ISAPP 2021, 21-30 June, Madrid/zoom

DarkSUSY 6

More than supersymmetric dark matter

Torsten Bringmann

With **Joakim Edsjö,** Paolo Gondolo,
Piero Ullio and Lars Bergström

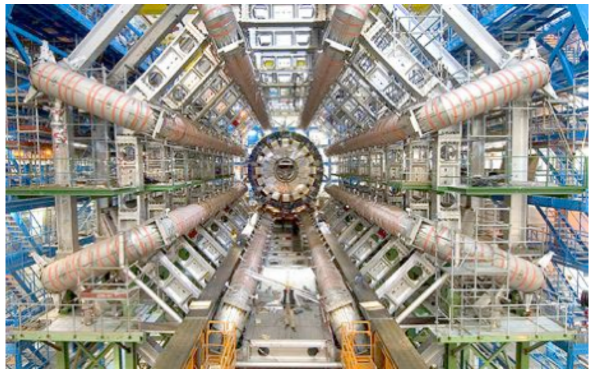
JCAP 1807 (2018)

www.darksusy.org

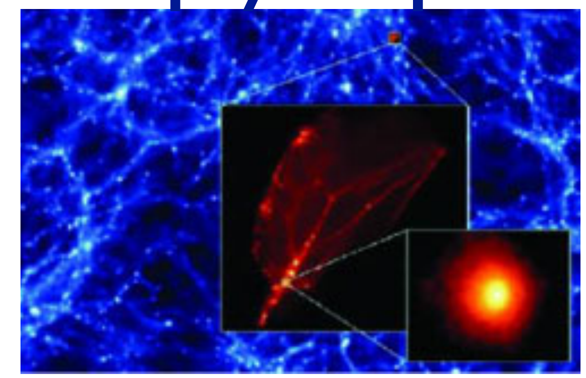
UiO : University of Oslo

Strategies for dark matter searches

at colliders



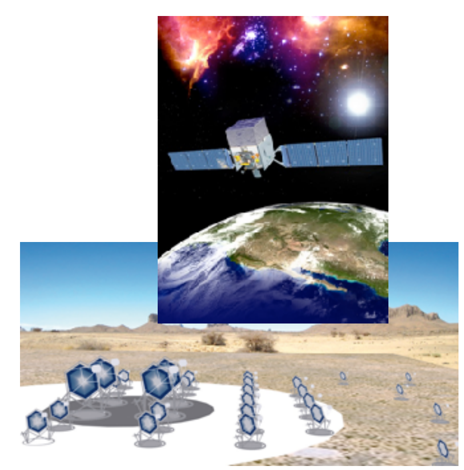
astrophysical probes



of matter distribution

want to calculate expected rates in a consistent manner – both regarding particle and astrophysics!

directly



indirectly

disclaimer: impossible to cover everything in 20 minutes…!

Calculation flowchart

DarkSUSY can do all of these steps

Particle physics model parameters	Choose model parameters for pMSSM, CMSSM, Scalar Singlet, SIDM, generic WIMP, etc…
Masses, couplings	Spectrum calculator (e.g. RGE solver)
[Accelerator and other lab constraints]	[Direct searches, rare decays, precision measurements]
Thermal freeze-out calculation	Annihilation & scattering cross section, Boltzmann solver
Direct and indirect rates, self-interaction-rates	Various rate calculators
Compare with data!	Compare individual rates or perform global fits

main focus

For the **MSSM**, this partially relies on implementing

Isajet, FeynHiggs, Higgsbounds, HiggsSignal, Superiso,…

What is DarkSUSY ?

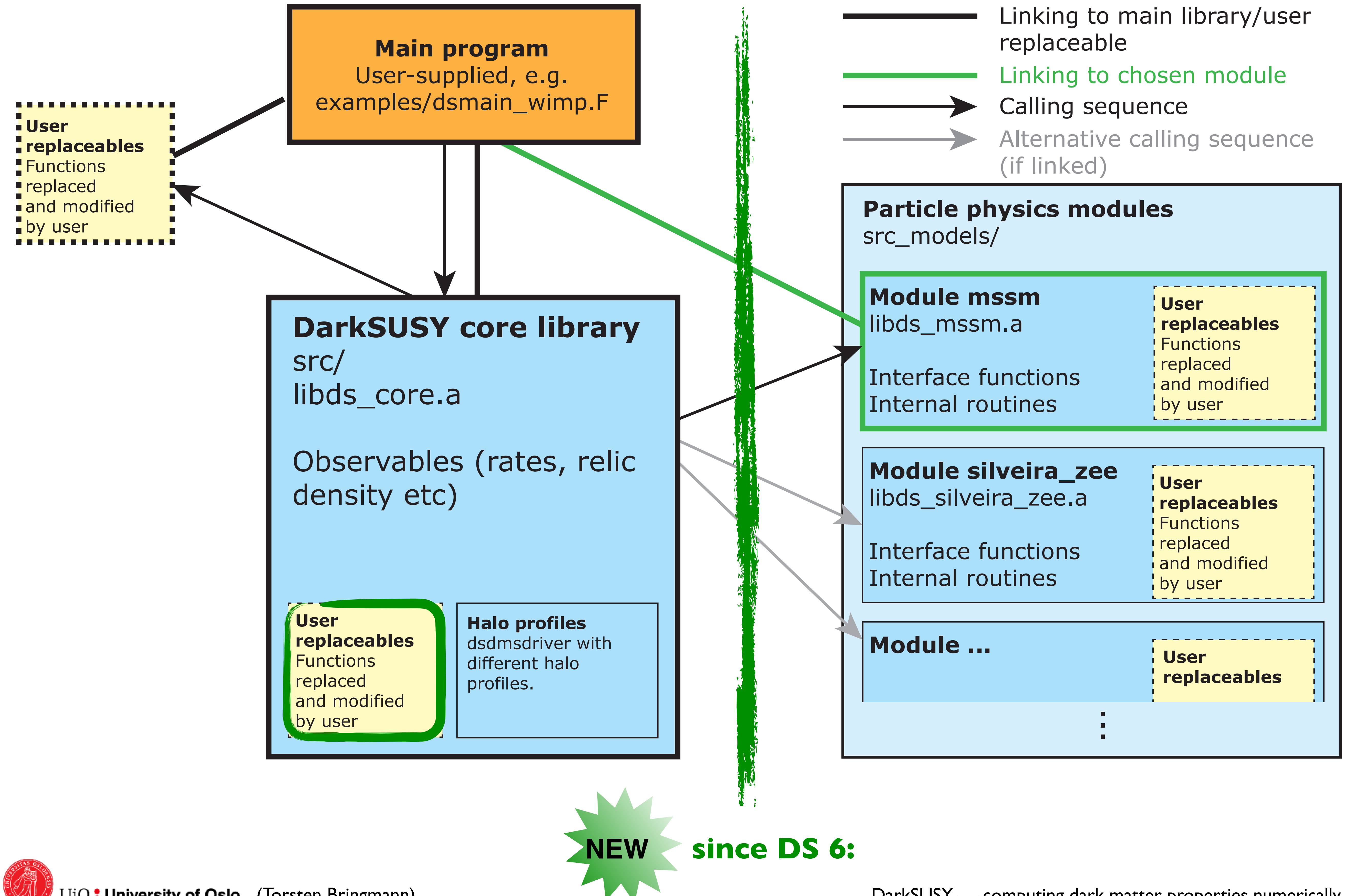
- A FORTRAN library of subroutines and functions
  ~100k lines of code, mostly F77
- Flexible, modular structure (given FORTRAN constraints)
- Fast and accurate
- Simple to use (!)

