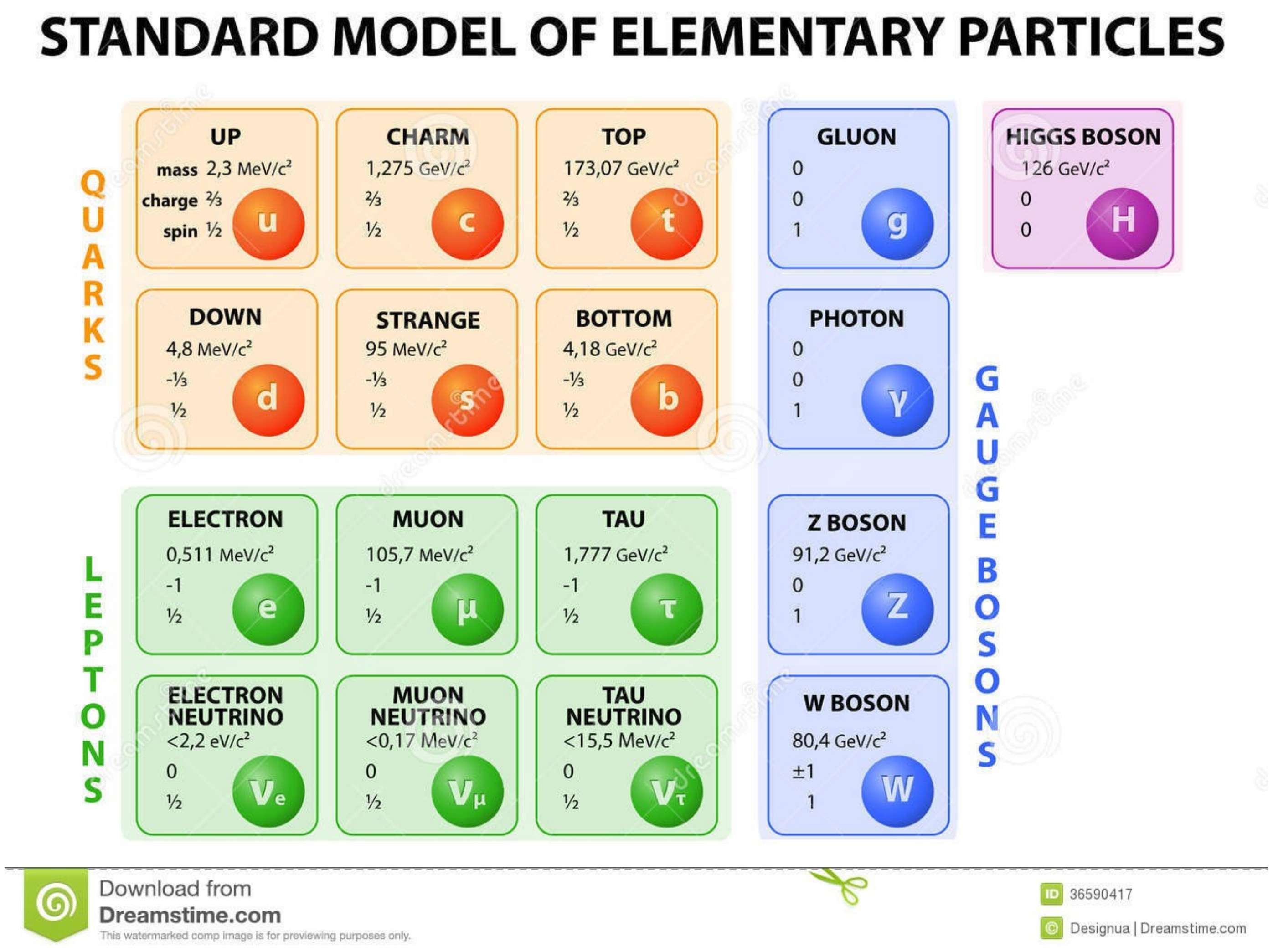
GAMBIT

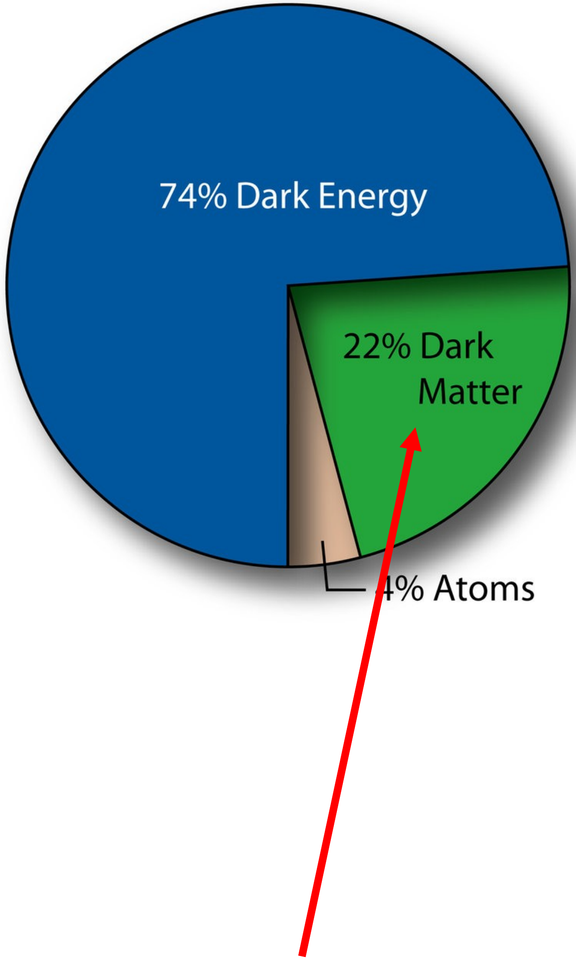
(Global and Modular BSM Inference Tool)

