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 (d*N*/d*S*), 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 **d*N*/d*S*** with high accuracy
  (complementary to catalogs resolving sources individually)
- **extend sensitivity** for d*N*/d*S* 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

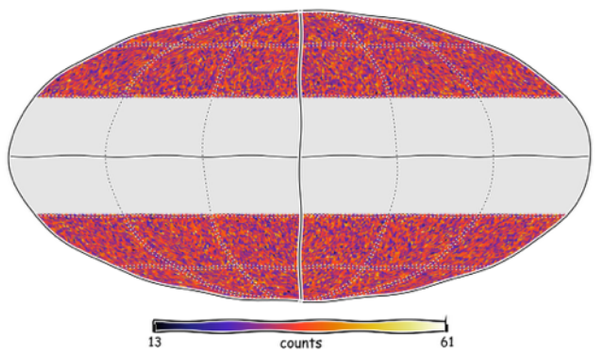
see also
Lee et al., 2009; Dodelson et al., 2009;
Baxter et al., 2010; Massari et al., 2015

1p-PDF Analysis (simple setup)

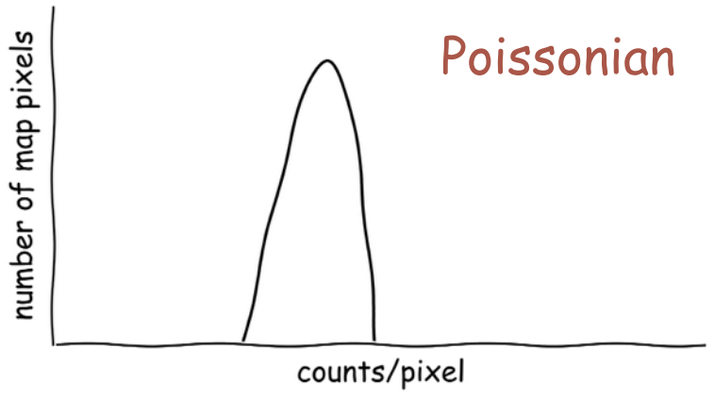
Idea: **consider statistics of photon counts per pixel**

Examples:

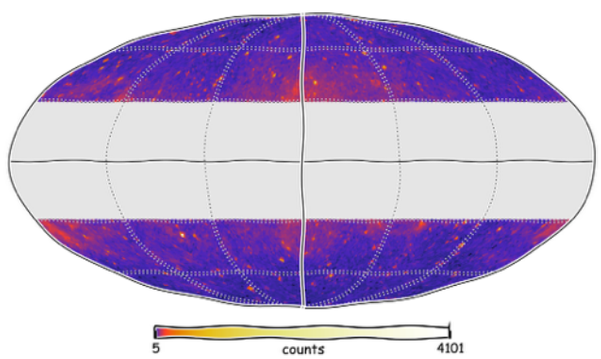
(A) diffuse isotropic background



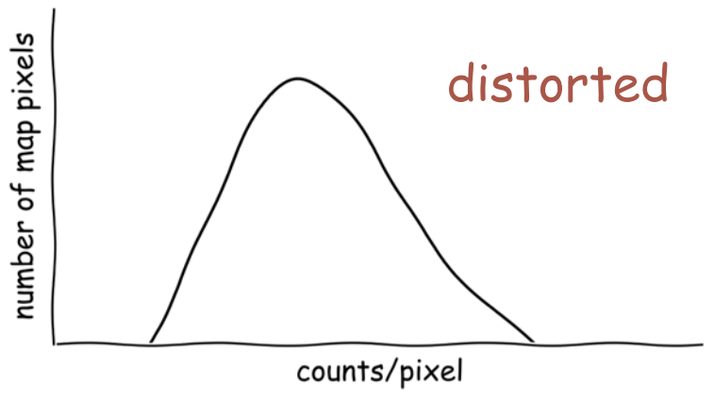
1p-PDF



(B) adding point sources, Galactic foreground, …



1p-PDF



1p-PDF Analysis

modeling of 1p-PDF: probability generating functions

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

P(t): generating functional p_k: discrete probability distribution

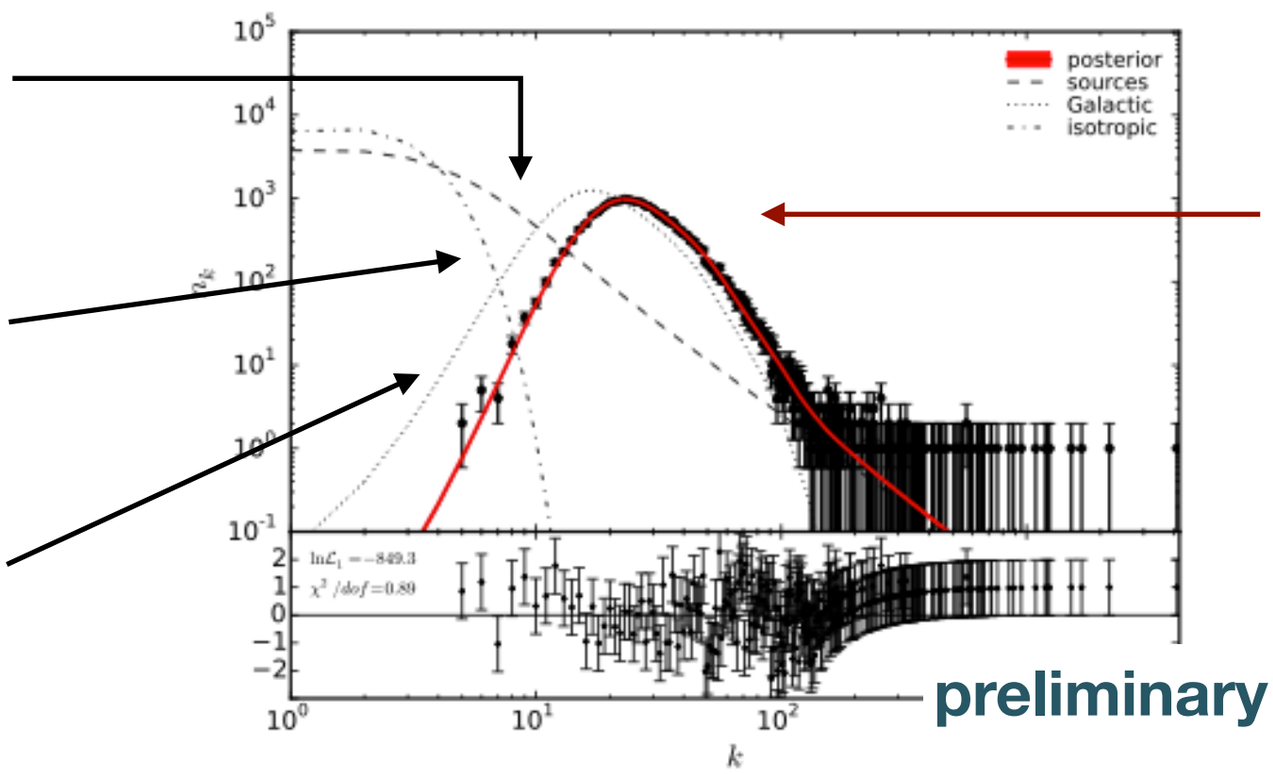
→ see M&H '11 for details

individual contributions:

point sources (d*N*/d*S* distribution)

diffuse isotropic background (F_{iso})

Galactic foreground template (A_{gal})



combined PDF

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(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 (gtpsf)

  - **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)

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

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

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

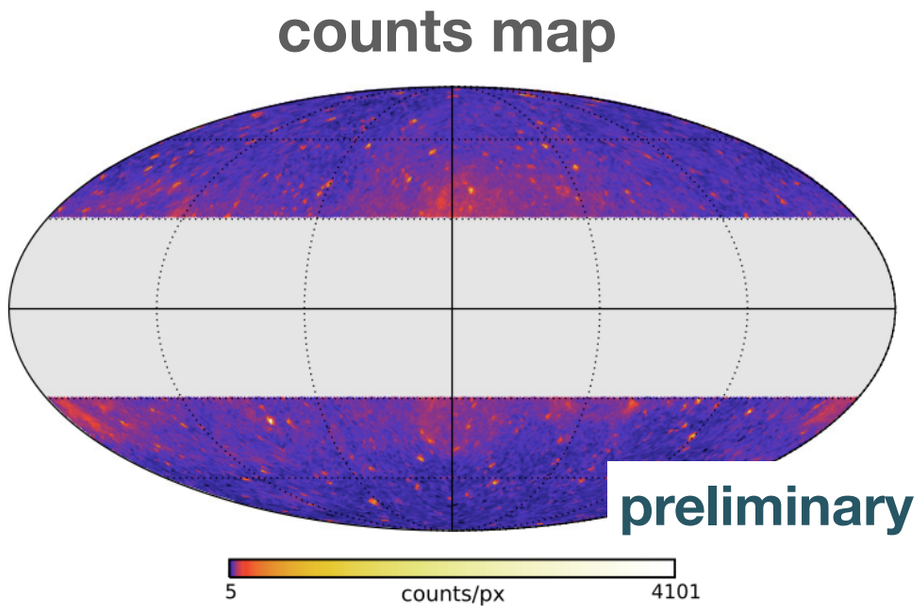
- sampling: **MultiNest** [Feroz & Hobson, 2008]

