A Gamma-Ray Excess in the Inner Galaxy

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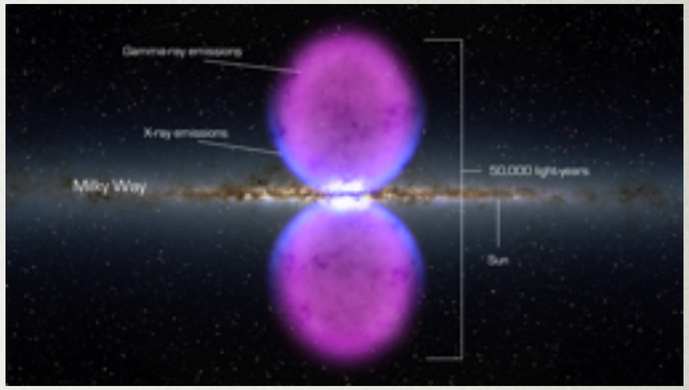
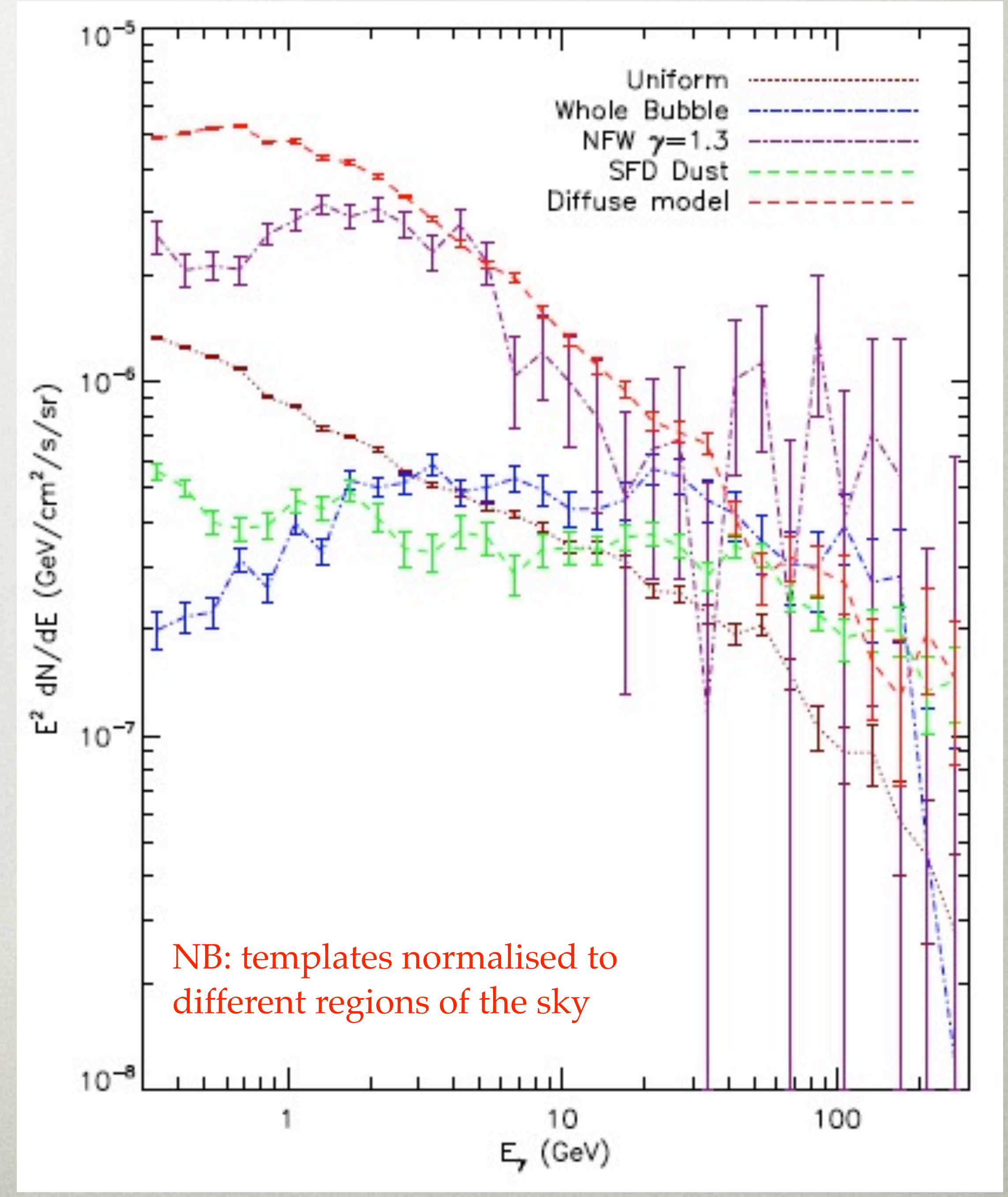
Outline

- This talk focusses on the **inner galaxy:** region within several tens of degrees around the GC, except for the plane ($|b|<1$)
  - Overview of template fitting
  - Properties of the excess
  - Interpreting the excess as Dark Matter

Template Fitting

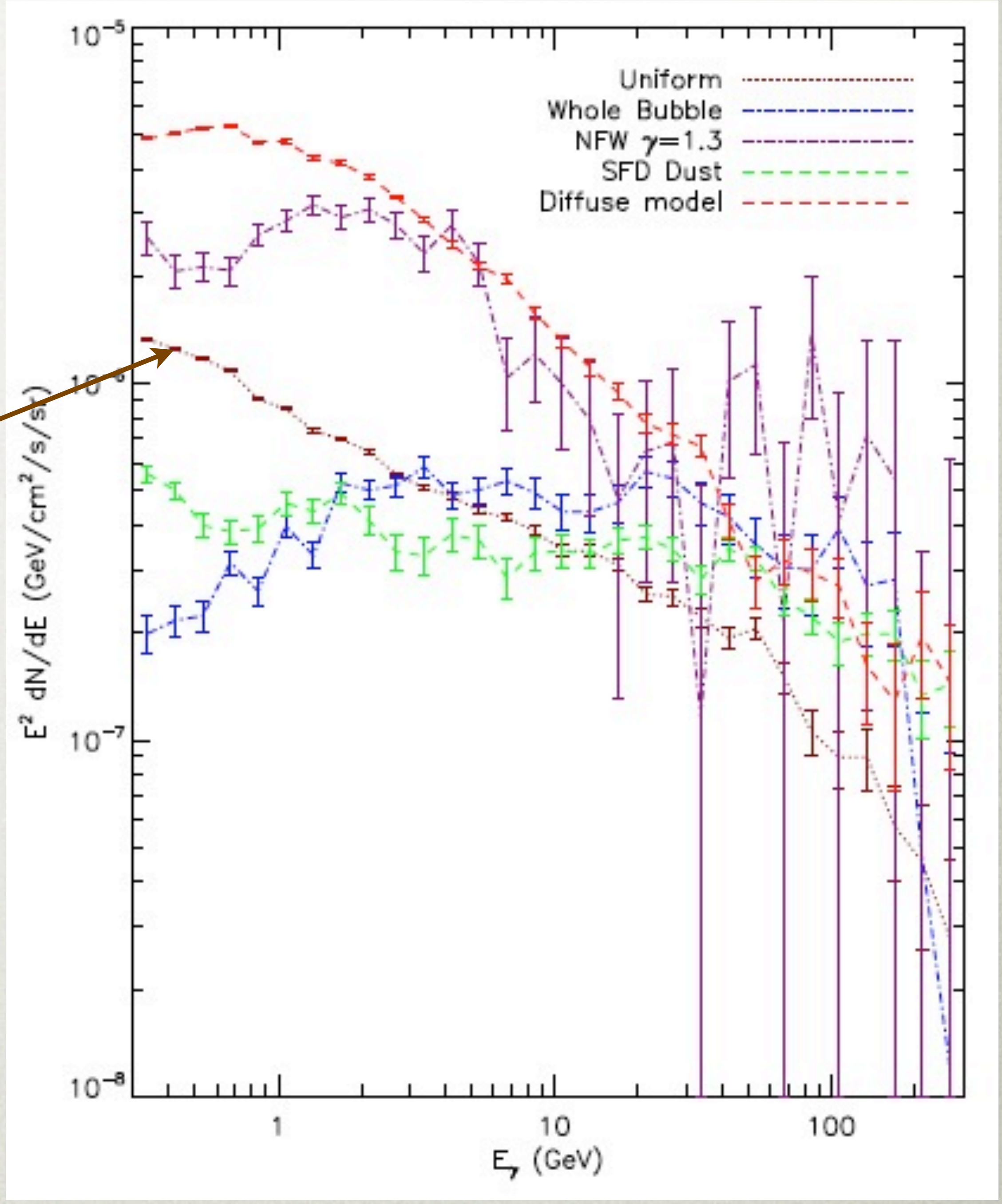
- How the method works:
  - Describe the expected contributions by spatial templates at each energy (relative normalisations unknown)
  - Determine the normalisations by a pixel-based maximum likelihood analysis, fitting the data to a weighted sum of the spatial templates
  - Returns coefficients for the various templates (see plot for an example)
  - Repeat this independently for 30 energy bins between 300 MeV and 300 GeV
  - The fit is characterised by the likelihood and the spatial residual
- Input:
  - Spatial templates of the backgrounds
  - No spectral information is inserted - recovering expected spectrum for backgrounds is a cross check



