Searches for dark matter and new physics with GAMBIT

Pat Scott

University of Queensland

on behalf of the GAMBIT Community

gambit.hepforge.org

Combining searches

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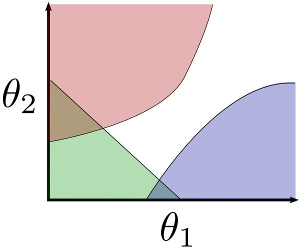

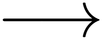

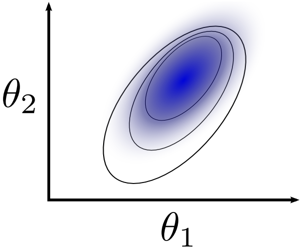

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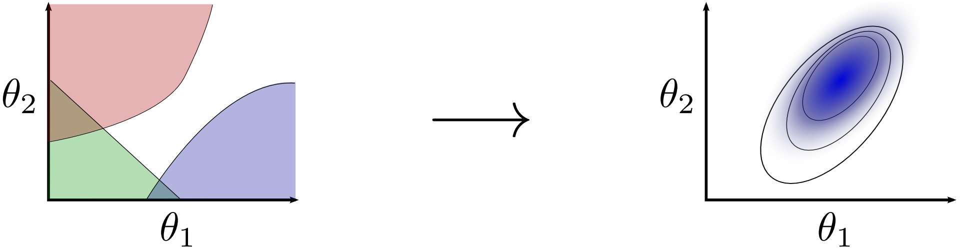

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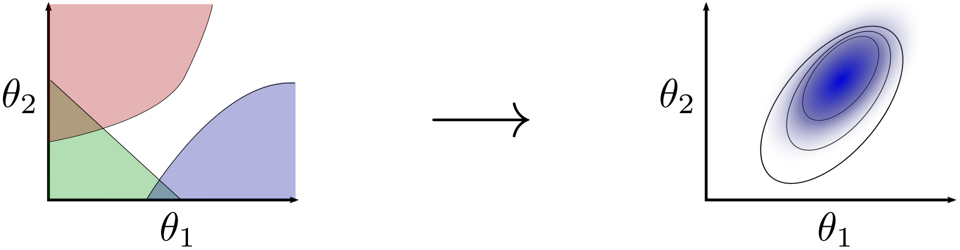

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Q. And what if you want to do it all again for many different **models**?

GAMBIT: The Global And Modular BSM Inference Tool

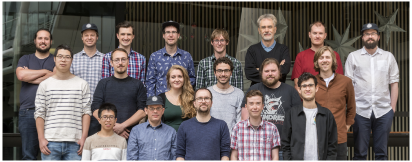
gambit.hepforge.org EPJC **77** (2017) 784 arXiv:1705.07908

- 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

Members of:
ATLAS, Belle-II, CLiC, CMS, CTA, *Fermi*-LAT, DARWIN, IceCube, LHCb, SHiP, XENON

Authors of:
DarkSUSY, DDCalc, Diver, FlexibleSUSY, gamlike, GM2Calc, IsaTools, nulike, PolyChord, Rivet, SoftSUSY, SuperISO, SUSY-AI, WIMPSim

- Fast definition of new datasets and theories
- Plug and play scanning, physics and likelihood packages



Recent collaborators:
P Athron, C Balázs, A Beniwal, S Bloor, T Bringmann, A Buckley, J Eliel Camargo-Molina, C Chang, M Chrzaszcz, J Conrad, J Cornell, M Danninger, J Edsjö, B Farmer, A Fowlie, T Gonzalo, P Grace, W Handley, J Harz, S Hoof, F Kahlhoefer, N Avis Kozar, A Kvellestad, P Jackson, R Jardine, A Ladhu, N Mahmoudi, G Martinez, M Prim, F Rajec, A Raklev, J Renk, C Rogan, R Ruiz, I Sáez Casares, N Serra, A Scaffidi, P Scott, P Stöcker, W Su, J Van den Abeele, A Vincent, C Weniger, M White, Y Zhang

40+ participants in 11 experiments and 14 major theory codes

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Modules

Physics modules

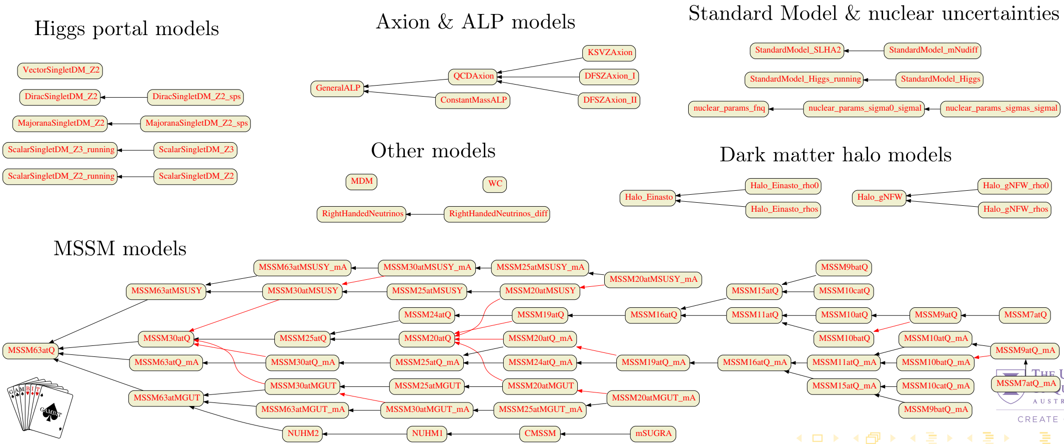
- DarkBit – dark matter observables (EPJC / arXiv:1705.07920)
- ColliderBit – collider observables (EPJC / arXiv:1705.07919)
- FlavBit – flavour physics (EPJC / arXiv:1705.07933)
- SpecBit – generic BSM spectrum object (EPJC / arXiv:1705.07936)
- DecayBit – decay widths (EPJC / arXiv:1705.07936)
- PrecisionBit – precision SM/BSM tests (EPJC / arXiv:1705.07936)
- NeutrinoBit – neutrino physics (arXiv:1908.02302)

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

Statistics module

- ScannerBit: stats & sampling (EPJC / arXiv:1705.07959)

- Models are defined by their parameters and relations to each other
- Models can inherit from (be subspaces of) **parent models**
- Points in child models can be **automatically translated** to ancestor models



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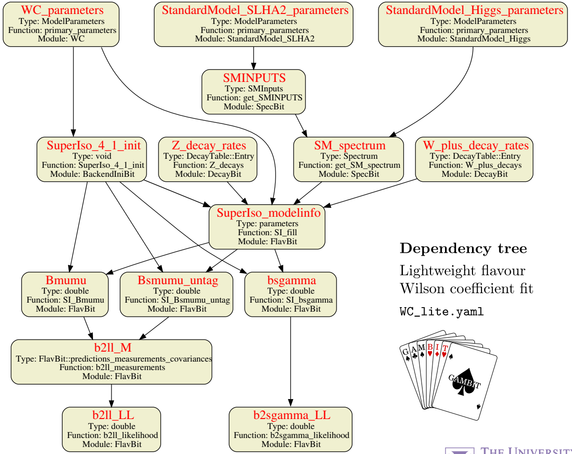
A GAMBIT run in a nutshell

- User chooses a model to scan, which observables to include, and the scanning method
- GAMBIT constructs a **dependency tree**
  1. Identifies which functions and inputs are needed to compute the requested observables
  2. Obeys **rules** at each step: allowed models, backends, constraints from input file, etc
     → tree constitutes a directed acyclic graph
  3. Uses graph-theoretic methods to 'solve' the graph to determine function evaluation order
- GAMBIT scans the parameter space by calling the necessary module and backend functions in the optimal order, for each parameter point



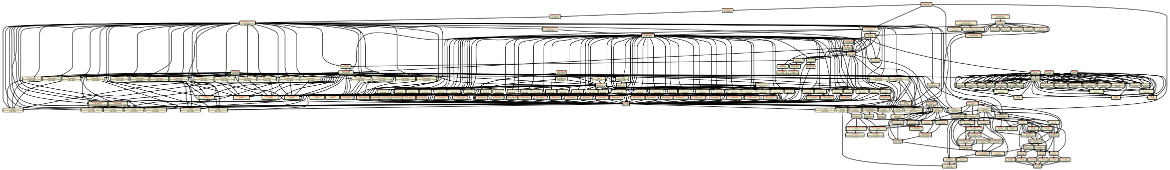
Dependency tree

Lightweight flavour Wilson coefficient fit

`WC_lite.yaml`

Dependency Resolution

CMSSM:



