Hypercharged Dark Matter
and
A New Approach to Halo-Independent Direct Detection Analysis

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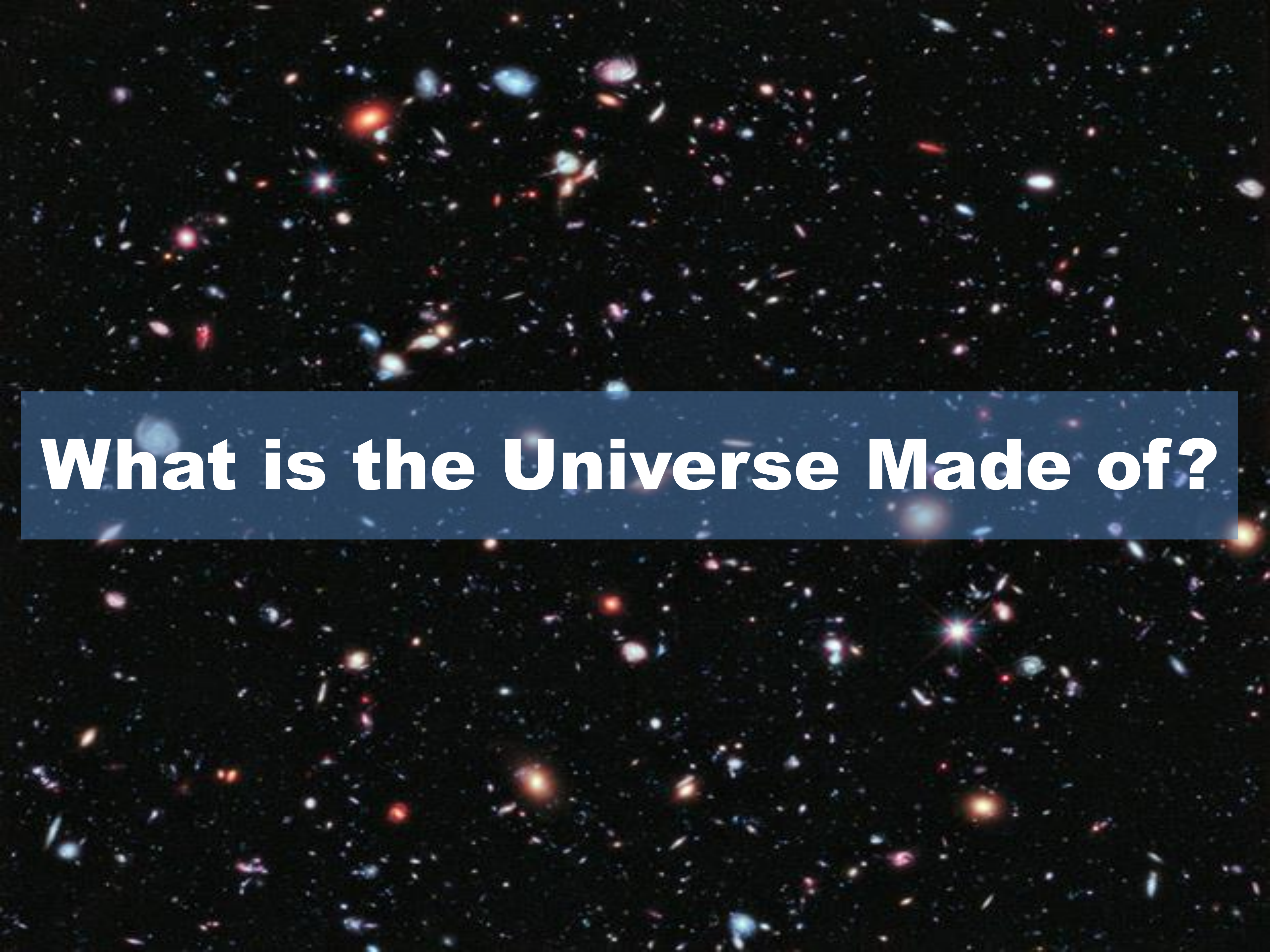
-B.F., F. Kahlhoefer

In progress

What is the Universe Made of?



The Energy Budget of the Universe

5% ordinary matter

- Protons, neutrons, electrons..
- A little bit of neutrinos and photons.

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- Energy which does not dilute as the universe expands.
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- Energy which does not dilute as the universe expands.
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25% dark matter

- Dilutes like ordinary matter, but we have no idea what it is!

The Energy Budget of the Universe

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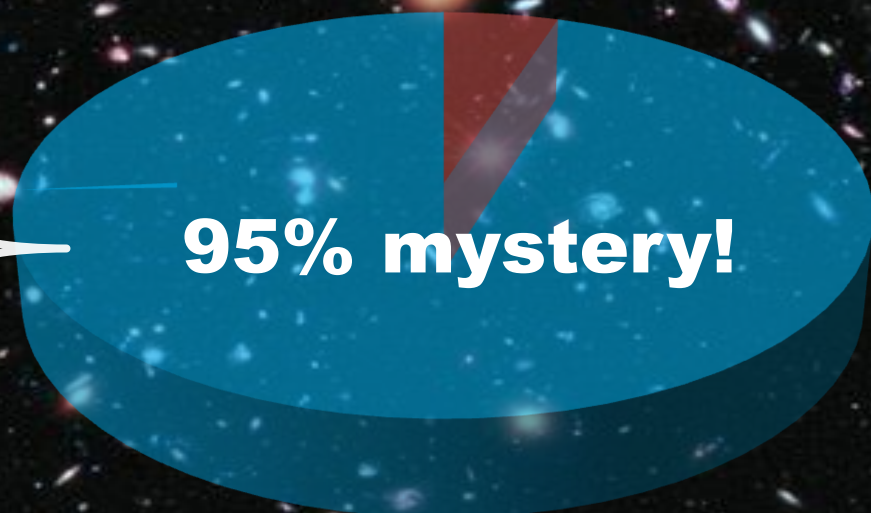
25% dark matter



Dark Matter

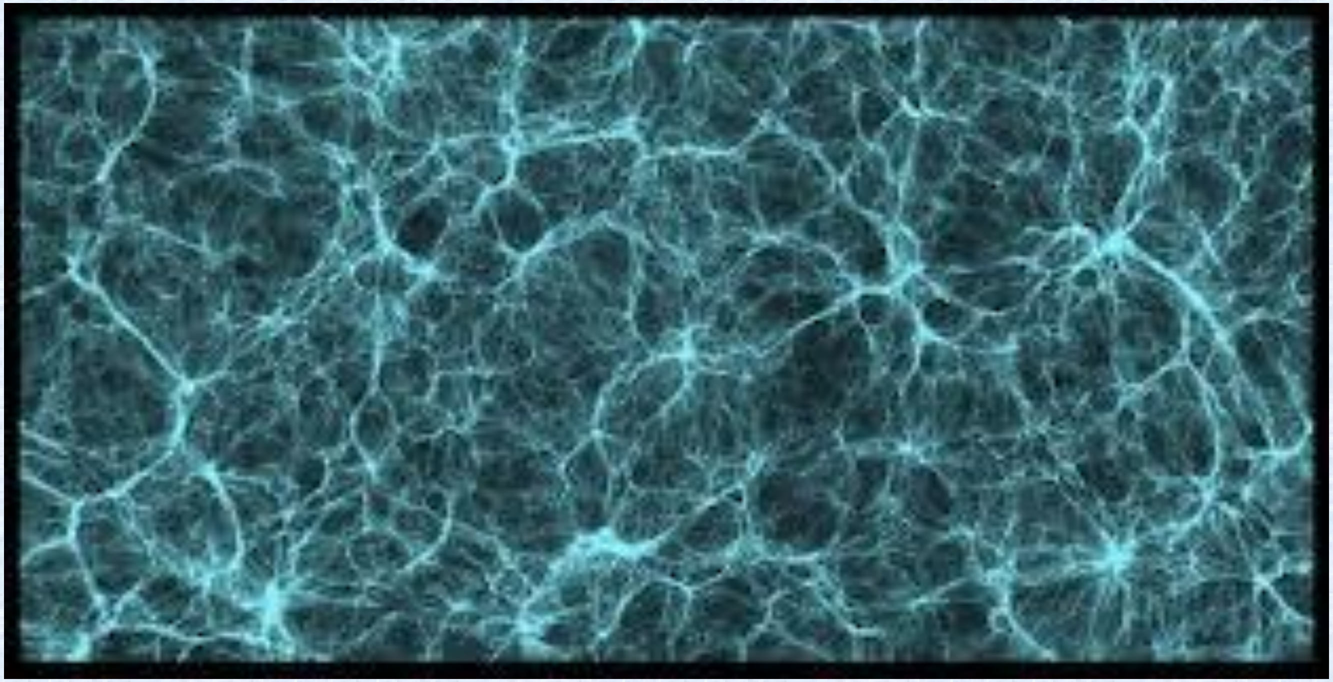
How do we know its there?

