DarkSUSY 6

Why using DarkSUSY ? A teaser.

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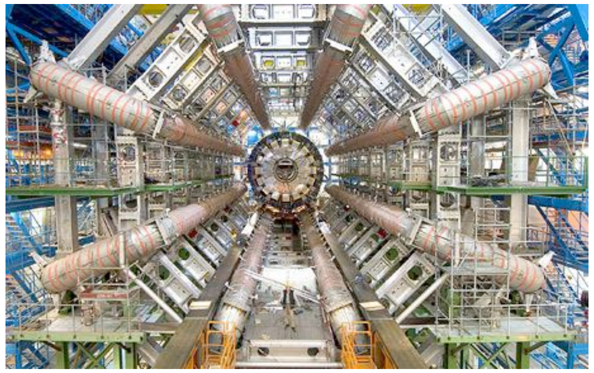
JCAP 1807 (2018)

www.darksusy.org

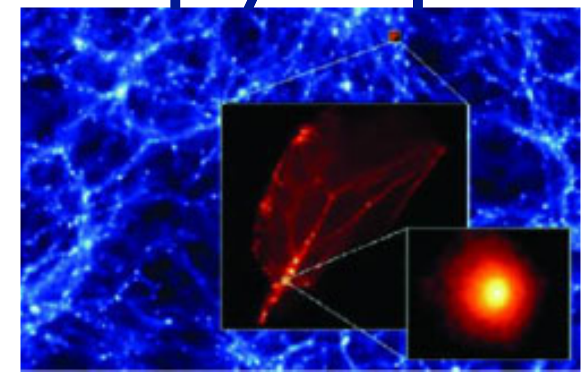
UiO : **University of Oslo**

Strategies for dark matter searches

at colliders



astrophysical probes

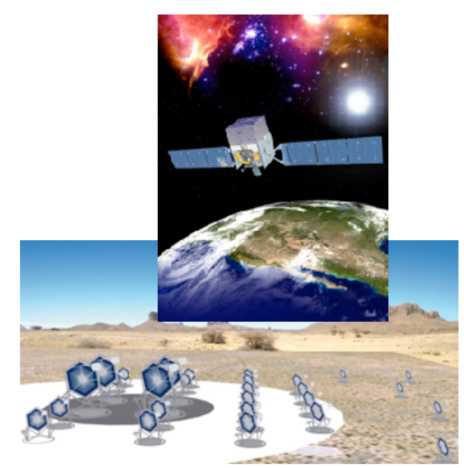


of matter distribution

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

Dark SUSY

directly



indirectly

disclaimer: clearly impossible to cover everything in 30 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** — Detailed rate calculators
- **Compare with data!** — Compare individual rates or perform global fits

For the **MSSM**, this partially relies on implementing Isajet, FeynHiggs, Higgsbounds, HiggsSignal, Superiso,…

main focus

What is DarkSUSY ?

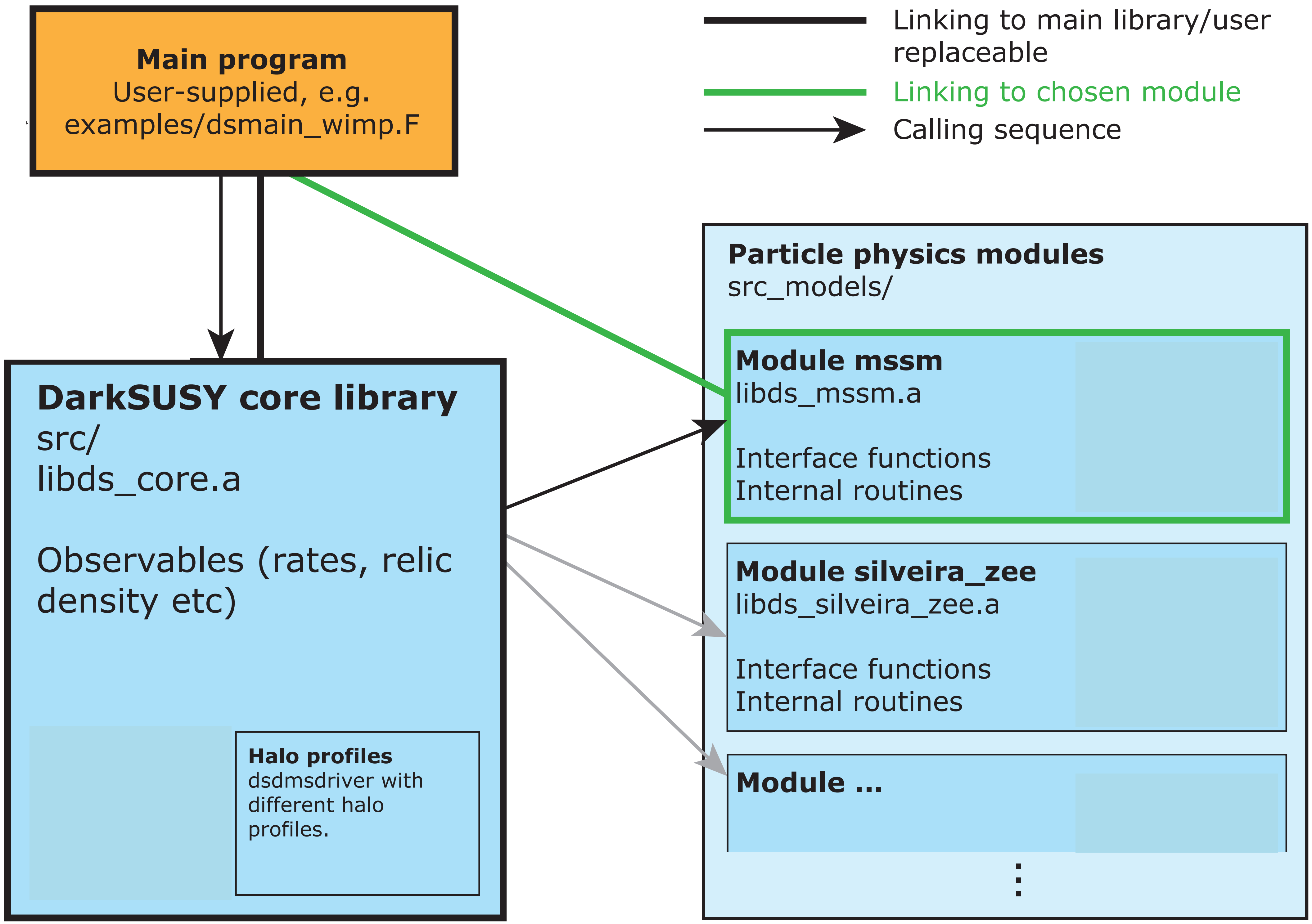
- A FORTRAN library of subroutines and functions

