

Indirect Searches For Particle Dark Matter

Dan Hooper

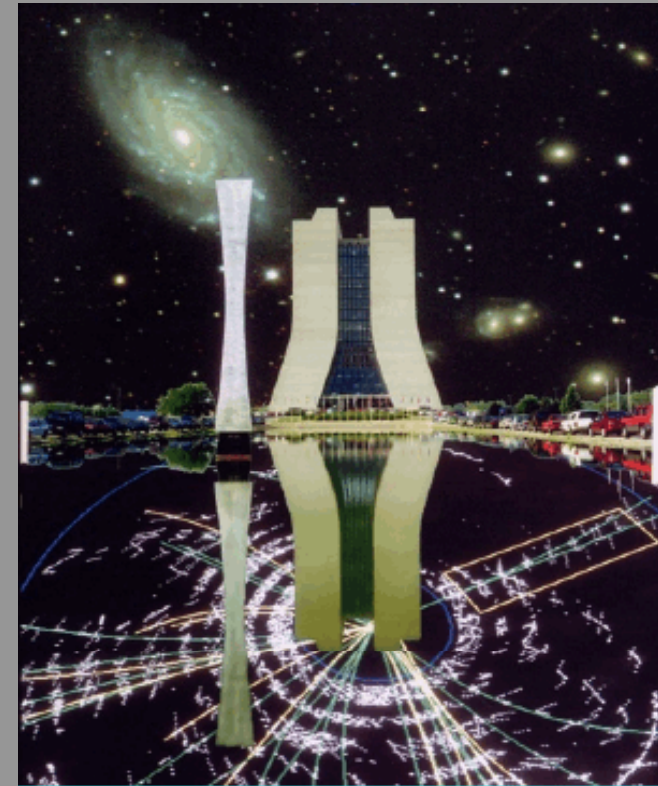
Particle Astrophysics Center

Fermi National Accelerator Laboratory

dhooper@fnal.gov

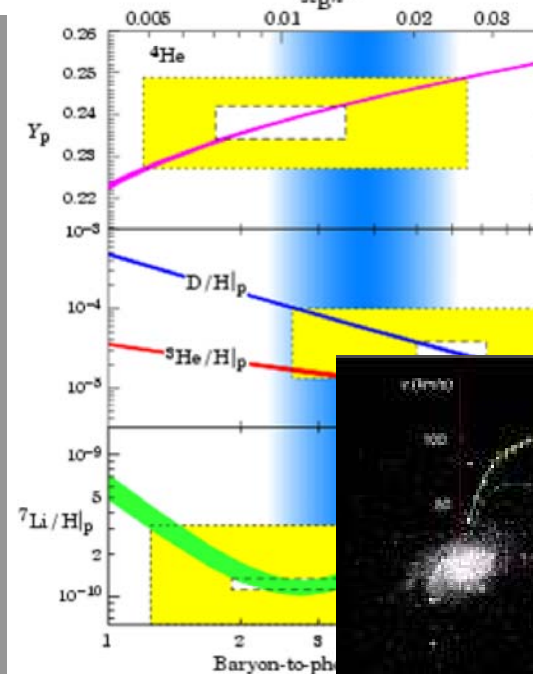
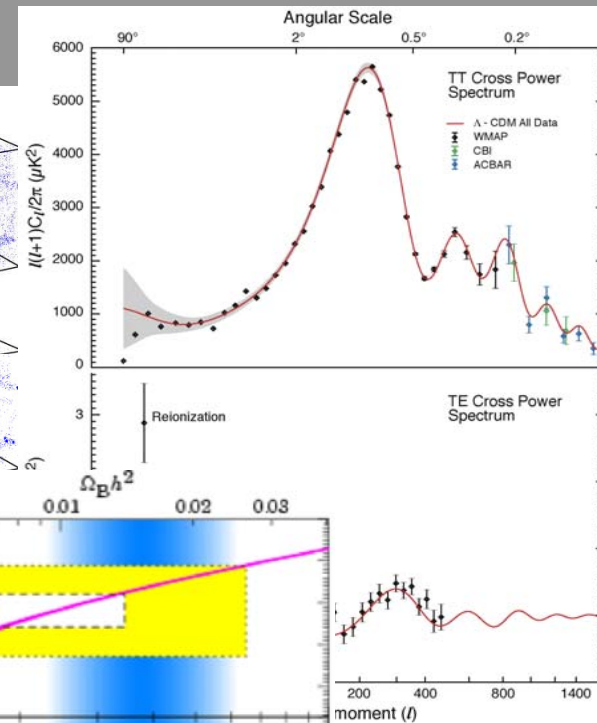
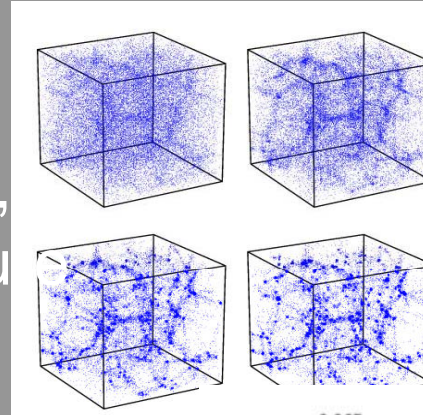
SUSY 2007

August 1, 2007



Dark Matter

- Evidence from a wide range of astrophysical observations including rotation curves, CMB, lensing, clusters, BBN, SN, large scale structure
- Each detects dark matter through its gravitational influence
- Still no conclusive observations of dark matter's electroweak interactions (or other non-gravitational interactions)
- Little known about dark matter's particle identity



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Dark Matter and the Electroweak Scale

- We expect new physics to appear at or near the EW scale (hierarchy problem, etc.)
- The nature of this new physics is highly constrained by precision measurements of LEP \longrightarrow Suggestive of an additional symmetry (R-parity, T-parity, KK-parity, etc.), naturally (or at least plausibly) leading to a stable new particle

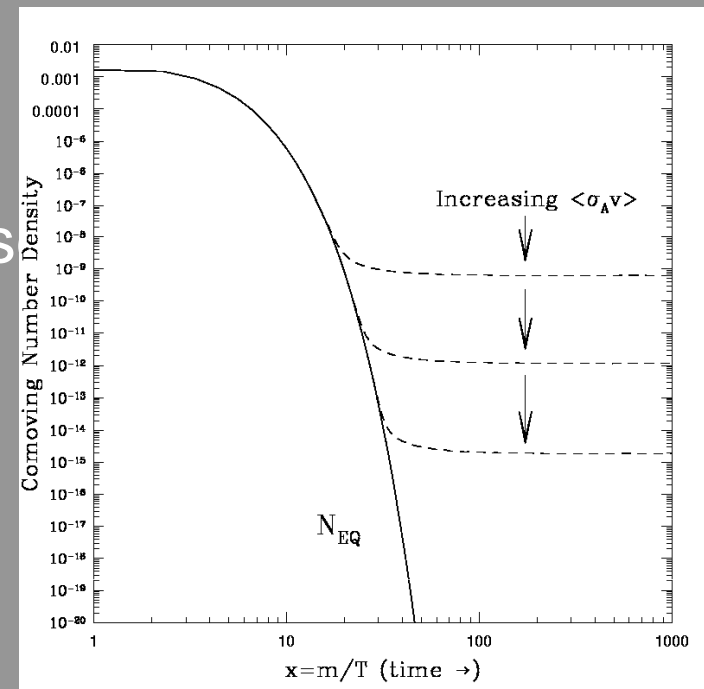
- A stable, neutral, non-colored EW scale particle will freeze-out in the early universe; For a weak-scale cross s

$$\langle\sigma v\rangle \sim \alpha^2 (100 \text{ GeV})^{-2} \sim \text{pb} ,$$

$$\text{This leads to, } \Omega h^2 \sim x_F / \langle\sigma v\rangle \sim 0.1-1.0$$

\Rightarrow **The “WIMP Miracle”**

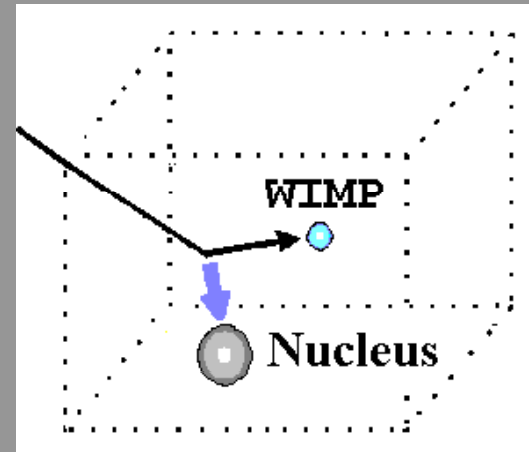
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Astrophysical Probes of Particle Dark Matter

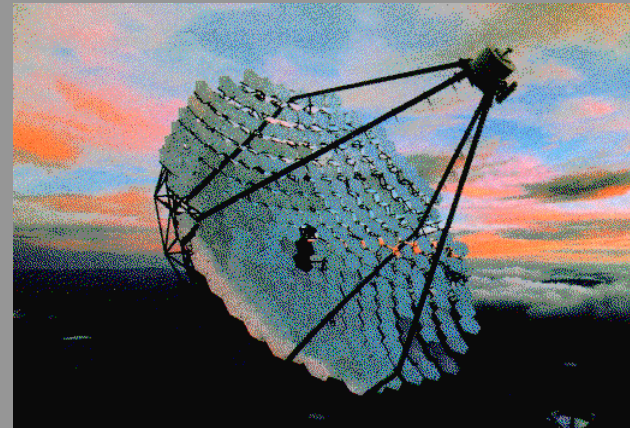
Direct Detection

- Momentum transfer to detector through elastic scattering (talk by Laura Baudis)



Indirect Detection

- Observation of annihilation products (γ , ν , e^+ , \bar{p} , etc.)



