DarkSUSY 6

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With Torsten Bringmann, Paolo Gondolo, Piero Ullio and Lars Bergström

Preparing for dark matter particle discovery
2018-06-11 – 2018-06-15

Ways to search for dark matter

Accelerator searches

- LHC
- Rare decays
- ...

Direct searches

- Spin-independent scattering
- Spin-dependent scattering

Indirect searches

- Gamma rays from the galaxy
- Neutrinos from the Earth/Sun
- Antiprotons from the galactic halo
- Antideuterons from the galactic halo
- Positrons from the galactic halo
- Dark Stars
- ...

Need to treat all of these in a consistent manner, both regarding particle physics and astrophysics

Current version: 6.1.0, darksusy.org

Will not cover all of these...

Outline

DarkSUSY

- Introduction to DarkSUSY
- Relic density
- Direct detection
- Indirect detection:
  - gamma rays
  - charged cosmic rays
  - neutrinos (from the Sun/Earth)
- Layout and general principles

Focus will be on the new DarkSUSY 6, differences with DarkSUSY 5 will be highlighted

Stockholm University

What is DarkSUSY?

- A Fortran code for Dark Matter calculations
- Originally developed for supersymmetric (SUSY) dark matter


Other WIMPs?
Axions?
Something completely different?
Decaying DM?
UED?
?
SUSY
Scalar singlet?

What is DarkSUSY?

- A Fortran code for Dark Matter calculations
- Originally developed for supersymmetric (SUSY) dark matter
- Includes code for both relic density, direct and indirect detection rates as well as kinetic decoupling
- Much of this does NOT depend on SUSY though, hence we have unsusyfied DarkSUSY…

Particle physics models included

- DarkSUSY is modular and can work with many particle physics models, included ones are
  - MSSM (SUSY)
  - Scalar Singlet (Silveira-Zee model)
  - generic WIMP
  - generic decaying dark matter
  - velocity dependent self-interacting dark matter (vdSIDM) ← as of ver. 6.1 released yesterday!

+ whatever you add!

New things in DarkSUSY 6 (I)

- Relic density routines have become more general. Parallellization using OpenMP. New degrees of freedom calculation included (Drees 2015)
- Kinetic decoupling added
- Direct detection more general, set up for using effective operators
- Using new Pythia runs including anti-deuterons
- New routines for charged cosmic ray diffusion
- New capture rate calculation in the Sun, more flexible and accurate. Tabulation to speed it up. New WimpSim results added

New things in DarkSUSY 6 (II)

- A completely new structure that separates the model-independent parts and the particle physics dependent part. Makes it much easier to use DarkSUSY for other particle physics models. Included in release: mssm, silveira_zee (scalar singlet), generic_wimp, generic_decayingDM
- For mssm: the internal bremsstrahlung of both U(1), SU(2) and SU(3) gauge bosons has been fully implemented,
- Ultra-compact minihalos added (code by Pat Scott)

Relic density – illustration

Decoupling occurs when

$$\Gamma < H$$

We have that

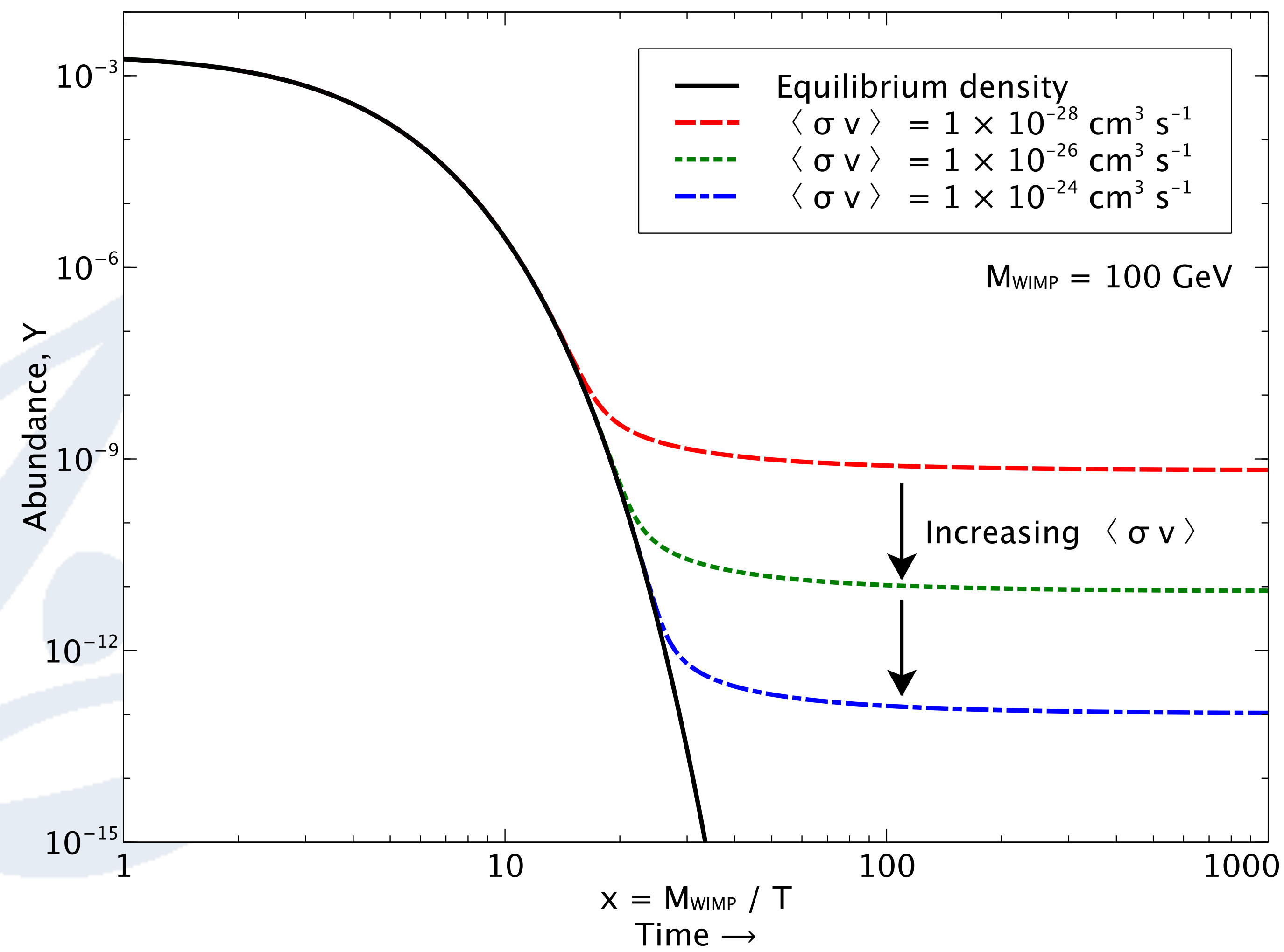
$$\Gamma = \langle \sigma_{\rm ann} v \rangle n_\chi$$

$$n_\chi^{\rm eq} = g_\chi \left(\frac{m_\chi T}{2\pi} \right)^{3/2} e^{-m_\chi / T}$$

$$H(T) = 1.66 g_*^{1/2} \frac{T^2}{m_{\rm Planck}}$$

$$\Gamma \simeq H \quad \Rightarrow \quad T_f \simeq \frac{m_\chi}{20}$$

$$\Omega_\chi h^2 \simeq \frac{3 \times 10^{-27} cm^3 s^{-1}}{\langle \sigma_{\rm ann} v \rangle}$$



$$\langle \sigma_{\rm ann} v \rangle \simeq \langle \sigma_{\rm ann} v \rangle_{WIMP} \simeq 3 \times 10^{-26} cm^3 s^{-1} \quad \Rightarrow \quad \Omega_\chi h^2 \simeq 0.1$$

