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

J. Ellis, A. Fowlie, L. Marzola, and M. Raidal, Phys. Rev. D 97, 115014 (2018), arXiv:1711.09912 [hep-ph]

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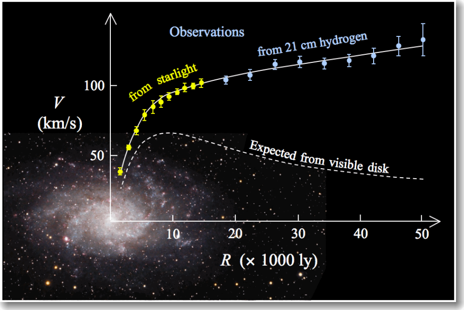
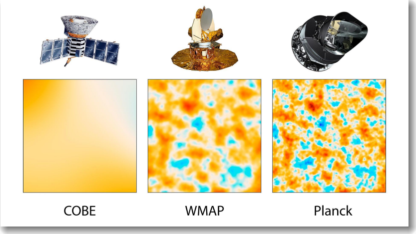
There is evidence for dark matter (DM) in gravitational interactions.

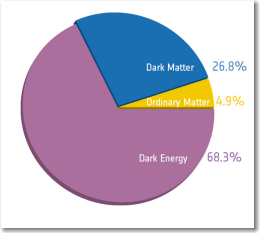


Galaxy rotation curves [2] suggest there is a halo of dark matter.

Dark matter experimental evidence

There is evidence for dark matter (DM) in gravitational interactions.

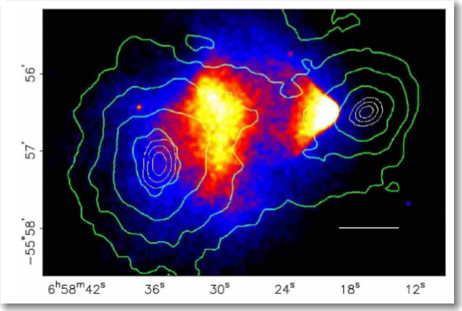




Planck [3] measurements of the cosmic microwave background require a transparent matter that forms gravitational potentials — dark matter.

Dark matter experimental evidence

There is evidence for dark matter (DM) in gravitational interactions.



The Bullet cluster [4] — collision between clusters of galaxies. Dark and ordinary components of galaxies revealed from gravitational lensing (lines) and x-rays (colors).

What is dark matter?

We need a massive, stable, electrically neutral particle.

Unfortunately, the Standard Model of particle physics contains no candidates.

Neutrinos are impossible — they are light and would be hot, ripping apart the galactic structure that we observe

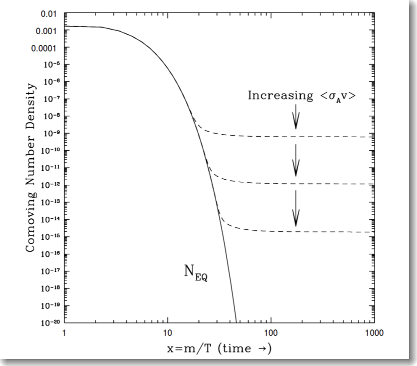
Weakly Interacting Massive Particles (WIMPs)

WIMPs naturally appear in many theories of new physics, e.g., supersymmetry.

Once it is cold enough, dark matter particles cannot overcome Hubble expansion and thus cannot annihilate or decay to ordinary particles.

This “freeze-out” of thermal equilibrium with bath of ordinary particles sets the dark matter density.

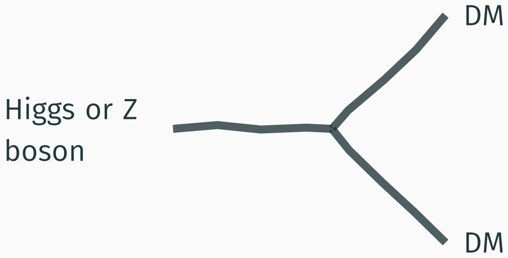
The correct dark matter density is achieved for weak interactions [5] — this is the WIMP miracle.



Simplest theories of DM

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

The WIMP interacts with ordinary matter through a Z or Higgs boson.