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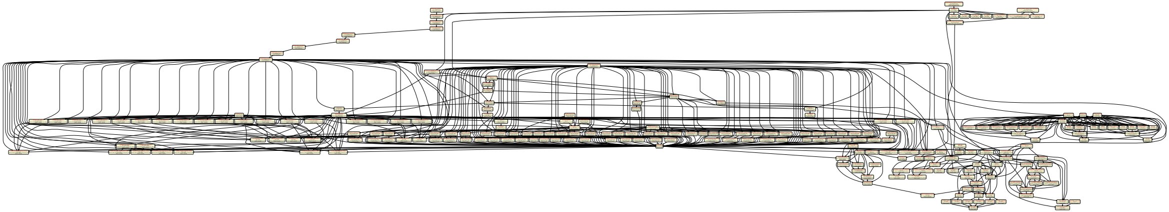

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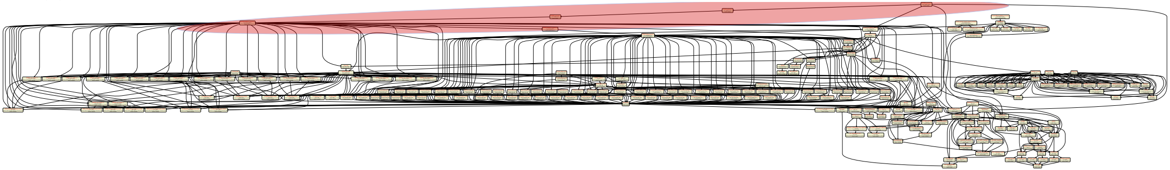

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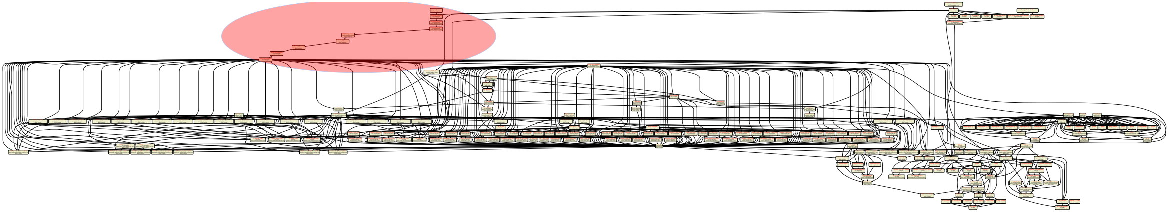

Red: Model parameter translations

Dependency Resolution

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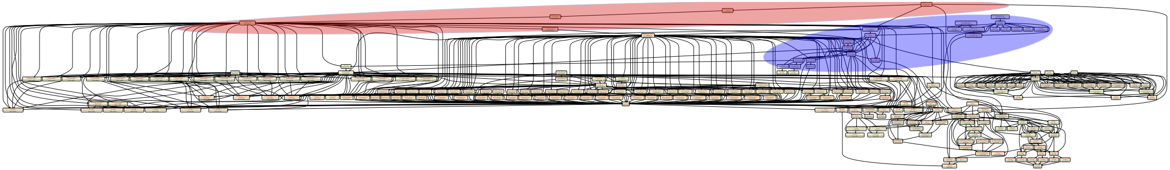

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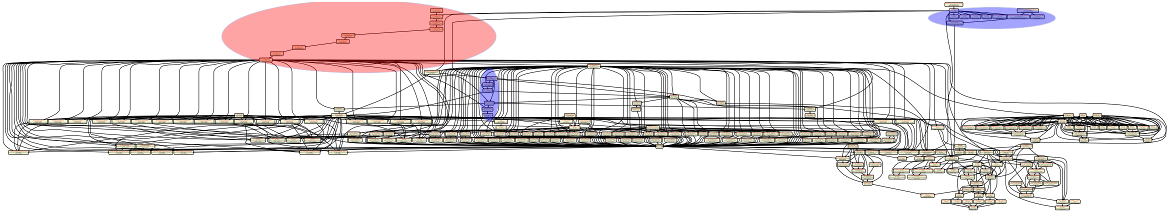

Red: Model parameter translations

Blue: Precision calculations

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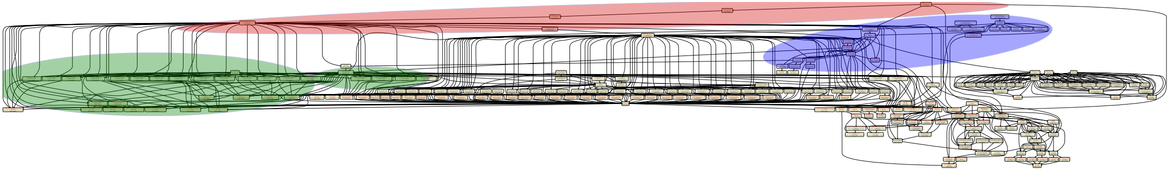

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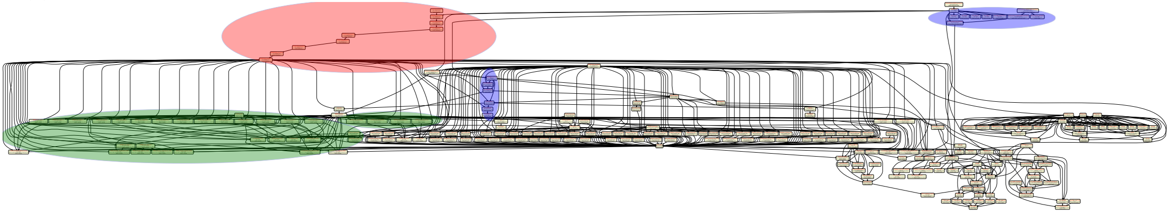

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Green: LEP rates+likelihoods

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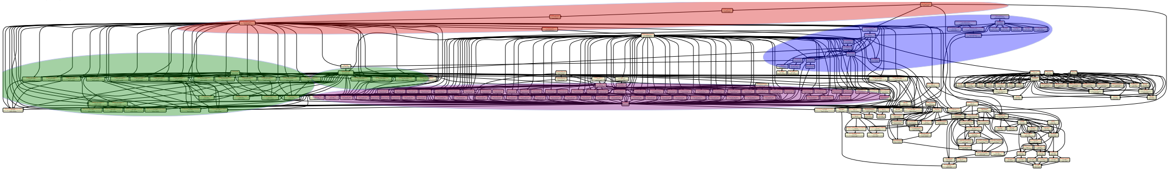

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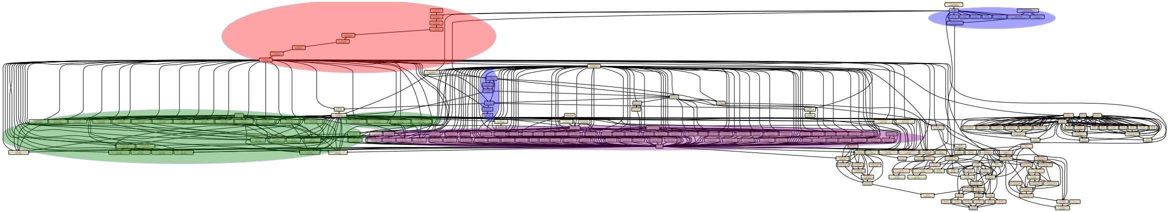

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Purple: Decays

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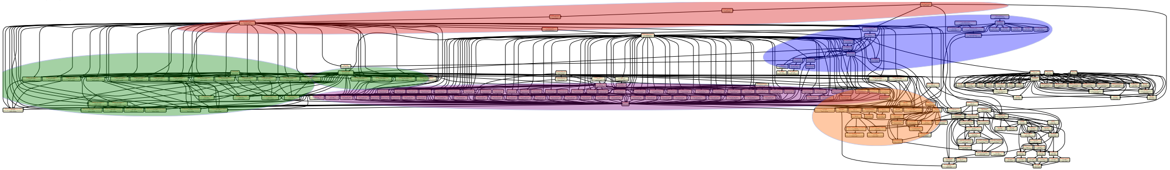

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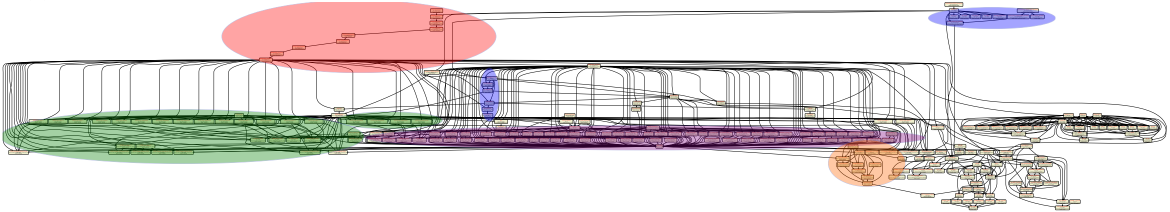