Indirect Detection With Gamma-Rays

Advantages of Gamma-Rays:

- Propagate undeflected (point sources possible, angular information)
- Propagate without energy loss (spectral information)
- Rapid development in both space (GLAST) and ground-based (HESS, MAGIC, VERITAS) technologies



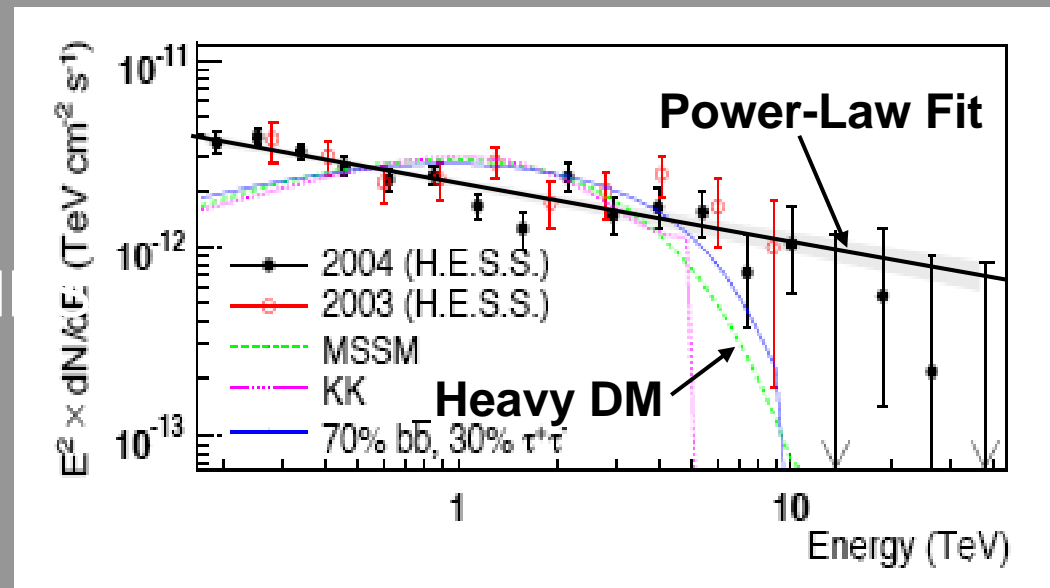
Gamma-Rays From The Galactic Center

- Simulations predict that the GC contains very high densities of dark matter (and high annihilation rates)
- Long considered likely to be the brightest dark matter annihilation region in the sky
- HESS, MAGIC, WHIPPLE and CANGAROO each claim positive detection of \sim TeV gamma-rays
- Evidence for dark matter, or other astrophysics?



Gamma-Rays From The Galactic Center

- Spectrum as measured by HESS extends to at least ~ 10 TeV
- Consistent with a constant power-law spectrum
- To fit with dark matter would require a very heavy particle (15-30 TeV) - Far too heavy for a neutralino
- A very heavy dark matter candidate also fails to match the spectral shape reported by H



HESS Collaboration, PRL, astro-ph/0610509

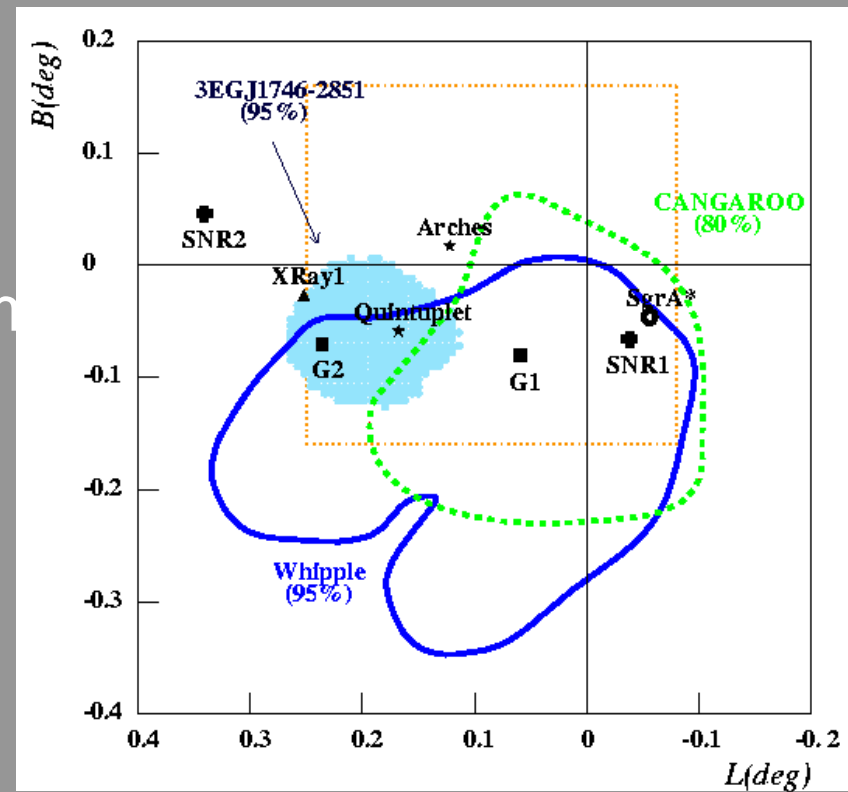
Gamma-Rays From The Galactic Center

- The GC is a region rich in extreme astrophysical objects
- Particle acceleration associated with supermassive black hole?

Aharonian and Neronov (astro-ph/0408303),

Atoyan and Dermer (astro-ph/0410243)

- This astrophysical source represents a very daunting background for future dark matter searches to compete with

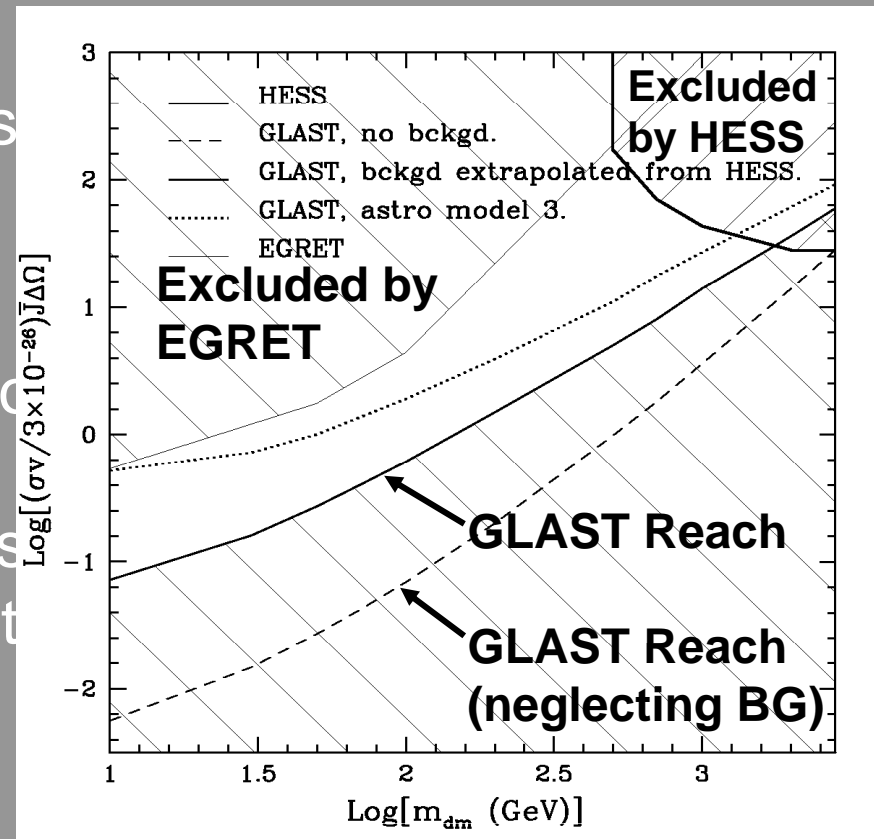


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Hooper, Perez, Silk, Ferrer and Sarkar,
JCAP, astro-ph/0404205

Gamma-Rays From The Galactic Center

- Prospects for GLAST and other future gamma-ray experiments are reduced as a result of this new background
- Range of annihilation rates observable with GLAST is reduced considerably
- Other potential sources of dark matter annihilation radiation become more interesting (dwarf spheroidal galaxies, the diffuse background, etc)



Gamma-Rays From Galactic Substructure

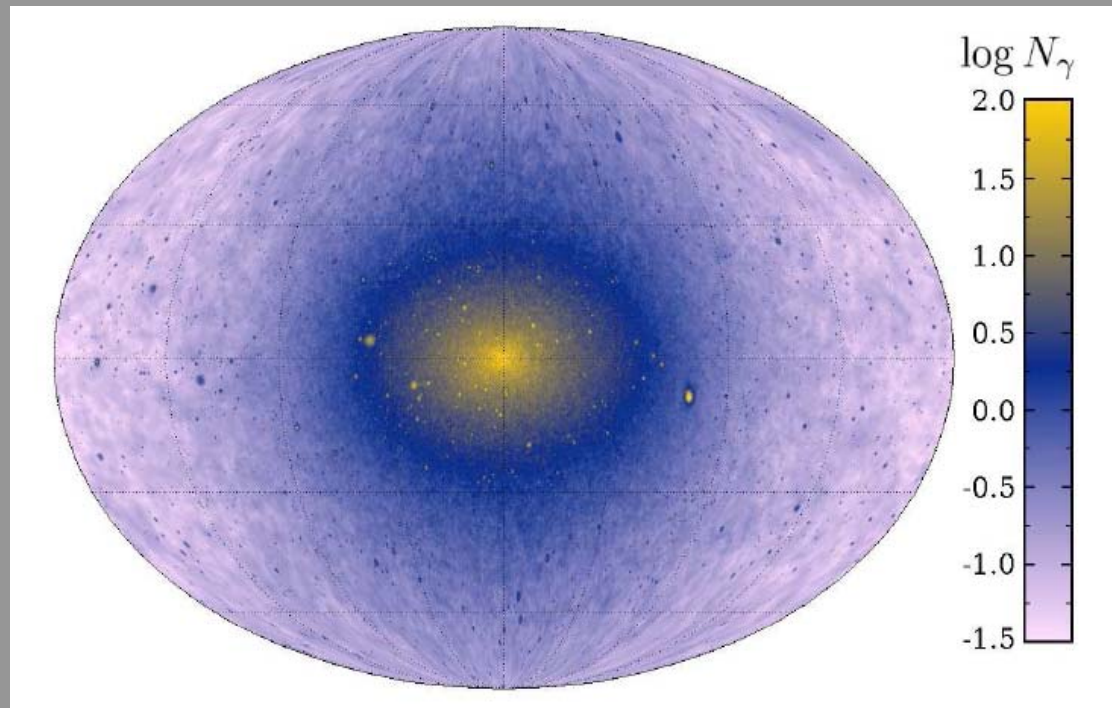
- EW scale dark matter is expected to form structures down to very small (typically $\sim 10^{-6} M_{\odot}$) scales
- Simulations have been used to project gamma-ray sky maps

Warnings: 1) Results rely on extrapolations and depend critically on the degree of structure assumed to be present at the smallest scales, very far beyond resolution of N-body simulations

