Statistical Measurement of the Gamma-ray Source-count Distribution as a Function of Energy

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in collaboration with:
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based on:
- Zechlin et al. (2016), ApJS, 225, 2, 18
- Zechlin et al. (2016), ApJL, 826, 2, L31

UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

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INFN Istituto Nazionale di Fisica Nucleare

Statistical Image Analysis

- statistical analyses 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)**

Aim: 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

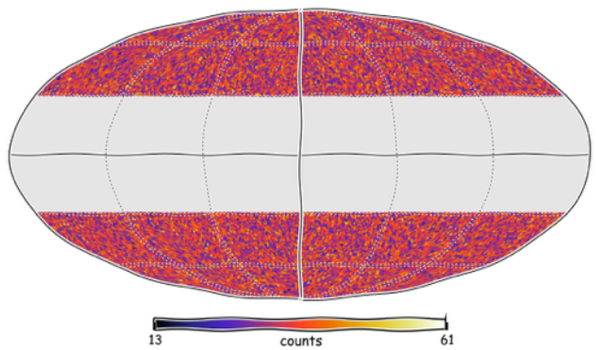
see also:
Lee et al., 2009; Dodelson et al., 2009;
Baxter et al., 2010; Massari et al., 2015;
Lee et al., 2016

1p-PDF Analysis (simple setup)

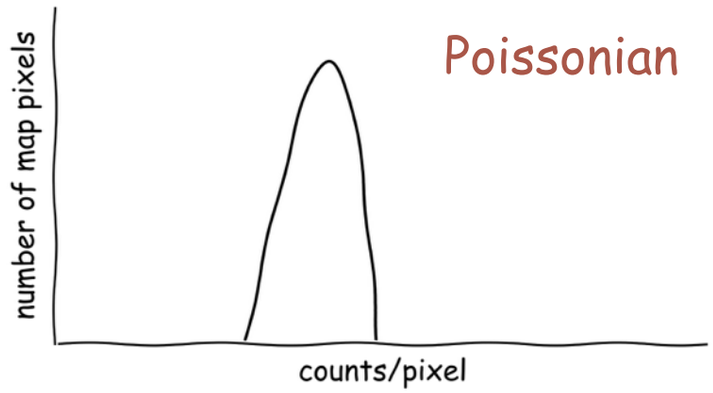
Idea: consider statistics of photon counts per single pixel

Examples:

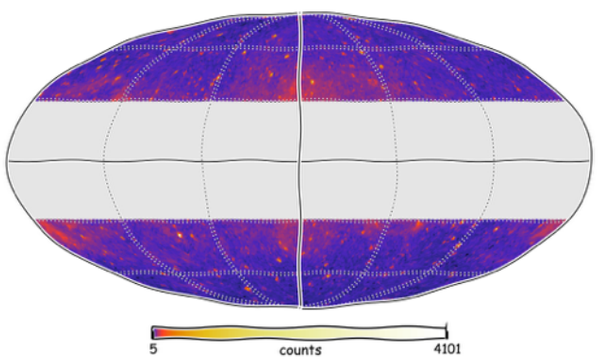
(A) diffuse isotropic background



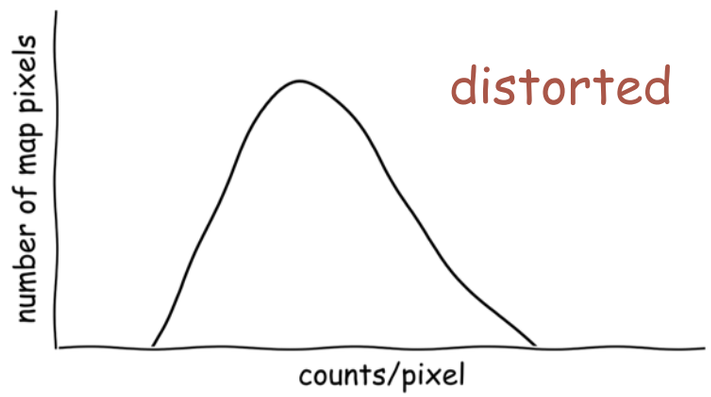
1p-PDF



(B) adding point sources, Galactic foreground, …



1p-PDF



- 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

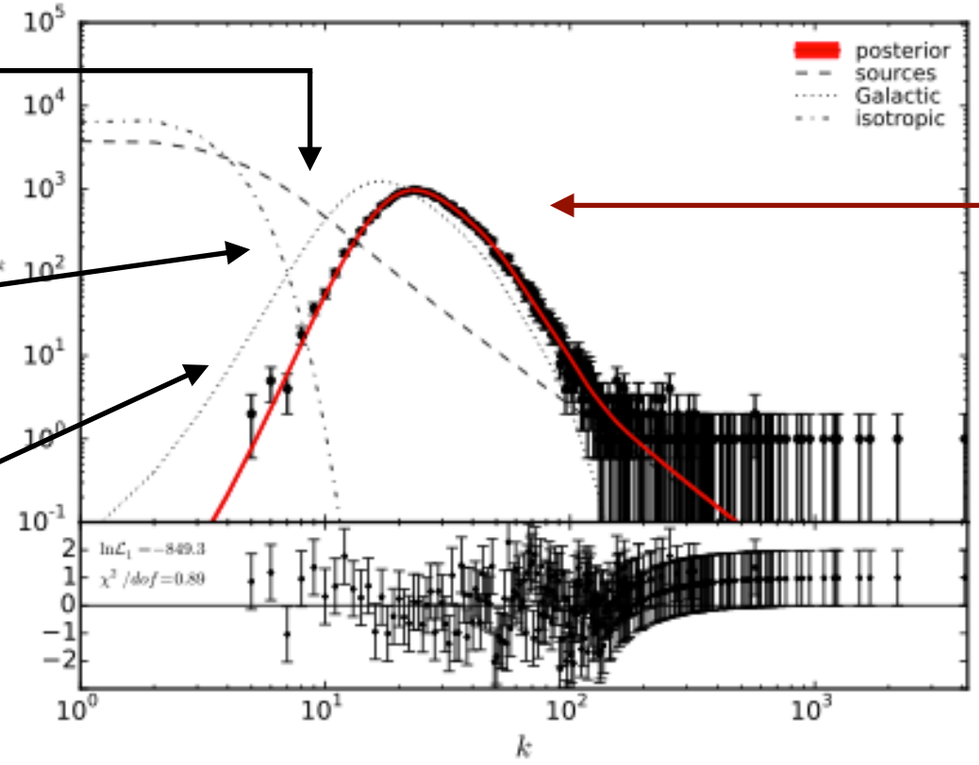
→ see M&H 2011 and Zechlin+ 2016, ApJS, for details

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 from data
  - **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:** full exploitation of spatial templates (see Zechlin+ 2016)

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

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

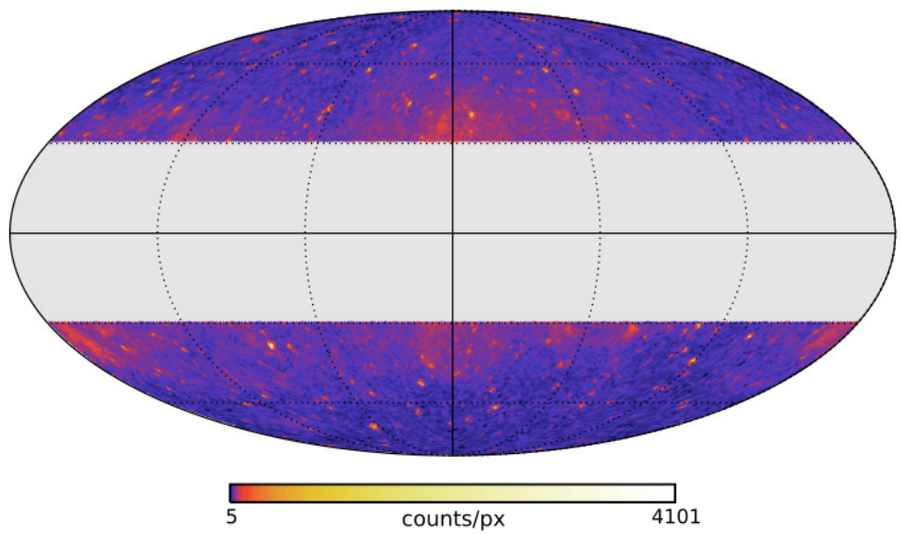
- parameter estimation: **Bayesian inference, profile likelihood (frequentist)**

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

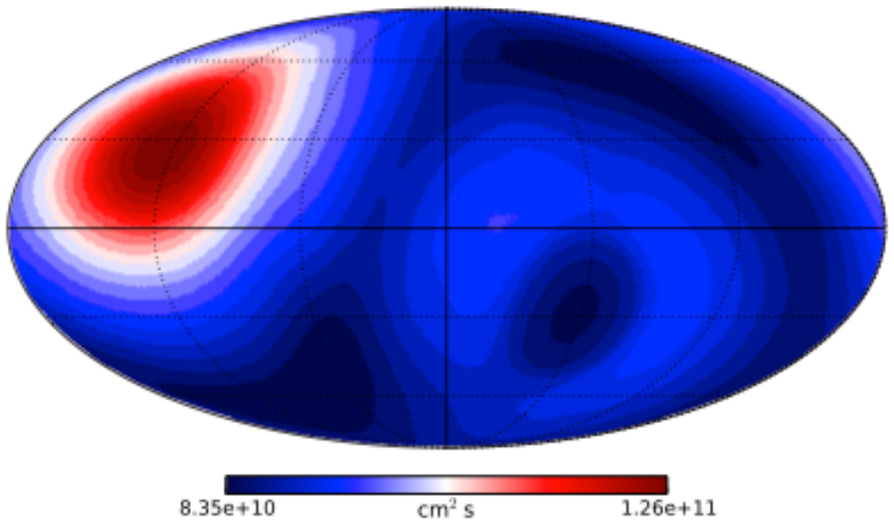
Fermi-LAT Data

- data set: P7REP
- observation time: 6 years
- event selection:
  - CLEAN, conversion: front/all
  - standard quality cuts
  - zenith-angle cut: 90 deg
  - **1 GeV —10 GeV**
  - **1 GeV — 171 GeV in 5 bins**
- high Galactic latitudes:
  |b| > 30 deg
- HEALPix grid, order 6,7

