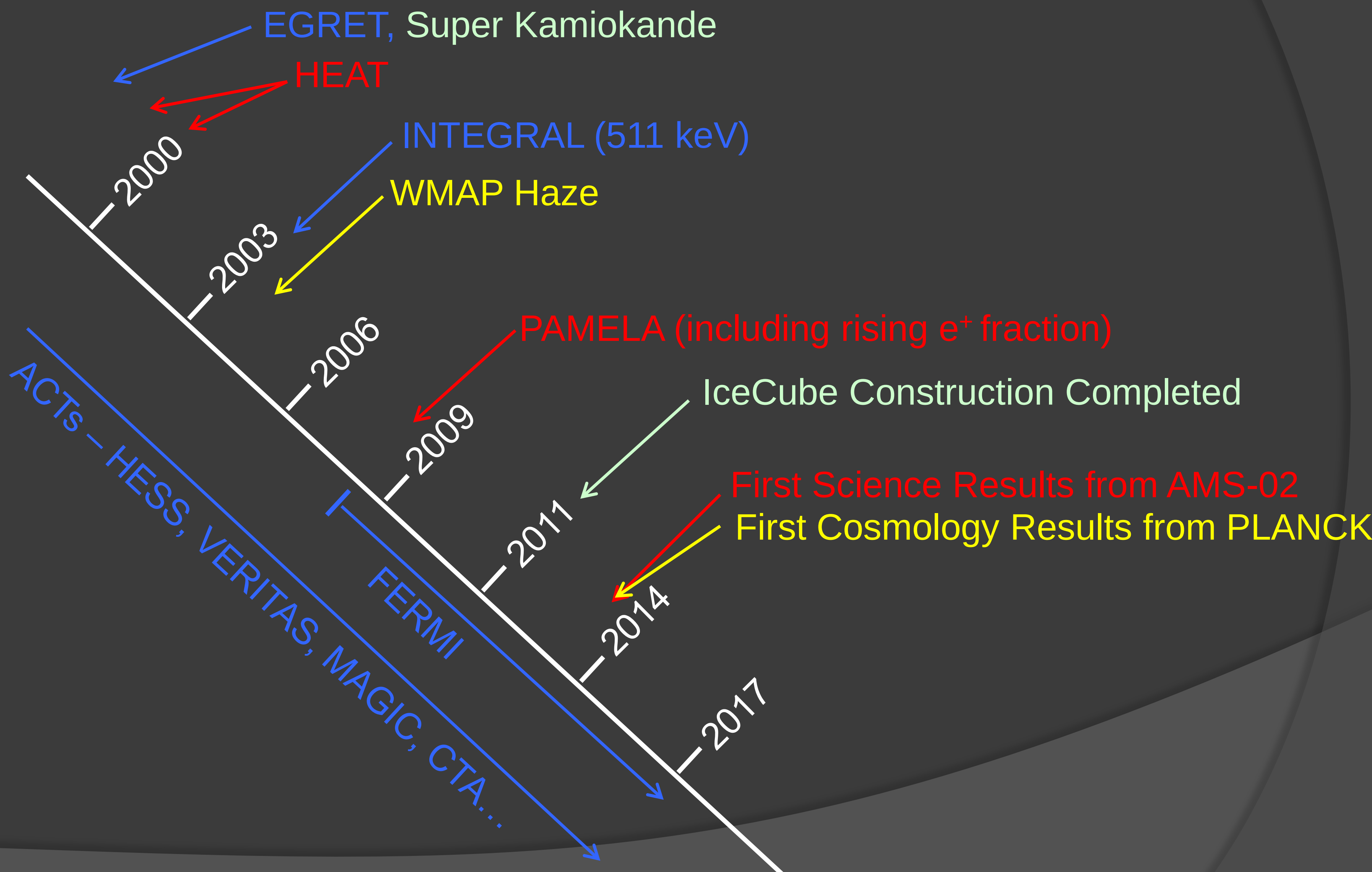
Dan Hooper - Fermilab/University of Chicago

Aspen Center for Physics

Closing in on Dark Matter - January 29th, 2013

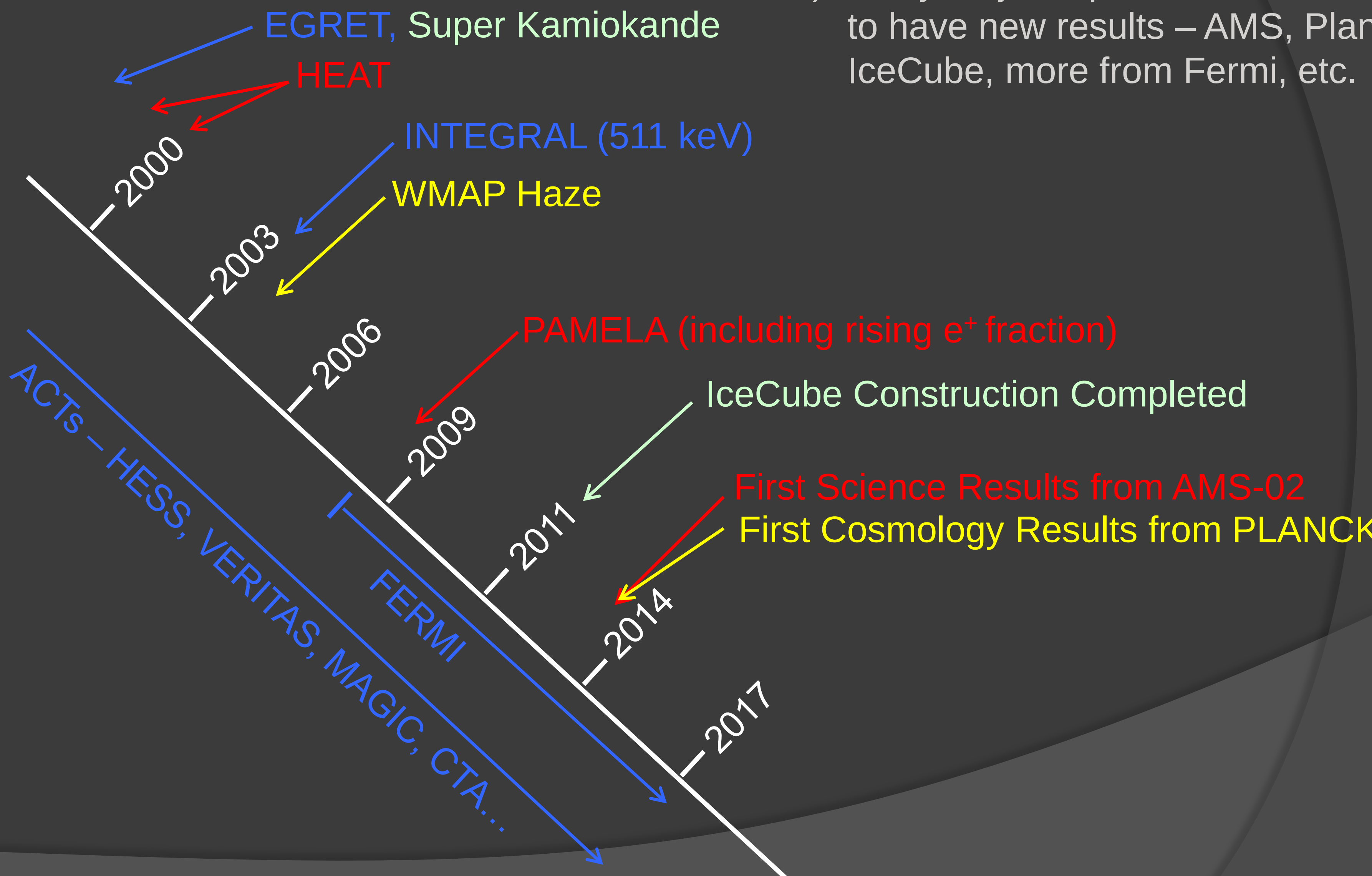
Exciting Times in Indirect Searches for Dark Matter

Some Highlights in Indirect Detection



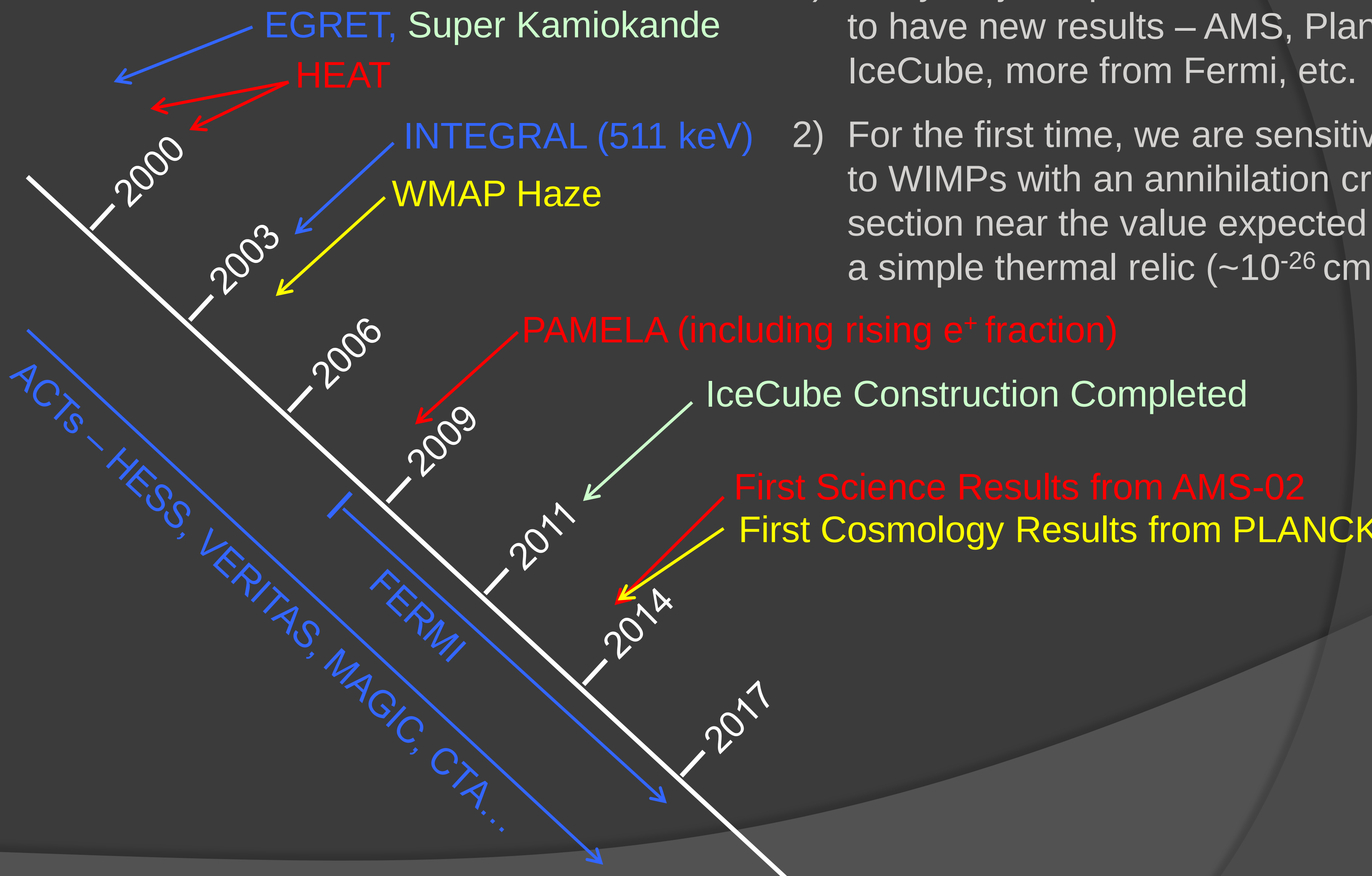
Some Highlights in Indirect Detection

1) Many major experiments are soon to have new results – AMS, Planck, IceCube, more from Fermi, etc.



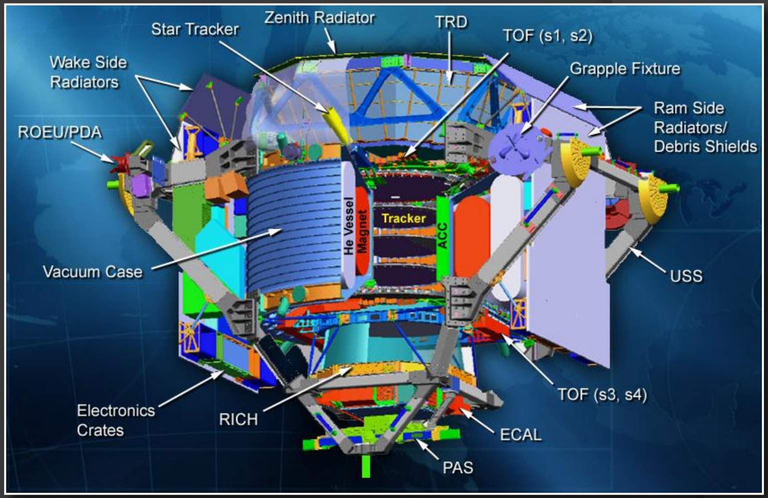
Some Highlights in Indirect Detection

1) Many major experiments are soon to have new results – AMS, Planck, IceCube, more from Fermi, etc.
2) For the first time, we are sensitive to WIMPs with an annihilation cross section near the value expected for a simple thermal relic ($\sim 10^{-26}$ cm^3/s)



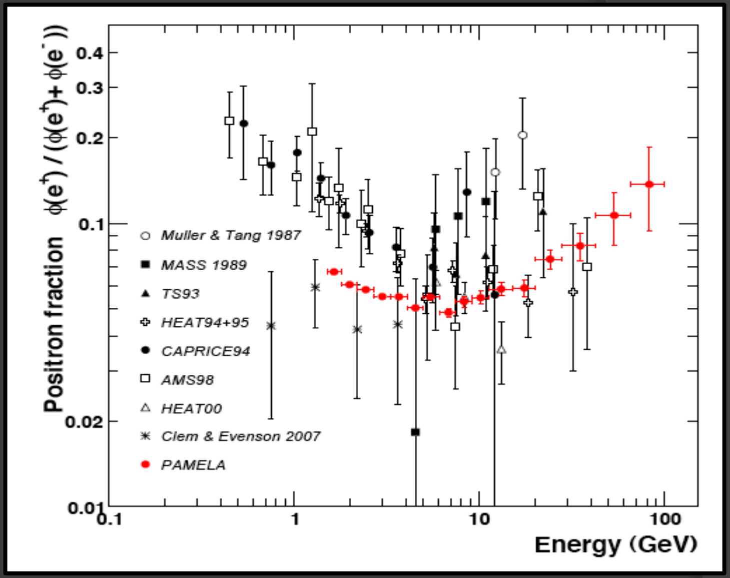
AMS' Great Leap Forward

- AMS-02 has been deployed on the International Space Station since May 2011, and is expected to announce their first science results soon
- With ~10^2 times greater acceptance than PAMELA, and significantly greater ability to distinguish between electrons, positrons, protons, antiprotons, and various species of nuclei, AMS represents a major leap forward



What We'll Learn From AMS

1) Hopefully settle the question of why the cosmic ray positron fraction climbs so rapidly with energy (as observed by both PAMELA and Fermi) – pulsars?
TeV WIMPs with light force carriers?



