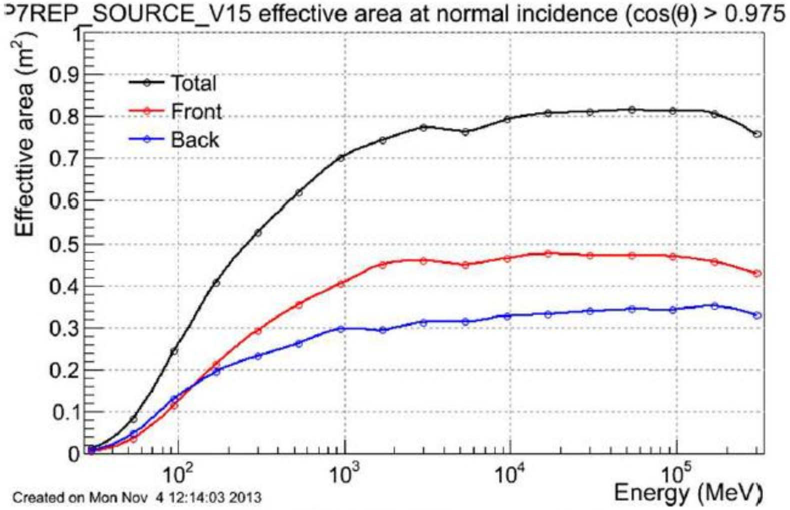
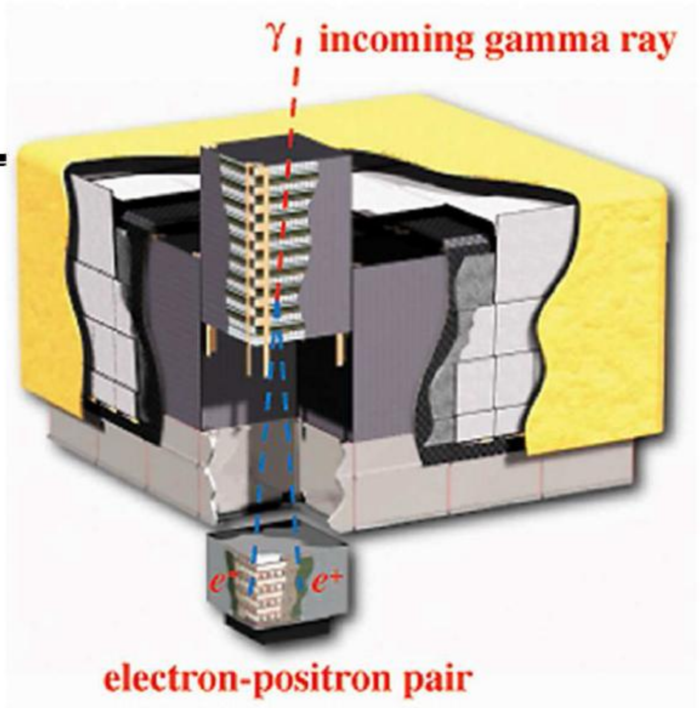
Latest results from Fermi-LAT and the impact on neutrino observations

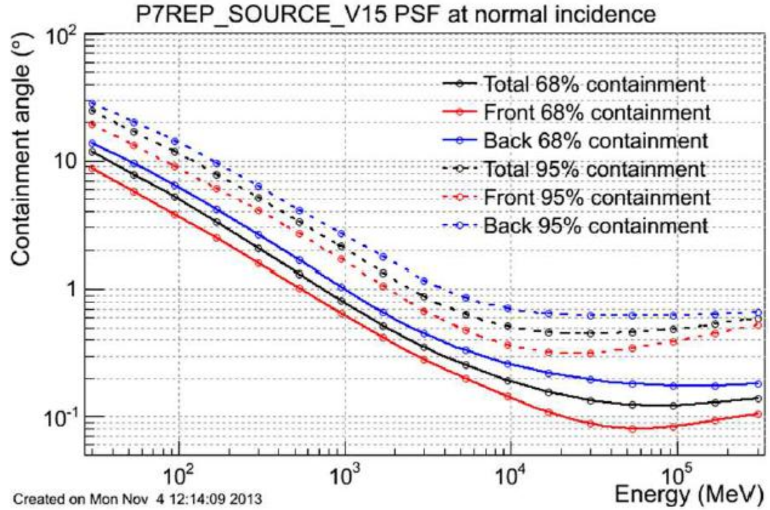
Paolo Giommi
ASI-ASDC

LAT performance

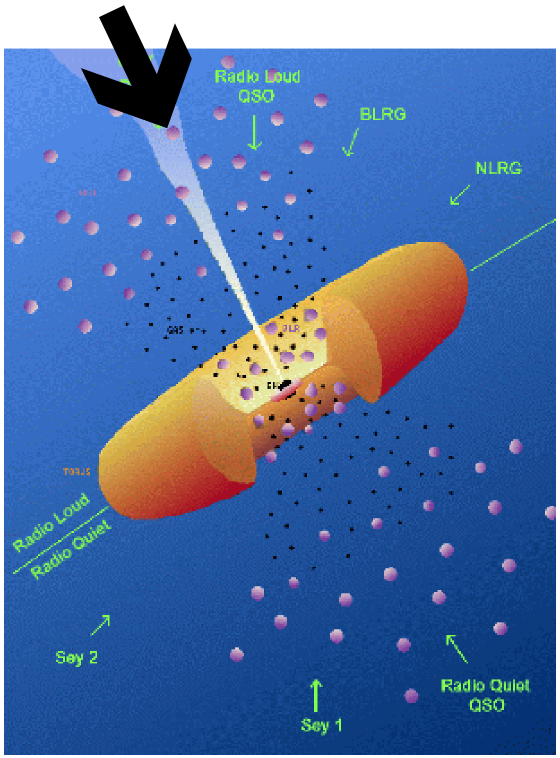
http://www-glast.slac.stanford.edu/software/IS/glast_lat_performance.htm







- **energy range: 30 MeV - 300 GeV**
- **large FOV: 2.4 sr**
- **PSF: $\theta_{68\%}$~0.8° at 1 GeV**
- **A_{eff}:~8000 cm^2 at 1 GeV**
- **altitude: 565 km**
- **inclination: 25.6°**
- **orbital period: 91 min**
- **whole sky covered in 2 orbits in survey mode (rocking angle 50°)**
- **public data, available within 12 h**
- **operation garanteed until 2018**



AGN : Two main categories

1. *Dominated by (mostly) thermal emission from accretion disk -*

   Radio quiet AGN (>~90 %)

(normal QSO powered by accretion onto a SM black hole)

1. *Dominated by Non-Thermal radiation –*

   Jet dominated AGN (< 10%)

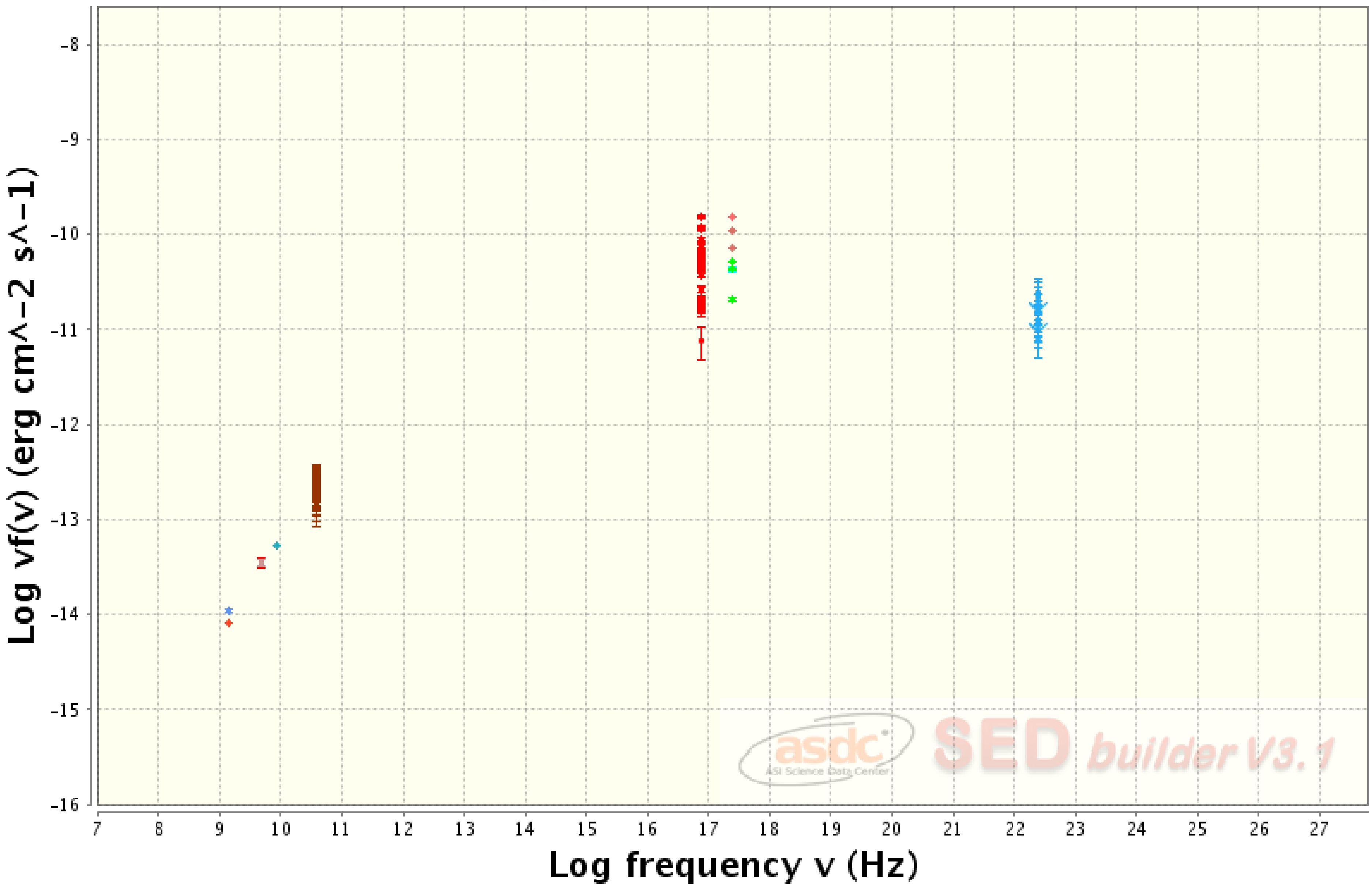
When **$\Theta < \theta_{blazar}$** → **Blazar**

As of today, about 3,561 blazars are known (Bzcat, edition 5., Massaro et al. 2015).

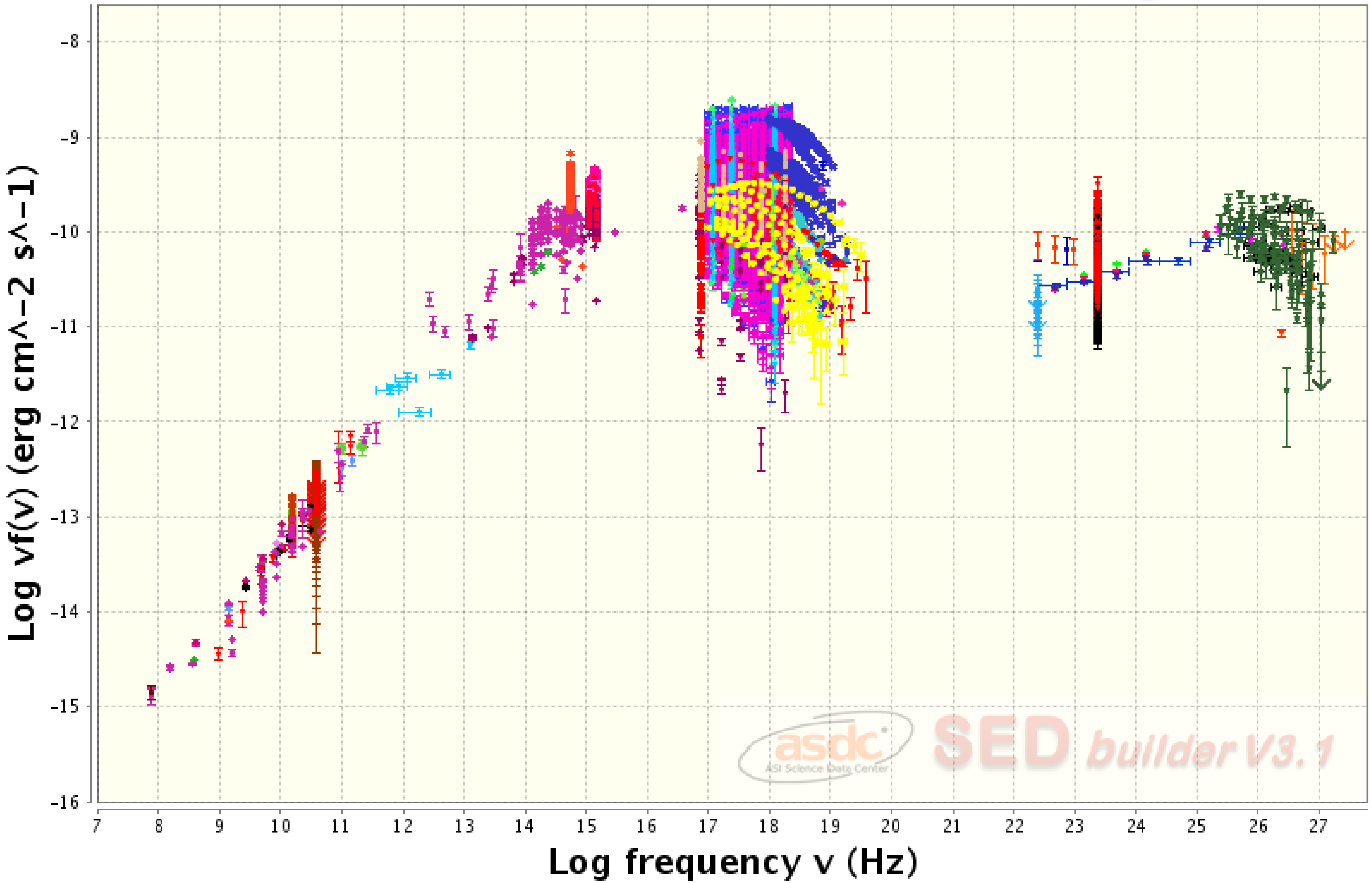
This number is increasing rapidly but it remains a small percentage of the over one million AGN known

