Hunting for Point Sources in the Extragalactic Gamma-Ray Sky

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Work with M. Lisanti, L. Necib and B.R. Safdi [1606.04101]

TeV Particle Astrophysics, CERN, Geneva
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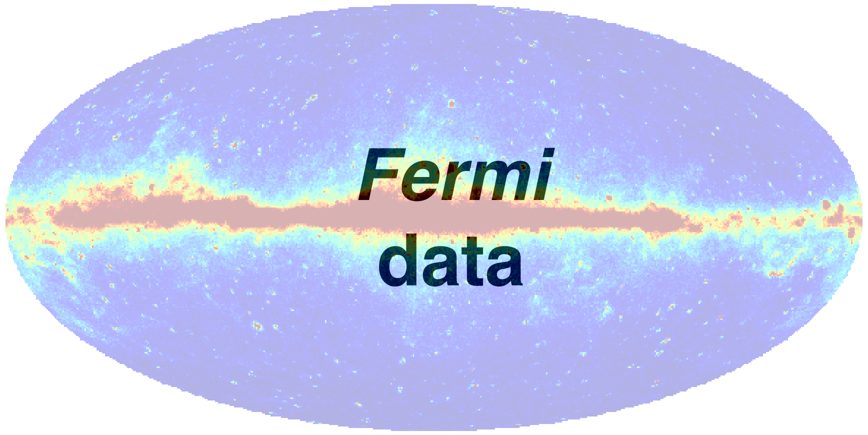
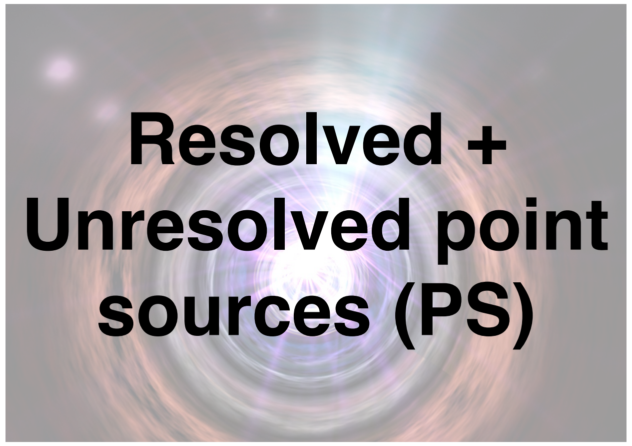
Origin of the Extragalactic γ-ray Background

***Fermi* EGRB** = 

- Galactic diffuse emission

Origin is an open question. Possible contributions:



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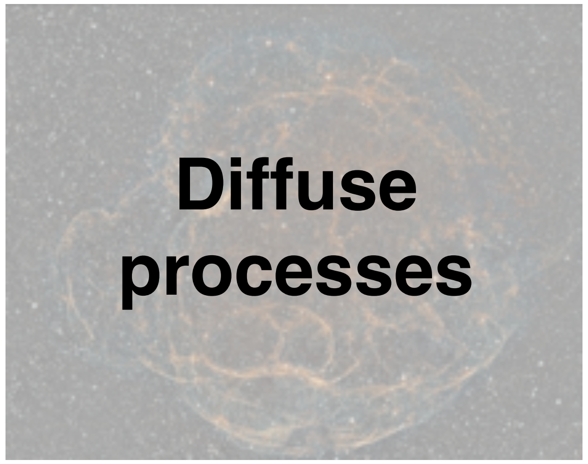

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Goals and Motivations

Goal:

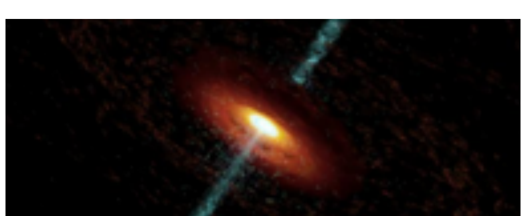
Derive the **energy spectrum of point sources (PS)** in the *Fermi* EGRB in a data-driven way **from 2 GeV up to 2 TeV** using photon statistics.

Some motivations:

Unveil the properties of astrophysical PS

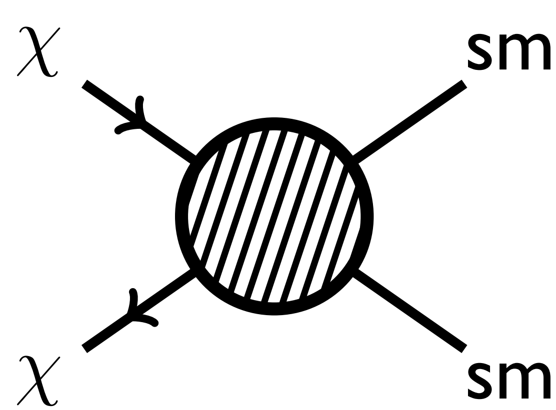
Directly measure the luminosity function of unresolved PS

Predict number of PS expected to be resolved by future telescopes



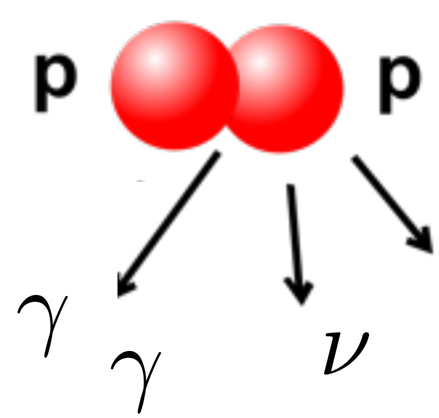
Elucidate the possible dark matter contribution

Understanding PS contribution constrains possible DM interpretations



Understand the origin of IceCube's PeV neutrinos

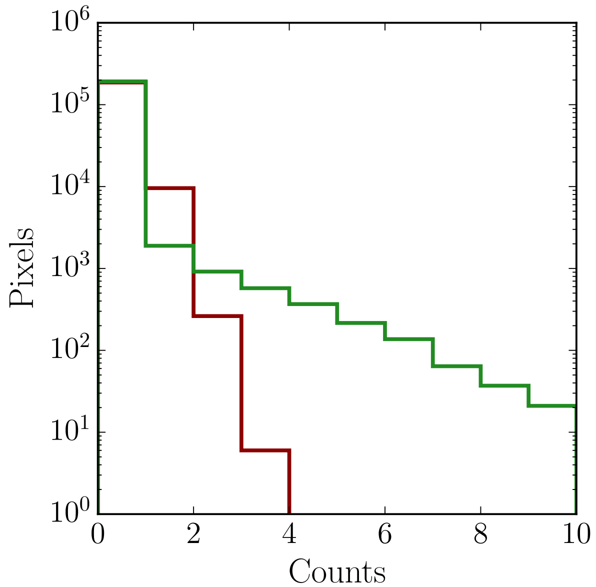
Same sources may contribute to *Fermi*'s unresolved EGRB and IceCube neutrinos flux

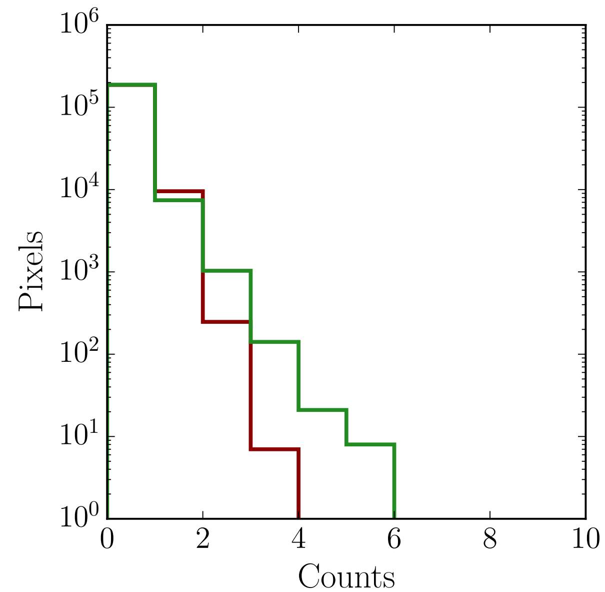


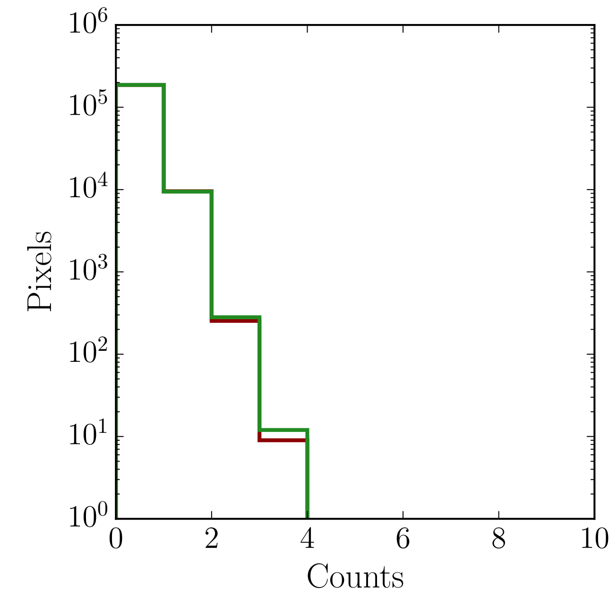
Point Sources and Photon Statistics

PS maps tend to have **more bright and dim pixels** compared to truly diffuse/poissonian emission (*i.e.* their flux distribution is non-poissonian)

More sources

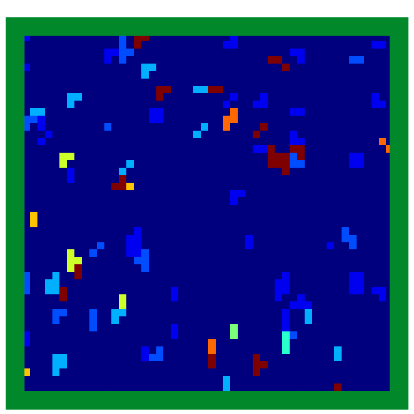




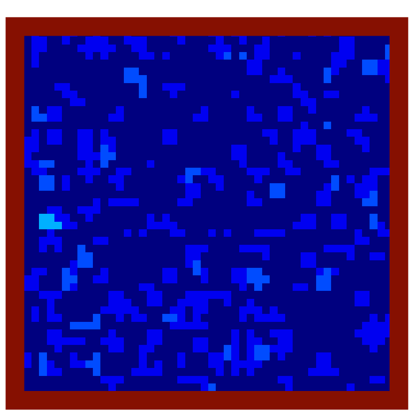


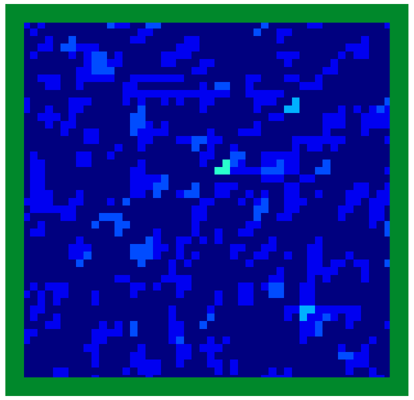
Brighter sources

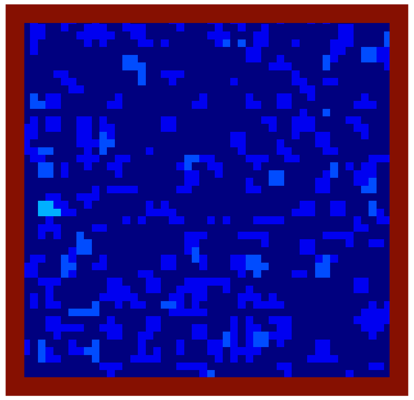
PS



Smooth



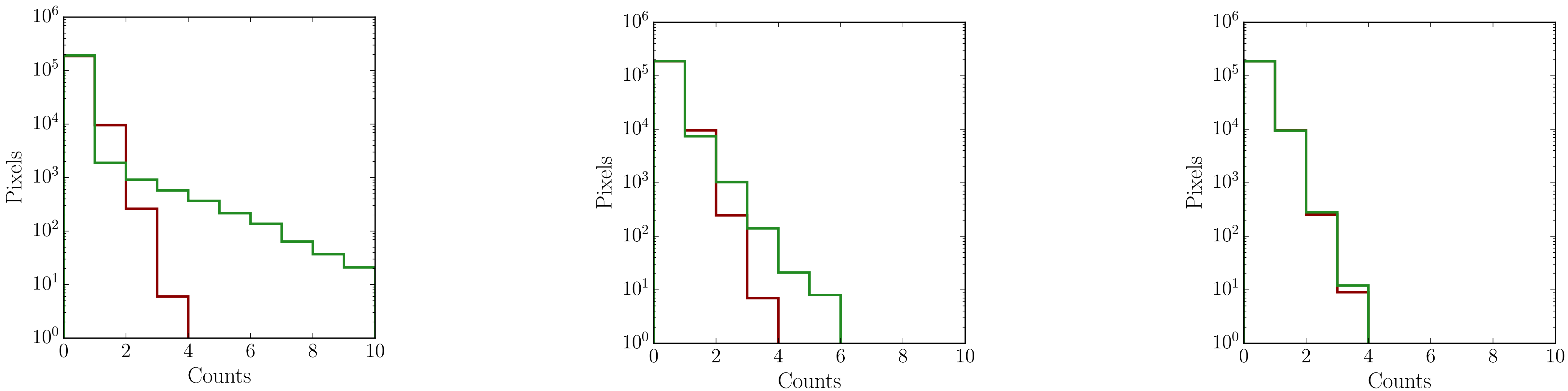




Point Sources and Photon Statistics

PS maps tend to have **more bright and dim pixels** compared to truly diffuse/poissonian emission (*i.e.* their flux distribution is non-poissonian)

