The High Energy Tail of the Galactic Centre Excess

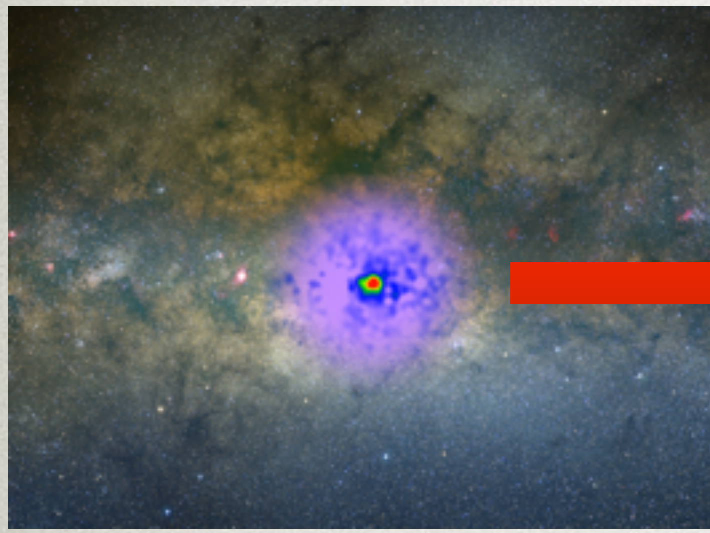
Nick Rodd - MIT

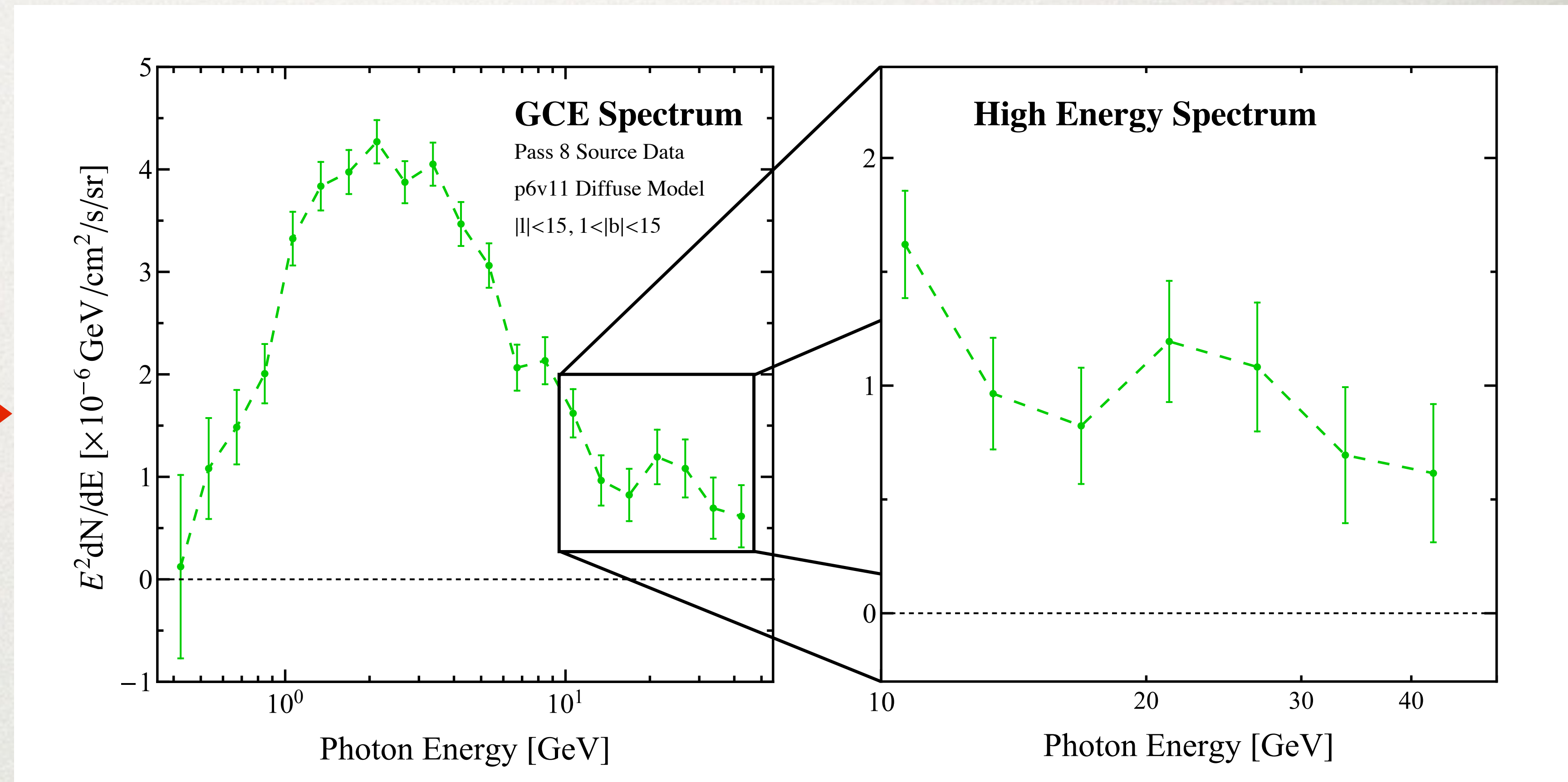
Based on ongoing work w/ Tim Linden, Ben Safdi and Tracy Slatyer

Gamma Rays and Dark Matter
8 December 2015

Motivation

- How high in energy does the GCE emission extend?

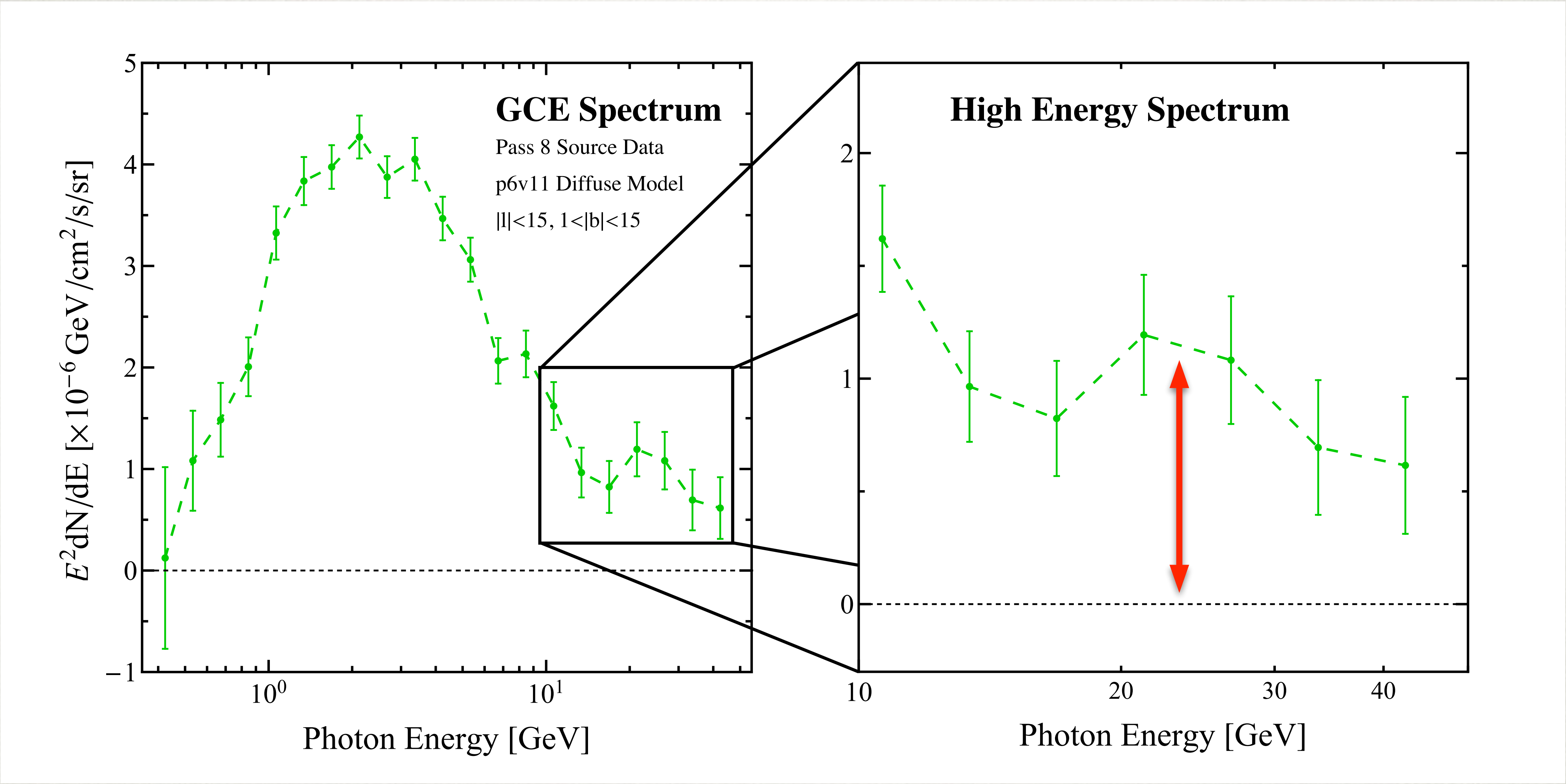




- Important handle on whatever is creating the excess:
  - Millisecond Pulsars: is there an exponential cutoff or is it a harder spectrum?
  - Dark Matter: tail of the spectrum reveals a lot about the mass and annihilation mechanism (see e.g. Agrawal et al 1411.2592, Calore et al 1411.4647, NLR et al 1503.01773)

Motivation

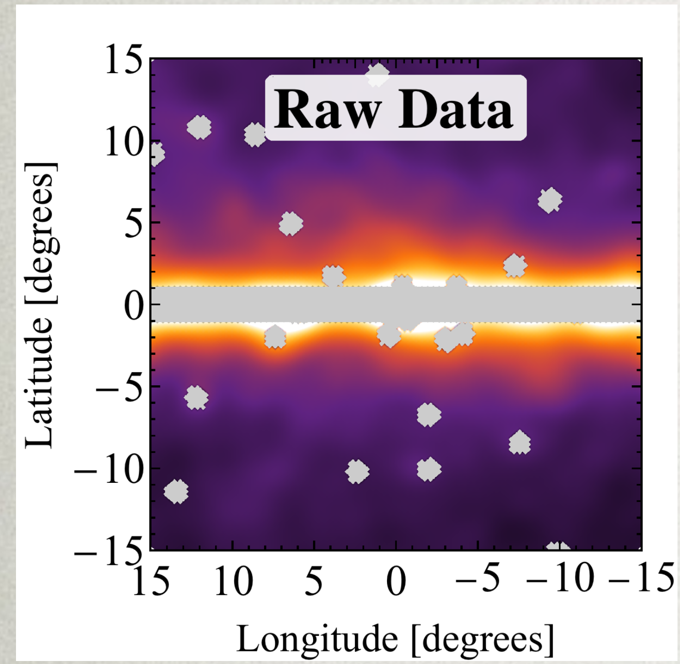
- Looks like we're already done: non-zero emission at high energies



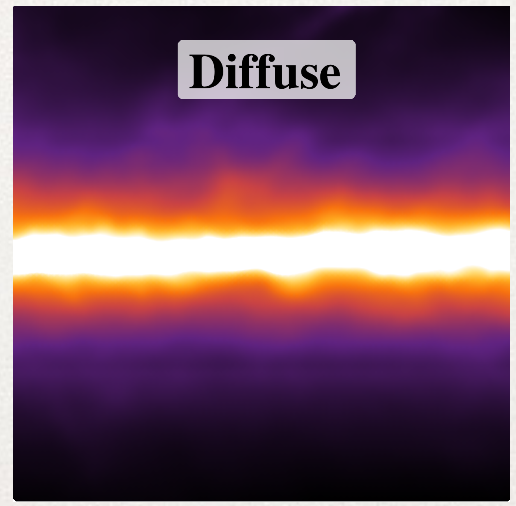
- But shouldn't be so quick! The spectrum should be interpreted carefully - especially at high energies
- To see why let's quickly review where it comes from

