Review of Dark Matter Tools

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Introductory comments

Every review talk needs a disclaimer...

· There are *many* dark matter – related tools available in the community!

· I have not used all of them, let alone all of their functionalities.

· I apologize in advance if I don't mention or misrepresent your favourite tool.

Cf also reviews on DM Tools at TOOLS2020, 2022

· Most DM codes evolve constantly (sometimes even silently), not obvious to keep up with new functionalities/features. Ultimately, one *must* read the manuals.

The fact that we've reached a level at which it's actually hard to give a review talk on DM tools is a good thing

Which are the public dark matter tools?

For the sake of the presentation, let’s split them into two categories:

Tools that compute the DM relic abundance

(but which may also serve other purposes!)

· micrOMEGAs: Generic BSM models.

· DarkSUSY: Generic BSM models.

· MadDM: Generic BSM models.

· Dark Pack: Evolutions of Superiso Relic, Generic BSM models.

NB: All of these codes also perform (at least) the most standard calculations for direct/indirect detection.

Tools that don’t compute the DM relic abundance

(and which definitely serve other purposes!)

· Direct detection: DirectDM, RunDM, RAPIDD, DaMaSCUS, DDCalc...

EFT matching, RGE evolution, scattering in the earth...

· Indirect detection: GALPROP, DRAGON, USINE, CLUMPY, PPPC4DMID, HDMSpectra...

Cosmic ray propagation, annihilation spectra...

· Additional functionalities: DarkBit, DarkHistory...

NB: Some of these codes are/can be linked to relic abundance calculation codes.

General workflow of DM tools

Come up with your Lagrangian ↓

Code it in as an intuitive form as possible ↓

Generate model files for matrix element/cross-section calculators ↓

Use them to compute dark matter observables ↓

Link to other pieces of software computing additional observables ↓

Compare with experiments

The traditional way (for the moment).

Model file generators.

e.g. LanHEP, FeynRules, SARAH...

Abundance, direct/indirect detection cross-sections and spectra...

May require additional input (astro etc)

Collider constraints, BBN bounds, flavour observables...

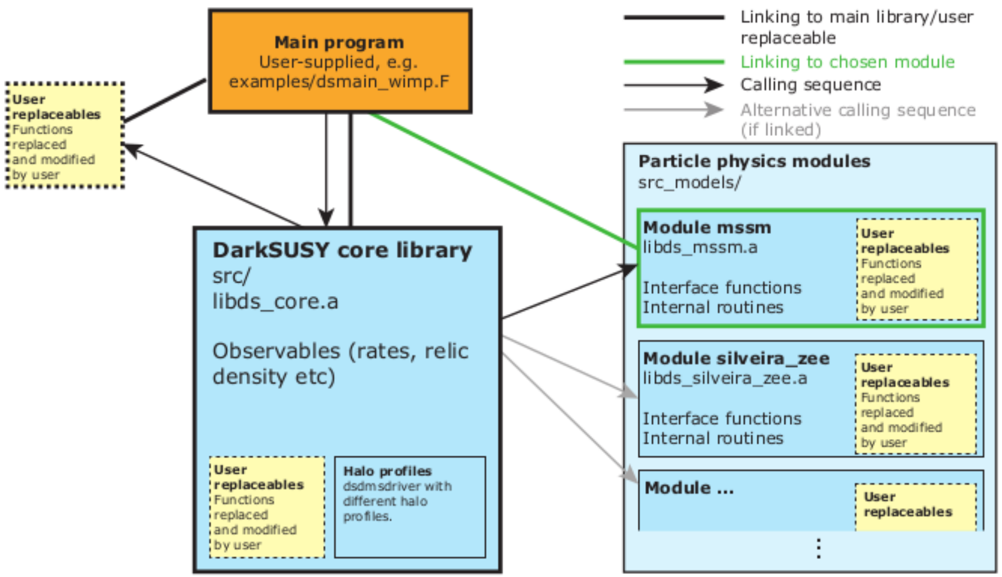
+ Do all of that reasonably fast.

Public codes develop through the interaction between users and developers (*who are also users*!).

DarkSUSY

https://darksusy.hepforge.org/

A Fortran code to compute numerous dark matter observables for different dark matter candidates (current version: v6).



· Underwent *major* upgrade ~6 years ago, no longer SUSY-specific.

· Freeze-out, direct detection (incl. upscattering), indirect detection (under different astro assumptions).