- Currently included particle physics modules:
  - *MSSM (SUSY)*
  - *Scalar Singlet (Silveira-Zee model)*
  - *self-interacting DM (simplified dark sector model)*
  - *generic WIMP*
  - *generic decaying DM*
  - *Kaluza-Klein DM (in progress)*
  - *+ whatever YOU add!*

NEW **since DS 6:**

Dark SUSY has been 'unsusyfied' !

DarkSUSY 6 structure



since DS 6:

Very active development

NEW since DS 6:

darksusy.hepforge.org

darksusy – Hepforge

darksusy is hosted by Hepforge, IPPP Durham

- Home
- Download
- Documentation
- Tutorials
- Source Code
- Contact

Dark SUSY

make sure to always check out latest version!

DarkSUSY download

Below you will find the full current release of DarkSUSY for you to download, as well as older versions of the code. Instead, you can also access the (released) code directly via the hepforge repository.

Current version

- **Current version:** darksusy-6.2.3.tgz
- **News:** Full support for generic dark sector relic density calculations (as in 2007.03696), alternative yield tables to DS default (from 1812.07424 and 1911.11147), various minor bug fixes a
- **Release date:** October 31, 2020
- **Tested on:** Mac OS X (Mojave) with gfortran 7.5.0, Red Hat Linux 7.9 wi
- **System requirements:** You need to have approximately 1 GB of hard di 250 MB. Perl is required for the make to proceed properly. autoconf is re create new particle physics modules.

Previous versions

- **Previous version:** darksusy-6.2.2.tgz
- **News:** New adaptive way of solving Boltzmann equation for relic density, absorption of CRDM (as in 1909.08632), larger range of models included
- **Release date:** December 14, 2019
- **Tested on:** Mac OS X (Mojave) with gfortran 7.4.0, Red Hat Linux 7.6 wi
- **System requirements:** You need to have approximately 1 GB of hard di

250 MB. Perl is required for the make to proceed properly. autoconf is required if you want to use the scripts to create new particle physics modules.

- **Previous version:** darksusy-6.2.1.tgz
- **News:** Various improvements in MSSM module (consistent treatment of widths from SLHA files, flavour-ordering of sfermions in different schemes), cosmic-ray induced DM fluxes (numerical stability, momentum-dependent scattering) and other minor updates.
- **Release date:** June 2, 2019
- **Tested on:** Mac OS X (Mojave) with gfortran 7.4.0, Red Hat Linux 7.6 with gfortran 4.8.5.
- **System requirements:** You need to have approximately 1 GB of hard disk space. The download itself is about 250 MB. Perl is required for the make to proceed properly. autoconf is required if you want to use the scripts to create new particle physics modules.

- **Previous version:** darksusy-6.2.0.tar.gz
- **News:** Direct detection routines for cosmic-ray induced dark matter flux (1810.10543), enhanced direct detection capabilities of generic_WIMP module, various new example programs (e.g. for an improved line-of-sight integration based on HEALPIX) and other minor updates.
- **Release date:** February 16, 2019
- **Tested on:** Mac OS X (Mojave) with gfortran 7.4.0, Red Hat Linux 7.6 with gfortran 4.8.5.
- **System requirements:** You need to have approximately 1 GB of hard disk space. The download itself is about 250 MB. Perl is required for the make to proceed properly. autoconf is required if you want to use the scripts to create new particle physics modules.

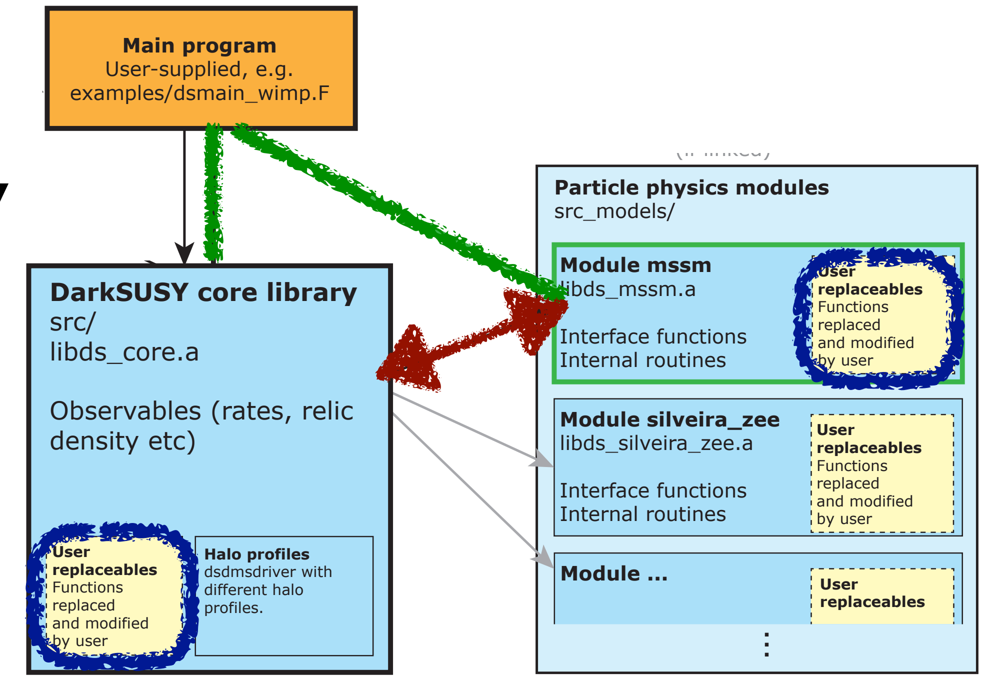
- **Previous version:** darksusy-6.1.1.tar.gz
- **News:** Various improvements, you can e.g. now compile DarkSUSY as a shared library.
- **Release date:** September 19, 2018
- **Tested on:** Mac OS X (Sierra and High Sierra) with gfortran 6.2.0 and 6.4.0, Ubuntu 17 Linux with gfortran 7.2.0.
- **System requirements:** You need to have approximately 1 GB of hard disk space. The download itself is about 250 MB. Perl is required for the make to proceed properly. autoconf is required if you want to use the scripts to create new particle physics modules.

