The First Fermi-LAT Catalog of Sources Above 10 GeV (1FHL catalog)

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Outline of this talk

- Motivation (differences from the 2FGL catalog)
- Some results
  - Detection, localization and spectral analysis with gtlike
  - Associated sources
  - Variability
  - Candidate sources for detection with IACTs (above 100GeV)
- Conclusions

Motivation (differences from the 2FGL catalog)

Dedicated source characterization at the highest LAT energies (>10 GeV).

- Shape of the spectrum at > 10 GeV might not be well characterized if we use a single fit in the energy range 0.1 GeV – 100 GeV. *Low energies have larger stat. weight*

- The variability at the highest Fermi-LAT energies could be different from that at the lowest energies, which might indicate the presence of a separate population of particles

Understand better the population of sources emitting above 10 GeV

Which are the source-types dominating the highest Fermi-LAT energies ?
Quantify differences from LogN-LogS for sources emitting at >0.1 GeV ?
What is the contribution to the Extragalactic Gamma-Ray Background (EGB) ?

Identify promising source candidates to lead current IACTs to new VHE (>100 GeV) discoveries

Fermi-LAT in 2 years (2FGL) vs All TeV instruments in 20+ years (TeV Catalog)

~1900 sources vs ~140 sources

Fermi-LAT benefits from a large duty cycle and all-sky observation.
Useful to increase the efficiency in the searches for new TeV sources
Through various Memoranda of Understanding, the Fermi-LAT collaboration has successfully helped IACTs to find new TeV sources since 2009

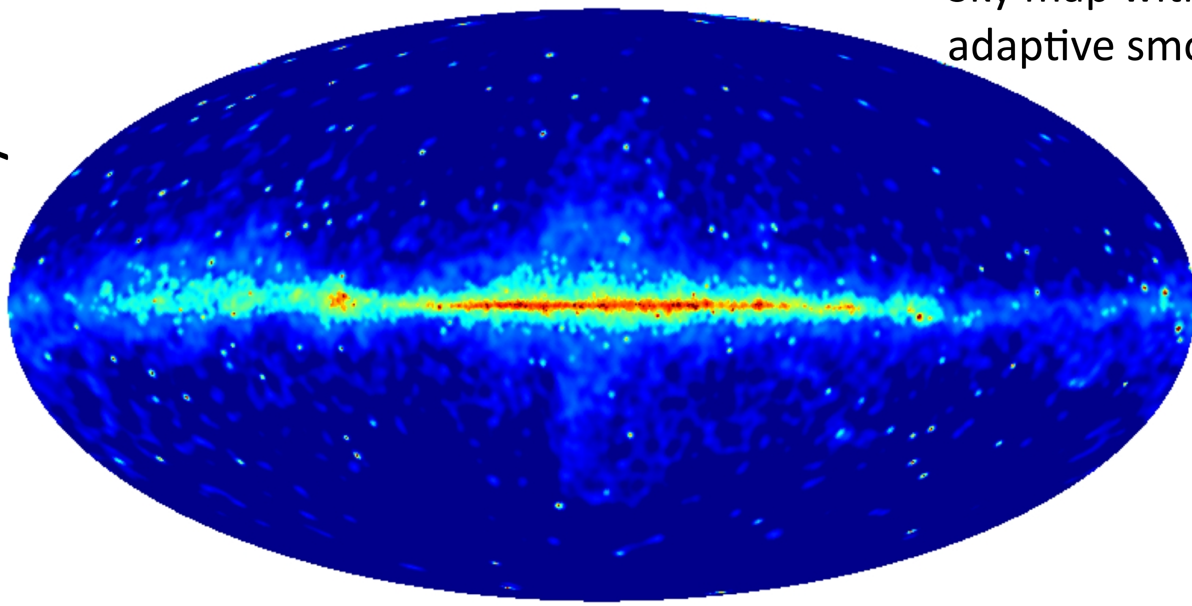
Detection, localization and gtlike analysis

LAT data from August 2008 through July 2011 (nearly three years)

P7_V6_Clean event selection

Sky map with > 10 GeV events and adaptive smoothing (10 photon kernel)

Preliminary



LAT saw more than 1.5×10^5 gamma-rays in only 3 years

Big improvement with respect to EGRET !!!
1.5×10^3 evts in 9 years
(Thompson et al. 2005)

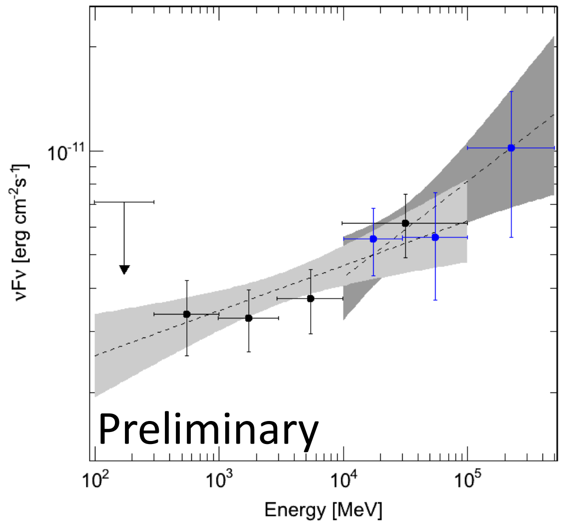
The analysis pipeline used is the same as that for the 2FGL catalog:
candidate sources ("seeds") are identified and localized, and then a maximum likelihood analysis extracts results on statistical significance, flux, and energy spectrum.
Galactic and isotropic diffuse background models similar to those used for the 2FGL catalog (available through the Fermi Science Support Center)

Only sources with a Test Statistic (TS) larger than 25 are reported

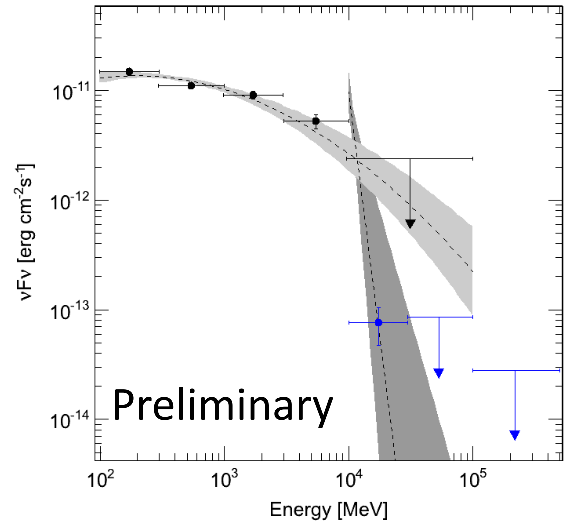
514 sources ***(63 not contained in 2FGL)***
(*All sources could be fitted with a simple power law*)

