Astrophyiscal Detection of Dark Matter

Douglas Finkbeiner

Fermi Summer School

30 May, 2013

Outline

- Overview of dark matter
- Excess ~ 100 GeV positrons: signs of DM annihilation?
- Testing with the CMB (*WMAP, Planck*)
- Gamma ray lines (*Fermi*)

Overview

- "Standard model" cosmology contains ~30% matter
- 5/6 is "dark" (= invisible)
- No known interactions with photons, electrons...
- Discovered only by gravitational effects

Gravitational Evidence for Dark Matter

- Galaxies in nearby clusters move too fast (Zwicky, 1930s)

Virgo cluster
SDSS

Gravitational Evidence for Dark Matter

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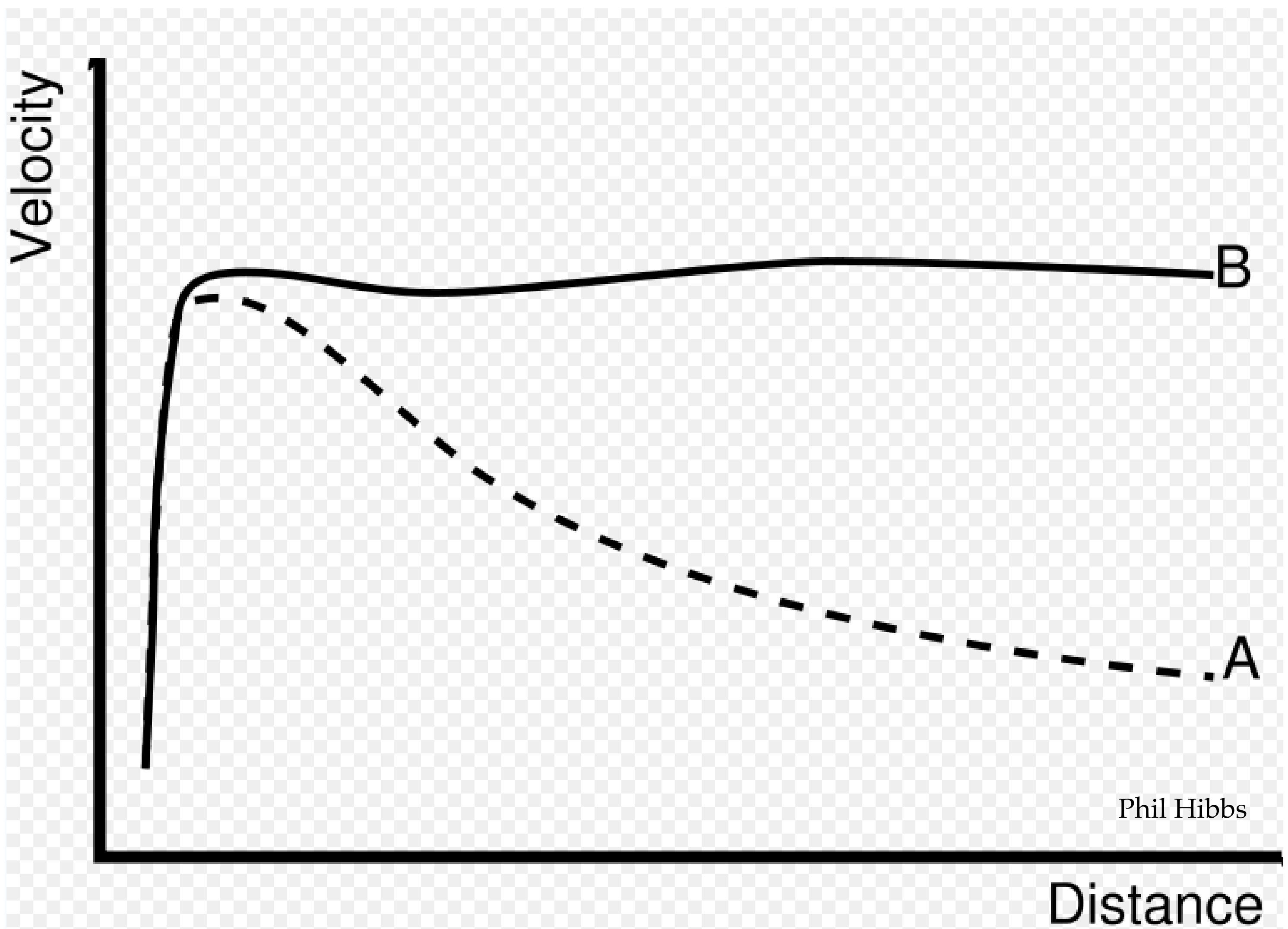
- Flat galactic rotation curves (Rubin, 1970s/80s)



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- Gravitational lensing

Abell 2218, HST

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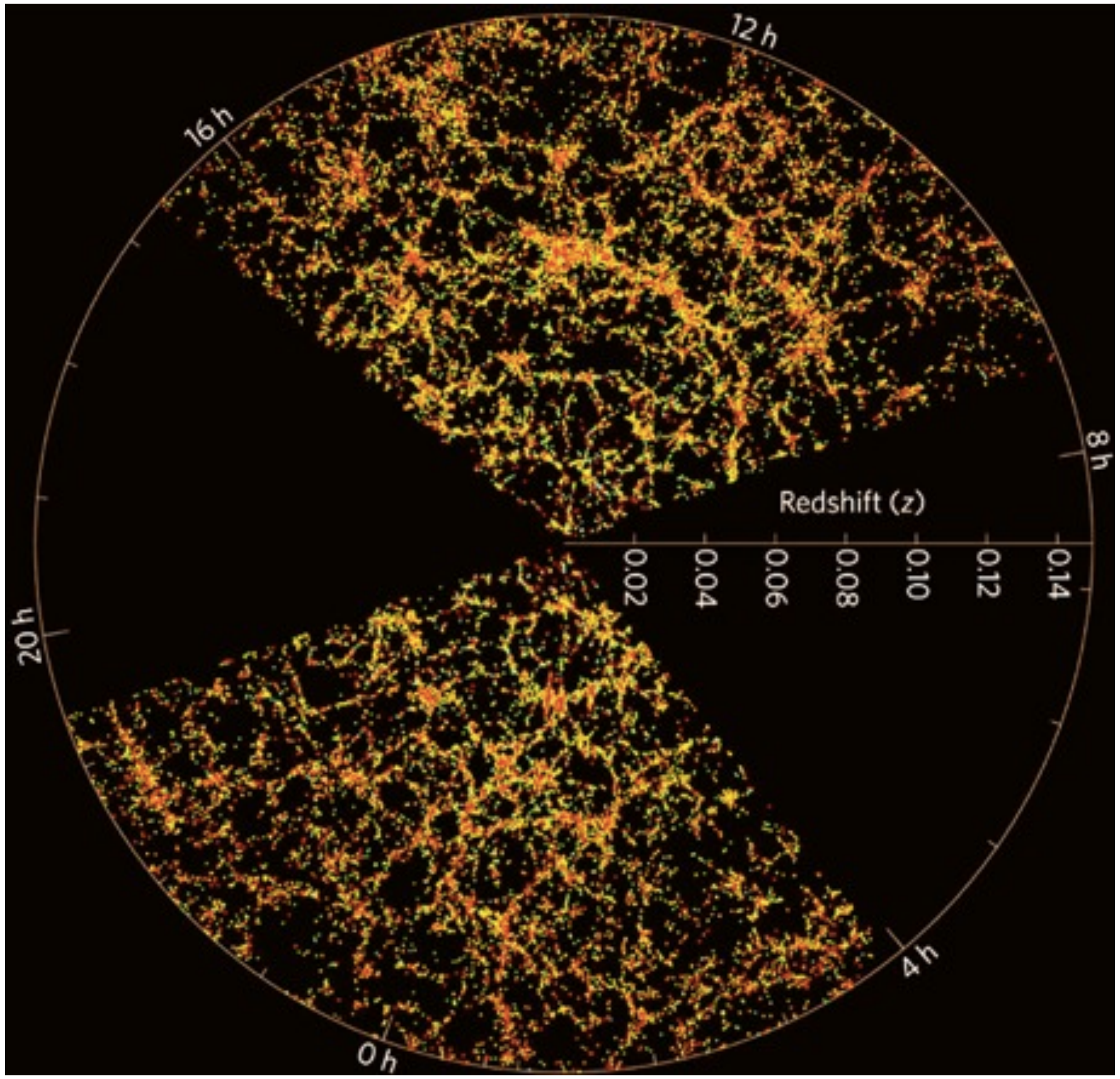

SDSS

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- Galaxies in nearby clusters move too fast (Zwicky, 1930s)
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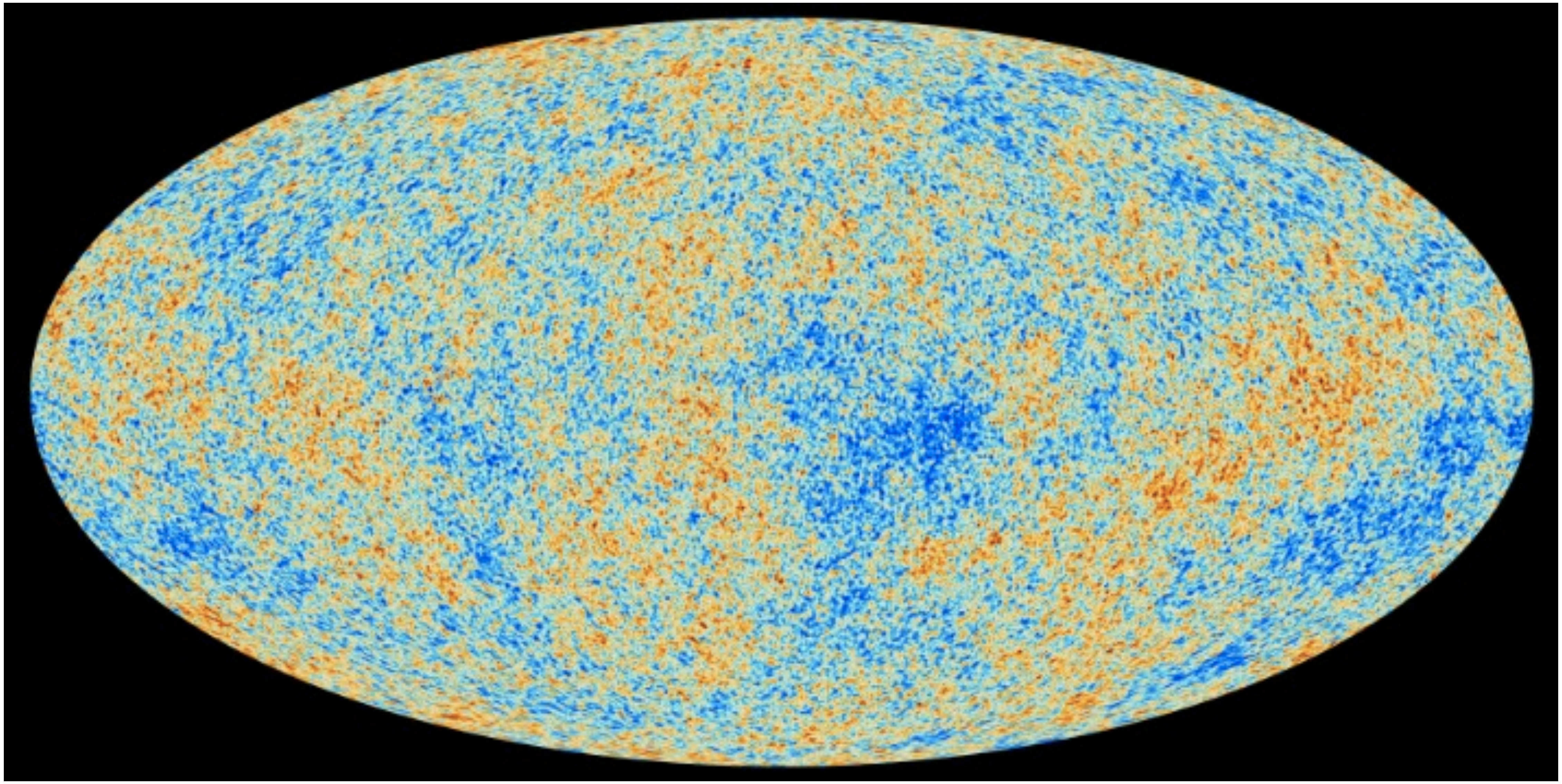
- Gravitational lensing
- Structure formation (must be *cold* DM)
- Cosmic microwave background (CMB) anisotropy



Planck (2013)

Gravitational Evidence for Dark Matter

The CMB tells us what fraction of the matter was coupled to the photon-baryon fluid at early times. 5/6 of it wasn't.

This is why dark matter cannot be anything baryonic.

But what is it?

One idea:

The weakly interacting massive particle, or WIMP

The WIMP is (for many of us) the most compelling candidate. *Why?*

Thermal relic freeze-out argument:

In the early universe, everything is produced and annihilated all the time, no matter how weakly interacting. (because the density and temperature are so high)

As the temperature drops, annihilations win, and the density drops exponentially (Boltzmann factor)

When the annihilation timescale ~ age of the Universe, particles cannot find each other any more to annihilate, so annihilation turns off.

Thermal relic argument:

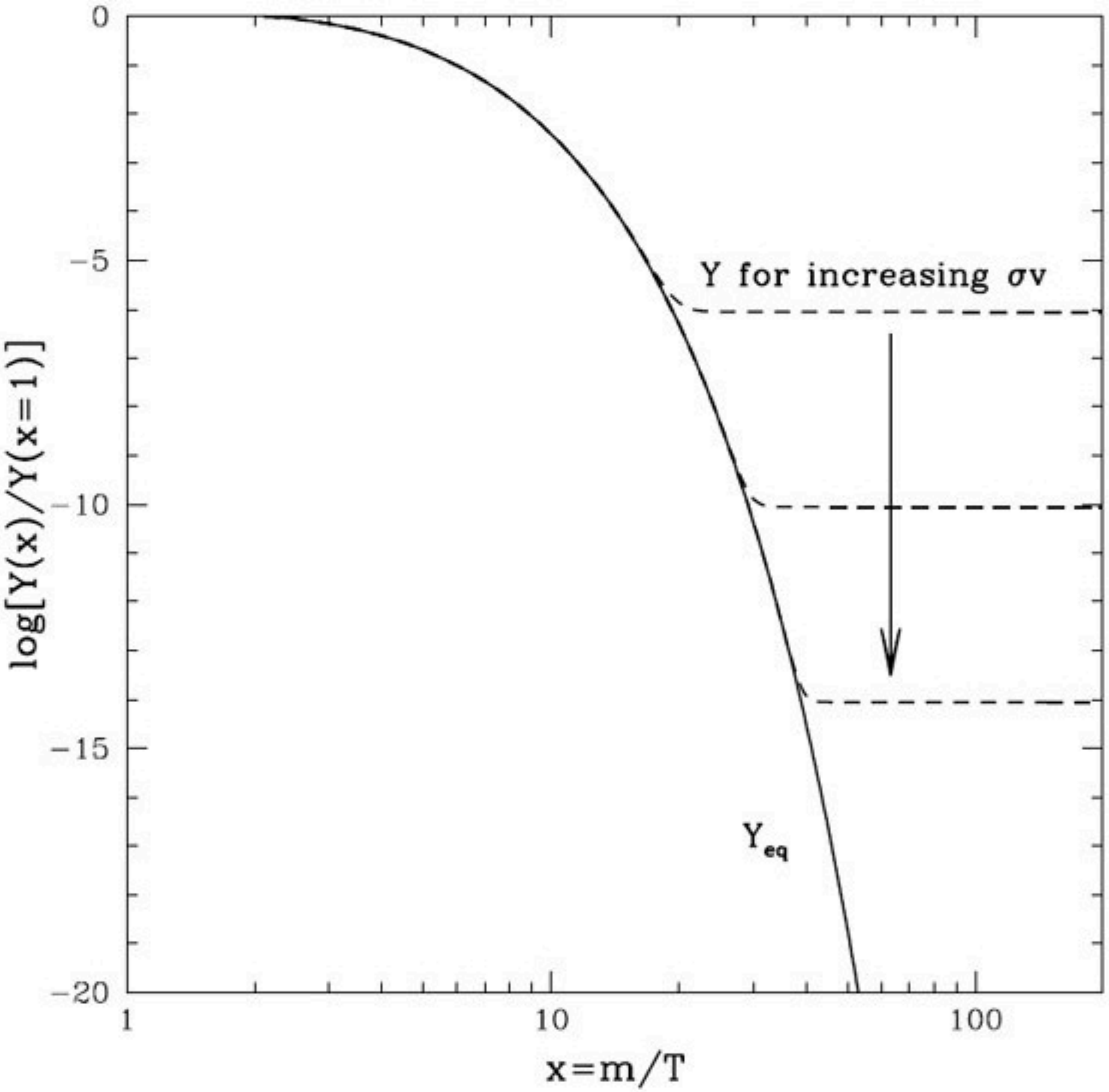
The relic density depends on $<\sigma v>$ at freeze-out time, when kT ~ $M_{wimp}/20$.

$<>$ denotes a thermal average

Higher annihilate rate means less DM left over.

From the relic density today (about 1 m_p/m^3) we know that $<\sigma v> = 3\times10^{-26}$ cm^3/s.

Thermal relic argument:



Implications of a thermal relic WIMP

This is amazing - we don't know what the WIMP is, but we know the cross section at freeze-out!

For "s-wave" annihilation, $\langle\sigma v\rangle$ is independent of v.
For "p-wave" annihilation, $\langle\sigma v\rangle \sim v^2$.

So, for a "standard" WIMP, e.g. a supersymmetric neutralino, the cross section must be $\langle\sigma v\rangle = 3\times10^{-26}$ cm^3/s.
Or it could be less.
(or it could be more, but I'll come back to that).

Implications of a thermal relic WIMP

Important thing:

The annihilations *only* turned off in the early Universe because the density dropped.

Today we have high density in the centers of galaxies, so there should be some annihilation (at a low level) today.

Use up about 10^{-12} of our dark matter per Hubble time. (We won't run out).

Our mission:

These ongoing annihilations today produce SM particles and photons (either directly or indirectly).

Our task is to search for these particles and their photon signals from synchrotron and inverse Compton scattering.

Is this picture too simple?

A single new particle with a mass and a coupling.

(Simple... perhaps *too* simple...)

What WIMP dark matter could be:

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- Composite particles
- Bound by new forces?
- *"Dark sector physics"*

Neutrino analogy...

(This may only be the tip of the iceberg)

WIMP Self-interaction?

In most models, WIMPs have some self-interaction.
(even if only weak interactions via Z boson exchange or via fermion loops)

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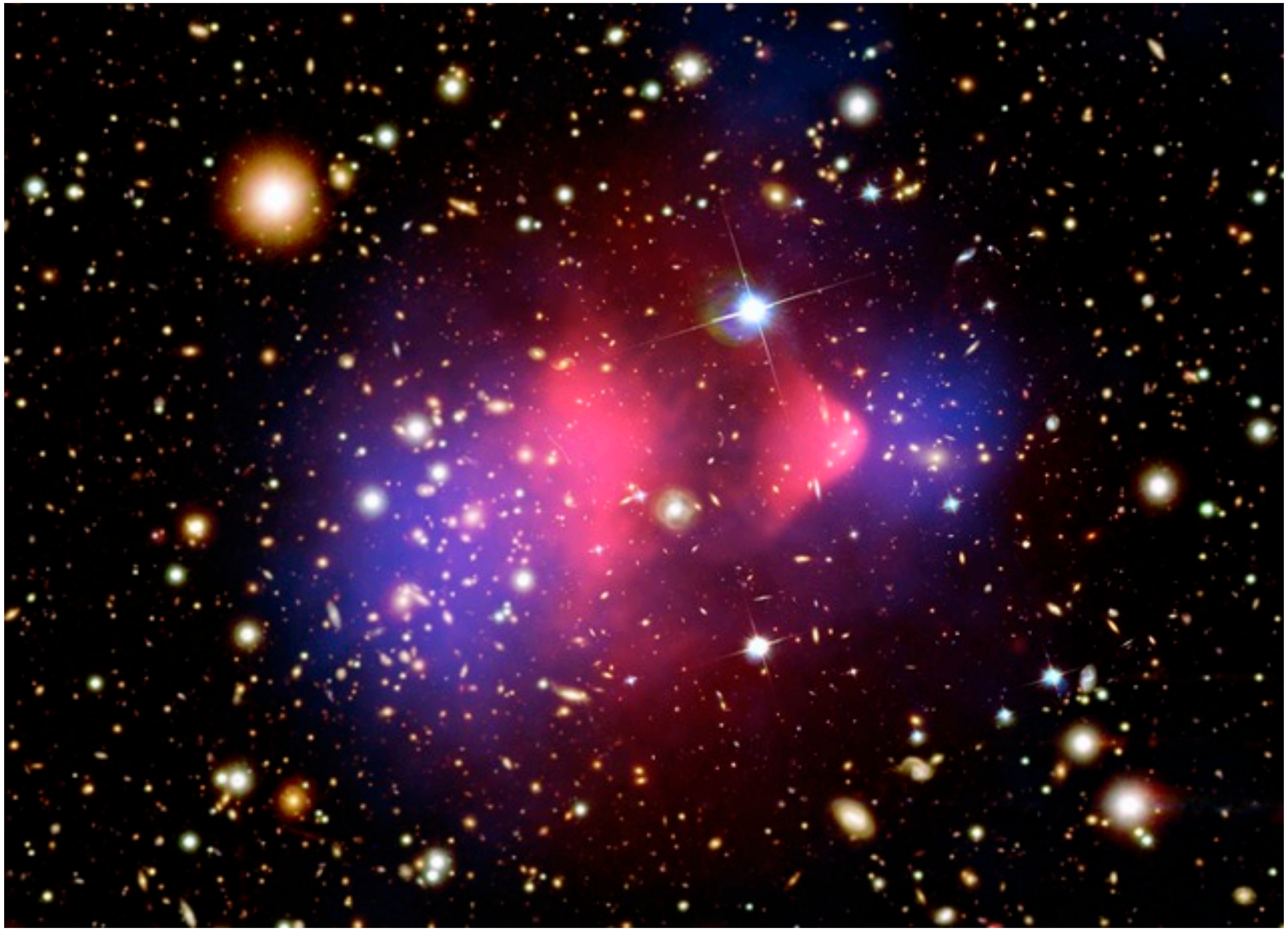
Limits from e.g. the Bullet Cluster:



blue: DM; red: X-ray gas.   Galaxies and dark matter stay together.