counts map, 1 GeV —10 GeV



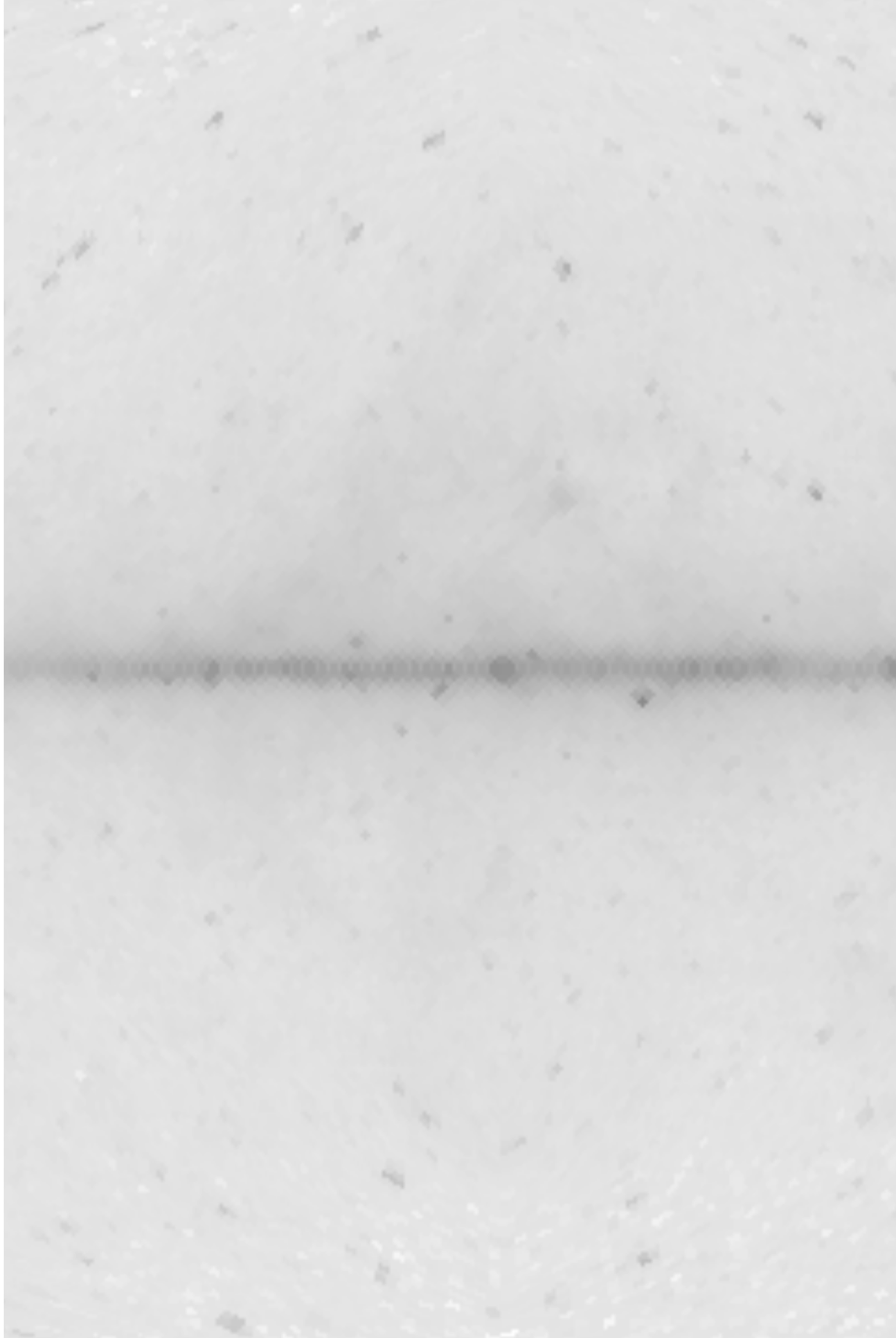
exposure in 20 iso-contours



Results

1 — 10 GeV

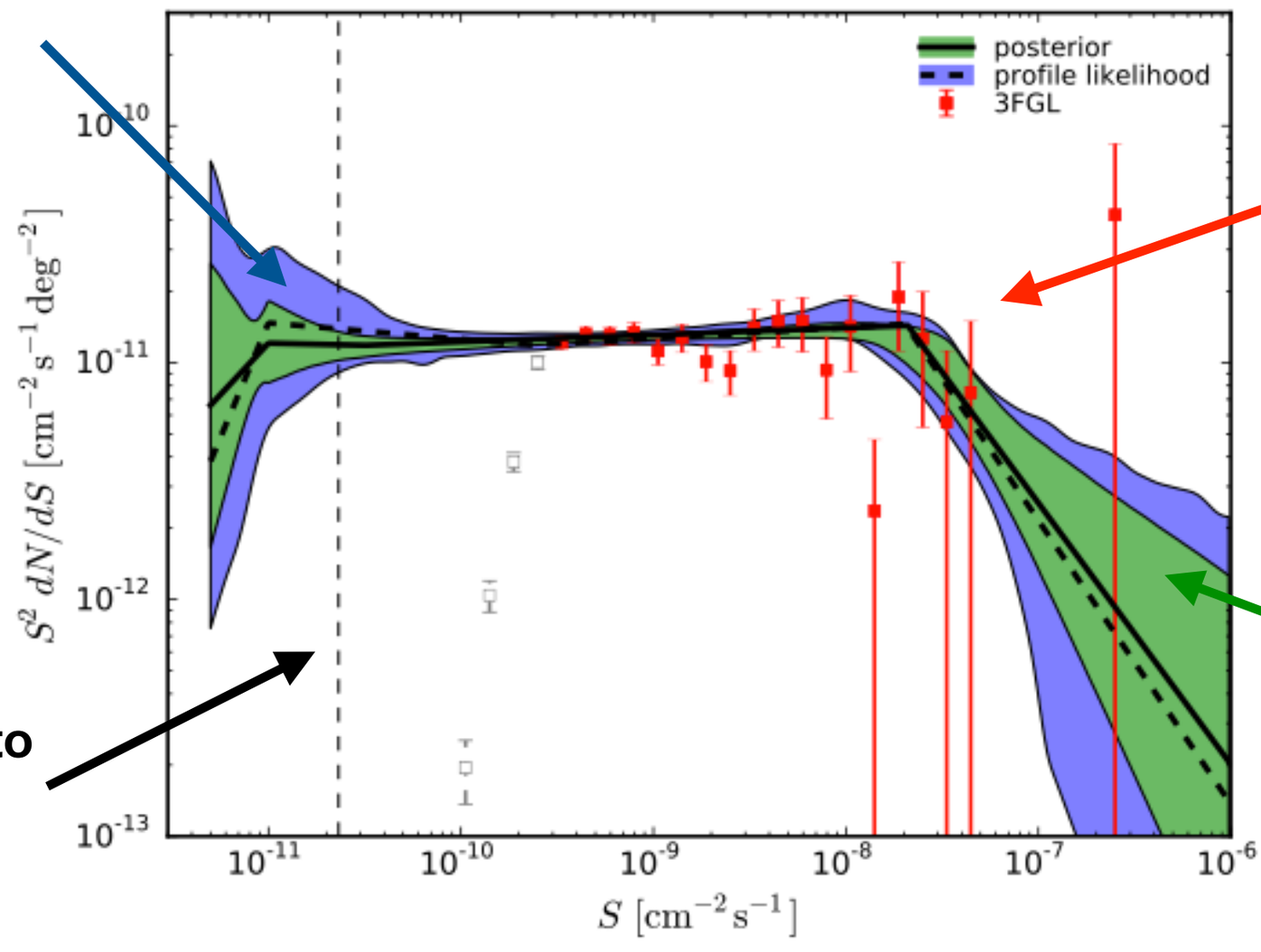
Zechlin et al. (2016), ApJS, 225



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:**
  - multiply broken PL (MBPL), 2 free breaks
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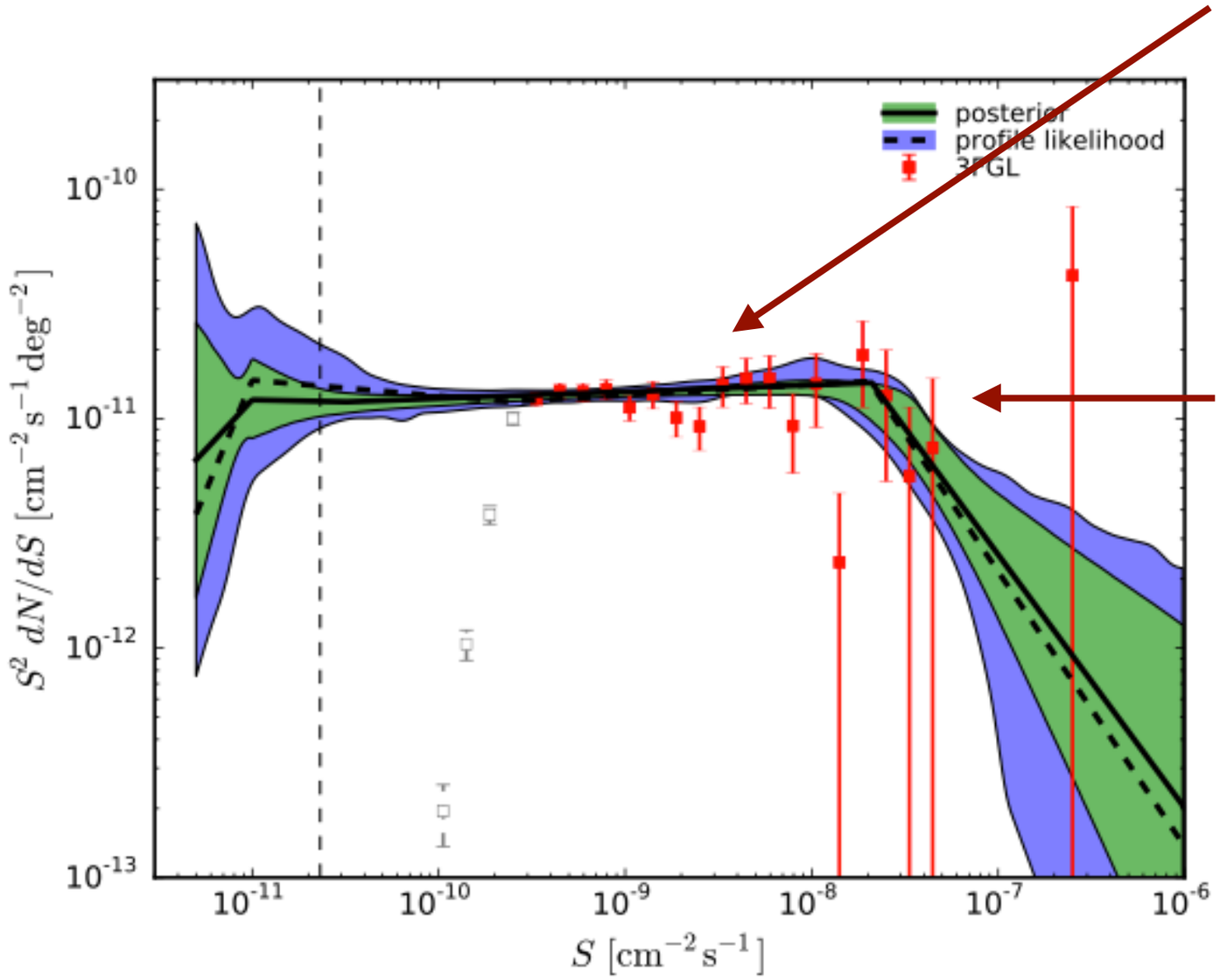


