Dark matter codes

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Stockholm University

Oskar Klein centre

Outline

- General comments on DM codes
- DarkSUSY as an example of a DM code

Ways to search for dark matter

Accelerator searches

- LHC
- Rare decays
- ...

Direct searches

- Spin-independent scattering
- Spin-dependent scattering

You and your dark matter codes

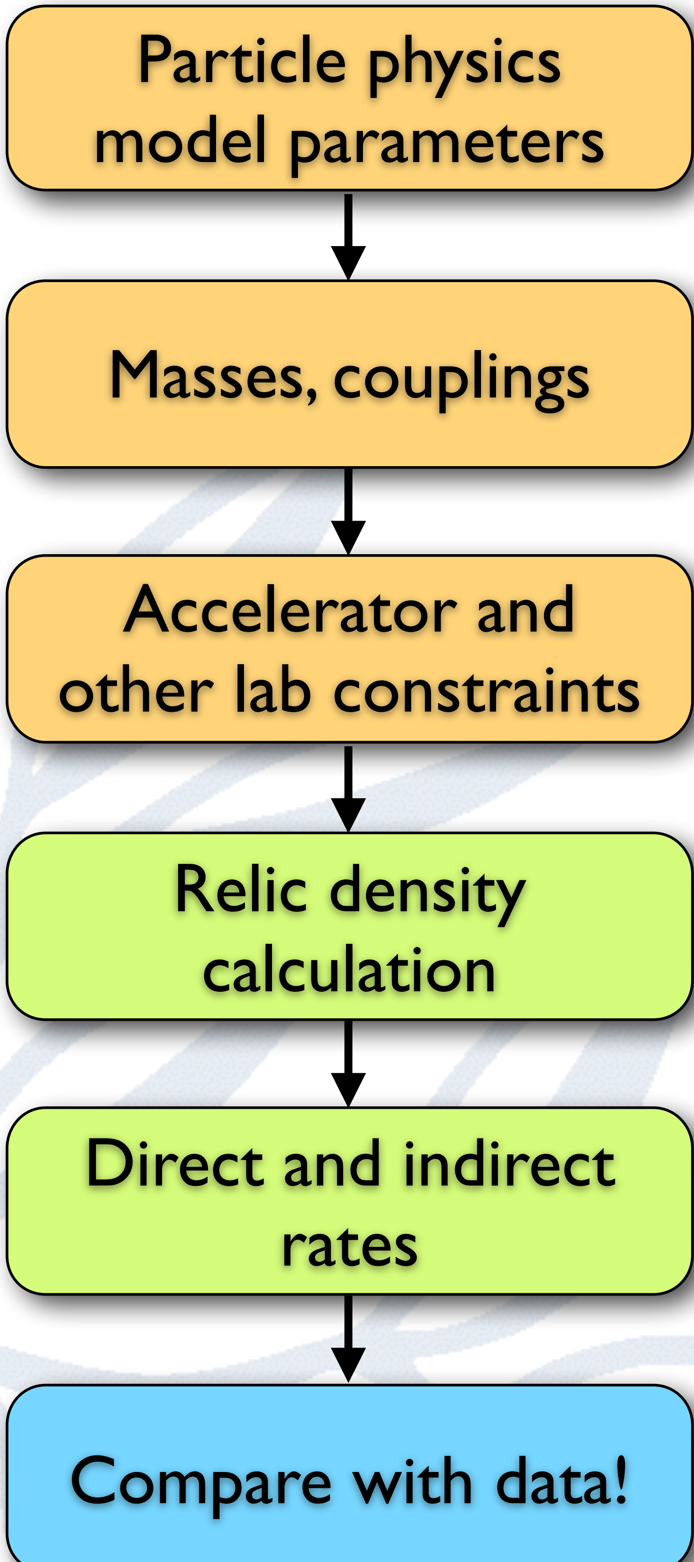
Indirect searches

- 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

Will not cover all of these...

Calculation flowchart



Parameters within a model, e.g. pMSSM, CMSSM, KK, 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

Default WIMP model

- As before, I will use the neutralino in SUSY as the default WIMP model, as most codes exist for SUSY
- I will specify when a code is applicable to more generic WIMPs

Example codes: SUSY

- Spectrum calculators: SoftSUSY, Suspect, Isasugra, …
- Rare decays: SUSYBsg, SuperISO, etc
- Mass spectrum: FeynHiggs, HDecay, SDecay, …
- Accelerator contraints: HiggsBounds, HiggsSignals, …

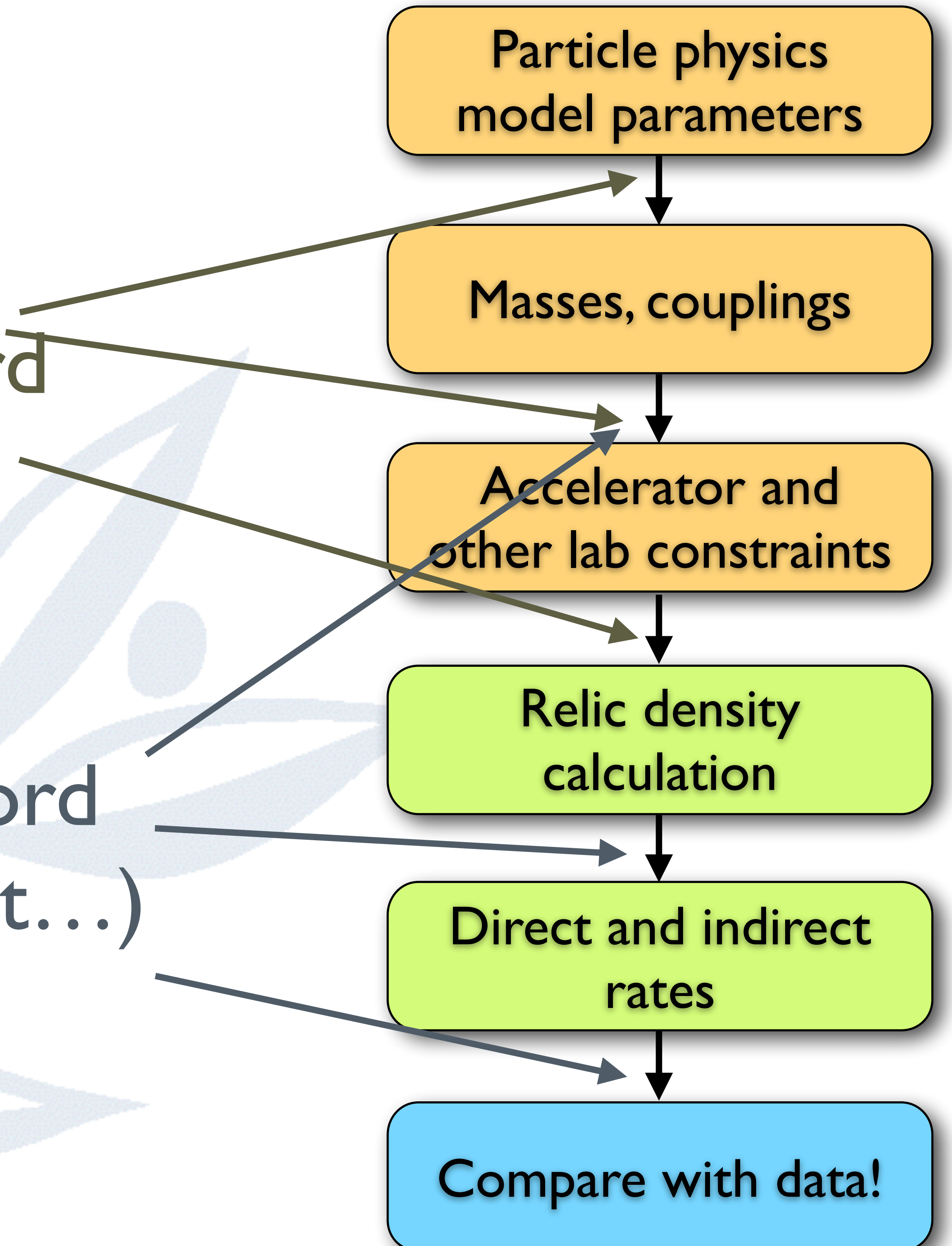
Example codes: DM

- Relic density:
  DarkSUSY, micrOmegas, IsaRed, SuperIso Relic, …
- Rate calculators:
  DarkSUSY, micrOmegas, …
- Global fits: SuperBayes, GAMBIT, …

What is the glue between the codes?

