Gamma-ray astronomy with the Fermi-LAT instrument

David Paneque

MPP Project Review 2014

Outline

1 – Brief introduction to the Fermi mission (→ Large Area Telescope)

→ Great synergy with the MAGIC scientific program

2 – Work done/led by MPP Munich

→ Overview

→ Two selected topics

→ Fermi HE sky and search for new VHE sources

→ Development of the Calorimeter-only event class

3 – Conclusions

MPP has major contributions to MAGIC and CTA (→ LST), including also hosting the spokespersons from both MAGIC and CTA-LST, Razmik and Masahiro, respectively.
Neither MAGIC nor CTA-LST would exist without MPP
→ See talks later on by Razmik and Thomas, reporting about MAGIC and CTA

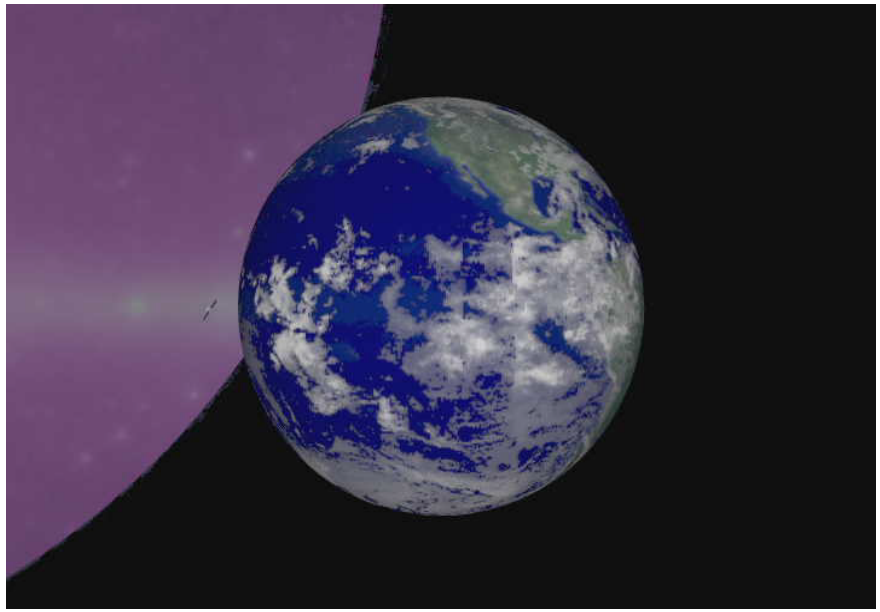
The MPP contribution to Fermi-LAT is minor, although visible within the Fermi-LAT collaboration. We are mostly focused on topics with great synergy with the Very High Energy gamma-ray domain (>50-100 GeV)

The Fermi-LAT instrument

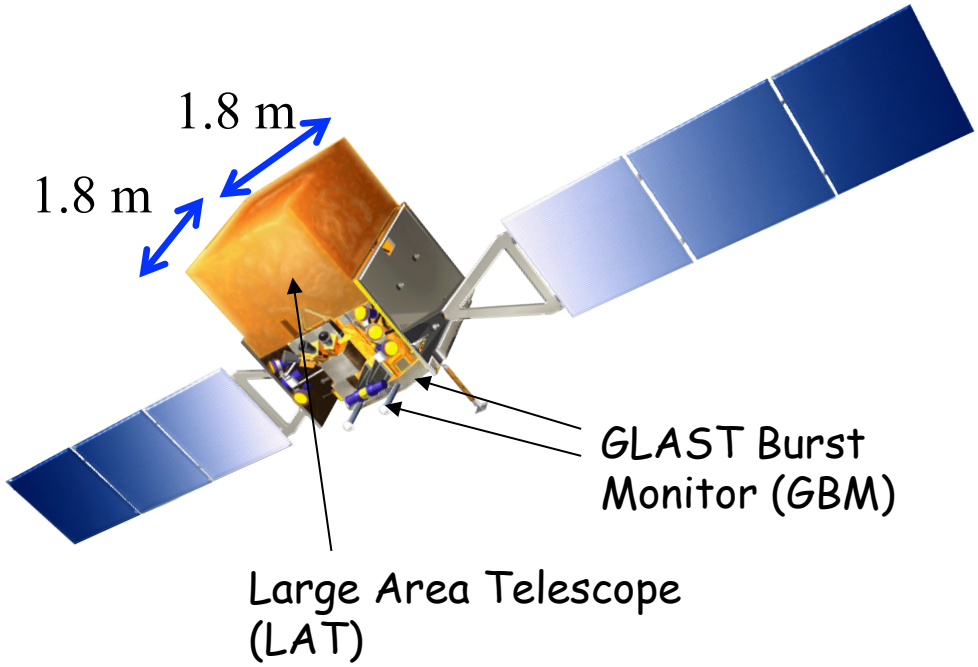
- **Fermi: An International Science Mission to perform gamma-ray astronomy, with an additional X-ray detector for GRBs**
  - Large Area Telescope (LAT); 20 MeV – >300 GeV
  - GLAST Burst Monitor (GBM); 10 keV – 40 MeV

