Evidence for Unresolved Gamma-Ray Point Sources in the Inner Galaxy

Ben Safdi

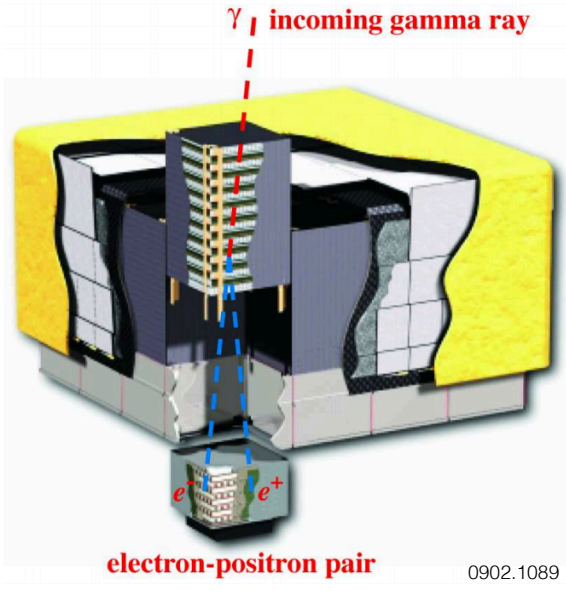
Massachusetts Institute of Technology

2015

B.S., S. Lee, M. Lisanti, and B.S., S. Lee, M. Lisanti, T. Slatyer, W. Xue
[1412.6099 and 1506.05124]

The Fermi Large-Area Telescope (LAT)

Fermi (NASA)

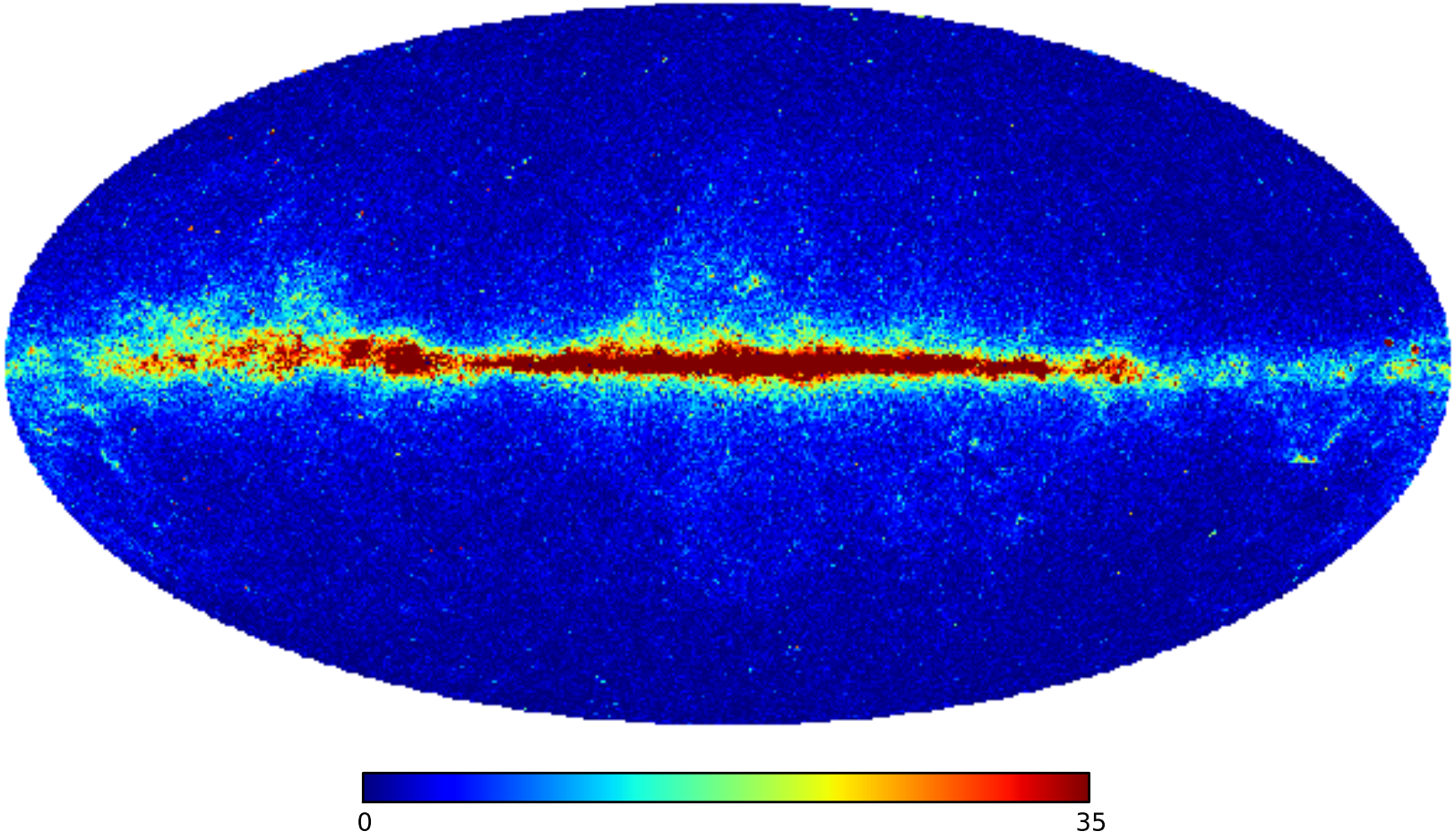


PSs important for gamma-ray signals of DM

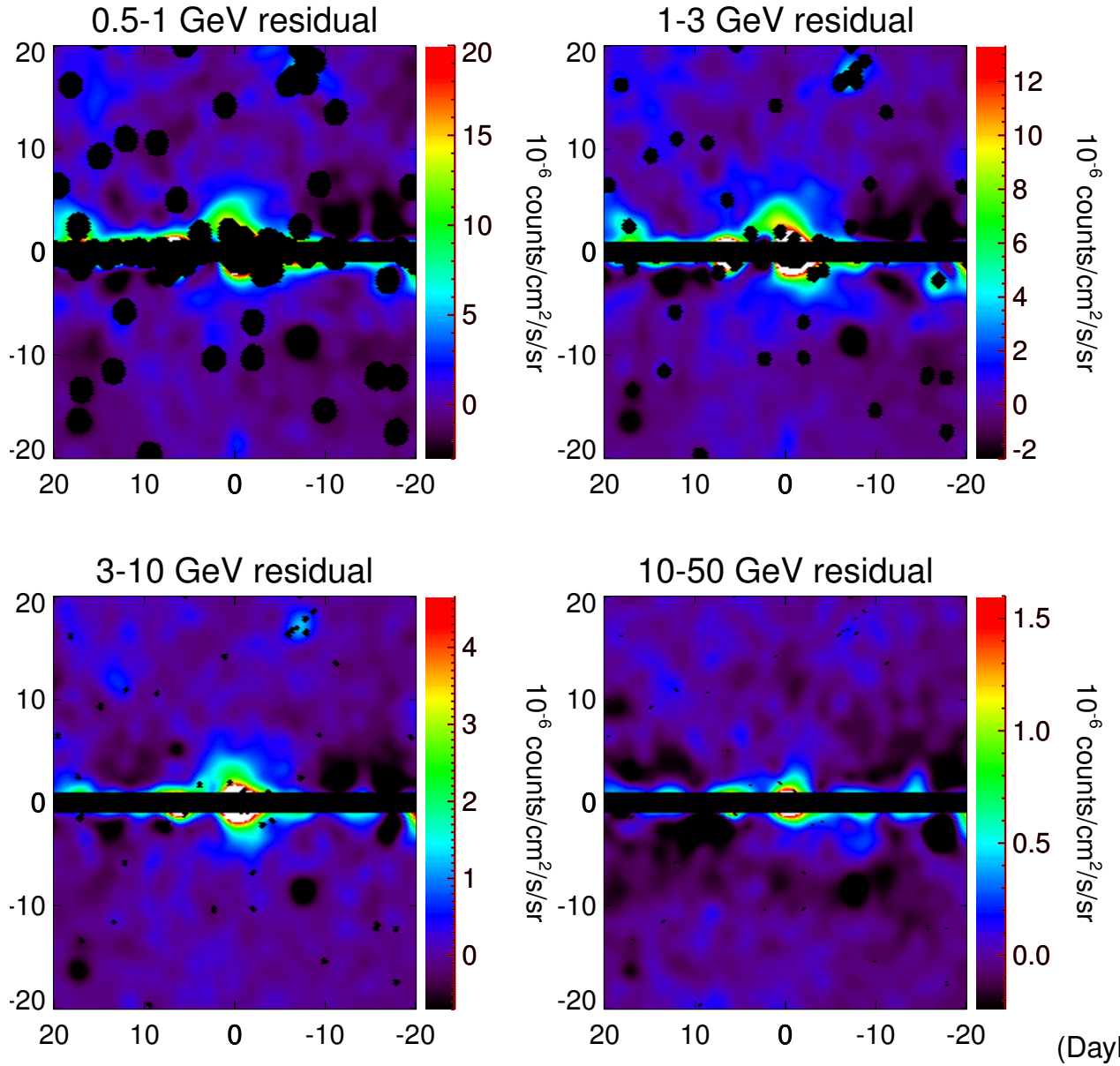
Import to understand contributions from unresolved PSs to gamma-ray background to constrain contributions from dark matter (DM)

The Fermi Gamma-Ray Sky

Data taken from ∼August 4, 2008 to December 5, 2013
HEALPIX $nside = 128$ ($N_{\text{pix}} = 196,608$)
∼2–12 GeV

