High Energy Astrophysics and the Search for Dark Matter

Tim Linden

With much thanks to:

Stefano Profumo, Vicky Kalogera, Jeremy Sepinsky, Jennifer Siegal-Gaskins, Vaso Pavlidou, Brandon Anderson, Paul Kiel

Candidacy Exam UC - Santa Cruz May 18, 2010

Outline

- Current Research and Results
  - High Mass X-Ray Binaries
  - The Fermi Haze
  - The WMAP Haze
- Future Research Plan
  - Fermi Anisotropies
  - Multiwavelength constraints on diffuse emission
  - Milli-Second Pulsars as Gamma-ray sources

High Mass X-Ray Binaries

- Modeling Code
- Classifying the HMXB Population
- The metallicity dependence of HMXB
- Conclusions

The StarTrack Modeling Code

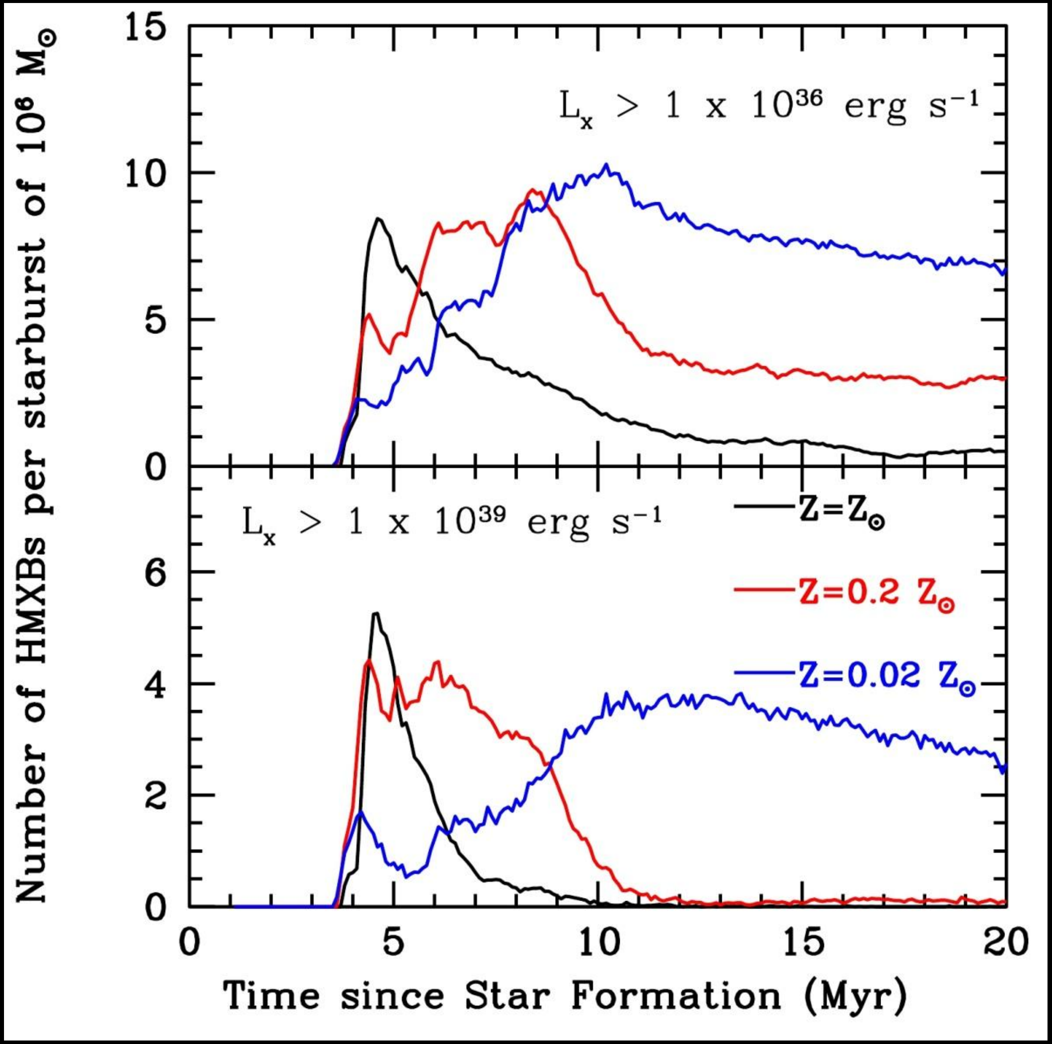
- Developed by Chris Belczynski (Belczynski et al. 2002, 2008) to determine the populations of X-Ray binaries, NS-NS binaries, etc.

- In this research we simulate a delta function starburst of 10^6 solar masses and follow it for 20 Myr

- We employ standard prescriptions for common envelope efficiencies, X-Ray luminosities, Roche Lobe overflow, etc.

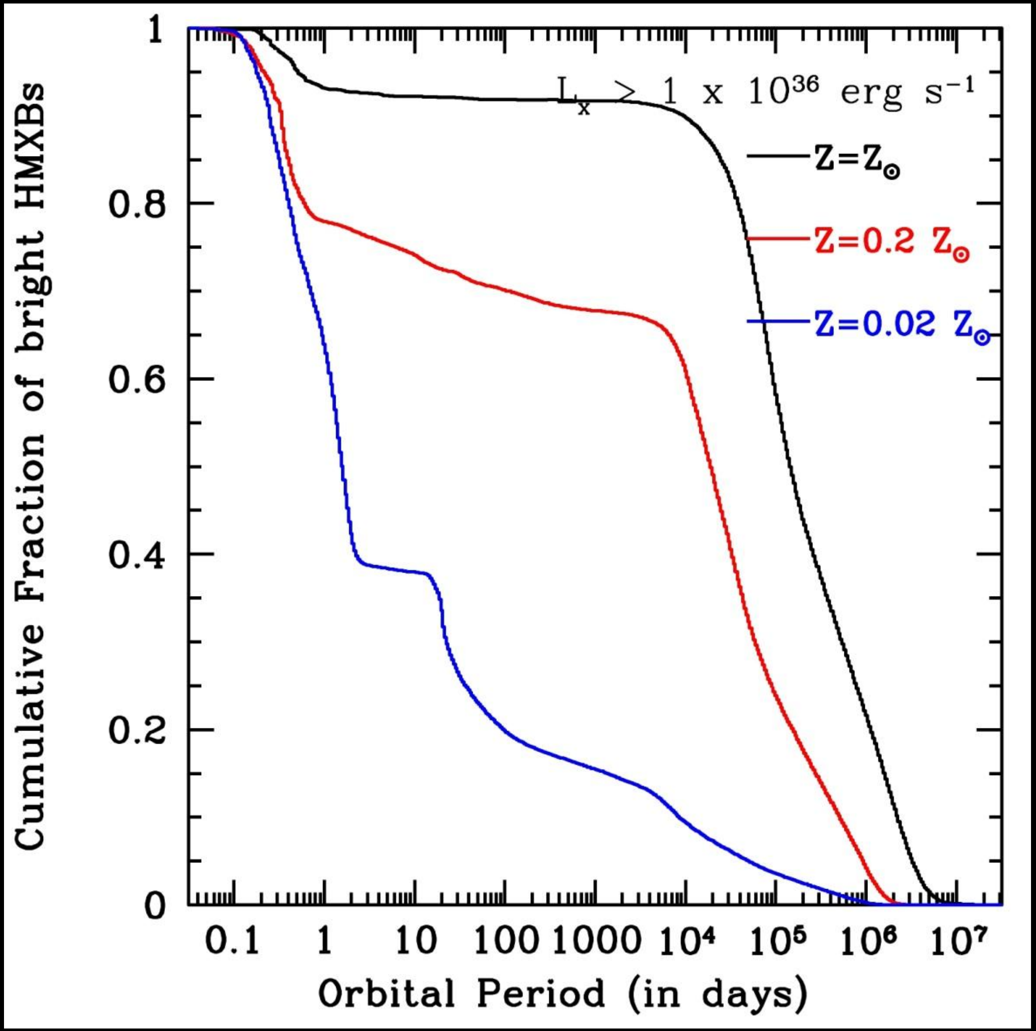
The Young HMXB Population

- Low metallicity HMXBs are preferred by a factor of 3.5 at the low luminosity cutoff and 5.0 at the ULX cutoff
- HMXB number peaks earlier at high metallicity, and decays much faster

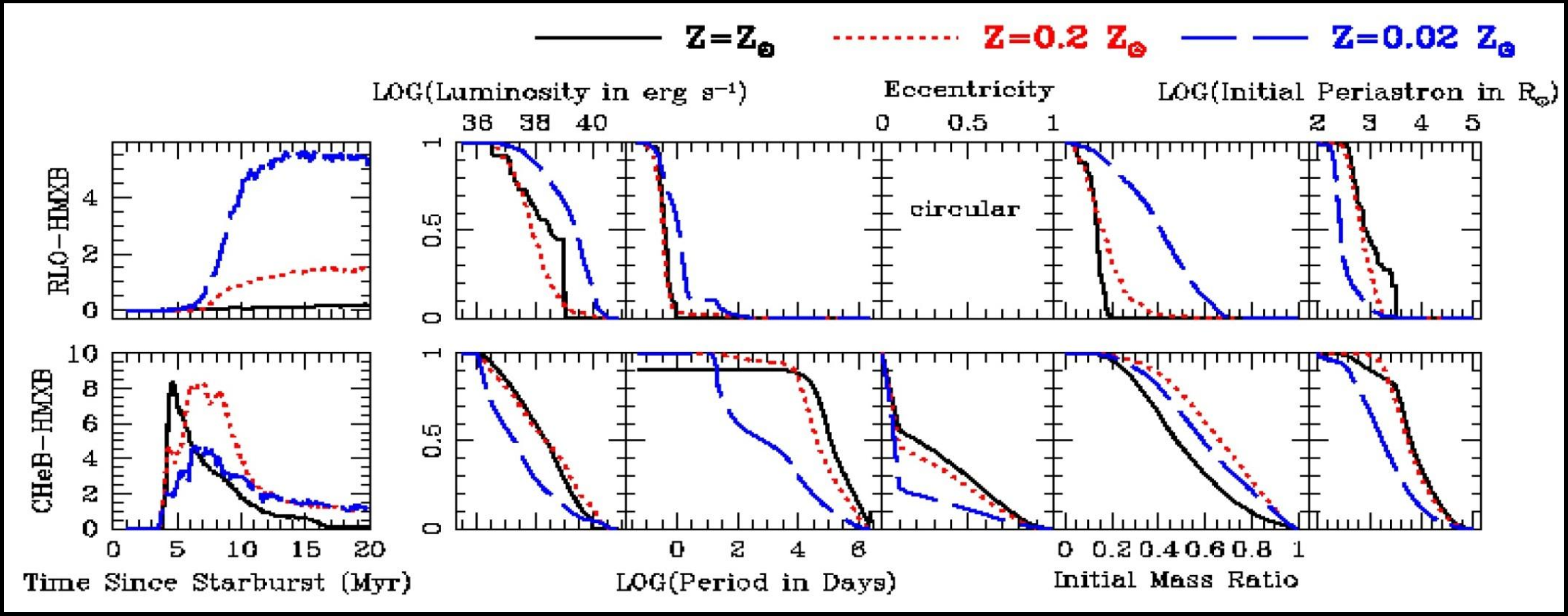


The Smoking Gun

- Orbital period data clearly shows two separate classes of HMXBs
- The relative number of systems moving through each pathway is strongly metallicity dependent

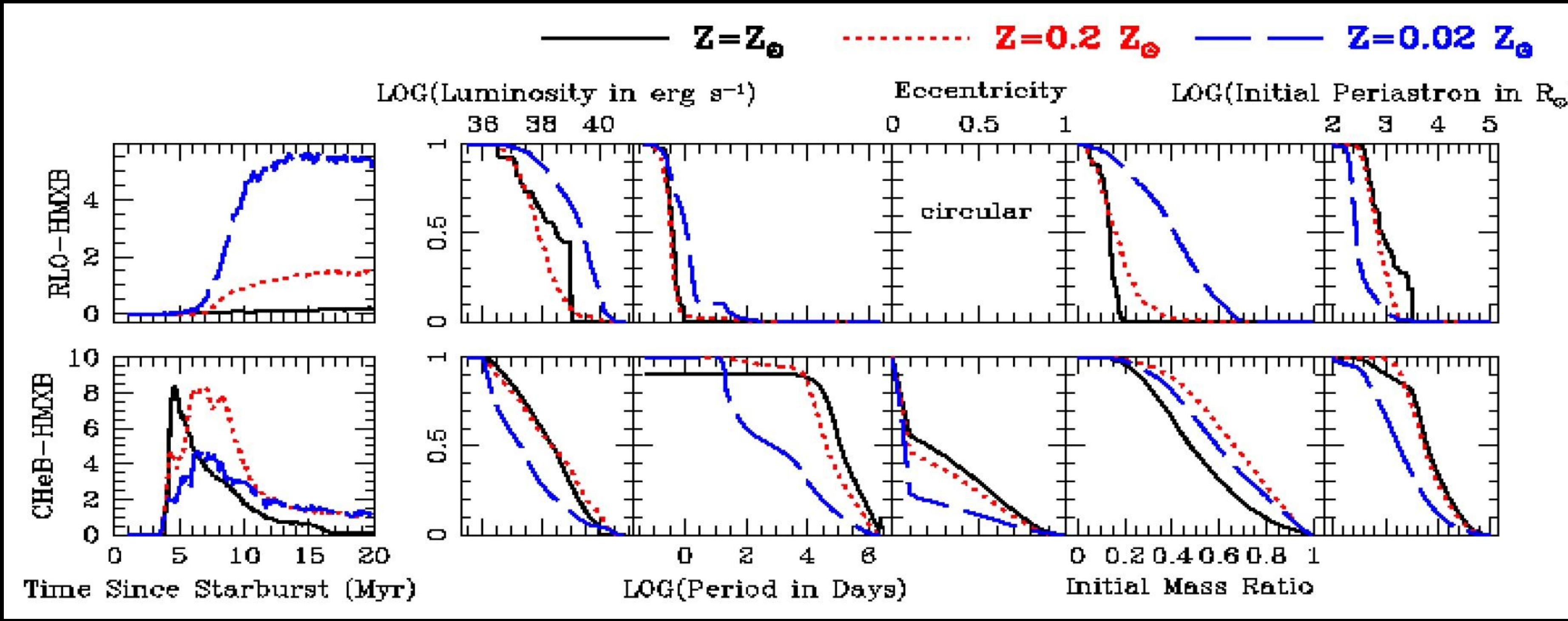


HMXB Pathways



We divide the HMXB population between two pathways, systems undergoing Roche Lobe overflow, and systems with supergiant donors

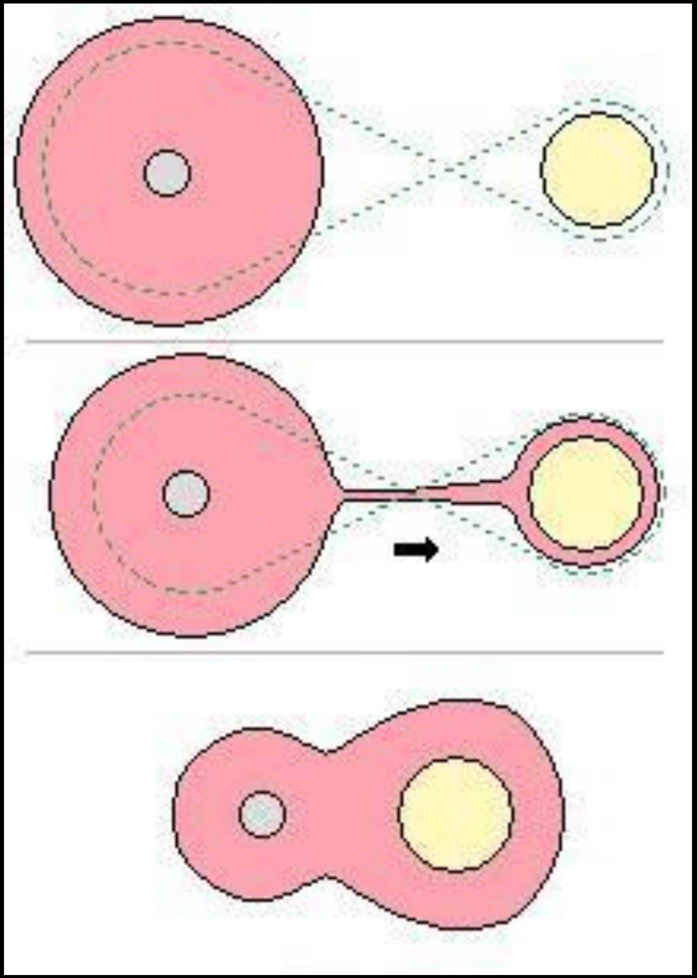
HMXB Pathways



Within each evolution pathway, the metallicity dependence is minimal, but metallicity greatly affects the number of systems moving through each pathway

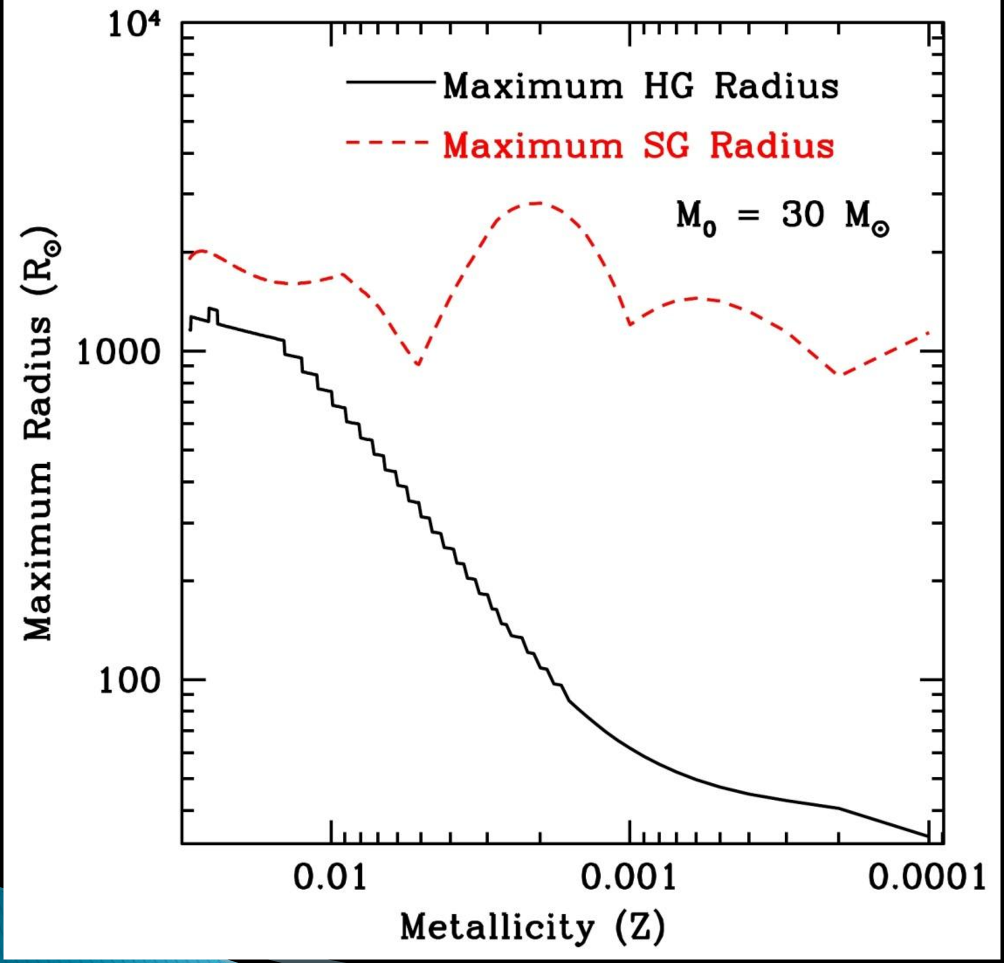
The Roche Lobe Overflow Pathway

- Roche Lobe overflow HMXBs require common envelope phases to achieve tight binary orbits



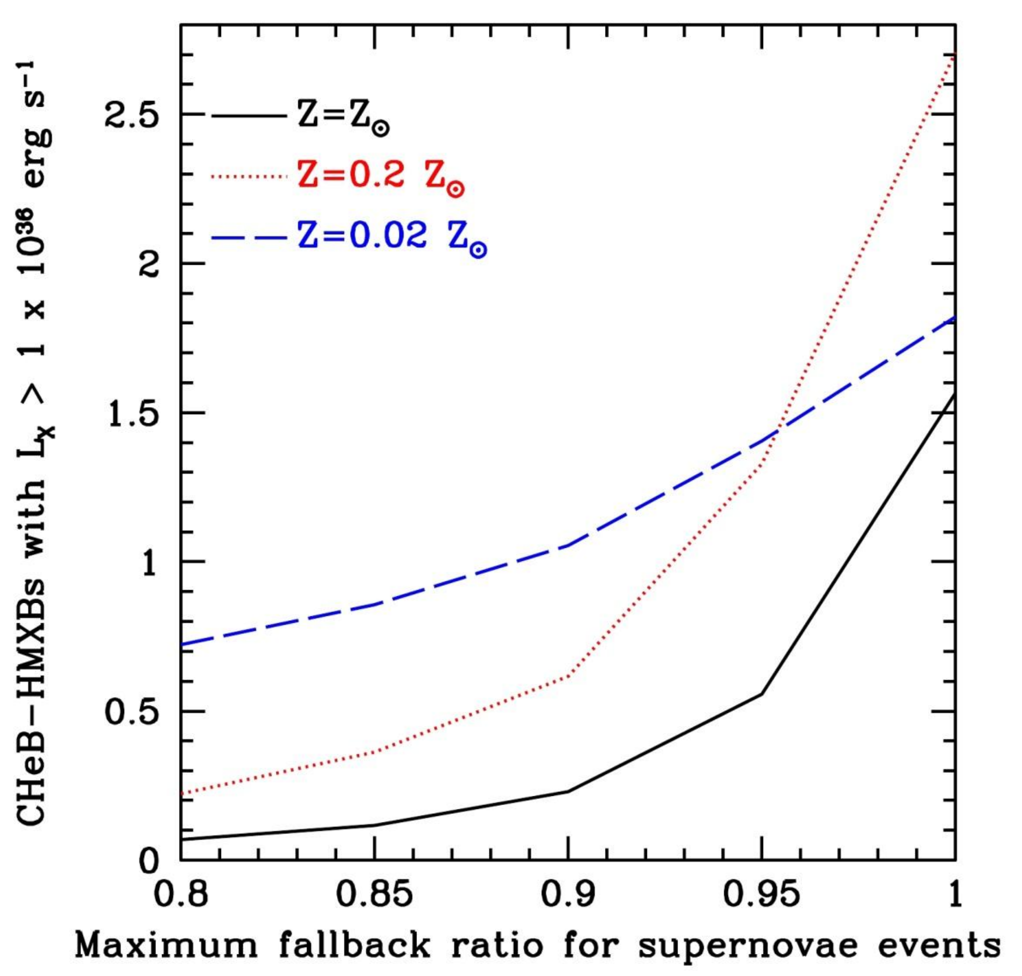
http://en.wikipedia.org/wiki/File:Common_envelope_diagram.jpg

The Roche Lobe Overflow Pathway



Roche Lobe overflow HMXBs require common envelope phases, which are preferentially formed at low metallicity

The (super)Giant Pathway



- The progenitors of supergiant HMXBs require large orbital separations to allow the donor to evolve

- This makes the systems highly susceptible to natal kicks

HMXB: Conclusions

1.) We can produce a robust population of bright and Ultra-Luminous HMXBs at all metallicity

2.) HMXB formation is prefered at low metallicities, matching observations

3.) The overabundance of low metallicity HMXBs is due to the details of their formation pathways, rather than the final BH mass

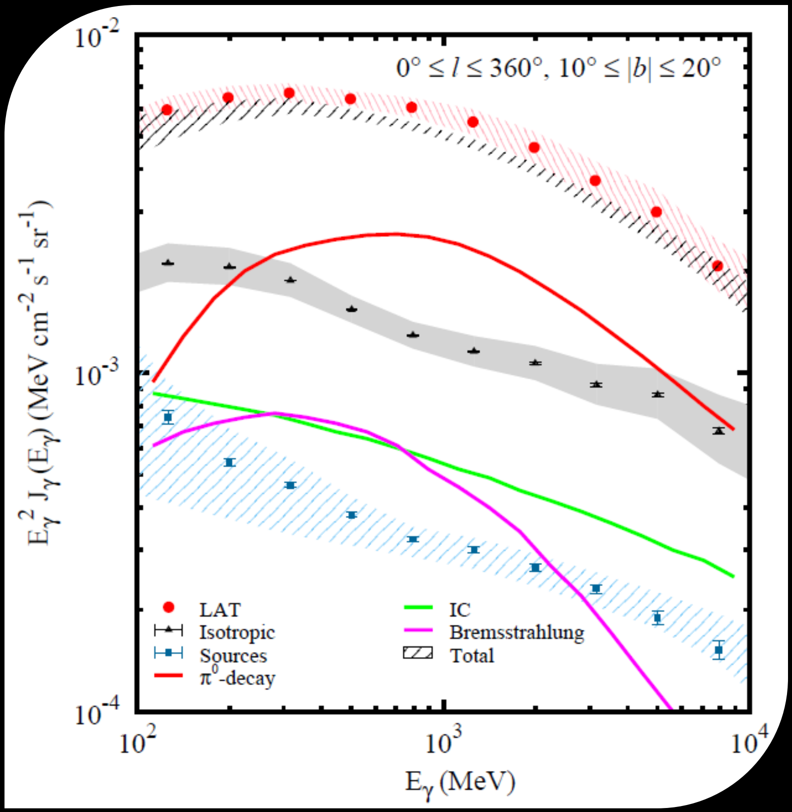
Linden, Kalogera, Sepinsky, Prestwich, Zezas, Gallagher, 2010 (Submitted to ApJ, arXiv: 1005.1639)

HMXB: Future Work

1.) Compare our theoretical models to observations of young extremely metal poor starbursts (Chandra Grant GO-12018, PI - Prestwich)

2.) Create detailed models which take into account effects such as non-spherical stellar winds and eccentric mass transfer

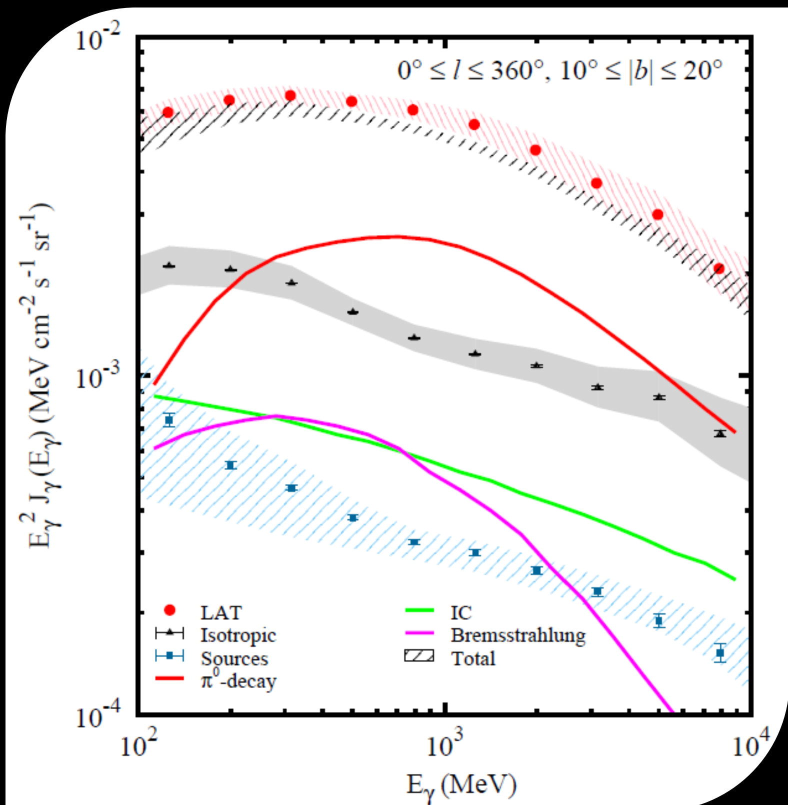
Observations of Diffuse Emission



T. Porter, 2009 (0907.0294)

- Many sources:
  - Extragalactic
  - π^0 decay
  - Inverse Compton Scattering
  - Bremsstrahlung Emission
  - Unresolved Point Sources

Is There Any Room Left for DM?

