Resolving the Extragalactic γ-ray Background above 50 GeV with Fermi-LAT

arXiv:1511.00693

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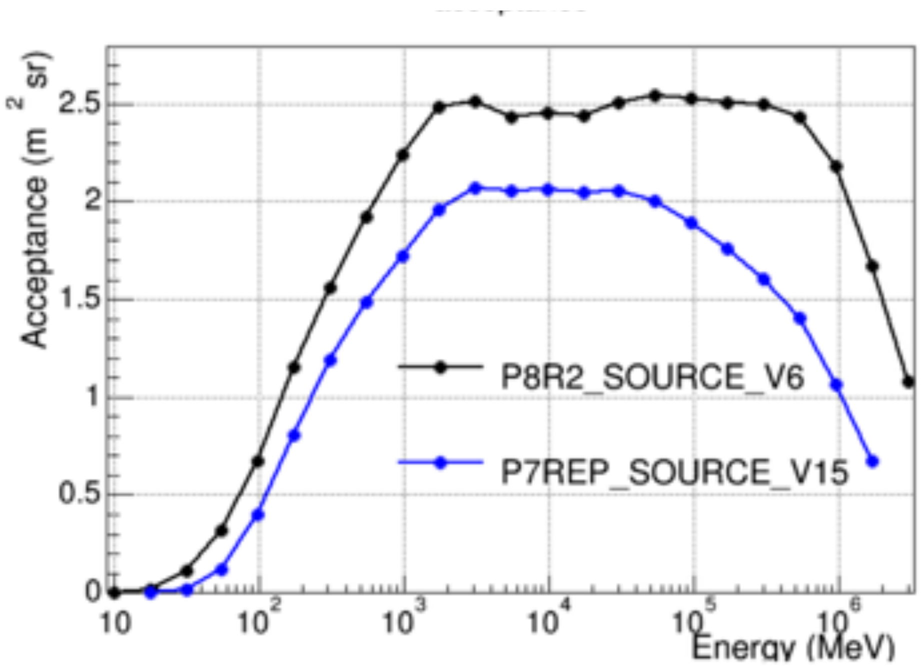
On behalf of the Fermi-LAT Collaboration

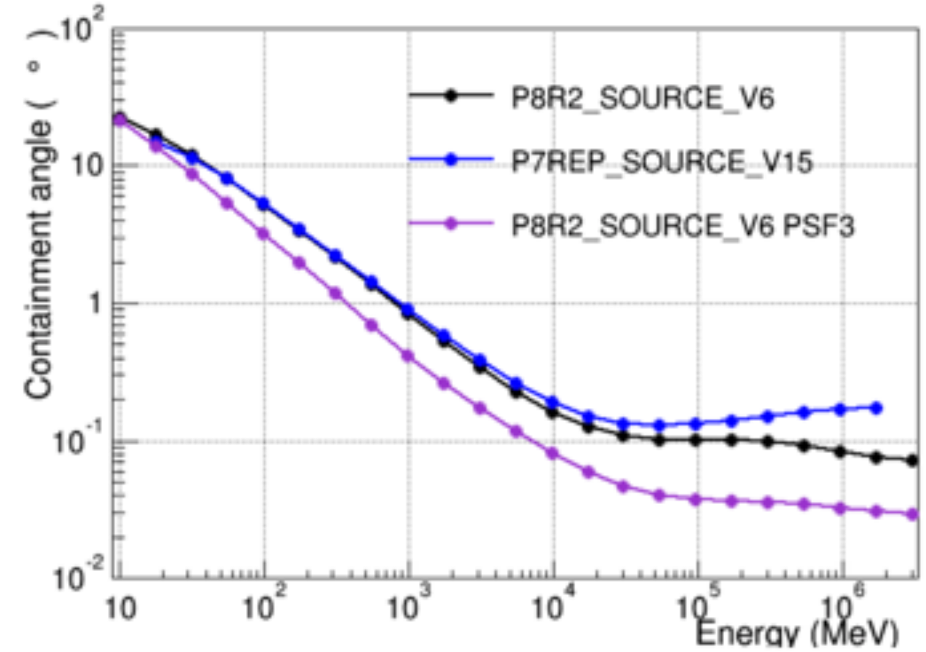
Sixth International Fermi Symposium, Washington D.C., 2015-11-11

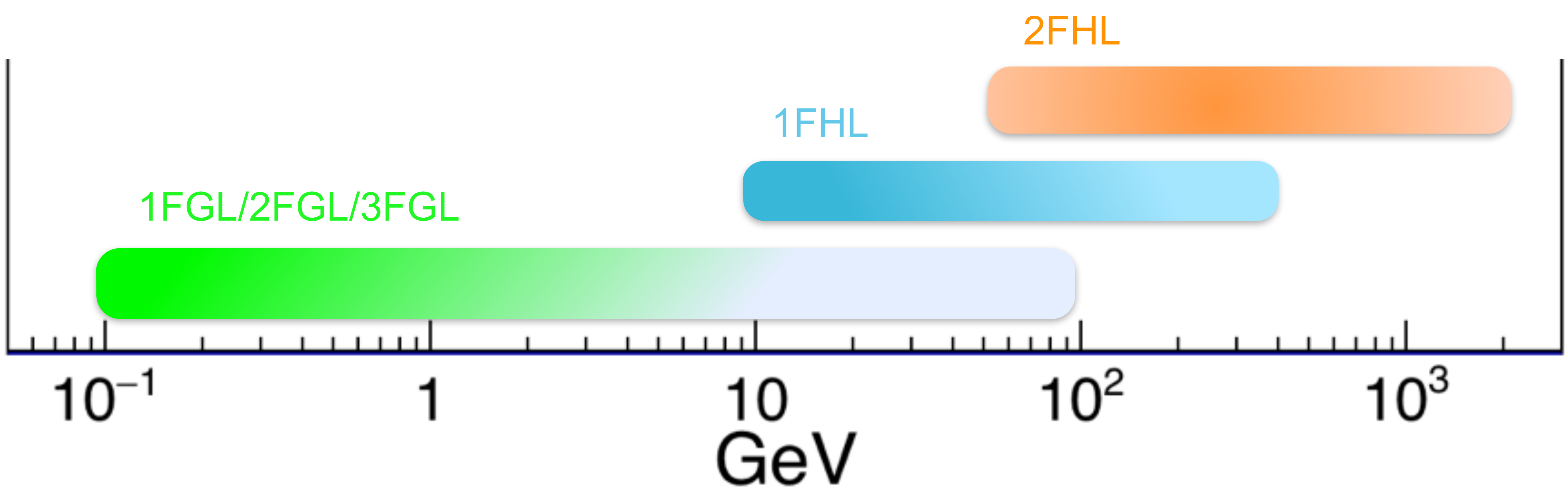
2FHL CATALOG

*n*FGL Catalogs detect and characterize sources in the ~0.1-100 GeV Catalogs
*n*FHL Catalogs explore the higher-energy sky
Why 2FHL ? Improvement delivered by Pass 8 enables study of the EBL, EGB, Galactic plane, and connects well to the TeV world

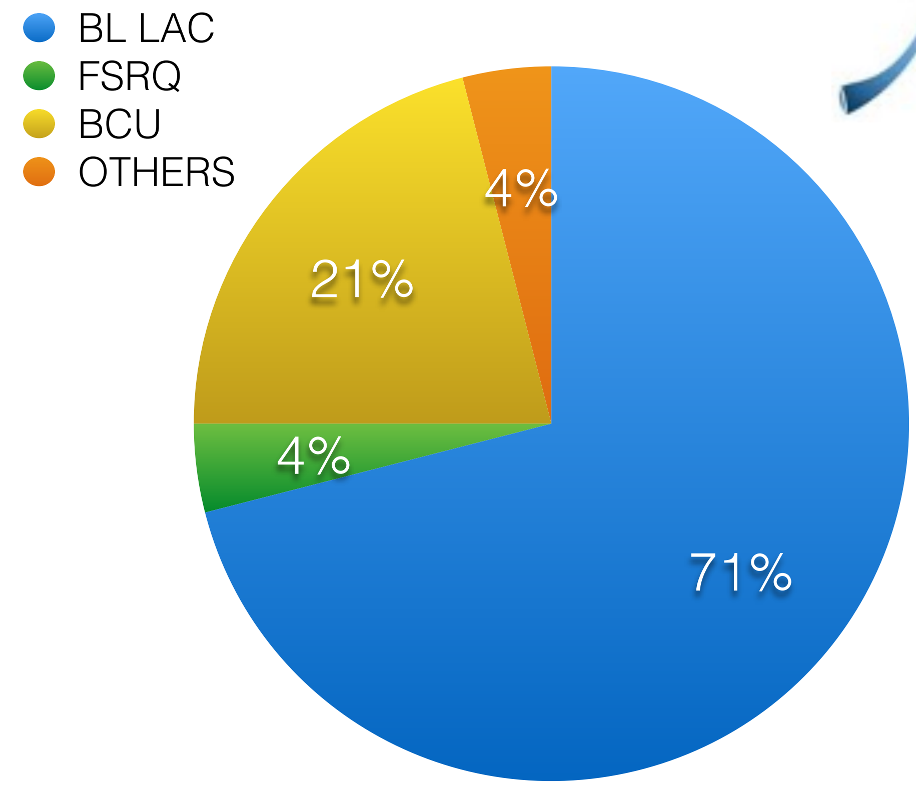


R_{68} Containment



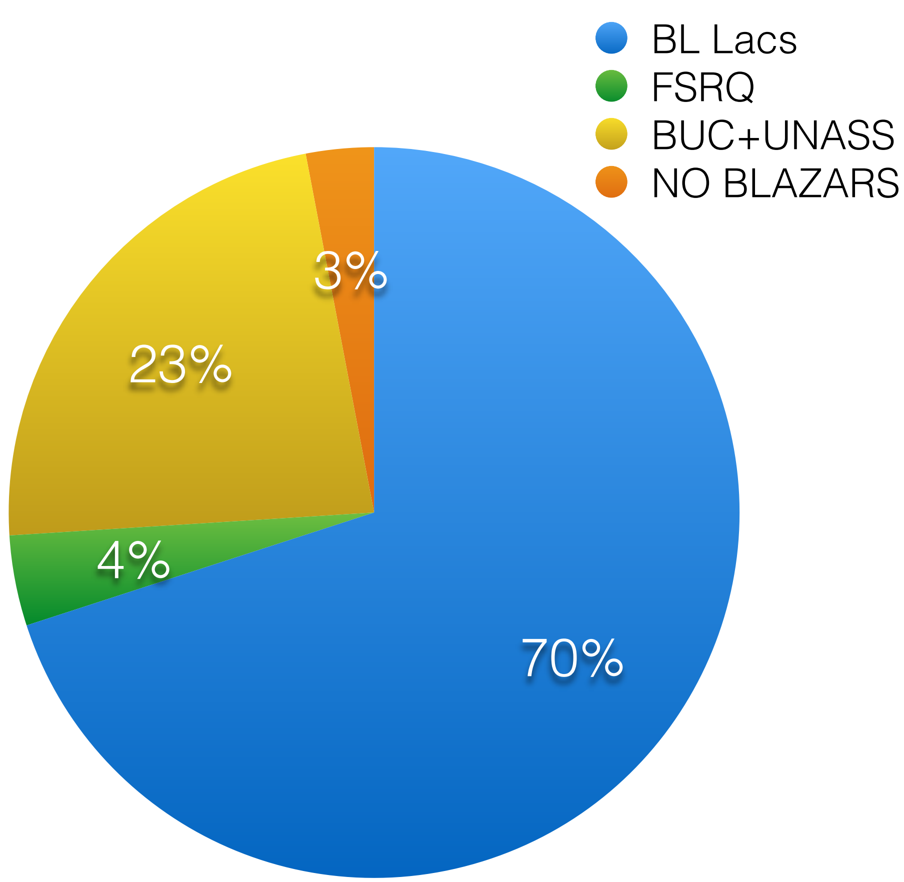


ANALYSIS DETAILS



ANALYSIS DETAILS

- **Energy Range: 50-2000 GeV**
- **IRFs: P8R2_SOURCE_V6**
- **~80 months of data**
- **Unbinned likelihood**

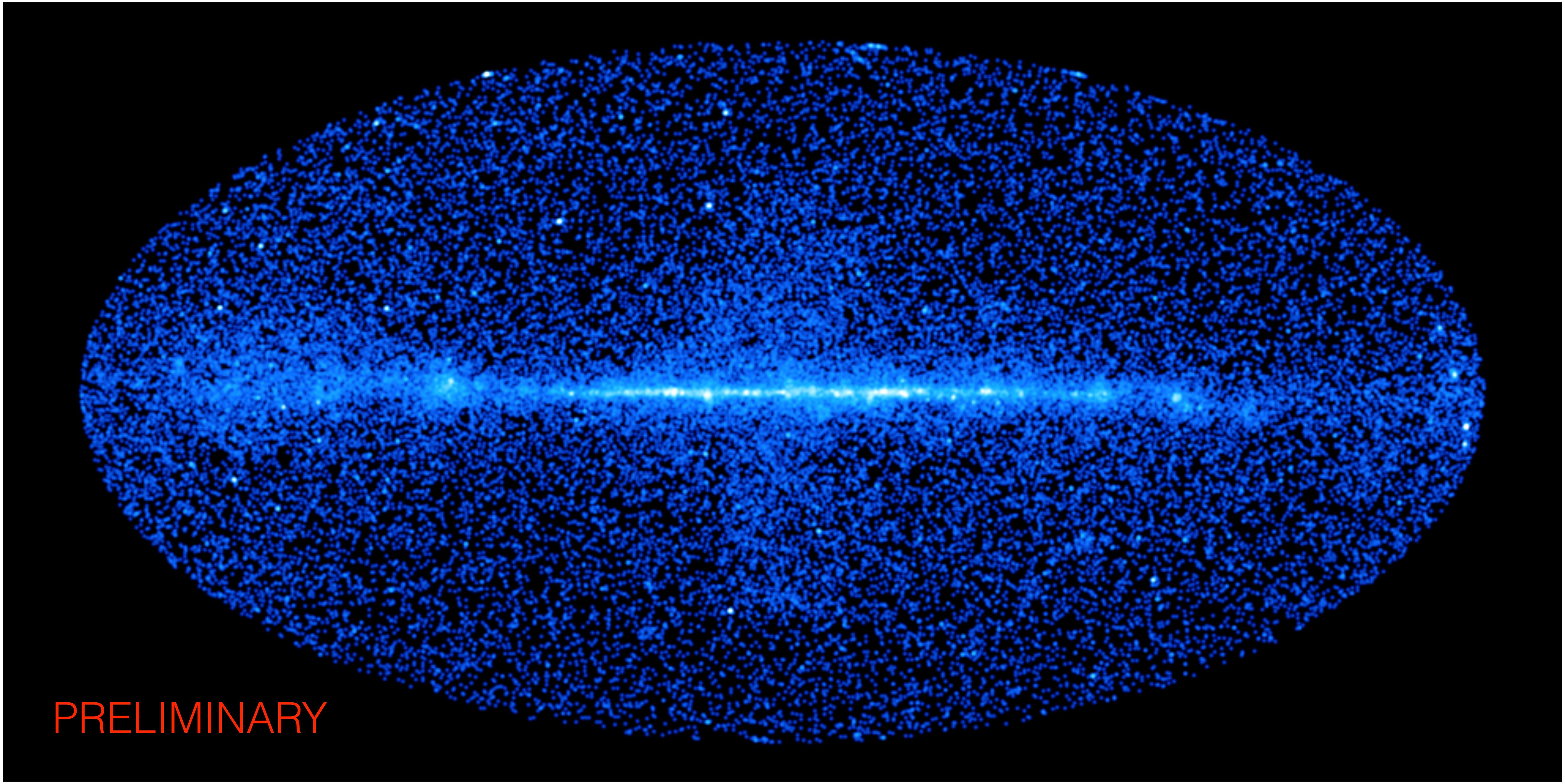


DETECTIONS

- **~360 sources: 75% blazars, 11% Galactic sources, 14% unassociated**
- **At |b|>10° —> 70% BL Lacs and only 7 % No BL Lacs**
- **BCU type and unassociated sources —> 23%.**
- **The median of BCU ν_{sy} and the Γ of unassociated sources are very similar to that one of BL Lacs**
- **This means that the fraction of likely blazars in the high-latitude 2FHL sample is 97%.**

