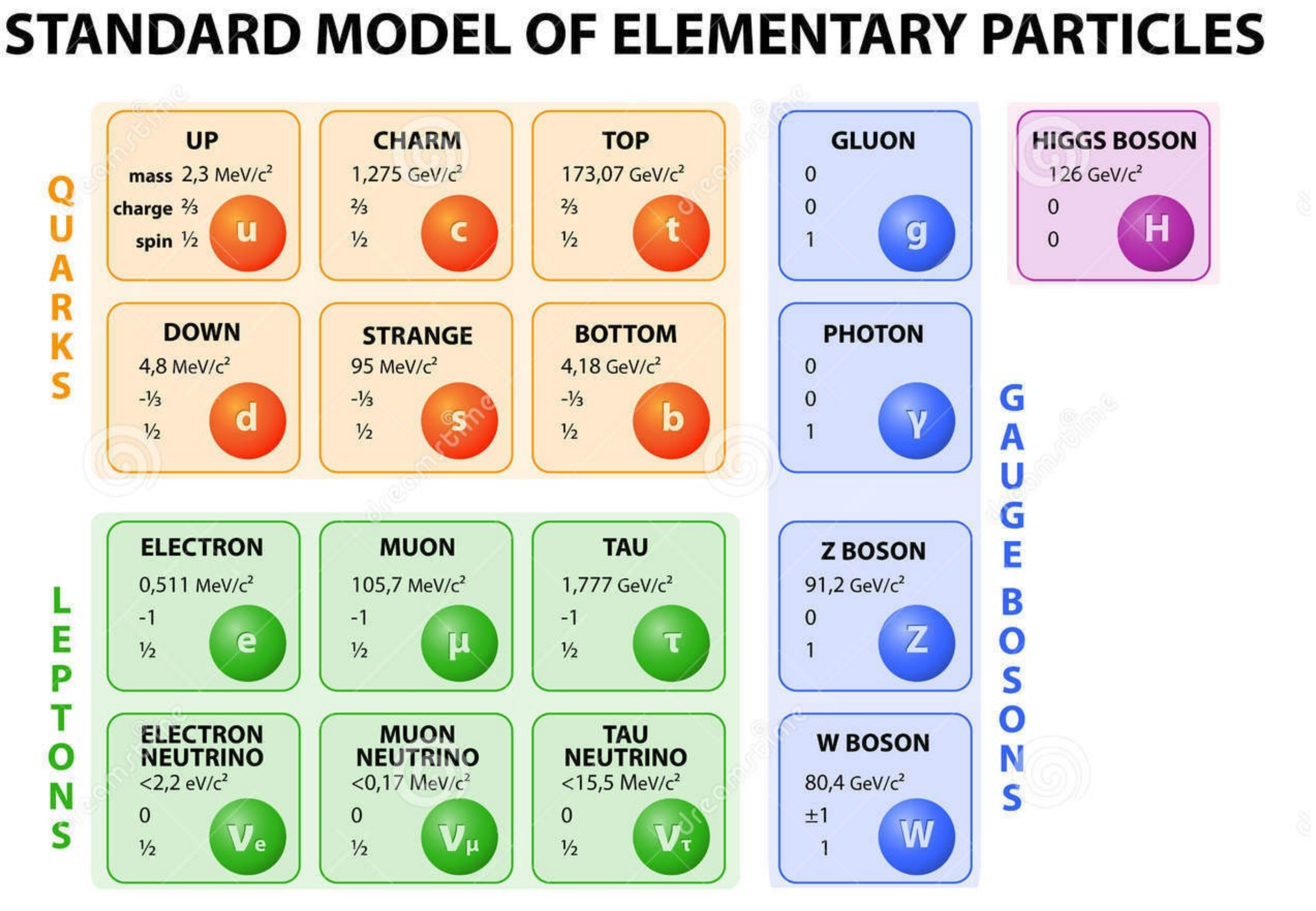
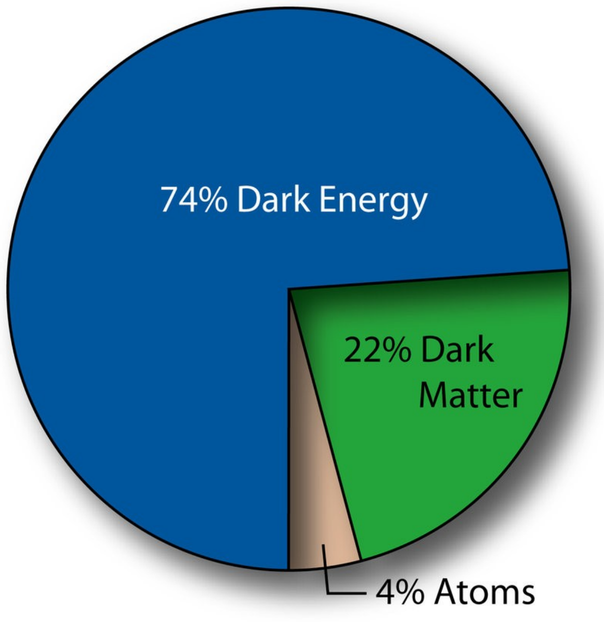
Dark matter constraints from GAMBIT

