National Science Centre Poland

Towards robust predictions for thermal production of multicomponent dark ~~matter~~ sectors

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Based on:

S. Chatterjee & A.H. 2411.xxxxx

T. Binder, T. Bringmann, M. Gustafsson & A.H. 1706.07433, 2103.01944

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Takeaway Messages

1. Freeze-out encompasses a plethora of models, ideas and possibilities, that have a similar theoretical standing to the simplest WIMP-like freeze-out, while possibly quite different phenomenology

2. In recent years a significant progress in refining the relic density calculations (not yet fully implemented in public codes!)

3. Kinetic equilibrium is a necessary (often implicit) assumption for standard relic density calculations in the numerical tools…

…while it is not always warranted!

(we are working on extending DRAKE to multi-component models with regimes beyond kinetic equilibrium)

THERMAL RELIC DENSITY

STANDARD SCENARIO

(chemical and kinetic)

T			time
↑	$\Gamma_{\rm ann} > H$	DM in full equilibrium	↓
	$\Gamma_{\rm ann} \sim H$	chemical decoupling	
	$\Gamma_{\rm ann} < H$	freeze-out	
	$\Gamma_{\rm scatt} \sim H$	kinetic decoupling	

non-equilibrium

time evolution of $f_\chi(p)$ in kinetic theory:

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

Liouville operator in FRW background

the collision term

THERMAL RELIC DENSITY
STANDARD APPROACH

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

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

*assumptions for using Boltzmann eq: classical limit, molecular chaos,...

...for derivation from thermal QFT see e.g., 1409.3049

integrate over p (i.e. take 0th moment)

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

for a process of DM DM ↔ SM SM

Critical assumption:
kinetic equilibrium at chemical decoupling

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

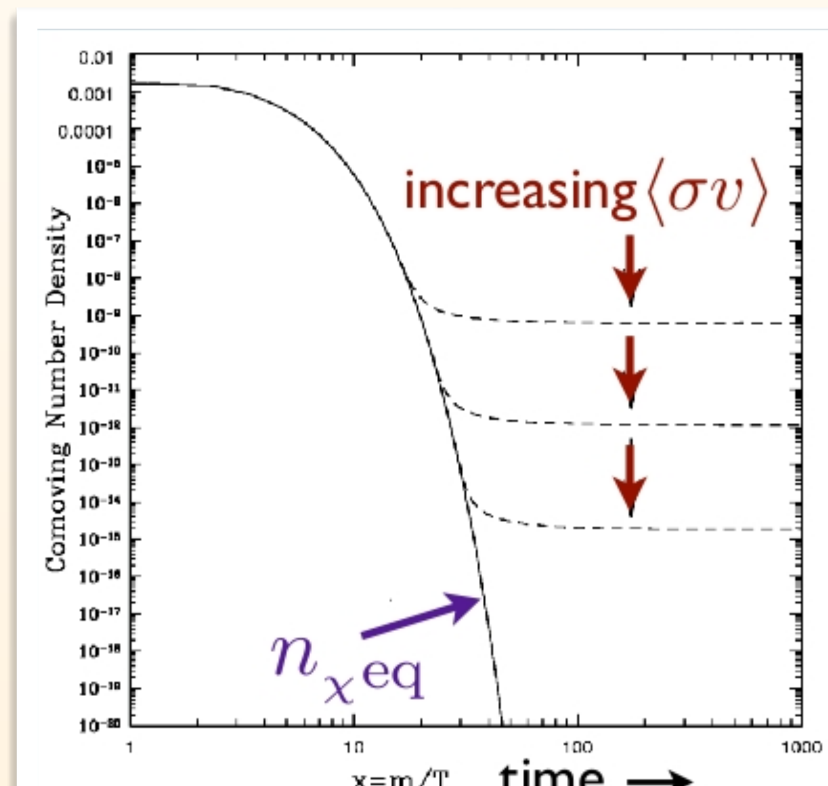


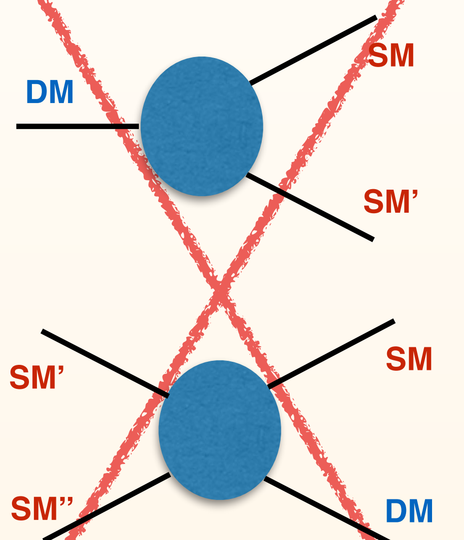
Fig.: Jungman, Kamionkowski & Griest, PR'96

What goes into C in general?

