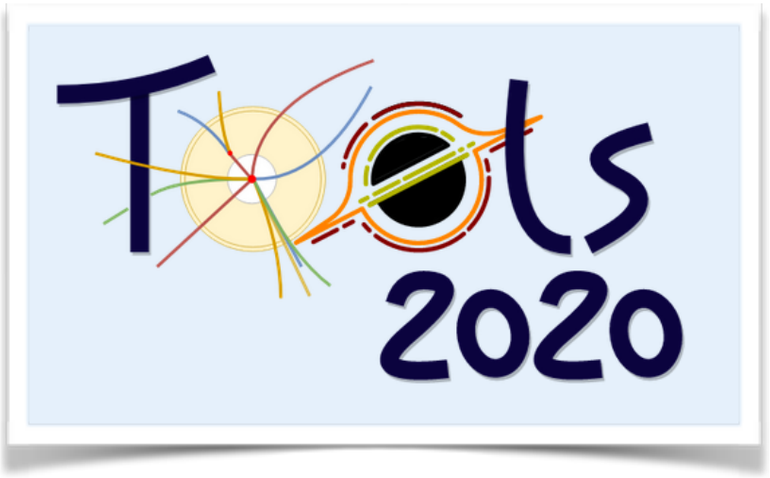
*Review on Dark Matter tools**

* possibly unbiased…

Chiara Arina

November 2nd 2020



RÉGION DE BRUXELLES-CAPITALE
BRUSSELS HOOFDSTEDELIJK GEWEST

INNOV IRIS
EMPOWERING RESEARCH

attract
BRAINS FOR BRUSSELS

UCLouvain

IRMP

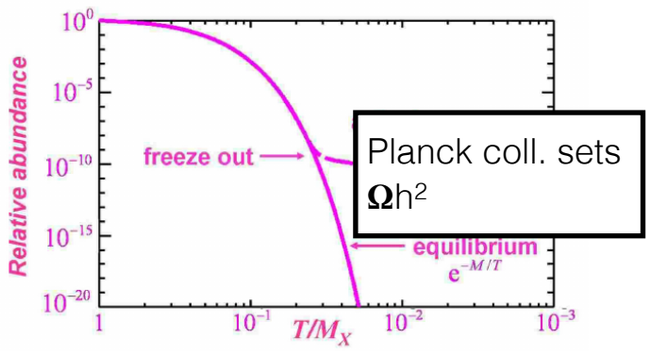
Phenomenologist dream

Model Predictions

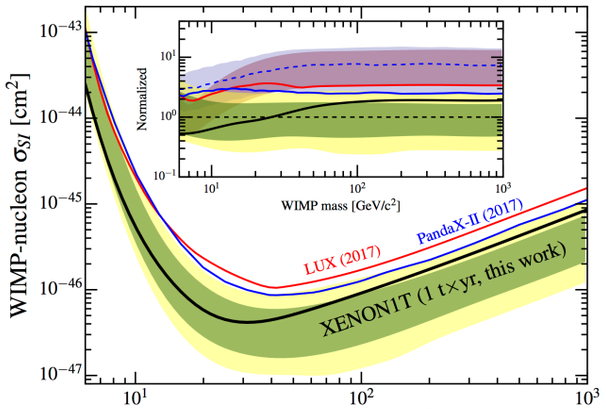
- relic density
- direct detection rates
- indirect detection signals
- collider signatures

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm BSM}$$

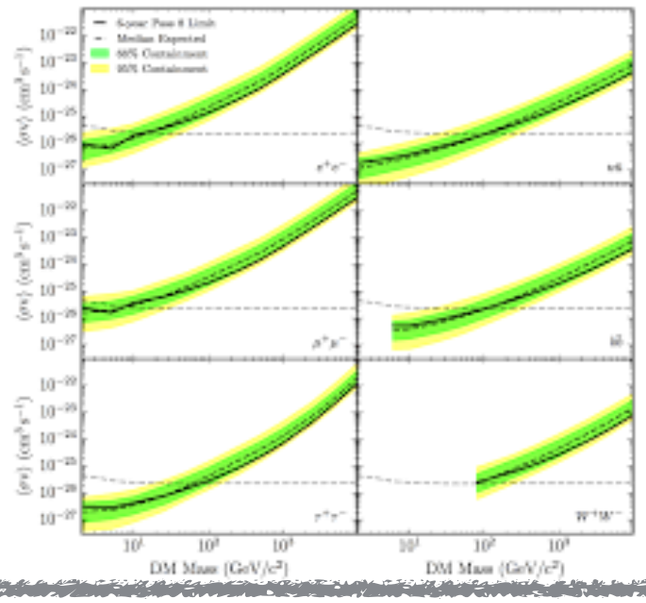
Experimental observations



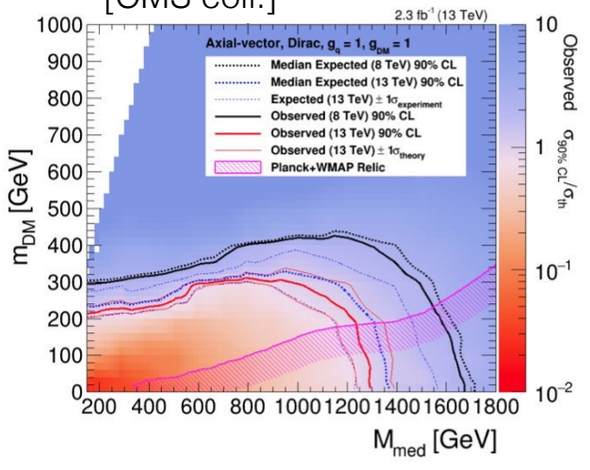
[XENON1T coll.]



[FermiLAT coll.]



[CMS coll.]



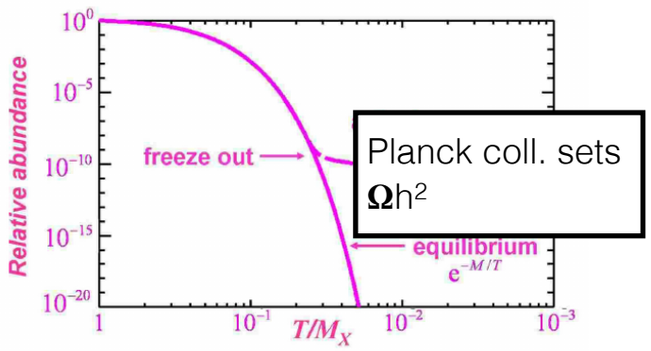
Phenomenologist dream

Model Predictions

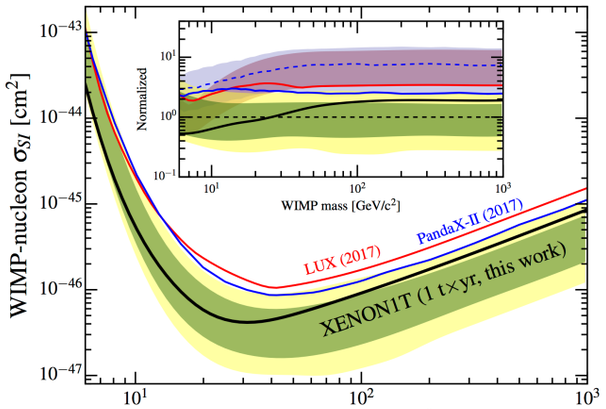
- relic density
- direct detection rates
- indirect detection signals
- collider signatures

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm BSM}$$

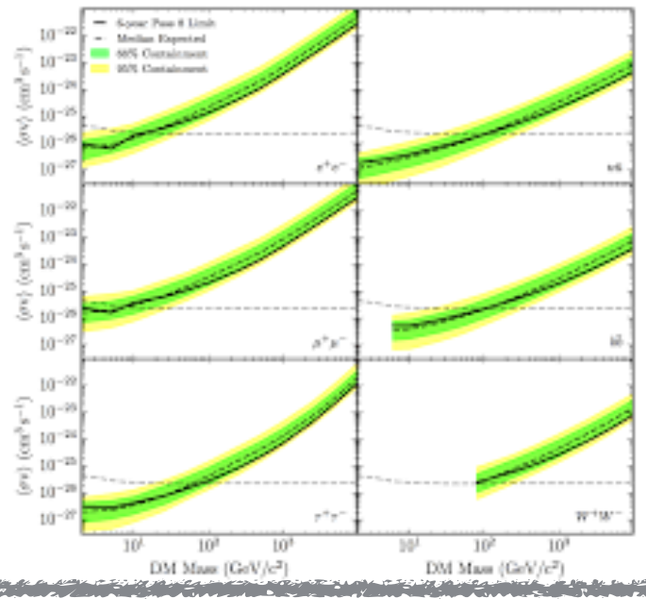
Experimental observations



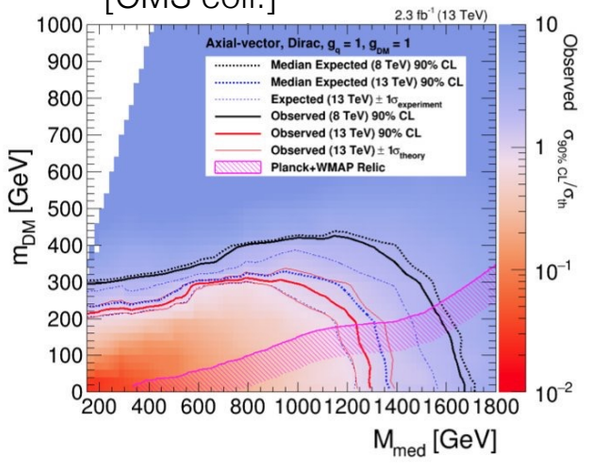
[XENON1T coll.]



[FermiLAT coll.]



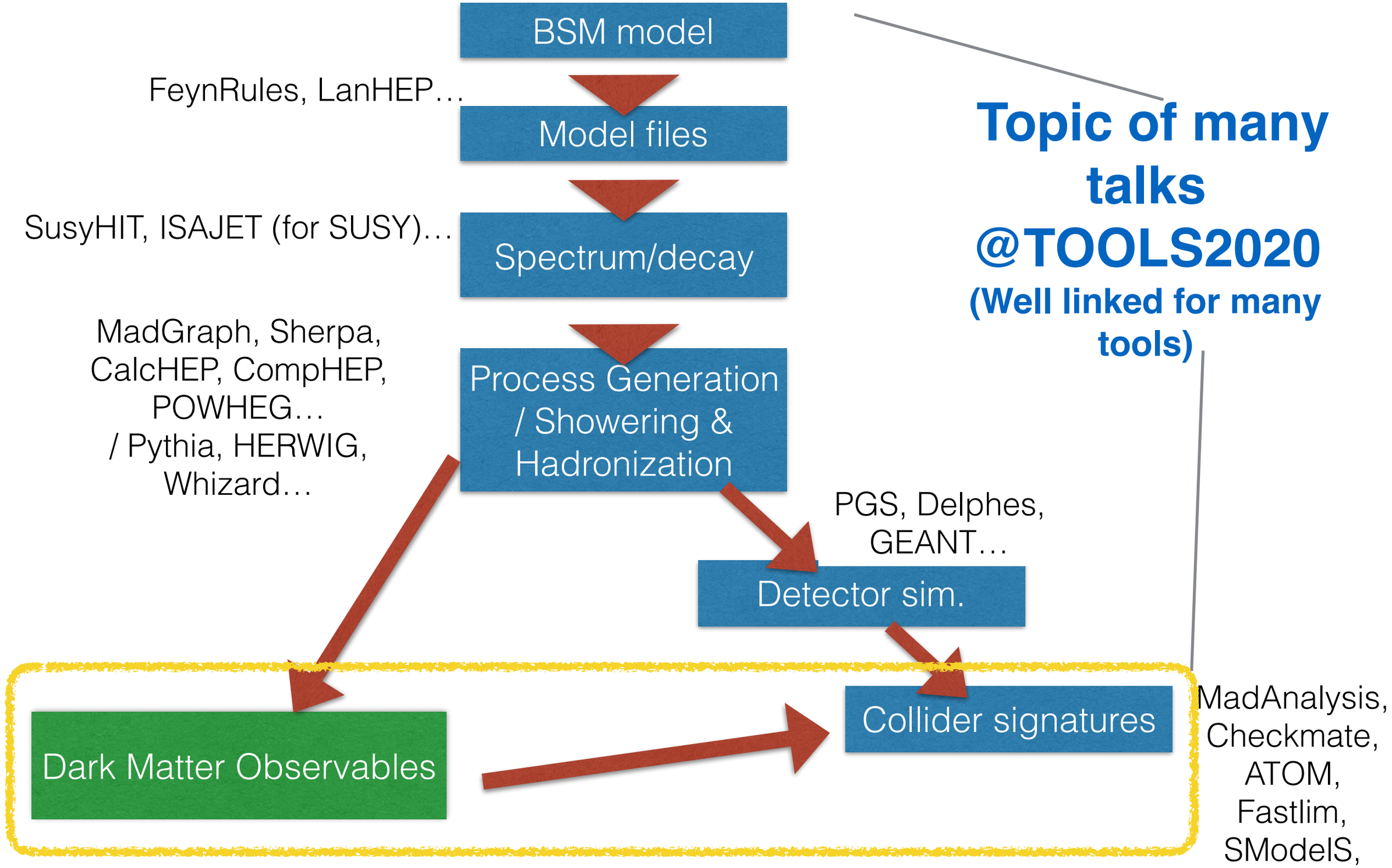
[CMS coll.]



