Astrophysical Detection of Dark Matter

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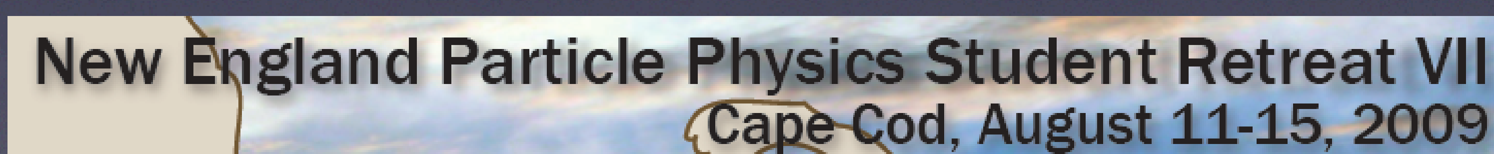


What am I doing here?

Michigan undergrad: BNL, IUCF experiments

Berkeley grad student: SSC got killed. “Particle physics is dead... if you’re smart you’ll do astro.”

Cosmology... large-scale structure of galaxies... interstellar dust... microwave foregrounds...

Microwave excess in inner Galaxy: “the haze...” DM annihilation... back to particle physics...

What is an “astrophysicist?”

Someone who tries to learn about physics by studying celestial phenomena.

Instrumentation is modest compared to LHC, but still ambitious, e.g.

Tpixel images of the sky with Gpixel cameras (SDSS)

radio telescopes with 7500 ton moving parts, 100m dishes, aligned to 100 microns... etc.

Questions to ponder this morning:

What is dark matter? WIMPs? Axions?

If WIMPs, could it be other than a simple particle? Excited states? Internal structure? Weakly broken symmetry?

Is SU(3) x SU(2) x U(1) everything, or could there be a new force in the dark sector (“dark force”) that only acts on dark matter?

These questions appear to be intractable. Why?

There are *so* many options, and we have very little information. How can we proceed?

We can start with "deep" problems, e.g. hierarchy problem, and invent new theories that solve them, making observable predictions, or

We can look for anomalies in astronomy and physics that could be related to new physics, and ask "what would it take."

Strategy:

There are many astrophysical signals (microwaves, gamma-rays, cosmic rays) to search for, both near Earth and in the Galactic center. Some anomalies have been found.

Direct detection experiments also constrain WIMP models. (DAMA claims?)

Take observed signals seriously, with the understanding that some of them are wrong, or are simply not from dark matter.

WIMP detection, near and far:

Dark
Matter?

WIMP detection, near and far:

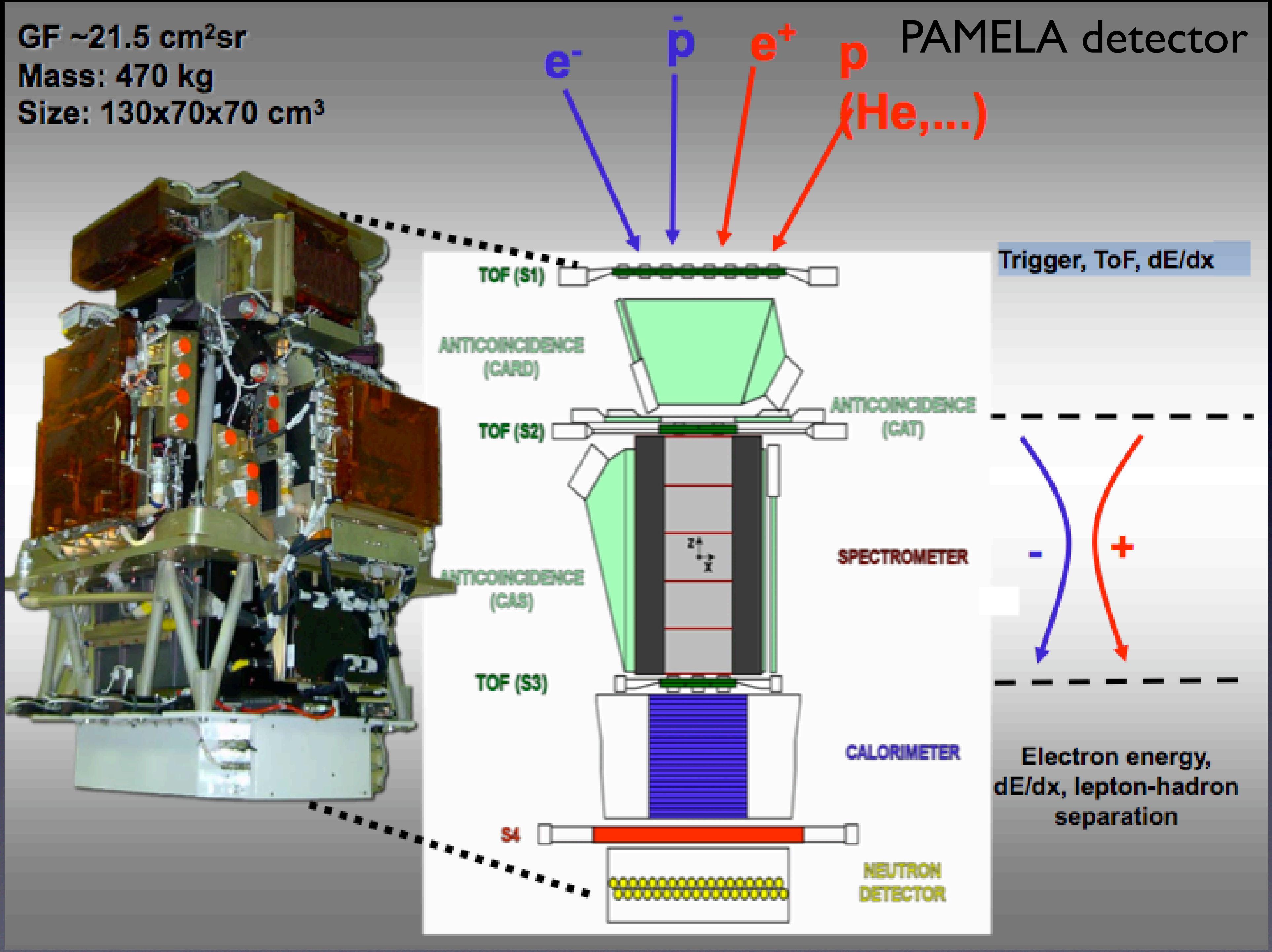
Local
(near Earth)

PAMELA
positrons

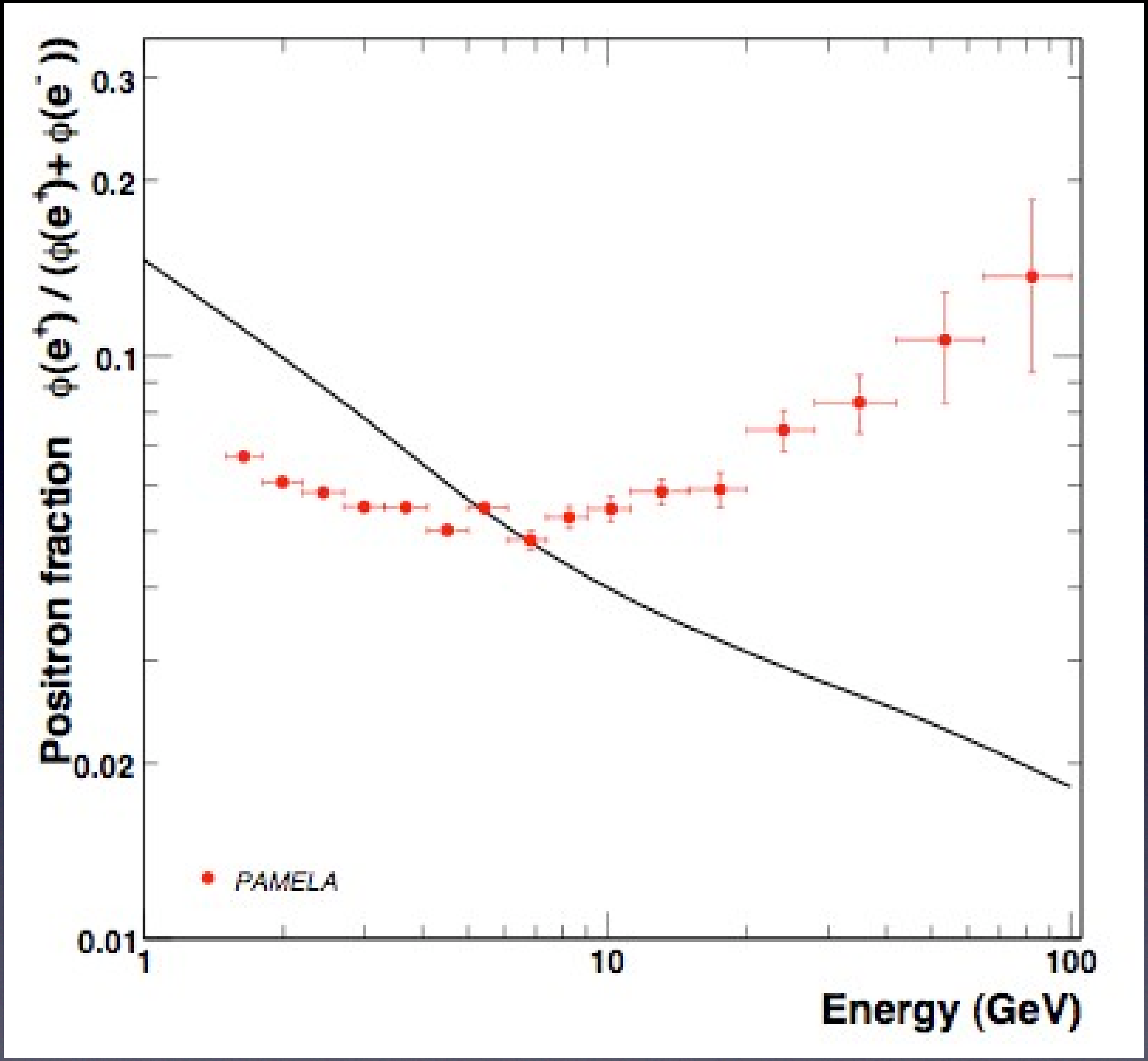
ATIC/
Fermi
e+ e-

Dark
Matter?

PAMELA detector



courtesy Mirko Boezio



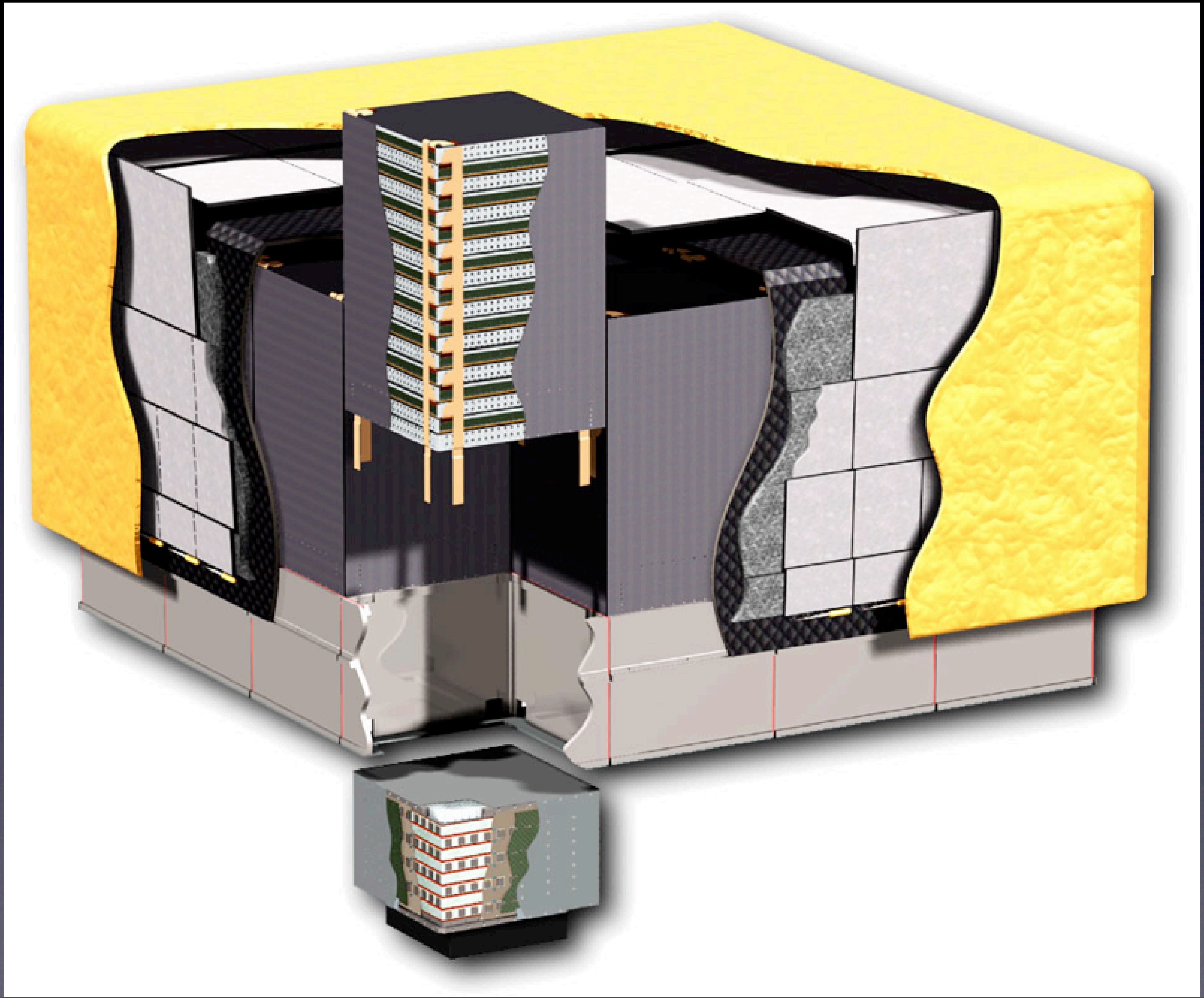
PAMELA positron fraction spectrum, Adriani et al. (2008)