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

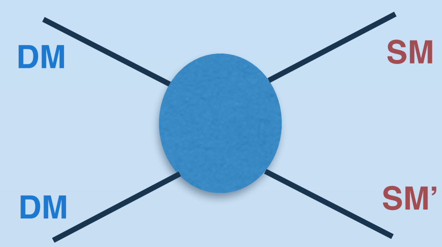
changing processes ⇒ number density

1 DM particle



stability

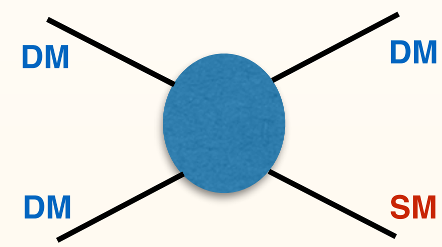
2 DM particles



often the only one being considered

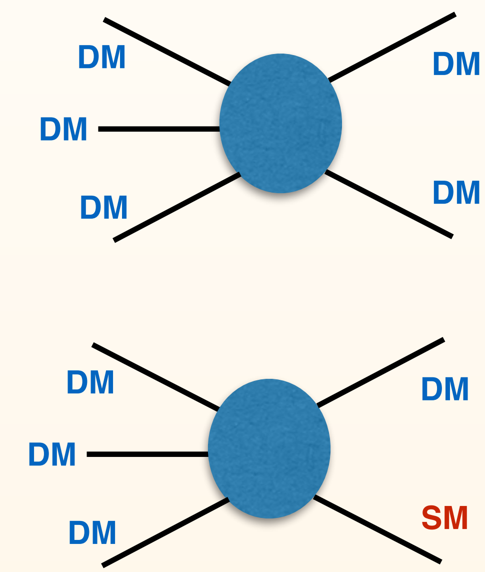
annihilation

3 DM particles



semi-annihilation

4+ DM particles



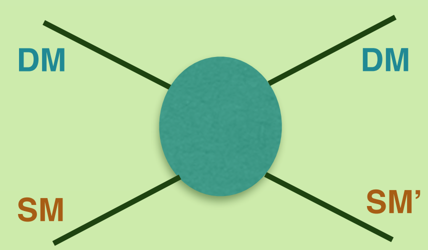
…

cannibalization

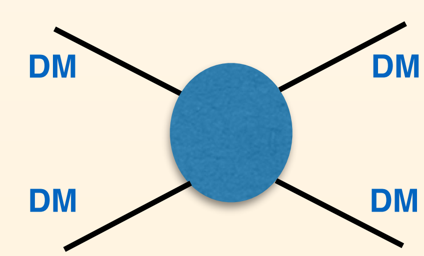
…

conserving processes ⇒ energy density

often assumed to be "∞"