Extracting the GCE Spectrum: Template Fitting

Break 3D sky (l,b,E) into energy bins {E^i} and fit as a sum of templates

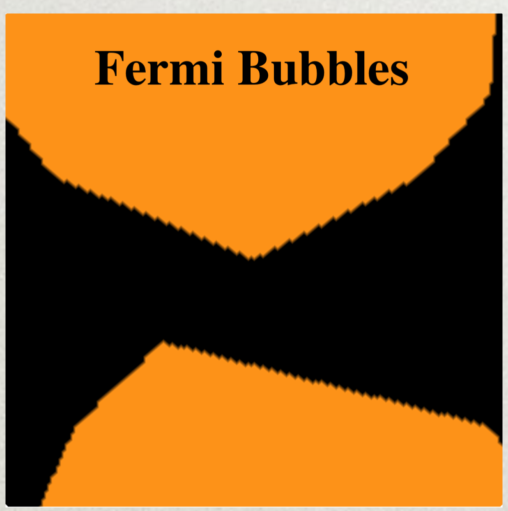


$= \alpha^i_{\rm diff}$

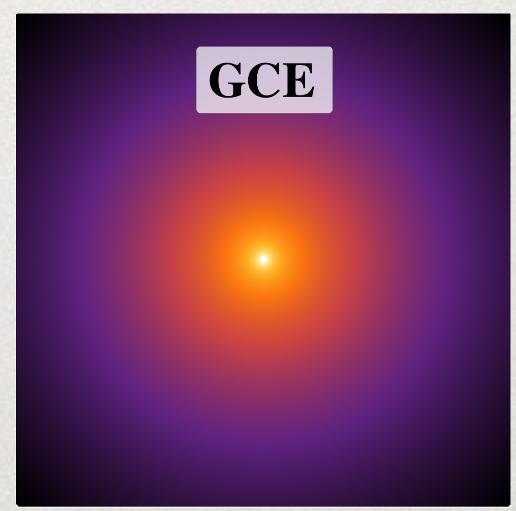


$+\alpha^i_{\rm iso}$

$+\alpha^i_{\rm bub}$



$+\alpha^i_{\rm GCE}$



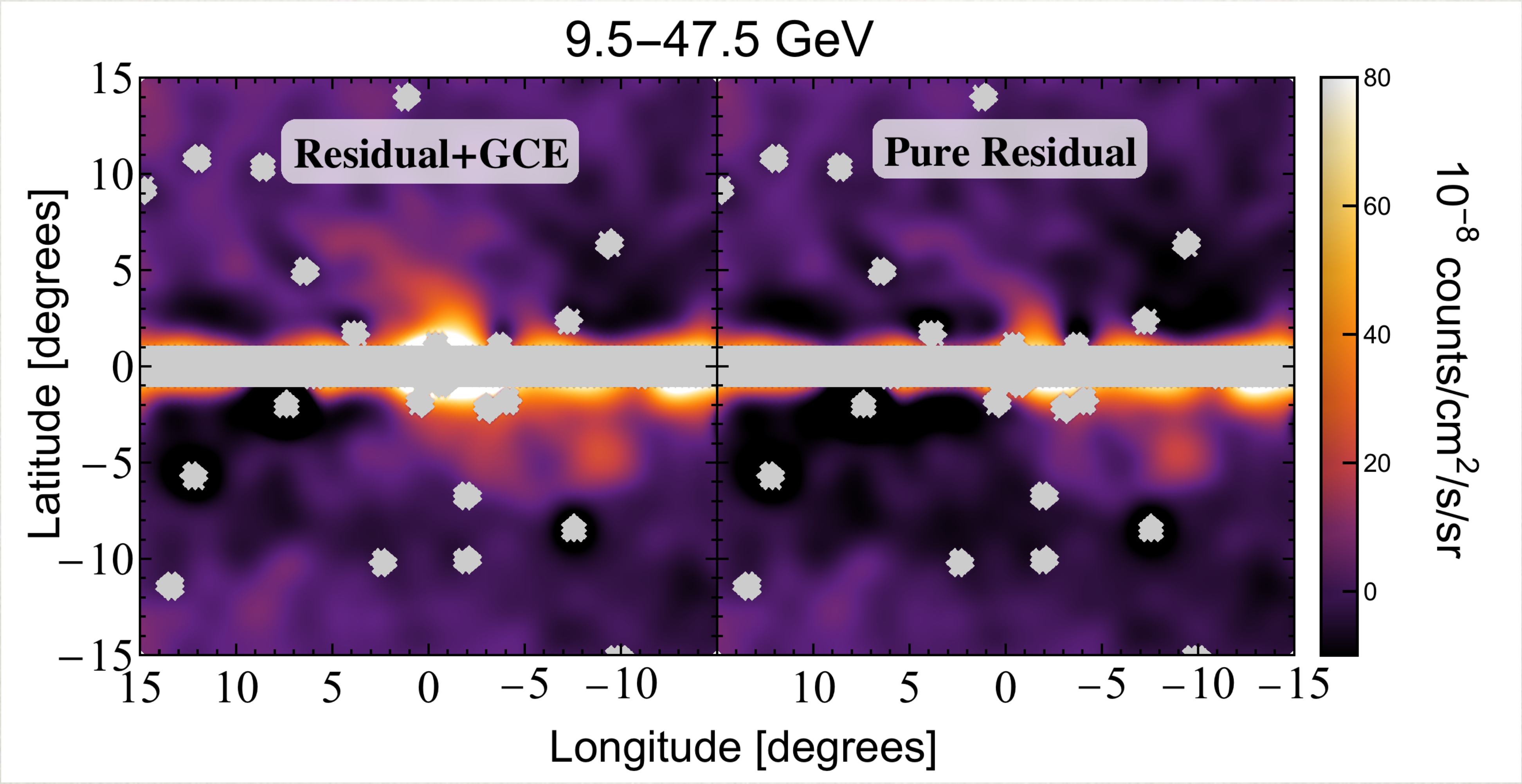
$+{\rm Residual}^i$

Convert to $E^2 dN/dE$ - build up spectrum

Useful diagnostic of the fit quality (complements the Test Statistic)

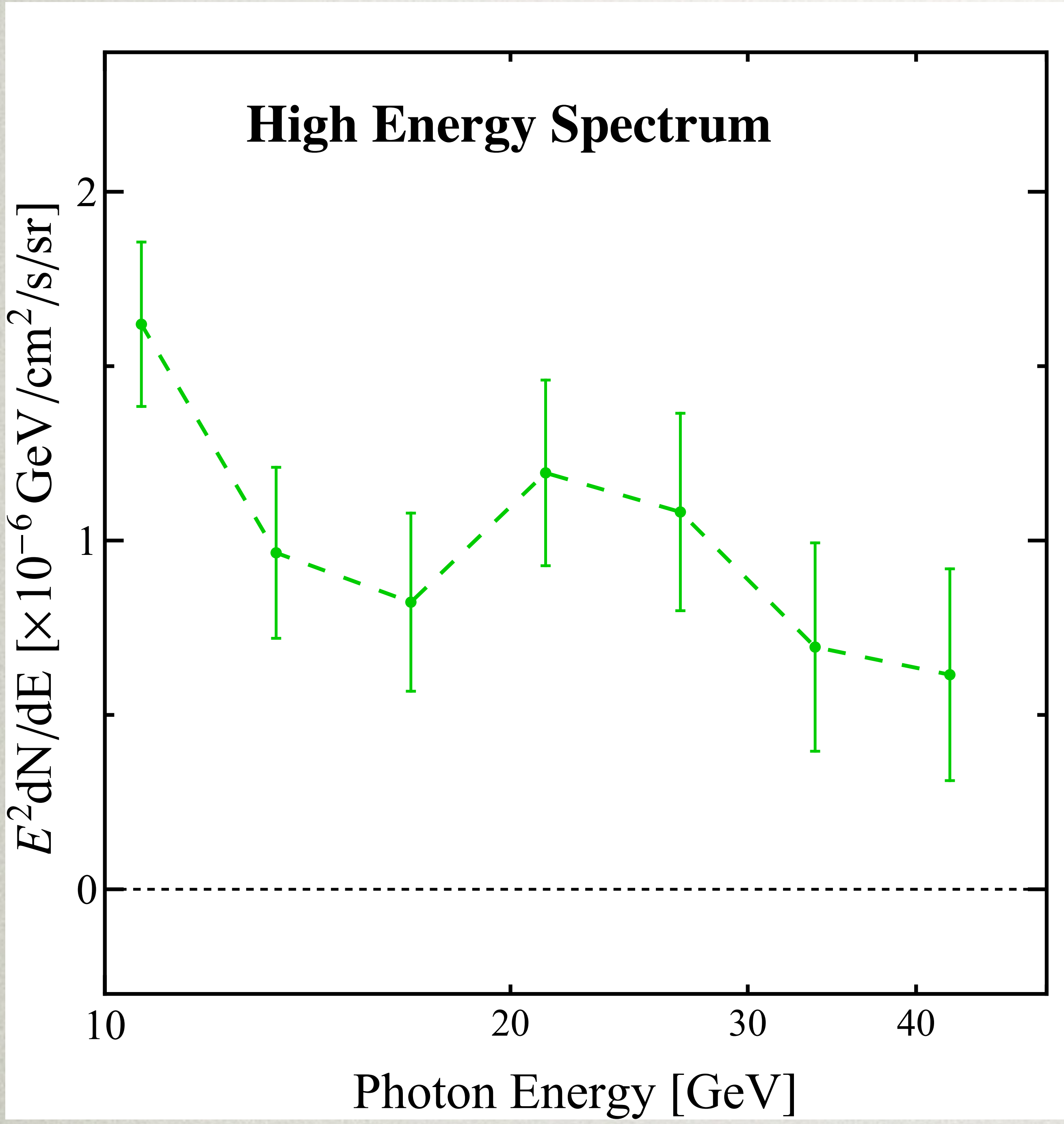
Extracting the GCE Spectrum: Template Fitting

At high energies consider: Data - diff - bub - iso (- GCE):



- If the excess is really present at high energies it is of a comparable size to the spatial residuals, which could fake a contribution
- Instead need to look for peculiar spatial properties we know the GCE exhibits: sphericity, profile's inner slope, non-poiss stats, etc

Analysing Spatial Properties



1. Galactic Centre

- Small ROI: 15°x15°
- No Mask - model PS
- Based on Fermi Tools

2. Inner Galaxy

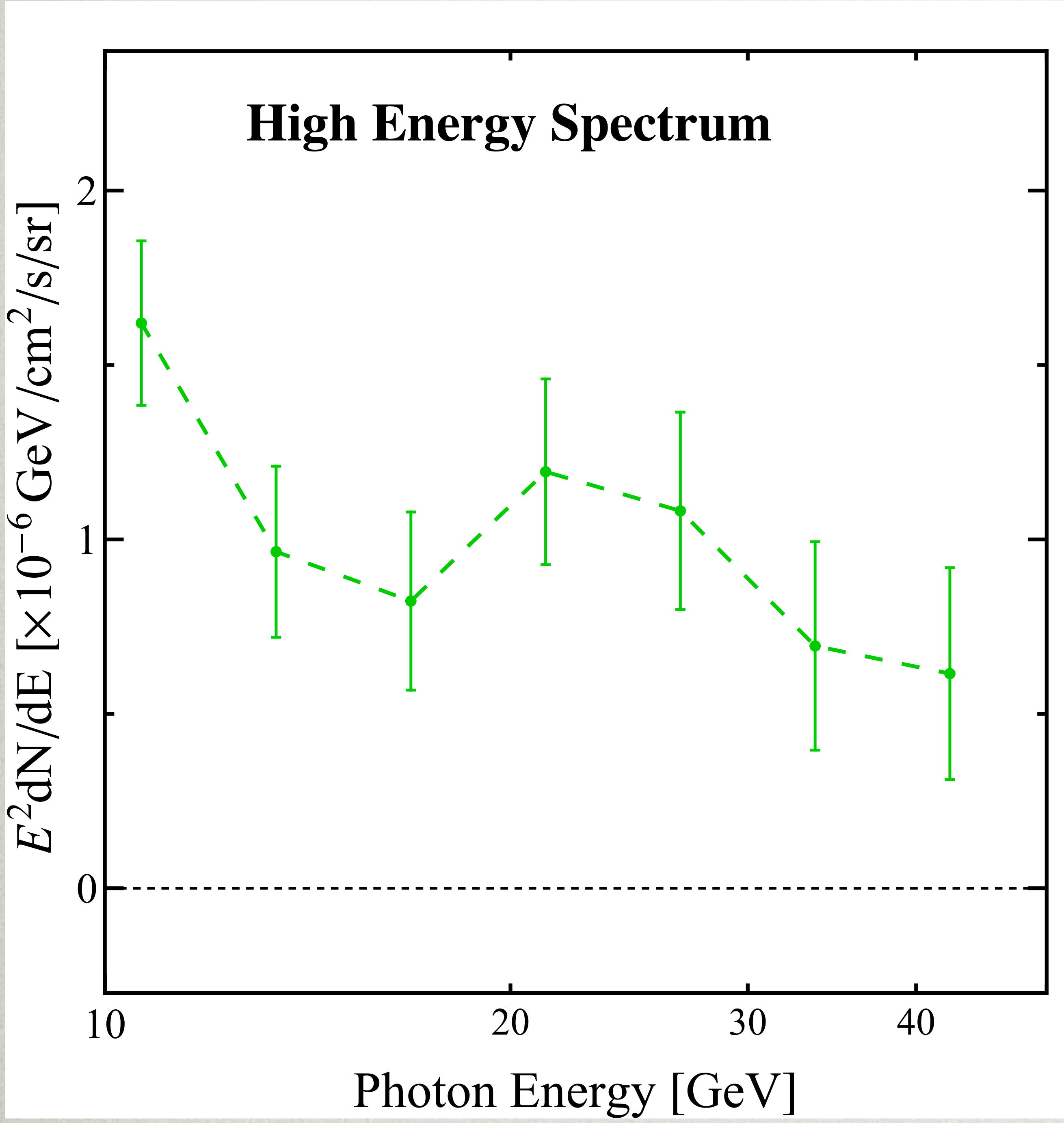
- Larger ROI: 30°x30°
- Mask plane and bright PS
- Frequentist template fitting

3. Non-Poissonian Stats

- Similar to IG, except:
- Bayesian template fitting
- Different treatment of PS

- In all three analyses use the majority of source class Pass 8 events:
  - At high energies statistics, not angular resolution, is the biggest problem
- Number of systematic checks to confirm results not a relic of low stats

