Charged Cosmic Rays And Particle Dark Matter

Dan Hooper
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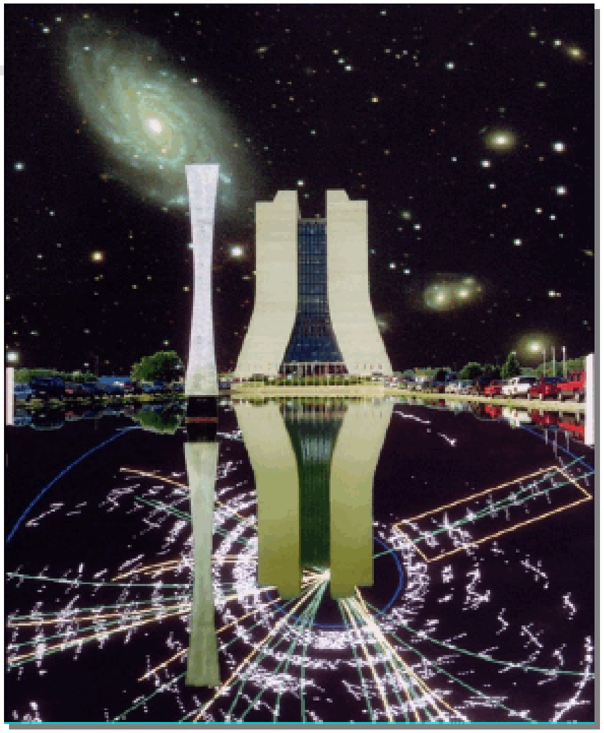


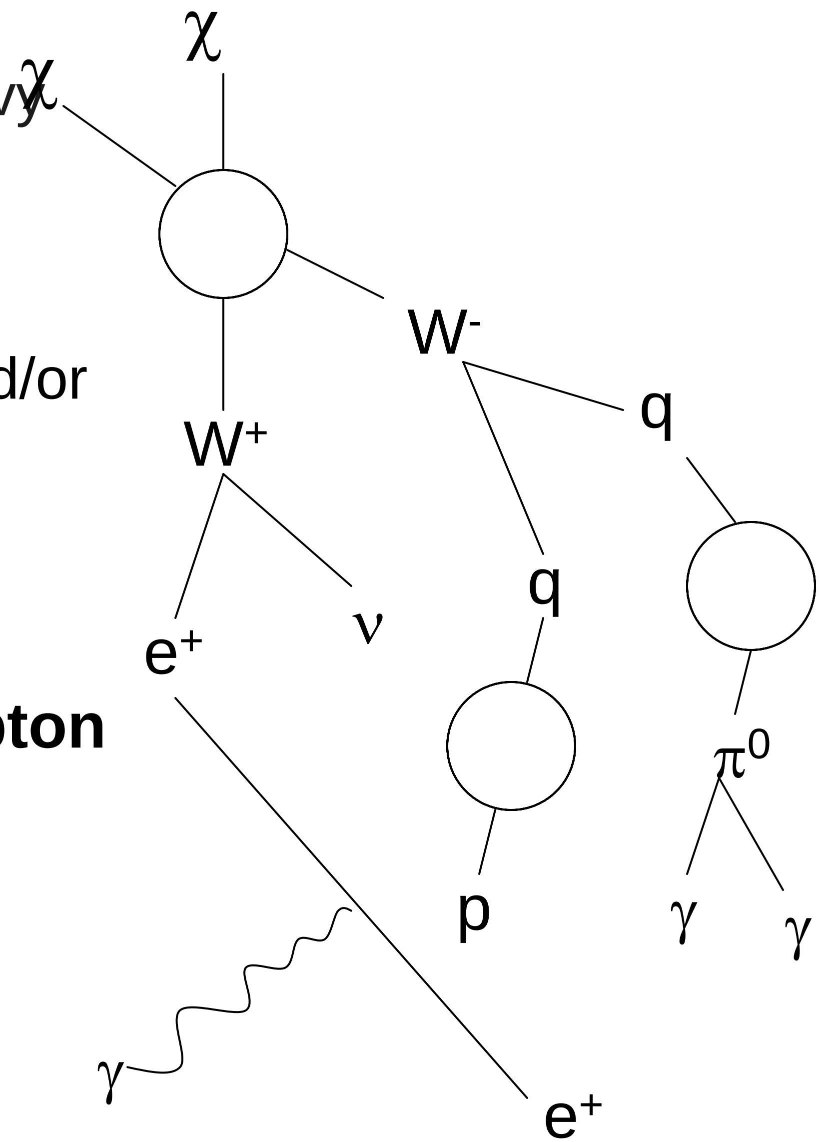
University of Maryland
Shedding Light on Dark Matter Workshop
April 2, 2009

The Indirect Detection of Dark Matter

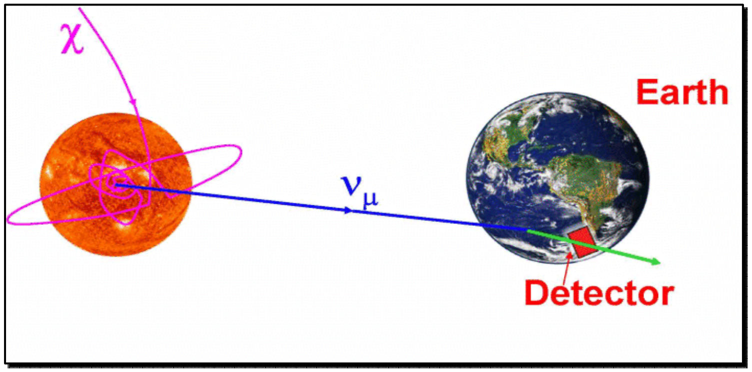
1. **WIMP Annihilation**
   Typical final states include heavy fermions, gauge or Higgs bosons

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

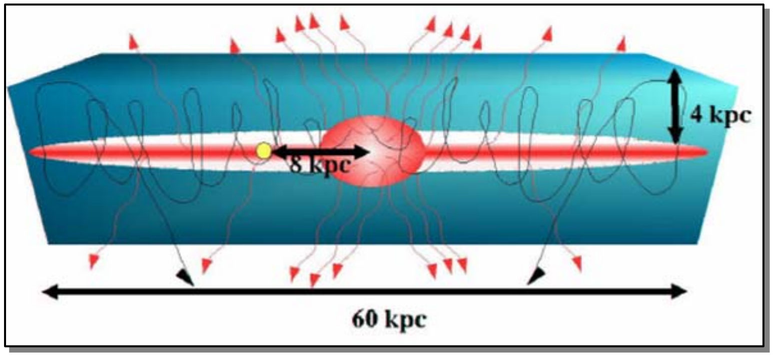


The Indirect Detection of Dark Matter



- **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.

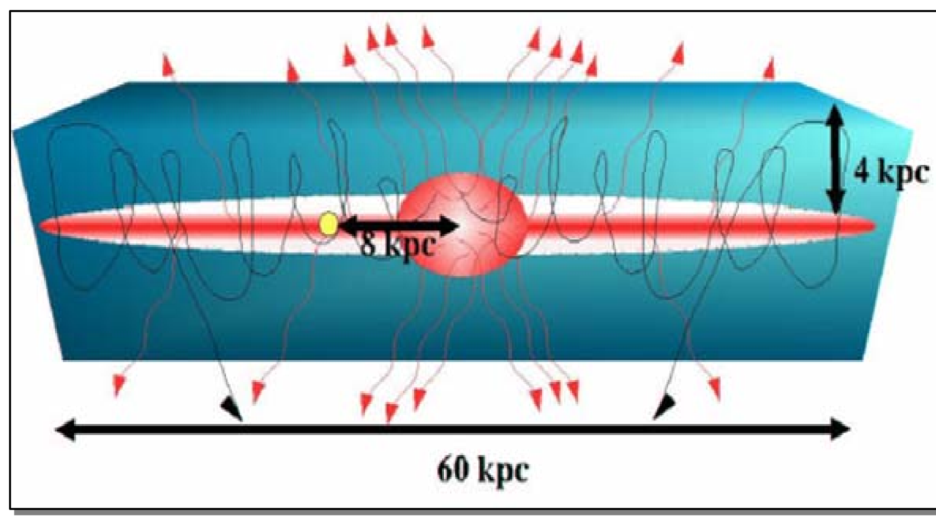
- **Positrons/Antiprotons** from annihilations throughout the galactic halo



- **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 y

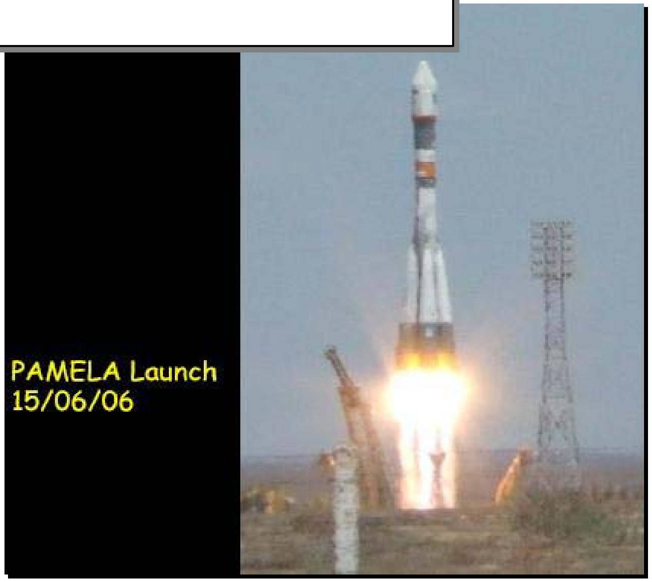


Charged Particle Astrophysics With Pamela

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

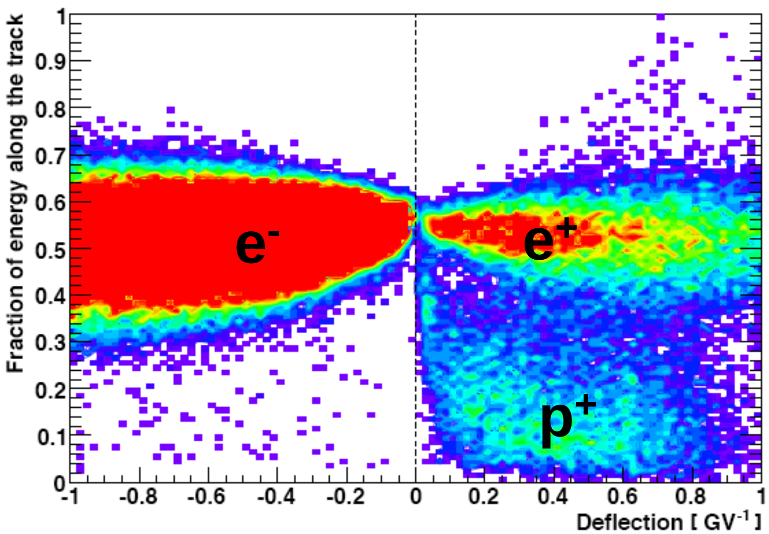
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

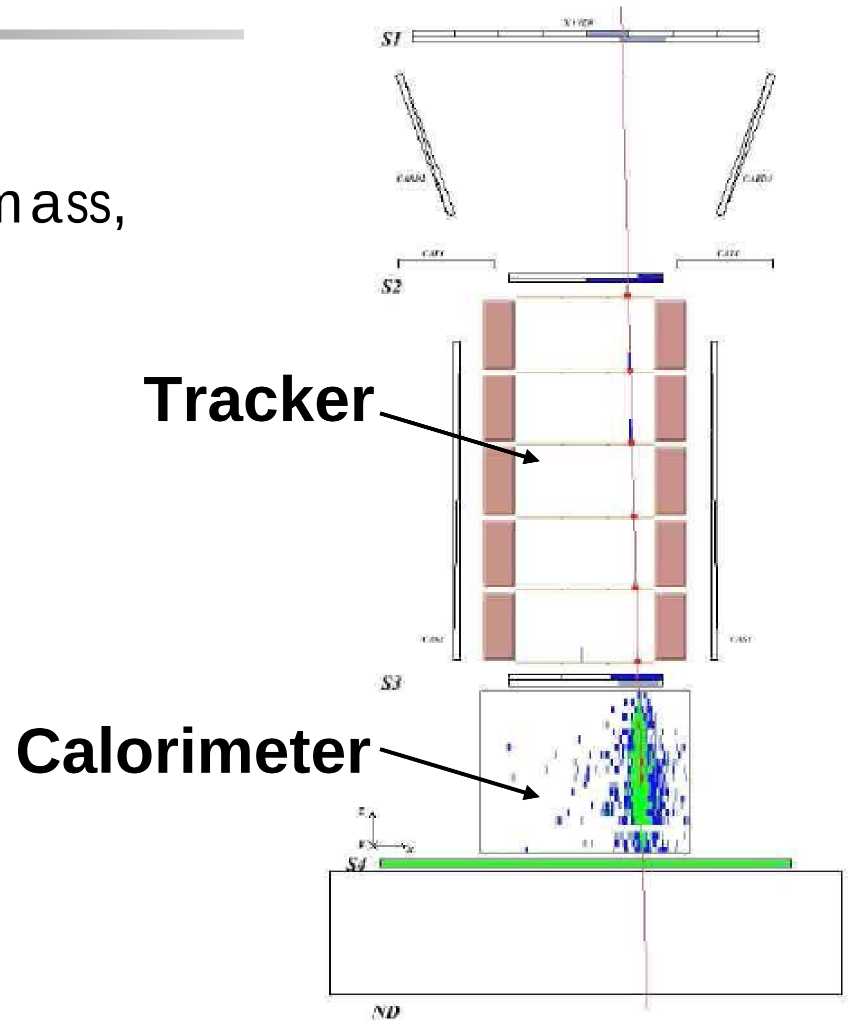
- Among other science goals, PAMELA hopes to identify or constrain dark matter annihilations in the Milky Way halo by measuring the cosmic positron and antiproton spectra



Charged Particle Astrophysics With Pamela

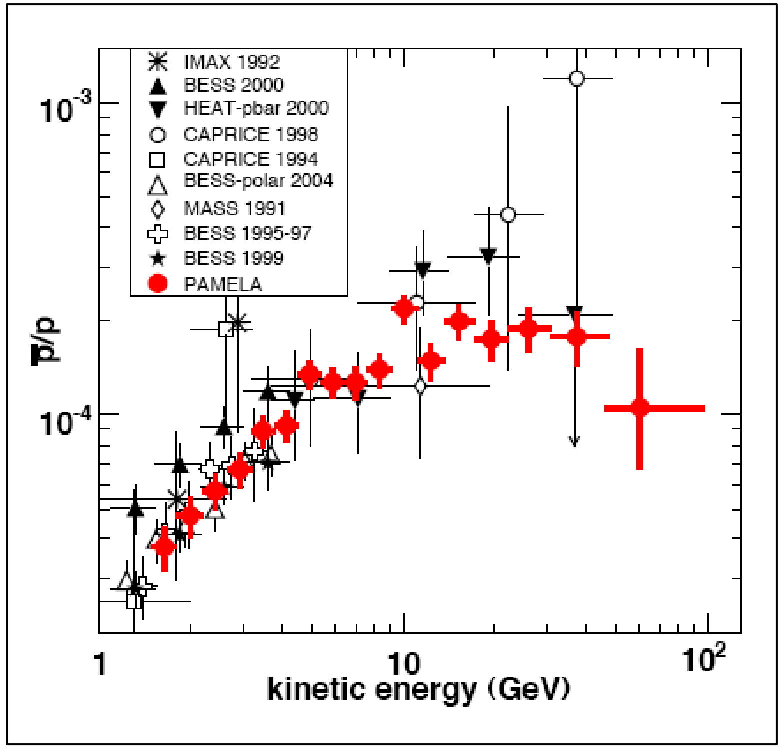
- Combination of tracker and calorimeter enable charge, mass, and energy determinations
- Very accurate particle ID