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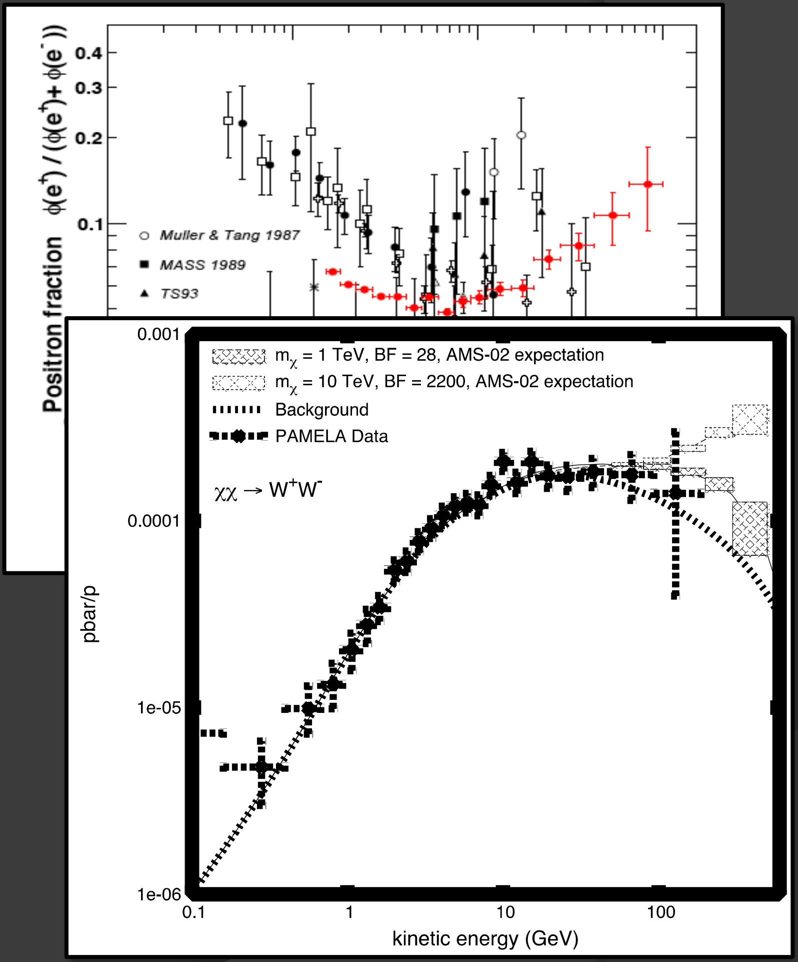
2) Search for excess high energy anti-protons – sensitive to WIMPs with thermal cross section and masses up to a few hundred GeV



I. Cholis, arXiv:1007.1160

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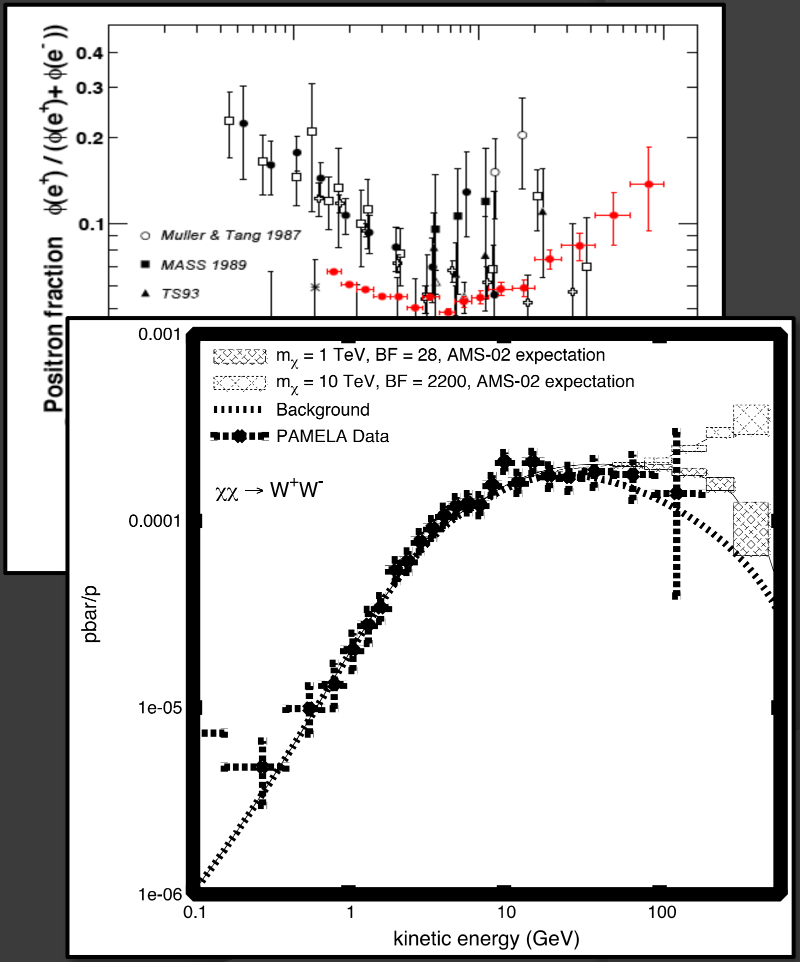
3) Nail down cosmic ray propagation model – help strengthen dark matter limits derived from antiproton, positron channels



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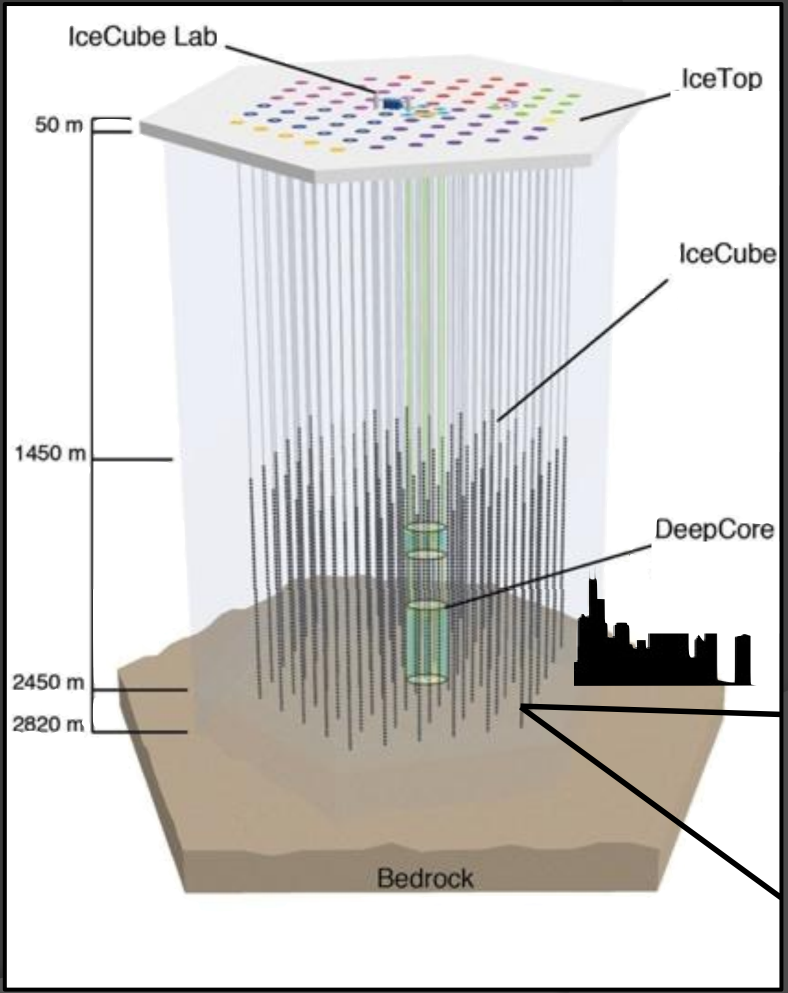
IceCube's Coming of Age

- IceCube's detector, including low-threshold DeepCore, is now complete and taking data
- IceCube is sensitive to dark matter annihilation taking place in the core of the Sun – complementary to other indirect searches; sensitive to elastic scattering, not annihilation cross section



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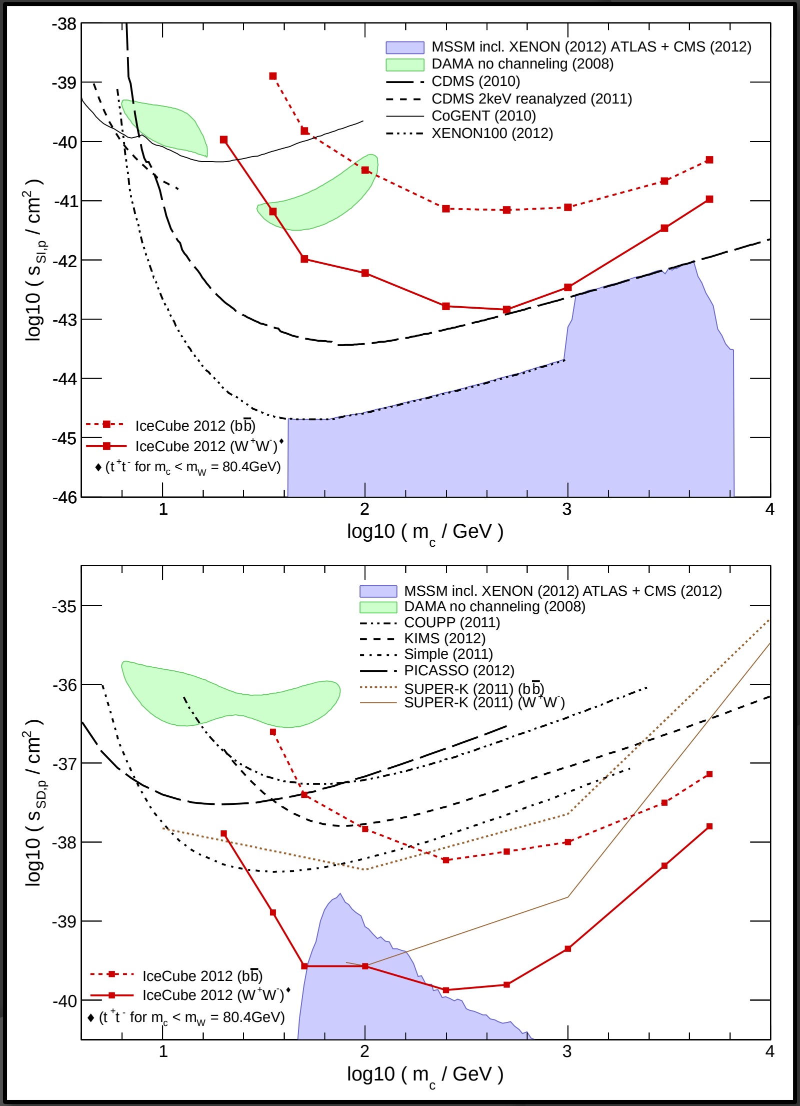
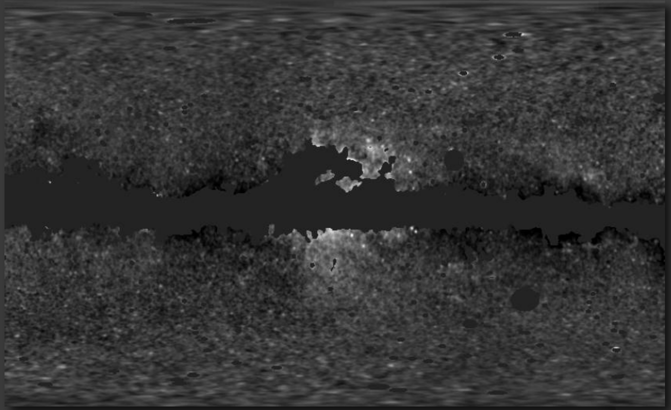
- Most recent constraints were derived using 317 days of data from the nearly complete (79-string) detector
- Most sensitive to spin-dependent scattering (hydrogen/proton targets); currently competitive with best spin-dependent limits from direct detection experiments (depending on annihilation channels under consideration)

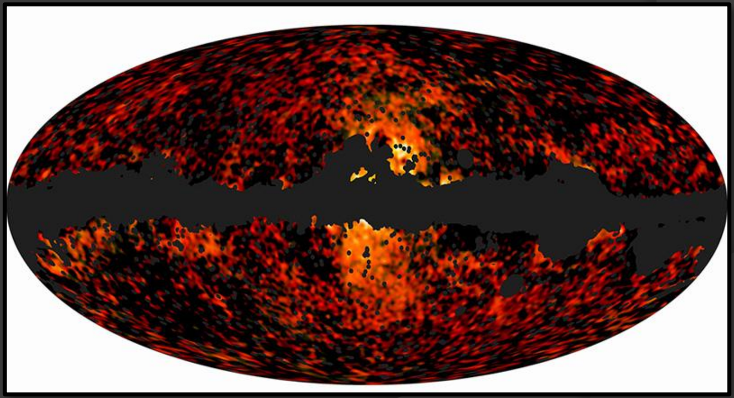


Dark Matter with Microwave and Radio Telescopes

- Electrons/positrons produced in dark matter annihilations lose energy via synchrotron emission, producing signals at radio/microwave wavelengths
- In 2004, Doug Finkbeiner discovered an excess of hard synchrotron emission around the Inner Galaxy in WMAP data; morphology was similar to that expected from dark matter annihilation
- In 2012, the Planck collaboration "unambiguously" confirmed the presence of this synchrotron haze



WMAP (22 GHz)

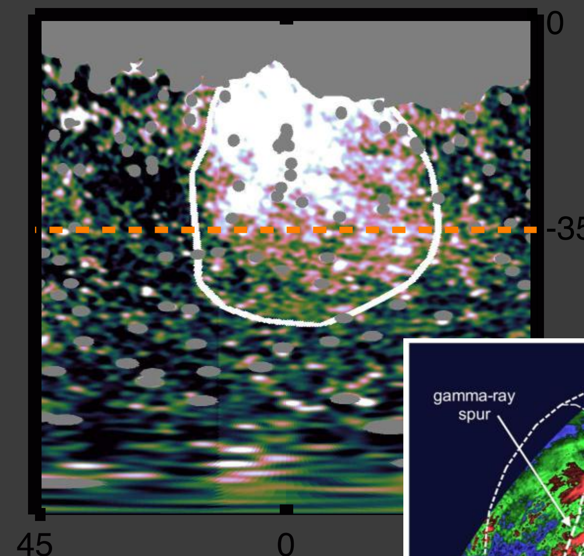


Planck (30 and 44 GHz)

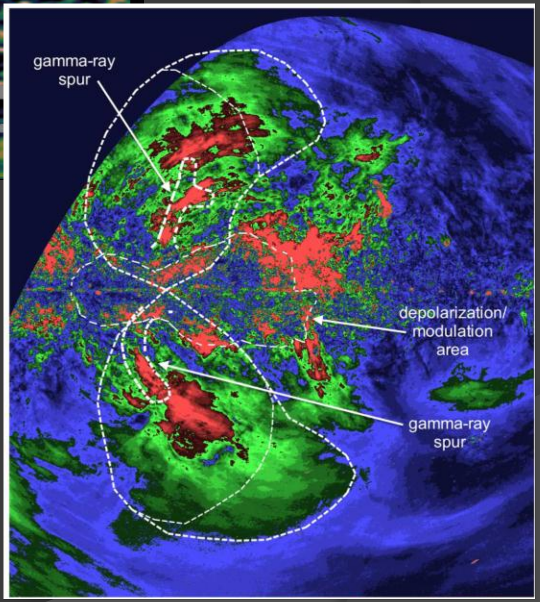
Finkbeiner, astro-ph/0409027;
Hooper, Finkbeiner, Dobler, PRD (2007);
Dobler, Finkbeiner, ApJ (2008)