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Orange: LHC observables and likelihoods

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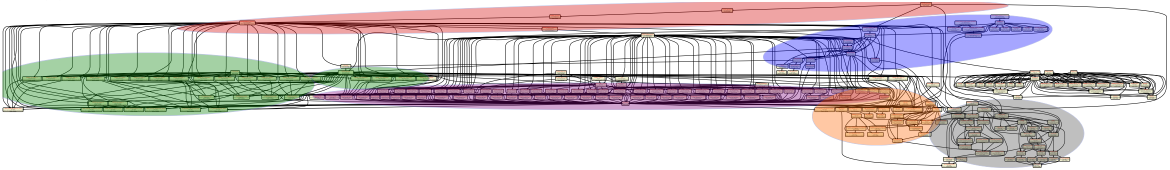

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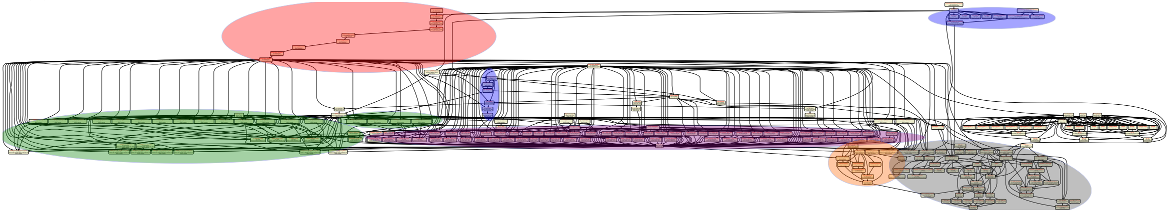

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Grey: DM direct, indirect and relic density

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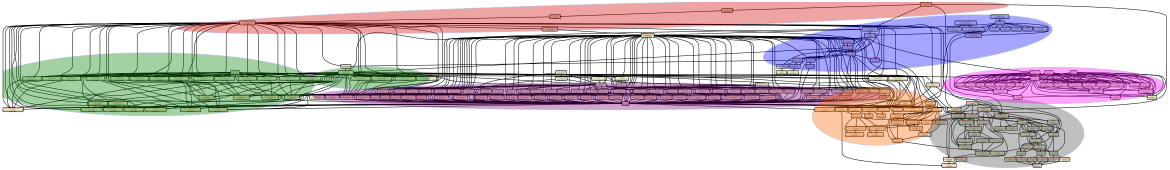

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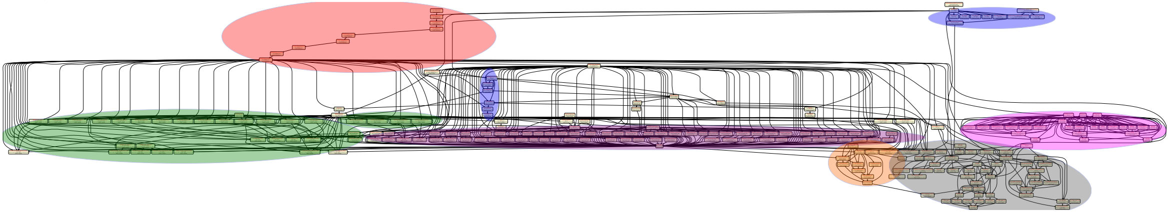

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Pink: Flavour physics

Dark matter constraints in GAMBIT (EPJC, arXiv:1705.07920)

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- Direct detection: XENON1T, LZ, LUX, PandaX, PICO, DarkSide, SuperCDMS, CDMSLite, CRESST-II, SIMPLE

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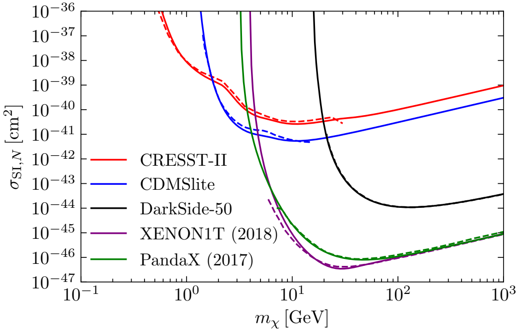

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ColliderBit details

(EPJC / arXiv:1705.07919)

LEP likelihoods

- model-independent recast of direct sparticle searches

Higgs likelihoods:

- for now: HiggsSignals + HiggsBounds + ATLAS/CMS invisible width likelihoods
- future: full simulation and ATLAS+CMS combination, more correlations, CP info, no SM-like coupling assumptions

Fast LHC likelihoods

- no simplified models, just faster direct simulation

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LHC likelihoods:

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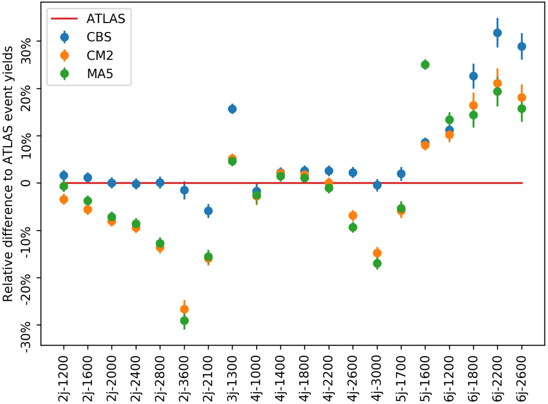

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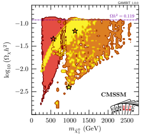
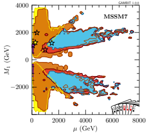
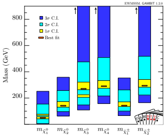
GAMBIT results



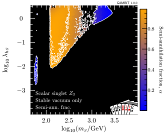
CMSSM/NUHM1/NUHM2
(EPJC / arXiv:1705.07935)



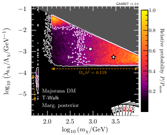
MSSM7
(EPJC / arXiv:1705.07917)



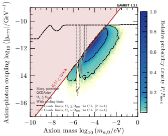
EWMSSM
(EPJC / arXiv:1809.02097)



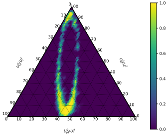
Scalar singlet dark matter
(EPJC / arXiv:1806.11281)



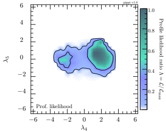
Fermion/vector Higgs portal
(EPJC / arXiv:1808.10465)



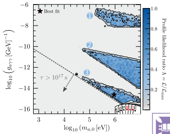
Axions & ALPs
(JHEP / arXiv:1810.07192)



Right-handed neutrinos
(arXiv:1908.02302)



Two Higgs Doublet Models
(coming soon)



Cosmological models
(coming soon as CosmoBit)

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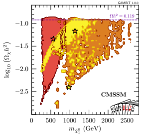
GAMBIT results



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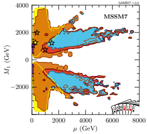

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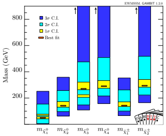
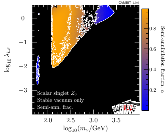
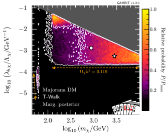


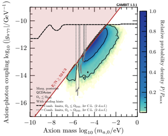
EWMSSM
(EPJC / arXiv:1809.02097)



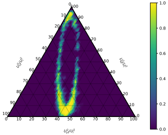
Scalar singlet dark matter
(EPJC / arXiv:1806.11281)



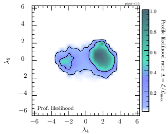
Fermion/vector Higgs portal
(EPJC / arXiv:1808.10465)



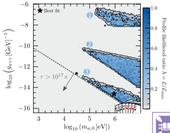
Axions & ALPs
(JHEP / arXiv:1810.07192)



Right-handed neutrinos
(arXiv:1908.02302)



Two Higgs Doublet Models
(coming soon)



Cosmological models
(coming soon as CosmoBit)

GAMBIT dark matter fits

A couple of important notes about the parameter scans:

- All dark matter signals consistently scaled for predicted abundance
- Both profile likelihoods and Bayesian posteriors
- Sampling mostly with Diver (differential evolution) & T-walk (ensemble MCMC)

Higgs Portal Scalar Singlet Dark Matter

Simplest example of a dark matter theory

$$\mathcal{L}_S = \frac{\mu_S^2}{2} S^2 + \frac{\lambda_{hS}}{2} S^2 H^\dagger H + \frac{1}{4}\lambda_S S^4 + \ldots$$