They are known particles with masses about 100 protons.

SM portal models

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` [6, 7] via the model building program `calcHEP` [8].

Higgs portal Lagrangians

We couple the Higgs (h) to dark matter (χ).

Dirac/Majorana fermion DM — scalar and pseudoscalar couplings

$$\mathcal{L} \supset c\,\bar{\chi}\left(g_s + i g_p \gamma^5\right)\chi\, h$$

Scalar DM

$$\mathcal{L} \supset c\,\lambda\left(vh\,|\chi|^2 + \frac{1}{2}h^2\,|\chi|^2\right)$$

Vector DM

$$\mathcal{L} \supset c\,g\left(vh\chi^\mu\chi^\dagger_\mu + \frac{1}{2}h^2\chi^\mu\chi^\dagger_\mu\right)$$

We consider real ($c = \frac{1}{2}$) and complex ($c = 1$) dark matter.

Z portal Lagrangians

We couple the Z-boson (Z) to dark matter (χ).

Dirac fermion

$$\mathcal{L} \supset \bar{\chi}\gamma^\mu \left(g_v + g_a\gamma^5\right) \chi \, Z_\mu$$

Majorana fermion

$$\mathcal{L} \supset \frac{g_a}{2}\bar{\chi}\gamma^\mu\gamma^5\chi \, Z_\mu$$

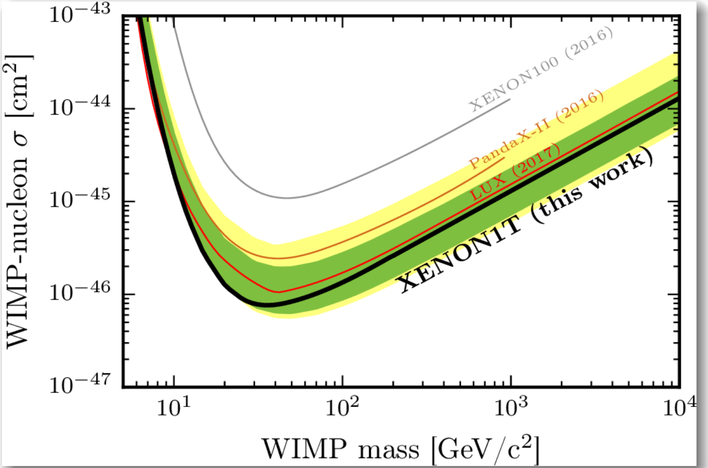
Scalar

$$\mathcal{L} \supset ig \, \chi^\dagger \overleftrightarrow{\partial}^\mu \chi \, Z_\mu + g^2 \left|\chi\right|^2 Z^\mu Z_\mu$$

Vector

$$\mathcal{L} \supset ig \, \left(Z^\mu \chi^{\nu\dagger} \, \partial_{[\mu}\chi_{\nu]} + \chi^\dagger_\mu \chi_\nu \, \partial^\mu Z^\nu\right) + \text{h.c.}$$

Dark matter searches and constraints



10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
WIMP-nucleon σ [cm^2]
10^1
10^2
10^3
10^4
WIMP mass [GeV/c^2]
XENON100 (2016)
PandaX-II (2016)
LUX (2017)
XENON1T (this work)

Waning of the WIMP?

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Dark-matter hunt fails to find the elusive particles

Physicists begin to embrace alternative explanations for the missing material.

News › Science

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Not finding dark matter is still useful, because it tells scientists what the elusive stuff can't do

Andrew Griffin | @_andrew_griffin | Thursday 21 July 2016 11:16 | 95 comments

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Waning of the WIMP?

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?

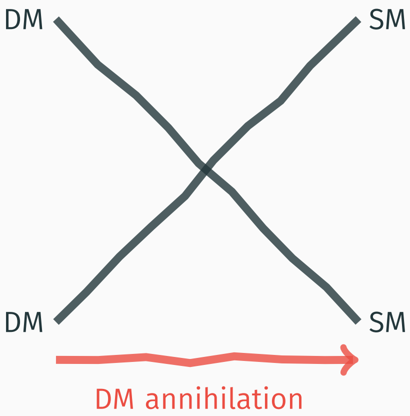
Many global fits of models of dark matter, or models containing a DM candidate (e.g., minimal supersymmetric standard model).

