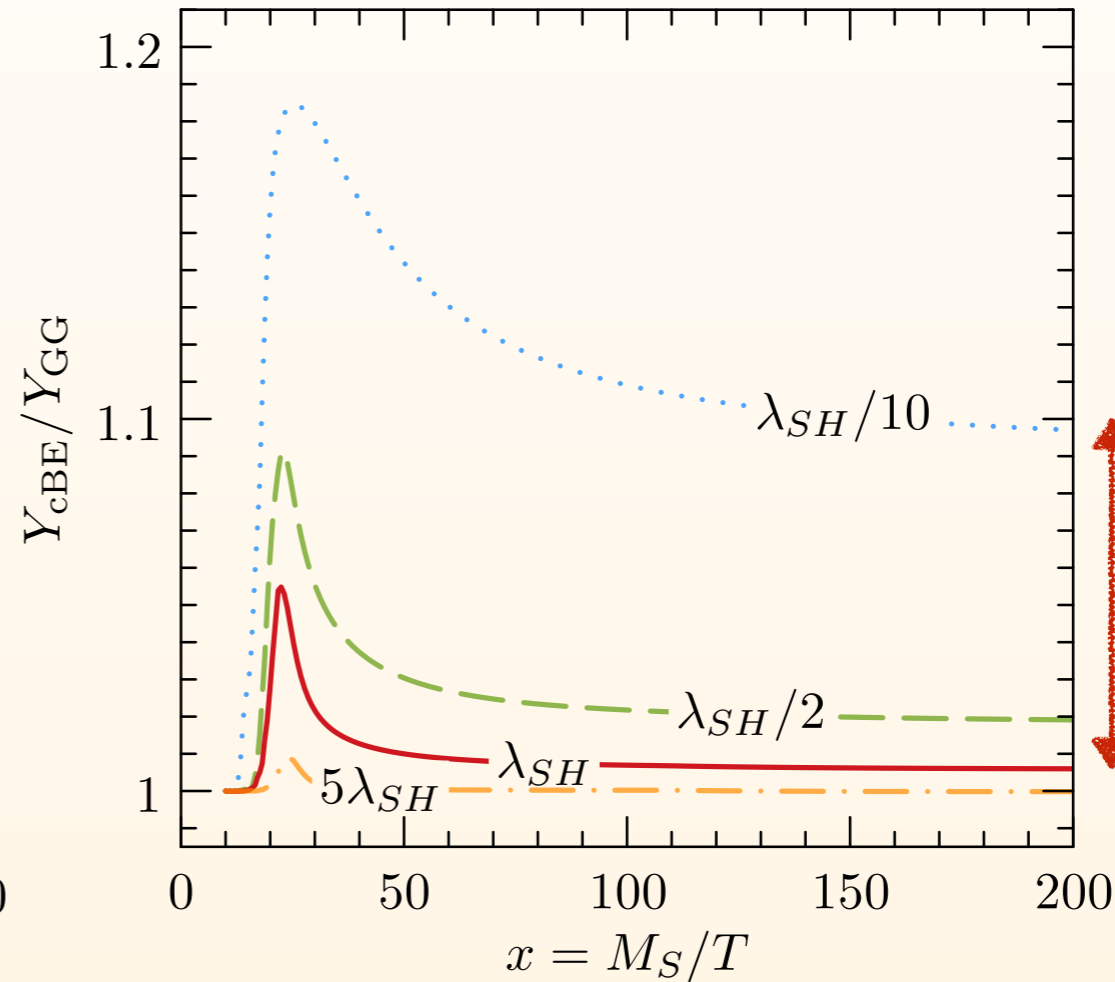
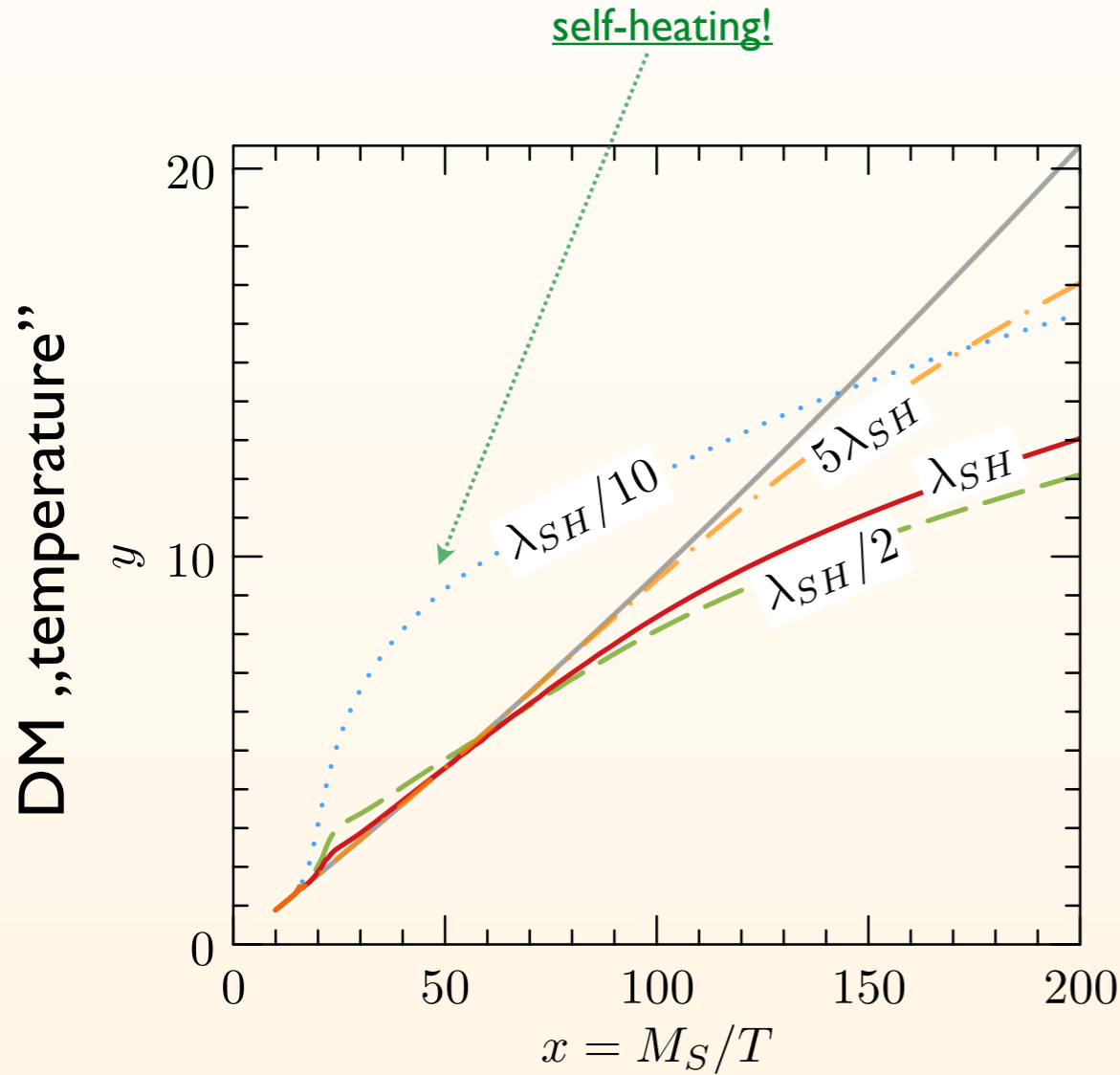
Belanger, Kannike, Pukhov, Raidal '13