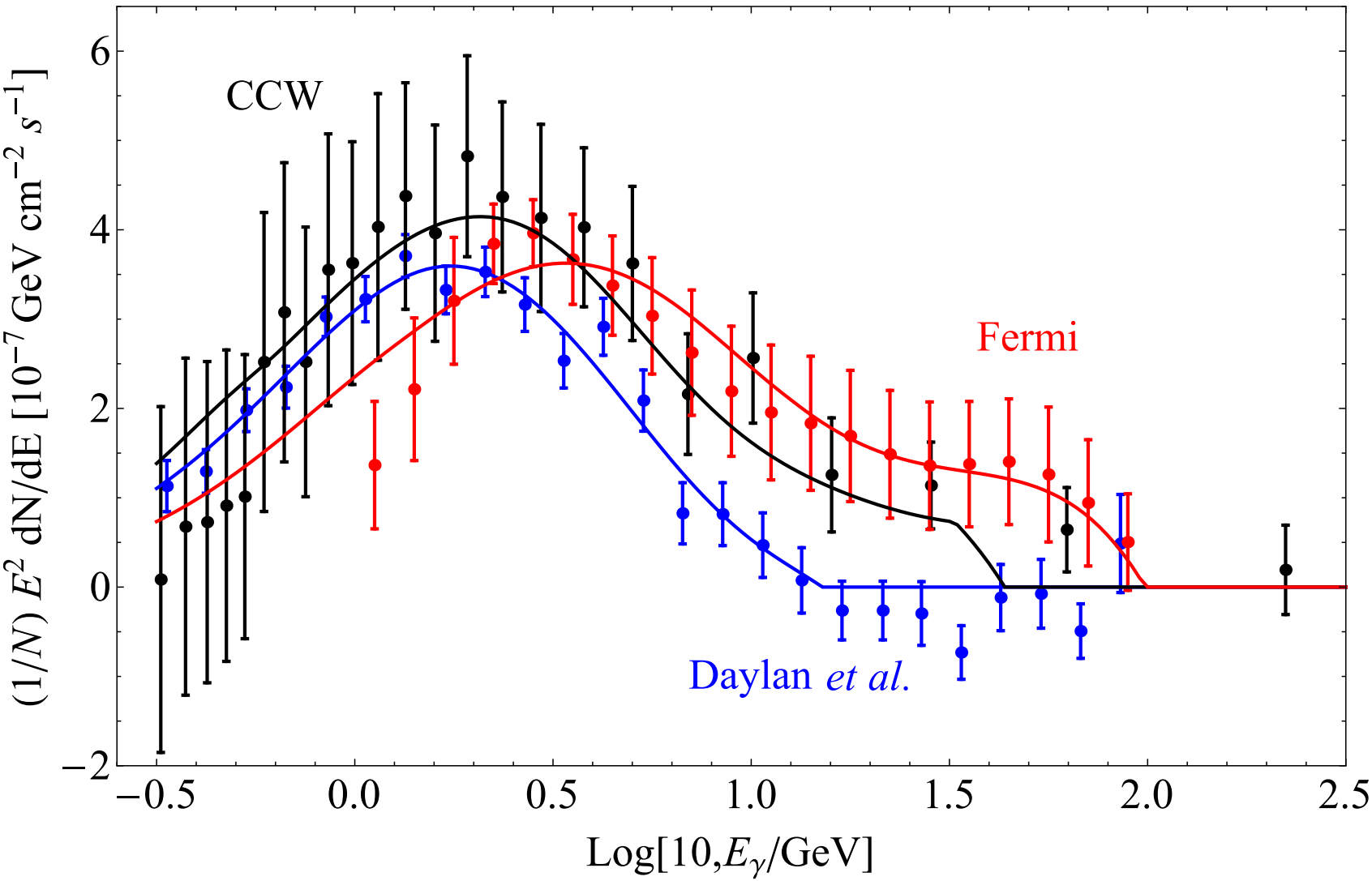


GeV Excess: Inner Galaxy



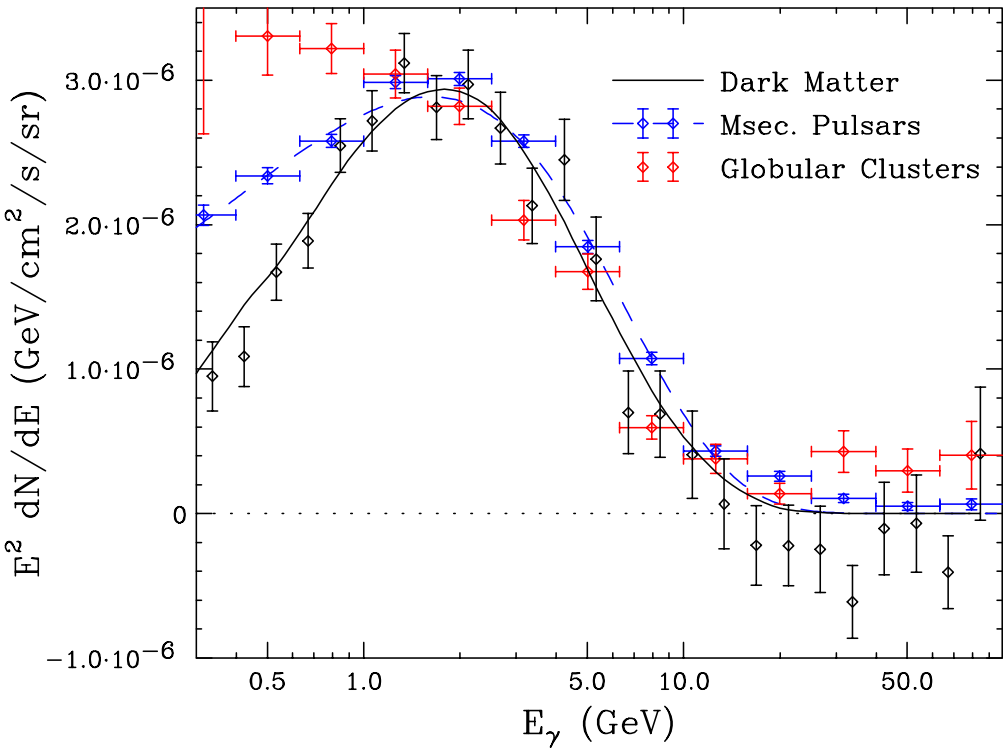
(Daylan et al.)

GeV Excess: Spectrum



Pulsars: Spectrum

Millisecond pulsar spectrum similar to excess (from 61 millisecond pulsars and 36 globular clusters)



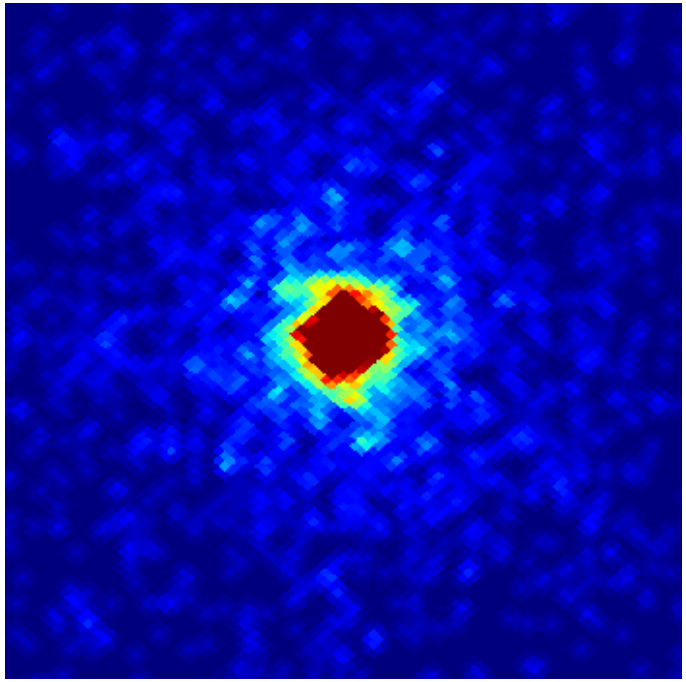
1507.05616: disrupted globular clusters can explain pulsar distribution

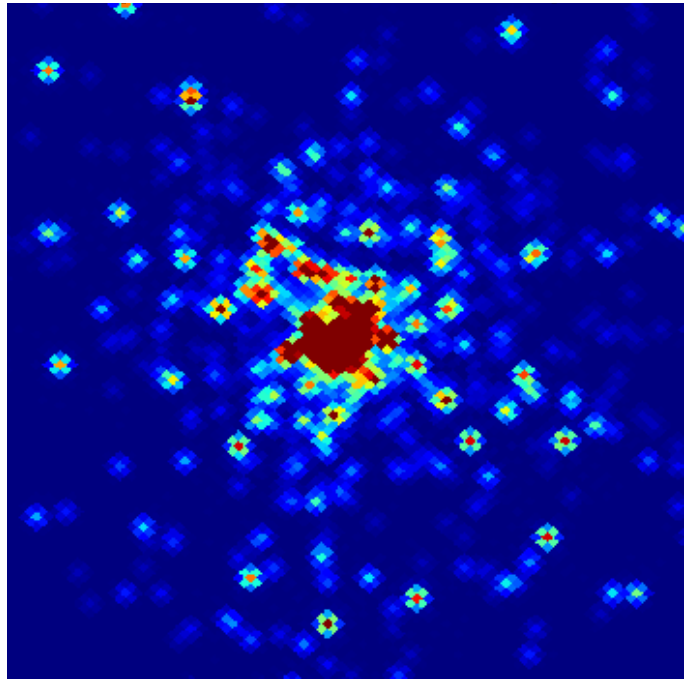
(Cholis, Hooper, Linden)

Astrophysical Scenarios

Can we use the *Fermi* data to differentiate between smooth and unresolved PS emission?

Photon Statistics: DM vs. Point Sources





Photon Statistics: Point Sources

- $p_k^{(p)}$ = probability of finding k photons in pixel p

Photon Statistics: Point Sources

- $p_k^{(p)}$ = probability of finding k photons in pixel p
- Smooth emission: Poissonian counting statistics: $p_k^{(p)} = \lambda^k e^{-\lambda}/k!$

Photon Statistics: Point Sources

- $p_k^{(p)}$ = probability of finding k photons in pixel p
- Smooth emission: Poissonian counting statistics: $p_k^{(p)} = \lambda^k e^{-\lambda}/k!$
- Point-source emission: Non-Poissonian counting statistics

Photon Statistics: Point Sources

- $p_k^{(p)}$ = probability of finding k photons in pixel p
- Smooth emission: Poissonian counting statistics: $p_k^{(p)} = \lambda^k e^{-\lambda}/k!$
- Point-source emission: Non-Poissonian counting statistics
  - (1) What is probability to find a PS in a given pixel?

Photon Statistics: Point Sources

- $p_k^{(p)}$ = probability of finding k photons in pixel p
- Smooth emission: Poissonian counting statistics: $p_k^{(p)} = \lambda^k e^{-\lambda}/k!$
- Point-source emission: Non-Poissonian counting statistics
  - (1) What is probability to find a PS in a given pixel?
  - (2) Given a PS, what is the probability it produces k photons?

Photon Statistics: Point Sources

- $p_k^{(p)}$ = probability of finding k photons in pixel p
- Smooth emission: Poissonian counting statistics: $p_k^{(p)} = \lambda^k e^{-\lambda}/k!$
- Point-source emission: Non-Poissonian counting statistics
  - (1) What is probability to find a PS in a given pixel?
  - (2) Given a PS, what is the probability it produces k photons?
  - Source-count: $$\frac{dN^{(p)}}{dF} = A^p \begin{cases} \left(\frac{F}{F_b}\right)^{-n_1}, & F \geq F_b \\ \left(\frac{F}{F_b}\right)^{-n_2}, & F < F_b \end{cases}$$
  - F is average flux (photons / cm^2 / s)

Photon Statistics: Point Sources

- $p_k^{(p)}$ = probability of finding k photons in pixel p
- Smooth emission: Poissonian counting statistics: $p_k^{(p)} = \lambda^k e^{-\lambda}/k!$
- Point-source emission: Non-Poissonian counting statistics
  - (1) What is probability to find a PS in a given pixel?
  - (2) Given a PS, what is the probability it produces k photons?
  - Source-count: $$\frac{dN^{(p)}}{dF} = A^p \begin{cases} \left(\frac{F}{F_b}\right)^{-n_1}, & F \geq F_b \\ \left(\frac{F}{F_b}\right)^{-n_2}, & F < F_b \end{cases}$$
  - F is average flux (photons / cm^2 / s)
  - A^p follow a spatial template

Non-Poissonian template fit (NPTF)

- data set d (counts in each pixel $\{n_p\}$)

Non-Poissonian template fit (NPTF)

- data set d (counts in each pixel $\{n_p\}$)
- model $\mathcal{M}$ with parameters θ

Non-Poissonian template fit (NPTF)

- data set d (counts in each pixel $\{n_p\}$)
- model $\mathcal{M}$ with parameters θ
- The likelihood function:

$$p(d|\theta, \mathcal{M}) = \prod_{\text{pixels } p} p^{(p)}_{n_p}(\theta)$$

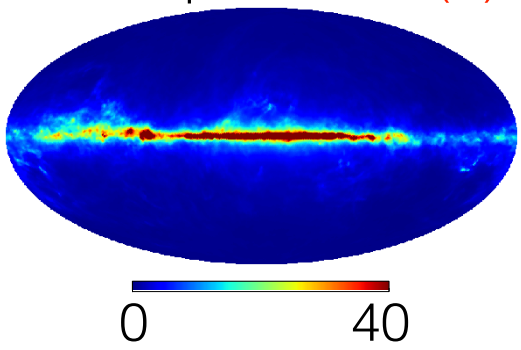
Non-Poissonian template fit (NPTF)

- data set d (counts in each pixel $\{n_p\}$)
- model $\mathcal{M}$ with parameters θ
- The likelihood function:

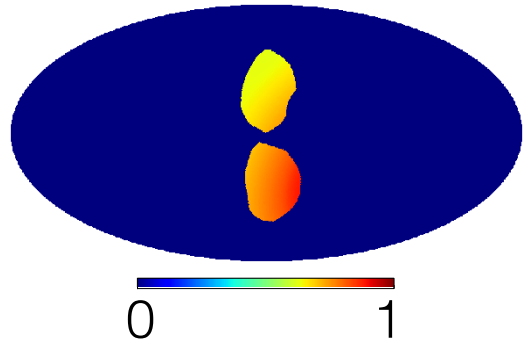
$$p(d|\theta, \mathcal{M}) = \prod_{\text{pixels } p} p^{(p)}_{n_p}(\theta)$$

The models: templates

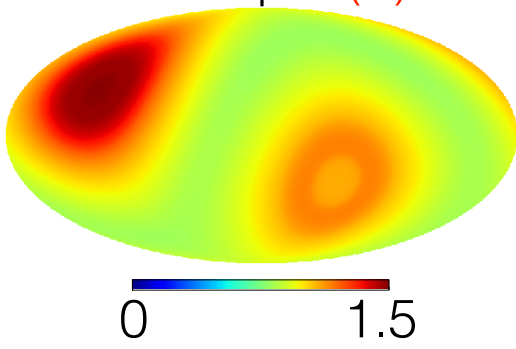
Fermi p6 diffuse (1)



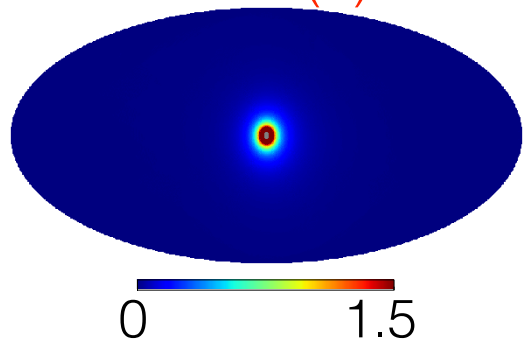
Fermi bubbles (1)