Prof Martin White

QCHSC 2024

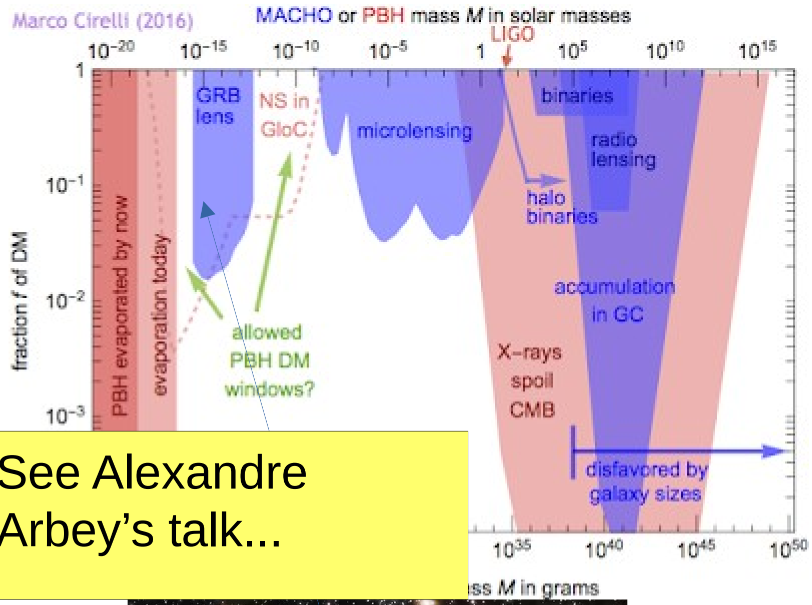
What we know and don't know



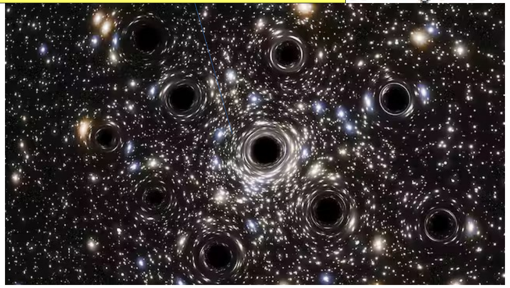


Need beyond-Standard Model (BSM) physics...

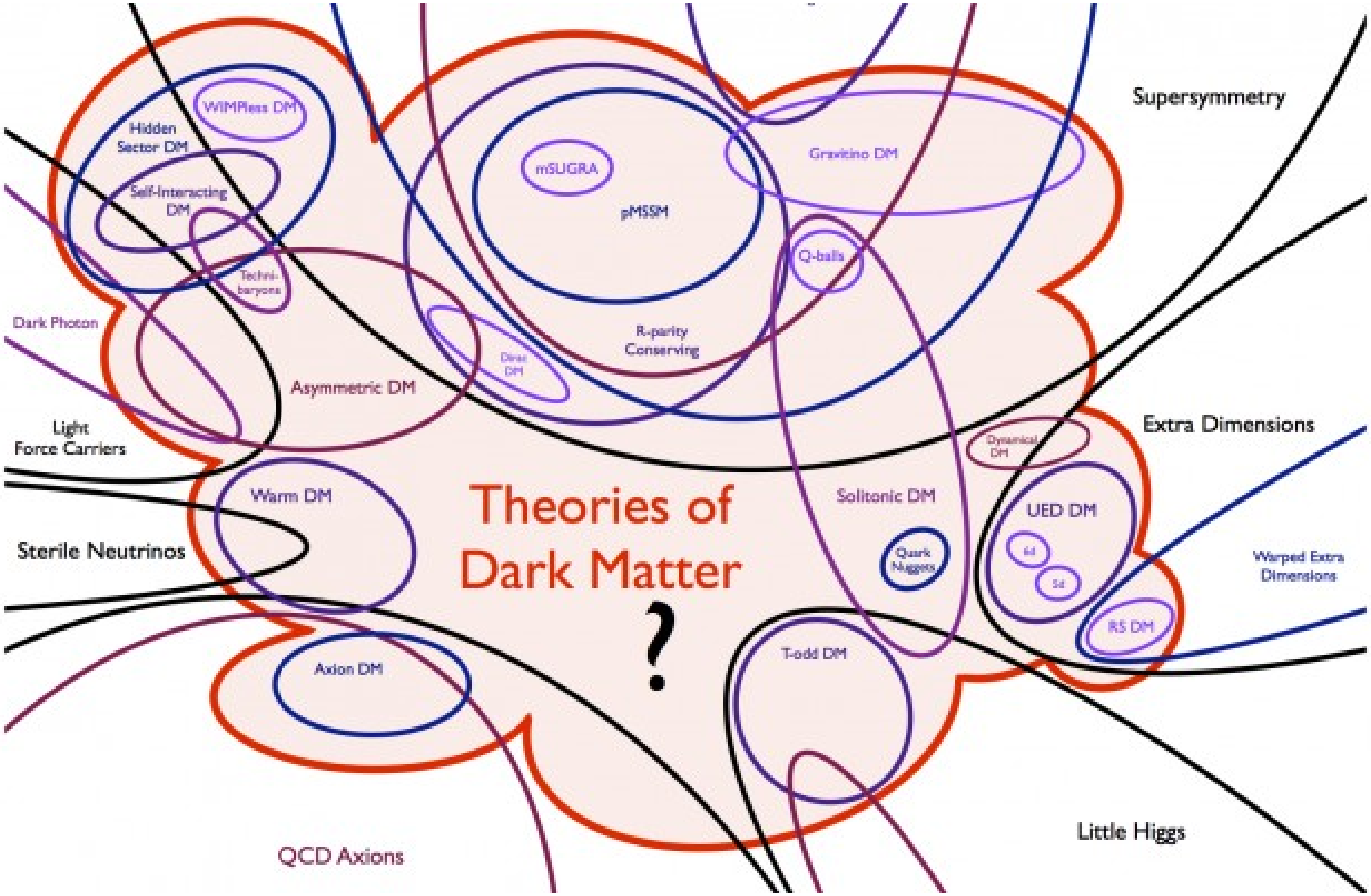
The dark sector might be very complicated



See Alexandre Arbey's talk...



See e.g. 1907.06485



Places where BSM physics might appear

- low-energy accelerators
- measurements of the magnetic moment of the muon
- beam dump/fixed target
- electroweak precision tests
- dark matter direct detection experiments
- searches for antimatter in cosmic rays
- nuclear cosmic ray ratios
- radio astronomy data
- effects of dark matter on reionisation, recombination and helioseismology
- the observed dark matter cosmological abundance
- neutrino masses and mixings
- gamma ray searches (e.g. FERMI-LAT, HESS, CTA, etc)

How to validate new theories

- Correct answer is to use a global statistical fit
- Frequentist or Bayesian methods available
- Calculate a **combined likelihood**:

$$\mathcal{L} = \mathcal{L}_{\mathrm{collider}} \mathcal{L}_{\mathrm{DM}} \mathcal{L}_{\mathrm{flavor}} \mathcal{L}_{\mathrm{EWPO}} \cdots$$

<u>Parameter estimation</u>

Given a particular model, which set of parameters best fits the available data

(Rigorous exclusion limits and parameter measurements)

<u>Model comparison</u>

Given a set of models, which is the best description of the data, and how much better is it?