SEMI-ANNIHILATION

EXAMPLE EFFECT ON EARLY KD ON RELIC DENSITY

A. Hektor, AH and K. Kannike [1901.08074](#)



Note: here the **final effect is relatively mild** (though still larger than the observational error), but only because in the simplest model the **velocity dependence of annihilation is mild as well...**

LESS SIMPLE EXAMPLE

Inert doublet model H_1, H_2 and with additional scalar singlet S :

$$\mathbb{Z}_3 \quad H_1 \rightarrow H_1, \quad S \rightarrow \omega S, \quad H_2 \rightarrow \omega H_2 \quad \omega^3 = 1$$

SM Higgs

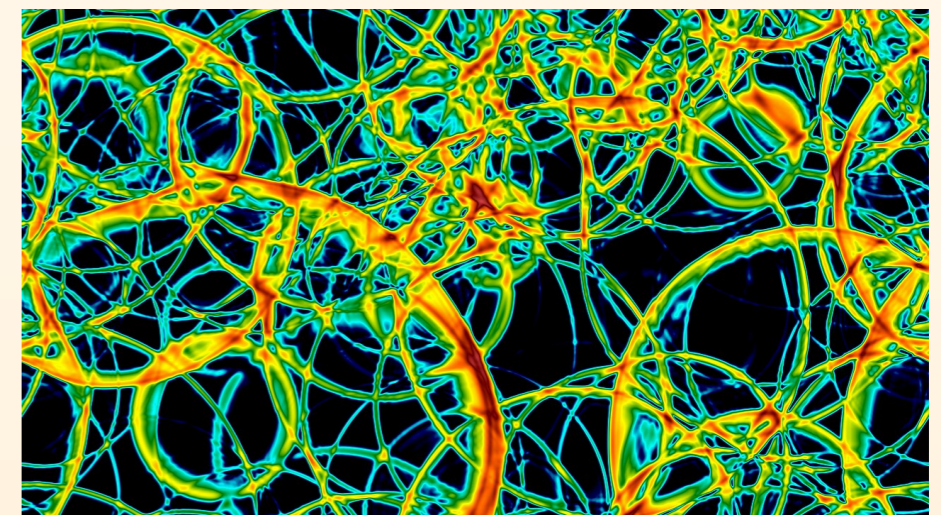
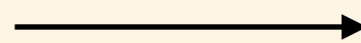
Classical Inert Doublet Model

Classical Scalar Singlet Model (\mathbf{Z}_2)