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Other limits from the fact DM halos do not collapse.

Current limits of order 0.1-1 cm^2/g.

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None has been detected.
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Other limits from the fact DM halos do not collapse.
Current limits of order 0.1-1 cm^2/g.
This is still enough to have interesting effects in astrophysics...

So let's keep in mind that things could be complicated.

How to search for WIMP dark matter

- Direct detection (coherent nuclear scattering, detect recoil)
- Indirect detection (astrophysical detection)
- Colliders (produce WIMPs or their friends)

Direct detection

Many experiments (e.g. CDMS, XENON-100...)
Look for coherent WIMP-nucleon scattering.
Measure phonons, scintillation, ionization.
Rapid improvements in upper limits.
No convincing detection of WIMP scattering yet.

But there have been claims...

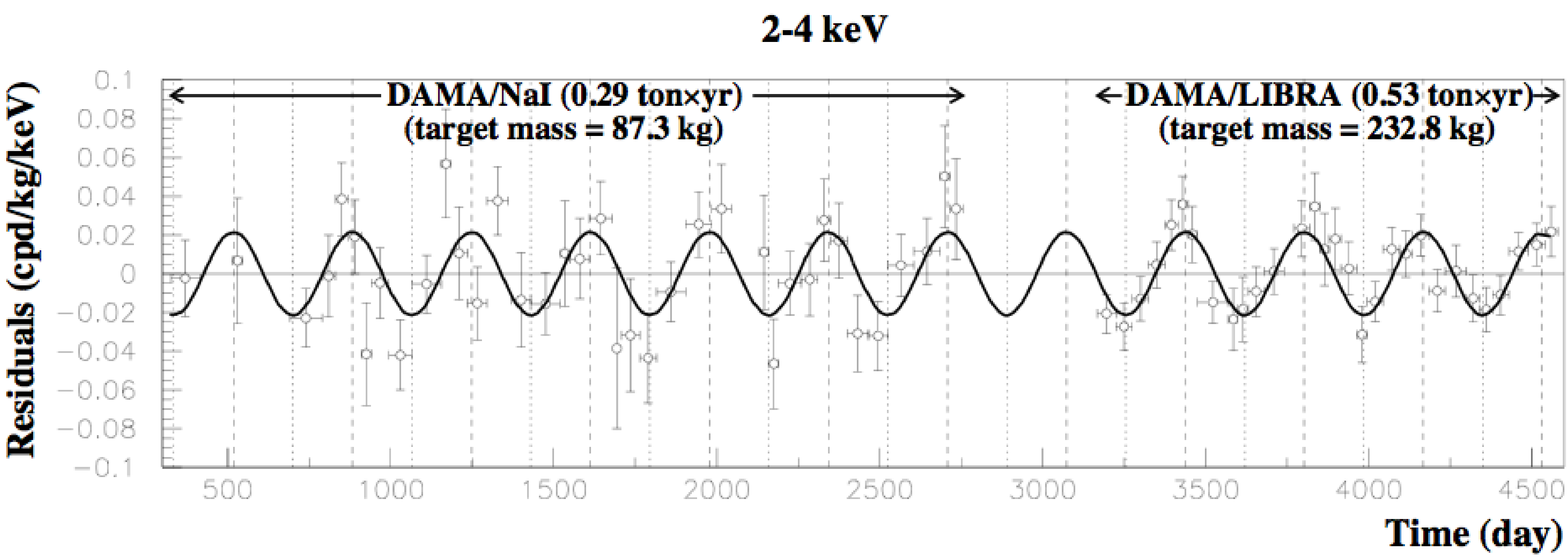
DAMA

No per-event discrimination. Relies on annual modulation of signal.

Vastly larger exposure than most experiments.

Claimed detection 12 years ago, now at 10σ.

Not accepted by most (after many passionate debates!)



DAMA

DAMA sees a convincing signal (~10 sigma) but other experiments rule out *elastic nuclear scattering* at this level (by orders of magnitude).

Conclusion: DAMA is *not* seeing elastic nuclear scattering of WIMPs.

Claims that DAMA is *wrong* are based on a theoretical prejudice that the scattering must be elastic.

Direct detection

Idea: DAMA is seeing *inelastic* nuclear scattering of ~ 200 GeV WIMPs with 100 keV mass splitting.

Why does inelastic scattering help?

1. On tail of velocity distribution: annual modulation signal can be much larger than expected (30-100%)

2. Bigger nuclei better (I better than Ge, worse than W)

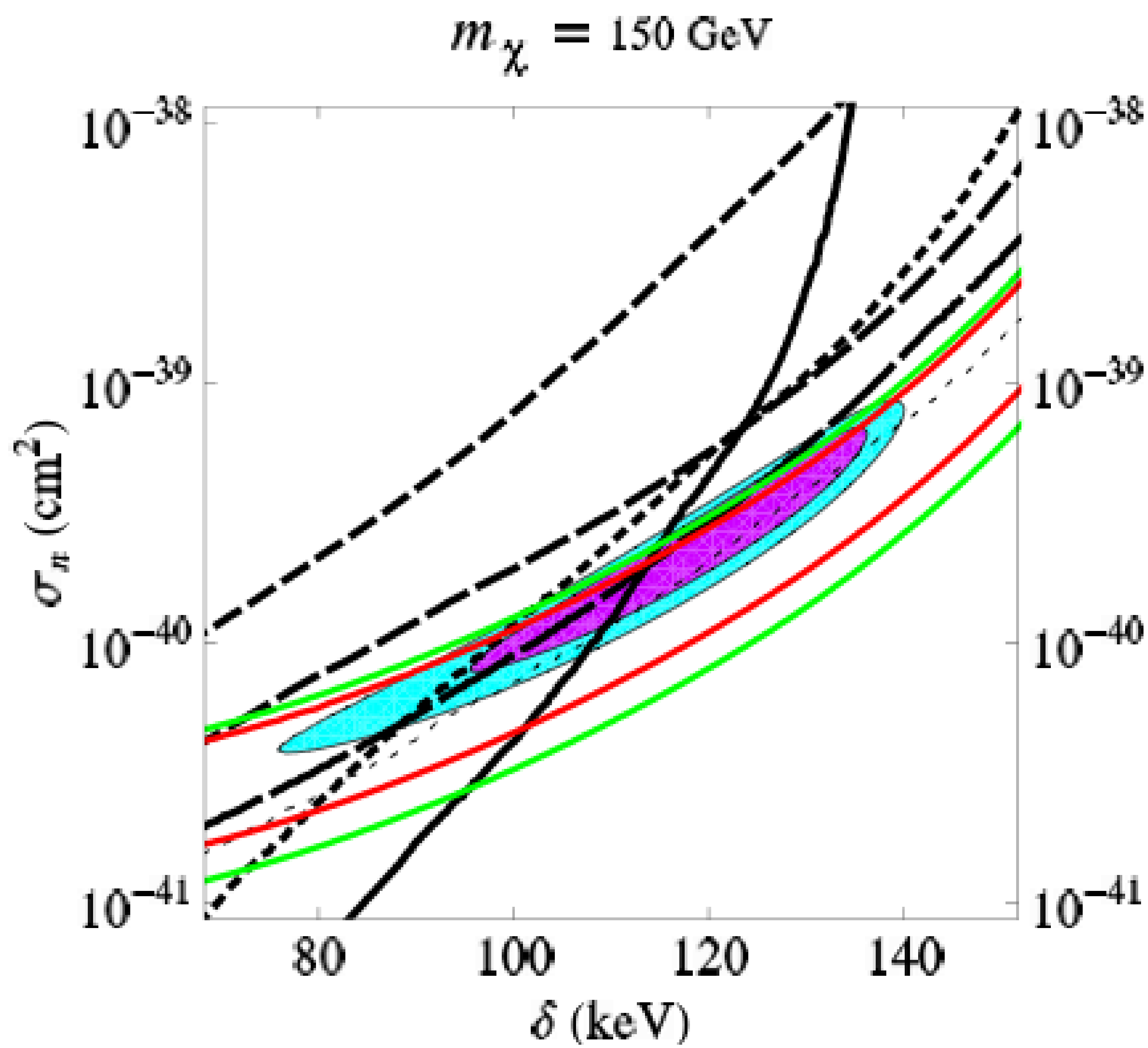
3. Higher energies are better (because of built-in energy scale). DAMA has huge exposure time but little sensitivity to low energy events.

Smith & Weiner (2001), Chang et al. (2008)

Direct detection

If you want DAMA to be seeing WIMPs, inelastic scattering helps a lot.

Smith & Weiner (2001), Chang et al. (2008)



Direct detection

If you want DAMA to be seeing WIMPs, inelastic scattering helps a lot.

This proves nothing, but let's keep in mind as we explore various other signals...

Indirect detection (astrophysics)

Search for annihilation (and/or decay) products from WIMP annihilation.

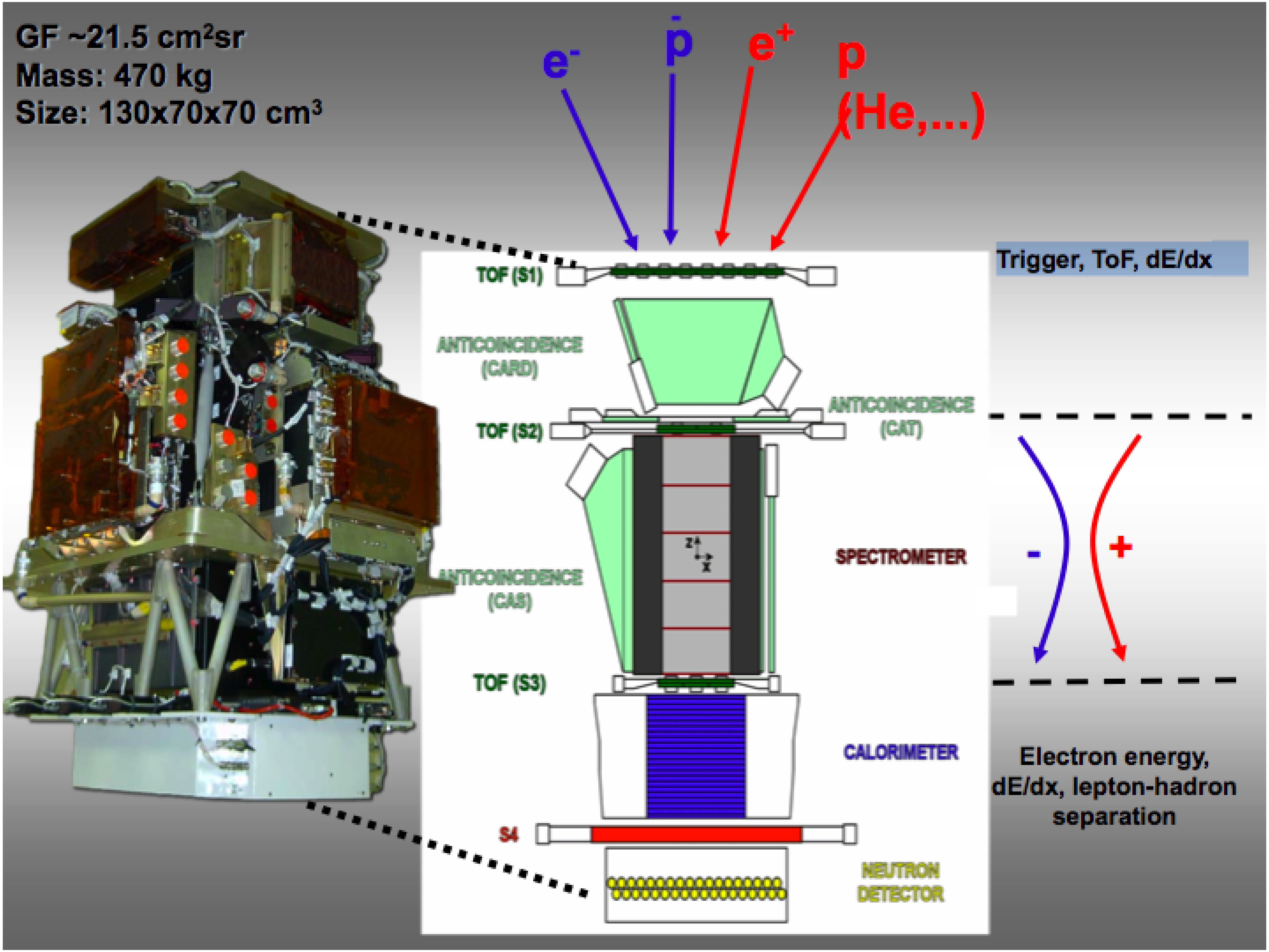
Usually go directly or indirectly to gammas, e^+e^-, or neutrinos.

I will focus on two of the many searches:
- high energy positrons near the Earth
- a possible gamma-ray line at 130 GeV.

PaMeLa

a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics

In 2008, PAMELA found that there were far more positrons than expected at high (~ 100 GeV) energy.

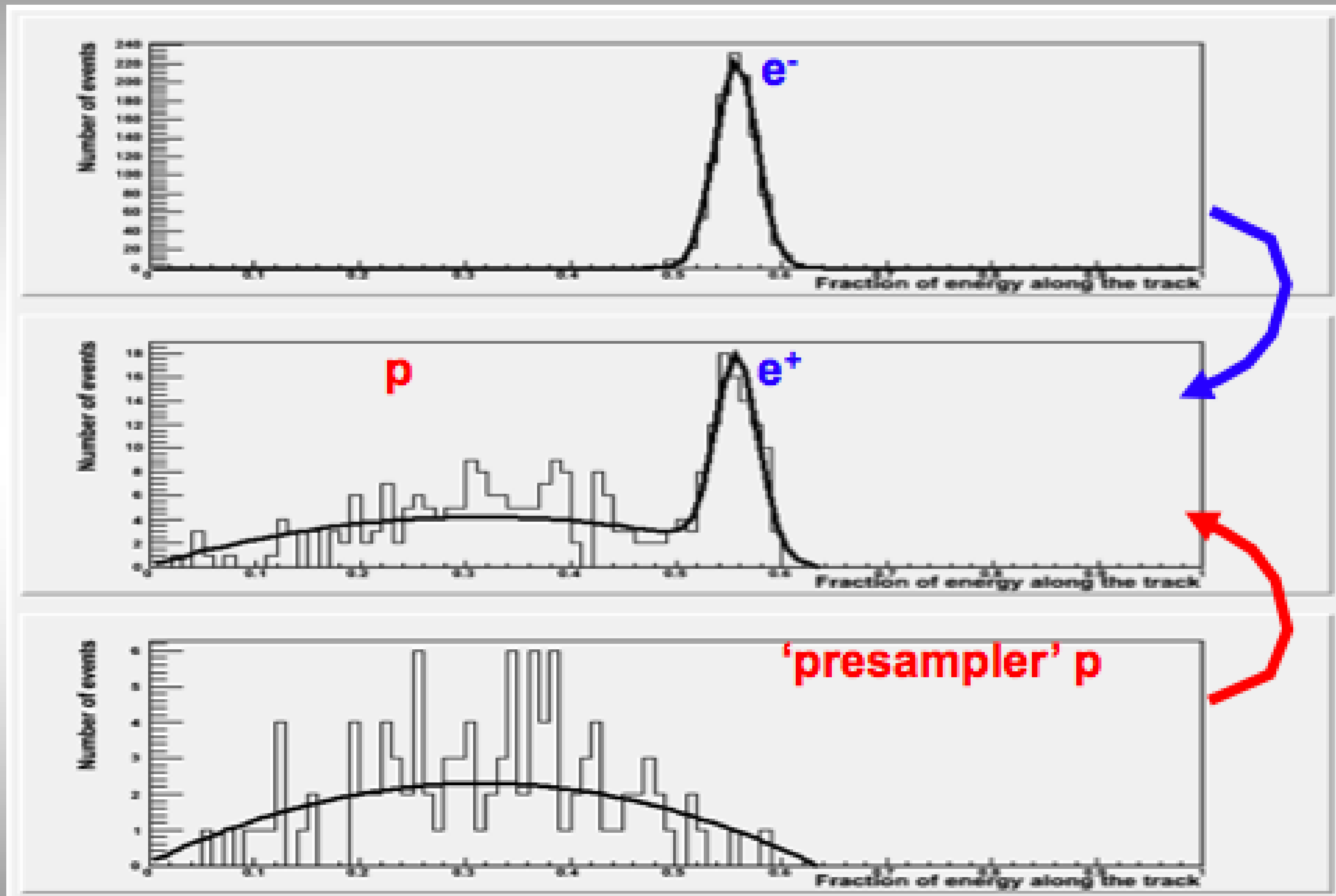


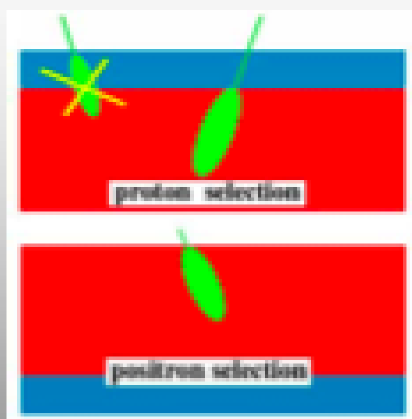
Courtesy Mirko Boezio

e^+ background estimation from data

Rigidity: 20-30 GV

Preliminary



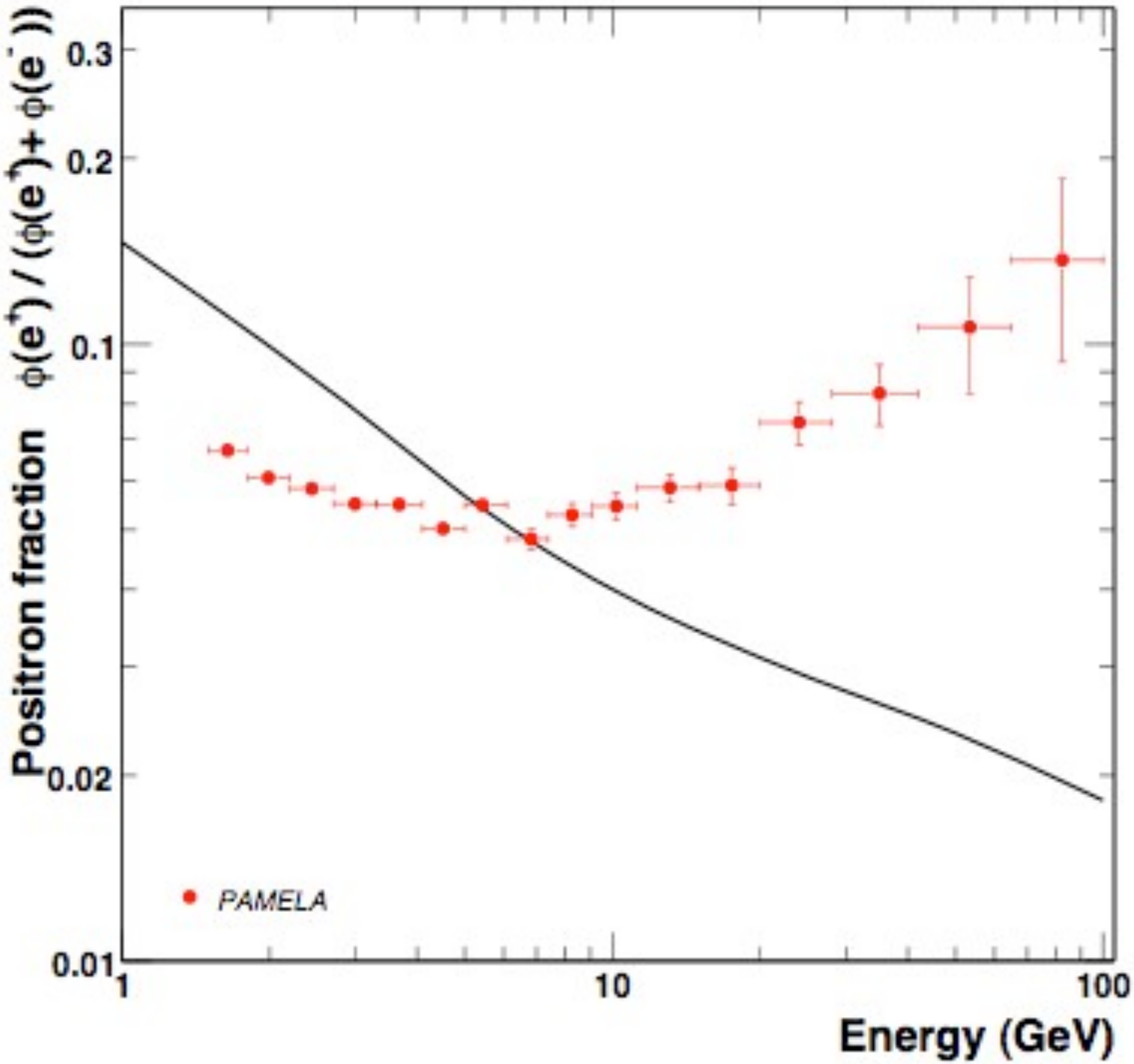


Fraction of charge released along the calorimeter track (left, hit, right)