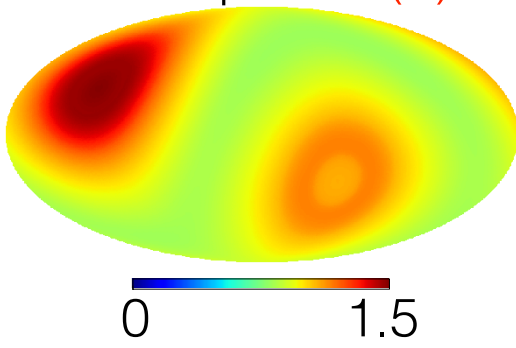
Isotropic (1)



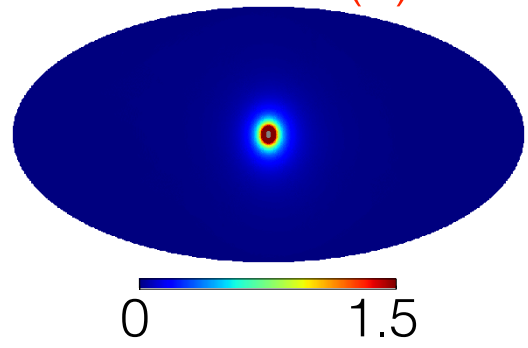
NFW (1)



Isotropic PS (4)

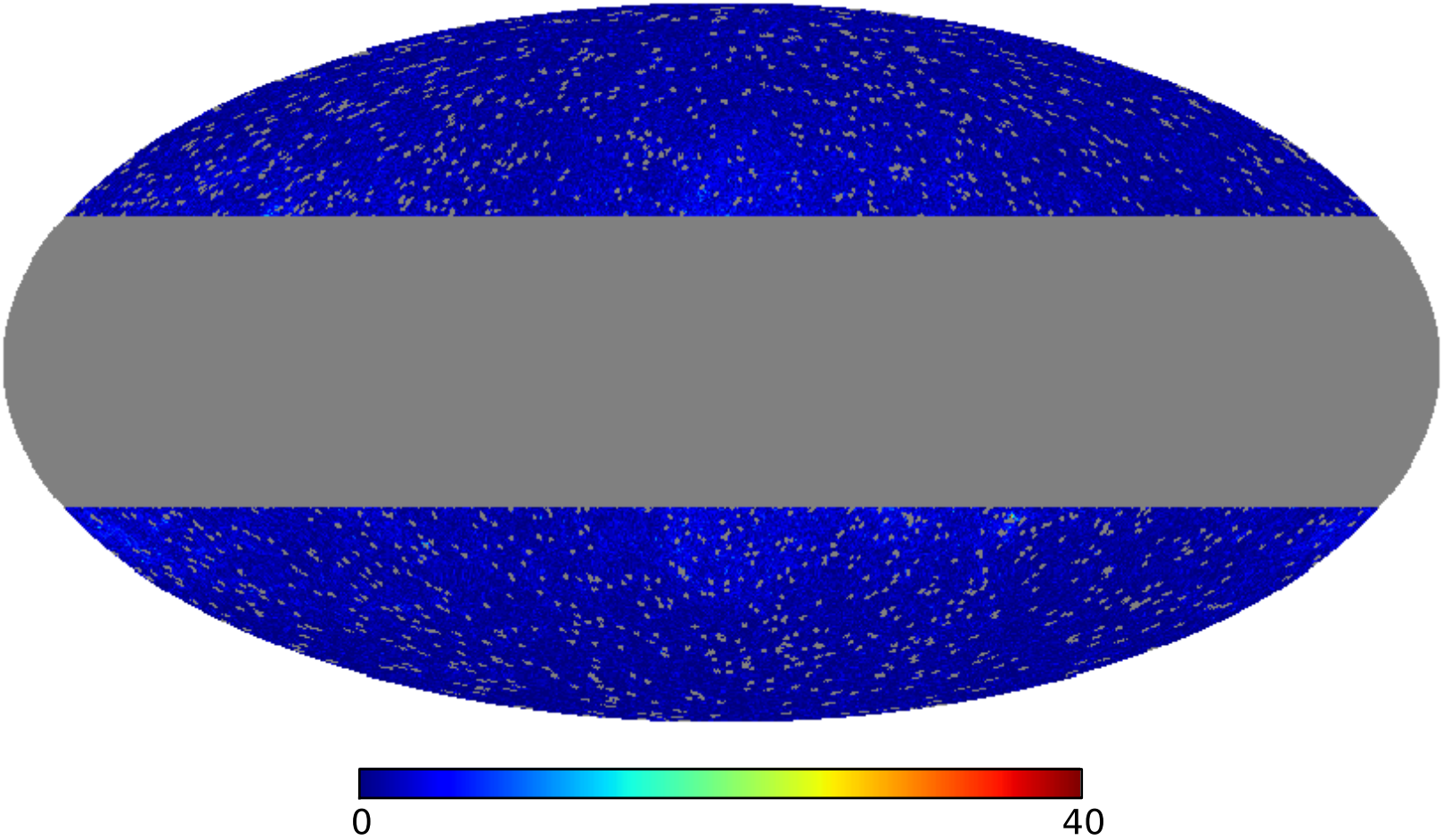


NFW PS (4)