• • •

DarkSUSY modularity: key concepts

- Main program always links to DS_core and *one* particle module

- Interface functions communicate model-dependent input to core library
  - *'Set of interface functions defines particle module'*
  - *No further exchange between core and modules*
  - *Minimal: about a dozen in total*
  - *A particle module <u>can</u> provide less — this only restricts possible applications in main program*
    [error at linking stage points to missing interface function]



- *Most functions are* replaceable functions
  - *Can be individually replaced at linking stage (when building the main program)*
  - *DarkSUSY installation remains unchanged*
  - *User-supplied function will still be consistently used in rest of code*
  - *Examples: external annihilation rate for relic density calculation; different yields for indirect detection routines, etc…*

Recent physics highlights

NEW since DS 6:

- Relic density routines further generalized
  - *Full support for dark sectors with* $\xi(T) \equiv T_{\rm dark}/T$
  - *Options to solve Boltzmann eq. adaptively, partially parallelized*
- Kinetic decoupling and cutoff in matter power spectrum
- More general direct detection routines
  - *structure to add effective operators*
  - *cosmic-ray accelerated (light) dark matter*
- Dark matter self-interactions
- New cosmic-ray propagation routines
- Highly detailed capture rates of DM in Sun and Earth
  - *large number of elements implemented*
- Radiative corrections in MSSM
  - *Full yield contributions from* $U(1), SU(2)$ & $SU(3)$ *Internal Bremsstrahlung*
- Sommerfeld, $\Delta N_{\rm eff}$, HEALPIX l.o.s., …

Example programs

- Extensive main programs to illustrate range of potential usage:

```
/darksusy-6.2.3/examples> ls dsmain*.F
dsmain_decay.F  dsmain_wimp.F
```

→ ***Identical*** **program can be used for different particle modules**

- Various more specific, 'minimal' application examples:

```
darksusy-6.2.3/examples/aux> ls *.f
DDCR_flux.f             DMhalo_predef.f         oh2_dark_sector.f
DDCR_limits.f           DMhalo_table.f          oh2_generic_wimp.f
DD_example.f            ScalarSinglet_RD.f      ucmh_test.f
DMhalo_bypass.f         caprates.f              vdSIDM_RD.f
DMhalo_bypass_prep.f    caprates_ff.f           wimpyields.f
DMhalo_los.f            flxconv.f
DMhalo_new.f            flxconvplot.f
```

direct detection examples

+self-interactions!

indirect detection

relic density [+ kinetic decoupling]

usage of halo model database

Ultra-compact minihalos

1st physics example

Relic Density

Boltzmann equation

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle \left(n_\chi^2 - n_{\chi\,\mathrm{eq}}^2\right)$$

- An accurate approach requires to:
  - *properly take into account thermal average* <...>
  - *include full annihilation cross section* (all final states, resonances, thresholds)
  - *include co-annihilations* (e,g,, all neutralinos, charginos & sfermions)
  - ...

- (Almost) only required input from particle physics: invariant rate
  - *tabulated for better efficiency*
  - *NEW option since 6.2.2: dynamical tabulation, automatic fit to Breit-Wigner resonances*

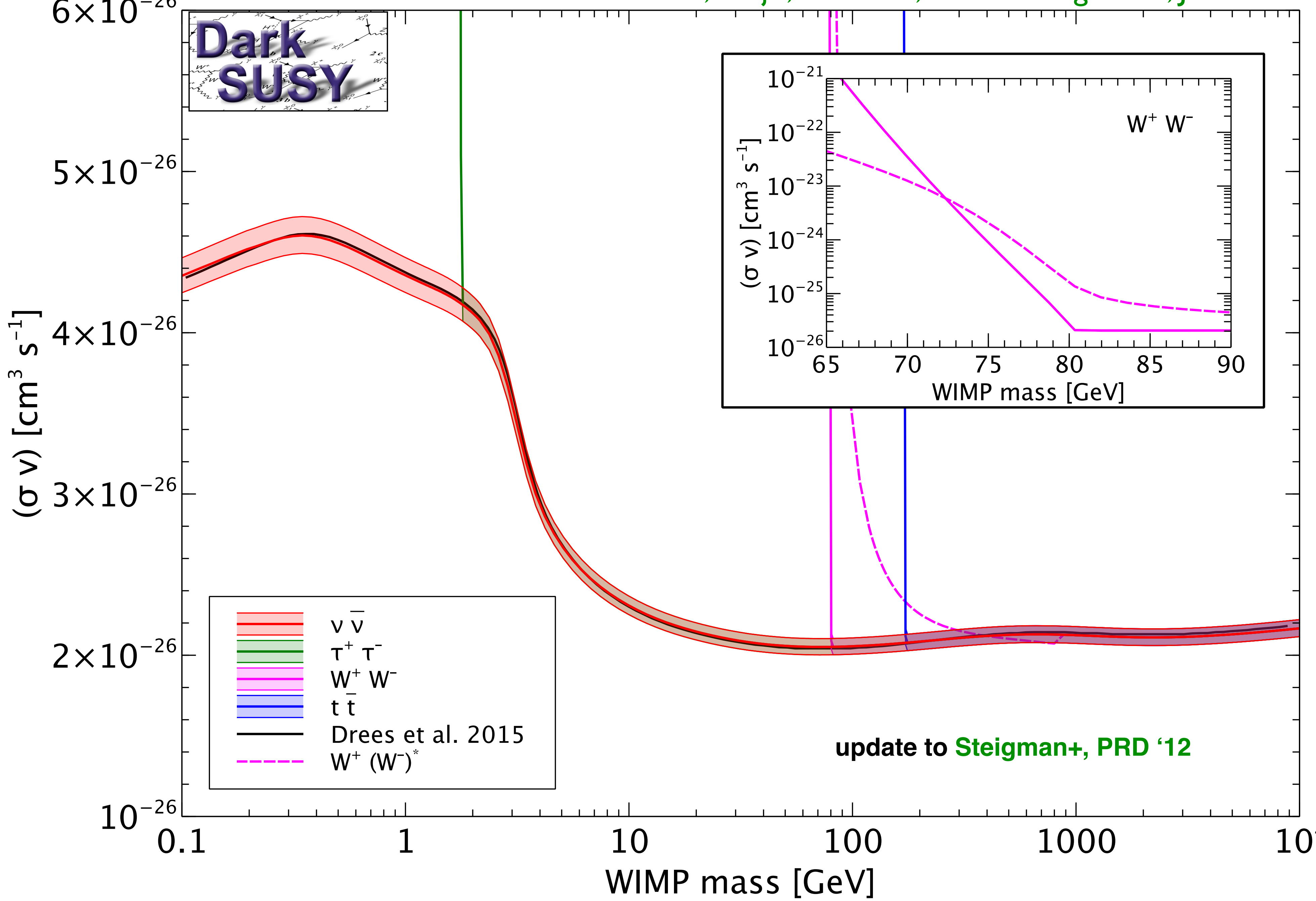
$$W_{\mathrm{eff}} = \sum_{ij} \frac{p_{ij}}{p_{11}} \frac{g_i g_j}{g_1^2} W_{ij} \quad ; \quad W_{ij} = 4E_1E_2\sigma_{ij}v_{ij}$$

$$\langle\sigma_{\mathrm{eff}}v\rangle = \frac{\int_0^\infty dp_{\mathrm{eff}}\, p_{\mathrm{eff}}^2 W_{\mathrm{eff}} K_1\left(\frac{\sqrt{s}}{T}\right)}{m_1^4 T \left[\sum_i \frac{g_i}{g_1} \frac{m_i^2}{m_1^2} K_2\left(\frac{m_i}{T}\right)\right]^2}$$

