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

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Outline

- The Fermi-LAT instrument
- Motivation for the 1FHL catalog (differences from the 2FGL)
- Some (few) selected results
  - Source associations
  - Variability
  - Candidate sources for detection with IACTs

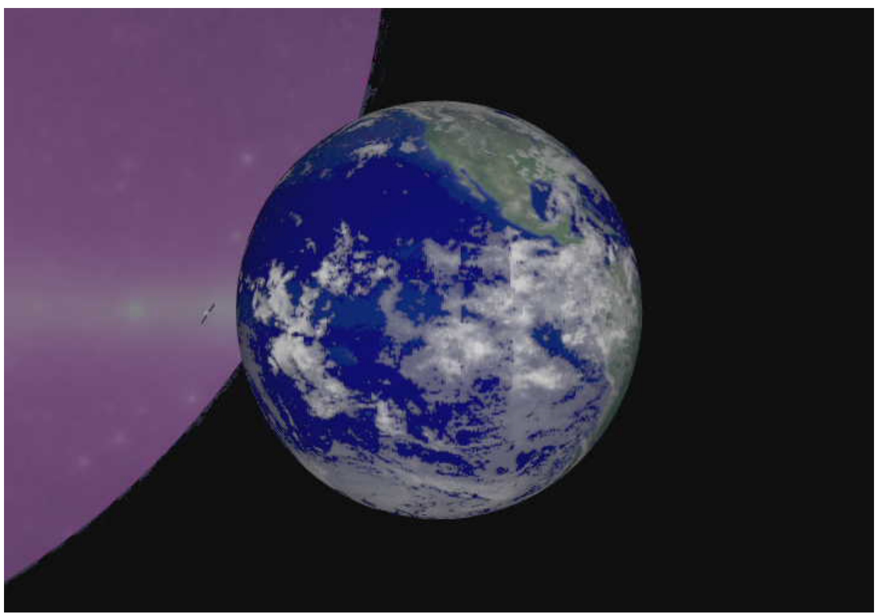
Conclusions and outlook

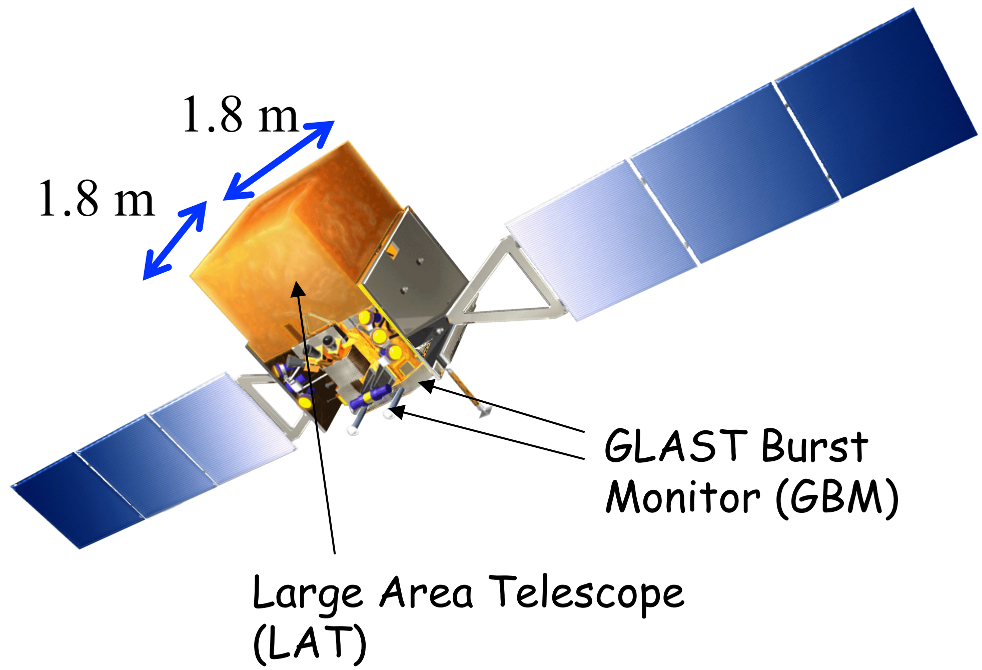
The Fermi-LAT instrument

- **Fermi: An International Science Mission to perform gamma-ray astronomy, with an additional X-ray detector for GRBs**
  - Large Area Telescope (LAT); 20 MeV – >300 GeV
  - GLAST Burst Monitor (GBM); 10 keV – 40 MeV

Launch:
June 11th 2008
Cape Canaveral

- **The strategy** *(goal to operate beyond 2018)*
  - Sensitivity ~ 30 better than EGRET
  - **Survey mode ⇒ entire sky every three hours (2 orbits)**





Rock north for one orbit and south for the next

1 - Fermi mission (brief overview): The LAT instrument

modular design

4x4 array of identical towers: Tracker + Calorimeter + Electronics Module.

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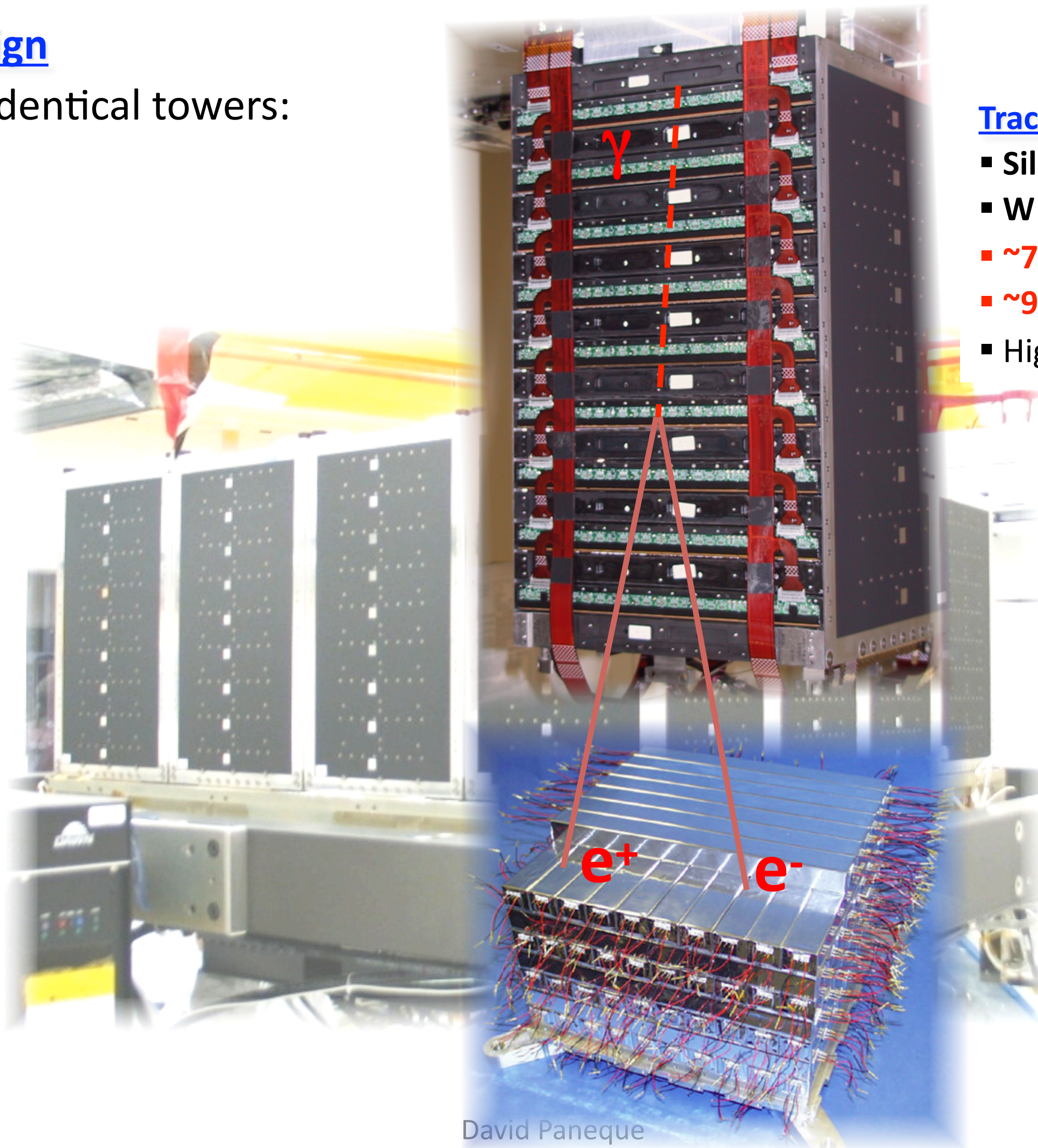
4x4 array of identical towers:



Tracker/Converter (TKR):

- **Silicon strip detectors .**
- **W conversion foils.**
- **~73 m^2 of silicon (total).**
- **~9x10^5 electronic chans**.
- High precision tracking,

Calorimeter (CAL):

- **1536 CsI crystals.**
- 8.5 radiation lengths.
- Hodoscopic.
- Shower profile reconstruction (leakage correction)

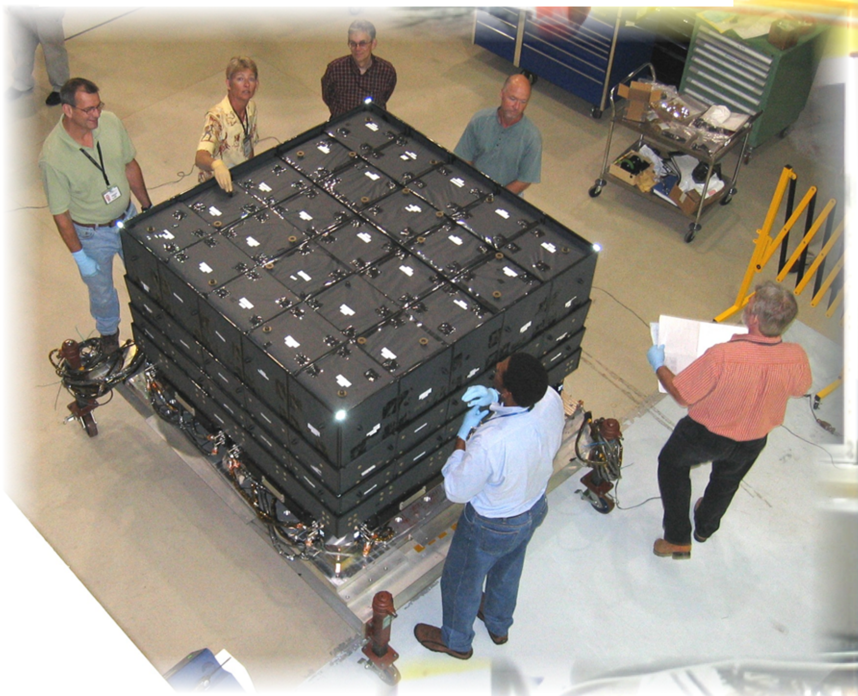
1 - Fermi mission (brief overview): The LAT instrument

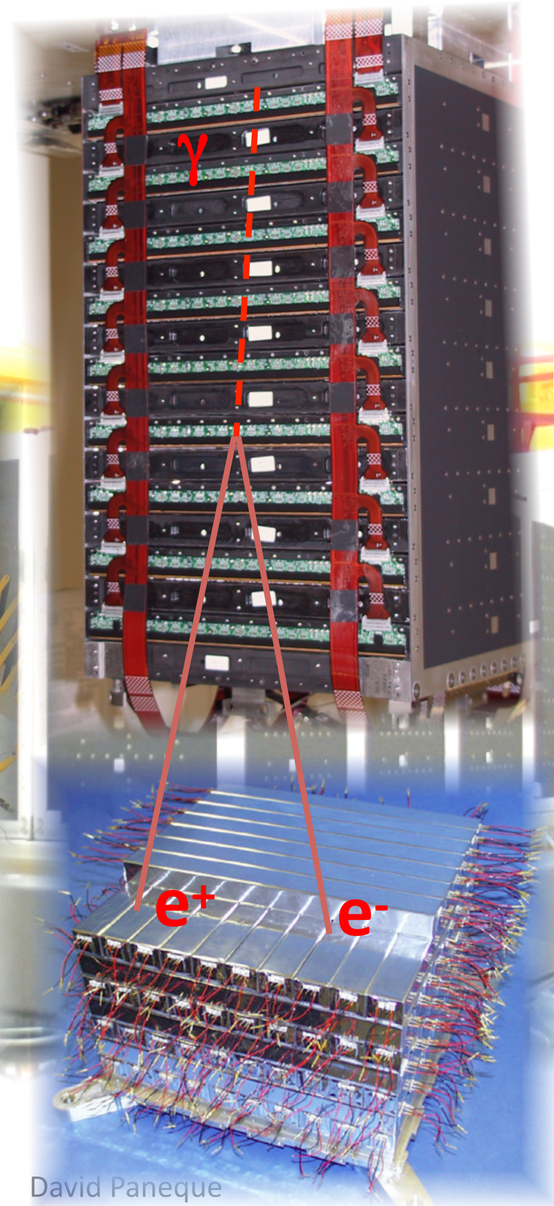
Challenging design: 1.8m x 1.8m x 1.2m ; 2800 kg, 1M channels; but only 650 W

modular design

4x4 array of identical towers:

Anti-Coincidence (ACD):
- Segmented (89 tiles).
- Self-veto @ high energy limited.
- 0.9997 detection efficiency (overall).