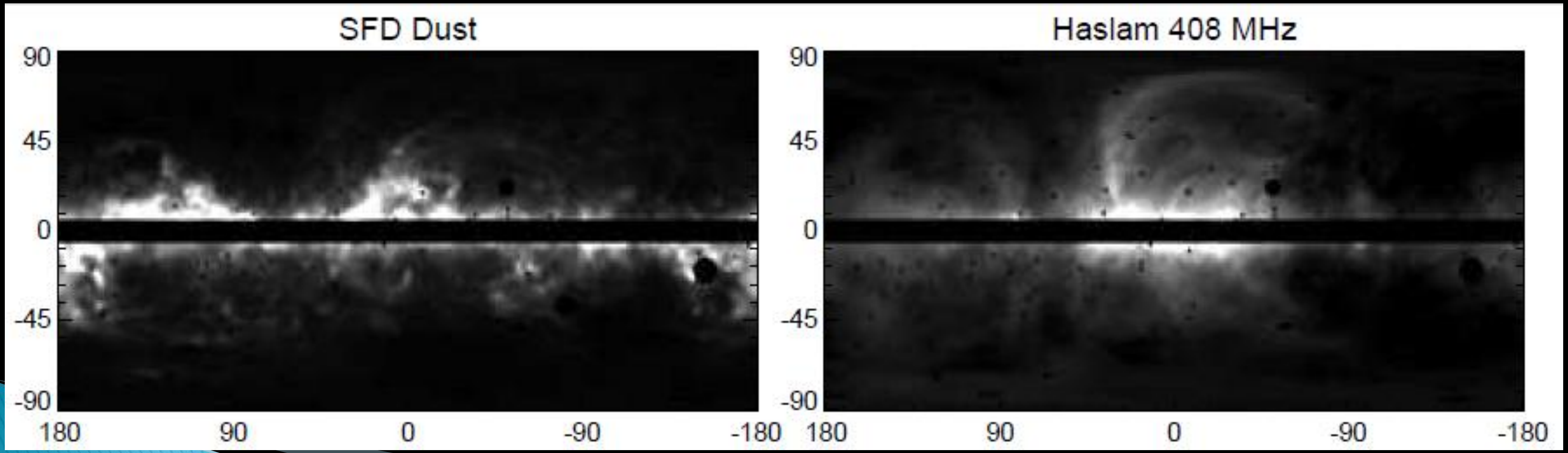


T. Porter, 2009 (0907.0294)

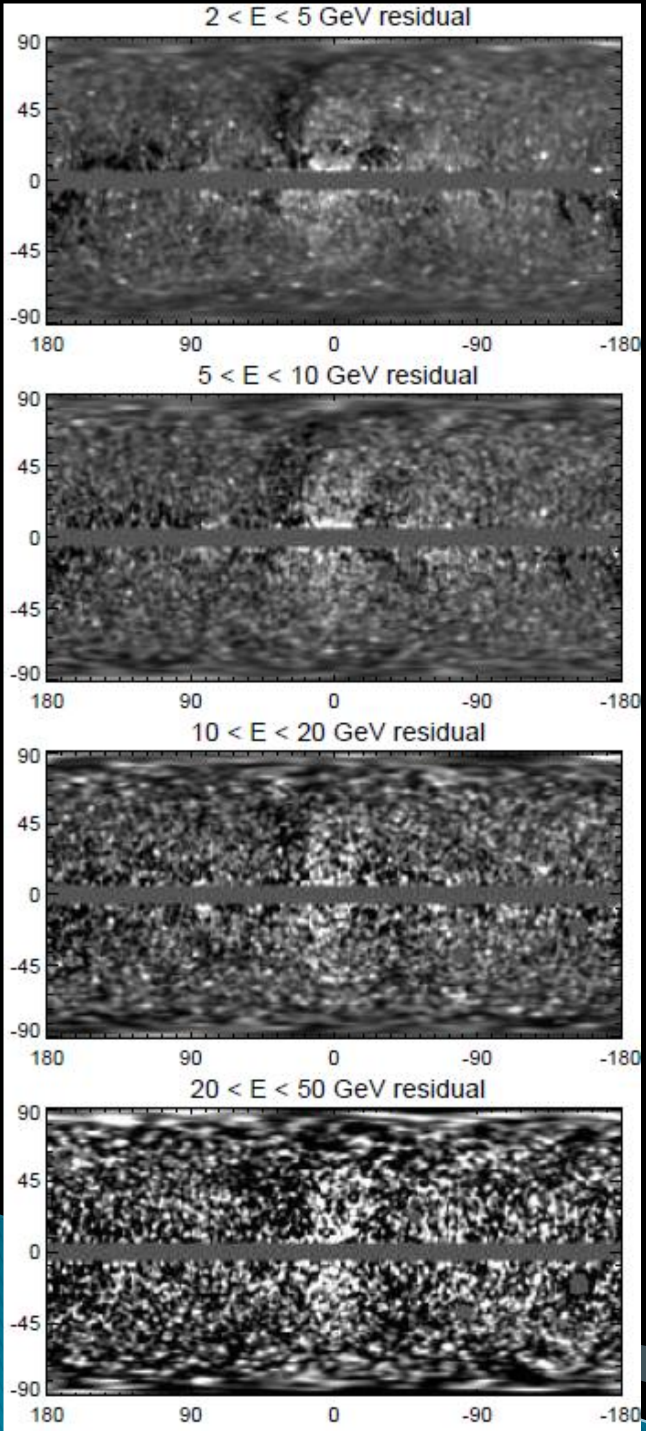
- How large are the astrophysical uncertainties in each of these background signals?
- Playing a very different game than direct dark matter detection (e.g. CDMS)
  - Should see millions of events
  - But no background rejection

Modeling Astrophysical Sources

- Dobler et al. (2009) created models for the morphology of these astrophysical components
  - Point sources subtracted from 3-month Fermi catalog
  - SFD Dust Map for π^0 decay
  - Haslam 408 Mhz map for ICS
  - Residual Map mean subtracted to eliminate isotropic



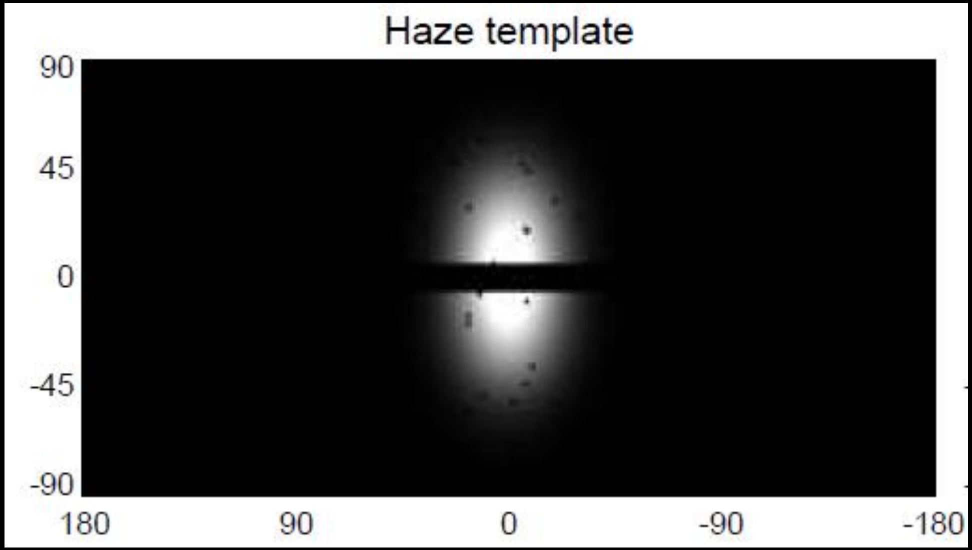
Dobler et al (2009) (0910.4583)



An Enticing Residual!

- Dobler et al. finds a significant residual when these maps are applied
- Residual has a pronounced morphology above and below the galactic center

Modeling this residual



- To map this residual, Dobler et al add an ad hoc template

This template is a bivariate gaussian with latitudinal scale height $\sigma_b = 25^o$, and a longitudinal scale height of $\sigma_l = 15^o$

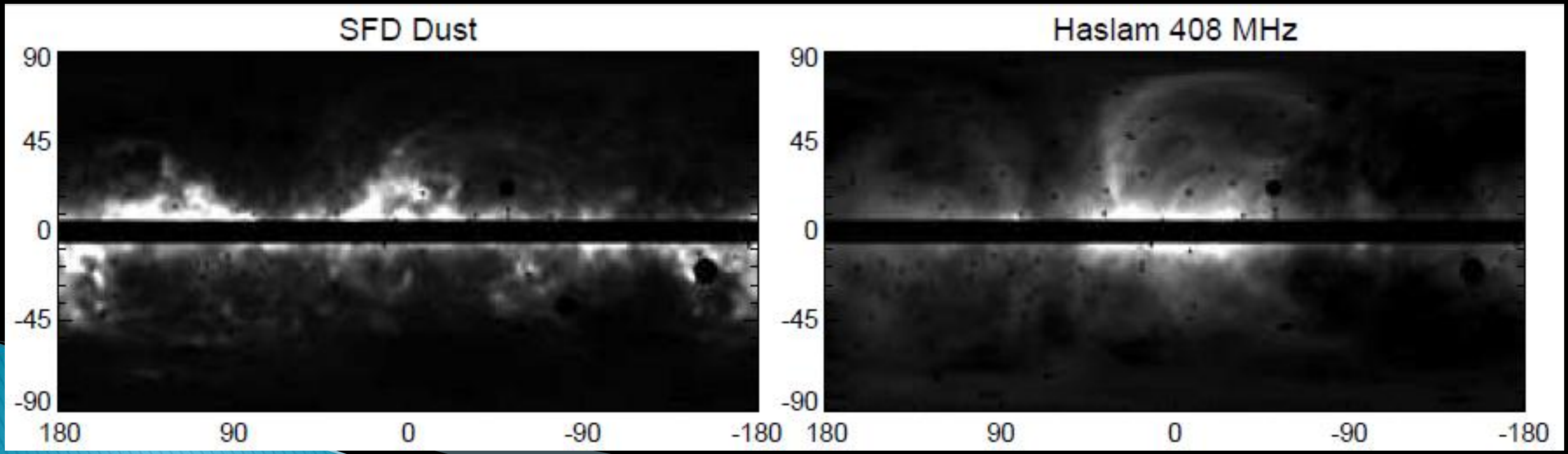
But do we trust these templates?

- SFD Dust Map for π^0 decay
  - But the cosmic ray distribution is not isotropic!

$$\Phi_{\pi 0} = \text{BEAM x TARGET}$$

Cosmic rays

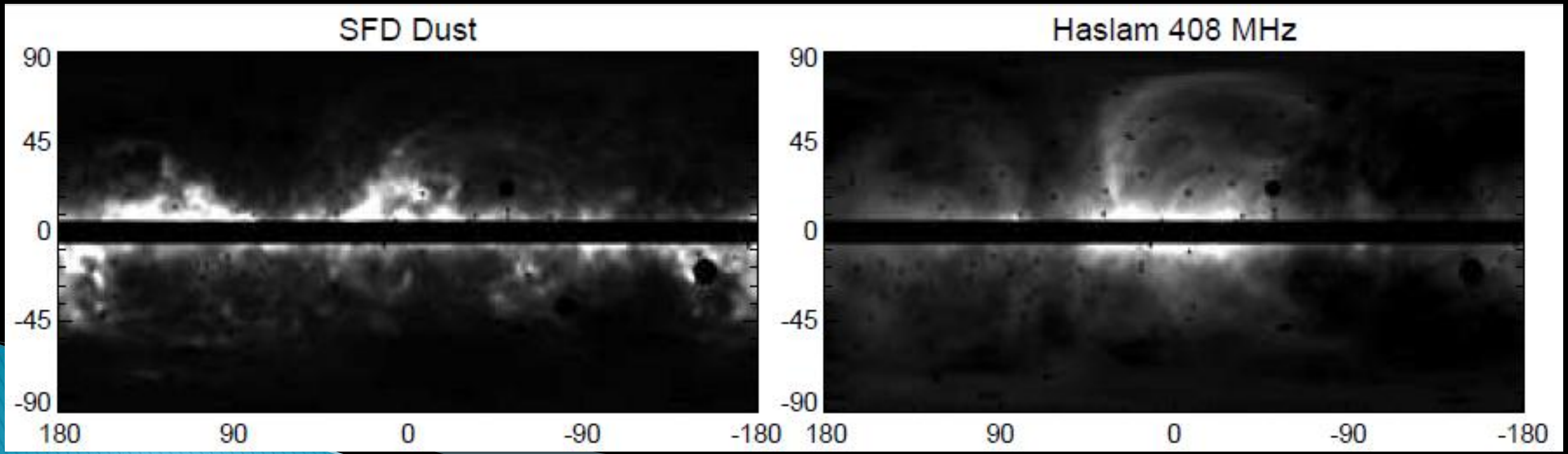
Galactic Gas



But do we trust these templates?

- Haslam 408 Mhz skymap for inverse Compton scattering
  - The morphology of the interstellar radiation field is not the same as the morphology of the galactic magnetic fields.

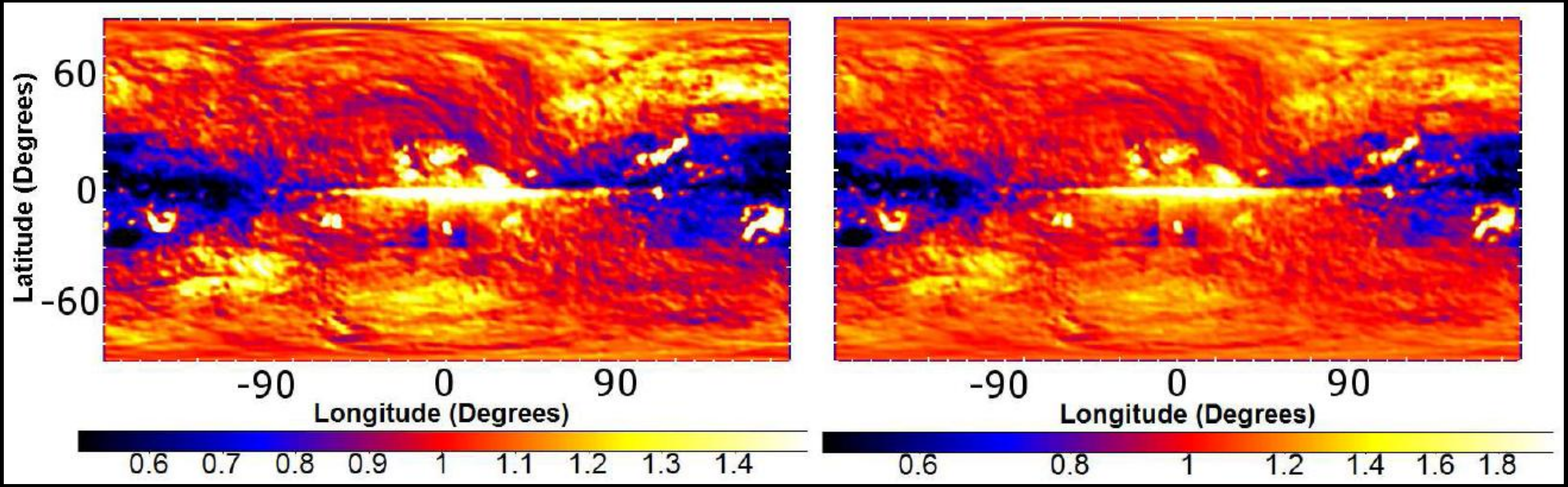
$$\frac{\text{ISRF}}{B^2} \neq 1$$



Our Setup

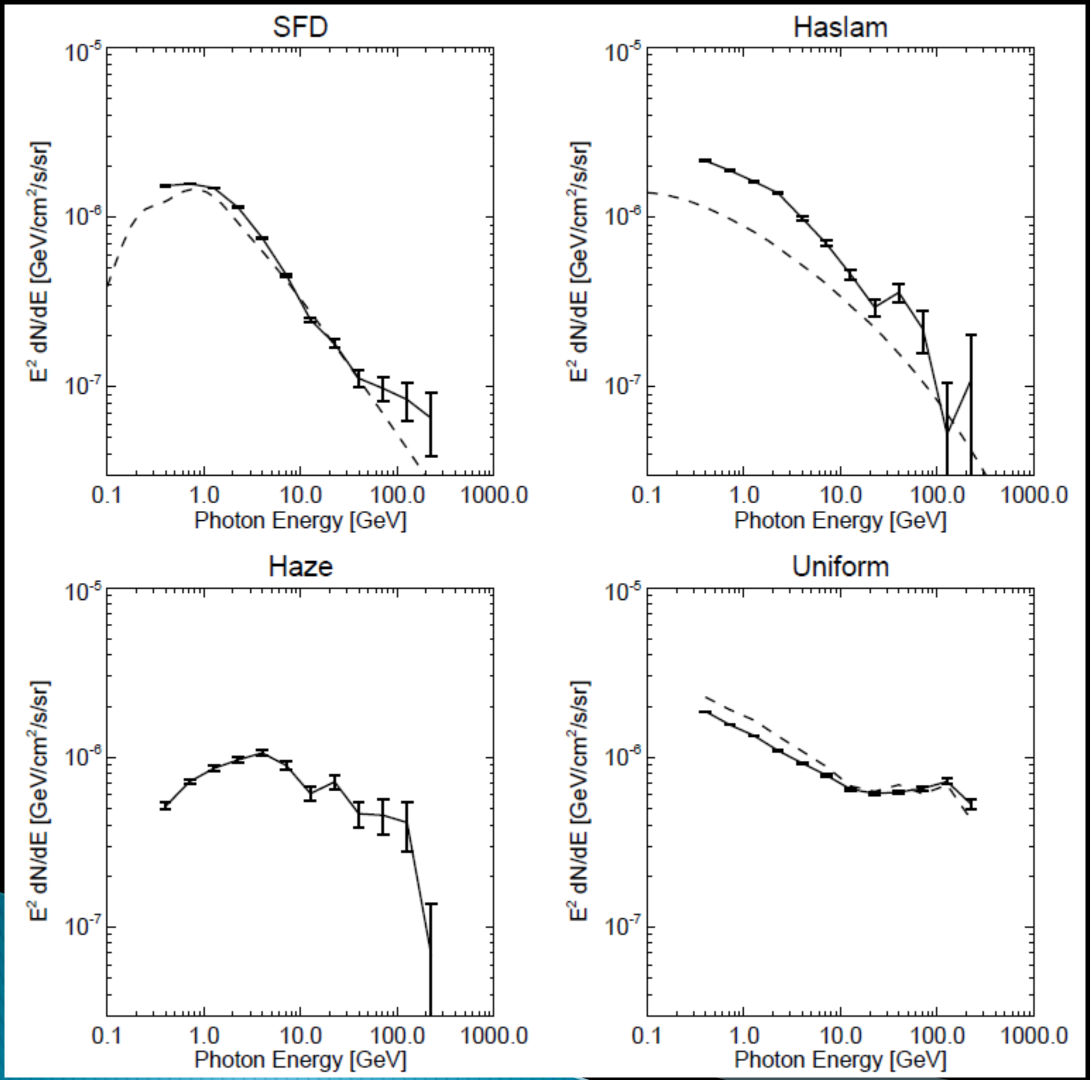
- We use GALPROP models to test the morphological consistency of:
  - 1.) The π^0 decay morphology and the input gas map
  - 2.) The ICS decay morphology and the 408 Mhz synchrotron morphology

π^0 Decay divided by Gas Map



- The resulting skymap has a haze-like morphology that can be fit with a Gaussian 17% as strong as the estimated π^0 skymap

Important at low energies



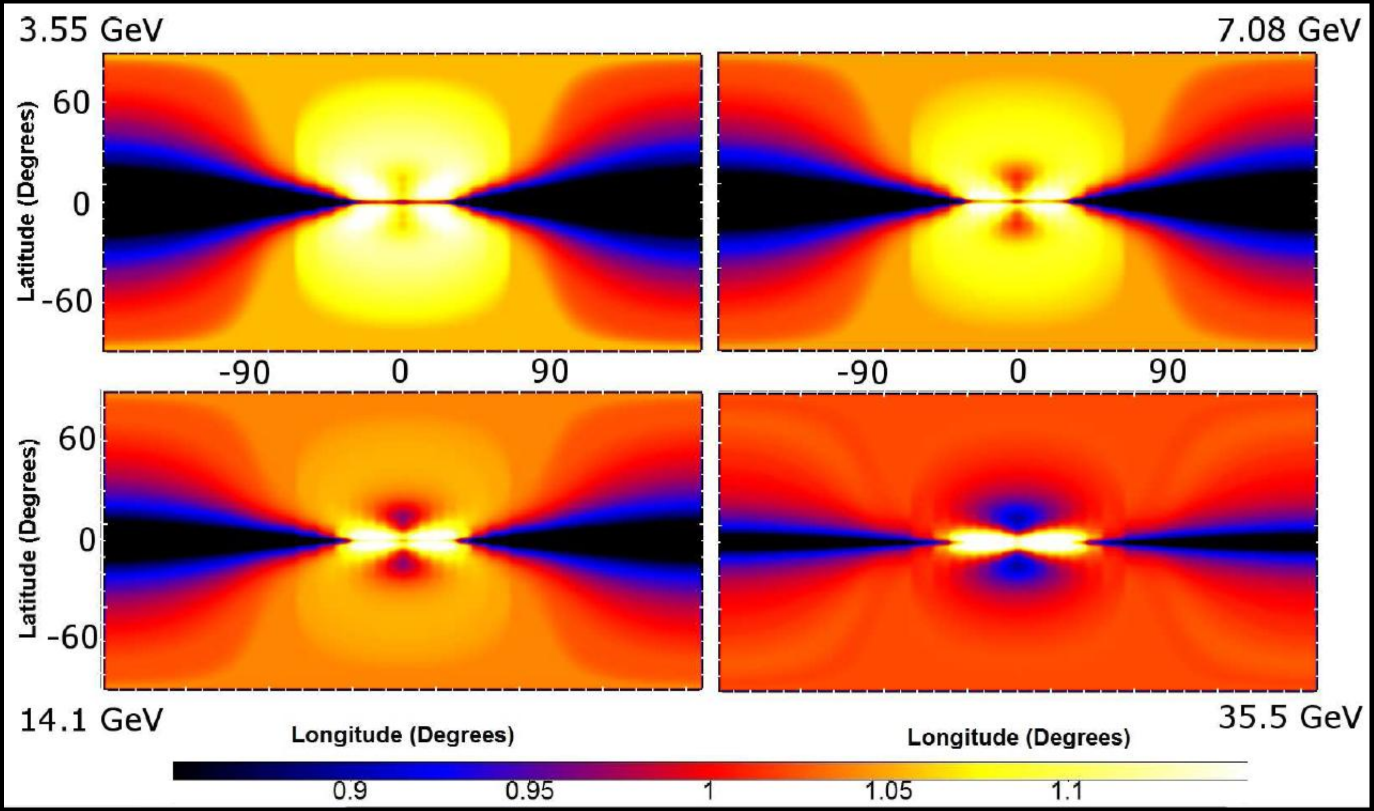
- The π^0 decay morphology is dominant up to several GeV
- A 17% Gaussian residual can explain the majority of the haze around 1 GeV