..and the ~one billion stars/galaxies known

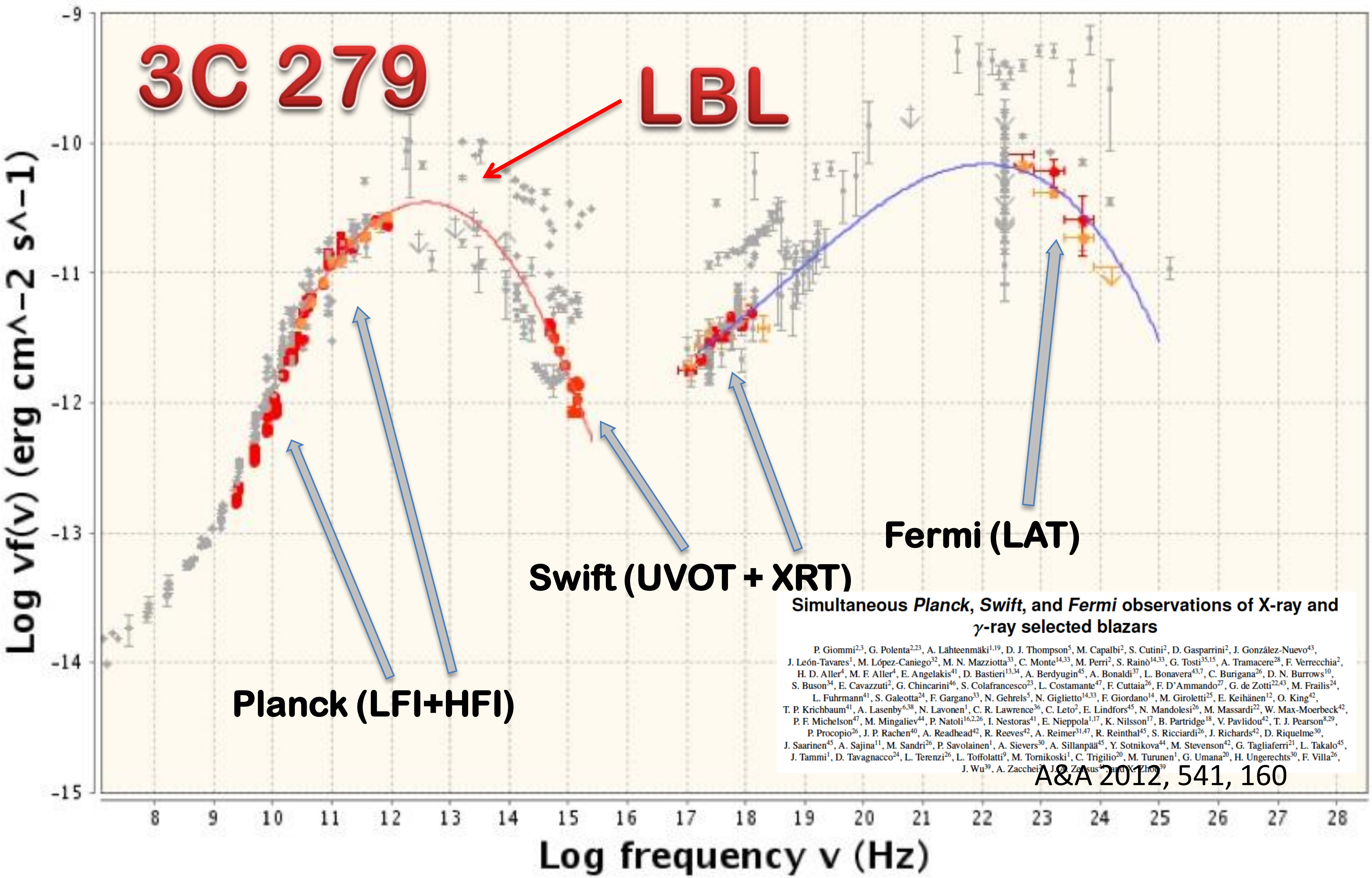
MRK 421, the SED in 1995

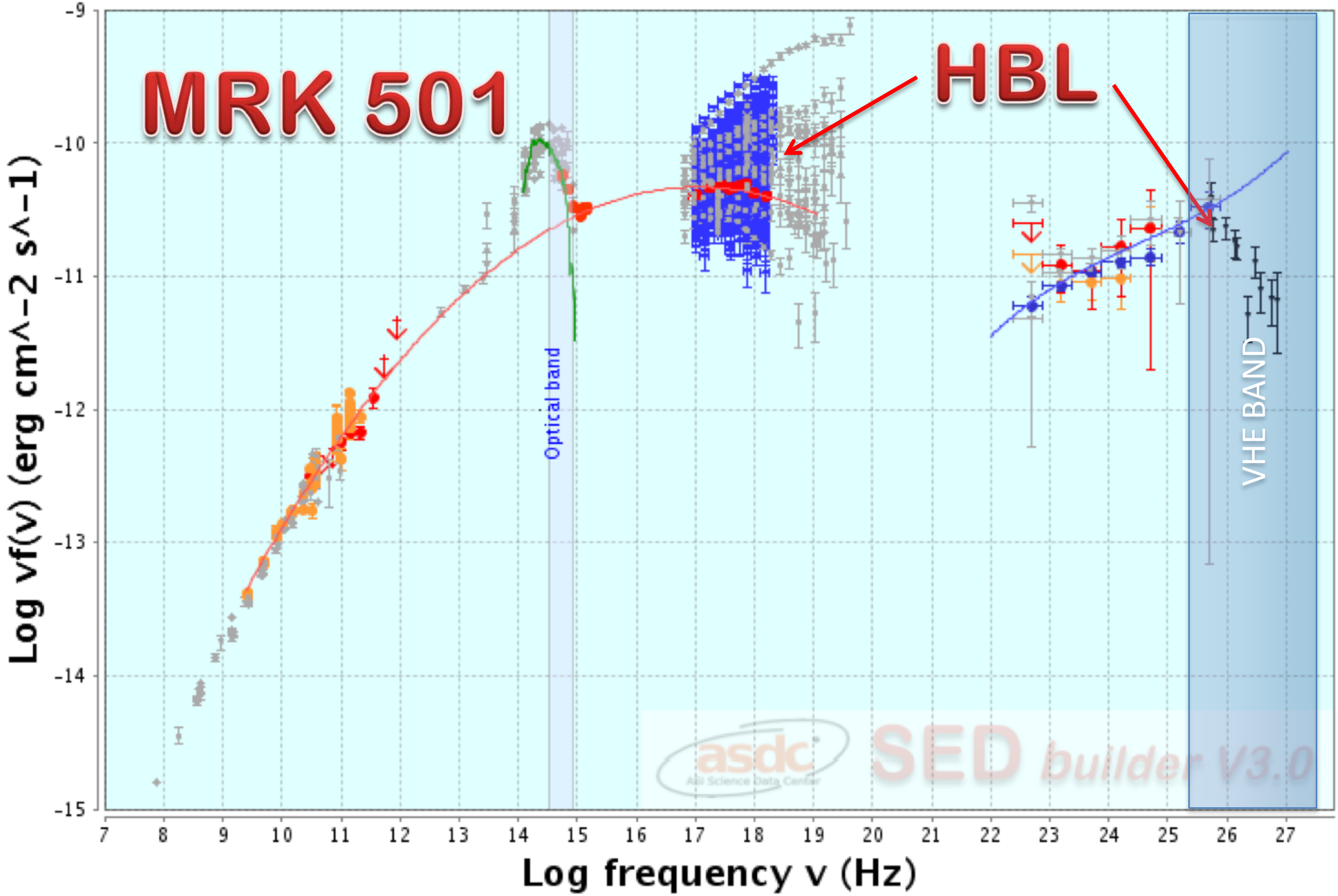


MRK 421, the SED today



asdc
ASI Science Data Center




MRK 501
HBL
VHE BAND
Optical band
Log νf(ν) (erg cm^-2 s^-1)
Log frequency ν (Hz)
-9
-10
-11
-12
-13
-14
-15
7
8
9
10
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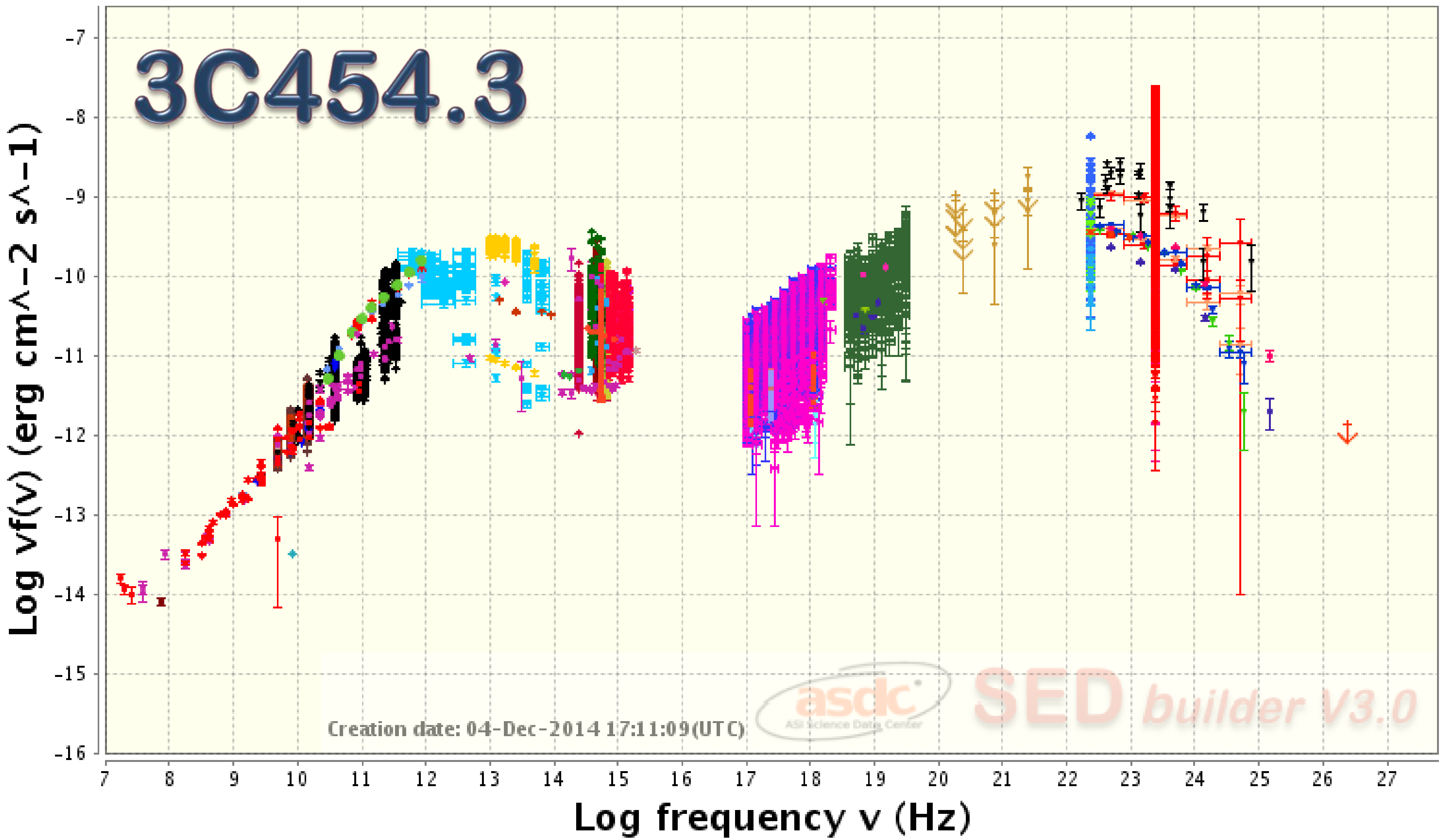
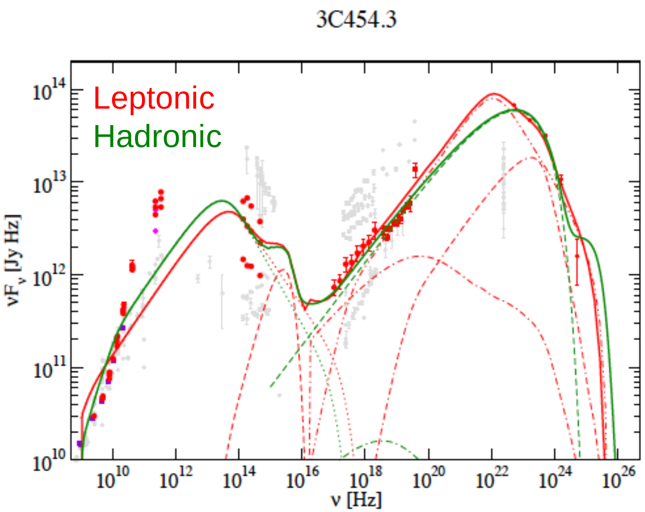
SED builder V3.0

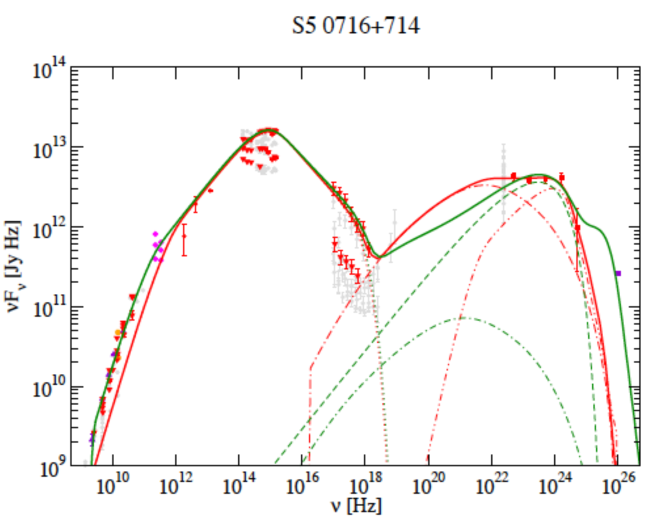

asdc
ASI Science Data Center


3C454.3
Log νf(ν) (erg cm^-2 s^-1)
-7
-8
-9
-10
-11
-12
-13
-14
-15
-16
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
Log frequency ν (Hz)
Creation date: 04-Dec-2014 17:11:09(UTC)
asdc
SED builder V3.0

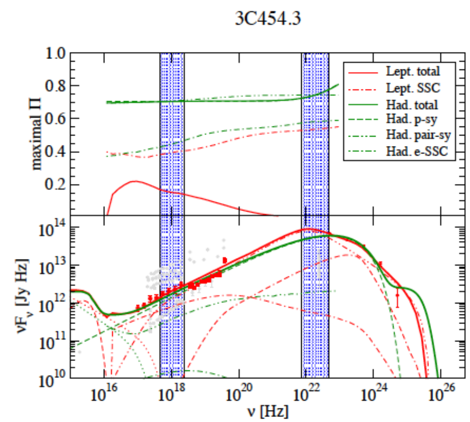
Leptonic or hadronic emission??

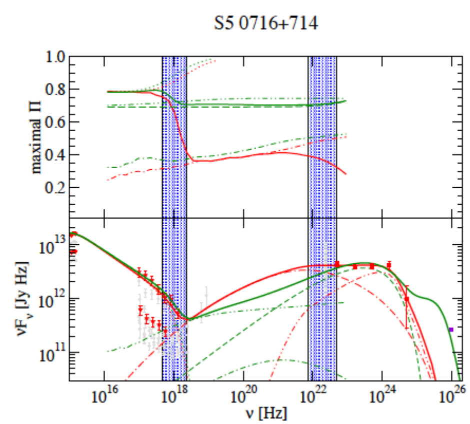
Most blazar spectra well fit by leptonic models



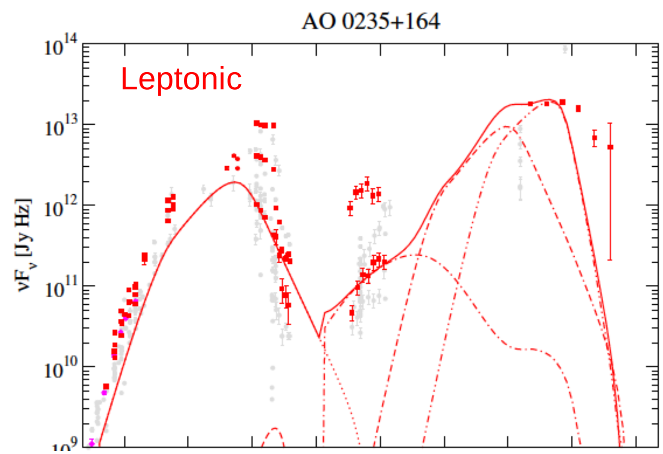


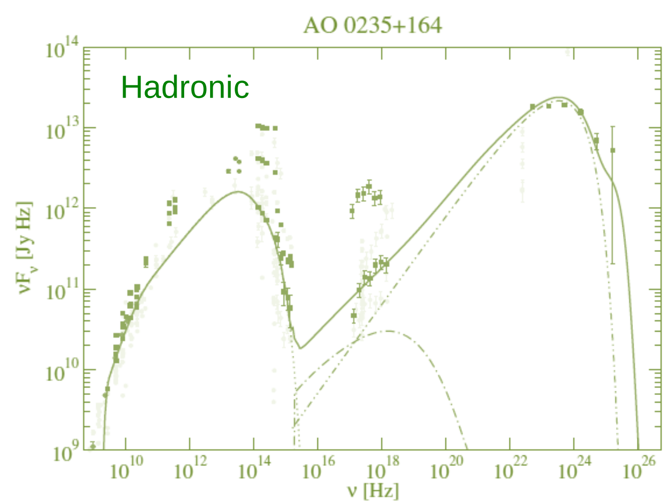
Optical/X-ray polarization can decide





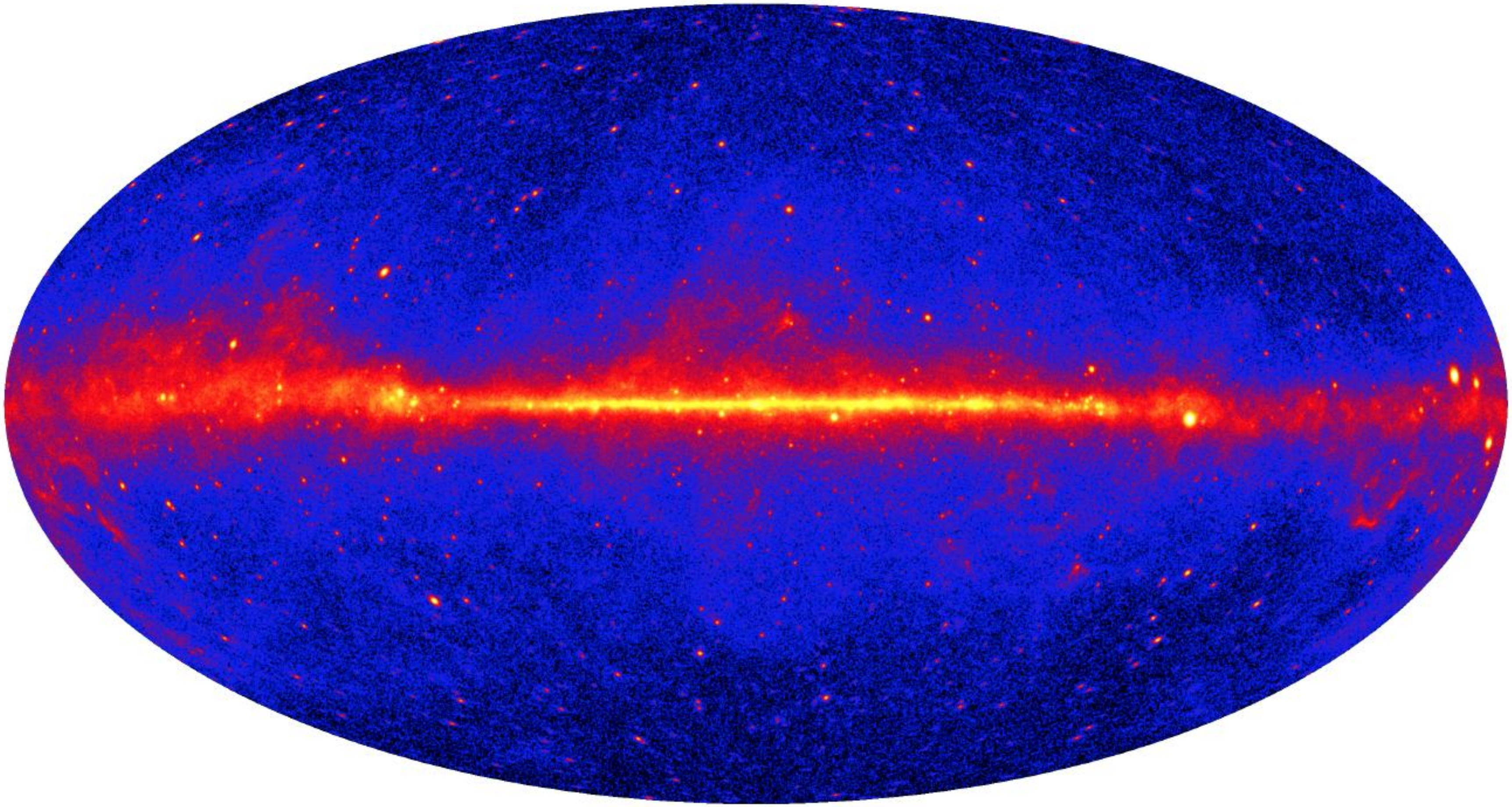
But a few are better fit by hadronic models