More sources



Brighter sources

Exploit this property to resolve PSs as a population:

Non-Poissonian Template Fitting (NPTF)

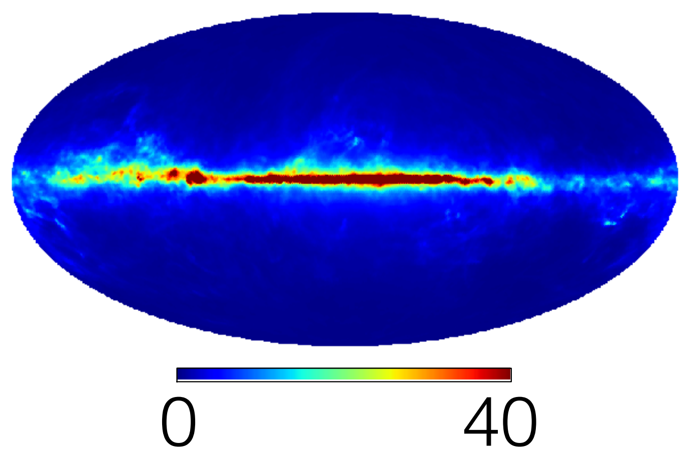
Malyshev and Hogg [1104.0010]
Lee et al [1412.6099, 1506.05124]
Zechlin et al [1512.07190, 1605.04256]

The Templates

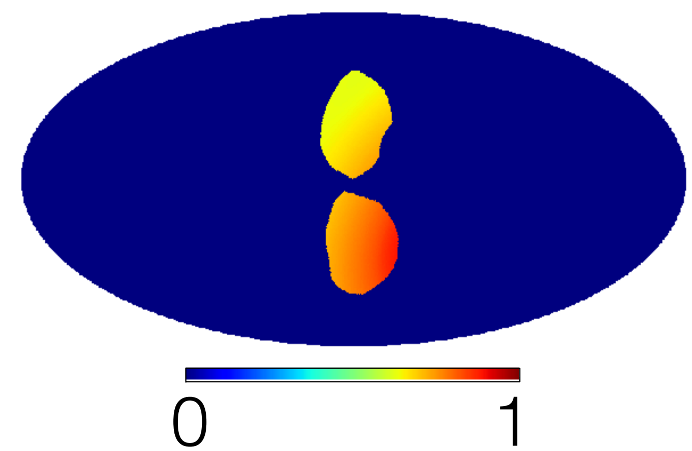
A template is a spatial map modeling a distinct contribution to the data.

Templates used in the analysis:

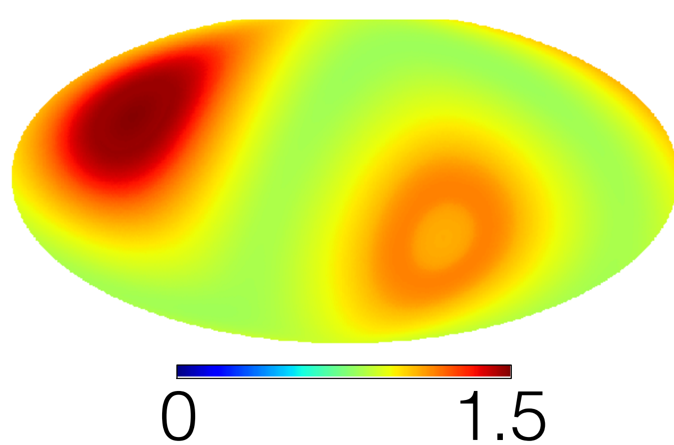
Fermi p8 diffuse



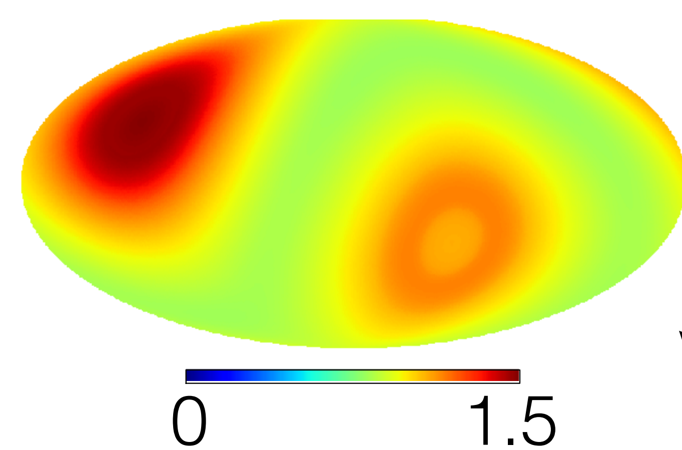
Fermi bubbles



Isotropic



Isotropic PS

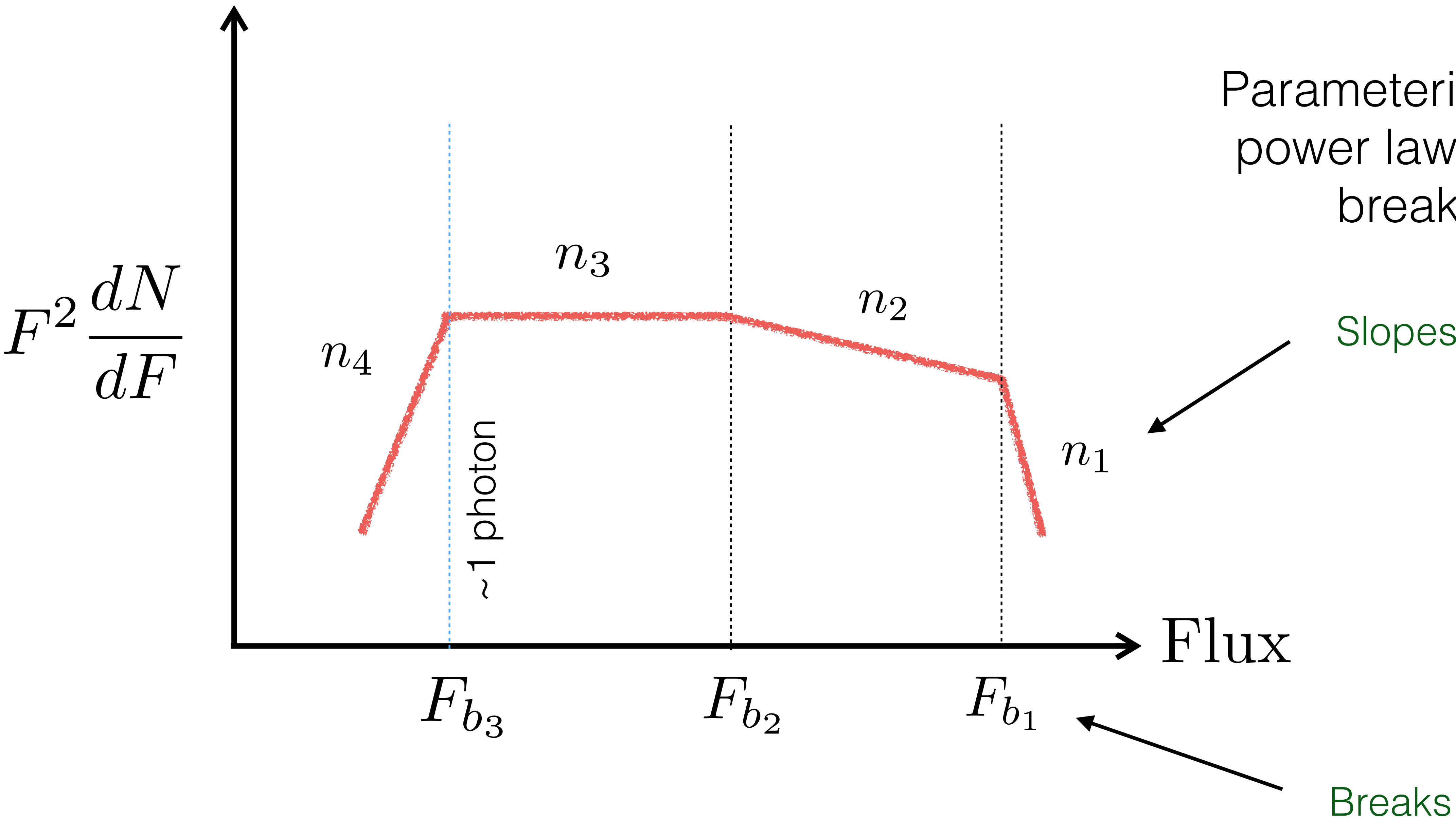


Assumes poissonian flux distribution

Assumes non-poissonian flux distribution

The Source Count Function

Used to model underlying flux distribution of sources. Gives **number of sources** in a given pixel with a flux between *F* and *F+dF*.



Parameterize as a power law with 3 breaks:

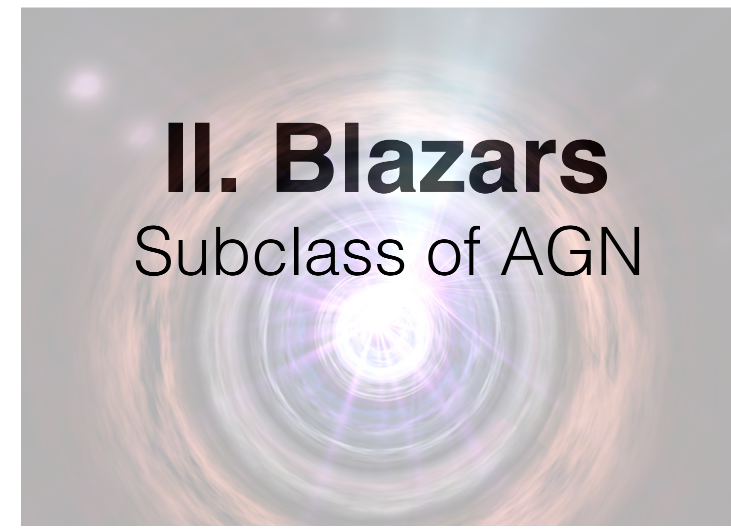
We use Bayesian methods to find the posterior distributions

Simulations: Astrophysical PS

Simulations allow us to:

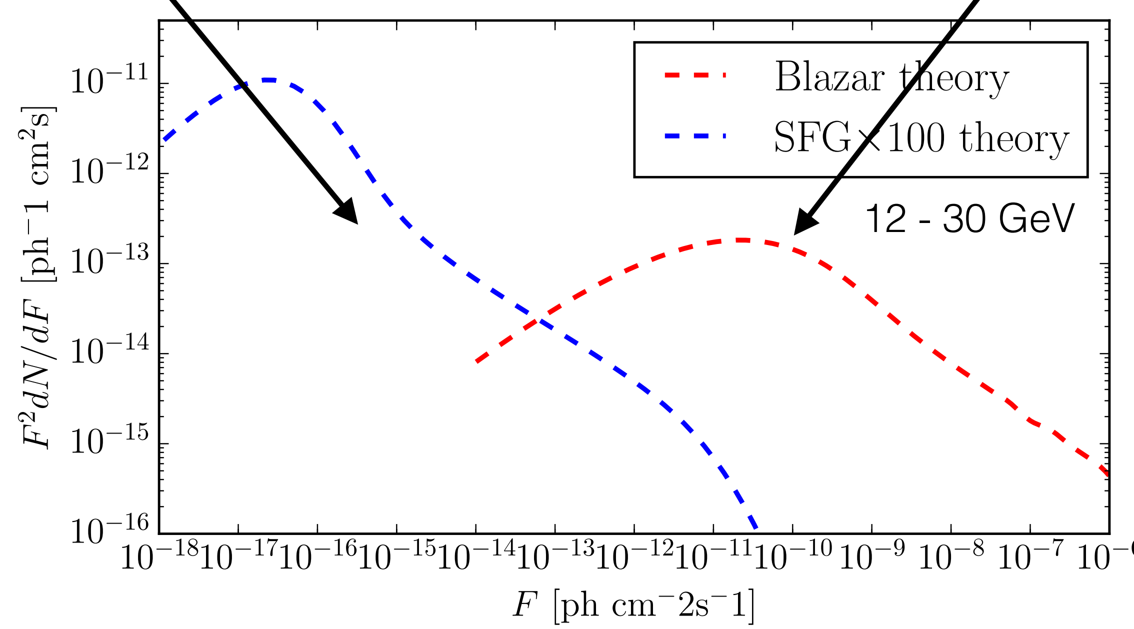
1. Validate our analysis procedure
2. Understand behavior of astrophysical PS under our method