Compute observables for a BSM model (SUSY, hidden sector,…)

Compare with experiments

Where do we stand in hep?



Topic of many talks @TOOLS2020

(Well linked for many tools)

Where do we stand in dark matter?

Generic BSM model:

- MicrOMEGAs [2001]
- DarkSUSY [2004]
- MadDM [2013]

SUSY related:

- DarkSUSY [2004]
- SuperBayes [Ruiz De Astrui, Trotta, … 2010]
- SuperIso Relic [2009]

Model independent

- PPPC4DM, NREFT [Cirelli et al. 2010]
- DarkBit [GAMBIT coll. 2017]
- Direct detection: DirectDM, RAPIDD, RunDM, DAMASCUS… [Bishara, Cheek, Kavanagh, Kouvaris, et al.]
- Indirect detection: USINE, DRAGON, GALPROP, CLUMPY, … [Hütten, Evoli, Maurin, Moskalenko, et al.]

Private codes [Drees, Roszkowski,Olive, …]

Where do we stand in dark matter?

Generic BSM model:

- MicrOMEGAs [2001]
- DarkSUSY [2004]
- MadDM [2013]

SUSY related:

- DarkSUSY [2004]
- SuperBayes [Ruiz De Astrui, Trotta, … 2010]
- SuperIso Relic [2009]

Model independent

- PPPC4DM, NREFT [Cirelli et al. 2010]
- DarkBit [GAMBIT coll. 2017]
- Direct detection: DirectDM, RAPIDD, RunDM, DAMASCUS… [Bishara, Cheek, Kavanagh, Kouvaris, et al.]
- Indirect detection: USINE, DRAGON, GALPROP, CLUMPY, … [Hütten, Evoli, Maurin, Moskalenko, et al.]

Private codes [Drees, Roszkowski,Olive, …]

COMPREHENSIVE
Coverage of a very wide range of functions and theoretical predictions

PRECISION
Capability of handling automatically complex manipulations

PORTABILITY
Capability of easy link with other tools and built-in chain of functionalities

INNOVATION
New features that incur in models beyond WIMPs

SuperIso Relic

Current version v4

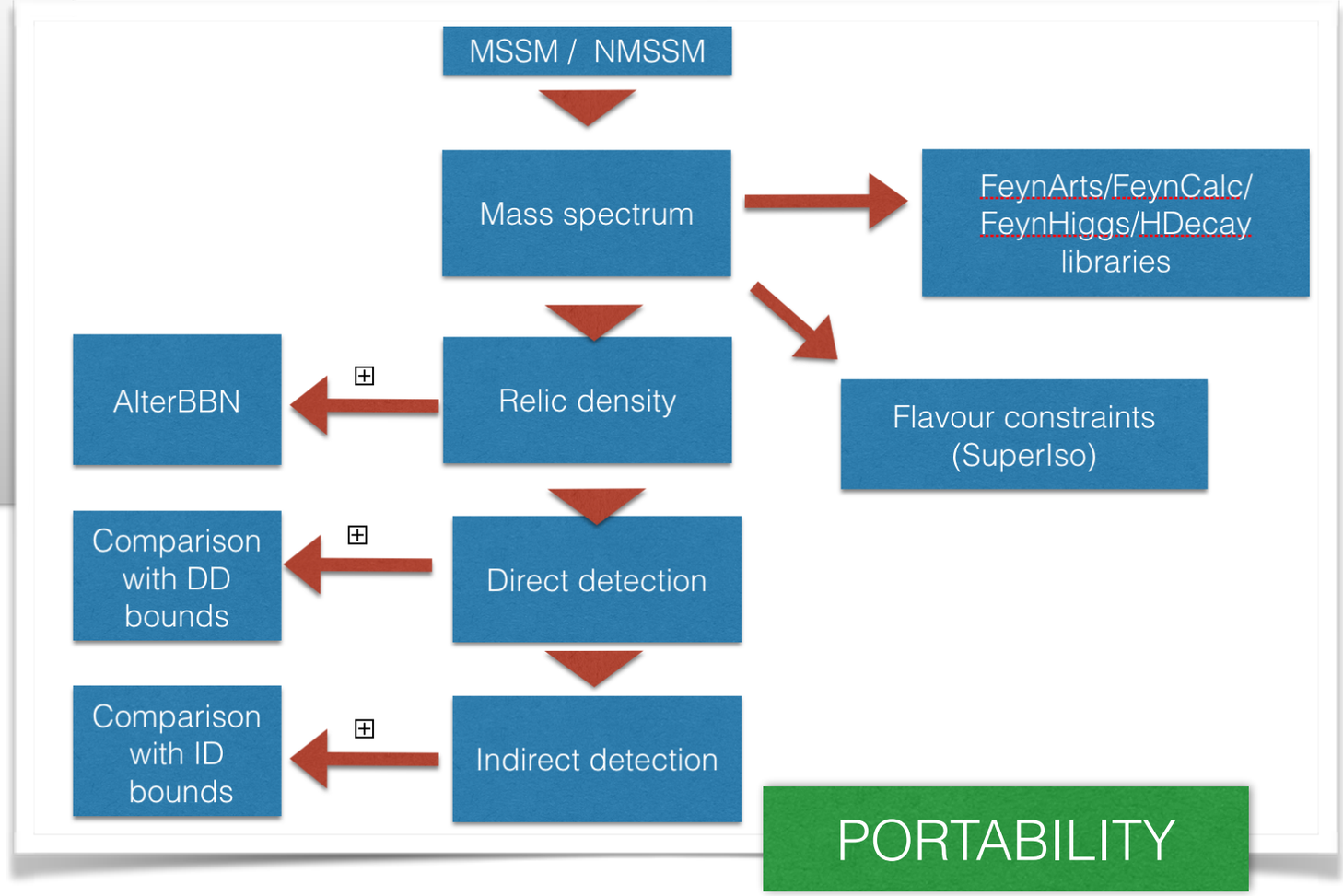
Manual, Website

A. Arbey, F. Mahmoudi, G. Robbins

Fortran/C code that computes dark matter observables in the MSSM and NMSSM

- relic density
- direct detection (DD)
- indirect detection (ID)
- cosmic-ray propagation
- nuclear and astrophysical uncertainties
- flavour constrains
- …

Very COMPREHENSIVE for SUSY



PORTABILITY

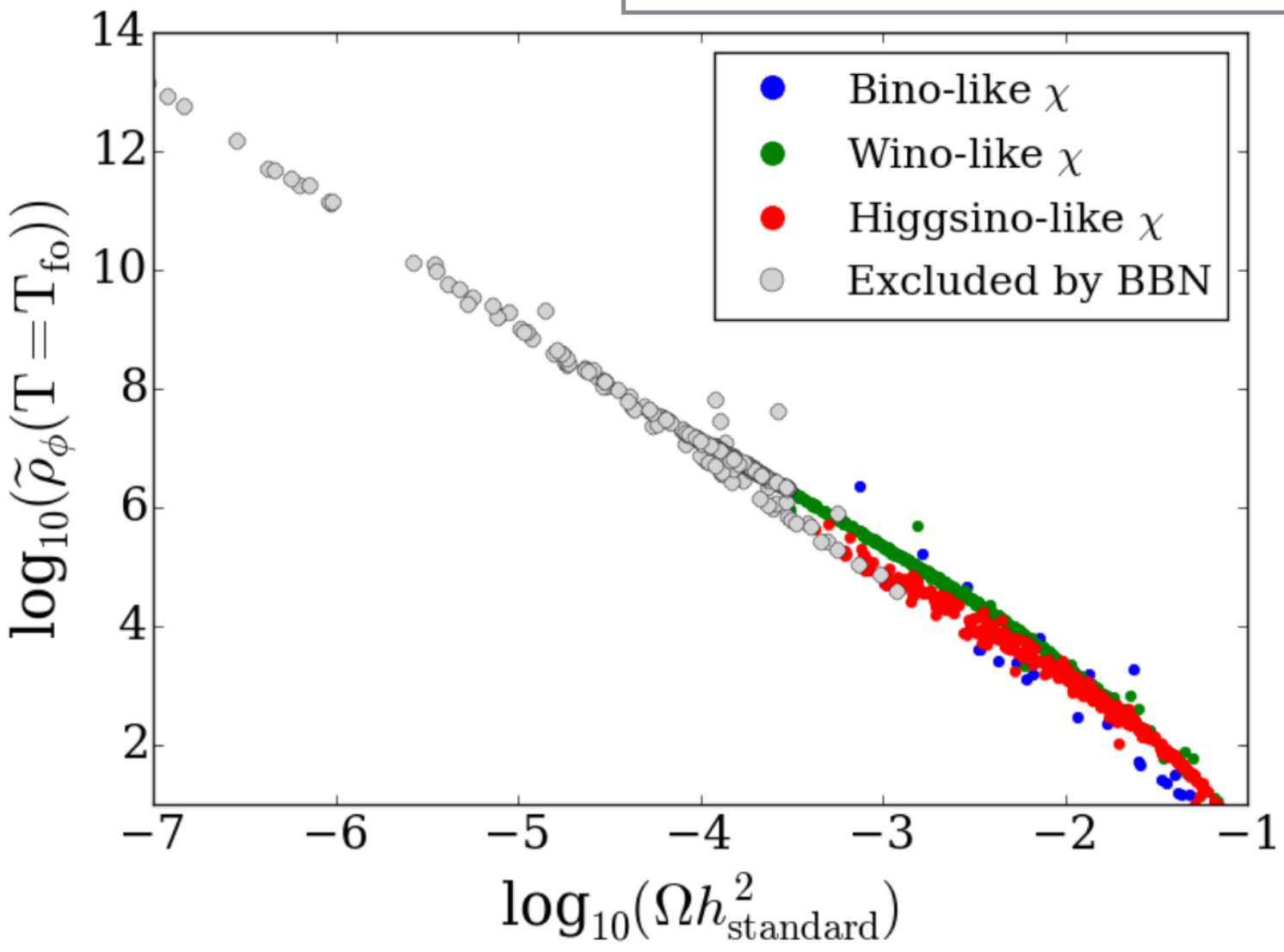
SuperIso Relic (v4) notable features

- Multiprocessor relic density calculation (OpenMP)
- Relic density calculation in modified early universe cosmologies by connecting with the AlterBBN code [Arbey,Auffinger,Hickerson,Jenssen 2018] (see talk by C. Pitrou Wednesday on BBN tools)

PRECISION

INNOVATION

[Arbey,Ellis,Mahmoudi,Robbins 2018]

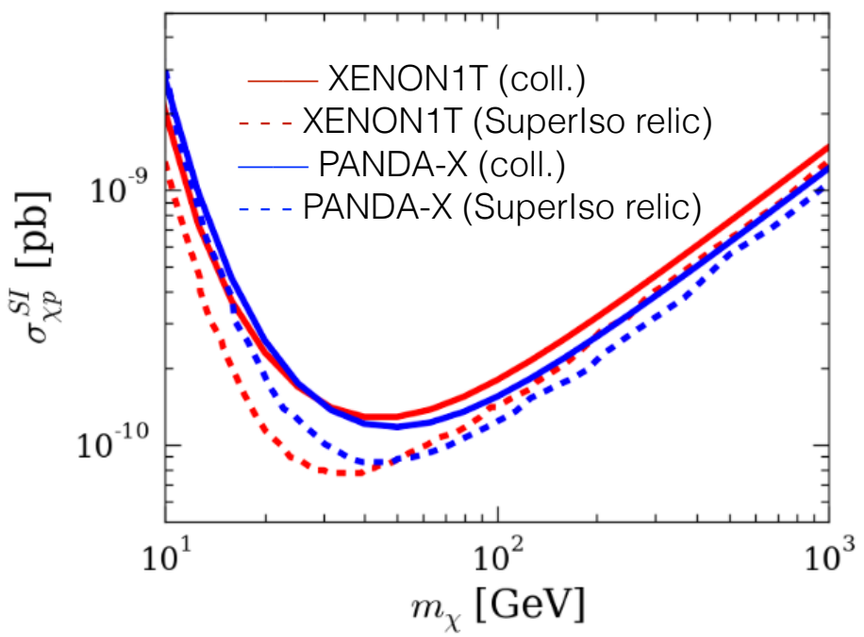


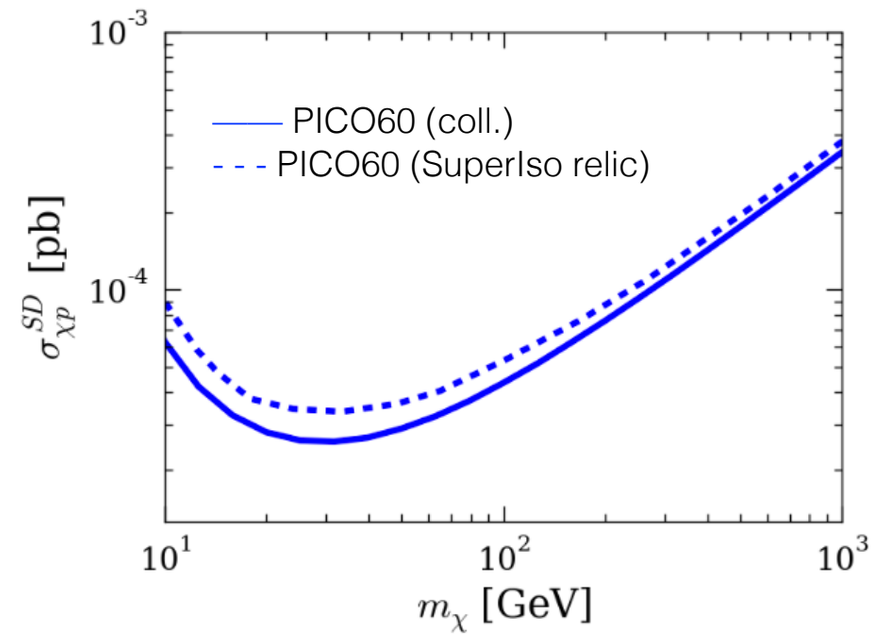
SuperIso Relic (v4) notable features

- Comparison with experimental constraints: indirect detection (Fermi-LAT and AMS02) and direct detection (XENON1T, PANDA-X, PICO60) [see also Arbey,Boudaud,Mahmoudi,Robbins 2017]

PRECISION

INNOVATION





Thanks to Alexandre for the feedback!