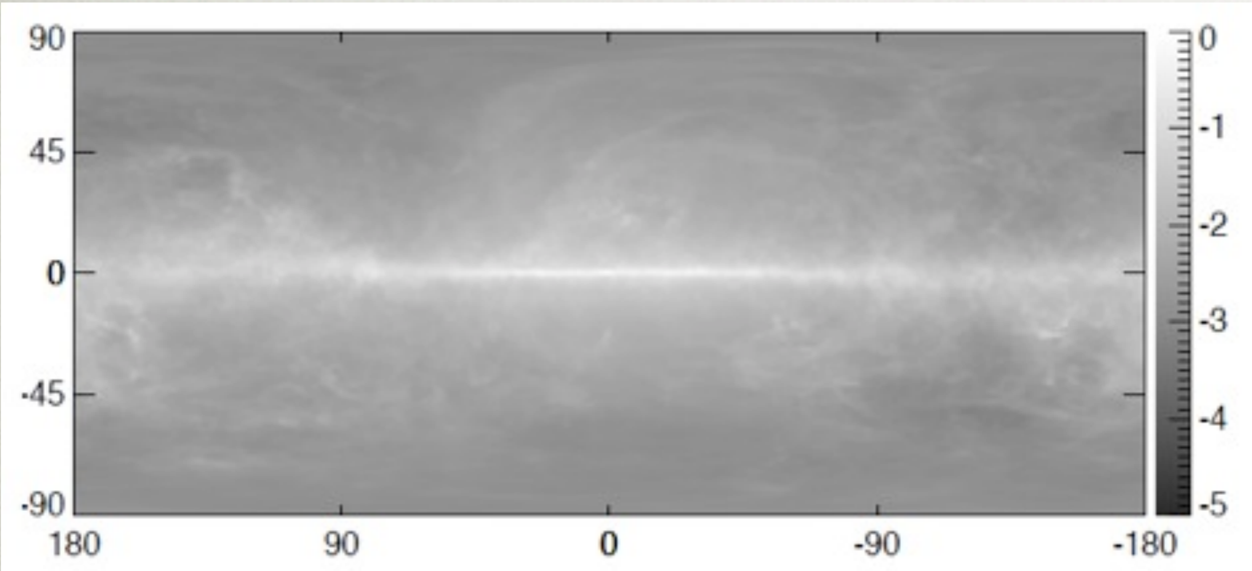


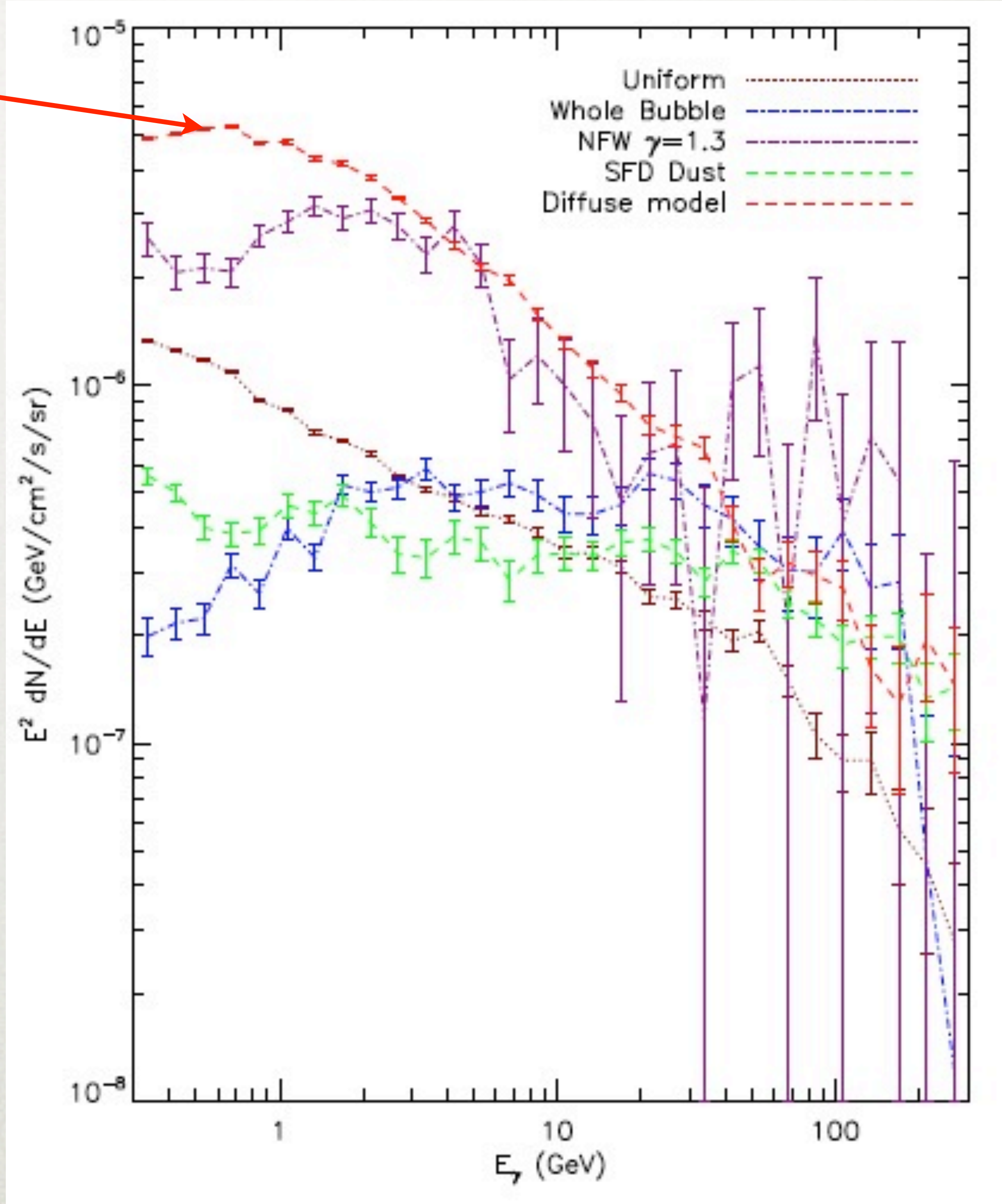
Template Fitting: Inputs

- Isotropic map: Absorbs extragalactic background and any residual contamination



Template Fitting: Inputs

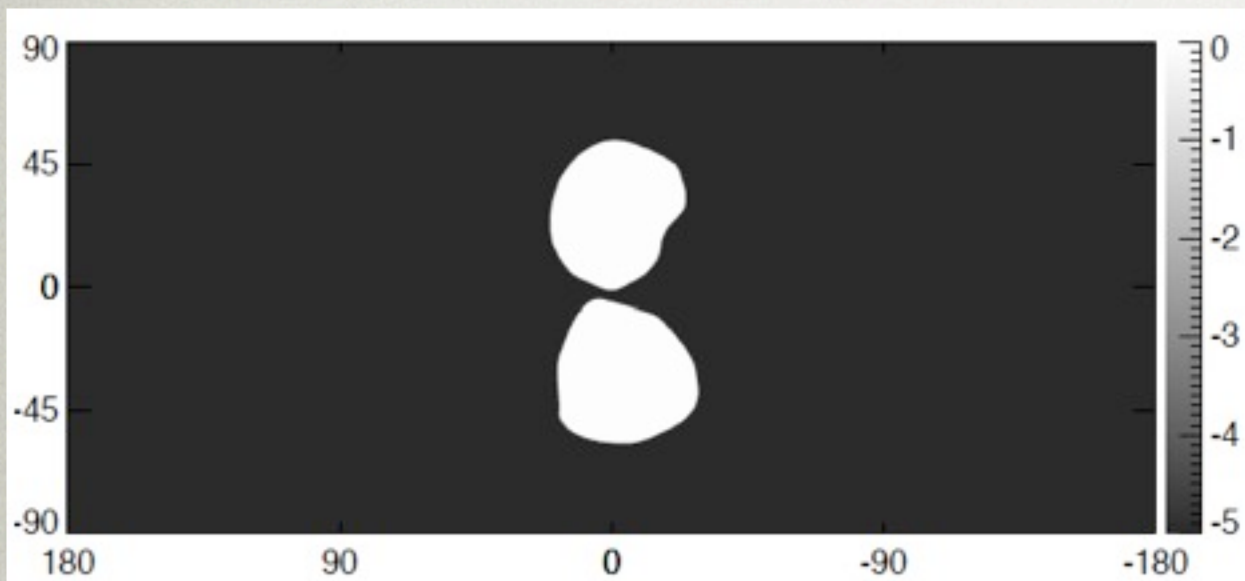


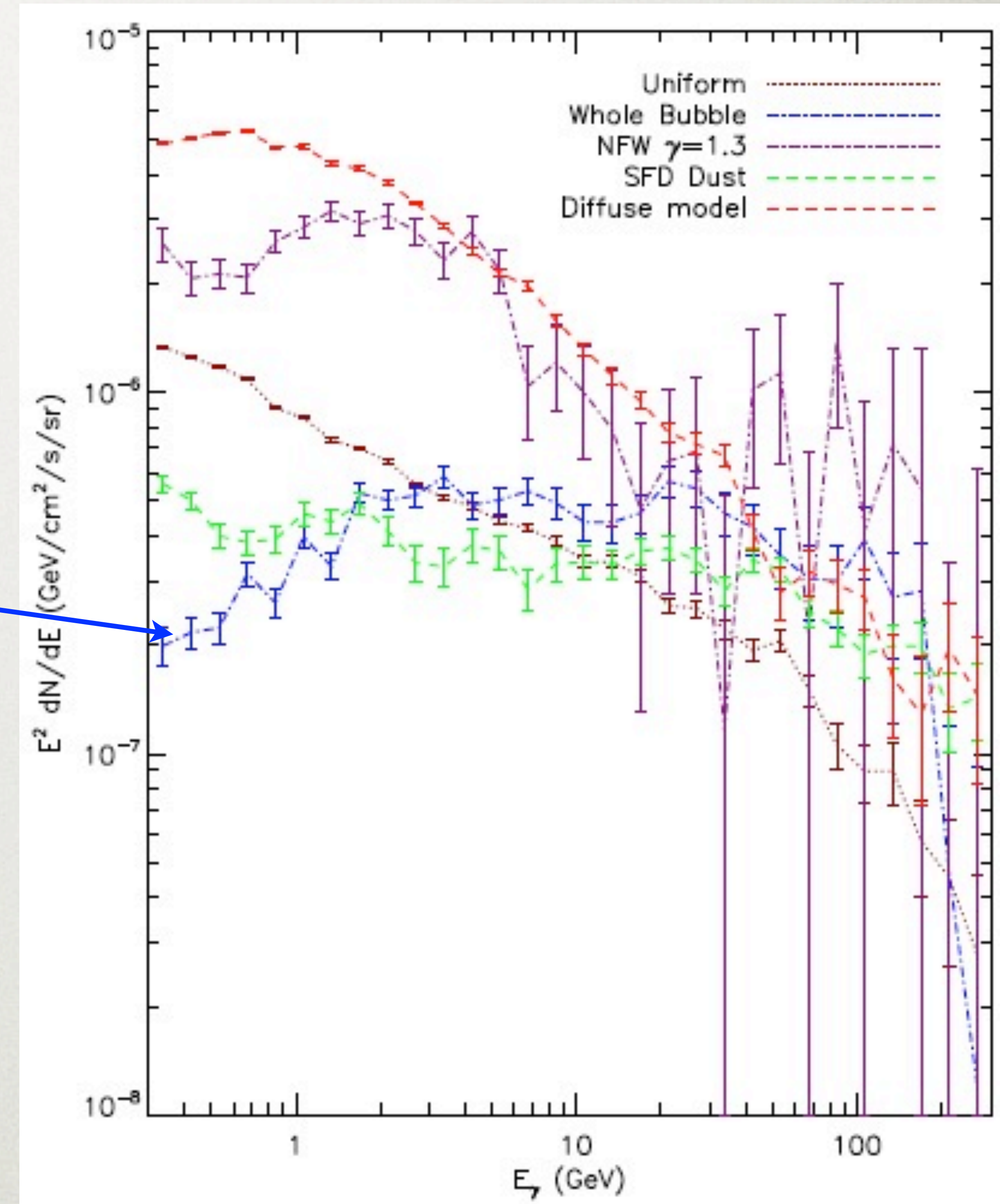


- Fermi Diffuse Model (p6v11): model of π^0 decay, inverse Compton scattering and bremsstrahlung
    - π^0 and brem: arises from interactions of cosmic rays with the gas; modelled by gas maps divided into galactocentric rings to account for variations in the cosmic ray (CR) population
    - Inverse Compton: arises from the scattering of CR electrons on the radiation field; modelled using GALPROP
- Describes the diffuse emission well but there are systematic residuals above the expected level of Poisson noise

Template Fitting: Inputs

- Fermi bubbles (version of the diffuse model used does not include these)