Synchrotron Haze and Gamma-Ray Bubbles

- Planck's confirmation of the synchrotron haze also revealed a high degree of spatial correlation with the gamma-ray bubbles (or lobes, if you prefer) observed within the Fermi data
- The north-south elongation of this signal is *not* what one would expect from dark matter annihilation – instead, the haze appears to be synchrotron emission from jets/shocks associated with the Fermi bubbles, not from the dark matter halo



Planck Collaboration



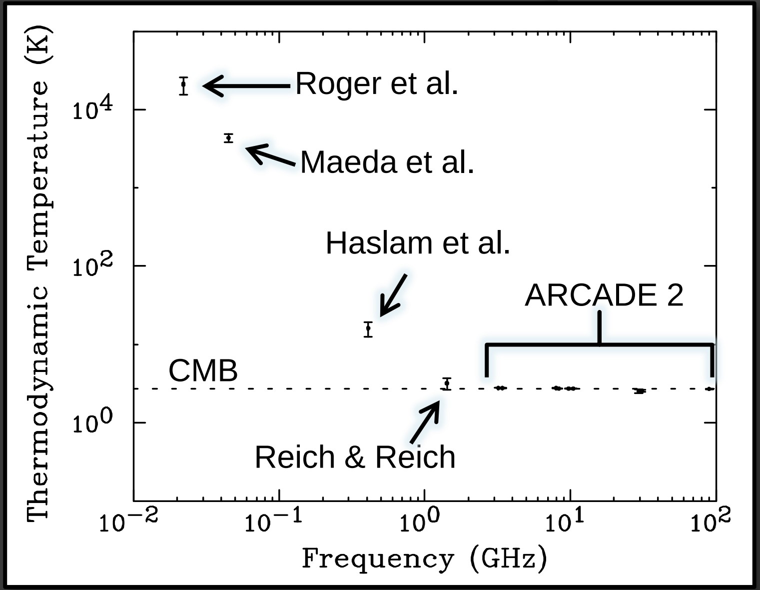
Carretti, Crocker, et al, Nature, arXiv: 1301.0512

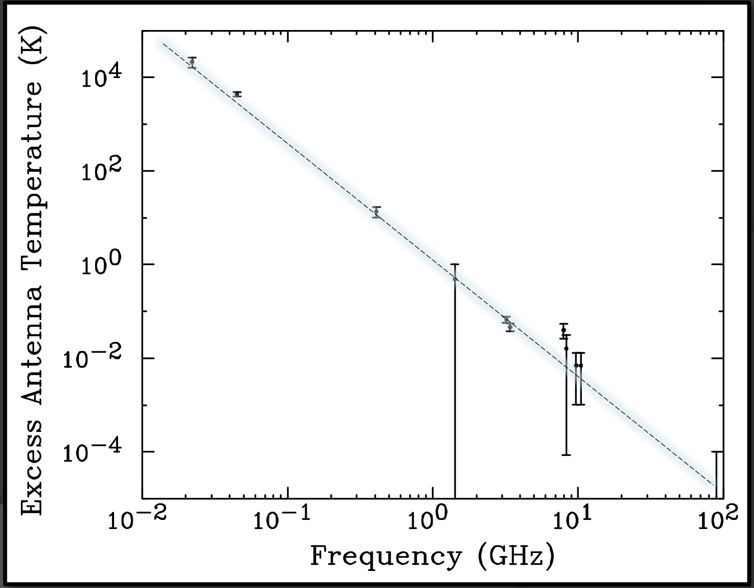
(I'll return to this issue later in my talk)

Dark Matter with Microwave and Radio Telescopes

- A number of observations at radio frequencies, including those of the ARCADE 2 collaboration, have revealed an isotropic background with a power-law spectrum, $\sim E^{-2.6}$
- Estimates of the contribution from unresolved radio sources fall short of this flux by a factor of ~5-6
- Could synchrotron emission from cosmological dark matter annihilations provide a significant contribution?

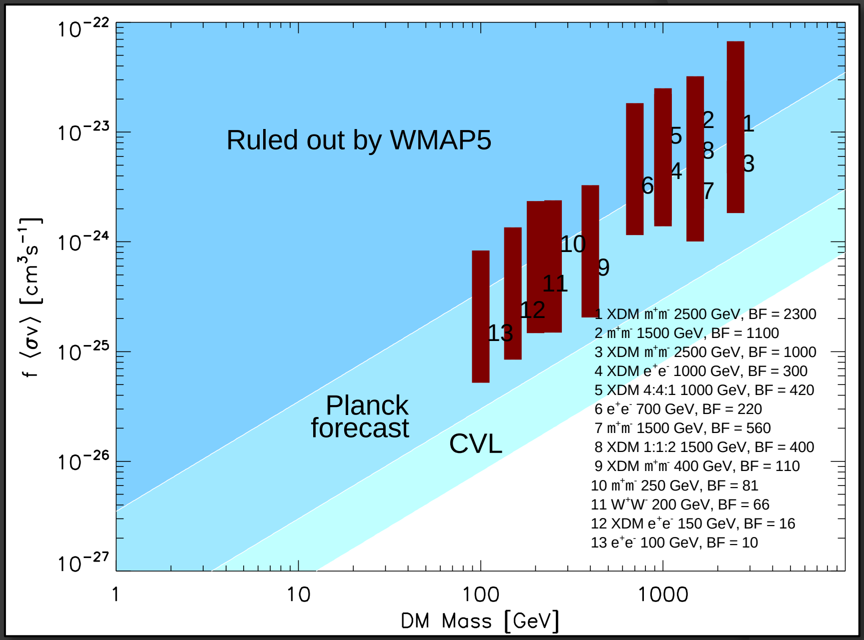
- Yes, possibly, but requires light masses and leptonic annihilation channels





Probing Dark Matter Annihilations During Recombination with Planck

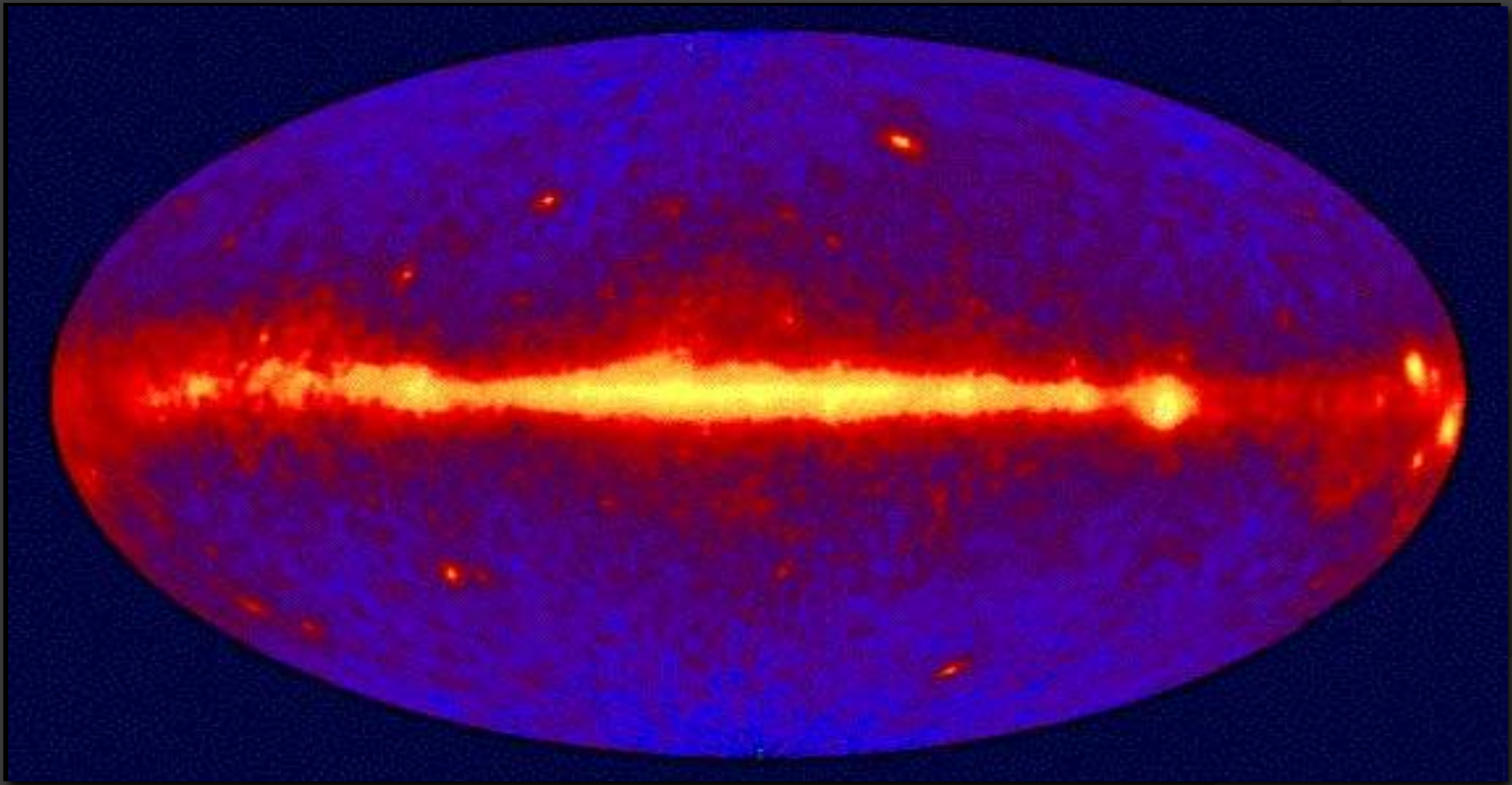
- Dark matter annihilations taking place at z~1000 can heat and ionize the photon-baryon plasma, impacting the observed angular power spectrum of the CMB
- Planck's sensitivity to this signal is expected to exceed WMAP's by about an order of magnitude
- For a $3x10^{-26}$ cm^3/s annihilation cross section to quarks, Planck should be sensitive to WIMPs with masses up to a few tens of GeV – comparable to Fermi dwarfs and Galactic Center, but with less uncertainty associated with astrophysical backgrounds and dark matter distributions

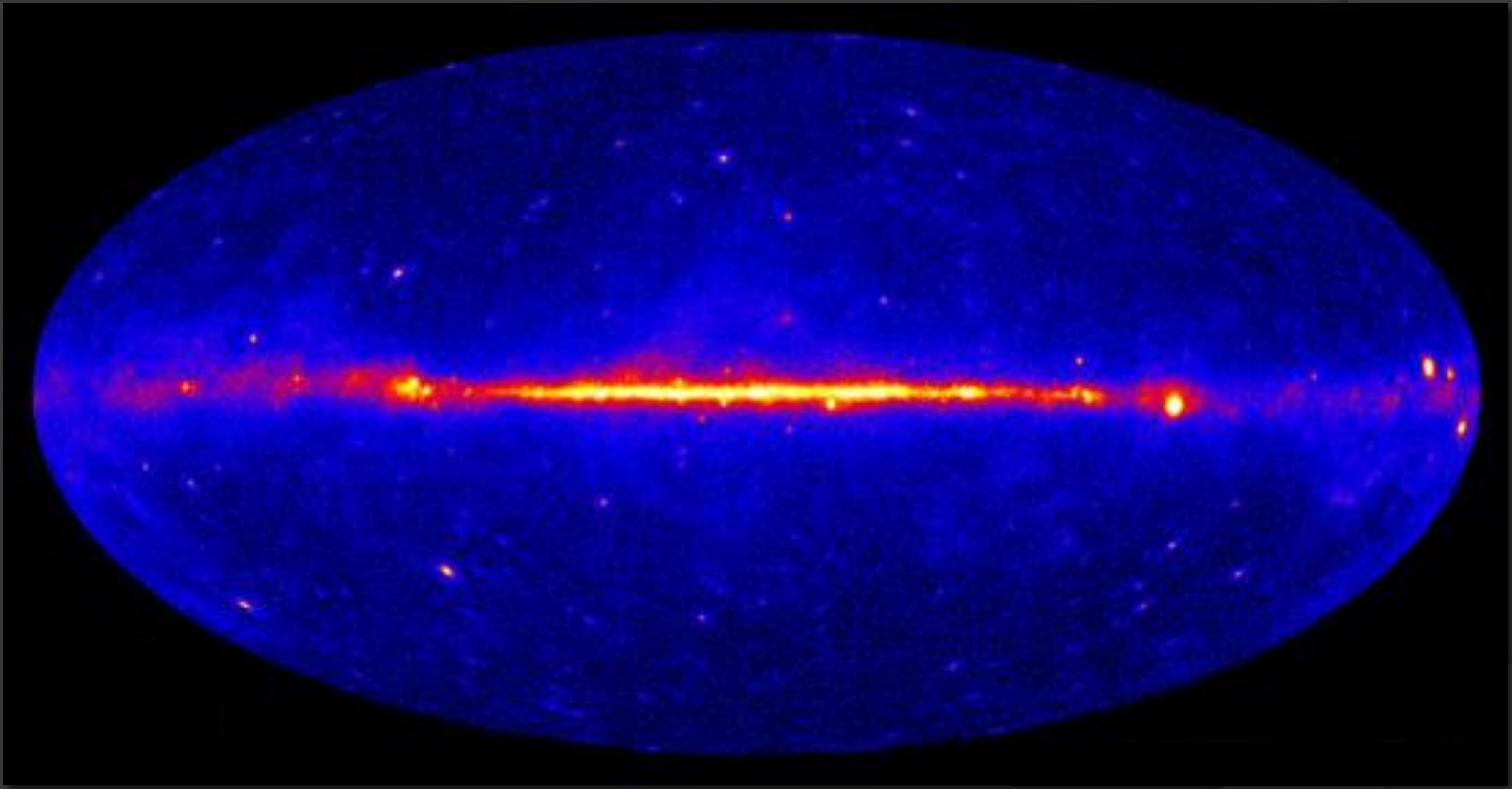


Slatyer et al. arXiv:0906.1197 (Finkbeiner et al. arXiv:1109.6322; Slatyer, arXiv:1211.0283)