- It affects rotation curves of galaxies.

Dark Matter

How do we know its there?

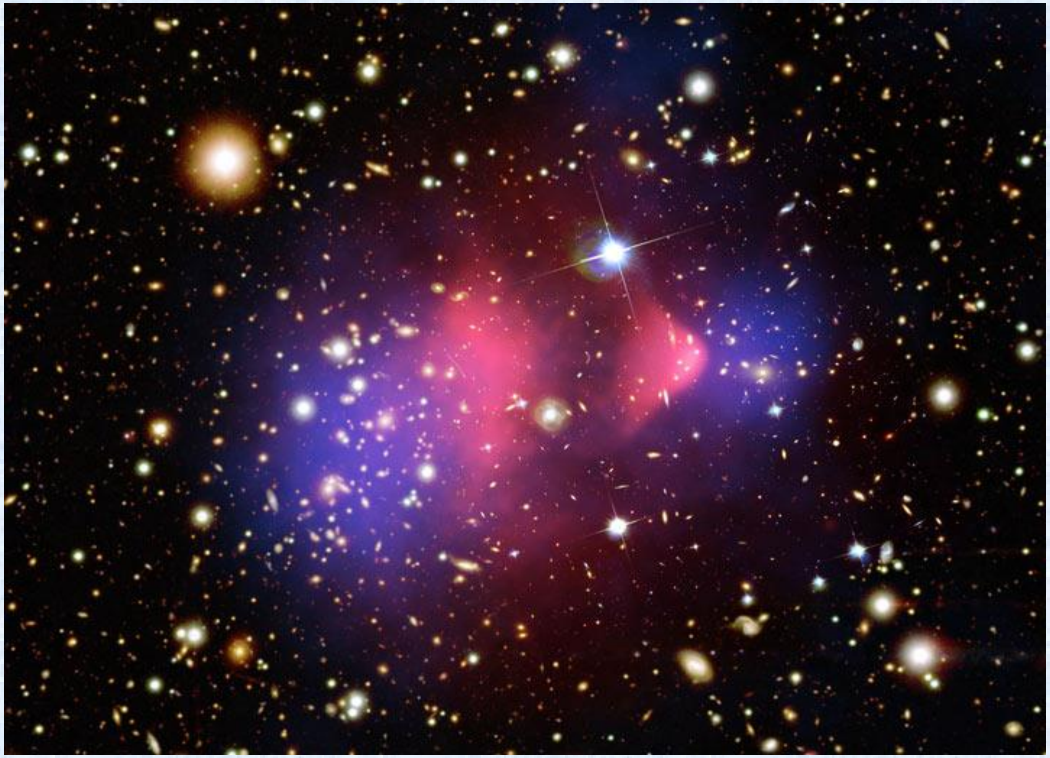
- It collapses and helps form structure.



Dark Matter

How do we know its there?

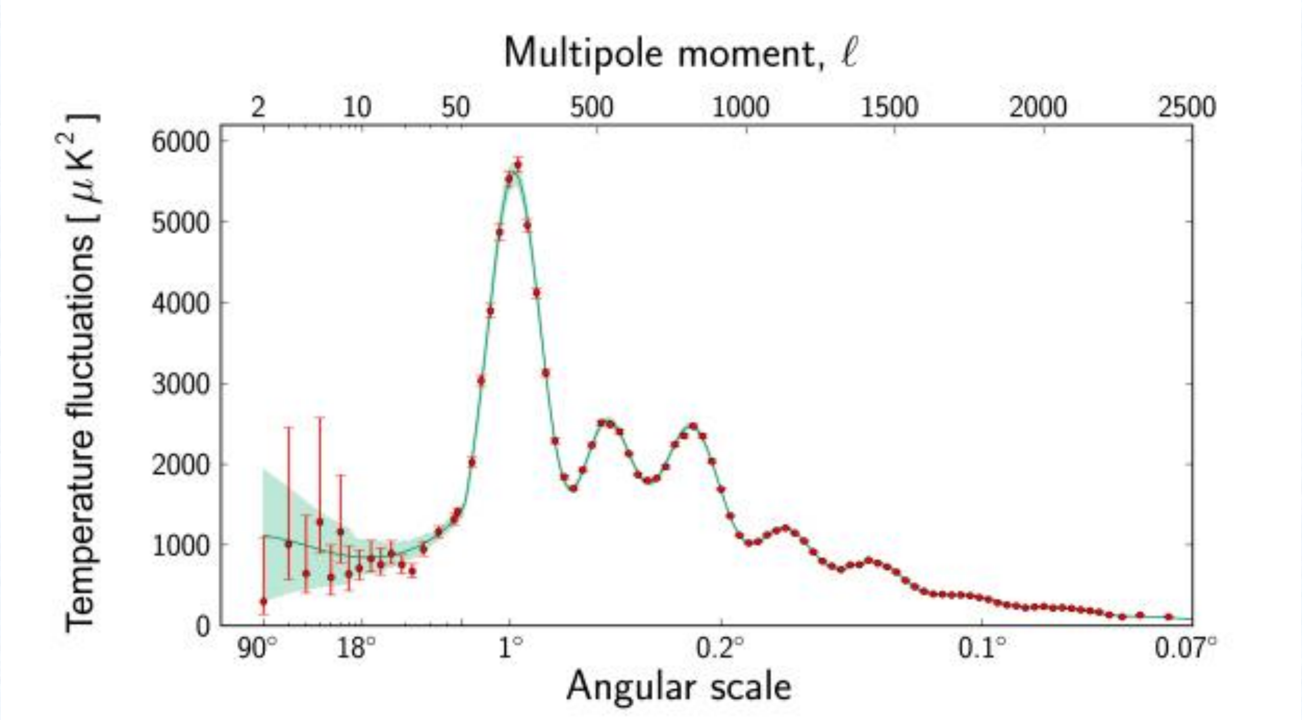
- It causes gravitational lensing.



Dark Matter

How do we know its there?

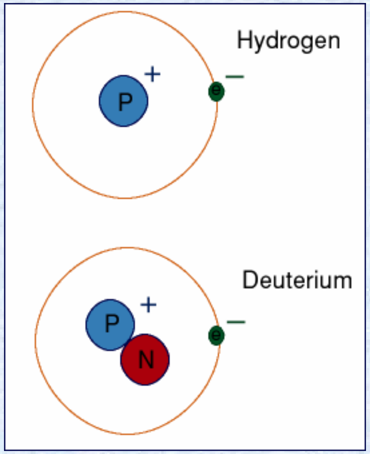
- It affected the cosmic microwave background radiation.



Dark Matter

What else do we know about it?

- Roughly spherical galactic halos, with about 10 times the radii of galactic disks.



- It is not made of baryons.

- If it has non-gravitational interactions, they have yet to be (definitively) noticed..

Dark Matter

What else do we want to know about it?

Basic properties:

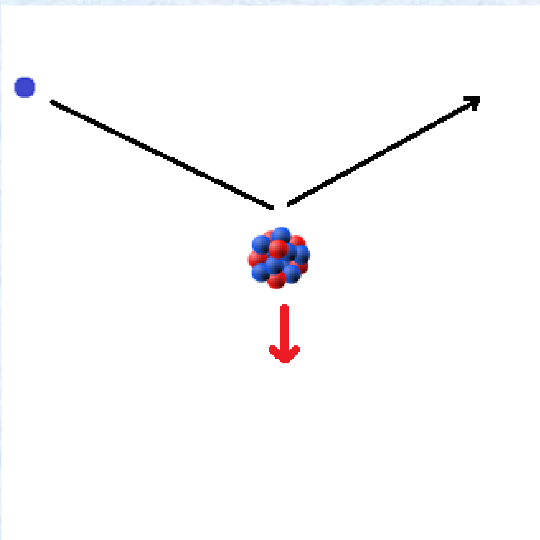
- Mass.. could span 80 orders of magnitude!
- Spin
- Non-gravitational interactions?

