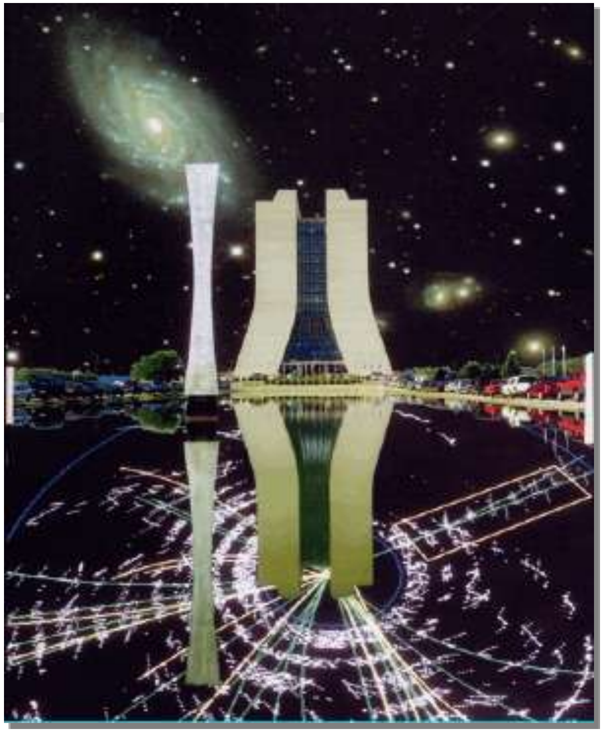
Recent Developments in the Indirect Detection of Dark Matter

Dan Hooper

Fermilab/University of Chicago



The University of Tokyo, IPMU

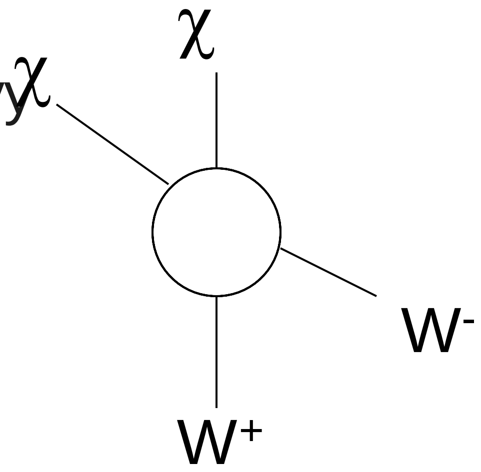
Focus Week on Indirect Dark Matter Searches

December 10, 2009

The Indirect Detection of Dark Matter

1. **WIMP Annihilation**

Typical final states include heavy fermions, gauge or Higgs bosons



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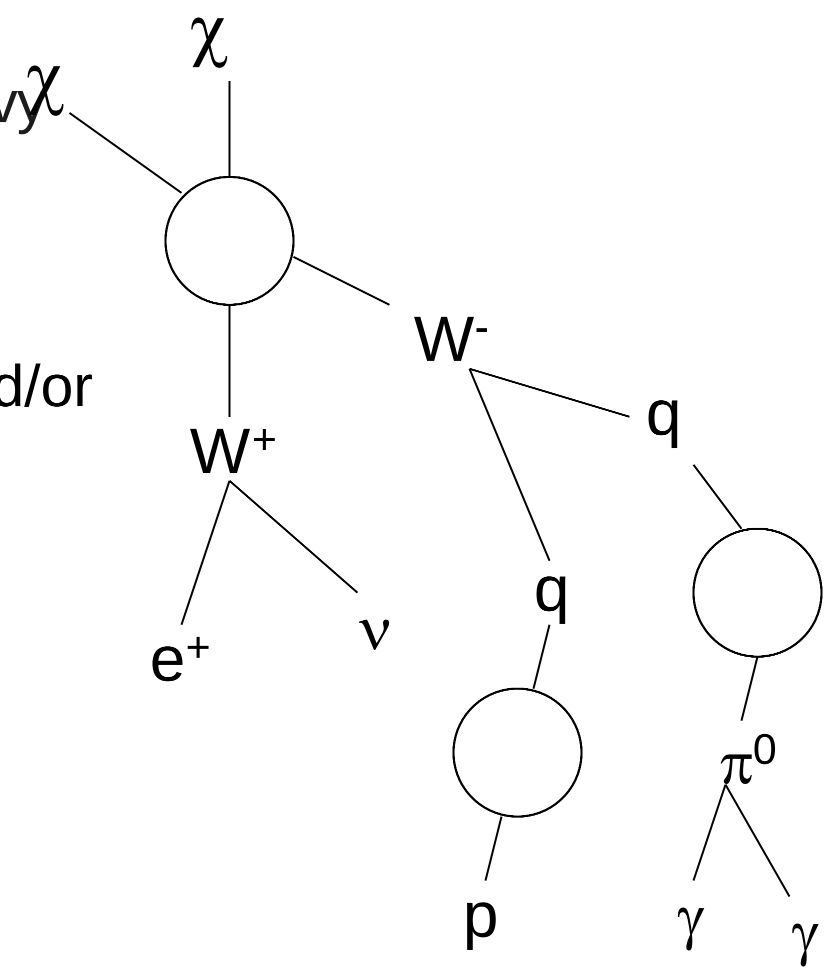
2. **Fragmentation/Decay**
   Annihilation products decay and/or fragment into combinations of
   electrons, protons, deuterium, neutrinos and gamma-rays



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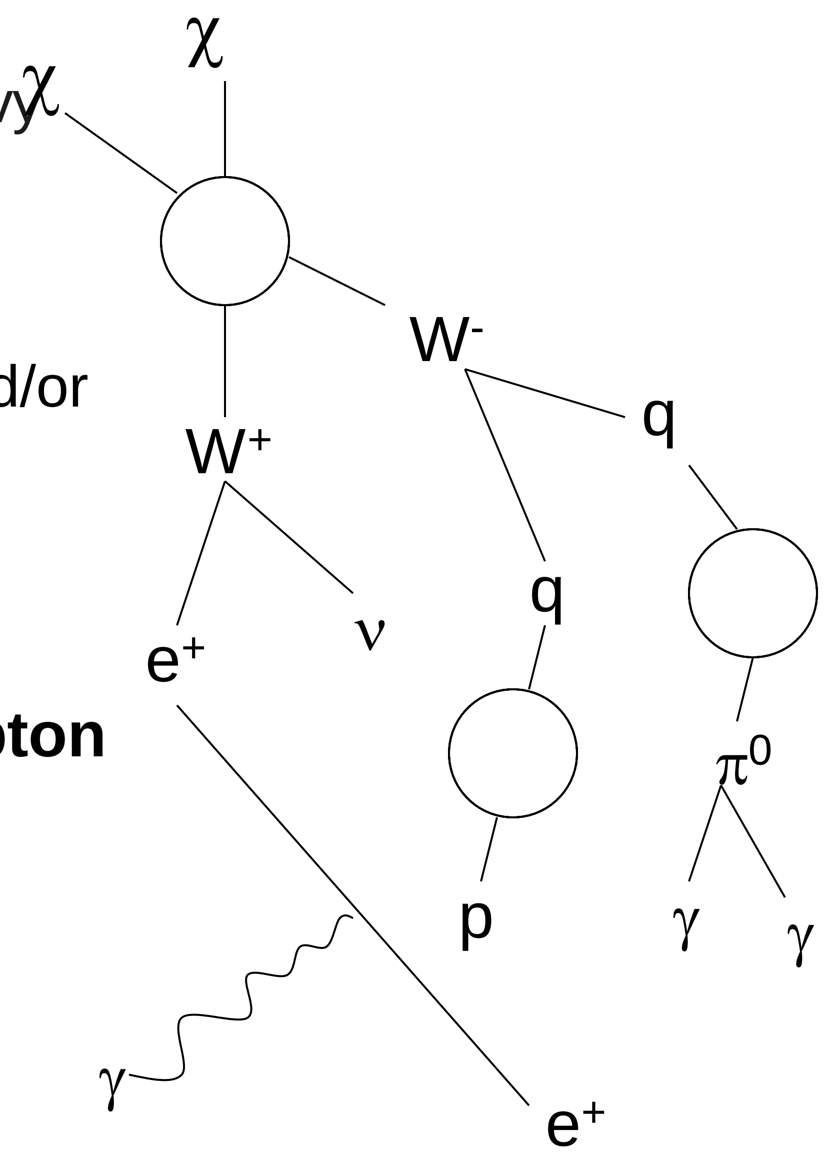
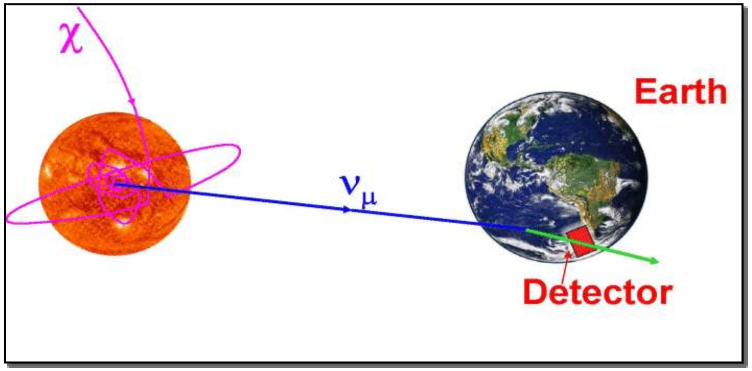
2. **Fragmentation/Decay**
   Annihilation products decay and/or fragment into combinations of electrons, protons, deuterium, neutrinos and gamma-rays

3. **Synchrotron and Inverse Compton**
   Relativistic electrons up-scatter starlight/CMB to MeV-GeV energies, and emit synchrotron photons via interactions with magnetic fields



The Indirect Detection of Dark Matter

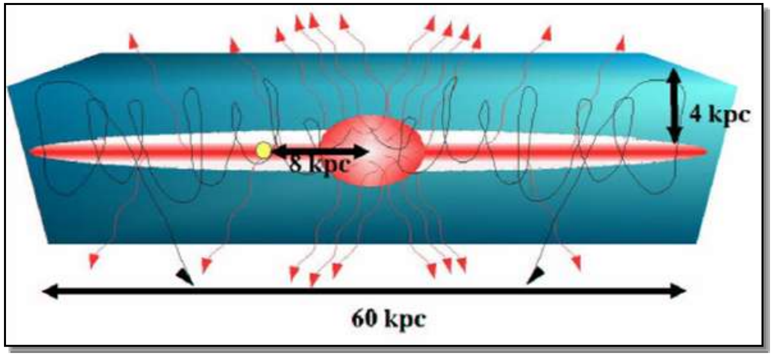
- **Neutrinos** from annihilations in the core of the Sun



- **Gamma Rays** from annihilations in the galactic halo, near the galactic center, in dwarf galaxies, etc.

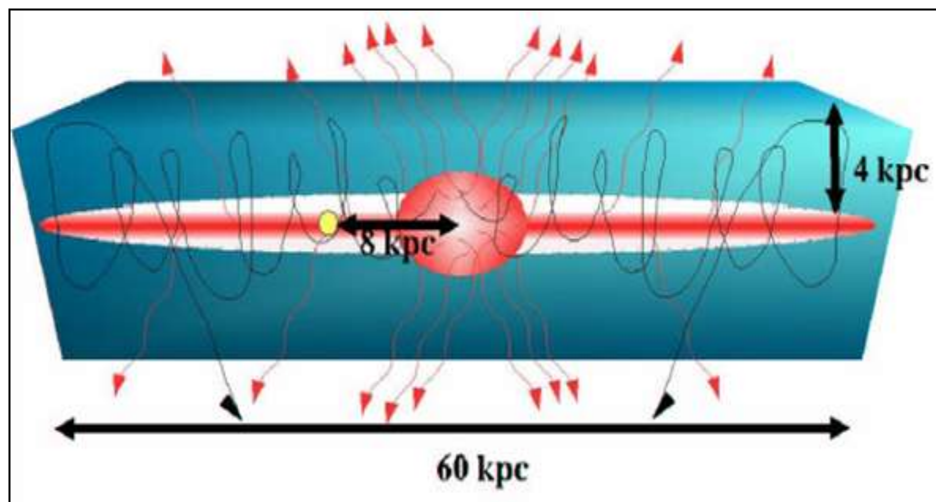
- **Positrons/Antiprotons** from annihilations throughout the galactic halo

- **Synchrotron Radiation** from electron/positron interactions with the magnetic fields of the inner galaxy



Dark Matter With Charged Cosmic Rays

- WIMP annihilation products fragment and decay, generating equal numbers of electrons and positrons, and of protons and antiprotons
- Charged particles move under the influence of the Galactic Magnetic Field; Electrons/positrons lose energy via synchrotron and inverse Compton scattering
- Astrophysical sources are expected to produce matter than antimatter; positron/antiproton the cosmic ray could provide matter



Cosmic Rays Propagation In The Milky Way

- Many effects and processes impact the way that cosmic rays propagate through our galaxy, including: spatial diffusion, energy losses, diffusion in momentum space (diffusive reacceleration), electron K-capture, convection, spallation, radioactive decay; modeled by:

QuickTime™ and a
decompressor
are needed to see this picture.

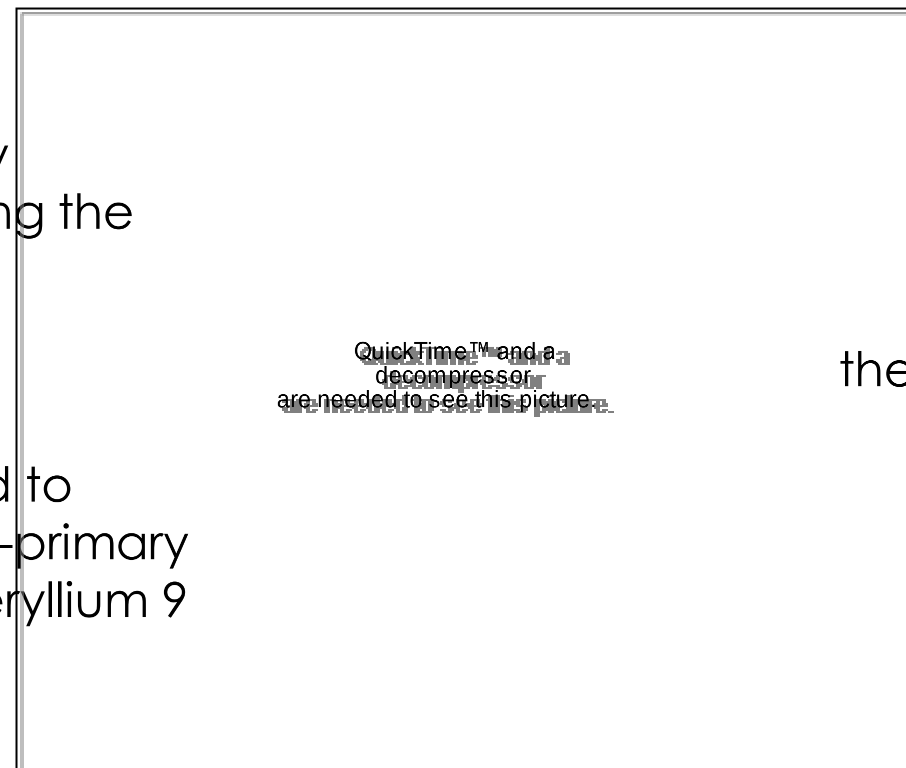
- To solve (in the steady-state limit), we need: the diffusion constant, convection velocity, matter and radiation/magnetic field distributions, Alfven speed, source distribution/spectrum, and boundary conditions

Constraining The Diffusion Model

- The diffusion parameters can be constrained by measurements of stable secondary-to-primary ratios (such as boron-to-carbon) in the cosmic ray spectrum

- This provides a measure of how much material an average cosmic ray traveled through before reaching the Solar System

- To break the degeneracy between the size of the diffusion zone and the diffusion constant, we also need to consider unstable secondary-to-primary ratios, such as Beryllium 10-to-Beryllium 9



Simet and Hooper, JCAP, 0904.2398

Constraining The Diffusion Model

- Using a simple diffusion model (cylindrical symmetry, uniform diffusion, neglecting convection), we can use stable and unstable secondary-to-primary ratios, along with models of the ISM matter and radiation fields, to attain a well defined, constrained model

- Free parameters:

1) diffusion coefficient, D_{0xx}
2) Rigidity dependence of D_{xx}, α
3) Free escape boundary condition, L_{eff}

QuickTime™ and a
decompressor
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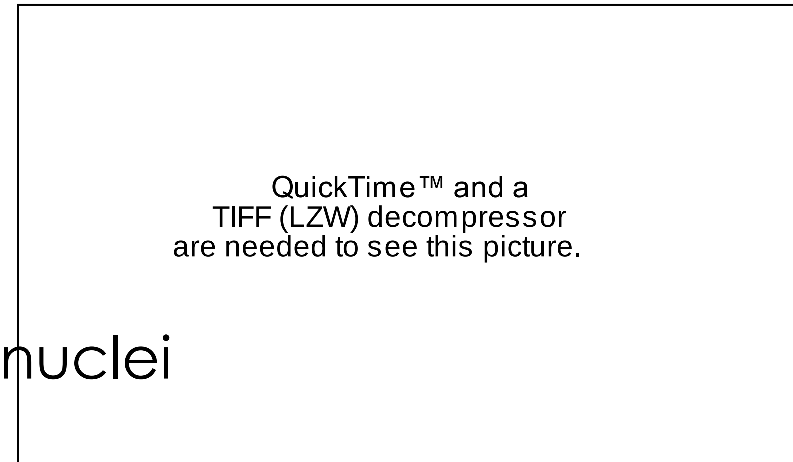
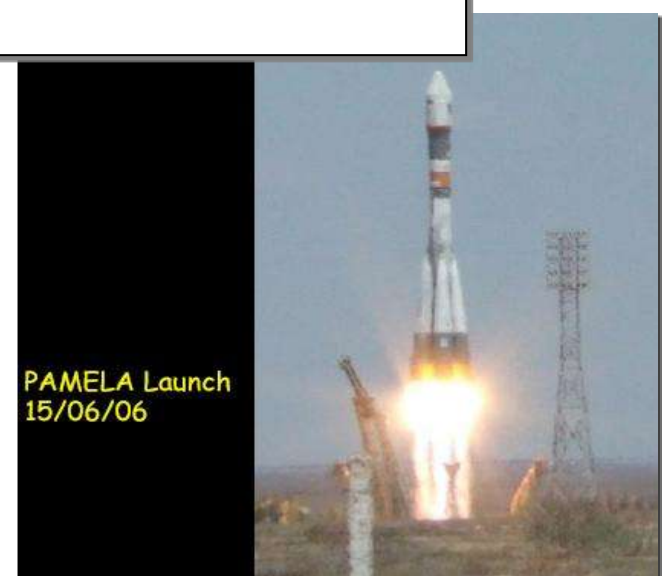
Simet and Hooper, JCAP, 0904.2398

Charged Particle Astrophysics With Pamela

- Major step forward in sensitivity to GeV-TeV cosmic ray electrons, positrons, protons, antiprotons, and light nuclei

