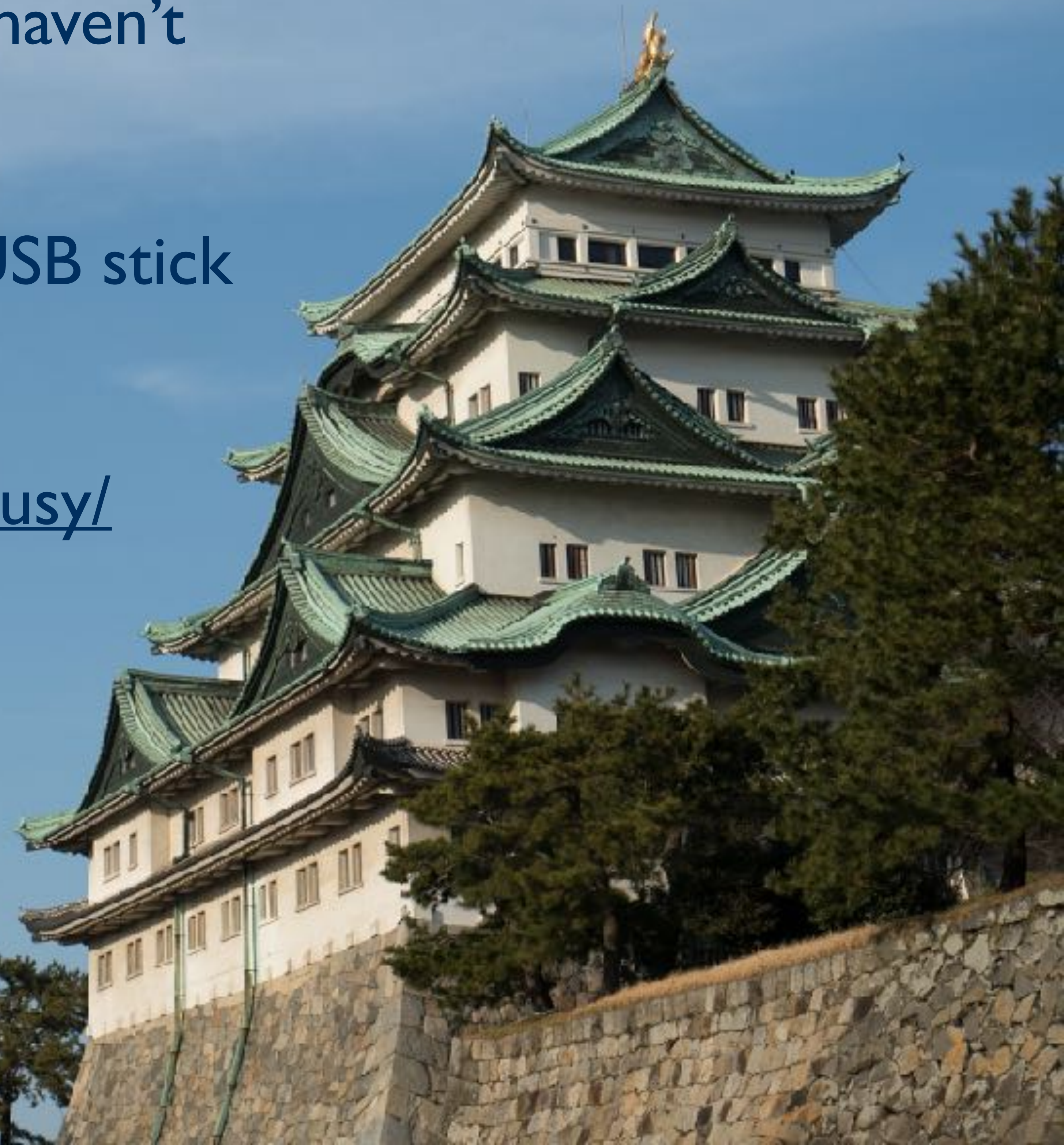
DarkSUSY 6

Download and install (if you haven't done so already):

Preferred option: borrow a USB stick from the registration desk

www.fysik.su.se/~edsjo/darksusy/nagoya18/



DarkSUSY 6
Introduction

Joakim Edsjö
edsjo@fysik.su.se

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

Stockholm University

KMI School
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Oskar Klein centre

About this tutorial I

- Will assume that the audience is varied (some with and some without prior DarkSUSY knowledge)
- Will focus on the newly released DarkSUSY 6, arXiv:1802.03399
- Will highlight differences with DarkSUSY 5 for those familiar with the earlier version

About this tutorial II

- This tutorial comes before Joe Silk's lectures

  ⇒ I will go through some of the physics

  involved very shortly and refer to Joe's lectures for more details

About this tutorial III

- Part 1 (Feb 28, 15-16.30):
  - intro to DarkSUSY, what DarkSUSY can do
  - installation, running simple example programs and write programs on your own
- Part 2 (Mar 1, 14-15.30): more advanced examples, rates, non-standard astrophysics, more advanced build options for modified setups
- Part 3 (Mar 1, 16-17.30): more advanced examples, setting up a new particle physics module

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
- …

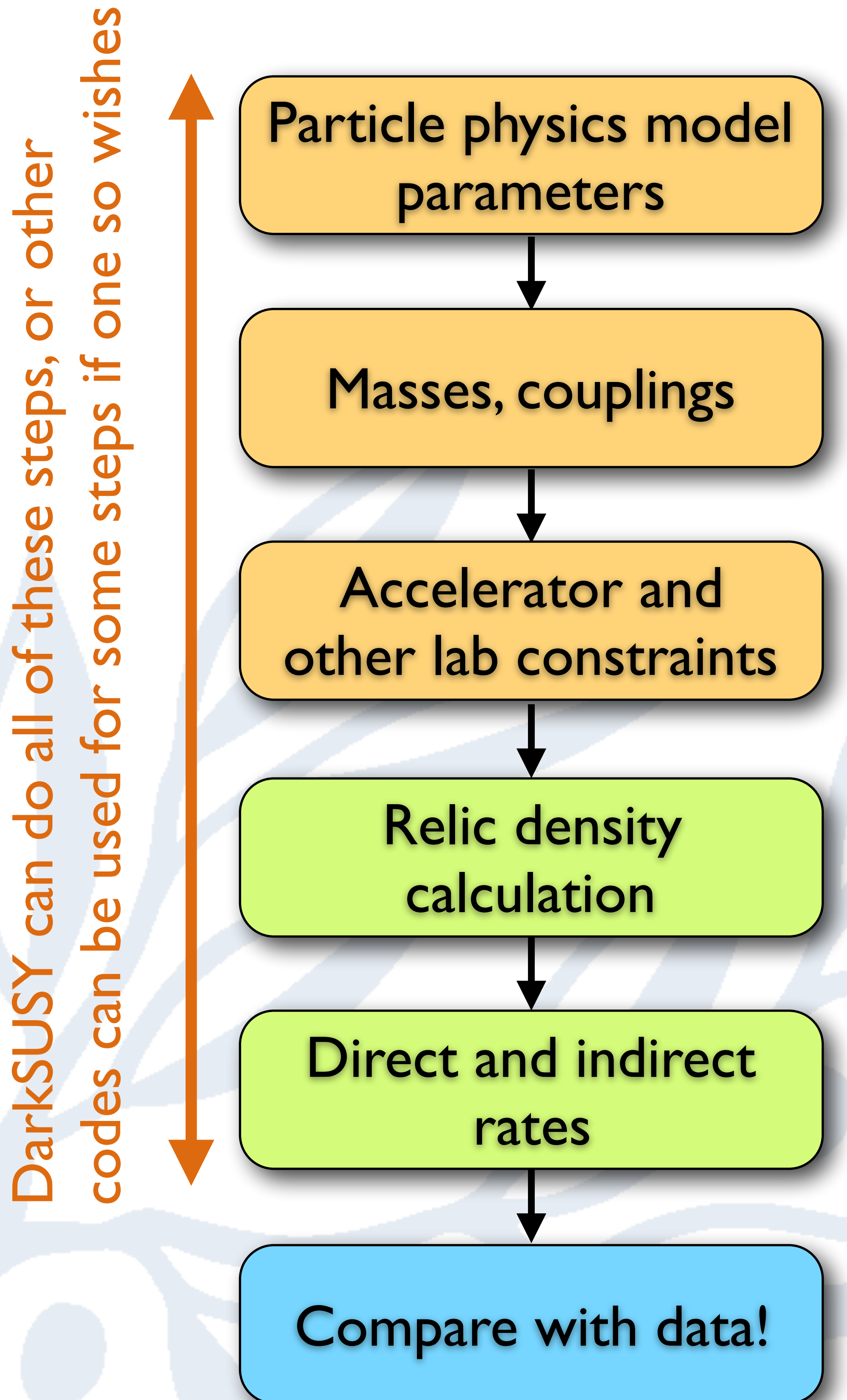
Need to treat all of these in a consistent manner, both regarding particle physics and astrophysics

Current version: 6.0.0, darksusy.org

Will focus on sDarkSUSY 6

Will not cover all of these…

Calculation flowchart



Parameters within a model, e.g. pMSSM, CMSSM, KK, scalar singlet, generic Wimp etc

Spectrum calculator (e.g. RGE solver)

Direct searches, rare decays, precision measurements

Annihilation cross section calculator and Boltzmann equation solver

Rate calculator

Compare individual rates or perform global fits

Outline

- 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

What is DarkSUSY?

