

Unveiling the Gamma-ray Source Count distribution below the Fermi Detection Limit with Photon Statistics

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Statistical Image Analysis

- employed for decades in radio and X-ray astronomy; statistical analysis of intensity maps or photon counts maps
—> **source-count distributions (dN/dS), population properties, correlation studies**
- **1 dimension** —> $P(D)$ distribution or **1-point PDF (1p-PDF)**

Aim: adapt method to gamma-ray band, using Fermi-LAT data

- measure **dN/dS** with high accuracy
(complementary to catalogs resolving sources individually)
- **extend sensitivity** for dN/dS below 3FGL detection limit
- **decompose** the total **gamma-ray sky**:
(a) point sources, (b) Galactic foreground,
(c) isotropic diffuse background, (d) additional components (?)

- first application: Malyshev & Hogg (2011)
—> **developed theoretical framework, proof of principle**

see also

Lee et al., 2009; Dodelson et al., 2009;
Baxter et al., 2010; Massari et al., 2015

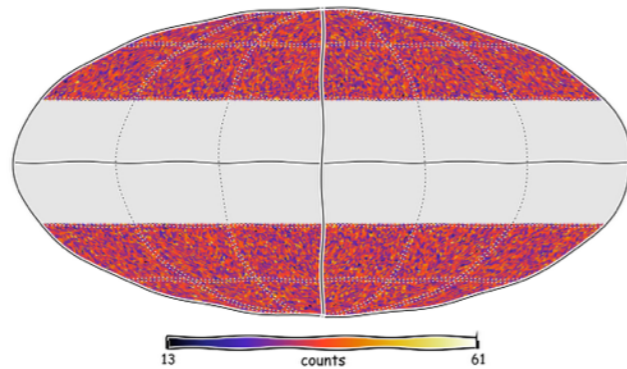
application to Galactic Center excess:
Lee et al., 2015 (Talk on Friday)

1p-PDF Analysis (simple setup)

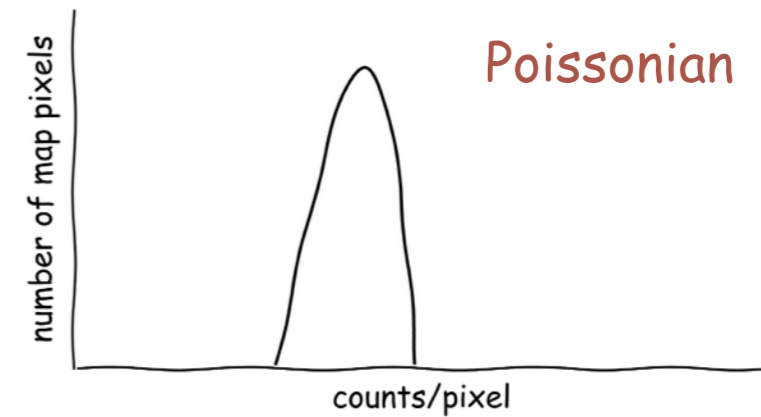
Idea: consider statistics of photon counts per pixel

Examples:

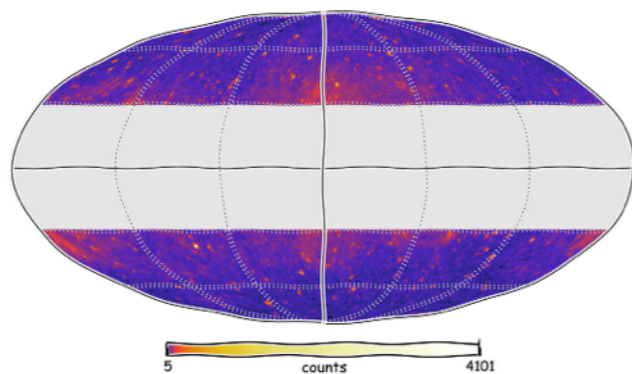
(A) diffuse isotropic background



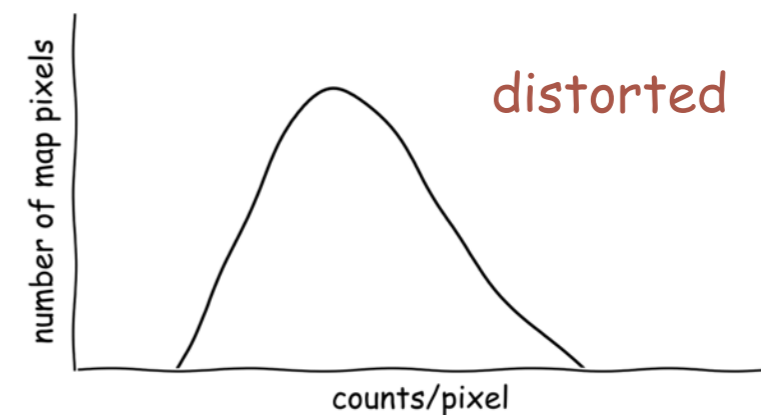
1p-PDF →



(B) adding point sources, Galactic foreground, ...



1p-PDF →



1p-PDF Analysis

modeling of 1p-PDF: probability generating functions

$$\mathcal{P}(t) = \sum_{k=0}^{\infty} p_k t^k,$$

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



see M&H '11
for details

$\mathcal{P}(t)$: generating functional

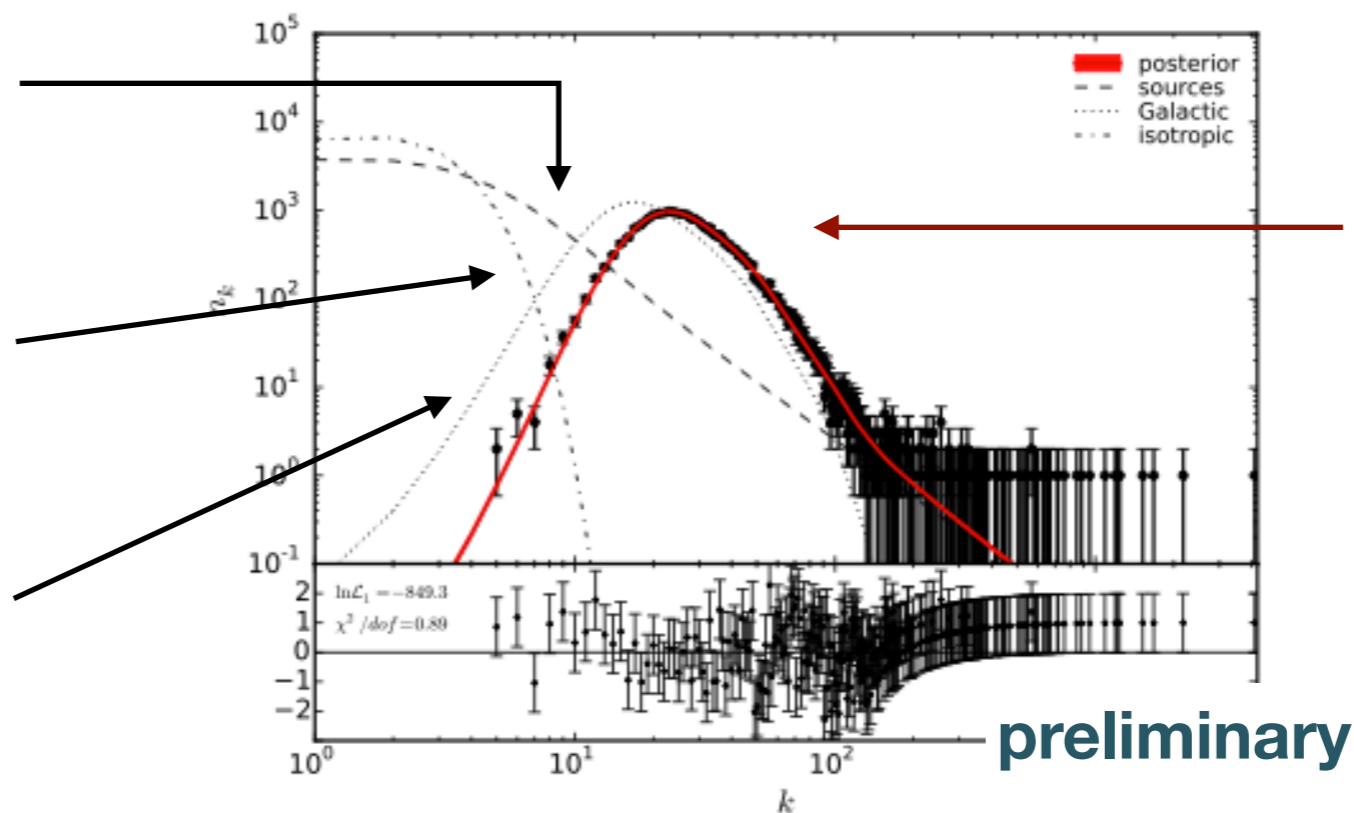
p_k : discrete probability distribution

individual contributions:

point sources
(dN/dS distribution)

diffuse isotropic
background (F_{iso})

Galactic foreground
template (A_{gal})