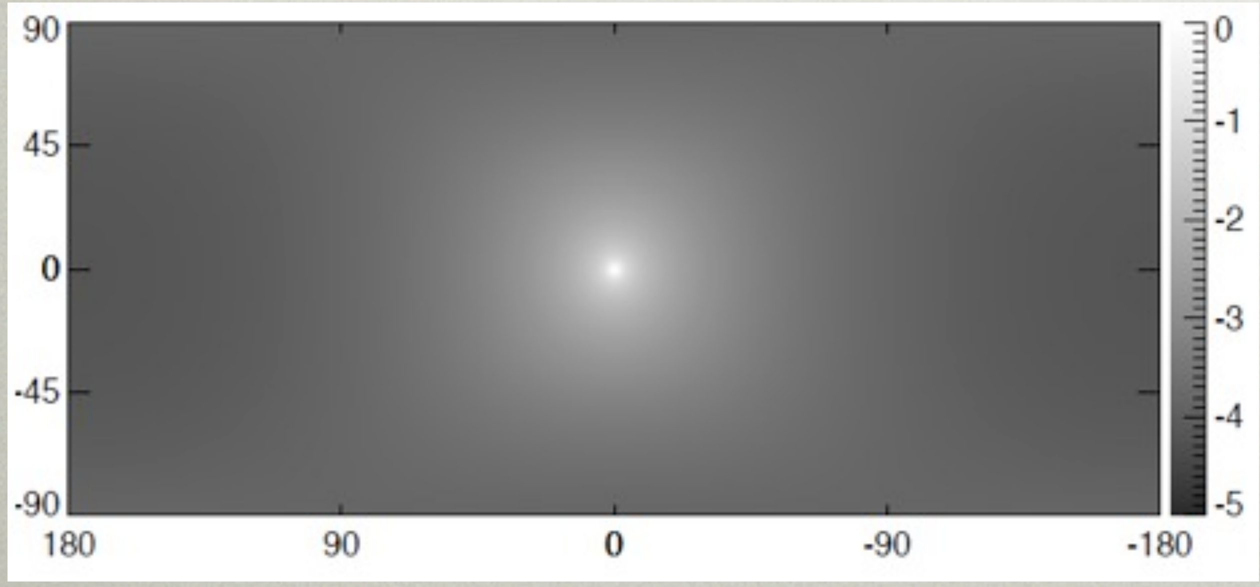


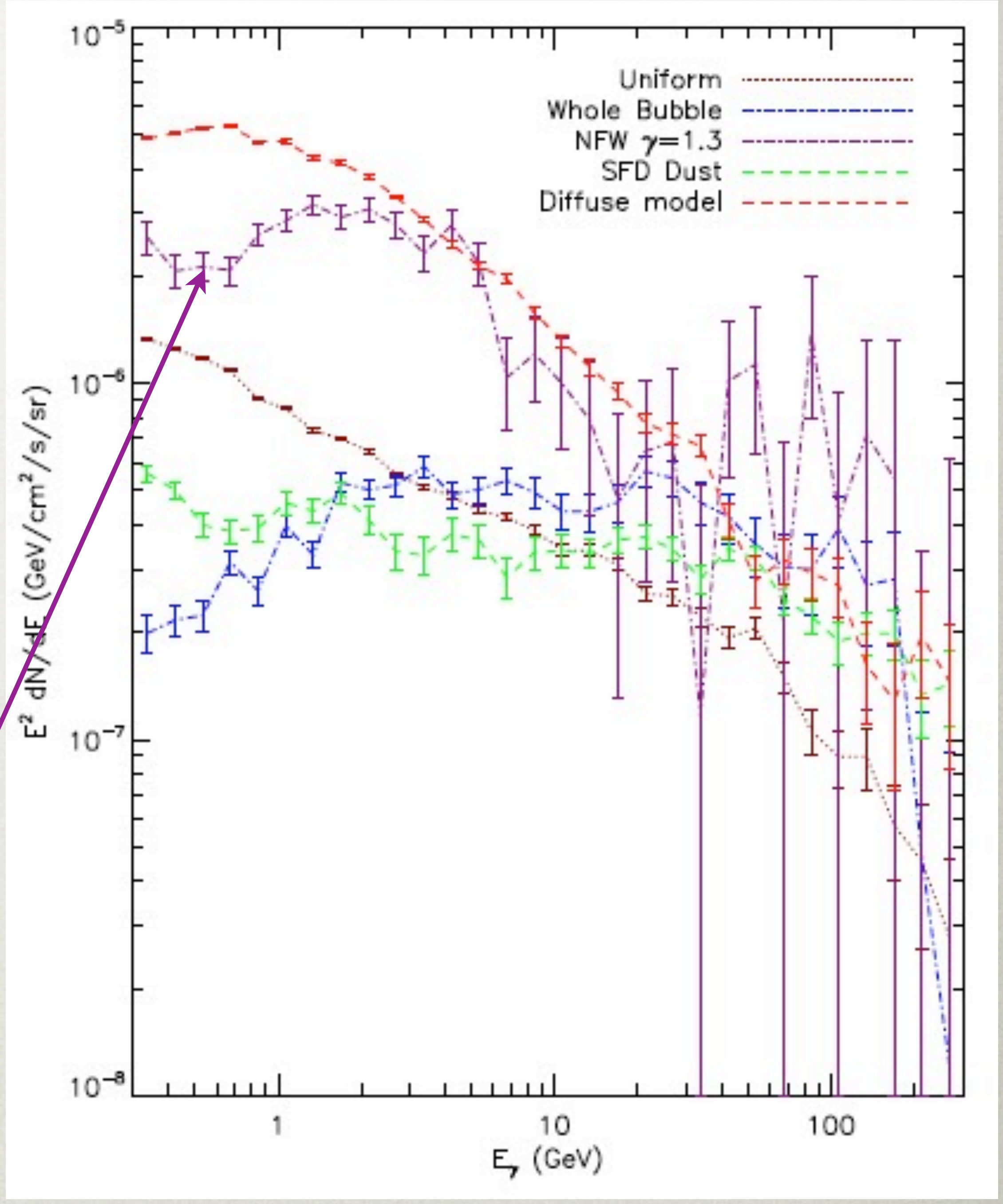
Template Fitting: Inputs

- Template for the excess in the form of a generalized Navarro-Frenk-White (NFW) halo profile (squared and projected along the line of sight), remaining agnostic as to γ

$$\rho(r) = \rho_0 \frac{(r/r_s)^{-\gamma}}{(1 + r/r_s)^{3-\gamma}}$$

$$r_s = 20 \text{ kpc}$$

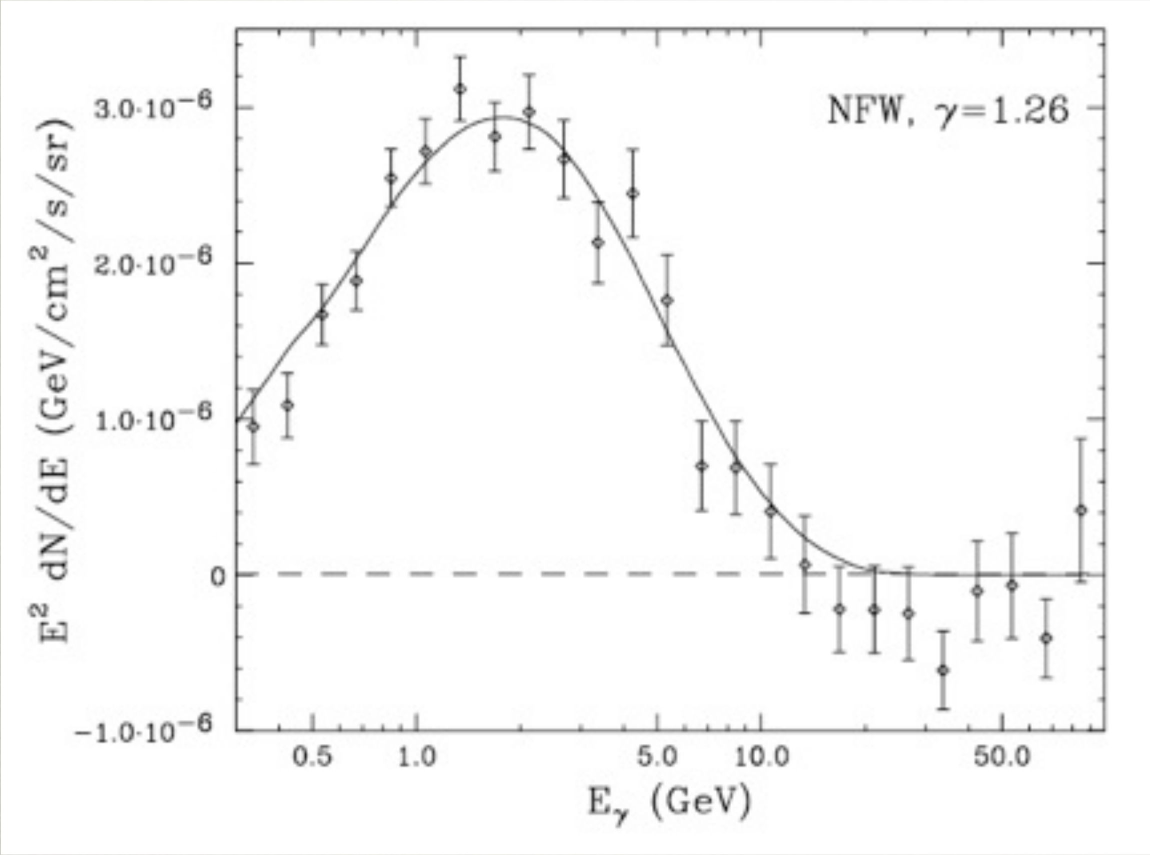


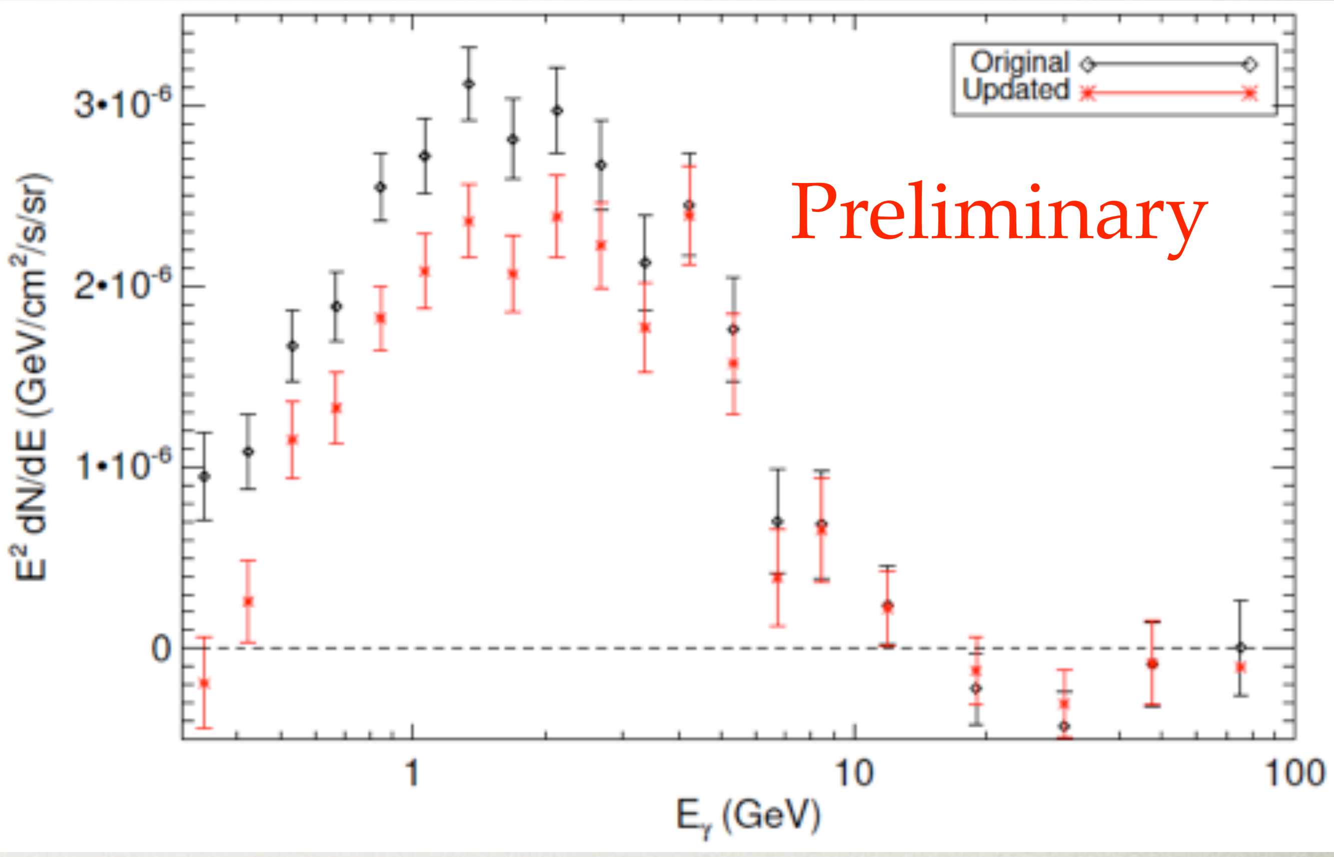


Inner Galaxy: Update

- We recently identified an error in the smoothing of the diffuse model in the Inner Galaxy analysis of 1402.6703
  - A corrected and updated analysis is in progress; qualitative conclusions do not appear to change, differences are similar to those found by varying the diffuse model or region of interest in 1402.6703
  - **NB:** results from Galactic Center (Tim Linden's talk) and "ring fit" (Tansu Daylan's talk) are unaffected by the update
- After the change, the peak of the spectrum drops by ~20%, whilst the error bars do not change significantly. Accordingly the change in log likelihood corresponds to $\Delta\chi^2$ ~ 1000 rather than 1600

