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

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Simplified dark matter models

Simplified dark matter models describe effective dark matter (DM) interactions without integrating out the mediating particle (like in traditional effective field theories).

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

I'll discuss my work on performing global fits of s-channel vector-mediated simplified dark matter models with GAMBIT (arXiv:2209.13266).

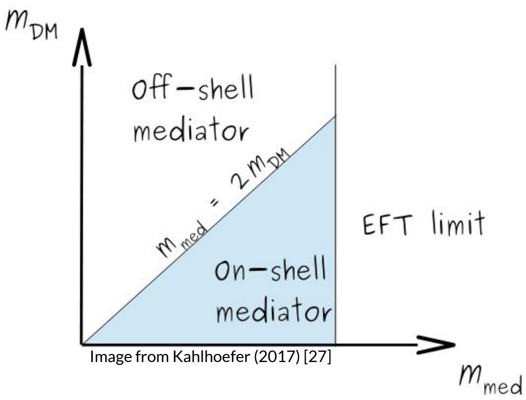
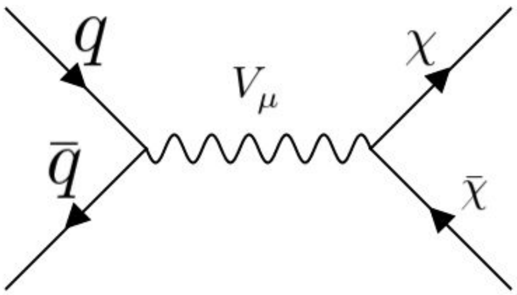


Image from Kahlhoefer (2017) [27]



Model Lagrangians

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:

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

Assumptions:

No lepton couplings (only quarks)
-> 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]

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

[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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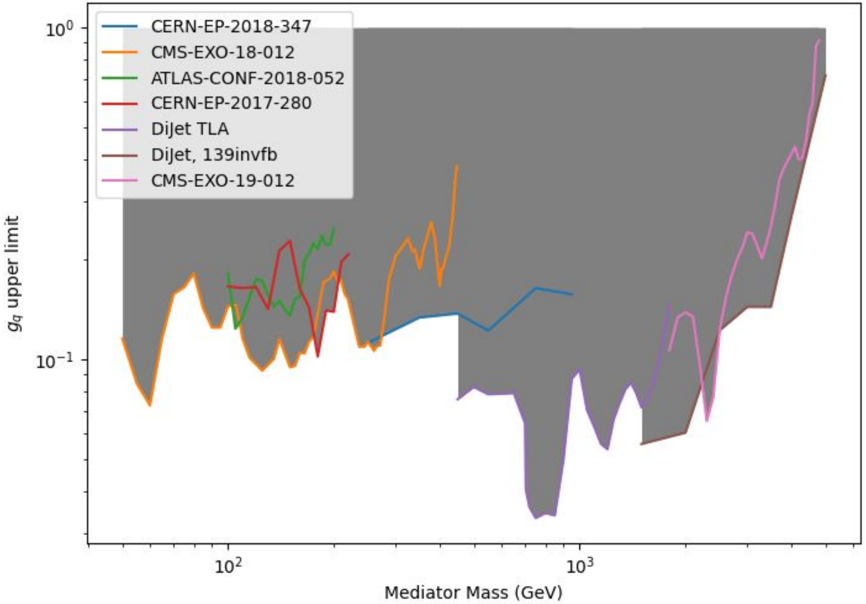
Constraints - Dijets