  ~100k lines of code, mostly F77
- Simple to use (!)
- Fast and accurate
- Flexible, highly modular structure (given FORTRAN constraints)
- Currently included particle physics modules:
  - *MSSM (SUSY)*
  - *Scalar Singlet (Silveira-Zee model)*
  - *self-interacting DM (simplified dark sector model)*
  - *generic WIMP*
  - *generic decaying DM*
  - *generic FIMP*
  - *+ whatever YOU add!*

since DS 6:

Dark SUSY has been 'unsusyfied' !

DarkSUSY 6 structure



Some physics highlights

- Very accurate relic density routines. Non-standard features:
  - *Full support for dark sectors with* $\xi(T) \equiv T_{\rm dark}/T$
  - *Coupled Boltzmann equations out of kinetic equilibrium*
  - *Asymmetric DM*
- Freeze-in routines *(with finite-T corrections, quantum statistics)*
- Kinetic decoupling and cutoff in matter power spectrum
- Extensive direct detection routines
  - *cosmic-ray accelerated (light) dark matter*
- Highly detailed capture rates of DM in Sun and Earth
- Neutrino and cosmic-ray propagation routines
- Radiative corrections in MSSM
  - *Full yield contributions from* $U(1), SU(2)$ & $SU(3)$ *Internal Bremsstrahlung*
- Dark matter self-interactions
- Modified $H(t)$, (simp.) Sommerfeld, $\Delta N_{\rm eff}$, HEALPIX l.o.s., …

Active development

darksusy.hepforge.org

darksusy – Hepforge

darksusy is hosted by Hepforge, IPPP Durham

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- Source Code
- Contact

make sure to always check out latest version!

NEW

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-6.4.0.tgz
- **News:** Major updates in relic density routines, including support for asymmetric dark matter as well as improvements in speed and accuracy. Updated treatment of cosmic-ray induced DM fluxes (as in 2209.03360). Various further improvements (neutrino oscillations, yield routines, QCD corrections).
- **Release date:** December 9, 2022
- **Tested on:** Mac OS X (Ventura on Apple Silicon M1) with gfortran 12, and Ubuntu 20.04 with gfo
- **System requirements:** You need to have approximately 2.7 GB of hard disk space. The downloa 480 MB. Perl is required for make to proceed properly. Further required packages (for contributed compile): cmake, curl + libcurl, aclocal, autoconf, automake.

Previous versions

- **Previous version:** darksusy-6.3.1.tgz
- **News:** New yield tables based on Pythia8 runs. Further alternative yield tables (from 2007.15001 2202.11546). Improvements in build system.
- **Release date:** March 19, 2022
- **Tested on:** Mac OS X (Monterey on Apple Silicon M1) with gfortran 11, and Ubuntu 20.04 with gf 9.4.0 and 10.3.0.
- **System requirements:** You need to have approximately 2.5 GB of hard disk space. The downloa 470 MB. Perl is required for make to proceed properly. Further required packages (for contributed compile): cmake, curl + libcurl, aclocal, autoconf, automake.
- **Previous version:** darksusy-6.3.0.tgz
- **News:** Relic density calculations via freeze-in, including quantum statistics and other finite-tempe (2111.14871). New particle physics module 'generic_FIMP'. Hadronic Higgs decay widths.
- **Release date:** December 3, 2021

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.

Example programs

- Detailed main programs to illustrate range of potential usage:

```
/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:

