Hypercharged Dark Matter and Direct Detection as a Probe of Reheating

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Dark Matter

- We have only detected its influence gravitationally..

→ Rotation curves of galaxies, gravitational lensing, CMB, structure formation..

.. We still have very basic questions..

- Mass? Could span 80 orders of magnitude!
- Spin?
- Non-gravitational interactions?

Basic question:

Does the dark matter particle carry standard model gauge interactions?

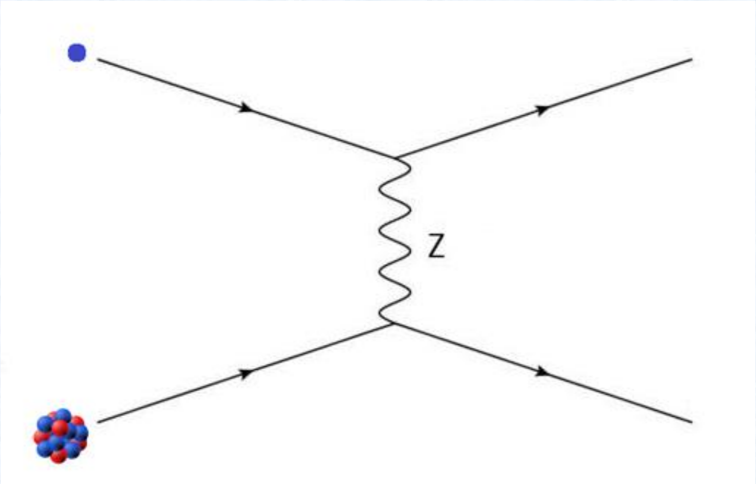
$$\underset{\text{Color}}{SU(3)} \times \underbrace{\underset{\text{Weak}}{SU(2)} \times \underset{\text{Hypercharge}}{U(1)_Y}}_{\substack{U(1)_{EM} \\ \text{Electromagnetism}}}$$

Suppose dark matter carries hypercharge..

Then it must also carry SU(2) to have an electrically neutral component.

e.g. $$(SU(2), U(1)_Y) = (2, \pm\frac{1}{2}),\ (3, \pm 1),\ (4, \pm\frac{1}{2}),\ (4, \pm\frac{3}{2})...$$

Such particles interact via the Z-boson:



(assuming either: - A simple theory with no mixing with other new particles
or - The mass is heavier than ~10^8 GeV)

The cross section is very large compared to what is usually assumed these days..

The Weakly Interacting, Massive Particle Paradigm

Assumptions:

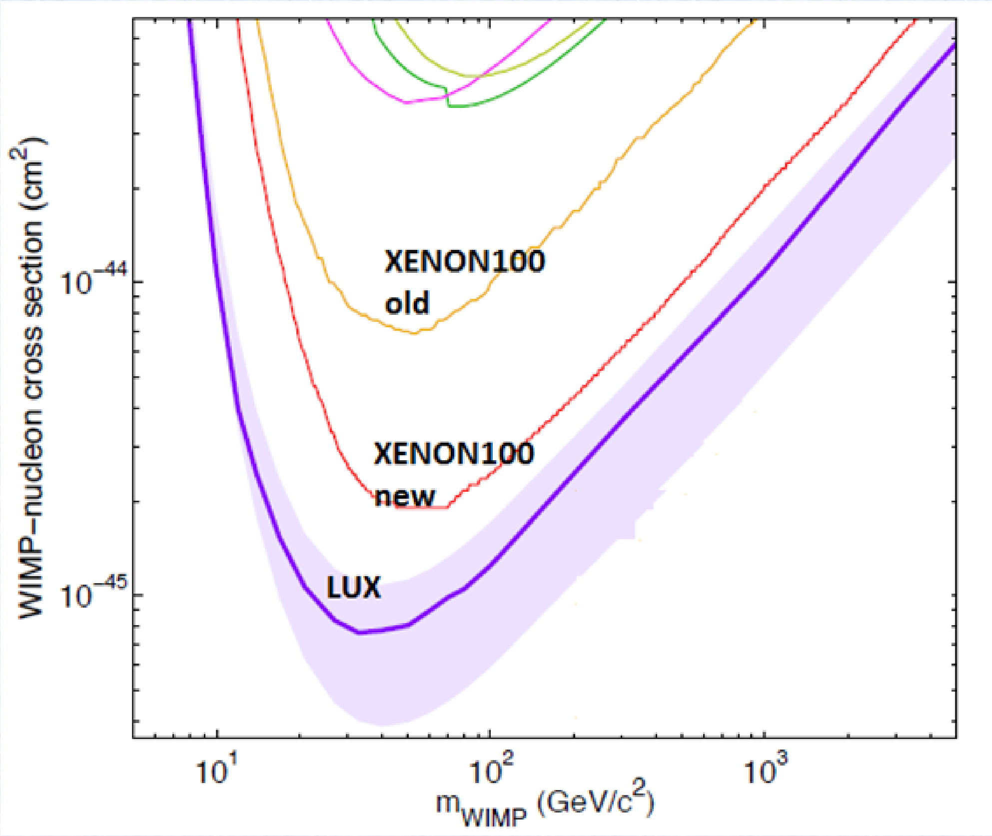
- The temperature of the early universe was larger than M_{DM}.
- Dark matter was in thermal equilibrium.
- Dark matter particles can annihilate.

Then:

$$M_{DM} \sim \text{TeV}.$$

Where we have expected new physics anyway!

Hypercharged dark matter with TeV mass is very ruled out!



.. By about 5 orders of magnitude..

So far we have not found new physics at the TeV scale.

What about larger mass?

$\gtrsim 6 \times 10^7 \mathrm{GeV}$ is allowed.

→With thermal WIMP assumptions, this gives way too much dark matter.

However..

If we relax the assumption that $M_{DM} << T$..

A second value of M_{DM}, >> TeV also gives the correct abundance!

The universe had some maximum temperature..

→ If we take $M_{DM} > T_{max}$ ..

the relic abundance will be suppressed by $\sim e^{-2M_{\rm DM}/T_{\rm max}}$

- Kolb, Chung and Riotto

→ It turns out that $M_{DM} \sim 25\ T_{max}$ gives the correct abundance.

(Though we do not know what T_{max} was..)

We can now turn the direct detection constraint on its head:

If upcoming experiments find evidence for hypercharged DM, we will have a probe of the maximum temperature of the universe!

The hypercharged coupling is fixed, so the rate reveals the mass!

- M_{DM} of ~ $10^8 – 10^{10}$ GeV could lead to a signal at planned experiments!

(I simplified a bit..)