2) Stringent EGRET constraints

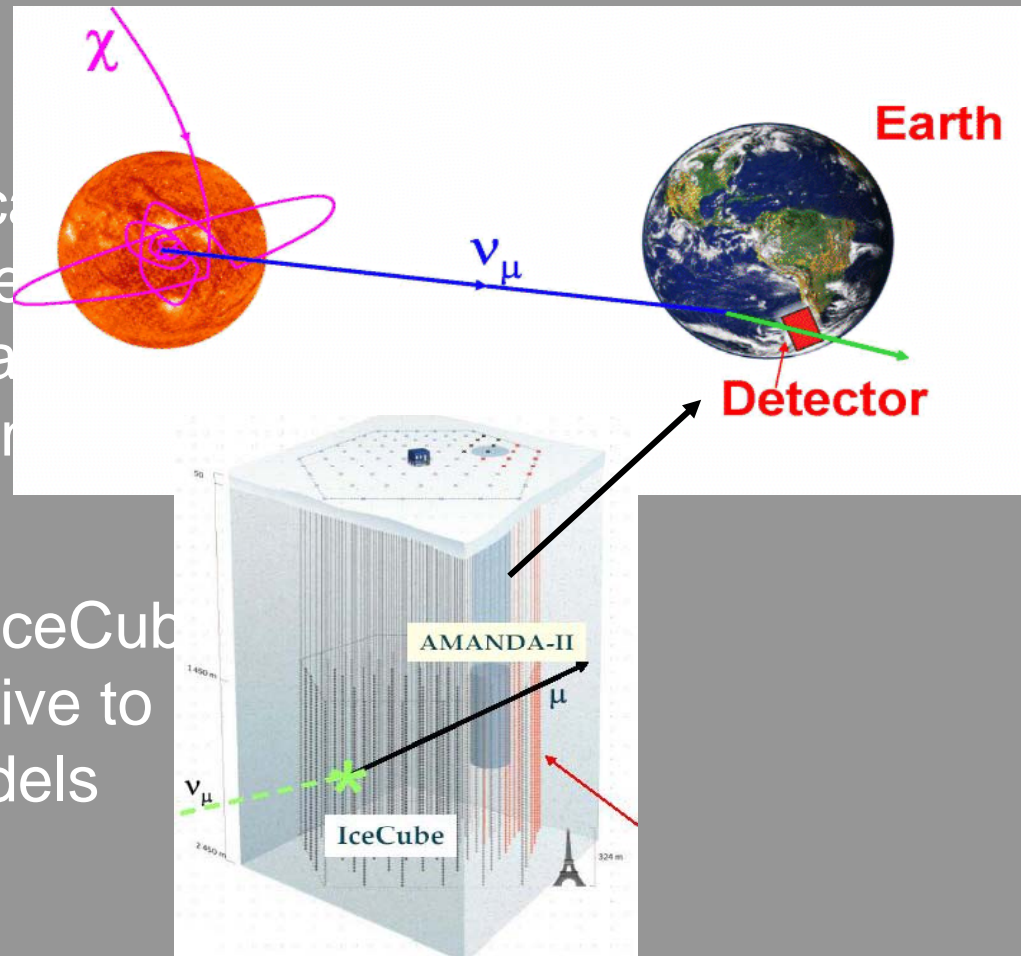
3) Optimistic particle physics

Rates may be turn out to be much smaller



Indirect Detection With Neutrinos

- WIMPs elastically scatter with nuclei in the Sun, becoming gravitationally bound, and annihilate, producing high-energy neutrinos
- After \sim Gyr, annihilation and capture rates typically reach equilibrium, generating a potentially observable flux of high-energy neutrinos
- Cubic kilometer-scale experiments, such as IceCube or KM3, will be sensitive to dark matter models



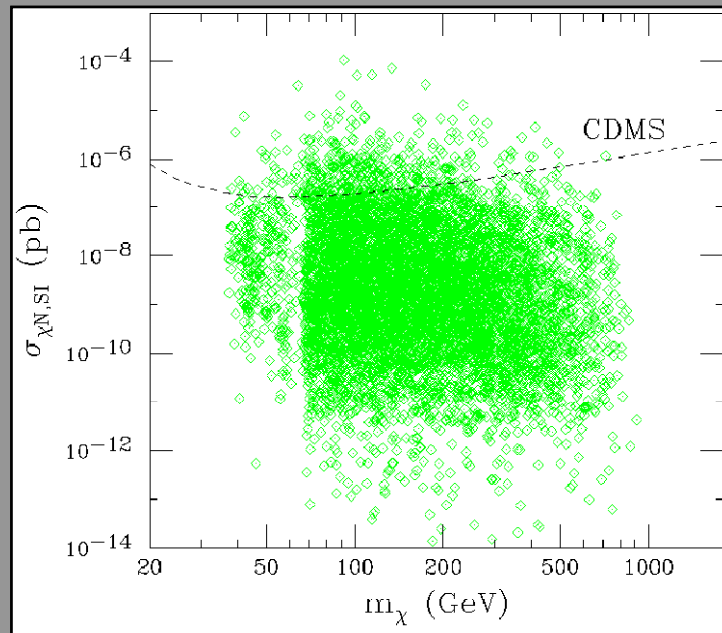
Indirect Detection With Neutrinos

- Rate observed at IceCube depends primarily on the neutralino capture rate in the Sun (the elastic scattering cross section)
- The reach of neutrino telescopes is, therefore, expected to be tied to that of direct detection experiments

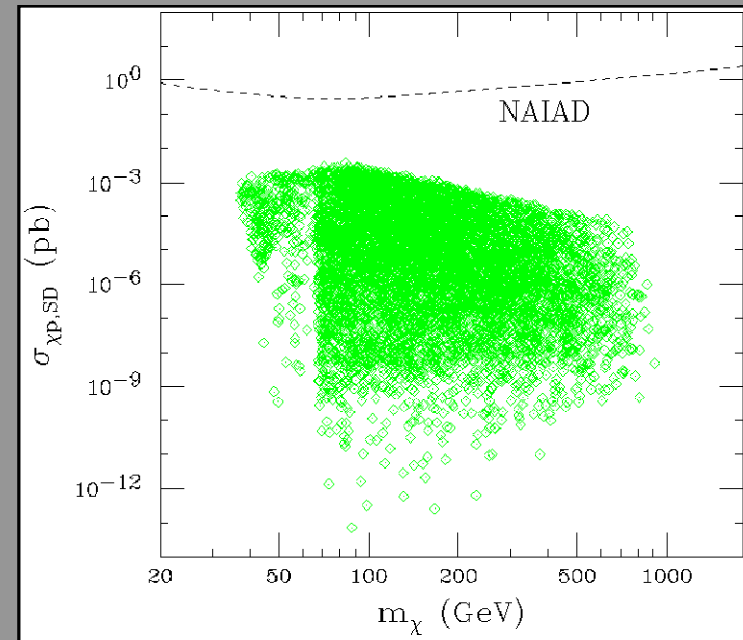
Indirect Detection With Neutrinos

- Important Caveat: WIMPs scatter with nuclei in the Sun through *both* spin-independent and spin-dependent scattering
- Sensitivity of direct detection to spin-dependent scattering is currently very weak

Spin-Independent

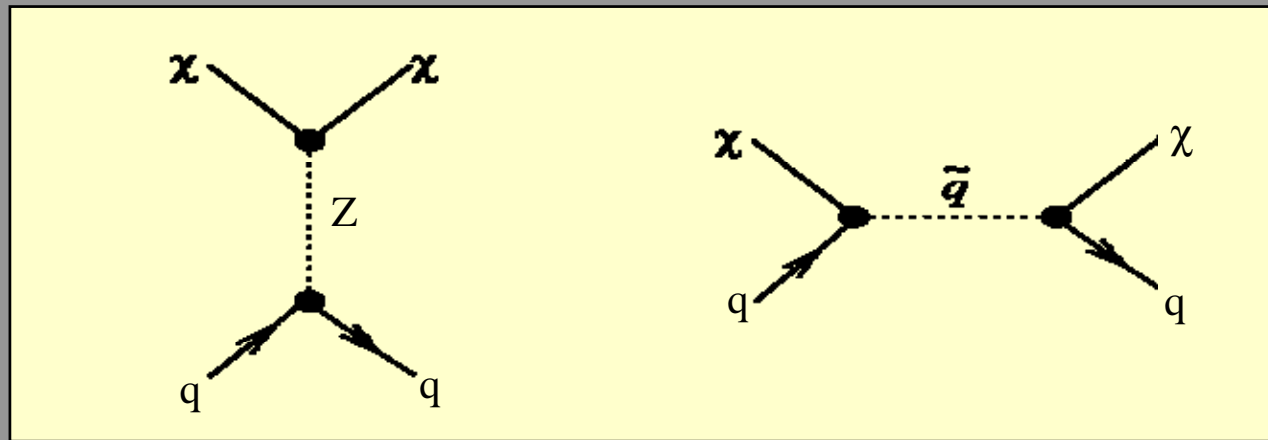


Spin-Dependent



Indirect Detection With Neutrinos

What kind of neutralino has large spin-dependent couplings?