Detection, localization and gtlike analysis

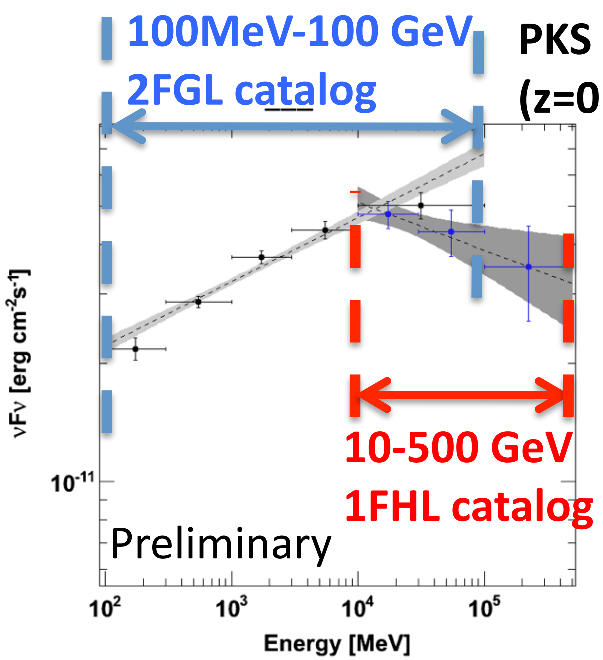
1ES 0033+595 (z=0.086)



B2 2308+34 (z=1.8)



PKS 2155-304 (z=0.12)



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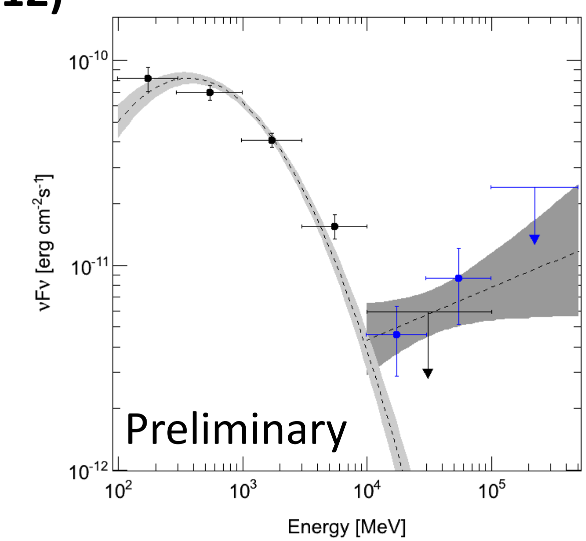


Large diversity in the spectra obtained above 10 GeV (in comparison with that obtained when integrating above 100 MeV)

Some sources show a >10 GeV spectrum that is roughly a continuation of that at > 100 MeV

Others show internal breaks

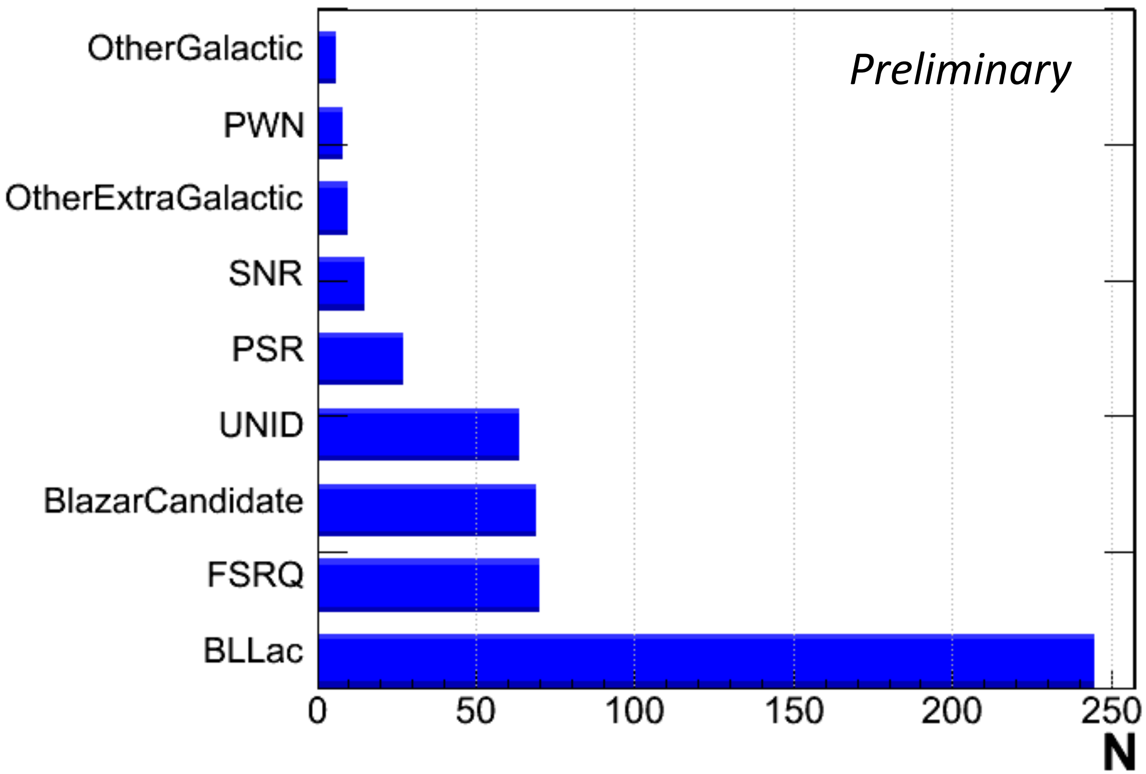
Others show attenuations due to the absorption in the EBL

Others show new components

Need 1FHL catalog to characterize Fermi sources at the highest energies

Associated sources (All)

514 sources in the 1FHL catalog

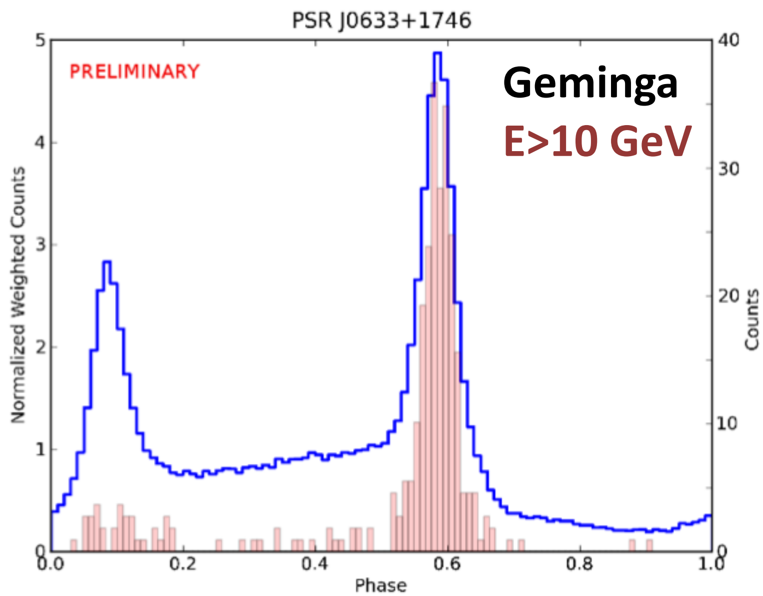


6	(**1%**)
8	(**2%**)
10	(**2%**)
15	(**3%**)
27	(**5%**)
64	(**12%**)
69	(**13%**)
70	(**14%**)
245	(**47%**)

AGN (mostly BL Lacs) dominate the Fermi-LAT sky above 10 GeV (394 objects→ 76%)

12.5% of the sources remain unassociated

Associated sources (Pulsars)