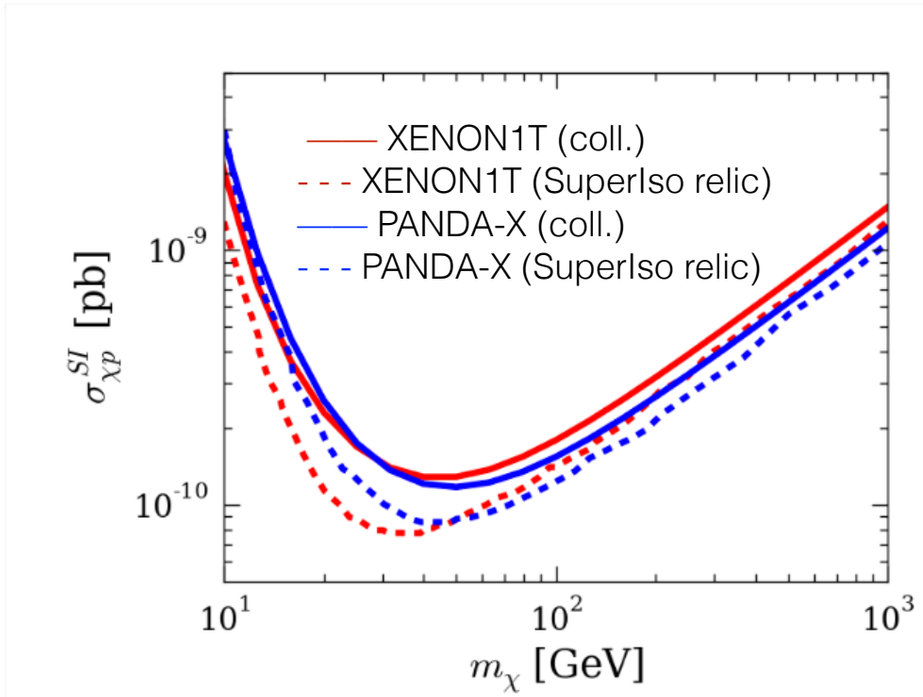
More about the usage of SuperIso relic this afternoon with the tutorial by ….

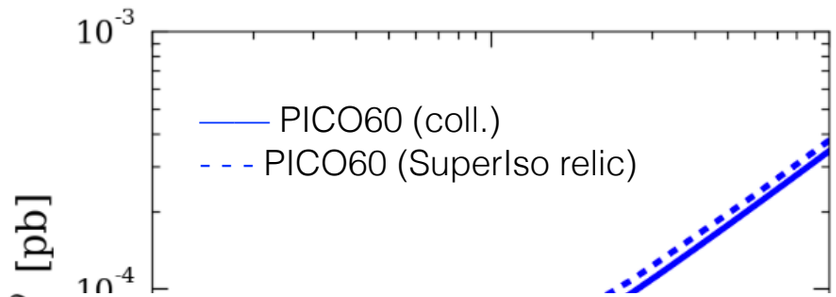
SuperIso Relic (v4) notable features

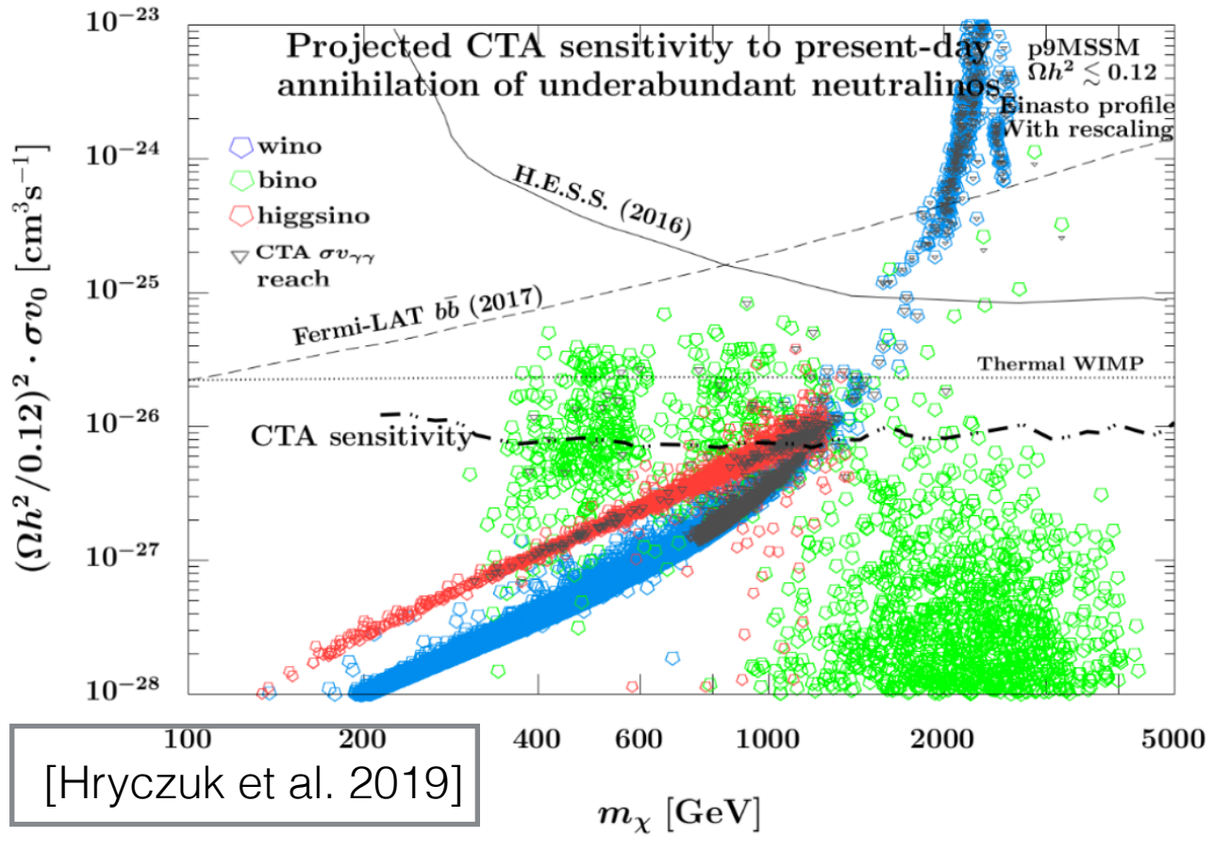
- Comparison with experimental constraints: indirect detection (Fermi-LAT and AMS02) and direct detection (XENON1T, PANDA-X, PICO60) [see also Arbey,Boudaud,Mahmoudi,Robbins 2017]

PRECISION

INNOVATION







[Hryczuk et al. 2019]

Thanks to Alexandre for the feedback!

More about the usage of SuperIso relic this afternoon with the tutorial by ….

Current version v6 no longer restricted to supersymmetric dark matter
(new release yesterday)

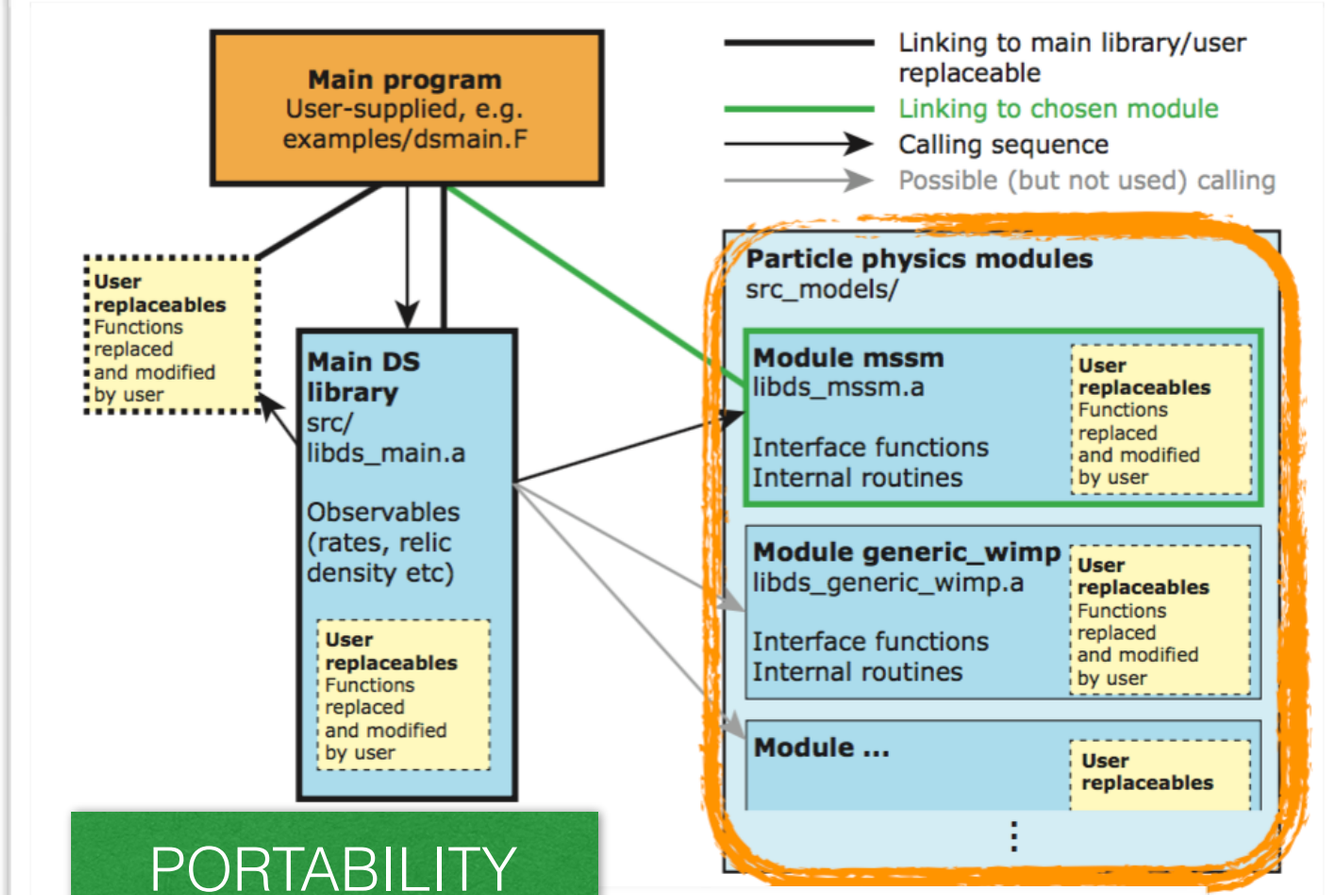
JCAP 1807 (2018) 033 , Website

T. Bringmann, J. Edsjö, P. Gondolo, P. Ullio, L. Bergström, M. Schelke, T. Baltz and G. Duda

Fortran package that computes dark matter observables

- relic density
- direct detection
- indirect detection (tables for spectra)
- propagation of cosmic-rays
- neutrino signals from the Sun
- accurate predictions for SUSY
- …

COMPREHENSIVE



PORTABILITY

Very modular, model is user supplied

JCAP 1807 (2018) 033 , Website

Current version v6 no longer restricted to supersymmetric dark matter
(new release yesterday)

