Global Fits of vector-mediated simplified dark matter models with GAMBIT

Christopher Chang

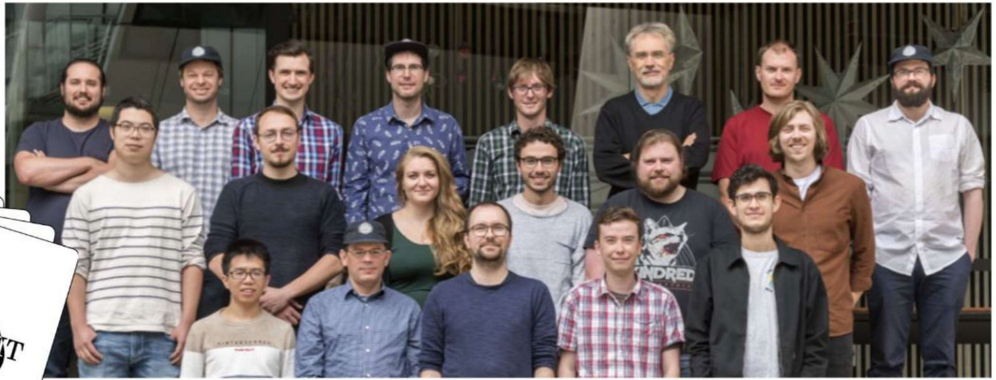
Dark Side of the Universe 2022

The University of Queensland
Australia

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 packages
- 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: P Athron, C Balázs, A Beniwal, S Bloor, T Bringmann, A Buckley, J-E Camargo-Molina, C Chang, M Chrzaszcz, J Conrad, J Cornell, M Danninger, J Edsjö, T Emken, A Fowlie, T Gonzalo, W Handley, J Harz, S Hoof, F Kahlhoefer, A Kvellestad, P Jackson, D Jacob, C Lin, N Mahmoudi, G Martinez, MT Prim, A Raklev, C Rogan, R Ruiz, P Scott, N Serra, P Stöcker , W. Su, A Vincent, C Weniger, M White, Y Zhang, ++

70+ participants in many experiments and numerous major theory codes

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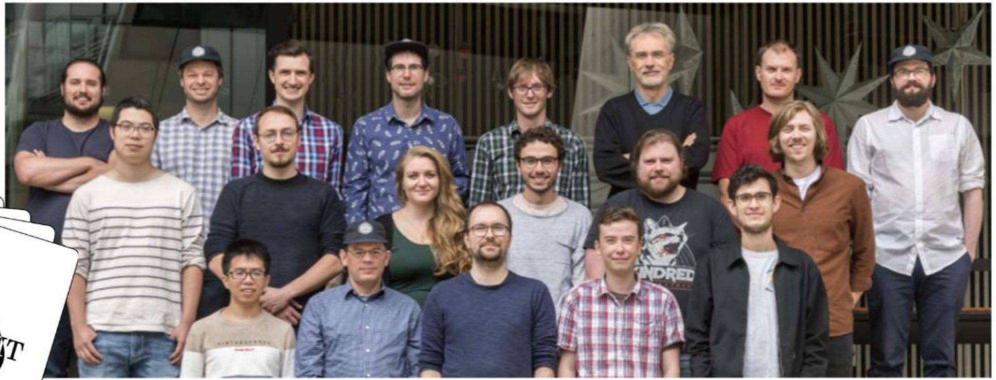

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See also talks by Ankit Beniwal (Thursday) and Csaba Balazs (Friday)

Simplified dark matter models

Simplified dark matter models describe effective dark matter (DM) interactions without integrating out the mediating particle.

They're a useful tool for studying how both low and high energy experimental probes affect BSM physics.

In this talk I will discuss recent global constraints of s-channel vector-mediated simplified dark matter models with GAMBIT (arXiv:2209.13266).

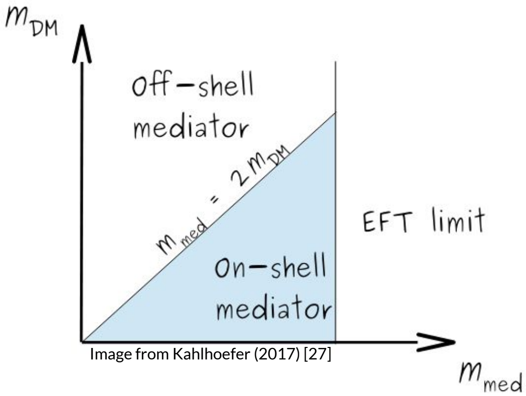
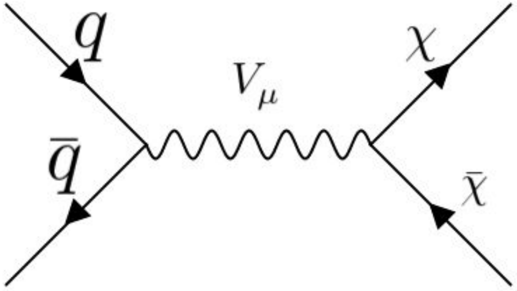


Image from Kahlhoefer (2017) [27]



Models

Scalar DM:

$$\mathcal{L}_{BSM} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_{DM}^2\phi^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m_M^2 V_\mu V^\mu + g_q V_\mu \bar{q}\gamma^\mu q + i g_{DM}^V V_\mu \left(\phi^\dagger(\partial^\mu\phi) - (\partial^\mu\phi^\dagger)\phi\right)$$

Dirac fermion DM:

$$\mathcal{L}_{BSM} = i\bar{\chi}\gamma^\mu\partial_\mu\chi - m_{DM}\bar{\chi}\chi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m_M^2 V_\mu V^\mu + g_q V_\mu \bar{q}\gamma^\mu q + V_\mu\bar{\chi}(g_{DM}^V + g_{DM}^A\gamma^5)\gamma^\mu\chi$$

Majorana fermion DM:

$$\mathcal{L}_{BSM} = \frac{1}{2}i\bar{\psi}\gamma^\mu\partial_\mu\psi - \frac{1}{2}m_{DM}\bar{\psi}\psi - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} - \frac{1}{2}m_M^2 V_\mu V^\mu + g_q V_\mu \bar{q}\gamma^\mu q + \frac{1}{2}g_{DM}^A V_\mu \bar{\psi}\gamma^5\gamma^\mu\psi$$

Vector DM:

$$\mathcal{L}_{BSM} = -\frac{1}{2}X_{\mu\nu}^\dagger X^{\mu\nu} + m_{DM}^2 X_\mu^\dagger X^\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m_M^2 V_\mu V^\mu + g_q V_\mu \bar{q}\gamma^\mu q - i g_{DM}^V \left(X_\nu^\dagger \partial_\mu X^\nu - (\partial_\mu X^{\dagger\nu})X_\nu\right)V^\mu$$

Assumptions:

No lepton couplings
-> To avoid strong di-lepton searches.