How did it get here?

Why is it stable?

Direct Detection Experiments

→ Look for dark matter hitting normal matter



First find a signal...

… Then try to deduce properties of dark matter!

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:

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

$f(\vec{v})$: 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

Key points for this talk:

$$\frac{d\sigma}{dE_R} \propto (\frac{f_p}{f_n} N_p + N_n)^2 / v^2$$

→ All halo velocity dependence is contained in

$$g(v_{\min}(E_R)) \equiv \int_{v_{\min}} d^3v \frac{f(\vec{v})}{v}$$

At fixed v_{min}, *it is the same factor for all targets!*

The Dark Matter Halo

- Nearby density similar to interstellar medium

  ~ proton/cm^3

- The typical velocities involved are of order v_s ~ 200 km/s.

  → ~10 keV energy deposits at direct detection experiments

- A standard ansatz:

$$f_0(\overrightarrow{v}) \propto e^{-\overrightarrow{v}^2/\overline{v}^2}$$

with $\overline{v}$ ~ 200 km/s

and a cutoff at v_{esc} ~ 600 km/s

- But simulations show:
  - Non-Gaussianity
  - Anisotropy
  - Clumps, streams
  - Rotating disk component

→ Uncertainty in the dark matter velocity distribution can have an important impact on the interpretation of results from direct detection experiments!

.. We could mistake halo properties for dark matter properties!

→ In this talk we will discuss a new method for dealing with this uncertainty, but first, we need a case study..

Hypercharged Dark Matter

- B.F. with M. Ibe and T. Yanagida

- An interesting scenario in its own right.
- An excellent case study for our method.

Basic question:

Does the dark matter particle carry standard model gauge interactions?

$SU(3) \times SU(2) \times U(1)_Y$

Color Weak Hypercharge

$U(1)_{EM}$

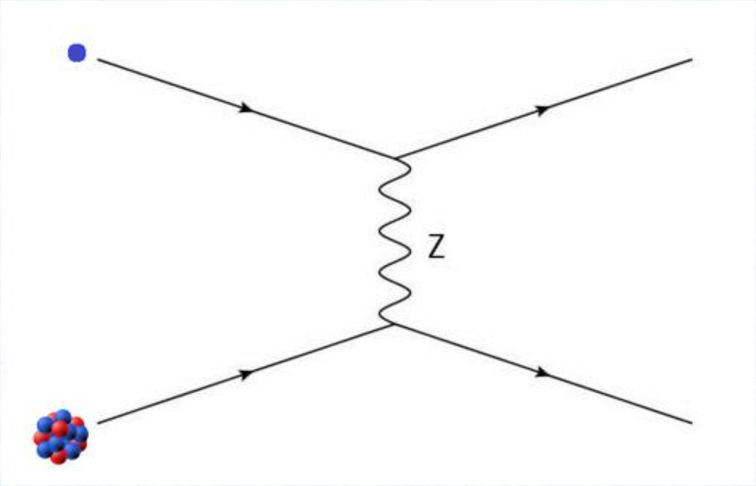
Electromagnetism

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

Suppose:

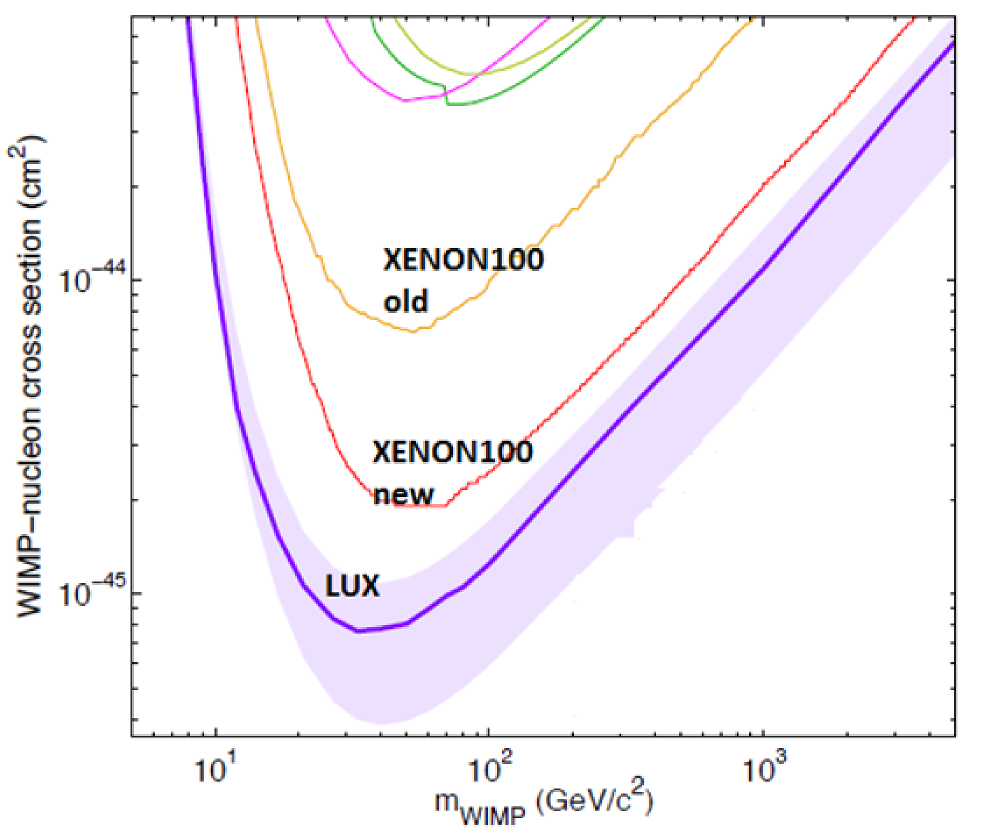
- The temperature of the early universe were larger than M_{DM}.
- Dark matter was in thermal equilibrium.
- Dark matter particles can annihilate.

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 $T >> M_{DM}$..

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

We think the universe had some maximum temperature.

→ If we take $M_{DM} > T_{max}$ ..

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

- 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..)

(I have simplified a little but this gives the essential idea..)

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!

Returning to 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 $$(\frac{f_p}{f_n}N_p + N_n)^2$$

→ The Z boson has $f_p/f_n \sim -.04$

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?

No!

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

Remember:

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

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

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

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*..

The standard method:

Imagine that we observe events caused by e.g. hypercharged DM.

(But we don't know that's what caused them)

Parameterize the halo, as e.g.

$$f_0(\overrightarrow{v}) \propto e^{-\left(\overrightarrow{v}^2/\overline{v}^2\right)^\alpha}$$

with $\overline{v}$, α, etc. as free parameters.

→ Scan over all dark matter and halo parameters, ruling out dark matter parameter regions which are found to be too unlikely to have yielded the data.

→ e.g. see if fp/fn > 1 is too unlikely given the data.

What's wrong with this?

- The halo will not be general.. we could still get fooled?
- It's time consuming… integrals must be done numerically over and over, for many different initial boundaries.
- We must assume some "a priori" underlying distributions for all of the scanning parameters.

→ What should the a priori distribution of f_p/f_n be??

..there must be a better way..

The Better Way

- B.F. with F. Kahlhoefer

- Don't marginalize over $f(\vec{v})$ parameters, optimize over $g(v)$!

  - Because we work with $g(v)$, no need to do any repeated integration → much faster.

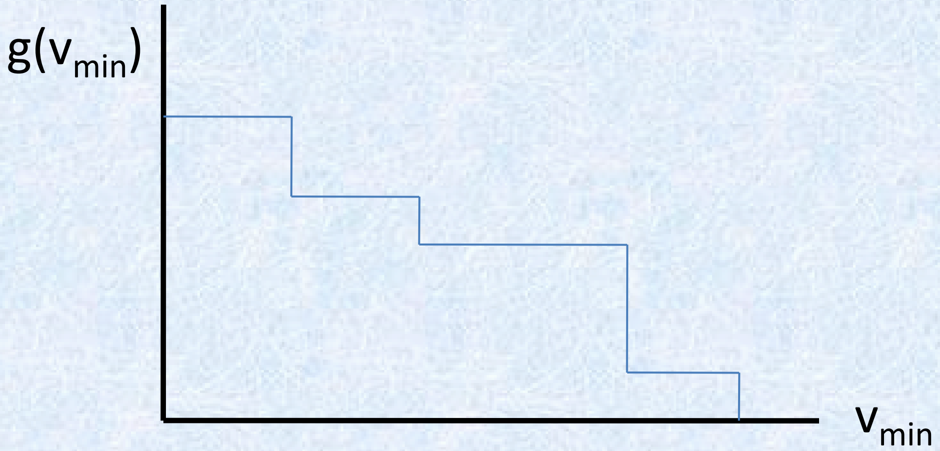
Goal: Find the best possible function $g(v)$ given all the data.