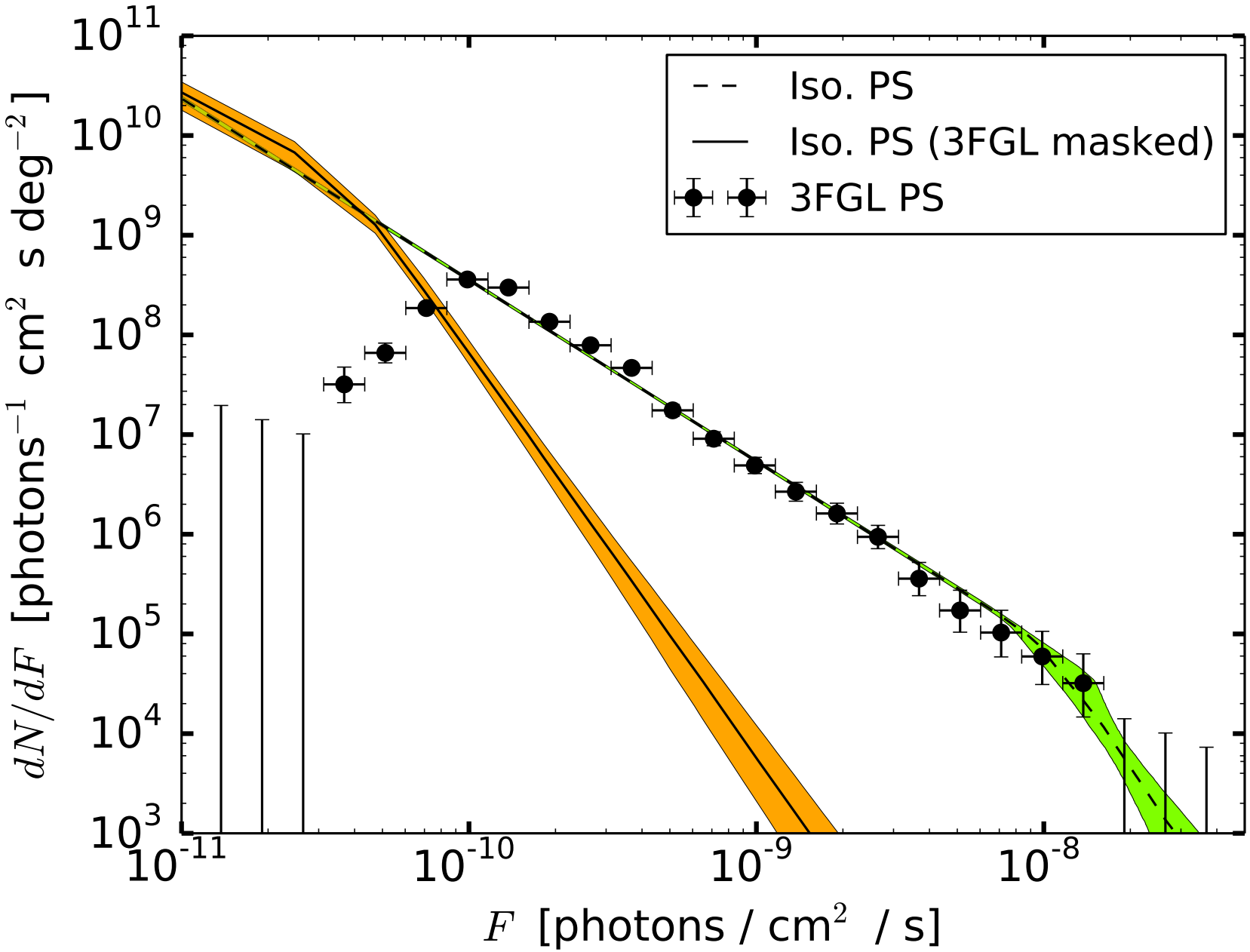
Isotropic point sources

- Region: mask 30° around plane

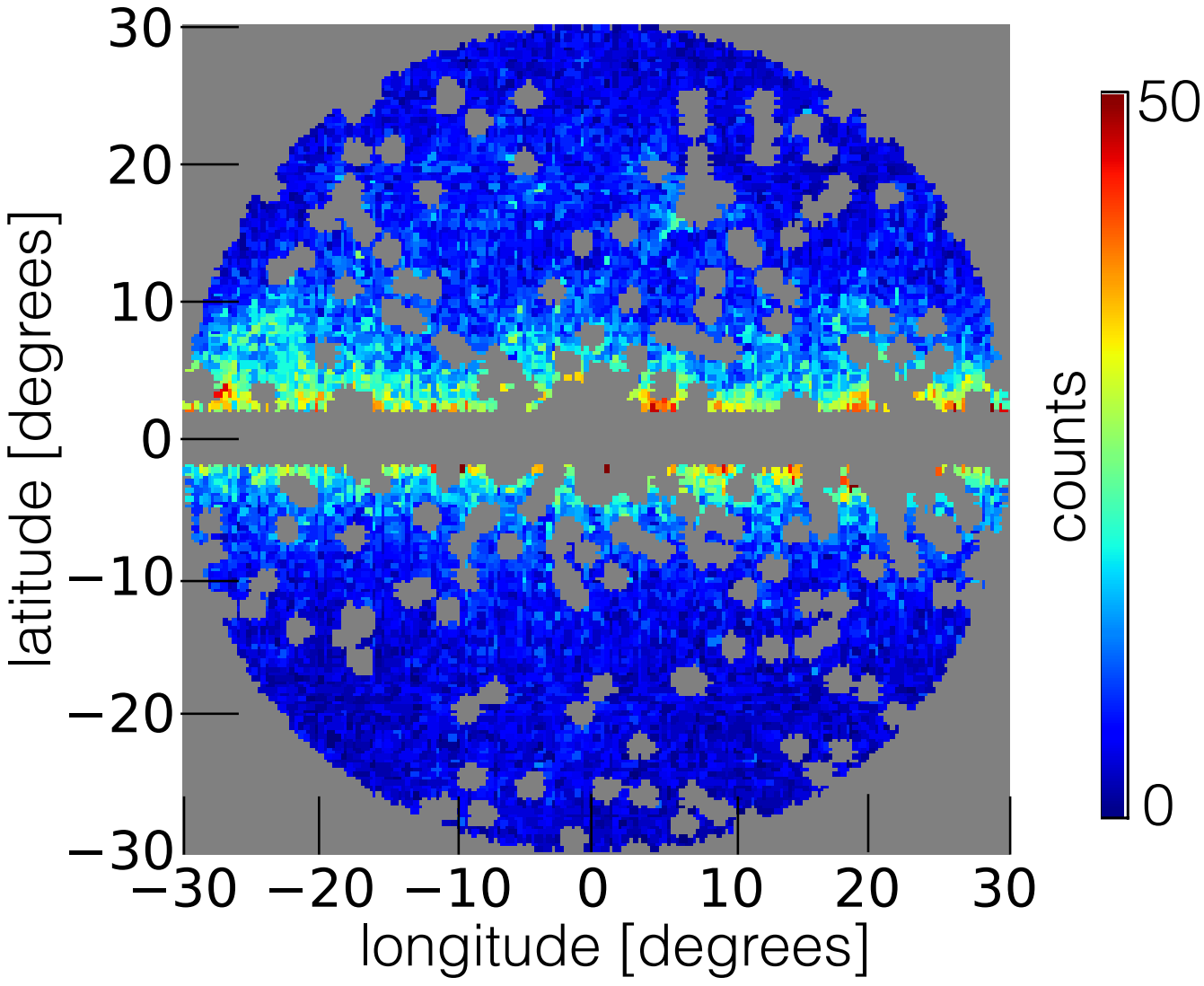


- include diffuse, bubbles, isotropic, and isotropic PS

Isotropic point sources: source-count function

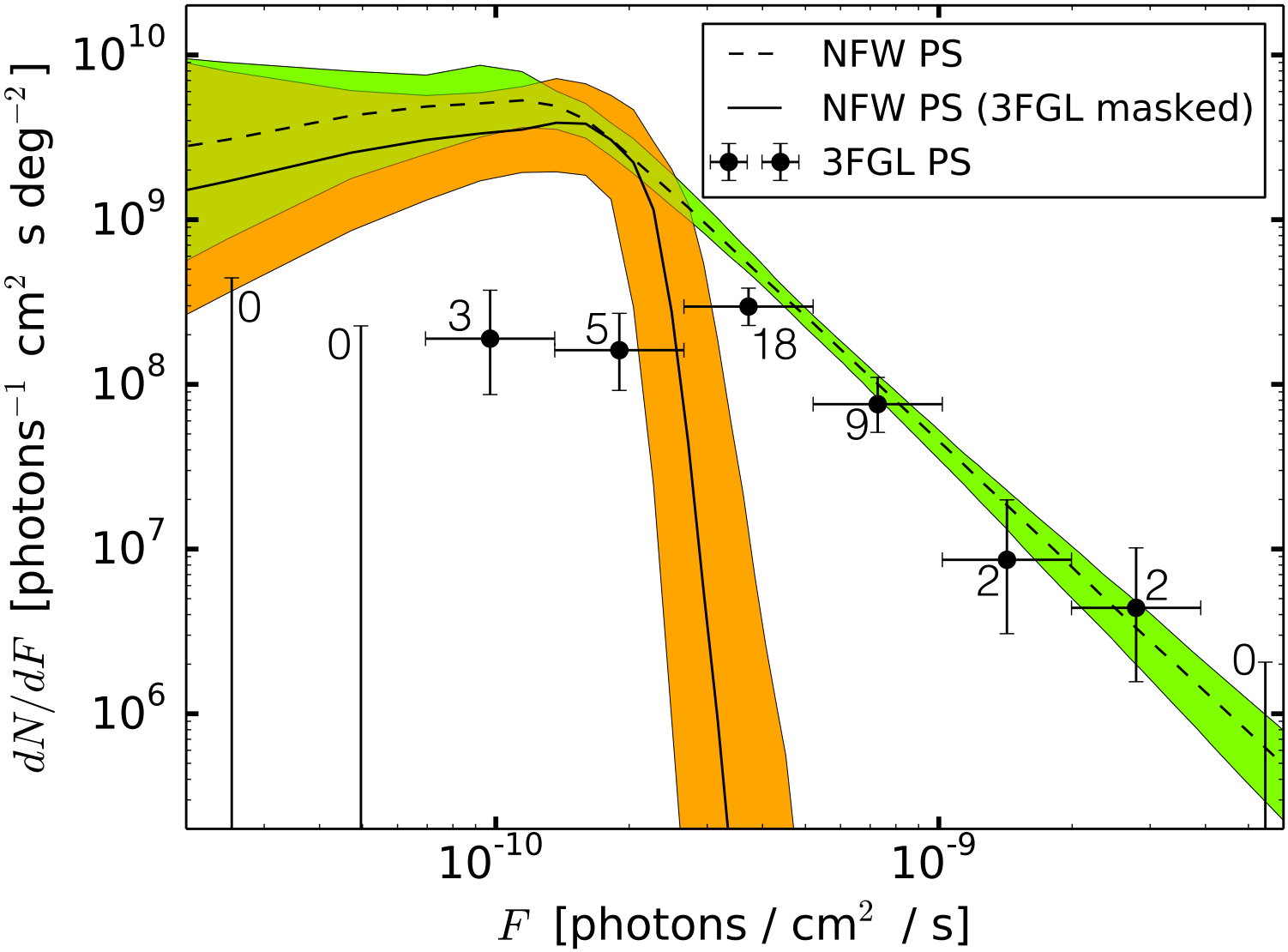


Region: mask 4° around plane, out to 30°



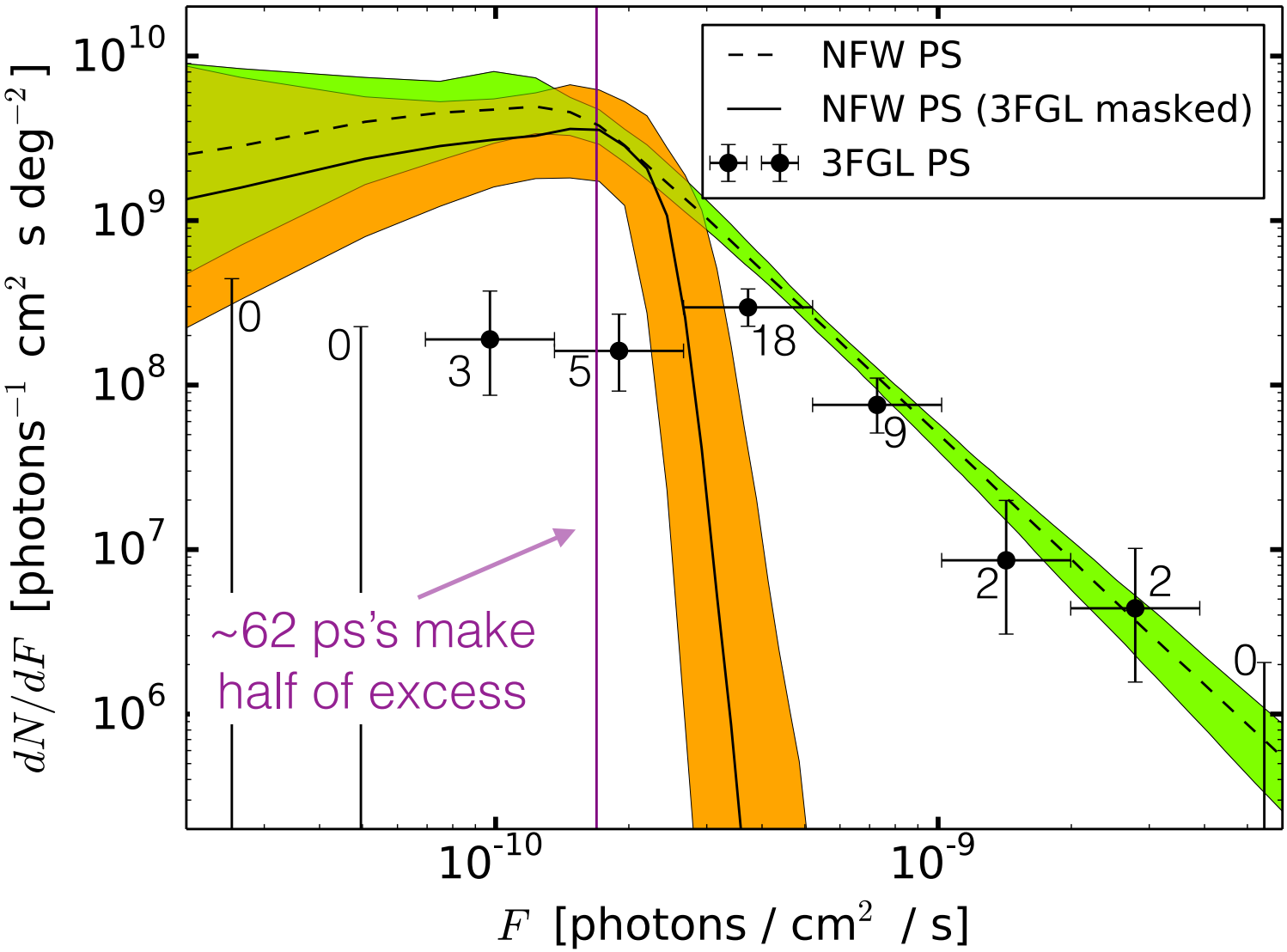
NFW point sources: source-count function

- For ROI out to 10°, with 4° around plane masked



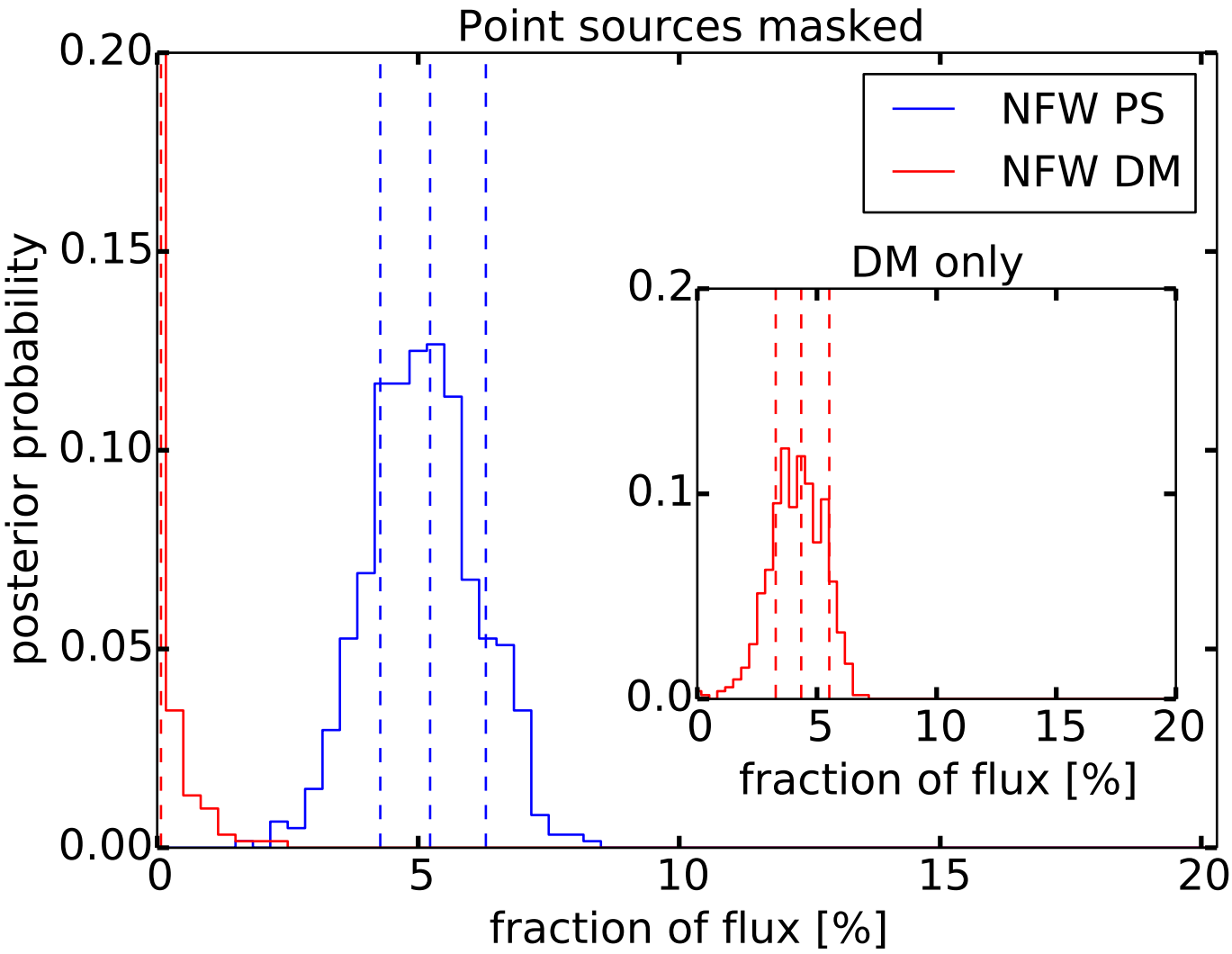
NFW point sources: source-count function

- Prediction: $\sim$200 PS's in inner galaxy (large uncertainties)



NFW point sources: flux fraction

- For ROI out to 10°, with 4° around plane masked



Model comparison

- NFW DM + NFW PS favored over NFW DM with Bayes factor $\sim 10^6$ (very strong evidence)

Model comparison

- NFW DM + NFW PS favored over NFW DM with Bayes factor $\sim 10^6$ (very strong evidence)

Tentative conclusion: GeV excess better fit by point-source emission than smooth (DM) emission

Future

- Incorporate energy dependence in NPTF! (in progress, ask after to see preliminary plots)

Future

- Incorporate energy dependence in NPTF! (in progress, ask after to see preliminary plots)
- Find the PS's! (work in progress with Fermi data and X-rays)

Future

- Incorporate energy dependence in NPTF! (in progress, ask after to see preliminary plots)
- Find the PS's! (work in progress with Fermi data and X-rays)
- In depth study of NPTF using simulated data (in progress)

Future

- Incorporate energy dependence in NPTF! (in progress, ask after to see preliminary plots)
- Find the PS's! (work in progress with Fermi data and X-rays)
- In depth study of NPTF using simulated data (in progress)
- New method, new applications: apply more carefully to high latitudes (energy dependence) (in progress)

Future

- Incorporate energy dependence in NPTF! (in progress, ask after to see preliminary plots)
- Find the PS's! (work in progress with Fermi data and X-rays)
- In depth study of NPTF using simulated data (in progress)
- New method, new applications: apply more carefully to high latitudes (energy dependence) (in progress)
- New applications: PSs in other data sets, such as IceCube (in progress)

Questions?