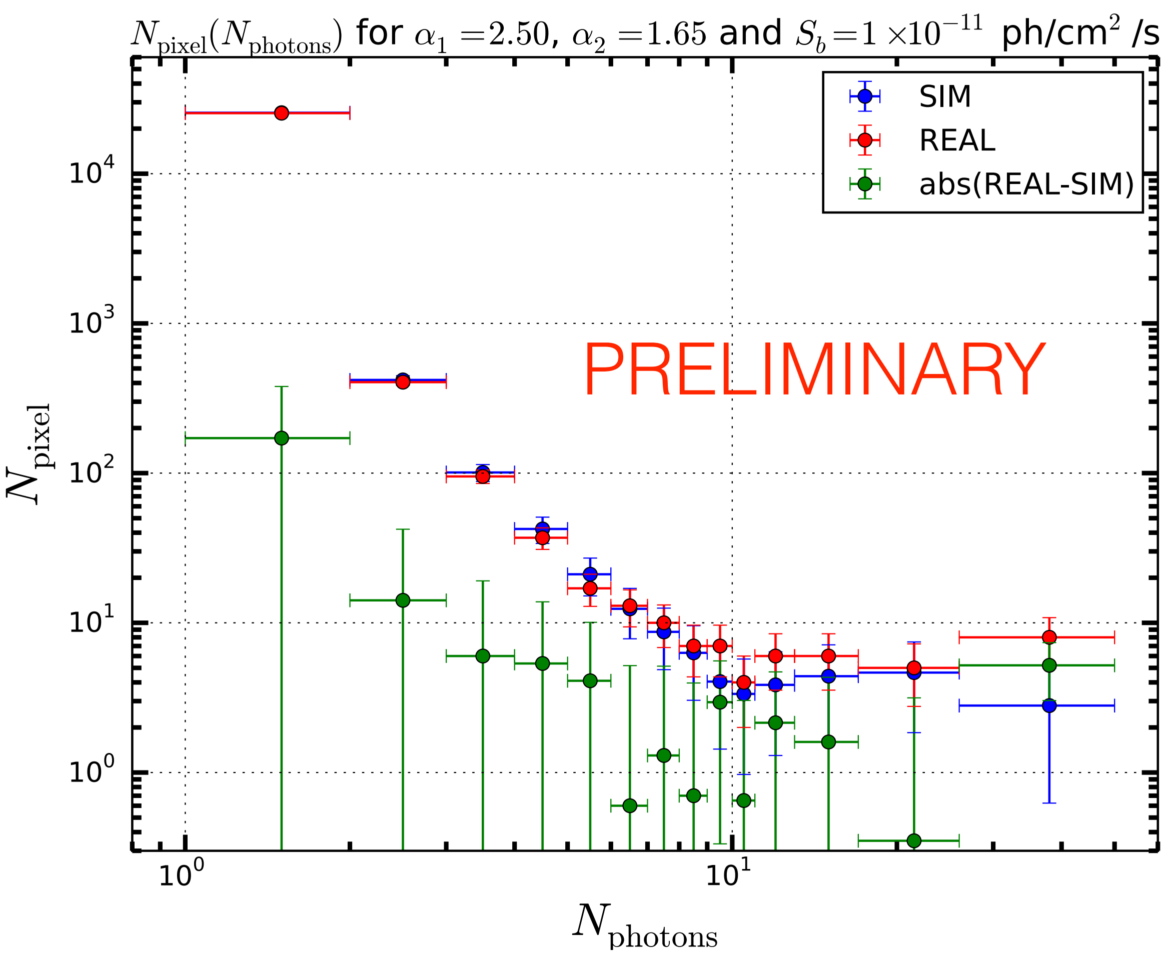
GAMMA-SKY FOR E>50 GeV

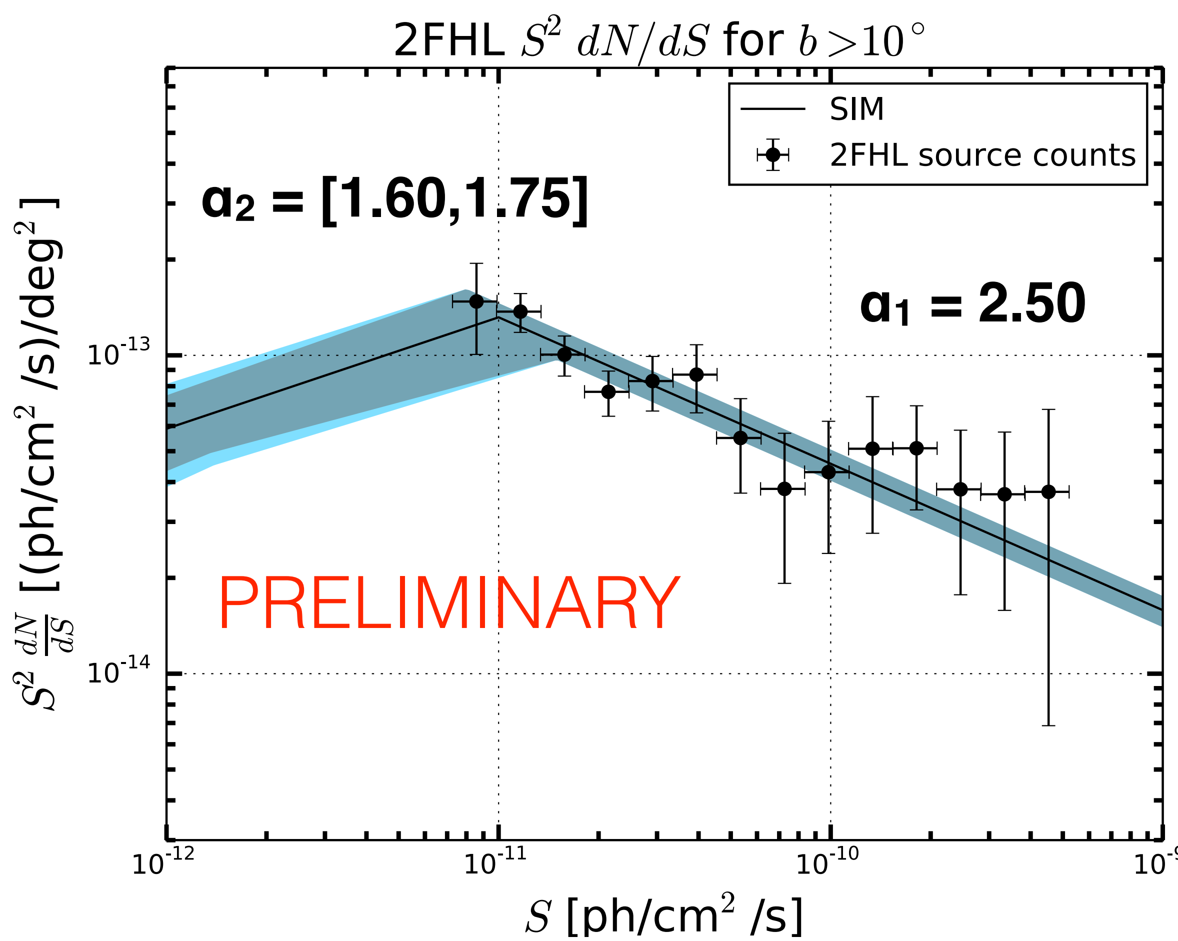
61,000 photons E > 50 GeV
18,000 photons E > 100 GeV → 1.5 ph/deg^2
2,000 photons E > 500 GeV



PHOTON FLUCTUATION ANALYSIS 1

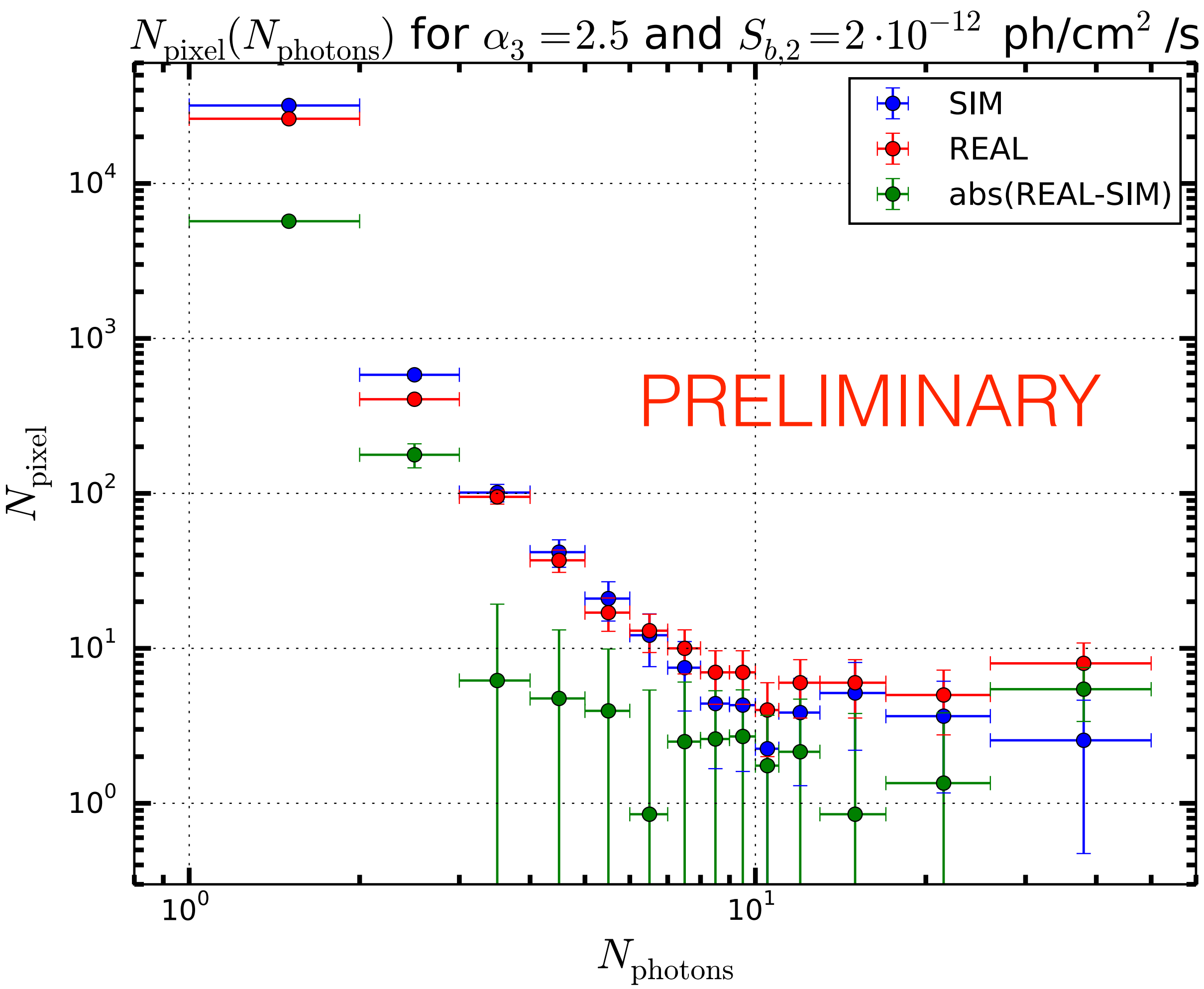
- We employed the photon fluctuation analysis to derive the shape of the flux distribution below the sensitivity of the 2FHL cat.
- Simulations with different value of the break and of the slope below the break have been tested.
- The flux distribution results to be consistent with a broken power law with a break in the range $S_b = [0.8,1.5] \cdot 10^{-11}$ ph/cm²/s and a slope above and below the break $\alpha_1 = 2.50$ and $\alpha_2=[1.6,1.75]$
- The sensitivity of this method is around $1.3 \cdot 10^{-12}$ ph/cm²/s



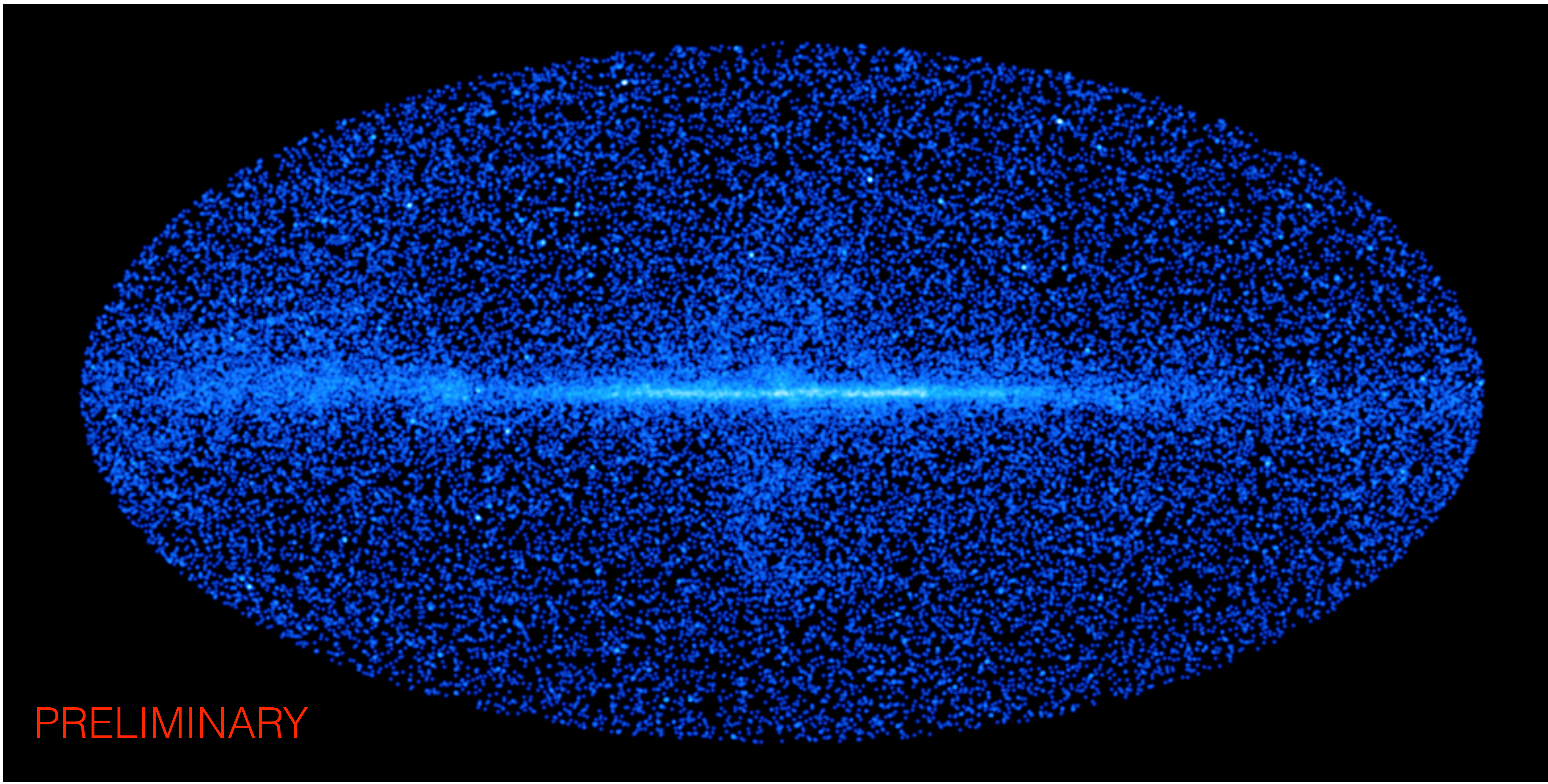


PHOTON FLUCTUATION ANALYSIS 2

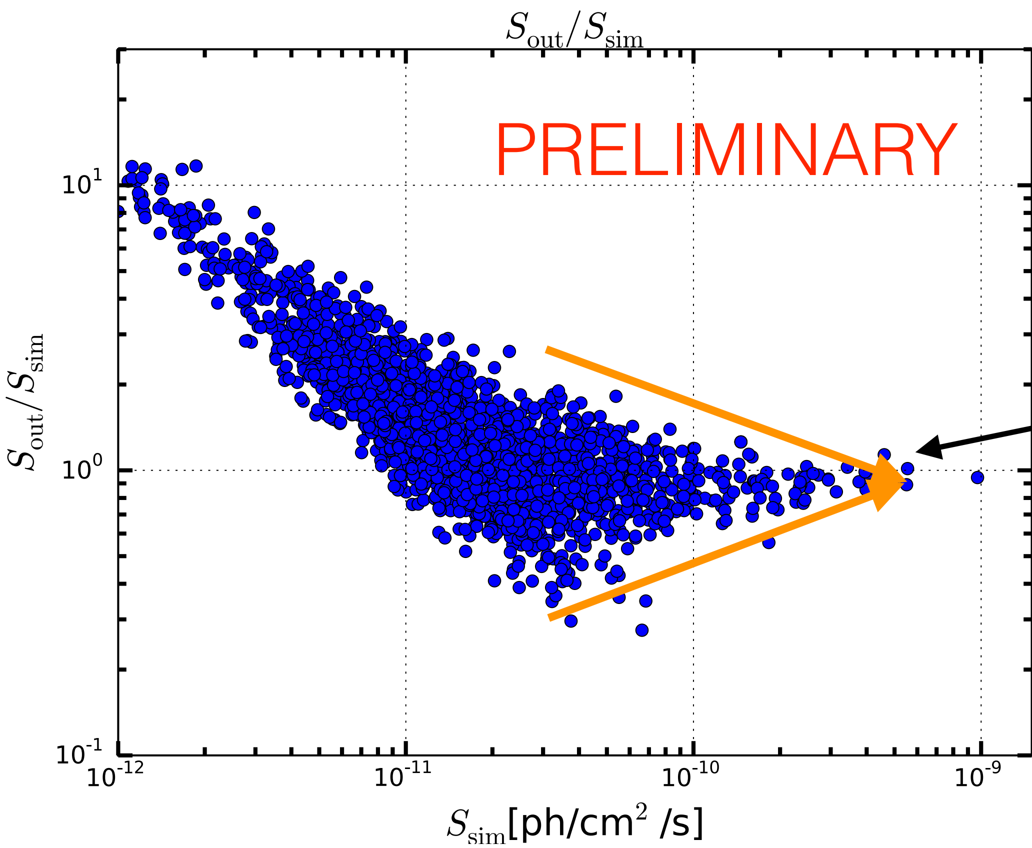
- Test a re-steepening with $\alpha_3 = 2.50$.
- This may occur with a new source population as Star Forming Galaxies.
- We consider $S_b=10^{-11}$ ph/cm²/s and a slope above and below the break $\alpha_1 = 2.50$ and $\alpha_2 = 1.60$
- We add a second break between $[0.5,5]\cdot 10^{-12}$ ph/cm²/s and a slope below the break $\alpha_3 = 2.50$.
- The upper limit for the position of this second break $7\cdot 10^{-13}$ ph/cm²/s