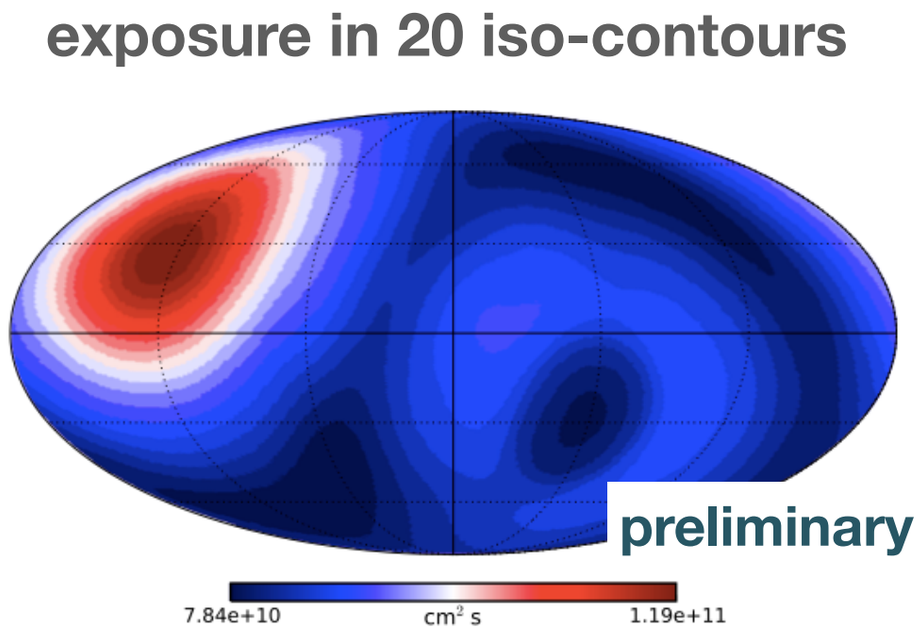
- parameter estimation: **Bayesian inference, profile likelihood**

- all results derived using pixel-dependent **L_2-likelihood**

Fermi-LAT Data

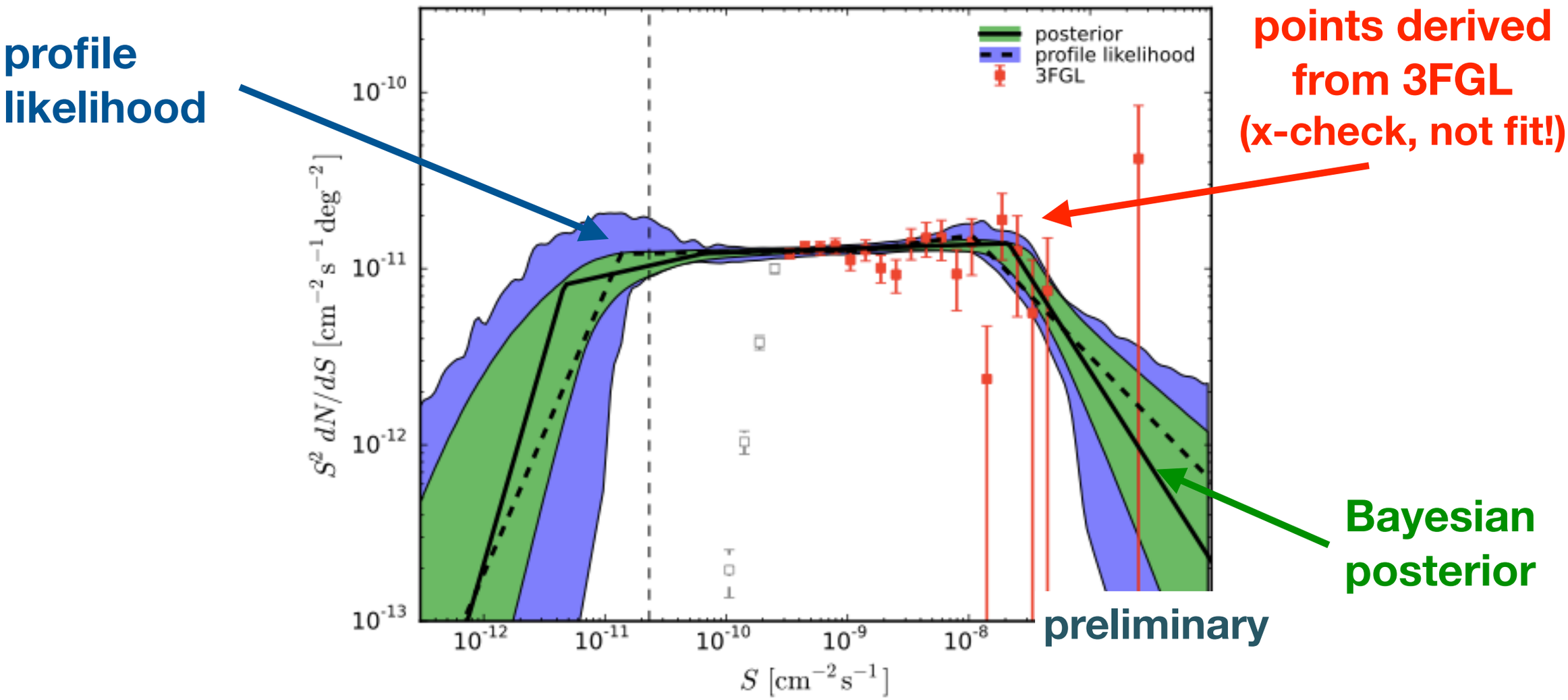
- data set: P7REP
- observation time: 6 years
- event selection:
  - CLEAN, front converted
  - standard quality cuts
  - zenith-angle cut: 90 deg
  - **1 GeV — 10 GeV**
- high Galactic latitudes:
  |b| > 30 deg
- HEALPix grid, order 6