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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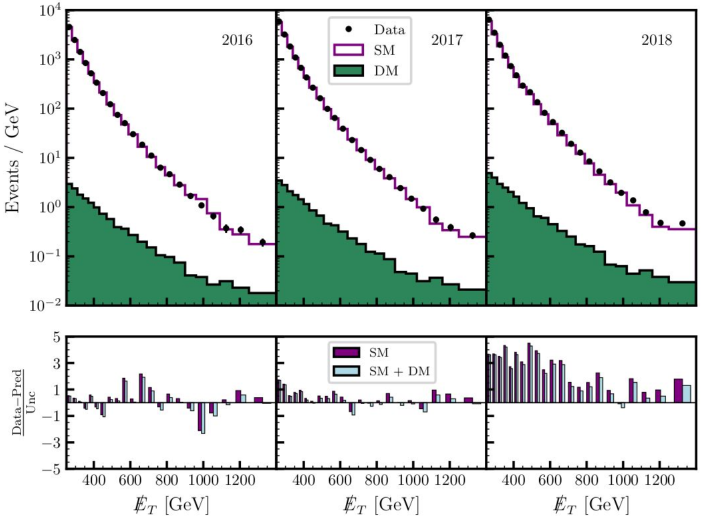
Planck 2018: Ωh^2 [26]
Nuisances

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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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.

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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
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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.

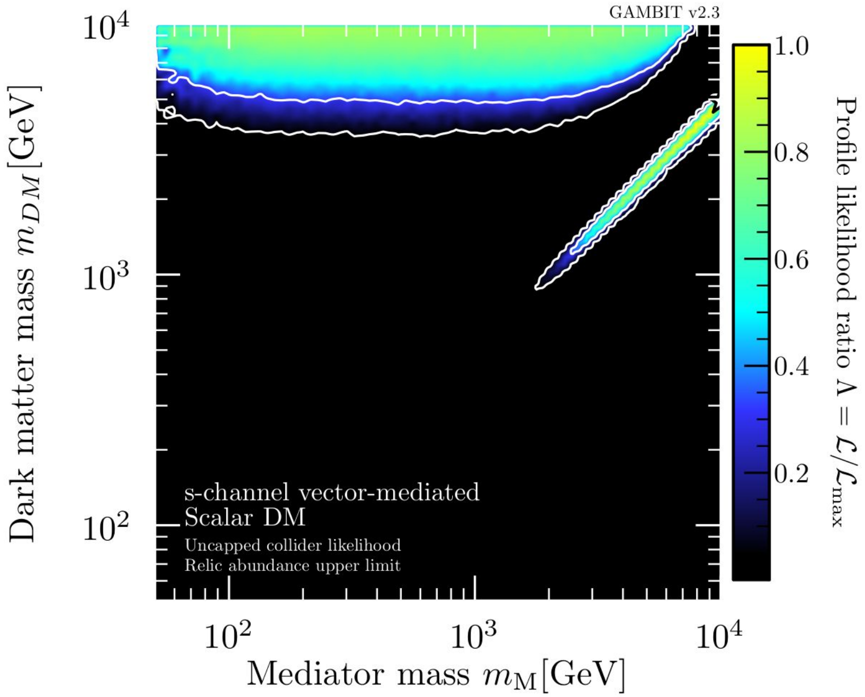
Up to 4 scans per model.

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	$[-0.22, -0.01]$ GeV^{-2}
Local DM density, ρ_0	$[0.2, 0.8]$ GeV cm^{-3}
Most probably speed, v_{esc}	$[216, 264]$ km s^{-1}
Galactic escape speed, v_{peak}	$[453, 603]$ km s^{-1}

