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

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

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8 March 2018. Melbourne University

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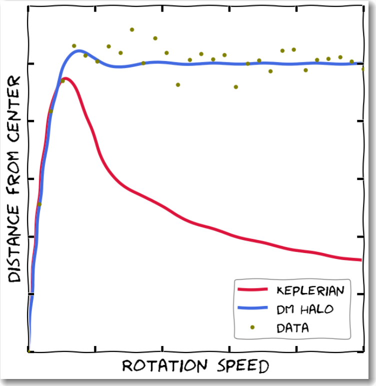
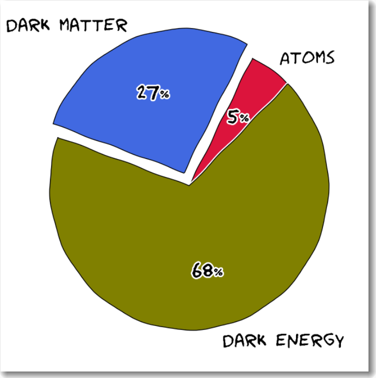
Portal models of dark matter

Dark matter experimental evidence

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



(I) Rotation curves [2]



(II) CMB [3]

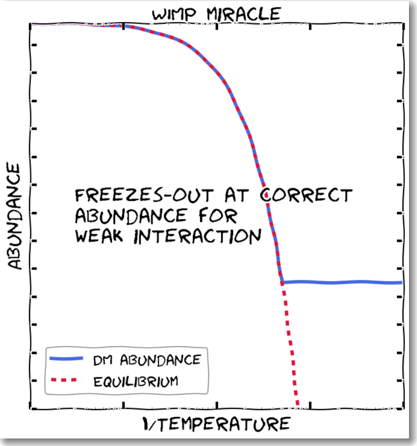
WIMP miracle

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.

WIMP miracle

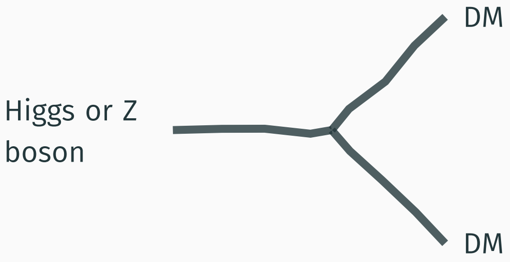
This is the WIMP miracle — as correct density achieved for weak interactions.



Simplest theories of DM

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.

SM portal models

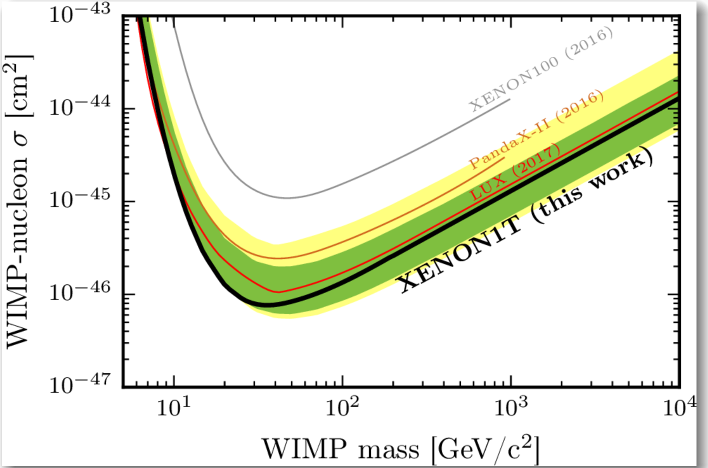
There are many models

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

We added them all to the DM program `microMEGAs` [4, 5] via the model building program `calcHEP` [6].

Waning of the WIMP?

Waning of the WIMP?



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.

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MACHOs are dead. WIMPs are a no-show. Say hello to SIMPs: New candidate for dark matter

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?

Current knowledge

Many “global fits” of models of dark matter, or models containing a DM candidate (e.g., MSSM).

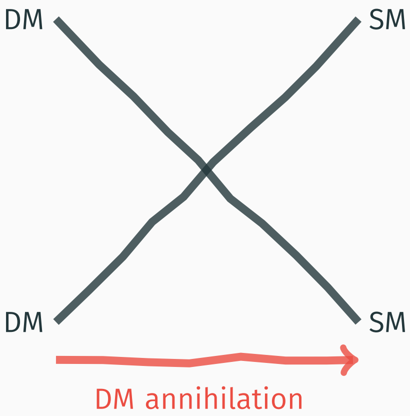
Few (no?) statistical analysis of damage to the plausibility dark model models from the latest wave of dark matter searches.

