Title: GeV Gamma-Rays from the Central Milky Way and the Case for Annihilating Dark Matter

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Abstract: Past studies have identified a spatially extended excess of ~1-3 GeV gamma rays from the Galactic Center and inner Galaxy, consistent with the emission expected from annihilating thermal relic dark matter. I will describe recent improvements in the characterization of this signal, which demonstrate that it is spherically symmetric, centered on the Galactic Center, and with a spatial profile consistent with annihilation from a cusped NFW profile. The excess can be detected out to 10 degrees from the Galactic Center, which poses challenges for a millisecond pulsar origin; I will discuss the implications of a dark matter interpretation.

GeV Gamma-Rays from the Central Milky Way and the Case for Annihilating Dark Matter

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March 26, 2014

Based on arXiv:1402.6703 with

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Nick Rodd — MIT

Dan Hooper, Tim Linden — University of Chicago / Fermilab

The claim

- After subtracting modeled backgrounds, we detect a broad-spectrum gamma-ray excess in the Galactic Center and inner Galaxy, with the following properties:
  - Peaking at ~1-2 GeV in $E^2 dN/dE$ and no strong detection below 0.5 GeV or above 10 GeV.
  - Consistent with spherical symmetry about the GC; we can exclude axis ratios larger than ~1.2 along the Galactic plane. (Mild hint of extension along an axis 35 degrees off the plane, with axis ratio ~1.3).
  - When modeled by a squared, projected NFW profile, prefers a small-r slope ~1.1-1.2 in the Galactic Center analysis, 1.2-1.3 in the inner Galaxy analysis (hints of steepening at larger radii).
  - Centered on Sgr A* to within 0.05 degrees.
  - Detected out to 10 degrees from the GC.
  - Spectrum well described by 20-50 GeV DM annihilating to (mostly) quarks with a ~thermal relic annihilation cross section.

• Spectrum well described by 20-50 GeV
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Outline

- Review of previous studies of this excess in the Galactic Center + inner Galaxy.
- Methodology - characterizing the diffuse background, modeling a potential dark matter signal.
- What is new - implementation of cut on CTBCORE, allowing new analyses testing sphericity, centering, density profile.
- Interpretation as dark matter, brief overview of alternatives.

Why WIMPs?

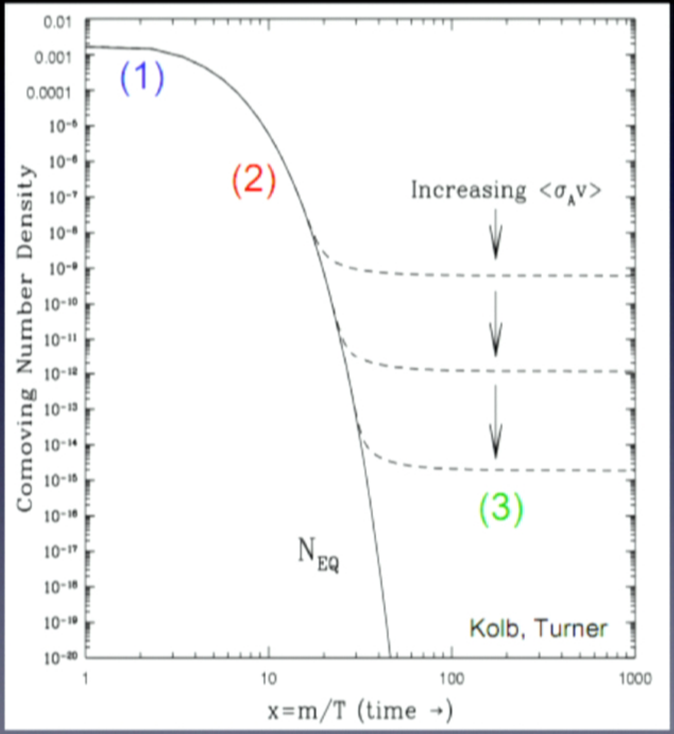
- In the early universe, let the DM particle be thermally coupled to the SM. Can annihilate to SM particles, or SM particles can collide and produce it.

$$\chi\chi \leftrightarrow \mathrm{SM\,SM} \quad (1)$$

- Temperature(universe) < particle mass => can still annihilate, but can't be produced.

$$\chi\chi \rightarrow \mathrm{SM\,SM}$$
$$\chi\chi \not\leftarrow \mathrm{SM\,SM} \quad (2)$$

- Abundance falls exponentially, cut off when timescale for annihilation ~ Hubble time. The *comoving* dark matter density then <u>freezes out</u>.



So (known) late-time density is set by annihilation rate.

$$\langle\sigma v\rangle \sim 3\times 10^{-26}\mathrm{cm}^3/\mathrm{s} \sim \pi\alpha^2/(100\,\mathrm{GeV})^2 \quad (3)$$


density then freezes out.
$\langle \sigma v \rangle \sim 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$

Dark matter in gamma rays

- DM does not carry electric charge, does not couple directly to photons (it is "dark").
- But it can annihilate to something that produces photons - those photons should be in a similar energy range to the DM mass (but lower).
- For WIMPs, this means gamma rays.

Line signal - typically suppressed

$$\chi\chi \to \gamma\gamma \qquad \chi\chi \to \gamma Z$$

"Smoking gun" - distinctive spectral feature

We can use both spectral information (dependence on energy) and spatial information (dependence on location) to try to distinguish dark matter signals from astrophysics.

Continuum signal (example)

$$\chi\chi \underset{?}{\to} \tau^+\tau^-$$

$$\tau^- \underset{25\%}{\to} \pi^-\pi^0\nu_\tau$$

$$\underset{9\%}{\to} \pi^-2\pi^0\nu_\tau$$

$$\pi^0 \underset{99\%}{\to} \gamma\gamma$$

Expected to be a much larger signal in generic models, but not background-free.

Features of a DM signal

- Spectral information: backgrounds are mostly fairly smooth and power-law-like, a DM signal can be peaked and have a sharp cutoff near the DM mass.
- Spatial information: DM should have a roughly spherical distribution, not following the Galactic plane.
- There may be hot-spots corresponding to localized clumps of DM / satellite galaxies, but the signal is generally predicted to be brightest from the Galactic Center.
- The signal scales as DM density squared as annihilation is a two-particle process, we parameterize DM density by "generalized NFW profile" (motivated by simulations):

$$\rho \propto \frac{r^{-\gamma}}{\left(1 + \frac{r}{R_s}\right)^{3-\gamma}}$$

$\gamma = 1$ for classic NFW

"Scale radius" r_s ~ 20 kpc for Milky Way

The Fermi Gamma-Ray Space Telescope

- Launched successfully from Cape Canaveral on 11 June 2008.
- Now in low-Earth orbit, 340 mile altitude.
- Scans the entire sky every two orbits (~3 hours).
- Sensitive to gamma-rays from 300 MeV up to several TeV.
- All data is public.

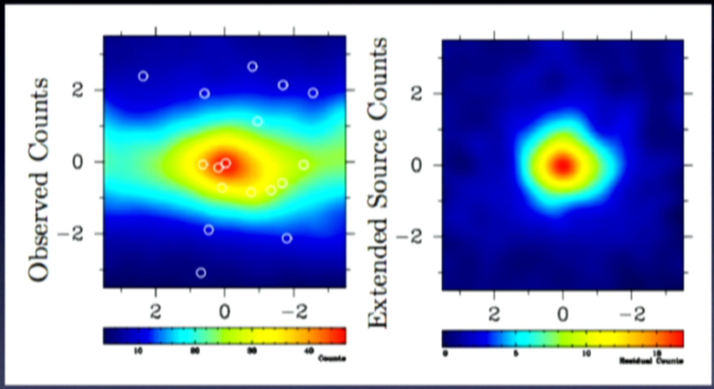
The Galactic Center excess

- First detected by Goodenough & Hooper 2009.
- Since confirmed by several groups (Hooper & Goodenough 1010.2752, Boyarsky, Malyshev & Ruchayskiy 1012.5839, Hooper & Linden 1110.0006, Abazajian & Kaplinghat 1207.6047, Gordon & Macias 1306.5725 + 1312.6671, Abazajian, Canac, Horiuchi & Kaplinghat 1402.4090).
- Diffuse background modeling usually done using Fermi Collaboration diffuse model. Early studies used power-law extrapolation in to Galactic center. Most recent studies add templates for gas clouds.
- Most studies done using software tools released by the Fermi Collaboration.

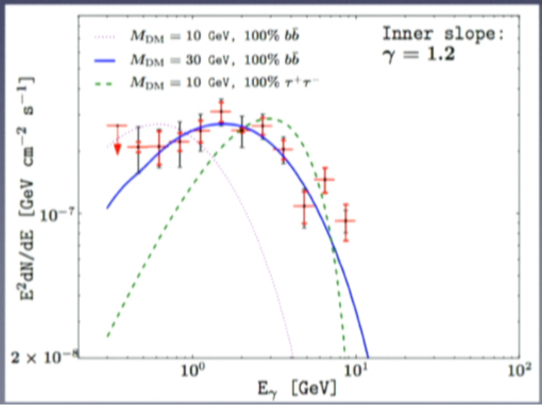
The Galactic Center

- Excess peaks at a few GeV, spectrum consistent with ~30 GeV DM annihilating to $b\bar{b}$.
- Localized around the GC (typical ROIs are a few degrees around the GC).
- Roughly spherical morphology, with flux/volume scaling with Galactocentric radius approximately as $r^{-2.0\text{-}2.6}$
- Some variation in preferred spectrum depending on background modeling (e.g. whether light DM to tau's is acceptable).

spatial distribution Abazajian & Kaplinghat 2012



spectrum Gordon & Macias (1306.5725)



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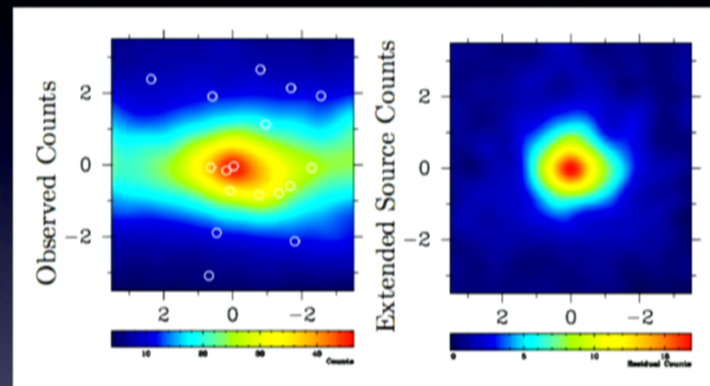

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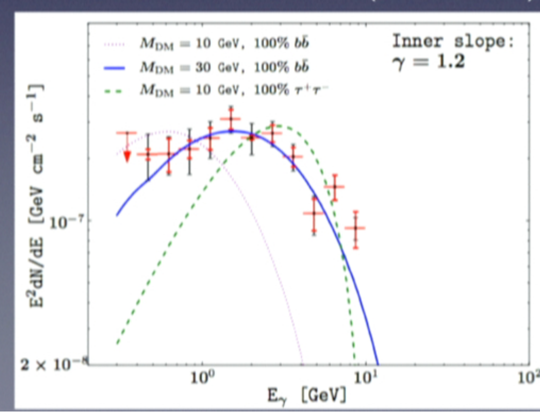

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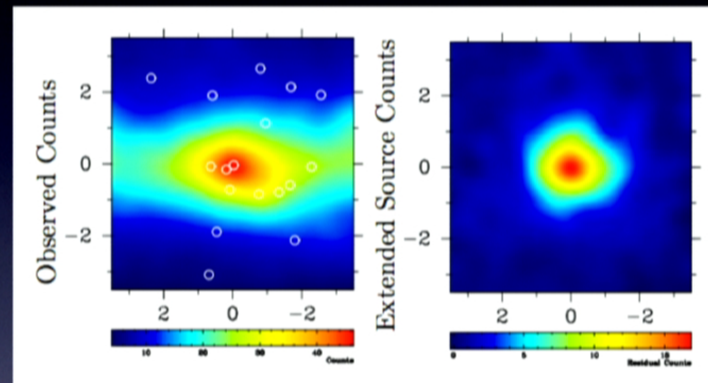