Pamela's New Antiproton Measurement

- Best measurement to date
- Dramatically smaller error bars above ~1-10 GeV

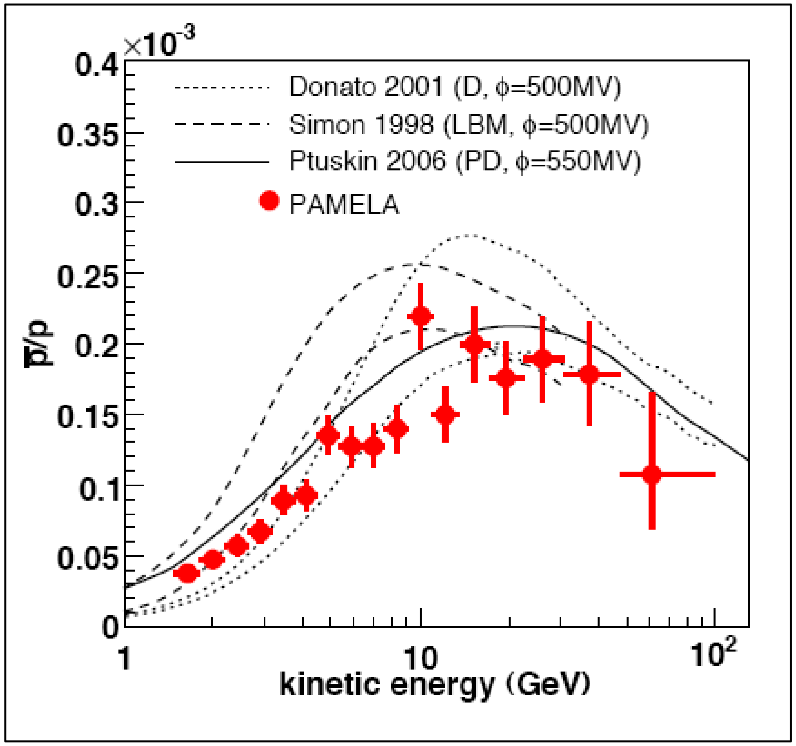


Pamela Collaboration, arXiv:0810.4994

Pamela's New Antiproton Measurement

- Best measurement to date
- Dramatically smaller error bars above ~1-10 GeV

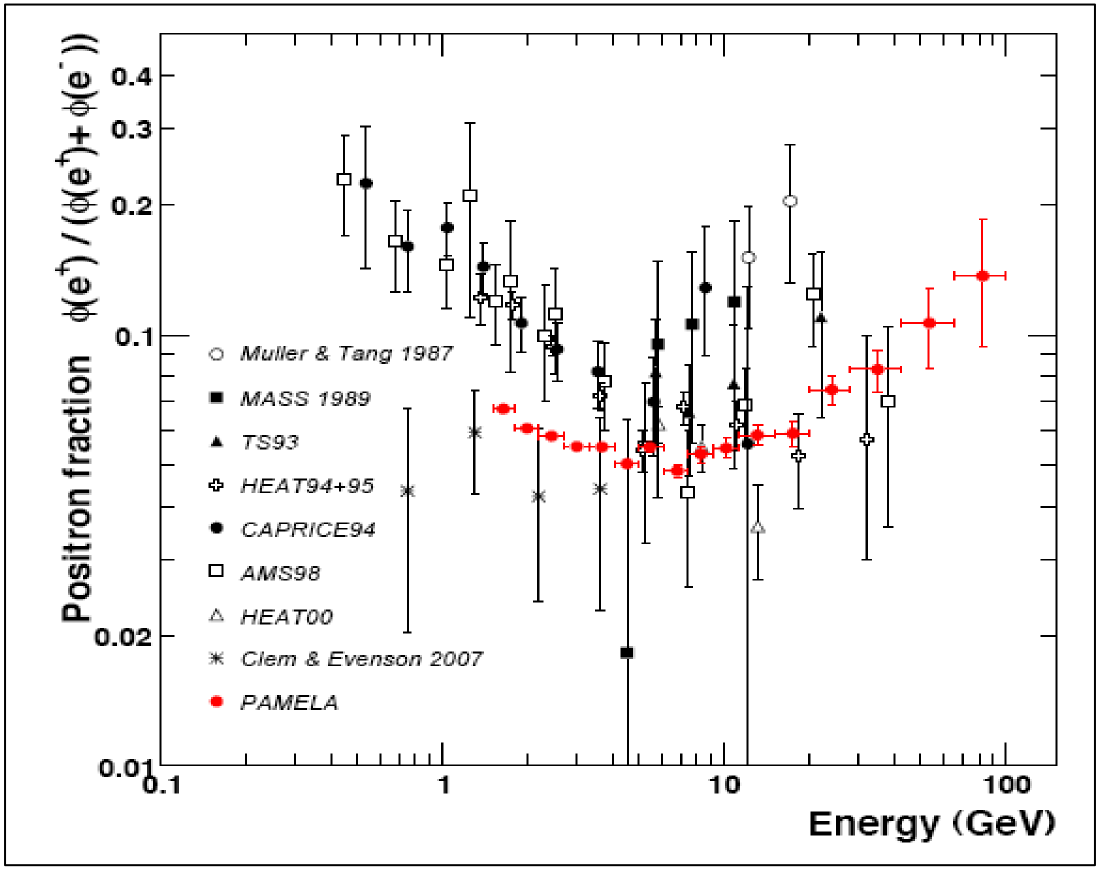
- The antiprotons detected by Pamela are consistent with being entirely from secondary production (byproduct of cosmic ray propagation)



Pamela Collaboration, arXiv:0810.4994

Dan Hooper - *Charged Cosmic Rays And Particle Dark Matter*

Pamela's New Positron Measurement



Dan Hooper - *Charged Cosmic Rays And Particle Dark Matter*

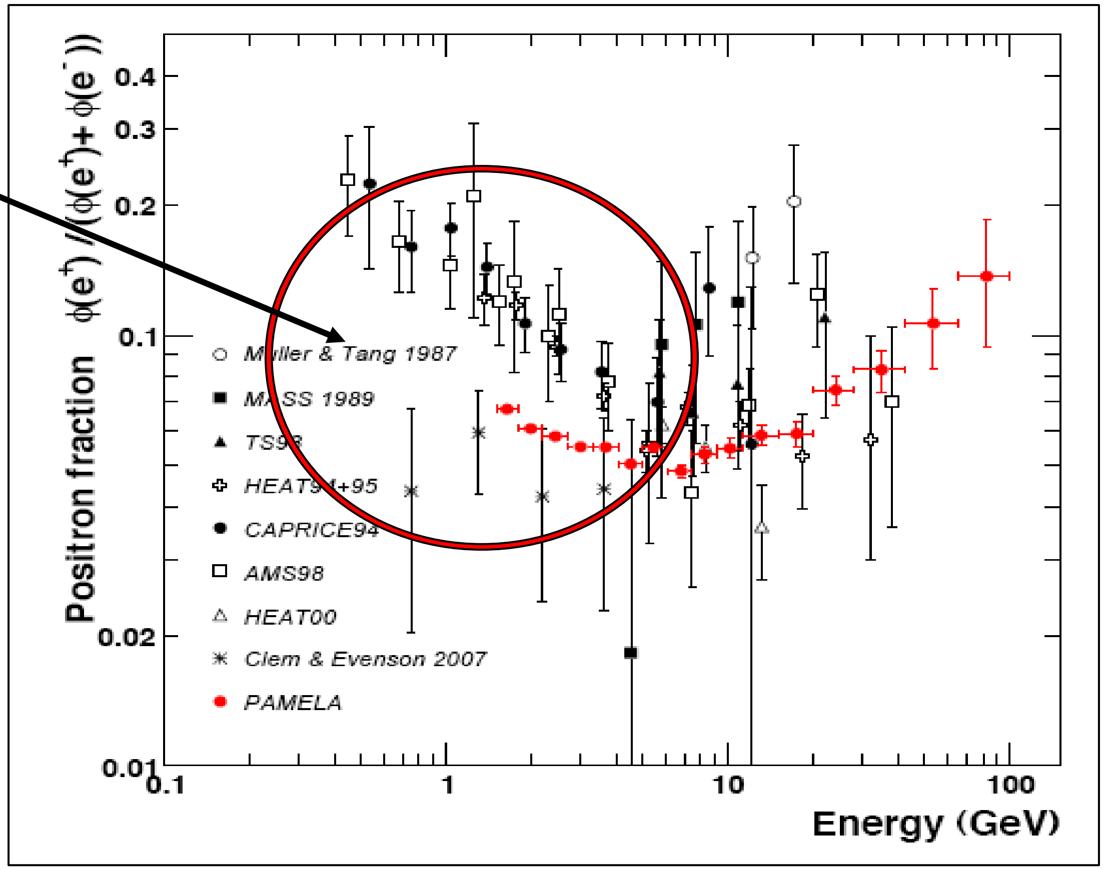
Pamela Collaboration, arXiv:0810.4995

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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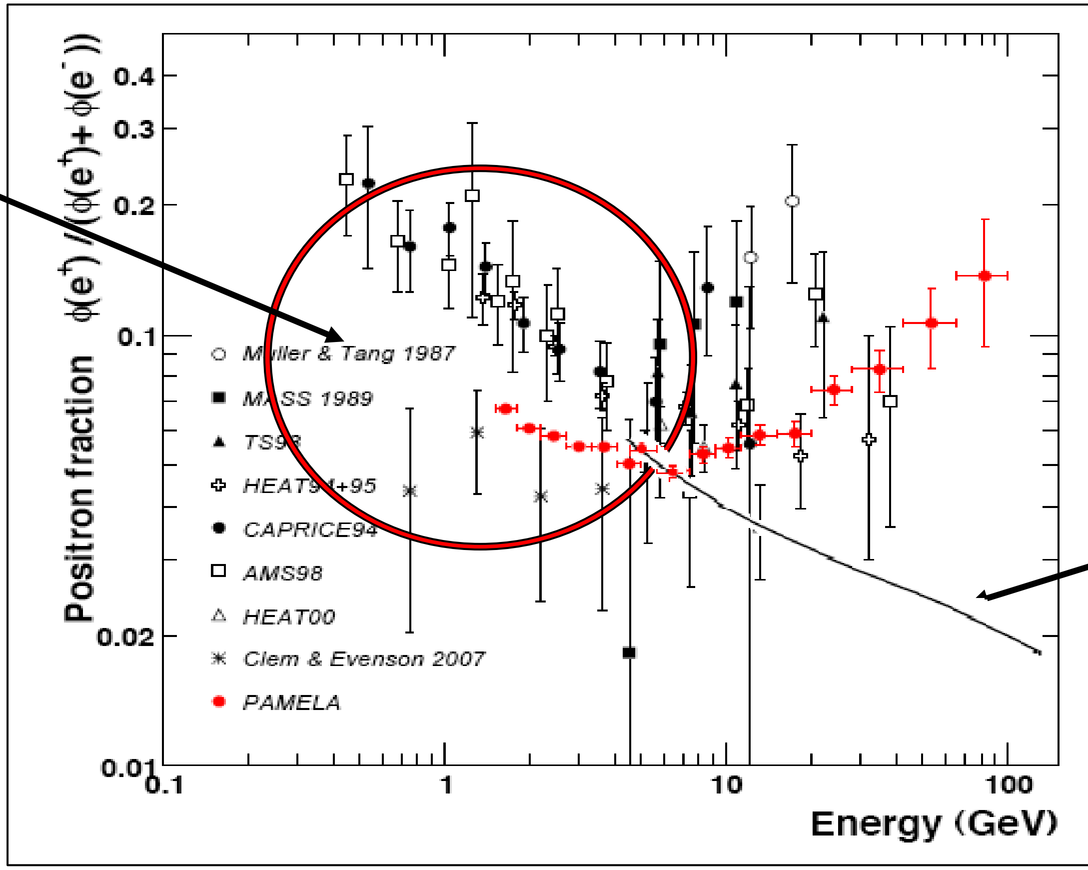

Astrophysical expectation (secondary production)

Pamela Collaboration, arXiv:0810.4995

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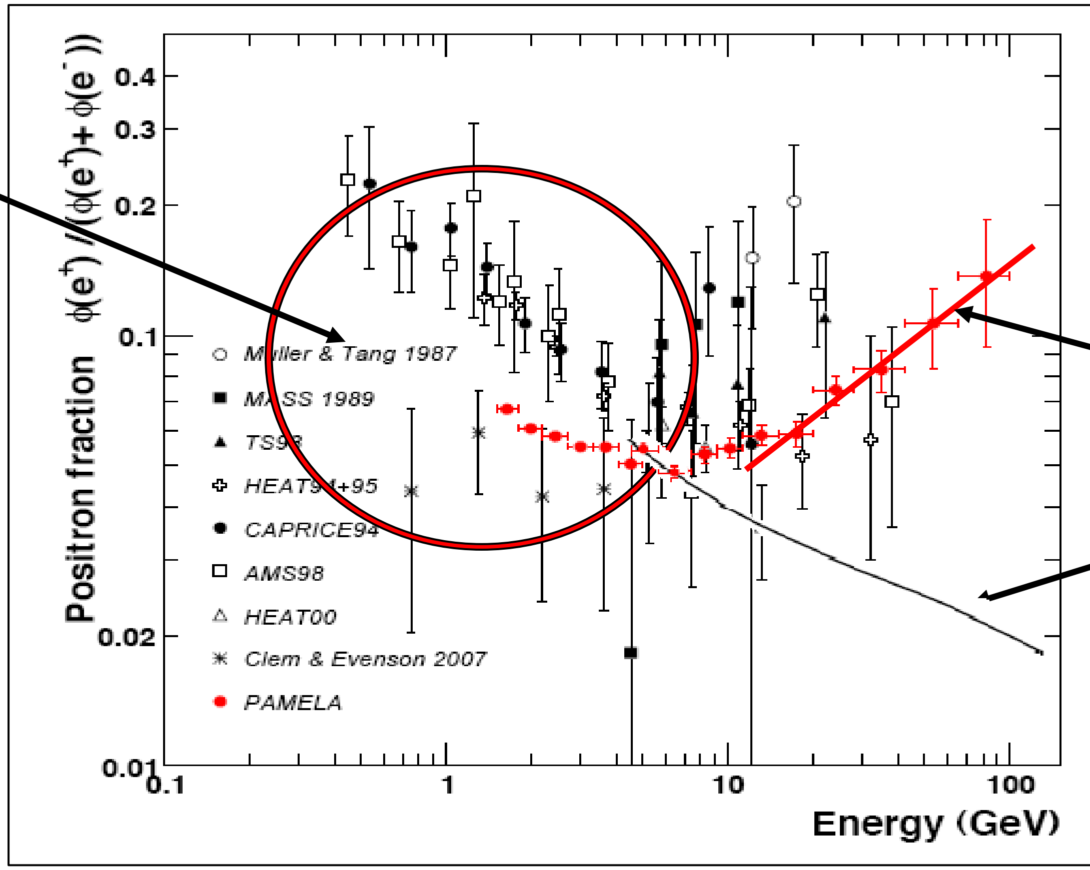


Rapid climb above 10 GeV indicates the presence of a <u>primary source of cosmic ray positrons!</u>