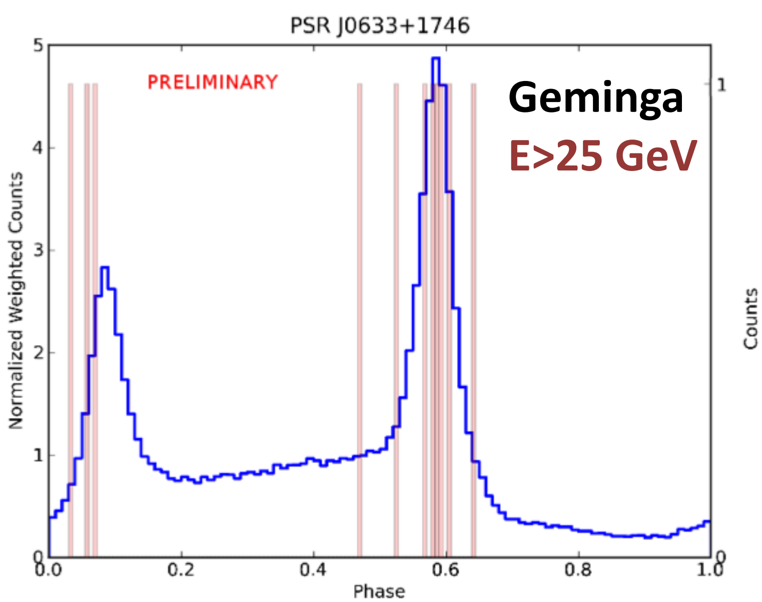


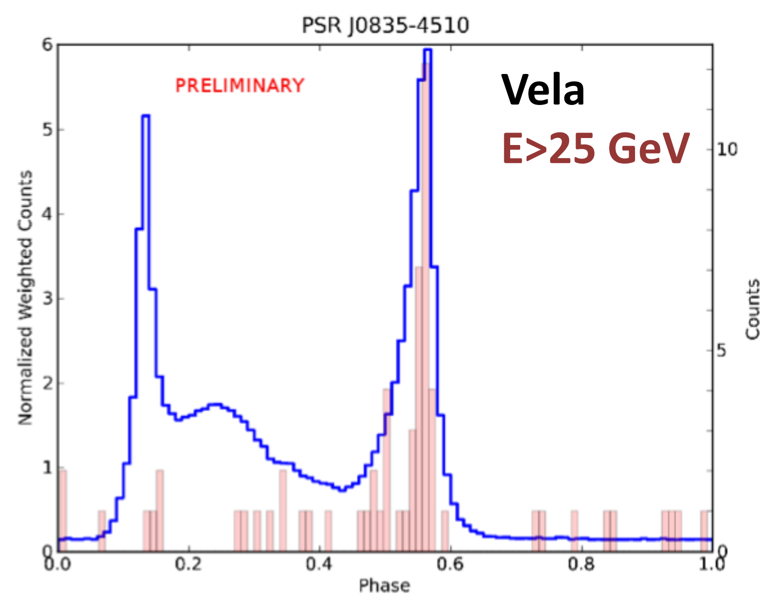
Pulsations observed above 10 GeV for 11 (out of 27)

J0007+7303 (CTA1)
J0534+2200 (Crab)
J0614-3329
J0633+1746 (Geminga)
J0835-4510 (Vela)
J1028-5819
J1048-5832
J1709-4429
J1808-2332
J2021+3651 (Dragonfly)
J2032+4127

Normalized weighted light curve (100 bins) in the 0.3-10 GeV range (blue) and unweighted light curve above 10 GeV (pink).

→ 0.6 (1.2) deg RoI for Front (Back) evts

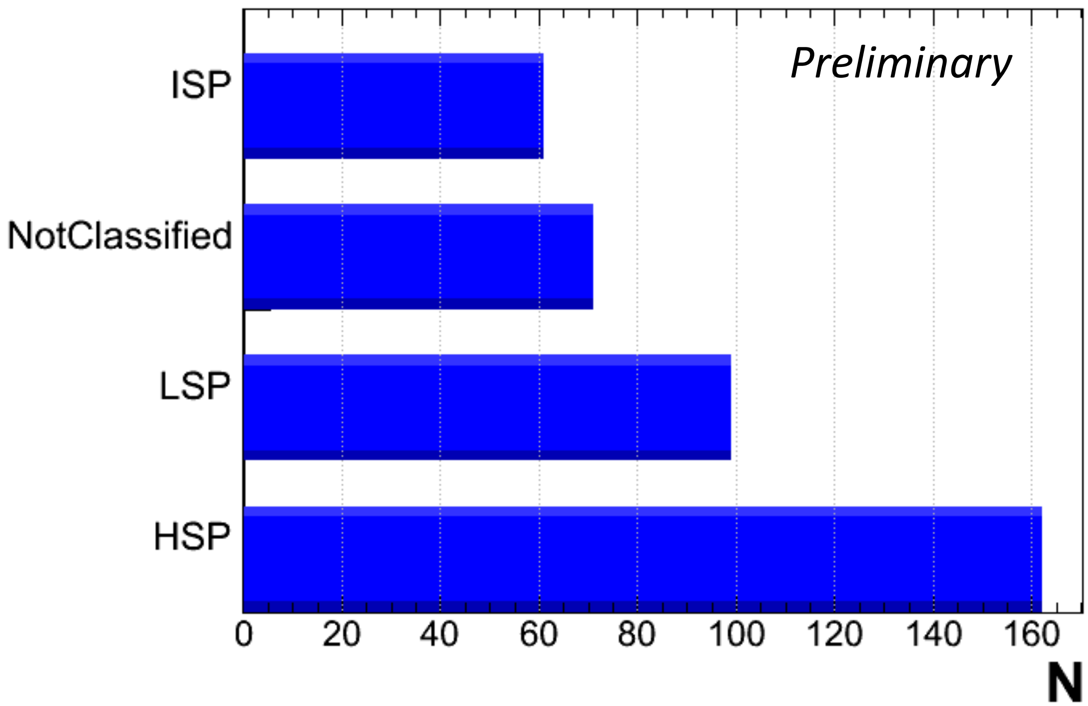


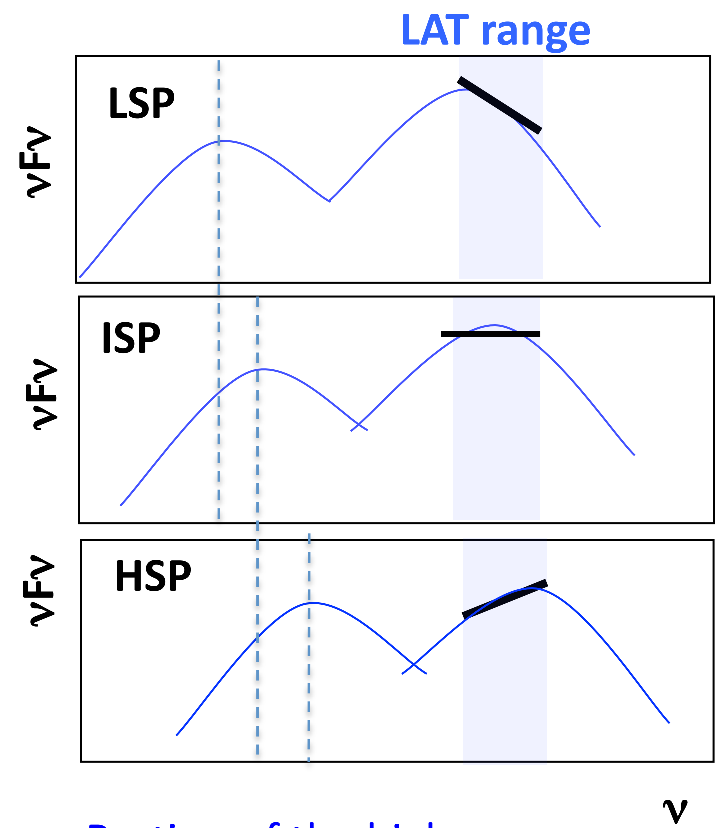


Associated sources (AGNs)