Relic density – DarkSUSY implementation

- We solve the Boltzmann equation,

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{\rm eff} v \rangle \left(n^2 - n_{\rm eq}^2 \right)$$

numerically, calculating the thermally averaged annihilation cross section,

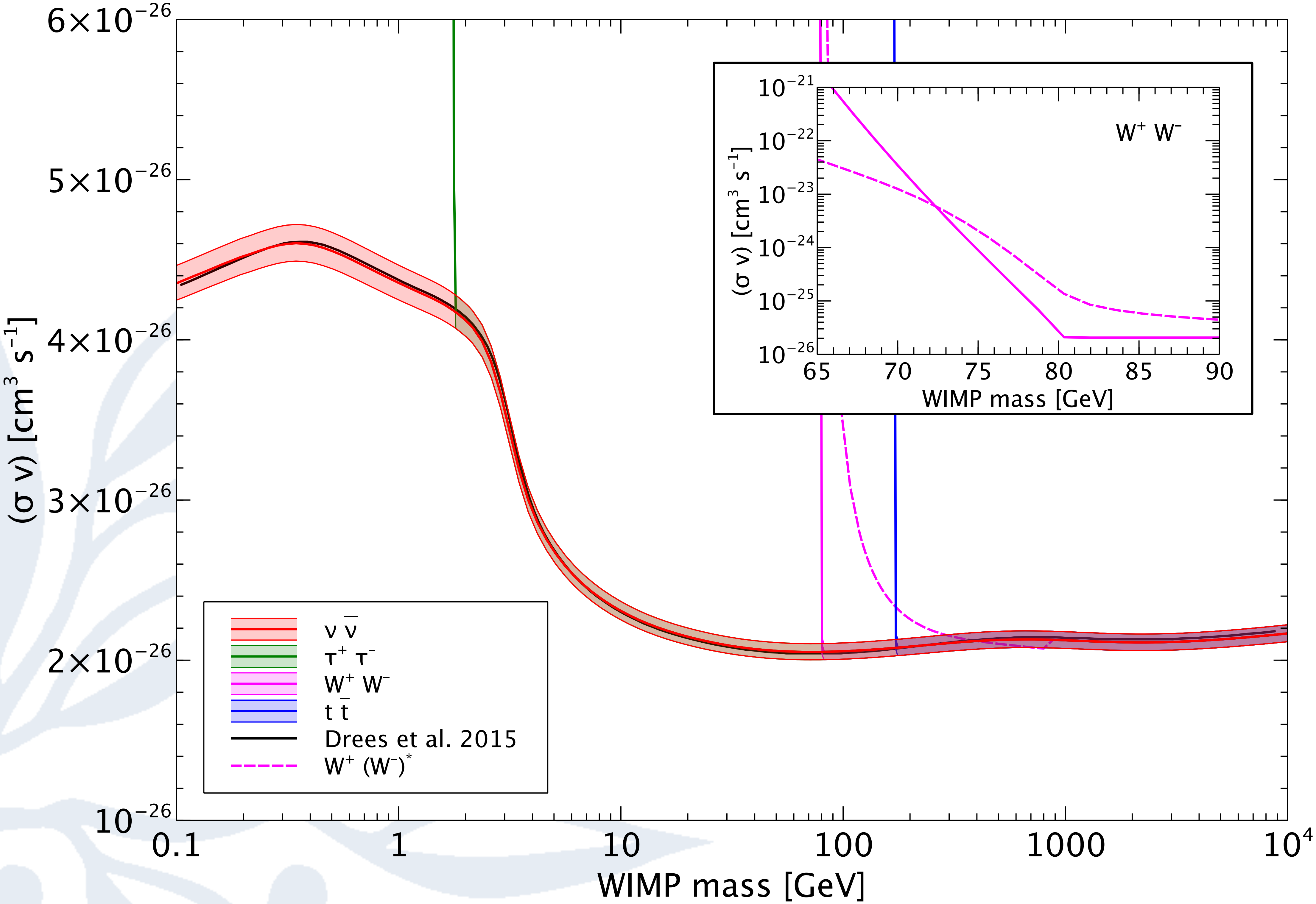
$$\langle \sigma_{\rm eff} v \rangle = \frac{\int_0^\infty dp_{\rm eff} p_{\rm eff}^2 W_{\rm eff} K_1 \left(\frac{\sqrt{s}}{T} \right)}{m_1^4 T \left[\sum_i \frac{g_i}{g_1} \frac{m_i^2}{m_1^2} K_2 \left(\frac{m_i}{T} \right) \right]^2}$$

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

in every step using tabulated $W_{\rm eff}(p)$.

DarkSUSY can calculate $W_{\rm eff}$ for SUSY or you can supply your own and use DarkSUSY as a Boltzmann equation solver. Interface to DM@NLO for SUSY coming.