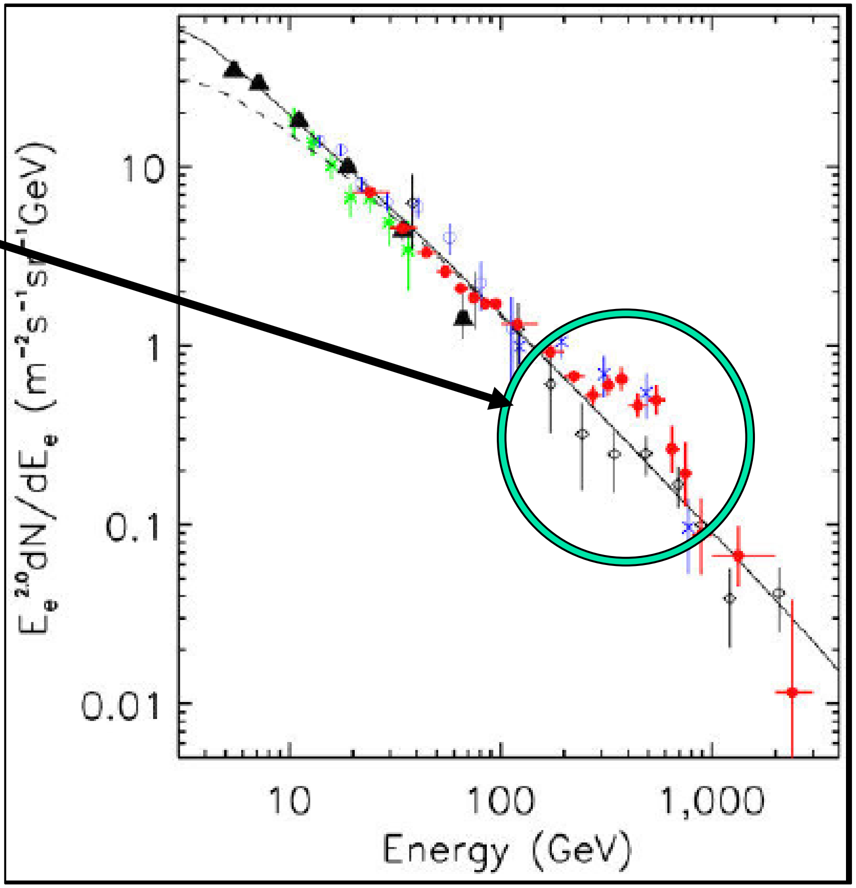
Astrophysical expectation (secondary production)

Pamela Collaboration, arXiv:0810.4995

And if you think the Pamela result is interesting…

The New Cosmic Ray Electron Spectrum From ATIC

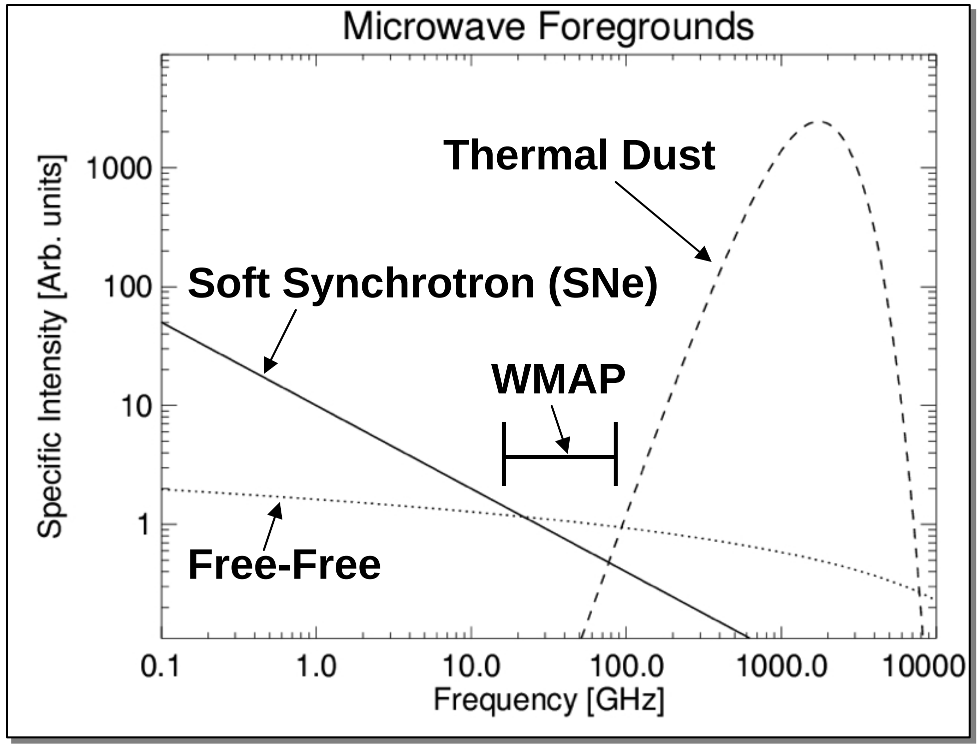
- In a series of balloon flights, ATIC has measured a 4-5σ excess of cosmic ray electrons between 300 and 800 GeV (Nature, Nov. 21, 2008)
- This requires a ***local*** source of cosmic ray electrons/positrons (within ~1 kpc)
- If we extrapolate the Pamela positron fraction up to higher energies, the ATIC result approximately matches

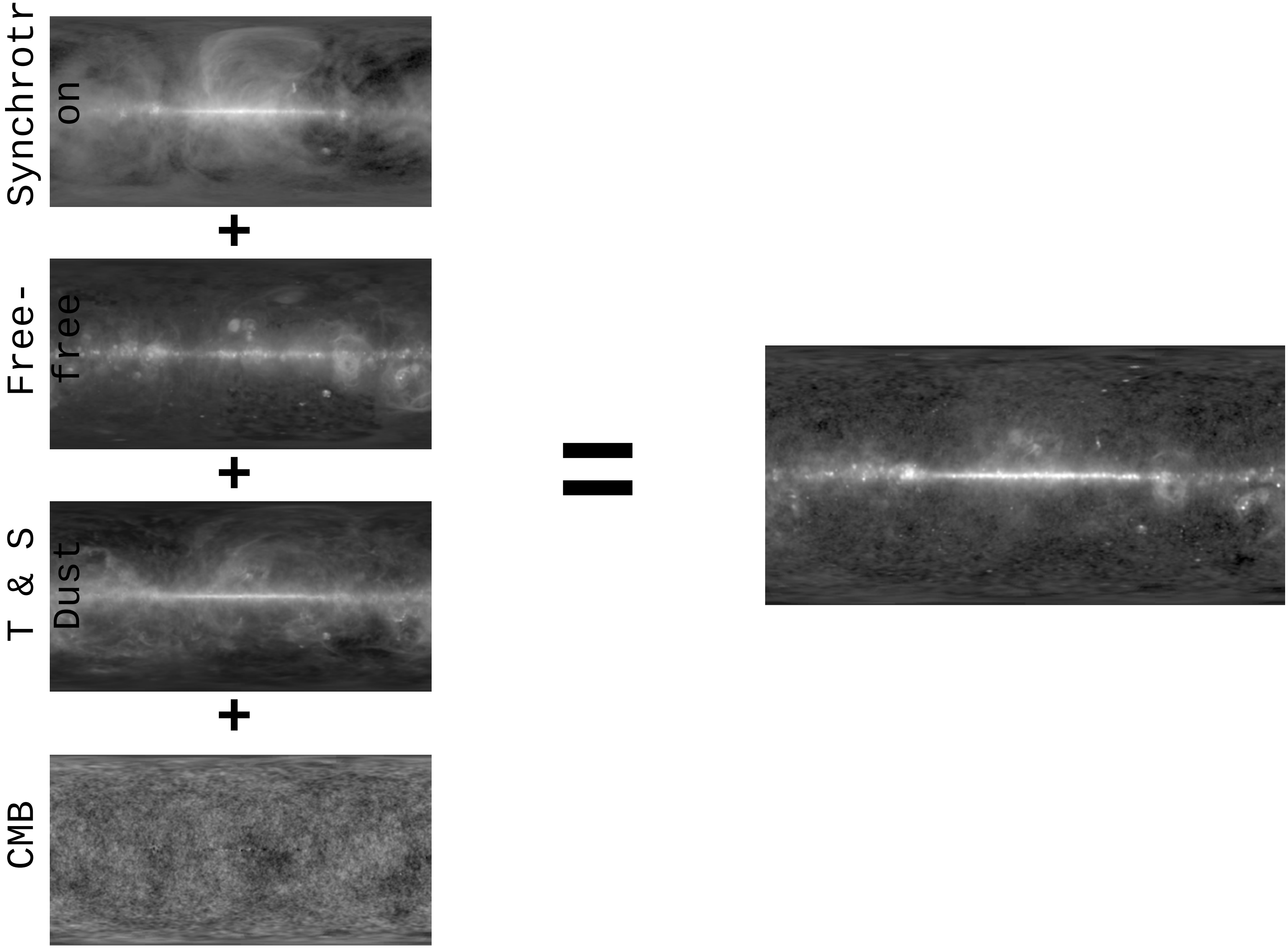


WMAP and Energetic Electrons/Positrons

- WMAP does not only detect CMB photons, but also a number of galactic foregrounds

- GeV-TeV electrons emit synchrotron in the range of WMAP





Synchrotr
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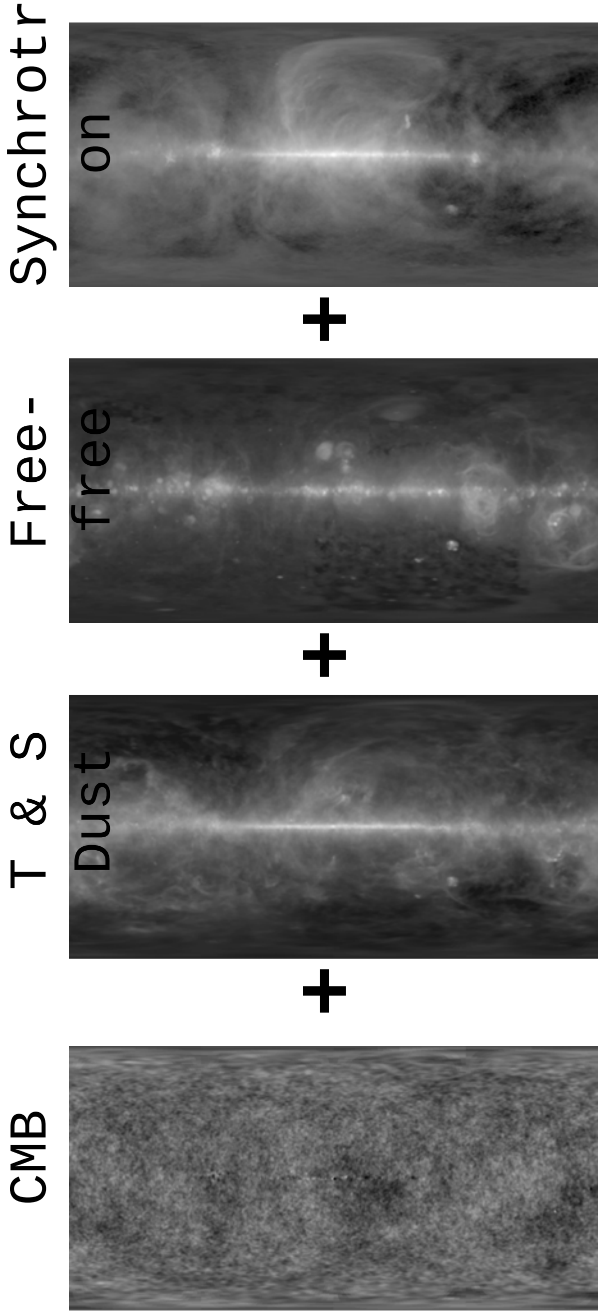
T & S
Dust
CMB



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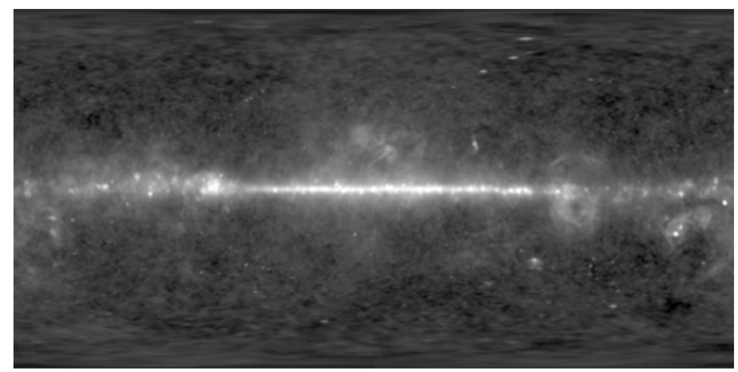
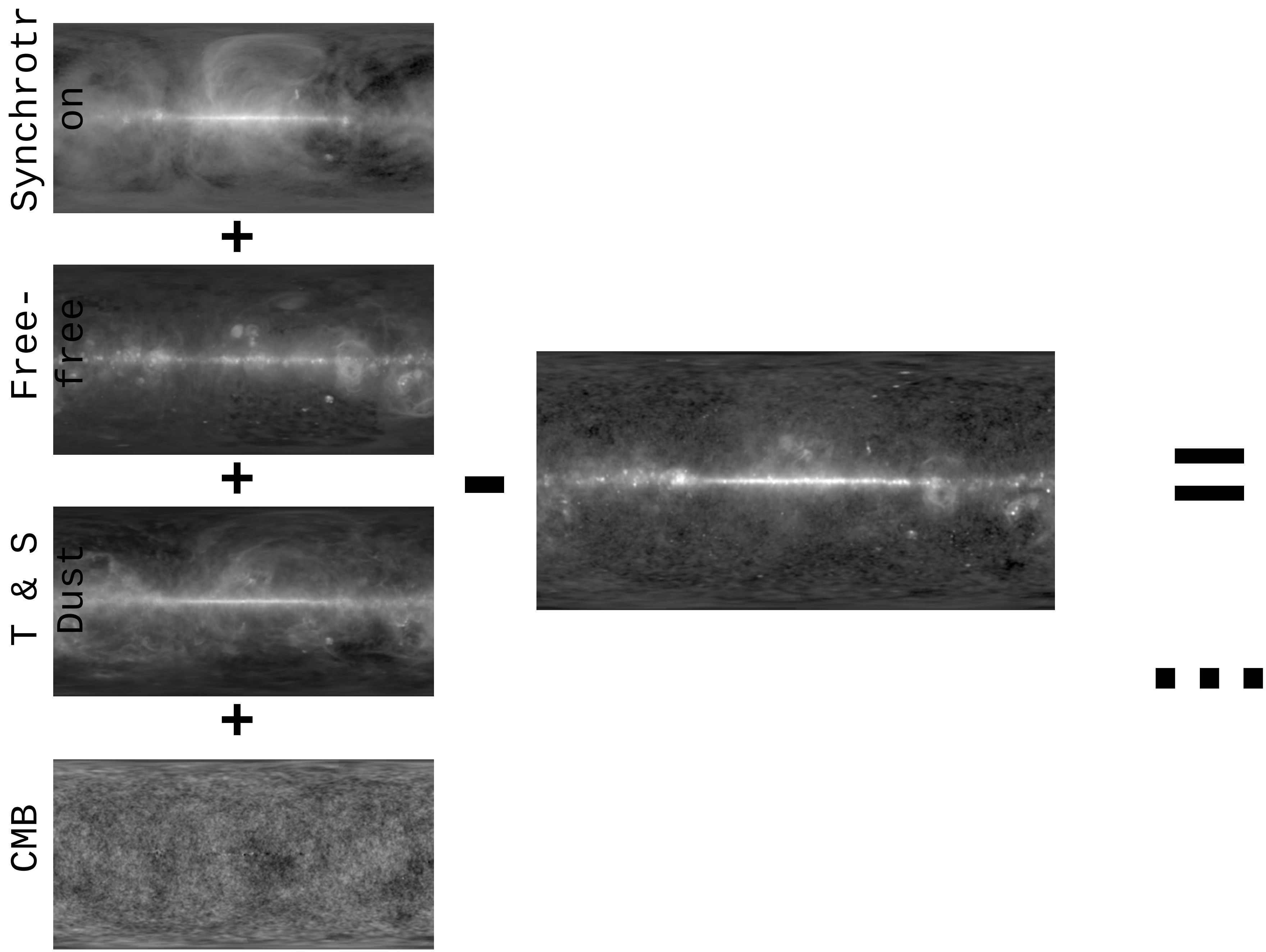