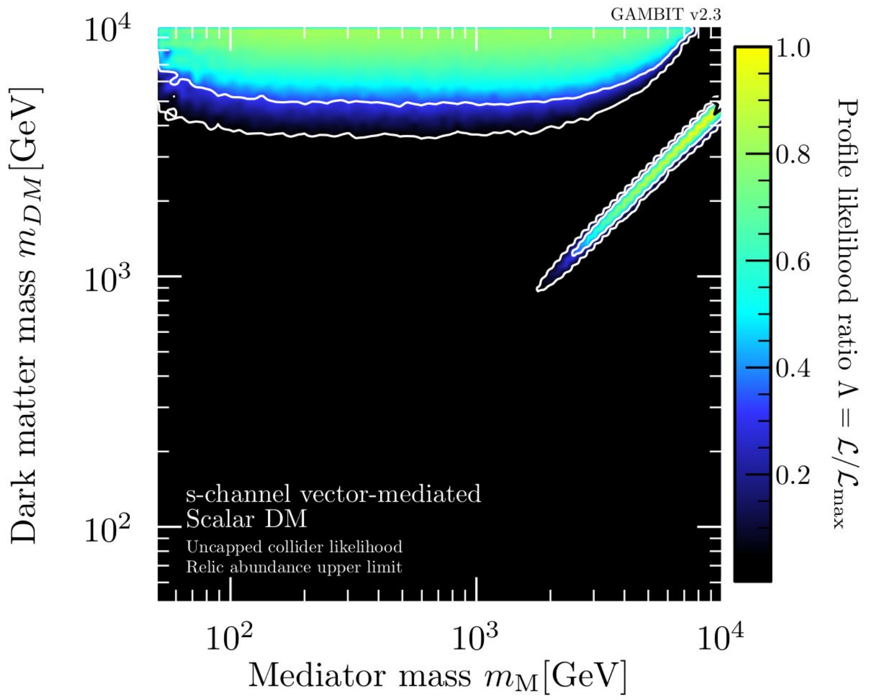
Results - Scalar DM

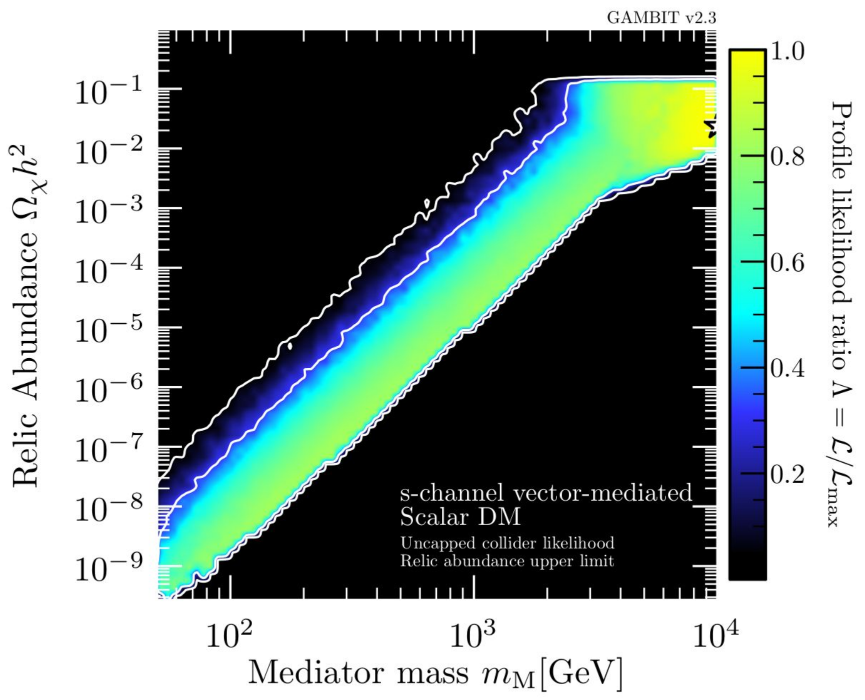
Capped results are not necessary as any collider preferences occur where already excluded by other experiments.