· Possibility to link to other, model-specific packages.

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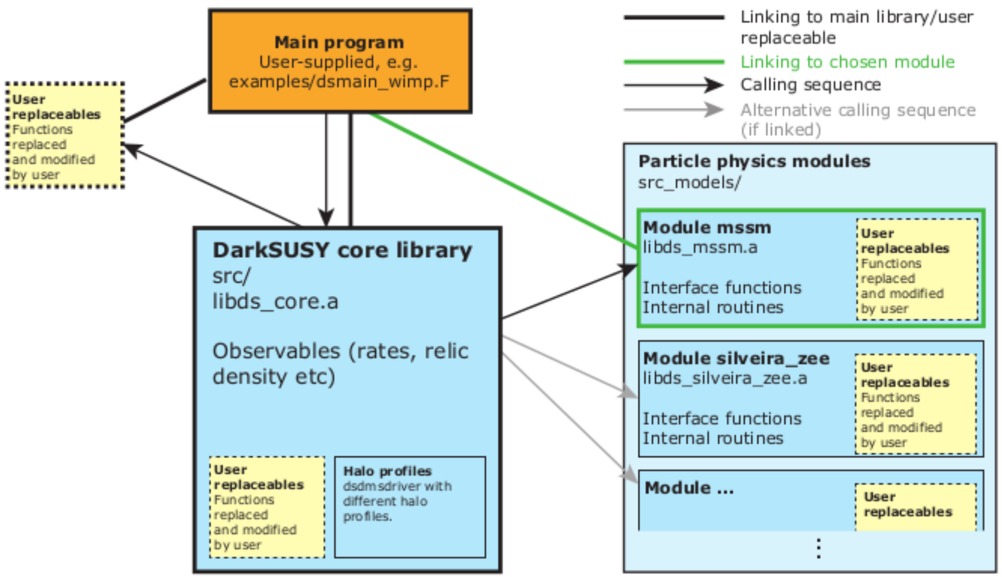

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· Freeze-out, direct detection (incl. upscattering), indirect detection (under different astro assumptions).

· Possibility to link to other, model-specific packages.

Highlights:

· Very modular.

· Dark freeze-out computations w/ different sector temperatures.

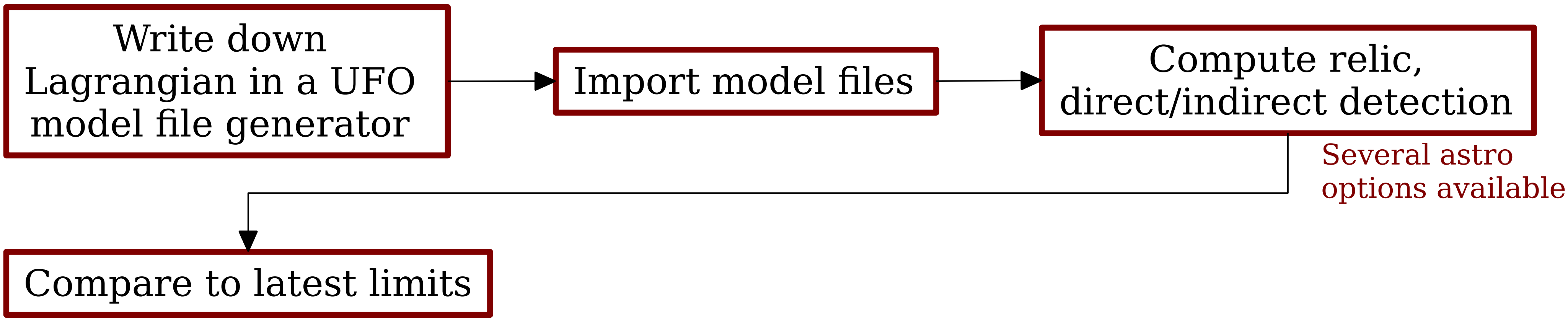
· Possibility to account for late kinetic decoupling, Sommerfeld enhancement.

· Possibility to compute self-interaction effects.

MadDM

https://launchpad.net/maddm/

A Fortran/Python code to compute dark matter observables for generic dark matter candidates (current version: v3).



