Statistical Analyses of Higgs- and Z-Portal Dark Matter Models

J. Ellis, A. Fowlie, L. Marzola, and M. Raidal, Phys. Rev. D 97, 115014 (2017), arXiv:1711.09912 [hep-ph]

Andrew Fowlie

6 July 2018

Monash University

Table of contents

1. Portal models of dark matter — the teams

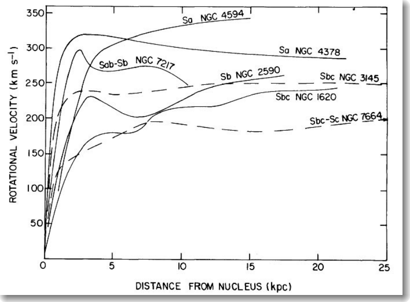
2. WIMP searches and constraints

3. Statistical methodology — the format of the competition

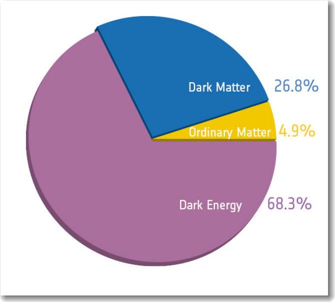
4. Results of the portal DM World Cup

Portal models of dark matter — the teams

We all know the evidence for dark matter (DM) in gravitational interactions, e.g.



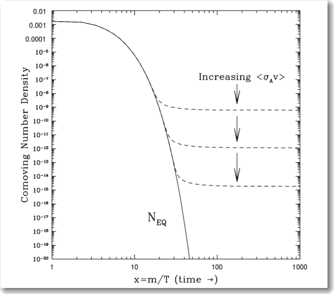
(I) Rotation curves [2]



(II) CMB [3]

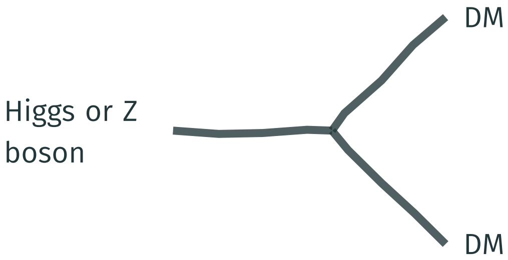
Once it is cold enough, DM particles cannot overcome Hubble expansion and thus cannot annihilate.

This freeze-out of thermal equilibrium with bath of Standard Model (SM) particles sets relic density. This is the WIMP miracle — as correct density achieved for weak interactions [4]



We construct the simplest WIMP models of DM by adding a single particle to the SM: the WIMP itself.

The WIMP interacts with SM by a Z or Higgs portal:



We consider all dimension ≤ 4, Lorentz invariant interactions for WIMPs with spin-0, 1/2 and 1.

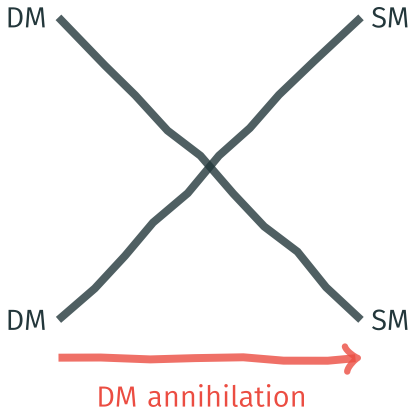
There are many models

(scalar, Majorana fermion, Dirac fermion, vector) spin of WIMP
$\times$ (Higgs, Z) mediator

We added them all to the DM program `microMEGAs` [5, 6] via the model building program `calcHEP` [7].

WIMP searches and constraints

DM must annihilate in the early Universe to set the relic density measured by Planck.