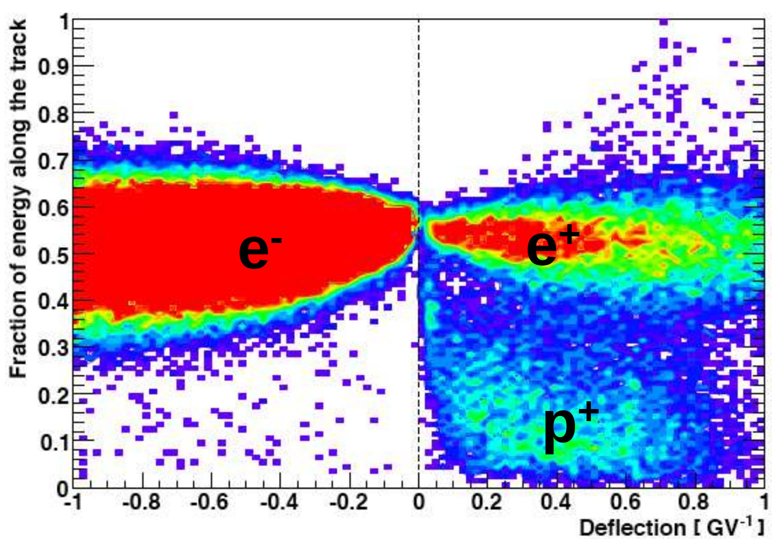


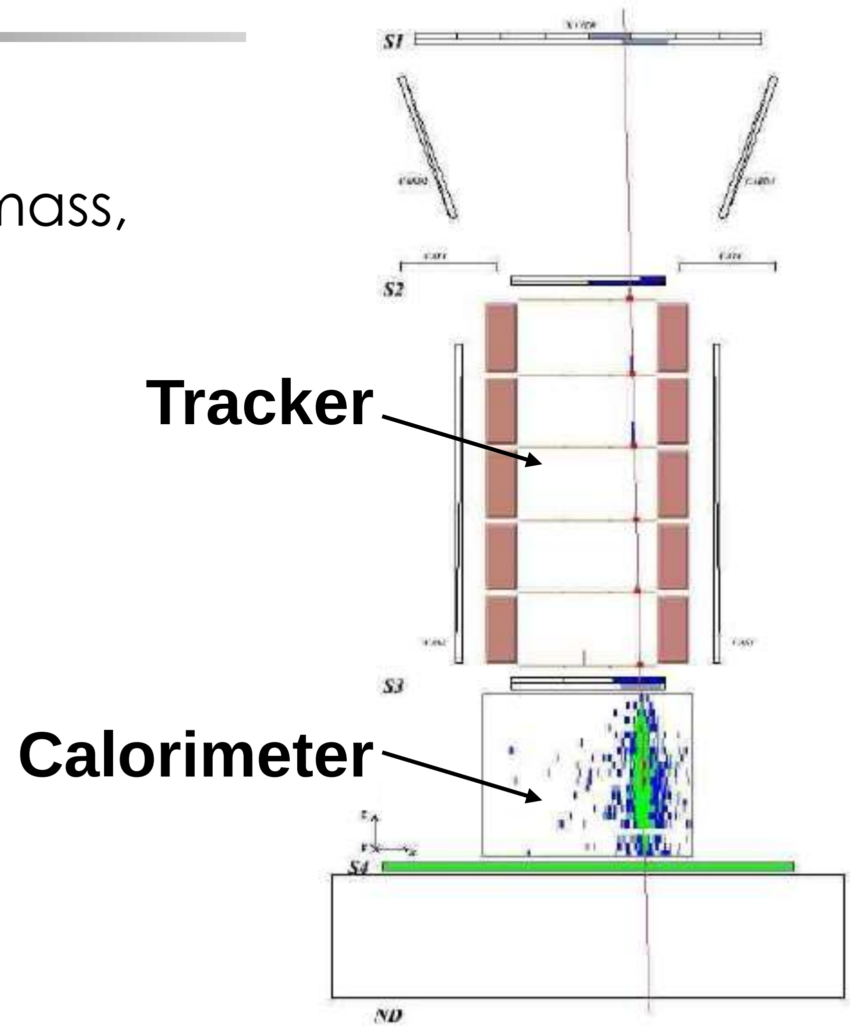
- Among other science goals, PAMELA hopes to identify or constrain dark matter annihilations in the Milky Way halo by measuring the cosmic positron and antiproton spectra



Charged Particle Astrophysics With Pamela

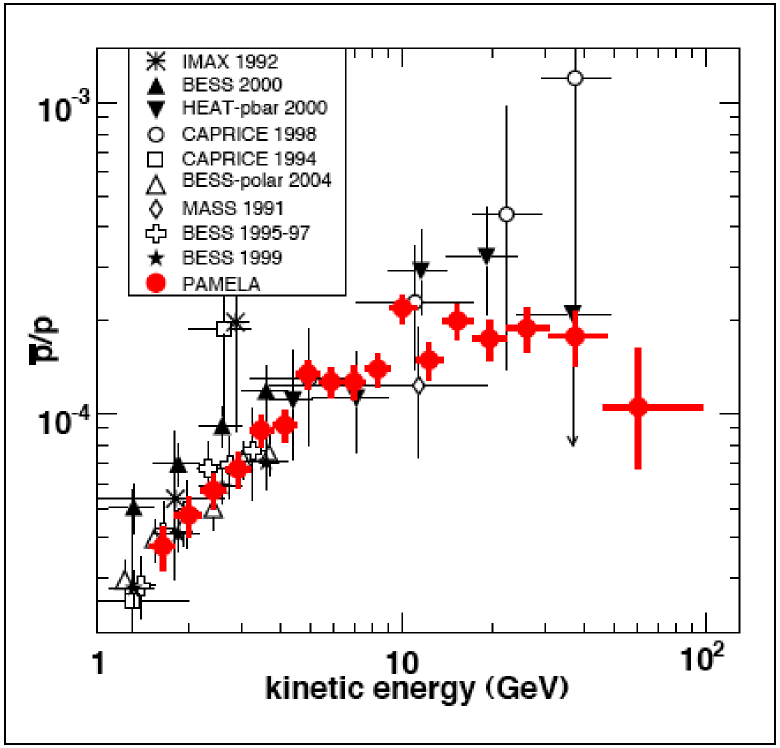
- Combination of tracker and calorimeter enable charge, mass, and energy determinations
- Very accurate particle ID





Pamela's New Antiproton Measurement

- A secondary-to-primary ratio, like B/C, but also a potential probe of dark matter
- Best measurement to date
- Dramatically smaller error bars above ~1-10 GeV



Pamela Collaboration, arXiv:0810.4994

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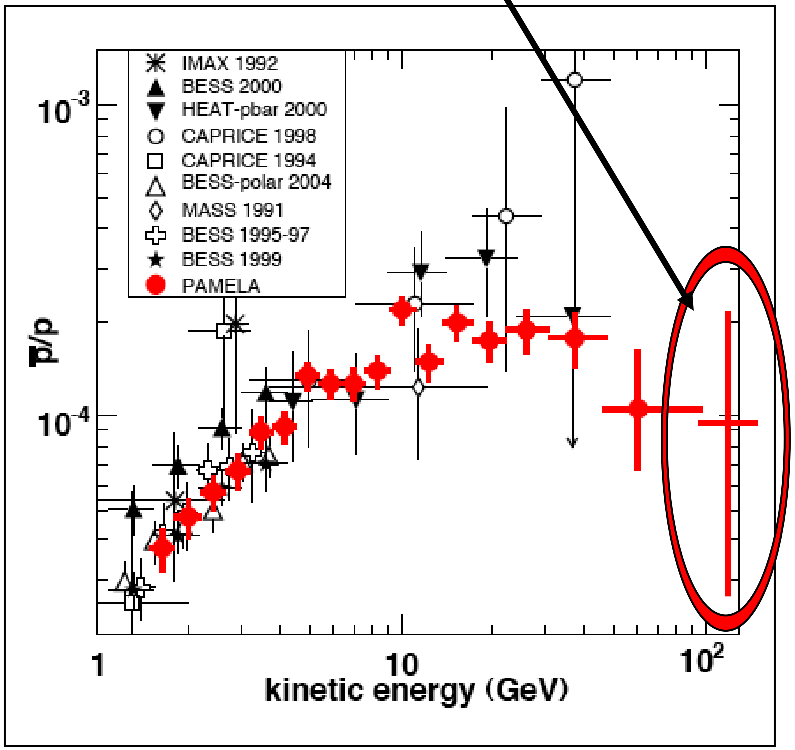
New error bar! (preliminary)



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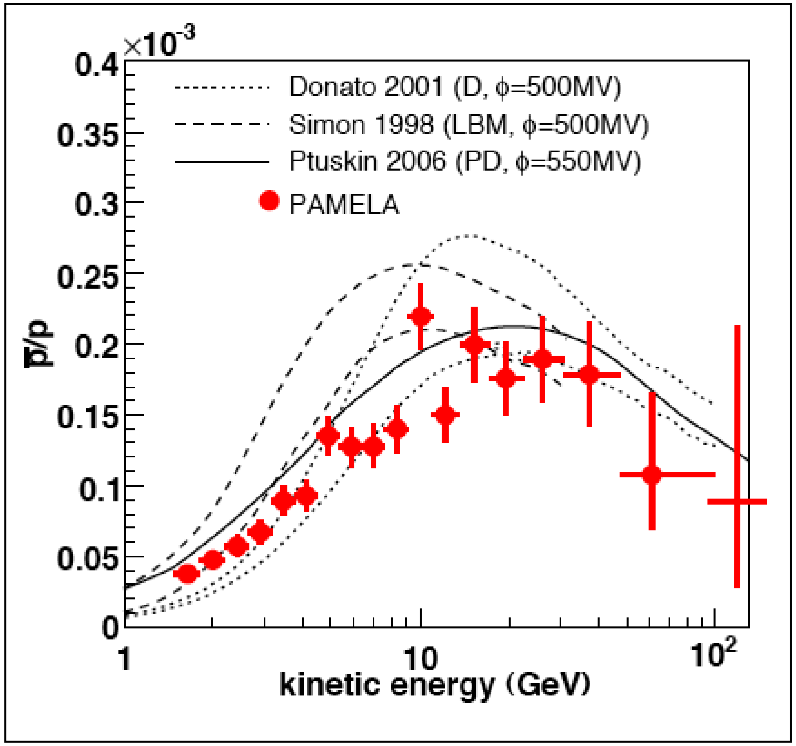
- A secondary-to-primary ratio, like B/C, but also a potential probe of dark matter
- Best measurement to date
- Dramatically smaller error bars above ~1-10 GeV
- The antiprotons detected by Pamela are consistent with being entirely from secondary production (byproduct of cosmic ray propagation)



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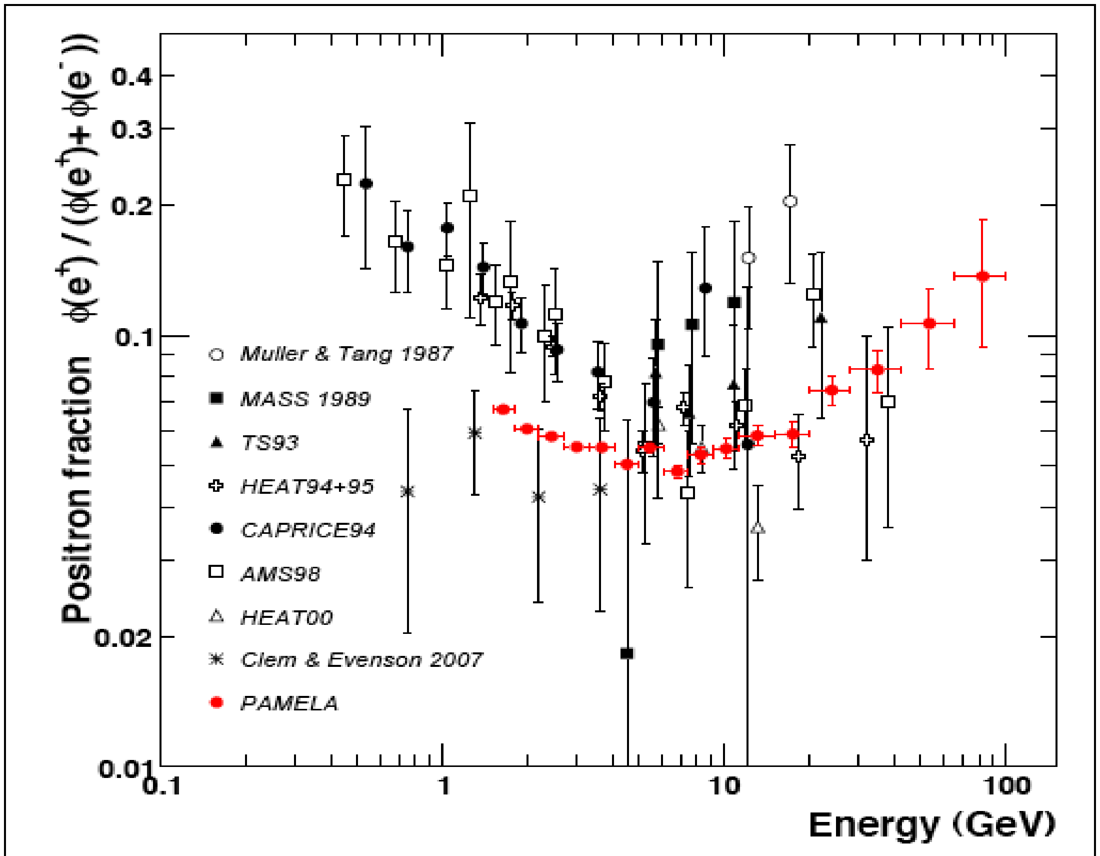


Dan Hooper - *Charged Cosmic Rays and Dark Matter*

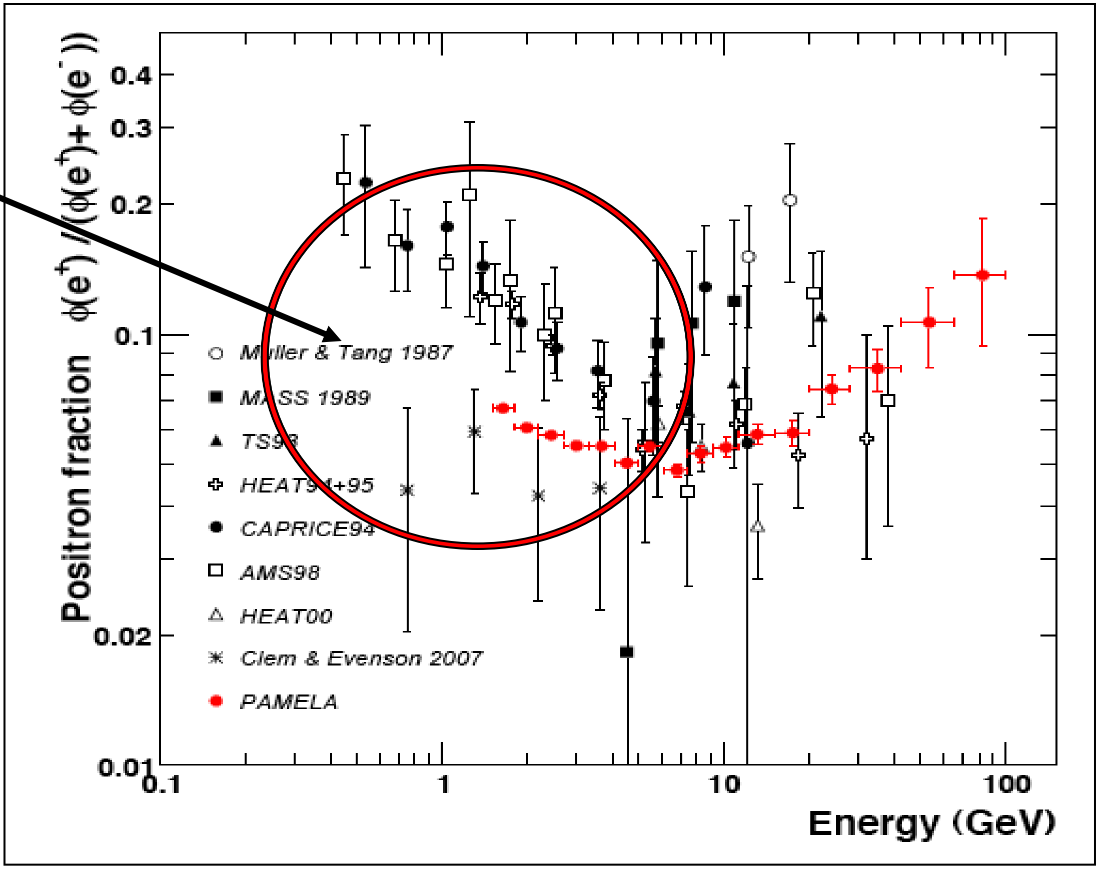
Pamela Collaboration, arXiv:0810.4995

Pamela's New Positron Measurement

First glance:
-Is this all screwed up?

Charge-dependent solar modulation important below 5-10 GeV!

(Pamela's sub-10 GeV positrons appear as they should!)



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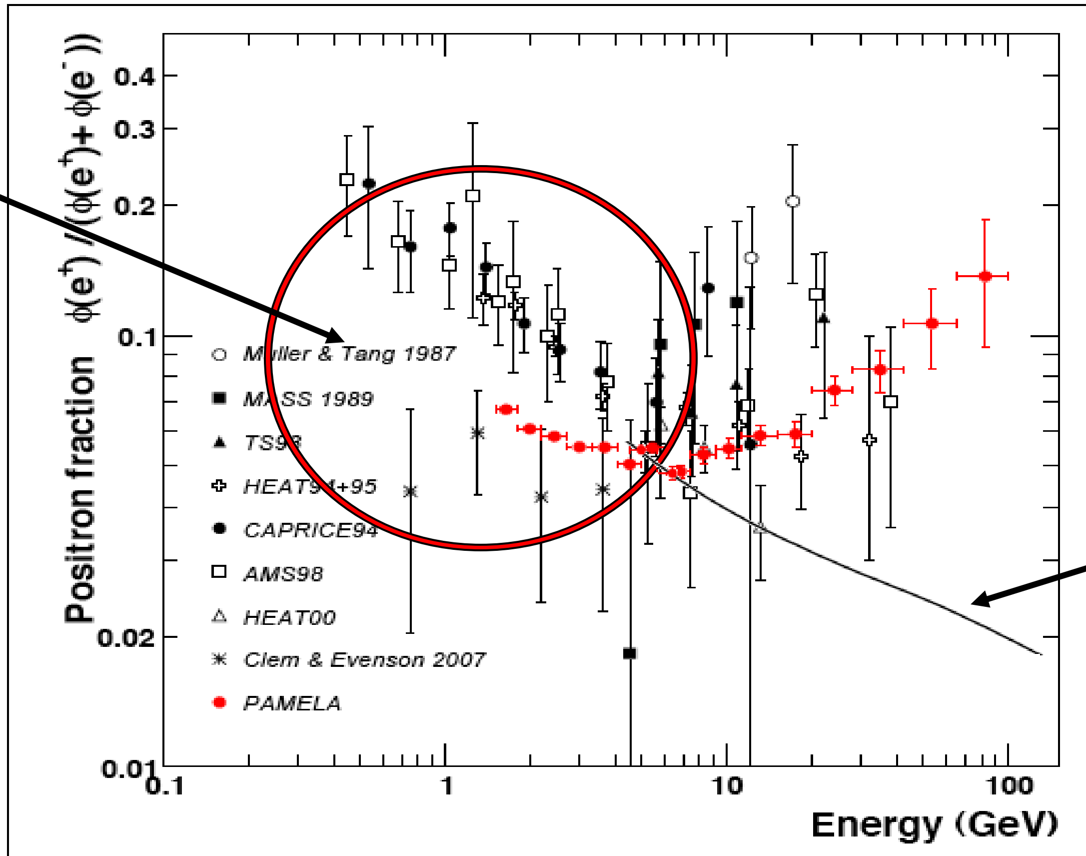

Astrophysical expectation (secondary production)

Pamela Collaboration, arXiv:0810.4995

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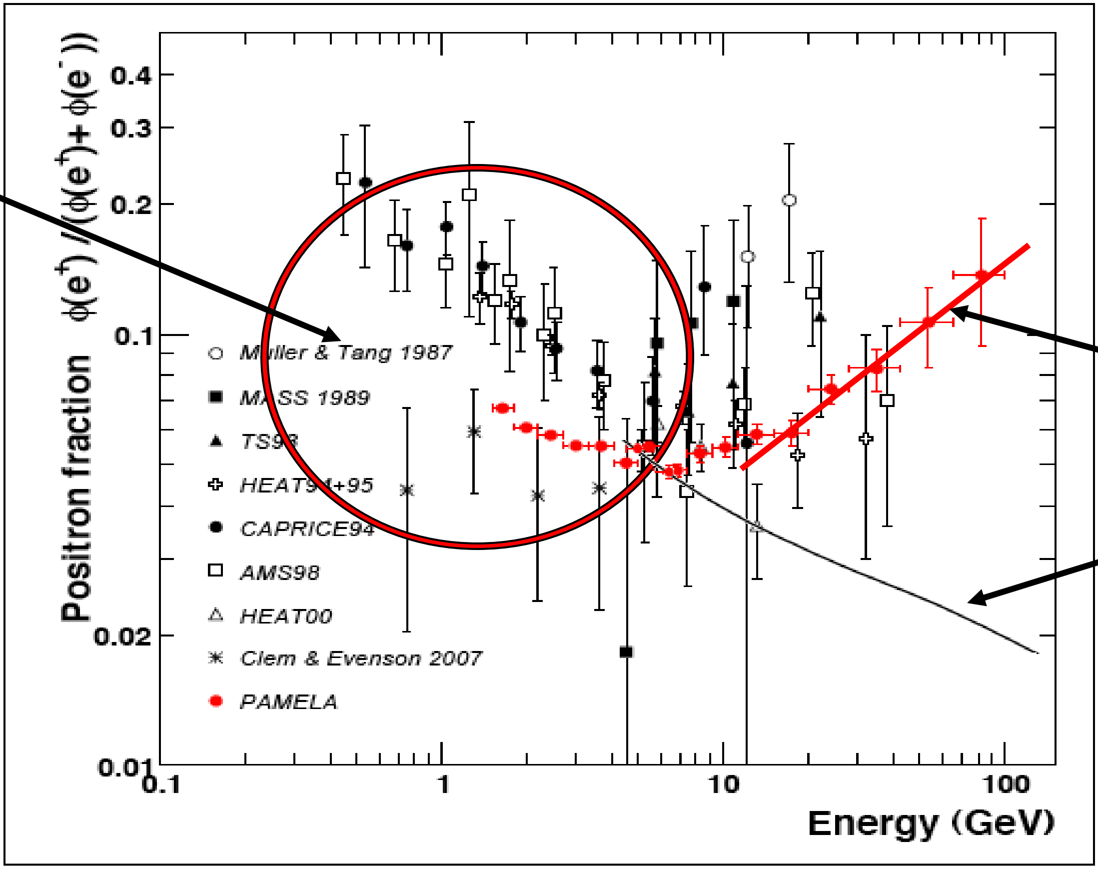