We consider two representative source classes:



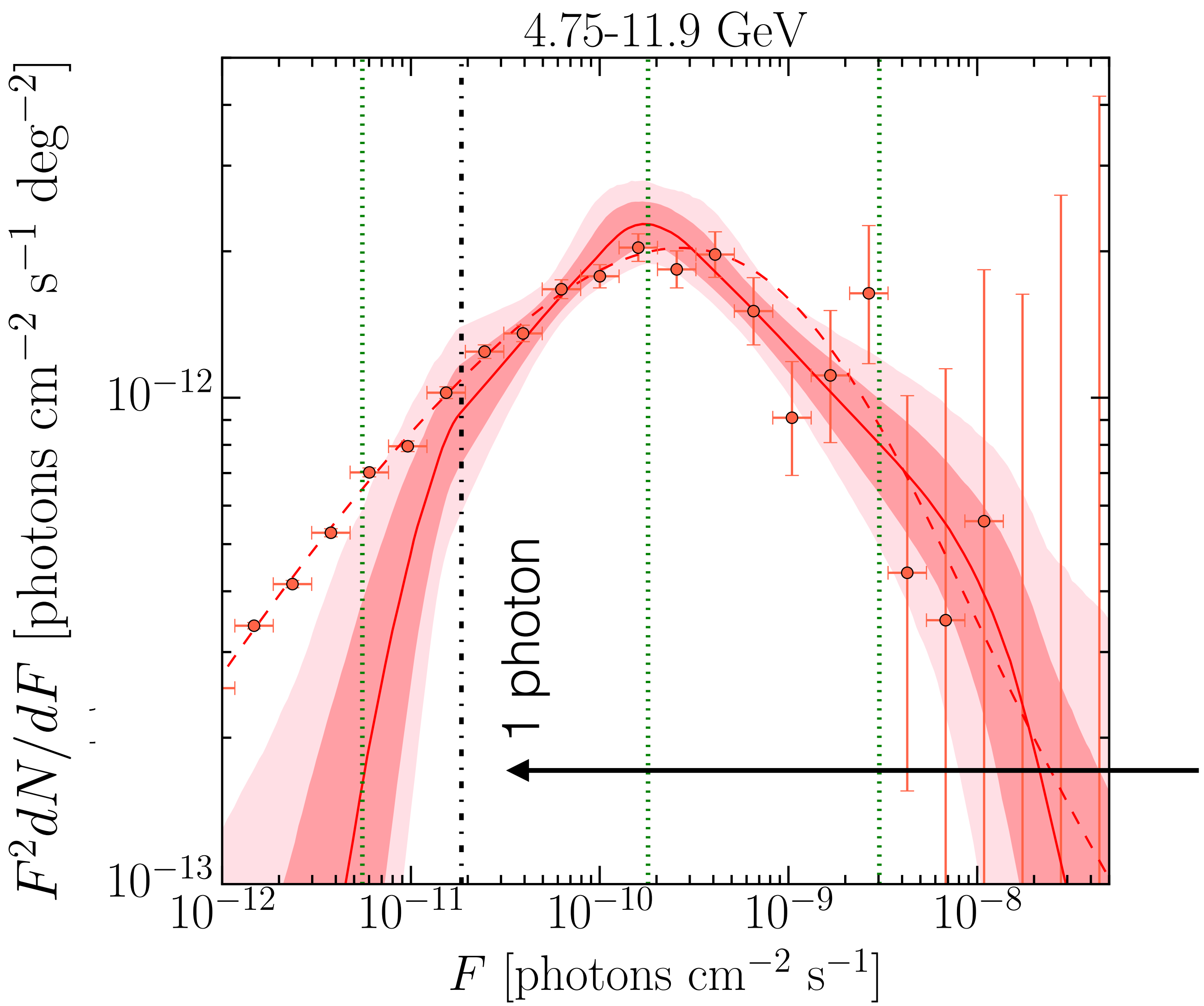
Numerous and dim

Fewer and brighter



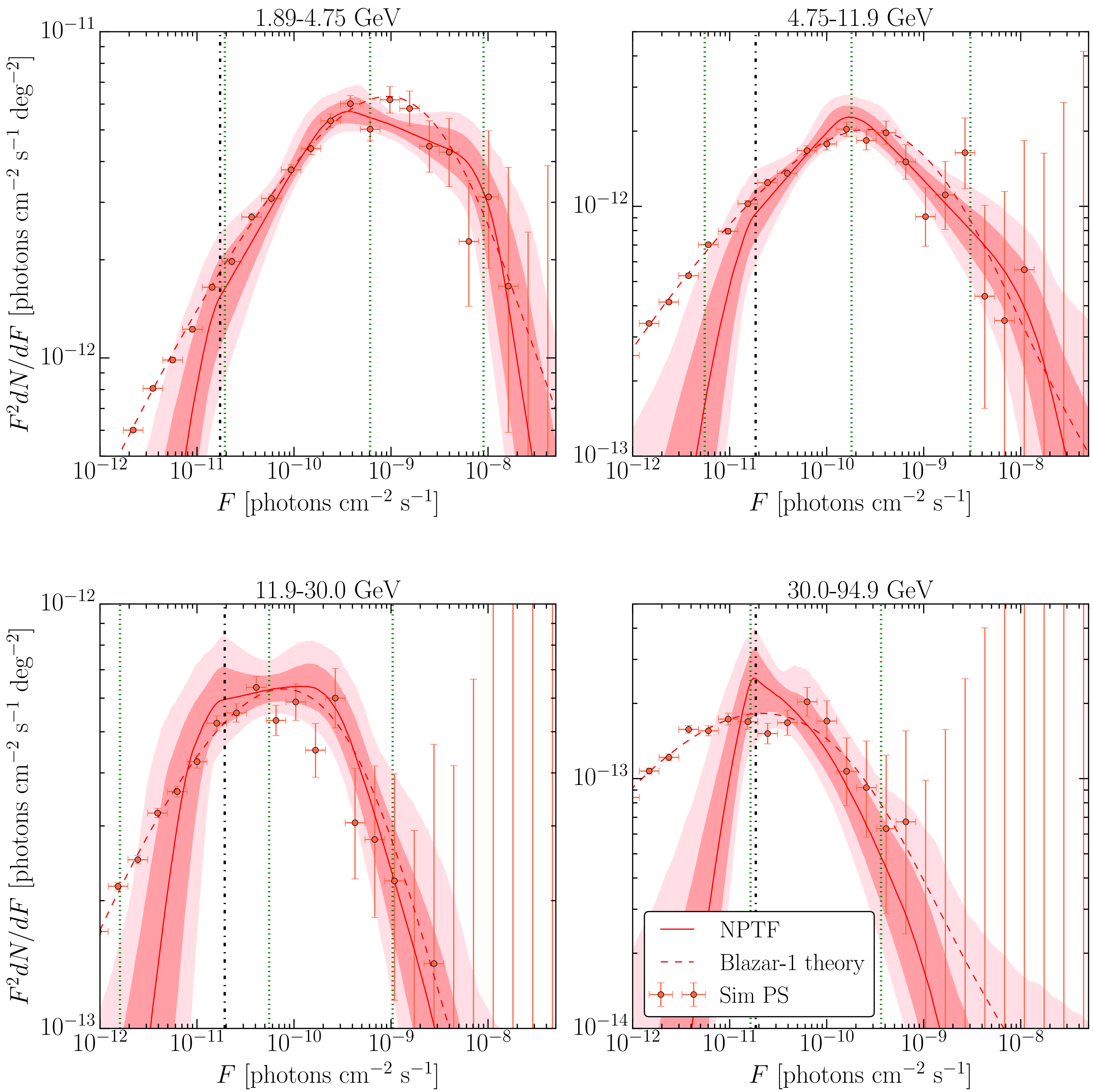
Blazar theory from Ajello et al [1501.05301]
SFG theory from Tamborra et al [1404.1189]

Simulation: Blazars



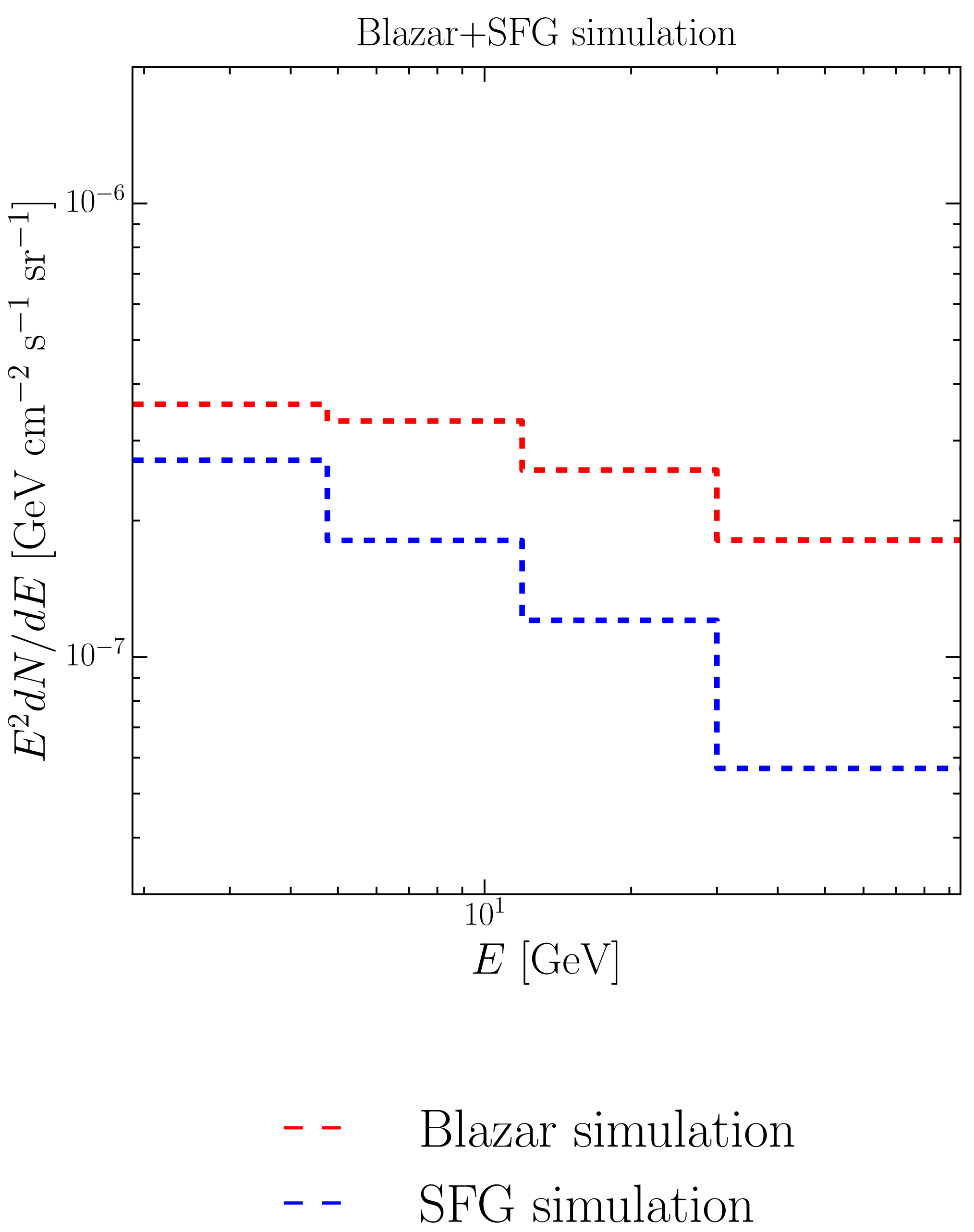
- **Simulate blazars** from theory
- Find that we can **recover the source count function** down to the single photon threshold