Inflation →

Inflaton Matter Domination + Inflaton Decay →

Radiation Domination

T_{max}

T_{reheat}

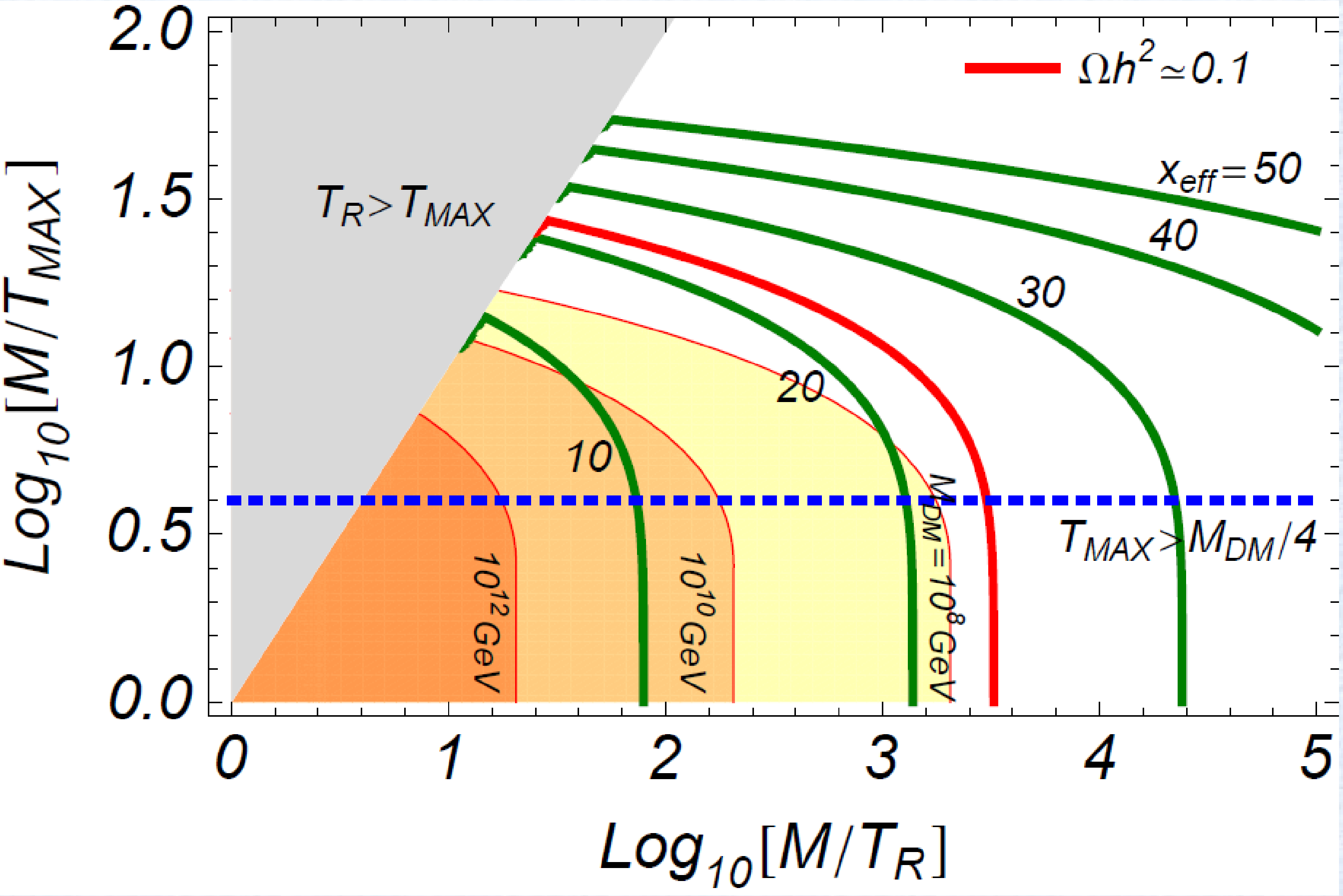
→ So far we have assumed $T_{reheat} = T_{max}$.

→For smaller T_{reheat}, the dark matter abundance obtains an additional suppression.

$$\sim (T_{reheat}/M_{DM})^7$$

.. So how much can we really learn about the thermal history?

Look at the T_{reheat}, T_{max} plane:



→ In any case obtain a 2 order of magnitude window on T_R!

A comment about fine tuning..

- The amount of fine tuning to get the relic abundance depends on how much Boltzmann suppression is involved.

→ It is ~ 2% at worst, and there is no fine tuning if the low reheat temperature effect dominates.

Direct Detection

How could we know we had found hypercharged dark matter?

By comparing signals at different elements!

Recall:

- The event rate is proportional to $\left(\frac{f_p}{f_n} N_p + N_n\right)^2$

→ The Z boson has f_p/f_n ~ -.04

Note: This is very uncommon. Essentially all popular models have $f_p/f_n \geq 1$.

Measuring f_p/f_n is non-trivial..

- N_n/N_p doesn't vary so much..

Xe: 1.43 Ge: 1.28 Ar: 1.22

- Different experiments probe different parts of the halo:

Xe: 60 – 190km/s Ge: 80 – 255km/s Ar: 190 – 355km/s

Hypercharged DM vs Slightly Steeper Halo!

Is measuring f_p/f_n impossible due to halo uncertainty?

Direct Detection Event Rates

-Collisions/time for one target particle: $n_{DM}<\sigma\ v>$

number density

cross section

relative velocity

-Obtain a spectrum by differentiating with energy, and averaging ever DM velocities:

$$\frac{dR}{dE_R} = \int_{v_{\min}(E_R)} d^3v f(\overrightarrow{v})\ n_{\mathrm{DM}} \frac{d\sigma}{dE_R} v$$

dark matter velocity distribution

- Here $V_{min}(E_R)$ is the minimum DM velocity needed to deposit energy E_R.

→ It increases with energy and gets bigger for lighter nuclei

→ Different experiments do overlap in v_{min} space.

- All halo velocity dependence is contained in $g(v_{\rm min}(E_R)) \equiv \int_{v_{\rm min}} d^3v \frac{f(\vec{v})}{v}$

$$\left.\frac{dR}{dE_R}\right|_{\rm Xe} \propto (\frac{f_p}{f_n} N_{p{\rm Xe}} + N_{n{\rm Xe}})^2 \times g\left(v_{\rm min}^{\rm Xe}(E_R)\right)$$