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

Other WIMPs
Decaying DM?
UED?
Scalar singlet?
ething
y different?
?
When you are handsome - what difference
does it make that the ski poles are too short
Jan Stenmark

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

+ whatever you add!

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.

= 3x3 complex matrices

= 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

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

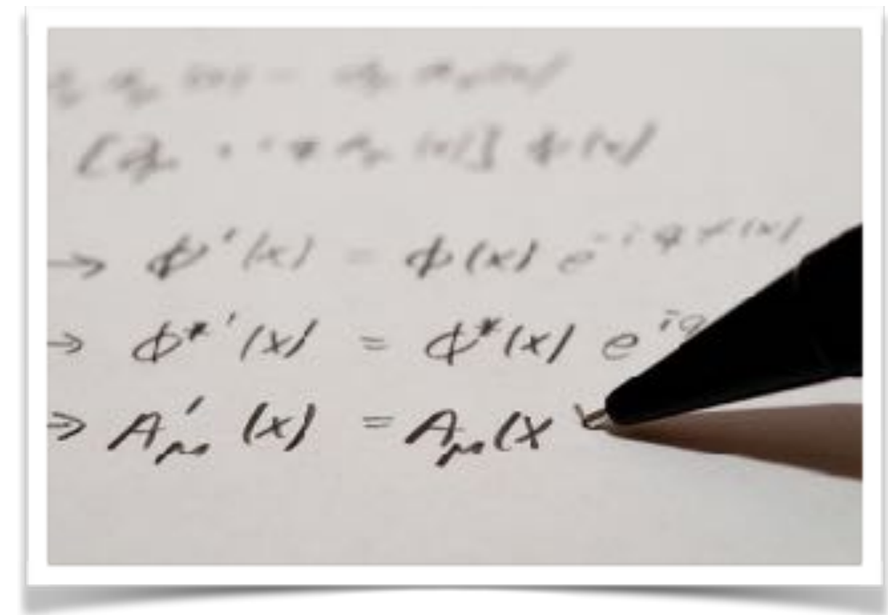
New things in DarkSUSY 6 (II)

- 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,
- Ulta-compact minihalos added

Other codes

- There are other codes on the market that do similar things, e.g.
  - micrOmegas
  - SuperIso Relic (no astrophysical rates)
  - Isasugra relic (no astrophysical rates)

Alternatives to codes



- Analytical calculations and approximations
- Data tables based on numerical calculations.
  - Some (Pythia tables) are built into e.g. DarkSUSY
  - Another alternative (Mathematica based): PPPC 4 DM ID – A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection, see www.marcocirelli.net/PPPC4DMID.html

Relic density

simple approach (more advanced in real life)

Decoupling occurs when

$$\Gamma < H$$

We have that

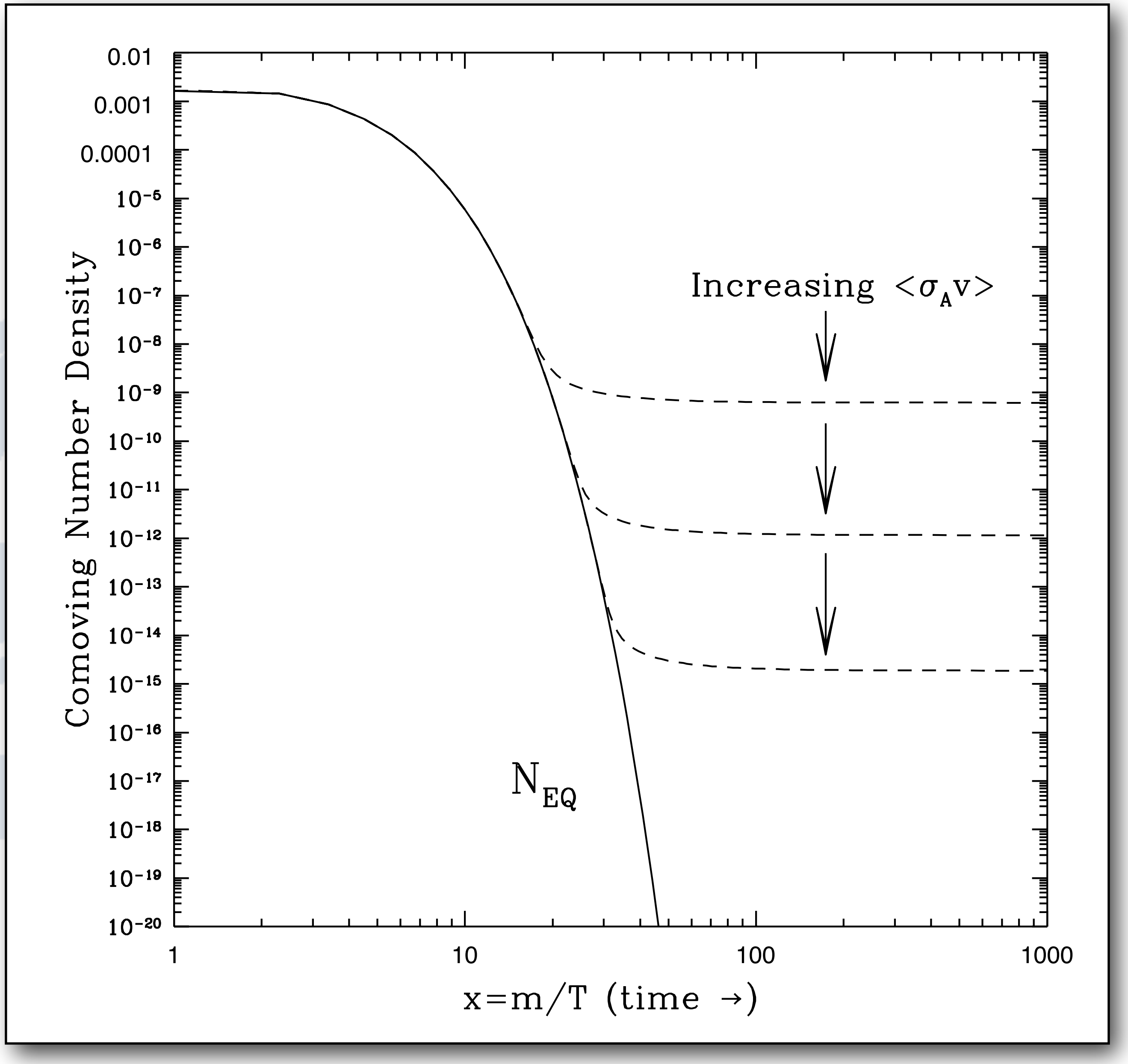
$$\Gamma = \langle \sigma_{\rm ann} v \rangle n_\chi$$

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

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

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

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



$$\langle \sigma_{\rm ann} v \rangle \simeq \langle \sigma_{\rm ann} v \rangle_{WIMP} \quad \Rightarrow \quad \Omega_\chi h^2 \simeq 1$$