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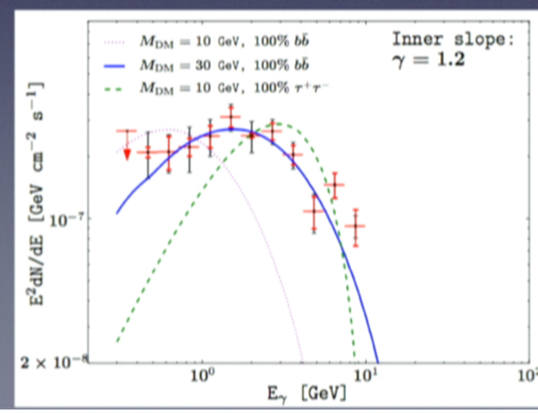
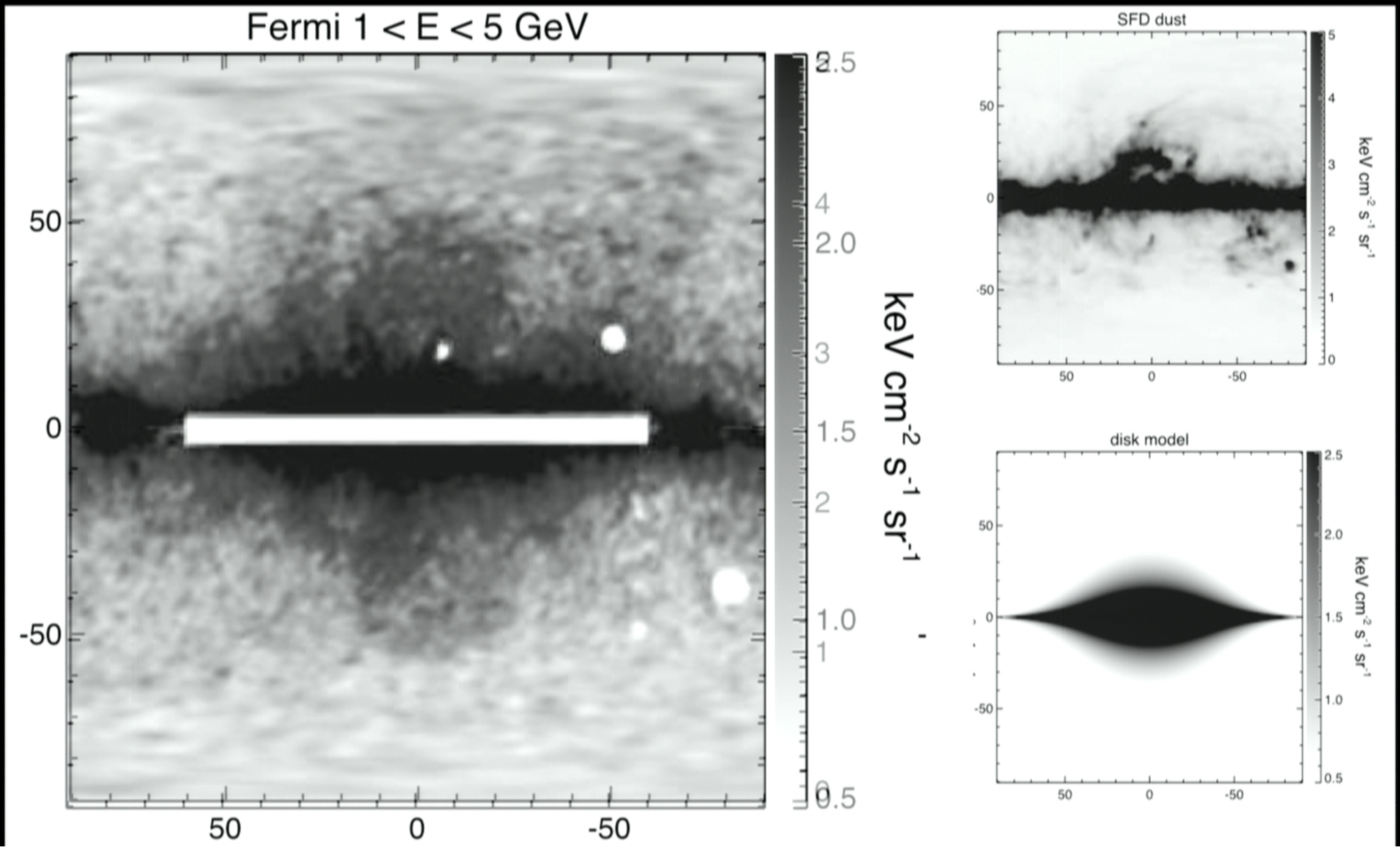
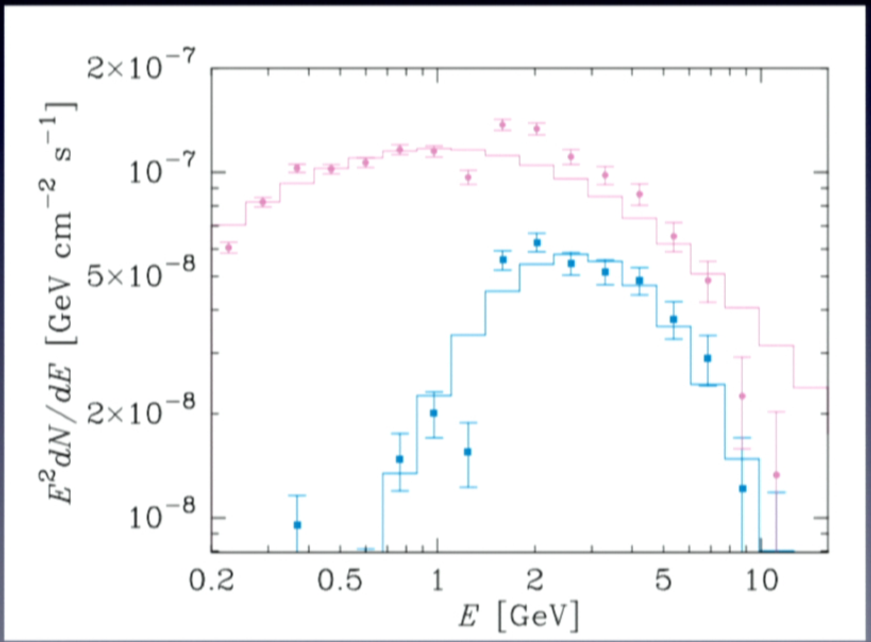


Dust and ICS removal



Notes

- Angular resolution of Fermi at low energies is non-negligible compared to signal extent.
- Questions about robustness of results to diffuse background modeling, especially at low energies.
- Not a statistical fluctuation - delta log likelihood is always large, ~100 or higher depending on background modeling.
- Seems possible to explain with either (a few thousand) millisecond pulsars or DM.



Abazajian, Canac, Horiuchi & Kaplinghat 1402.4090

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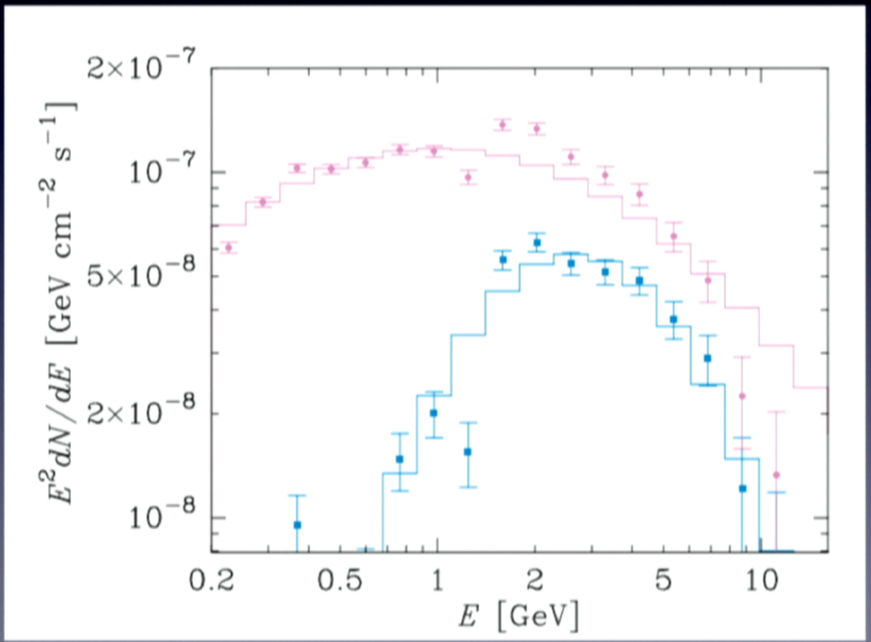


Abazajian, Canac, Horiuchi & Kaplinghat 1402.4090

The sources of diffuse weak-scale gamma rays

- Two main types of charged cosmic rays - electrons and protons.
- Two main targets - the interstellar gas, and the sea of photons pervading the galaxy:
  - Starlight
  - Infrared radiation from thermal emission
  - The cosmic microwave background (residual photons from early universe)
- These scatterings produce diffuse gamma rays, from upscattering of radiation-field photons or decay of neutral pions produced in hadronic collisions.
- There are also gamma-ray point sources, Galactic and extra-Galactic - pulsars, active galactic nuclei, etc.

A simple model for Galactic gamma rays

Good maps!

:-)

Roughly constant across the Galaxy; assume constant

gas density x cosmic ray proton density

\+ gas density x cosmic ray electron density

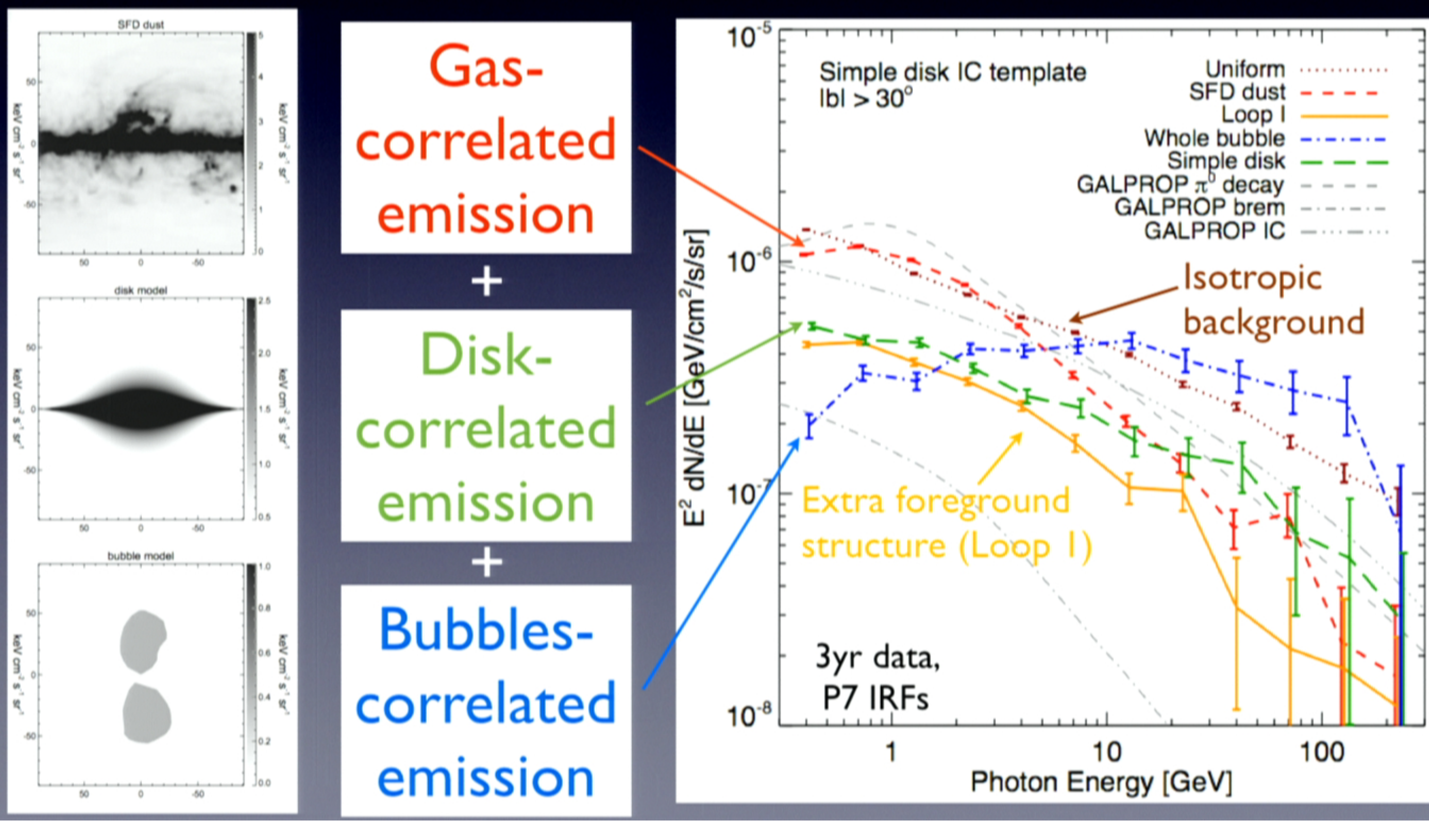
Always subdominant; neglect

\+ photon density x cosmic ray electron density

Should follow disk, where stars + supernovae are concentrated - put in some simple disk-like profile