AGN SED classification

→ *according to location of Sync peak*



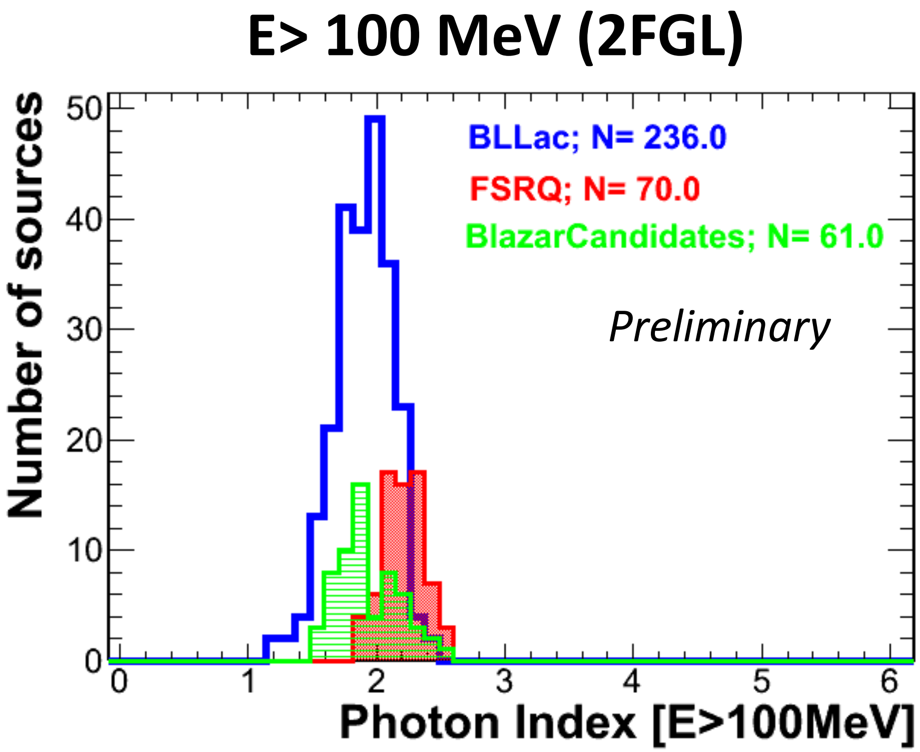


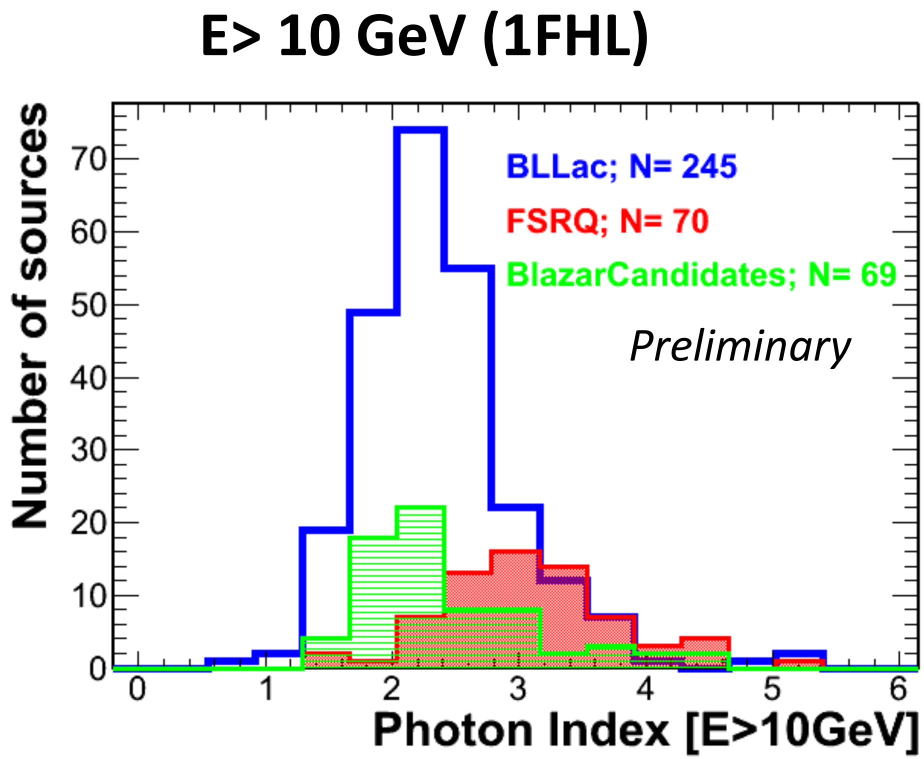
From the 394 AGN sources in the 1FHL catalog, 373 already existed in the 2[nd] LAT AGN Catalog (2LAC)

Portion of the high-energy bump covered by LAT depends on the blazar SED classification

HSP (162 objects, 41%) are the source class that dominates the Fermi-LAT "AGN" sky above 10 GeV

Associated sources (AGNs)





<u>Photon indices get softer at E>10 GeV</u>

→ Intrinsic softening of the AGN spectra

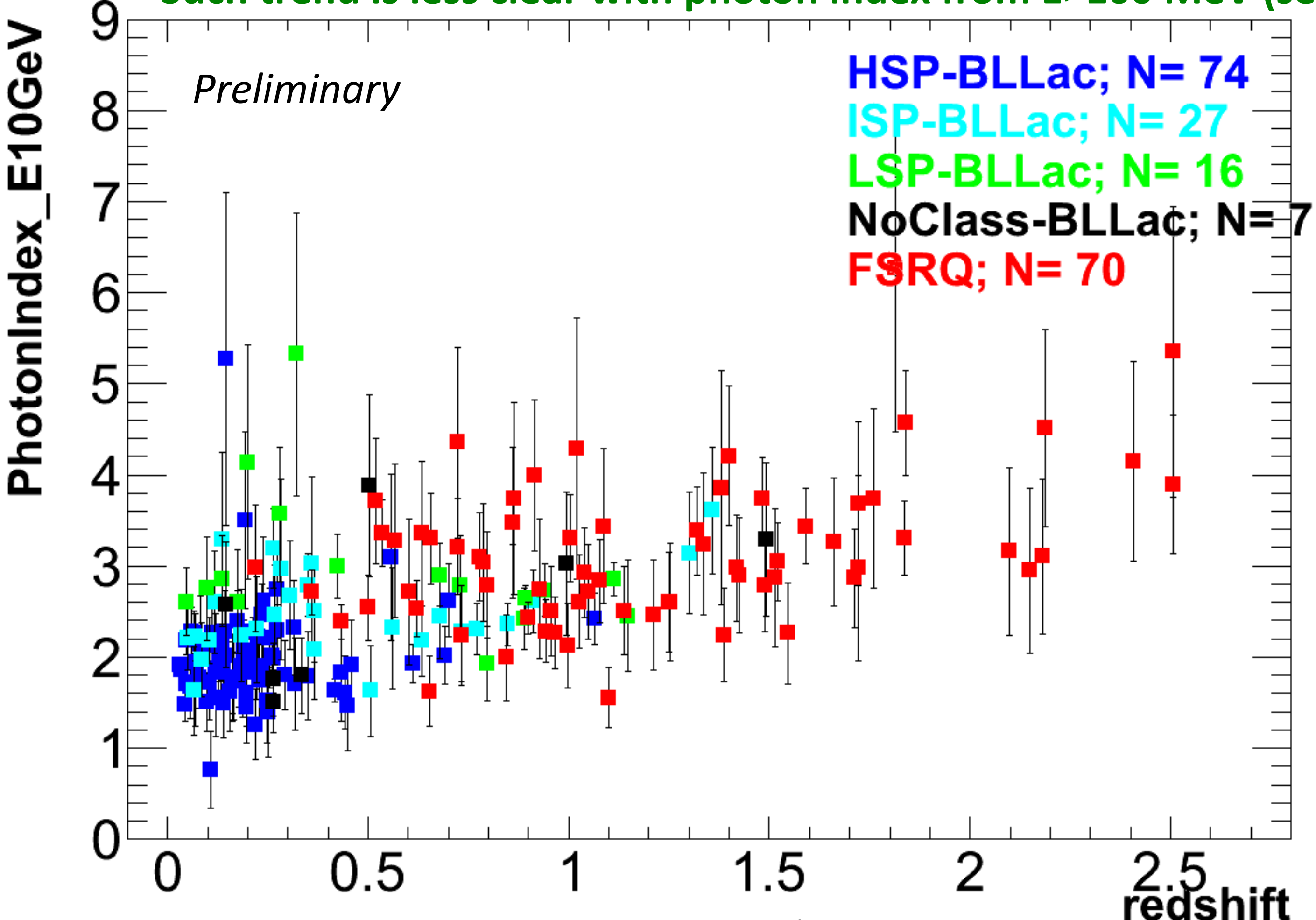
→ Impact of absorption of gamma-rays in the (UV) EBL