Let’s check the impact on Higgs and Z portal models.

WIMP searches and constraints

DM annihilates to SM

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



From measurements of the CMB Planck [3] found

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

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.

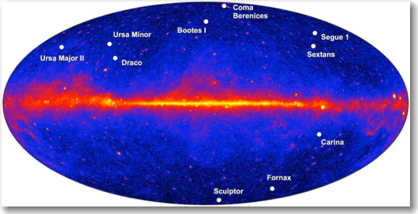
If $m_\chi \simeq m_h/2$ or $M_Z/2$, annihilation is enhanced by an on-shell propagator.

This allows a tiny coupling between DM and mediator.

We do not consider effect of kinetic decoupling [7, 8], though may in the future.

Indirect detection

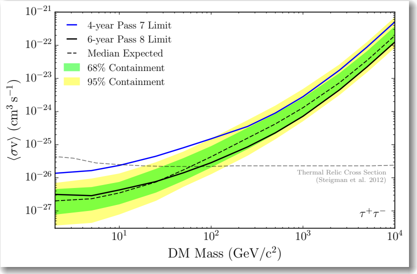
DM annihilation could result in signals from high mass-to-light galaxies such as dwarf spheroidal galaxies.



Fermi-LAT [9] 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.

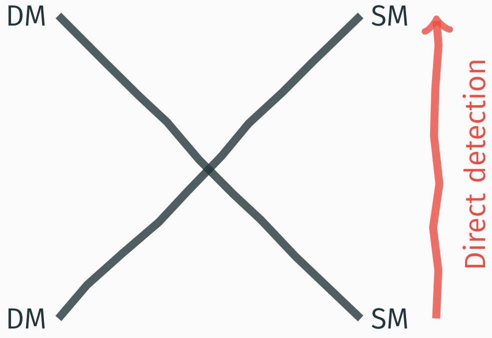
Other constraints (not included)

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.

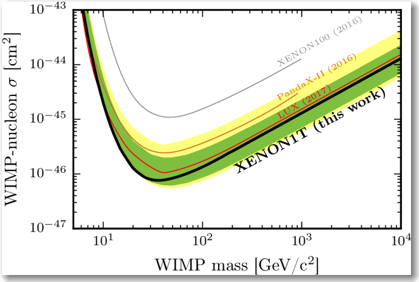
DM scatters with SM

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



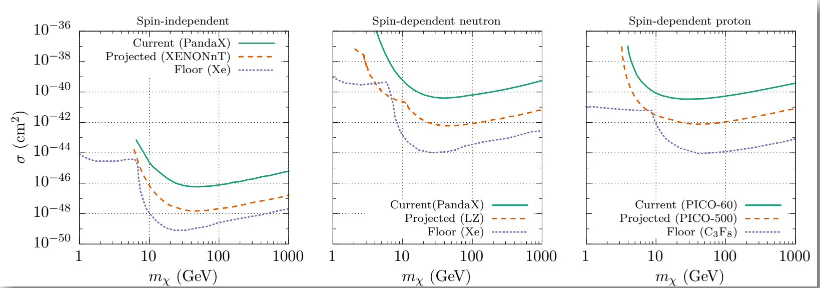
There is a wind of WIMP particles from the Earth's motion in the dark matter halo.

The Panda [10], LUX [11], XENON [12] and PICO [13] 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.

Direct detection



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

Uncertainties

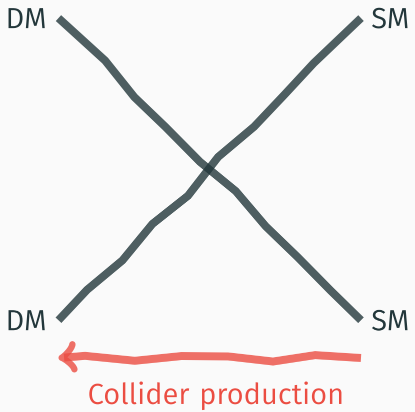
The constraints depend upon a few uncertainties:

- What is the local density of DM?
- What is the velocity distribution of the DM interacting with the detector (see [14])?
- What are the nuclear form factors that dress parton-level amplitudes to nucleon ones?

Our treatment is possibly the most comprehensive yet.