Inner Galaxy: Spectrum

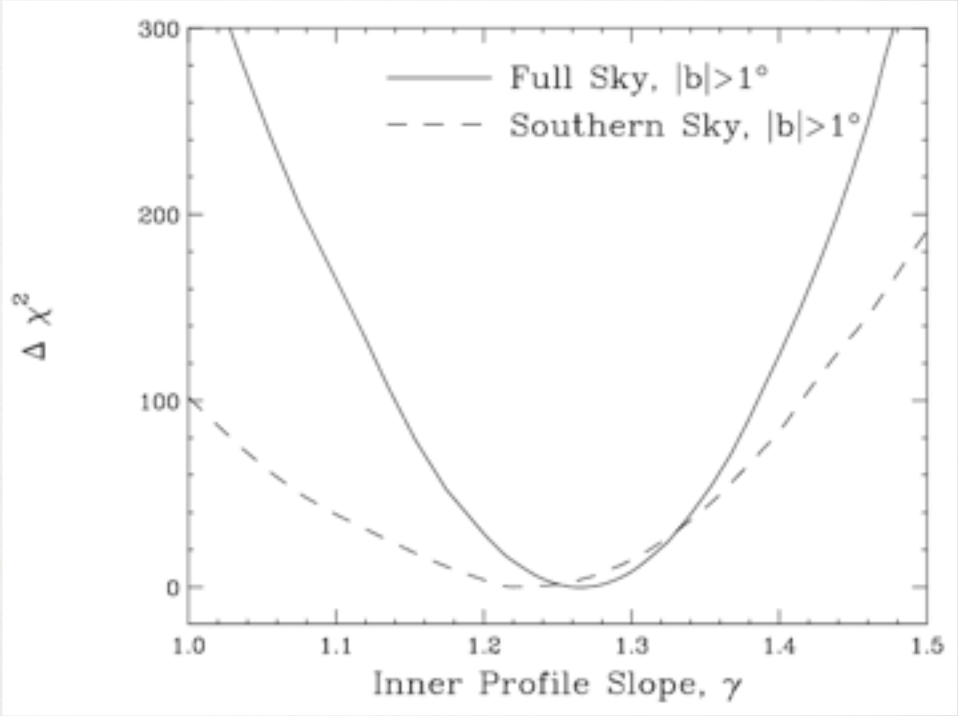


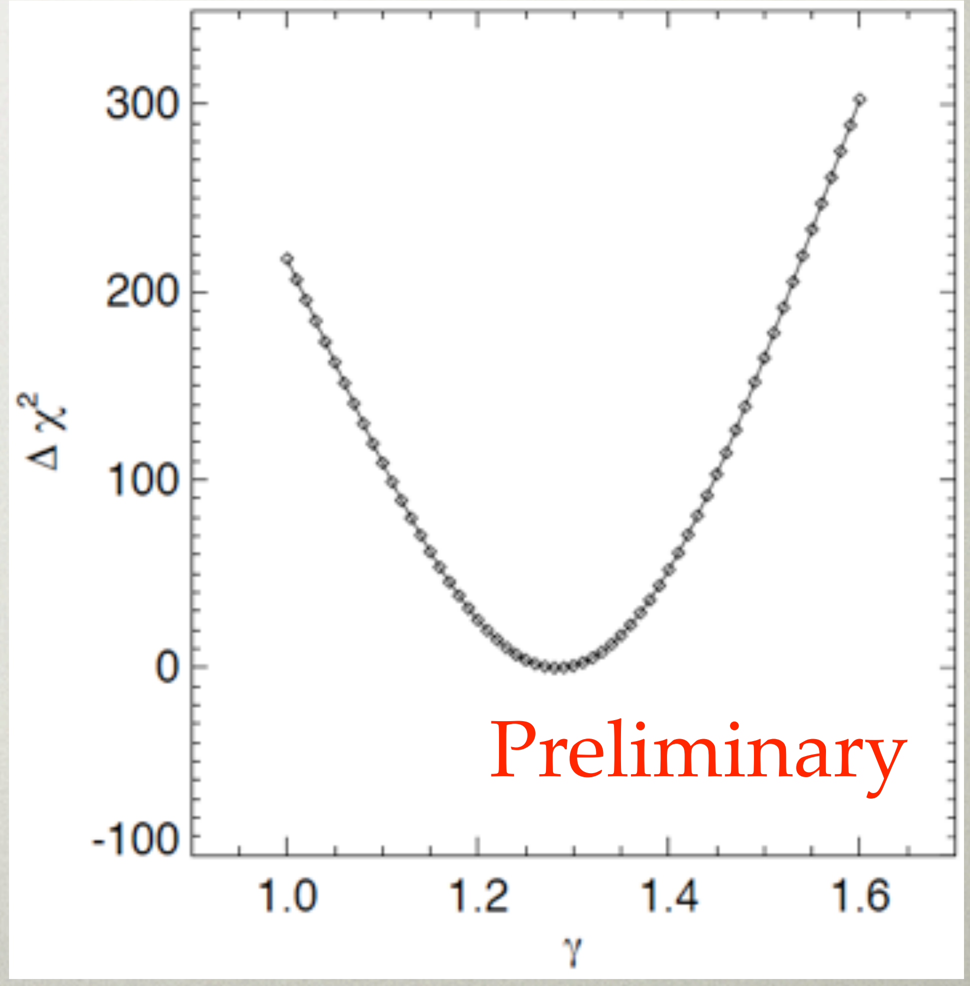


- Left: spectrum as it appeared in our paper overlaid with a fit to ~35 GeV DM annihilating to b quarks
- Right: comparison to the new spectrum
  - For annihilation to b quarks, the best-fit mass shifts upward by ~10% to ~40 GeV, whilst the best-fit cross section drops by ~10% to 1.8x10^{-26} cm^3/s

Inner Galaxy: Preferred Slope

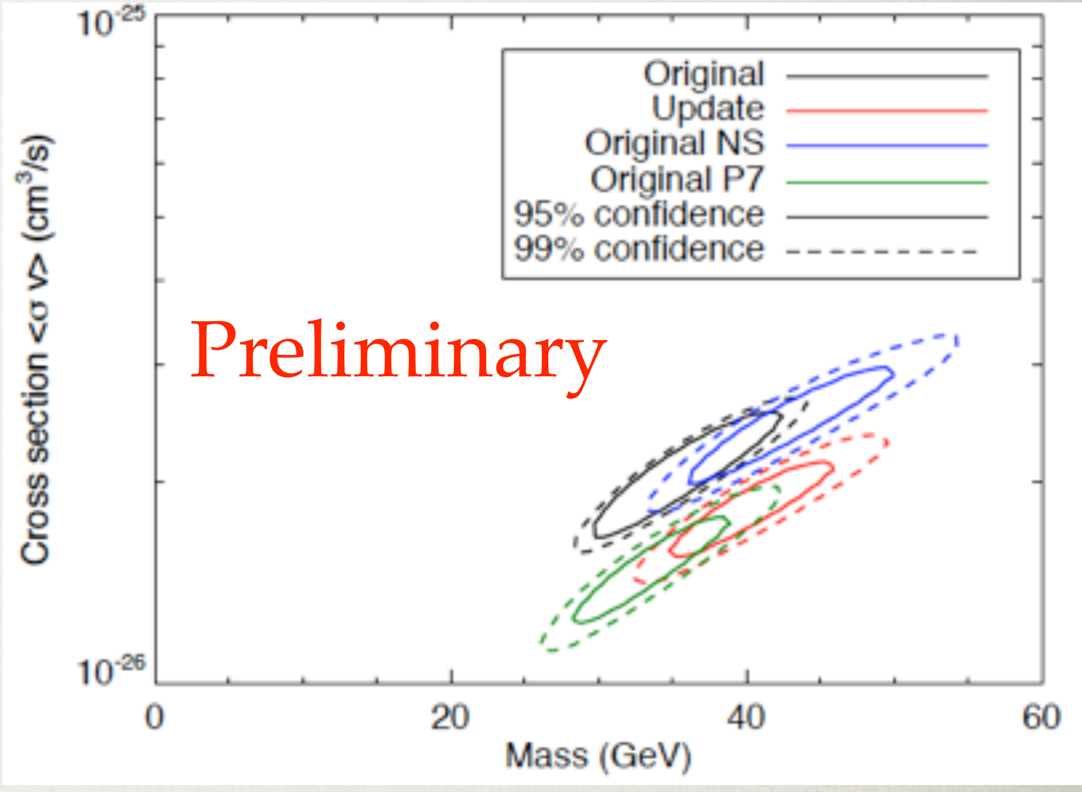
- We find a preferred slope slightly steeper than canonical NFW
  - Top: in 1402.6703 the best-fit slope was γ=1.26
  - Bottom: after the update we find γ=1.28
- Analyses of other spatial properties of the signal are ongoing

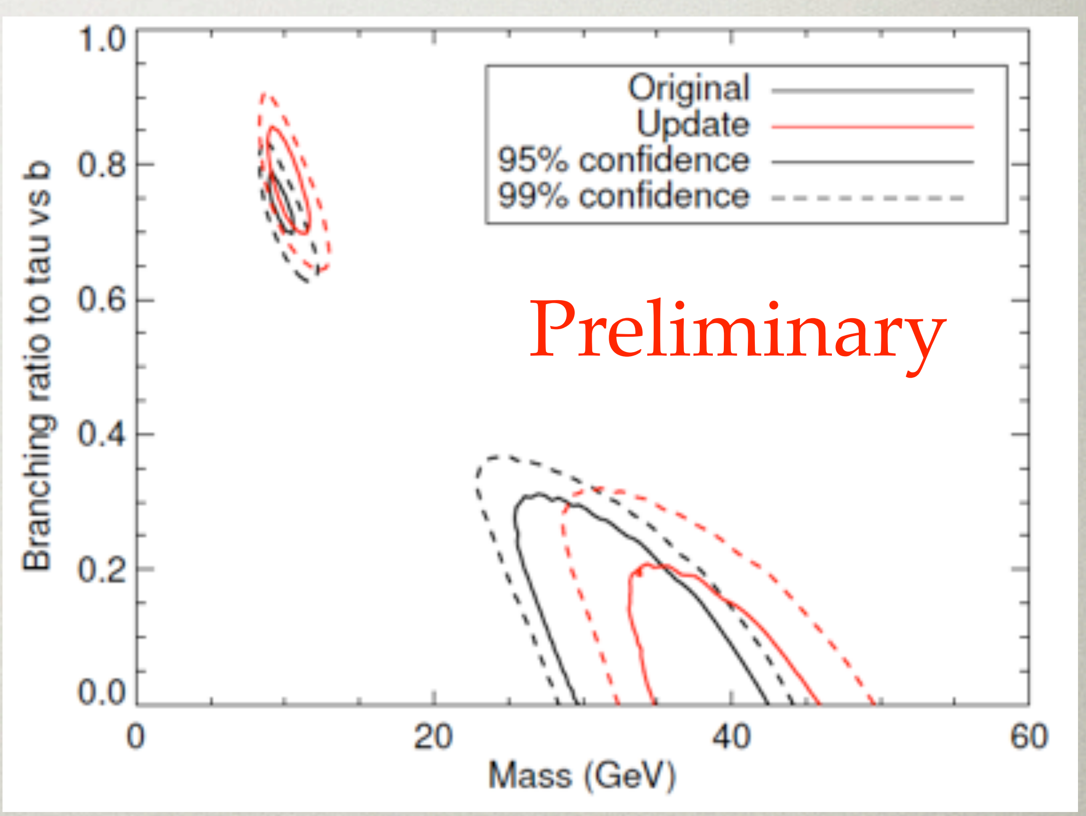




Inner Galaxy: Dark Matter Fit

- Many DM models have been proposed as an explanation of the signal (see talks by Dan Hooper and Sam McDermott earlier in the meeting)
  - Here we show a few simple cases
- Top: preferred mass and cross section for DM annihilating 100% to b quarks
  - For this channel the preferred cross section is close to the thermal relic value
  - Updated analysis prefers slightly lower cross section and higher mass than original, as expected
  - Also show preferred regions from original paper for a different diffuse model (P7V6) and region of interest (NS = north south region, where |b|>|l|). Gives a rough estimate of the size of systematic uncertainties
    - Impact of the updated analysis is similar
- Bottom: consider annihilation to an admixture of b's and tau's, we show preferred mass and branching fraction into tau's (vs b's), marginalising over cross section