(Model *X* is now worse than model *Y*)

The dream

Global fit results

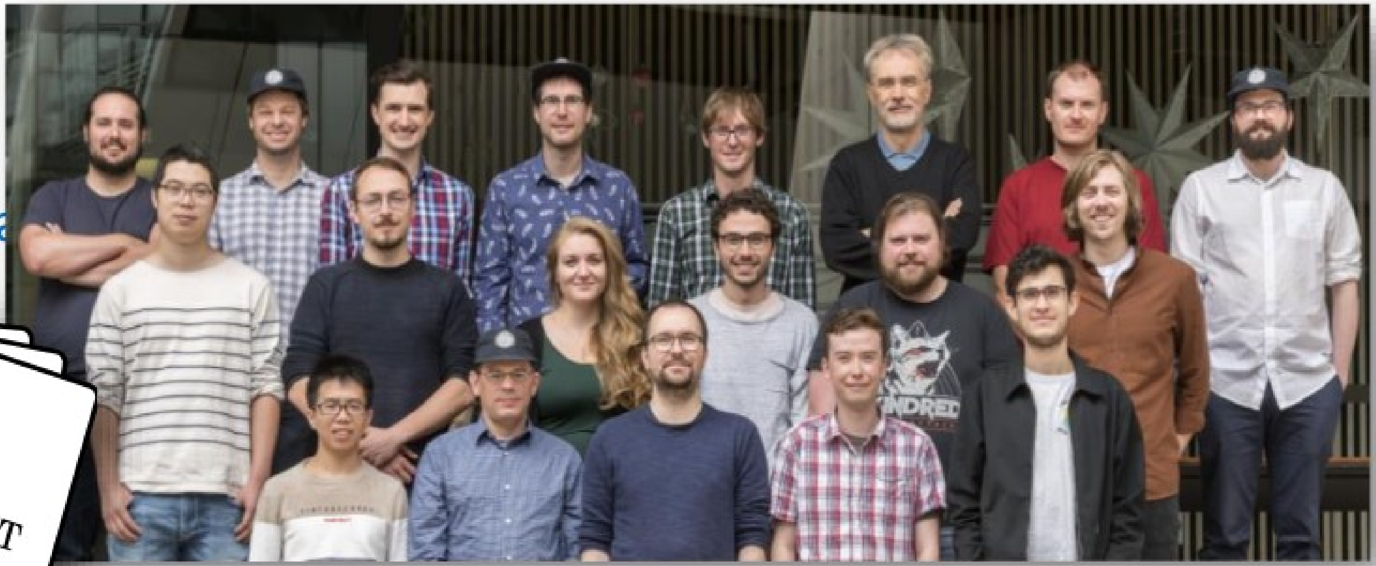
- A general global fit tool requires some very tricky innovations:

  - calculations are not allowed to know about Lagrangian parameters – how do you do that?
  - how do you make an easy interface for tying existing code together?
  - how do you store parameters in a scale independent way, but reintroduce scales in calculations?
  - how do you make LHC constraints model independent?
  - how do you make astrophysical constraints model independent?
  - ***how do we do all of this fast enough to get convergence within the age of the universe?***

GAMBIT: The Global And Modular BSM Inference Tool

gambitbsm.org github.com/GambitBSM EPJC 77 (2017) 784 arXiv:1705.07908

- Extensive model database, beyond SUSY
- Fast definition of new datasets, theories
- Extensive observable/data libraries
- Plug&play scanning/physics/likelihood packa
- Various statistical options (frequentist /Bayesian)
- Fast LHC likelihood calculator
- Massively parallel
- Fully open-source



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

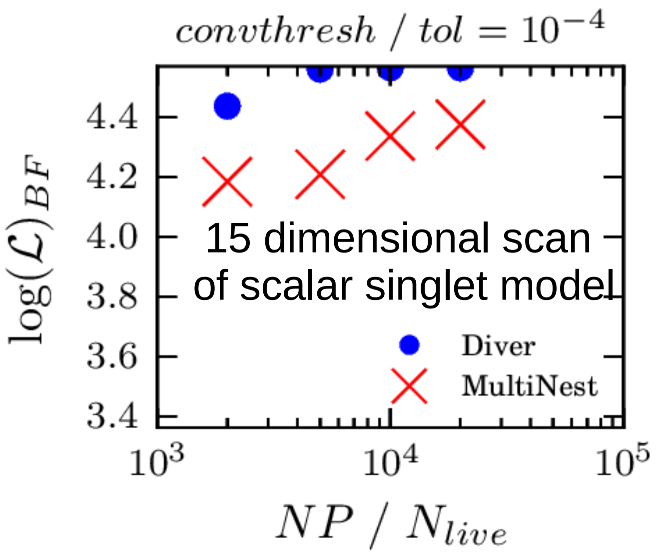
Authors of: BubbleProfiler, Capt'n General, Contur, DarkAges, DarkSUSY, DDCalc, DirectDM, Diver, EasyScanHEP, ExoCLASS, FlexibleSUSY, gamLike, GM2Calc, HEPLike, IsaTools, MARTY, nuLike, PhaseTracer, PolyChord, Rivet, SOFTSUSY, SuperIso, SUSY-AI, xsec, Vevacious, WIMPSim