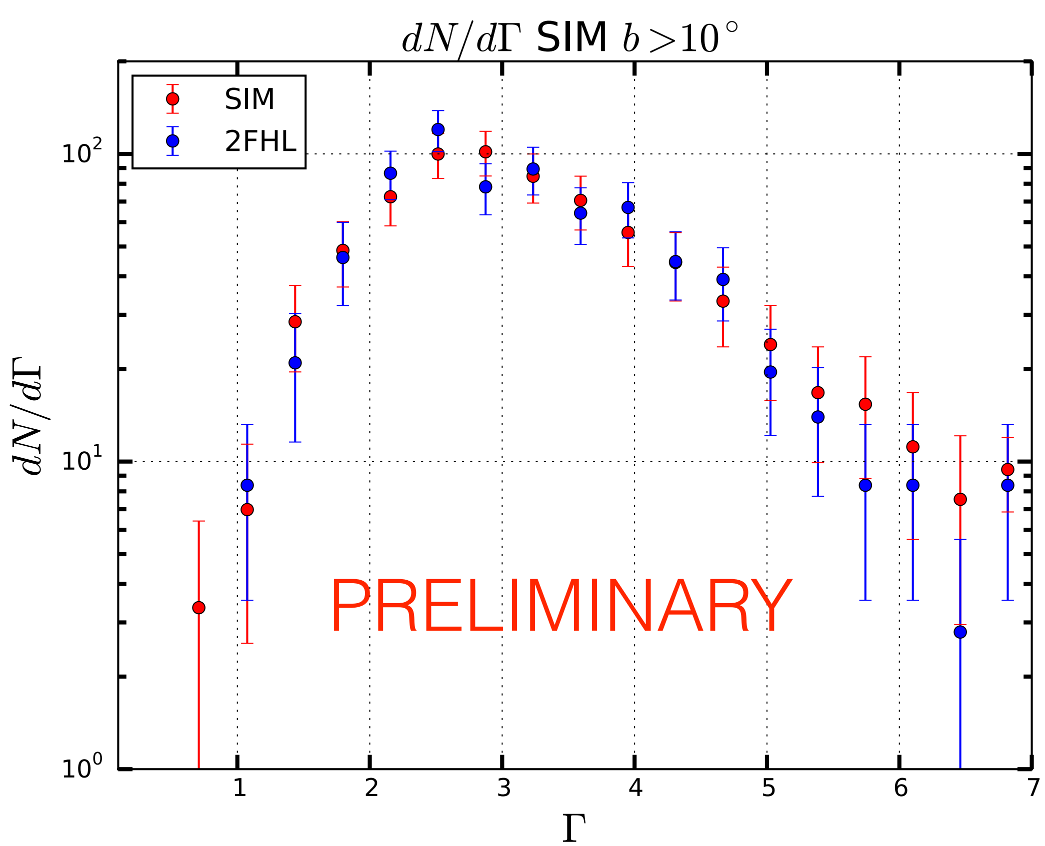
SIMULATED SKY MAP FOR E>50 GeV



CONSISTENCY CHECKS



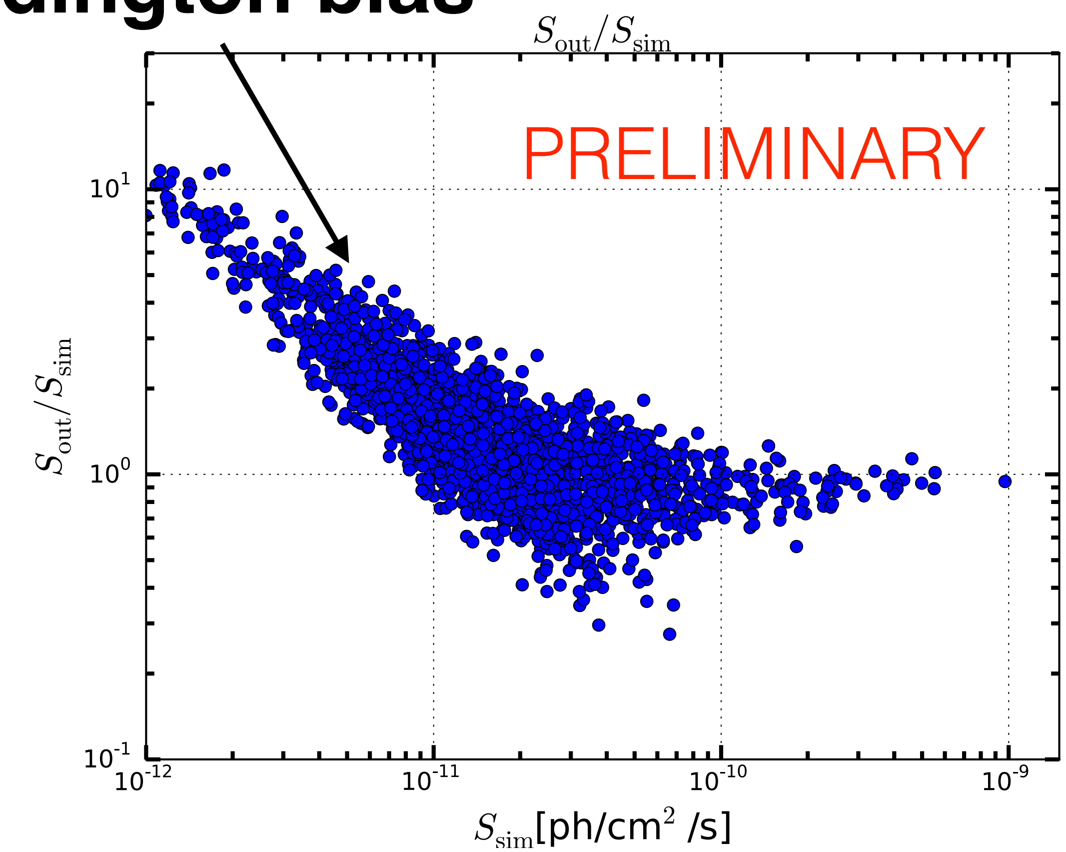
THE RATIOS CONVERGE TO 1!!

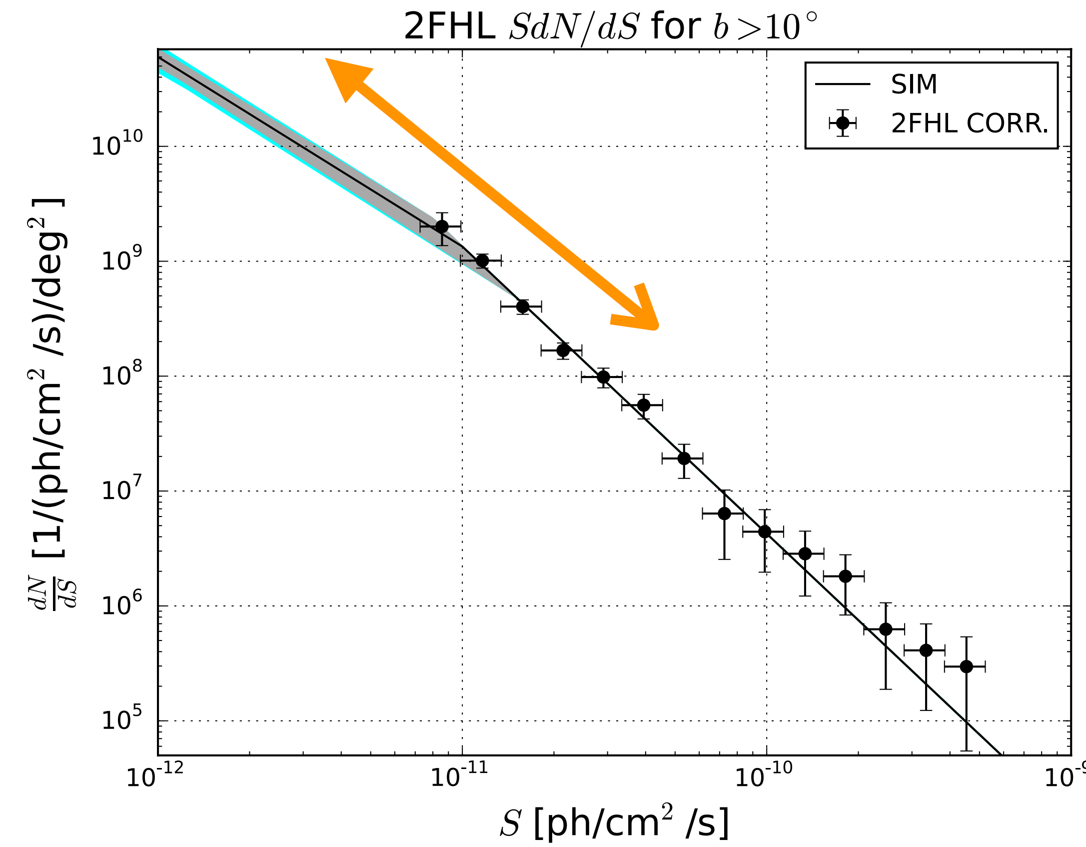


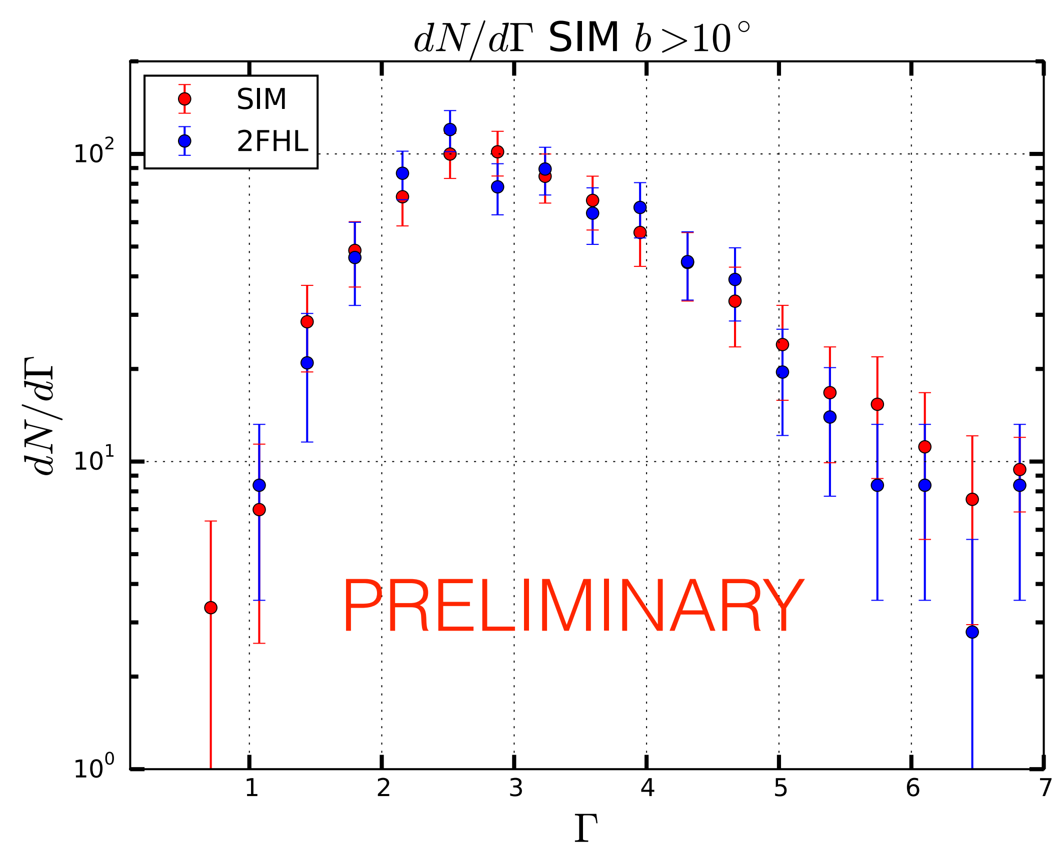
The photon index distribution of the analyzed simulations is consistent with the one of the 2FHL catalog

CONSISTENCY CHECKS

Eddington bias







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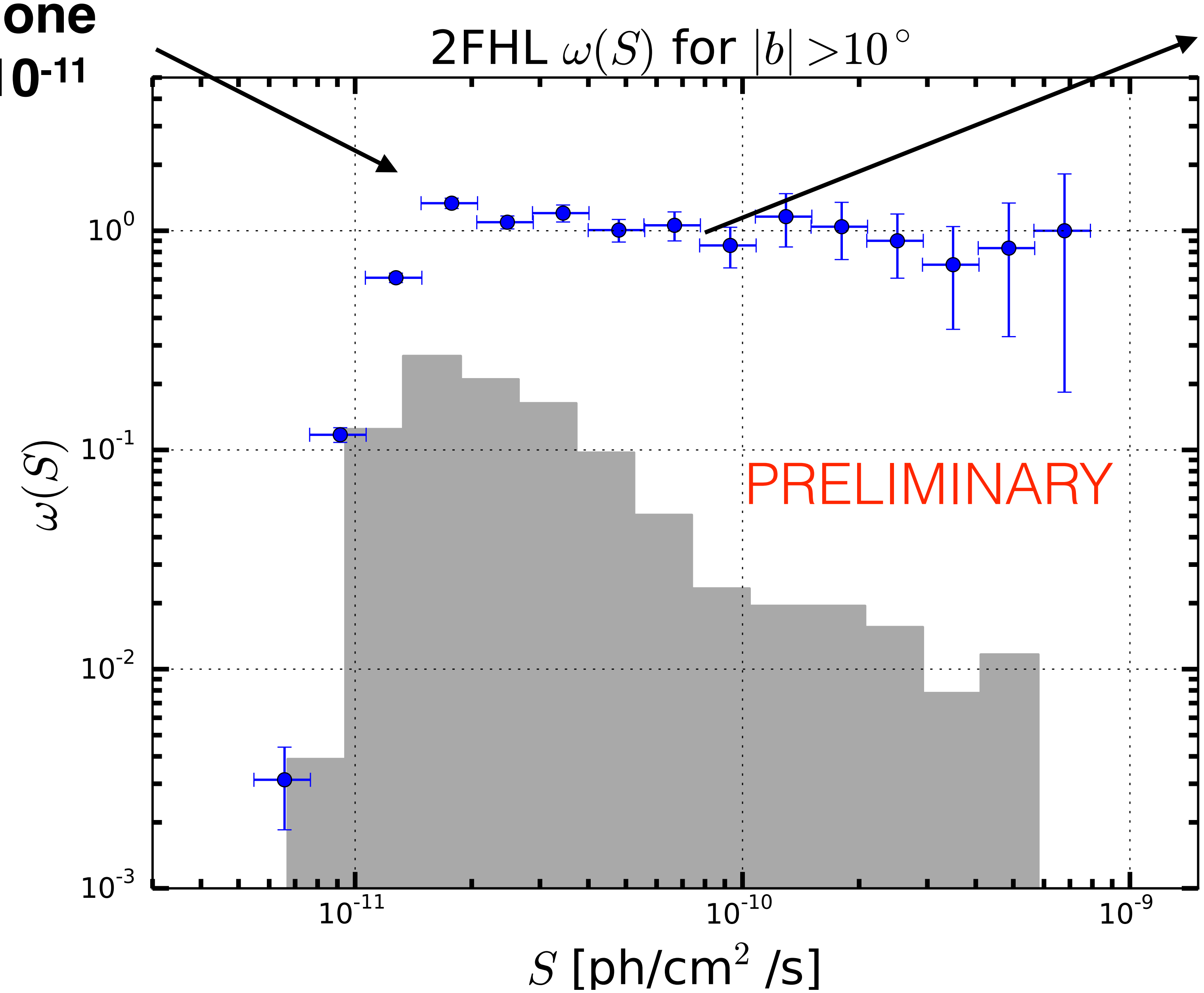
Detection Efficiency

$$\omega(S^i \in [S^i_{\rm min}, S^i_{\rm max}]) = \frac{N^i_{\rm meas}}{N^i_{\rm true}}$$

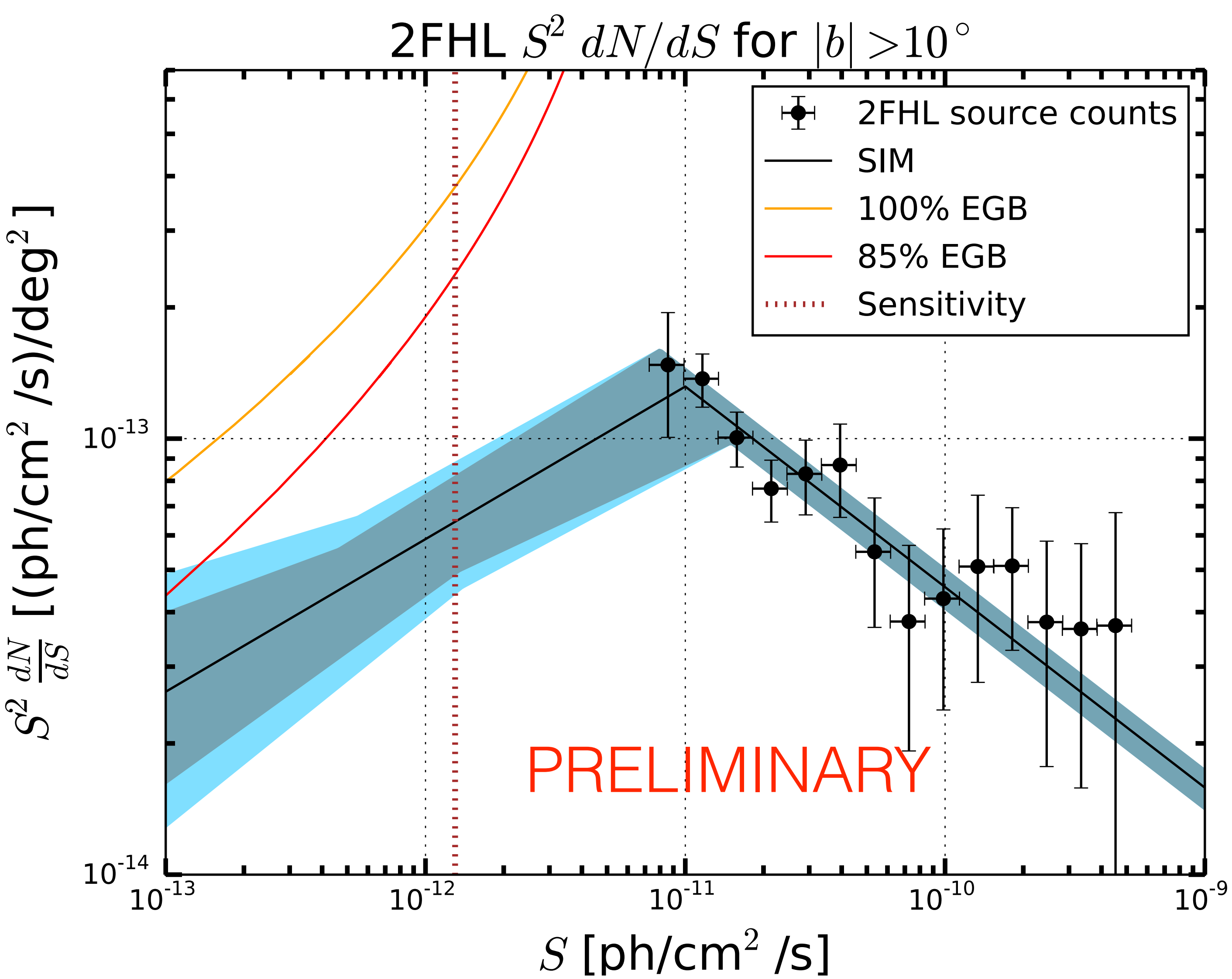
The efficiency starts to deviate from one for F < 1.3-1.5 · 10^{-11} ph/cm²/s

Efficiency~1 for bright sources



CORRECTED LOGN-LOGS

- **A fit to the corrected LogN-LogS of the 2FHL gives α = 2.49 ± 0.12!**
- **This is the result of 10 simulations.**
- **The band takes into account the uncertainty of the flux distribution given by the photon fluctuation analysis.**



The orange and red curves indicate where 85% and 100% of the EGB intensity above 50 GeV would be produced when extrapolating the flux distribution below the break with different values of faint-end slope, α_2.