Rapid climb above 10 GeV indicates the presence of a <u>primary source of cosmic ray positrons!</u>

Astrophysical expectation (secondary production)

Pamela Collaboration, arXiv:0810.4995

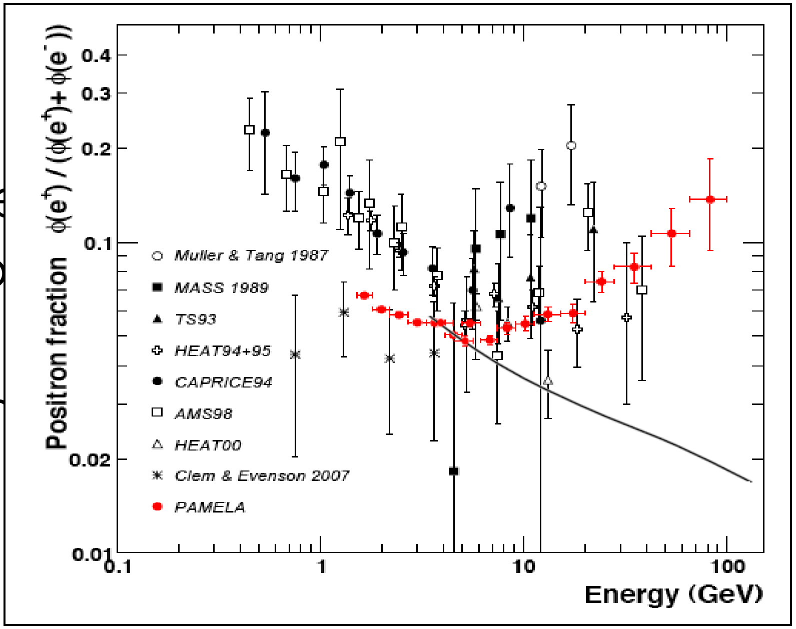
Conventional Explanations For PAMELA's Positron Excess

Conventional Explanations For PAMELA's Positron Excess

An Attempt At A Conventional Explanation For PAMELA's Positron Excess

- The standard prediction for secondary positron production is calculated by combining the spectrum of cosmic ray protons, the density of targets, and the spectrum of cosmic ray electrons; Unavoidably leading to the prediction of a steadily falling positron fraction

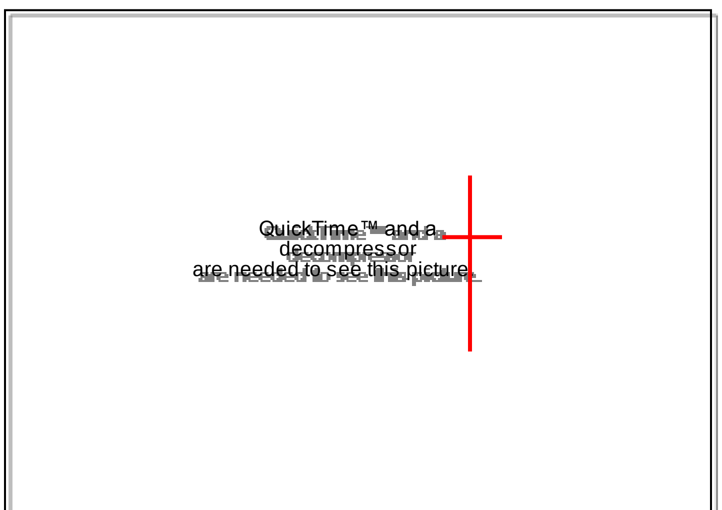
- It has recently been suggested that if secondary positrons are produce *inside of* cosmic ray acceleratio regions, their spectrum may be hardened, potentially causing th positron fraction to rise



P. Blasi, arXiv:0903.2794

An Attempt At A Conventional Explanation For PAMELA's Positron Excess

- The acceleration of positron secondaries, however, should be accompanied by the acceleration of antiproton, boron, and other secondary species
- This is not observed



Blasi and Serpico, PRL, arXiv:0904.0871

Sarkar and Mertsch, PRL, arXiv:0905.3152

High-Energy Positrons From Nearby Pulsars

- Rapidly spinning (~msec period) neutron stars, accelerate electrons to very high energies (power from slowing rotation - spindown)

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Blasi and Serpico, arXiv:0810.1527 Yukse
Kistler, Stanev, arXiv:0810.2784 Profumo,
arXiv:0812.4457

High-Energy Positrons From Nearby Pulsars

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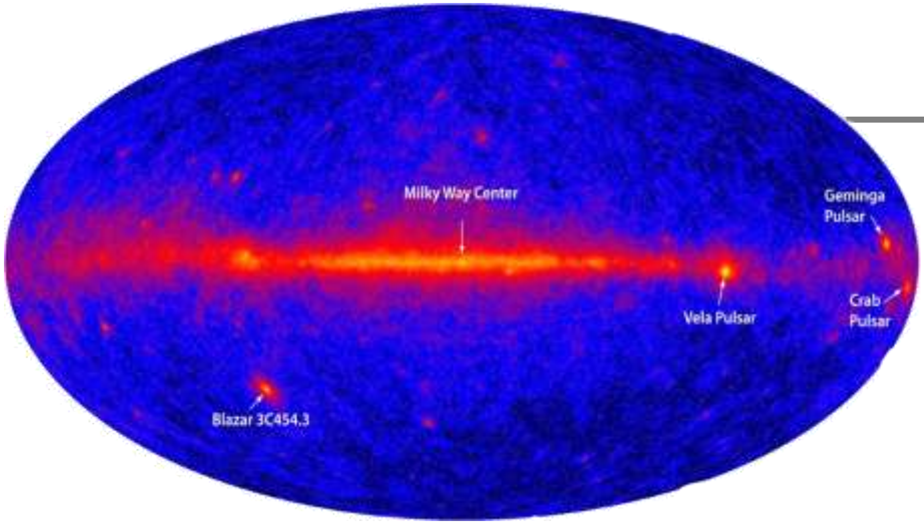

Fermi/Glast Sky Map

High-Energy Positrons From Nearby Pulsars

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Vela Pulsar (12,000 years old)

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- Most of the spindown power is expended in first ~10^5 years

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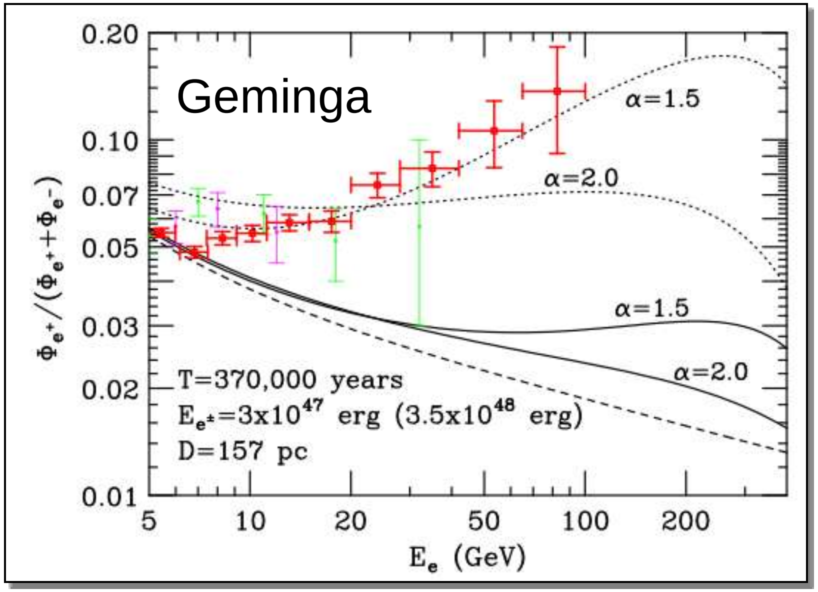
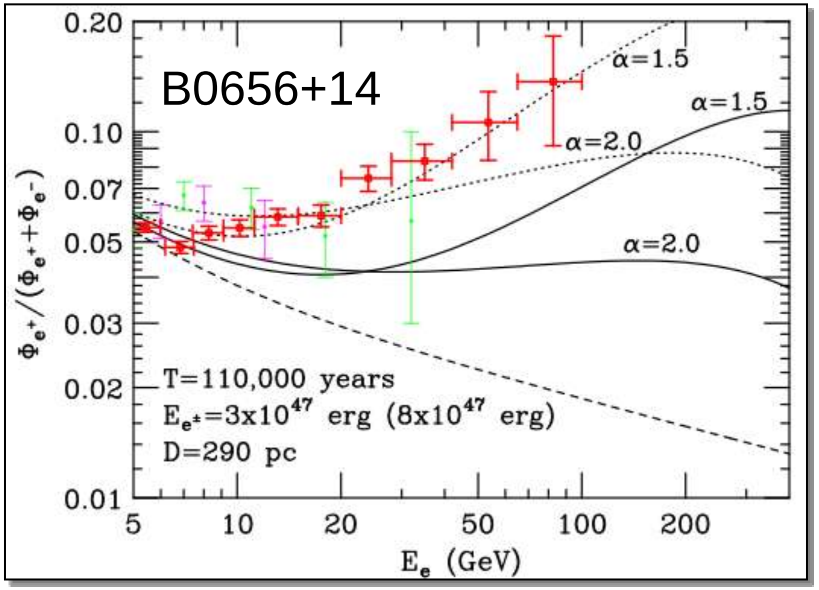
Vela Pulsar (12,000 years old)

High-Energy Positrons From Nearby Pulsars

Two promising candidates:

- Geminga (157 pc away, 370,000 years old)
- B0656+14 (290 pc, 110,000 years)





Hooper, P. Blasi, P. Serpico, JCAP, arXiv:0810.1527

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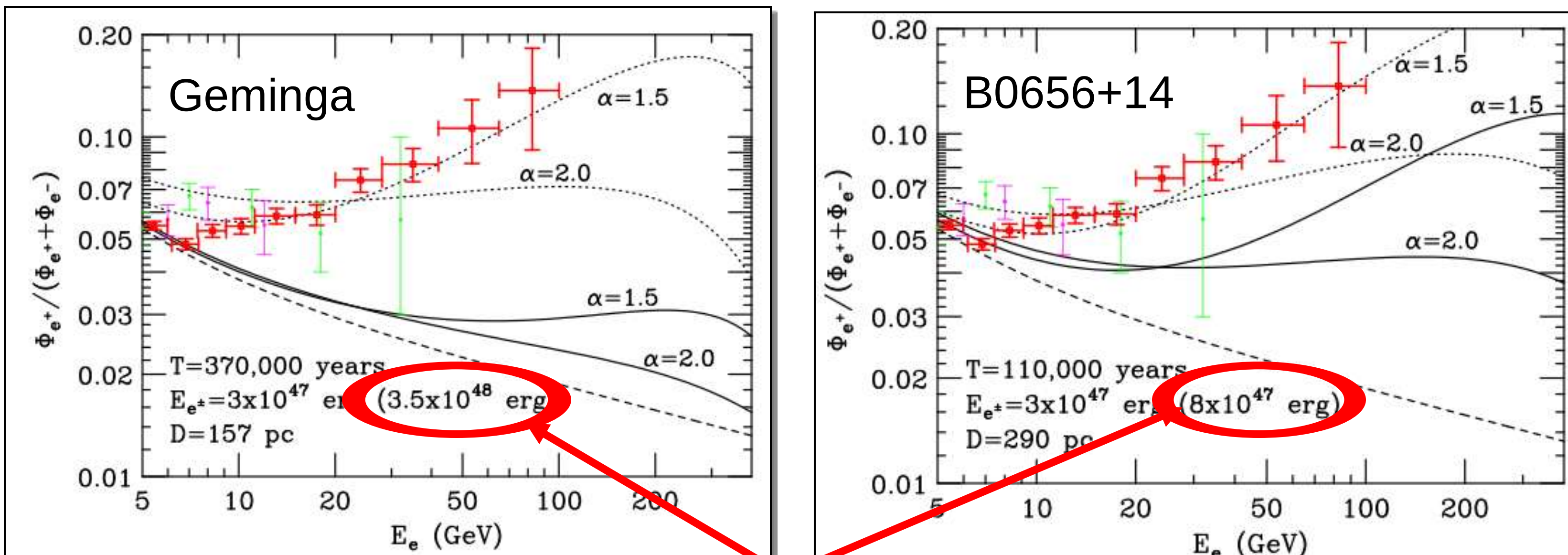


Tens of percent of the total spindown energy is needed in high energy e^+e^- pairs!

Hooper, P. Blasi, P. Serpico, JCAP, arXiv:0810.1527

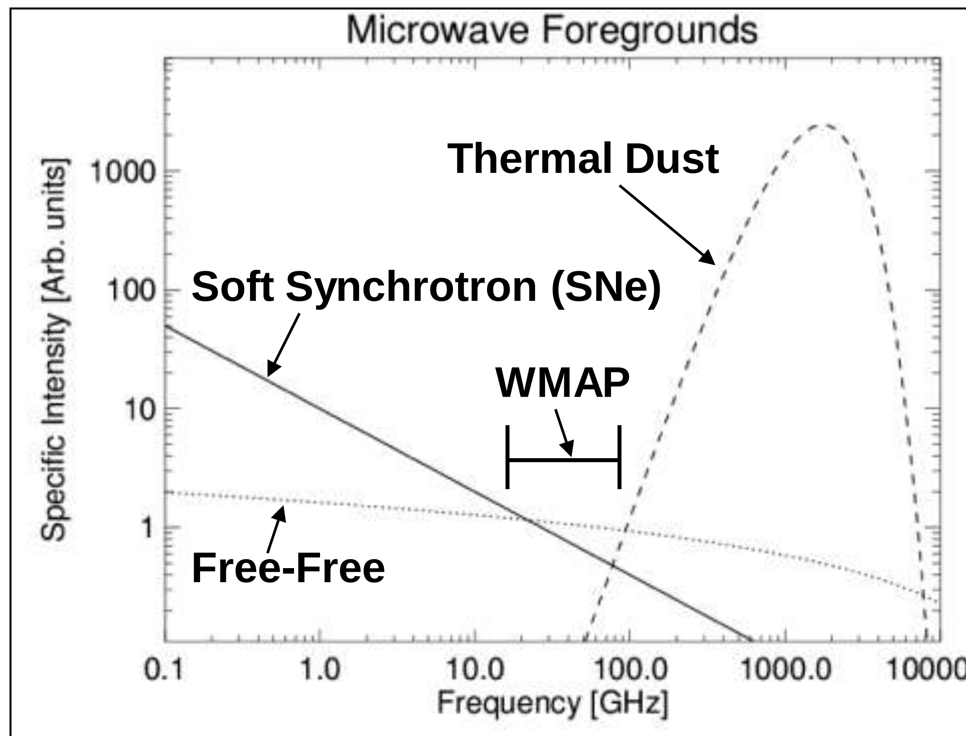
The Cosmic Ray Electron Spectrum

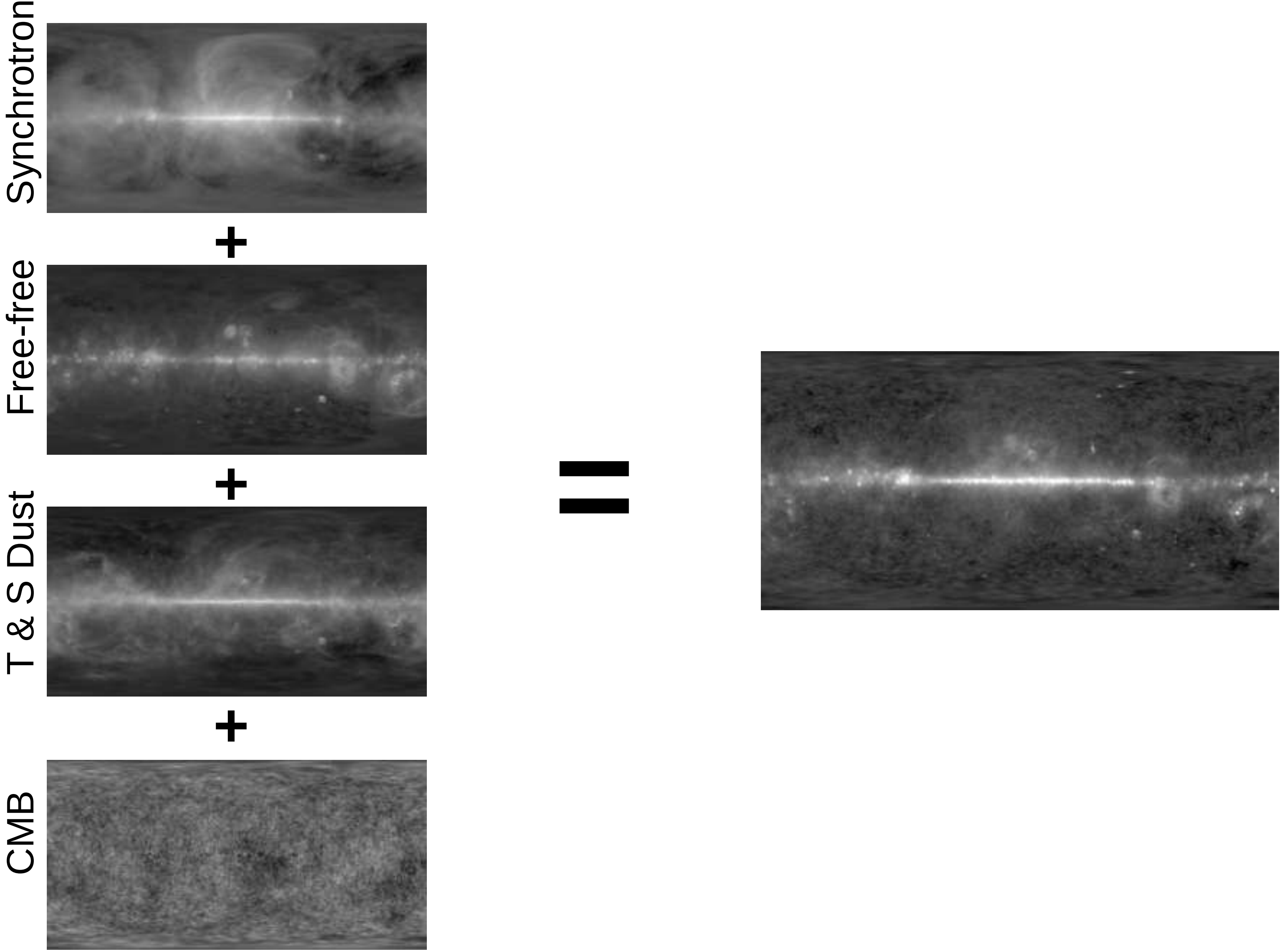
- In a series of balloon flights, ATIC measured an excess of cosmic ray electrons between 300 and 800 GeV (Nature, Nov. 21, 2008)

- More recent results from Fermi and HESS measure a less pronounced feature, but still an excess relative to a simple power-law