Important:

To be physically meaningful, $g(v)$ must be monotonically decreasing.

Our Method

- 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!

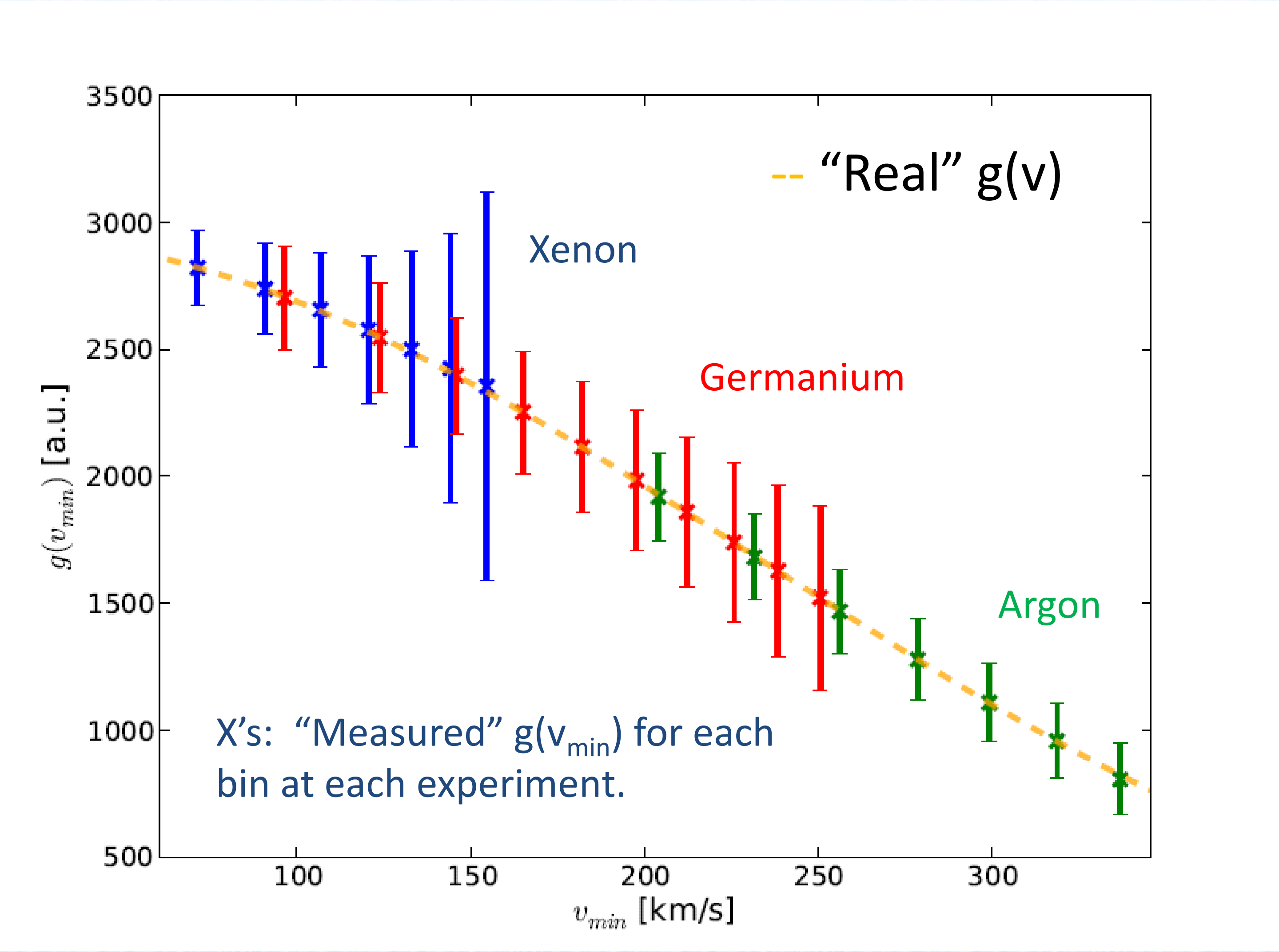
- Look at the f_p/f_n confidence intervals with N → Infinity.