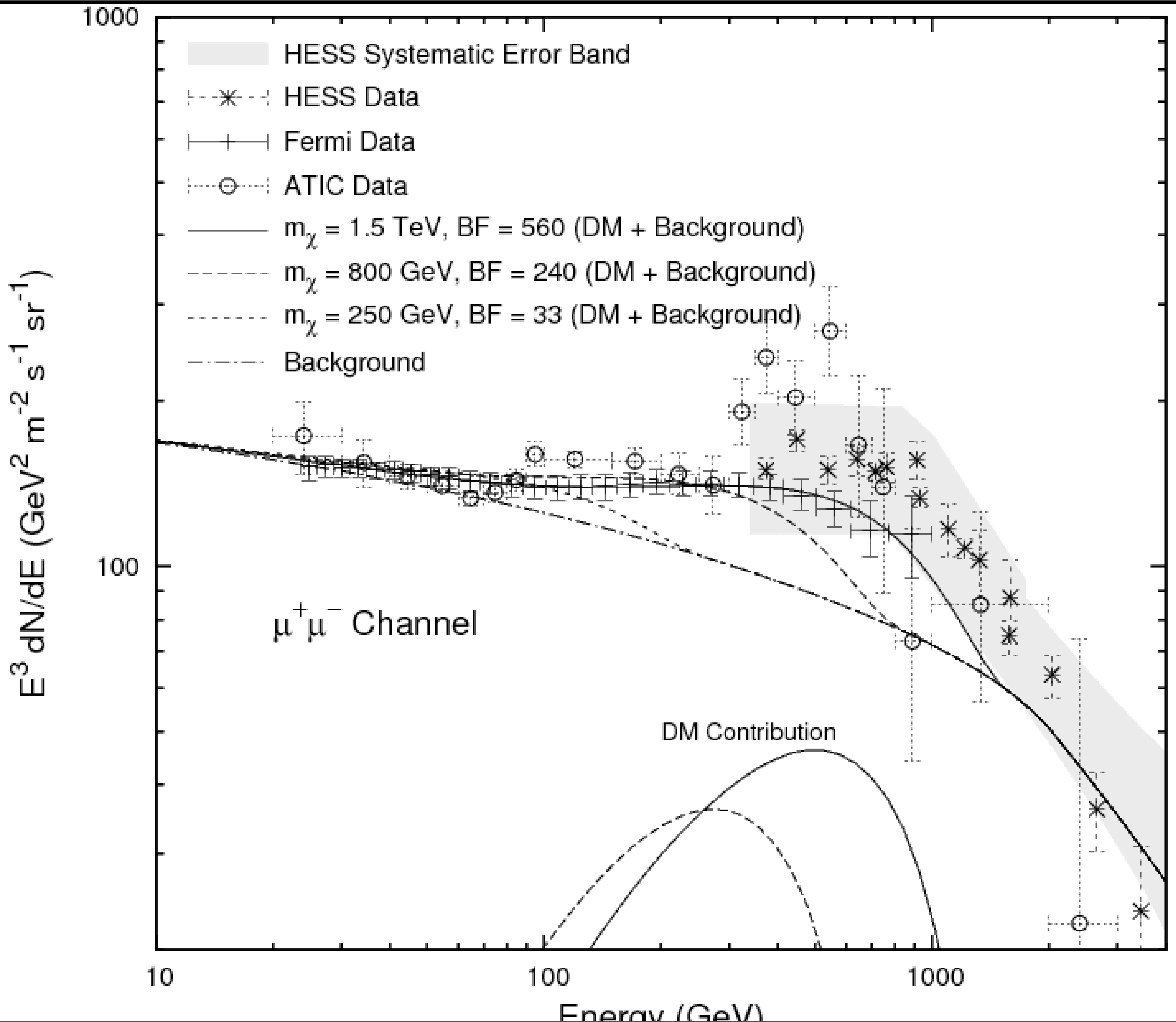
ATIC and Fermi electrons

ATIC = Advanced thin ionization calorimeter: Balloon experiment to observe e+ and e- (cannot tell the difference) up to ~ 1 TeV

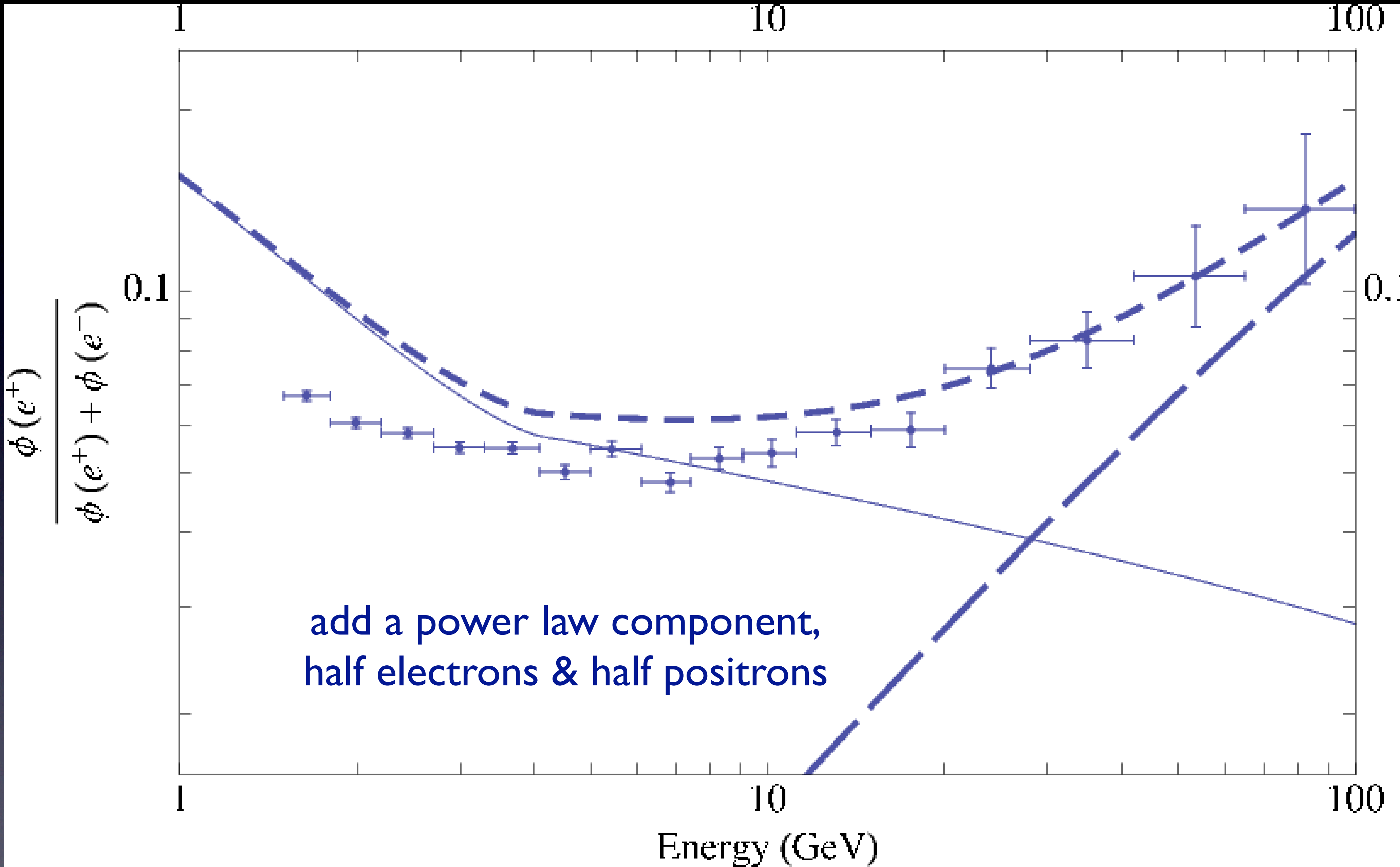
Fermi = Fermi Gamma-ray Space Telescope: pair conversion telescope, observes gammas up to 300 GeV and particles up to ~ 1 TeV.

Fermi LAT (large area telescope)

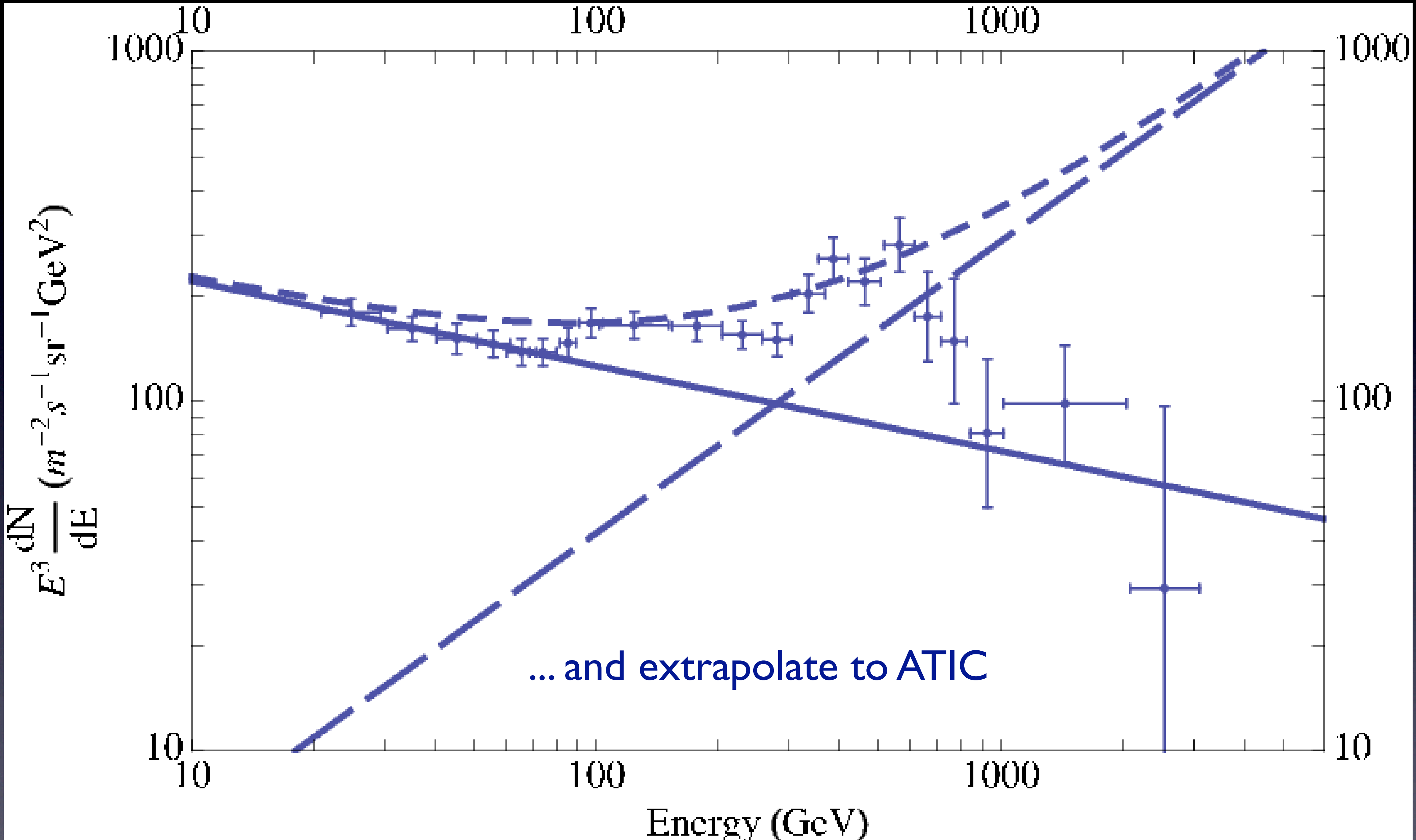



HESS Systematic Error Band
HESS Data
Fermi Data
ATIC Data
m_χ = 1.5 TeV, BF = 560 (DM + Background)
m_χ = 800 GeV, BF = 240 (DM + Background)
m_χ = 250 GeV, BF = 33 (DM + Background)
Background
$\mu^+\mu^-$ Channel
DM Contribution
$E^3 dN/dE$ ($GeV^2 m^{-2} s^{-1} sr^{-1}$)
1000
100
10
100
1000
Energy (GeV)

Do the excess PAMELA positrons and the excess ATIC/Fermi e+e- have anything to do with each other?