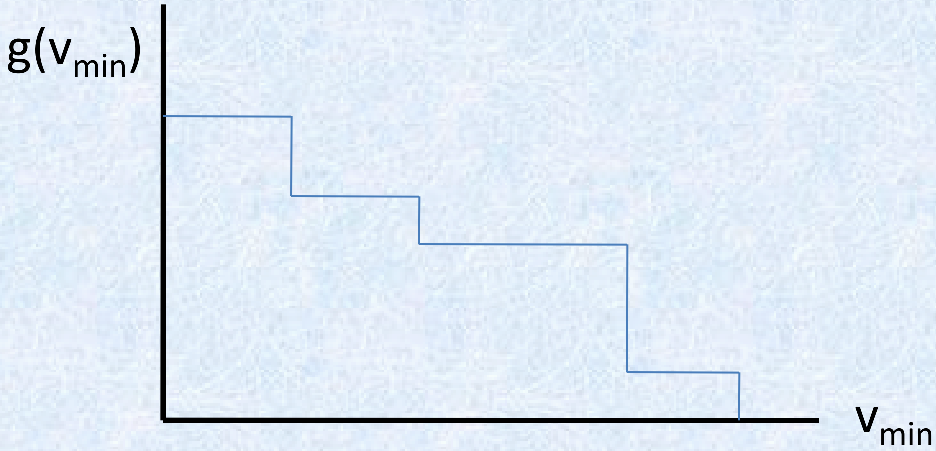
$$\left.\frac{dR}{dE_R}\right|_{\rm Ge} \propto (\frac{f_p}{f_n} N_{p{\rm Ge}} + N_{n{\rm Ge}})^2 \times g\left(v_{\rm min}^{\rm Ge}(E_R)\right)$$

If we could compare spectra at the same v_{min}, the halo dependence would drop out! - Fox, Liu and Weiner

.. In practice though, we measure *events* not *spectra*..

Our Method in Brief

- Take g(v) to be a decreasing step function with N steps.



→ The predictions are now just linear functions of the step heights.. it's easy to find the best heights!

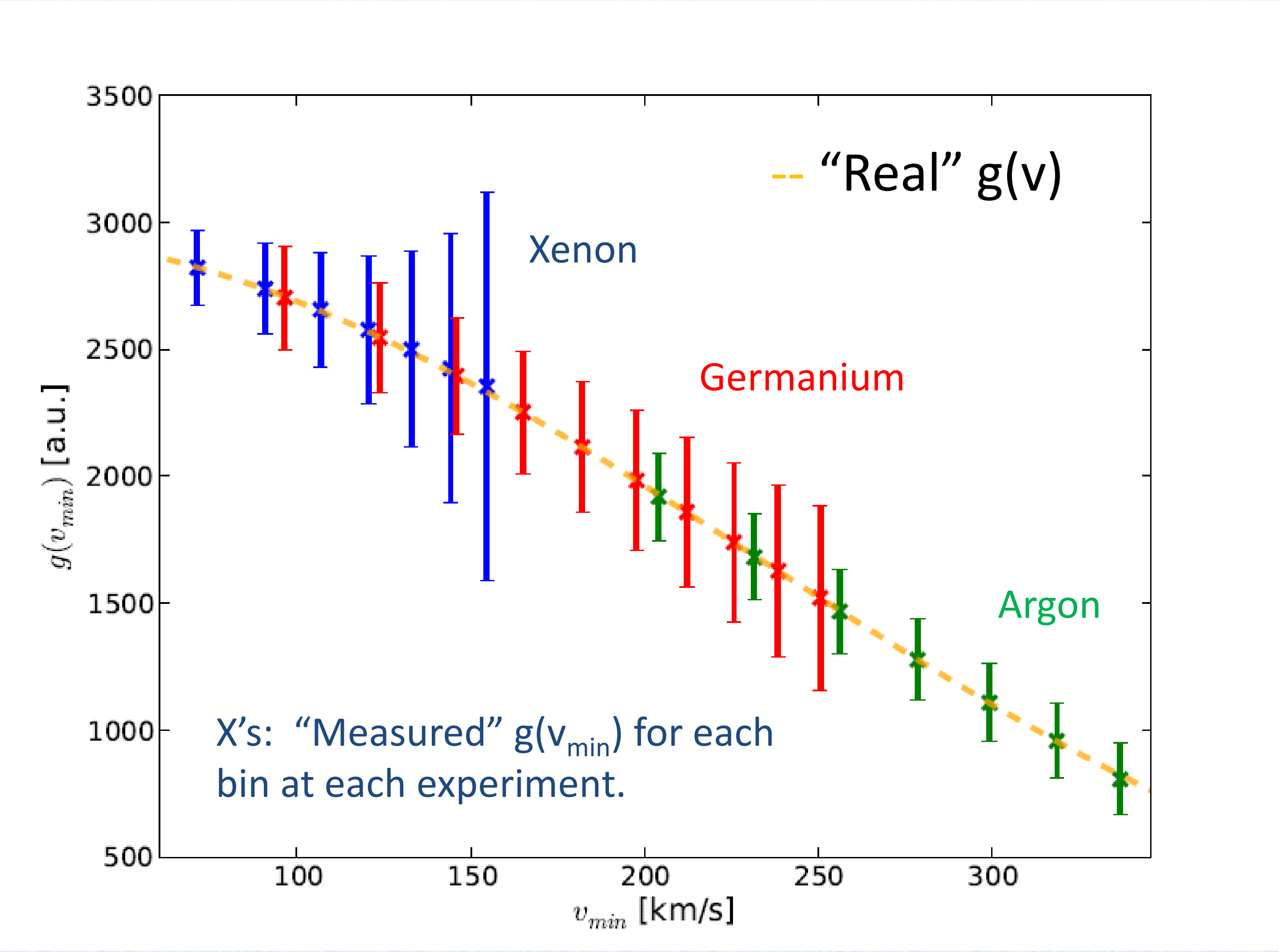
- Look at the f_p/f_n confidence intervals with N → Infinity.

(In practice N ~ 30 is enough.)