Simulation: Blazars



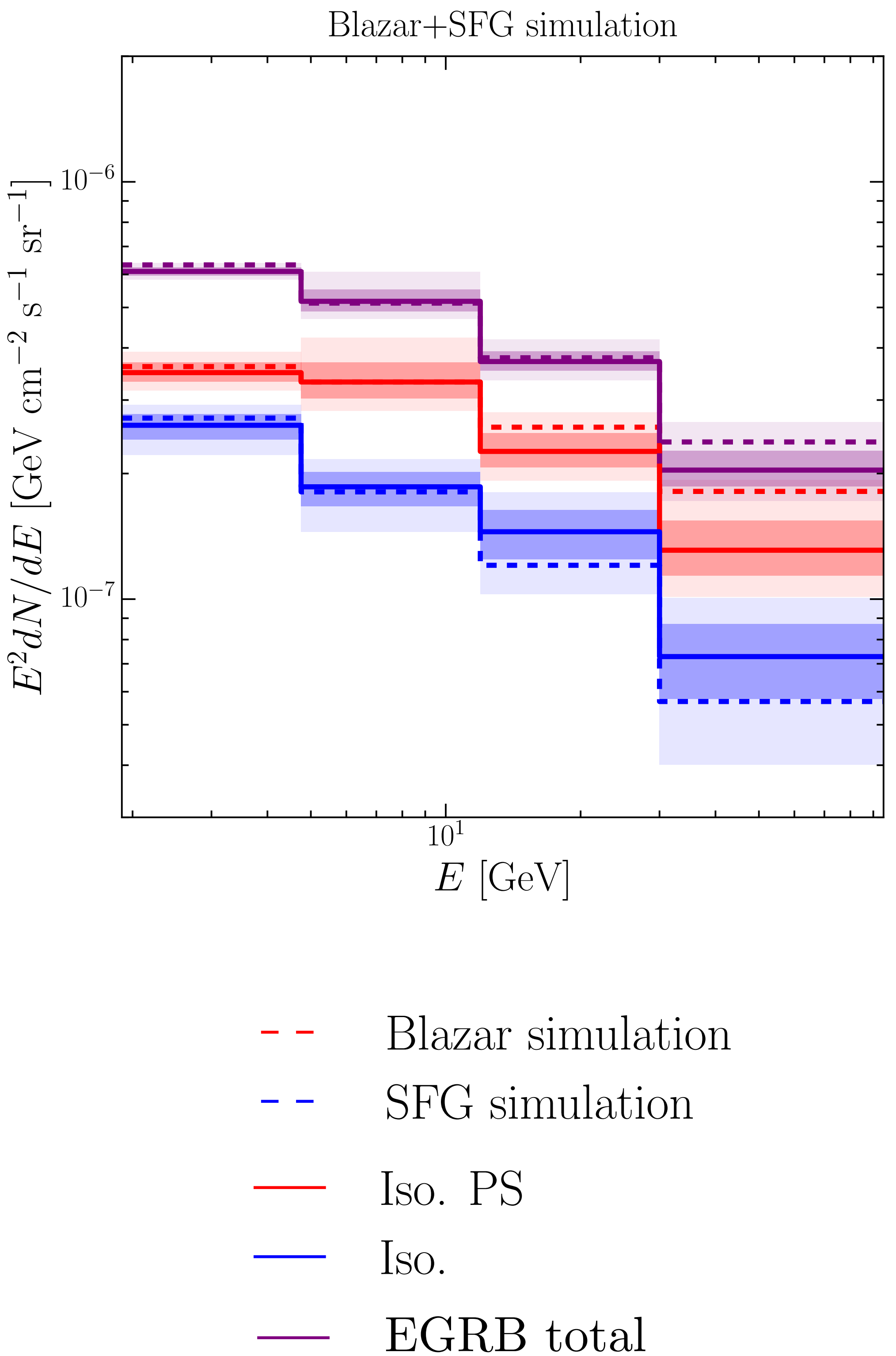
Repeat over different energy bins to **obtain an energy spectrum** of PS

Simulation: Energy Spectrum



Simulate **Blazars+SFGs**

Simulation: Energy Spectrum

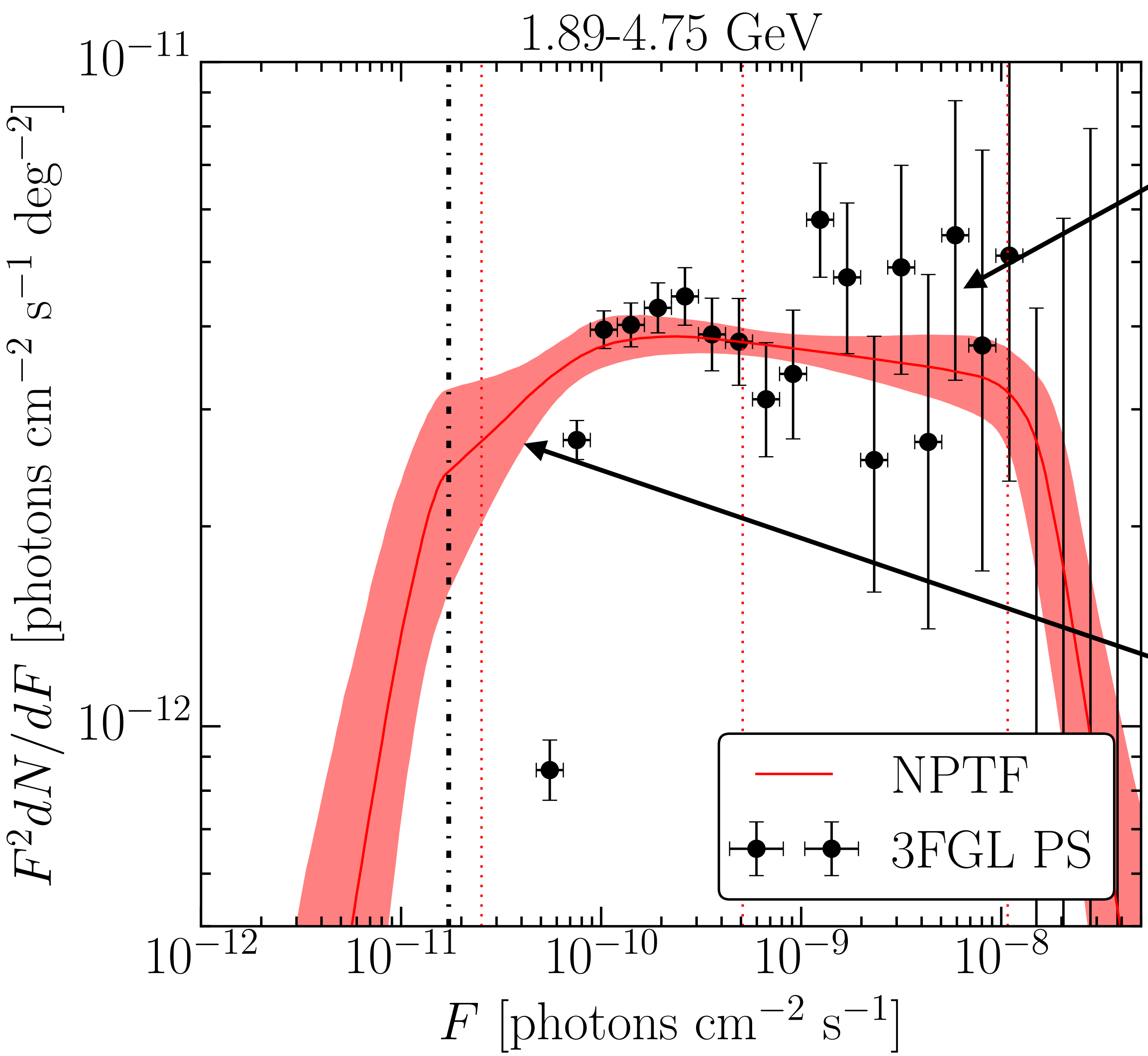


Simulate **Blazars+SFGs**

Blazars are recovered in the **non-poissonian** template

SFGs are absorbed by the diffuse **poissonian** template

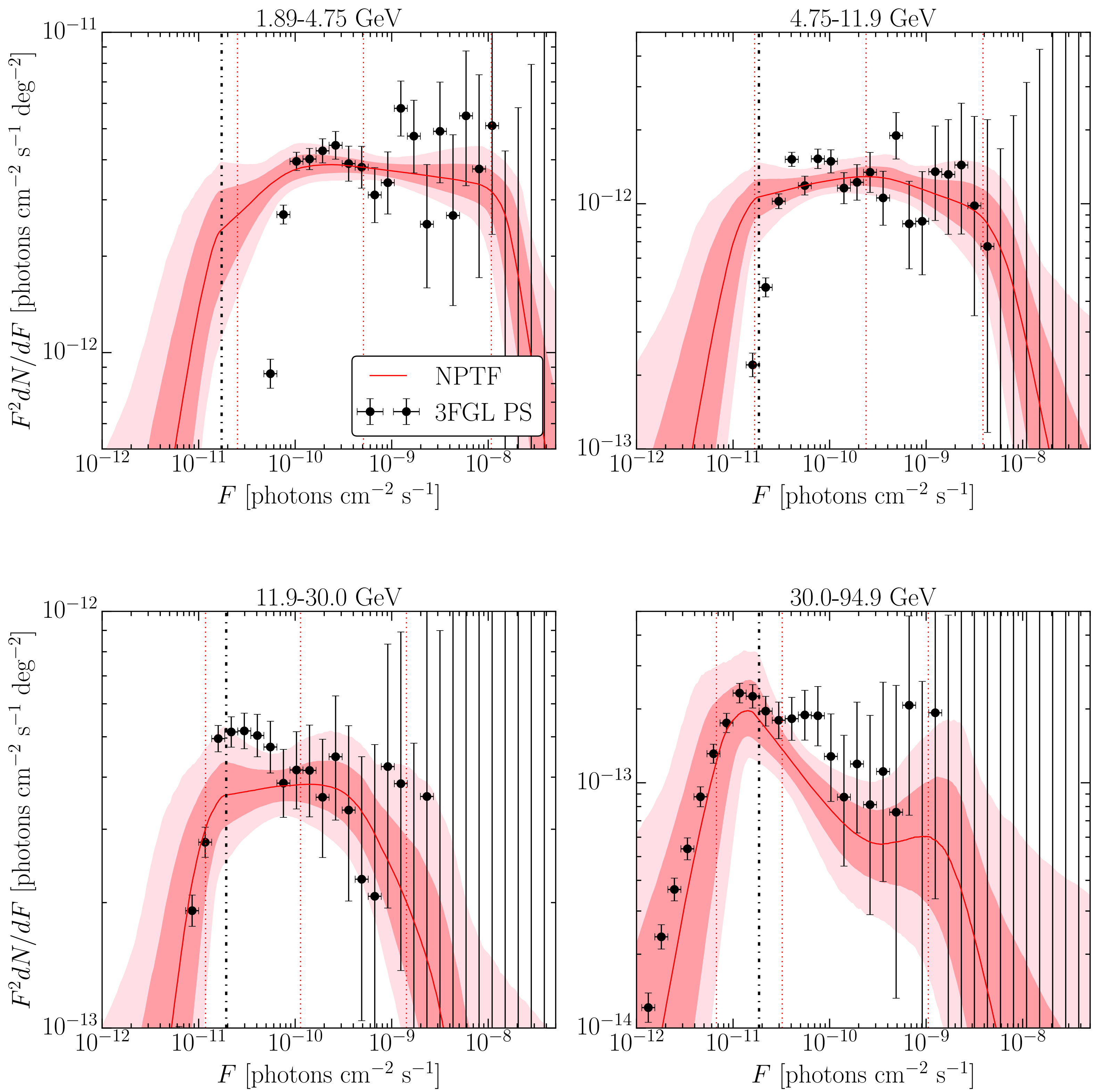
Analysis on Data: Source Counts



Can recover resolved sources

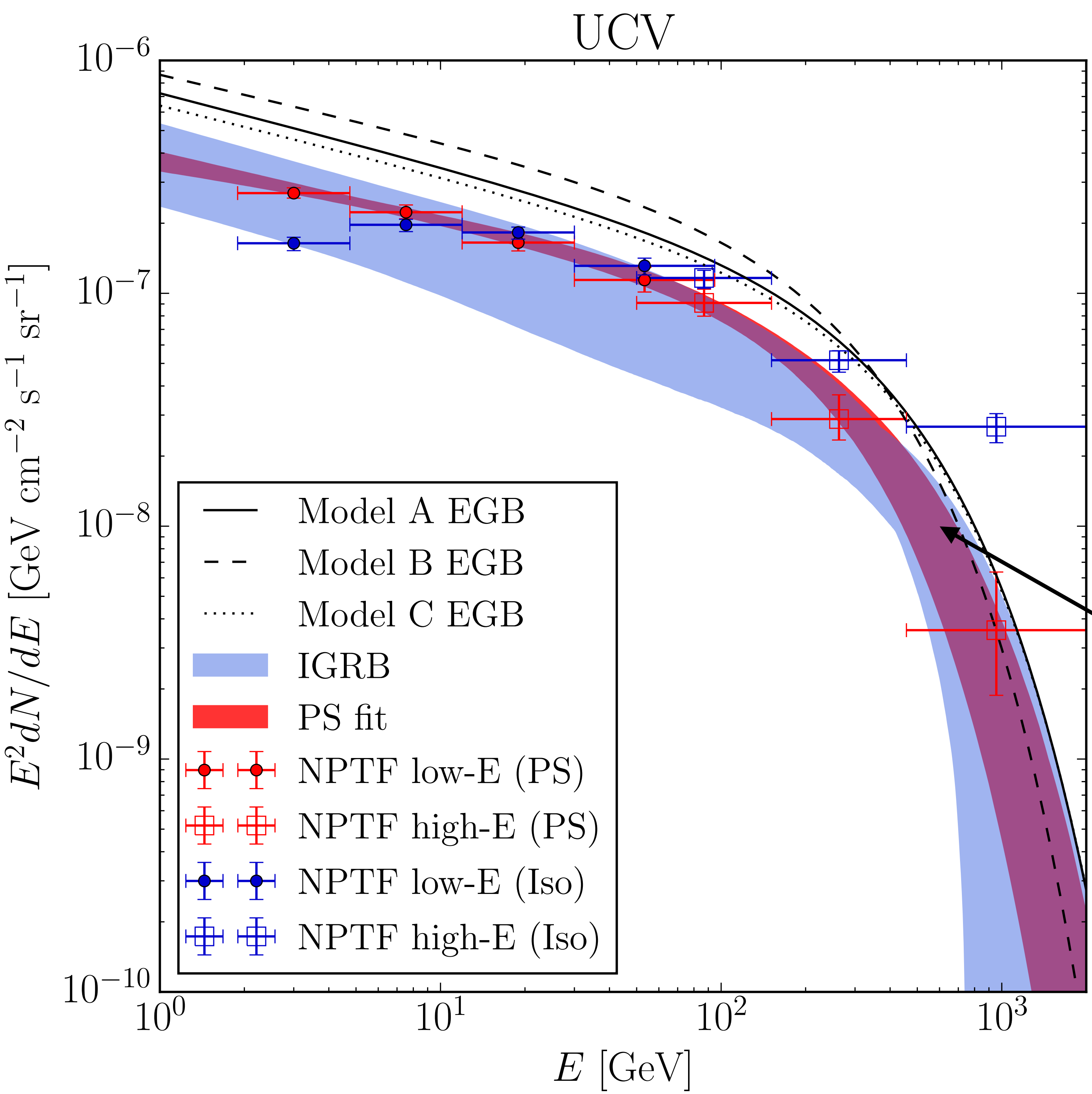
Can **measure unresolved sources** down to single photon