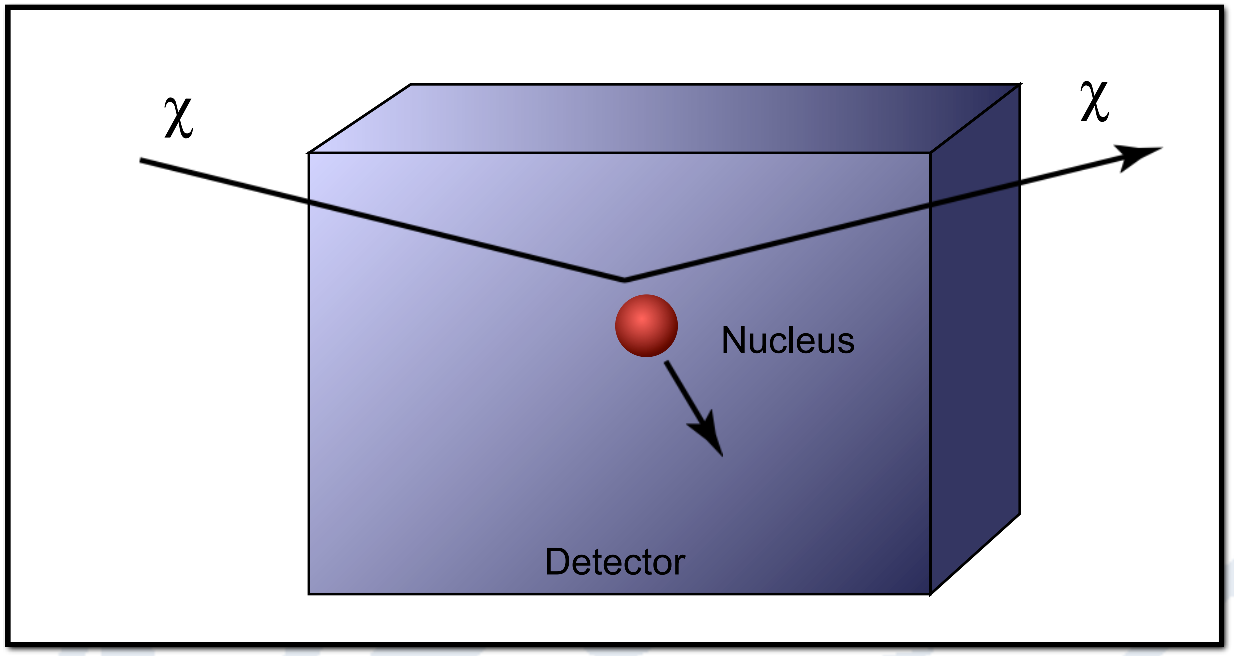
Example, generic WIMP



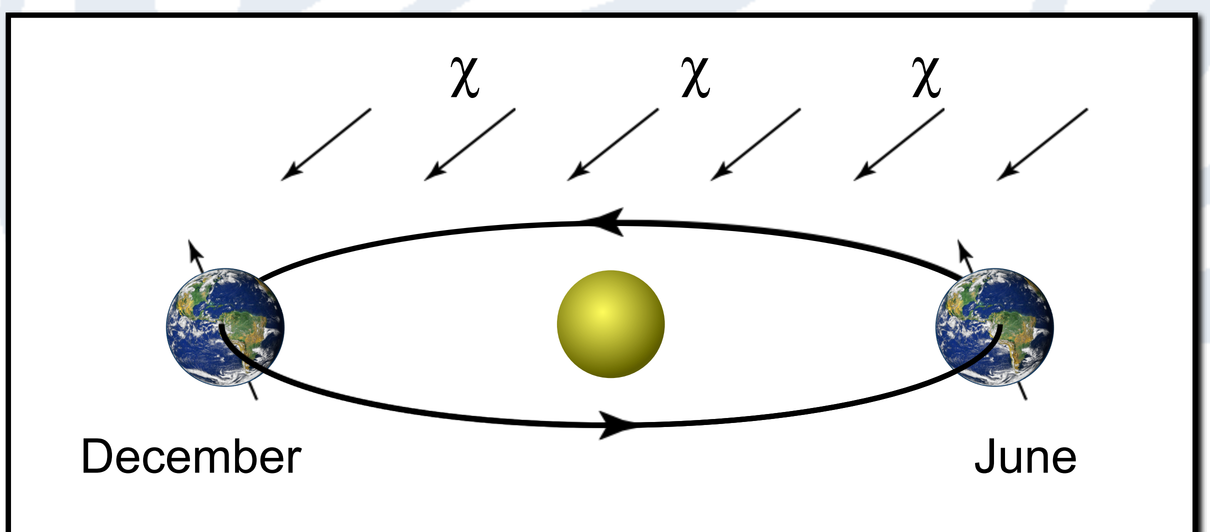
$$\Omega h^2 = 0.1165 - 0.1221$$ (Planck ±2σ)

Direct detection

general principles



- WIMP + nucleus → WIMP + nucleus
- Measure recoil energy
- Suppress background enough to be sensitive to a signal, or...



- Search for an annual modulation due to the Earth's motion in the halo

- Differential rates on different targets
- Annual modulation
- Different halos and velocity distributions
- Different form factors

Indirect rates – Annihilation channels

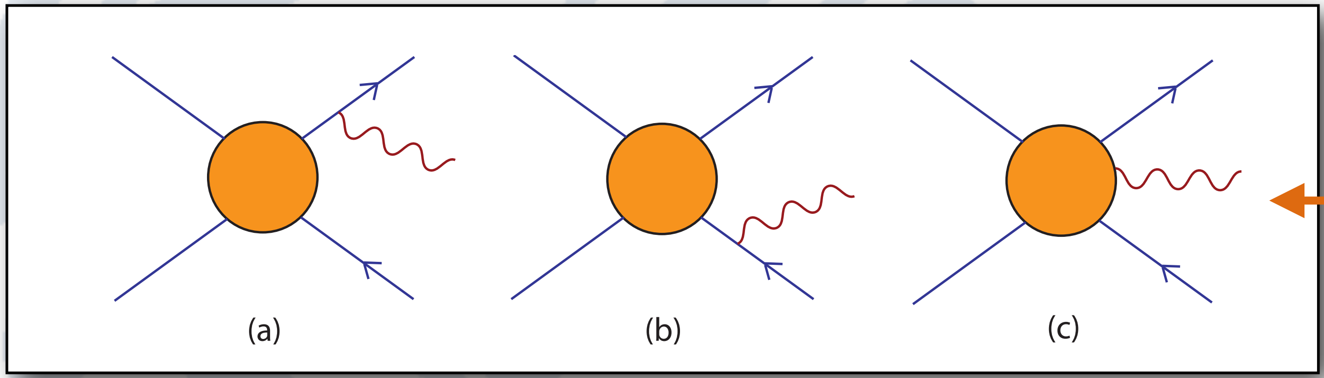
$$\chi\chi \rightarrow \begin{cases} b\bar{b} \\ t\bar{t} \\ \tau^-\tau^+ \\ W^-W^+ \\ Z^0Z^0 \\ \nu_\alpha\bar{\nu}_\alpha \\ H^\pm W^\pm \\ H_i^0 Z^0 \end{cases}$$

- Yields for different channels
- Simulated with Pythia for 3 GeV – 20 TeV
- Tables and interpolation routines in DarkSUSY

Gamma rays

- DarkSUSY includes generic WIMP routines to calculate gamma yields from WIMP annihilations
  - Based on Pythia simulations for WIMP masses between 3 GeV and 20 TeV
  - Line signals
  - Internal Bremsstrahlung added separately

Works for any WIMP

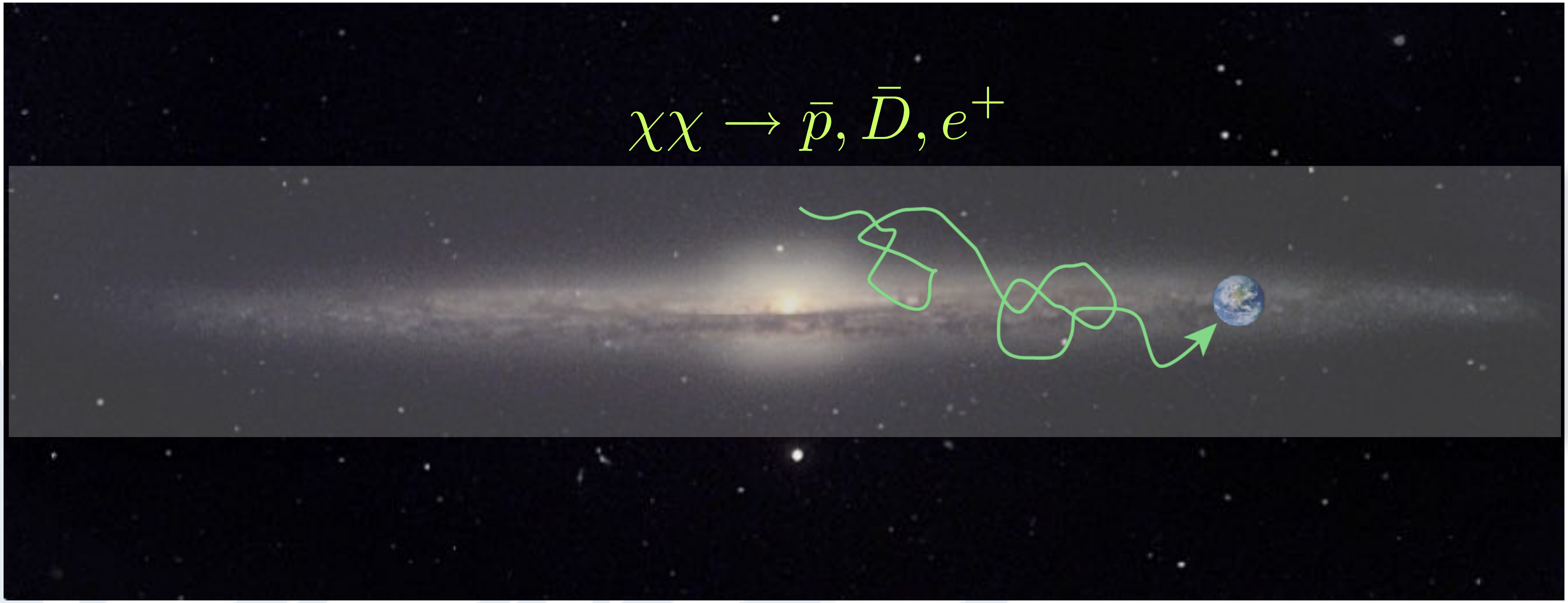


Virtual internal bremsstrahlung is model dependent!
SUSY calculation included.