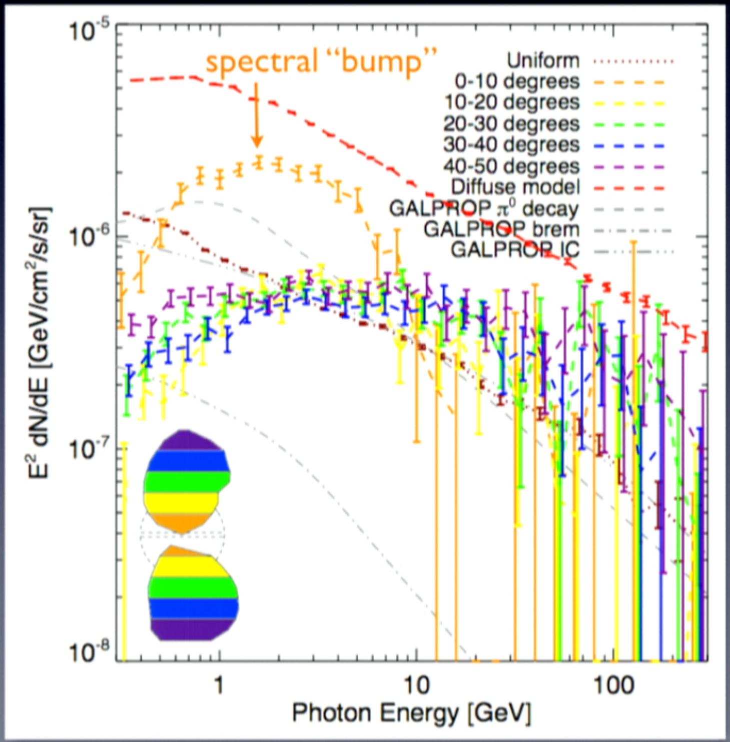
Detailed model by the Fermi Collaboration uses same principles, models cosmic ray distribution using GALPROP.

Template fitting



The inner Galaxy excess

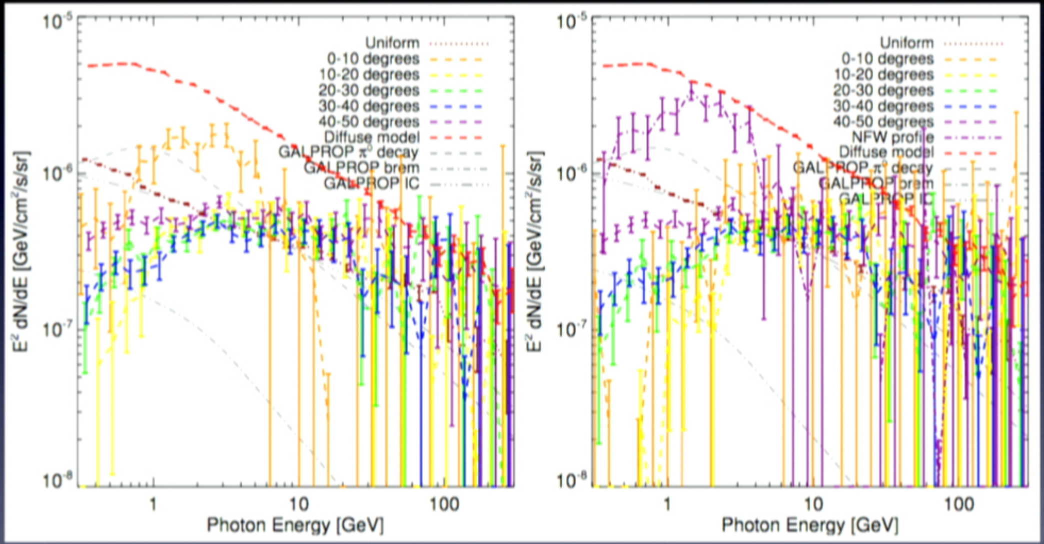
- Use Fermi diffuse model as background template (+ isotropic background).
- Allow Bubbles spectrum to vary with latitude.
- The spectrum of the Bubbles develops pronounced curvature at low Galactic latitudes.
- Consistent with two components, one flat in $E^2 dN/dE$ and latitude, the other with a bump at few-GeV energies and falling rapidly with latitude (flux/volume~$r^{-2.4}$).



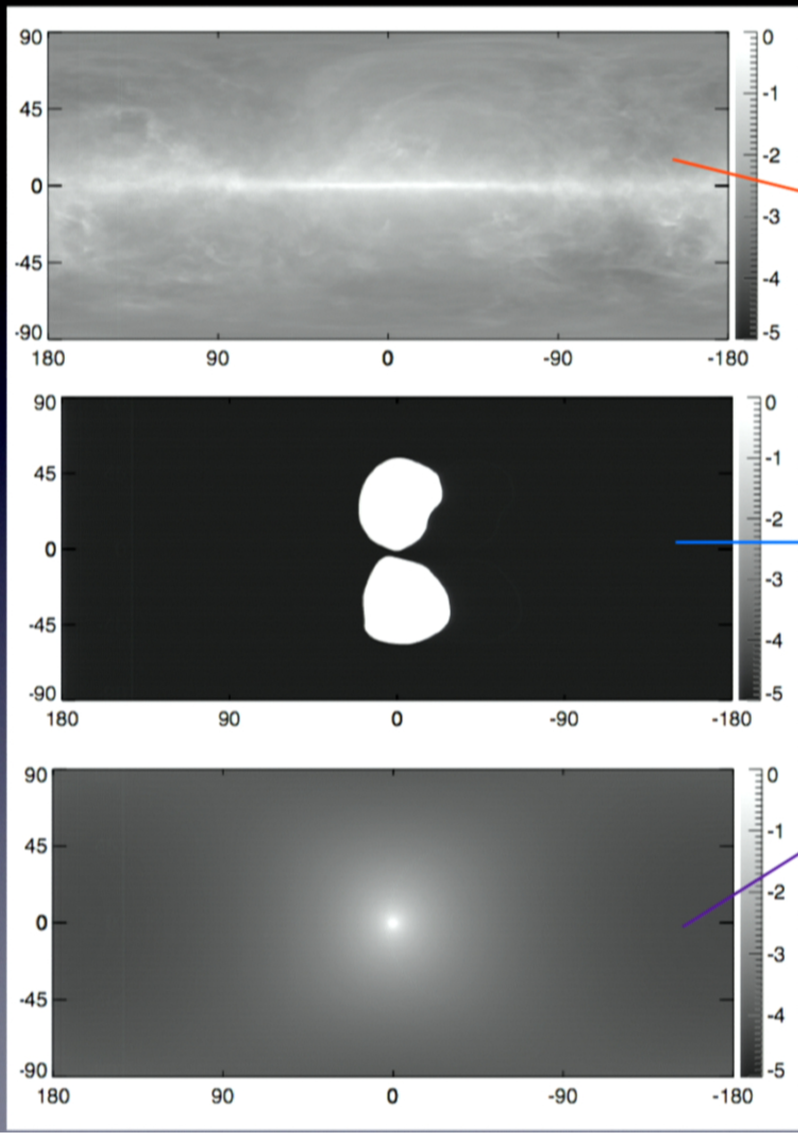
A DM-like morphology?

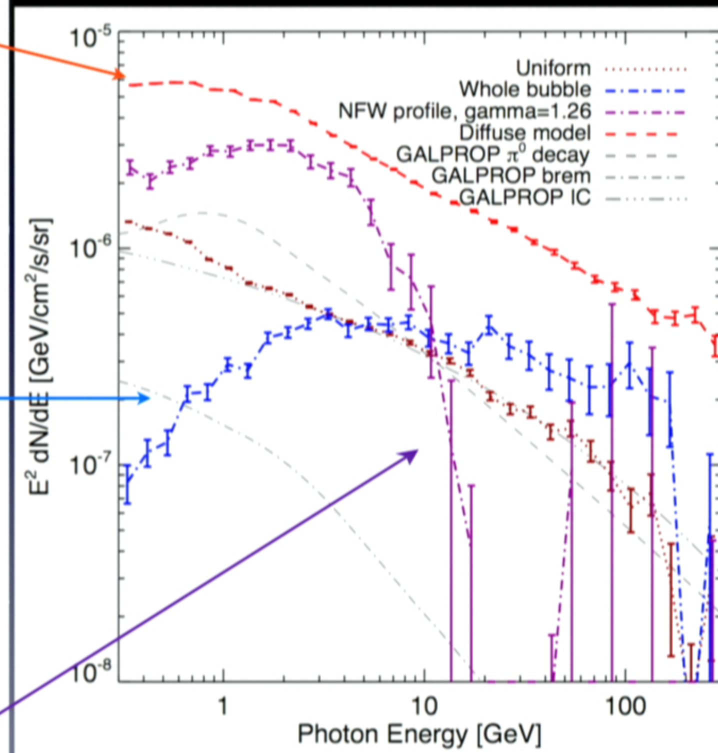
When given the choice, the fit prefers to correlate the spectral bump with a DM-like template, not the bubbles.

We subsequently adopted this approach (correlation with a DM-like template) for extracting the spectrum of the excess.



- To avoid structures in the north (e.g. Loop 1), fit in the southern sky only; mask the area where b > -5° to minimize disk emission. This should be a "clean" fit (and no spatial overlap with previous GC analyses).
- Left panel: bubble templates only, right panel: NFW profile included.

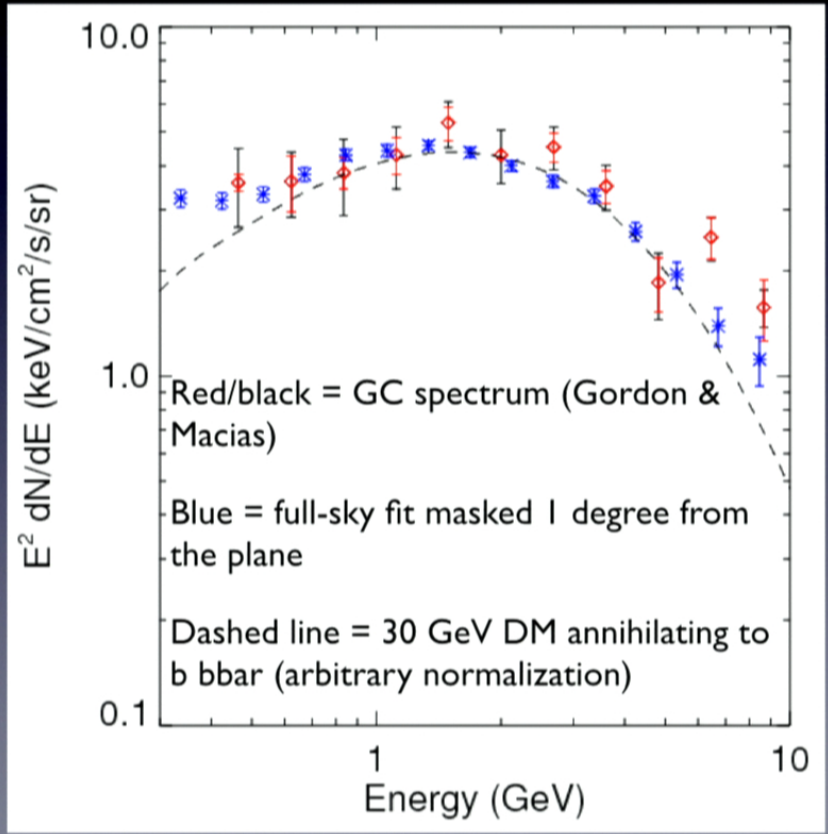




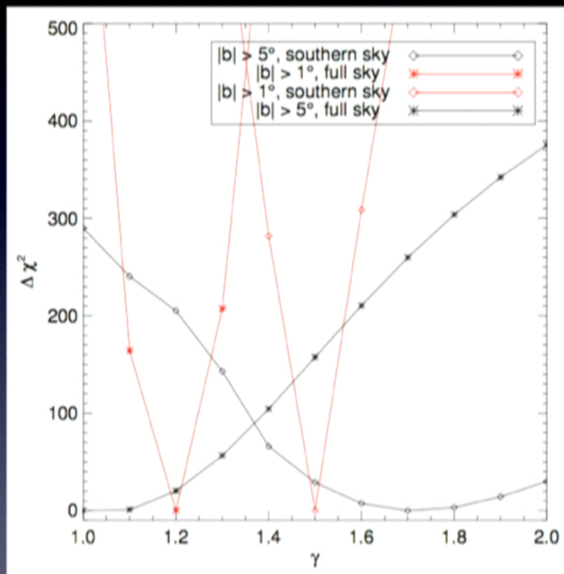
Use a single template for the Bubbles for simplicity; we have tested this does not bias the DM-template-correlated spectrum.