Conclusion

- Thanks to cuts on CTBCORE, template analysis techniques applied to the inner galaxy reveal an excess that is consistent with that seen at the galactic centre using different techniques
- This excess can be explained by dark matter annihilation with a roughly thermal relic cross section and a density slope somewhat steeper than classic NFW
    - Further as Tim mentioned cannot presently be easily explained by any known astrophysics
- Yet corroborating evidence from one of the many other searches for dark matter will be required to definitively pin down its identity

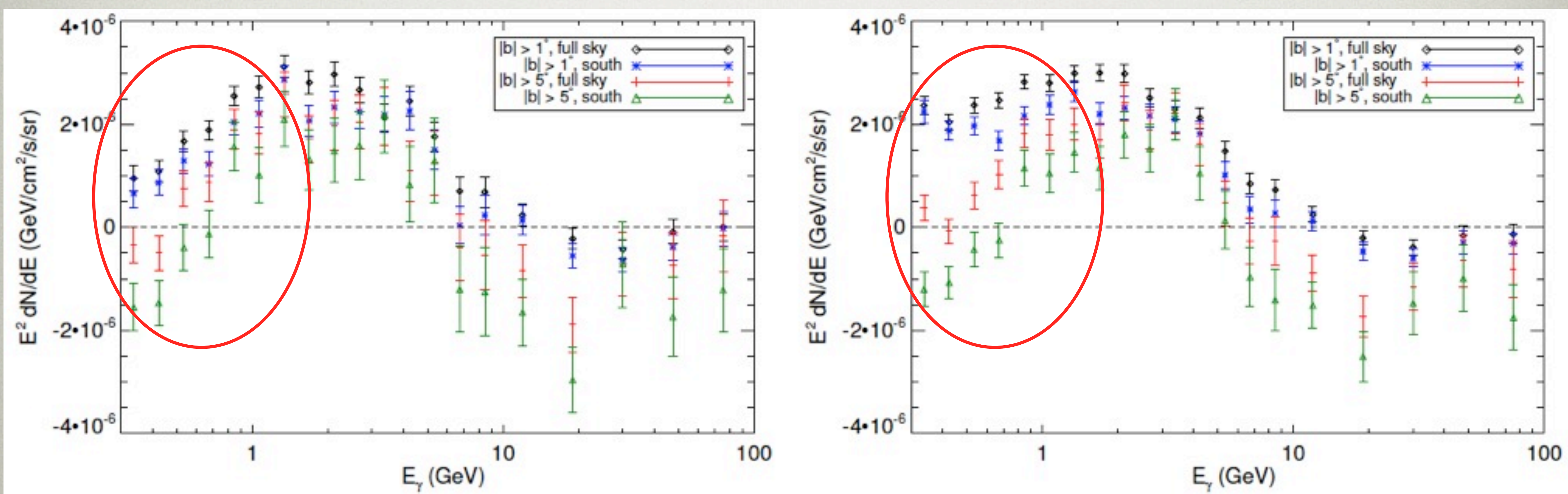
Backup Slides

Smoothing and Point Source Subtraction

- We have used the discovery of the bug as an opportunity to update our smoothing procedure:
  - Old: we smoothed the data and our models **to** 2 degrees using Gaussian smoothing
  - New: we smooth the diffuse model to the Fermi PSF at the appropriate energy, using the Fermi Tools, whilst we still use Gaussian smoothing for the other less bright templates
    - If time permits Tansu will mention plans to improve on this smoothing
- Point sources in the 1FGL are subtracted and we mask out the 200 brightest and most variable sources

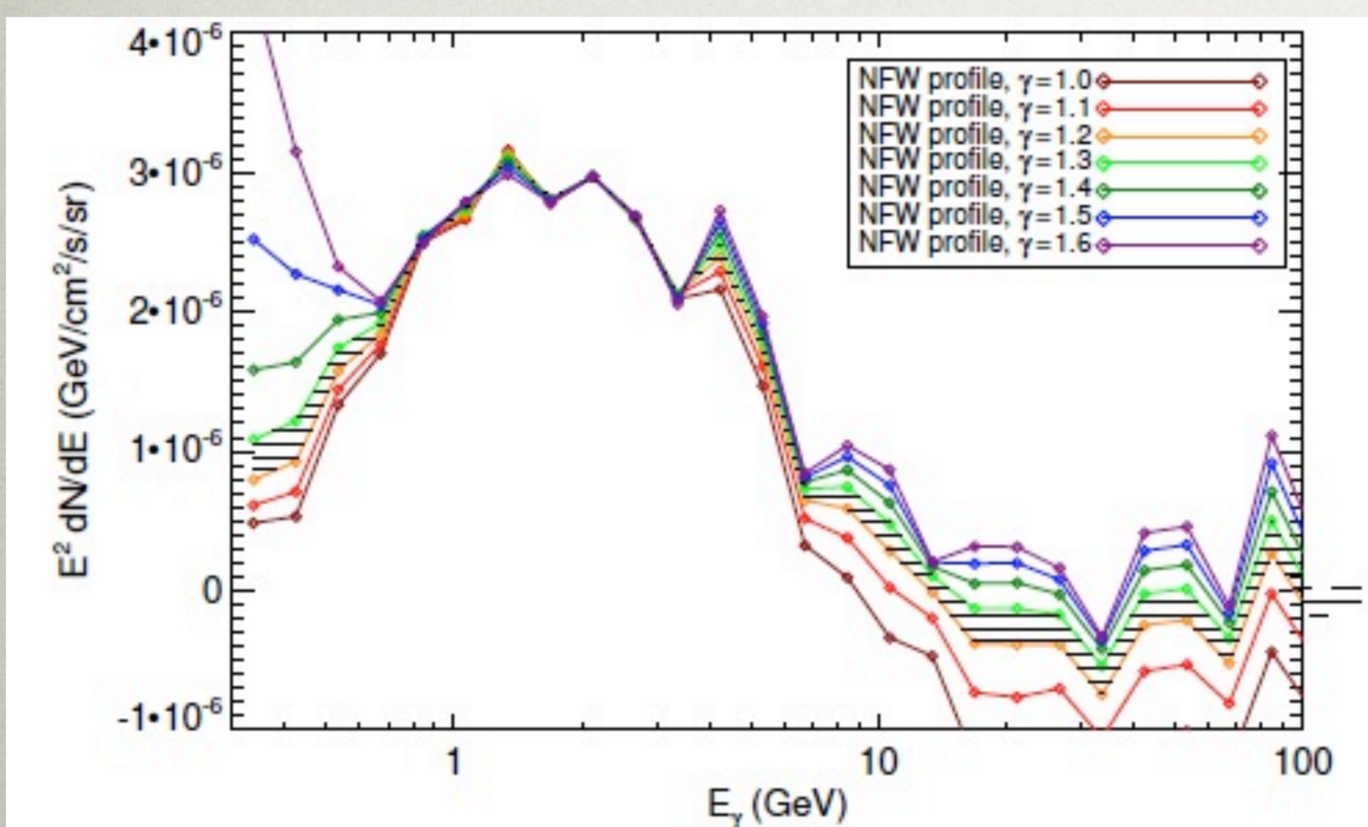
CTBCORE: Implications (pre bug fix)

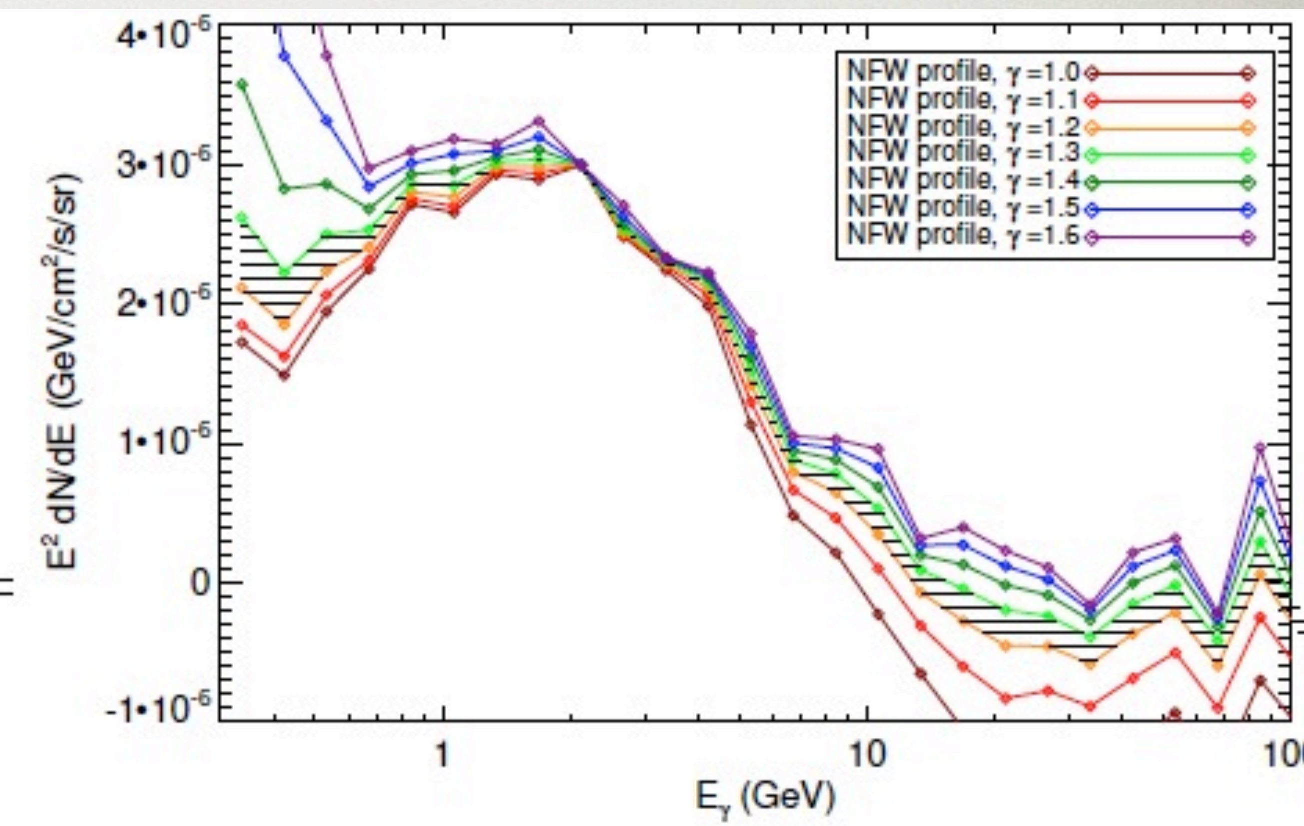
- To demonstrate the improvement, the figure below shows the extracted dark matter spectrum in different regions of the sky: it depicts with the CTBCORE cut (left) and without (right)
- With CTBCORE the results are more consistent - especially at low E
    - Plots are created assuming an NFW halo profile with γ=1.26



