Understanding dark matter with GAMBIT

The Global and Modular Beyond-the-Standard-Model Inference Tool

Csaba Balazs[1,*] for the GAMBIT Community

[1]Monash University, School of Physics and Astronomy, Melbourne, Victoria 3800 Australia

Abstract.
GAMBIT is an open-source framework for testing dark matter models against experimental data. Over seven years, the GAMBIT community has published 18 papers constraining candidates like WIMPs and axion-like particles, using advanced statistical methods and tools such as DarkBit. These studies guide future experiments and deepen our understanding of dark matter.

1 Introduction

The GAMBIT (Global And Modular Beyond-the-Standard-Model Inference Tool) community is an international collaboration of about 70 scientists focused on developing comprehensive tools for studying particle physics, astrophysics, and cosmological models beyond the Standard Models of particles and cosmology. The community brings together expertise in theoretical physics, experimental data, and statistical analysis to produce flexible, powerful software capable of performing global fits across a wide range of particle physics and cosmology scenarios.

Their GAMBIT computer code is an open-source, modular framework designed to test and constrain theoretical models against experimental data, including results from collider experiments, dark matter searches, neutrino observatories, and cosmological measurements. GAMBIT integrates a variety of physics modules and data sources, enabling researchers to efficiently analyse the viability of new physics models, explore parameter spaces, and provide robust statistical inferences. It is particularly valued for its versatility in supporting complex model testing across a variety of experimental constraints.

2 Dark matter studies with GAMBIT

Over the past seven years, the GAMBIT community has published 18 research papers focused on dark matter, leveraging the collective effort to advance our understanding of dark matter models. These studies rigorously apply the latest experimental constraints from particle colliders, direct and indirect dark matter searches, and astrophysical observations to the parameter spaces of various popular dark matter scenarios, such as Weakly Interacting Massive Particles (WIMPs), axion-like particles, and scalar dark matter.

By applying these constraints, GAMBIT generates probability distributions and exclusion limits, offering valuable insights into the most viable regions of parameter space for each

*e-mail: csaba.balazs@monash.edu

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model. These probability maps provide a powerful statistical measure to gauge the likelihood of different dark matter candidates and inform future experimental efforts by highlighting promising directions in dark matter parameter space.

The 18 dark matter related GAMBIT papers span the following mainstream particle physics models:

Effective field theories, including gauge singlet extensions of the Standard Model The status of the scalar singlet dark matter model has been reviewed with key constraints identified [1]. The effects of vacuum stability, perturbativity, and XENON1T on $\mathbb{Z}_2$ and $\mathbb{Z}_3$ scalar singlet dark matter fits have been analysed [2]. Higgs portal singlet dark matter models have been globally analysed using GAMBIT [3]. Global fits of Dirac dark matter effective field theories have explored thermal WIMPs and the scale of new physics [4].

Simplified dark matter models Global fits of simplified models for dark matter with GAMBIT: I. Scalar and fermionic models with s-channel vector mediators [5]. Global fits of simplified models for dark matter with GAMBIT: II. Vector dark matter with an s-channel vector mediator [6]. Resonant or asymmetric: The status of sub-GeV dark matter [7].

Axions and axion-like particles Simplified dark matter models with scalar and fermionic candidates coupled via s-channel vector mediators have been analysed using global fits in GAMBIT [5]. Global fits have been performed for vector dark matter interacting via an s-channel vector mediator within the GAMBIT framework [6]. The current status of sub-GeV dark matter, focusing on resonant or asymmetric scenarios, has been explored [7].

Supersymmetric models containing dark matter candidates GUT-scale SUSY models have been studied through global fits using the GAMBIT framework [8]. A global fit of the Minimal Supersymmetric Standard Model (MSSM) has been performed with GAMBIT [9]. Collider data has been used to derive combined constraints on neutralinos and charginos [10]. Electroweakino constraints have been analysed in the presence of a light gravitino using collider data [11].

Right-handed neutrinos A frequentist analysis has been conducted for three right-handed neutrinos using GAMBIT [12].

Code papers describing essential dark matter related GAMBIT modules DarkBit is a GAMBIT module designed to compute dark matter observables and likelihoods [13]. CosmoBit is a GAMBIT module developed for calculating cosmological observables and likelihoods [14]. The GAMBIT Universal Model Machine enables a seamless calculation from Lagrangians to likelihoods [15].

A selection of the latest representative key results from the above publications is depicted in figures 1 and 2. These results illustrate the power of the GAMBIT framework in exploring a diverse range of dark matter scenarios, from sub-GeV thermal WIMPs to axion-like particles. By rigorously constraining parameter spaces with cutting-edge experimental data, GAMBIT provides a clear roadmap for future experimental efforts, highlighting regions of interest that remain unexplored or marginally constrained.

