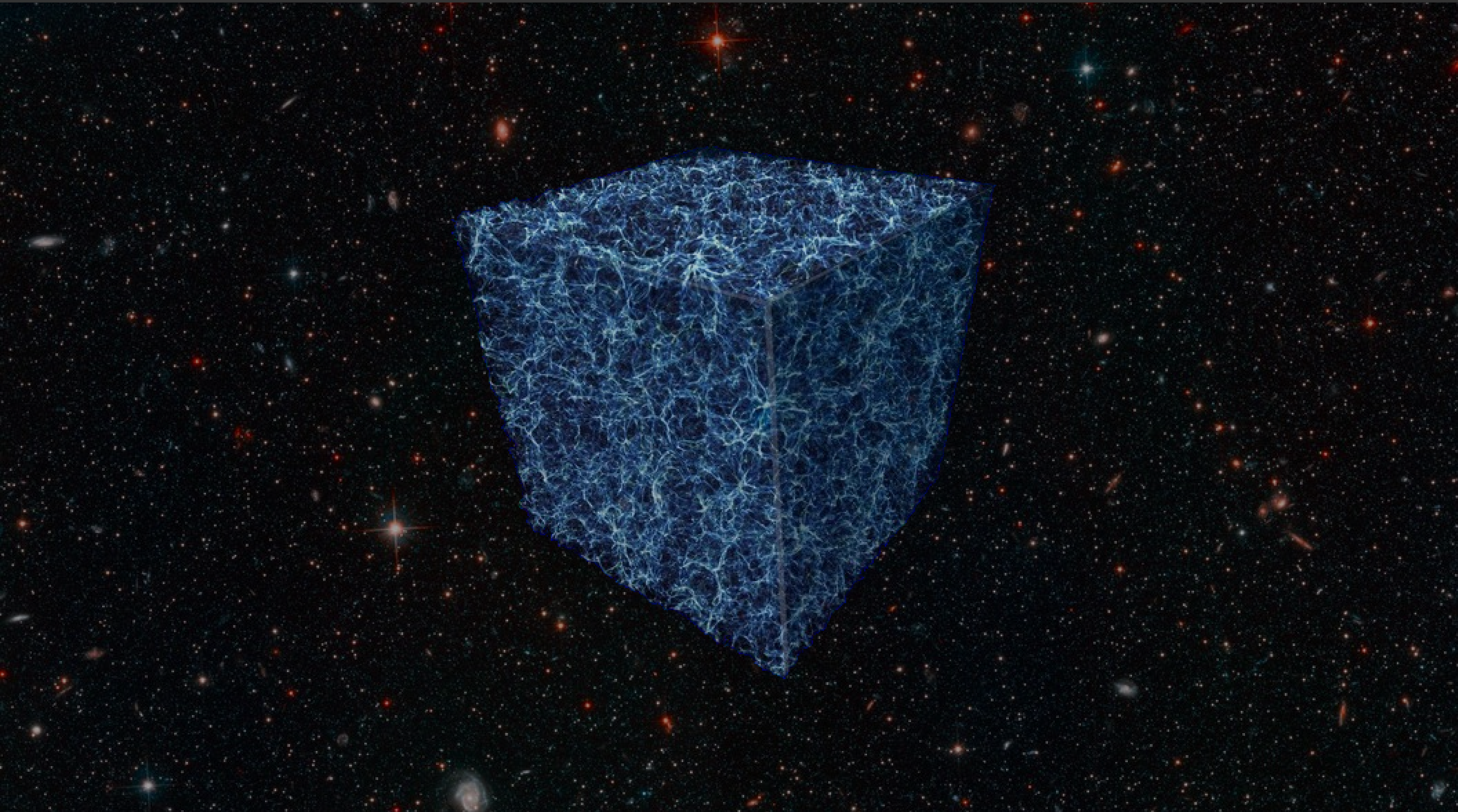
Update on Singlet DM with GAMBIT



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For the GAMBIT collaboration

TeVPA, Tokyo, 29 Oct 2015

GRAPPA

GRavitation AstroParticle Physics Amsterdam

NWO

GAMBIT in a nutshell

Global and **M**odular **B**SM **I**nference **T**ool

(see earlier talk by ***Pat Scott*** for more details)

The situation

- We have a massive amount of data (LHC, EWPT, Flavor, DM searches, ...)
- There are *many* theoretical ideas for BSM physics (MSSM, NMSSM, extended Higgs sectors, effective field theories, axions, axion-like particles, sterile neutrinos, ...)

The problem

- How confront a maximal number of BSM scenarios with the most accurate data in an efficient way?
- How to avoid reinventing the wheel over and over again (coding up the same likelihood functions, models, etc, instead of reusing codes)?

Our solution: GAMBIT

- Most accurate and massively parallelized likelihood functions
- Fast scanning algorithms
- Modular, extensible, can be used for many models

Dark matter observables with *DarkBit*

"DarkBit" is the GAMBIT unit that is responsible for all DM-related calculations.

Design principles

- Wherever possible, we use functionality of existing codes (DarkSUSY, micrOMEGAs), which are imported as backends
- Where needed, we implement
  - Our own new backends (e.g. Fermi LAT, XENON/LUX, IceCube)
  - GAMBIT native code (e.g. cascade annihilations)
  - Patches to improve backend functionality (e.g. DS SLHA reader, parallelized RD calculation)

Powered by:

DarkSUSY

micrOMEGAs

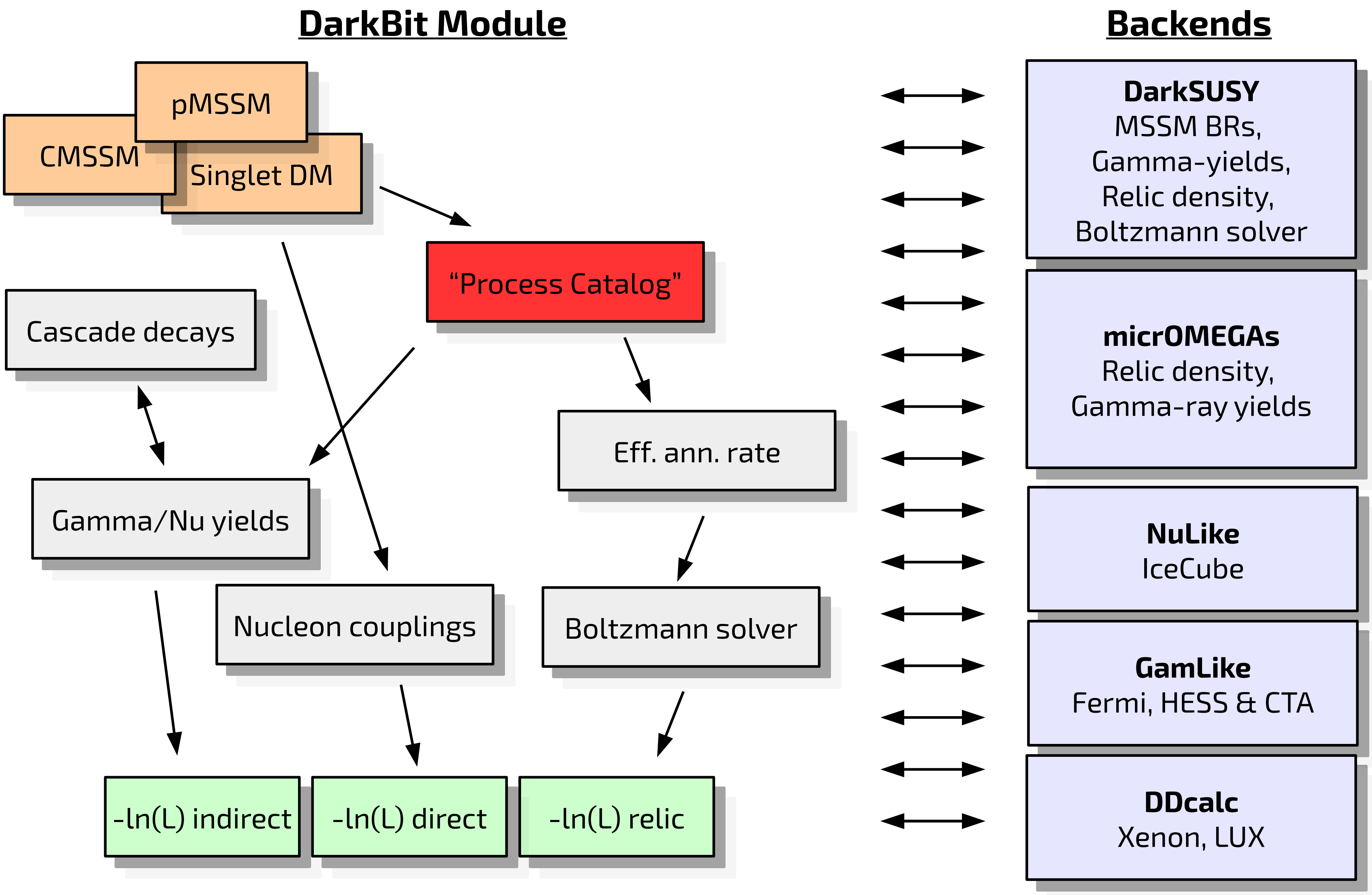
PPPC4DMID

Group members

Torsten Bringmann, Jan Conrad, Jonathan Cornell, Lars Dal, Joakim Edsjö, Antje Putze, Chris Savage, Pat Scott, Christoph Weniger, Martin White

(GAMBIT in total: about 30 members)

DarkBit – An (incomplete) overview

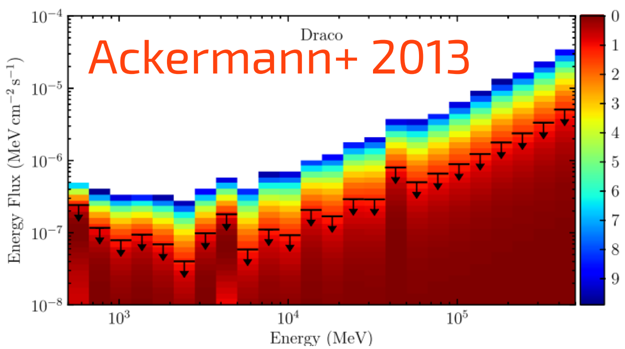


Gamma-ray likelihoods with *gamLike*

GamLike provides the most common gamma-ray likelihoods with a unified interface.

Limits from dwarf spheroidal galaxies

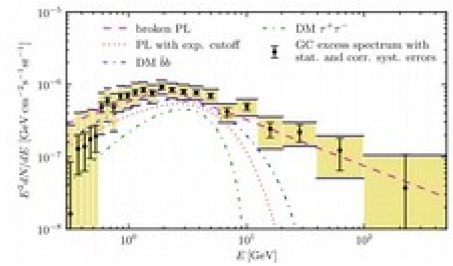
- Fermi LAT results available as tabulated likelihoods



$$\mathcal{L}(\langle\sigma v\rangle, m_\chi, dN/dE, \vec{J}) = \mathcal{L}(\vec{\phi}, \vec{J})$$

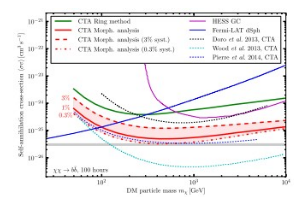
$$\phi_i = \frac{\langle\sigma v\rangle}{m_\chi^2} \int_{\Delta E_i} dE' \, \frac{dN}{dE_i}$$

- Internal correct treatment of J-value uncertainties by marginalization or profiling
- Likelihood for 15 dwarf spheroidal galaxies (pass 7 & pass 8)



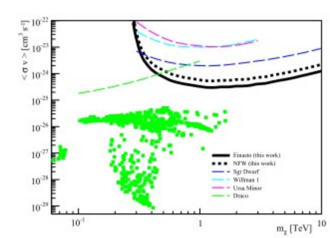
Galactic center likelihood (Galactic center excess only)

- Based on Calore+ 2014 results, includes correlated systematic errors, assuming all bulge emission is DM signal:



$$-2 \ln \mathcal{L} = \sum_{ij} (\phi_i - f_i) \Sigma_{ij}^{-1} (\phi_j - f_j)$$

- Assuming that *all* emission from Galactic bulge comes from DM annihilation



Also: CTA projected limits, HESS Galactic halo limits

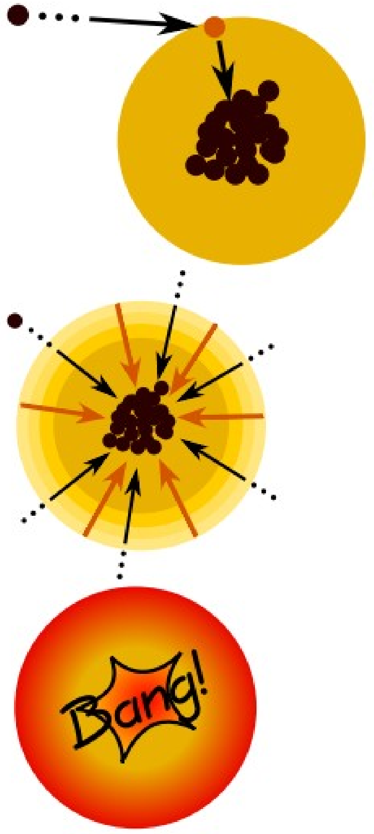
IceCube likelihoods with *nuLike*

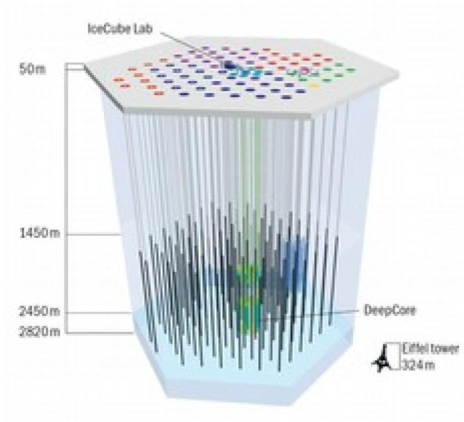
Main features

- Event-level unbinned likelihood functions for IceCube-79 and projected IceCube-86 results for Sun observations (in cooperation with IceCube collaboration)

$$\mathcal{L}_{\text{unbin}} = \mathcal{L}_{\text{num}}(n_{\text{tot}}|\theta_{\text{tot}}) \prod_{i=1}^{n_{\text{tot}}} (f_S \mathcal{L}_{S,i} + f_{BG} \mathcal{L}_{BG,i})$$