ICS divided by Synchrotron

- The ratio of the ICS map to the synchrotron map also show a haze morphology

Highly energy dependent

Low intensity 16% to -4%



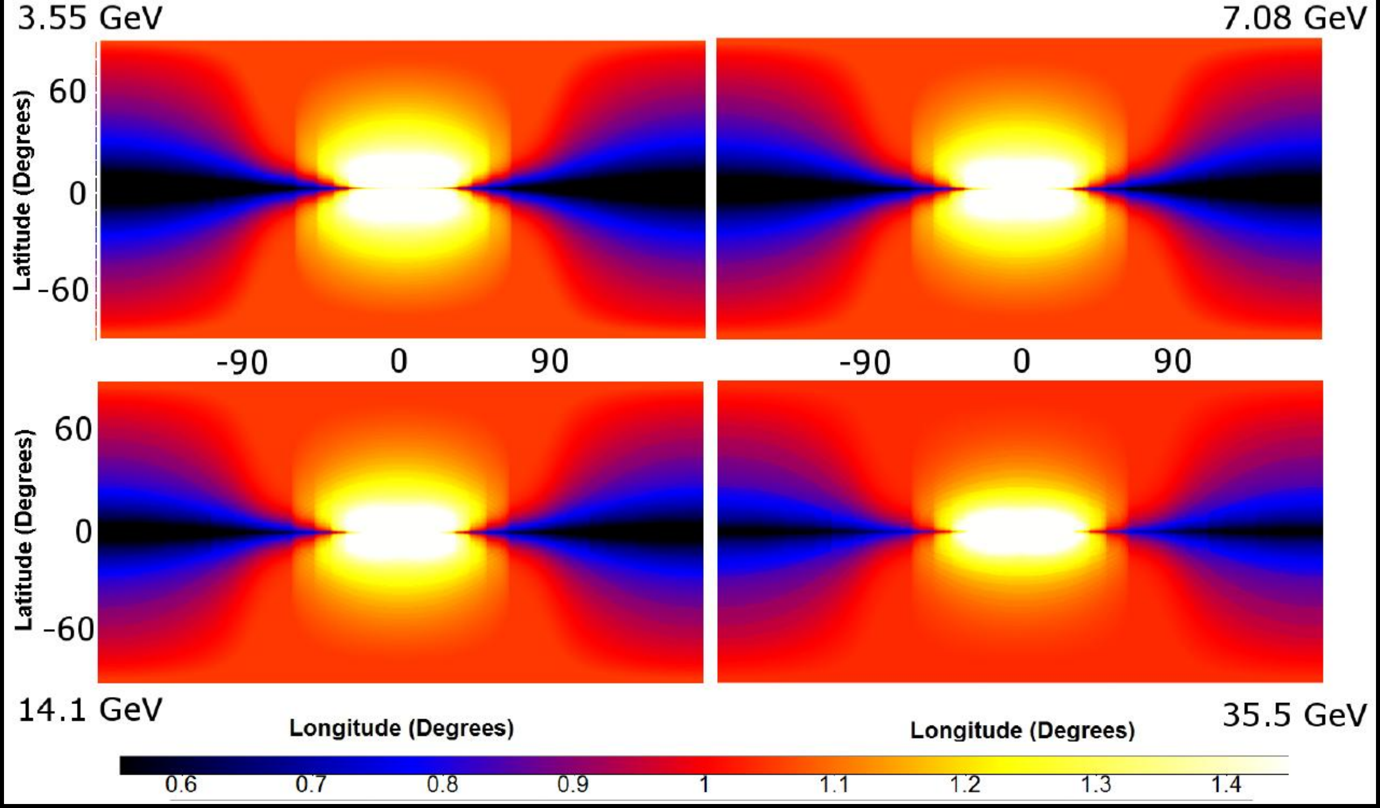
$B = 11.6\ \mu G\ e^{-r/10\ kpc\ -z/2kpc}$

ICS / Sync is very uncertain

- By slightly altering the magnetic field morphology, we can create larger deviations

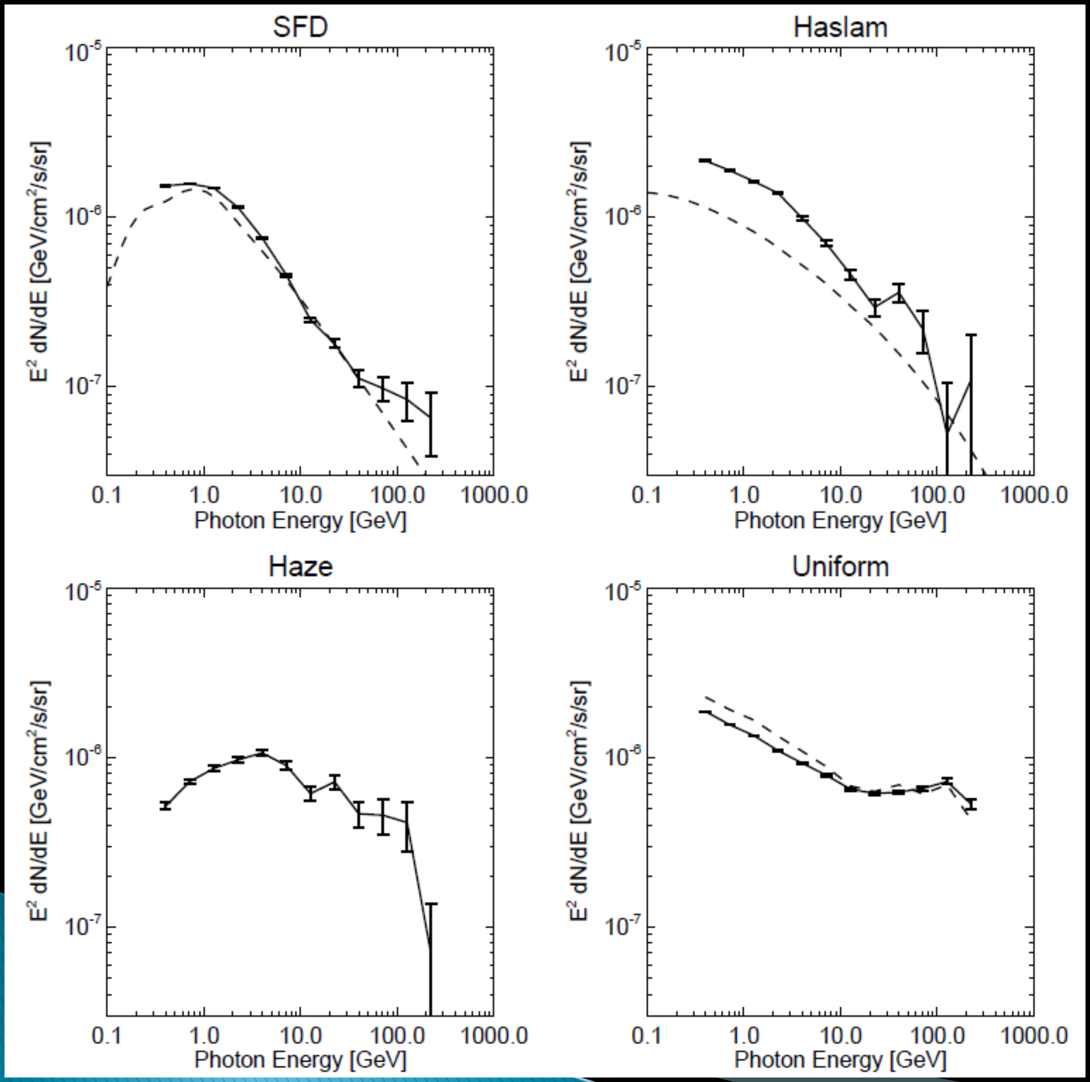
Same energy dependence as before

Large Gaussian errors (54% to 40%)



$B = 11.6\ \mu G\ e^{-r/20\ kpc\ -z/2kpc}$

Also Important at low energies



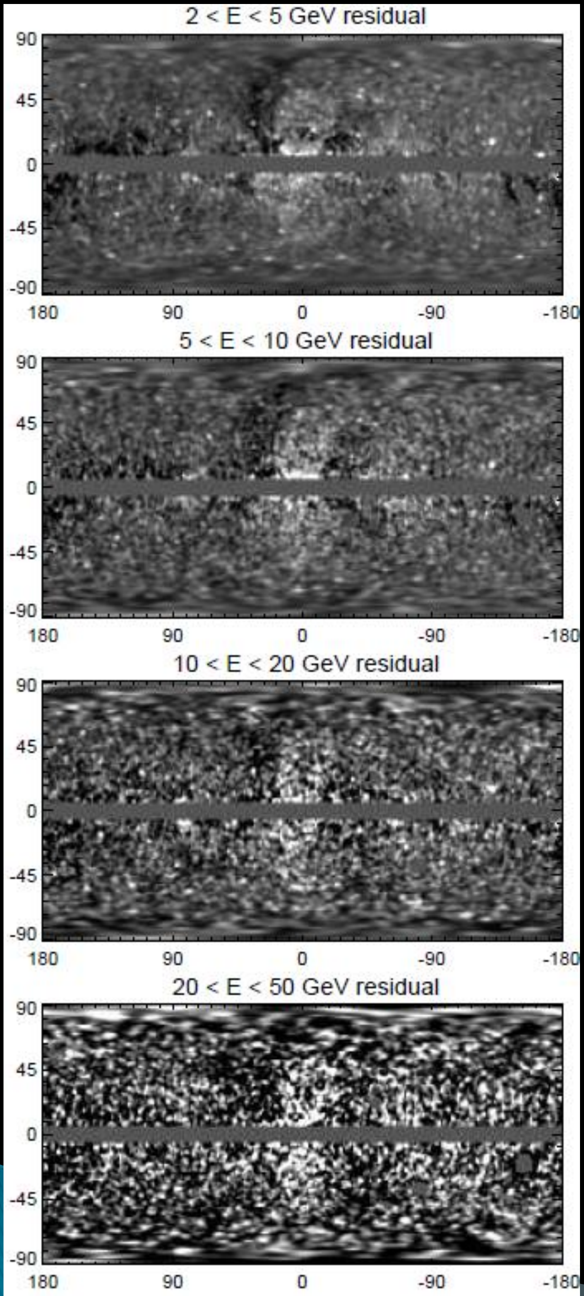
- Expected ICS signal is a significant fraction of the haze residual below 10 GeV
- This appears to leave a discrepancy at high energies, but eliminates it below ~10 GeV

First Conclusions

- The current analysis of the Fermi-Haze is insufficient to determine either the intensity or the spectrum of any Fermi residual

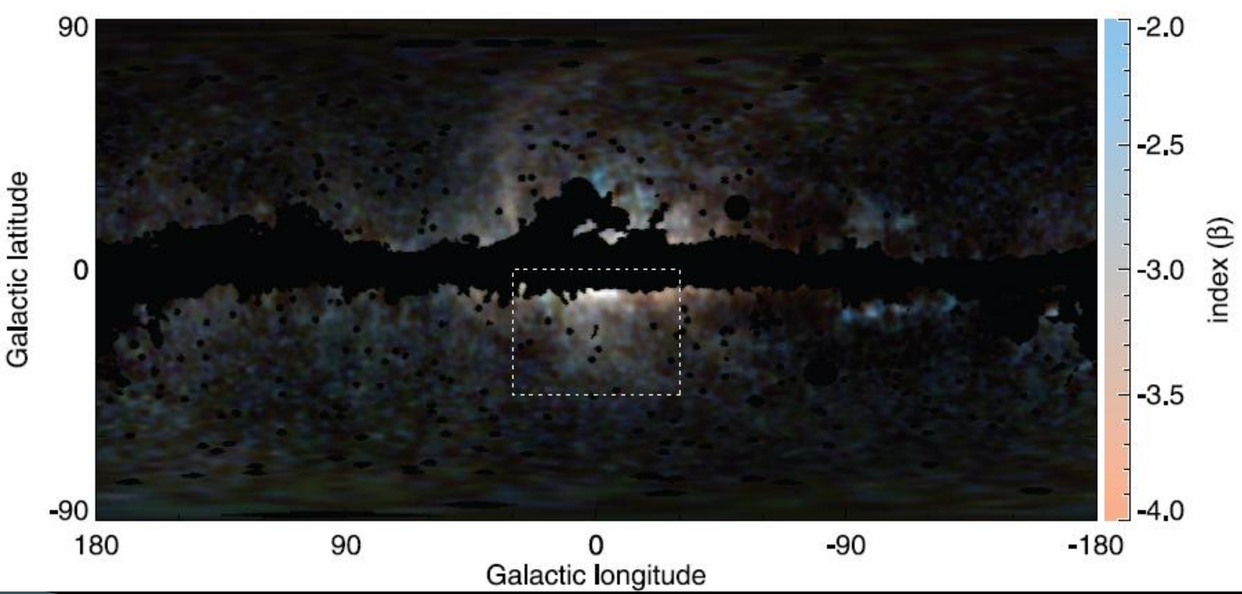
- Early measurements suggest that the Fermi haze at low energies (<10 GeV) could be entirely explained with theoretically correct templates for π^0 and astrophysical ICS emission.

Linden and Profumo, 2010 (ApJL 714:228)



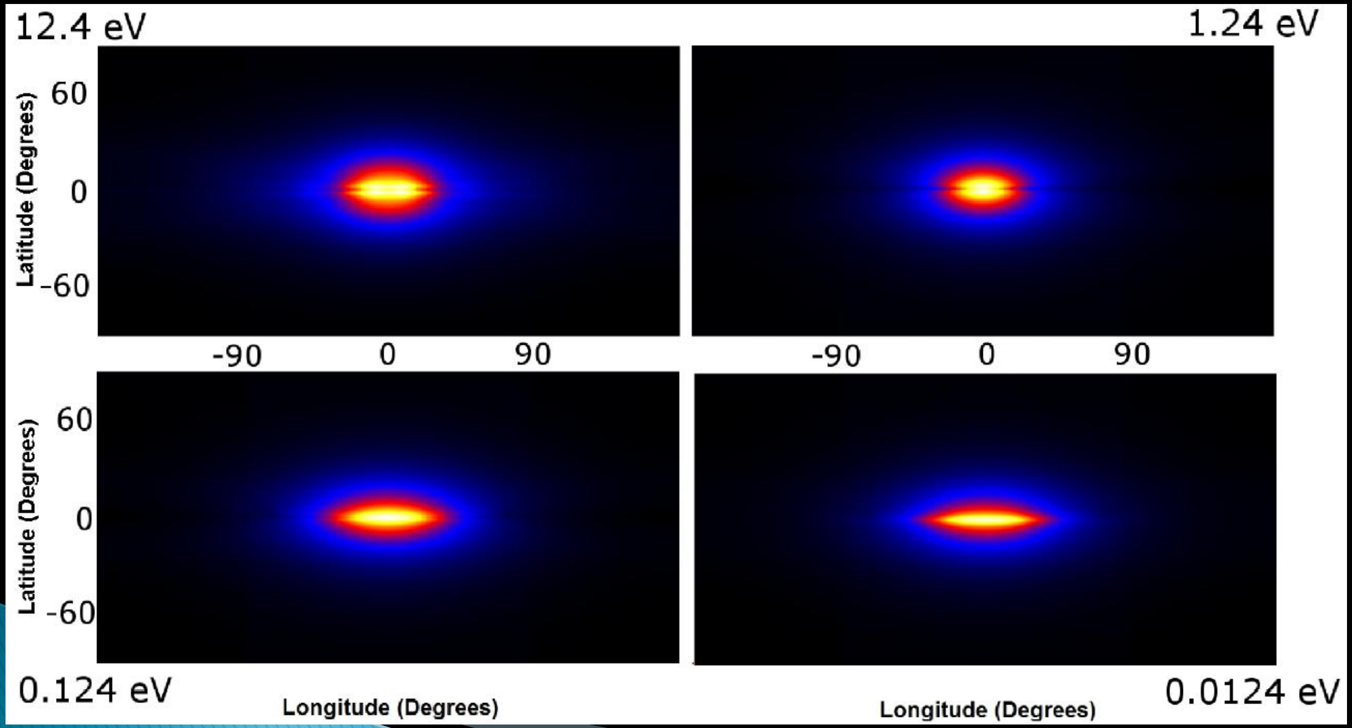
Understanding Residuals

- Dobler et al note a correlation between the Fermi haze and the WMAP haze
- Find that this suggests a new primary electron source near the galactic center



Understanding Residuals

But it is difficult to model the Fermi haze with only a new lepton input class, as the interstellar radiation function falls off too quickly.

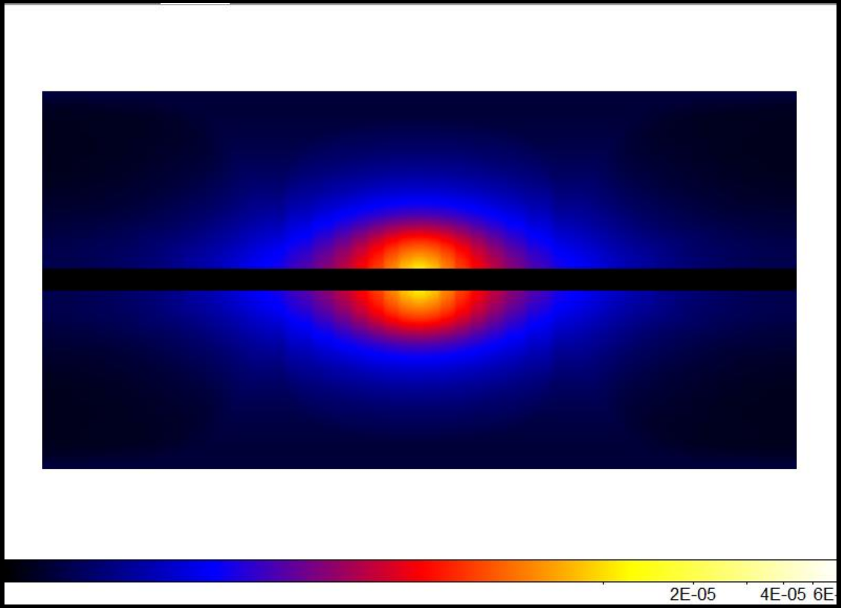


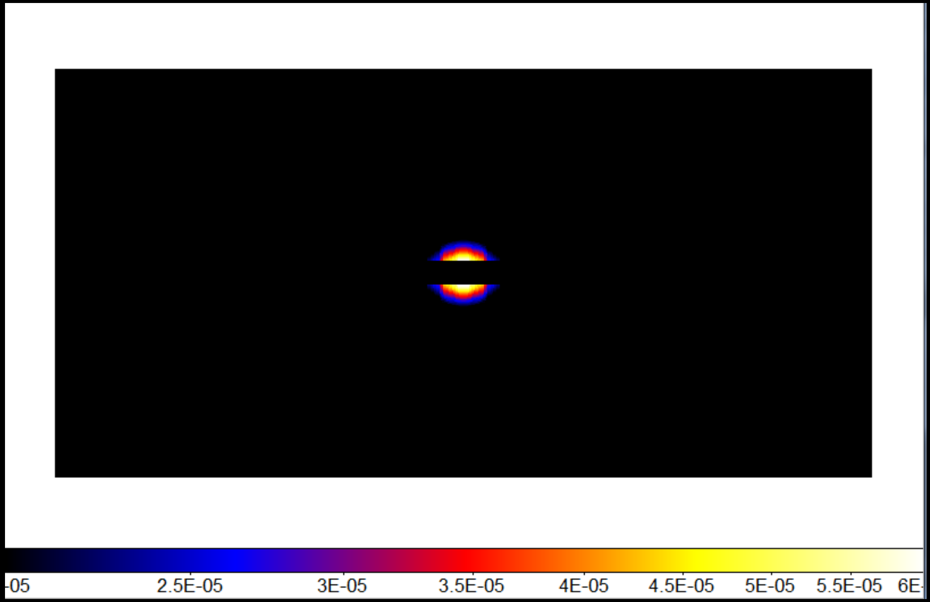
Between 10^o to 30^o latitude, the ISRF dims by between 63-72%

The longitudinal to latitudinal extent moves from 5-4 to 9-1 at low energies

DM Interpretation?

Simulated Dark matter models produce a haze that decays much too quickly at high latitudes to match the observed haze.





1500 GeV -> $\mu^+\mu^-$
Snapshot at 8 GeV

Future Studies

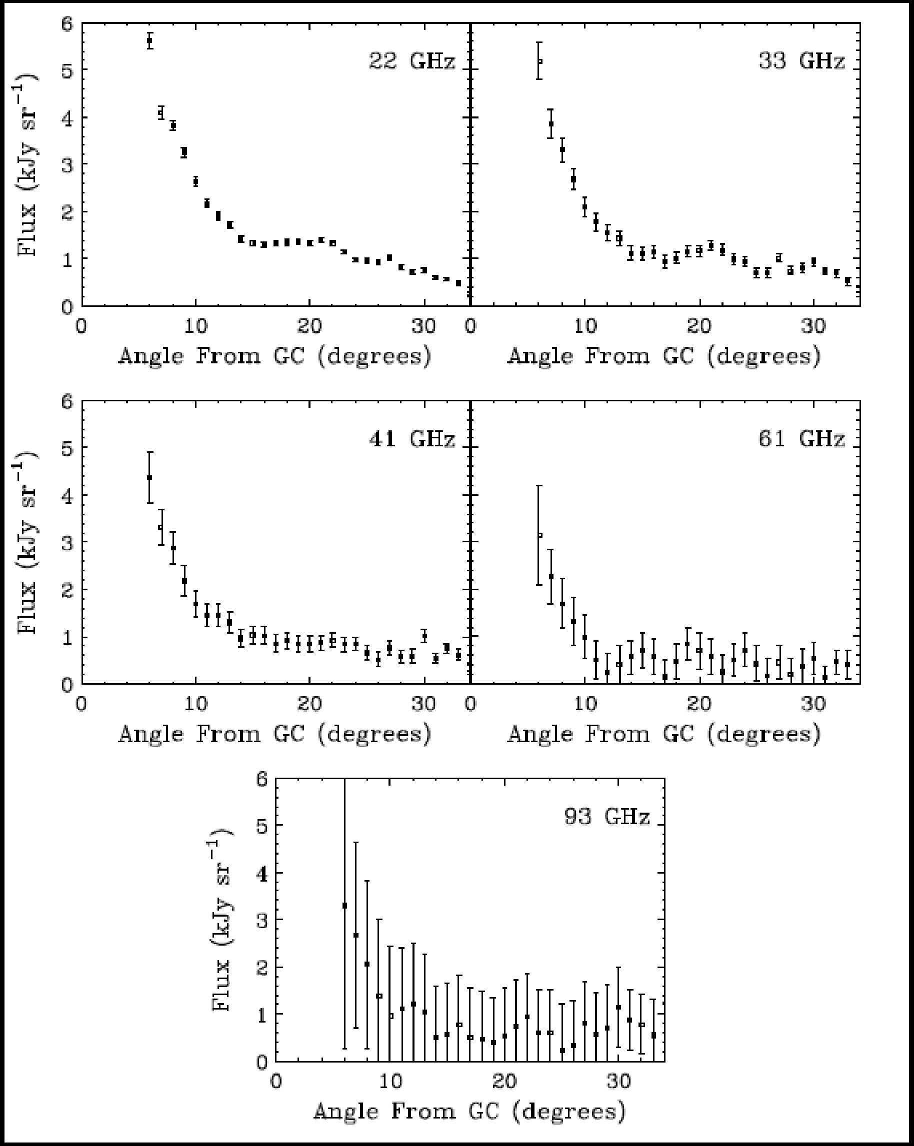
- There does appear to be excess high latitude emission

- Possible Sources:
  - Errors in cosmic ray propagation models
  - New source classes
  - New ISRF/gas densities

- Ways to differentiate
  - Multiwavelength studies
  - Anisotropies

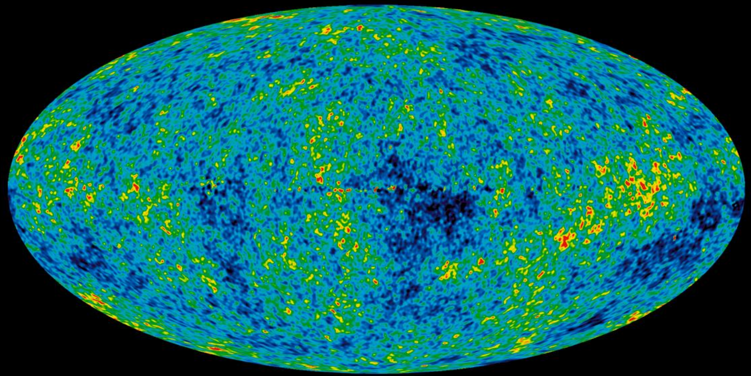
The WMAP Haze

- Finkbeiner (2004) pointed out an unexplained residual in the WMAP dataset
- The existence of this residual is controversial, and is not detected by the WMAP team (Gold et al. 2010)