(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



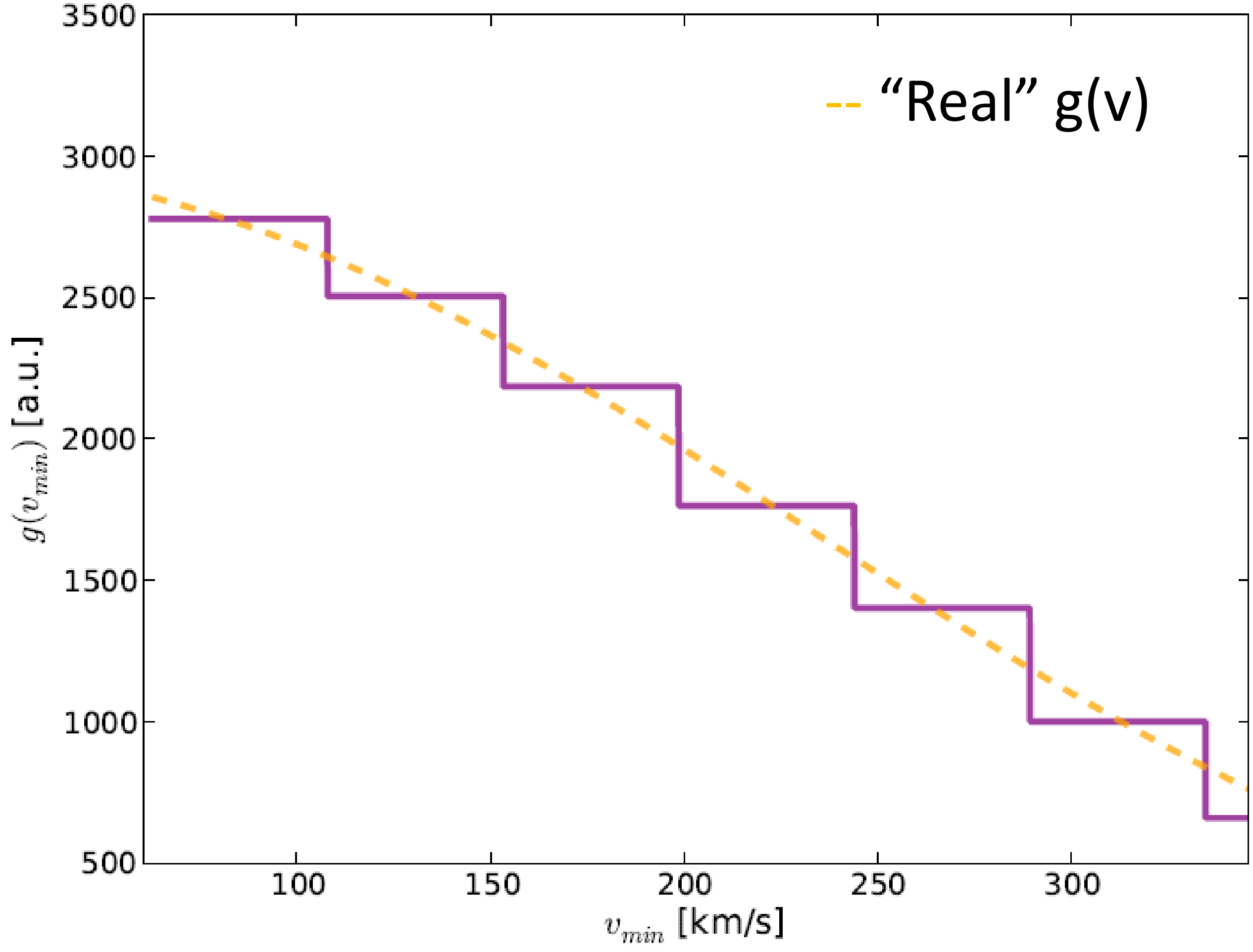
First, a trivial example

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

Hypothesis: correct model

N = 7

$\chi^2 = .93$



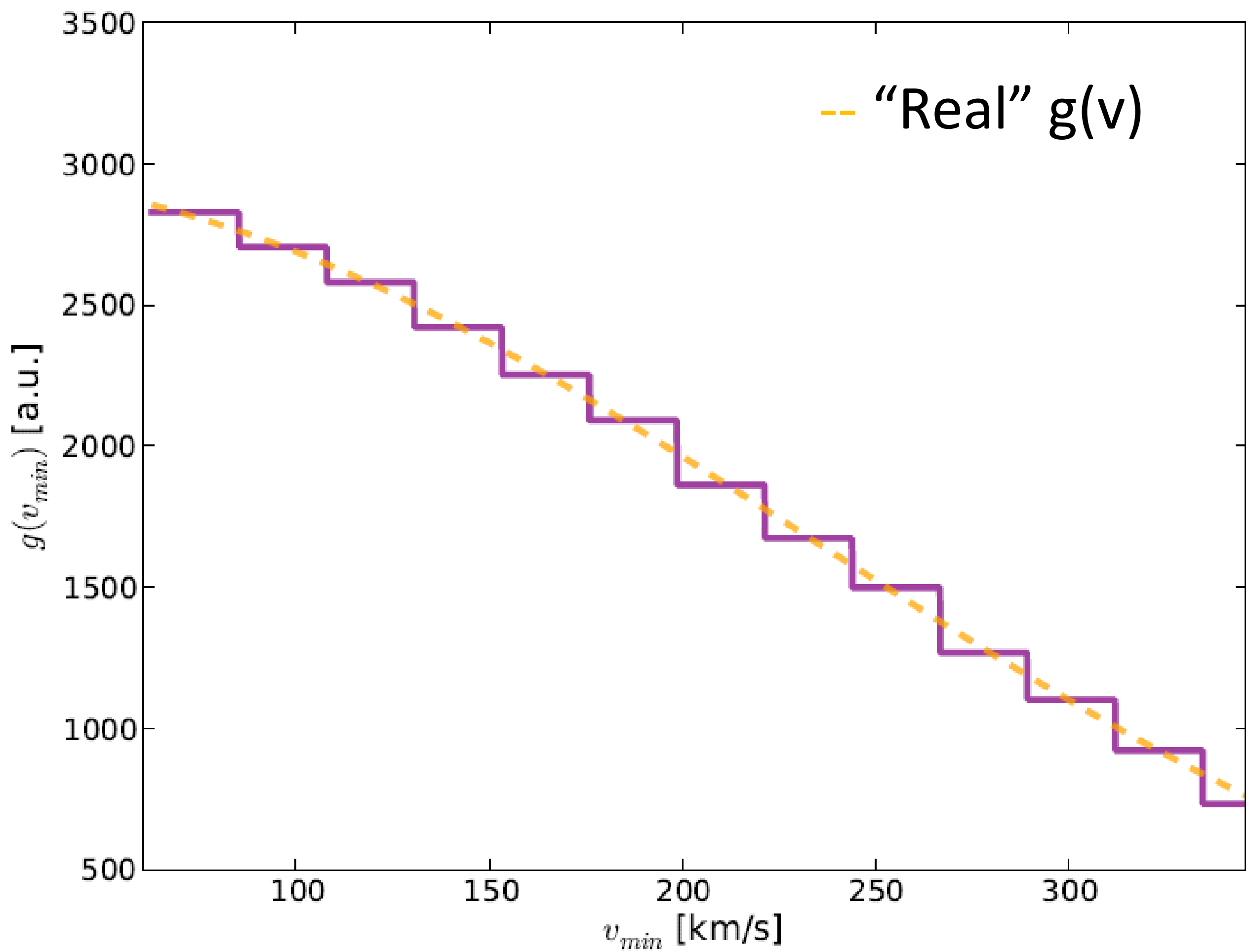
First, a trivial example

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

Hypothesis: correct model

N = 14

$$\chi^2 = .031$$