Results - MBPL Approach

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



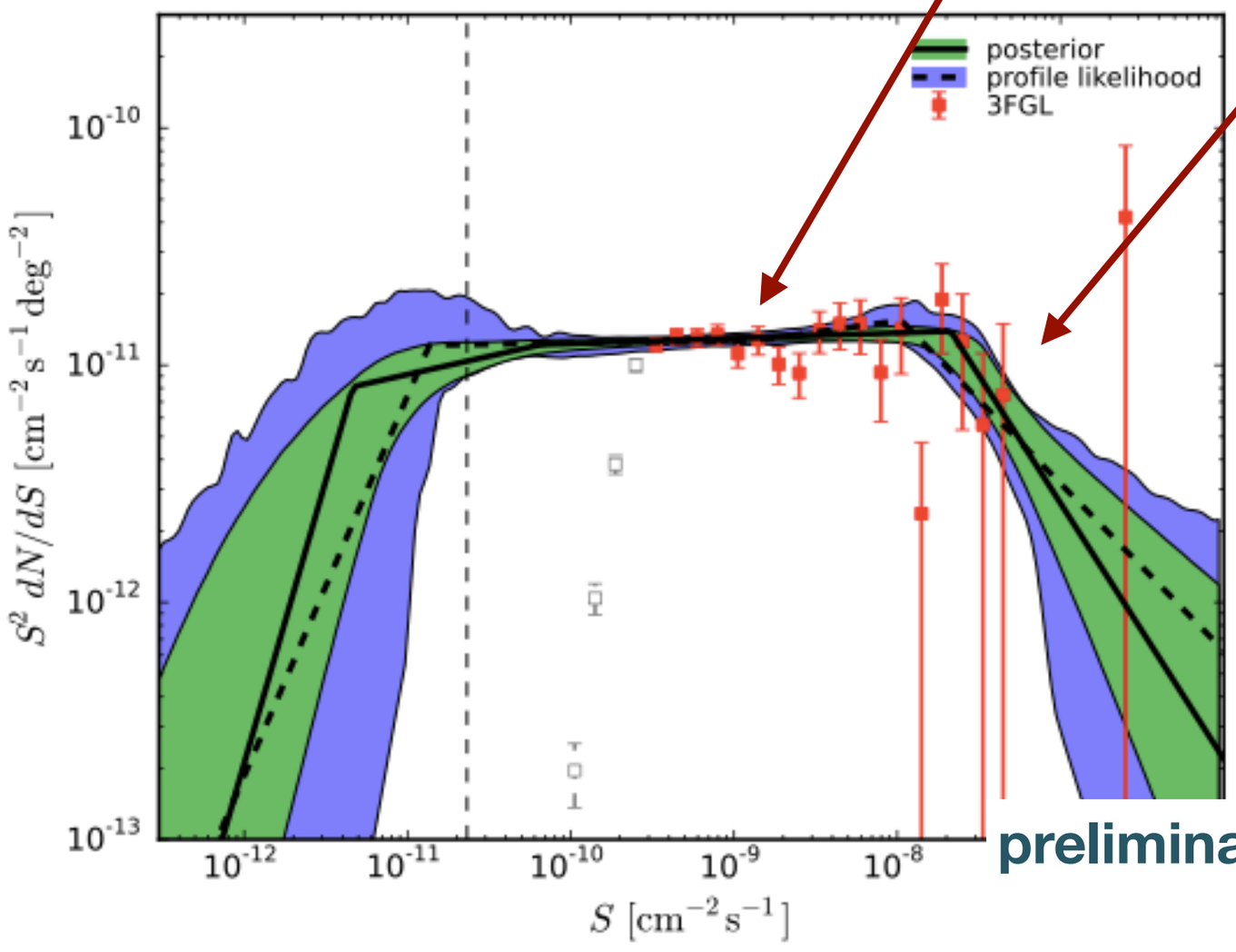
(a) MBPL, $N_\mathrm{b} = 3$

Results - MBPL Approach

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

intermediate flux range fit with high accuracy; index n_2=1.98 ± 0.03

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



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(a) MBPL, $N_\mathrm{b} = 3$

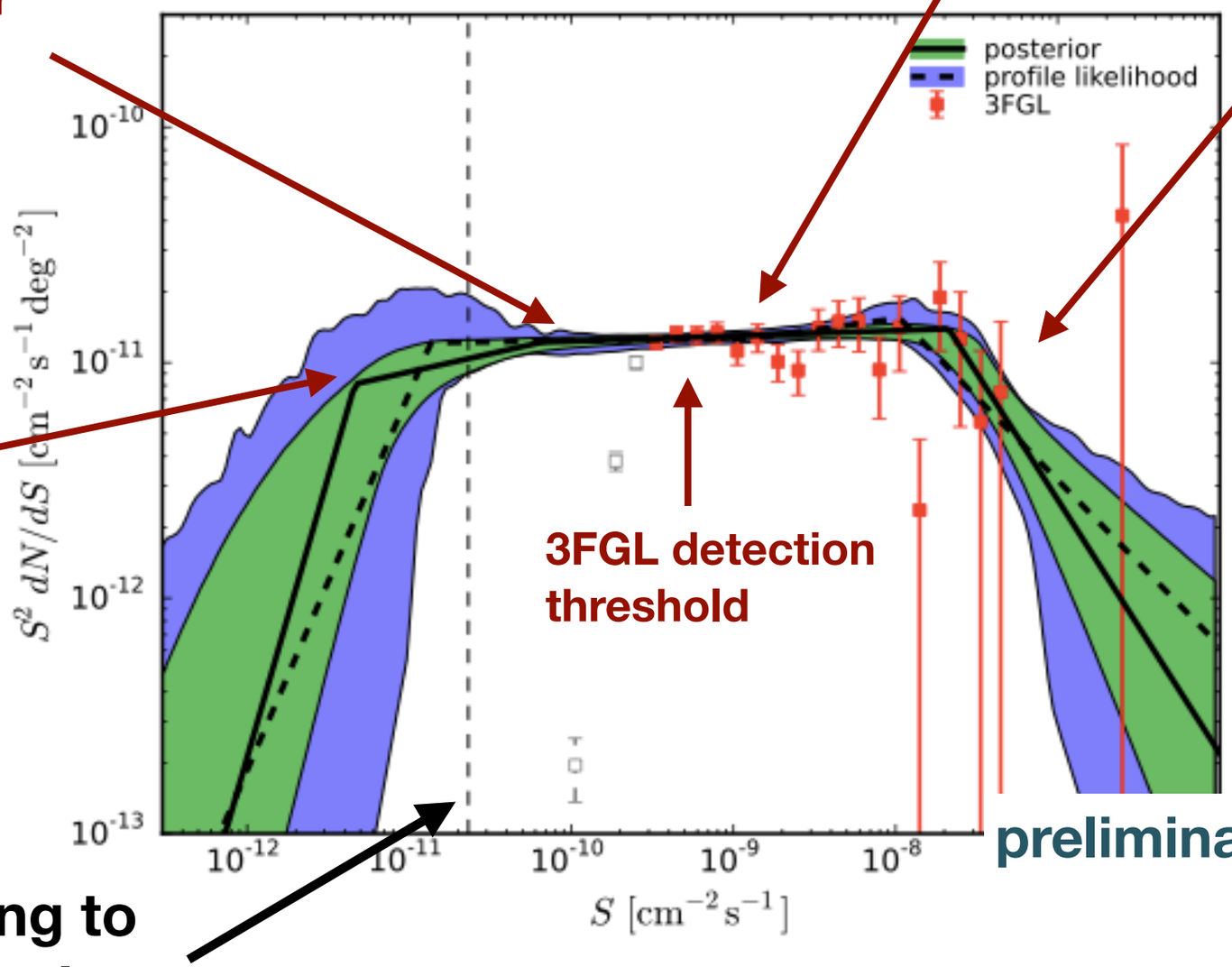
Results - MBPL Approach

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

intermediate flux range fit with high accuracy; index n_2=1.98 ± 0.03

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

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



sensitivity cutoff

3FGL detection threshold

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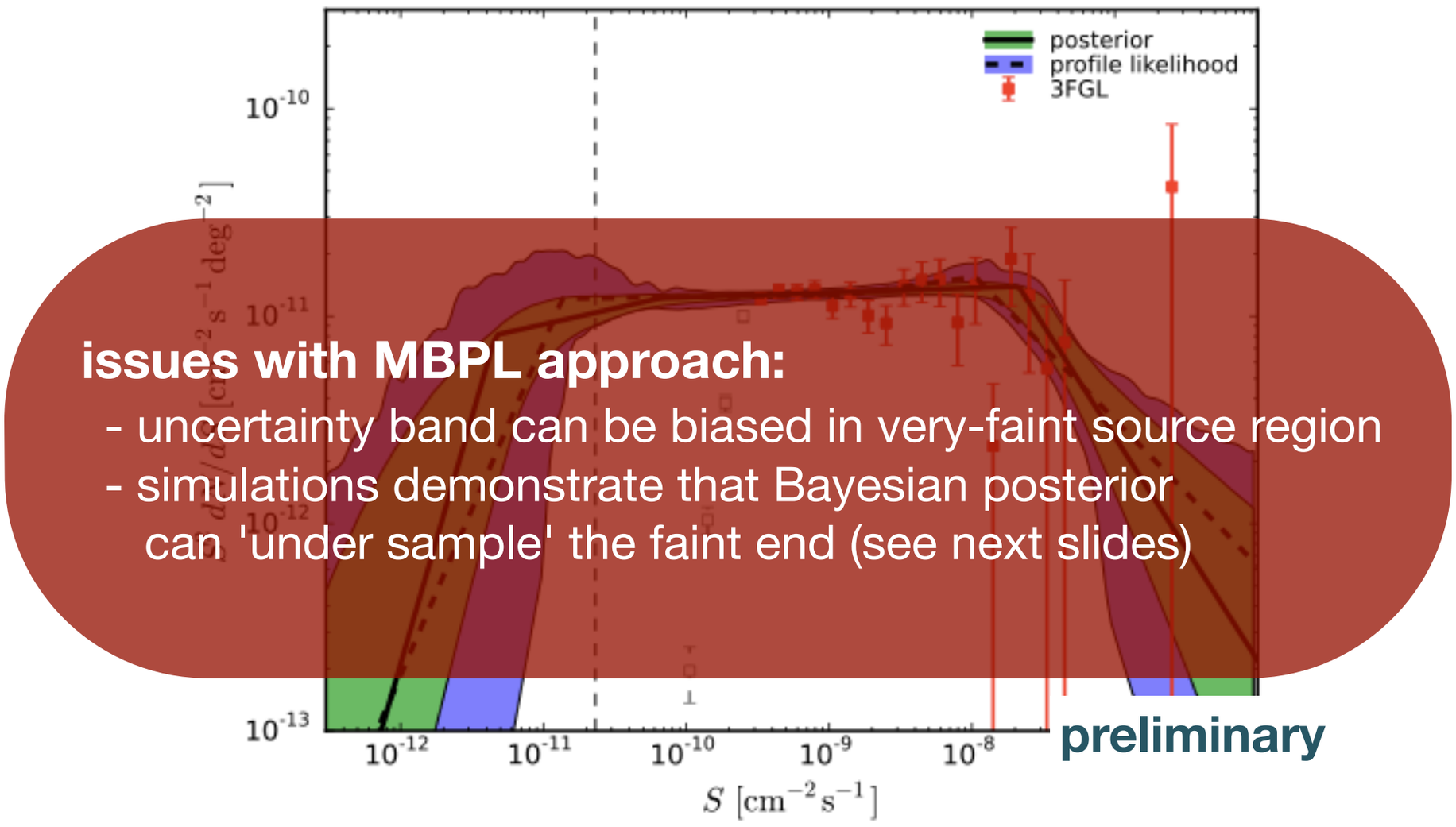
flux corresponding to 2 photons per pixel