NPTF Systematics

- Spatially mis-modeled background: real concern, can affect source-count function, but pref. for PSs seems robust

NPTF Systematics

- Spatially mis-modeled background: real concern, can affect source-count function, but pref. for PSs seems robust
- Mis-modeling signal (NFW profile): appears to have minimal effect

NPTF Systematics

- Spatially mis-modeled background: real concern, can affect source-count function, but pref. for PSs seems robust
- Mis-modeling signal (NFW profile): appears to have minimal effect
- Mis-modeling angular resolution: predictable but minimal effect.

NPTF Systematics

- Spatially mis-modeled background: real concern, can affect source-count function, but pref. for PSs seems robust
- Mis-modeling signal (NFW profile): appears to have minimal effect
- Mis-modeling angular resolution: predictable but minimal effect.
- Over-constrained source-count function: added more degrees of freedom, results consistent within uncertainties

NPTF Systematics

- Spatially mis-modeled background: real concern, can affect source-count function, but pref. for PSs seems robust
- Mis-modeling signal (NFW profile): appears to have minimal effect
- Mis-modeling angular resolution: predictable but minimal effect.
- Over-constrained source-count function: added more degrees of freedom, results consistent within uncertainties
- Side-band study: study of bright excess 30° from GC (no pref for PSs)

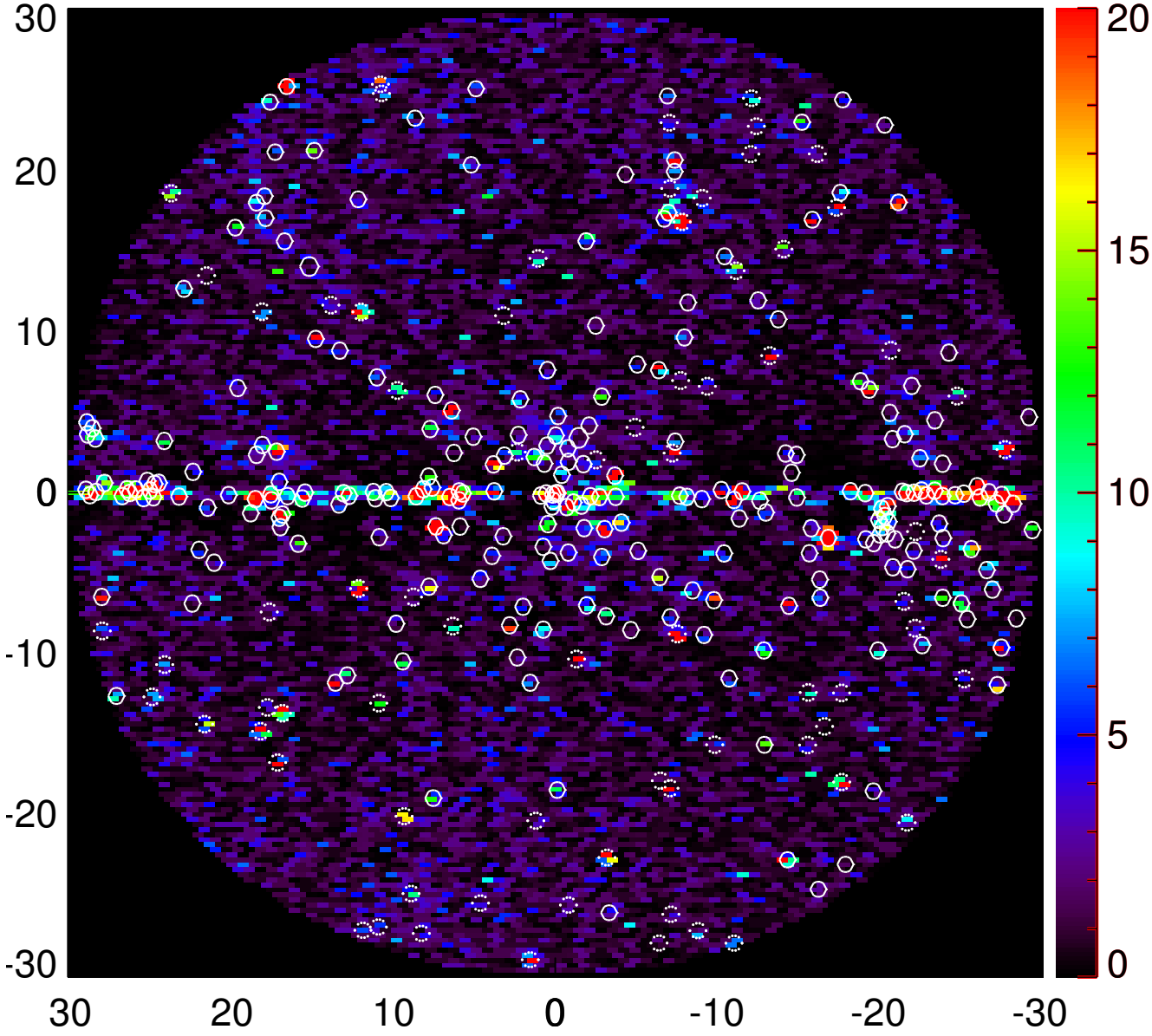
NPTF Systematics

- Spatially mis-modeled background: real concern, can affect source-count function, but pref. for PSs seems robust
- Mis-modeling signal (NFW profile): appears to have minimal effect
- Mis-modeling angular resolution: predictable but minimal effect.
- Over-constrained source-count function: added more degrees of freedom, results consistent within uncertainties
- Side-band study: study of bright excess 30° from GC (no pref for PSs)
- Increased dataset: ($\sim$5.5 years Pass 7 to 7 years Pass 7 to 7 years Pass 8), significance increases within prediction from Monte Carlo

NPTF Systematics

- Spatially mis-modeled background: real concern, can affect source-count function, but pref. for PSs seems robust
- Mis-modeling signal (NFW profile): appears to have minimal effect
- Mis-modeling angular resolution: predictable but minimal effect.
- Over-constrained source-count function: added more degrees of freedom, results consistent within uncertainties
- Side-band study: study of bright excess 30° from GC (no pref for PSs)
- Increased dataset: ($\sim$5.5 years Pass 7 to 7 years Pass 7 to 7 years Pass 8), significance increases within prediction from Monte Carlo
- Validation with Monte-Carlo-generated “fake” data

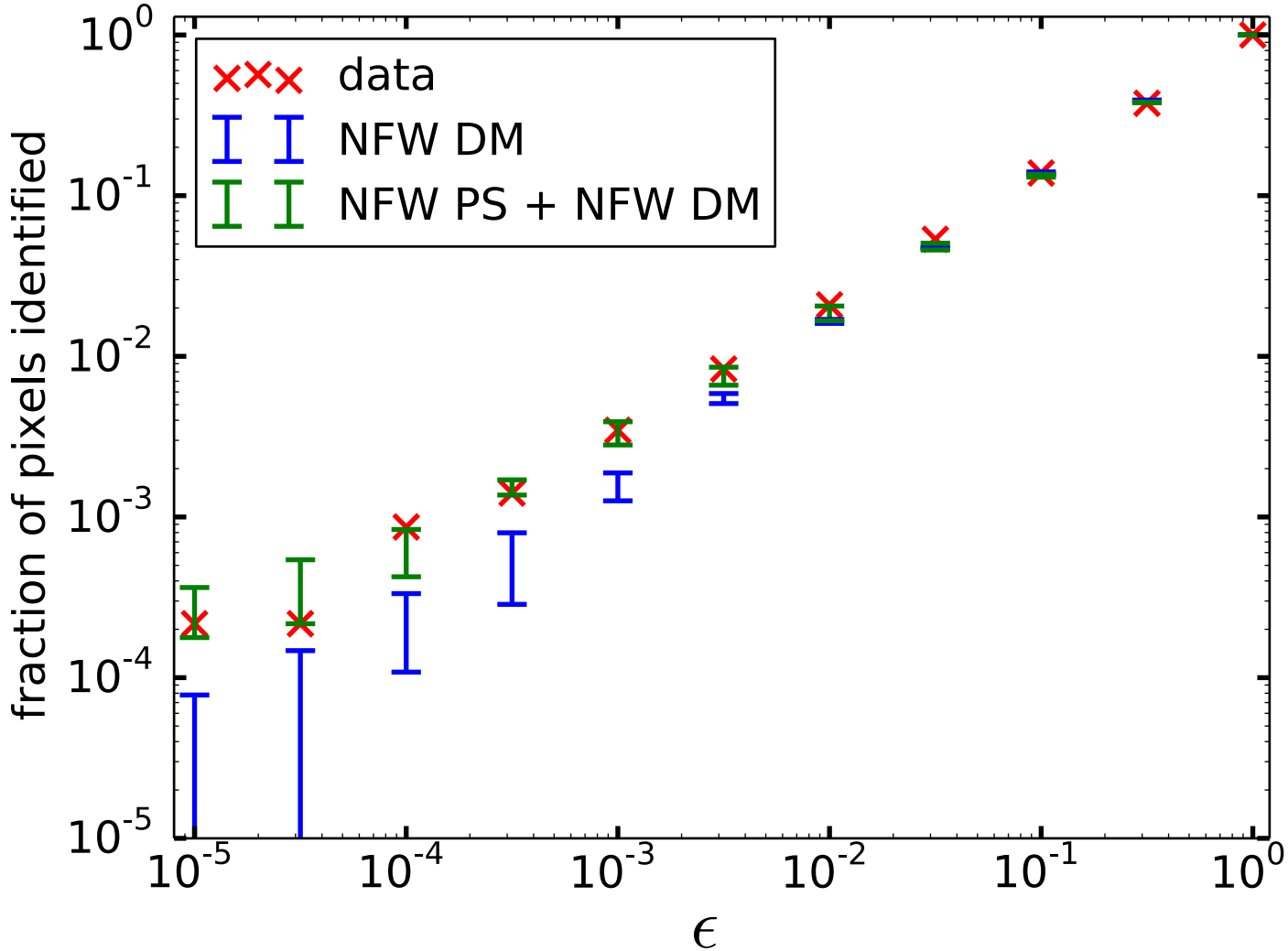
Where are the PSs? $-\log[1 - \mathrm{CDF}(\mathrm{data};\ \mathrm{DM\ model})]$



Statistics of CDF(data; DM model)

- In each pixel: $\epsilon^{(p)} \equiv 1 - \text{CDF(data; DM model)}$

- Use PS-masked maps (within 30° of GC and $|b| \geq 2°$)



Energy-dependent non-Poissonian template fit

- PRELIMINARY!!! (L. Necib and B.S.)

Energy-dependent non-Poissonian template fit

- PRELIMINARY!!! (L. Necib and B.S.)
- Data set: new Pass 8 data

Energy-dependent non-Poissonian template fit

- PRELIMINARY!!! (L. Necib and B.S.)
- Data set: new Pass 8 data
- mask: $|b| \geq 1^\circ$ within 30° of GC

Energy-dependent non-Poissonian template fit

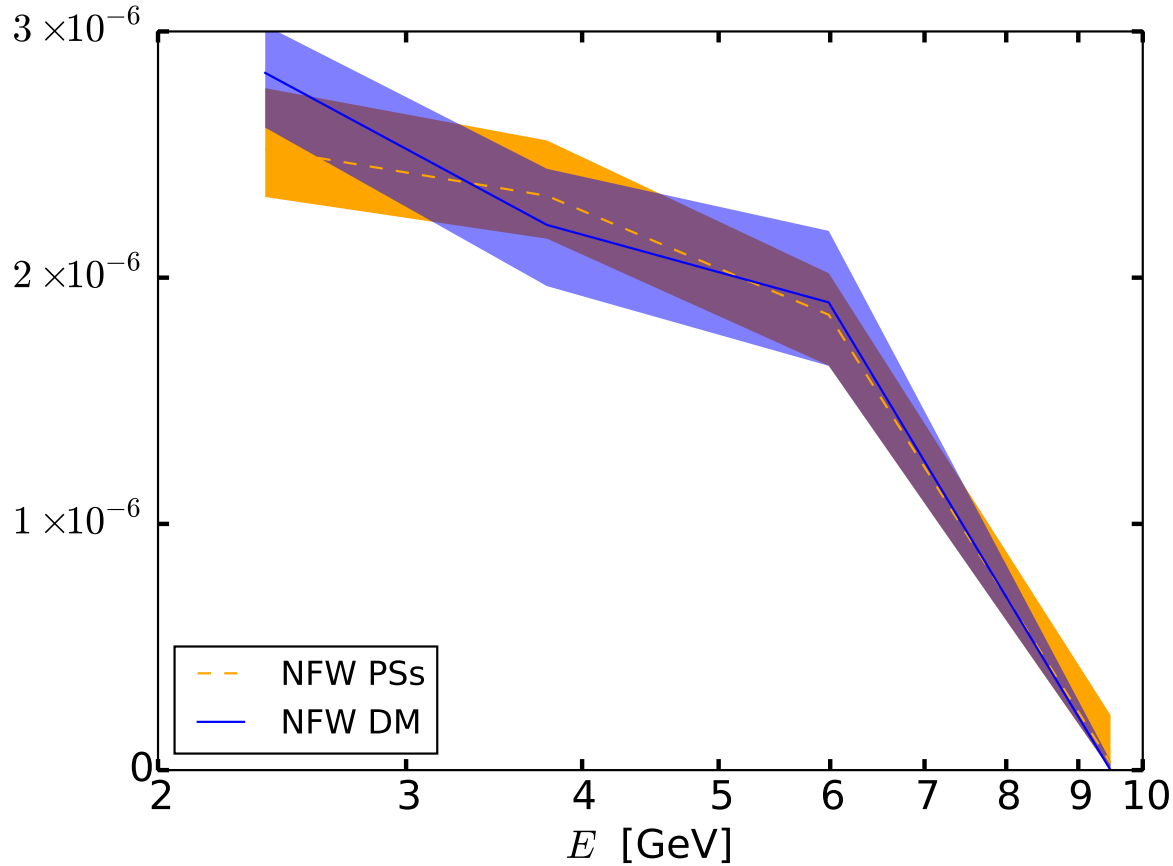
- PRELIMINARY!!! (L. Necib and B.S.)
- Data set: new Pass 8 data
- mask: $|b| \geq 1^\circ$ within 30° of GC
- mask: top 300 PSs masked + all 3FGL PSs modeled