→ **further improvement in performance *and* accuracy**

Example: generic WIMP

TB, Edsjö, Gondolo, Ullio & Bergström, JCAP '20



width = observational uncertainty in DM density

<u>code</u>: examples/aux/oh2_generic_wimp.f

Example: generic WIMP *in dark sector*

- Secluded dark sector

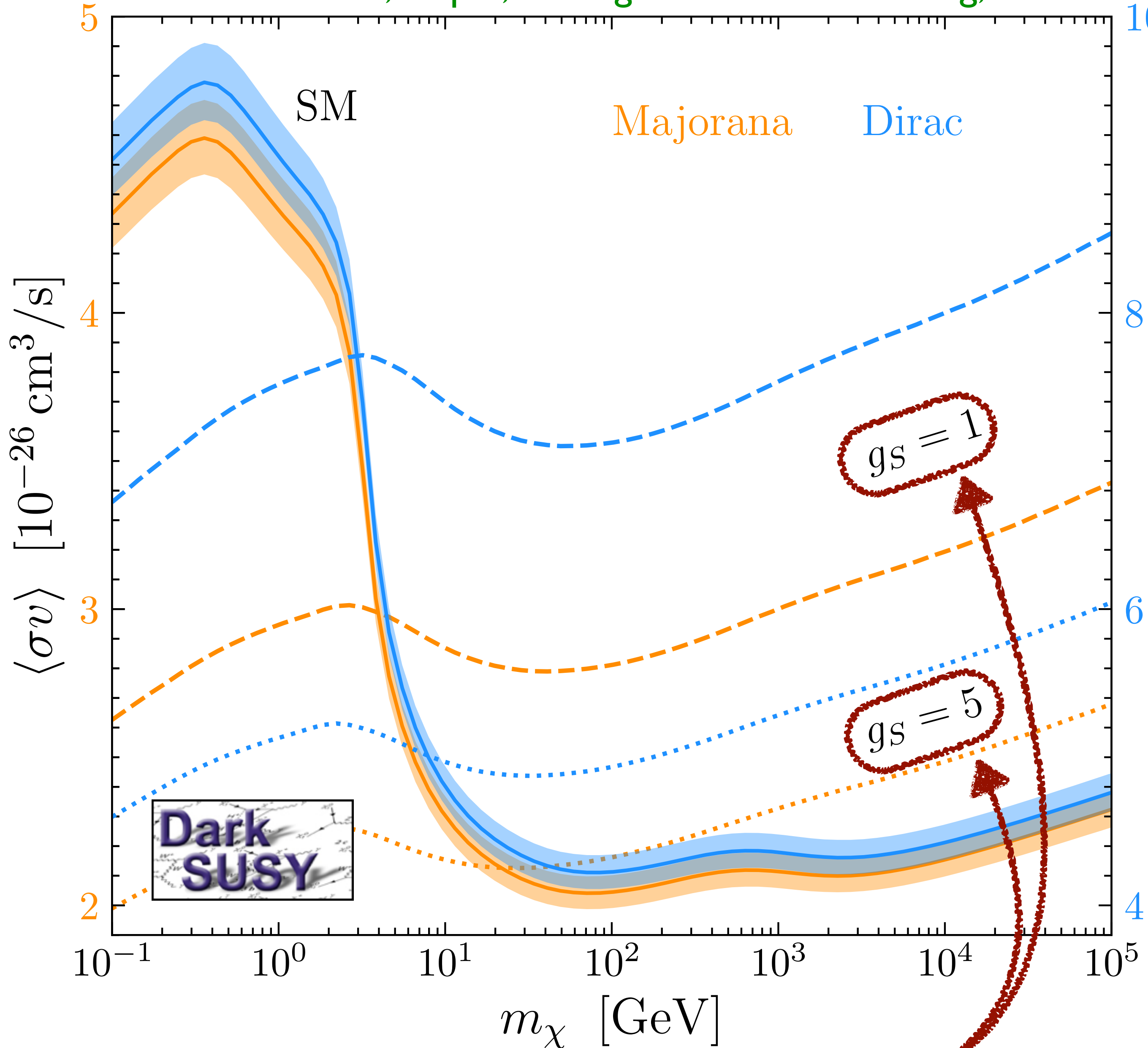
separate **entropy conservation**

$$\xi(T) \equiv \frac{T_\chi(T)}{T} = \frac{\left[g_*^{\rm SM}(T)/g_*^{\rm SM}(T_{\rm dec})\right]^{\frac{1}{3}}}{\left[g_*^{\rm DS}(T)/g_*^{\rm DS}(T_{\rm dec})\right]^{\frac{1}{3}}}$$

- Changes to relic density calculation:
  - $\langle\sigma v\rangle_T \longrightarrow \langle\sigma v\rangle_{T_\chi}$
  - $n_{\chi\,\rm eq}(T) \longrightarrow n_{\chi\,\rm eq}(T_\chi)$
  - $H^2 \propto g_{\rm eff} T^4 \longrightarrow g_{\rm eff} T^4 + g_{\rm eff}^{\rm DS} T_\chi^4$

require two new interface functions
[$\xi(T)$ uniquely determined if entropy conserved + decoupling at $T \to \infty$]

TB, Depta, Hufnagel & Schmidt-Hoberg, PLB '21



relativistic DS d.o.f.

code: examples/aux/oh2_dark_sector.f

2nd physics example

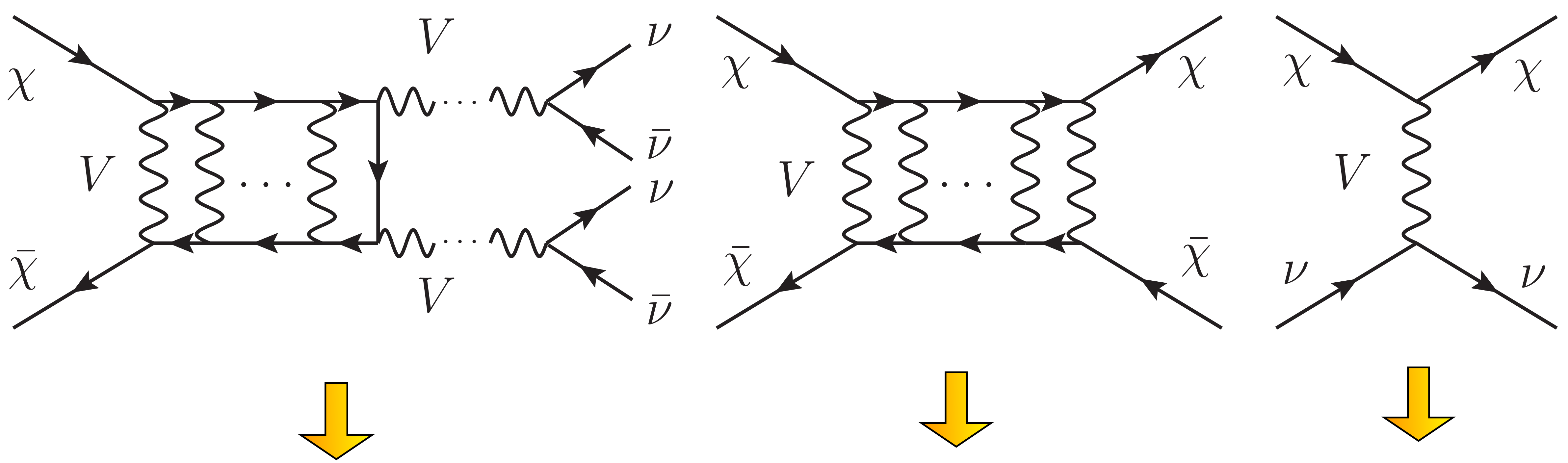
DM self-interactions
(and power-spectrum cutoff)