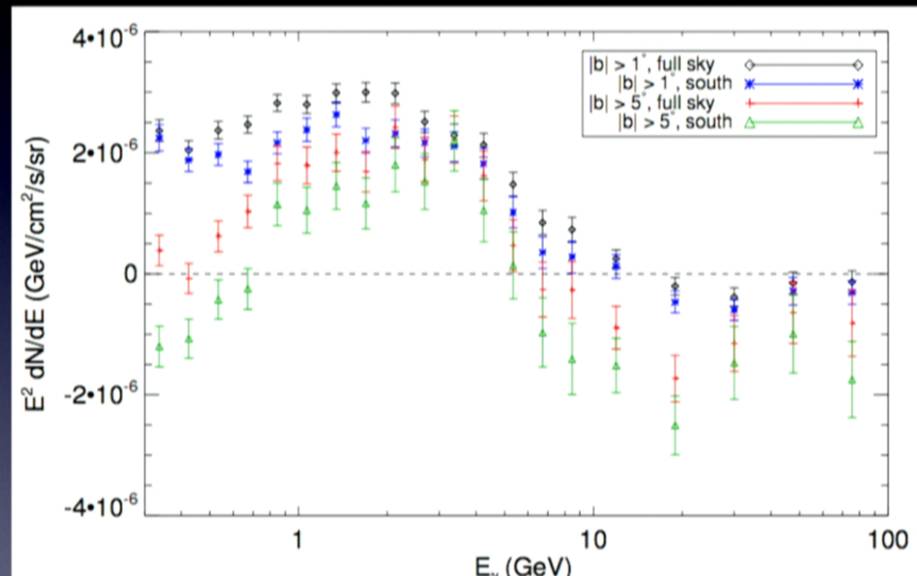
Inner Galaxy vs the GC

- Red/black points = Gordon & Macias '13 analysis of Galactic Center signal, normalized assuming a generalized NFW profile with $\gamma=1.2$.
- Blue points = spectrum correlated with DM-like template from the full-sky fit in 1302.6589, masking 1 degree from the Galactic plane.
- The two signals are in remarkable agreement, and almost certainly share an origin.



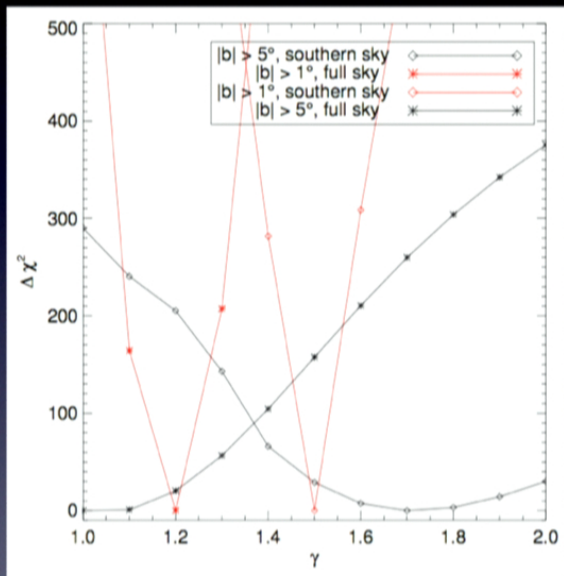
Spectral variation

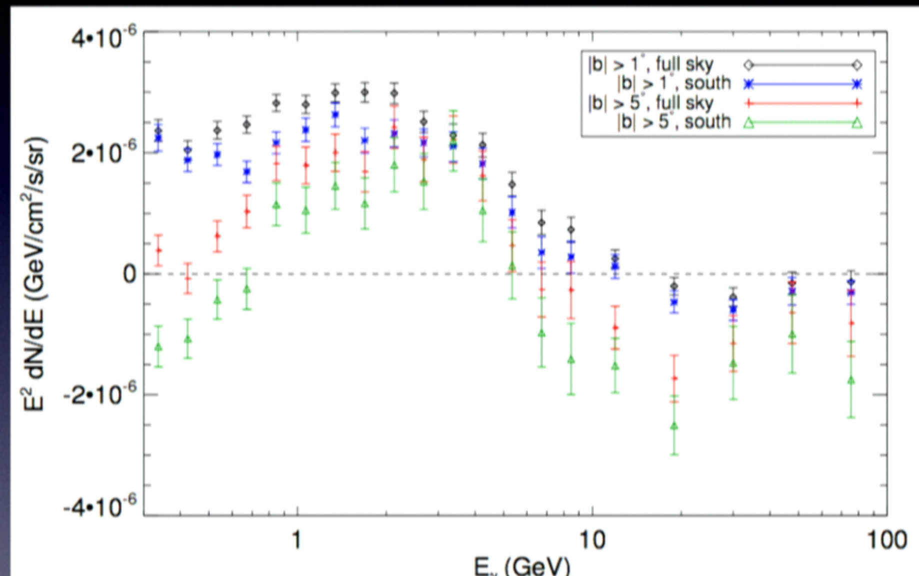




- Extracted spectrum depends on masking of the Galactic plane and north/south, as does power-law slope of profile.
- Differences between spectra well explained by mis-subtraction of few percent of diffuse background.

Spectral variation





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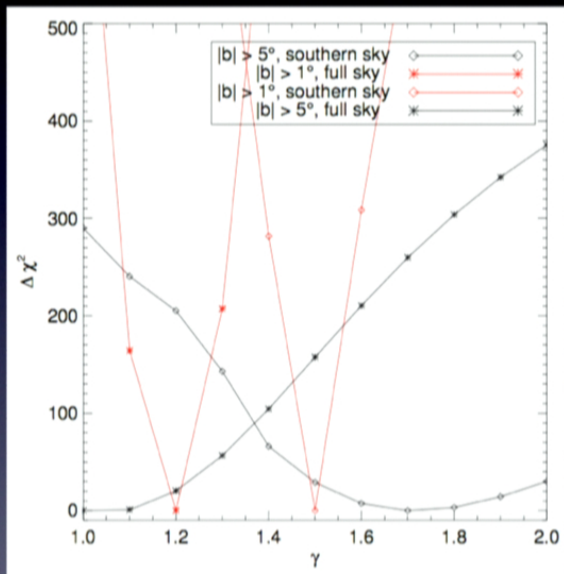

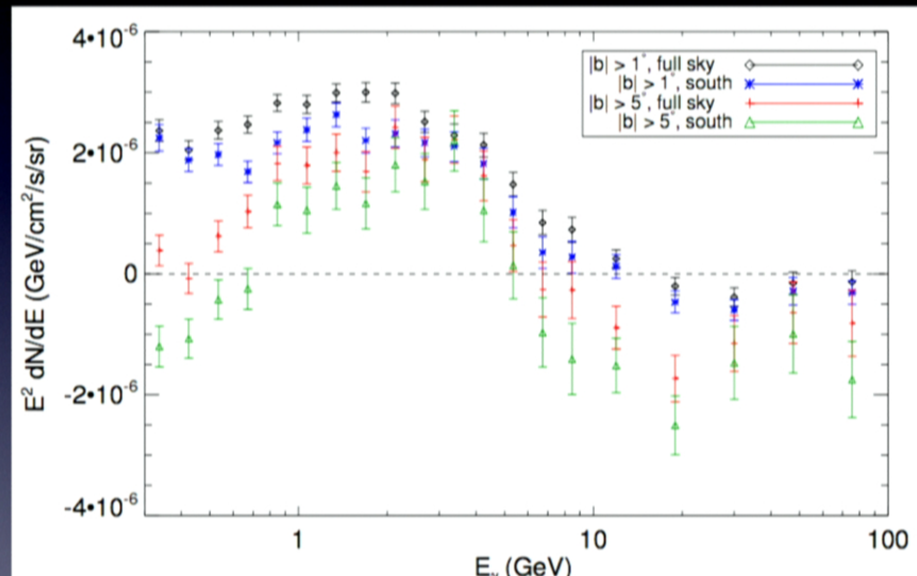

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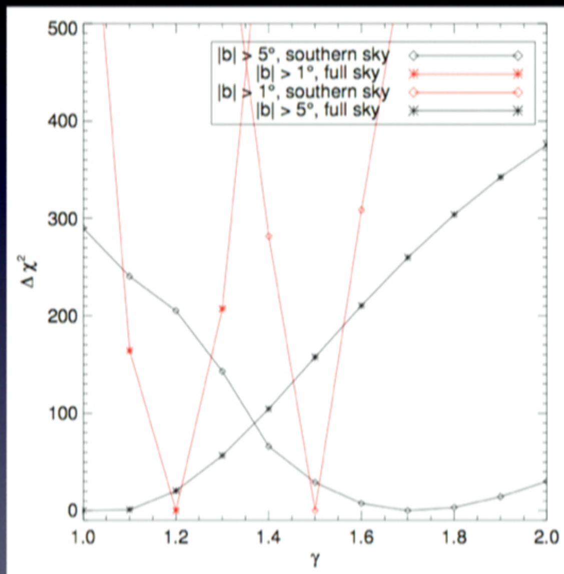

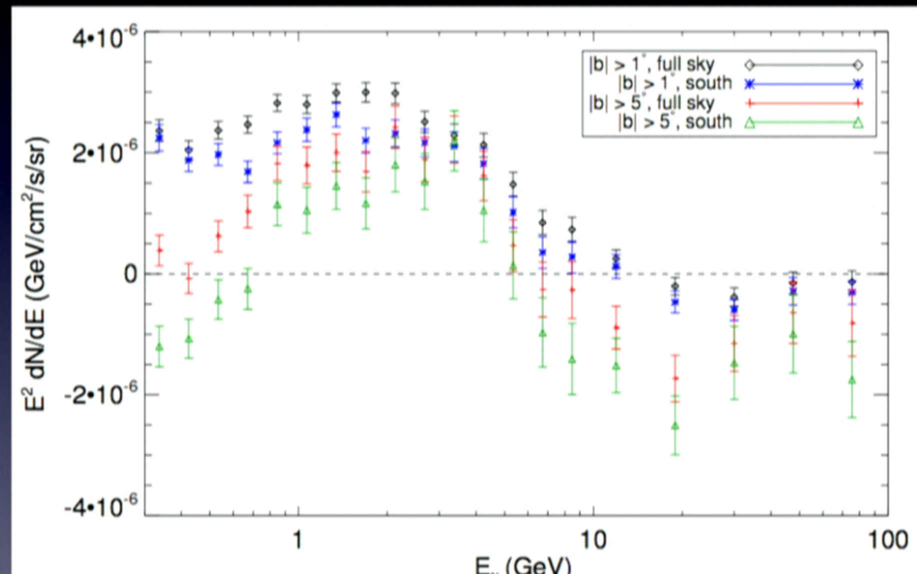

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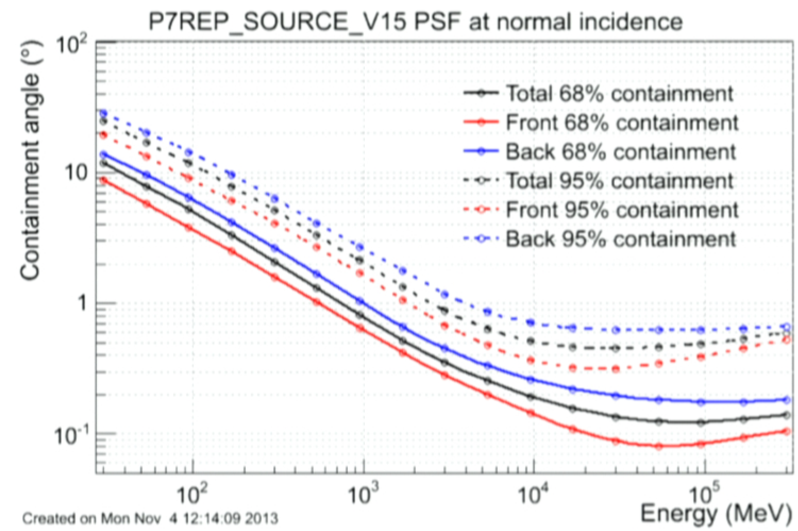
A high-angular-resolution data sample

- We are relying entirely on spatial information to distinguish the different diffuse emission components.
- The angular resolution of Fermi is quite poor at low energies, and the tails of the point spread function (PSF) are significantly non-Gaussian.
- Could better angular resolution improve our ability to separate out the diffuse background?

