Dissecting the High-latitude Gamma-ray Sky with Photon-count Statistics

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in collaboration with:
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based on:
- Zechlin et al. (2015), submitted to ApJS, arXiv:1512.07190

UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

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INFN Istituto Nazionale di Fisica Nucleare

Statistical Image Analysis

- statistical analysis of intensity or photon-count maps; employed for decades in radio and X-ray astronomy (CMB, radio maps, etc.)

—> source-count distributions (d*N*/d*S*), population properties, correlation studies (auto-correlation, cross-correlation, …)

—> ***1 dimension:*** P(D) distribution or **1-point PDF (1p-PDF)**

adapt method to gamma-ray band - explore 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)
  —> development of theoretical framework, proof of principle

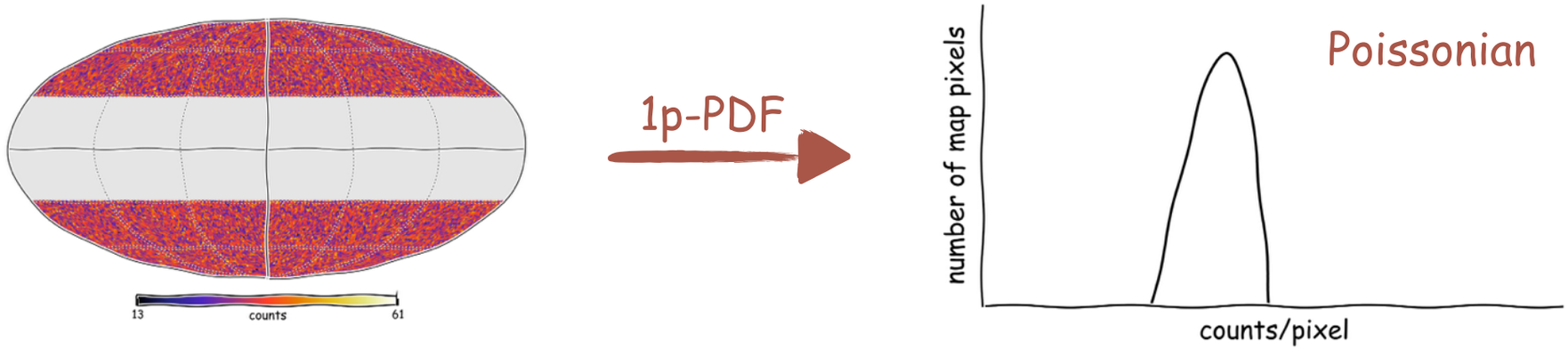
see also:
Lee et al., 2009; Dodelson et al., 2009;
Baxter et al., 2010; Massari et al., 2015;
Lee et al., 2016

1p-PDF Analysis (simple setup)

Idea: consider statistics of pixel wise photon counts

Examples:

(A) diffuse isotropic background



(B) adding point sources, Galactic foreground, …

- not to scale -

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

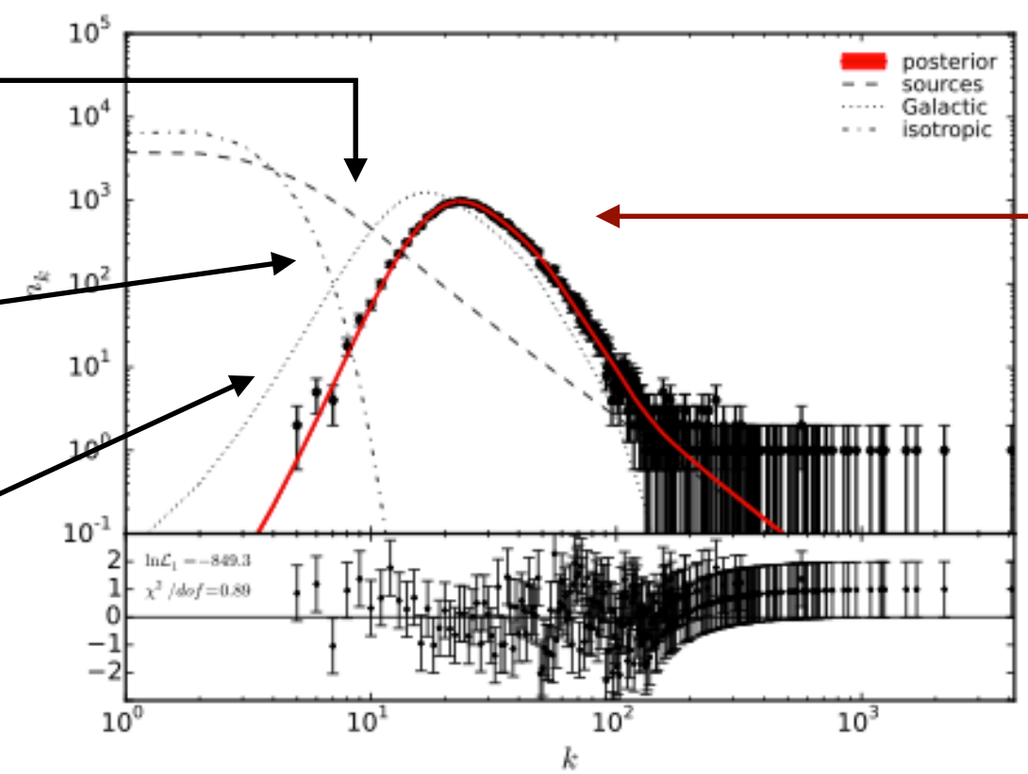
→ see Zechlin et al. (2015) arXiv:1512.07190

individual contributions:

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

diffuse isotropic background (F_{iso})

Galactic foreground template (A_{gal})



combined PDF

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 parametrized with a **multiply broken power law (MBPL)**
  - **correction** for **exposure inhomogeneities**
  - **correction** for **PSF effects** using effective PSF derived from data (gtpsf)
  - **correction** for point-source **spectral indices** (assuming an index of 2.4)
  - **Galactic foreground** modeled using **Fermi-LAT template,** 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 (see HSZ '15)

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

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

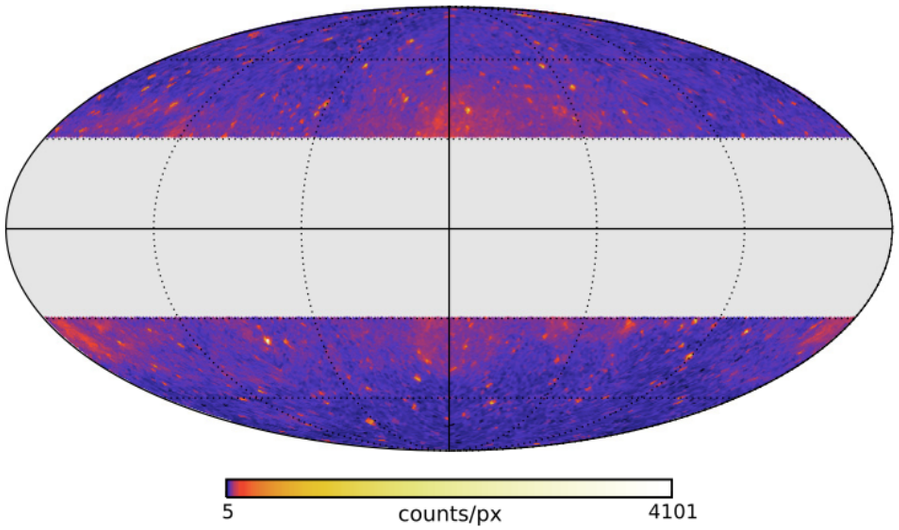
- parameter estimation: **Bayesian inference, profile likelihood (frequentist)**