elastic scattering



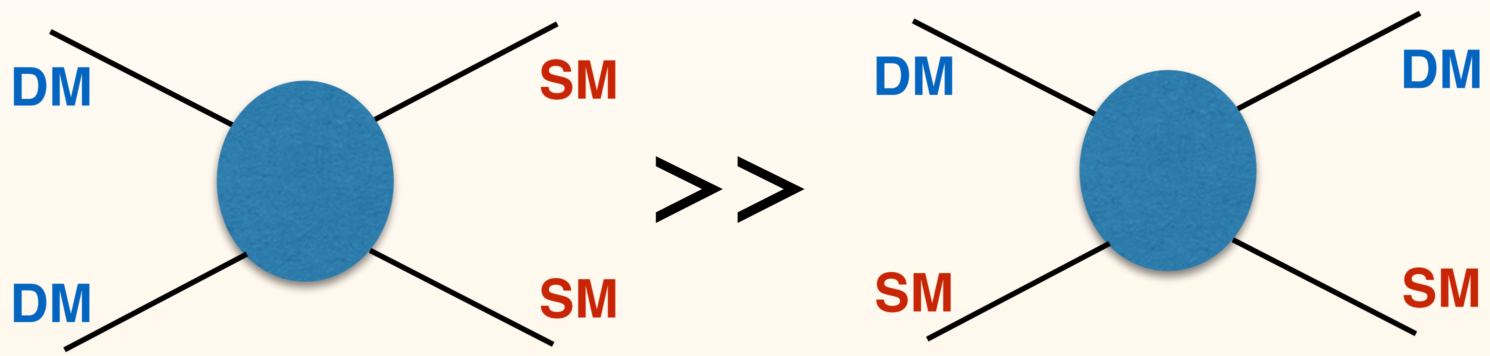
self scattering

EARLY KINETIC DECOUPLING?

A necessary and sufficient condition: scatterings weaker than annihilation

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

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 $f_\chi(p)$

0-th moment: n_χ
2-nd moment: T_χ
$\ldots$

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

finite range of validity
no insight on the distribution

NEW TOOL!

GOING BEYOND THE STANDARD APPROACH

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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

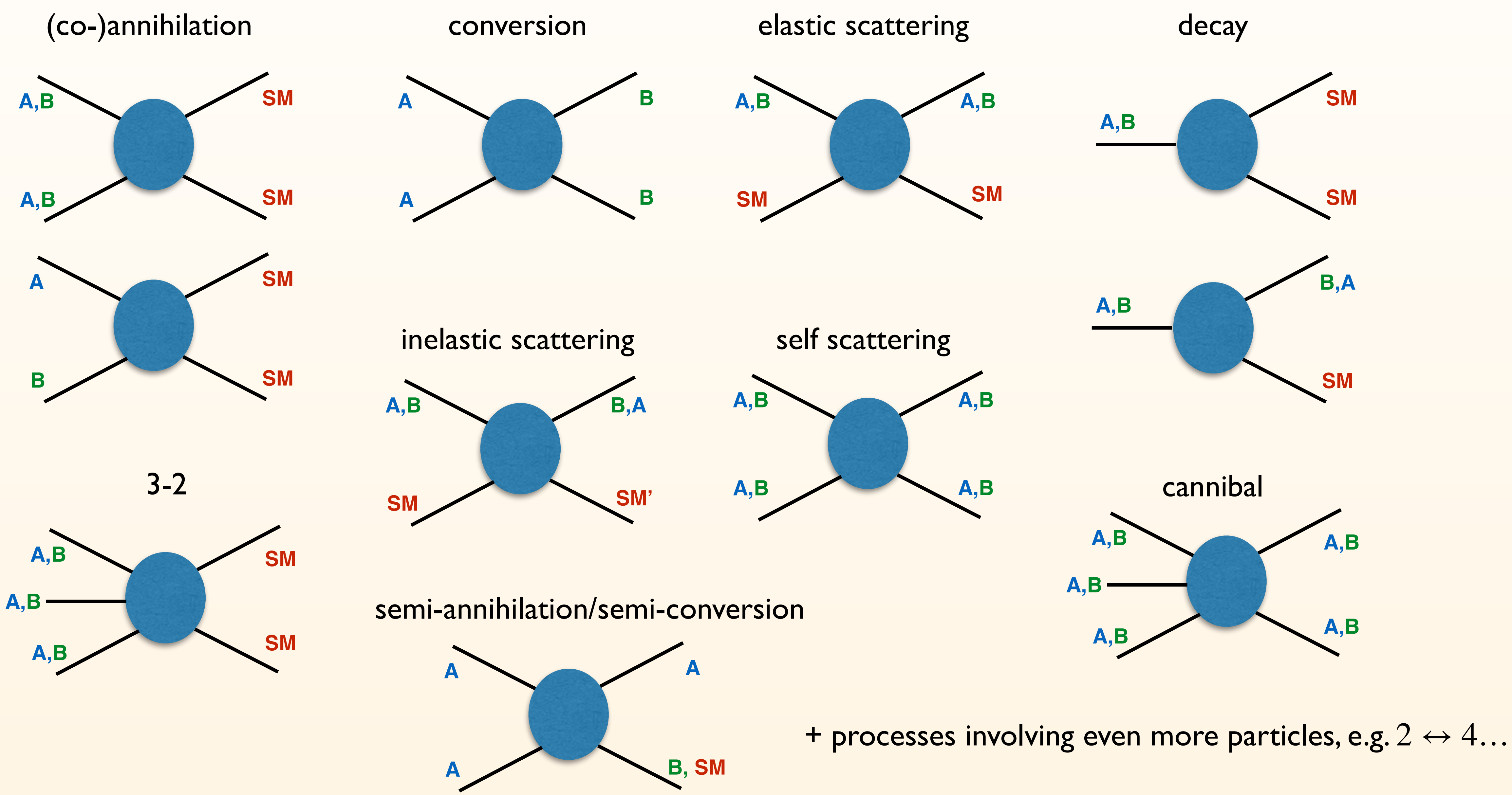
…

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

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

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!