```
/examples/aux> ls *.f
DDCR_flux.f            FreezeIn_ScalarSinglet.f             oh2_ScalarSinglet.f
DDCR_limits.f          FreezeIn_generic_fimp.f              oh2_aDM.f
DD_example.f           ScalarSinglet_thermal_averages.f     oh2_cBE_ScalarSinglet.f
DMhalo_bypass.f        caprates.f                           oh2_dark_sector.f
DMhalo_bypass_prep.f   caprates_ff.f                        oh2_generic_wimp.f
DMhalo_los.f           flxconv.f                            oh2_vdSIDM.f
DMhalo_new.f           flxconvplot.f                        ucmh_test.f
DMhalo_predef.f        neutrinospectra.f                    wimpyields.f
DMhalo_table.f         neutrinoyields.f
```

+self-interactions!

direct detection examples

indirect detection

usage of halo model database

relic density [+ kinetic decoupling]

Ultra-compact minihalos

➡ ***Compile individual programs with 'make oh2_aDM' etc…***

1st physics example

Relic Density

Boltzmann equation

- Standard Boltzmann equation for freeze-out

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

  - *NB: only valid in kinetic EQ — DarkSUSY also has routines to handle more general cases*

- Input from particle physics: invariant rate
  - *provided as interface function*
  - *dynamical tabulation, automatic fit to Breit-Wigner resonances*

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

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

- Freeze-in production:
  - *Quantum statistics*
  - *Thermal masses*
  - *Effect of EW & QCD phase transitions*

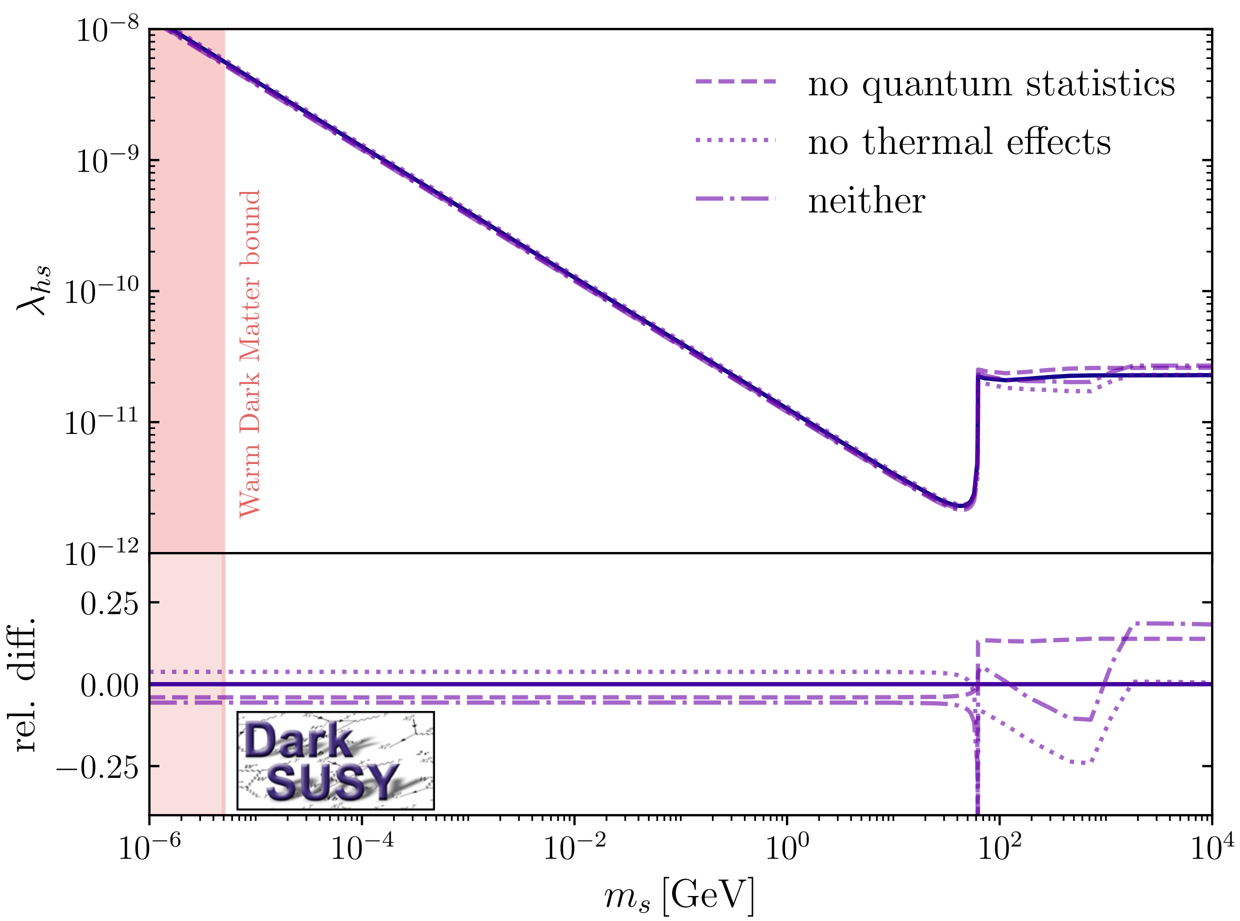
$$W_{\mathrm{eff}}\left(p_{\mathrm{CM}}\right) \to W_{\mathrm{eff}}\left(T, p_{\mathrm{CM}}\right)$$

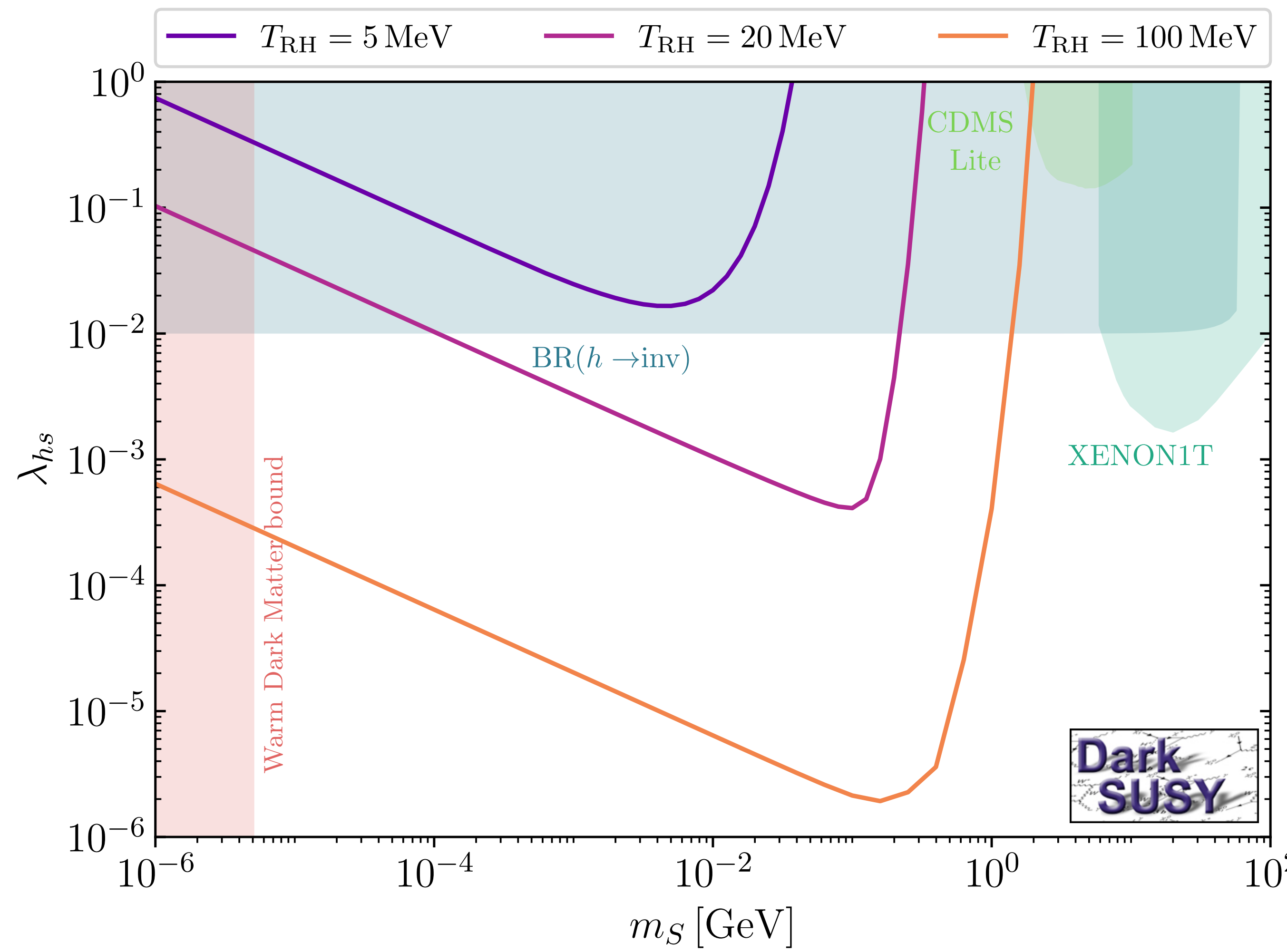
NEW **since DS 6.3**

Freeze-In of Scalar Singlet DM

