# RelExt: A New Dark Matter Tool for the Exploration of Dark Matter Models

16.06.2025

Johann Plotnikov in collaboration with R. Capucha, K. Elyaouti, M. M. Mühlleitner, R. Santos

DEPARTMENT OF PHYSICS, INSTITUTE OF THEORETICAL PHYSICS

# Introduction into Dark Matter (DM)

It exists.

# It exists.

With a relic density of $\Omega h^2 = 0.120 \pm 0.001$ [PLANCK 2018]

# Why another one?

# Why another one?

DarkPack [Palmiotto et al.]

# Why another one?

DarkPack [Palmiotto et al.]

MadDM [Ambrogi et al.]

# Why another one?

DarkPack [Palmiotto et al.]

MadDM [Ambrogi et al.]

MicrOMEGAs [Goudelis et al.]

# Why another one?

DarkPack [Palmiotto et al.]

MadDM [Ambrogi et al.]

MicrOMEGAs [Goudelis et al.]

DarkSUSY [Bringmann et al.]

# Why another one?

DarkPack [Palmiotto et al.]

MadDM [Ambrogi et al.]

MicrOMEGAs [Goudelis et al.]

DarkSUSY [Bringmann et al.]

SuperIso Relic [Mahmoudi et al.]

# Motivation

Distinguish between two types of freeze-out models:

# Motivation

Distinguish between two types of freeze-out models:

- Models with few particles and parameters

# Motivation

Distinguish between two types of freeze-out models:

- Models with few particles and parameters

**RxSM**

# Motivation

Distinguish between two types of freeze-out models:

- Models with few particles and parameters

**RxSM** **CxSM**

# Motivation

Distinguish between two types of freeze-out models:

- Models with few particles and parameters

**RxSM** **CxSM** **TRSM**

# Motivation

Distinguish between two types of freeze-out models:

- Models with few particles and parameters

**RxSM** **CxSM** **TRSM**

$\rightarrow$ Easy to obtain the **full** relic density

# Motivation

Distinguish between two types of freeze-out models:

- Models with few particles and parameters

**RxSM** **CxSM** **TRSM**

→ Easy to obtain the **full** relic density

- Models with many particles and parameters

# Motivation

Distinguish between two types of freeze-out models:

- Models with few particles and parameters

**RxSM** **CxSM** **TRSM**

$\rightarrow$ Easy to obtain the **full** relic density

- Models with many particles and parameters

**2HDM**

# Motivation

Distinguish between two types of freeze-out models:

- Models with few particles and parameters

**RxSM** **CxSM** **TRSM**

$\rightarrow$ Easy to obtain the **full** relic density

- Models with many particles and parameters

**2HDM** **BDM5**

# Motivation

Distinguish between two types of freeze-out models:

- Models with few particles and parameters

**RxSM** **CxSM** **TRSM**

$\rightarrow$ Easy to obtain the **full** relic density

- Models with many particles and parameters

**2HDM** **BDM5** **SUSY**

# Motivation

Distinguish between two types of freeze-out models:

- Models with few particles and parameters

**RxSM** **CxSM** **TRSM**

$\rightarrow$ Easy to obtain the **full** relic density

- Models with many particles and parameters

**2HDM** **BDM5** **SUSY**

$\rightarrow$ Difficult to obtain the **full** relic density

# Motivation

Distinguish between two types of freeze-out models:

- Models with few particles and parameters

**RxSM** **CxSM** **TRSM**

$\rightarrow$ Easy to obtain the **full** relic density

- Models with many particles and parameters

**2HDM** **BDM5** **SUSY**

$\rightarrow$ Difficult to obtain the **full** relic density
$\rightarrow$Resort to **agnosticism** about additional particles

**Agnosticism** *noun* [u]
the fact that someone does not know or does not have an opinion about whether something is true, good, correct, etc. [Cambridge Dictionary]

