The MicrOMEGAs dark matter code

Dark Tools 2025 workshop

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Context

A bit of history: $\chi_1{}^0$ freeze-out relic density

· Already since the early 80’s, different groups wanted to compute the $\chi_1{}^0$ relic abundance in the MSSM. In principle, this involves:

- Calculating matrix elements for ∼3000 processes.
- Writing down numerical code to evaluate them.
- Writing down the relevant Boltzmann equations.
- Developing numerical code to solve them.

· Common feature: all relevant expressions were *hard-coded*.

· Moreover: if you came up with a different dark matter model, you had to repeat the entire procedure.

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However:

· Automatic matrix element generators existed already since the 80s.

· At the end of the day, one only needed a single Boltzmann equation.

Could this procedure be automatized?

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 micrOMEGAs and how does it work?

So, what is micrOMEGAs ?

MicrOMEGAs

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

A C code to compute dark matter observables for user-defined dark matter models and according to different dark matter generation mechanisms.

Concretely, given a (appropriately defined, *cf* later) BSM model, the code can:

· Work out which particle is the "DM candidate" (*i.e.* the lightest stable state).

Within a particle physics-inspired, "Boltzmann equation"-like approach

· Figure out many processes which are relevant for its number density evolution.

By default tree-level 1/2 ↔ 2, possibility for 2 → 3/4 and to replace <σv> with own expression.

· Compute the necessary matrix elements/cross-sections.

Based on CalcHEP

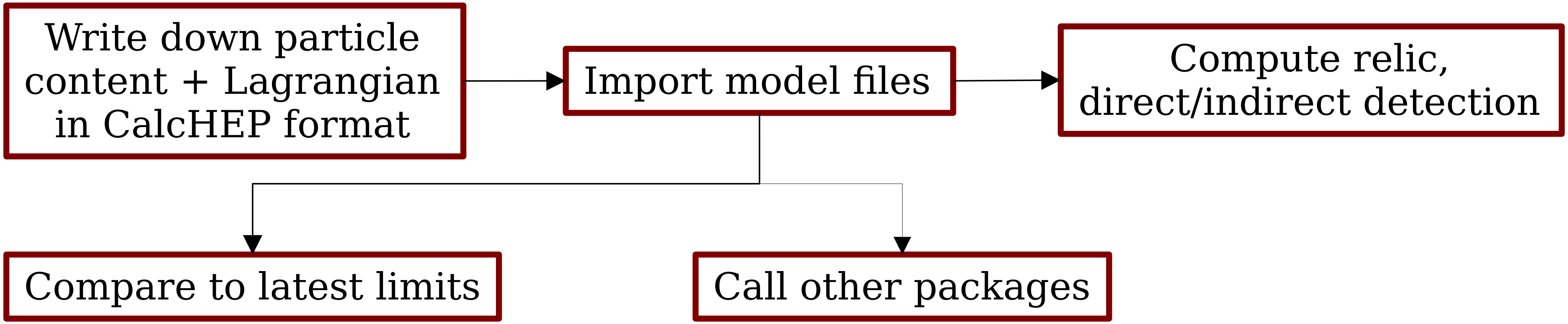
· Work out and solve the necessary Boltzmann equations, to compute the predicted DM relic abundance.

· Compute observables for several direct/indirect dark matter searches.

