More than supersymmetric dark matter

Torsten Bringmann

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

JCAP 1807 (2018)
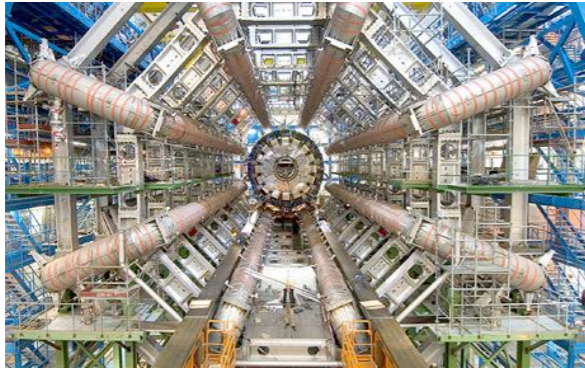
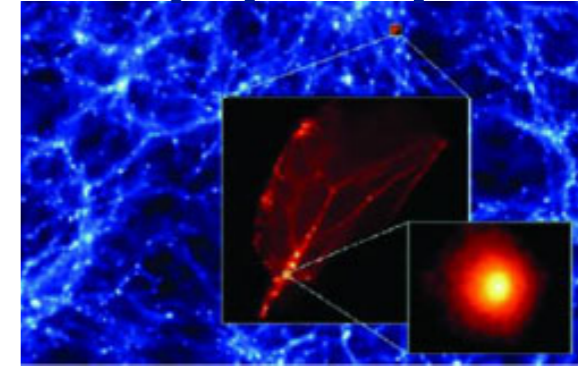**www.darksusy.org**

UiO **: University of Oslo**

Strategies for dark matter searches

at colliders

astrophysical probes

of matter distribution

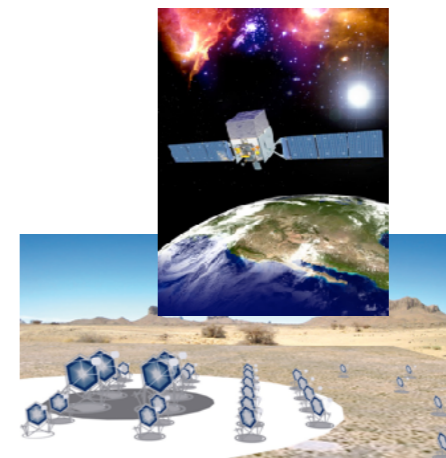want to calculate expected rates in a consistent manner – both regarding particle and astrophysics!
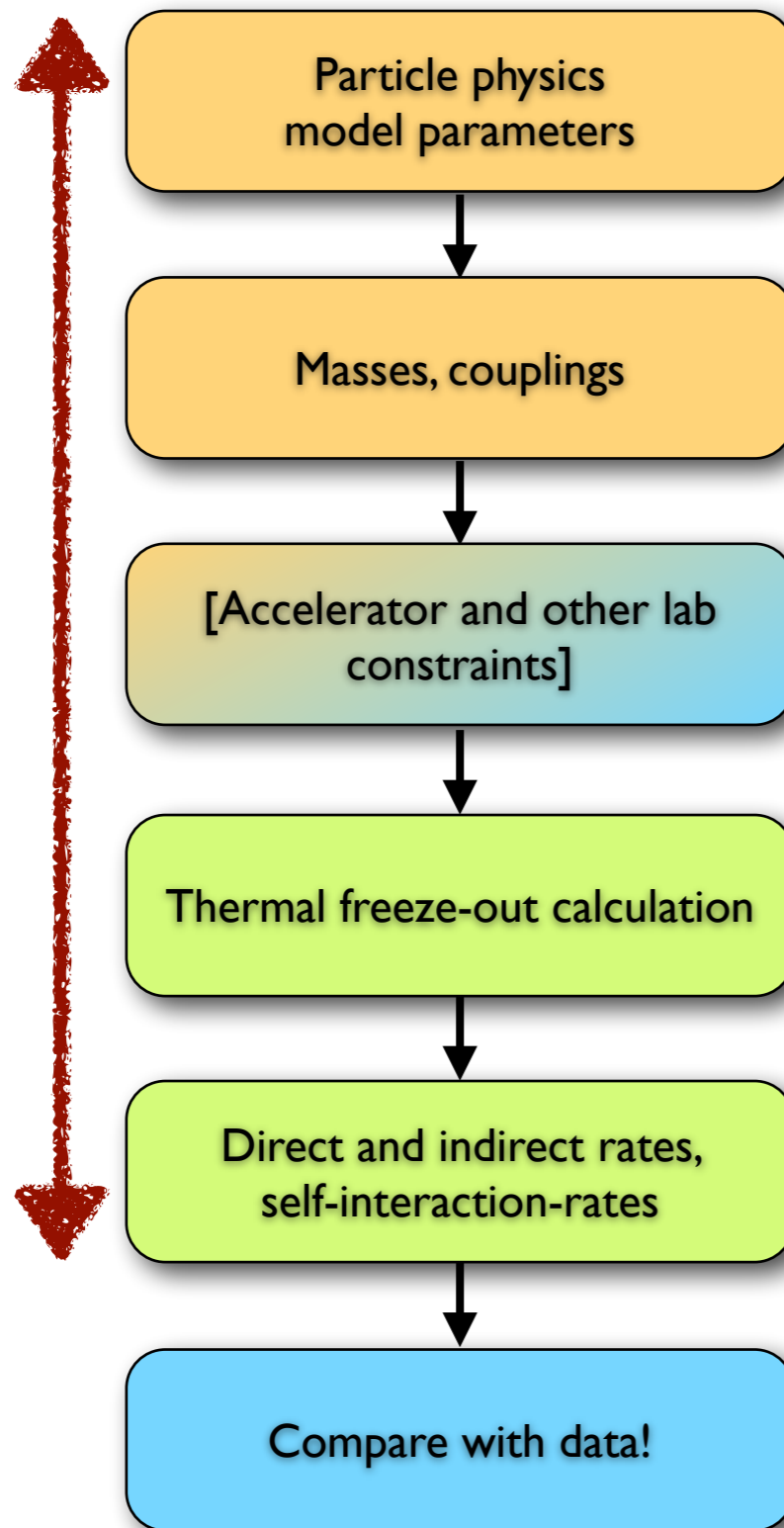
directly

Dark SUSY

indirectly

<u>disclaimer</u>: 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 — **main focus**

Compare with data!
→ Compare individual rates or perform global fits

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 (!)