SUSY
Les Houches Accord
(SLHA)

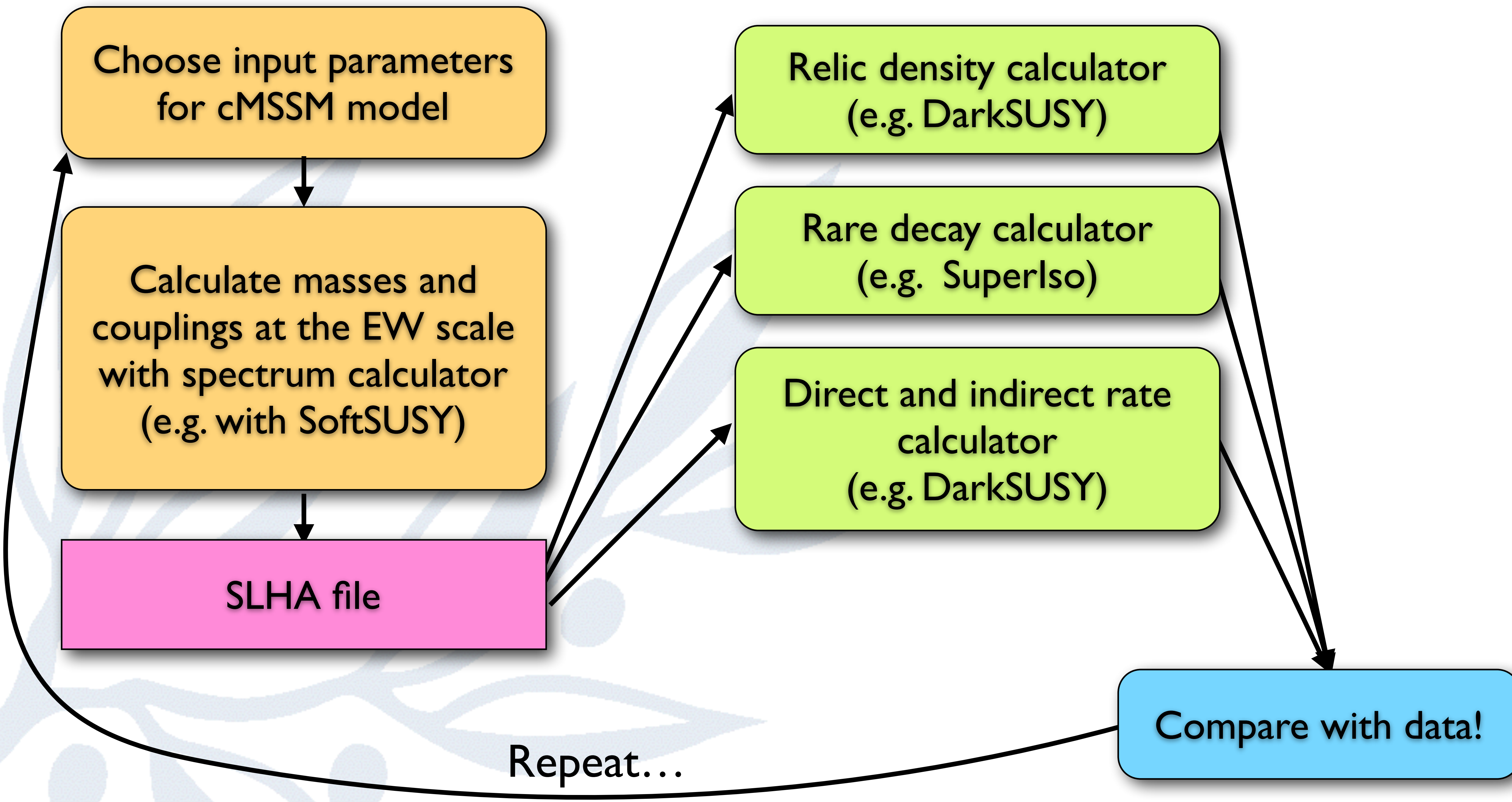
Dark Matter
Les Houches Accord
(not really there yet…)
(DMLHA)