Few statistical analysis of damage to the plausibility dark model models from the latest wave of dark matter searches.

Let's check the impact on Higgs and Z portal models. First, let's review the constraints in detail.

DM annihilates to SM

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



Relic abundance

From measurements of the CMB Planck [3] found

$$\text{Relic density} = \Omega h^2 = 0.1199 \pm 0.0022$$

in dark energy + cold dark matter model of the Universe.

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.

If $m_\chi \simeq m_h/2$ or $M_Z/2$, annihilation is enhanced by an on-shell propagator, e.g.,

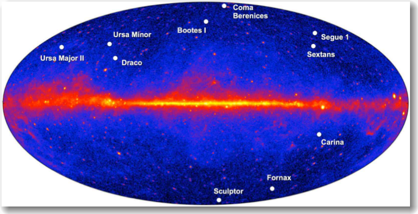
$$\sigma \propto \frac{g^2}{(s^2 - m_h^2)^2}$$

If $\sqrt{s} \simeq 2m_\chi \simeq m_h$, the coupling, g, between DM and mediator may be tiny.

We do not consider effect of kinetic decoupling [9, 10], though may in the future.

Indirect detection

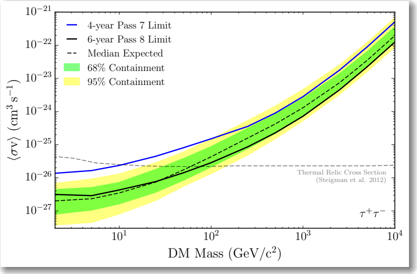
DM annihilation could result in signals from high mass-to-light galaxies such as dwarf spheroidal galaxies.



Fermi-LAT [11] searched for a γ-ray signal but saw nothing, resulting in constraints on DM annihilation cross section.

Constraint from Fermi-LAT

This results in an upper limit on $\langle \sigma v \rangle|_{v \to 0}$.



The constraint depends on the "softness" of the final state, as γ-rays are mainly from pion decay from $\chi\chi \to bb$ etc.

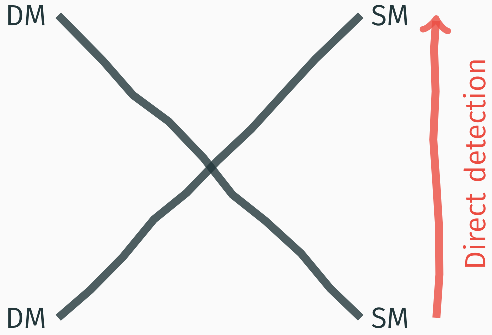
Other constraints (not included)

We do not consider observations of the galactic centre by Fermi-LAT or HESS, or constraints from neutrino telescopes.

The constraints are weak and suffer from uncertainties.

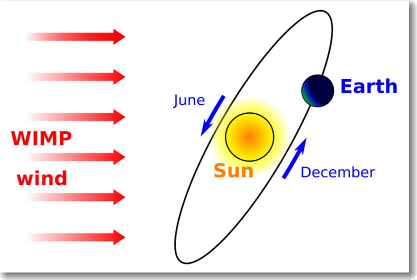
DM scatters with SM

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



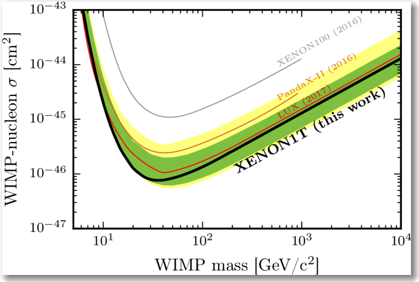
This is arguably the main prediction of WIMP dark matter.

There is a wind of WIMP particles from the Earth's motion in the dark matter halo [12] — like the rain on the windscreen of a car.