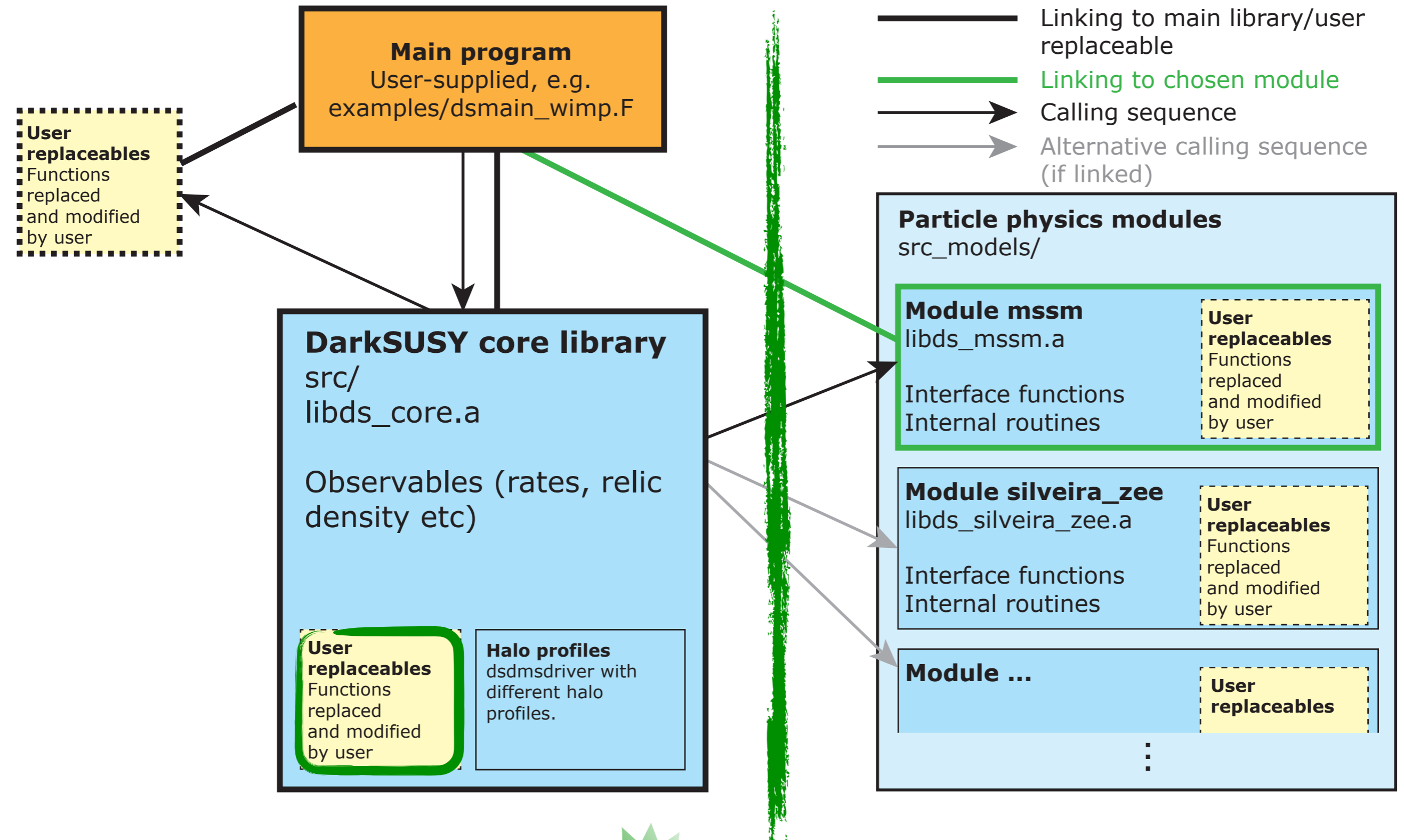- Currently included particle physics modules:
    - *MSSM (SUSY)*
    - *Scalar Singlet (Silveira-Zee model)*
    - *self-interacting DM (simplified dark sector model)*
    - *generic WIMP*
    - *generic decaying DM*
    - *Kaluza-Klein DM (in progress)*
    - *+ whatever YOU add!*

NEW   **since DS 6:**
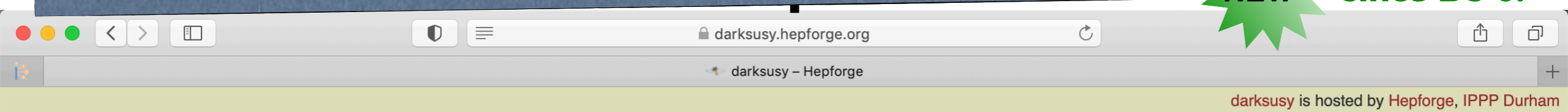
Dark SUSY is now 'unsusyfied' !