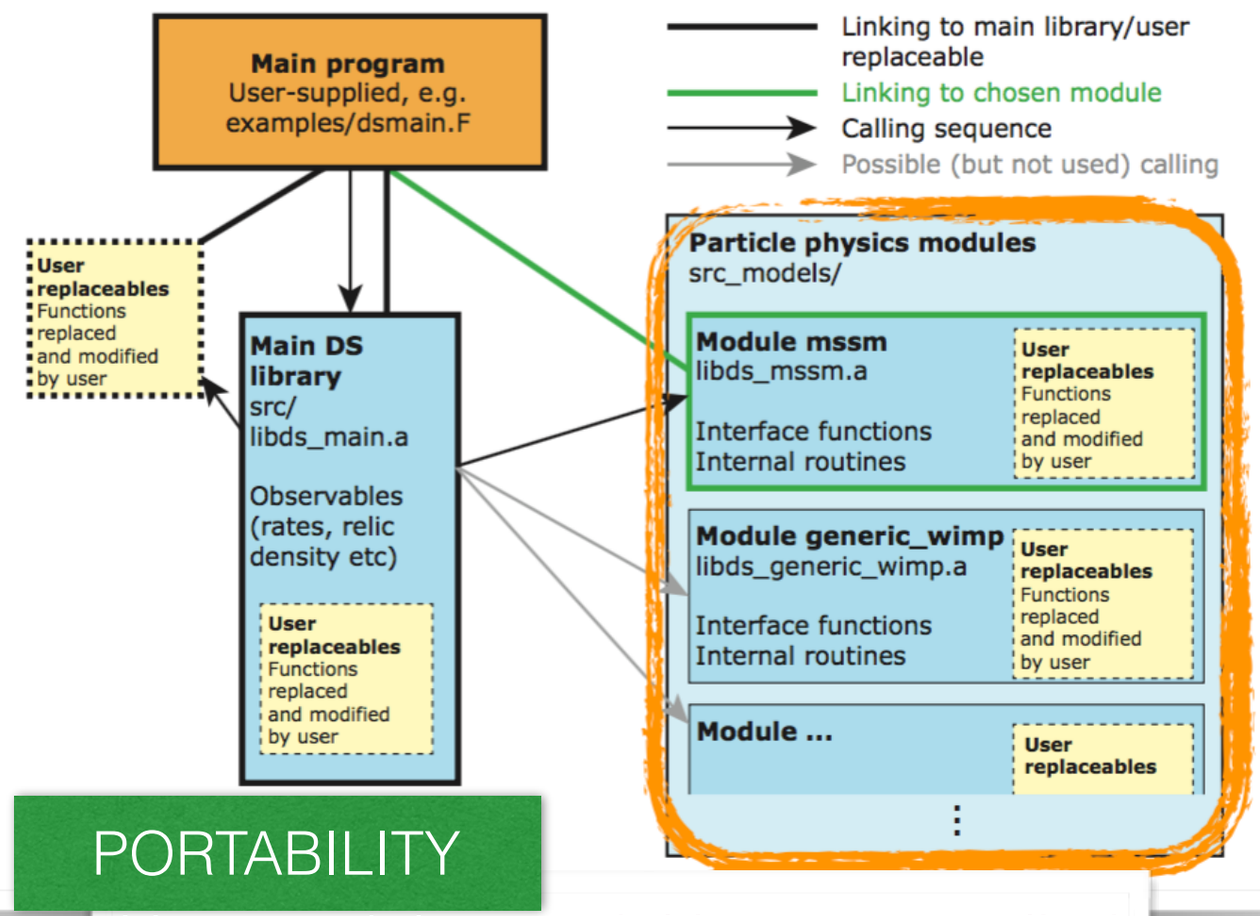
T. Bringmann, J. Edsjö, P. Gondolo, P. Ullio, L. Bergström, M. Schelke, T. Baltz and G. Duda

Fortran package that computes dark matter observables

- relic density
- direct detection
- indirect detection (tables for spectra)
- propagation of cosmic-rays
- neutrino signals from the Sun
- accurate predictions for SUSY
- …

COMPREHENSIVE

Basics are very well covered!



PORTABILITY

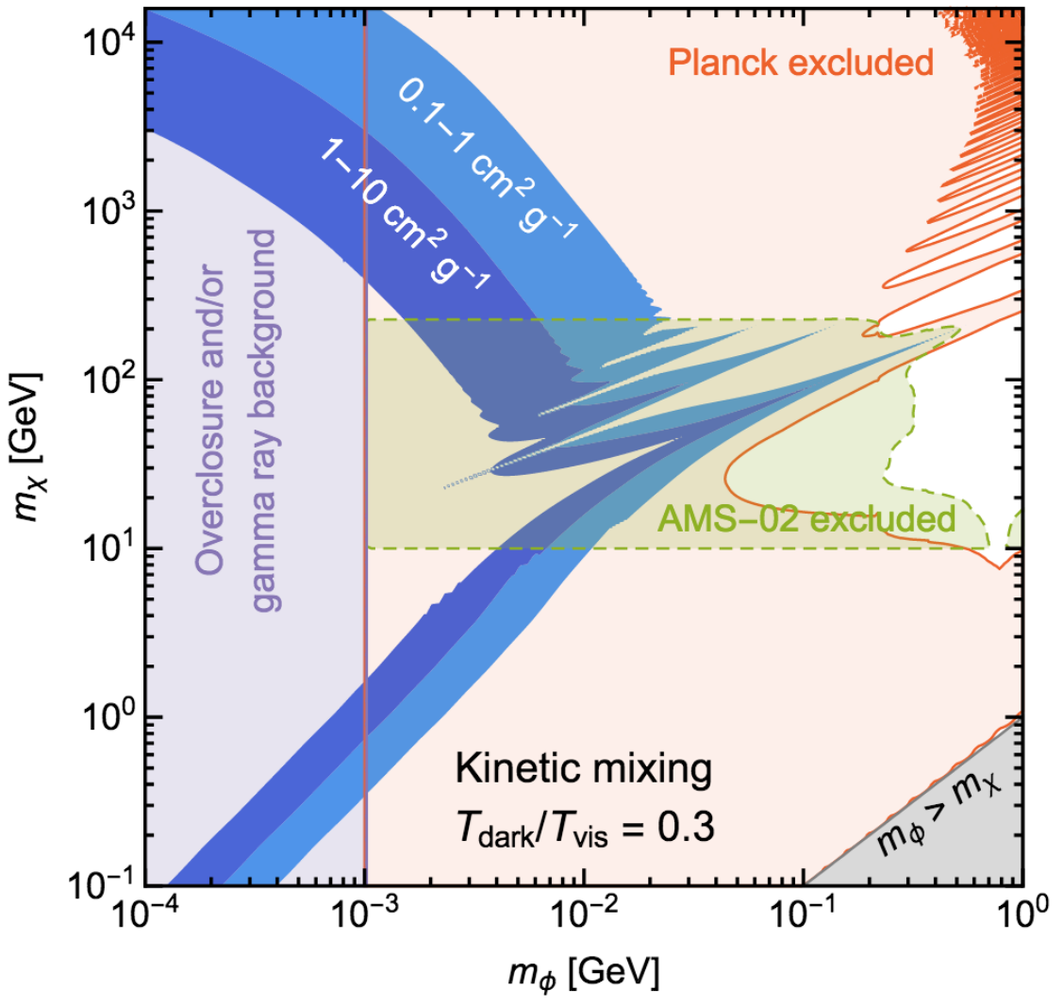
Very modular, model is user supplied

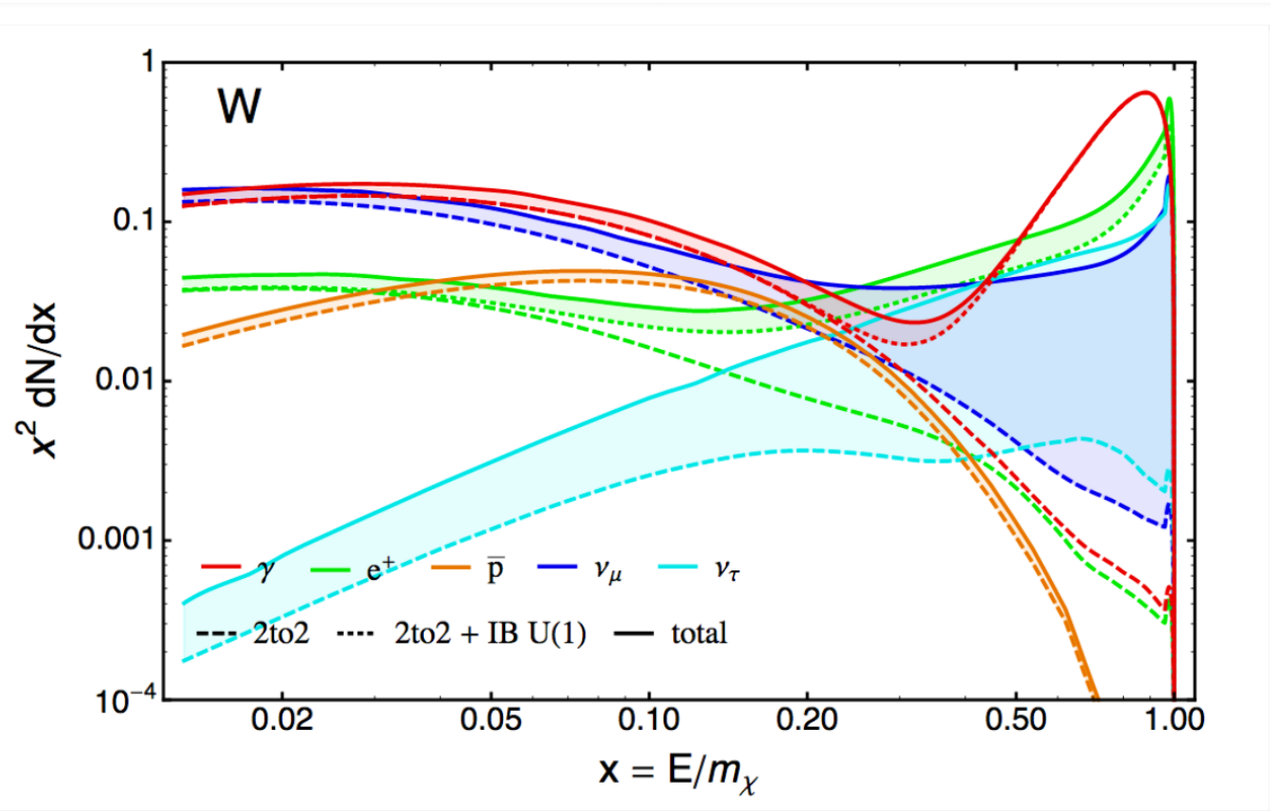
DarkSUSY (v6) notable features

- relic density computation with different sector temperatures
- kinetic decoupling
- self-interacting dark matter [Bringmann, Kalhoefer, Schmidt-Hoberg 2016]
- hidden sectors sigmav [Bringmann, Depta, Hufnagel, Schmidt-Hoberg 2017]
- Sommerfeld effect (analytic)
- U(1), SU(2), SU(3) corrections to final states (analytic) [Bringmann, Calore, Galea, Garny, 2017]
- …

PRECISION

INNOVATION



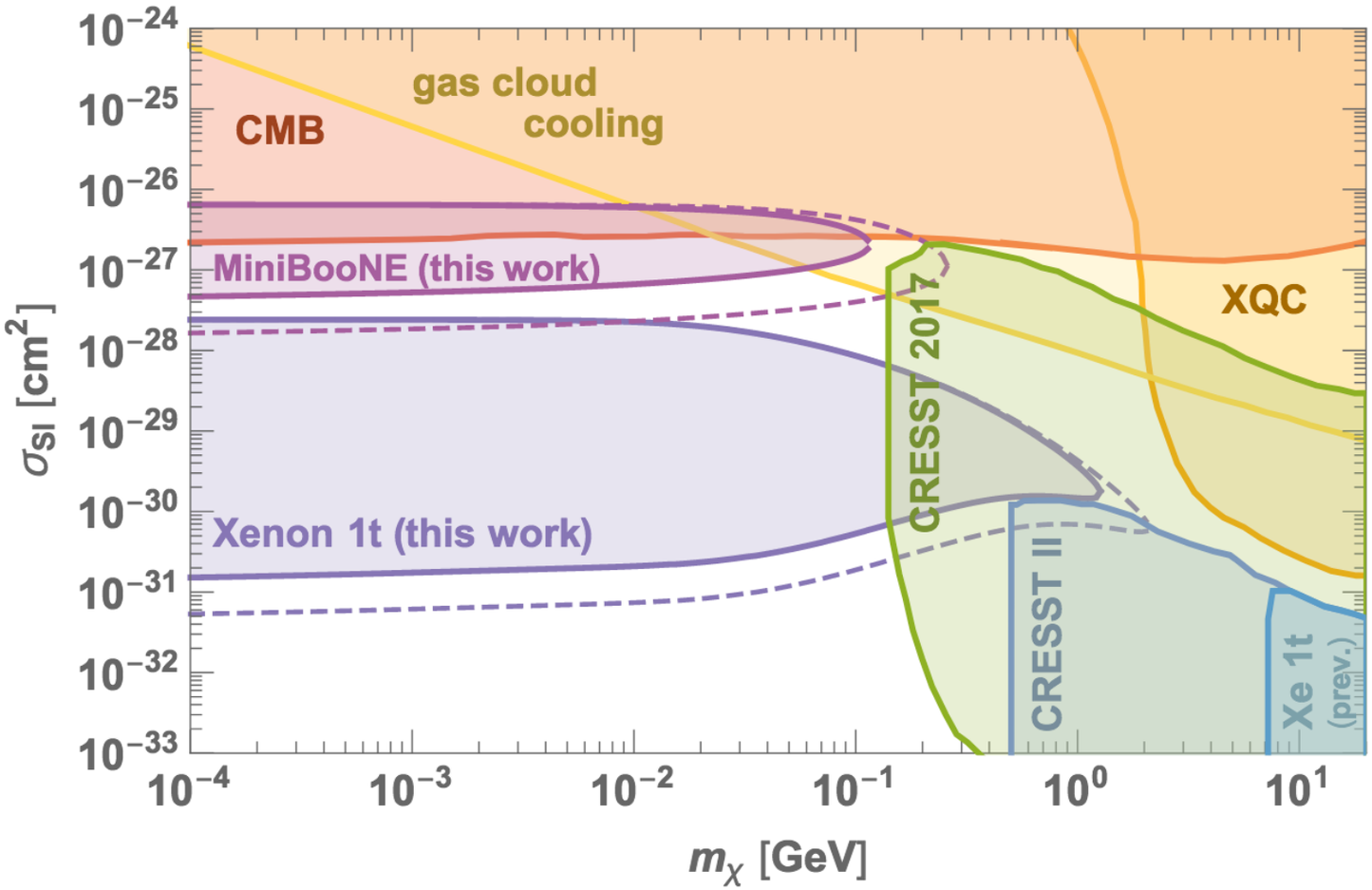


DarkSUSY (v6) notable features

- Direct detection with q2 dependence
- Direct detection for very light dark matter (cosmic ray assisted)
  [Bringmann, Pospelov 2019, Bordarenko et al. 2020]

PRECISION

INNOVATION



Thanks to Torsten for the feedback!