No axial-vector quark couplings
-> To avoid strong electroweak precision tests.

Flavour universal couplings
-> To require minimal flavour violation.

Mass generation mechanism has no observable impact on experiments
-> Could be achieved by e.g. a dark Higgs with mass well above the other particle masses.
-> example model studied in [2]

In each model, there are 4 or 5 model parameters: DM mass (m_{DM}), Mediator mass (m_M), mediator-quark coupling (g_q), mediator-DM coupling (g_{DM}) (either vector or axial-vector)

[2] M. Duerr, F. Kahlhoefer, K. Schmidt-Hoberg, T. Schwetz, and S. Vogl, How to save the WIMP: global analysis of a dark matter model with two s-channel mediators, JHEP 09 (2016) 042

Unitarity violation

The presence of an axial-vector couplings for the Dirac and Majorana models implies a bound from unitarity: [3]

$$m_{DM} \leq \sqrt{\frac{\pi}{2}} \frac{m_M}{g_{DM}^A}$$

The vector DM model will also face unitarity violation, but to date no unitarity bound for this model exists in the literature.

[3] F. Kahlhoefer, K. Schmidt-Hoberg, T. Schwetz, and S. Vogl, Implications of unitarity and gauge invariance for simplified dark matter models, JHEP 02 (2016) 016

Constraints

Experiment
CDMSlite [4]
CRESST-II [5]
CRESST-III [6]
DarkSide 50 [7]
LUX 2016 [8]
PICO-60 [9, 10]
PandaX [11, 12]
XENON1T [13]
LZ 2022 [28]
LHC Dijets [14–22]
ATLAS monojet [23]
CMS monojet [24]
Fermi-LAT [25]
Planck 2018: Ωh^2 [26]
Nuisances

Constraints - Direct Detection

Effective Operator	Relevant models
$1_{DM}1_N$	Scalar, Dirac
$i\hat{\mathbf{S}} \cdot \left(\hat{\mathbf{S}}_N \times \frac{\hat{q}}{m_N}\right)$, $\hat{\mathbf{S}} \cdot \hat{\mathbf{v}}^{\perp} 1_N$	Dirac, Majorana

Relic DM should be non-relativistic -> Majorana model should be suppressed.

This should have very weak direct detection constraints relative to the other models.

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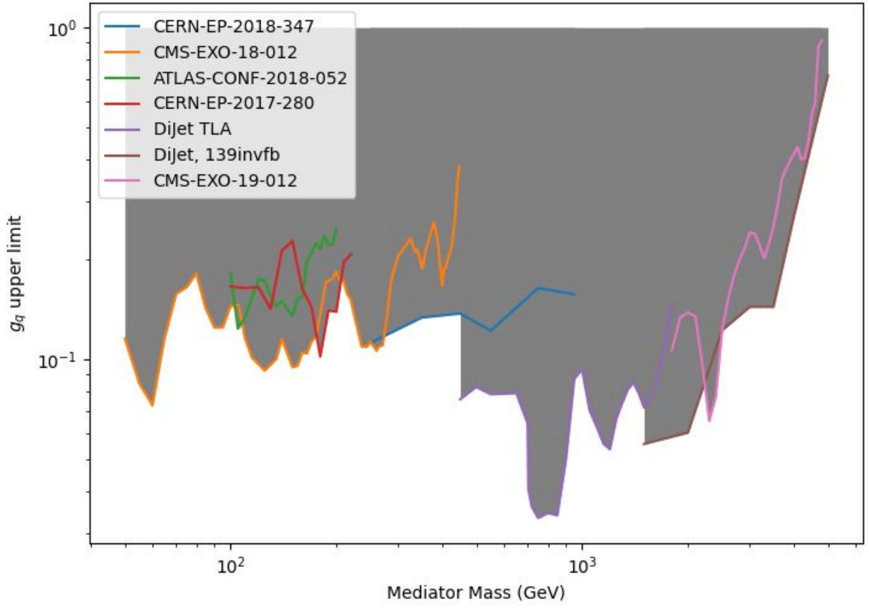
Nuisances

Constraints - Dijets

Limits are formed from the most constraining dijet search at a given mediator mass, scaled by the branching fraction into quarks.



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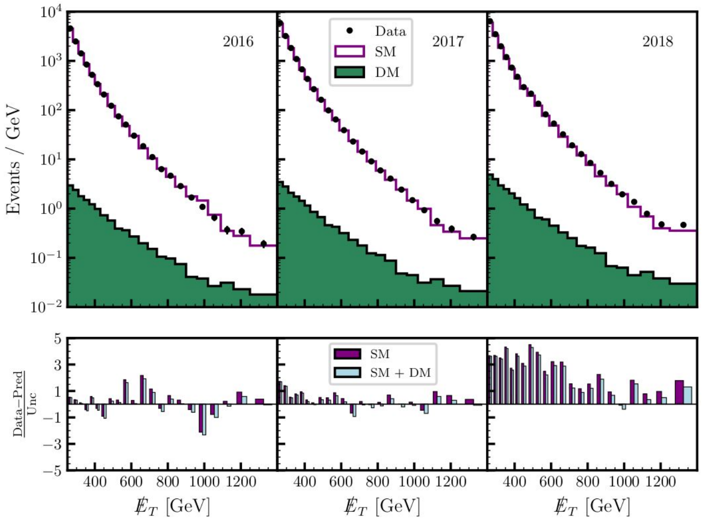
Constraints - Monojets



Excesses in individual signal regions tends to drive our likelihood to regions that fit these. In particular, the 2018 data for the CMS significantly underpredicts the # of events.