**combined
PDF**

preliminary

(c) 1pPDF, $N_b = 2$, posterior

Analysis Procedure

- **measured 1p-PDF can be fit with a given model**
- **we aimed at improving the simple 1p-PDF analysis setup:**
 - dN/dS distribution modeled with a **multiply broken power law (MBPL)**
 - **correction for exposure inhomogeneities**
 - **correction for PSF effects** using PSF derived from data (gtpsfsf)
 - **correction for point-source spectral indices** (assuming an index of 2.4)
 - **Galactic foreground** modeled using **Fermi-LAT template** (gll_iem_v05_rev1.fit); overall **normalization** kept as a **free** fit parameter (A_{gal})
 - template spectrum used for **isotropic background**; **normalization** kept as a **free** parameter (F_{iso})

Data Fitting

two ways of defining the likelihood:

- **simple 1p-PDF**, assuming Poisson statistics (see M&H '11)

$$\mathcal{L}_1(\Theta) = \prod_{k=0}^{k_{\max}} \frac{\nu_k(\Theta)^{n_k}}{n_k!} e^{-\nu_k(\Theta)}$$

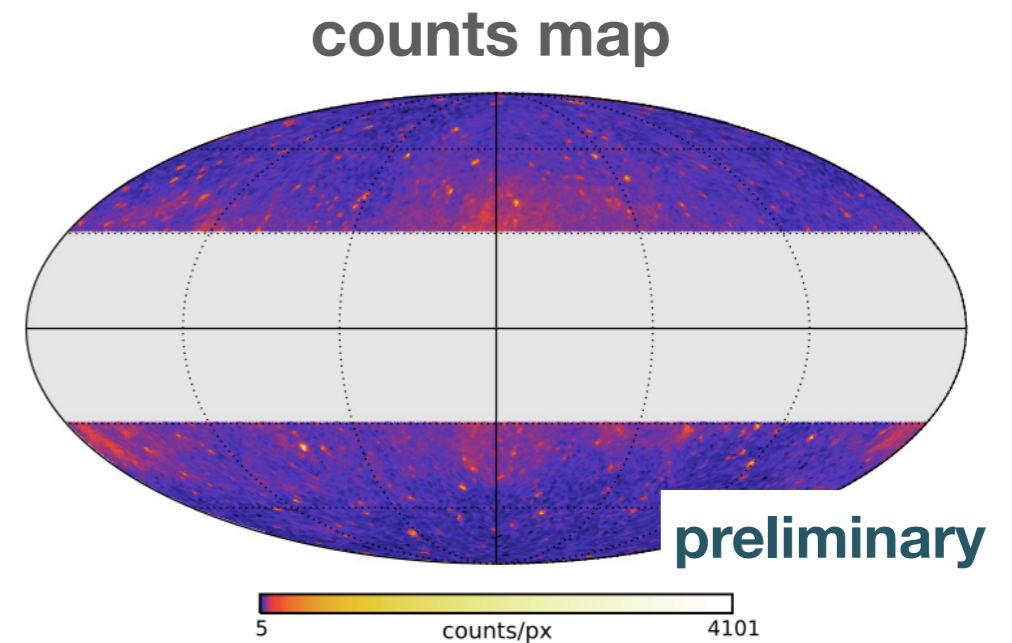
- **pixel dependent** (allows full exploitation of spatial templates)

$$\mathcal{L}_2(\Theta) = \prod_{p=1}^{N_{\text{pix}}} P(k_p)$$

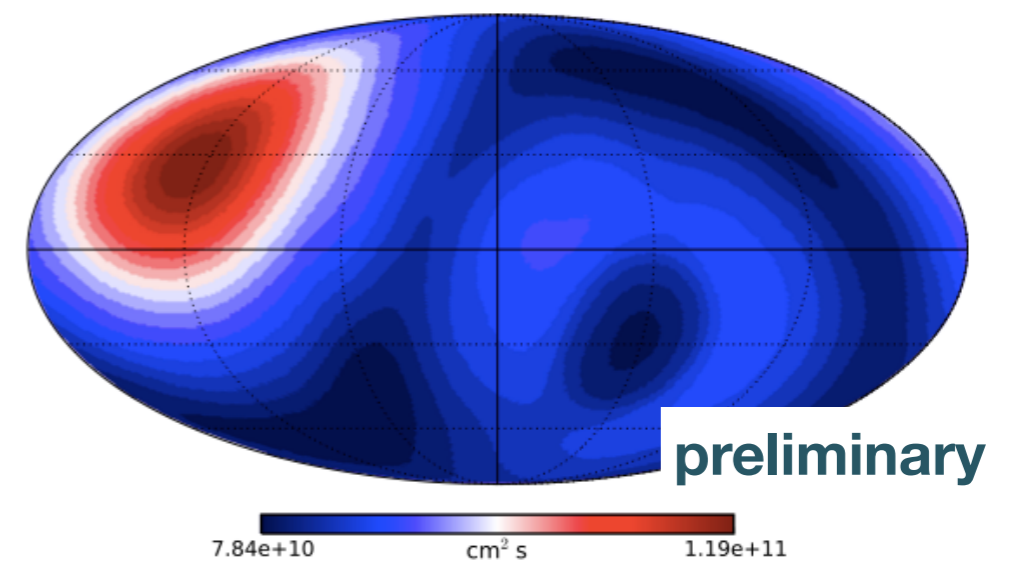
- sampling: **MultiNest** [Feroz & Hobson, 2008]
- parameter estimation: **Bayesian inference, profile likelihood**
- all results derived using pixel-dependent **L₂-likelihood**

Fermi-LAT Data

- data set: P7REP
- observation time: 6 years
- event selection:
 - CLEAN, front converted
 - standard quality cuts
 - zenith-angle cut: 90 deg
 - **1 GeV – 10 GeV**
- high Galactic latitudes:
 $|b| > 30$ deg
- HEALPix grid, order 6