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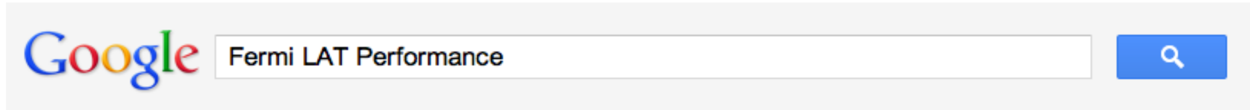
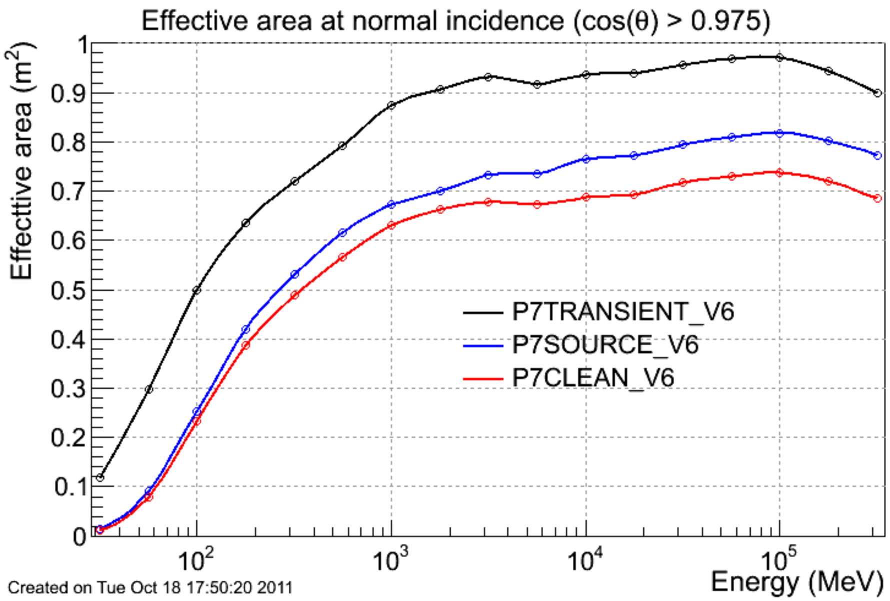
LAT performance: summary





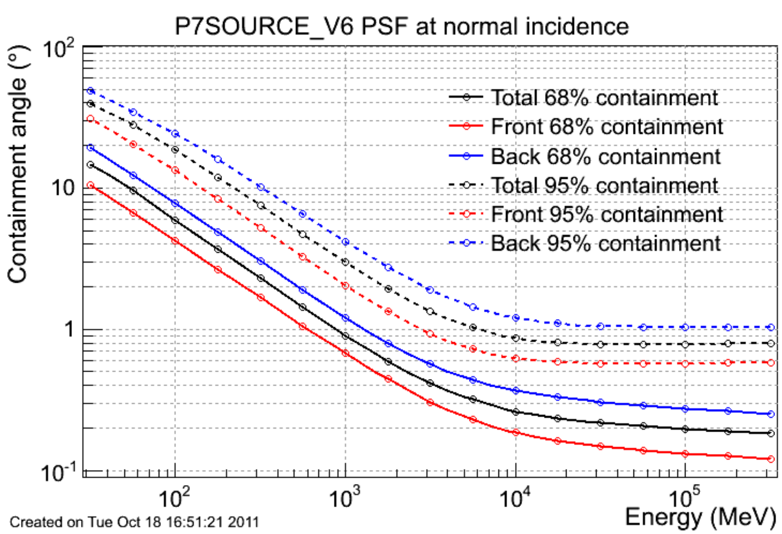
Effective Area: ~ 0.7 m² (on axis)

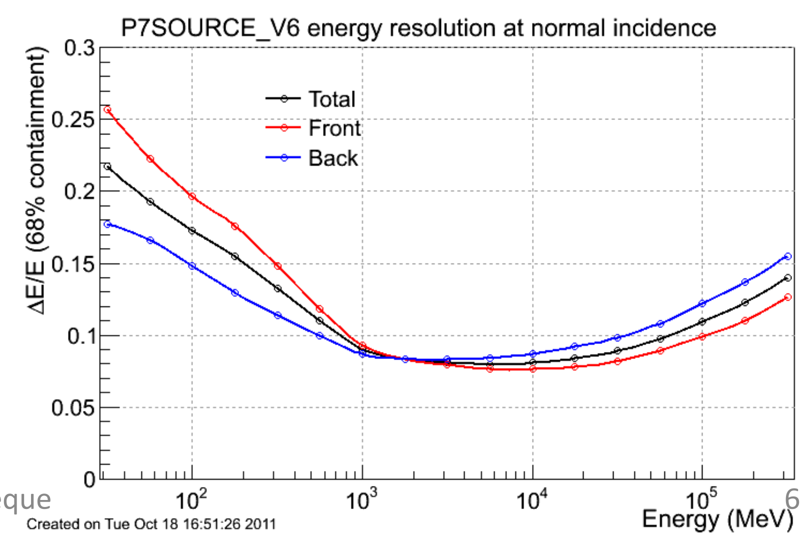
Energy Resolution: ~10%

PSF (68%) at 100 MeV ~ 5°

PSF (68%) at 10 GeV ~ 0.2°

Field Of View: 2.4 sr (20% of the full sky)





Motivation for 1FHL catalog (differences from 2FGL)

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) ?
and what about the contribution to the Galactic diffuse ?

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

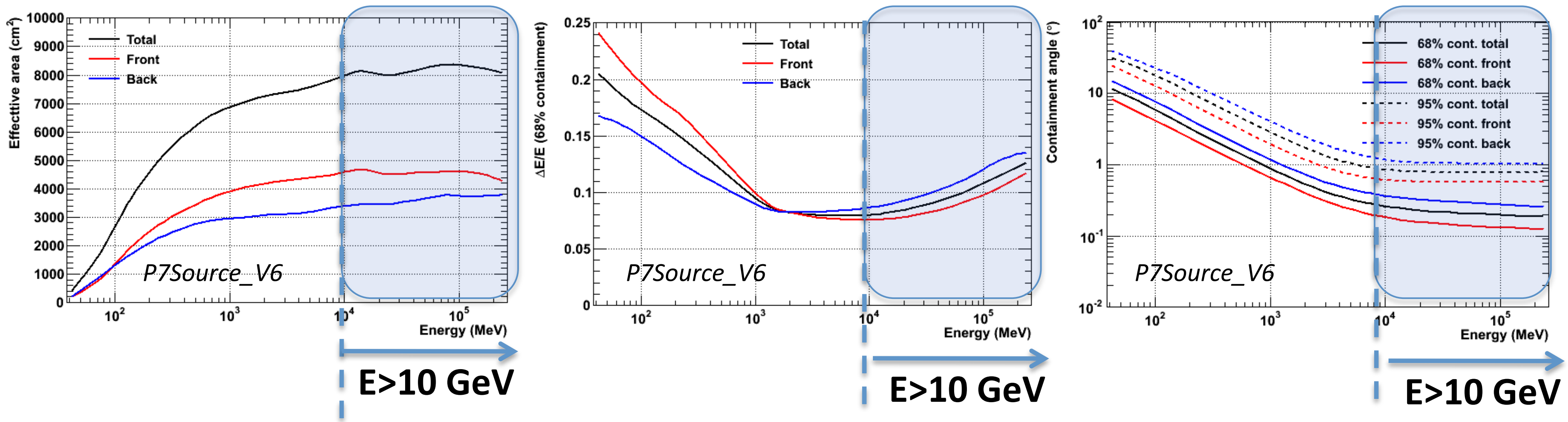
Fermi-LAT in 2 years (2FGL) vs All TeV instruments in 20+ years (TeV Catalog)

~1900 sources (>100 MeV) vs ~150 sources (>100 GeV)

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

Performance of LAT for astronomy above 10 GeV

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



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

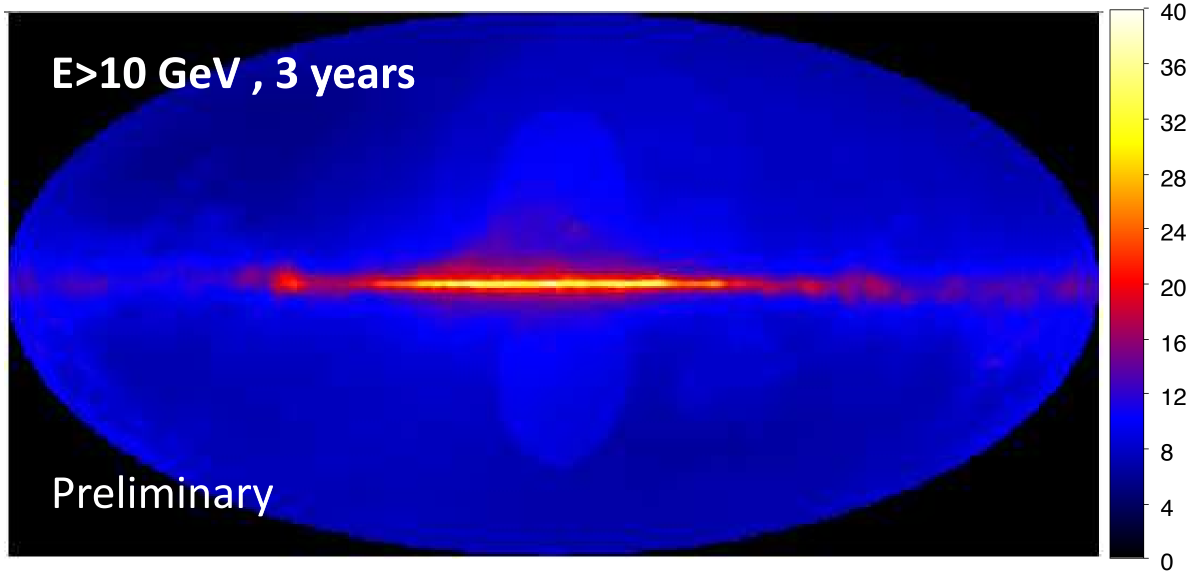
Best possible effective area and PSF occur at the highest energies
Slightly worse energy resolution due to worse shower containment

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/cm^2/s**



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

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

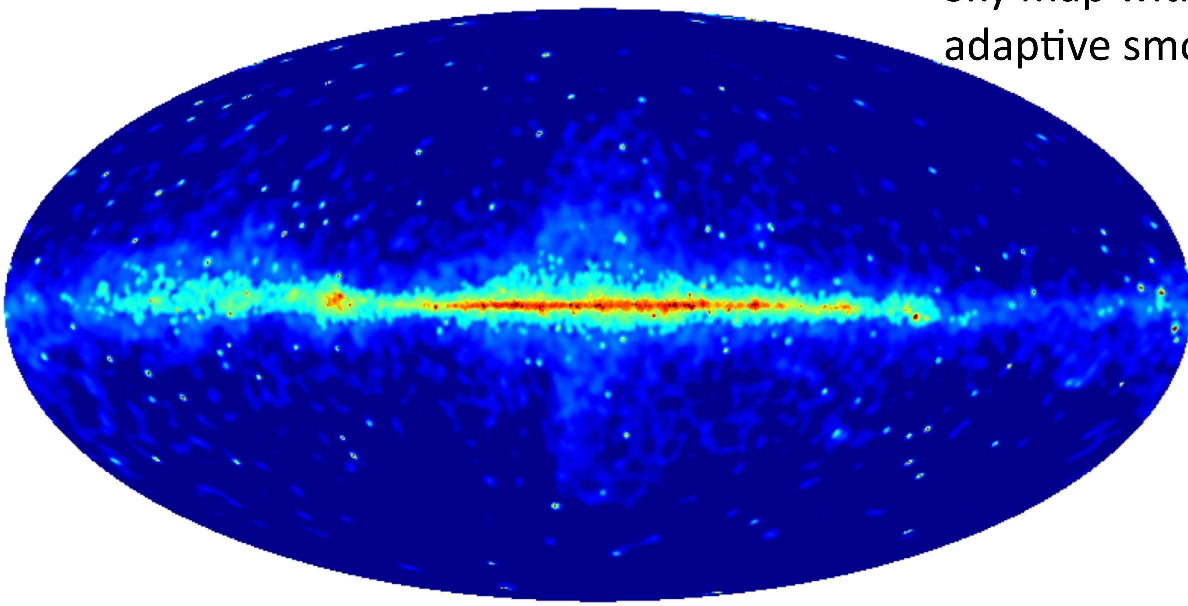
At E>100 GeV (3 years) the flux limit is about 3x10^{-11} ph/cm^2/s which corresponds to the sensitivity of achieved by current IACTs for an observation of 6 hours (effective time)