+
- Energy-momentum match
- Starting point of shower

Courtesy Mirko Boezio

PAMELA (2010)

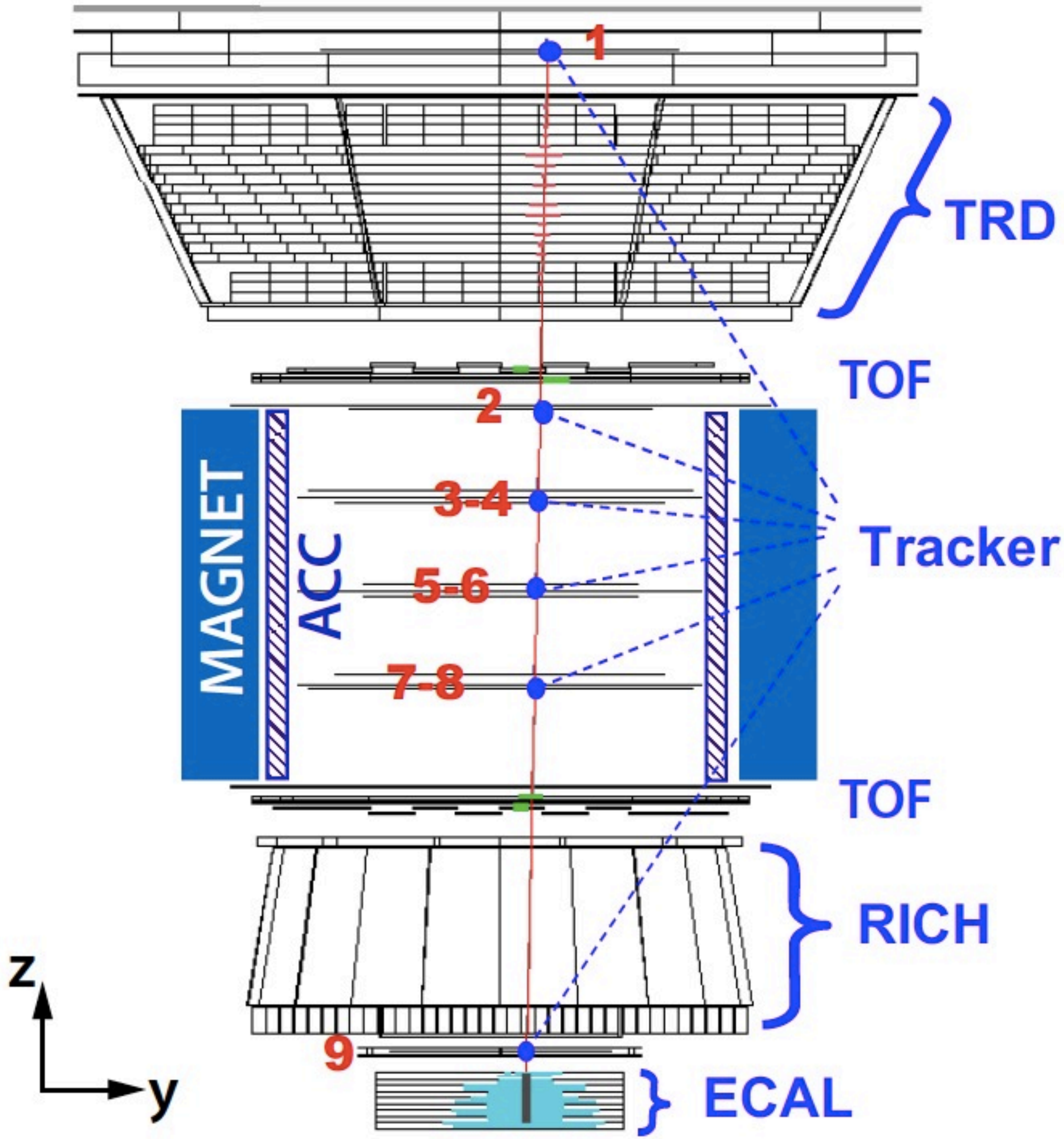


Adriani+ (2010)

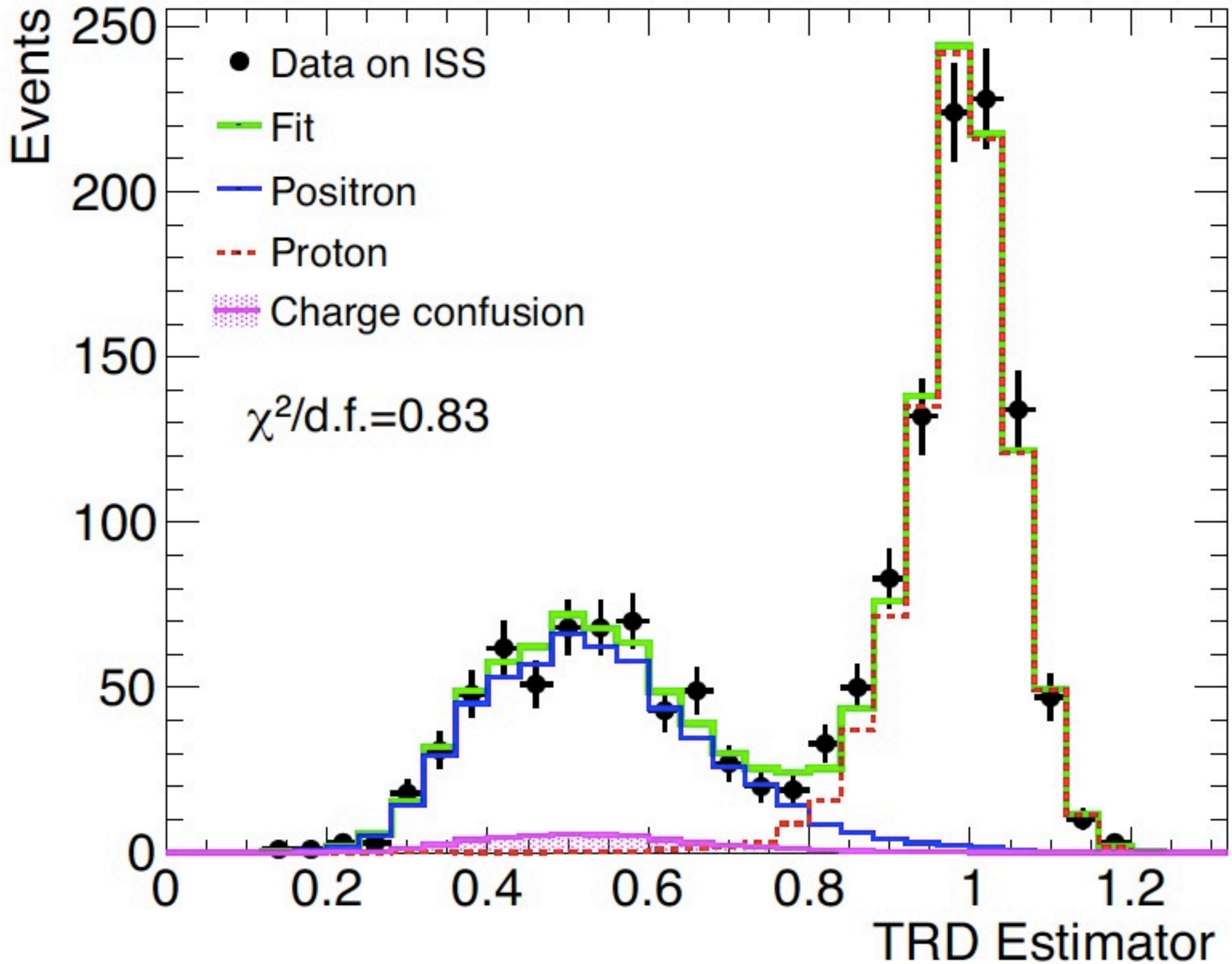
Late-breaking news (April 3)

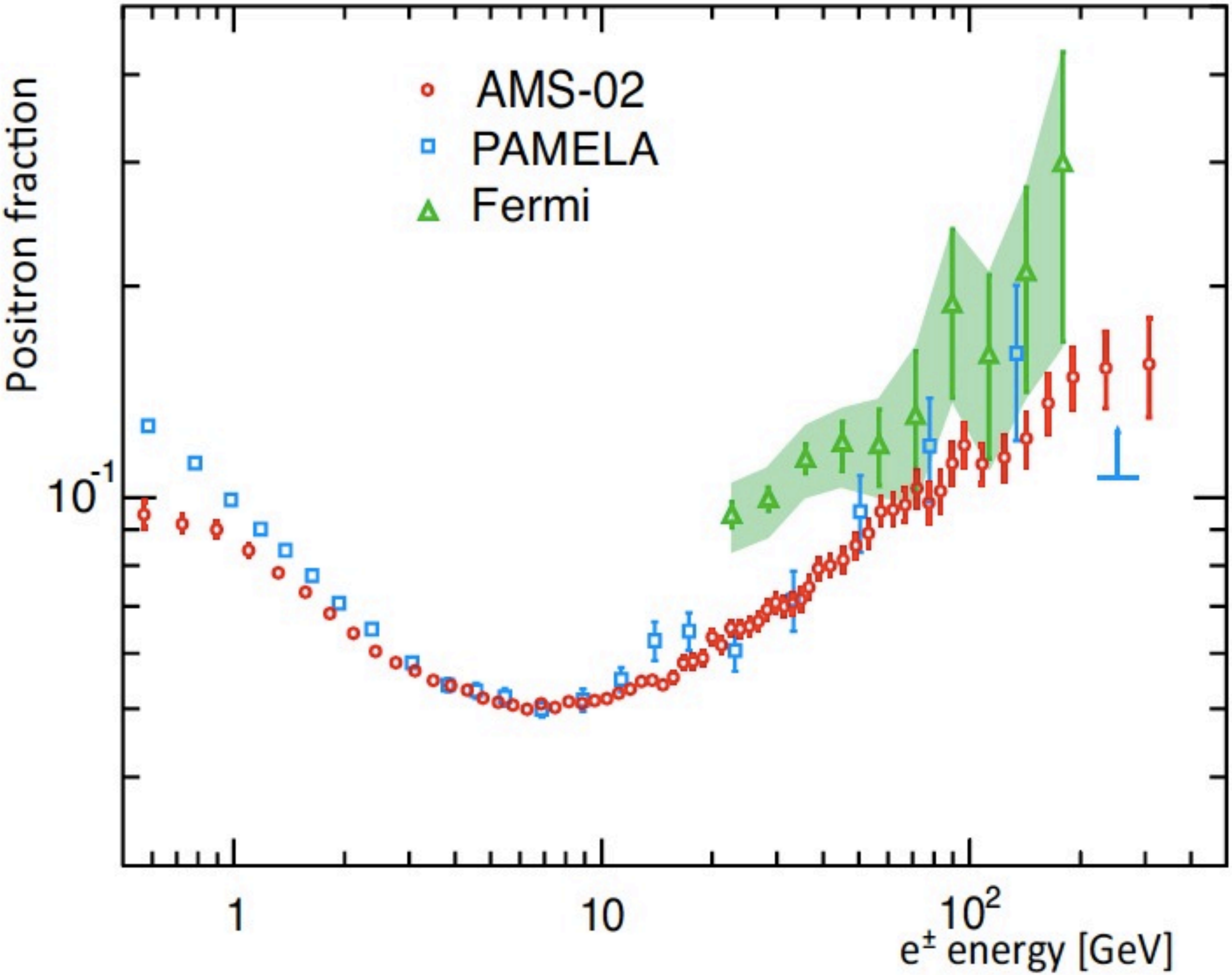
AMS-02: Bigger and better...

Note the TRD (Transition radiation detector)

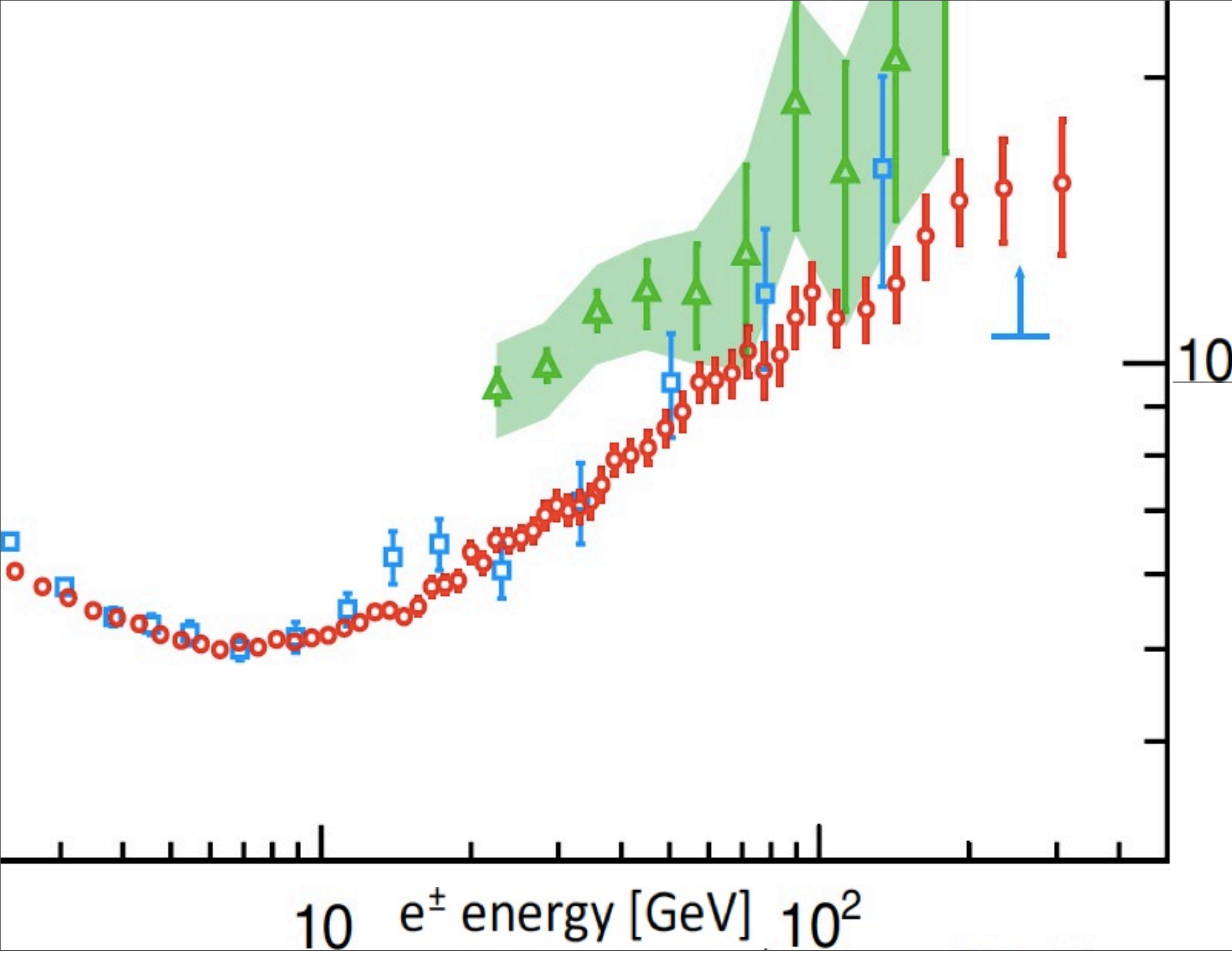


TRD provides independent e-p discrimination.





AMS-02
PAMELA
Fermi
Positron fraction
10^{-1}
1
10
10^2
$e^{\pm}$ energy [GeV]


10
e± energy [GeV]
10
10^2

AMS-02 has far smaller error bars, and much higher confidence in positron-proton separation than PAMELA. It is a beautiful measurement.

However, the picture we had from PAMELA is unchanged.

The mystery remains: what could produce these e^+ up to 300 GeV and beyond?

- Exotic pulsars?
- Dark matter?
- None of the above.

There have been headlines implying that the AMS positrons may be a discovery of dark matter.

Hints of Dark Matter Have NASA Scientists Over the Moon

by Miriam Kramer, SPACE.com Staff Writer
Date: 04 April 2013 Time: 07:02 AM ET

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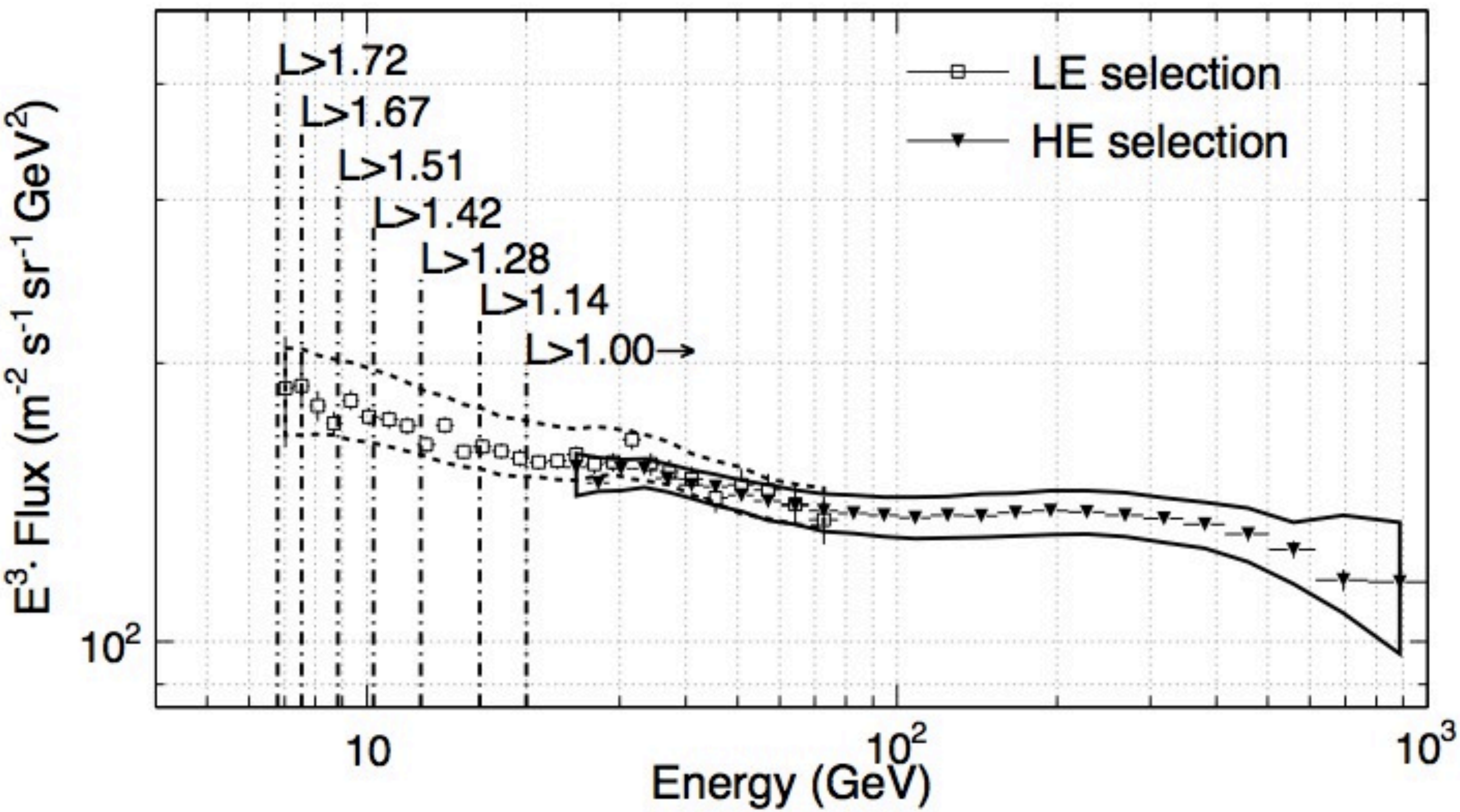
The Alpha Magnetic Spectrometer experiment hangs on the side of the International Space Station, July 12, 2011.
CREDIT: NASA
View full size image

Pin it

WASHINGTON — Patience and meticulous science were cause for celebration when an international team of scientists announced new results pointing to the possible detection of dark matter Wednesday (April 3).

Although the James E. Webb Auditorium was nearly empty here at NASA Headquarters, it did not stop space agency officials and scientists from enthusiastically unveiling new findings in a news conference Wednesday.