Well, actually… No


Synchrotron
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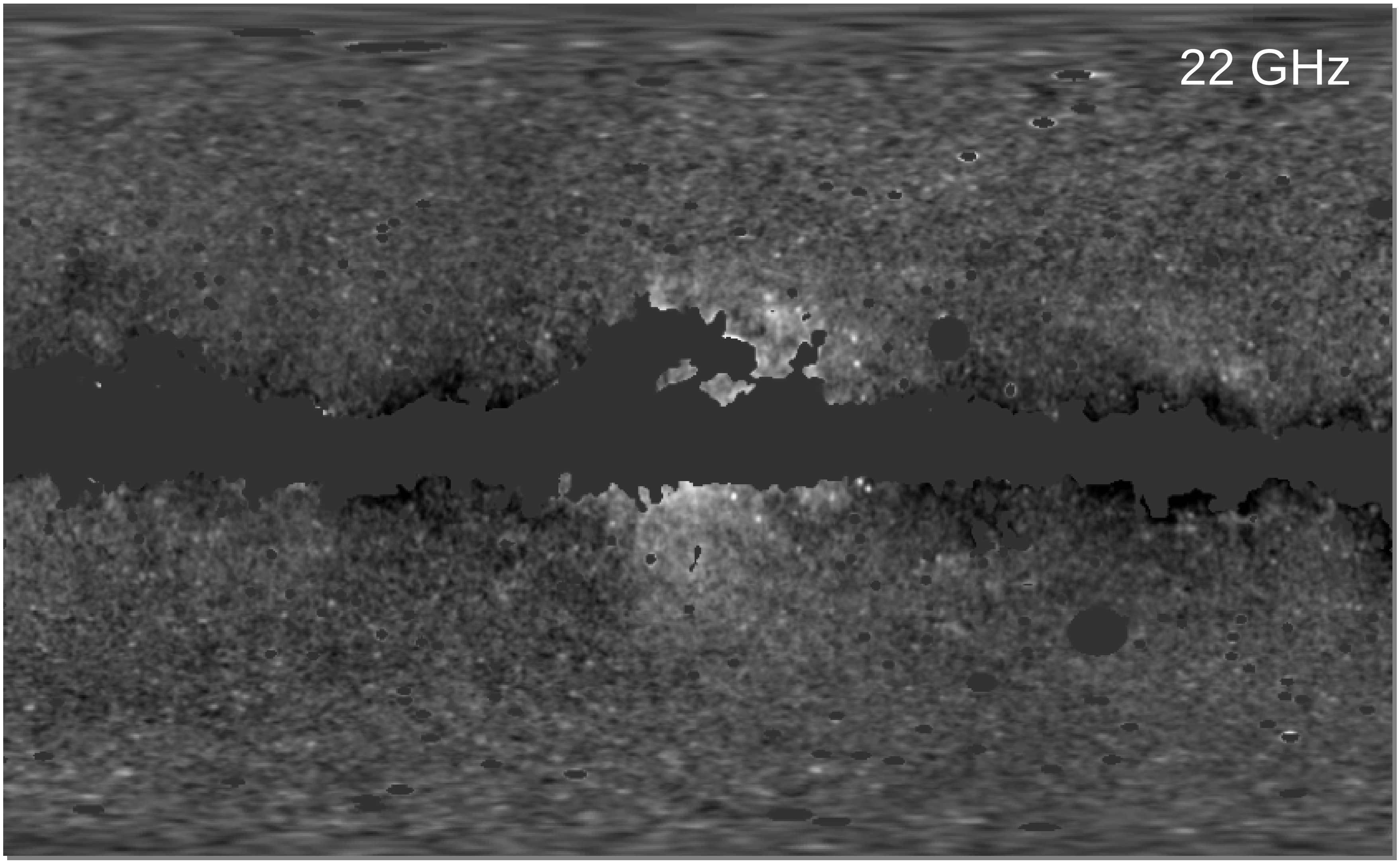
“The WMAP Haze”



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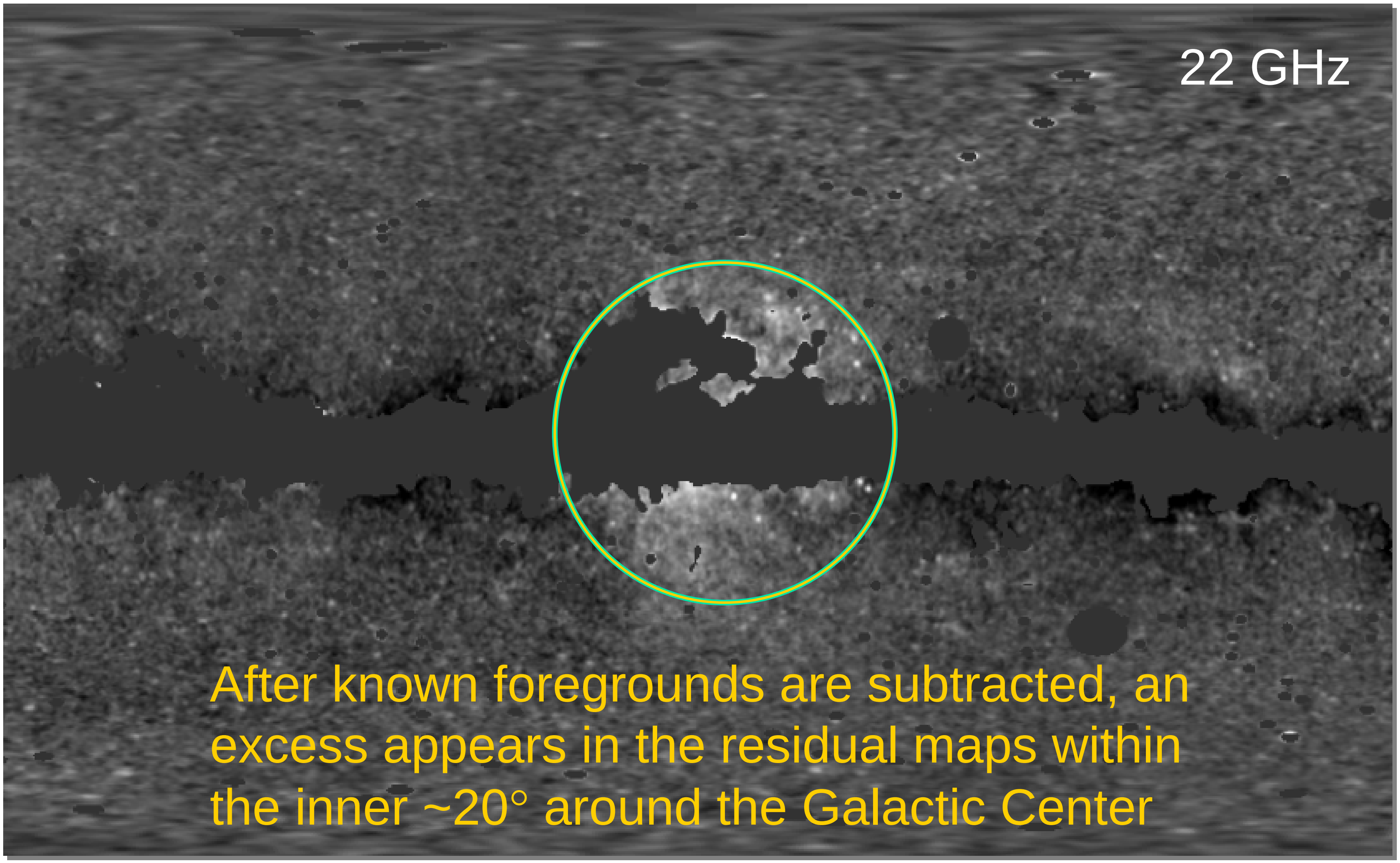
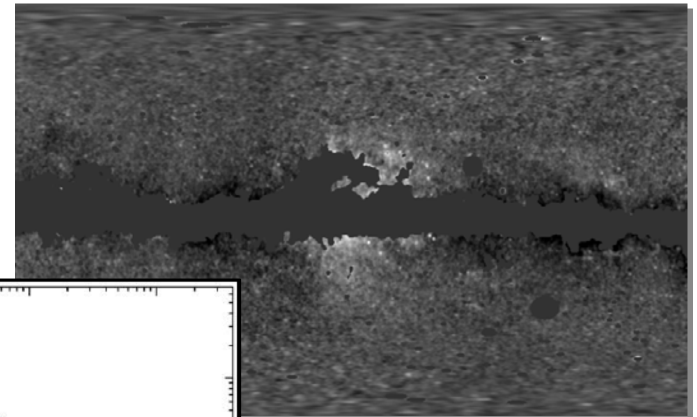


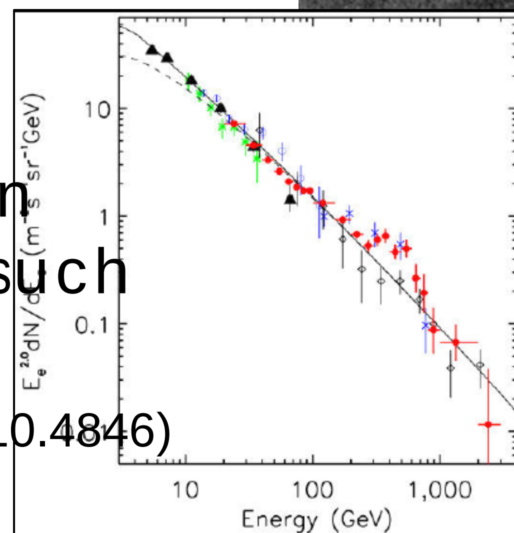
Pamela, ATIC, and WMAP

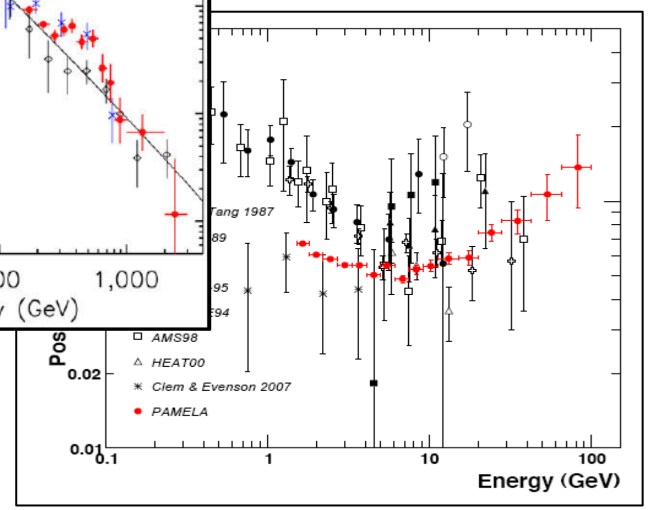
- Highly energetic electrons and positrons are surprisingly common both locally, and in the central kiloparsecs of the Milky Way

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

  (see P. Serpico, arXiv:0810.4846)





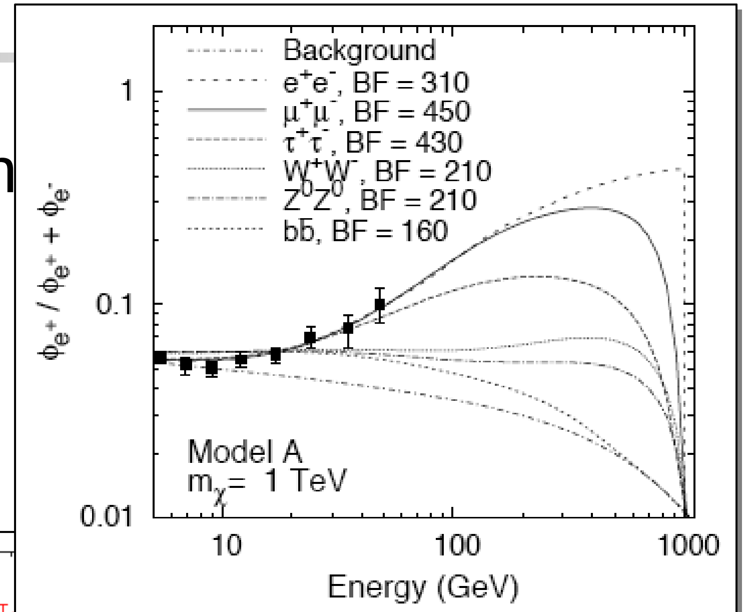


- Constitutes the discovery of bright sources of e^+e^- pairs with a very hard spectral index

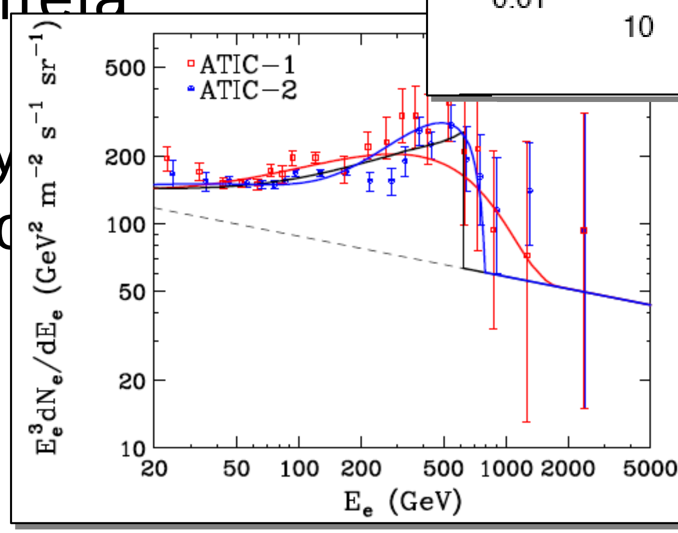
Dark Matter as the Source of the Pamela, ATIC, and WMAP Signals

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

- The spectral features observed by Pamela and ATIC 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 ATIC Signals

… but not necessarily easily.