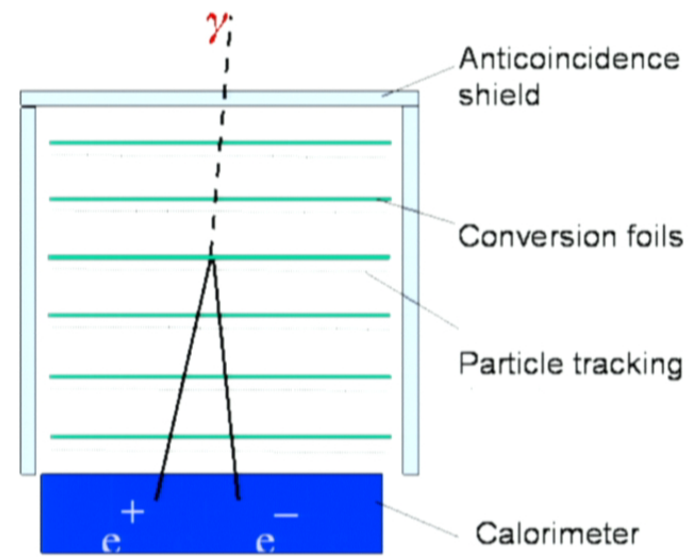


Fermi-LAT Performance

http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

CTBCORE

- Gamma rays pair produce in tungsten conversion foils. Resulting shower of secondaries is tracked through silicon strip detectors.
- Below 10 GeV, PSF limited by multiple scattering of pair in conversion foil.
- Missed tracker hits and hard scattering contribute to PSF tails.
- Classification tree estimates quality of direction reconstruction on event-by-event basis, parameterizes by "CTBCORE".



Fermi Science Support Center Cicerone
http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/

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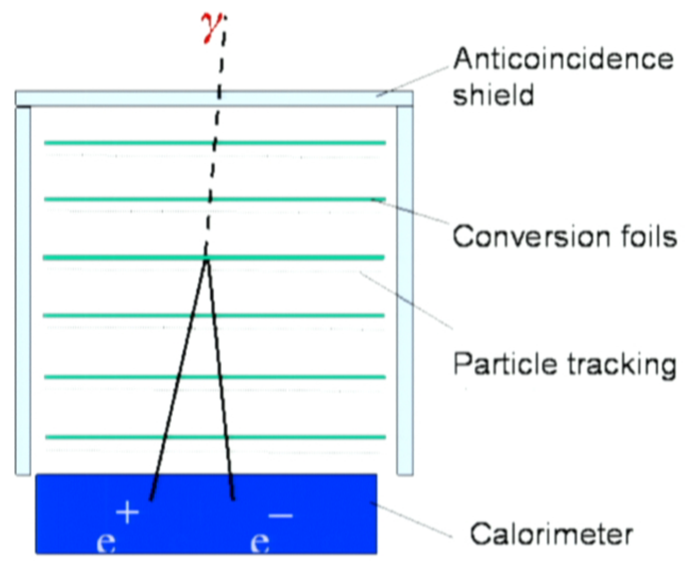

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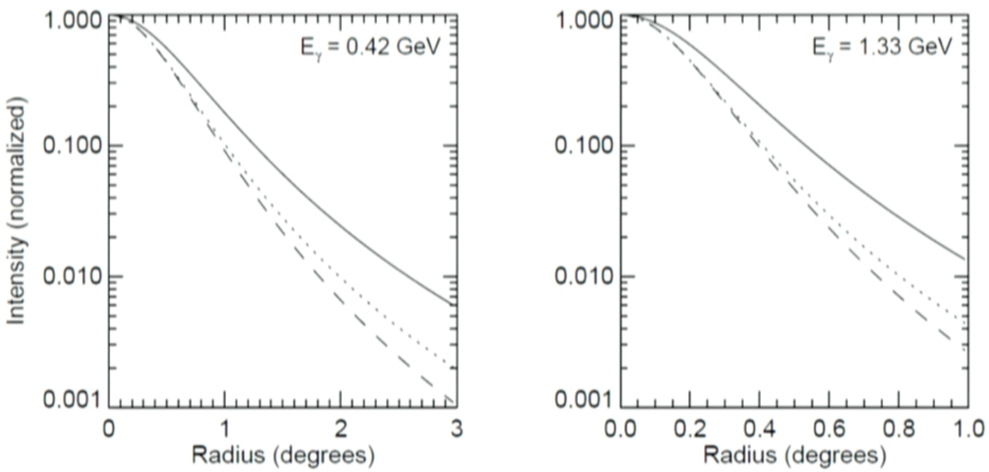
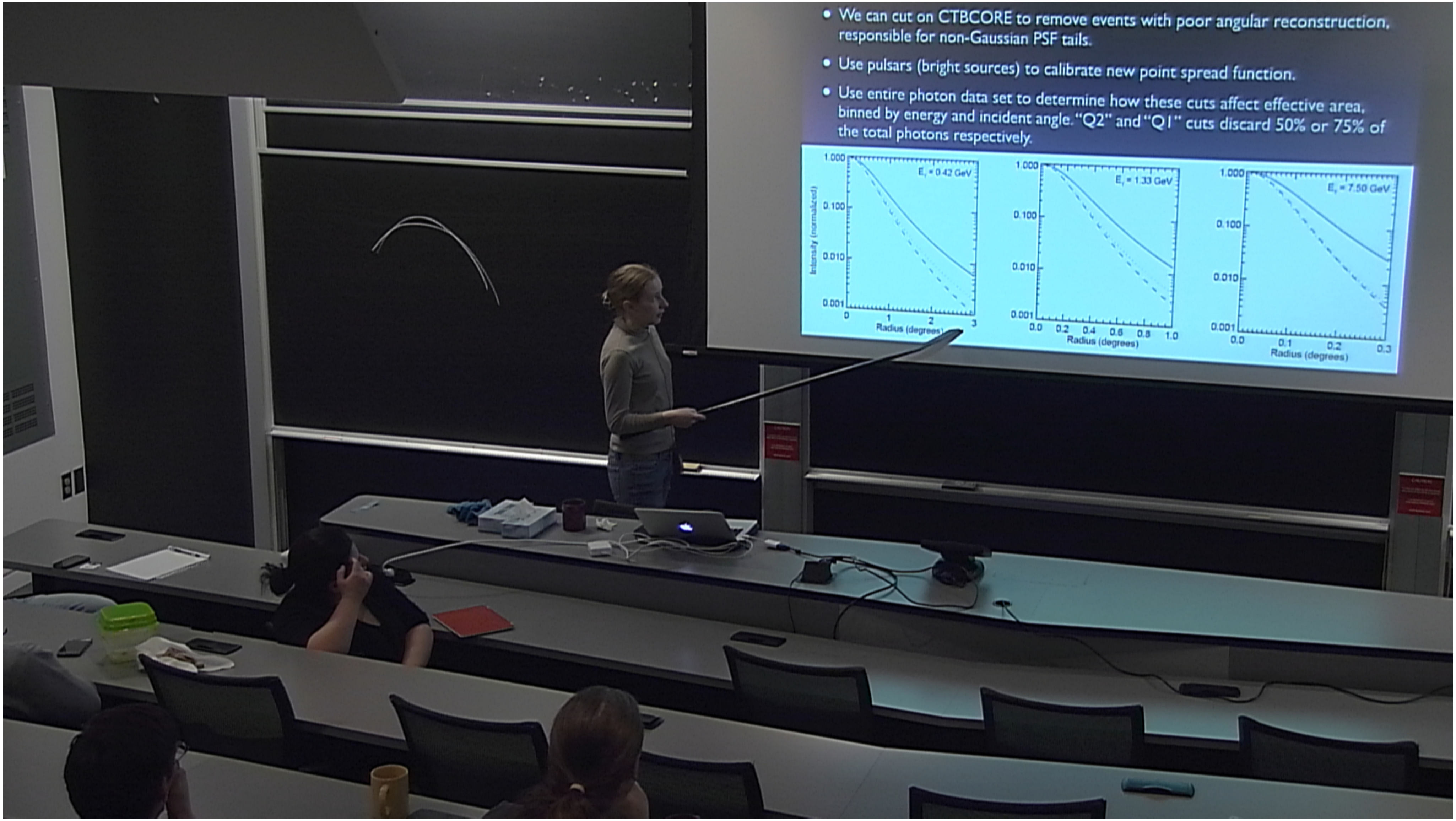
Using CTBCORE

- We can cut on CTBCORE to remove events with poor angular reconstruction, responsible for non-Gaussian PSF tails.
- Use pulsars (bright sources) to calibrate new point spread function.
- Use entire photon data set to determine how these cuts affect effective area, binned by energy and incident angle. "Q2" and "Q1" cuts discard 50% or 75% of the total photons respectively.





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E = 0.42 GeV
E = 1.33 GeV
E = 7.50 GeV
Intensity (normalized)
Radius (degrees)

Using CTBCORE

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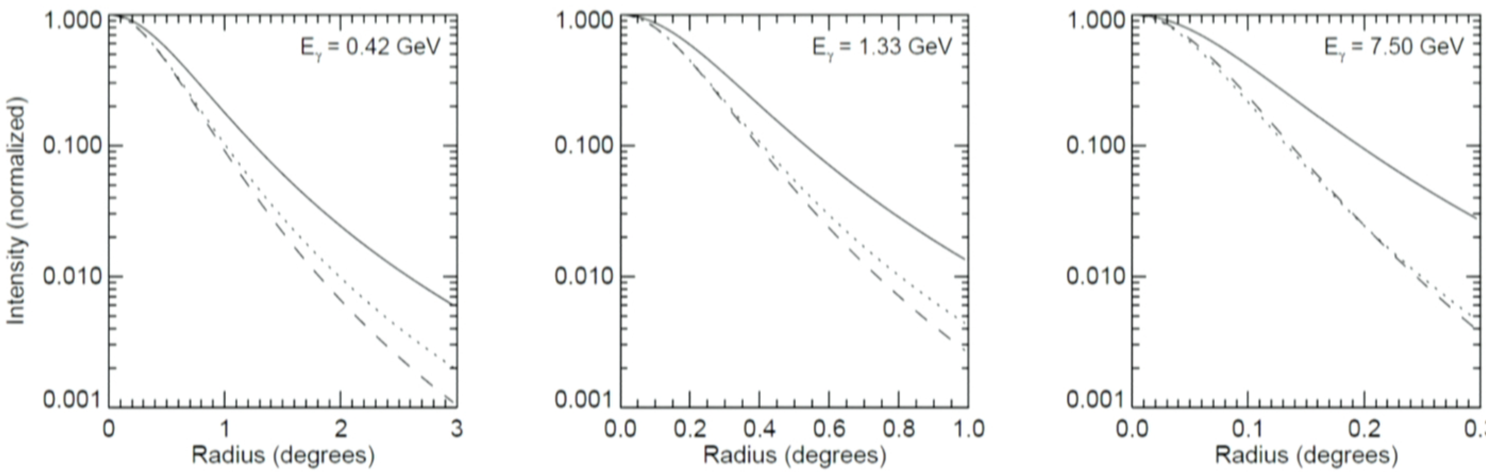
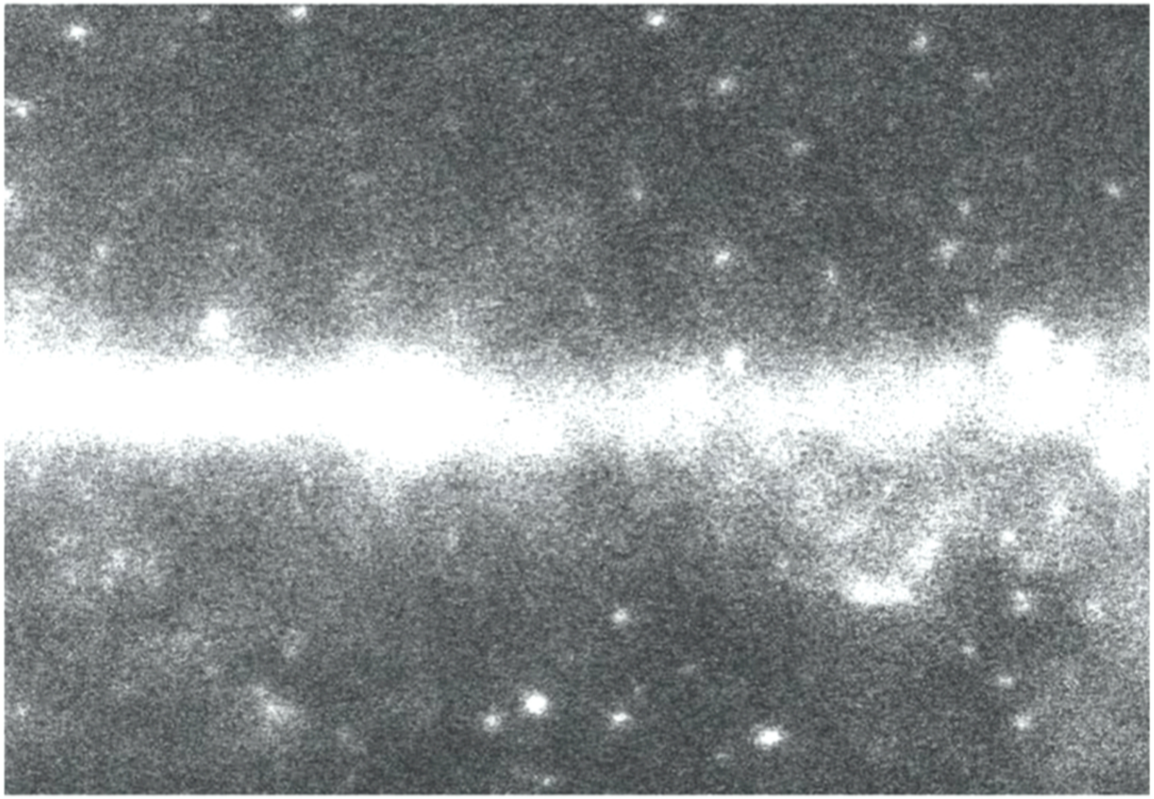
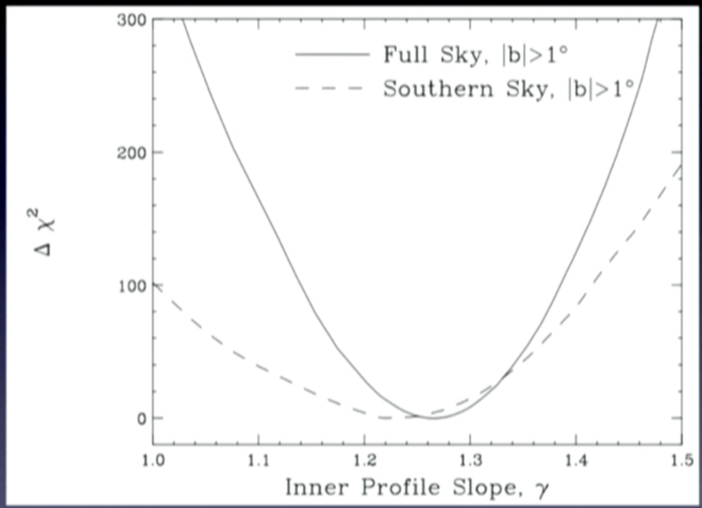