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



The Fermi-LAT collaboration

~400 Scientific Members (NASA / DOE & International Contributions)

→ **But only 130 Full team members**

→ ~270 are affiliated scientists, postdocs and/or grad students

Only four full LAT team members in Germany !!!

http://www-glast.stanford.edu/cgi-bin/people

Most of the European LAT full collaboration members are in Italy and France

Andy Strong, *Max-Planck Institut für extraterrestrische Physik, München*
David Paneque, *Max-Planck-Institut für Physik, München* **(since Nov 2010)**
Markus Ackermann, *DESY Zeuthen* **(since mid-2011)**
Rolf Buehler, *DESY Zeuthen* **(since fall-2012)**

Within the German groups, the Fermi-LAT activities from MPP are actually very substantial

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

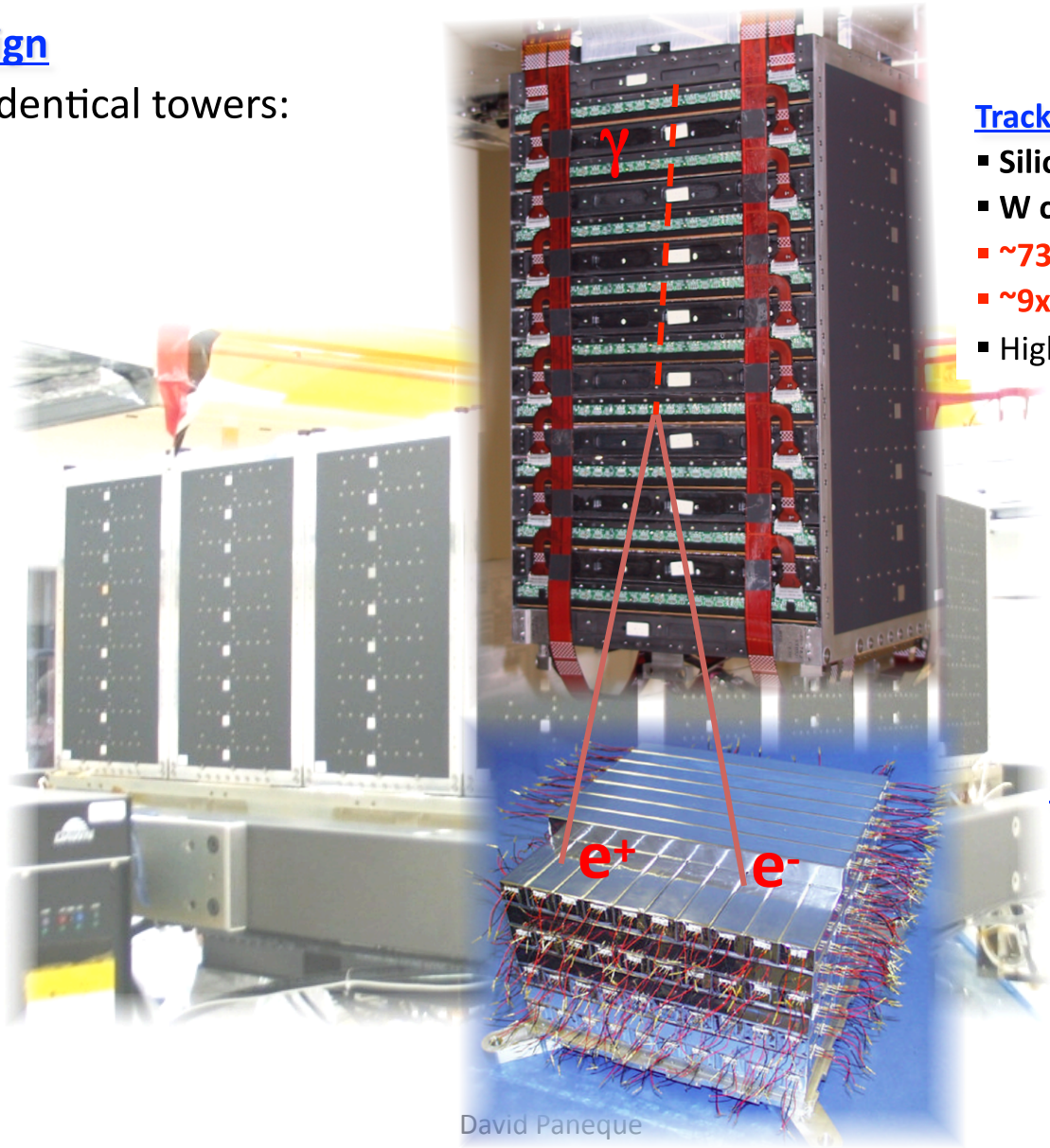
modular design

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

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

modular design

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

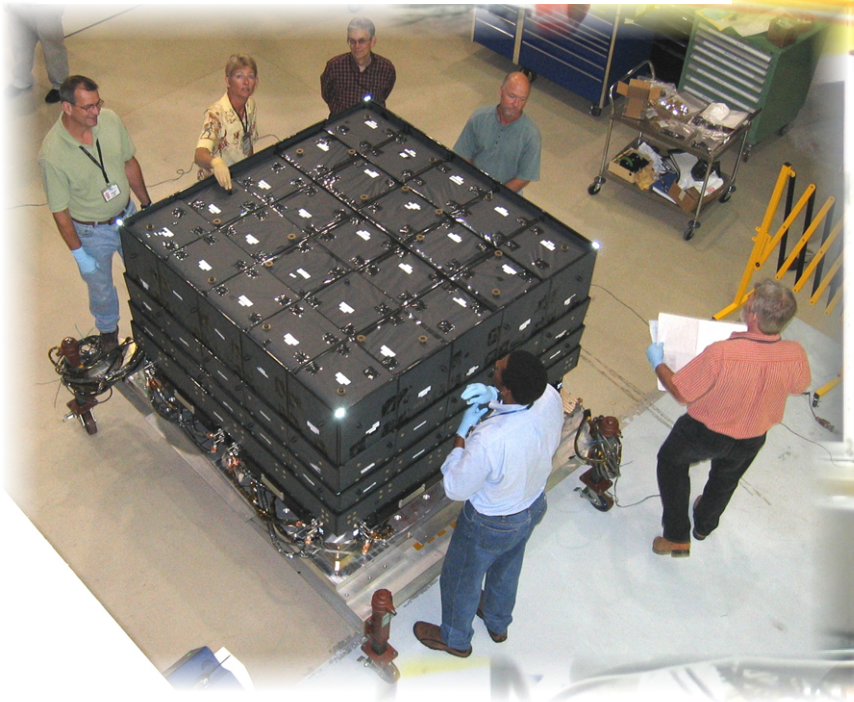
Challenging design: 1.8m x 1.8m x 1.2m ; 2800 kg, 1M channels; but only 650 W