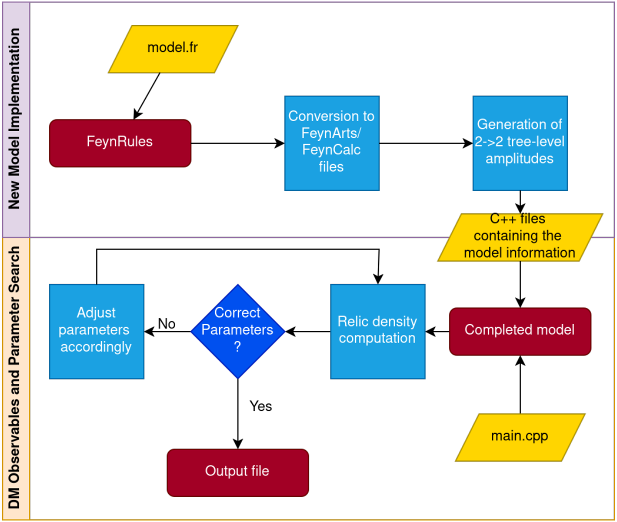
**Agnosticism** *noun* [u]
the fact that someone does not know or does not have an opinion about whether something is true, good, correct, etc. [Cambridge Dictionary]

**Knowledge** *noun*
actually knowing stuff. [Me]

## Goal of RelExt:

Find parameter regions which lead to the **full** measured relic density

# RelExt


New Model Implementation
model.fr
FeynRules
Conversion to FeynArts/ FeynCalc files
Generation of 2->2 tree-level amplitudes
C++ files containing the model information
DM Observables and Parameter Search
Adjust parameters accordingly
No
Correct Parameters ?
Relic density computation
Completed model
Yes
main.cpp
Output file

# Search Algorithms

# Search Algorithms

- Monte Carlo Grid Search

# Search Algorithms

- Monte Carlo Grid Search
  - Points of initial run do not lead to the **full** relic density

# Search Algorithms

- Monte Carlo Grid Search
  - \- Points of initial run do not lead to the **full** relic density
  - \+ Fast generation of new parameter points

# Search Algorithms

- Monte Carlo Grid Search
  - \- Points of initial run do not lead to the **full** relic density
  - \+ Fast generation of new parameter points
  - \+ Search improves with each run

# Search Algorithms

- Monte Carlo Grid Search
  - \- Points of initial run do not lead to the **full** relic density
  - \+ Fast generation of new parameter points
  - \+ Search improves with each run
- Single Parameter Search

# Search Algorithms

- Monte Carlo Grid Search
  - \- Points of initial run do not lead to the **full** relic density
  - \+ Fast generation of new parameter points
  - \+ Search improves with each run
- Single Parameter Search
  - \- Adjustment of only one parameter of the model

# Search Algorithms

- Monte Carlo Grid Search
  - \- Points of initial run do not lead to the **full** relic density
  - \+ Fast generation of new parameter points
  - \+ Search improves with each run
- Single Parameter Search
  - \- Adjustment of only one parameter of the model
  - \+ Fast, since only 1-dimensional

# Search Algorithms

- Monte Carlo Grid Search
  - \- Points of initial run do not lead to the **full** relic density
  - \+ Fast generation of new parameter points
  - \+ Search improves with each run
- Single Parameter Search
  - \- Adjustment of only one parameter of the model
  - \+ Fast, since only 1-dimensional
  - \+ Easy to investigate impact of parameters

# Search Algorithms

- Monte Carlo Grid Search
  - \- Points of initial run do not lead to the **full** relic density
  - \+ Fast generation of new parameter points
  - \+ Search improves with each run
- Single Parameter Search
  - \- Adjustment of only one parameter of the model
  - \+ Fast, since only 1-dimensional
  - \+ Easy to investigate impact of parameters
- Random Walk

# Search Algorithms

- Monte Carlo Grid Search
  - \- Points of initial run do not lead to the **full** relic density
  - \+ Fast generation of new parameter points
  - \+ Search improves with each run
- Single Parameter Search
  - \- Adjustment of only one parameter of the model
  - \+ Fast, since only 1-dimensional
  - \+ Easy to investigate impact of parameters
- Random Walk
  - \- Slow, since n-dimensional and random