(a) MBPL, $N_b = 3$

Results - MBPL Approach

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

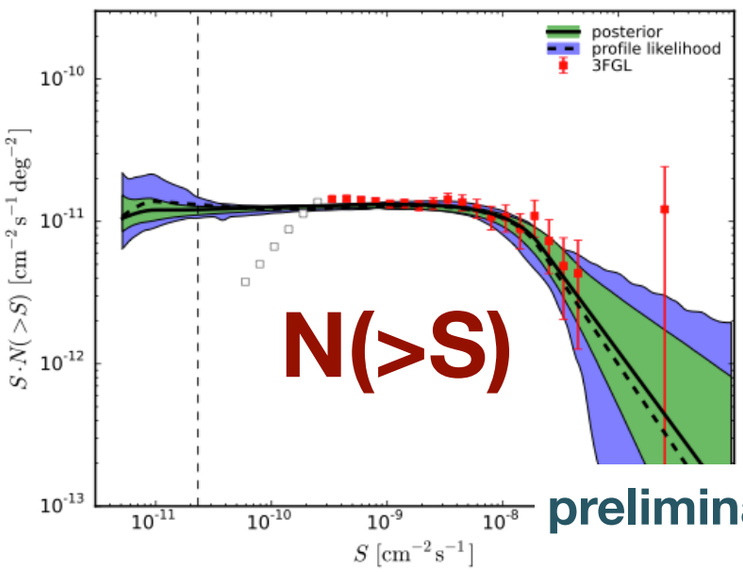


(a) MBPL, $N_\mathrm{b} = 3$

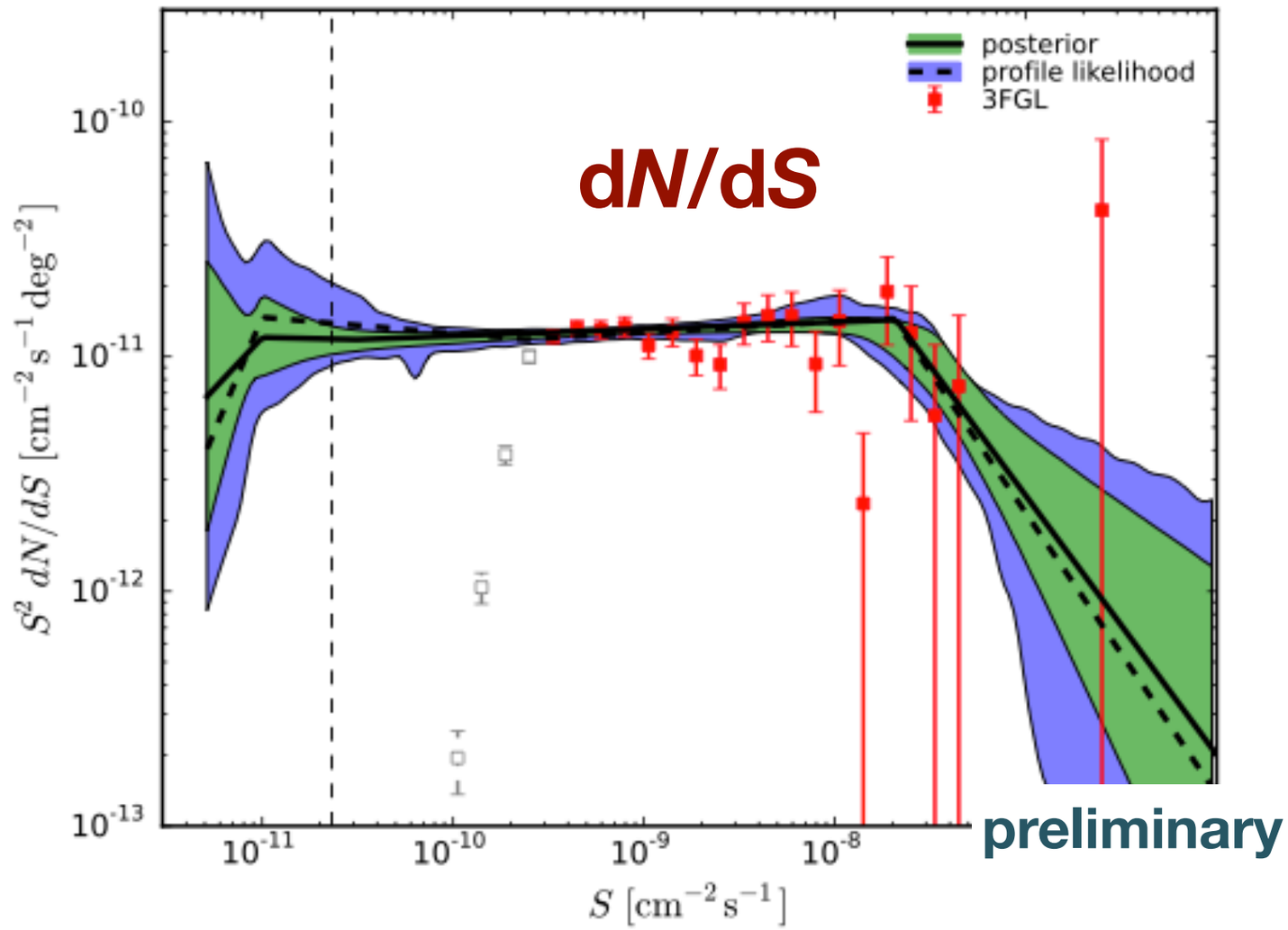
Results - Hybrid Approach

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

- confirms MBPL results
- solves possible issues with uncertainty bands



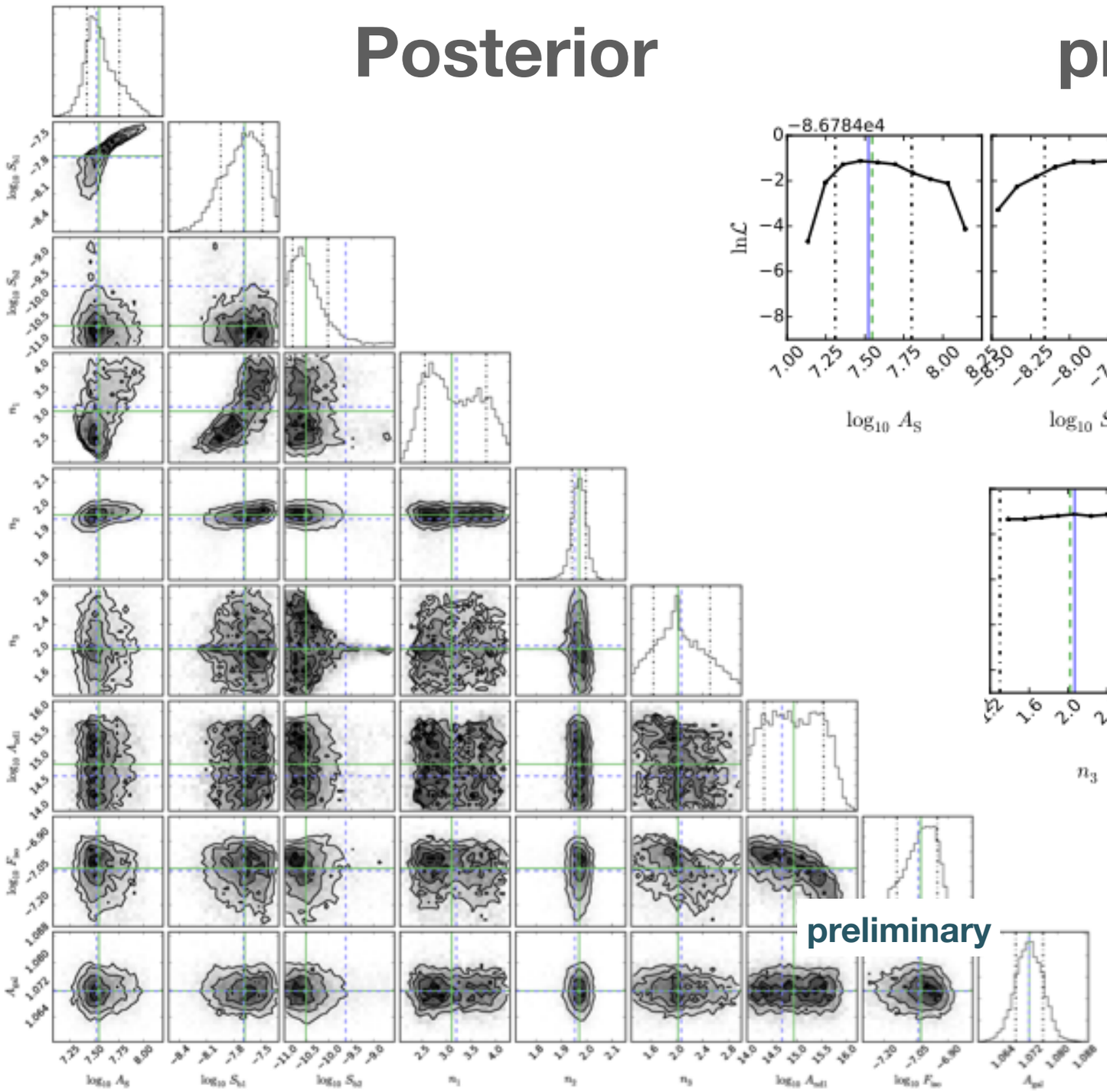
(d) $N(> S)$, hybrid, $N_{\rm b} = 2$



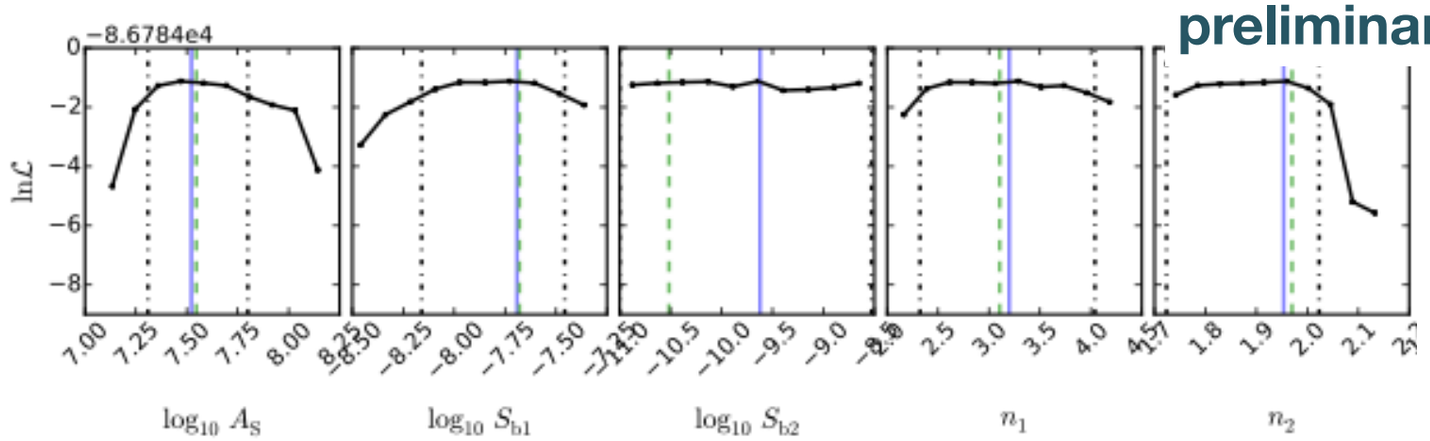
(c) $\mathrm{d}N/\mathrm{d}S$, hybrid, $N_{\rm b} = 2$

Hybrid Approach - Sampling

Posterior



profile likelihood