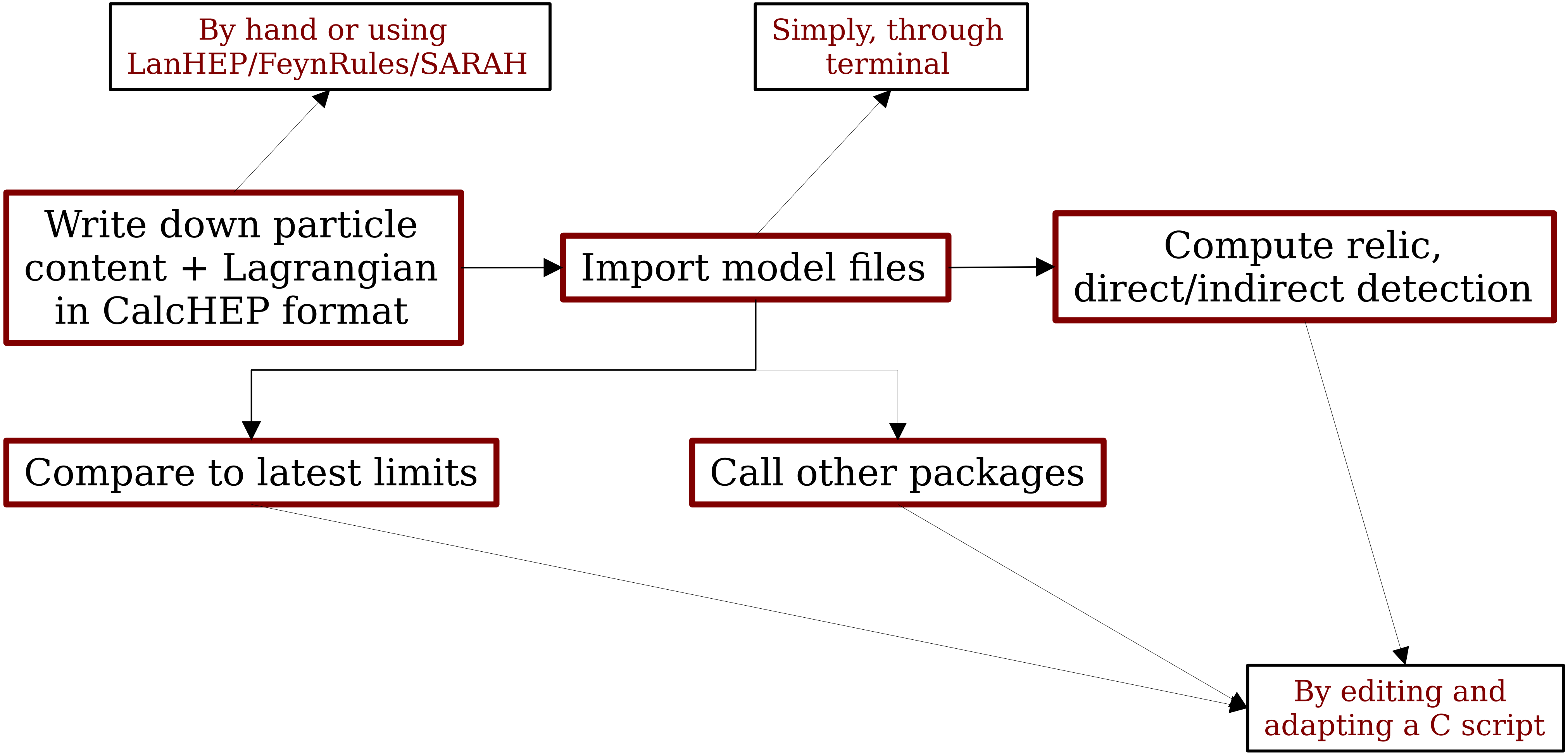
· Compute decay widths and cross-sections.

· Link to other packages for additional HEP constraints etc.