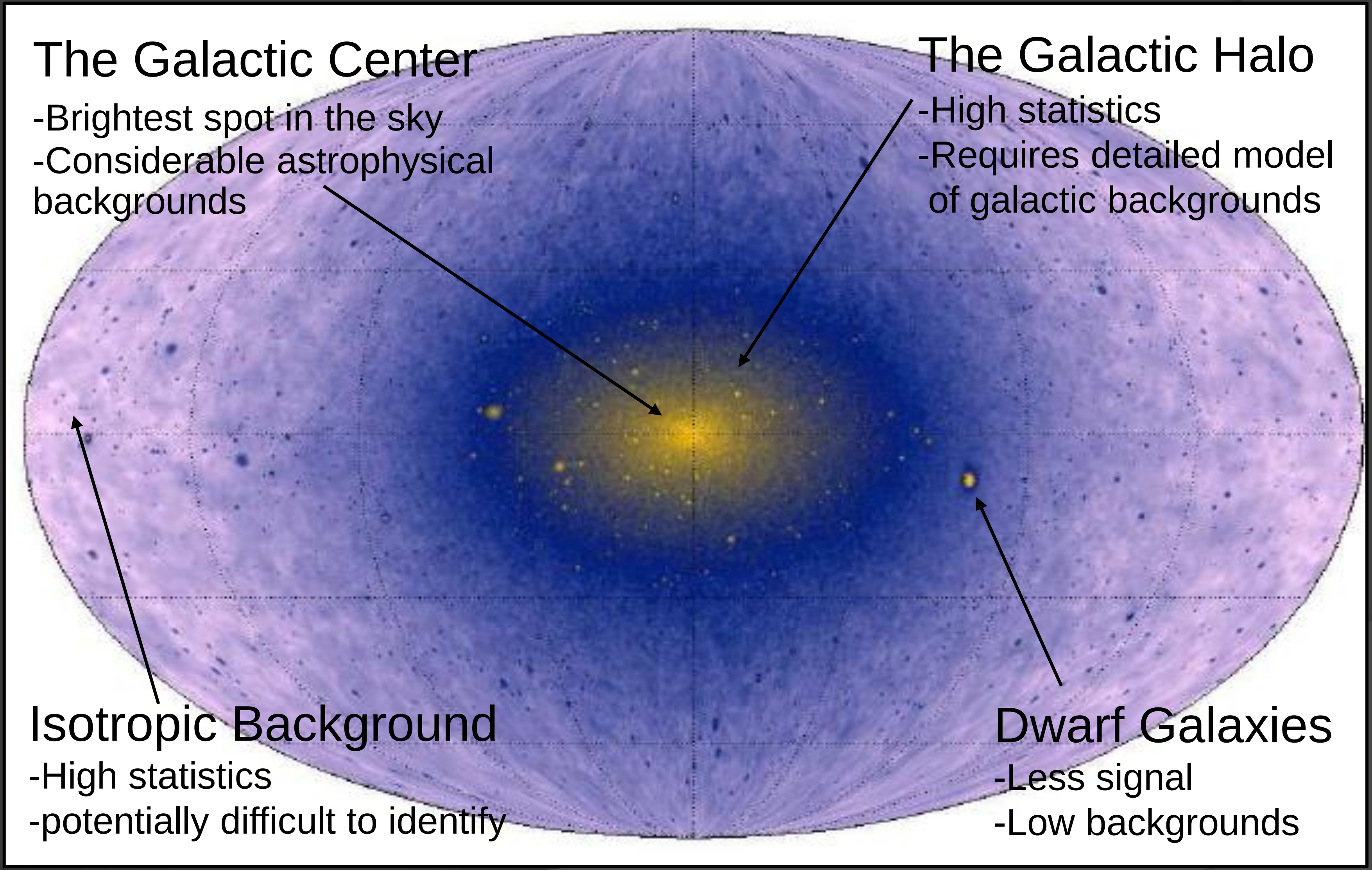
Indirect Detection With Fermi

- In my opinion, no single indirect detection experiment has more potential to constrain or discover dark matter than the Fermi Gamma Ray Space Telescope (FGST)
- Fermi's Large Area Telescope (LAT) offers far more effective area (~8000 cm^2), better angular resolution (sub-degree), and energy resolution (~10%) than any other space-based gamma-ray telescope
- Unlike ground-based telescopes, Fermi observes the entire sky and can study gamma rays down to ~100 MeV (ACTs are limited to ~100 GeV and up)





Where to look for Dark Matter with Fermi?



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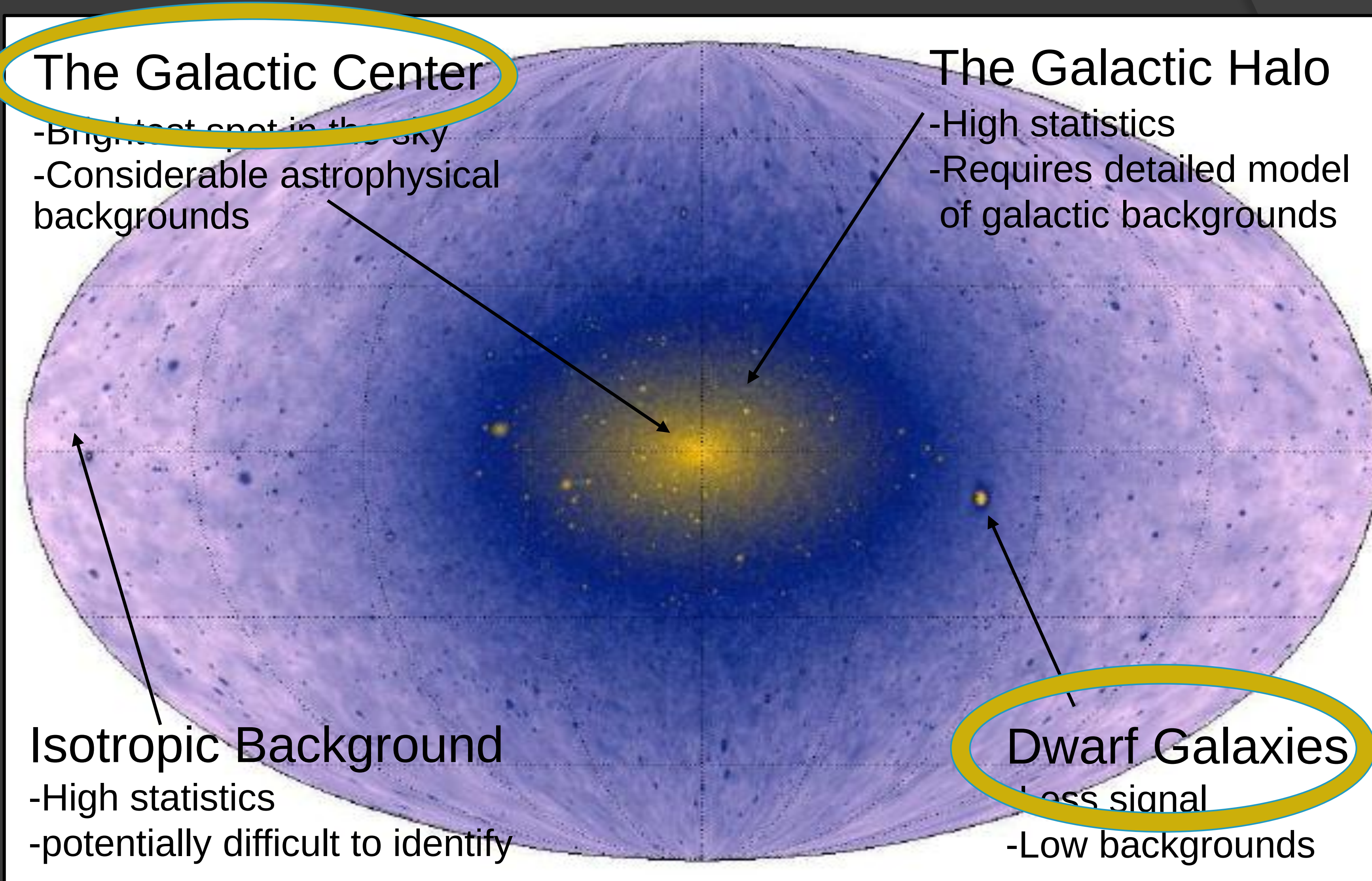
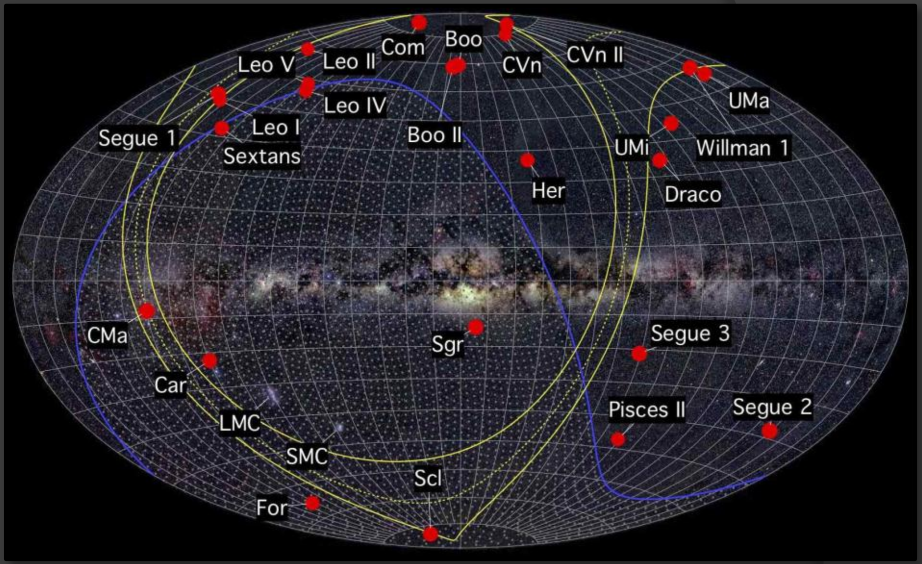


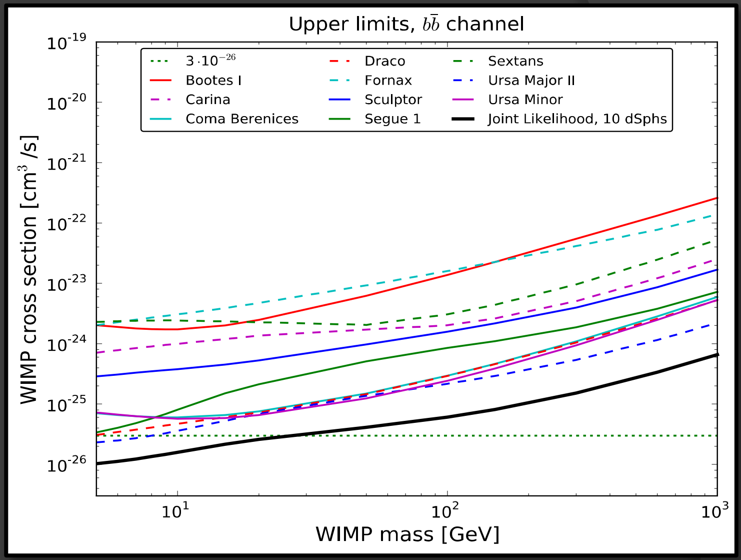
Dark Matter in Dwarf Galaxies

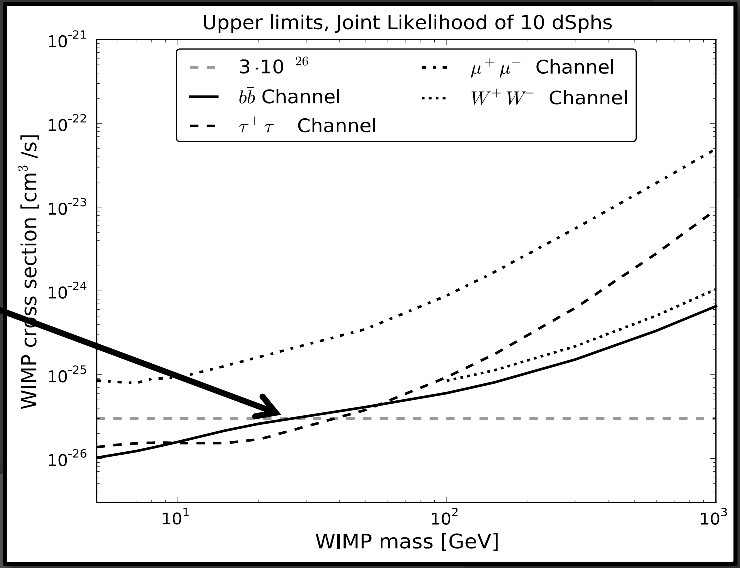
- The halo of the Milky Way contains numerous smaller halos, the largest of which are dwarf galaxies
- Dwarf galaxies are the most dark matter dominated known systems, with mass-to-light ratios as high as ~10^3
- These objects represent potentially bright sources of gamma rays from dark matter annihilations, with little astrophysical backgrounds



Dark Matter in Dwarf Galaxies

- In the summer of 2011, the results of two analyses of Fermi dwarfs were released (one by Geringer-Sameth & Koushiappas, and another by the Fermi Collaboration)
- Although no excess was reported, the lack of observed gamma rays was used to derive a stringent constraint on the dark matter's annihilation cross section
- For the first time, Fermi began to rule out dark matter models with a cross section equal to the naïve estimate for a simple thermal relic (σv~3x10^{-26} cm^3/s) – reaching masses up to ~30-50 GeV

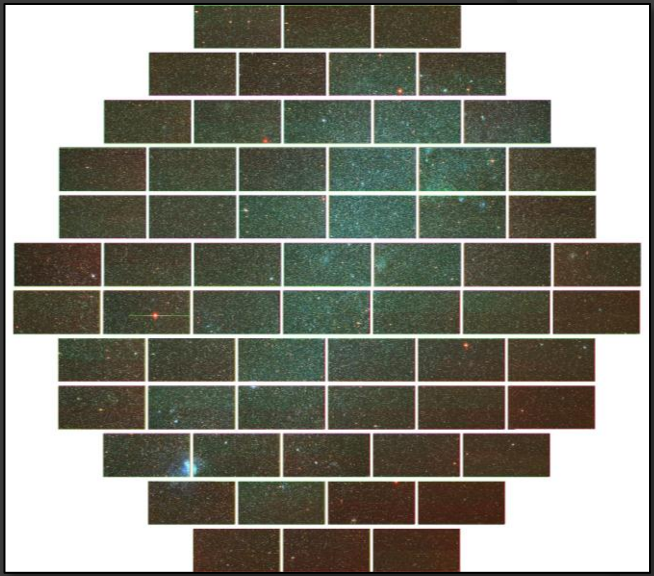




Dark Matter in Dwarf Galaxies

And much yet to do…

- Cosmological surveys, such as DES, are expected to discover many new dwarf galaxies (especially in the largely unexplored southern hemisphere)
- With the full (10 yr.) Fermi data set and anticipated DES dwarfs, Fermi will likely be sensitive to simple thermal WIMPs as massive as several hundred GeV