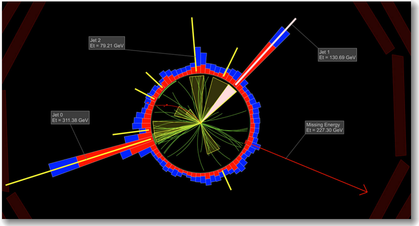
SM annihilates to DM

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



Collider searchers

The LHC [15] saw nothing — wanted to find missing energy as DM escapes from the detector.



LEP [16] saw nothing — wanted to find Z decaying into DM particles.

Something + MET

We search for MET and a recoil against a photon or a jet.

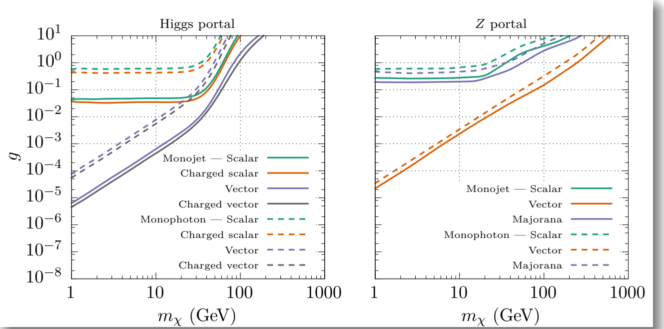
Without recoil, the DM particles are almost back-to-back in the laboratory frame and won't leave MET.

We interpreted monojet and monophoton searches for DM at the LHC via `CheckMATE-2` [17–22].

Something + MET

Analysis	$\sqrt{s}$ (TeV)	$\int \mathcal{L}$ (fb^{-1})
ATLAS monojet [23]	8	20.3
ATLAS monojet [24]	8	20.3
ATLAS monojet [25]	13	3.2
CMS monojet [26]	8	19.7
ATLAS monophoton [27]	8	20.3
ATLAS monophoton [28]	13	3.2
ATLAS monophoton [29]	13	36.1

The monojet searches (solid lines) were marginally stronger.



Invisible widths

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

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

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 [30]
BR_h^{inv}	$\lesssim 0.24$	LHC [31]
$\sigma_{\text{SI}}^{p,n}$	$\lesssim 10^{-46}\text{cm}^2$	PandaX [10]
σ_{SD}^{n}	$\lesssim 10^{-40}\text{cm}^2$	PandaX [32]
σ_{SD}^{p}	$\lesssim 10^{-40}\text{cm}^2$	PICO [11]
$\langle \sigma v \rangle$	$\lesssim 10^{-26}\text{cm}^3/\text{s}$	Fermi-LAT [9]
Mono-X searches	$\sqrt{s} = 8\,\text{TeV}$ and $13\,\text{TeV}$	LHC [15]

Statistical methodology

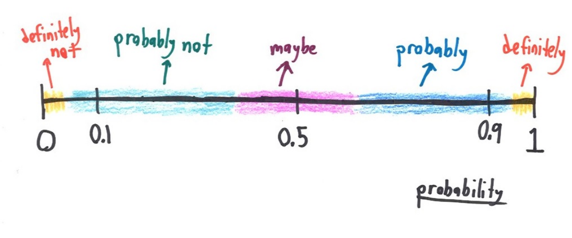
We have models and data. We need a statistical methodology to judge the models in light of the data.

Our approach is two-pronged: Bayesian and frequentist.

Models + observed data + unobserved data (!?) + methodology

$\Rightarrow$ conclusions

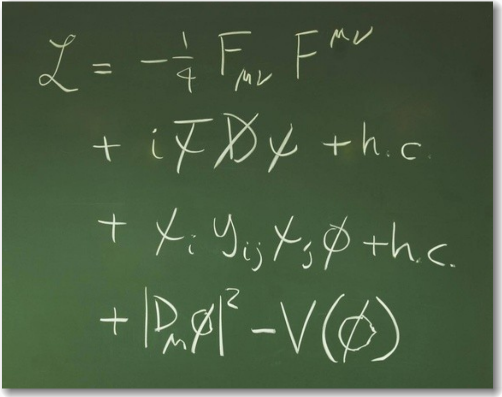
What is probability? A measure of plausibility.



Probability $\Leftrightarrow$ plausibility

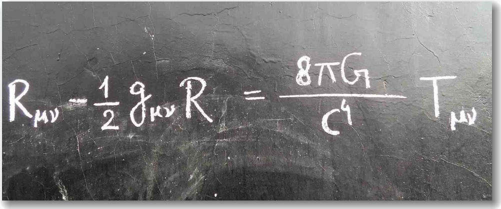
What about applying it to scientific theories?