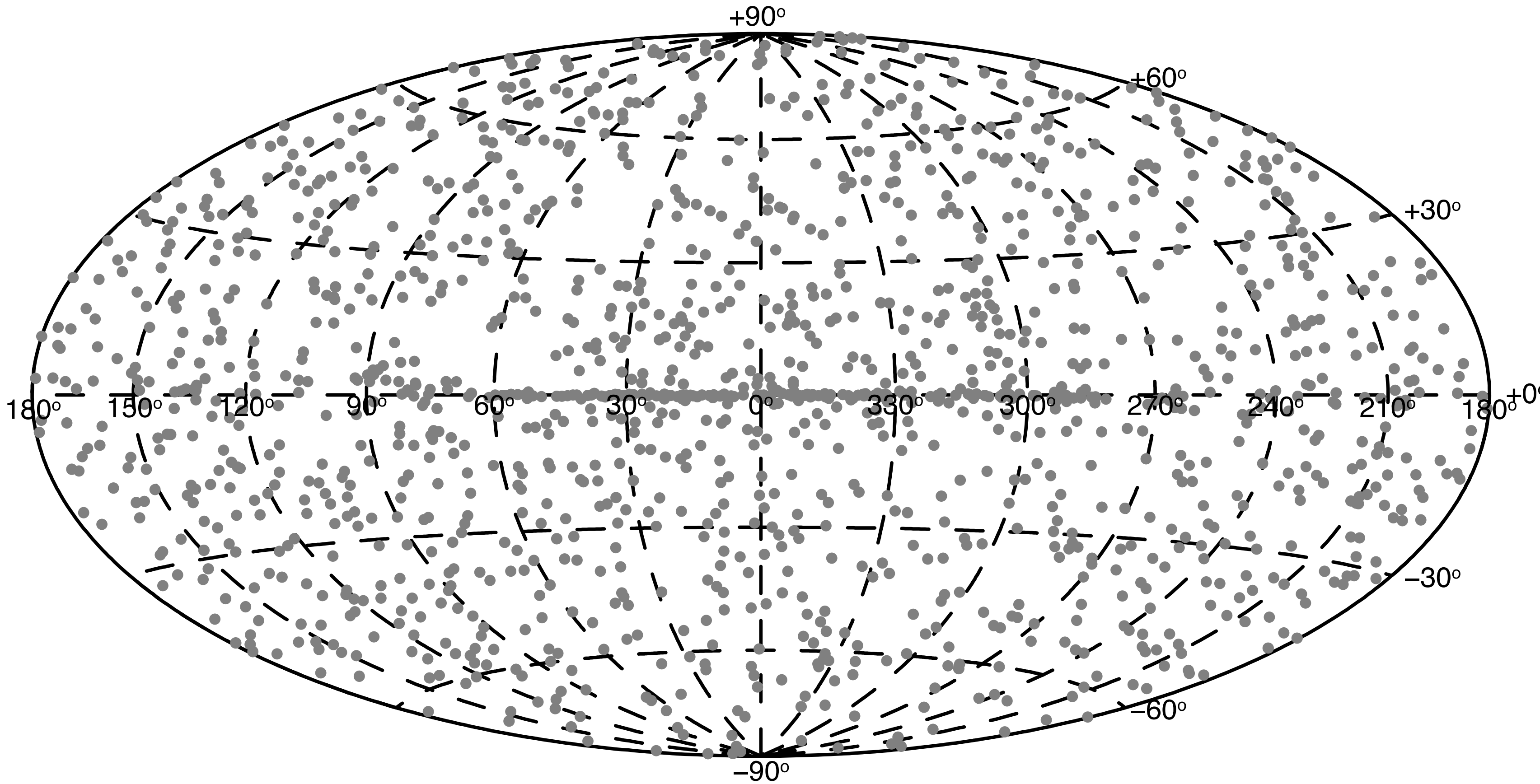


Bottcher et al. 2013

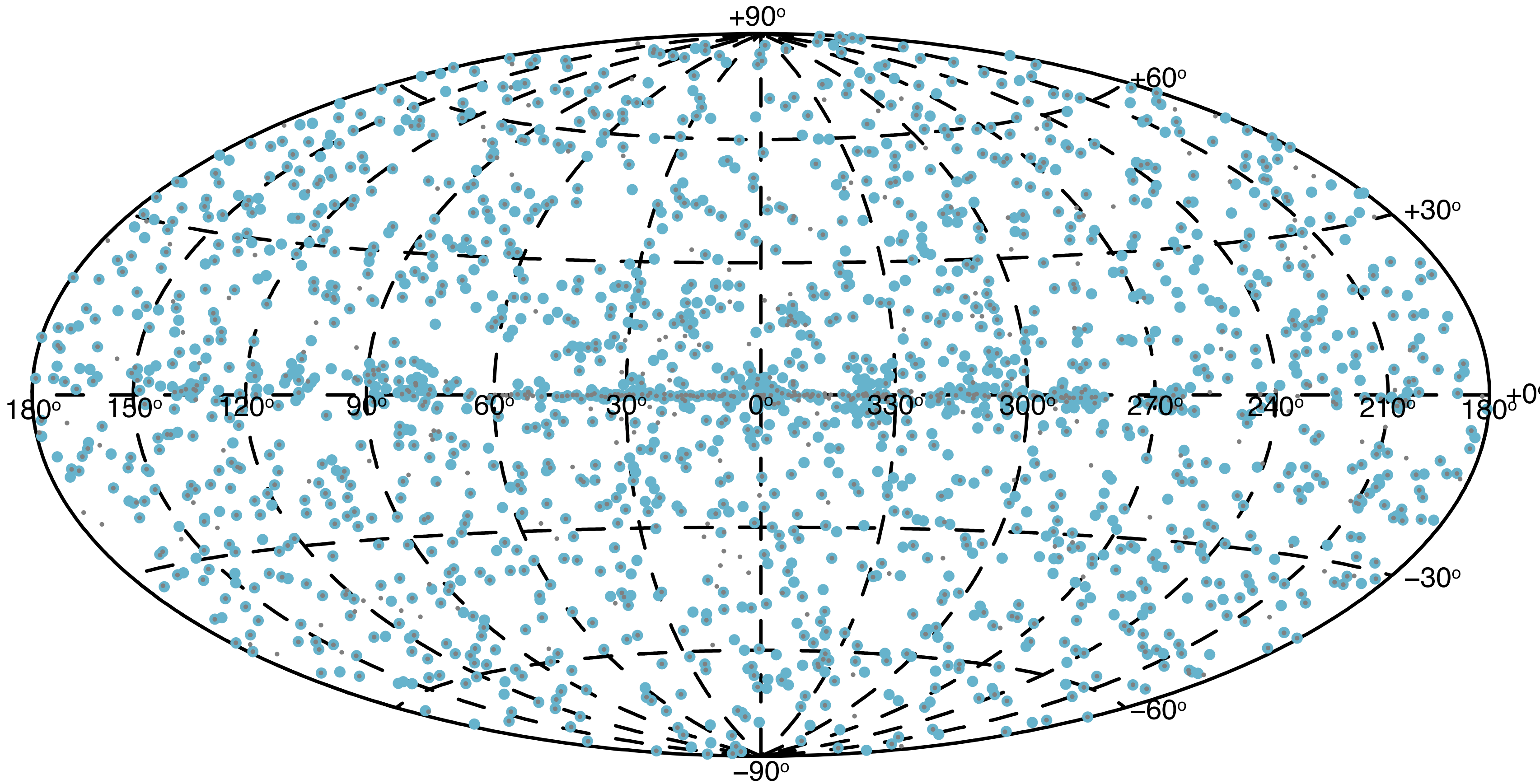
The GeV sky seen by Fermi



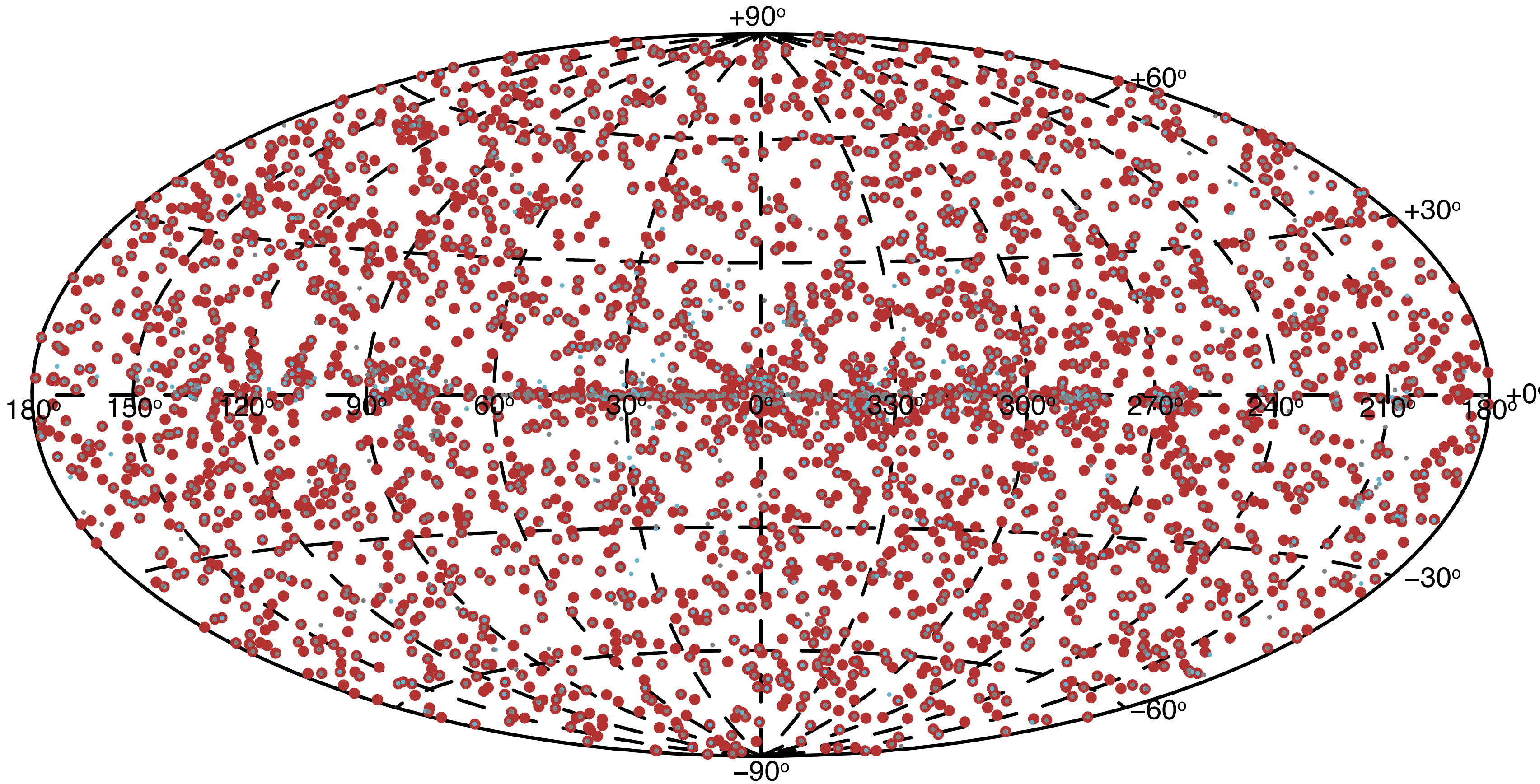
The 100-MeV-100 GeV sky: Fermi 1FGL - 11 months of data 1451 sources



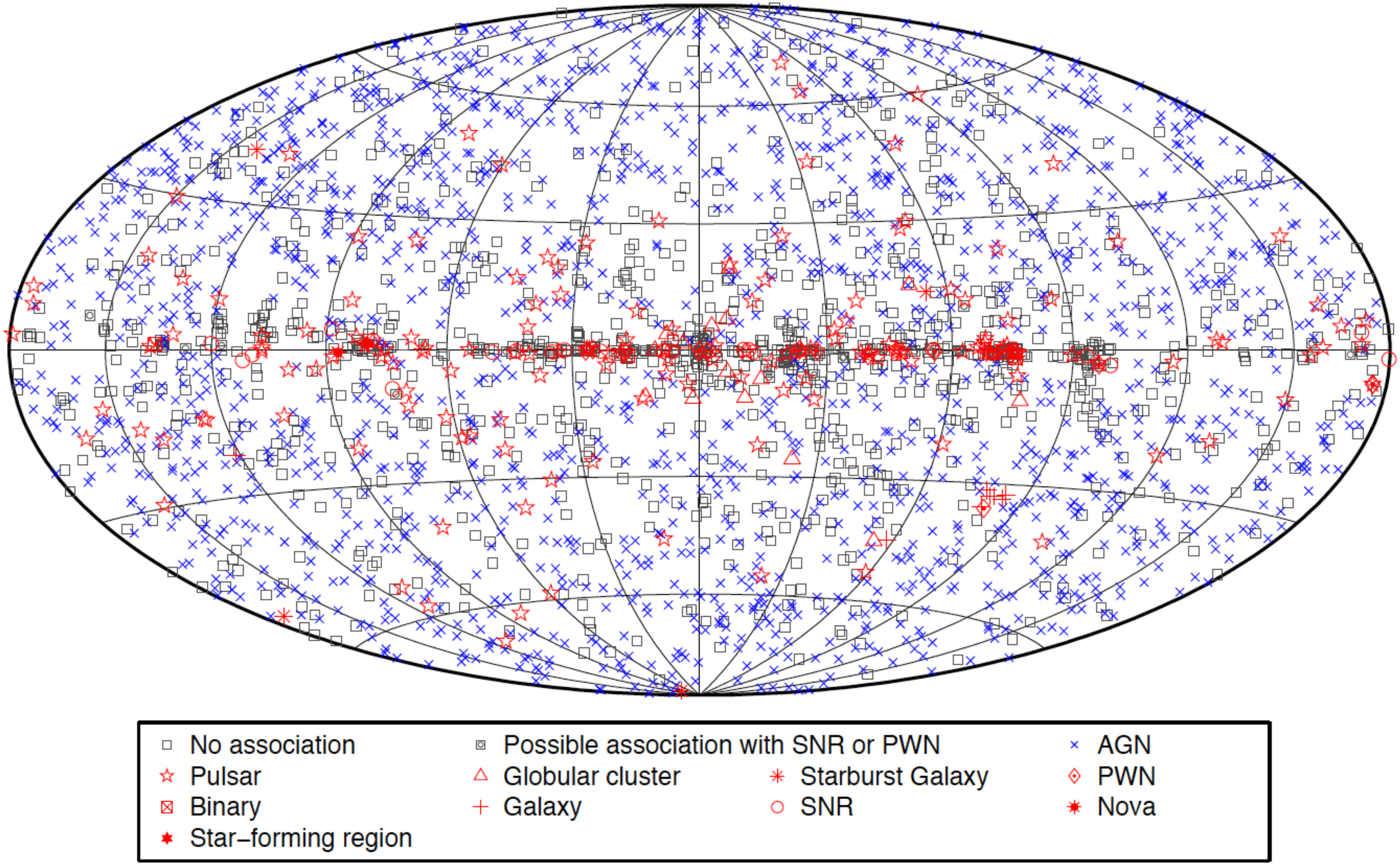
The 100-MeV-100 GeV sky: Fermi 2FGL - 2 years of data 1873 sources



The 100-MeV-100 GeV sky: Fermi 3FGL - 4 years of data 3033 sources



Fermi 3FGL catalog: Ackermann et al. 2015, ApJ 810, 14, arXiv:1501.06054

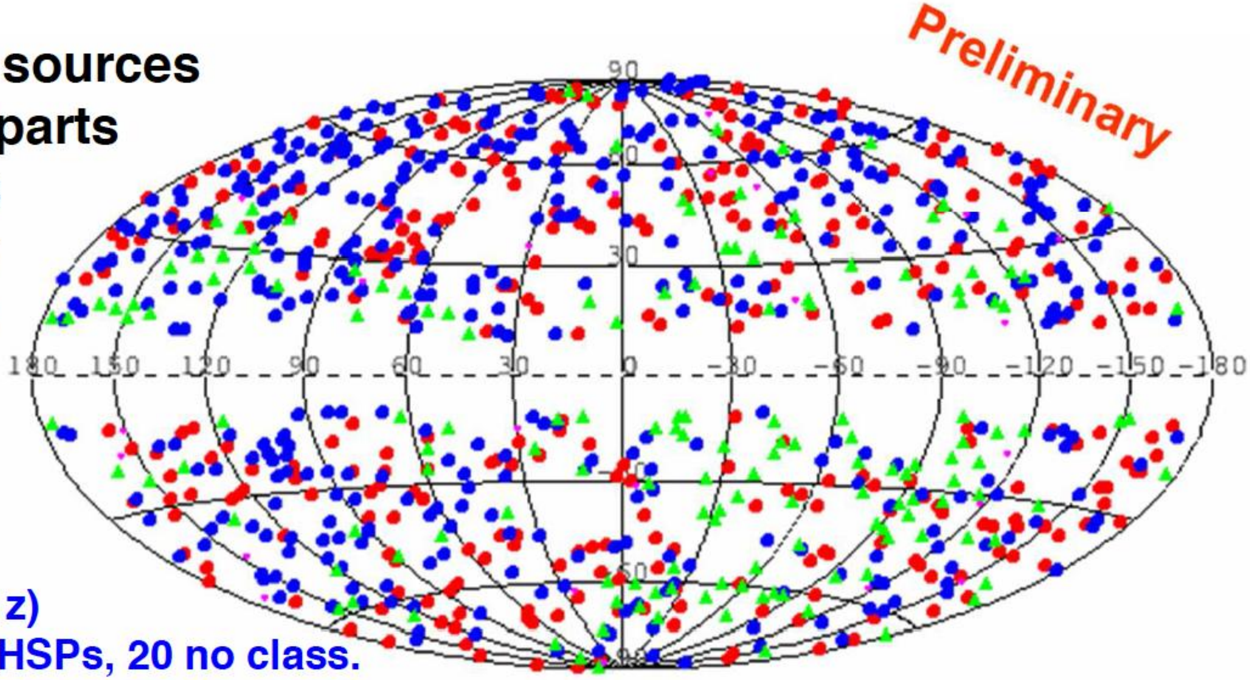


The Third LAT AGN catalog (3LAC)

- **48 month data set**

Ackermann M. et al., arXiv:1501.06054

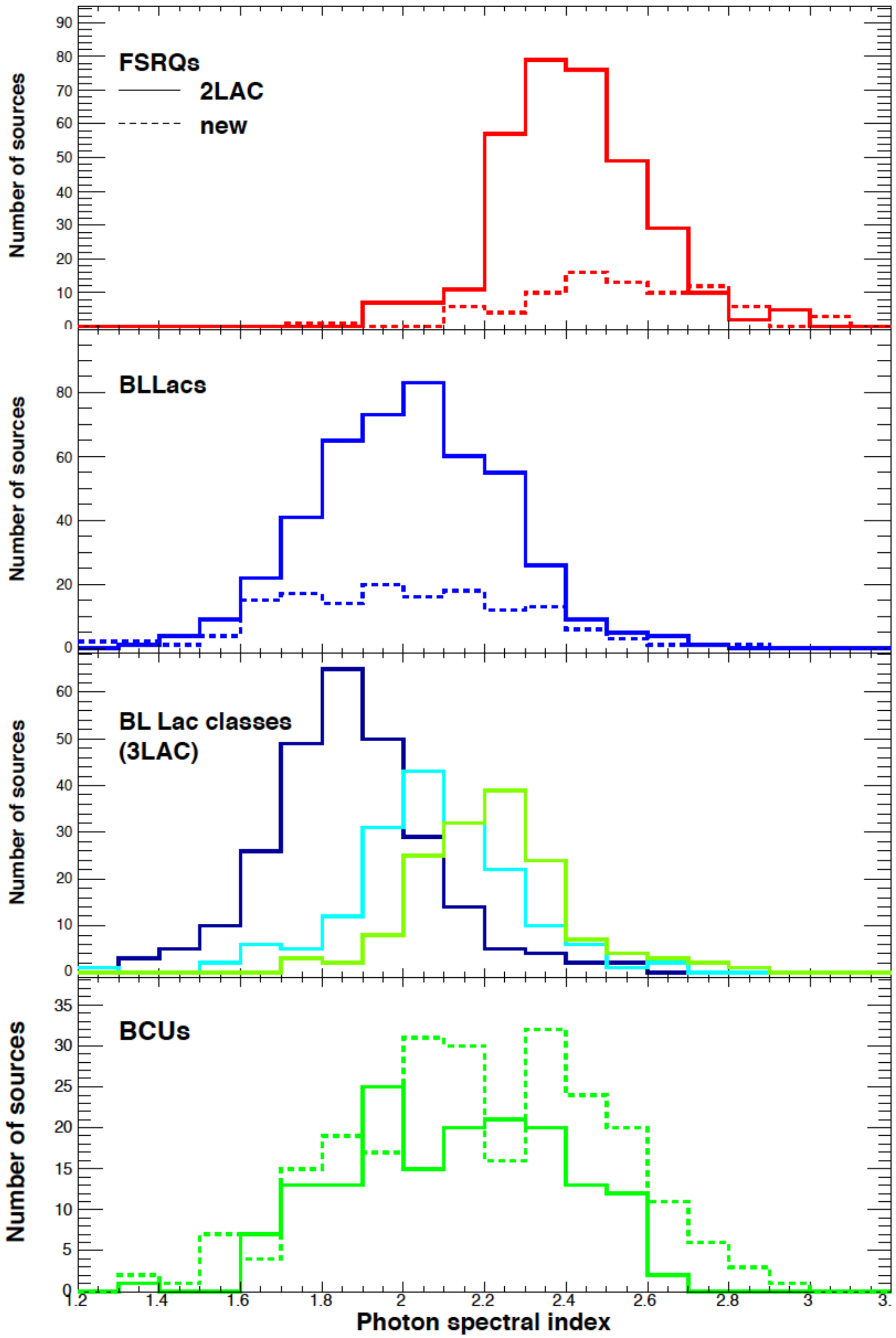
- **2192 TS>25, |b|>10° sources**
- **3LAC: 1591 counterparts**
  1563 sources
- **1444 AGNs in *Clean Sample*** (no dup., no flags)