DES's view of the Small Magellanic Cloud

Dark Matter in Dwarf Galaxies

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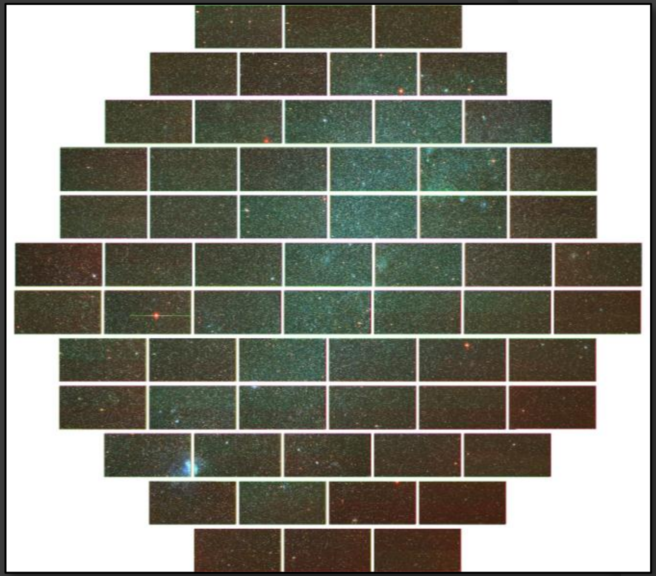
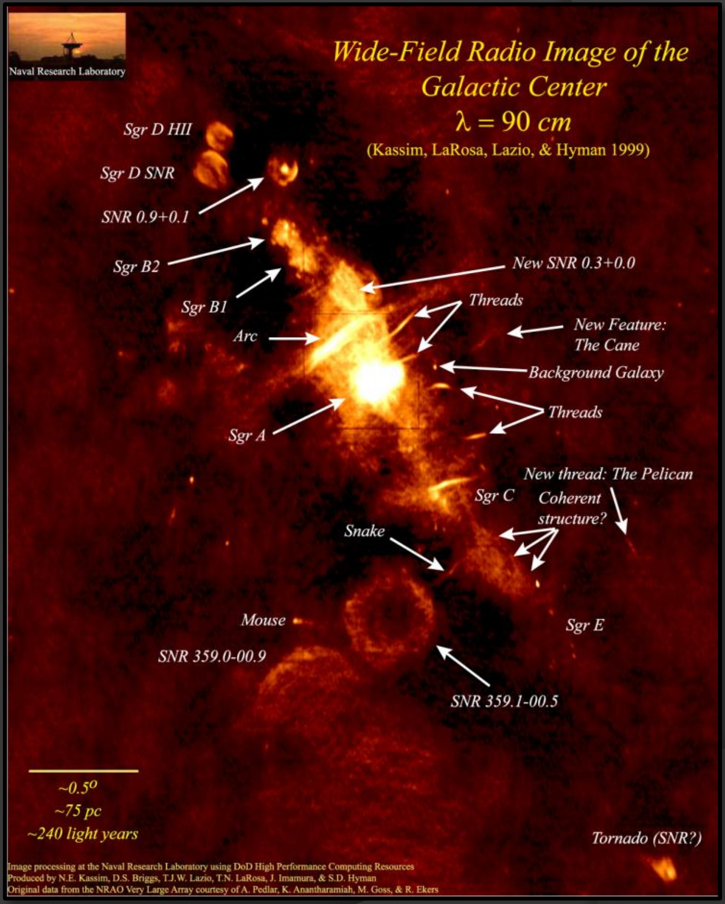
- With the full (10 yr.) Fermi data set and anticipated DES dwarfs, Fermi will likely be sensitive to simple thermal WIMPs as massive as several hundred GeV
- Questions remain as to the dark matter distribution in dwarfs – some have argued for cored distributions, and others for cusps; no consensus has emerged
- How such uncertainties impact the limits quoted by the Fermi collaboration (and by other groups) is a question in merit of further attention; we should move beyond NFW



DES's view of the Small Magellanic Cloud

Dark Matter in The Galactic Center

- The volume surrounding the Galactic Center is complex; backgrounds present are not necessarily well understood
- This does not, however, make searches for dark matter region intractable
- The flux of gamma rays predicted from dark matter annihilations around the Galactic Center is very large – tens of thousands of times brighter than that predicted from the brightest dwarf galaxies
- But to separate dark matter annihilation products from astrophysical backgrounds, one must take advantage of the distinct observational features of these components



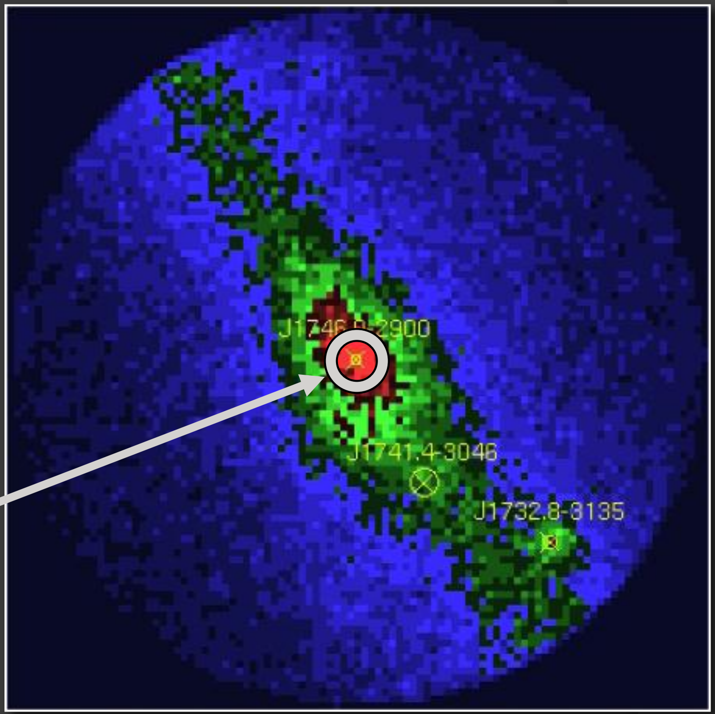
Dark Matter in The Galactic Center

The gamma ray signal from dark matter annihilations is described by:

$$\Phi_\gamma(E_\gamma,\psi) = \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}\frac{\langle\sigma v\rangle}{8\pi m_X^2}\int_{\mathrm{los}}\rho^2(r)\mathrm{d}l$$

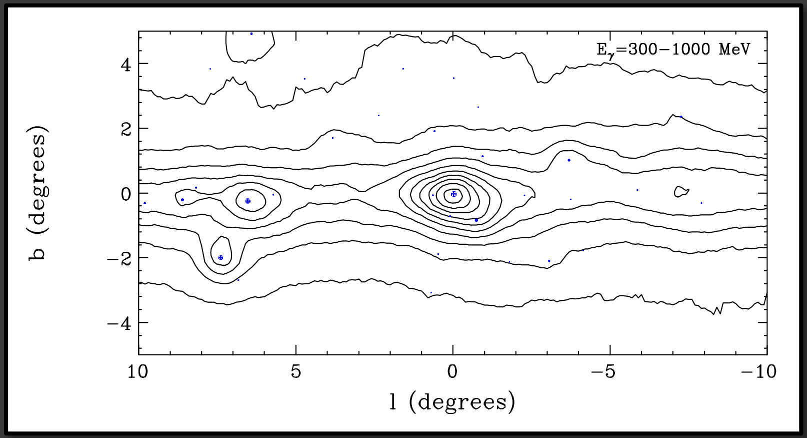
1) Distinctive “bump-like” spectral feature

2) Signal highly concentrated around the Galactic Center (but not entirely point-like); precise morphology determined by the dark matter distribution



A Simple (but effective) Approach to the Galactic Center

1) Start with a raw map (smoothed out over 0.5° circles)



Hooper and Linden, PRD, arXiv:1110.0006

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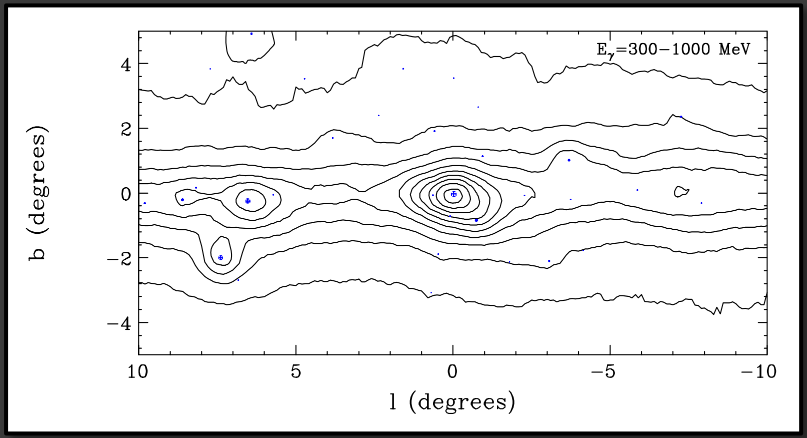

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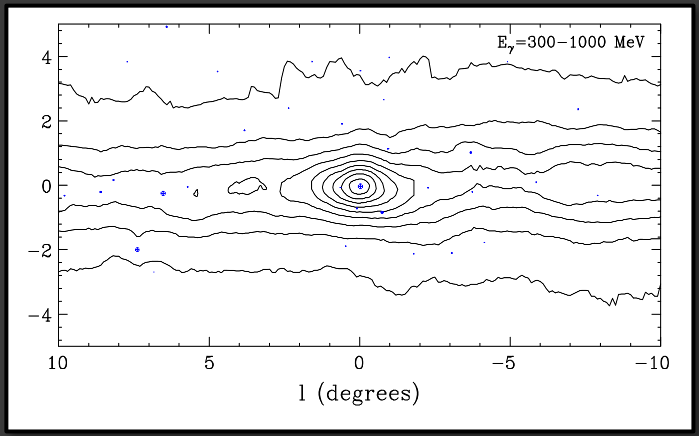

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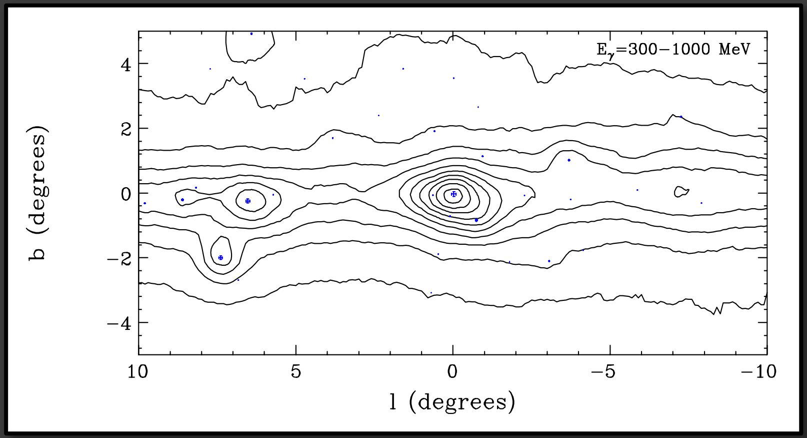
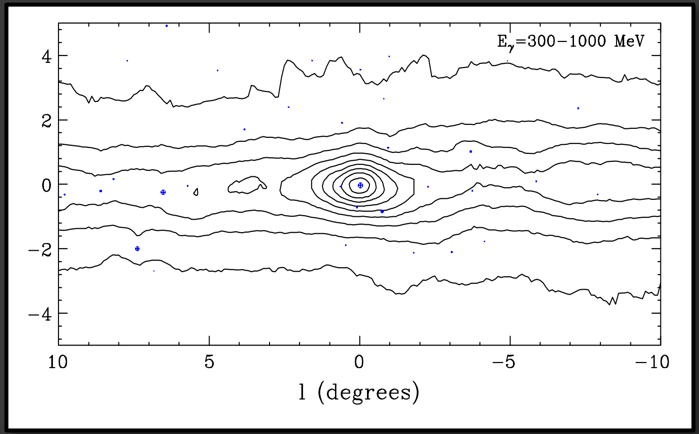
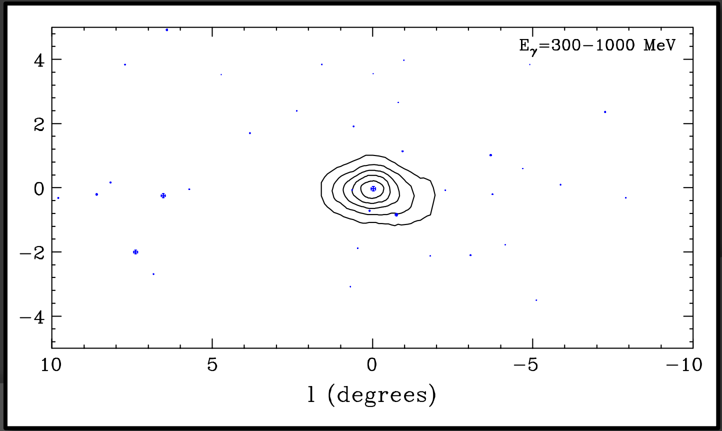
3) Subtract line-of-sight gas density template (empirical, good match to 21-cm)



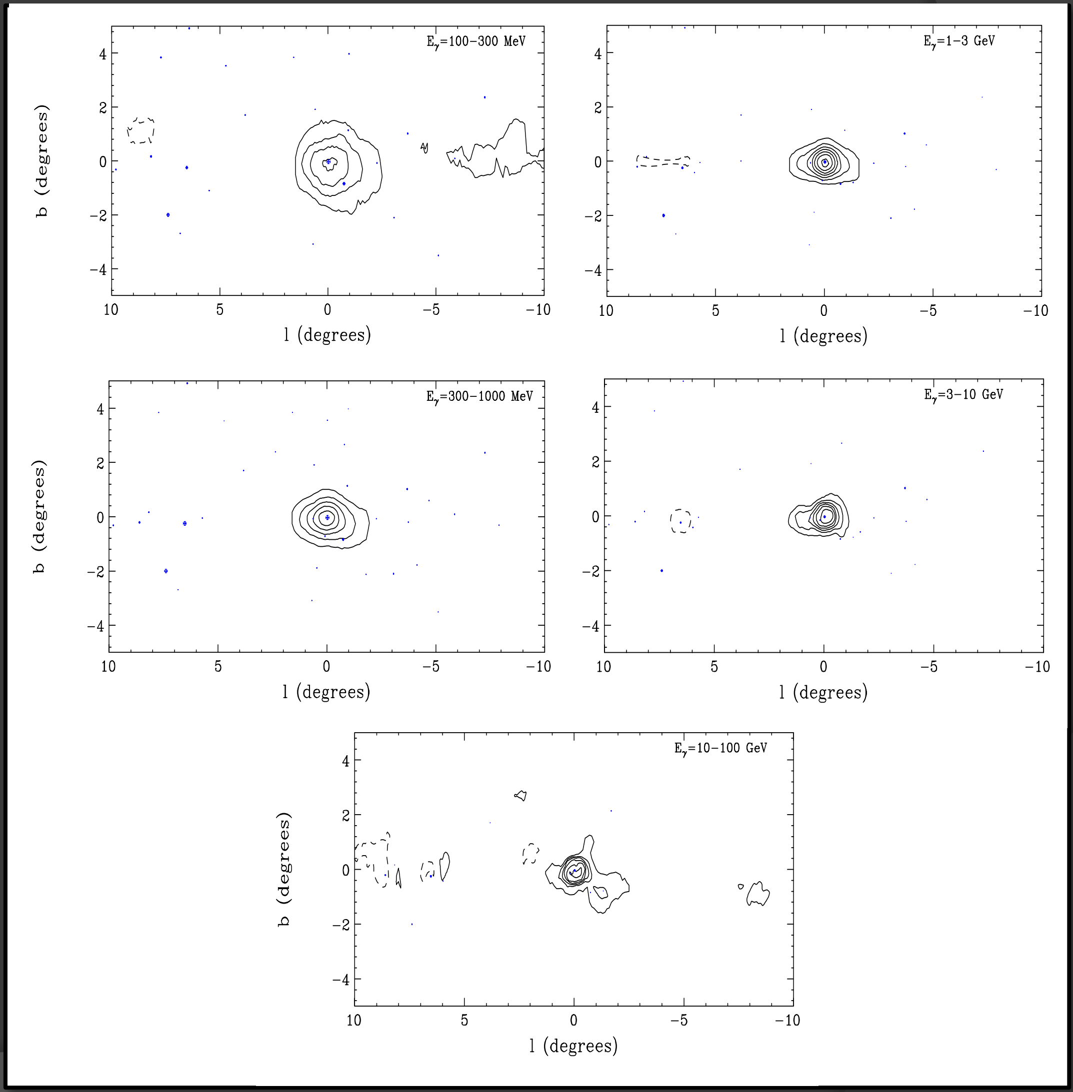




Hooper and Linden, PRD, arXiv:1110.0006

A Simple (but effective) Approach to the Galactic Center

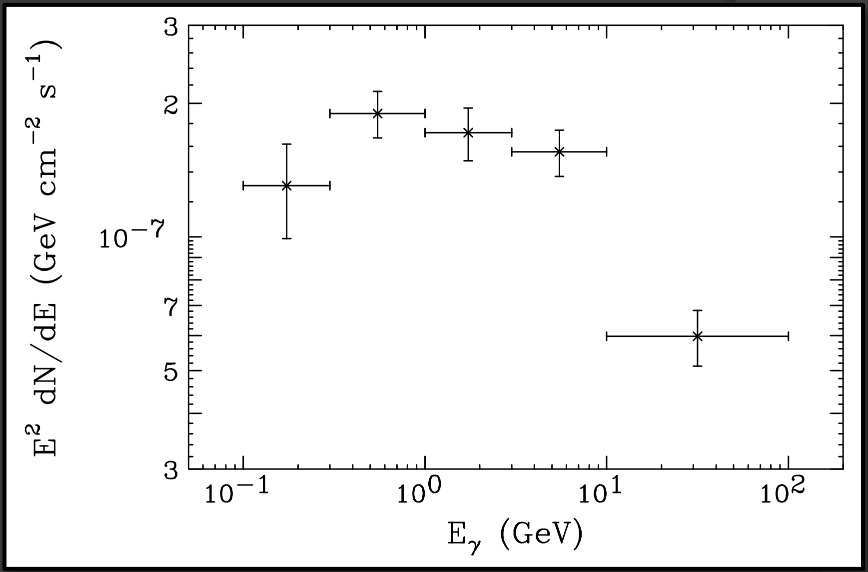
- This method removes ~90% of the emission in the inner galaxy (outside of the innermost few degrees)
- Typical residuals are ~5% or less as bright as the inner residual – spatial variations in backgrounds are of only modest importance
- Clearly isolates the emission associated with the inner source or sources (supermassive black hole? Dark matter? Pulsars?), along with a subdominant component of "ridge" emission