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



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

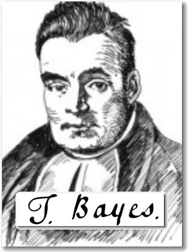
Probabilities depends upon priors.

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

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 [33].



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.

Bayes factors

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,

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

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,

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

p-value and evidence

The p-value is the frequency with which we expect to find a test statistic at least as extreme as that observed, under the null.

The p-value is not equal to the Bayesian evidence, $p(D \mid M)$

$$\text{p-value} \neq p(D \mid M)$$

There is no general mapping between p and $P(M \mid D)$ or $p(D \mid M)$.

It is not a matter of multiplying a p-value by a prior.

Interpretation

We could set a threshold on p, e.g, $\alpha = 5\%$, and “reject” the model if the observed p is less than α (Neyman-Pearson). This would result in an error rate of α in repeated trials, were the model true.

We didn’t do that, so I guess our interpretation of p is that small p is evidence against the model (Fisher).

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 and nuisance parameters

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 [34]	Gaussian
$\sigma_{\pi N}$	$37.2 \pm 2.6^{+4.7}_{-2.9}$ MeV	Lattice, ETM [34]	Flat + tails
	58 ± 5 MeV	Pheno [35]	
m_u / m_d	0.38 – 0.58	Lattice [30]	Flat
m_s / m_d	17 – 22	Lattice [30]	Flat

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

Priors nuisance parameters

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

Astrophysical		
ρ_{DM}	$0.3\,\text{GeV}/\text{cm}^3$	Log-normal
v_{esc}	$550 \pm 35\,\text{km}/\text{s}$	Gaussian
v_{rel}	$235 \pm 20\,\text{km}/\text{s}$	Gaussian
v_0	$235 \pm 20\,\text{km}/\text{s}$	Gaussian
J-factor for dSphs		Log-normal [9]

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 [30]
m_h	$125.09 \pm 0.24\,\mathrm{GeV}$	Gaussian	LEP [30]

Statistical analysis of portal 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` [36–38].

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

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.

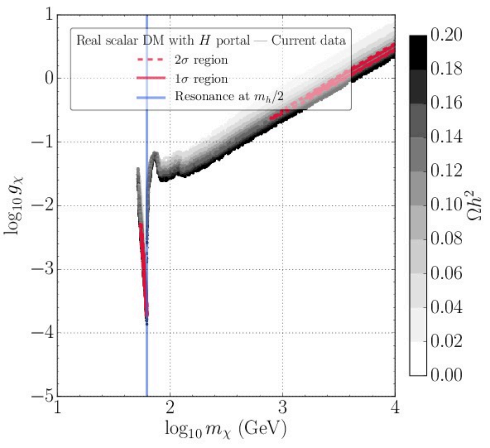
Damage to simple DM models

	$\Delta\chi^2$		
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

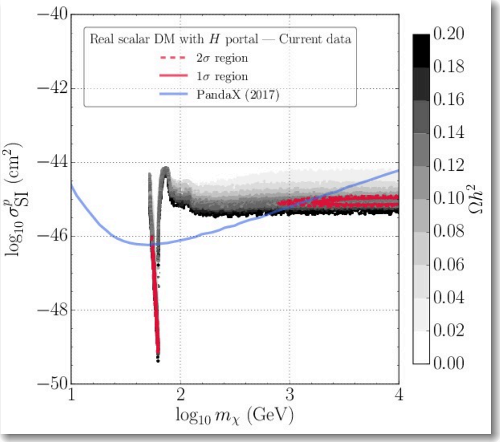
What's going on?

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.

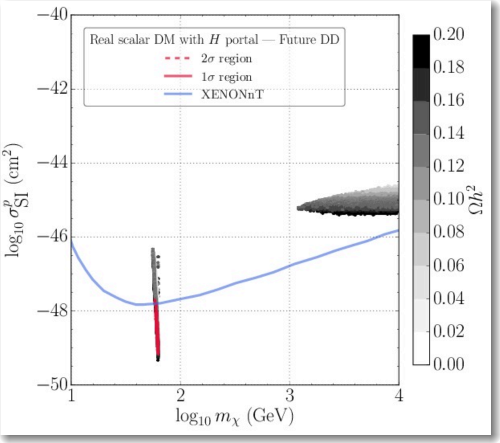
With current data, the mass of scalar DM with a Higgs portal is pushed to multi-TeV region in red or the narrow resonance region by DD constraints.



We require sensitivity for multi-TeV dark matter and/or low cross sections — future experiment XENONnT [39] 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.



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

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