A simple dark sector framework

van den Aarssen, TB & Pfrommer, PRL '12

- Assume light vector mediator coupling to dark matter and (sterile) neutrinos:
  - *'vdSIDM' module*

$$\mathcal{L}_{\rm int} \supset -g_\chi \bar{\chi} \not{V} \chi - g_\nu \bar{\nu} \not{V} \nu$$



relic density
(+indirect detection signal!?)

changes inner density and velocity profiles of dwarf galaxies
(Yukawa potential)

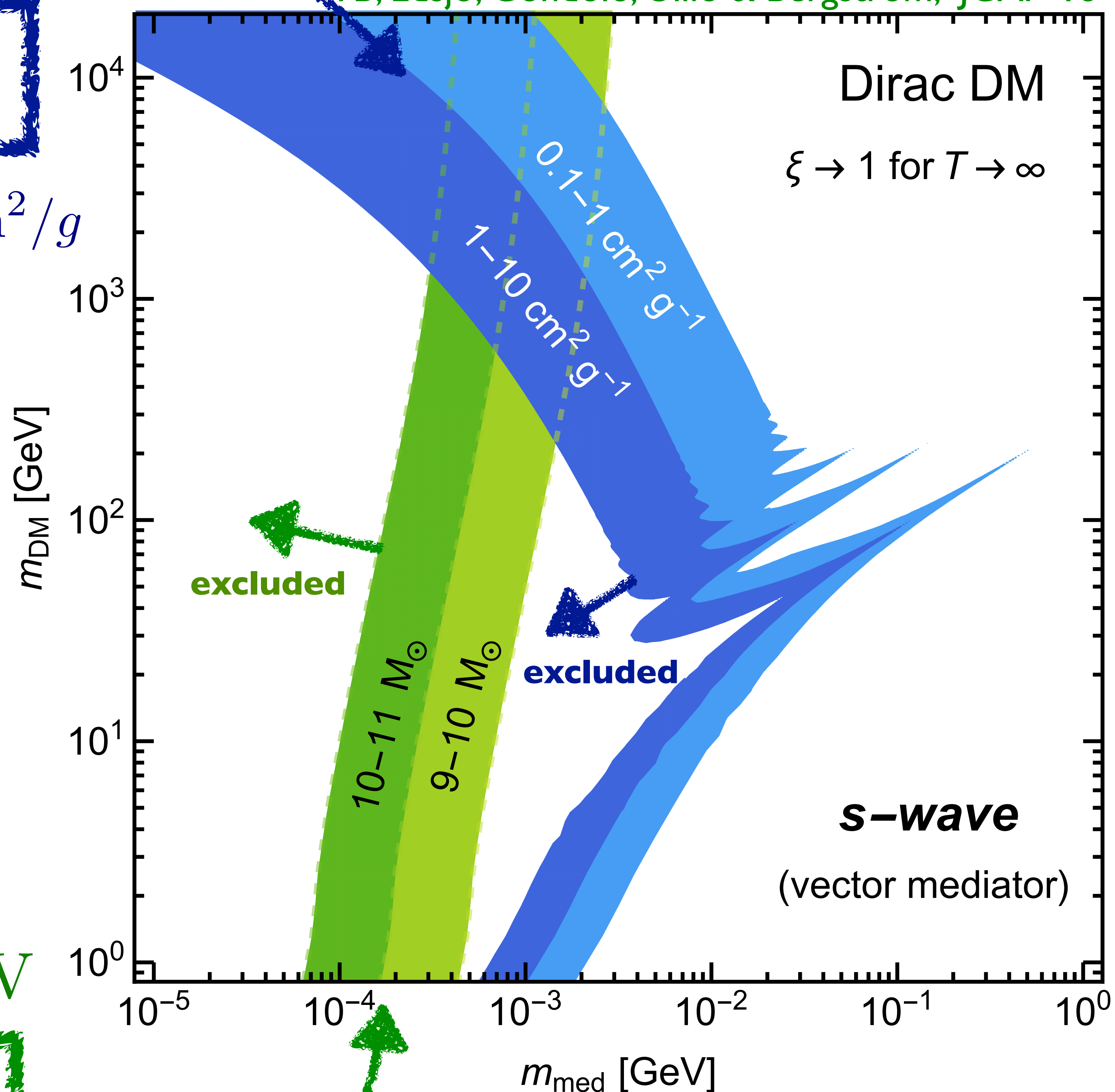
Large $M_{\rm cut}$
(late kinetic decoupling)

Solving the ΛCDM small-scale issues(?)

affect core/ cusp + TBTF

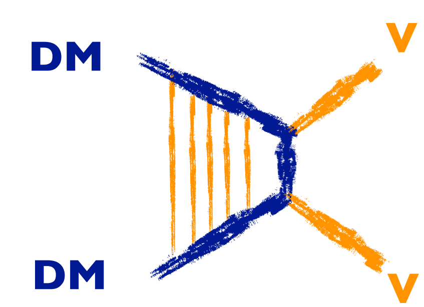
$\langle \sigma_T \rangle / m_\chi \sim 1\,\mathrm{cm}^2/g$

TB, Edsjö, Gondolo, Ullio & Bergström, JCAP '18



- NEW since v6.1:
  - SIDM
  - Sommerfeld
  - handle varying $\xi \equiv T_{\rm dark}/T_{\rm photon}$

→ **coupling fixed by thermal relic density**



$T_{\rm kd} \sim 0.1\,\mathrm{keV}$

address missing satellites ?