First, a trivial example

"Real" model of the world: $f_p/f_n = -.04$, $M_{DM} = 6 \times 10^7$ GeV

Hypothesis: correct model



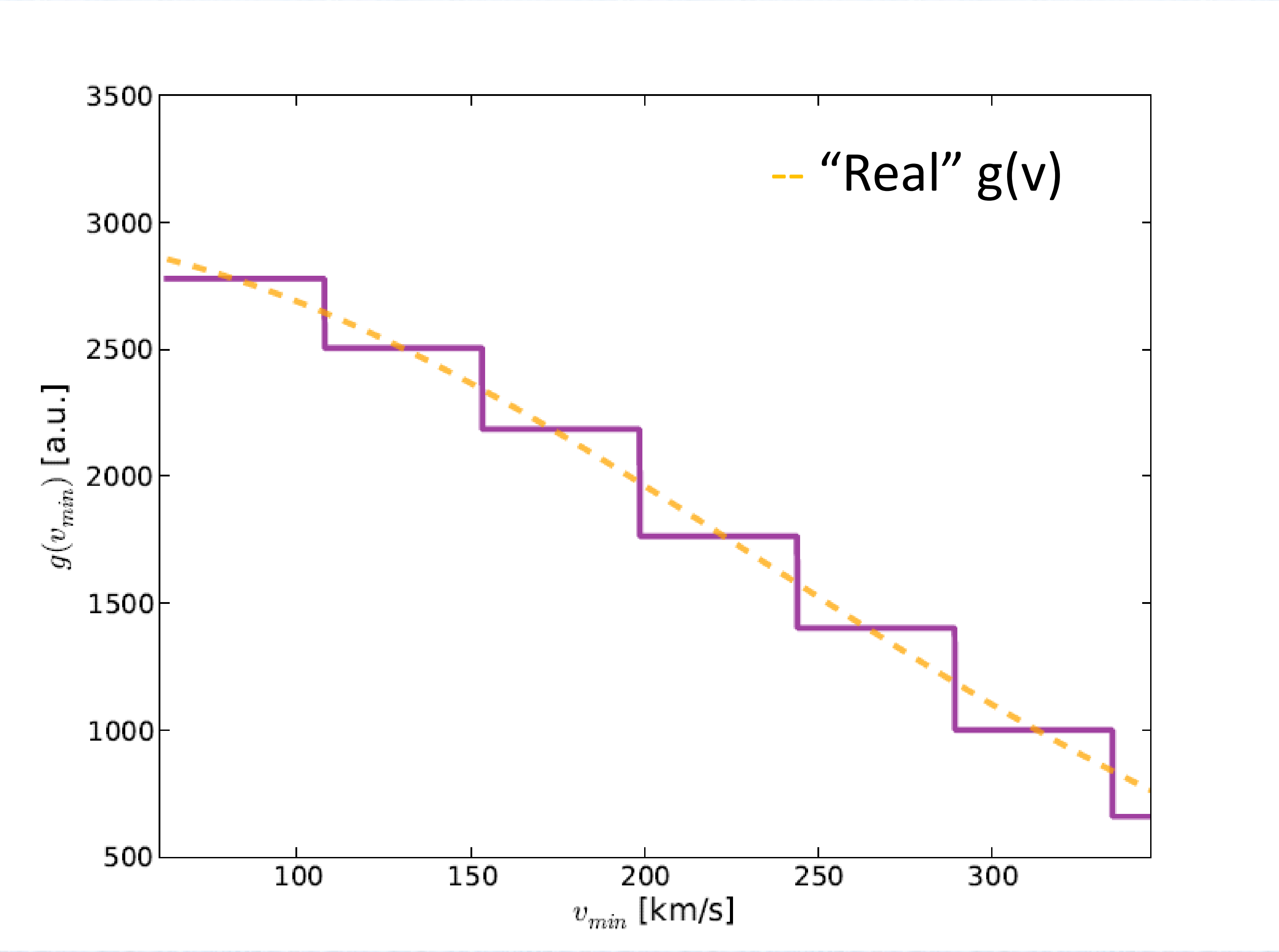
First, a trivial example

"Real" model of the world: f_p/f_n = -.04, M_{DM} = 6 x 10^7 GeV

Hypothesis: correct model

N = 7

$$\chi^2 = .93$$