This is an artifact of their simplified likelihood, and is avoided in their full fit of control and signal regions.

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Nuisances

Constraints - Indirect Detection

2 Annihilation channels:

- DM DM -> quark pair
- DM DM -> mediator pair

Only the Dirac fermion DM model has dominant velocity independent (s-wave) annihilation to quarks.

The other models will have weak gamma ray signatures when the mediator channel is closed.

Experiment
CDMSlite [4]
CRESST-II [5]
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Planck 2018: Ωh^2 [26]
Nuisances

Constraints - Relic Abundance

Direct and indirect detection signals are scaled by the proportion of DM that each candidate would comprise:

$$f_{DM} = \frac{\Omega_{DM}}{\Omega_{DM,obs}}$$

The 2 different annihilation channels will give 2 regions in parameter space where DM is not overproduced.

Experiment
CDMSlite [4]
CRESST-II [5]
CRESST-III [6]
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Nuisances

Scans

Each scan has 4 or 5 model parameters and 7 nuisance parameters.

Collider:

1) uncapped

2) capped collider likelihood

Relic Density: DM candidate …

1) is a subcomponent of the observed abundance

2) saturates the observed abundance.

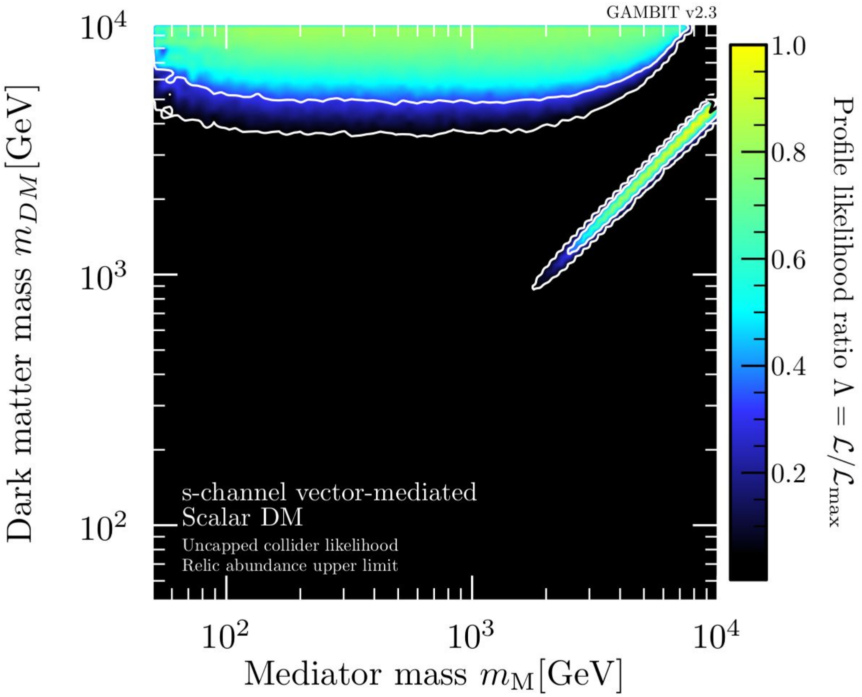
Up to 4 scans per model.

I will only show a subset of these results.

Parameters	**Range**
DM mass, m_{DM}	$[50, 10000]$ GeV
Mediator mass, m_M	$[50, 10000]$ GeV
quark-mediator coupling, g_q	$[0.01, 1.0]$
mediator-DM coupling (vector), g^V_{DM}	$[0.01, 3.0]$
mediator-DM coupling (axial vector), g^A_{DM}	$[0.01, 3.0]$
Nuisance Parameters	
Pion-nucleon sigma term, $\sigma_{\pi N}$	$[5, 95]$ MeV
strange quark cont. to nucleon spin, Δ_s	$[-0.062, -0.008]$
strange quark nuclear tensor charge, g^s_T	$[-0.075, 0.021]$
strange quark proton charge radius, r^2_s	$[-0.22, -0.01]\,\mathrm{GeV}^{-2}$
Local DM density, ρ_0	$[0.2, 0.8]\,\mathrm{GeV\,cm}^{-3}$
Most probably speed, v_{esc}	$[216, 264]\,\mathrm{km\,s}^{-1}$
Galactic escape speed, v_{peak}	$[453, 603]\,\mathrm{km\,s}^{-1}$