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

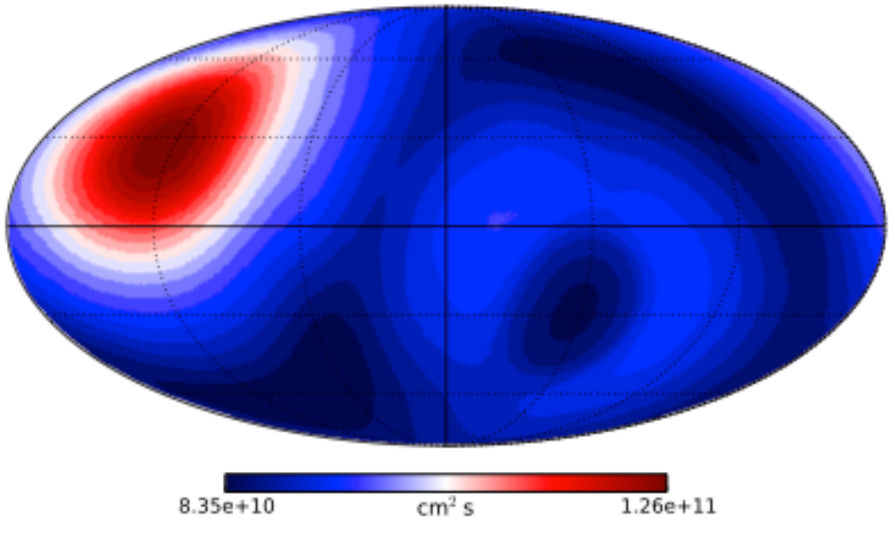
Fermi-LAT Data

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

counts map, 1 GeV —10 GeV



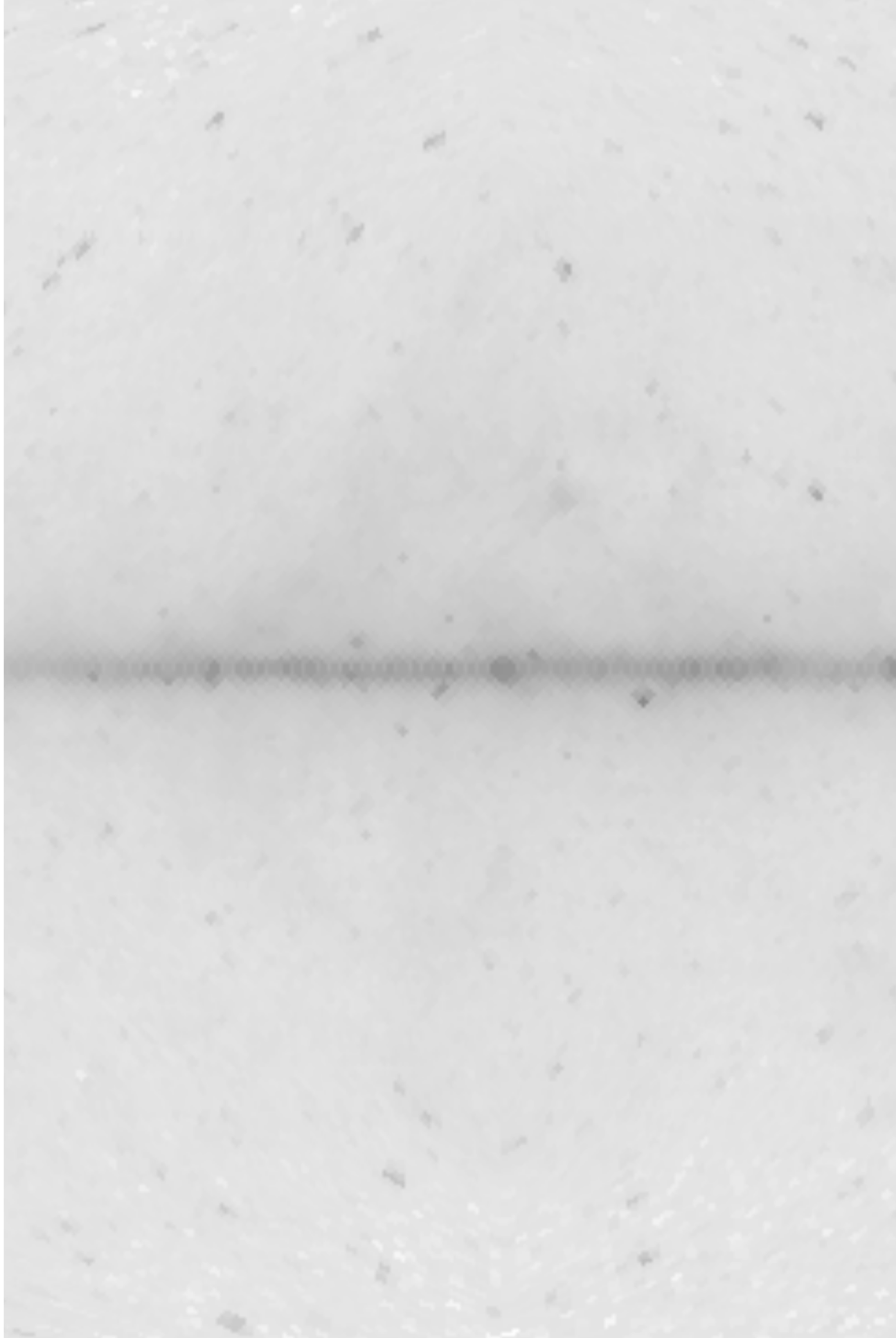
exposure in 20 iso-contours



Results

1 GeV — 10 GeV

Zechlin et al. (2015), arXiv:1512.07190

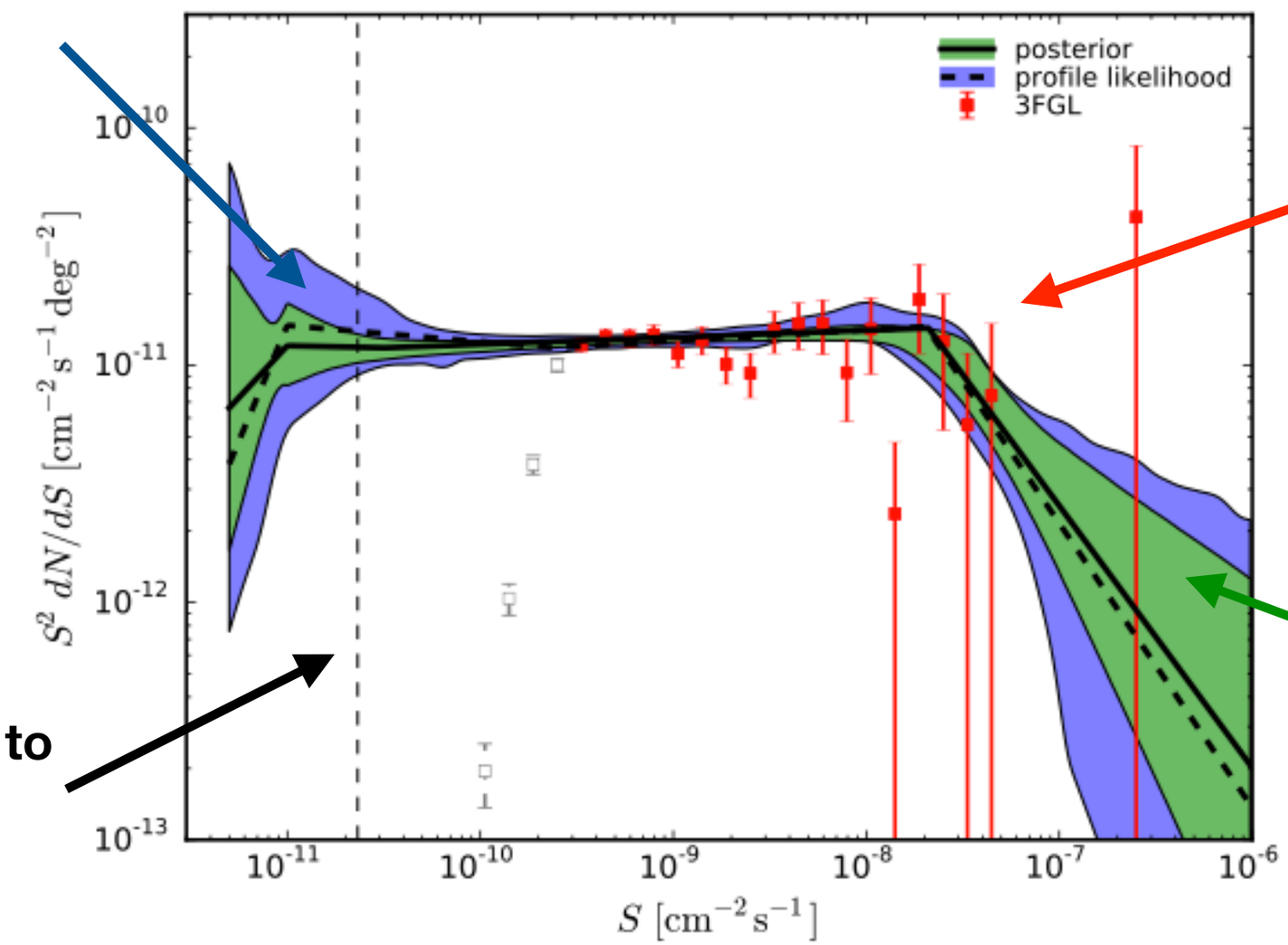


Results (1-10 GeV) - Hybrid Approach

- **d*N*/d*S* parametrization:**
  - multiply broken PL (MBPL), 2 free breaks
  - node at fixed faint flux position to stabilize uncertainty band
  (d*N*/d*S* is assumed zero below last node)

profile likelihood

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



Bayesian posterior

flux corresponding to 2 photons per pixel

Results (1-10 GeV) - Hybrid Approach

- **d*N*/d*S* parametrization:**
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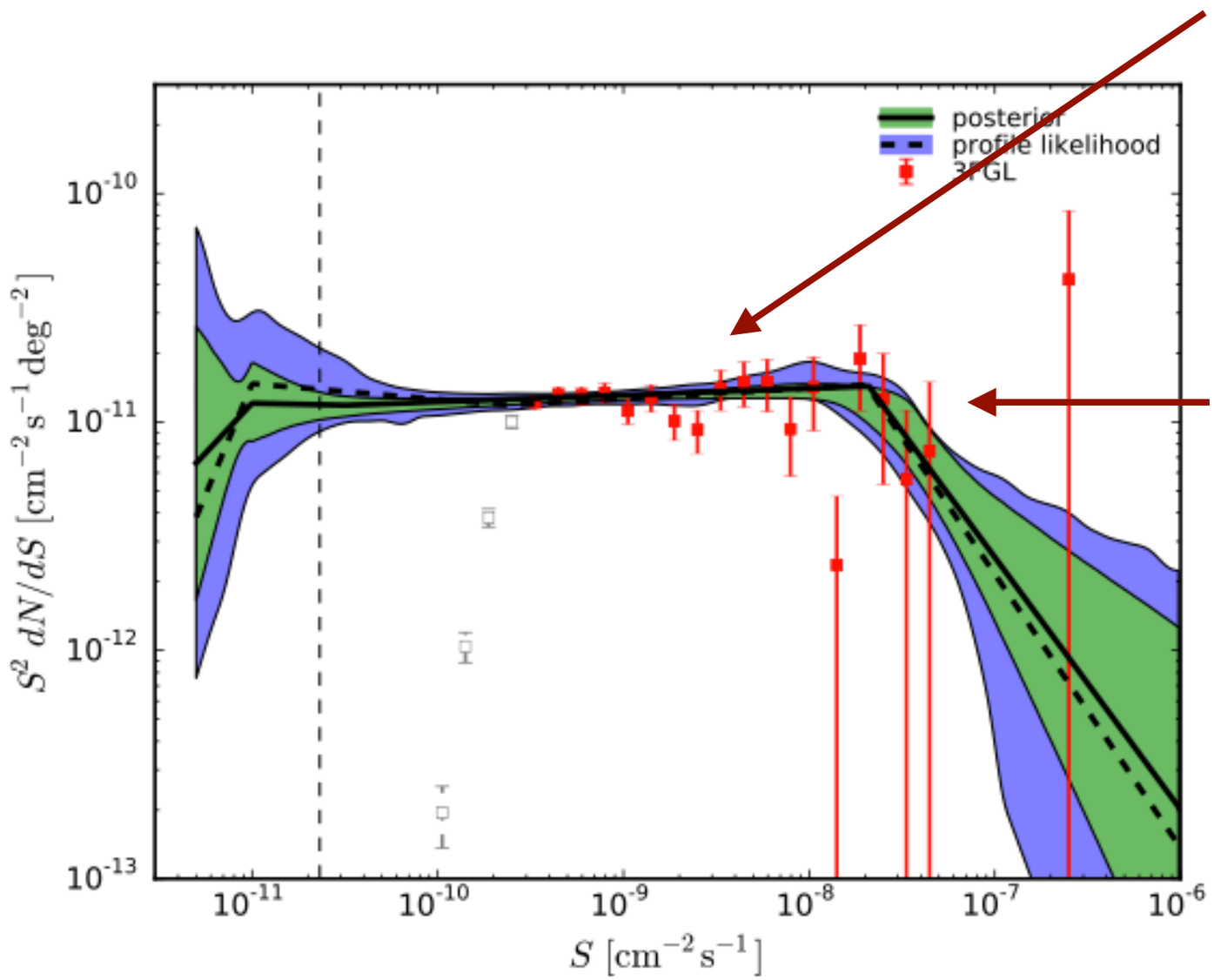
  - node at fixed faint flux position to stabilize uncertainty band