Dark Matter: Sensitivity to Assumed Morphology (pre bug fix)

- May worry that the extracted spectral shape is biased by uncertainties in the morphology of the best fit NFW template. Can see this is not the case from the stability against changes in the inner slope value in the left plot - very stable above 600 MeV
- Right plot shows what you get without the CTBCORE cuts - another example of the improvement that is gained



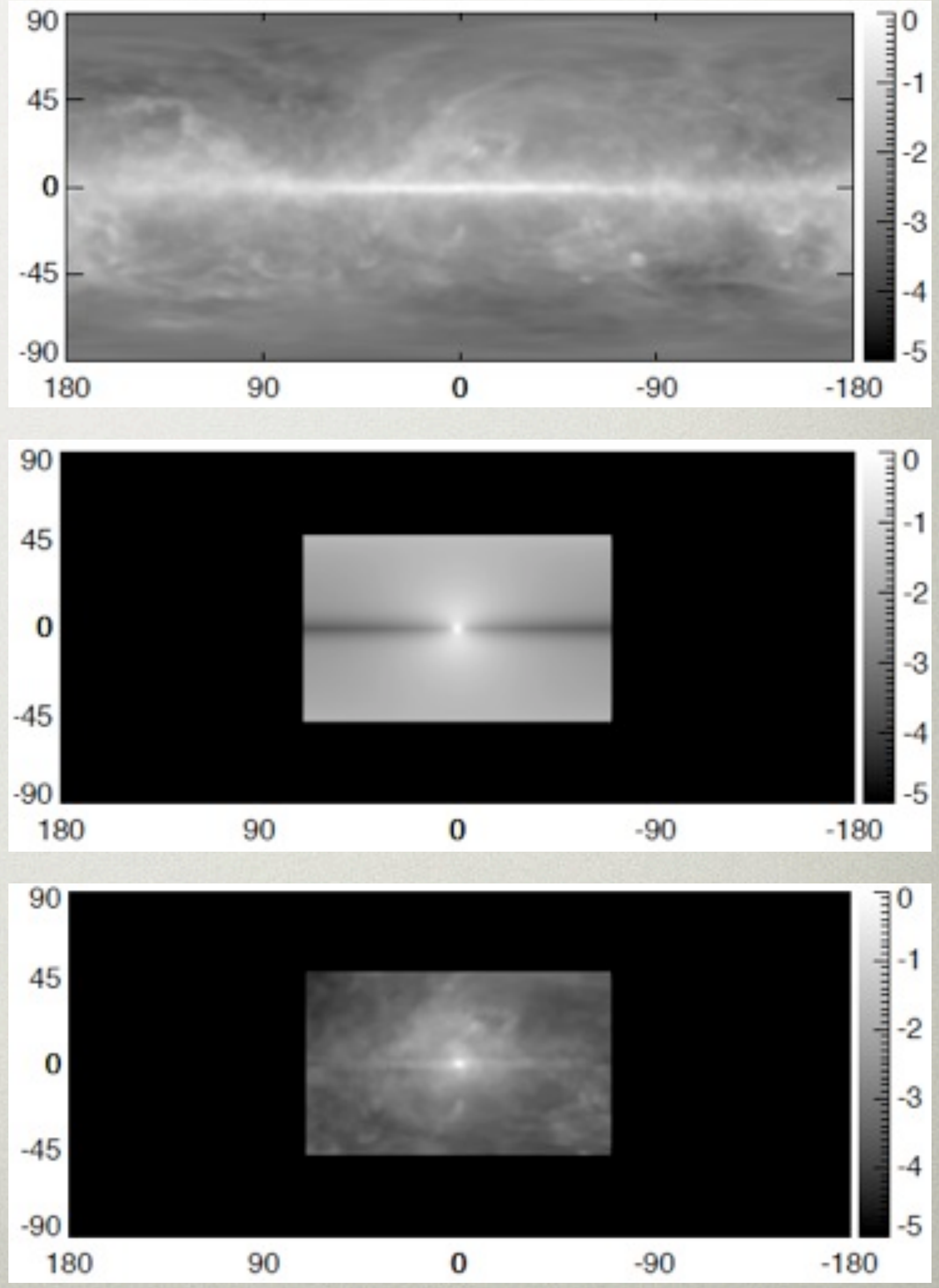


Cross Checks: Modulated proton distribution (pre bug fix)

- π^0 is modelled on the assumption that CR proton distribution is spatially uniform. But if there was an increase towards the GC could this be what we are seeing?
- To test this we added an additional template:

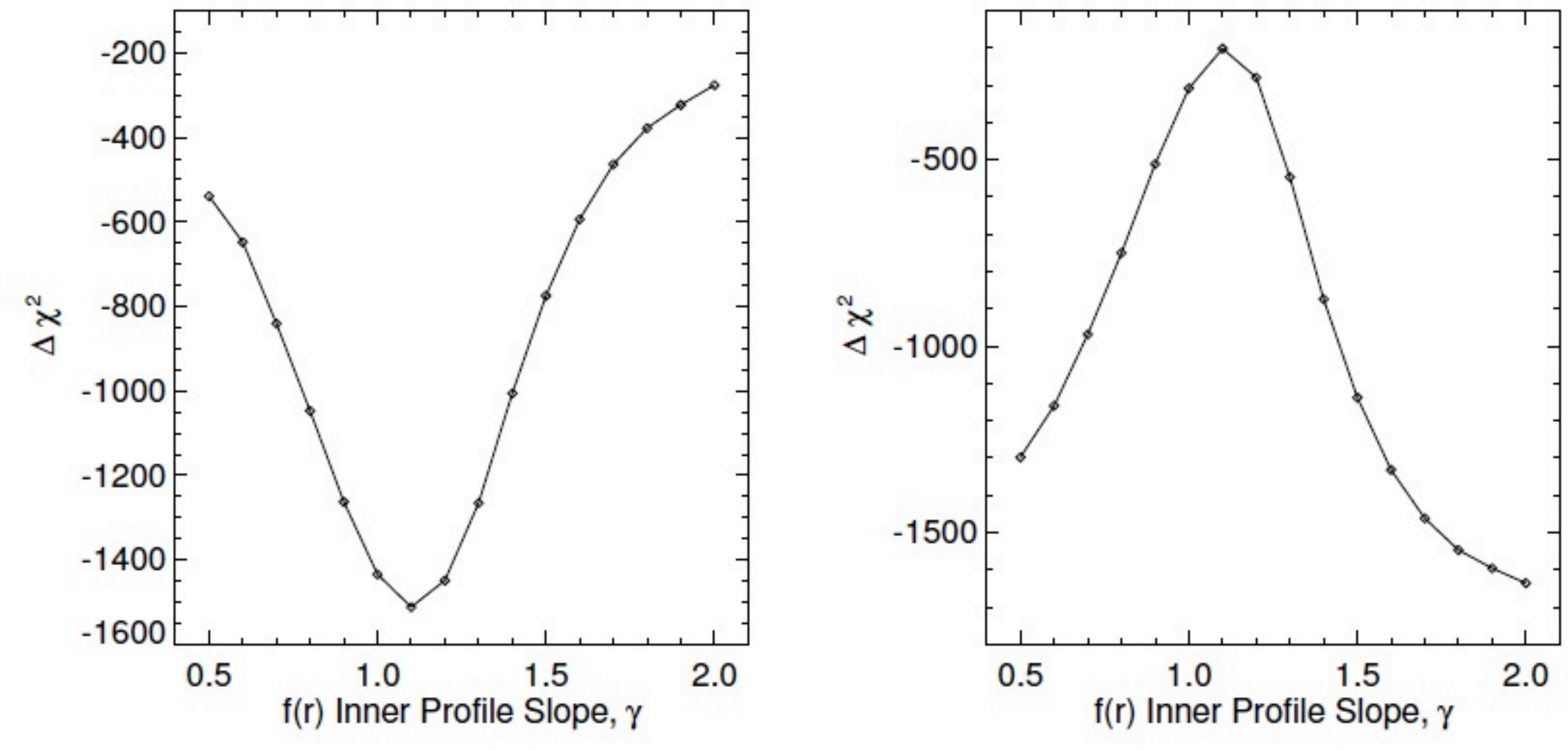
$$\text{Modulation} = (\text{SFD dust map}) \times \frac{f(r)}{g(r)}$$

- where f(r) is an NFW template and g(r) is a simple model for how the dust map falls off
- The map is spatially correlated with the dust, but increases towards the centre like an NFW template
- This is not physically motivated - requires a cosmic ray proton density to be aligned perpendicular to the Galactic Plane
  - Trying to give it every chance to mimic our signal



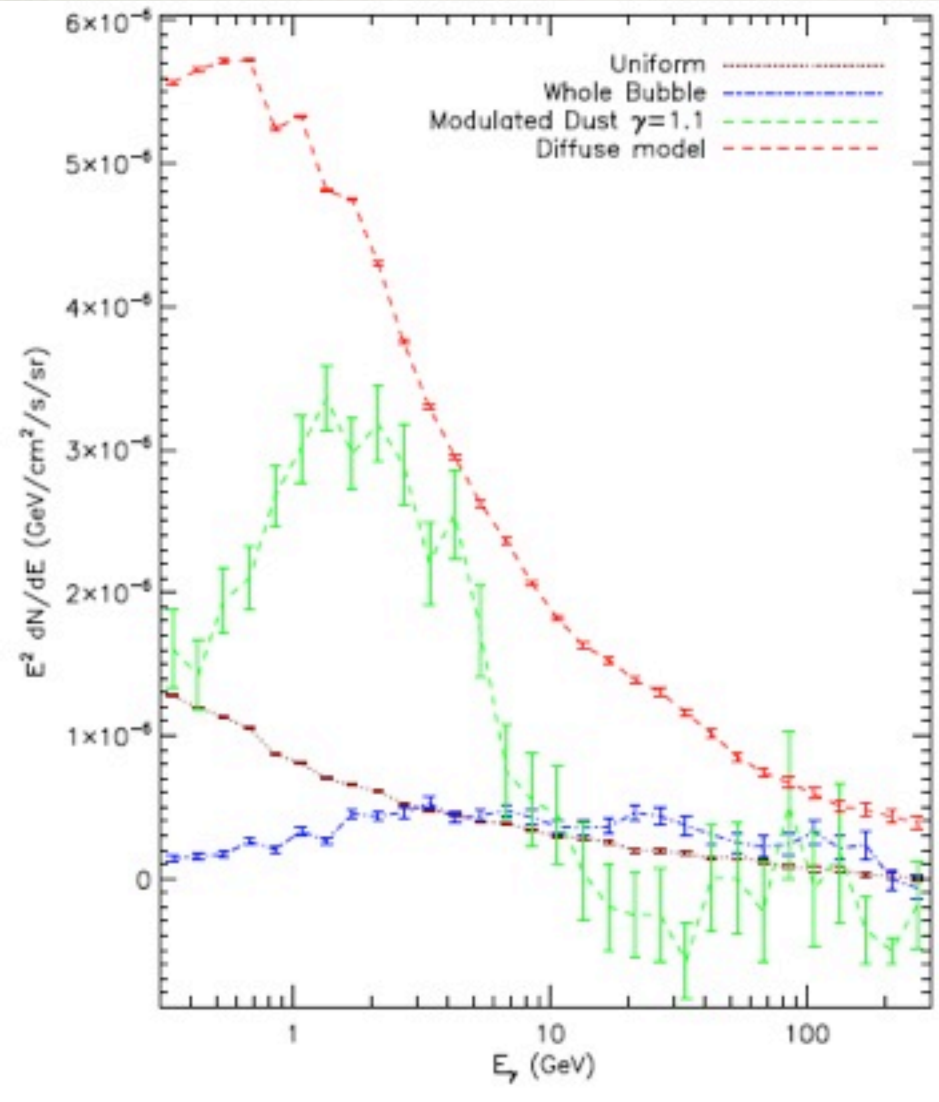
Cross Checks: Modulated proton distribution (pre bug fix)