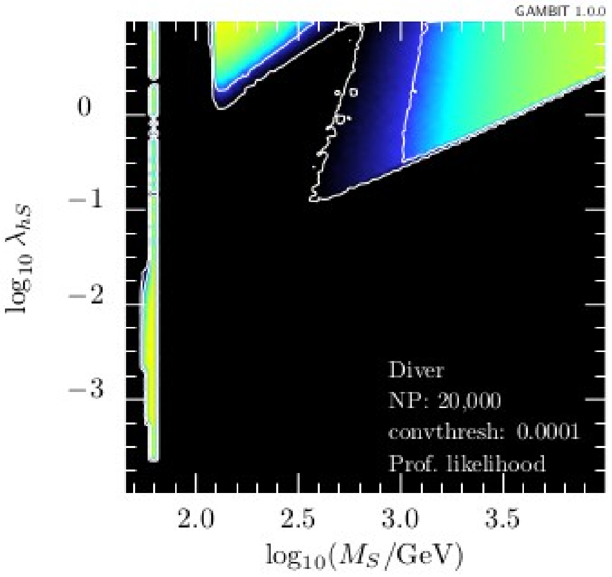
Recent collaborators: V Ananyev, P Athron, N Avis-Kozar, C Balázs, A Beniwal, LL Braseth, T Bringmann, A Buckley, J Butterworth, JE Camargo-Molina, C Chang, J Cornell, M Danninger, A Fowlie, T Gonzalo, W Handley, S Hoof, A Jueid, F Kahlhoefer, A Kvellestad, M Lecroq, C Lin, M Lucente, FN Mahmoudi, DJE Marsh, G Martinez, H Pacey, MT Prim, T Procter, F Rajec, A Raklev, R Ruiz, A Scaffidi, P Scott, W Shorrock, C Sierra, P Stöcker, W Su, J Van den Abeele, A Vincent, M White, A Woodcock, Y Zhang ++

70+ participants in many experiments and numerous major theory codes

Global

- Complete global statistical fit framework
- Can be Bayesian, Frequentist or other (random, grid, etc)
- Interfaced to the best + fastest scanners available: Multinest, MCMC, Diver (new differential evolution scanner)



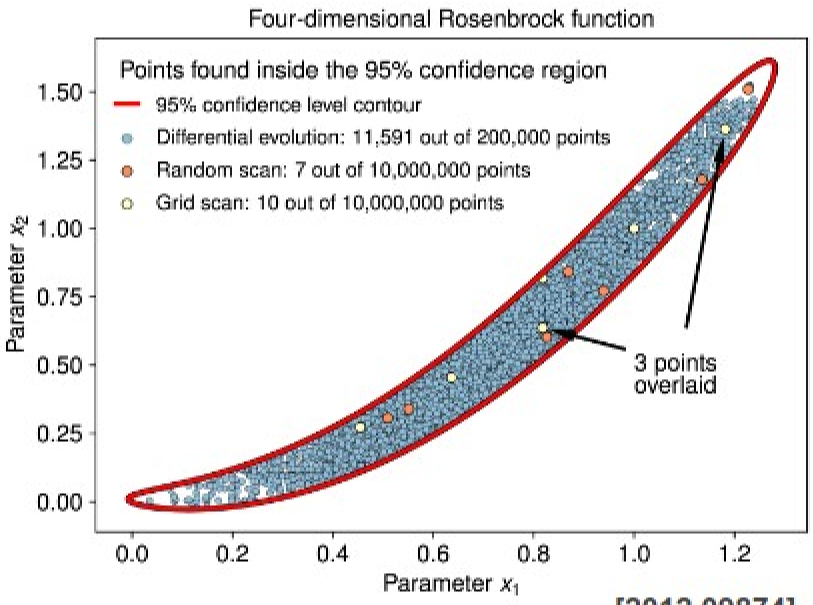


Publication ready plots available using *pippi* plotting code on the GAMBIT HDF5 output

Sampling for global fits

Why the need for speed?

- First, BSM parameter spaces are **high-dimensional**!
  - And theorists have limited CPU resources :)
- Second, in **global fits** we seek statistically rigorous conclusions about **regions of BSM parameter spaces**
  - Need properly **converged** explorations of the **likelihood function / posterior distribution**
  - Must use **adaptive sampling algorithms**, that focus on higher-likelihood regions
  - So the problem is **not trivially parallelisable** (we can't just sample first, simulate later)

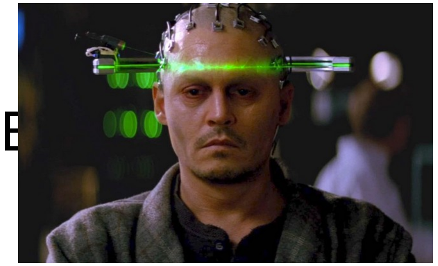


[2012.09874]

See https://arxiv.org/abs/2309.01454 for MCMC+diffusion model!
See also: https://raw.githubusercontent.com/williamjameshandley/talks/munich_2024/will_handley_munich_2024.pdf

Global and Modular

- **ColliderBit:** collider observables including Higgs + SUSY Searches from ATLAS, CMS, LEP
- **DarkBit:** dark matter observables (relic density, direct & indirect detection)
- **FlavBit:** including $g-2$, $b \to s\gamma$, B decays (new channels), angular obs., theory unc., LHCb likelihoods
- **SpecBit:** generic BSM spectrum object, providing RGE running, masses, mixings
- **DecayBit:** decay widths for all relevant SM and BSM particles
- **PrecisionBit:** precision EW tests (mostly via interface to FeynHiggs or SUSY-POPE
- **ScannerBit:** manages stats, sampling and optimisation
- **CosmoBit:** cosmological observables (e.g. BAO, CMB)



What's in a module?

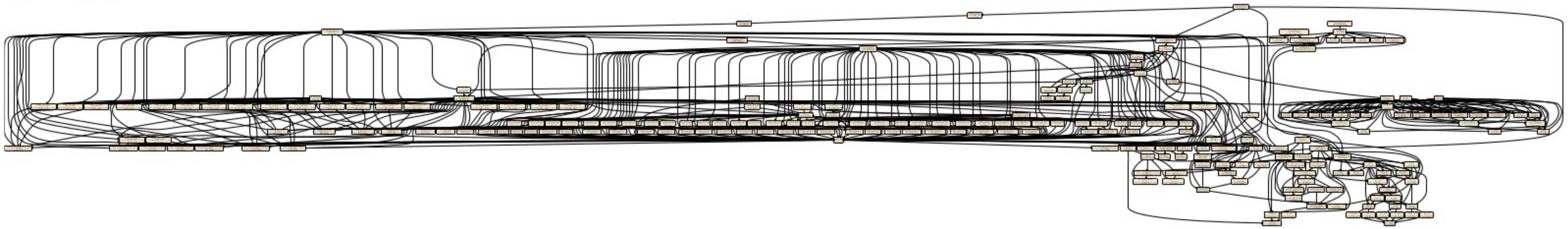
- Module functions (actual bits of GAMBIT C++ code)
- These can depend on other module functions
- Or can they can depend on *backends*(external codes)
- Adding new things is ***easy*** (detailed manual)
- Hooking up new backends or swapping them is ***easy***
- Module functions are **tagged** according to what they can calculate → plug and play!