The GAMBIT Community continues to set benchmarks in various dark matter models, fostering synergy between theoretical predictions and experimental searches. The versatility of its tools ensures its relevance in tackling emerging challenges in particle physics, astrophysics, and cosmology. Further advancements in experimental precision and computational techniques will undoubtedly extend GAMBIT's impact, solidifying its role as a cornerstone in the quest to unravel the mysteries of dark matter.

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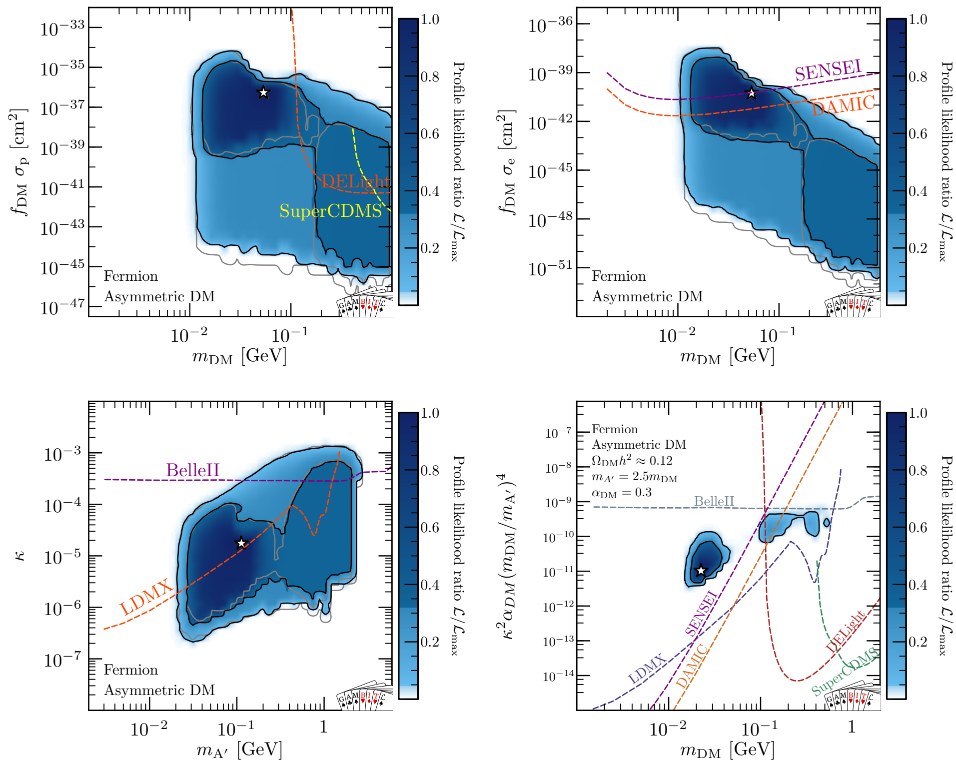

Figure 1. Allowed parameter regions for asymmetric fermionic dark matter, with the star indicating the best-fit point, compared to projected experimental sensitivities. Panels show: rescaled dark matter-nucleus cross section vs. dark matter mass (top-left), dark matter-electron cross section vs. dark matter mass (top-right), kinetic mixing vs. dark photon mass (bottom-left), and effective coupling $\kappa^2\alpha_{\rm DM}(m_{\rm DM}/m_{A'}^4)$ vs. Dark matter mass (bottom-right), with $m_{A'} = 2.5m_{\rm DM}$ and $\alpha_{\rm DM} = 0.3$ fixed. For more details consult ref. [7].

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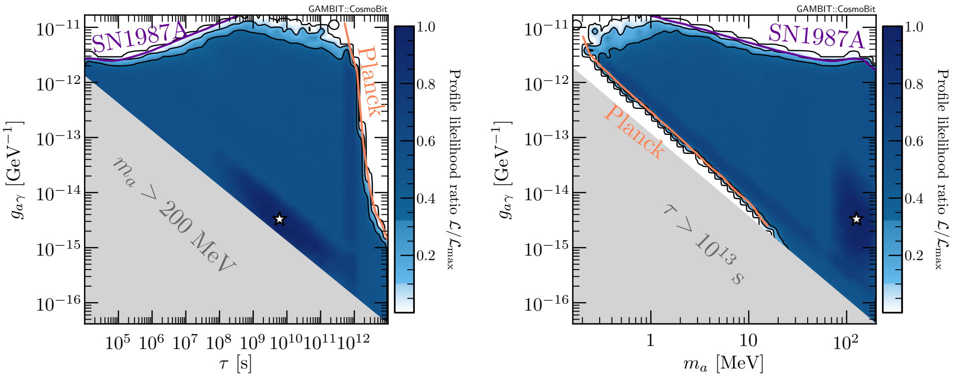

Figure 2. Profile likelihood for various combinations of the parameters. Black lines correspond to the 1σ, 2σ, and 3σ contours around the best-fitting point (white star), whereas coloured lines are 99.7% CL limits from the individual likelihoods. Shaded grey regions are excluded from our study as they are beyond the scan ranges. For more details consult ref. [16].

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