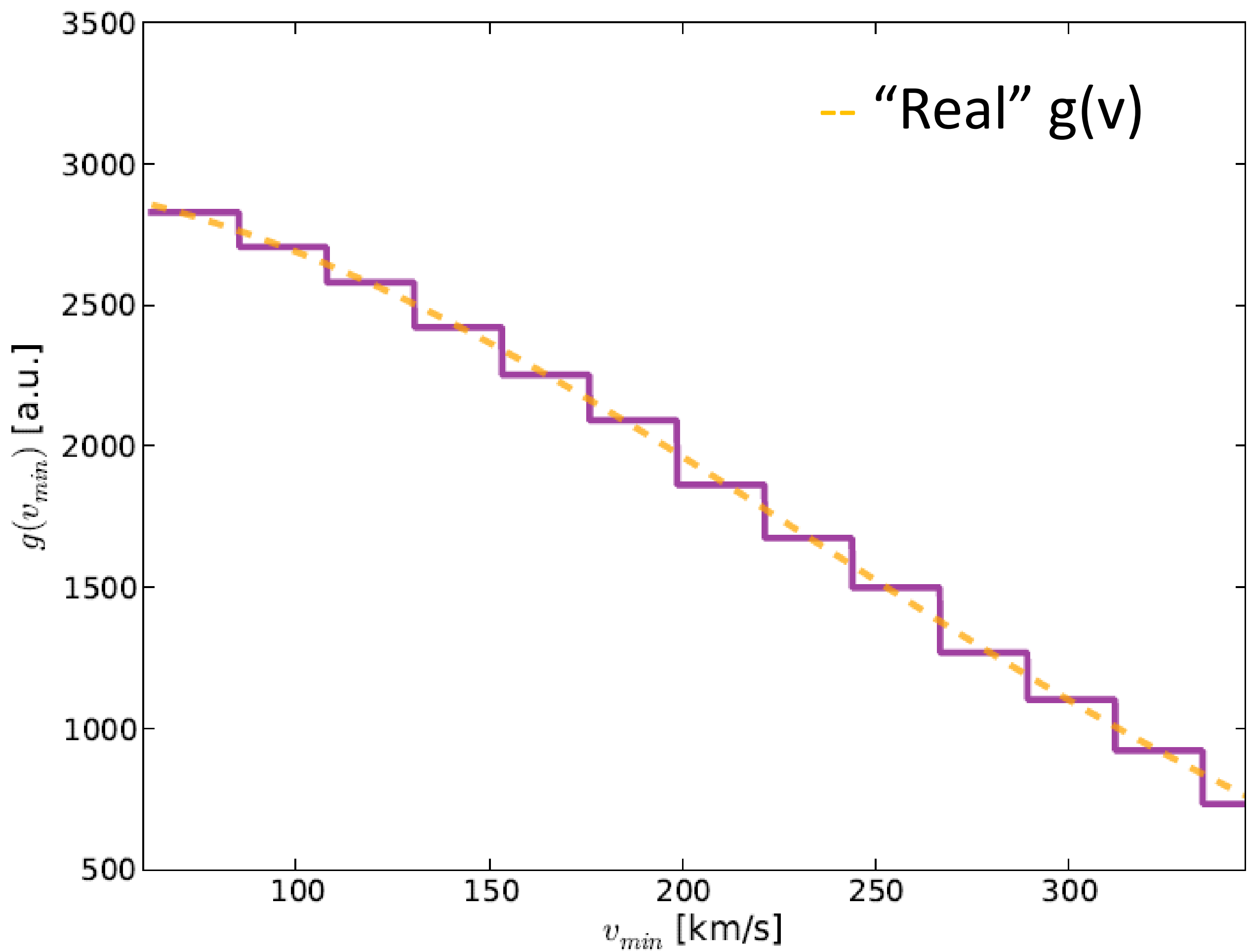
First, a trivial example

"Real" model of the world: $f_p/f_n = -.04$, $M_{DM} = 6 \times 10^7$ GeV

Hypothesis: correct model

N = 14

$$\chi^2 = .031$$



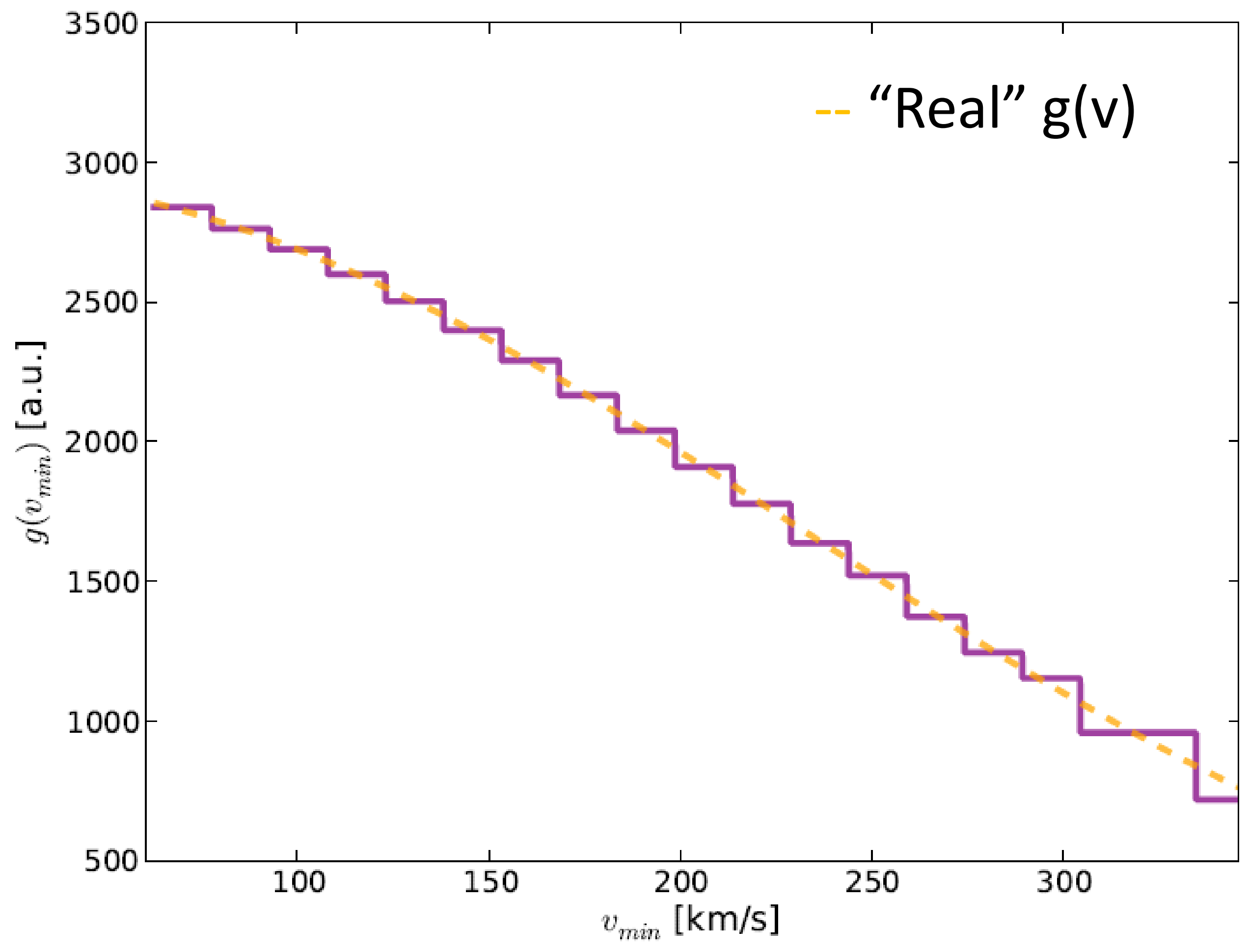
First, a trivial example

"Real" model of the world: $f_p/f_n = -.04$, $M_{DM} = 6 \times 10^7$ GeV