Relic density – DarkSUSY implementation

- We solve the Boltzmann equation,

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

numerically, calculating the thermally averaged annihilation cross section,

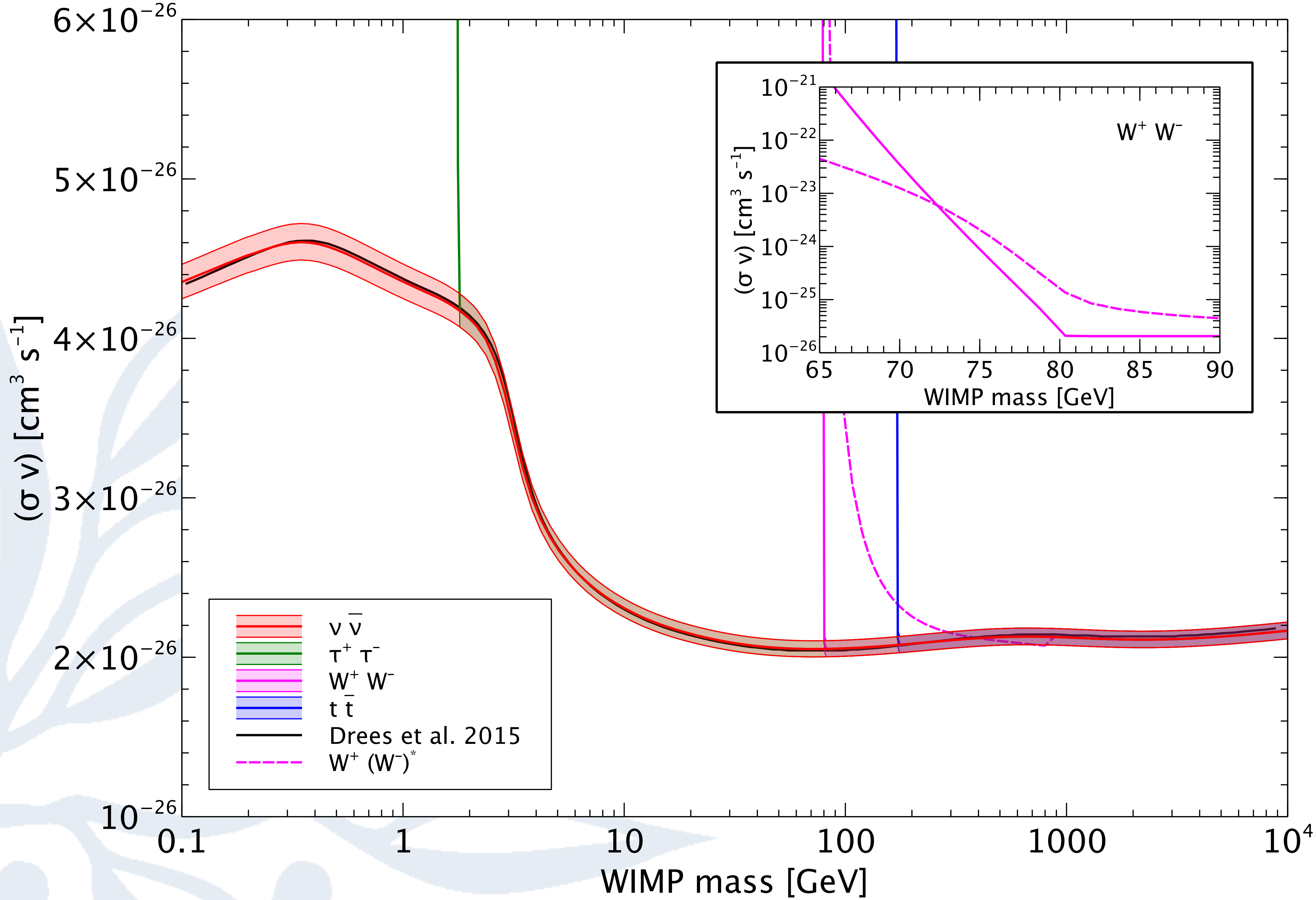
$$\langle \sigma_{\mathrm{eff}} v \rangle = \frac{\int_0^\infty dp_{\mathrm{eff}} p_{\mathrm{eff}}^2 W_{\mathrm{eff}} K_1 \left(\frac{\sqrt{s}}{T} \right)}{m_1^4 T \left[\sum_i \frac{g_i}{g_1} \frac{m_i^2}{m_1^2} K_2 \left(\frac{m_i}{T} \right) \right]^2}$$

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

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

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

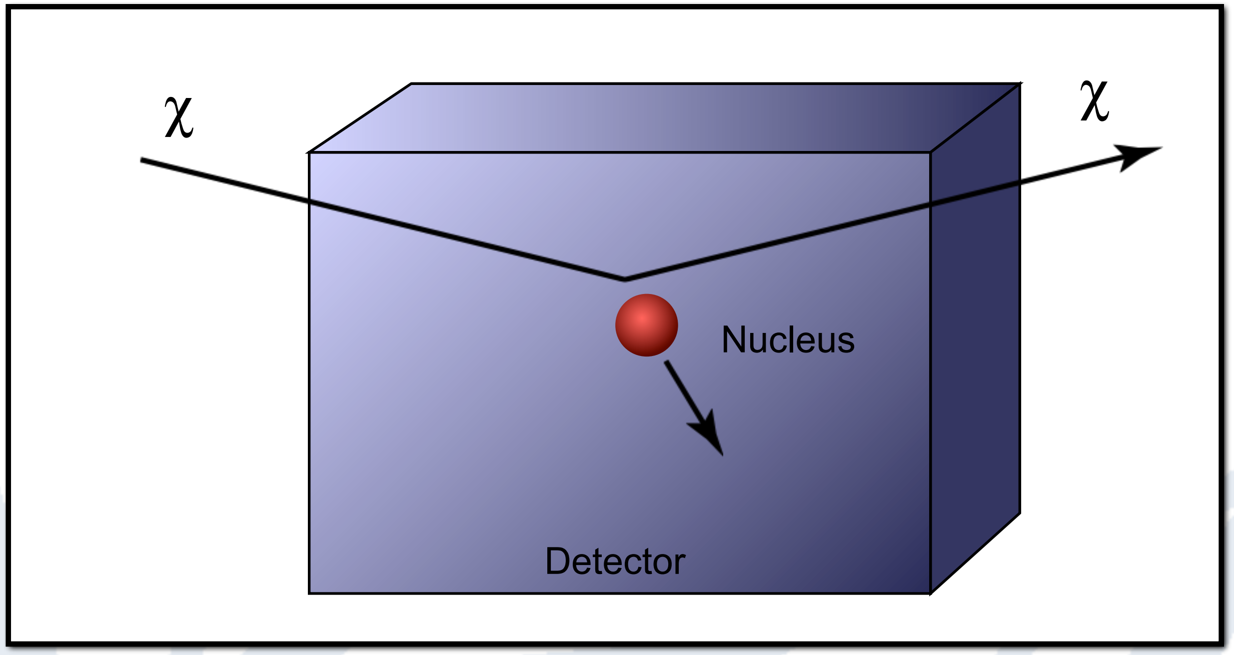
Example, generic WIMP



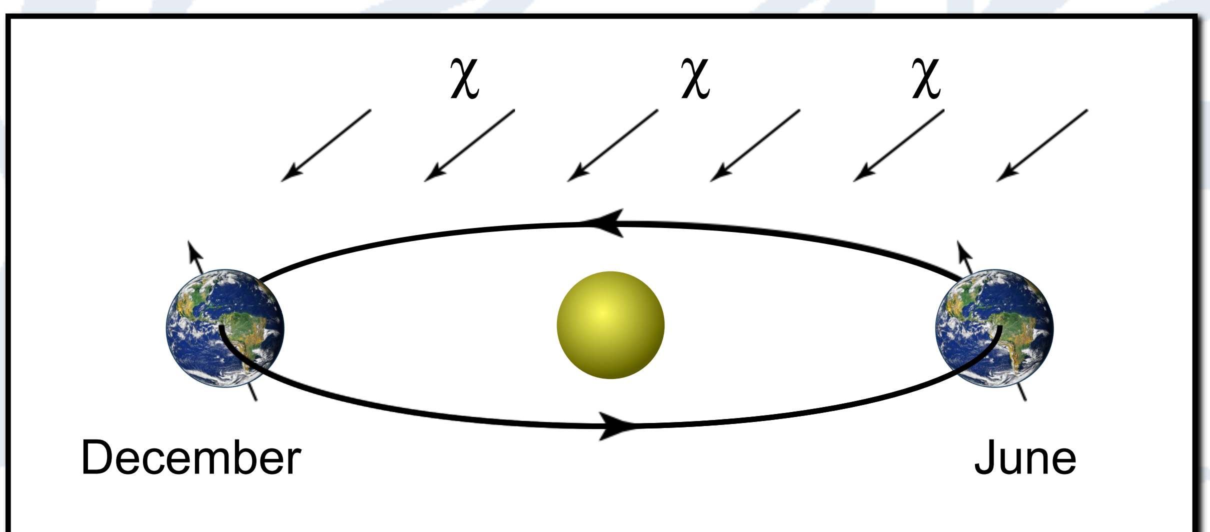
$$\Omega h^2 = 0.1165 - 0.1221$$ (Planck ±2σ)

Direct detection

general principles



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



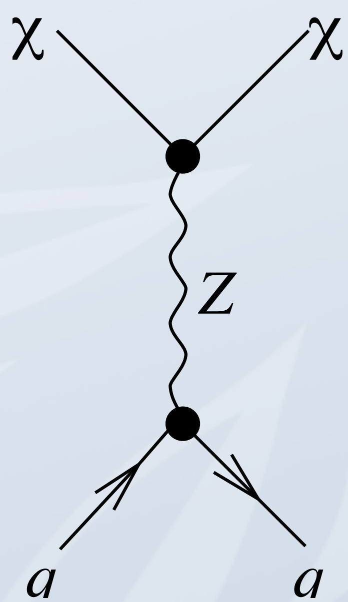
- Search for an annual modulation due to the Earth's motion in the halo

