Ben Farmer
(on behalf of the
GAMBIT collaboration)

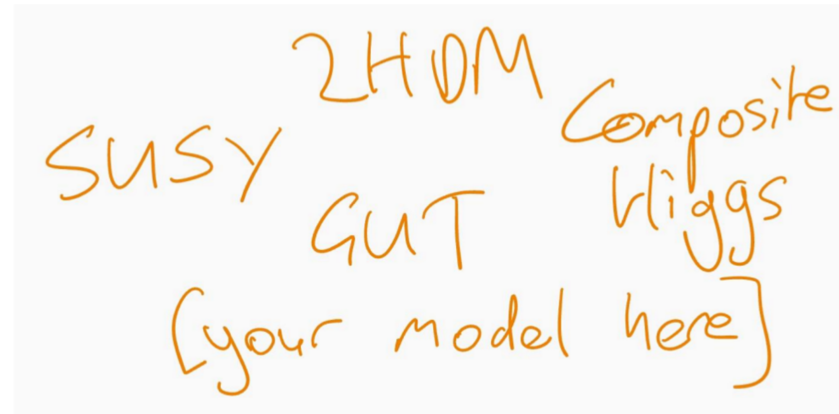
TeVPA 2016

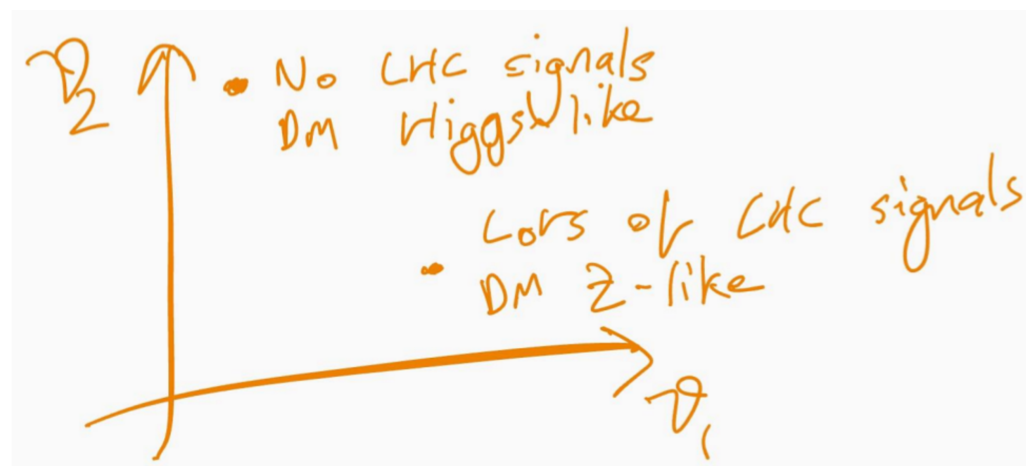
Overview

- **Why global fits?**
- **GAMBIT overview**
- **Simple examples**
- **A few fit results**
- **Summary**

Why global fits?

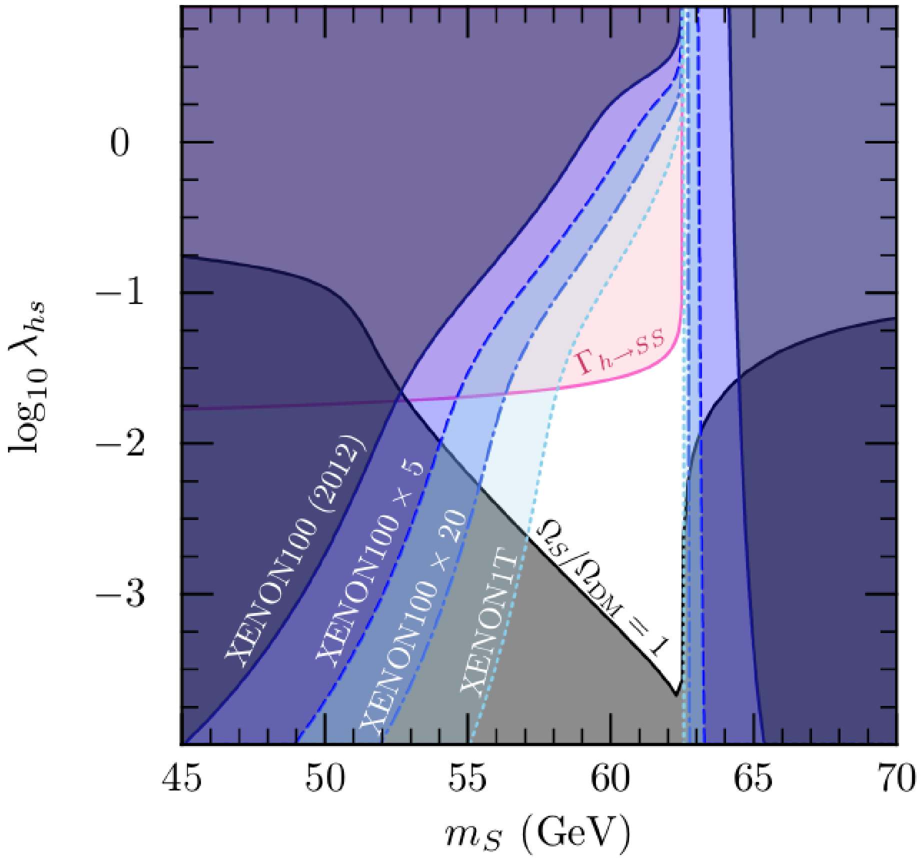
- Lots of theories of TeV scale physics
- For each theory, a parameter space of varying phenomenology
- What new physics scenarios are preferred / ruled out? - Compare to data!





Why global fits?

- In/out cuts based on 95% confidence limits are useful to get a quick heuristic picture.
- But representing the results from higher-dimensional scans can become tricky:
  - Count number of surviving points, projected onto some plane? (Strange pseudo-Bayesian approach; interpretation unclear)
  - “Profile” binned surviving points, or just project them on a plane? (Strange pseudo-frequentist approach; interpretation a bit clearer)
  - In either case can’t tell much more than that yes, some points survive all the cuts. But they may not have survived a more sophisticated treatment!



Cline, Kainulainen, Scott & Weniger, PRD, 1306.4710

- But ultimately, we want to make valid statistical inferences.
- To do this, we must perform full likelihood calculations, and sample parameter spaces in a statistically valid way.

But it is a hard problem

- **Even for a comprehensive in/out analysis, the problem is multi-faceted:**
  - Pick a model
  - Compute predictions for all physical observables of interest
  - Compare these predictions to experimental limits
    - Sometimes limits already exist directly on the relevant quantities for a model.
    - Usually need to recast limits
      - May involve numerically intensive simulations of specific experiments, e.g. simulating LHC collisions, neutrino events (IceCube), gamma ray events (Fermi-LAT), WIMP-nucleon scattering.
      - **Limits often dependent on background model assumptions (e.g. dark matter halo models, cosmology, simplified model assumptions). Need to treat these assumptions *consistently* across likelihoods.**

But it is a hard problem

- **For full statistically valid global fit, even harder**
  - Need likelihood calculations for many experiments – can be numerically intensive
  - Need computations at many (millions - hundreds of millions) of model points, for moderately complex models (e.g. MSSM7-30)

A lot of effort just for one model family.