- In both cases, the FSRQ objects cluster at the highest (softest) index values, while BL Lac objects show the lowest (hardest) values.
- Blazar candidates are spread, but probably a bit more similar to that of BL Lacs
- There is a large number of BL Lac objects with spectra harder than 2, even when the spectra are determined using E>10 GeV

Index vs Redshift

209 associated sources have measured redshifts
194 objects with redshifts are associated with FSRQs or BL Lacs
(Photon Index is computed with events with Energy > 10GeV)

Sources get softer with redshift (possibly due to attenuation on the EBL).
Such trend is less clear with photon index from E>100 MeV (see 2LAC paper)



Quantification of variability

This is not an easy topic because many of the sources are WEAK sources for Fermi-LAT

→ we have very few photons to work with

For the typical source we get about 10 photons (E>10 GeV) in 3 years (*range is 4 - 952*)

Because of the low photon count, the Bayesian Block algorithm proposed by Scargle in 1998 is the most suitable method to evaluate potential flux variations

→ It takes the raw event count and determines "time blocks" with constant photon rate

→ More than one "time block" implies variability

→ The impact of the prior in number of blocks can be quantified via simulations

→ Variability can be computed for several "false positive thresholds"

Preliminary

False positive threshold	Number of sources flagged as variable	Expected number of false positives
0.1%	27	0.5
1%	41	5
2%	56	10
5%	80	25

458 objects flagged as variable in 2FGL (1873 objects)

Photon statistics is a limiting factor to determine variability (at >10 GeV)

→ **Only few sources flagged as variable (if fake pos. thr. is stringent: 0.1—1%)**

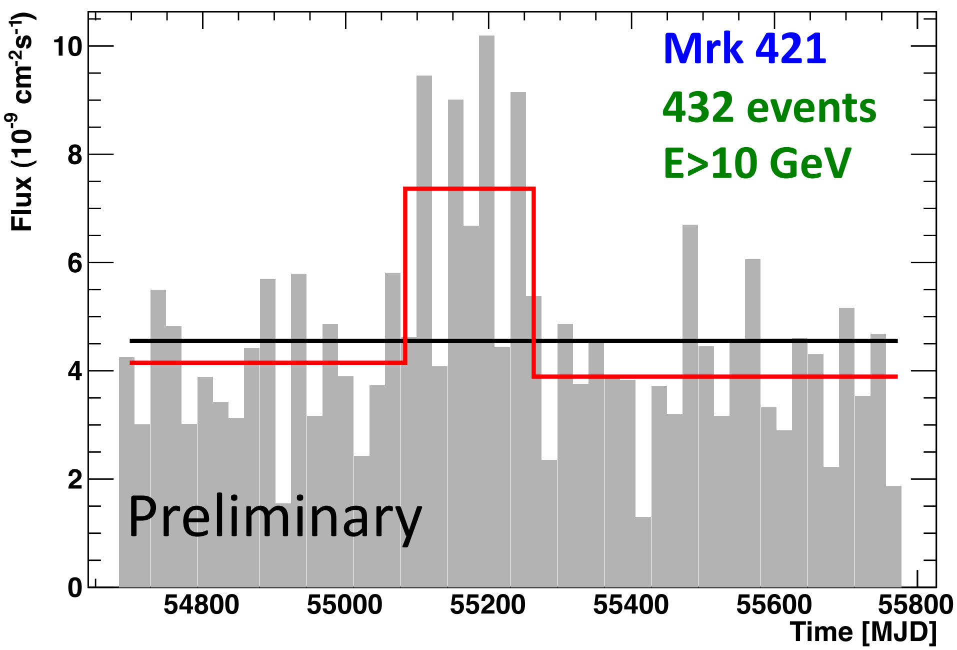
→ Brightest sources are NOT necessarily the ones with the highest variability

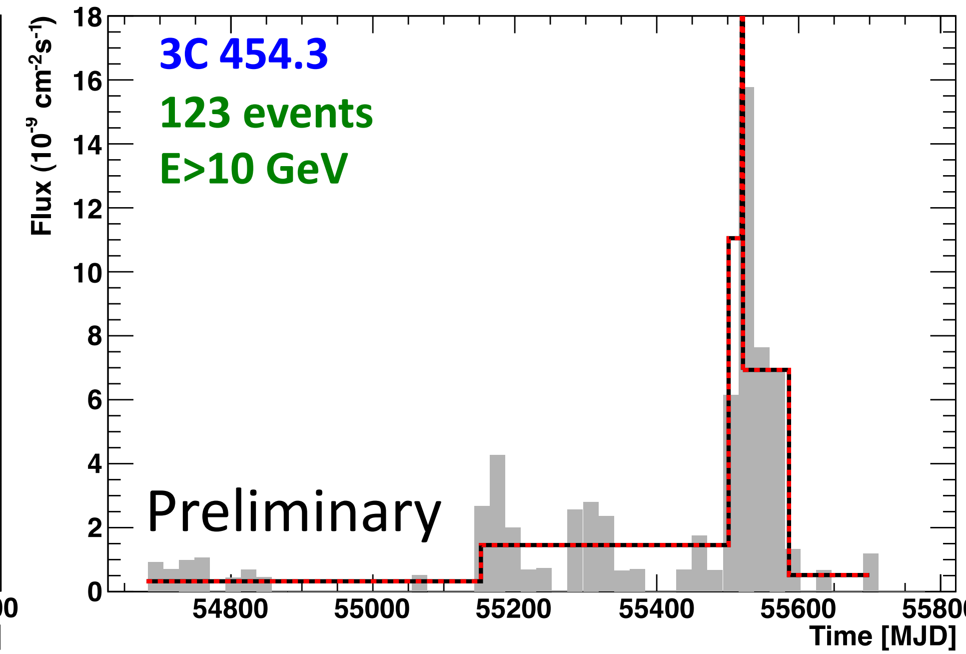
Bayesian blocks (with light curves overlayed)