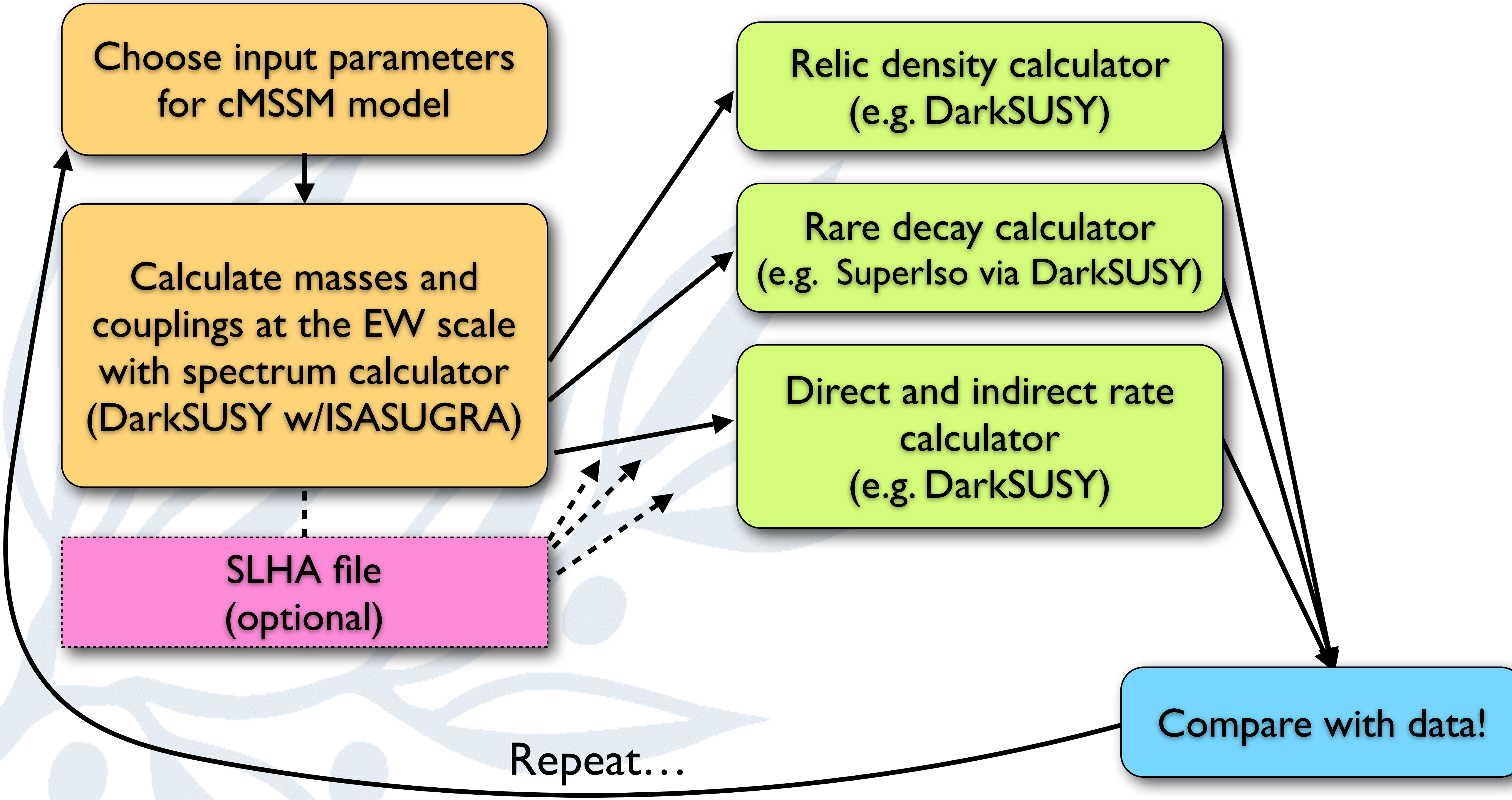
SLHA files

- SLHA files contain blocks
- Typically a spectrum calculator reads input blocks (e.g. parameters at the GUT scale) and returns a new SLHA file with output blocks filled in (e.g. masses and couplings at the EW scale).
- Other codes can read the files and add new blocks, e.g. particle decay tables
- DM codes typically read SLHA files, but does not output new SLHA files (except for the particle physics part of the calculation)

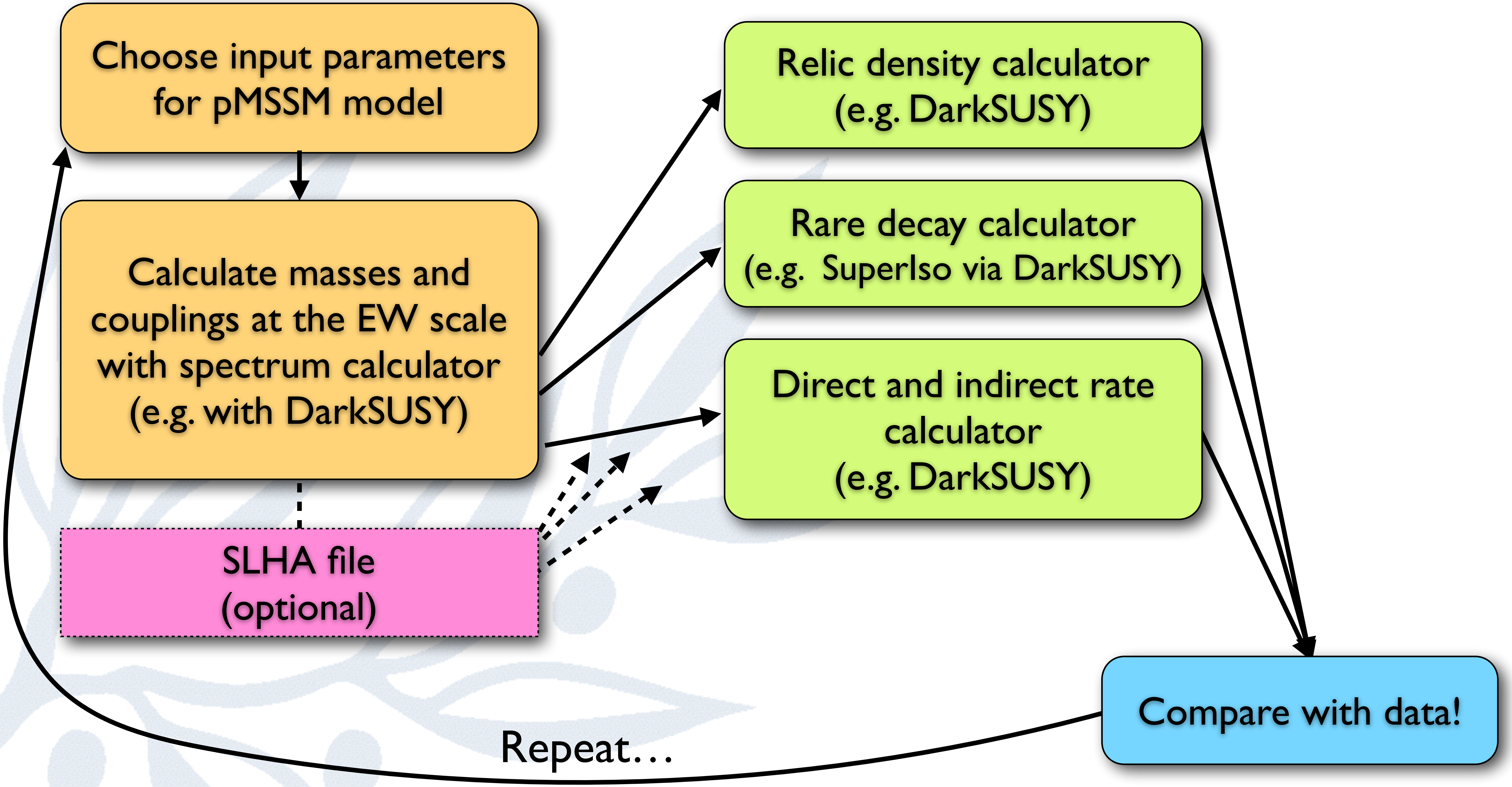
Typical calculation flowchart
CMSSM with generic spectrum calculator



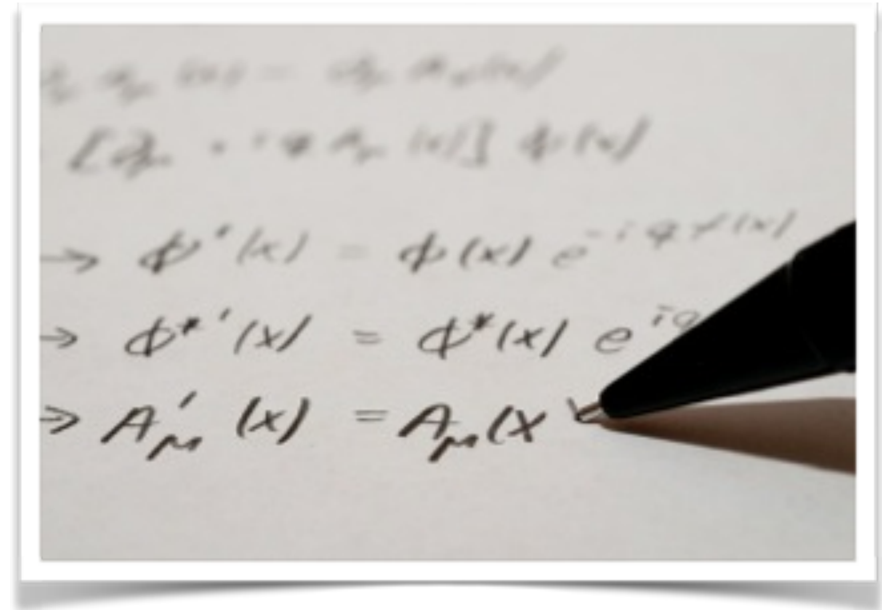
Typical calculation flowchart
CMSSM with DarkSUSY w/ ISASUGA



Typical calculation flowchart
pMSSM (all parameters at EW scale)



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

Question time

Discuss with your neighboring student(s) for two minutes!

Q Imagine you want to calculate the relic density and the gamma ray flux for an mSUGRA/CMSSM model. What kind of codes do you need?