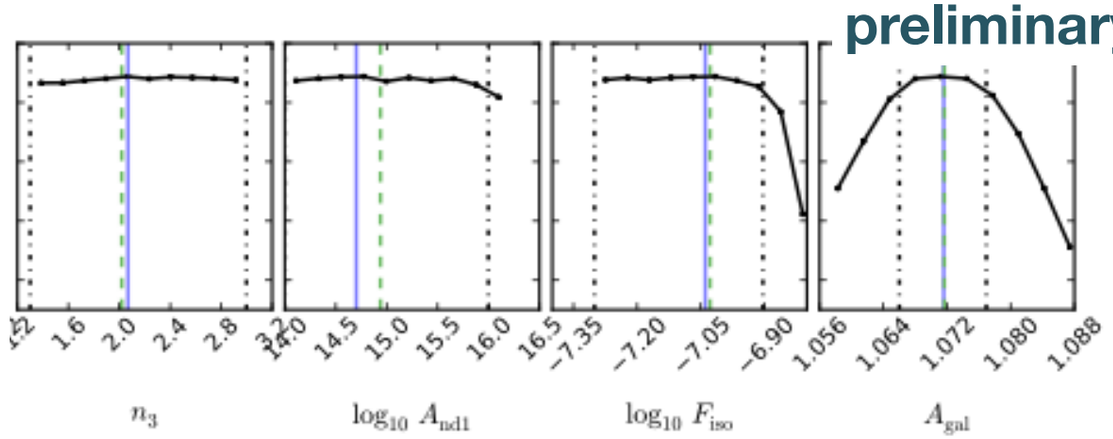


figure legend:
green: Bayesian median,
blue: profile likelihood fit
dashed: 1-sigma errors

Composition of the Gamma-ray Sky

- **composition of the** high-latitude **gamma-ray sky can be measured** by integrating d*N*/d*S* and the Galactic foreground fit

- integral flux from **point sources** $F_{ps} = (3.9 \pm 0.3)\ 10^{-7}\ cm^{-2}\ s^{-1}\ sr^{-1}$, corresponding to **(26±2)%** of the total flux

- integral **diffuse isotropic background** $F_{iso} = (0.9 \pm 0.2)\ 10^{-7}\ cm^{-2}\ s^{-1}\ sr^{-1}$, corresponding to **(6±2)%** of the total flux