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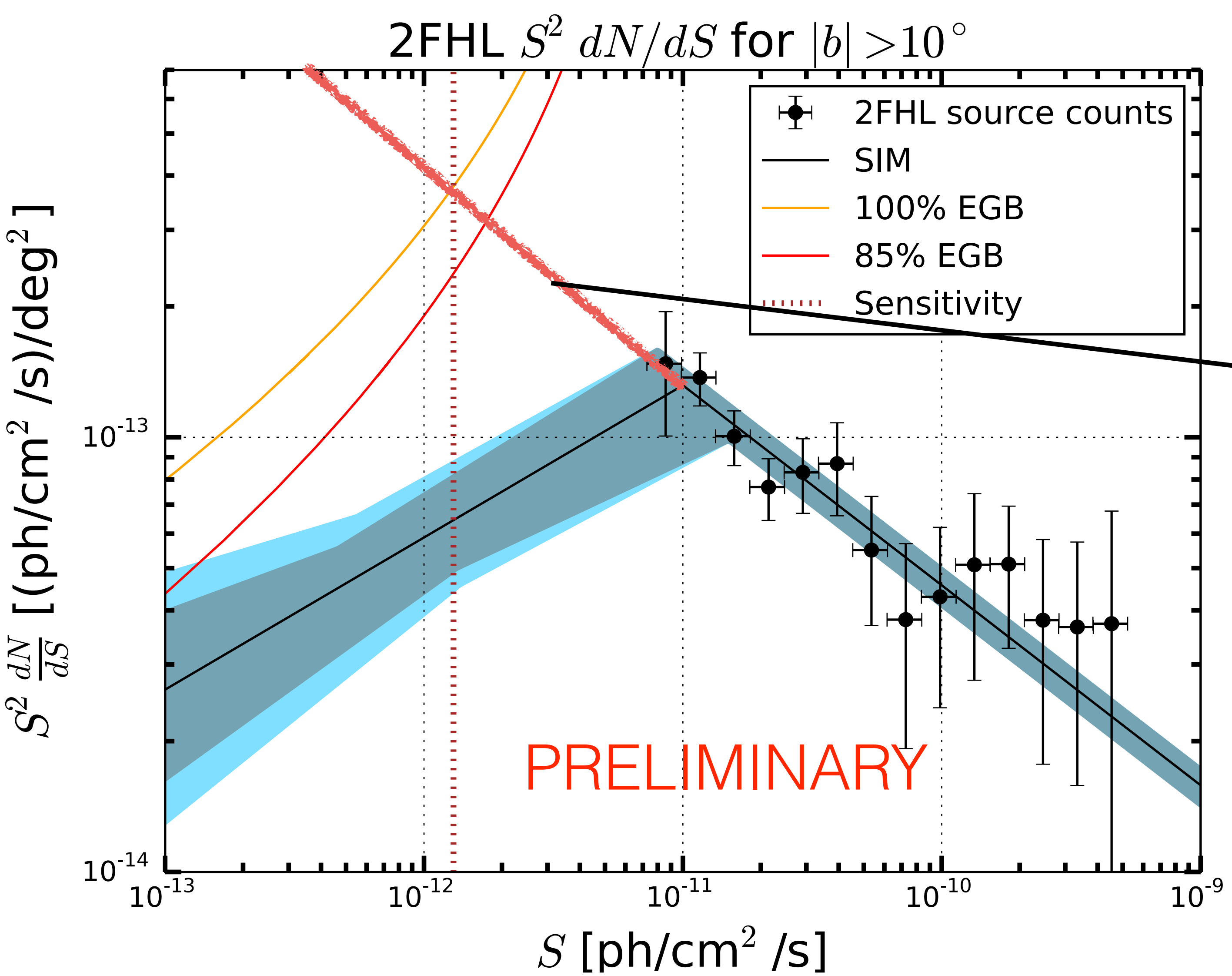
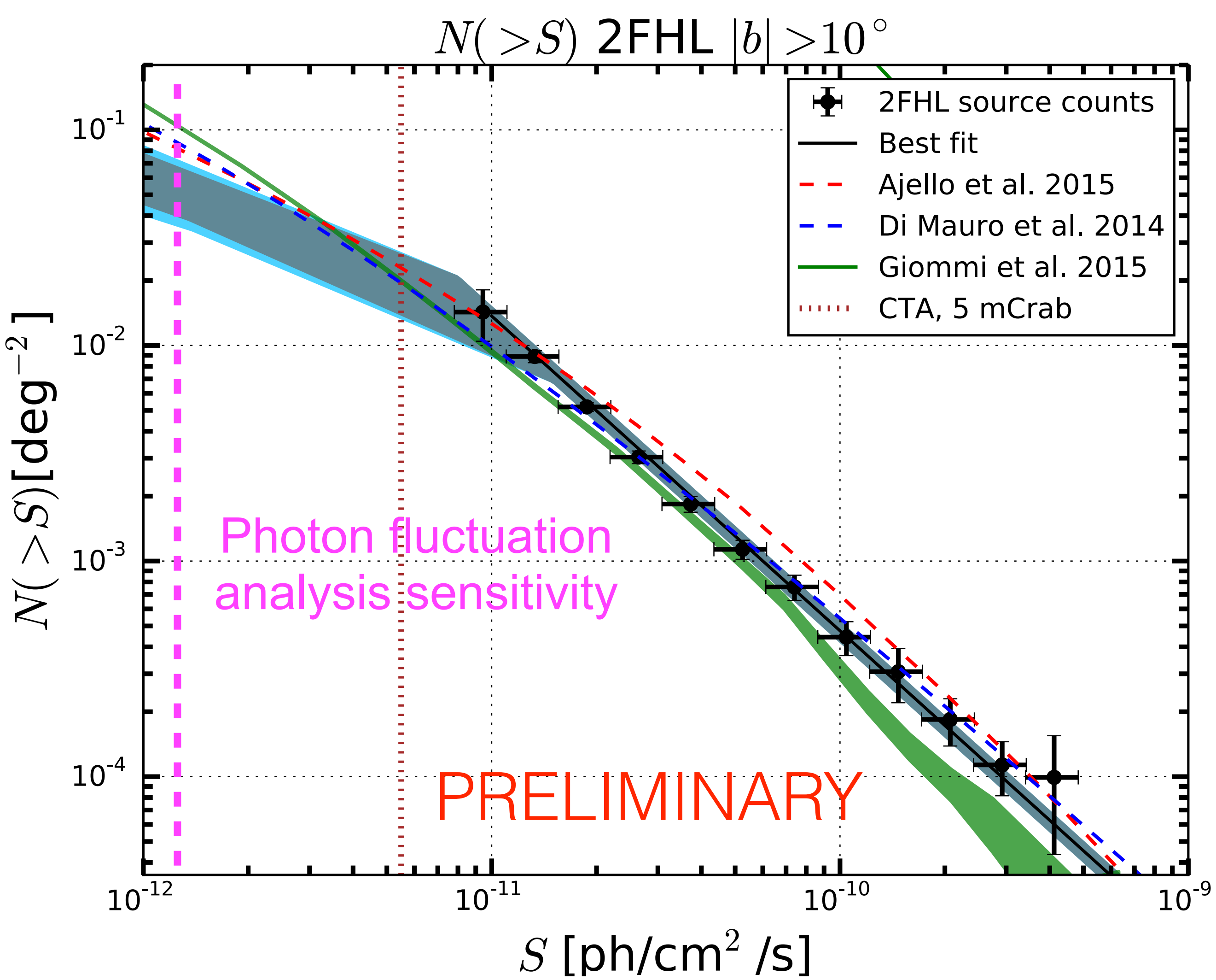


The Euclidean distribution below the 2FHL cat threshold is constrained by the EGB.

CUMULATIVE SOURCE COUNT DISTRIBUTION

- The observed cumulative source count distribution is consistent with theoretical prediction of Di Mauro et al. 2014, Giommi et al. 2015 and Ajello et al. 2015.
- The expected sensitivity of CTA is just below the Fermi-LAT sensitivity.
- We have already resolved almost all the gamma-ray sky CTA will observe!!



- The CTA sensitivity is reachable in 240 hours in the most sensitive pointing strategy.
- At these fluxes the source density is 0.0194±0.0044 deg^{-2}, which translates into the serendipitous detection of **200 ± 45** sources in a field of one quarter of the entire sky

CONTRIBUTION TO THE IGRB AND ANISOTROPY

$$I = \int_{S_{\min}}^{S_{\max}} S \frac{dN}{dS} dS \qquad [\mathrm{ph\,cm^{-2}\,s^{-1}\,sr^{-1}}]$$

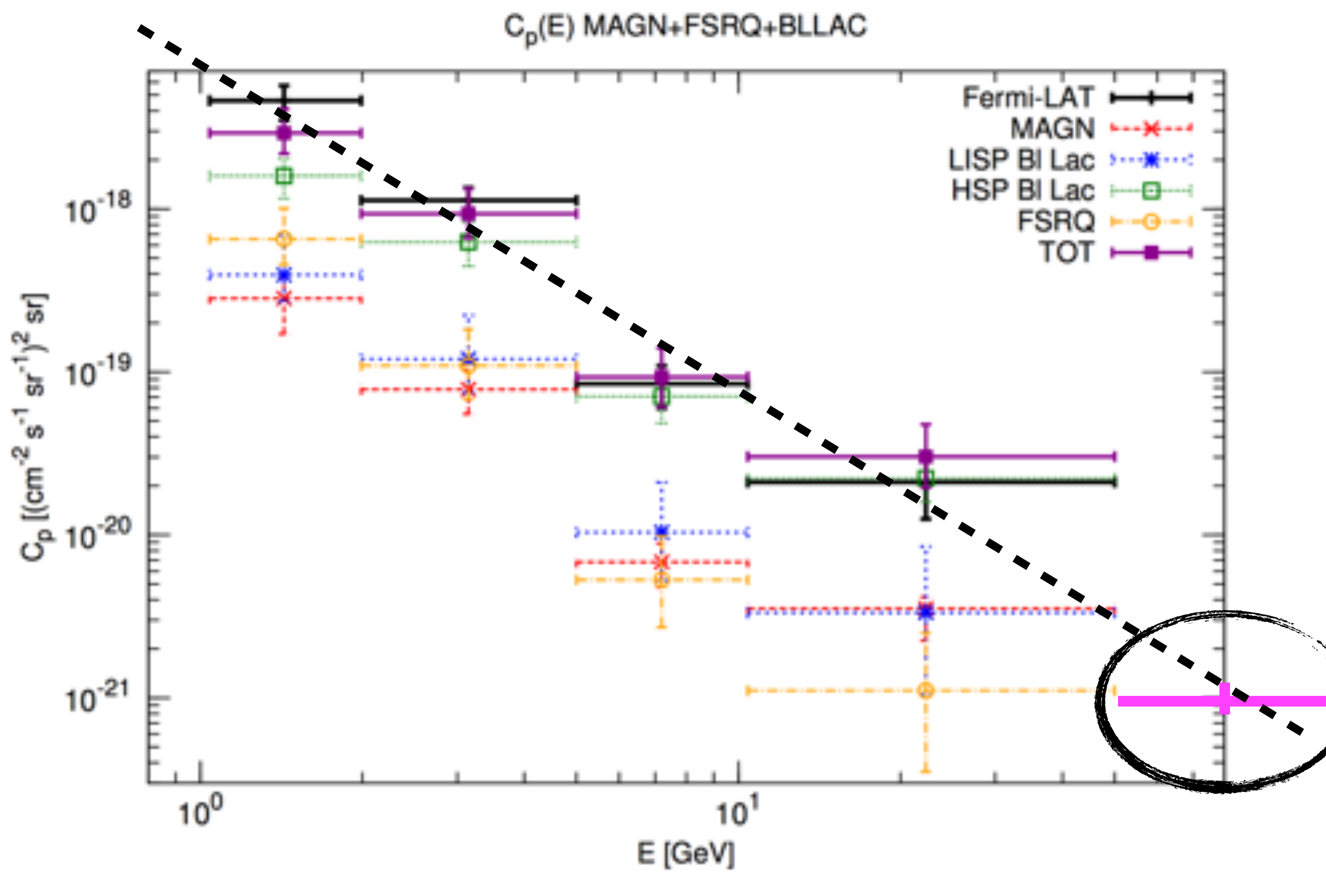
EGB —> (2.40±0.30)·10^{-9} ph/cm^2/s/sr

2.07$^{+0.40}_{-0.35}$·10^{-9} ph/cm^2/s/sr

86%$^{+16}_{-14}$ of the EGB

$$C_P = \int_0^\infty (1-\omega(S))\, S^2 \frac{dN}{dS} dS \qquad [(\mathrm{ph/cm^2/s})^2\ \mathrm{sr^{-1}}]$$

C$_p$(E > 50 GeV) = 9.4$^{+1.0}_{-1.5}$ 10^{-22} (ph/cm^2/s)^2/sr



Di Mauro et al. 2014

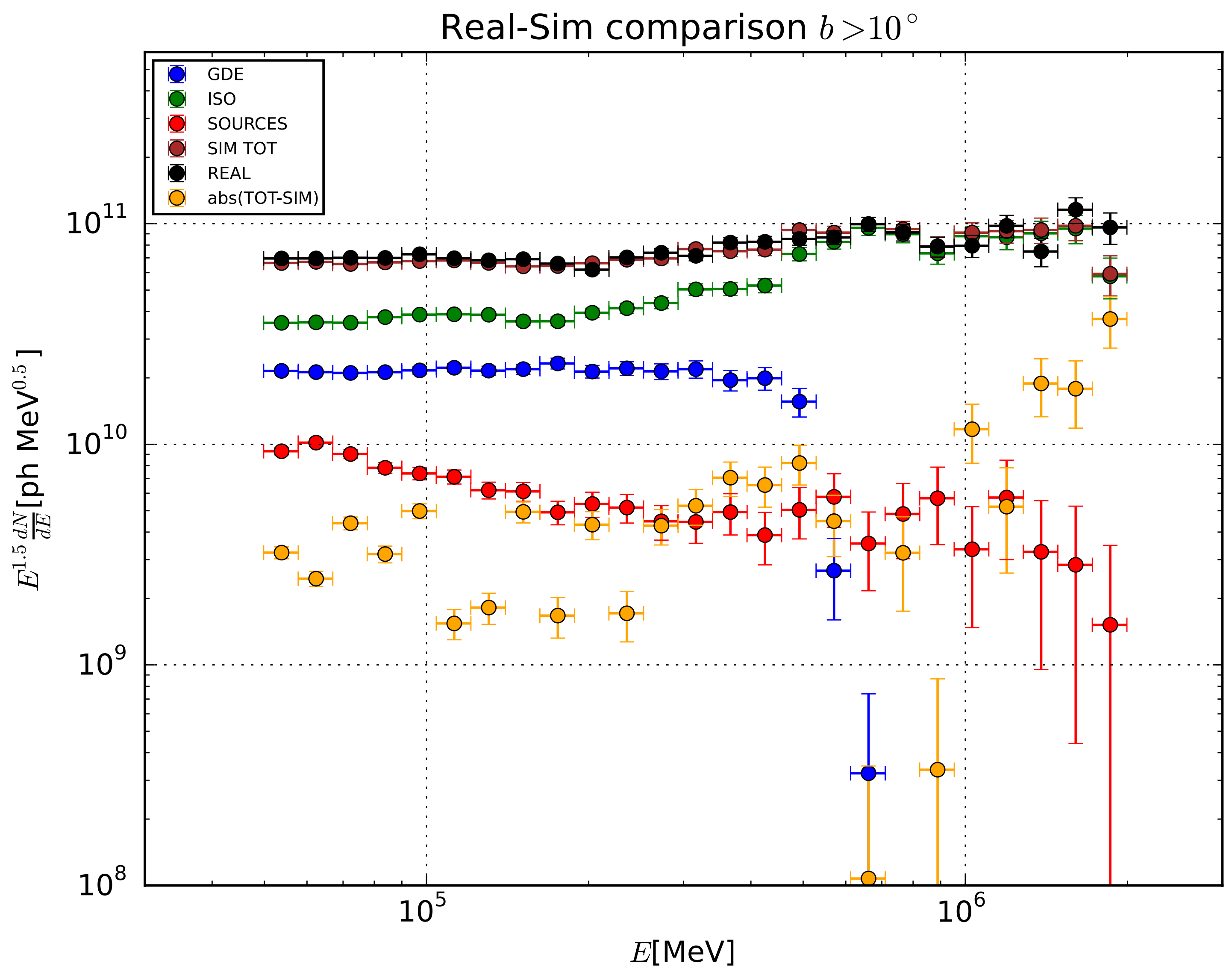
CONCLUSIONS

- **We have performed a detailed analysis of the gamma-ray sky for E>50 GeV using the 2FHL catalog and simulations of the sky.**
    - A. **dN/dS is a broken power-law with S_{break}=[0.8,1.5]*10^{-11} ph/cm^2/s, α_2 = [1.6,1.75] and α_1 = 2.50.**
    - B. **The photon fluctuation analysis permits us to lower with about a factor of 8 the sensitivity with respect to the threshold of the 2FHL cat.**
- **The 2FHL opens a new window for the high-energy gamma-ray sky.**
    - C. **The Fermi-LAT sensitivity is just above the expected sensitivity of CTA.**
    - D. **For the first time the LAT resolve 86% of EGB with point sources.**
- **Consequences**
    - E. **Small room (<14%) is left to other exotic channels as gamma rays produced from annihilation or decay of DM particles and emission from other diffuse processes as interaction of UHECRs with EBL.**
    - F. **These results will have a strong impact also on the interpretation of IceCube detected astrophysical flux of neutrinos. (See Justin's poster and K. Bechtol, M. Ahlers, M. Di Mauro, M. Ajello, J. Vandenbroucke arXiv:1511.00688!!)**
    - G. **The blazar SED in 2FHL catalog confirm the presence of attenuation of very high-energy gamma rays given by the absorption with the EBL (A. Dominguez and M. Ajello arXiv:1510.07913).**

BACKUP

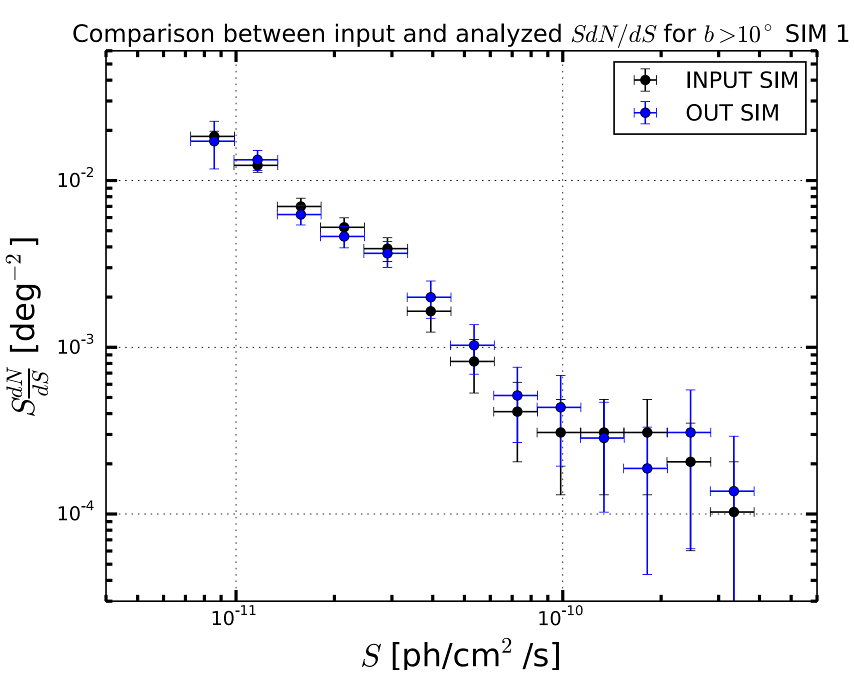
SIMULATION OF THE SKY FOR E>50GeV AND |b|>10deg