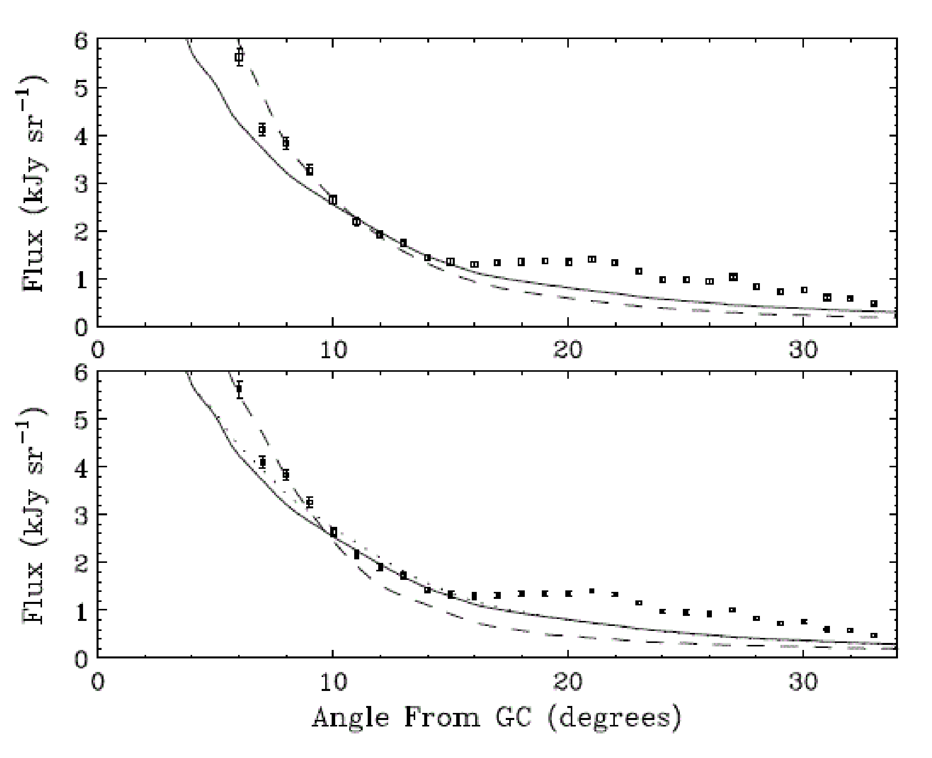
Hooper et al. (2007) (0705.3655)

The WMAP Haze



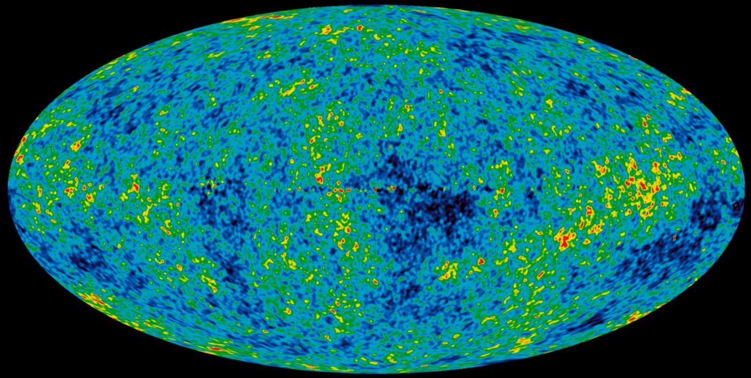
- Hooper et al. (2007) explained the WMAP haze as the result of dark matter annihilation

- Also explained by pulsars (Kaplinghat et al. 2009)



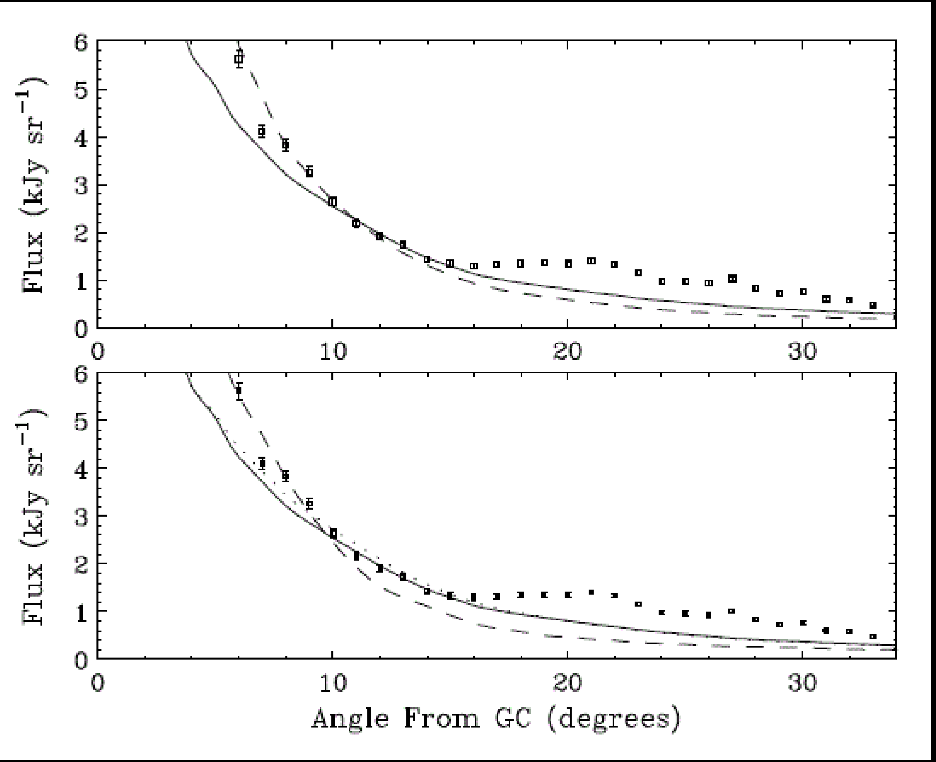
Hooper et al. (2007) (0705.3655)

The WMAP Haze



- The dark matter matches to this haze depended on non-standard diffusion parameters

- M_X = 100 GeV
- B = 10 μG
- XX → e^+e^-
- NFW Profile
- $D_0 = 1.58 \times 10^{28}\ cm^2 s^{-1}$ (4 GeV)



Hooper et al. (2007) (0705.3655)

Research Goals

- Evaluate a select range of well motivated WIMP theories

- Test the DM interpretation of the WMAP haze using cosmic ray propagation models that are consistent with all current observations and data

Our modeling code

- Use DarkSUSY to calculate the primary e^+e^- spectrum for a range of well motivated DM models
- Use Galprop to determine the synchrotron emission and nuclear abundances in each propagation model
- Isolate the simulated DM haze by subtracting the synchrotron component from the corresponding simulation with DM disabled.

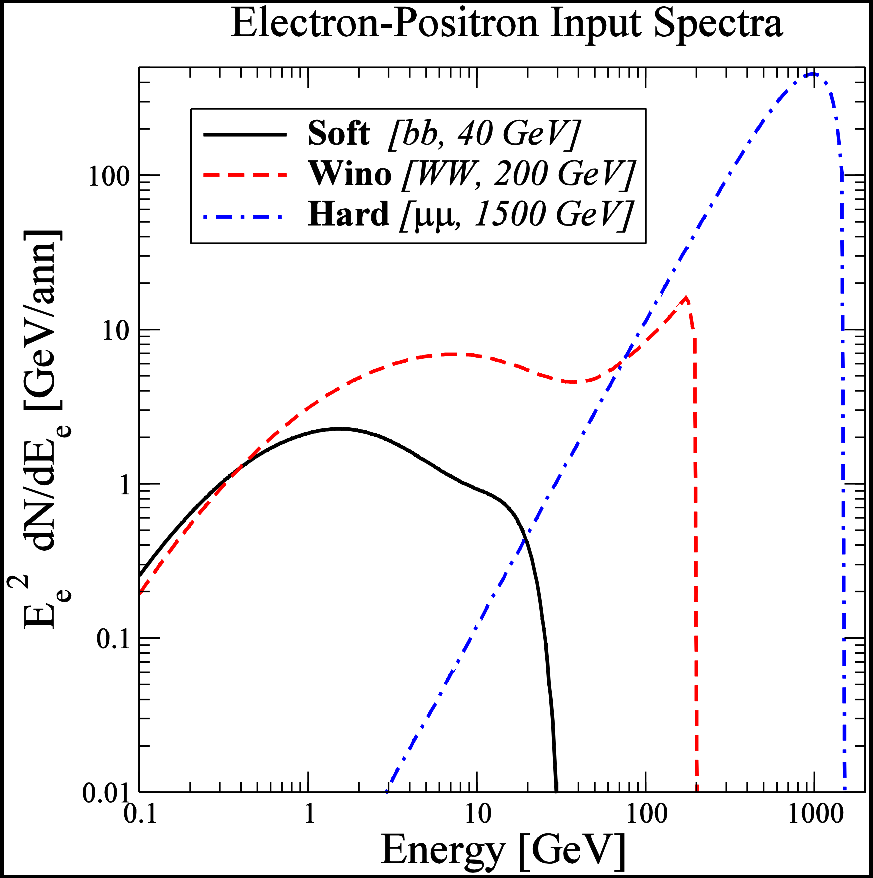
Dark Matter Models

- We test three DM annihilation channels which span a range of motivated WIMP decay models

Soft (40 GeV XX → b b-bar)

Wino (200 GeV XX → W^+W^-)

Hard (1500 GeV XX → $\mu^+\mu^-$)

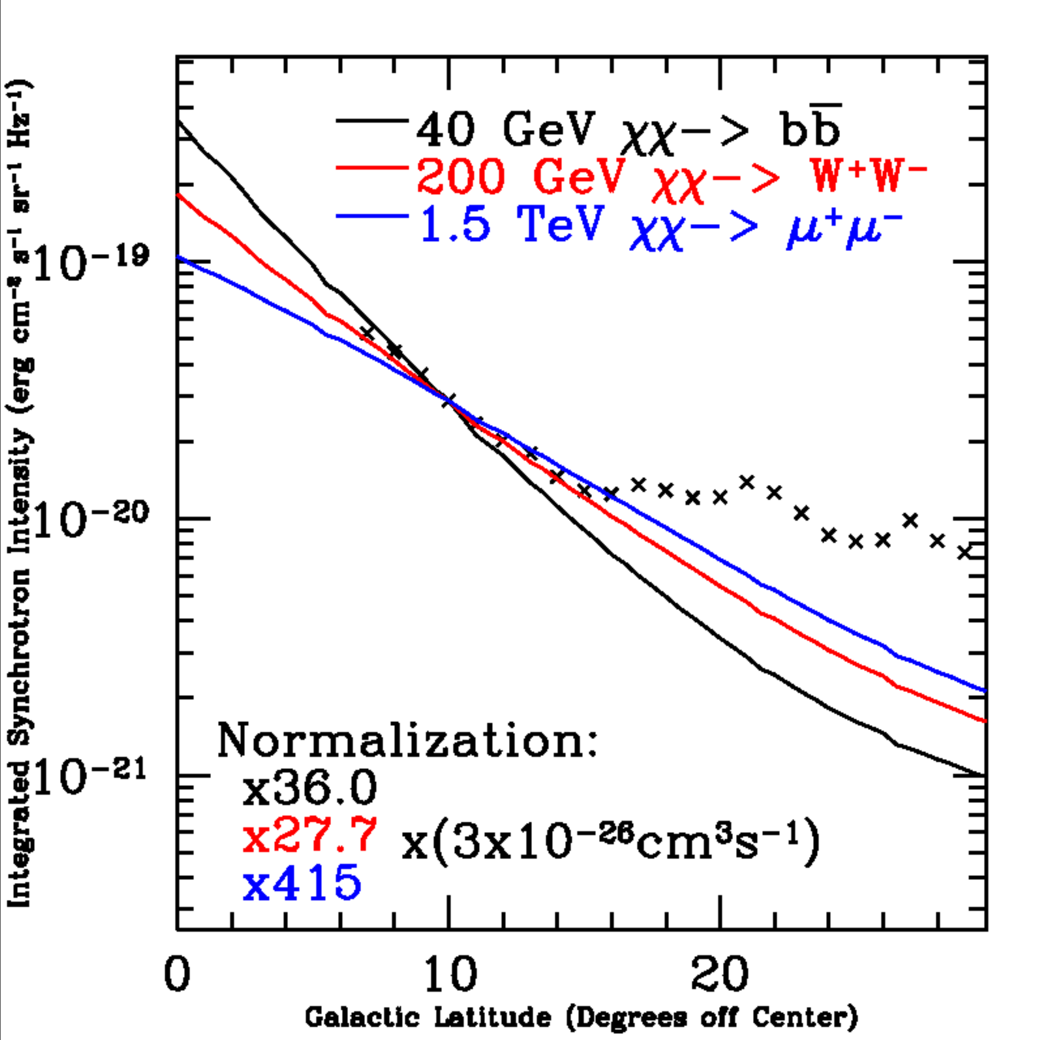


Galprop Models

- Employing the public version of Galprop, we use the following parameters in our default setup:
  - $D_0 = 5.0 \times 10^{28}$ cm^2 s^{-1}
  - Simulation Height = 4 kpc
  - $V_{alfven} = 25$ km s^{-1}
  - Convection = Disabled
  - $B = 11.6 \exp(-r / 10\text{kpc} - z / 2\text{kpc})$ μG

Default Model Predictions

- Our default model shows a morphology which falls off much faster as a function of latitude than the observed haze
- Similar underestimates as in Fermi Haze?
- The WMAP haze requires large boost factors



Role of Diffusion

- We test four diffusion parameters:
  - Diffusion Constant (D_0)
    - Ability of charged particles to move through galaxy
    - Can be thought of as the "thickness" of the soup the particles move through
  - Simulation height (z)
  - Alfvén Velocity (v_α)
  - Convection Velocity

Role of Diffusion

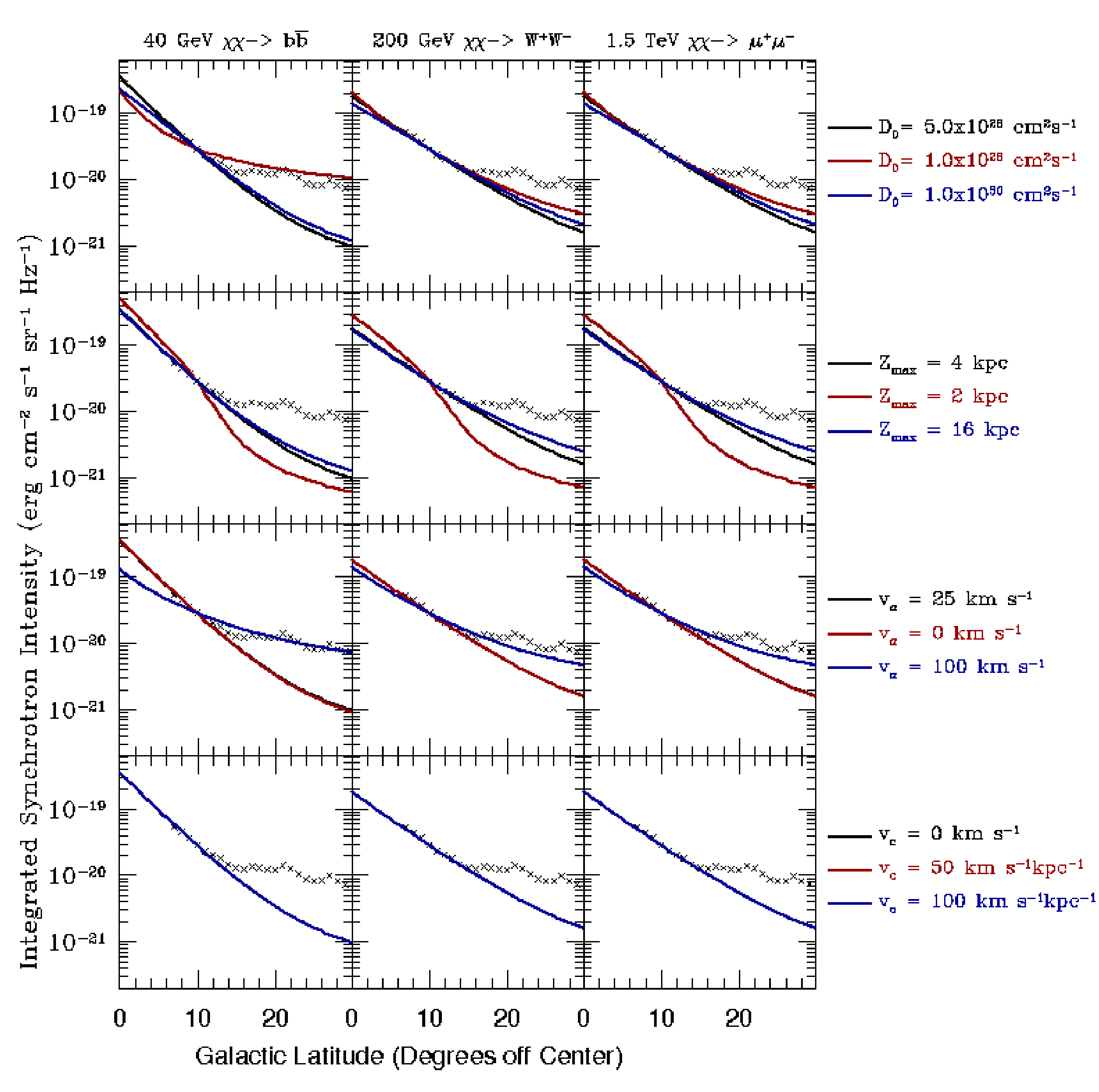
- We test four diffusion parameters:
  - Diffusion Constant (D_0)
  - Simulation height (z)
    - Height of zone which particles move through before they exit the "soup" of the galaxy
  - Alfvén Velocity (v_α)
  - Convection Velocity

Role of Diffusion

- We test four diffusion parameters:
  - Diffusion Constant (D_0)
  - Simulation height (z)
  - Alfvén Velocity (v_α)
    - Diffusion of particles through momentum space
    - Reacceleration of particles
  - Convection Velocity

Role of Diffusion

- We test four diffusion parameters:
  - Diffusion Constant (D_0)
  - Simulation height (z)
  - Alfvén Velocity (v_α)
  - Convection Velocity
    - Cosmic "wind" pushing particles out of the galaxy

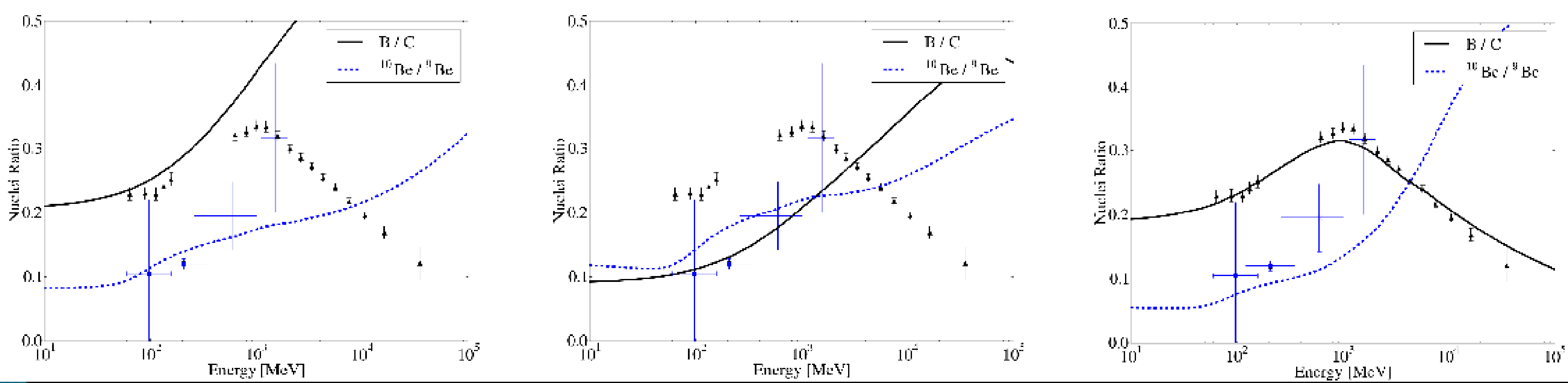


Role of Diffusion

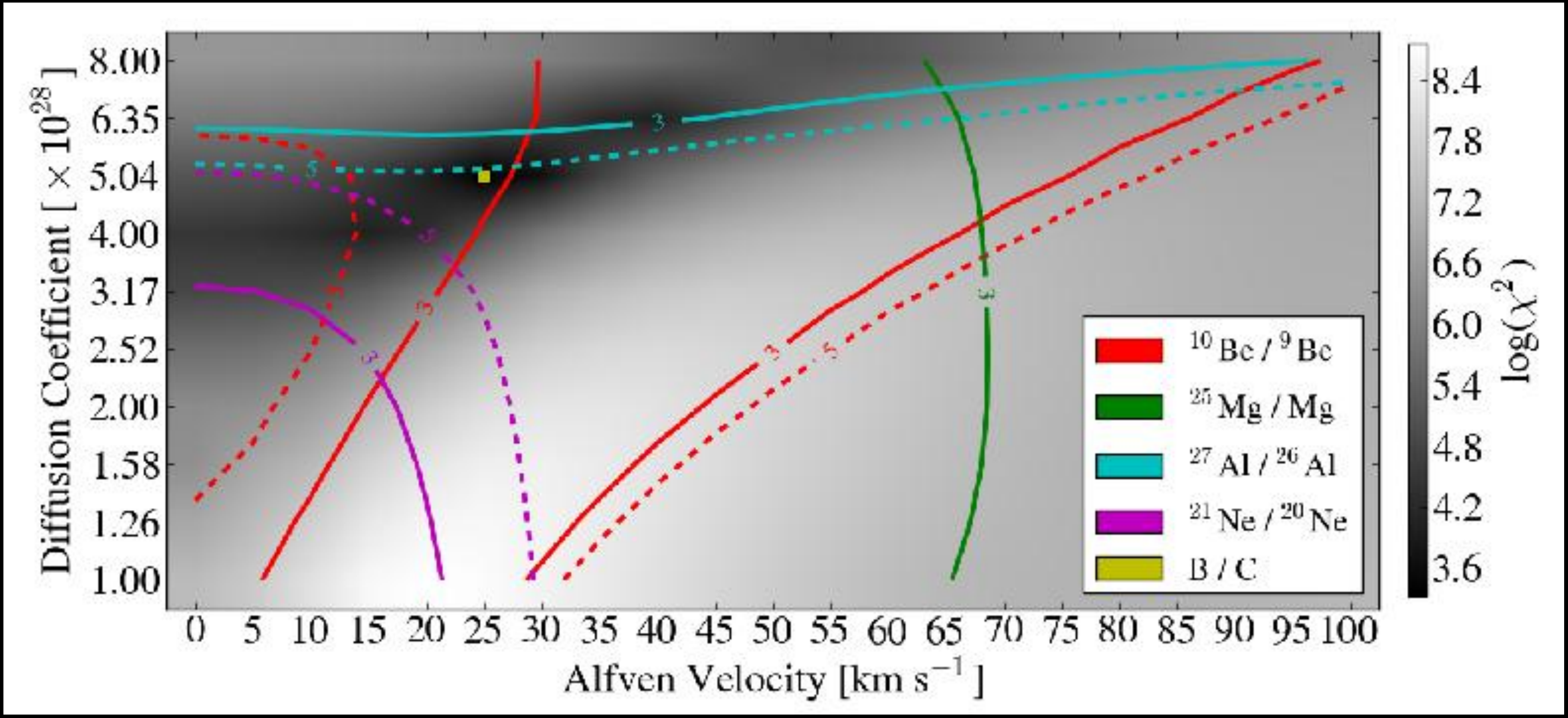
- The diffusion constant and Alfvén velocity greatly affect the Haze morphology .