DarkSUSY 6 structure

Main program
User-supplied, e.g.
examples/dsmain_wimp.F

User replaceables
Functions replaced and modified by user

DarkSUSY core library
src/
libds_core.a

Observables (rates, relic density etc)

User replaceables
Functions replaced and modified by user

Halo profiles
dsdmsdriver with different halo profiles.

Linking to main library/user replaceable
Linking to chosen module
Calling sequence
Alternative calling sequence (if linked)

Particle physics modules
src_models/

Module mssm
libds_mssm.a

Interface functions
Internal routines

User replaceables
Functions replaced and modified by user

Module silveira_zee
libds_silveira_zee.a

Interface functions
Internal routines

User replaceables
Functions replaced and modified by user

Module ...

User replaceables

NEW since DS 6:

Very active development

NEW **since DS 6:**

- Home
- Download
- Documentation
- Tutorials
- Source Code
- Contact
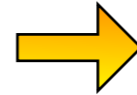
➡️ *make sure to always check out latest version!*

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
  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.
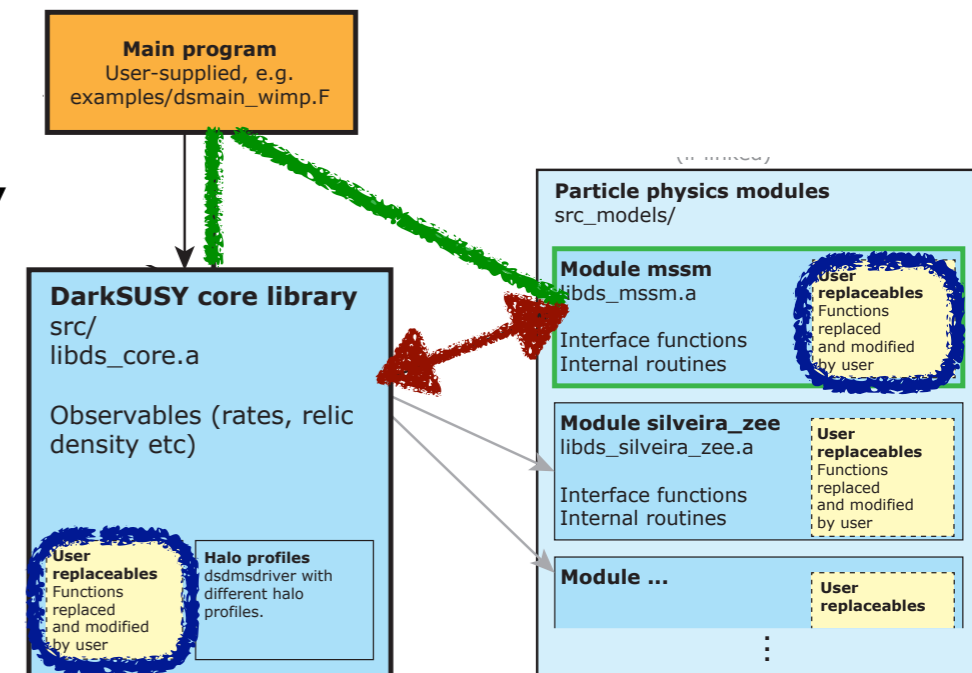
Previous versions

- **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 can 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…*

Main program
User-supplied, e.g.
examples/dsmain_wimp.F

Particle physics modules
src_models/

Module mssm
libds_mssm.a

Interface functions
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dsdmsdriver with different halo profiles.

Module silveira_zee
libds_silveira_zee.a

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Module ...

User replaceables

Recent physics highlights

NEW **since DS 6:**

- ● Relic density routines further generalized
  - ◦ *Full support for dark sectors with* $\xi(T) \equiv T_{\mathrm{dark}}/T$
  - ◦ *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, ΔN_{eff}, HEALPIX l.os, …

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)
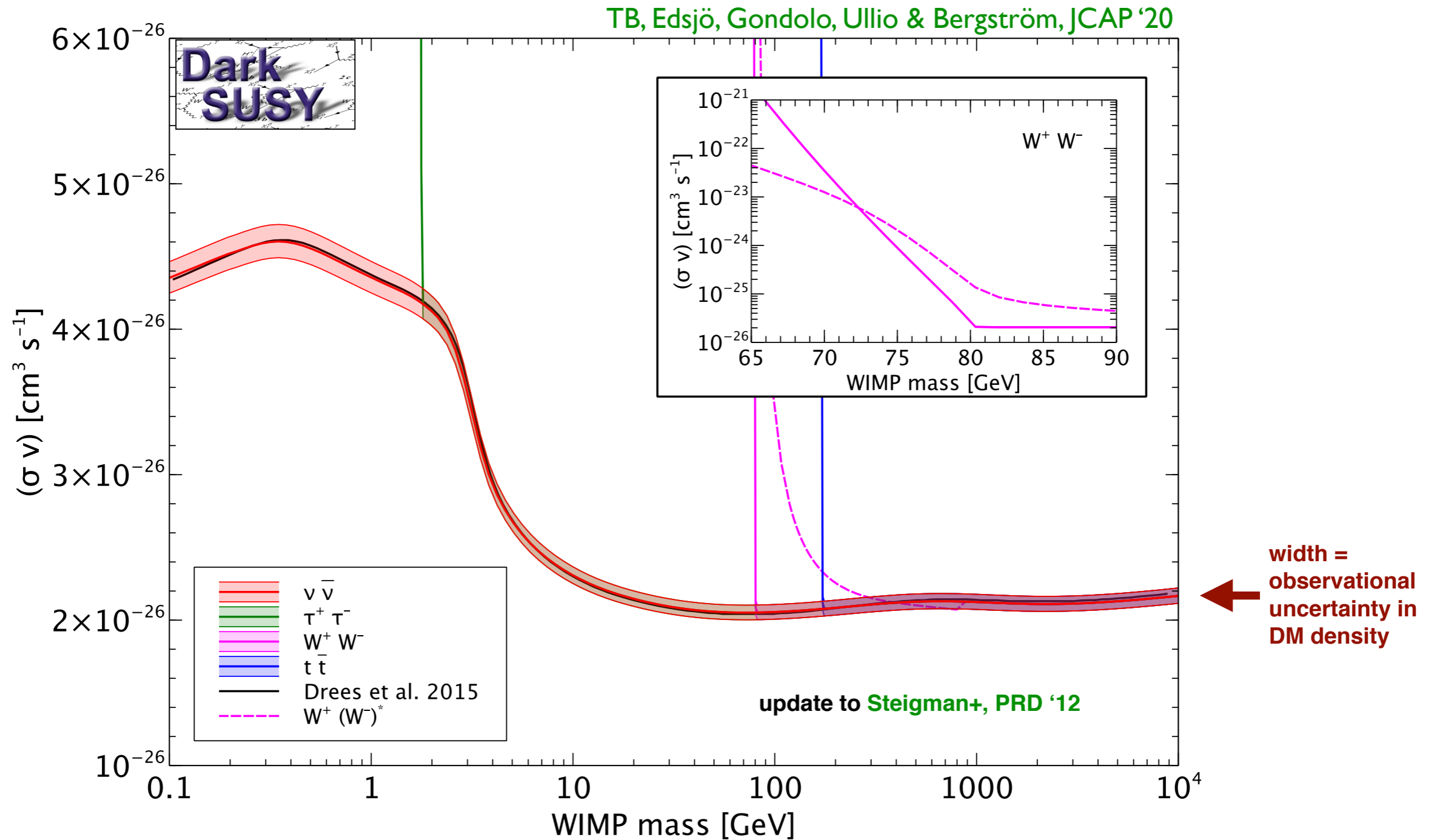 - *...*