Halo profiles

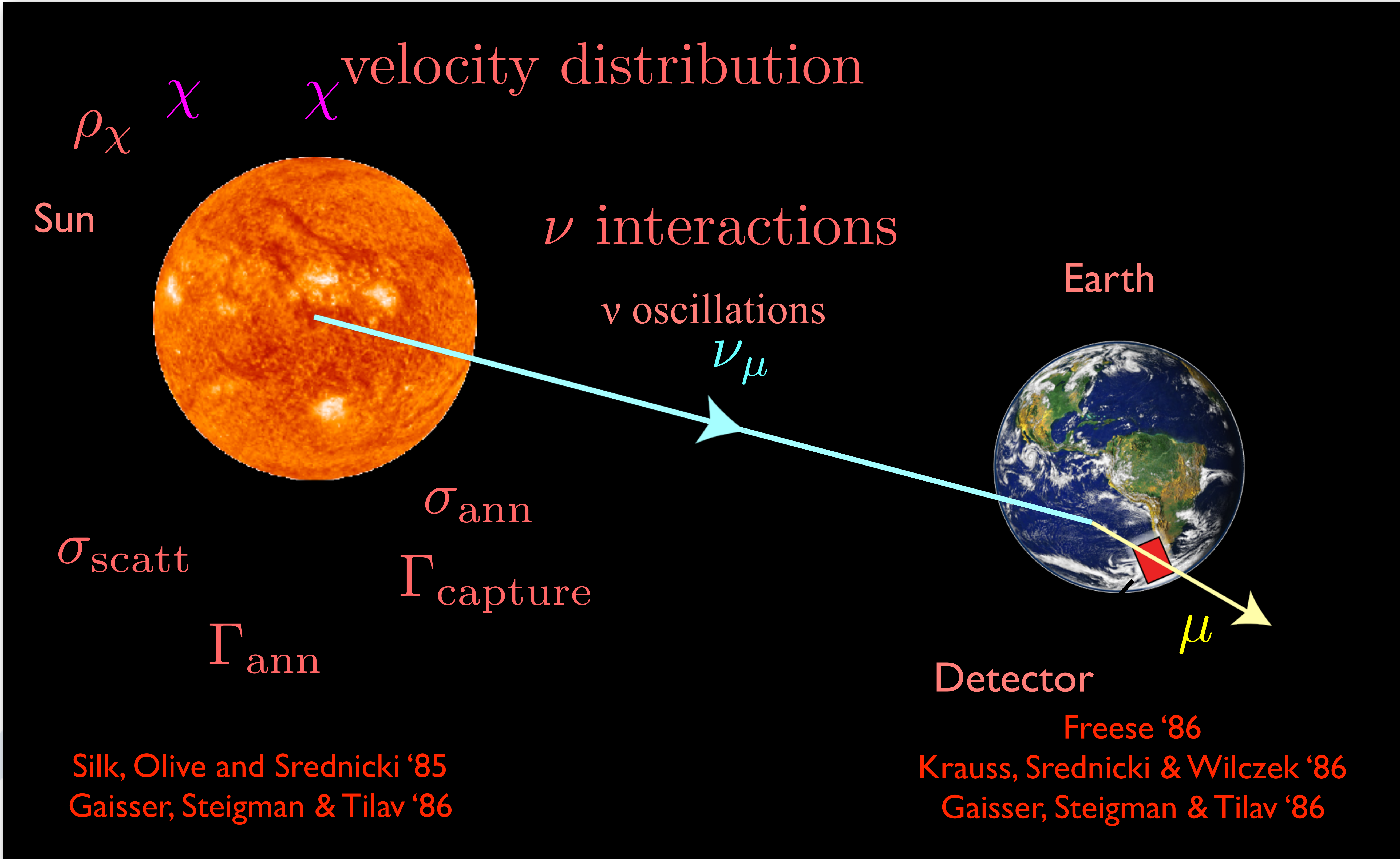
- Any spherically symmetric profile can be entered into DarkSUSY. Presets are available for
  - NFW
  - Burkert
  - Einasto
- In principle, a corresponding velocity distribution should be set simultaneously.

Charged cosmic rays – diffusion model

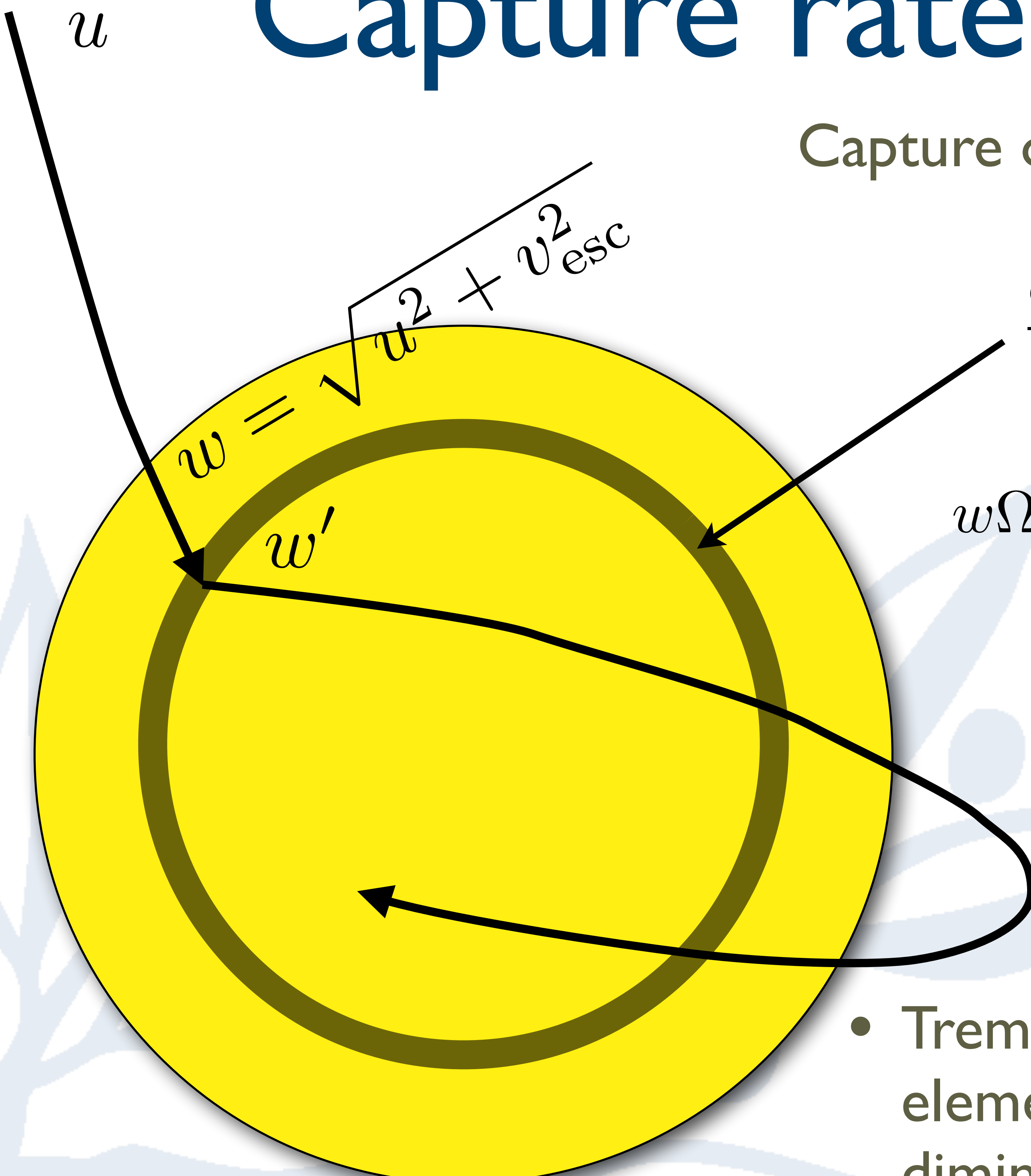


- Cylindrical diffusion model with free escape at the boundaries
- Energy losses on the interstellar medium (for antiprotons and antideuterons) or starlight and CMB (for positrons)
- Semi-analytic expressions in DarkSUSY (new improved ones in DS 6)
- New in DS6: new Pythia runs and new anti-deuteron calculations (MC based coalescence)