STATE-OF-THE-ART…

There are numerous results for two-component dark sectors… but without full generality and in fact narrowly tailored to specific models

The most general tool so far is the newly released:

micrOMEGAs 6.0: N-component dark matter

2312.14894

G. Alguero[1], G. Bélanger[2], F. Boudjema[2], S. Chakraborti[3], A. Goudelis[4], S. Kraml[1], A. Mjallal[2], A. Pukhov[5]

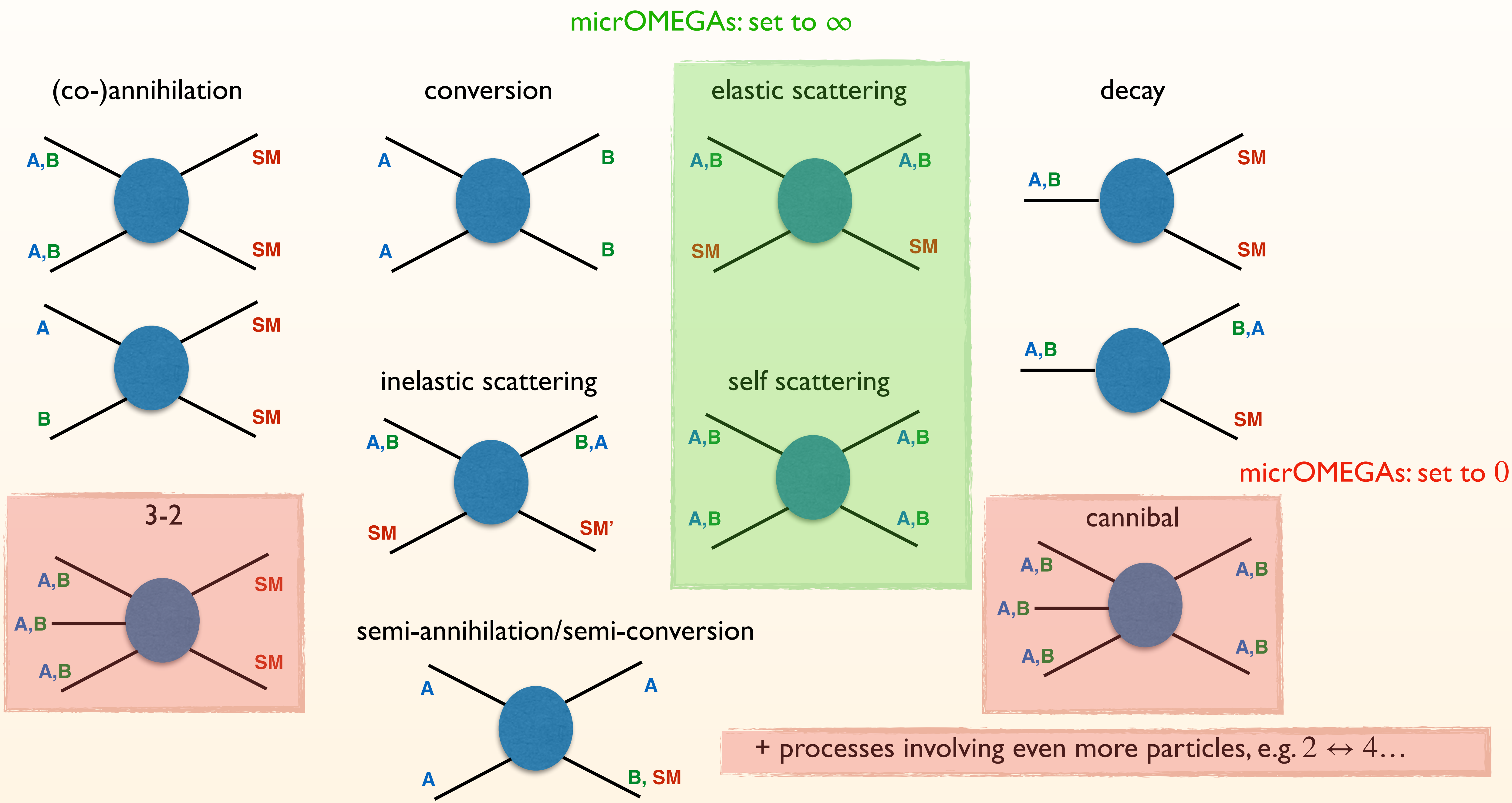
`micrOMEGAs` is a numerical code to compute dark matter (DM) observables in generic extensions of the Standard Model of particle physics. We present a new version of `micrOMEGAs` that includes a generalization of the Boltzmann equations governing the DM cosmic abundance evolution which can be solved to compute the relic density of N-component DM. The direct and indirect detection rates in such scenarios take into account the relative contribution of each component such that constraints on the combined signal of all DM components can be imposed. The co-scattering mechanism for DM production is also included, whereas the routines used to compute the relic density of feebly interacting particles have been improved in order to take into account the effect of thermal masses of t-channel particles. Finally, the tables for the DM self-annihilation - induced photon spectra have been extended down to DM masses of 110 MeV, and they now include annihilation channels into light mesons.