intermediate flux range fit with high accuracy; index n_2=1.97 ± 0.03

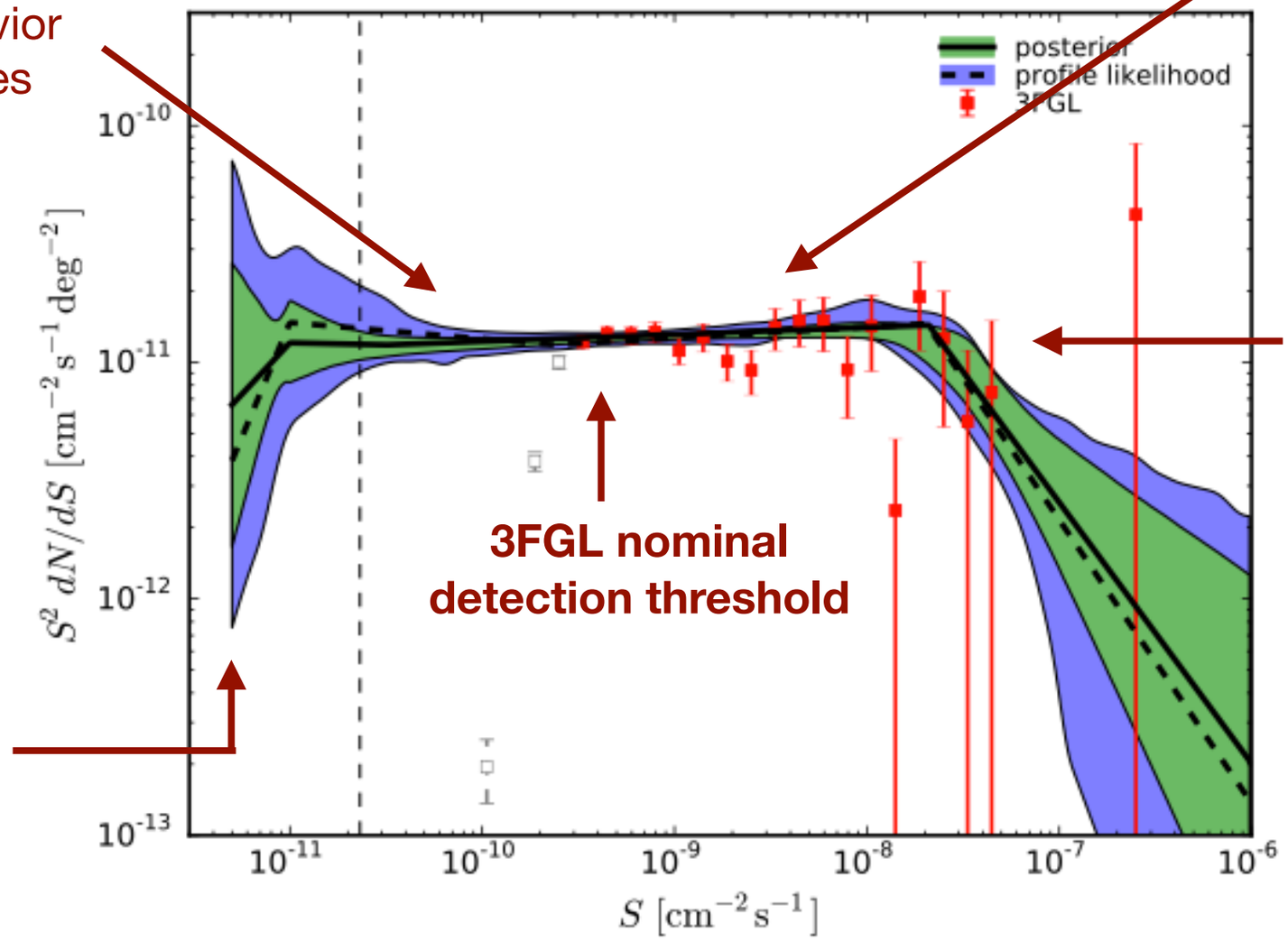
bright-source end correctly reproduced; first break resolved fairly well (sig. ~3σ)

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

fit prefers a flat behavior for unresolved sources

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)

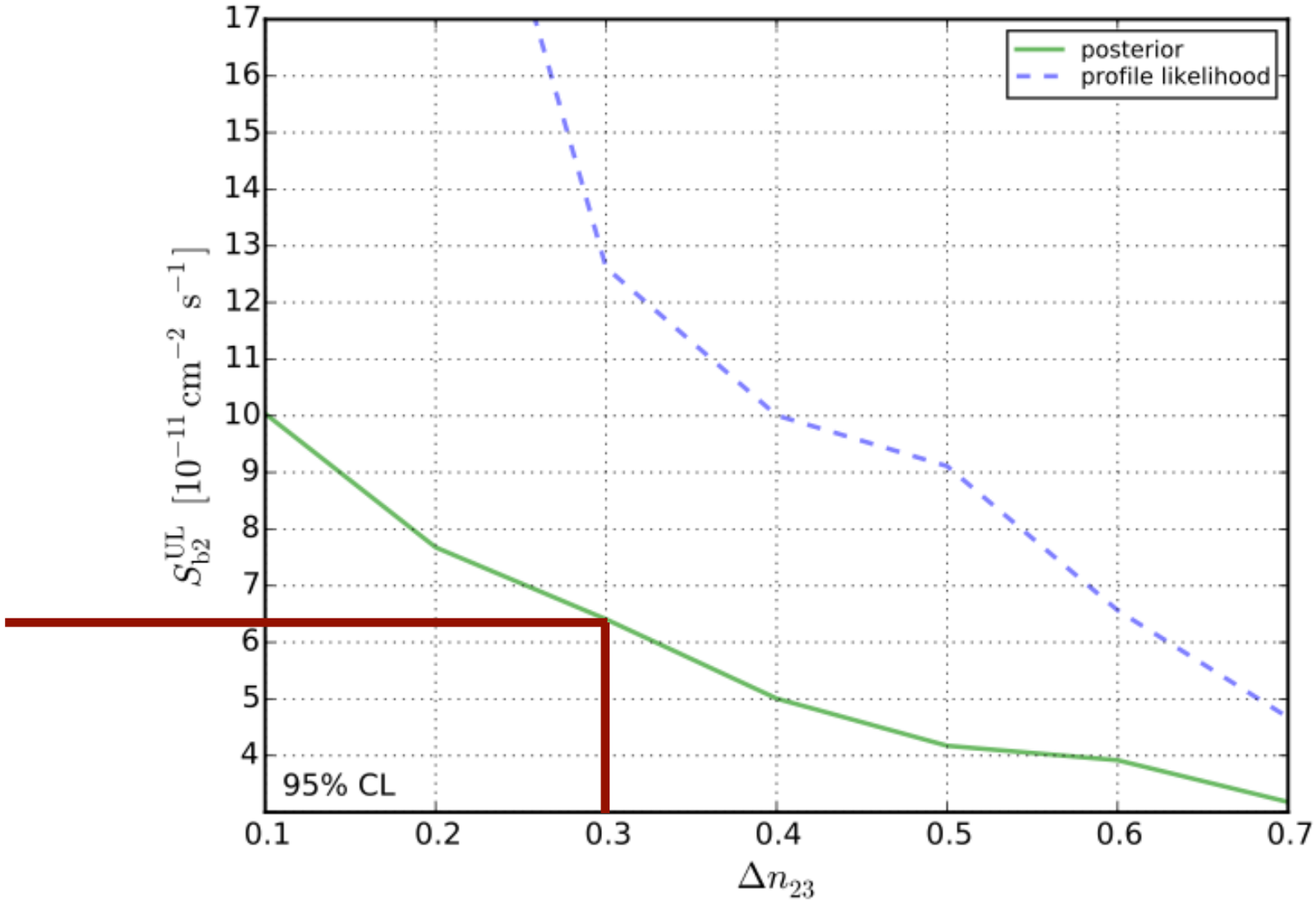
faint node:
models sensitivity cutoff found with pure MBPL fit

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

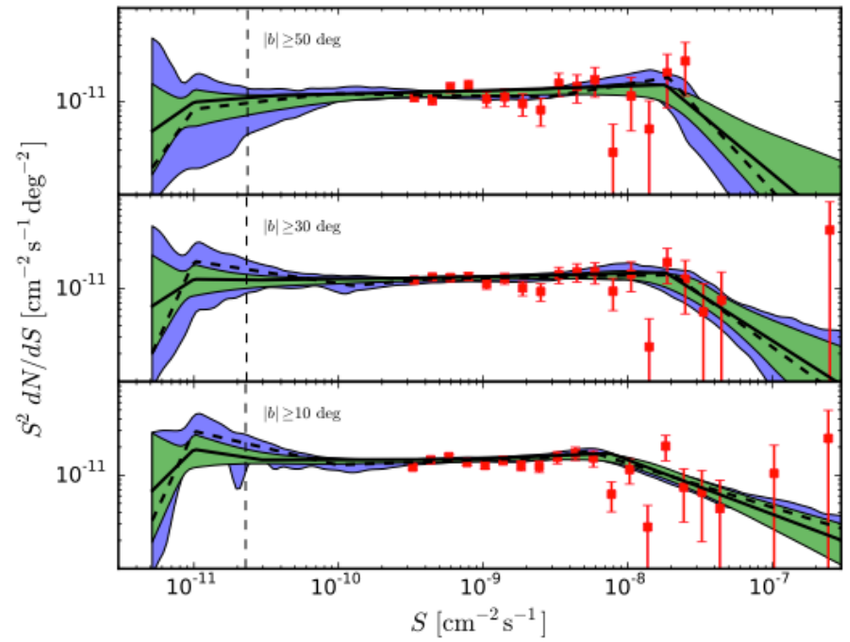
- fiducial upper limit: $S_{b2} < 6.4 \times 10^{-11}$ cm^{-2} s^{-1} for $\Delta n_{23} = 0.3$



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

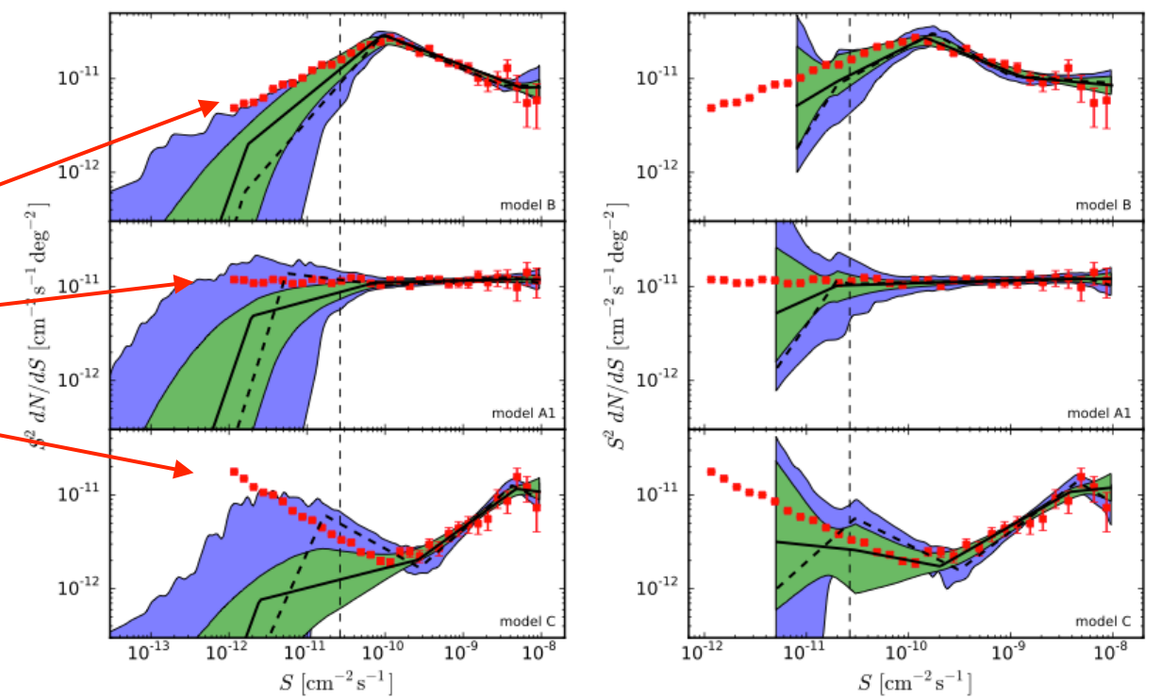
Galactic latitude cuts



- validation with Monte-Carlo simulations (gtobssim)