code: examples/aux/vdSIDM_RD.f

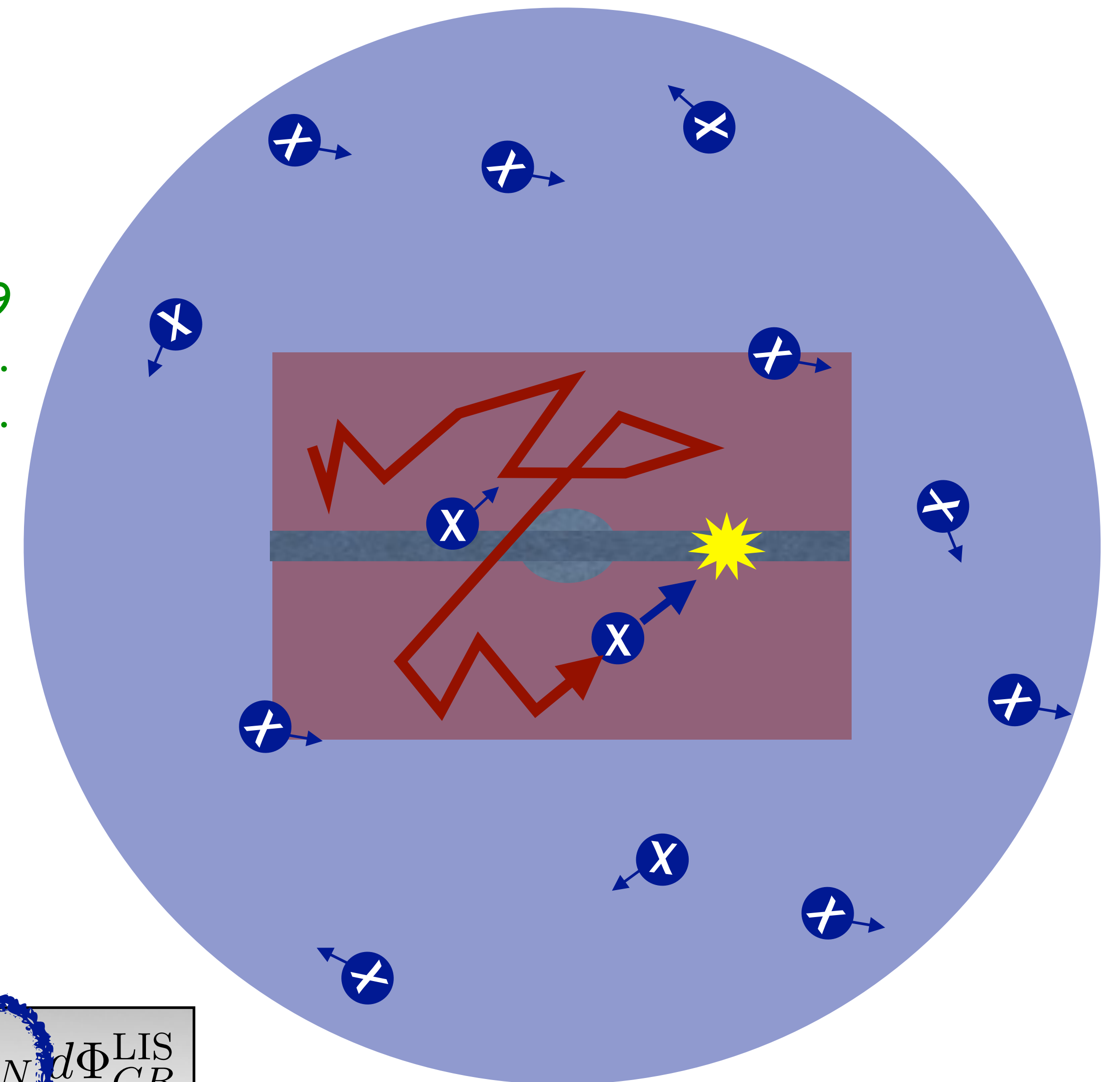
3rd physics example

Cosmic-ray accelerated DM

Reverse direct detection

- *New idea:* high-energy cosmic rays should up-scatter DM initially (almost) at rest!

TB & Pospelov, PRL '19
…
…



➡ *Even sub-GeV DM becomes kinematically accessible in direct detection (and neutrino!) experiments*

- *Three steps:*
  - *production*

$$\frac{d\Phi_\chi}{dT_\chi} = D_{\rm eff}\frac{\rho_\chi^{\rm local}}{m_\chi}\int_{T_{CR}^{\rm min}}^{\infty} dT_{CR}\,\frac{d\sigma_{\chi N}}{dT_\chi}\frac{d\Phi_{CR}^{\rm LIS}}{dT_{CR}}$$

  - *soil/atmosphere attenuation*

$$\frac{dT_\chi^z}{dz} = -\sum_N n_N \int_0^{T_N^{\rm max}} dT_N\,\frac{d\sigma_{\chi N}}{dT_N}\,T_N$$

  - *detection*

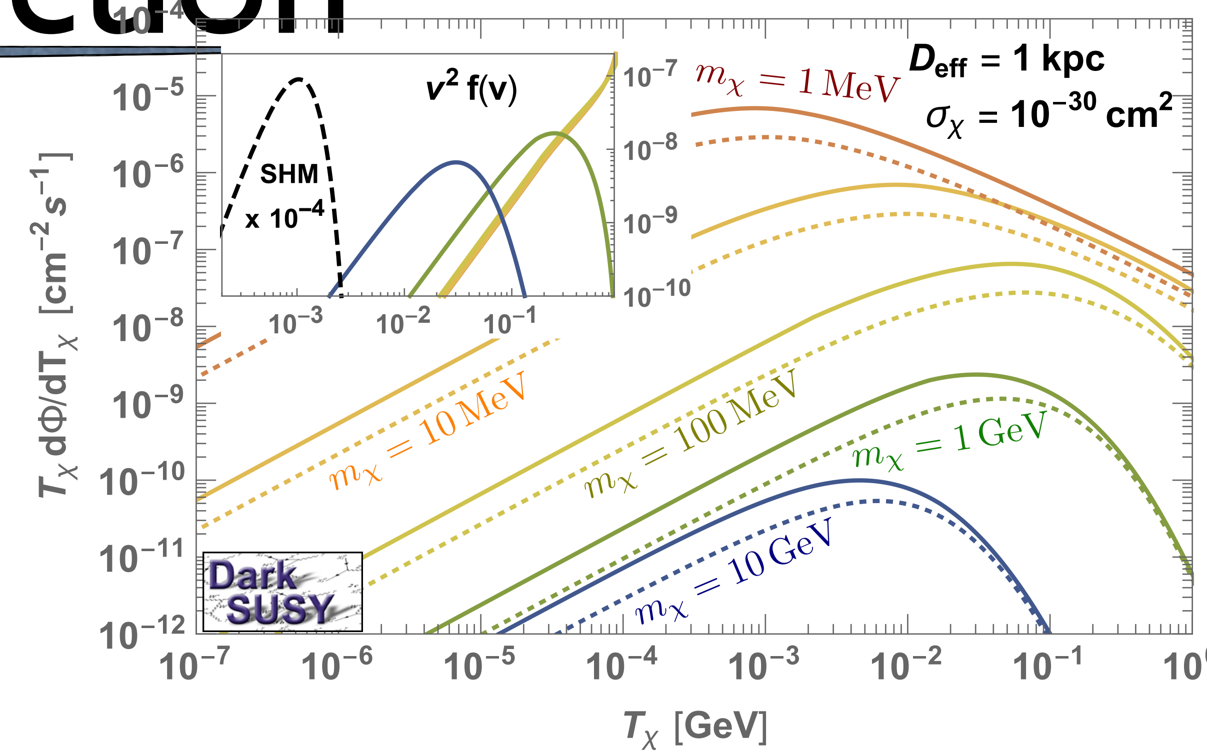
$$\frac{d\Gamma_N}{dT_N} = \int_{T_\chi(T_\chi^{z,\rm min})}^{\infty} dT_\chi\,\frac{d\sigma_{\chi N}}{dT_N}\frac{d\Phi_\chi}{dT_\chi}$$