Constraints on Diffusion

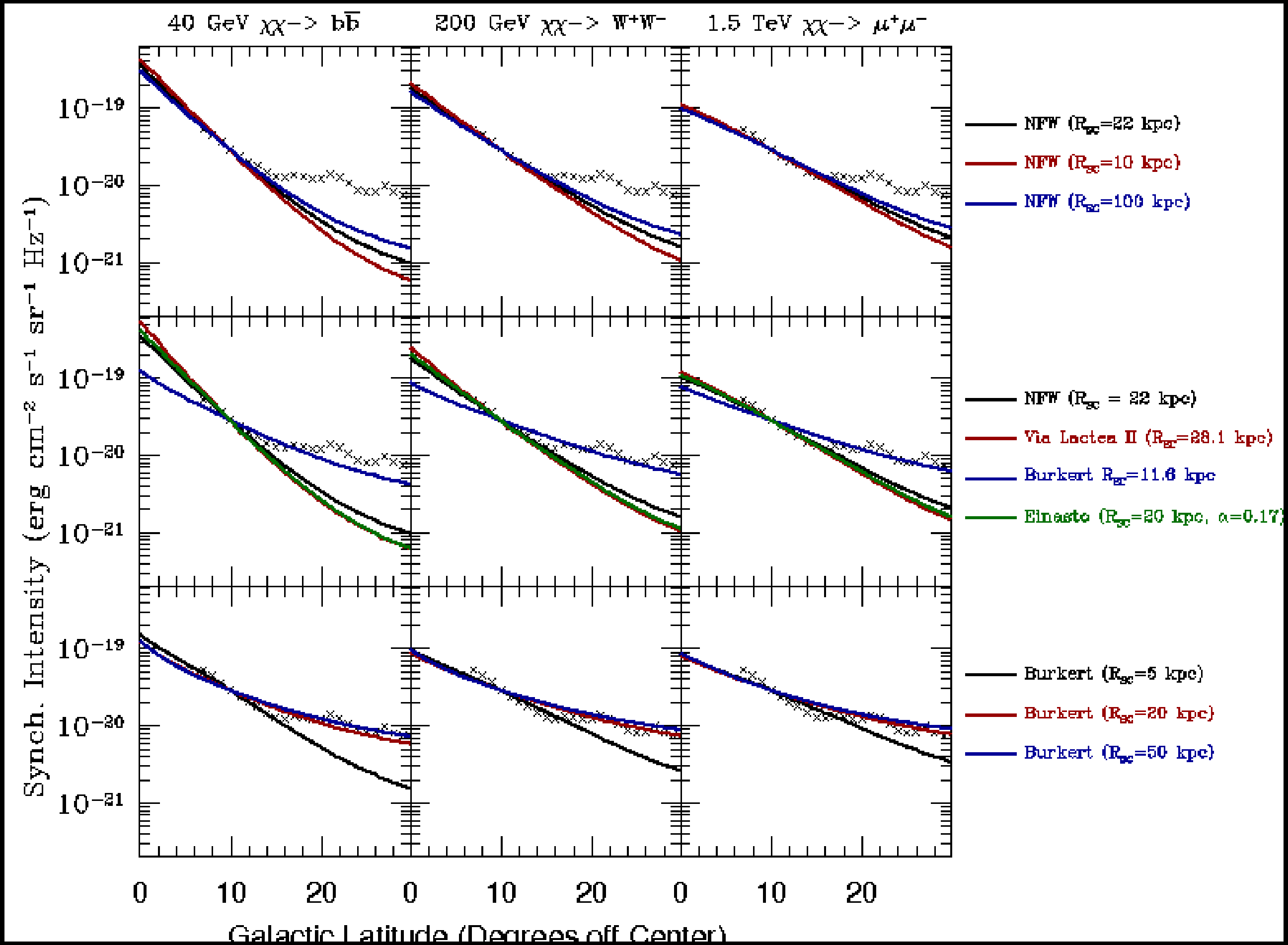
- Changes in the diffusion setup will affect the ratio of cosmic ray primary to secondary species
- This allows changes in the diffusion setup to be constrained by local cosmic ray observations



Constraints on Diffusion



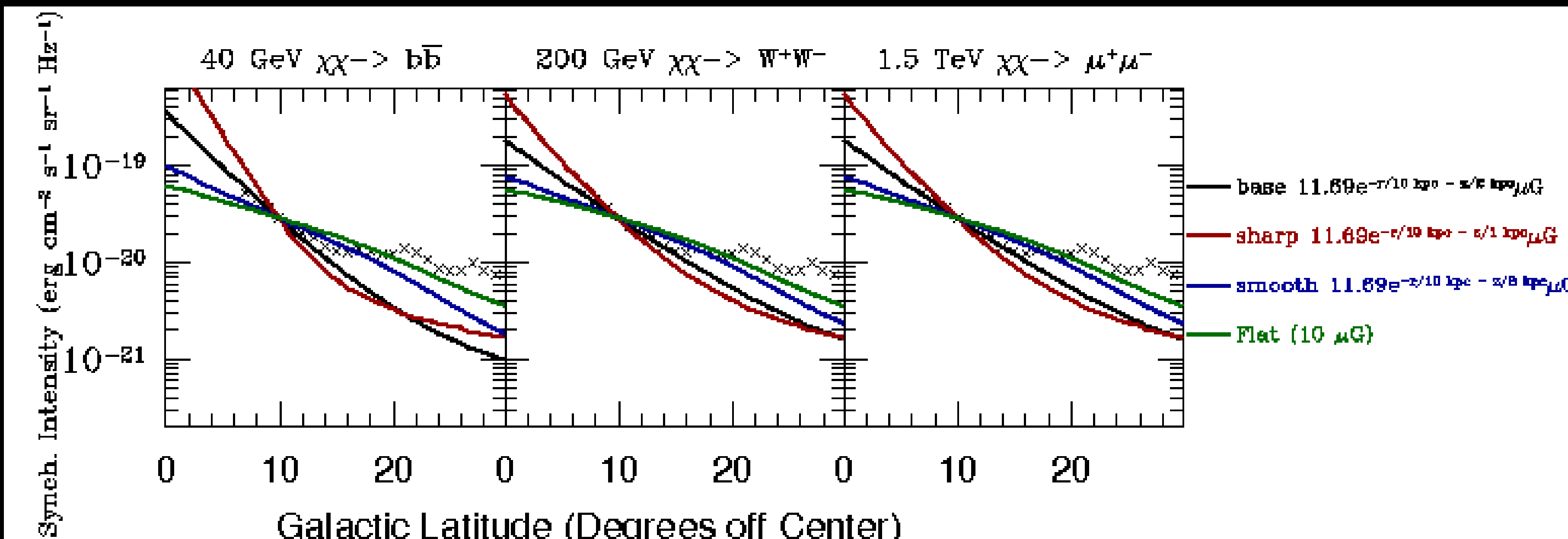
DM Profiles



Only profile which brings a reasonable match to the WMAP haze is a Burkert profile

- Profiles with dense galactic centers are unable to recreate the haze

Magnetic Field Models

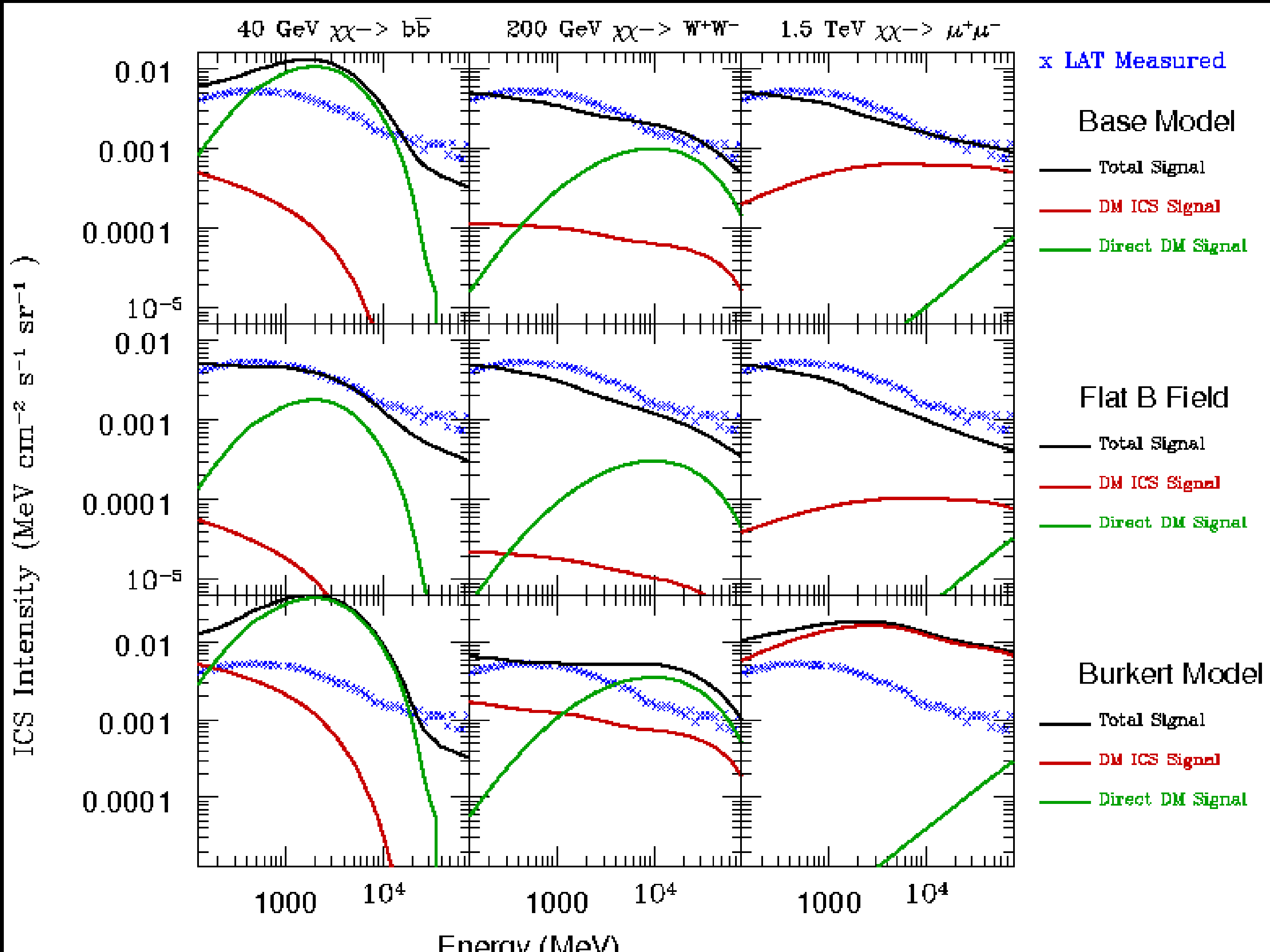


- Magnetic fields are an important uncertainty in our models

WMAP Matches?

- We have two possible matches to the morphology of the WMAP haze:
  - Changes in the magnetic field distribution (Flat magnetic field)
  - Changes in the DM density distribution (Burkert profile)
- Changes in the diffusion parameters have been ruled out by cosmic ray constraints

ICS



- Fermi emission rules out many of these models

Conclusions

- Standard Dark Matter/Diffusion setups do not provide a reasonable match to the WMAP haze
- Diffusion setups that would match the WMAP haze are well constrained by cosmic ray observations
- DM profiles which move annihilations to higher latitudes are well constrained by Fermi observations
- Magnetic field models are a major uncertainty

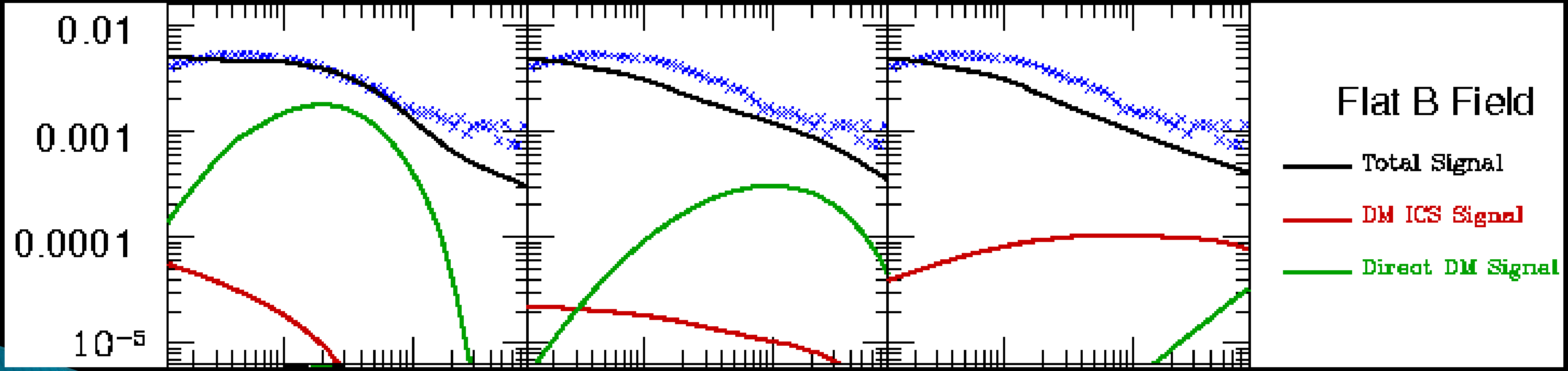
Linden, Profumo, Anderson (Submitted to PRD, arXiv: 1004.3998)

Current/Future Studies

- Anisotropy Studies
- Multiwavelength Studies
- Millisecond Pulsars

Anisotropy Studies

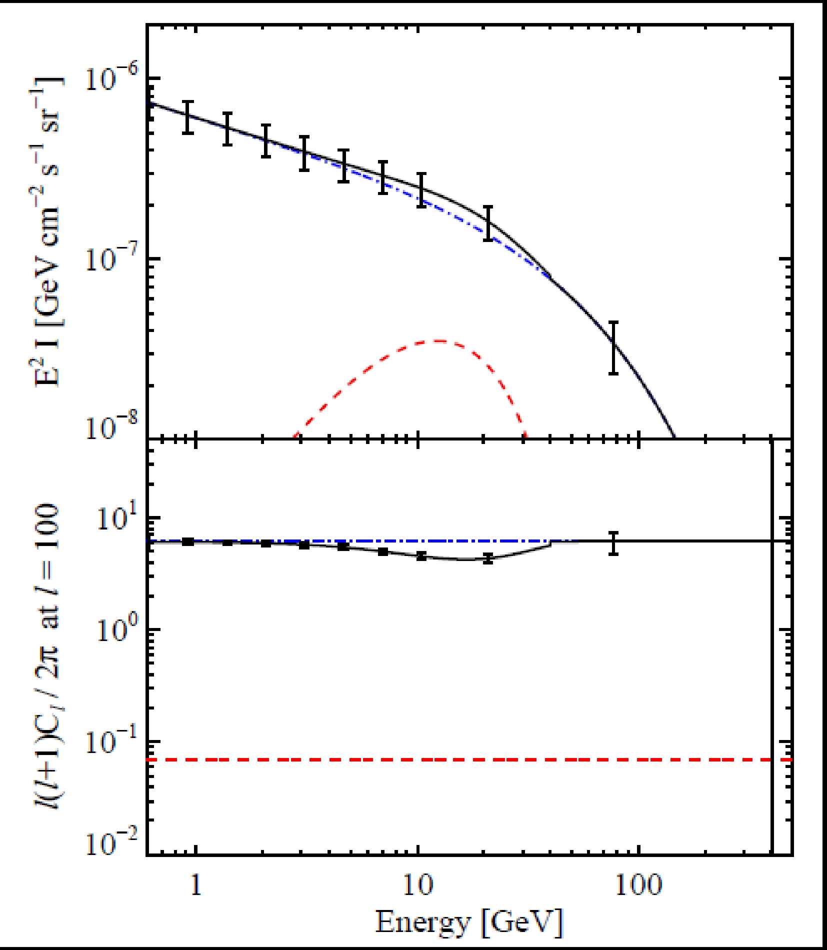
- Very large backgrounds can be hiding inside the Fermi signal
- Uncertainties in astrophysical backgrounds make it difficult to distinguish between signals



Anisotropy Studies

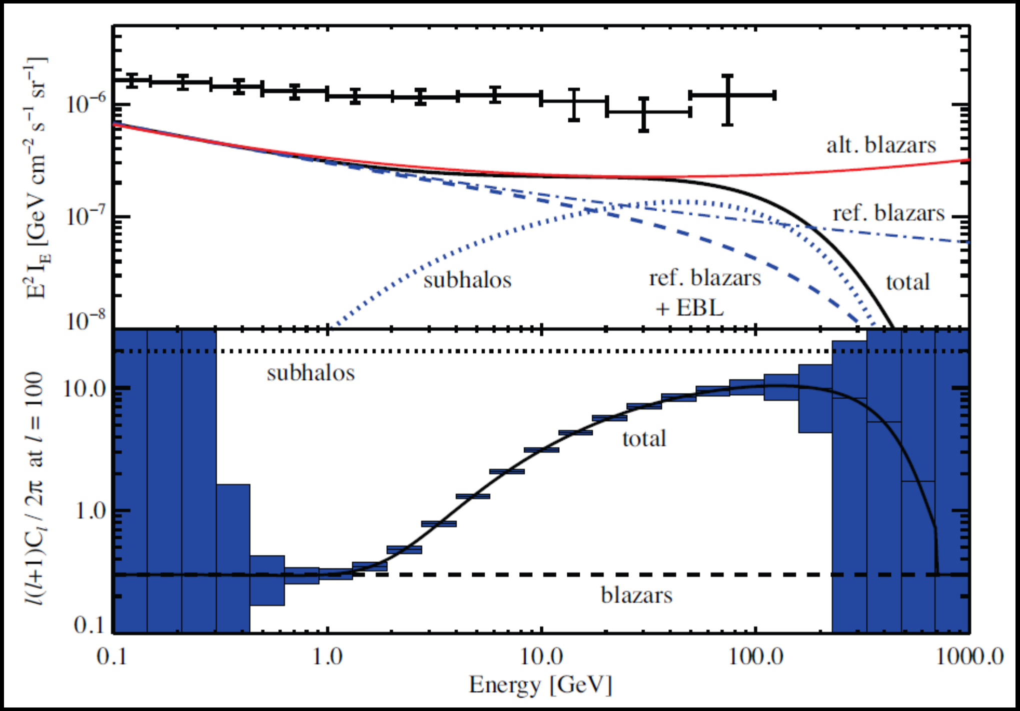
- Studying anisotropies allow us to pick small backgrounds out of large foreground signals

- The accuracy relies on the relative intensity of the background to foreground, rather than the uncertainties in the foreground



Hensley, Siegal-Gaskins, Pavlidou (2009)

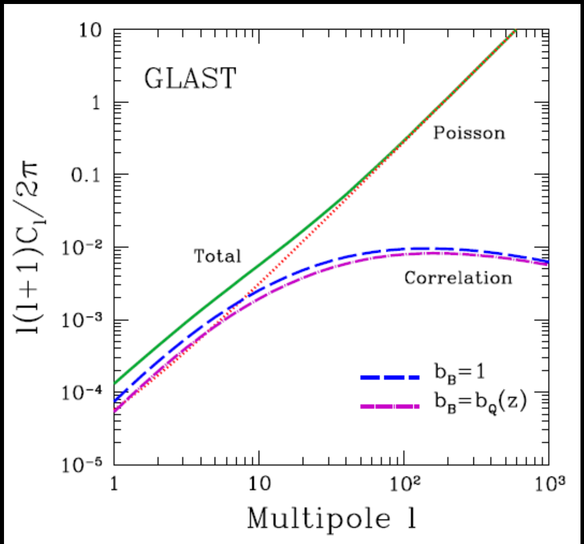
Anisotropy Studies



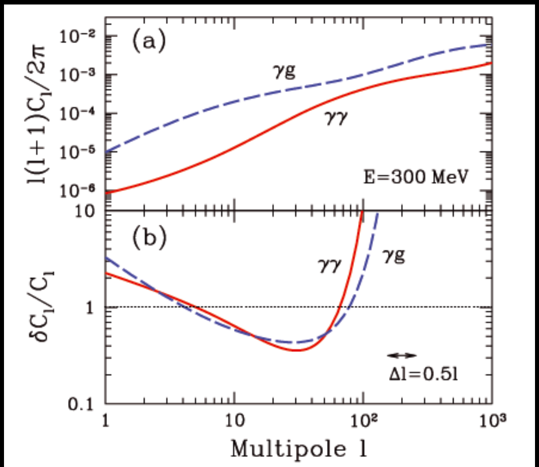
Siegal-Gaskins and Pavlidou (2009)

- Measurements of the anisotropy as a function of energy allow us to differentiate between different source classes.

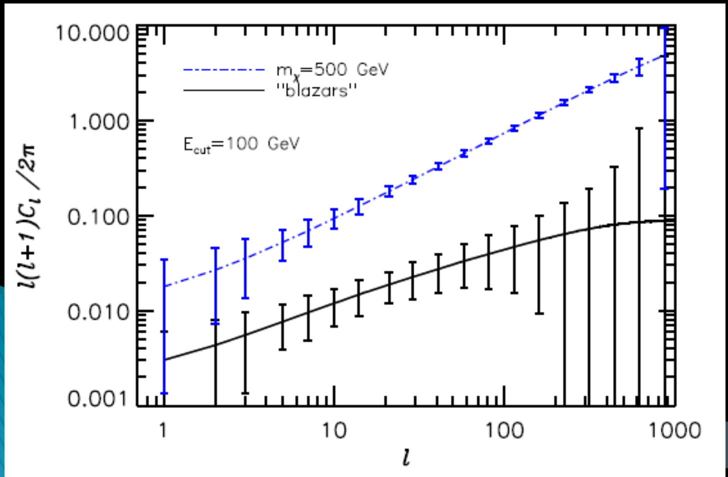
Anisotropy Studies



Blazars – Ando et al (2007)



Starforming Galaxies – Ando and Pavlidou (2009)



Extragalactic DM
Cuoco et al. (2008)

Methodology and Data Pipeline

- Extract LAT data from the DataPortal
  - P6_public_v1 diffuse class photons
  - MET = {239557418 – 289512580 (mission start to March 5, 2010)

- Data are cleaned using the following steps:
  - gtselect (zenith angle < 105º)
  - gtmktime (DATA_QUAL==1, LAT_CONFIG==1, IN_SAA!=T, ABS(ROCK_ANGLE < 52º)

Methodology and Data Pipeline

- Gtltcube (calculated livetime)
  - Divide dataset into four parts for processing speed:
    - 239557418 – 252500000
    - 252500000 – 265000000
    - 265000000 – 277500000
    - 277500000 – 289512580
  - Extrafine gridding is used (pixel_size = 0.125 degrees, cos(theta) = 0.01)
- Gtexpcube then calculates the exposure cubes
  - Healpix nside = 512 (pixel size = 0.125 degrees)
  - 75 energy bins from 1 GeV to 1 TeV (25/decade)

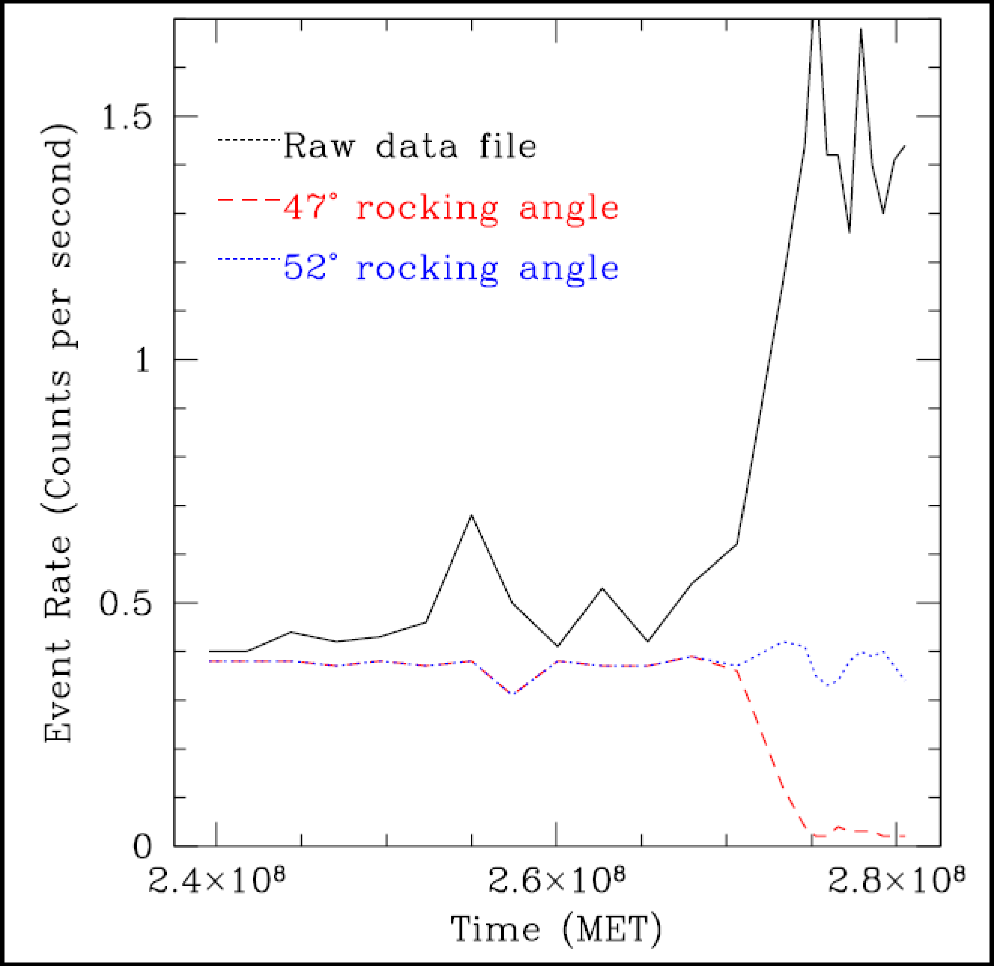
Methodology and Data Pipeline

- The generated exposure cubes and photon files (after the gtselect and gtmktime cuts) are converted to Healpix format (Gardian)
  - Healpix order 9
  - 75 energy bins (1 GeV – 1 TeV)

- The flux is generated in two ways
  - Simply dividing counts maps by exposure maps in each energy bin
  - Using gardian to interpolate the exposure on a photon by photon basis as a function of energy

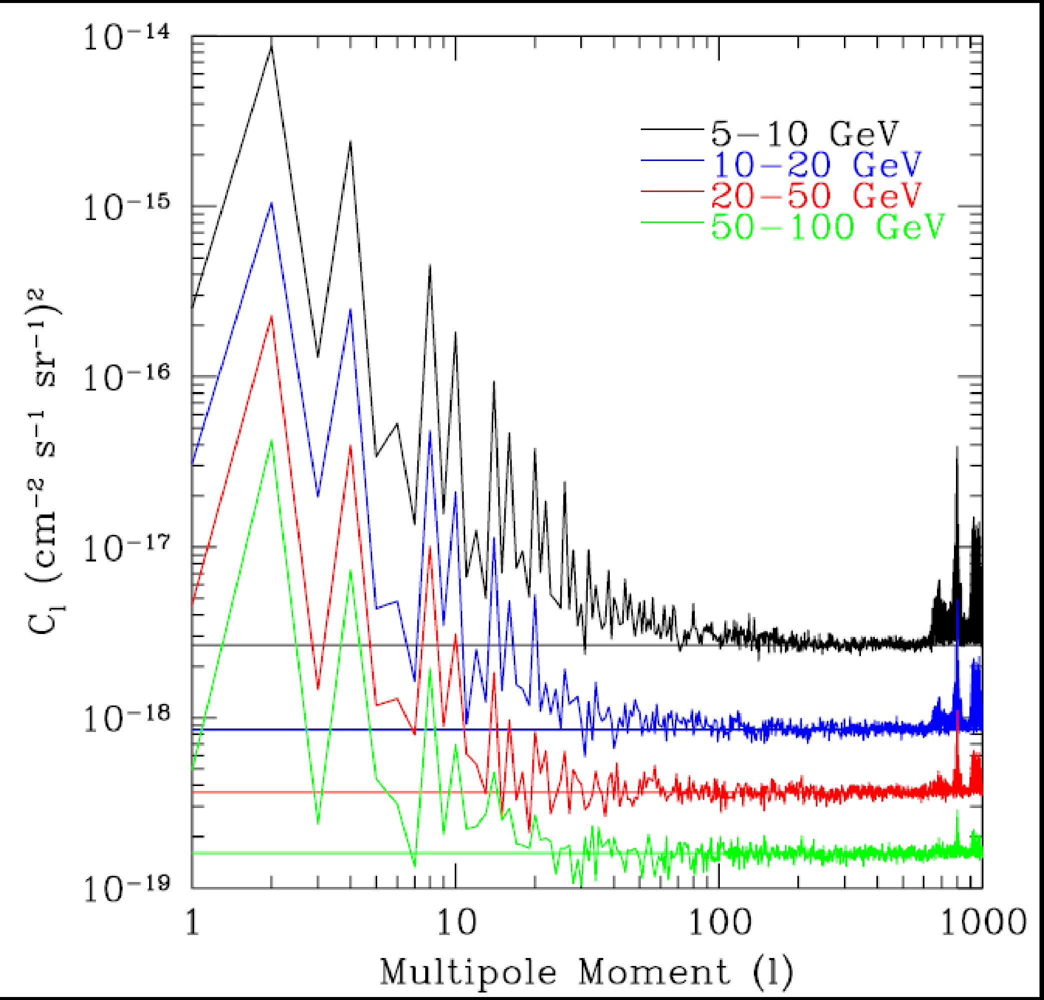
Very preliminary Results

- The rocking angle cut is shown to be effective, as it maintains a reasonably constant number of photons as a function of time