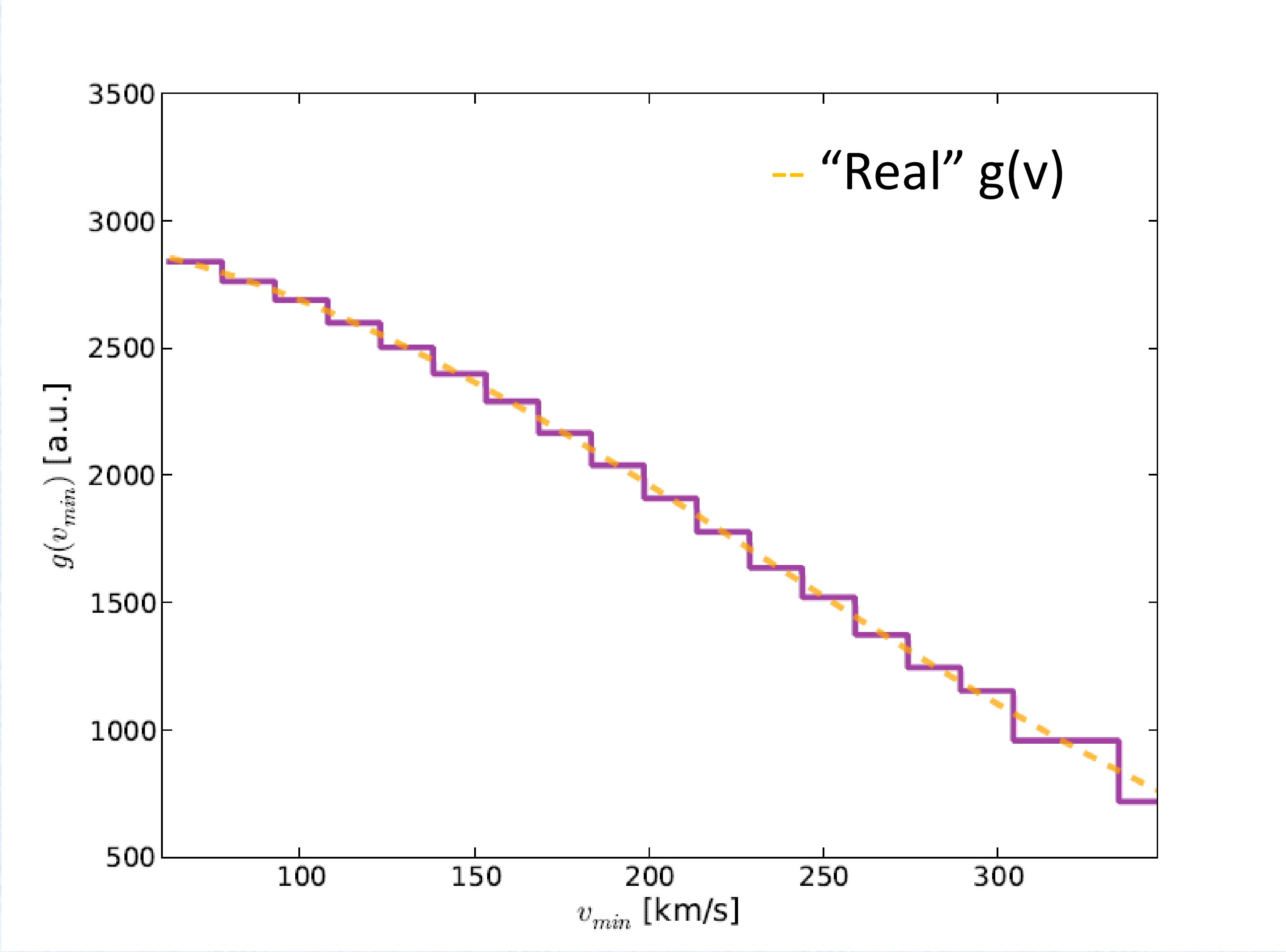
First, a trivial example

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

Hypothesis: correct model

N = 21

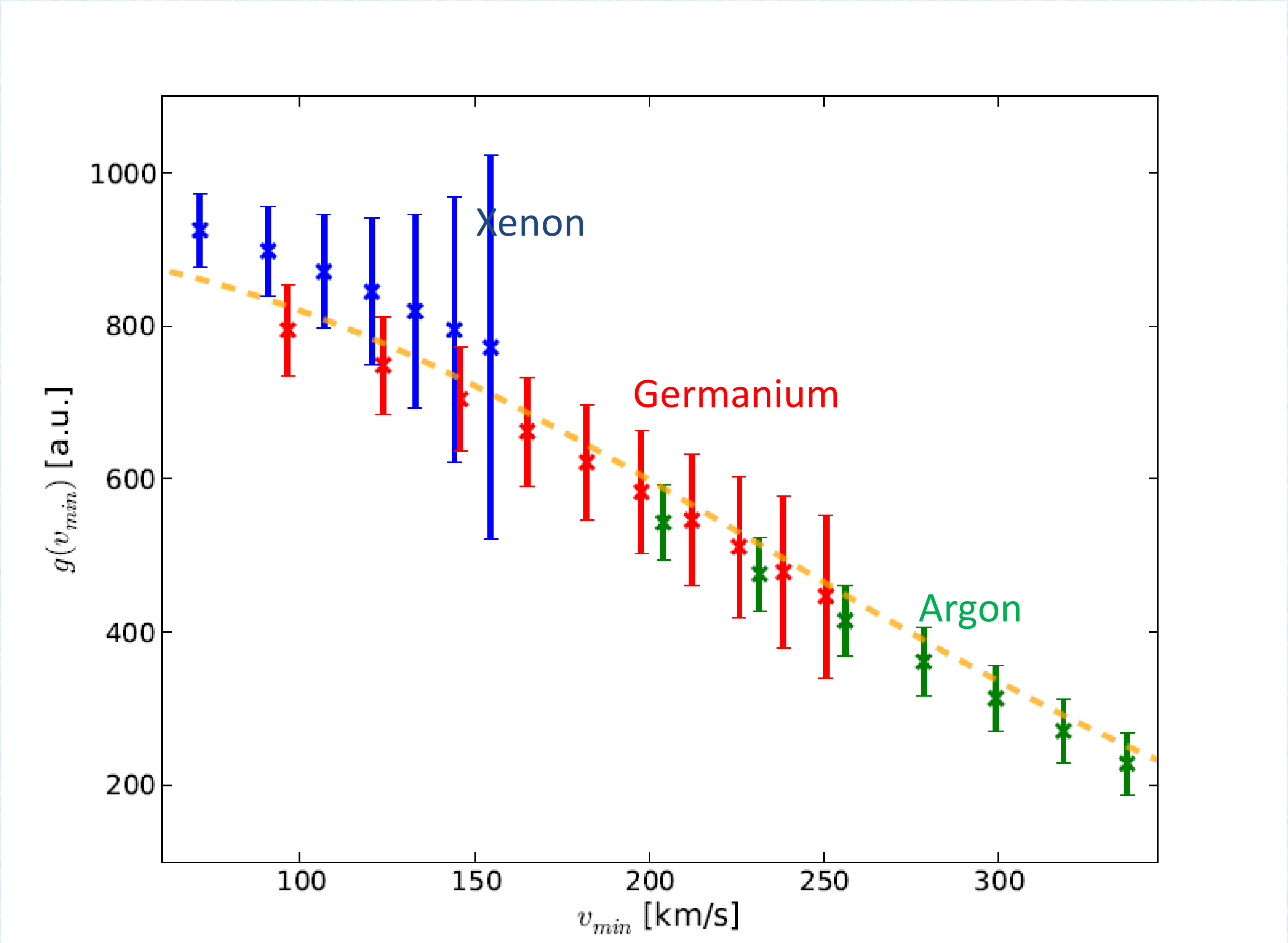
$$\chi^2 = .00029$$



Next, a non-trivial example

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

Hypothesis : f_p/f_n = 1



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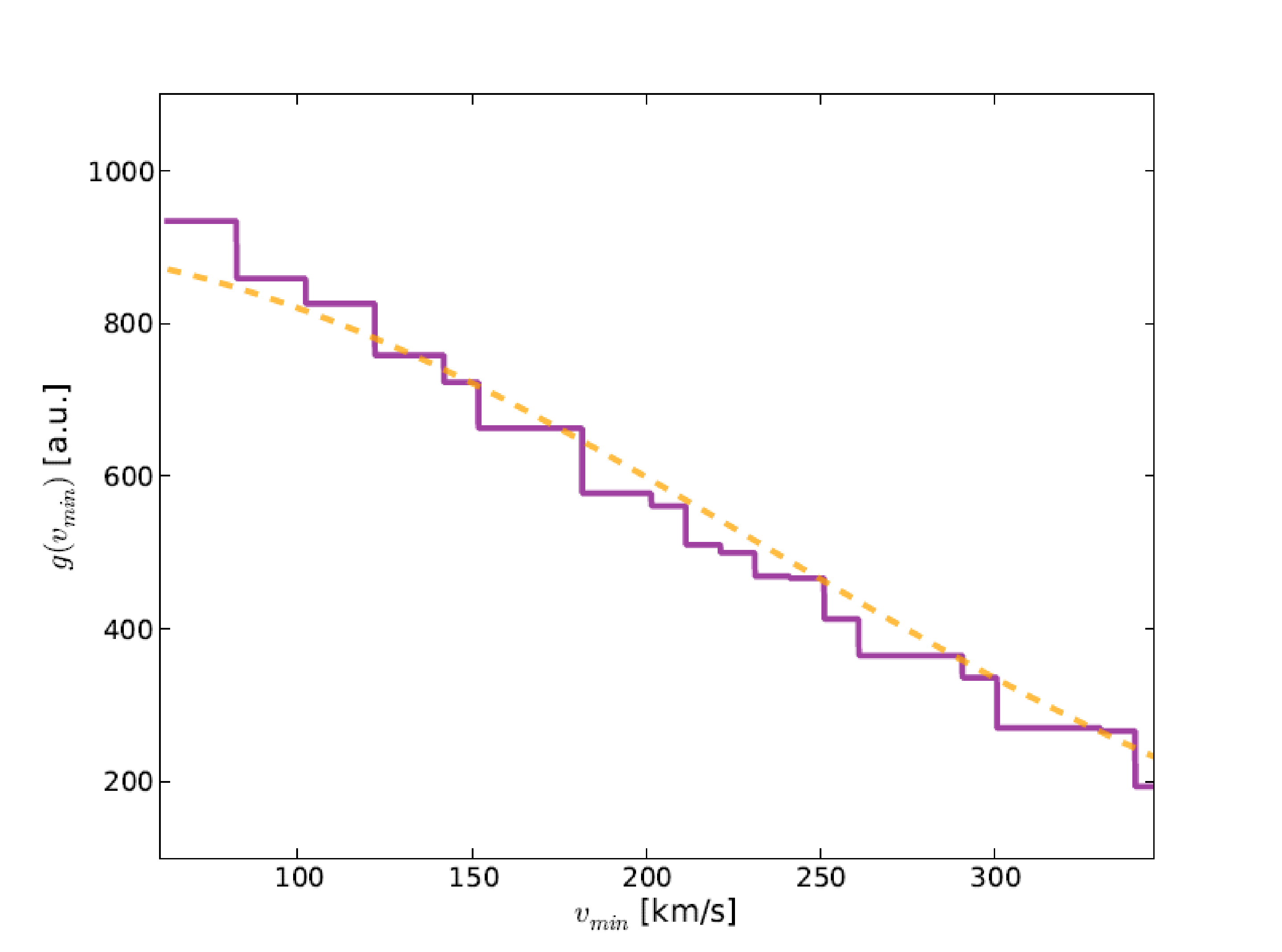