# Search Algorithms

- Monte Carlo Grid Search
  - \- Points of initial run do not lead to the **full** relic density
  - \+ Fast generation of new parameter points
  - \+ Search improves with each run
- Single Parameter Search
  - \- Adjustment of only one parameter of the model
  - \+ Fast, since only 1-dimensional
  - \+ Easy to investigate impact of parameters
- Random Walk
  - \- Slow, since n-dimensional and random
  - \+ Adjusts multiple parameters at once

# Example

# CP in the Dark [Azevedo et al. 2018]

# CP in the Dark [Azevedo et al. 2018]

Extend the scalar sector of the SM with one complex scalar doublet $\Phi_2$ and one real scalar singlet $\Phi_s$ with the following $\mathbb{Z}_2$-symmetry

$$\Phi_{SM} \to \Phi_{SM}\ ,\ \Phi_2 \to -\Phi_2\ ,\ \Phi_s \to -\Phi_s$$

Institute for Theoretical Physics

# CP in the Dark [Azevedo et al. 2018]

Extend the scalar sector of the SM with one complex scalar doublet $\Phi_2$ and one real scalar singlet $\Phi_s$ with the following $\mathbb{Z}_2$-symmetry

$$\Phi_{SM} \to \Phi_{SM}\ ,\ \Phi_2 \to -\Phi_2\ ,\ \Phi_s \to -\Phi_s$$

$$\begin{aligned} V_{\text{Scalar}} = \ & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + \frac{\lambda_1}{2}\left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger \Phi_2\right)^2 \\ & + \lambda_3 \Phi_1^\dagger \Phi_1 \Phi_2^\dagger \Phi_2 + \lambda_4 \Phi_1^\dagger \Phi_2 \Phi_2^\dagger \Phi_1 + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger \Phi_2\right)^2 + \text{h.c.}\right] \\ & + \frac{1}{2} m_s^2 \Phi_s^2 + \frac{\lambda_6}{8}\Phi_s^4 + \frac{\lambda_7}{2}\Phi_1^\dagger \Phi_1 \Phi_s^2 + \frac{\lambda_8}{2}\Phi_2^\dagger \Phi_2 \Phi_s^2 \\ & + (A \Phi_1^\dagger \Phi_2 \Phi_s + \text{h.c.}) \end{aligned}$$

# CP in the Dark [Azevedo et al. 2018]



After electroweak symmetry breaking

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(\rho_1 + i\eta) \end{pmatrix}, \quad \Phi_s = \rho_s$$

and mass diagonalization with angles $\alpha_{1,2,3}$

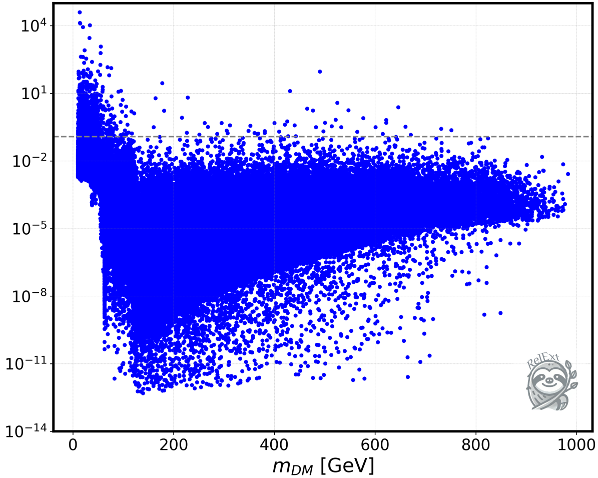
$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \eta \\ \rho_s \end{pmatrix}$$

We are left with 11 input parameters

$$m_{h_1}, \quad m_{h_2}, \quad m_{H^+}, \quad \alpha_1, \quad \alpha_2, \quad \alpha_3, \quad \lambda_2, \quad \lambda_6, \quad \lambda_8, \quad m_{22}, \quad m_s$$