- (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*

$$W_{\mathrm{eff}} = \sum_{ij} \frac{p_{ij}}{p_{11}} \frac{g_i g_j}{g_1^2} W_{ij} \quad ; \quad W_{ij} = 4E_1 E_2 \sigma_{ij} v_{ij}$$

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

further improvement in performance *and* accuracy

Example: generic WIMP

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

Dark SUSY

Legend:
- $\nu \, \bar{\nu}$
- $\tau^+ \tau^-$
- $W^+ W^-$
- $t \, \bar{t}$
- Drees et al. 2015
- $W^+ (W^-)^*$

Inset plot: $W^+ W^-$, axes (σv) [cm^3 s^{-1}] vs WIMP mass [GeV]

Main axes: (σv) [cm^3 s^{-1}] vs WIMP mass [GeV]

width = observational uncertainty in DM density

update to Steigman+, PRD '12

code: examples/aux/oh2_generic_wimp.f

Example: generic WIMP *in dark sector*

Secluded dark sector

➡ *separate* **entropy conservation**

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

Changes to relic density calculation:

- $\langle \sigma v \rangle_T \longrightarrow \langle \sigma v \rangle_{T_\chi}$

- $n_{\chi\,\mathrm{eq}}(T) \longrightarrow n_{\chi\,\mathrm{eq}}(T_\chi)$

- $H^2 \propto g_{\mathrm{eff}} T^4 \longrightarrow g_{\mathrm{eff}} T^4 + g_{\mathrm{eff}}^{\mathrm{DS}} T_\chi^4$

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

TB, Depta, Hufnagel & Schmidt-Hoberg, 2007.03696

SM — Majorana — Dirac

$g_S = 1$

$g_S = 5$
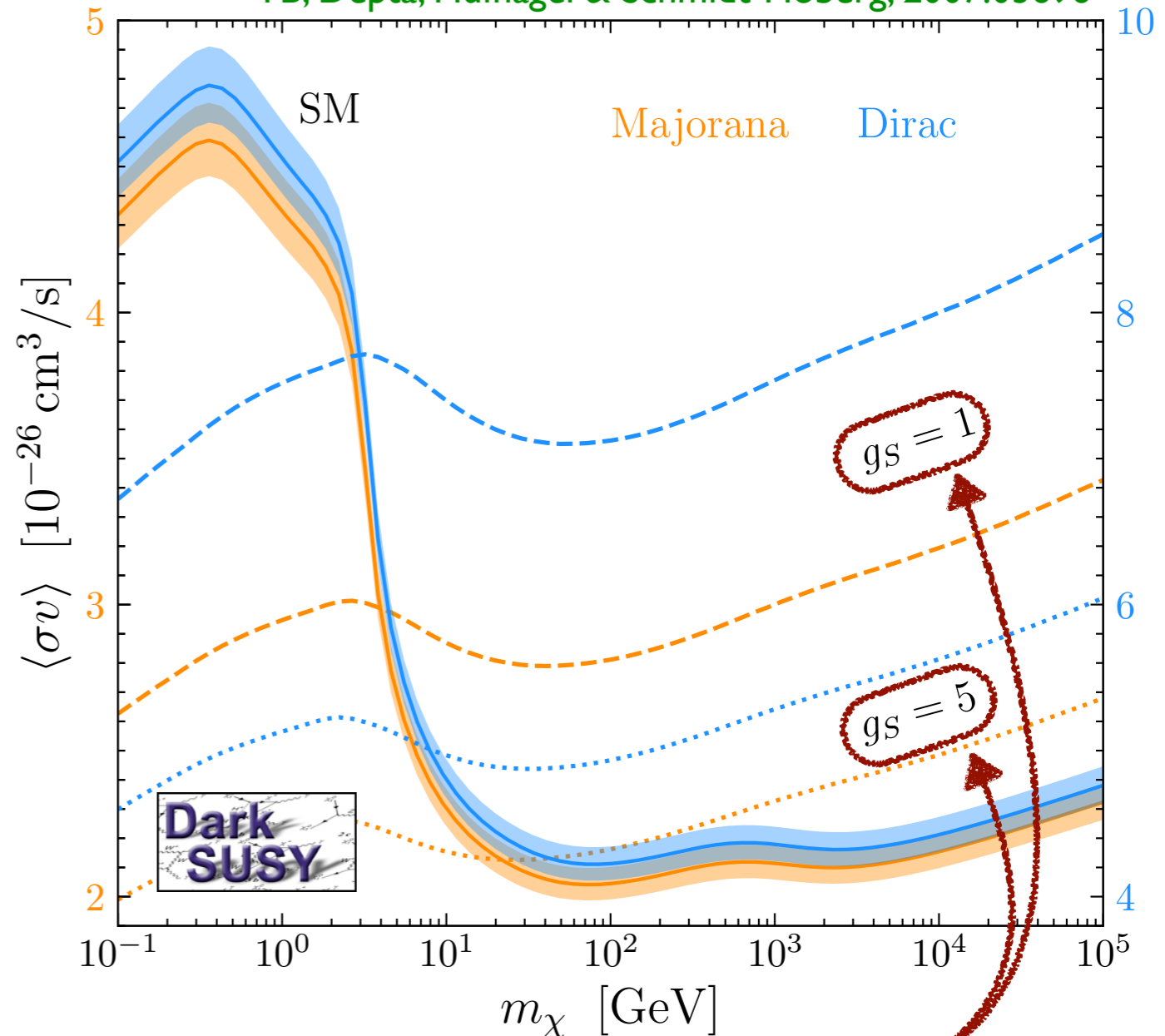
relativistic DS d.o.f.