intermediate flux range fit with high accuracy; index n_2=1.97 ± 0.03



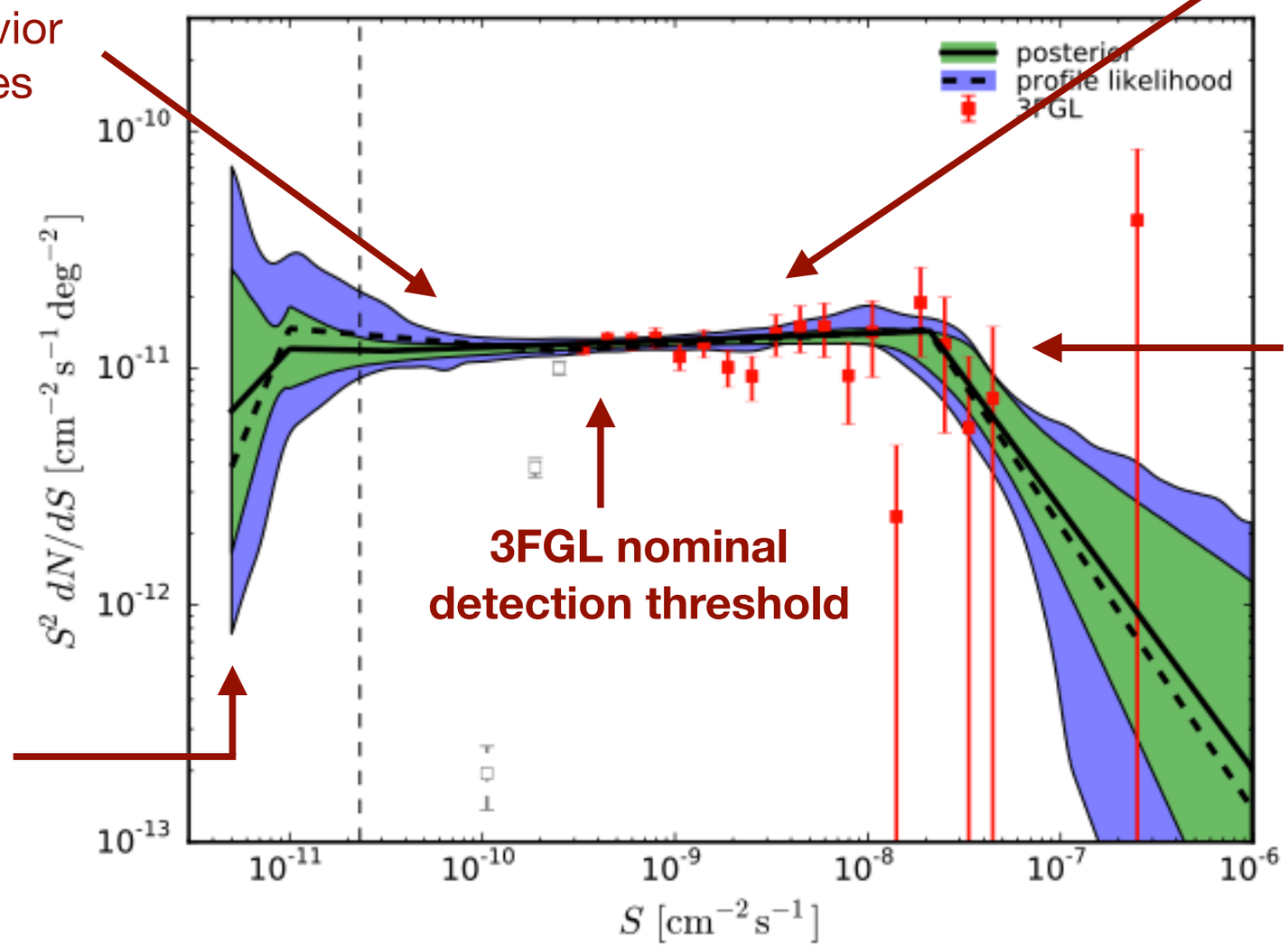
bright-source end correctly reproduced; first break resolved fairly well (sig. ~3σ)

Results (1-10 GeV) - Hybrid Approach

- **d*N*/d*S* parametrization:**
  - multiply broken PL (MBPL), 2 free breaks
  - node at fixed faint flux position to stabilize uncertainty band

intermediate flux range fit with high accuracy; index n_2=1.97 ± 0.03

fit prefers a flat behavior for unresolved sources



bright-source end correctly reproduced; first break resolved fairly well (sig. ~3σ)

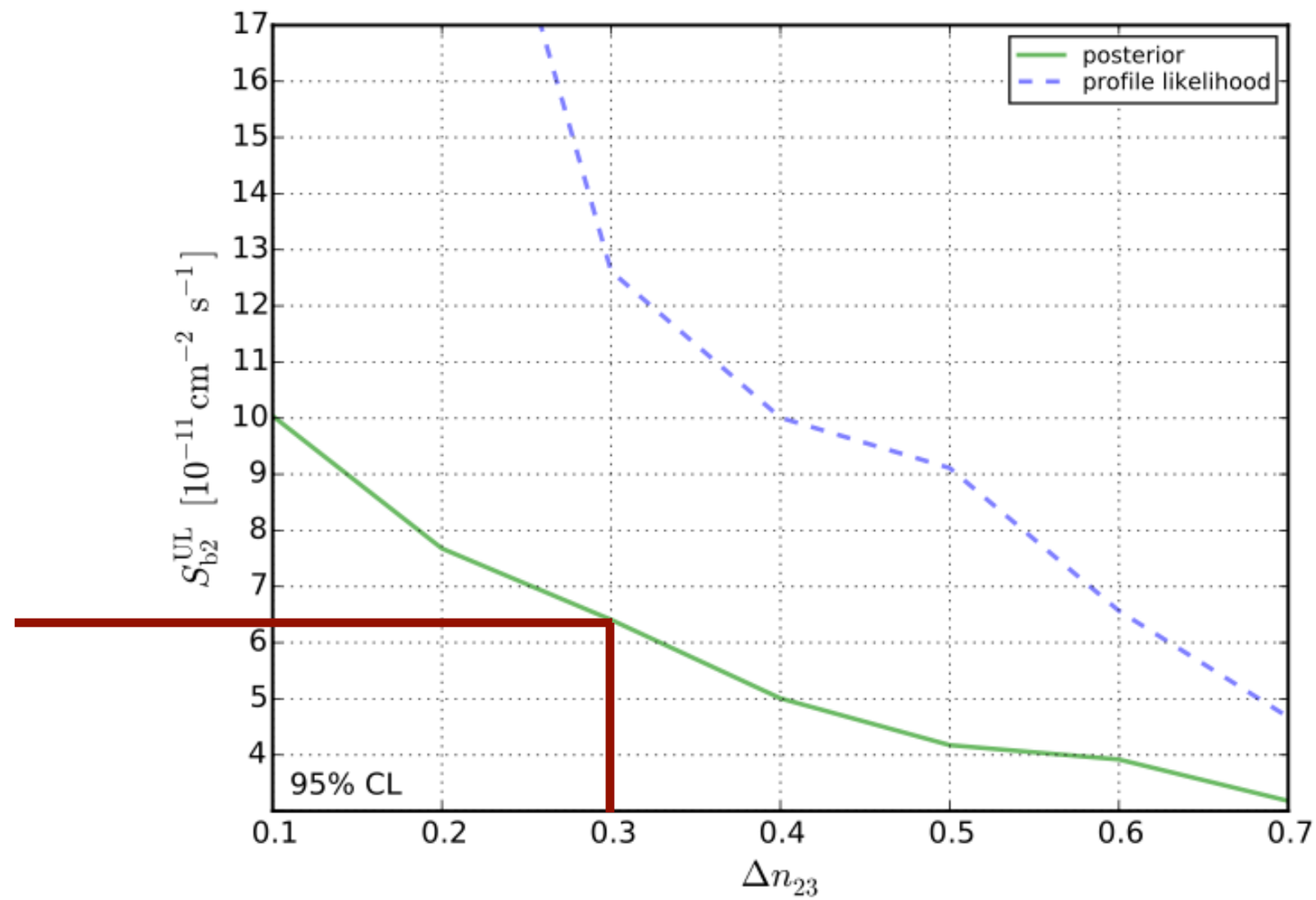
faint node: models sensitivity cutoff found with pure MBPL fit

Results (1-10 GeV) - Upper Limit on 2nd Break

- **conclusions:**
  - **d*N*/d*S* consistent with a *broken* PL**
  - **bright-source break preferred by ~3σ**
  - **no evidence for second break;**
  - **—> upper limits**

- here, second break S_{b2} defined by $|n_2 - n_3| > \Delta n_{23}$, where n_2, n_3 PL indices around break position