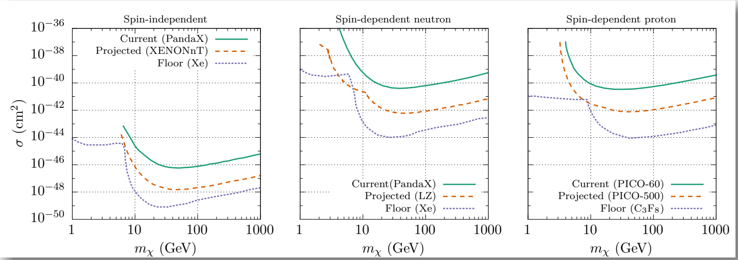
The WIMPs could interact with detectors on Earth.

The Panda [13], LUX [14], XENON [15] and PICO [16] 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 include all current limits (green).



We also consider projected limits from future experiments with more material (orange) and limits down to the neutrino floor (purple). At the neutrino floor, it is difficult to distinguish WIMPs from scattering with neutrinos.

Uncertainties

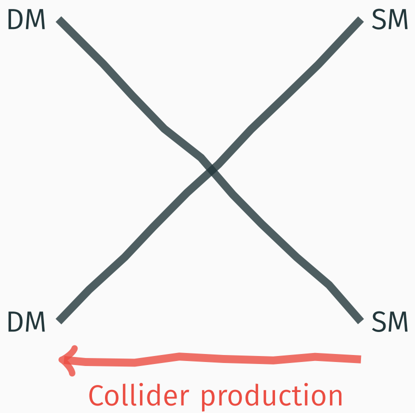
The signal from a WIMP depends upon a few uncertainties:

- What is the local density of DM (about one proton per cm^3)?
- What is the velocity distribution of the DM interacting with the detector (about 250 km/s)?
- What are the nuclear form factors that dress parton-level amplitudes to nucleon ones?

Our treatment is possibly the most comprehensive yet.

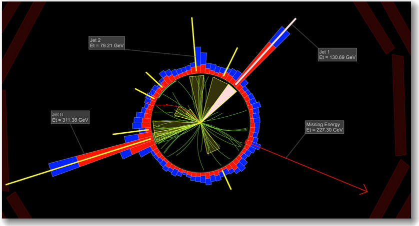
SM annihilates to DM

We can search for DM produced from collisions of ordinary Standard Model particles.



Collider searchers

The LHC [17] collided protons at $\sqrt{s} = 13\,\text{TeV}$.



LEP [18] collided electrons at $\sqrt{s} \lesssim 200\,\text{GeV}$. They had strategies for finding dark matter.

A photon or a jet + missing energy

At the LHC, we search for missing energy (MET, as don't know initial longitudinal momentum) and a recoil against a photon or a jet.

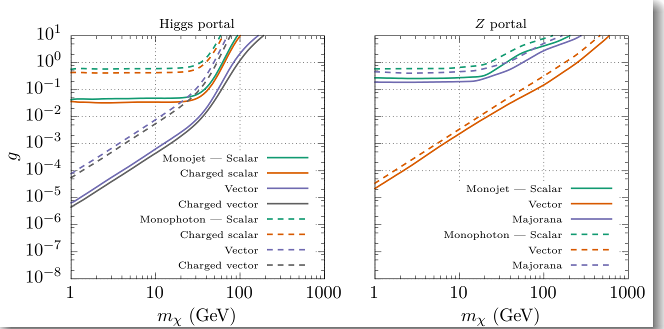
Without recoil, the DM particles are almost back-to-back in the laboratory frame and won't leave MET.

We interpreted monojet and monophoton searches for DM at the LHC via CheckMATE-2 [19–24].

LHC searches included

Analysis	$\sqrt{s}$ (TeV)	$\int \mathcal{L}$ (fb^{-1})
ATLAS monojet [25]	8	20.3
ATLAS monojet [26]	8	20.3
ATLAS monojet [27]	13	3.2
CMS monojet [28]	8	19.7
ATLAS monophoton [29]	8	20.3
ATLAS monophoton [30]	13	3.2
ATLAS monophoton [31]	13	36.1

The monojet searches (solid lines) were marginally stronger.



Invisible widths

The Higgs and Z boson could decay into DM, if e.g., $2m_\chi < M_Z$.

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.