General workflow



General workflow



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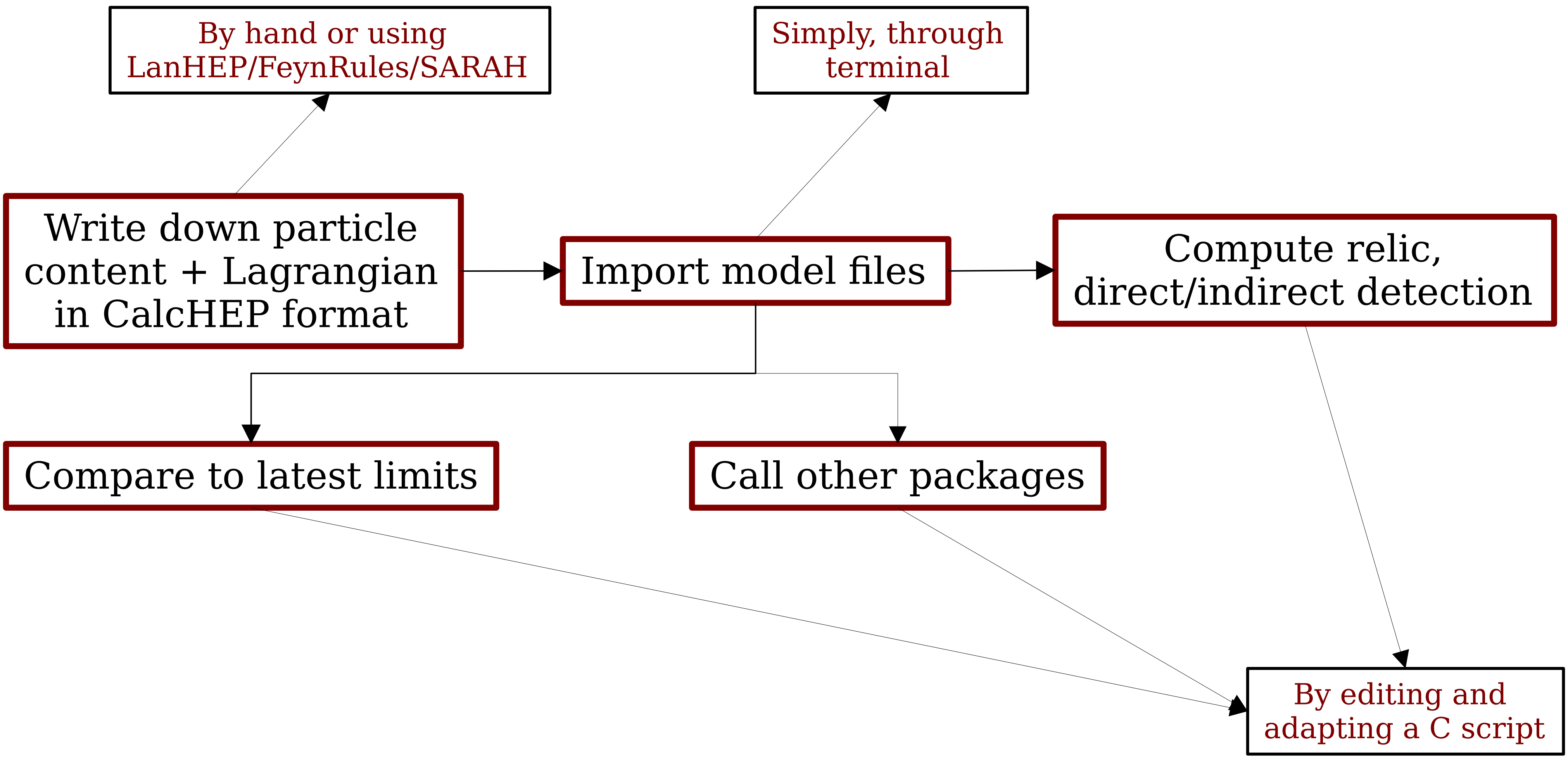

Current version:

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]

arXiv:2312.14894

Example model: singlet scalar DM

Consider an extension of the Standard Model by a real singlet scalar field *s* which is odd under a discrete $\mathbf{Z}_2$ symmetry, with all the SM particles being even.

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu s)(\partial^\mu s) - \frac{\mu_s^2}{2} s^2 - \frac{\lambda_s}{4} s^4 - \frac{\lambda_{sh}}{2} s^2 (H^\dagger H)$$

Once EW symmetry is broken, *s* can interact (at tree-level and max 2 ↔ 2):

· In pairs, with a single Higgs boson (s-*s*-*h* vertex).

· In pairs, with a pair of Higgs bosons (s-*s*-*h*-*h* vertex).

In order to use micrOMEGAs we need to specify (in CalcHEP format):

· The nature of the particles in the model (how many particles, their names, spins and $\mathbf{Z}_2$ charges).

· How they interact with each other (the vertices).

→ This can be done by directly writing this information down in CalcHEP format or using external packages.

Elements of a micrOMEGAs model

Each model is described by a basic set of files:

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SingletScalarDM
 Particles
 Full   name   |A           |A+          | number |2*spin| mass            |width           |color|aux|>LaTex(A)<|>LaTeX(A+)   <|
Photon         |a           |a           |22      |2     |0                |0               |1    |G  |a         |a             |
Z              |Z           |Z           |23      |2     |MZ               |!WZ             |1    |G  |Z         |Z             |
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H           |H           |H           |H           |x1x0                         |1
```

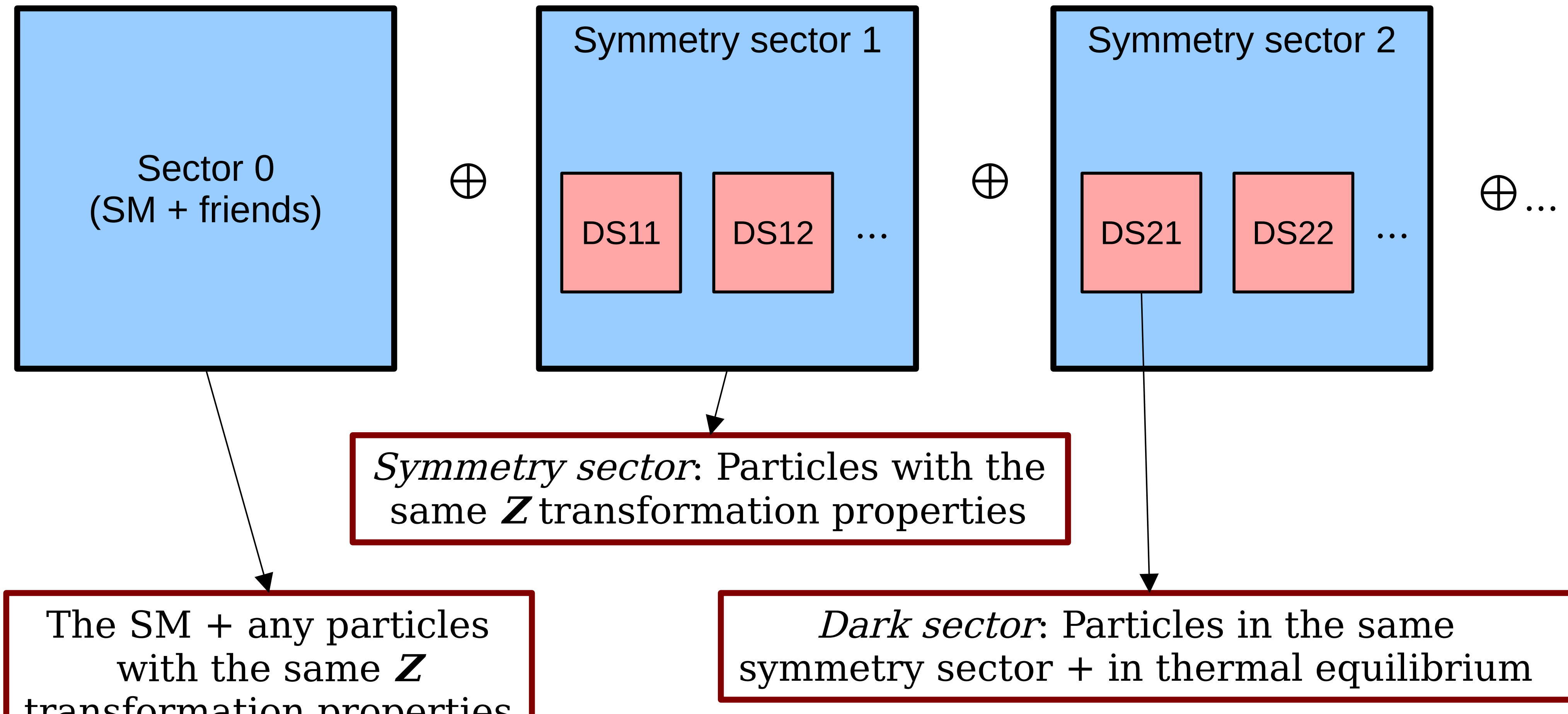
· A file containing all the internal parameters of the model (func1.mdl)