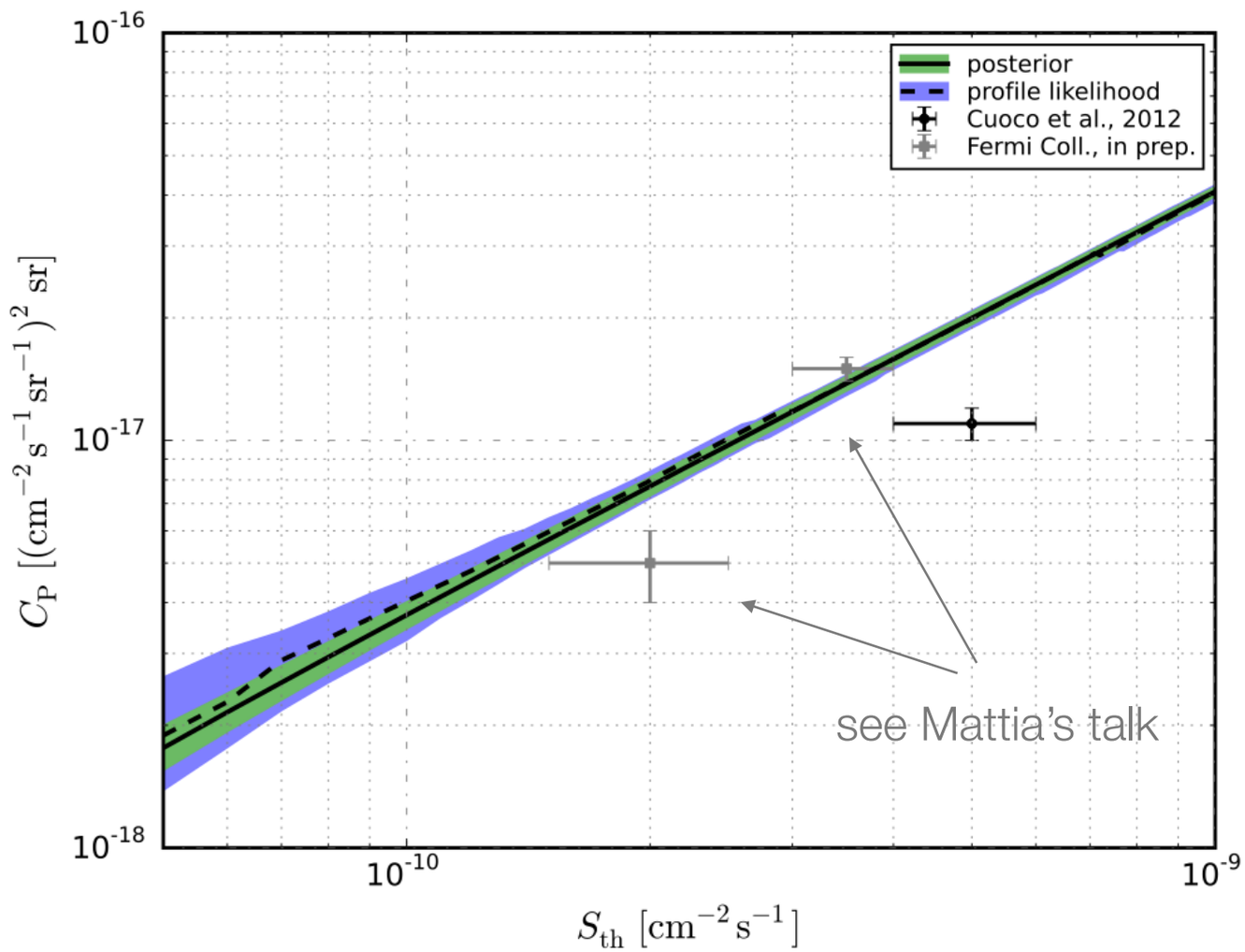
- fiducial upper limit: $S_{b2} < 6.4 \times 10^{-11}$ cm^{-2} s^{-1} for $\Delta n_{23} = 0.3$



Results (1-10 GeV) - Anisotropies

- **anisotropy derived from sampled d*N*/d*S*:**

$$C_{\mathrm{P}} = \int_0^{S_{\mathrm{th}}} \mathrm{d}S\, S^2 \frac{\mathrm{d}N}{\mathrm{d}S}$$



Composition of the Gamma-ray Sky (1-10 GeV)

- **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** $F_{ps} = (3.9\pm0.3)\times10^{-7}$ cm^{-2} s^{-1} sr^{-1}, corresponding to **(25±2)%** of the total flux

- integral **diffuse isotropic background** $F_{iso} = (0.9\pm0.2)\times10^{-7}$ cm^{-2} s^{-1} sr^{-1}, corresponding to **(6±2)%** of the total flux

- rest: Galactic foreground

profile likelihood for integral point-source flux

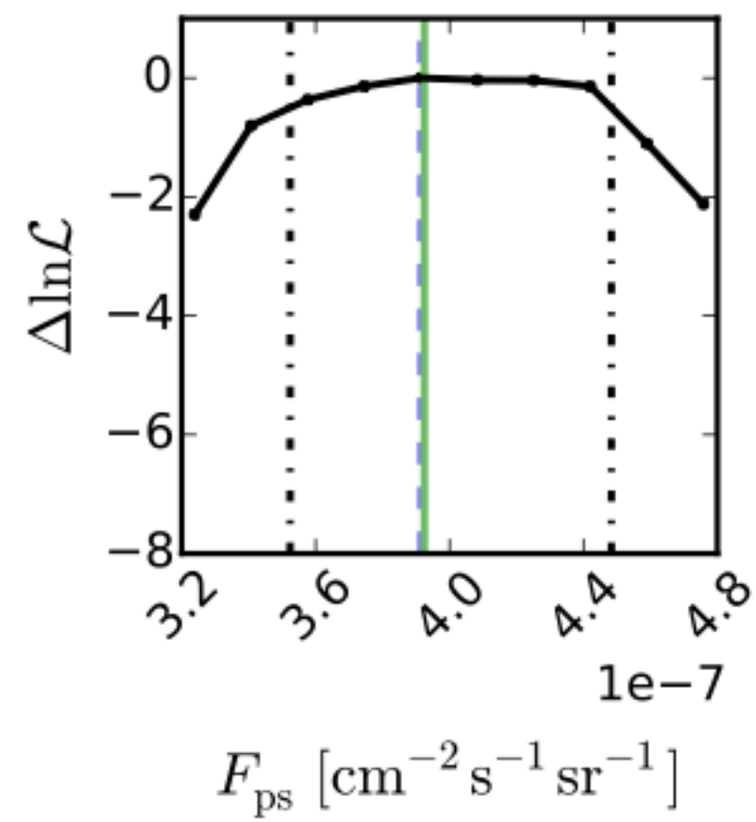


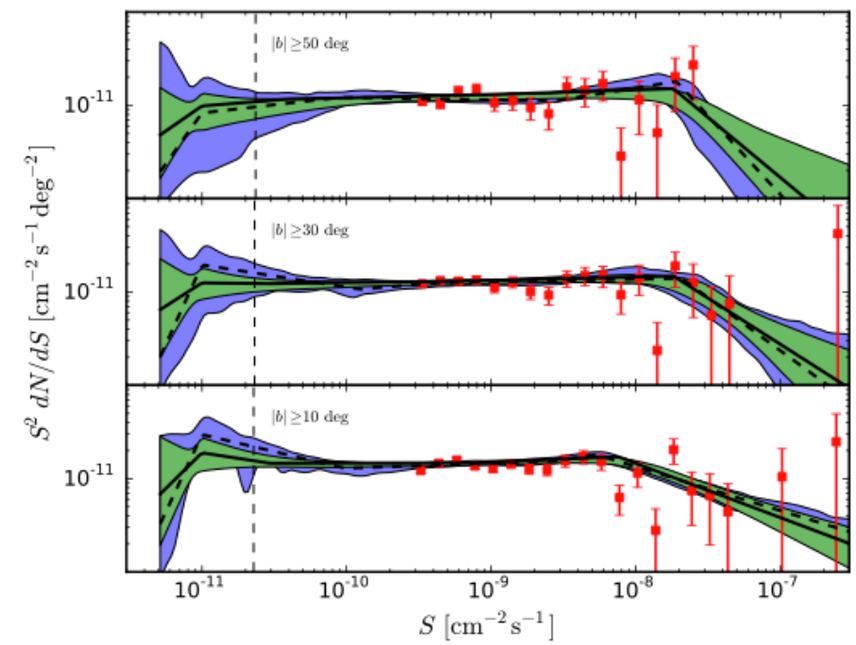
figure legend:
green: posterior median, blue: max. likelihood
dashed: 1-sigma errors (δln L = 0.5)

Systematics/Validation

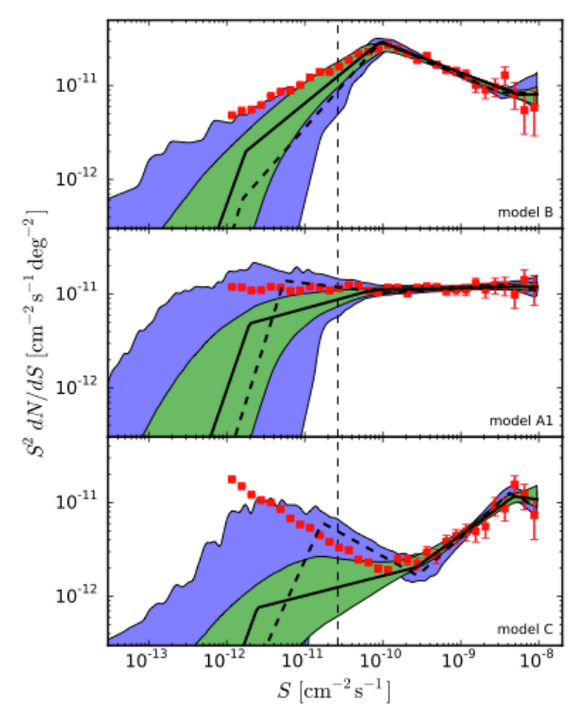
- analysis underwent several **systematic/modeling checks**:
  - masking bright point sources
  - pixel size
  - different *b*-cuts and Galactic foreground templates
  - point-source spectral index distribution

- validation with Monte-Carlo simulations (gtobssim)