→ *More than one block indicates variability*

Black → 1% false positive threshold

Red → 5% false positive threshold



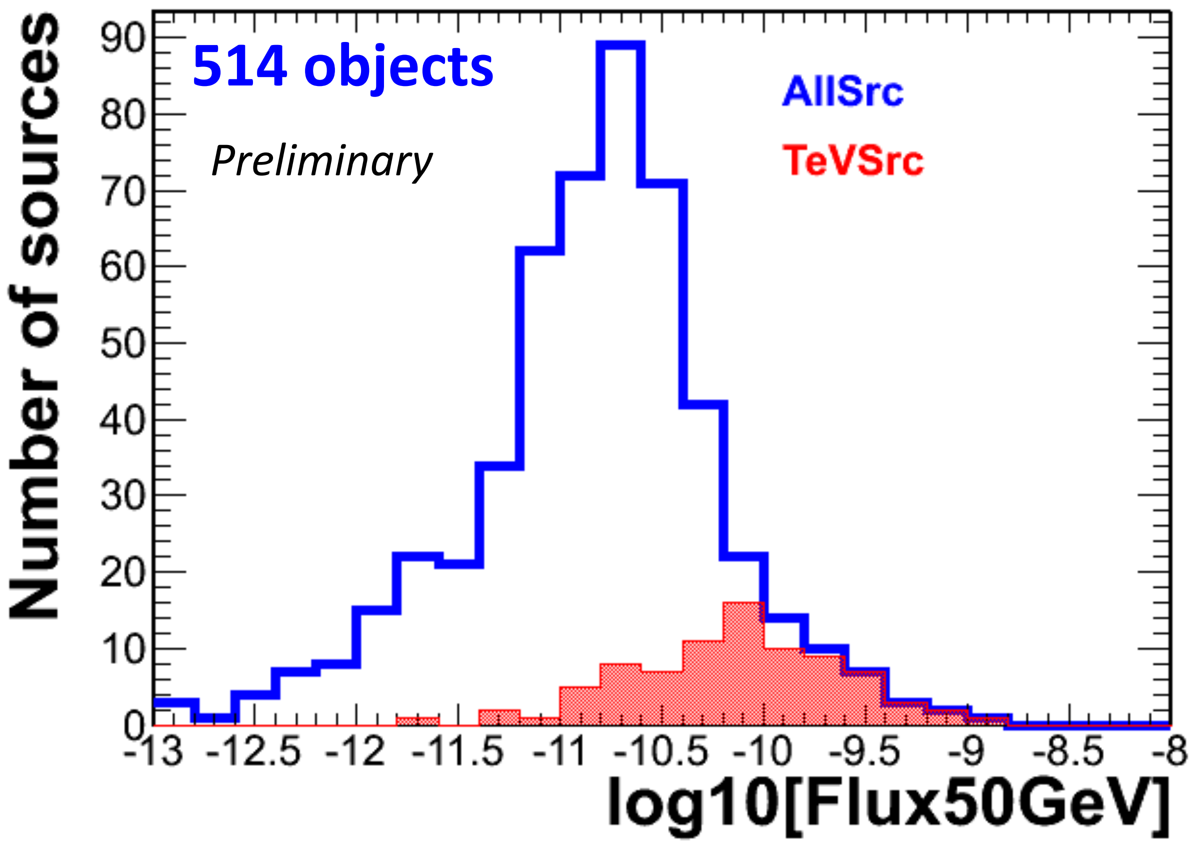


Variability not observed for Mrk 421 unless we use a (loose) false positive threshold of 5%. Yet in 2010, Mrk 421 showed VHE (E>100 GeV) flux variations larger than one order of magnitude. **Similar situation for other HSPs (PKS 2155-304, Mrk 501 …)**

Highly-significant variability typically detected for sources which are "not-too-faint" and for which Fermi-LAT sees the falling edge of the high-energy SED bump (→ LSPs)
Examples: PKS 1222, 3C 454, 3C 279, BL Lac …

Source candidates for detection at VHE (E>100 GeV)

Distribution of LAT flux above 50 GeV for all the 1FHL objects



Flux above 50 GeV determined using the power law fit derived with events above 10 GeV

84 objects from the 1FHL list have been already detected with IACTs at VHE (→ TeV Src) http://tevcat.uchicago.edu/

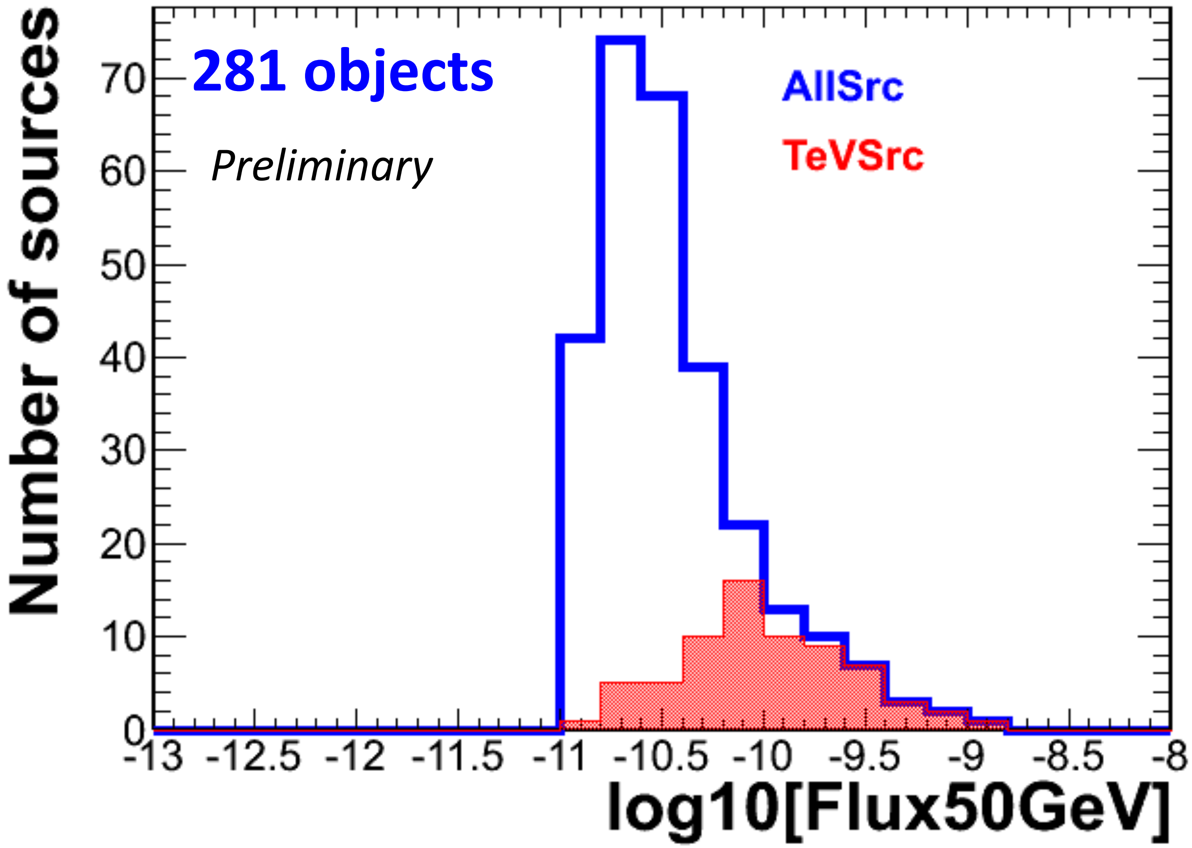
430 objects from the 1FHL list have not been detected with IACTs