Hooper and Linden, PRD, arXiv:1110.0006

Characteristics of the Observed Gamma Ray Residual

1) The spectrum peaks between ~300 MeV and ~10 GeV

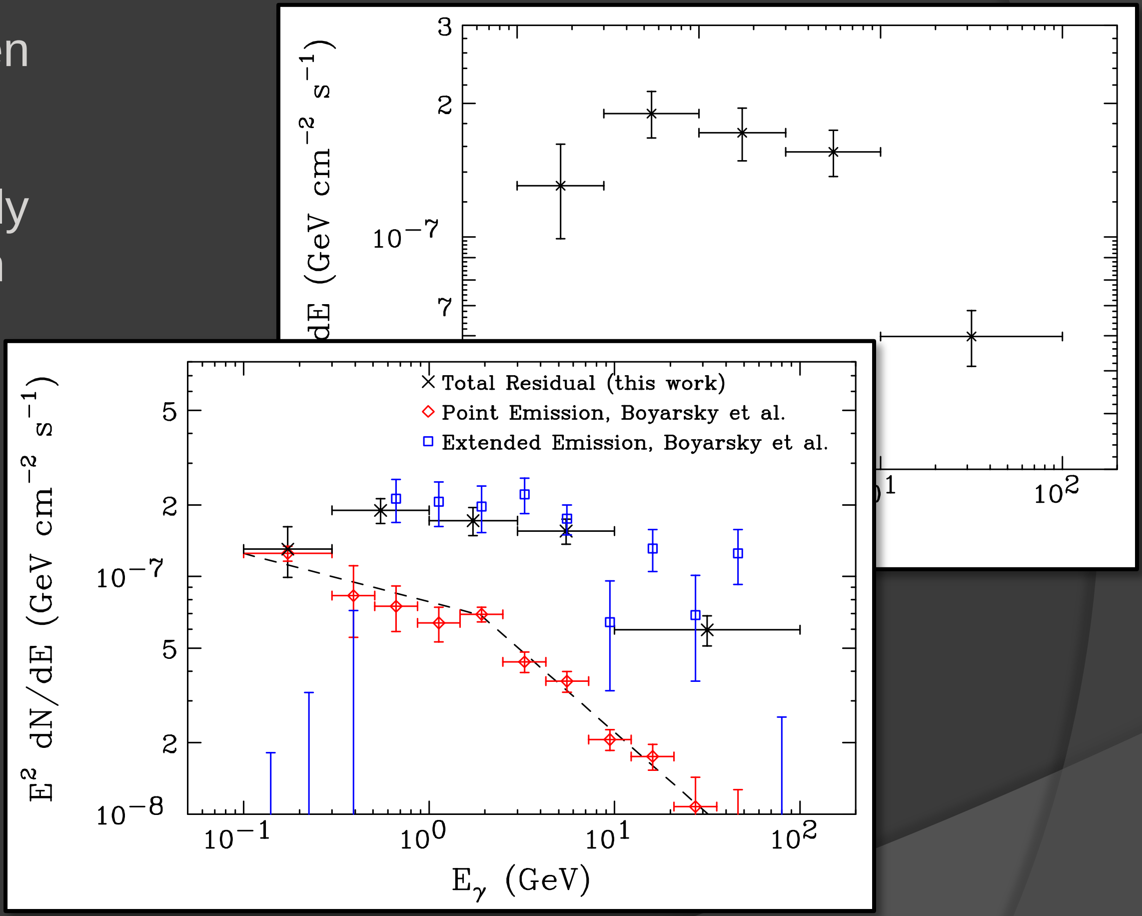


Hooper and Linden, PRD, arXiv:1110.0006

Characteristics of the Observed Gamma Ray Residual

1) The spectrum peaks between ~300 MeV and ~10 GeV

2) Clear spatial extension – only a small fraction of the emission above ~300 MeV is point-like



Hooper and Linden, PRD, arXiv:1110.0006

Characteristics of the Observed Gamma Ray Residual

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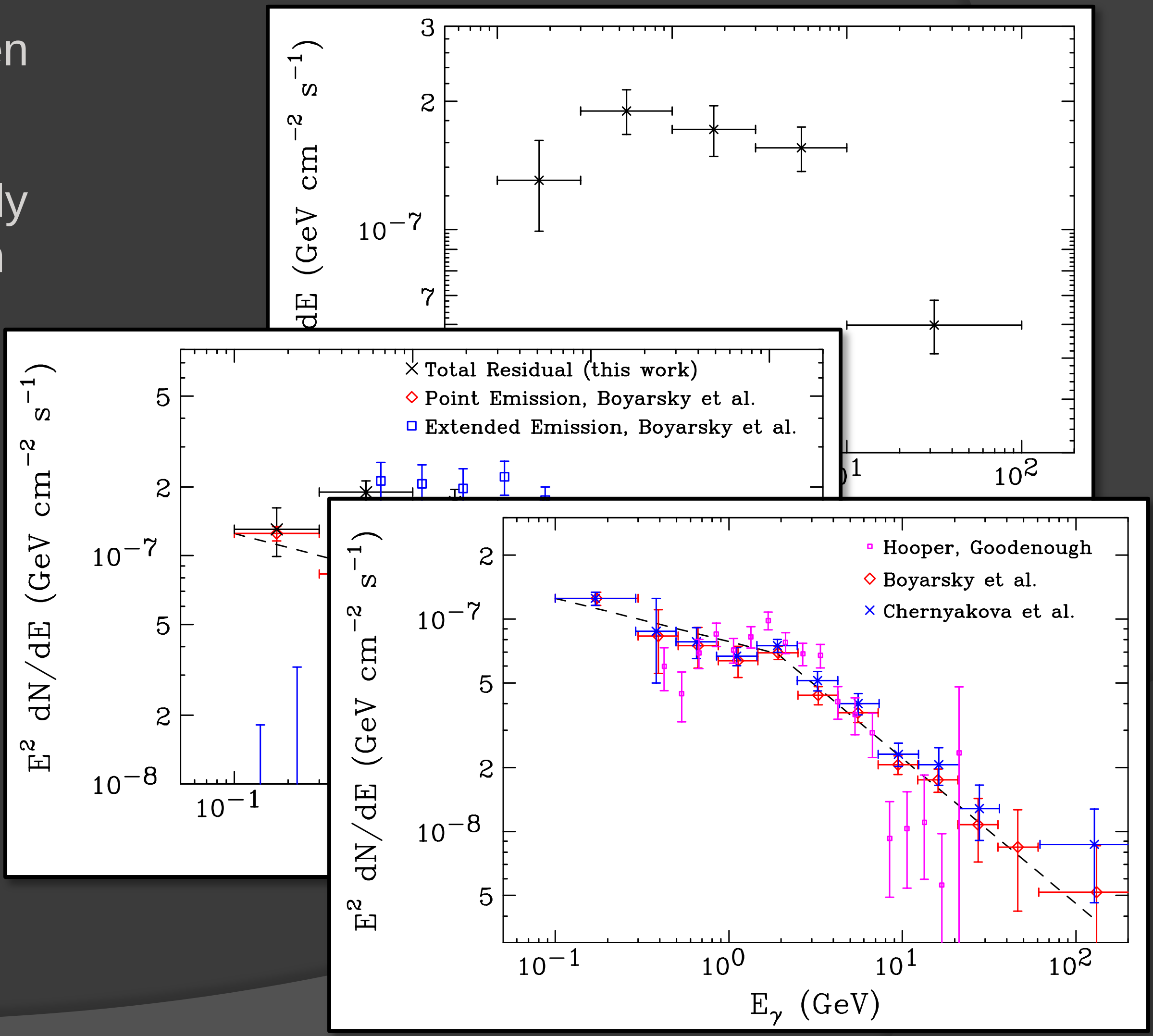
2) Clear spatial extension – only a small fraction of the emission above ~300 MeV is point-like

3) Good agreement is found between our analysis and those of other groups (see the recent analysis by Abazajian and Kaplinghat, for example)

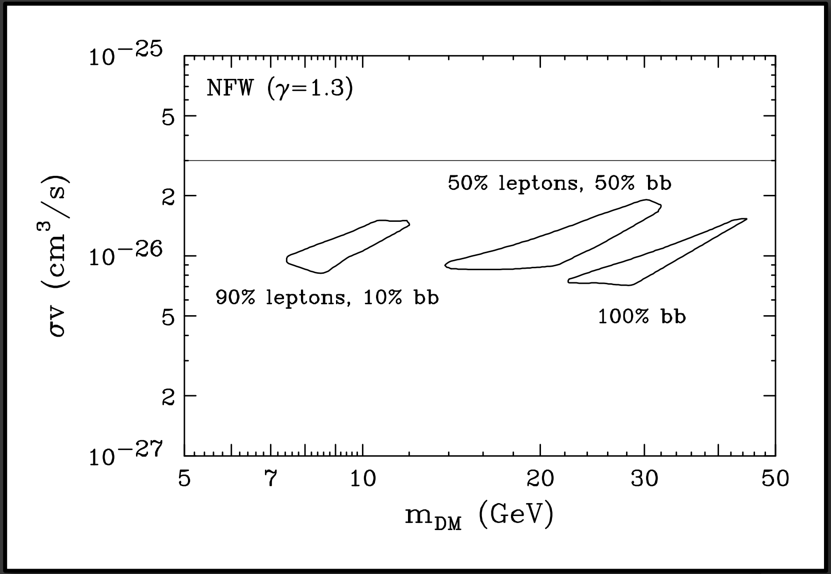


Hooper and Linden, PRD, arXiv:1110.0006

The Dark Matter Interpretation

The extended emission residual can be explained by annihilating dark matter with the following characteristics:

- The spectral shape of the residual is well fit by a dark matter particle with a mass in the range of 7 to 12 GeV (*similar to that required by CoGeNT, DAMA, and CRESST*), annihilating primarily to $\tau^+\tau^-$ (possibly among other leptons)



- The angular distribution of the signal is well fit by a halo profile with $\rho(r) \sim r^{-\gamma}$, with $\gamma \sim 1.2$ to 1.4 (in good agreement with expectations from simulations)
- The normalization of the signal requires the dark matter to have an annihilation cross section within a factor of a few of $\sigma v \sim 10^{-26}$ cm^3/s, similar to the value predicted for a simple thermal relic

Hooper and Linden, PRD, arXiv:1110.0006

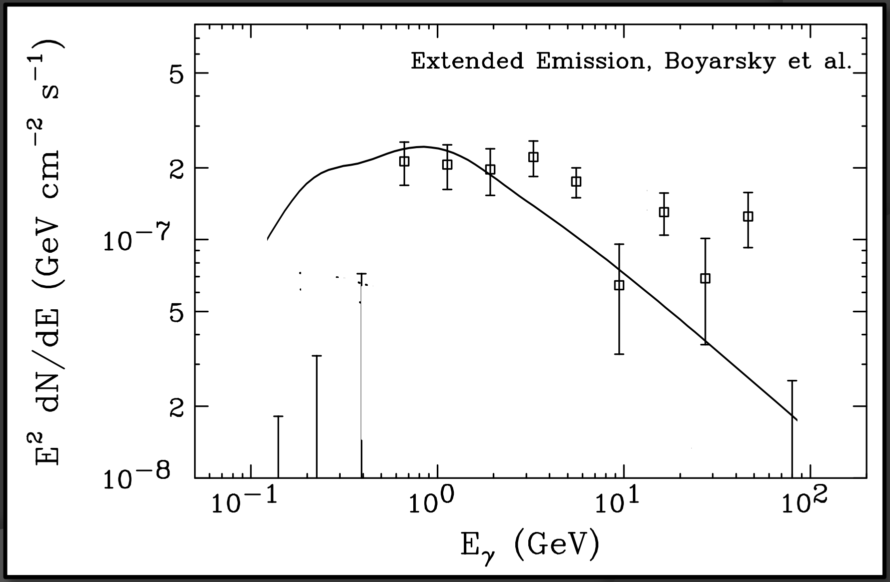
Other Interpretations?

Unresolved Point Sources?

- Perhaps a population of several/many unresolved point sources distributed throughout the inner tens of parsecs of the Milky Way could produce the observed signal – millisecond pulsars have been suggested
- Highly concentrated distribution is difficult to accommodate, however; signal goes as $F \propto r^{-2.5}$, while the observed stellar distribution is $n_{star} \propto r^{-1.25}$ (possibly a population of pulsars formed by star-star interactions? – could also "tether" newly-formed pulsars against the effects of pulsar-kicks)

Pions From Cosmic Ray Interactions With Gas?