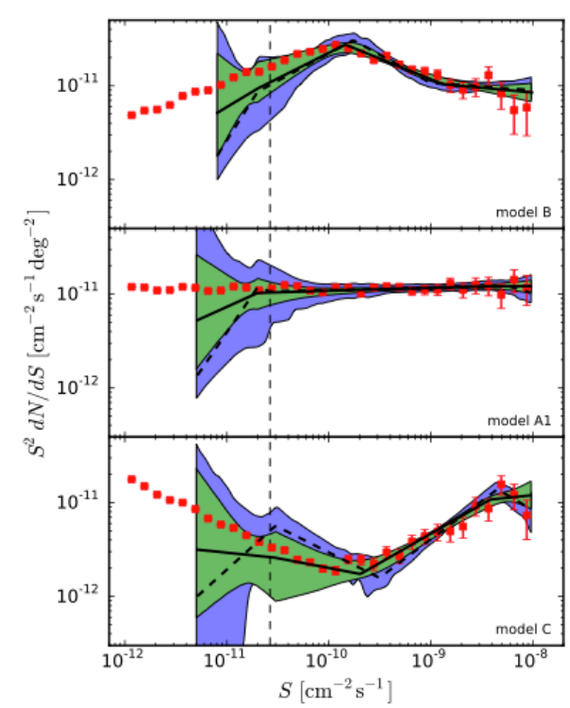
Galactic latitude cuts



MBPL



Hybrid



Summary

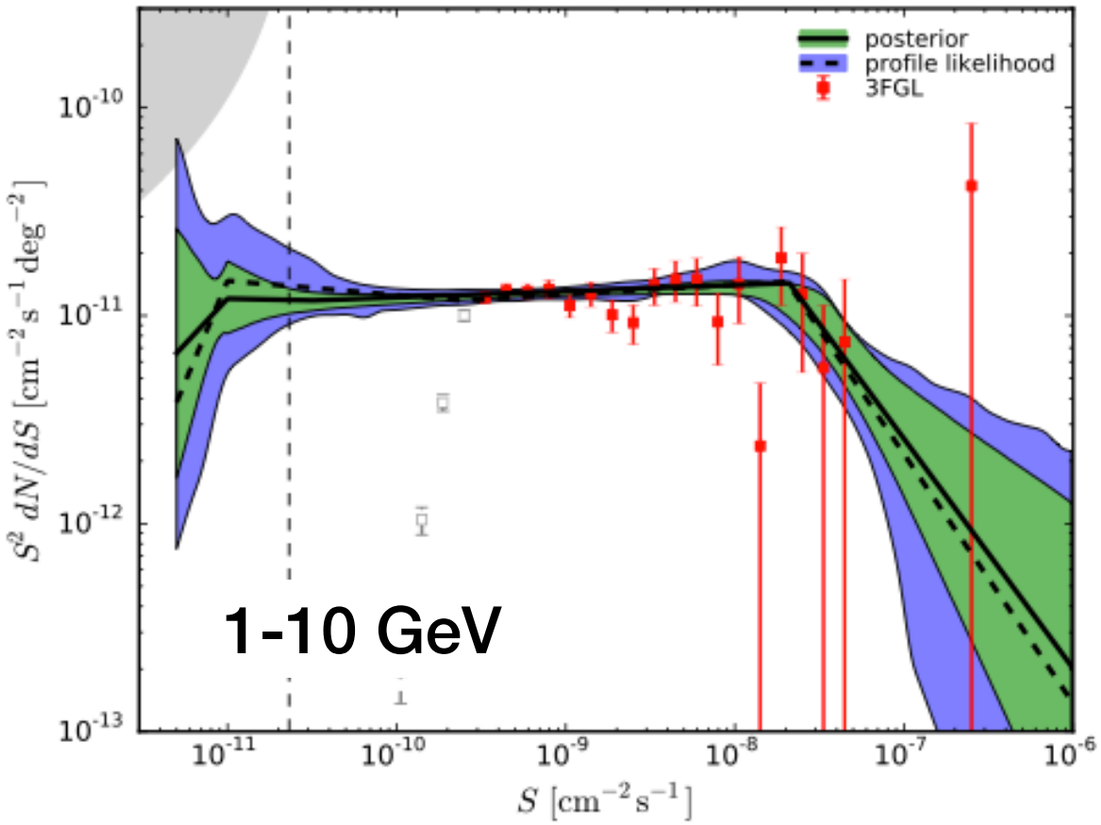
Thanks for your attention!

- 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) for 1 — 10 GeV energy band

- 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 between 1 GeV and 10 GeV remains almost flat in the region of unresolved sources; no evidence for second break

- analysis will offer the possibility to set significant constraints on the GLF and spectrum of unresolved blazar populations



Backup

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 →

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

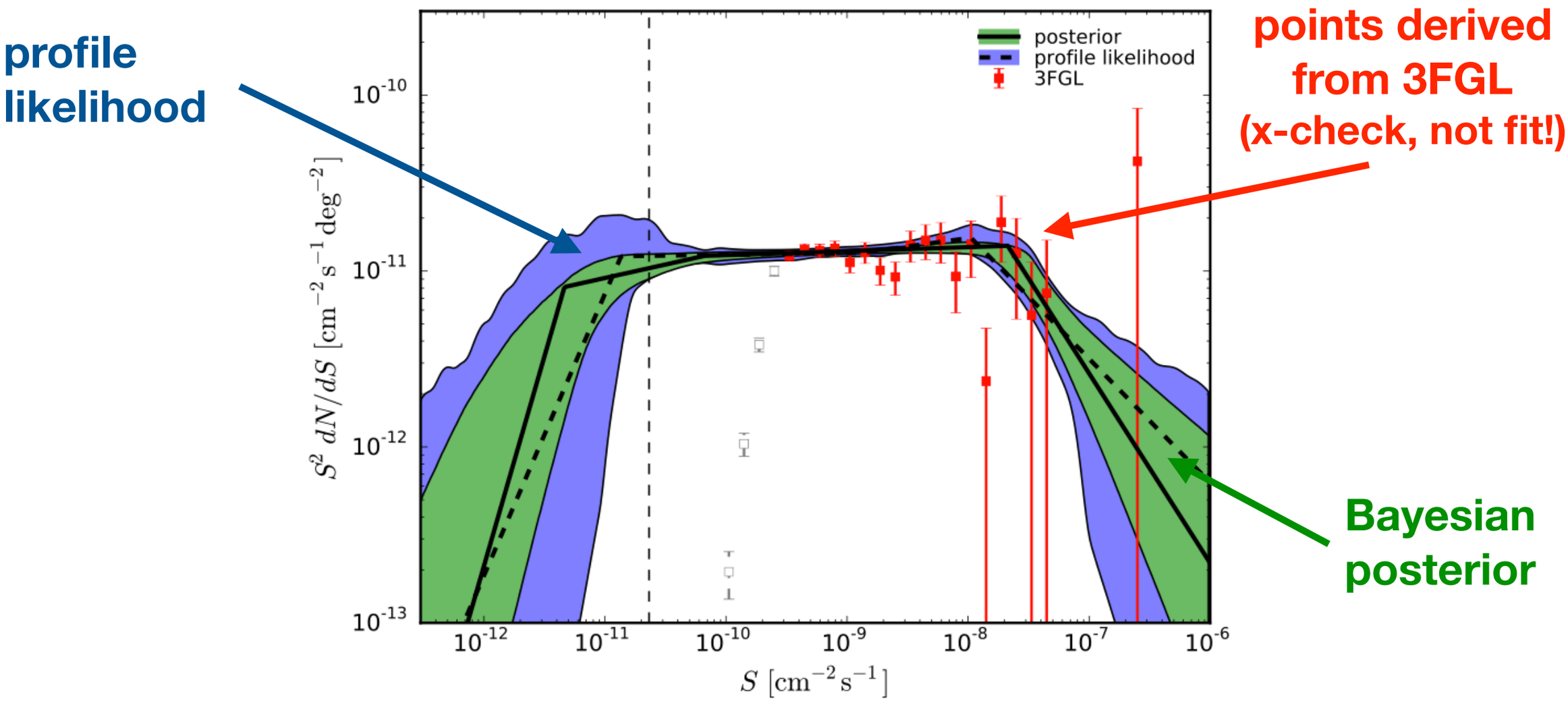
(expected) number of sources contributing *m* photons to pixel *p;* contributions

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

enter here.