- rest: Galactic foreground

profile likelihood for integral point-source flux

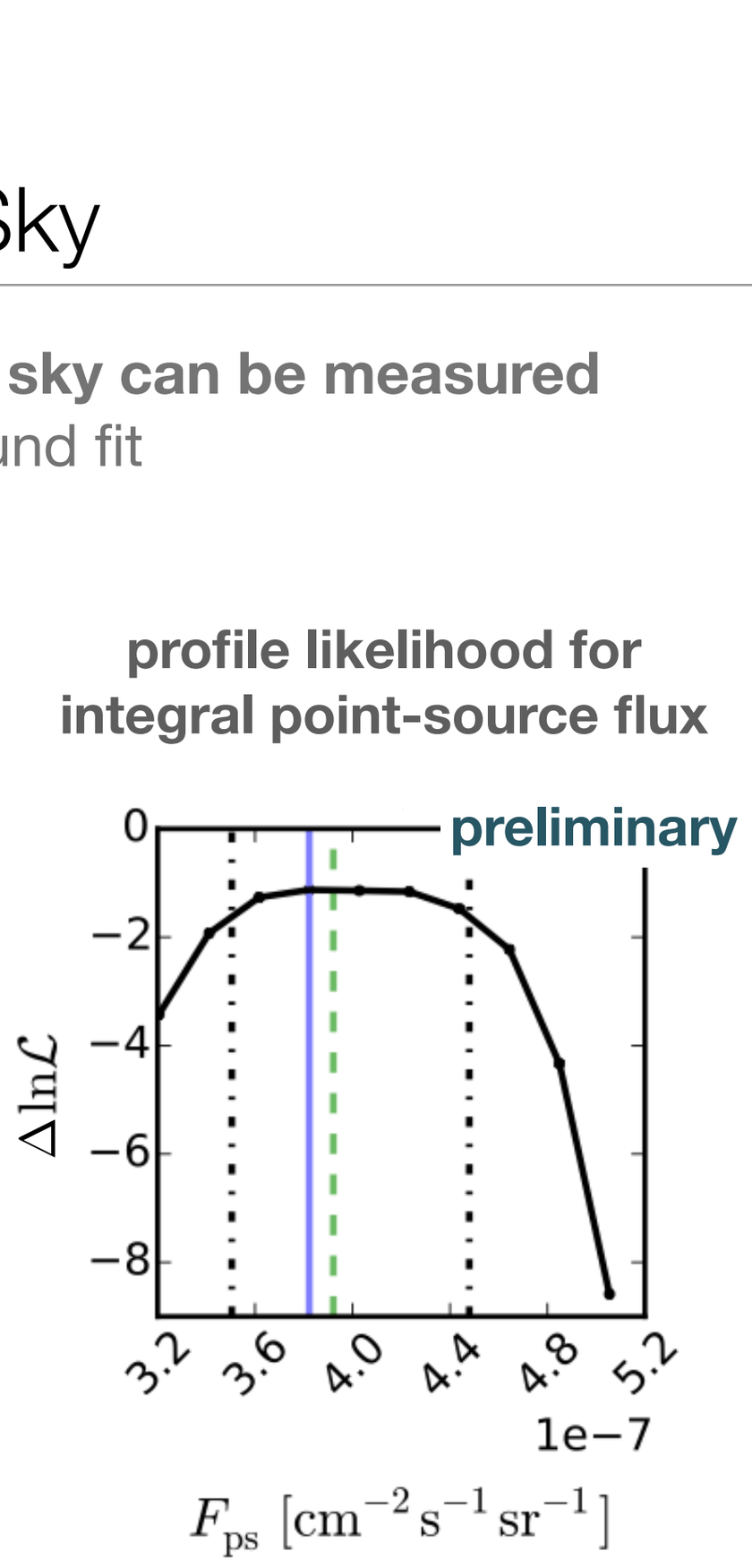
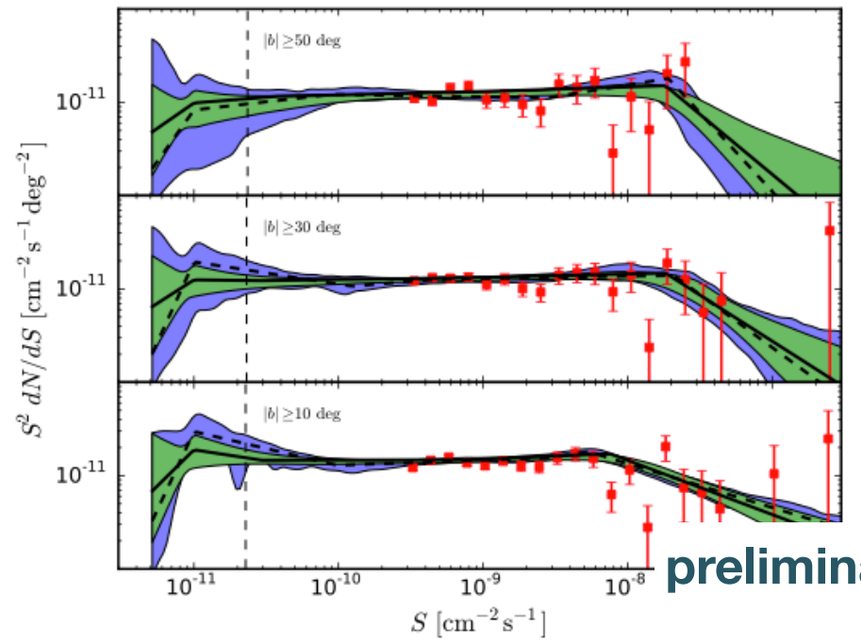


figure legend:
green: Bayesian median, blue: profile likelihood fit
dashed: 1-sigma errors (δln L = 0.5)

Systematics/Validation

- analysis underwent several **systematic/modeling checks**:
  - masking bright point sources
  - pixel size
  - different *b*-cuts and Galactic foreground templates
  - point-source spectral index distribution

Galactic latitude cuts



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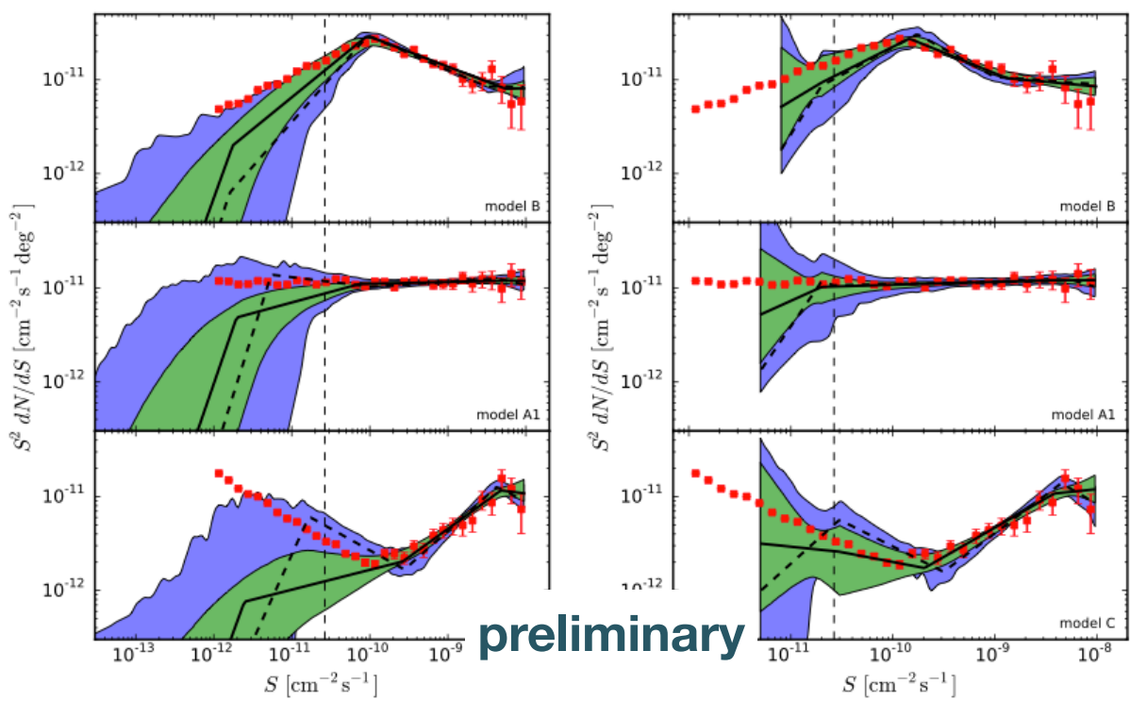
- validation with Monte-Carlo simulations (gtobssim)

MBPL **Hybrid**



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Summary

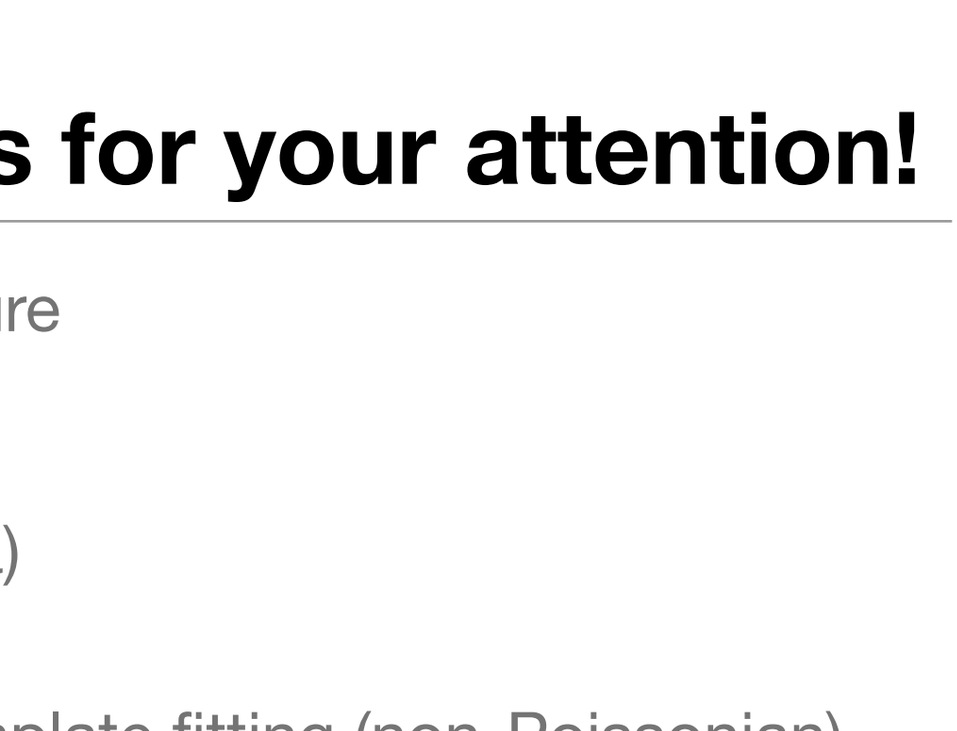
Thanks for your attention!