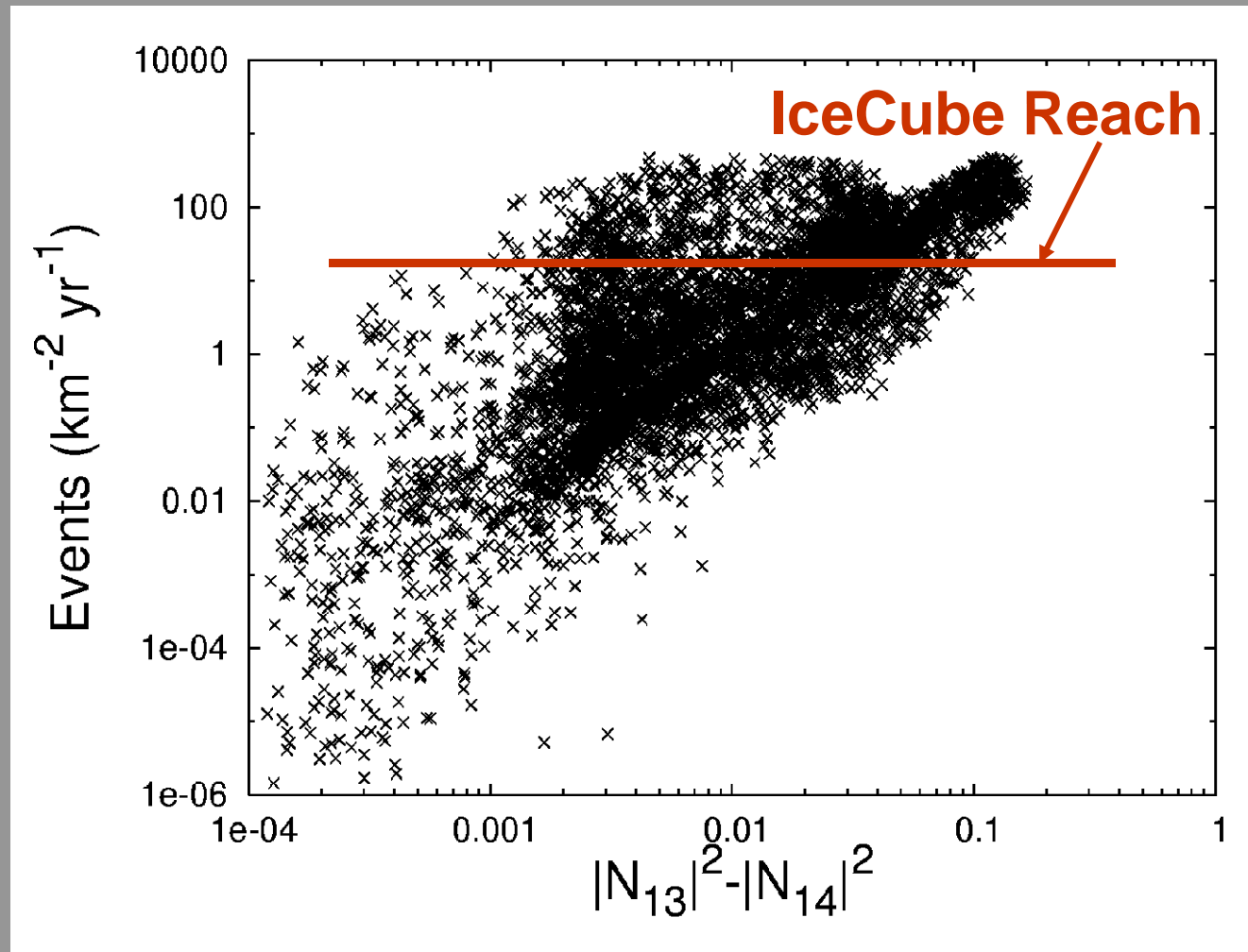


$$\propto [|N_{13}|^2 - |N_{14}|^2]^2$$

Always Small

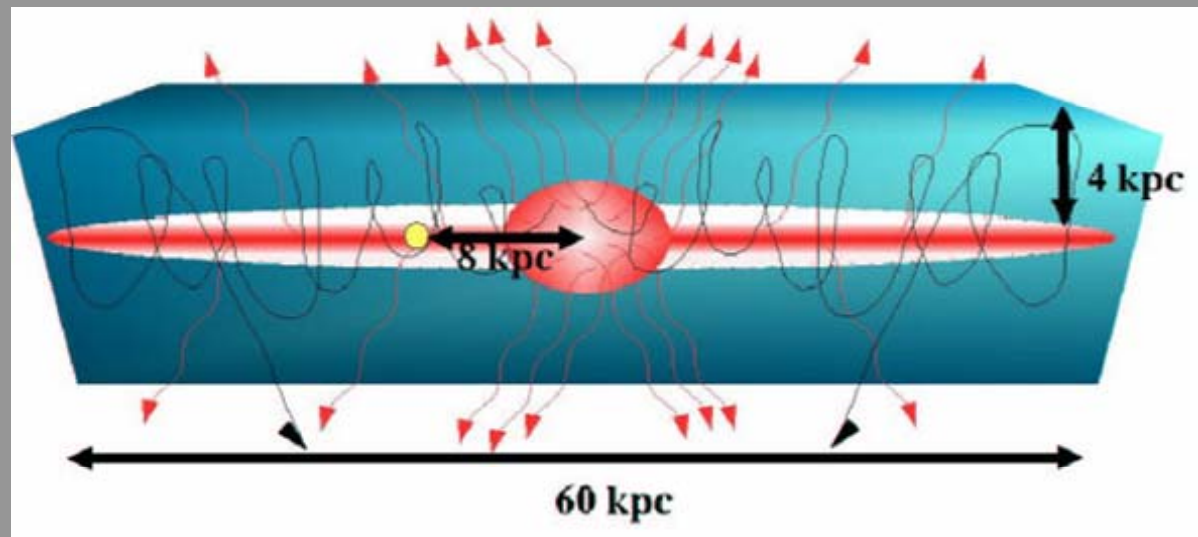
Substantial Higgsino Component Needed

Indirect Detection With Neutrinos



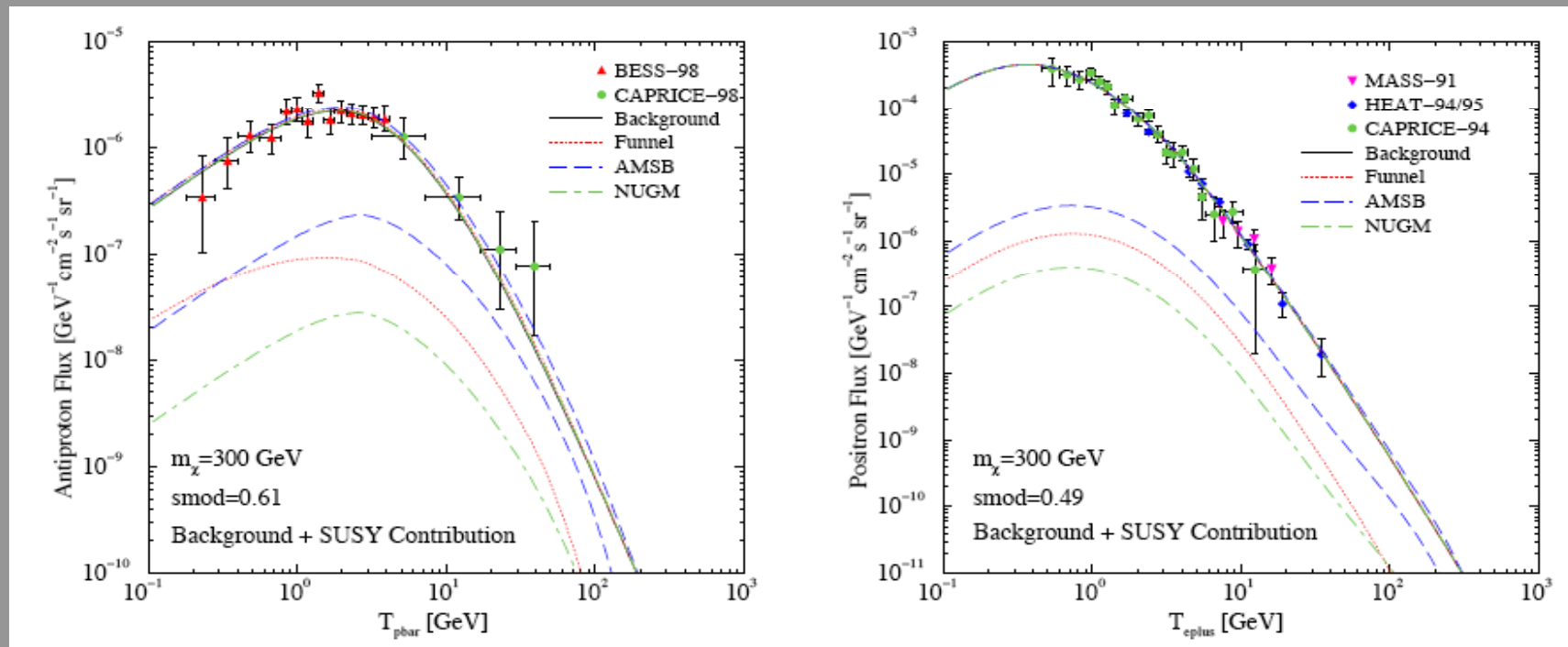
Indirect Detection With Antimatter

- Matter and anti-matter are generated in equal quantities in dark matter annihilations (unlike other astrophysical processes)
- Charged cosmic rays diffuse through the galaxy under the influence of tangled magnetic fields
- Cosmic positron, anti-proton and anti-deuteron spectra may contain signatures of particle dark matter



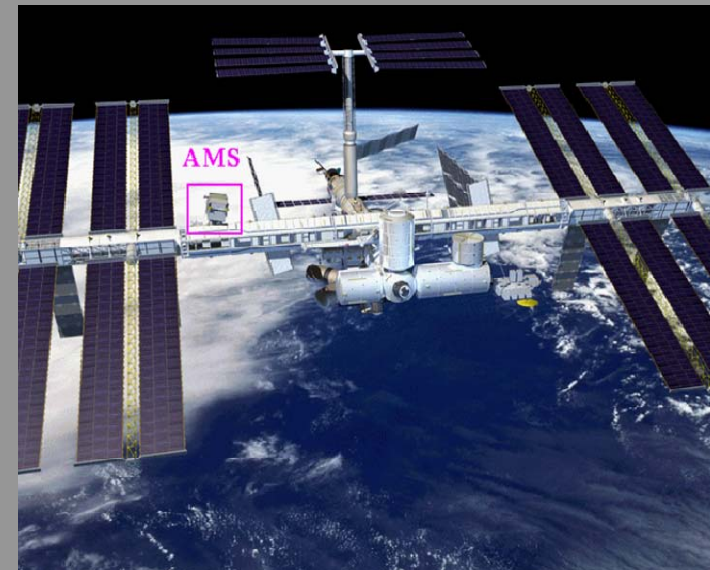
Indirect Detection With Antimatter

- Antimatter signal from dark matter has to compete with astrophysical backgrounds (secondaries from cosmic ray interactions in the interstellar medium)
- Unless the annihilation rate is very (surprisingly) high, the signal will be smaller than the background - high precision required