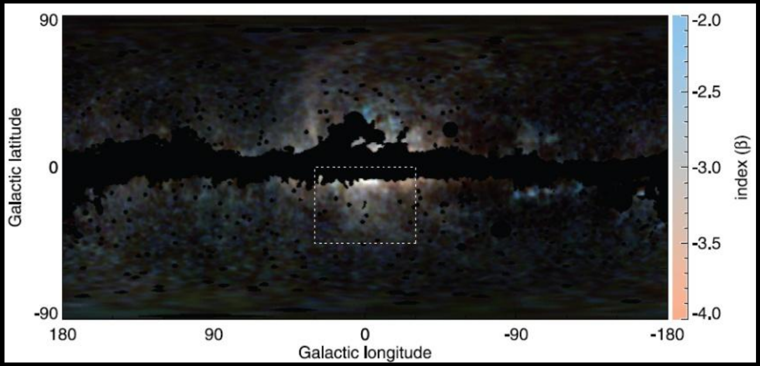
Very preliminary Results

- We see anisotropies at low multipoles, which correctly match the photon noise in the limit of high multipoles

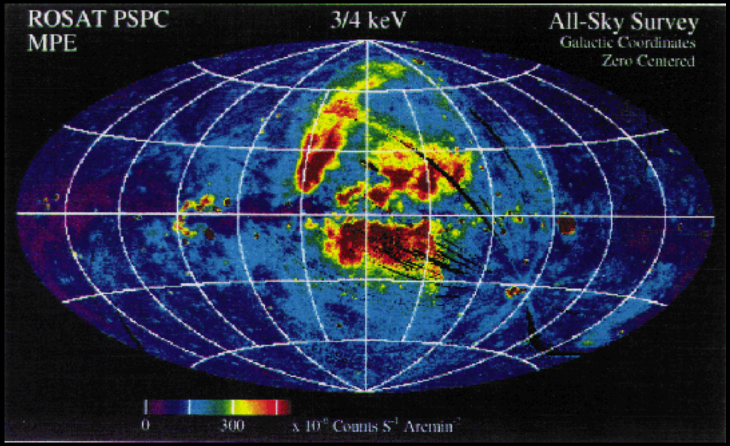


Multiwavelength Studies

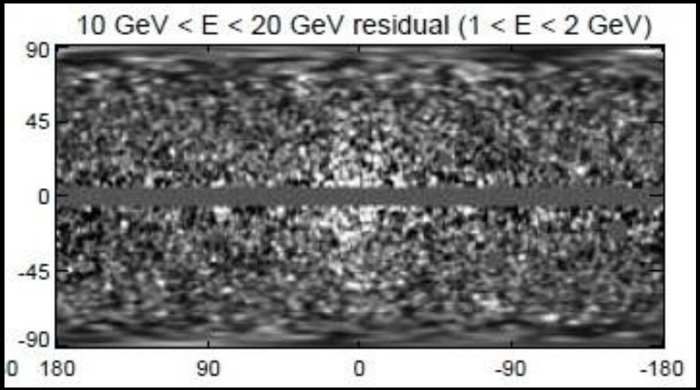
High latitude emission found in many observations



WMAP (Dobler & Finkbeiner, 2008)



ROSAT 0.75 kev (NASA)



Fermi (Dobler et al. 2009)

Project Methodology

- Use Fermi maps of the ICS (high energy Fermi diffuse) to understand the Interstellar radiation field

- Along with local e^+e^- fluxes, use this to estimate the e^+e^- spectrum

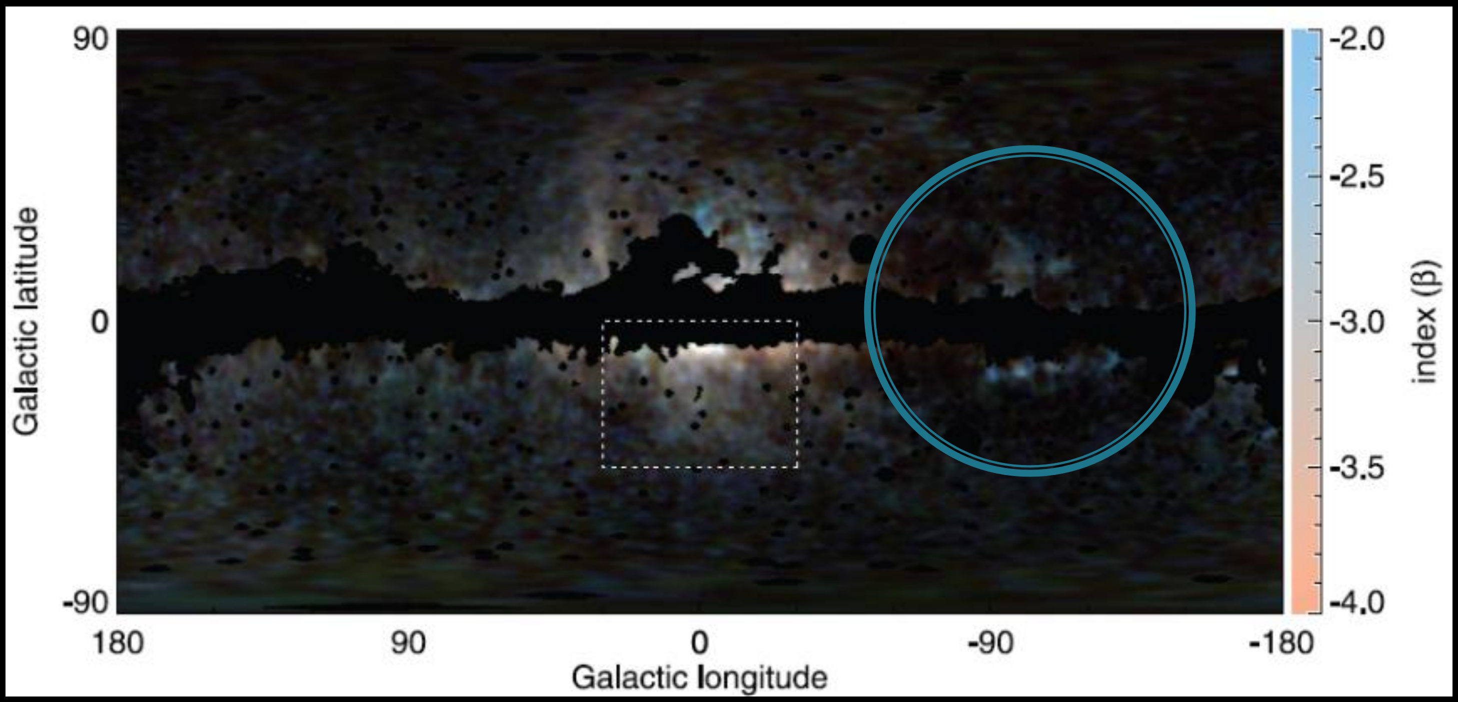
- Create a spectral study of polarized synchrotron emission from DM annihilation which can be detected by Planck

Project Methodology – Part 2

- Understand why this high latitude e+e- population exists
  - 1.) Cosmic ray transport
  - 2.) New sources
    - A.) Nearby
    - B.) Galactocentric
  - 3.) New ISRF/Magnetic field/Gas (targets)

Evidence for Nearby sources

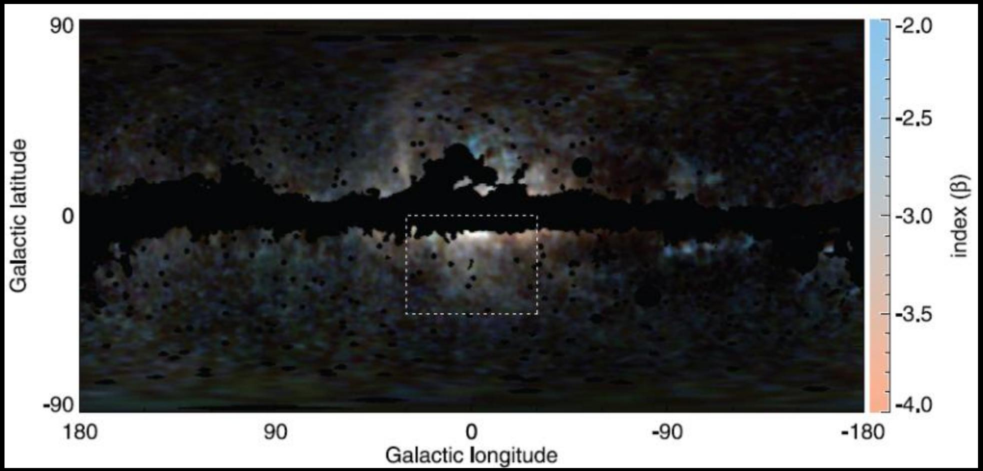
The second largest residual region is coincidence with Gum 19 – which indicates star formation may play a role in the WMAP haze



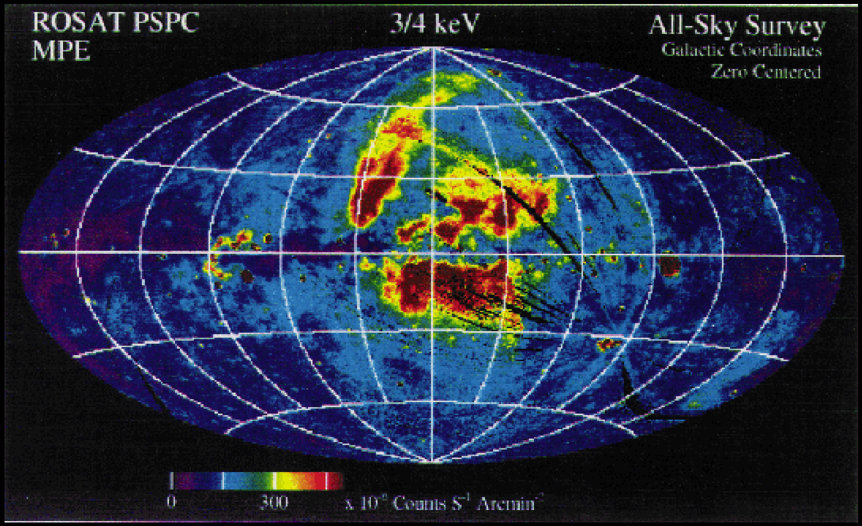
WMAP (Dobler & Finkbeiner, 2008)

Evidence for Target Distributions

X-ray hot region to left of galactic center is the magnetic anomaly



WMAP (Dobler & Finkbeiner, 2008)

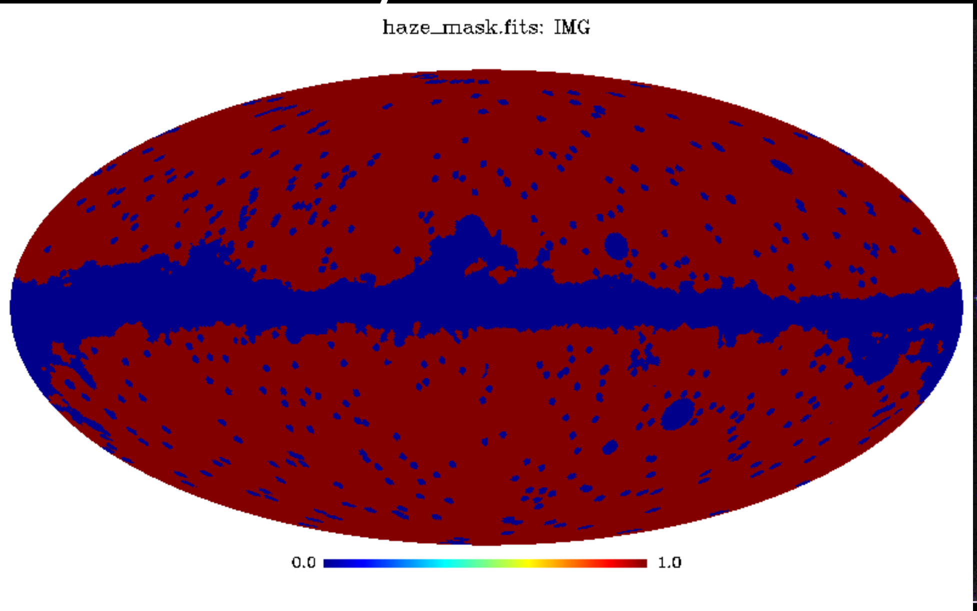


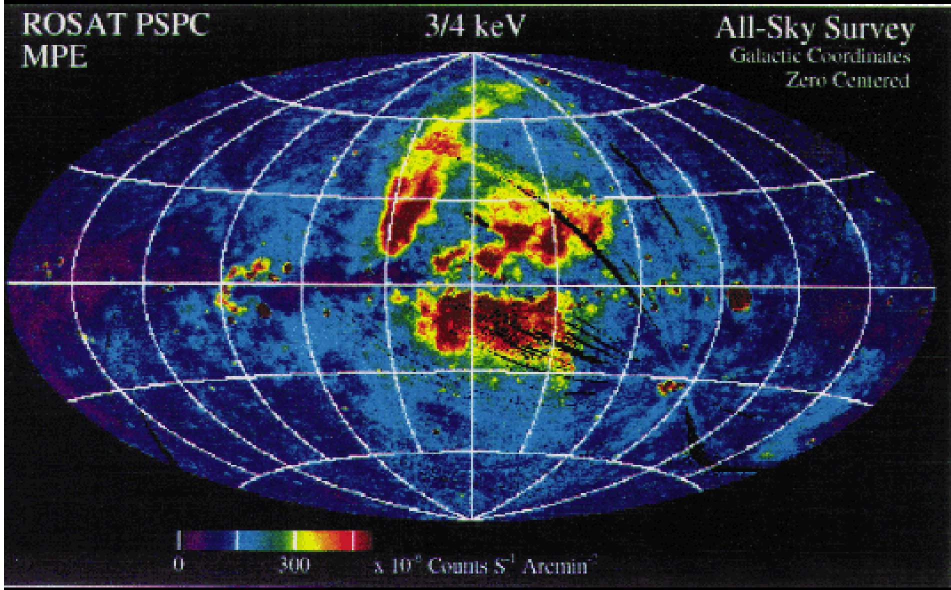
ROSAT 0.75 kev (NASA)

Furthermore, the low emission ROSAT region is coincident with the high dust region in the SFD Dust map

Evidence for Target Distributions

X-ray hot region to left of galactic center is the magnetic anomaly





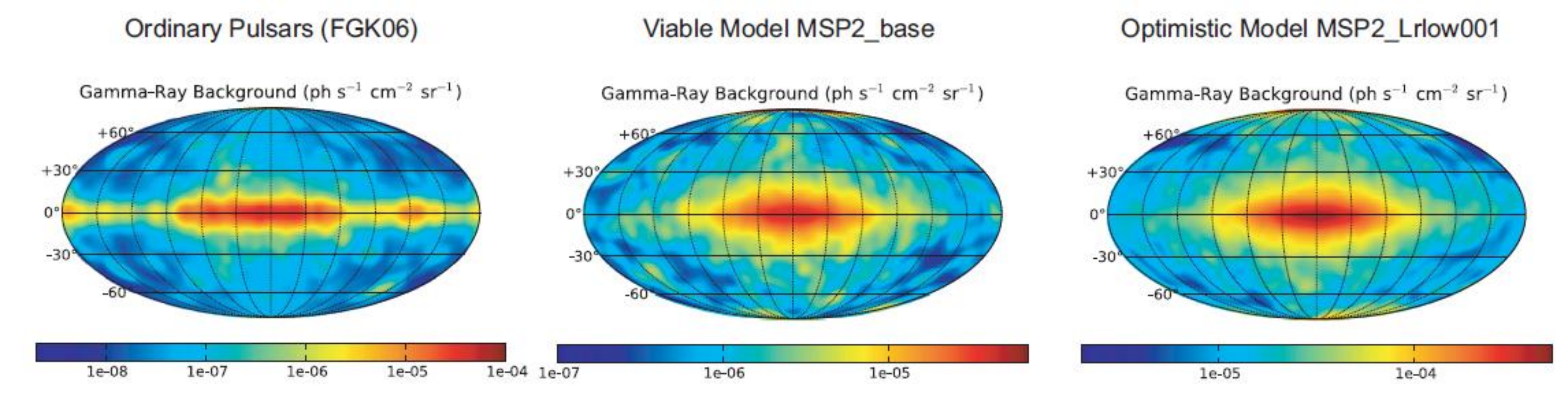
WMAP (Dobler & Finkbeiner, 2008)

ROSAT 0.75 kev (NASA)

Furthermore, the low emission ROSAT region is coincident with the high dust region in the SFD Dust map

Gamma-Rays from Pulsars

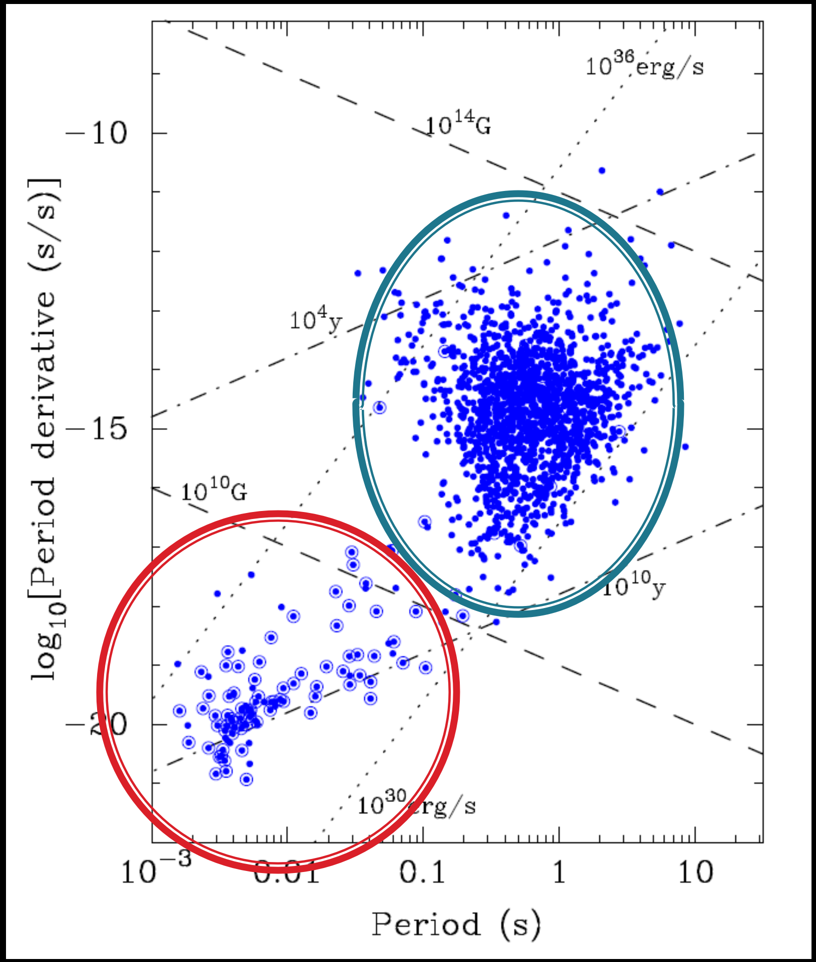
- Normal pulsars create both radio waves and γ-rays
- γ-rays beams appear to be wider, many γ-ray pulsars may be undetectable in radio (Fermi)



Faucher-Giguere & Loeb (2008)

Millisecond Pulsars

- May be many Gyr old
- Have smaller magnetic fields than the normal pulsar population



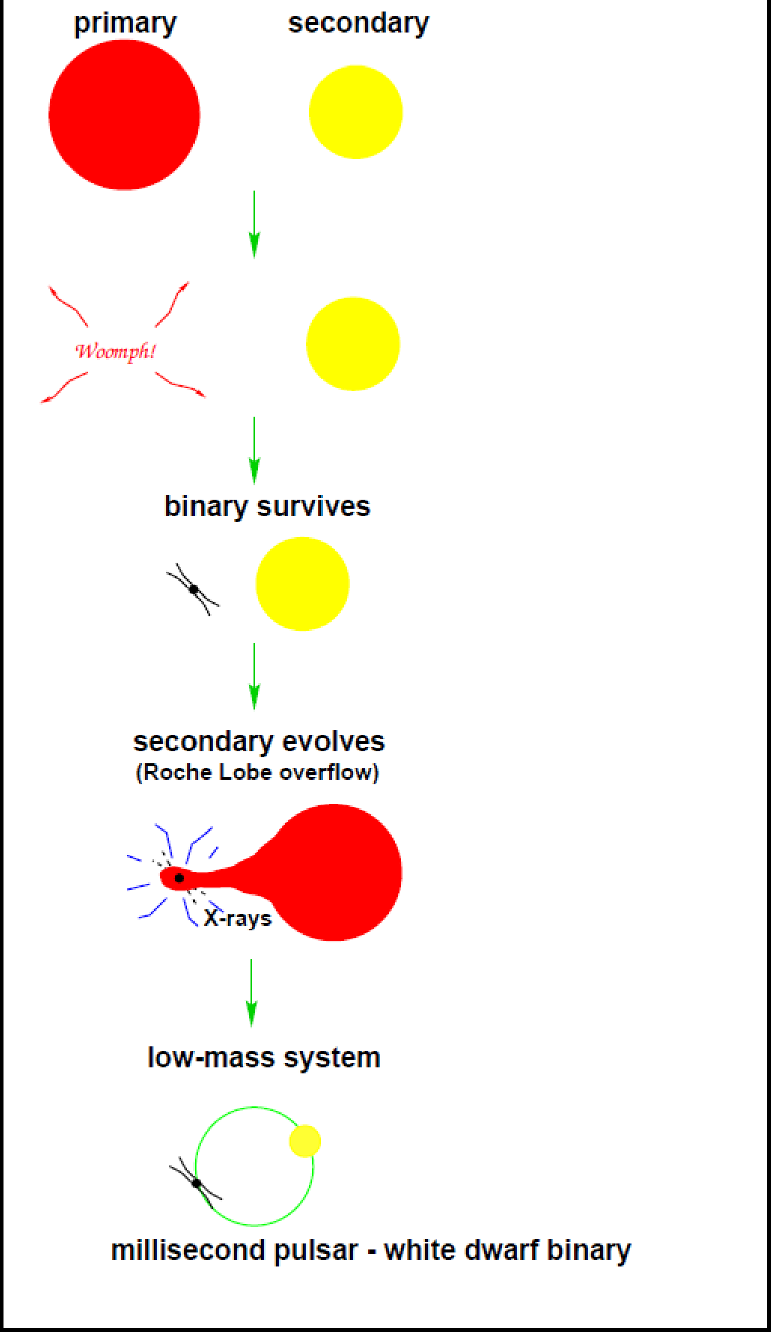
MSPs

Pulsars

Lorimer (2008)

Millisecond Pulsars as XRBs

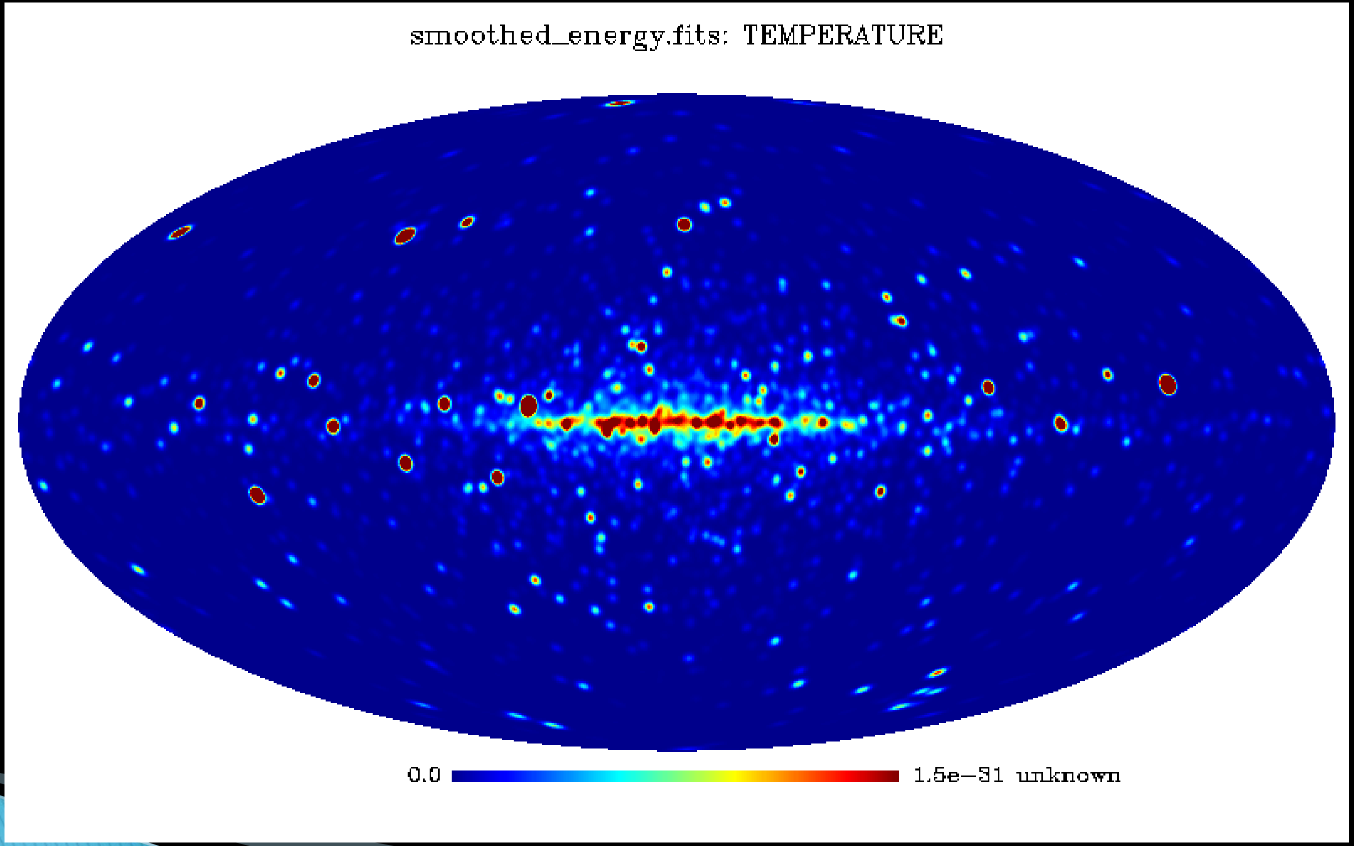
- Rotational Velocities for MSPs are expected velocity from collapse
- Instead, MSPs are thought to be spun up during a LMXB phase