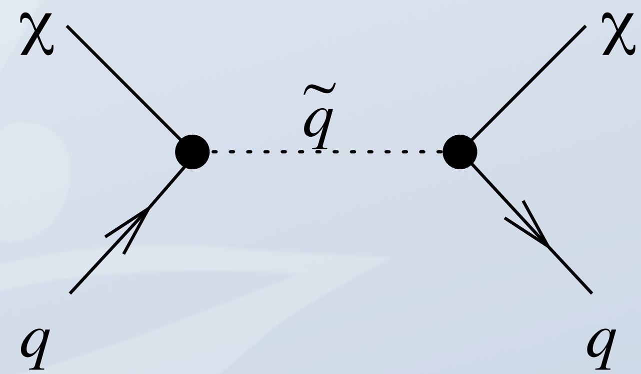
Direct detection

- Routines to calculate the spin-independent and spin-dependent scattering cross sections on protons and neutrons. These are most easily used to compare with experimental results.
- Also routines to calculate the differential rates on various targets including both spin-independent and spin-dependent form factors. In general, the particle physics module should supply the couplings needed for the general rate calculations.
- Halo model and velocity distribution can be chosen arbitrarily
- Annual modulation signal can be calculated
- Different sets of form factors available

Spin-dependent (SD) scattering

- Spin-dependent scattering, couples to the total spin of the nucleus. In case of SUSY it comes from

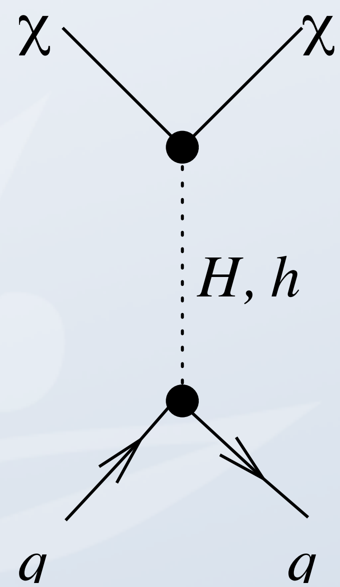


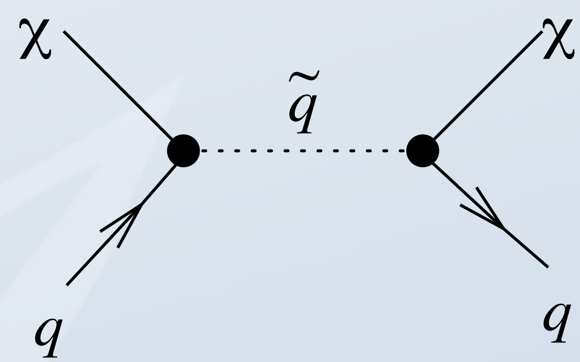


- Not all target nuclei have spin

Spin-independent (SI) scattering

- Couples to all nucleons in the nucleus coherently. For SUSY it looks like





$$\sigma = \sigma_p^{\mathrm{SI}} A^2 \left(\frac{M_\chi m_N}{M_\chi + m_N} \right)^2 \left(\frac{M_\chi m_{\mathrm{p}}}{M_\chi + m_{\mathrm{p}}} \right)^{-2}$$

Scattering cross section on proton

Coherence factor

Phase space factor (kinematics)

Differential rate as A^2 / bin

Form factor suppression (decoherence) adds on top of this though, taking some of the enhancement away.

Indirect rates – Annihilation channels

- As we are very interested in trying to observe the annihilation products from dark matter annihilation, we need to investigate what they are. Some of the relevant are:

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

Note: ν final states are absent for some WIMPS, like neutralinos

- These will hadronize/decay and produce electrons, positrons, antiprotons, gamma rays, neutrinos etc
- As the neutralino is a Majorana fermion, the annihilation cross section to fermions go as

$$\sigma_{f\bar{f}} \propto \frac{m_f^2}{m_\chi^2}$$

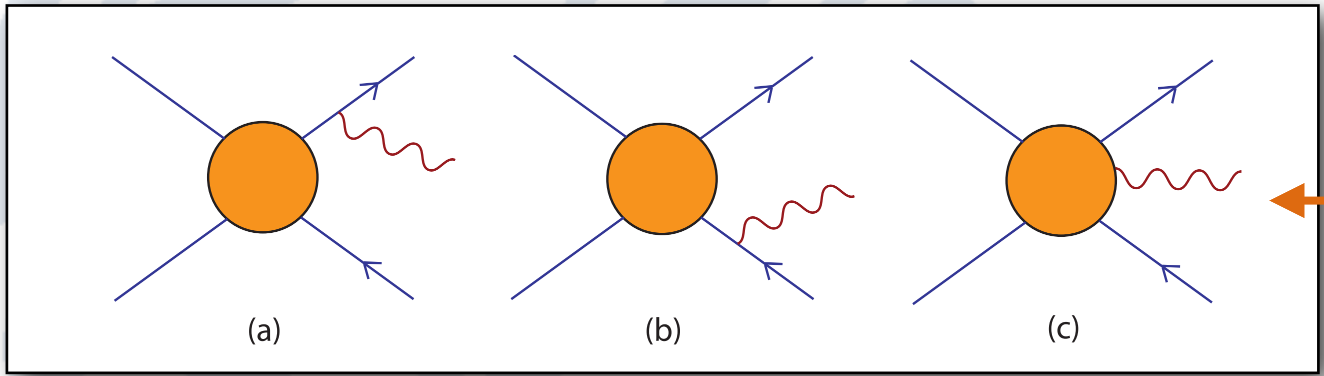
which means that we will be dominated by the heavy fermions (b and t quarks).

- Yield calculated with Pythia and tabulated for use by DarkSUSY (3 GeV – 20 TeV)
- Higgs bosons are let to decay in flight summing up the yields from the decay products

Gamma rays

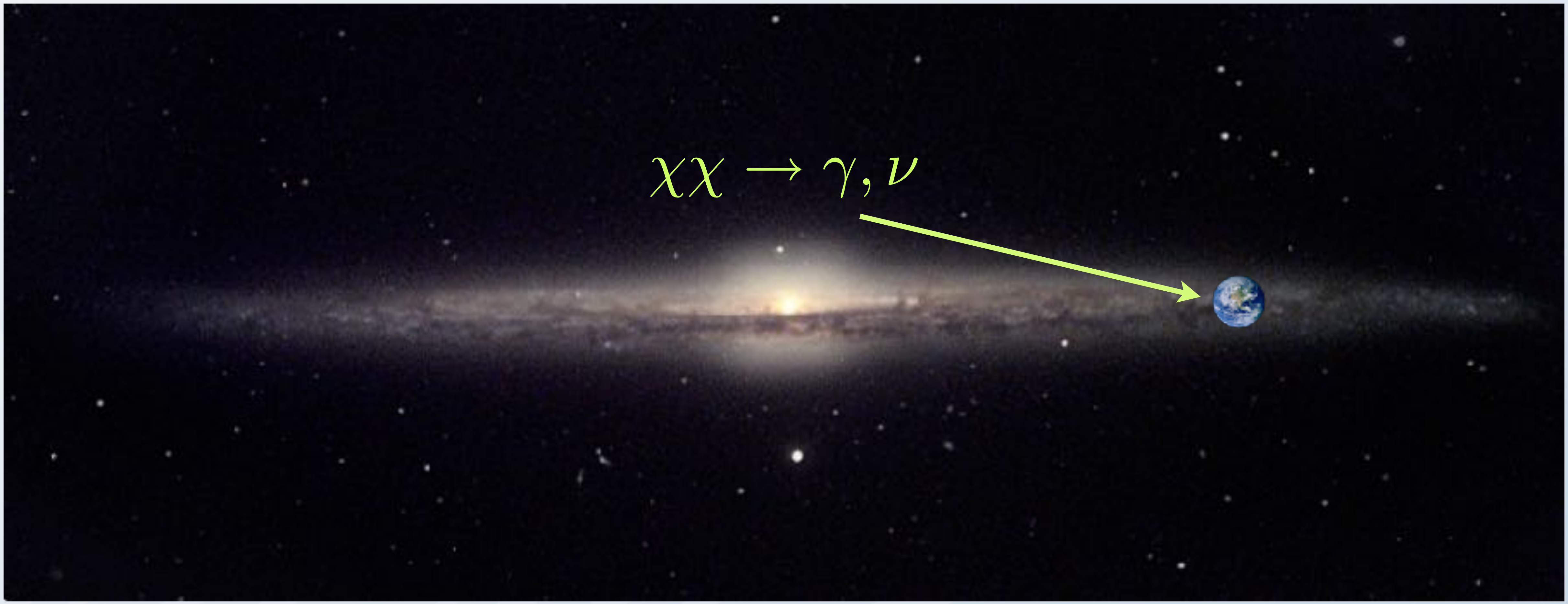
- DarkSUSY includes generic WIMP routines to calculate gamma yields from WIMP annihilations
  - Based on Pythia simulations for WIMP masses between 3 GeV and 20 TeV
  - Line signals
  - Internal Bremsstrahlung added separately

Works for any WIMP



Virtual internal bremsstrahlung is model dependent!
SUSY calculation included.