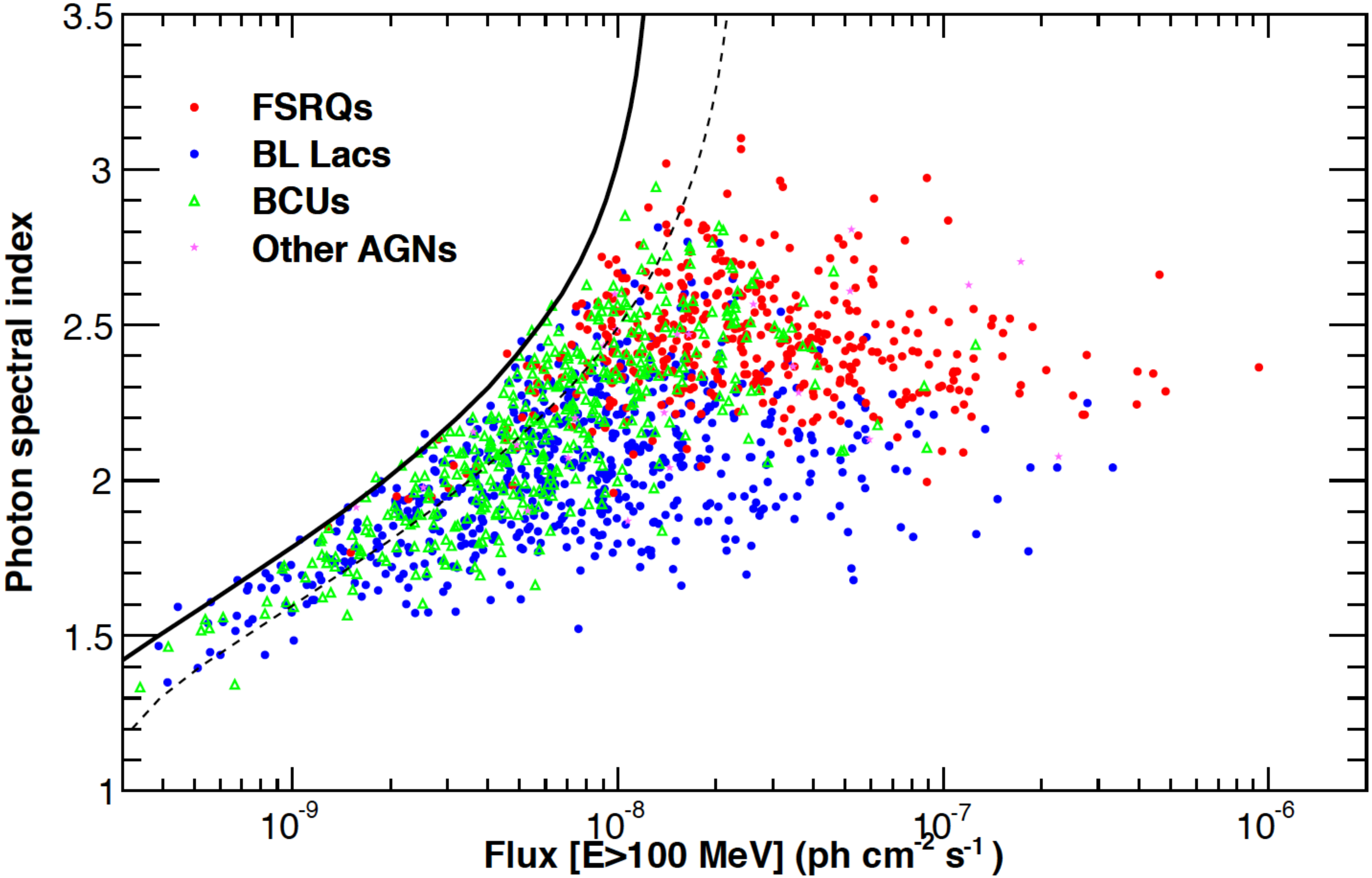
- **Census :**
  - **415 FSRQs**
  - **602 BLLacs**
    (~50% with measured z)
    162 LSP, 178 ISP, 272 HSPs, 20 no class.
  - **413 of unknown type**
  - **23 other AGNs**

Differences between Northern and Southern Hemispheres:
40% of BL Lacs in Southern Hemisphere

Benoît Lott



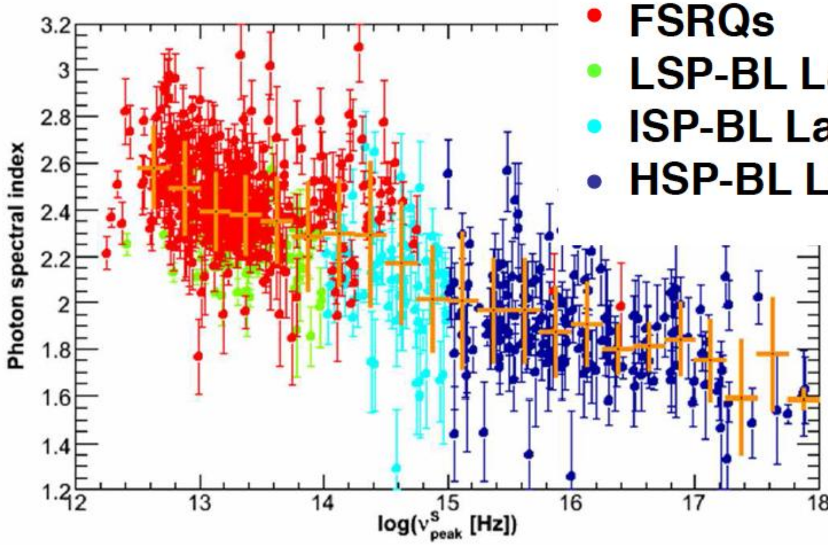
FSRQs
2LAC
new
BLLacs
BL Lac classes
(3LAC)
BCUs
Number of sources
Photon spectral index



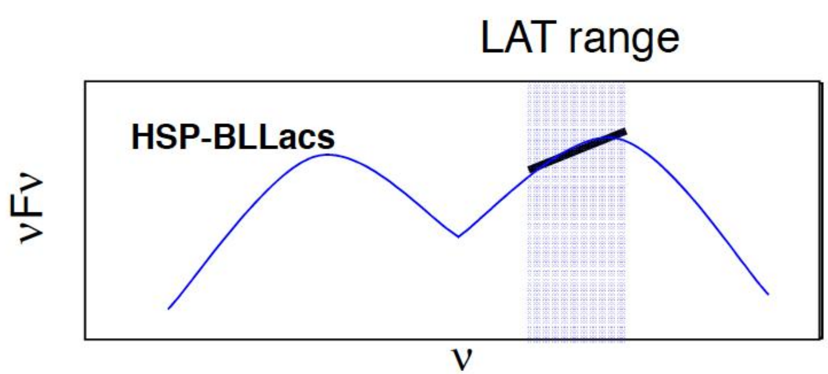
FSRQs
BL Lacs
BCUs
Other AGNs
Photon spectral index
Flux [E>100 MeV] (ph cm-2 s-1)
3.5
3
2.5
2
1.5
1
10-9
10-8
10-7
10-6

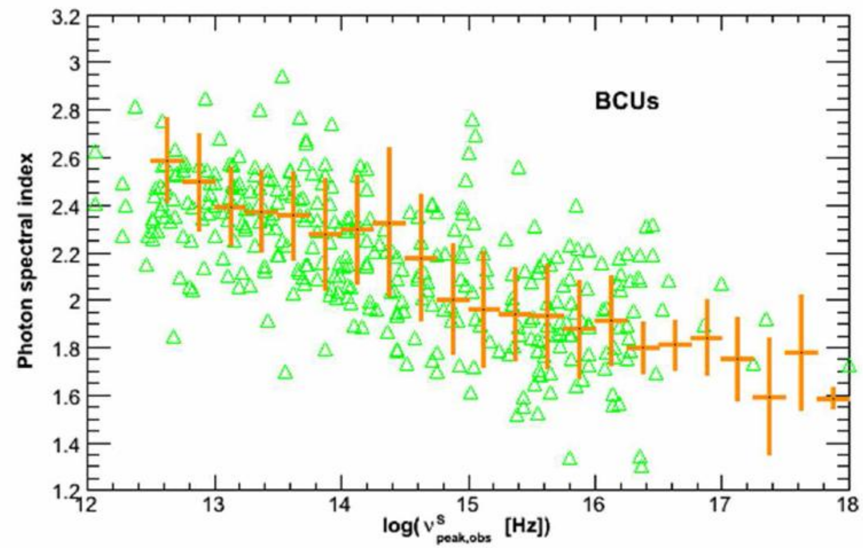
Spectral photon index vs ν_{peak}

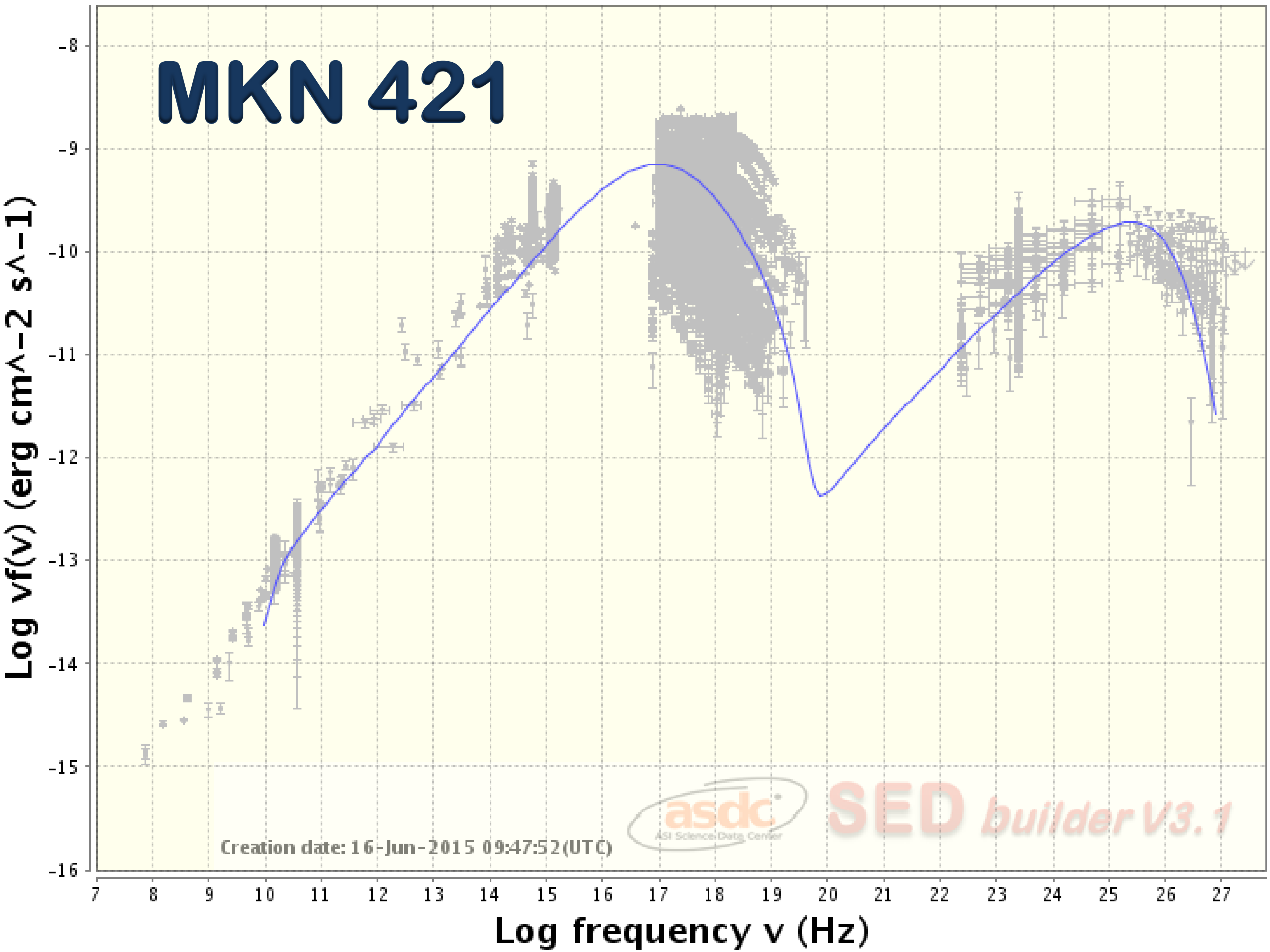
Preliminary



- Correlation between spectral hardness and ν_{peak} confirmed
- Same implies to BCUs







MKN 421
Log νf(ν) (erg cm^-2 s^-1)
-8
-9
-10
-11
-12
-13
-14
-15
-16
7
8
9
10
11
12
13
14
15
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27
Log frequency ν (Hz)
Creation date: 16-Jun-2015 09:47:52(UTC)
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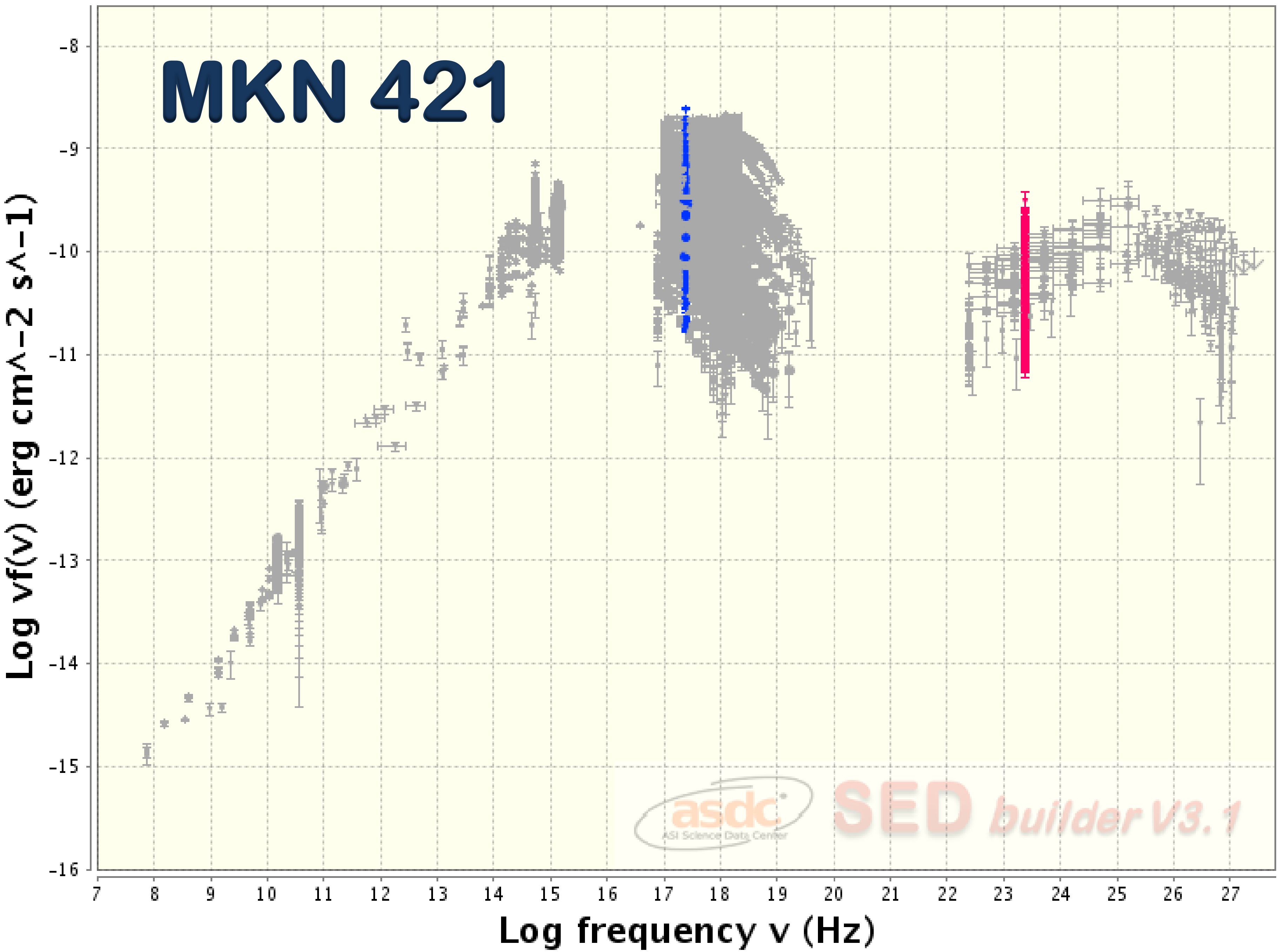
SED builder V3.1


MKN 421
Log νf(ν) (erg cm^-2 s^-1)
Log frequency ν (Hz)
-8
-9
-10
-11
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-15
-16
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asdc
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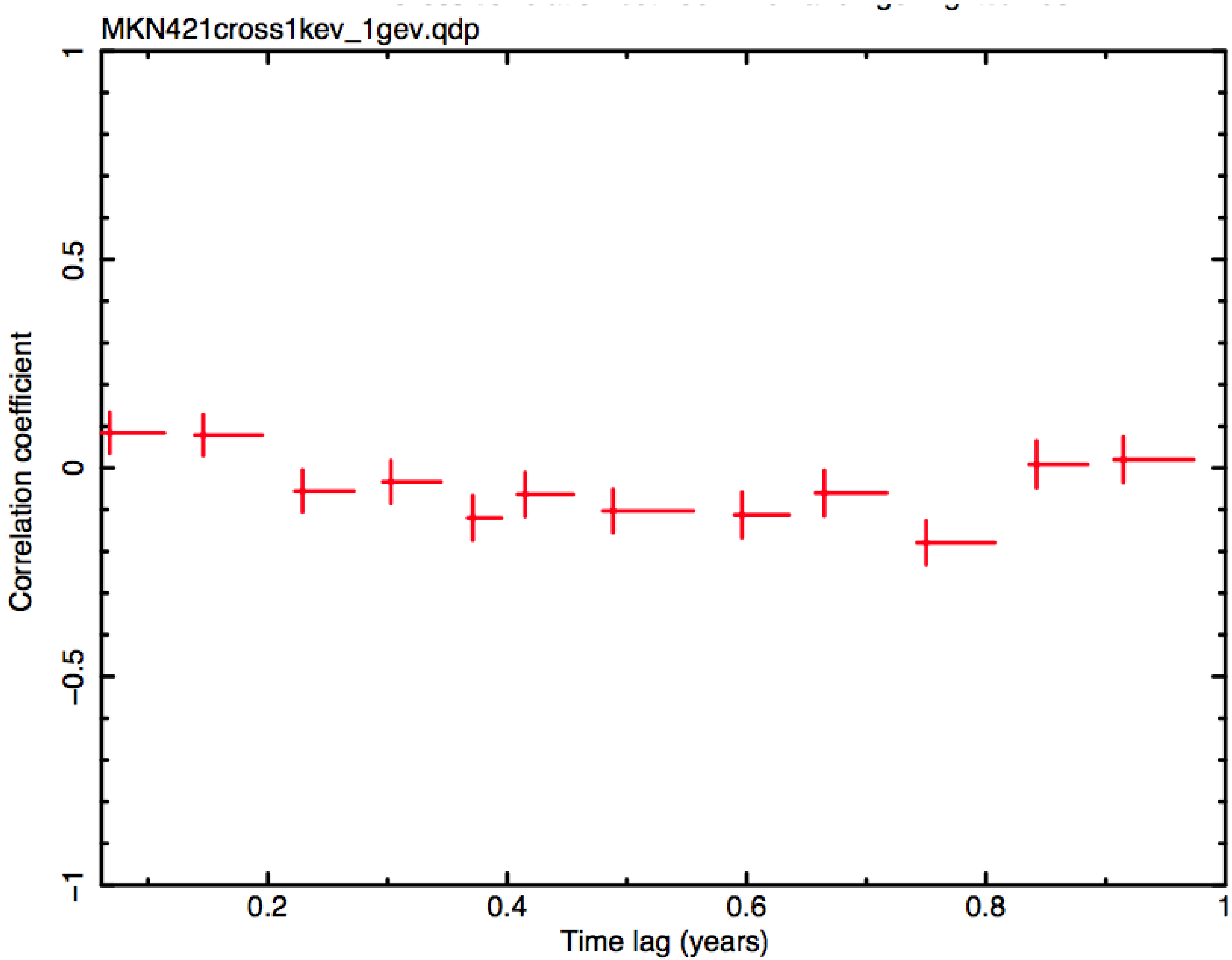
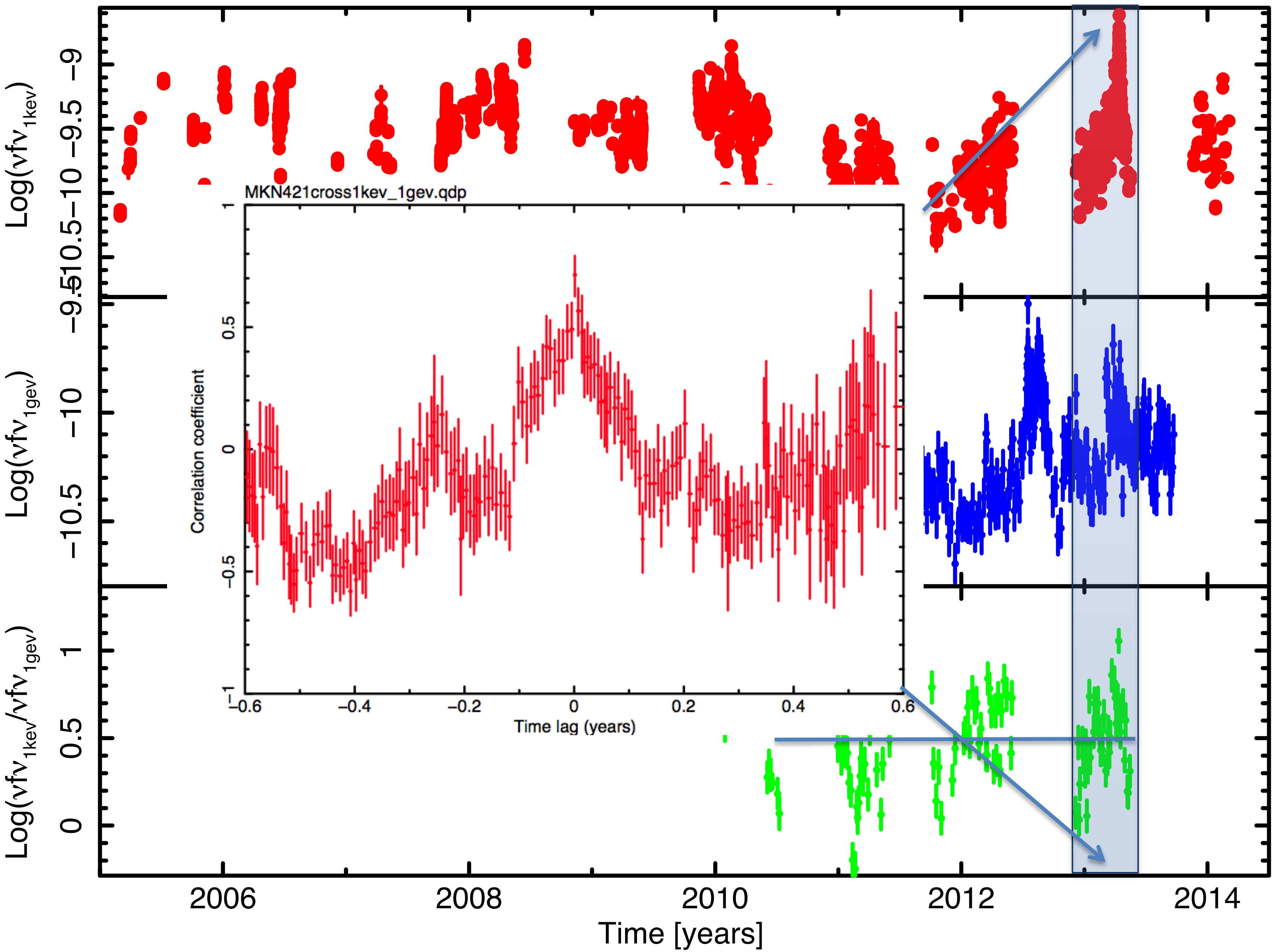
Cross correlation between 1keV and 1 GeV
Period 2008.5 – 2013.5