- S = gauge singlet scalar
- S odd under an unbroken $\mathcal{Z}_2$ symmetry $\rightarrow$ absolutely stable
- Interaction with Higgs boson h gives usual WIMP-like phenomenology:
  - direct detection
  - indirect detection
  - thermal production
  - monojets @LHC

  but also: potential for invisible Higgs decays $h \rightarrow SS$ @LHC

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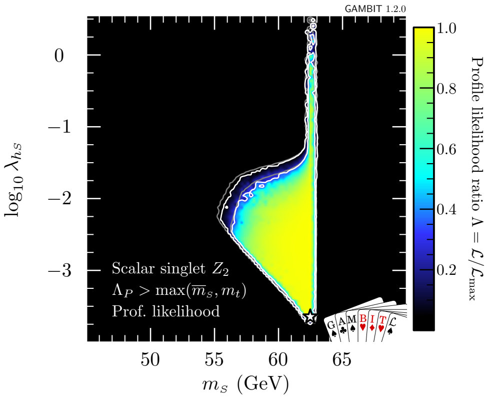
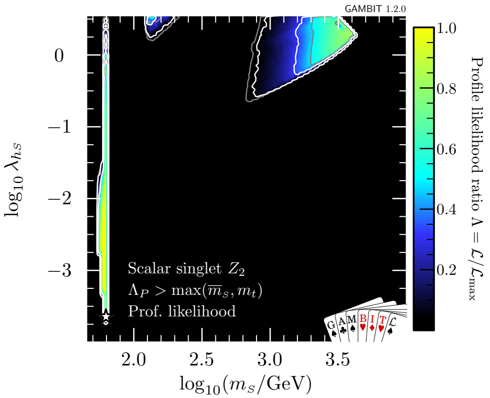


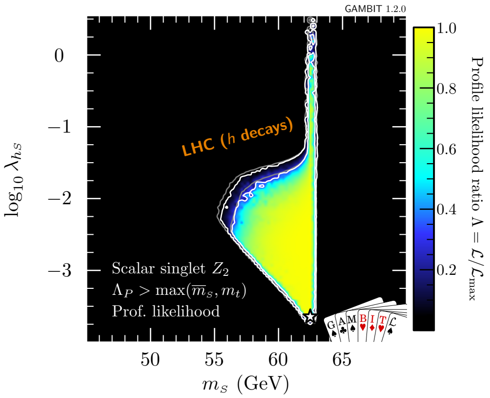


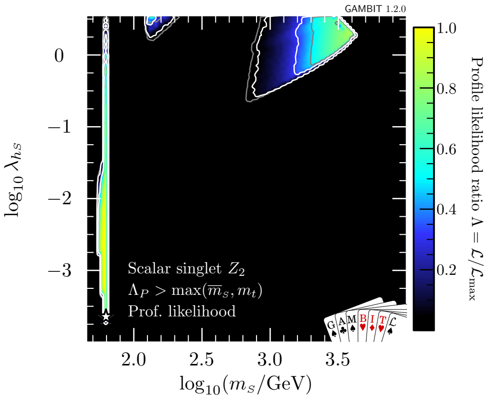
White = 1σ, 2σ with XENON1T 2018

Direct detection and relic density the most constraining

Scalar Higgs Portal DM

(EPJC, arXiv:1806.11281)





White = 1σ, 2σ with XENON1T 2018

Direct detection and relic density the most constraining

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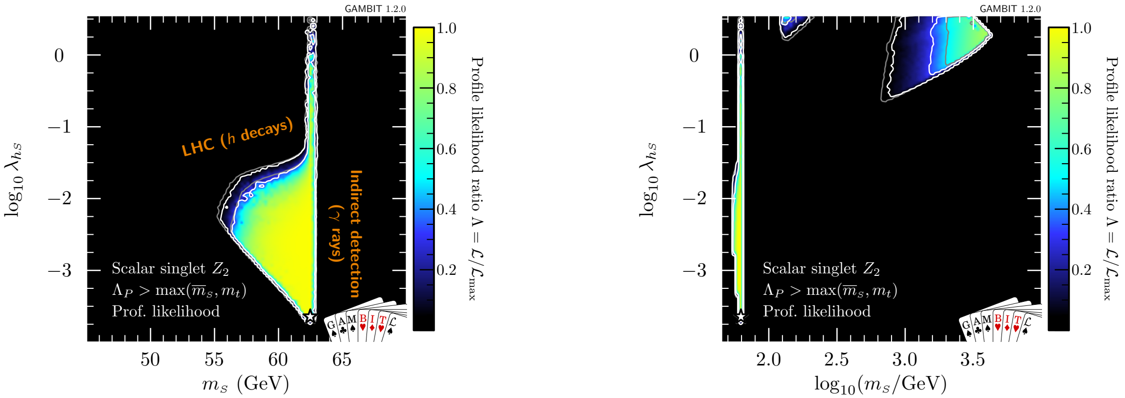
Scalar Higgs Portal DM

(EPJC, arXiv:1806.11281)



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Direct detection and relic density the most constraining

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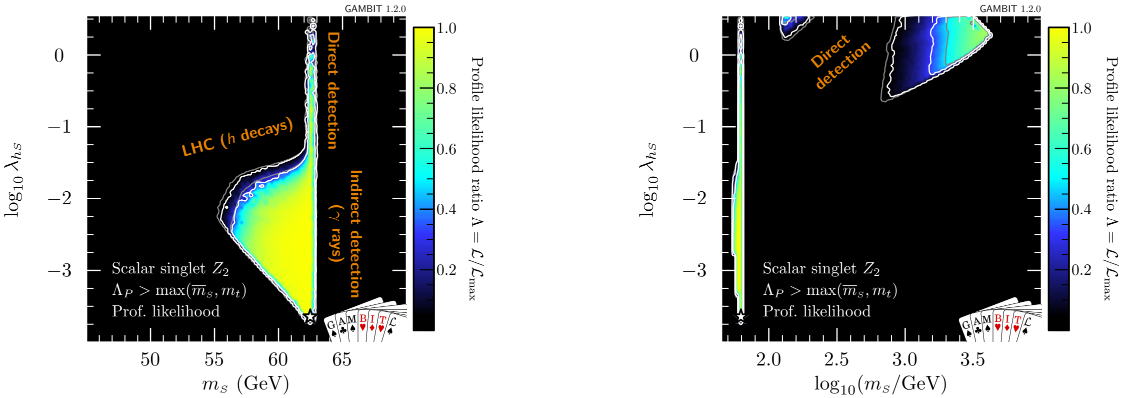
Scalar Higgs Portal DM

(EPJC, arXiv:1806.11281)



White = 1σ, 2σ with XENON1T 2018

Direct detection and relic density the most constraining

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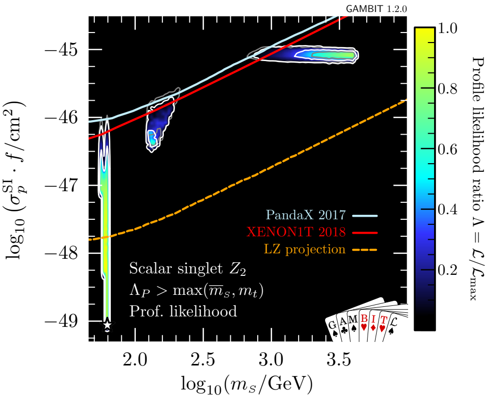
Scalar Higgs Portal DM

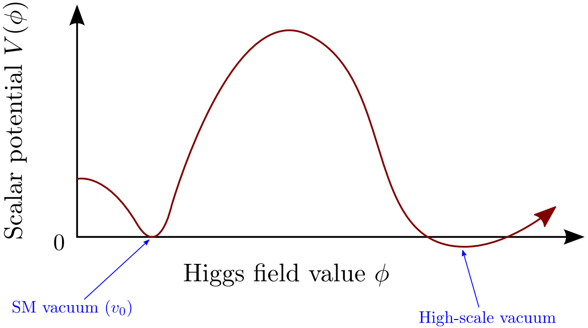
(EPJC, arXiv:1806.11281)



White $= 1\sigma$, 2σ with XENON1T 2018

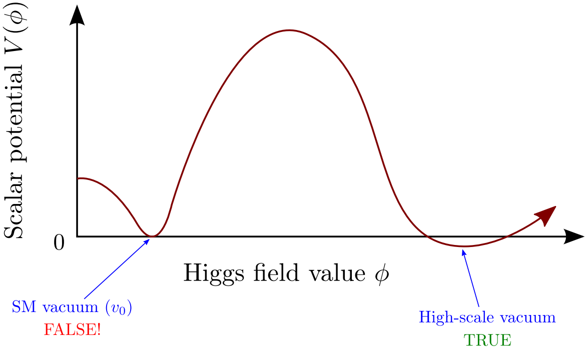
Direct detection and relic density the most constraining