Annihilation in the halo



- Gamma rays can be searched for with e.g. Air Cherenkov Telescopes (ACTs) or Fermi-LAT (launched June, 2008).
- Signal depends strongly on the halo profile,

$$\Phi \propto \int_{\text{line of sight}} \rho^2 dl$$

Annihilation to gamma rays

- **Monochromatic**
  At loop-level, annihilation can occur to

$$\gamma\gamma \quad \Rightarrow \quad E_\gamma = m_\chi$$

$$Z\gamma \quad \Rightarrow \quad E_\gamma = m_\chi - \frac{m_Z^2}{4m_\chi}$$

Features
- directionality – no propagation uncertainties
- low fluxes, but clear signature
- strong halo profile dependence

- **Continuous**
  WIMP annihilation can also produce a continuum of gamma rays

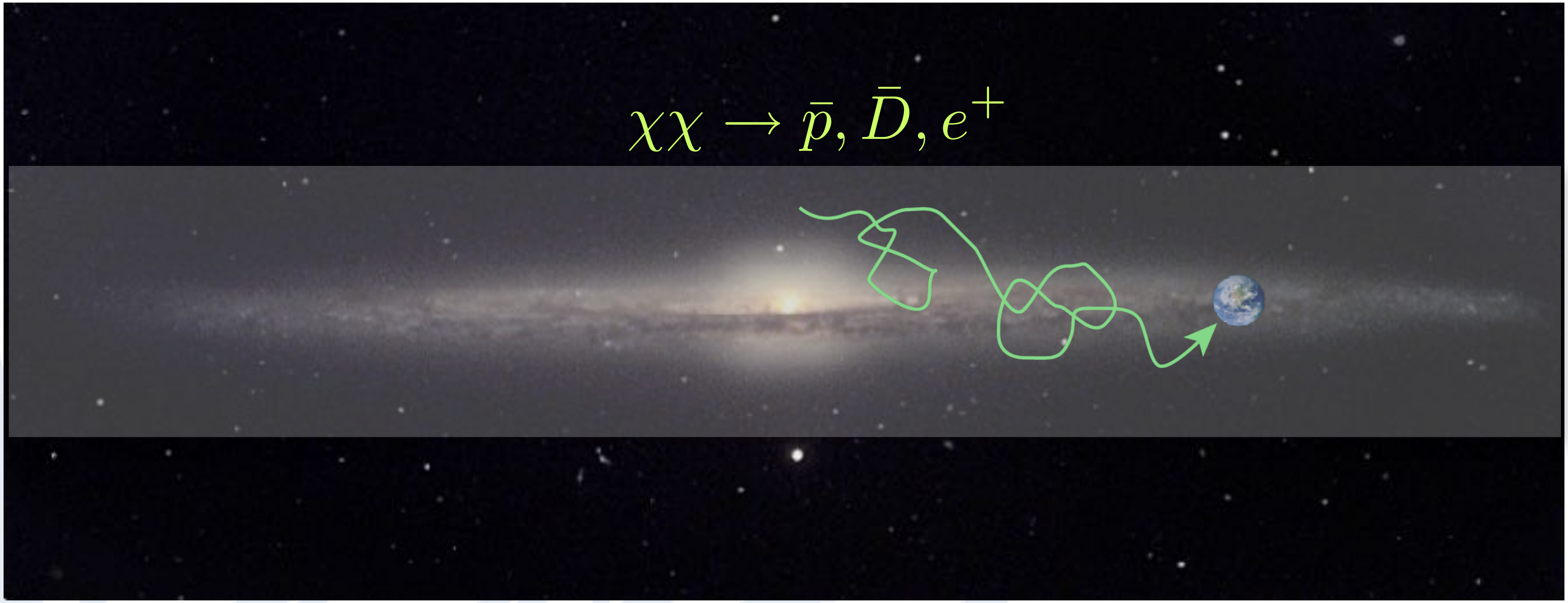
$$\chi\chi \to \cdots \to \pi^0 \to \gamma\gamma$$

Features (compared to lines)
- lower energy
- more gammas / annihilation
- rather high fluxes
- not a very clear signature

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)

Diffusion equation

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

Wind

Spatial diffusion

Energy losses

Energy diffusion (reacceleration)