MKN 421



Log(νfν1kev)
−9
−9.5
−10
−10.5
−11
Log(νfν1gev)
−9.5
−10
−10.5
Log(νfν1kev/νfν1gev)
1
0.5
0
2006
2008
2010
2012
2014
Time [years]
MKN421cross1kev_1gev.qdp
Correlation coefficient
1
0.5
0
−0.5
−1
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
Time lag (years)

Fermi 2FHL

The Fermi-LAT view of the Very High Energy Sky

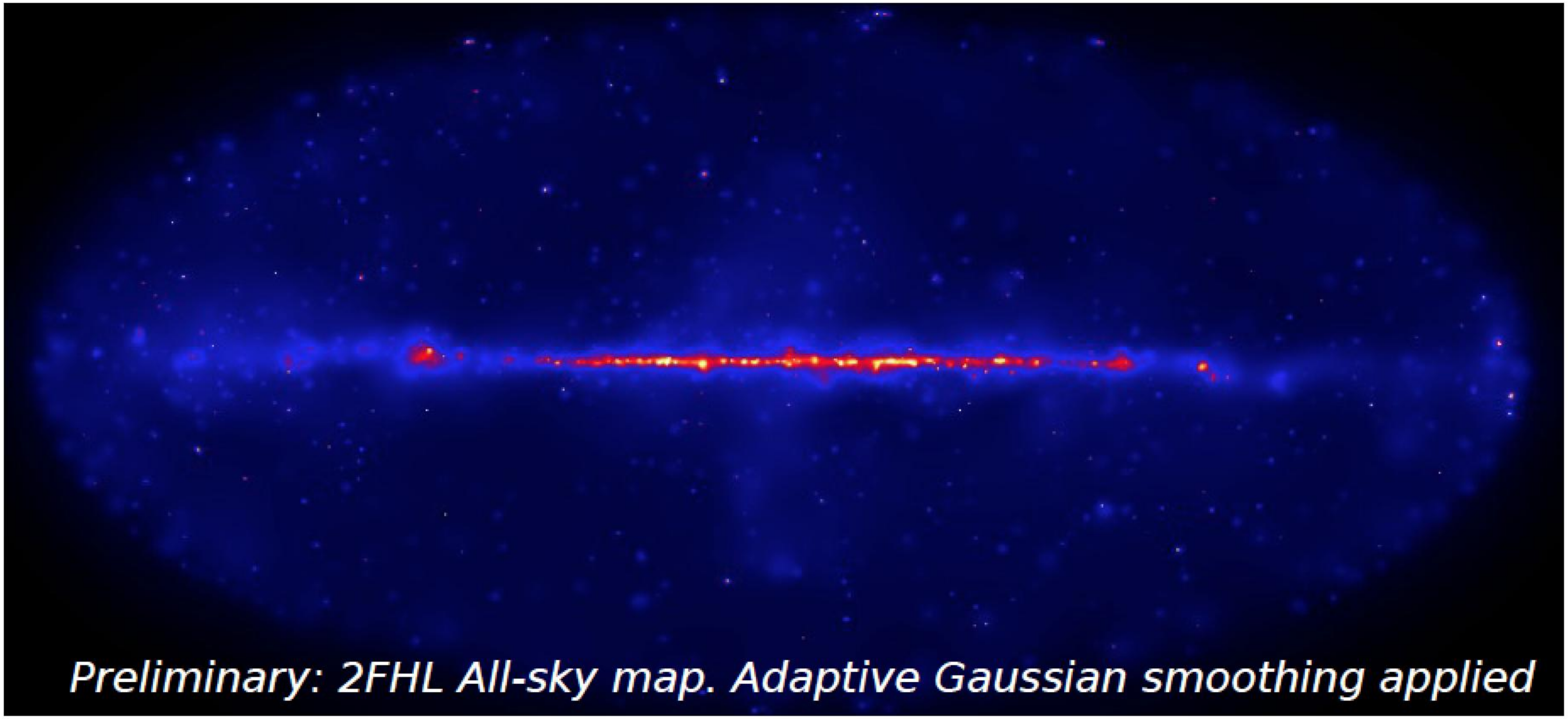
Ackermann et al. 2015, submitted. arXiv:1508.04449

Count Map

Approximately 6 years of P8 data (50 GeV – 2 TeV)

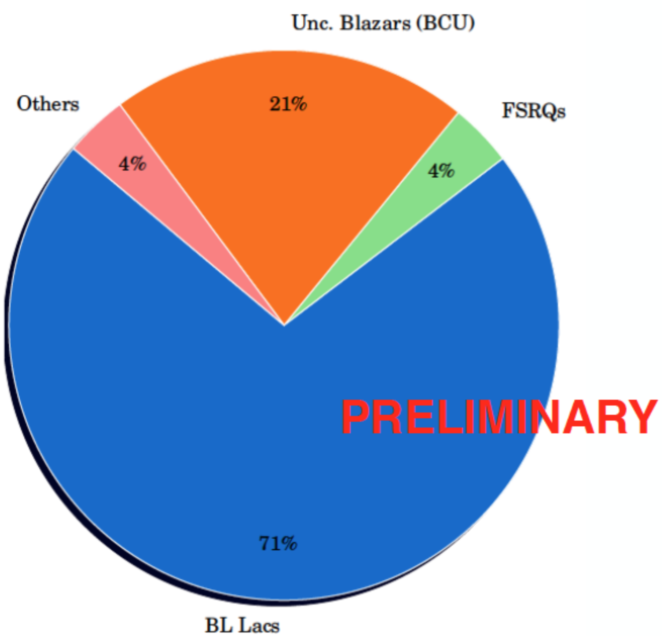
51,000 photons E > 50 GeV
18,000 photons E > 100 GeV
2,000 photons E > 500 GeV

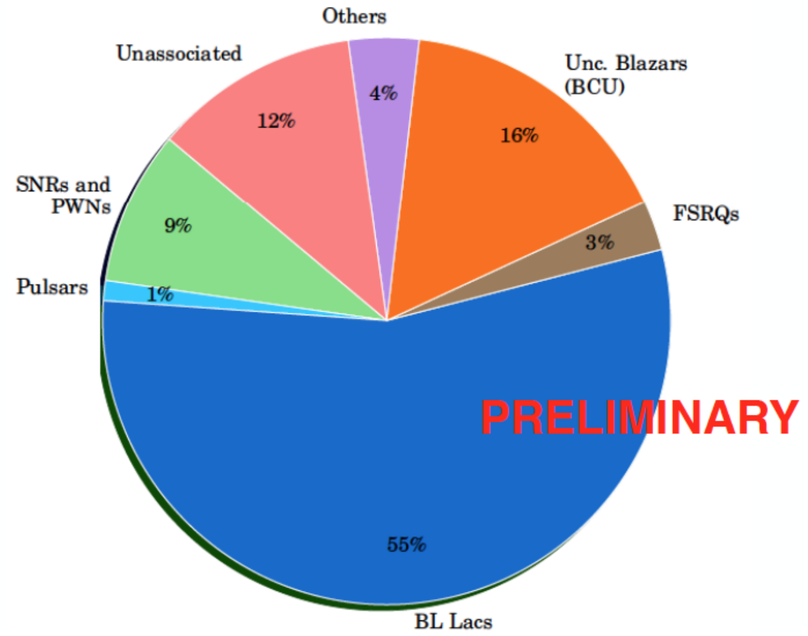
about 1 photon every deg^2



2FHL CATALOG

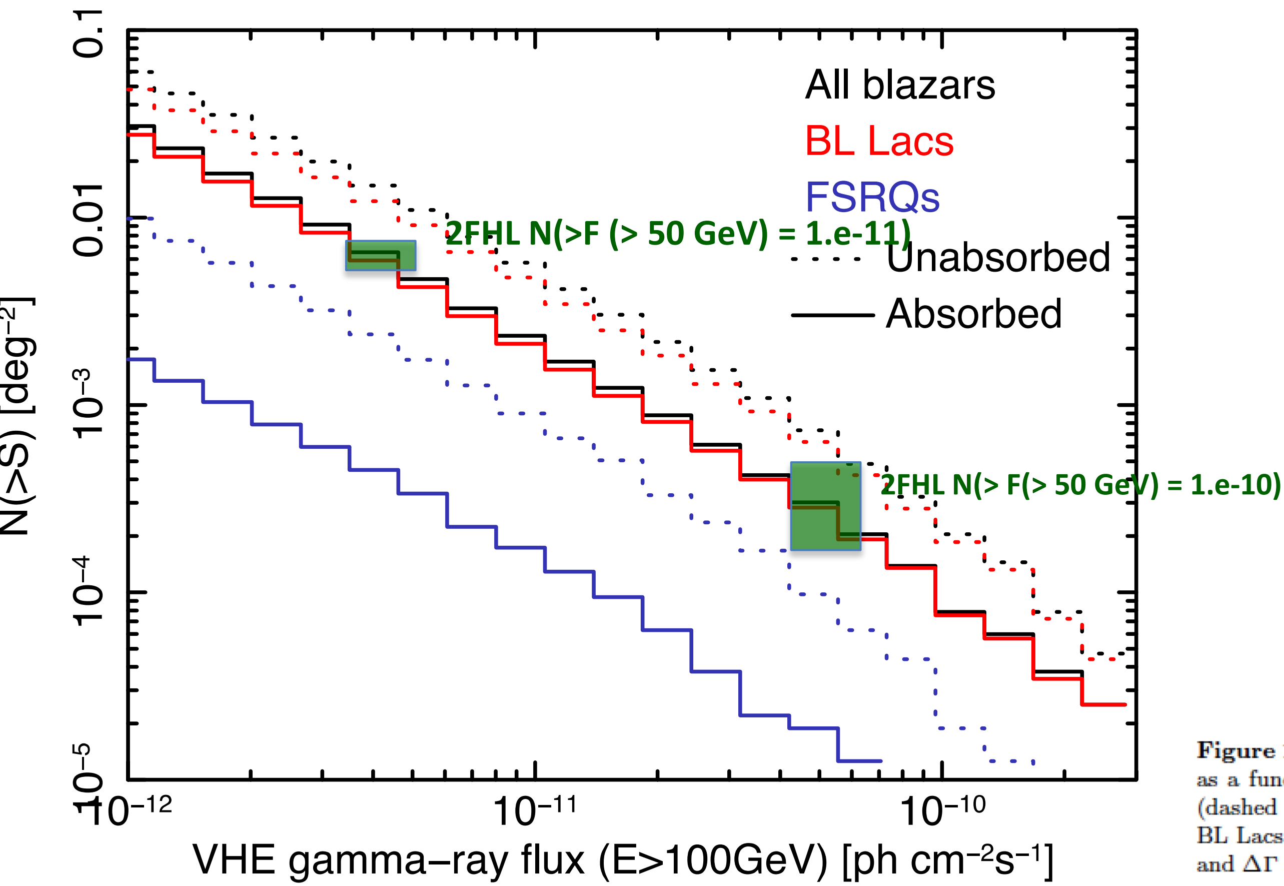
- Energy Range: 50-2000 GeV using IRFs: P8R2_SOURCE_V6
- ~80 months of data
- ~360 sources
- only 25% already detected by ACTs (TeVCat)
- 206 detected in 1FHL
- 234 detected in 3FGL (4 years, up to 300 GeV)
- ~100 sources not in 1FHL and ~250 not in TeVCat





A simplified view of blazars: the very high energy γ-ray vision

P. Padovani[1,2*], P. Giommi[3,4,5]
[1]European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748 Garching bei München, Germany
[2]Associated to INAF - Osservatorio Astronomico di Roma, via Frascati 33, I-00040 Monteporzio Catone, Italy
[3]ASI Science Data Center, via del Politecnico s.n.c., I-00133 Roma Italy
[4]ICRANet-Rio, CBPF, Rua Dr. Xavier Sigaud 150, 22290-180 Rio de Janeiro, Brazil
[5]Associated to INAF - Osservatorio Astronomico di Brera, via Brera 28, I-20121 Milano, Italy

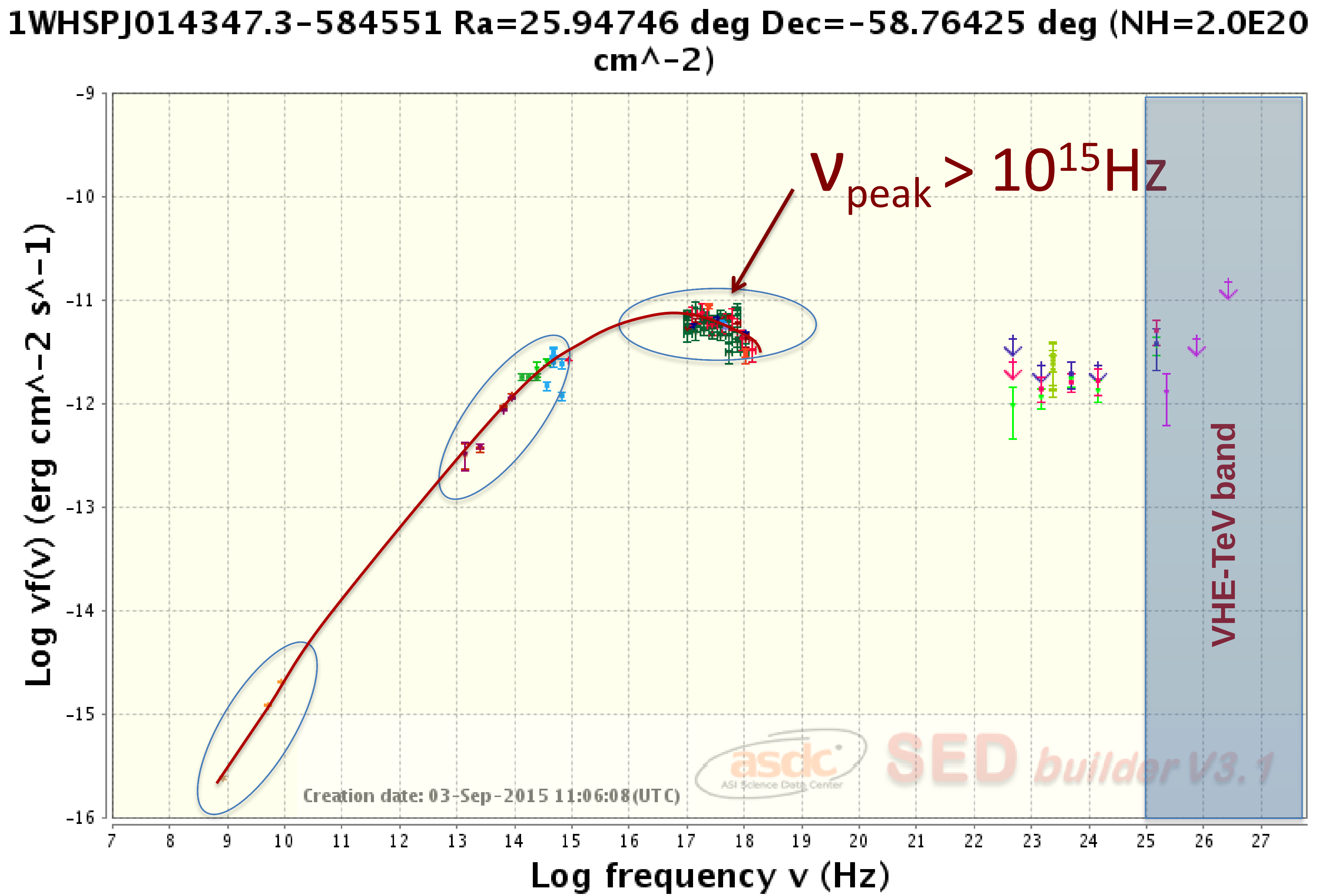


MNRAS 2015, 446L, 41
arXiv 1410.0497

Figure 1. The predicted integral number counts at $E \geqslant 100$ GeV as a function of photon flux with and without EBL absorption (dashed and solid lines respectively) for all blazars (black lines), BL Lacs (red lines), and FSRQs (blue lines) ($E_{\rm break} = 100$ GeV and $\Delta\Gamma = 1$).