code: examples/aux/oh2_dark_sector.f

2nd physics example

DM *self-interactions*
(and power-spectrum cutoff)

A simple dark sector framework

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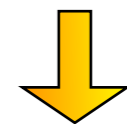 - 'vdSIDM' module Dark SUSY

$$\mathcal{L}_{\mathrm{int}} \supset -g_\chi \bar{\chi} \slashed{V} \chi - g_\nu \bar{\nu} \slashed{V} \nu$$
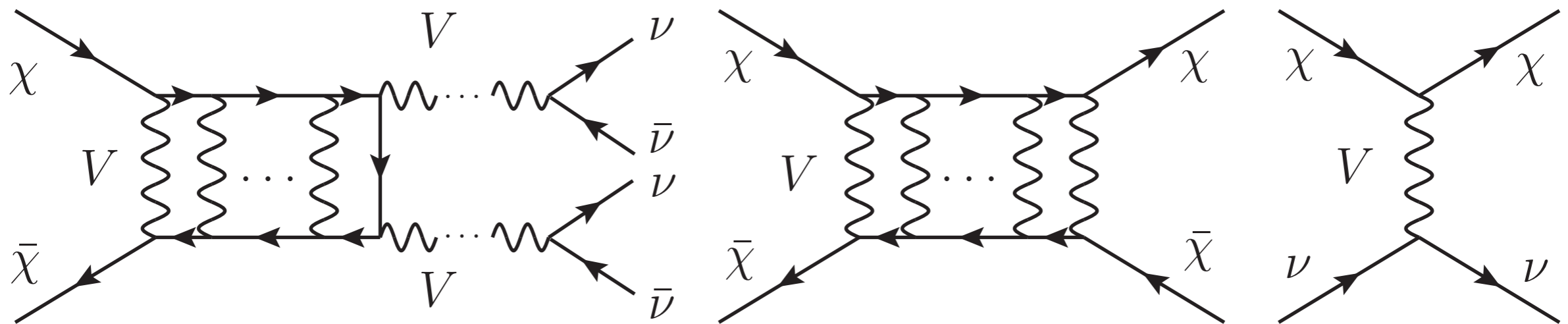
relic density
(+indirect detection signal!?)
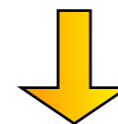
changes inner density and velocity profiles of dwarf galaxies
(Yukawa potential)

Large M_{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

Dirac DM

$\xi \to 1$ for $T \to \infty$

0.1–1 cm² g⁻¹

1–10 cm² g⁻¹

excluded

10–11 M⊙

9–10 M⊙

excluded

m_{DM} [GeV]

s–wave

(vector mediator)

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

address
missing
satellites ?

DR   DR

m_{med} [GeV]

Dark SUSY

NEW since v6.1:

- SIDM
- Sommerfeld
- handle varying

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

coupling fixed by
thermal relic density

DM

DM

V

V

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*
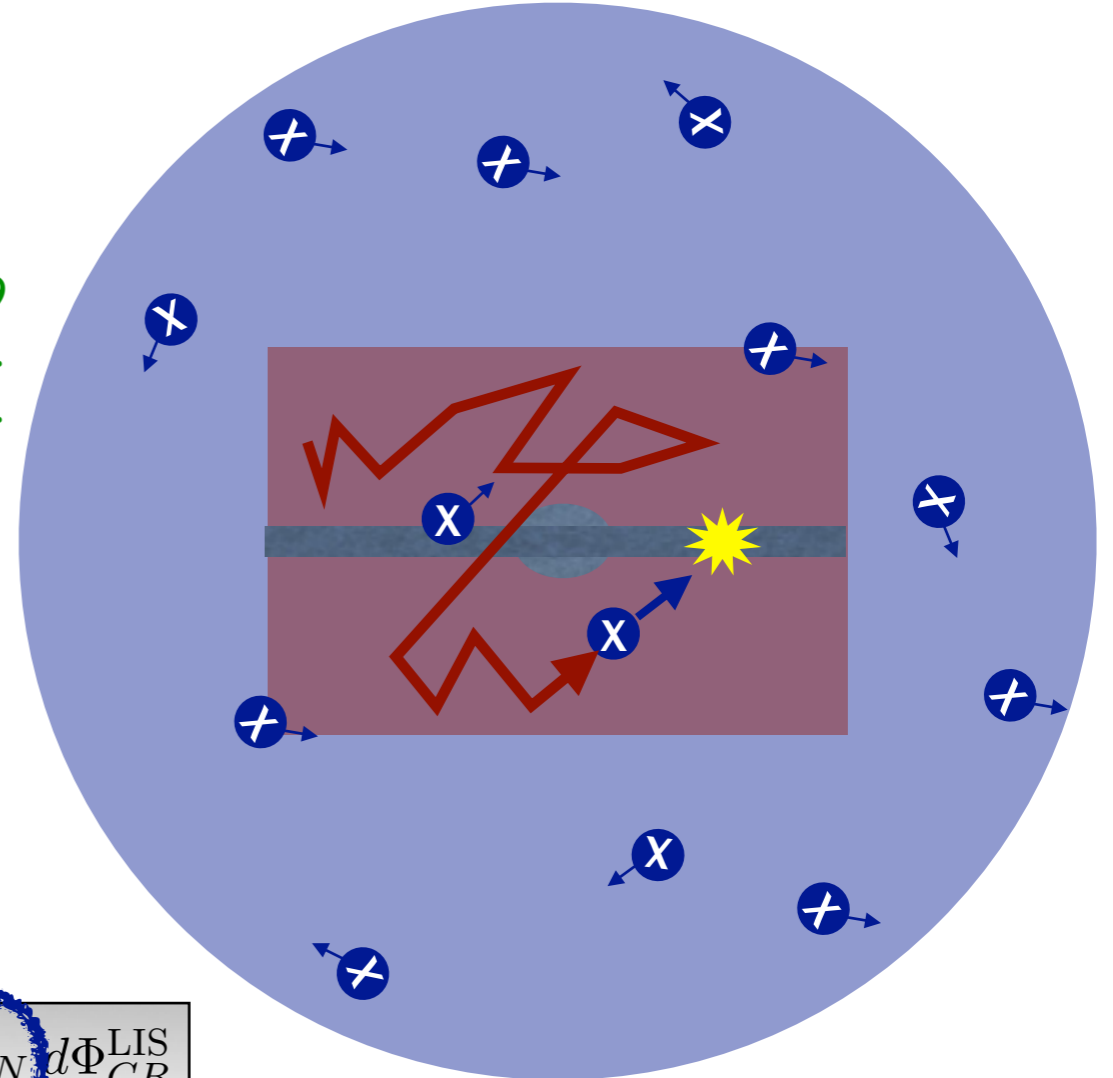
- *Three steps:*

  - *production*

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

  - *soil/atmosphere attenuation*

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

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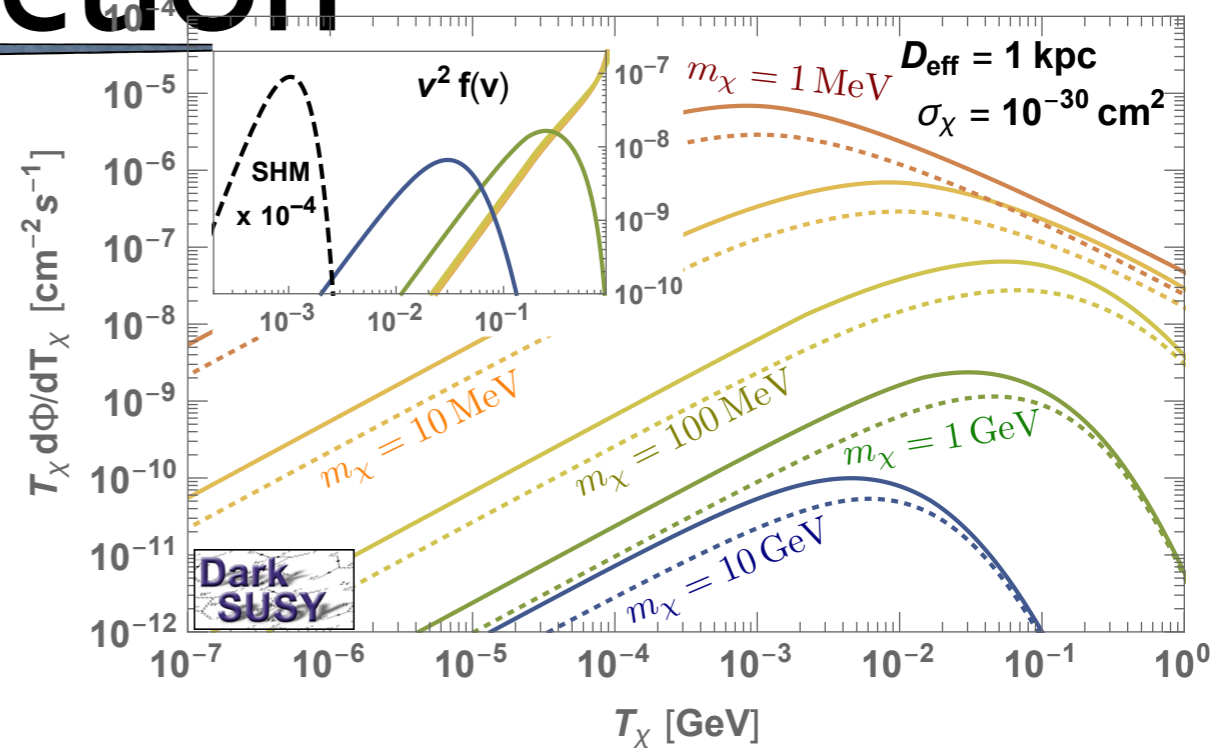
    $$\frac{d\Gamma_N}{dT_N} = \int_{T_\chi(T_\chi^{z,\min})}^\infty dT_\chi \frac{d\sigma_{\chi N}}{dT_N} \frac{d\Phi_\chi}{dT_\chi}$$