Analysing Spatial Properties



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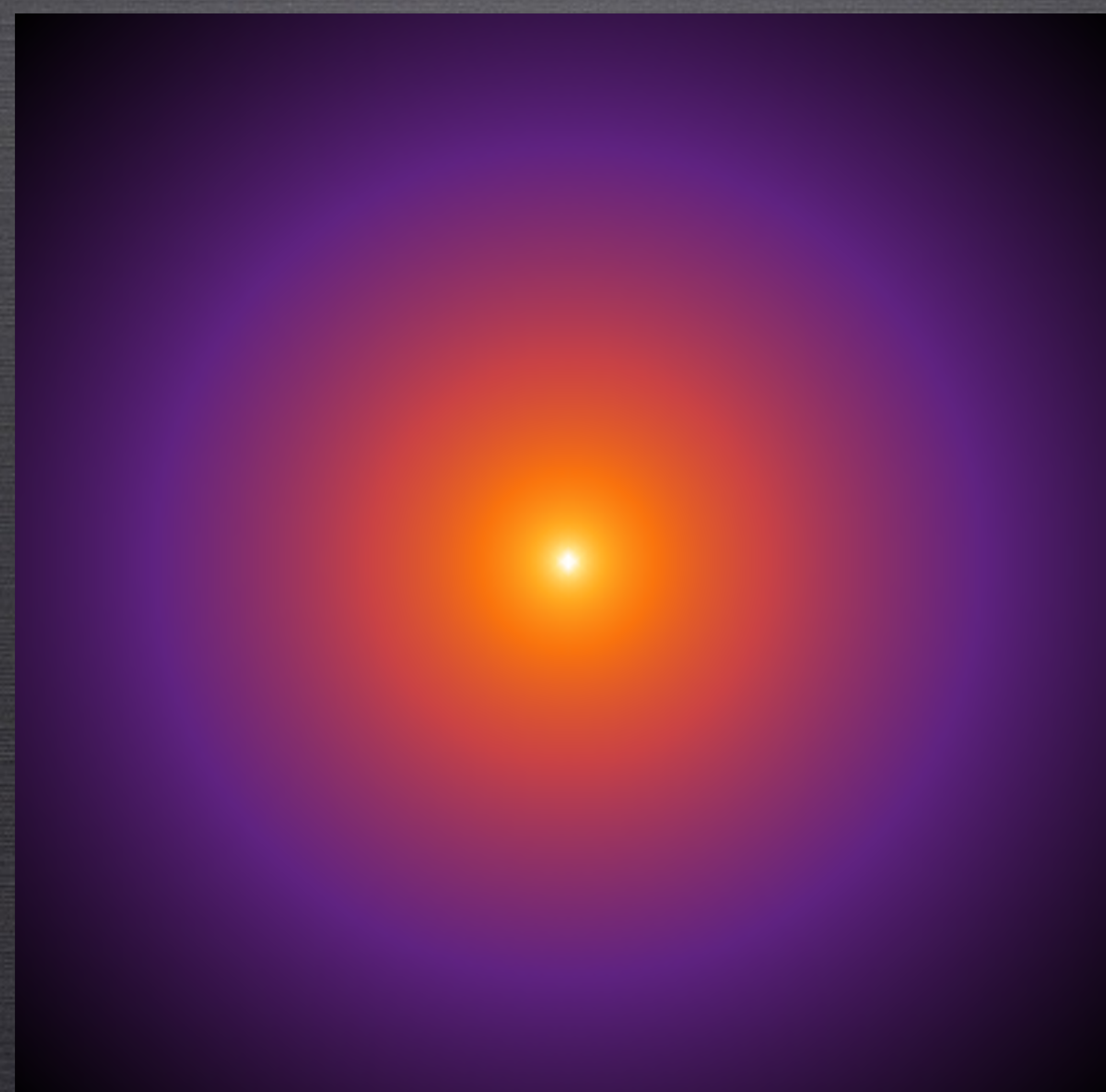
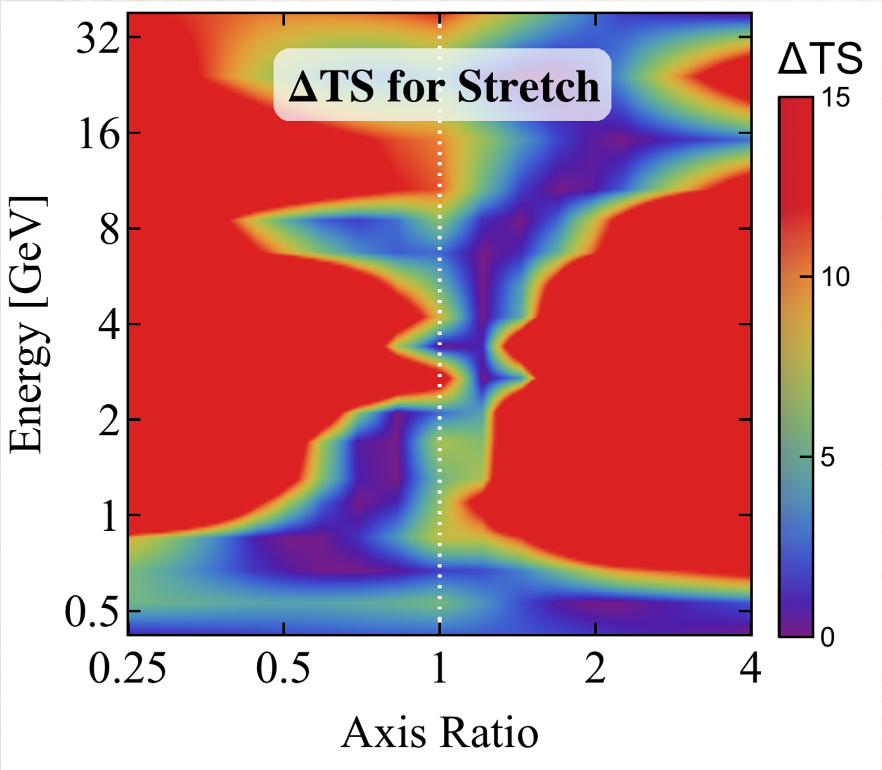
Spatial Properties In the Inner Galaxy

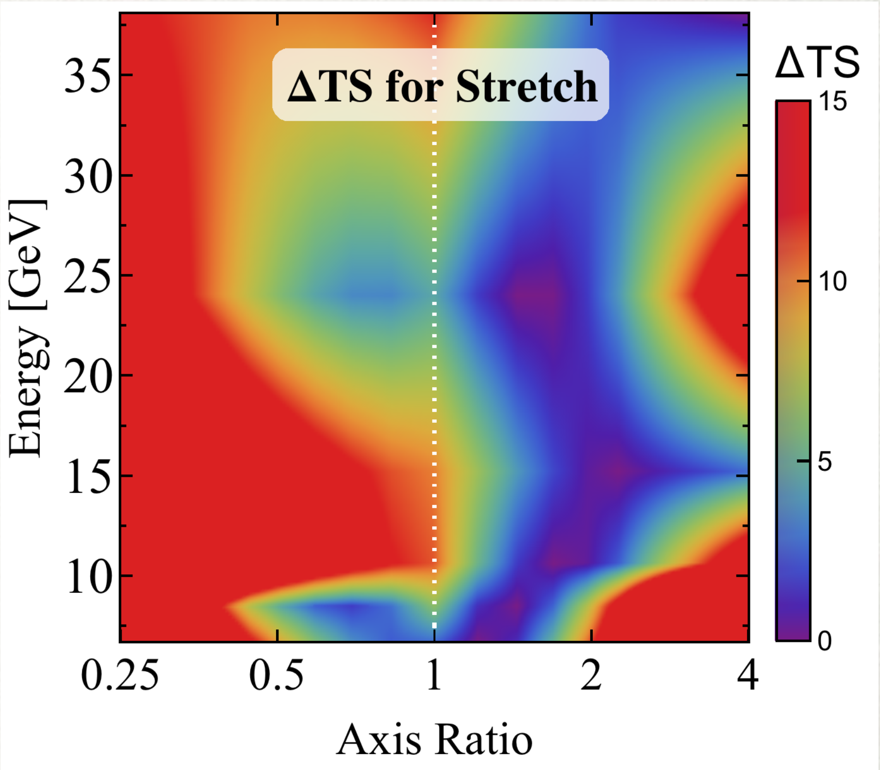


Bin by Bin Sphericity

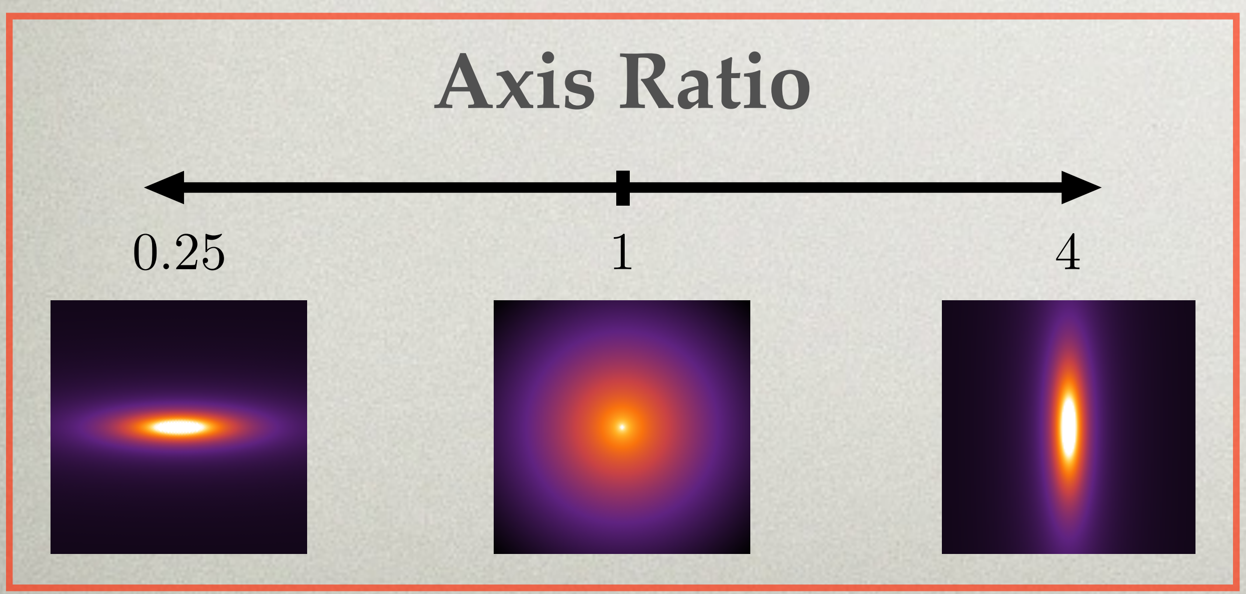
All Energies

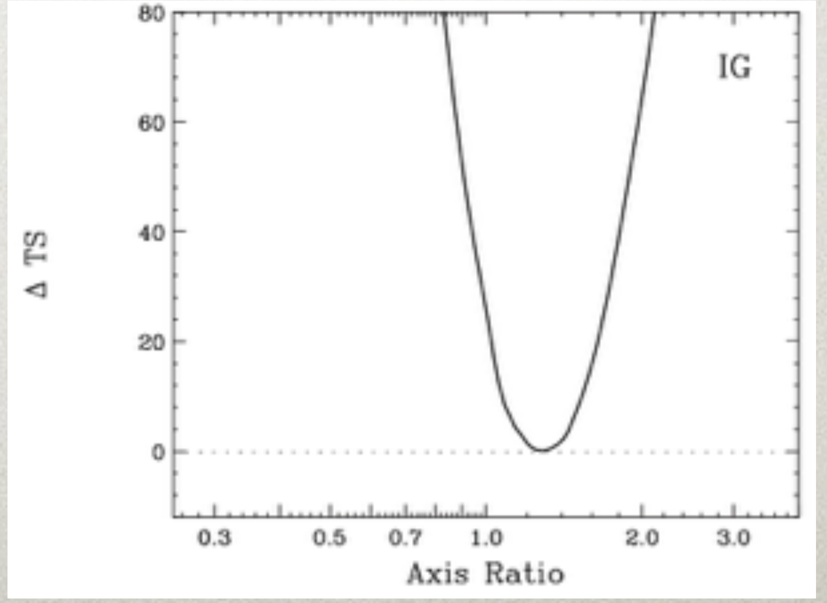


High Energy



- Increase in preference for GCE to be stretched perpendicular to the plane
- Stretch along the plane still disfavoured