- we employed pixel-count statistics to measure the source-count distribution d*N*/d*S* 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 d*N*/d*S* model with multiple breaks, PSF correction, and exposure correction

- d*N*/d*S* distribution remains almost flat in the region of unresolved sources

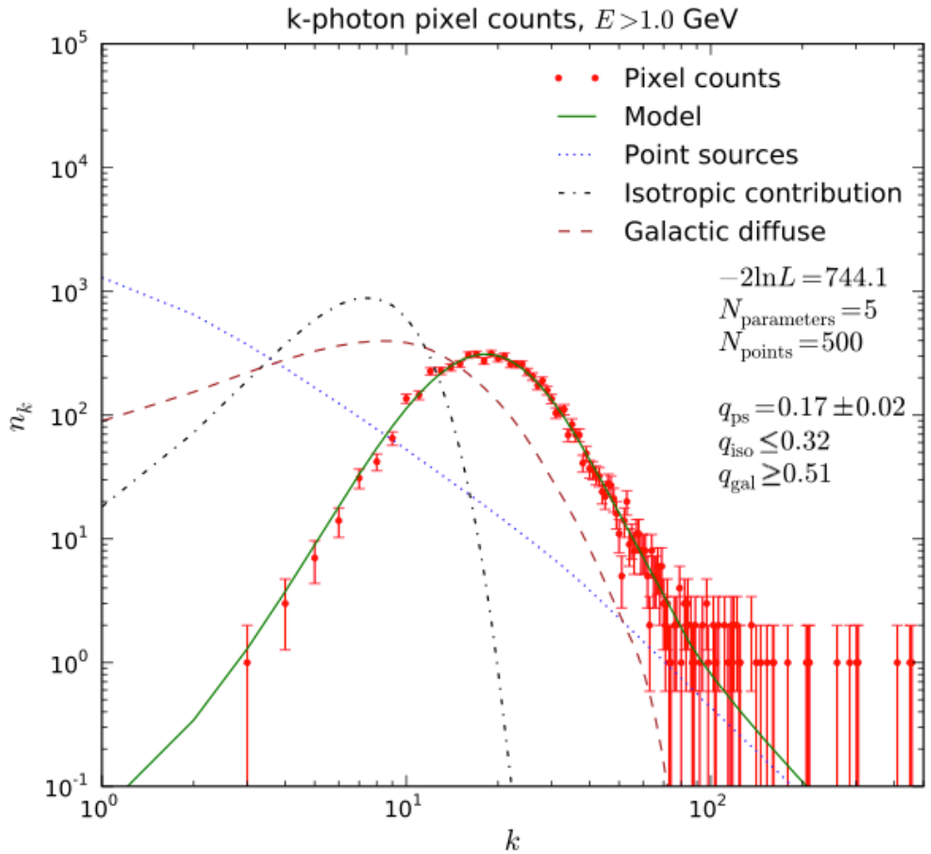
- new measurement of the composition of the gamma-ray sky



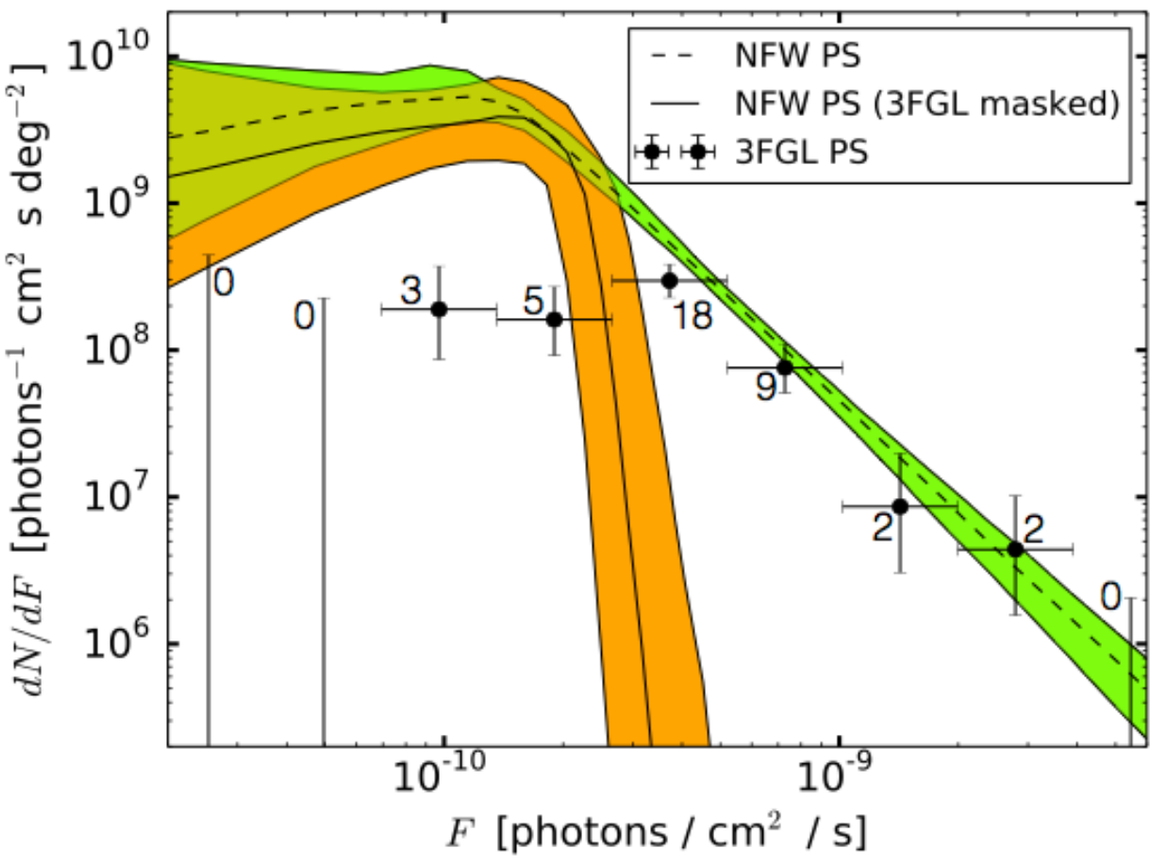
Backup

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

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

modeling (M&H '11)

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

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

(a) point sources (d*N*/d*S* distribution),
(b) Galactic foreground template (A_{gal})
(c) diffuse isotropic background (F_{iso})
(d) …

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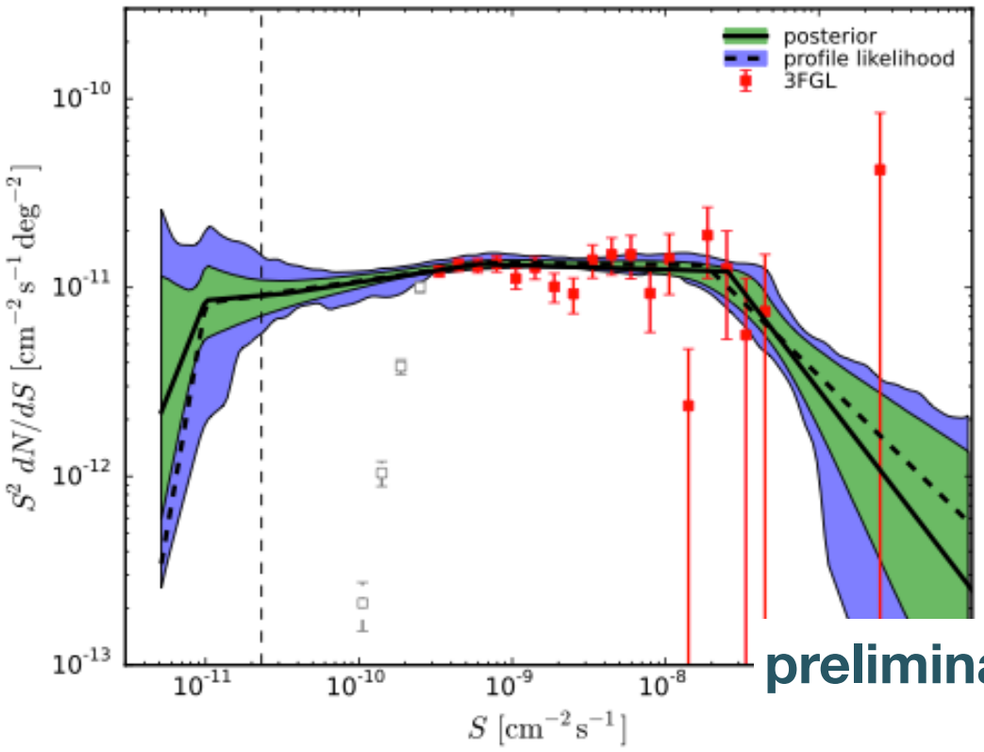
Systematics - Pixel Size and PS masking