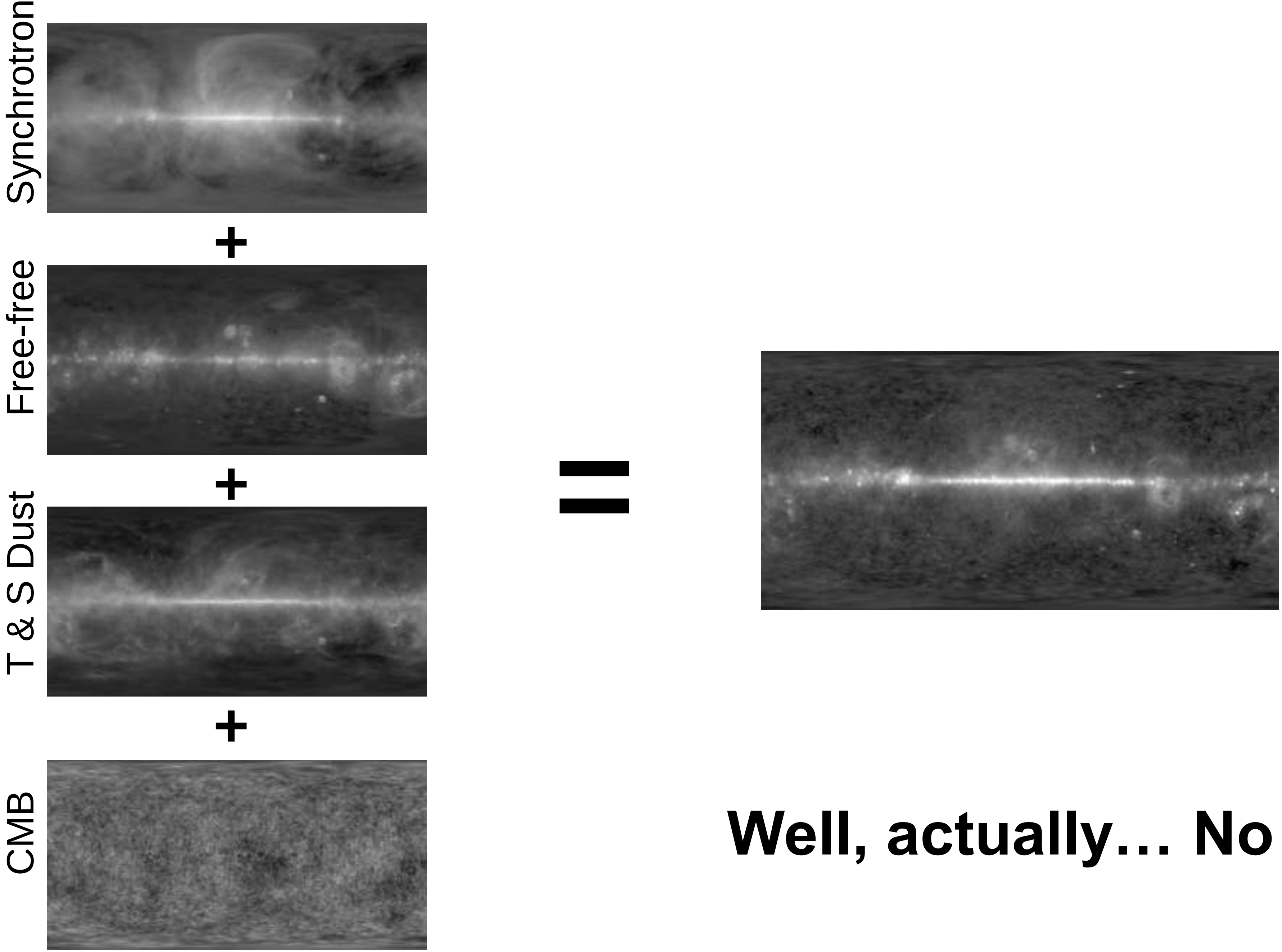
WMAP and Energetic Electrons/Positrons

- WMAP does not only detect CMB photons, but also a number of galactic foregrounds
- GeV-TeV electrons emit synchrotron in the range of WMAP

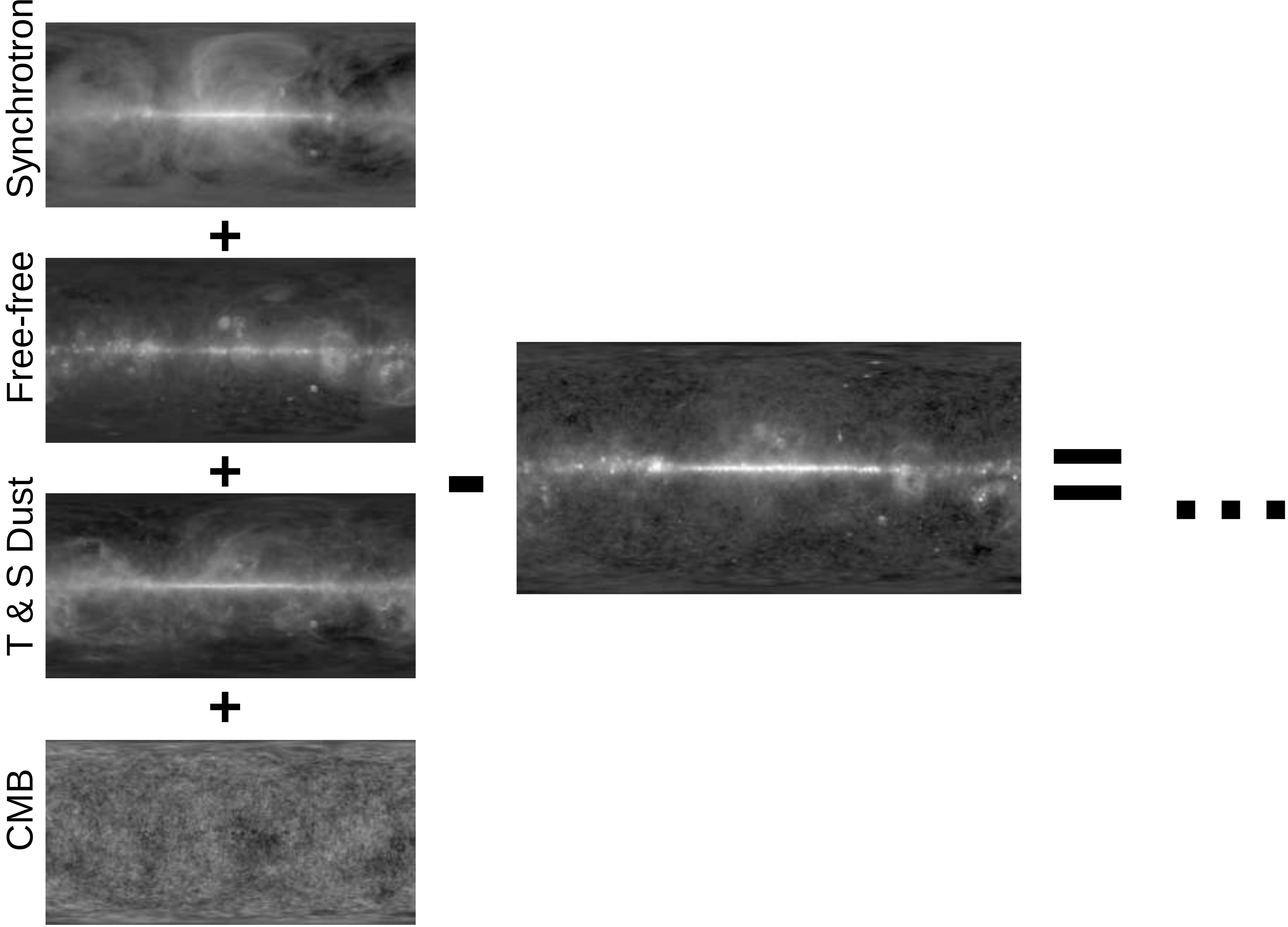




Synchrotron
+
Free-free
+
T & S Dust
+
CMB
=



Well, actually… No


Synchrotron
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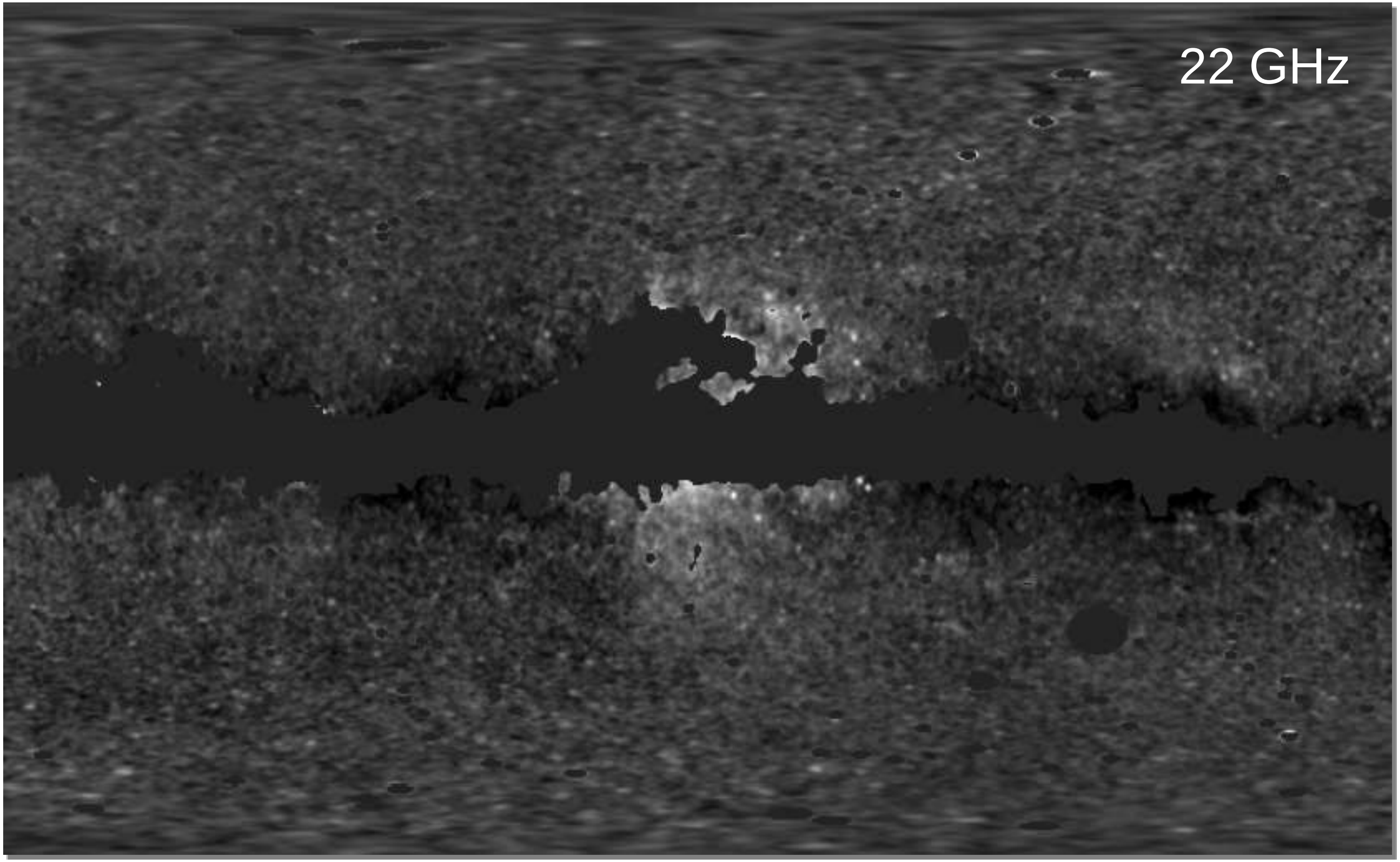
"The WMAP Haze"



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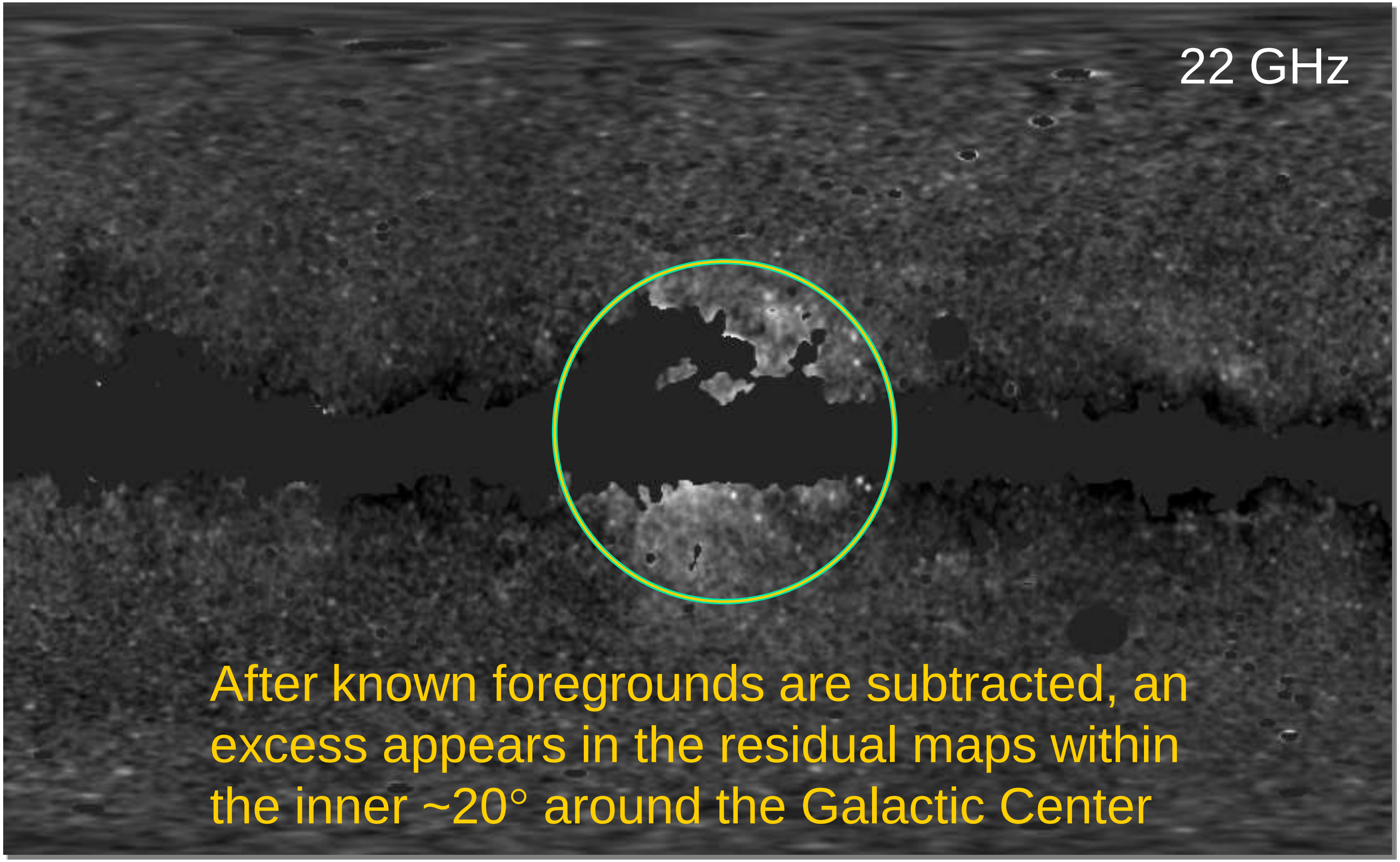


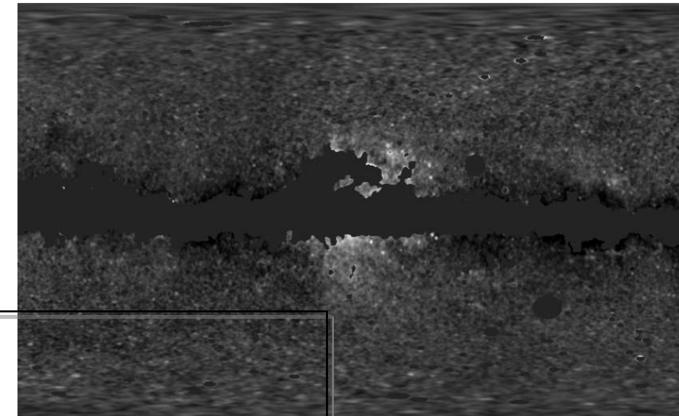
Pamela, Fermi, and WMAP

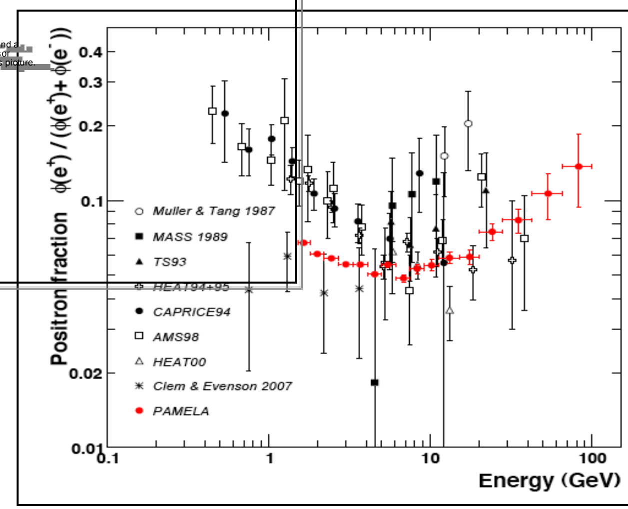
- Highly energetic electrons and positrons are surprisingly common both locally, and in the central kiloparsecs of the Milky Way

- Not the product of any plausible propagation mechanism or other such effect

  (see P. Serpico, arXiv:0810.4846)

- Constitutes the discovery of bright sources of e^+e^- pairs with a very hard spectral index



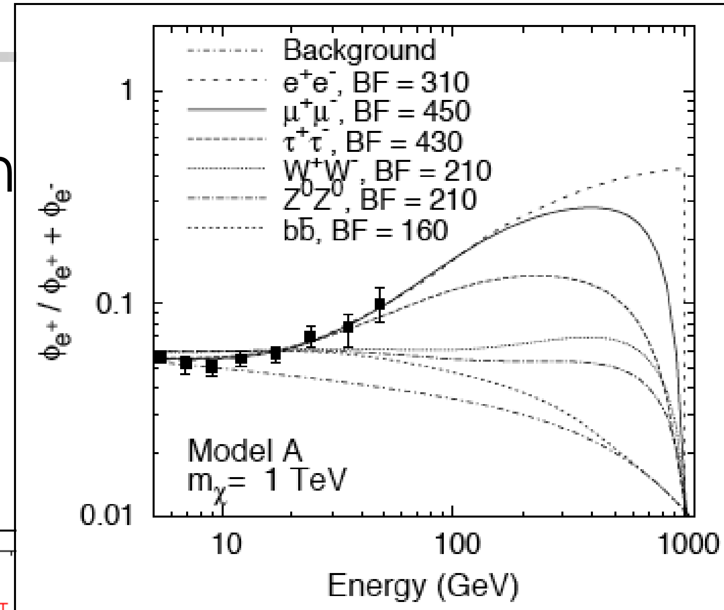


Dan Hooper - *Charged Cosmic Rays and Dark Matter*

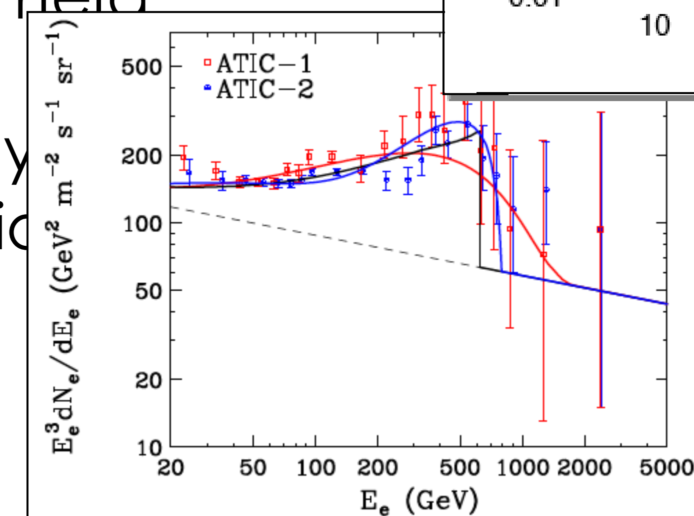
Dark Matter as the Source of the Pamela, Fermi, and WMAP Signals

- The distribution and spectrum of th
WMAP haze are consistent with being of dark matter origin

- The spectral features observed by Pamela and Fermi could also be generated by matter annihilatio



Cholis, Goodenough, Hooper, Simet, Weiner arXiv:0809.1683



Hall and Hooper, arXiv:0811.3362

Dark Matter as the Source of the Pamela and Fermi Signals

… but not necessarily easily.