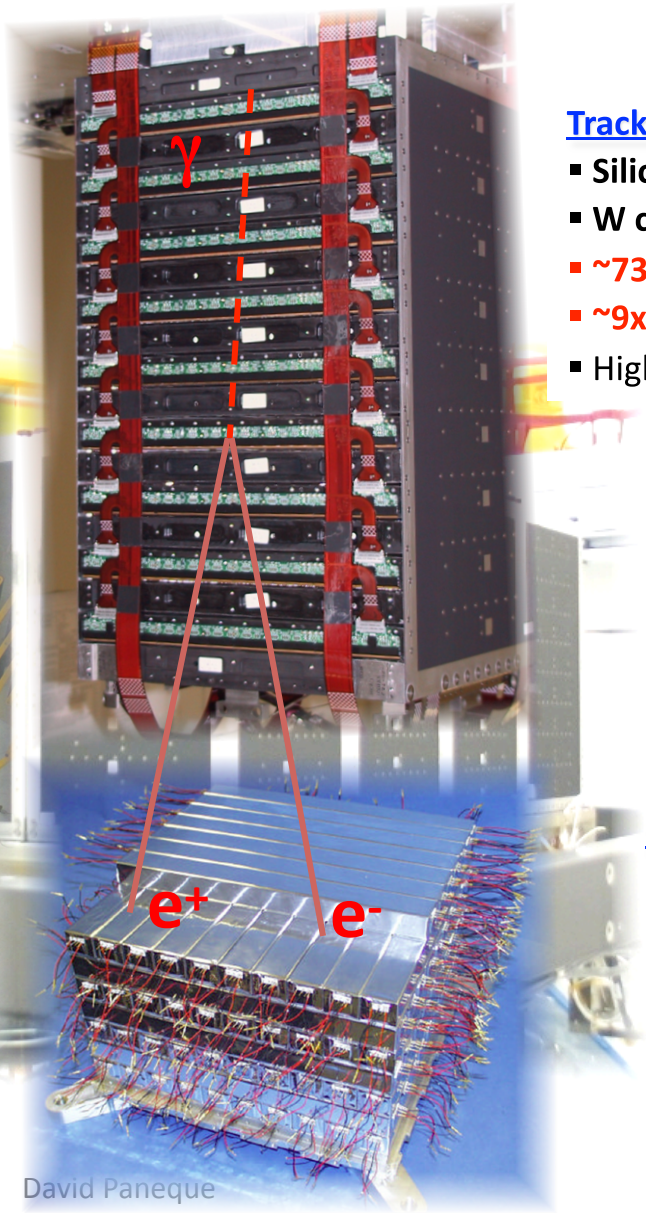
modular design

4x4 array of identical towers:

Anti-Coincidence (ACD):

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





Tracker/Converter (TKR):

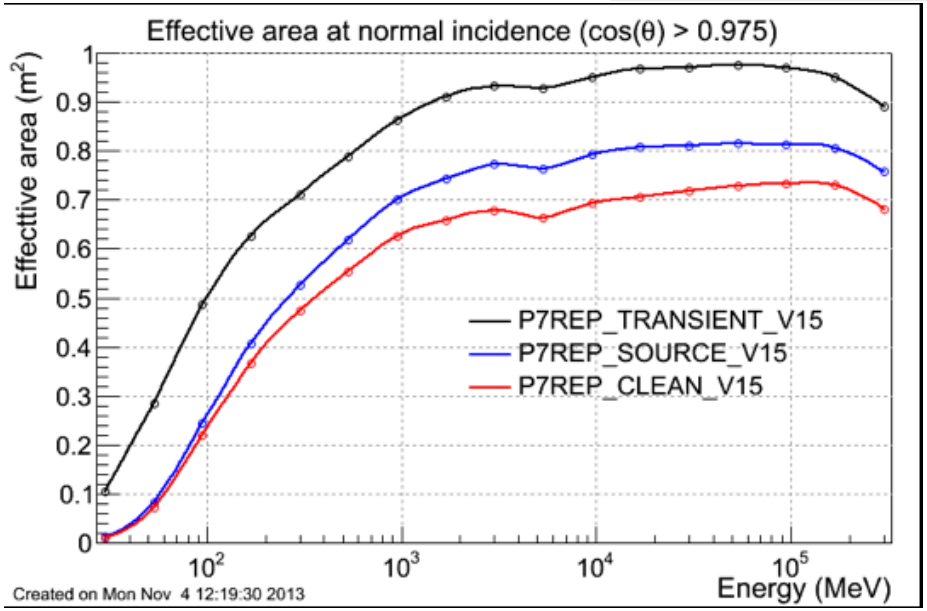
- **Silicon strip detectors.**
- **W conversion foils.**
- **~73 m^2 of silicon (total).**
- **~9x10^5 electronic chans.**
- High precision tracking