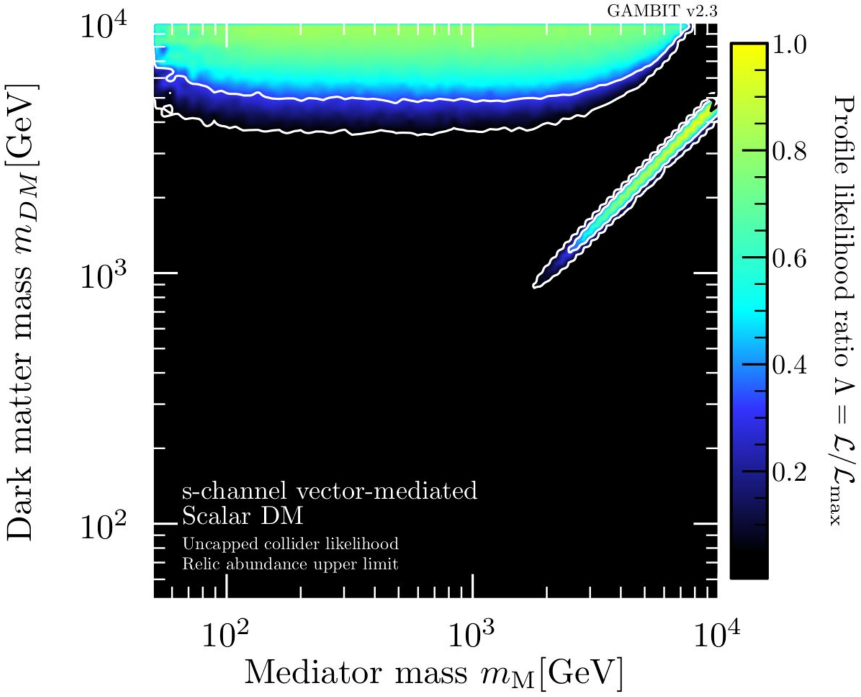
Results - Scalar DM

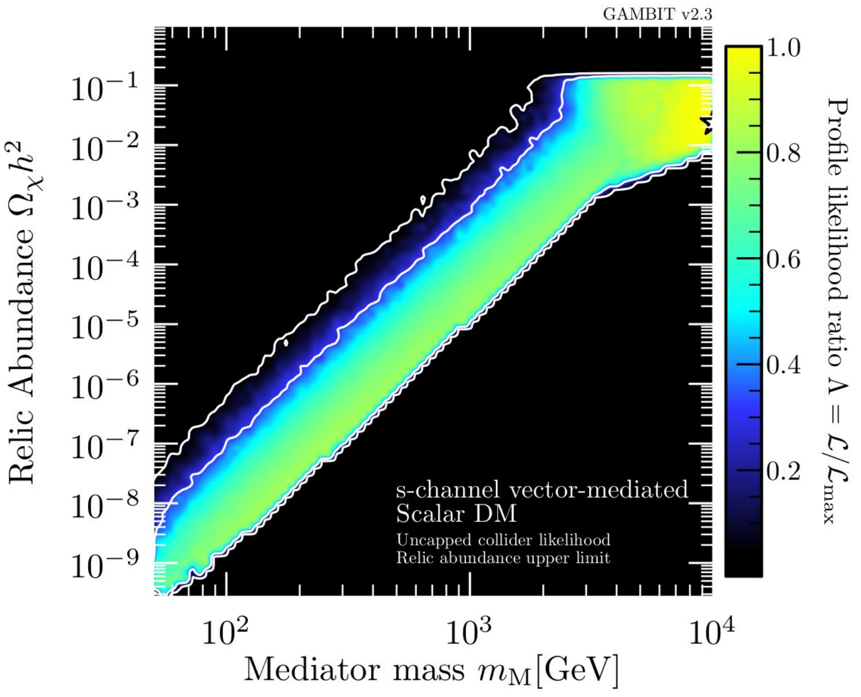
Capped results are not necessary as any collider preferences occur where already excluded by other experiments.



Results - Scalar DM

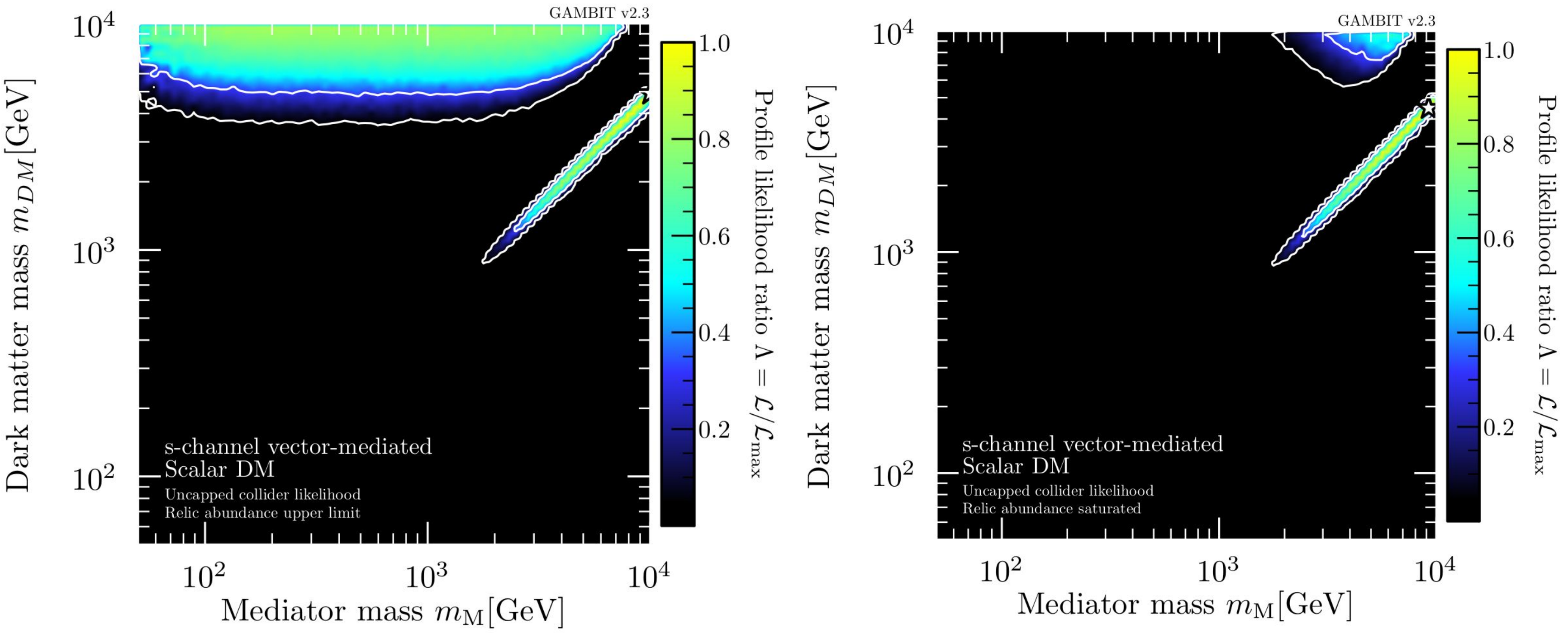
Much of the surviving parameter space predicts a very low DM relic abundance.