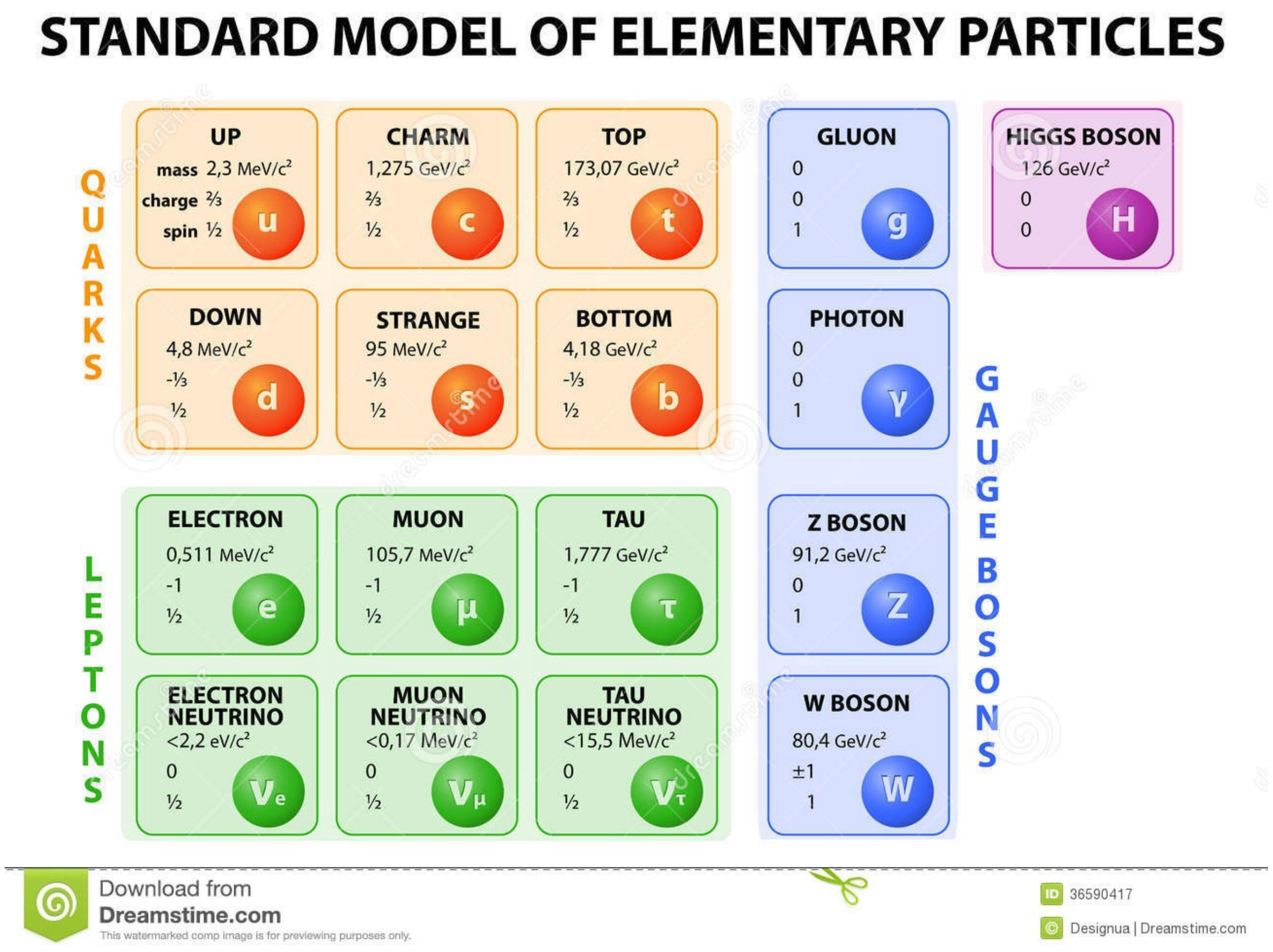
Martin White

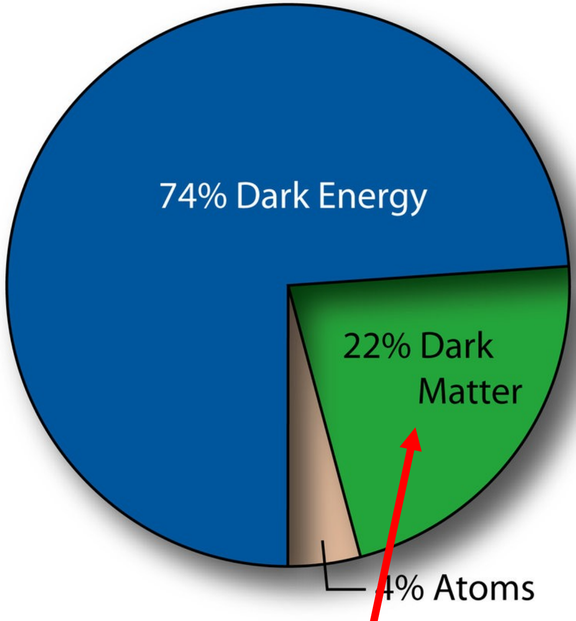
What we know and don't know





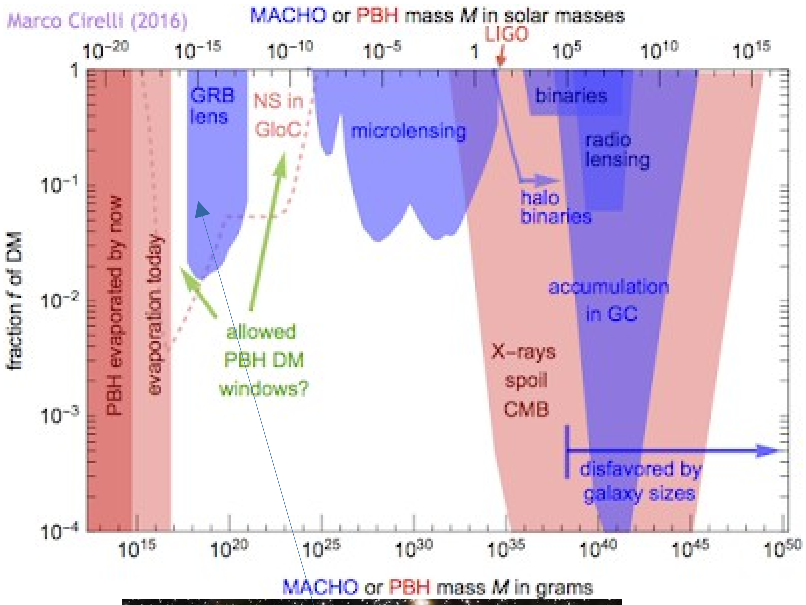
What we know and don’t know

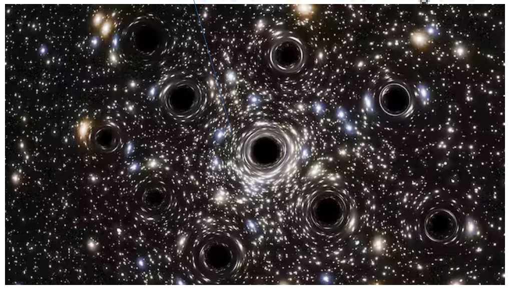


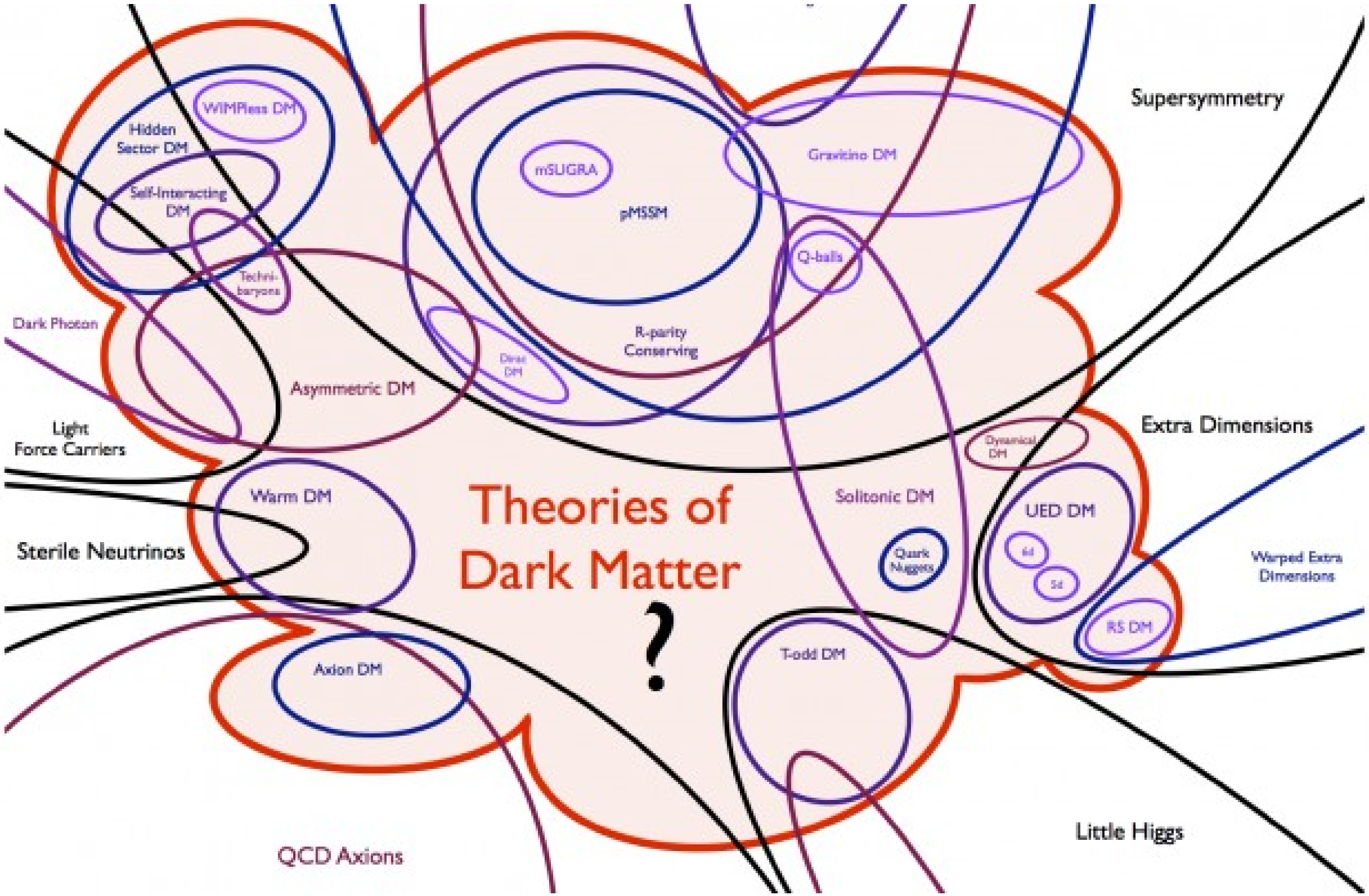


Need beyond-Standard Model (BSM) physics...

