Update on Singlet DM with GAMBIT

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For the GAMBIT collaboration
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Global and Modular BSM Inference Tool
(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
“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)

**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

DarkBit Module

- pMSSM
- CMSSM
- Singlet DM
- Cascade decays
- Gamma/Nu yields
- Nucleon couplings
- Boltzmann solver
- Eff. ann. rate
- "Process Catalog"
- -ln(L) indirect
- -ln(L) direct
- -ln(L) relic

Backends

- DarkSUSY
  MSSM BRs,
  Gamma-yields,
  Relic density,
  Boltzmann solver
- micrOMEGAs
  Relic density,
  Gamma-ray yields
- NuLike
  IceCube
- GamLike
  Fermi, HESS & CTA
- DDcalc
  Xenon, LUX
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
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
Effective annihilation rate

\[ W_{ij} = 4p_{ij} \sqrt{s} \sigma_{ij} = 4\sigma_{ij} \sqrt{(p_i \cdot p_j)^2 - m_i^2 m_j^2} = 4E_i E_j \sigma_{ij} v_{ij} \]

\[ W_{\text{eff}} = \sum_{ij} \frac{p_{ij} g_i g_j}{p_{11} g_1^2} W_{ij} \]

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 $\lambda_{hS}$
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

\[ \Omega_S = \Omega_{DM} \]
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) \( \mathcal{L}(\hat{\theta}) = \max_{\hat{n}} \mathcal{L}(\hat{\theta}, \hat{n}) \)
- Marginalization (Bayesian) \( \mathcal{L}(\hat{\theta}) = \int d\hat{n} \mathcal{L}(\hat{\theta}, \hat{n}) P(\hat{n}) \)
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)

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**Marginalization over SM parameters (Higgs mass)**
- Resonance region is smeared out
- Simple example for fine-tuning penalization by scan over Higgs mass

\[
\mathcal{L}(\theta) = \int dm_H P(m_H) \mathcal{L}(\theta, m_H)
\]

**Fine-tuning between \( \lambda_{S_h} \) and \( m_S \)**
- effectively panelized (only for posterior!)

**PRELIMINARY**

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C. Weniger - GAMBIT Update on Singlet DM
Global scans - Singlet DM

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
Global scans – Singlet DM

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!