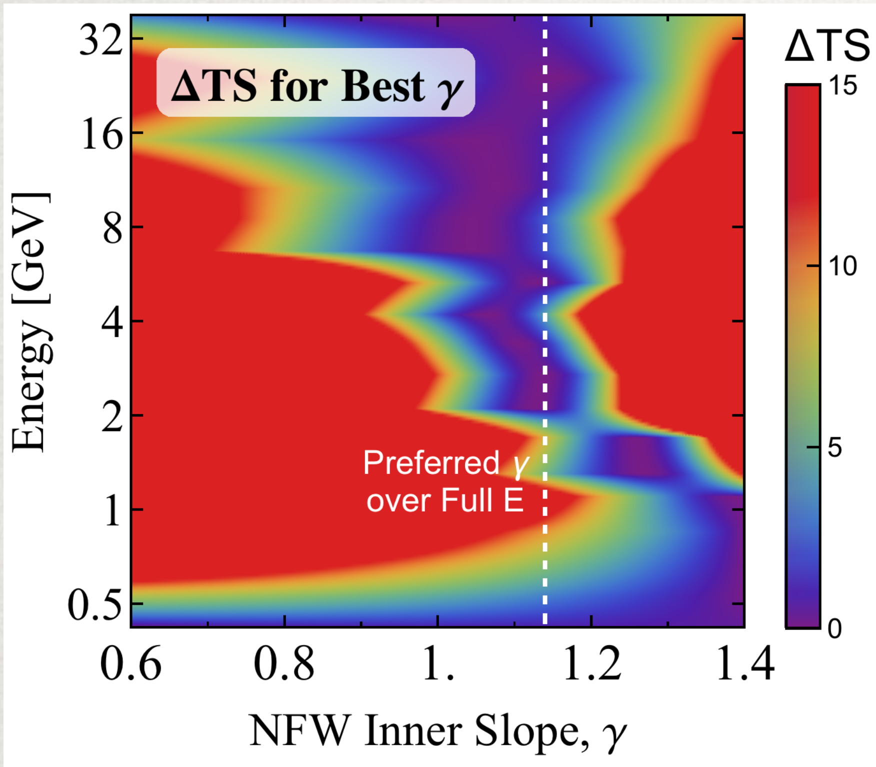




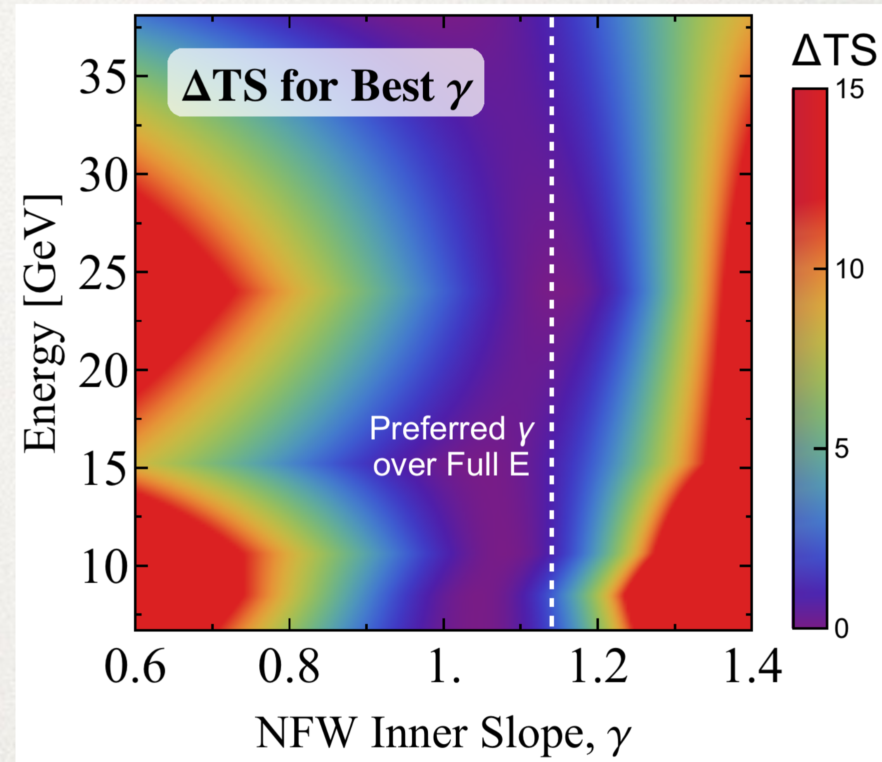
Daylan, NLR, et al 1402.6703

Bin by Bin Inner Slope

All Energies

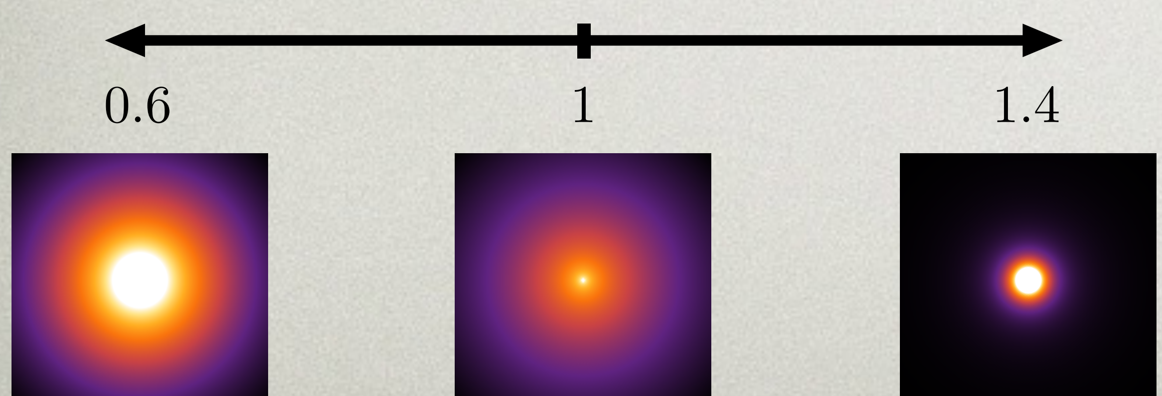


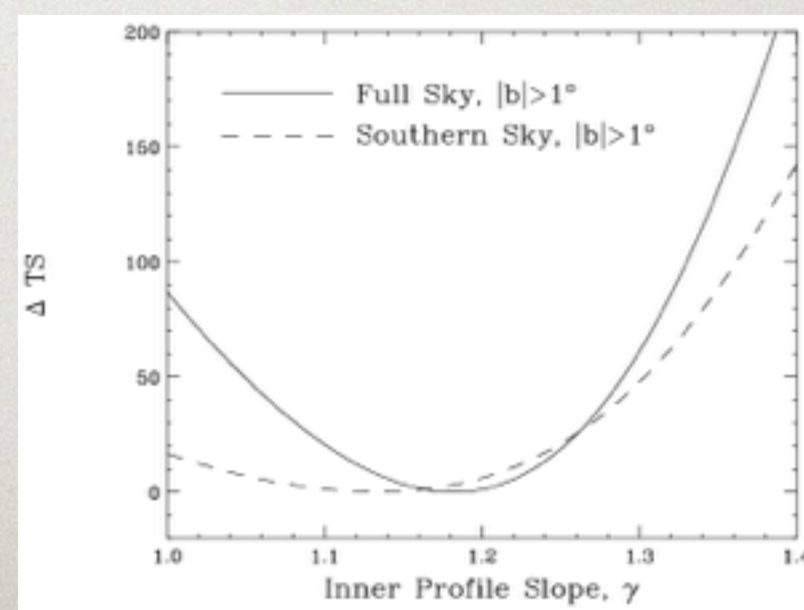
High Energy



- Preferred γ at high energy roughly consistent with excess as a whole
- Over the full energy range there is a downward trend in preferred γ

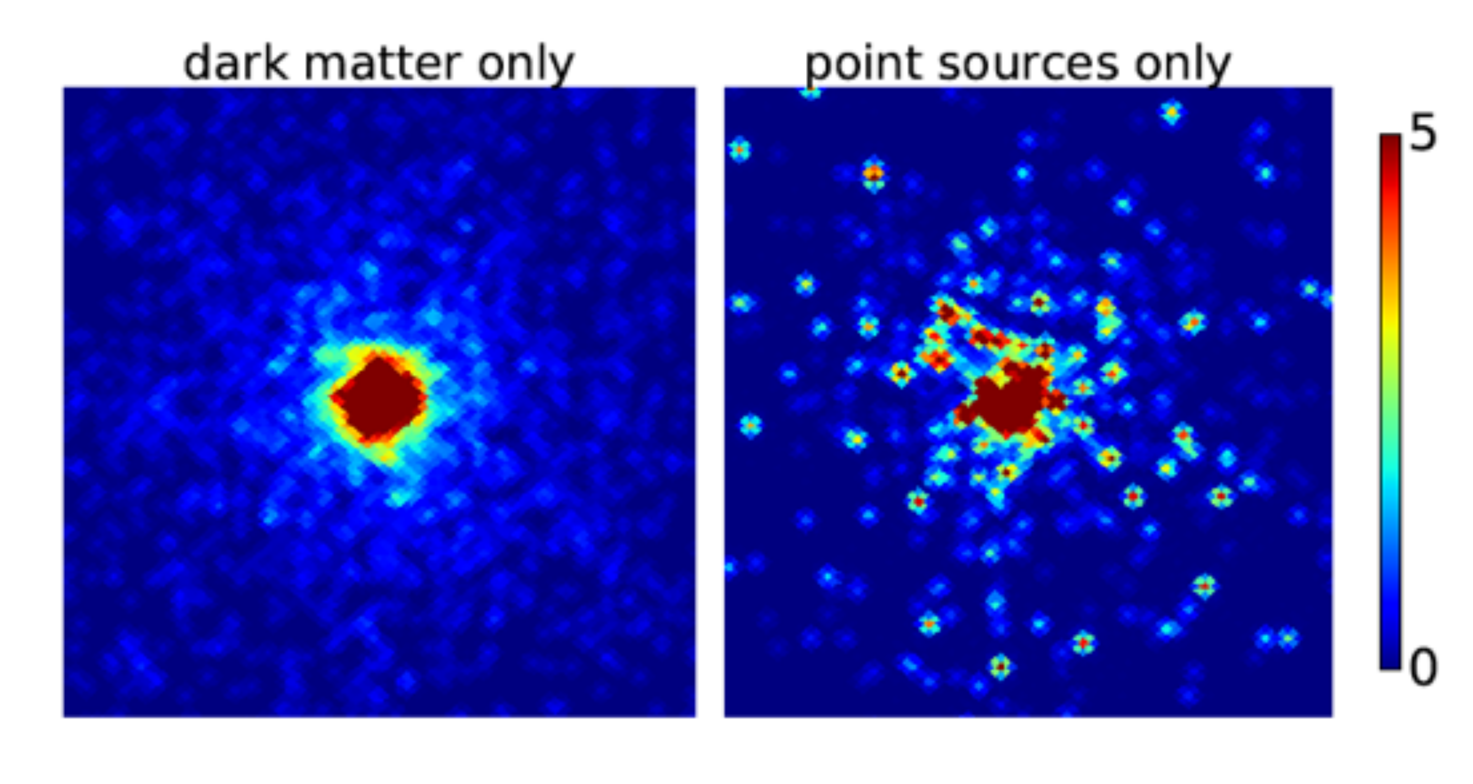
NFW Inner Slope, γ





Daylan, NLR, et al 1402.6703

Point Source Origin Of the GCE



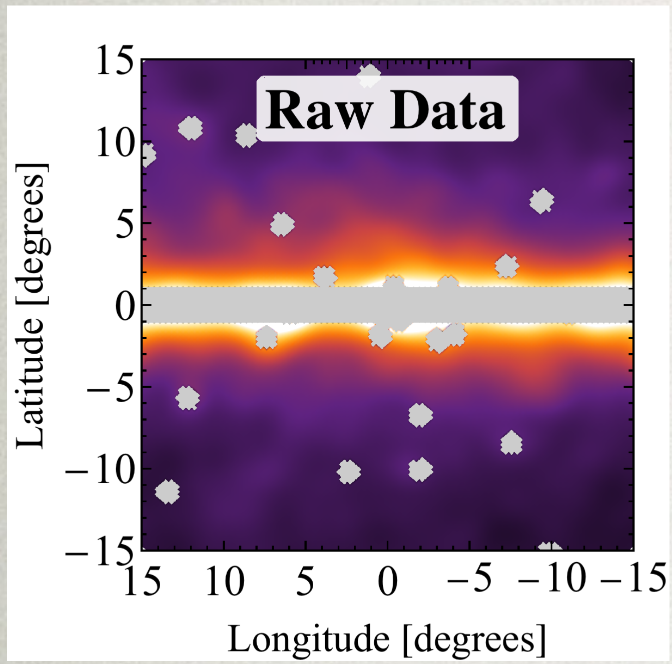
See Lee, Lisanti, Safdi, Slatyer & Xue (1506.05124) and Malyshev & Hogg (1104.0010), Lee, Lisanti & Safdi (1412.6099) for additional details

Bartels, Krishnamurthy & Weniger (1506.05104) for Similar analysis using wavelets (see Bartels talk tomorrow)

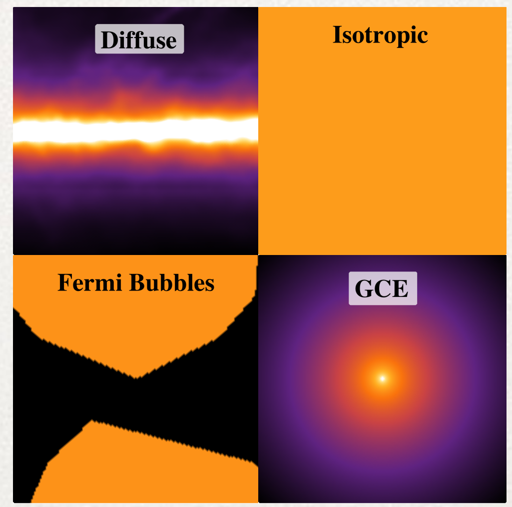
Probabilistic Catalogues provide another approach to this Issue (talks by Daylan and Portillo also tomorrow)

Template Fitting Revisited

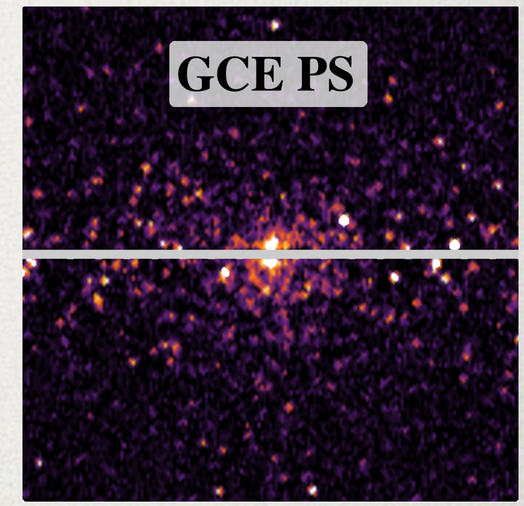
Break 3D sky (l,b,E) into energy bins $\{E^i\}$ and fit as a sum of templates