Fermi-LAT provides a true >100 GeV scan of the sky with a sensitivity that could be comparable to 6 hours of (*good or effective time*) observation with a current IACT in every direction

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)

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)

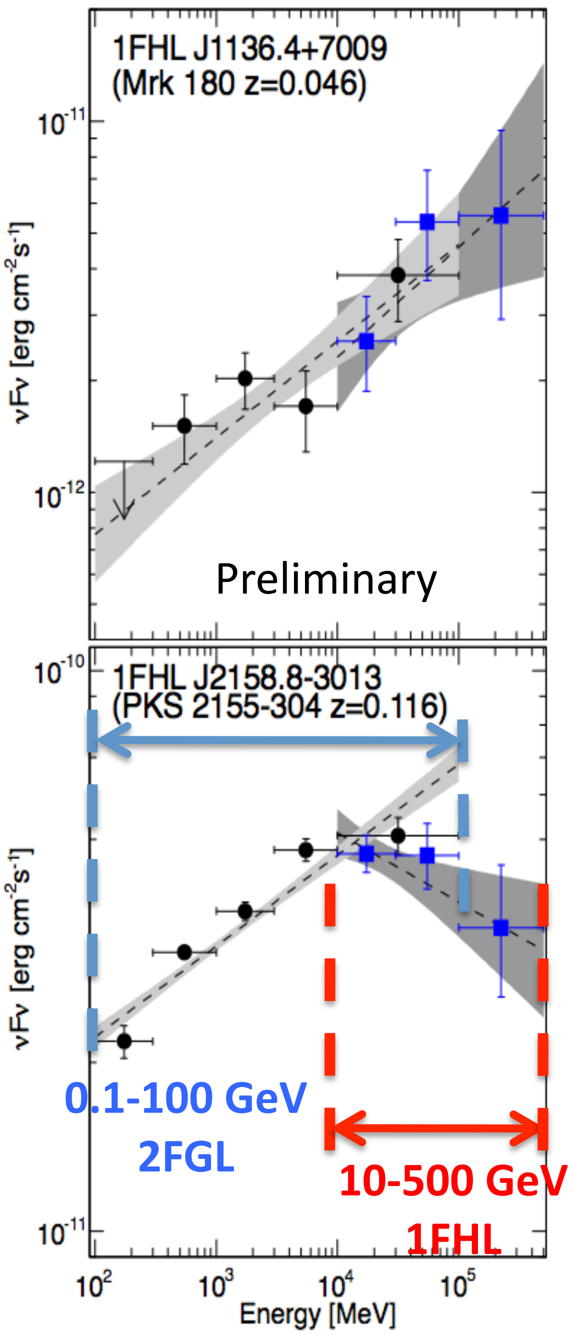
Only sources with a Test Statistic (TS) larger than 25 are reported

514 sources ***(63 not contained in 2FGL)***

***9 of the 63 sources are extended, while in* 2FGL exist as point-like sources**

All sources could be fitted with a simple power law

Detection, localization and gtlike analysis



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, likely due to the absorption in the EBL

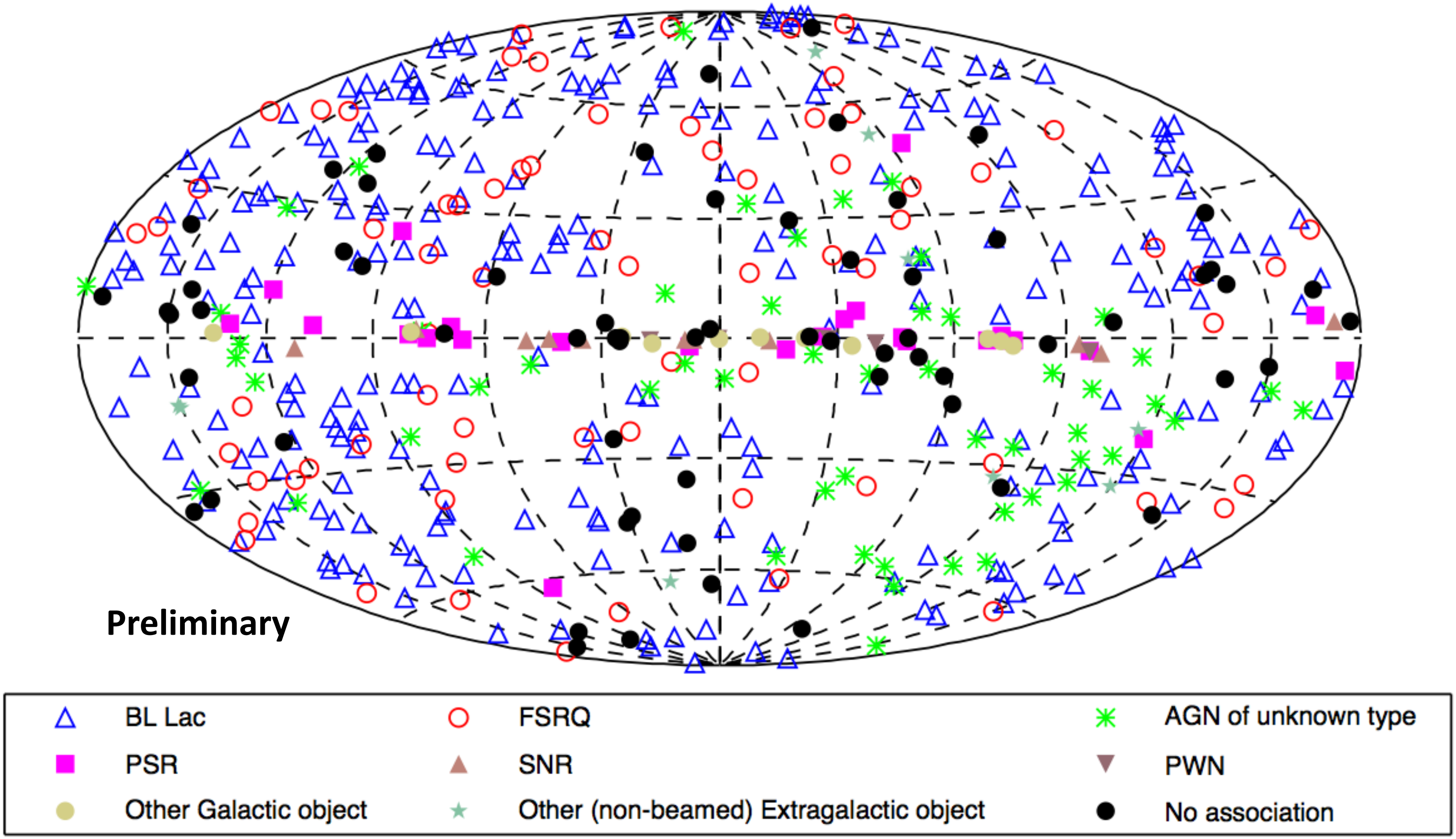
Others show new hard components

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

Skymap with all the 1FHL sources

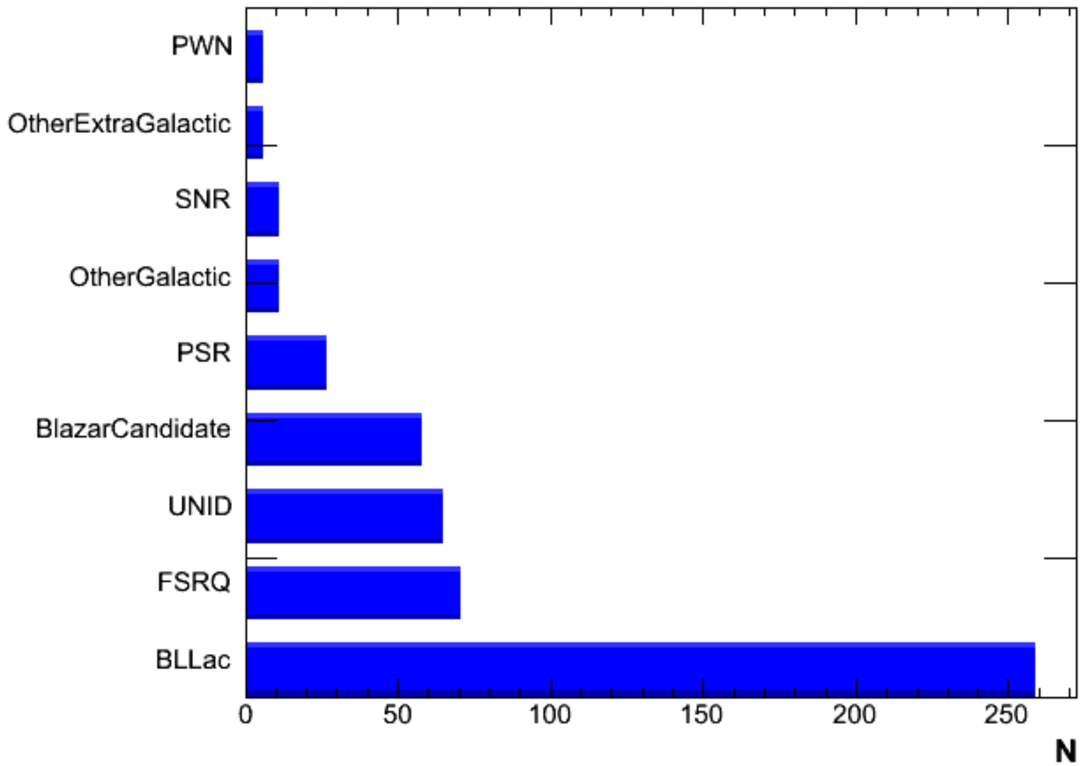
514 sources in the 1FHL catalog

→ The sky is full of high-energy gamma-ray sources



Associated sources (All)

514 sources in the 1FHL catalog



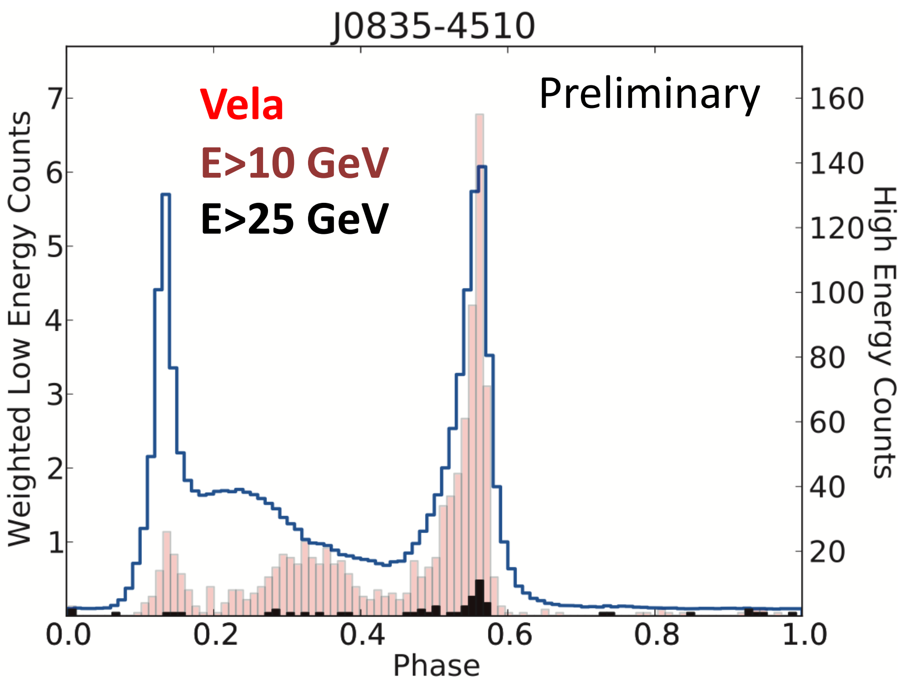
6 (**1%**)
6 (**1%**)
11 (**2%**)
11 (**2%**)
27 (**5%**)
58 (**12%**)
65 (**13%**)
71 (**14%**)
259 (**50%**)