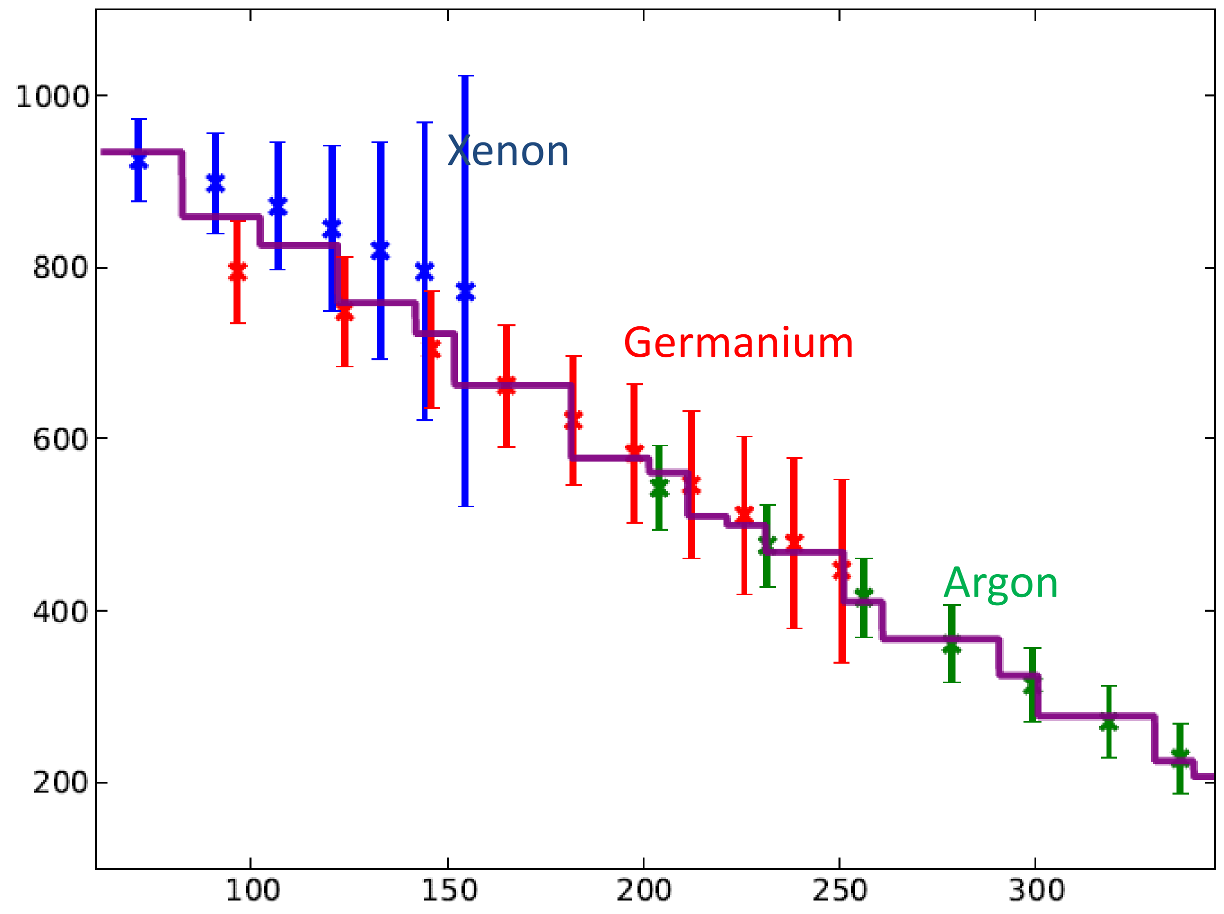
Next, a non-trivial example

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

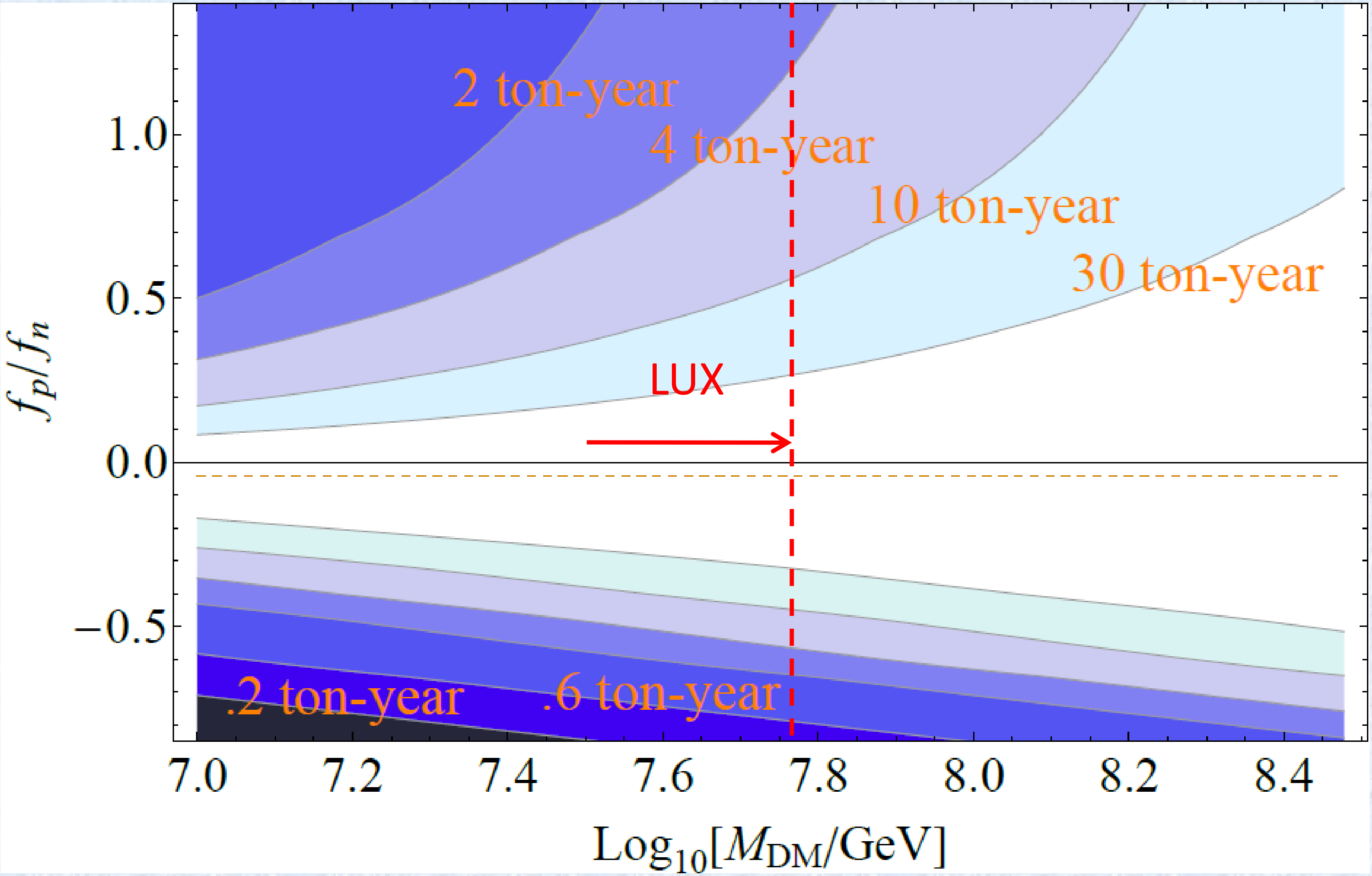
Hypothesis : $f_p/f_n = 1$

N = 32

$$\chi^2 = 2.5$$



Narrowing in on f_p/f_n..



Future Directions

- This is a general approach with many possible uses!

- Analyze data looking for inelastic dark matter, form factor dark matter, etc..

- Adapt to deal with “null” experiments.

- Impact of neutron form factor?

- Analytic results?

Summary

- Hypercharged dark matter is a simple, generic dark matter candidate.
- If observed by direct detection it could yield otherwise unobtainable 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.

Bonus Slides

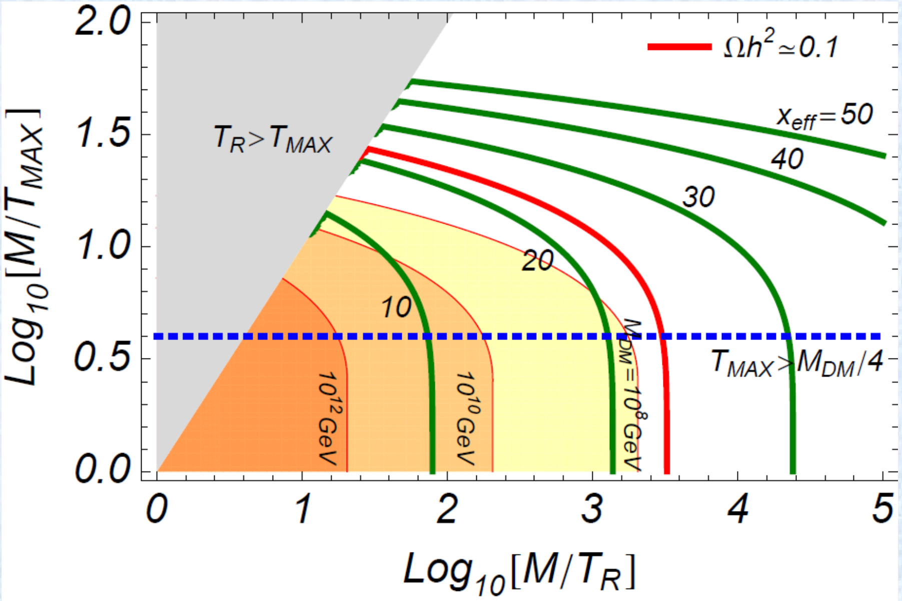
(I simplified a little bit..)