The dark sector might be very complicated





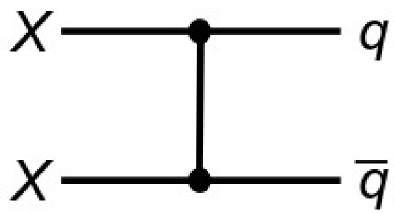


See e.g. 1907.06485

The “WIMP miracle”

- Get correct thermal relic abundance for DM with weak annihilation cross-section and mass ~100 GeV

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$



- Note: Need to measure $\langle \sigma v \rangle$ to rule out WIMP hypothesis

Making a WIMP theory

- Many theoretical options exist
- Bottom up approach: simply add particles to SM by hand, stabilise with a Z_2 symmetry

e.g. Scalar singlet DM

$$\mathcal{L} = \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\lambda_{hS} S^2 |H|^2 + \frac{1}{4}\lambda_S S^4 + \frac{1}{2}\partial_\mu S \partial^\mu S.$$

See e.g. 1907.06485, 1808.10465, 1705.07931, 1512.06458

- Top down approach: take a BSM model and exploit particles with the right properties

e.g. supersymmetric models, universal extra dimensions, little Higgs, some composite Higgs theories, etc

See e.g. 2309.05709, 2303.09082, 1809.02097, 1705.07917, 1705.07935

WIMP theories should show up in lots of places

- accelerators (LHC and previous, plus intensity frontier)
- 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
- indirect searches

How to test BSM physics models

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

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

Parameter estimation

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

(Rigorous exclusion limits and parameter measurements)

Model comparison

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

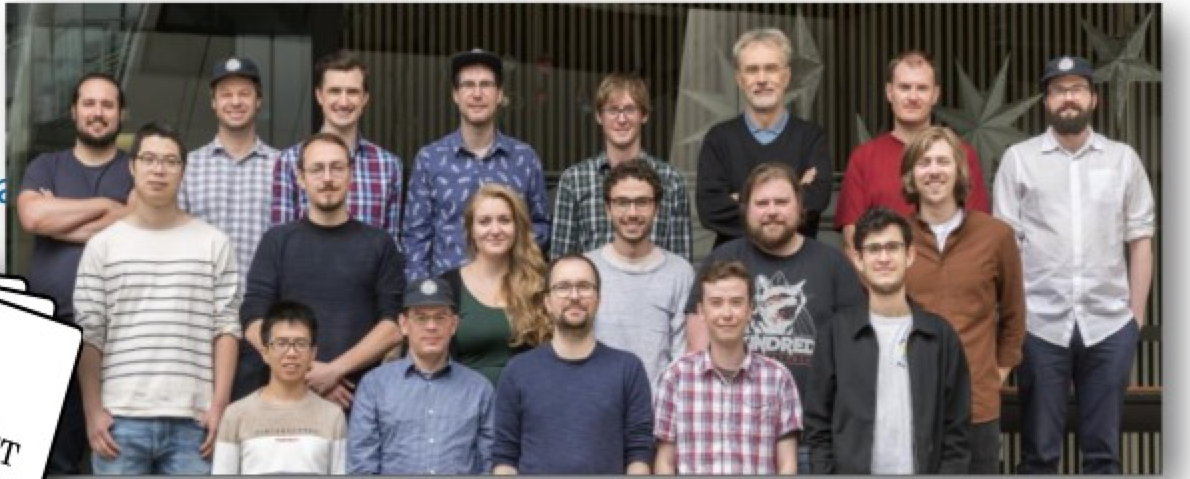
- A general global fit tool requires some very tricky innovations:

  - 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

gambit.hepforge.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



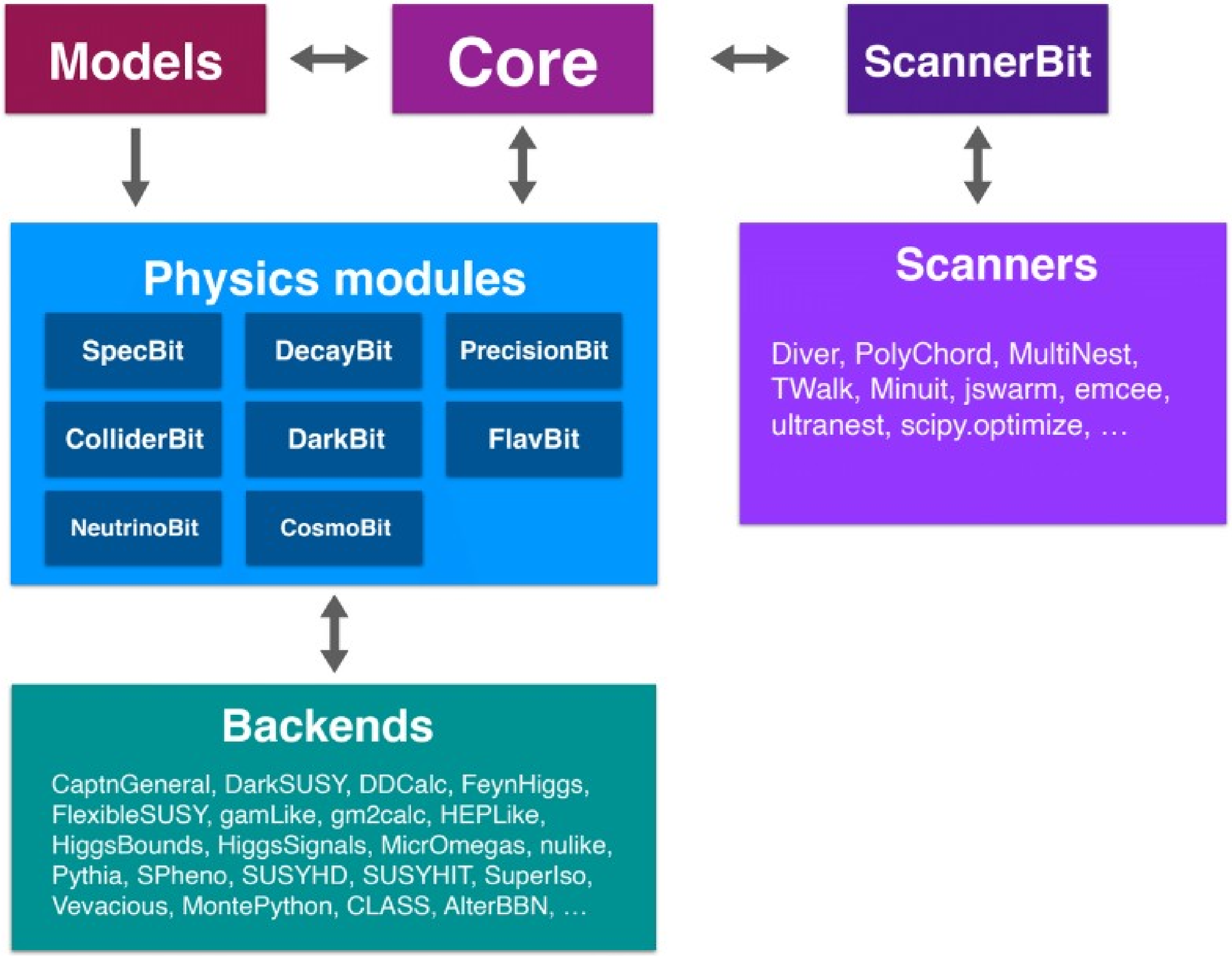
Members of: ATLAS, Belle-II, CLiC, CMS, CTA, Fermi-LAT, DARWIN, IceCube, LHCb, SHiP, XENON

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, Superlso, SUSY-AI, xsec, Vevacious, WIMPSim