input d*N*/d*S*

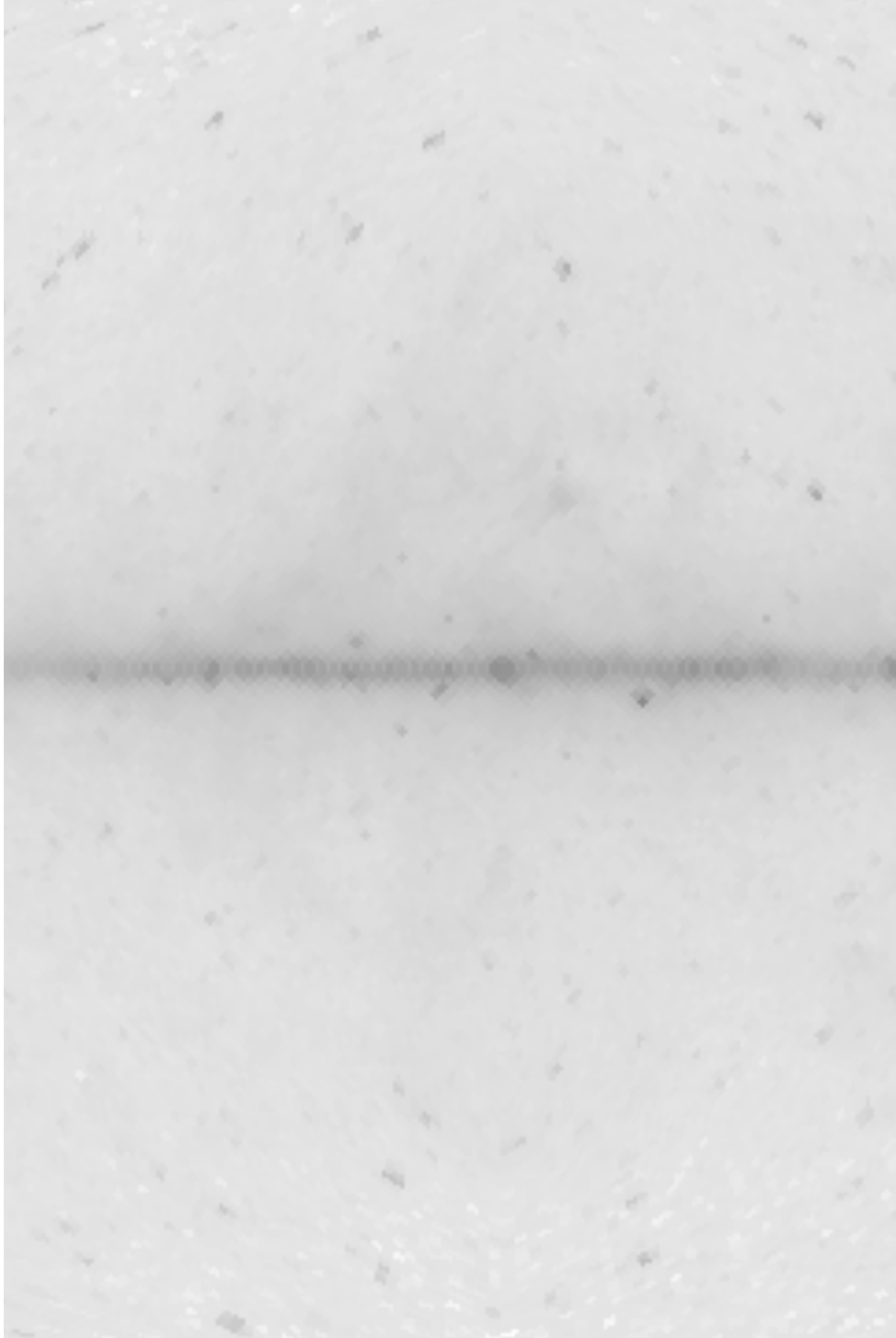
MBPL **Hybrid**



Results

1 — 2 GeV
2 — 5 GeV
5 — 10 GeV
10 — 50 GeV
50 — 171 GeV

Zechlin et al. (2016), ApJL, 826, L31



Energy-binned Analysis

- in general, d*N*/d*S* function of energy
  —> energy-binned analysis

- same method/data as used for 1—10 GeV

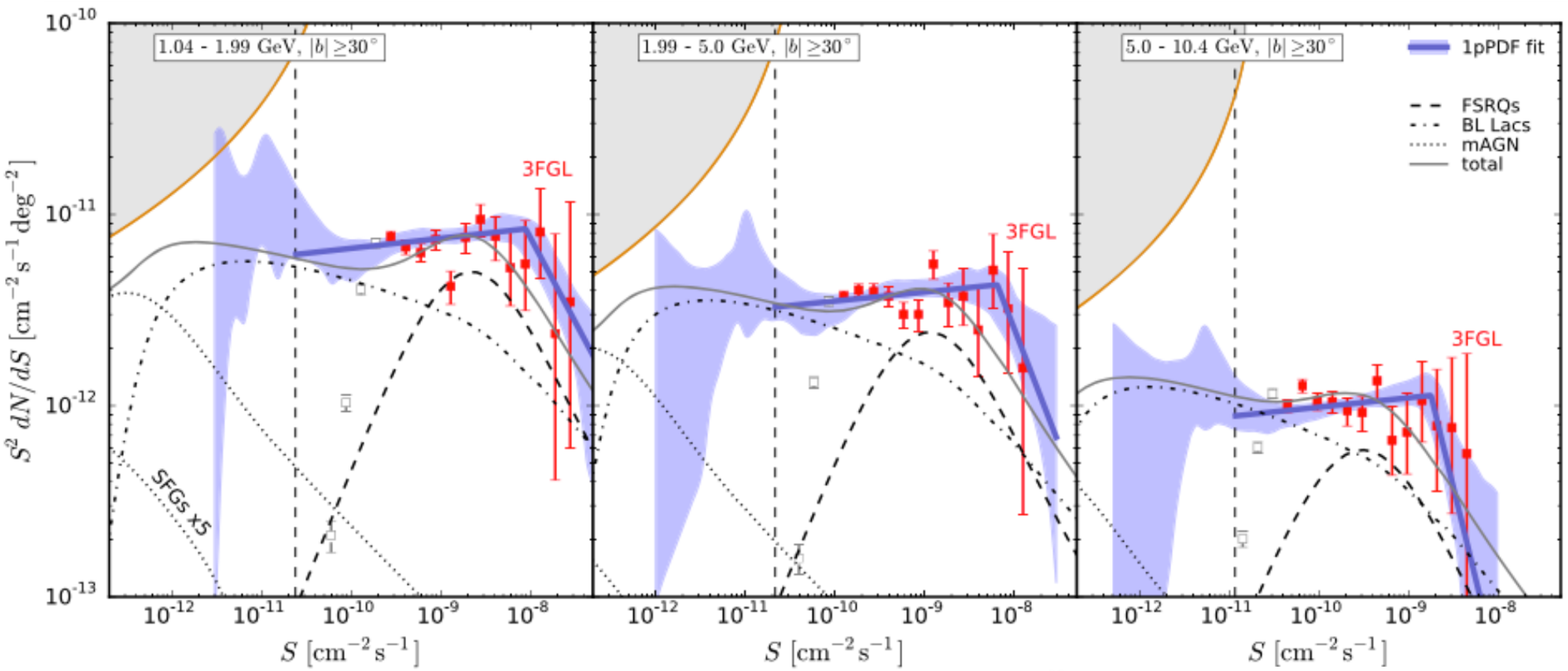
definition of bins as in anisotropy analysis by Ackermann et al., 2012

2FHL first bin →

Energy Bands and Analysis Parameters

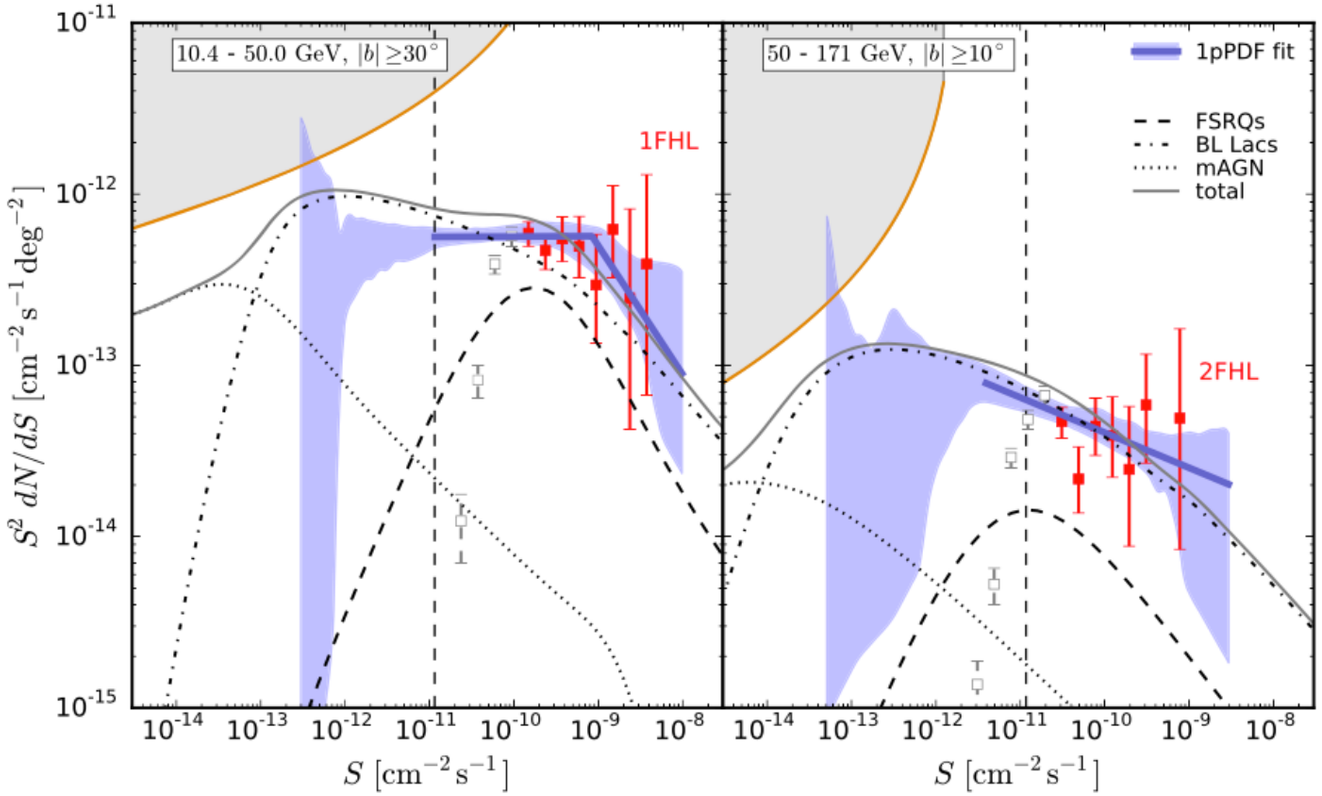
$E_{\rm min}$ (GeV)	$E_{\rm max}$ (GeV)	$\lvert b\rvert$ (°)	κ	$\sigma_{\rm psf}$ (°)	Γ	$S_0/10^{-9}$ (cm^{-2}s^{-1})	$N_{\rm b}^{\rm h}$
1.04	1.99	$\geqslant$30	6	0.52	2.4	30	1, 2, 3
1.99	5.0	$\geqslant$30	6	0.31	2.4	5	1, 2, 3
5.0	10.4	$\geqslant$30	6	0.23	2.4	1	1, 2
10.4	50.0	$\geqslant$30	6	0.15	2.2	0.1	1, 2
50	171	$\geqslant$10	7	0.13	2.2	0.1	1, 2