- Strategy: Precompute partial likelihoods for each event, then reweight according to nu spectrum at Earth
- Fully exploits spectral and directional information
- Fast and efficient, thanks to tabulated responses
- Neutrino yields at Earth can be calculated with DarkSUSY, or any other backend if desired
  → Fully model independent!

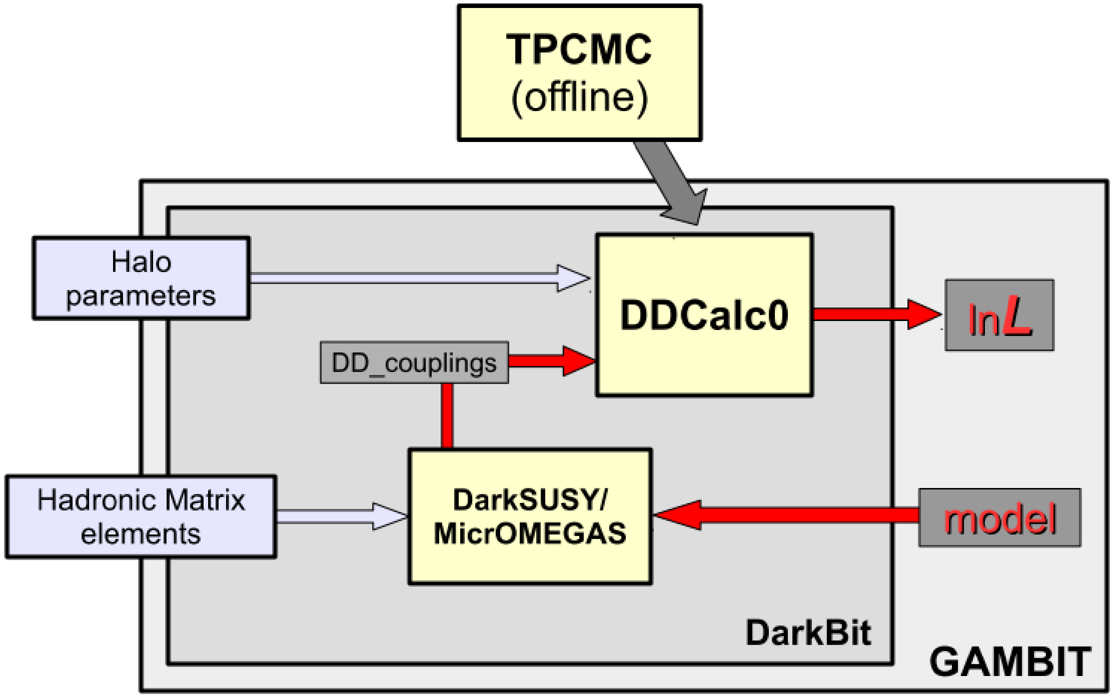




Direct detection likelihoods with *DDcalc*

Overview

- Accurate direct detection likelihoods for the most relevant experiments
- To be released as command line tool and with GAMBIT interface
- Implemented up to now:
- XENON 100 2012, LUX 2013, SuperCDMS 2014, SIMPLE 2014
  and more to come (e.g. Darwin-Xe and Darwin-Ar)
- Within GAMBIT, consistent treatment of hadronic couplings, quark masses and halo parameters as nuisance parameters



Relic density

Model

Process Catalog

DarkSUSY

Effective annihilation rate

$$W_{ij} = 4p_{ij}\sqrt{s}\sigma_{ij} = 4\sigma_{ij}\sqrt{(p_i \cdot p_j)^2 - m_i^2 m_j^2} = 4E_iE_j\sigma_{ij}v_{ij}$$

$$W_{\rm eff} = \sum_{ij} \frac{p_{ij}}{p_{11}} \frac{g_i g_j}{g_1^2} W_{ij}$$

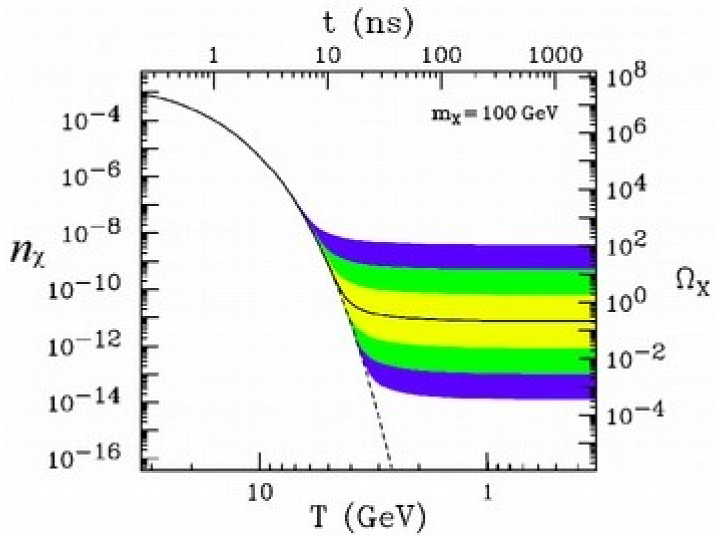
Boltzmann solver
(DarkSUSY)

Planck Likelihood

micrOMEGAs

Overview

- Effective annihilation yields can be obtained directly from backends or derived from process catalog
- Boltzmann solver comes from DarkSUSY (but can be replaced by anything else)



The simplest DM model

A real scalar field, coupled to the SM via the Higgs portal, is arguably the most simple WIMP dark matter model on the market.

Silveira & Zee 1985; McDonald 1994; Burgess+ 2001; Cline+ 2013; ...