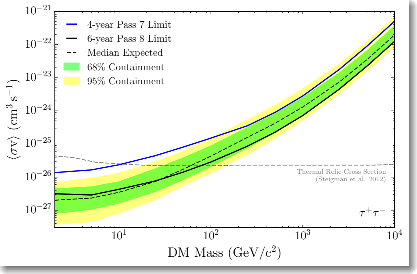


From measurements of the CMB Planck [3] found

$$\Omega h^2 = 0.1199 \pm 0.0022$$

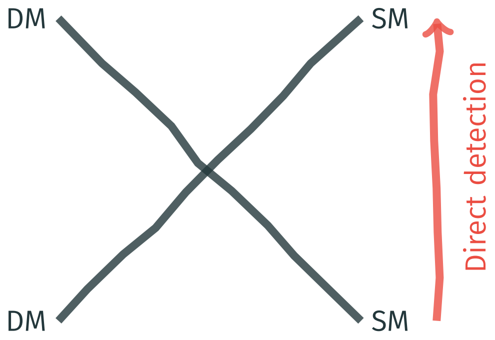
in ΛCDM. The WIMP in our model must make up all of DM, not just a fraction of it. We use a Gaussian likelihood with a 10% theoretical uncertainty.

DM annihilation could result in signals from high mass-to-light galaxies such as dwarf spheroidal galaxies.



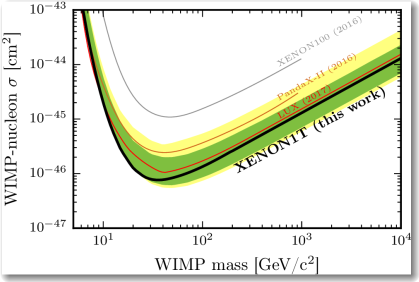
Fermi-LAT [8] searched for a γ-ray signal but saw nothing, resulting in upper limits on $\langle\sigma v\rangle|_{v\to0}$. We included astrophysical uncertainty in a J-factor.

We can search for DM in direct detection experiments. DM elastic scatters with nucleons in a detector on Earth.

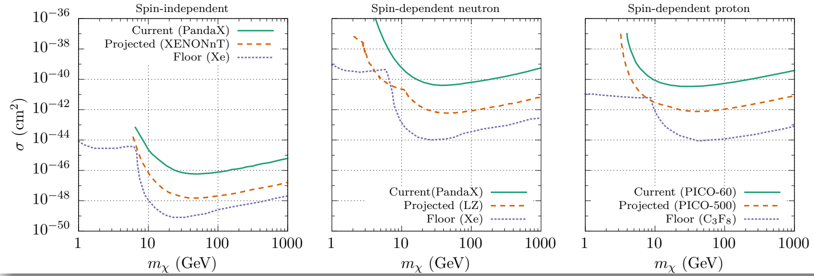


There is a wind of WIMP particles from the Earth's motion in the dark matter halo.

The Panda [9], LUX [10], XENON [11] and PICO [12] experiments saw nothing, resulting in exclusion contours on the (mass, cross section) planes

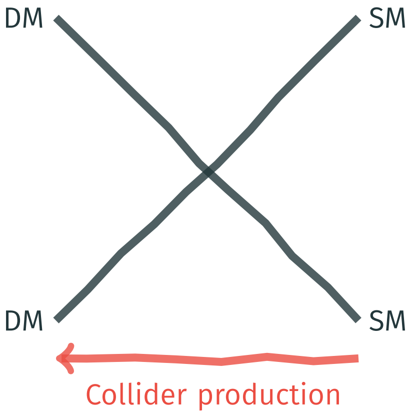


Our likelihood function for this data was a step-function. We included uncertainty in nuclear form factors and the local density of dark matter.

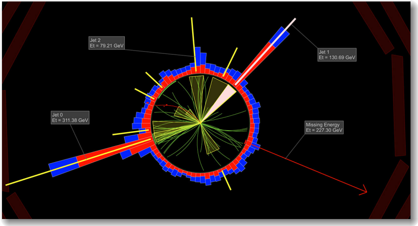


We also consider projected limits and limits down to the neutrino floor.