Organisation is essential

- **It requires a huge amount of manpower to prepare analyses of this kind even for one model class (e.g. MSSM).**

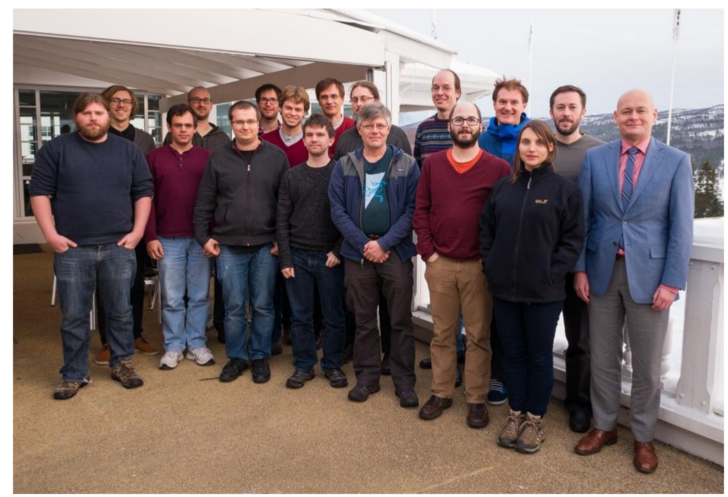
- **Need to reuse as many calculations and as much "book-keeping" code as possible.**

GAMBIT: The Global And Modular BSM Inference Tool

gambit.hepforge.org

- Fast definition of new datasets and theoretical models
- Plug and play scanning, physics and likelihood packages
- Extensive model database – not just SUSY
- Extensive observable/data libraries
- Many statistical and scanning options (Bayesian & frequentist)
- *Fast* LHC likelihood calculator
- Massively parallel
- Fully open-source

ATLAS	A. Buckley, P. Jackson, C. Rogan, M. White,
LHCb	M. Chrząszcz, N. Serra
Belle-II	F. Bernlochner, P. Jackson
Fermi-LAT	J. Conrad, J. Edsjö, G. Martinez, P. Scott
CTA	C. Balázs, T. Bringmann, J. Conrad, M. White
HESS	J. Conrad
IceCube	J. Edsjö, P. Scott
XENON/DARWIN	J. Conrad, R. Trotta
Theory	P. Athron, C. Balázs, T. Bringmann, J. Cornell, J. Edsjö, B. Farmer, T. Gonzalo, A. Fowlie, J. Harz, S. Hoof, F. Kahlhoefer, A. Krislock, A. Kvellestad, M. Pato, F.N. Mahmoudi, J. McKay, A. Raklev, R. Ruiz, P. Scott, R. Trotta, C. Weniger, M. White, S. Wild



31 Members, 9 Experiments, 4 major theory codes, 11 countries

Key GAMBIT design points

- Reuse calculations to the maximum theoretically permissible extent

- Graph-based dependency resolution for run-time “plug and play”
  - Keep calculations as modular as possible so that any piece can be easily “swapped out” for an alternate calculation.
  - Seamless integration of new calculations as they become available (minimise “hacking” of existing code).

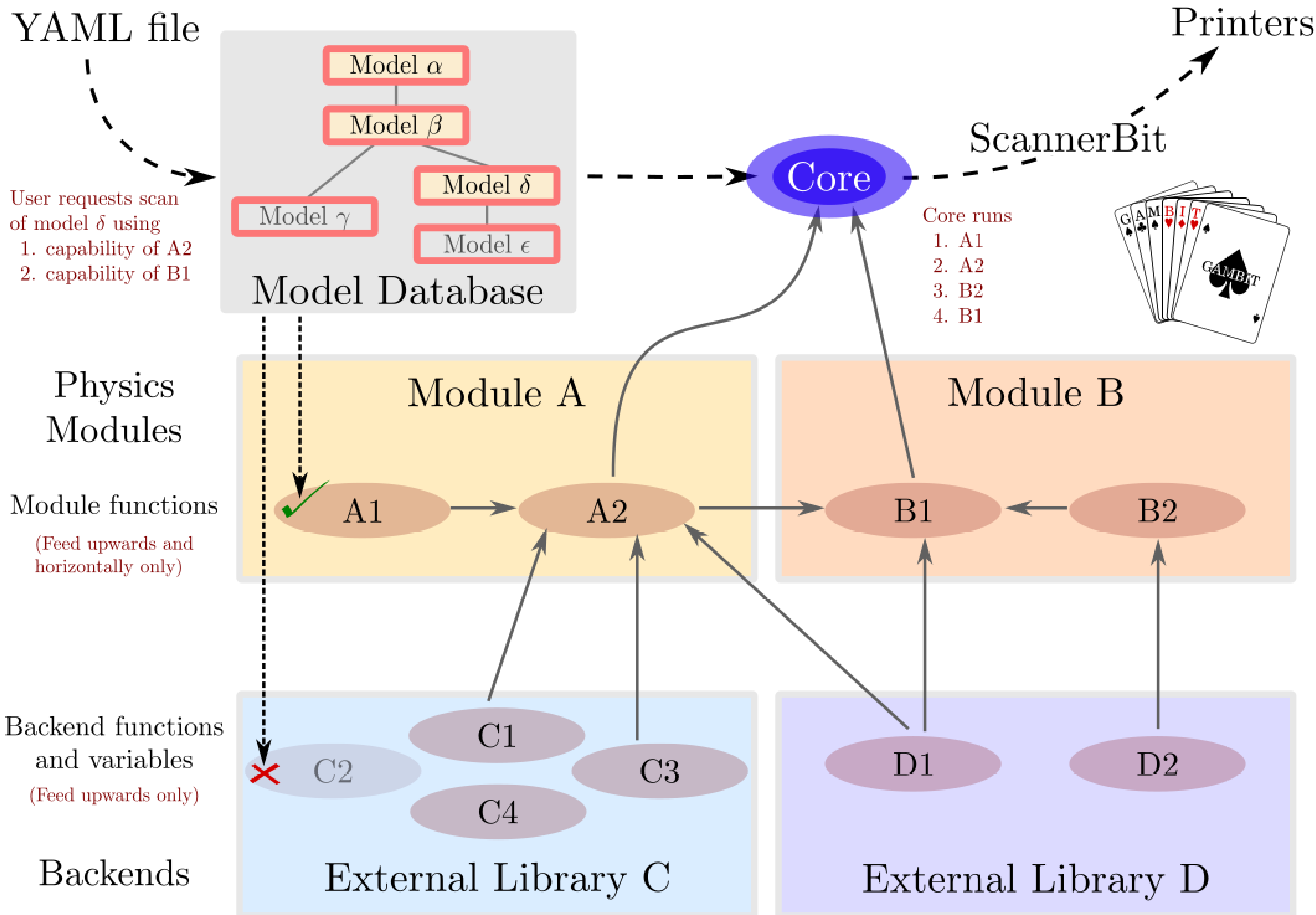
Modular structure

Physics modules

- DarkBit – dark matter observables (relic density, direct +indirect detection)
- ColliderBit – collider observables inc. Higgs + SUSY searches from ATLAS, CMS + LEP
- FlavBit – flavour physics inc. $g-2$, $b \rightarrow s\gamma$, B decays (new channels, angular obs., theory uncerts, LHCb likelihoods)
- SpecBit – generic BSM spectrum object, providing RGE running, masses, mixings, etc via interchangeable interfaces to different RGE codes
- DecayBit – decay widths for all relevant SM & BSM particles
- PrecisionBit – SM likelihoods, precision BSM tests (W mass, $\Delta\rho$ etc)

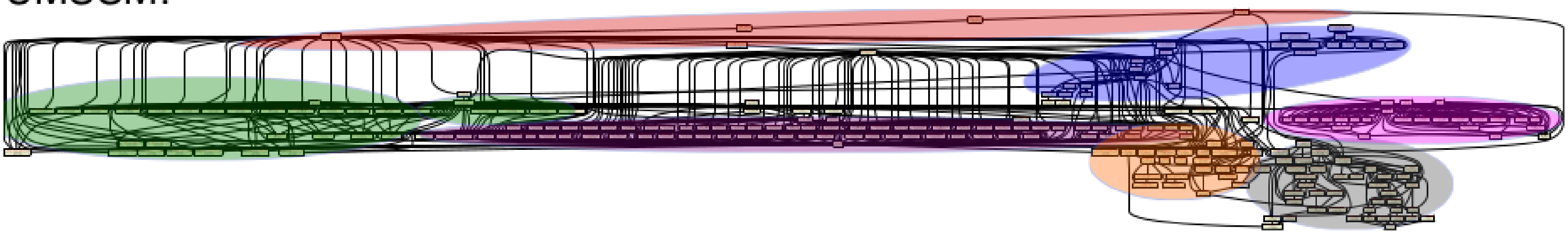
Each consists of a number of **module functions** that can have **dependencies** on each other.