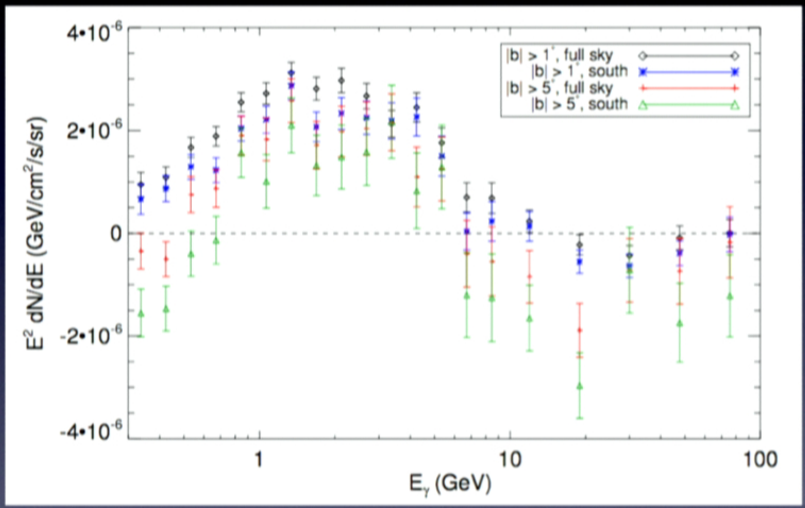
0.3-0.5 GeV, CLEAN (front)



Thanks to Stephen Portillo for providing these slides

Effects of CTBCORE cut





- Removing PSF tails seems to significantly improve consistency between spectra in different regions of the sky, removes north-south asymmetry.
- Preferred slope in inner Galaxy analysis is now 1.26 - consistent for all bins between 0.5 GeV and 10 GeV.

CTBCORE in the Galactic Center

- Redo likelihood analysis using CTBCORE-cut data and new instrument response functions.
- Model backgrounds with diffuse model + 2FGL point sources + template tracing observed 20cm emission. Allow flux and spectrum of bright sources to vary, or just amplitude of spectrum for more distant or lower-significance sources.
- Take iterative approach - start with seed spectrum for dark matter component, fit for normalization and spectral shape of astrophysical components. Then fix astrophysical components to their best-fit values, fit for DM component in each energy bin. Iterate resulting DM spectrum.

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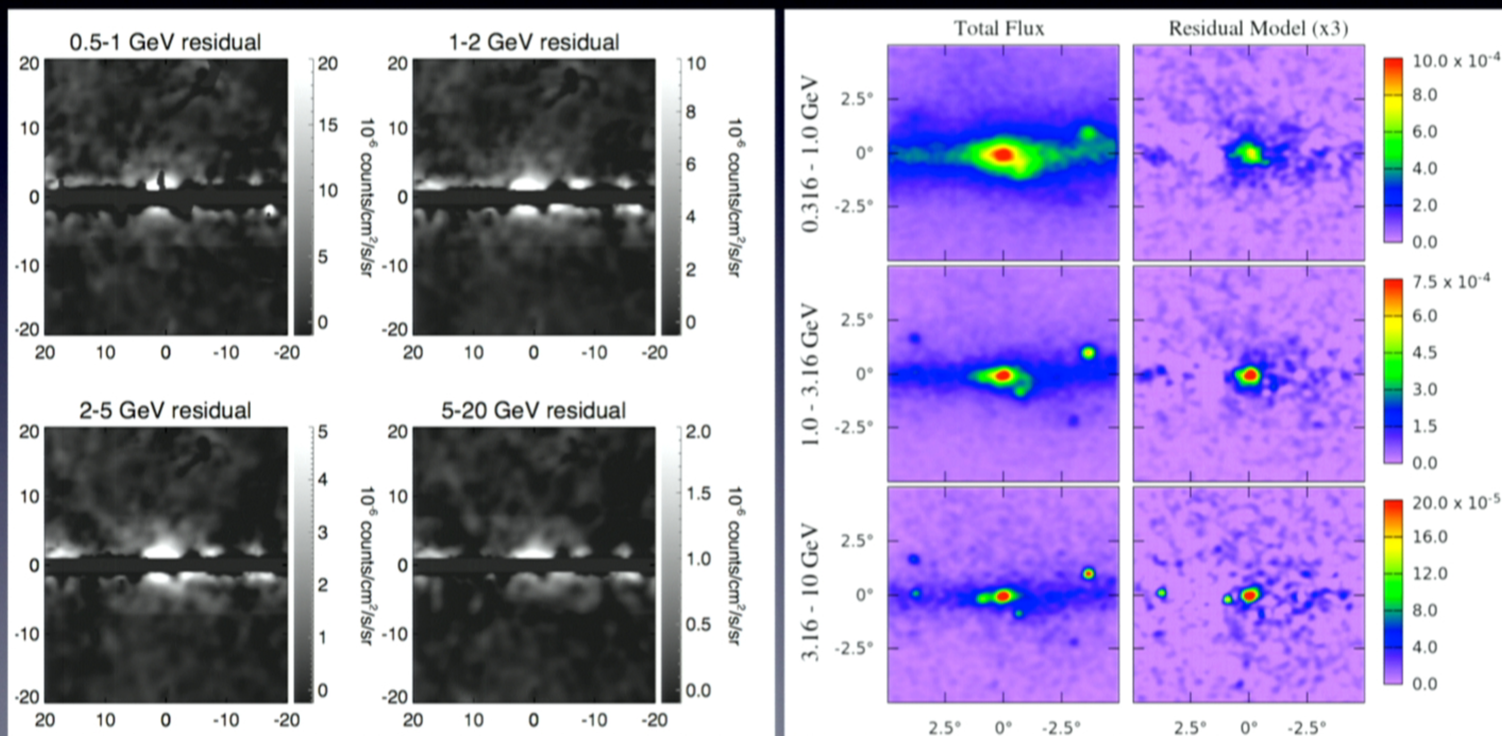
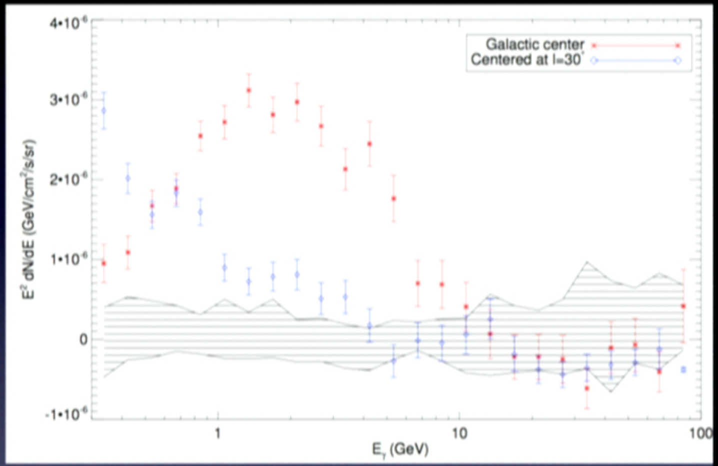
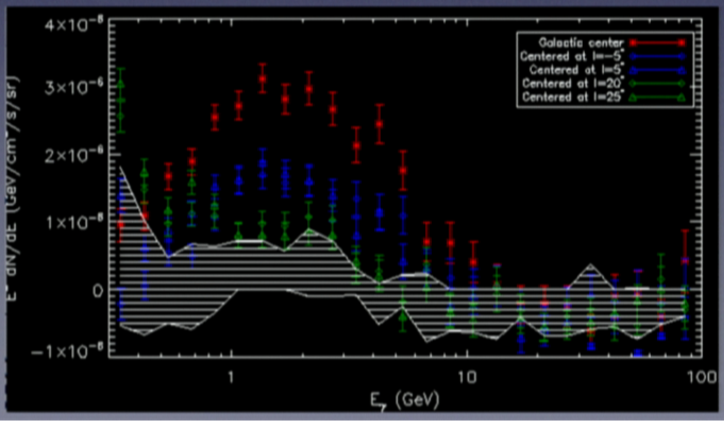
Spatial residuals



Residual disk emission

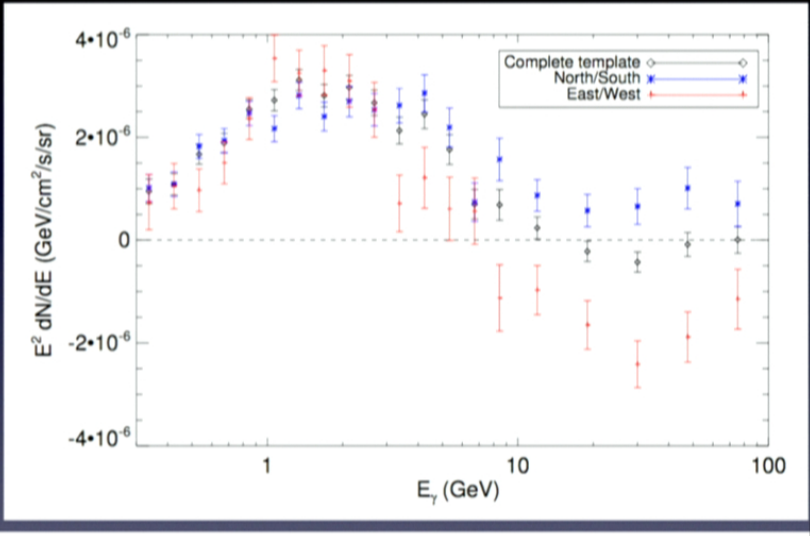
- Simple look-elsewhere test: do we see this spectral feature elsewhere along the plane?
- Shift DM-like template in 30 degree steps along the Galactic plane, check correlated emission. (Lower panel: 5 degree steps within the inner 60 degrees.)
- We find one example of a substantial signal with a soft spectrum unlike the bump (around l~20-30 degrees), the other sample points show very little emission.