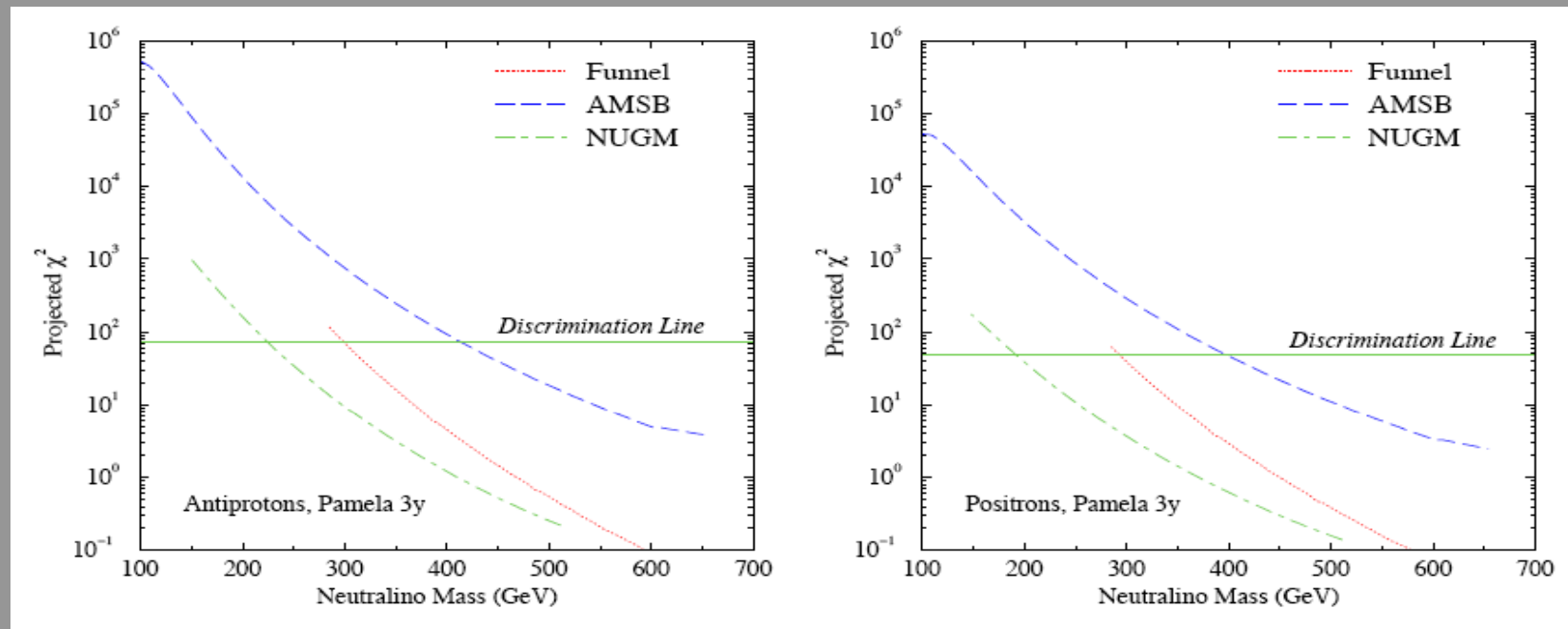
Indirect Detection With Antimatter

- PAMELA satellite was launched last year - first positron/antiproton data this summer
- AMS-02 experiment - has faced difficulties in getting its required shuttle flight, but is now planning to deploy to ISS in 2010
- These experiments will be capable of measuring the cosmic antimatter spectrum with much greater precision, and at much higher energies



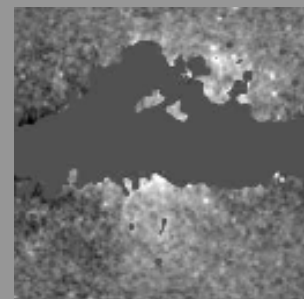
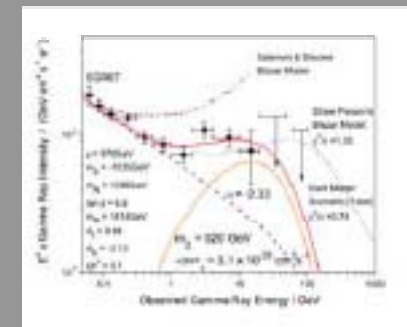
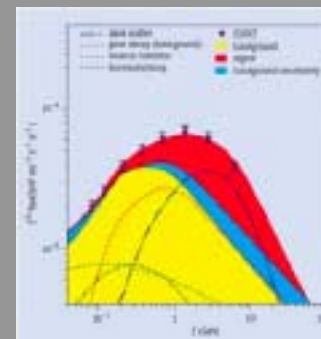
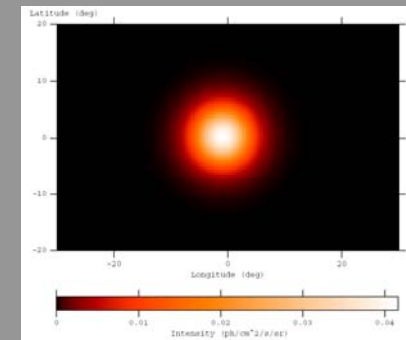
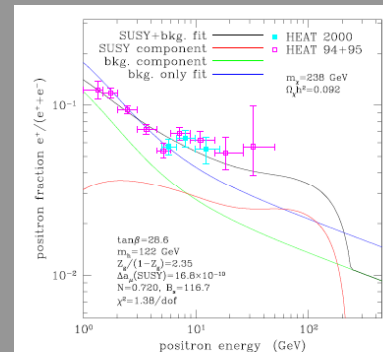
Indirect Detection With Antimatter

- For light neutralinos (or other WIMPs), PAMELA will likely be able to discriminate from background
- For a highly cusped halo profile, or large degree of inhomogeneities, signal can be considerably stronger
- AMS-02 will be able to do considerably better



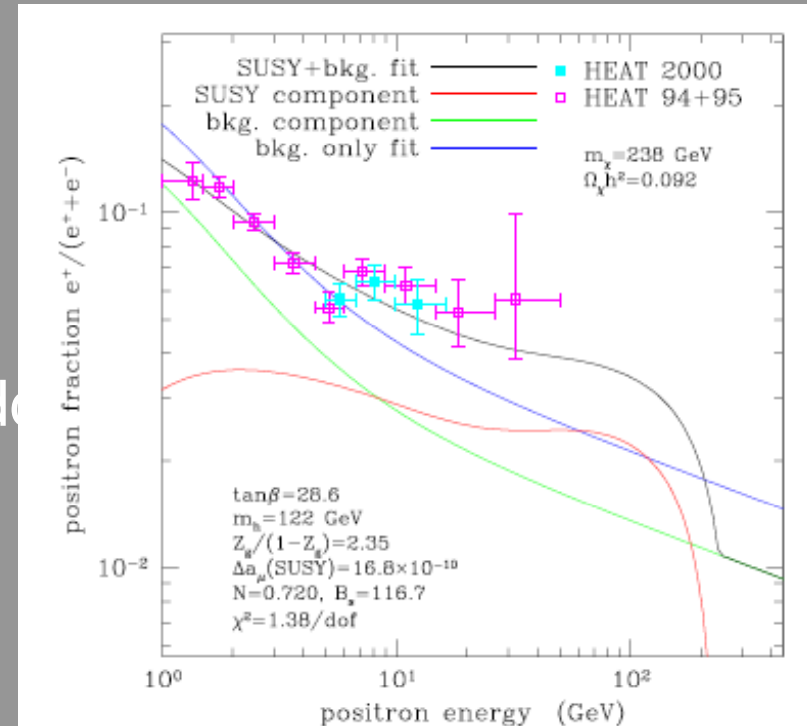
Hints Of Dark Matter Annihilation?

- The HEAT positron excess
- 511 keV emission from the galactic bulge
- EGRET's galactic gamma ray spectrum
- EGRET's extragalactic gamma ray spectrum
- The WMAP haze



The HEAT Positron Excess

- In its 1994-95, 2000 flights, the HEAT balloon-based cosmic ray detector observed an excess of positrons relative to electrons in the 7-30 GeV range
- Measurements from AMS-01 add some support (see talk by Jan Olzem)
- Combined statistical significance of several (4-5) sigma, neglecting (likely important, but difficult to evaluate) systematic uncertainties



E. Baltz and J. Edsjo,
PRD, astro-ph/9808243

The HEAT Positron Excess

Strengths:

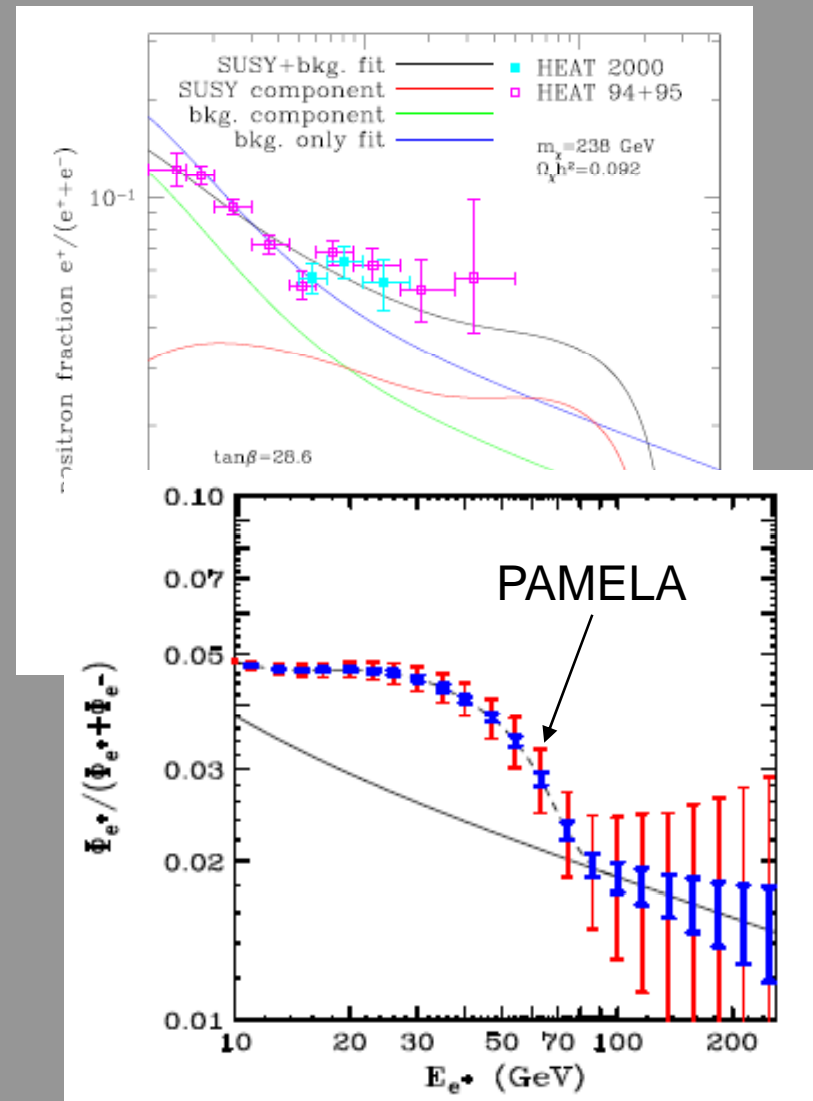
- Fit to data can be easily improved if dark matter component is included

Weaknesses:

- Messy astrophysics
- Requires annihilation boost of ~ 50 or more (possible, but unlikely), or non-thermal dark matter production

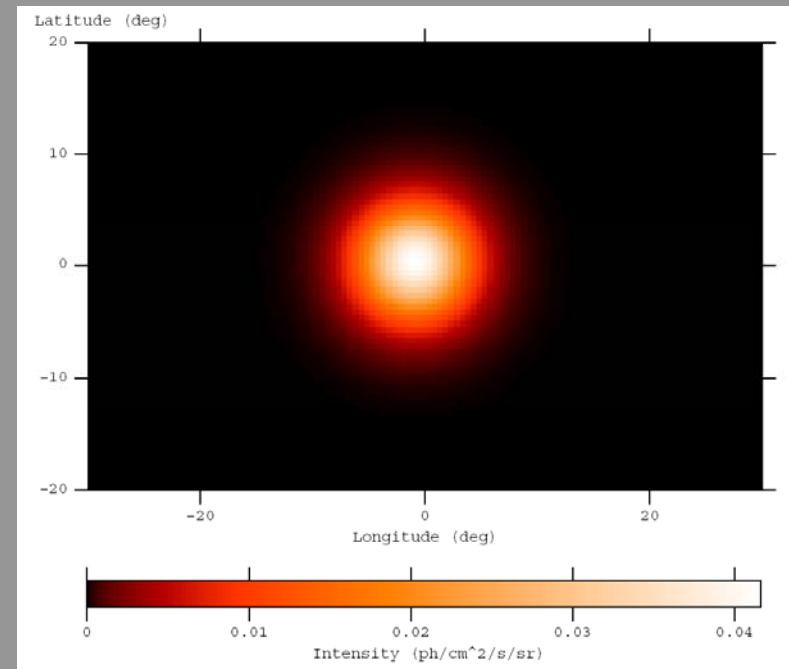
Prospects:

- PAMELA data (August?) should clearly confirm or refute this signal, and measure the spectrum up to much higher energies



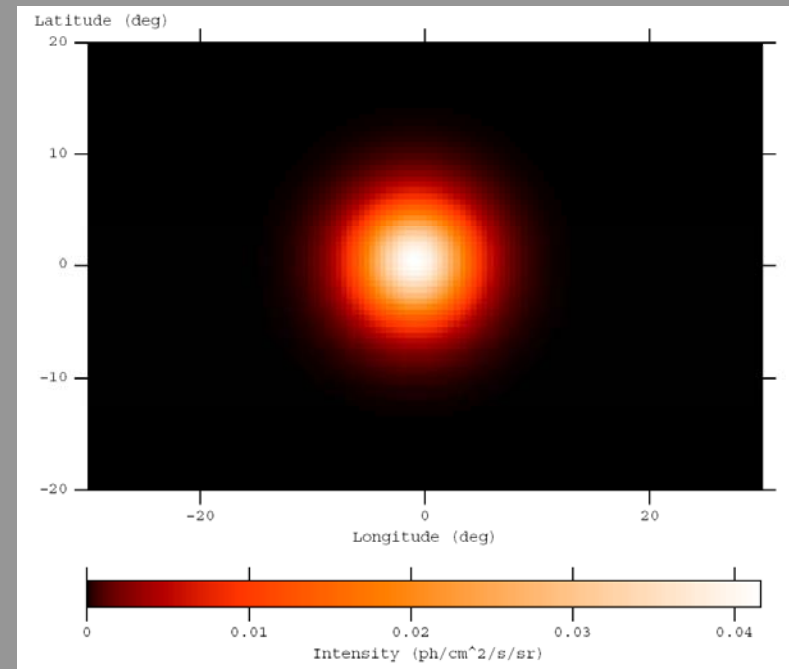
511 keV Emission from the Galactic Bulge

- INTEGRAL/SPI observed bright 511 keV emission from the bulge of the Milky Way (1.3×10^{43} positrons injected per second)
- Gaussian, spherically symmetric morphology (FWHM of 8°)
- The source of these positrons remains unknown



511 keV Emission from the Galactic Bulge

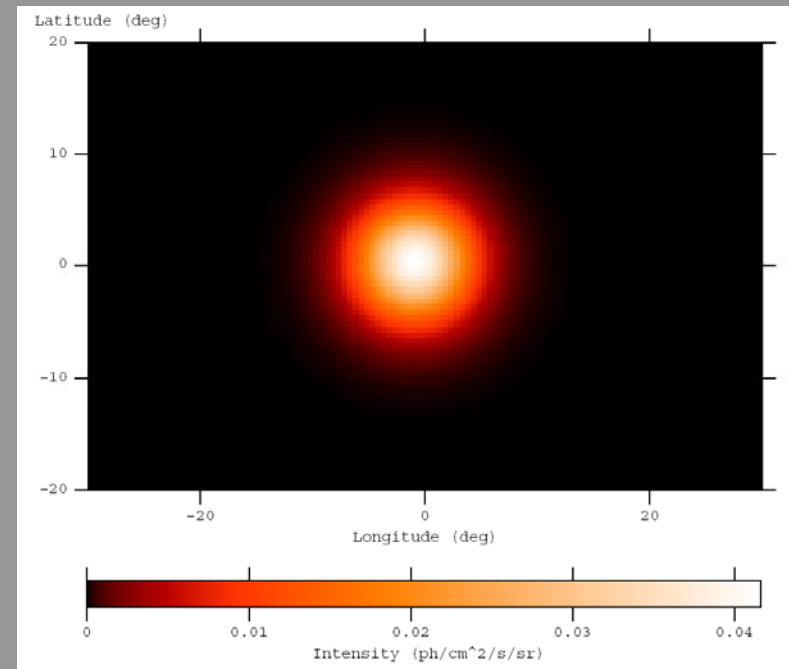
- Type Ia supernovae are unable to generate the observed injection rate (too few escape)
- Hypernovae (type Ic SNe) or gamma ray bursts could potentially generate enough positrons if high estimates for rates are considered
- Even if the injection rate is sufficient, a mechanism is required to transport from disk to bulge - appears difficult



511 keV Emission and MeV Dark Matter

- The INTEGRAL morphology matches well that which would be generated through the annihilation (or decay) of dark matter
- 1-10 MeV dark matter particles annihilating to e^+e^- could simultaneously generate the measured dark matter relic abundance, and the observed 511 keV emission

(Boehm, Hooper, Silk, Casse, Paul, PRL, astro-ph/0309686)



511 keV Emission and MeV Dark Matter

Strengths:

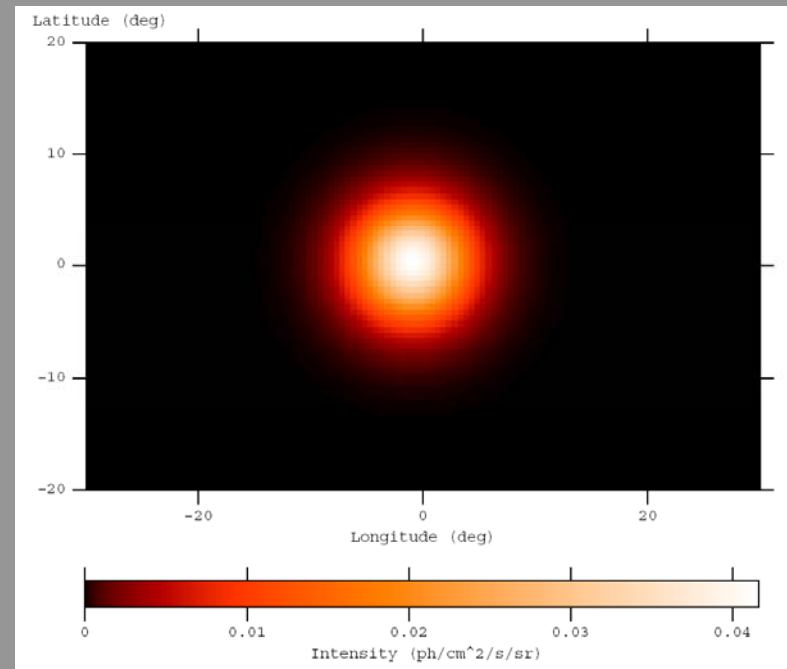
- Challenging to explain 511 signal with non-exotic astrophysics

Weaknesses:

- Somewhat difficult to construct a viable particle physics model with an MeV WIMP

Prospects:

- No clear path to confirmation or exclusion of the MeV dark matter hypothesis (perhaps 511 emission from dwarf galaxies?)

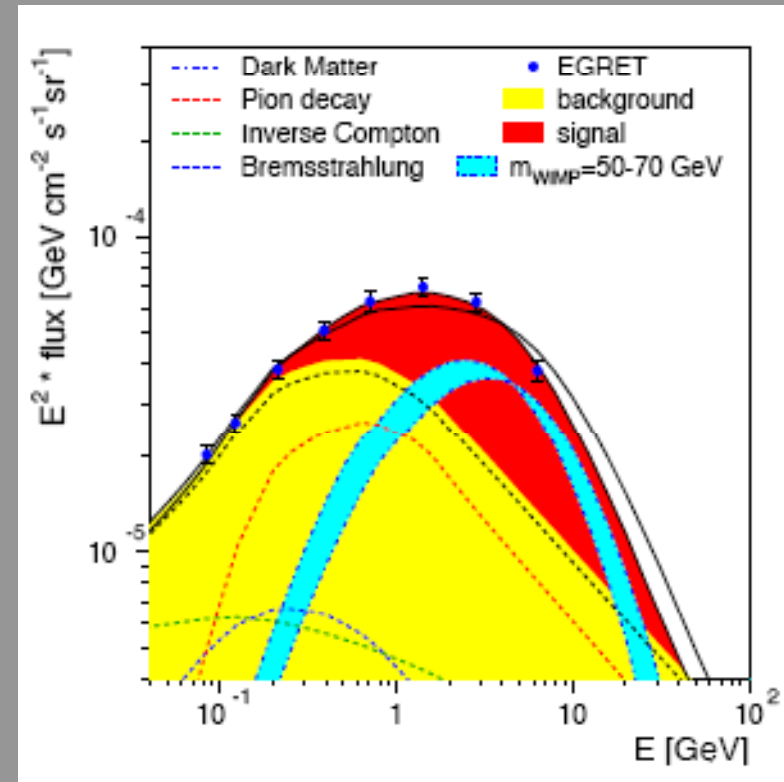


EGRET's Galactic Gamma Ray Spectrum

- EGRET observed an excess of gamma rays above 1 GeV, compared to the the most simple galactic cosmic ray models

- Could be the product of a $\sim 50\text{-}100$ GeV WIMP

(W. de Boer et al, PLB, hep-ph/0511154;
Astron.Astrophys, astro-ph/0508617;
astro-ph/0408272)