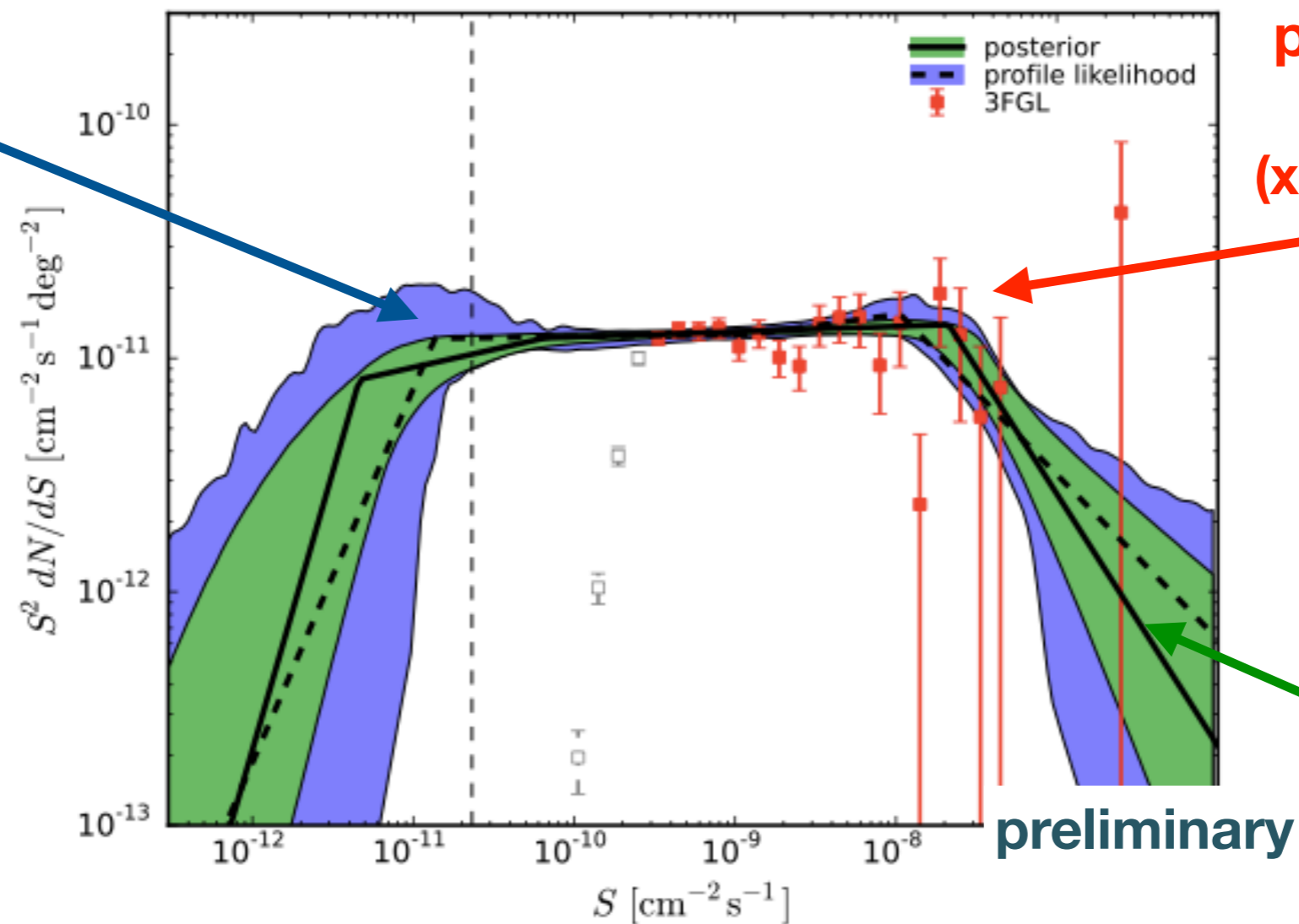
exposure in 20 iso-contours



Results - MBPL Approach

- **MBPL approach:**
fit of a pure multiply broken PL; 3 free breaks

profile likelihood



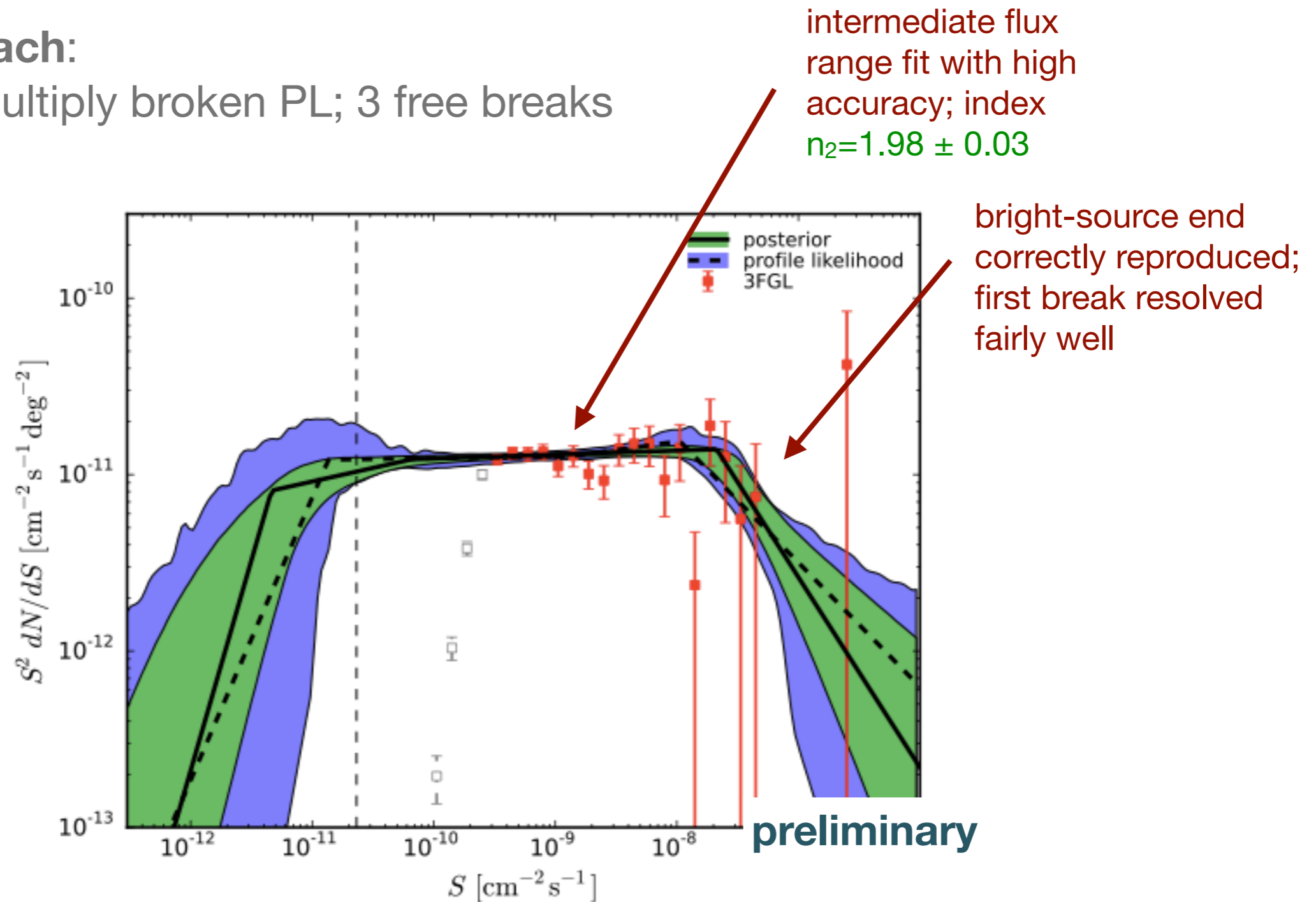
points derived from 3FGL (x-check, not fit!)

Bayesian posterior

(a) MBPL, $N_b = 3$

Results - MBPL Approach

- **MBPL approach:**
fit of a pure multiply broken PL; 3 free breaks



(a) MBPL, $N_b = 3$

Results - MBPL Approach

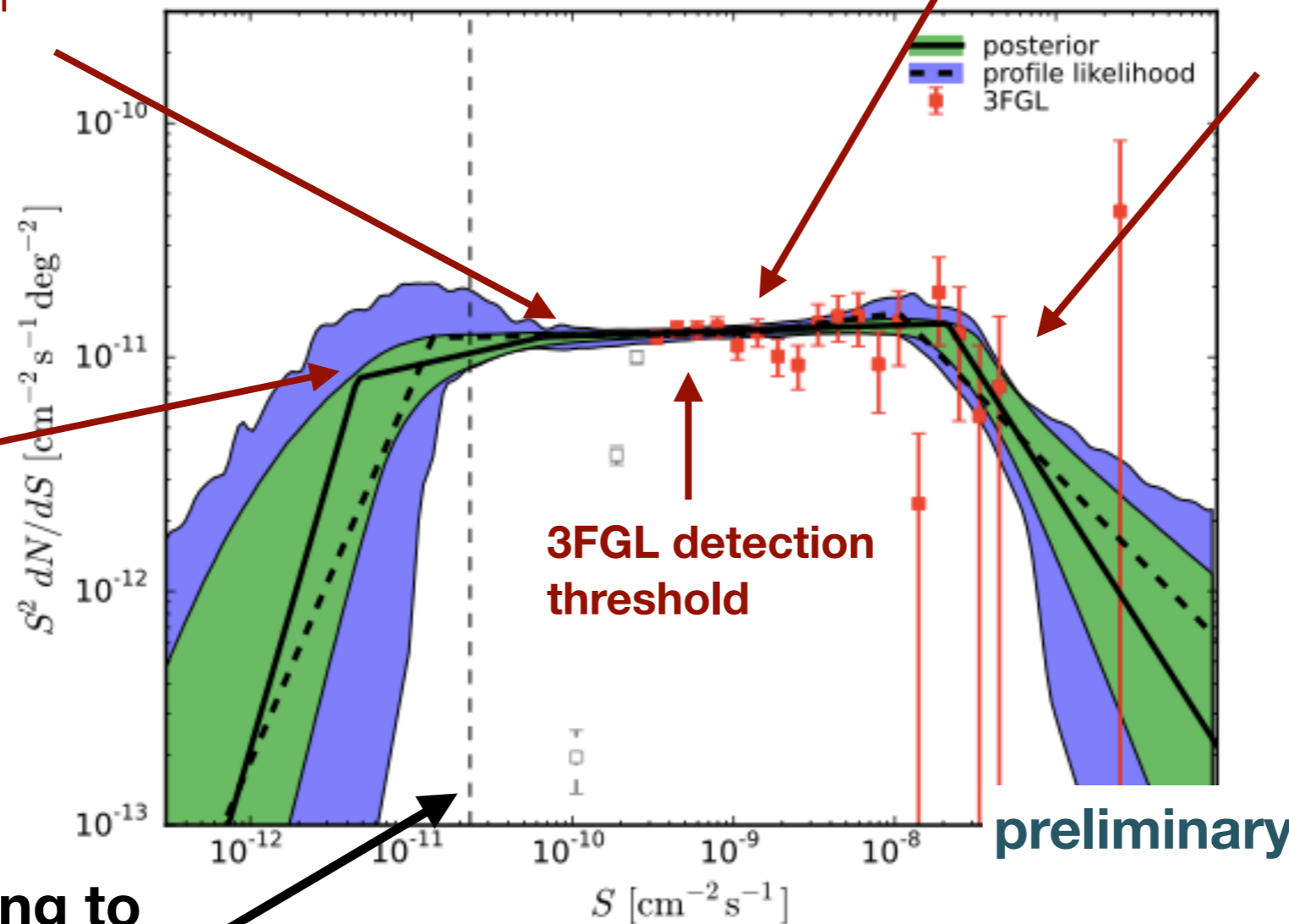
- **MBPL approach:**
fit of a pure multiply broken PL; 3 free breaks

fit prefers a flat behavior for unresolved sources; index $n_3 = 1.85^{+0.18}_{-0.25}$