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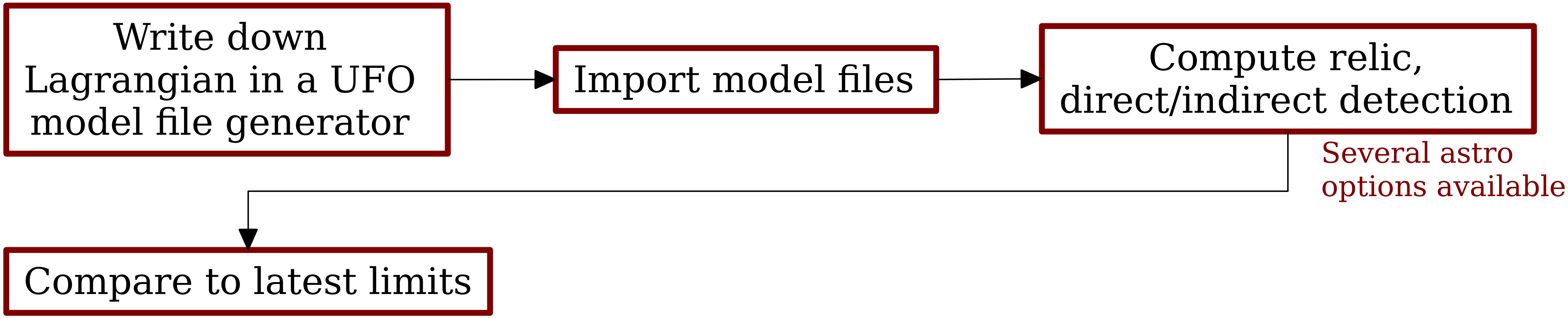

Highlights:

· Handles generic extensions of the SM, no need to compute cross-sections by hand.

· Relies on MG5_aMC, extensively used in collider physics.

· Readily linked with numerous HEP packages.

· Possibility to compute 2 → n/loop-induced processes for ID via MadLoop.

micrOMEGAs

https://lapth.cnrs.fr/micromegas/

A C/Fortran code to compute dark matter observables for generic dark matter candidates (current version: v6). For any BSM model, the code can:

· Figure out which processes are relevant for the evolution of the freeze-out/freeze-in dark matter cosmic abundance.

· Compute the relevant matrix elements.

Based on CalcHEP. By default tree-level $1/2 \leftrightarrow 2$, possibility for some $2 \rightarrow 3/4$. Possibility to replace $\langle\sigma v\rangle$ with own expression.

· Solve the necessary Boltzmann equations.

· Compute additional observables, compare to EXP limits, link to other packages.

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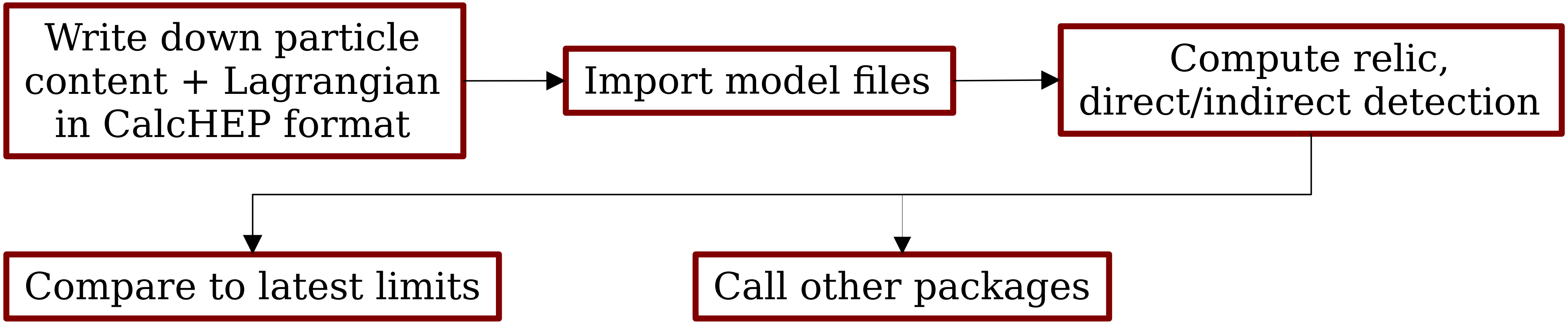

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· Solve the necessary Boltzmann equations.

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Highlights:

· Can handle multi-component dark matter models.

· Includes semi-annihilations, conversion-driven freeze-out.

· Freeze-in (incl. backreactions).

· Readily linked with numerous HEP packages.