Aside: Vacuum Stability



- The electroweak vacuum of the Standard Model is not stable

Aside: Vacuum Stability



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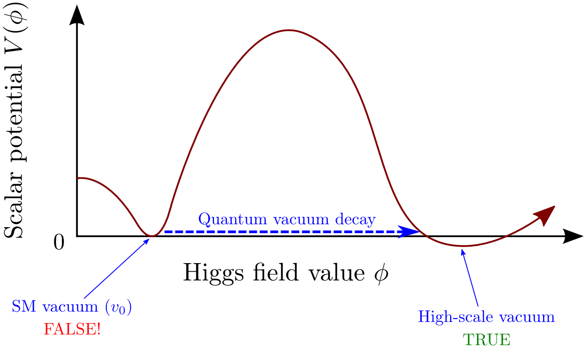

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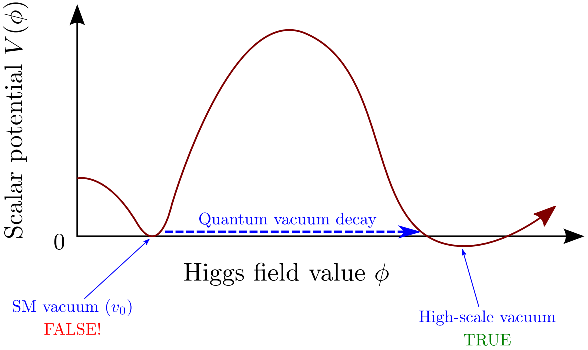
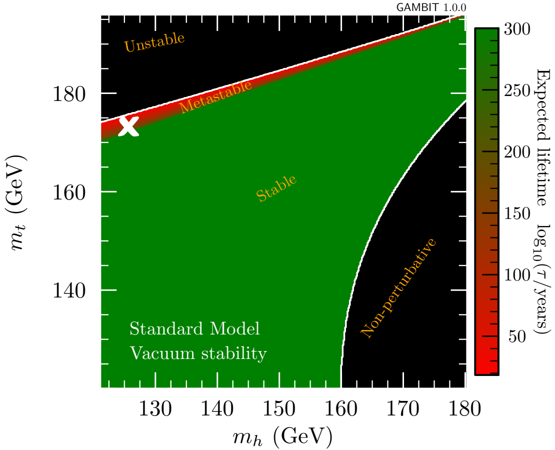
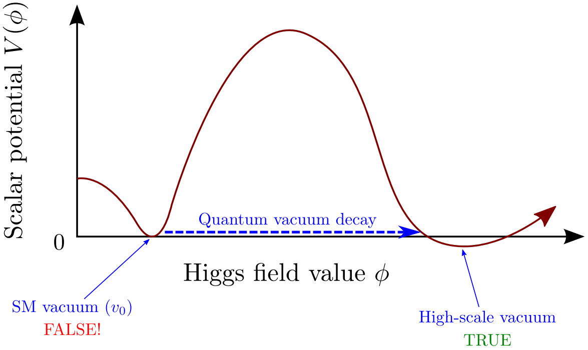
Aside: Vacuum Stability

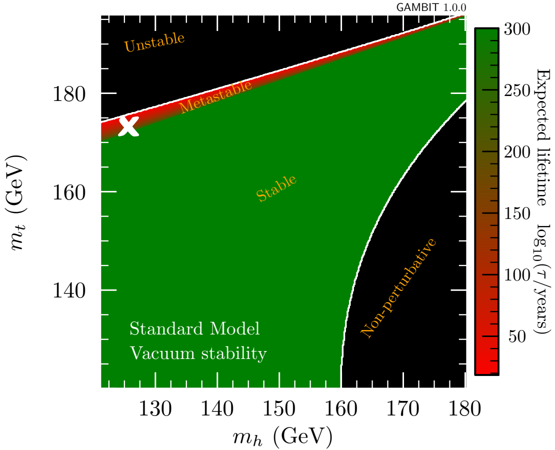




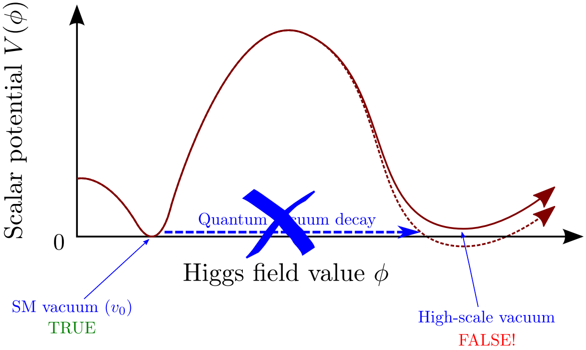
- The electroweak vacuum of the Standard Model is not stable
- Lifetime for decay to the global minimum is $\gg$ age of the Universe
  $\implies$ metastable

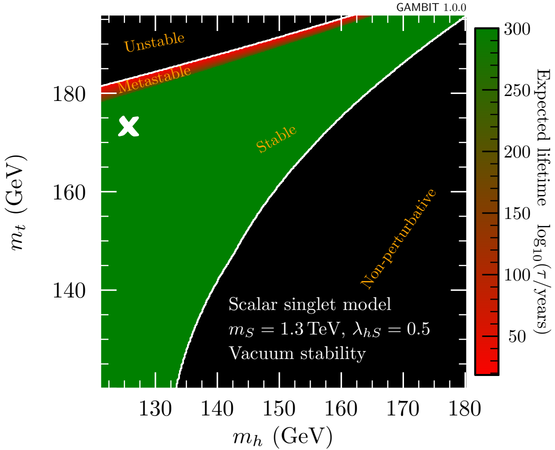
Aside: Vacuum Stability





- Can be spoilt by Planck-scale effects
- Unclear how inflation would have put us in a metastable state
  $\rightarrow$ metastability makes Standard Model seem rather fine-tuned



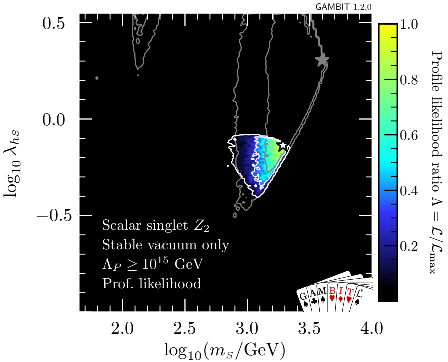


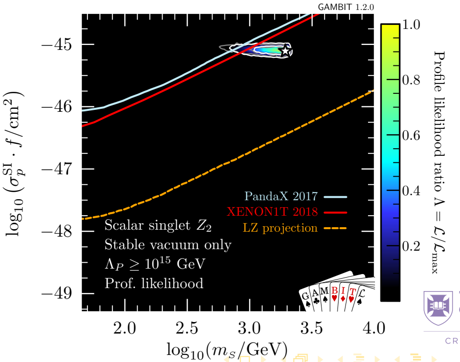
- Exact depth of minimum is very sensitive to running of couplings due to renormalisation
  $\rightarrow$ new particles can make our vacuum absolutely stable
  & remove the fine-tuning issue

Can the $\mathbb{Z}_2$ scalar singlet provide vacuum stability?

$\mathbb{Z}_2$ scalar singlet can stabilise the electroweak vacuum

- Preferred mass of $\sim$2 TeV, $\sigma_{\rm SI} \sim 10^{-45}$ cm^2 to do so
- explains all of DM
- matches slight preference for signal in XENON1T data
- good fit to all observables ($p \sim 0.5$) $\implies$ interesting. . . (?)





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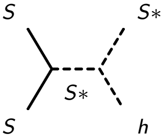
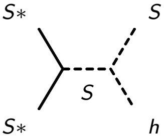
But why only $\mathbb{Z}_2$? $\mathbb{Z}_3$ works too, right?