Source term

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

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

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

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

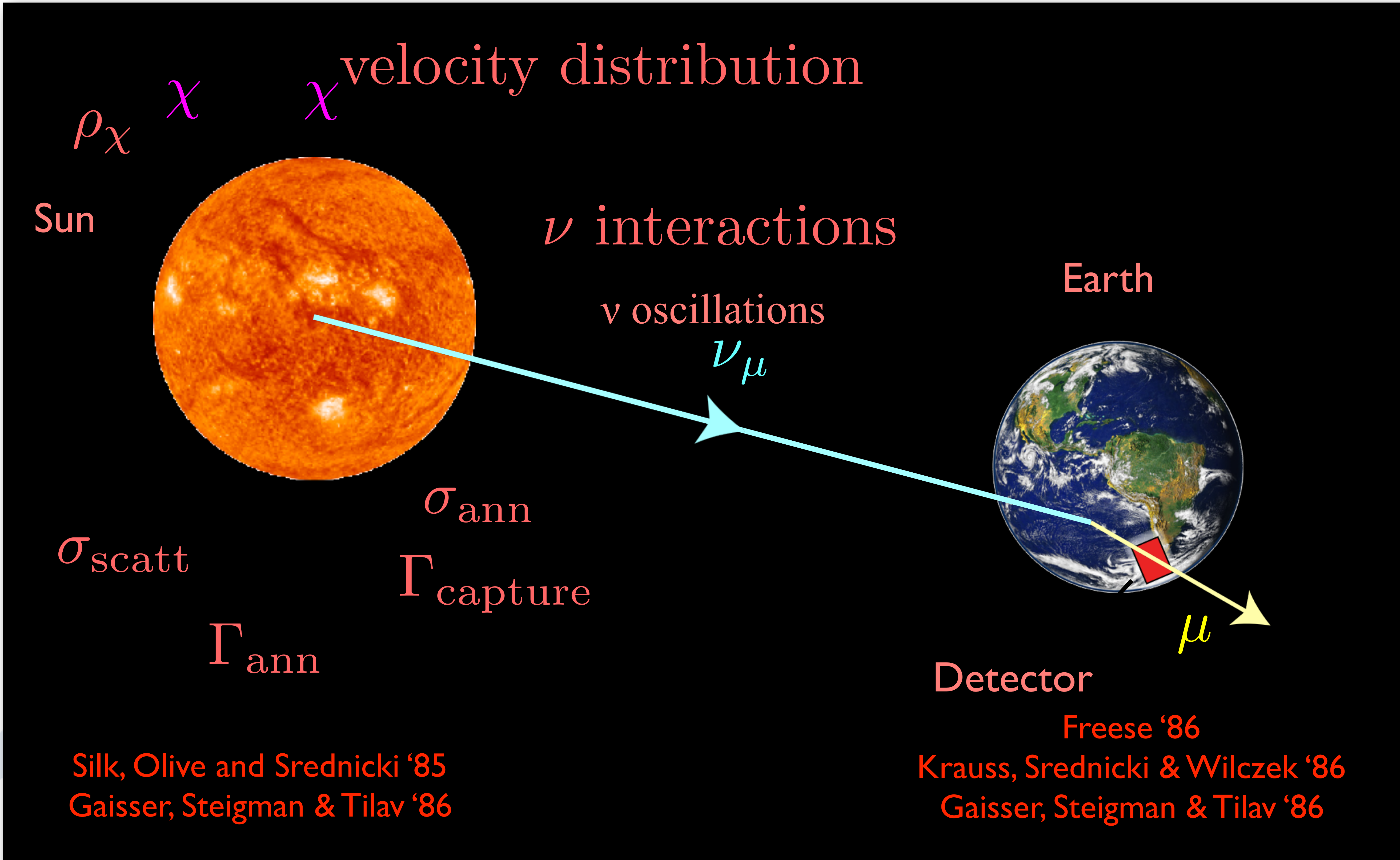
  K_0 (D_0) – diffusion coefficient

  δ – exponent for energy dependence of diffusion coefficient

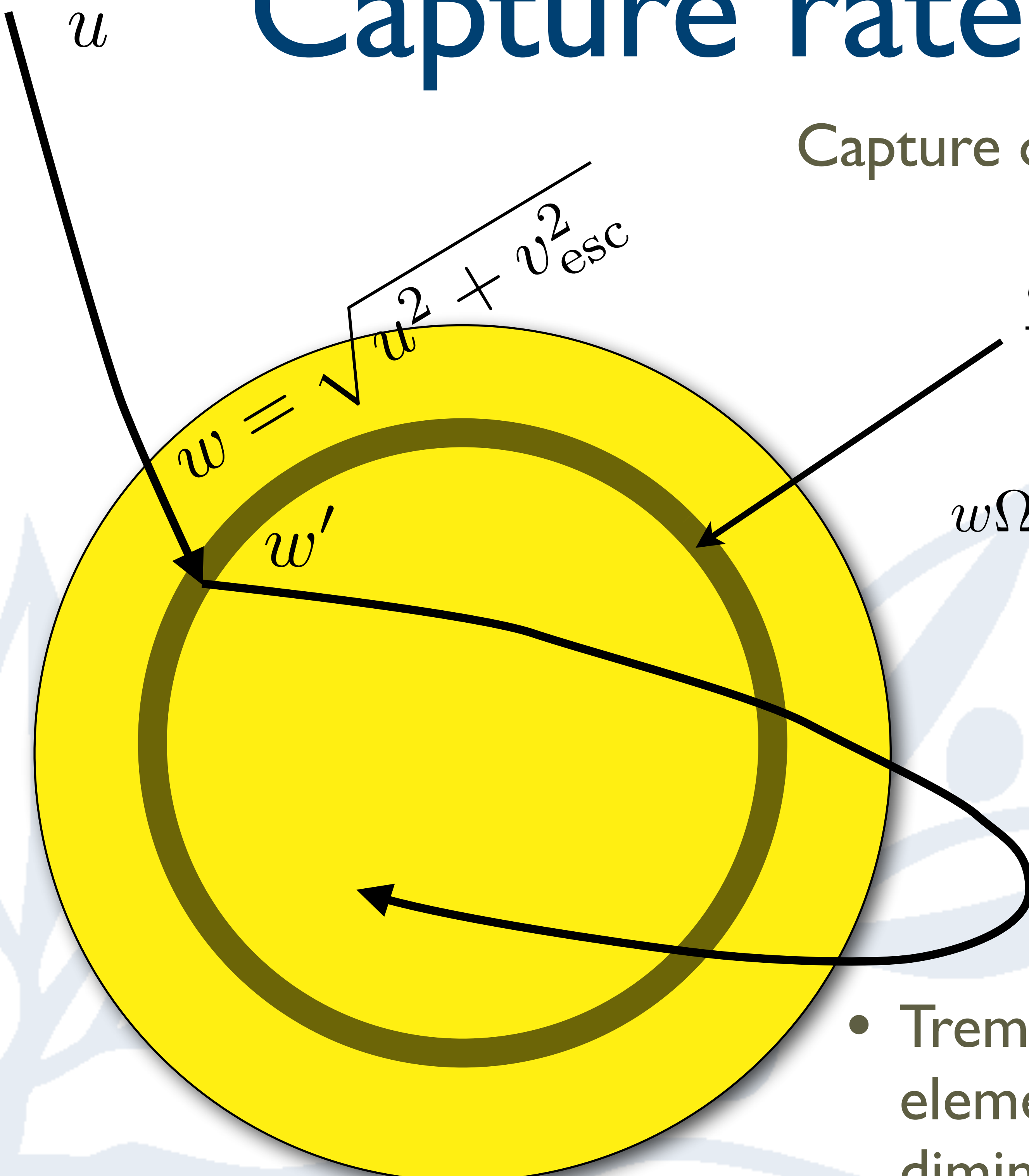
  L – diffusion zone half height

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

Neutrinos from the Earth/Sun



Capture rate calculation



Capture on element i in volume element

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

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

~A^2 ~A^2

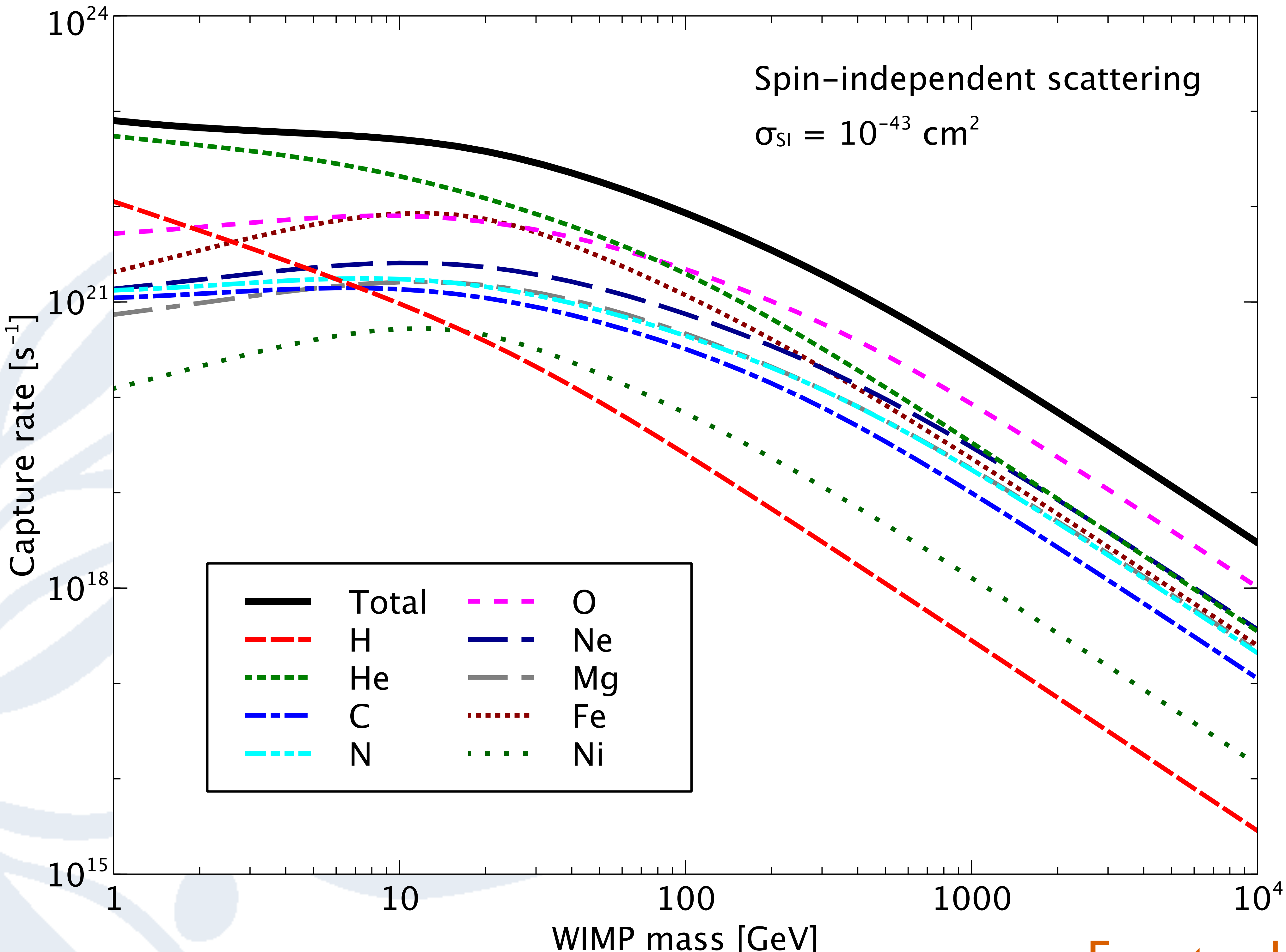
~A^4 A=atomic number

- 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

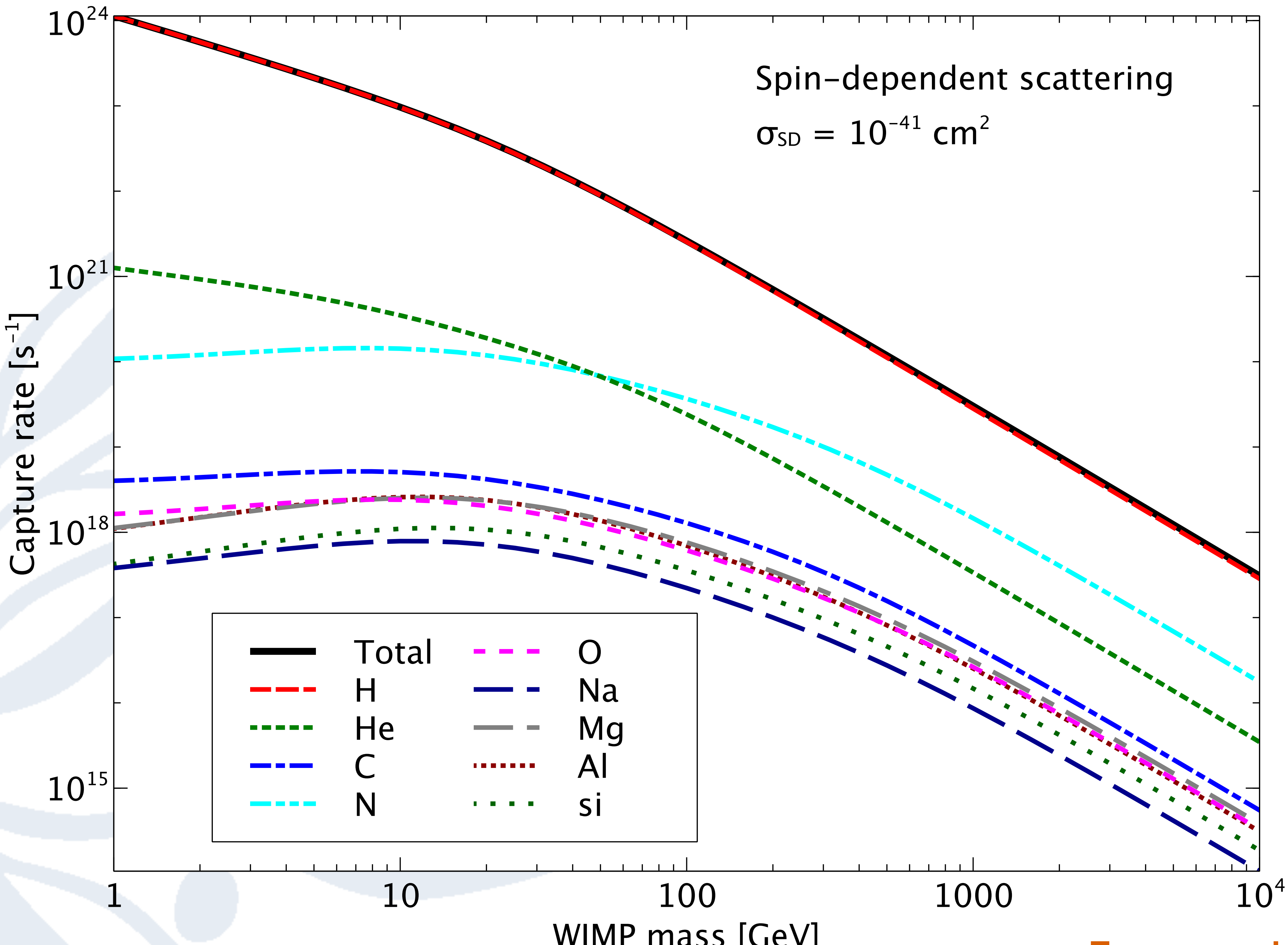
- Full numerical integration over solar radius, summing most relevant elements (up to 289 for SI and 112 for SD in DS 6)
- Full numerical integration over velocity distribution, no need to assume Maxwell-Boltzmann distribution
- In DS 6: full numerical integration over momentum transfer: arbitrary form 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.