Neutrinos from the Earth/Sun



Capture rate calculation



Capture on element i in volume element

$$\frac{dC_i}{dV} = \int_0^{u_{max}} \mathrm{d}u \frac{f(u)}{u} w\Omega_{v,i}(w),$$

$$w\Omega_{v,i} \propto \sigma_{\chi i} n_i(r) P(w' < v_{\rm esc})[\text{FF suppr.}]$$

$\sim A^2$ $\sim A^2$

$\sim A^4$ A=atomic number

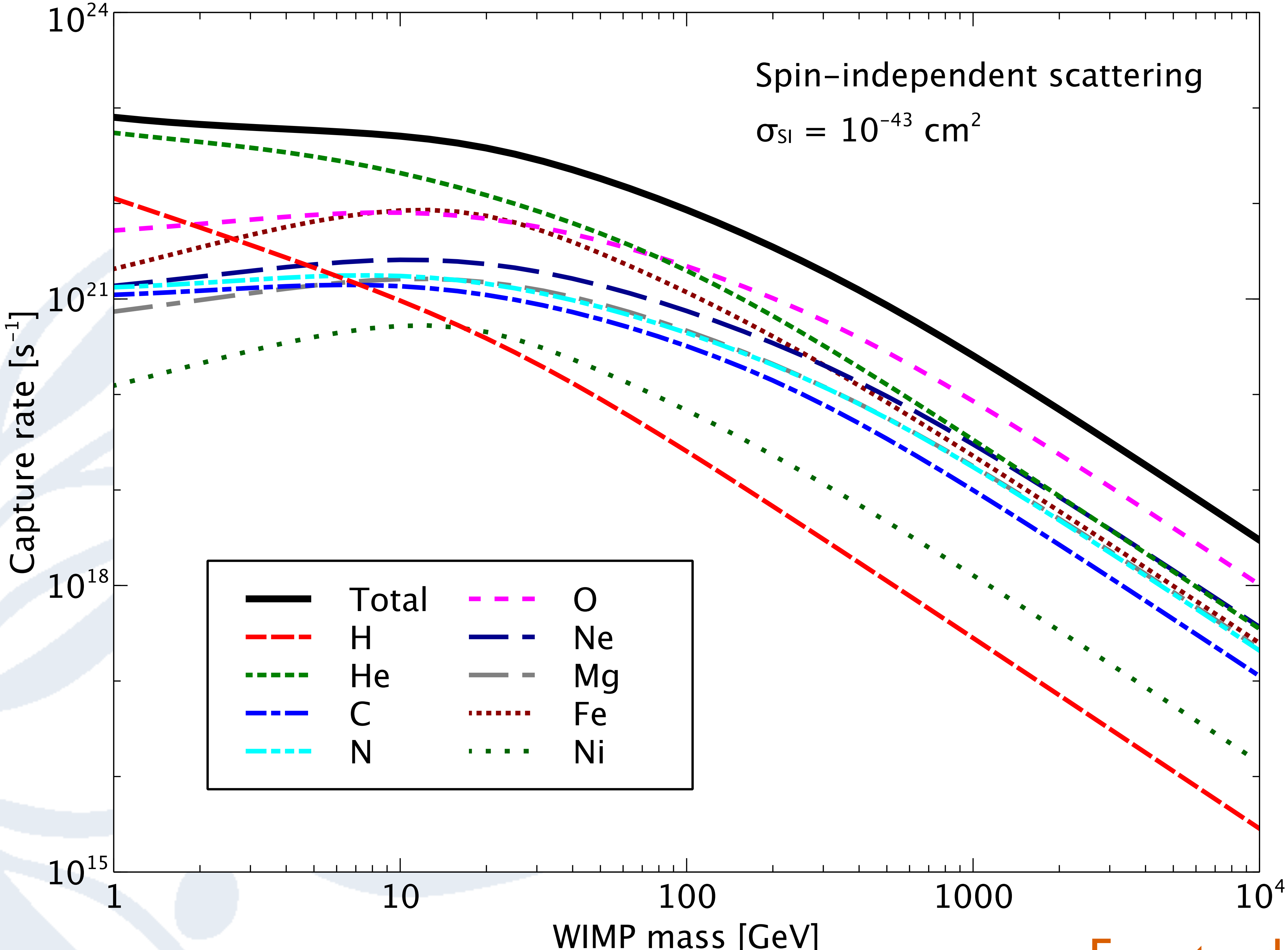
- Tremendous enhancements for heavy elements in the Sun. The form factor diminishes it somewhat though by reducing the first A^2.
- Low velocity WIMPs are easier to capture.

Neutrinos from the Earth/Sun

- Full numerical integration over solar radius, summing most relevant elements (up to 289 for SI and 112 for SD in DS 6)
- Full numerical integration over velocity distribution, no need to assume Maxwell-Boltzmann distribution
- In DS 6: full numerical integration over momentum transfer: arbitrary form factors can be used (do not need to be exponential). Database of form factors included.
- Interactions and oscillations in the Sun and to the detector simulated with WimpSim, results available as data tables in DarkSUSY.

See talk by Carl Niblaeus yesterday about solar atmospheric neutrinos, will eventually be included in DarkSUSY as well

Example: SI capture rate in Sun



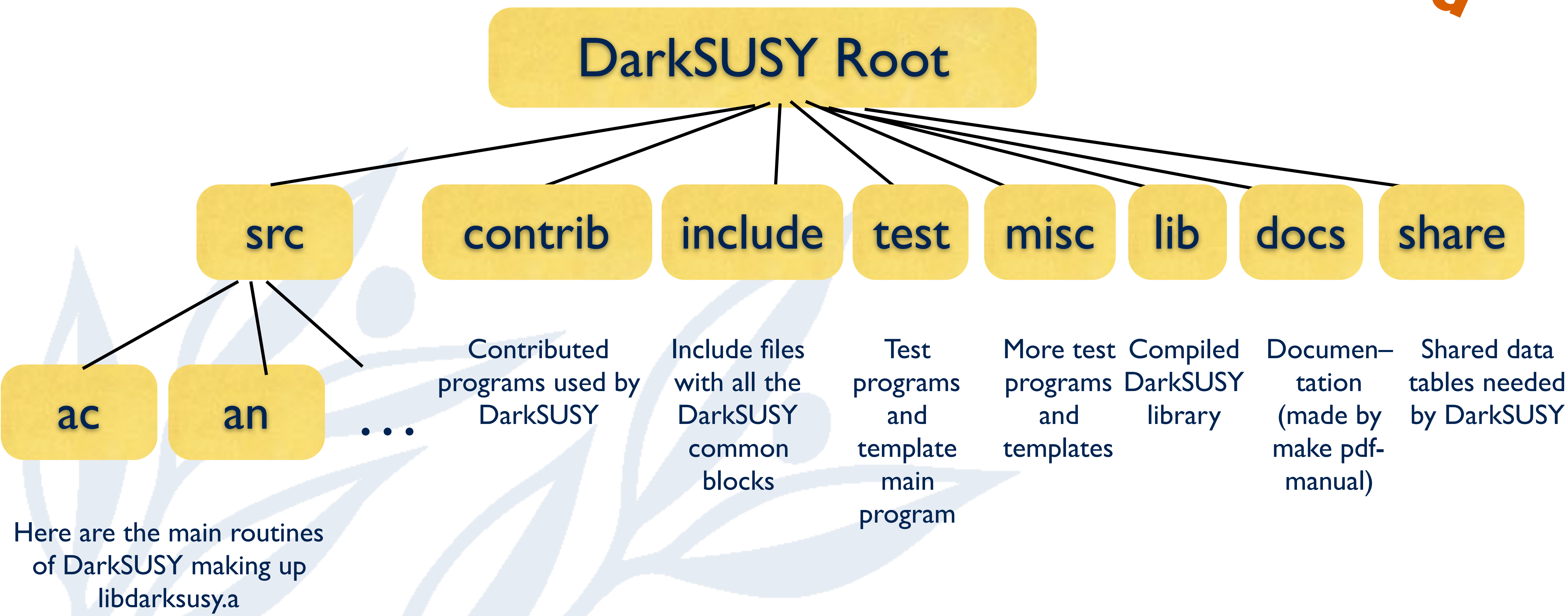
For standard halo

Philosophy

- Modular structure (given the Fortran constraints...)
- Library of subroutines and functions
- Fast and accurate
- "Standard" Fortran - works on many platforms
- Flexible
- Version control (subversion) for precise version tagging