(EPJC, arXiv:1806.11281)

- All we were trying to achieve with the $\mathbb{Z}_2$ symmetry was to prevent $S \to SM + SM$
- Can be achieved with any other discrete symmetry, e.g. $\mathbb{Z}_3$
- $\mathcal{L}_S = \mu_S S^\dagger S + \lambda_{hs} S^\dagger S H^\dagger H + \frac{\mu_3}{2}(S^3 + S^{\dagger 3}) + \frac{1}{4}\lambda_S S^4 + \ldots$
- Complex scalar dark matter $\to$ singlet (S) and anti-singlet (S^*)
- Semi-annihilation: $SS \to S^* h$, $S^* S^* \to Sh$





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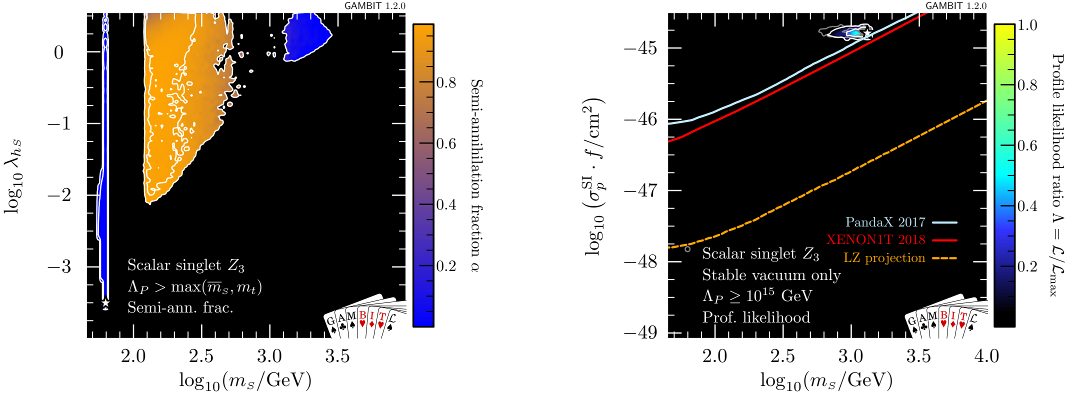
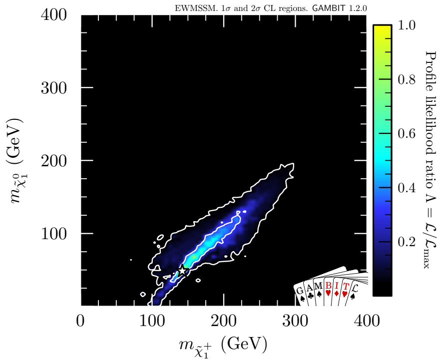


Can the $\mathbb{Z}_3$-symmetric scalar singlet stabilise the vacuum?
Excluded at >99% CL ($p < 0.01$) as all of dark matter
Excluded at >98% CL ($p < 0.02$) as *any* of dark matter
mainly due to extra factors of 2 from complex vs real scalar



- Low-mass neutralinos & charginos
- everything else decoupled
- $M_1, M_2, \mu, \tan\beta$ free
- m_h fixed to 125.09 GeV

→ 3.3σ (local) combined signal significance

Electroweak analyses included in likelihood:

- ATLAS multi-lepton: $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^\pm\tilde{\chi}_1^\pm$, $\tilde{l}\tilde{l}$; final states with 2–3 leptons + 0–5 jets
- ATLAS 2/3-lepton recursive jigsaw searches for $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$
- CMS 2SFOSlep-soft: $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$, virtual W^* and $Z^* \to ll$; final state with two same-flavour opposite-sign leptons
- CMS 2SFOSlep: as above but with hard leptons (W, Z not virtual)
- CMS multi-lepton: similar to ATLAS, but exclusively $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$ production
- ATLAS 4-lepton SUSY search
- ATLAS 4-b Higgsino search
- CMS 1lep(H)bb: single-lepton final states including $H \to bb$
- Assorted LEP likelihoods
- h/Z invisible widths

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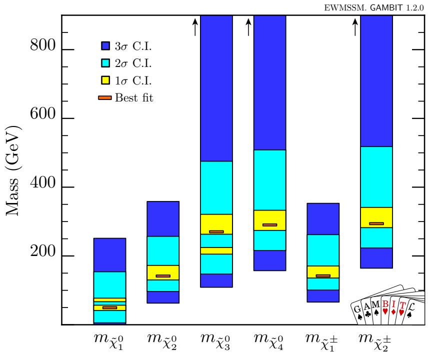
Supersymmetry

(EPJC, arXiv:1809.02097)



- Low-mass neutralinos & charginos
- everything else decoupled
- $M_1, M_2, \mu, \tan\beta$ free
- m_h fixed to 125.09 GeV

$\rightarrow$ 3.3σ (local) combined signal significance

Electroweak analyses included in likelihood:

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- Assorted LEP likelihoods
- h/Z invisible widths

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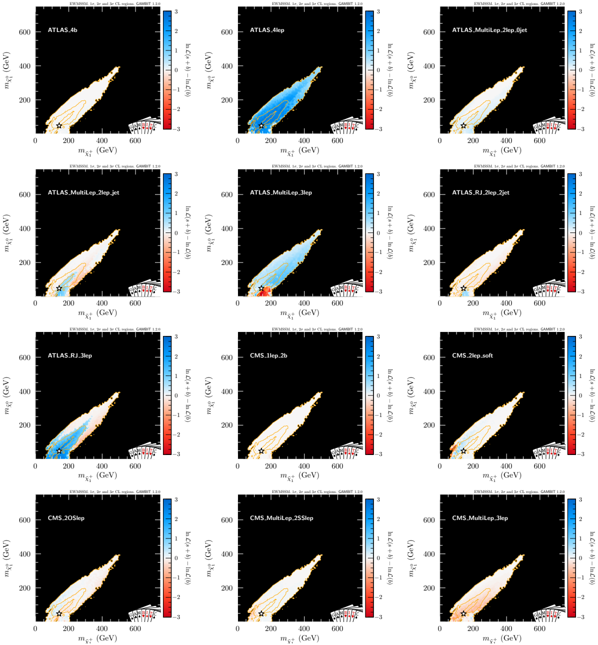
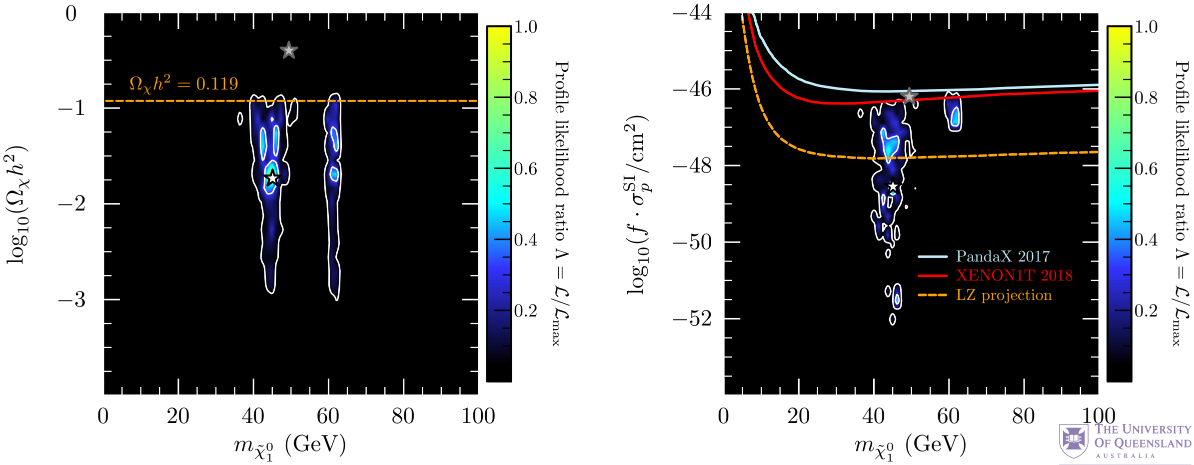
Likelihood contributions of individual analyses



Just taking the points within our 3σ regions for the LHC-only fit:



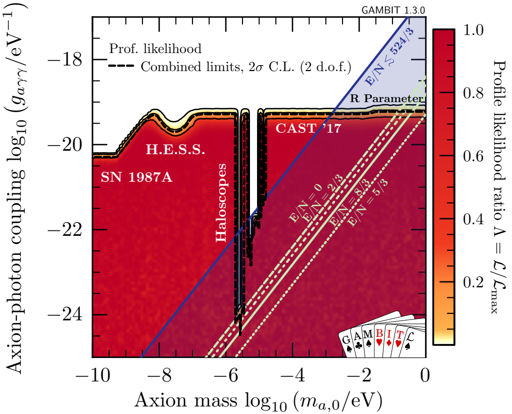
Z and h funnel mechanisms can give sensible relic densities

Parameters:

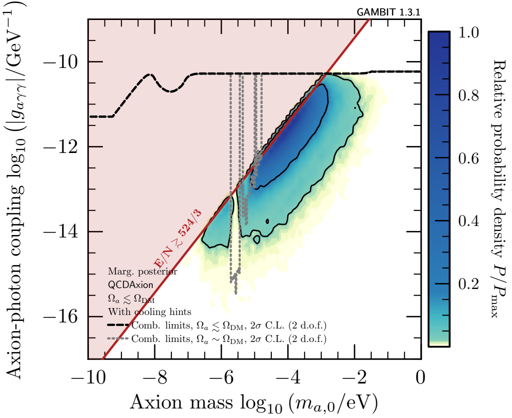
- couplings $g_{a\gamma\gamma}$ + g_{aee}
- decay constant f_a
- initial misalignment angle θ_i
- zero-temperature mass $m_{a,0}$
- $2\times$ nuisance parameters for T-dependence of mass