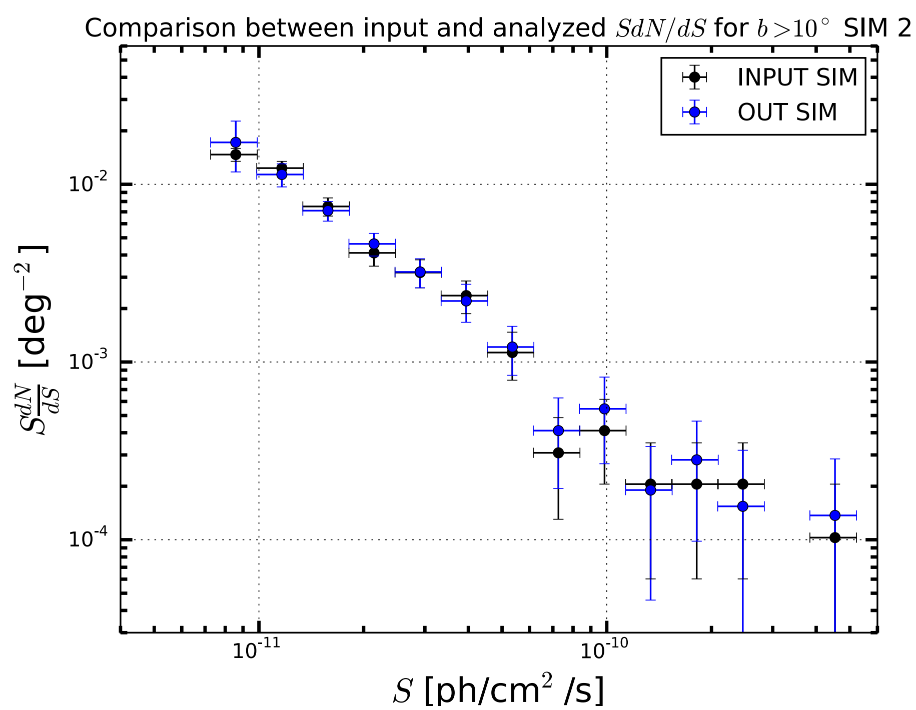
- **We simulate the gamma-ray sky at E>50 GeV with GTOBSSIM part of the Fermi Science Tools**
- **Galactic diffuse template: gll_iem_v06.fits .**
- **Isotropic diffuse template: iso P8R2_SOURCE_V6_v06.txt.**
- **Isotropic distribution of sources with an Euclidian distribution above the Fermi-LAT sensitivity (~10^{-11} ph/cm^2/s)**

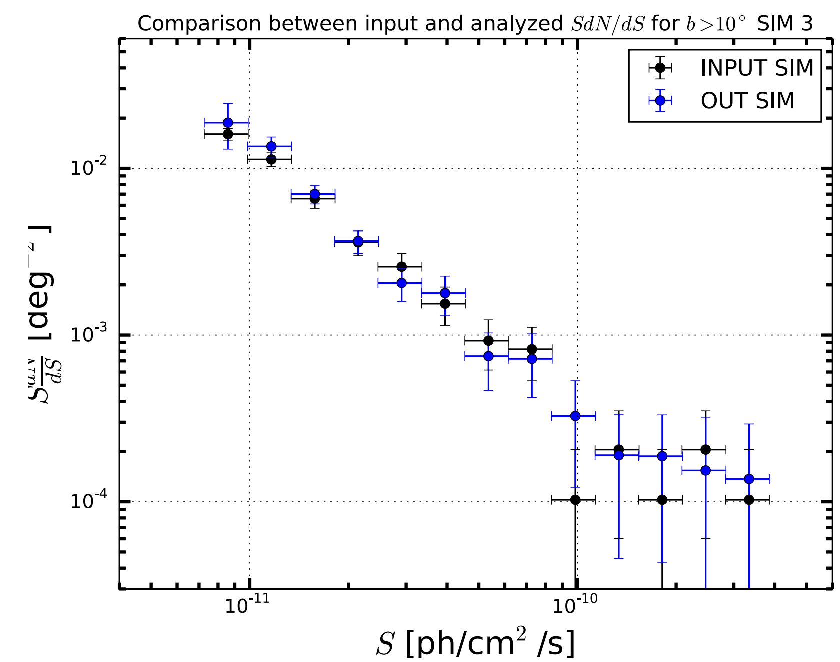


EDDINGTON BIAS

- The Eddington bias is given by statistical fluctuation of sources with a simulated flux below the threshold to a flux above the threshold.
- Our analysis is affected by this effect.
- We have checked with our simulations that we are able to re-construct the simulated flux distribution from the observed one using the efficiency.







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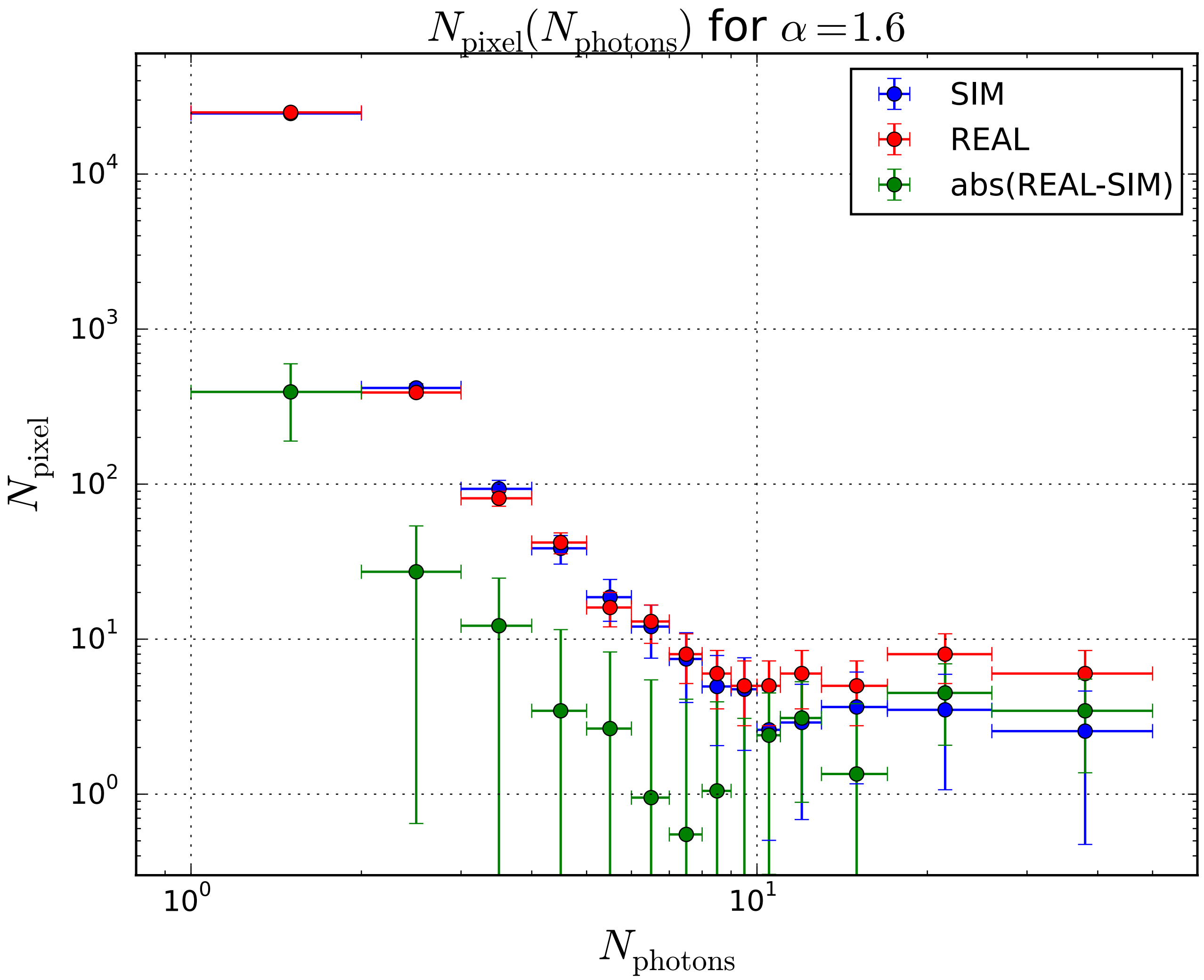
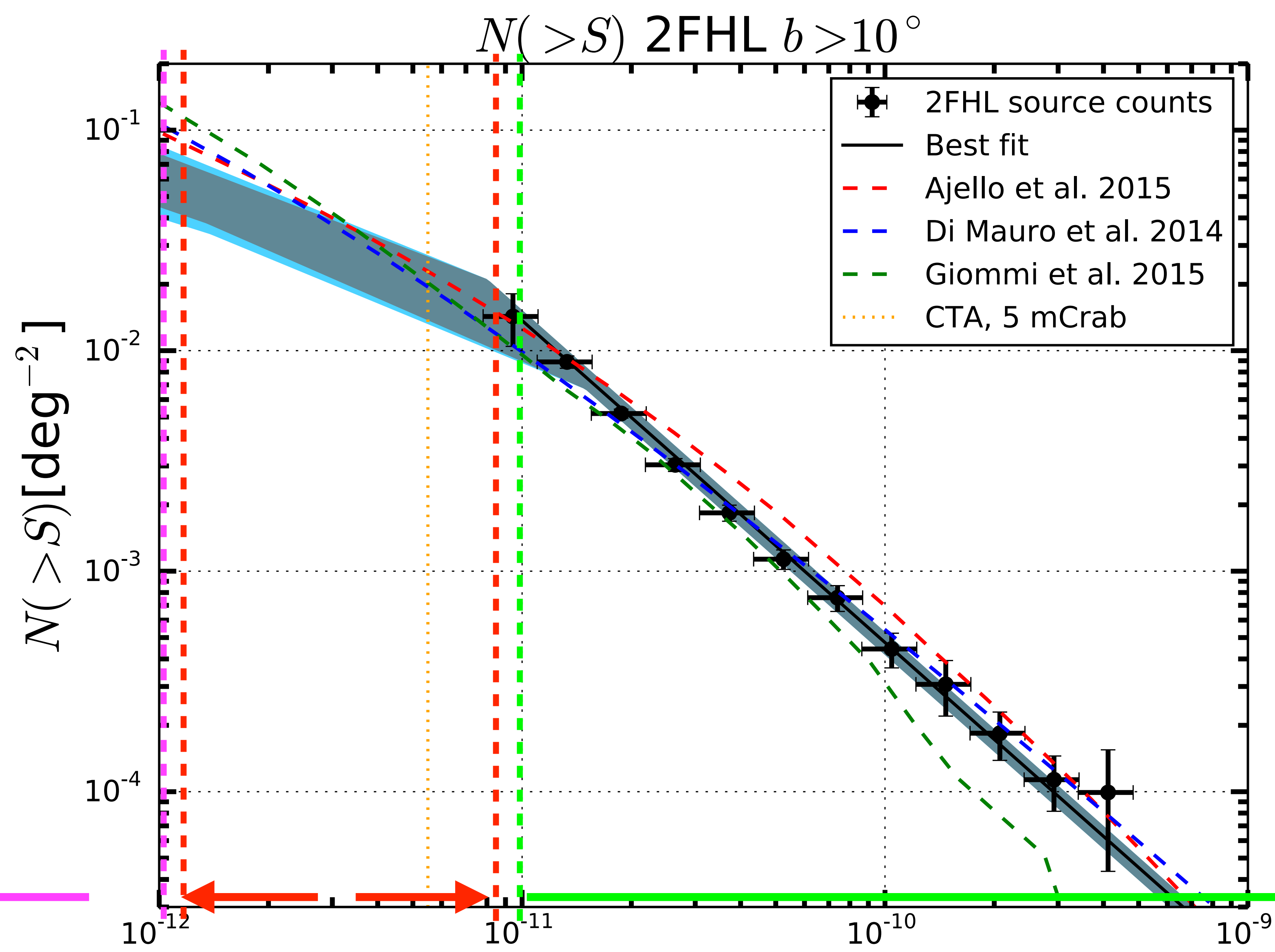


S_{break}(ph/cm2/s)	α_2	χ^2
$6\cdot 10^{-12}$	1.40 ± 0.10	25.0
$8\cdot 10^{-12}$	1.60 ± 0.03	15.5
$1\cdot 10^{-11}$	1.65 ± 0.03	12.4
$1.5\cdot 10^{-11}$	1.75 ± 0.03	14.6
$2\cdot 10^{-11}$	1.85 ± 0.02	17.0

ANALYSIS OF THE SIMULATIONS

- The 10 simulations are analyzed exactly as the real data.
- This starts from the detection of seeds using a **sliding-cell algorithm and a wavelet analysis.** The seed list contains real sources and also statistical fluctuations of the background.
- A ROI of 5deg is created for each seed. A sky model, that includes all the potential sources and diffuse backgrounds is fitted to the data using the **un-binned ML** with Fermi Science Tools (version v10 r01 00).
- The position of each seed is refined repeating the fit three times, after the spectral parameters of each model component have been optimized.
- Detected sources are those with a TS>25 and a number of emitted photons (as predicted by the likelihood) of $N_{pred} \geq 3$.
- Typically, this leads to the detection of on average 270 sources for lbl > 10 which is in good agreement with the 253 sources

CONTRIBUTION TO THE EXTRAGALACTIC GAMMA-RAY SI



$6.0^{+2.0}_{-1.0} \cdot 10^{-10}$ ph/cm²/s/sr

$7.9^{+1.5}_{-2.0} \cdot 10^{-9}$ ph/cm²/s/sr

$(6.8 \pm 0.5) \cdot 10^{-10}$ ph/cm²/s/sr

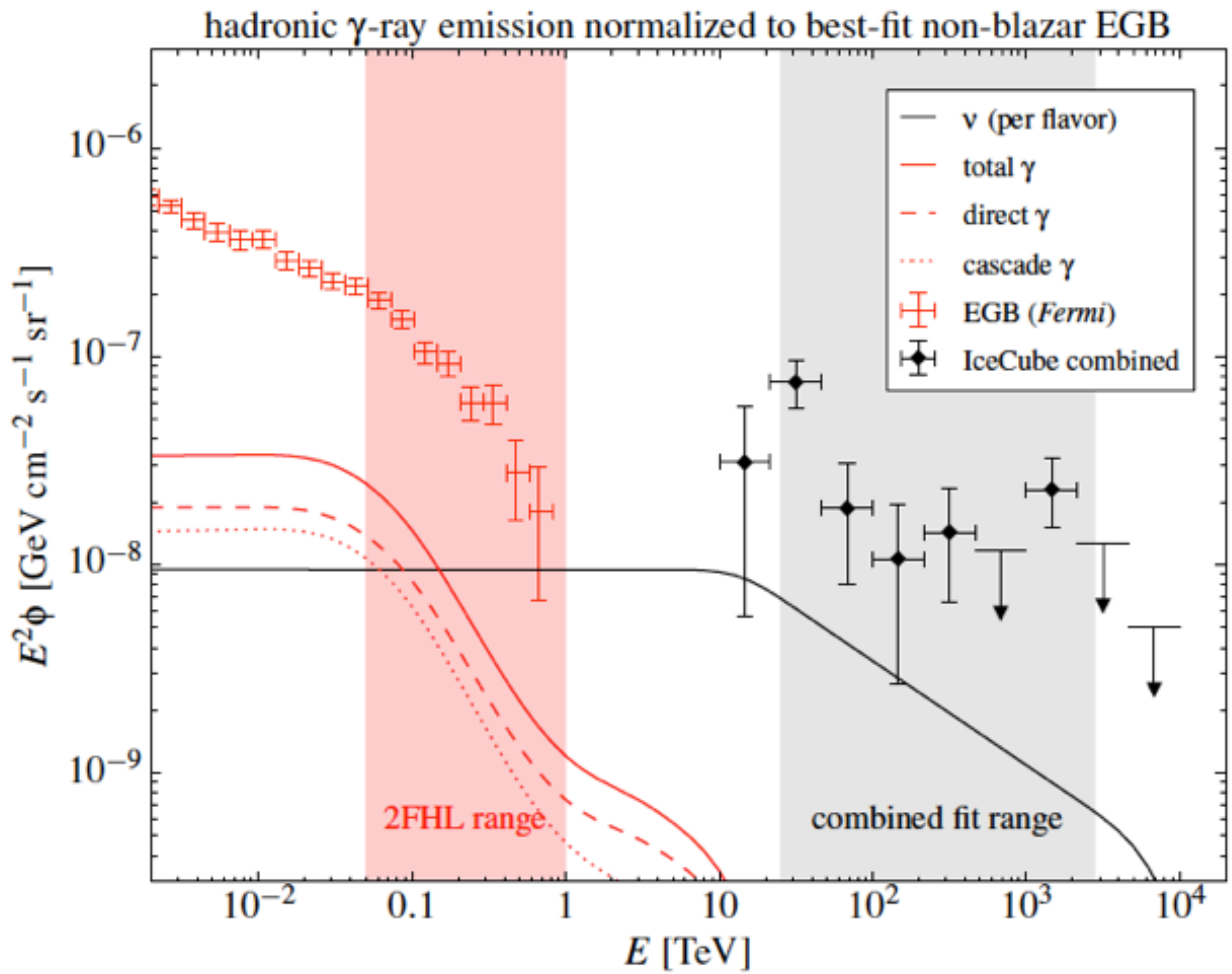
$2.07^{+0.40}_{-0.35} \cdot 10^{-9}$ ph/cm²/s/sr

EGB —> $(2.40 \pm 0.30) \cdot 10^{-9}$ ph/cm²/s/sr

Evidence against star-forming galaxies as the dominant source of IceCube neutrinos