Energy-dependent non-Poissonian template fit

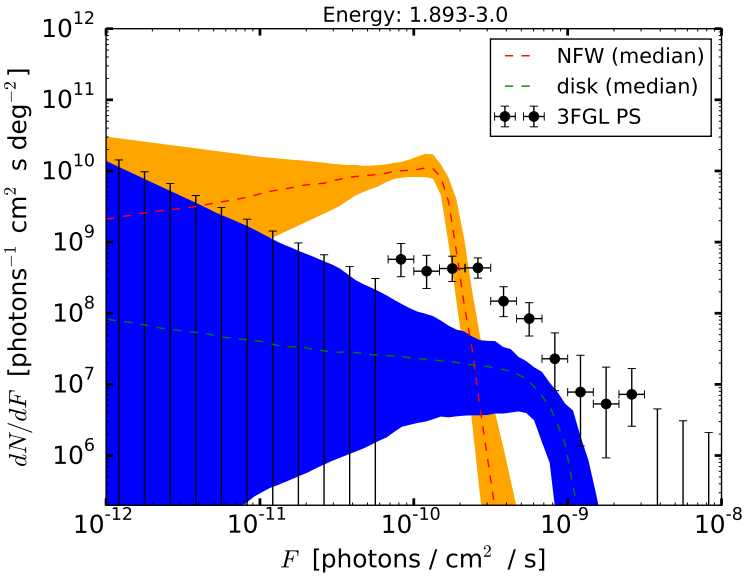
- PRELIMINARY!!! (L. Necib and B.S.)
- Data set: new Pass 8 data
- mask: $|b| \geq 1^\circ$ within 30° of GC
- mask: top 300 PSs masked + all 3FGL PSs modeled
- Energy range: 4 log-spaced bins $\in [1.89, 11.94]$ GeV.

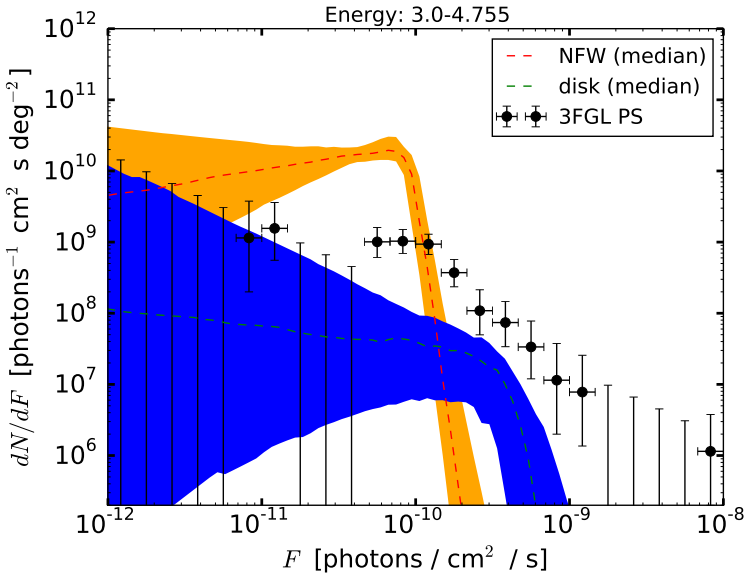
Energy-dependent non-Poissonian template fit

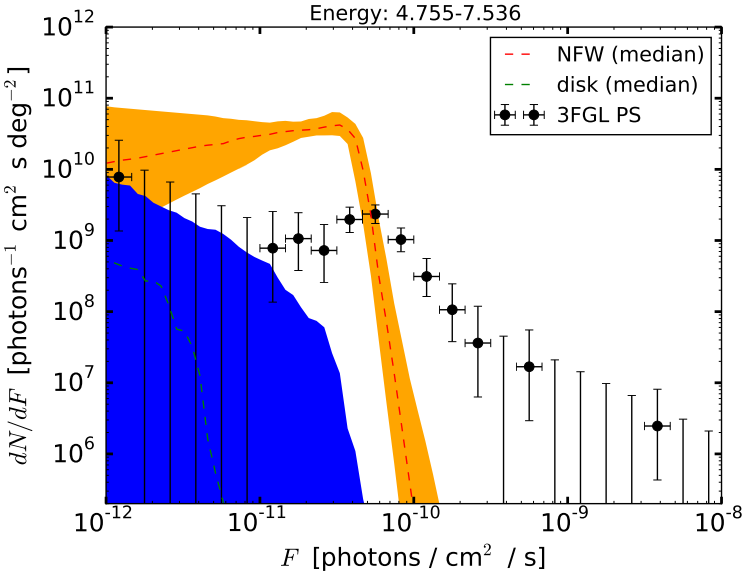
- PRELIMINARY!!! (L. Necib and B.S.)
- Data set: new Pass 8 data
- mask: $|b| \geq 1^\circ$ within 30° of GC
- mask: top 300 PSs masked + all 3FGL PSs modeled
- Energy range: 4 log-spaced bins $\in [1.89, 11.94]$ GeV.