+ScannerBit: manages stats, sampling and optimisation

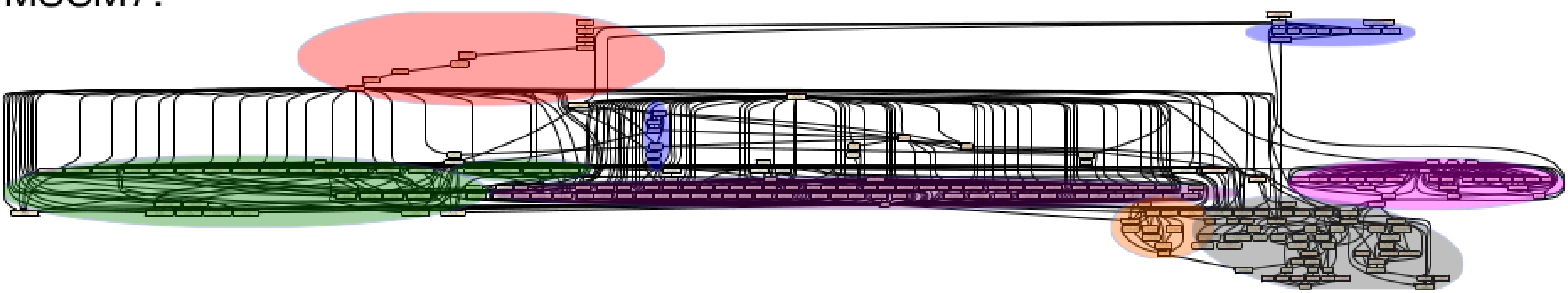

YAML file
Model α
Model β
Model γ
Model δ
Model ϵ
Model Database
User requests scan
of model δ using
1. capability of A2
2. capability of B1
Printers
ScannerBit
Core
Core runs
1. A1
2. A2
3. B2
4. B1
GAMBIT
Physics
Modules
Module functions
(Feed upwards and
horizontally only)
Module A
Module B
A1
A2
B1
B2
Backend functions
and variables
(Feed upwards only)
C1
C2
C3
C4
D1
D2
Backends
External Library C
External Library D

Example dependency graphs

CMSSM:



MSSM7:



Red: Model parameter translations
Blue: Precision calculations
Green: LEP rates+likelihoods
Purple: Decays
Orange: LHC observables and likelihoods
Grey: DM direct, indirect and relic density
Pink: Flavour physics

Mix and match backends

BACKENDS	VERSION	PATH TO LIB	STATUS	#FUNC	#TYPES	#CTORS
DDCalc0	0.0	Backends/installed/DDCalc/0.0/libDDCalc0.so	OK	62	0	0
DarkSUSY	5.1.1	Backends/installed/DarkSUSY/5.1.1/lib/libdarksusy.so	OK	68	0	0
FastSim	1.0	Backends/installed/fastsim/1.0/libfastsim.so	absent/broken	1	0	0
FeynHiggs	2.11	Backends/installed/FeynHiggs/2.11.2/lib/libFH.so	OK	14	0	0
HiggsBounds	4.2.1	Backends/installed/HiggsBounds/4.2.1/lib/libhiggsbounds.so	OK	10	0	0
HiggsSignals	1.4	Backends/installed/HiggsSignals/1.4.0/lib/libhiggssignals.so	OK	11	0	0
LibFarrayTest	1.0	Backends/examples/libFarrayTest.so	OK	9	0	0
LibFirst	1.0	Backends/examples/libfirst.so	OK	8	0	0
	1.1	Backends/examples/libfirst.so	OK	15	0	0
LibFortran	1.0	Backends/examples/libfortran.so	OK	6	0	0
MicrOmegas	3.5.5	Backends/installed/micromegas/3.5.5/MSSM/MSSM/libmicromegas.so	OK	15	0	0
MicrOmegasSingletDM	3.5.5	Backends/installed/micromegas/3.5.5/SingletDM/SingletDM/libmicromegas.so	OK	13	0	0
Pythia	8.186	Backends/installed/Pythia/8.186/lib/libpythia8.so	absent/broken	0	27	105
	8.209	Backends/installed/Pythia/8.209/lib/libpythia8.so	OK	0	28	107
SUSYPOPE	0.2	no path in config/backend_locations.yaml	absent/broken	3	0	0
SUSY_HIT	1.5	Backends/installed/SUSY-HIT/1.5/libsusyhit.so	OK	55	0	0
SuperIso	3.4	Backends/installed/SuperIso/3.4/libsuperiso.so	OK	32	0	0
gamLike	1.0.0	Backends/installed/gamLike/1.0.0/lib/gamLike.so	OK	3	0	0
nulike	1.0.0	Backends/installed/nulike/1.0.0/lib/libnulike.so	OK	4	0	0

Other tools:

CMake build system to organise compilation of many tools and modules.

Scanners: MultiNest, Diver (diff. evolution), twalk (population MC), GreAT (MCMC), with uniform interface

Parallelisation: Mixed mode MPI + openMP, mostly automated

Backends: dynamic loading of C++ classes from backends (BOSS)

POSIX signal handling: for safe early shutdown/resuming

Multi-format output: Currently ASCII and HDF5, but extensible.

Comparison of tools

Model point description	Ωh^2 DarkSUSY	Ωh^2 micrOMEGAs	$\sigma_{\mathrm{SI},p}$ $[10^{-46}\mathrm{cm}^2]$ DarkSUSY	$\sigma_{\mathrm{SI},p}$ $[10^{-46}\mathrm{cm}^2]$ micrOMEGAs	$\sigma_{\mathrm{SD},p}$ $[10^{-40}\mathrm{cm}^2]$ DarkSUSY	$\sigma_{\mathrm{SD},p}$ $[10^{-40}\mathrm{cm}^2]$ micrOMEGAs
Resonant annihilation via A^0, gaugino-like neutralino	0.08110	0.07877	4.317	4.778	10.20×10^{-6}	9.381×10^{-6}
Resonant annihilation via A^0, mixed neutralino	0.08067	0.08521	1.827	1.937	5.713	5.422
Resonant annihilation via A^0, Higgsino-like neutralino	0.08063	0.08543	0.7372	0.6826	1.564×10^{-4}	1.485×10^{-4}
Sfermion coannihilations, gaugino-like neutralino	0.1775	0.2461	1.667	1.716	4.209×10^{-3}	24.59×10^{-3}
Sfermion coannihilations, mixed neutralino	0.09823	0.1112	404.1	378.5	0.2476	0.2125
Sfermion coannihilations, Higgsino-like neutralino	7.549×10^{-3}	0.1095	18.74	29.87	1.686×10^{-3}	1.464×10^{-3}
Chargino coannihilations	0.09655	0.09997	0.5142	0.4848	16.92	16.05
Chargino coannihilations	0.08138	0.08720	4.147	3.954	9.122	8.657

Table 20: A table showing the dark matter relic density and proton scattering cross-sections, both spin-independent and spin-dependent, for a range of MSSM model points. The points were chosen to have different types of processes contribute to the relic density calculation as shown in the model point description column. All quantities were calculated through `DarkBit_standalone_MSSM` using both the DarkSUSY and micrOMEGAs backends.