Hypothesis: correct model

N = 21

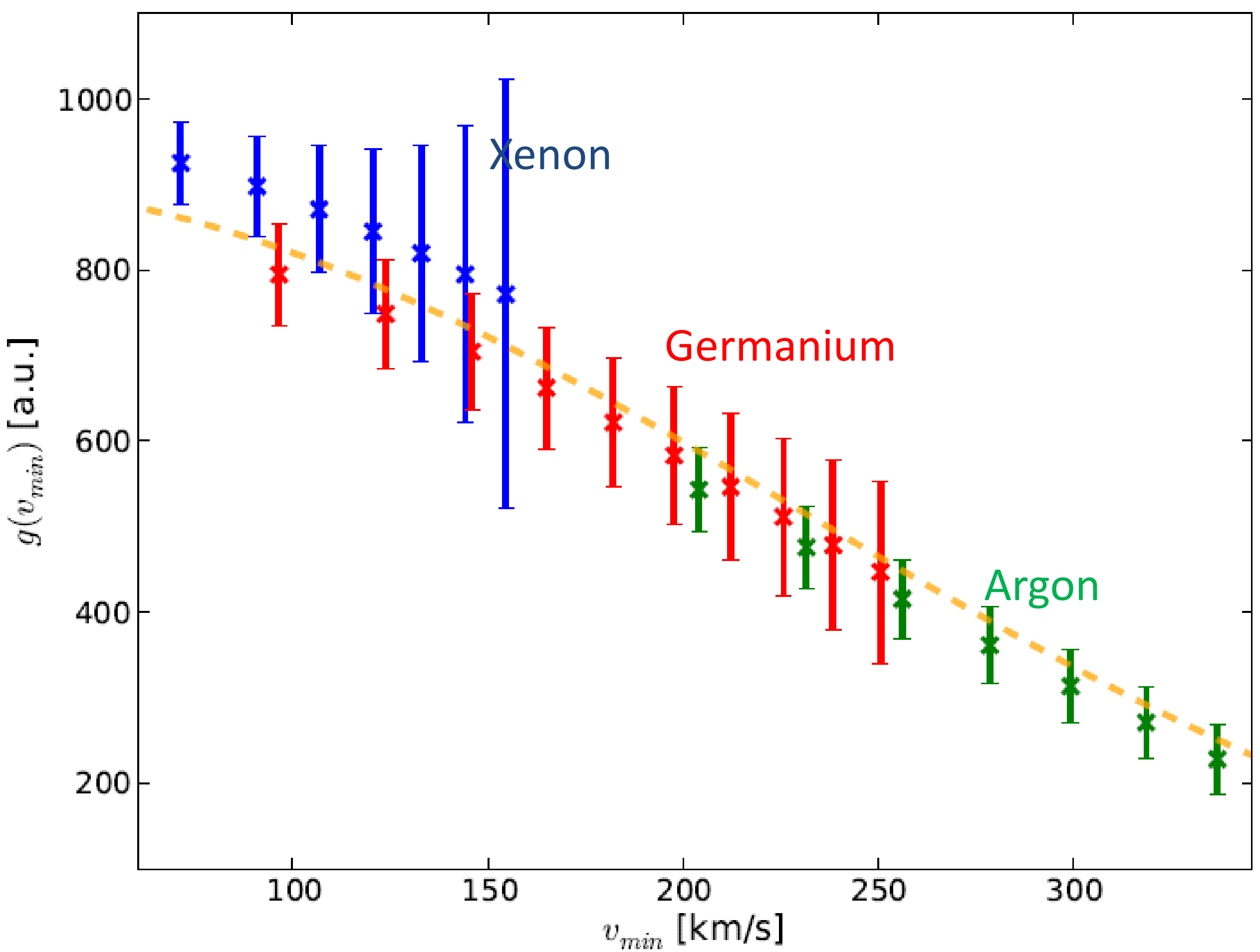
$$\chi^2 = .00029$$



Next, a non-trivial example

"Real" model of the world: $f_p/f_n = -.04$, $M_{DM} = 6 \times 10^7$ GeV

Hypothesis : $f_p/f_n = 1$



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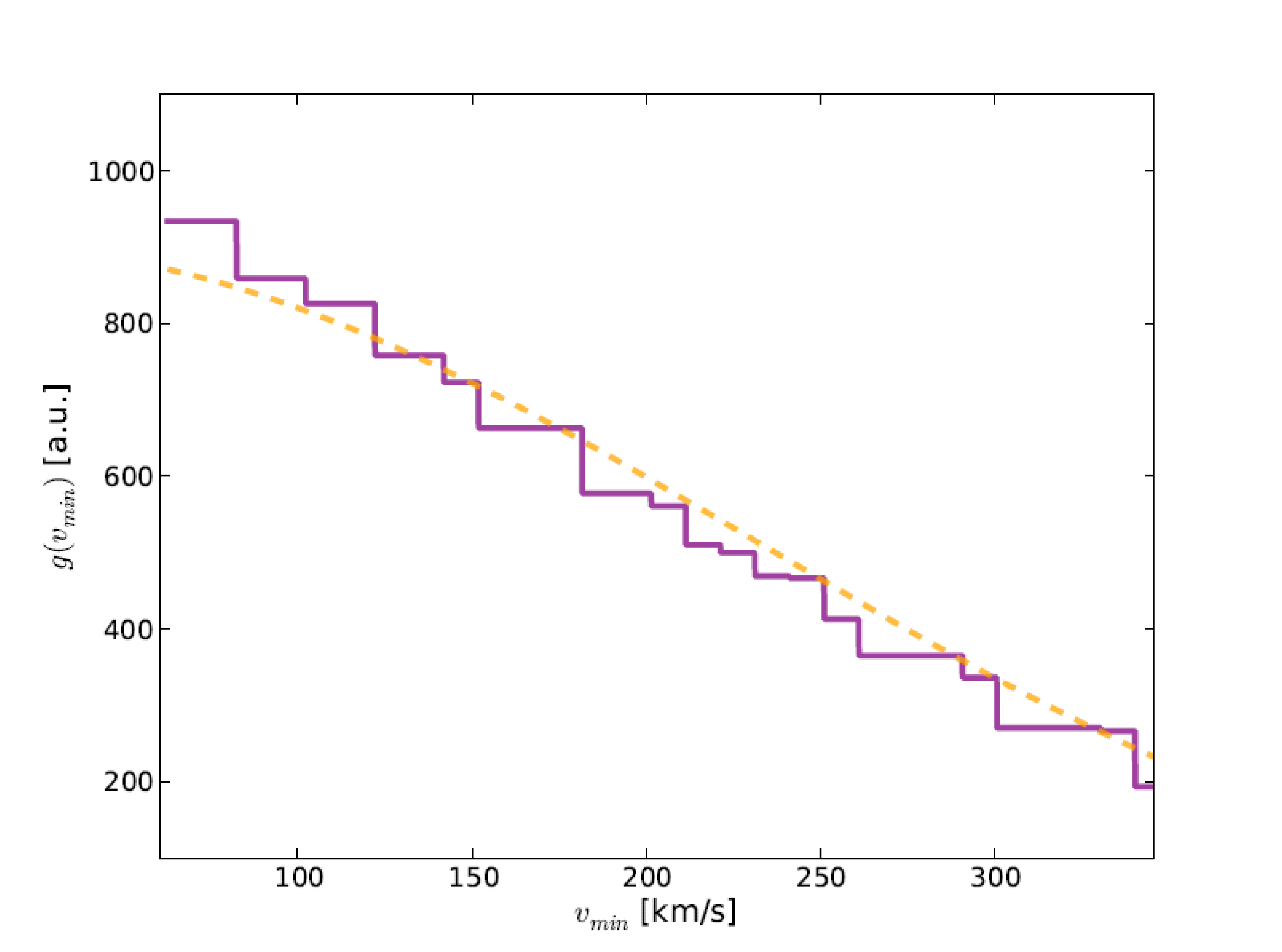