Results (1-10 GeV) - MBPL Approach

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



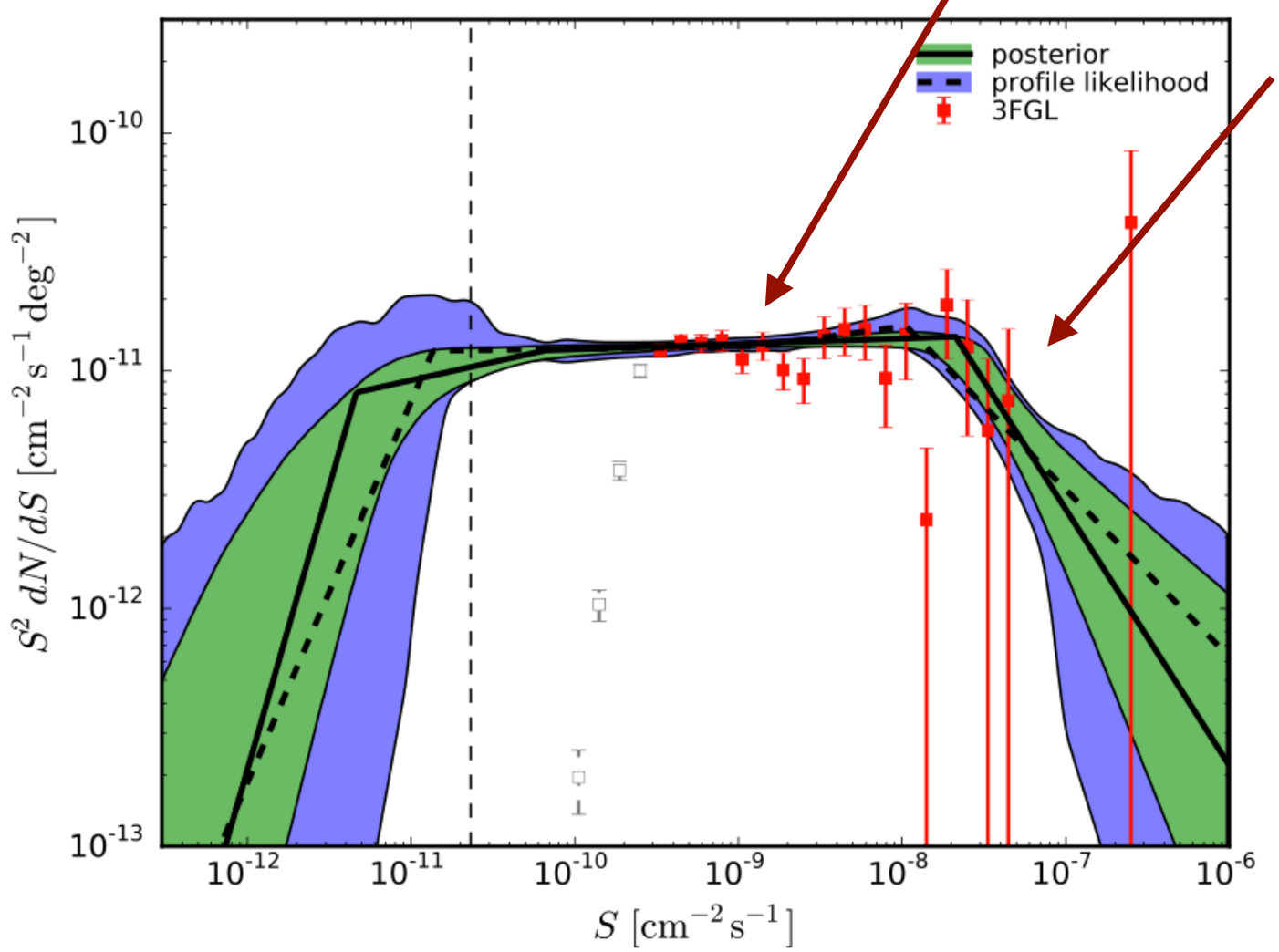
(b) MBPL, $N_b = 3$

Results (1-10 GeV) - 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



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

Results (1-10 GeV) - MBPL Approach

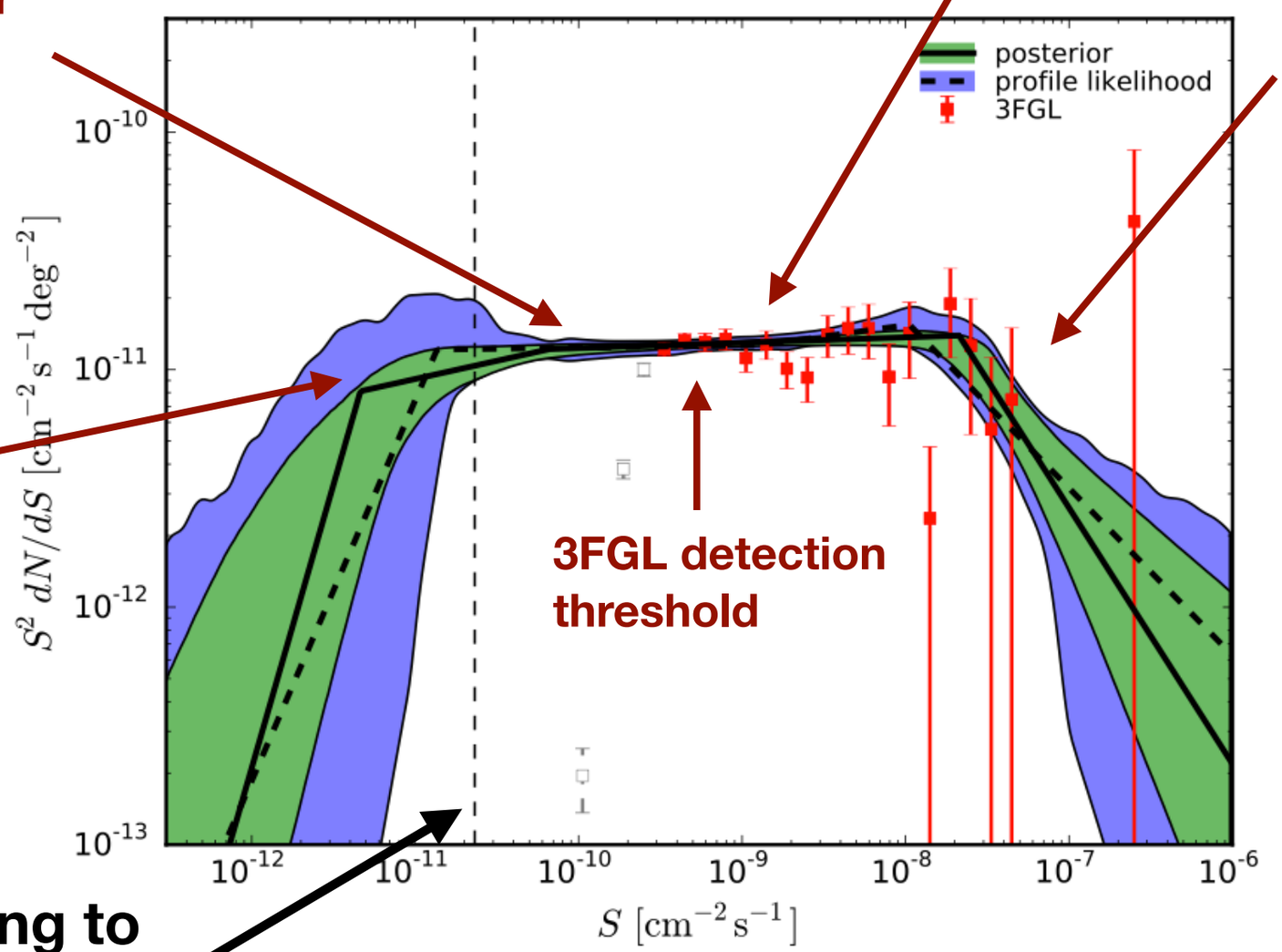
- **MBPL approach**:
  fit of a pure multiply broken PL; 3 free breaks