How does GAMBIT work?

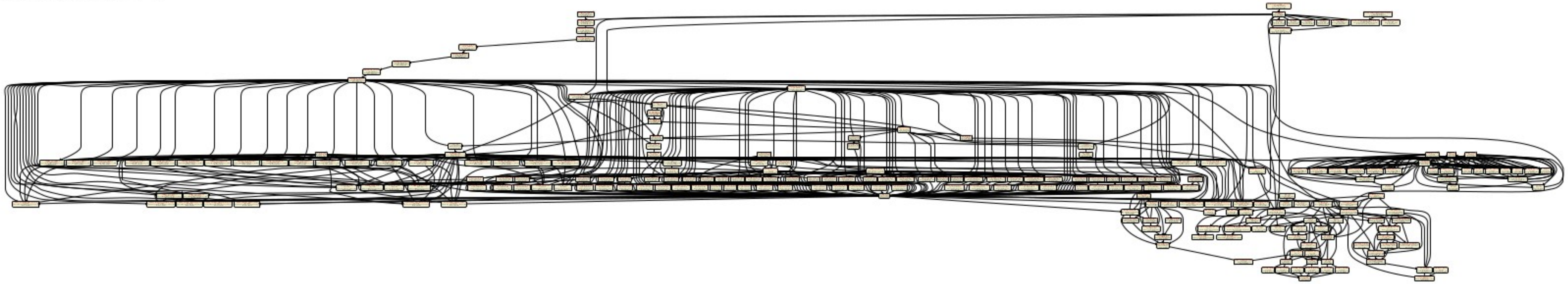
- You specify what to calculate and how (yaml input file)
- GAMBIT checks to see which functions can do it
- A dependency resolver stitches things together in the right order, and calculations are also ordered by speed
- GAMBIT performs the scan and writes output
- Pippi makes the plots
- You(r student) write(s) the paper

Dependency resolution in action

CMSSM:



MSSM7:



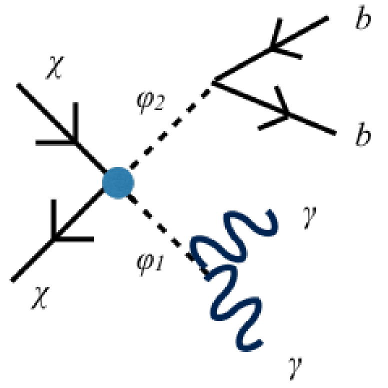
ColliderBit

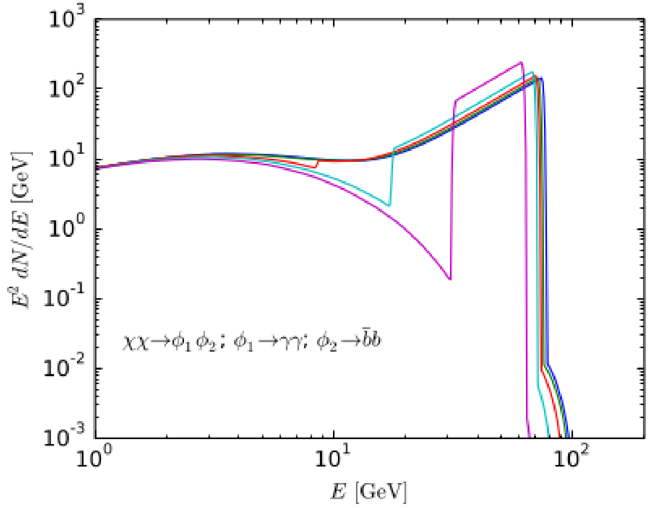
- Handles LHC and LEP limits
- LEP: complete recast of sparticle xsec limits
- SUSY & Exotic LHC search limits from real-time MC simulation
- LHC resonance search limits from HiggsBounds+HiggsSignals
- ATLAS/CMS phase space measurements via Contur
- Model-independent ATLAS/CMS search limits via Pythia + custom detector simulation and analysis

DarkBit: indirect detection

Gamma rays:

- Theoretical spectra calculated using branching fractions and tabulated gamma-ray yields
- Non-SM final state particles and Higgs are decayed on the fly with cascade Monte Carlo
- gamLike (gamlike.hepforge.org): New standalone code with likelihoods for DM searches from Fermi-LAT (dwarf spheroidals, galactic centre) and H.E.S.S. (galactic halo)



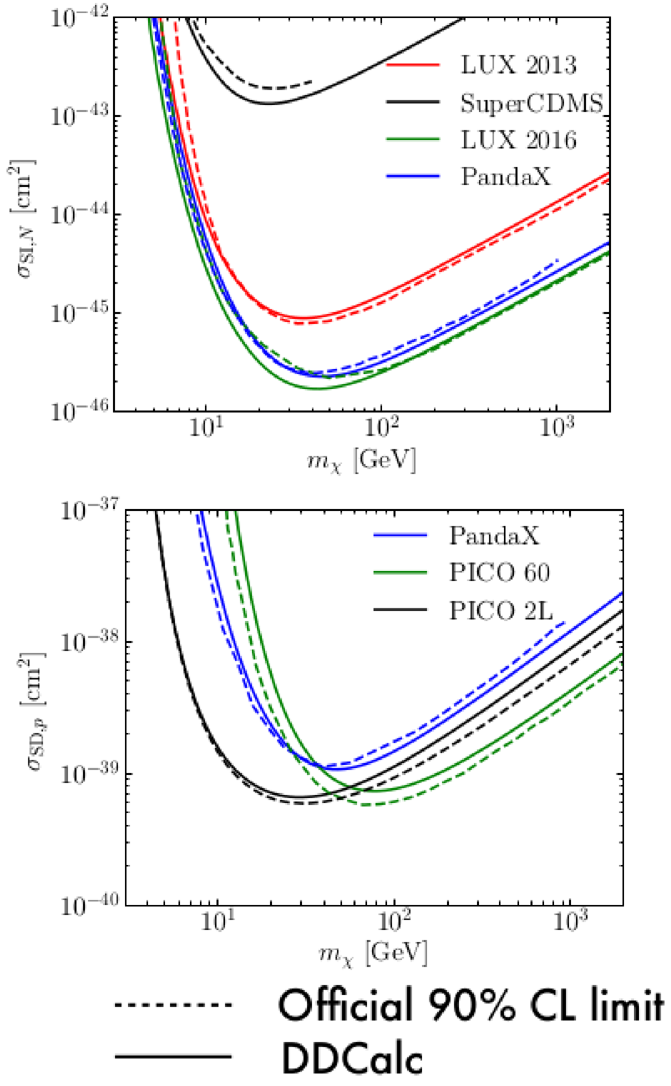


Solar neutrinos:

- Yields from DM annihilation in sun calculated by DarkSUSY. IceCube likelihoods contained in nulike (nulike.hepforge.org) standalone code.

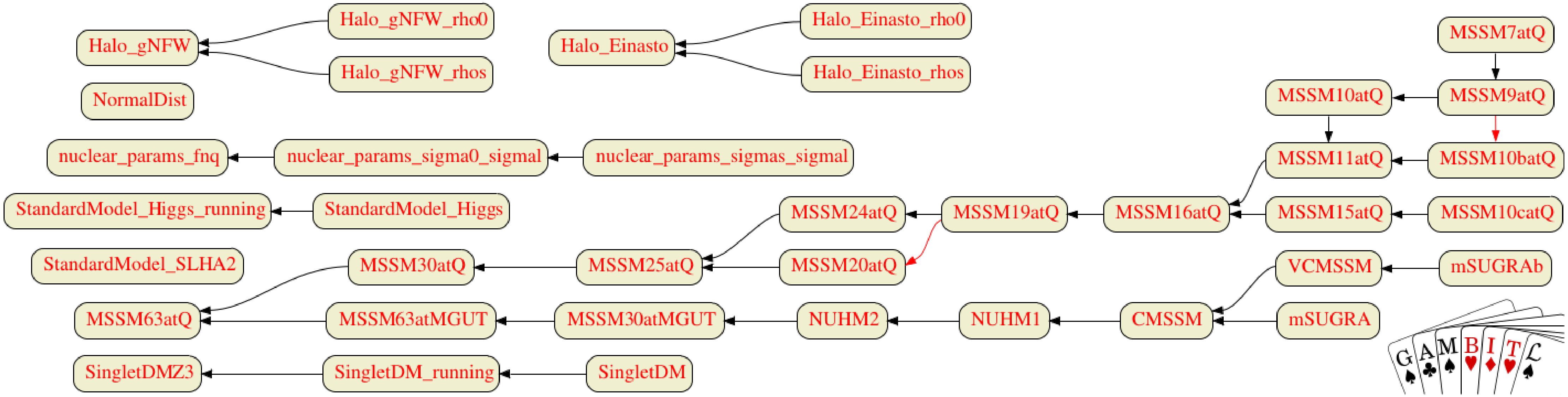
DarkBit: direct detection

- In parallel with GAMBIT, we introduce *DDCalc* (ddcalc.hepforge.org), a tool to calculate event rates and complete likelihood functions for direct detection experiments taking into account:
  - A mix of both spin-independent and dependent contributions to the scattering rate.
  - Halo parameters (local density, DM velocity dispersion, etc.) chosen by the user.
- We currently have implemented likelihoods for Xenon(1T, 100), LUX, PandaX, SuperCDMS, PICO(60, 2L), and SIMPLE



Global and Modular BSM

- Models are defined by their parameters and relations to each other
- Models can inherit from parent models, easy translation between relations



Global and Modular BSM Inference

Physics Analyses

- Collider constraints on electroweakinos in the presence of a light gravitino, Eur. Phys. J. C 83 (2023) 6, 493, arXiv:2303.09082.
  Supplementary data, including samples: DOI 10.5281/zenodo.7704832
- Global fits of simplified models for dark matter with GAMBIT II. Vector dark matter with an s-channel vector mediator, Eur.Phys.J.C 83 (2023) 8, 692, arXiv:2303.08351.
  Supplementary data, including samples: DOI 10.5281/zenodo.7710586
- Fast and accurate AMS-02 antiproton likelihoods for global dark matter fits, JCAP 08 (2023) 052, arXiv:2303.07362.
  Supplementary data, including samples: DOI 10.5281/zenodo.7952765
- Global fits of simplified models for dark matter with GAMBIT: I. Scalar and fermionic models with s-channel vector mediators, Eur. Phys. J. C 83 (2023) 3, 249, arXiv:2209.13266.
  Supplementary data, including samples: DOI 10.5281/zenodo.6615830
- Cosmological constraints on decaying axion-like particles: a global analysis, JCAP 12 (2022) 027, arXiv:2205.13549.
  Supplementary data, including samples: DOI 10.5281/zenodo.6573347
- Thermal WIMPs and the Scale of New Physics: Global Fits of Dirac Dark Matter Effective Field Theories, Eur. Phys. J. C 81 (2021) 11, 992, arXiv:2106.02056.
  Supplementary data, including samples: DOI 10.5281/zenodo.4836397
- Strengthening the bound on the mass of the lightest neutrino with terrestrial and cosmological experiments, Phys. Rev. D 103 (2021) 12, 123508, arXiv:2009.03287.
  Supplementary data, including samples: DOI 10.5281/zenodo.4005381
- Global fits of axion-like particles to XENON1T and astrophysical data, JHEP 05 (2021) 159, arXiv:2007.05517.
  Supplementary data, including samples: DOI 10.5281/zenodo.4384061
- A model-independent analysis of $b \to s\mu^+\mu^-$ transitions with GAMBIT's FlavBit, Eur. Phys. J. C 81 (2021), arXiv:2006.03489.
  Supplementary data, including samples: DOI 10.5281/zenodo.5749787
- A frequentist analysis of three right-handed neutrinos with GAMBIT, Eur. Phys. J. C 80 (2020) 6, 569, arxiv:1908.02302.
  Supplementary data, including samples: DOI 10.5281/zenodo.3334971
- Axion global fits with Peccei-Quinn symmetry breaking before inflation using GAMBIT, JHEP 03 (2019) 191, arXiv:1810.07192.
  Supplementary data, including samples: DOI 10.5281/zenodo.1423692
- Combined collider constraints on neutralinos and charginos, Eur. Phys. J. C 79 (2019) 395, arXiv:1809.02097.
  Supplementary data, including samples: DOI 10.5281/zenodo.1410335
- Global analyses of Higgs portal singlet dark matter models using GAMBIT, Eur. Phys. J. C 79 (2019) 38, arXiv:1808.10465.
  Supplementary data, including samples: DOI 10.5281/zenodo.1400654
- Impact of vacuum stability, perturbativity and XENON1T on global fits of Z_2 and Z_3 scalar singlet dark matter, Eur. Phys. J. C 78 (2018) 830, arXiv:1806.11281.
  Supplementary data, including samples: DOI 10.5281/zenodo.1298566
- A global fit of the MSSM with GAMBIT, Eur. Phys. J. C 77 (2017) 879, arXiv:1705.07917.
  Supplementary data, including samples: DOI 10.5281/zenodo.801639
- Global fits of GUT-scale SUSY models with GAMBIT, Eur. Phys. J. C 77 (2017) 824, arXiv:1705.07935.
  Supplementary data, including samples: DOI 10.5281/zenodo.801641
- Status of the scalar singlet dark matter model, Eur. Phys. J. C 77 (2017) 568, arXiv:1705.07931.
  Supplementary data, including samples: DOI 10.5281/zenodo.801510