Results

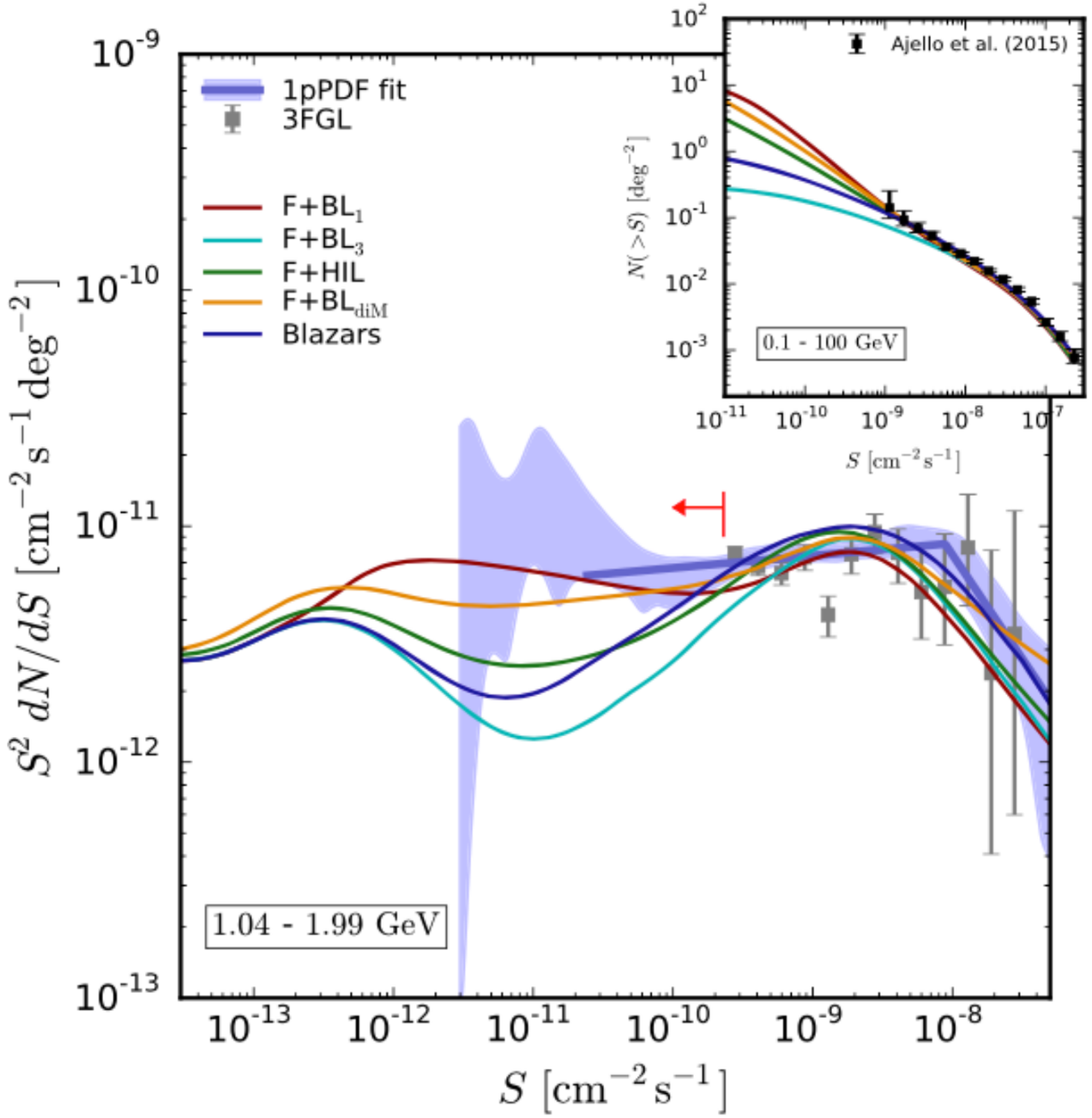


blue bands:
d*N*/d*S* estimate from profile likelihood

- MBPL and hybrid approaches used in consecutive order; number of free breaks adjusted to available statistics
- depicted models based on standard literature (see next slide; mostly adjusted to 1FGL data)



Comparison to Blazar Models



- models of blazar GLF built to agree with cataloged d*N*/d*S*
- can lead to very different predictions for unresolved component

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

BL Lac: Ajello et al. (2014)
FSRQ: Ajello et al. (2012)
Blazars: Ajello et al. (2015)
mAGN: Di Mauro et al. (2014)
SFG: Ackermann et al. (2012), Gruppioni et al. (2013)

Anisotropies

- **anisotropy derived from the d*N*/d*S* fit:**

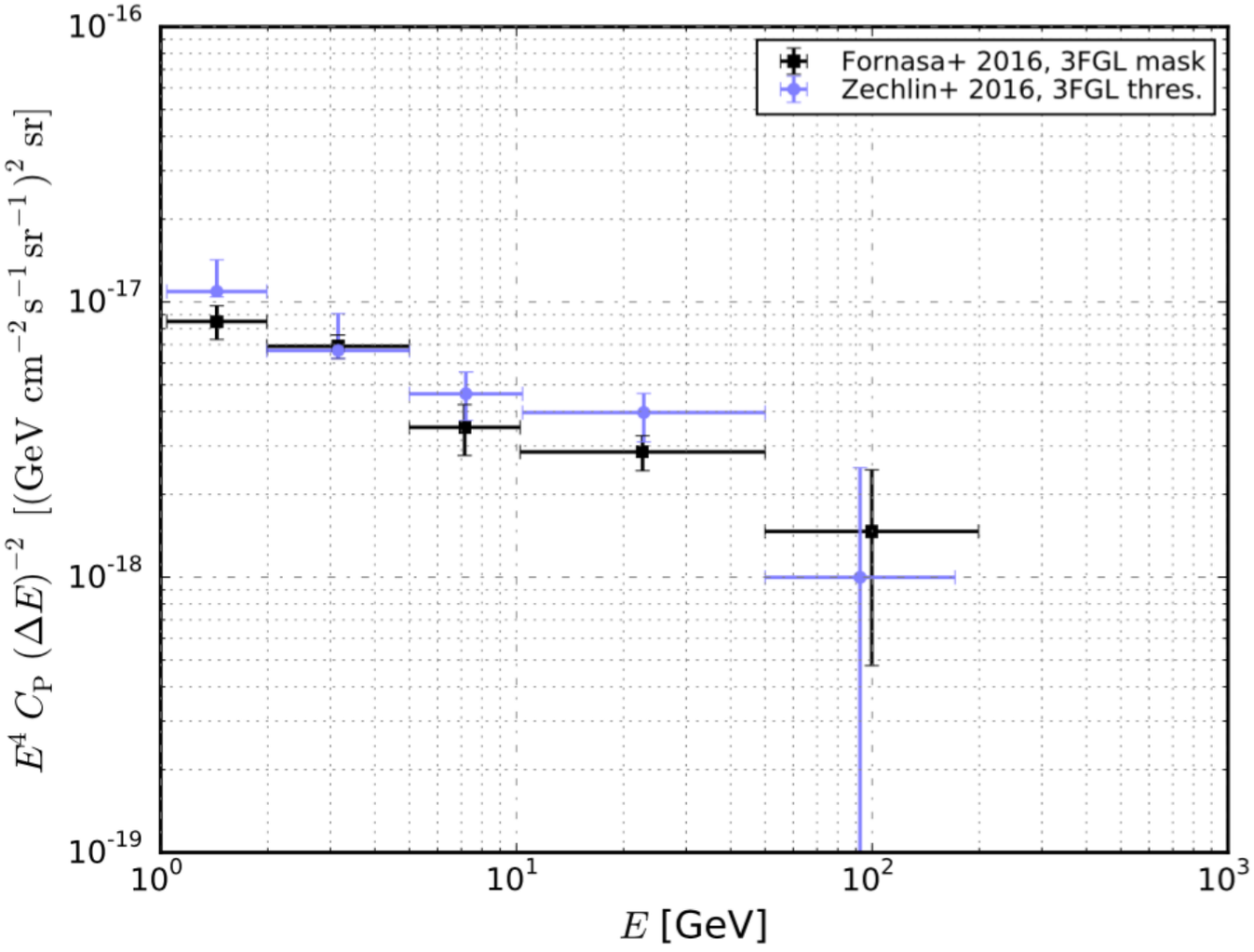
$$C_{\rm P} = \int_0^{S_{\rm th}} {\rm d}S\, S^2 \frac{{\rm d}N}{{\rm d}S}$$

- 3FGL catalog threshold not well defined. Effective threshold:

$$C_{\rm P}(S_{\rm th}^{\rm 3FGL}) \approx C_{\rm P}(S_{\rm th}^{<1}) - C_{\rm P}^{\rm cat}(S_{\rm th}^{<1})$$

$S_{th}^{<1}$: nominal threshold (catalog completeness)

- **conclusion:**
  we match the new anisotropy measurement of Fornasa+ 2016



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

- fractional contribution from point sources to the extragalactic gamma-ray background (EGB, Ackermann et al., 2015) as a function of energy, **F_{ps}/F_{EGB}** :

1-2 GeV	2-5 GeV	5-10 GeV	10-50 GeV	50-171 GeV
$0.83^{+0.07}_{-0.13}$	$0.79^{+0.04}_{-0.16}$	$0.66^{+0.20}_{-0.07}$	$0.66^{+0.28}_{-0.05}$	$0.81^{+0.52}_{-0.19}$

profile likelihood for integral point-source flux F_{ps} (1-10 GeV)

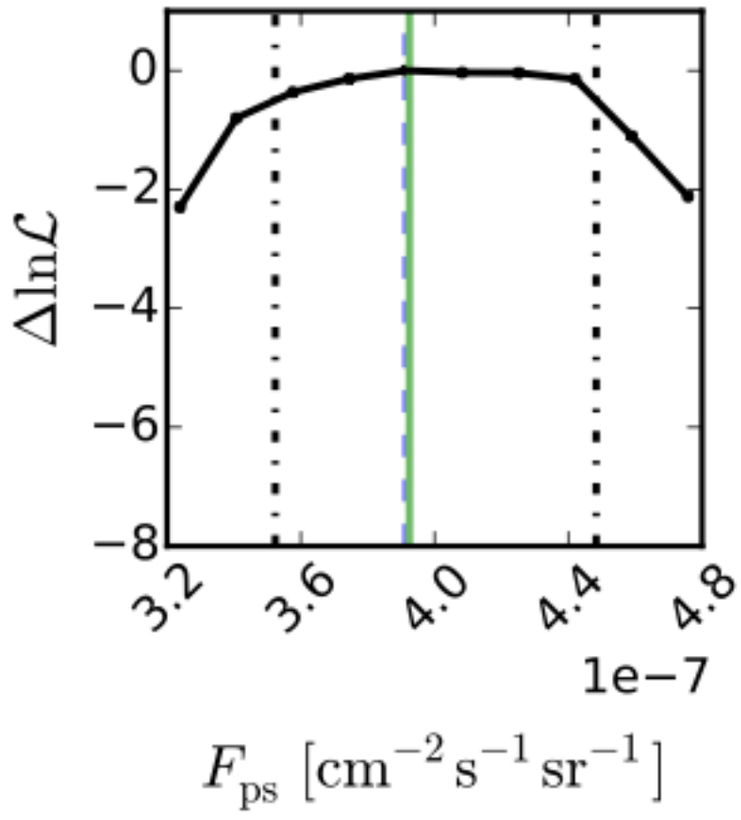


figure legend:
green: posterior median, blue: max. likelihood
dashed: 1-sigma errors (δln L = 0.5)