Example: SI capture rate in Sun



For standard halo

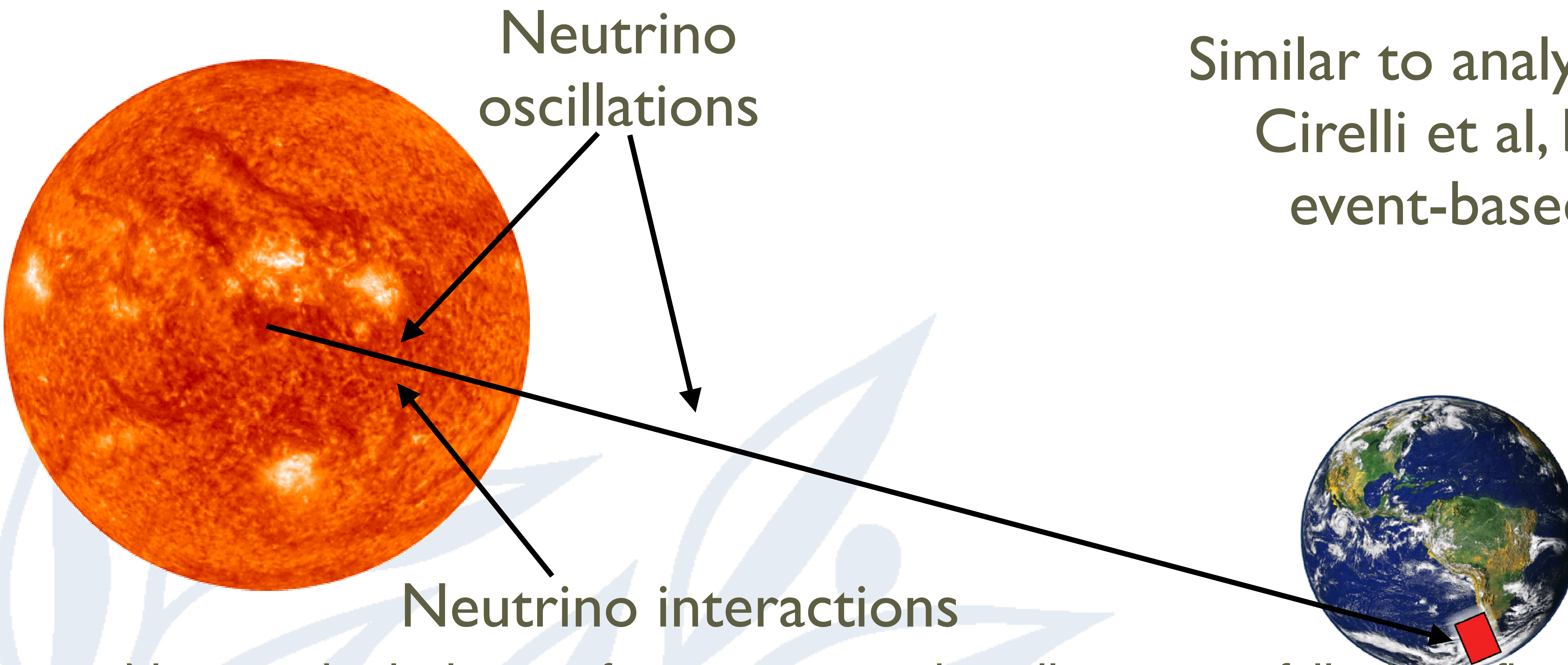
Example: SD capture rate in Sun



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: www.physto.se/~edsjo/wimpsim
- Main results are included in DarkSUSY.
- New calculation of solar atmospheric background (from CR) to be included in DarkSUSY later [arXiv:1704.02892]

Accelerator constraints and likelihoods

- For SUSY, DarkSUSY contains routines to check lab constraints (accelerators, rare decays etc)
- Also links to other codes like HiggsBounds and SuperIso
- We are working on going away from hard cuts to likelihoods when possible
- To do this, we need publicly available data and background estimates/simulations
- If you want to include many different constraints in a consistent way, you should do a global fit with a tool like MasterCode (see John's talk) or Gambit (public code). Gambit includes DarkSUSY (currently v. 5)

Philosophy

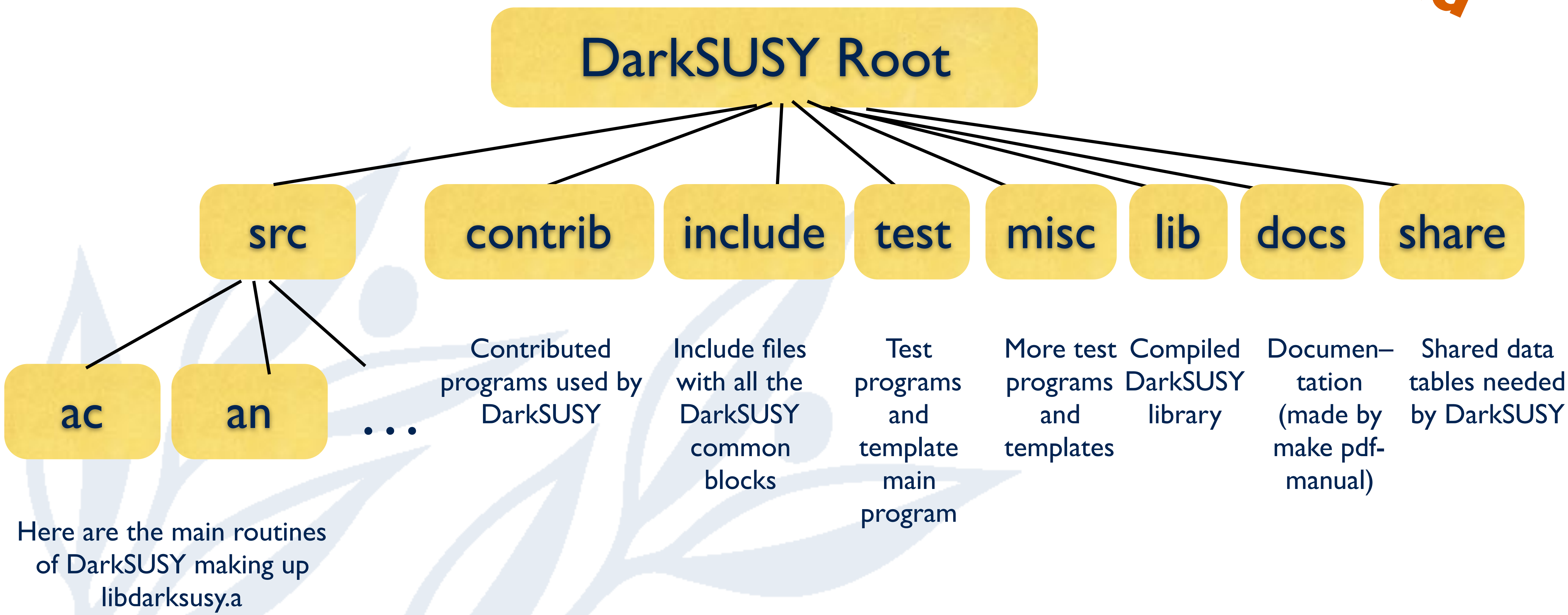
- Modular structure (given the Fortran constraints...)
- Library of subroutines and functions
- Fast and accurate
- “Standard” Fortran - works on many platforms
- Flexible
- Version control (subversion) for precise version tagging