particle physics input:
interface functions

Reverse direct detection

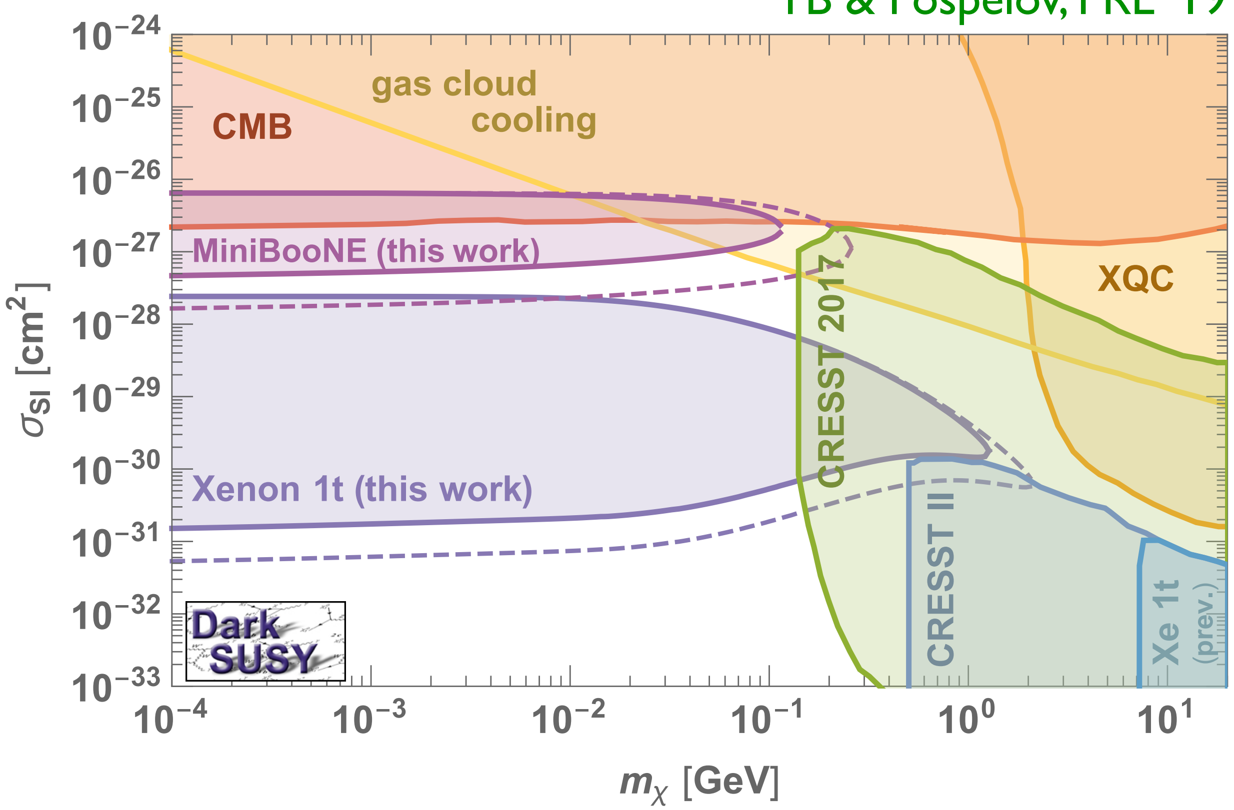
- An unavoidable **high-energy DM flux**
  - *(but highly subdominant)*

<u>code</u>: examples/aux/DDCR_flux.f

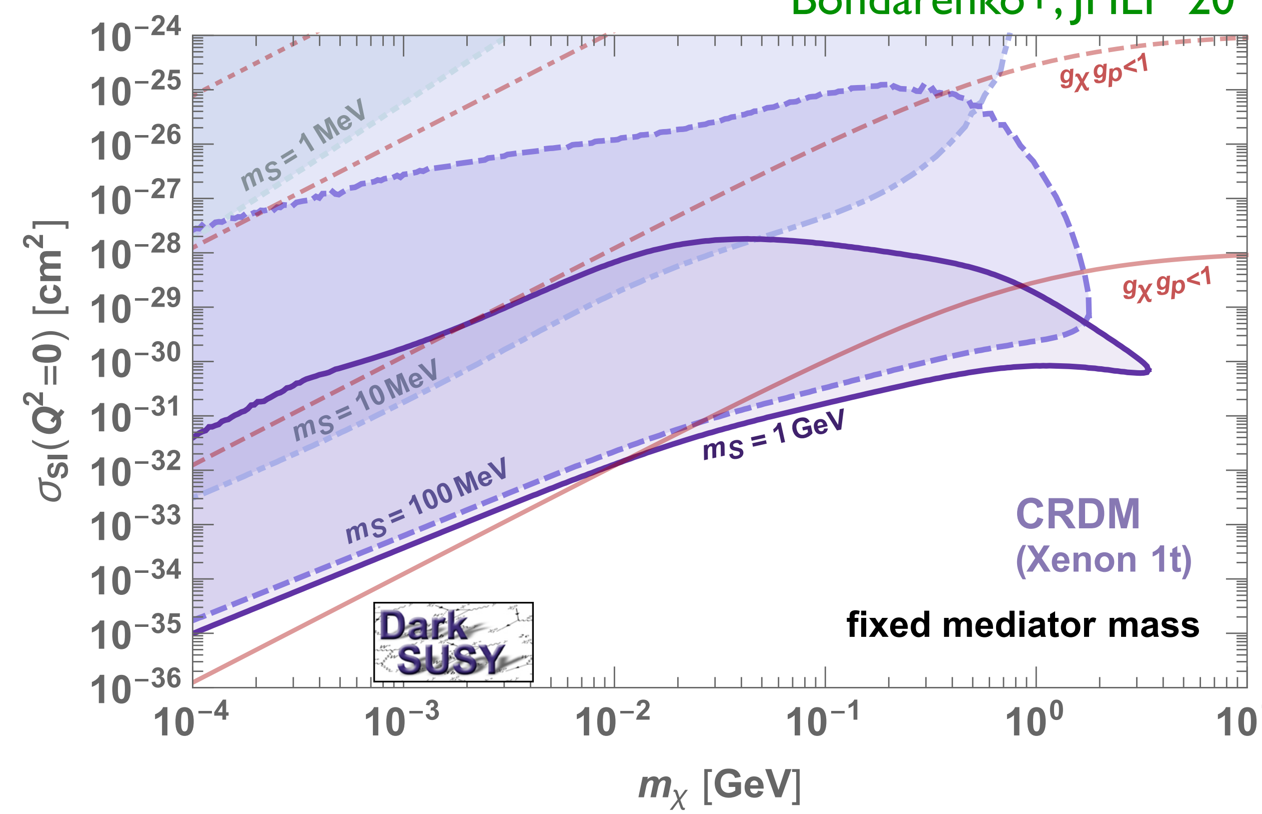


- Resulting low-mass limits
  - *constant scattering cross section*
  - *full Q²-dependence* (here: Higgs portal)