Clear relation:
sources detected at VHE with IACTs have high fluxes above 50 GeV

Source candidates for detection at VHE (E>100 GeV)

Distribution of LAT flux above 50 GeV for the 1FHL objects that survive the <u>selection of *good TeV candidates*</u>

Power-law index < 3
Significance (>30GeV) > 3σ
Log10(F50GeV] > -11



From the 84 TeV src in 1FHL, 69 objects survive the *TeV candidate selection cuts*

212 objects are flagged as good TeV candidates for being detected with IACTs

In September 2012 we informed HESS/MAGIC/VERITAS about the best 72 candidates

→ **log10[F50GeV] > -10.5**

Clear relation:
sources detected at VHE with IACTs have high fluxes above 50 GeV

Source candidates for detection at VHE (E>100 GeV)

Few candidate sources for detection >100 GeV with IACTs (sorted with decreasing F>50 GeV)

→ Information shared with IACTs through Memoranda of Understanding

Association	Distance	Src Type
PMN J1603-4904	?	BL Lac (LSP)
η Carinae	2.4 kpc	Binary System
PKS 0537-441	z= 0.892	BL Lac (LSP)
B3 0133+388	z>0.4	BL Lac (HSP)
PKS 0301-243	z=026	BL Lac (HSP)
KUV 00311-1938	z=0.61	BL Lac (HSP)
4C +55.17	z=0.899	FSRQ (LSP)
PG 1246+586	z=0.8	BL Lac (ISP)

Majority of sources are blazars, some of **them with high redshift !**

Detecting the high-redshift blazars with IACTs has a large scientific return (blazar physics and cosmology)

Should they be detected at VHE, these sources could be used as tools to study a large variety of things related to the environment traversed by the gammas-rays:

1 - Extragalactic Background Light
2 - Intergalactic Magnetic Fields
3 - Tests of Lorentz Invariance Violation
4 - Search for Axion Like Particles

Source candidates for detection at VHE (E>100 GeV)

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IACT Observation triggered by the information provided by LAT collaboration back in October 2009

VHE detection with MAGIC announced in Gamma 2012 (July, 2012)

→ Highlights from MAGIC (D. Mazin)

VHE detection with HESS announced in Gamma 2012 (July, 2012)

→ Highlights from HESS (C. Stegmann)

Search for new VHE AGNs is best when performed in 3 dimensions: RA, Dec and Time

Fermi-LAT data can help to determine WHERE and WHEN to look with IACTs

Conclusions

Searched for gamma-ray sources at E>10 GeV using data from LAT accumulated during the first 3 years of the Fermi Gamma-ray Space Telescope mission.

<u>Detected 514 sources (TS>25)</u>, measured their spectra, quantified their variability, and studied their associations with cataloged sources at other wavelengths. *This list, **the 1FHL catalog**, complements the 2FGL catalog, which was based on 2 years of data in the energy range 100 MeV – 100 GeV and so included many sources with softer spectra.*

About 88% of the objects could be associated with known sources.
76% are AGNs, ~5% are pulsars, and ~5% are SNR/PWN .
Pulsation detected above 10 GeV for 11 pulsars
Observed trend of *softer spectral index with increasing redshift in blazars*

Variability is found for 41 objects (8%).
→ The most variable source-type above 10 GeV is LSP blazars (not HSP !!)
→ *Sources for which Fermi-LAT sees the falling segment of the high-energy SED peak are more variable than sources for which Fermi-LAT sees the rising segment*

Several good candidates for detection with current IACTs were identified. They have variety of natures: SNRs, Binary system, UNIDs and <u>Blazars (with redshift of up to 1)</u>
→ *Gamma-ray (and optical/X-ray) variability can further increase the chances for detection of new blazars at VHE*

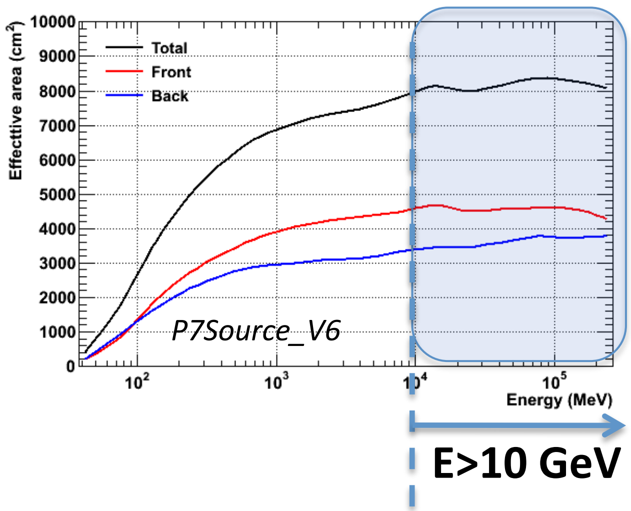
backup

Performance of LAT for astronomy above 10 GeV

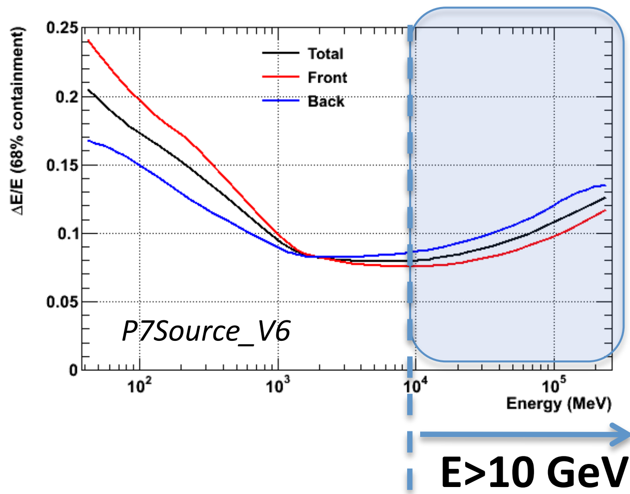
<u>The LAT instrument</u> → See "Fermi mission overview" talk by Julie McEnery (Monday)

Performance of LAT for E> 10 GeV is excellent (compared to that for E>100 MeV)