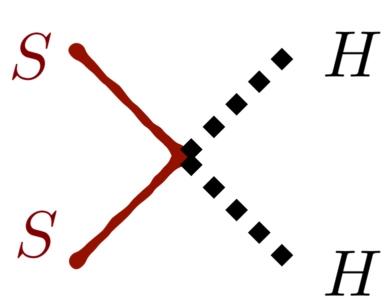
TB, Heeba, Kahlhoefer & Vangsnes, JHEP '22

$$\mathcal{L} = \frac{1}{2}\partial_\mu S \partial^\mu S + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\lambda_{hs} S^2 |H|^2 + \frac{1}{4}\lambda_s S^4$$

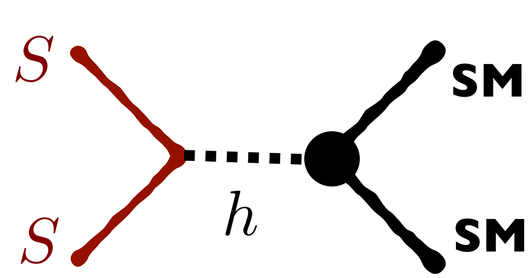




- High reheating temperature
  - before EWSB:



  - after EWSB:



- Low reheating temperature

$$\mathcal{L} \supset \frac{1}{\Lambda_f} \bar{f} f S^2$$

2nd physics example

DM self-interactions

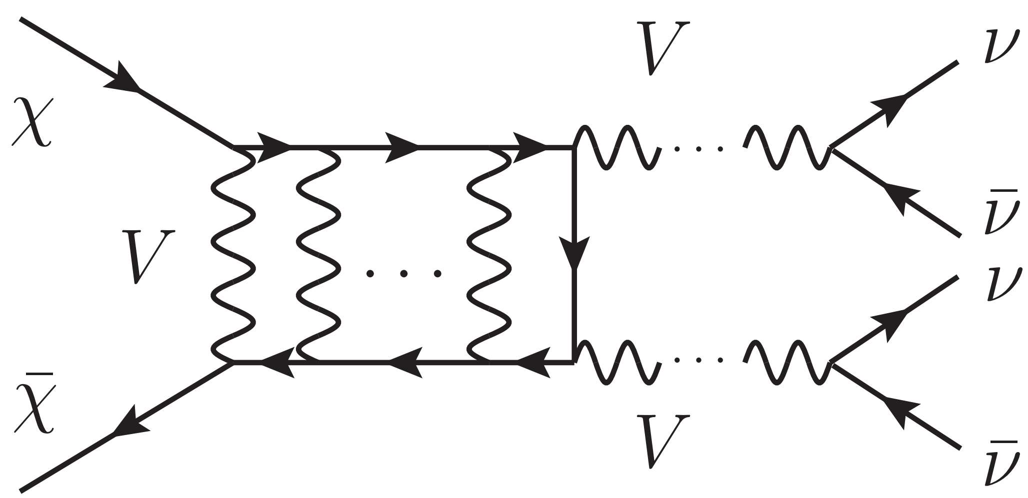
(and cutoff in power-spectrum)

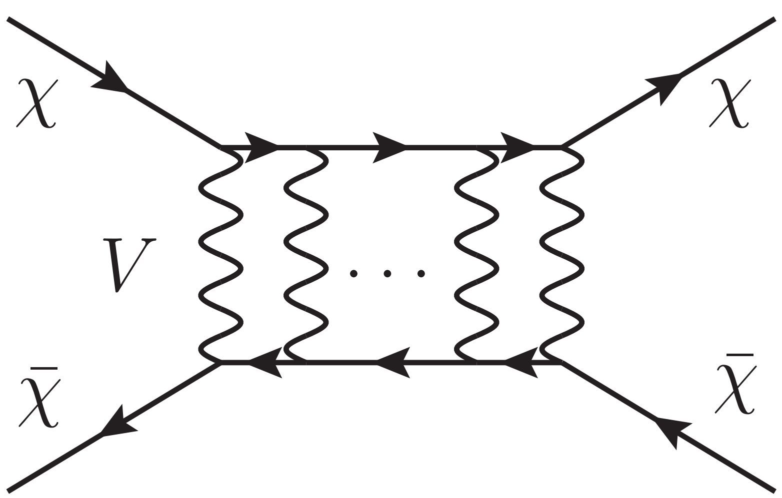
A simple dark sector framework

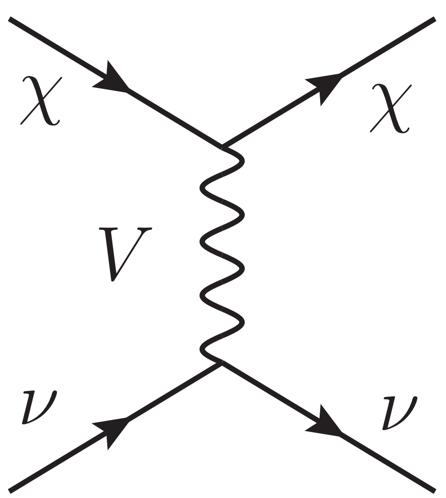
van den Aarssen, TB & Pfrommer, PRL '12

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

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







relic density
(+indirect detection signal!?)