Lorimer (2008)

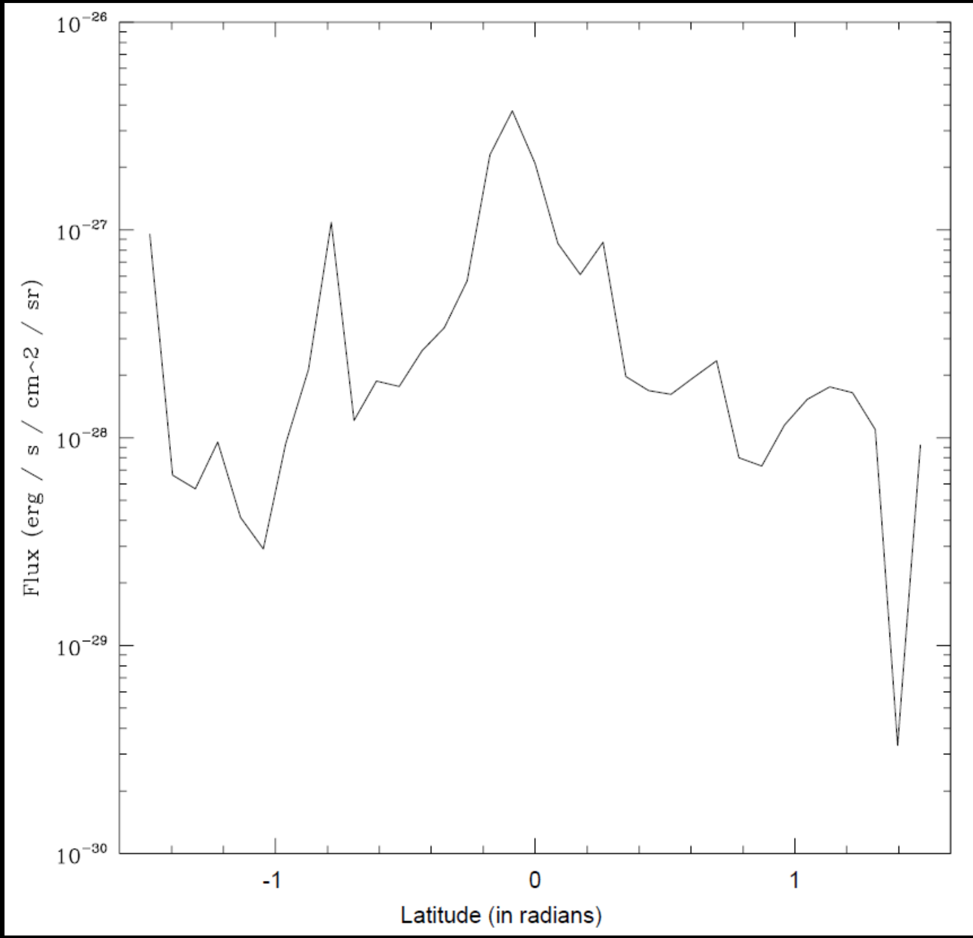
Early Results

- Distribution of MSPs has a significant high energy dependence



Early Results

- Longitude cut of −20 < l < 20
- Relevant power as a fluctuation of latitude appears to have a galactic center component, plus a nearly isotropic component

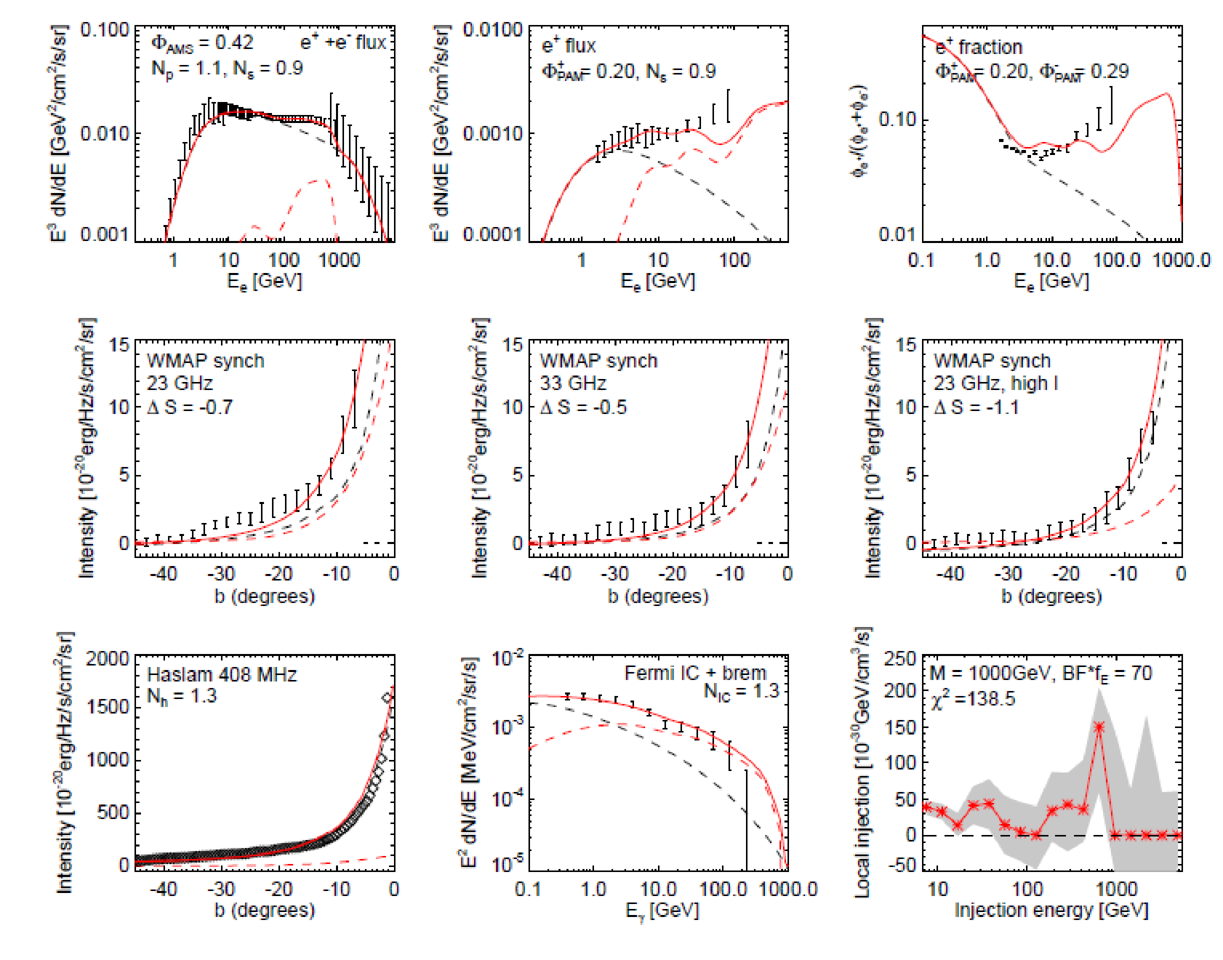


Conclusions

- Diffuse emission is a complicated process, necessary to search for a signal from dark matter annihilation
- Anisotropies and Multiwavelength studies provide hope of disentangling this emission
- Astrophysical models of unknown source classes like MSPs are also necessary

EXTRA SLIDES

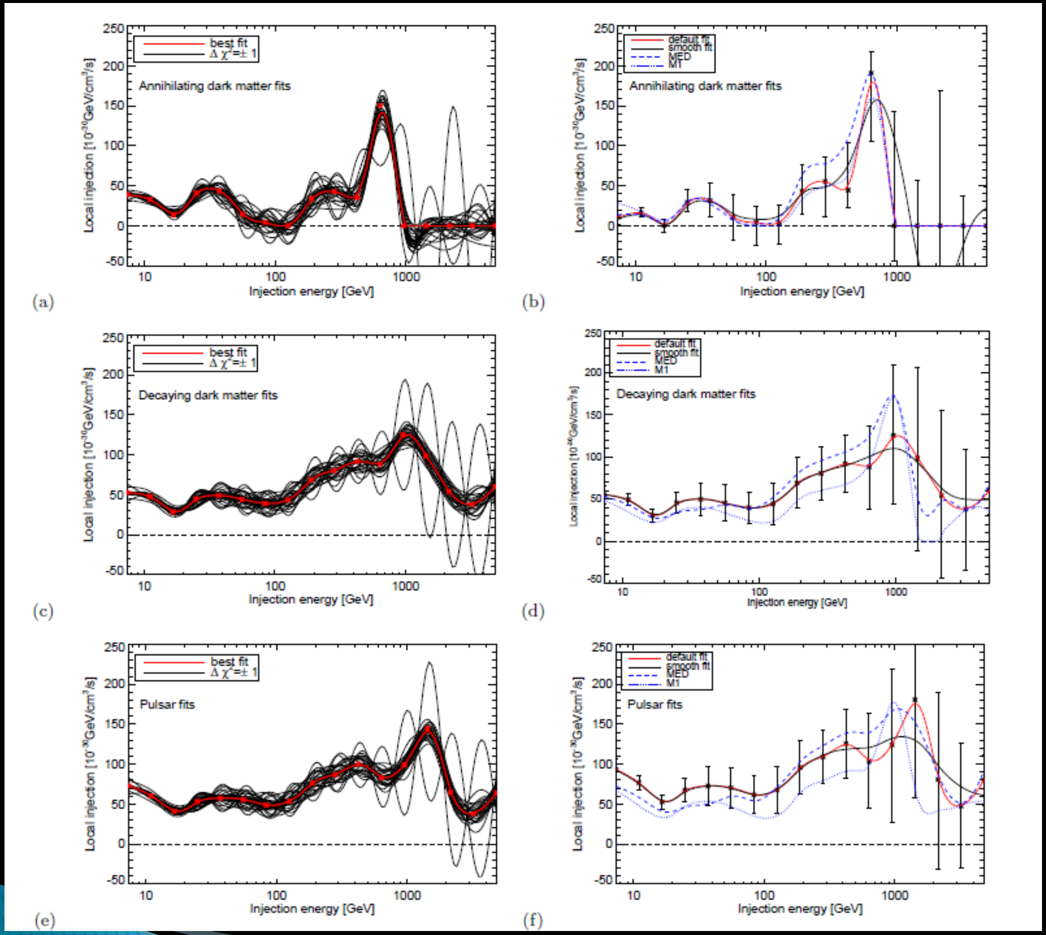
Matching the Fermi Haze



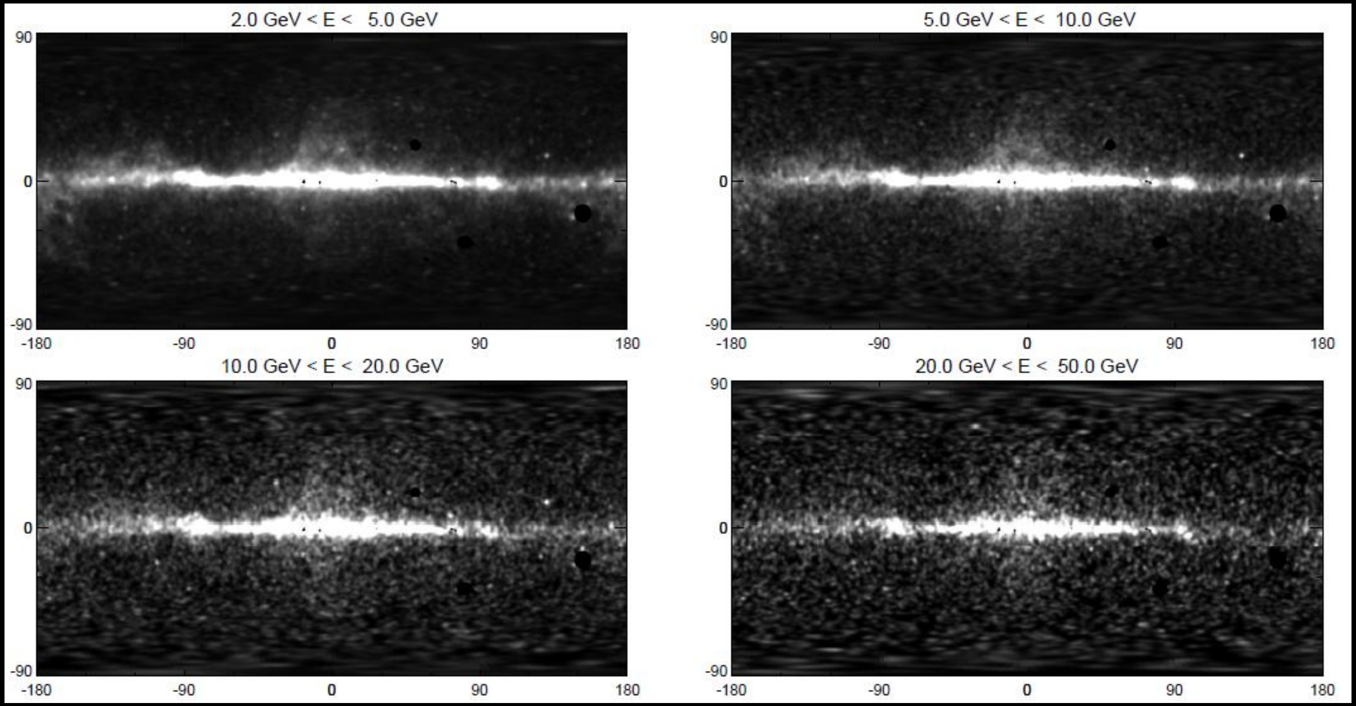
Liu et al. (2010)

Matching the Fermi Haze

Liu et al. (2010)



The Fermi Sky

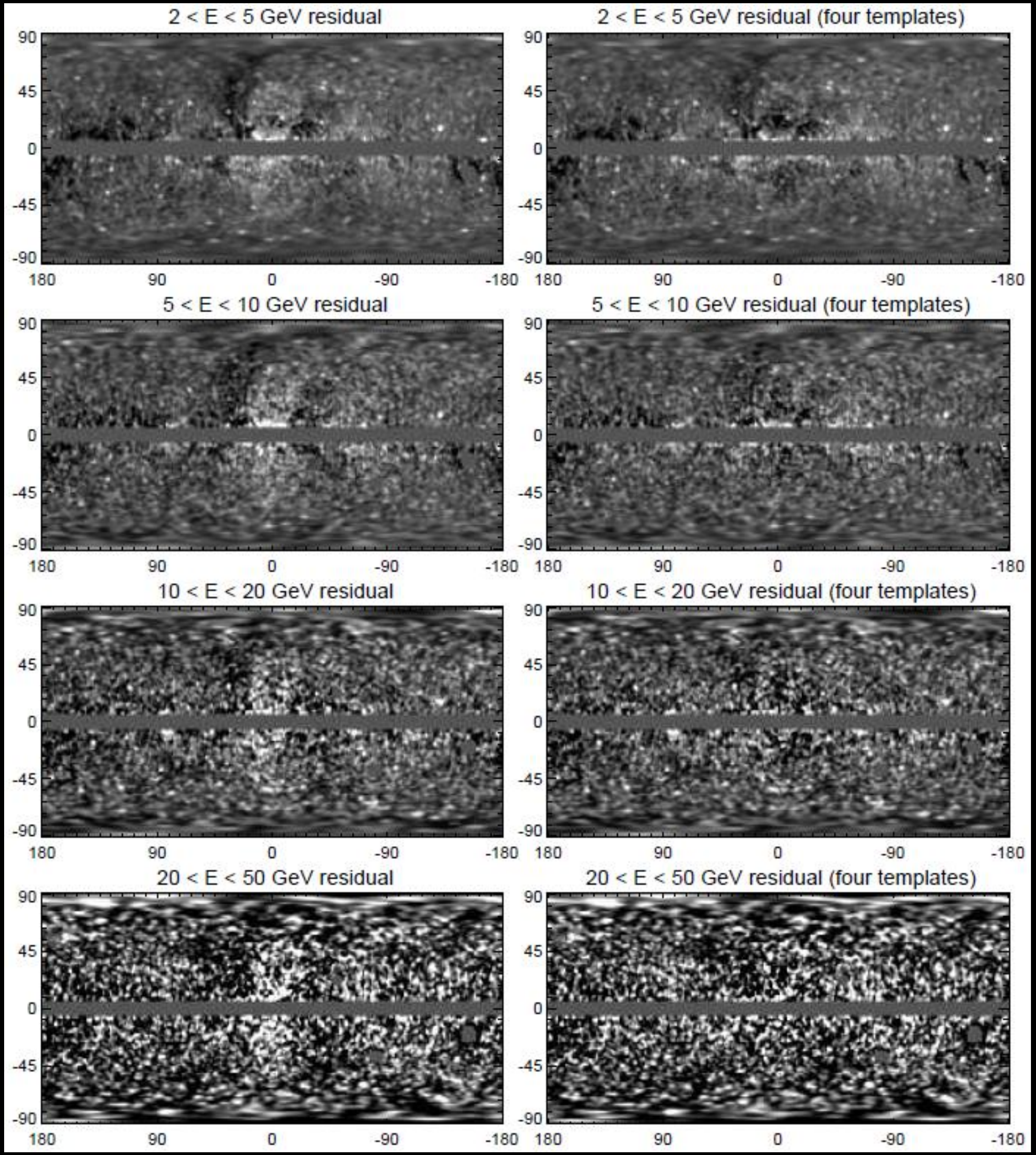


Dobler et al (2009) produced skymaps of the Fermi diffuse emission

- This skymaps come from many classes –

Results

- Haze template effectively eliminates the morphology of the residual
- Residual now appears to be random noise



Matching this spectrum

- Nevertheless, it is worth testing whether we can match this spectrum with new electron inputs (specifically dark matter)
- We employ Galprop models including a dark matter contribution, and determine the morphology of the output WMAP spectrum

Matching this spectrum

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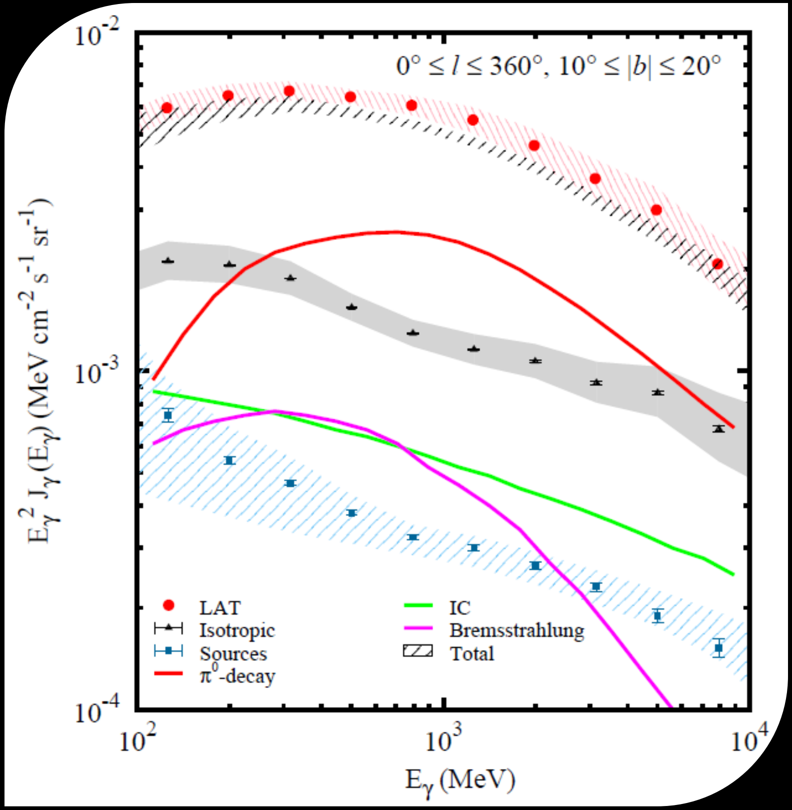
- We employ Galprop models including a dark matter contribution, and determine the morphology of the output WMAP spectrum

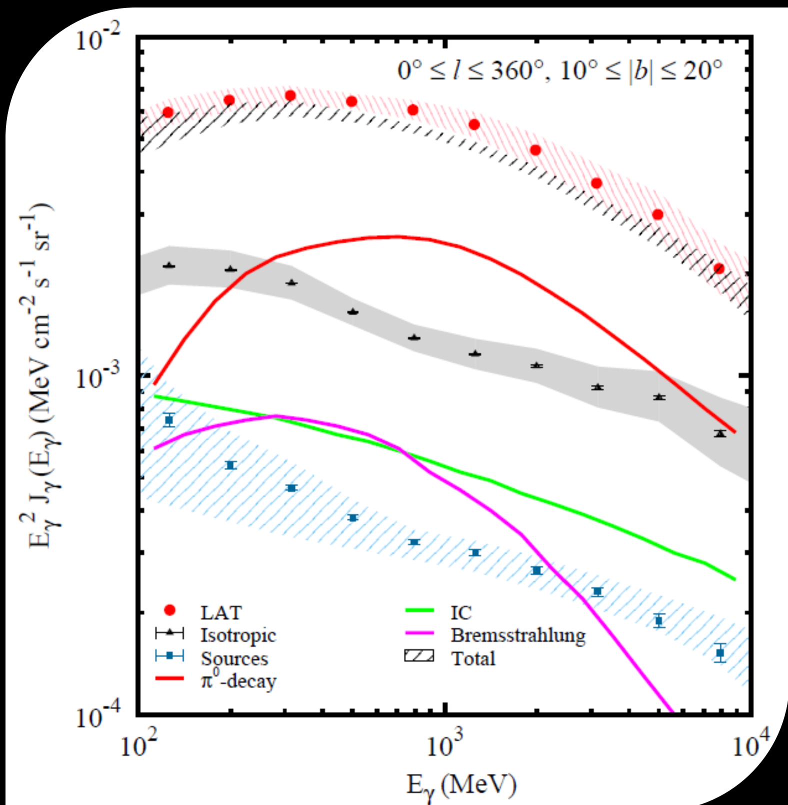
Observations of Diffuse Emission



T. Porter, 2009 (0907.0294)

- Many sources:
  - Extragalactic
    - Isotropic Source Classes
    - Sources include blazars, starburst galaxies
  - π^0 decay
  - Inverse Compton Scattering
  - Bremsstrahlung Emission
  - Unresolved Point Sources

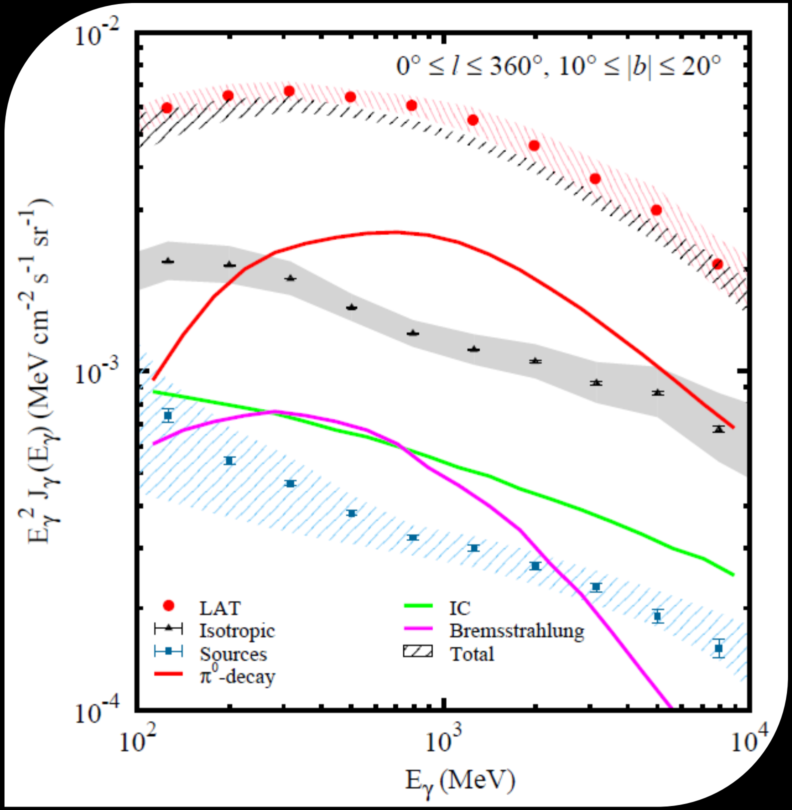
Observations of Diffuse Emission



T. Porter, 2009 (0907.0294)

- Many sources:
  - Extragalactic
  - π^0 decay
    - Proton collisions with galactic dust
    - Well defined emission spectra
  - Inverse Compton Scattering
  - Bremsstrahlung Emission
  - Unresolved Point Sources