intermediate flux range fit with high accuracy; index $n_2 = 1.98 \pm 0.03$

bright-source end correctly reproduced; first break resolved fairly well

sensitivity cutoff



flux corresponding to 2 photons per pixel

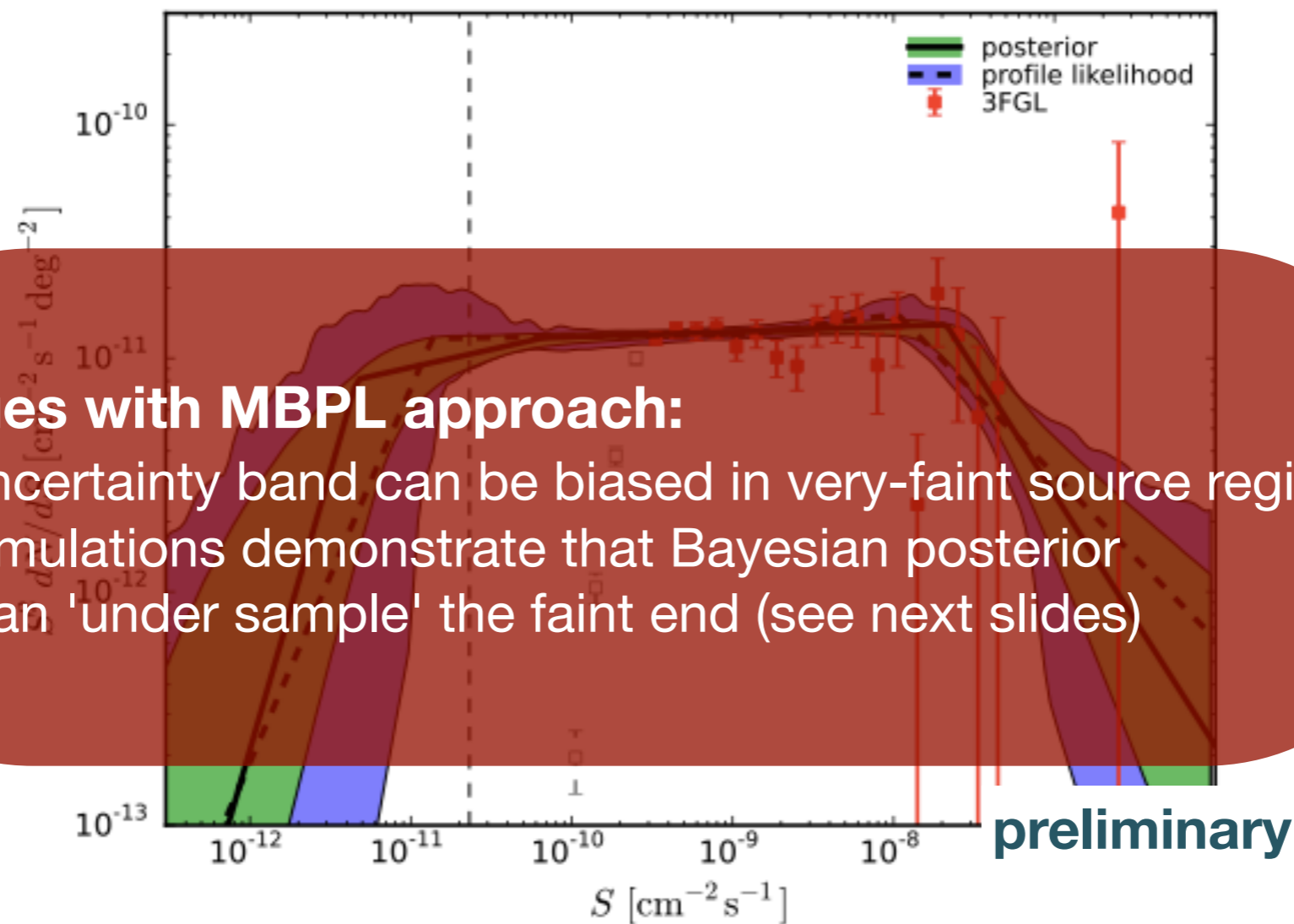
(a) MBPL, $N_b = 3$

Results - MBPL Approach

- **MBPL approach:**
fit of a pure multiply broken PL; 3 free breaks

issues with MBPL approach:

- uncertainty band can be biased in very-faint source region
- simulations demonstrate that Bayesian posterior can 'under sample' the faint end (see next slides)

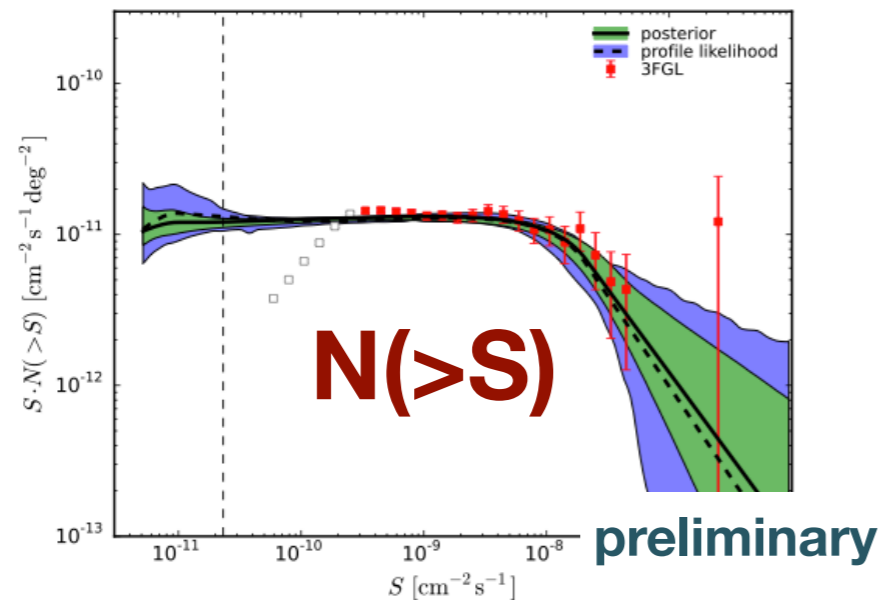


(a) MBPL, $N_b = 3$

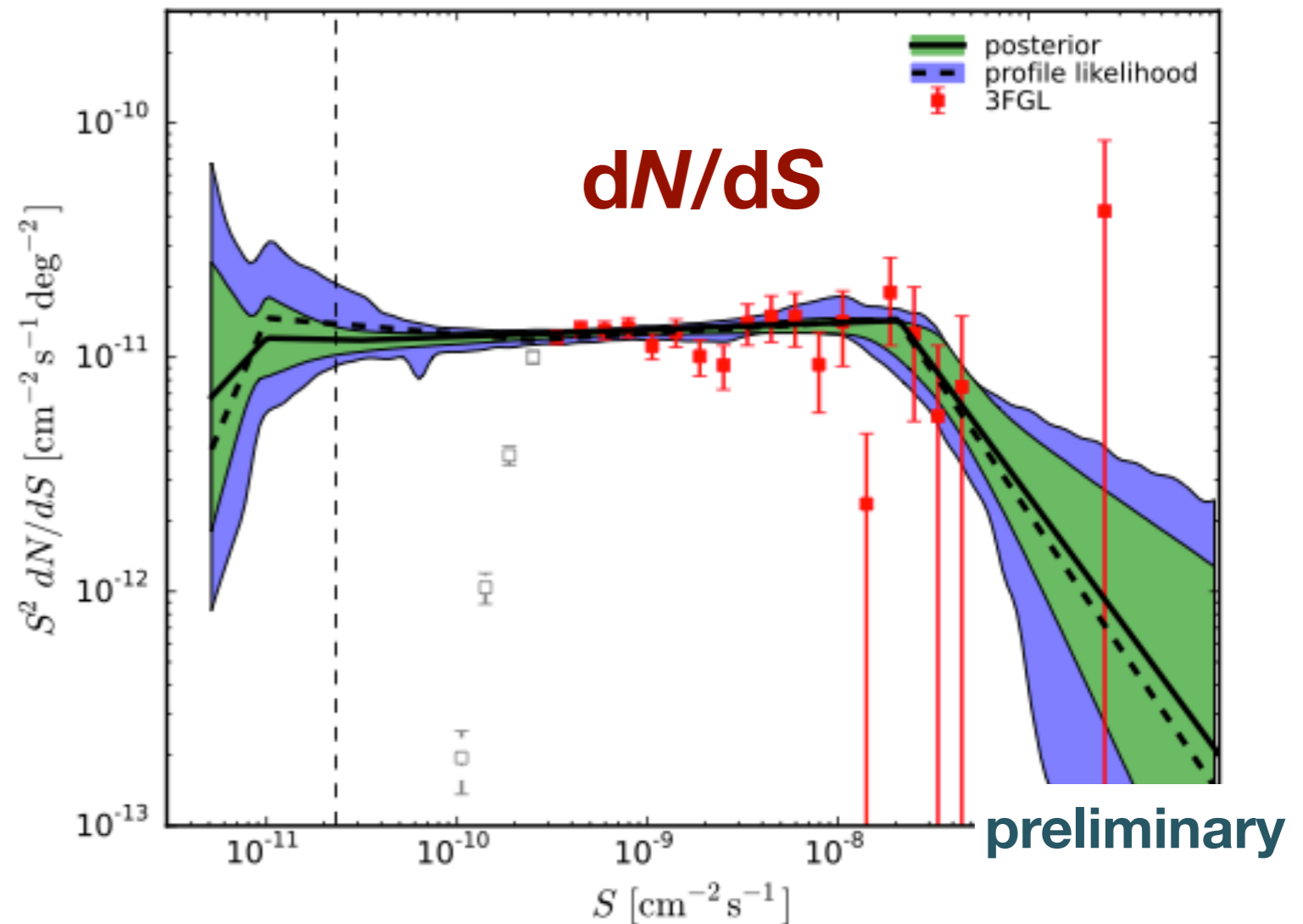
Results - Hybrid Approach

improve MBPL fit by placing a **fixed node** in the faint end
(dN/dS is assumed zero below last node)