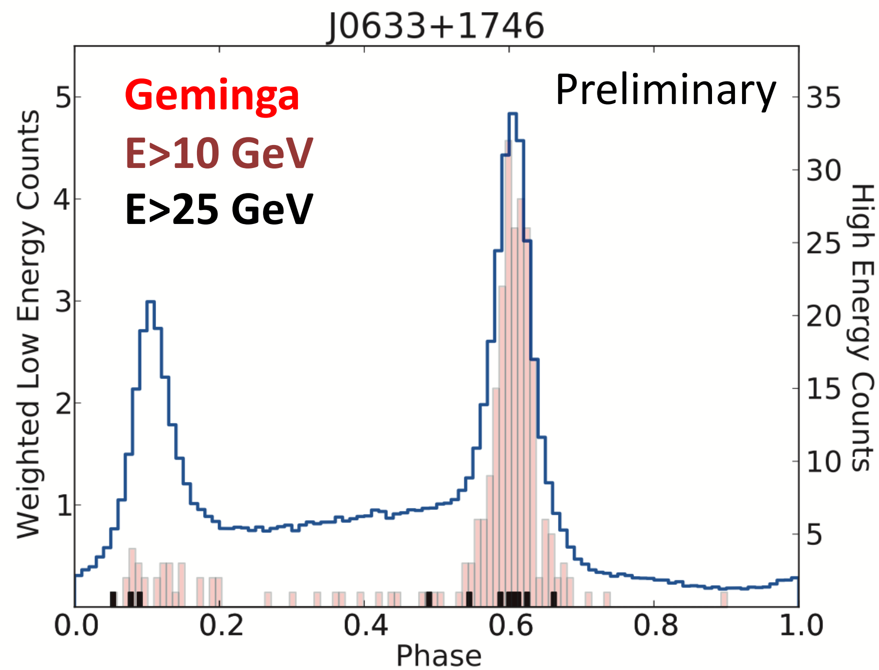
AGN (mostly BL Lacs) dominate the Fermi-LAT sky above 10 GeV (394 objects→ 76%)

12.6% of the sources remain unassociated

Pulsars in the 1FHL catalog

Pulsations >10 GeV (>25GeV) significantly detected for 20 (11) out of 27 sources associated with pulsars

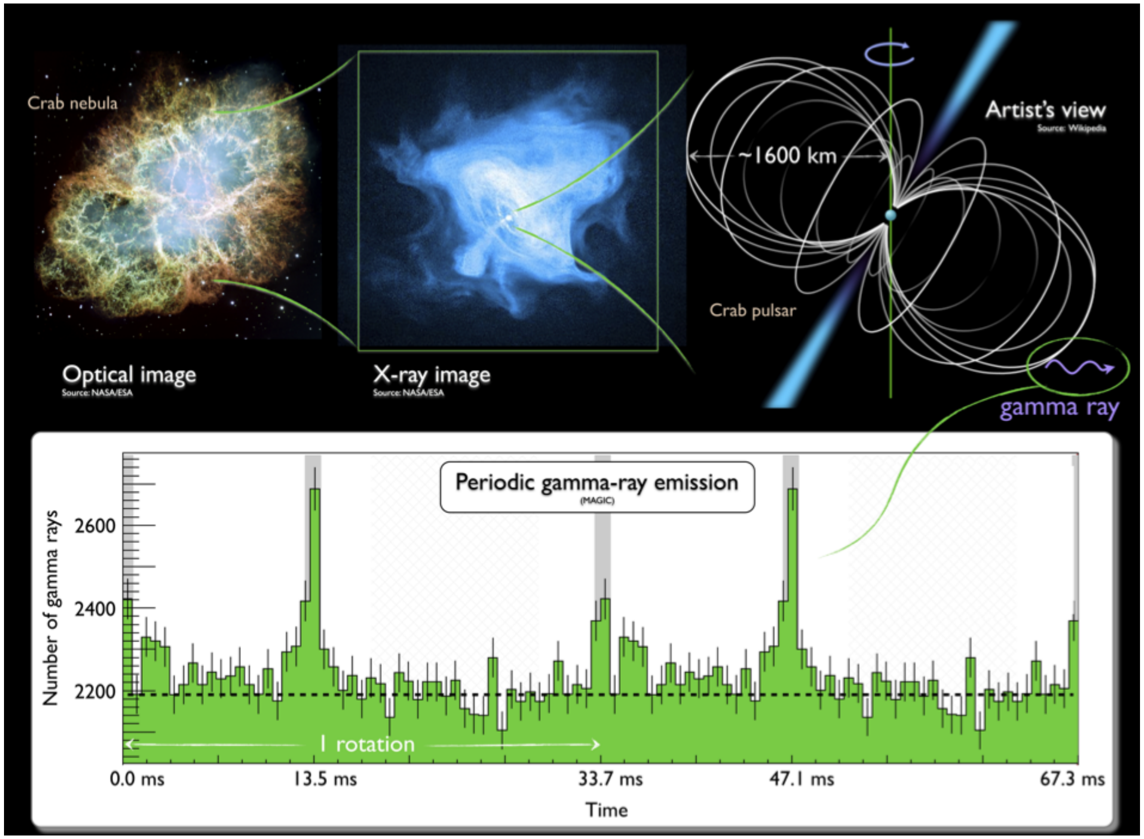




*Normalized weighted light curve (100 bins) in the 0.1-10 GeV range (blue) and un-weighted light curve above 10 GeV (pink) and above 25 GeV (**black**)*
(0.6 and 1.2 deg RoI were used for Front and Back evts respectively)

The light curves show some evolution with energy in the pulse profiles

Pulsars detected at VHE: So far only the Crab

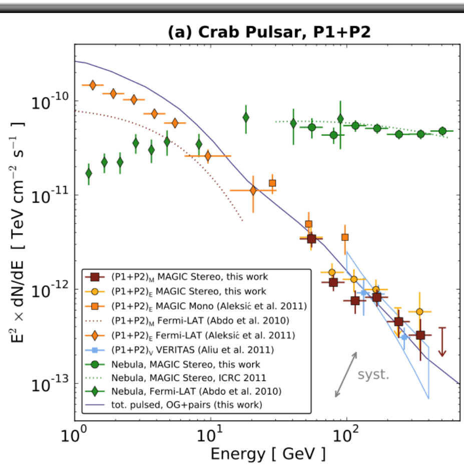


Aliu et al. (MAGIC collab.)
Science 322 (2008) 1221
First time emission > 25GeV

Aliu et al. (VERITAS collab.)
Science 334 (2011) 69-72
First time emission > 100GeV

Aleksic et al (MAGIC collab.),
ApJ, 742 (2011) 43,
First spectrum 25-100GeV

Aleksic et al (MAGIC collab.),
A&A, 540 (2012) A69
First spectrum 50-400GeV



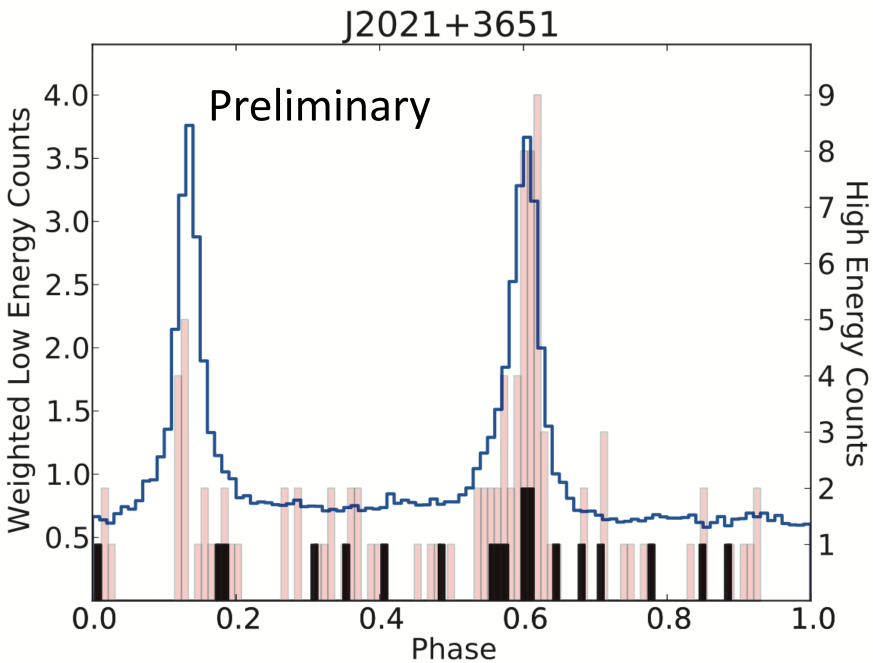
Fermi + MAGIC → Spectrum from 0.1 GeV up to 400 GeV

The VHE pulsed emission from the Crab pulsar was totally unexpected, and posed many challenges for conventional pulse emission theories. **VHE had to be produced close to the light cylinder, or even outside the light cylinder**

Pulsars in the 1FHL catalog

Pulsations >10 GeV (>25GeV) significantly detected for 20 (11) out of 27 sources associated with pulsars

Non-super bright (non-EGRET) pulsars are also detected at the highest Fermi-LAT energies



PSR J2021+3651
E>10 GeV
E>25 GeV

Cherenkov Telescopes expected to detect few more pulsars over the next years

*Normalized weighted light curve (100 bins) in the 0.1-10 GeV range (blue) and un-weighted light curve above 10 GeV (pink) and above 25 GeV (**black**) (0.6 and 1.2 deg RoI were used for Front and Back evts respectively)*

The light curves show some evolution with energy in the pulse profiles

AGNs in the 1FHL catalog

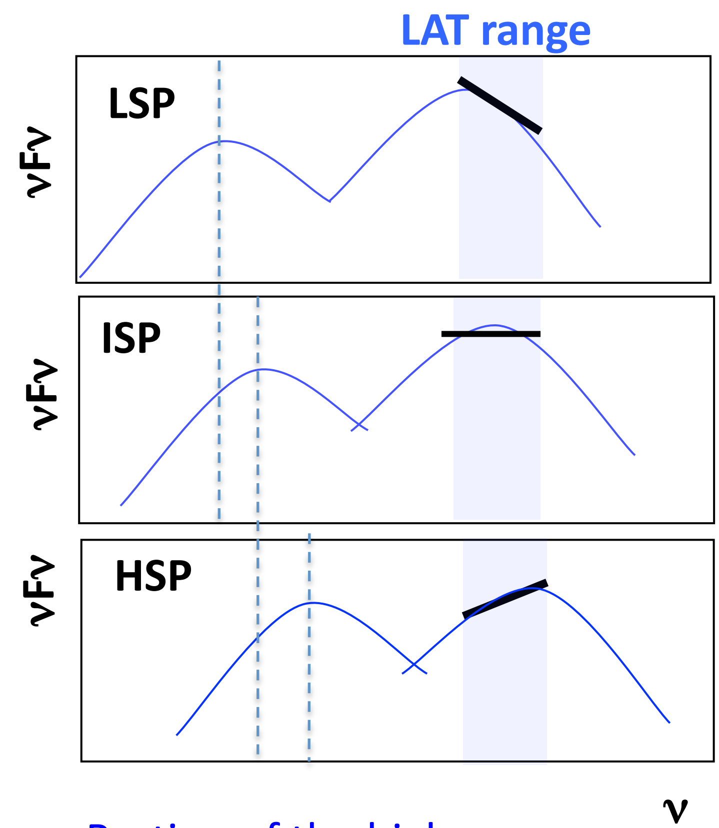
AGN SED classification

→ *according to location of Sync peak*

LSP = Low Synchrotron Peaked (<10^{14} Hz)

ISP = Intermediate Synchrotron peaked

HSP = High Synchroton peaked (>10^{15} Hz)