Solves set of equations for the yields (only):

$$3H\frac{dY_\mu}{d\mathfrak{s}} = \sum_{\alpha\leq\beta;\,\gamma\leq\delta} Y_\alpha Y_\beta C_{\alpha\beta}\langle v\sigma_{\alpha\beta\gamma\delta}\rangle\left(\delta_{\mu\alpha}+\delta_{\mu\beta}-\delta_{\mu\gamma}-\delta_{\mu\delta}\right).$$

WHAT IF A NON-MINIMAL SCENARIO?

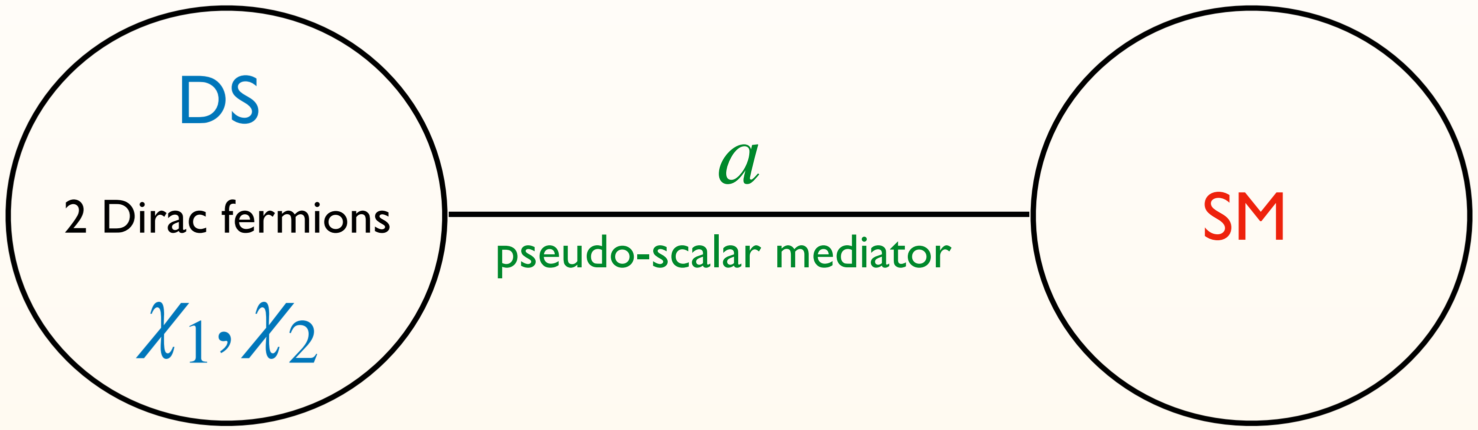
A,B — two different dark sector states (at least one needs to be stable)



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:



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

coupled directly to SM fermions in a MFV way

New fields: χ_1, χ_2, a

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

Parametrically:

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

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

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

$$\Downarrow$$

Varying:

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

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

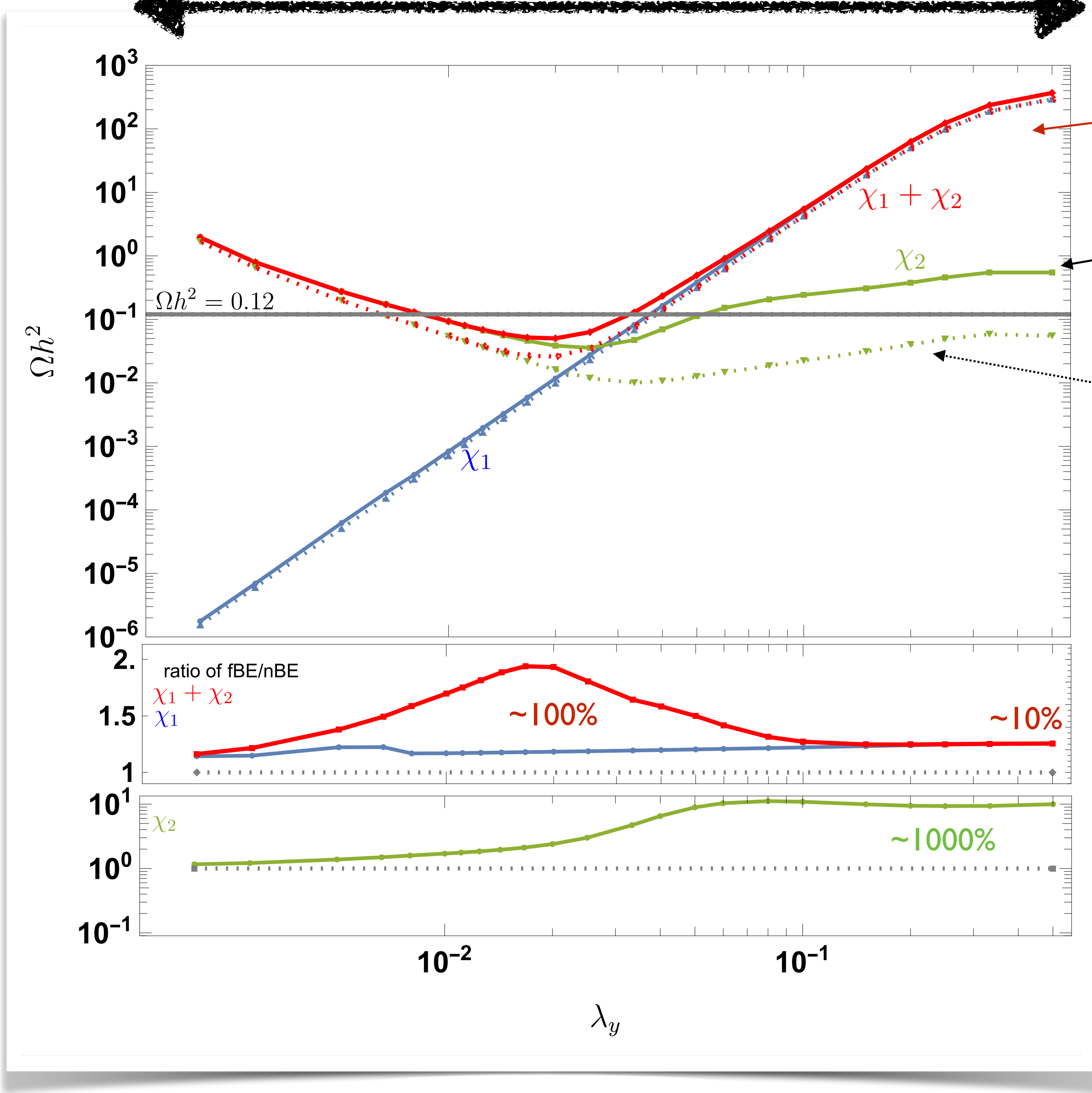
(see e.g. „Coy DM")

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!

strong conversions weak conversions



total relic abundance

phase space calculation (fBE)