Development of micrOMEGAs

MicrOMEGAs is a numerical code for the calculation of dark matter properties

micrOMEGAs: A program for calculating the relic density in the MSSM G. Bélanger[1], F. Boudjema[1], A. Pukhov[2], A. Semenov[1]	Neutralino DM relic density in the MSSM. Based on CompHEP for ME calculation. arXiv:hep-ph/0112278
micrOMEGAs 2.0: a program to calculate the relic density of dark matter in a generic model . G. Bélanger[1], F. Boudjema[1], A. Pukhov[2], A. Semenov[3]	Freeze-out calculation of DM relic density in generic extensions of the SM. CalcHEP. arXiv:hep-ph/0607059
micrOMEGAs_3 : a program for calculating dark matter observables G. Bélanger[1], F. Boudjema[1], A. Pukhov[2], A. Semenov[3]	Asymmetric DM, semi-annihilations, generalized thermodynamics, DD/ID/LHC. arXiv:1305.0237
micrOMEGAs4.1: two dark matter candidates G. Bélanger[1], F. Boudjema[1], A. Pukhov[2], A. Semenov[3]	Two generic frozen-out dark matter components. arXiv:1407.6129
micrOMEGAs5.0 : freeze-in G. Bélanger[1†], F. Boudjema[1‡], A. Goudelis[2§], A. Pukhov[3¶], B. Zaldivar[1††]	Incorporation of freeze-in dark matter production mechanism (one-component). arXiv:1801.03509
micrOMEGAs 6.0: N-component dark matter G. Alguero[1], G. Bélanger[2], F. Boudjema[2], S. Chakraborti[3], A. Goudelis[4], S. Kraml[1], A. Mjallal[2], A. Pukhov[5]	Arbitrary number of (frozen in/out) dark matter components. arXiv:2312.14894

+ intermediate versions. Until 2013, the *only* DM code to handle generic SM extensions.

What is new in MO6 ?

Numerous new features have been implemented in the latest version :

· Major upgrade : possibility to compute the DM cosmic abundance in models with multiple WIMP+FIMP dark matter candidates + consistent computation of relevant experimental constraints.

· Major upgrade : inclusion of conversion-driven freeze-out (“co-scattering”) and decay terms.

· Possibility to define (and, partly, check) which sets of particles are in thermal equilibrium.

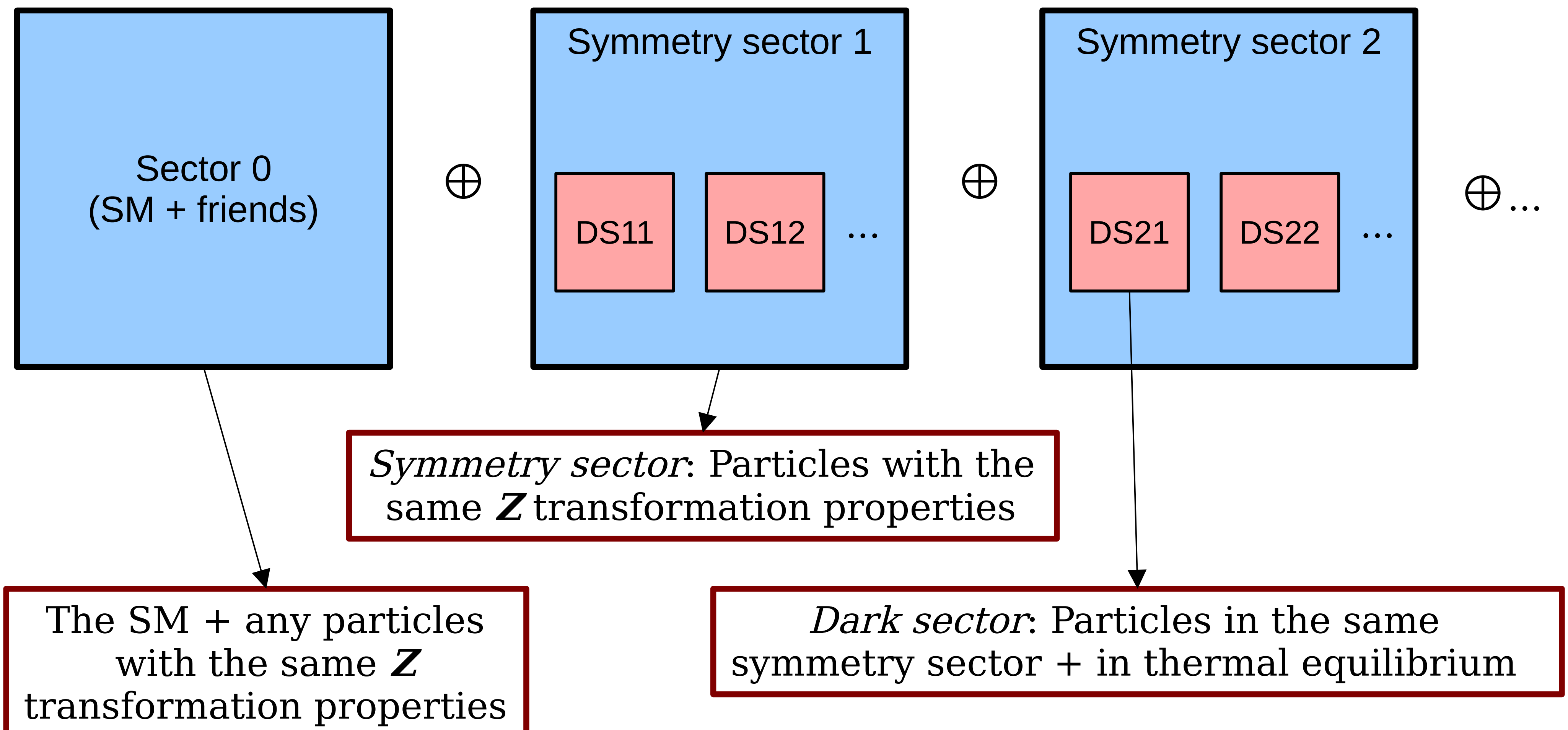
· Possibility to include $2 \to 3$ and $2 \to 4$ processes in single-component DM models.