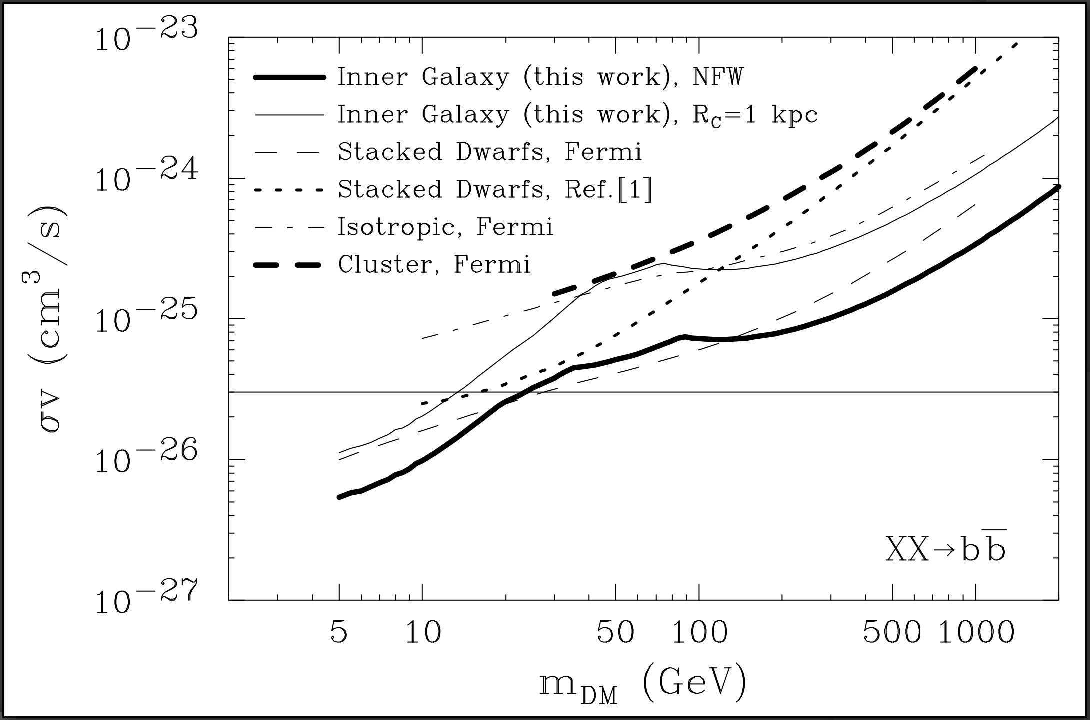
- Cosmic rays interacting with gas is an obvious possibility
- The spectrum from pion decay, however, is not not consistent with the lack of extended emission observed below ~500 MeV (true for *any* spectrum of cosmic rays)
- Furthermore, Linden, Lovegrove and Profumo have convincingly argued that the observed morphology is not consistent with this interpretation (arXiv:1203.3539)



Boyarsky et al., arXiv:1012.5839

And Impressive Limits...

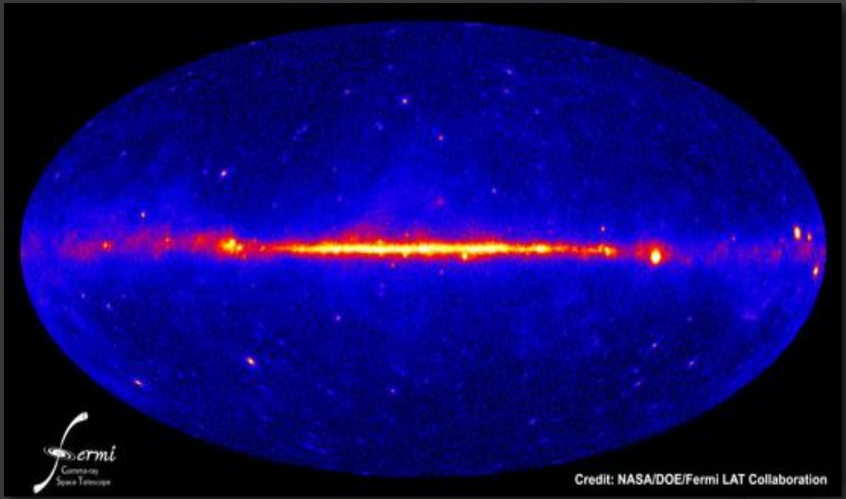
- Regardless of the actual origin of the observed gamma-ray emission, the Galactic Center currently provides the most stringent and robust constraints on the dark matter annihilation cross section
- These constraints were derived using conservative density normalizations (95% CL lower limits), and for a variety of dark matter distributions, including NFW or cored (R_c=1 kpc) profiles
- At a minimum, these constraints are competitive with those derived from dwarf galaxies



Hooper, Kelso, Queiroz, arXiv:1209.3015

Annihilation Products in the Fermi Bubbles?

- If dark matter annihilation products are responsible for the extended gamma-ray signal seen around the Galactic Center, then gamma-rays should also be discernable at higher Galactic Latitudes as well – this flux should be comparable in brightness to the Fermi Bubbles, for example
- This provides an important test which can be used to discriminate between dark matter, pulsar, and cosmic ray interpretations of the extended Galactic Center signal

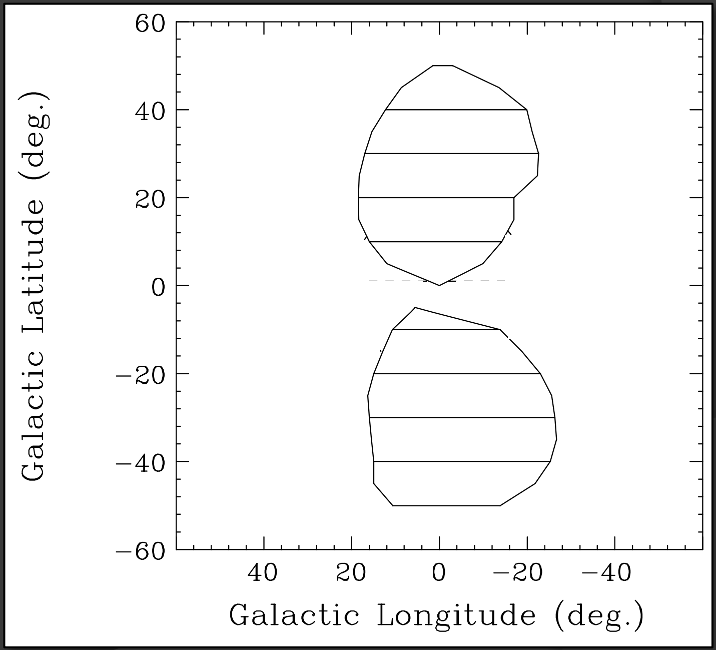


Is this high latitude emission present?

If so, can we see it?

Annihilation Products in the Fermi Bubbles?

- We employ a template analysis to the Fermi data – the same approach as was previously used to discover the bubbles
- We start by breaking up the bubbles into different latitude ranges – if dark matter annihilation products are present, they should be prominent at low latitudes, and largely absent at high latitudes



Hooper and Slatyer, in progress

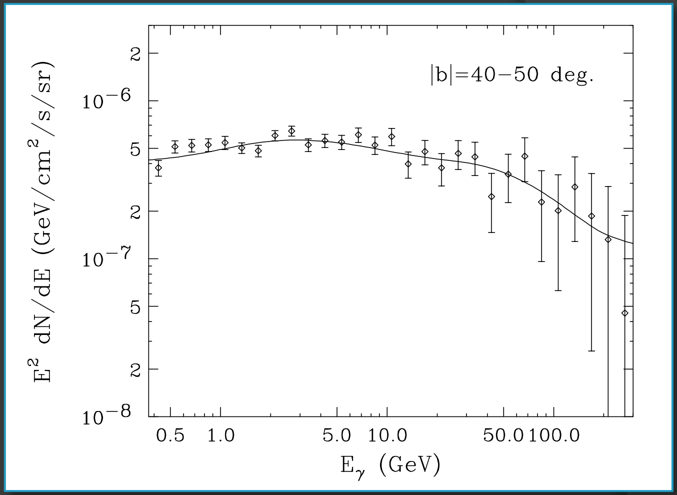
Annihilation Products in the Fermi Bubbles?

- Very strong spectral variation with Galactic Latitude is observed in the Fermi bubbles

Hooper and Slatyer, in progress

Annihilation Products in the Fermi Bubbles?

- Very strong spectral variation with Galactic Latitude is observed in the Fermi bubbles
- At high latitudes (|b|>30°), the observed emission is highly consistent with the inverse Compton scattering of an approximately power-law spectrum of electrons ($dN_e/dE_e \sim E^{-3}$)



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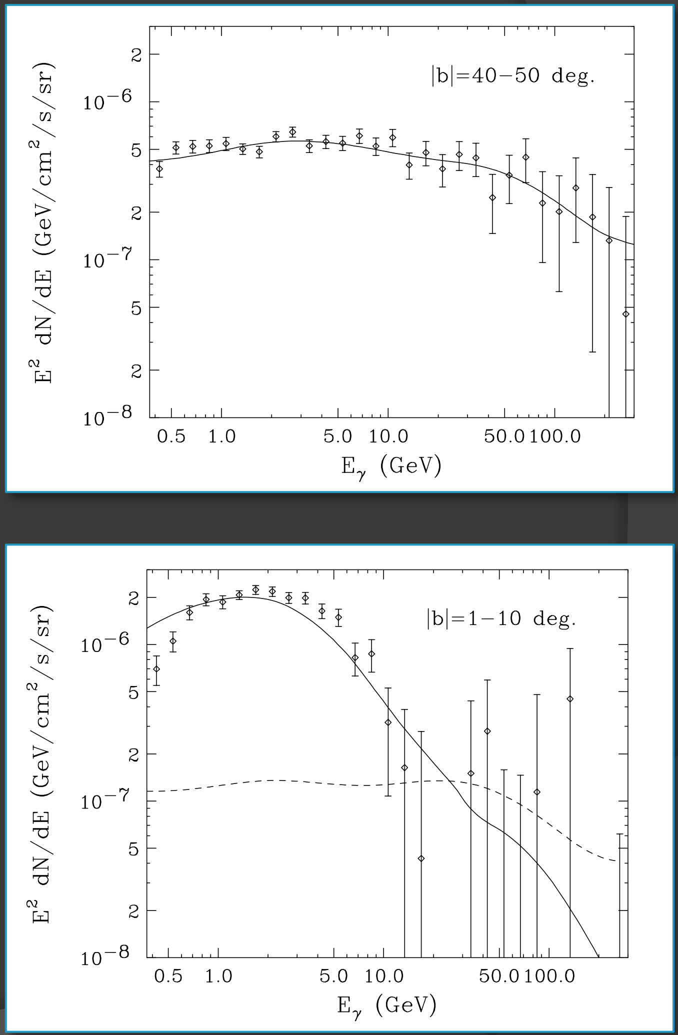
Annihilation Products in the Fermi Bubbles?

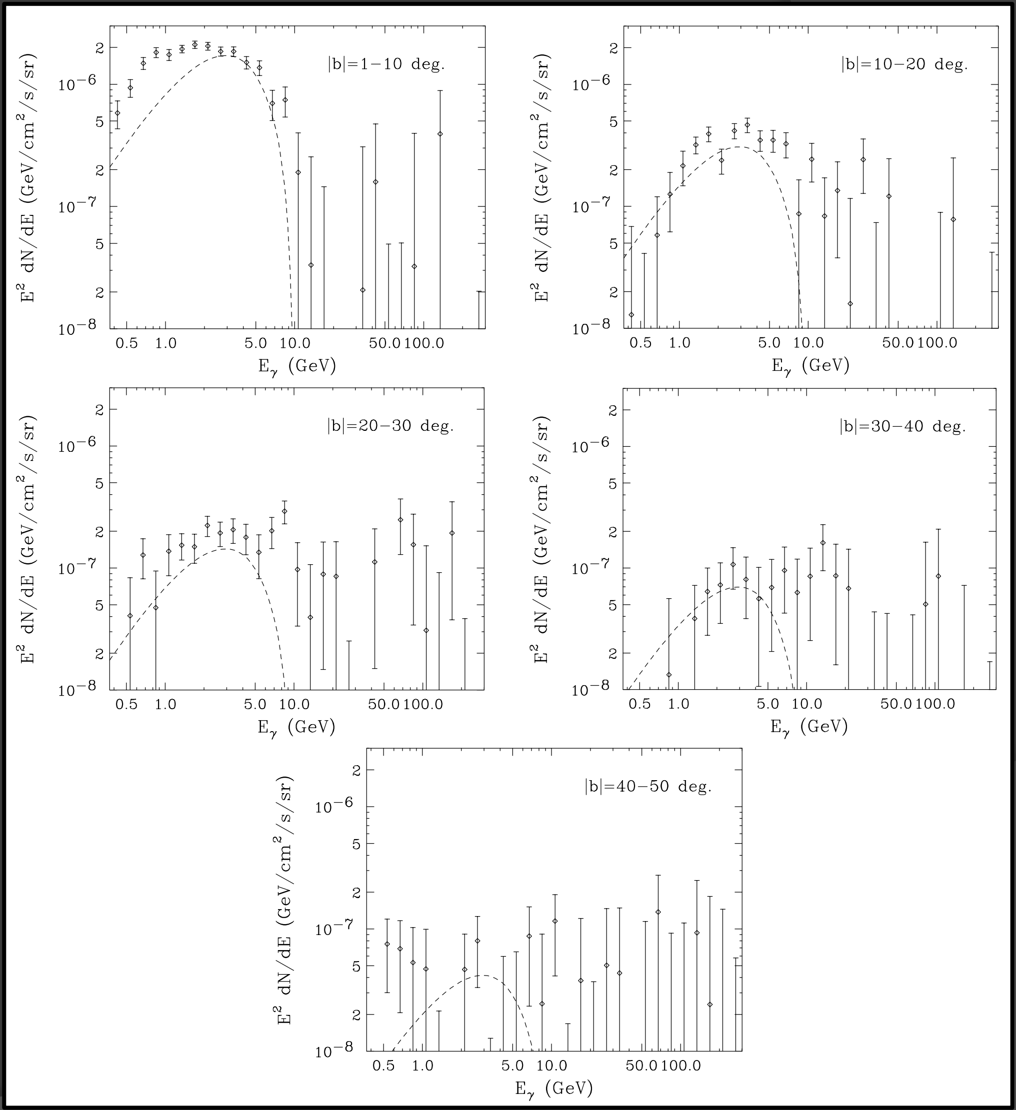
- Very strong spectral variation with Galactic Latitude is observed in the Fermi bubbles
- At high latitudes (|b|>30°), the observed emission is highly consistent with the inverse Compton scattering of an approximately power-law spectrum of electrons ($dN_e/dE_e \sim E^{-3}$)
- At low latitudes (|b|<20°), however, the observed emission is inconsistent with the inverse Compton scattering of *any* spectrum of electrons
- An additional spectral component is present , concentrated at low galactic latitudes, and that peaks at a few GeV



Hooper and Slatyer, in progress

Annihilation Products in the Fermi Bubbles?