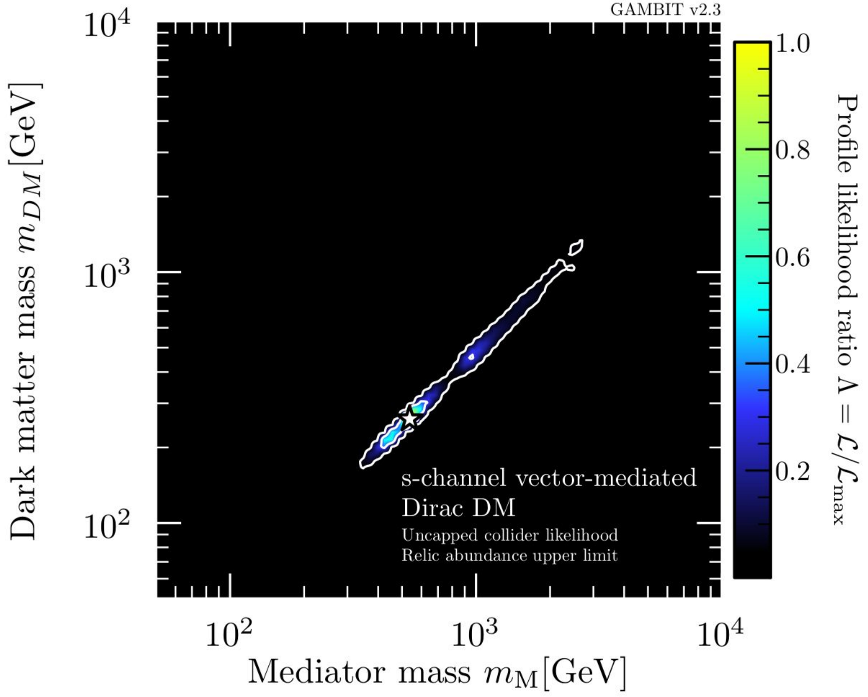
Results - Scalar DM

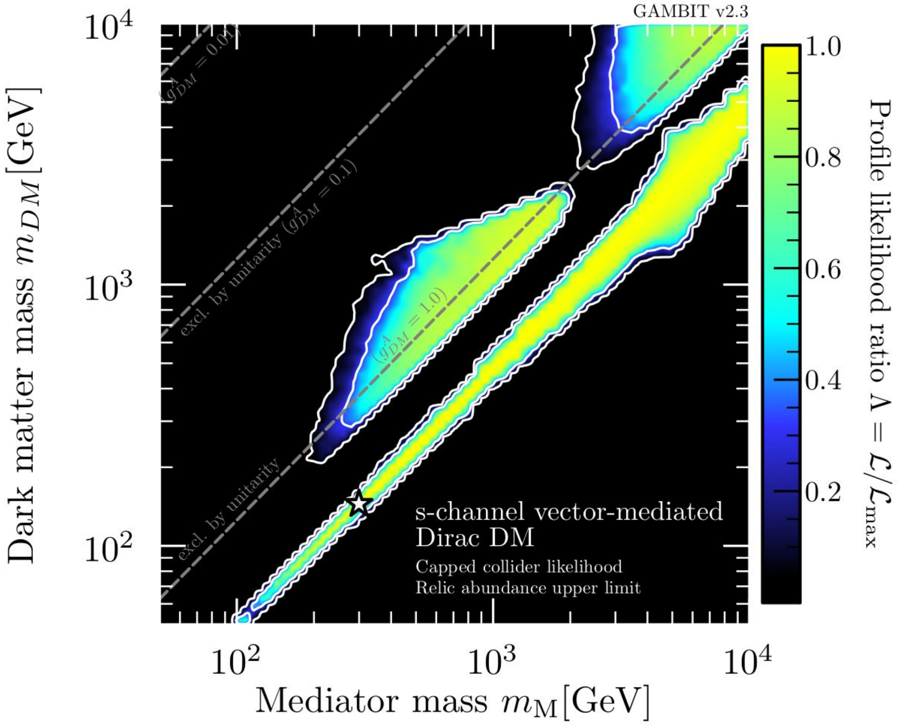
Requiring DM abundance is saturated reduces the off-resonance allowed parameter space.



Results- Dirac Fermion DM

Monojet likelihood gives preference to regions along the resonance.