Inflation → Inflaton Matter Domination + Inflaton Decay → Radiation Domination

T_{max} T_R

→ Earlier slide was for $T_R = T_{max}$.

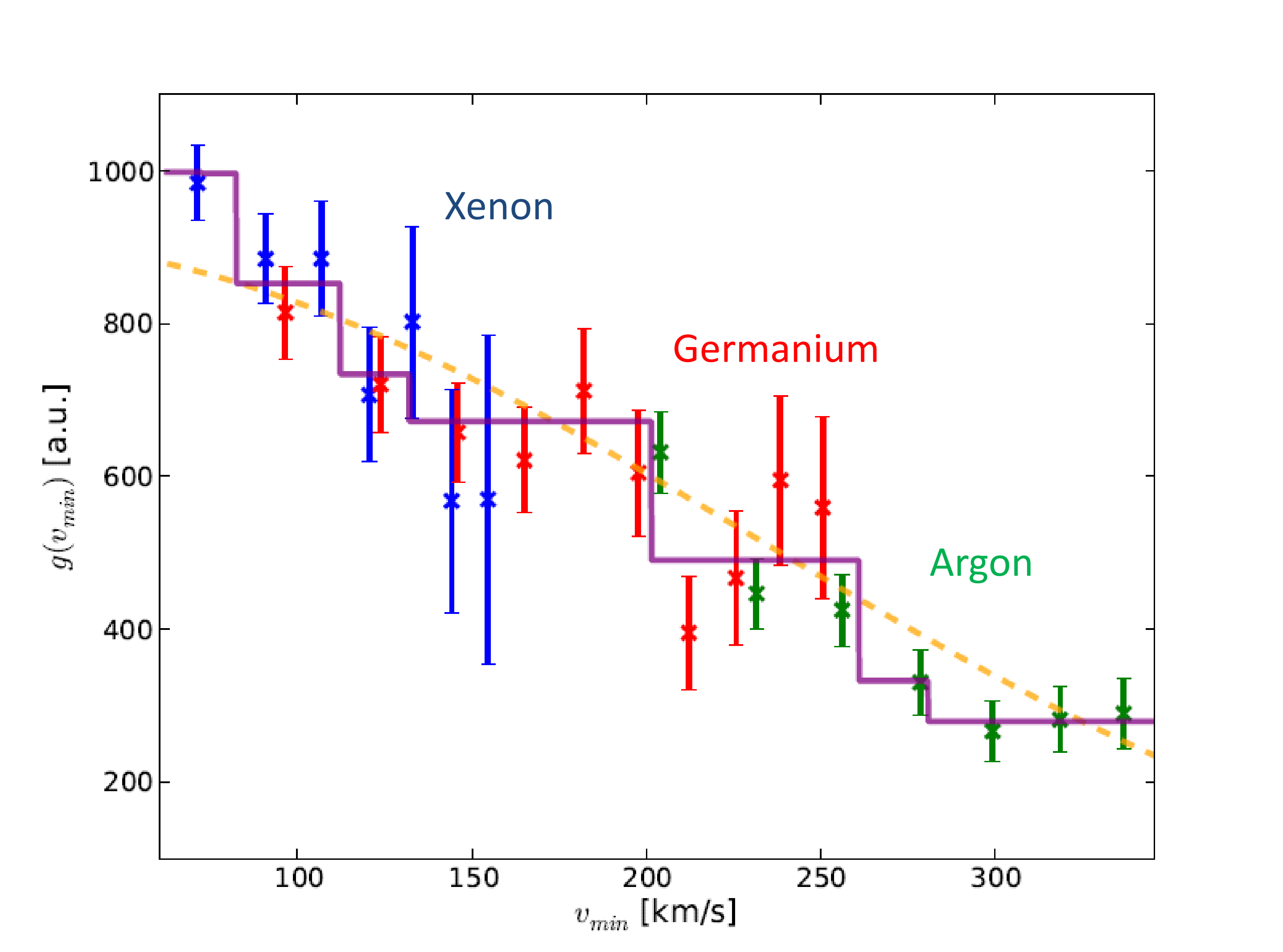
→ In any case obtain a 2 order of magnitude window on T_R.



Now With Poisson Fluctuations

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

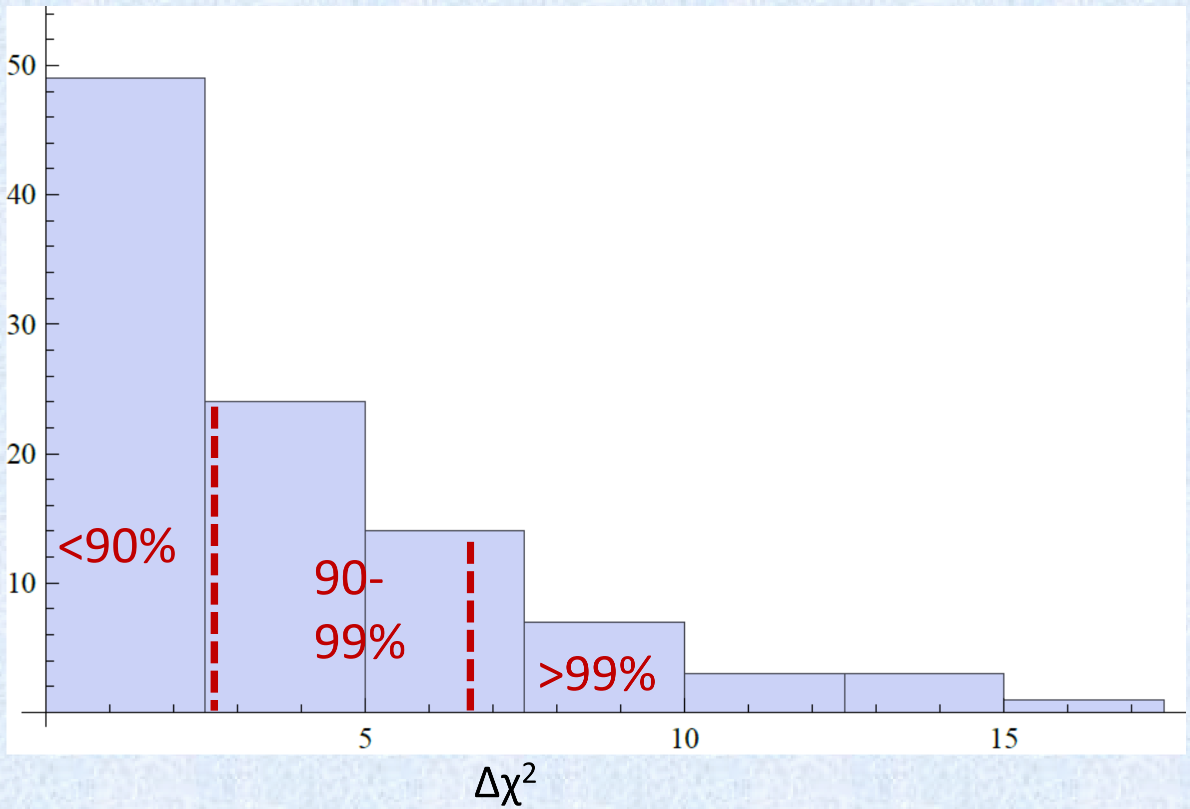
Hypothesis : f_p/f_n = 1



Distribution of Exclusions with Poisson Fluctuations

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

Hypothesis : $f_p/f_n = 1$



The minimization is numerically very simple!

- We must minimize:

observations in each bin

$$\chi^2 = \Sigma_j \frac{(P_j - N_j)^2}{P_j}$$

predictions in each bin

with $P_j = \Sigma_i C_{ji} \Delta_i$

step sizes

known positive coefficients

- With all Δ's positive, it turns out there is a unique local minimum!

..even when the number of steps is very large!

(Assuming non-trivial data which cannot be perfectly fit.)