The model

- Simple Lagrangian (assuming Z_2 symmetry for DM stability)

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}|\partial_\mu S|^2 + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\lambda_{hS}|H|^2 S^2$$

- Two free parameters:
  - DM mass

$$m_S = \sqrt{\mu_S^2 + \frac{1}{2}\lambda_{hs} v_0^2}$$

  - DM coupling strength λ_{hS}

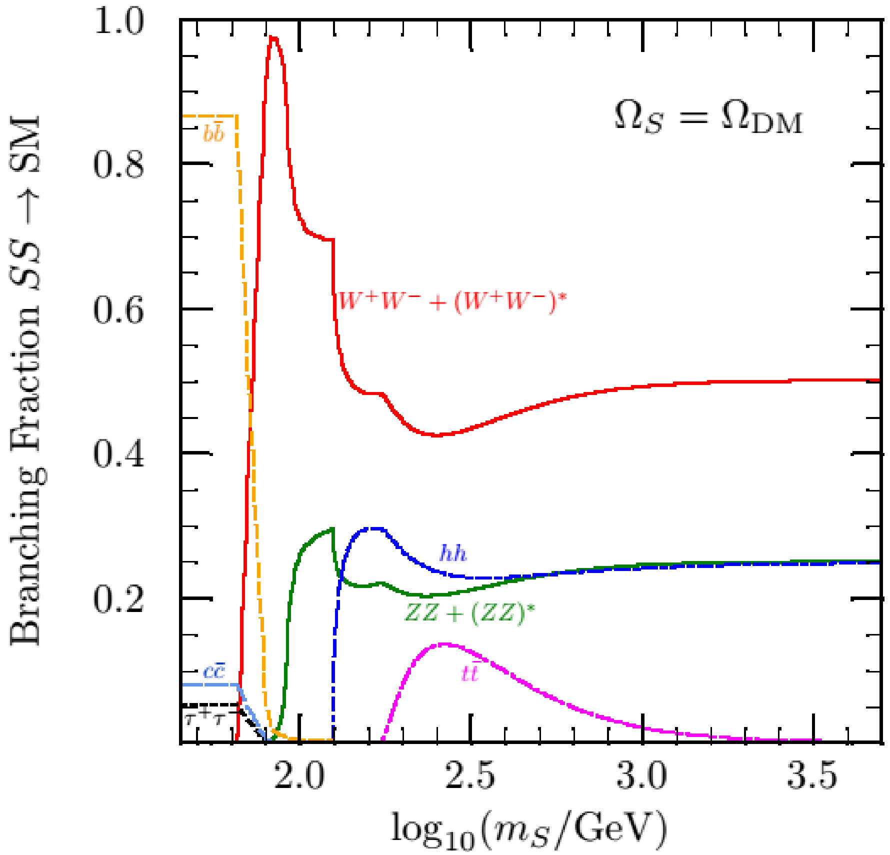
Signatures and experimental constraints

Scalar singlet dark matter features most of the typical WIMP indirect and direct signals, with only weak limits from LHC.

Signatures & Experiments:

- Annihilation into (mostly) W-boson and b-quark pairs ↔ Fermi LAT dwarf Spheroidal, HESS Galactic center
- Spin independent coupling to nuclei ↔ XENON-100 & LUX
- Higgs decay into scalar singlet, if kin. allowed ↔ Higgs inv. width
- Freeze-out relic density ↔ Planck CMB results

Cline+ 2013



Nuisance parameters

Often, the model parameters are accompanied by a much larger number of *nuisance parameters*, which need to be taken into account to obtain credible and robust results. Singlet dark matter is ideal to illustrate this.

Model parameters (2)

- Dark matter mass
- Higgs portal coupling

Nuisance parameters (>10)

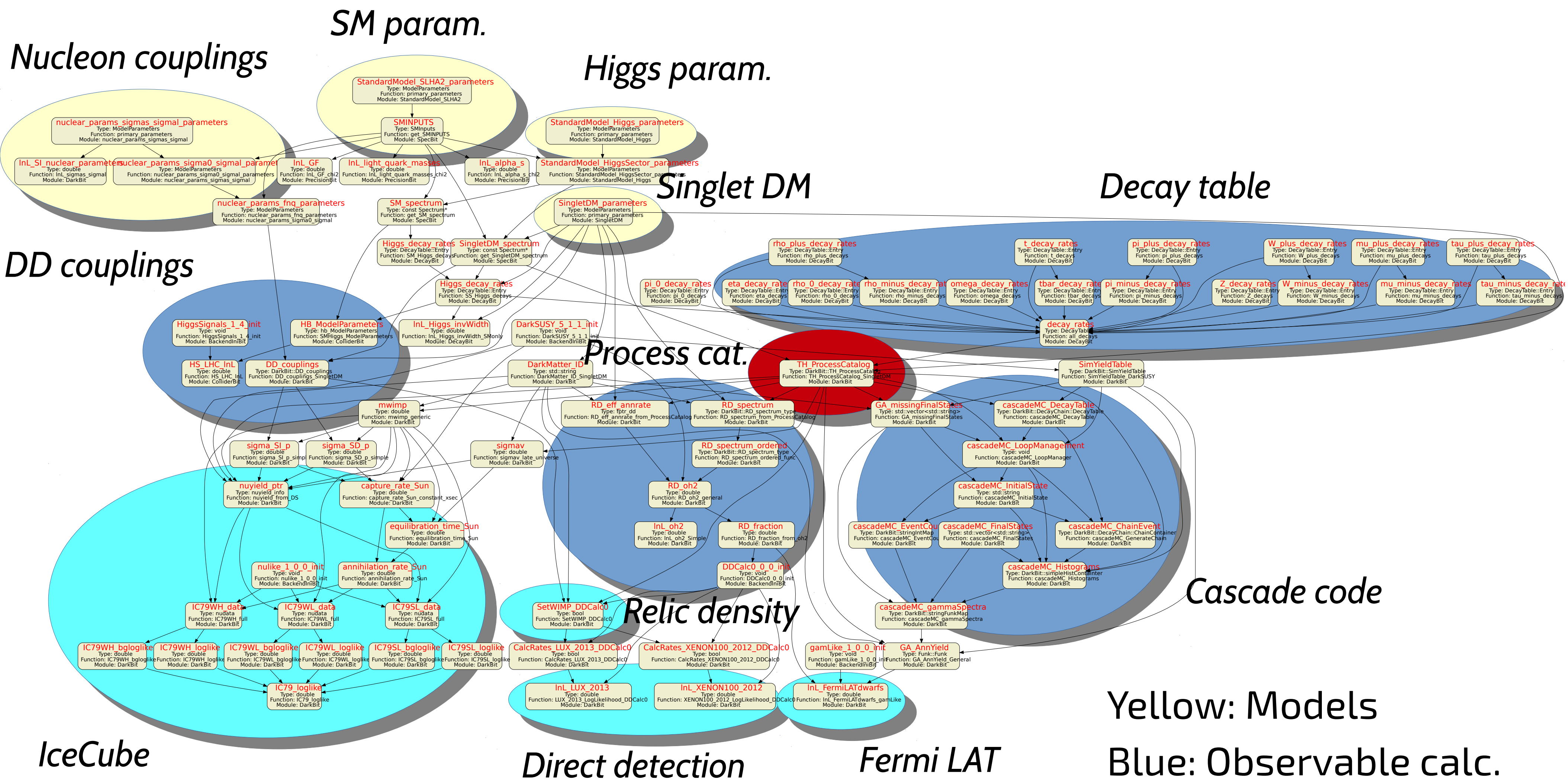
- Local DM density & velocity distribution
- Dark matter content in dSphs
- SM masses and couplings (Higgs mass, Fermi constant, masses and mass ratios of light quarks, ...)
- Hadronic matrix elements
- Instrumental sensitivities ...