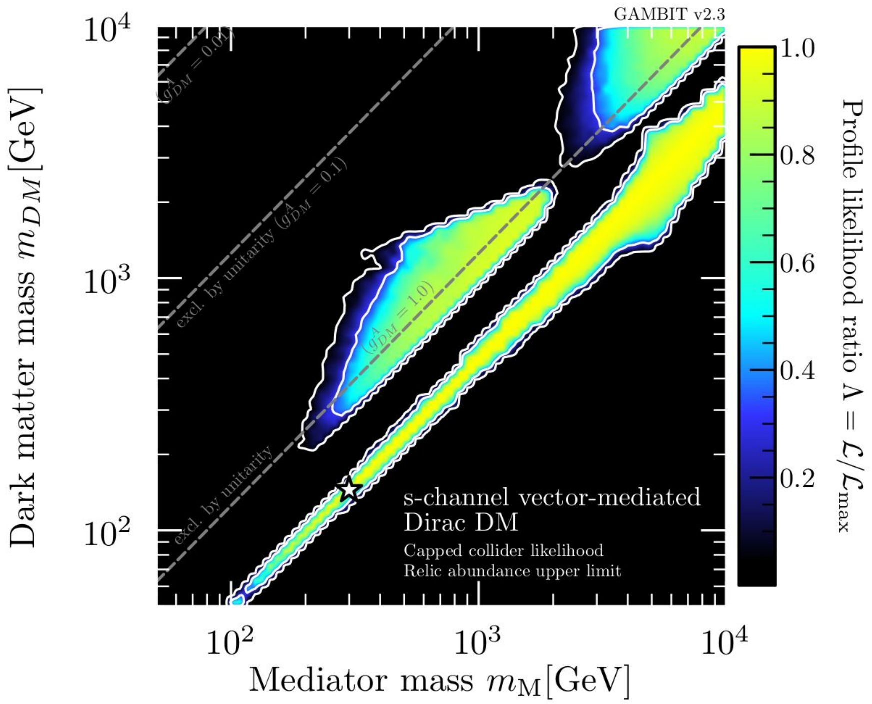




Results- Dirac Fermion DM

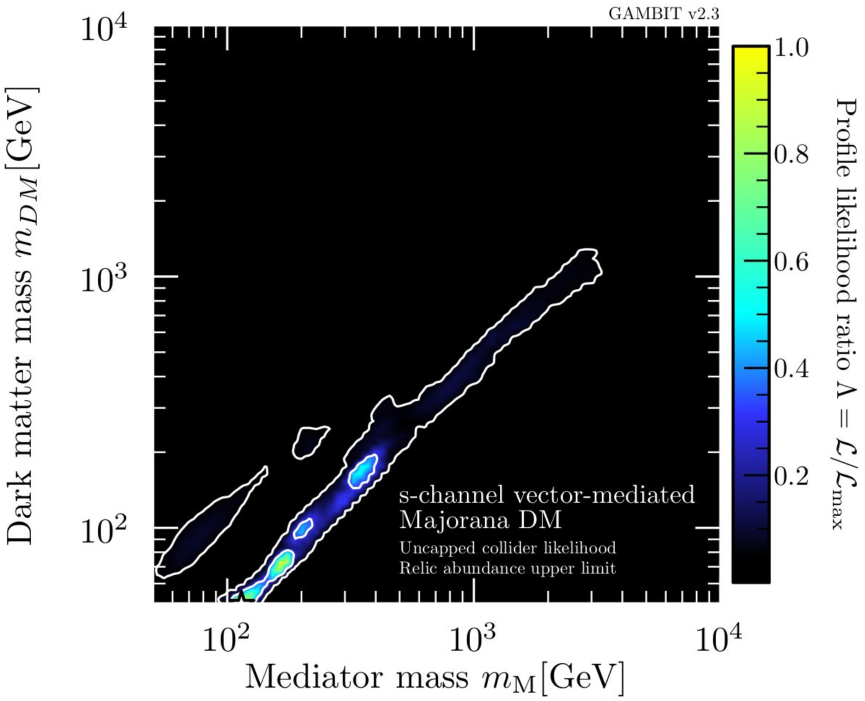
This interesting off resonance region is due to a combination of two things:

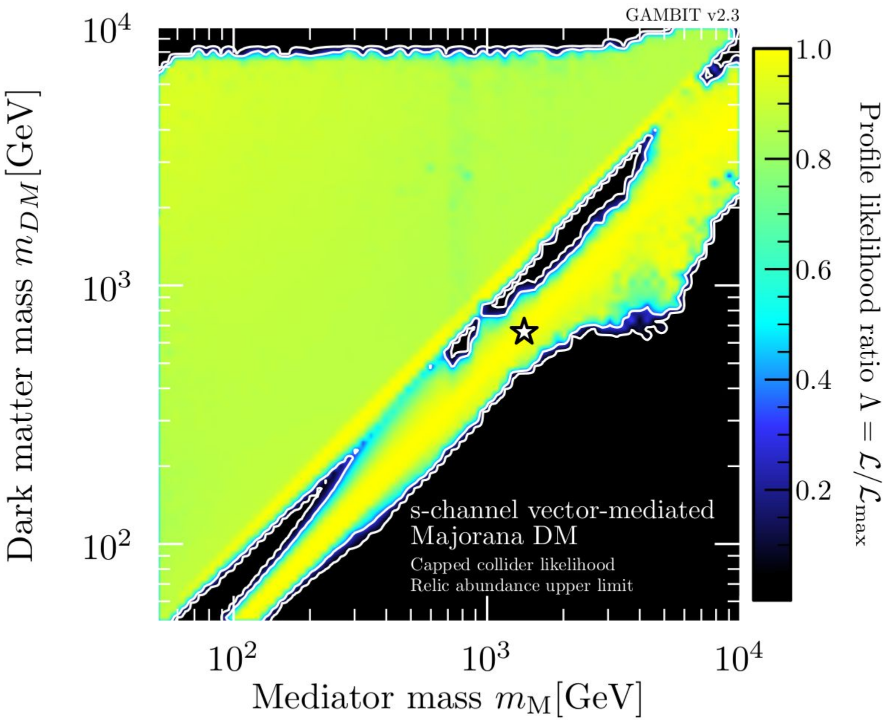
- DD limits give a lower bound on mediator masses.
- To avoid unitarity bounds, the axial-vector DM coupling must be low, however this will prevent sufficient annihilation of DM -> exceeding relic abundance



Results - Majorana fermion DM

Monojet excesses are also fit by this model, but not only along the resonance.