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

AGNs in the 1FHL catalog

AGN SED classification

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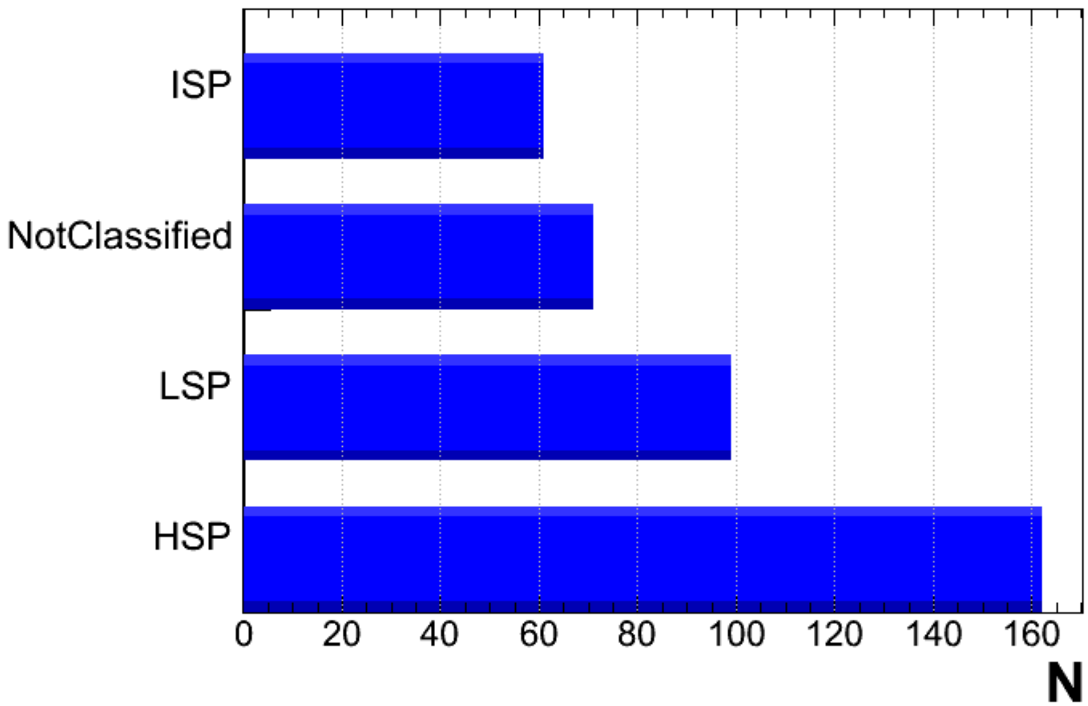
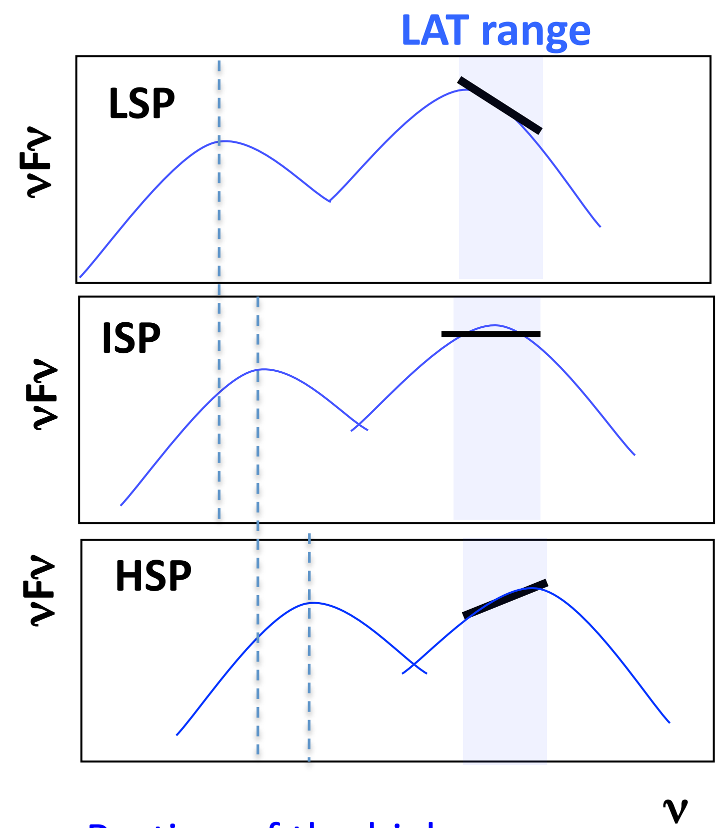


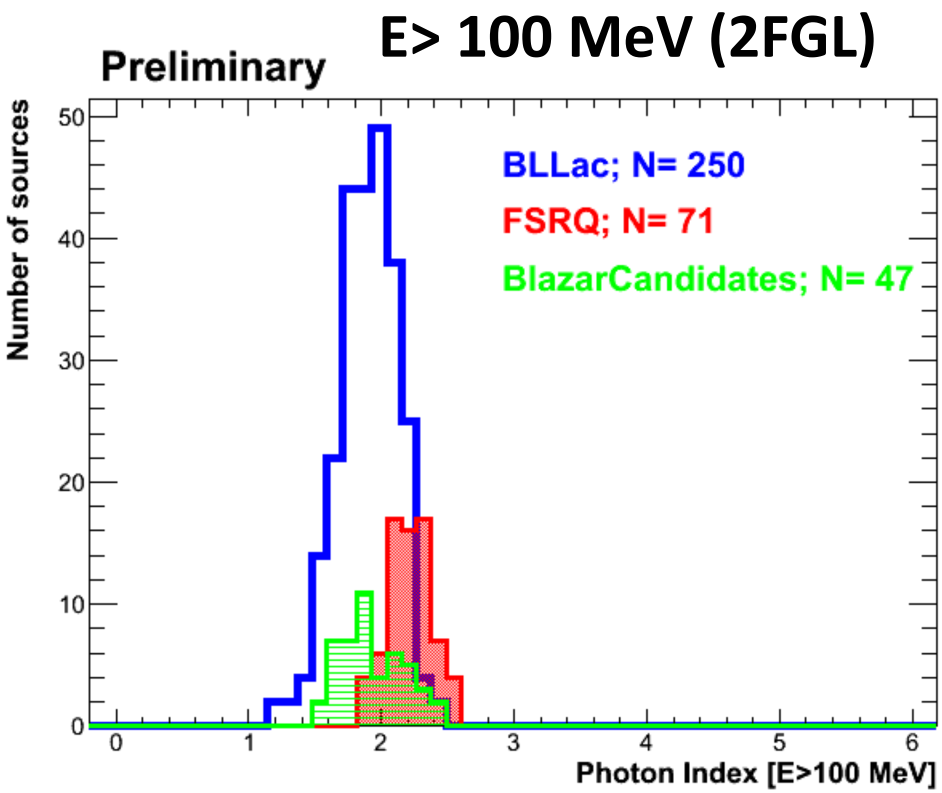


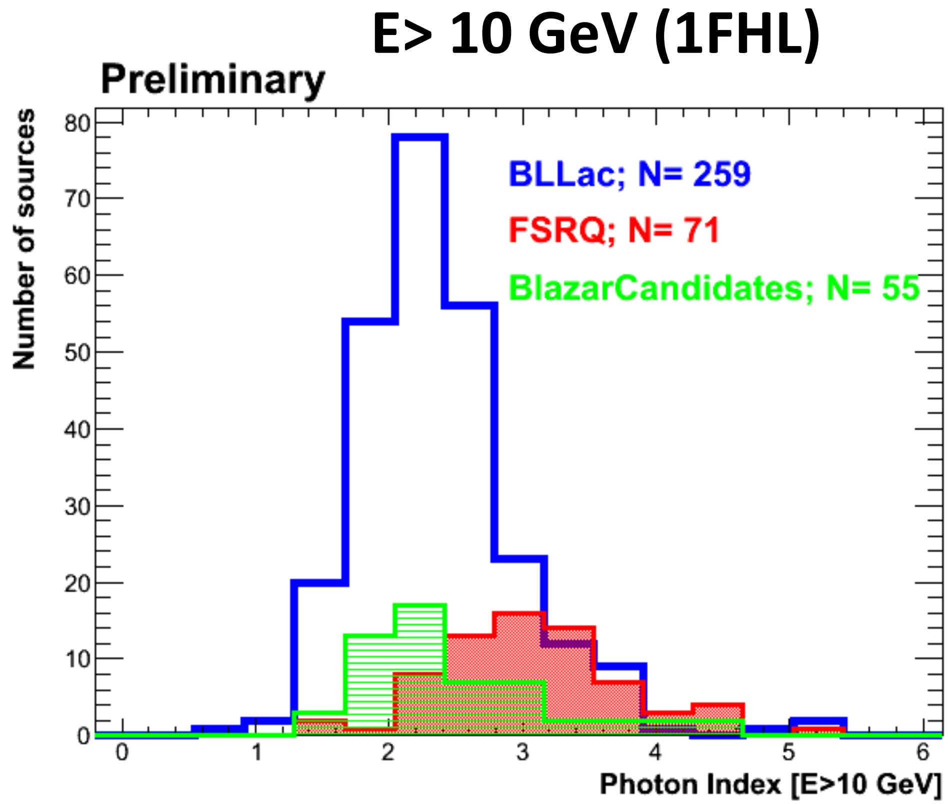
From the 394 AGN sources in the 1FHL catalog,
373 already existed in the 2nd LAT AGN Catalog (2LAC)

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

AGNs in the 1FHL catalog





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

→ Intrinsic softening of the AGN spectra

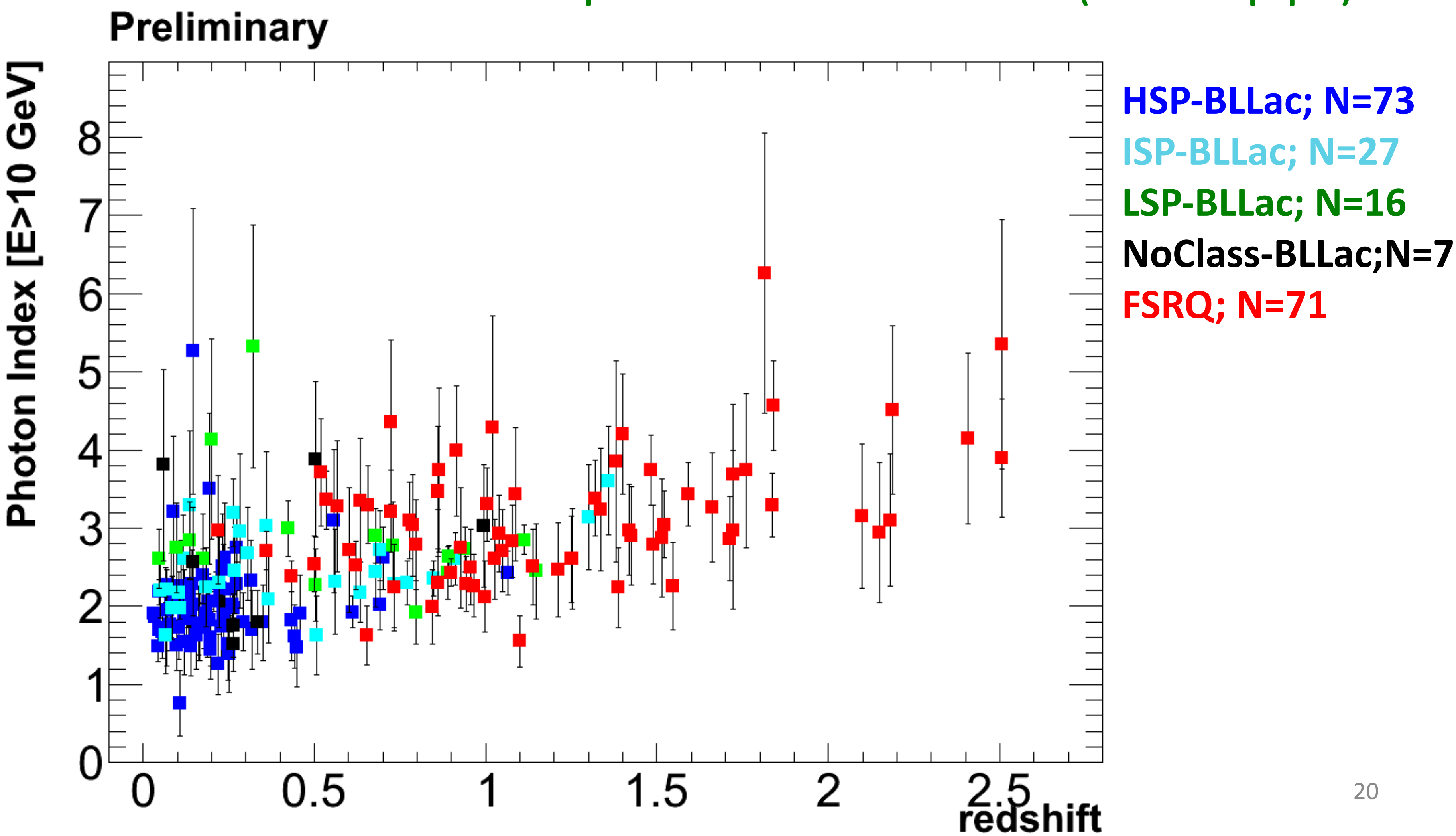
→ Impact of absorption of gamma-rays in the (UV) EBL

- 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

208 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 (unbinned) 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"

With a 1% false positive threshold, we find that 43 sources are variable (out of the 514 FHL objects). All variable objects are AGNs

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

Quantification of variability

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

→ Only few sources (8%) flagged as variable
(if false positive threshold is set to 1%)