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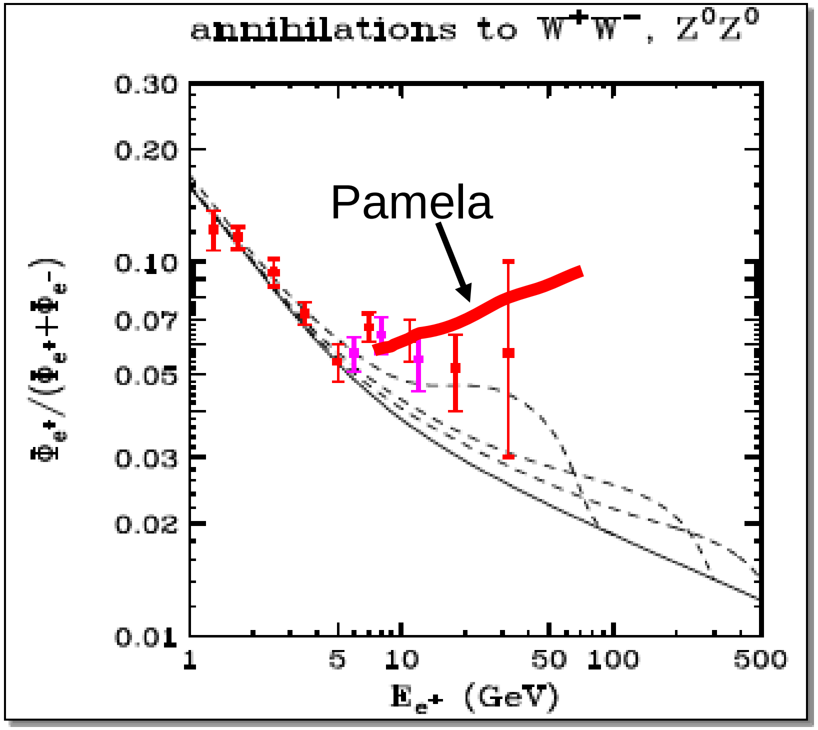
<u>Challenges Faced Include:</u>

1) Very hard spectrum



Hooper and J. Silk, PRD, hep-ph/04091040

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<u>Challenges Faced Include:</u>

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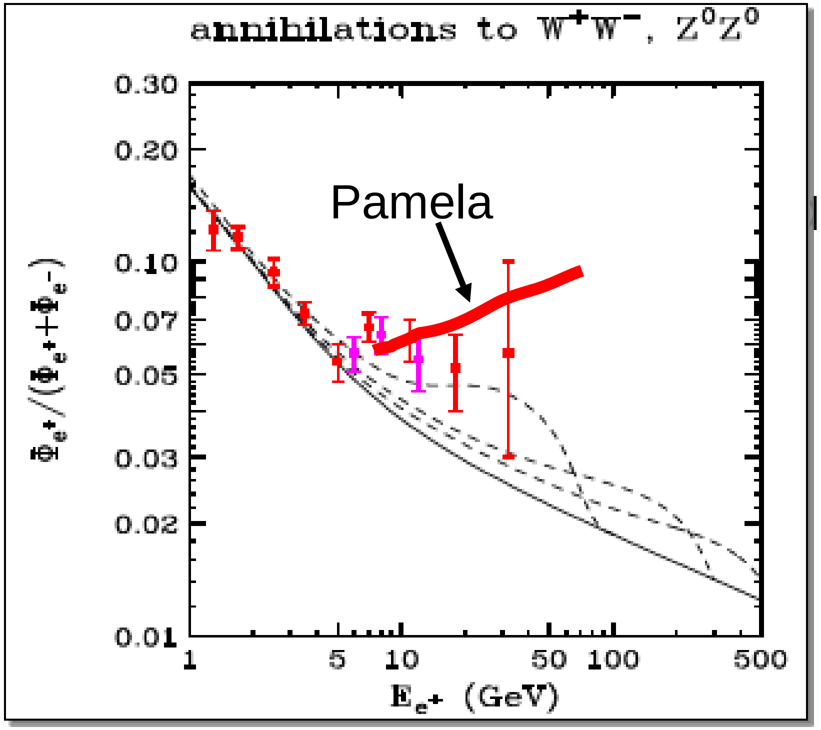
2) Too many antiprotons, gamma rays, synchrotron



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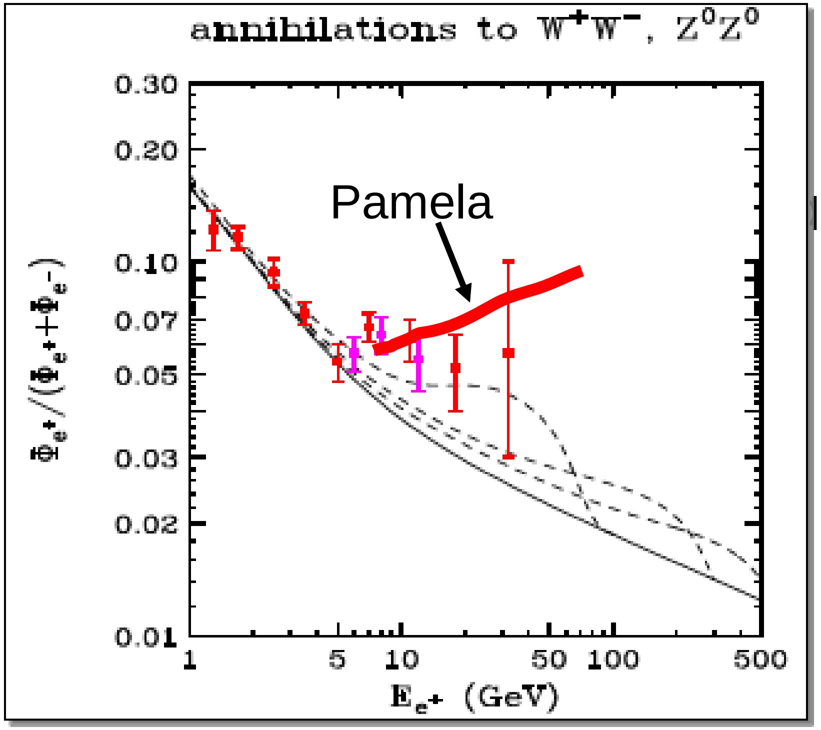
<u>Challenges Faced Include:</u>

1) Very hard spectrum

2) Too many antiprotons, rays, synchrotron

3) Requires a very high annihilation rate



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Dark Matter as the Source of the Pamela and Fermi Signals

Particle Physics Solutions:

Dark Matter as the Source of the Pamela and Fermi Signals

Particle Physics Solutions:

1) Very hard injection spectrum (a large fraction of annihilations to e^+e^-, $\mu^+\mu^-$ or $\tau^+\tau^-$)

Cholis, Goodenough, Hooper, Simet, Weiner arXiv:0809.1683; Bergstrom, Edsjo, Zaharijas, 2009

Dark Matter as the Source of the Pamela and Fermi Signals

<u>Particle Physics Solutions:</u>

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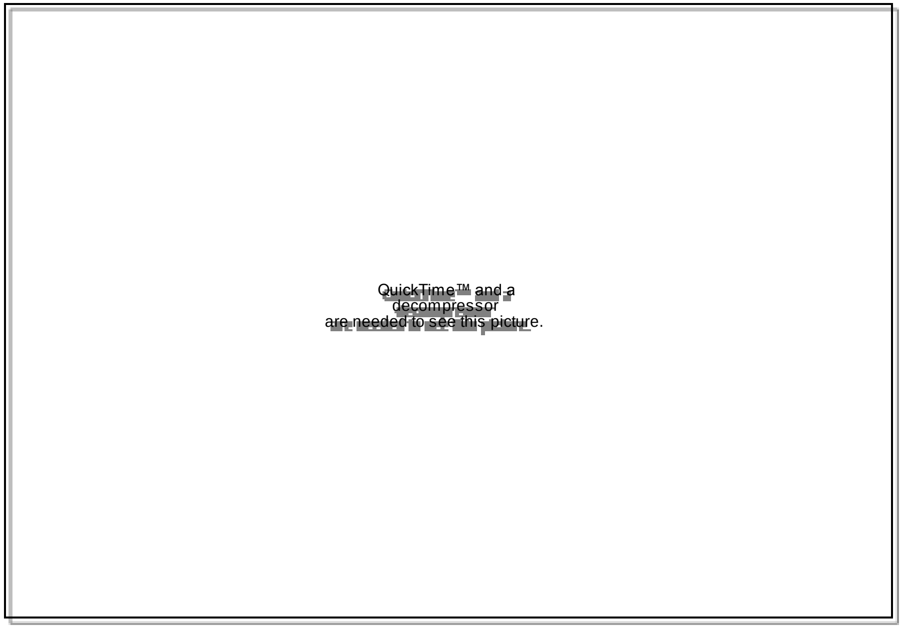


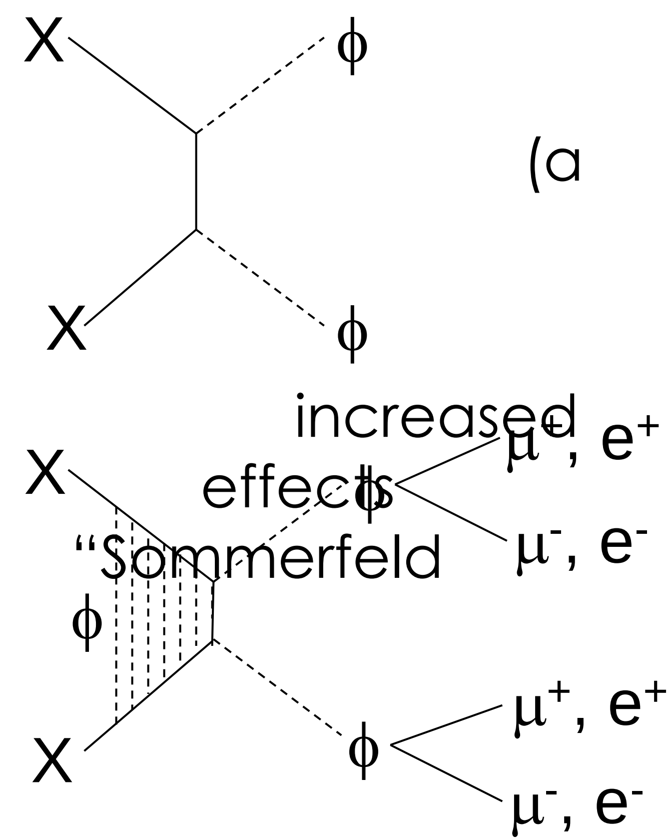
Bergstrom, Edsjo, Zaharijas, 2009

Dark Matter as the Source of the Pamela and Fermi Signals

<u>Particle Physics Solutions:</u>

1) Very hard injection spectrum (a large fraction of annihilations to e^+e^-, $\mu^+\mu^-$ or $\tau^+\tau^-$)

2) Annihilation rate dramatically increased by non-perturbative effects known as the "Sommerfeld Enhancement"
   - Very important for $m_\phi \ll m_X$ and $v_X \ll c$ (such as in the halo, where $v_X/c \sim 10^{-3}$)

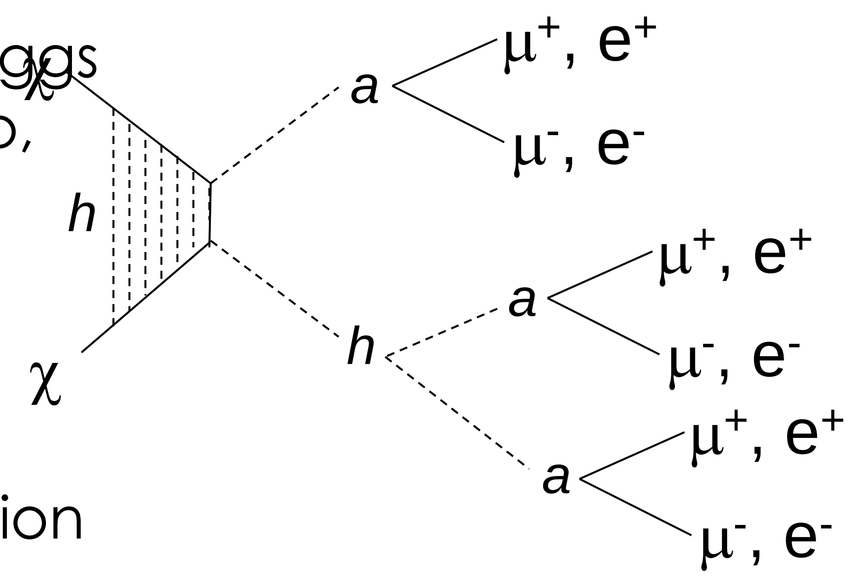


Arkani-Hamed, Finkbeiner, Slatyer, Weiner, arXiv:0810.0713; Cirelli and Strumia, arXiv:0808.3867; Fox and Poppitz,

Dark Matter as the Source of the Pamela and Fermi Signals

A Supersymmetric Realization:

- In the MSSM extended by a higgs singlet, the LSP can be a singlino, coupled to light singlet-like scalar (*h*) and psedoscalar (*a*) higgs bosons



- Can provide the PAMELA/FGST signals, including large annihilation rate via a higgs induced Sommerfeld effect

Hooper and T. Tait, arXiv:0906.0362

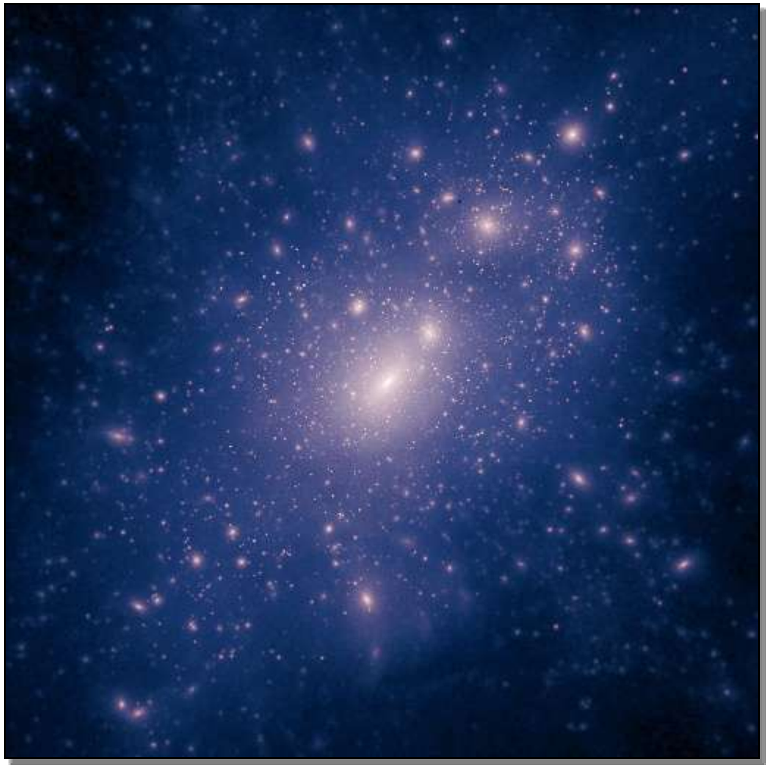
Dark Matter as the Source of the Pamela and Fermi Signals

<u>Astrophysical Solutions:</u>

Dark Matter as the Source of the Pamela and Fermi Signals

Astrophysical Solutions:

1) More small-scale structure than expected (a "boost factor" of ~10^3)

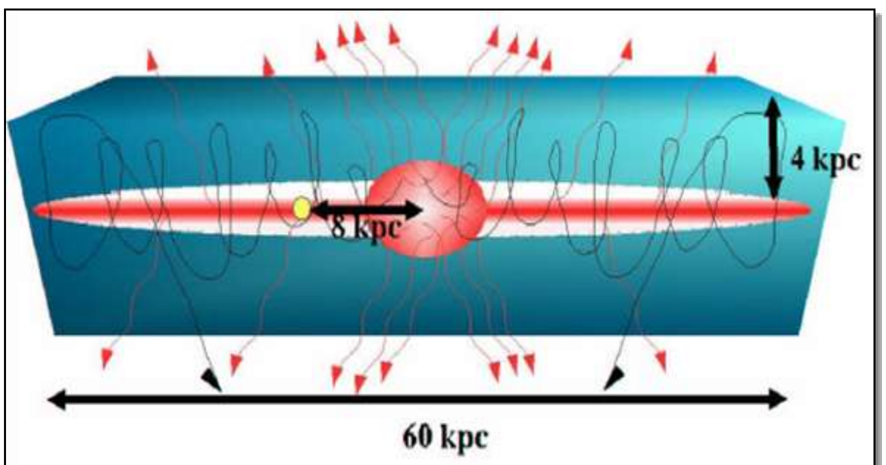


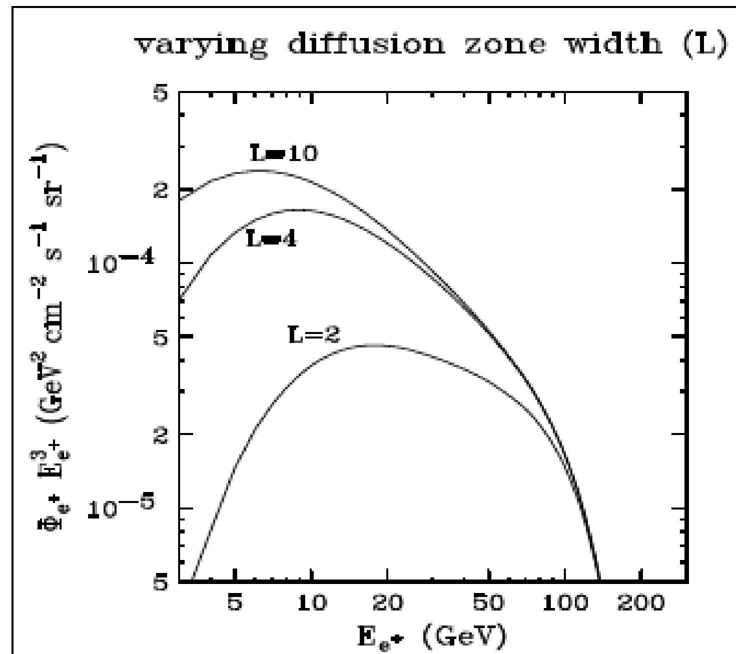
Dark Matter as the Source of the Pamela and Fermi Signals

Astrophysical Solutions:

1) More small-scale structure than expected (a "boost factor" of ~10^3)

2) A narrow diffusion region





D. Hooper and J. Silk, PRD, hep-ph/04091040

Dark Matter as the Source of the Pamela and Fermi Signals

Astrophysical Solutions:

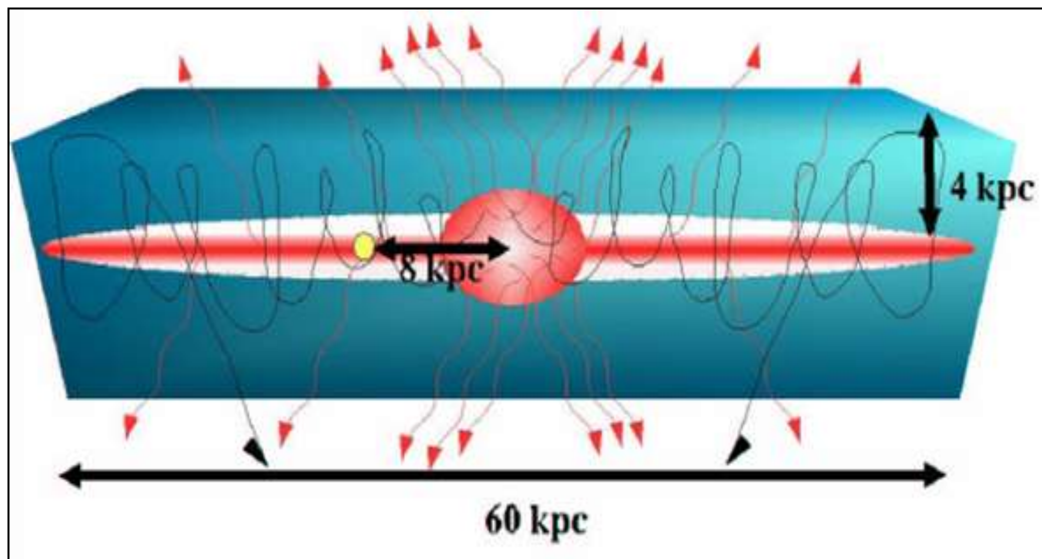
1) More small-scale structure than expected (a "boost factor" of ~10^3)

2) A narrow diffusion region

3) A large nearby clump of dark matter

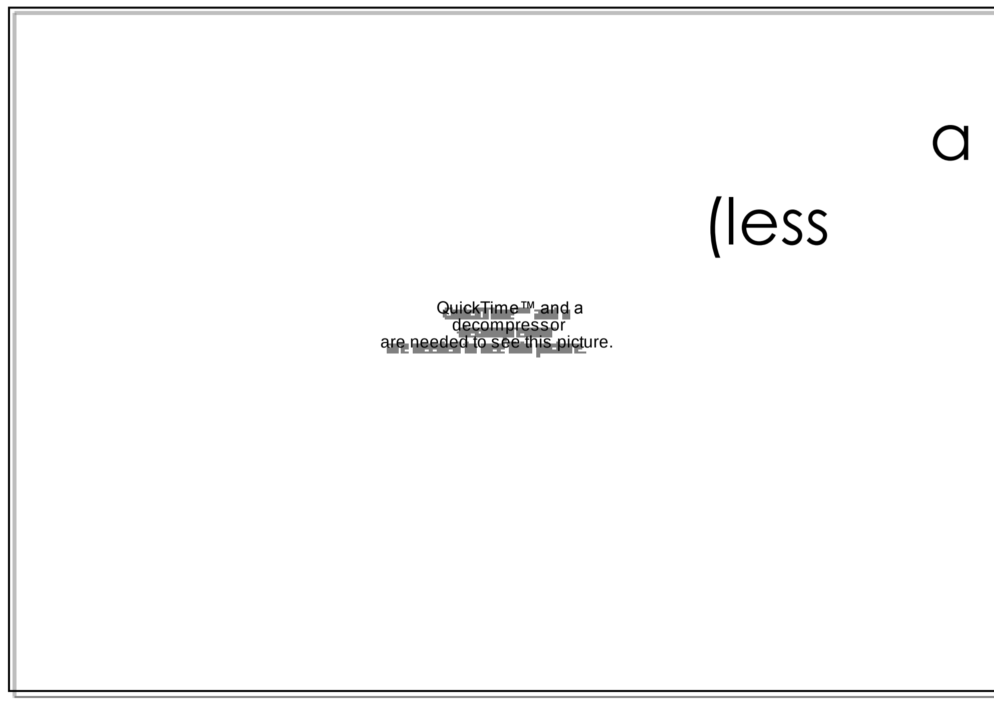
A Nearby Clump of Dark Matter?