A We need
1) a spectrum calculator (RGE solver)
2) a relic density calculator (Boltzmann equation solver)
3) a gamma ray rate calculator
4) a halo model, and line-of-sight integrator

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Example code

- Will use DarkSUSY as an example on how things can be done for SUSY (or more generic WIMP) calculations
- Other general alternatives are e.g. micrOmegas or the Mathematica-based PPPC 4 DM ID

Outline

- Introduction to and layout of DarkSUSY
- SUSY setup
- Accelerator constraints
- Relic density
- Direct detection
- Indirect detection:
  - gamma rays
  - charged cosmic rays
  - neutrinos (from the Sun/Earth)

Will focus on supersymmetric neutralinos as dark matter, but many results/ routines are applicable to any WIMP

Introduction and layout

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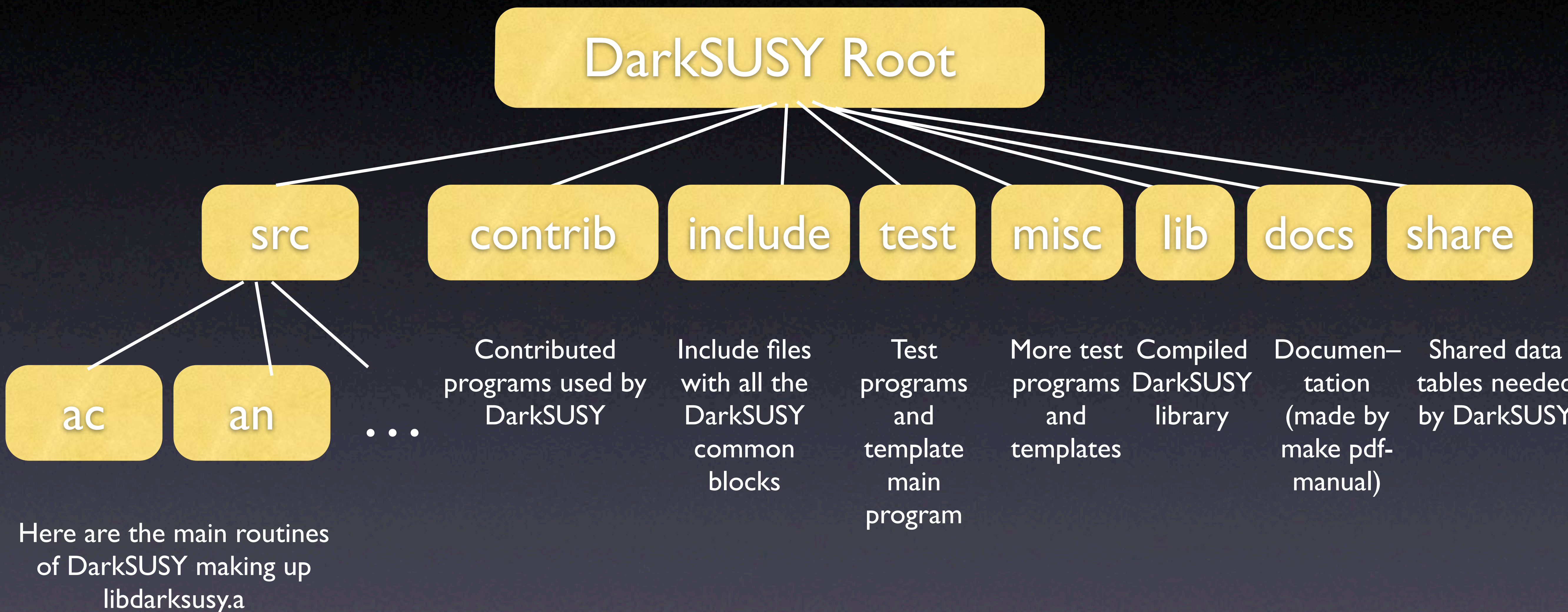
Philosophy

- Modular structure (given the F77 constraints...)
- Library of subroutines and functions
- Fast and accurate
- "Standard" Fortran - works on many platforms (g77 support dropped though)
- Flexible
- Version control (subversion) for precise version tagging

Current version: 5.1.1
darksusy.org

Program layout



Compile and install

- To compile and install DarkSUSY, do

  ```
  ./configure [optional arguments]
  make
  ```

- Works on most platforms and with most compilers (gfortran, ifort, ...)

Manual

- A manual (not fully up-to date yet and doesn't cover everything) is distributed with DarkSUSY, create with

  make pdf-manual (to make the default manual)

  make pdf-manual-short to make a short version (without subroutine headers).

- Also see the headers of various subroutines for instructions.

[Show manual]

SUSY setup

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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

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

and the soft supersymmetry-breaking potential

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

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

How to choose parameters

- 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
- Currently they have to be real (but not necessarily diagonal)

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Supersymmetric models

- Input parameters at EW scale (MSSM), or
- Input parameters at GUT scale (mSUGRA/CMSSM)
- Higgs sector with FeynHiggs
- Higgs decay widths from literature or from FeynHiggs
- mSUGRA interfaces: ISASUGRA, and other codes via SLHA2 (e.g. softsusy).
- SUSY Les Houches Accord 2 implemented (both read and write)

Routines

- dsgive_model: sets an MSSM-7 model
- dsgive_model13: sets an MSSM-13 model
- dsgive_model_isasugra: sets an mSUGRA model

- There are also routines in misc/wimpexample.f to setup a generic WIMP model (i.e. not SUSY)

Typical program

call dsinit

[make general settings]

[determine your model parameters your way]

call dsgive_model [or equivalent]

call dssusy [or equivalent]- to set up DarkSUSY for that model

[then calculate what you want]

See dsmain.f, dstest.f and dstest-isasugra.f in test/

*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 dshmset('default') chooses the default halo model (NFW)
- All these *set routines are called with the argument 'default' by dsinit, but can be changed later by the user.

Accelerator constraints

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Direct accelerator searches

- Squarks
- Sleptons
- Neutralinos
- Charginos
- Higgs bosons

From PDG (Squarks, Sleptons, Neutralinos, Charginos)

From HiggsBounds (Higgs bosons)

Higher order corrections

- Rare decays, $b \to s \gamma$, ...
- Magnetic moment of the muon, a_μ
- Invisible width of Z boson

Currently from literature, other tools (SuperIso etc) via SLHA2
SuperIso interfaced with DarkSUSY but not yet in the public release

General checks

- Accelerator constraints are most easily checked with a call to

  call dsacbnd(excl)

- excl is non-zero if excluded and the set bits of excl tells why it is excluded.
- For backwards-compatibility, we keep old versions of the accelerator constraints as well, but dsacbnd always points to the latest set of constraints.
- It takes some time for new constraints (or signals!) to make it into the code though.

Meaning of excl

From header of dsacbnd9.f:

```
c      bit set   dec.   oct.   reason
c      -------   ----   ----   ------
c            0      1      1   chargino mass
c            1      2      2   gluino mass
c            2      4      4   squark mass
c            3      8     10   slepton mass
c            4     16     20   invisible z width
c            5     32     40   higgs mass
c            6     64    100   neutralino mass
c            7    128    200   b -> s gamma
c            8    256    400   rho parameter
c            9    512   1000   (g-2)_mu
```

Likelihoods

- We are working on going away from hard cuts to likelihoods when possible
- For example, in DarkSUSY 5.1 we include IceCube likelihoods
- To do this, we need publicly available data and background estimates/simulations

Relic density

DarkSUSY implementation

- We solve the Boltzmann equation,

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

numerically, calculating the thermally averaged annihilation cross section,

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

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

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

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Relic density routines

- The main routine for SUSY neutralinos is dsrdomega that calculates the relic density of neutralinos
- However, the relic density routines are more general than that and can be used for any WIMP with a call to dsrdens.