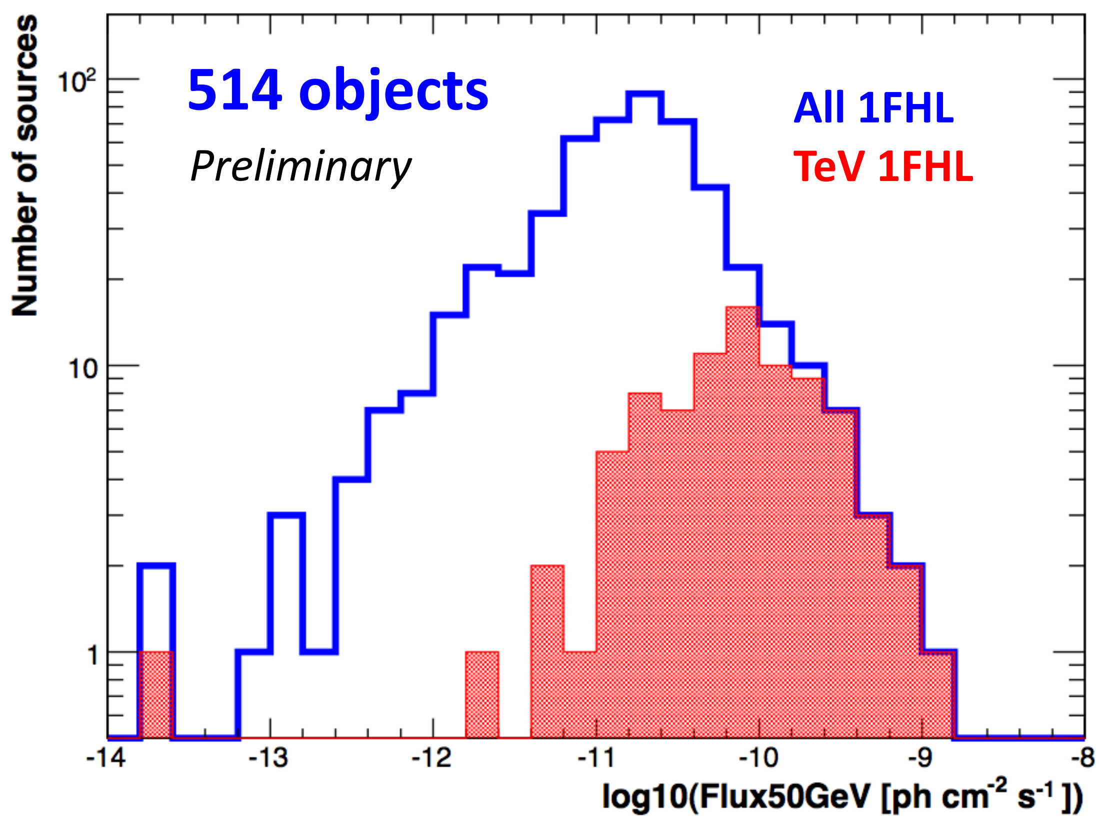
→ **Brightest sources are NOT necessarily the ones with the highest variability**

Highly-significant variability typically detected for sources which are "not-too-faint" (>30 events) 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 …

The classical TeV (HSP) sources like Mrk421, Mrk501 or PKS2155 are not found to be variable (*with a false positive threshold of 1%*), despite being very bright in the LAT energy range above 10 GeV

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

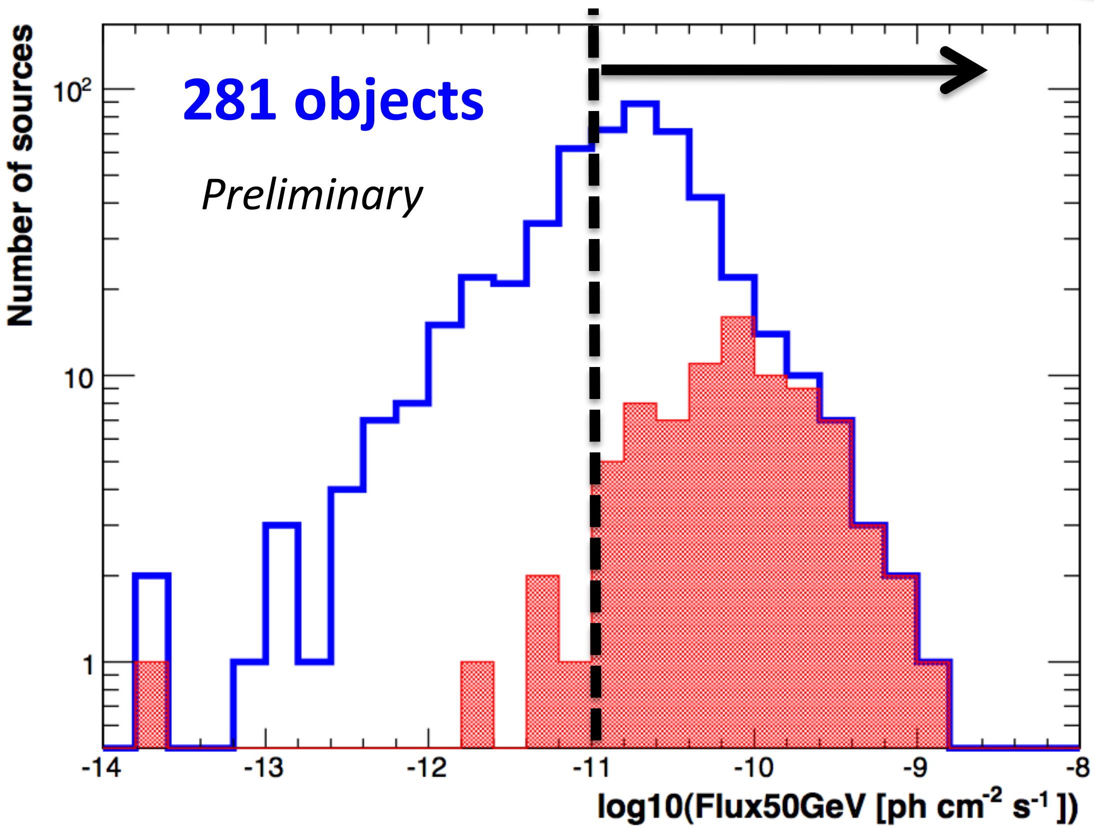
84 objects from the 1FHL list have been already detected with IACTs at VHE (→ TeV Src)
http://tevcat.uchicago.edu/

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

Sources detected at VHE with IACTs have high extrapolated 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 selection of *good TeV candidates*



Log10(F50GeV] > -11
(Flux >~ 1% Crab Nebula)
Power-law index < 3
Significance (>30GeV) > 3σ

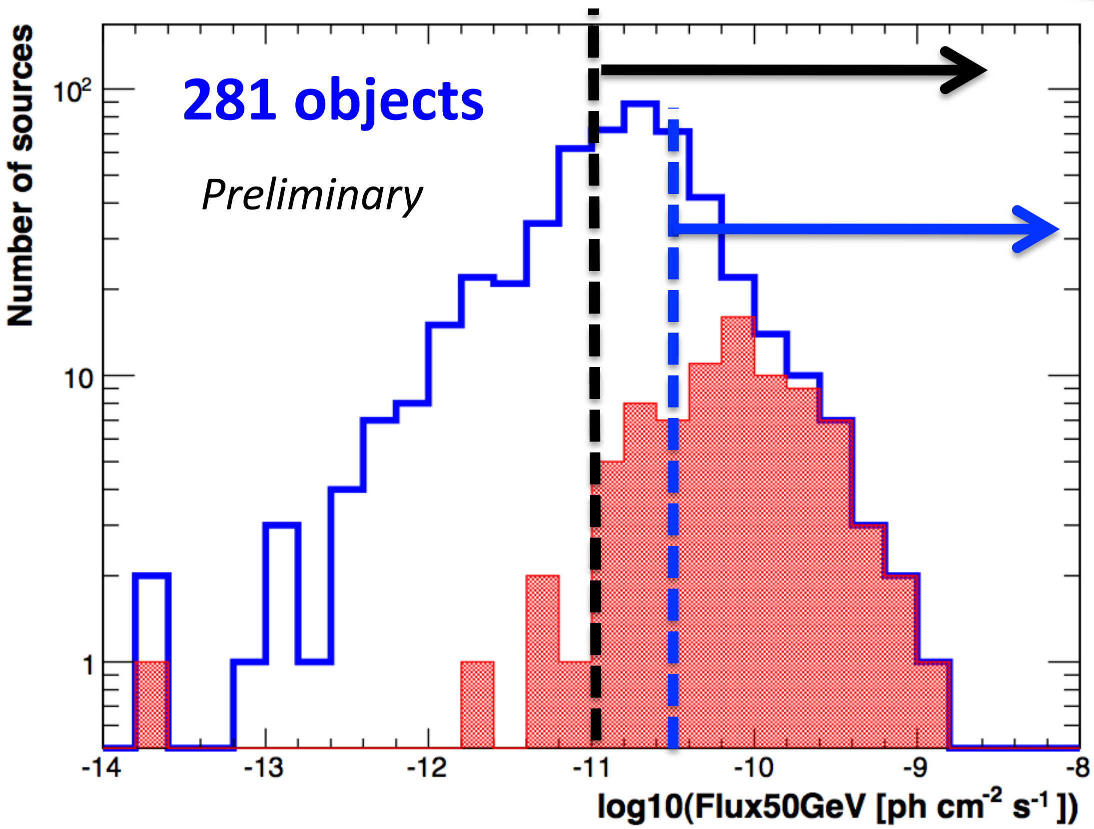
From the 84 TeV src in 1FHL, 69 objects survive the *TeV candidate selection cuts*

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

Sources detected at VHE with IACTs have high extrapolated 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 selection of *good TeV candidates*



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

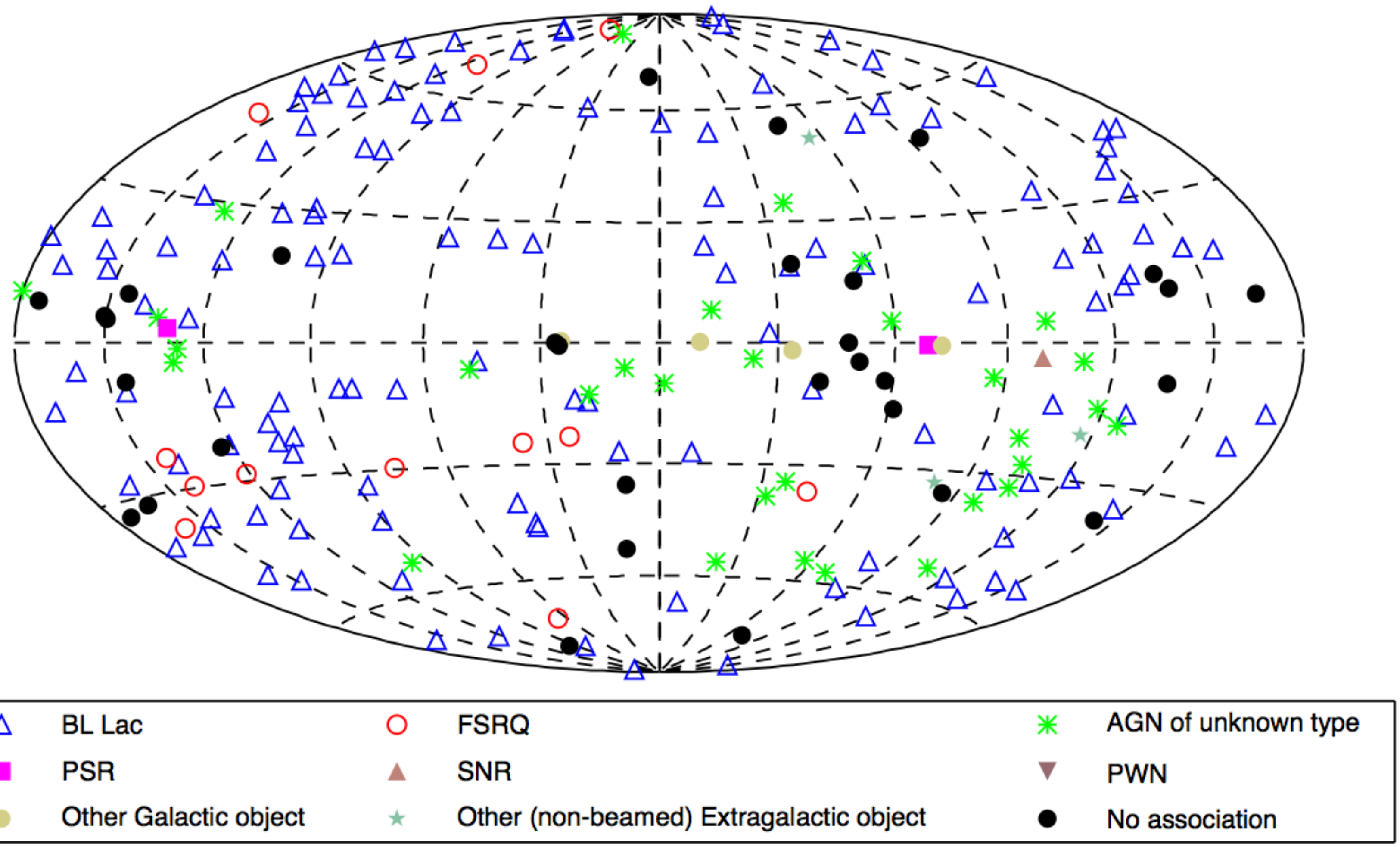
→ **log10[F50GeV] > -10.5**

Sources detected at VHE with IACTs have high extrapolated fluxes above 50 GeV

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

Sky map showing the 1FHL sources that we identify as good candidates for VHE detection.