Keith Bechtol, M. Ahlers, M. Di Mauro, M Ajello and J. Vandenbroucke

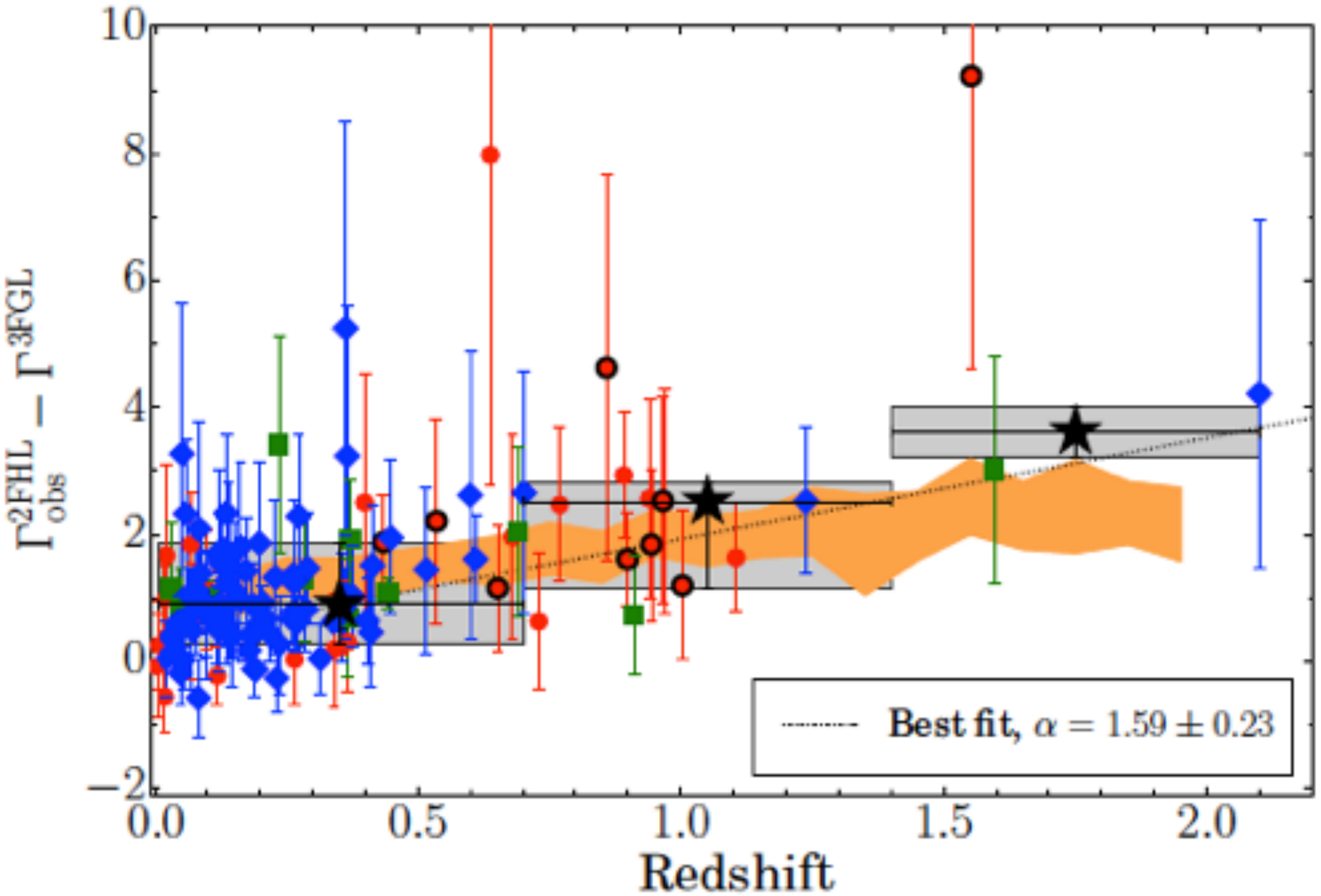
- **This is a cat III paper (https://www-glast.stanford.edu/cgi-prot/pub_download?id=1214).**

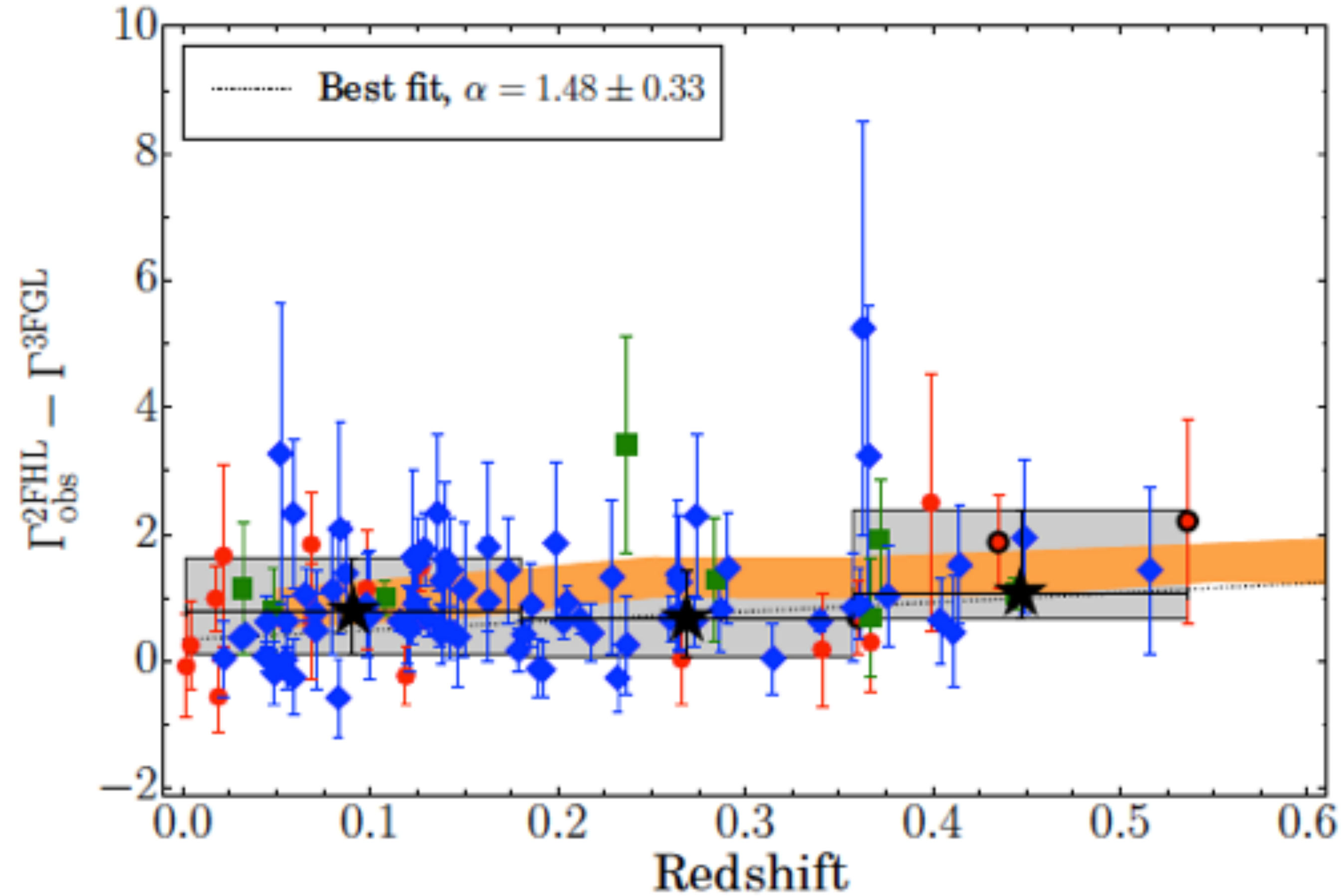


SPECTRAL ANALYSIS OF FERMI -LAT BLAZARS ABOVE 50 GEV

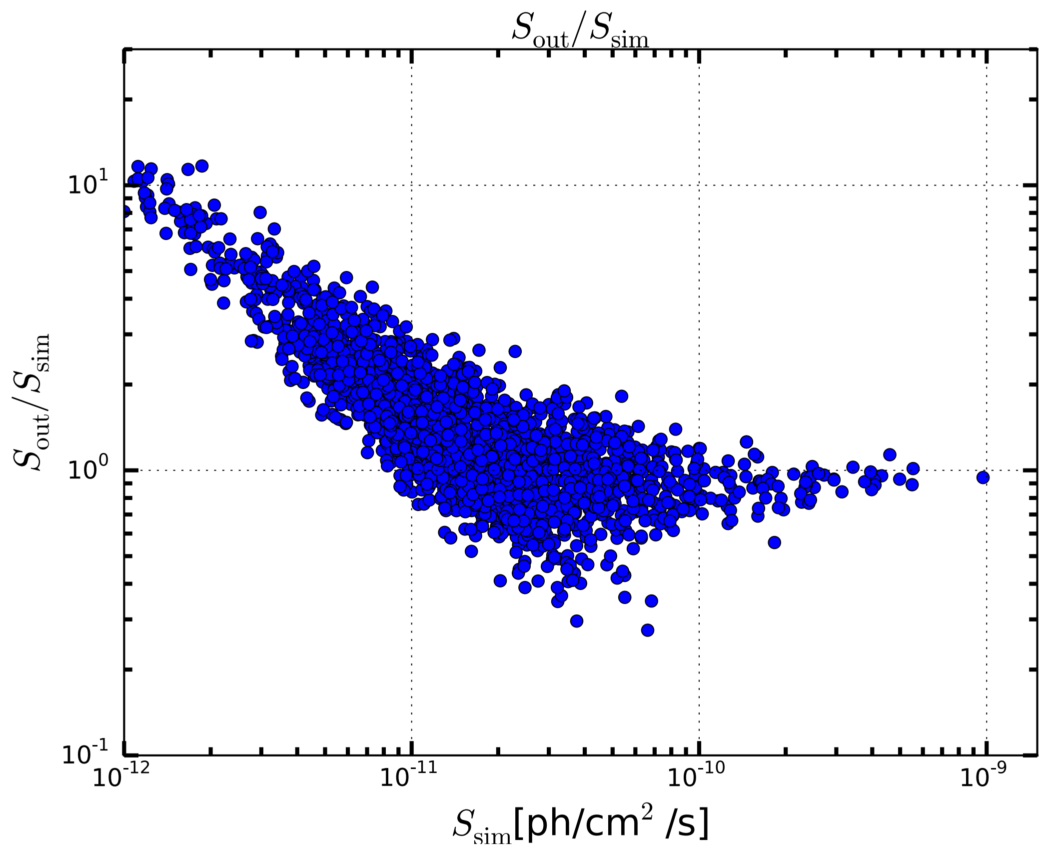
Alberto Dominguez and Marco Ajello

- **This is a cat II paper https://www-glast.stanford.edu/cgi-prot/pub_download?id=1198)**
- **They present an analysis of the intrinsic (unattenuated by the extragalactic background light, EBL) power-law spectral indices of 128 extragalactic sources detected up to z=2.**
- **They find that our data are compatible with simulations that include intrinsic blazar curvature and EBL attenuation.**

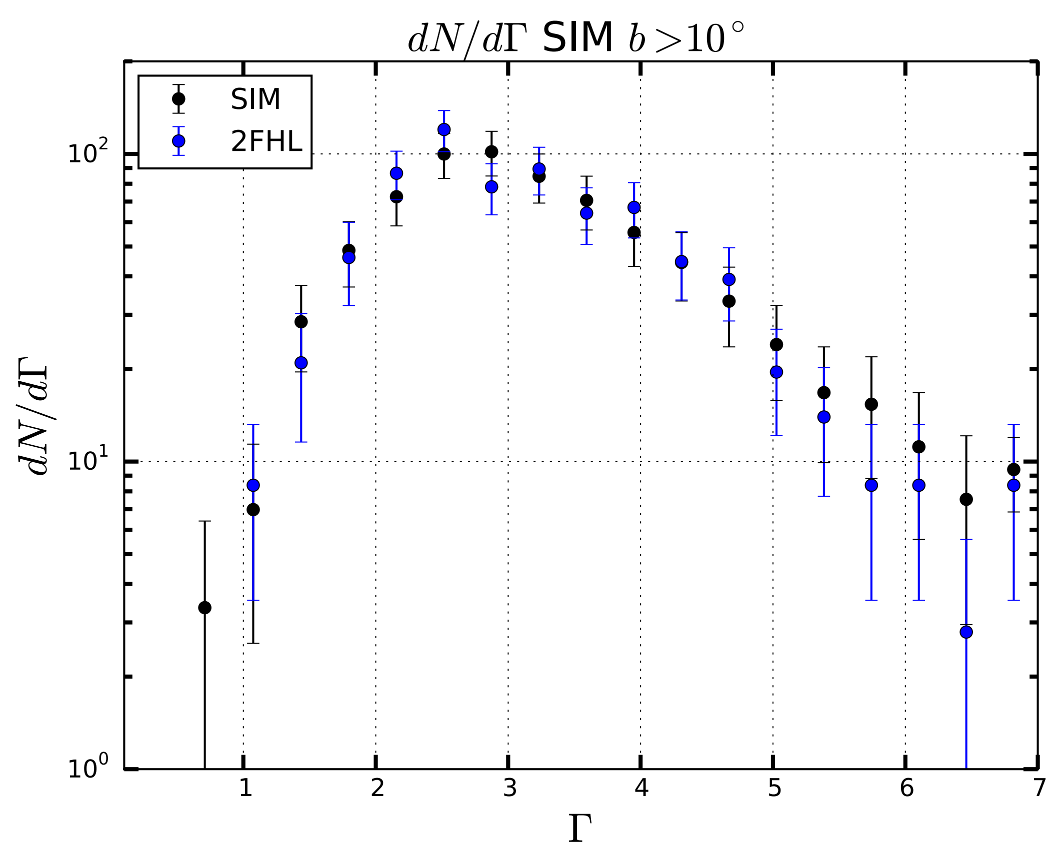




SANITY CHECKS



THE RATIOS CONVERGE TO 1!!



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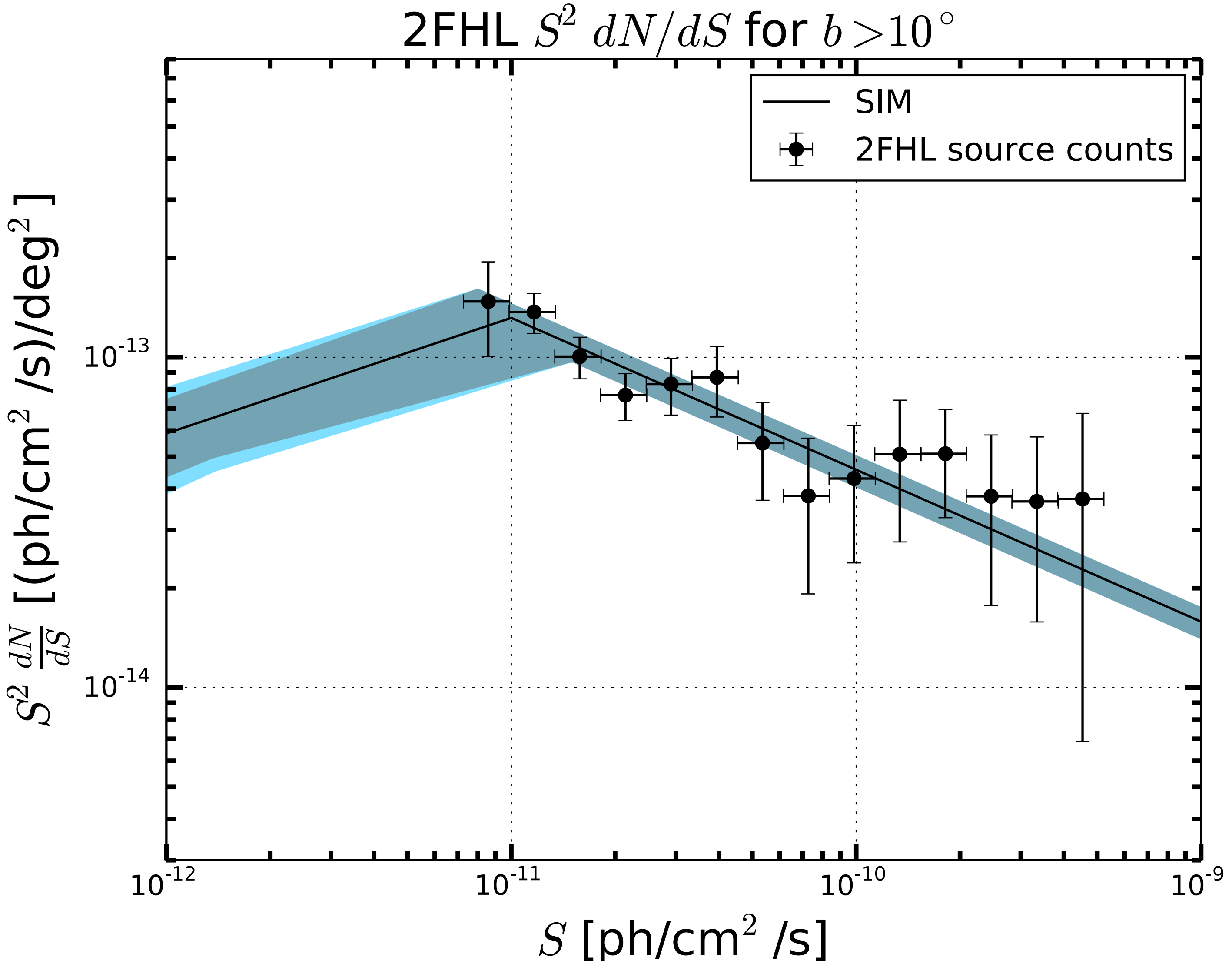


2FHL CATALOG

ANALYSIS

- Energy Range: 50-2000 GeV
- IRFs: P8R2_SOURCE_V6
- ~80 months of data (MET 239557417 - 444440679)
- |b|>10 deg