Statistical treatment

- Profiling (Frequentist) $\mathcal{L}(\vec{\theta}) = \max_{\vec{n}} \mathcal{L}(\vec{\theta}, \vec{n})$
- Marginalization (Bayesian) $\mathcal{L}(\vec{\theta}) = \int d\vec{n}\, \mathcal{L}(\vec{\theta}, \vec{n}) P(\vec{n})$

Dependency resolution

Dependency tree of module functions, inferred by GAMBIT



Yellow: Models

Blue: Observable calc.

Red: Process Catalog

Green: Likelihoods

Global scans – Singlet DM

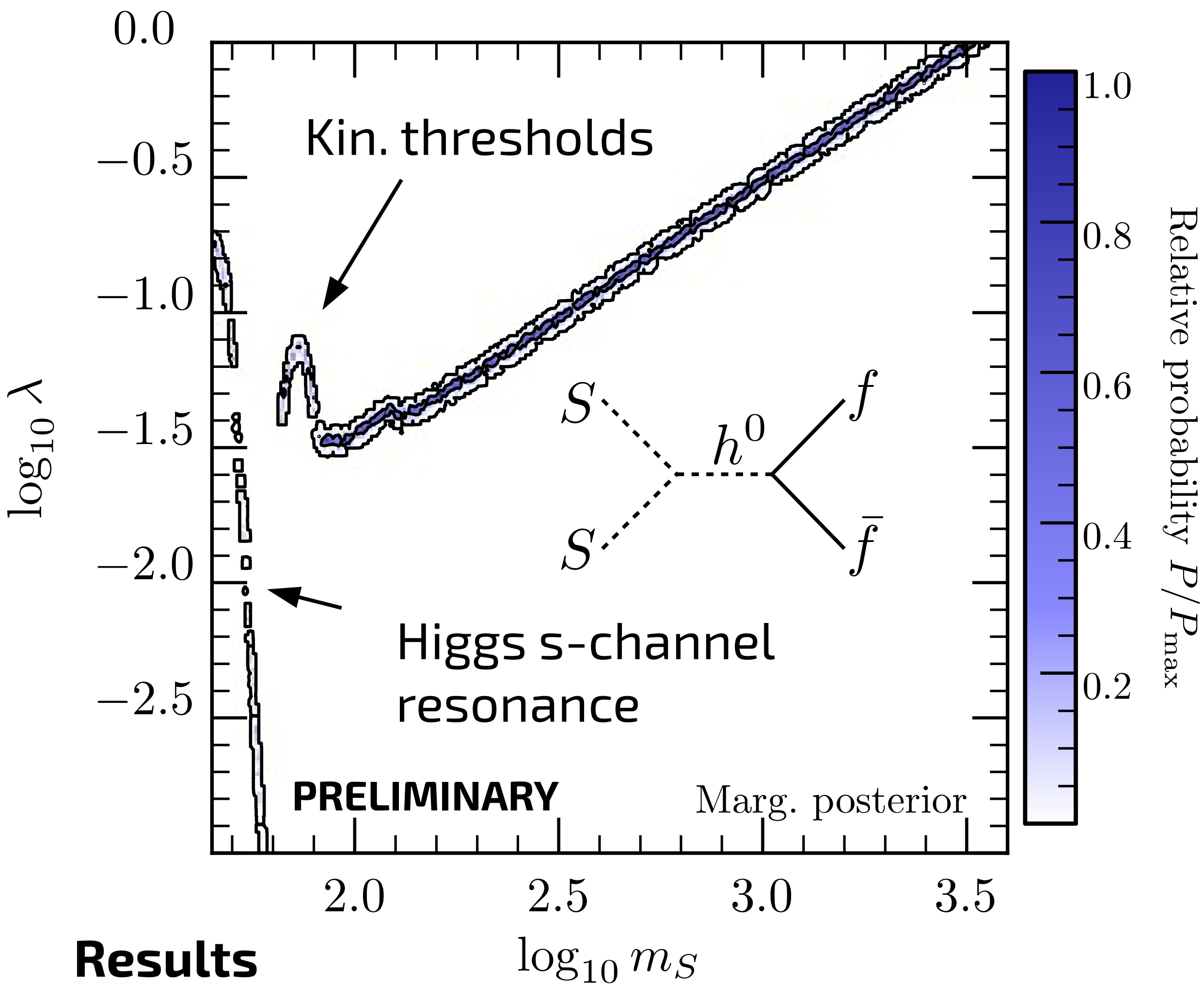
Free parameters (2)

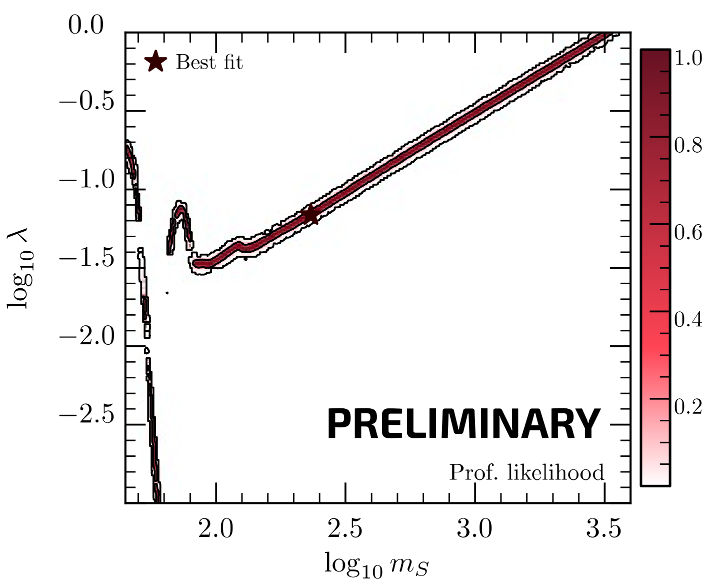
- DM mass and coupling

Likelihoods

- Relic density (DarkSUSY, Planck)

(scanner: MultiNest)





Results

- S-channel Higgs resonance clearly resolved
- Threshold effects for different annihilation channels
- Perfectly reproduces results from e.g. Cline+ 2013