Cholis et al. (2008)



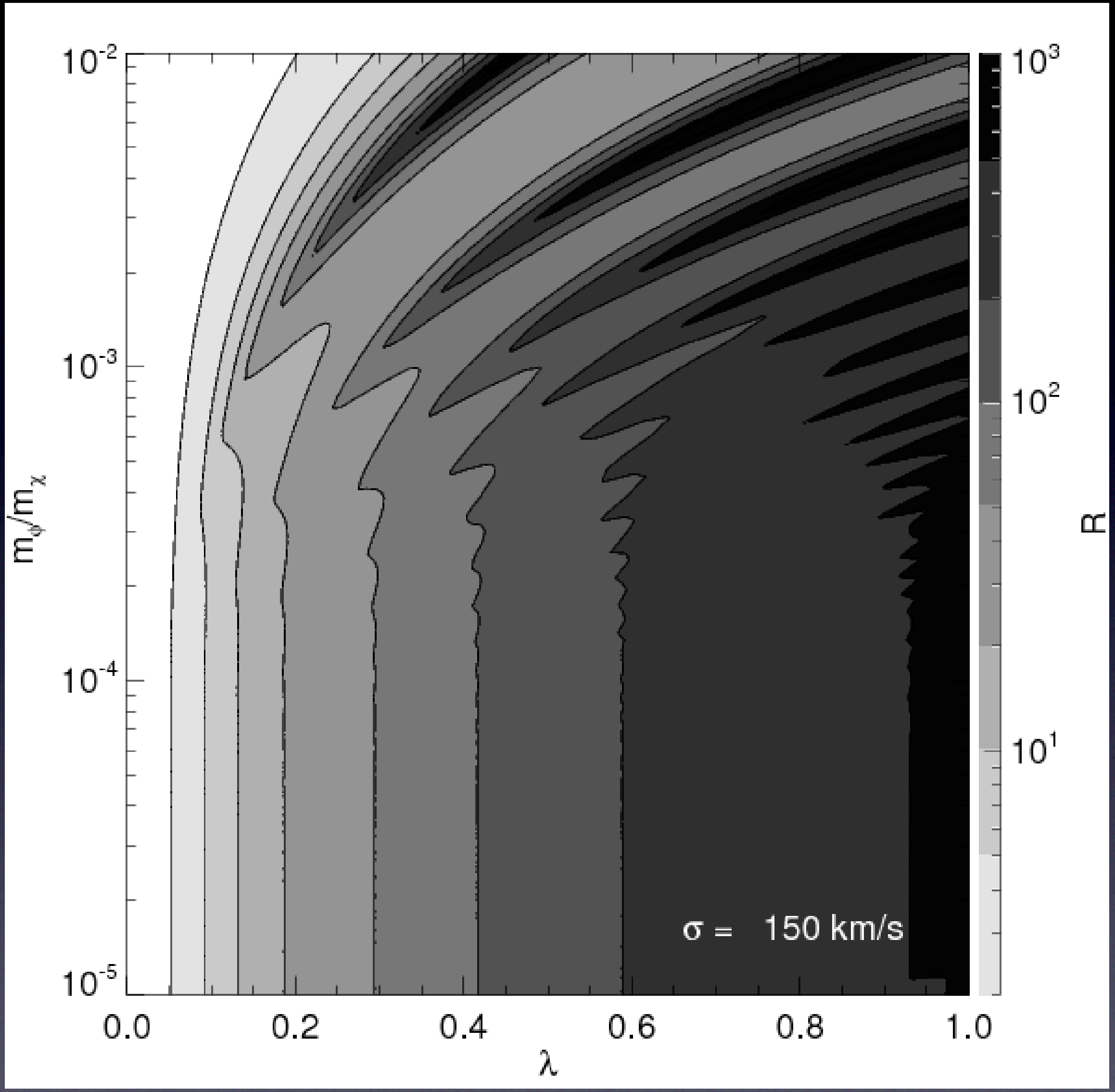
Cholis et al. (2008)

But both ATIC & PAMELA require a large cross section.

Sommerfeld enhancement:

QM analog of gravitational focusing.

Depends on WIMP mass ratio, coupling to phi, and velocity



Arkani-Hamed et al. (2008) see also Nomura et al (2009)

Editorial comment:
Yes, theorists can explain anything. But sometimes observations push theory in surprising directions.

If we want the high cross section needed for PAMELA/ATIC, we have left MSSM-land.

i.e. there must be some new structure in the dark sector, beyond what you expect from minimal SUSY. This could be a new force, mirror dark matter, strongly-interacting DM (mesonic or baryonic) or "Axion Portal" DM, etc. But *something* is going on.

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Local
(near Earth)

PAMELA
positrons

Fermi
e+ e-

Dark
Matter?

WIMP detection, near and far:

Local
(near Earth)

PAMELA
positrons

Fermi
e+ e-

Dark
Matter?

INTEGRAL
511 keV

EGRET
gammas

WMAP haze
(microwaves)

Galactic Center

The WMAP haze

The Interstellar Medium:

Gas and dust between the stars.

Mostly H and He, density is ~ 1 cm^{-3}.
(That's 1 atom, not 1 gram!)

Column density is ~ 10^{20} - 10^{21} cm^{-2}.

There is also dust (graphite, silicates, PAHs, etc.)
What is the total column density of dust?

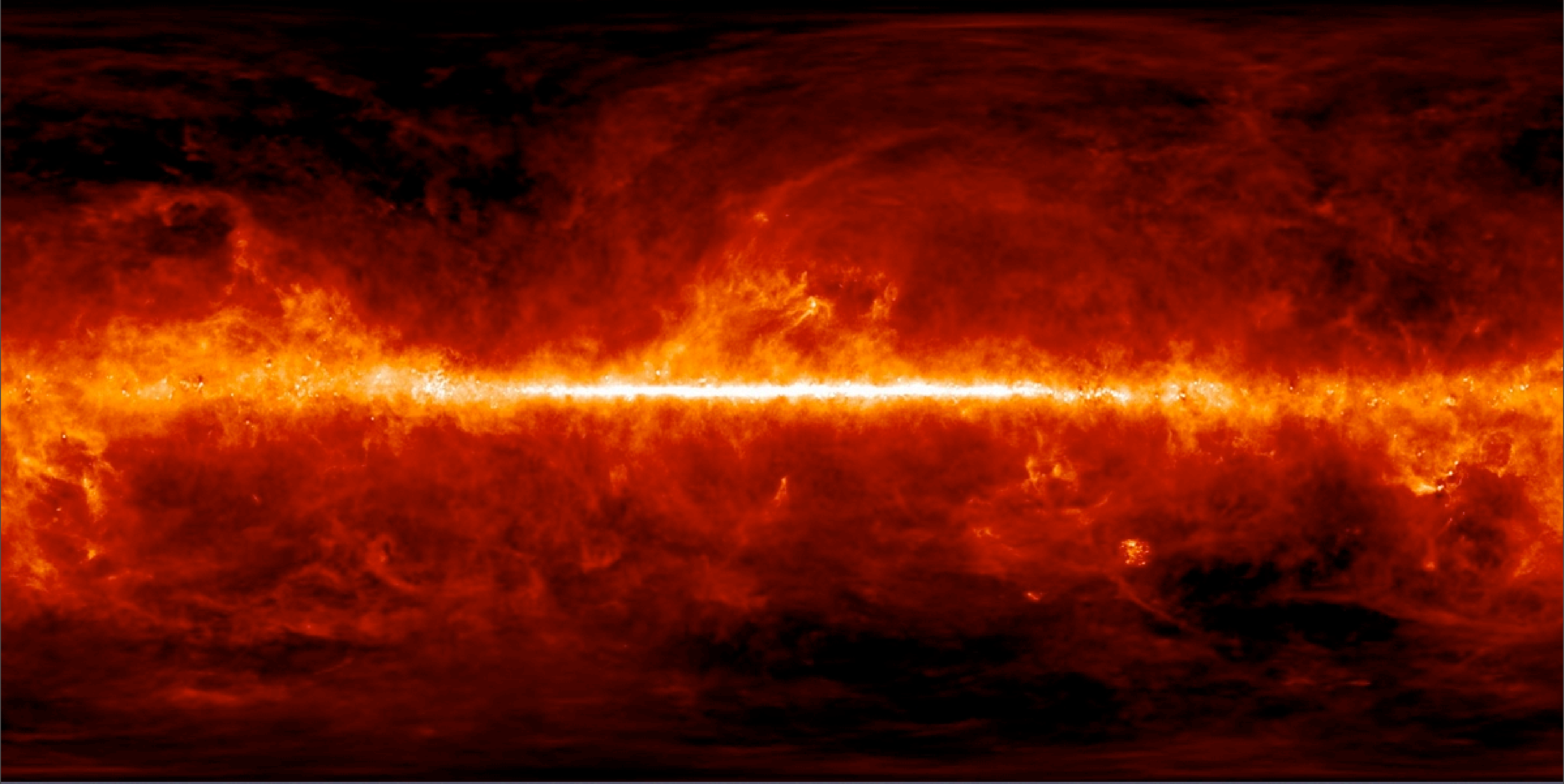
The Galaxy as a detector

For particle physics that happens on larger spatial scales and long time scales, the Galaxy is not a bad detector. (Not optimal, but we use what we have).

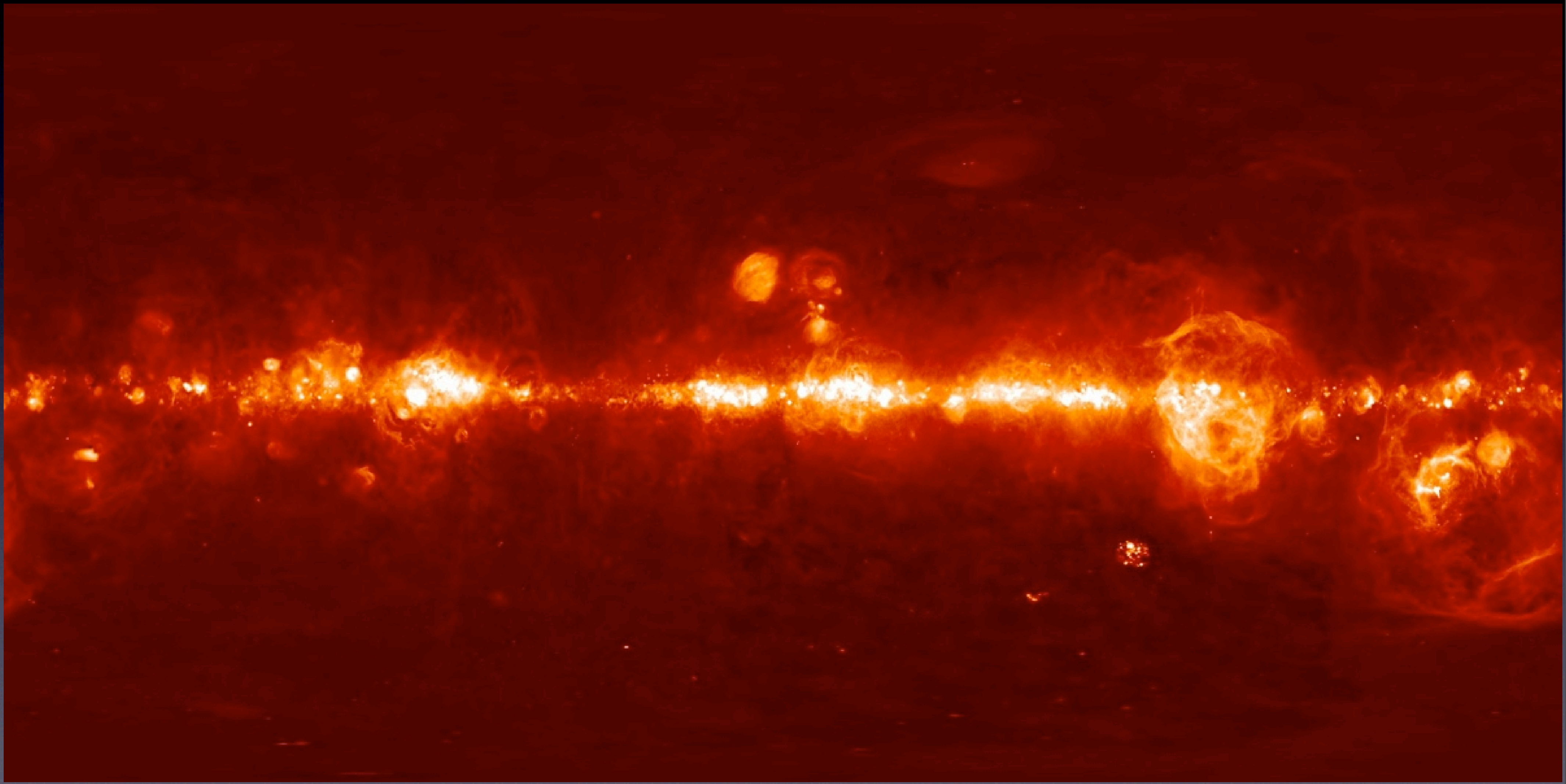
CRs produce synchrotron
ionized gas produces thermal bremsstrahlung
dust grains emit thermally (vibrationally) and rotationally.

There is a lot going on just from "conventional" astrophysics - how do we model it?