Summary

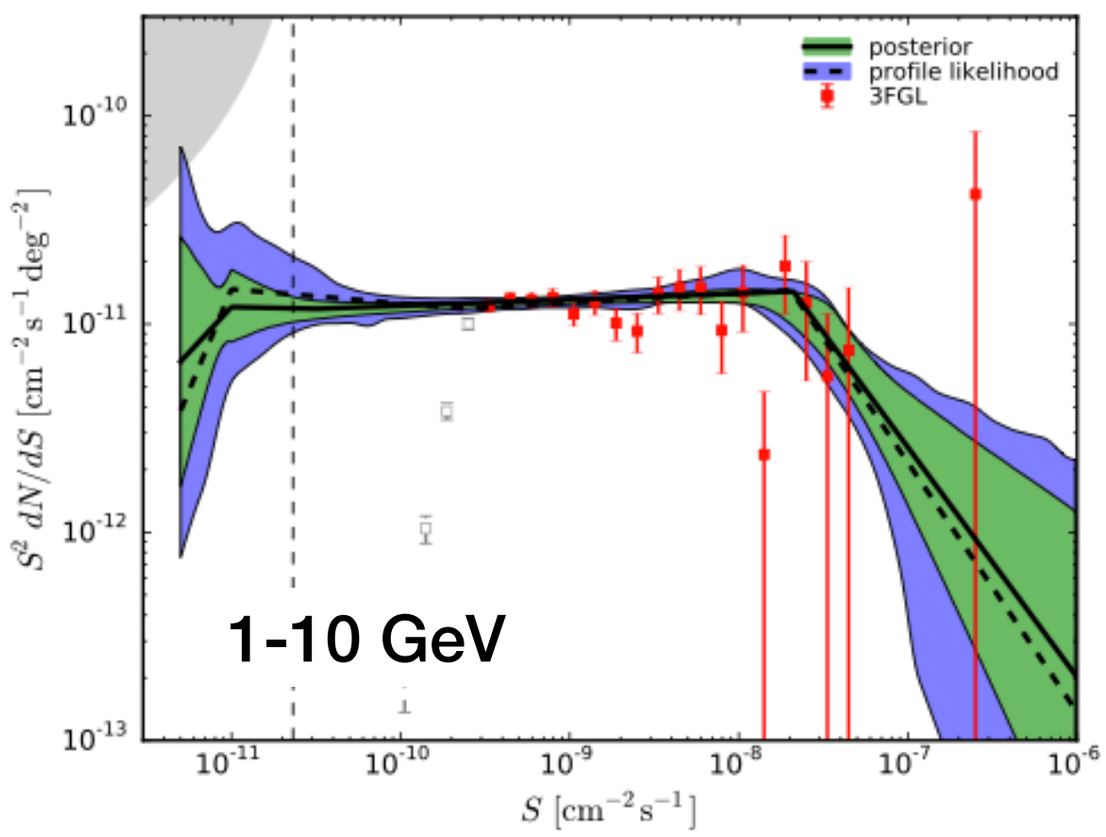
Thank you for your attention!

- 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 different energy bands > 1 GeV

- new statistical method developed including spatial template fitting, a d*N*/d*S* model with multiple breaks, PSF correction, and exposure correction

- d*N*/d*S* below 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

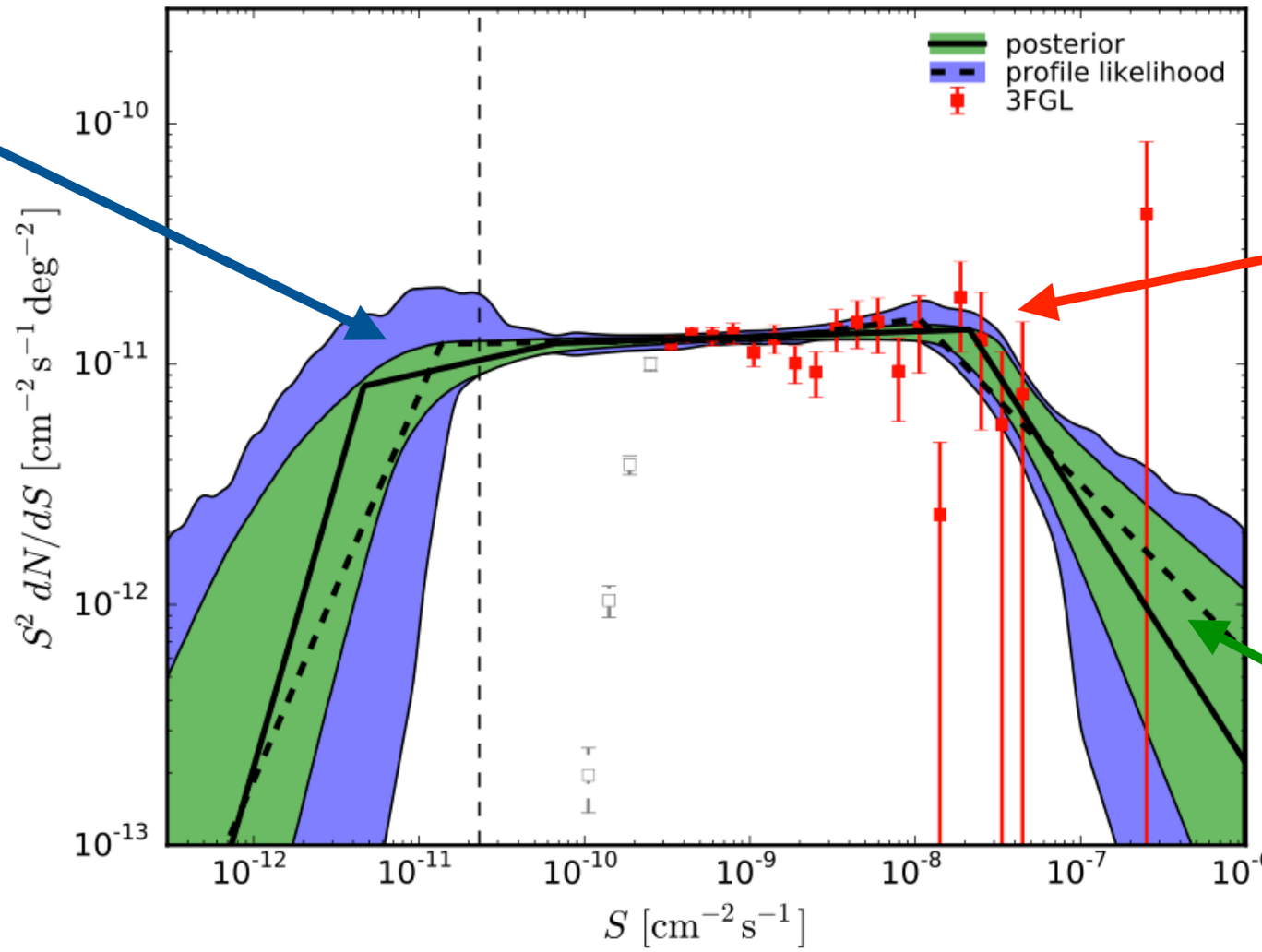
(a) point sources (d*N*/d*S* distribution),
(b) Galactic foreground template (A_{gal})
(c) diffuse isotropic background (F_{iso})
(d) …

enter here.