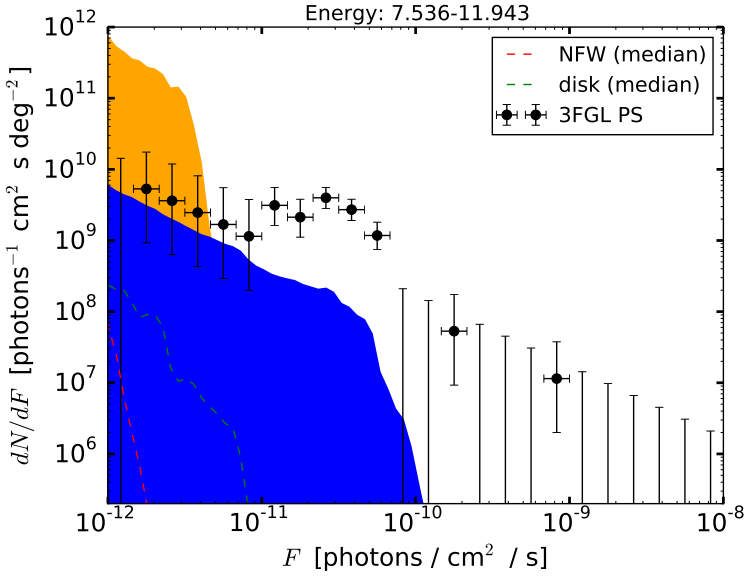


Energy-dependent non-Poissonian template fit

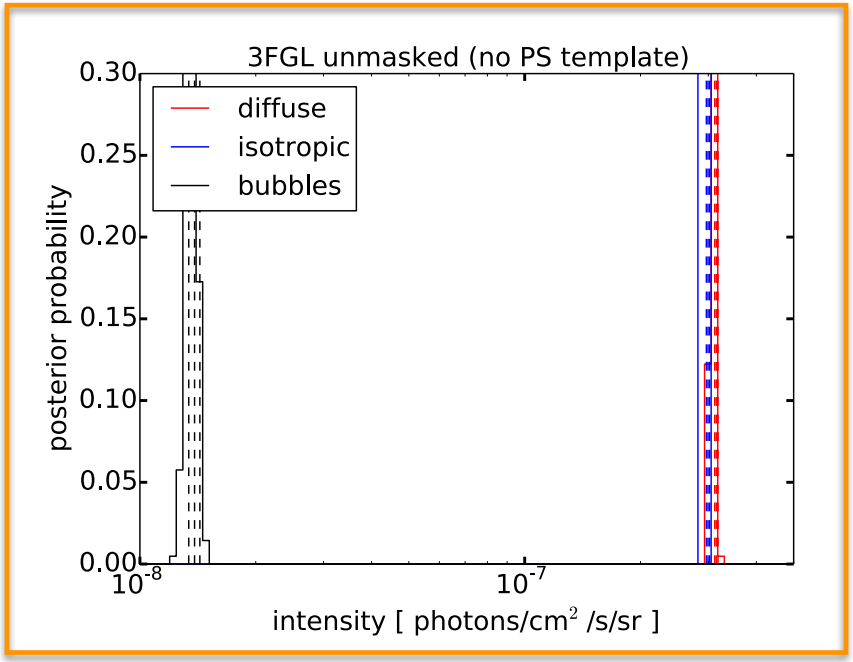


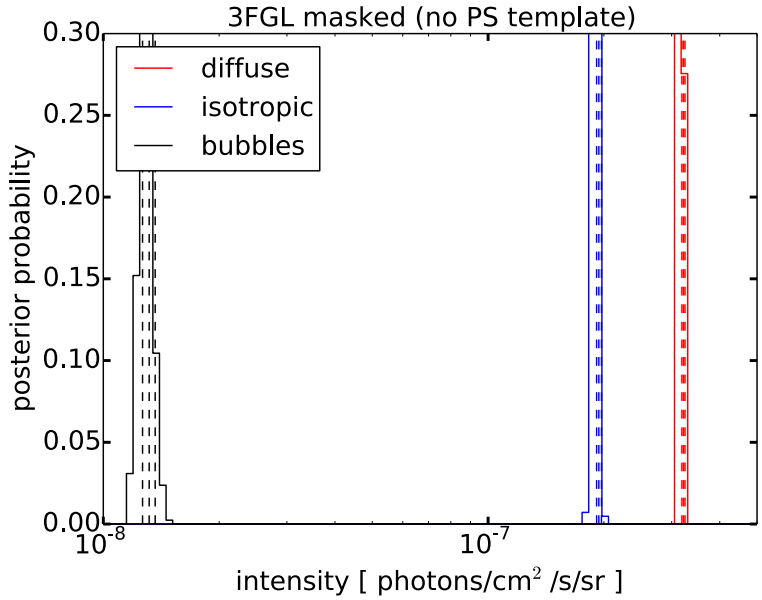


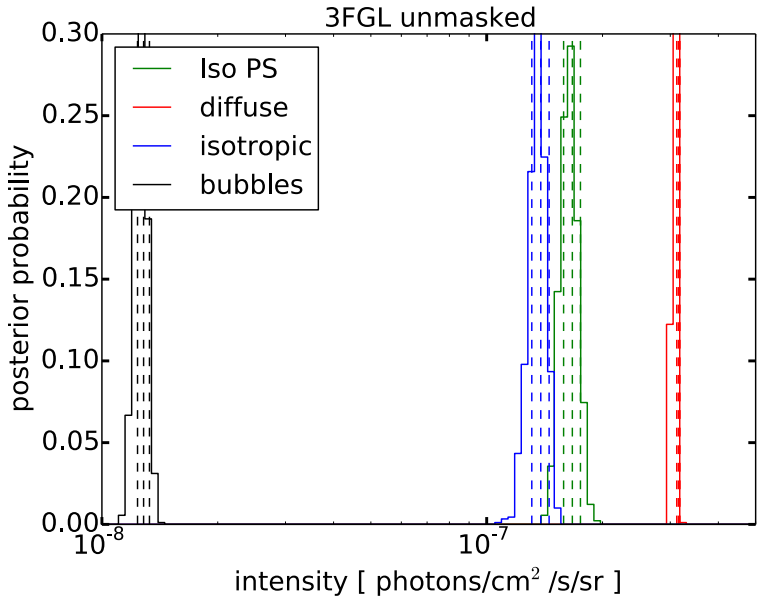


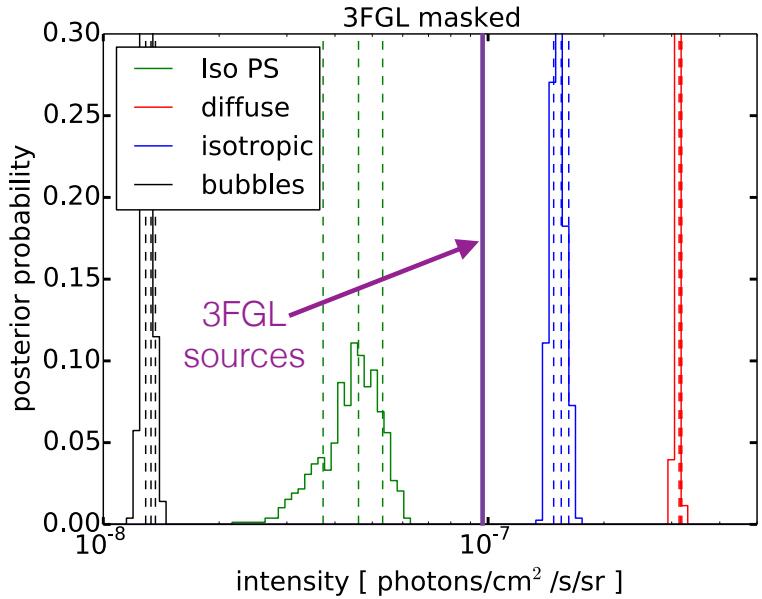


Isotropic point sources: fluxes

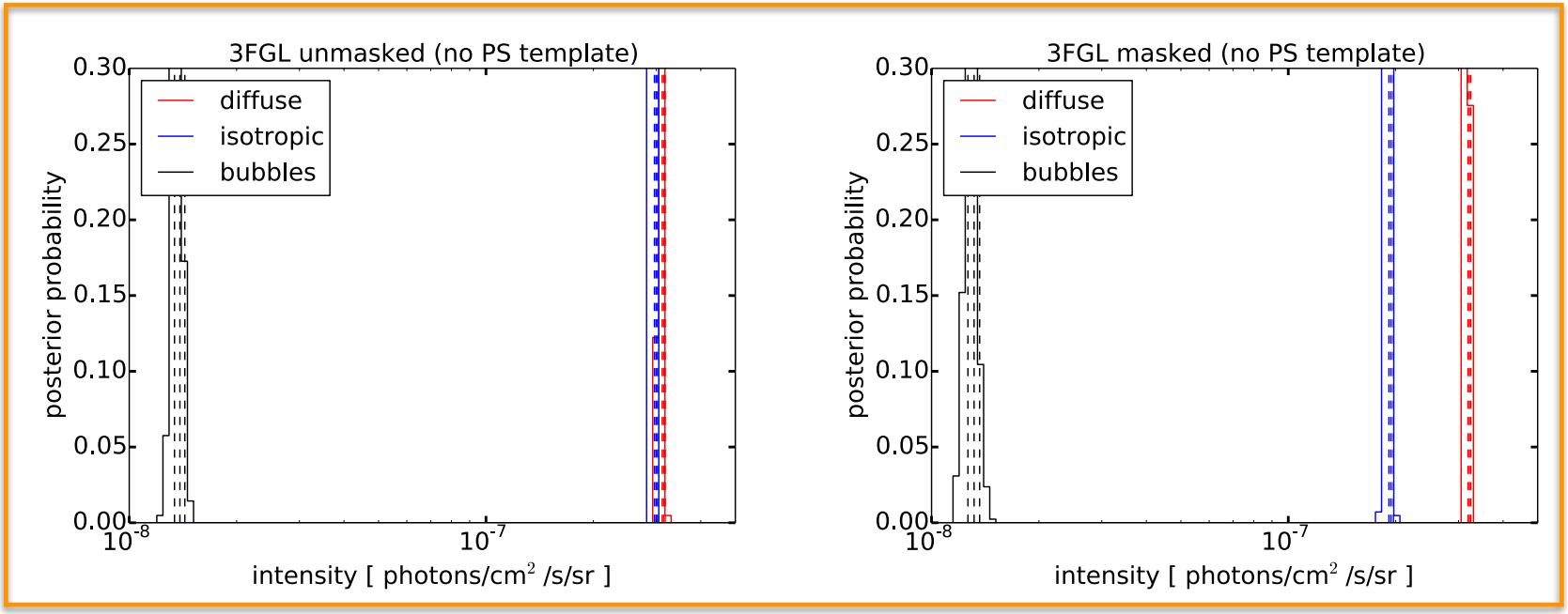




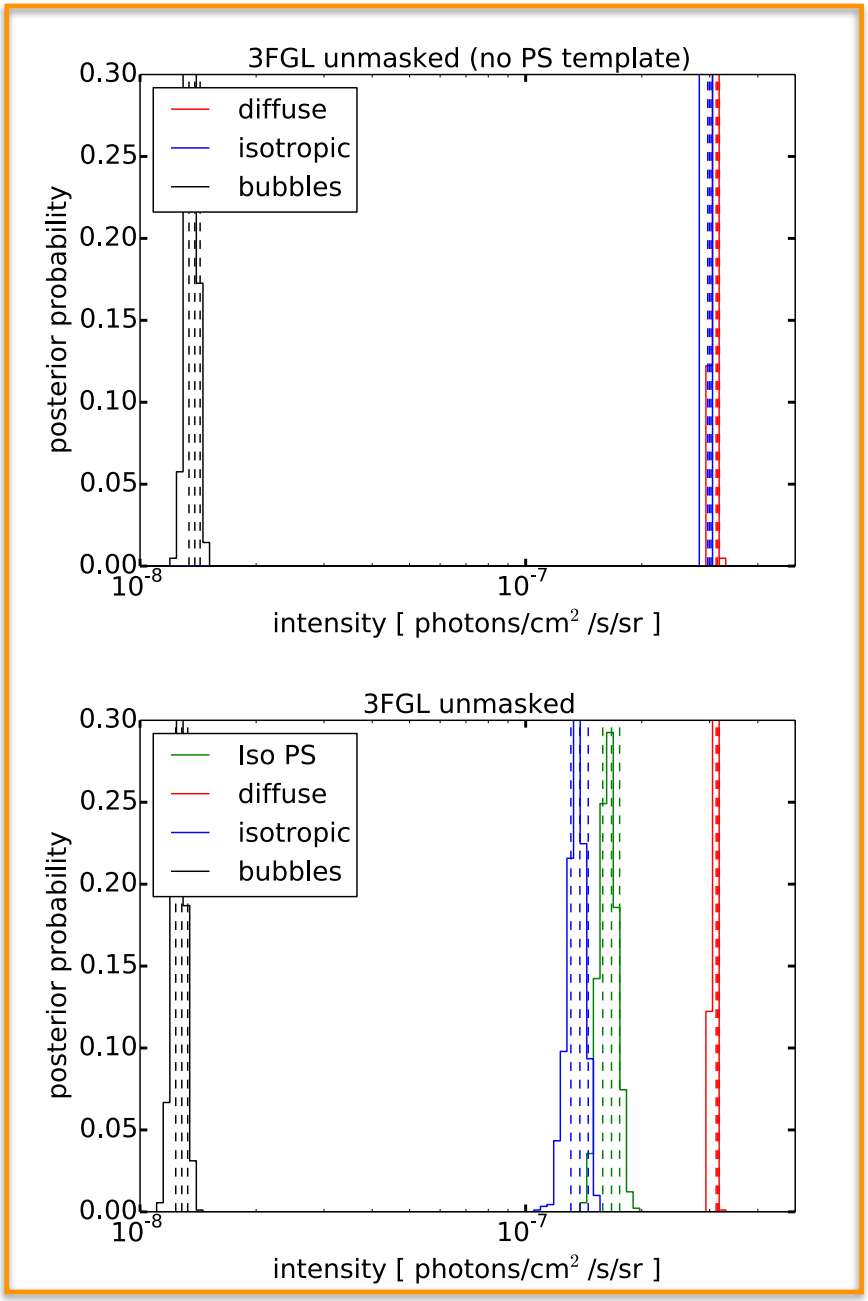


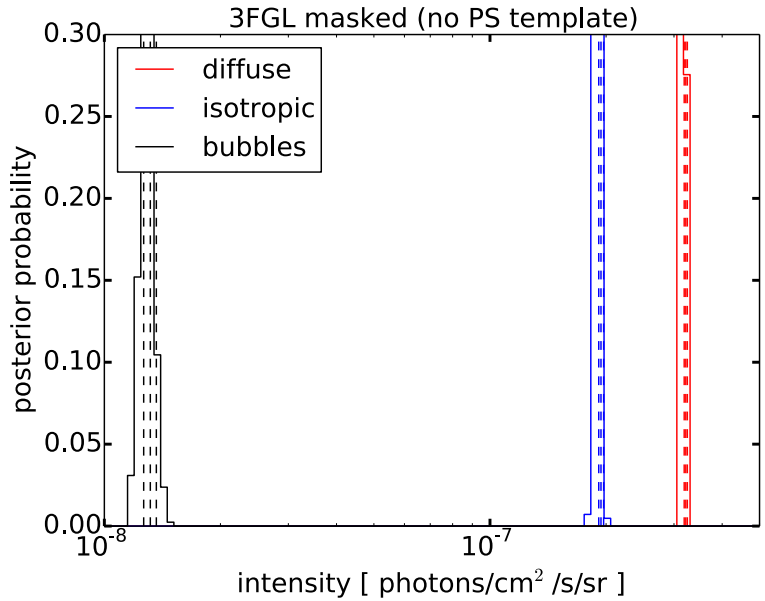


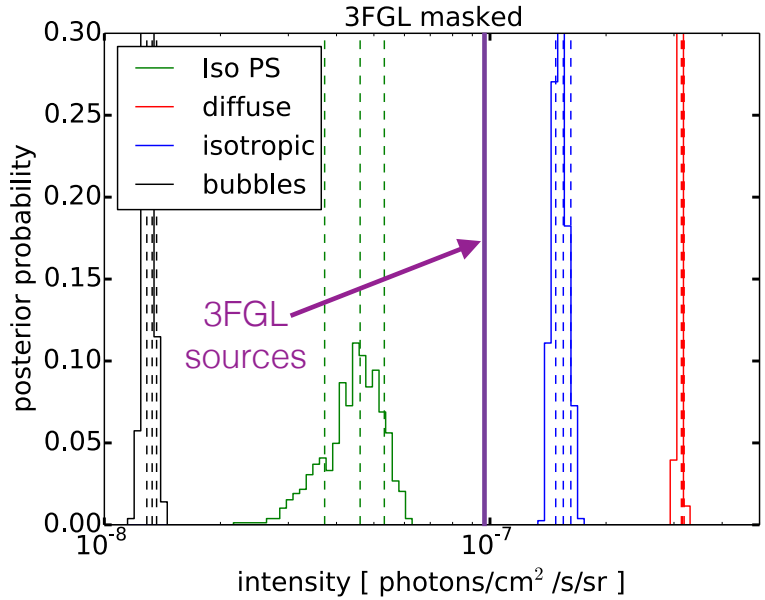
Isotropic point sources: fluxes



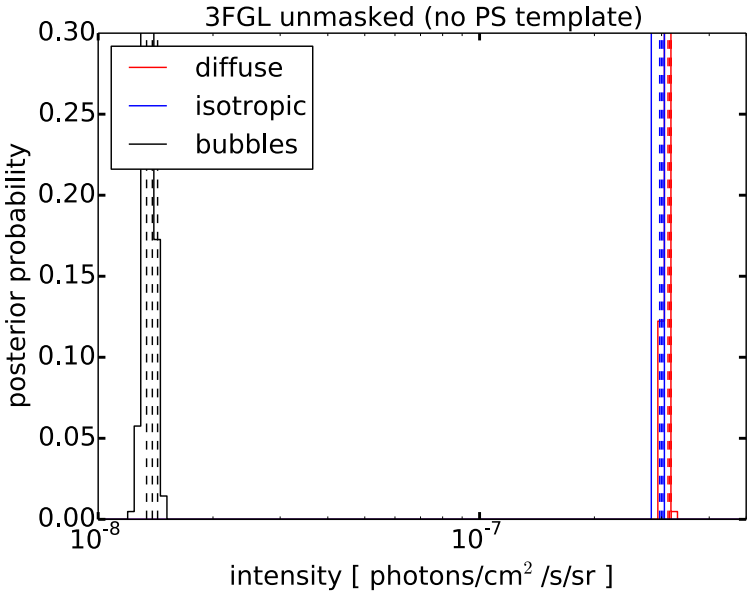
Isotropic point sources: fluxes

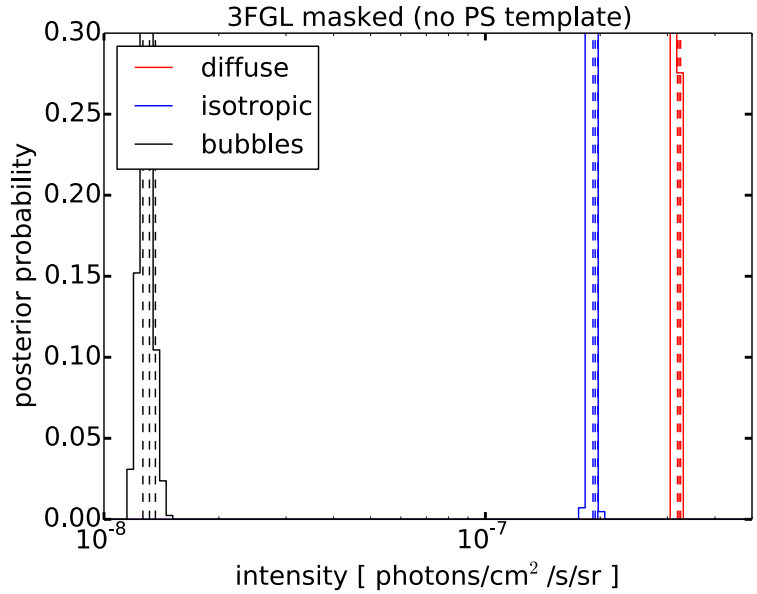


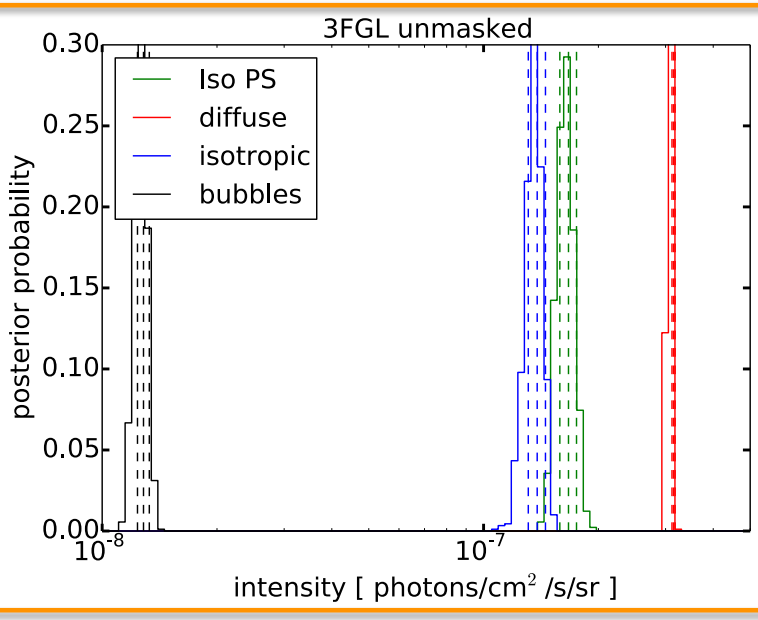


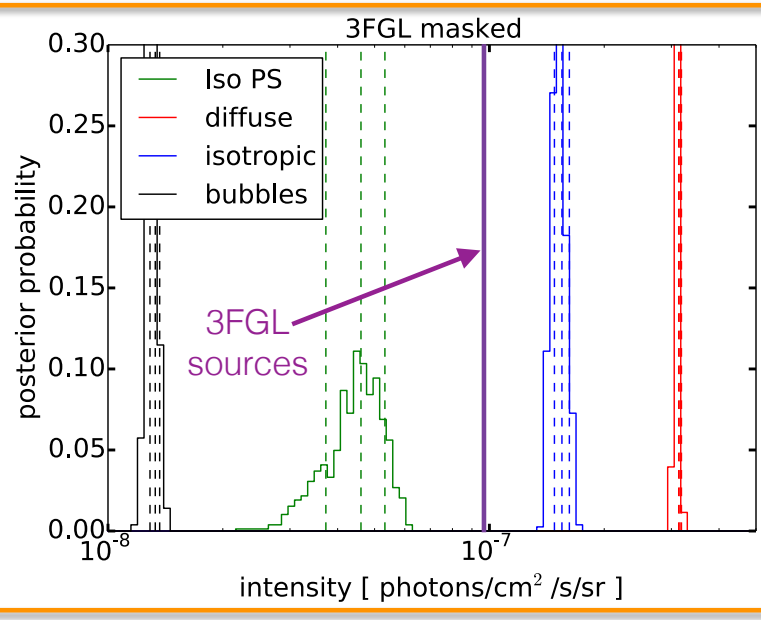


Isotropic point sources: fluxes

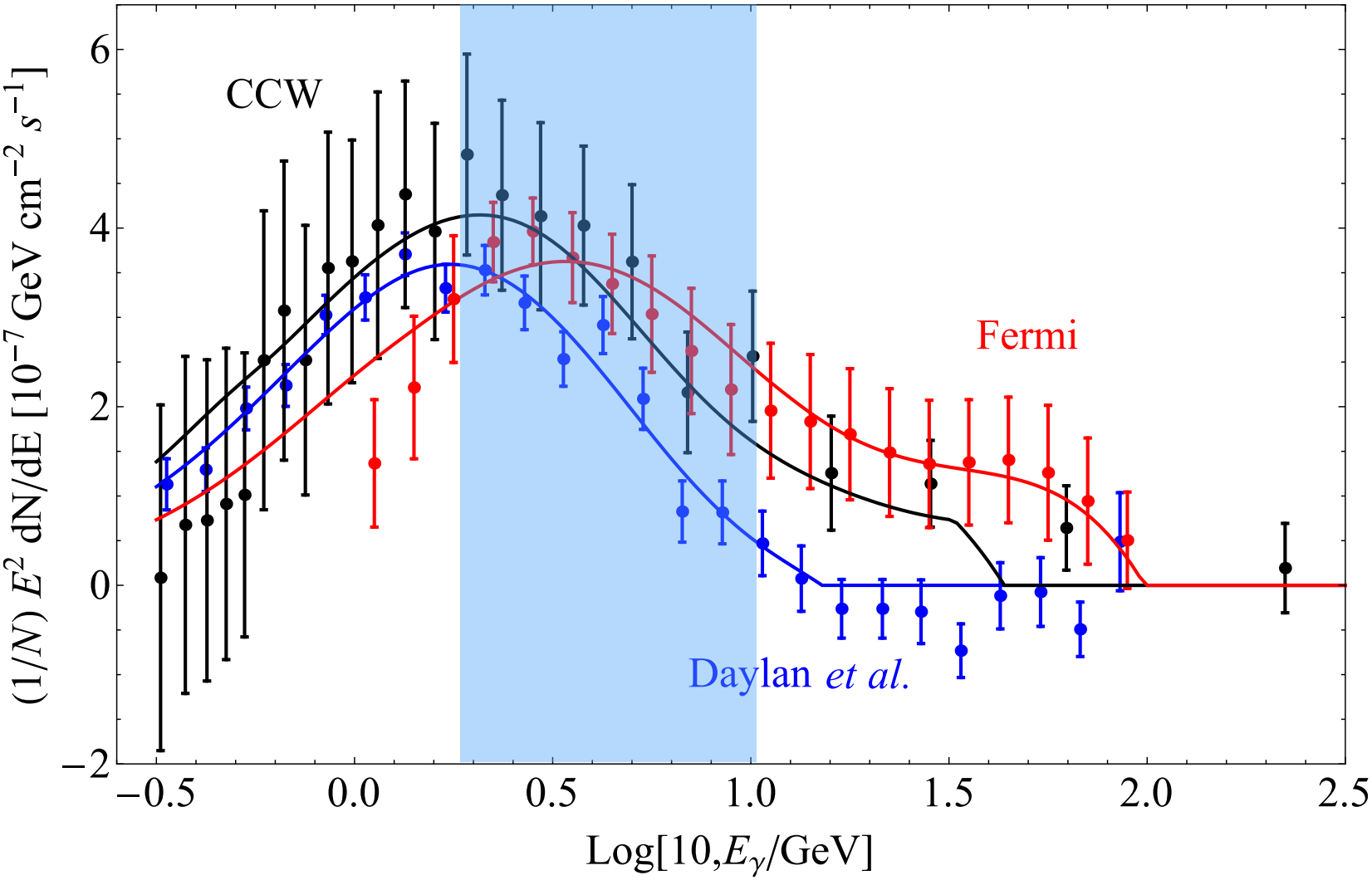








GeV Excess: Spectrum



Photon Statistics: Point Sources

- $p_k^{(p)}$ = probability of finding k photons in pixel p

Photon Statistics: Point Sources

- $p_k^{(p)}$ = probability of finding k photons in pixel p
- Generating function:

$$\mathcal{P}^{(p)}(t) = \sum_{k=0}^{\infty} p_k^{(p)} t^k \quad \leftrightarrow \quad p_k^{(p)} = \frac{1}{k!} \frac{d^k \mathcal{P}^{(p)}}{dt^k}\bigg|_{t=0}$$

Photon Statistics: Point Sources

- $p_k^{(p)}$ = probability of finding k photons in pixel p
- Generating function:

$$\mathcal{P}^{(p)}(t) = \sum_{k=0}^{\infty} p_k^{(p)} t^k \quad \leftrightarrow \quad p_k^{(p)} = \frac{1}{k!} \frac{d^k \mathcal{P}^{(p)}}{dt^k}\bigg|_{t=0}$$

- Point sources:

$$P^{(p)}(t) = \exp\left[\sum_{m=1}^{\infty} x_m^p (t^m - 1)\right], \quad x_m^p = \int dS \, \frac{dN^{(p)}}{dS} \frac{S^m}{m!} e^{-S}$$

Photon Statistics: Point Sources

- $p_k^{(p)}$ = probability of finding k photons in pixel p
- Generating function:

$$\mathcal{P}^{(p)}(t) = \sum_{k=0}^{\infty} p_k^{(p)} t^k \quad \leftrightarrow \quad p_k^{(p)} = \frac{1}{k!} \frac{d^k \mathcal{P}^{(p)}}{dt^k}\bigg|_{t=0}$$

- Point sources:

$$P^{(p)}(t) = \exp\left[\sum_{m=1}^{\infty} x_m^p (t^m - 1)\right], \quad x_m^p = \int dS \, \frac{dN^{(p)}}{dS} \frac{S^m}{m!} e^{-S}$$

  - Source-count: $\dfrac{dN^{(p)}}{dS} = A^p \begin{cases} \left(\dfrac{S}{S_b}\right)^{-n_1}, & S \geq S_b \\ \left(\dfrac{S}{S_b}\right)^{-n_2}, & S < S_b \end{cases}$
  - S is average number of photon counts

Photon Statistics: Point Sources

- $p_k^{(p)}$ = probability of finding k photons in pixel p
- Generating function:

$$\mathcal{P}^{(p)}(t) = \sum_{k=0}^{\infty} p_k^{(p)} t^k \quad \leftrightarrow \quad p_k^{(p)} = \frac{1}{k!} \frac{d^k \mathcal{P}^{(p)}}{dt^k}\bigg|_{t=0}$$

- Point sources:

$$P^{(p)}(t) = \exp\left[\sum_{m=1}^{\infty} x_m^p (t^m - 1)\right], \quad x_m^p = \int dS \, \frac{dN^{(p)}}{dS} \frac{S^m}{m!} e^{-S}$$

  - Source-count: $\dfrac{dN^{(p)}}{dS} = A^p \begin{cases} \left(\dfrac{S}{S_b}\right)^{-n_1}, & S \geq S_b \\ \left(\dfrac{S}{S_b}\right)^{-n_2}, & S < S_b \end{cases}$
  - S is average number of photon counts
  - A^p follow a spatial template

Photon Statistics: Point Sources

- $p_k^{(p)}$ = probability of finding k photons in pixel p
- Generating function:

$$\mathcal{P}^{(p)}(t) = \sum_{k=0}^{\infty} p_k^{(p)} t^k \quad \leftrightarrow \quad p_k^{(p)} = \frac{1}{k!} \frac{d^k \mathcal{P}^{(p)}}{dt^k}\bigg|_{t=0}$$

- Point sources:

$$P^{(p)}(t) = \exp\left[\sum_{m=1}^{\infty} x_m^p (t^m - 1)\right], \quad x_m^p = \int dS \, \frac{dN^{(p)}}{dS} \frac{S^m}{m!} e^{-S}$$

  - Source-count: $\dfrac{dN^{(p)}}{dS} = A^p \begin{cases} \left(\dfrac{S}{S_b}\right)^{-n_1}, & S \geq S_b \\ \left(\dfrac{S}{S_b}\right)^{-n_2}, & S < S_b \end{cases}$
  - S is average number of photon counts
  - A^p follow a spatial template