· Improvements in freeze-in computations.

· Additional functionalities for direct/indirect detection.

Multi-component dark matter : strategy

Types of models handled in MO : one (or more) discrete symmetries $\boldsymbol{Z}_i$ are imposed at the Lagrangian. Different (sets of) particles may transform differently under the direct product $\boldsymbol{Z} = \boldsymbol{Z}_1 \otimes \boldsymbol{Z}_2 \otimes \ldots \otimes \boldsymbol{Z}_N$ of these symmetries. We divide the model content in *sectors*.



NB: Kinetic equilibrium with Sector 0 is assumed throughout

Multi-WIMP case

Any DS may (or may not) contain a dark matter candidate. The evolution of the μ-th candidate's abundance as a function of the entropy density follows :

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

where:

$$\langle v\sigma_{\alpha\beta\gamma\delta}\rangle = \frac{1}{C_{\alpha\beta}\bar{n}_\alpha(T)\bar{n}_\beta(T)} \sum_{\substack{a\in\alpha,b\in\beta,c\in\gamma,d\in\delta \\ \mathrm{if}(\alpha=\beta)a\leq b;\ \mathrm{if}(\gamma=\delta)c\leq d}} \bar{N}_{a,b\to c,d}$$

$$\bar{N}_{a,b\to c,d} = \frac{Tg_a g_b}{8\pi^4}\int\sqrt{s}p_{ab}^2(s)K_1(\frac{\sqrt{s}}{T})C_{ab}\sigma_{a,b\to c,d}(s)ds$$

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If some particle species in a DS decay slowly, we get additional terms of the type :

$$\frac{1}{\mathfrak{s}^2(T)}\sum_{\alpha;\ \gamma\leq\delta}\left(\frac{Y_\alpha}{\bar{Y}_\alpha}-\frac{Y_\beta}{\bar{Y}_\beta}\frac{Y_\gamma}{\bar{Y}_\gamma}\right)(\delta_{\mu\alpha}-\delta_{\mu\beta}-\delta_{\mu\gamma})\sum_{a\in\alpha,c\in\beta,d\in\gamma}\bar{N}_{a\to c,d}$$

where: $$\bar{N}_{a\to c,d} = \frac{Tg_a}{2\pi^2}m_a^2\Gamma^0(a\to c,d)K_1\left(\frac{m_a}{T}\right)$$