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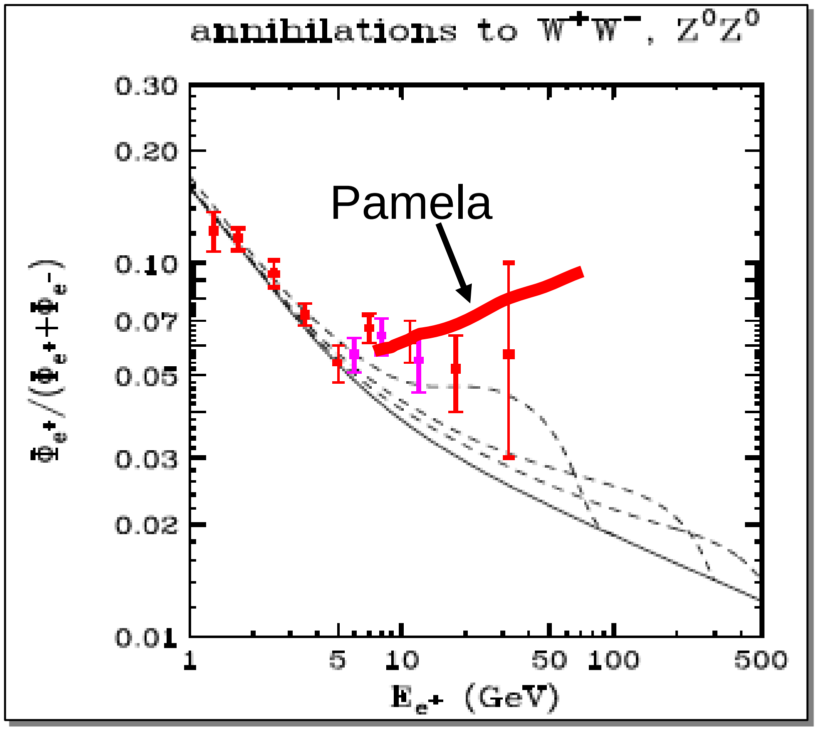
<u>Challenges Faced Include:</u>

1)Very hard spectrum



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

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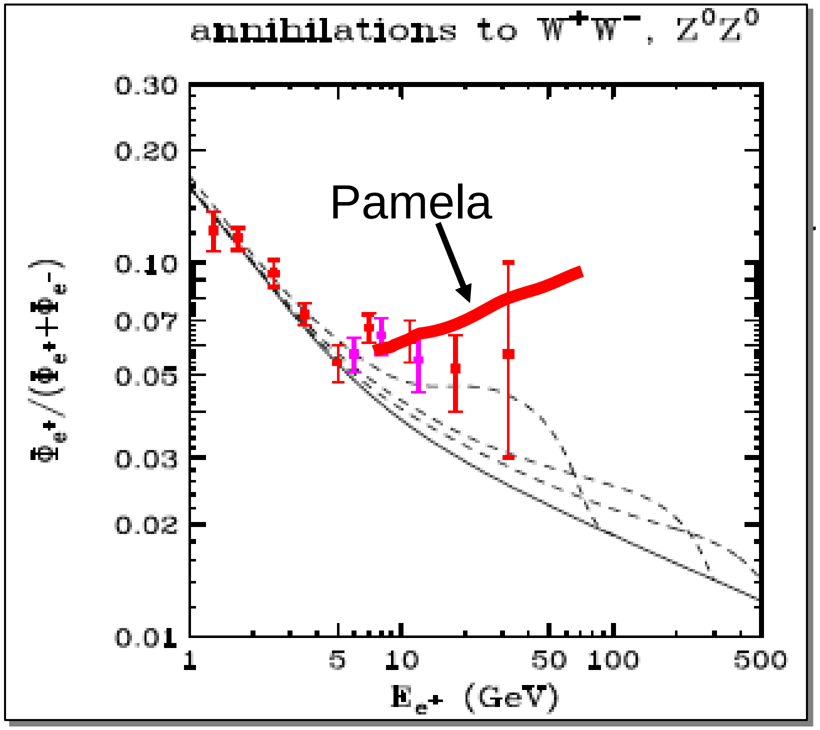
2)Too many antiprotons, rays, synchrotron



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Challenges Faced Include:

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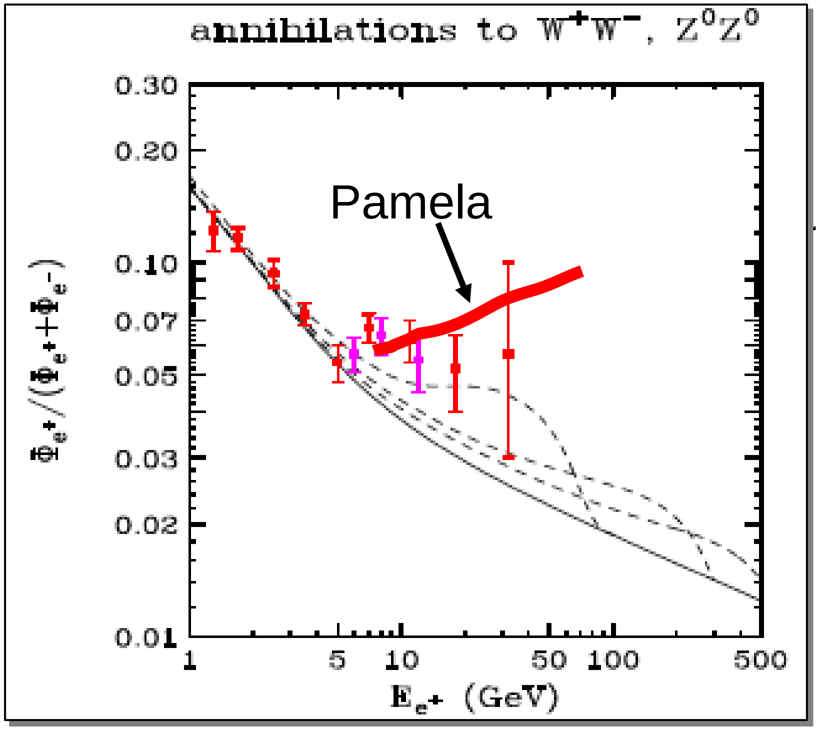
3) Requires a very high annihilation rate



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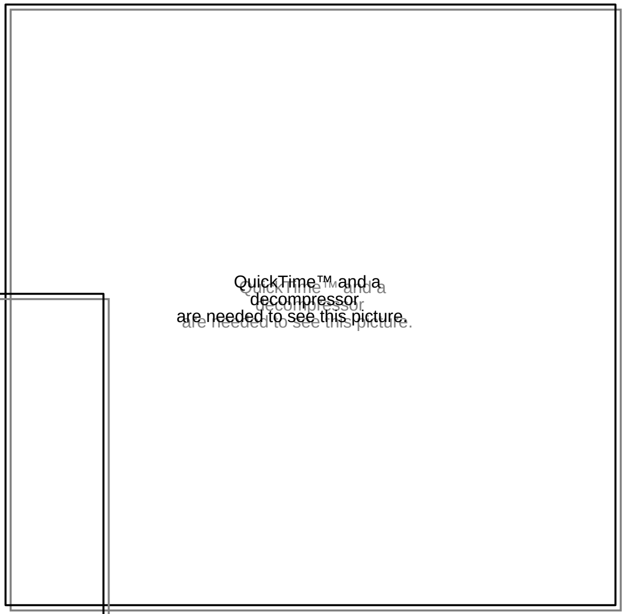
Dark Matter as the Source of the Pamela and ATIC Signals

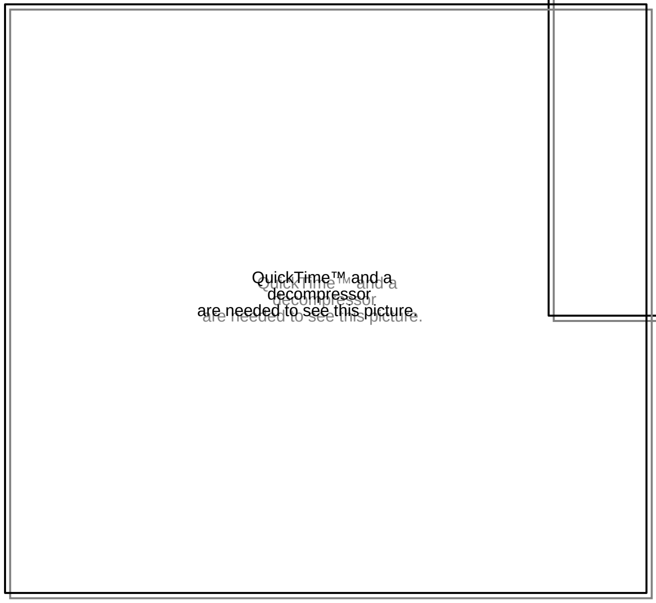
Particle Physics Solutions:

Dark Matter as the Source of the Pamela and ATIC Signals

<u>Particle Physics Solutions:</u>

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





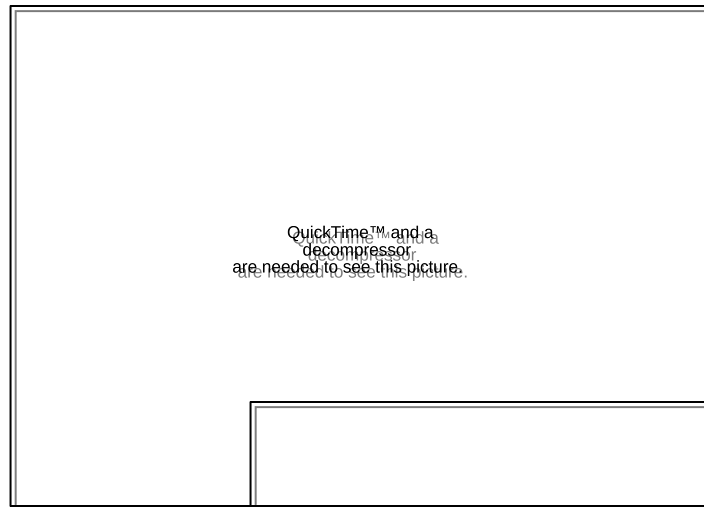
Cholis, Goodenough, Hooper, Si Weiner arXiv:0809.1683

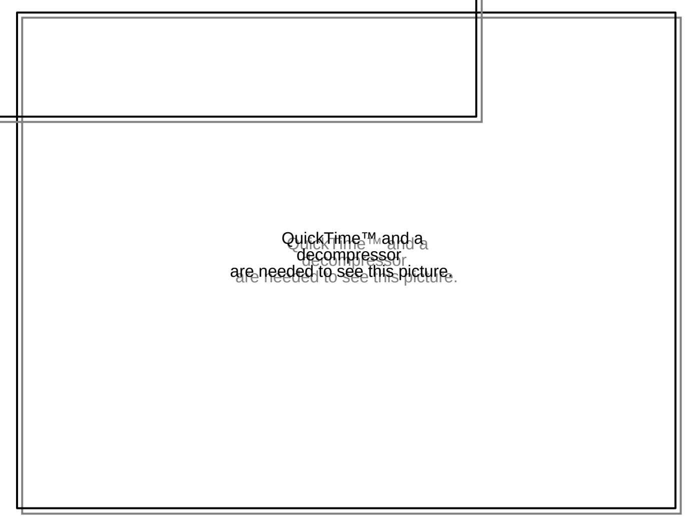
Dark Matter as the Source of the Pamela and ATIC Signals

<u>Particle Physics Solutions:</u>

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

- For example, the lightest Kaluza-Klein state in a model with a universal extra dimenison (UED) fits remarkably well (or a KK-ν or other particle which annihilates to light fermions through a Z)





Hooper, K. Zurek, arXiv:0902.0593;
Hooper, G. Kribs, PRD, hep-ph/0406026;

Dark Matter as the Source of the Pamela and ATIC Signals

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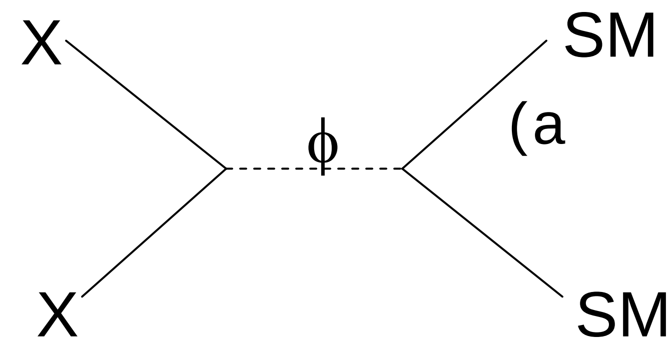
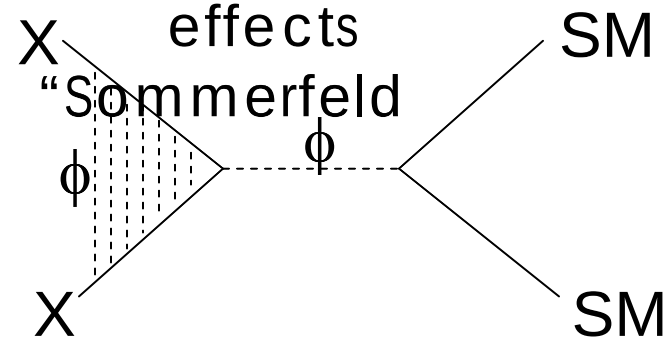


2)Annihilation rate dramatically increased by non-perturbative effects known as the "Sommerfeld Enhancement"

-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, arXiv:0811.0399

Dark Matter as the Source of the Pamela and ATIC Signals

Astrophysical Solutions:

Dark Matter as the Source of the Pamela and ATIC Signals

<u>Astrophysical Solutions:</u>

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

Dark Matter as the Source of the Pamela and ATIC Signals

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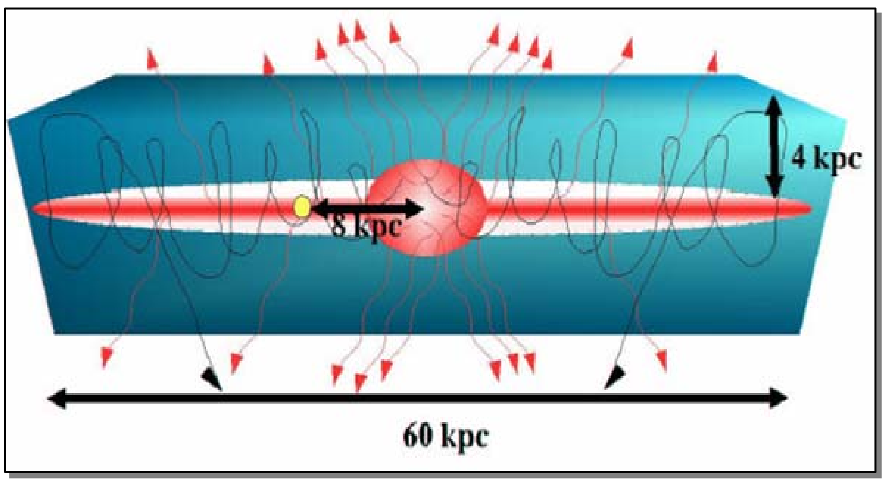
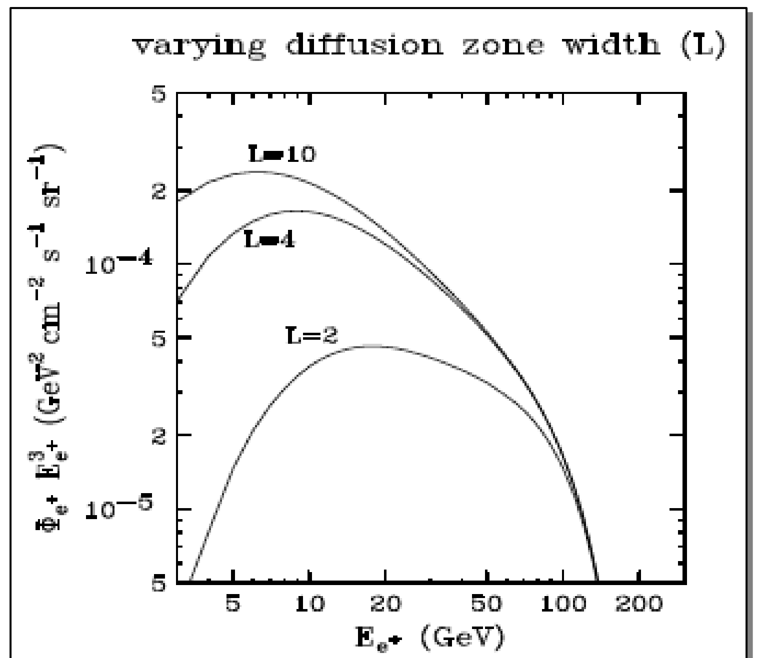
2) A narrow diffusion region