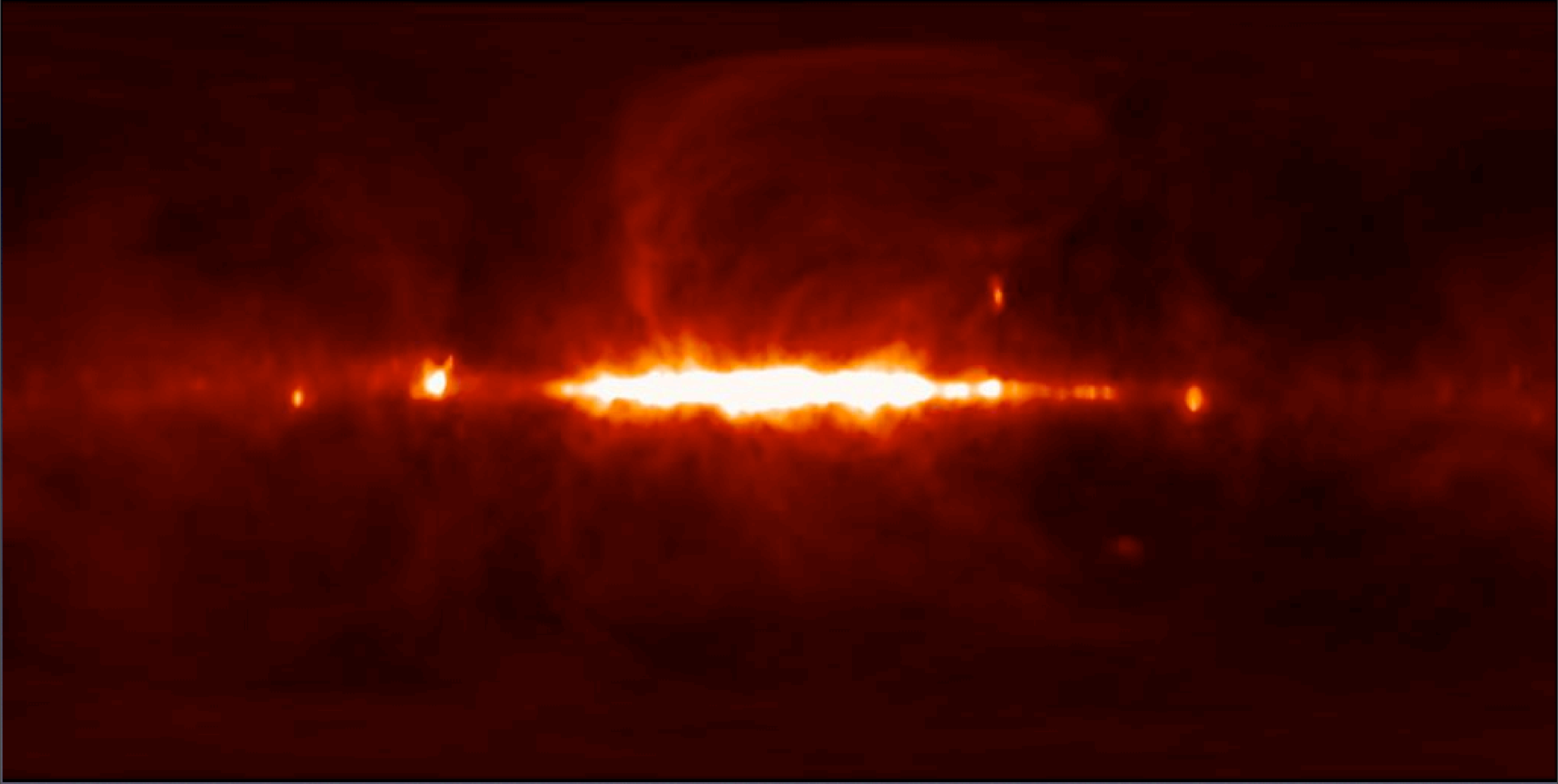
Interstellar Dust from IRAS, DIRBE (Finkbeiner et al. 1999) Map extrapolated from 3 THz (100 micron) with FIRAS.

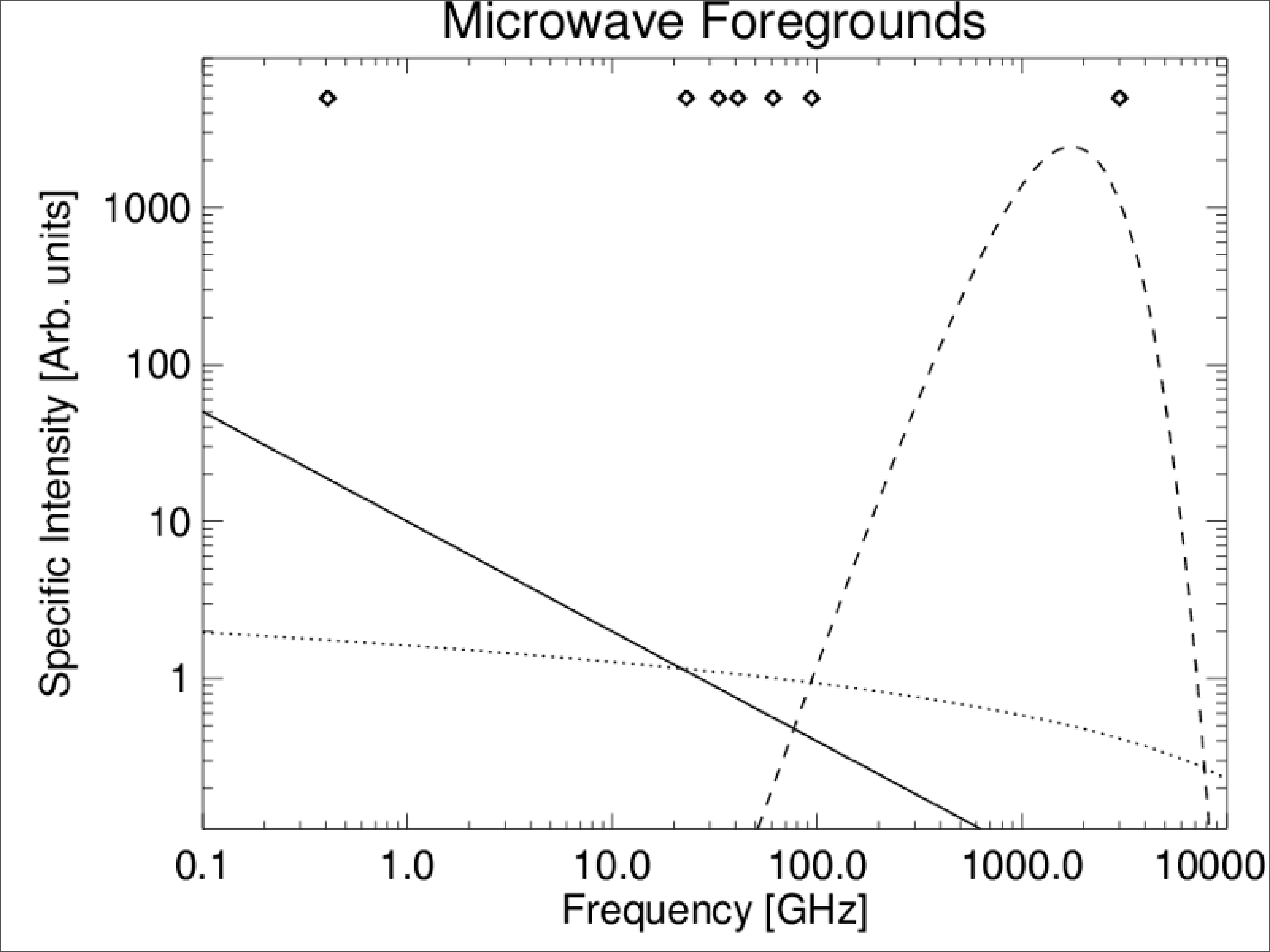


Ionized Gas from WHAM, SHASSA, VTSS (Finkbeiner 2003)
H-alpha emission measure goes as thermal bremsstrahlung.



Synchrotron at 408 MHz (Haslam et al. 1982)



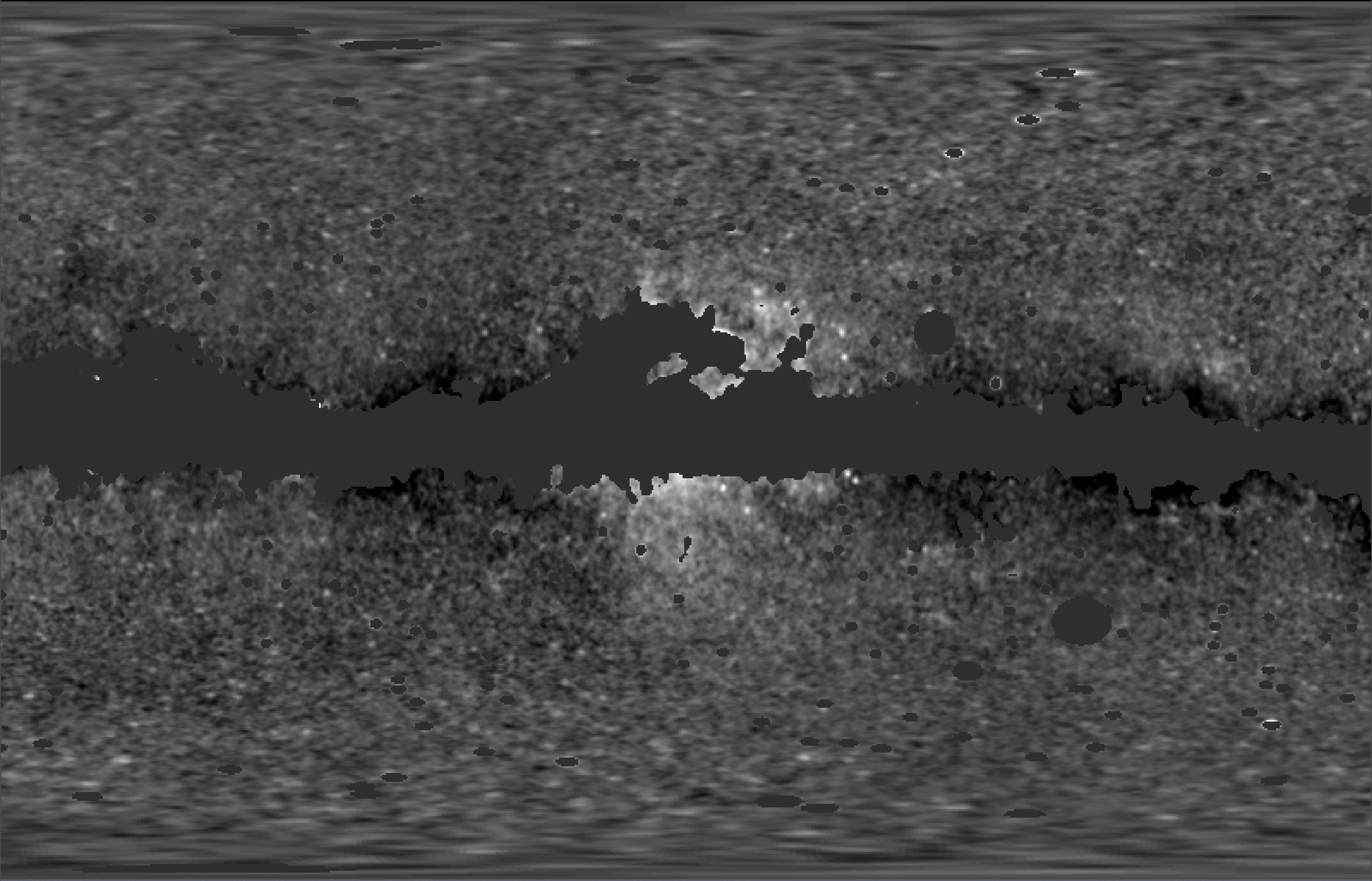

Microwave Foregrounds
Specific Intensity [Arb. units]
1000
100
10
1
0.1
1.0
10.0
100.0
1000.0
10000
Frequency [GHz]

There is also “spinning dust” emission,
i.e. electric dipole emission from rapidly rotating small dust grains.

This emission is spatially similar to the thermal dust, but spectrally different.

(Kogut et al 1996; Draine & Lazarian 1998;
de Oliveira-Costa et al., 1998,1999,2000,2002,2004;
Finkbeiner et al. 2002, 2004, etc...)

Subtracting all known Galactic foregrounds from the WMAP maps, we a residual in the inner ~ 25 deg of the Galaxy:

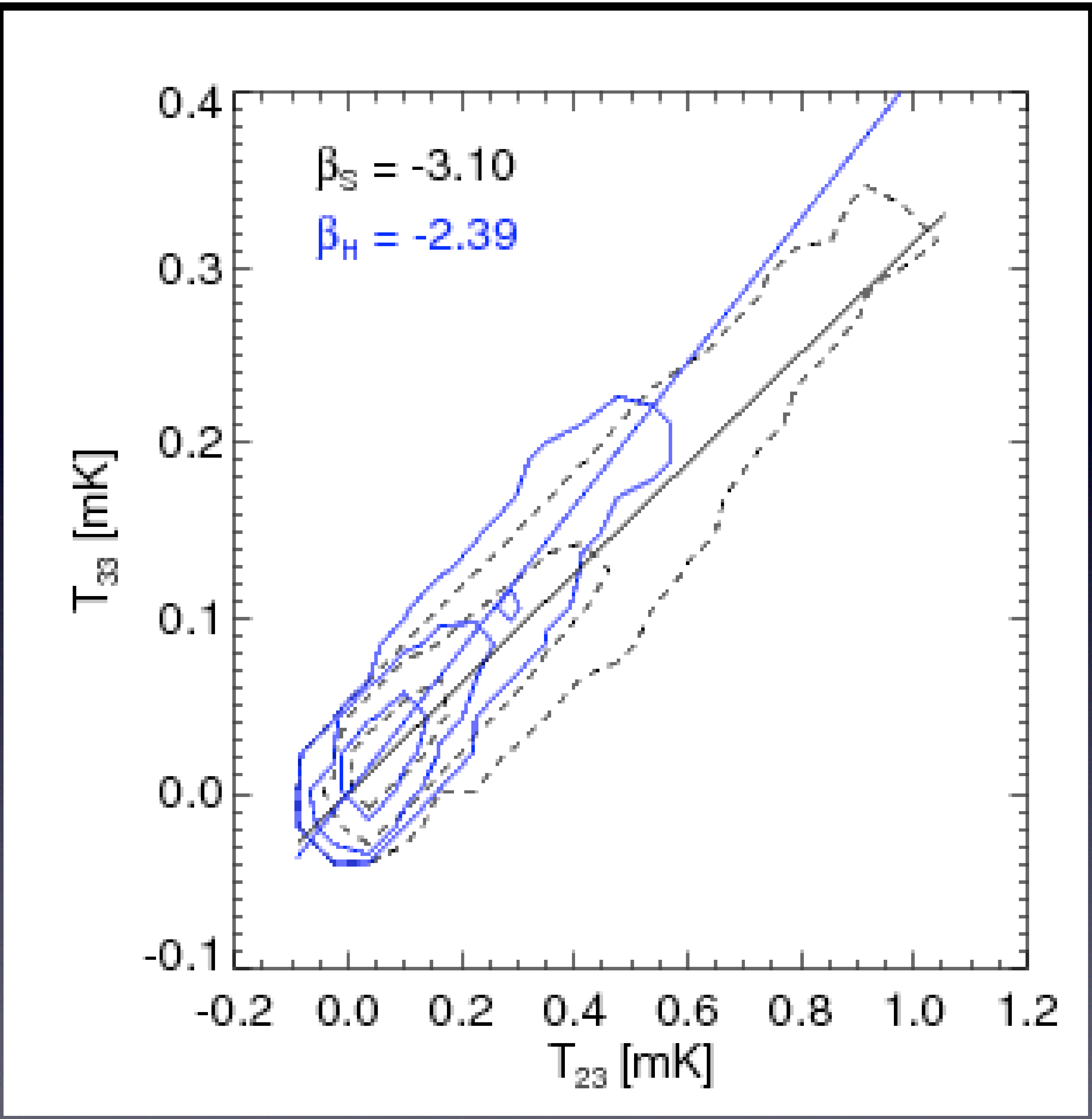


Bottom line

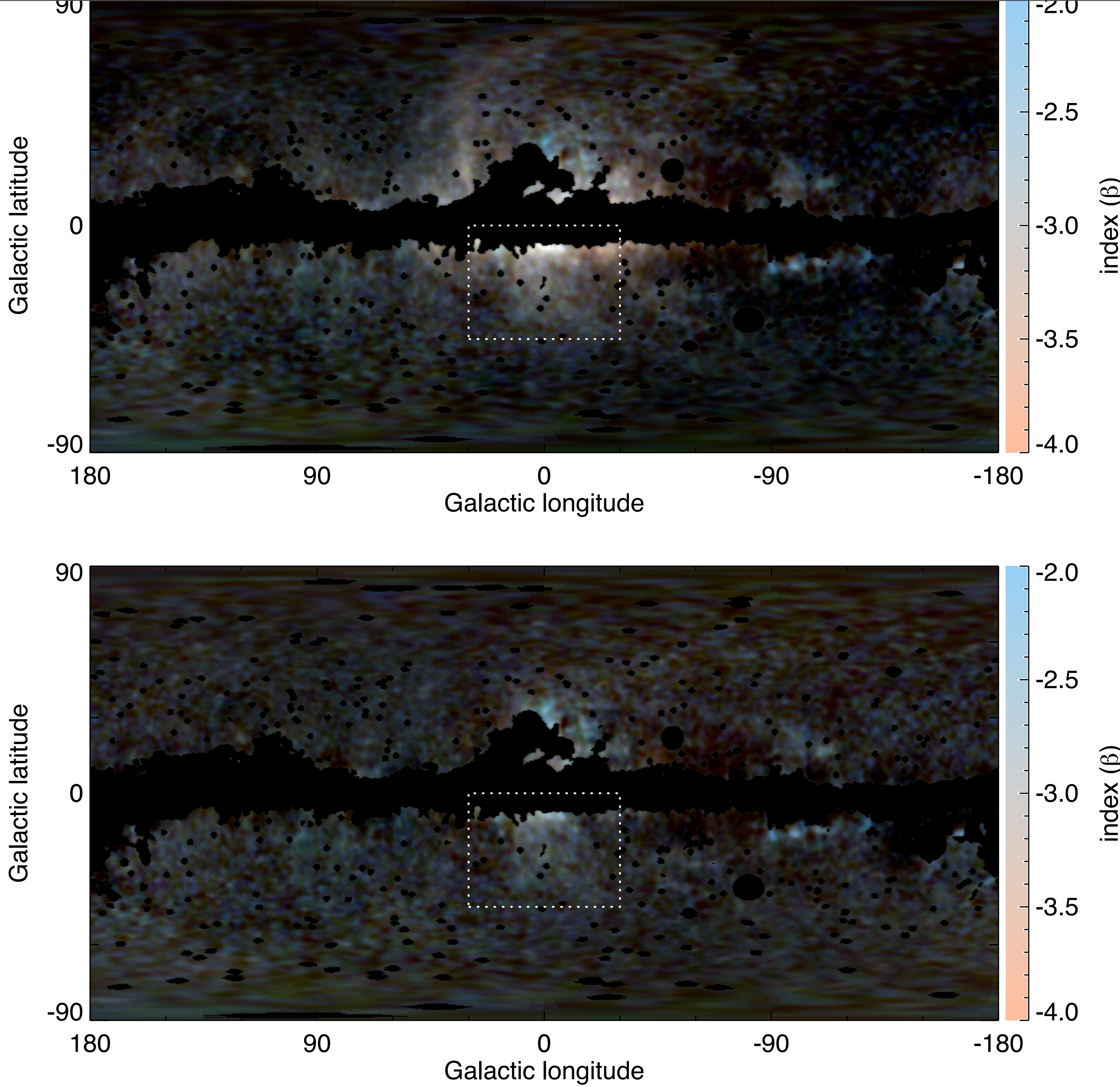
The Galaxy is complicated, but we understand it pretty well.

There seems to be a microwave excess in the center.

Could it be new physics? Or is it just extra supernovae?



βS = -3.10
βH = -2.39
T33 [mK]
T23 [mK]
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2

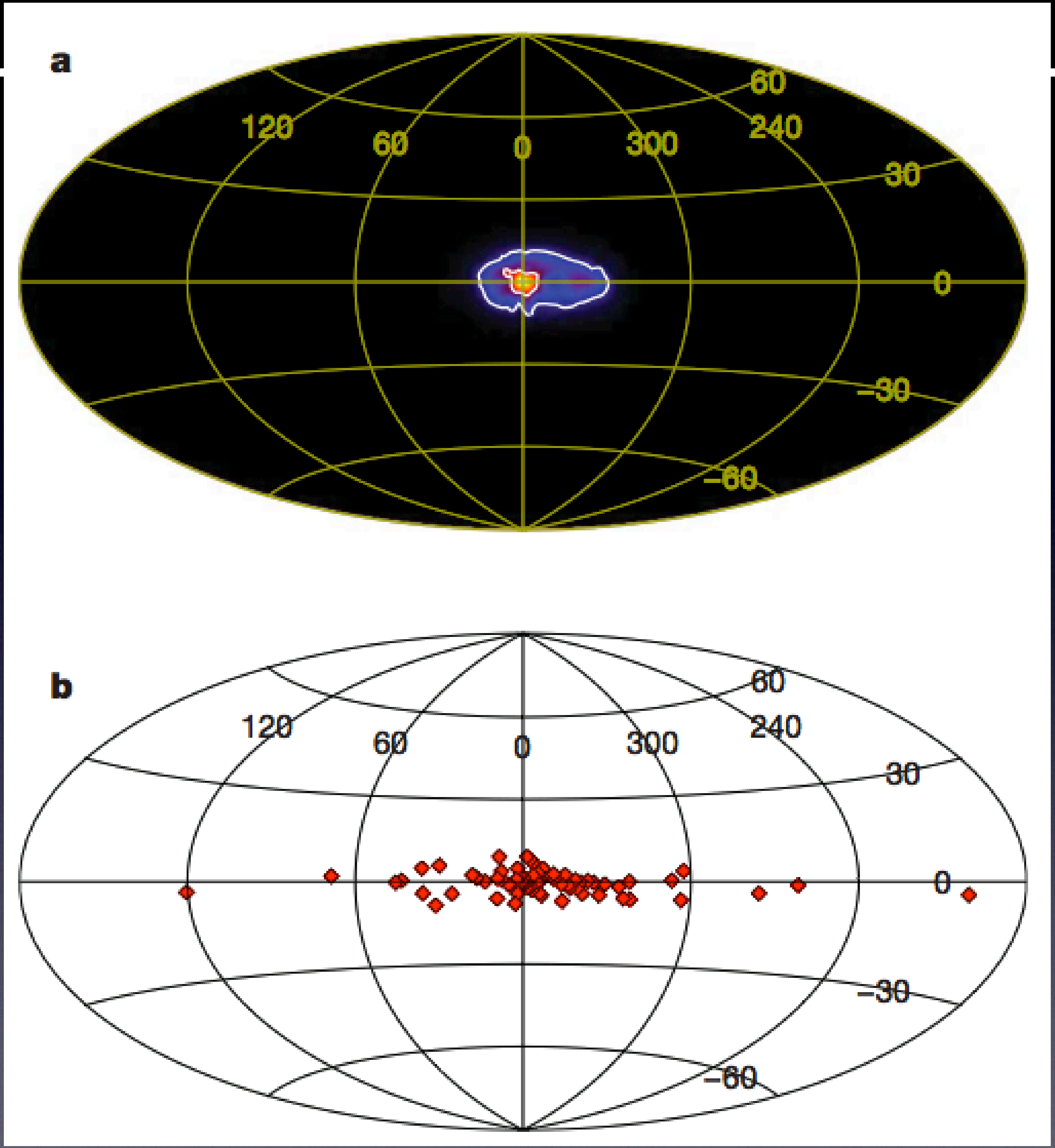


90
0
-90
Galactic latitude
180
90
0
-90
-180
Galactic longitude
-2.0
-2.5
-3.0
-3.5
-4.0
index (β)
90
0
-90
Galactic latitude
180
90
0
-90
-180
Galactic longitude
-2.0
-2.5
-3.0
-3.5
-4.0
index (β)

INTEGRAL

Too many 511 keV photons from center of Galaxy.

37 year old result, still not understood.



Weidenspointner et al. (2008) Integral signal (top) and LMXBs (bottom)

Weidenspointner (2006)

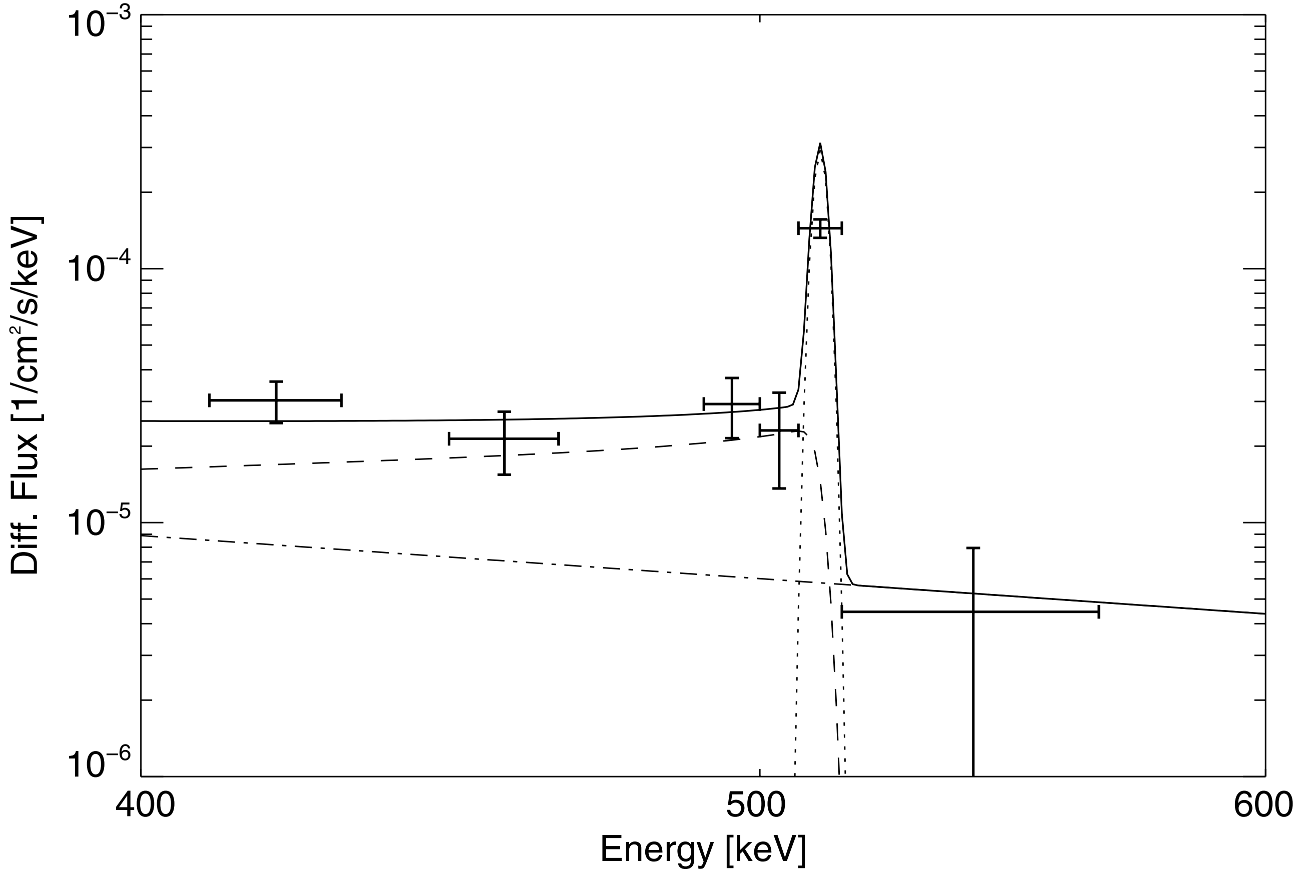


Fig. 2. A fit of the SPI result for the diffuse emission from the GC region ($|l|, |b| \leq 16°$) obtained with a spatial model consisting of an 8° *FWHM* Gaussian bulge and a CO disk. In the fit a diagonal response was assumed. The spectral components are: 511 keV line (dotted), Ps continuum (dashes), and power-law continuum (dash-dots). The summed models are indicated by the solid line. Details of the fitting procedure are given in the text.