$= \sum_{\text{Templates}}$



$+\beta^i$



$-\text{Residual}^i$

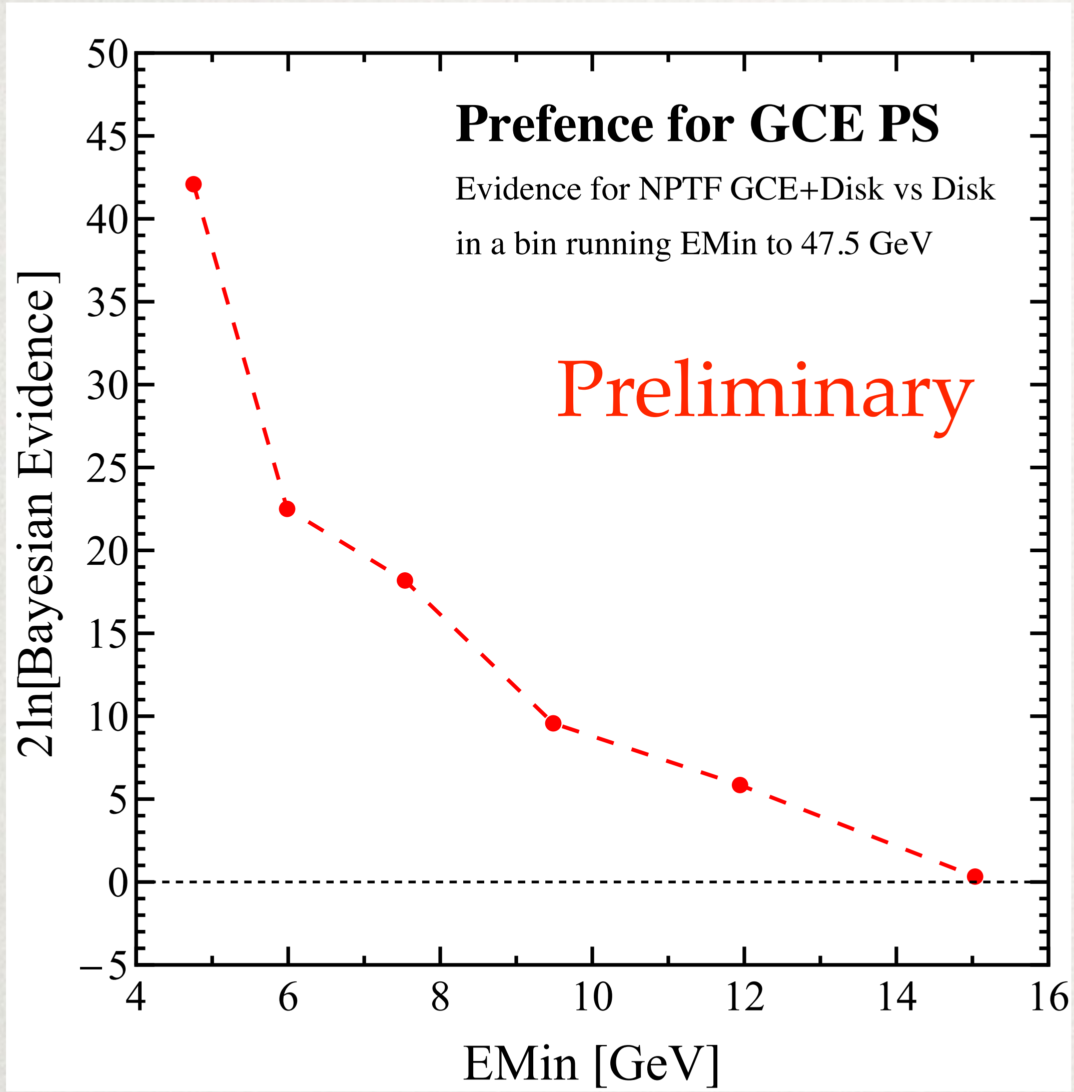
Fit with Poissonian Statistics

Fit with non-Poissonian Statistics

- A non-Poissonian template fit (NPTF) allows the fit to incorporate templates that look more point-like than smooth
  - NPTF can find evidence of point sources below Fermi detection threshold
  - Has been used to show evidence that the GCE is made up of unresolved point sources (1506.05124)
  - Does this preference for point sources extend to higher energies?

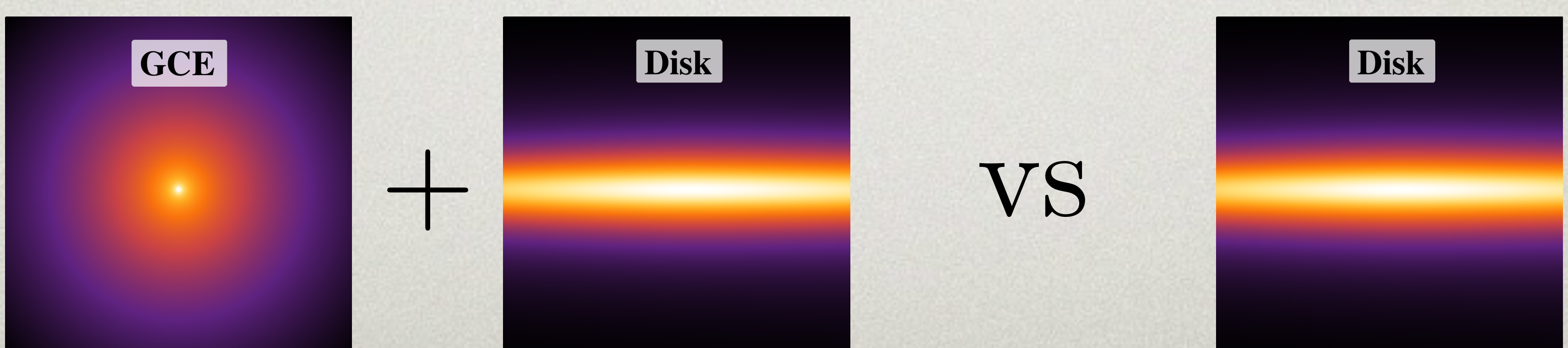
GCE Distributed Point Sources at High Energies

Can loosely think of as ΔTS or $-2\Delta\ln\mathcal{L}$



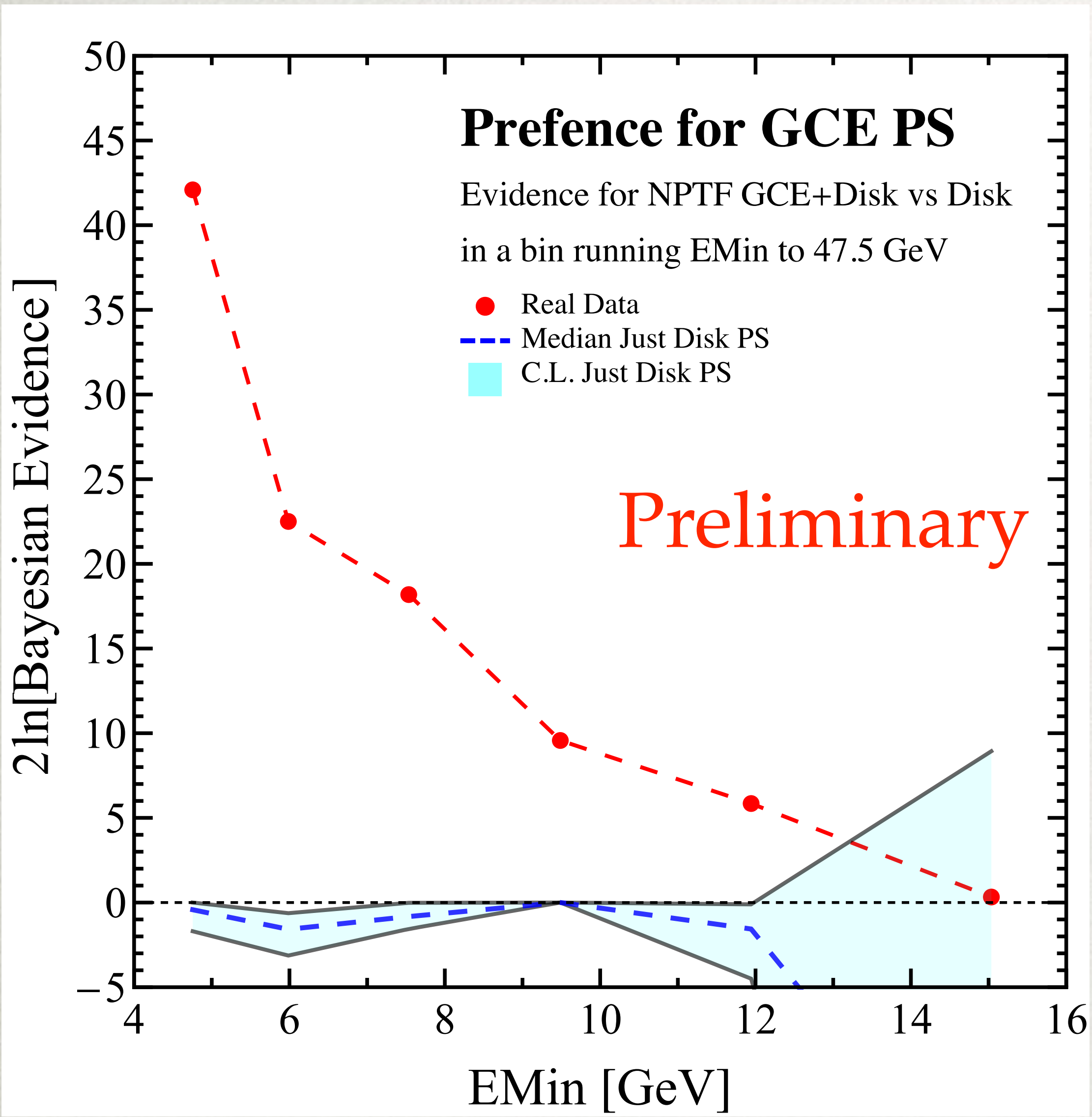
- Evidence for GCE PS persists to high energies
  - NB: both fits contain a Poissonian GCE template
- But begins to disappear as statistics run out
- Is this what we'd expect?
- Need simulated data!

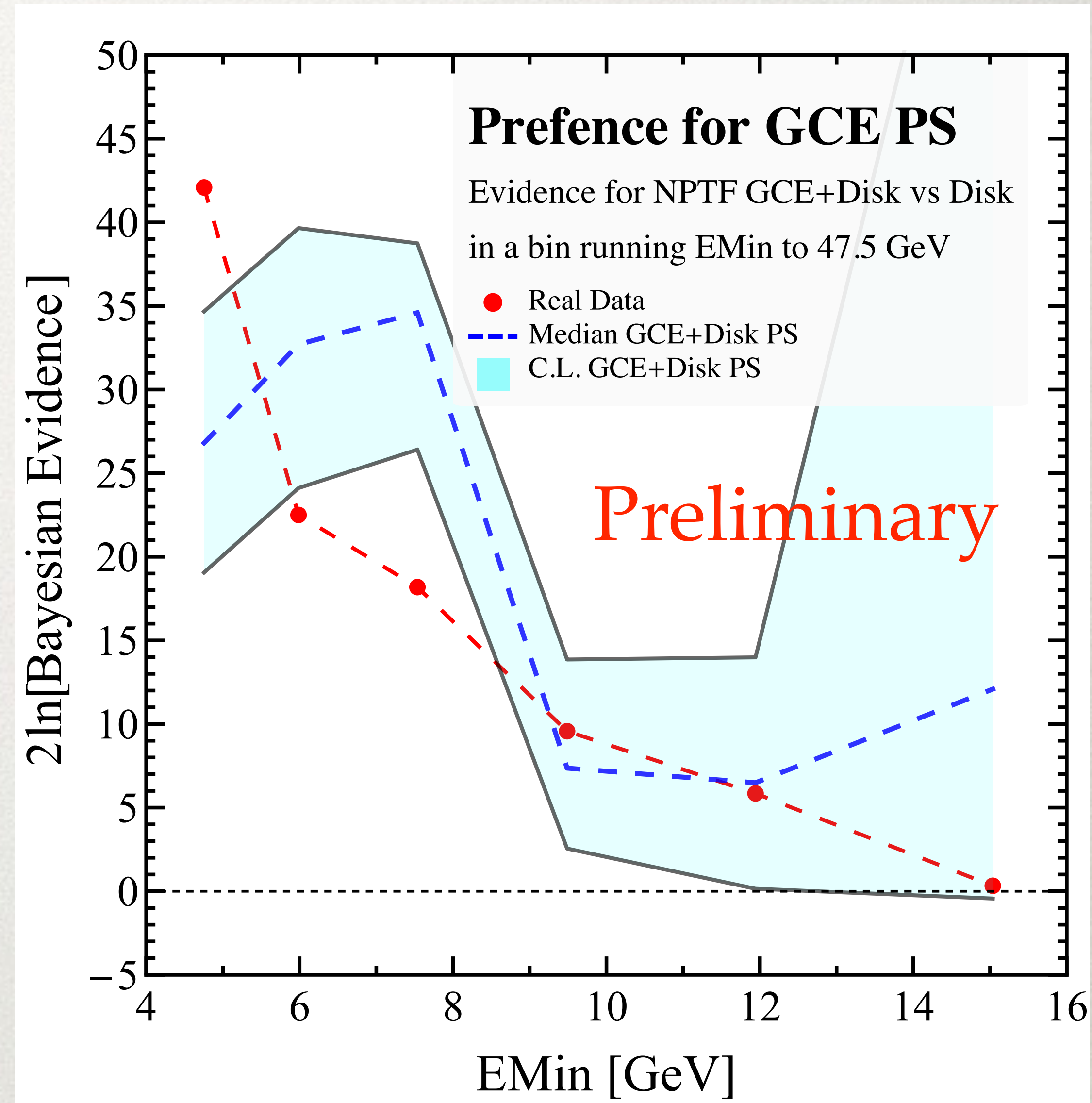
Figure shows the preference for GCE + Disk correlated PS vs Disk only, i.e.