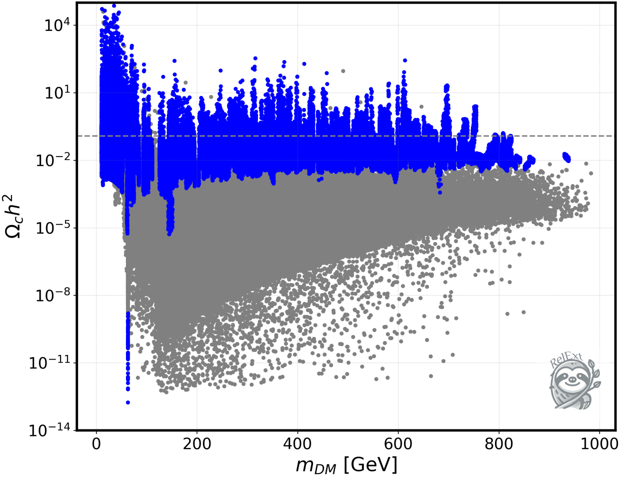
# Initial Monte Carlo

# Initial Monte Carlo



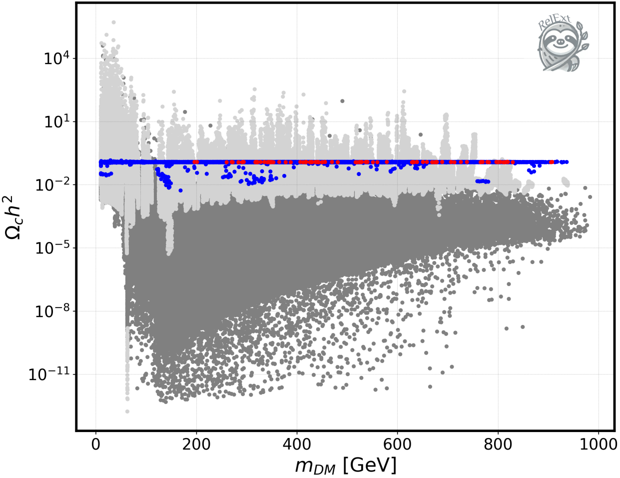
# Second Monte Carlo

# Second Monte Carlo



# Random Walk

# Random Walk



$10^4$
$10^1$
$10^{-2}$
$10^{-5}$
$10^{-8}$
$10^{-11}$
$\Omega_c h^2$
0
200
400
600
800
1000
$m_{DM}$ [GeV]
RelExt

# Computation Time

| Method | points | % within $2\sigma$ | [good points]/[CPU time] |
|---|---|---|---|
| Random $m_{\text{DM}} > m_h$ | $10^5$ | 0.% | $\sim$0 s$^{-1}$ |
| Random $m_{\text{DM}} < m_h$ | $10^5$ | 0.027% | $\sim$0.0012 s$^{-1}$ |
| Best cells $m_{\text{DM}} > m_h$ | $10^5$ | 0.29% | $\sim$0.0178 s$^{-1}$ |
| Best cells $m_{\text{DM}} < m_h$ | $10^5$ | 3.66% | $\sim$0.135 s$^{-1}$ |
| Best cells with `RWalk` $m_{\text{DM}} > m_h$ | $10^4$ | 97.5% | $\sim$0.065 s$^{-1}$ |
| Best cells with `RWalk` $m_{\text{DM}} < m_h$ | $10^4$ | 97.3% | $\sim$0.085 s$^{-1}$ |

# Conclusions

# Conclusions

# Conclusions

- Automated relic density computation: **RelExt** facilitates relic density calculations for various DM models with a $\mathbb{Z}_2$ symmetry

# Conclusions

- Automated relic density computation: **RelExt** facilitates relic density calculations for various DM models with a $\mathbb{Z}_2$ symmetry
- Efficient scanning methods, which improve the search for viable DM candidates