- confirms MBPL results
- solves possible issues with uncertainty bands

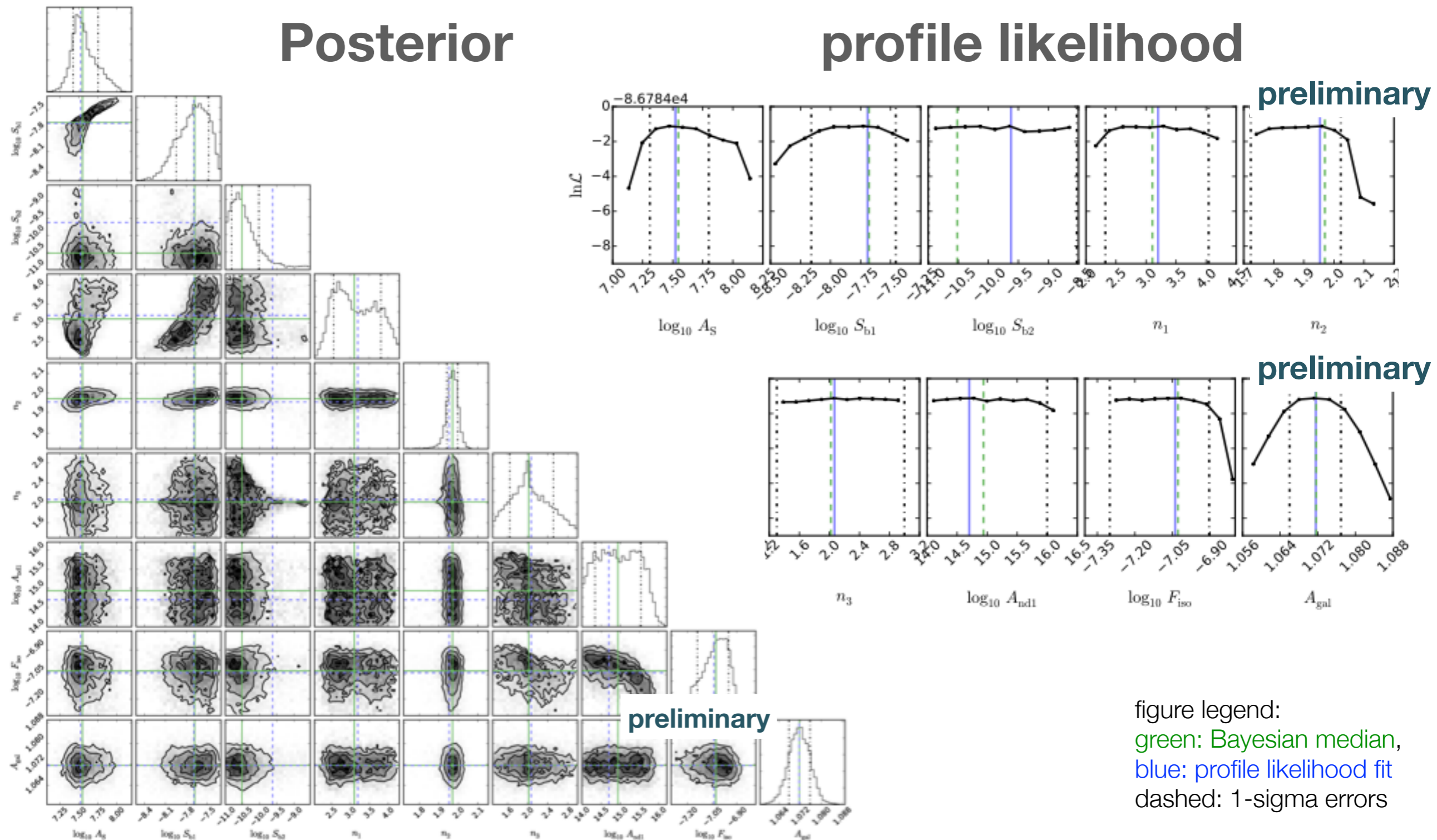


(d) $N(>S)$, hybrid, $N_b = 2$



(c) dN/dS , hybrid, $N_b = 2$

Hybrid Approach - Sampling



Composition of the Gamma-ray Sky

- **composition of the high-latitude gamma-ray sky can be measured** by integrating dN/dS and the Galactic foreground fit
- integral flux from **point sources**
 $F_{ps} = (3.9 \pm 0.3) 10^{-7} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$,
corresponding to **(26±2)%** of the total flux
- integral **diffuse isotropic background**
 $F_{iso} = (0.9 \pm 0.2) 10^{-7} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$,
corresponding to **(6±2)%** of the total flux
- rest: Galactic foreground

profile likelihood for
integral point-source flux

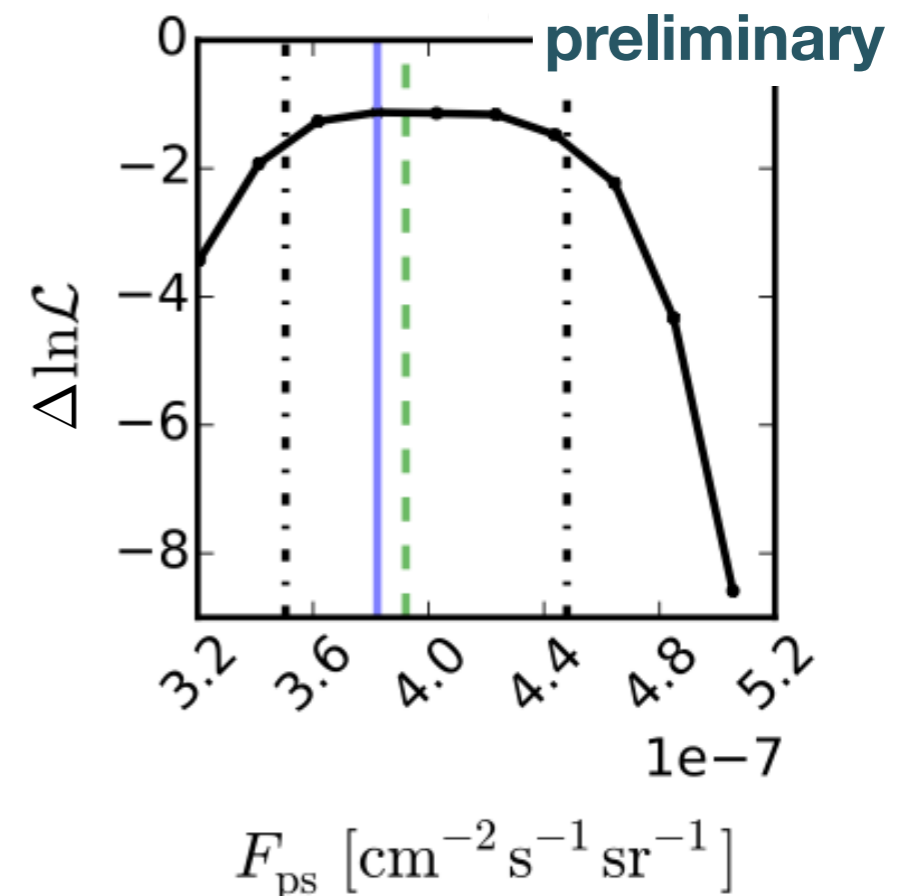


figure legend:

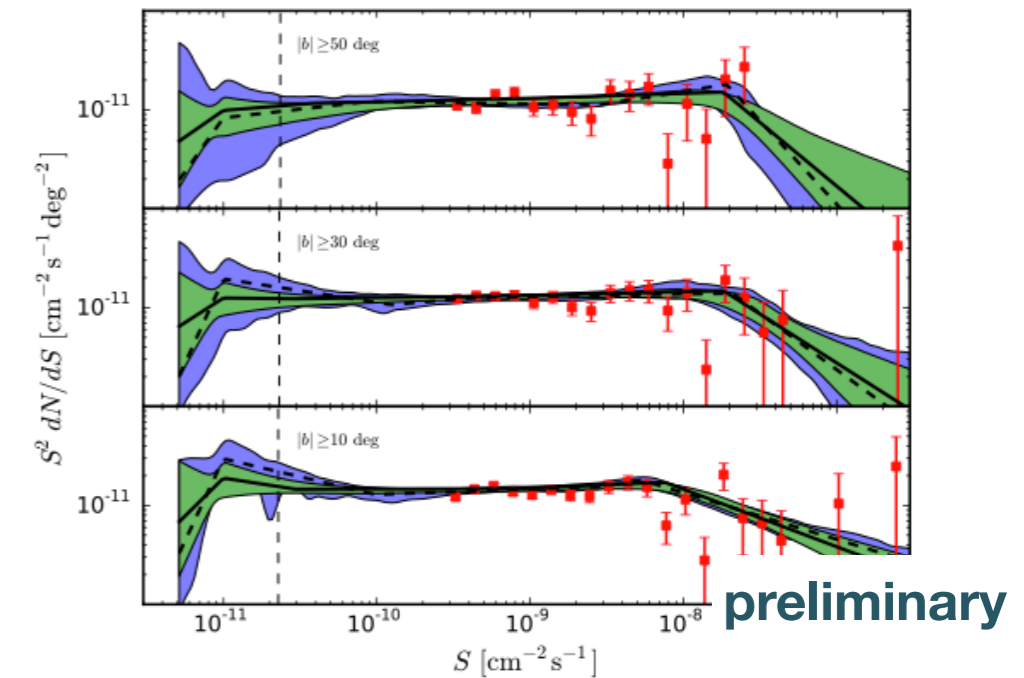
green: Bayesian median, blue: profile likelihood fit

dashed: 1-sigma errors ($\delta \ln L = 0.5$)