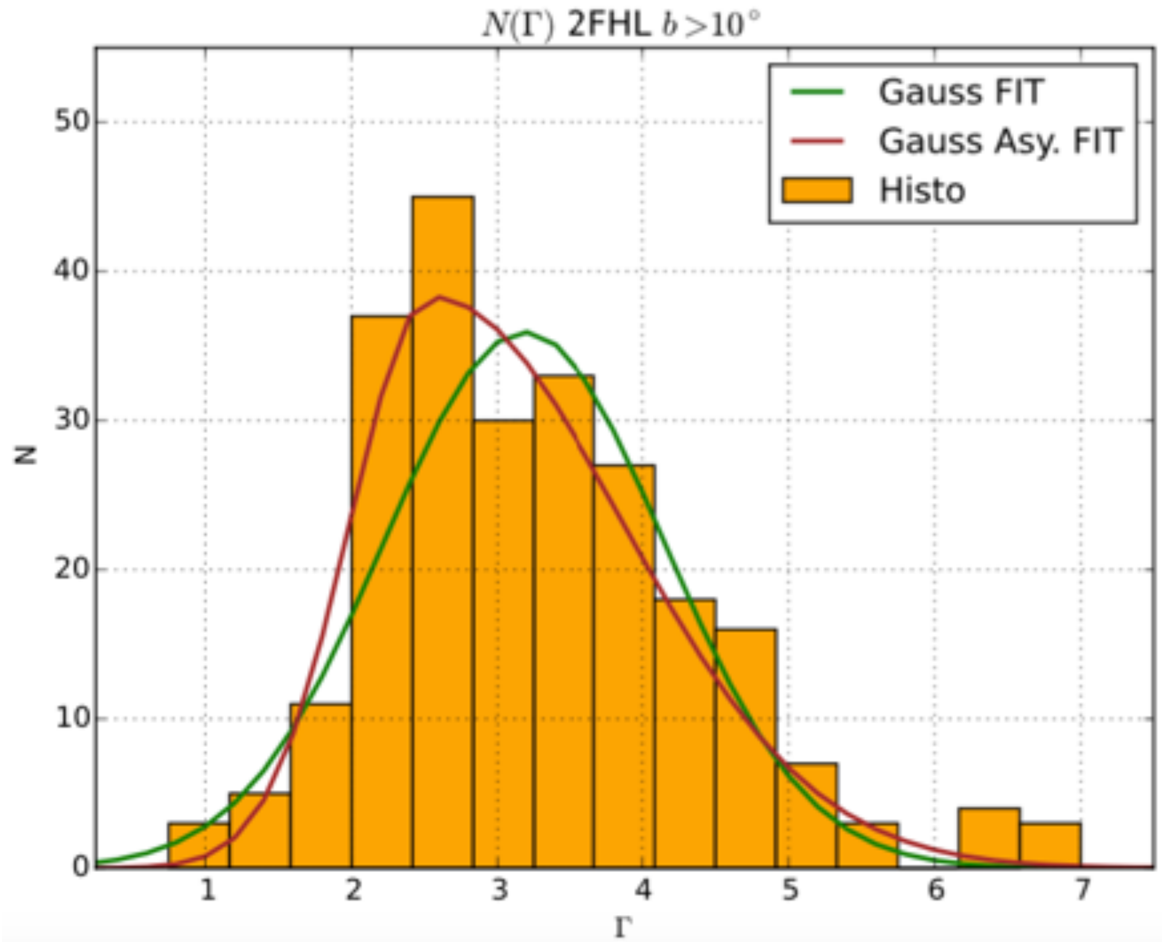
DATA CUTS:

- gtselect zmax=105
- gtmktime ‘IN_SAA!=T&&DATA_QUAL==1&&LAT_CONFIG==1'
- roicut=no
- gtltcube zmax=105

DETECTIONS

- Catalog version v4
- ~360 sources
- 71 detected by ACTs (TeVCat)
- 206 detected in 1FHL
- 234 detected in 3FGL (4 years, up to 300 GeV)
- ~60 brand new sources
- ~100 sources not in 1FHL and ~250 not in TeVCat

2FHL CAT PROPERTIES b>10 deg

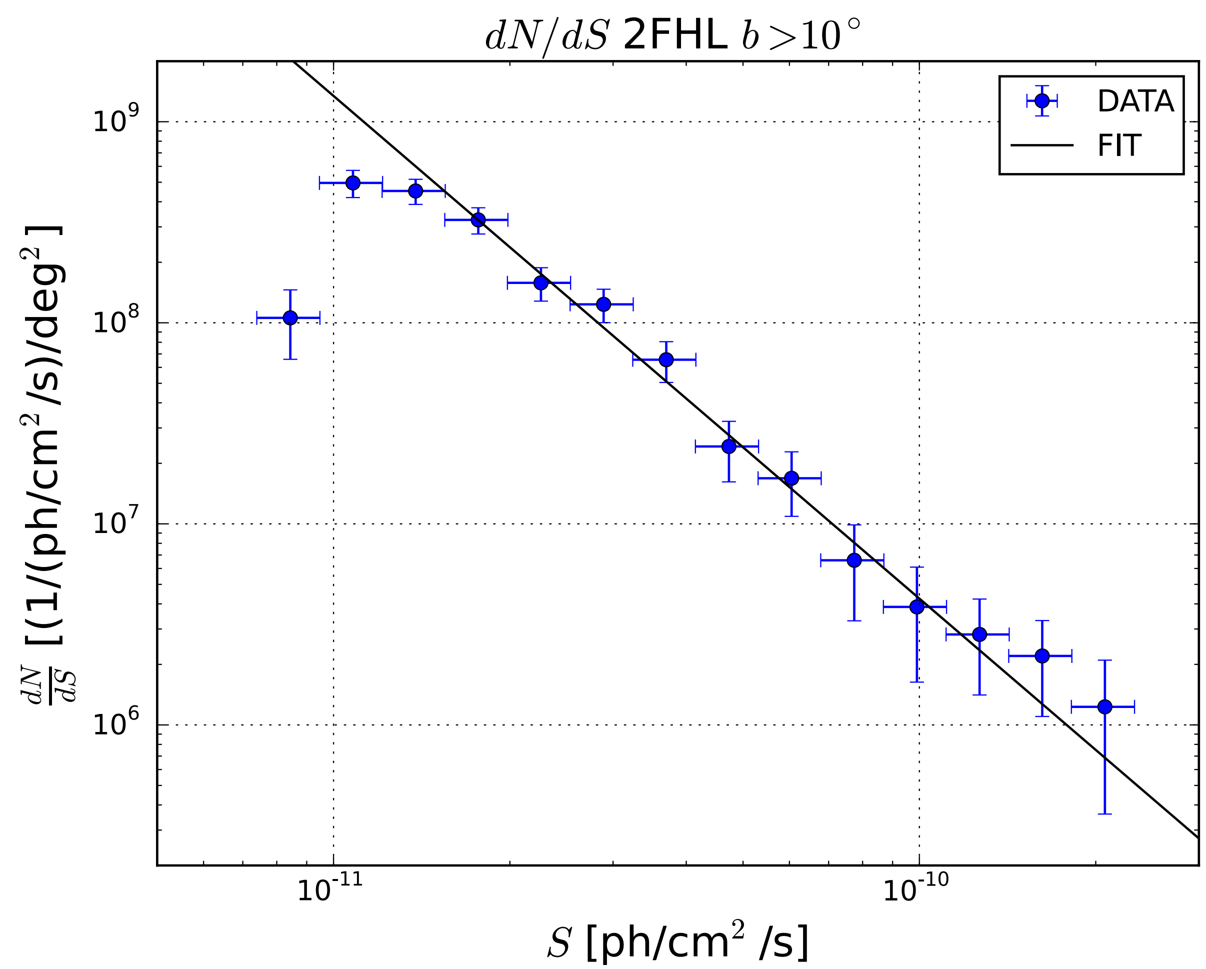


$\Gamma = 3.5 \pm 1.6$

Fit for F(>50 GeV)> $2 \cdot 10^{-11}$ ph/cm^2/s

$\alpha_1 = 2.50 \pm 0.12$

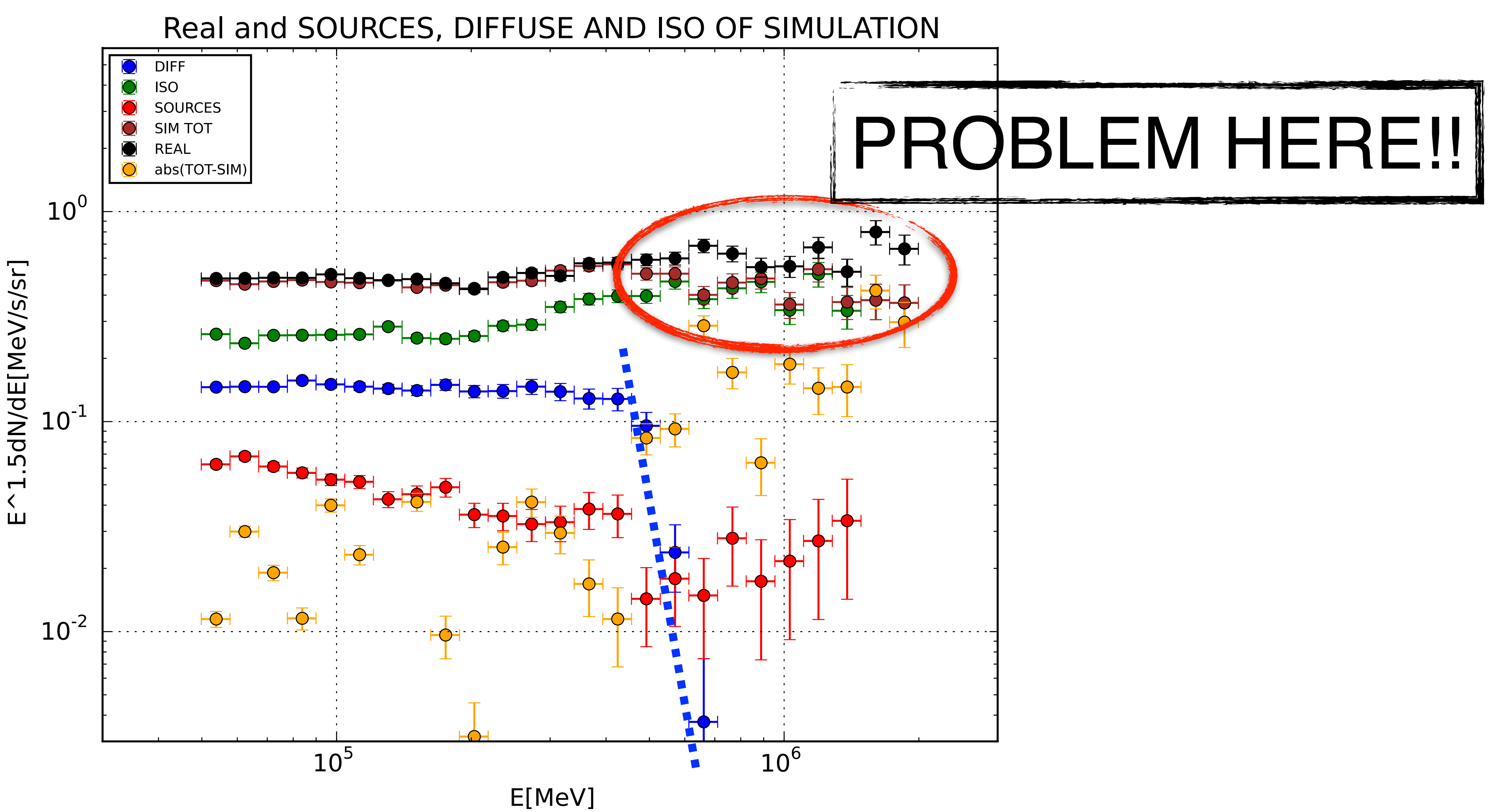
$dN/dS \sim S^{-\alpha}$



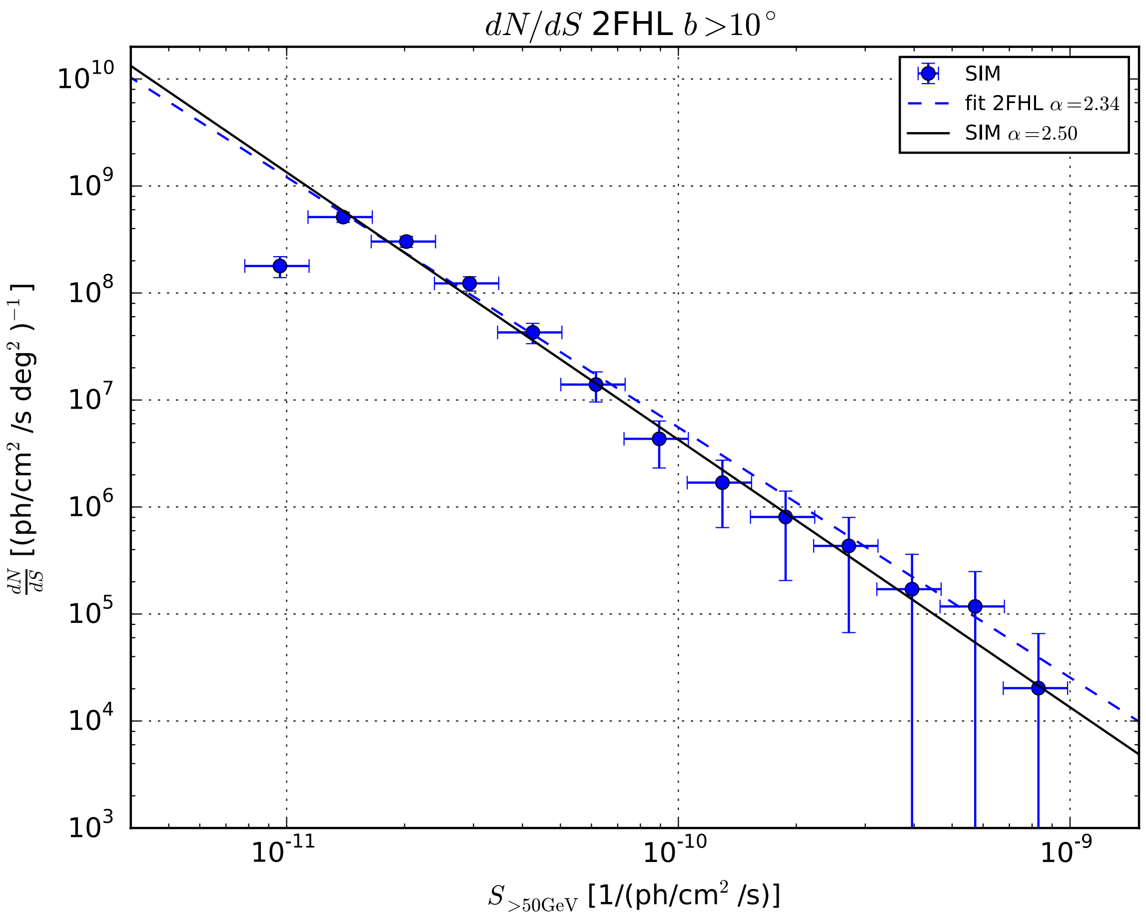
SIMULATION OF THE SKY FOR E>50GeV

- Sources with a dN/dS slope of 2.5 and a photon index of 3.2 ± 0.7
- Extended isotropic diffuse using: isotropic_source_4years_P8V3_extended.txt
- Galactic diffuse using: template_4years_P8_V2_scaled.fits

- We have used the command gtobssim with version ScienceTools-10-01-00

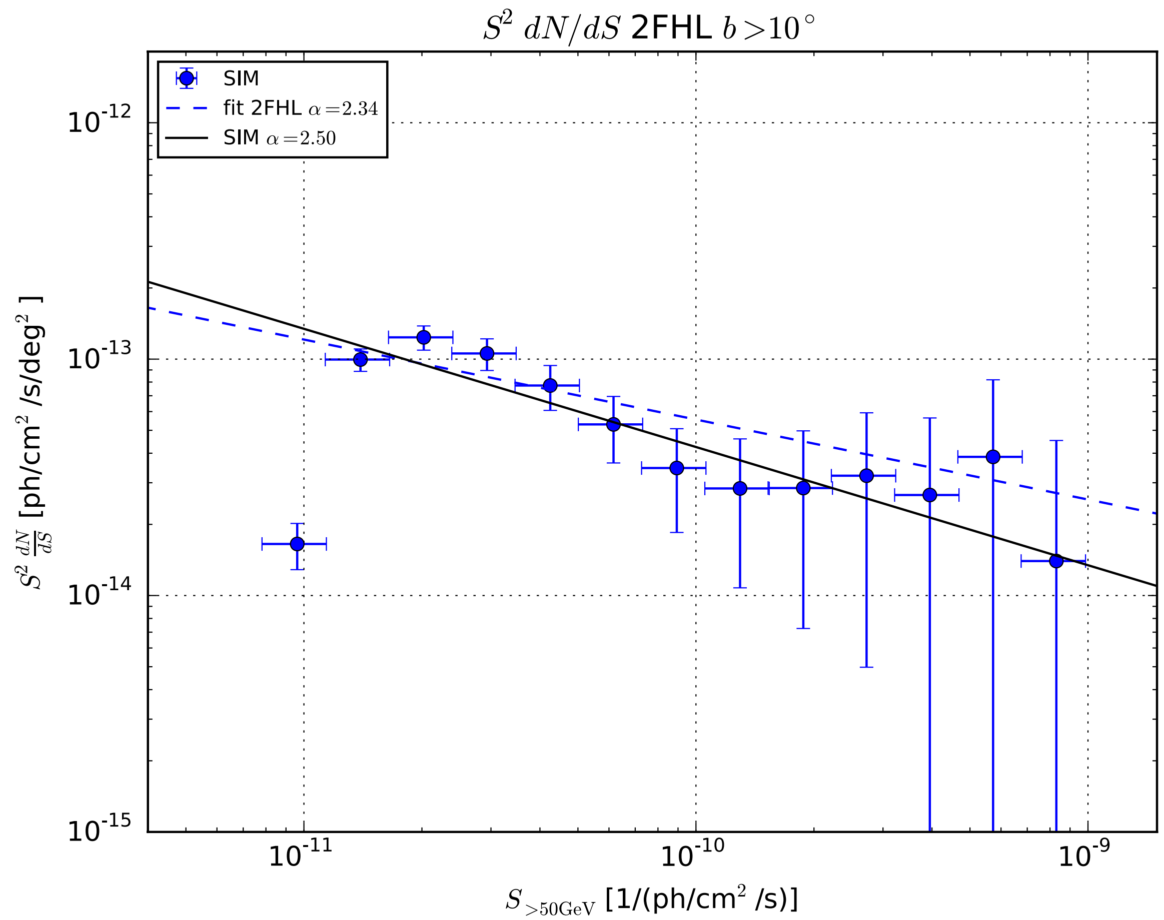


dN/dS of the Simulation



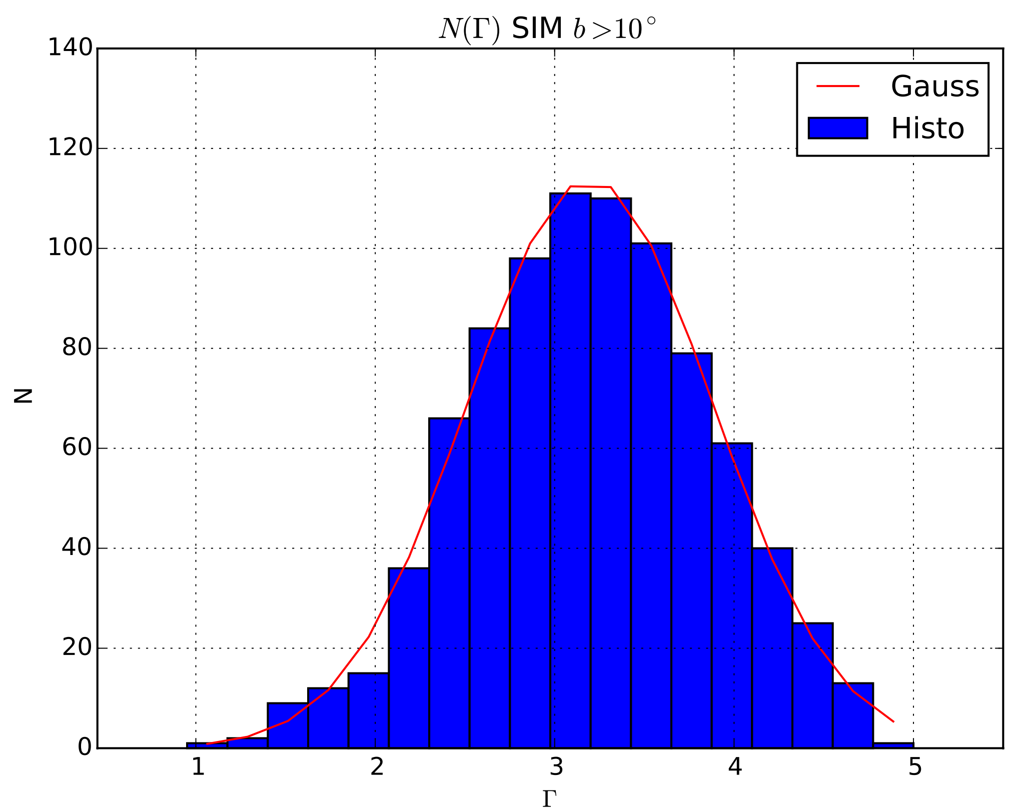
We obtain from the analysis of the simulations on average 264 sources