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

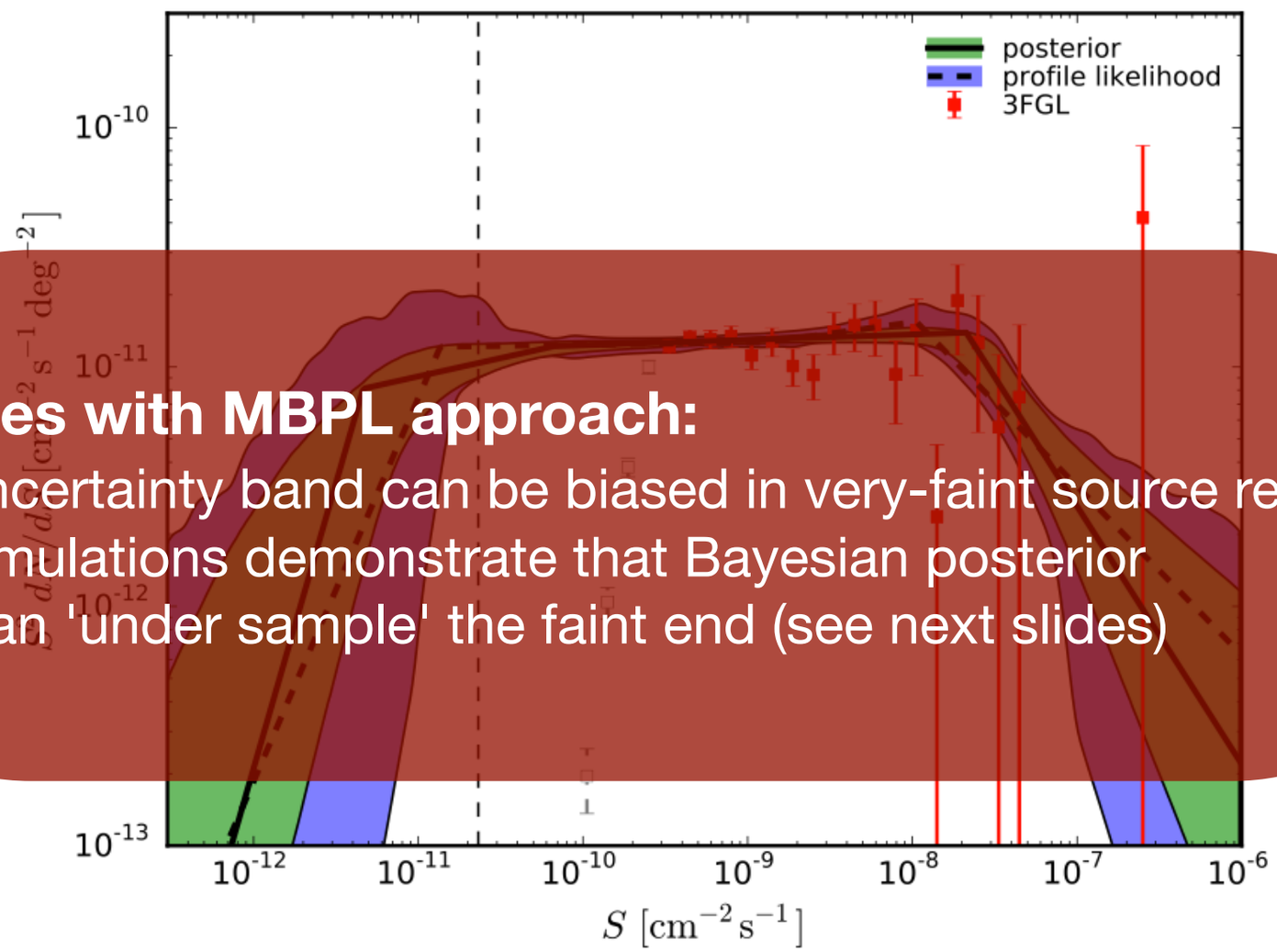


flux corresponding to 2 photons per pixel

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

Results (1-10 GeV) - MBPL Approach

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

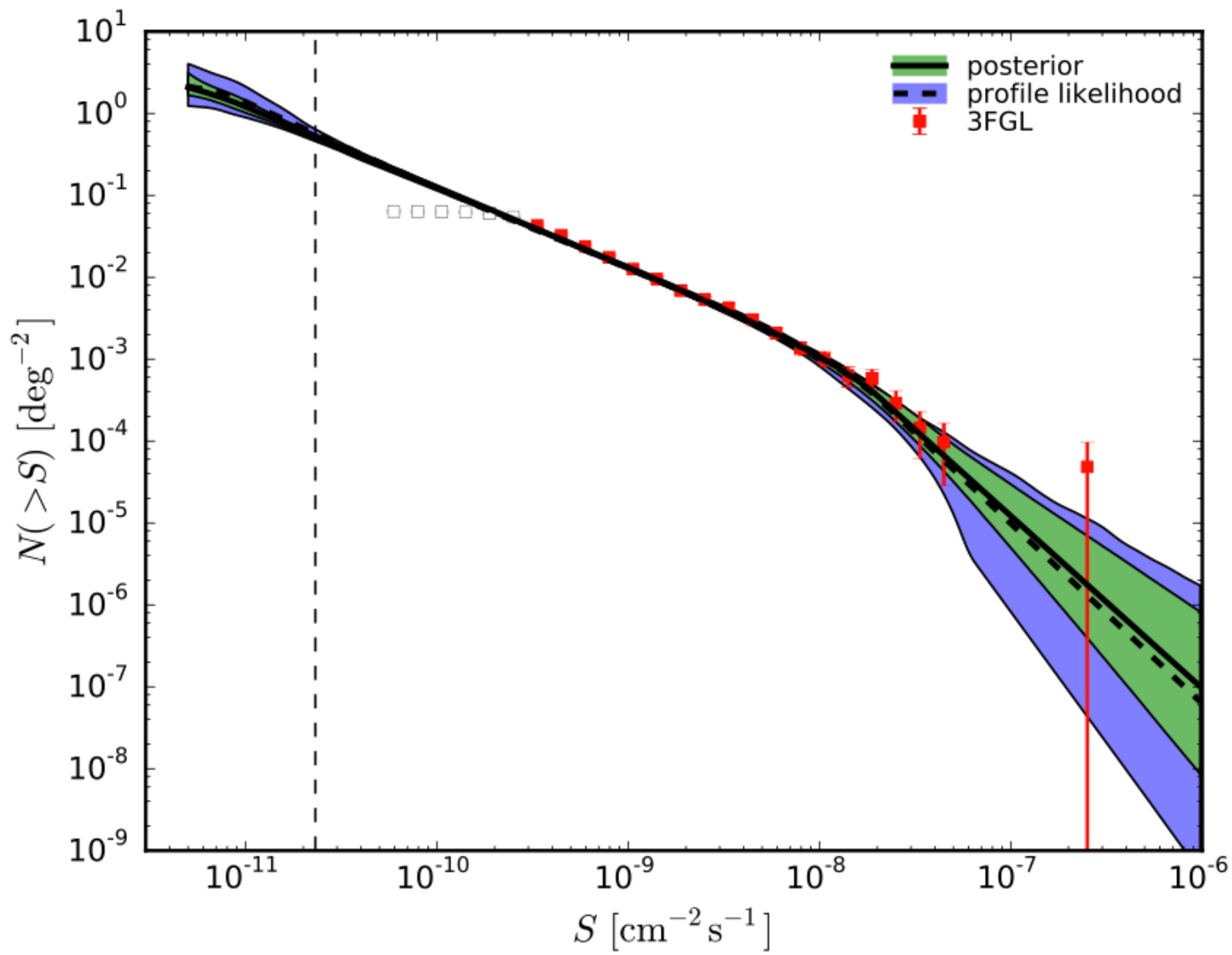


issues with MBPL approach:
- uncertainty band can be biased in very-faint source region
- simulations demonstrate that Bayesian posterior can 'under sample' the faint end (see next slides)