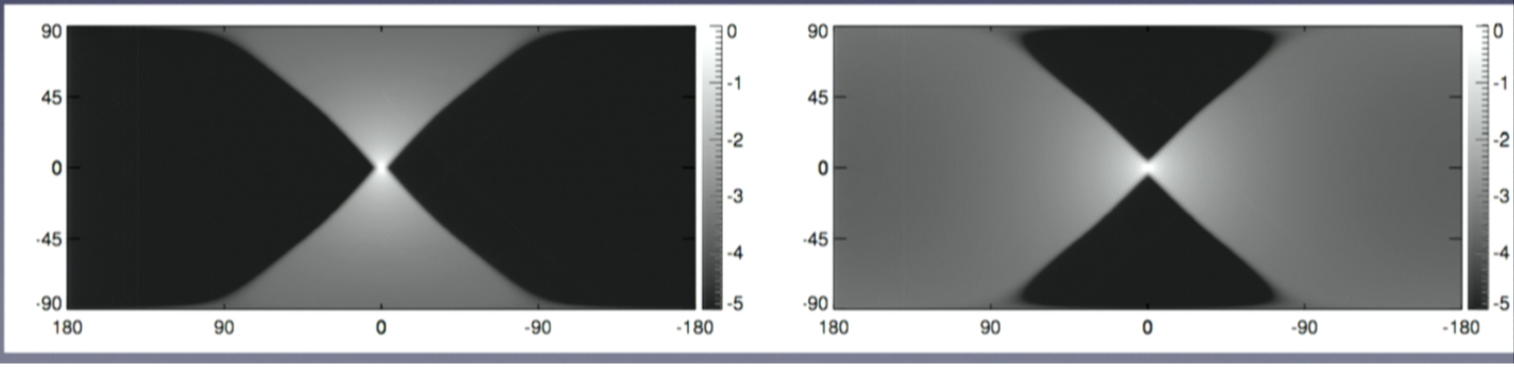




Symmetry about the GC

- Previous attempts to test e.g. presence of signal outside Bubbles suffered from large contamination by Galactic plane spectrum.
- CTBCORE cuts alleviate this problem.





Sphericity

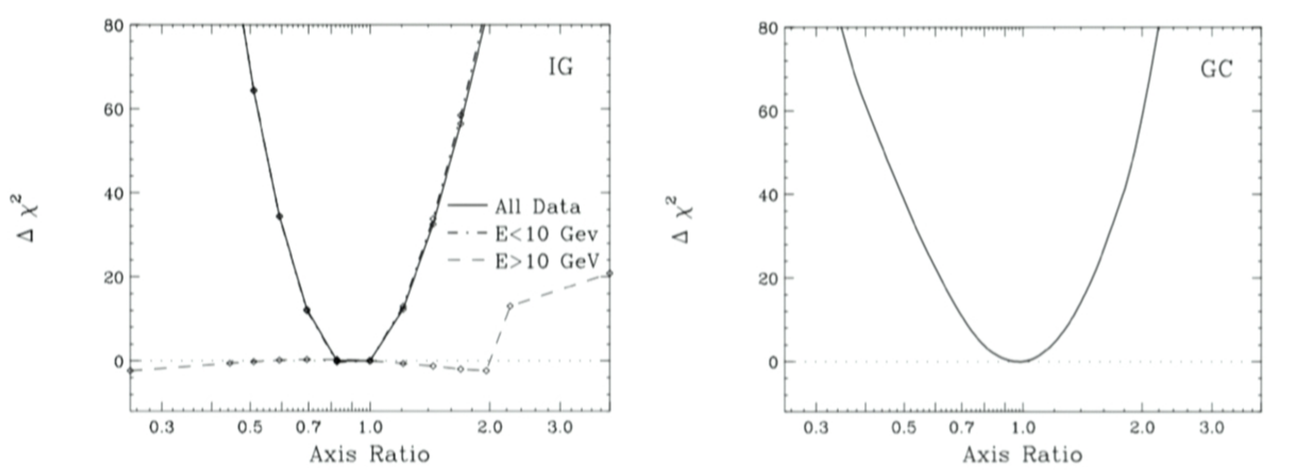


FIG. 10: The change in the quality of the fit, as performed in Sec. IV's Inner Galaxy analysis (left frame) and Sec. V's Galactic Center analysis (right frame), when breaking our assumption of spherical symmetry for the dark matter template. The axis ratio is defined such that values less than one are elongated along the Galactic Plane, whereas values greater than one are elongated with Galactic latitude. The fit strongly prefers a morphology for the anomalous component that is approximately spherically symmetric, with an axis ratio near unity.

- More generally, take NFW profile, stretch it along l or b. Test delta log likelihood for fit with stretched vs unstretched profile.
- In both IG and GC, can exclude axis ratio > 1.2 along plane, best-fit at axis ratio 1.

Orientation & centering

- Some mild evidence for a preference for elongation (axis ratio ~1.3) along an axis rotated 35 degrees from the Galactic plane.
- Test of centering constrains center to be within 0.05° of Sgr A*.

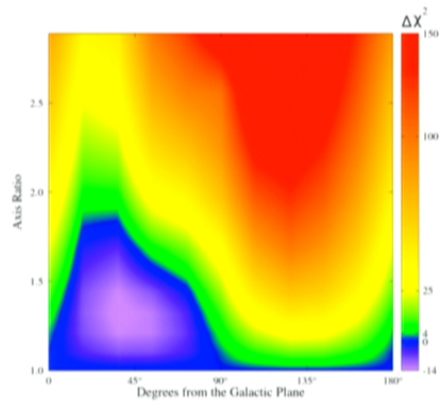


FIG. 11: The change in the quality of the fit in our Galactic Center analysis, for a dark matter template that is elongated along an arbitrary orientation (x-axis) and with an arbitrary axis ratio (y-axis). As shown in Fig. 10, the fit worsens if the this template is significantly stretched either along or perpendicular to the direction of the Galactic Plane (corresponding to 0° or 90° on the x-axis, respectively). A mild statistical preference, however, is found for a morphology with an axis ratio of ~1.3-1.4 elongated along an axis rotated ~35° counterclockwise from the Galactic Plane.

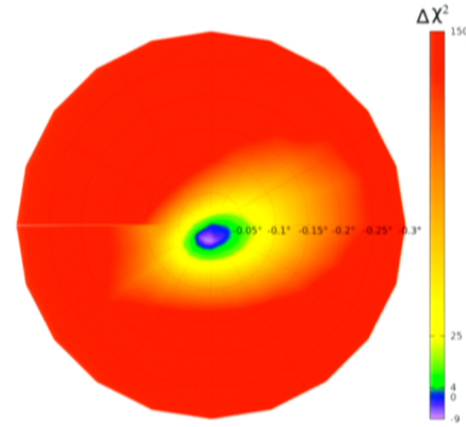


FIG. 12: To test whether the excess emission is centered around the dynamical center of the Milky Way (Sgr A*), we plot the $\Delta\chi^2$ of the fit found in our Galactic Center analysis, as a function of the center of our dark matter template. The fit clearly prefers this template to be centered within ~0.05° degrees of the location of Sgr A*.

Extension of the excess

- Instead of putting in a DM-like template for the emission by hand, model the emission as a series of concentric rings with the same spectrum (extracted from the inner Galaxy analysis) and allow the amplitude of each ring to vary independently.
- The signal is detected out to 10 degrees from the Galactic center.
- Prefers a steeper profile than earlier fits, $\gamma \sim 1.4$ (could be due to steepening of slope at larger r, or diffuse background mis-subtraction).

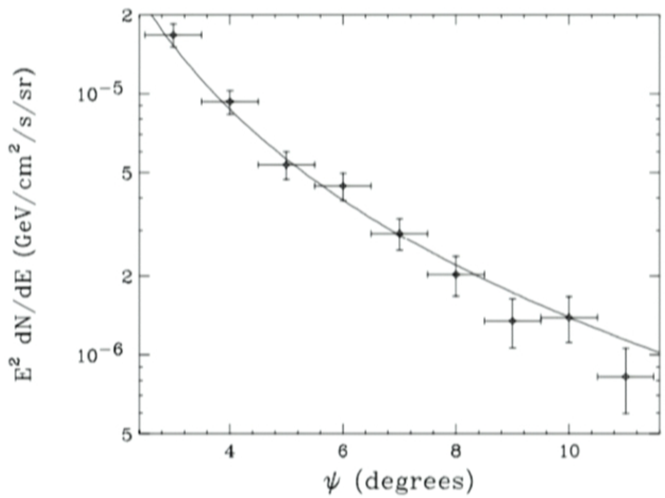


FIG. 13: To constrain the degree to which the gamma-ray excess is spatially extended, we have repeated our Inner Galaxy analysis, replacing the dark matter template with a series of concentric ring templates centered around the Galactic Center. The dark-matter-like emission is clearly and consistently present in each ring template out to $\sim 12^\circ$, beyond which systematic and statistical limitations make such determinations difficult. For comparison, we also show the predictions for a generalized NFW profile with $\gamma = 1.4$.

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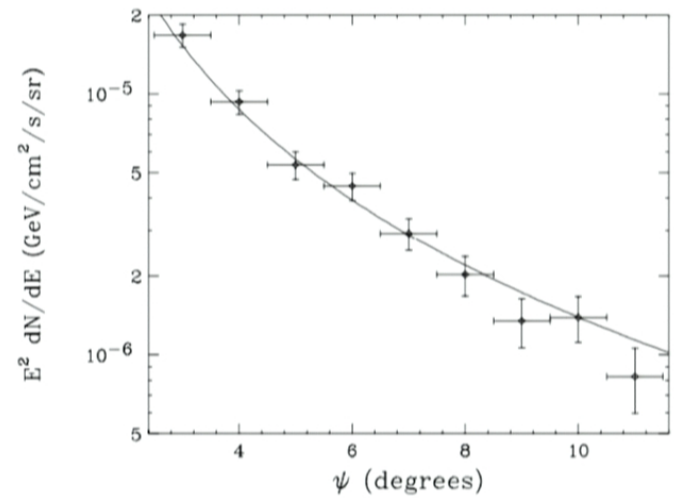

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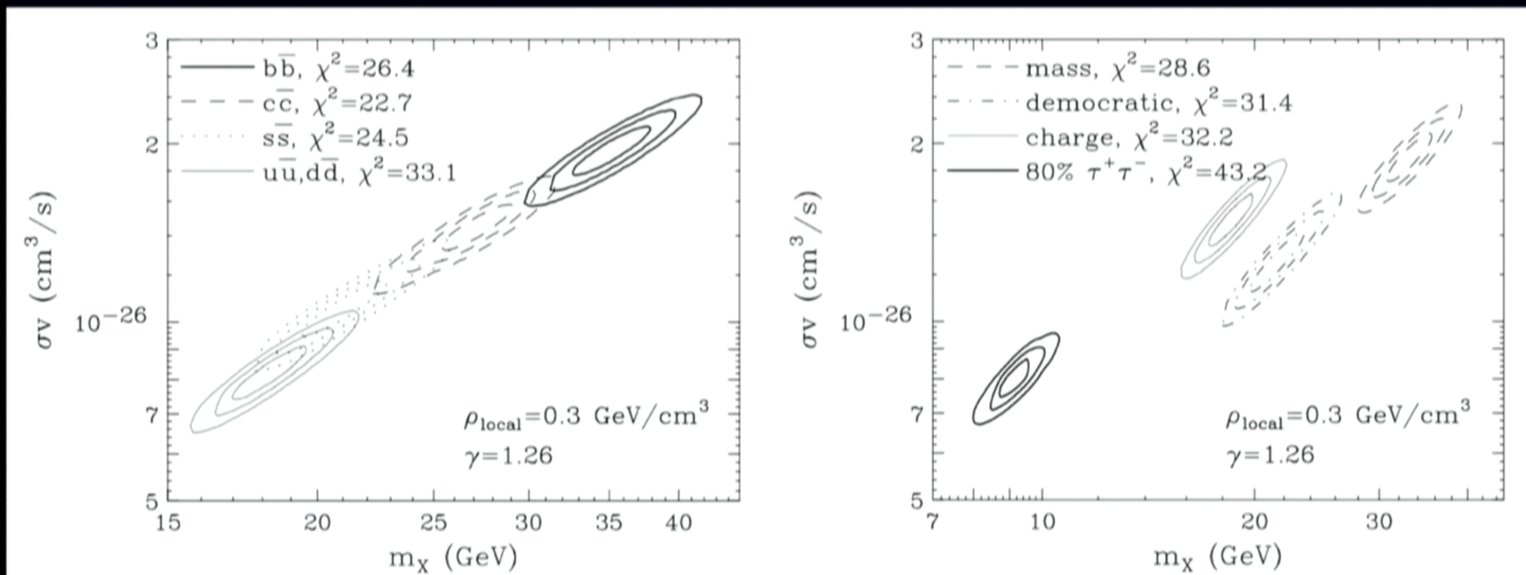
DM analysis by annihilation final state