NPTF Expectation Via Simulated Data

Compare the real data result to what we would get from simulations of disk only (left) or disk+GCE PS (right)

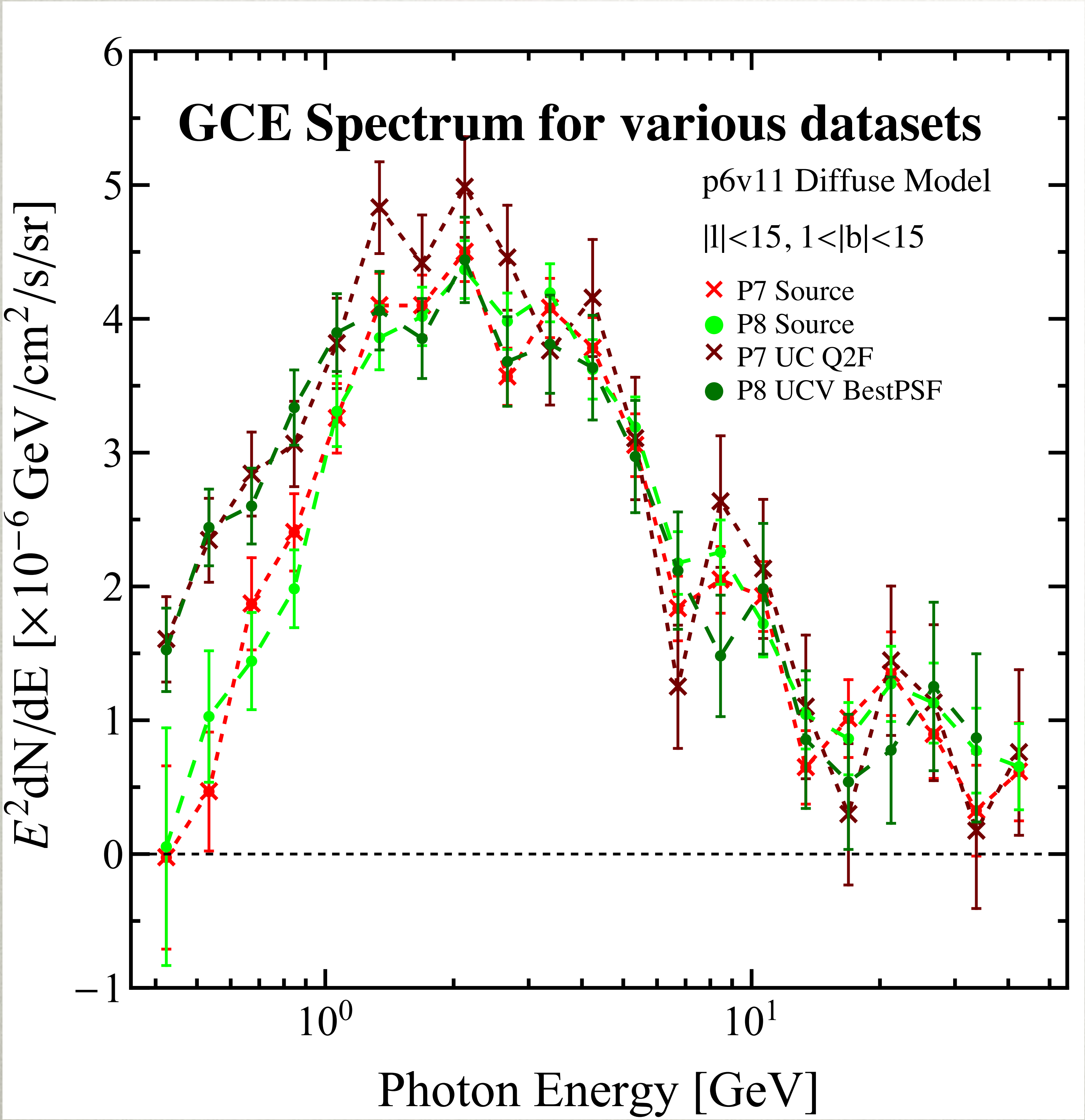




- Results are clearly more consistent with the presence of GCE correlated point sources at high energies rather than simply disk only
- But not perfectly consistent - following up some leads on the spike in the simulated GCE PS data at 6-8 GeV

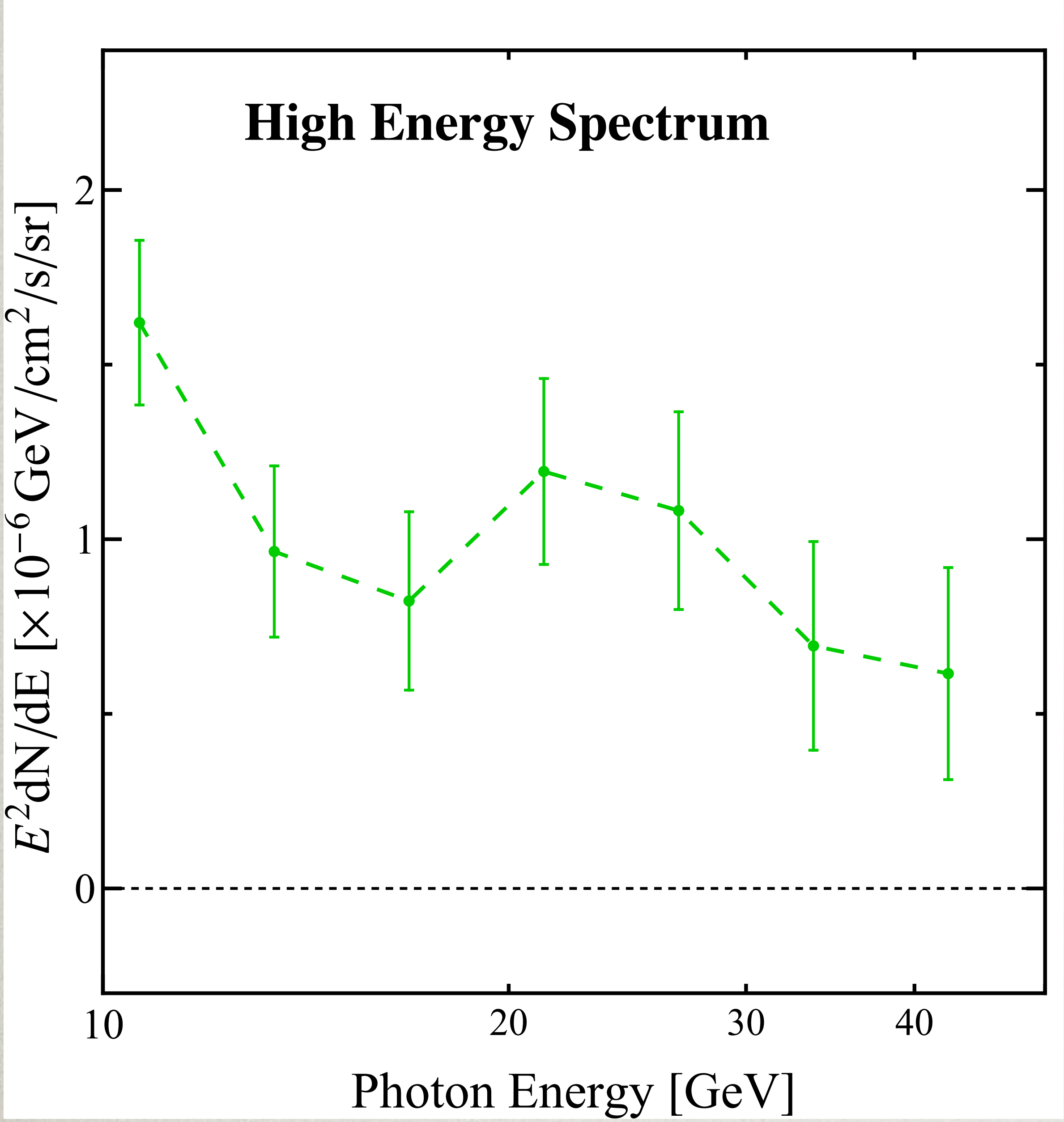
Systematics and Cross-Checks

Pass 7 vs Pass 8



- Largely unchanged by Pass 7 to 8 transition
- More variance by changing eventclass and eventtype
- Difference at low energy related to larger point source mask covering more of the ROI for source data

Conclusions



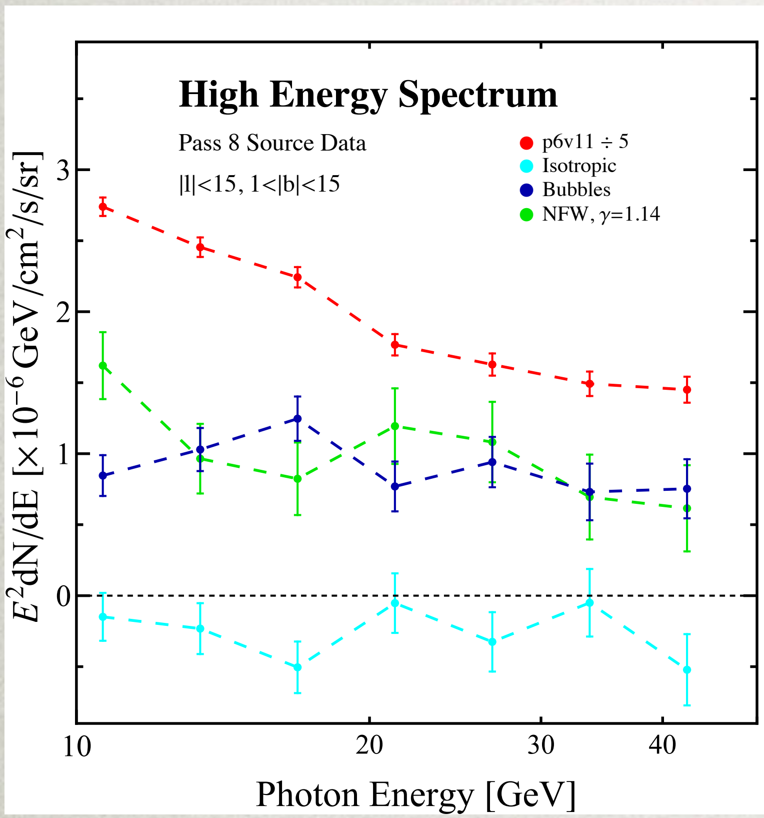
- At 10 GeV and maybe even higher the GCE exhibits similar spatial properties to those at ~1 GeV
  - See this in sphericity, preferred inner slope and NPTF analysis
- Appear to run out of statistics before seeing any clear change in behaviour

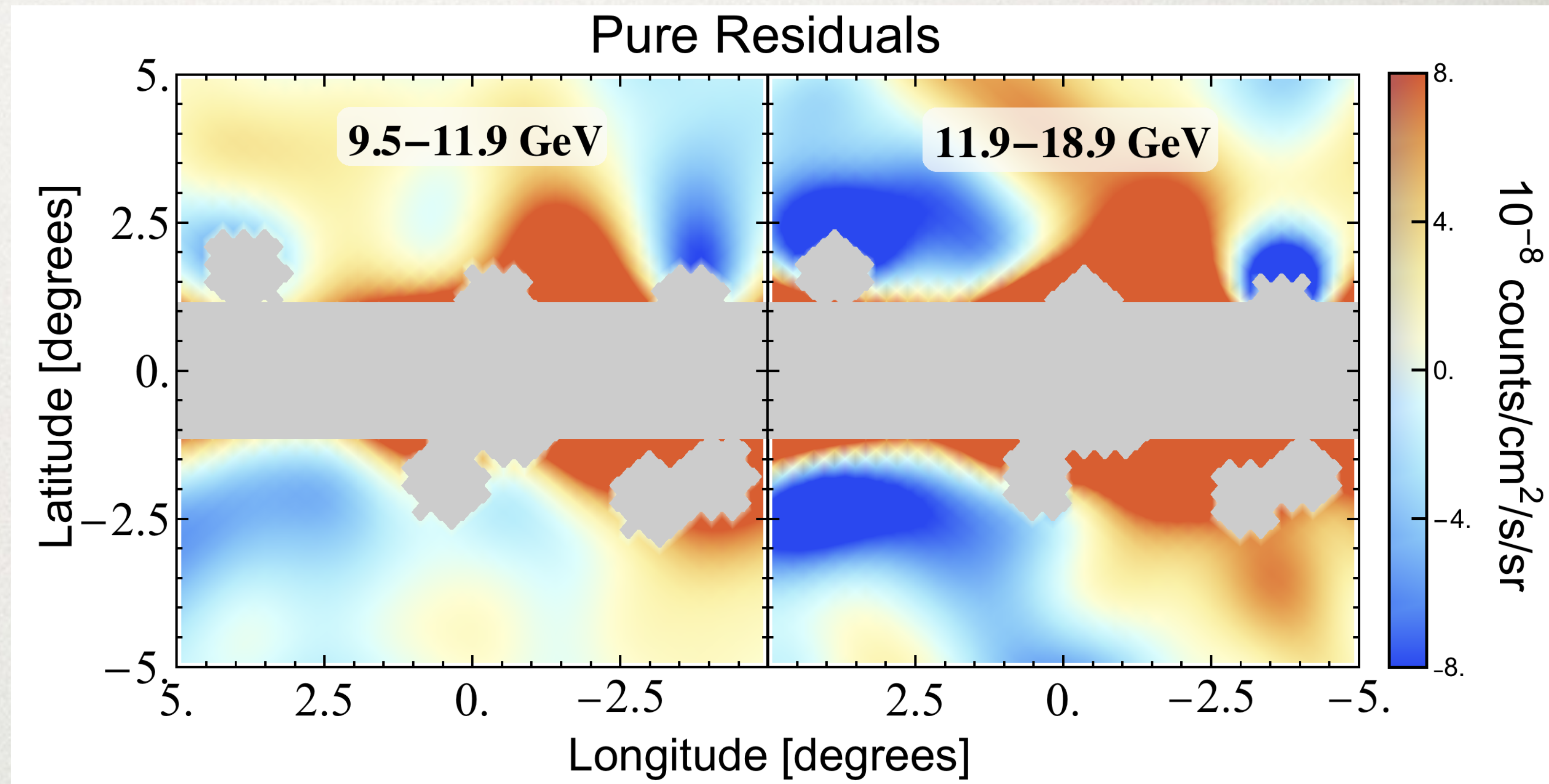
- Lots of details not shown, e.g. is that dip at 11.9-18.9 a real feature? Probably not!
- **Advertisement:** working with Lina Necib, Ben Safdi and Siddharth Sharma to have the NPTF code publicly released early next year, so watch out for this!
  - Also see Siddharth's talk Friday for another application of this code