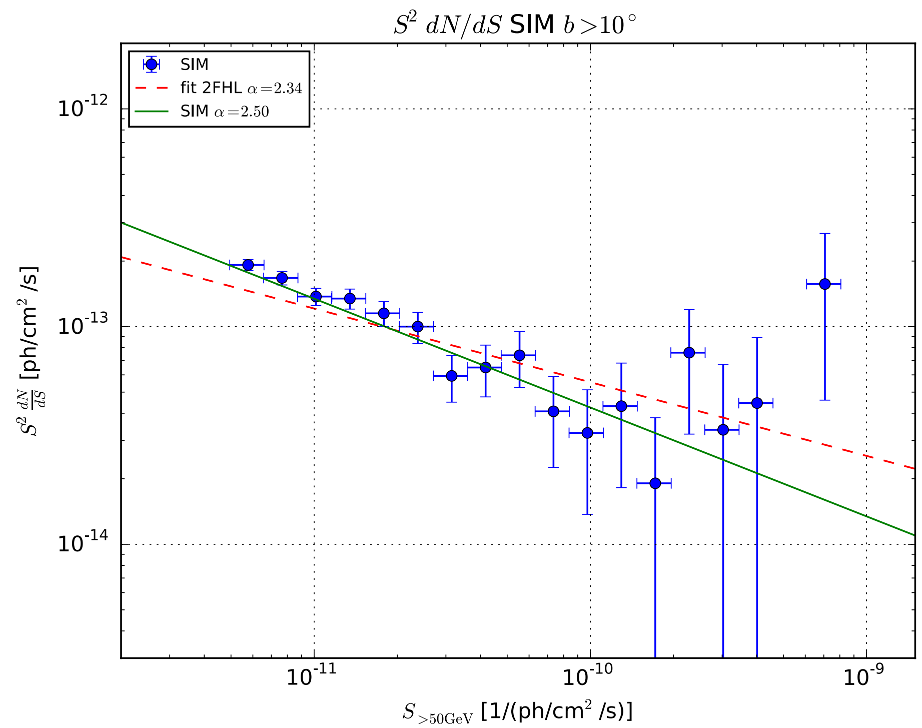
The slope of the dN/dS is consistent with 2.5



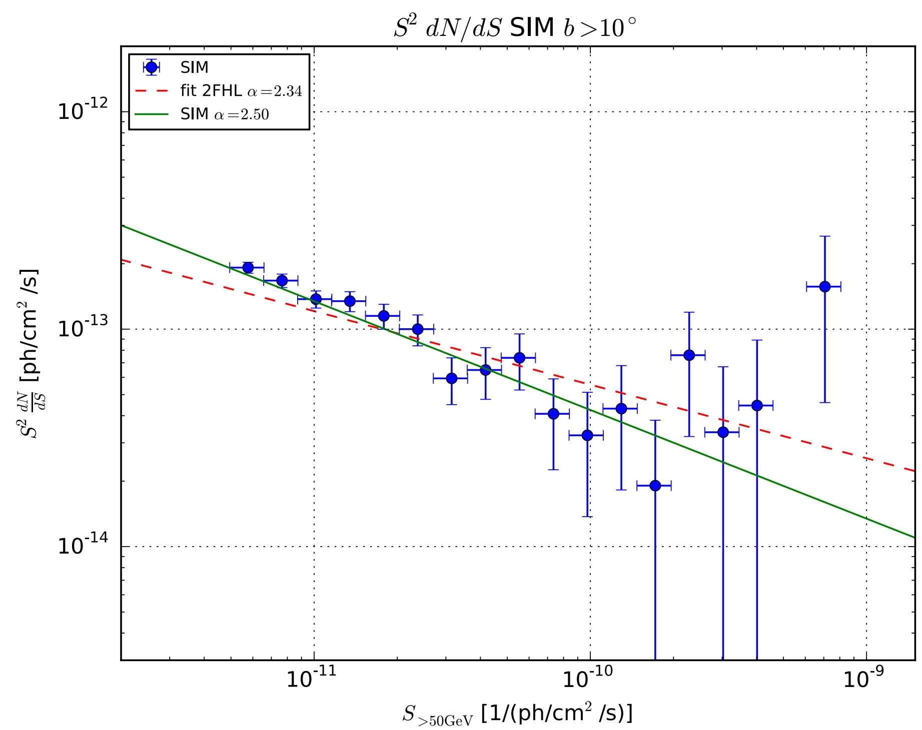
dN/dS and dN/dΓ

$\Gamma = 3.2 \pm 0.7$

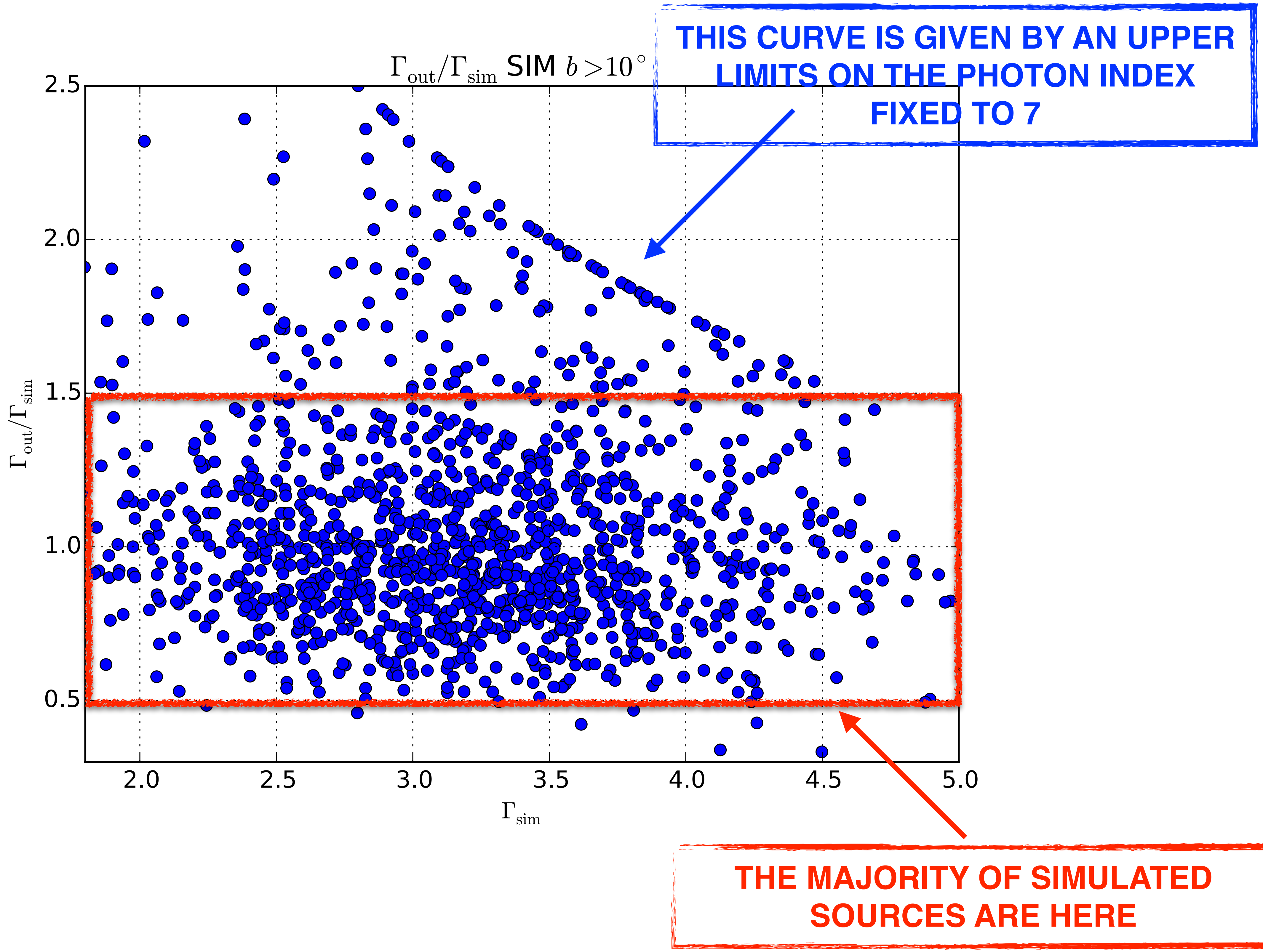




$\alpha = 2.50$



Γ Ratio



$\Gamma_{out}/\Gamma_{sim}$ SIM $b>10^\circ$
2.5
2.0
1.5
1.0
0.5
$\Gamma_{out}/\Gamma_{sim}$
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Γ_{sim}
THIS CURVE IS GIVEN BY AN UPPER LIMITS ON THE PHOTON INDEX FIXED TO 7
THE MAJORITY OF SIMULATED SOURCES ARE HERE

PIXEL COUNTING 1

- We use the pixel counting method in order to infer the slope of dN/dS below the threshold ($8 \cdot 10^{-12}$ ph/cm^2/s).
- We consider a broken power-law.
- The slope of the dN/dS above the threshold is the one of the catalog $\alpha_1 = 2.50$.
- We make different choices of the flux break $[0.6,0.8,1,1.5,2] \cdot 10^{-11}$ ph/cm^2/s.
- For each choice of the flux break we take a value for the slope ranging between [1.3,2.7].
- We generate for each choice of the flux break and for each value of the slope below the break 20 simulations of the sky.
- We compare, using a χ^2 method, the real sky and the simulation pixel counting distributions.
- The sensitivity of this method is around $1.3 \cdot 10^{-12}$ ph/cm^2/s

ANALYSIS OF SIMULATIONS

- **We have performed 10 simulations.**
- **Each simulation has been analyzed with an unbinned method using rungt.py.**
- **This starts from the detection of source candidates (called seeds).**
- **A region of interest (ROI) is created for each seed and a sky model is fitted to the data using the unbinned ML algorithm (Fermi Science Tools version v10_r01_00).**
- **The result of each simulation is used as a starting point to analyze again the simulation in order to improve position calculation of the sources**
- **Because the significance of a source depends both on its optimized position and the spectral parameters, this procedure is repeated three times to make sure that all the parameters have been refined successfully**
- **As in the 2FHL catalog, detected sources are those with a TS>25 and a number of emitted photons (as predicted by the likelihood) of $N_{pred} > 3$. Typically, this leads to the detection of ~270 sources for |b| > 10° which is in good agreement with the 253 sources detected in the 2FHL**

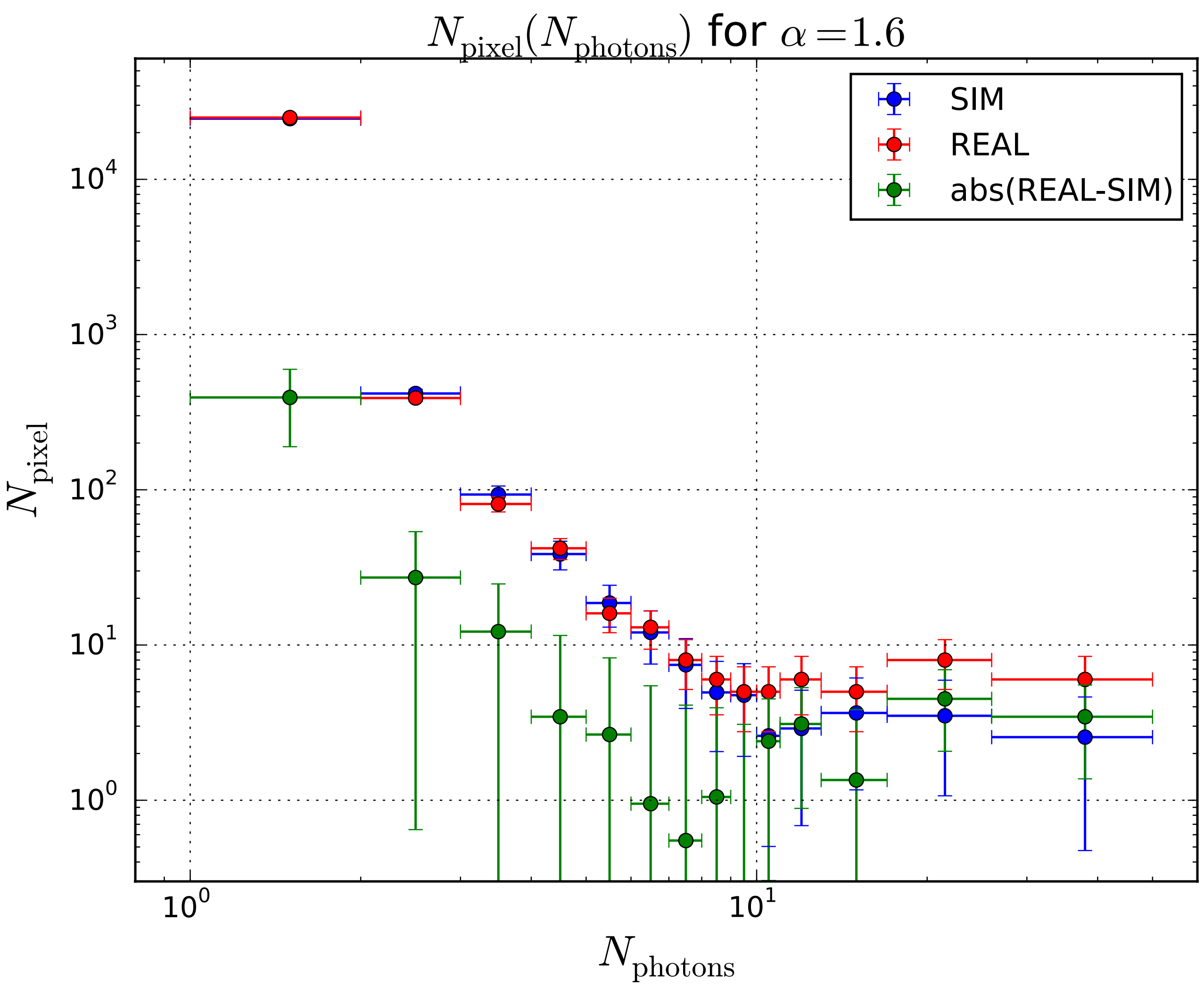
PIXEL COUNTING SENSITIVITY

- In order to find the sensitivity of the pixel counting method we have considered a double broken power law with the first break at $1 \cdot 10^{-11}$ ph/cm²/s and the second break ranging between $[0.5,5] \cdot 10^{-12}$ ph/cm²/s.
- The slope above and below the first break is fixed to be 2.50 and 1.60 respectively.
- The slope below the second break is fixed to be 1.80 which is not the best fit value of the slope!
- We generate for each choice of the flux break 20 simulations and we compare the real sky and simulations pixel counting distributions with a χ^2 method.

S_{break}(ph/cm2/s))	χ^2
$5 \cdot 10^{-13}$	14
$7 \cdot 10^{-13}$	14
$1 \cdot 10^{-12}$	14
$1.3 \cdot 10^{-12}$	17
$1.5 \cdot 10^{-12}$	19
$2 \cdot 10^{-12}$	21
$3 \cdot 10^{-12}$	25
$5 \cdot 10^{-12}$	34

PIXEL COUNTING 2

- **We employed the photon fluctuation analysis to derive the shape of the flux distribution below the sensitivity if the 2FHL cat.**
- **Simulations with different value of the break and of the slope below the break have been tested.**
- **The flux distribution results to be consistent with a broken power law with a break in the range [0.8,1.5]·10^{-11} ph/cm²/s and a slope above and below the break α_1 = 2.50 and [1.6,1.75]**



$S_{break(ph/cm2/s))}$	α_2	χ^2
$6 \cdot 10^{-12}$	1.40 ± 0.10	25.0
$8 \cdot 10^{-12}$	1.60 ± 0.03	15.5
$1 \cdot 10^{-11}$	1.60 ± 0.03	12.4
$1.5 \cdot 10^{-11}$	1.75 ± 0.03	14.6
$2 \cdot 10^{-11}$	1.85 ± 0.02	17.0

PIXEL COUNTING 3

- The flux break can vary between [0.8,1,1.5]$\cdot 10^{-11}$ ph/cm²/s with a slope below the threshold ranging between $\alpha_2 = [1.6, 1.75]$.
- The choice of a break lower than $0.8 \cdot 10^{-11}$ ph/cm²/s gives large value for χ^2.
- Our benchmark model for the flux differential distribution is a broken power-law with a break at $1 \cdot 10^{-11}$ ph/cm²/s and with a slope above and below the break of $\alpha_1 = 2.50$ and $\alpha_2 = 1.60$ respectively.