Including co-scattering, freeze-in

Co-scattering corresponds to processes of the type $\mu + 0 \to \nu + 0$. It turns out that these contributions enter the Boltzman eqs. similarly to decay terms $\mu \to \nu + 0$

$$3H\frac{dY_\mu}{d\mathfrak{s}} \approx (Y_\mu - Y_\nu \frac{\bar{Y}_\mu}{\bar{Y}_\nu})\,\Gamma_{\mu\to\nu}$$

where:

$$\Gamma_{\mu\to\nu} = Y_0 \langle \sigma_{\mu 0 \nu 0} v \rangle (T) + \frac{\sum_{a\in\mu, c\in\nu} g_a m_a^2 \Gamma^0(a\to c, 0) K_1\left(\frac{m_a}{T}\right) + \sum_{a\in\nu, c\in\mu} g_a m_a^2 \Gamma^0(a\to c, 0) K_1\left(\frac{m_a}{T}\right)}{\sum_{a\in\mu} g_a m_a^2 K_2\left(\frac{m_a}{T}\right)}$$

can be seen as an effective width between sectors μ and ν.

Freeze-in can also be implemented through the same set of equations, but setting the initial DM abundance to zero as usual.

· Important difference wrt single-component case: DM annihilations *are* taken into account.

NB: Kinetic equilibrium is assumed even for FIMPs, otherwise need to solve un-integrated Boltzmann eqs!

Validation and example results

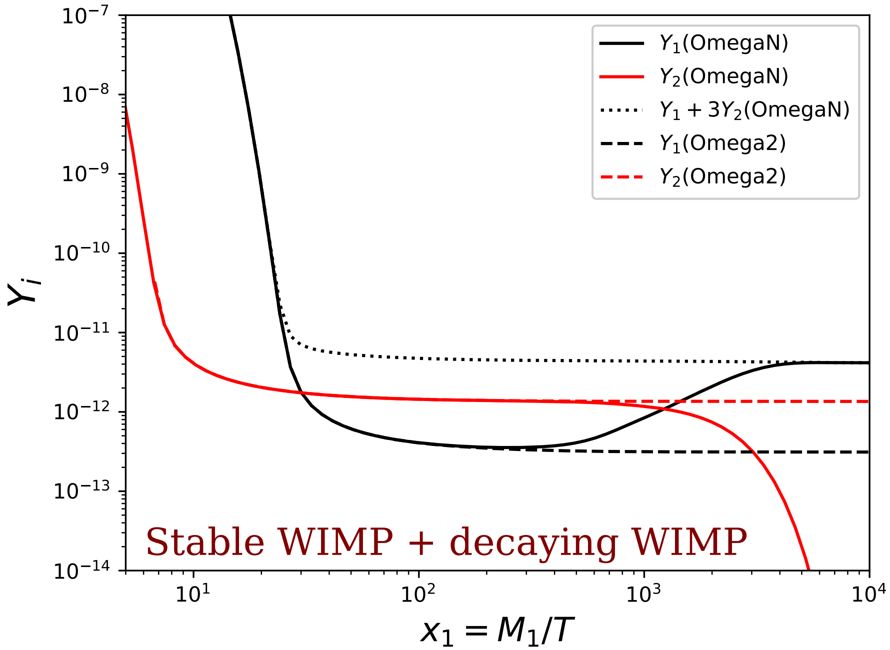
The code was validated using different models as examples :

· Singlet scalar (sanity checks for single-component DM, 1 WIMP or 1 FIMP).

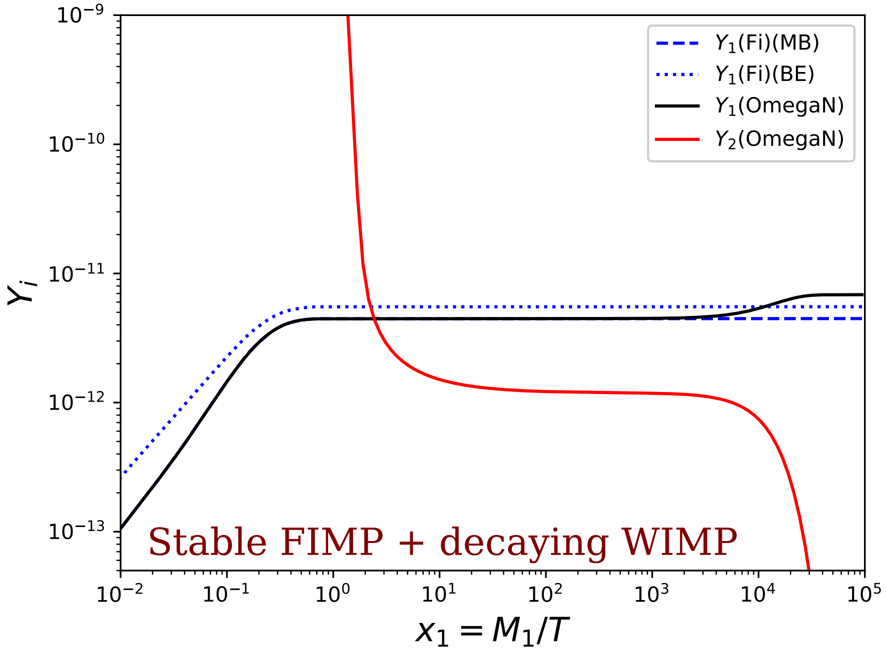
· Z5M (two singlets w/ $\mathbb{Z}_5$ symmetry, 2 WIMPs or 1 WIMP + 1 FIMP).