# Conclusions

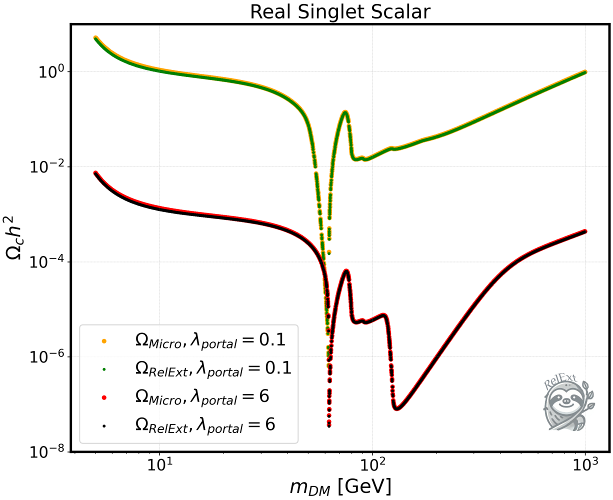
- Automated relic density computation: **RelExt** facilitates relic density calculations for various DM models with a $\mathbb{Z}_2$ symmetry
- Efficient scanning methods, which improve the search for viable DM candidates
- Compatible with other tools like **ScannerS** [Basler et al.] and **BSMPT** [Biermann et al.]

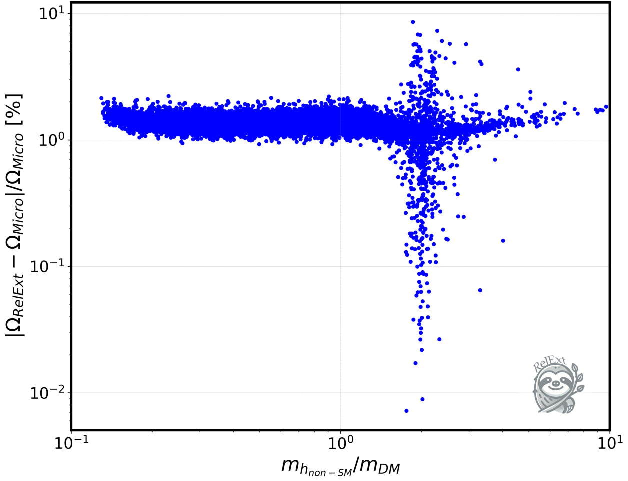
# Conclusions

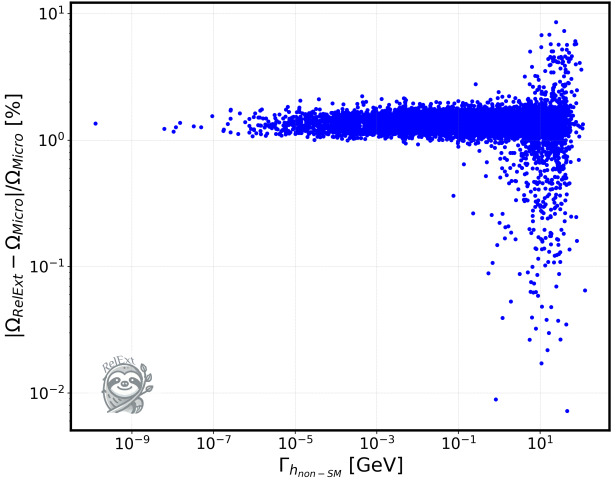
- Automated relic density computation: **RelExt** facilitates relic density calculations for various DM models with a $\mathbb{Z}_2$ symmetry
- Efficient scanning methods, which improve the search for viable DM candidates
- Compatible with other tools like **ScannerS** [Basler et al.] and **BSMPT** [Biermann et al.]
- Next steps: Further optimizations, inclusion of additional DM production mechanisms and new models, next-to-leading order calculations, computation of direct detection

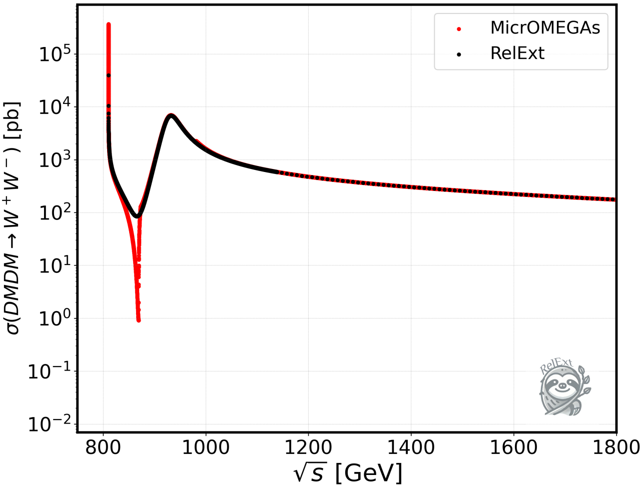
# Thank you for listening!