More about the usage of DarkSUSY this afternoon with the tutorial by T. Bringmann

MicrOMEGAs

Current version v5

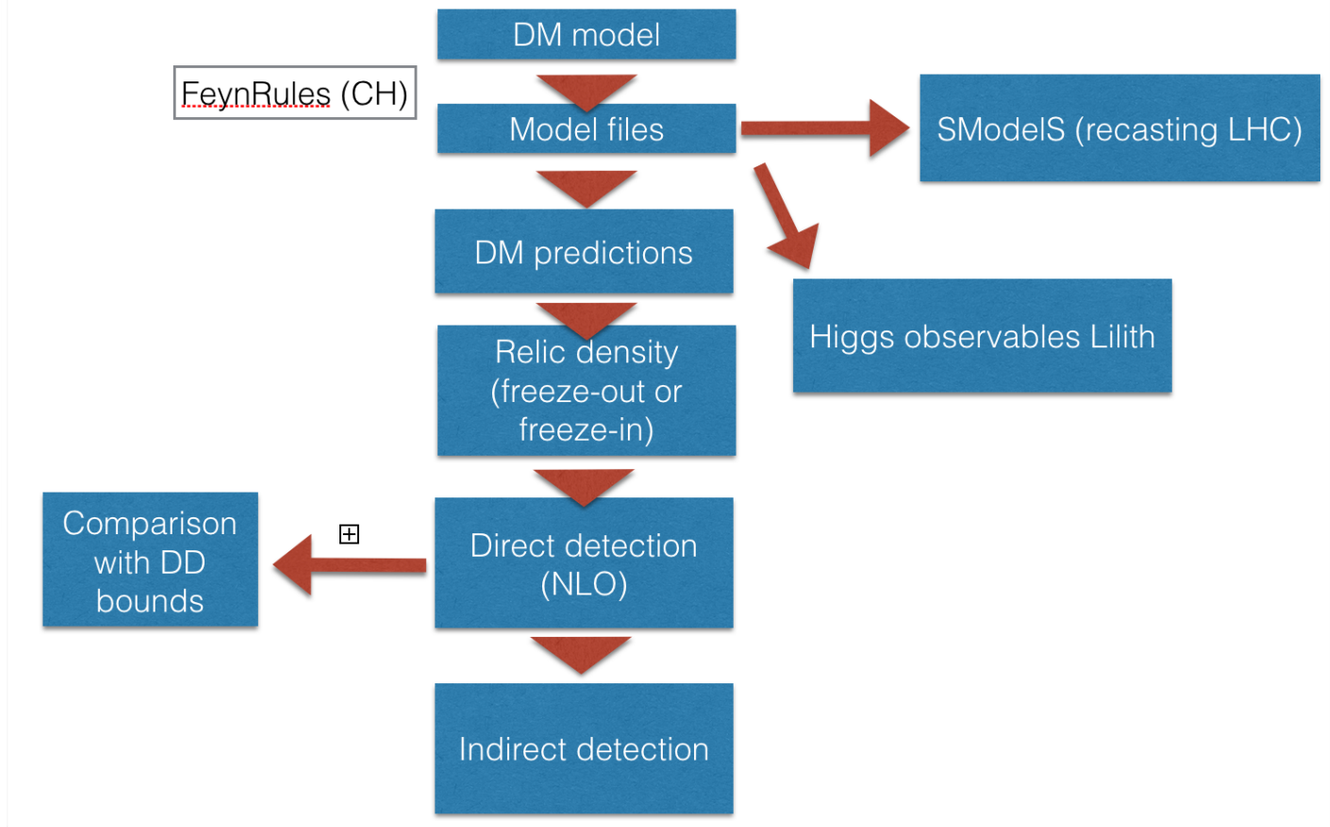
Website with documentation

D. Barducci, G. Bélanger, J. Bernon, F. Boudjema, J. Da Silva, A. Goudelis, S. Kraml, U. Laa, A. Pukhov, A. Semenov, B.

C/C++/fortran code that computes dark matter observables

- relic density
- direct detection
- indirect detection (tabulated energy spectra)
- propagation of cosmic-rays
- neutrinos from the Sun
- …

COMPREHENSIVE



Highly PORTABLE

μΩ

MicrOMEGAs

Current version v5

Website with documentation

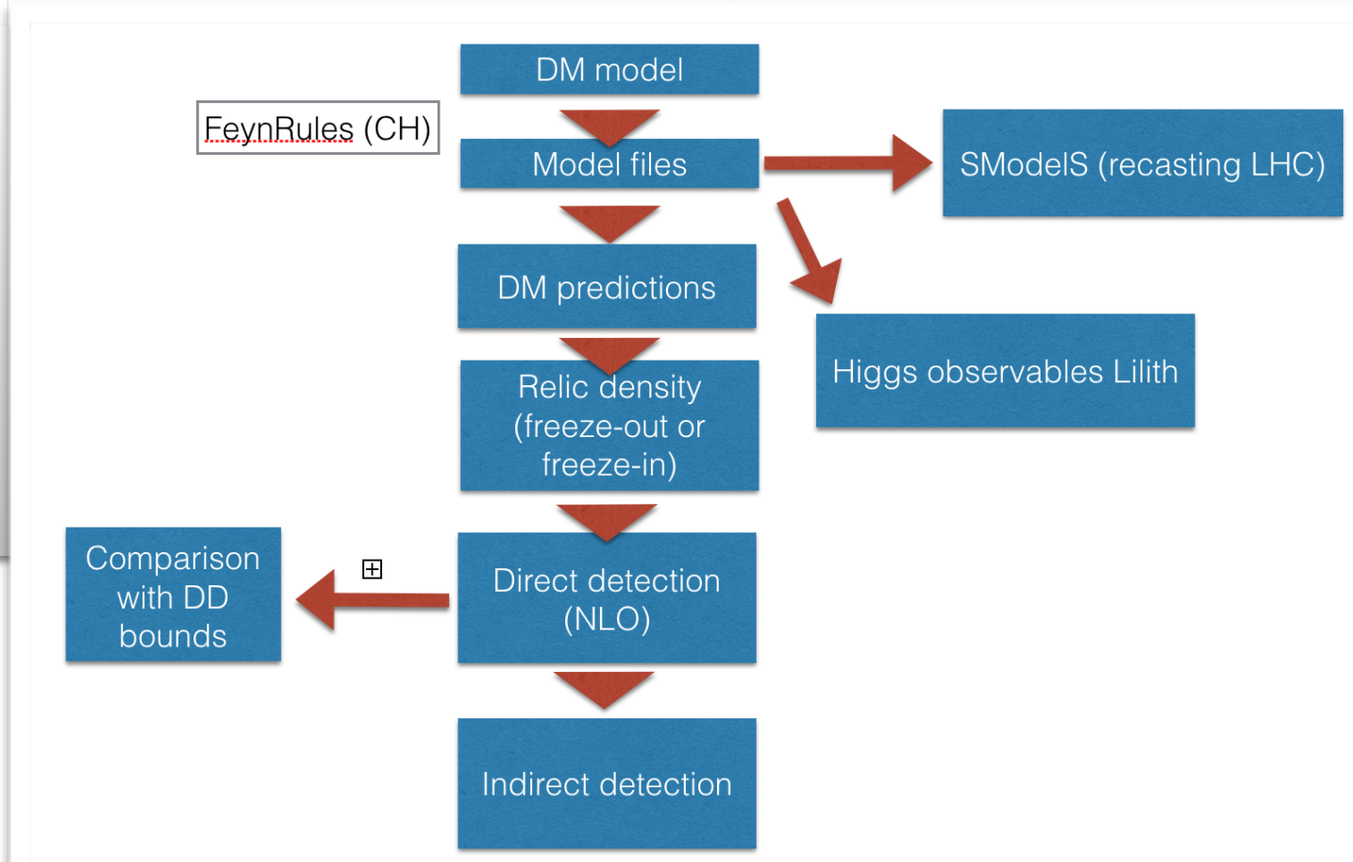
D. Barducci, G. Bélanger, J. Bernon, F. Boudjema, J. Da Silva, A. Goudelis, S. Kraml, U. Laa, A. Pukhov, A. Semenov, B.

C/C++/fortran code that computes dark matter observables

- relic density
- direct detection
- indirect detection (tabulated energy spectra)
- propagation of cosmic-rays
- neutrinos from the Sun
- …

COMPREHENSIVE

Basics are very well covered!