particle physics input:

interface functions

Reverse direct detection

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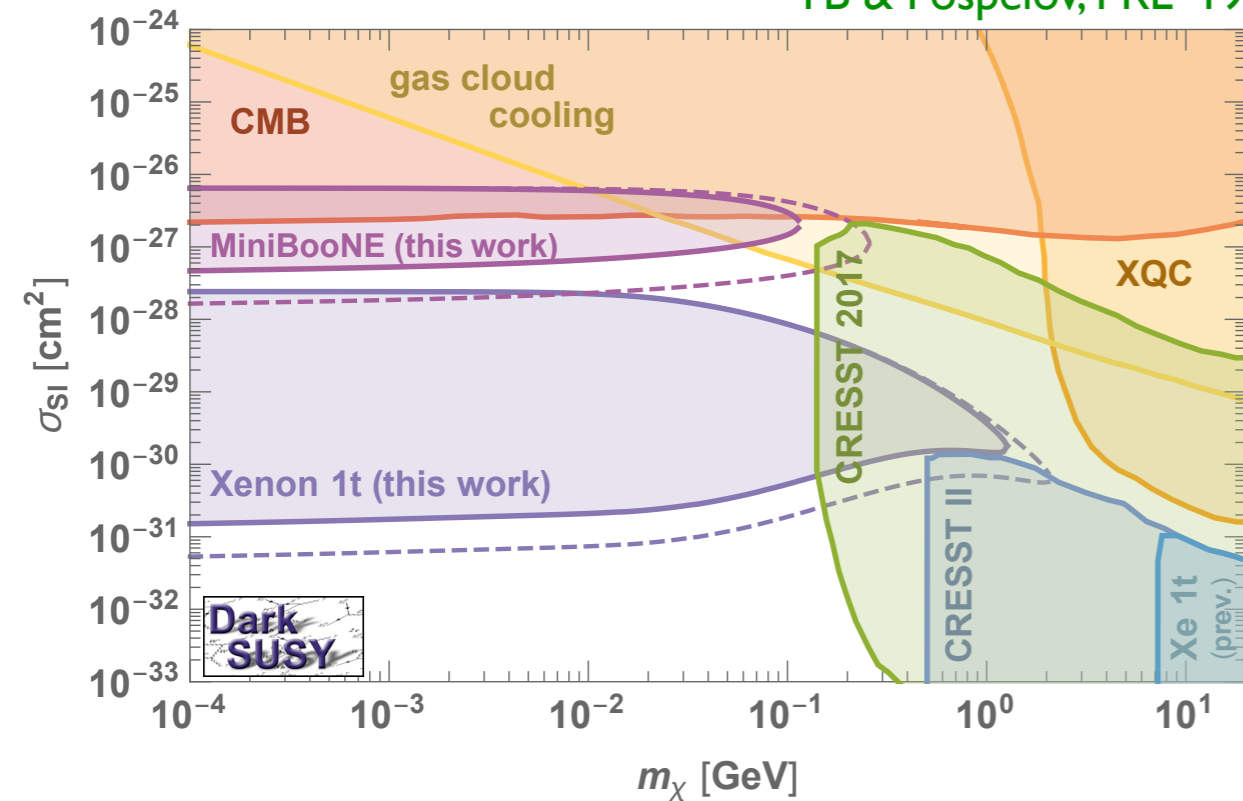 - *(but highly subdominant)*