Calorimeter (CAL):

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

LAT performance: summary

Google Fermi LAT Performance



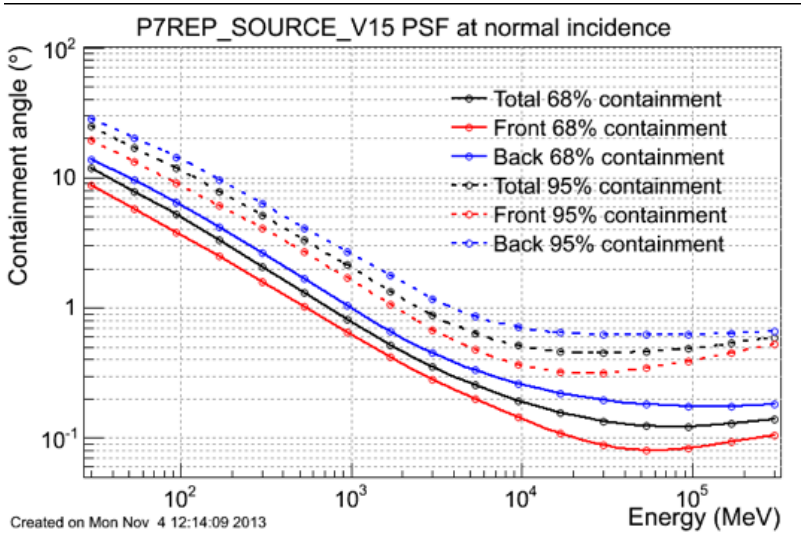
Effective Area: ~ 0.7 m² (on axis)