New large samples of high-energy synchrotron peaked blazars

(likely VHE emitters)



1WHSPJ014347.3-584551 Ra=25.94746 deg Dec=-58.76425 deg (NH=2.0E20 cm^-2)
$\nu_{peak} > 10^{15}$Hz
VHE-TeV band
Log νf(ν) (erg cm^-2 s^-1)
Log frequency ν (Hz)
Creation date: 03-Sep-2015 11:06:08(UTC)
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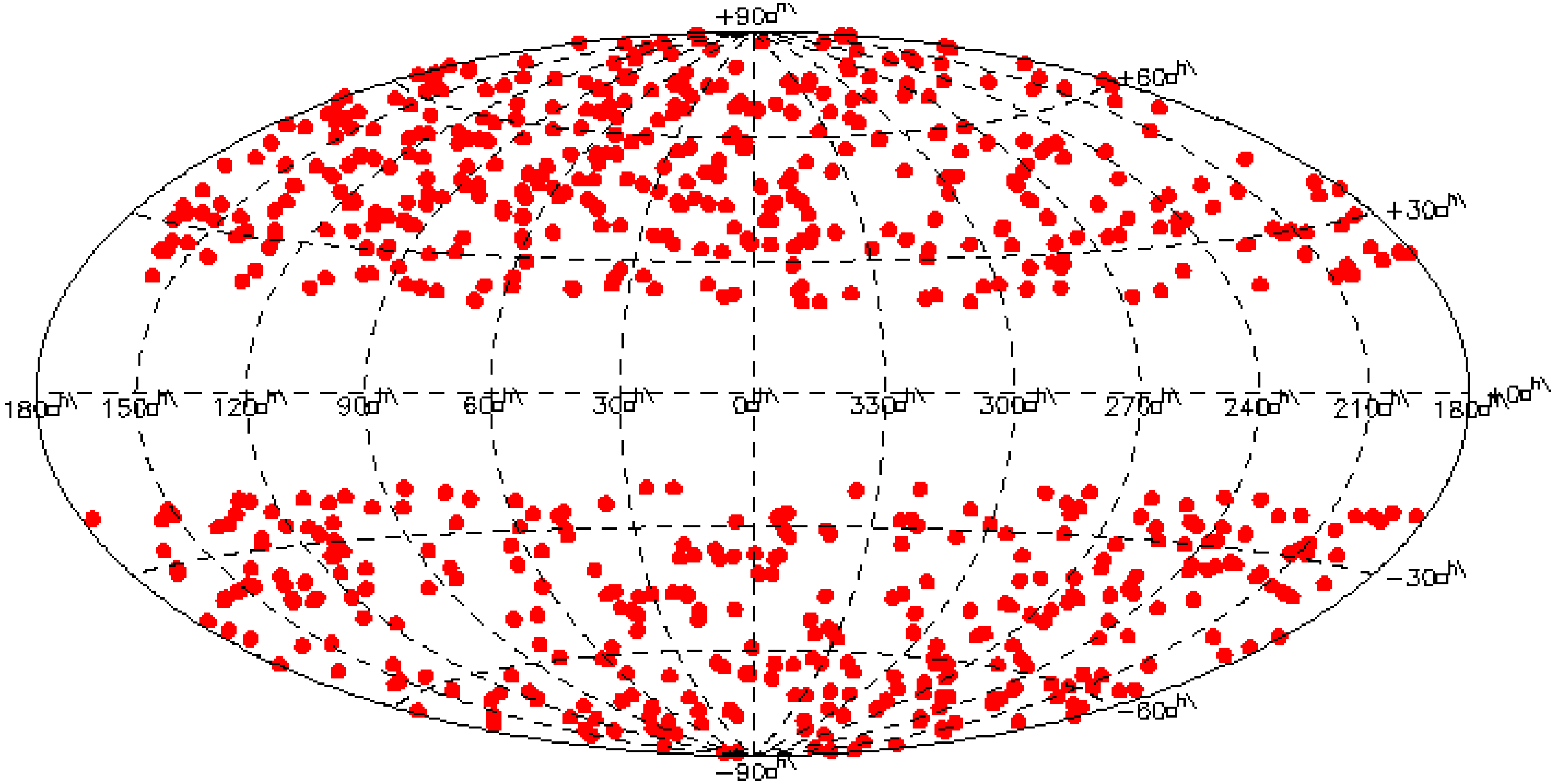
SED builder V3.1

1WHSP: an IR-based sample of ~1,000 VHE γ-ray blazar candidates

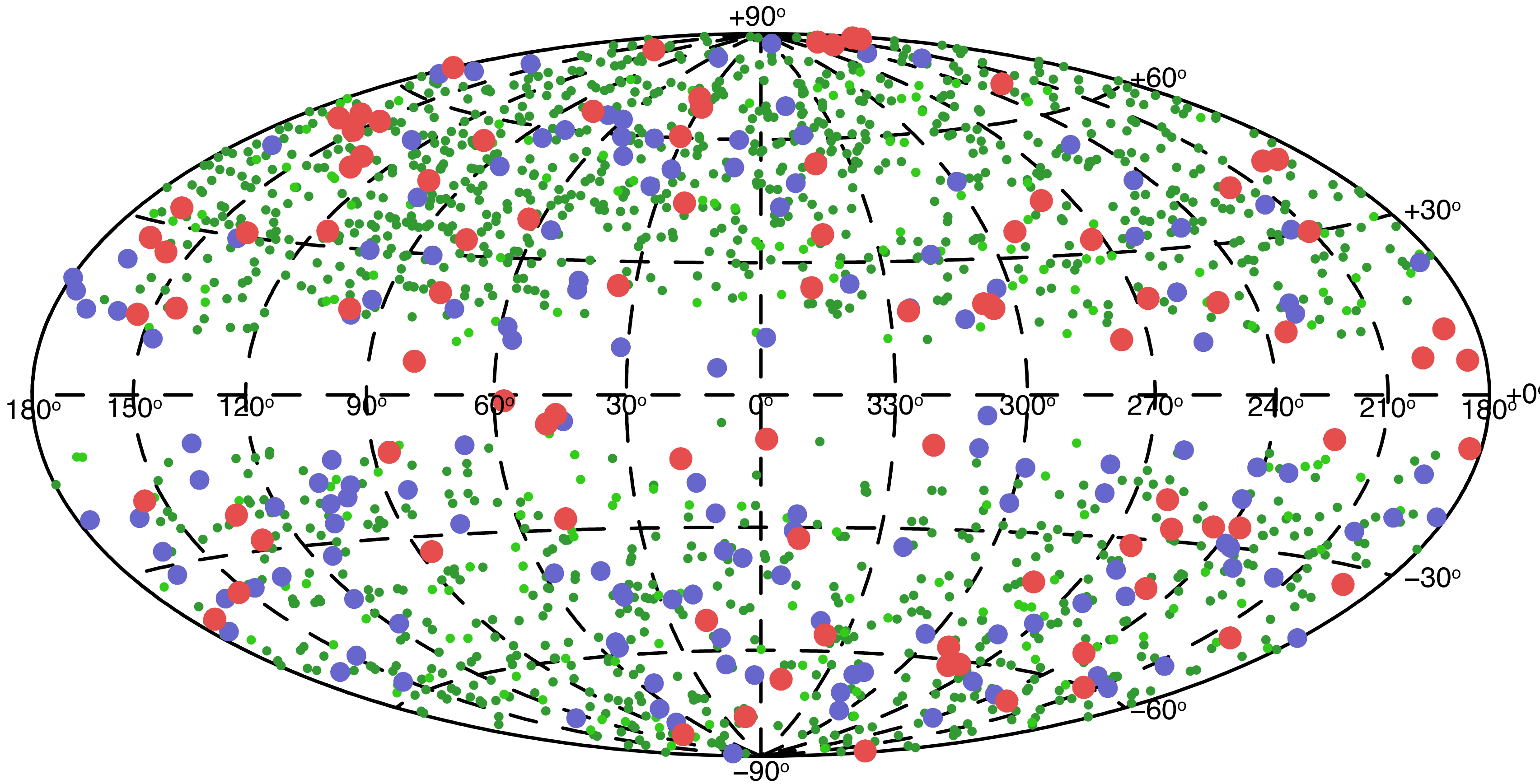
B. Arsioli[1,2], B. Fraga[1,2], P. Giommi[3], P. Padovani[4,5], and M. Marrese[3]

A&A 2015, A&A, 2015, 579, 34
DOI: 10.1051/0004-6361/201424148

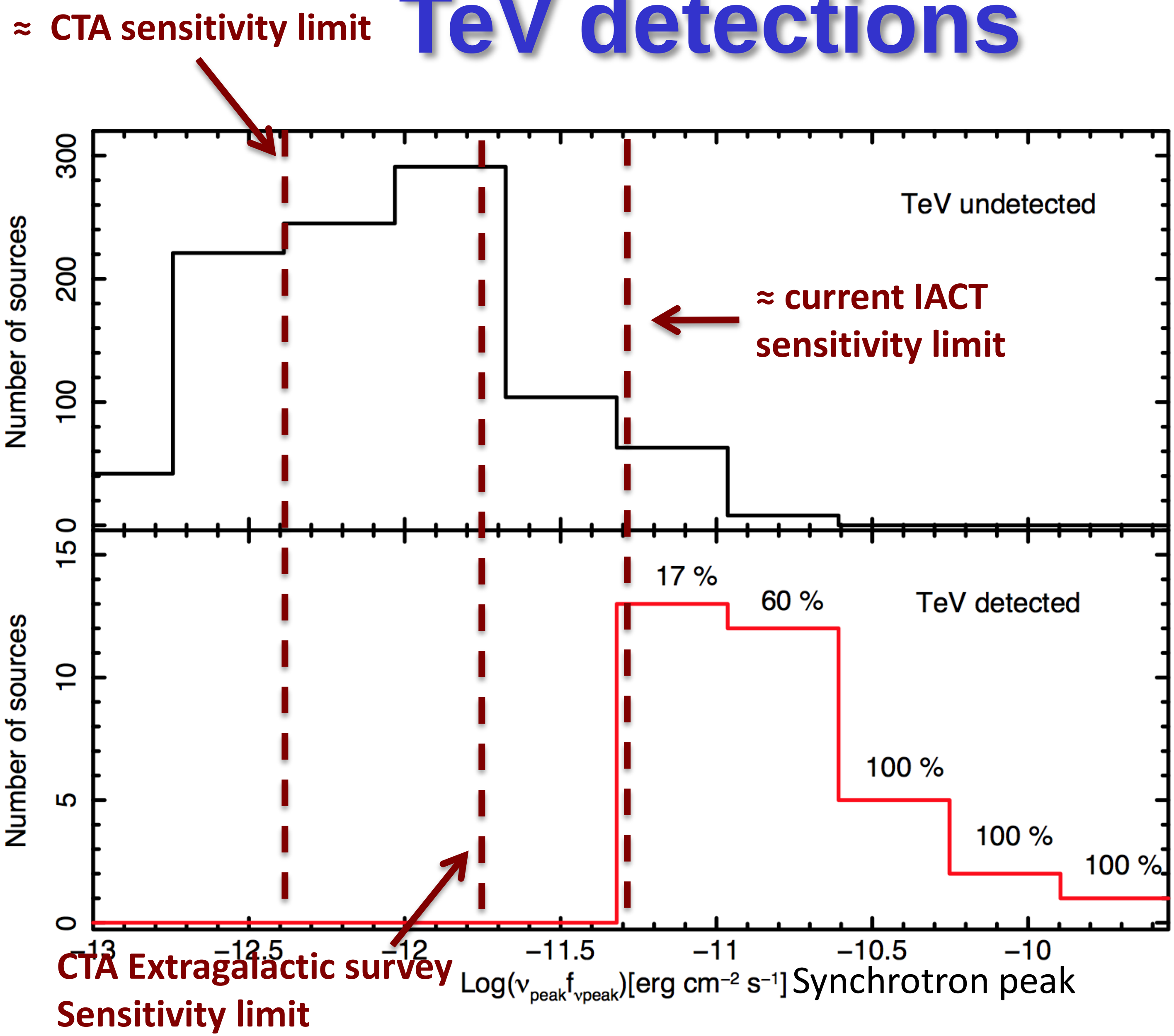


2WHSP ~ 1,800 objects

Y-L. Chang, B. Arsioli, P. Giommi, P. Padovani, 2015 in preparation

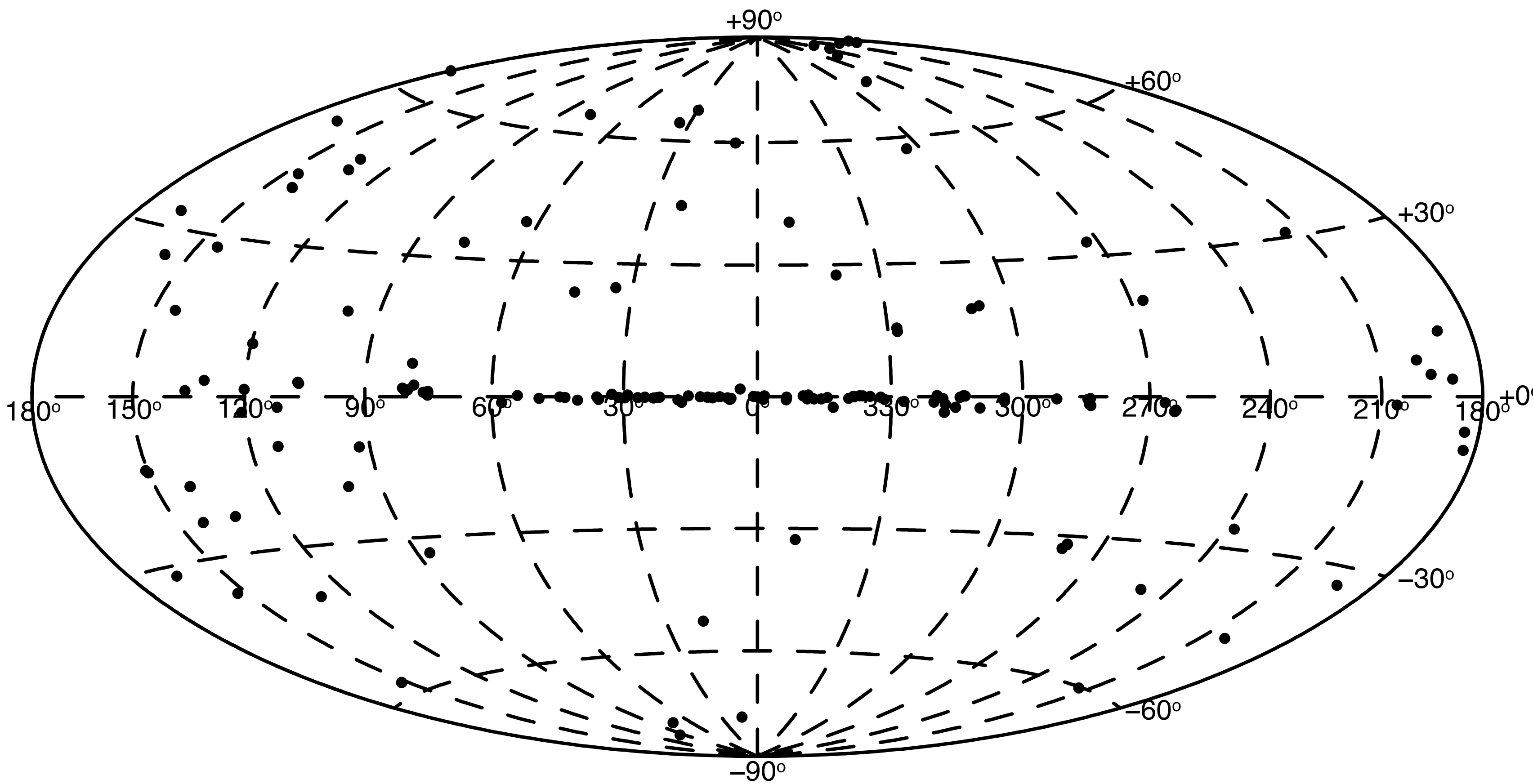


TeV detections



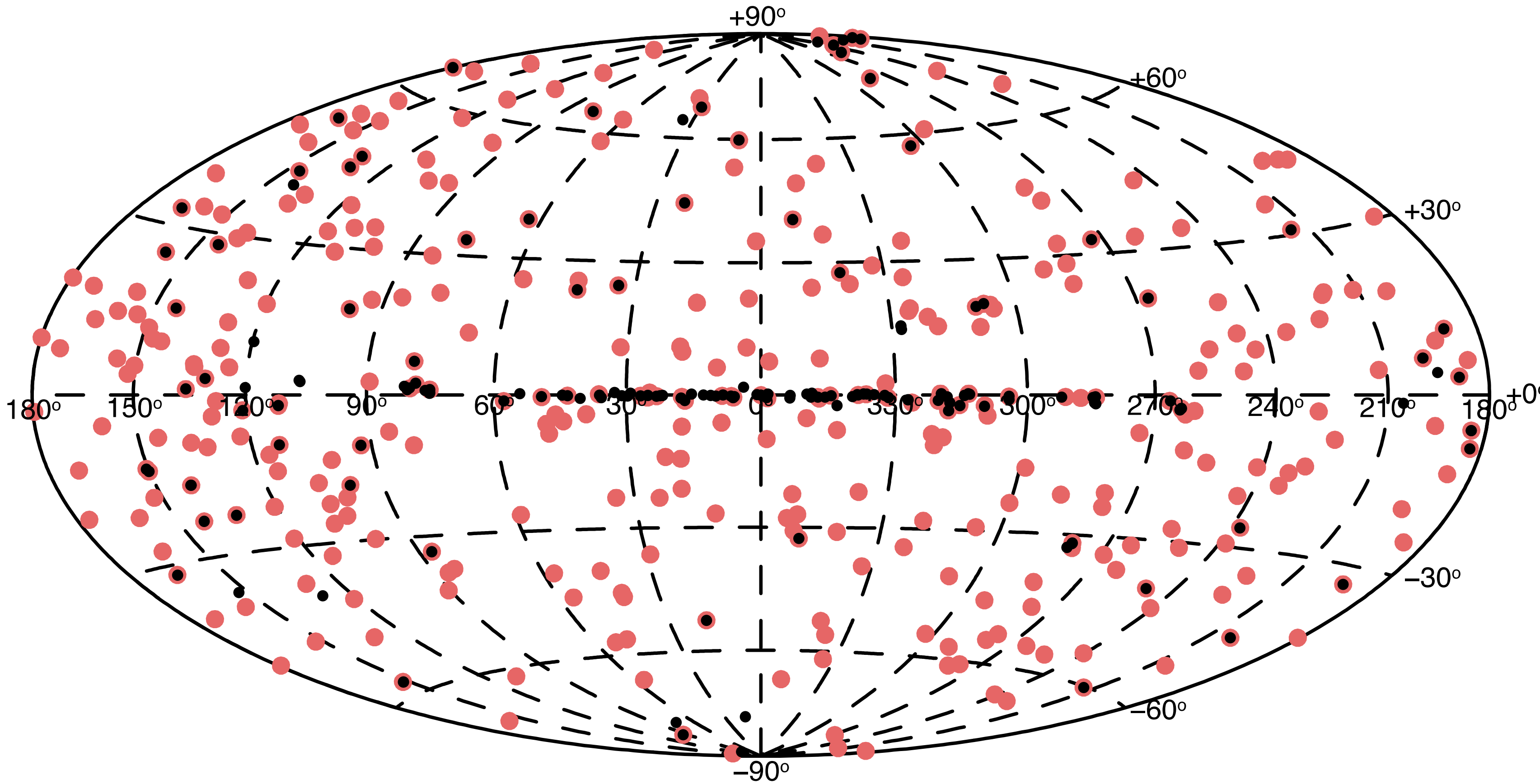
The multi-messenger very high energy (E > 50 GeV) sky

The VHE sky (IACTs)



The VHE sky (IACTs+Fermi 2FHL)