Systematics/Validation

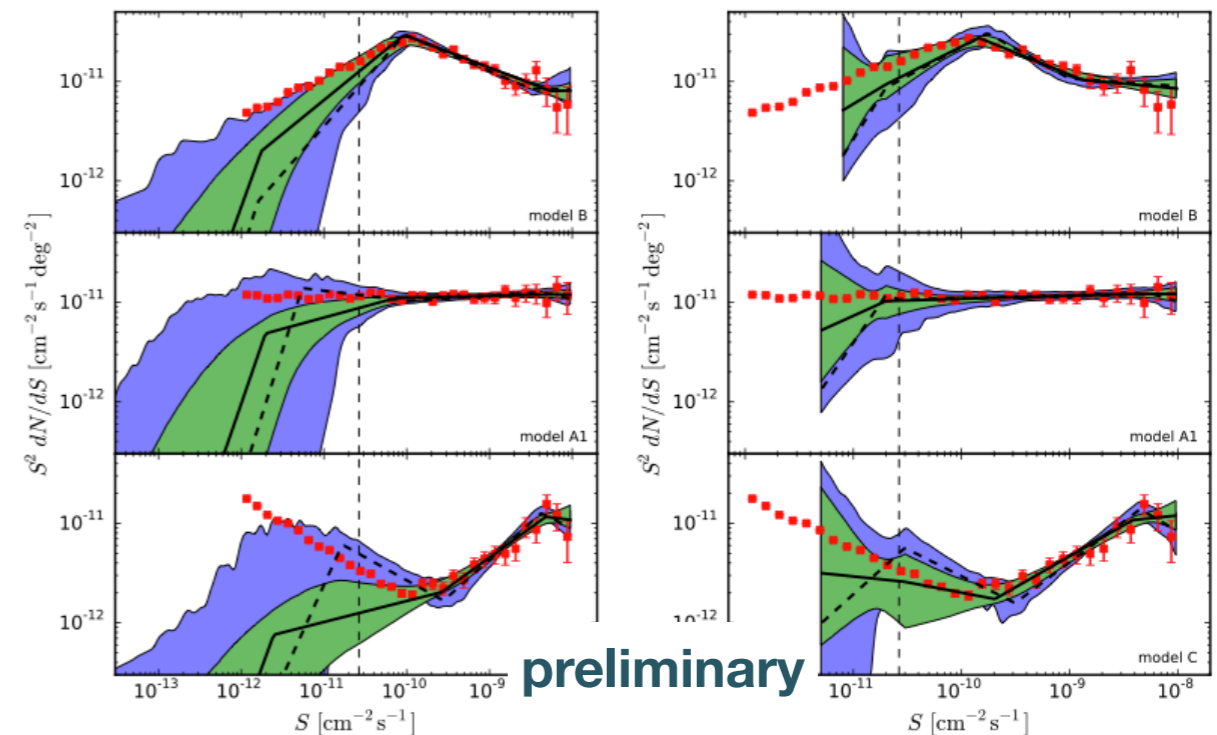
- analysis underwent several **systematic checks**:
 - masking bright point sources
 - pixel size
 - different b -cuts and Galactic foreground templates
 - point-source spectral index distribution
- validation with Monte-Carlo simulations (gtobssim)