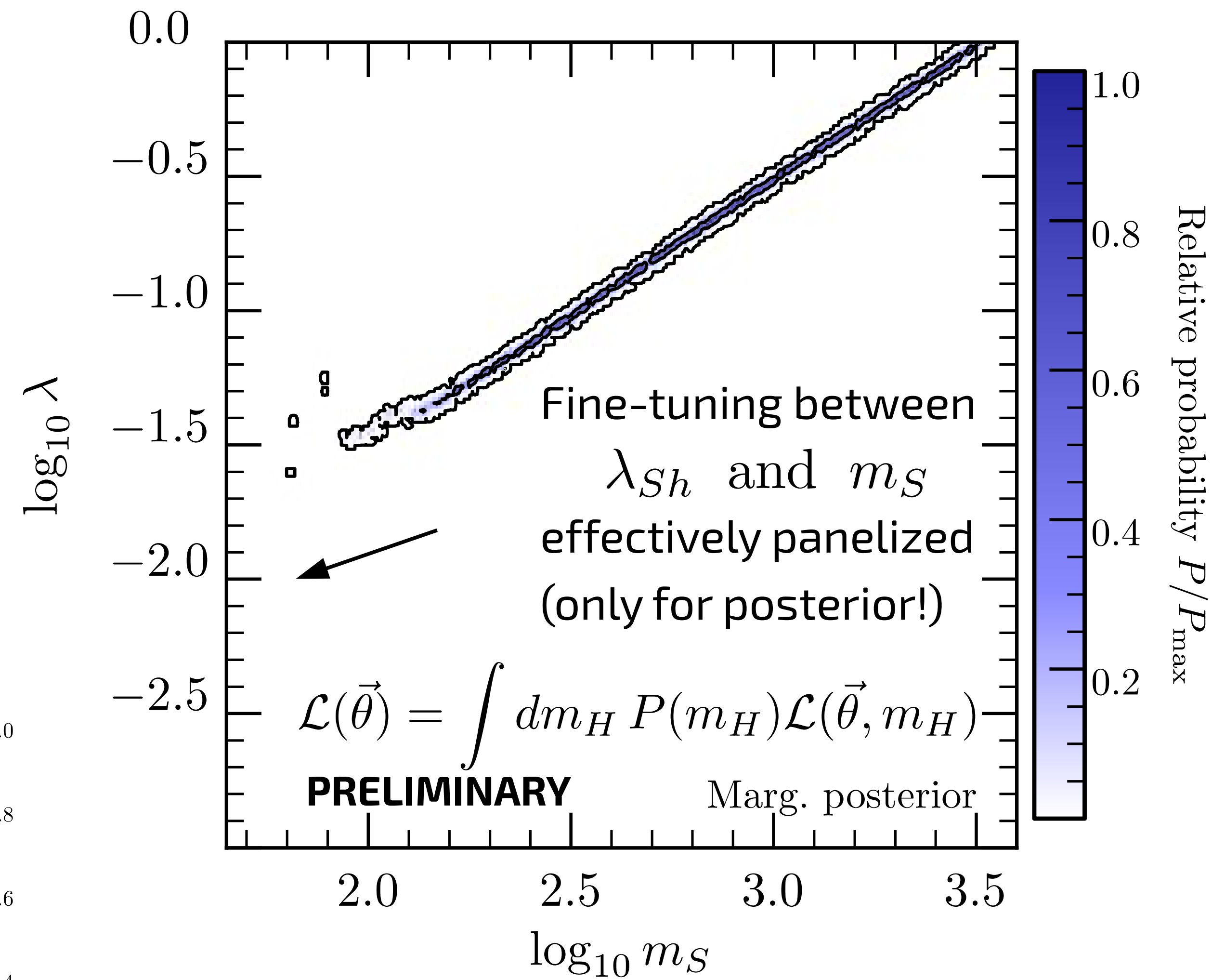
Global scans – Singlet DM

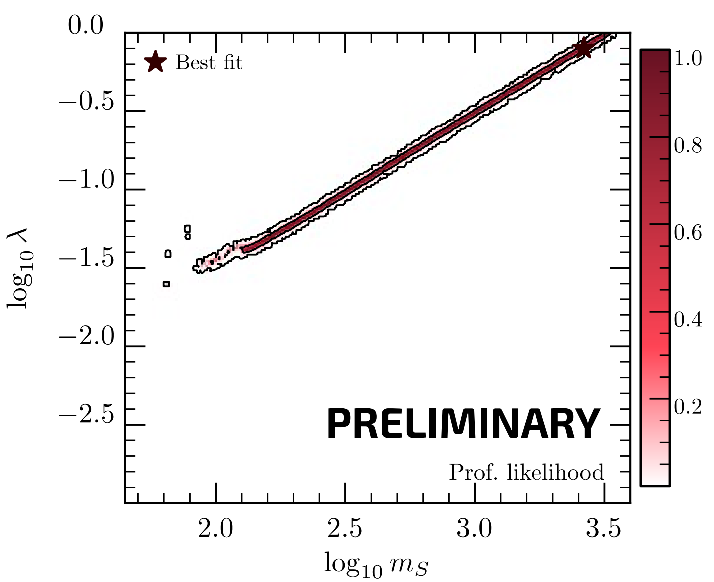
Free parameters (5)

- DM mass and coupling
- Higgs mass, strong and weak couplings

Likelihoods

- Relic density (DarkSUSY, Planck)





Marginalization over SM parameters (Higgs mass)