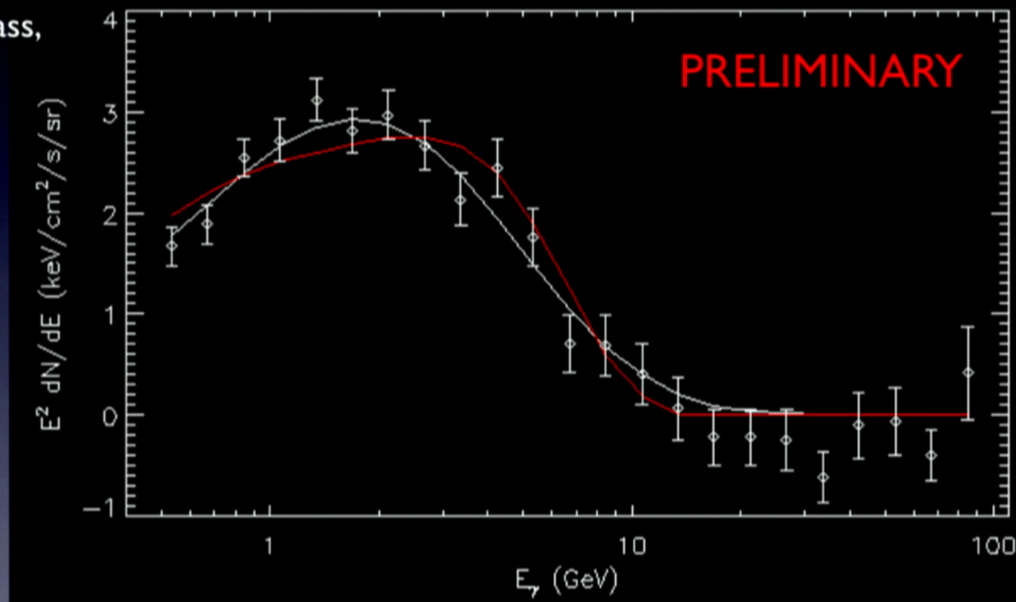
- Preferred cross section ~10^{-26} cm^3/s, ~15-50 GeV DM annihilating to quarks or mixed final states.

~10 GeV DM?

Example: float cross section, mass, branching ratio to b's vs tau's

White curve: best fit, 100% to b's, 34.7 GeV, 2×10^{-26} cm^3/s, $\Delta\chi^2$ = 23.4 over 23 error bars (10.7 over 13 error bars below 10 GeV)

Red curve: 32% to b's, 68% to taus, 11.3 GeV, 1×10^{-26} cm^3/s, $\Delta\chi^2$ = 34.7 over 23 error bars (22.7 over 13 error bars below 10 GeV)



- There are degeneracies between the DM mass, annihilation cross section and branching ratio to quarks vs tau-rich final states - lower DM masses require a lower cross section and harder spectrum, favoring a higher branching ratio to taus vs quarks.
- Our fit prefers slightly heavier DM annihilating to quarks, but degeneracies in the spectrum mean the preferred branching ratio is quite sensitive to the modeling of the diffuse background.

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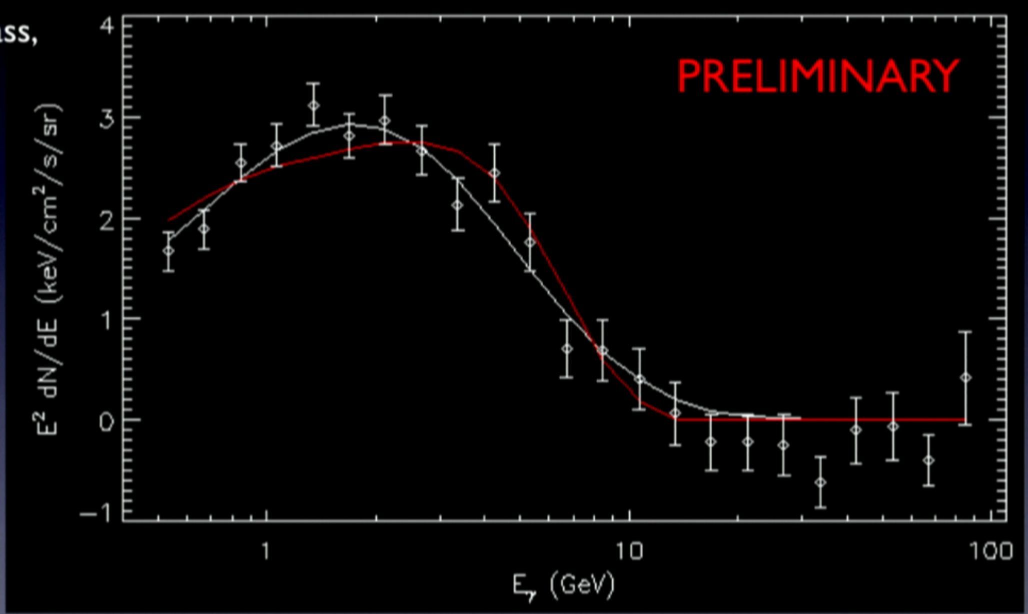

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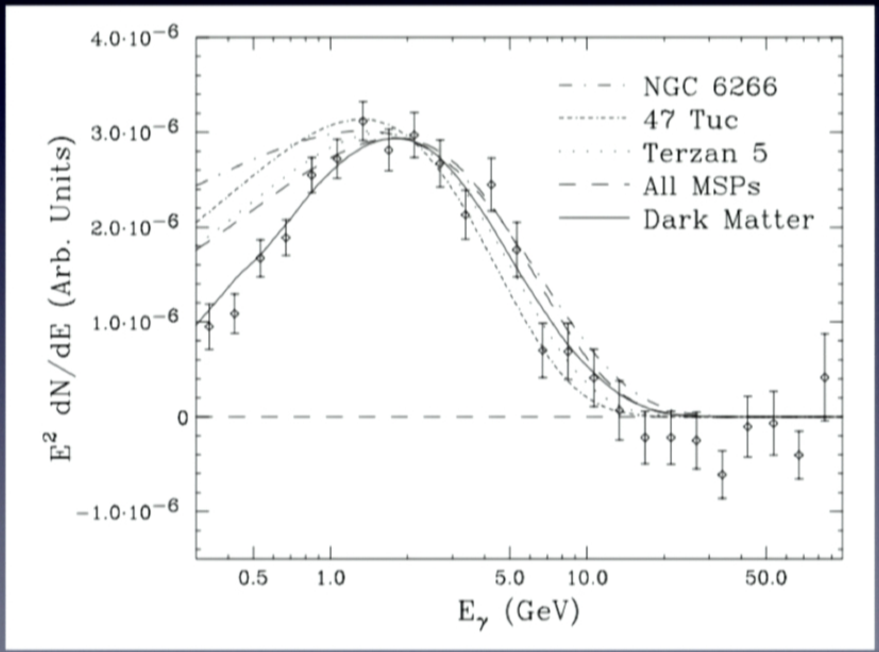
Reading on model-building for this signal (not comprehensive)

- Papers preferring ~10 GeV DM to taus: right-handed sneutrino annihilating to fermions 1106.3583; singlet scalar DM in 2HDM 1010.4214, 1106.3368; MSSM extension with singlet DM and additional leptophilic Higgs 1102.0492; Dirac neutralinos 1307.3561; neutralino annihilation via stau exchange 1308.6738
- Effective field theory analysis (favors axial vector / pseudo vector couplings) + Higgs-portal toy model, 1310.7609
- Higgs portal DM also considered in1305.4625, 1310.5991 (works best around ~60 GeV close to Higgs resonance)
- Coy DM - annihilation through a pseudoscalar to b quarks 1401.6458
- Another effective field theory analysis with the updated data, 1403.5027, also finds a small set of operators that work (scalar-type coupling to quarks or interaction with gluons for scalar DM, a dimension-6 vector-type operator or dimension-7 scalar-type operators for fermionic DM)

What else could it be?

- The sphericity of the excess, improvement with angular resolution cuts and lack of correlation with the gas disfavors a simple mismodeling of the diffuse emission.
- Most widely discussed candidate is pulsars - their observed gamma-ray spectrum cuts off at the right energy.
- Would need thousands of pulsars, each one too faint to be detected individually.



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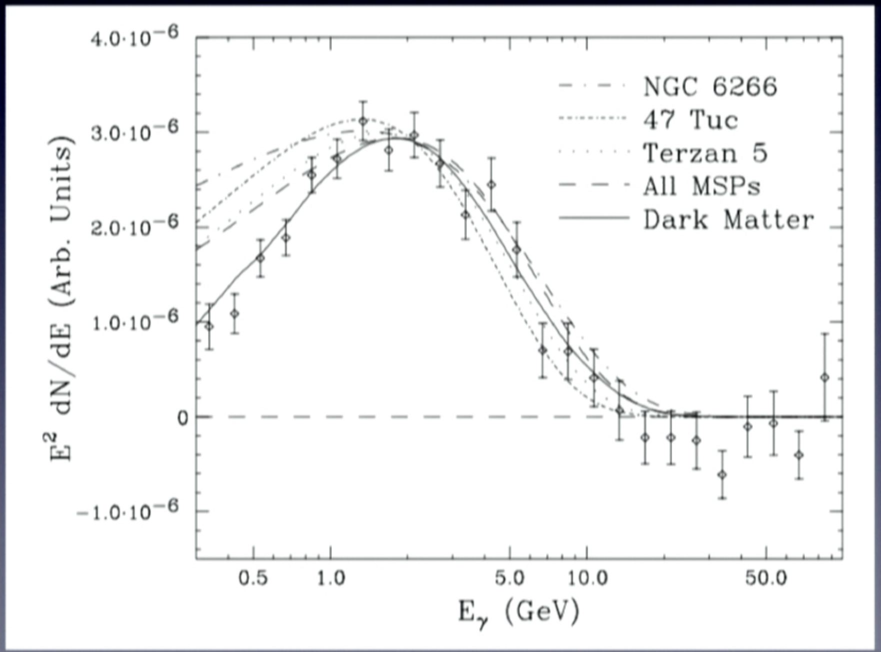

Pulsars?

- Challenges:
  - Signal appears very spherical - axis ratio of 1.2 is much smaller than e.g. the Galactic bulge (axis ratio ~2).
  - Signal extends to quite high latitude, ~10 degrees from the Galactic plane, corresponding to ~1.5 kpc.
  - Some tension at low energies between observed pulsar spectra and measured spectrum for this excess (however, difficult to assess impact of systematic uncertainties due to the diffuse background modeling).
- Known/expected pulsar populations do not appear to have the right spatial distribution or luminosity properties (e.g. Hooper, Cholis, Linden, Siegal-Gaskins & TRS 1305.0830) - even if we hypothesize a new abundant bulge population, if it had a similar luminosity function to the disk pulsars and enough faint pulsars to generate this signal, visible bright pulsars should have been detected.
- Are we seeing a new astrophysical population of faint sources? Mechanism to produce them?

The claim

- After subtracting modeled backgrounds, we detect a broad-spectrum gamma-ray excess in the Galactic Center and inner Galaxy, with the following properties:
  - Peaking at ~1-2 GeV in $E^2 dN/dE$ and no strong detection below 0.5 GeV or above 10 GeV.
  - Consistent with spherical symmetry about the GC; we can exclude axis ratios larger than ~1.2 along the Galactic plane. (Mild hint of extension along an axis 35 degrees off the plane, with axis ratio ~1.3).
  - When modeled by a squared, projected NFW profile, prefers a small-r slope ~1.1-1.2 in the Galactic Center analysis, 1.2-1.3 in the inner Galaxy analysis (hints of steepening at larger radii).
  - Centered on Sgr A* to within 0.05 degrees.
  - Detected out to 10 degrees from the GC.
  - Spectrum well described by 20-50 GeV DM annihilating to (mostly) quarks with a ~thermal relic annihilation cross section.