- In the standard picture, WIMPs distributed throughout the halo contribute to the spectrum of cosmic ray electrons and positrons



A Nearby Clump of Dark Matter?

- In the standard picture, WIMPs distributed throughout the halo contribute to the spectrum of cosmic ray electrons and positrons
- Nearby sources produce a harder spectrum (less propagation)
- Motion of clump hardens the spectrum further

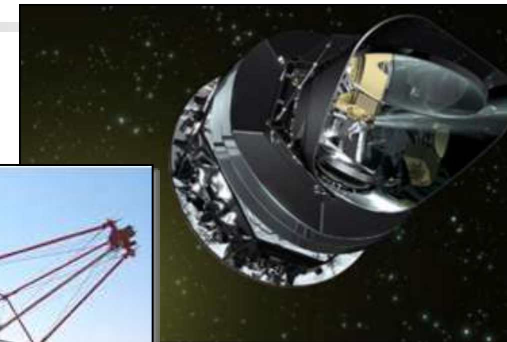


Hooper, A. Stebbins and K. Zurek, arXiv:0812.3202

Many Questions, Few Answers

- The current set of data does not allow us to identify the origin of the Pamela, FGST, and WMAP signals

- Further complementary measurements are going to be required to answer the question of these particles' origin



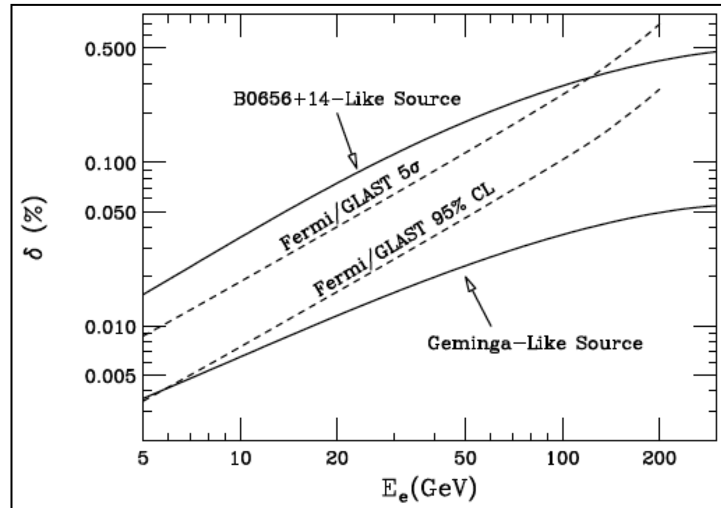
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Test #1:
Search For An Electron/Positron Dipole Anisotropy With Fermi

- Diffusion of electrons/positrons remove *almost* all directional information

- If the Pamela/FGST signal arises from a single nearby source (pulsar, dark matter clump), *a 0.1% dipole anisotropy can remain*

- Too small to be seen by Pamela, but may be within the reach of Fermi

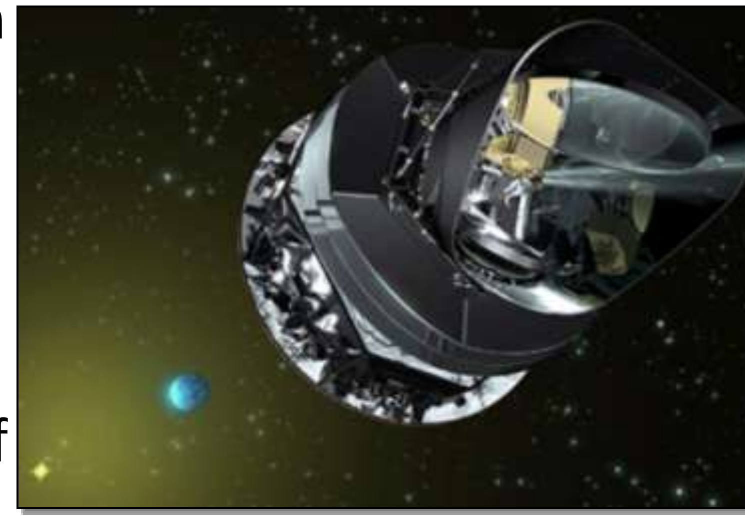


QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Hooper, P. Blasi, P. Serpico, JCAP, arXiv:0810.1527

Test #2:
Study the Synchrotron Haze With Planck

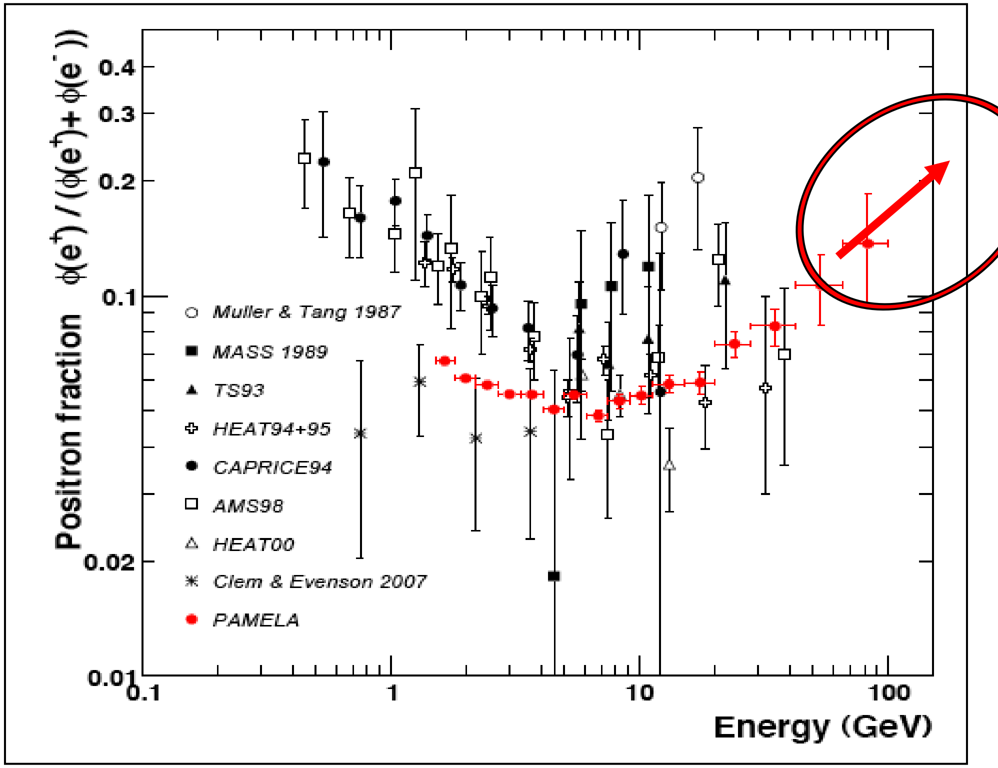
- The Planck satellite began its mission in May, 2009
- With far superior angular resolution and frequency coverage than WMAP, Planck will measuring in much greater detail the properties of the synchrotron haze from the Galactic Center



Test #3: More Data From Pamela

- As the Pamela collaboration accumulates and analyzes more data, they project that they will measure the positron fraction up to approximately 270 GeV

- Such information can be used to further constrain the properties of a WIMP or other source



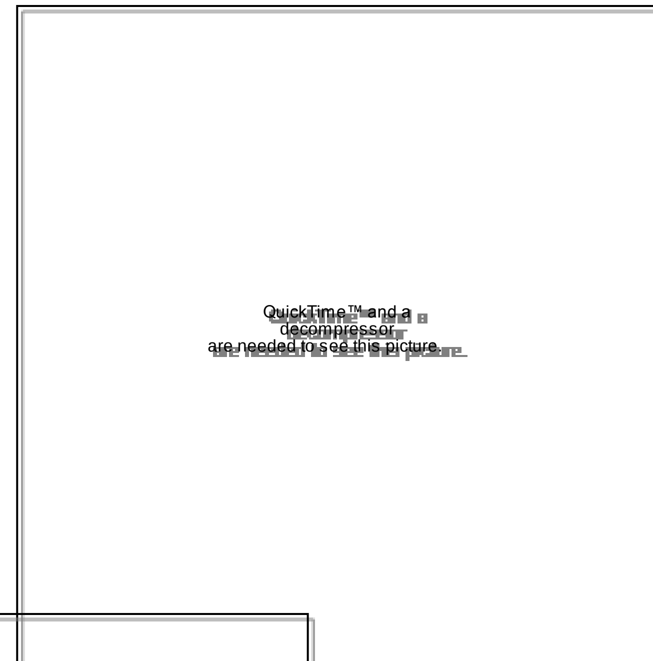
Test #3 1/2: Even Better Data From AMS

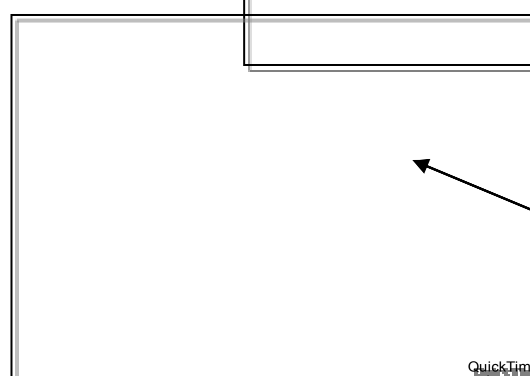
- AMS-02 is scheduled for a spac shuttle payload to the ISS in 2010
- Very large acceptance (~20 times more than PAMELA)
- Superior particle ID (including nuclei up to Z~26)
- Capable of measuring the positron fraction up to approximately ~1 TeV

QuickTime™ and a
decompressor
are needed to see this picture.

Test #3 1/2: Even Better Data From AMS

- In many cases, AMS-02 will measure cosmic ray secondary-to-primary ratios with far greater precision
- B/C, ^{10}Be/^{9}Be, D/p, Sub-Fe/Fe, will all be measured at energies ~10 times higher than currently possible
- Vast improvement in constraining propagation models!



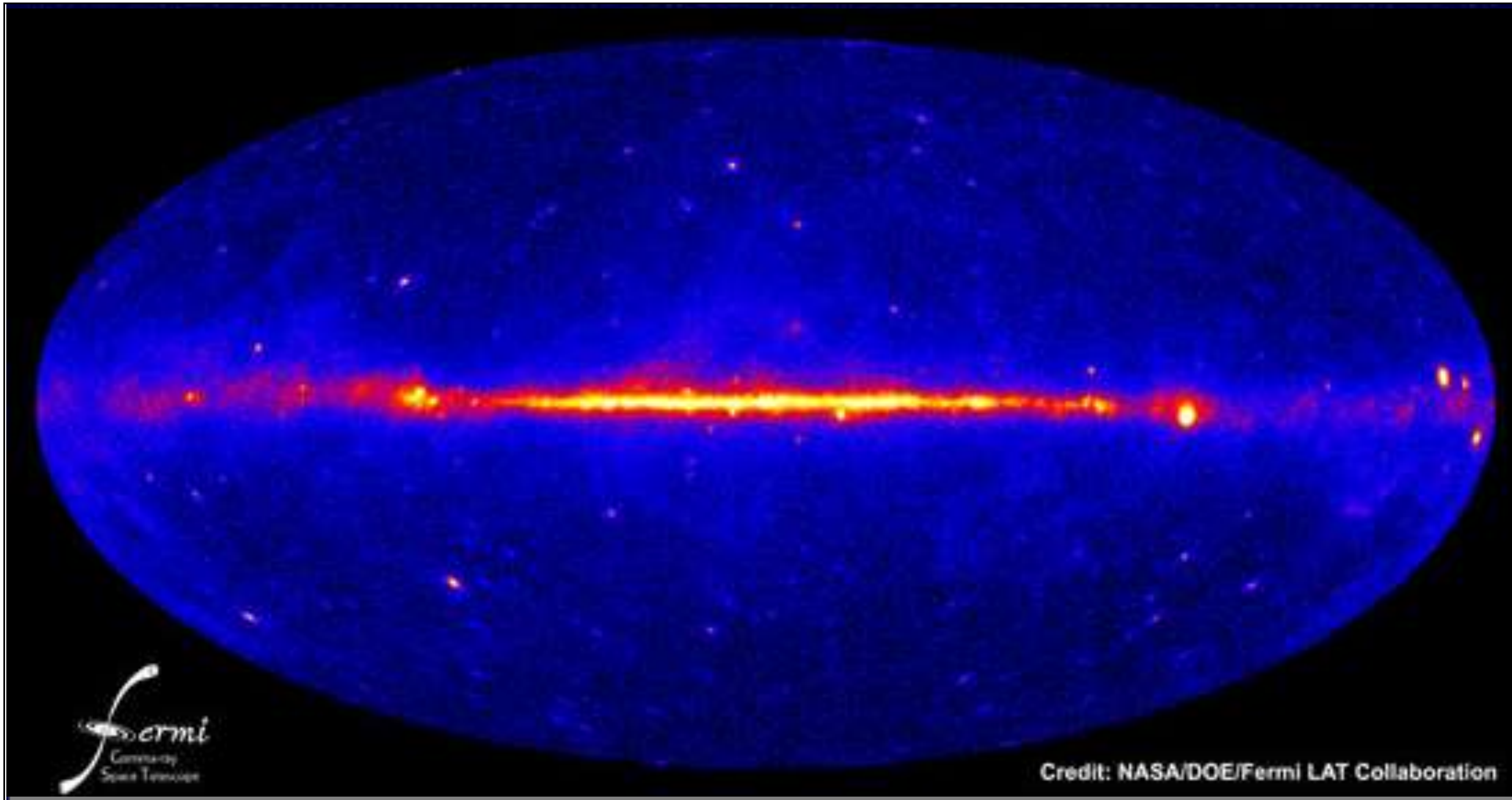


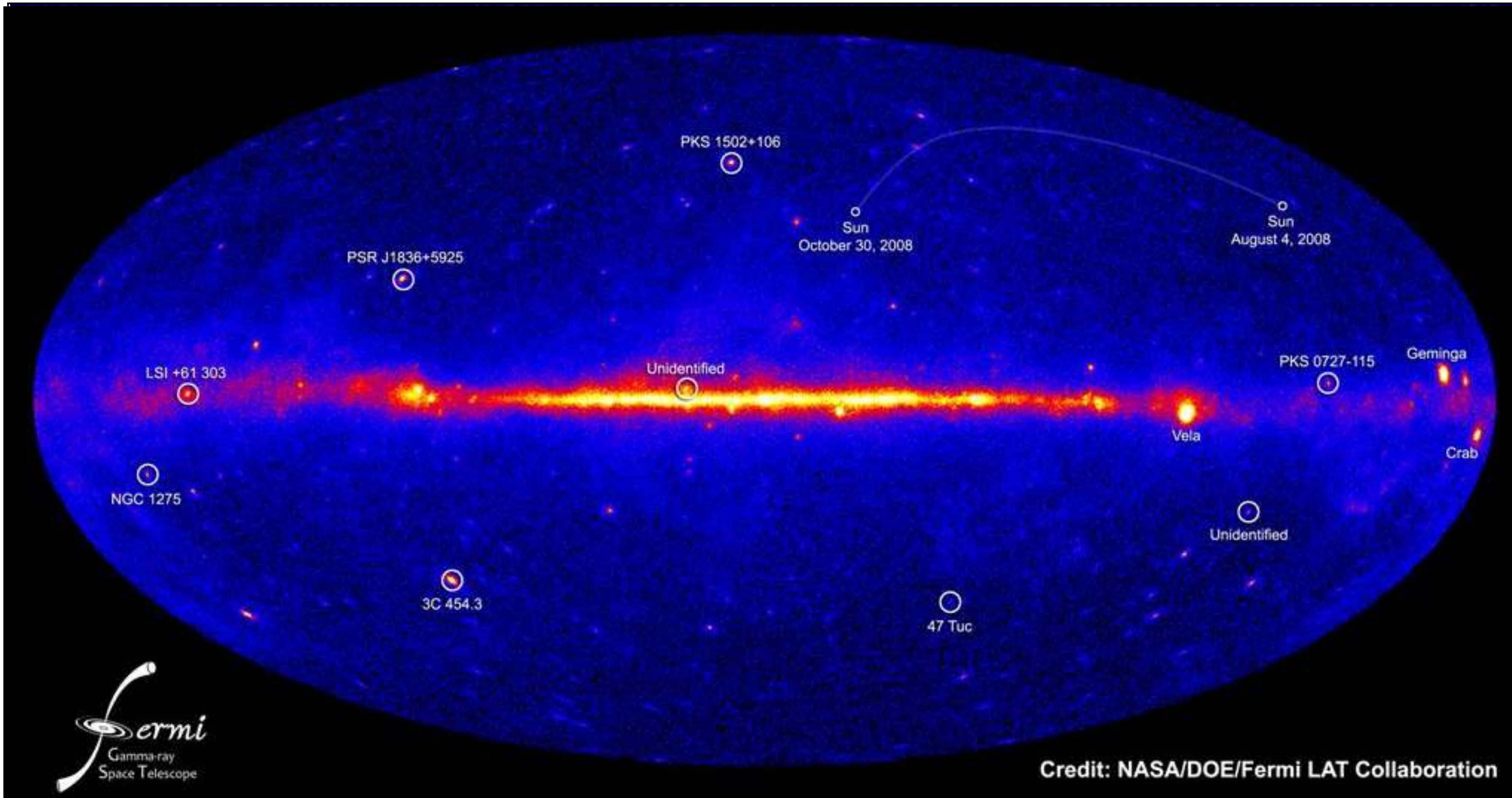
Break L/D degeneracy

Test #4:
Search For Gamma Ray Dark Matter Annihilation Products With Fermi

- Last year, the FERMI/GLAST collaboration announced their first results!
- In August, their first year data became publicly available
- Signatures of dark matter annihilation could appear clearly and quickly, or over years o exposure, or not at all, depending on the dark matter distribution, annihilation cross section, mass, and astrophysical backgrounds