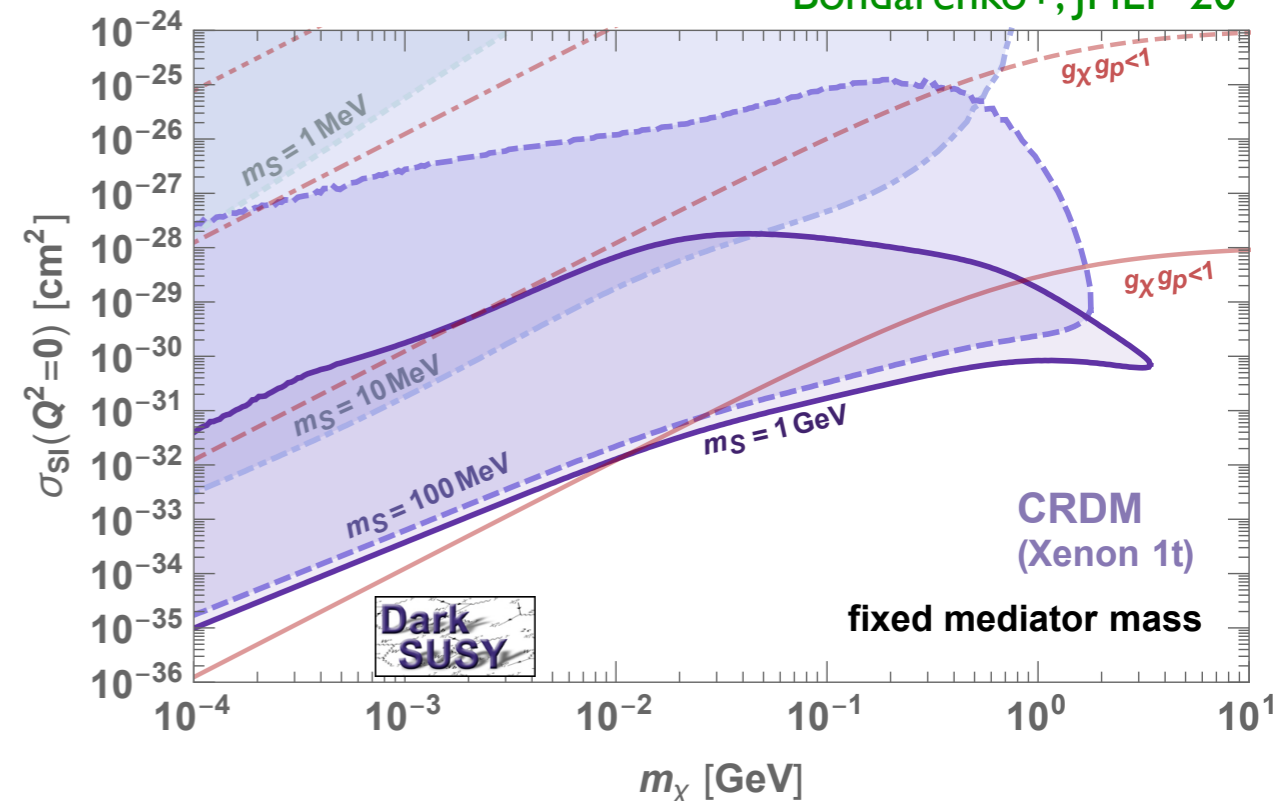   **code**: examples/aux/DDCR_flux.f

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

    TB & Pospelov, PRL '19

  - *full Q2-dependence* (here: Higgs portal)

    Bondarenko+, JHEP '20

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

4th physics example

Indirect detection yields

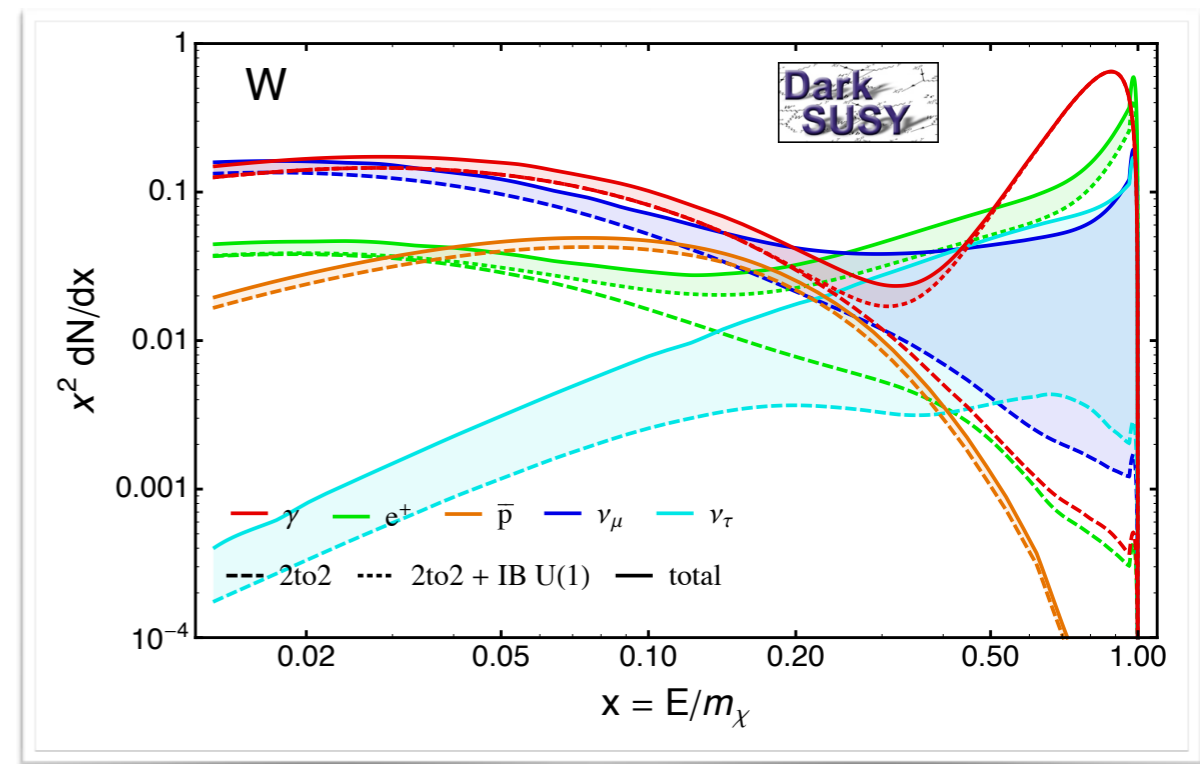# Particle spectra from DM annihilation

- `'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

  see talk by Peter Reimitz !

- ## Can easily be switched for any indirect detection application

  <u>**code**</u>: **examples/aux/wimpyields.f**
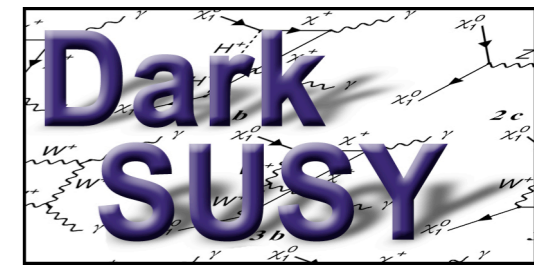
```
42   c...Change default yield tables
43         call dsanyield_set('yieldtables','default')
44   c     call dsanyield_set('yieldtables','Amoroso')
45
46   c     call dsanyield_set('yieldtables','Plehn')
```

- 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

Conclusions

Go to

http://www.darksusy.org

and get started…!

🙂