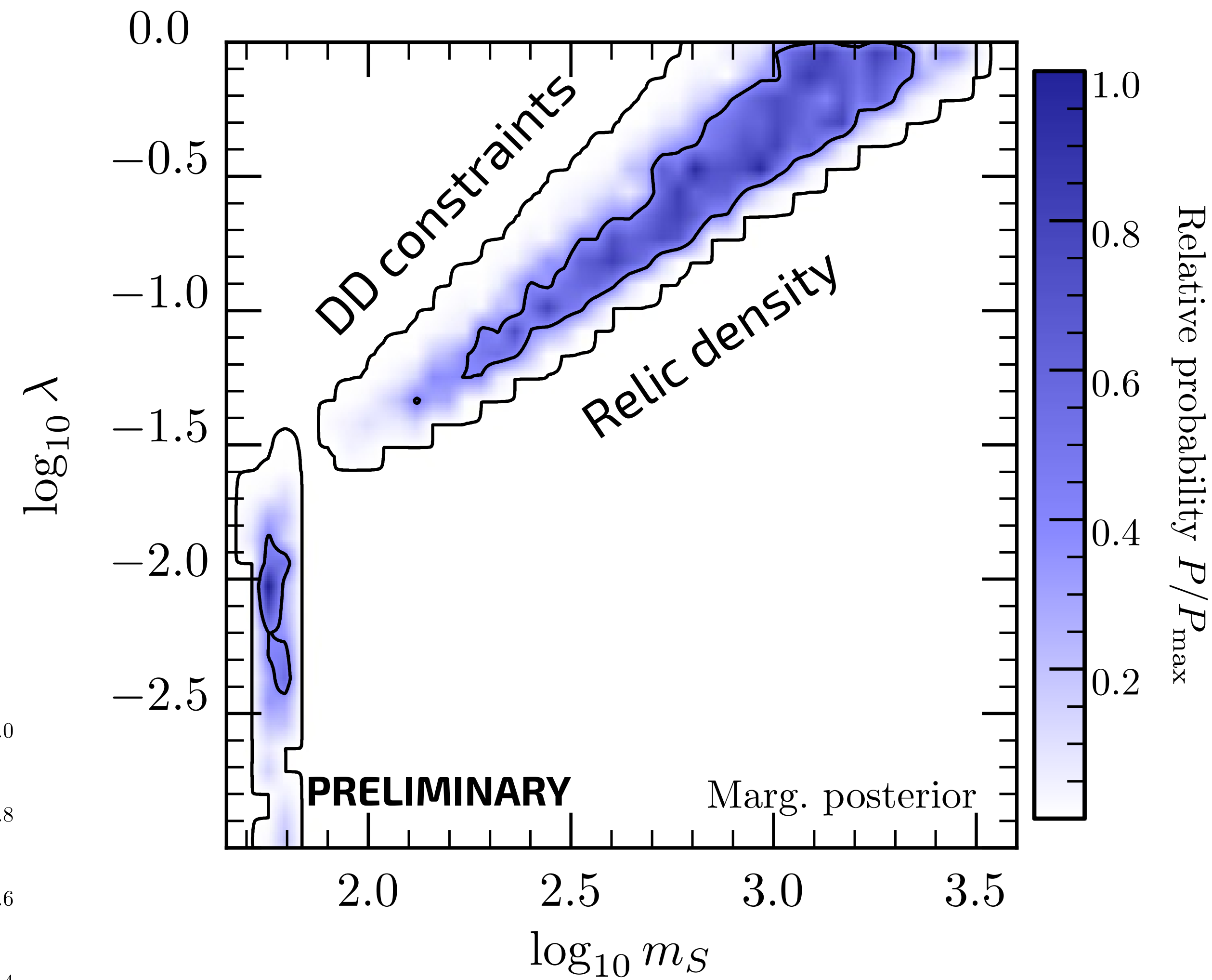
- Resonance region is smeared out
- Simple example for fine-tuning penalization by scan over Higgs mass

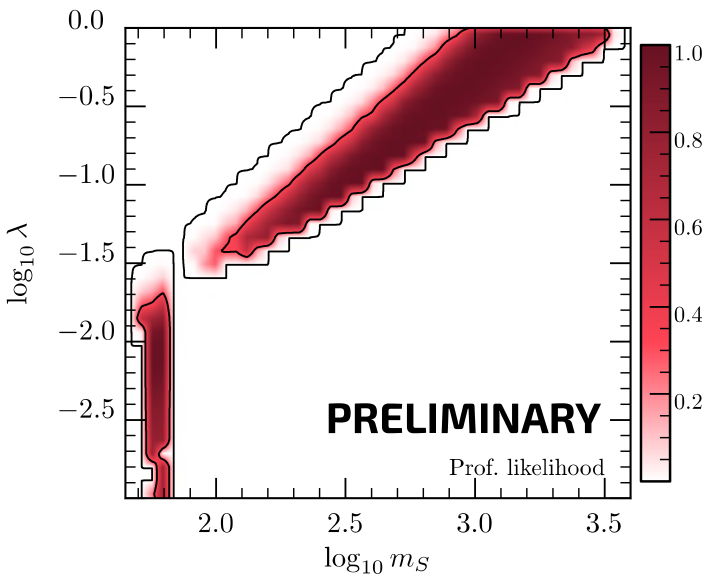
Free parameters (2)