But we already knew the spectrum of electrons PLUS positrons:



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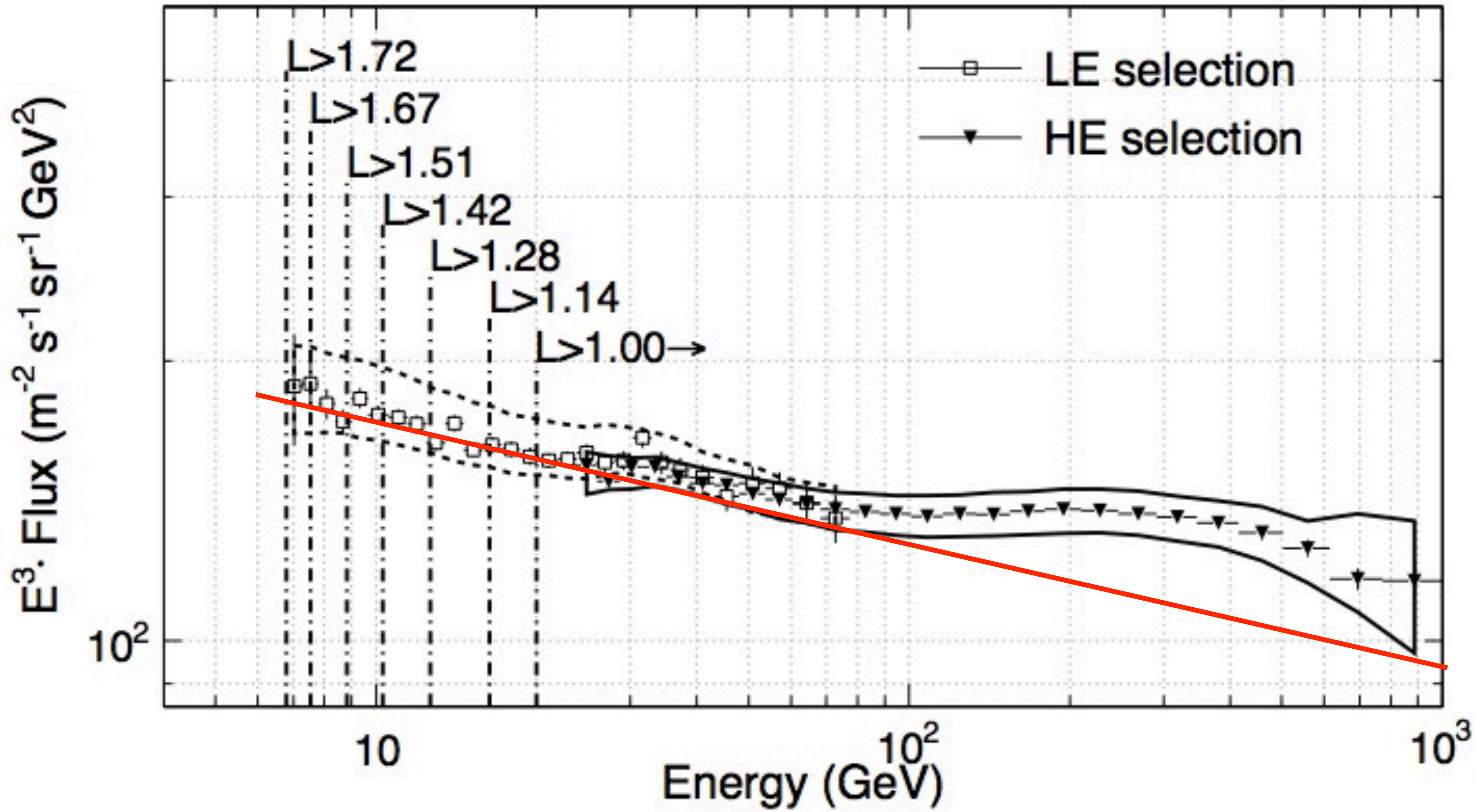


We also knew electrons and positrons from PAMELA and from Fermi (with less fidelity).

In 2011 I said:

"As a technical feat, it is beautiful," says Harvard University physicist Doug Finkbeiner. Still, he says it's too soon to say whether the new data say anything about dark matter. A close look at the results from PAMELA and Fermi suggests that the positron signal likely continues to get stronger at higher energies, Finkbeiner says, even beyond the upper end of the latest Fermi measurement. That is, maybe this isn't a distinct spike but rather a broad trend in cosmic ray spectrum, the source of which is impossible to say. The new paper is "a wonderful confirmation of the PAMELA result," he says, "however the positron signal will likely be there whether the positrons come from dark matter annihilation, or from pulsars, or from tooth fairies."

http://news.sciencemag.org/sciencenow/2011/11/cosmic-antimatter-excess-confirm.html

What does it take for dark matter to explain PAMELA?

It must have
- a high annihilation cross section (well above thermal),
- a high branching ratio to leptons, and
- a low branching ratio to protons.

Not difficult to do this with a new ~0.1-1 GeV mediator that increases the annihilation rate (Sommerfeld enhancement).

Annihilations go to this new particle, which then decays to electrons / muons because of its low mass.

(Arkani-Hamed, DF, Slatyer, Weiner, 2009)

This idea can explain PAMELA, but has consequences for the CMB.

Planck will make a decisive test of whether Sommerfeld enhanced dark matter can explain the PAMELA (now AMS-02) positrons.

How to detect DM annihilation with the CMB:

The CMB originates at the time of "last scattering," when the Universe first becomes transparent.
($z \approx 1100 \quad t \approx 380{,}000$ yr)

WIMP annihilation (or decay) can inject high-energy particles and photons into the gas at $z \sim 100$-1000.

This energy modifies the "recombination" history of the Universe (really, *ionization fraction* as a function of time).

The CMB power spectrum is sensitive to this change in the ionization history.

By measuring the CMB we can:

•Search for departures from the "standard recombination" scenario,

•Place limits on energy injection at z=100-1000,

•Translate these limits to exclusions in WIMP parameter space (e.g. the cross-section / mass plane, etc.)

Note that these results are quite robust -- we understand recombination and the CMB *quite well,* and the measurements are good and rapidly improving!

There is less “wiggle room” in CMB constraints at z=100-1000 than constraints based on e.g. annihilation in late-time halos.

Selected key papers:

2004: Chen & Kamionkowski - calculated effect of DM decay on recombination history. (to explain high tau in WMAP 1)

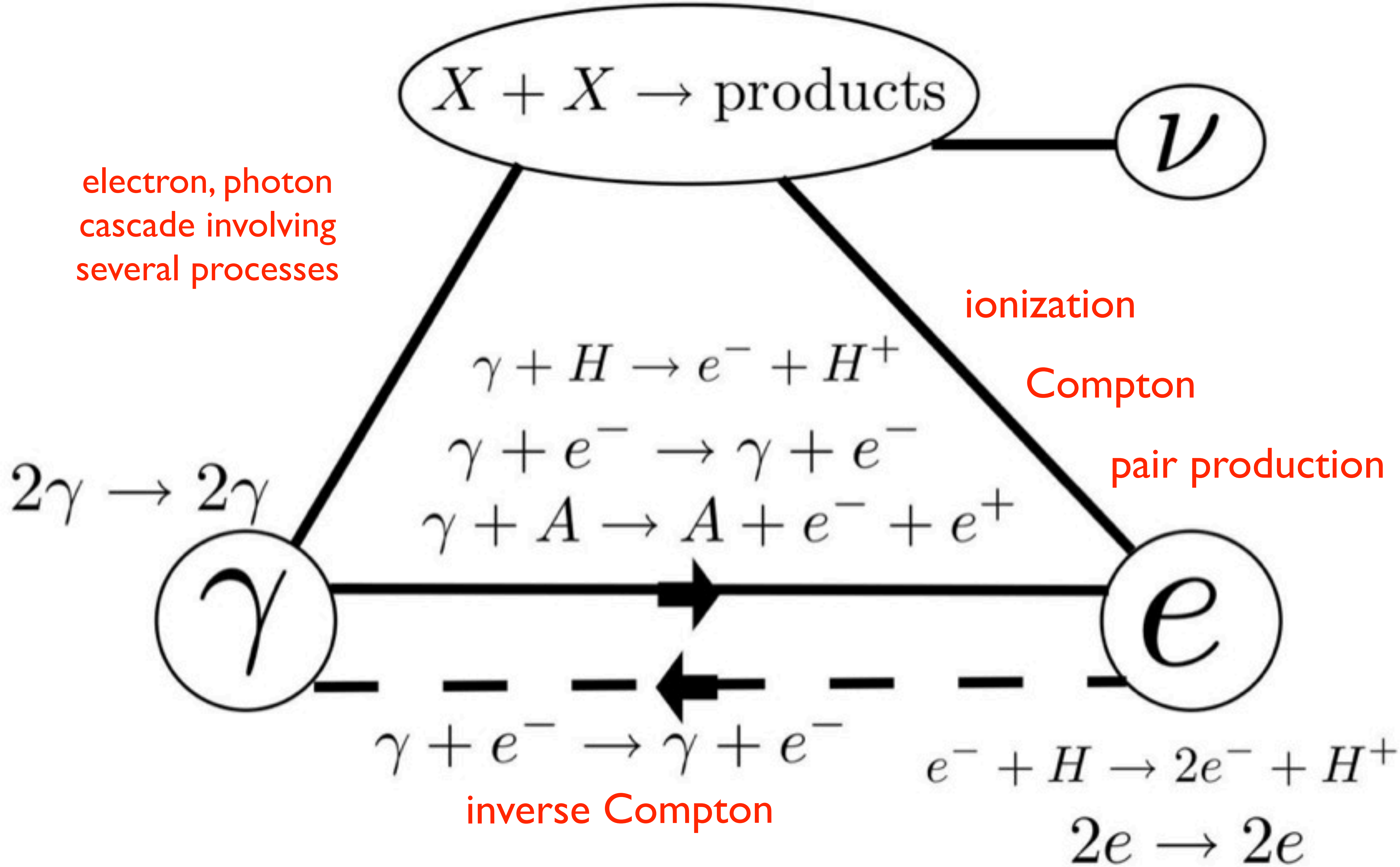
2005: Padmanabhan & Finkbeiner - repeated calculation for WIMP annihilation, obtained limits from WMAP.

2009: Galli, Iocco, Bertone, & Melchiorri - computed limits from WMAP 5 on Sommerfeld-enhanced DM.

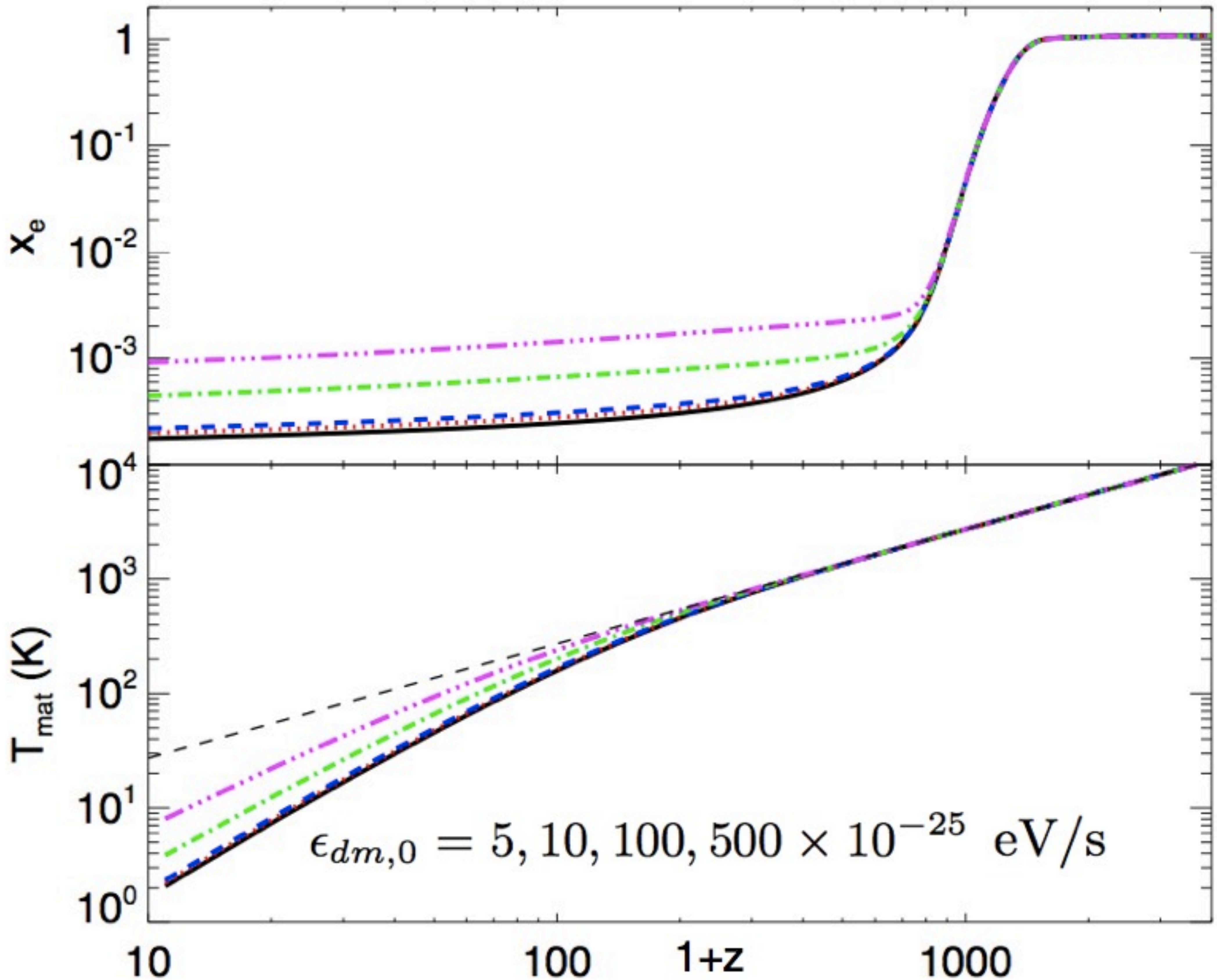
2009: Slatyer, Padmanabhan, & Finkbeiner - careful calculation of deposition efficiency of WIMP annihilation energy as a function of z, $f(z)$. Computed actual limits for 42 benchmark WIMP masses / annihilation channels.

2011: Finkbeiner, Galli, Lin, & Slatyer - introduce PCA formalism for robust model-independent constraints.

Annihilation produces photons, electrons, neutrinos

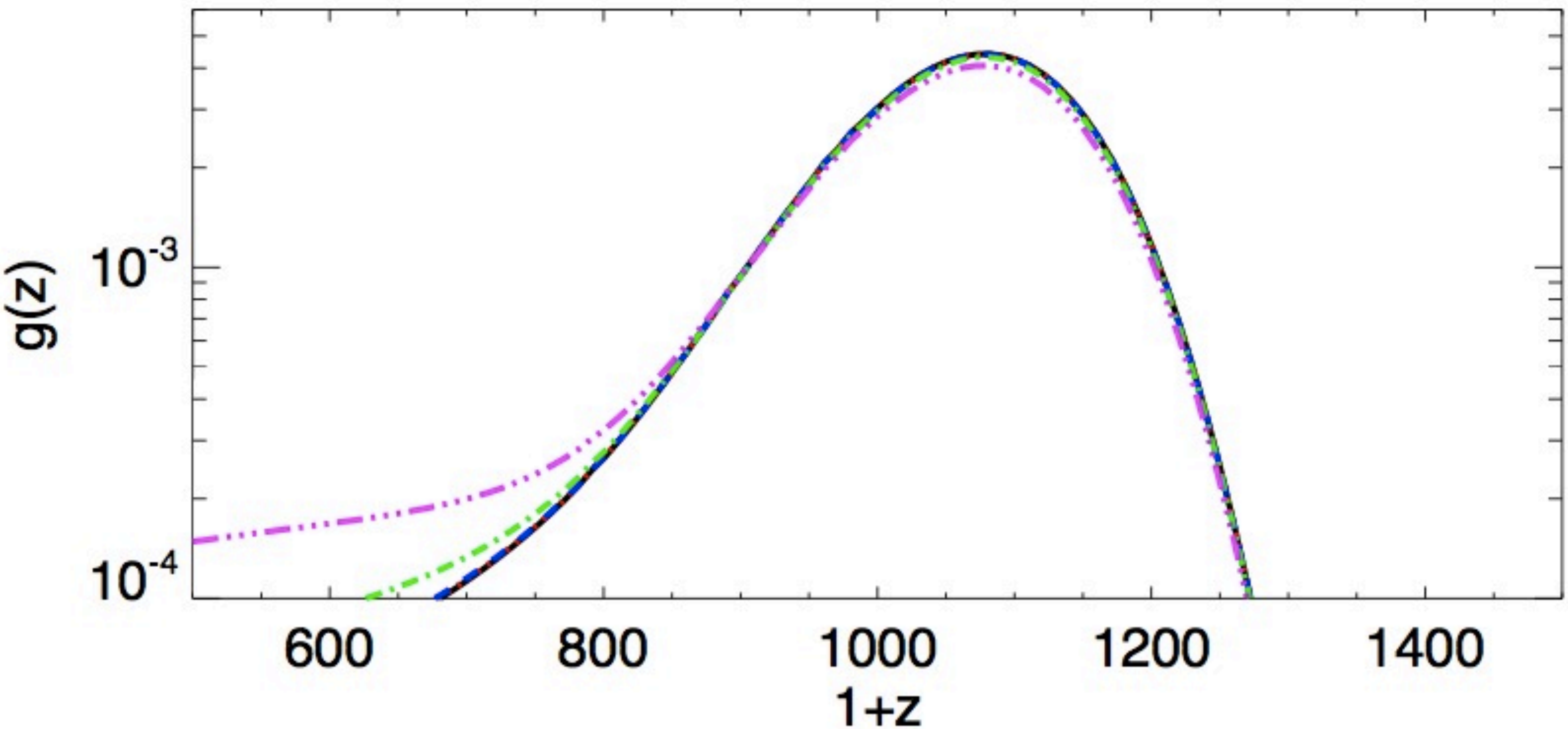


Ionization fraction (x_e) and gas temperature change...



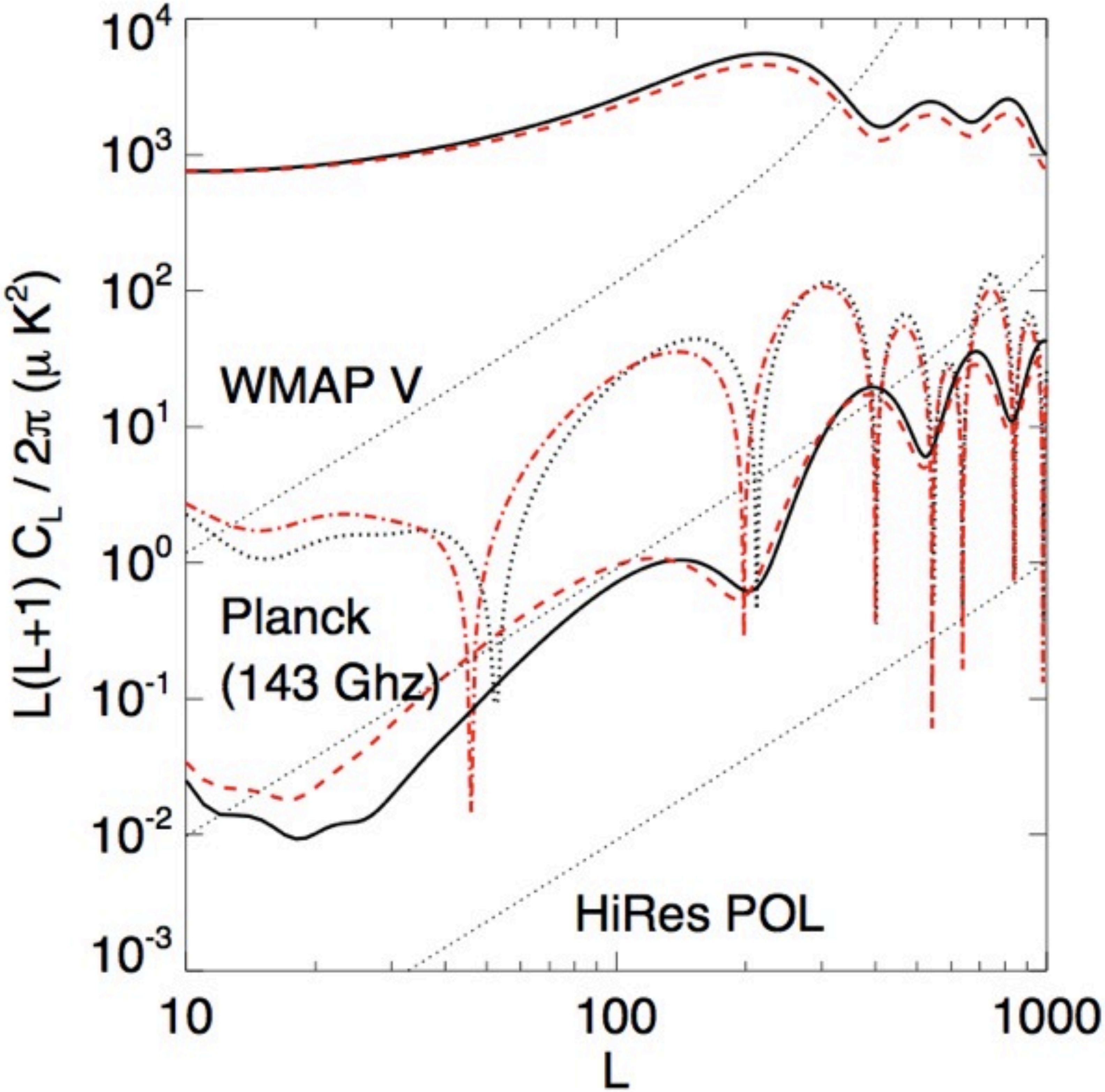
Padmanabhan & Finkbeiner (2005)

... and this changes the visibility function ...
(= the distribution function of the last scattering redshift of CMB photons)



Padmanabhan & Finkbeiner (2005)

... and increased scattering at z ~ 600 modifies the power spectrum.