Couples to other codes

- FeynHiggs - Higgs physics
- HiggsBounds and HiggsSignals - Higgs searches and properties
- SuperIso - rare decays
- IsaSugra - RGE solver (or use any other via the SLHA interface)

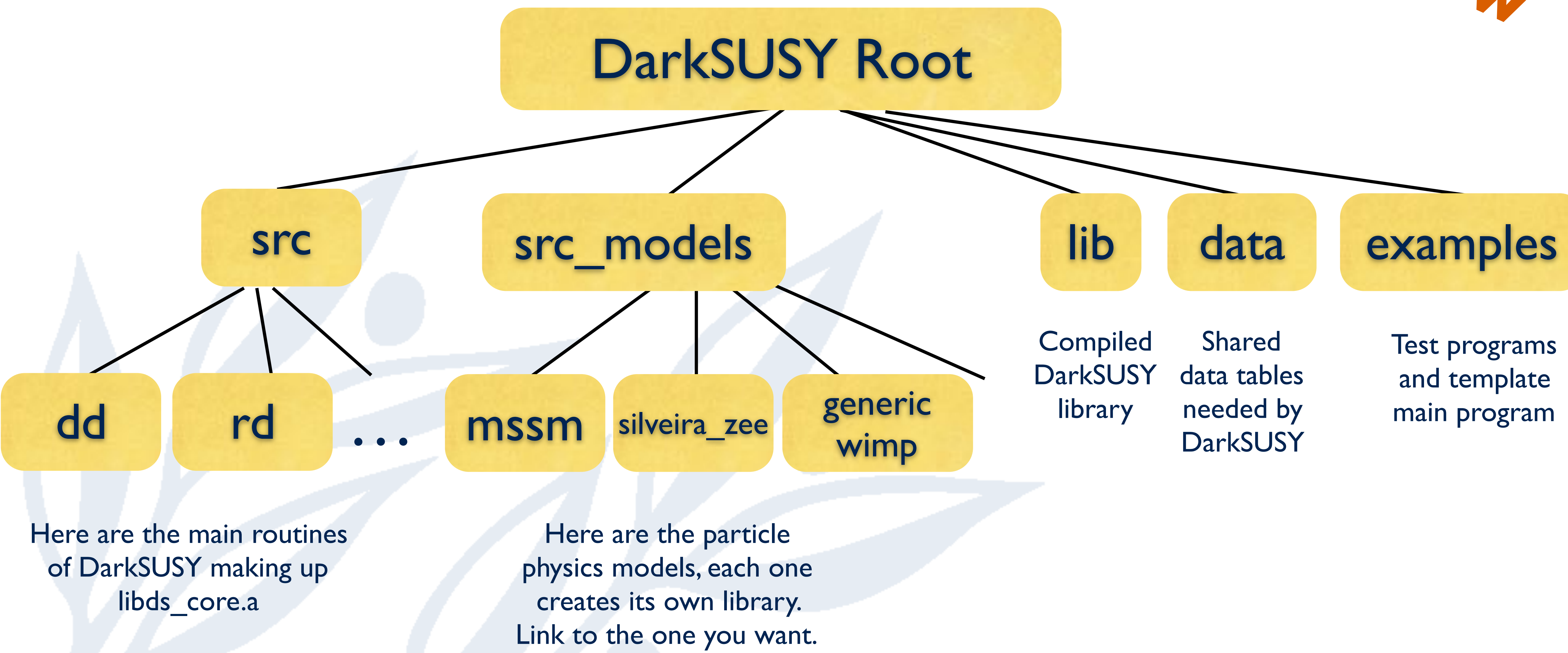
DarkSUSY 5 layout

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/

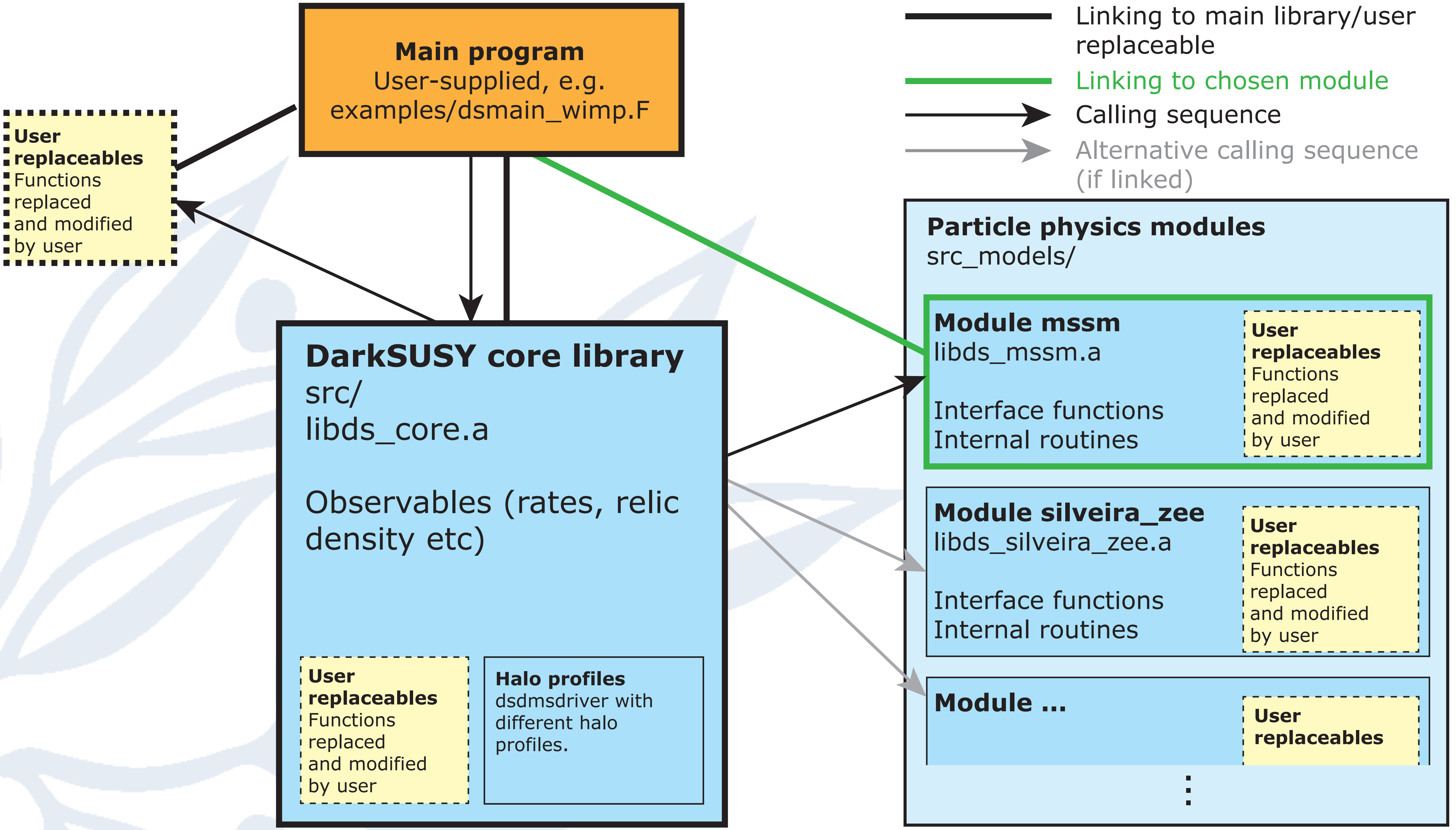
DarkSUSY 6 concepts

- **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

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/

*set routines

- Essentially all the packages in DarkSUSY have a corresponding *set routine that determines how those routines are going to be used, which parameter sets to use etc.
- As an example,
  call dssenu_set('default') chooses the default way to calculate capture rates in the Sun/Earth
- All these *set routines are called with the argument 'default' by dsinit, but can be changed later by the user.

And then we have the name…

- DarkSUSY does now mean… Dark SUsy Samt Ytterligare Modeller

Your thoughts and input

- We are now done with the introduction and come to the hands-on tutorial part. I want to know what you want to learn from this DarkSUSY tutorial
- Any specific physics problems?
- Any other thoughts on what you want me to bring up?

Go to menti.com and enter the code 98 63 15 and enter your thoughts

Reference / download

- DarkSUSY 6.0.0 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 t
Compute Dark Matter Propertie
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

Stockholm University

Joakim Edsjö
edsjo@fysik.su.se

Oskar Klein centre