We can search for DM produced from collisions of SM particles.

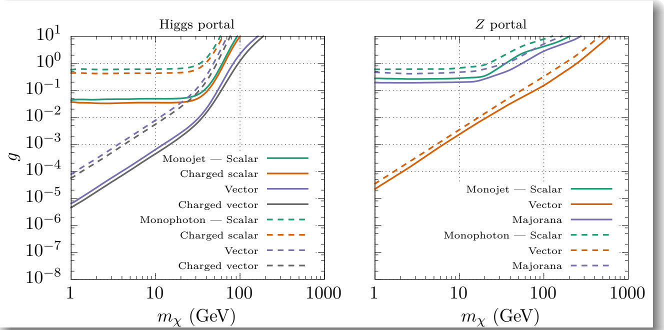


The LHC [13] saw nothing — wanted to find missing energy as DM escapes from the detector.



We interpreted monojet and monophoton searches for DM at the LHC via `CheckMATE-2` [14–19].

The monojet searches (solid lines) were marginally stronger.



We made sure that constraints on the Higgs invisible branching ratio from the LHC

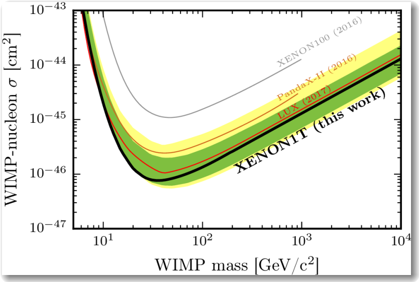
$$\text{BR}_h^{\text{inv}} \lesssim 24\%$$

and Z width from LEP were satisfied.

Data

Ωh^2	$0.1199 \pm 0.0022 \pm 10\%$	Planck [3]
Γ_Z^{inv}	$499.0 \pm 1.5 \pm 0.014\,\text{MeV}$	LEP [20]
BR_h^{inv}	$\lesssim 0.24$	LHC [21]
$\sigma_{\text{SI}}^{p,n}$	$\lesssim 10^{-46}\,\text{cm}^2$	PandaX [9]
σ_{SD}^{n}	$\lesssim 10^{-40}\,\text{cm}^2$	PandaX [22]
σ_{SD}^{p}	$\lesssim 10^{-40}\,\text{cm}^2$	PICO [10]
$\langle \sigma v \rangle$	$\lesssim 10^{-26}\,\text{cm}^3/\text{s}$	Fermi-LAT [8]
Mono-X searches	$\sqrt{s} = 8\,\text{TeV}$ and $13\,\text{TeV}$	LHC [13]

In light of the failure to discover DM in direct detection experiments, many doubting the plausibility of WIMP DM.



WIMP DM models can be fine-tuned to agree with data but was their plausibility damaged?

Let's check the impact on Higgs and Z portal models — confront all models with data.

DM WORLD CUP

ICHEP 2018

There are 10 models. Which one will be the champion?

Statistical methodology — the format of the competition

We have models and data. We need a statistical methodology to judge the models in light of the data.

Our approach is two-pronged: Bayesian and frequentist.

We calulate *p*-values and Bayes factors — the change in relative plausibilty of models in light of experimental data.

We picked logarithmic priors for DM mass and coupling, since we are ignorant of their scale.

DM mass, m_χ	$1\,\text{GeV} - 10\,\text{TeV}$	Log
DM coupling with SM, g	$10^{-6} - 4\pi$	Log

Results of the portal DM World Cup

Current data

First let's consider the impact of all current data.

For the Bayes factor, we consider the change in plausibility relative to Majorana Z-portal, which had the highest evidence.