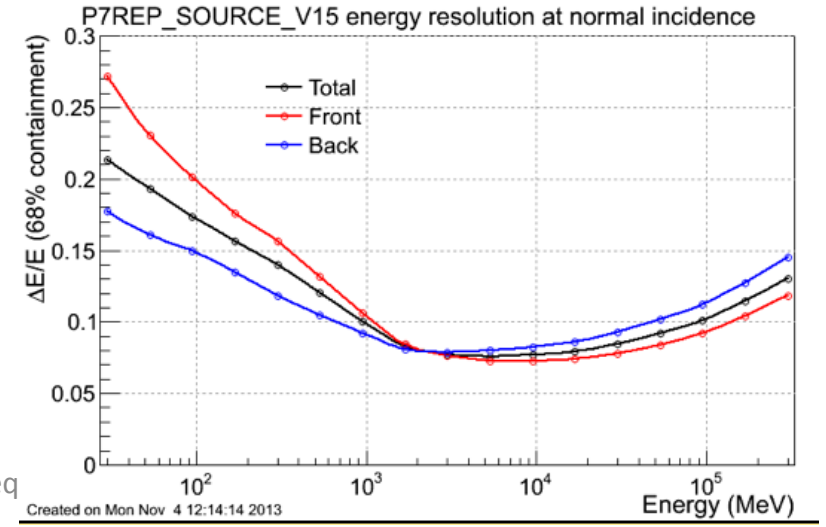
Energy Resolution: ~10%

PSF (68%) at 100 MeV ~ 5°

PSF (68%) at 10 GeV ~ 0.2°

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



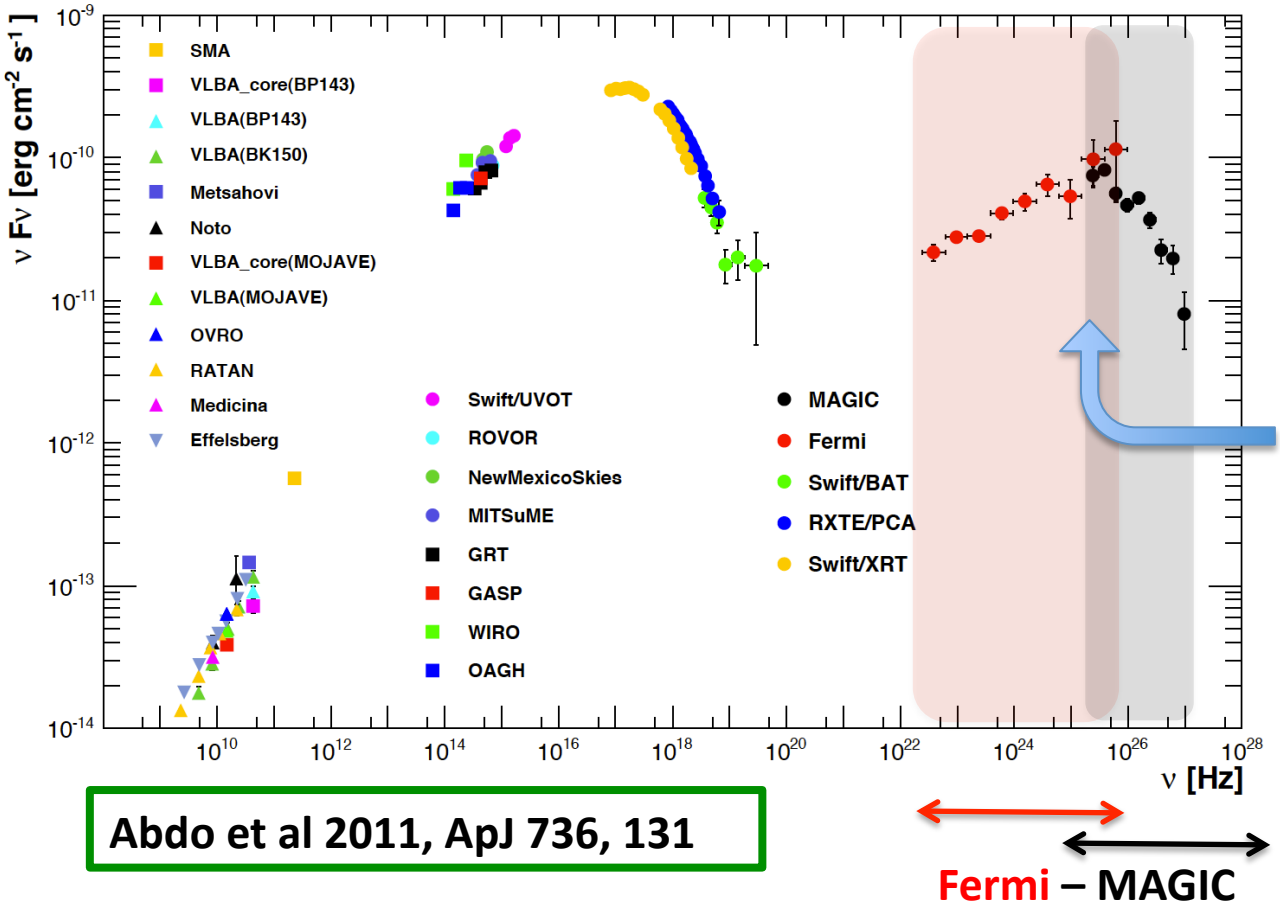


Synergy between MAGIC and Fermi-LAT

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*



Abdo et al 2011, ApJ 736, 131

Spectral energy distribution (SED) of the Blazar Markarian 421

Fermi – MAGIC spectra cover, <u>for the first time</u>, the complete high energy component over 5 orders of magnitude without gaps

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

<u>Great synergy between Fermi-LAT and Cherenkov Telescopes</u>

→ Particularly with the **<u>MAGIC Telescope</u>**, because it is the one with the lowest gamma-ray energy threshold (~60 GeV)

About 500 scientific publications since fall 2008

Category I and II papers in refereed journals

Journal	Published	In press	Total
Advances in Space Research	0+1=1	-	1
Astronomy and Astrophysics	6+38=44	0+4=4	48
Astroparticle Physics	2+6=8	-	8
Astrophysical Journal	82+63=145	2+2=4	149
Astrophysical Journal Letters	22+22=44	-	44
Astrophysical Journal Supplement	8+2=10	-	10
Journal of Cosmology and Astroparticle Physics	3+5=8	-	8
Journal of Geophysical Reserch	0+1=1	-	1
Monthly Notices of the RAS	0+30=30	0+1=1	31
Nature	2+1=3	-	3
Nuclear Instruments and Methods	0+1=1	-	1
Physical Review D	8+2=10	-	10
Physical Review Letters	7+0=7	-	7
Publications of the ASJ	0+1=1	-	1
Science	19+0=19	-	19
Total	159+173=332	2+7=9	341