# Backup

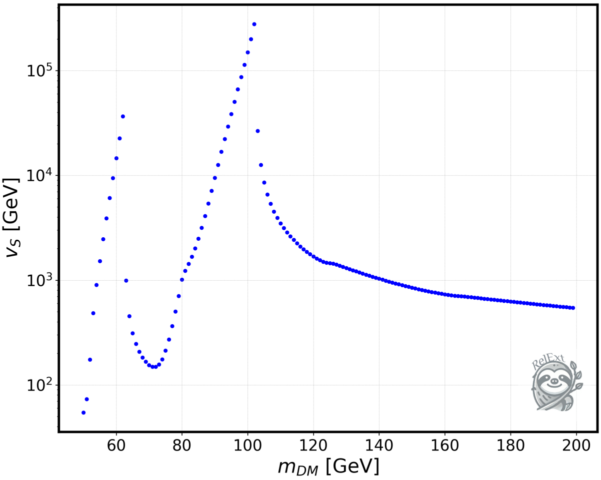

Real Singlet Scalar
$\Omega_c h^2$
$10^{0}$
$10^{-2}$
$10^{-4}$
$10^{-6}$
$10^{-8}$
$10^{1}$
$10^{2}$
$10^{3}$
$m_{DM}$ [GeV]
$\Omega_{Micro}, \lambda_{portal} = 0.1$
$\Omega_{RelExt}, \lambda_{portal} = 0.1$
$\Omega_{Micro}, \lambda_{portal} = 6$
$\Omega_{RelExt}, \lambda_{portal} = 6$
RelExt


$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$|\Omega_{RelExt} - \Omega_{Micro}|/\Omega_{Micro}$ [%]
$10^{-1}$
$10^0$
$10^1$
$m_{h_{non-SM}}/m_{DM}$


$|\Omega_{RelExt} - \Omega_{Micro}|/\Omega_{Micro}$ [%]
$10^{1}$
$10^{0}$
$10^{-1}$
$10^{-2}$
$10^{-9}$
$10^{-7}$
$10^{-5}$
$10^{-3}$
$10^{-1}$
$10^{1}$
$\Gamma_{h_{non-SM}}$ [GeV]
RelExt


MicrOMEGAs
RelExt
$10^{5}$
$10^{4}$
$10^{3}$
$10^{2}$
$10^{1}$
$10^{0}$
$10^{-1}$
$10^{-2}$
$\sigma(DMDM \to W^+W^-)$ [pb]
800
1000
1200
1400
1600
1800
$\sqrt{s}$ [GeV]
RelExt

| | N2HDM |
|---|---|
| $m_{h_{\text{SM}}}$ | 125.09 |
| $m_{h_{\text{non-SM}}}$ | 927.082 |
| $m_{H_D}$ | 405.215 |
| $m_{A_D}$ | 595.853 |
| $m_{H_D^{\pm}}$ | 628.737 |
| $\alpha$ | -0.248593 |
| $v_s$ | 292.978 |
| $m_{22}$ | 133.912 |
| $\lambda_2$ | 3.49988 |
| $\lambda_8$ | 2.34688 |
| $\Gamma_{h_{\text{SM}}}$ | 0.00490257 |
| $\Gamma_{h_{\text{non-SM}}}$ | 38.9219 |
| $\Omega_{\text{RelExt}} h^2$ | 0.000314878 |
| $\Omega_{\text{Micro}} h^2$ | 0.000339666 |


$10^5$
$10^4$
$10^3$
$10^2$
$v_S$ [GeV]
60
80
100
120
140
160
180
200
$m_{DM}$ [GeV]
RelExt