Model	Bayes factor	$\min \chi^2$	p-value
Real scalar h-portal	0.55	2.6	0.27
Complex scalar h-portal	0.28	2.6	0.27
Real vector h-portal	0.23	2.6	0.27
Complex vector h-portal	0.059	2.6	0.27
Majorana h-portal	0.59	2.6	0.27
Dirac h-portal	0.71	2.6	0.27
Scalar Z-portal	3×10^{-14}	55	1.4×10^{-12}
Vector Z-portal	6.8×10^{-10}	35	2.2×10^{-8}
Majorana Z-portal	1	2.6	0.27
Dirac Z-portal	0.24	2.6	0.27

Two models excluded

A lot of information. Most models just fine. No clear winner!

The vector Z and scalar Z portal models predicted substantial scattering cross sections. They were excluded by direct detection experiments.

The results of the Bayesian and frequentist analysis are consistent.

Perhaps the failed searches for DM in direct detection experiments damaged plausibility of all portal models?

The Bayes factors shown the change in relative plausibility amongst the portal models.

Let's compare against an hypothetical model that predicts no signature in DD experiments with current and future DD limits.

Model	Damage to plausibility from DD: Present	Future	Neutrino floor
Real scalar h-portal	0.3	0.006	5×10^{-5}
Complex scalar h-portal	0.1	0.002	1×10^{-5}
Real vector h-portal	0.1	0.0009	9×10^{-7}
Complex vector h-portal	0.02	0.001	6×10^{-10}
Majorana h-portal	0.2	0.2	0.1
Dirac h-portal	0.2	0.1	0.1
Scalar Z-portal	1×10^{-14}	7×10^{-73}	7×10^{-129}
Vector Z-portal	3×10^{-10}	7×10^{-54}	2×10^{-101}
Majorana Z-portal	0.3	0.2	0.1
Dirac Z-portal	0.08	0.04	0.01

Direct detection experiments did not greatly damage the plausibility of many of the simplest models!

Hypothetical future results from LZ, XENONnT, and PICO might begin to damage a few models.

But fermionic models survive even once limits on the spin-independent cross section reach the neutrino floor!

The story from the change in χ^2 is similar, though disagreement about change in status of e.g., scalar DM interacting through Higgs portal.

	$\Delta\chi^2$		
Model	Present	Future	Neutrino floor
Real scalar h-portal	0	0	0.87
Complex scalar h-portal	0	0	2.4
Real vector h-portal	0	0	8.5
Complex vector h-portal	0	0	14
Majorana h-portal	0	0	0
Dirac h-portal	0	0	0
Scalar Z-portal	52	3.2×10^2	5.7×10^2
Vector Z-portal	33	2.3×10^2	4.5×10^2
Majorana Z-portal	0	0	0
Dirac Z-portal	0	0	0

Conclusions

- We constructed many simple models of WIMP DM that interact with the SM through the Higgs or Z boson
- We carefully considered all relevant experimental data and uncertainties
- We analyzed the models with Bayesian and frequentist statistics
- No clear winner to the DM world cup, but many contenders
- Lmited support for claims that WIMP DM is under pressure — a few models knocked out/implausible, but there is a long way to go in DD searches
- Waning of the WIMP is premature

References

[1] J. Ellis, A. Fowlie, L. Marzola, and M. Raidal, "Statistical Analyses of Higgs- and Z-Portal Dark Matter Models," Phys. Rev. D 97, 115014 (2017), arXiv:1711.09912 [hep-ph].

[2] V. C. Rubin, W. K. Ford Jr., and N. Thonnard, "Rotational properties of 21 SC galaxies with a large range of luminosities and radii, from NGC 4605 /R = 4kpc/ to UGC 2885 /R = 122 kpc/," Ap.J. 238, 471–487 (1980).

[3] P. A. R. Ade et al., “Planck 2015 results. XIII. Cosmological parameters,” Astron. Astrophys. 594, A13 (2016), arXiv:1502.01589 [astro-ph.CO].

[4] G. Jungman, M. Kamionkowski, and K. Griest, “Supersymmetric dark matter,” Phys. Rept. 267, 195–373 (1996), arXiv:hep-ph/9506380 [hep-ph].