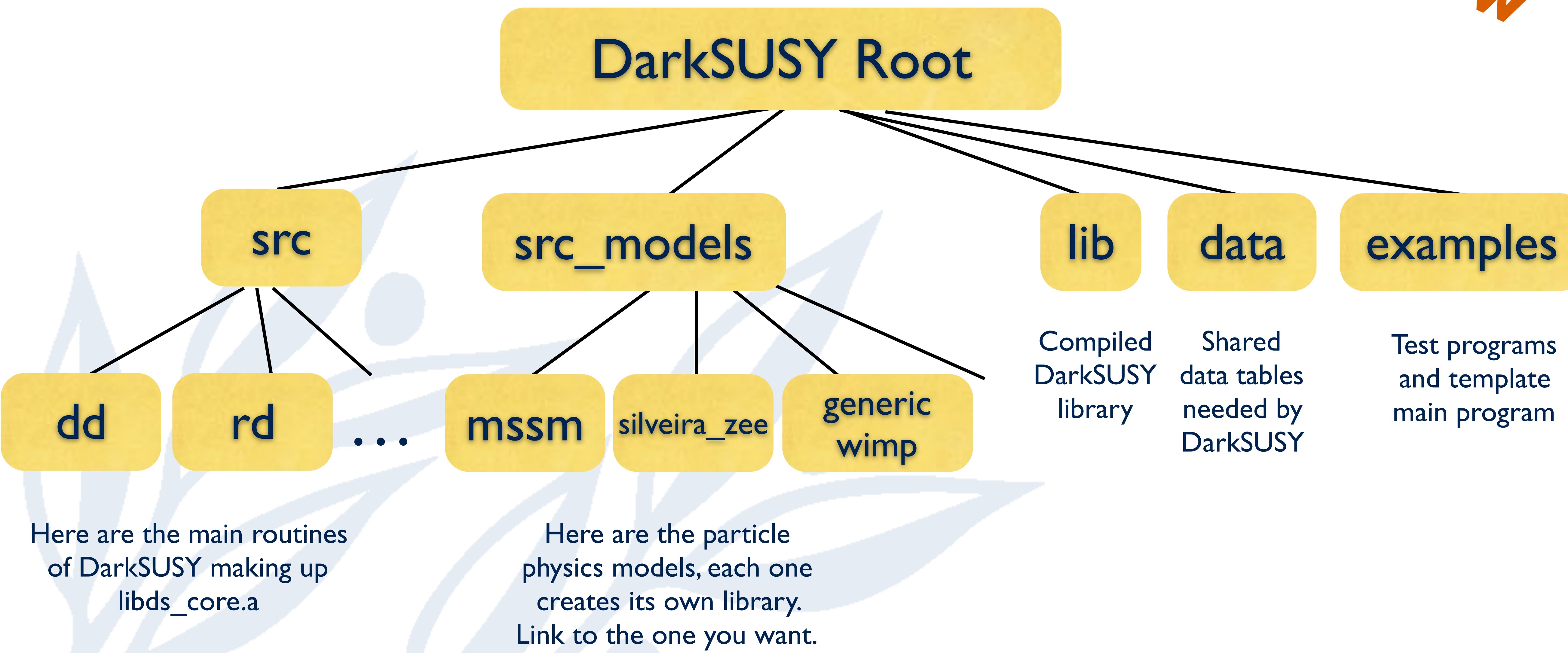
DarkSUSY 5 layout

Old



DarkSUSY 6 layout

New



- In DarkSUSY 6 you link to the particle physics model you want to use
- More clear division between particle physics model and general routines
  - General DS routines in src/
  - Particle physics model dependent routines in src_models/

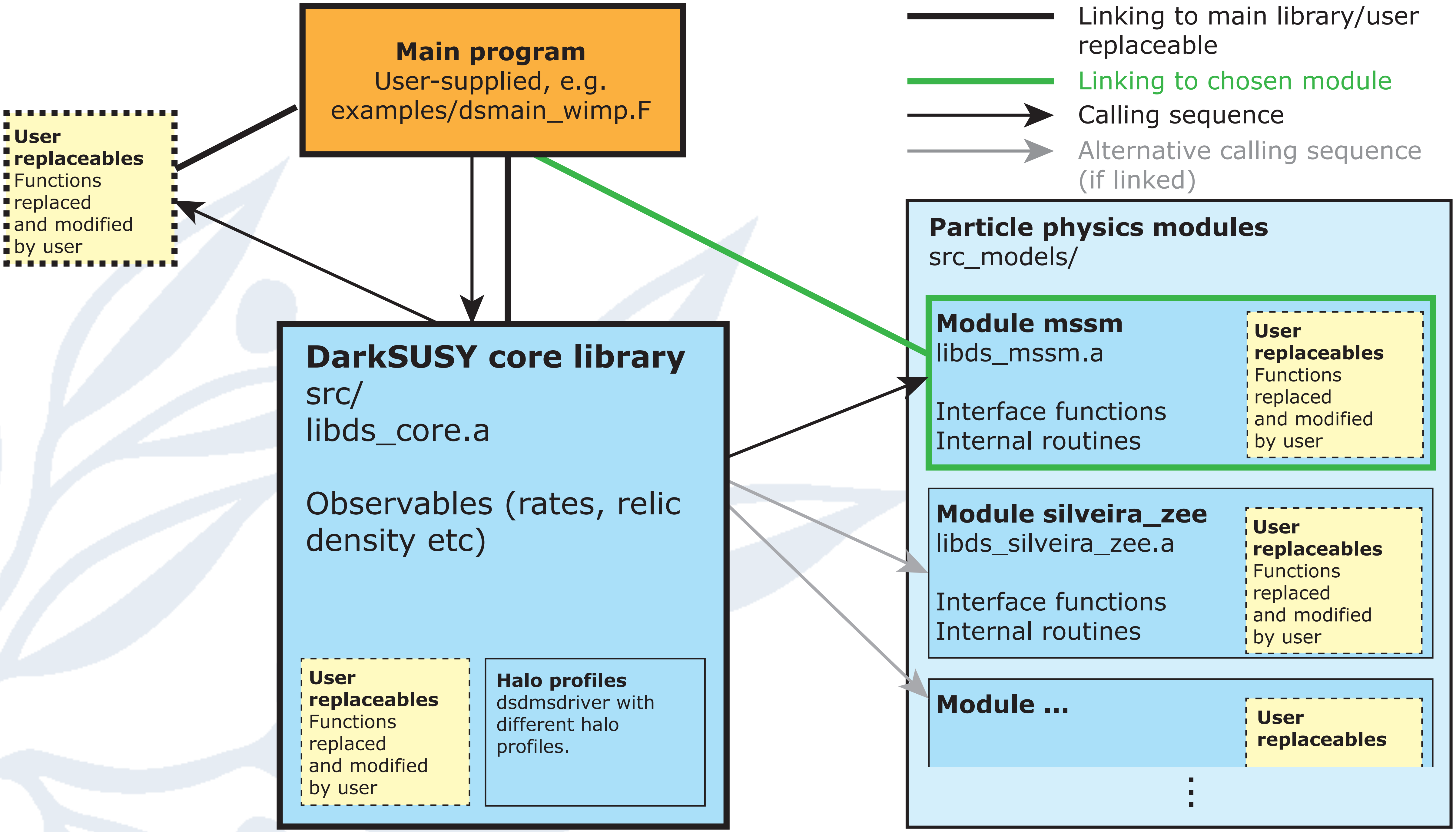
DarkSUSY 6 concepts

- **Interface functions.** Functions/routines that the particle physics module should provide if you want to calculate a given observable, e.g.
  - W_{eff} is an interface function and is needed by ds_core to calculate the relic density
  - The CR source function is an interface function:

$$\mathcal{S}_2(E_f) = \frac{1}{N_\chi m_\chi^2} \sum_i \sigma_i v \frac{dN_i}{dE_f} ,$$

- **Replaceable functions.** Any function/routine in DarkSUSY can be replaced by a user-supplied version.
  - e.g. you might want to have your own velocity distribution then you can just replace the standard routine

DarkSUSY 6 structure



Compile and install

- To compile and install DarkSUSY, do

  ./configure [optional arguments]
  make

- Works on most platforms and with most compilers (gfortran, ifort, …)
- When you link, you link to ds_core and to the particle physics module of your choice, e.g. ds_mssm, ds_generic_wimp, etc

```
gfortran -o dsmain dsmain.f -lds_core -lds_mssm
```
- for MSSM

```
gfortran -o dsmain dsmain.f -lds_core -lds_generic_wimp
```
- for generic Wimp

And then we have the name…

- DarkSUSY does now mean… Dark SUsy Samt Ytterligare Modeller

Reference / download

- DarkSUSY 6.1.0 is available at

www.darksusy.org

- Long paper, describing DarkSUSY 5 available as JCAP 06 (2004) 004 [astro-ph/0406204]
- Long paper, describing DarkSUSY 6 available as arXiv:1802.03399
- Manual (pdf) available

PREPARED FOR SUBMISSION TO JCAP

DarkSUSY 6: An Advanced Tool to Compute Dark Matter Properties Numerically

T. Bringmann,[a] J. Edsjö,[b] P. Gondolo,[c] P. Ullio[d] and L. Bergström[b]

Conclusions

- DarkSUSY 6 publically available
- DarkSUSY 6 is much more modular and include other improvements.
- When comparing different signals, it is crucial to perform these calculations in a consistent framework, with e.g. a tool like DarkSUSY

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BACKUP

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University

SUSY model setup

We work in the framework of the minimal $N = 1$ supersymmetric extension of the standard model defined by, besides the particle content and gauge couplings required by supersymmetry, the superpotential

$$W = \epsilon_{ij}\left(-\hat{\mathbf{e}}_R^* \mathbf{Y}_E \hat{\mathbf{l}}_L^i \hat{H}_1^j - \hat{\mathbf{d}}_R^* \mathbf{Y}_D \hat{\mathbf{q}}_L^i \hat{H}_1^j + \hat{\mathbf{u}}_R^* \mathbf{Y}_U \hat{\mathbf{q}}_L^i \hat{H}_2^j - \mu \hat{H}_1^i \hat{H}_2^j\right) \quad (2)$$

and the soft supersymmetry-breaking potential

$$\begin{aligned} V_{\text{soft}} = \; & \epsilon_{ij}\left(-\tilde{\mathbf{e}}_R^* \mathbf{A}_E \mathbf{Y}_E \tilde{\mathbf{l}}_L^i H_1^j - \tilde{\mathbf{d}}_R^* \mathbf{A}_D \mathbf{Y}_D \tilde{\mathbf{q}}_L^i H_1^j + \tilde{\mathbf{u}}_R^* \mathbf{A}_U \mathbf{Y}_U \tilde{\mathbf{q}}_L^i H_2^j - B\mu H_1^i H_2^j + \text{h.c.}\right) \\ & + H_1^{i*} m_1^2 H_1^i + H_2^{i*} m_2^2 H_2^i \\ & + \tilde{\mathbf{q}}_L^{i*} \mathbf{M}_Q^2 \tilde{\mathbf{q}}_L^i + \tilde{\mathbf{l}}_L^{i*} \mathbf{M}_L^2 \tilde{\mathbf{l}}_L^i + \tilde{\mathbf{u}}_R^* \mathbf{M}_U^2 \tilde{\mathbf{u}}_R + \tilde{\mathbf{d}}_R^* \mathbf{M}_D^2 \tilde{\mathbf{d}}_R + \tilde{\mathbf{e}}_R^* \mathbf{M}_E^2 \tilde{\mathbf{e}}_R \\ & + \frac{1}{2} M_1 \tilde{B}\tilde{B} + \frac{1}{2} M_2 \left(\tilde{W}^3 \tilde{W}^3 + 2\tilde{W}^+ \tilde{W}^-\right) + \frac{1}{2} M_3 \tilde{g}\tilde{g}. \end{aligned} \quad (3)$$

Here i and j are SU(2) indices ($\epsilon_{12} = +1$), $\mathbf{Y}$'s, $\mathbf{A}$'s and $\mathbf{M}$'s are 3×3 matrices in generation space, and the other boldface letter are vectors in generation space.

[orange box] = 3x3 complex matrices   [blue box] = complex parameters

SUSY setup

- The full MSSM-124 has 124 free parameters (including complex phases)
- The goal is to be able to choose all of these arbitrarily
- We are not fully there yet, even if most things can be chosen quite arbitrarily in DarkSUSY (i.e. fully general 3x3 matrices, i.e. MSSM-63)
- Two typical approaches
  - pMSSM-x or MSSM-x: specify all parameters at the EW or SUSY scale
  - cMSSM or mSUGRA: specify parameters at the GUT scale running the RGE equations down to the EW or SUSY scale

Diffusion equation

$$\partial_z \left(V_C \, \psi\right) - K \, \Delta\psi + \partial_E \left\{ b^{\text{loss}}(E) \, \psi - K_{EE}(E) \, \partial_E \psi \right\} = Q \left(\mathbf{x}, E\right)$$

Wind — Spatial diffusion — Energy losses — Energy diffusion (reacceleration) — Source term

Spatial diffusion:

$$K(E) = K_0 \, \beta \, \left(\mathcal{R}/1 \text{ GV}\right)^{\delta}$$

Energy diffusion (reacceleration):

$$K_{EE} = \frac{2}{9} \, V_a^2 \, \frac{E^2 \beta^4}{K(E)}$$

Source term:

$$Q(\mathbf{x}, E) \propto \rho^2 \langle \sigma v \rangle \frac{dN}{dE}$$

As the source term depends on the DM density squared, we are very sensitive to the halo profile and substructure.