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

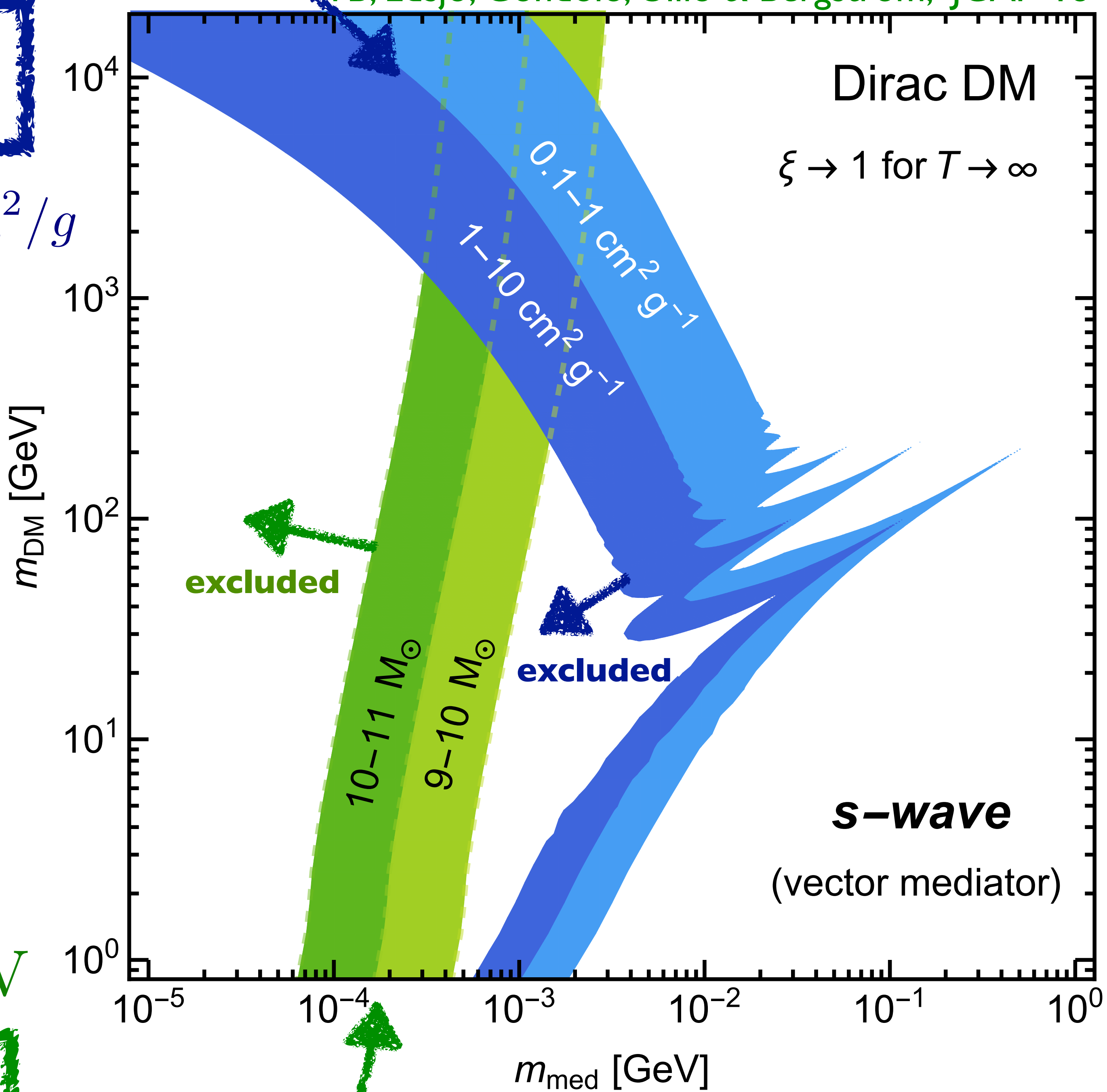
Large $M_{\rm cut}$
(late kinetic decoupling)

Solving the ΛCDM small-scale issues(?)

affect core/ cusp + TBTF

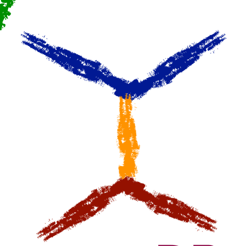
$\langle\sigma_T\rangle/m_\chi \sim 1\,\mathrm{cm}^2/g$

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



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

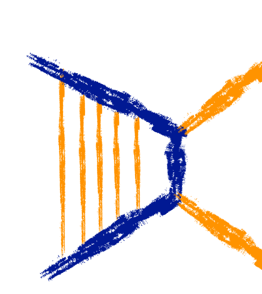
address missing satellites ?



- New since v6.1:
  - Self-interacting DM
  - Sommerfeld
  - handle varying

$\xi \equiv T_{\rm dark}/T_{\rm photon}$

→ **coupling fixed by thermal relic density**



code: examples/aux/vdSIDM_RD.f

3^{rd} physics example

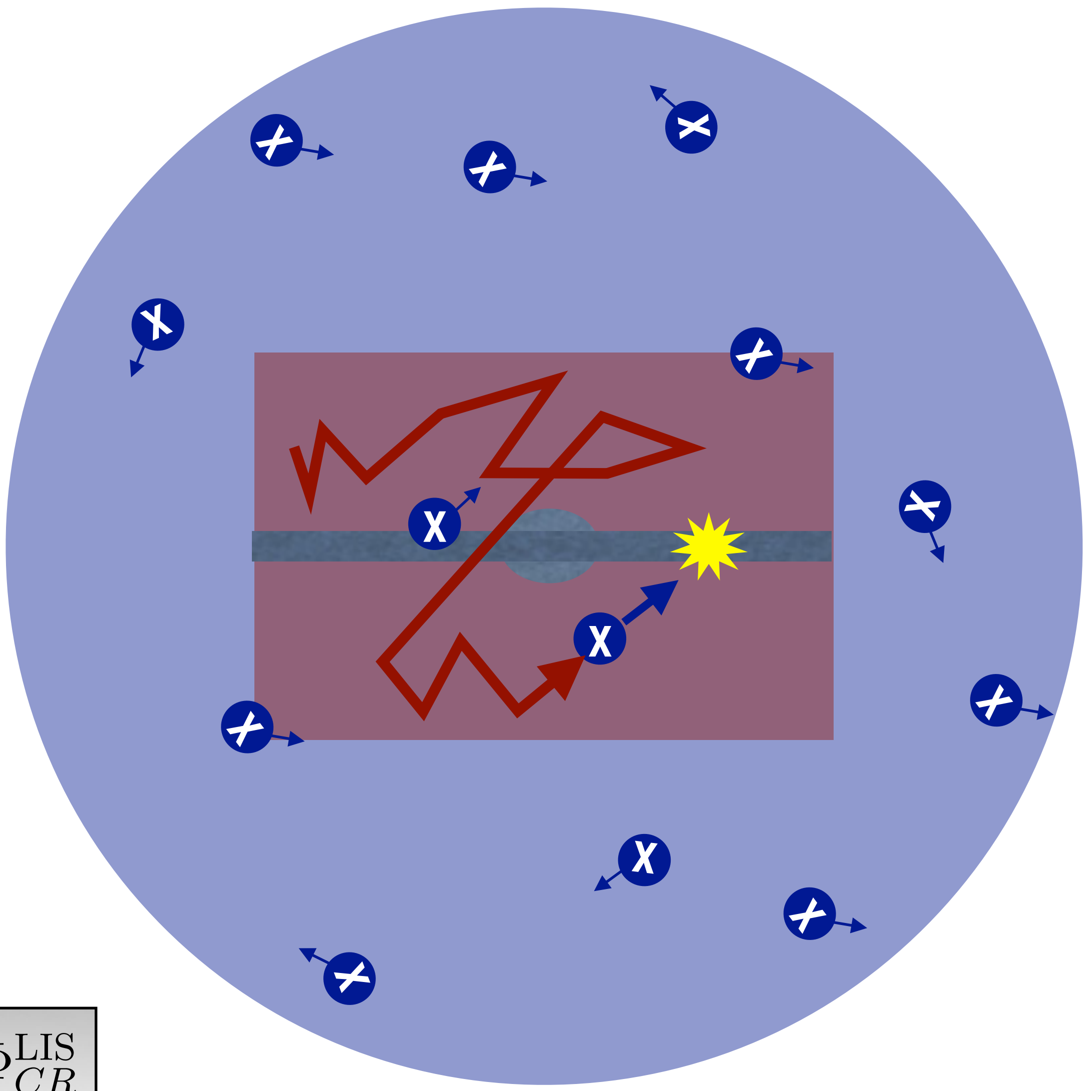
Cosmic-ray accelerated DM

Reverse direct detection

- 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*

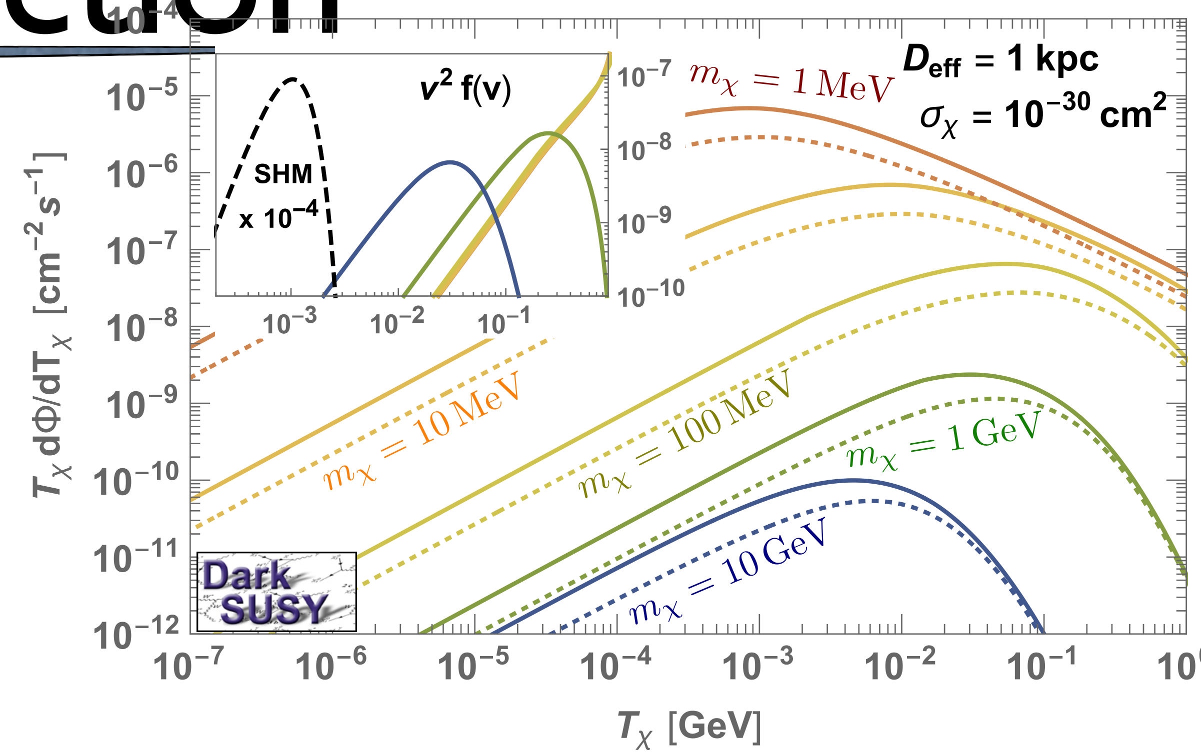