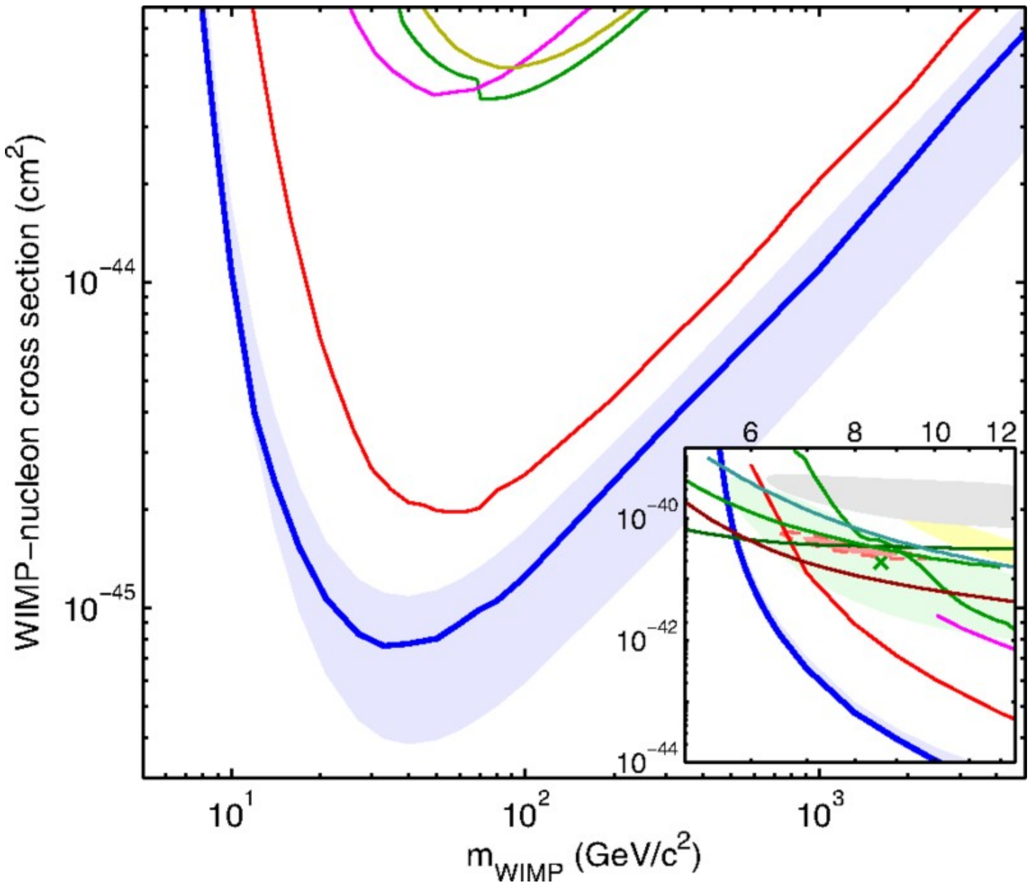
Recent collaborators: V Ananyev, P Athron, N Avis-Kozar, C Balázs, A Beniwal, LL Braseth, T Bringmann, A Buckley, J Butterworth, JE Camargo-Molina, C Chang, J Cornell, M Danninger, A Fowlie, T Gonzalo, W Handley, S Hoof, A Jueid, F Kahlhoefer, A Kvellestad, M Lecroq, C Lin, M Lucente, FN Mahmoudi, DJE 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 ++

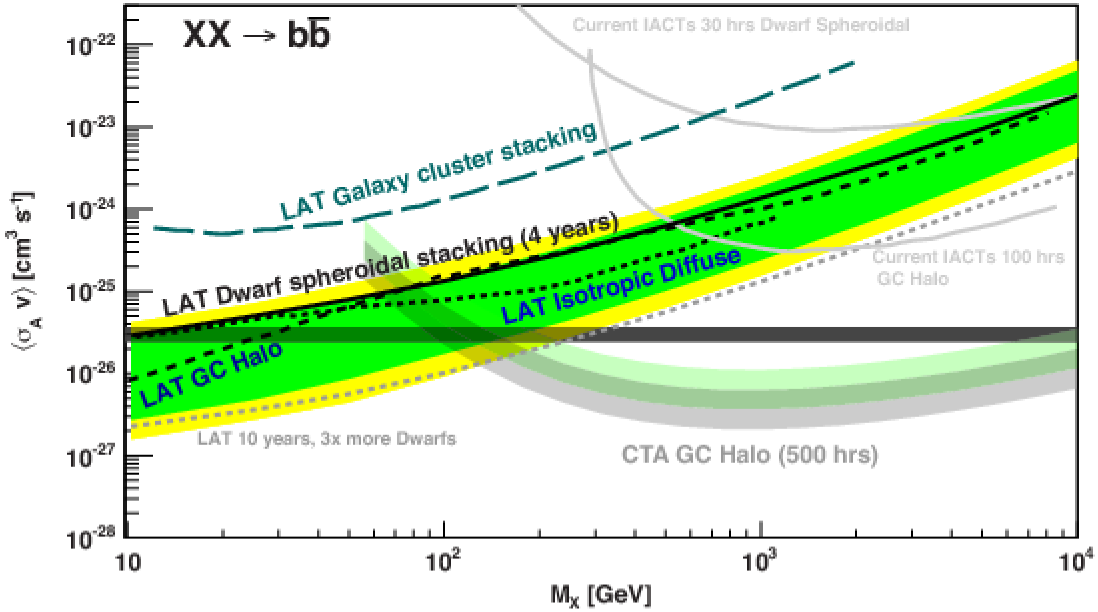
70+ participants in many experiments and numerous major theory codes