· Z4IDSM (Inert Doublet plus Singlet w/ $\mathbb{Z}_4$ symmetry, 1 WIMP + 1 FIMP).

Two examples from the Z5M :



Decay occurs through $\lambda\, \varphi_2\, \varphi_1^3$ coupling



Decay occurs through $\mu\, \varphi_2\, \varphi_1^2$ coupling

Excellent agreement w/ previous versions until decays become relevant.

Another application: FI at strong coupling

Usually, relic abundance calculations are performed assuming T_R to be much larger than all mass scales in the theory. However, this is an arbitrary assumption.

· Consider the singlet scalar model : $-\Delta\mathcal{L}_{\rm scal} = \frac{1}{2}\,\lambda_{hs} H^\dagger H\, s^2$

· If $T_R < m_s$ → Production becomes Boltzmann-suppressed → Larger couplings required for successful freeze-in.

· Backreactions can become relevant → Can be computed with micrOMEGAs 6.

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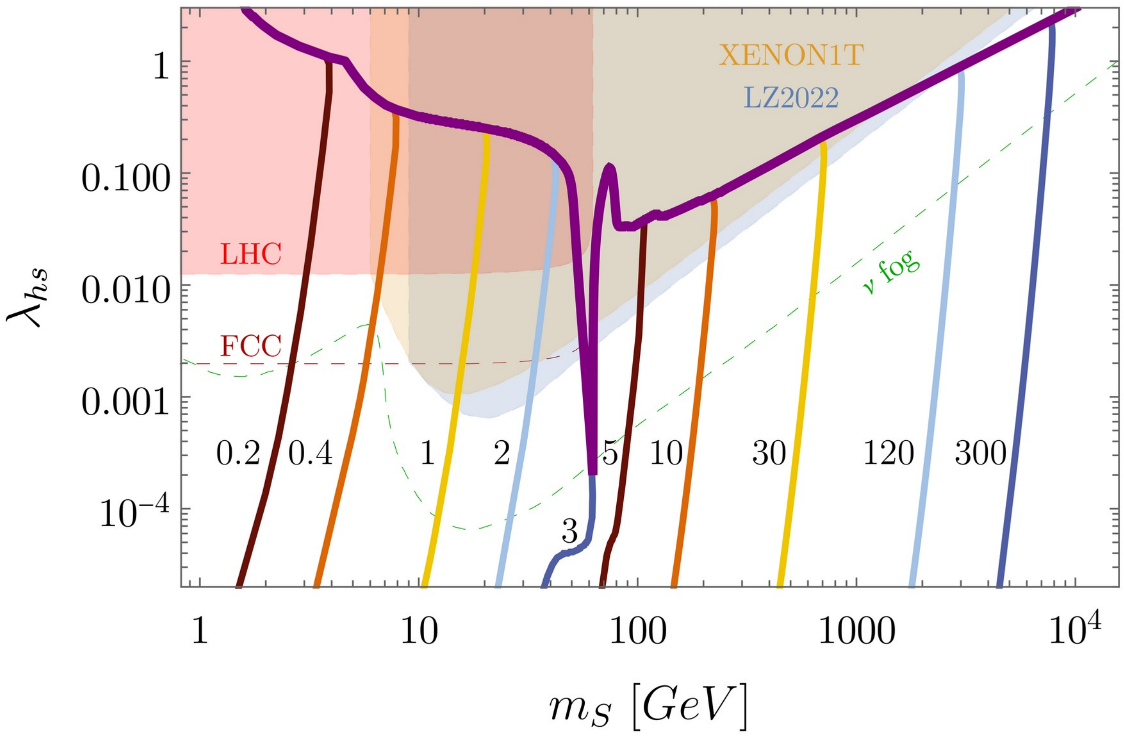
arXiv:2405.03760



· Smooth passage from freeze-in to freeze-out, as backreactions become more important.