Publications include various catalogs of sources (1FGL, 2FGL, 2LAC, GRBs, 1FHL, Pulsars …)

→ *Very useful for the community*

+ 153 published Cat3 papers (*no new experimental results*)

+ 18 papers already submitted to journals

308 Astronomer Telegrams + GCN Circulars (informing community about transient events)

About 500 scientific publications since fall 2008

Category I and II papers in refereed journals

Journal	Published	In press	Total
Advances in Space Research	0+1=1	-	1
Astronomy and Astrophysics	6+38=44	0+4=4	48
Astroparticle Physics	2+6=8	-	8
Astrophysical Journal	82+63=145	2+2=4	149
Astrophysical Journal Letters	22+22=44	-	44
Astrophysical Journal Supplement	8+2=10	-	10
Journal of Cosmology and Astroparticle Physics	3+5=8	-	8
Journal of Geophysical Reserch	0+1=1	-	1
Monthly Notices of the RAS	0+30=30	0+1=1	31
Nature	2+1=3	-	3
Nuclear Instruments and Methods	0+1=1	-	1
Physical Review D	8+2=10	-	10
Physical Review Letters	7+0=7	-	7
Publications of the ASJ	0+1=1	-	1
Science	19+0=19	-	19
Total	159+173=332	2+7=9	341

Publications include various catalogs of sources (1FGL, 2FGL, 2LAC, GRBs, 1FHL, Pulsars …)

→ *Very useful for the community*

+ 153 published Cat3 papers (*no new experimental results*)

+ 18 papers already submitted to journals

308 Astronomer Telegrams + GCN Circulars (informing community about transient events)

2 – Work done/led by MPP Munich

2.1 – Overview

2.2 - Report on two topics

→ Fermi HE sky and search for new VHE sources

→ Development of the Calorimeter only event class

The MPP experimental gamma-ray group

Scientists : 20 physicists (approx.)

Director: Masahiro Teshima
Senior (3): Razmik Mirzoyan, Thomas Schweizer, **David Paneque**

Otto Hahn (1): Daniel Mazin (→ In September moved to ICRR Tokyo)
Other grants (1): Ievgen Vovk (Swiss grant)
Postdoc (4): Pierre Colin, Koji Noda, Francesco Dazzi, **Elena Moretti (*since July 2014*)**
guest postdocs (1): Susumu Inoue

Students (8): Shangyu Sun (*left in October 2014*), Francesco Borracci, Christian Fruck, Takeshi Toyama, **Jezabel Garcia**, Priyadarshini Bangale, Uta Menzel, Marcel Strzys

Only few people analyze Fermi data (**names in blue**)
→ **Although many of them (all working on MAGIC science) use Fermi-LAT results**

MPP Fermi-LAT related activities (in a nutshell)

Fermi-LAT operations and data analysis (in framework of ISOC)

Maintain and upgrade (when necessary) the C++ code to perform a systematic monitoring of the technical performance of LAT during scientific operation

→ **David**

Develop analysis procedure to use events without tracker information (Cal-only evts)

→ **David + Mitsunari Takahashi (student at University of Tokyo)**

See later on

MAGIC- Fermi cross-calibration (probably more beneficial for MAGIC) → **Ievgen Vovk**

Science related topics (all them with great synergy with MAGIC)

Active Galactic Nuclei (AGNs)

- Source characterization at highest Fermi Energies (>10 GeV) and usage to increase efficiency in the detection of new VHE AGNs → **David**
- Automatic Fermi pipeline to monitor activity of sources (trigger MAGIC)→ **Ievgen Vovk**

See later on

- Deep studies through multi-year and multi-instrument programs → **David**

Pulsars

- Characterization of Fermi pulsars at the highest energies, TeV candidates for MAGIC

→ **Jezabel Garcia** (*just started*)

Gamma Ray Bursts

- Investigation of Fermi GRBs related to MAGIC observations → **Elena Moretti** (*just started*)