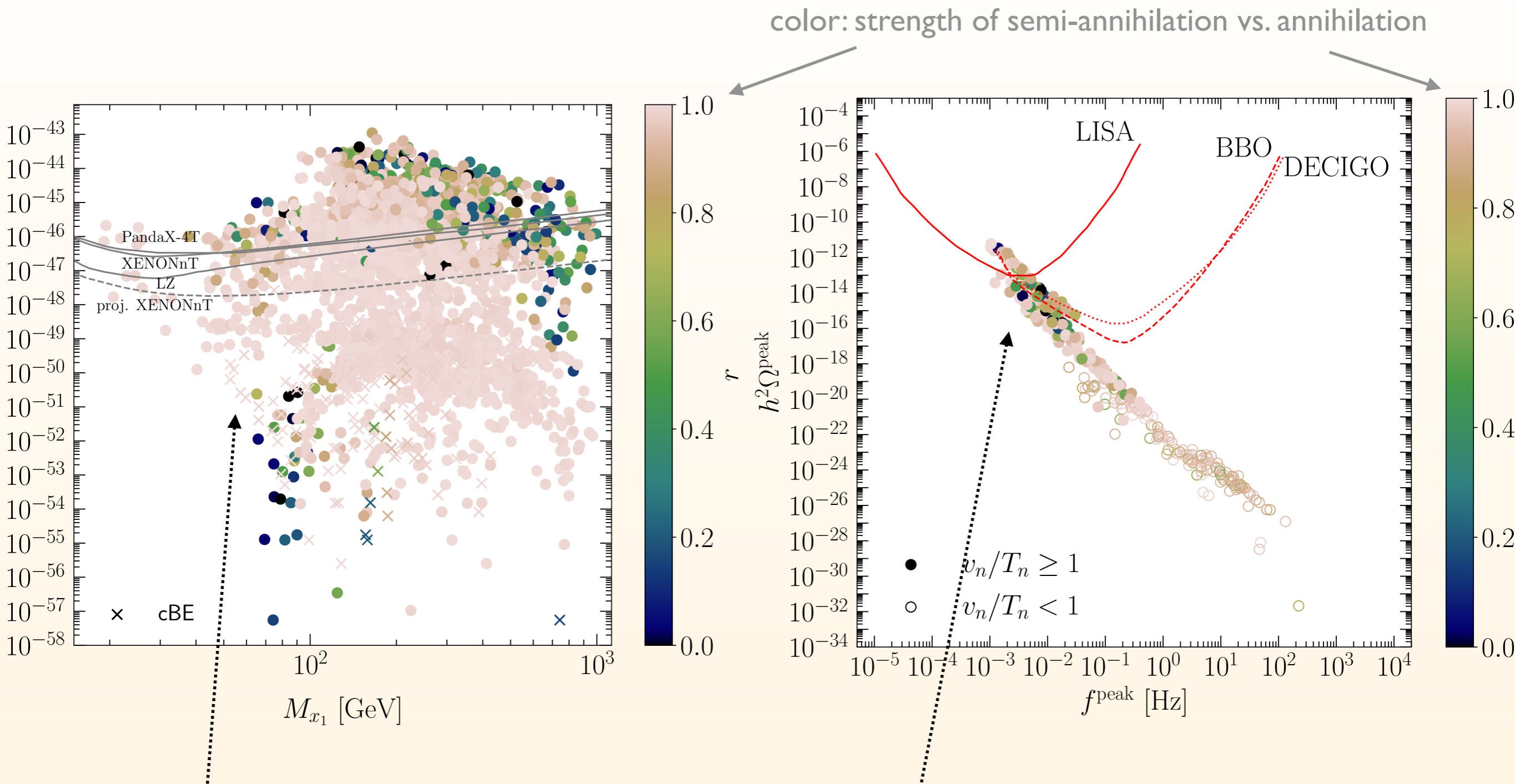
$$V = \underbrace{\mu_1^2 |H_1|^2 + \lambda_1 |H_1|^4}_{\text{SM Higgs}} + \underbrace{\mu_2^2 |H_2|^2 + \lambda_2 |H_2|^4}_{\text{Classical Inert Doublet Model}} + \underbrace{\mu_S^2 |S|^2 + \lambda_S |S|^4}_{\text{Classical Scalar Singlet Model (Z}_2\text{)}} \\ + \underbrace{\lambda_{S1} |S|^2 |H_1|^2 + \lambda_{S2} |S|^2 |H_2|^2}_{\text{Z}_3 \text{ mixing terms}} + \underbrace{\lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1)}_{\text{Z}_3 \text{ mixing terms}} \\ + \frac{\mu_S''}{2} (S^3 + S^{\dagger 3}) + \frac{\lambda_{S12}}{2} (S^2 H_1^\dagger H_2 + S^{\dagger 2} H_2^\dagger H_1) + \frac{\mu_{SH}}{2} (S H_2^\dagger H_1 + S^\dagger H_1^\dagger H_2)$$

\mathbf{Z}_3 mixing terms

Such a scalar potential allows
for FOPT \Rightarrow nucleation of bubbles
& **stochastic GW background**



SCAN RESULTS



BACKUP