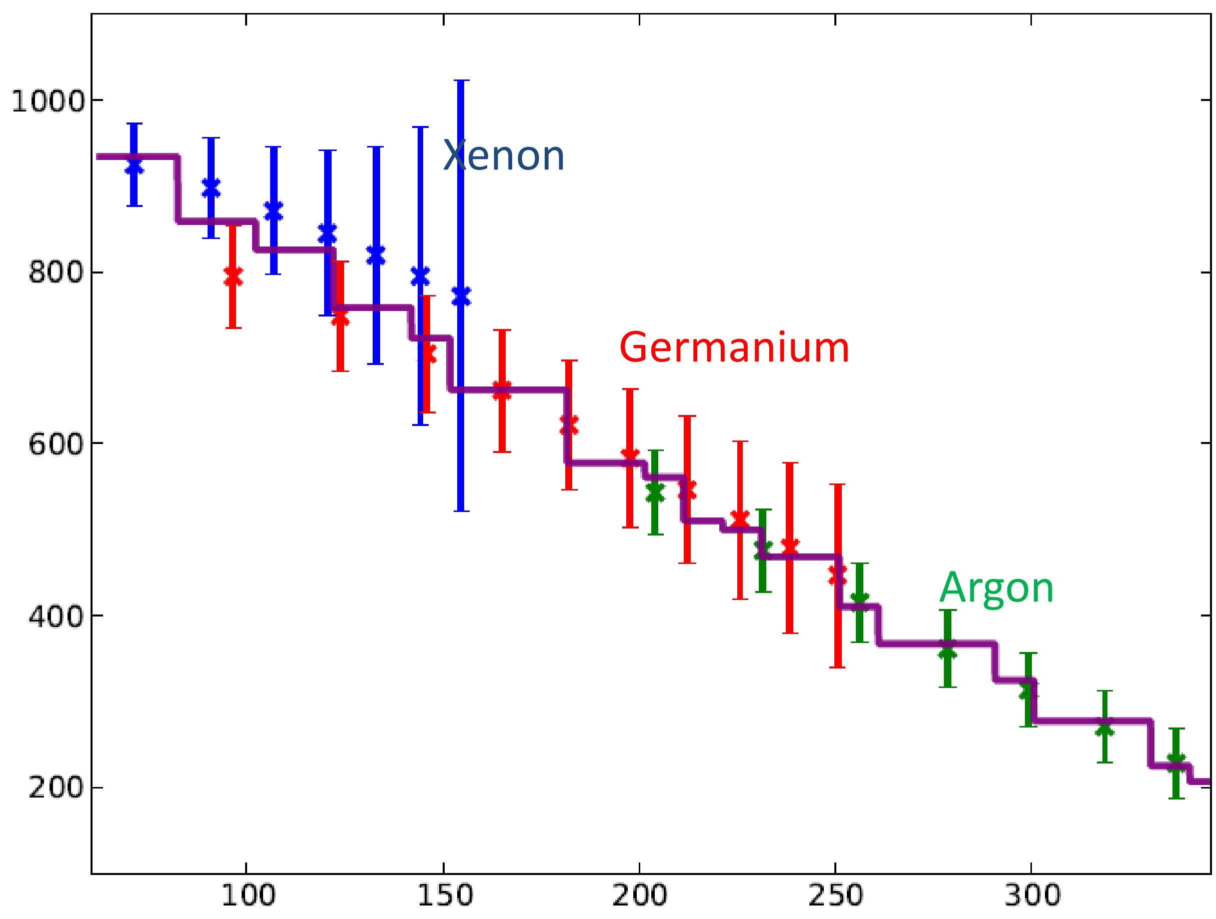
Next, a non-trivial example

"Real" model of the world: $f_p/f_n = -.04$, $M_{DM} = 6 \times 10^7$ GeV

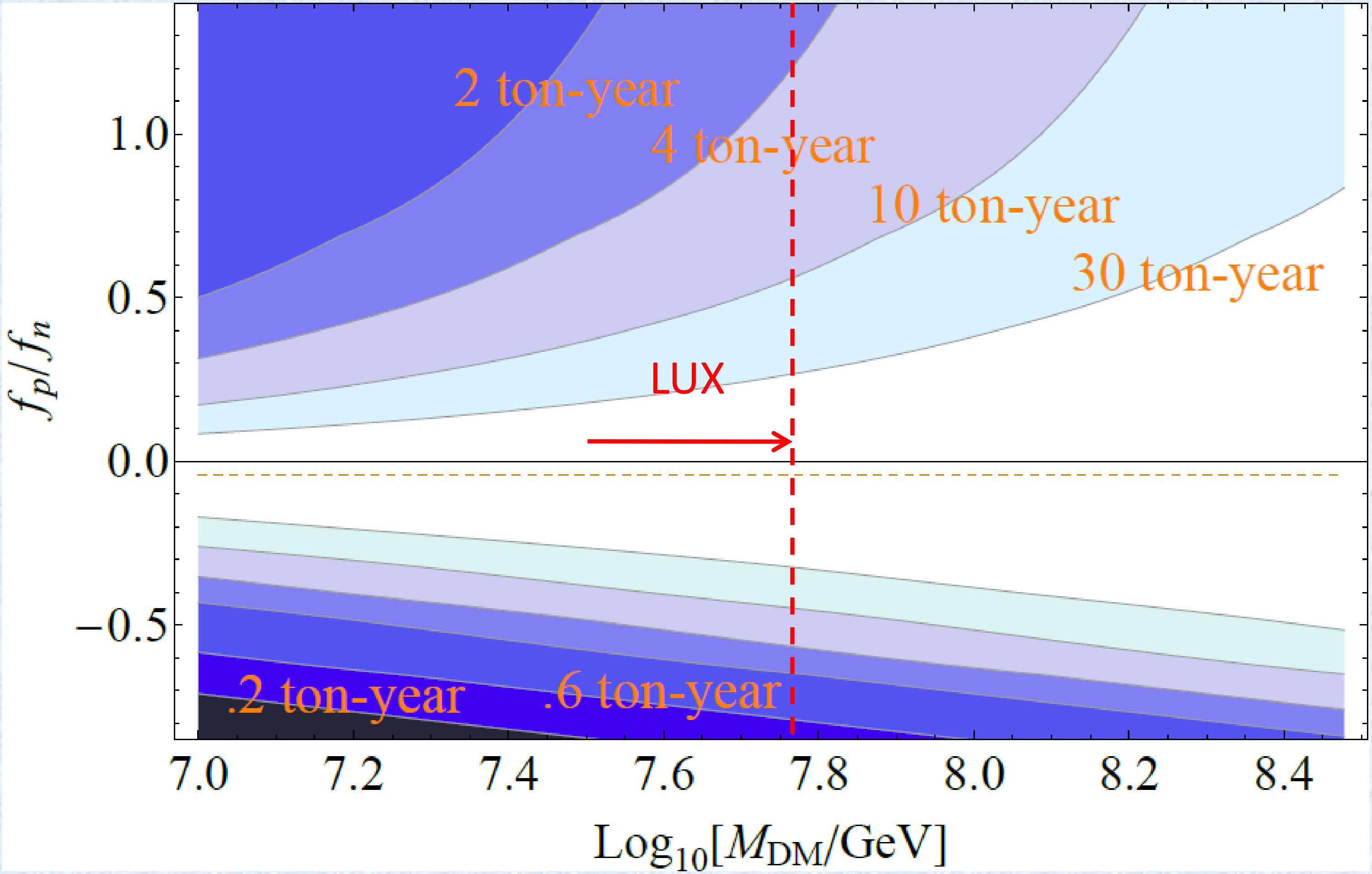
Hypothesis : $f_p/f_n = 1$

N = 32

$$\chi^2 = 2.5$$



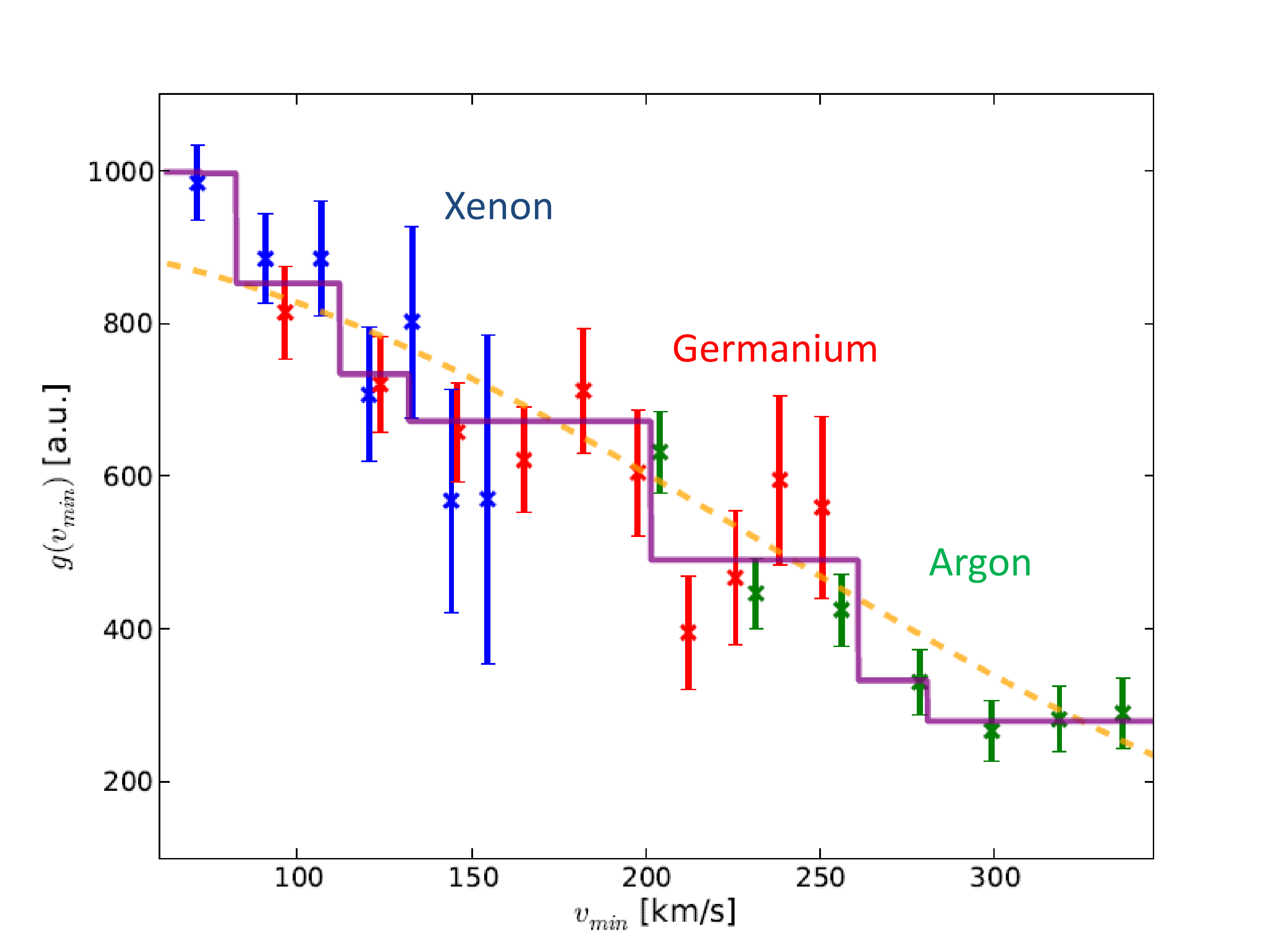
Narrowing in on f_p/f_n..



Now With Poisson Fluctuations

"Real" model of the world: $f_p/f_n = -.04$, $M_{DM} = 6 \times 10^7$ GeV

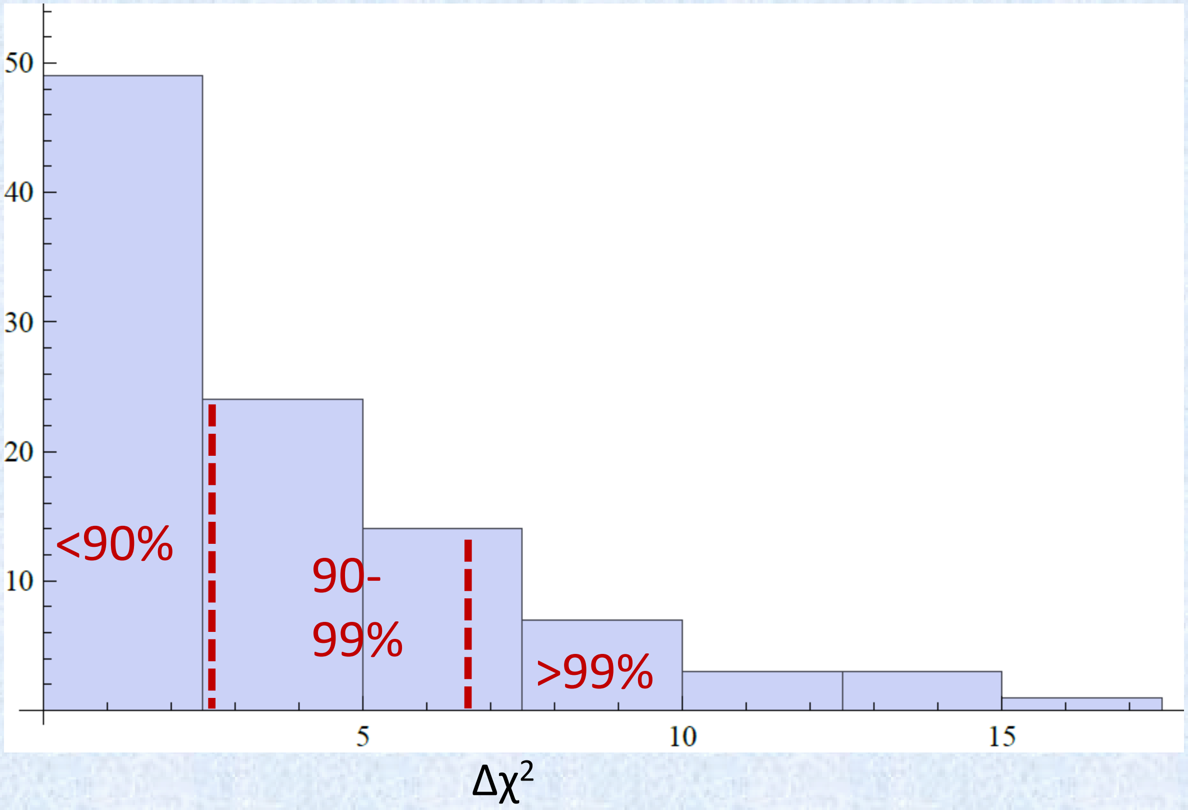
Hypothesis : $f_p/f_n = 1$



Distribution of Exclusions with Poisson Fluctuations

"Real" model of the world: f_p/f_n = -.04, $M_{DM} = 6 \times 10^7$ GeV

Hypothesis : $f_p/f_n = 1$



Summary

- Hypercharged dark matter is a simple, generic dark matter candidate.
- If observed by direct detection it could yield concrete information about the universe’s thermal history.
- We have developed a new and improved technique to glean dark matter properties from direct detection data, which completely removes uncertainty from the dark matter velocity distribution.