WIMP detection, near and far:

Local
(near Earth)

PAMELA
positrons

DAMA
annual mod.

Na I scintillation;
exposure:
200,000 kg day.

Fermi
e+ e-

Dark
Matter?

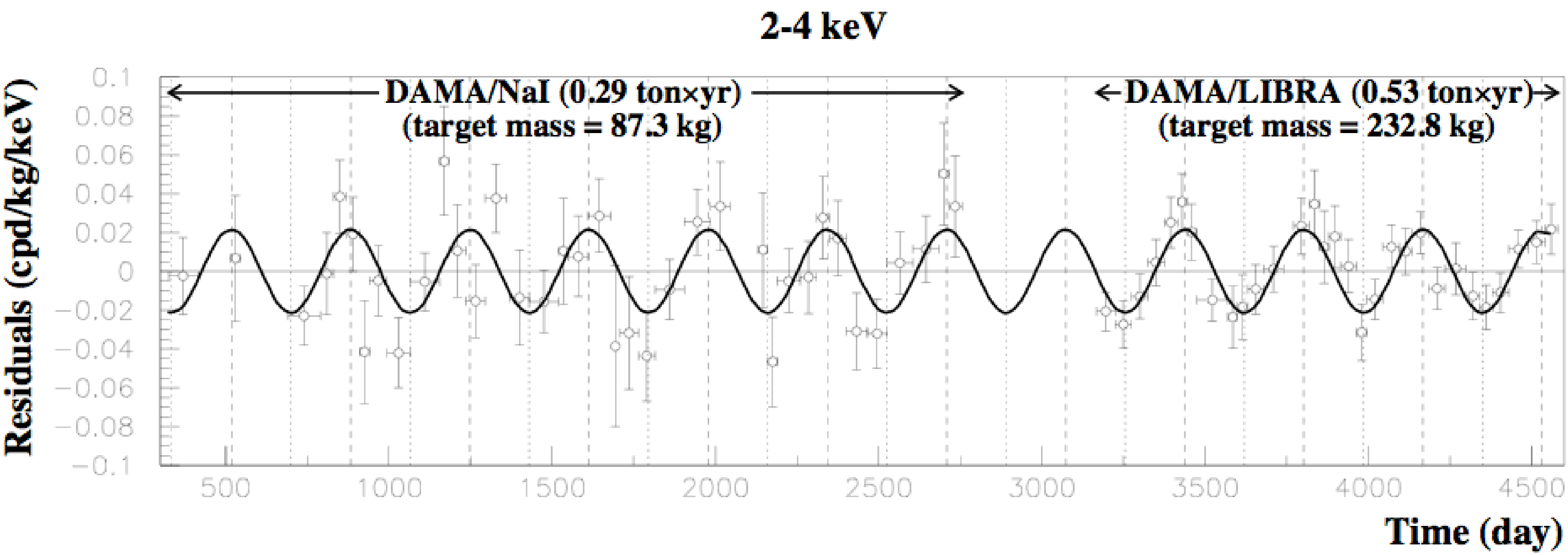
INTEGRAL
511 keV

EGRET
gammas

WMAP haze
(microwaves)

Galactic Center

Bernabei et al. (DAMA/LIBRA, 2008)



DAMA sees a convincing signal (8.2 sigma) but other experiments rule out *elastic nuclear scattering* at this level (by large factors).

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

Claims that DAMA is "wrong" are dependent on a narrow theoretical bias that the scattering must be elastic.

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%)

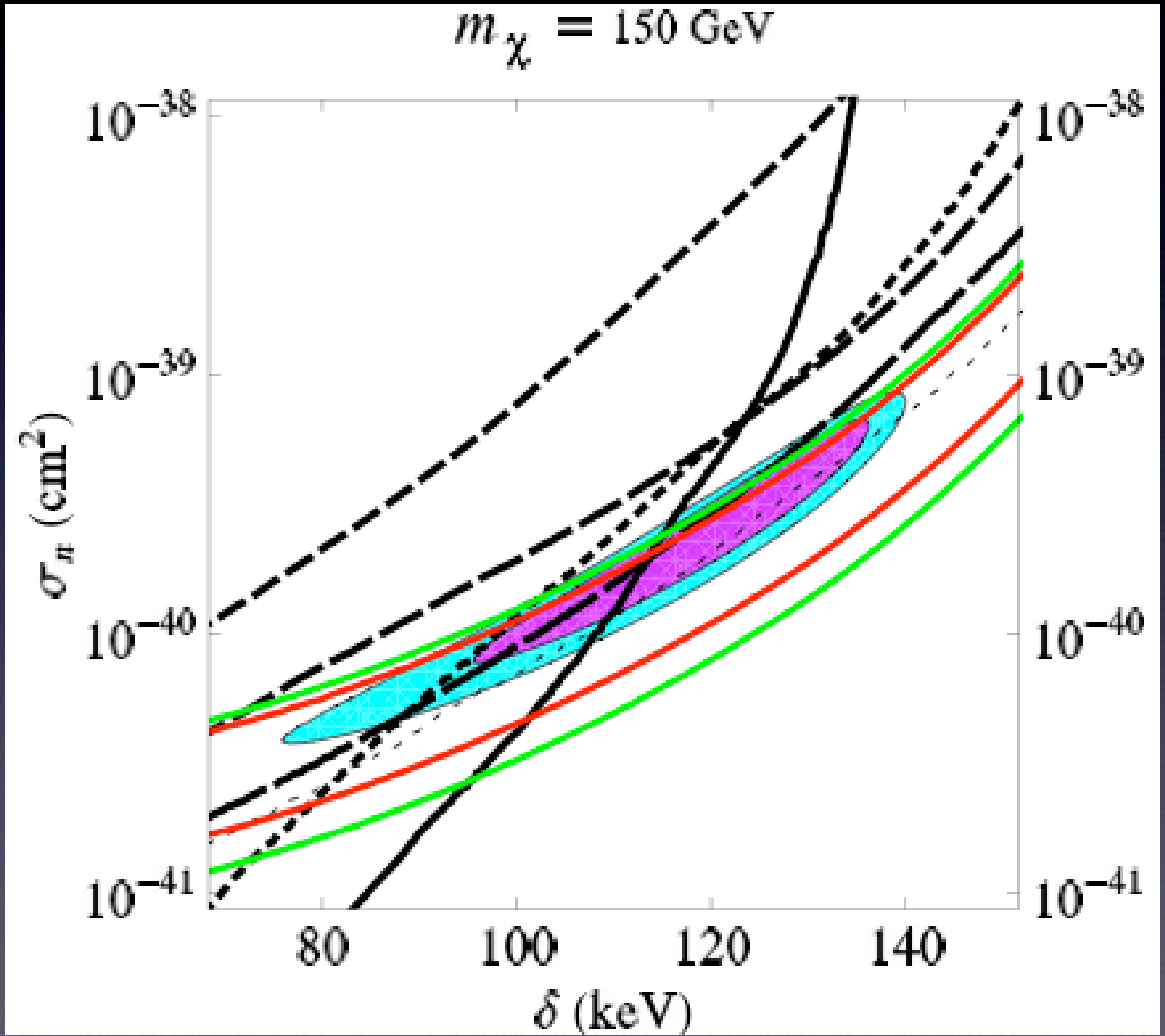
2. Bigger nuclei better (I better than Ge, worse than W)

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

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

Channeling is also possible, but forces us to a mass of < 5 GeV. Energy dependence of events looks wrong.

So, DAMA (most likely) implies inelastic scattering.



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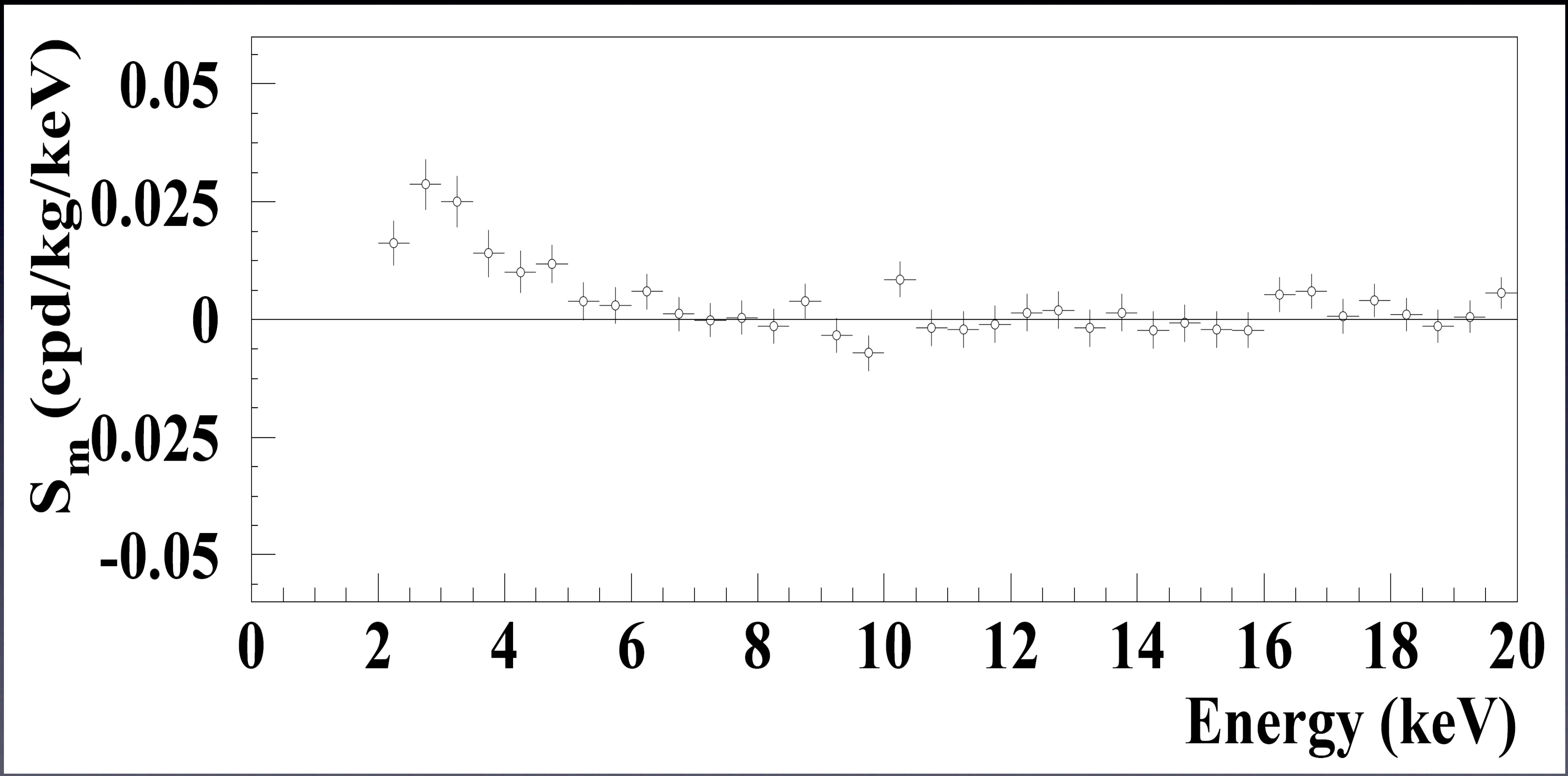


Bernabei et al. (2008)

XENON-100, LUX will provide much better results in the next few years.

WIMP detection, near and far:

Local
(near Earth)

PAMELA
positrons

DAMA
annual mod.

Physics

Fermi
e+ e-

Dark
Matter?

muon
g-2

INTEGRAL
511 keV

EGRET
gammas

WMAP haze
(microwaves)

Galactic Center

Strategy:

Lots of signals; some may be wrong; some may have nothing to do with dark matter.

Let's take claimed signals seriously, and build models to explain them, searching for conclusions that are robust to the exact subset of results that are "right."

High Energy Physics - Phenomenology

A Theory of Dark Matter

Nima Arkani-Hamed, Douglas P. Finkbeiner, Tracy R. Slatyer, Neal Weiner

(Submitted on 6 Oct 2008 (v1), last revised 31 Oct 2008 (this version, v2))

We propose a comprehensive theory of dark matter that explains the recent proliferation of unexpected observations in high-energy astrophysics. Cosmic ray spectra from ATIC and PAMELA require a WIMP with mass M_chi ~ 500 - 800 GeV that annihilates into leptons at a level well above that expected from a thermal relic. Signals from WMAP and EGRET reinforce this interpretation. Taken together, we argue these facts imply the presence of a GeV-scale new force in the dark sector. The long range allows a Sommerfeld enhancement to boost the annihilation cross section as required, without altering the weak scale annihilation cross section during dark matter freezeout in the early universe. If the dark matter annihilates into the new force carrier, phi, its low mass can force it to decay dominantly into leptons. If the force carrier is a non-Abelian gauge boson, the dark matter is part of a multiplet of states, and splittings between these states are naturally generated with size alpha m_phi ~ MeV, leading to the eXciting dark matter (XDM) scenario previously proposed to explain the positron annihilation in the galactic center observed by the INTEGRAL satellite. Somewhat smaller splittings would also be expected, providing a natural source for the parameters of the inelastic dark matter (iDM) explanation for the DAMA annual modulation signal. Since the Sommerfeld enhancement is most significant at low velocities, early dark matter halos at redshift ~10 potentially produce observable effects on the ionization history of the universe, and substructure is more detectable than with a conventional WIMP. Moreover, the low velocity dispersion of dwarf galaxies and Milky Way subhalos can greatly increase the substructure annihilation signal.