How to call dsrdens for general WIMPs

Call

dsrdens(wrate,npart,mgev,dof,nrs,rm,rw,nt,tm,oh2,tf,ierr,iwar)

where you have to supply

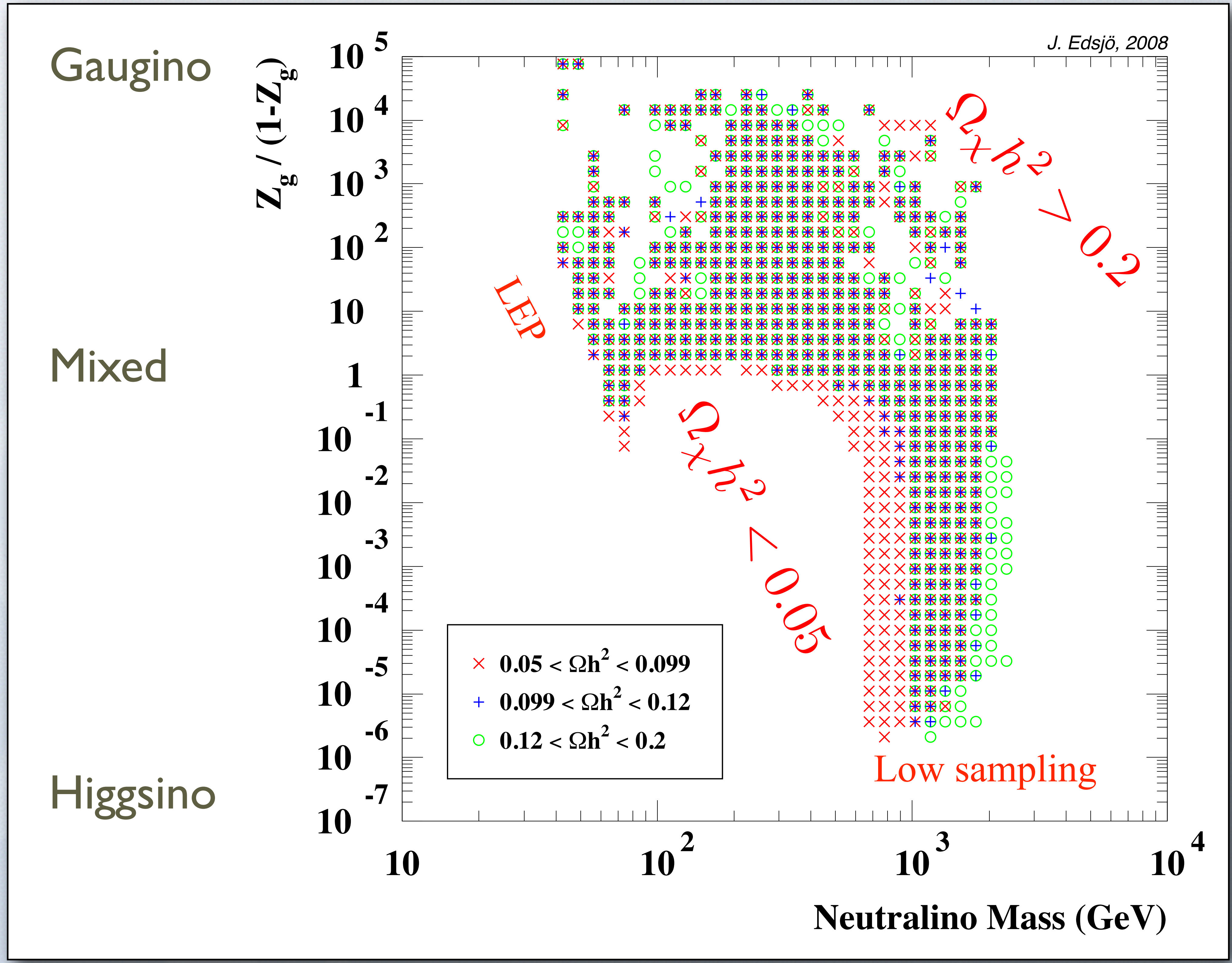
- wrate - invariant effective annihilation rate (function)
- npart - number of coannihilating particles
- mgev - mass of these
- dof - internal degrees of freedom of these
- nrs - number of resonances
- rm - mass of resonances
- rw - width of resonances
- nt - number of thresholds
- tm - equivalent mass of thresholds

The routine then returns

- oh2 - omega h^2
- tf - freeze-out temperature

Note: All this is taken care of for neutralinos in dsrdomega

The $m_\chi - Z_g$ parameter space



Direct detection

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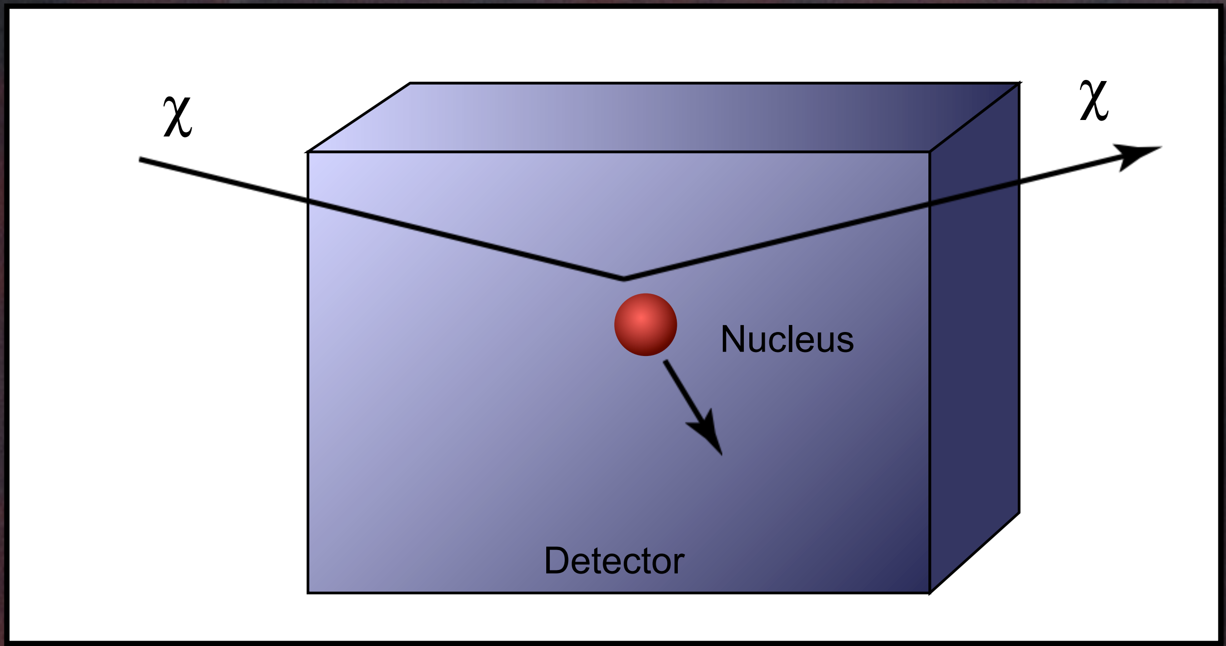
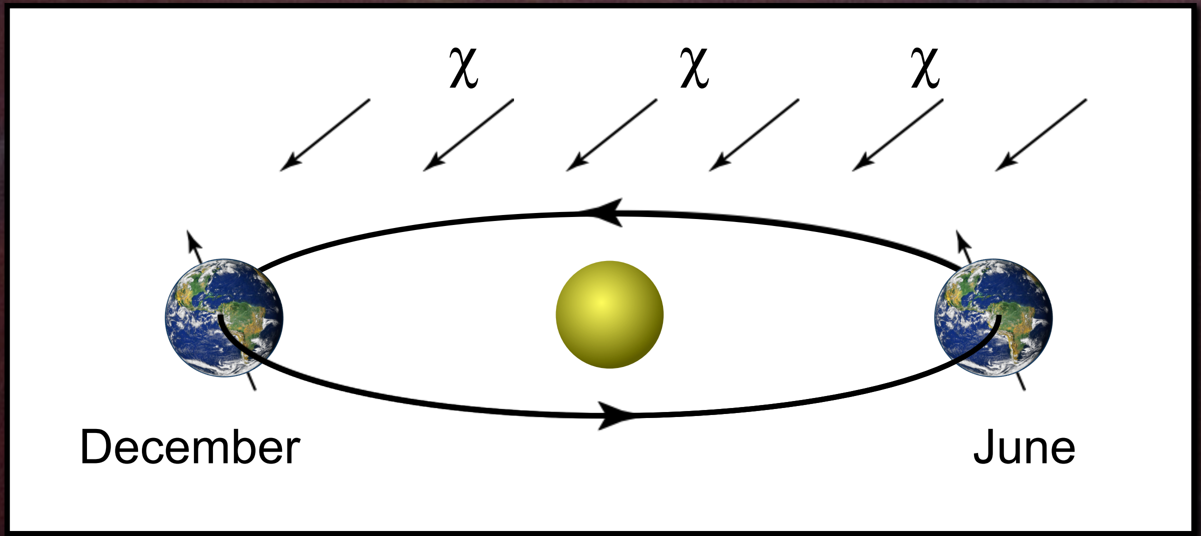
Direct detection