TB & Pospelov, PRL '19



Bondarenko+, JHEP '20



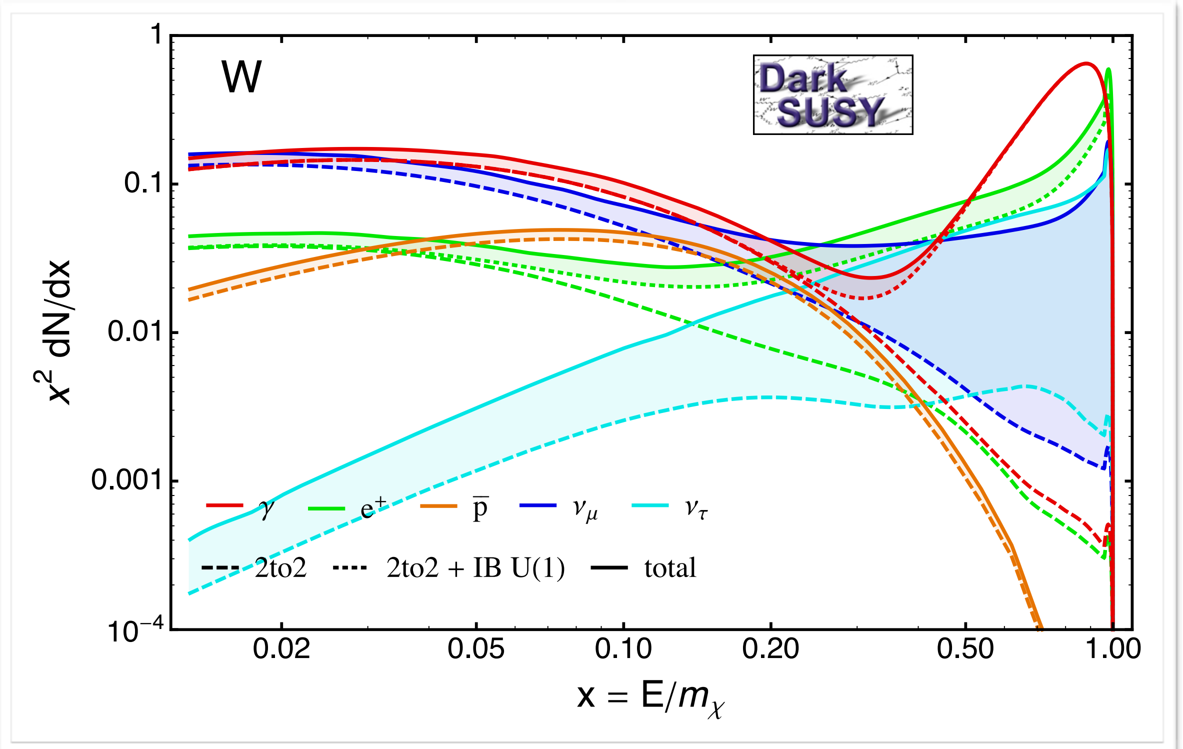
same(!) <u>code</u>: examples/aux/DDCR_limits.f

4th physics example

Indirect detection yields

Particle spectra from DM annihilation

- `Model-independent' spectra from fragmentation or decay of final states
  - *Tabulated default PYTHIA runs*
  - *Alternative spectra* (improving on QCD uncertainties) — Amoroso+, JCAP'19
  - *Dedicated spectra for low-mass DM annihilations* — Plehn, Reimitz & Richardson, SPP '20
- Particle yields including *U(1)*, *SU(2)* and *SU(3)* radiative corrections
  - *For MSSM module, in particular internal bremsstrahlung*



TB, Calore, Galea & Garny, JHEP '17

- Can easily be switched for any indirect detection application

code: examples/aux/wimpyields.f

```
c...Change default yield tables
      call dsanyield_set('yieldtables','default')
c      call dsanyield_set('yieldtables','Amoroso')

c      call dsanyield_set('yieldtables','Plehn')
```

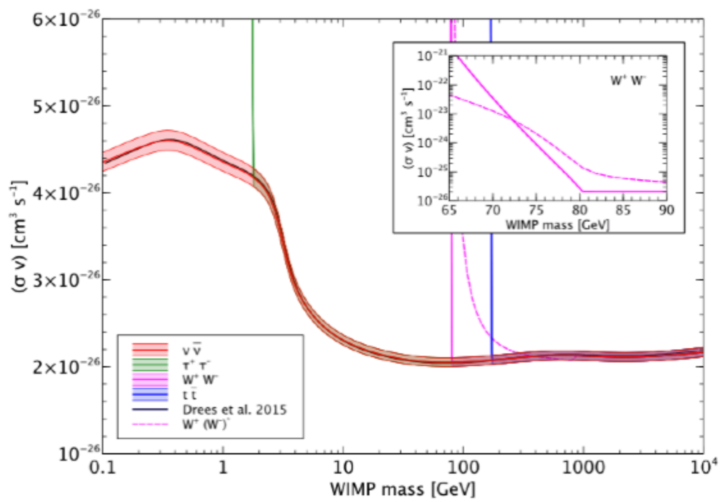
More physics examples?

- Home
- Download
- Getting started
- Examples
- Documentation
- Contact

Examples

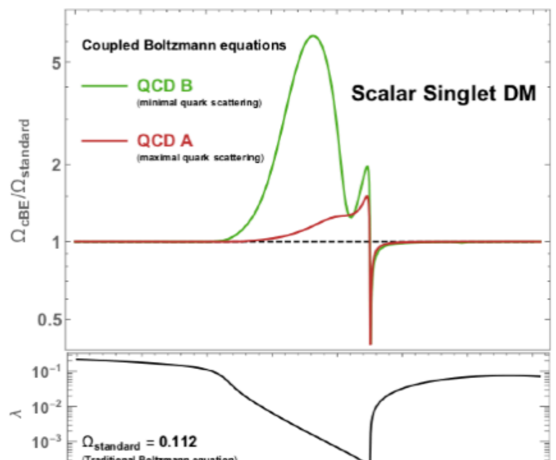
Here we showcase some selected physics applications that illustrate results you can obtain with DarkSUSY. Many of those are based on examples programs located in exampels/aux. Have ***you*** obtained interesting results with DarkSUSY that you want us to advertise here? Let us know!

Thermal annihilation cross section



- **Description**
  Thermally averaged annihilation rate during freeze-out that is needed to obtain the observed dark matter relic density. Often used for benchmarking purposes, in particular in the context of indirect searches for dark matter. The inset shows the impact of a hard kinematic cutoff for two-body annihilation vs. allowing for off-shell final states.
- **Code**
  examples/aux/oh2_generic_wimp.f
- **Journal Ref**
  JCAP 1807 (2018) 033 [arXiv:1802.03399]

Freeze-out beyond kinetic equilibrium



- **Description**
  Dark matter annihilation via an *s*-channel resonance is one of the examples where the usual Boltzmann equation may be incorrect because kinetic equilibrium is not maintained during the entire freeze-out process. The plot illustrates the size of this effect for the Scalar Singlet model. (The couplings are here chosen as indicated in the bottom panel; for the standard - in this case incorrect - calculation this would result in a relic density matching the measured one).
- **Code**
  examples/aux/ScalarSinglet_RD_cBE.f
- **Journal Ref**

Conclusions

Let's go to

http://www.darksusy.org

and get started…

…AFTER a short break!

🙂