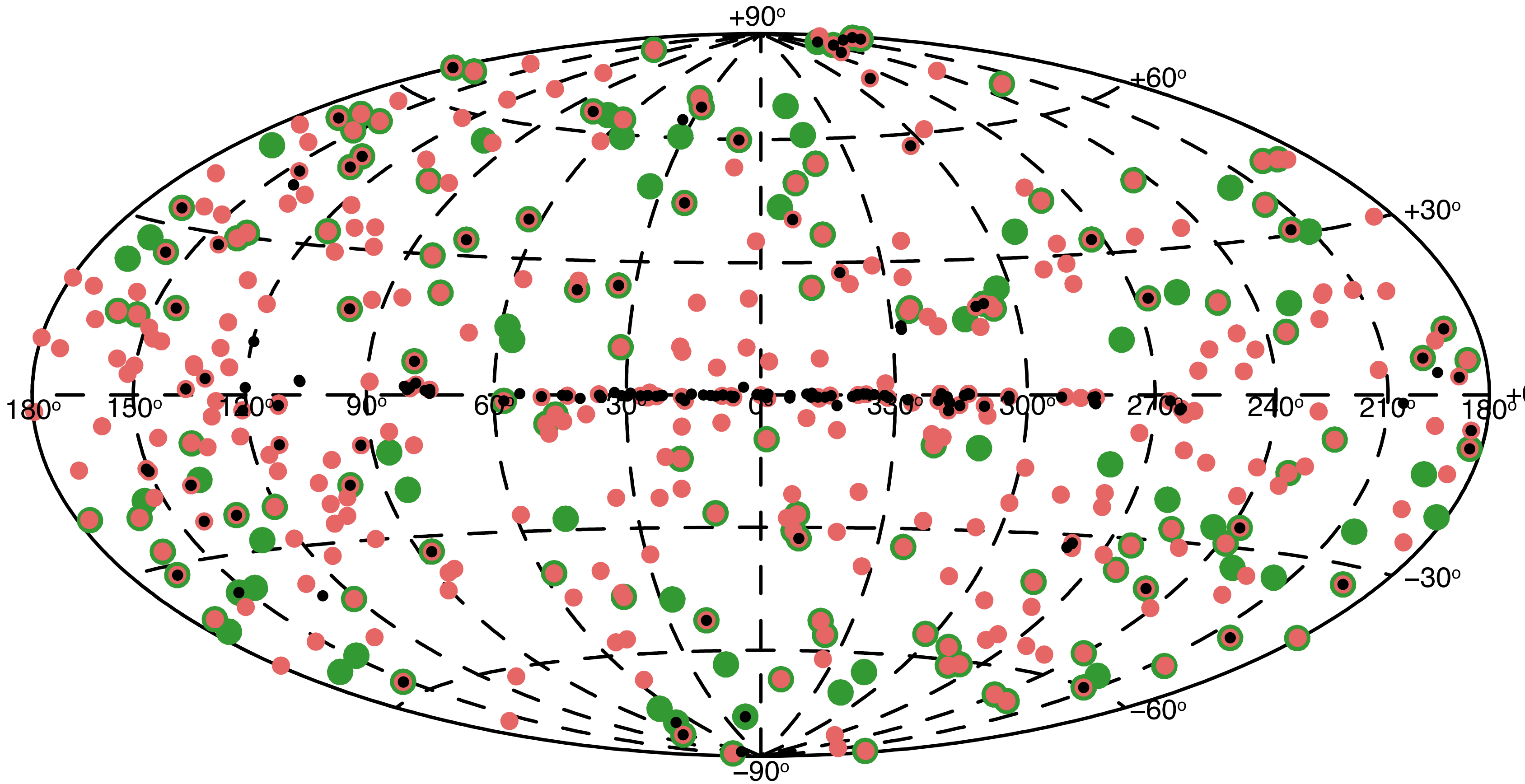
Submitted to ApJ arXiv:1508.04449



The VHE sky (IACTs+Fermi 2FHL+2WHSP bright)

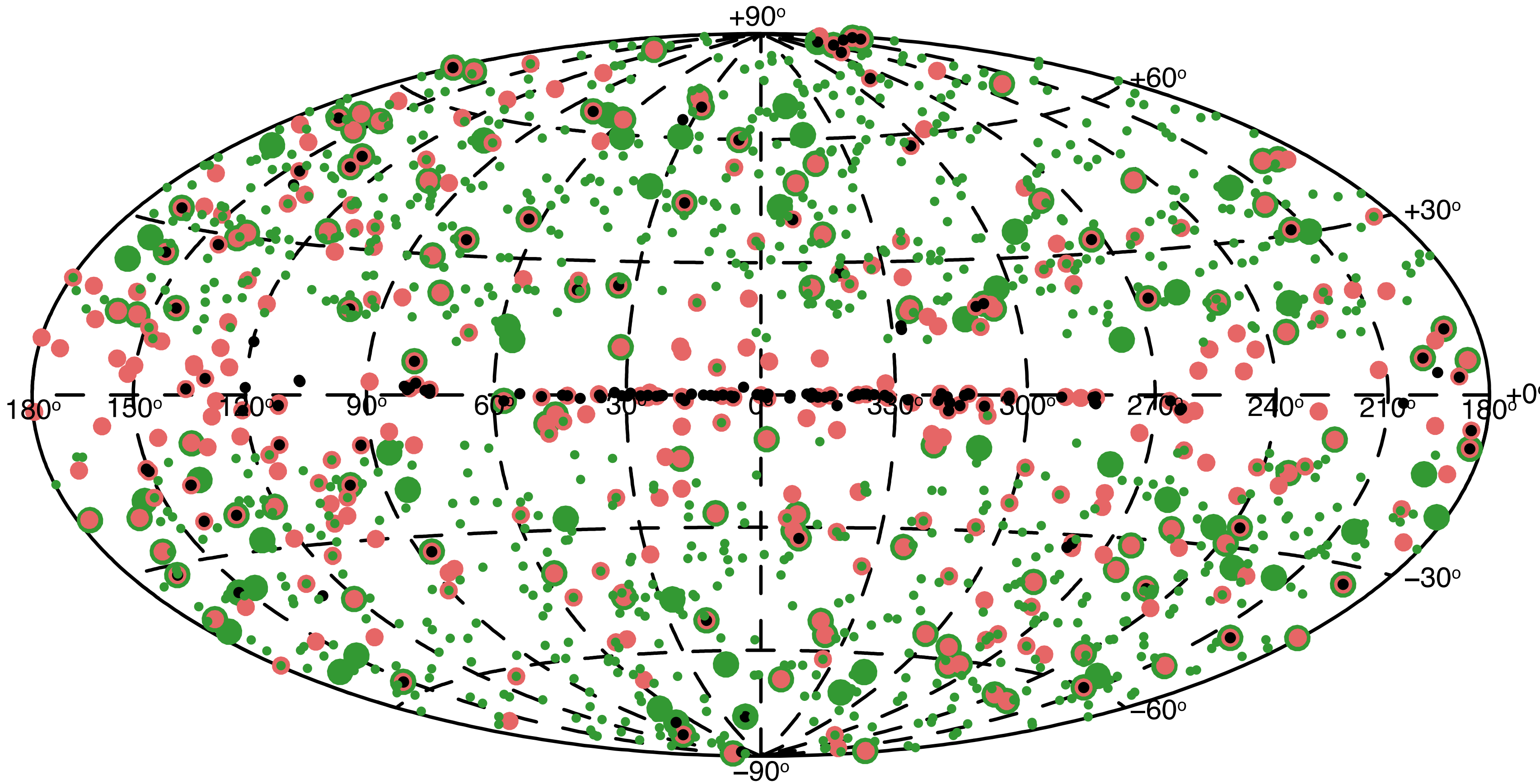
Submitted to ApJ arXiv:1508.04449

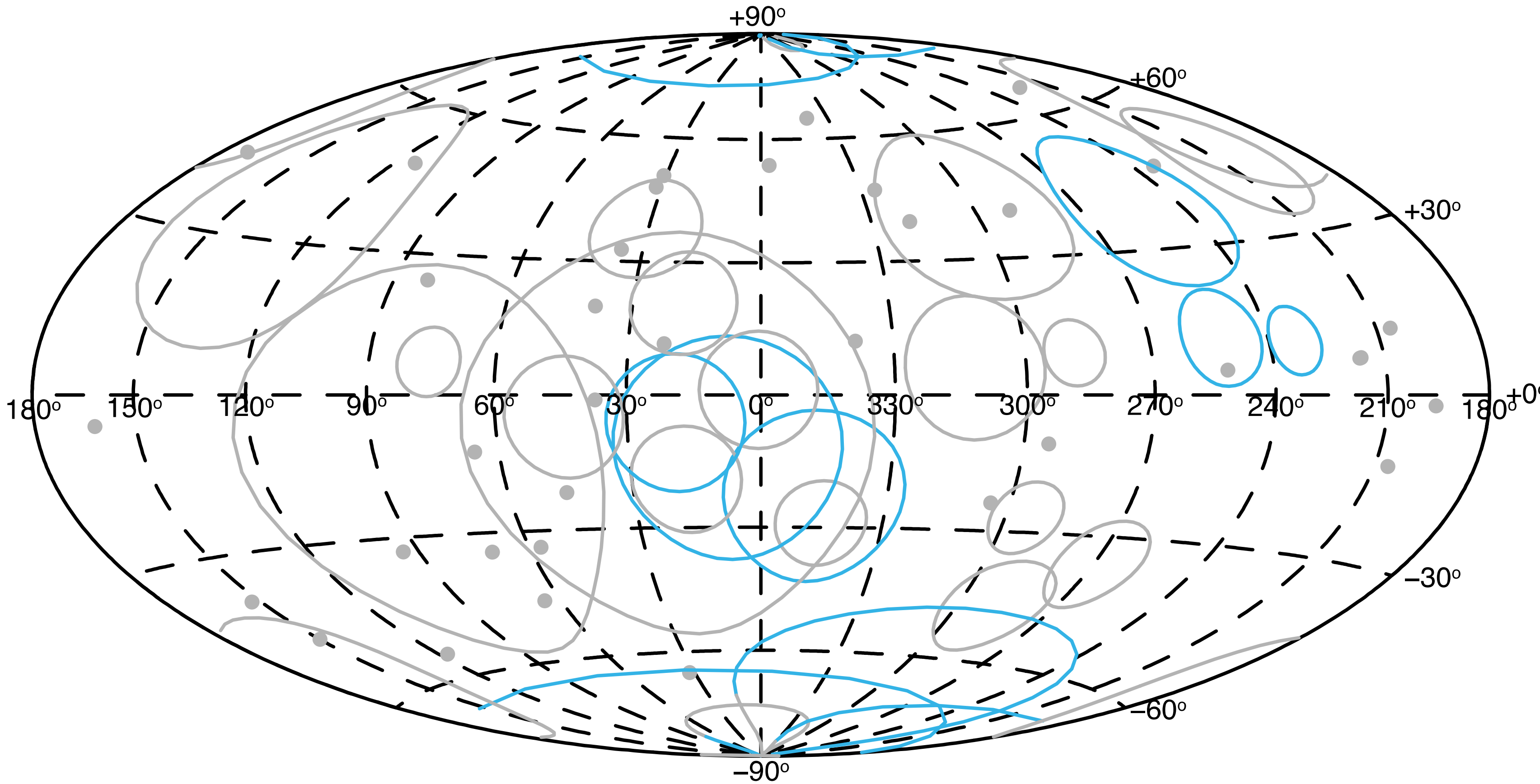
PRELIMINARY



The VHE sky (IACTs+Fermi 2FHL+2WHSP bright + faint)

PRELIMINARY

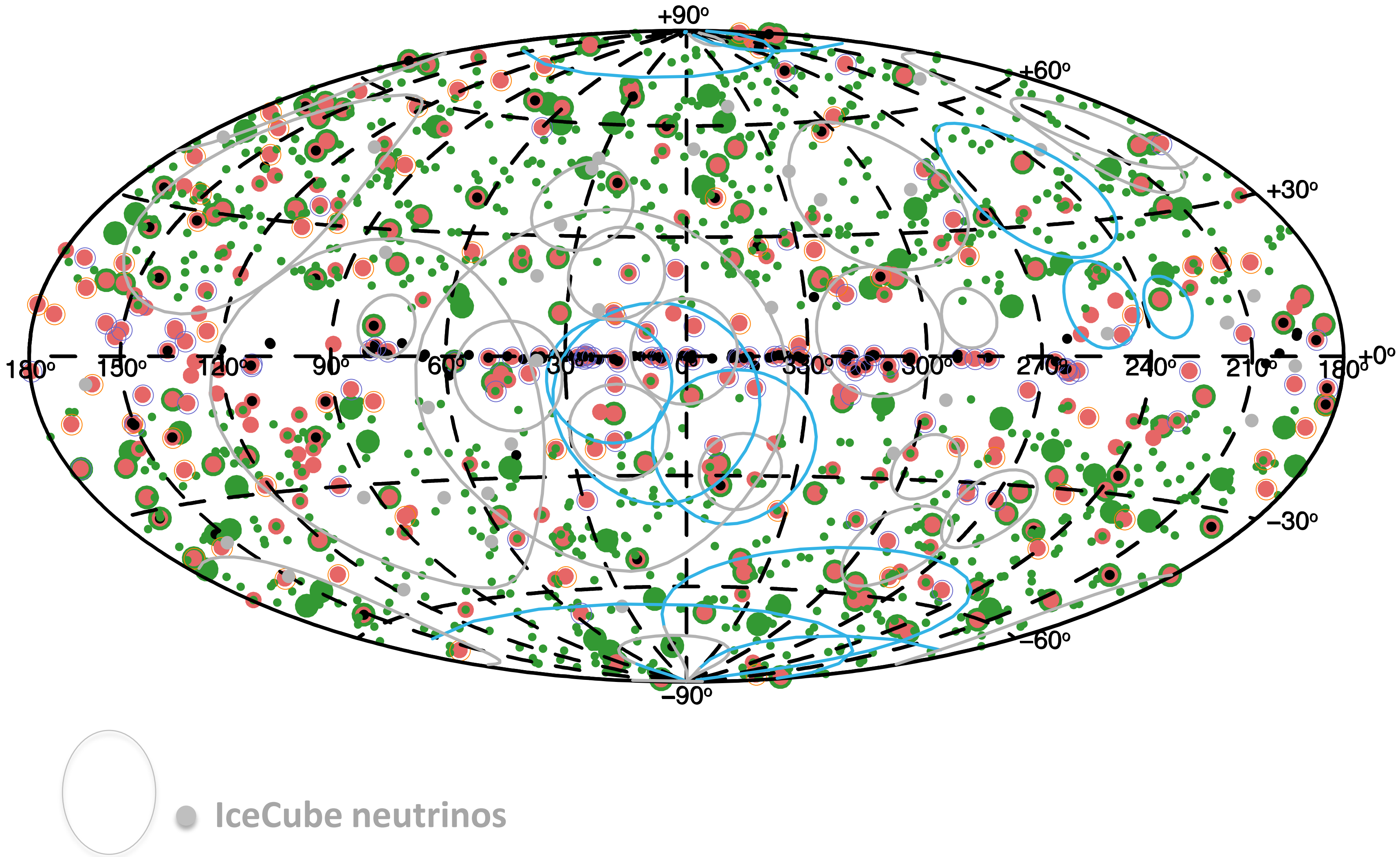




+90°
+60°
+30°
+0°
−30°
−60°
−90°
180°
150°
120°
90°
60°
30°
0°
330°
300°
270°
240°
210°
180°

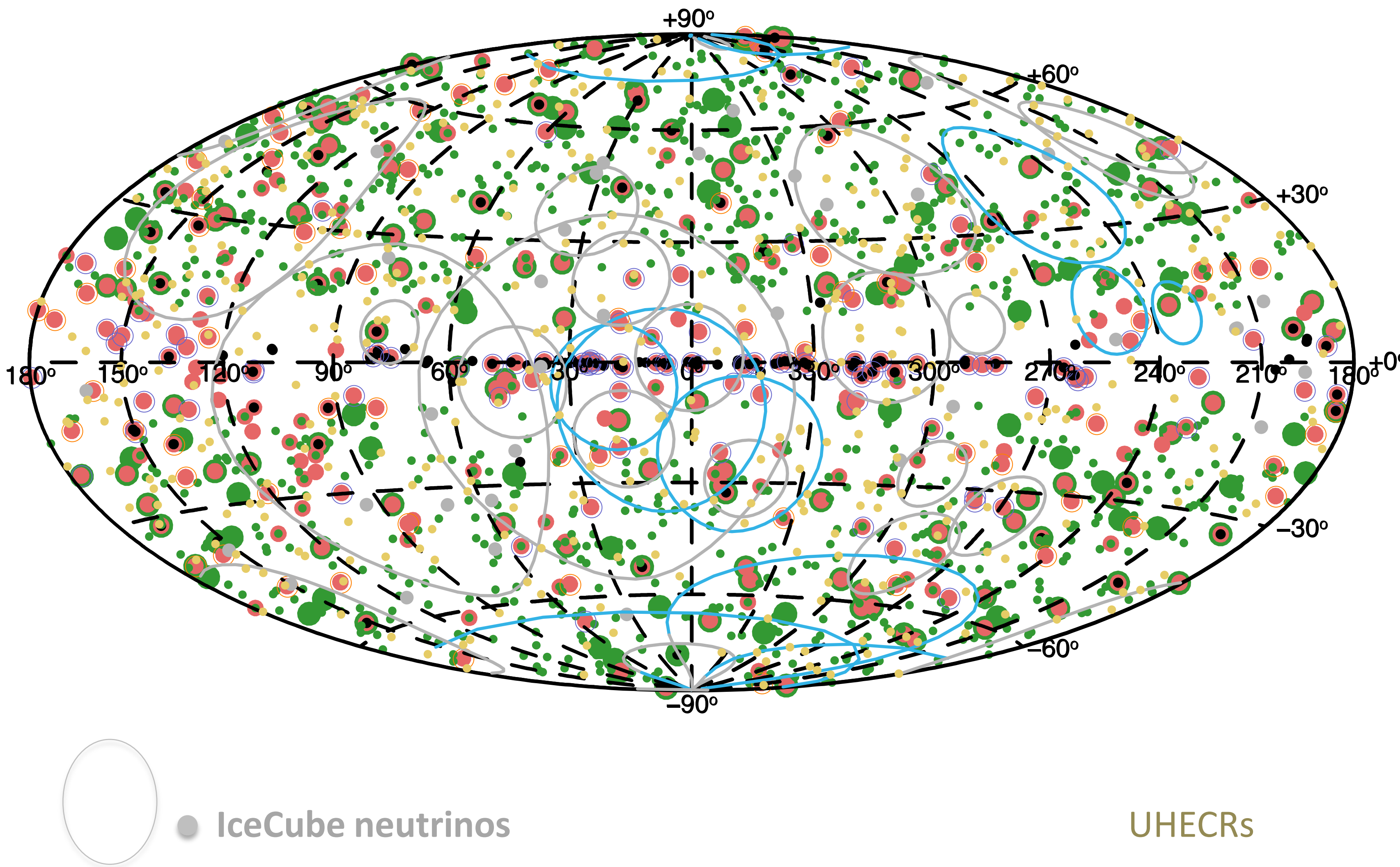
The VHE sky (IACTs+Fermi 2FHL+2WHSP bright + faint)

PRELIMINARY



The VHE sky (IACTs+Fermi 2FHL+2WHSP bright + faint)

PRELIMINARY



Are both BL Lacs and pulsar wind nebulae the astrophysical counterparts of IceCube neutrino events?