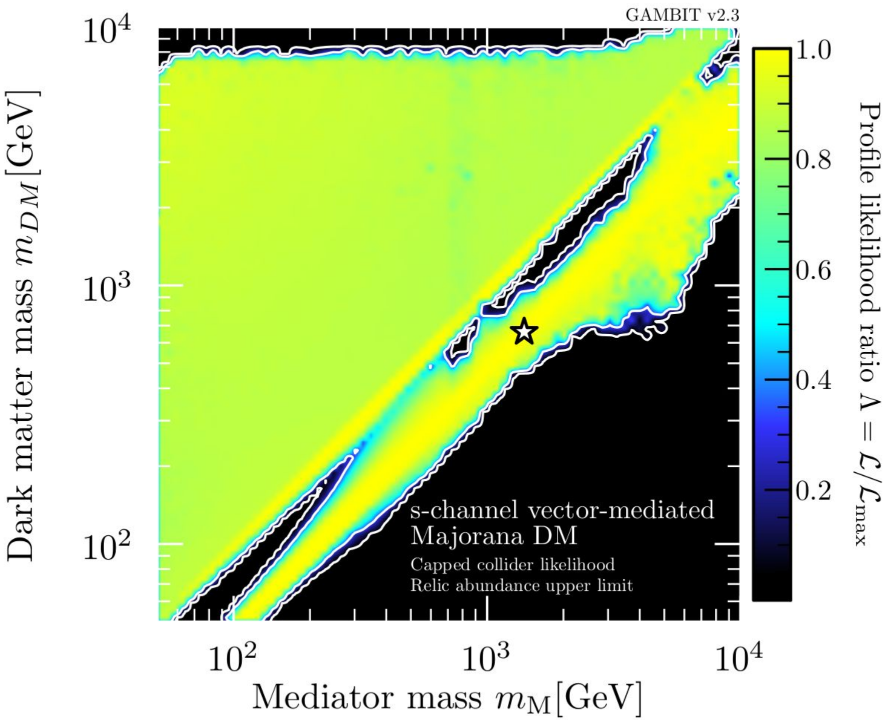




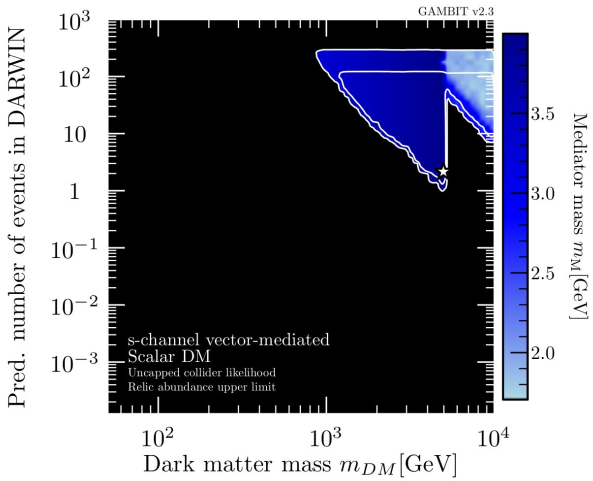
Results - Majorana fermion DM

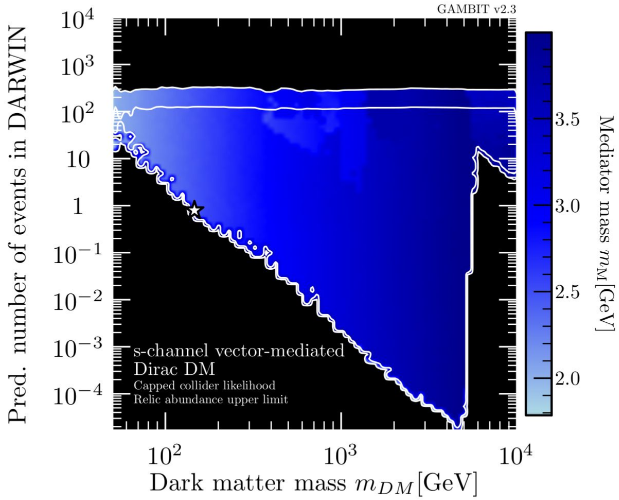
The reason why a lot of the off resonance parameter space survives (where it doesn't in the Dirac model) is because the DD signals are suppressed for this model.

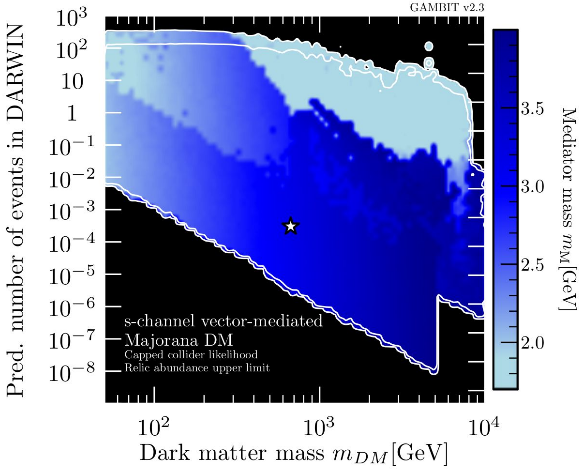
The non-smooth resonance region is due to competing effects monojet, dijet and RD constraints.



Future Prospects - DARWIN







Vector DM - Unitarity Bound

Unitarity bound from partial wave analysis of DM self-scattering in the high energy limit:

$$s \lesssim \frac{\sqrt{48\pi} m_{DM}^2}{g_{DM}}$$

This is very similar to the bound you would get by requiring that the off-shell decay width is physical:

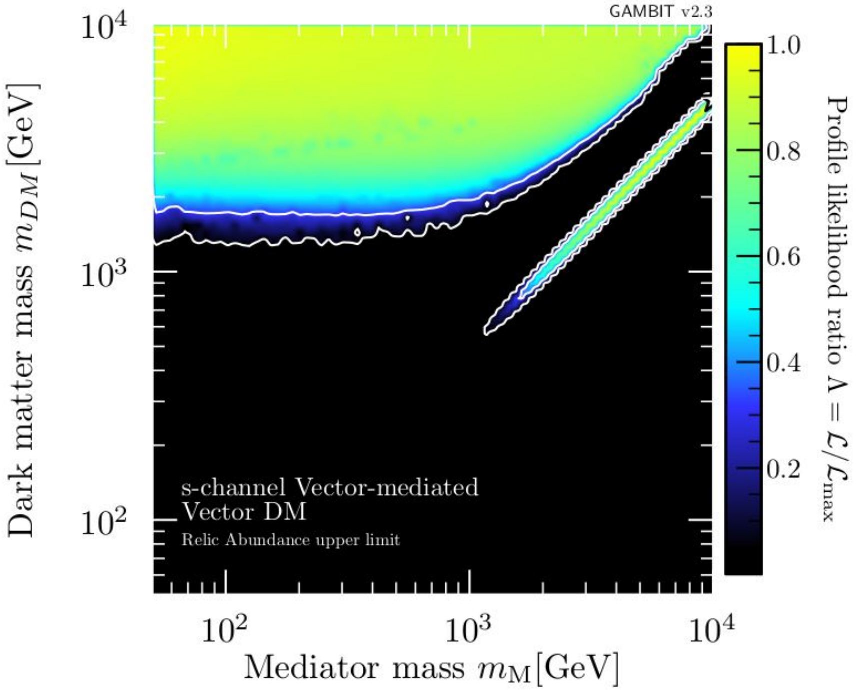
$$\Gamma(\sqrt{s}) < \sqrt{s}$$

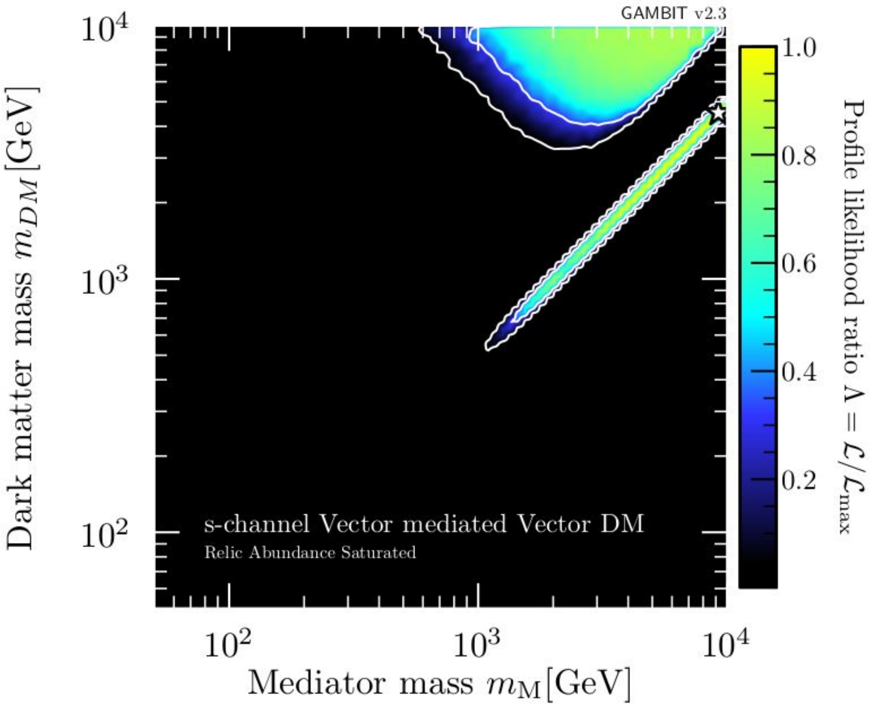
We reject any Monte Carlo events fail this bound, along with any parameter points where the on-shell decay width is unphysical ($\Gamma(m_M) < m_M$

Results - Vector DM

Vector DM produces very similar bounds to the scalar DM, just a bit weaker.

Any regions where the unitarity violation is important, is already ruled out by direct detection alone.





Summary

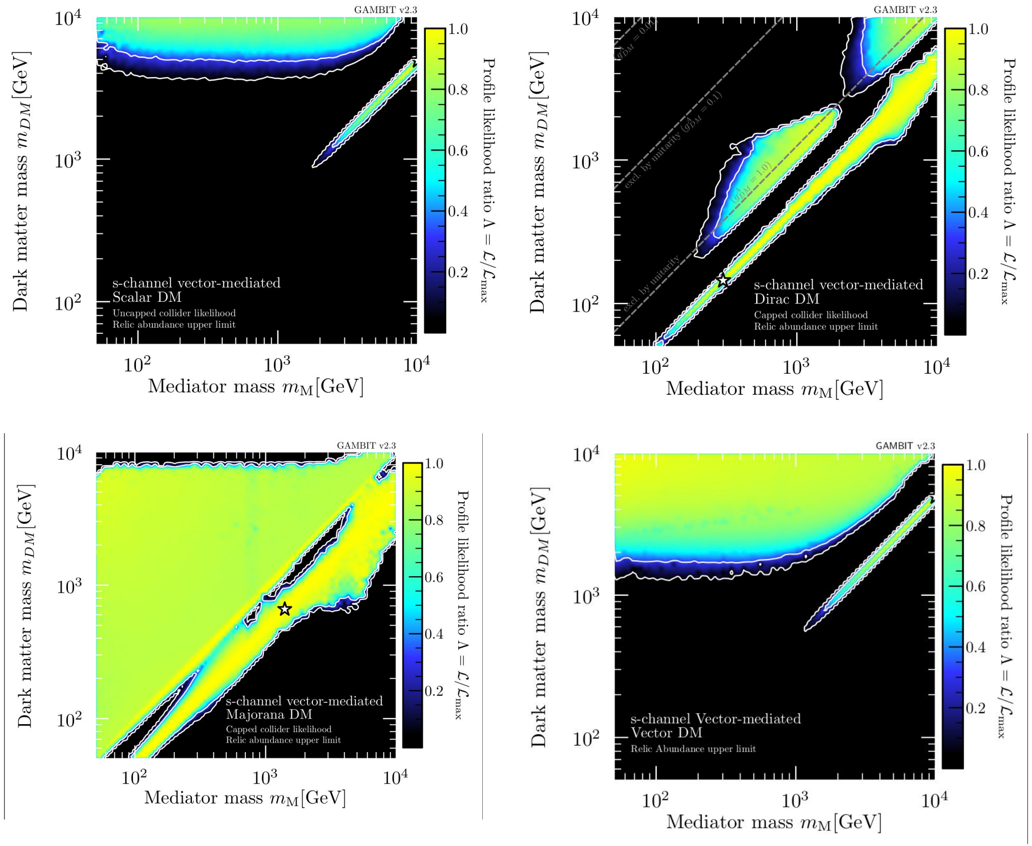
By combining constraints from direct detection, indirect detection and colliders, simplified dark matter models can be constrained greatly.

Scalar DM: Most of the parameter space that survives is for large DM masses. However, most of that underpredicts the DM abundance.

Dirac/Majorana DM: Scans are driven toward monojet excesses. No lower bound on DM masses for the parameters in these scans.

Vector DM: Low energy direct detection experiments already rule out much of the parameter space affected by unitarity violation.

Thanks for Listening!



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