Galactic latitude cuts

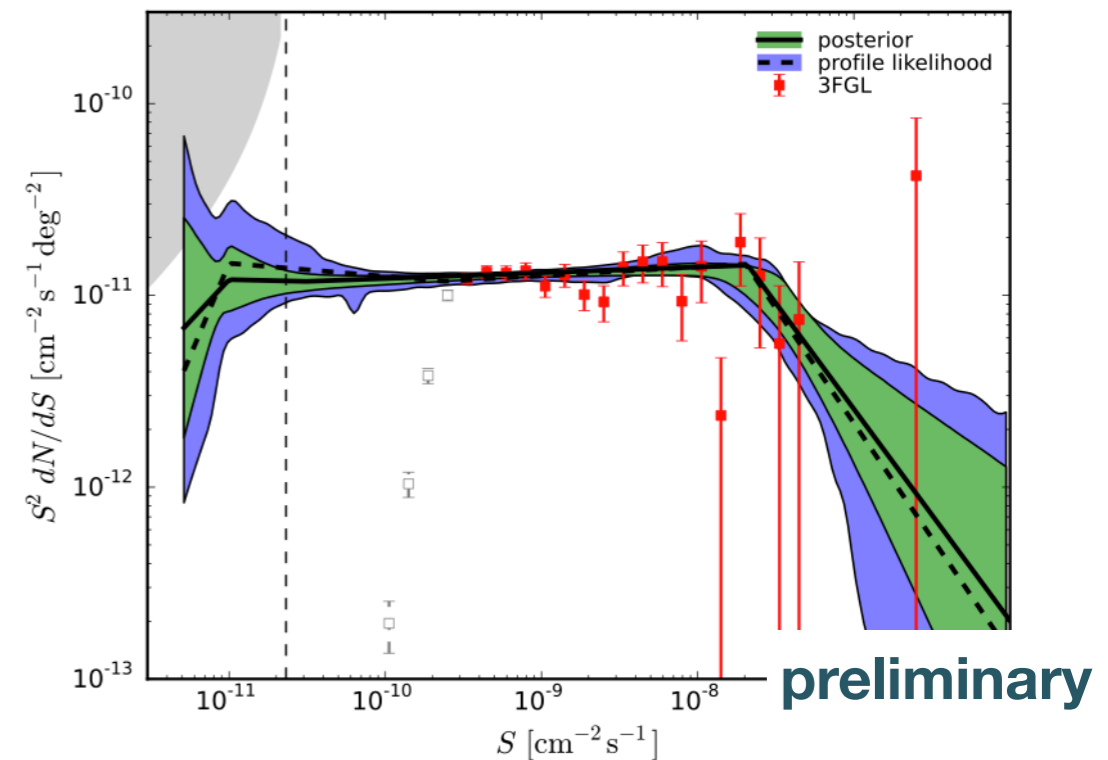


MBPL

Hybrid



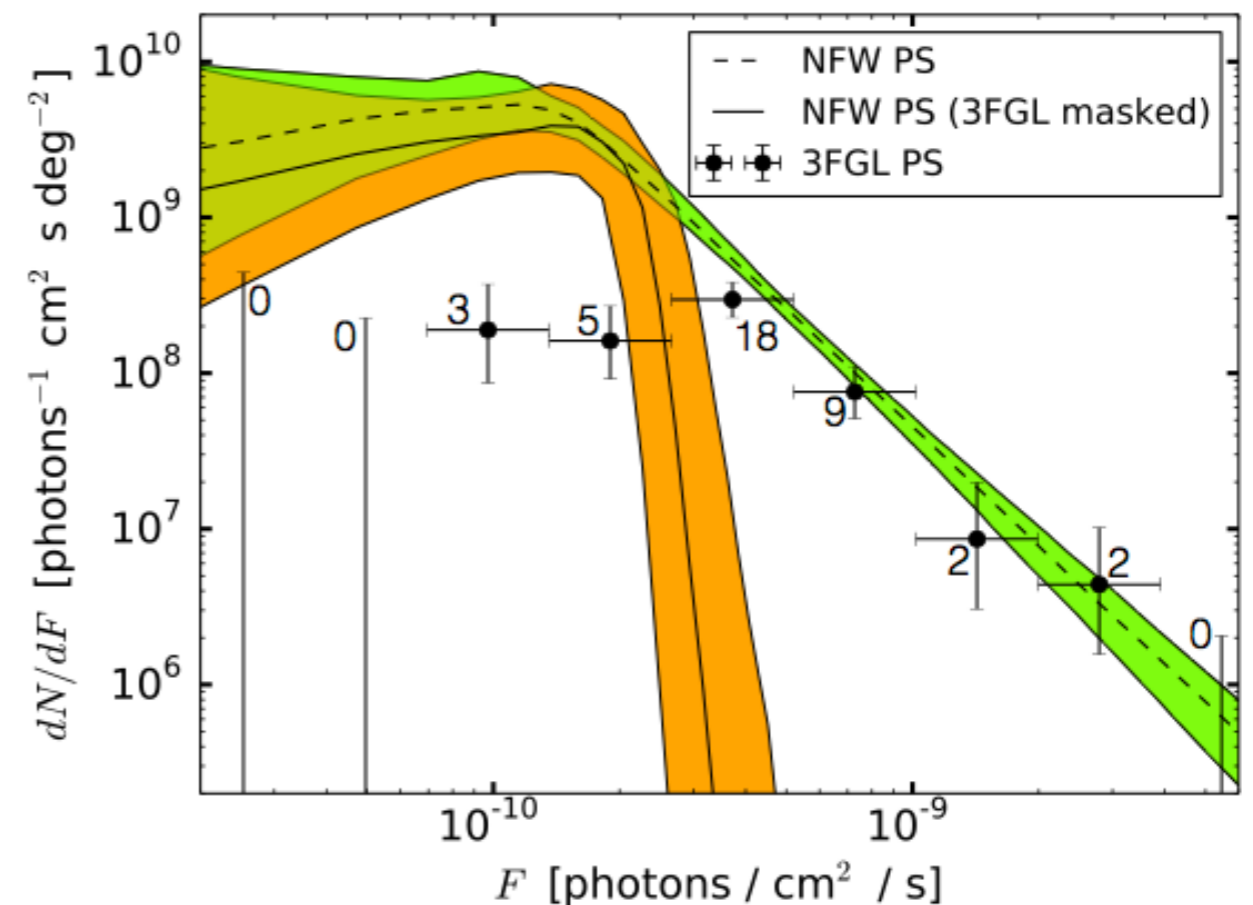
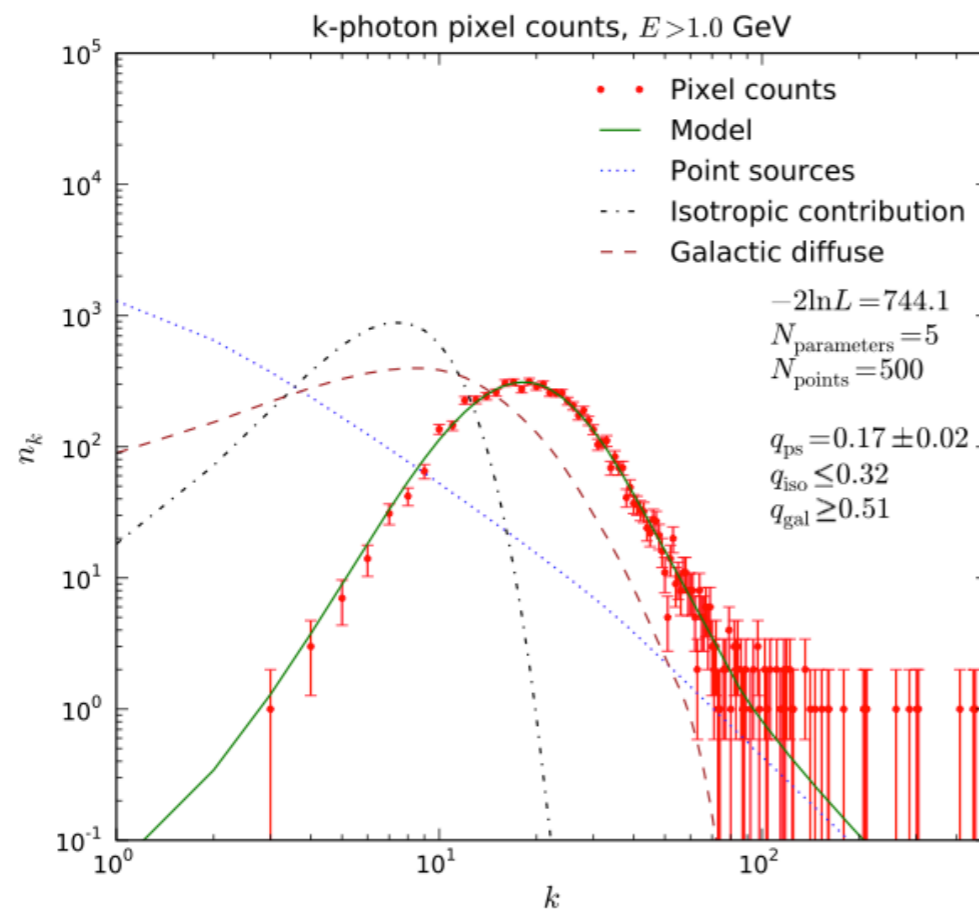
- we employed pixel-count statistics to measure the source-count distribution dN/dS and the composition of the gamma-ray sky at high galactic latitudes (6yr Fermi-LAT data)
- new method developed including spatial template fitting (non-Poissonian), a dN/dS model with multiple breaks, PSF correction, and exposure correction
- dN/dS distribution stays almost flat in the region of unresolved sources
- new measurement of the composition of the gamma-ray sky



Backup

1p-PDF Analysis of Gamma-ray Data

- Fermi-LAT data first considered by Malyshev & Hogg (2011)
 —> **development of theoretical framework, proof of principle**
- Lee et al. (2015) recently applied the method to the Galactic Center region
 —> gamma-ray excess consistent with undetected PS



see also:

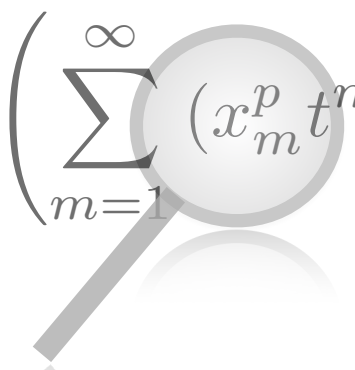
Lee et al., 2009; Dodelson et al., 2009; Baxter et al., 2010;
 Massari et al., 2015; Lee et al., 2015

1p-PDF modeling

modeling of 1p-PDF: probability generating functions

$$\mathcal{P}(t) = \sum_{k=0}^{\infty} p_k t^k, \quad p_k = \frac{1}{k!} \left. \frac{d^k \mathcal{P}(t)}{dt^k} \right|_{t=0}$$

modeling (M&H '11) \longrightarrow

$$\sum_{k=0}^{\infty} p_k t^k = 1/N_{\text{pix}} \sum_{p=1}^{N_{\text{pix}}} \exp \left(\sum_{m=1}^{\infty} (x_m^p t^m - x_m^p) \right)$$


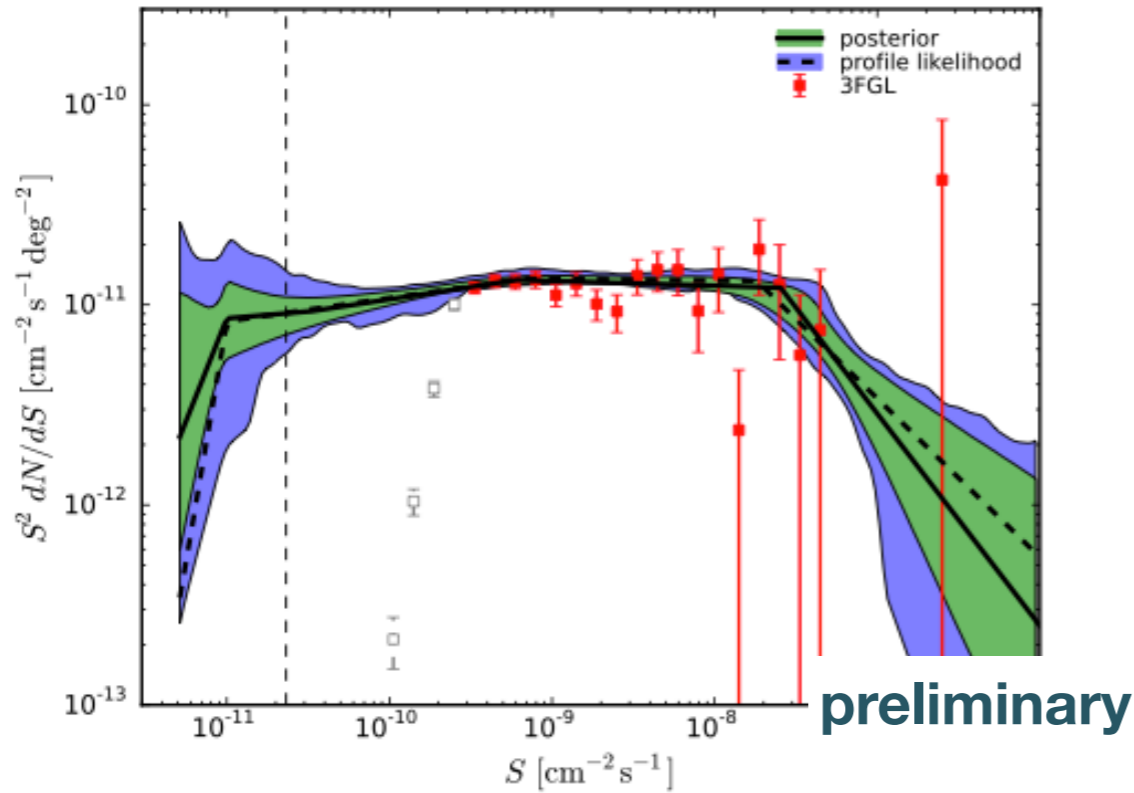
(expected) number of sources contributing m photons to pixel p ;
contributions

- (a) point sources (dN/dS distribution),
- (b) Galactic foreground template (A_{gal})
- (c) diffuse isotropic background (F_{iso})
- (d) ...