P. Padovani[1] and E. Resconi[2*]
[1] European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748 Garching bei München, Germany
[2] Technische Universität München, James-Frank-Str. 1, D-85748 Garching bei München, Germany

MNRAS, 2014, 443, 474

TANAMI Blazars in the IceCube PeV Neutrino Fields

F. Krauß[1,2], M. Kadler[2], K. Mannheim[2], R. Schulz[1,2], J. Trüstedt[1,2], J. Wilms[1], R. Ojha[3,4,5], E. Ros[6,7,8], G. Anton[9], W. Baumgartner[3], T. Beuchert[1,2], J. Blanchard[10], C. Bürkel[1,2], B. Carpenter[5], T. Eberl[9], P.G. Edwards[11], D. Eisenacher[2], D. Elsässer[2], K. Fehn[9], U. Fritsch[9], N. Gehrels[3], C. Gräfe[1,2], C. Großberger[12], H. Hase[13], S. Horiuchi[14], C. James[9], A. Kappes[2], U. Katz[9], A. Kreikenbohm[1,2], I. Kreykenbohm[1], M. Langejahn[1,2], K. Leiter[1,2], E. Litzinger[1,2], J.E.J. Lovell[15], C. Müller[1,2], C. Phillips[11], C. Plötz[13], J. Quick[16], T. Steinbring[1,2], J. Stevens[11], D. J. Thompson[3], and A.K. Tzioumis[11]

ArXiv 1406.0645V1

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **448**, 2412–2429 (2015) doi:10.1093/mnras/stv179

Photohadronic origin of γ-ray BL Lac emission: implications for IceCube neutrinos

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Accepted 2015 January 23. Received 2015 January 14; in original form 2014 December 4

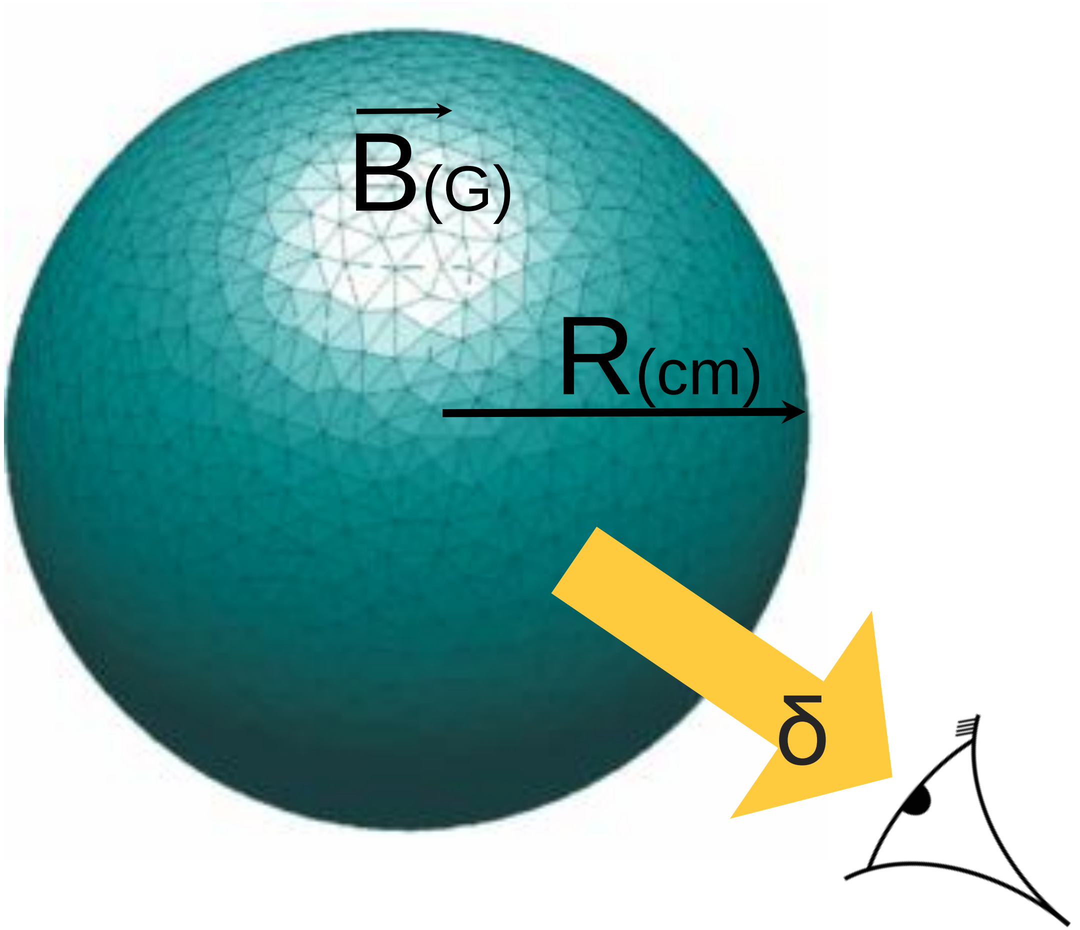
ABSTRACT

The recent IceCube discovery of 0.1–1 PeV neutrinos of astrophysical origin opens up a new era for high-energy astrophysics. Although there are various astrophysical candidate sources, a firm association of the detected neutrinos with one (or more) of them is still lacking. A recent analysis of plausible astrophysical counterparts within the error circles of IceCube events showed that likely counterparts for nine of the IceCube neutrinos include mostly BL Lacs, among which Mrk 421. Motivated by this result and a previous independent analysis on the neutrino emission from Mrk 421, we test the BL Lac–neutrino connection in the context of a specific theoretical model for BL Lac emission. We model the spectral energy distribution (SED) of the BL Lacs selected as counterparts of the IceCube neutrinos using a one-zone leptohadronic model and mostly nearly simultaneous data. The neutrino flux for each BL Lac is self-consistently calculated, using photon and proton distributions specifically derived for every individual source. We find that the SEDs of the sample, although different in shape and flux, are all well fitted by the model using reasonable parameter values. Moreover, the model-predicted neutrino flux and energy for these sources are of the same order of magnitude

Theoretical modelling

Input:

- electrons and protons accelerated by some mechanism
- injected isotropically in the blob, constant rate
- interaction with magnetic field, production of secondaries



Theoretical modelling

Output: five stable particle populations

- protons lose energy by:
  - ✓ synchrotron radiation, Bethe-Heitler (*pe*) pair production ($p+\gamma \rightarrow e^+ + e^-$), photopion interaction
- electrons lose energy by:
  - ✓ synchrotron radiation, inverse Compton scattering
- photons: gain and lose energy in various ways
- neutrons: escape
- neutrinos: escape

Interplay of the processes described by a set of time-dependent kinetic equations, solved by a numerical code.

The cumulative neutrino emission from BL

A simplified view of blazars: the neutrino background

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MNRAS, 2015, 452, 1877

Accepted ... Received ...; in original form ...

ABSTRACT
Blazars have been suggested as possible neutrino sources long before the recent IceCube discovery of high-energy neutrinos. We re-examine this possibility within a new framework built upon the *blazar simplified view* and a self-consistent modelling of neutrino emission from individual sources. The former is a recently proposed paradigm that explains the diverse statistical properties of blazars adopting minimal assumptions on blazars' physical and geometrical properties. This view, tested through detailed Monte Carlo simulations, reproduces the main features of radio, X-ray, and γ-ray blazar surveys and also the extragalactic γ-ray background at energies $\gtrsim 10$ GeV. Here we add a hadronic component for neutrino production and estimate the neutrino emission from BL Lacs as a class, "calibrated" by fitting the spectral energy distributions of a preselected sample of BL Lac objects and their (putative) neutrino spectra. Unlike all previous papers on this topic, the neutrino background is then derived by summing up at a given energy the fluxes of each BL Lac in the simulation, all characterised by their own redshift, synchrotron peak energy, γ-ray flux, etc. Our main result is that BL Lacs as a class can explain the neutrino background seen by IceCube above ~ 0.5 PeV while they only contribute $\sim 10\%$ at lower energies, leaving room to some other population(s)/physical mechanism. However, one cannot also exclude the possibility that individual BL Lacs still make a contribution at the $\approx 20\%$ level to the IceCube low-energy events. Our scenario makes specific predictions testable in the next few years.

Key words: neutrinos — radiation mechanisms: non-thermal — BL Lacertae objects: general — gamma-rays: galaxies

1 INTRODUCTION

Blazars are a class of Active Galactic Nuclei (AGN), which host a jet oriented at a small angle with respect to the line of sight. Highly relativistic particles moving within the jet and in a magnetic field emit non-thermal radiation (Blandford & Rees 1978; Urry & Padovani 1995). This is at variance with most other AGN whose energy is mainly thermal and produced through accretion and rapid variability, and strong emission over the entire electromagnetic spectrum. The two main blazar subclasses, namely BL Lacertae objects (BL Lacs) and flat-spectrum radio quasars (FSRQ), differ mostly in their optical spectra, with the latter displaying strong, broad emission lines and the former instead being characterised by optical spectra showing at most weak emission lines, sometimes exhibiting absorption features, and in many cases being completely featureless.

Neutrino spectra

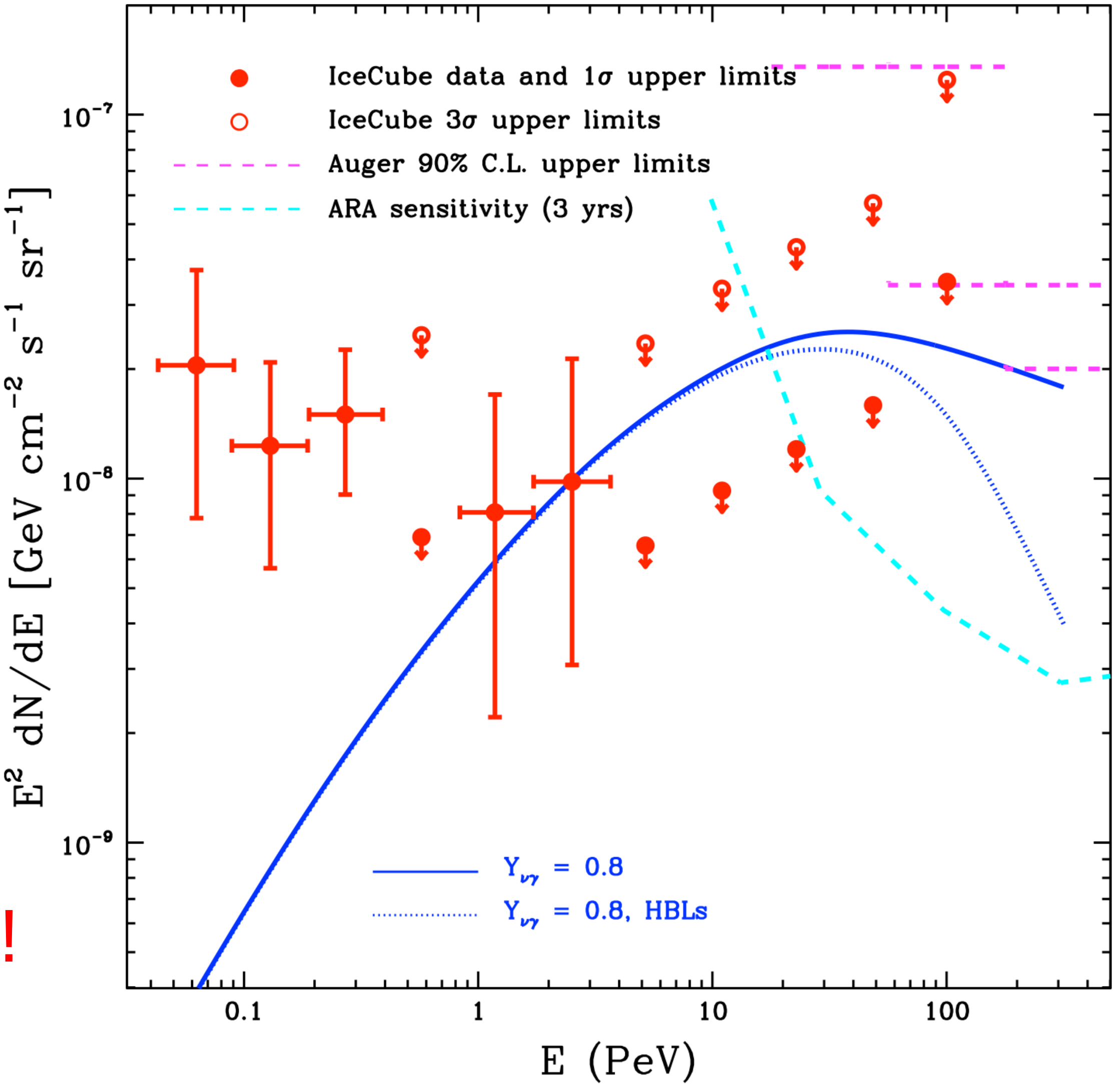
= L_ν/L_γ

$$E_\nu F(E_\nu) \propto Y_{\nu\gamma} E_\nu^{1-s} \exp(-E_\nu / E_0) F_\gamma(>10\,GeV)$$

$$E_0 \approx \frac{17.5\,PeV}{(1+z)^2} \left(\frac{\delta}{10}\right)^2 \left(\frac{\nu_{synch,peak}}{10^{16}\,Hz}\right)^{-1}$$

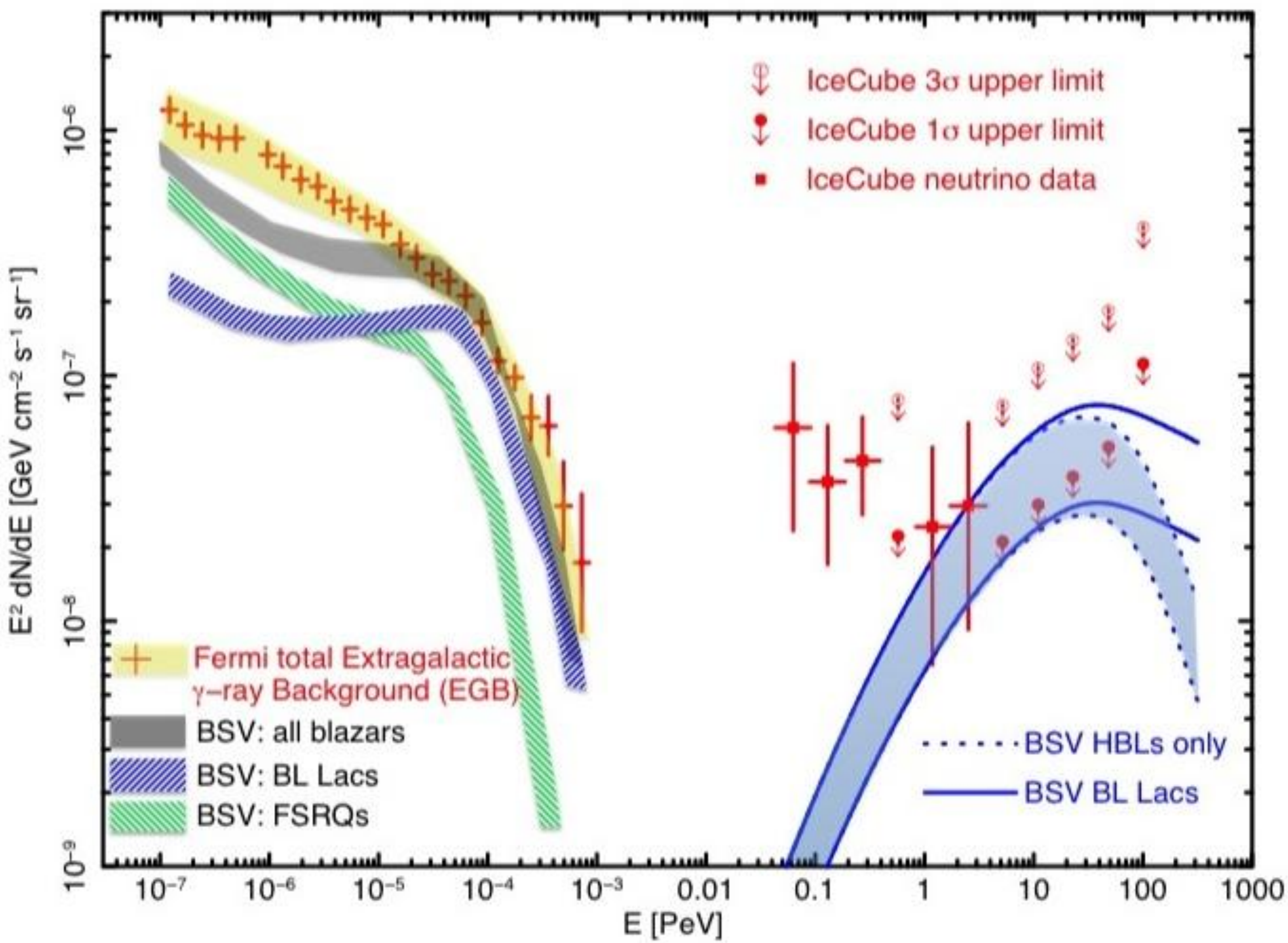
Plus: γ-ray luminosity function, evolution, source class, etc.

The cumulative neutrino emission



No free parameters!

The big picture



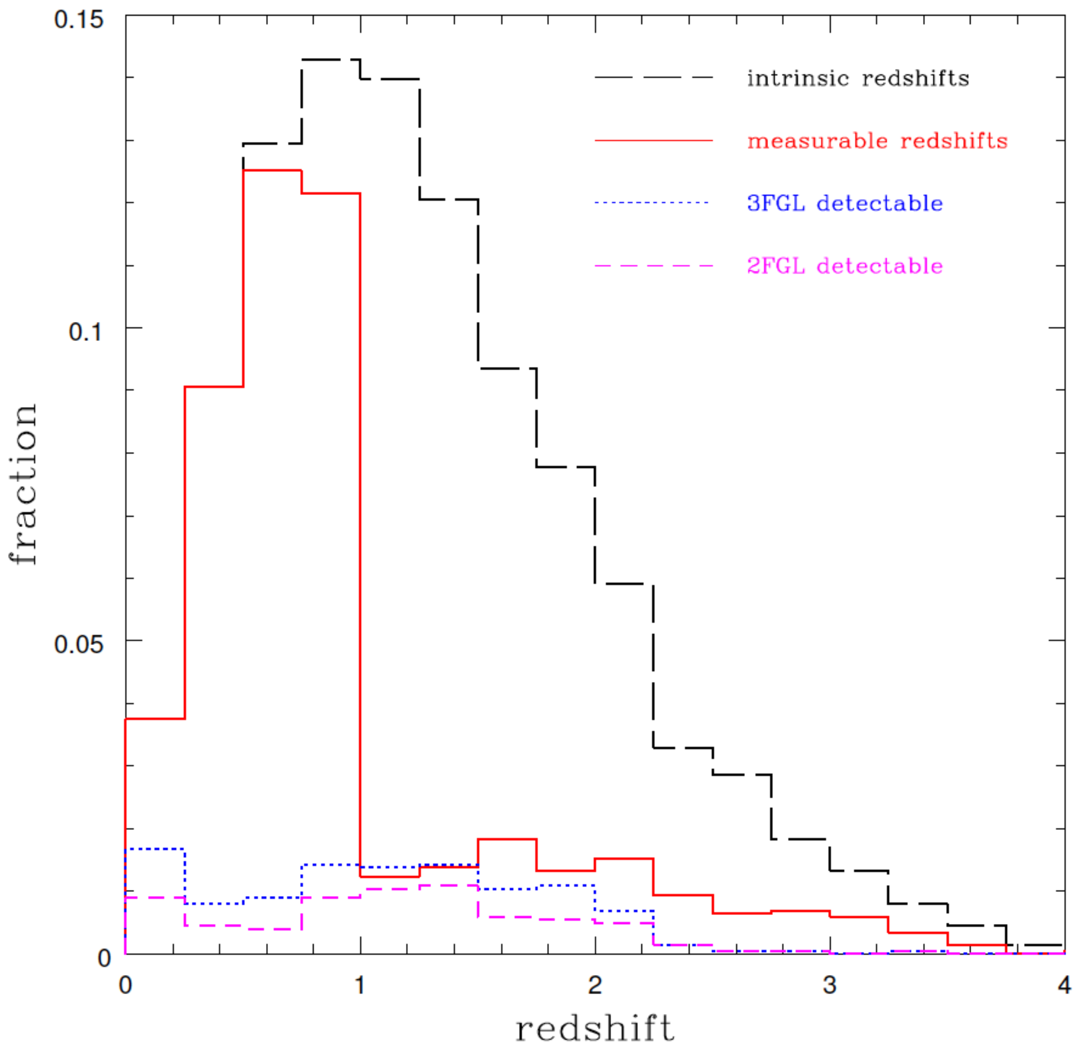


Figure 3. The redshift distribution for the BL Lacs contributing $\sim 95\%$ of the background associated with the benchmark case at 1 PeV (black long-dashed line) and for those with a measurable redshift (red solid line). The sources detectable by the 3FGL (blue dotted line) and 2FGL (magenta short-dashed line) catalogues are also indicated.

Conclusions - 1:

- Blazars were once a topic for a few specialists, now they are becoming central to very high energy and perhaps multi-messenger astrophysics
- Their behaviour, in terms of population studies - statistical distributions, can now be understood and predictions for future surveys (e.g. CTA) can be done
- Despite the rapid growth of multi-frequency data the details of the physical mechanisms behind the emission in blazars are far from fully understood
- More theoretical work and new software tools for exploiting the available data are necessary

Conclusions - 2:

- BL Lacs are excellent (probable?) candidates for IceCube neutrinos, both from the observational and theoretical point of view
- BL Lacs can explain the high-energy (> 0.5 PeV) part of the IceCube diffuse emission
- A different population is needed at lower energies
- A few BL Lacs should be at the sensitivity level of IceCube
- This scenario is testable with IceCube:
  - ✓ > 2 PeV events
  - ✓ point sources