GAMBIT code structure



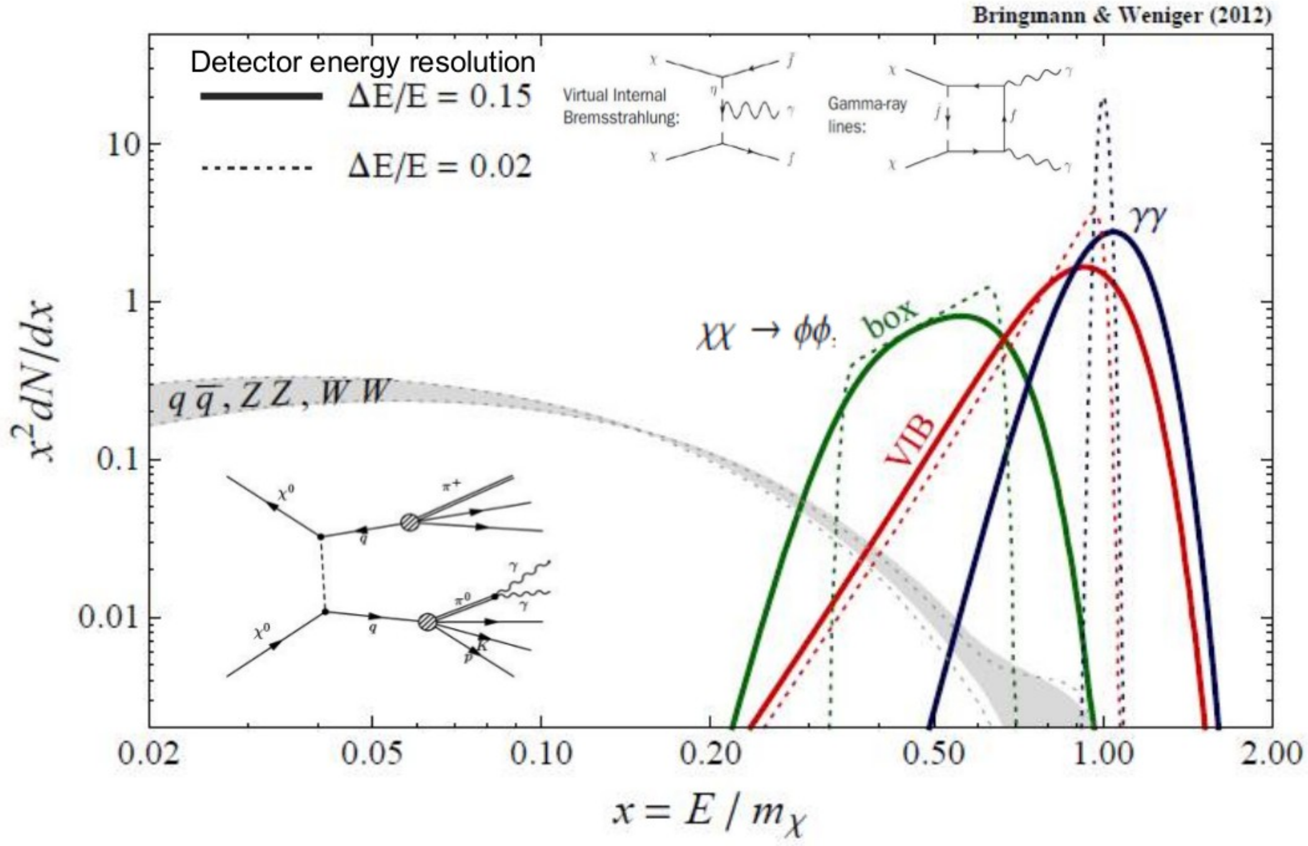
Astro limits: the problem



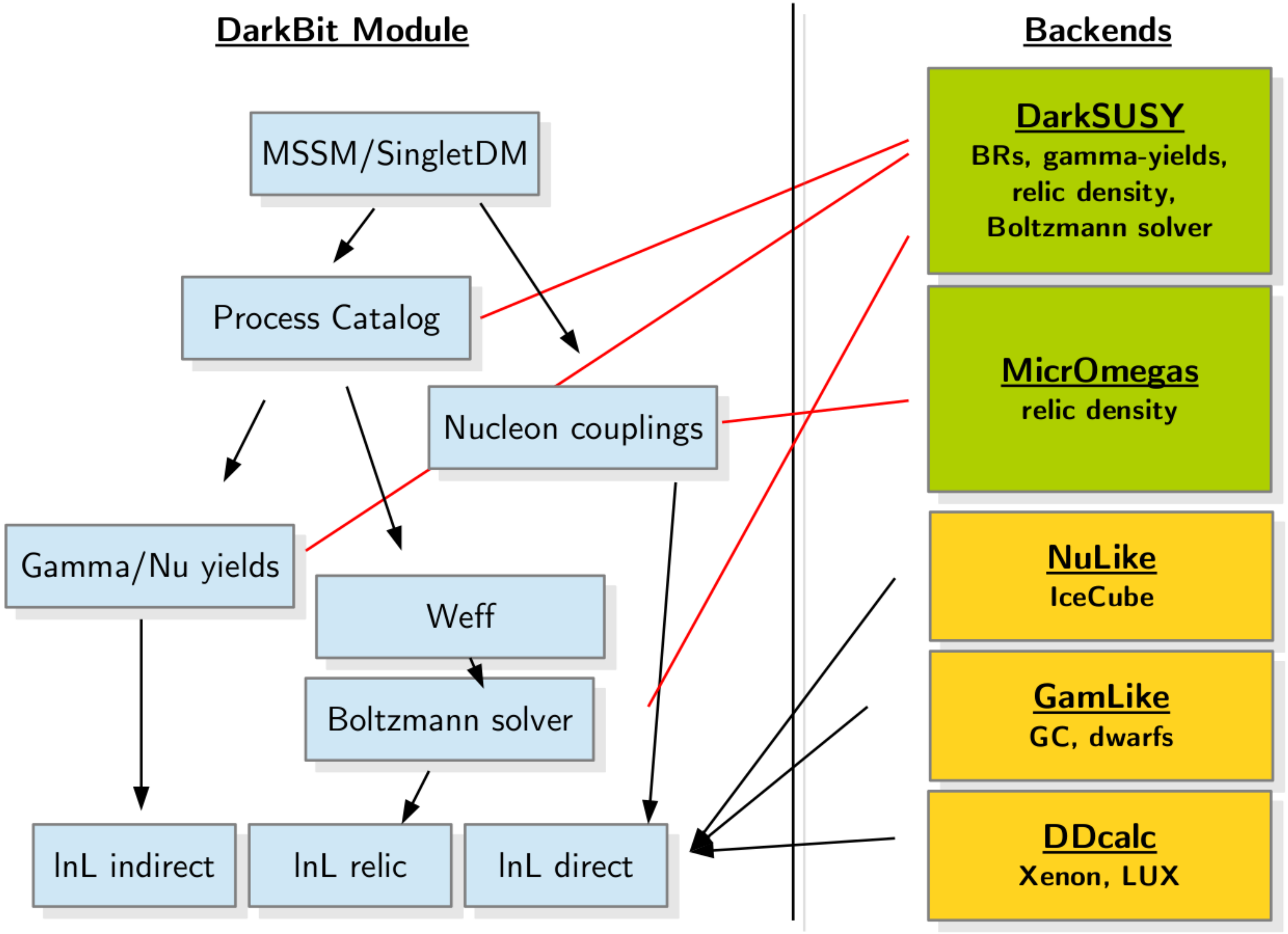


Reality is something like this

$$\frac{d\Phi_\gamma(\Delta\Omega, E_\gamma)}{dE_\gamma} = \frac{1}{8\pi} \underbrace{\frac{\langle\sigma v\rangle}{m^2} \sum_i BR_i \frac{dN^i_\gamma}{dE_\gamma}}_{Particle\ Physics} \times \underbrace{\int_{\Delta\Omega}\int_{LOS} \rho(r[s])^2 ds\, d\Omega}_{Astrophysics},$$



DarkBit



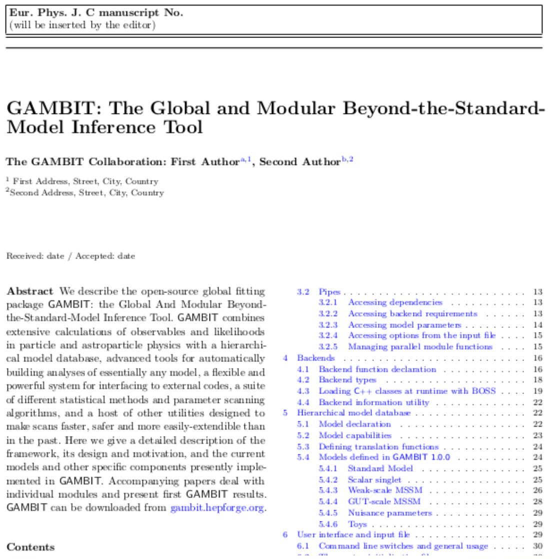
- **Event level neutrino telescope and gamma ray likelihoods!**
- **First principles treatment of direct search limits → easily extendable to non-trivial operators**
- **Very large range of experiments included (includes future, e.g. CTA)**

GAMBIT status

- GAMBIT was released as an ***open source public tool*** in 2017
- Lots of physics studies performed so far (supersymmetry, DM effective field theory and simplified models, axions, neutrino physics, flavour physics)
- New cosmology module added in 2021

See https://gambitbsm.org/ for more info, all samples are available via **Zenodo**

NEW! Super easy version: **GAMBIT light**
https://github.com/GambitBSM/gambit_light_1.0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GAMBIT: The Global and Modular Beyond-the-Standard-Model Inference Tool

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Received: date / Accepted: date

Abstract We describe the open-source global fitting package GAMBIT: the Global And Modular Beyond-the-Standard-Model Inference Tool. GAMBIT combines extensive calculations of observables and likelihoods in particle and astroparticle physics with a hierarchical model database, advanced tools for automatically building analyses of essentially any model, a flexible and powerful system for interfacing to external codes, a suite of different statistical methods and parameter scanning algorithms, and a host of other utilities designed to make scans faster, safer and more easily-extendible than in the past. Here we give a detailed description of the framework, its design and motivation, and the current models and other specific components presently implemented in GAMBIT. Accompanying papers deal with individual modules and present first GAMBIT results. GAMBIT can be downloaded from gambit.hepforge.org.

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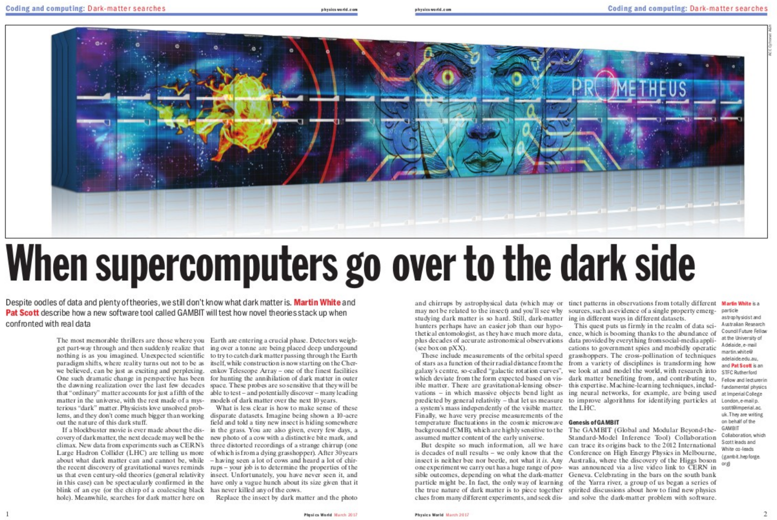

Coding and computing: Dark-matter searches

physicsworld.com

When supercomputers go over to the dark side

Despite oodles of data and plenty of theories, we still don't know what dark matter is. Martin White and Pat Scott describe how a new software tool called GAMBIT will test how novel theories stack up when confronted with real data

A very 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)