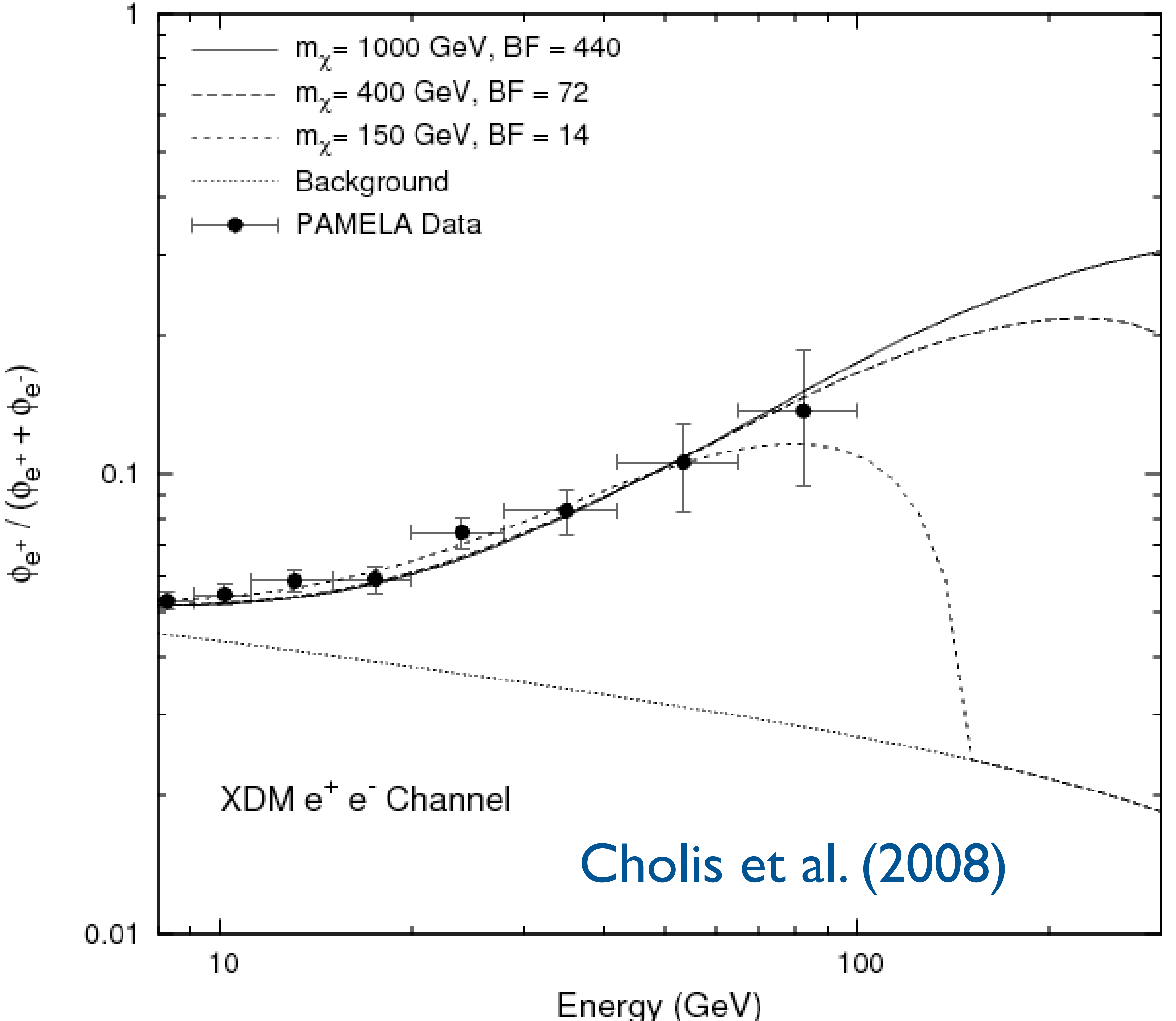
Summary of "Theory of DM" paper:

A new force in the dark sector, mediated by a new gauge boson, ϕ, has these appealing features:

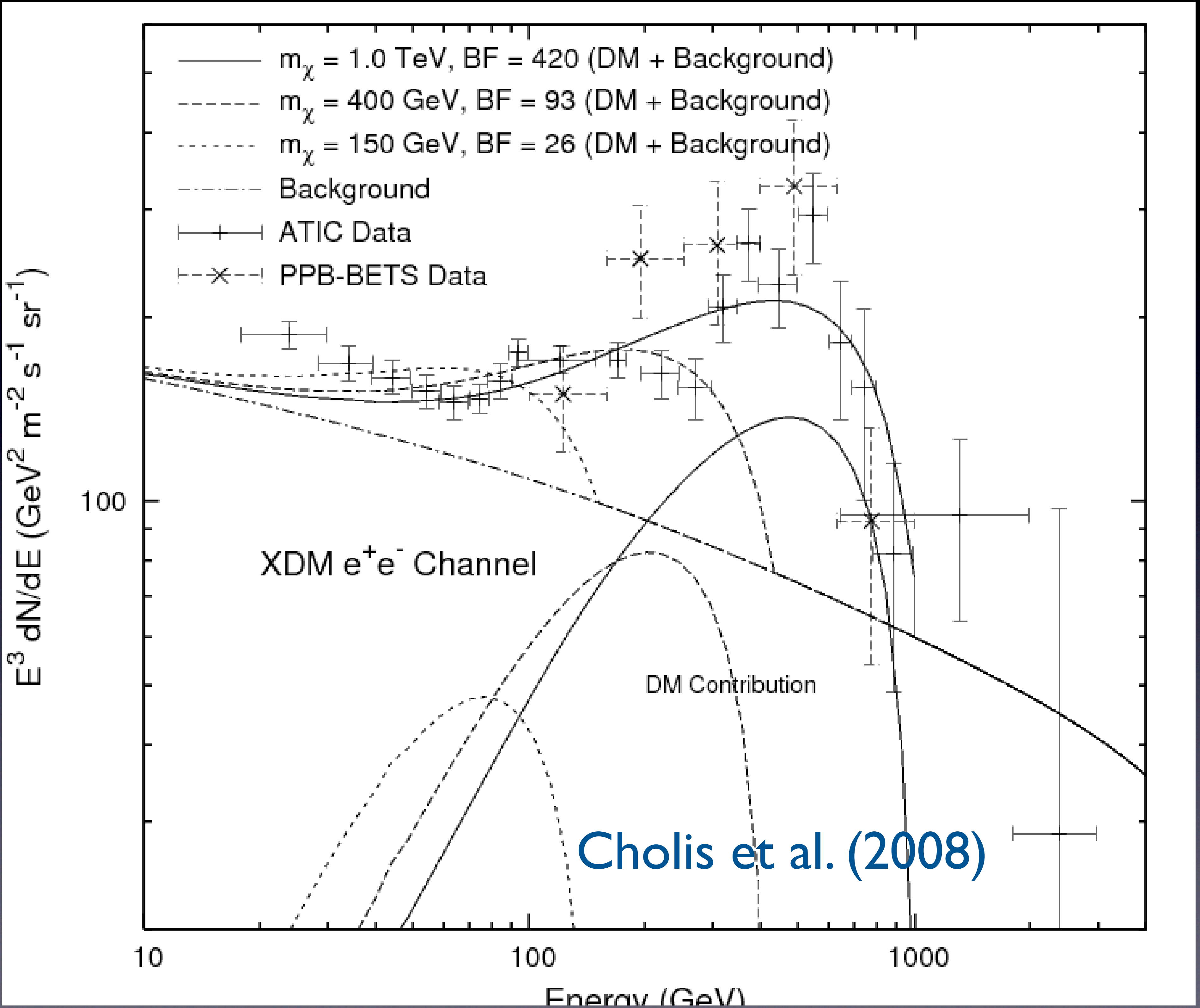
- It can mediate scatterings.
- The ϕ vev can generate mass splittings,
- ... so the scatterings can be inelastic.
- The WIMP annihilates through the ϕ so if the mass is O(1 GeV) can annihilate to leptons.
- Attractive force mediated by ϕ gives rise to Sommerfeld enhancement to annihilation Xsec.

- This is a framework - there are specific realizations... (Arkani-Hamed & Weiner 2008)

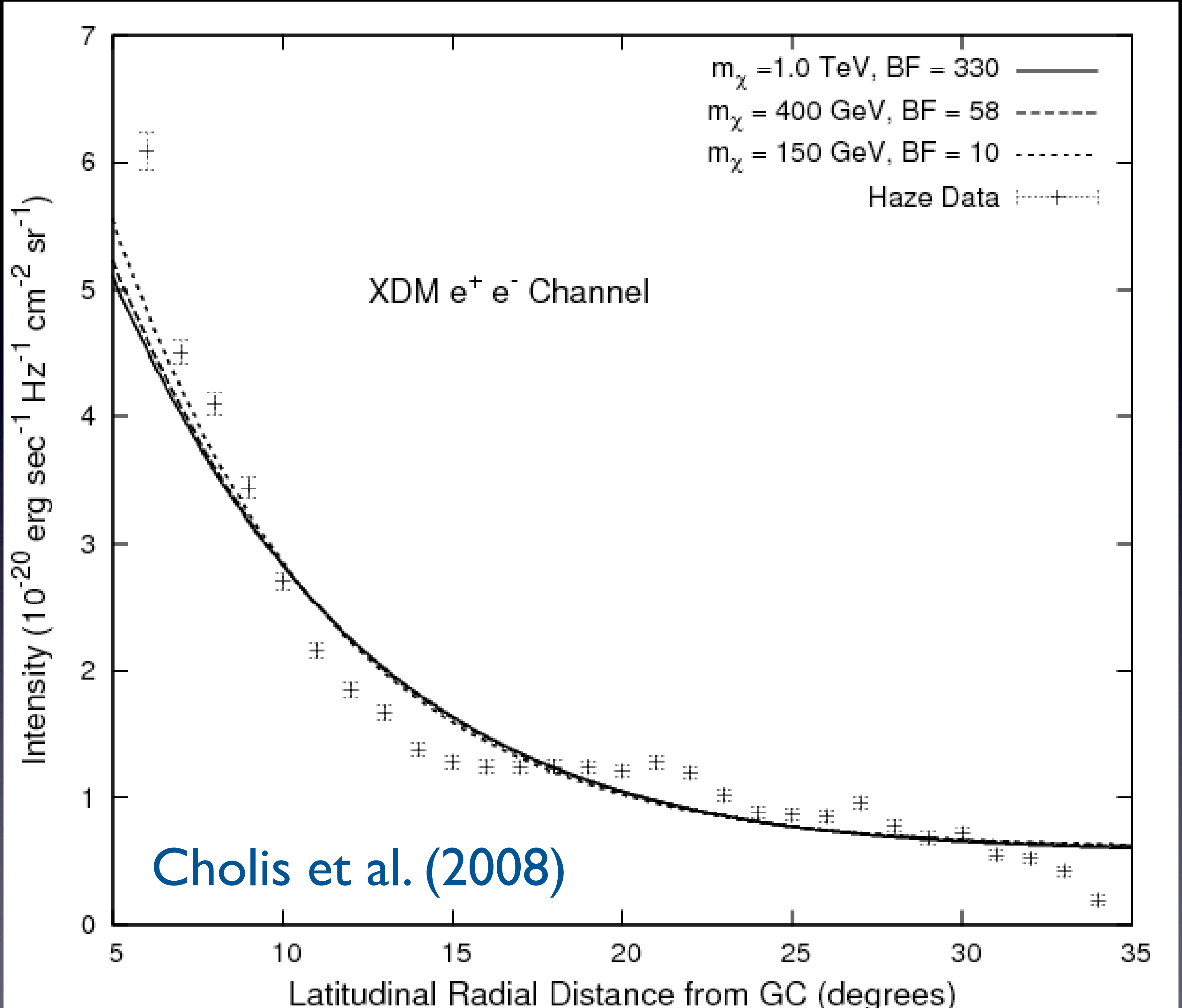
And it fits...