Summary of dark matter data

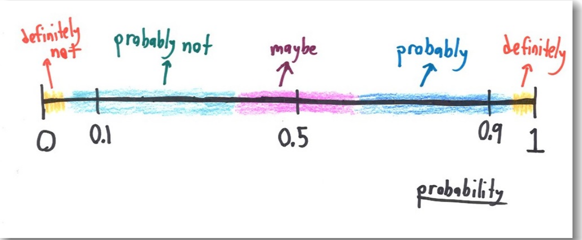
Ωh^2	$0.1199 \pm 0.0022 \pm 10\%$	Planck [3]
Γ_Z^{inv}	$499.0 \pm 1.5 \pm 0.014$ MeV	LEP [32]
BR_h^{inv}	$\lesssim 0.24$	LHC [33]
$\sigma_{\text{SI}}^{p,n}$	$\lesssim 10^{-46}\text{cm}^2$	PandaX [13]
σ_{SD}^{n}	$\lesssim 10^{-40}\text{cm}^2$	PandaX [34]
σ_{SD}^{p}	$\lesssim 10^{-40}\text{cm}^2$	PICO [14]
$\langle\sigma v\rangle$	$\lesssim 10^{-26}\text{cm}^3/\text{s}$	Fermi-LAT [11]
Mono-X searches	$\sqrt{s} = 8$ TeV and 13 TeV	LHC [17]

Statistical methodology

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.

What is probability? A measure of plausibility.

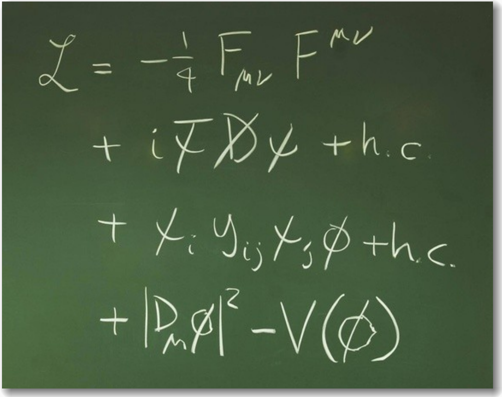


Probability $\Leftrightarrow$ plausibility

Scientific theories

What about applying it to scientific theories?

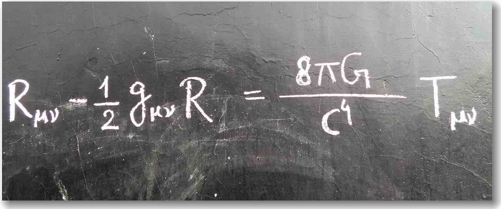
What is the probability of this theory in light of LHC experiments?



Scientific theories

What about applying it to scientific theories?

What about this one in light of LIGO's discoveries?



Prior knowledge

Probabilities depends upon priors.

The probability of a heads from the toss of a coin depends on prior belief about the dynamics and initial conditions of the coin.

Prior knowledge

Probabilities depends upon priors.

The probability of a winning hand depends on prior belief about the shuffled pack of cards and the integrity of the dealer.

Prior knowledge

Probabilities depends upon priors. The probability of a scientific theory in light of data depends on prior beliefs about the theory's parameters, the theory itself and alternative theories.

Bayesian statistics

Bayesian statistics is a mathematical framework for describing plausibility — a calculus of beliefs [35].

Developed by Bayes, Laplace and Jeffreys in 18th, 19th and 20th centuries.

Bayes' theorem

The most important equation is Bayes' theorem — a unique rule for updating plausibility in light of data:

$$p(M \mid D) = \frac{p(D \mid M)}{p(D)} \cdot p(M).$$

Our posterior belief in a model, M, is found by updating our prior belief with data, D.

Model comparison

To update our belief in a model in light of data, we must consider more than one model.

If we believe absolutely in a single model, we obtain

$$p(M \mid D) = p(M) = 1.$$

We simply find that we are certain about the model before and after data.