(b) MBPL, $N_b = 3$

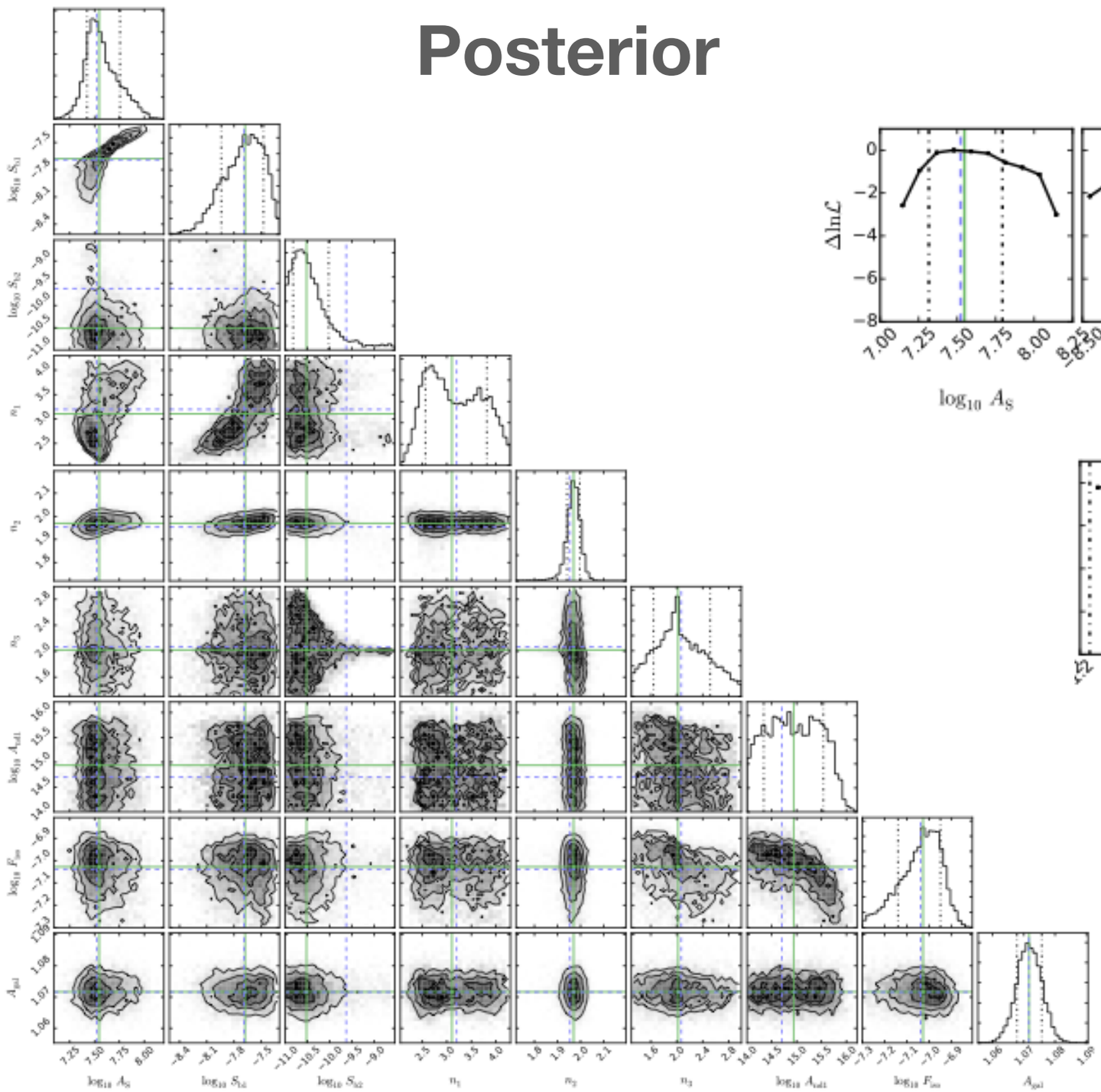
Results (1-10 GeV) - Hybrid Approach

- **integral source-count distribution N(>S)**



Hybrid Approach (1-10 GeV) - Sampling

Posterior



profile likelihood

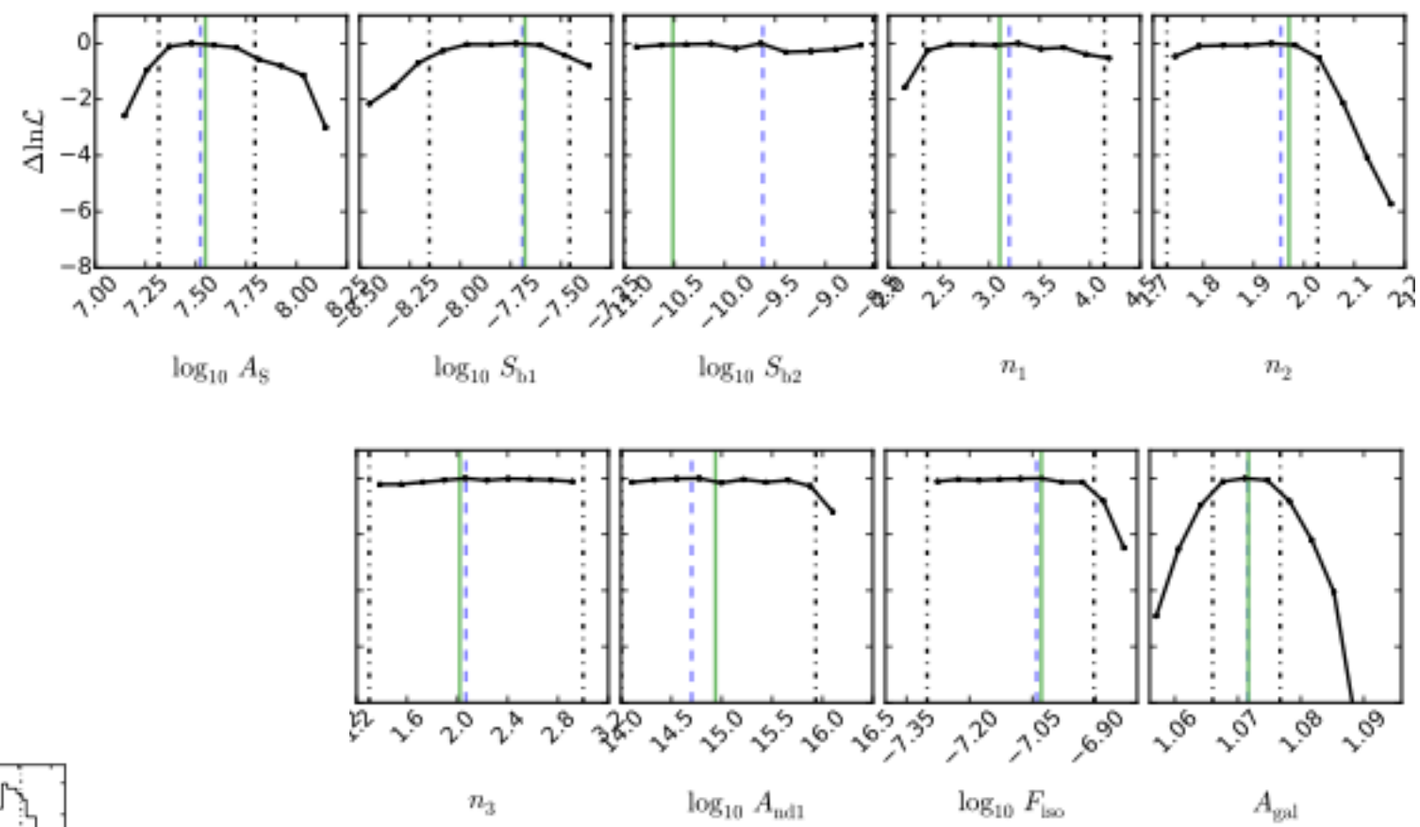
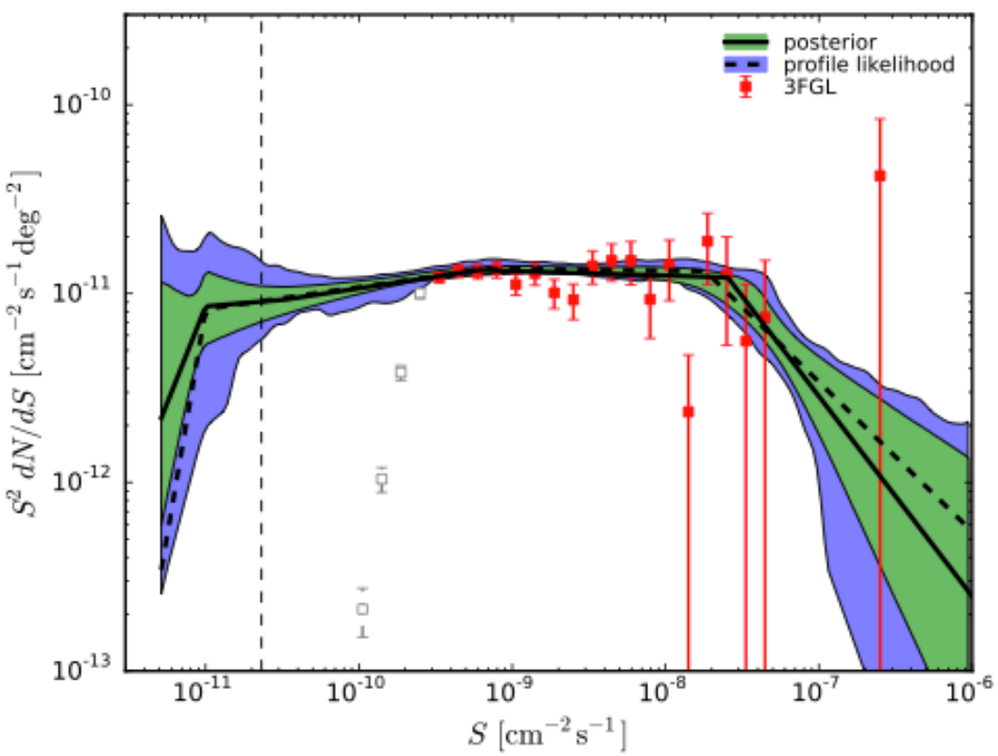
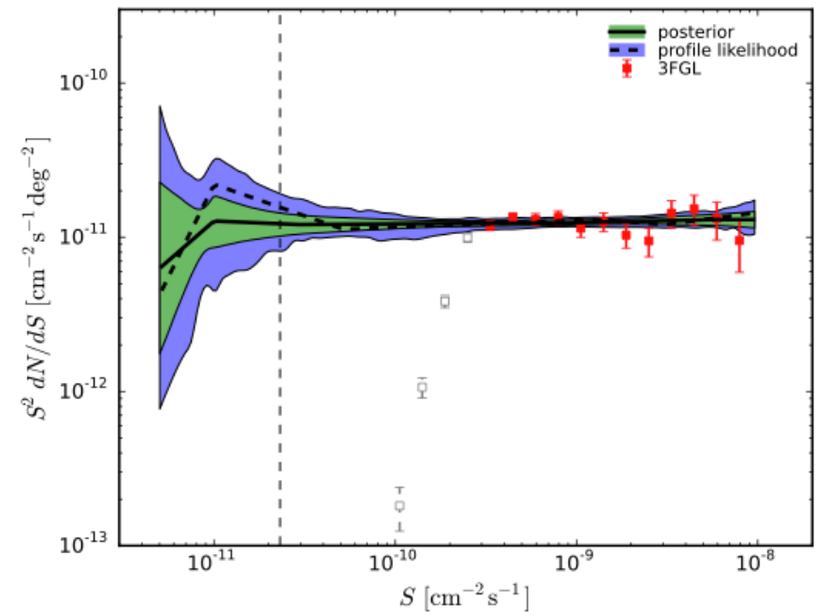


figure legend:
green: posterior median
blue: max. likelihood
dashed: 1-sigma errors

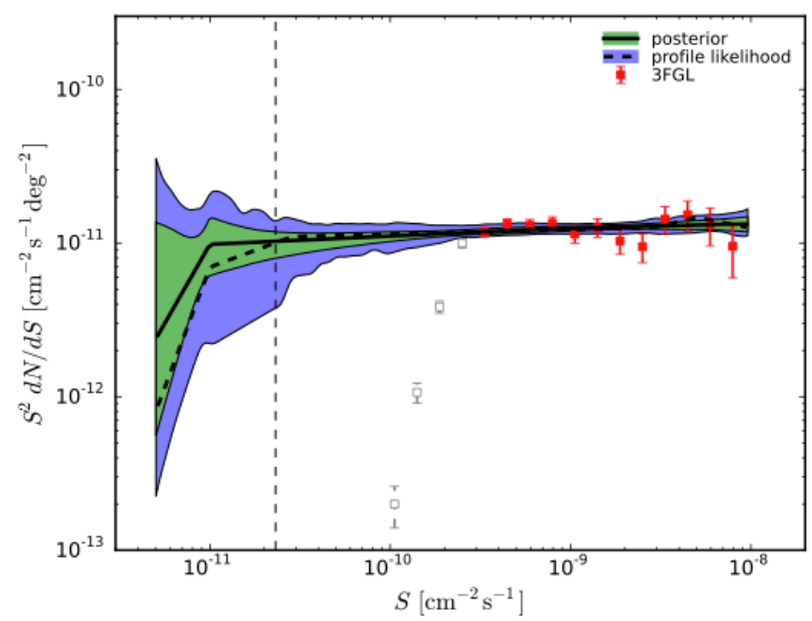
Systematics - Pixel Size and PS masking

HEALPix order 7





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



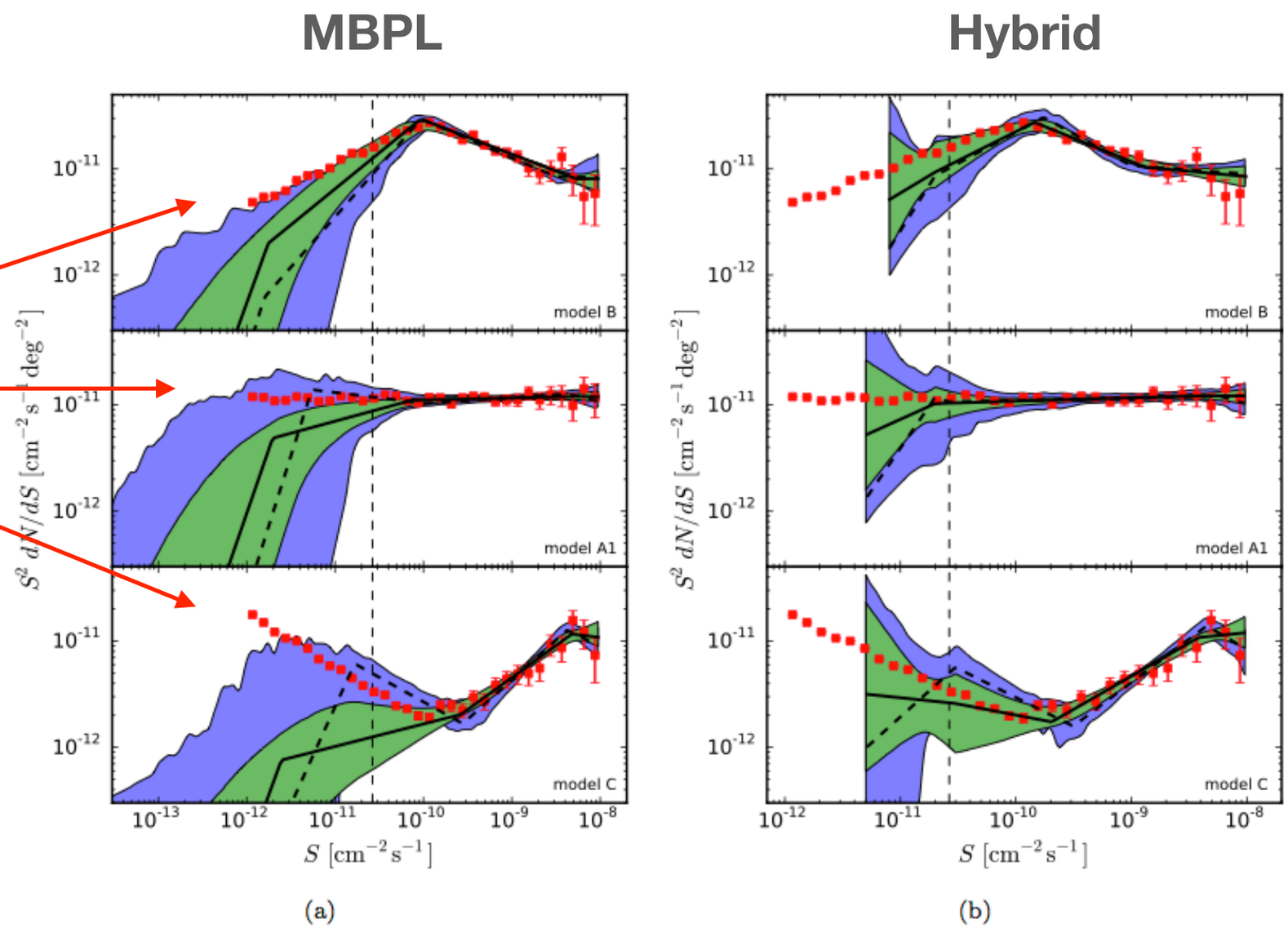
(b) point-source mask, HEALPix resolution $\kappa = 7$

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

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