Likelihoods:

- Light shining through wall: ALPS
- Helioscopes: CAST(2007), CAST(2017)
- Haloscopes: RBF, UF, ADMX(1998-2009), ADMX(2018)
- DM relic density: *Planck*
- Astrophysics: HESS, SN1987a, HB/RGB stars (R parameter)



Bayesian analysis gives preferred axion mass range and couplings:
- small $m_a \Rightarrow$ fine-tuning in θ_i to avoid DM overproduction
- large $m_a \Rightarrow$ fine-tuning in E/N (i.e. $g_{a\gamma\gamma}$) to avoid experiments



(with log priors on f_a, C_{aee}; flat priors prefer lower masses)

Summary

- Global analyses complete for many models
- If DM is singlet Higgs portal & responsible for stabilising the EW vacuum, it is real not complex, and is already starting to appear in XENON1T data
- Supersymmetry is *not* "ruled out" by the LHC (quite the contrary) – and models that fit LHC excesses also fit dark matter
- The QCD axion mass is expected to be between 0.1 μeV and 10 meV ($10^{-7} - 10^{-2}$ eV)

- GAMBIT code is public: gambit.hepforge.org
- GAMBIT results, samples, run files, best fits, benchmarks, etc are *all* available to download from Zenodo: www.zenodo.org/communities/gambit-official/
- Coming soon: CosmoBit & GUM (GAMBIT direct from DM Lagrangian)

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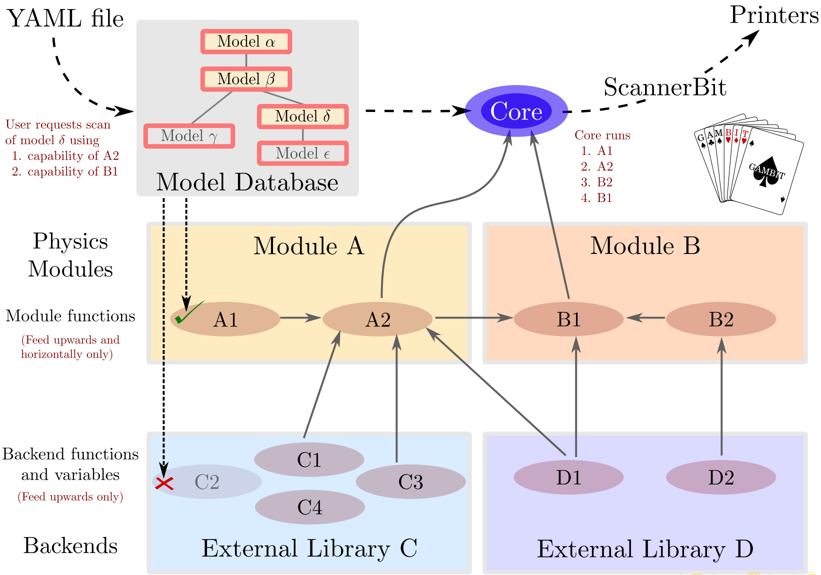
Backup slides

Functional overview of GAMBIT

(EPJC / arXiv:1705.07908)



Other nice technical features

- **Scanners**: Nested sampling, differential evolution, MCMC, T-walk, particle swarm, . . .
- Mixed-mode **MPI + openMP** parallelisation, mostly automated
  $\rightarrow$ scales to 10k+ cores
- **Automatic getters** for downloading, configuring + compiling backends
- **Currently interfaced backends**: `CalcHEP`, `Capt'n General`, `DDCalc`, `DarkSUSY`, `FeynHiggs`, `Flavio`, `gamLike`, `HepLike`, `HiggsBounds`, `HiggsSignals`, `Micromegas`, `nulike`, `Pythia8`, `SPheno`, `SUSYHD`, `SUSY-HIT`, `SuperIso`
- **BOSS**: dynamic loading of C++ classes from backend shared libraries (!)
- **All-in or module standalone** modes – easily implemented from single cmake script
- Diskless generalisation of various Les Houches Accords
- **Flexible output streams** (ASCII, databases, HDF5, . . .)
- Available as docker plugin or vagrant virtual machine
- more more more. . .

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Backends: mix and match

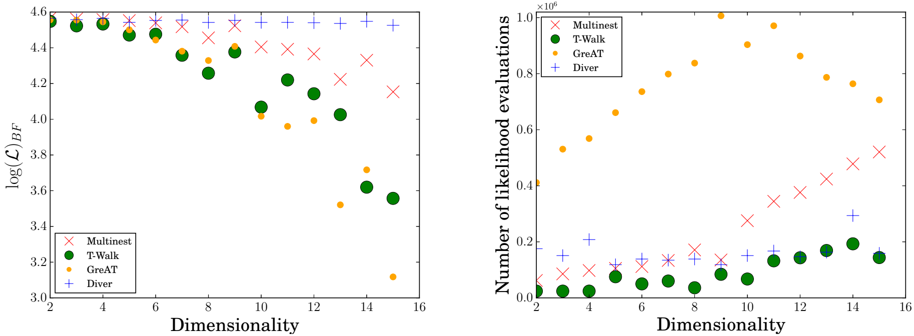
- Module functions can require specific functions from **backends**
- Backends are external code libraries (DarkSUSY, FeynHiggs, etc) that include different functions
- GAMBIT automates and abstracts the interfaces to backends $\rightarrow$ backend functions are tagged according to what they calculate
- $\rightarrow$ with appropriate module design, different backends and their functions can be used interchangeably
- GAMBIT dynamically adapts to use whichever backends are actually present on a user's system (+ provides details of what it decided to do of course)

Backends: mix and match

(EPJC / arXiv:1705.07908)

BACKENDS	VERSION	PATH TO LIB	STATUS	#FUNC	#TYPES	#CTORS
CaptnGeneral	1.0	Backends/installed/capgen/1.0/gencaplib.so	OK	4	0	0
DDCalc	1.0.0	Backends/installed/ddcalc/1.0.0/lib/libDDCalc.so	absent/broken	36	0	0
	1.1.0	Backends/installed/ddcalc/1.1.0/lib/libDDCalc.so	absent/broken	38	0	0
	1.2.0	Backends/installed/ddcalc/1.2.0/lib/libDDCalc.so	absent/broken	39	0	0
	2.0.0	Backends/installed/ddcalc/2.0.0/lib/libDDCalc.so	OK	50	0	0
DarkSUSY	5.1.3	Backends/installed/darksusy/5.1.3/lib/libdarksusy.so	OK	79	0	0
FeynHiggs	2.11.2	Backends/installed/feynhiggs/2.11.2/lib/libFH.so	absent/broken	14	0	0
	2.11.3	Backends/installed/feynhiggs/2.11.3/lib/libFH.so	OK	14	0	0
	2.12.0	Backends/installed/feynhiggs/2.12.0/lib/libFH.so	absent/broken	14	0	0
Flavio	0.30.0	Backends/installed/Flavio/0.30.0/flavio/flavio	absent/broken	2	0	0
HepLike	1.0	build/heplike_1.0-prefix/src/heplike_1.0-build/libHEPLike.so	OK	0	9	18
HepLikeData	1.0	Backends/installed/heplikedata/1.0	OK	0	0	0
HiggsBounds	4.2.1	Backends/installed/higgsbounds/4.2.1/lib/libhiggsbounds.so	absent/broken	10	0	0
	4.3.1	Backends/installed/higgsbounds/4.3.1/lib/libhiggsbounds.so	OK	10	0	0
HiggsSignals	1.4	Backends/installed/higgssignals/1.4.0/lib/libhiggssignals.so	OK	12	0	0
LibFarrayTest	1.0	Backends/examples/libFarrayTest.so	OK	10	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
LibSecond	1.0	Backends/examples/libsecond/1.0/libsecond_1_0.py	needs Python 2	6	0	0
	1.1	Backends/examples/libsecond/1.1/libsecond_1_1.py	OK	6	0	0
	1.2	Backends/examples/libsecond/1.2/libsecond_1_2.py	OK	6	0	0
LibThird	1.0	Backends/examples/libthird/1.0/libthird_1_0	needs Python 2	8	0	0
	1.1	Backends/examples/libthird/1.1/libthird_1_1	OK	6	0	0
	1.2	Backends/examples/libthird/1.2/libthird_1_2	OK	6	0	0
MicrOmegas_DiracSingletDM_Z2	3.6.9.2	Backends/installed/micromegas/3.6.9.2/DiracSingletDM_Z2/libmicromegas.so	OK	20	0	0
MicrOmegas_MSSM	3.6.9.2	Backends/installed/micromegas/3.6.9.2/MSSM/libmicromegas.so	absent/broken	19	0	0
MicrOmegas_MajoranaSingletDM_Z2	3.6.9.2	Backends/installed/micromegas/3.6.9.2/MajoranaSingletDM_Z2/libmicromegas.so	absent/broken	20	0	0
MicrOmegas_ScalarSingletDM_Z2	3.6.9.2	Backends/installed/micromegas/3.6.9.2/ScalarSingletDM_Z2/libmicromegas.so	absent/broken	20	0	0
MicrOmegas_ScalarSingletDM_Z3	3.6.9.2	Backends/installed/micromegas/3.6.9.2/ScalarSingletDM_Z3/libmicromegas.so	absent/broken	20	0	0
MicrOmegas_VectorSingletDM_Z2	3.6.9.2	Backends/installed/micromegas/3.6.9.2/VectorSingletDM_Z2/libmicromegas.so	absent/broken	20	0	0
Pythia	8.212	Backends/installed/pythia/8.212/lib/libpythia8.so	OK	0	28	109