HEALPix order 7



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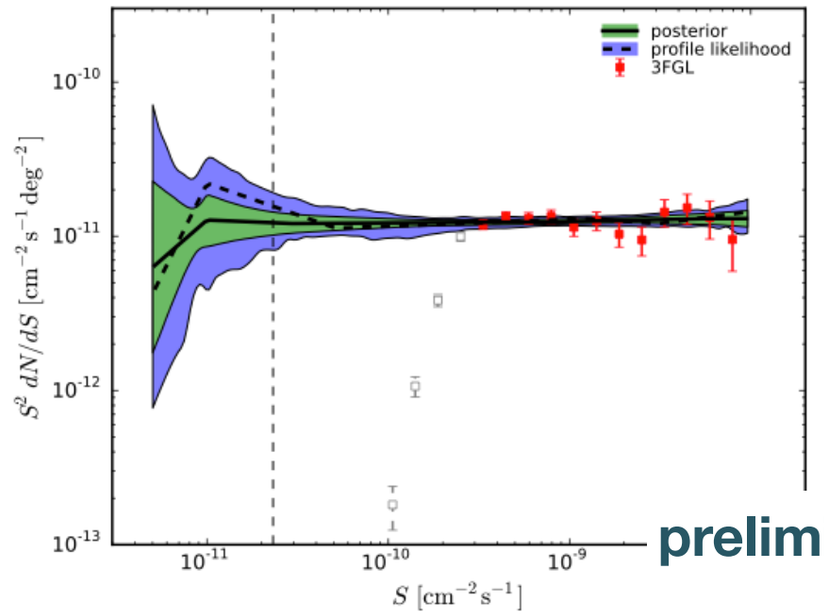
- consistent with HP order 6
- enhanced PSF smoothing increases uncertainty



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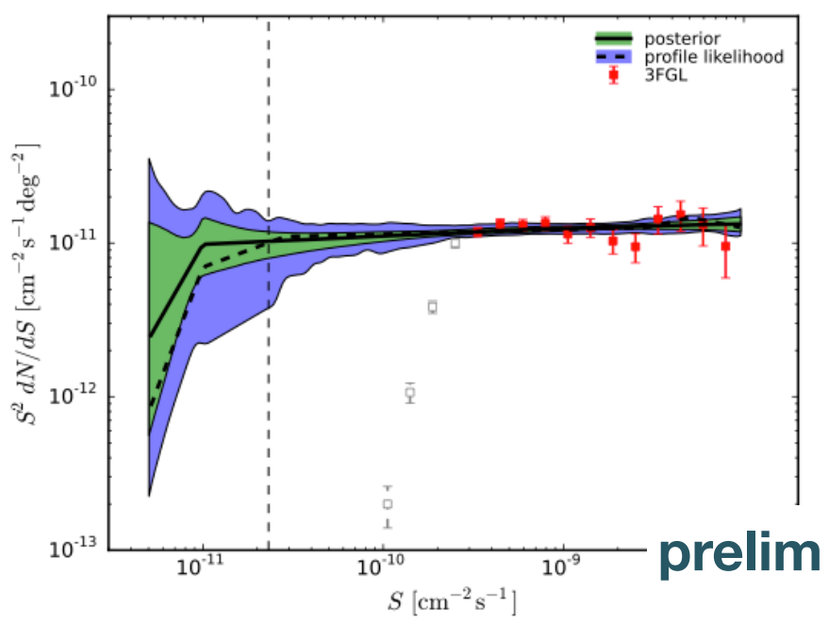
(a) point-source mask, HEALPix resolution $\kappa = 6$



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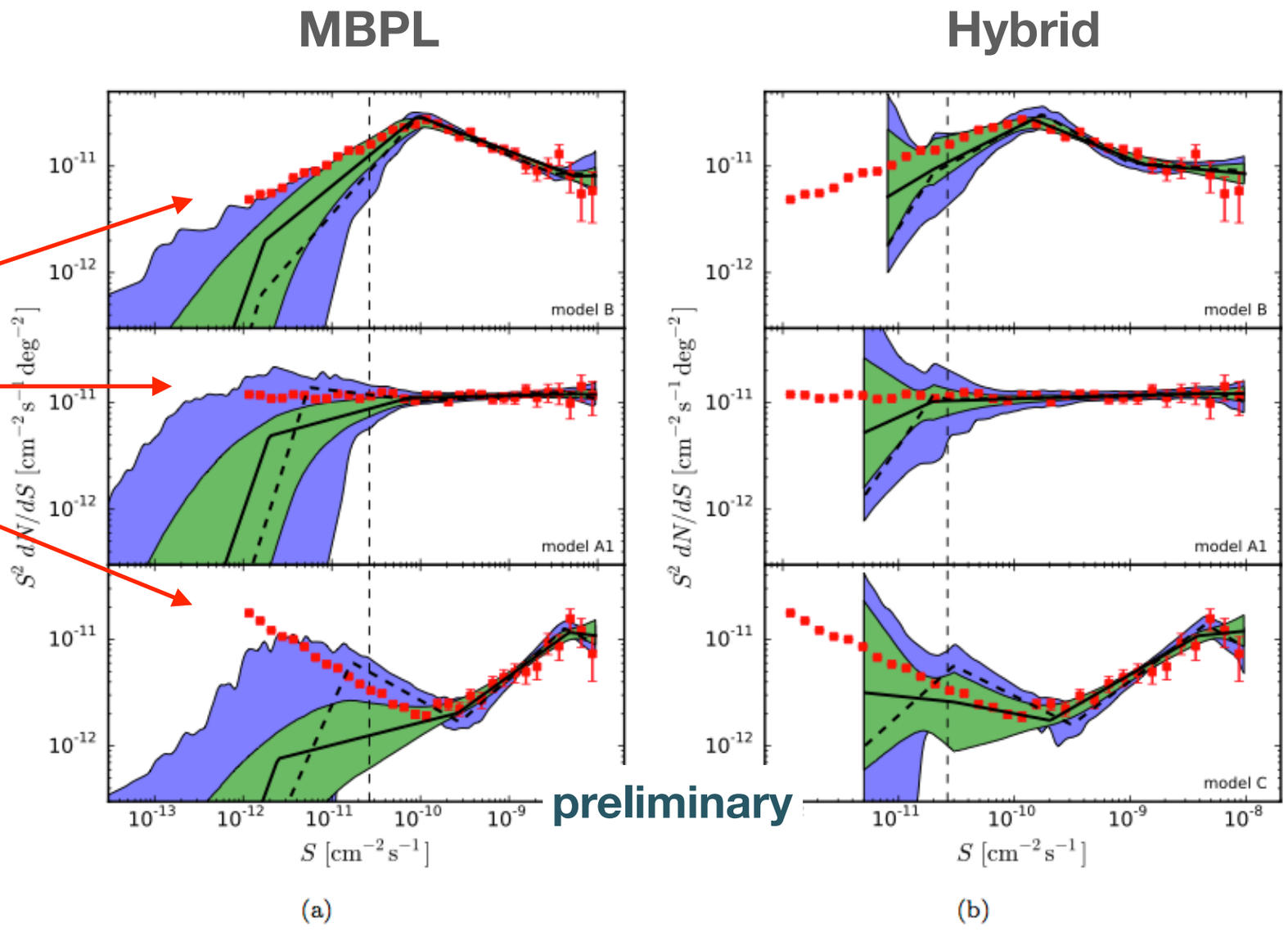
(b) point-source mask, HEALPix resolution $\kappa = 7$

Monte-Carlo Simulations

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

input d*N*/d*S*



Comparison to Abdo et al., 2010

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