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.
- Halo model and velocity distribution can be chosen arbitrarily
- Annual modulation signal can be calculated
- Different sets of form factors available

Direct detection routines

- **dsddneunuc:** calculates the spin-independent and spin-dependent scattering cross sections on neutrons and protons.
- **dsdddrde:** calculates the differential scattering rate on various targets as a function of time (can be used to predict annual modulation signals e.g.)

Indirect detection

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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 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 (10 GeV – 10 TeV)
- Higgs bosons are let to decay in flight summing up the yields from the decay products

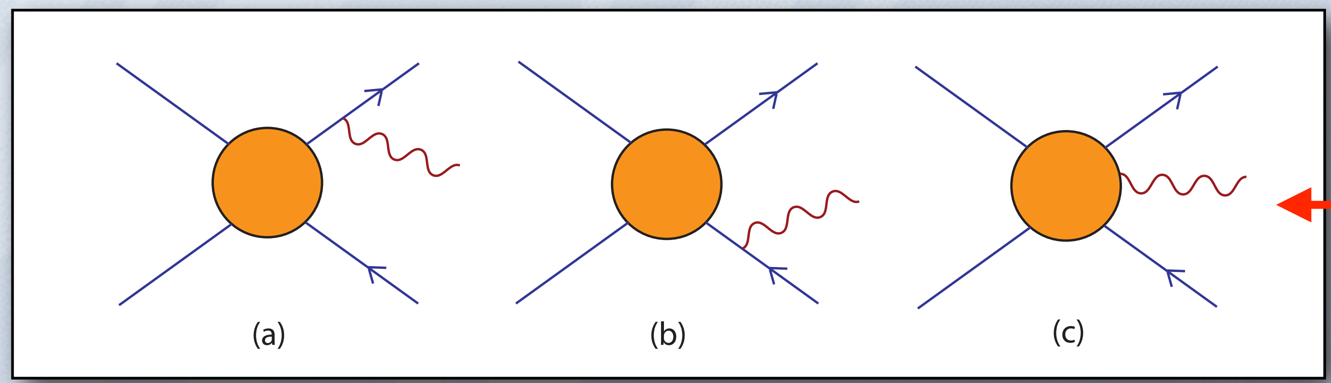
Indirect rates

- Gamma rays from the halo
- Antiprotons from the halo
- Antideuterium from the halo
- Positrons from the halo
- Neutrinos from the Sun/Earth

Continuous gamma rays

- DarkSUSY includes generic WIMP routines to calculate gamma yields from WIMP annihilations
  - Based on Pythia simulations for WIMP masses between 10 GeV and 10 TeV
  - Internal Bremsstrahlung added separately

Works for any WIMP



Virtual internal bremsstrahlung is model dependent!
(need to know details, like the propagating particle)

Gamma ray fluxes from the halo

We can write the flux as

$$\Phi_\gamma(\eta, \Delta\Omega) = 9.35 \cdot 10^{-14} S \times \langle J(\eta, \Delta\Omega) \rangle \ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$$

with

$$S = N_\gamma \frac{\langle \sigma v \rangle}{10^{-29}\ \mathrm{cm}^3\ \mathrm{s}^{-1}} \left(\frac{100\ \mathrm{GeV}}{m_\chi} \right)^2$$

Particle physics (SUSY, ...)

Focus now on this factor!

$$\langle J(\eta, \Delta\Omega) \rangle = \frac{1}{8.5\ \mathrm{kpc}} \frac{1}{\Delta\Omega} \int_{\Delta\Omega} \int_{\mathrm{line\ of\ sight}} \left(\frac{\rho(l)}{0.3\ \mathrm{GeV/cm}^3} \right)^2 dl(\eta) d\Omega$$

Astrophysics

Halo profiles

- A common spherically symmetric parameterization is

$$\rho(r) = \frac{\rho_s}{(r/a)^\gamma[1+(r/a)^\alpha]^{(\beta-\gamma)/\alpha}}$$

with e.g.

Profile	α	β	γ
NFW	1	3	1
Isothermal	2	2	0

- In principle, any distribution function (like a data file) can be used.
- DarkSUSY can calculate the J-factor for different directions in the sky

Halo profiles

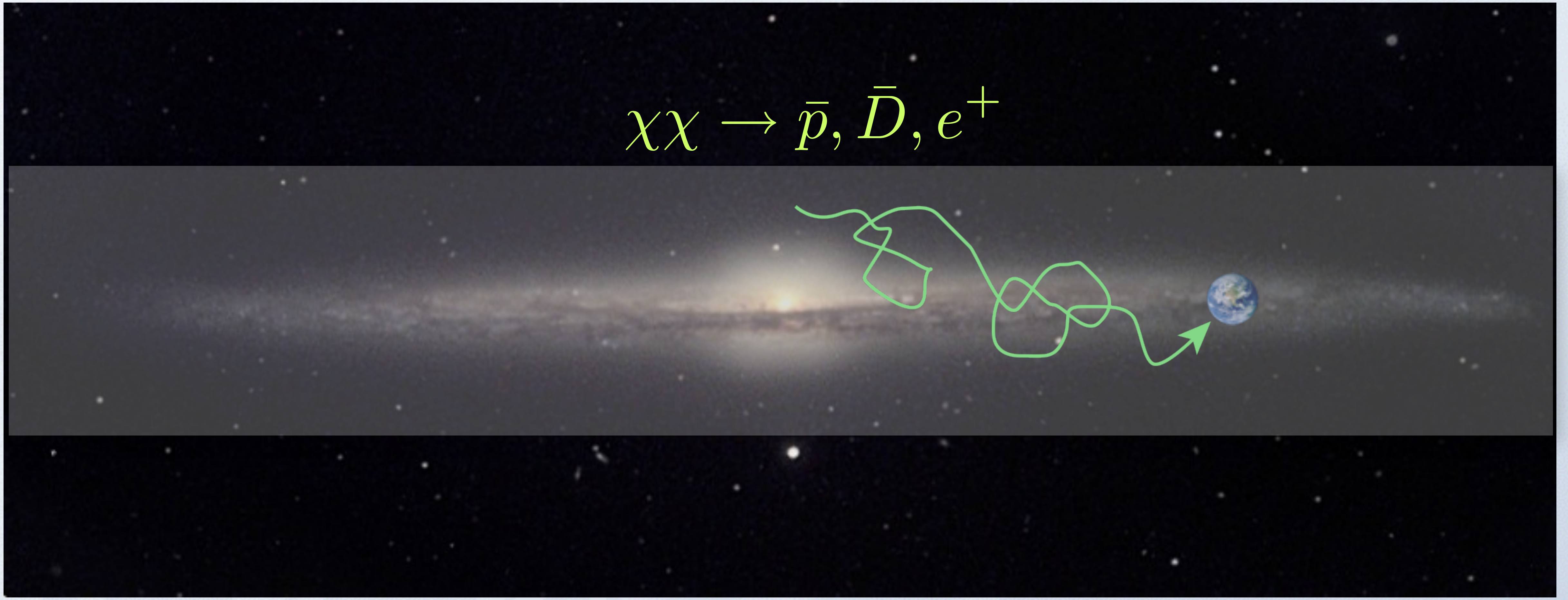
- Any spherically symmetric profile can be entered into DarkSUSY. Presets are available for
  - NFW
  - Moore
  - Burkert
  - Einasto
  - Adiabatically contracted profiles
  - Isothermal sphere
- In principle, a corresponding velocity distribution should be set simultaneously and DarkSUSY is set up to do this.
- Halo profiles are set with dshmset('name')