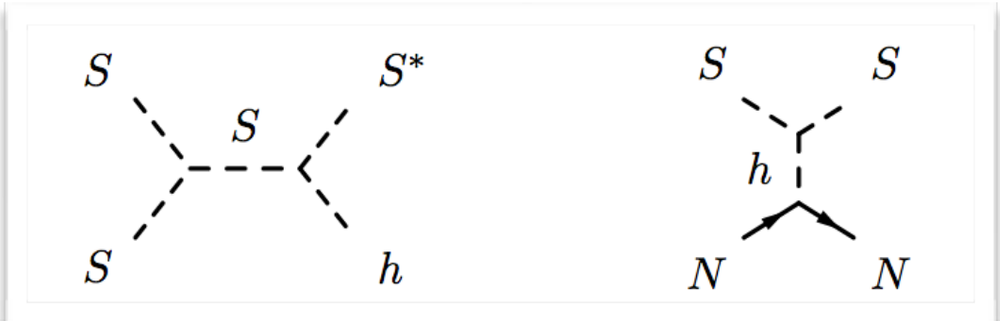
Highly PORTABLE

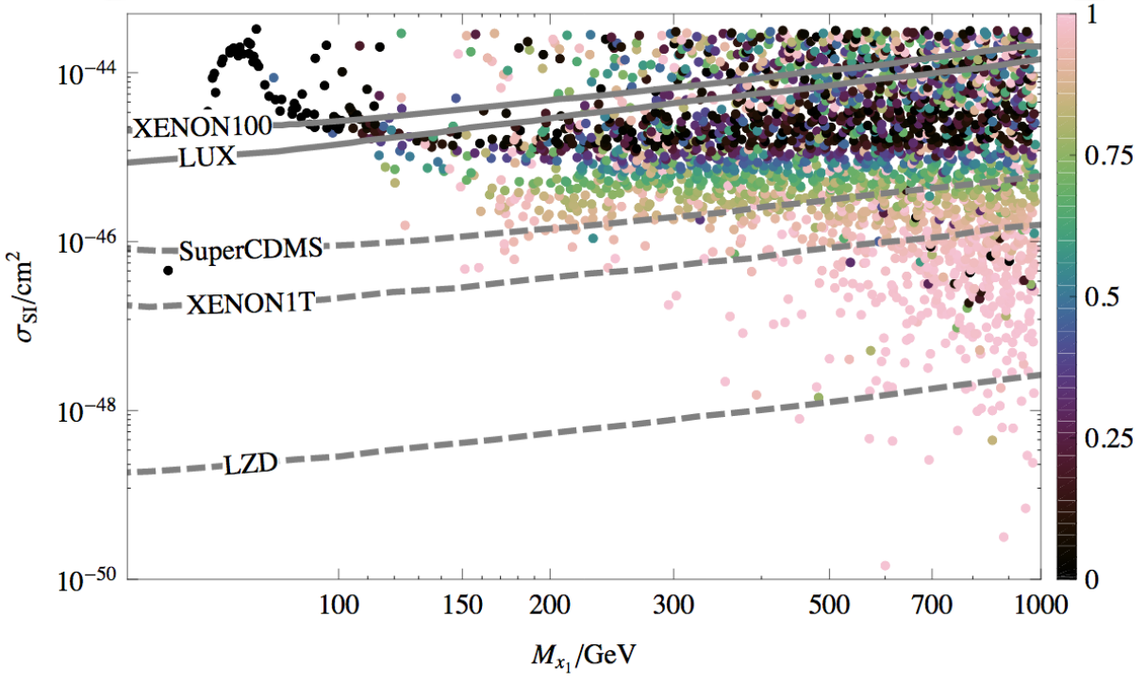
MicrOMEGAs (v5) notable features

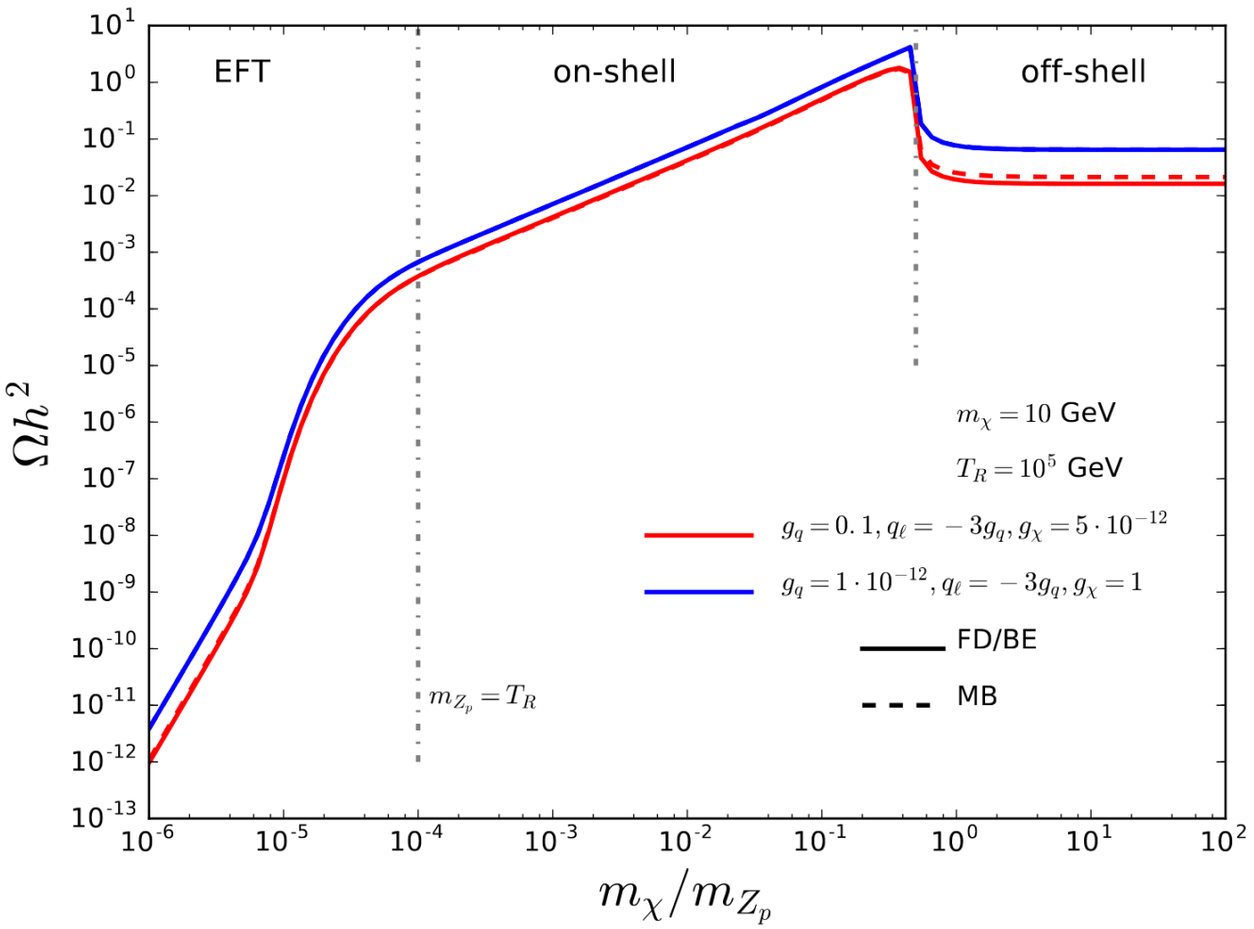
- Multicomponent dark matter (2 DM candidates)
- Boltzmann equations for Z_n symmetry are included (semi-annihilation) [Bélanger, Kannike, Pukhov, Raidal 2012]
- Freeze-in [Bélanger, Boudjema, Goudelis, Pukhov, Zaldivar 2018]
- User can improve sigmav for Relic density with specific routine
- …

PRECISION

INNOVATION





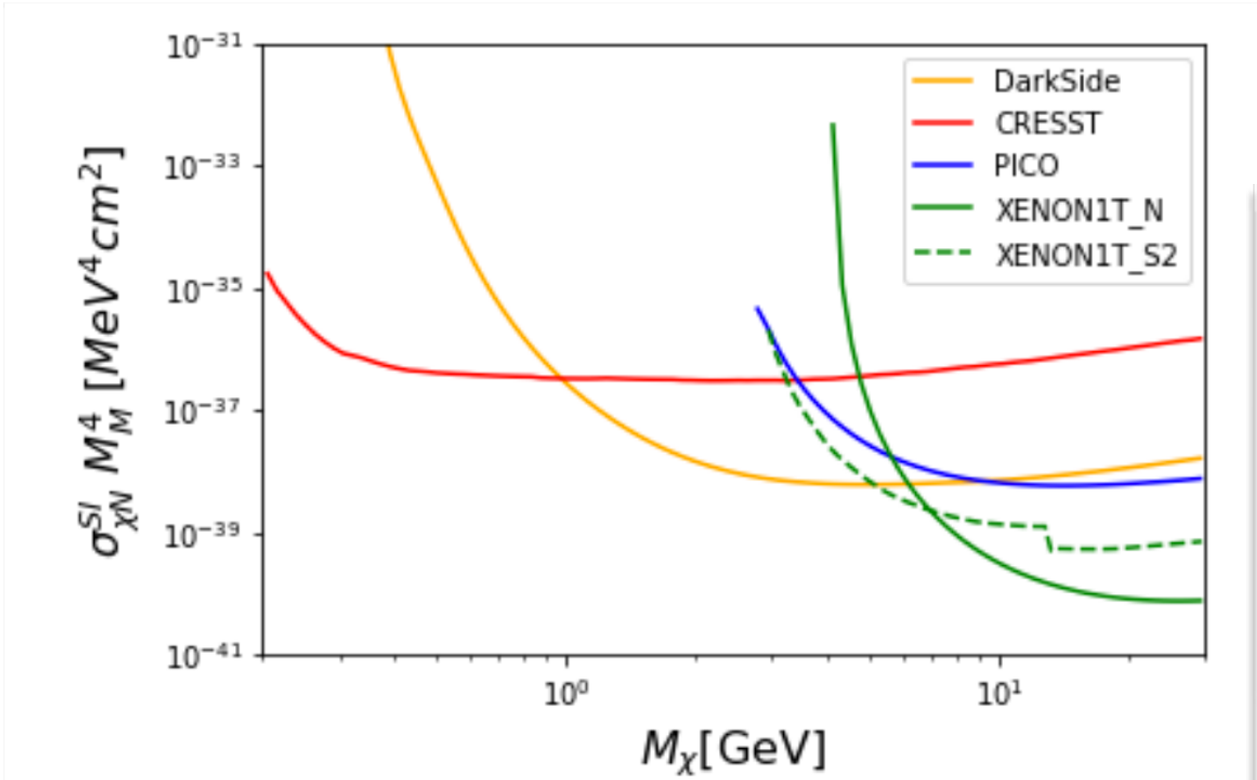


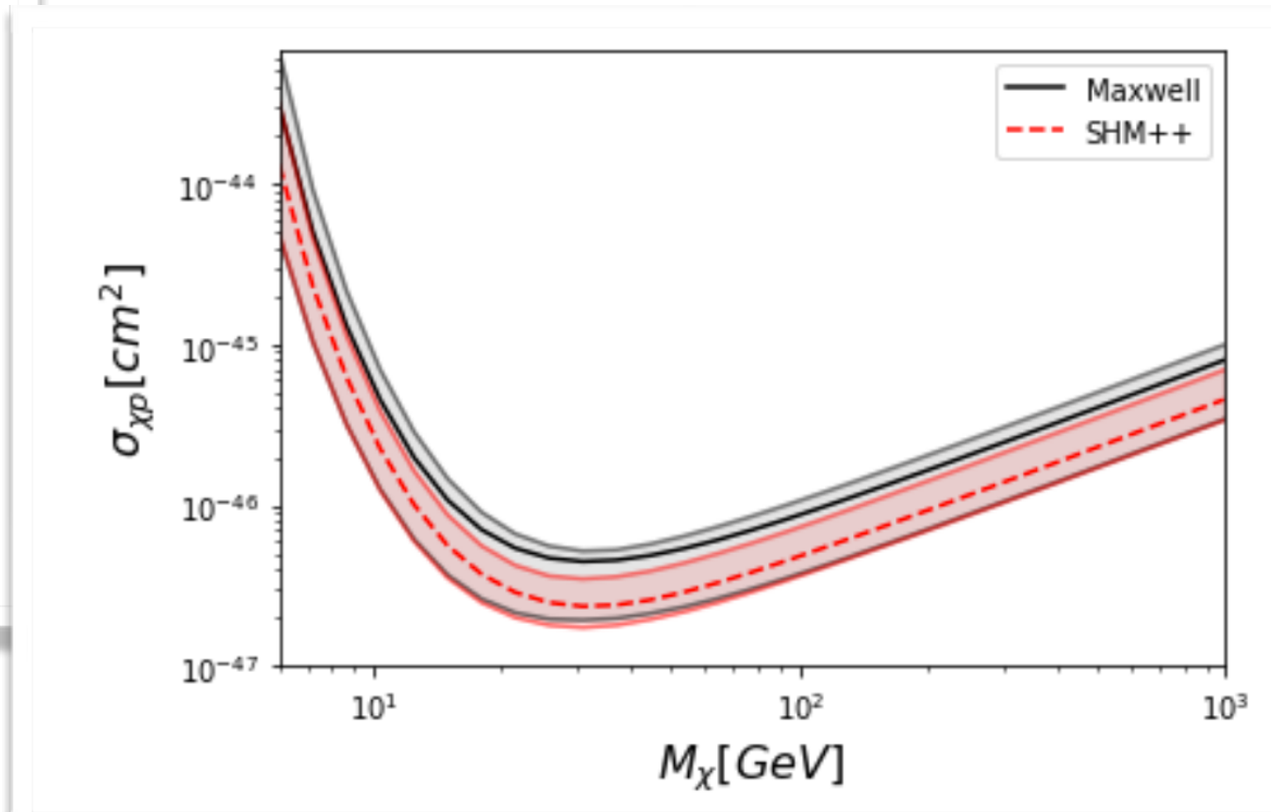
MicrOMEGAs (v5) notable features

- Direct detection at NLO
- Recasting of direct detection bounds [Bélanger, Mjallal, Pukhov 2020]
- Velocity dependence for the limits

PRECISION

INNOVATION





Thanks to Geneviève for the feedback!