```
muss          |pow(pow(mss,2)-lamssh*pow(vev,2),0.5)                                        % Dark scalar mass parameter
x1x0          |-6*lam                                                                       % H    H    H    H      coupling.
```

(In some sense)
The most general thing you can do with micrOMEGAs 6

Multi-component dark matter

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



Notation: DSs w/ greek indices, particles within a DS w/ latin ones

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:

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

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

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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 CDFO

CDFO involves 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.

Including CDFO, freeze-in

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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 routine: 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

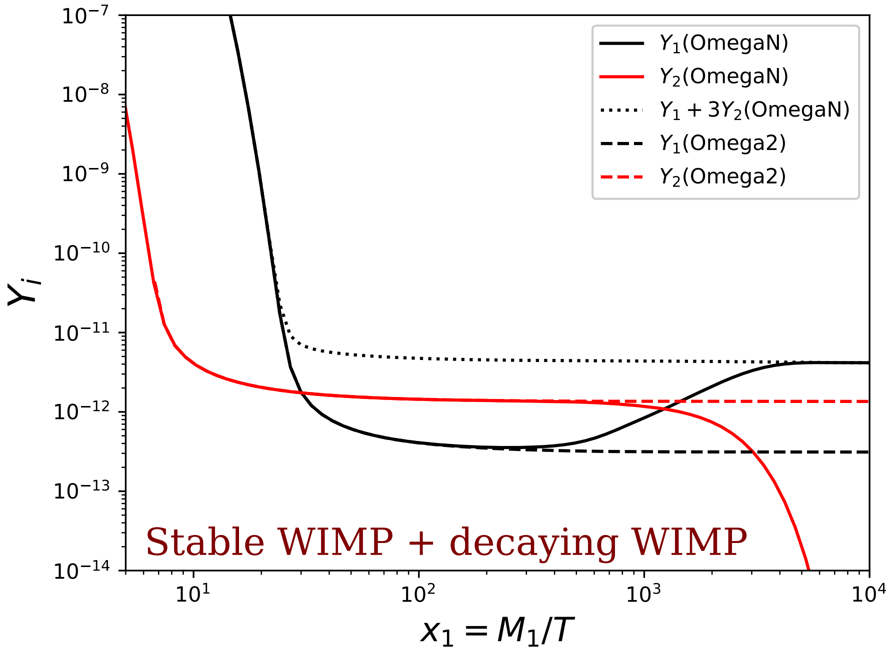
The code was validated using different models as examples :

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

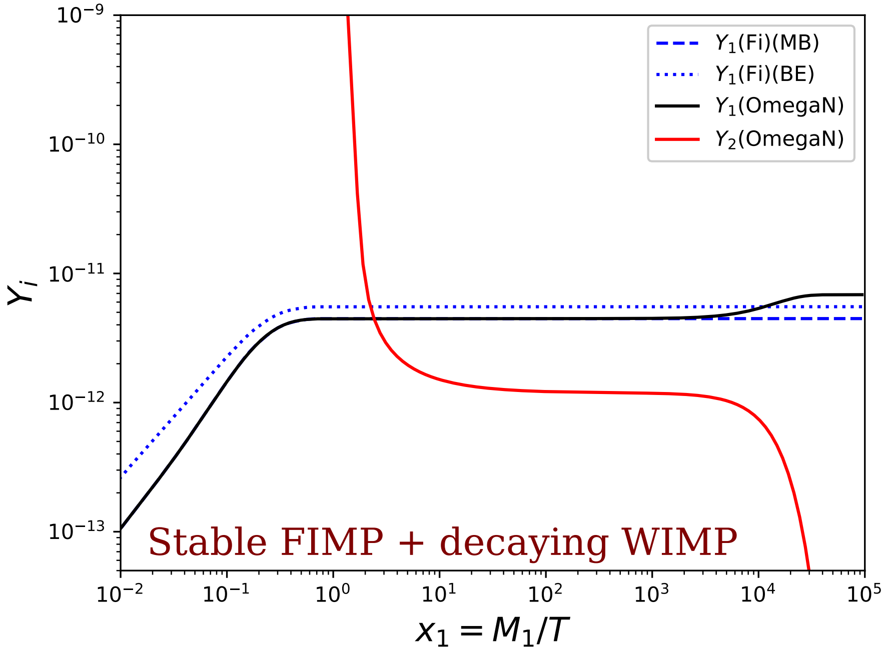
· Z5M (two singlets w/ $\boldsymbol{Z}_5$ symmetry, 2 WIMPs or 1 WIMP + 1 FIMP).

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

Two examples from the Z5M :



Decay occurs through λ $\varphi_2\ \varphi_1^3$ coupling



Decay occurs through μ $\varphi_2\ \varphi_1^2$ coupling

Excellent agreement w/ previous versions until decays become relevant.

(Some)
Concluding comments

(Highly biased) Development comments

MicrOMEGAs is a code that has been consistently developed since ∼25 years by physicists and for physicists.

Much like any other HEP code, it is clearly subject to its developers' bias as well as to the constraints imposed by its initial architecture.

Iron-clad principle (firmly imposed by G. Bélanger):

NEVER change a routine that works

Outcome:

You can use different functions in micrOMEGAs to do the same thing. This degeneracy can be useful for cross-checks and/or pointing out subtleties.

Although: some of them might involve different assumptions (*e.g.* particle statistics).

Much like any other DM code, micrOMEGAs makes sense to use for specific classes of DM theories (not axions, BPH's, confining sectors).

Summary and final comments

· micrOMEGAs is a computer program that allows you to compute the dark matter abundance in the Universe along with other observables in general extensions of the Standard Model of particle physics.

· There are other dark matter codes, (*cf* all the other dedicated talks!), *and this is a good thing* ! It allows for comparison, validation and versatility.

· Additional specialized tasks can be performed by other codes (*cf* the other hands-on sessions).

· Two of the strongest points of micrOMEGAs: capability to implement new models without modifying the core of the code, possibility to compute the freeze-in DM abundance and handle multi-component DM scenarios.

· Many ideas on how to further expand the code, also depending on requests from the community. Main current efforts: generalized cosmological histories.

Thank you!