Extensive scanner tests on scalar singlet model with different numbers of nuisance parameters



Diver scales far better with dimensionality than MultiNest or other scanners

Adding a new module function is easy:

1. Declare the function to GAMBIT in a module's **rollcall header**
    - Choose a capability
    - Declare any **backend requirements**
    - Declare any **dependencies**
    - Declare any specific **allowed models**
    - other more advanced declarations also available

```
#define MODULE FlavBit                          // A tasty GAMBIT module.
START_MODULE

  #define CAPABILITY Rmu                        // Observable: BR(K->mu nu)/BR(pi->mu nu)
  START_CAPABILITY
    #define FUNCTION SI_Rmu                     // Name of a function that can compute Rmu
    START_FUNCTION(double)                      // Function computes a double precision result
    BACKEND_REQ(Kmunu_pimunu, (my_tag), double, (const parameters*)) // Needs function from a backend
    BACKEND_OPTION( (SuperIso, 3.6), (my_tag) )                      // Backend must be SuperIso 3.6
    DEPENDENCY(SuperIso_modelinfo, parameters)  // Needs another function to calculate SuperIso info
    ALLOW_MODELS(MSSM63atQ, MSSM63atMGUT)       // Works with weak/GUT-scale MSSM and descendents
    #undef FUNCTION
  #undef CAPABILITY
```

2. Write the function as a standard C++ function (one argument: the result)

Expansion: adding new models

1. Add the model to the **model hierarchy**:
   - Choose a model name, and declare any **parent model**
   - Declare the model's parameters
   - Declare any **translation function** to the parent model

```
#define MODEL NUHM1
#define PARENT NUHM2
  START_MODEL
  DEFINEPARS(M0,M12,mH,A0,TanBeta,SignMu)
  INTERPRET_AS_PARENT_FUNCTION(NUHM1_to_NUHM2)
#undef PARENT
#undef MODEL
```

2. Write the translation function as a standard C++ function:

```
void MODEL_NAMESPACE::NUHM1_to_NUHM2 (const ModelParameters &myP, ModelParameters &targetP)
{
   // Set M0, M12, A0, TanBeta and SignMu in the NUHM2 to the same values as in the NUHM1
   targetP.setValues(myP,false);
   // Set the values of mHu and mHd in the NUHM2 to the value of mH in the NUHM1
   targetP.setValue("mHu", myP["mH"]);
   targetP.setValue("mHd", myP["mH"]);
}
```

3. If needed, declare existing or new module functions to work with the new model.

Interface: yaml file

Basic interface for a scan is a YAML initialisation file

- specify parameters, ranges, priors
- select likelihood components
- select other observables to calculate
- define generic rules for how to fill dependencies
- define generic rules for options to be passed to module functions
- set global options (scanner, errors/warnings, logging behaviour, etc)


```yaml
Parameters:
  StandardModel_SLHA2: !import StandardModel_SLHA2_defaults.yaml
  MSSM25atQ: !import LesHouches.in.MSSM_1.yaml

Priors:
    # none: all parameters fixed in this example.

Scanner:

  use_scanner: toy_mcmc

  scanners:
    toy_mcmc:
      plugin: toy_mcmc
      point_number: 2000
      output_file:  output
      like:  Likelihood

ObsLikes:

  # Test DecayBit
  - purpose:      Test
    capability:   decay_rates
    type:         DecayTable

  # 79-string IceCube likelihood
  - capability: IceCube_likelihood
    purpose: Likelihood
    function: IC79_loglike

Rules:

  - capability: MSSM_spectrum
    function: get_MSSMatQ_spectrum
    options:
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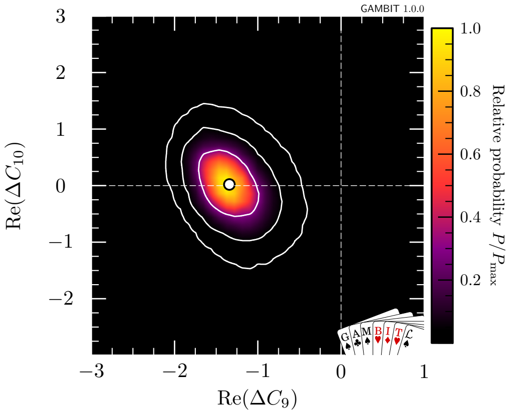
GAMBIT flavour EFT global fit:
$\mathcal{O}_7$ (photons)
$\mathcal{O}_9$ (leptons, vector)
$\mathcal{O}_{10}$ (leptons, axial-vector)



Flavour likelihoods in GAMBIT:

- $(g-2)_\mu$
- $B \to X_s \gamma$
- $B \to \mu\mu$
- $B_s \to \mu\mu$
- $B \to K^* \mu\mu$ + angular observables
- $B \to \tau\nu$
- $B \to D\mu\nu$
- $B \to D\tau\nu$
- $B \to D^*\mu\nu$
- $B \to D^*\tau\nu$
- $D \to \mu\nu$
- $D_s \to \mu\nu$
- $D_s \to \tau\nu$
- $\dfrac{\mathcal{B}(K \to \mu\nu)}{\mathcal{B}(\pi \to \mu\nu)}$

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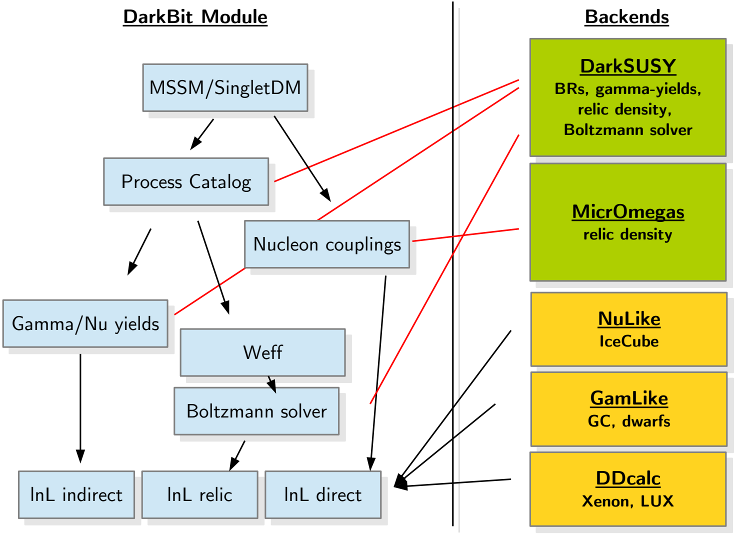
DarkBit overview



Backends – gamLike

C++ library with simple interface to most relevant likelihood functions from Fermi LAT and IACTs

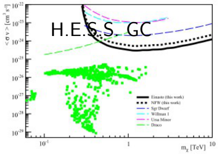
Particle physics input:

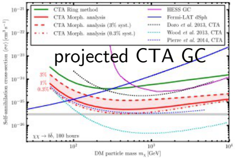
$$\frac{1}{m_\chi^2}\frac{d\sigma v}{dE}(v,E)$$

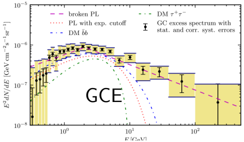
Output: lnL

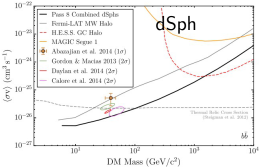
Uncertainties in the DM distribution (or astrophysical foregrounds) are internally marginalized over.

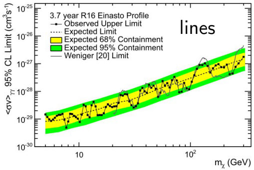
Correct treatment of energy dispersion and spectral singularities (lines, virtual internal Bremsstrahlung, boxes).











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