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

Dark Matter as the Source of the Pamela and ATIC Signals

Astrophysical Solutions:

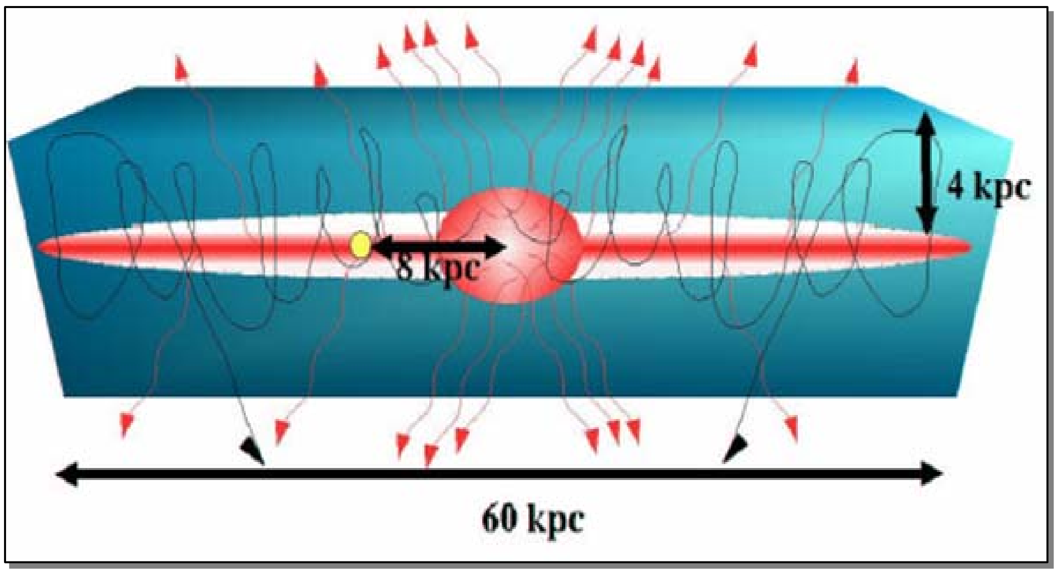
1) More small-scale structure than expected (a "boost factor" of $\sim 10^3$)

2) A narrow diffusion region

3) A large nearby clump of dark matter

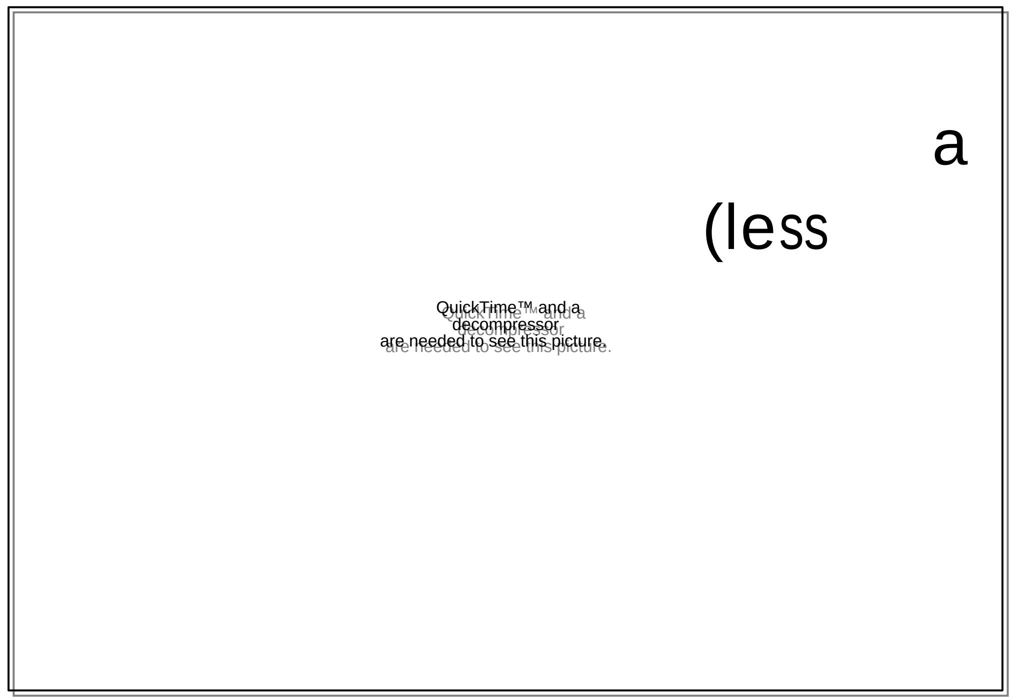
A Nearby Clump of Dark Matter?

- 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

A Nearby Clump of Dark Matter?

A clump of neutralino dark matter ~1 kpc from the Solar System provides an excellent fit to Pamela and ATIC while also:

- Evading constraints from antiproton, gamma ray, and synchrotron measurements
- Providing a plausible scenario for generating the required very high annihilation rate

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

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

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

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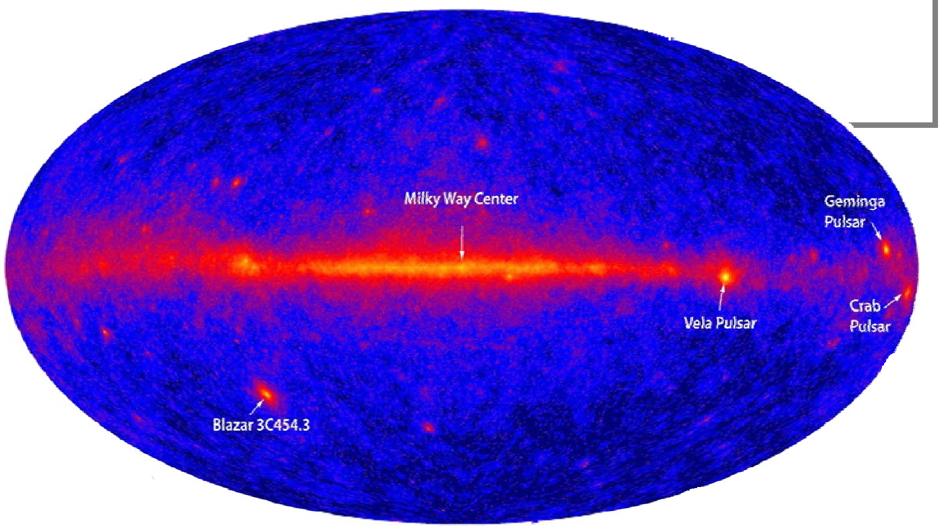

Fermi/Glast Sky Map

High-Energy Positrons From Nearby Pulsars

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- Very young pulsars ($\lesssim$10,000 years) are typically surrounded by a pulsar wind nebula, which can absorb energetic pairs

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Vela Pulsar (12,000 years old)

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- Very young pulsars ($\lesssim$10,000 years) are typically surrounded by a pulsar wind nebula, which can absorb energetic pairs
- Most of the spindown power is expended in first ~10^5 years

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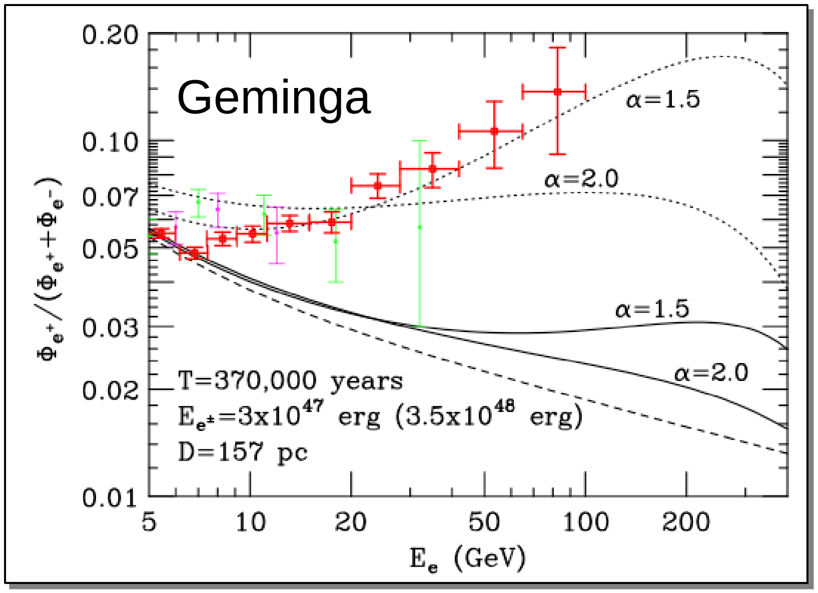
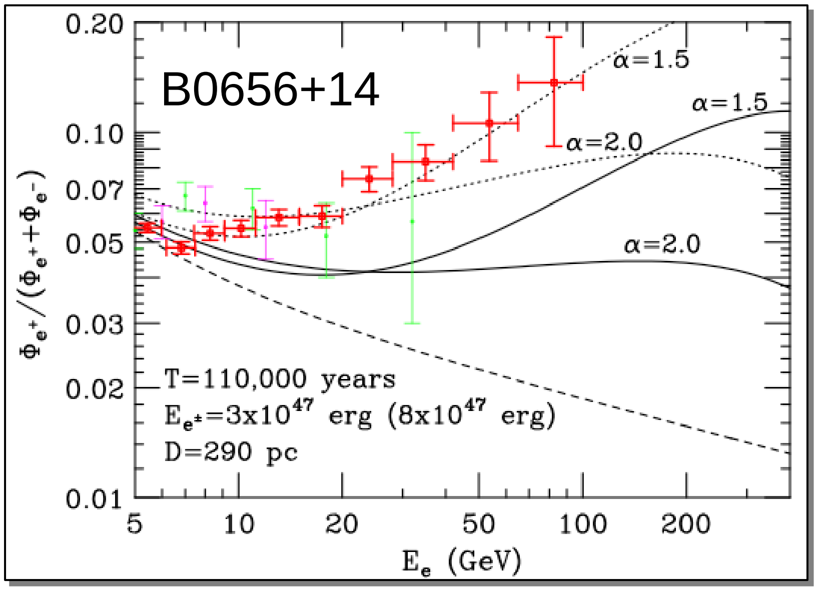
Vela Pulsar (12,000 years old)

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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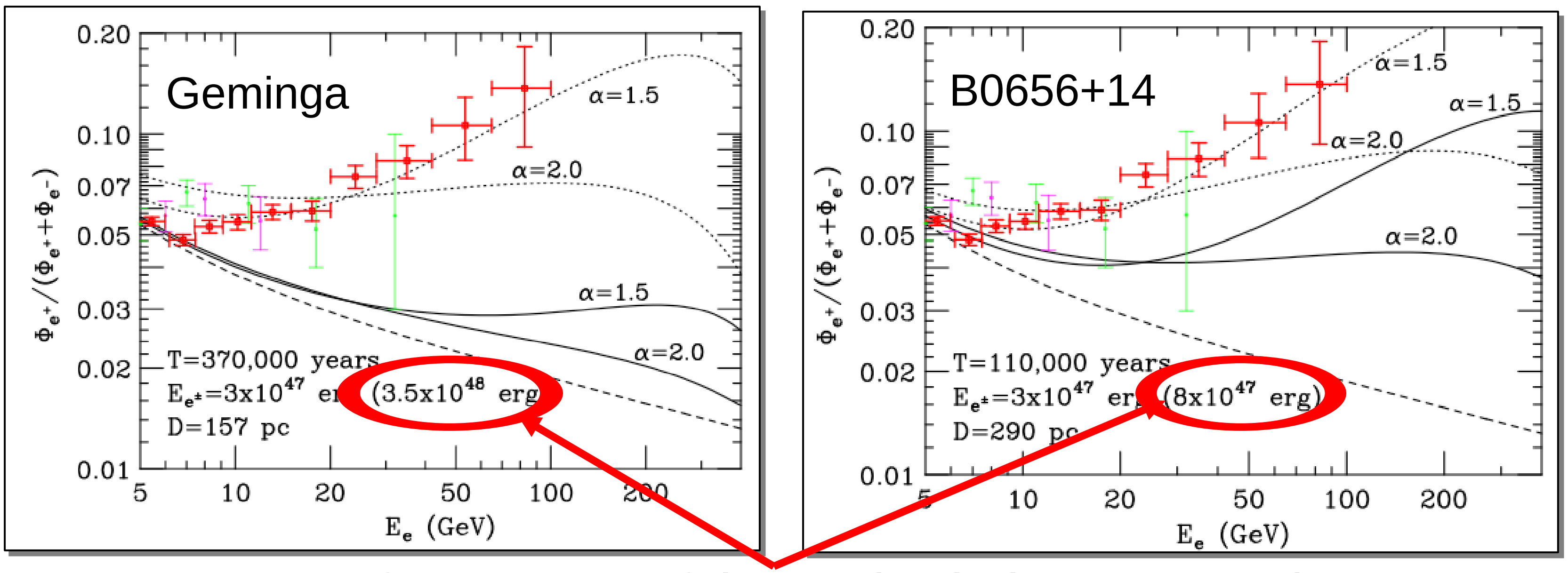


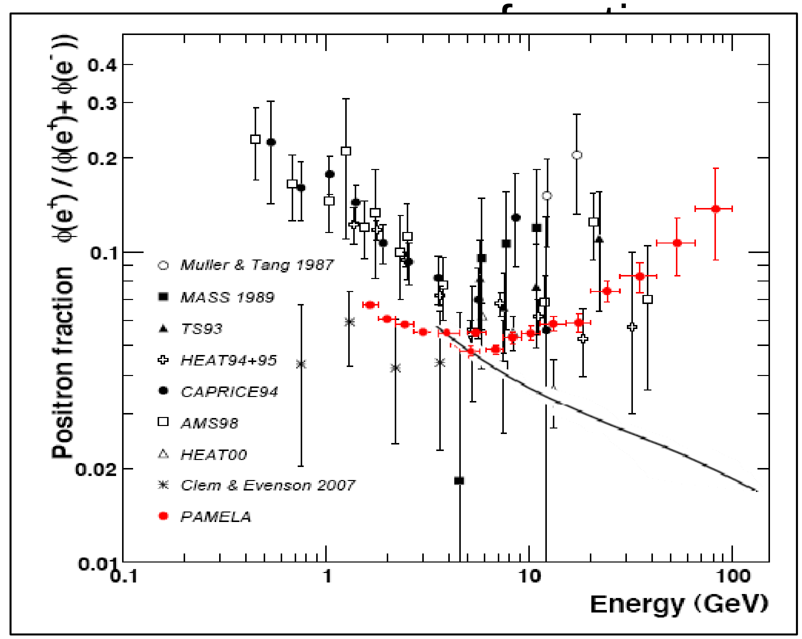
A few percent of the total spindown energy is needed in high energy e^+e^- pairs

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

Secondary Positrons From The Acceleration Region?

- 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; Leads to a steadily falling positron

- It has recently been suggested that if secondary positrons are produced *of* cosmic ray acceleration spectrum may be potentially causing the fraction to rise



P. Blasi, arXiv:0903.2794

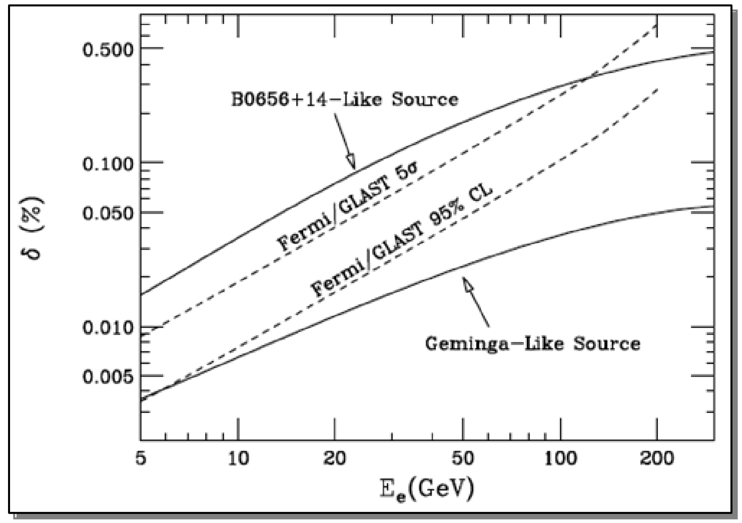
Many Questions, Few Answers

- The current set of data does not allow us to identify the origin of the Pamela, ATIC, 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/ATIC 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.