Backup Slides

Dip in the Spectrum at 11.9-18.9 GeV

Probably not a real feature of the GCE

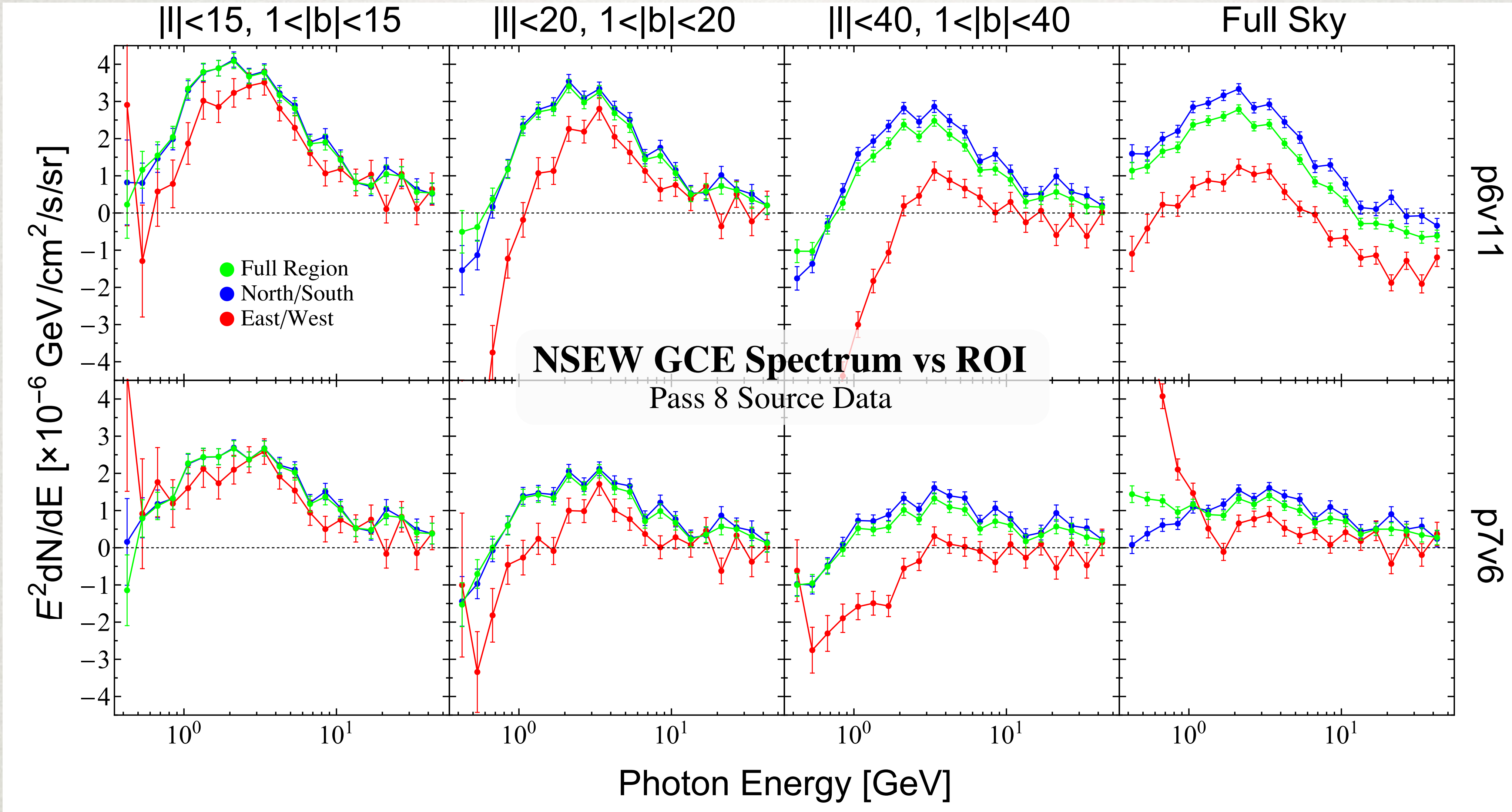


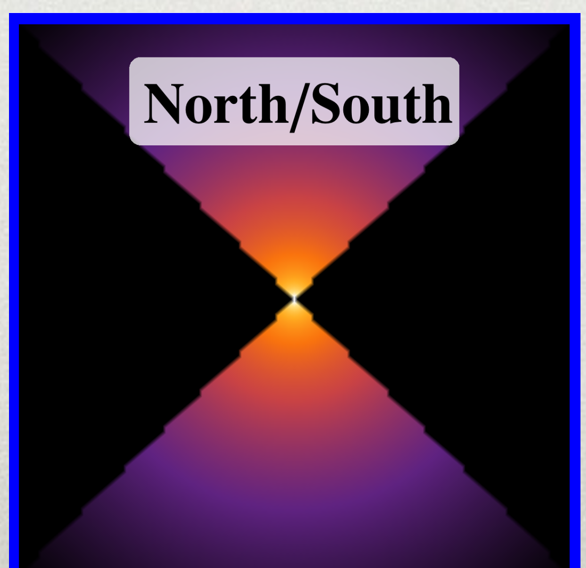


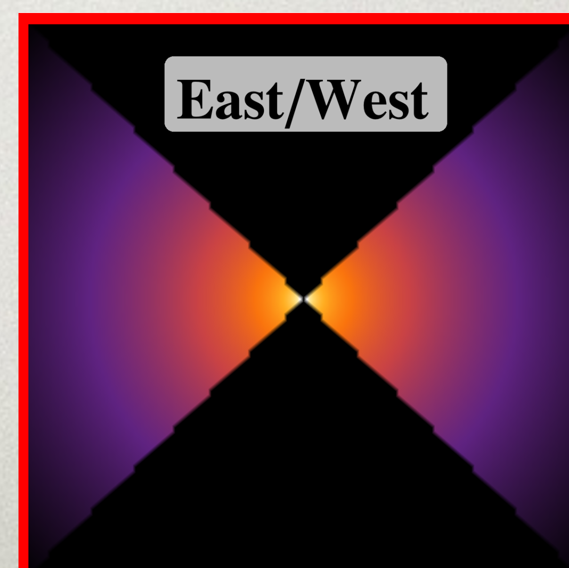
- Other backgrounds aren't stable at this energy
- If a real feature no reason for them to fluctuate too

- Can use the residual maps to diagnose if there are any issues
- Clear over subtraction in this bin which would penalise the GCE from having a large coefficient in a template fit