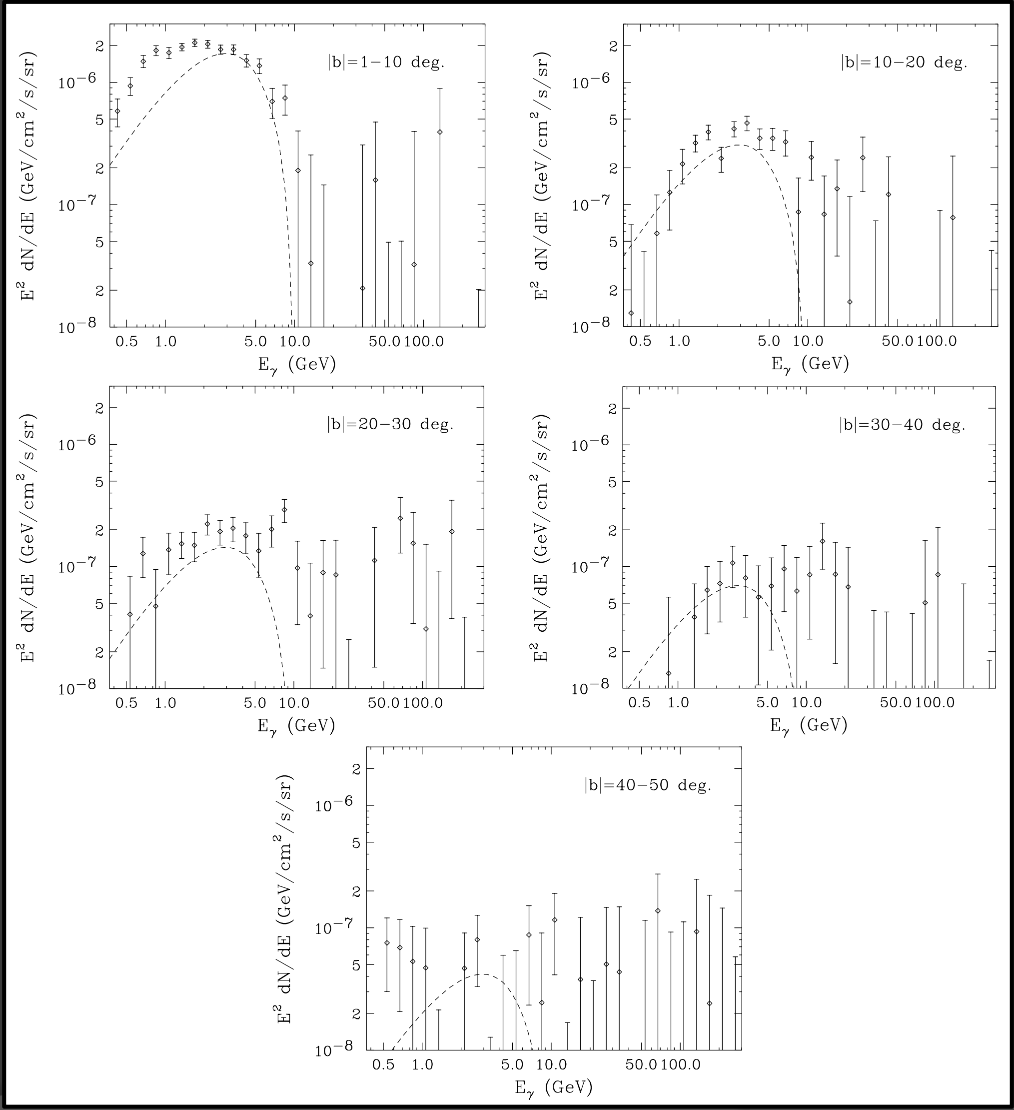
- If we assume that the electron spectrum does not vary significantly throughout the volume of the bubbles, we can subtract the Inverse Compton contribution from the observed spectrum



Hooper and Slatyer, in progress

Annihilation Products in the Fermi Bubbles?

- If we assume that the electron spectrum does not vary significantly throughout the volume of the bubbles, we can subtract the Inverse Compton contribution from the observed spectrum
- The residuals shown display a spectrum and morphology that is very similar to that observed from the Galactic Center region
- The dotted line is the prediction for a 10 GeV WIMP annihilating to $\tau^+\tau^-$, distributed according to an NFW-like profile with an inner slope of 1.2



Hooper and Slatyer, in progress

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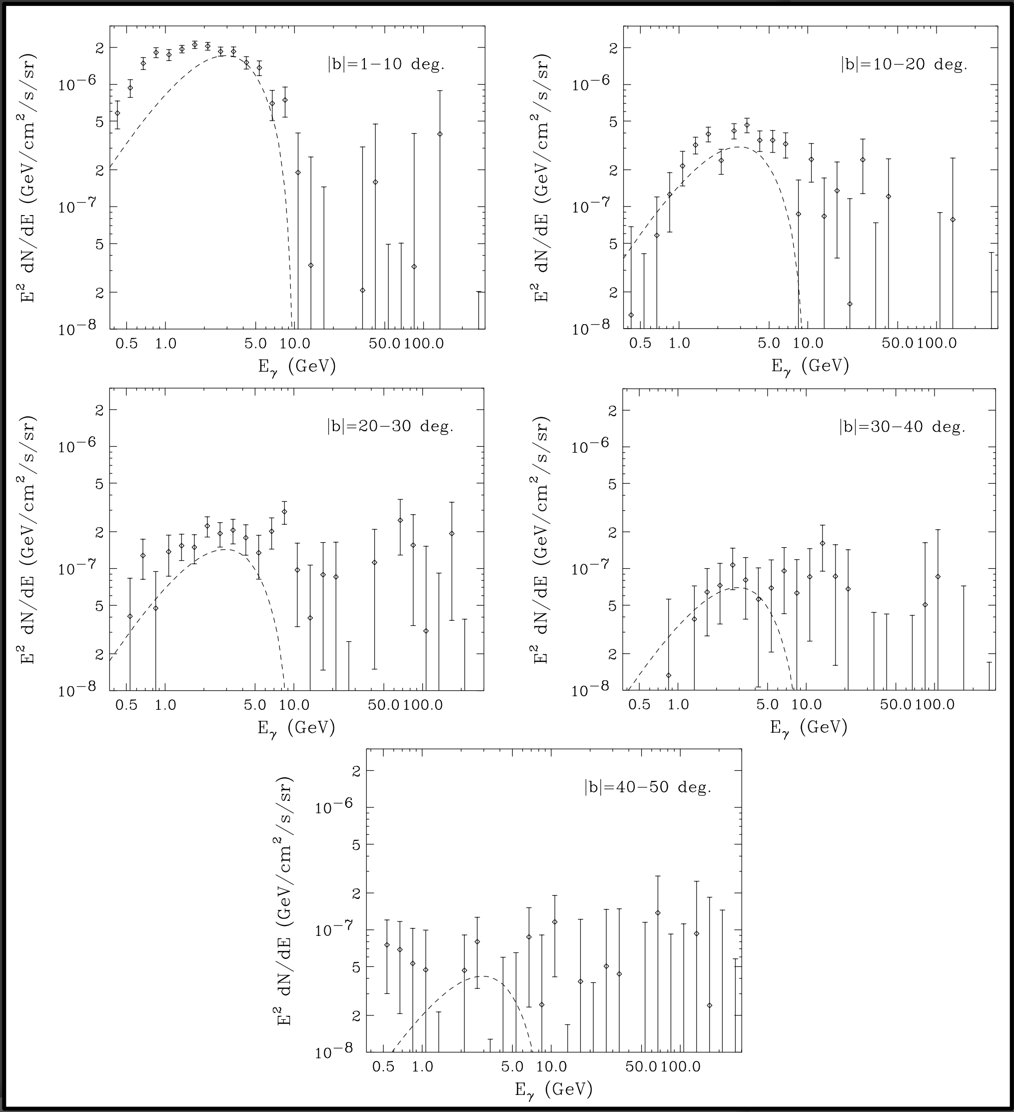
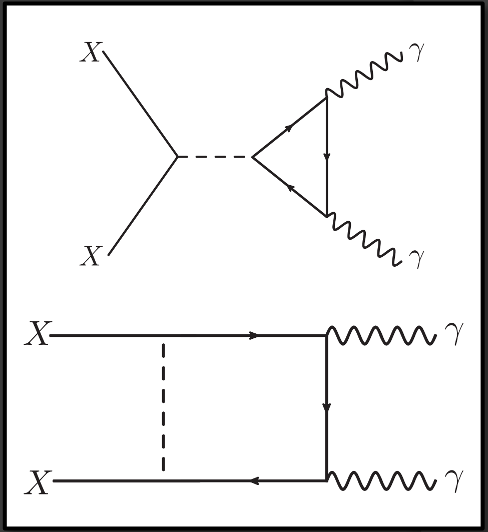
- Key Point: *The signal previously observed from the Galactic Center is not confined to the inner few hundred parsecs, but extends to at least ~5 kpc from the Inner Galaxy*

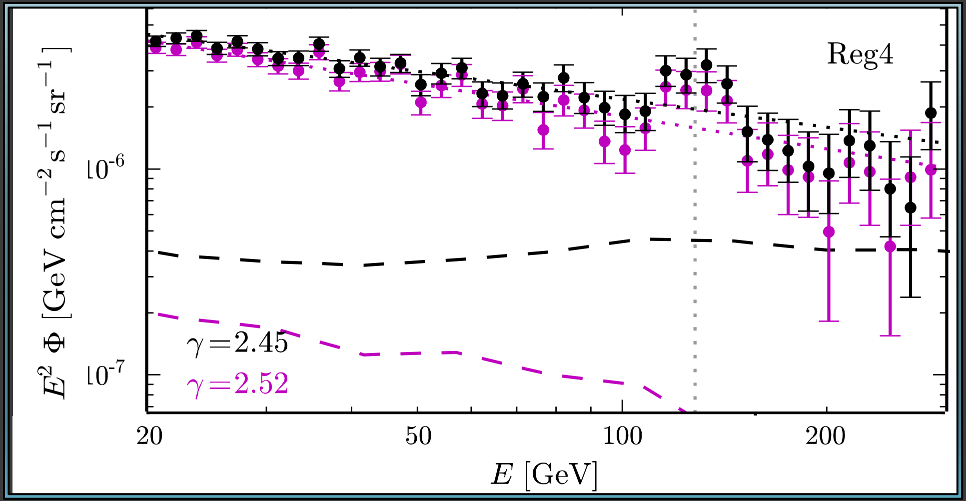


Hooper and Slatyer, in progress

A Gamma-Ray Line at 130 GeV?

- Evidence for a monoenergetic (up to resolution) gamma-ray line from the Inner Galaxy has been identified within Fermi's data (at 3.3σ, after LEE)
- Such a single has long been considered a "smoking gun" of dark matter annihilations, provided through loop-level diagrams
- Morphology of the signal is well fit to a that predicted from a cusped dark matter distribution, with a cross section of $\sigma v \sim 2 \times 10^{-27}$ cm^3/s





C. Weniger, arXiv:1204.2797

But is it real?

This is a Real Dark Matter Line?

Pros

Cons

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- Appears most brightly near the Galactic Center; overall structure looks consistent to that expected from dark matter annihilations

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- Peak brightness is about 200 pc (~1.5°) from Galactic Center (with fairly high significance)

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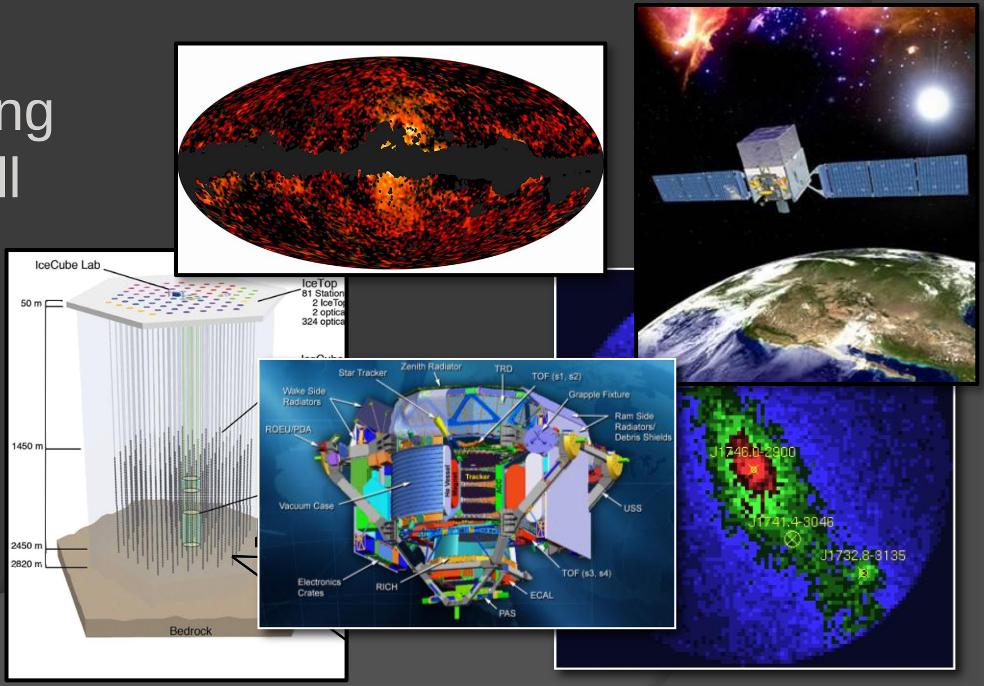
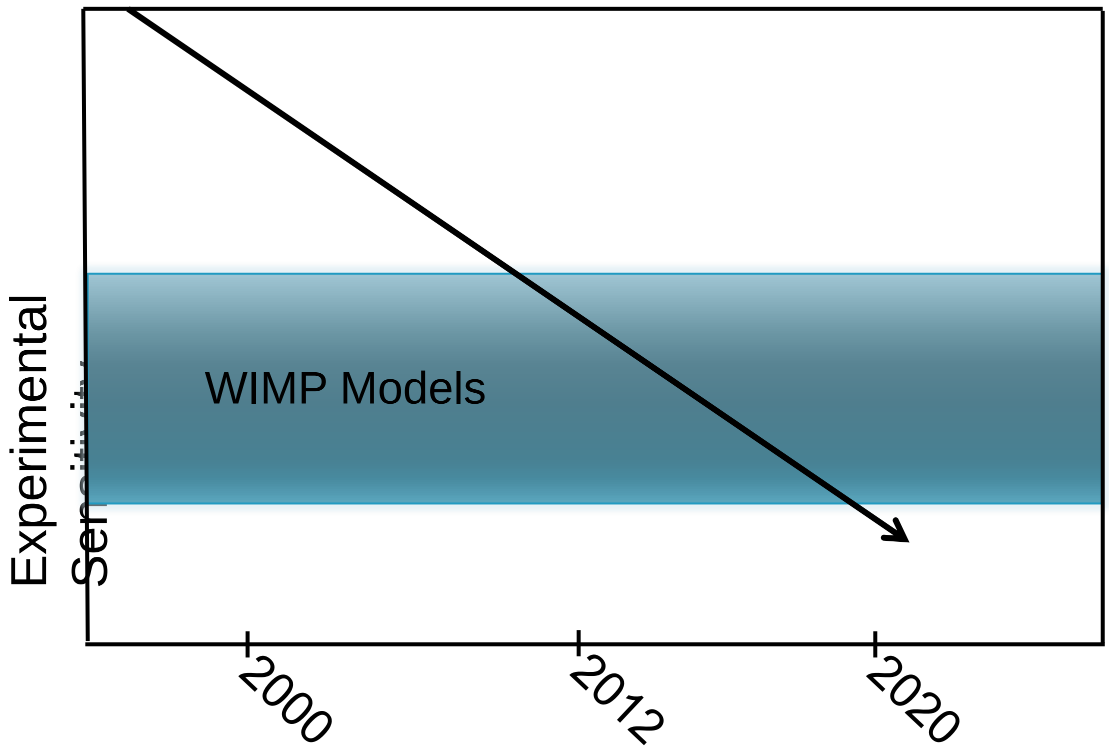
- Signs of a similar line appear in events associated with the Earth's albedo ("limb" photons) – signs of a systematic error in energy reconstruction?

➔ HESS-II should be able to settle

Summary

- We are living in the discovery age of dark matter – if WIMPs exist, we should expect to see the first evidence of them soon – and indirect searches are no exception
- New results from AMS, IceCube, Planck are anticipated soon (*ie*. 2013)
- For the first time, a number of experiments are sensitive to WIMPs with annihilation cross sections near that predicted for a simple thermal relic ($\sigma v \sim 10^{-26}$ cm^3/s)
- The combined results from existing indirect detection experiments will test a broad array of dark matter models, especially among those with masses below a few hundred GeV




Experimental
WIMP Models
2000
2012
2020