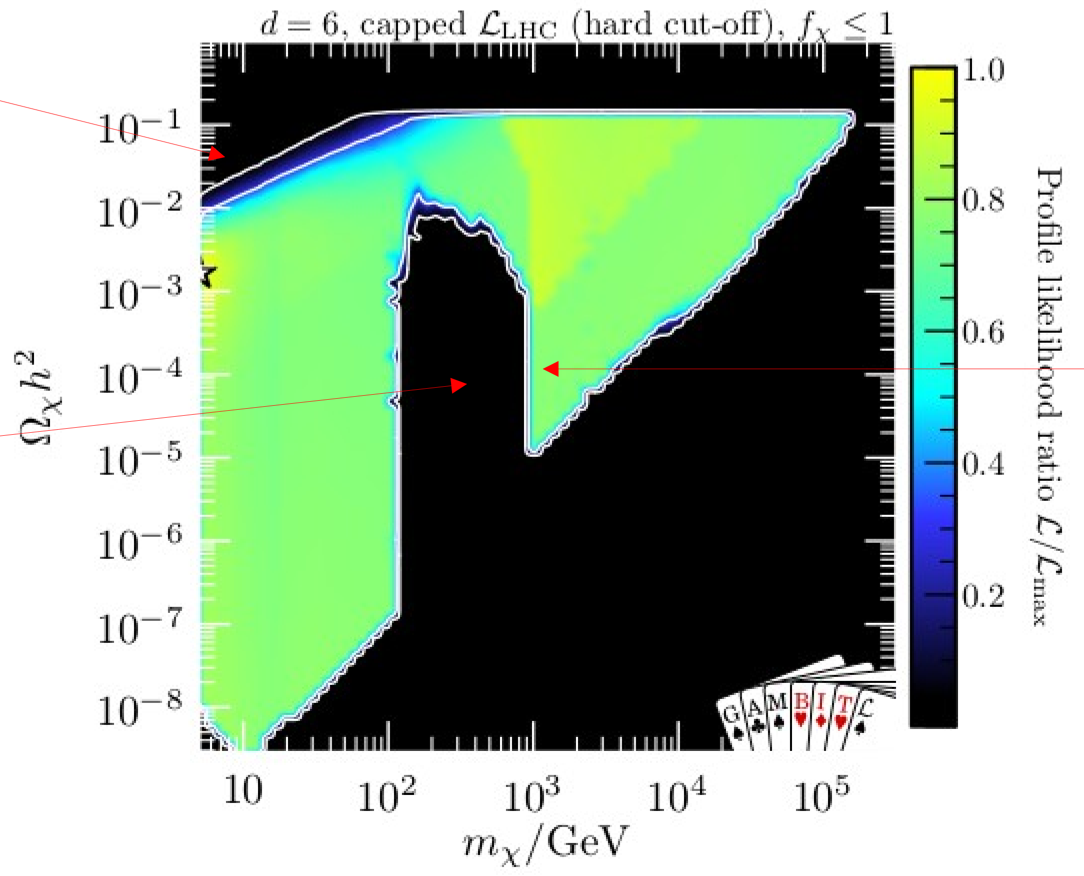
INDIRECT DM

- 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

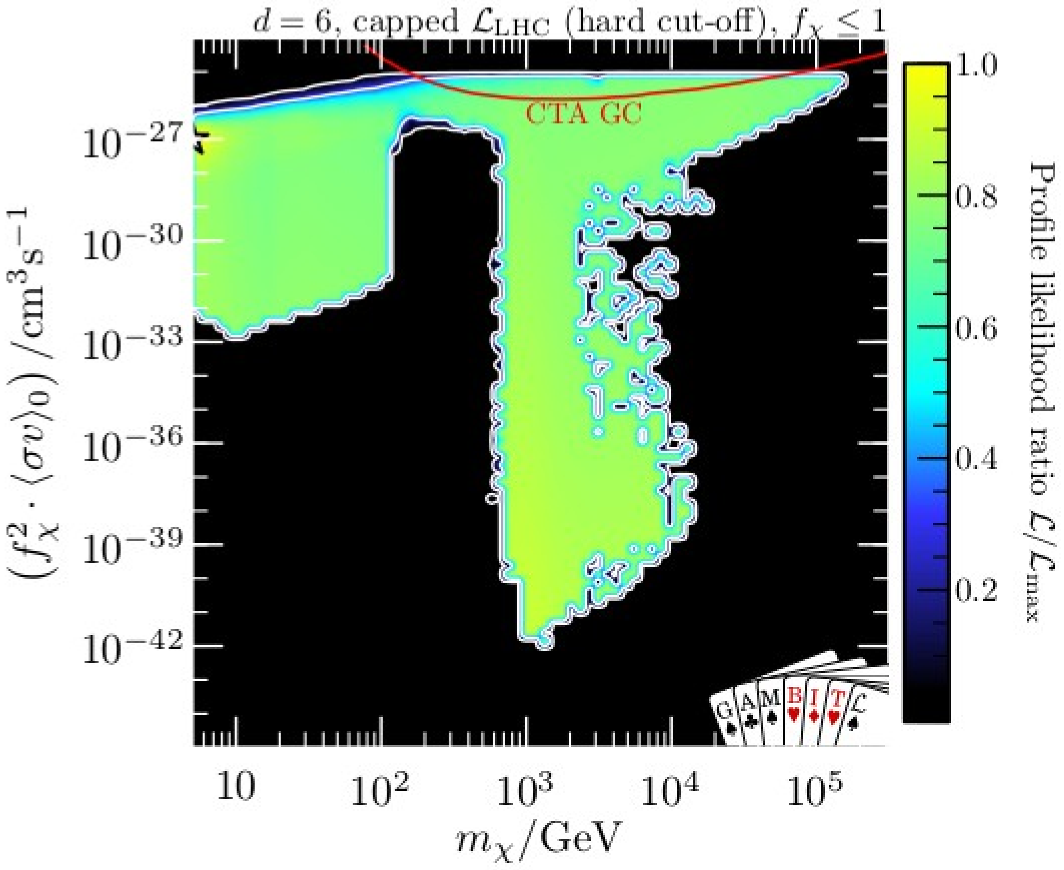
Cannot saturate relic density due to indirect and direct DM search constraints (but if DM is a subcomponent, these constraints are suppressed)

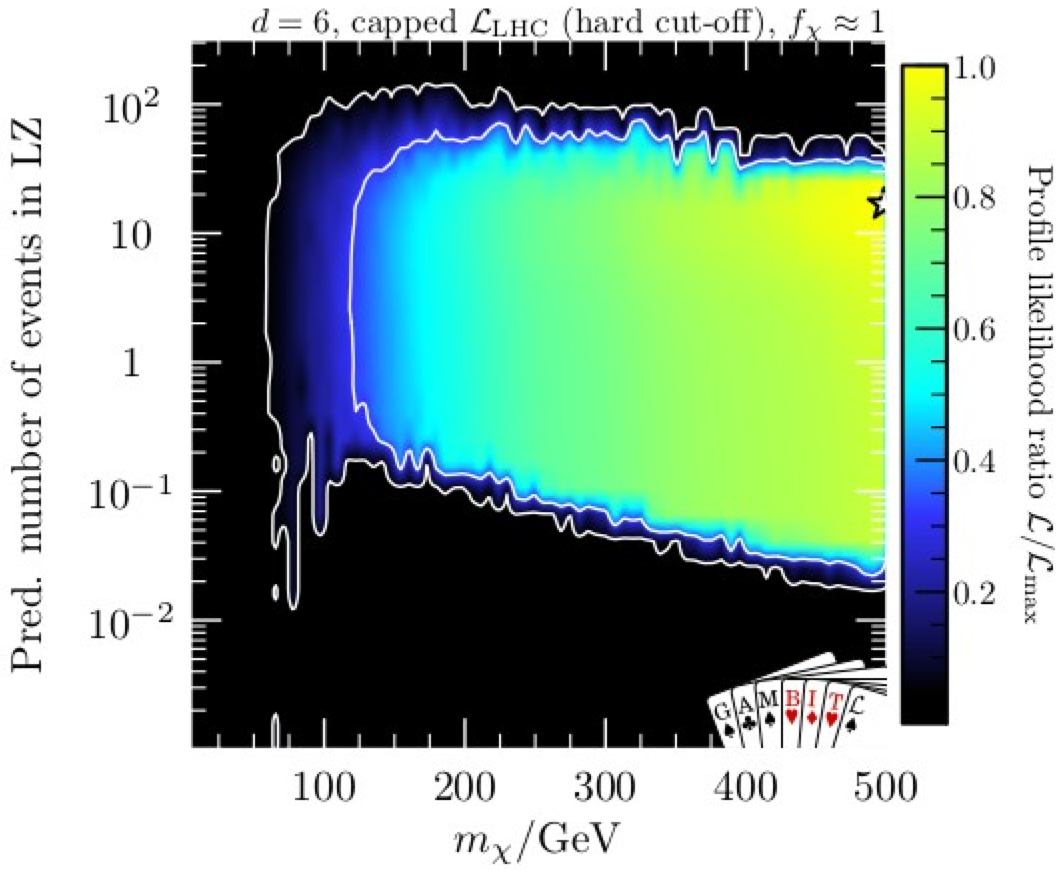
LHC constraints



LHC WIMP production cross-section drops

Results: Dim-6 scans (future projections)





Beyond DM EFT: simplified models

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gambit-physics-2022, TTP22-060, P3H-22-098, ADP-22-29/T1200

Global fits of simplified models for dark matter with GAMBIT

I. Scalar and fermionic models with s-channel vector mediators

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Abstract Simplified models provide a useful way to study the impacts of a small number of new particles on experimental observables and the interplay of those observables, without the need to construct an underlying theory. In this study, we perform global fits of simplified dark matter models with GAMBIT using an up-to-date set of likelihoods for indirect detection, direct detection and collider searches. We investigate models in which a scalar or fermionic dark matter candidate couples to quarks via an s-channel vector mediator. Large parts of parameter space survive for each model. In the case of Dirac or Majorana fermion dark matter, excesses in LHC monojet searches and relic density limits tend to prefer the resonance region, where the dark matter has approximately half the mass of the mediator. A combination of vector and axial-vector couplings to the Dirac candidate also leads to competing constraints from direct detection and unitarity violation.