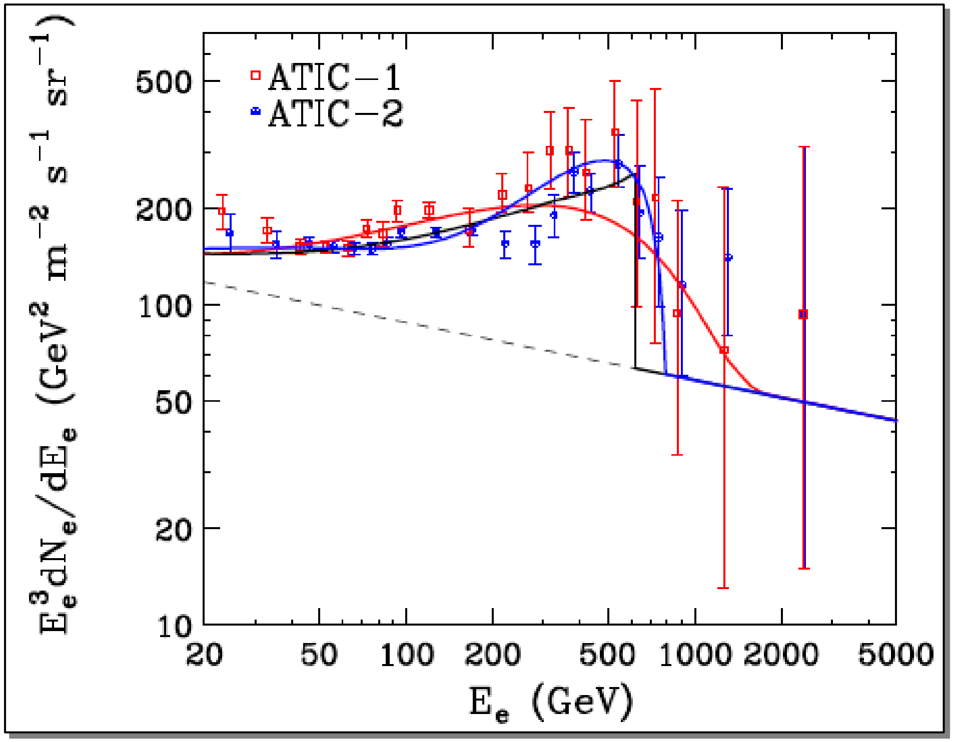
Hooper, P. Blasi, P. Serpico, JCAP, arXiv:0810.1527

Test #2: Measure The ATIC Feature With Gamma Ray Telescopes

The spectral feature observed by ATIC could be the product of:

- A nearby pulsar
- Dark matter annihilating to e^+e^- or other charged leptons
- Nearby dark matter annihilating to W^+W^-

Cannot be distinguished with current precision (exposure limited)



J. Hall and D. Hooper, arXiv:0811.3362

Test #2: Measure The ATIC Feature With Gamma Ray Telescopes

- Ground-based telescopes use the entire atmosphere as a target, and thus have much larger collecting areas (~10^5 m^2) than balloon experiments such as ATIC (~1 m^2)
- Ground-based telescopes, however, have a more diffic time identifying/separating showers produced by electr protons, and gamma-rays

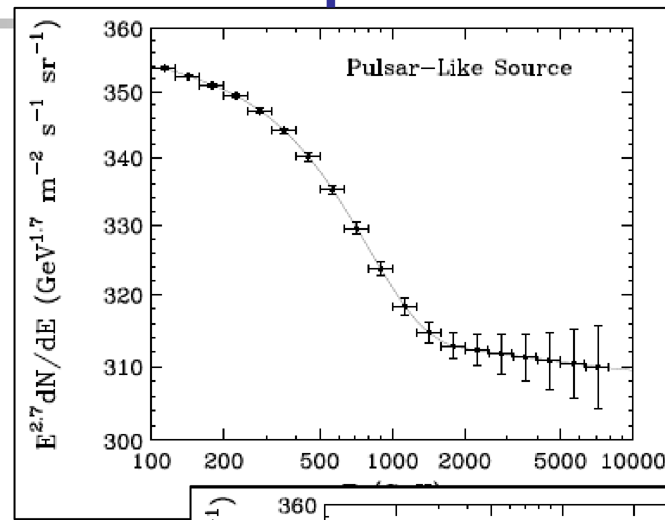
- The biggest challenge in measuring the cosmic ray electron spectrum lies in effic rejecting hadrons (~99% currently, moving toward 99.9% in the future)

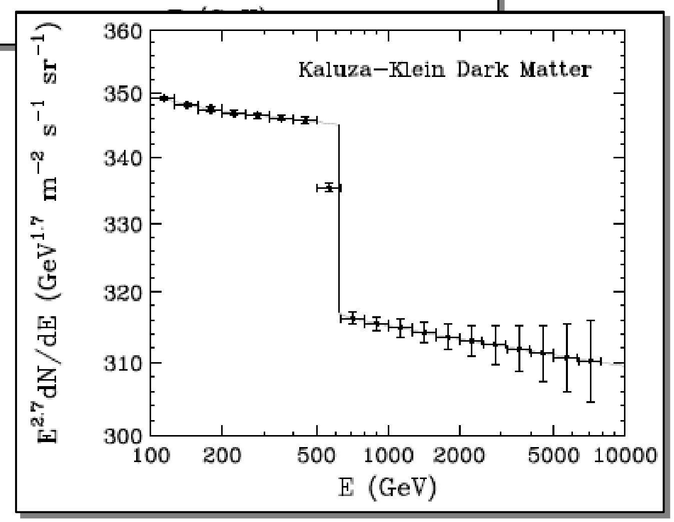
J. Hall and D. Hooper, arXiv:0811.3362

Test #2: Measure The ATIC Feature With Gamma Ray Telescopes

- Even with conservative assumptions regarding performance, ***existing data from HESS or VERITAS*** should be sufficient to distinguish between these possibilities with very high significance

- Once this analysis is performed, we should know one way or the other whether dark matter annihilating directly to e^+e^- is responsible for the excess observed by ATIC





J. Hall and D. Hooper, arXiv:0811.3362

Test #2: Measure The ATIC Feature With Gamma Ray Telescopes

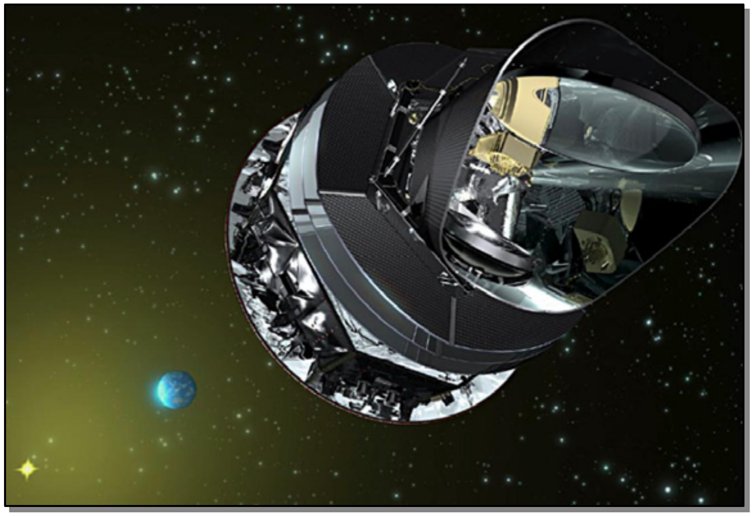
- Very recently, the HESS collaboration published its electron spectrum between ~700 GeV and several TeV (*ie*. just above the energy range of interest!)

- Considering how small the (statistical) error bars at ~700 GeV, there is every reason to believe that HESS (or VERITAS) will be capable of measuring the shape of the electron spectrum over the ATIC feature

HESS Collaboration, arXiv:0811.3894

Test #3:
Study the Synchrotron Haze With Planck

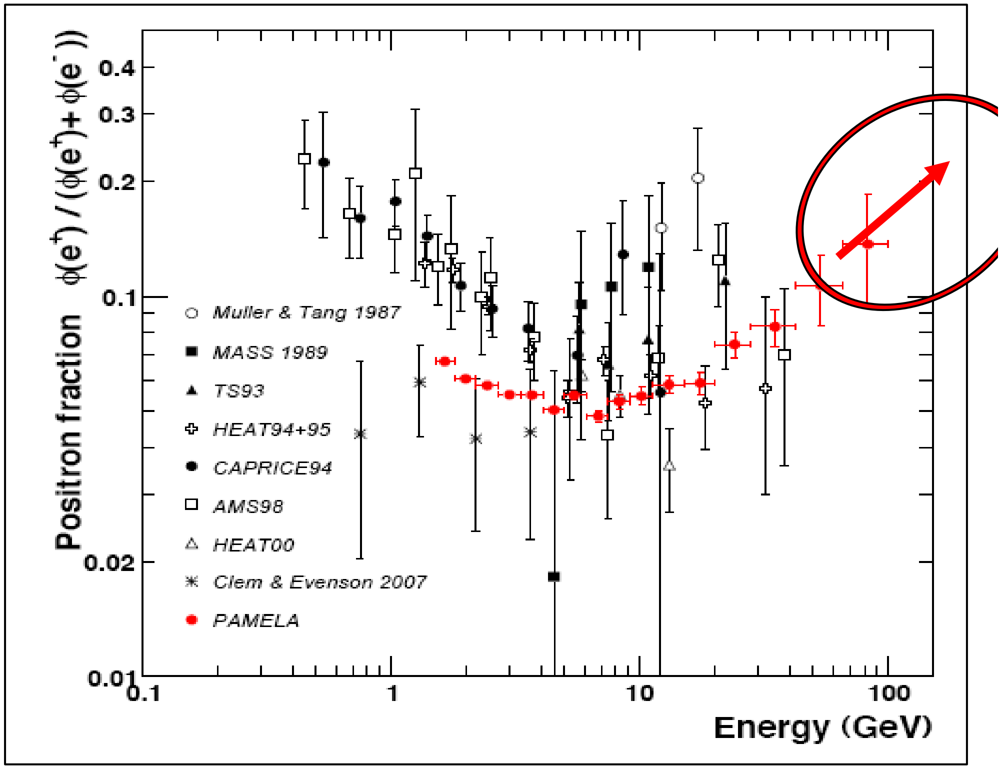
- The Planck satellite is scheduled for launch in April
- With far superior angular resolution and frequency coverage than WMAP, Planck will measuring in much greater detail the properties of the synchrotron haze from the Galactic Center



Test #4: 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 #5: Search For Gamma Ray Dark Matter Annihilation Products With Fermi

- In august, the FERMI collaboration announced their first results!
- The sky map collected by FERMI in its first four days was already more detailed than that obtained by EGRET over its entire mission

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

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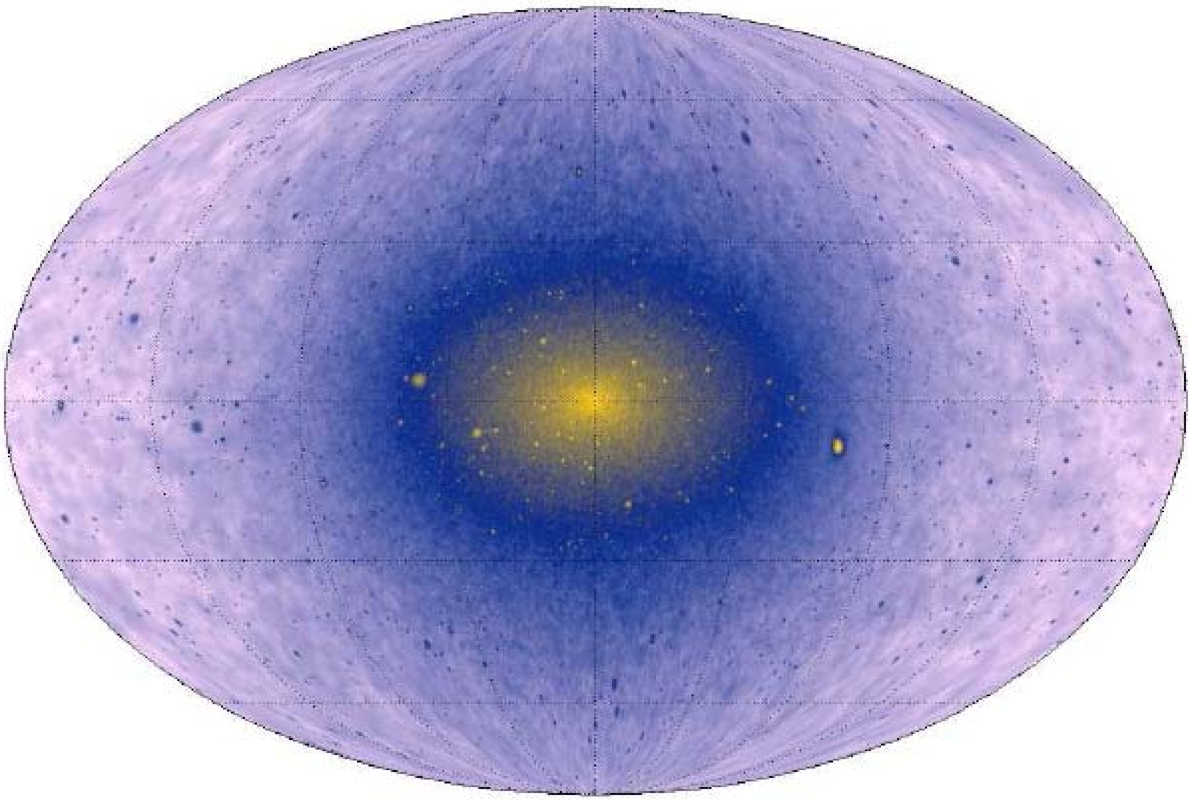
Where To Look For Dark Matter With Fermi?