Analysis on Data: Source Counts



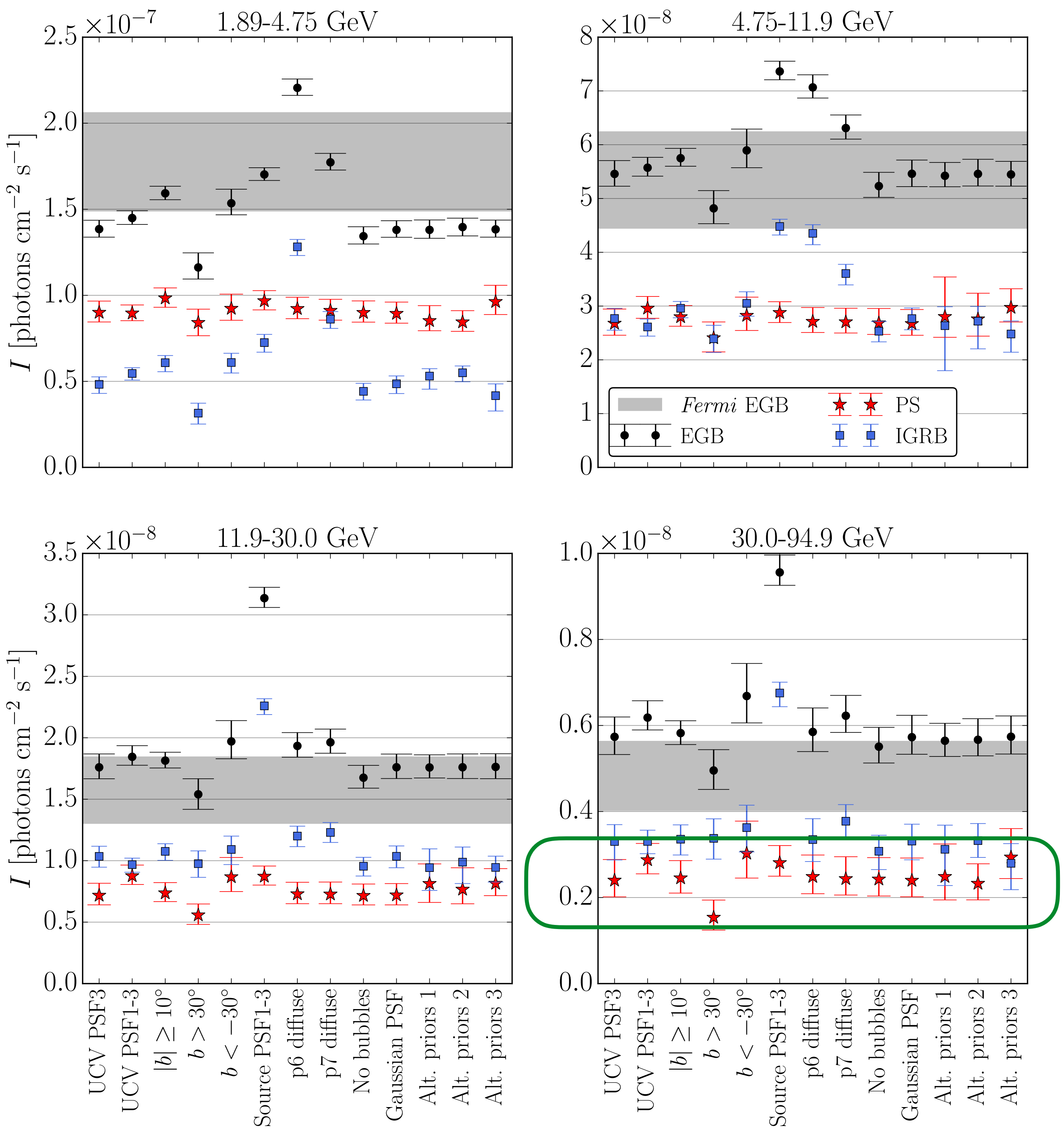
Repeat over different energy bins to **obtain an energy spectrum** of PS

Analysis on Data: Energy Spectrum



PS dominate the measured EGRB

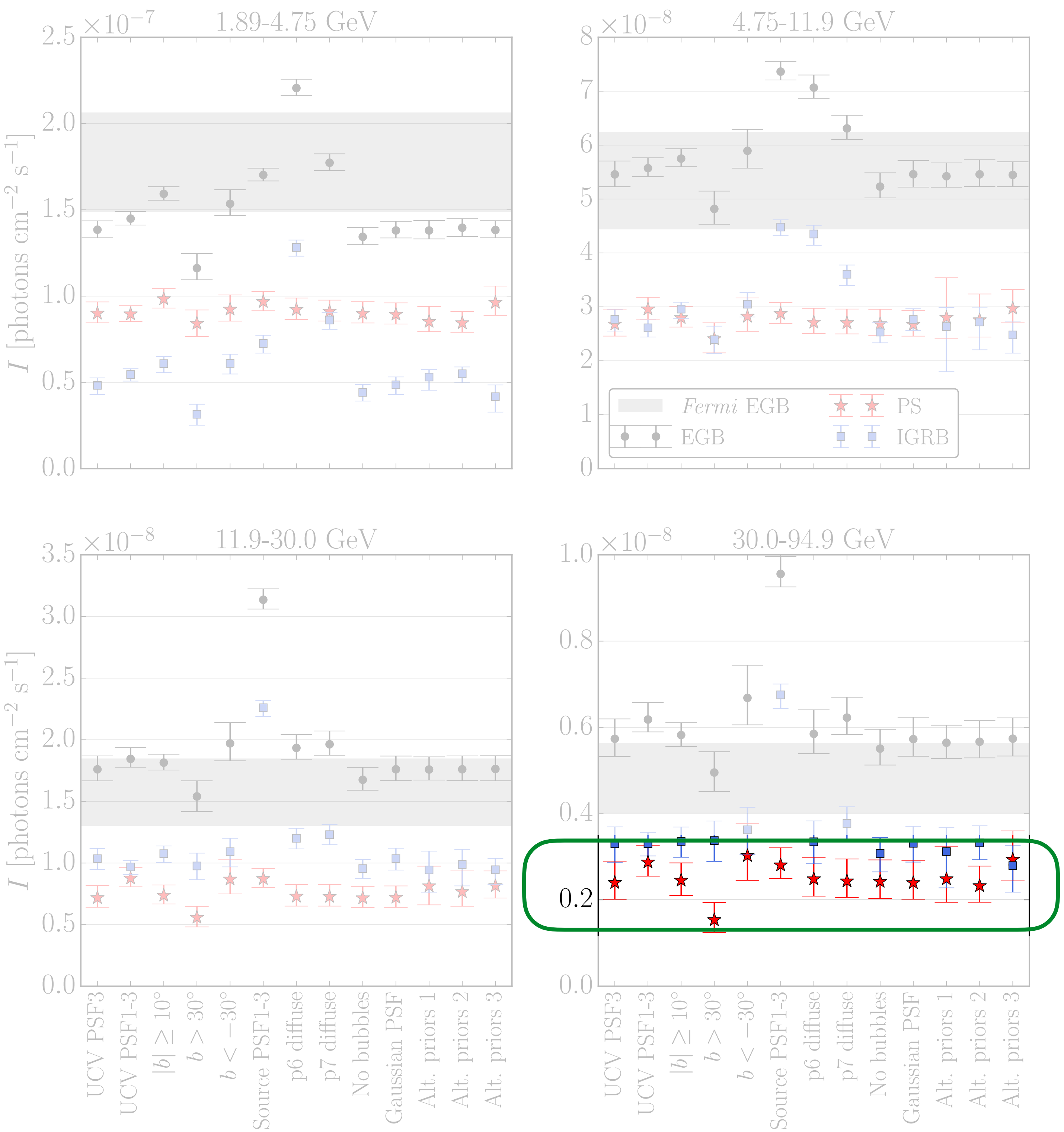
Analysis on Data: Systematics



Systematic checks: vary

- *Fermi* data classes
- Region of interest
- Diffuse background
- Modeling of *Fermi* point spread function
- Priors on parameters

Analysis on Data: Systematics

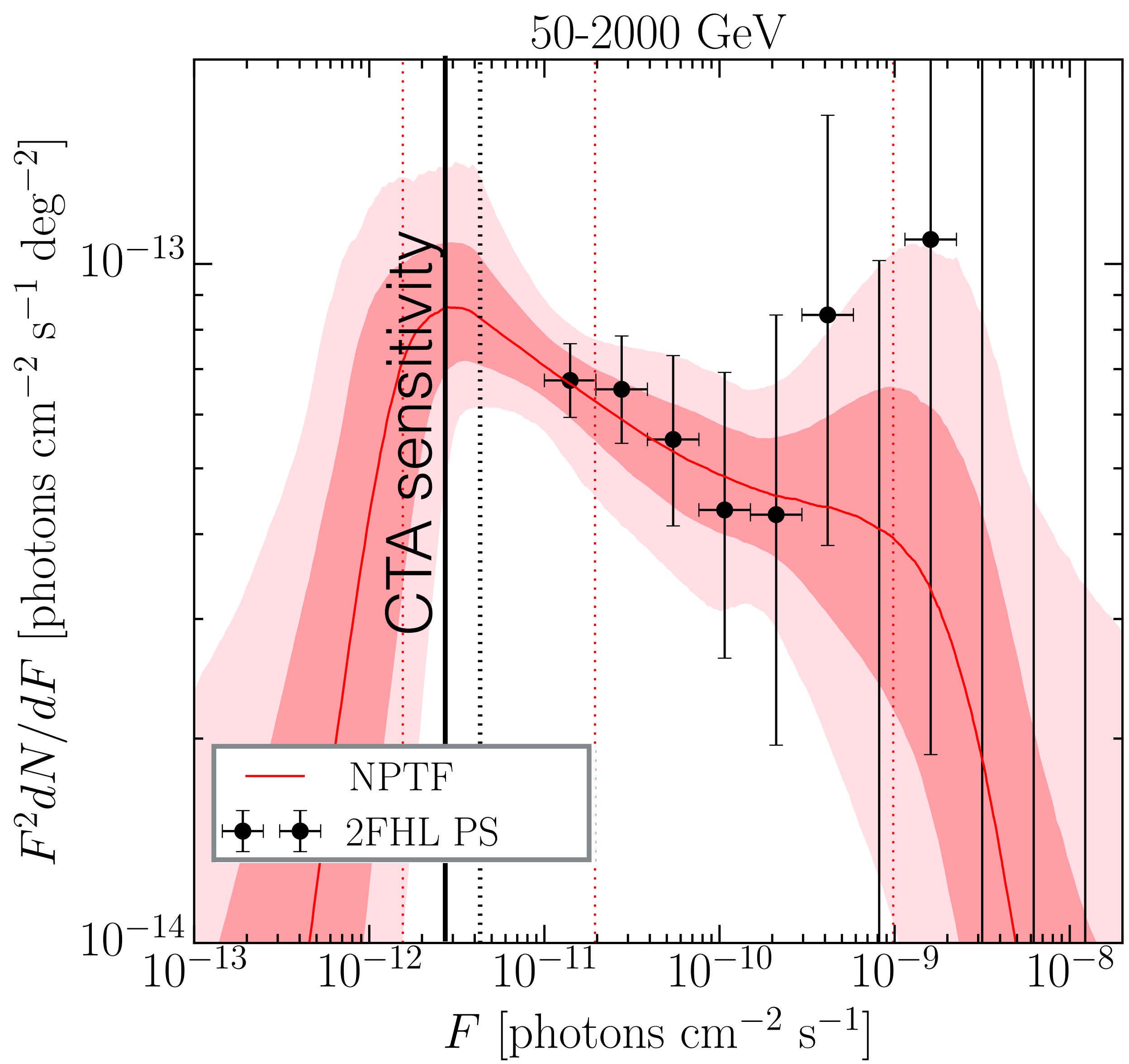


Systematic checks: vary

- *Fermi* data classes
- Region of interest
- Diffuse background
- Modeling of *Fermi* point spread function
- Priors on parameters