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1 Introduction

The Standard Model (SM) remains enormously successful as a theory of particle physics, but is widely thought to be incomplete and expected to be superseded by a more complete theory. One of the many motivations for searching for beyond-Standard Model (BSM) physics is to explain the dark matter (DM) evident in a number of astrophysical and cosmological observations [1–3]. The Weakly-Interacting Massive Particle (WIMP) hypothesis, in which DM is assumed to consist of a new species that interacts with a strength at least as weak as the weak nuclear force, is amongst the leading DM explanations due to its ability to explain the observed cosmological relic abundance of DM [4] at the same time as potentially being very tightly constrained in the near future by current experimental technologies [5].

Whilst there are plenty of UV-complete theories that include viable WIMP candidates, it is advantageous to take a model-independent approach and construct a low-energy effective theory that includes the relevant phenomenology for our current experimental probes, whilst remaining agnostic about the high energy physics that we cannot currently observe. The simplest way to construct such a theory is to write down an *effective field theory* (EFT), in which the SM Lagrangian density is extended with a number of effective operators that encode possible DM-SM interactions. An EFT is valid up to some scale Λ, at which point one would start to

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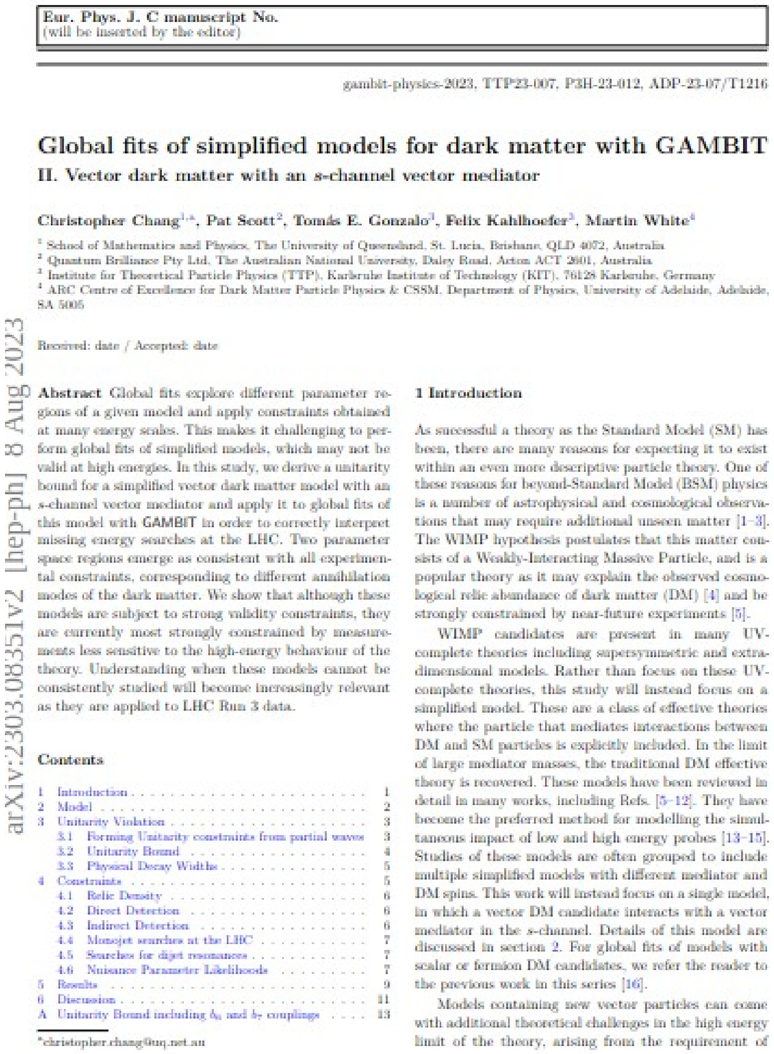

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gambit-physics-2023, TTP23-007, P3H-23-012, ADP-23-07/T1216

Global fits of simplified models for dark matter with GAMBIT

II. Vector dark matter with an s-channel vector mediator

Christopher Chang[1,a], Pat Scott[2], Tomás E. Gonzalo[3], Felix Kahlhoefer[3], Martin White[4]

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Abstract Global fits explore different parameter regions of a given model and apply constraints obtained at many energy scales. This makes it challenging to perform global fits of simplified models, which may not be valid at high energies. In this study, we derive a unitarity bound for a simplified vector dark matter model with an s-channel vector mediator and apply it to global fits of this model with GAMBIT in order to correctly interpret missing energy searches at the LHC. Two parameter space regions emerge as consistent with all experimental constraints, corresponding to different annihilation modes of the dark matter. We show that although these models are subject to strong validity constraints, they are currently most strongly constrained by measurements less sensitive to the high-energy behaviour of the theory. Understanding when these models cannot be consistently studied will become increasingly relevant as they are applied to LHC Run 3 data.

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A Unitarity Bound including b_0 and b_2 couplings . . . 13

1 Introduction

As successful a theory as the Standard Model (SM) has been, there are many reasons for expecting it to exist within an even more descriptive particle theory. One of these reasons for beyond-Standard Model (BSM) physics is a number of astrophysical and cosmological observations that may require additional unseen matter [1–3]. The WIMP hypothesis postulates that this matter consists of a Weakly-Interacting Massive Particle, and is a popular theory as it may explain the observed cosmological relic abundance of dark matter (DM) [4] and be strongly constrained by near-future experiments [5].

WIMP candidates are present in many UV-complete theories including supersymmetric and extra-dimensional models. Rather than focus on these UV-complete theories, this study will instead focus on a simplified model. These are a class of effective theories where the particle that mediates interactions between DM and SM particles is explicitly included. In the limit of large mediator masses, the traditional DM effective theory is recovered. These models have been reviewed in detail in many works, including Refs. [5–12]. They have become the preferred method for modelling the simultaneous impact of low and high energy probes [13–15]. Studies of these models are often grouped to include multiple simplified models with different mediator and DM spins. This work will instead focus on a single model, in which a vector DM candidate interacts with a vector mediator in the s-channel. Details of this model are discussed in section 2. For global fits of models with scalar or fermion DM candidates, we refer the reader to the previous work in this series [16].

Models containing new vector particles can come with additional theoretical challenges in the high energy limit of the theory, arising from the requirement of