- *Three steps:*
  - *production*
    $$\frac{d\Phi_\chi}{dT_\chi} = D_{\rm eff}\frac{\rho_\chi^{\rm local}}{m_\chi}\int_{T_{CR}^{\rm min}}^\infty dT_{CR}\,\frac{d\sigma_{\chi N}}{dT_\chi}\frac{d\Phi_{CR}^{\rm LIS}}{dT_{CR}}$$
  - *soil/atmosphere attenuation*
    $$\frac{dT_\chi^z}{dz} = -\sum_N n_N \int_0^{T_N^{\rm max}} dT_N\,\frac{d\sigma_{\chi N}}{dT_N}\,T_N$$
  - *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 function

Reverse direct detection

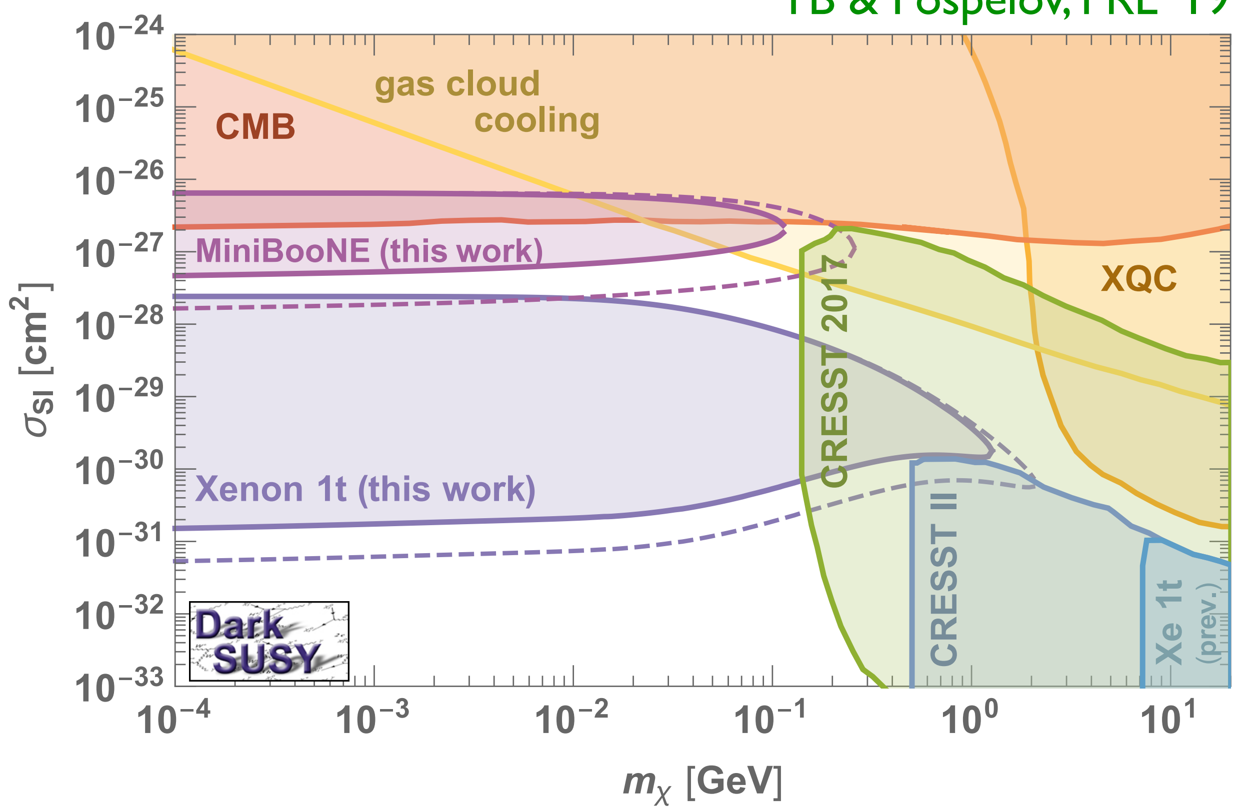
- An unavoidable **high-energy DM flux**
  - *(but highly subdominant)*



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

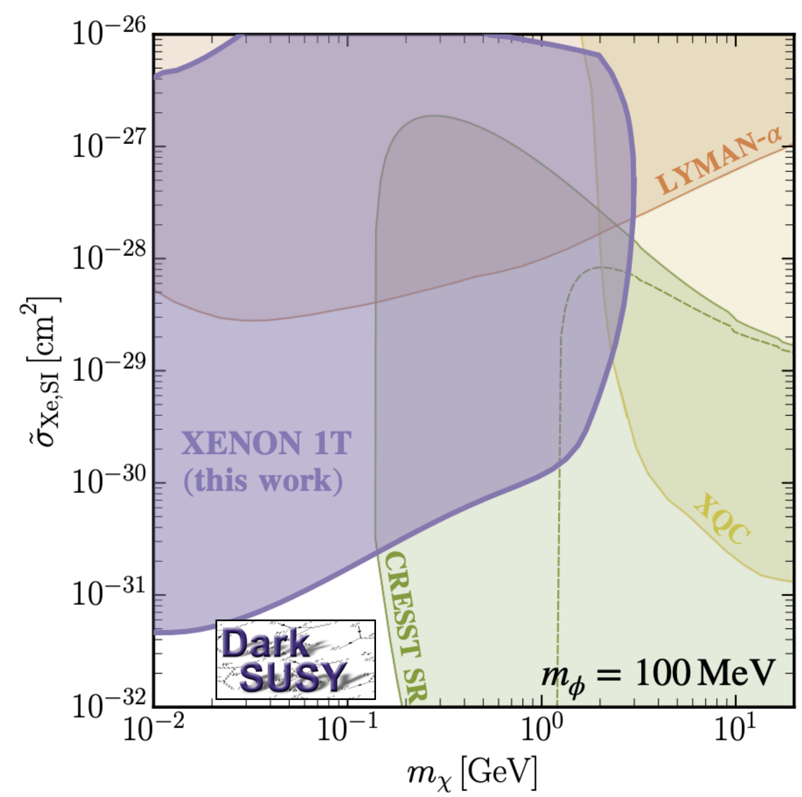
- Resulting low-mass limits
  - *constant scattering cross section*

TB & Pospelov, PRL '19



- *full Q*[2]*-dependence + inelastic scattering* (here: scalar mediator)

Alvey+, JHEP '23