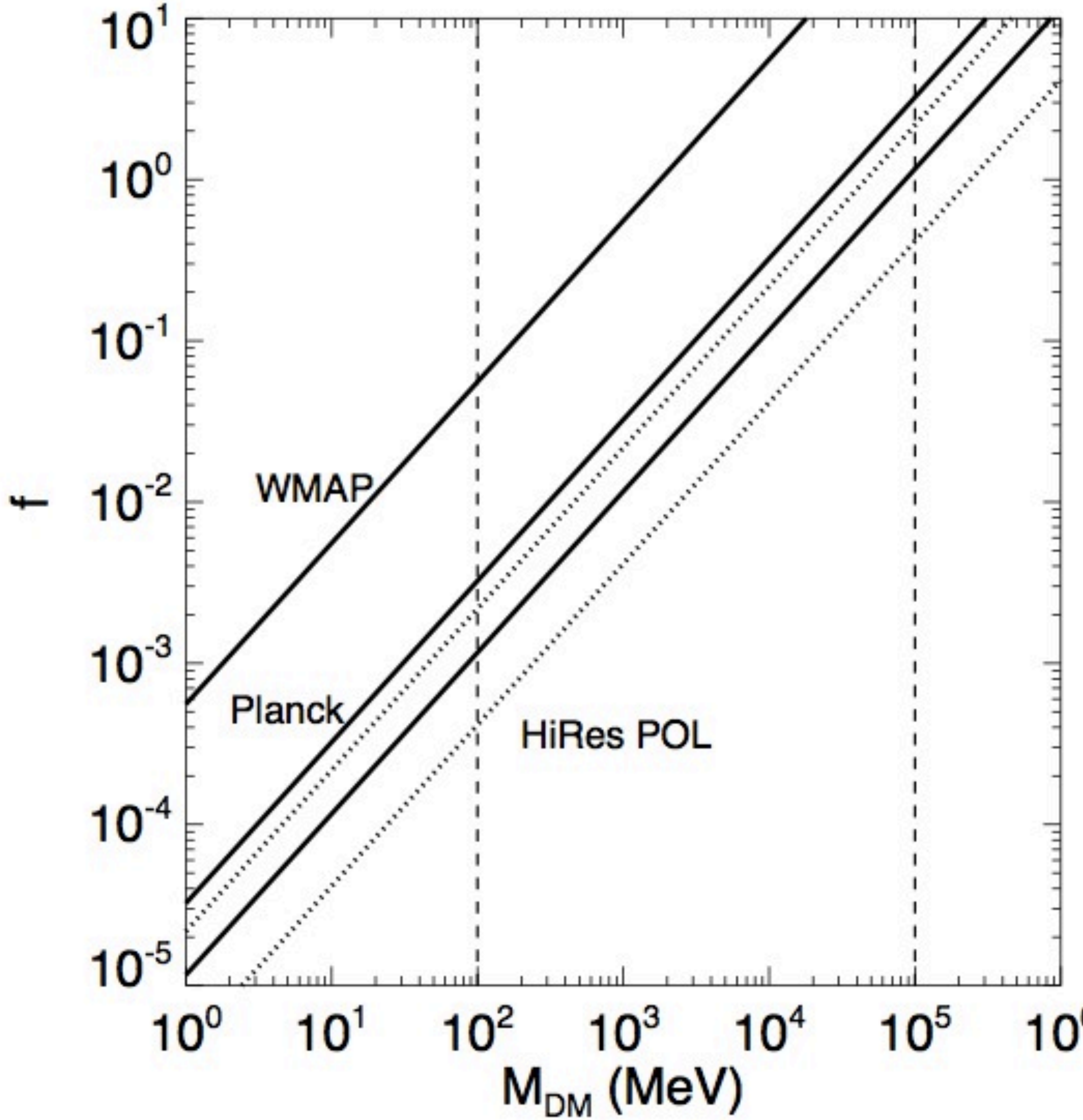


Padmanabhan & Finkbeiner (2005)

Constraints in f / M plane. (for thermal relic Xsec)

f is a “fudge factor” parameterizing energy deposition efficiency.

f =1 is “on the spot” approximation



Padmanabhan & Finkbeiner (2005)

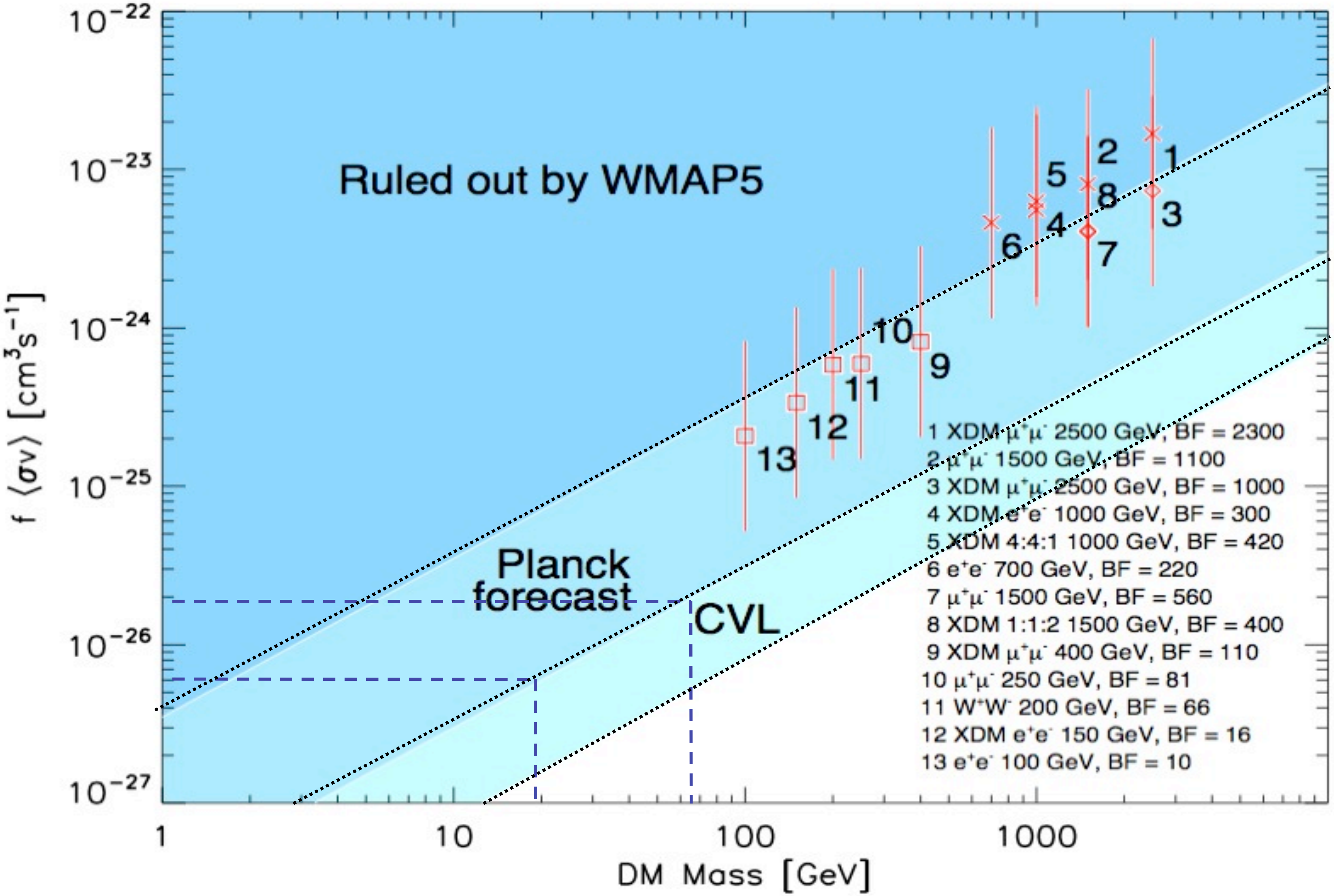
Cosmology

$$\left(\frac{dE}{dt\,dV}\right)_{\rm ann} = p_{\rm ann}(z)c^2\Omega^2_{\rm DM}\rho^2_c(1+z)^6$$

$$p_{\rm ann} = f(z)\langle\sigma v\rangle/m_{\rm DM}$$

Dark matter model

Benchmark models that fit PAMELA and AMS-02



From Slatyer, Padmanabhan, DF (2009), modeled on Galli+ (2009)

Note that the PAMELA - constrained models fall along the edge of the ruled-out region.

They all have ~ the same injection power. The CMB is approximately sensitive to injection power.

>> There must be a more general way to do this!

Preparing for Planck:
with Galli, Lin, & Slatyer (2011)

Idea: The energy injection is already constrained to be small, so we can linearize the problem and perturb about a fiducial model, i.e. the standard cosmology with no extra energy injection.

Various energy injection functions, *f(z)*, perturb the C_l spectrum in a small dimension subspace, allowing us to describe arbitrary (smooth, non-negative) energy injection with only a few numbers.

We can work out degeneracies, detectability, etc., by considering a few generic parameters.

Preparing for Planck:

This is a rich story if you want to consider all possible energy injection scenarios. However, for a wide range of WIMP models (like the 42 we considered in SPF09) there is only one relevant degree of freedom.

I.e. a single parameter describes the observable effect of WIMP annihilation on the CMB. Measure that parameter, and that's all you will ever get!

Planck has not yet released their polarization map, but when they do, we will get an answer quickly, and either detect this effect or rule out Sommerfeld-enhanced DM as the explanation for PAMELA/AMS-02 positrons.

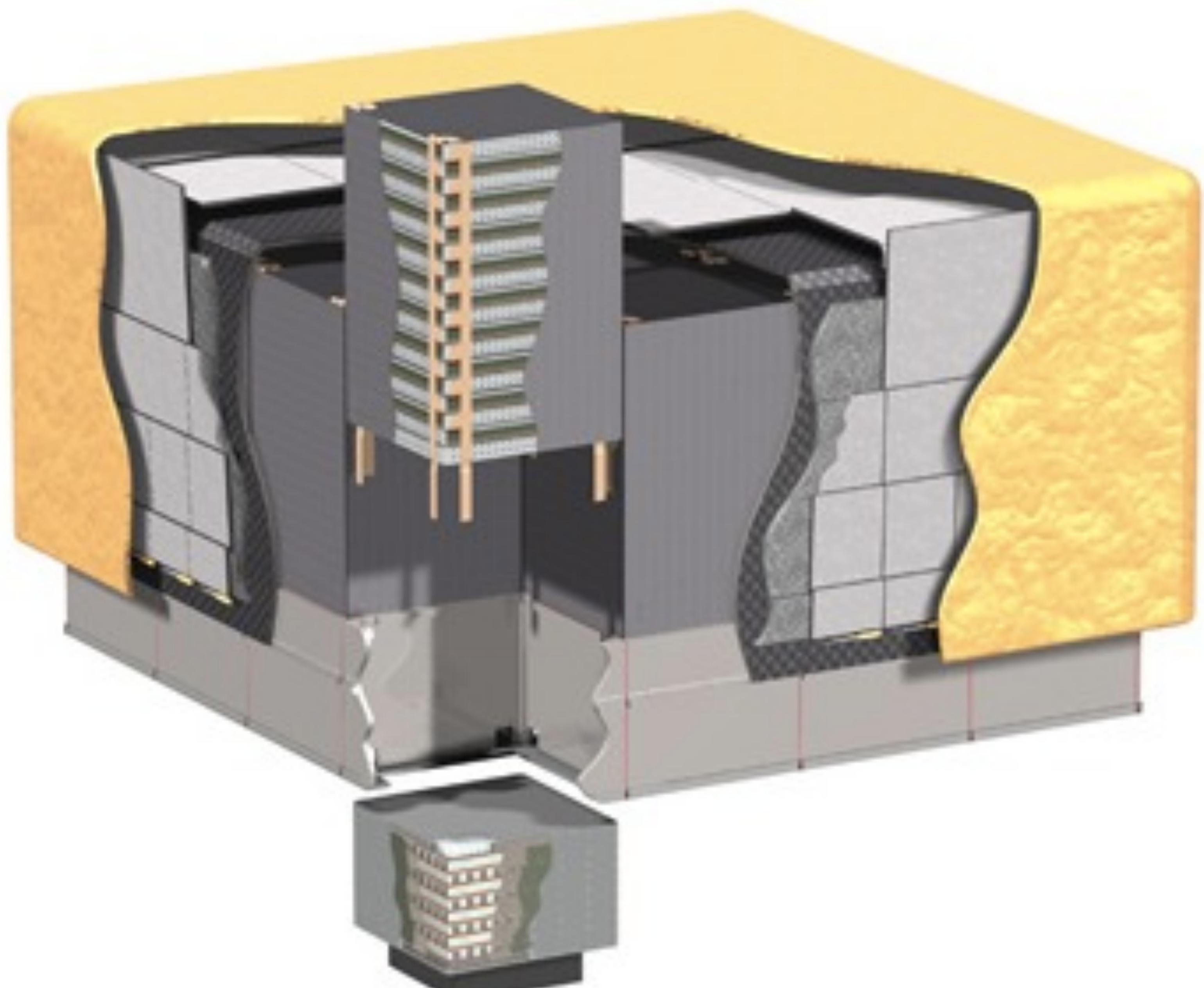
Fermi 130 GeV feature

3 papers by Su & Finkbeiner and Finkbeiner, Su, & Weniger on the arXiv...

The Fermi Large Area Telescope (LAT)

- Large FOV (2 sr)
- Scans the whole sky in two orbits
- Already has 4 years of data, mission extended to 2016
- Continual (daily) data release
- Pair-conversion telescope

A pair-conversion telescope converts a photon to e+e- and then tracks the particles through tracker layers to an imaging calorimeter.



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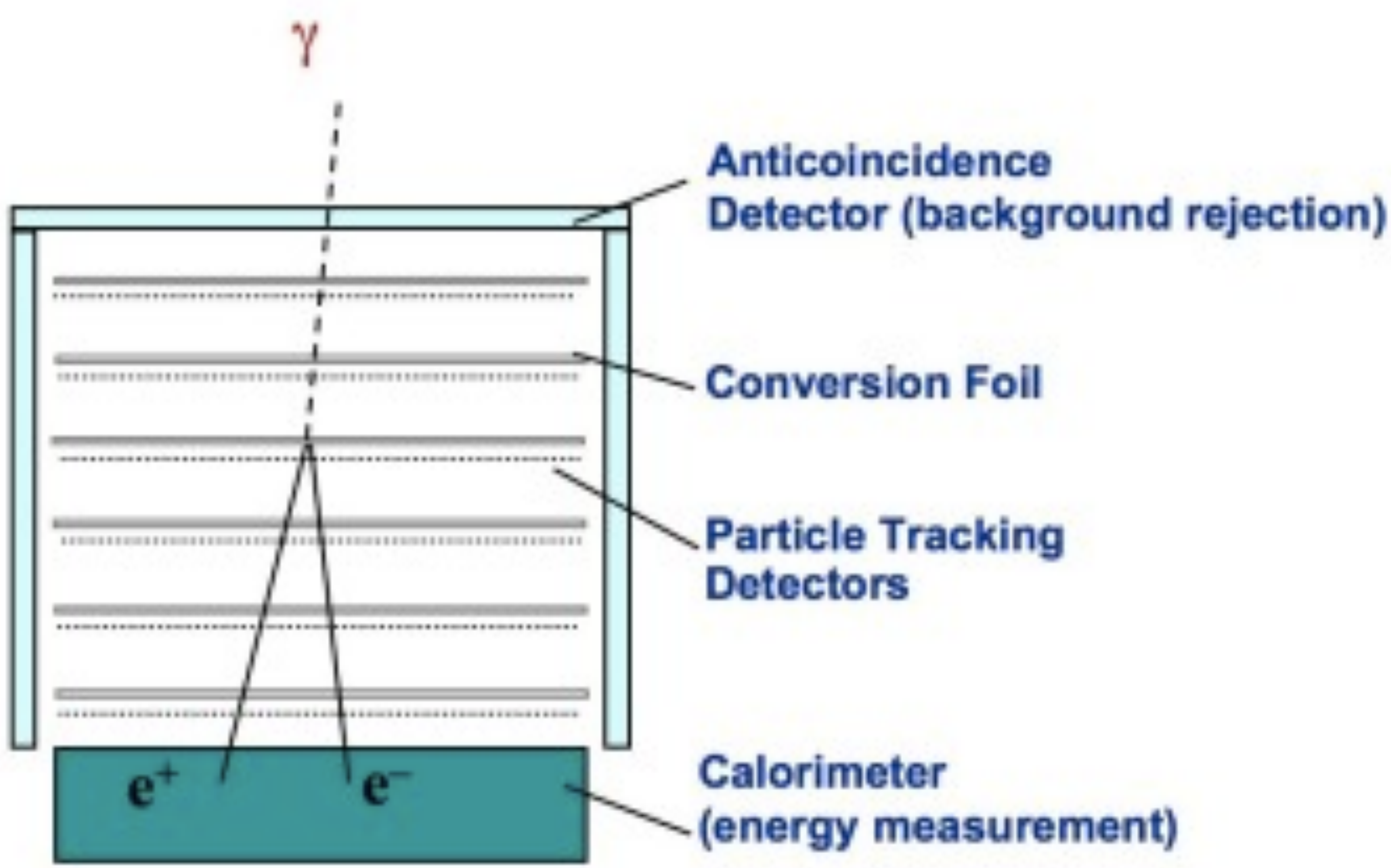
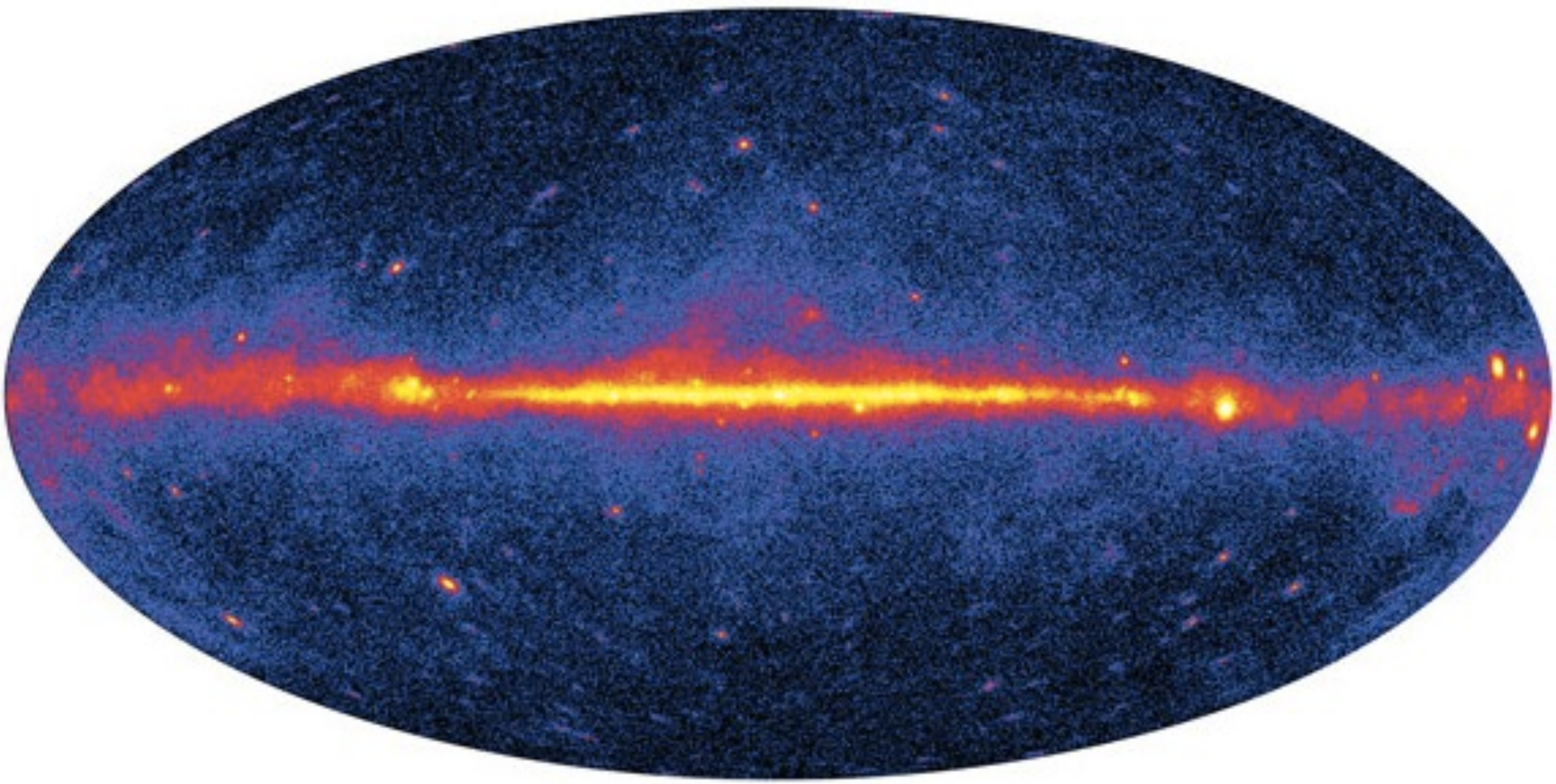