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

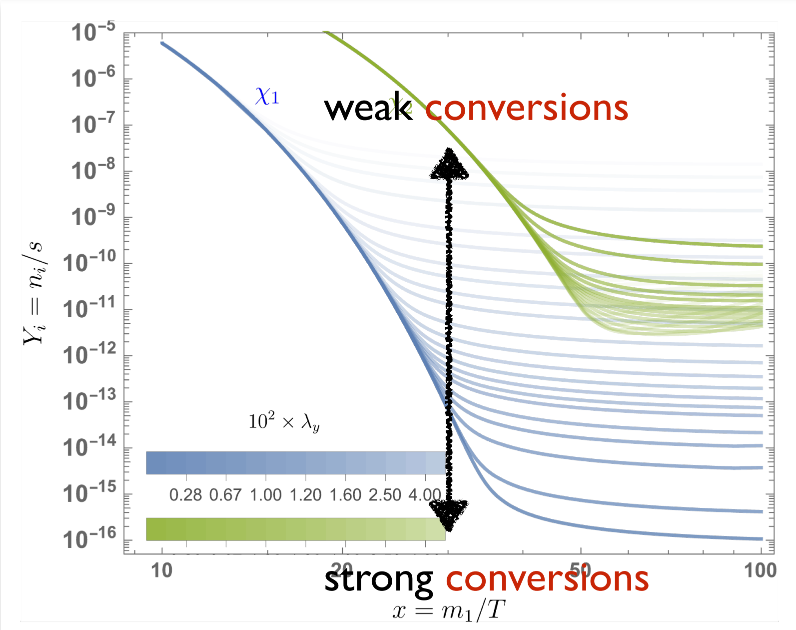
Ratio of the two for total and χ_1

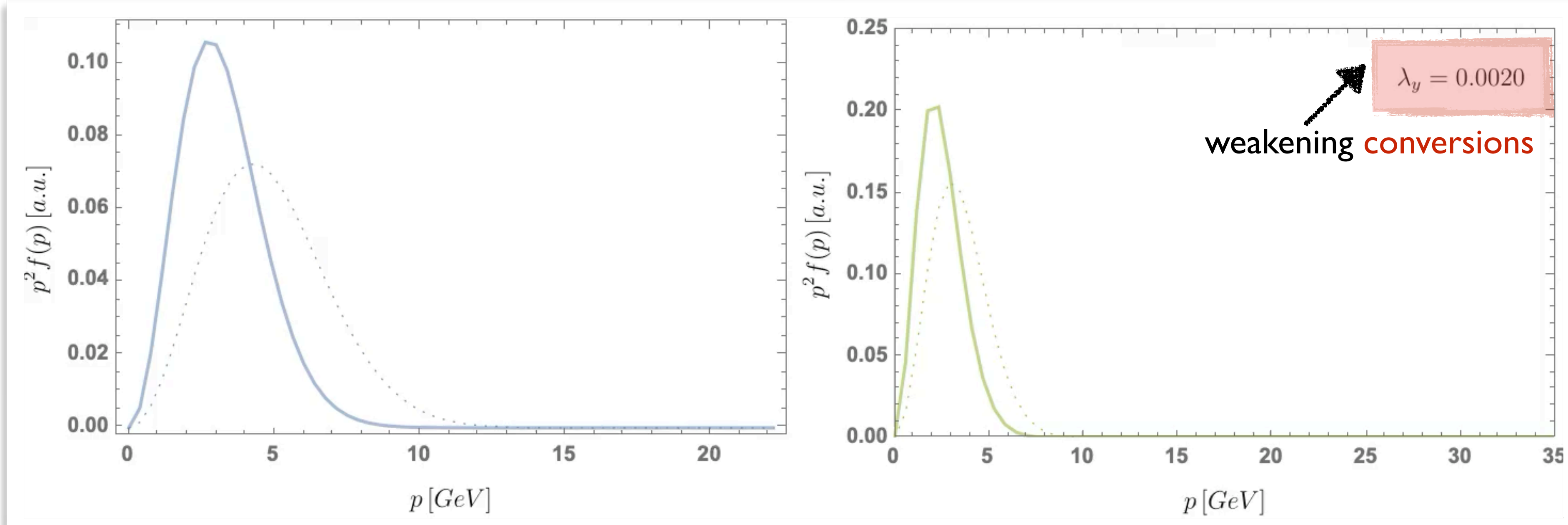
and χ_2

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

RESULTS: CONVERSION IMPACT

weaker conversions $\Rightarrow$ less depletion of χ_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 — 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

CONCLUSIONS

1. In order to accurately predict the abundance of multicomponent Dark Sectors one should carefully examine if kinetic equilibrium is kept, as many of the relevant process are working to disrupt it

2. In recent years a significant progress in refining the relic density calculations in DRAKE to include multicomponent case (with new code release in preparation)

Thank you!