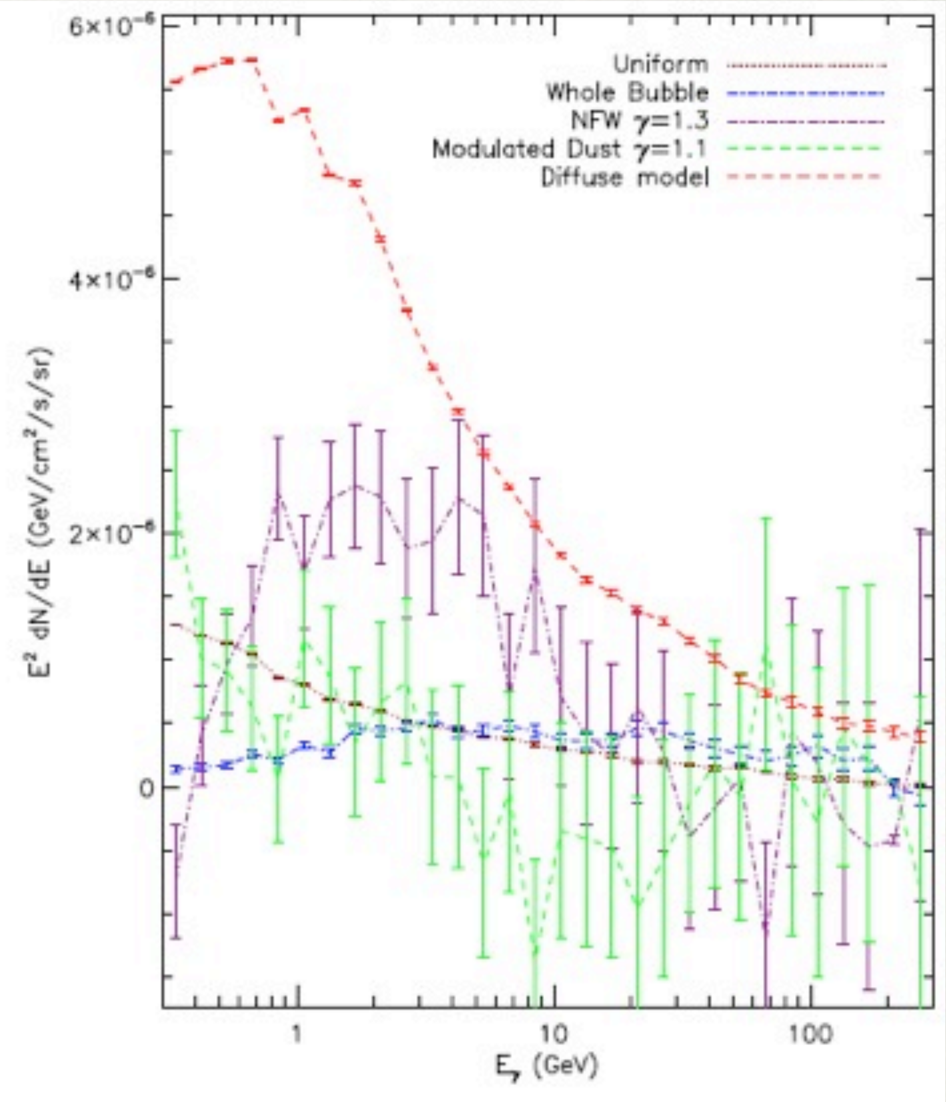
- Adding this template with just the backgrounds led to an improved fit (left plot), as the modulation picked up a coefficient in the energies where the signal had been seen
- But if we add an NFW template on top of this, the fit improves still further (right plot) and the excess acquires a larger coefficient than the modulation



Cross Checks: Modulated proton distribution (pre bug fix)

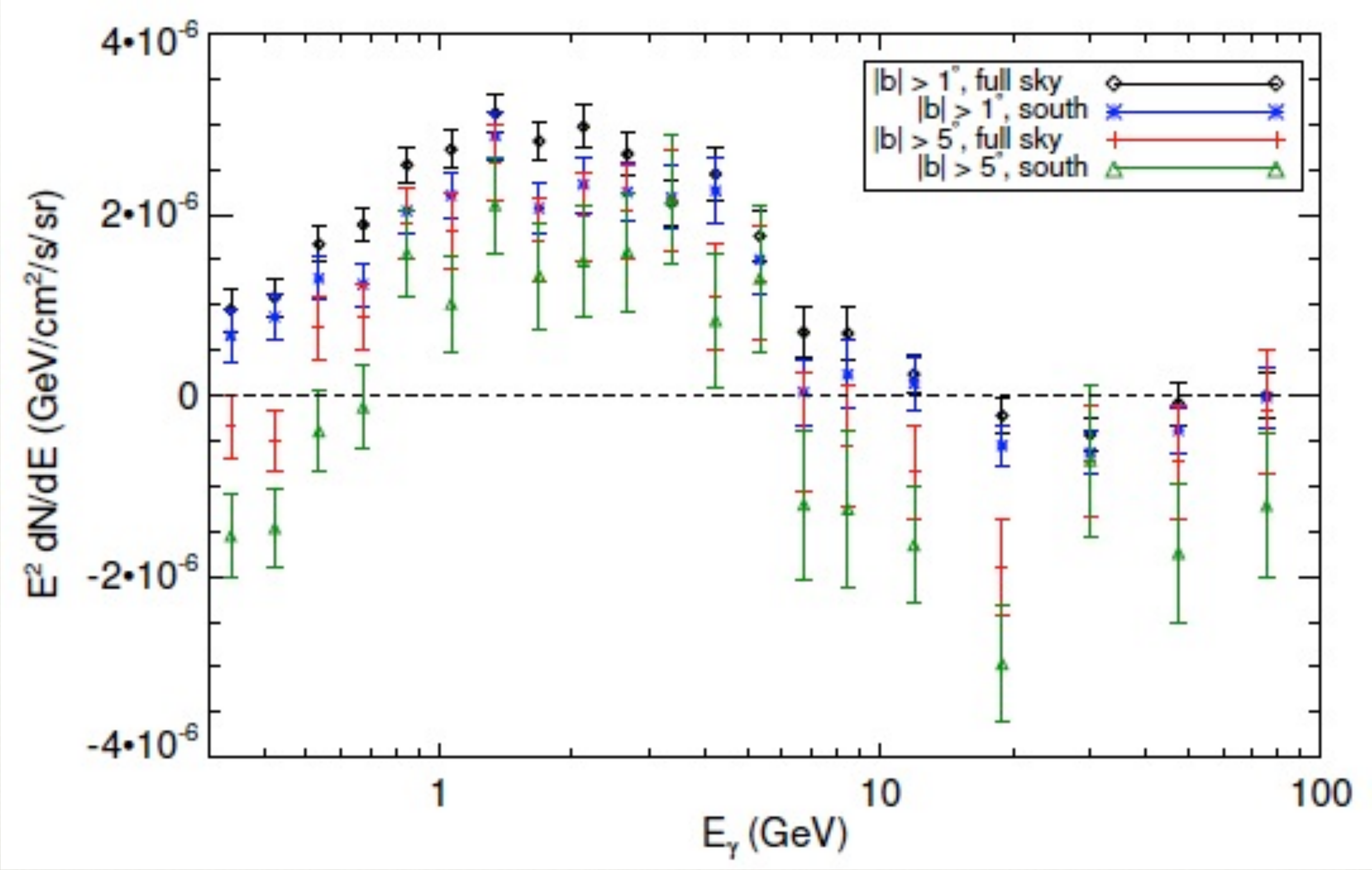
- Even in the case where the modulated template was preferred the most (an f(r) with γ=1.1), the fit clearly prefers to correlated the excess with an NFW template
- Plots show coefficients without (left) and with (right) an NFW template





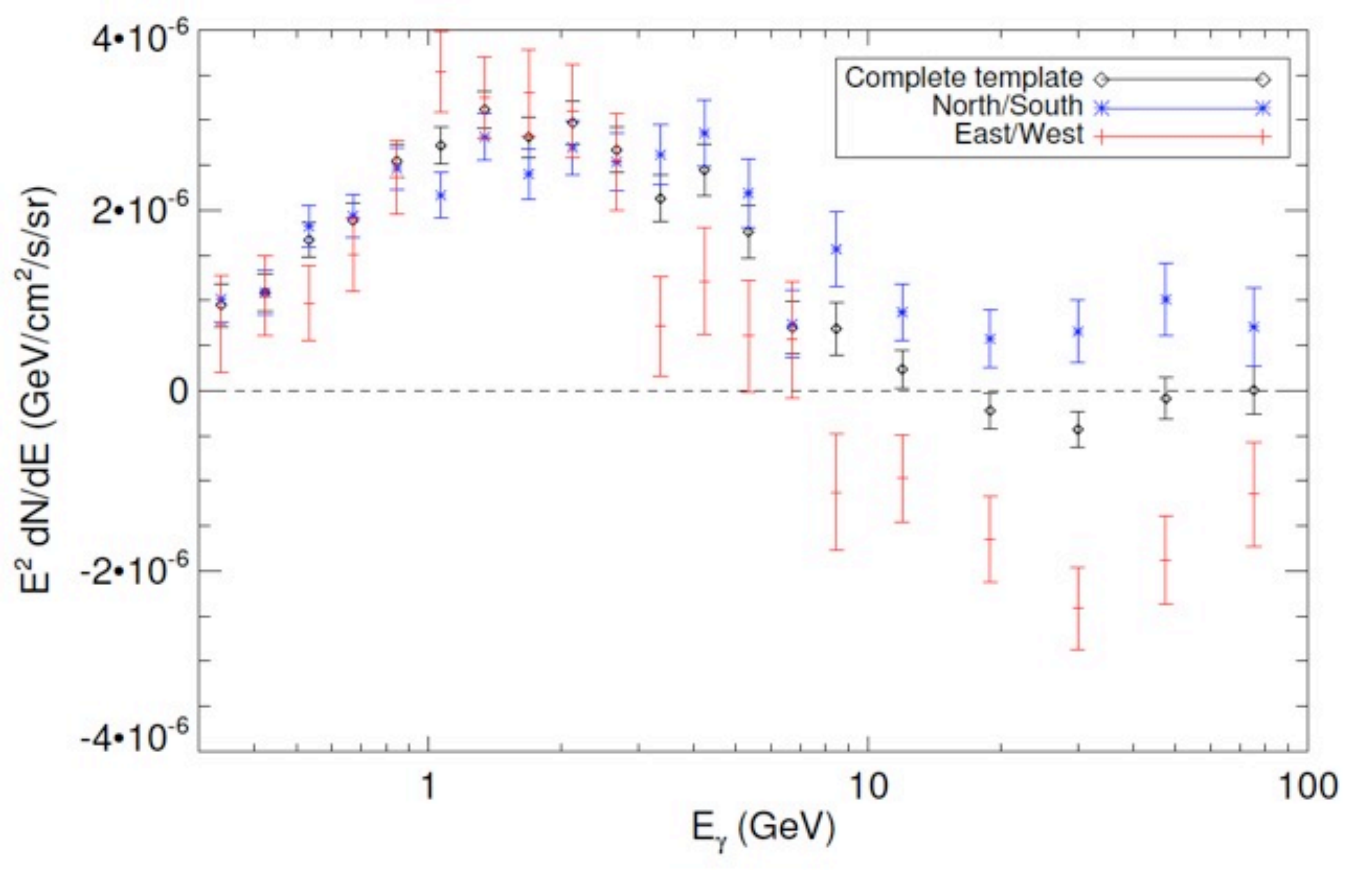
Cross Checks: Different Regions of the Sky (pre bug fix)