Thus we must compare models. We compare two models with a so-called Bayes factor

$$\text{Bayes factor} = \frac{\text{Relative plausibility after data}}{\text{Relative plausibility before data}}$$

in maths, by Bayes' theorem,

$$\text{Bayes factor} = \underbrace{\frac{p(D \mid M_a)}{p(D \mid M_b)}}_{\text{Calculate this ratio}} = \frac{\overbrace{\frac{p(M_a \mid D)}{p(M_b \mid D)}}^{\text{Posterior odds — output}}}{\underbrace{\frac{p(M_a)}{p(M_b)}}_{\text{Prior odds — input}}}$$

Bayesian evidence

A Bayes factor is itself a ratio of evidences, where

$$\text{Evidence} = p(D \mid M) = \int p(D \mid M, x) \cdot p(x \mid M) \, dx$$

The integrand is a product of likelihood and prior. Likelihood could be e.g. a Gaussian for Higgs mass measurement or Planck measurement of the dark matter relic density.

The integration is over the model's parameters x. The integration may be computationally challenging.

Frequentist

Probability is the frequency with which outcomes occur in hypothetical repeated trials,

$$p = \lim_{N \to \infty} \frac{n}{N}$$

Not a reflection of our knowledge/uncertainty but a property of an experimental process.

p-values

We are concerned about the probability of obtaining at least as discrepant data, were the model true. We construct a test-statistic

$$\lambda = -2 \ln \frac{\max \mathcal{L}(m_\chi, g, \cdots)}{\mathcal{L}_0}.$$

This is a random variable. The term $\mathcal{L}_0$ insures that the minimum test-statistic is zero for a model that perfectly matches observations.

We calculate the p-value,

$$\text{p-value} = P(\lambda \geq \lambda_{\text{observed}} \,|\, \text{model})$$

Approximation

The p-value is difficult to calculate because we don't know the distribution of the test statistic.

We make an assumption that it is like a chi-squared with two degrees of freedom

$$\lambda \sim \chi_2^2$$

We could, in principle, perform MC simulations to check this, but it's computationally demanding.

From now on I just call $\lambda = \chi^2$.

Priors for DM mass and couplings

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

DM mass, m_χ	1 GeV – 10 TeV	Log
DM coupling with SM, g	10^{-6} – 4π	Log

Sensitivity

There is a sensitivity analysis with linear priors in the paper.

The frequentist results don't depend upon these choices.

Priors nuisance parameters

In the frequentist analysis, priors on nuisance parameters were applied as likelihoods.

DM scattering rate with matter depends upon nuclear form factors.

Nuclear			
σ_s	$41.1 \pm 8.1^{+7.8}_{-5.8}$ MeV	Lattice, ETM [36]	Gaussian
$\sigma_{\pi N}$	$37.2 \pm 2.6^{+4.7}_{-2.9}$ MeV	Lattice, ETM [36]	Flat + tails
	58 ± 5 MeV	Pheno [37]	
m_u/m_d	0.38 – 0.58	Lattice [32]	Flat
m_s/m_d	17 – 22	Lattice [32]	Flat

We also investigated an alternative treatment of $\sigma_{\pi N}$.

DM flux on Earth depends on density and velocity distribution of DM.

Astrophysical		
ρ_{DM}	$0.3\,\mathrm{GeV/cm^3}$	Log-normal
v_{esc}	$550 \pm 35\,\mathrm{km/s}$	Gaussian
v_{rel}	$235 \pm 20\,\mathrm{km/s}$	Gaussian
v_0	$235 \pm 20\,\mathrm{km/s}$	Gaussian
J-factor for dSphs		Log-normal [11]

Priors nuisance parameters

DM annihilation sensitive to masses of Higgs and Z-boson.

SM			
M_Z	$91.1876 \pm 0.0021\,\mathrm{GeV}$	Gaussian	LHC [32]
m_h	$125.09 \pm 0.24\,\mathrm{GeV}$	Gaussian	LEP [32]

Results of statistical analysis of portal dark matter models

Putting the ingredients together

We now have

- Models, M_i: Scalar, fermion or vector DM that interacts with SM by Z or Higgs boson
- Data, D: Planck measurement of the relic density and failed searches for DM in direct detection, indirect detection and colliders
- Statistical framework: with Bayesian statistics we can calculate $p(M_i \mid D) / p(M_j \mid D)$; with frequentist statistics we can calculate p-value

We calculated the evidence integrals and explore parameter space with `MultiNest` [38–40].