Results - Scalar DM

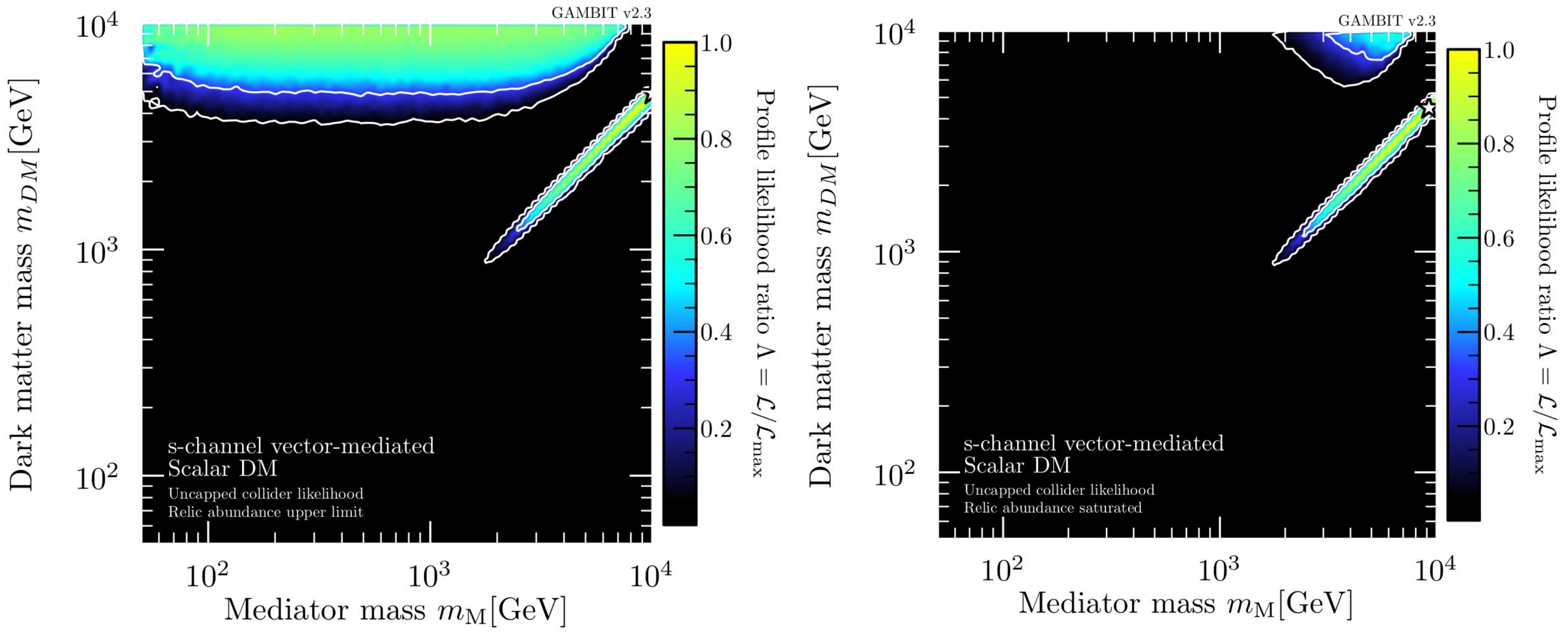
Much of the surviving parameter space predicts a very low DM relic abundance.