[5] D. Barducci, G. Belanger, J. Bernon, F. Boudjema, J. Da Silva, S. Kraml, U. Laa, and A. Pukhov, “Collider limits on new physics within micrOMEGAs,” (2016), arXiv:1606.03834 [hep-ph].

[6] G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov, "MicrOMEGAs: A Program for calculating the relic density in the MSSM," Comput. Phys. Commun. 149, 103–120 (2002), arXiv:hep-ph/0112278 [hep-ph].

[7] A. Belyaev, N. D. Christensen, and A. Pukhov, "CalcHEP 3.4 for collider physics within and beyond the Standard Model," Comput. Phys. Commun. 184, 1729–1769 (2013), arXiv:1207.6082 [hep-ph].

[8] M. Ackermann et al., "Searching for Dark Matter Annihilation from Milky Way Dwarf Spheroidal Galaxies with Six Years of Fermi Large Area Telescope Data," Phys. Rev. Lett. 115, 231301 (2015), arXiv:1503.02641 [astro-ph.HE].

[9] X. Cui et al., "Dark Matter Results From 54-Ton-Day Exposure of PandaX-II Experiment," (2017), arXiv:1708.06917 [astro-ph.CO].

[10] D. S. Akerib et al., "Results on the Spin-Dependent Scattering of Weakly Interacting Massive Particles on Nucleons from the Run 3 Data of the LUX Experiment," Phys. Rev. Lett. 116, 161302 (2016), arXiv:1602.03489 [hep-ex].

[11] E. Aprile et al., "First Dark Matter Search Results from the XENON1T Experiment," (2017), arXiv:1705.06655 [astro-ph.CO].

[12] C. Amole et al., "Dark Matter Search Results from the PICO-60 C_3F_8 Bubble Chamber," Phys. Rev. Lett. 118, 251301 (2017), arXiv:1702.07666 [astro-ph.CO].

[13] F. Kahlhoefer, “Review of LHC Dark Matter Searches,” Int. J. Mod. Phys. A32, 1730006 (2017), arXiv:1702.02430 [hep-ph].

[14] D. Dercks, N. Desai, J. S. Kim, K. Rolbiecki, J. Tattersall, and T. Weber, “CheckMATE 2: From the model to the limit,” (2016), arXiv:1611.09856 [hep-ph].

[15] J. de Favereau, C. Delaere, P. Demin, A. Giammanco, V. Lemaître, A. Mertens, and M. Selvaggi, “DELPHES 3, A modular framework for fast simulation of a generic collider experiment,” JHEP 02, 057 (2014), arXiv:1307.6346 [hep-ex].

[16] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet User Manual,” Eur. Phys. J. C72, 1896 (2012), arXiv:1111.6097 [hep-ph].

[17] M. Cacciari and G. P. Salam, “Dispelling the N^3 myth for the k_t jet-finder,” Phys. Lett. B641, 57–61 (2006), arXiv:hep-ph/0512210 [hep-ph].

[18] A. L. Read, “Presentation of search results: The CL_s technique,” J. Phys. G28, [,11(2002)], 2693–2704 (2002).

[19] M. Cacciari, G. P. Salam, and G. Soyez, “The Anti-k_t jet clustering algorithm,” JHEP 04, 063 (2008), arXiv:0802.1189 [hep-ph].

[20] C. Patrignani et al., “Review of Particle Physics,” Chin. Phys. C40, 100001 (2016).

[21] *Searches for invisible Higgs boson decays with the CMS detector.*, tech. rep. CMS-PAS-HIG-16-016 (CERN, Geneva, 2016).

[22] C. Fu et al., "Spin-Dependent Weakly-Interacting-Massive-Particle–Nucleon Cross Section Limits from First Data of PandaX-II Experiment," Phys. Rev. Lett. 118, 071301 (2017), arXiv:1611.06553 [hep-ex].