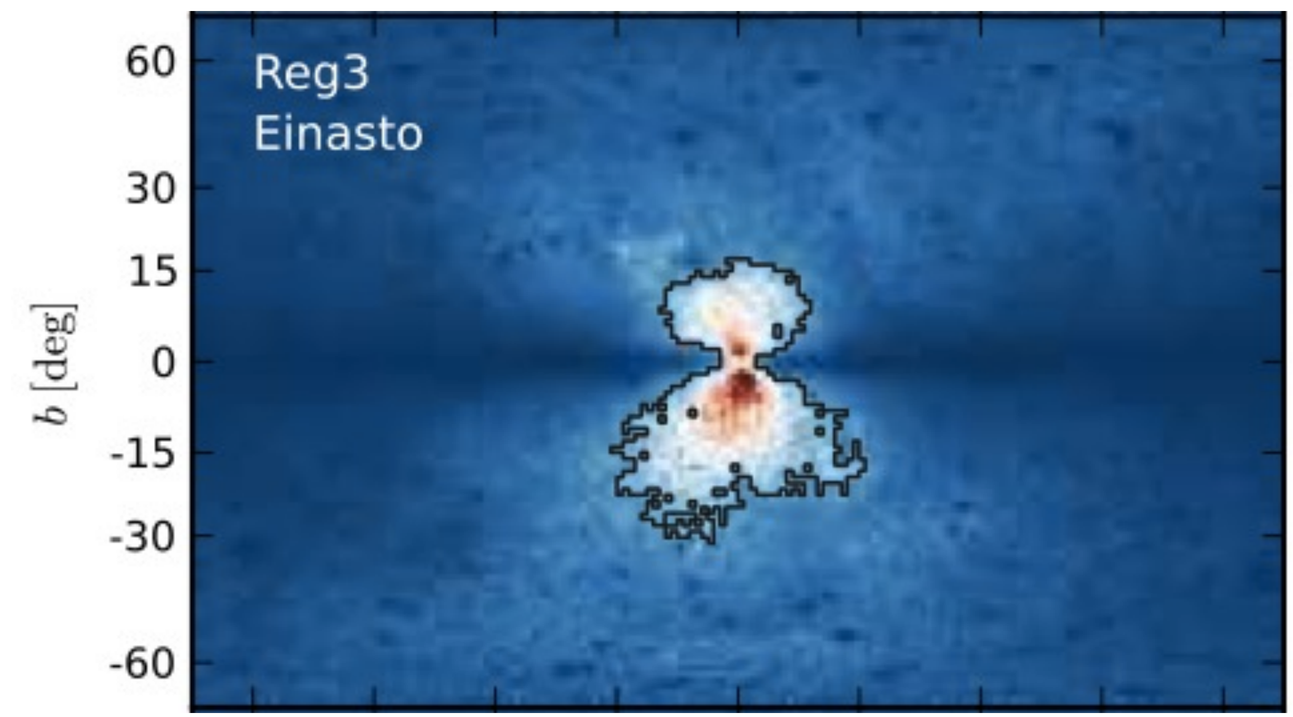
We accumulate photon events and bin them to make a map:

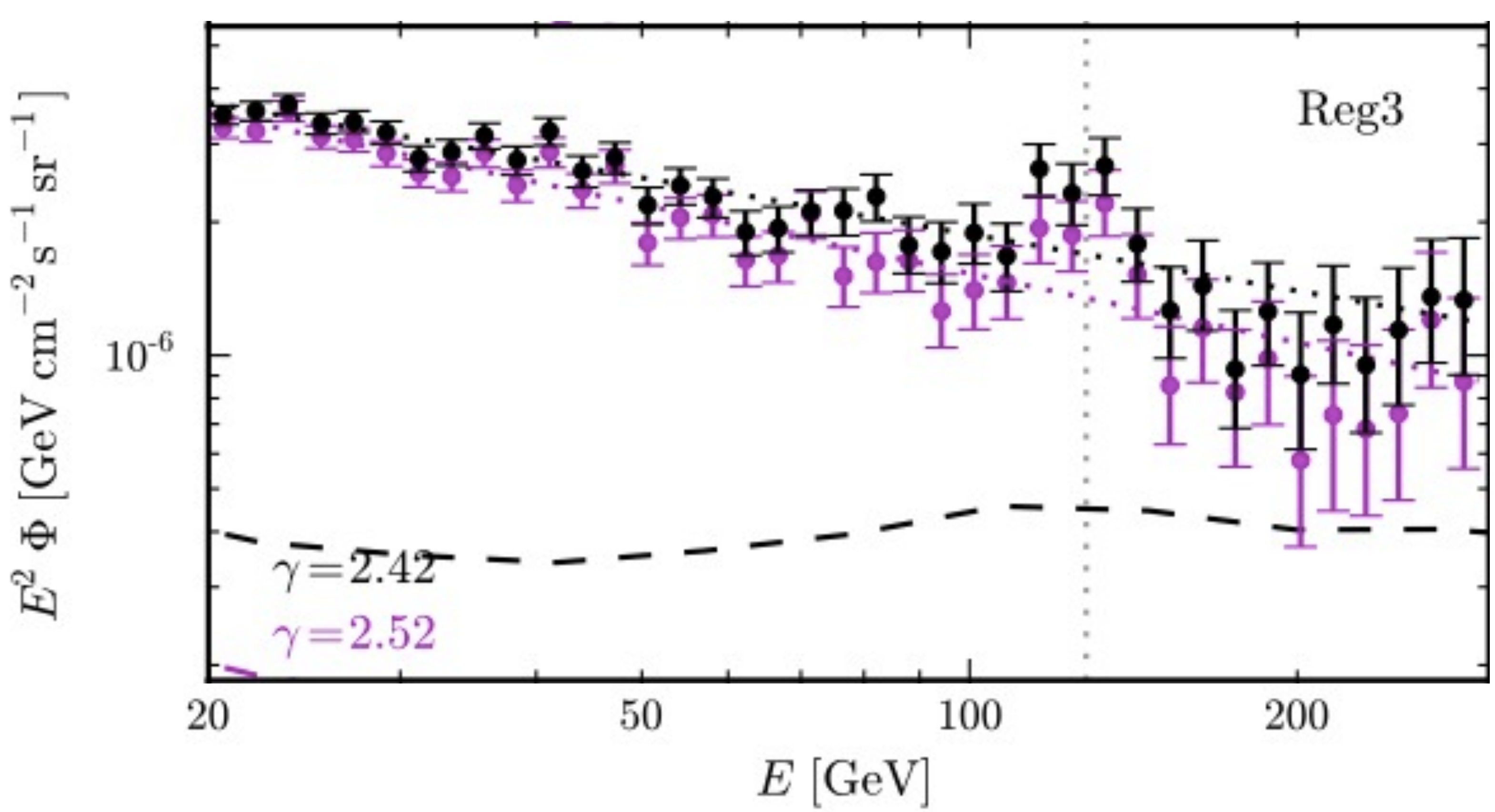


Looking for dark matter

- First suggestion of a line at 130 GeV by Weniger (2012)
- Discuss our approach (Su & Finkbeiner 2012)

Weniger (2012)





Timeline of 130 GeV line:

- 12 April - Weniger (looks like a line at 130 GeV)
- 26 April - Profumo & Linden (is it the Fermi bubbles?)
- 10 May - Tempel et al., (No, it's not a bubble, could be DM)
- 21 May - Boyarsky (lots of blobs, probably not DM)
- 25 May - Acharya, Kane... (It's a Wino)
- 29 May - Bergstrom (reviews claims as part of larger review)
- 30 May - Jim Cline (two lines)
- 30 May - Buckley & Hooper (theoretical models)
- 5 June - Geringer-Sameth & Koushiappas (Line search in dwarfs)
- 7 June - Su & Finkbeiner (Off center 1.5 deg, Einasto, 6.5 sigma, use high energy-resolution events)
- 13 June - Weiner & Yavin (MiDM explains it)
- (*As of today, Weniger has 155 citations*)

A simple test: consider linear combinations of maps

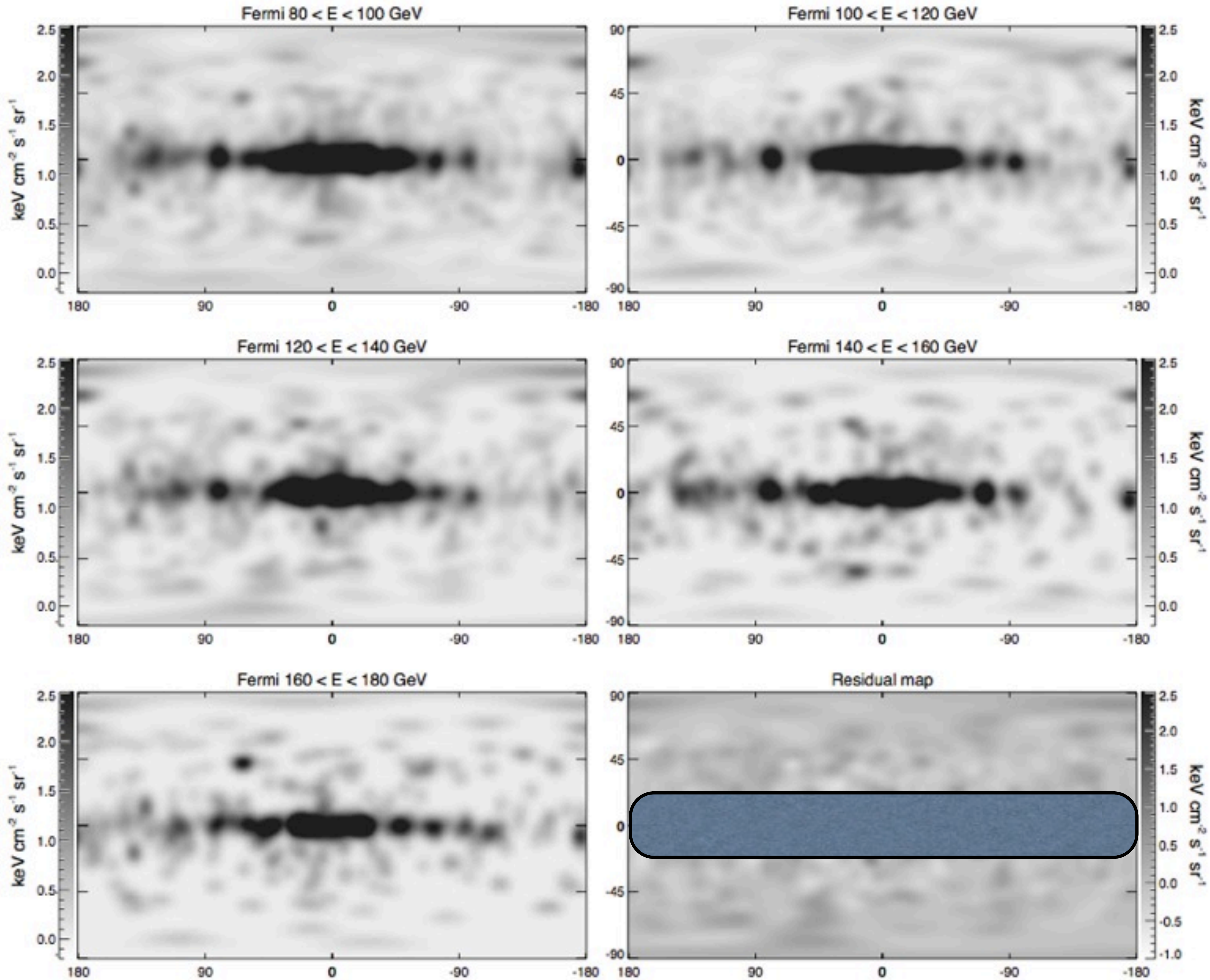


FIG. 3.— All-sky CLEAN 3.7 year maps in 5 energy bins, and a residual map (*lower right*). The residual map is the 120 – 140 GeV map minus a background estimate, taken to be the average of the other 4 maps where the average is computed in $E^2 dN/dE$ units. This simple

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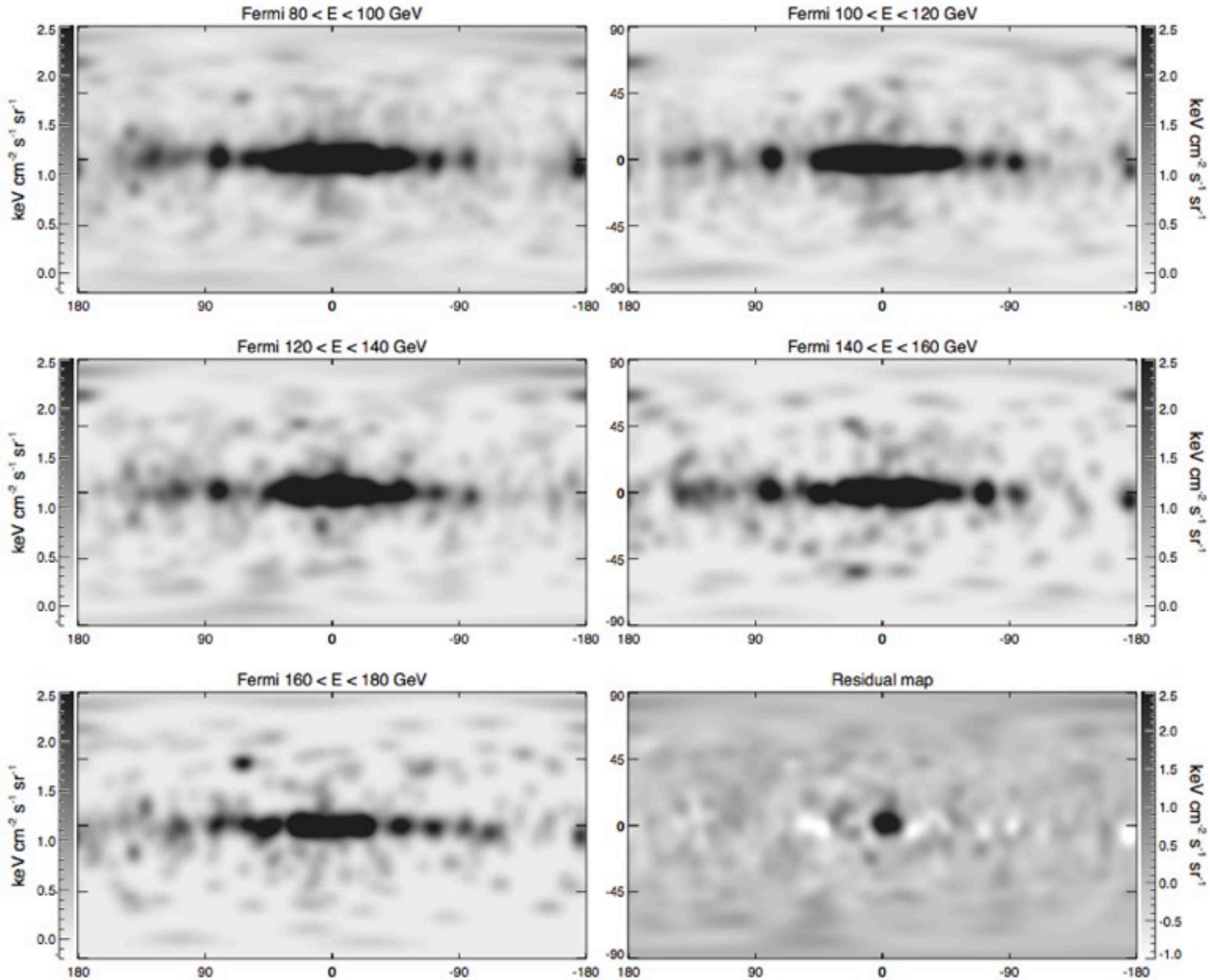
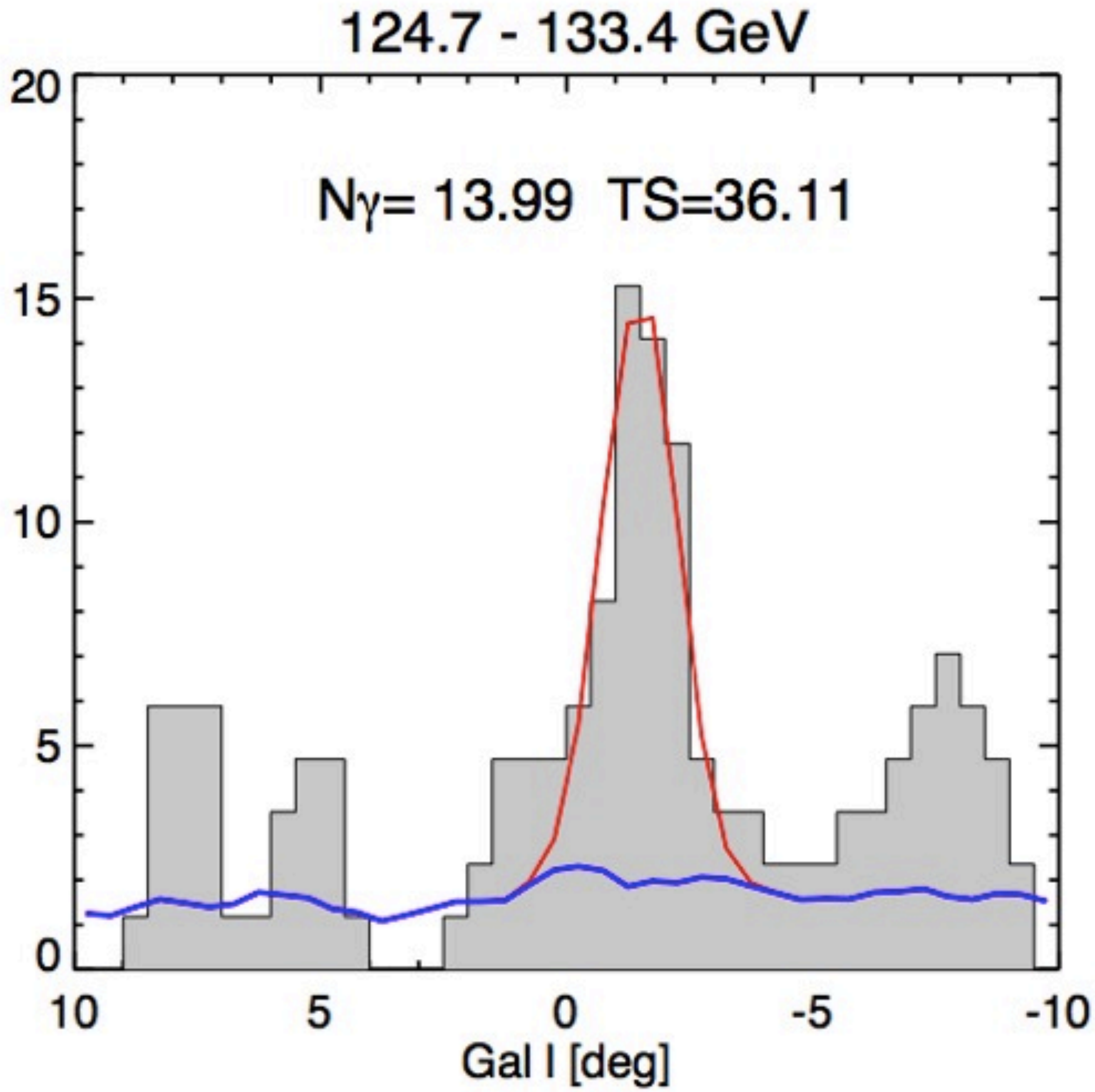


FIG. 3.— All-sky CLEAN 3.7 year maps in 5 energy bins, and a residual map (*lower right*). The residual map is the 120 – 140 GeV map minus a background estimate, taken to be the average of the other 4 maps where the average is computed in E^2dN/dE units. This simple



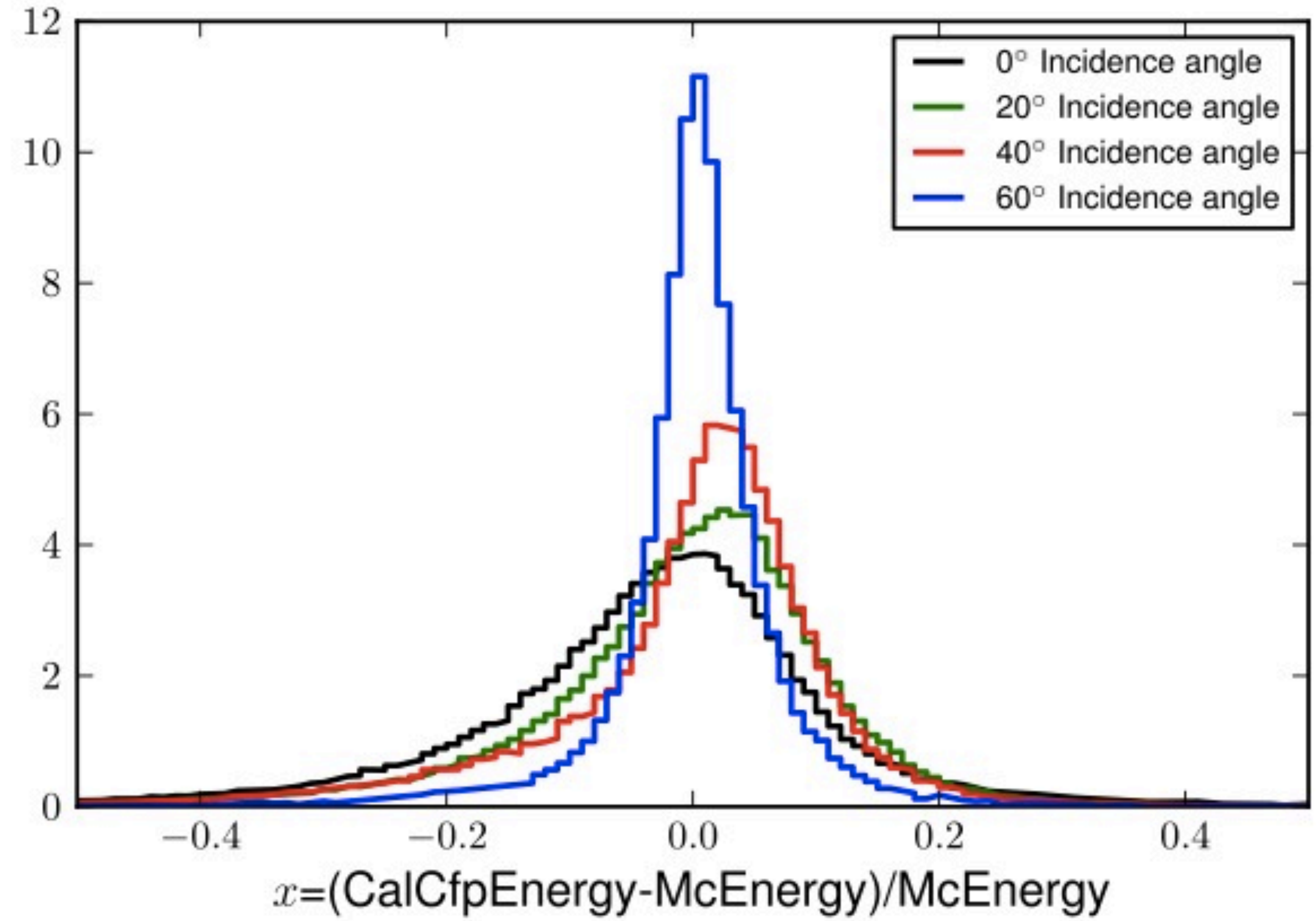
There is a bump... but offset by 1.5 deg in longitude. TS=36, which naively implies 6.0 sigma. Allowing for 3 new d.o.f., 5.25 sigma.