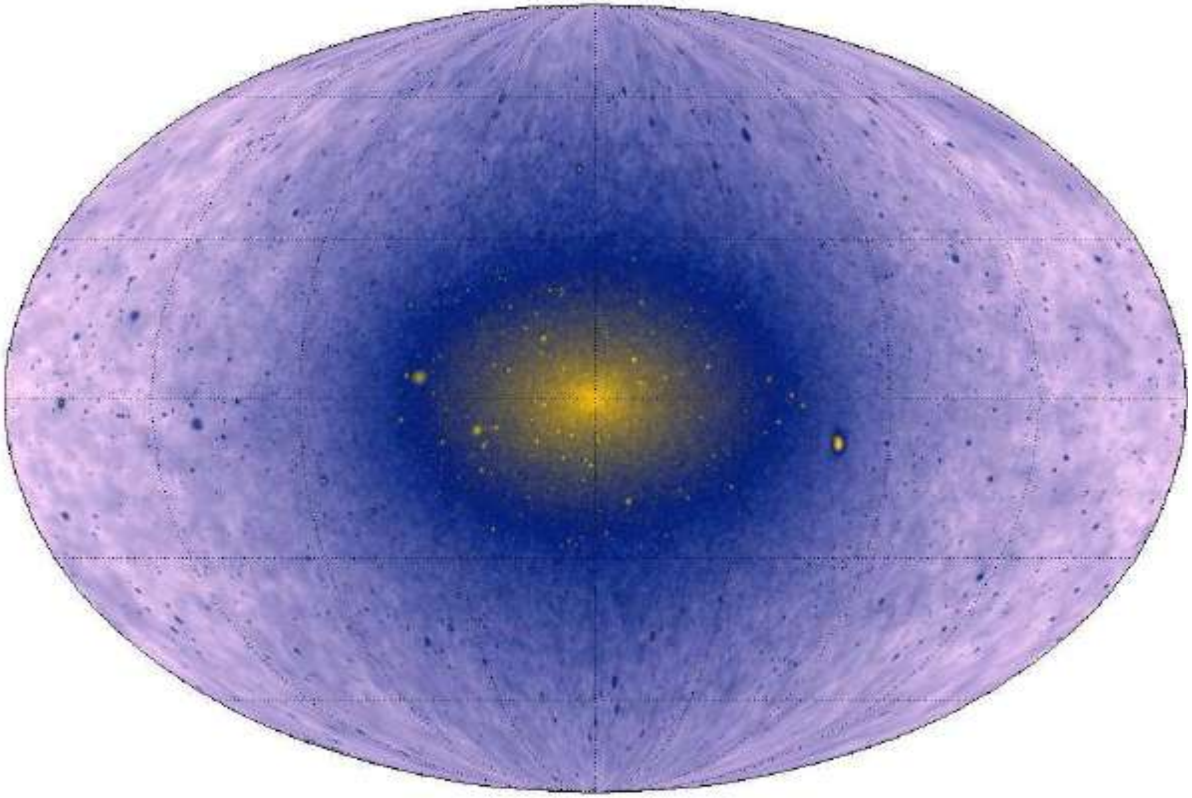
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.


Fermi
Credit: NASA/DOE/Fermi LAT Collaboration



Dan Hooper - *Charged Cosmic Rays and Dark Matter*

Where To Look For Dark Matter With Fermi?

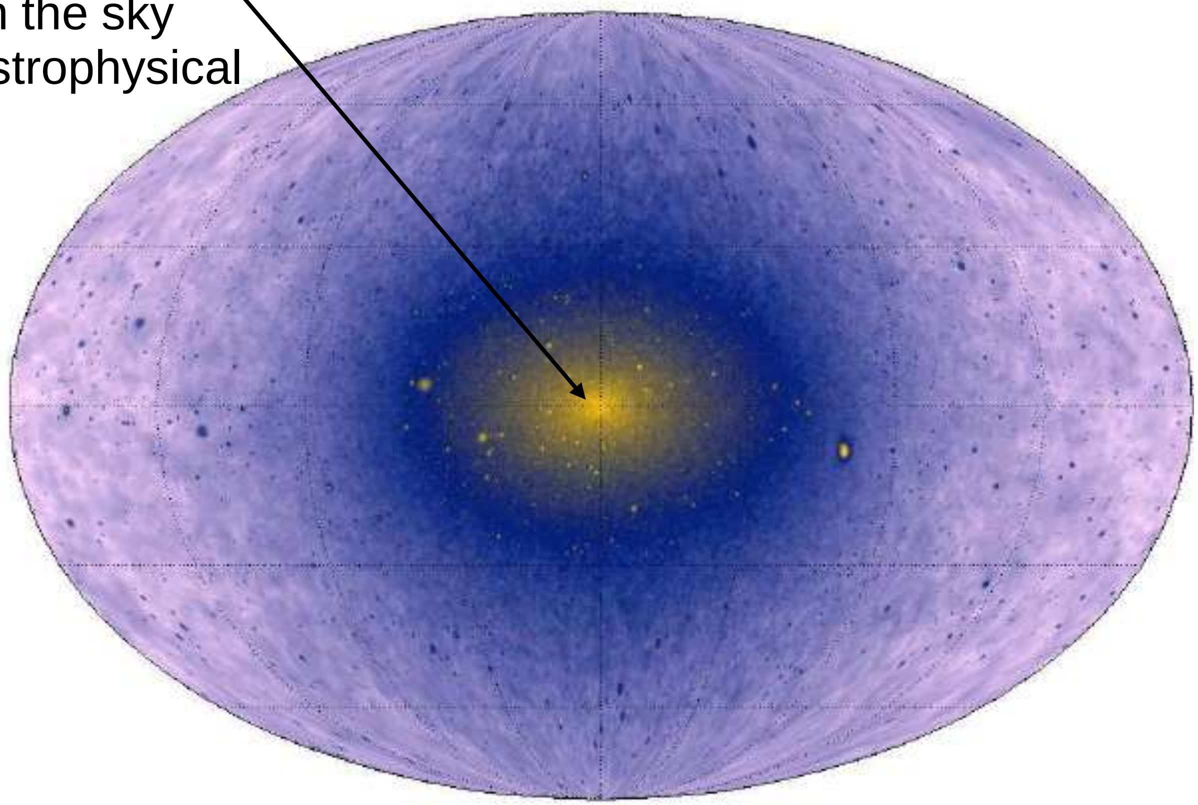


Diemand, Kuhlen, Madau, APJ, astro-ph/0611370

Where To Look For Dark Matter With Fermi?

The Galactic Center

-Brightest spot in the sky
-Considerable astrophysical backgrounds



Diemand, Kuhlen, Madau, APJ, astro-ph/0611370

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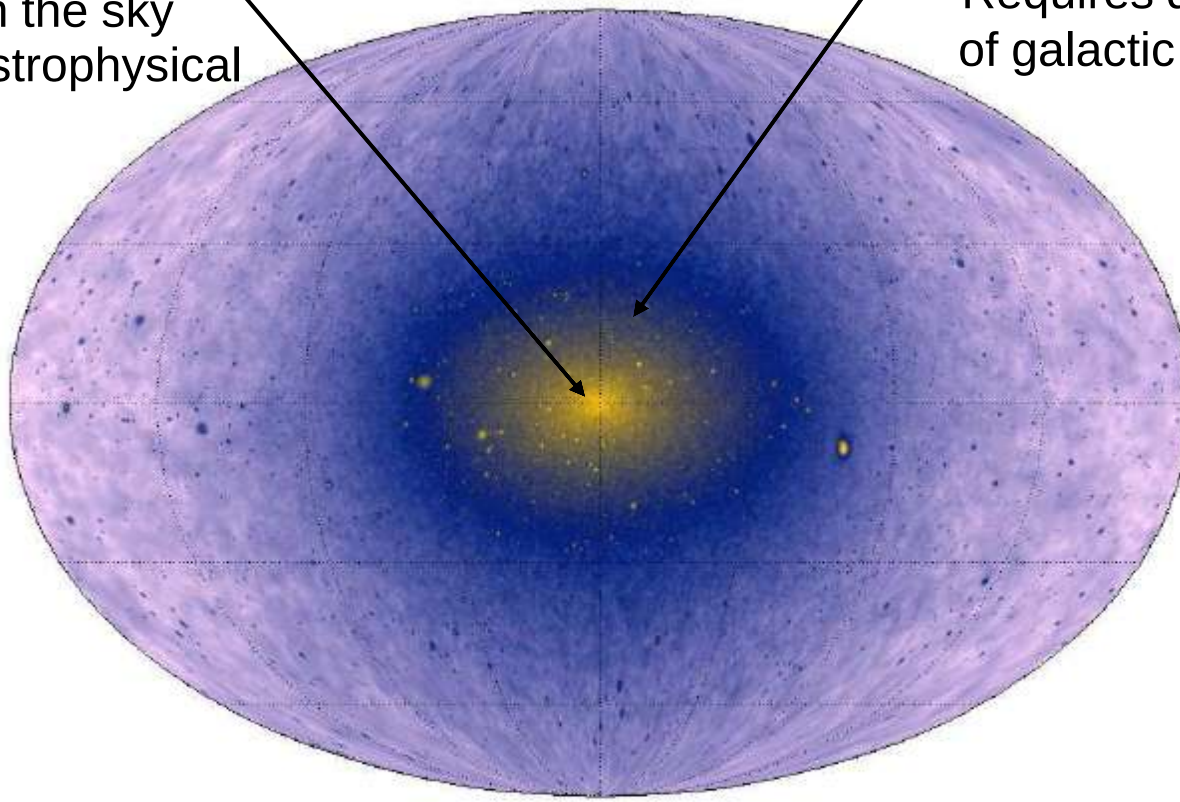
The Galactic Halo

-High statistics
-Requires detailed model of galactic backgrounds



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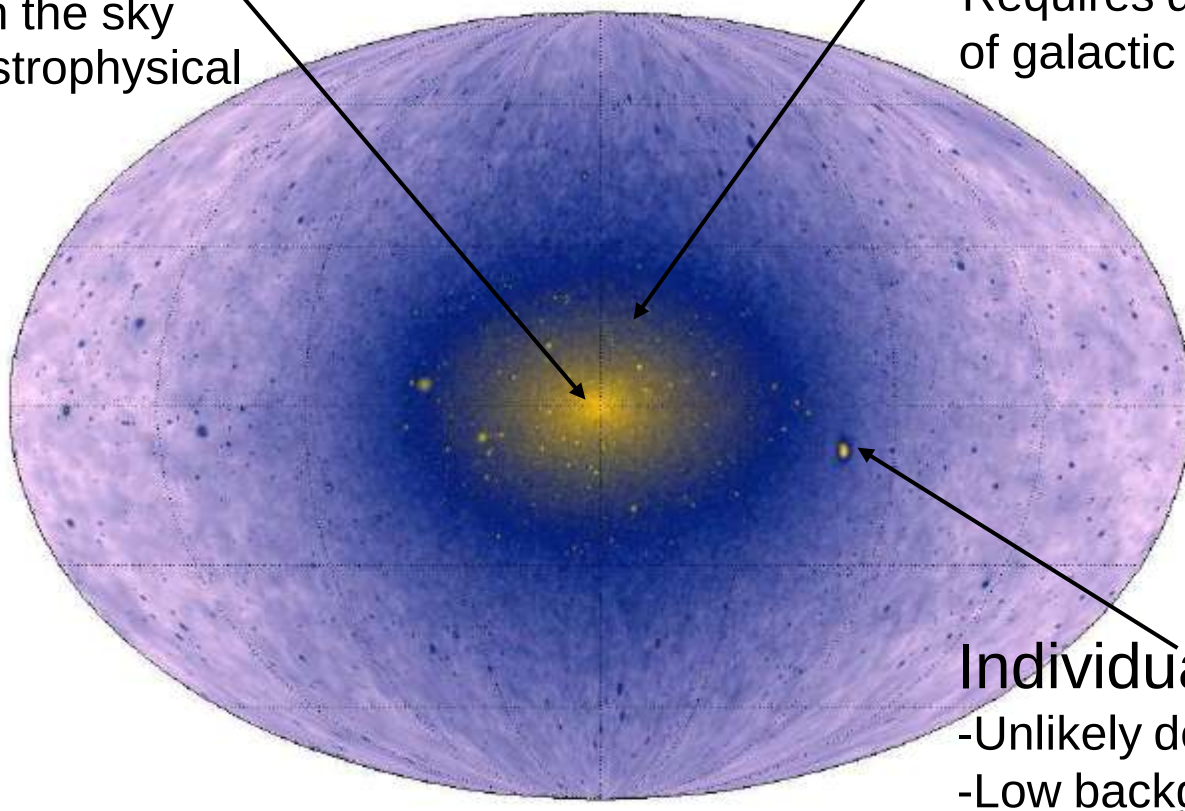

Individual Subhalos

-Unlikely detectable
-Low backgrounds

Diemand, Kuhlen, Madau, APJ, astro-ph/0611370

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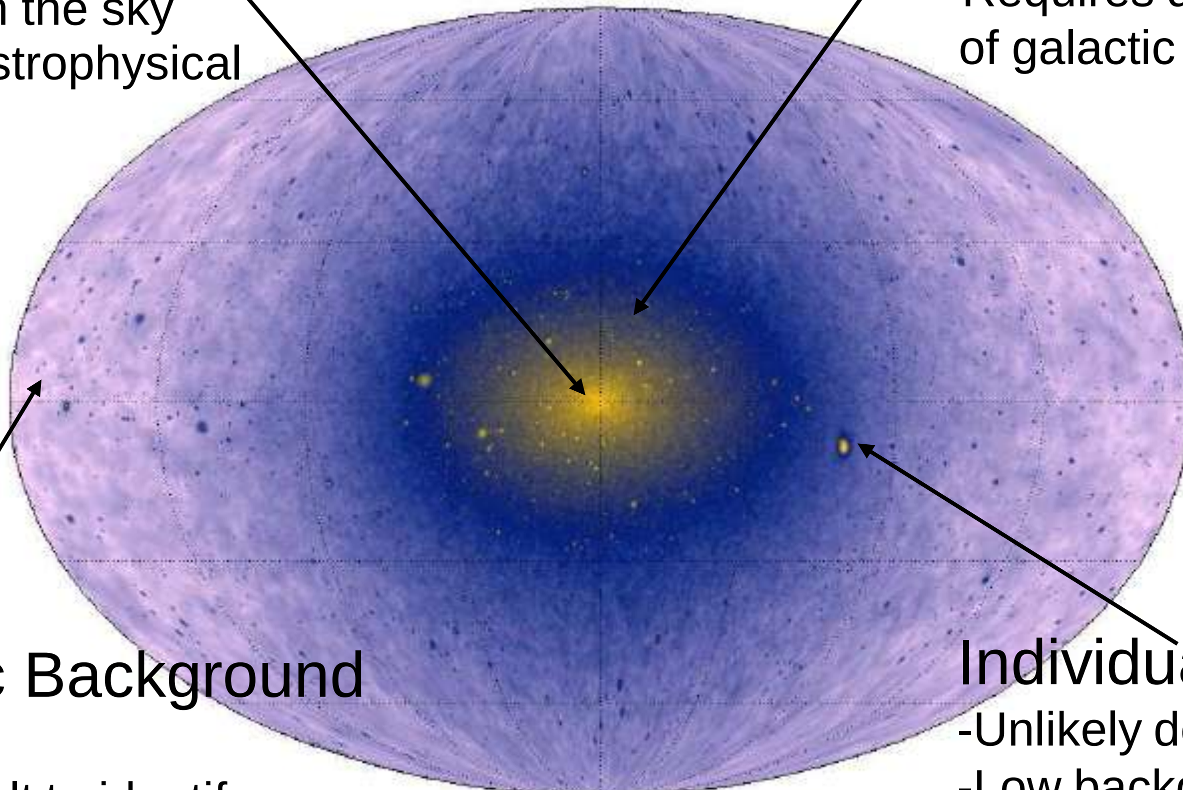


Extragalactic Background
- High statistics
- potentially difficult to identify

Individual Subhalos
- Unlikely detectable
- Low backgrounds

Dan Hooper - *Charged Cosmic Rays and Dark Matter*

Diemand, Kuhlen, Madau, APJ, astro-ph/0611370

Some of the most interesting early dark matter results from Fermi

1) Galactic Diffuse Emission Measurement

-Unlike in EGRET data, no sign of GeV Excess

-Consistent with emission from standard astrophysical mechanisms (cosmic rays propagation, etc.)

QuickTime™ and a
decompressor
are needed to see this picture.

Talk by Simona Murgia, TeVPA 2009

Some of the most interesting early dark matter results from Fermi

1) Galactic Diffuse Emission Measurement

2) The Galactic Center Region

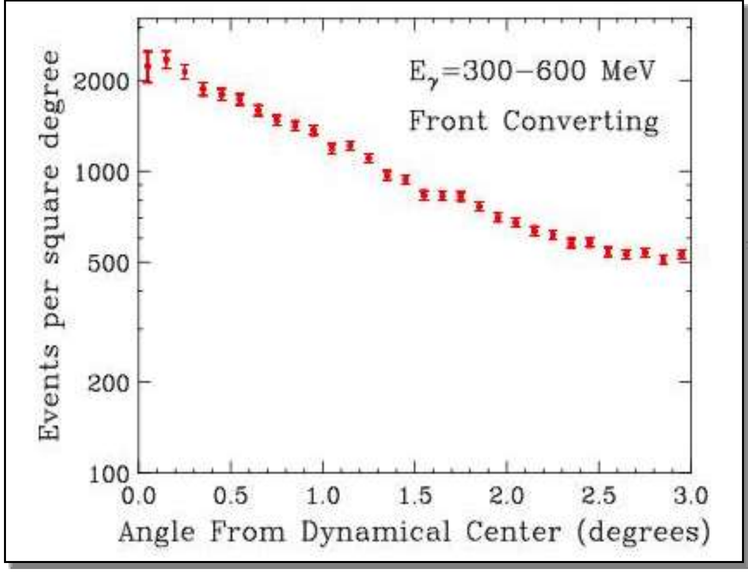
- -Many sources of background
- -Current analysis did not attempt to remove backgrounds
- -Fairly weak limit of $\sigma v \sim 3 \times 10^{-25}$ cm^3/s (ten times thermal WIMP estimate)

Talk by Christine Meuer, TeVPA 2009

The Galactic Center Region As Seen By FGST

- Within the inner few degrees around the Galactic Center, the emission observed by FGST steeply increases with angle

QuickTime™ and a decompressor are needed to see this picture.