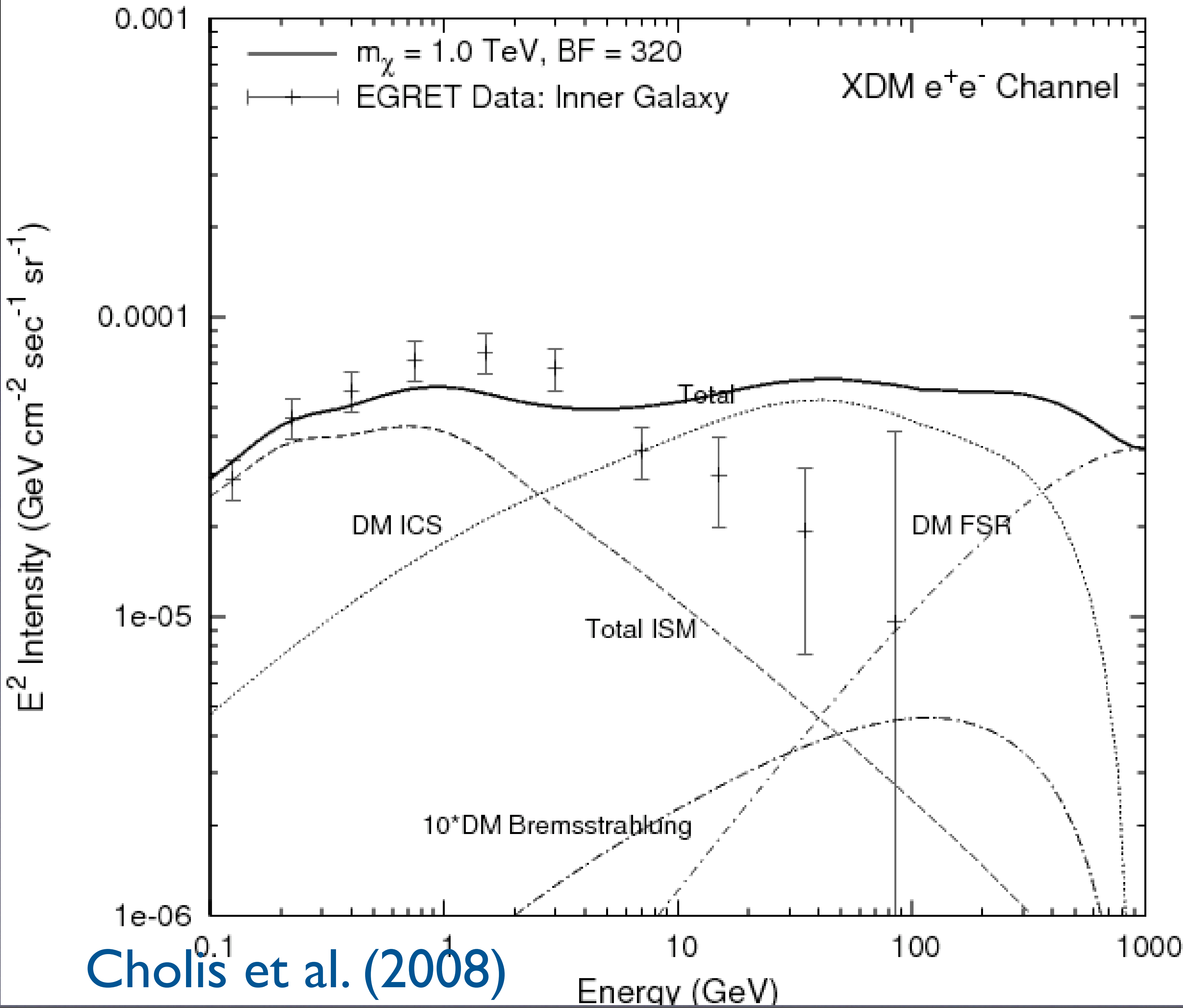
Cholis et al. (2008)



m_χ = 1.0 TeV, BF = 420 (DM + Background)
m_χ = 400 GeV, BF = 93 (DM + Background)
m_χ = 150 GeV, BF = 26 (DM + Background)
Background
ATIC Data
PPB-BETS Data
E^3 dN/dE (GeV^2 m^{-2} s^{-1} sr^{-1})
100
XDM e^+e^- Channel
DM Contribution
Cholis et al. (2008)
10
100
1000
Energy (GeV)



m_χ =1.0 TeV, BF = 330
m_χ = 400 GeV, BF = 58
m_χ = 150 GeV, BF = 10
Haze Data
XDM $e^+ e^-$ Channel
Intensity (10^{-20} erg sec^{-1} Hz^{-1} cm^{-2} sr^{-1})
Latitudinal Radial Distance from GC (degrees)
0
1
2
3
4
5
6
7
5
10
15
20
25
30
35
Cholis et al. (2008)



Cholis et al. (2008)

Which ingredients come from which experiments?

WIMP detection, near and far:

Local
(near Earth)

PAMELA
positrons

DAMA
annual mod.

Physics

Fermi
e+ e-

Dark
Matter?

muon
g-2

INTEGRAL
511 keV

EGRET
gammas

WMAP haze
(microwaves)

Galactic Center

WIMP detection, near and far:

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800 GeV

INTEGRAL
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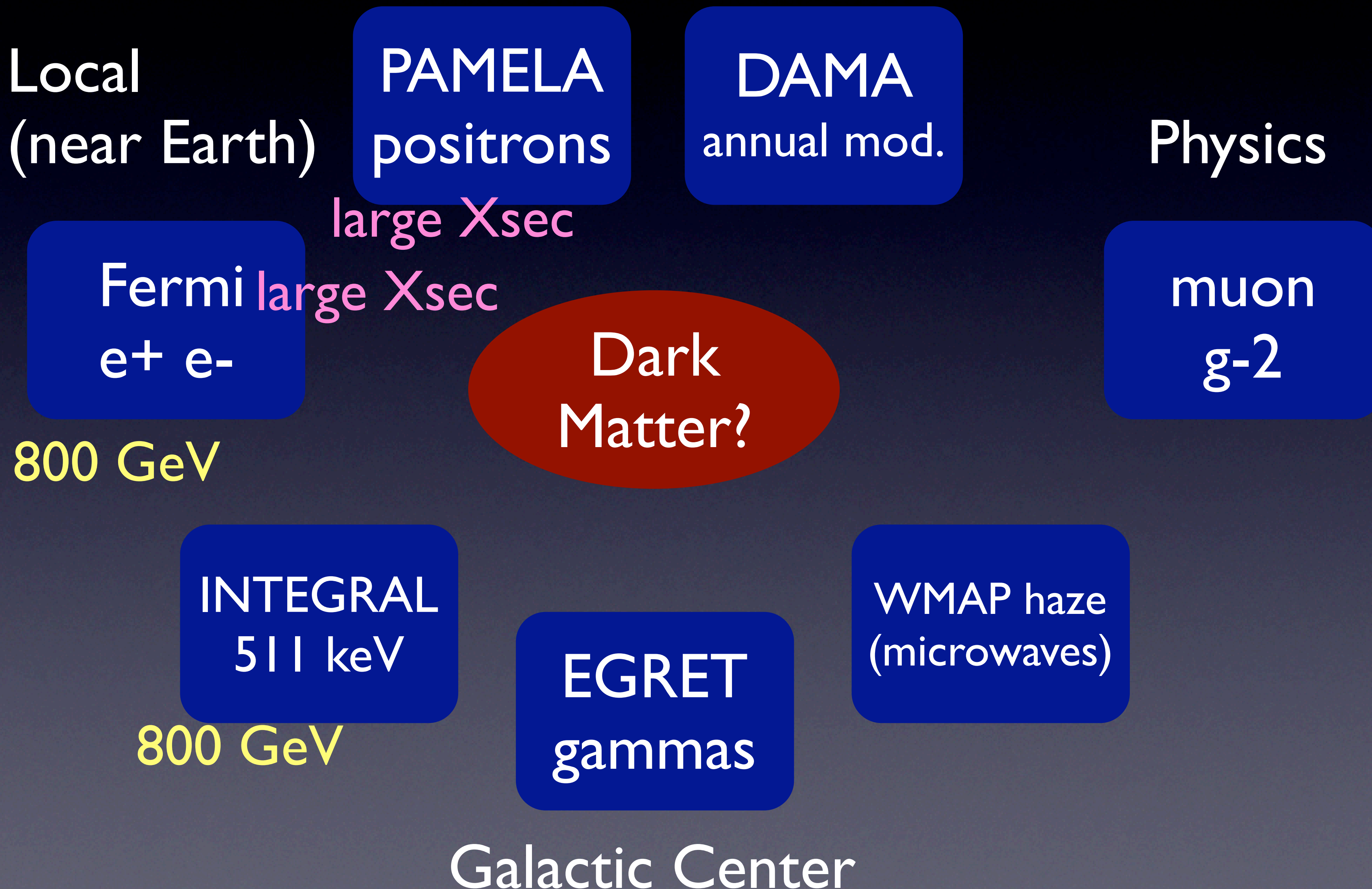
(microwaves)

Galactic Center

WIMP detection, near and far:



WIMP detection, near and far:

Local
(near Earth)

PAMELA
positrons

large Xsec

DAMA
annual mod.

inelastic

Physics

Fermi
e+ e-

large Xsec

800 GeV

Dark
Matter?

muon
g-2

INTEGRAL
511 keV

inelastic

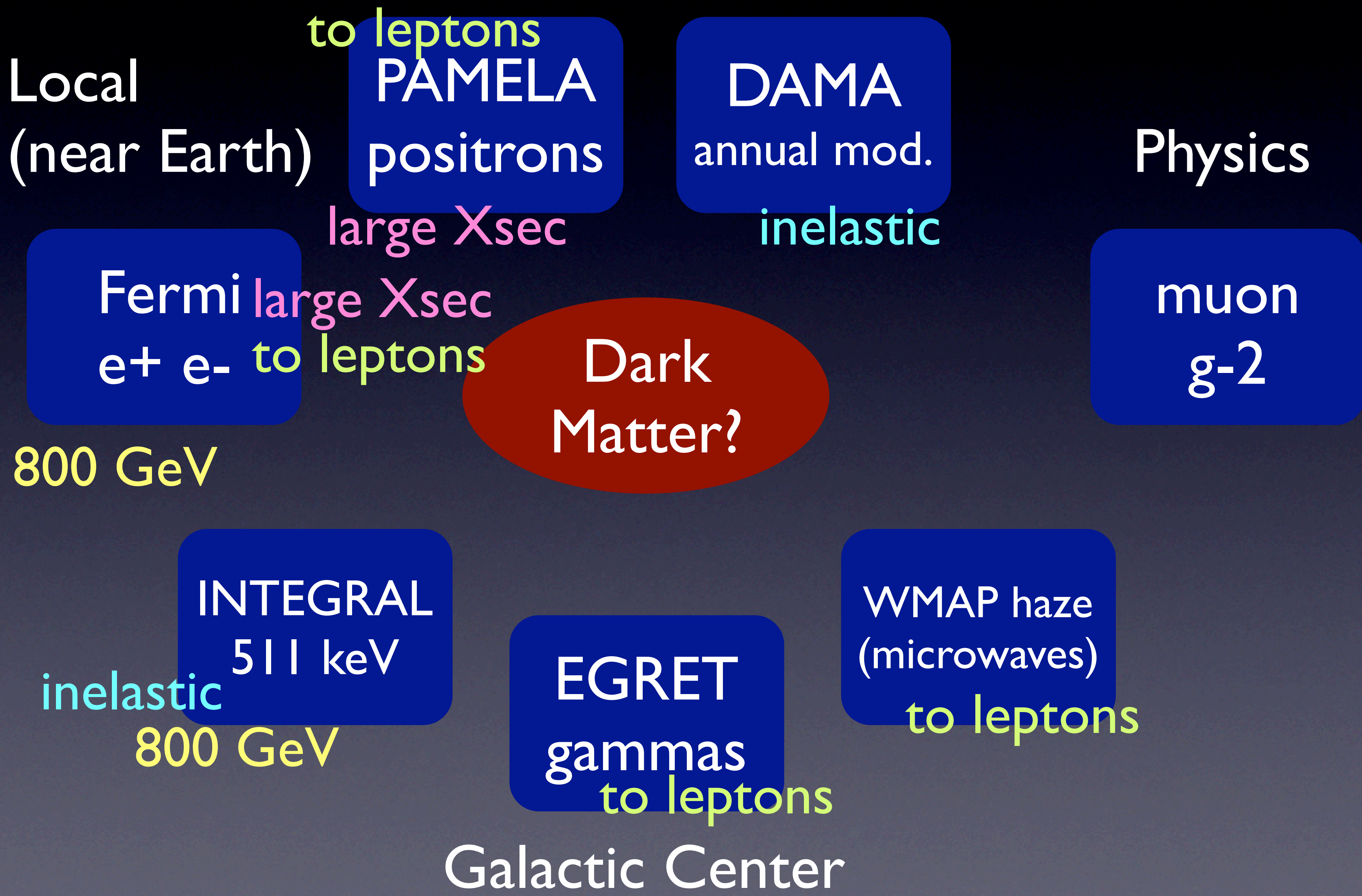
800 GeV

EGRET
gammas

WMAP haze
(microwaves)

Galactic Center

WIMP detection, near and far:



WIMP detection, near and far:

Local (near Earth)

to leptons

PAMELA positrons

large Xsec

photon mixing

DAMA annual mod.

inelastic

Physics

Fermi e+ e-

large Xsec

to leptons

800 GeV

Dark Matter?

muon g-2

photon mixing

INTEGRAL 511 keV

inelastic

800 GeV

EGRET gammas

to leptons

WMAP haze (microwaves)

to leptons

Galactic Center

Why is the claim of a new light gauge boson robust?

* If you only had PAMELA
  => high cross section => Sommerfeld
  => goes to leptons => annihilate through light state

* If you believe DAMA
  => inelastic scattering => mass splittings generated by phi vev

* If you have WMAP haze and/or Fermi ICS gammas
  => hard spectrum => decay through phi

So we are led to a new light state (most easily a non-Abelian vector boson) that couples to DM and very weakly to electric charge via a kinetic mixing.

Because this does *everything* I have talked about (including g-2) we have *over-fit* the model.

But if *any* part of this story is true, we have a new ~ GeV scale force in the dark sector.

Summary:

A new force in the dark sector, mediated by a new gauge boson, ϕ, has these appealing features:

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