- SM neutrino sector
- 2HDMs
- Updated DM EFT study
- SUSY after Run 2 of the LHC

Example: general approach to DM

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm int} + \overline{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi$$

$$\mathcal{L}_{\rm int} = \sum_{a,d} \frac{\mathcal{C}_a^{(d)}}{\Lambda^{d-4}} \mathcal{Q}_a^{(d)}$$

$$\mathcal{Q}_{1,q}^{(6)} = (\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu q)\,,$$
$$\mathcal{Q}_{2,q}^{(6)} = (\overline{\chi}\gamma_\mu\gamma_5\chi)(\overline{q}\gamma^\mu q)\,,$$
$$\mathcal{Q}_{3,q}^{(6)} = (\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu\gamma_5 q)\,,$$
$$\mathcal{Q}_{4,q}^{(6)} = (\overline{\chi}\gamma_\mu\gamma_5\chi)(\overline{q}\gamma^\mu\gamma_5 q)$$

$$\mathcal{Q}_1^{(7)} = \frac{\alpha_s}{12\pi}(\overline{\chi}\chi)G^{a\mu\nu}G^a_{\mu\nu}\,,$$
$$\mathcal{Q}_2^{(7)} = \frac{\alpha_s}{12\pi}(\overline{\chi}i\gamma_5\chi)G^{a\mu\nu}G^a_{\mu\nu}\,,$$
$$\mathcal{Q}_3^{(7)} = \frac{\alpha_s}{8\pi}(\overline{\chi}\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}\,,$$
$$\mathcal{Q}_4^{(7)} = \frac{\alpha_s}{8\pi}(\overline{\chi}i\gamma_5\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}\,,$$
$$\mathcal{Q}_{5,q}^{(7)} = m_q(\overline{\chi}\chi)(\overline{q}q)\,,$$
$$\mathcal{Q}_{6,q}^{(7)} = m_q(\overline{\chi}i\gamma_5\chi)(\overline{q}q)\,,$$
$$\mathcal{Q}_{7,q}^{(7)} = m_q(\overline{\chi}\chi)(\overline{q}i\gamma_5 q)\,,$$
$$\mathcal{Q}_{8,q}^{(7)} = m_q(\overline{\chi}i\gamma_5\chi)(\overline{q}i\gamma_5 q)\,,$$
$$\mathcal{Q}_{9,q}^{(7)} = m_q(\overline{\chi}\sigma^{\mu\nu}\chi)(\overline{q}\sigma_{\mu\nu}q)\,,$$
$$\mathcal{Q}_{10,q}^{(7)} = m_q(\overline{\chi}i\sigma^{\mu\nu}\gamma_5\chi)(\overline{q}\sigma_{\mu\nu}q)\,.$$

- Assume Dirac fermion gauge-singlet DM
- Note EFTs differ below and above EW scale, and are matched at that scale
- Ignore dim-6 operators with lepton interactions, also ignore operators with products of DM and Higgs currents above EW scale
- Drop additional dim-7 operators with derivatives (redundant information)

Scan details / constraints

- Have used differential evolution to scan over up to 24 parameters (DM mass, new physics scale, 14 Wilson coefficients, 8 nuisance parameters)

LHC

- New implementation of Madgraph-derived monojet simulations
- CMS and very recent ATLAS data
- Include interference effects

DIRECT DM

- Fully-automated RG evolution from Λ to low energies + matching to non-relativistic operators
- Data from Xenon1T, LUX (2016), PandaX (2016+2017) , CDMSLite, CRESST-II, CRESST-III, PICO-60 (2017+2019), DarkSide-50
- Include astrophysical and nuclear uncertainties

CMB

- Relic abundance constraint from Planck (2018). Separate scans cover cases where a) fermion is all of DM, b) fermion DM is a subcomponent
- Planck constraints on energy injection effects on the recombination history (also from Planck)