MadDM

Current version v3

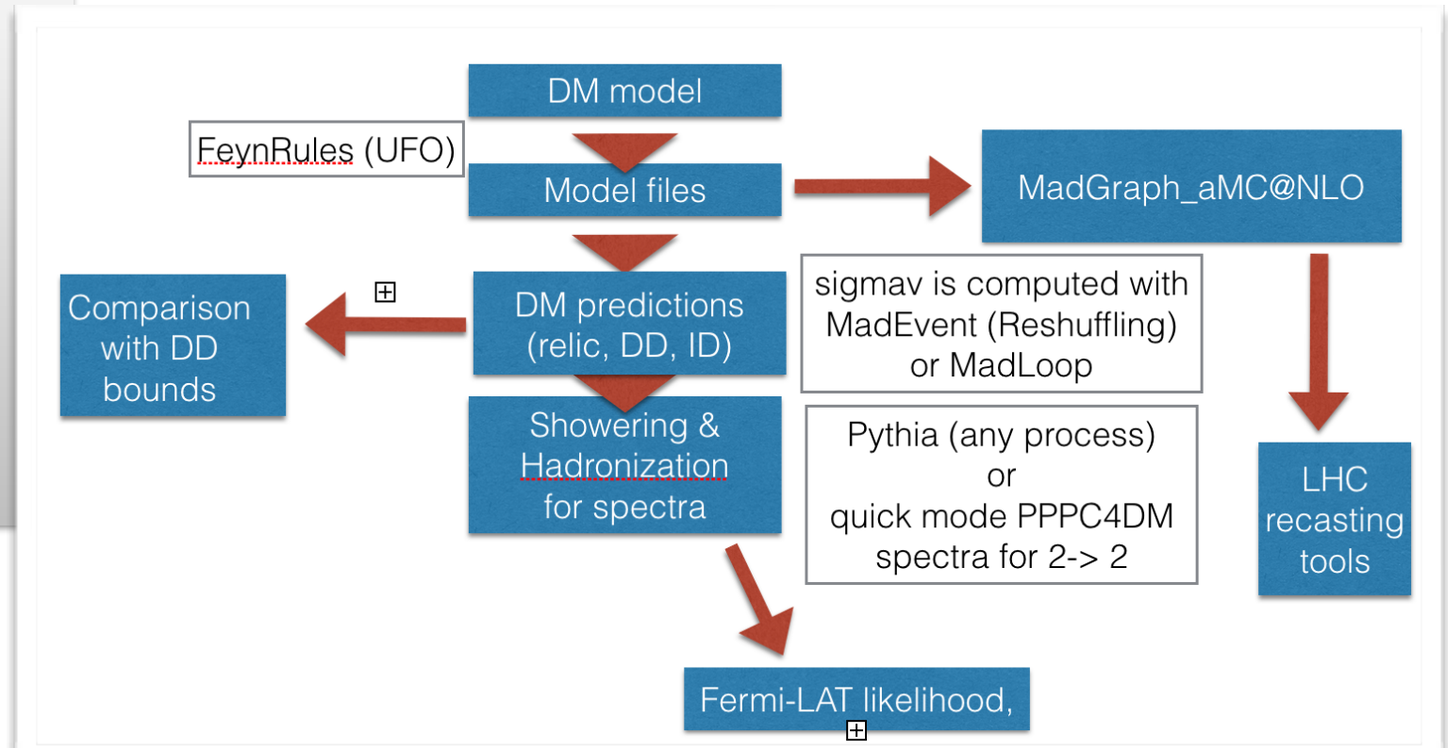
F. Ambrogi, C. Arina, M. Backovic, J. Heisig, K.C. Kong, F. Maltoni, A. Martini, D. Massaro, O. Mattelaer, M. McCaskey, G. Mohlabeng

Phys. Dark Univ. 24 (2019) , Website

Python/Fortran package that computes DM related quantities

- relic density
- direct detection
- indirect detection (energy spectra from Pythia directly)
- propagation of cosmic-rays via DRAGON code
- nested sampling via MULTINEST
- …

COMPREHENSIVE



Highly PORTABLE

MadDM

Current version v3

F. Ambrogi, C. Arina, M. Backovic, J. Heisig, K.C. Kong, F. Maltoni, A. Martini, D. Massaro, O. Mattelaer, M. McCaskey, G. Mohlabeng

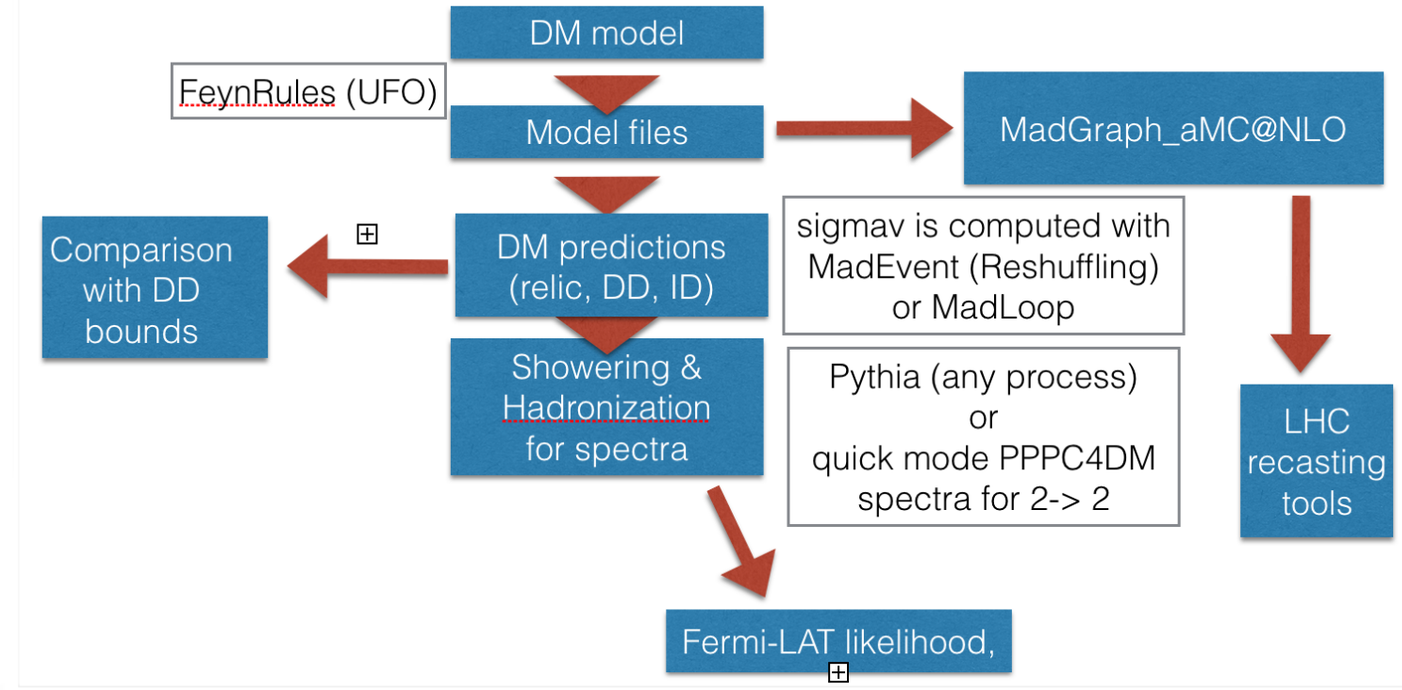
Phys. Dark Univ. 24 (2019) , Website

Python/Fortran package that computes DM related quantities

- relic density
- direct detection
- indirect detection (energy spectra from Pythia directly)
- propagation of cosmic-rays via DRAGON code
- nested sampling via MULTINEST
- …

COMPREHENSIVE

Basics are well covered!



Highly PORTABLE

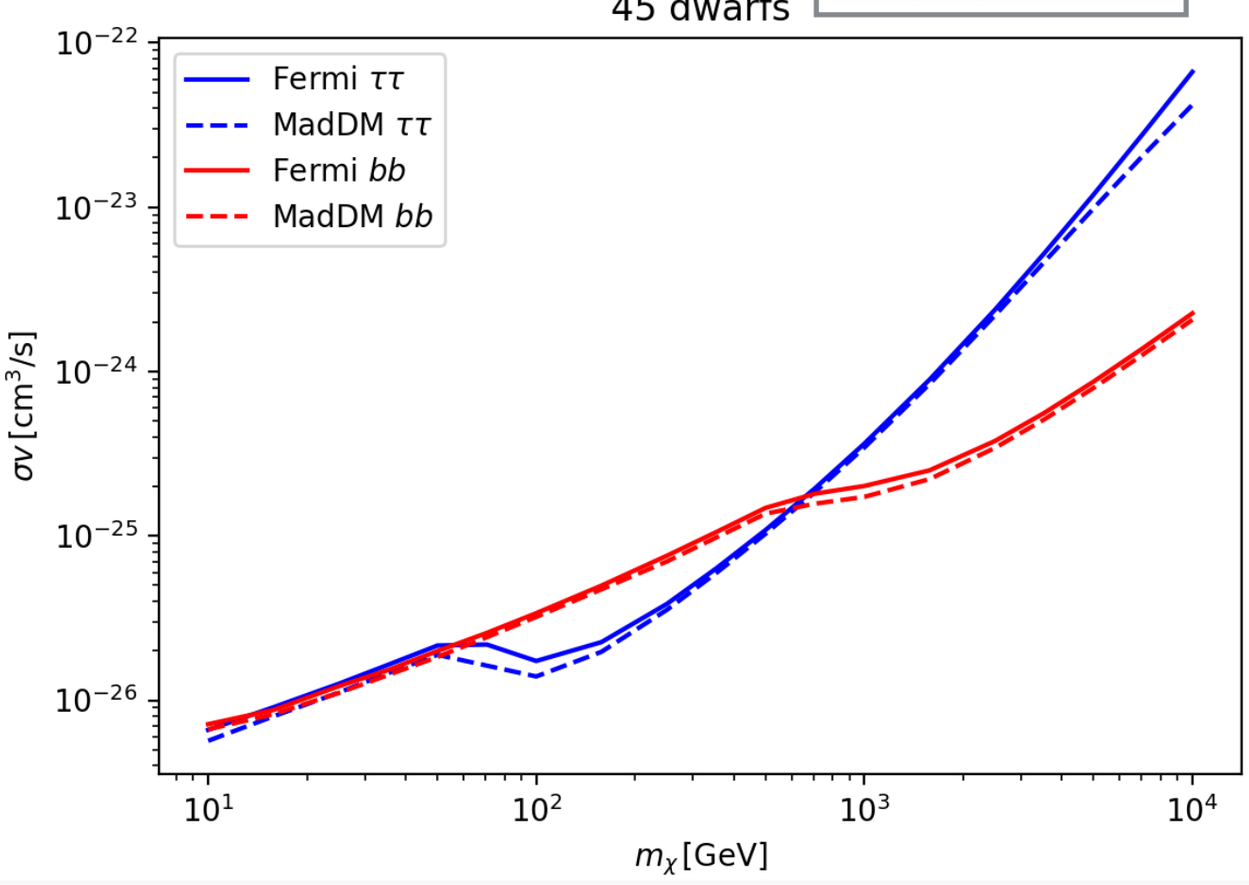
MadDM (v3) notable features

- indirect detection for any 2—>n process (automatic generation of energy spectrum)
- experimental module with likelihoods of selected experiments (LUX, Fermi-LAT dwarf spheroidal galaxies)

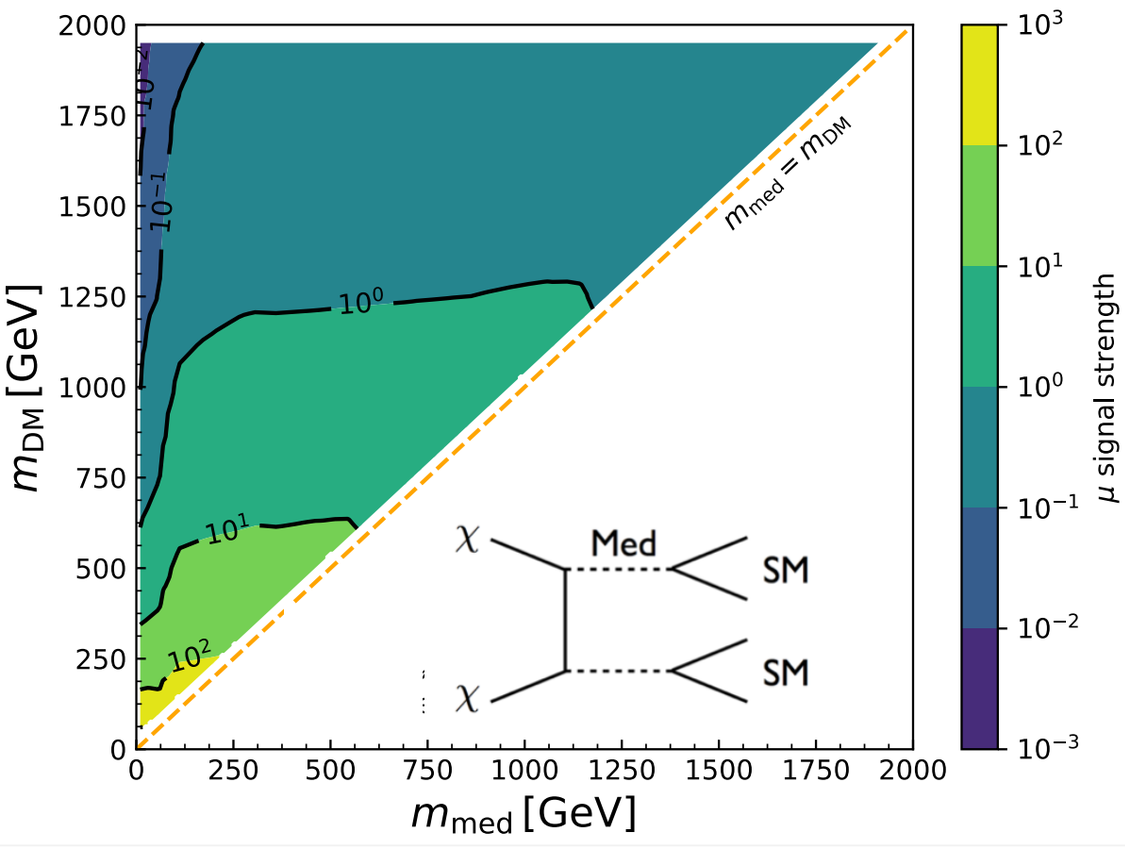
PRECISION

INNOVATION

validation



secluded dark matter [Pospelov 2009]