See Maurin's talk and the code CLUMPY

Indirect rates

- Gamma rays from the halo
- Antiprotons from the halo
- Antideuterium from the halo
- Positrons from the halo
- Neutrinos from the Sun/Earth

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)
- Reacceleration can change the energy of the particles (can partly be mimicked by a break in the diffusion coefficient)

Diffusion model solving

- Either one solves the diffusion equation analytically (requires some simplifying assumptions), or
- One solves it numerically, with all possible effects included.

Analytical solution

- Simplified axial symmetry (typically)
- Sometimes infinite radial extent of the diffusion zone
- Simplifying assumptions on reacceleration (diffusion in momentum space) and energy losses

\+ Fast

\+ Can give better understanding of what is going on

Numerical solutions

+ Can include all possible effects, different form of the diffusion coefficient, energy losses etc
+ Can include full 3D galaxy
+ "Easy" to include complementary signals, Inverse Compton gammas, synchrotron etc
- Slow

In both the analytical and numerical solutions, for a given halo model and propagation model, one can solve for the Green's functions once and for all, and just get the energy at Earth via a simple integral

$$\frac{d\Phi}{dE} \propto \int_0^{m_\chi} G(E') \frac{dN}{dE'} dE'$$

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Propagation

- There are at least 2–3 public codes:
  - Galprop (numerical)
  - USINE (semi-analytical), first release 2014?
  - Dragon (numerical)
- All of which should have interfaces to DarkSUSY and other signal codes. Rudimentary galprop interface in place. Usine interface in next DarkSUSY version (if Usine public by then)?

Routines in DarkSUSY

- Analytical expressions to calculate fluxes of
  - antiprotons
  - antideuterons
  - positrons
- Also, an interface to use Galprop (for experts only). More and better interfaces to come (Usine when made public).
- Typically, we produce many antiprotons and some antideuterons compared to background (antideutrons show a clearer signal at low energy). Positron signal usually smaller, but with more features.

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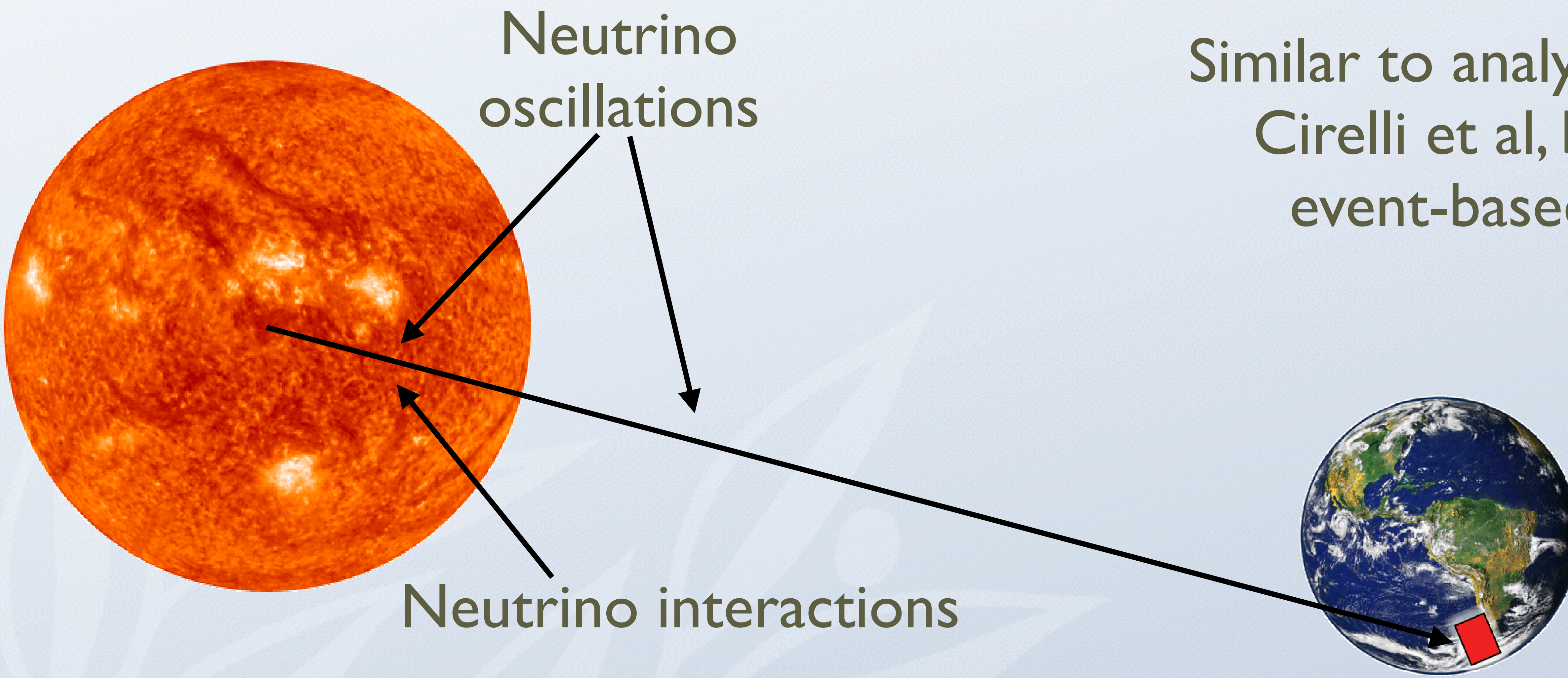
Indirect rates

- Gamma rays from the halo
- Antiprotons from the halo
- Antideuterium from the halo
- Positrons from the halo
- **Neutrinos from the Sun/Earth**

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

Neutrino oscillations



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

- New 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.fysik.su.se/~edsjo/wimpsim
- Main results are included in DarkSUSY as tables.

Neutrinos from Sun/Earth

- Rate of neutrino-induced muons in neutrino telescopes
- Neutrino scattering and absorption in Sun included
- Fully numerical capture calculation with any velocity distribution
- Neutrino oscillations, all flavours and hadronic showers

In the pipeline

- Include more refined solar models and form factors and allow for numerical solution for any form factor (not just Gaussian)
- Implement new solar system diffusion results (Sivertsson & Edsjö), even if free-space approximation works quite well for now

Question time

Discuss with your neighboring student(s) for two minutes!

Q Imagine you want to calculate neutrino fluxes from the Sun and Earth and compare with direct detection and gamma fluxes from the galaxy. What do you need to specify regarding the dark matter halo?

A We need
1) the *density profile* of dark matter, note the different spatial dependencies
2) the *velocity distribution*, note the different velocity dependencies for rates
3) the density profile and the velocity distribution need to be consistent

Reference / outlook

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Reference / download

- DarkSUSY 5.1.1 is available at

www.darksusy.org

- Long paper, describing DarkSUSY available as JCAP 06 (2004) 004 [astro-ph/0406204]
- Manual (pdf and html) available

WimpSim
for WIMP annihilations
in the Sun/Earth also
available.