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

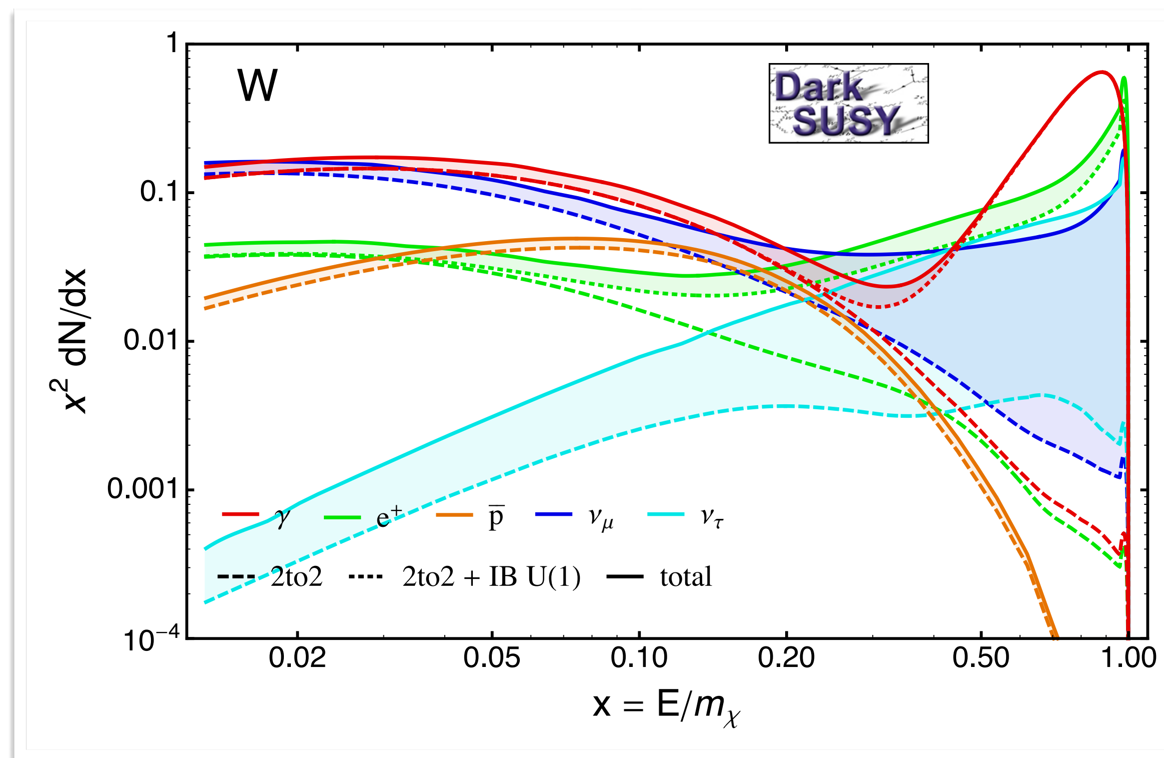
4th physics example

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

- Switch easily between options for indirect detection applications

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

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

code: **examples/aux/wimpyields.f**

More physics examples?

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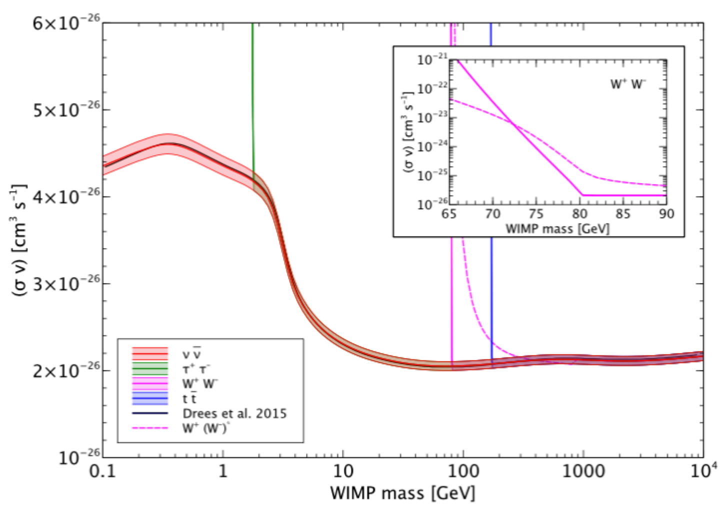
Examples

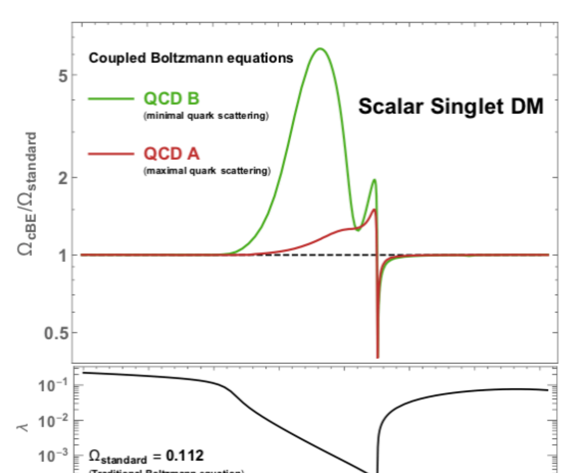
Here we showcase some selected physics applications that illustrate results you can obtain with DarkSUSY. Many of those are based on examples programs located in exampels/aux. Have ***you*** obtained interesting results with DarkSUSY that you want us to advertise here? Let us know!

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…

🙂