Benchmarking

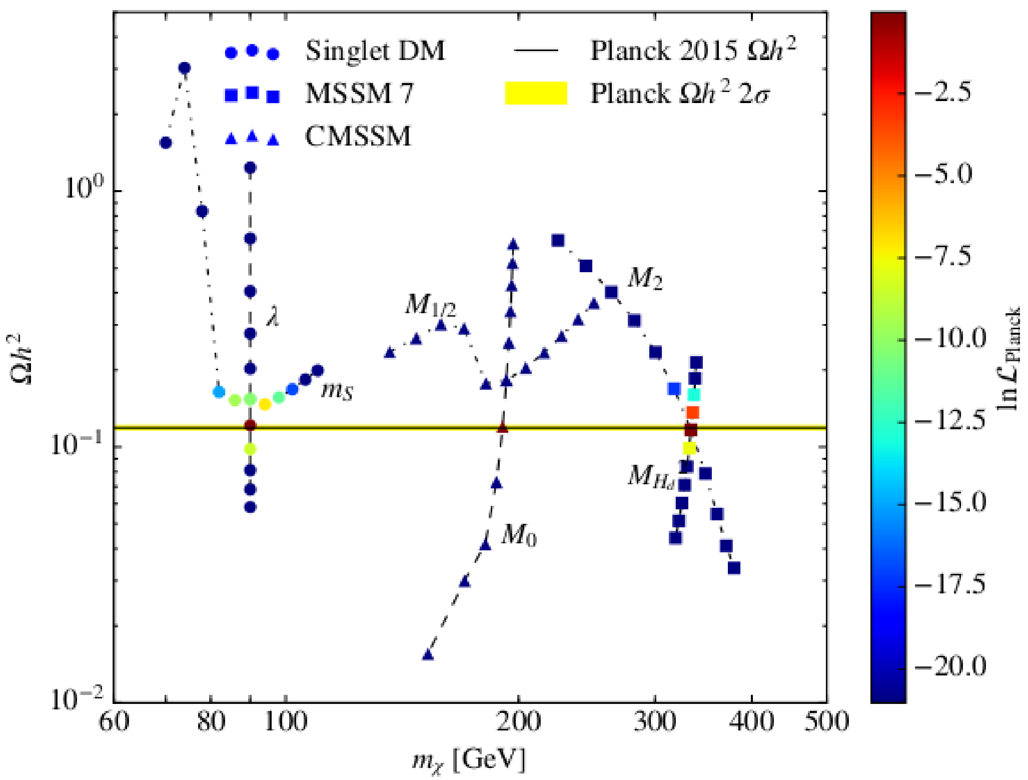
Model	Parameter	Value
Singlet DM	λ_{hS}	0.03
	m_S [GeV]	90
CMSSM	M_0 [GeV]	2800
	$M_{1/2}$ [GeV]	475
	$\tan\beta$	51
	A_0 [GeV]	1725
	sign(μ)	+
MSSM 7	M_2 [GeV]	690
	$m^2_{H_d}$ [GeV^2]	9.86×10^7
	$m^2_{H_u}$ [GeV^2]	1.4×10^4
	$\tan\beta$	23
	$m^2_{\tilde{f}}$ [GeV^2]	3.8×10^6
	A_d [GeV]	1000
	A_u [GeV]	2680
	sign(μ)	+

Table 21: Central points of spokes plotted in Fig. 6. All of the parameters of the MSSM 7 are defined at an energy scale of 1 TeV.

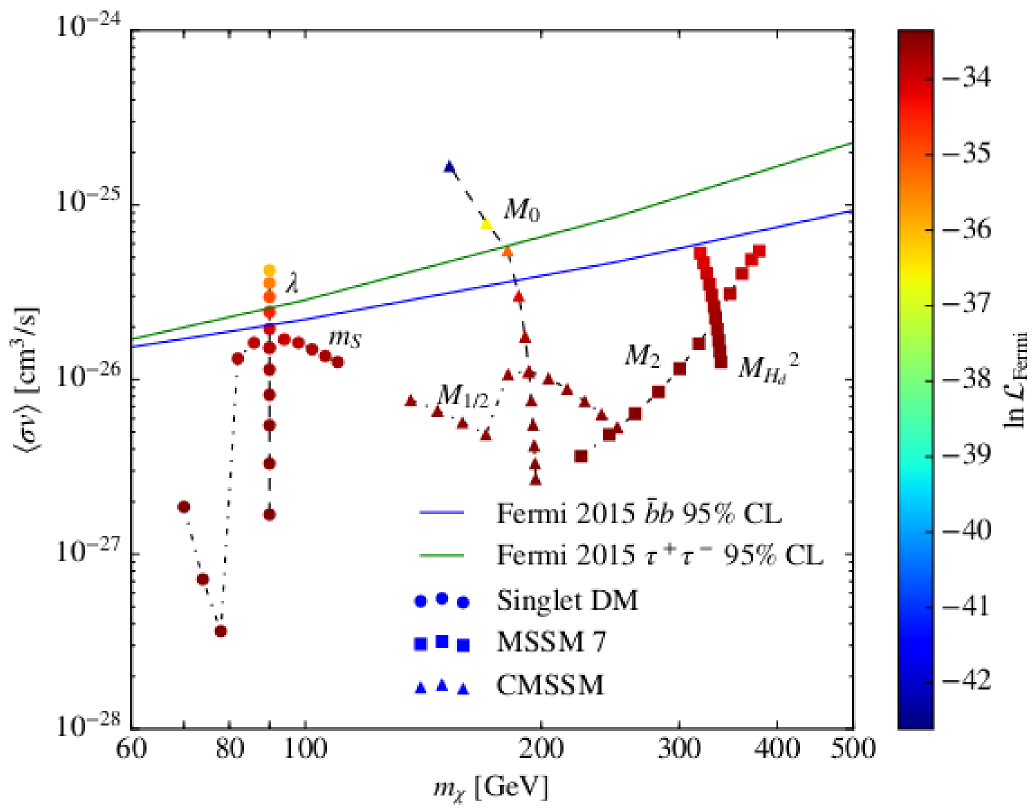
Model	Parameter	Range
Singlet DM	λ_{hS}	[0.01, 0.05]
	m_S [GeV]	[70, 110]
CMSSM	M_0 [GeV]	[2550, 3050]
	$M_{1/2}$ [GeV]	[350, 600]
MSSM 7	M_2 [GeV]	[450, 850]
	$m^2_{H_d}$ [GeV^2]	[9.2×10^7, 1.03×10^8]

Table 22: Ranges that parameters are varied over in Fig. 6. All of the parameters of the MSSM 7 are defined at an energy scale of 1 TeV.