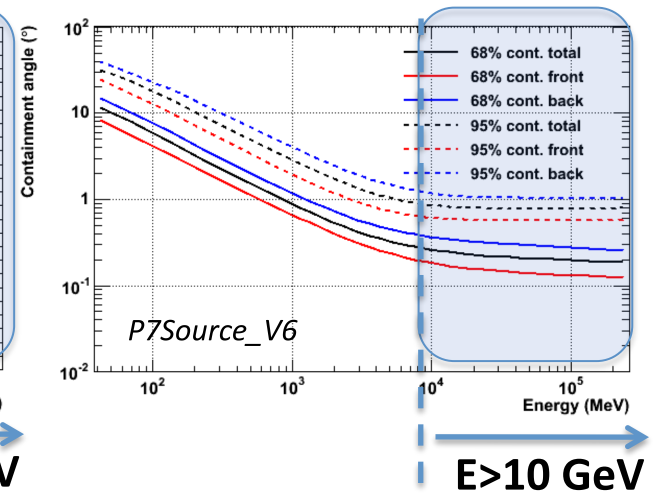
Effective Area



Energy resolution



Point Spread Function



http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

Best possible effective area and PSF occur at the highest energies

Slightly worse energy resolution due to worse shower containment

The Challenge: Nature of the sources we want to detect…

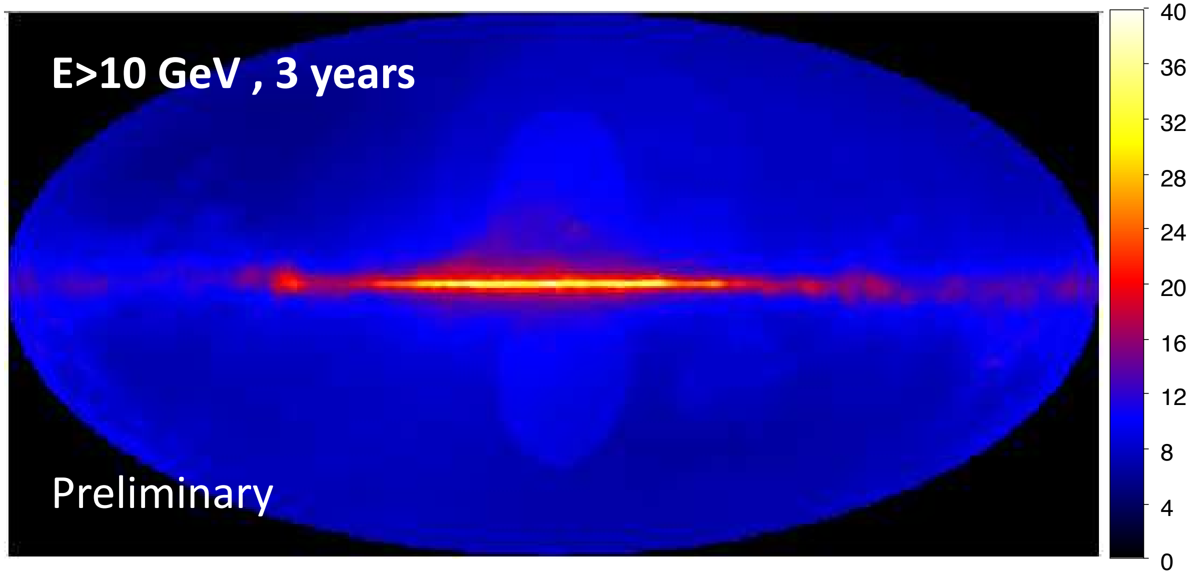
→ fluxes fall (typically) with power-law index of about 2.5

→ **Many detections will have fewer than 10 gamma rays**

Performance of LAT for astronomy above 10 GeV

Calculated point source flux limit using photons above 10 GeV after 3 years of operation

Minimum detectable flux in units of **10^{-11} ph/cm²/s**



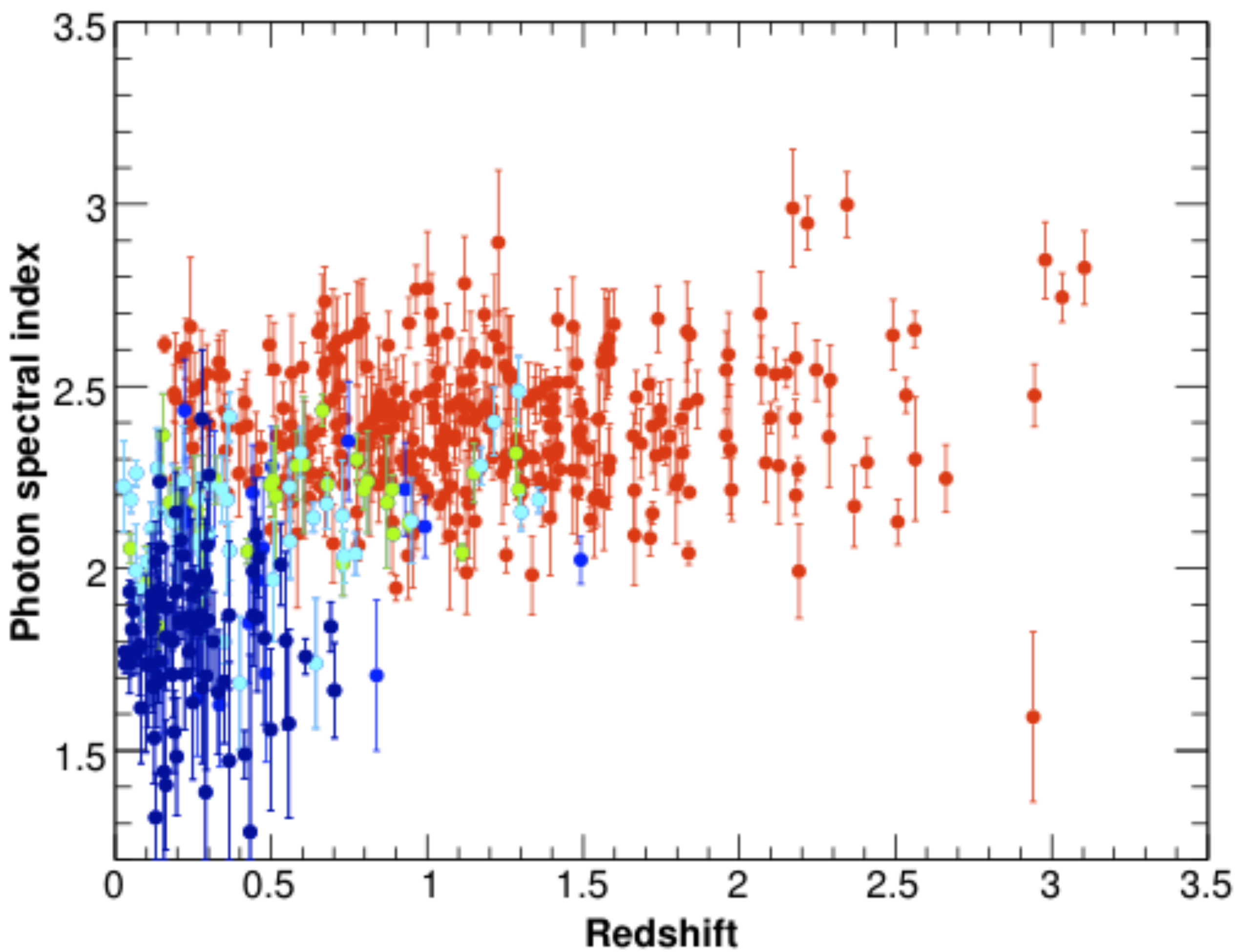
Apart from some structures (Galactic diffuse and Fermi bubbles) **the flux limit at >10 GeV after 3 years is about 10^{-10}ph/cm²/s** and rather uniform (within factor of 2)

This sensitivity is good enough to be able to detect hundreds of sources

At E>100 GeV (3 years) the flux limit is about 3x10^{-11} ph/cm²/s which is *only a factor of about 3 worse than the point source sensitivity in 50 hours from current IACTs*

Fermi-LAT provides a true >100 GeV scan of the sky with a sensitivity that could be comparable to 5 hours of (*good or effective time*) observation with a current IACT in every direction

Photon index vs redshift for the 2LAC sources with redshift



There is no trend of sources getting softer with increasing redshift