· New parameter space regions open up, which re-motivates old (and new) searches.

Traditional dark matter searches remain relevant

Issues with t-channels : the problems

Although in principle quite straightforward, processes involving particle exchange in the t-channel may present some peculiarities :

Spin-1 particle exchange leads to constant σ at high temperatures → $Y_{\rm DM} \sim T_{\rm R}$ even for renormalizable models.

Issue only appears in FI

If a stable particle is exchanged in the t-channel, σ diverges as the particle becomes on-shell.

Issue appears both in FI and in FO

Both problems appear due to the utilisation of zero-temperature, in-vacuum QFT. Physically, they are *ficticious*.

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Both problems appear due to the utilisation of zero-temperature, in-vacuum QFT. Physically, they are *ficticious*.

In particular, *in a medium*, at finite temperature :

- The vector mass receives a T-dependent contribution that scales as $M^2 \sim T^2$.
- Every particle (even a stable one) has a finite absorption probability ("width").

Issues with *t*-channels : solutions

Computing full-blown thermal corrections to masses/widths is beyond the scope of micrOMEGAs.

Matrix elements calculated at *tree-level*

NB: We *cannot* simply replace T-dependent masses (gauge invariance).

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Observation : consider $e^+ e^- \to \nu_e \bar{\nu}_e$ and compute the integrated cross-section with a cut c on the scattering angle

$$\sigma(\sqrt{s}, M_W, c) = 4\hat{\sigma}_{e\nu_e}\left(\frac{1}{2\mu^2+c} + \log\left(\frac{2\mu^2+c}{2}\right) + \mu^2\log\left(\frac{2\mu^2+c}{2}\right) + 1 - c + \frac{c^2}{4(-2+c-2\mu^2)} + \frac{c(c-4)}{4(c+2\mu^2)} - (1+\mu^2)\log\left(1+\mu^2-c/2\right)\right)$$

Where $\mu^2 = M_W^2/s, \quad \hat{\sigma}_{e\nu_e} = \pi\alpha^2/(8 s_W^4 s)$ and $\{\mu, c\}$ enter both singularities through the same combination $2\mu^2 + c$

> The effect of a T-dependent mass can be captured by a zero-temperature calculation with a T-dependent cut on the scattering angle (or the p_T).

In practice: user-defined p_T cuts for all relevant particles

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In practice: user-defined p_T cuts for all relevant particles

For stable particles: introduce a small width ~M/100 for t-channel particles.

Improvements for other observables

cf also Bryan's talk

- **Direct detection:**

In general multi-component models, one cannot naïvely impose DD limits: simple rescaling by the fraction of each component is not enough.

In MO6 a function is provided in order to compute whether a model is excluded or not by the leading DD experiments.

- **Indirect detection:**

Consistent tabulation of of DM annihilation photon spectra also for $m_{\rm DM} < 2$ GeV.

In MO6 the gamma-ray tables have been updated/improved to include annihilations into light leptons, pions, Kaons.

+ new Planck CMB constraints from electron/photon injection.

- **Structure formation:**

Free-streaming length of DM particles through:

$$\lambda_{FS} = \int_{T_2}^{T_1} \left(1 + \left(\frac{a(T)m}{a(T_1)p} \right)^2 \right)^{-\frac{1}{2}} \frac{dT}{a(T)\overline{H}(T)T}$$

Summary and outlook

· Dark matter tools have evolved *significantly* during the last few years, and they continue doing so.

· They are now capable of dealing with issues such as: generalized cosmological settings, self-interactions, loop-induced processes, alternative dark matter generations mechanisms, generic dark matter models.

· Which tool you should use really depends on what exactly it is that you're trying to do. Apart from a common core, each code may offer specific functionalities which might be best suited for your purposes.

· Specialized tasks may require specialized codes. Each code has its limitations!

cf codes that don't compute the DM abunance

· All of these tools have been developed by people from *within* our community and they evolve thanks to the feedback *from* the community.

· Future directions: DM production during/due to inflaton decay, phase transitions, unintegrated Boltzmann equations…

→ With N. Bernal