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.

Current data

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.

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.

Damage to simple DM models

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.

Damage to simple DM models

	Damage to plausibility from DD		
Model	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

Damage to simple DM models

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!

Damage to simple DM models

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.

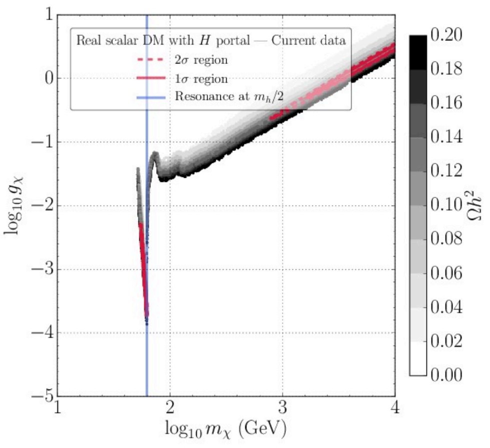
Damage to simple DM models

Model	$\Delta\chi^2$		
	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

What's going on?

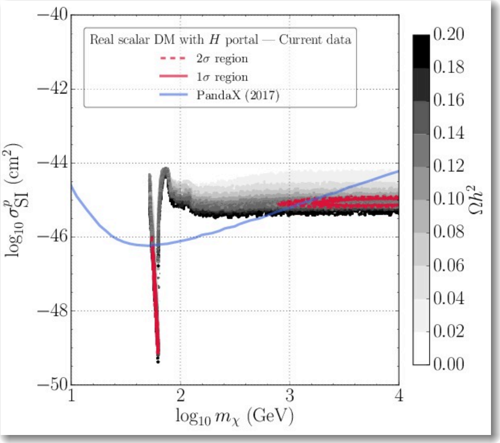
Let's see what is happening in the scalar DM interacting through Higgs portal — this is a popular model, and Bayesian and frequentist analysis somewhat disagreed.

With current data, the mass of scalar DM with a Higgs portal is pushed to multi-TeV region in red or the narrow resonance region by DD constraints.

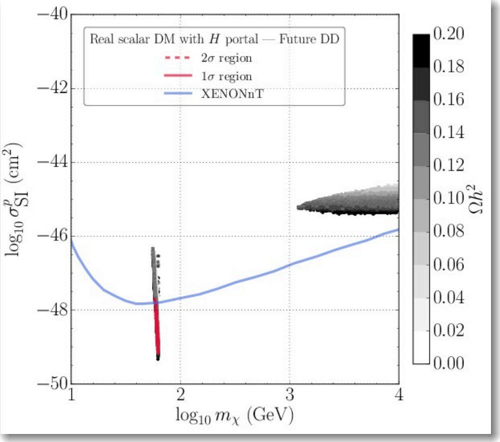


Direct detection prospects

We require sensitivity for multi-TeV dark matter and/or low cross sections — future experiment XENONnT [41] should probe it.



DM is pushed into the Higgs funnel by XENONnT. By this point this model becomes fine-tuned although there remain points with small chi-squared.



Direct detection prospects

The chi-squared may be small but only in a tiny region, hence the contrasting Bayesian and frequentist results.

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
- Found limited support for claims that WIMP DM is under pressure — a few models ruled 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 (2018), 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] D. Clowe, M. Bradac, A. H. Gonzalez, M. Markevitch, S. W. Randall, C. Jones, and D. Zaritsky, “A direct empirical proof of the existence of dark matter,” Astrophys. J. 648, L109–L113 (2006), arXiv:astro-ph/0608407 [astro-ph].

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

[6] 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].

7 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].

8 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].

9 T. Binder, T. Bringmann, M. Gustafsson, and A. Hryczuk, “Early kinetic decoupling of dark matter: when the standard way of calculating the thermal relic density fails,” (2017), arXiv:1706.07433 [astro-ph.CO].

[10] M. Duch and B. Grządkowski, "Resonance enhancement of dark matter interactions: the case for early kinetic decoupling and velocity dependent resonance width," (2017), arXiv:1705.10777 [hep-ph].

[11] 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].