L. Goodenough, D. Hooper, arXiv:0910.2998

The Galactic Center Region As Seen By FGST

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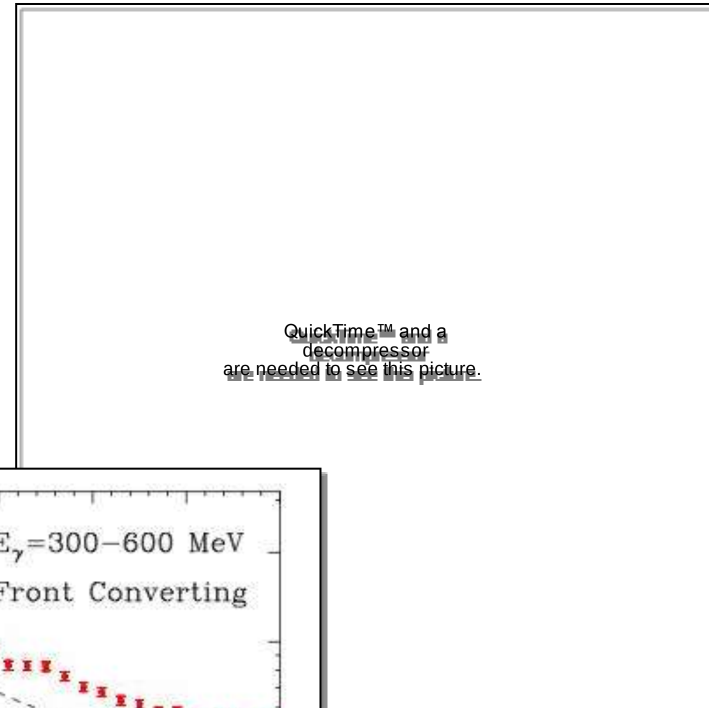
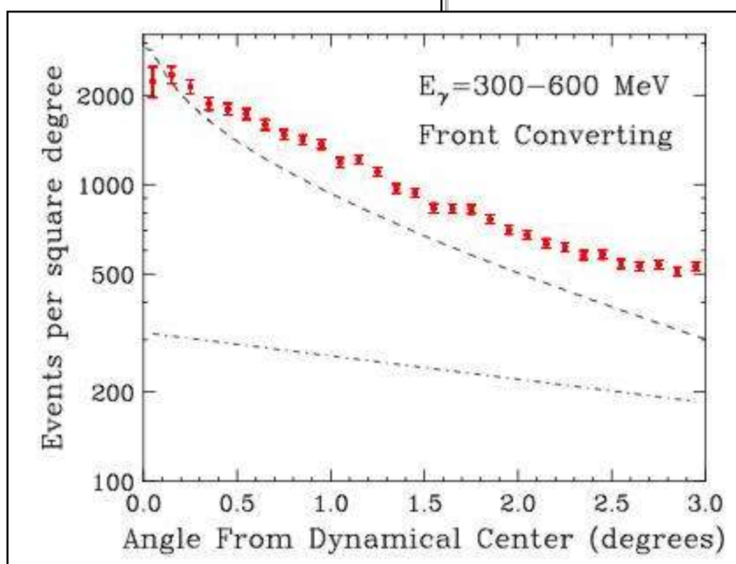
If we model the diffuse background with the shape of the disk emission between 3^{o} and 6° , another component is required which is more concentrated around the center





L. Goodenough, D. Hooper, arXiv:0910.2998

The Galactic Center Region As Seen By FGST

- We sum three components to the angular profile of events observed by FGST:
  1) Disk-like emission
  2) Emission from the known TeV HESS source
  3) Dark matter-like emission (γ=1.1)

- Below ~1 GeV, relatively little disk-like emission; no evidence for HESS source emission

L. Goodenough, D. Hooper, arXiv:0910.2998

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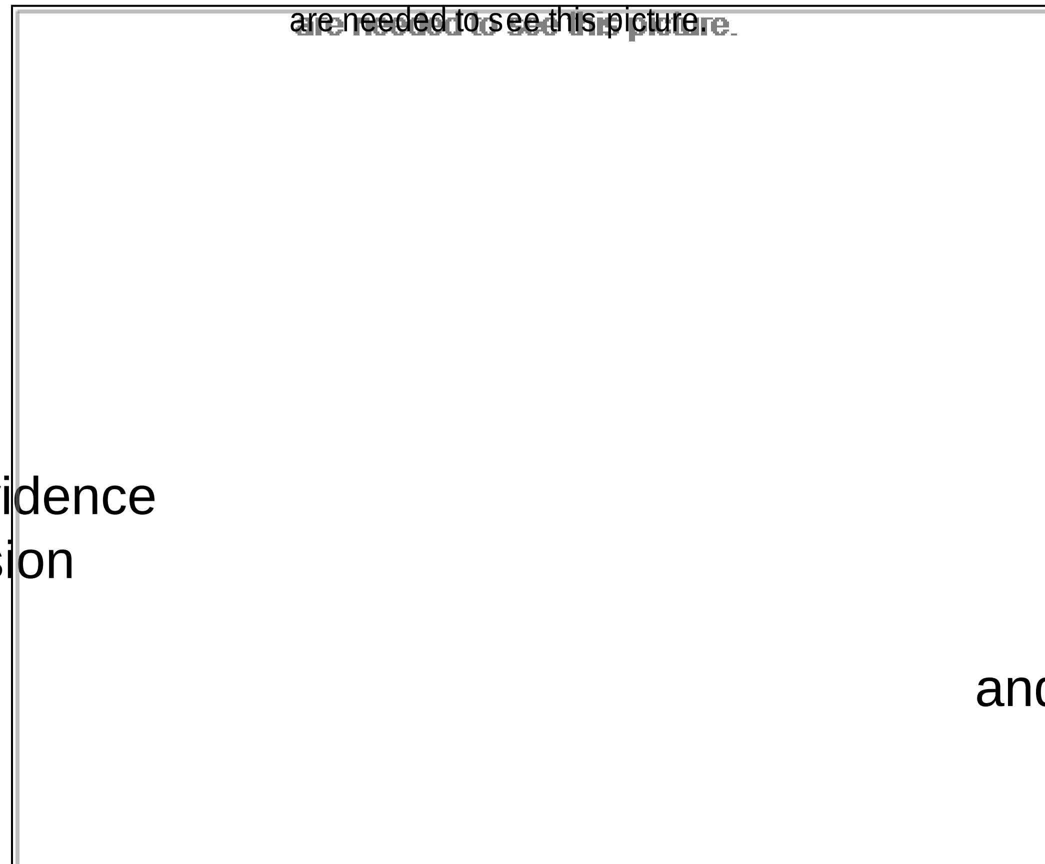
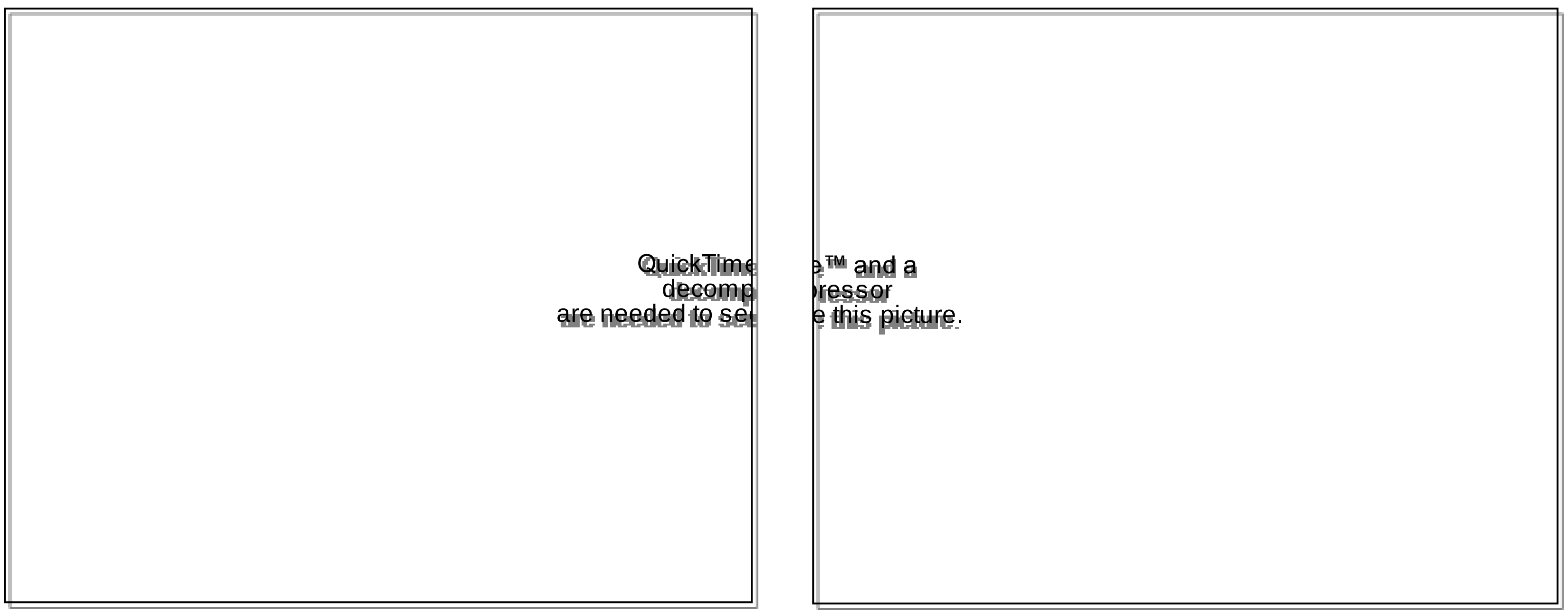
- Above ~1 GeV, HESS source and disk-like emission become increasingly significant



L. Goodenough, D. Hooper, arXiv:0910.2998

The Galactic Center Region As Seen By FGST

- The spectrum of the non-disk, non-HESS source emission contains a "bump-like" feature at ~1-5 GeV
- Can be fit quite well by a simple 25-30 GeV dark matter particle, in a cusped distribution (γ~1.1), annihilating to bb with $\sigma v \sim 9 \times 10^{-26}$ cm^3/s

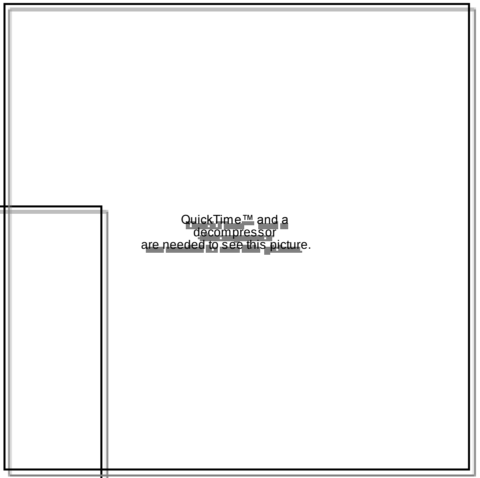


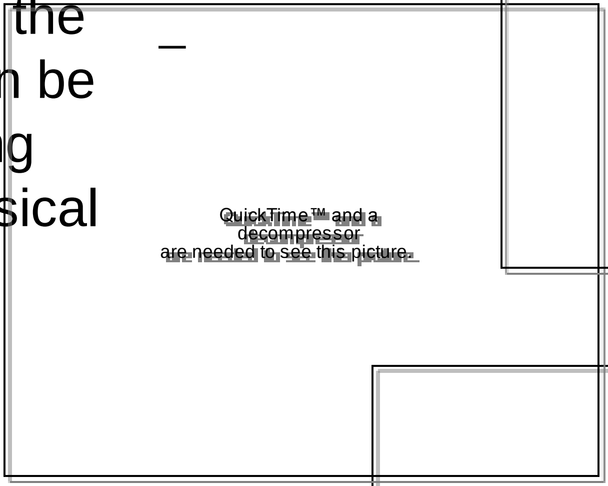
L. Goodenough, D. Hooper, arXiv:0910.2998

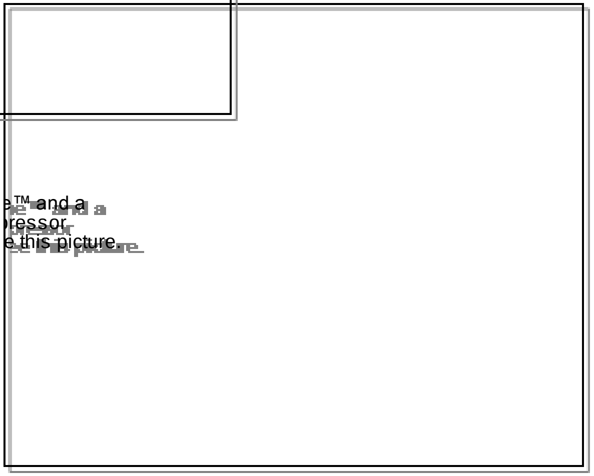
The Galactic Center Region As Seen By FGST

Some words of caution:

- Although the angular distribution and spectrum observed from the inner Milky Way by FGST can be well fit by a simple annihilating dark matter scenario, an astrophysical background with a similar angular distribution and spectrum cannot be ruled out
- The inner galaxy is a complex region, which must be scrutinized before any confident claims can be made
- Searches in other regions of the sky will be important to confirm or refute this interpretation







L. Goodenough, D. Hooper, arXiv:0910.2998

Some of the most interesting early dark matter results from Fermi

1) Galactic Diffuse Emission Measurement

2) The Galactic Center Region

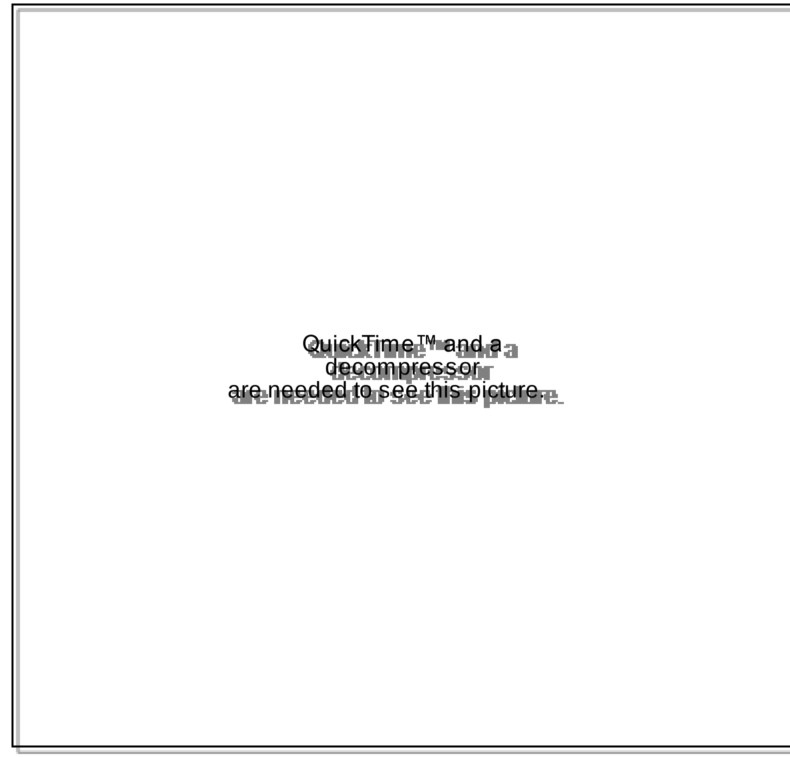
3) Subhalos

4) Galaxy Clusters

5) Dwarf Spheriodal Galaxies

Fermi and the Extragalactic Gamma-Ray Background

- In typical models, the diffuse background from extragalactic dark matter annihilation produces about ~1% of the flux observed by EGRET
- As Fermi resolves more sources (blazars, etc.), the background will decrease, leading to stronger limits on the dark matter annihilation rate



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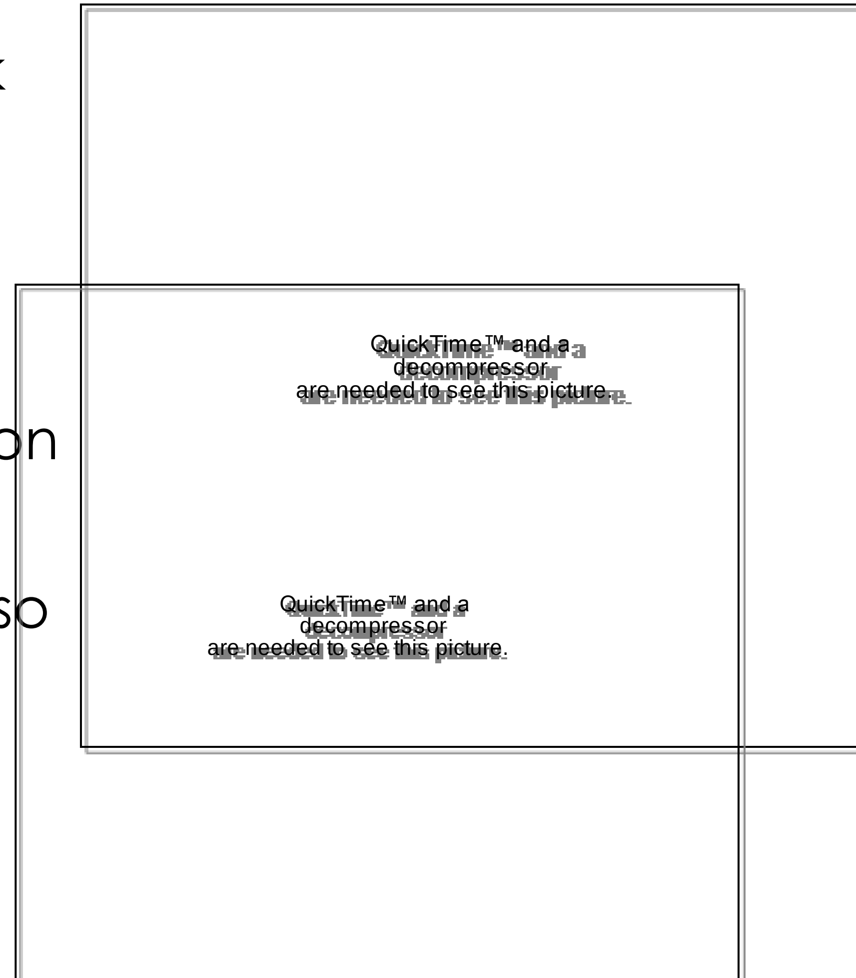
- Annihilations to charged leptons also lead to gamma-rays through inverse Compton scattering with the CMB (Pamela motivated models may produce an observable flux of IC photons)



Belikov and Hooper, arXiv:0906.2251;
Profumo and Jelta, arXiv:0906.0001

Fermi and the Extragalactic Gamma-Ray Background

Blazar Simulation

QuickTime™ and a
decompressor
are needed to see this picture.

Dark Matter Simulation

QuickTime™ and a
decompressor
are needed to see this picture.

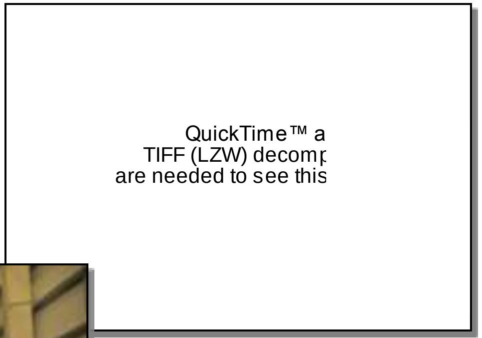
- Fermi's ability to identify signatures of dark matter annihilation in the extragalactic background depends critically on how much of the background can be resolved into individuals sources (blazars, etc.)
- If we are a bit lucky (large flux, resolvable background), Fermi should be able to identify this component after several years of exposure

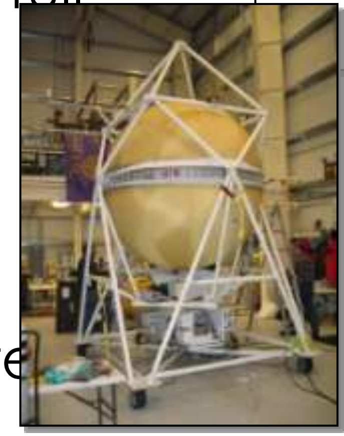
Belikov and Hooper, arXiv:0906.2251;
Profumo and Jelta, arXiv:0906.0001

Summary

- Observations from Pamela, FGST, and WMAP (as well as HEAT, AMS-01, PPB-BETS) each indicate that the the Milky Way is full of high energy electrons/positrons - a very surprising result!

- Although the origin of these particles is not known, the signal appears consiste with being the product of either dark matter annihilations or pulsars

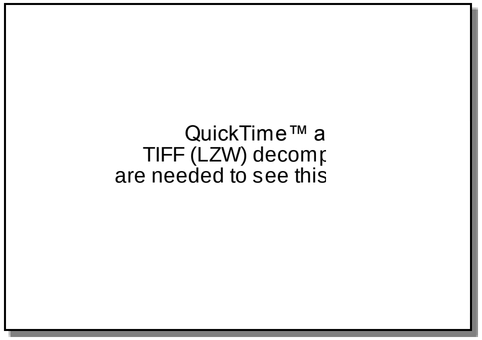




Summary

<u>One Year From Now</u>

- Pamela positron spectrum up to 270 GeV?
- More data from Fermi, and more analysis of Fermi data
  - -Dark matter searches (galactic center, diffuse emission, subhalos, dwarfs, etc.)
  - -Electron dipole anisotropy?
- First data from Planck?
- Further input from ground based gamma-ray telescopes, and observations at other wavelengths



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  - -Dark matter searches (galactic center, diffuse emission, subhalos, dwarfs, etc.)
  - -Electron dipole anisotropy?
- First data from Planck?
- Further input from ground based gamma-ray telescopes, and observations at other wavelengths
- Currently, we are facing a puzzling, ambiguous and incomplete picture
- With the wide range of observational tools available, we may be able to move from puzzle to discovery

QuickTime™ a
TIFF (LZW) decomp
are needed to see this

QuickTime™ and a
TIFF (Uncompressed) decompressor
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