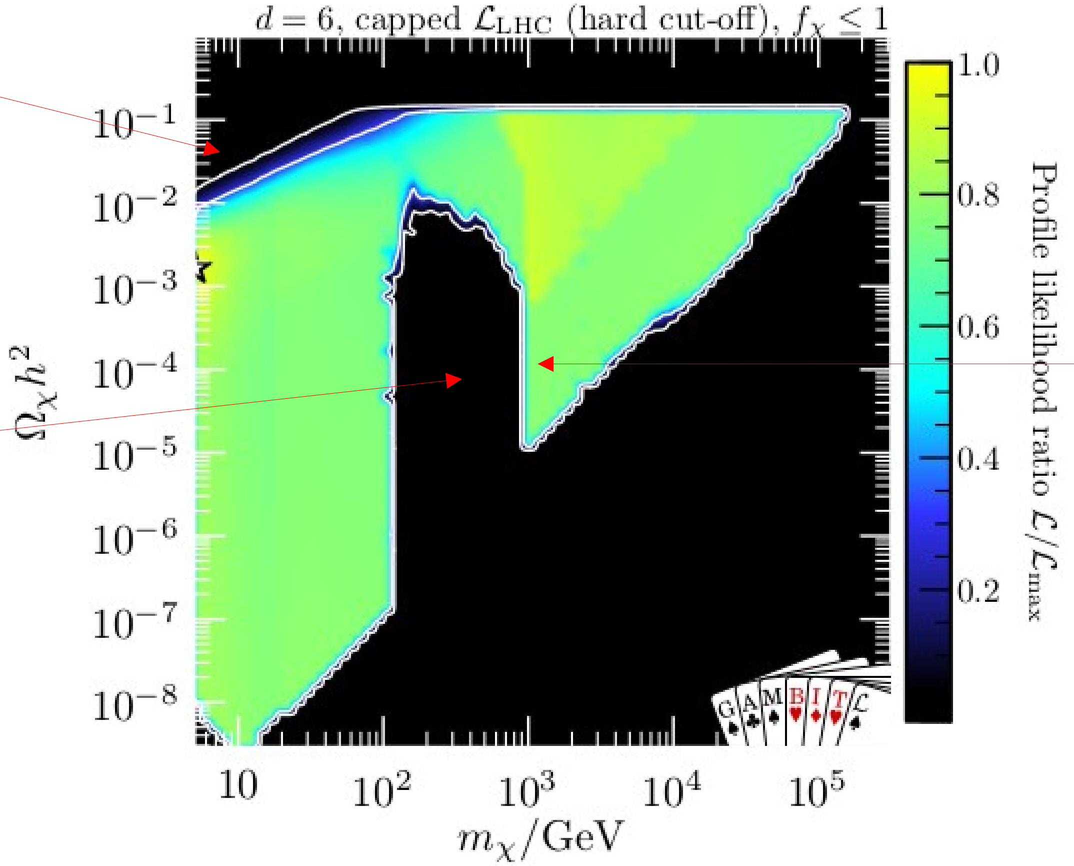
INDIRECT DM

- Automated calculation of cross-sections and γ-ray spectra using GUM
- Fermi-LAT dwarf spheroidal limits plus CTA projections
- Solar capture constraints using Capt'n General plus Icecube data

Results: Dim-6 scans

Cannot saturate relic density due to indirect and direct DM search constraints (but if DM is a subcomponent, these constraints are suppressed)

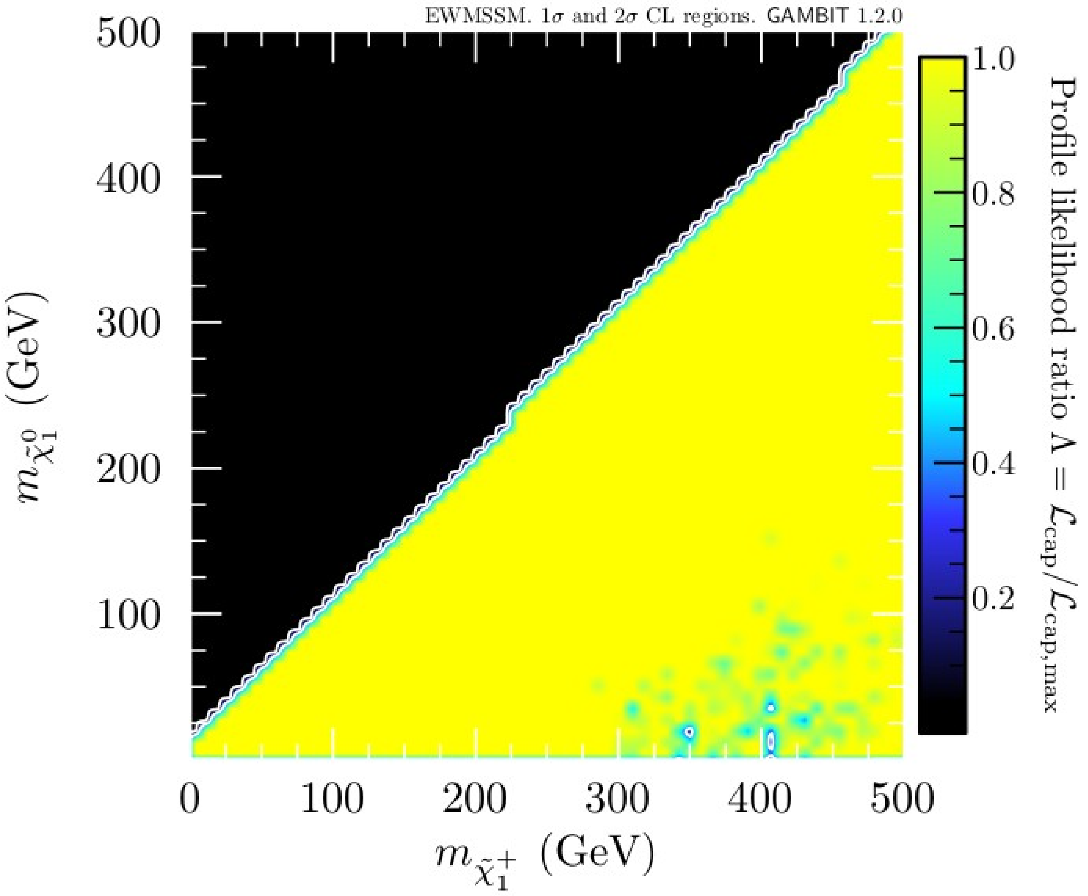
LHC constraints



LHC WIMP production cross-section drops

LHC constraints on SUSY (in 2017)

- We found ***no general constraint*** on the MSSM EW sector from the LHC in this case, and we also explained why (the searches are over-optimised on specific simplified SUSY models)
- New results are coming very soon, and the parameter space is starting to look more constrained...



Eur.Phys.J.C 79 (2019) 5, 395

Summary

- GAMBIT is an excellent tool for particle astrophysics studies
- Can currently handle constraints on generic theories of particle physics using a wide range of cosmology, astrophysics and particle physics data
- Many new results to come within the next few months (new papers on SUSY, neutrino physics and flavour physics are in the final stages of preparation)

Always looking for new collaborators (PhD, post-doc, junior, senior, exp, theory, pheno, whatever) … feel free to email martin.white@adelaide.edu.au