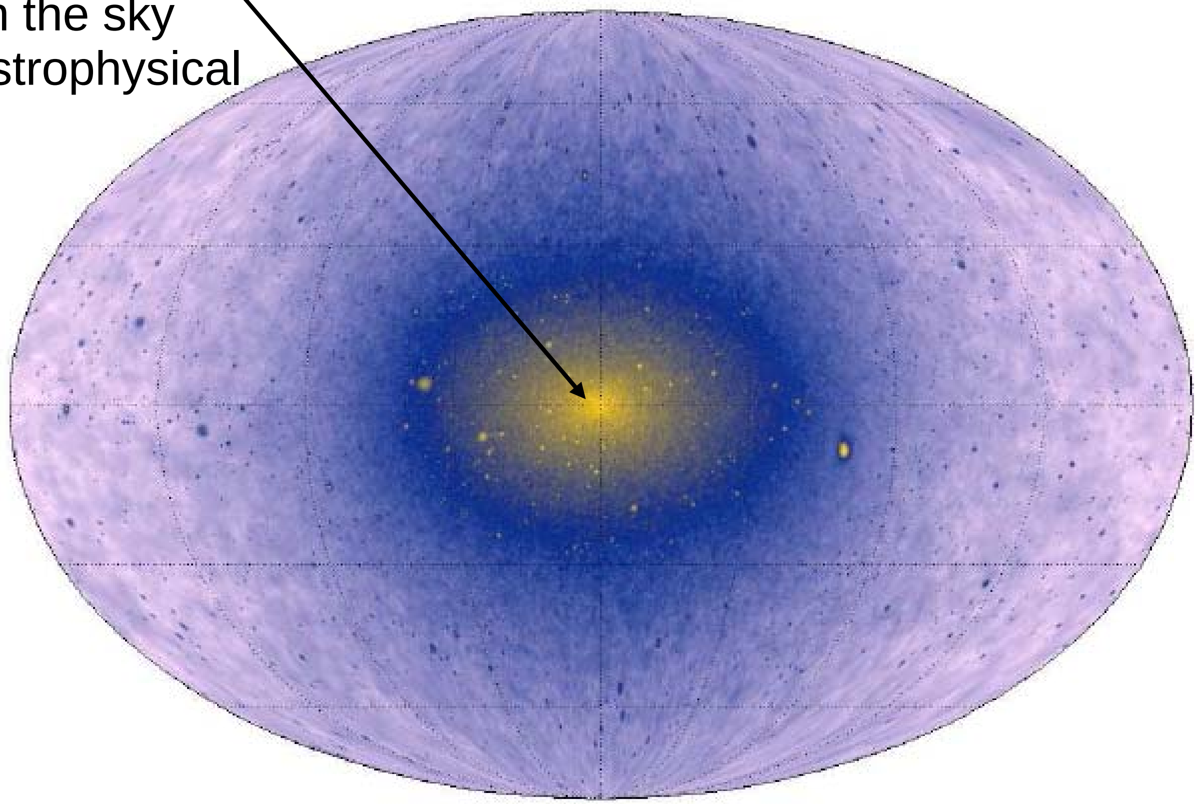


Diemand, Kuhlen, Madau, APJ, astro-ph/0611370

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

Where To Look For Dark Matter With Fermi?

The Galactic Halo

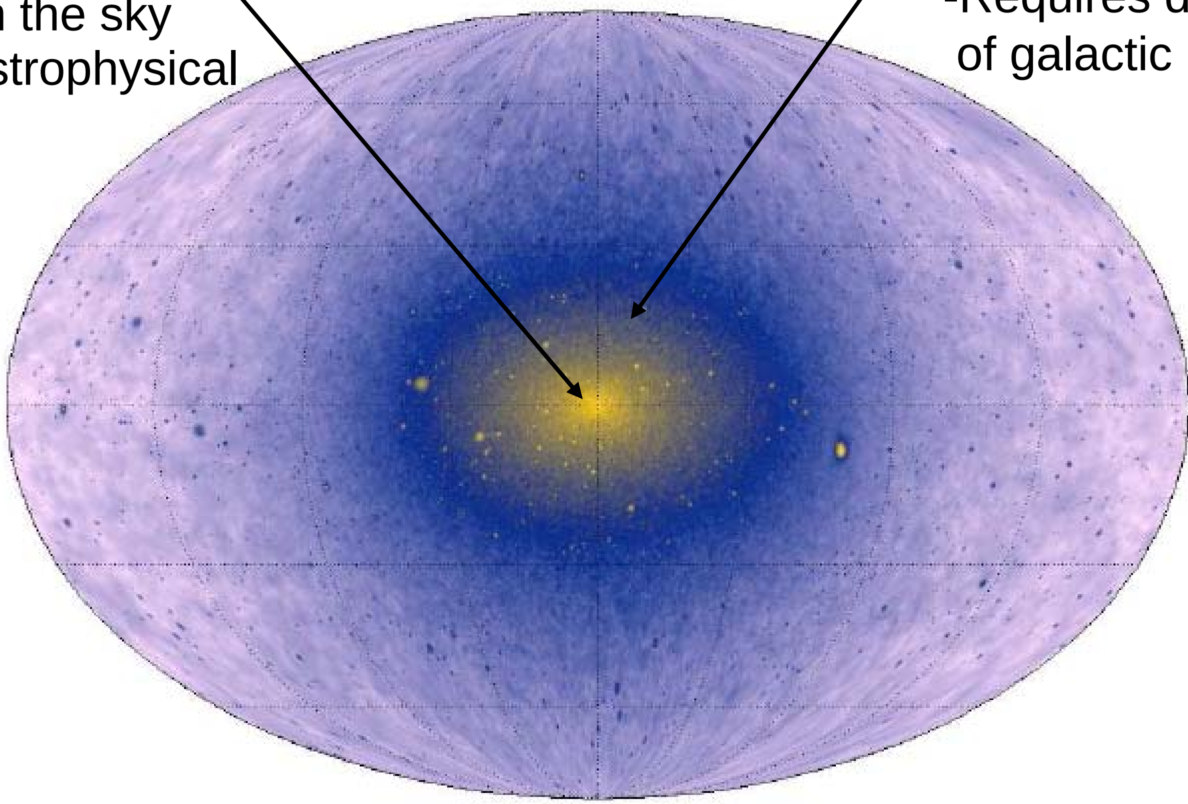
-High statistics

-Requires detailed model of galactic backgrounds

The Galactic Center

-Brightest spot in the sky

-Considerable astrophysical backgrounds



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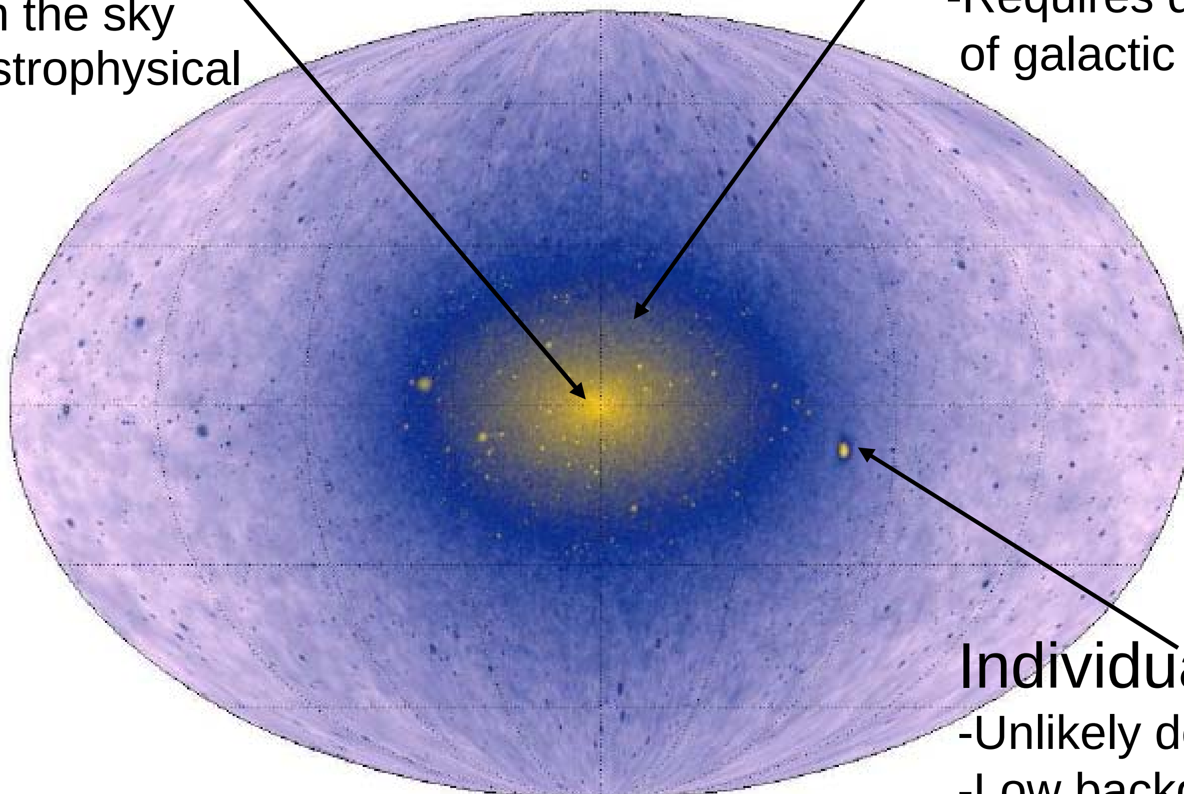

Individual Subhalos

-Unlikely detectable
-Low backgrounds

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

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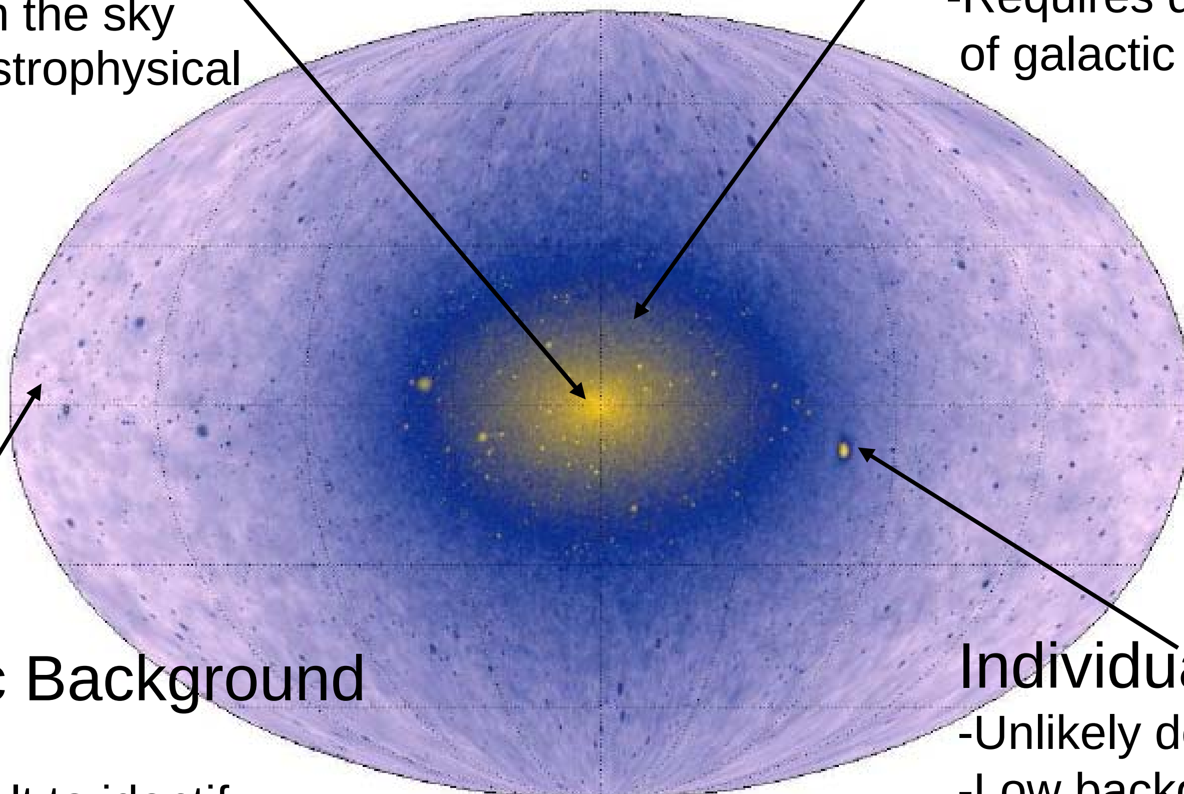
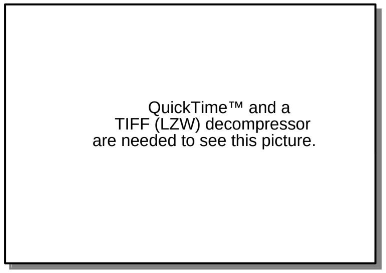


Extragalactic Background
-High statistics
-potentially difficult to identify

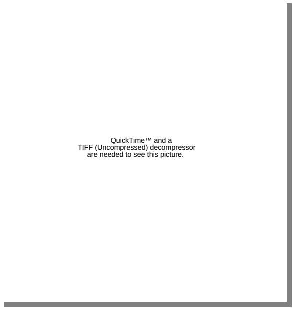
Individual Subhalos
-Unlikely detectable
-Low backgrounds

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

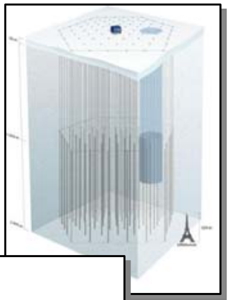
Summary



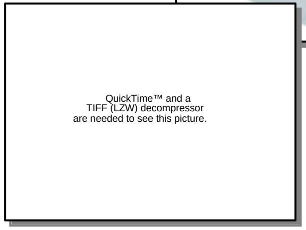
- The sensitivity of direct and indirect searches for dark matter and each rapidly advancing
- Pamela, ATIC, and WMAP have intriguing detections of 10-1000 GeV electrons/positrons in the Milky Way - *consistent with being the first detections of particle dark matter!*



- FERMI/GLAST will almost certainly shed a great deal of light on these observations - *more results expected soon!*



- New constraints from CDMS, XENON, and IceCube are beginning to exclude otherwise viable models (*ie*. focus point SUSY)



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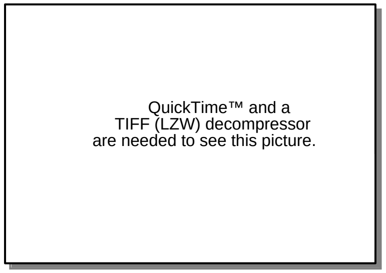
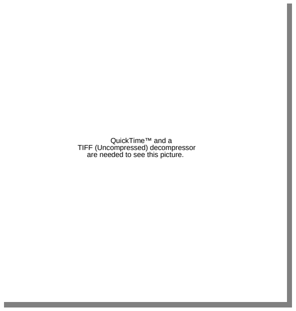
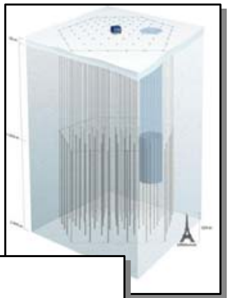
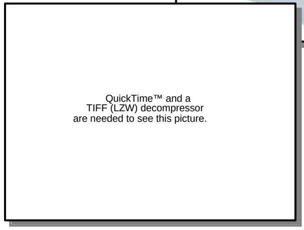


<u>One Year From Now</u>

- New limits from CDMS, XENON-100, at or below the $\sim 10^{-8}$ pb level, ruling out essentially the entire focus point SUSY region (or the first observation of WIMP-nuclei scattering)
- First full year of FERMI/GLAST data
- PAMELA positron spectrum up to 200-270 GeV?







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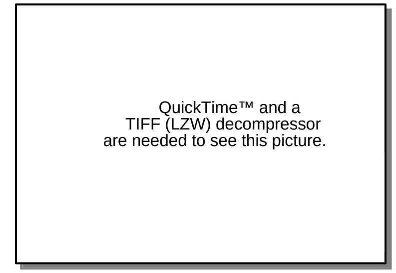

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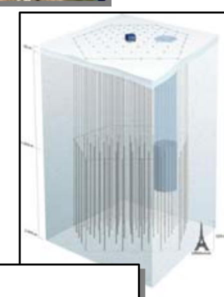
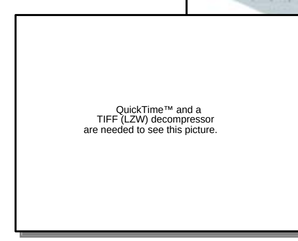
Three Years From Now

- Ton-scale direct detection experiments
- Results from Planck, IceCube, Glast, Pamela
- Discovery of SUSY or other new physics at the LHC





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Welcome to the Discovery Era!