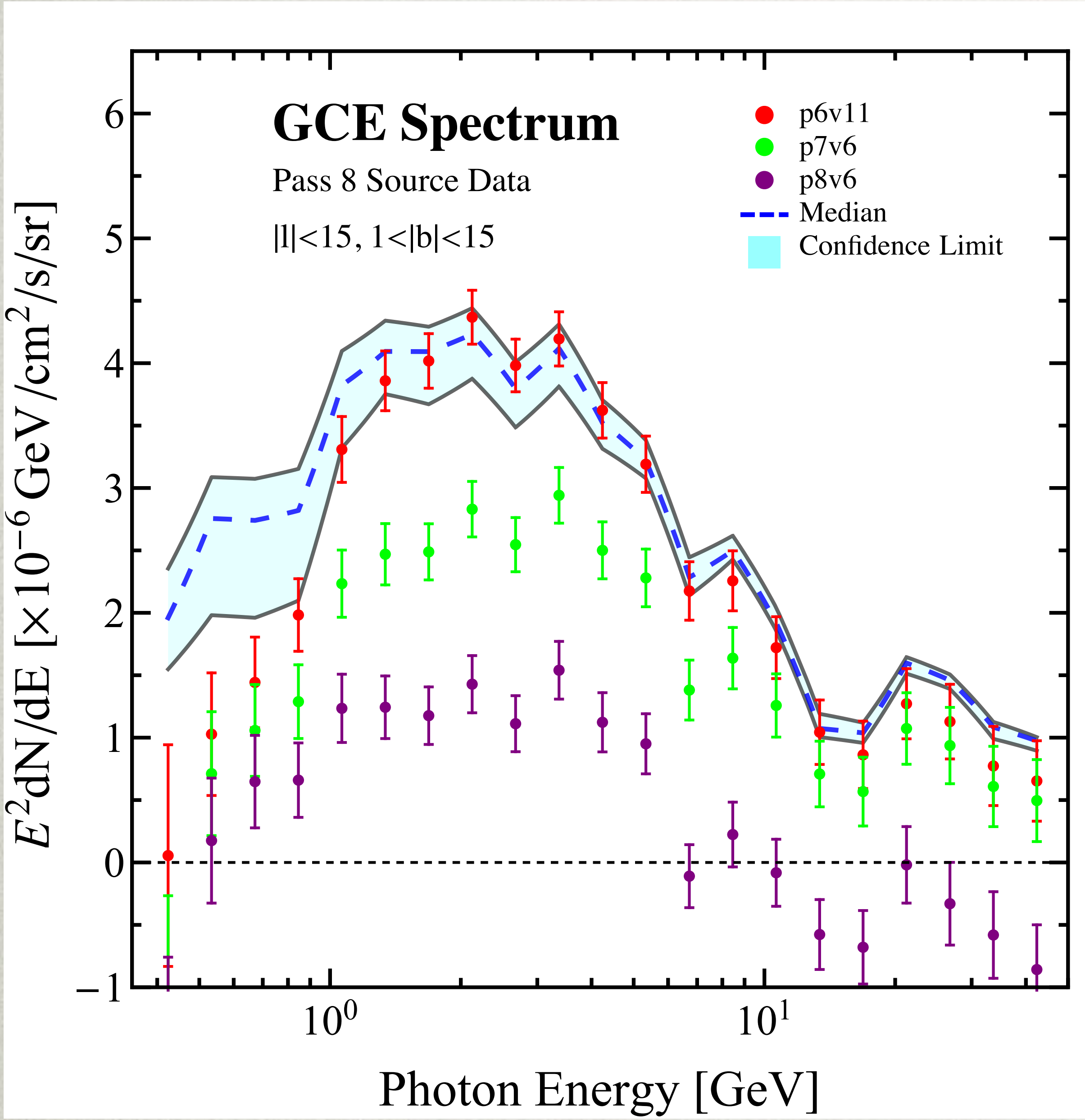
Impact of the ROI

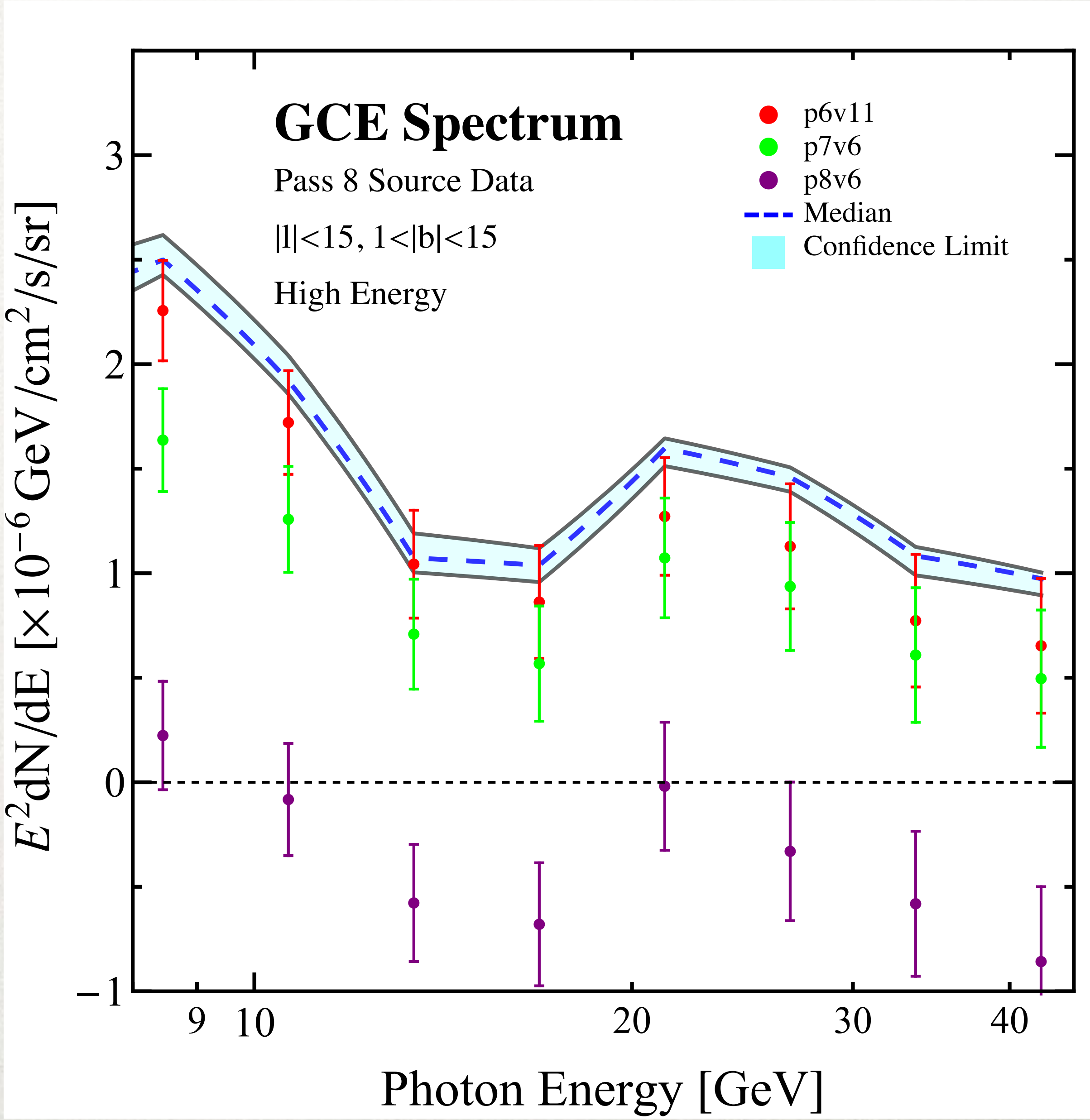






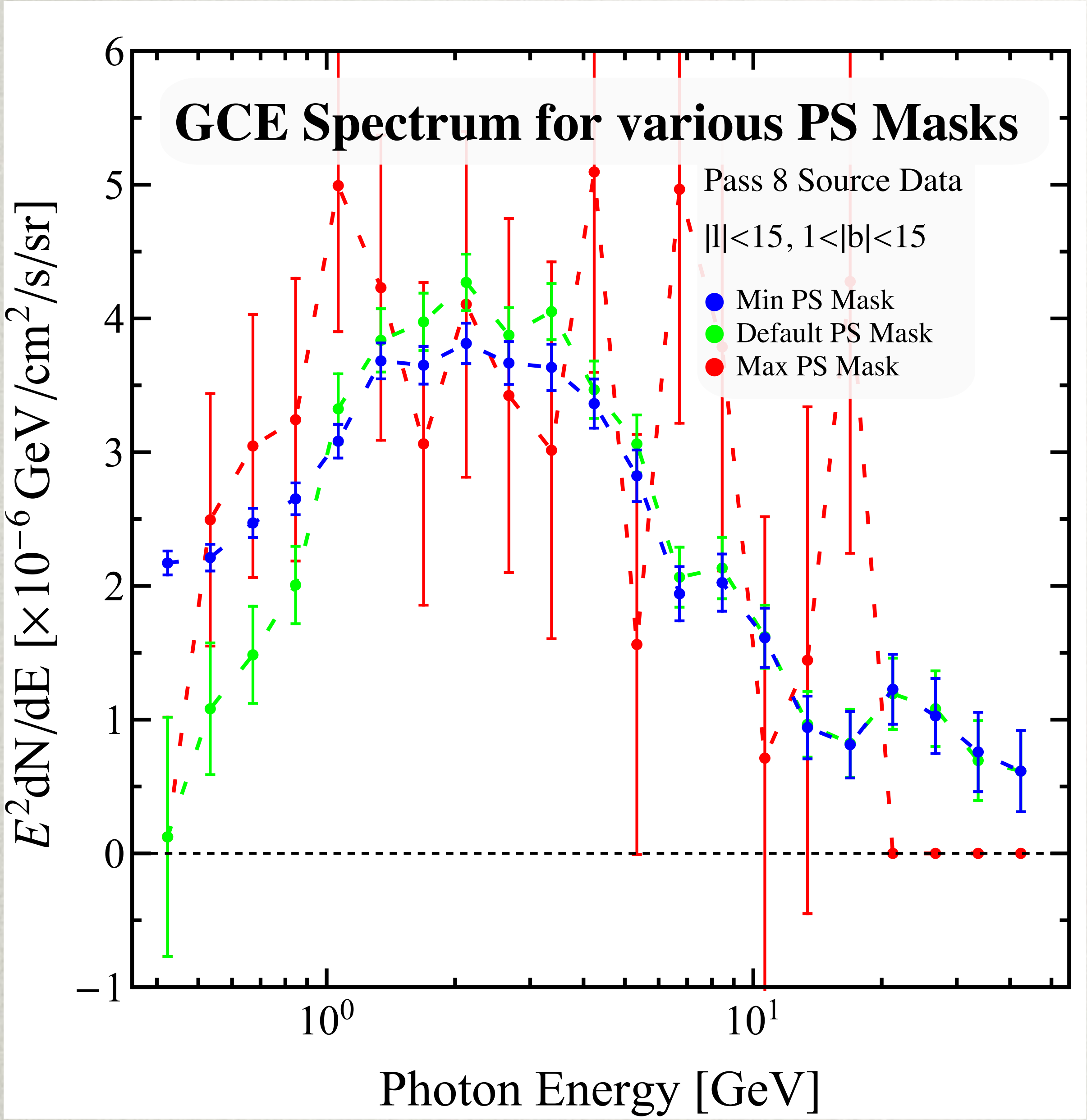
Robustness of the Spectrum

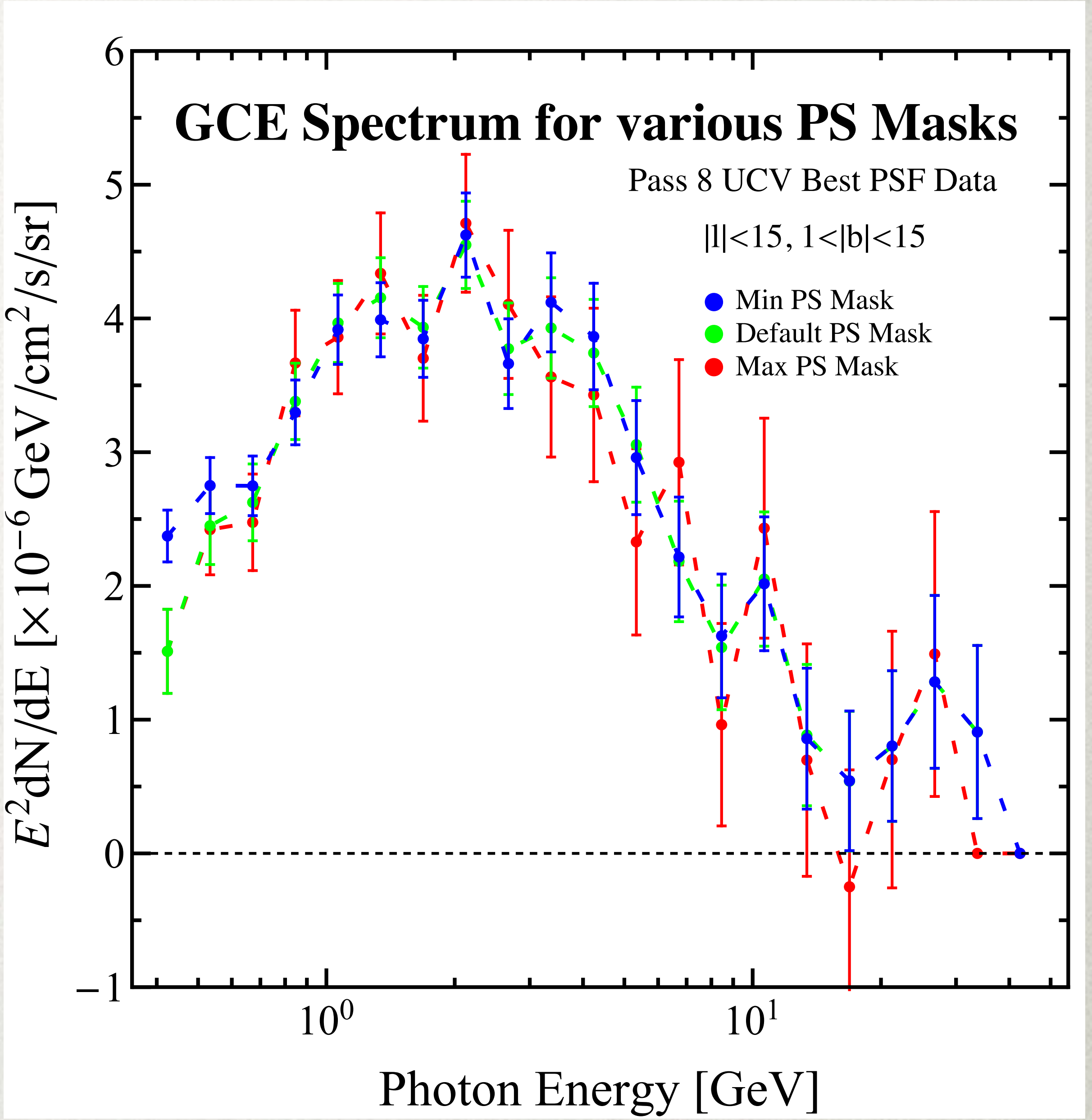




- Spectrum and its feature appear to be robust above ~1 GeV
- Expectation derived from 14 galprop models used in 1409.0042
- p7v6 and p8v6 break the trend, but are not well suited for an analysis of the GCE given they have large scale structures added

Impact of PS mask on Spectrum

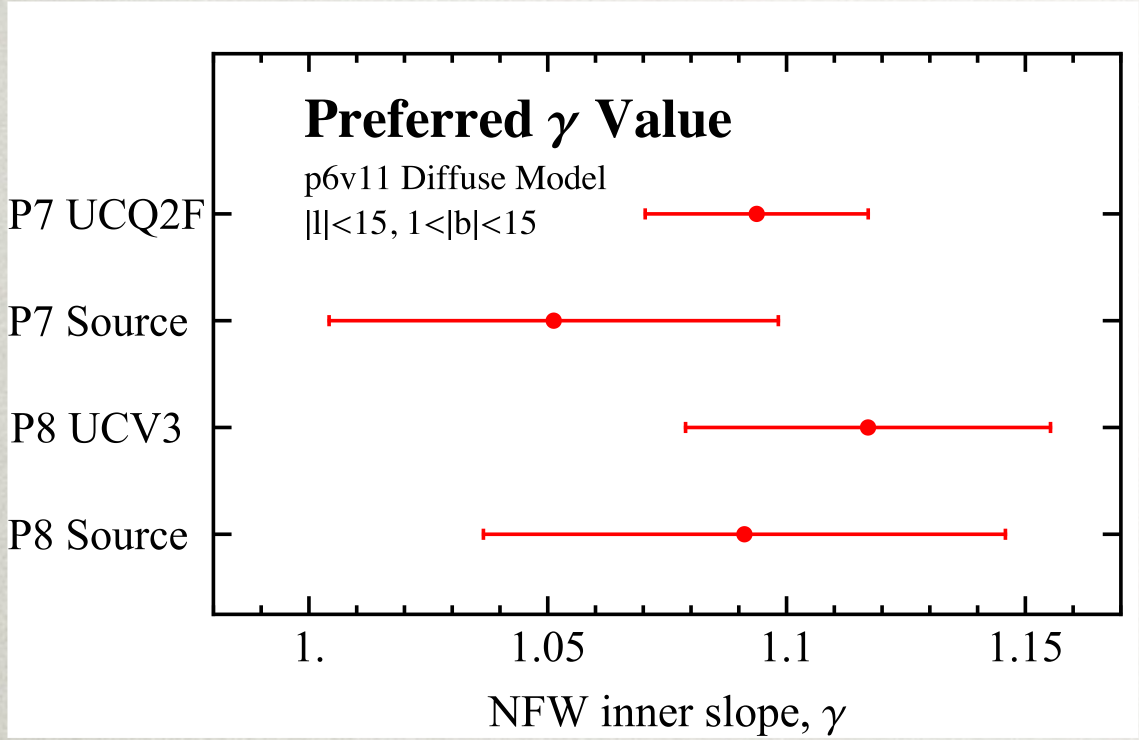




- IG analysis masks 300 brightest 3FGL sources - size of mask set by the PSF of Fermi - much larger in all source data (left) than ultracleanveto best psf (right)
- For source data, varying the size of the mask can greatly impact the slope of the spectrum below ~1 GeV and make it more consistent with UCV Best PSF

Preferred Inner Slope

The preferred inner slope we find is different to previous analyses, but this varies with dataset and diffuse model



Model	Preferred γ All Source	Preferred γ UCV Best PSF
p6v11	1.14	1.08
p7v6	1.16	1.15
p8v6	1.25	1.24
Model A	1.13	1.15
Model F	1.04	1.09

Bands on the left are derived from 17 diffuse models: p6v11, p7v6, p8v6 and 14 galprop models from 1409.0042

Significance of the GCE

Model	ΔTS for GCE		
	30x30	40x40	Full Sky
p6v11	2858.9	2289.7	3333.6
p7v6	1204.7	720.9	982.9
p8v6	266.0	239.9	798.6

Pass 8 Source Data

Model	ΔTS for GCE		
	30x30	40x40	Full Sky
p6v11	1541.8	1175.4	1268.5
p7v6	779.4	477.6	439.5
p8v6	521.7	405.8	560.4

Pass 8 UltracleanVeto BestPSF Data

DataSet	ΔTS for GCE			
	Bin 1	Bin 2	Bin 3	Bin 4
Pass 7	59.2	18.4	27.8	3.8
Pass 8	51.3	27.6	37.5	10.4

Source Data - High Energy bins (~10-50 GeV)

Slide taken from Tracy Slatyer, CERN Theory Colloquium, 29 July 2015

An example

I expect 10 photons per pixel, in some region of the sky. What is my probability of finding 0 photons? 12 photons? 100 photons?

<u>Case 1:</u> diffuse emission, Poissonian statistics

$P(12 \text{ photons}) = 10^{12}\, e^{-10}/12! \sim 0.1$

Likewise $P(0 \text{ photons}) \sim 5 \times 10^{-5}$, $P(100 \text{ photons}) \sim 5 \times 10^{-63}$

<u>Case 2:</u> population of rare sources.

Expect 100 photons/source, 0.1 sources/pixel - same expected # of photons

$P(0 \text{ photons}) \sim 0.9$, $P(12 \text{ photons}) \sim 0.1 \times 100^{12}\, e^{-100}/12! \sim 10^{-29}$, $P(100 \text{ photons}) \sim 4 \times 10^{-3}$

(plus terms from multiple sources/pixel, which I am not including in this quick illustration)

Slide taken from Tracy Slatyer, CERN
Theory Colloquium, 29 July 2015

Non-Poissonian statistics

- Easiest to recast probabilities in terms of generating functions:

$$p_k^{(p)} = \frac{1}{k!} \frac{d^k \mathcal{P}^{(p)}}{dt^k}\Big|_{t=0}$$

- Then total generating function for sum of model components = product of component generating functions.

$$\mathcal{P}^{(p)}(t) = \mathcal{D}^{(p)}(t) \cdot \mathcal{G}^{(p)}(t)$$

from non-Poissonian piece

from Poisson likelihood

generating function for point source population

$$\sum_{k=0}^{\infty} p_k t^k = \exp\left[\sum_{m=1}^{\infty} x_m (t^m - 1)\right] \equiv P(t)$$

expected number of m-photon sources

source count function

determined by Monte Carlo, accounts for finite angular resolution

$$x_m = \frac{\Omega_{\text{pix}}}{4\pi} \int_0^{\infty} dS \frac{dN}{dS}(S) \int df \rho(f) \frac{(fS)^m}{m!} e^{-fS}.$$

Statistics for a PS population are defined by source count function - # of sources with a given brightness.

Slide taken from Tracy Slatyer, CERN
Theory Colloquium, 29 July 2015

Non-Poissonian template fitting

- Can now add new templates to our model, which allow non-Poissonian statistics.

- 3 extra degrees of freedom for each such template, to describe source count function (parameterized as broken power law):

follows a spatial template

$$\frac{dN_p(S)}{dS} = A_p \begin{cases} \left(\frac{S}{S_b}\right)^{-n_1} & S \geq S_b \\ \left(\frac{S}{S_b}\right)^{-n_2} & S < S_b \end{cases}$$

- Source count function assumed constant over sky, but overall normalization can vary pixel to pixel - allows non-trivial spatial dependence of point source population.

- For now, restrict to a single broad energy bin (2-12 GeV) - no extraction of spectrum.