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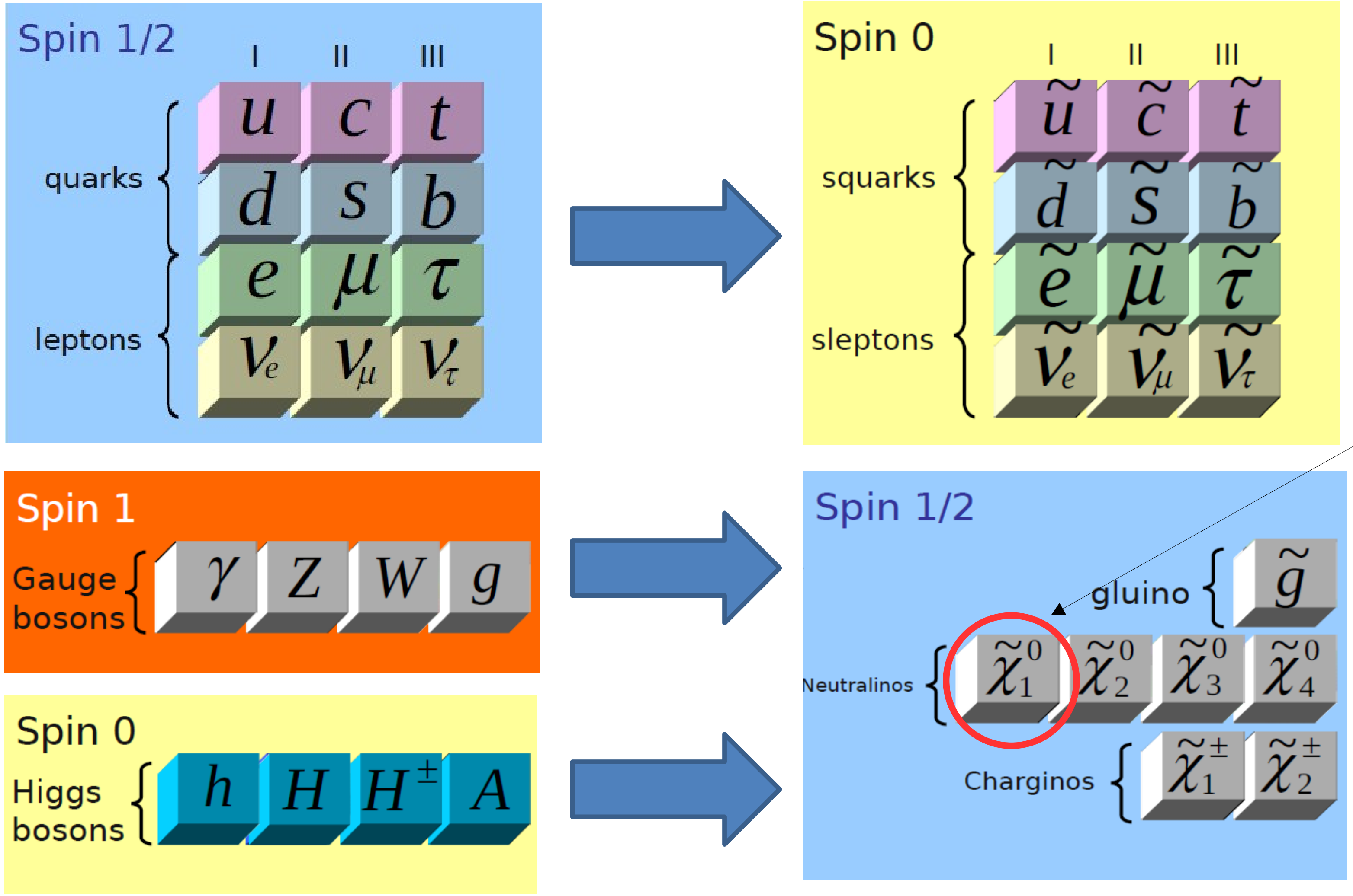
A question I get asked a lot by astrophysicists

- “We keep hearing that the lightest neutralino is a good dark matter candidate”
- “You’ve spent almost a decade not seeing supersymmetry at the LHC”
- ***“What are the LHC constraints on lightest neutralino dark matter?”***

Supersymmetry



- The lightest neutralino is a natural dark matter candidate, and is the subject of most studies

How the MSSM might appear...

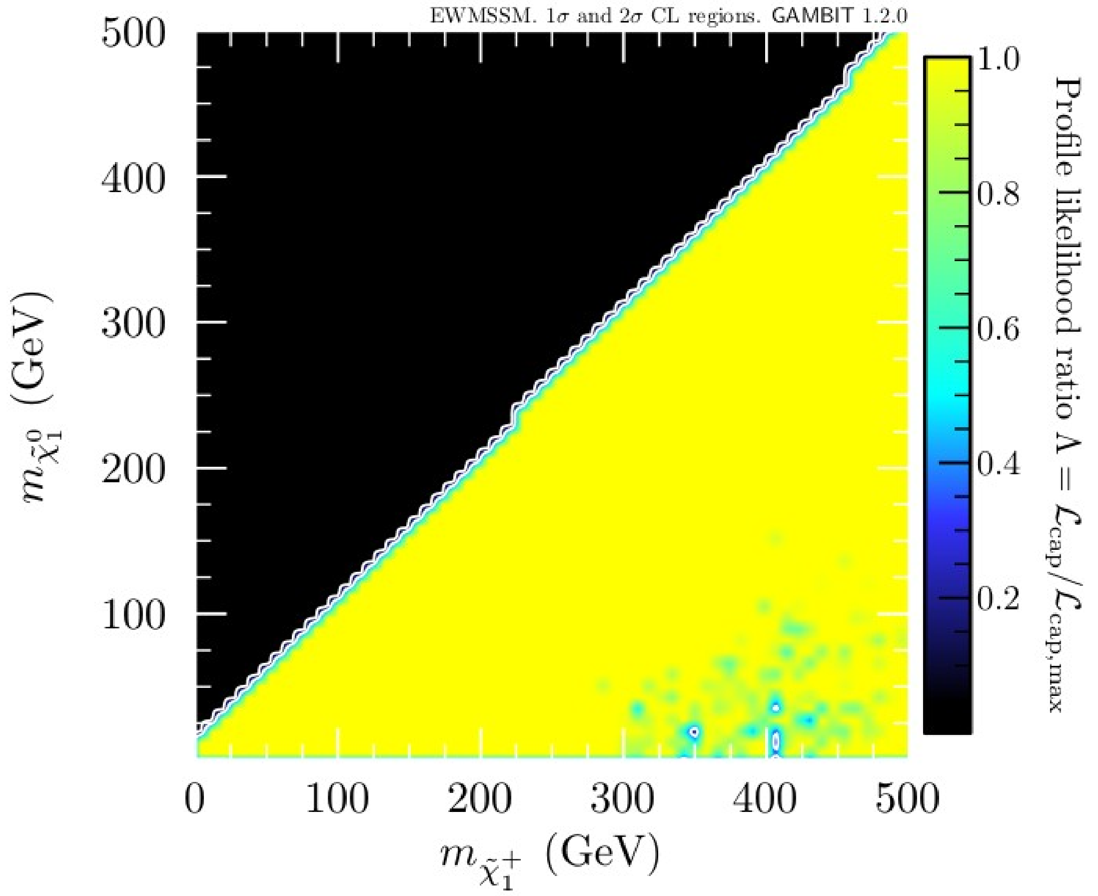
Name	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	H_u^0 H_d^0 H_u^+ H_d^-	h^0 H^0 A^0 $H^\pm$
			$\widetilde{u}_L$ $\widetilde{u}_R$ $\widetilde{d}_L$ $\widetilde{d}_R$	(same)
squarks	0	-1	$\widetilde{s}_L$ $\widetilde{s}_R$ $\widetilde{c}_L$ $\widetilde{c}_R$	(same)
			$\widetilde{t}_L$ $\widetilde{t}_R$ $\widetilde{b}_L$ $\widetilde{b}_R$	$\widetilde{t}_1$ $\widetilde{t}_2$ $\widetilde{b}_1$ $\widetilde{b}_2$
			$\widetilde{e}_L$ $\widetilde{e}_R$ $\widetilde{\nu}_e$	(same)
sleptons	0	-1	$\widetilde{\mu}_L$ $\widetilde{\mu}_R$ $\widetilde{\nu}_\mu$	(same)
			$\widetilde{\tau}_L$ $\widetilde{\tau}_R$ $\widetilde{\nu}_\tau$	$\widetilde{\tau}_1$ $\widetilde{\tau}_2$ $\widetilde{\nu}_\tau$
neutralinos	1/2	-1	$\widetilde{B}^0$ $\widetilde{W}^0$ $\widetilde{H}_u^0$ $\widetilde{H}_d^0$	$\widetilde{\chi}_1^0$ $\widetilde{\chi}_2^0$ $\widetilde{\chi}_3^0$ $\widetilde{\chi}_4^0$
charginos	1/2	-1	$\widetilde{W}^\pm$ $\widetilde{H}_u^+$ $\widetilde{H}_d^-$	$\widetilde{\chi}_1^\pm$ $\widetilde{\chi}_2^\pm$
gluino	1/2	-1	$\widetilde{g}$	(same)

Decoupled

Source: Anders Kvellestad

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...



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Opportunities

- We have mostly used GAMBIT so far to explore particle physics theories

- There are many astrophysics problems that could be tackled, e.g.
  - - consistent global fits of astrophysical models with multimessenger observations
  - - models where particle processes interact with astrophysics (e.g. see talk on cosmic ray-WIMP scattering)

Would love to chat with people interested in developing new likelihoods or performing “pure astrophysics” GAMBIT studies!

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) … chat to me at coffee or email martin.white@adelaide.edu.au