Benchmarking

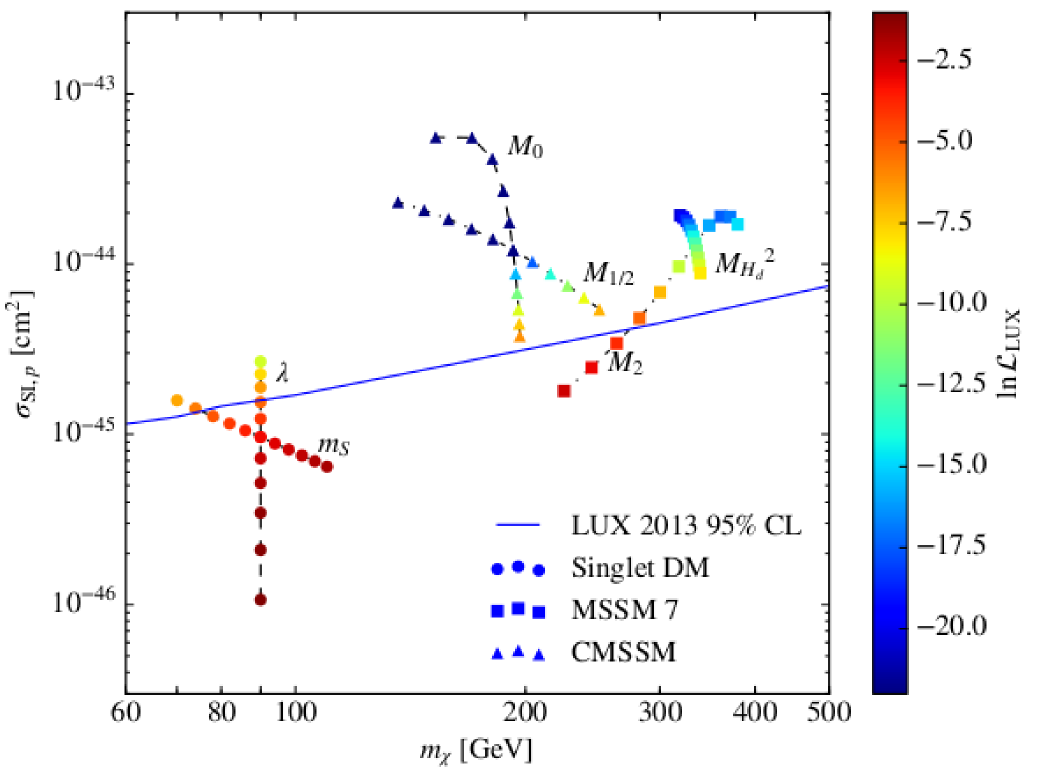


Relic Density

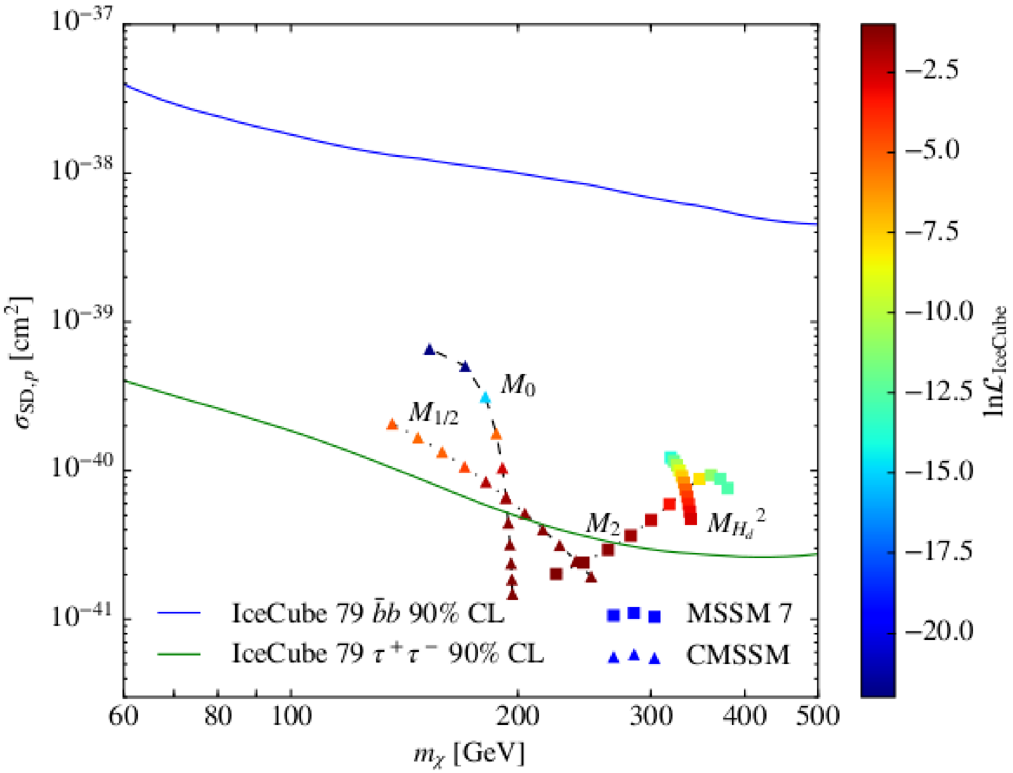


Velocity-averaged annihilation cross section

Benchmarking



SI cross section



SD cross section

Scalar singlet (“Higgs portal”) dark matter

Possibly the simplest class of models for DM

- new singlet X
- $\mathcal{Z}_2$ symmetry stabilises X
- effective interaction with Higgs $X^2|H|^2$

X may be **scalar**, **vector**, **Majorana** or **Dirac**

$$\mathcal{L}_{X=S} = \frac{1}{2}(\partial_\mu S)(\partial^\mu S) - \frac{1}{2}\mu_S^2 S^2 - \frac{1}{4!}\lambda_S S^4 - \frac{1}{2}\lambda_{hS}\, S^2 H^\dagger H, \quad (1)$$

$$\mathcal{L}_{X=V} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}\mu_V^2 V_\mu V^\mu - \frac{1}{4!}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{2}\lambda_{hV}\, V_\mu V^\mu H^\dagger H, \quad (2)$$

$$\mathcal{L}_{X=M} = \frac{1}{2}\overline{M}\,(i\partial\!\!\!/ - \mu_M)\, M - \frac{1}{2}\frac{\lambda_{hM}}{\Lambda_M}\left(\cos\theta\,\overline{M}M + \sin\theta\,\overline{M}i\gamma_5 M\right)H^\dagger H, \quad (3)$$

$$\mathcal{L}_D = \overline{D}\,(i\partial\!\!\!/ - \mu_D)\, D - \frac{\lambda_{hD}}{\Lambda_D}\left(\cos\theta\,\overline{D}D + \sin\theta\,\overline{D}i\gamma_5 D\right)H^\dagger H, \quad (4)$$

Scalar singlet ("Higgs portal") dark matter

Possibly the simplest class of models for DM

- new singlet X
- $\mathcal{Z}_2$ symmetry stabilises X
- effective interaction with Higgs $X^2|H|^2$

X may be **scalar**, **vector**, **Majorana** or **Dirac**

$$\mathcal{L}_{X=S} = \frac{1}{2}(\partial_\mu S)(\partial^\mu S) - \frac{1}{2}\mu_S^2 S^2 - \frac{1}{4!}\lambda_S S^4 - \frac{1}{2}\lambda_{hS}\, S^2 H^\dagger H, \quad (1)$$

$$\mathcal{L}_{X=V} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}\mu_V^2 V_\mu V^\mu - \frac{1}{4!}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{2}\lambda_{hV}\, V_\mu V^\mu H^\dagger H, \quad (2)$$

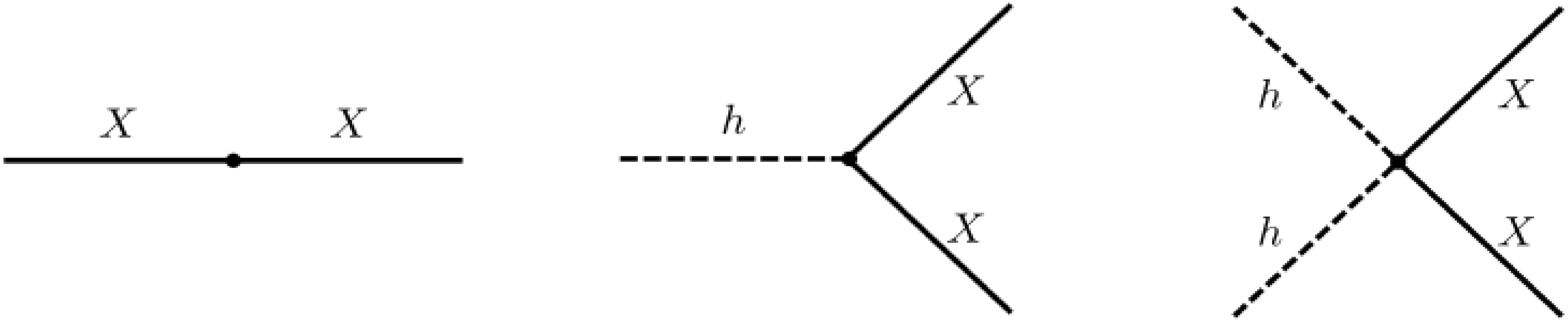
$$\mathcal{L}_{X=M} = \frac{1}{2}\overline{M}\,(i\not\partial - \mu_M)\, M - \frac{1}{2}\frac{\lambda_{hM}}{\Lambda_M}\left(\cos\theta\,\overline{M}M + \sin\theta\,\overline{M}i\gamma_5 M\right) H^\dagger H, \quad (3)$$

$$\mathcal{L}_D = \overline{D}\,(i\not\partial - \mu_D)\, D - \frac{\lambda_{hD}}{\Lambda_D}\left(\cos\theta\,\overline{D}D + \sin\theta\,\overline{D}i\gamma_5 D\right) H^\dagger H, \quad (4)$$