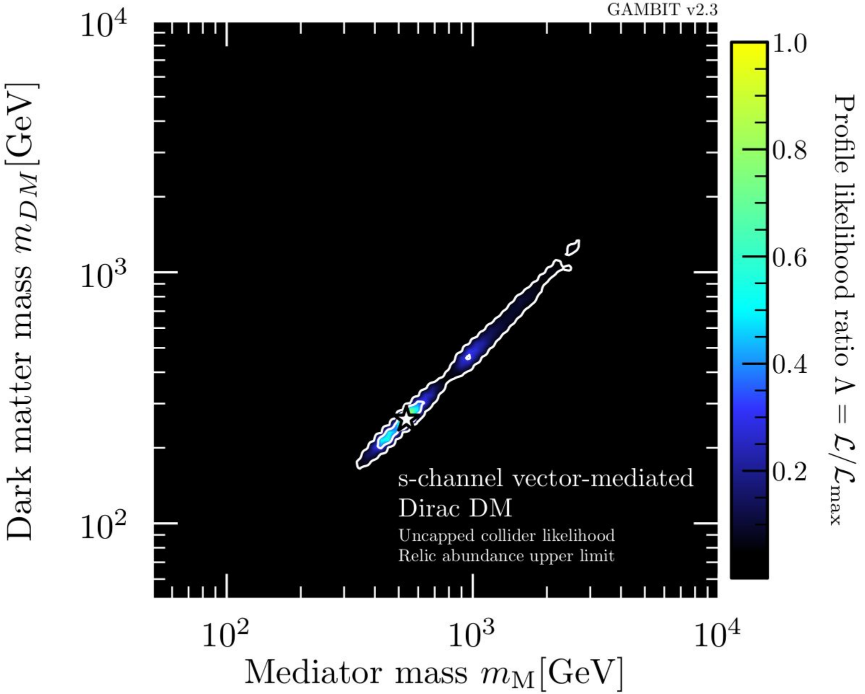
Results - Scalar DM

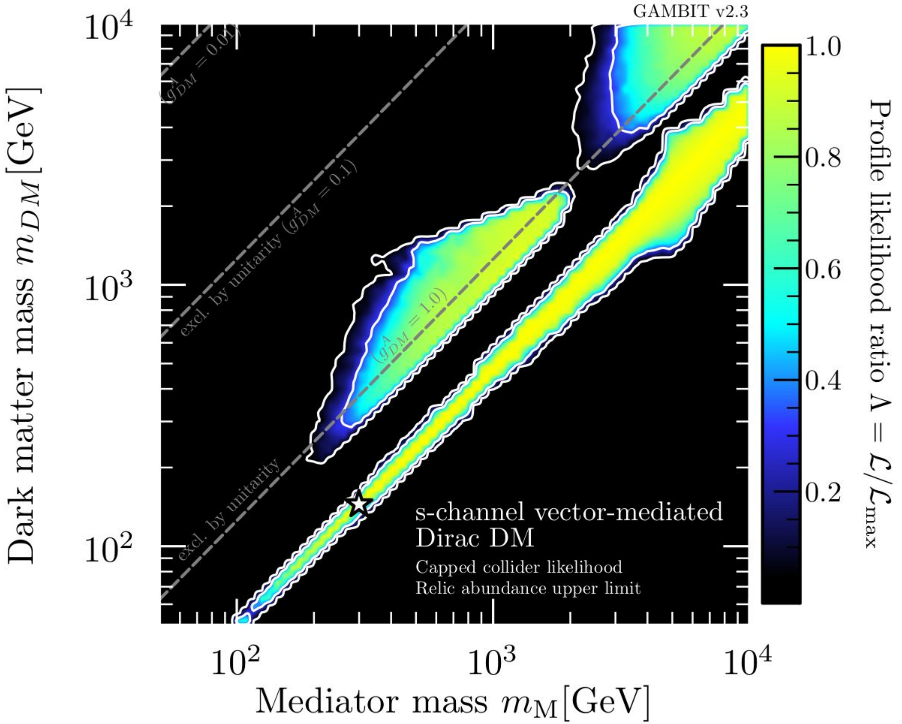
Requiring DM abundance is saturated reduces the off-resonance allowed parameter space.



Results- Dirac Fermion DM

Monojet likelihood gives preference to regions along the resonance.