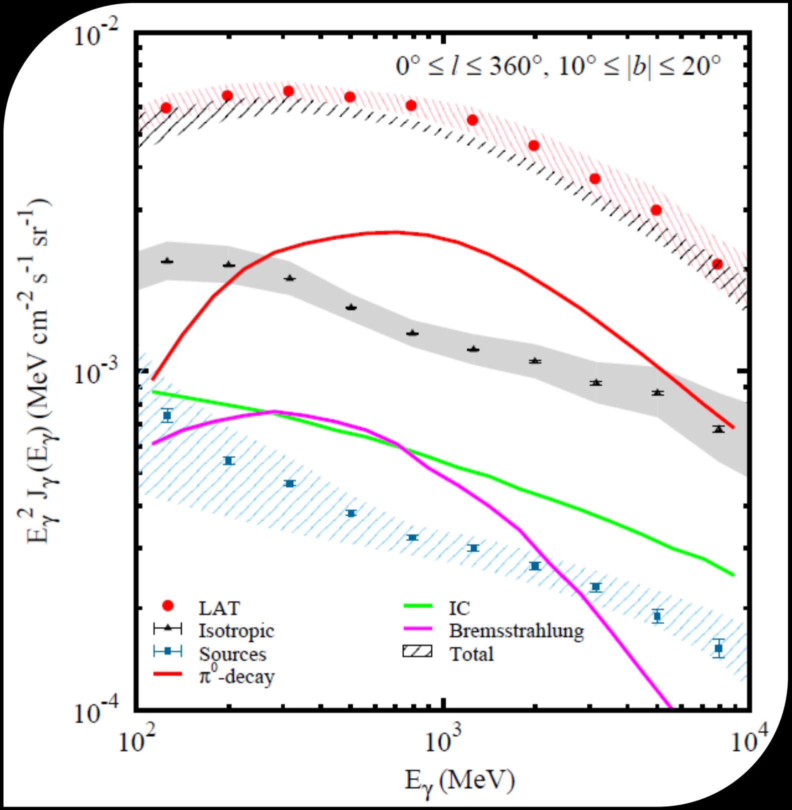
Observations of Diffuse Emission



T. Porter, 2009 (0907.0294)

- Many sources:
  - Extragalactic
  - π^0 decay
  - Inverse Compton Scattering
    - Interactions of charged leptons with interstellar radiation field
  - Bremsstrahlung Emission
  - Unresolved Point Sources

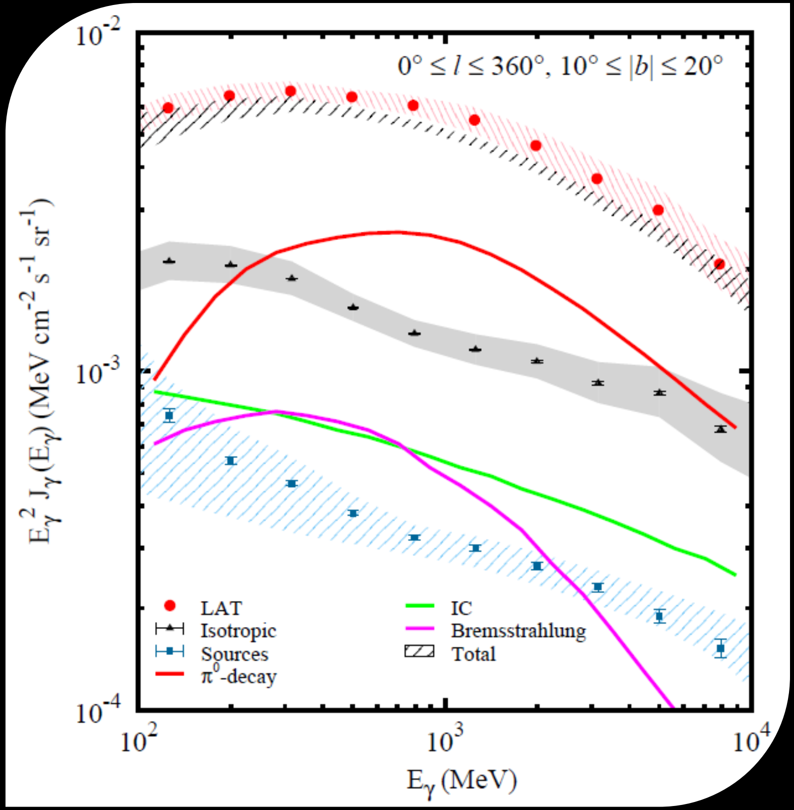
Observations of Diffuse Emission



T. Porter, 2009 (0907.0294)

- Many sources:
  - Extragalactic
  - π^0 decay
  - Inverse Compton Scattering
  - Bremsstrahlung Emission
    - Relatively weak sources at high energies and away from the galactic center
  - Unresolved Point Sources

Observations of Diffuse Emission

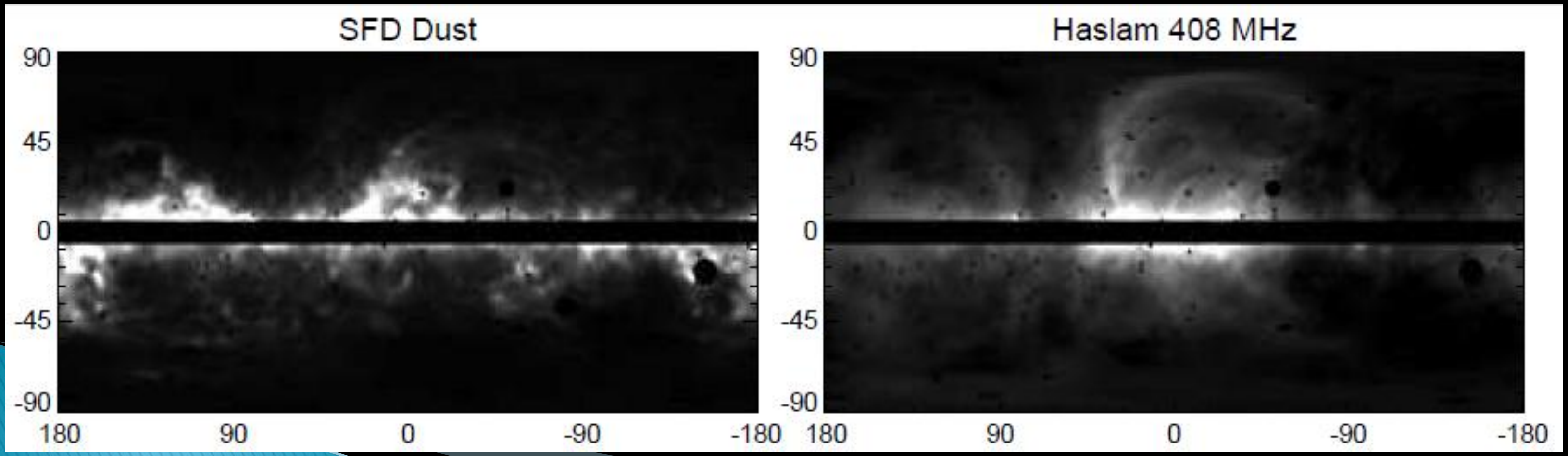


T. Porter, 2009 (0907.0294)

- Many sources:
  - Extragalactic
  - π^0 decay
  - Inverse Compton Scattering
  - Bremsstrahlung Emission
  - Unresolved Point Sources
    - Systematic error – Intensity and spectra changes over time

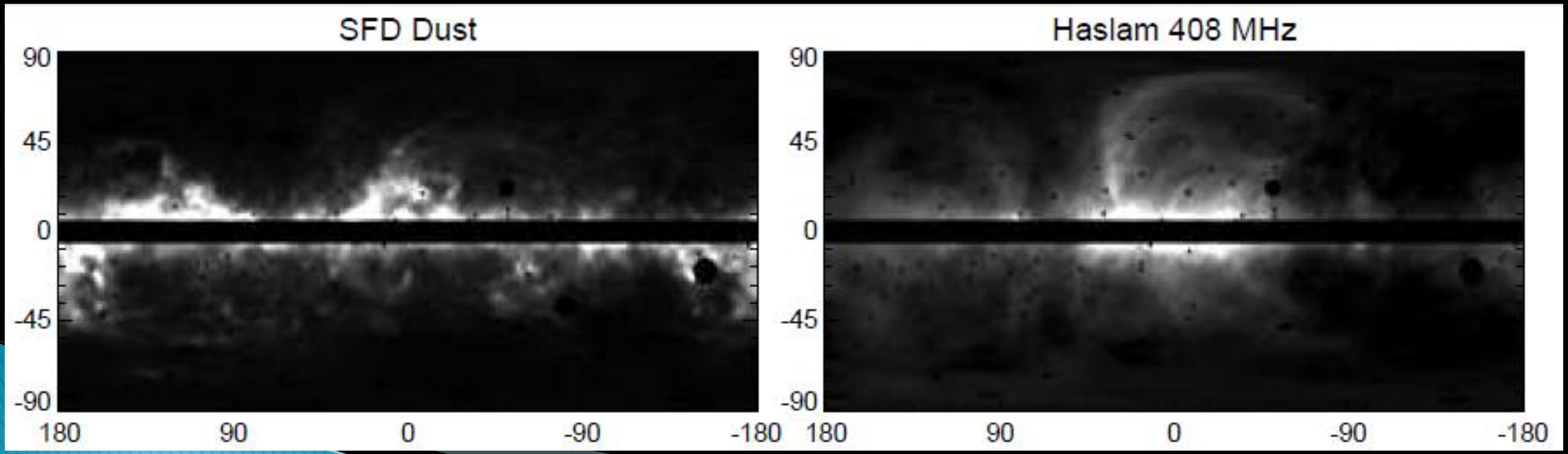
But do we trust these templates?

- SFD Dust Map for π^0 decay
  - Dust is a reasonable tracer for galactic gas
  - Gas acts as the target of energetic protons

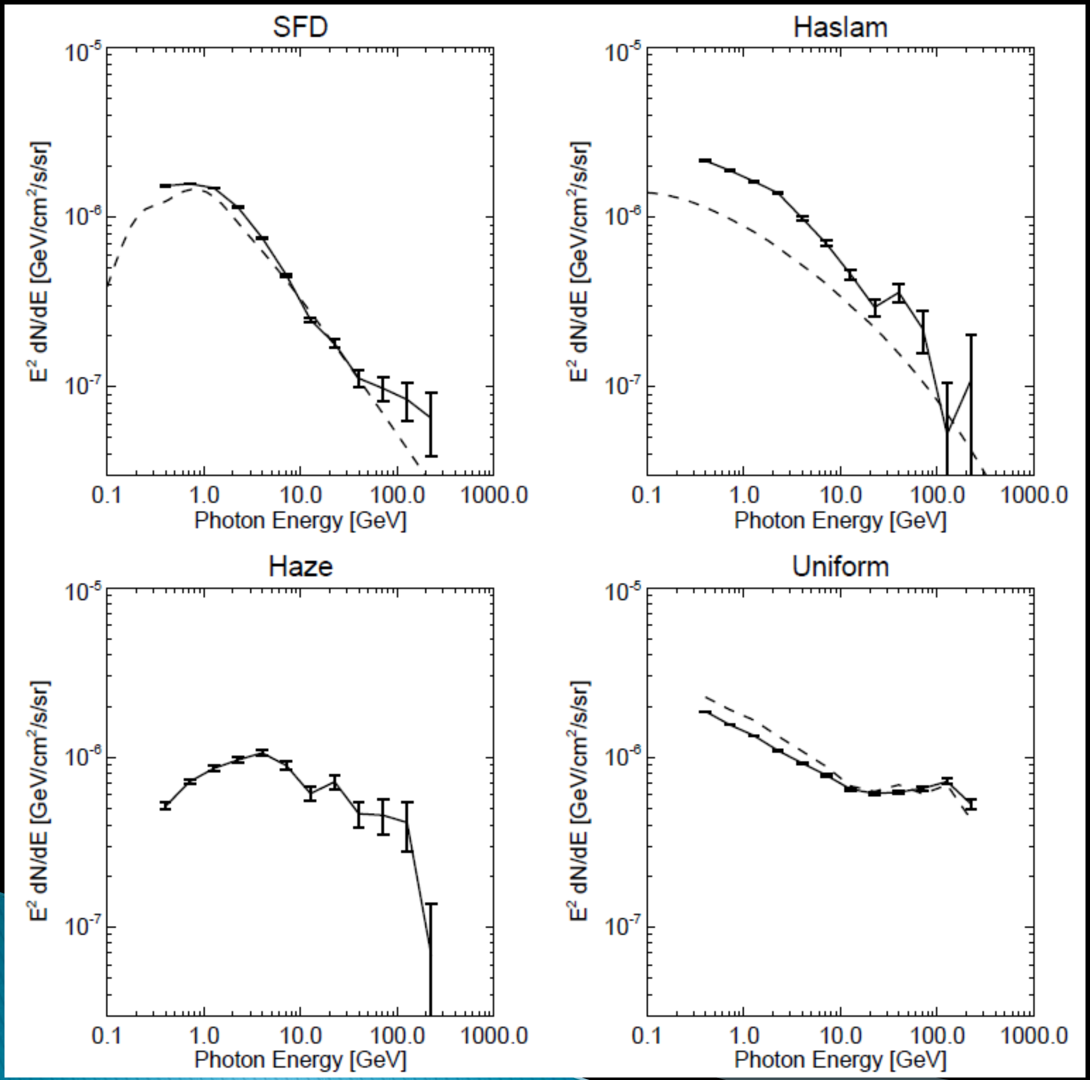


But do we trust these templates?

- Haslam 408 Mhz skymap for inverse Compton scattering
  - At 408 Mhz, the radio sky should be dominated by synchrotron of energetic leptons.
  - These same leptons should create γ-ray emission due to ICS of the interstellar radiation field.



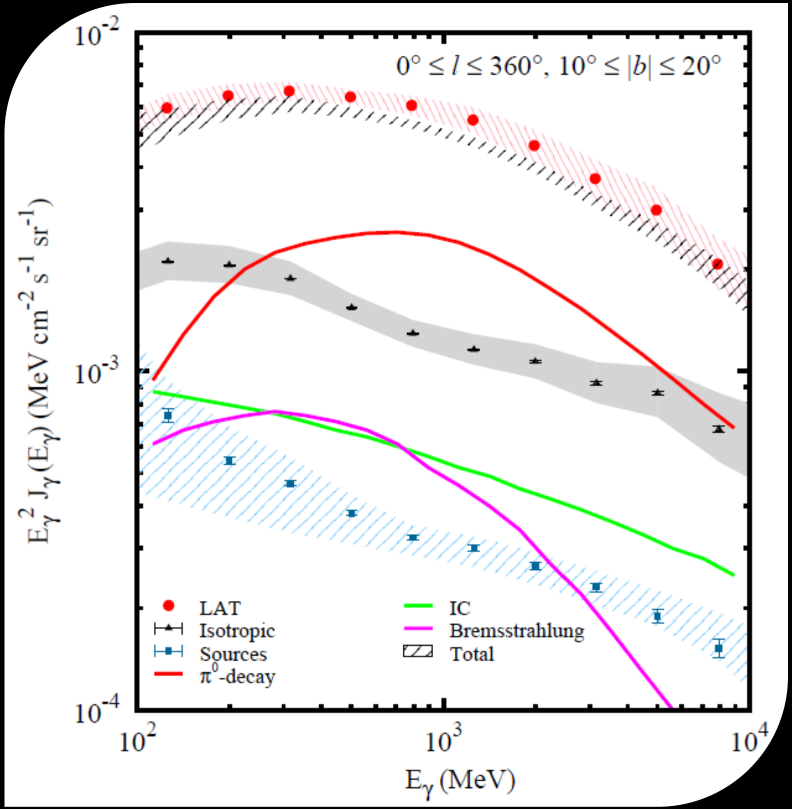
These residuals are large!



- The haze template is **co-dominant** with the isotropic background above 10 GeV
- Other templates have reasonable spectra

$|l| < 15^{o}$ $-30^{o} < b < -10^{o}$

A More Direct Analysis

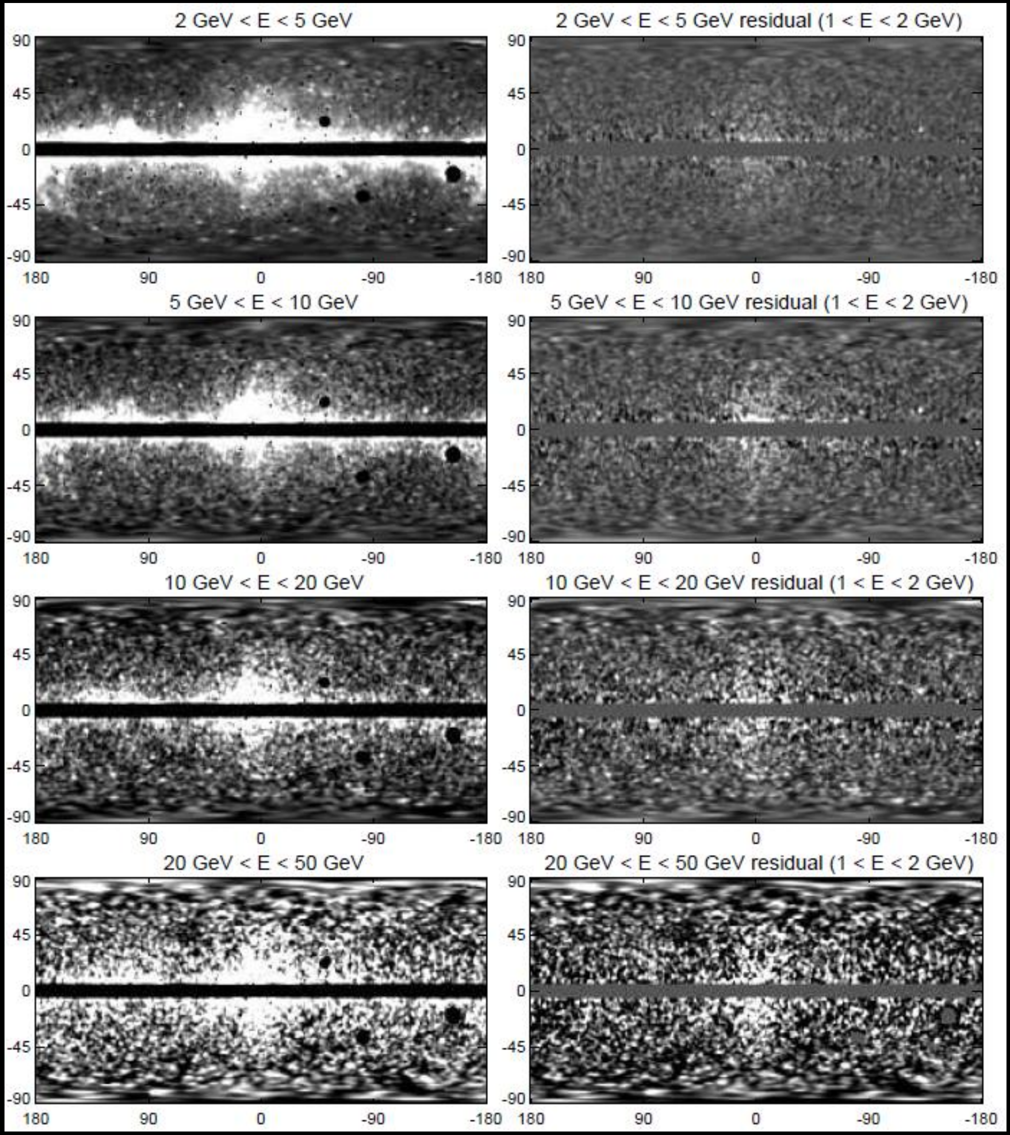


T. Porter, 2009 (0907.0294)

- At 1-2 GeV, emission from π^0 decay should be highly dominant
- Note that the π^0 decay morphology should be constant as a function of energy

Residuals!

- Process:
  - 1.) Subtract out the morphology of the 1-2 GeV map
  - 2.) Find the morphology of the residual
- Dobler et al. find there is **still** a visible haze
- Some/Most of this haze is likely astrophysical ICS
- Can't determine an intensity/spectrum



Conclusions

- 1.) While the spectrum and intensity of the Fermi haze is systematically uncertain due to foreground templates, there does appear to be an anomolous foreground

- 2.) Uncertainties in astrophysical templates make it very difficult to understand these anomolies

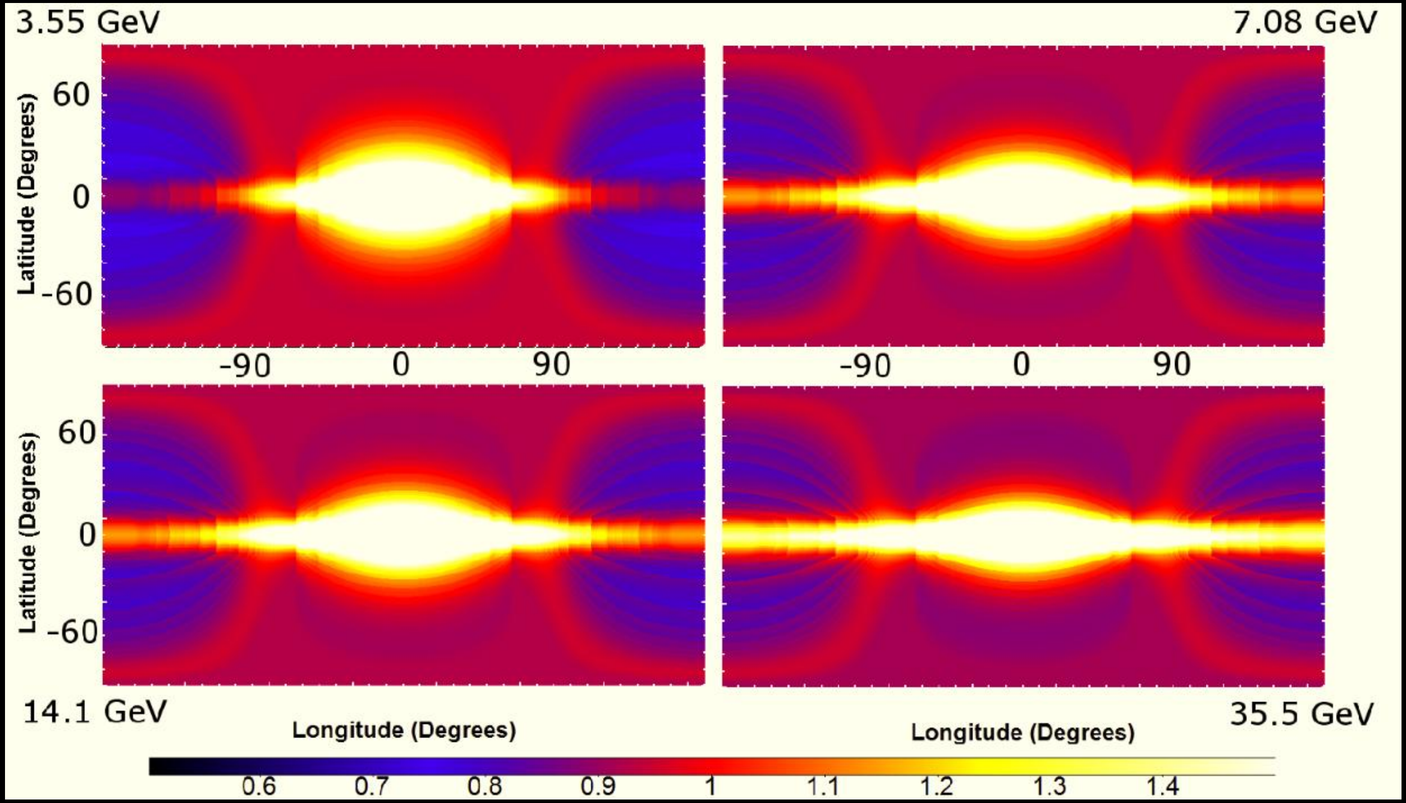
- 3.) New methods will be necessary to understand these observations

ICS / Sync is very uncertain

- By slightly altering the magnetic field morphology, we can create larger deviations

Flat magnetic field model

This model was used to generate the WMAP haze morphology



$$B = 10.0\ \mu G\ e^{-r/99.9\ kpc\ -z/99.9 kpc}$$

Possible Sources

- There are quite a few possible sources for this residual:
  - Nearby sources
  - Jets from galactic center
  - Magnetic anomalies (e.g. Loop 1 – Casandjian et al. 2009, 0912.3478)
  - Changes in the Interstellar radiation field
  - Energy dependence changes in diffusion parameters
- But it is very difficult to match emission using purely diffuse sources or spherical distributions, as they will always have more longitudinal extent.

How do we distinguish?

- New methods are necessary for distinguishing between various emission mechanisms
  - Multi-wavelength studies
  - Anisotropic studies

Multi-wavelength Studies

- Several Important cross-checks:
  - WMAP – Energetic leptons should also produce microwave radiation through synchrotron in the galactic B-field
  - ROSAT – SNR and galactic anomalies may produce X-ray signatures
  - PAMELA – New primary sources may match the observed positron/electron spectrum
  - HESS – Very high energy γ-ray's should match these observations

Boost Factors

- We multiply the simulated haze by a universal constant to match the observed WMAP haze at 10 degrees latitude and 23 Ghz.

$\Phi = \rho^2(x)/M_{DM}^2 \ \langle\sigma v\rangle$ $\qquad \langle\sigma v\rangle \sim 3 \times 10^{-26}\ cm^2 s^{-1}$

- Changes in $\langle\sigma v\rangle$
- Density fluctuations in DM substructure
- Sommerfield enhancements

Role of Diffusion

- Without diffusion, the DM profiles actually suggest a much flatter distribution
- Diffusion plays <u>counterintuitive</u> role of increasing the falloff in emission at high latitudes