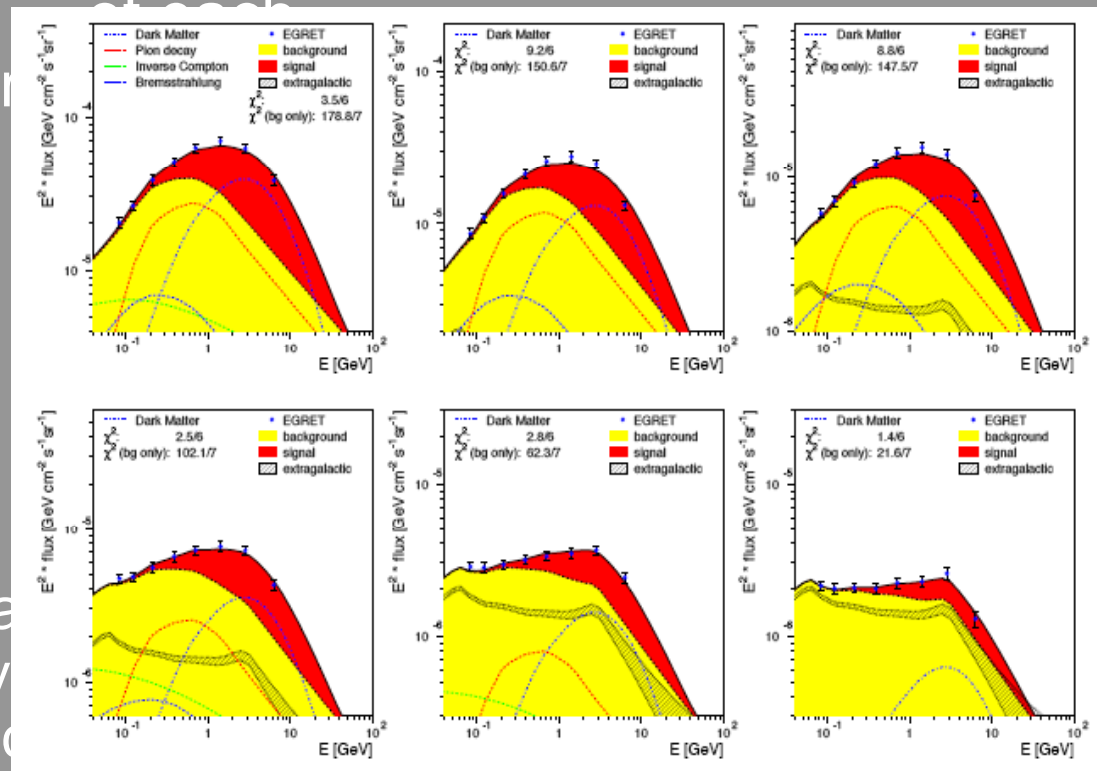
EGRET's Galactic Gamma Ray Spectrum

- The same dark matter annihilation spectrum can fit the shape of the GeV excess in all regions of the sky

- To normalize the intensity region, however, departure from simple halo profile

- De Boer, et al. introduce two rings of dark matter near the galactic plane at 4 and 14 kpc from galactic center ($8 \times 10^{10} M_{\odot}$ tidal disrupted dwarf galaxy motivated by rotation of

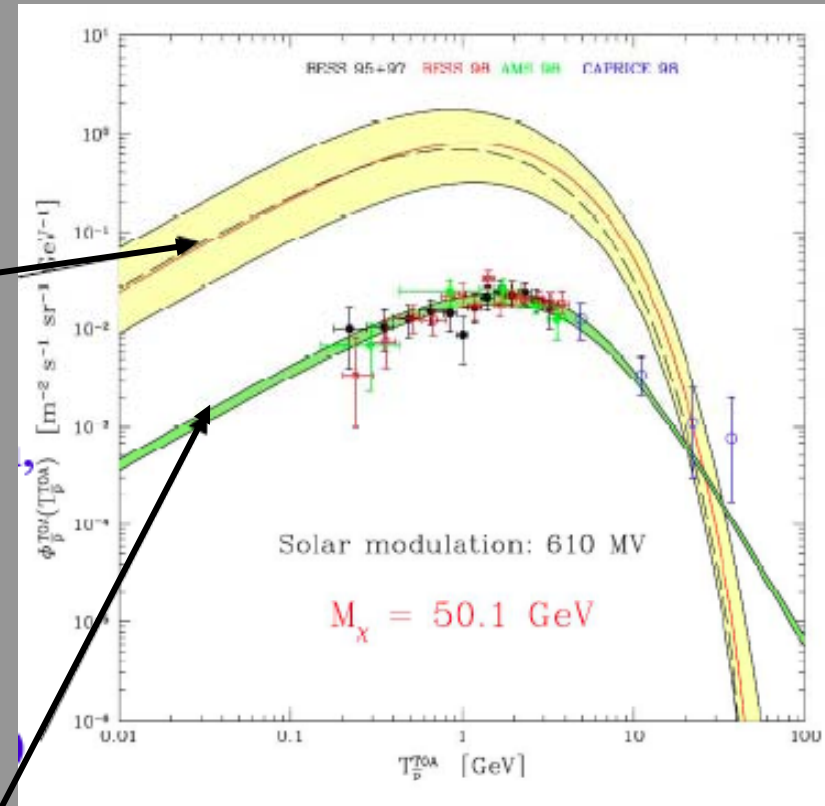
Region	Longitude l	Latitude $ b $	Description
A	330-30	0-5	Inner Galaxy
B	30-330	0-5	Disk without inner Galaxy
C	90-270	0-10	Outer Galaxy
D	0-360	10-20	Low longitude
E	0-360	20-60	High longitude
F	0-360	60-90	Galactic Poles



EGRET's Galactic Gamma Ray Spectrum

- With a standard treatment of cosmic ray diffusion, far too many antiprotons are produced in this scenario
- To reconcile, anisotropic diffusion, strong convection away from (and outside of) the disk and local spatial variations are required (see talk by Iris Gebauer)

Predicted in de Boer model



Prediction from standard secondary cosmic ray production

EGRET's Galactic Gamma Ray Spectrum

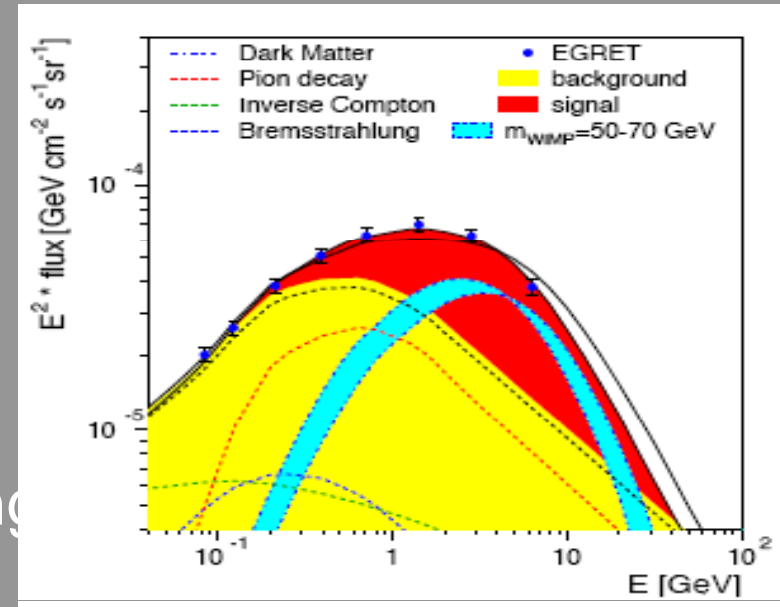
Strengths:

- Consistent with a neutralino or other EW-scale WIMP
- Similar spectral shape over sky

Weaknesses:

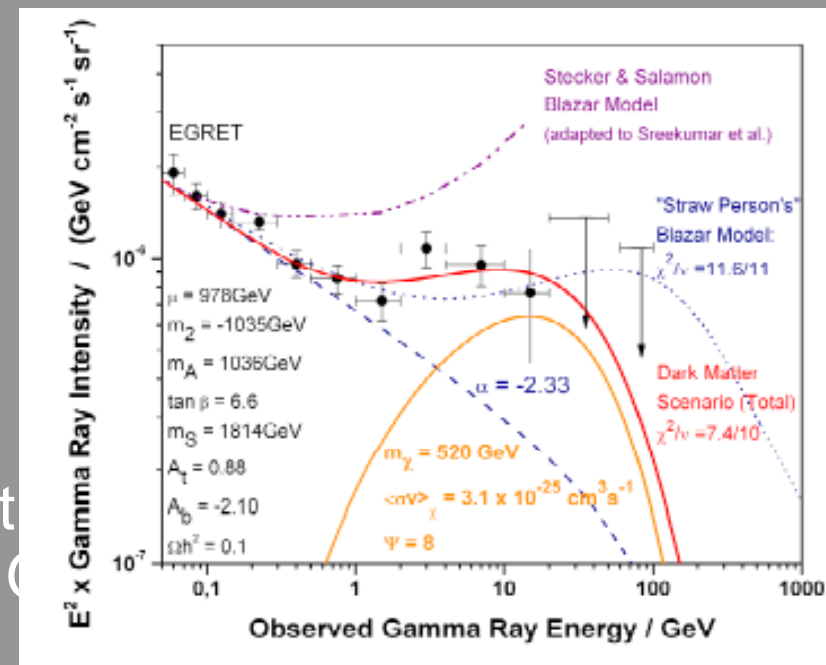
- Non-standard dark matter distribution is needed (two ring)
- Conflict with antiprotons unless non-standard cosmic ray diffusion is invoked
- The GeV excess can plausibly be reduced or eliminated without dark matter by modifying the diffusion model

Prospects: GLAST will clear up these questions considerably



EGRET's Extragalactic Gamma Ray Spectrum

- EGRET has also detected a diffuse, extragalactic gamma ray signal, which becomes more intense above 1 GeV
- Integrated signal from dark matter annihilations throughout the universe could produce a potentially observable signal (Ullio, Bergstrom, Edsjo 2002)
- Intensity depends critically on dark matter distribution - cuspy halos and substructure are required
- The EGRET extragalactic diffuse spectrum can be fit with dark matter annihilations from a ~ 500 GeV neutralino (or other WIMP)



EGRET's Extragalactic Gamma Ray Spectrum

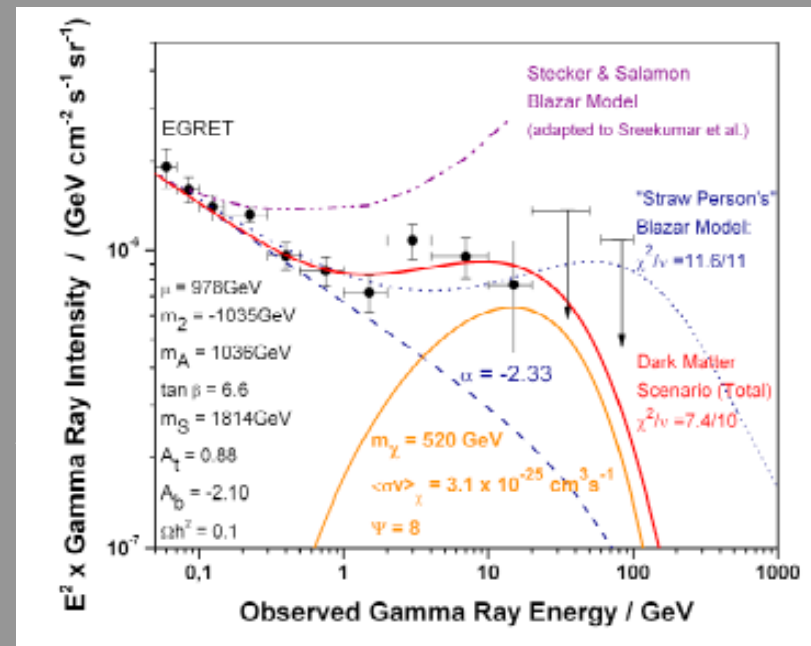
Strengths:

- Consistent with a (somewhat heavy) neutralino or other WIMP

Weaknesses:

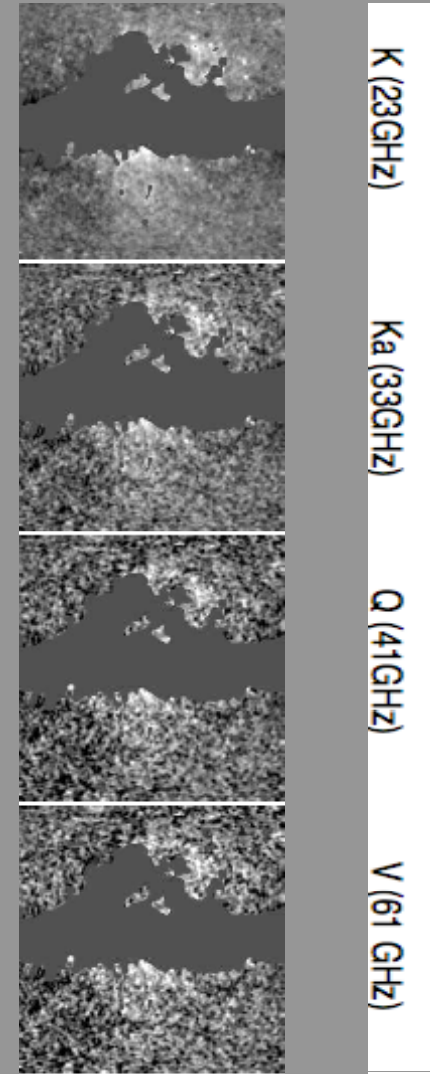
- Not a particularly distinctive signal - could easily be astrophysical
- High annihilation rate needed; either large degree of very cusped substructure, or a non-thermal
- Signal from our galactic center would have been seen, unless cusp is removed by tidal effects (S. Ando, PRL, astro-ph/0503006)

Prospects: GLAST will clearly resolve



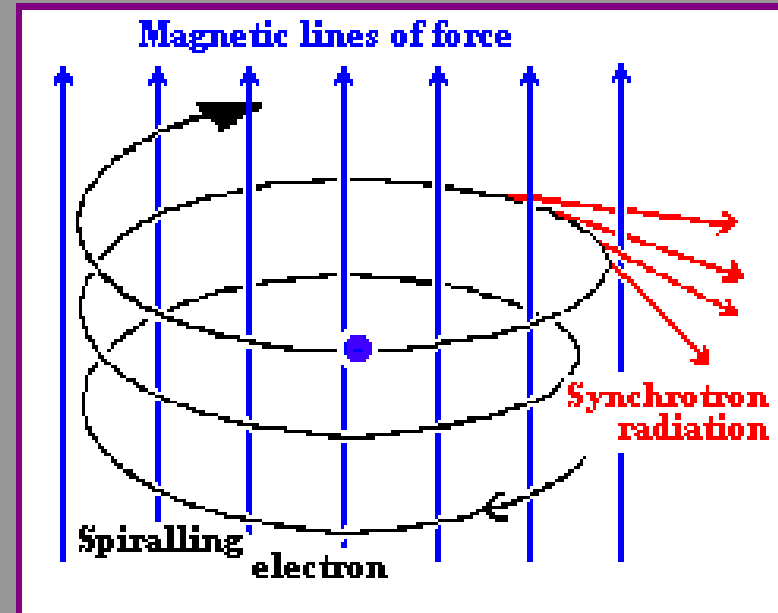
The WMAP Haze

- When known foregrounds are subtracted from the WMAP data, a residual around the Galactic Center remains in all five frequency channels
- Approximate spherical symmetry, 20-30° angular extension
- Initially interpreted as thermal bremsstrahlung (free-free emission) from hot gas, but now ruled out by the lack of corresponding X-ray line
- Possible synchrotron emission from dark matter annihilation products (e^+e^-)



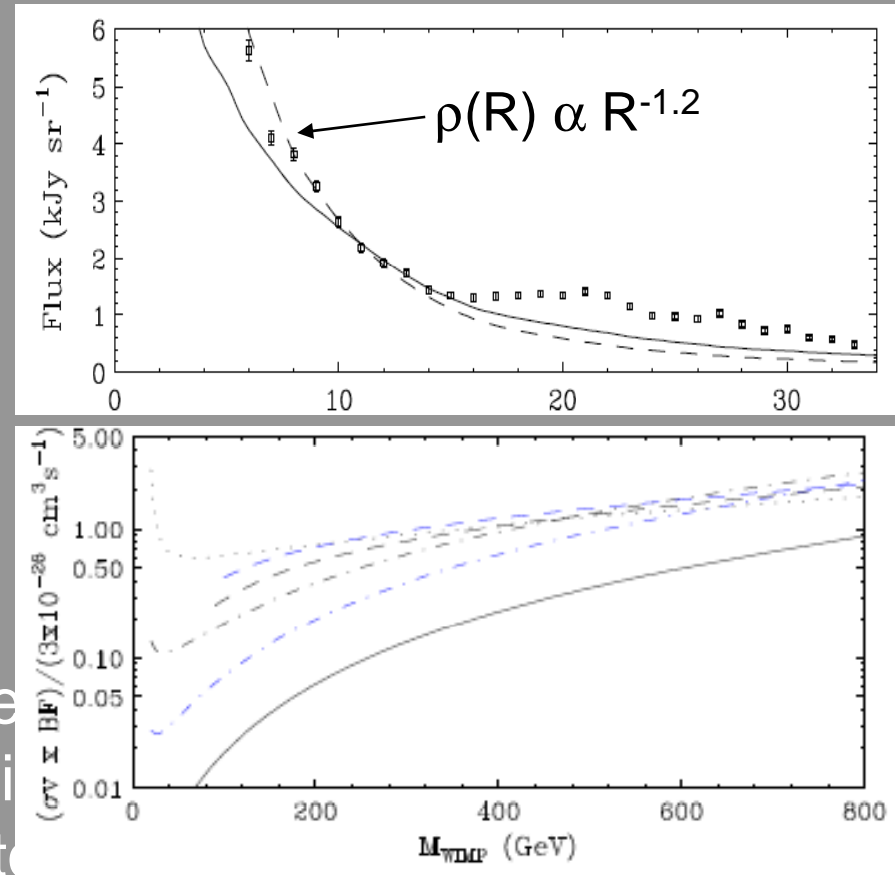
The WMAP Haze

- Electrons/positrons produced in dark matter annihilations will emit synchrotron photons as they propagate through the galactic magnetic fields
- For weak-scale dark matter, the synchrotron radiation falls within the frequency range of WMAP and other CMB experiments



Three Reasons to Think the WMAP Haze is produced by Dark Matter

- 1) Angular distribution of the haze matches that found for a cusped halo profile, with $\rho \propto R^{-1.2}$
- 2) Electron/positron spectrum from ~ 100 GeV to multi-TeV WIMP annihilations is consistent with haze spectrum
- 3) For 100-1000 GeV WIMP, the annihilation cross section needed to produce the measured intensity of the haze is within a factor of 2-3 of the value needed to generate the density of dark matter thermally (no boost factors are required)



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Hooper, G. Dobler and D. Finkbeiner,
arXiv:0705.3655

The WMAP Haze

Strengths:

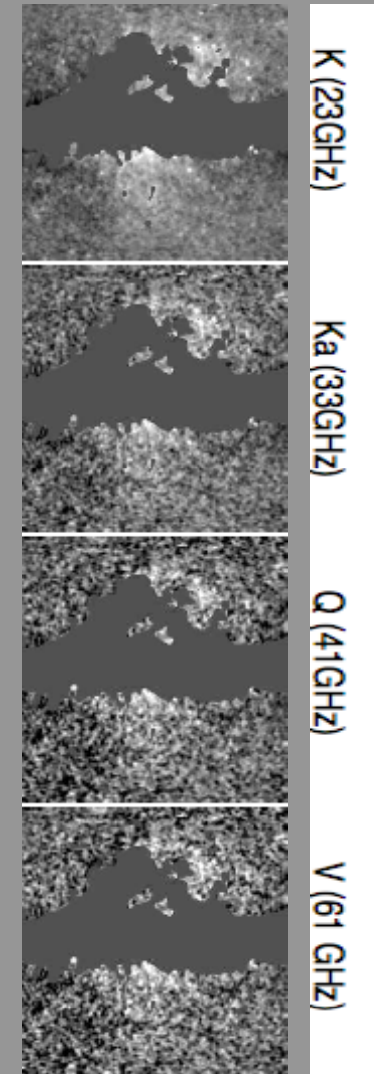
- Data is best fit to a standard electroweak scale, thermally produced WIMP (neutralino, etc.)
- No exotic astrophysics is required - standard cusped halo profile, reasonable magnetic fields, no boost factors, etc.)

Weaknesses:

- Not a particularly distinctive signal - it is hard to rule out all astrophysical possibilities completely

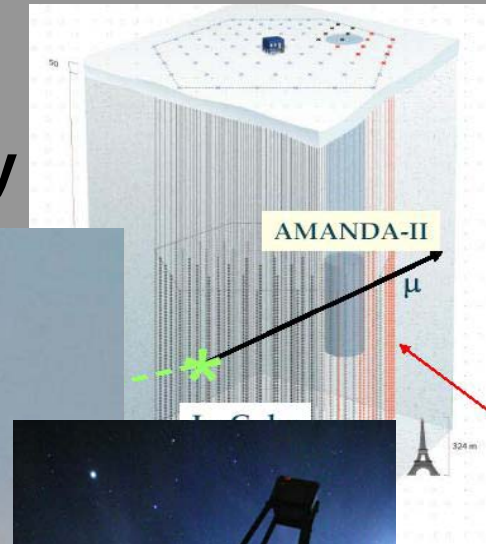
Prospects:

- PLANCK should strongly confirm (or refute) the presence of the WMAP haze
- GLAST should be capable of detecting gamma rays from the galactic center in this scenario



Conclusions

- We are in the midst of a very exciting time for collider, direct and indirect searches for new physics at the electroweak scale, including particle dark matter
- Searches with gamma rays, neutrinos and antimatter are each developing rapidly
- PAMELA, GLAST and ICECUBE will dramatically change the landscape of indirect searches for dark matter
- Tantalizing hints of dark matter annihilation exist in the data of INTEGRAL, EGRET and WMAP - GLAST, PAMELA and PLANCK will shed a great deal of light on these signals





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Let's use all of the tools we have to solve the puzzles of dark matter, supersymmetry and the TeV-scale!