We can do better than this. The energy resolution of Fermi-LAT depends on incidence angle.

Events with higher incidence angle (> 40)

- have longer path length inside the calorimeter, and therefore
- have better energy resolution (factor of ~ 2 better)

100 GeV line shape at various incidence angles

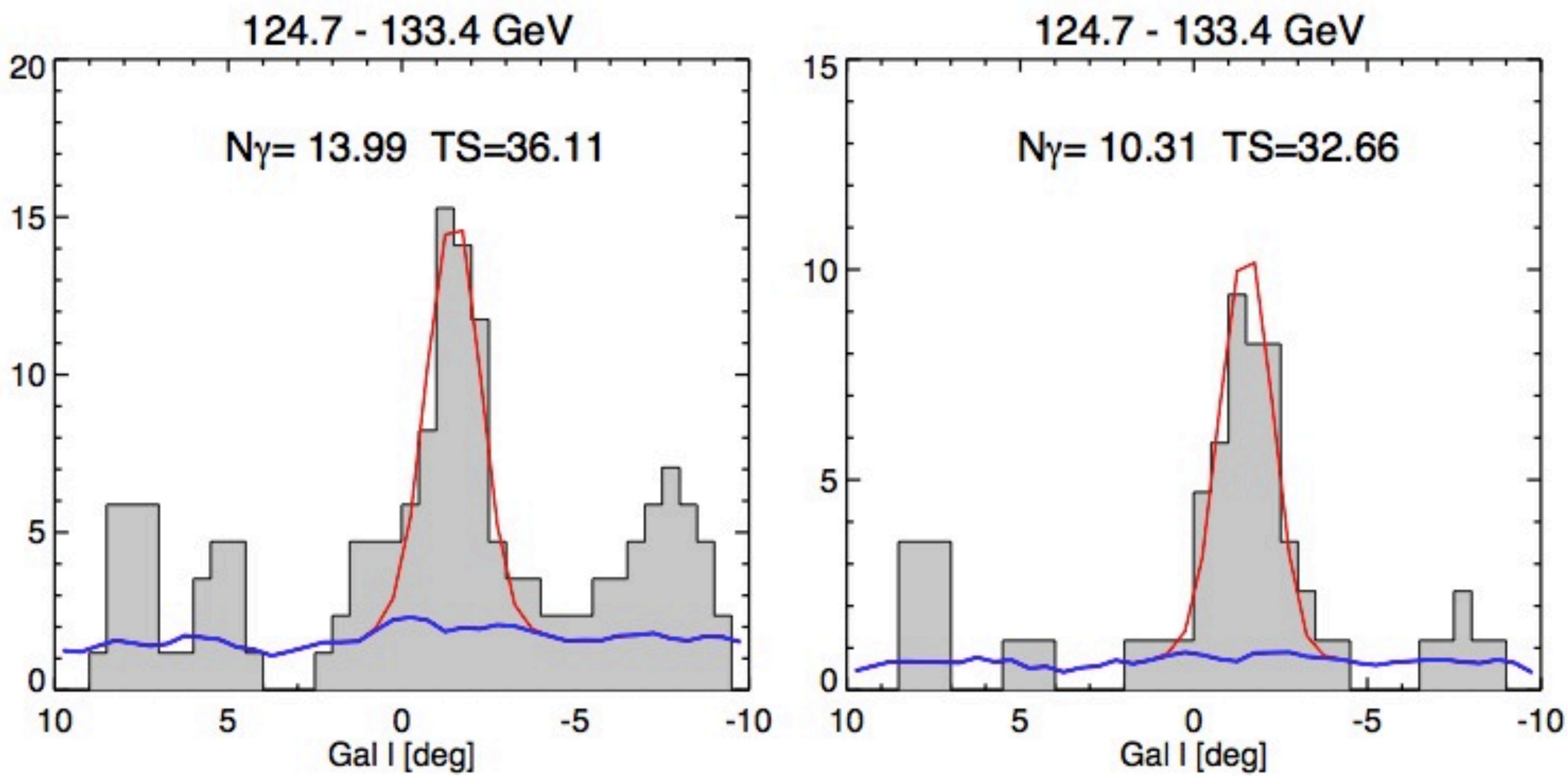


(a) Energy dispersion for MC 100 GeV spectral line at inclination of angles of 0°, 20°, 40°, and 60°. The histograms are normalized to an area of one

Y. Edmonds (thesis, 2011)

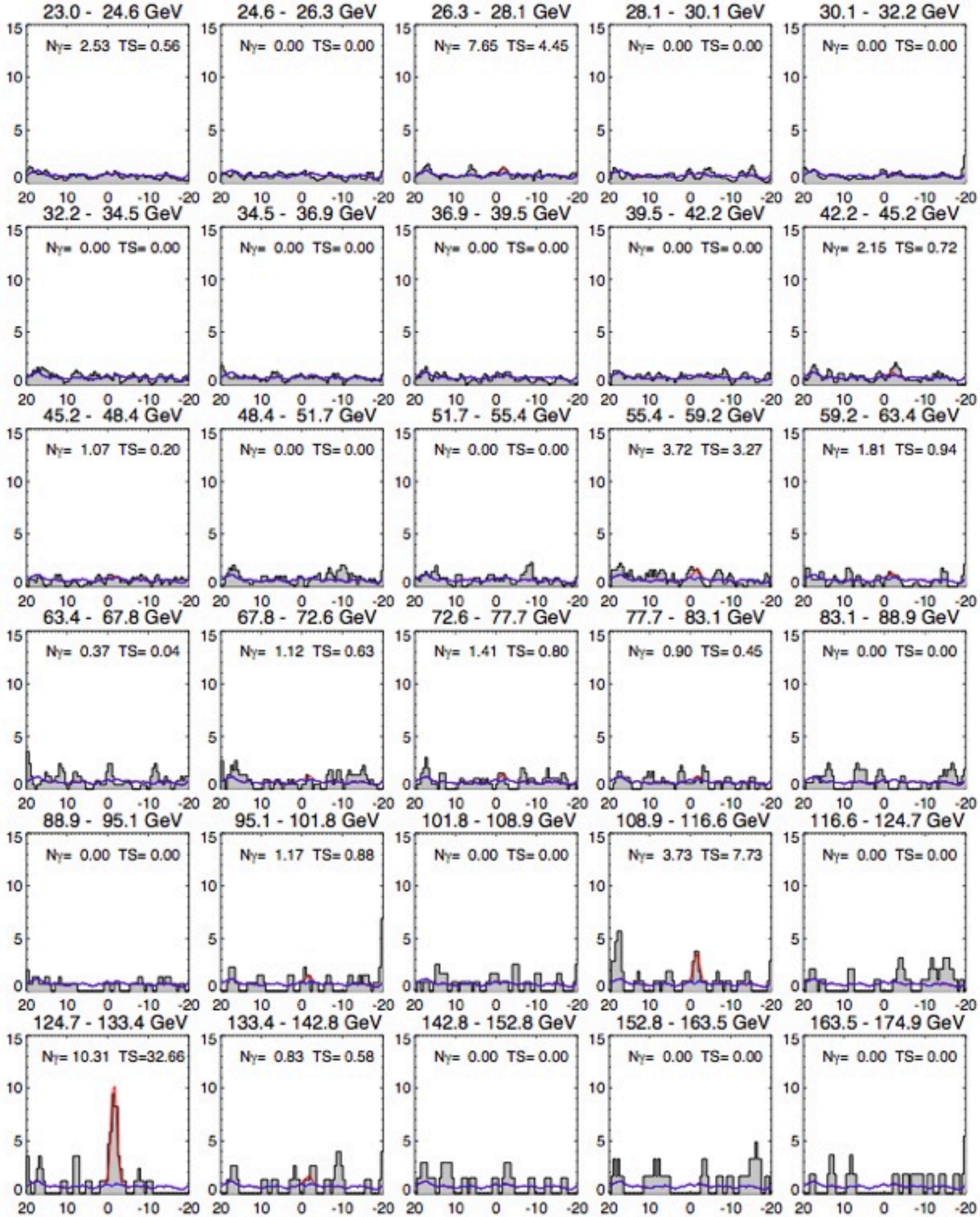
If we select events with better energy resolution, background is reduced.

Half as much data, almost the same significance!

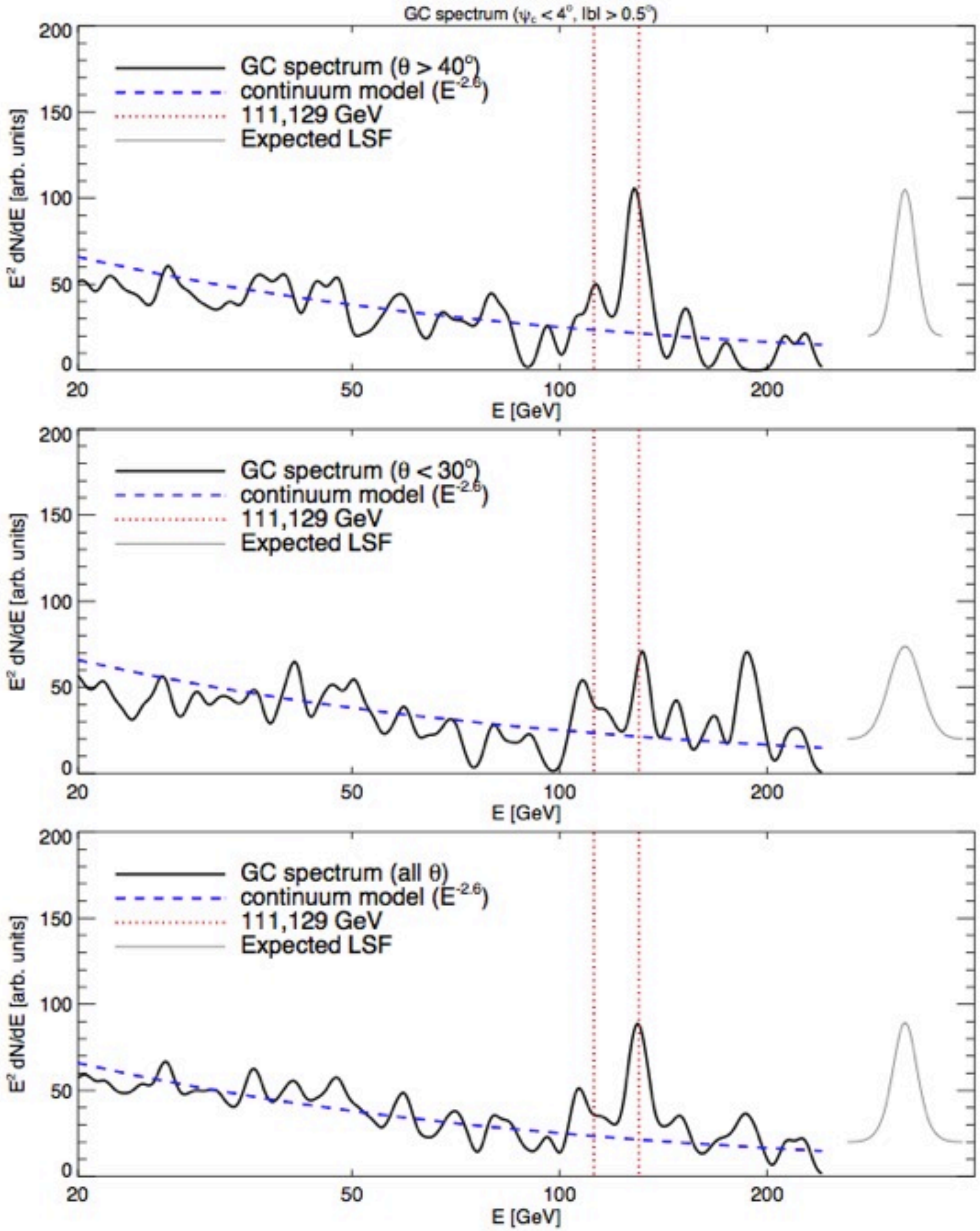


Background model generated by averaging 10-50 GeV assuming $dN/dE \sim E^{-2.6}$

See feature at 127 GeV, insignificant one at 113 GeV

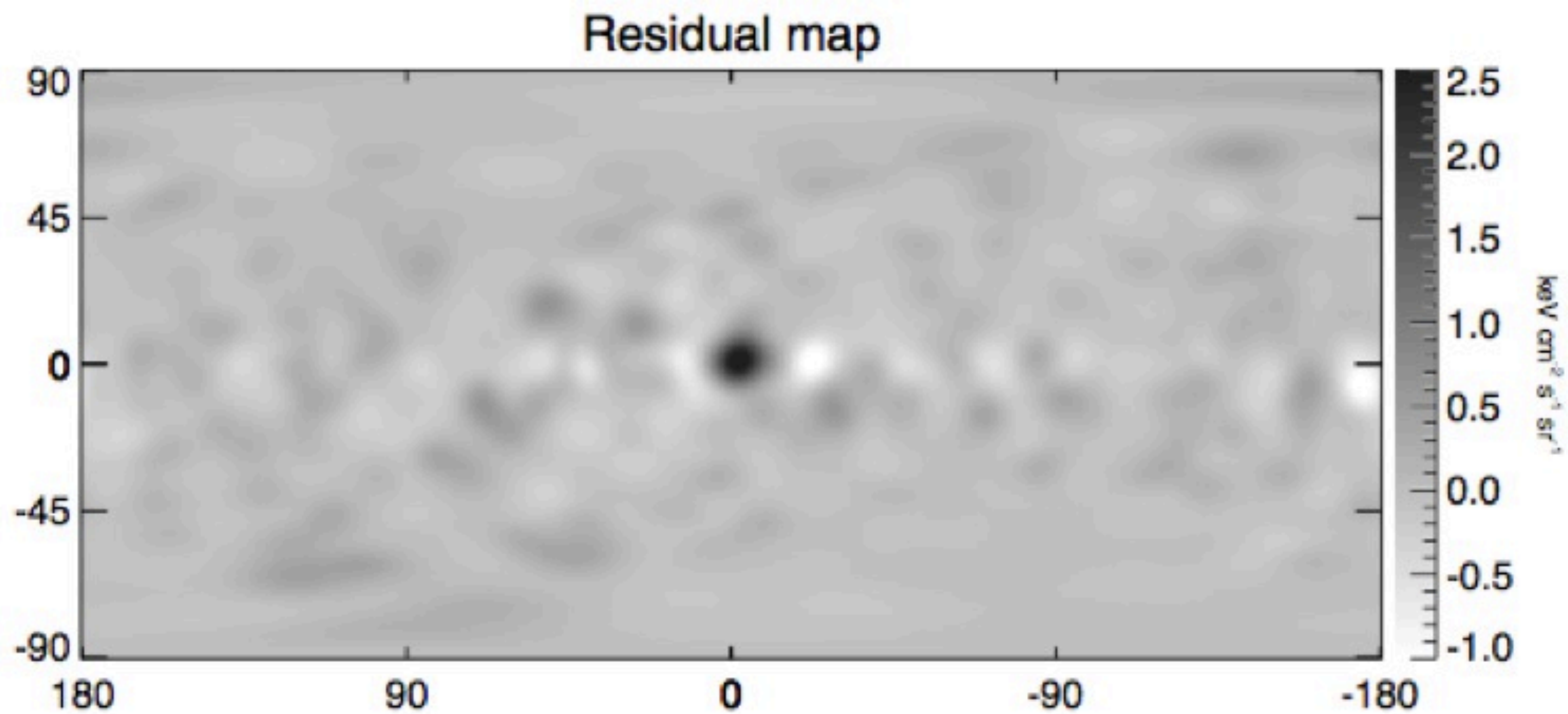


Now, what about the energy spectrum?



It looks more significant for events with better energy resolution, as it should for a true line signal.

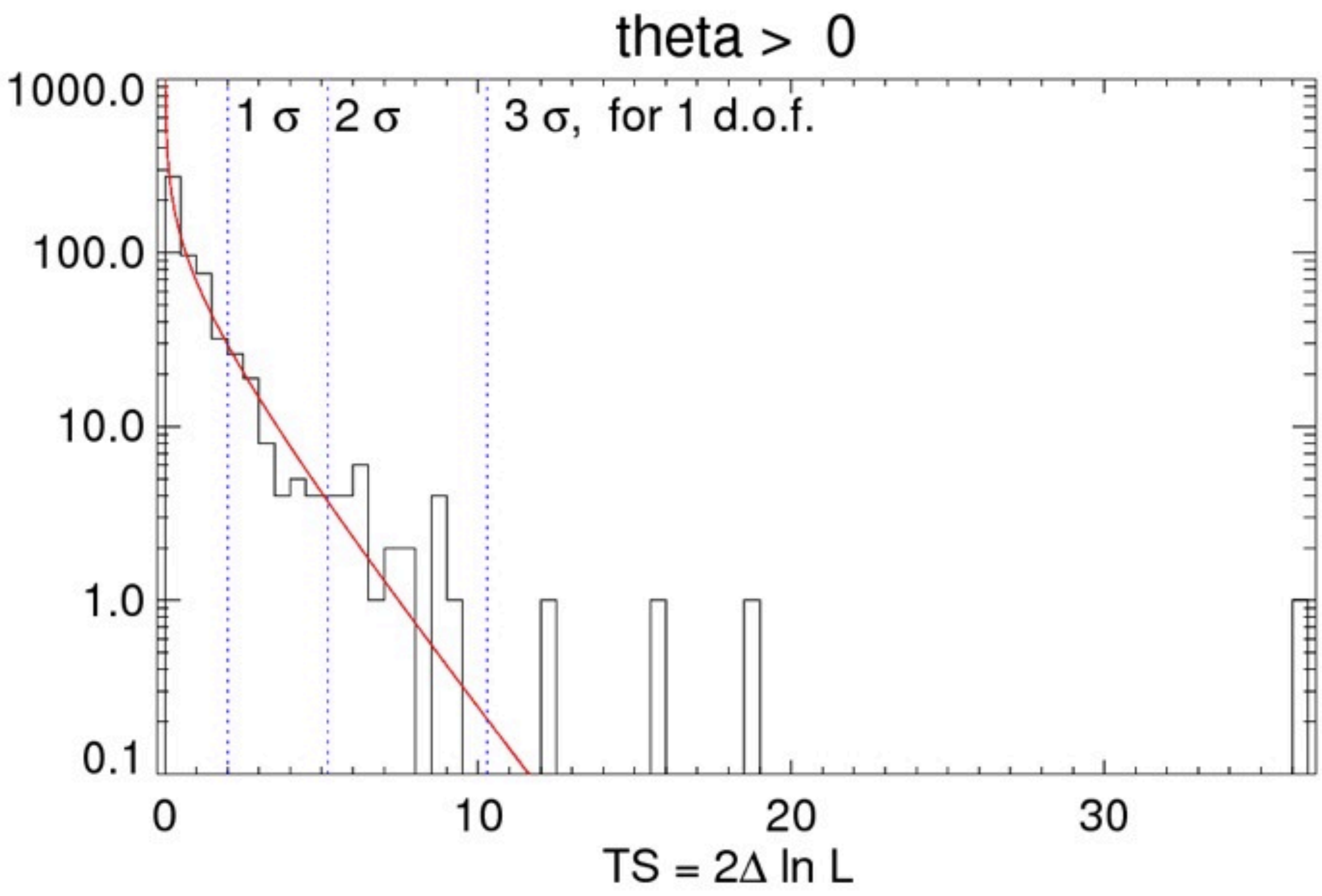
Residual map even looks better with the subsample of events:



Many papers on this topic are based on sloppy statistics. How to check that we have assessed the significance correctly?

We fit the amplitude of Gaussians at 1 deg intervals from -18.5 to +18.5 in longitude, and in 30 energy bins (so, > 1000 trials) and look at the TS distribution.