Find that **spectrum of PS is robust** to checks

Implications: Upcoming Measurements

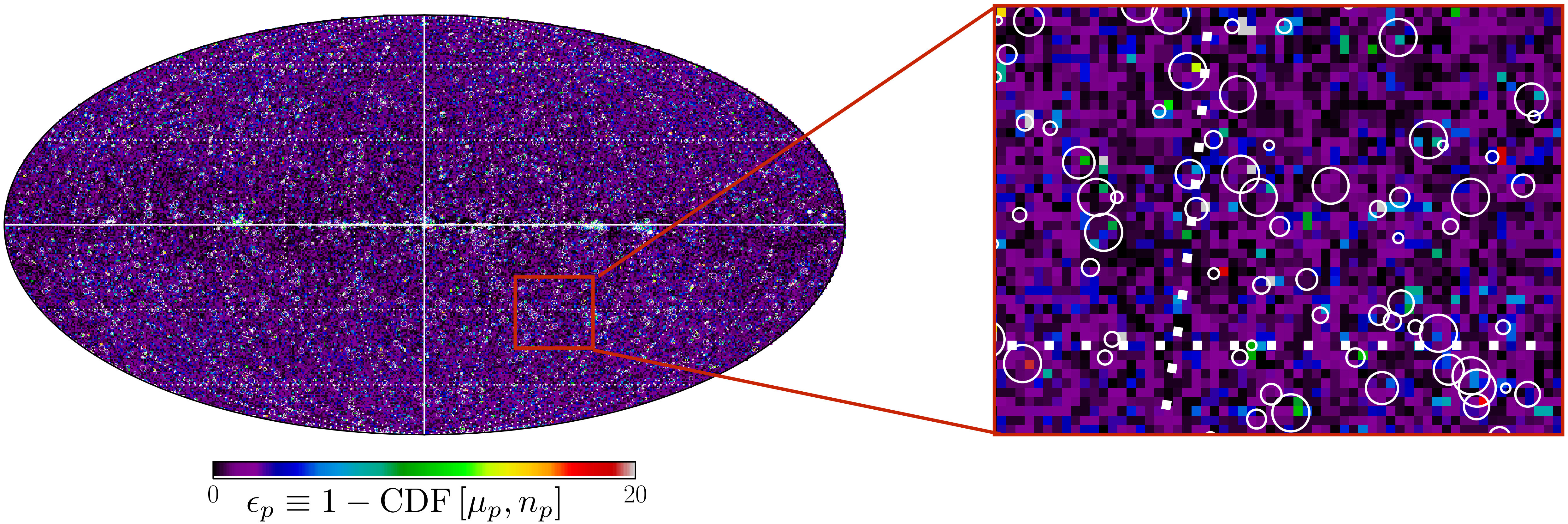


Use analysis at higher energies to predict **PS discovery potential** of upcoming ground-based telescopes

Expect CTA to discover **~5.51 new sources** over 250 hours of operation (twice that previously estimated)

Implications: Likely Sky Locations

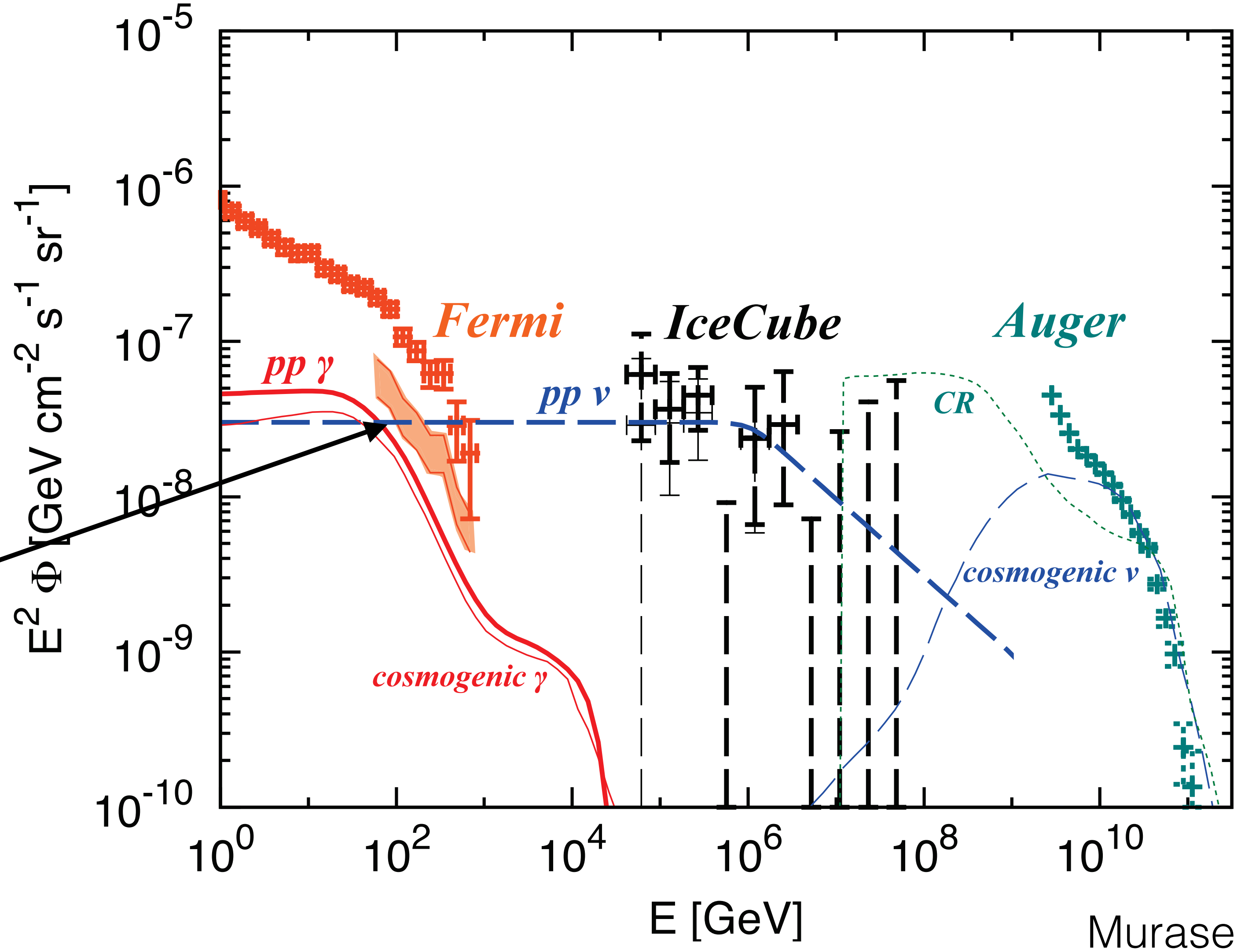
NPTF allows us to make **statistical statements** about populations of sources at the expense of knowing the precise location



However, can make **probabilistic statements about locations of PS** by looking at deviations from poissonian expectation around modeled background

Implications: IceCube PeV neutrinos

non-PS contribution



Murase et al [1607.01601]

Non-PS contribution leaves open the possibility that IceCube's neutrinos can be explained by *pp* interactions in star-forming galaxies or misaligned AGN

Conclusions

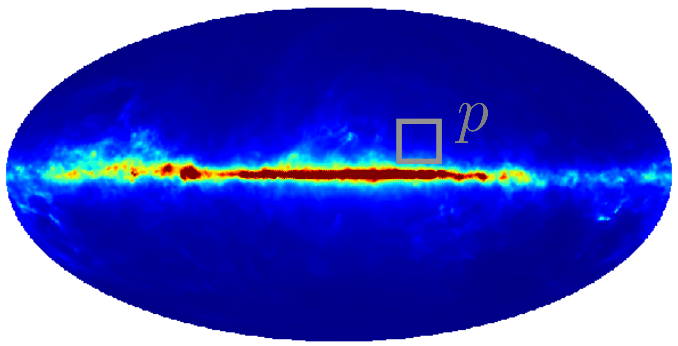
- We are able to use photon statistics to measure the energy spectrum and flux distribution of unresolved point sources below Fermi sensitivity up to 2 TeV
- Predictions on number of PS resolvable by CTA and likely sky locations of *Fermi* unresolved sources are obtained
- The extracted spectrum of PS leaves open the *pp* hadronic origin of IceCube's PeV neutrinos
- *Future work:* will be able to further constrain DM contribution to the *Fermi* EGRB

Backup

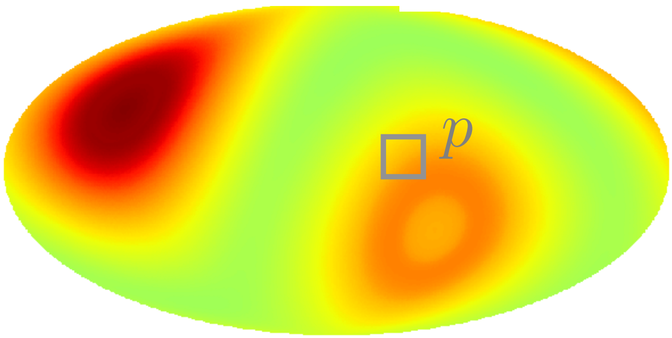
Standard Template Analysis

Spatial Templates

diffuse background



Isotropic



Expected number of photons in pixel *p*

$$\mu_{\mathrm{p}} = \mu_{\mathrm{p,diff}} + \mu_{\mathrm{p,iso}}$$

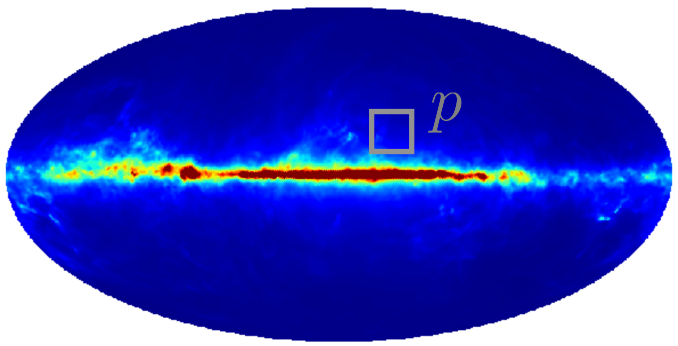
Probability of observing *k* photons in pixel *p*