MadDM provides exclusion limits in all SM final

MadDM (v3) notable features

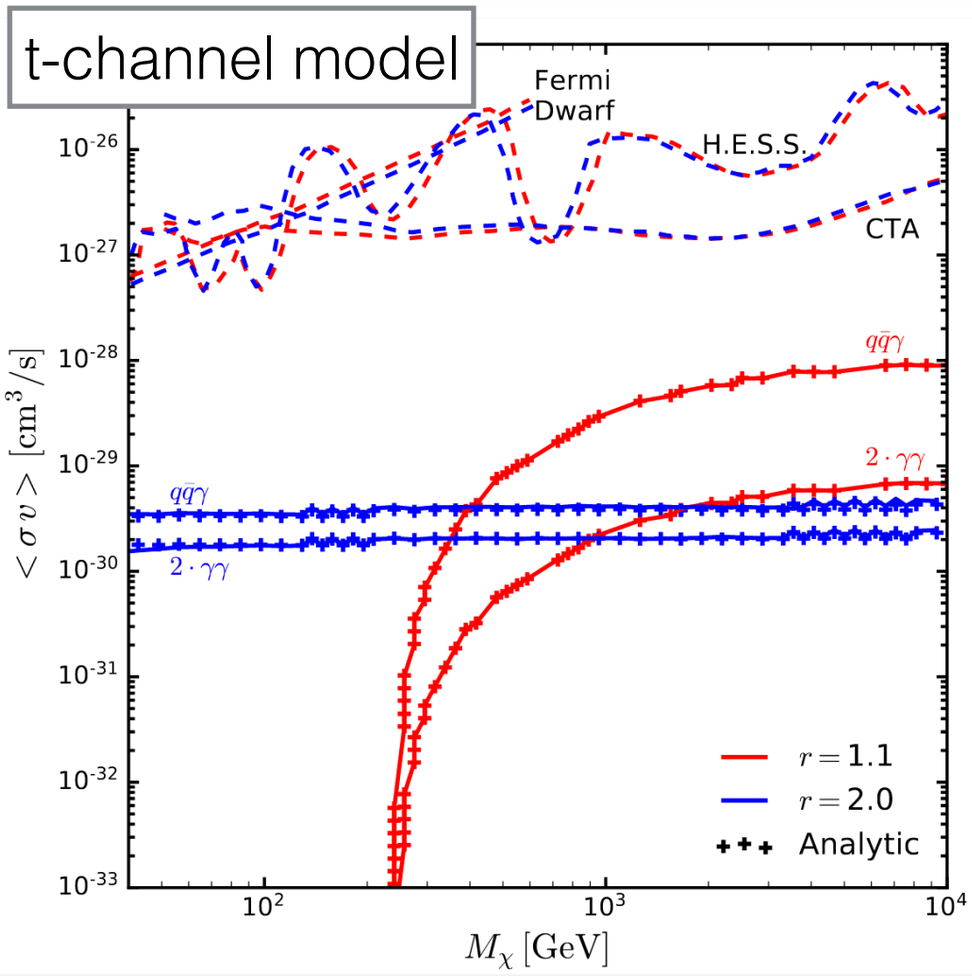
For any UFO model:

- Automatic loop-induced processes [CA,Fuks,Mantani 2020; CA,Heisig,Massaro, Mattelaer, in progress] —> available in the next release (soon!)
- This accounts in one for: gamma-ray lines, Za, Ha, gg final states and eventually others
- Automatic corrections (2—> 3 processes, can be U(1), SU(2), SU(3)…)

PRECISION

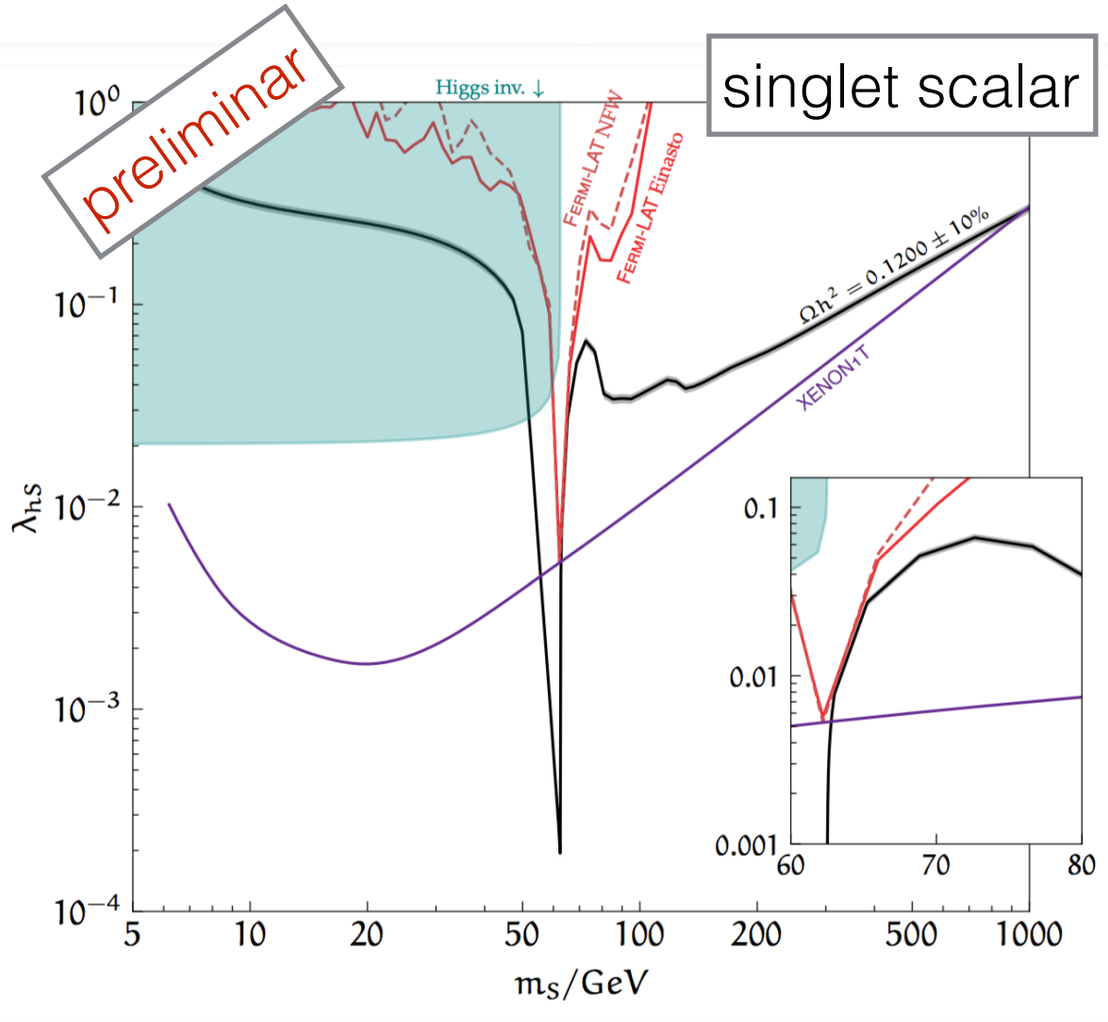
INNOVATION

t-channel model



preliminar

singlet scalar



More about the usage of MadDM this afternoon with the tutorial by J. Heisig

Summary: Are we getting close to the pheno dream?

- 5 - 10 years ago: NO
- Now: WE ARE GETTING VERY CLOSE TO IT

- The BASICS (WIMPs / standard freeze-out / standard predictions) are fully covered to various extent
- But actually we have much more

Very sophisticated predictions

1. For a good old model (SUSY, IDM, …)
2. For new fancy hidden sector models

Very easy to get predictions for generic BSM model in automatised codes such as MicrOMEGAs and MadDM, which can be linked to very different tools

✓ COMPREHENSIVE
Coverage of a very wide range of functions and theoretical predictions

✓ PRECISION
Capability of handling automatically complex manipulations

✓ PORTABILITY
Capability of easy link with other tools and built-in chain of functionalities

✓ INNOVATION
New features that incur in models beyond WIMPs

Automatised tools: Example of full chain

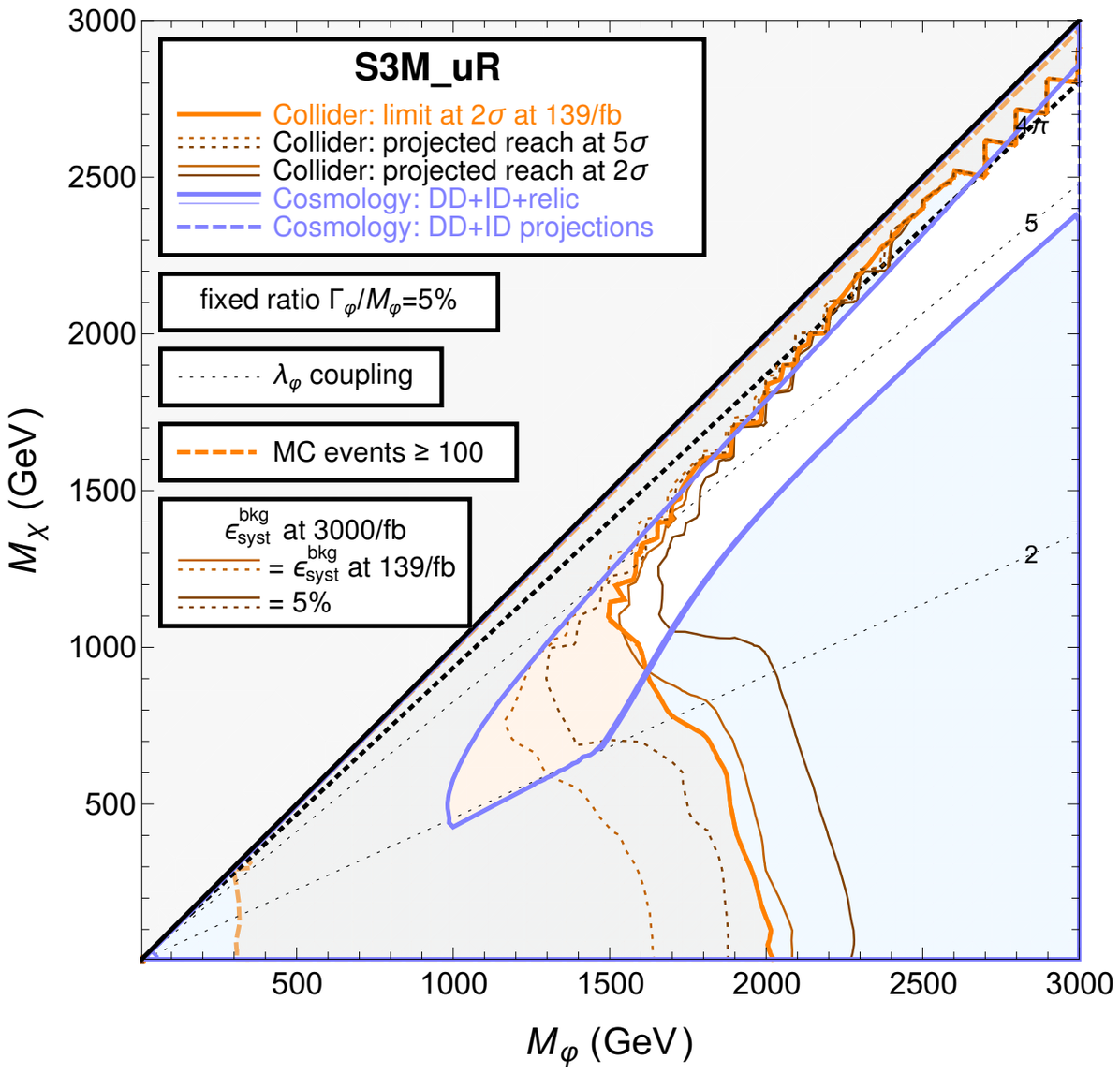
- <u>Combination of:</u>
- FeynRules and NLOCT (model lagrangian and model files @NLO)
- MicrOMEGAs (relic density + DD at NLO)
- MadDM (validation of 2->3 and loop induced processes)
- MadGraph_aMC@NLO
- MadAnalysis

PRECISION

INNOVATION

COMPREHENSIVE

PORTABILITY



[CA,Fuks,Mantani,Meis,Panizzi,Salko 2020]

*(Long-, short-) term future directions for MadDM **

* totally biased part of my talk…

Improvement for relic density calculation (freeze-in, non standard freeze-out, Sommerfeld enhancement, …)

Full data base with experimental likelihoods

Work in progress

Automatised Loop induced processes

Work in progress

Inclusion of non-relativistic operators for direct detection

Work in progress

Capture of DM in celestial bodies

Work in progress

More astrophysics: Synchrotron radiation (SKA,…), gamma-rays data, anti-deuteron energy spectra

Work in progress

Prospects and future directions

- What can we expect from MicrOMEGAs, DarkSUSY, SuperIso relic, etc?

Model-independent new version of SuperIso relic soon !

Stay tuned with TOOLS2020

All tools and tutorial presented today
(DarkSUSY tutorial by T. Bringmann, MadDM tutorial by J. Heisig, DirectDM tutorial by F. Bishara, Capt'n general by A. Vincent)

GAMBIT talk by T. Gonzalo (Friday)
AlterBBN tutorial by A. Arbey (Wednesday)

- Ideas, suggestions, comments, collaborations are welcome to continue improving the dark matter tools

Thank you for your attention!