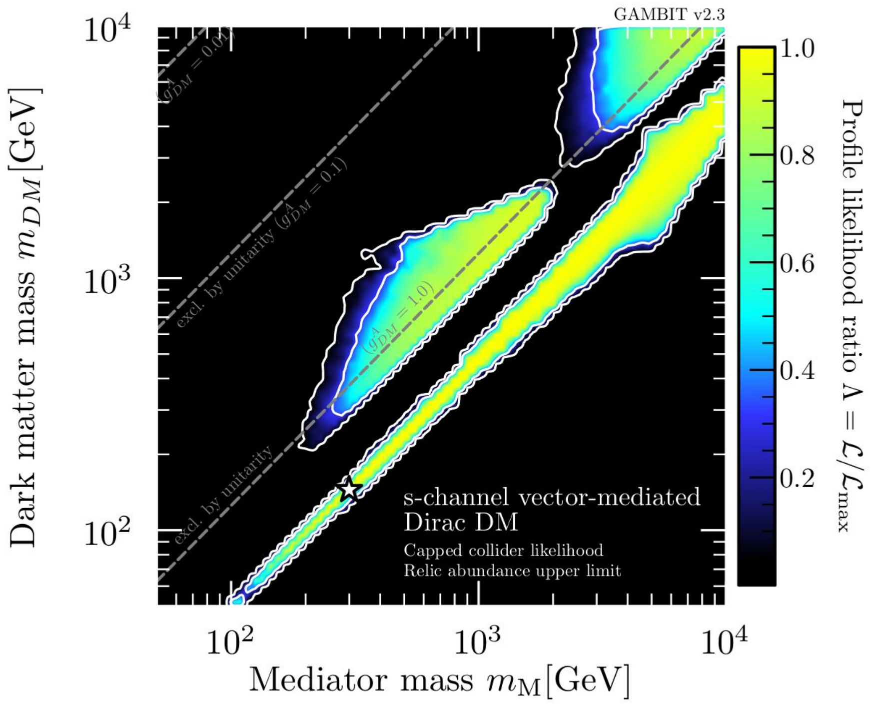




Results- Dirac Fermion DM

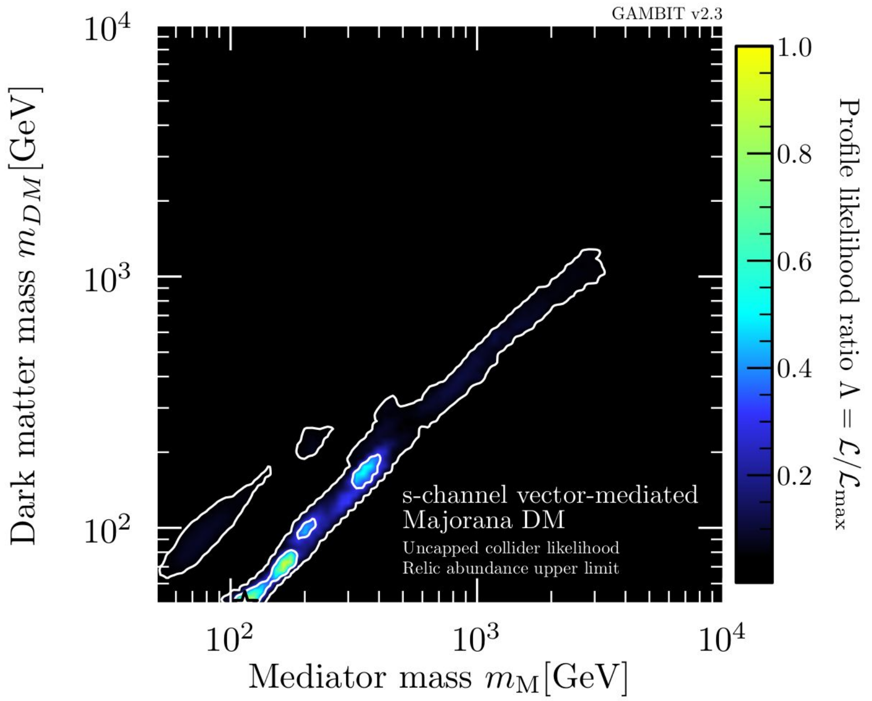
This interesting off resonance region is due to a combination of two things:

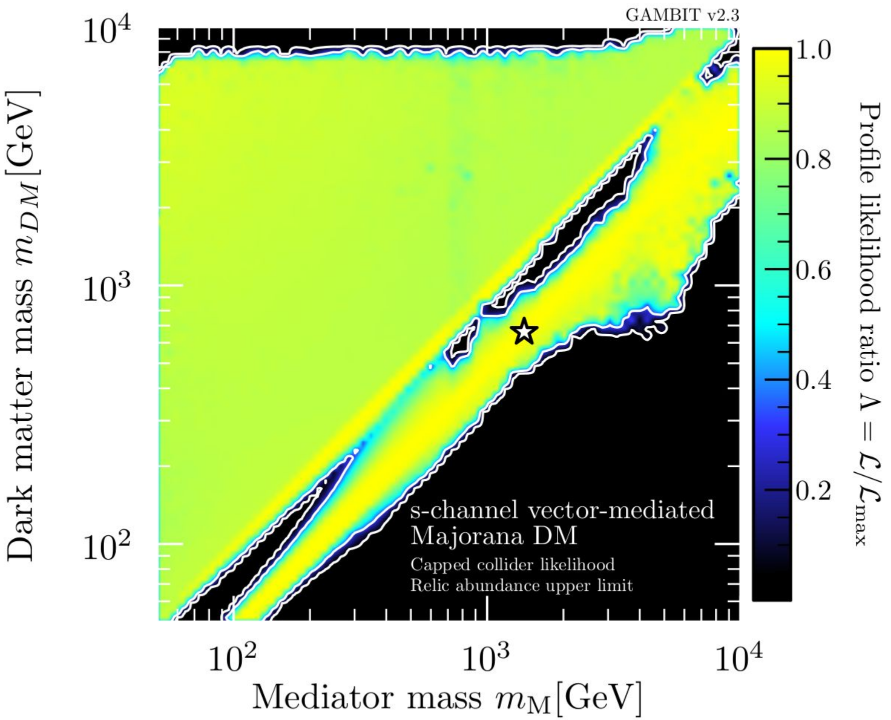
- DD limits give a lower bound on mediator masses.
- To avoid unitarity bounds, the axial-vector DM coupling must be low, however this will prevent sufficient annihilation of DM -> exceeding relic abundance