Results (1-10 GeV) - MBPL Approach

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

profile likelihood



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

Bayesian posterior

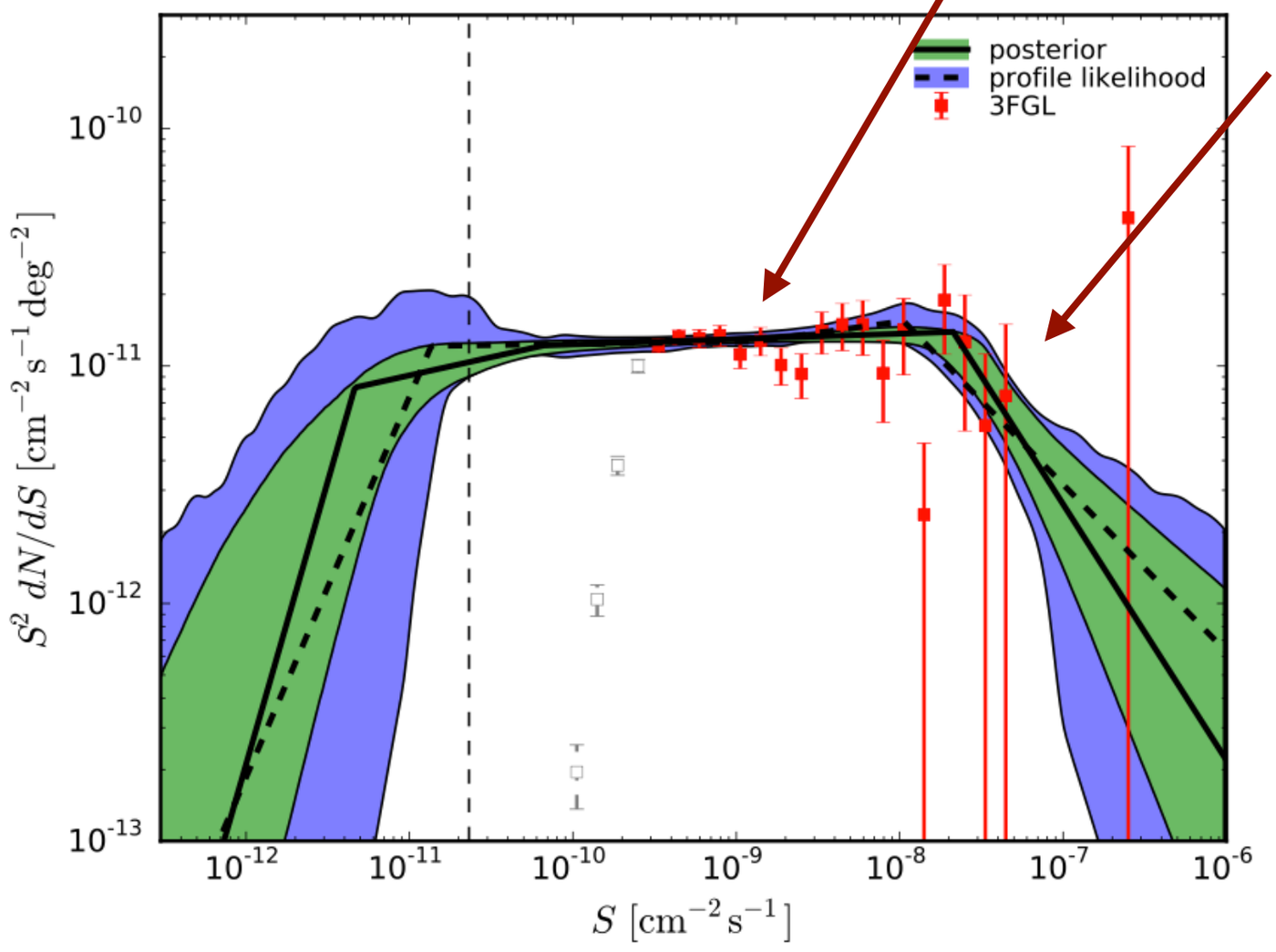
(b) MBPL, $N_\mathrm{b} = 3$

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

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



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

Results (1-10 GeV) - MBPL Approach

- **MBPL approach**:
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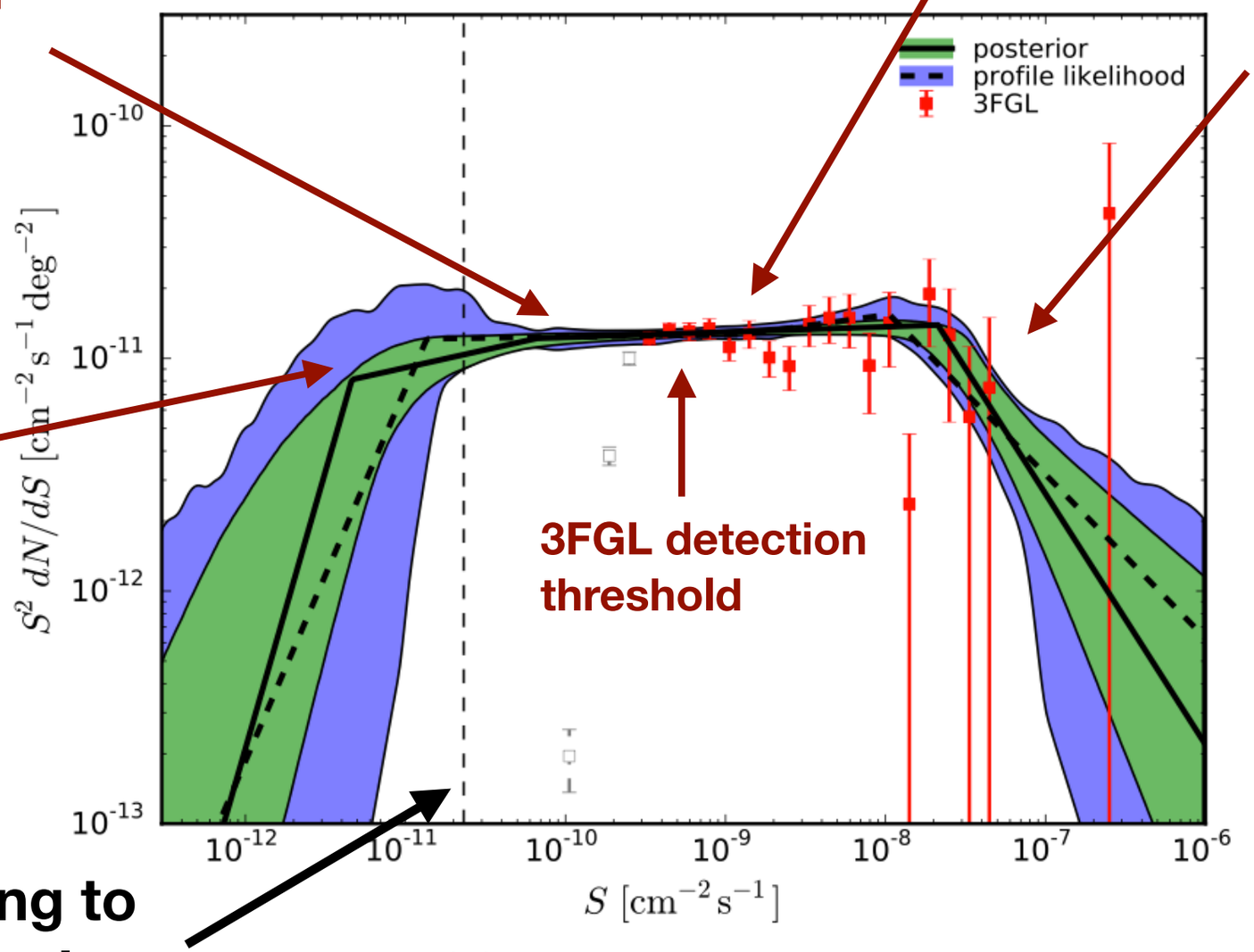
intermediate flux range fit with high accuracy; index n_2=1.98 ± 0.03

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



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

sensitivity cutoff

3FGL detection threshold

flux corresponding to 2 photons per pixel

Results (1-10 GeV) - MBPL Approach

- **MBPL approach**:
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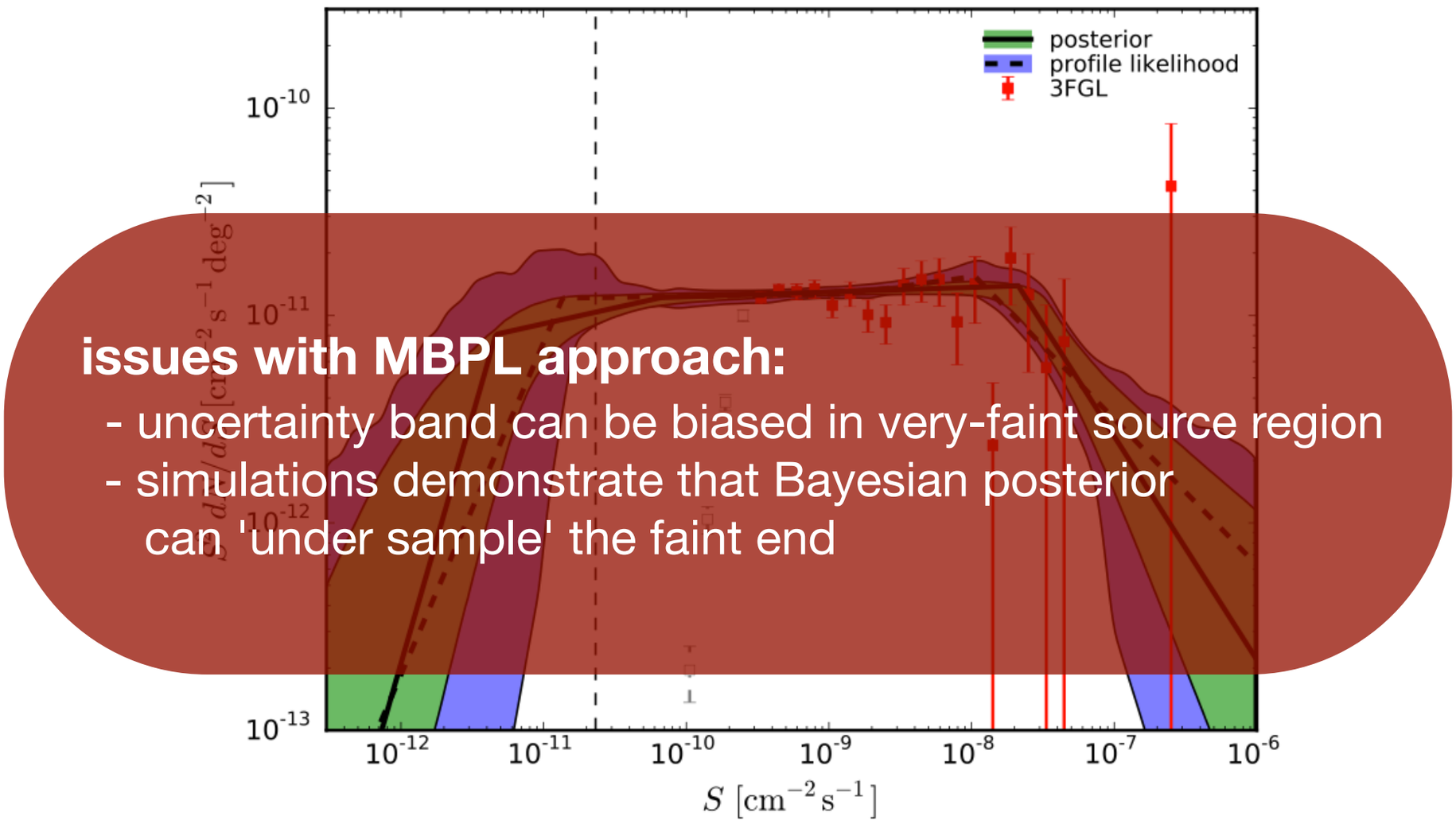
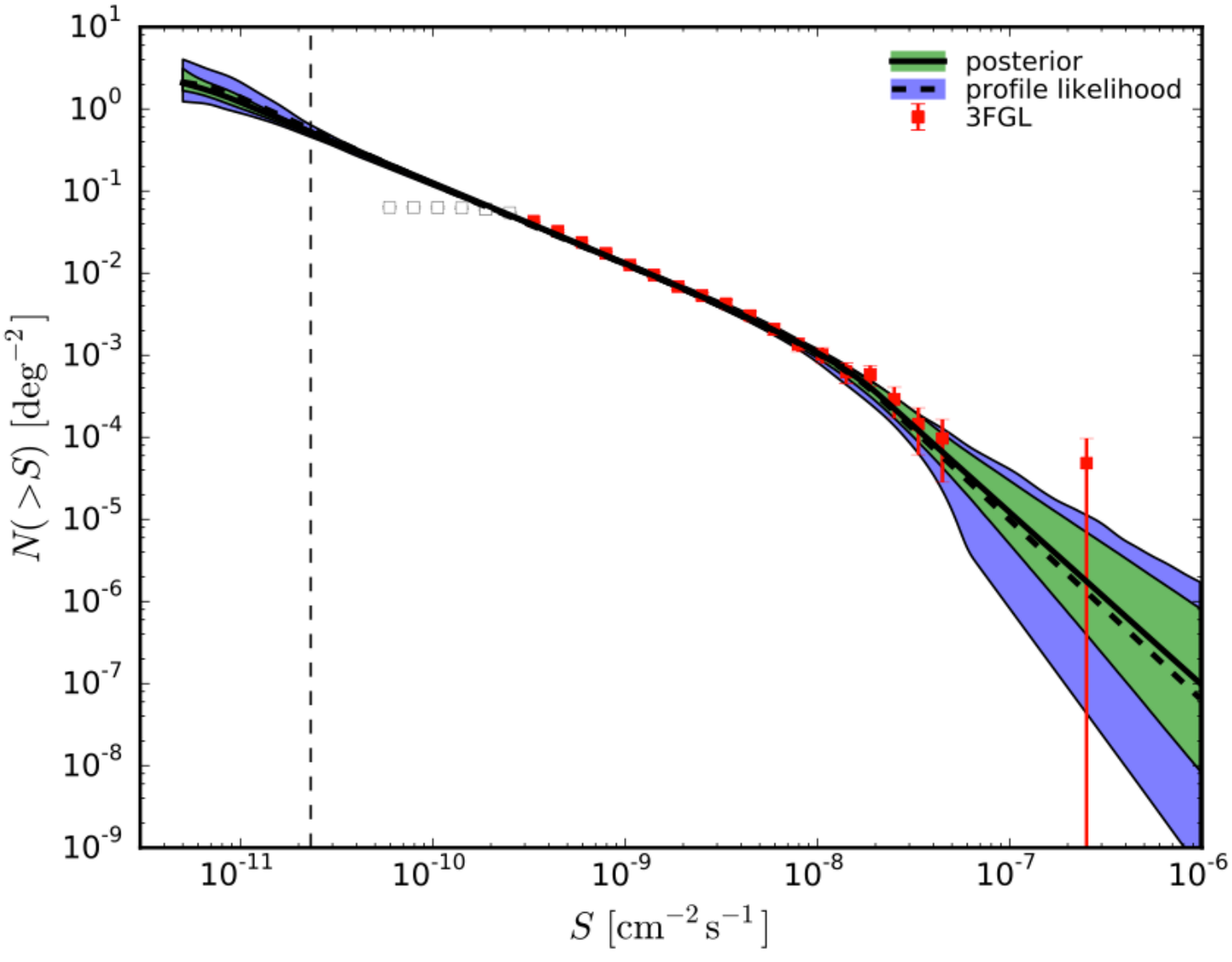


issues with MBPL approach:
- uncertainty band can be biased in very-faint source region
- simulations demonstrate that Bayesian posterior can 'under sample' the faint end