$$P_k^{(p)} = \frac{(\mu_p)^k e^{-\mu_p}}{k!}$$

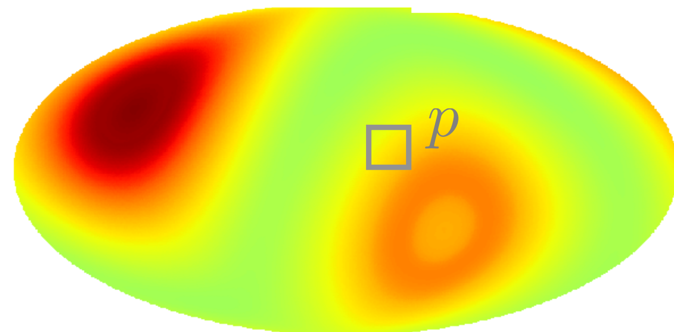
Non-Poissonian Template Fit

Spatial Templates

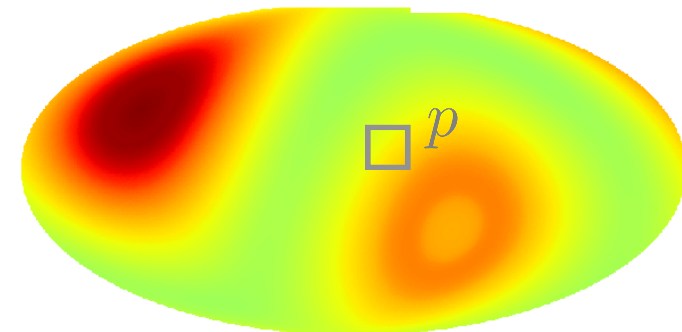
diffuse background



Isotropic



Isotropic point sources



Poisson

Non-Poissonian

Total Generating Function

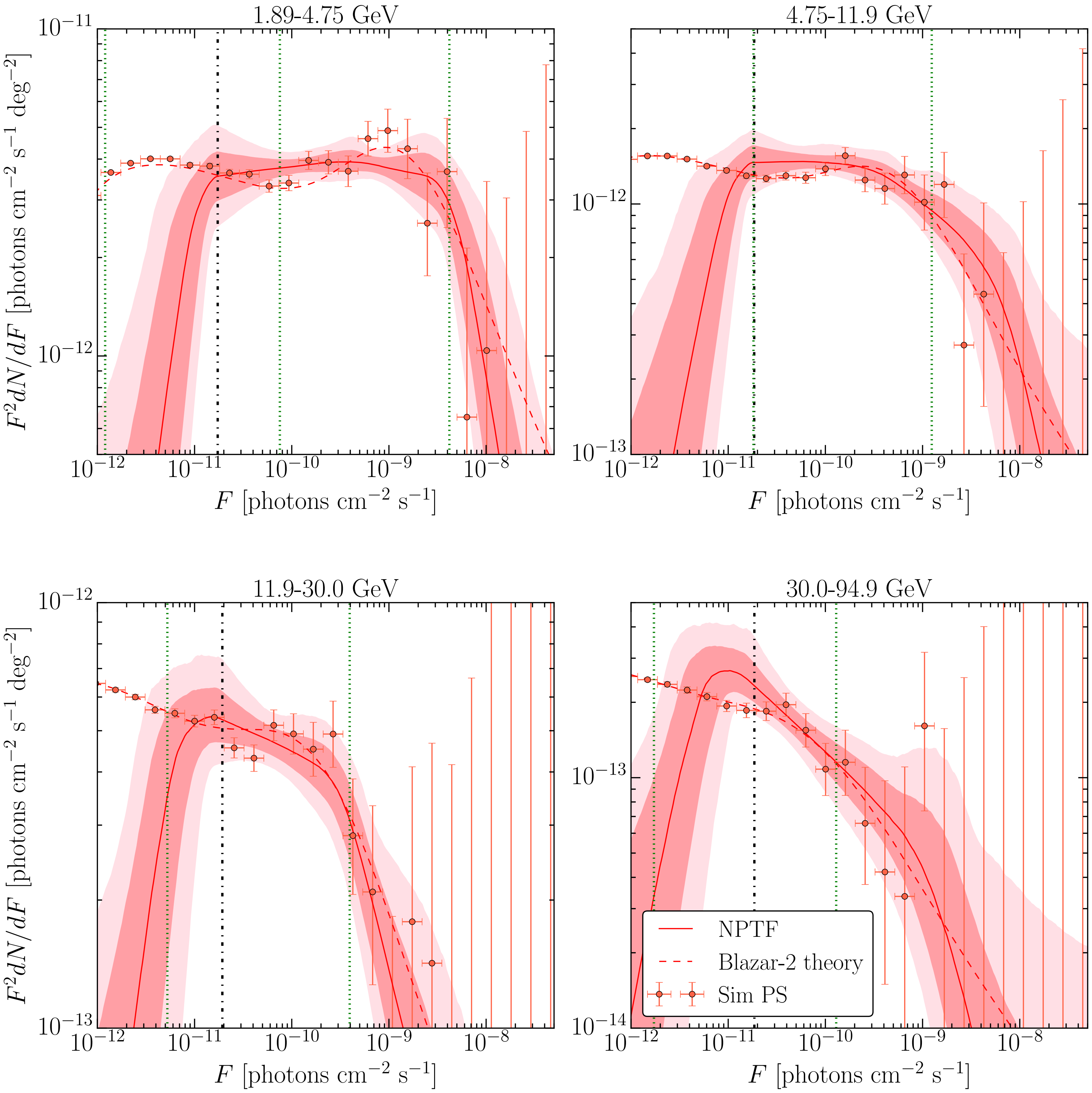
$$\mathcal{P}_k^{(p)} = \mathcal{D}^{(p)}(t) \cdot \mathcal{G}^{(p)}(t)$$

Probability of observing *k* photons in pixel *p*

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

Malyshev and Hogg [1104.0010]
Lee et al [1412.6099, 1506.05124]
Zechlin et al [1512.07190, 1605.04256]

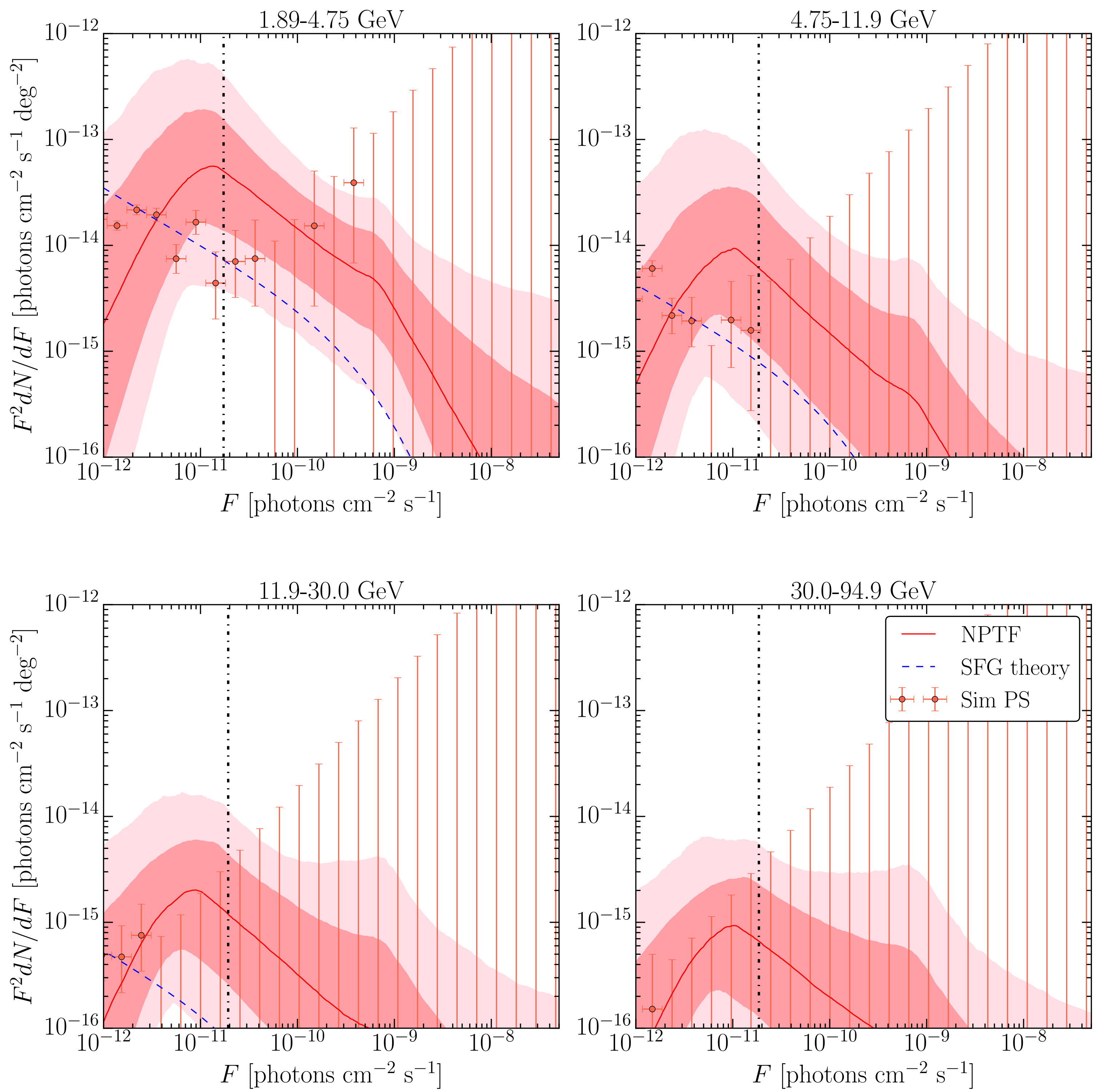
Simulation: Blazar-II model

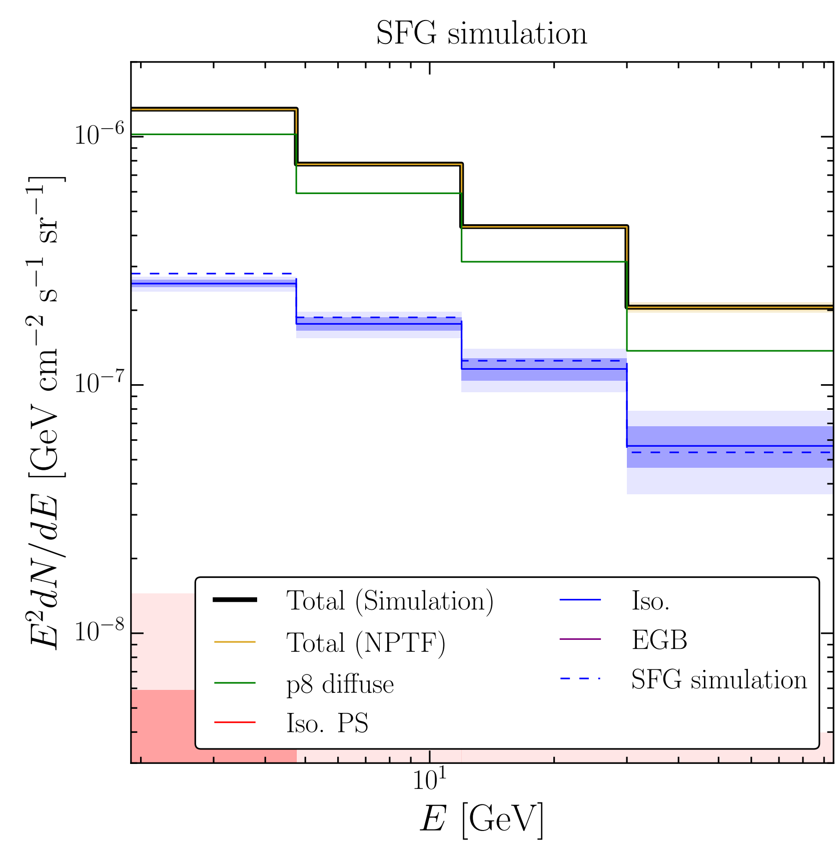


Ajello et al

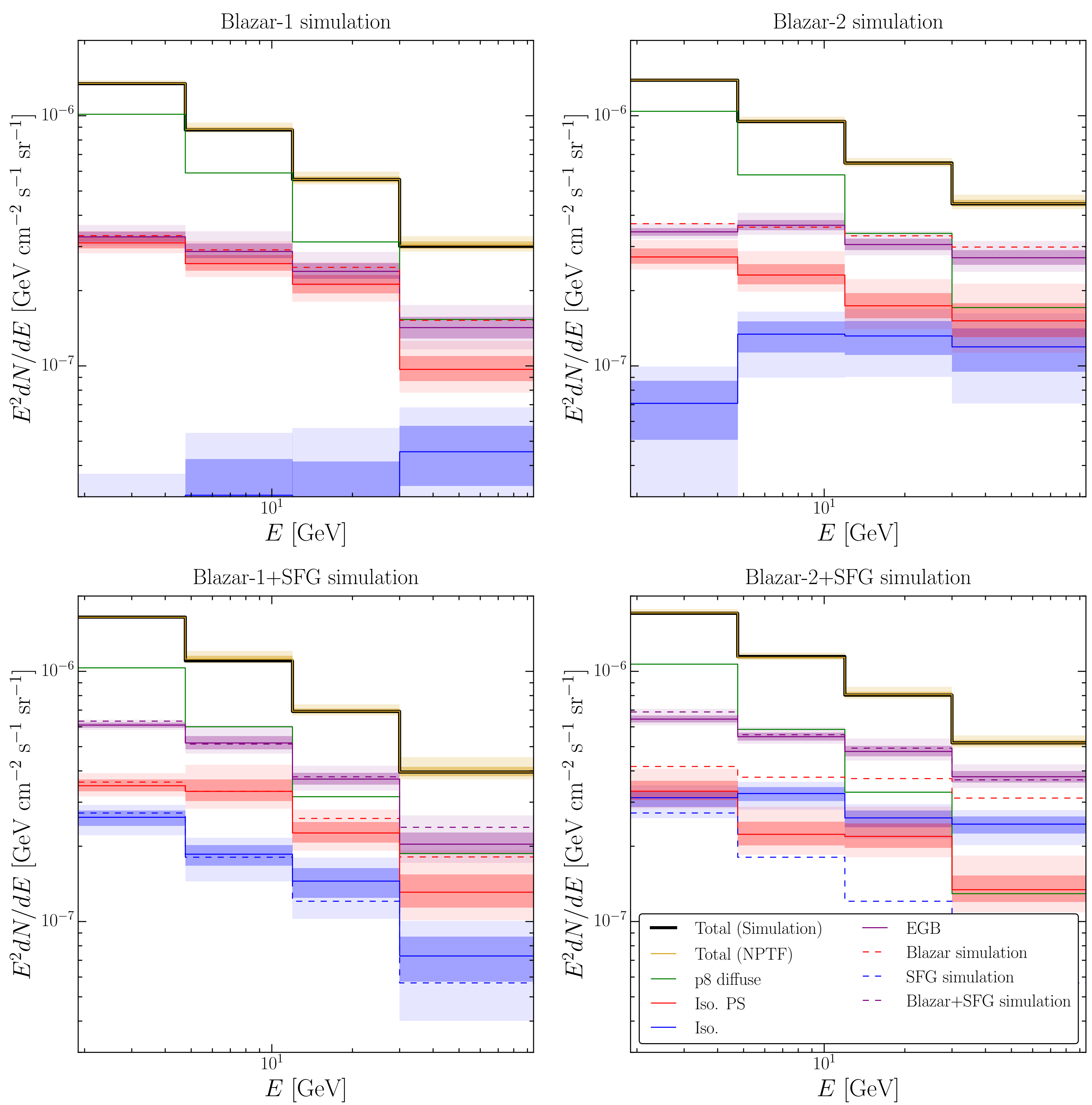
[1110.3787,1310.0006]