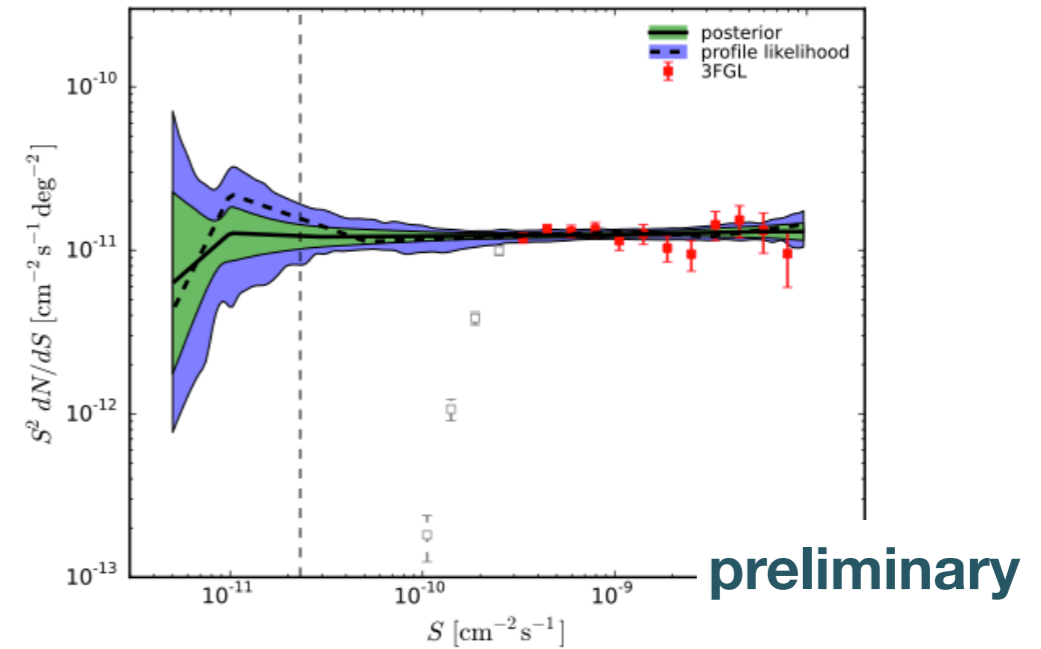
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Systematics - Pixel Size and PS masking

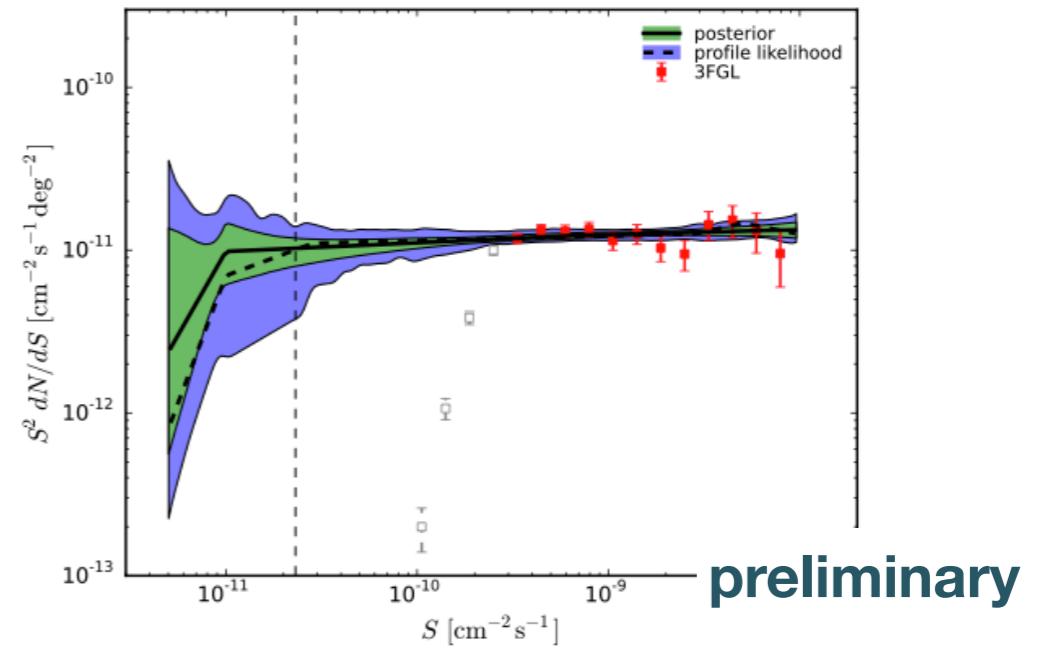
HEALPix order 7



- consistent with HP order 6
- enhanced PSF smoothing increases uncertainty



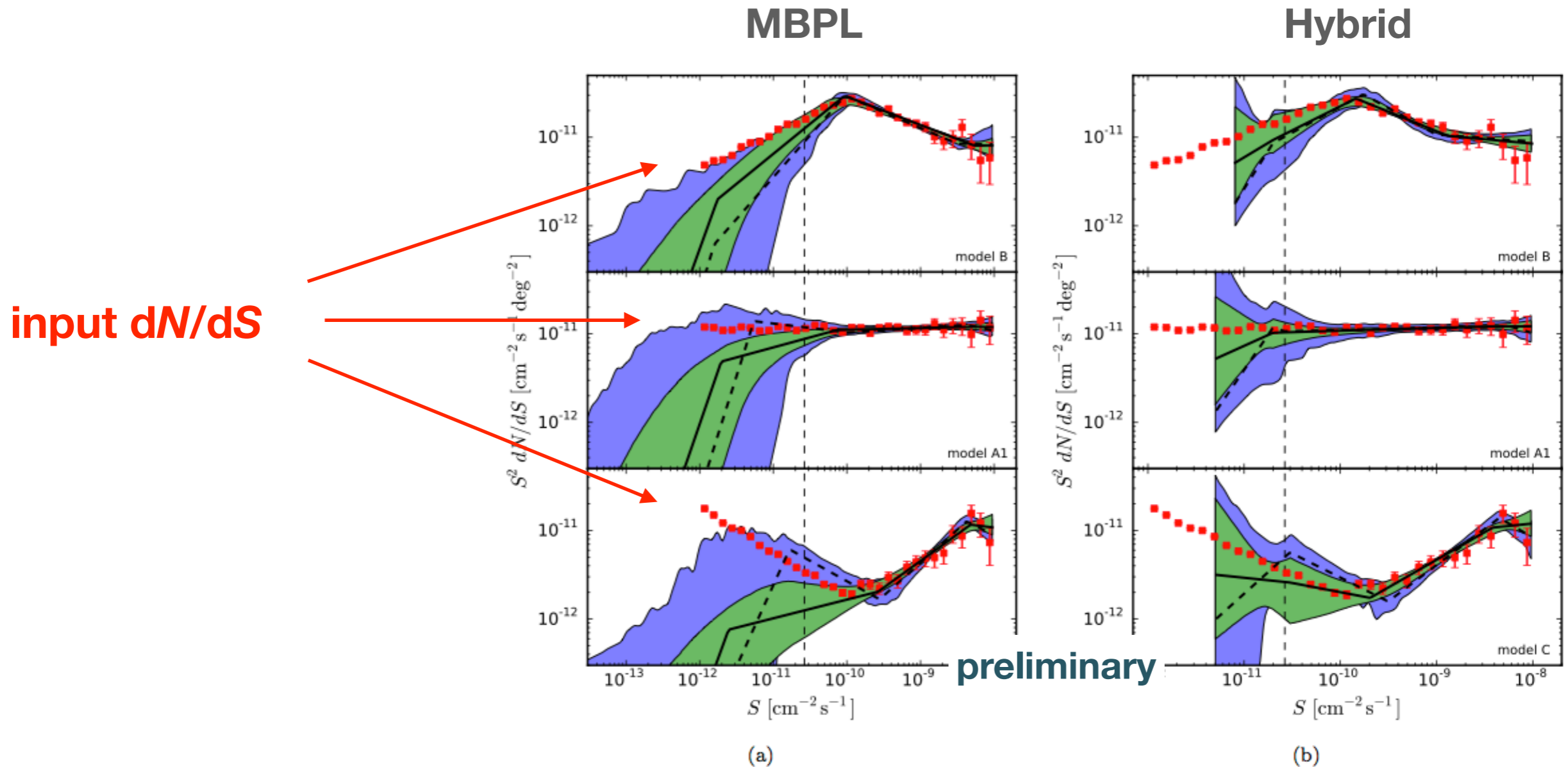
(a) point-source mask, HEALPix resolution $\kappa = 6$



(b) point-source mask, HEALPix resolution $\kappa = 7$

Monte-Carlo Simulations

- MC simulations of mock maps with different dN/dS distributions
—> gtobssim, 5 years, same analysis cuts



Comparison to Abdo et al., 2010

- dN/dS distribution published by Fermi-LAT Collaboration: Abdo et al., 2010
- based upon 1FGL catalog (11 months), P6 IRFs
- Galactic latitude cut: 10 deg