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

DarkSUSY: computing supersymmetric dark-matter properties numerically

P Gondolo[1], J Edsjö[2], P Ullio[3], L Bergström[2], M Schelke[2] and E A Baltz[4]

DarkSUSY Homepage

http://www.darksusy.org/

Overview

Download

Register

Documentation

Logos

DarkSUSY online

Internal pages (password restricted)

DarkSUSY Home Page

Welcome to DarkSUSY's home on the web!

DarkSUSY is a fortran package for supersymmetric dark matter calculations. It is written by Paolo Gondolo, Joakim Edsjö, Lars Bergström, Piero Ullio, Mia Schelke, Ted Baltz, Torsten Bringmann and Gintaras Duda. On these pages you will find information about DarkSUSY and you can also download the package.

If you use DarkSUSY, please refer to the following publication describing DarkSUSY:

> **P. Gondolo, J. Edsjö, P. Ullio, L. Bergström, M. Schelke and E.A. Baltz,**
> **JCAP 07 (2004) 008** [astro-ph/0406204]

Please also cite this web page as

> **P. Gondolo, J. Edsjö, P. Ullio, L. Bergström, M. Schelke, E.A. Baltz, T. Bringmann and G. Duda,**
> **http://www.darksusy.org.**

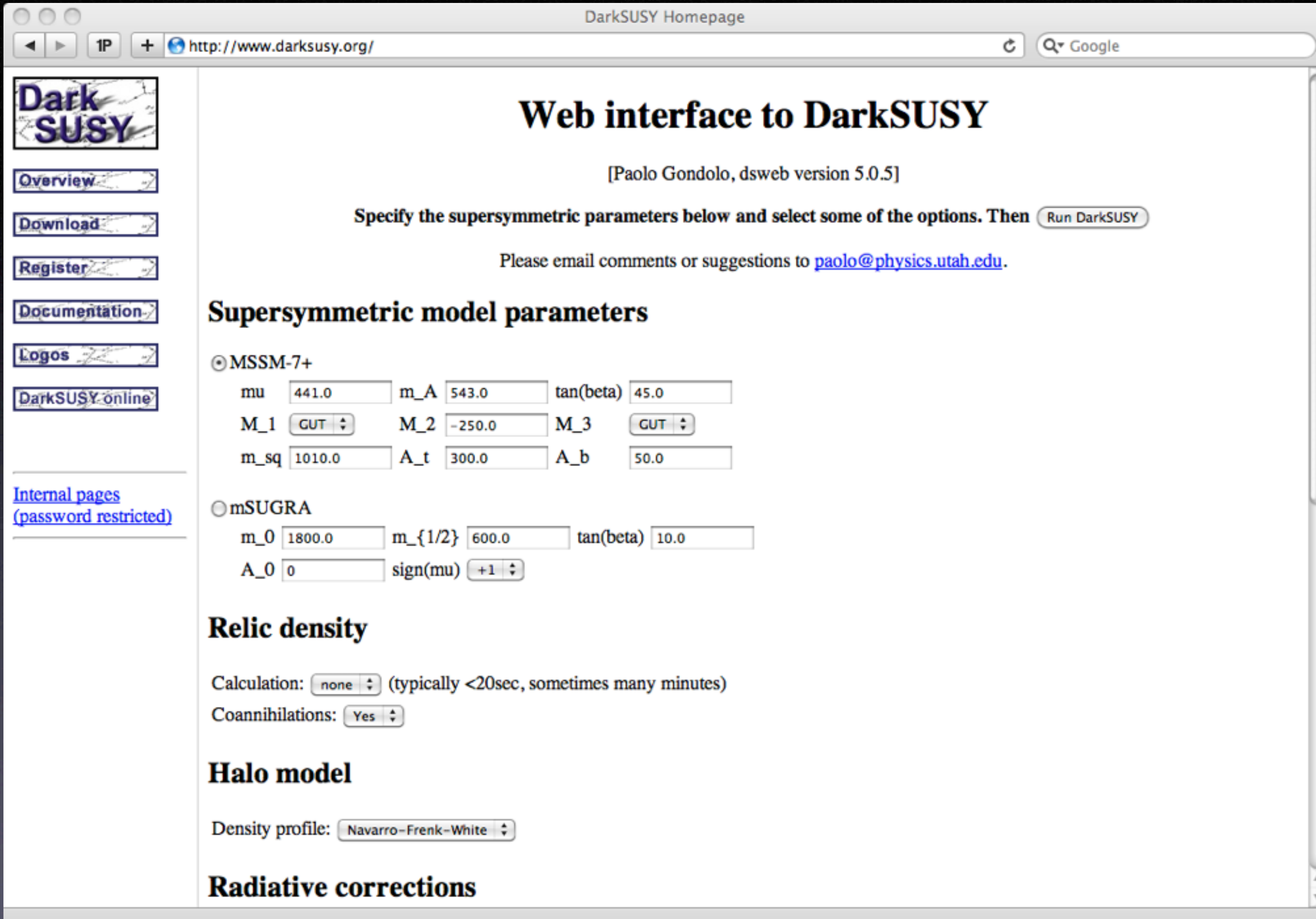
Note. You should also refer to the original physics work on which DarkSUSY is based and which DarkSUSY uses. Most notably, DarkSUSY is interfaced (and uses) the following codes:

- FeynHiggs - for Higgs masses and widths
- HiggsBounds - for Higgs boson constraints from accelerators
- ISAJET/ISASUGRA -for mSUGRA/CMSSM RGE running
- SLHALIB - for reading/writing SLHA2 files

and can (for the experienced user) be configured to run with

- Galprop - for cosmic ray propagation (not used by default).

Current version *New!*


DarkSUSY Homepage
http://www.darksusy.org/
Google
Dark SUSY
Overview
Download
Register
Documentation
Logos
DarkSUSY online
Internal pages (password restricted)
Web interface to DarkSUSY
[Paolo Gondolo, dsweb version 5.0.5]
Specify the supersymmetric parameters below and select some of the options. Then
Run DarkSUSY
Please email comments or suggestions to paolo@physics.utah.edu.
Supersymmetric model parameters
MSSM-7+
mu 441.0
m_A 543.0
tan(beta) 45.0
M_1 GUT
M_2 -250.0
M_3 GUT
m_sq 1010.0
A_t 300.0
A_b 50.0
mSUGRA
m_0 1800.0
m_{1/2} 600.0
tan(beta) 10.0
A_0 0
sign(mu) +1
Relic density
Calculation: none (typically <20sec, sometimes many minutes)
Coannihilations: Yes
Halo model
Density profile: Navarro-Frenk-White
Radiative corrections

Future: what is needed?

- We have been aiming at consistency in calculations, both regarding astrophysics and particle physics.
- Need even more of this and more interfaces to specialized codes,
  e.g. CharginoBounds, SusyBSG,
  SDecay, Galprop, Usine,
  Dragon, ...
- Make it easier to add other than regular SUSY models (BMSSM, IDM already done, but is currently done 'by hand')
- Beyond tree-level, e.g. DM@NLO (see Karol Kovarik's talk)

DarkSUSY 6

- Major update (later this year)
  - restructuring of code (even more modular)
  - New refined halo annihilation and neutrino routines
  - better solar models
  - Interface to Usine (?), Dragon
  - Maybe also DLHA = Dark matter Les Houches Accord

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Conclusions

- Many DM codes on the market
- Interfacing between different codes very much simplified with SLHA and the coming DMLHA file formats
- When comparing different signals, it is crucial to perform these calculations in a consistent framework, with e.g. a tool like DarkSUSY
- Need publicly available data!

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