Simulation: SFG Source Counts and Spectra





Simulation: Energy Spectra



Analysis on Data: PS Fractions

I_{EGB}	Low-Energy Analysis				High-Energy Analysis			
	1.89–4.75	4.75–11.9	11.9–30	30–94.9	50–151	151–457	457–2000	50–2000
Scenario A	$0.62^{+0.04}_{-0.02}$	$0.53^{+0.03}_{-0.03}$	$0.48^{+0.03}_{-0.03}$	$0.47^{+0.05}_{-0.04}$	$0.44^{+0.06}_{-0.05}$	$0.36^{+0.08}_{-0.06}$	$0.12^{+0.09}_{-0.06}$	$0.43^{+0.05}_{-0.04}$
Scenario B	$0.54^{+0.03}_{-0.03}$	$0.60^{+0.04}_{-0.03}$	$0.61^{+0.06}_{-0.05}$	$0.66^{+0.09}_{-0.07}$	$0.67^{+0.10}_{-0.09}$	$0.51^{+0.13}_{-0.09}$	$0.58^{+0.45}_{-0.27}$	$0.68^{+0.09}_{-0.08}$

Scenario A: compared to our EGRB
Scenario B: compared to *Fermi* EGRB

Analysis on Data: Intensities and Parameters

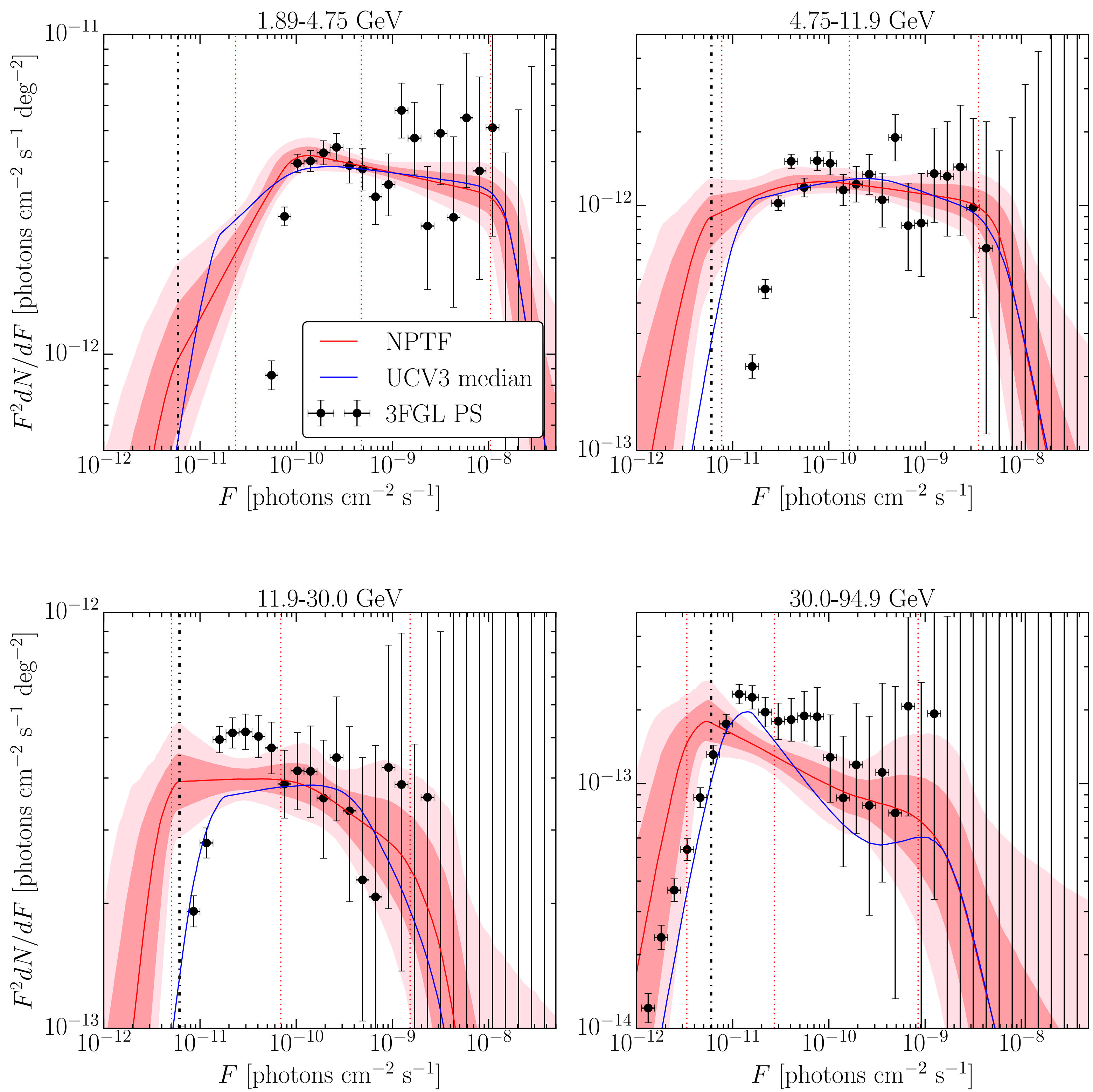
Best-fit intensities:

Energy [GeV]	I_{EGB}	$I_{\mathrm{iso}}^{\mathrm{PS}}$	I_{iso} $[\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}]$	I_{diff}	I_{bub}
1.89–4.75	$1.38^{+0.05}_{-0.04} \times 10^{-7}$	$9.00^{+0.66}_{-0.54} \times 10^{-8}$	$4.82^{+0.43}_{-0.52} \times 10^{-8}$	$3.22^{+0.02}_{-0.02} \times 10^{-7}$	$2.90^{+0.67}_{-0.69} \times 10^{-8}$
4.75–11.9	$5.46^{+0.24}_{-0.22} \times 10^{-8}$	$2.68^{+0.26}_{-0.21} \times 10^{-8}$	$2.77^{+0.18}_{-0.21} \times 10^{-8}$	$7.38^{+0.15}_{-0.16} \times 10^{-8}$	$1.44^{+0.39}_{-0.39} \times 10^{-8}$
11.9–30.0	$1.76^{+0.10}_{-0.09} \times 10^{-8}$	$7.17^{+0.99}_{-0.76} \times 10^{-9}$	$1.04^{+0.08}_{-0.08} \times 10^{-8}$	$1.63^{+0.07}_{-0.07} \times 10^{-8}$	$5.18^{+2.35}_{-2.23} \times 10^{-9}$
30.0-94.9	$5.74^{+0.46}_{-0.41} \times 10^{-9}$	$2.40^{+0.48}_{-0.38} \times 10^{-9}$	$3.30^{+0.39}_{-0.42} \times 10^{-9}$	$3.73^{+0.31}_{-0.33} \times 10^{-9}$	$1.46^{+1.25}_{-0.92} \times 10^{-9}$

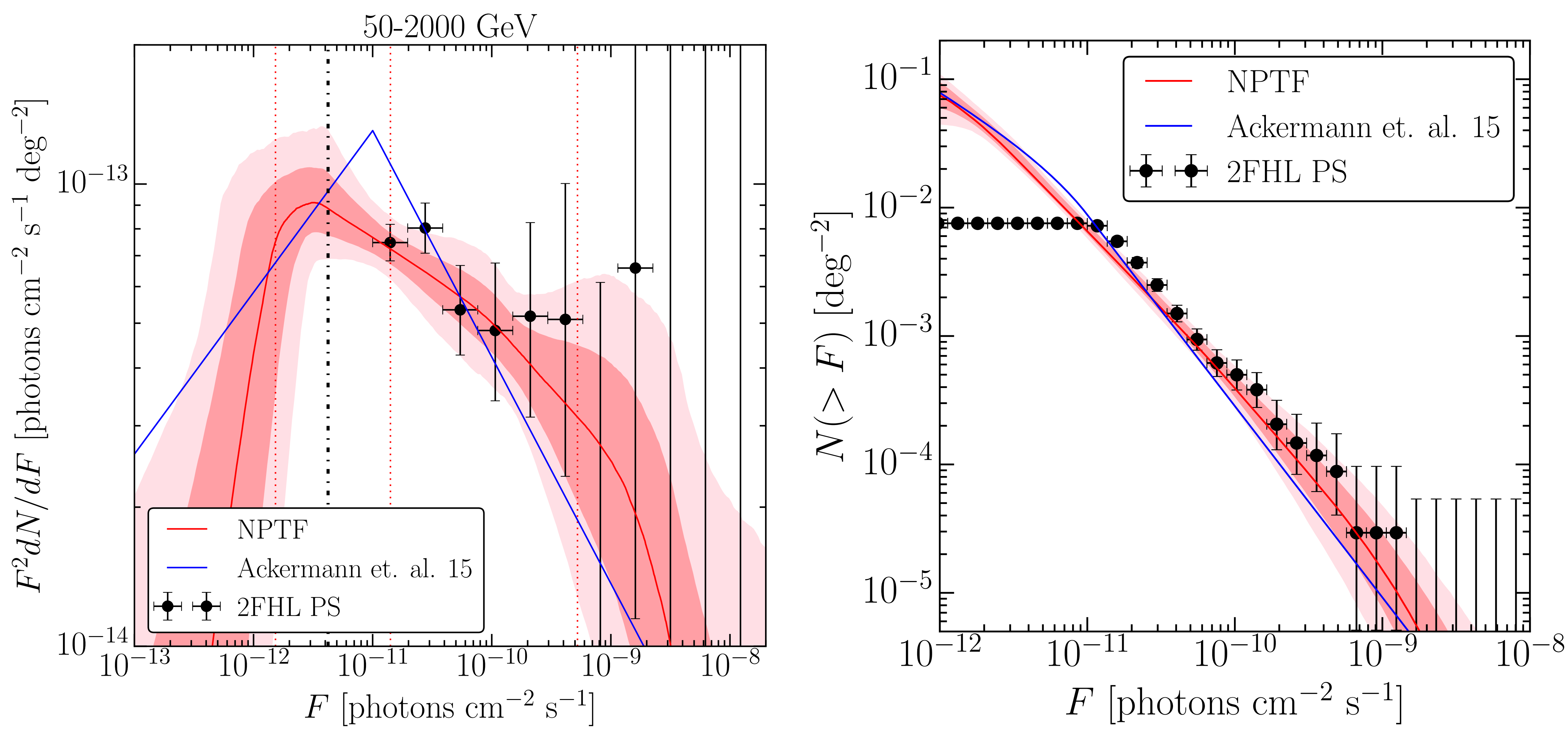
Best-fit parameters:

Energy [GeV]	n_1	n_2	n_3	n_4	$F_{b,3}$	$F_{b,2}$ $[\mathrm{cm}^{-2}\ \mathrm{s}^{-1}]$	$F_{b,1}$
1.89–4.75	$3.96^{+0.68}_{-0.80}$	$2.04^{+0.05}_{-0.05}$	$1.74^{+0.19}_{-0.37}$	$-0.40^{+1.18}_{-1.05}$	$1.13^{+0.39}_{-0.52} \times 10^{-11}$	$1.22^{+2.00}_{-0.56} \times 10^{-10}$	$1.43^{+0.51}_{-0.46} \times 10^{-8}$
4.75–11.9	$3.84^{+0.78}_{-0.86}$	$2.13^{+0.15}_{-0.13}$	$1.91^{+0.09}_{-0.12}$	$-0.44^{+1.21}_{-1.03}$	$1.16^{+0.47}_{-0.51} \times 10^{-11}$	$2.95^{+1.80}_{-1.79} \times 10^{-10}$	$5.52^{+2.66}_{-2.06} \times 10^{-9}$
11.9–30.0	$3.54^{+0.96}_{-0.91}$	$2.42^{+0.41}_{-0.32}$	$1.97^{+0.11}_{-0.13}$	$-0.14^{+1.13}_{-1.15}$	$1.11^{+0.52}_{-0.50} \times 10^{-11}$	$3.47^{+1.56}_{-1.76} \times 10^{-10}$	$2.83^{+1.34}_{-1.34} \times 10^{-9}$
30.0-94.9	$3.63^{+0.89}_{-0.98}$	$1.83^{+0.52}_{-0.47}$	$2.51^{+0.29}_{-0.21}$	$-0.20^{+1.15}_{-1.16}$	$1.02^{+0.47}_{-0.46} \times 10^{-11}$	$2.48^{+1.86}_{-1.36} \times 10^{-10}$	$1.68^{+0.68}_{-0.65} \times 10^{-9}$

Analysis on Data: UCV1-3 analysis



Comparison with Ackermann et al



Analysis on Data: High Energy Systematics