Scalar singlet ("Higgs portal") dark matter

After electroweak symmetry breaking (ignoring factors of $\sqrt{2}$)

$$X^2|H|^2 \rightarrow v^2X^2 + vhX^2 + h^2X^2$$

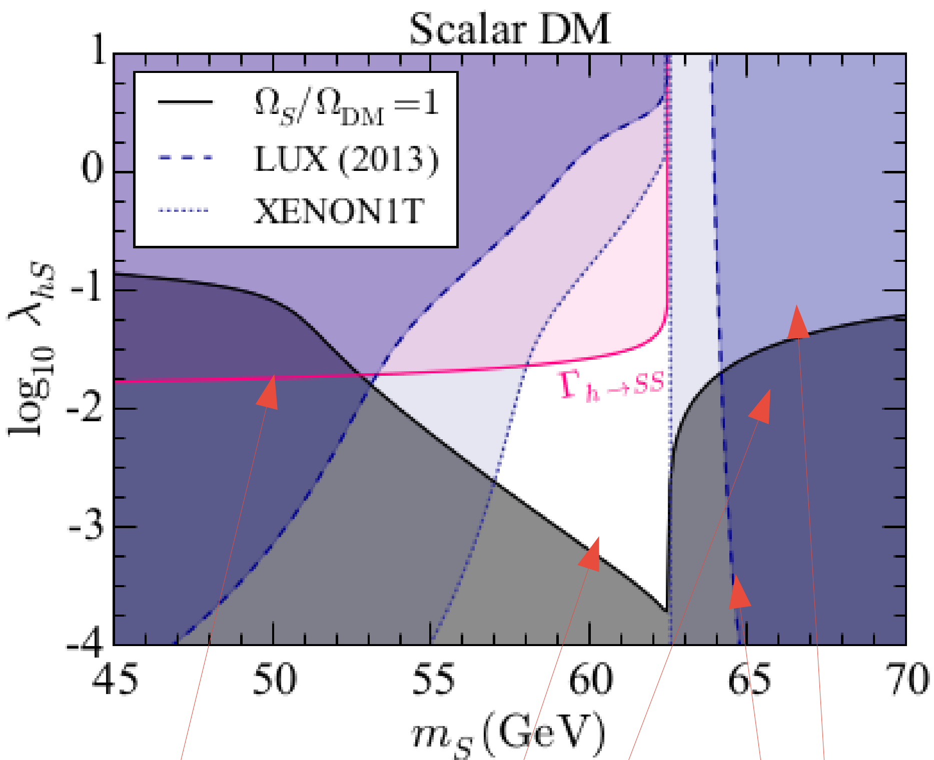


$\Longrightarrow$ All the regular WIMP pheno we know and love (direct, indirect, thermal relic density) plus $h \rightarrow \bar{X}X$

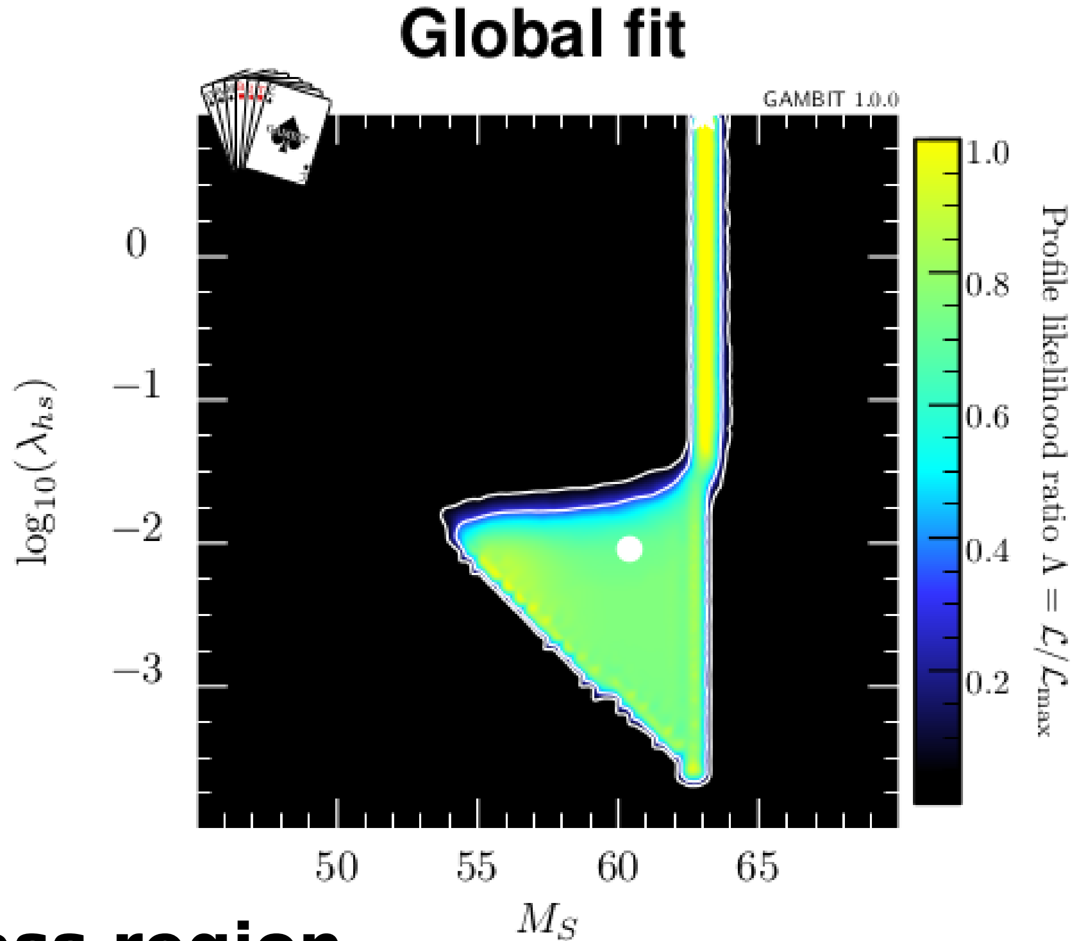
→ Apply all constraints consistently
→ ...varying SM parameters within their allowed range (Higgs mass, Top mass)
→ ...and nuclear parameters (quark content of nucleons)
→ ...future scans: halo parameters too.