- DM mass and coupling

Likelihoods

- Relic density (DarkSUSY, Planck) as upper limit
- XENON-100 & LUX 2013



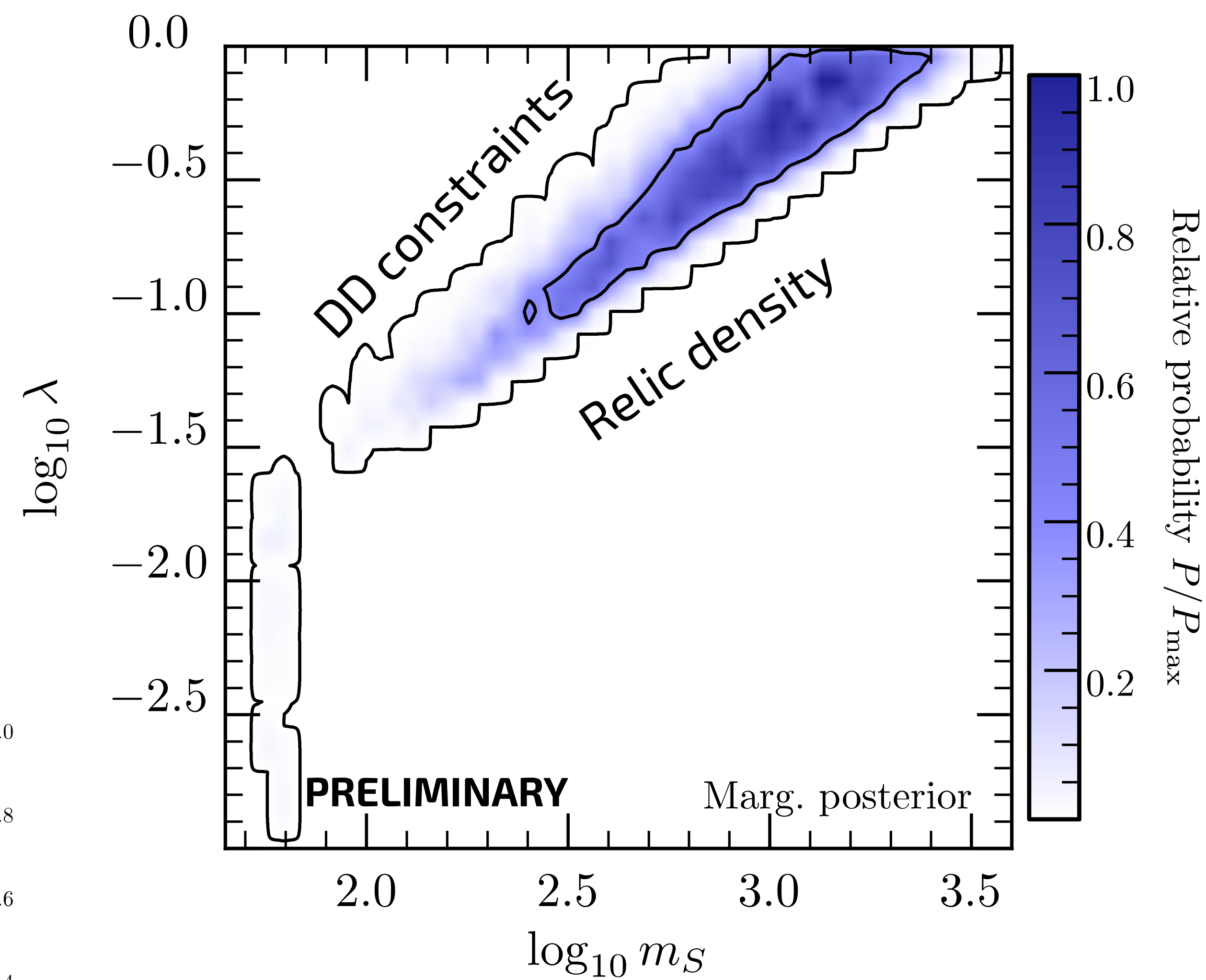


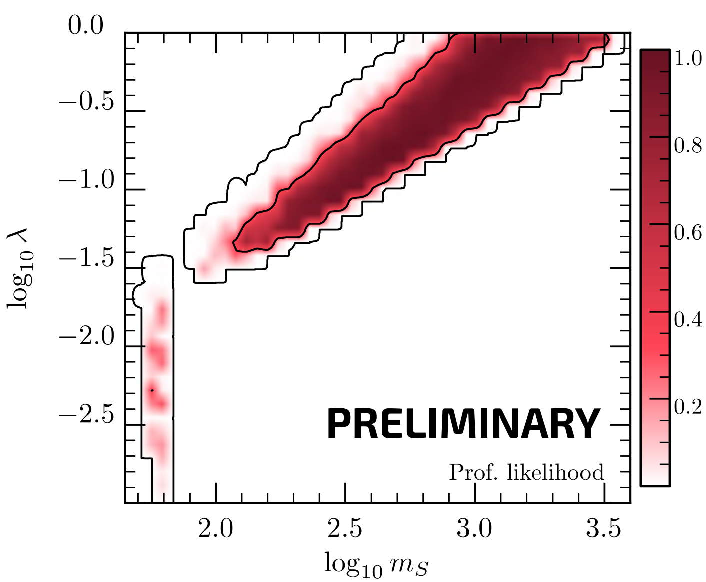
Note

- Using observed DM only as upper limit visualizes the impact of DD constraints on the full parameter space

Free parameters (7)
- DM mass and coupling
- Quark masses & ratios, nucleon couplings

Likelihoods
- Relic density (DarkSUSY, Planck) as upper limit
- XENON-100 & LUX 2013

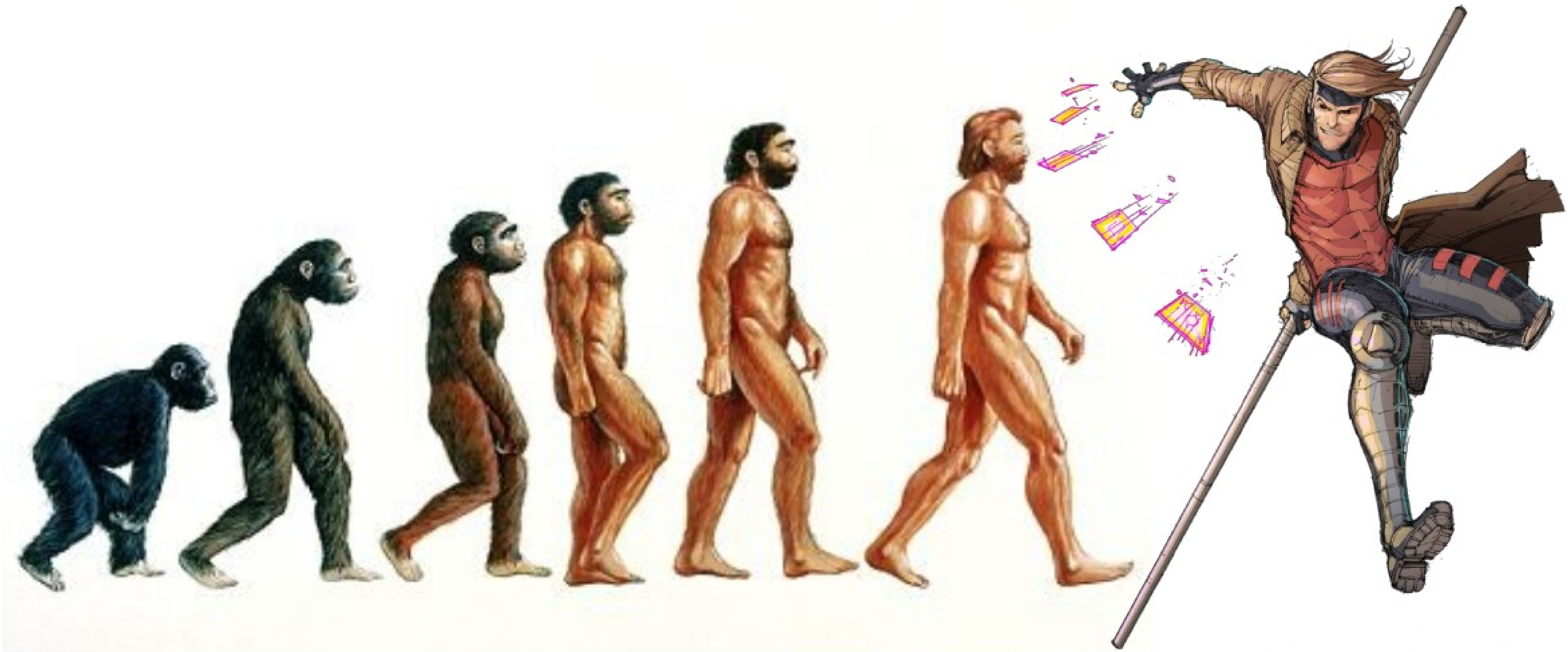




Results
- Marginalization over nuisance parameters can lead to weakening or strengthening of constraints, depending on the adopted parameters.

Conclusions

- DarkBit ships with numerous accurate likelihood functions
  - Direct detection (XENON 100, LUX)
  - Gamma rays (Fermi LAT, HESS, CTA)
  - Neutrinos (IceCube-79)
  - Relic density (Planck)
- General framework to calculate annihilation yields
  - New code for automated calculation of cascade decay spectra
- Model independent (currently implemented: various MSSM flavours, SingletDM)
- Backends to major codes in the field (DarkSUSY, micrOMEGAs)
- DarkBit allows marginalization over a large number of DM-related nuisance parameters – these *will* effect the results as demonstrated for the simple case of Singlet DM



is coming.

Thank you!