[12] K. Freese, M. Lisanti, and C. Savage, "Colloquium: Annual modulation of dark matter," Rev. Mod. Phys. 85, 1561–1581 (2013), arXiv:1209.3339 [astro-ph.CO].

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

[14] 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].

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

[16] 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].

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

[18] R. Barate et al., “Measurement of the Z resonance parameters at LEP,” Eur. Phys. J. C14, 1–50 (2000).

[19] 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].

[20] 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].

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

[22] 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].

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

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

[25] G. Aad et al., "Search for pair-produced third-generation squarks decaying via charm quarks or in compressed supersymmetric scenarios in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector," Phys. Rev. D90, 052008 (2014), arXiv:1407.0608 [hep-ex].

[26] G. Aad et al., "Search for new phenomena in final states with an energetic jet and large missing transverse momentum in pp collisions at $\sqrt{s}$ =8 TeV with the ATLAS detector," Eur. Phys. J. C75, [Erratum: Eur. Phys. J.C75,no.9,408(2015)], 299 (2015), arXiv:1502.01518 [hep-ex].

[27] M. Aaboud et al., "Search for new phenomena in final states with an energetic jet and large missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector," Phys. Rev. D94, 032005 (2016), arXiv:1604.07773 [hep-ex].

[28] V. Khachatryan et al., "Search for dark matter, extra dimensions, and unparticles in monojet events in proton–proton collisions at $\sqrt{s} = 8$ TeV," Eur. Phys. J. C75, 235 (2015), arXiv:1408.3583 [hep-ex].

[29] G. Aad et al., "Search for new phenomena in events with a photon and missing transverse momentum in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector," Phys. Rev. D91, [Erratum: Phys. Rev.D92,no.5,059903(2015)], 012008 (2015), arXiv:1411.1559 [hep-ex].

[30] M. Aaboud et al., "Search for new phenomena in events with a photon and missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector," JHEP 06, 059 (2016), arXiv:1604.01306 [hep-ex].

[31] M. Aaboud et al., "Search for dark matter at $\sqrt{s} = 13$ TeV in final states containing an energetic photon and large missing transverse momentum with the ATLAS detector," Eur. Phys. J. C77, 393 (2017), arXiv:1704.03848 [hep-ex].

[32] C. Patrignani et al., "Review of Particle Physics," Chin. Phys. C40, 100001 (2016).

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

[34] 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].

[35] P. Gregory, *Bayesian logical data analysis for the physical sciences: a comparative approach with mathematica® support*, (Cambridge University Press, 2005).

[36] A. Abdel-Rehim, C. Alexandrou, M. Constantinou, K. Hadjiyiannakou, K. Jansen, C. Kallidonis, G. Koutsou, and A. Vaquero Aviles-Casco, “Direct Evaluation of the Quark Content of Nucleons from Lattice QCD at the Physical Point,” Phys. Rev. Lett. 116, 252001 (2016), arXiv:1601.01624 [hep-lat].

[37] J. Ruiz de Elvira, M. Hoferichter, B. Kubis, and U.-G. Meißner, "Extracting the sigma-term from low-energy pion-nucleon scattering," (2017), arXiv:1706.01465 [hep-ph].

[38] F. Feroz and M. P. Hobson, "Multimodal nested sampling: an efficient and robust alternative to MCMC methods for astronomical data analysis," Mon. Not. Roy. Astron. Soc. 384, 449 (2008), arXiv:0704.3704 [astro-ph].

[39] F. Feroz, M. P. Hobson, and M. Bridges, "MultiNest: an efficient and robust Bayesian inference tool for cosmology and particle physics," Mon. Not. Roy. Astron. Soc. 398, 1601–1614 (2009), arXiv:0809.3437 [astro-ph].

[40] F. Feroz, M. P. Hobson, E. Cameron, and A. N. Pettitt, "Importance Nested Sampling and the MultiNest Algorithm," (2013), arXiv:1306.2144 [astro-ph.IM].

[41] E. Aprile et al., "Physics reach of the XENON1T dark matter experiment," JCAP 1604, 027 (2016), arXiv:1512.07501 [physics.ins-det].