Diffusion parameters

- The most important diffusion parameters are

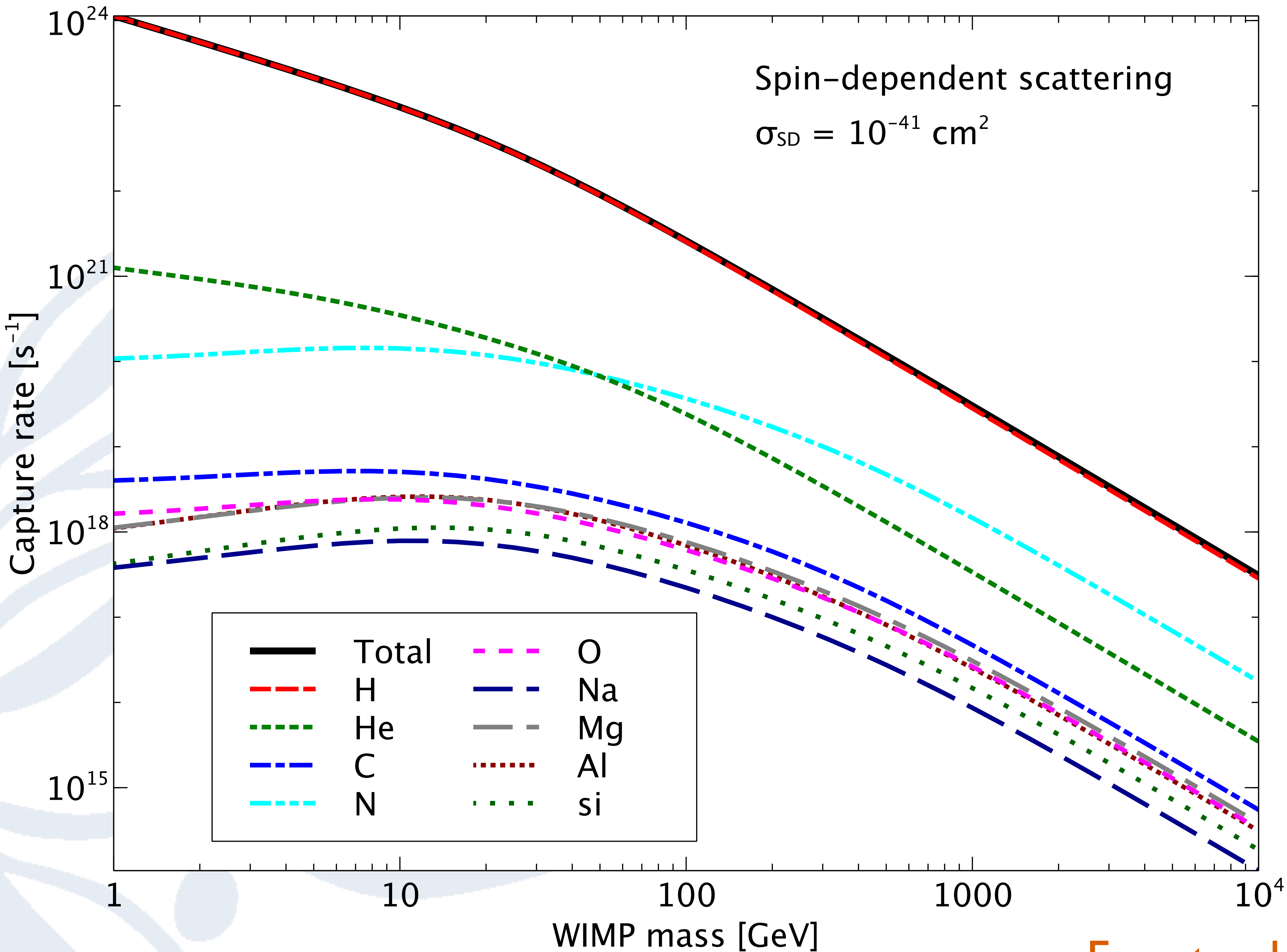
  K_0 (D_0) – diffusion coefficient

  δ – exponent for energy dependence of diffusion coefficient

  L – diffusion zone half height

- In addition, more parameters are needed for energy losses, galaxy radial extent, etc

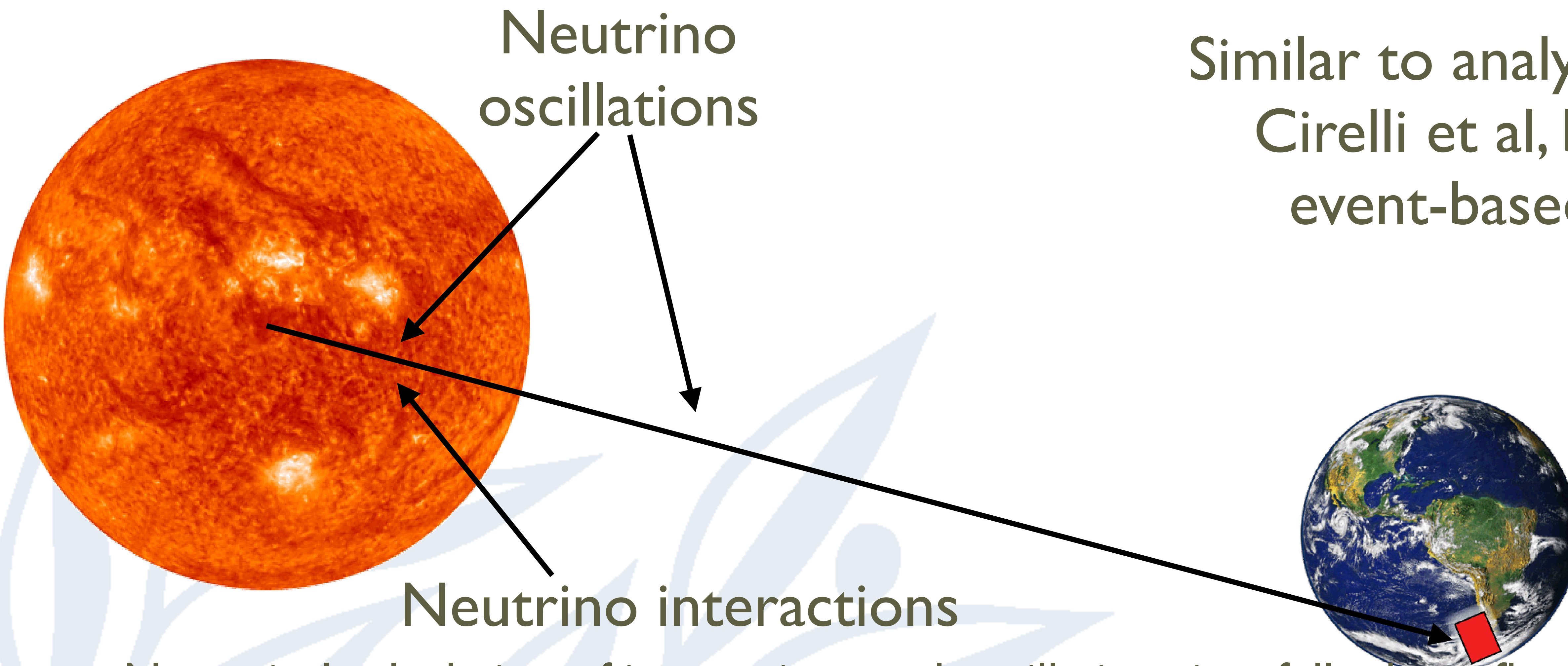
Example: SD capture rate in Sun



For standard halo

M. Blennow, J. Edsjö and T. Ohlsson, JCAP01 (2008) 021

Neutrino interactions and oscillations



Similar to analysis of Cirelli et al, but event-based.

- Numerical calculation of interactions and oscillations in a fully three-flavour scenario. Regeneration from tau leptons also included.
- **Publicly available code:** WimpSim: WimpAnn + WimpEvent suitable for event Monte Carlo codes: wimpsim.astroparticle.se
- Main results are included in DarkSUSY.
- New calculation of solar atmospheric background (from CR) to be included in DarkSUSY later [arXiv:1704.02892]

See talk by Carl Niblaeus yesterday

DarkSUSY

Typical program

- `call dsinit`
- [make general settings]
- [determine your model parameters your way]
- `call dsgive_model` [or equivalent]
- `call dsmodelsetup` [or equivalent]- to set up DarkSUSY for that model
- [then calculate what you want]

See example programs in examples/