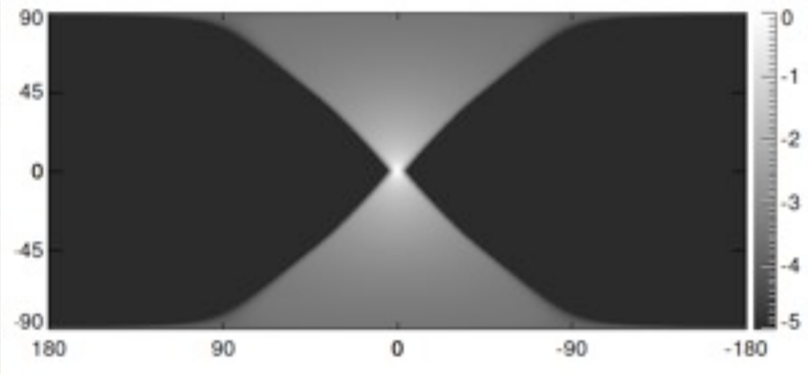
- Plot shows the extracted spectrum looks relatively consistent regardless of where in the sky you look
- See over subtraction is an issue at higher latitudes - again potentially due to systematic uncertainties in the diffuse model

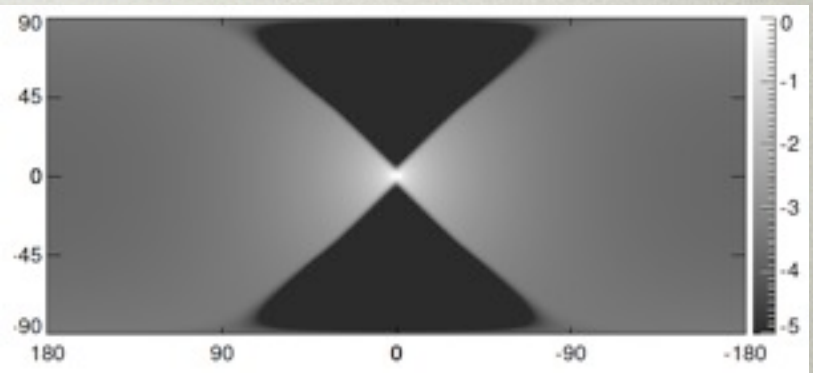


Cross Checks: Different Regions of the Sky (pre bug fix)

- Below show the spectrum extracted if the NFW template is broken up into a North/South and East/West component (see the template figures)
- The fact over subtraction is arising from the East/West component seems to give weight to the idea this may be associated with systematics in the Fermi diffuse model





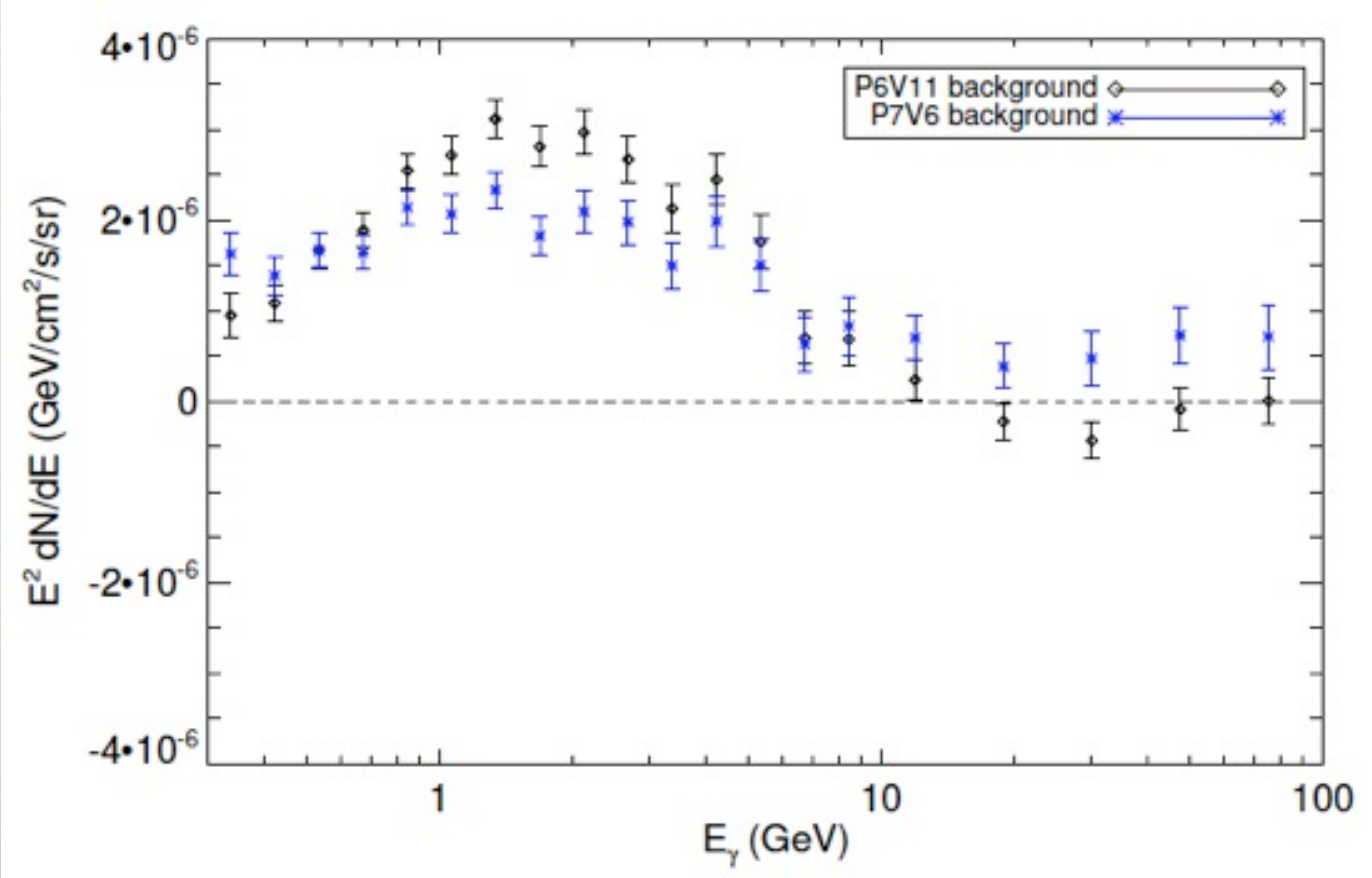


Cross Checks: Different Energies (pre bug fix)

- When we repeat the IG analysis one energy bin at a time, a preference is found for γ=1.2-1.3 in all energy bins between 0.5 and 10 GeV
  - At energies below 0.5 GeV the fit prefers a steeper slope (γ~1.6), which may be due to contamination from the galactic plane
  - At energies above 10 GeV the fit prefers a lower value (γ~1.0)

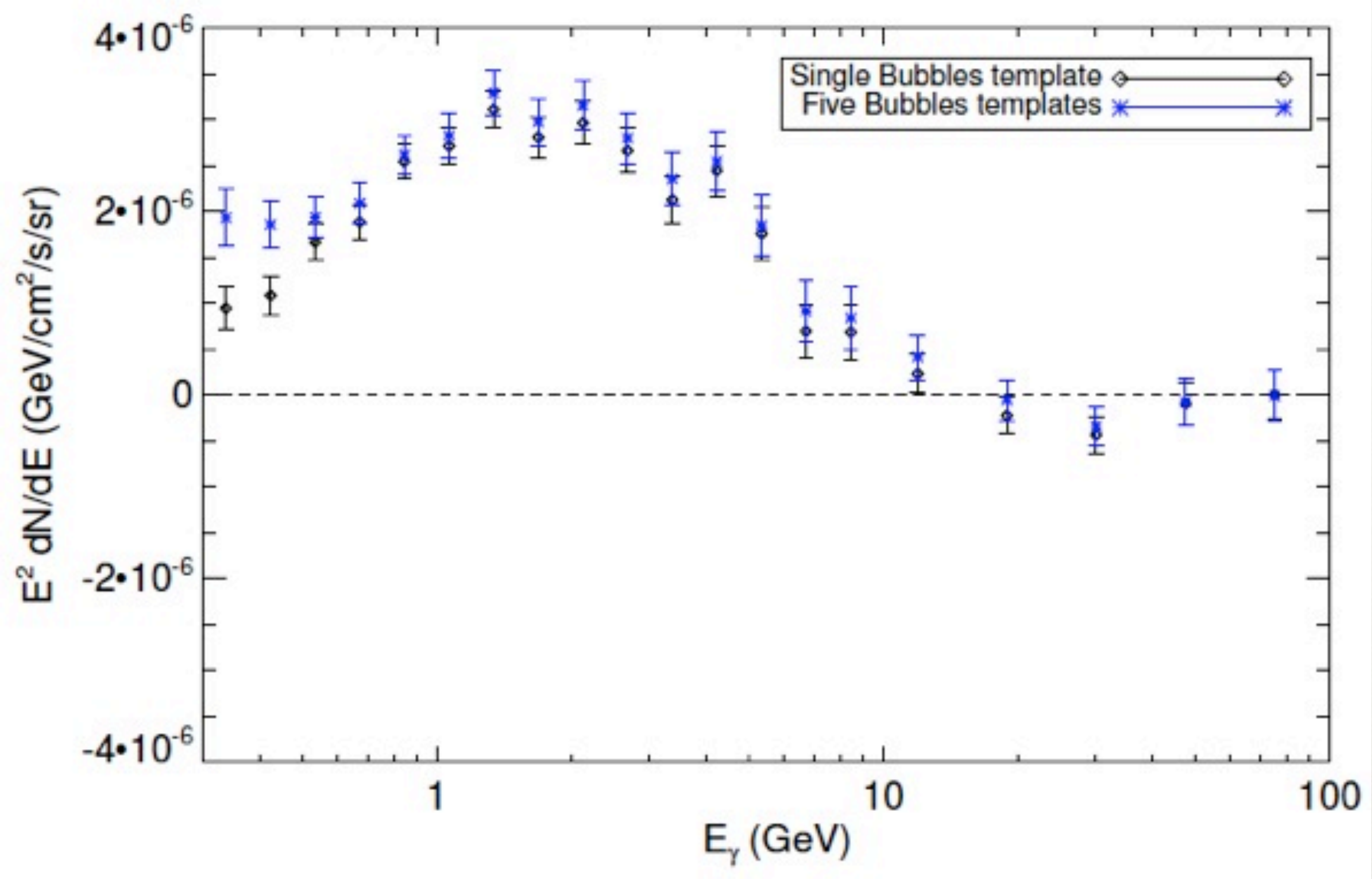
Cross Checks: Different Diffuse Model (pre bug fix)

- Below we show the extracted spectrum assuming an NFW profile with γ=1.26 using two different versions of the Fermi diffuse model. Note we used P6V11 throughout our analysis
  - Reason we used P6 is that P7 contains an artificial template for the Fermi bubbles, making it more difficult to interpret any residuals
  - Fits using P6 rather than P7 are preferred at high significance



Cross Checks: Additional Freedom in the Bubbles (pre bug fix)

- May worry that a varying spectrum throughout the bubbles could absorb the signal - indeed this is how the excess in the IG was first discovered
- Nevertheless cutting the bubbles into 10 degree latitude slices and letting each be an independent template does not significantly adjust the extracted spectrum correlated with an NFW template



Cross Checks: Mismodelling of the π^0 Component (pre bug fix)

- In addition to the modulated template method described earlier, one can also check for a mismodelling of the π^0 background by adding in an accurate dust map (due to Schlegel, Finkbeiner and Davis; astro-ph/9710327) as an additional template and see if it picks up a component
- Below we see that it does (left), but that this has little impact on the preference for an NFW template