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

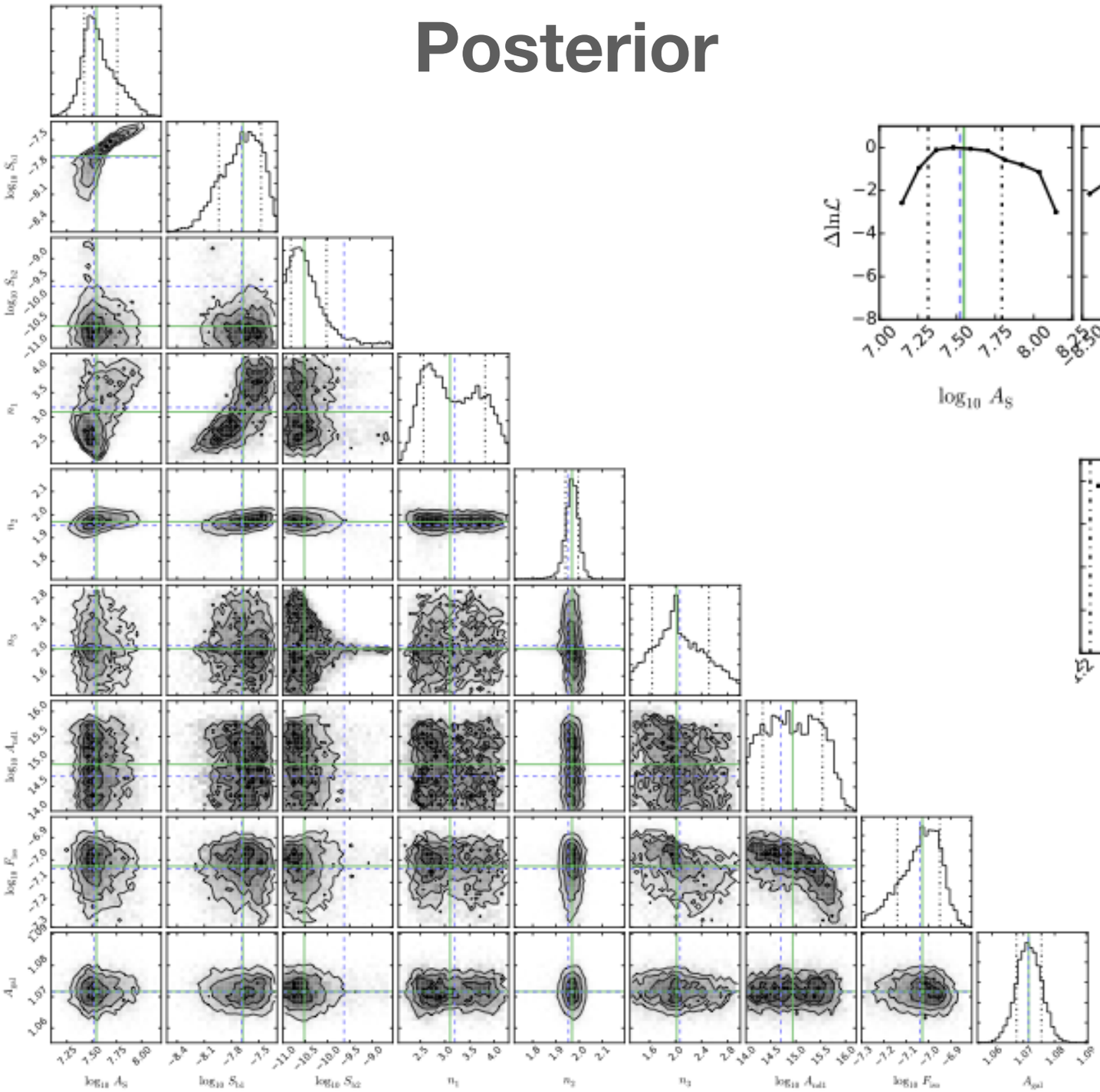
Results (1-10 GeV) - Hybrid Approach

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



Hybrid Approach (1-10 GeV) - Sampling

Posterior



profile likelihood

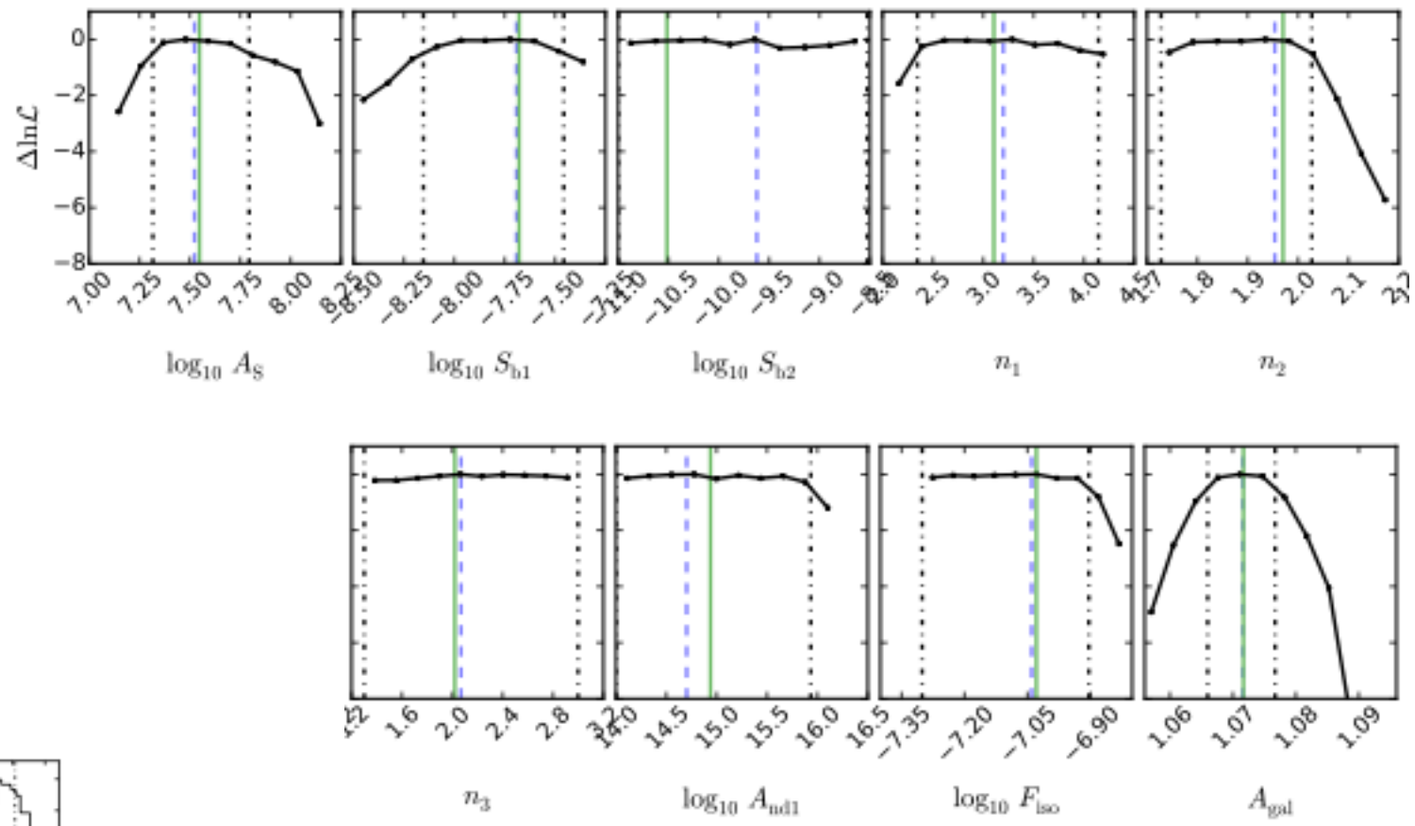
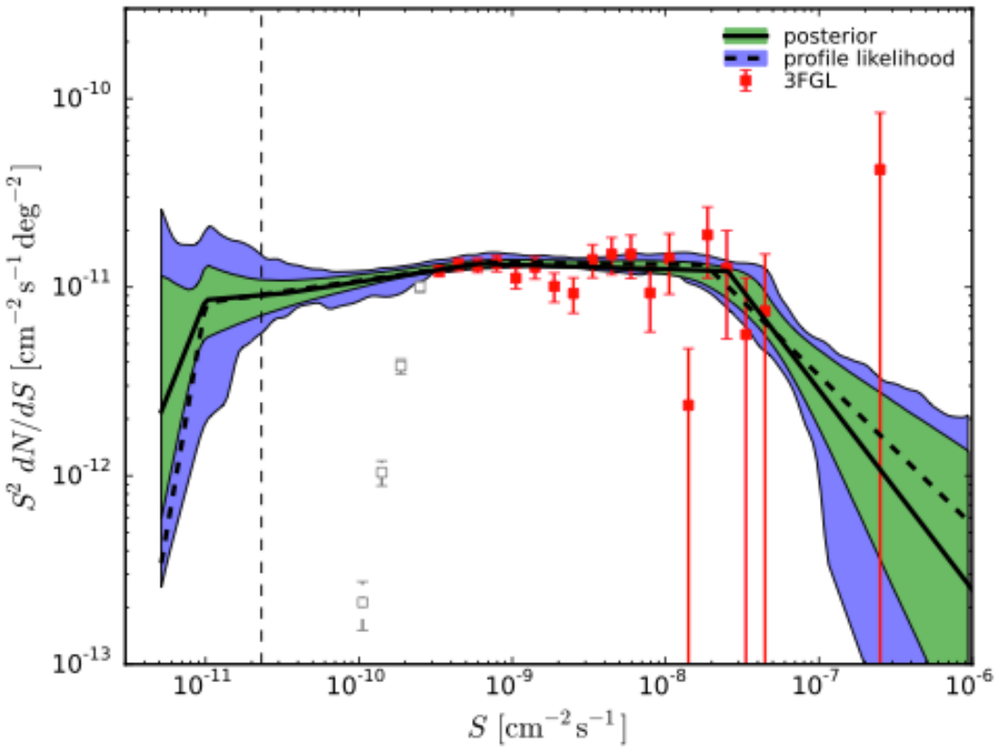


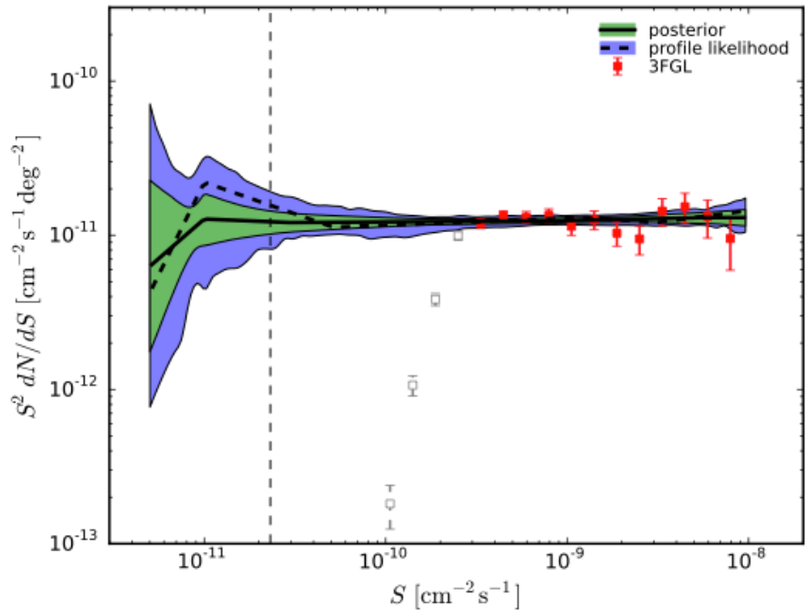
figure legend:
green: posterior median
blue: max. likelihood
dashed: 1-sigma errors

Systematics - Pixel Size and PS masking

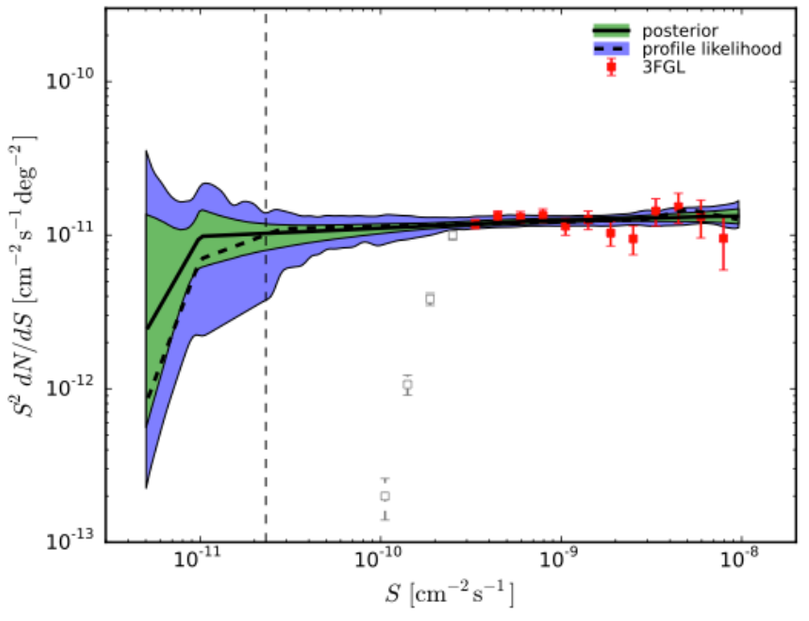
HEALPix order 7



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



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



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

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