Simple scan

Cline, Kainulainen, Scott & Weniger, PRD, 1306.4710



Global fit



Low mass region

$m_s < m_h / 2$
h→SS allowed, contributes to Higgs invisible width, constrained by LHC

$m_s \sim m_h /2$, resonant annihilation

Too little DM

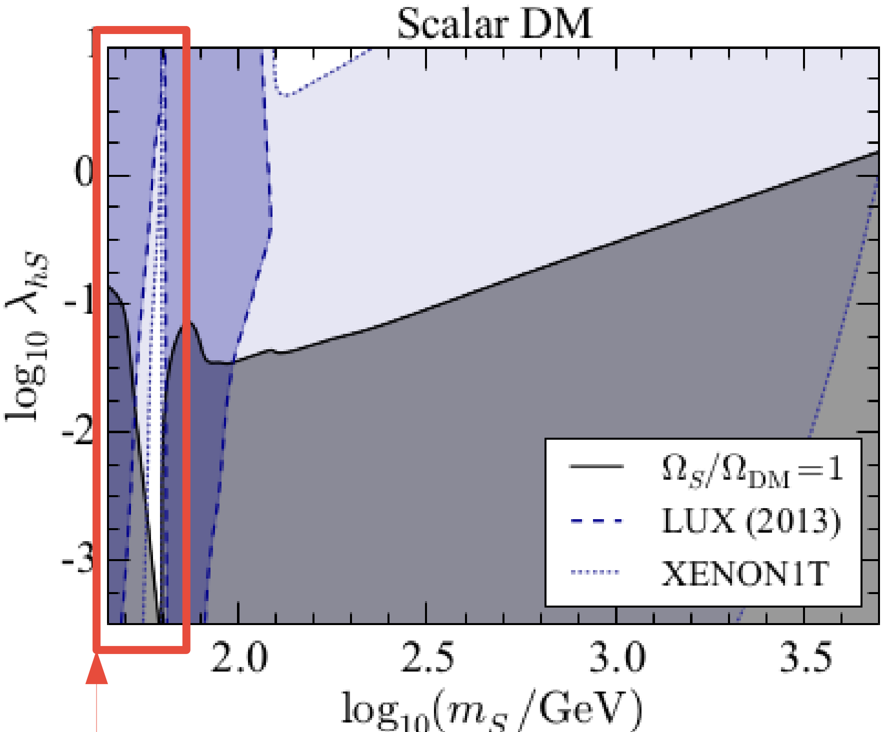
Too much DM

LUX (2013)

Constraints:
- IC79 (nulike)
- FermiLAT dwarfs (gamlike)
- LHC run1 Higgs inv. width (1306.2941)
- DM relic density (Planck)
- Xenon2012+LUX2013 (DDCalc)
- nuisance parameter constraints (nuclear, SM, DM velocity distribution (trunc. MB))

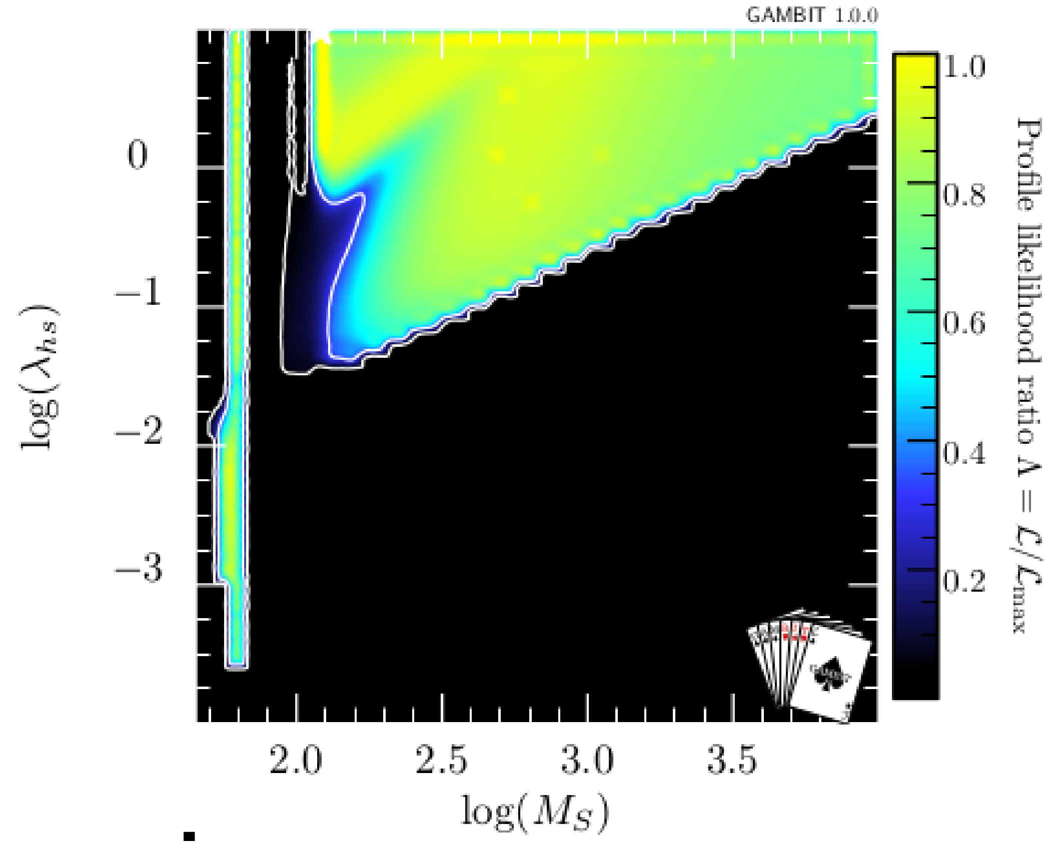
Simple scan

Cline, Kainulainen, Scott & Weniger, PRD, 1306.4710



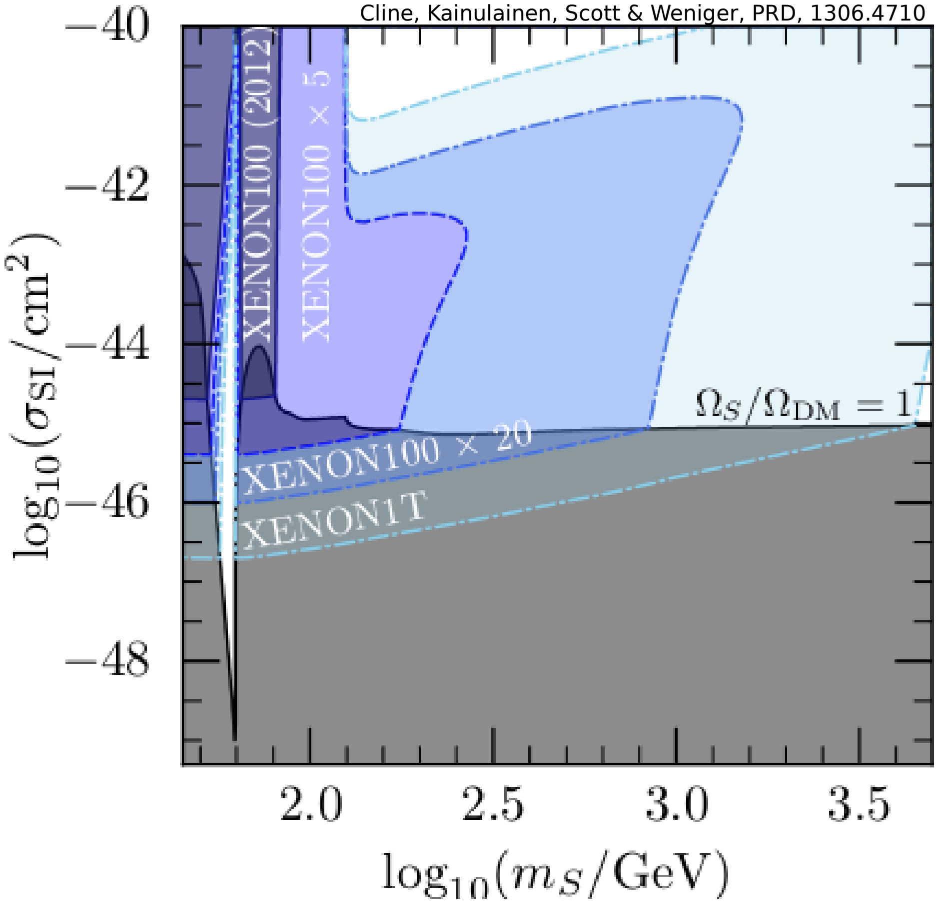
Previous slide
(low mass)