Results - Majorana fermion DM

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

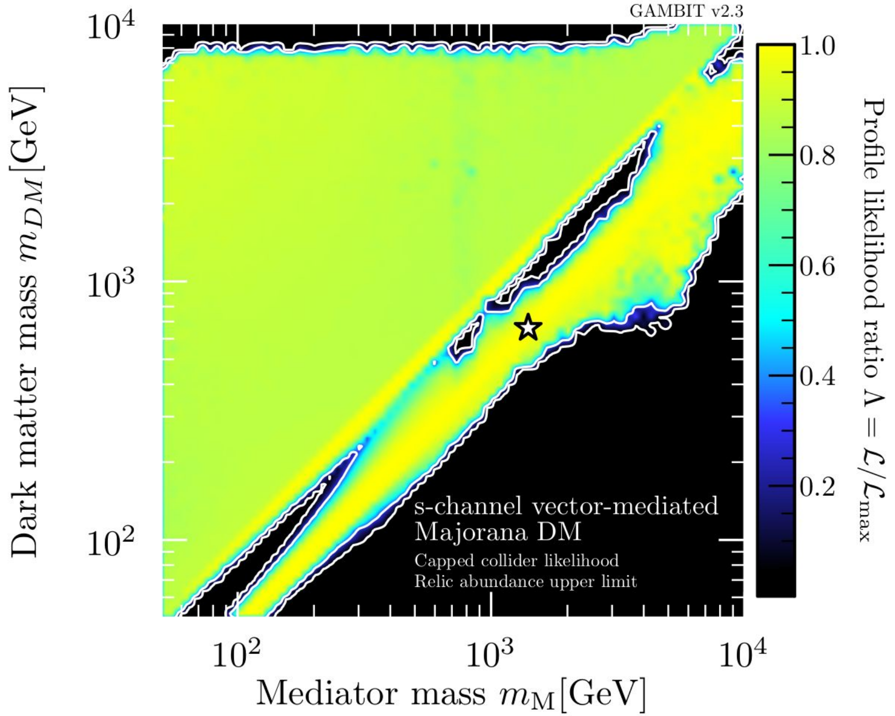




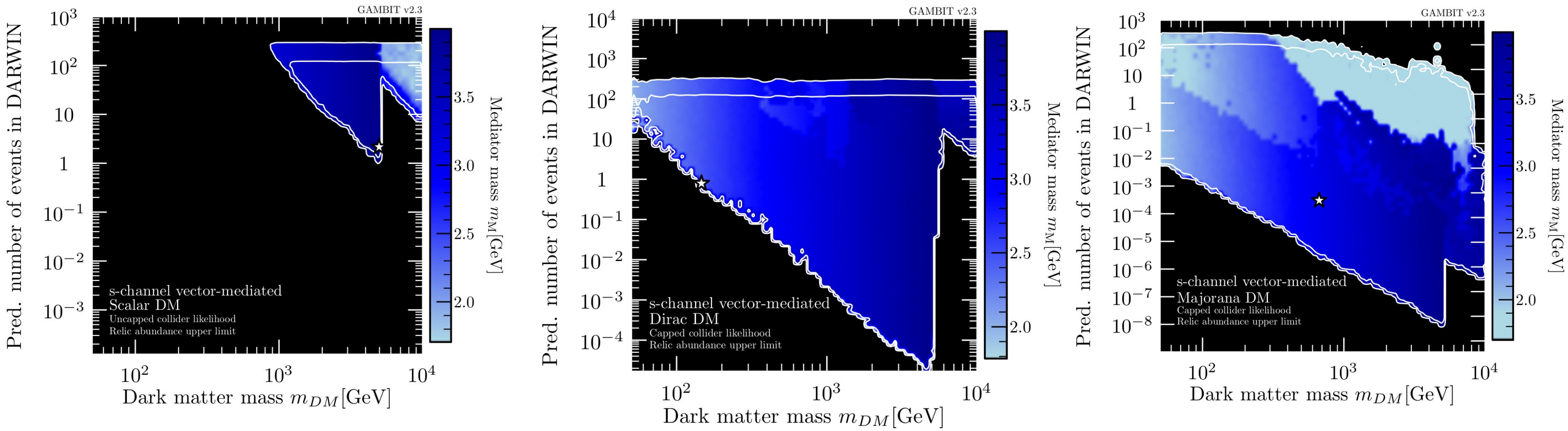
Results - Majorana fermion DM

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



Summary

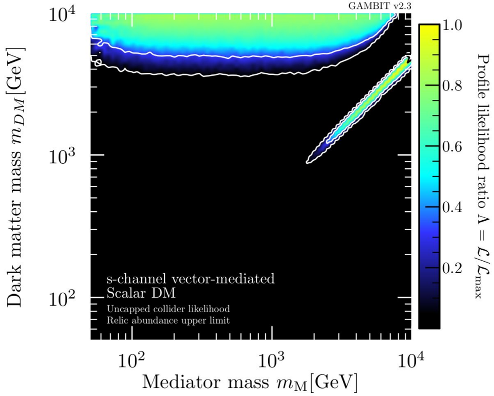
By combining constraints from direct detection, indirect detection and colliders, simplified dark matter models can be constrained greatly.

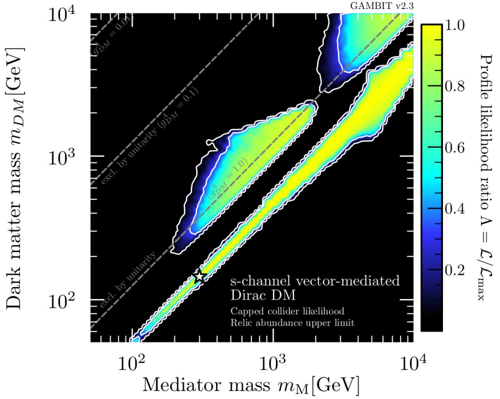
Scalar DM: Most of the parameter space that survives is for large DM masses. However, most of that underpredicts the DM abundance.

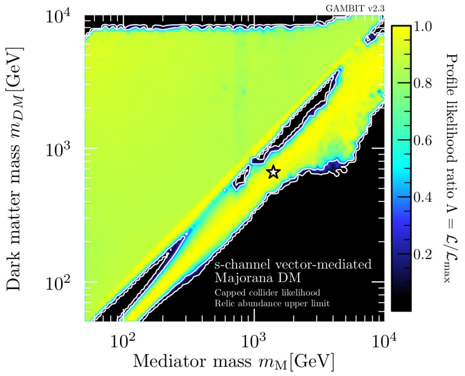
Dirac/Majorana DM: Scans are driven toward monojet excesses. No lower bound on DM masses for the parameters in these scans.

There is plenty of potential to constrain these further in near-future experiments.

Thanks for Listening!







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