→ The sky is full of (very probable) VHE sources



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

Among best 72 VHE candidates, we have 18 blazars with high redshift (z>0.2)

1FHL Name	RA	DEC	Association	z	$F50Crab$
J0538.8-4405	84.714	-44.088	PKS 0537-441	0.89	13.4
J0957.6+5522	149.421	55.377	4C +55.17	0.90	7.8
J0428.7-3756	67.178	-37.937	PKS 0426-380	1.11	6.6
J1936.8-4721	294.214	-47.356	PMN J1936-4719	0.26	5.7
J0250.6+1712	42.657	17.206	NVSS J025037+171209	1.10	5.2
J1248.1+5821	192.041	58.361	PG 1246+586	0.85	4.9
J1224.5+2437	186.146	24.628	MS 1221.8+2452	0.22	4.7
J0847.0+1132	131.773	11.544	RX J0847.1+1133	0.20	4.6
J0913.1-2104	138.289	-21.078	MRC 0910-208	0.20	4.5
J1501.0+2238	225.275	22.639	MS 1458.8+2249	0.23	4.4
J2001.1-1752	300.278	-17.868	PKS 1958-179	0.65	4.3
J1243.2+3628	190.807	36.468	Ton 116	1.06	3.9
J1309.3+4304	197.345	43.069	B3 1307+433	0.69	3.7
J0909.3+2312	137.339	23.205	RX J0908.9+2311	0.22	3.6
J1748.5+7006	267.127	70.101	S4 1749+70	0.77	3.5
J0325.7-1647	51.437	-16.792	RBS 0421	0.29	3.5
J1058.5+0133	164.628	1.564	4C +01.28	0.89	3.5
J2345.0-1556	356.261	-15.937	PMN J2345-1555	0.62	3.4

F50Crab is the extrapolated flux above 50 GeV normalized to the flux of the Crab nebula (in percentage)

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

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

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J1501.0+2238	225.275	22.639	MS 1458.8+2249	0.23	4.4
J2001.1-1752	300.278	-17.868	PKS 1958-179	0.65	4.3
J1243.2+3628	190.807	36.468	Ton 116	1.06	3.9
J1309.3+4304	197.345	43.069	B3 1307+433	0.69	3.7
J0909.3+2312	137.339	23.205	RX J0908.9+2311	0.22	3.6
J1748.5+7006	267.127	70.101	S4 1749+70	0.77	3.5
J0325.7-1647	51.437	-16.792	RBS 0421	0.29	3.5
J1058.5+0133	164.628	1.564	4C +01.28	0.89	3.5
J2345.0-1556	356.261	-15.937	PMN J2345-1555	0.62	3.4

Already detected at VHE (with MAGIC) Atel #5038 (May 2nd, 2013)

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

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

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.

Detected 514 sources (TS>25), measured their spectra, quantified their variability, and studied their associations with cataloged sources at other wavelengths. *The **1FHL catalog**, explores how the gamma-ray Universe evolves between the 2FGL catalog (>100 MeV) and the VHE sources detected with ground-based gamma-ray instruments (>100 GeV)*

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76% are AGNs, ~5% are pulsars, and ~5% are SNR/PWN .
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→ The most variable source-type above 10 GeV is LSP blazars (not HSP !!)
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Several good candidates for detection with current IACTs were identified. They have variety of natures: SNRs, Binary system, UNIDs and Blazars (with redshift of up to 1)
→ Helpful for current generation of IACTs to keep detecting new VHE sources
→ Sneak preview of the CTA VHE sky

backup

LAT performance: improvement at GeV energies

LAT is the next great step beyond EGRET in the GeV band, providing a huge leap in capabilities:

- *Large FOV (~20% of sky), factor 4 greater than EGRET*
- *Complete Sky coverage (~3 hours)*
- *Angular resol. for gamma rays (PSF)> 3x better than EGRET*
- *Large effective area > 5x larger than EGRET*
- *4 decades in energy, including Unexplored E > 10 GeV*

Results in factor > 30 improvement in sensitivity
> 100 above 10 GeV

- ***Smaller dead time (27 microsec; 4000x better than EGRET)***

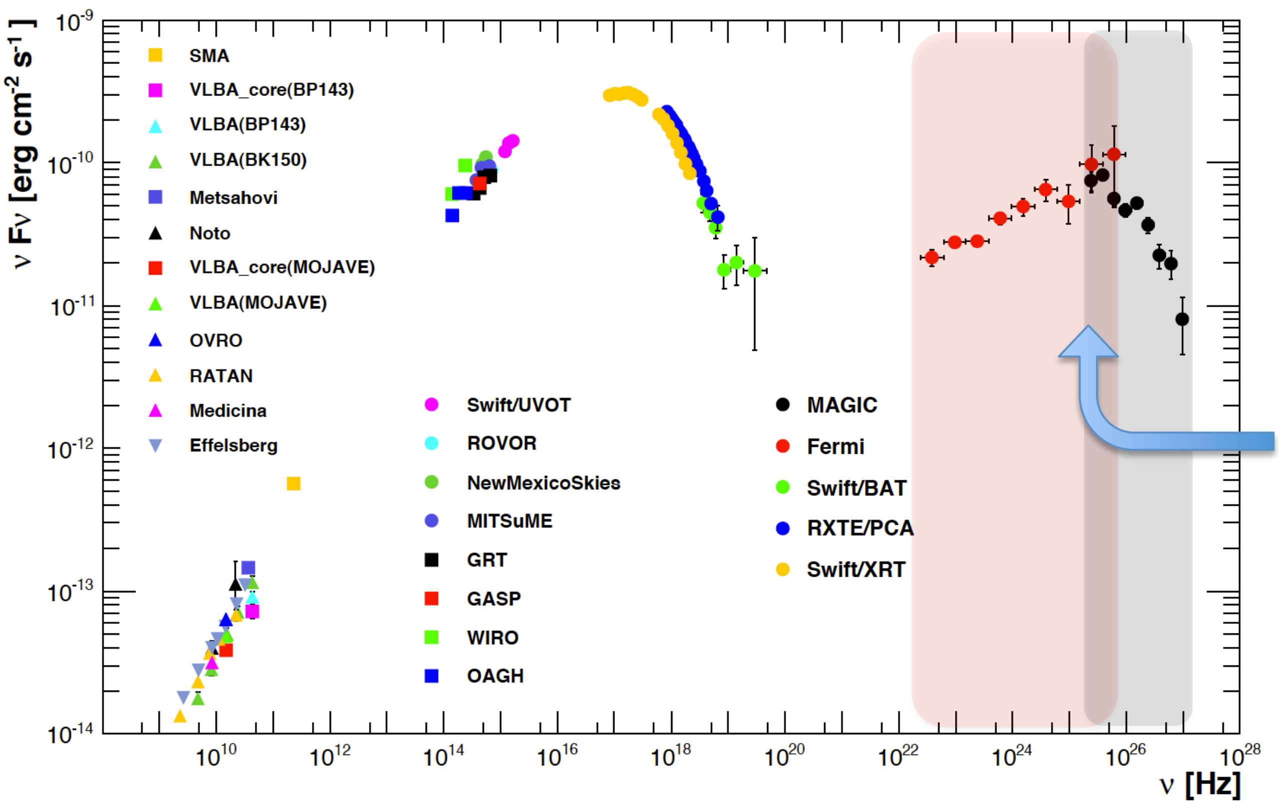
Excellent for fast&bright transient events

Synergy between Fermi-LAT and Cherenkov Telescopes

Most of the extreme particle accelerators emit radiation over a large energy range

Emission on differerent energy bands could be produced by same population of particles

→ *Need many instruments (covering many bands) to fully study these objects*



Spectral energy distribution (SED) of the Blazar Markarian 421

Fermi – **MAGIC** spectra cover, the complete high energy component over 5 orders of magnitude without gaps

→ *Crucial for the theoretical modeling of the broadband emission*

Abdo et al 2011, ApJ 736, 131

Fermi – MAGIC

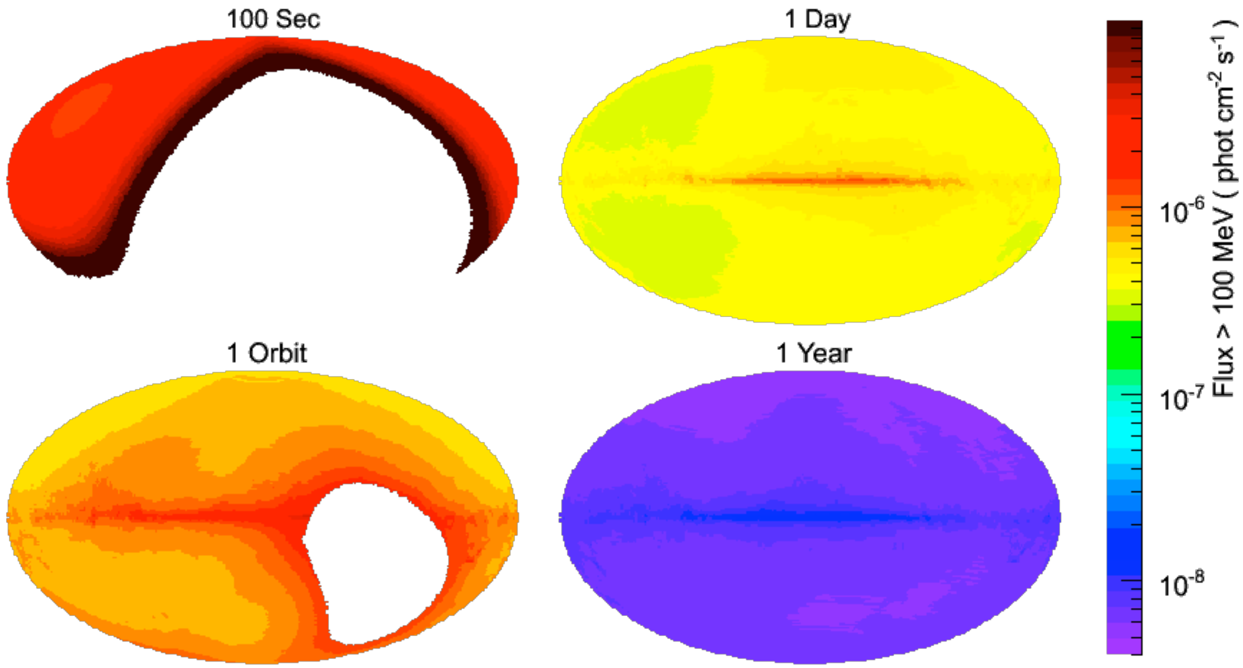
Great synergy between Fermi-LAT and Cherenkov Telescopes

→ Overlapping energy range for brightest sources (~50-300 GeV)

LAT performance: sensitivity

LAT sensitivity on 4 different timescales:

100 s, 1 orbit (96 mins), 1 day and 1 year



- **In survey mode, the LAT observes the entire sky every two orbits (~3 hours), each point on the sky receives ~30 mins exposure during this time.**
- **After 1 day, exposure is rather uniform (factor 2)**

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

→ **Only few sources flagged as variable (if false positive threshold is set to 1%)**

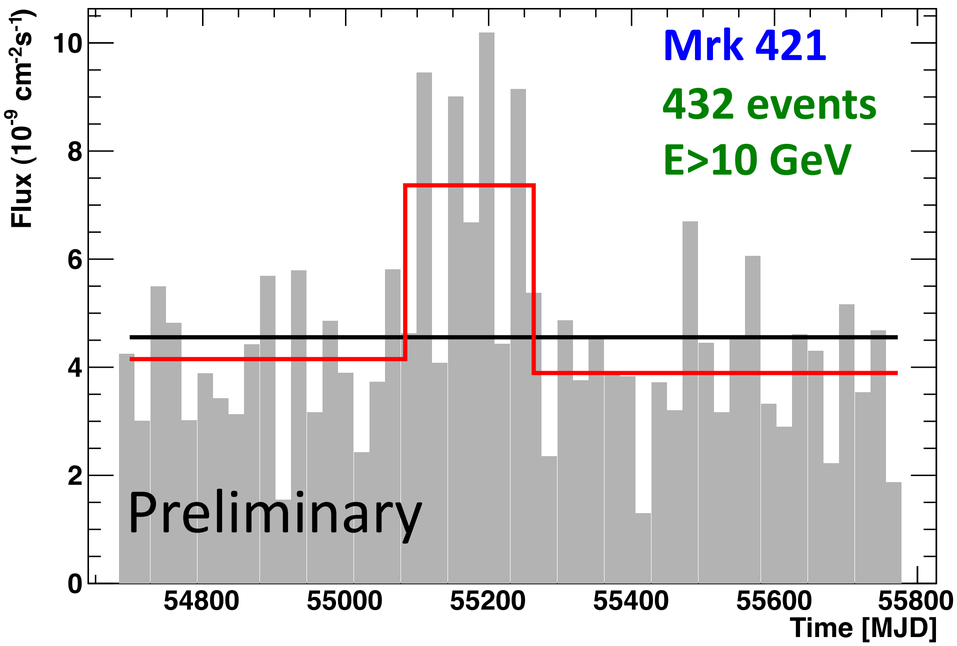
→ **Brightest sources are NOT necessarily the ones with the highest variability**