Global fit

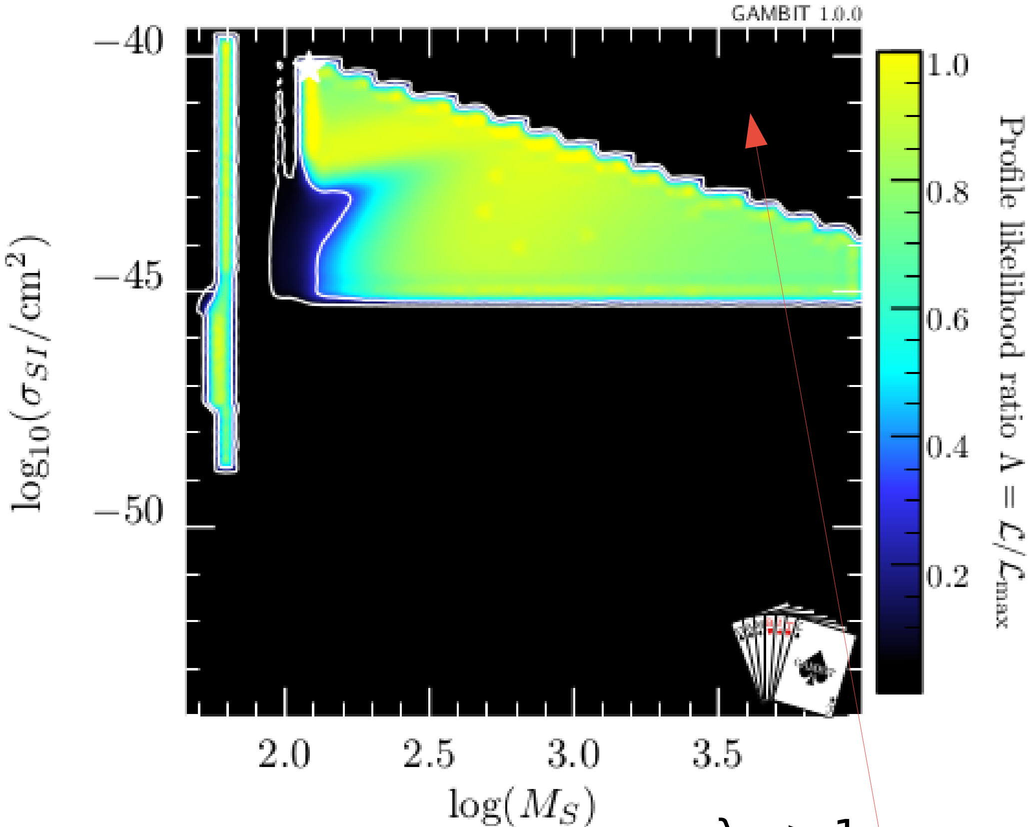


High mass region

Simple scan

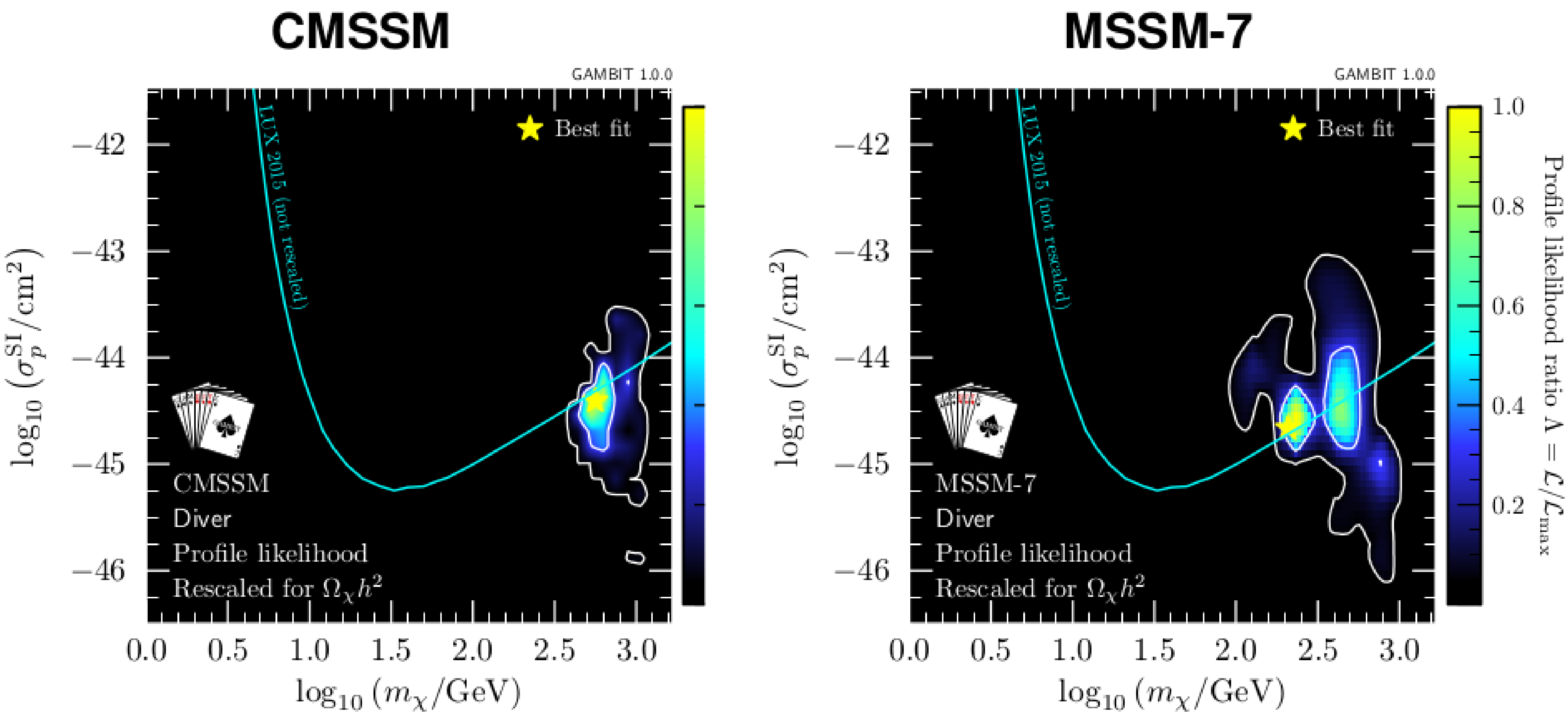


Global fit



$\lambda_{hS} > 1$
(edge of scan)

SI WIMP-nucleon cross section



Includes direct simulation of all relevant LHC Run 1 limits.

9(12) parameters:

4(**7**) $\times$ CMSSM(MSSM7) $+$ **2** $\times$ SM nuisances(α_S, m_t)
$+$**2** $\times$ nuclear(σ_s, σ_l) $+$ **1** $\times$ astro nuis.($\rho_{\chi,\mathrm{local}}$)

Summary

- GAMBIT first publications in preparation, with simultaneous code release.
- Global fits to many models for the first time
- Better global fits to familiar ones
- Highly modular, usable and extendable public code
- Faster, more complete and more consistent theory explorations + experimental analysis prototyping

- In preparation: EW-scale MSSMs, CMSSM± (NUHM, etc), Scalar Singlet, DarkBit, ColliderBit, FlavBit, Spec+Decay+PrecisionBits, GAMBIT framework, ScannerBit

Thank you!