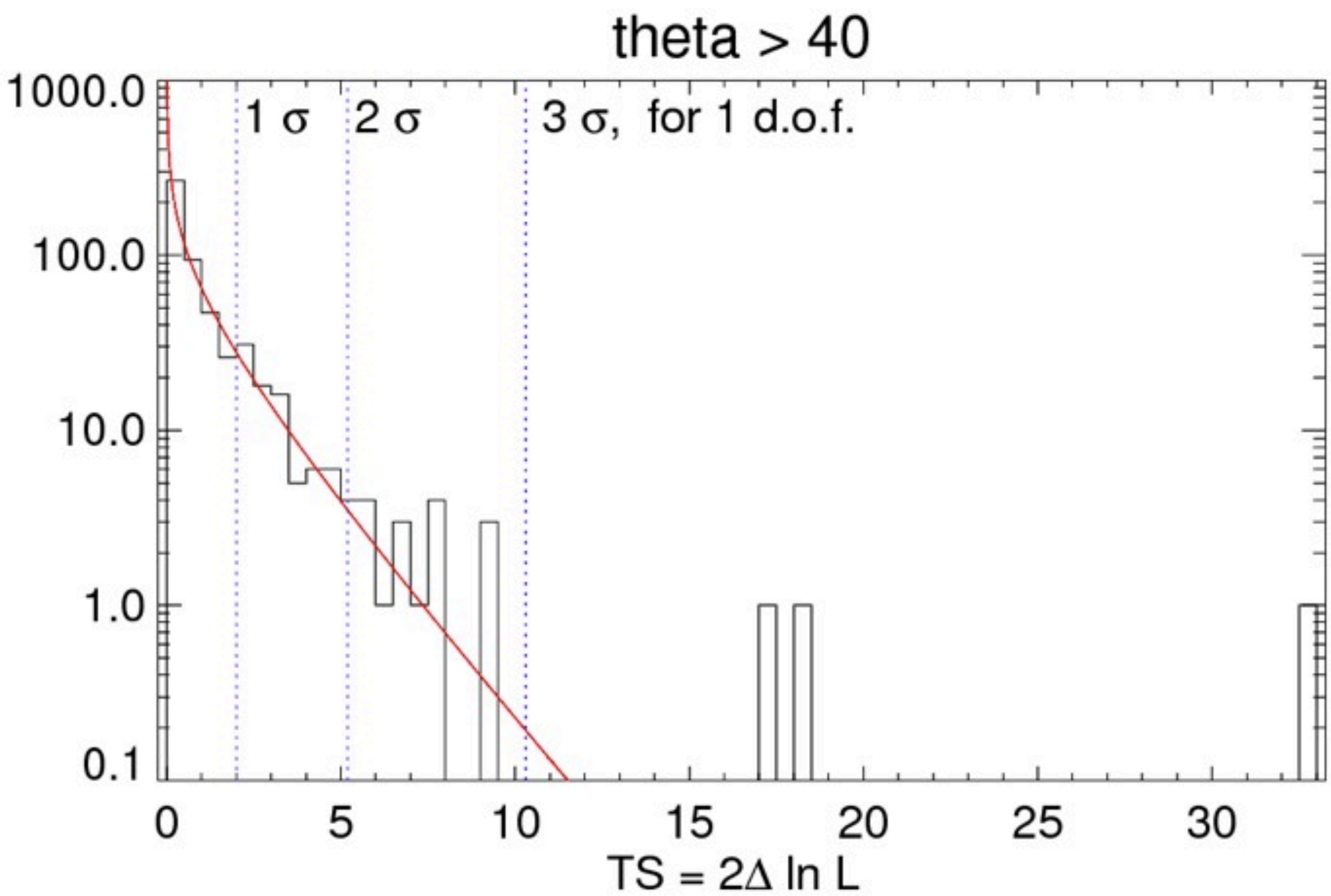
Is the TS distribution what we would expect?



TS	long.	E
36.11	-1.5	129.1
18.81	-2.5	129.1
15.94	-0.5	129.1
12.31	18.5	112.7
9.44	-15.5	86.0
8.94	-7.5	129.1

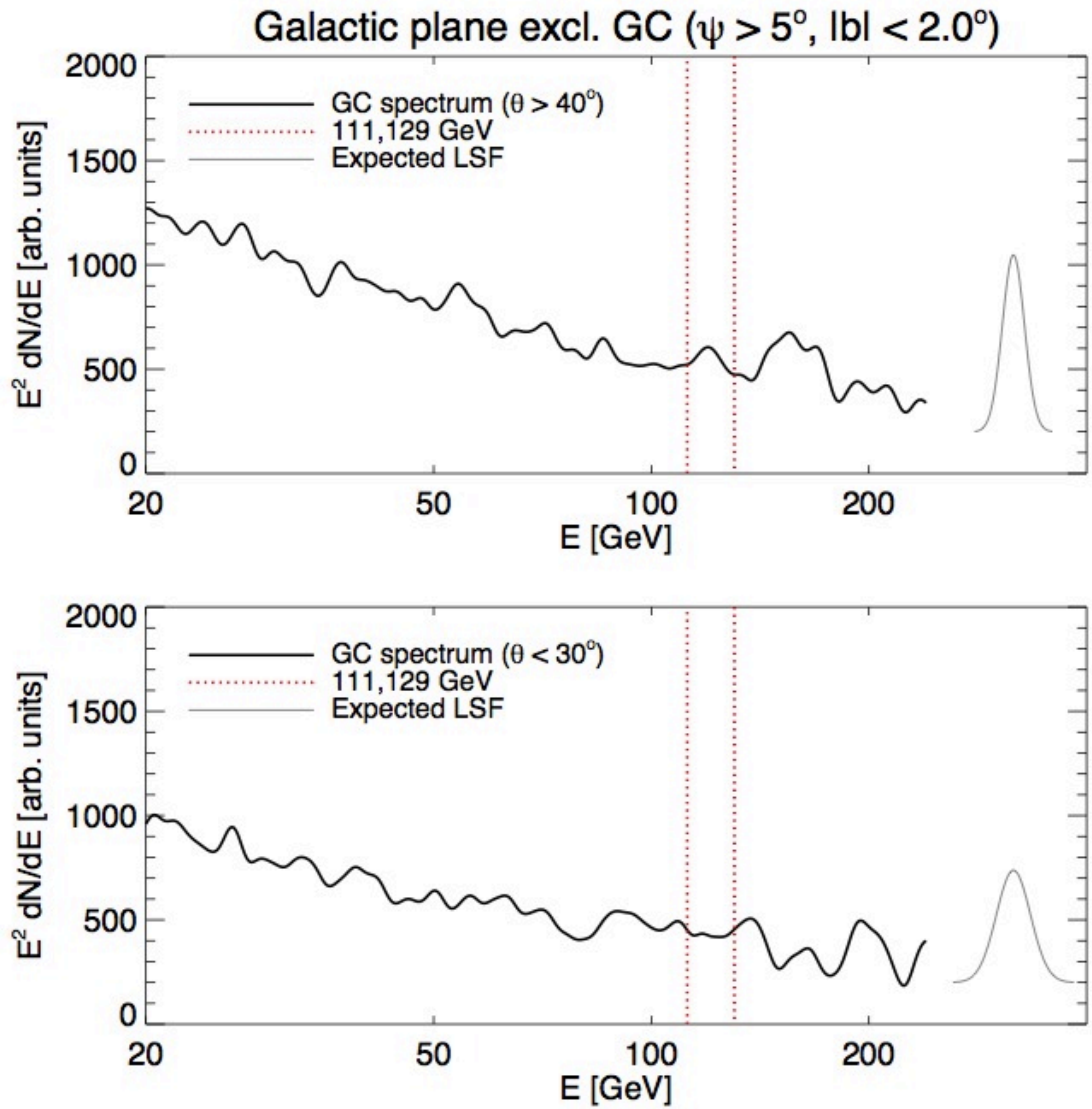
...etc.

Is the TS distribution what we would expect?

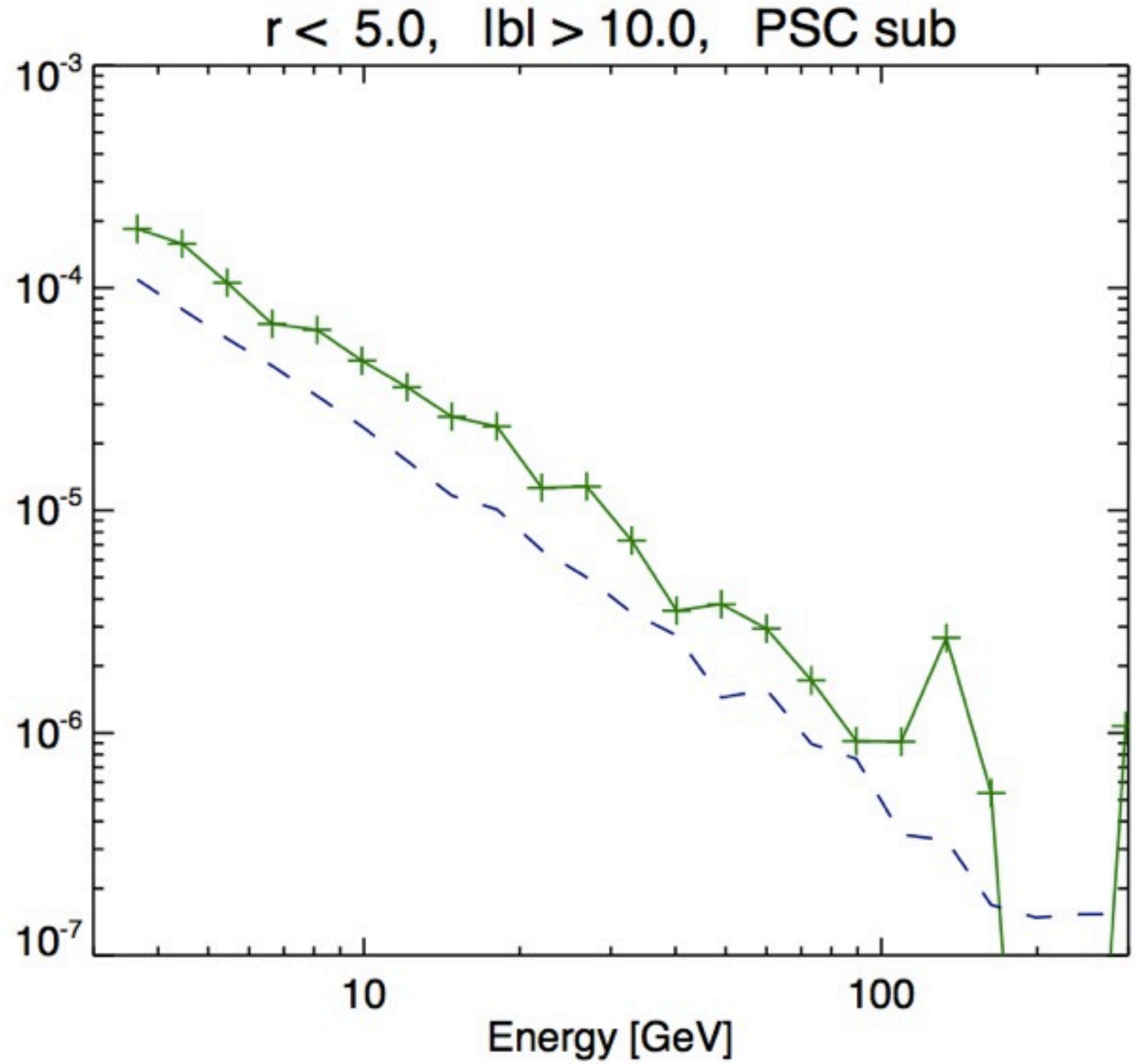


TS	long.	E
32.66	-1.5	129.1
18.24	-2.5	129.1
17.45	-0.5	129.1
9.43	-11.5	65.6
9.41	17.5	112.7
7.77	18.5	112.7
7.73	-1.5	112.7
7.73	-16.5	158.1

Tests: We *do not* see the signal elsewhere in the Galactic plane:



Recent news -- 130 GeV photons from near the Sun (see Whiteson 2013)

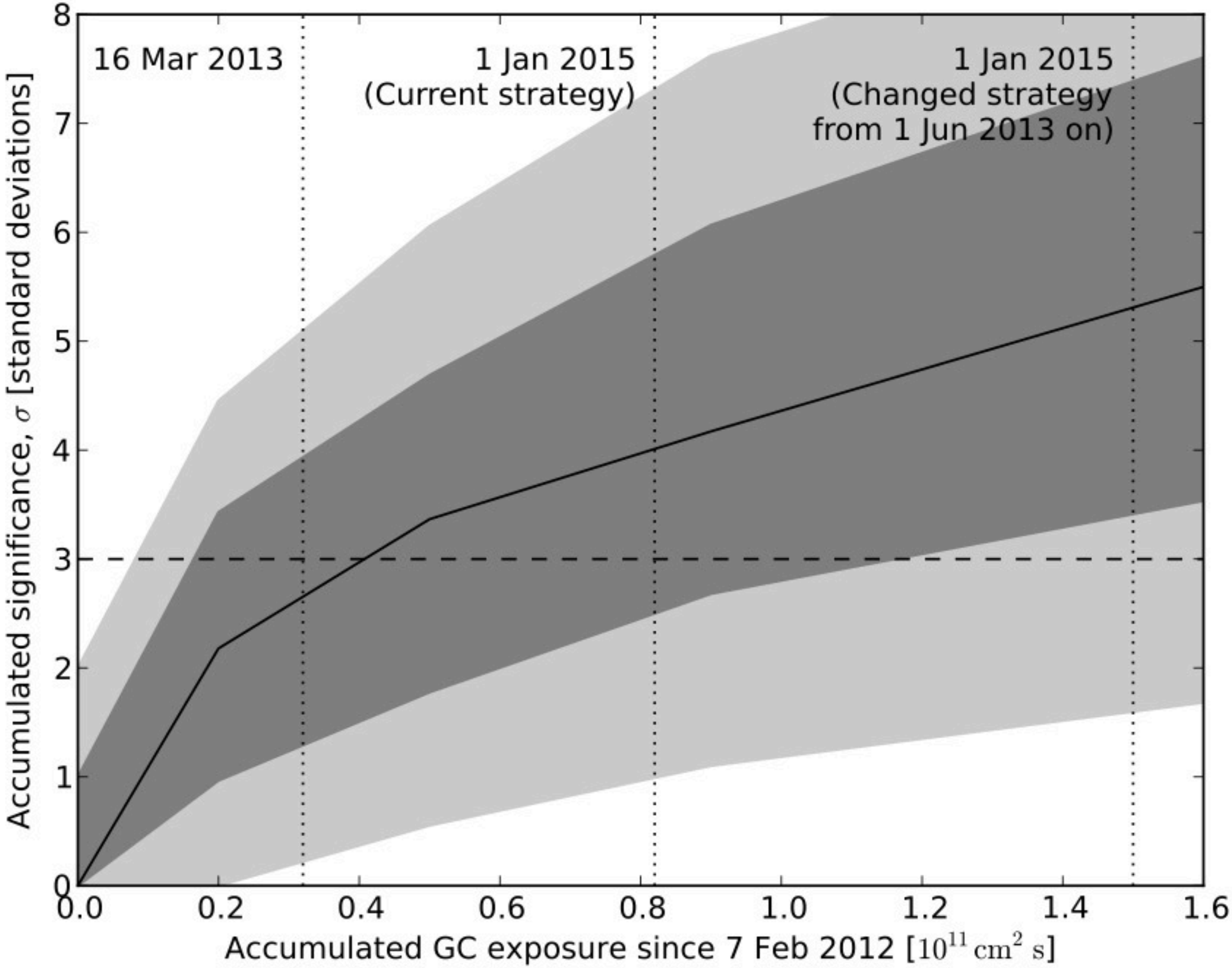


In inelastic scenarios we expect an overdensity of WIMPs *near* but not in the Sun.

They could produce signals like this.

Right now this is ~ 3 sigma after trials.

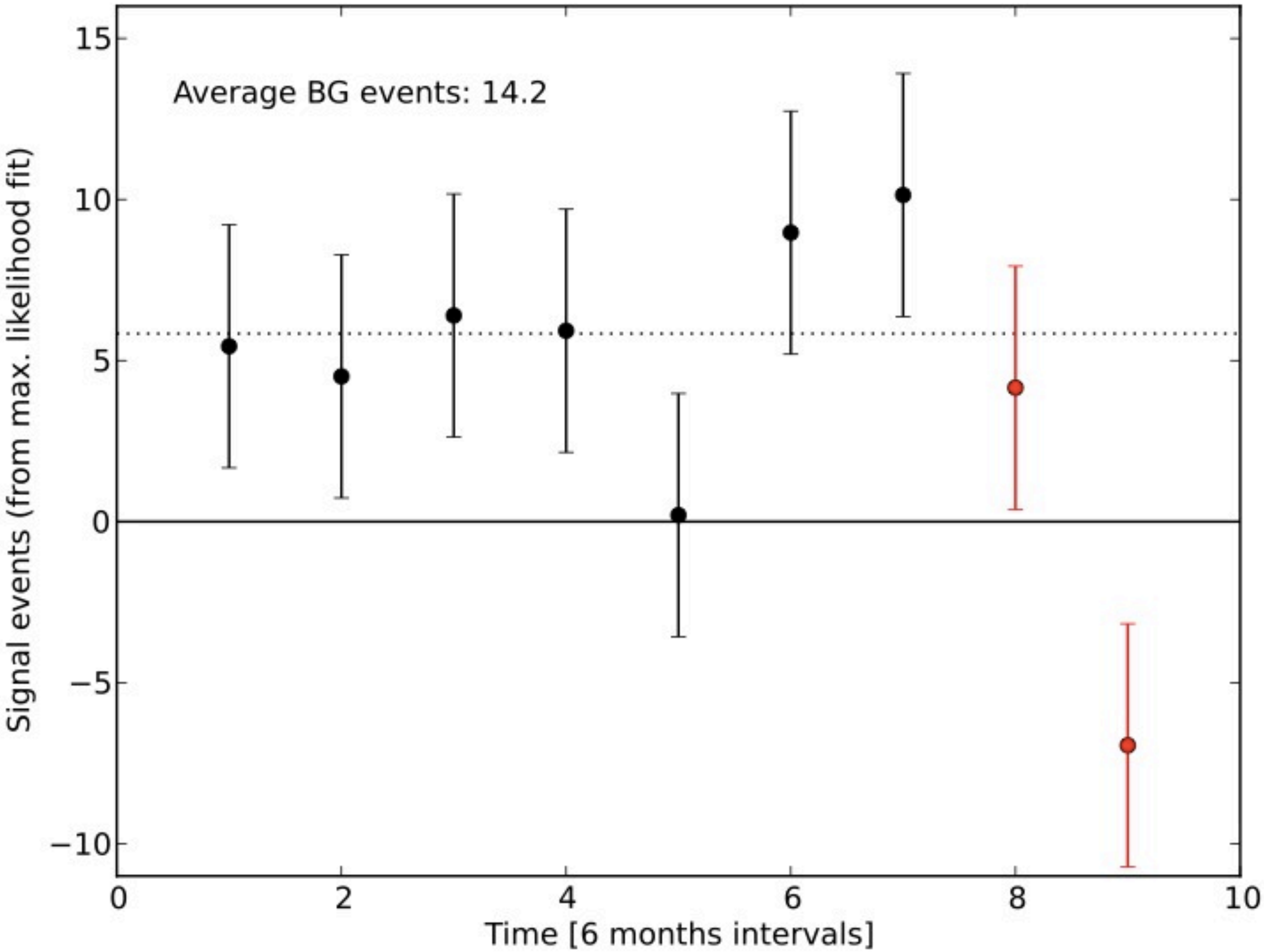
As usual, *more data needed!*



16 Mar 2013
1 Jan 2015
(Current strategy)
1 Jan 2015
(Changed strategy
from 1 Jun 2013 on)
Accumulated significance, σ [standard deviations]
Accumulated GC exposure since 7 Feb 2012 [$10^{11}\,\mathrm{cm}^2\,\mathrm{s}$]
0 1 2 3 4 5 6 7 8
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6

130 GeV conclusions:

var



Arguments in favor of a modified survey strategy

It is important: *discovery of a dark matter annihilation line in the Galactic center would be Fermi's greatest accomplishment, and define its legacy.*

Fermi can do it: *a modified survey strategy can obtain a decisive measurement, while the status quo cannot.*

A change is not bad for other science. *There will be winners and losers in any change, but more time on the inner Galaxy is good for lots of projects (better time coverage for pulsars and transients, etc.) the rest of the sky would still be observed with fairly good cadence.*

Future funding. *What looks good for the next senior review?*

130 GeV conclusions:

The line signal is not a discovery yet.
- need more data (trials factors!)
- can change survey strategy to get it fast

Want to know:
- Is it there at all?
- Is the cusp really off center?
- are there two lines (or more)?

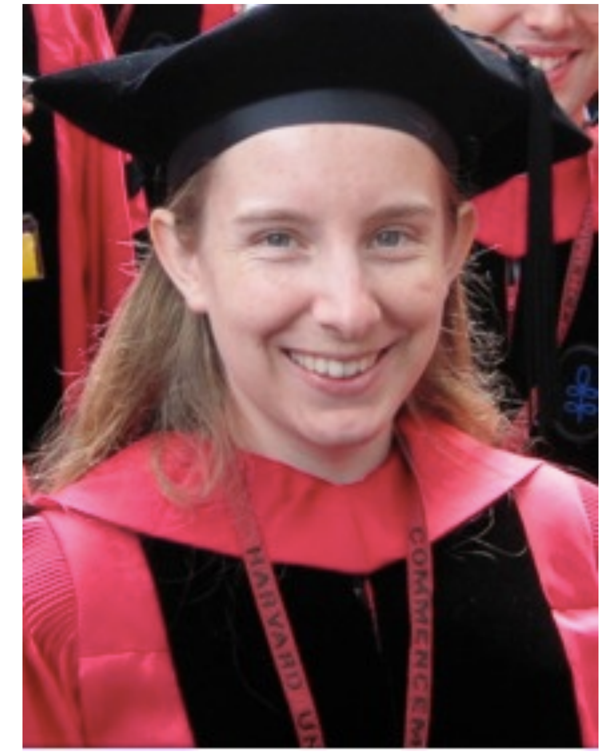
A change in survey strategy will address these questions...

(Also, HESS 2)

Imagine a discovery:

- More than a name and a mass
- New symmetries, forces
- Self interaction?
- Non-trivial properties feedback to astrophysics

Thanks to my students and postdocs,
to many supportive colleagues,
and of course the Fermi LAT team!



Tracy Slatyer

Stephen Portillo

Meng Su

Greg Dobler