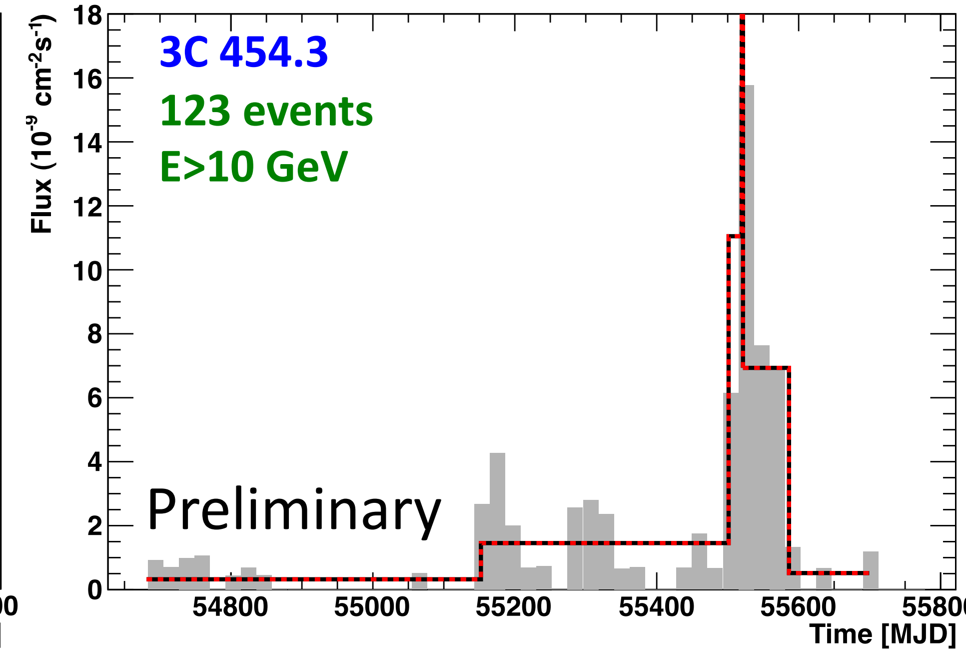
Bayesian Blocks (with light curves overlaid)

→ *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 …)**

Differential sensitivity plots with the performance of CTA
K. Bernloehr et al. Astroparticle Physics 43 (2013) 171–188

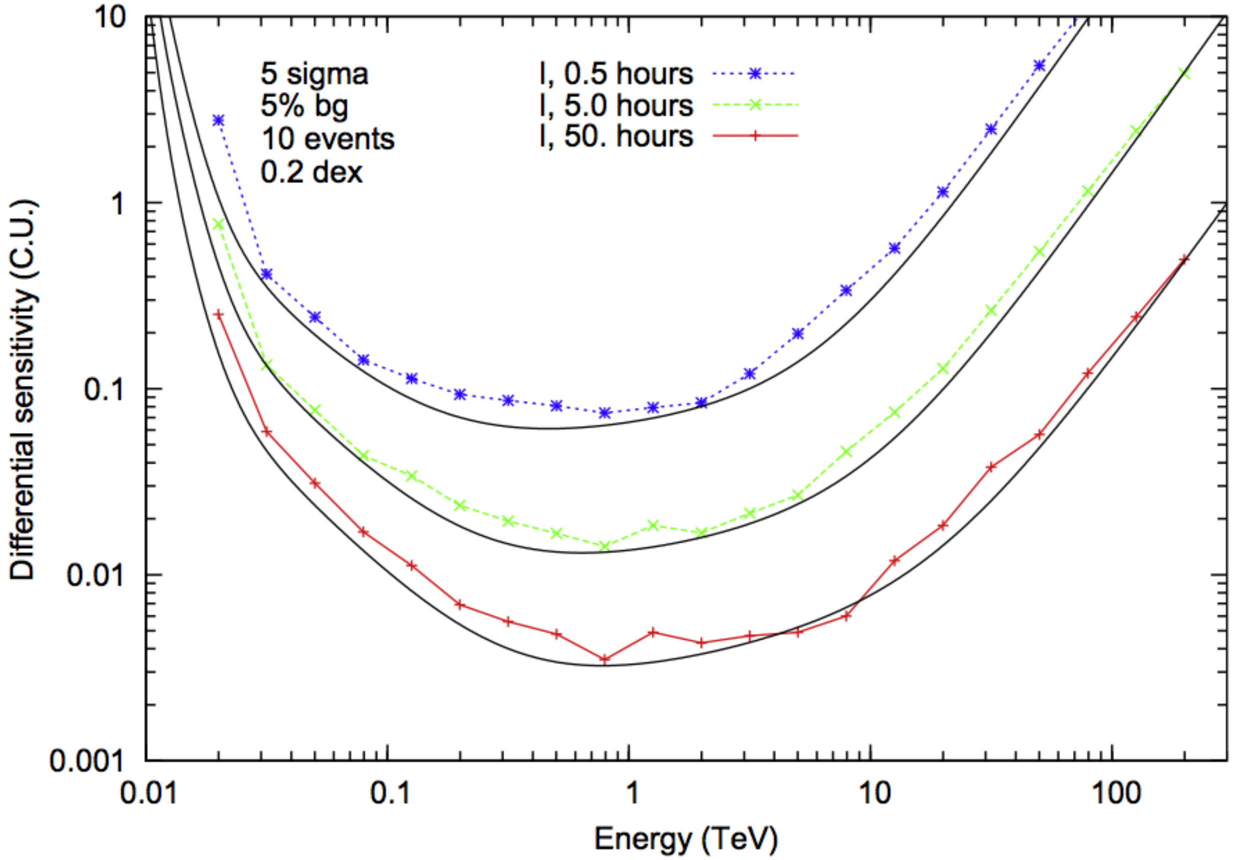


Fig. 8. Point source sensitivity of array I (in units of 1 C.U. $= 2.79 \times 10^{-7}(E/\mathrm{TeV})^{-2.57}$ m^{-2} s^{-1} TeV^{-1}) for observation times of 0.5 h, 5 h, and 50 h, respectively. Also shown as black solid lines are approximations to the best performance of any of the 11 CTA South arrays at any energy (as in Fig. 6), for the given observation times. Array I, being close to this optimum at all energies, is indeed a well-balanced array.

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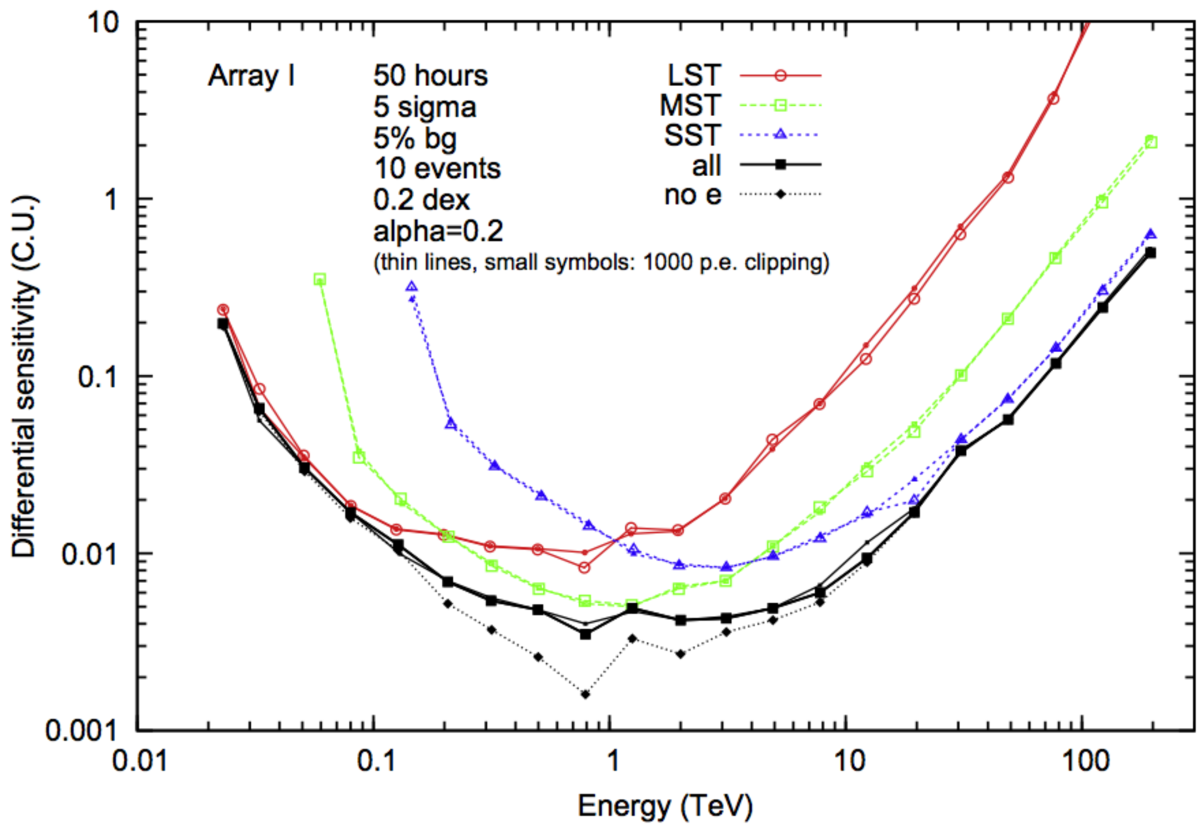
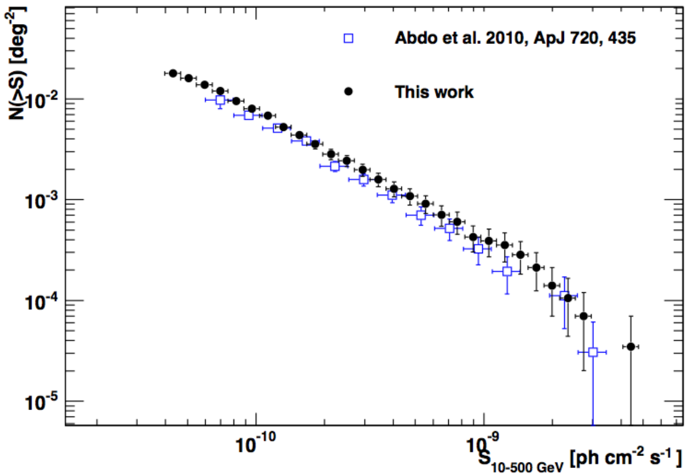


Fig. 9. Point source sensitivity of array I (solid black line, filled squares) and its components, 3 LSTs (red, open circles), 18 MSTs (green, open squares), 56 SSTs (blue, open triangles). Thin lines with small symbols illustrate the limited impact of a reduced dynamic range of PMT readout electronics. For the relevance of the electron background on the combined sensitivity see also the dashed black line with diamonds, where this background is ignored. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

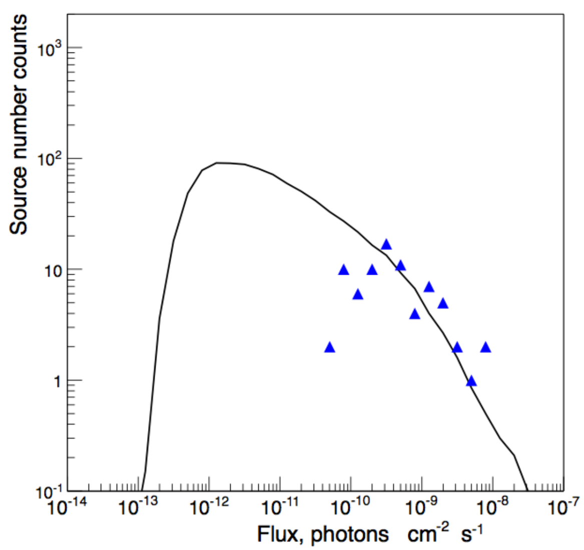
Population studies

Extragalactic



Unresolved FHL extragalactic objects (blazars with |b| > 15deg with a minimum flux of 4.e-11 ph/cm2/s)
account for 27%+/-8% of the IGRB above 10 GeV

Galactic



Unresolved 1FHL Galactic objects contribute about 5% of the luminosity of the Milky Way above 10 GeV