MPP Fermi-LAT related activities (in a nutshell)

"Fermi contact" within the MAGIC collaboration

Foster MAGIC-Fermi collaboration in many scientific projects

→Improve science output by combining Fermi and MAGIC data

(many of them become "*Fermi Category 2 papers*")

In 2014, the Scientific output of the MAGIC collaboration was large (see more in the report from Razmik Mirzoyan)

Papers published: 16

Papers accepted for publication: 3

Papers submitted: 8 (4 of them got referee report, positive)

Out of the 27 (=16+3+8) MAGIC papers from 2014, 20 papers contain Fermi data, and 14 of them are "Fermi Category 2 papers"

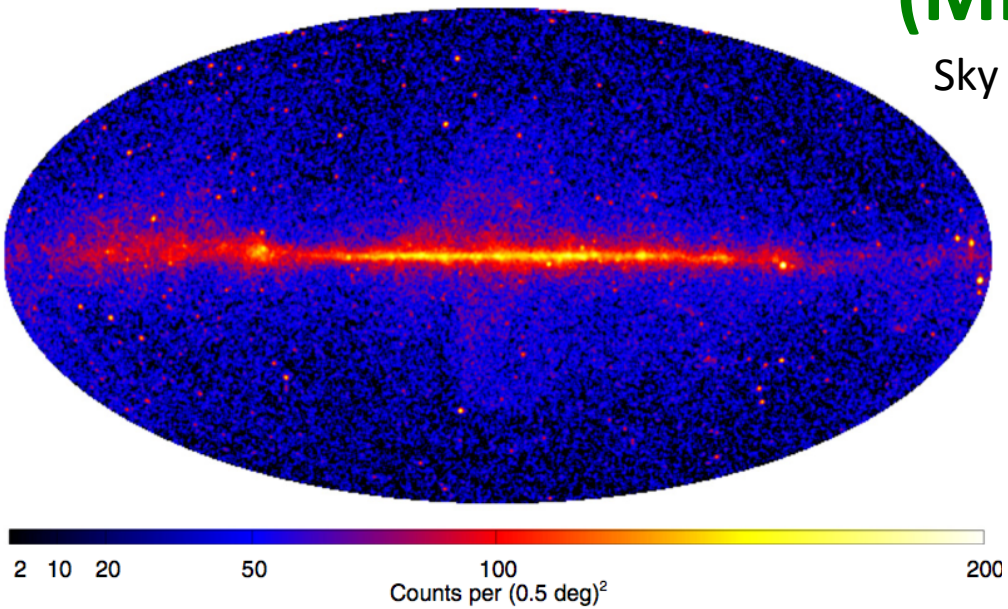
2.2 - Report on two topics

→ **Fermi HE sky and search for new VHE sources**

→ Development of the Calorimeter-only event class

The First Fermi-LAT Catalog of Sources above 10 GeV

(1FHL) Ackermann et al, 2013, ApJS 209, 34 (MPP-2013-174)



Sky map with > 10 GeV events

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

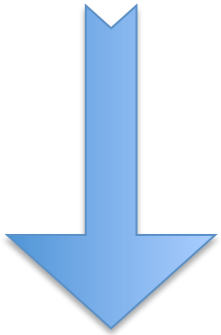
Big improvement with respect to EGRET !!!
1.5×10^3 evts in 9 years
(Thompson et al. 2005)

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

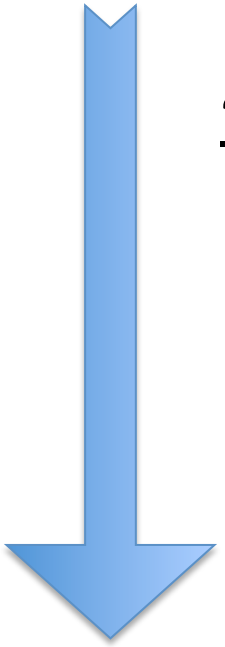
514 sources *(63 not contained in 2FGL)*
***9 of the 63 sources are extended, while in* 2FGL exist as point-like sources**
All sources could be fitted with a simple power law

~1000 AGNs @ > 0.1 GeV (Fermi low-energy, 2FGL & 2LAC)



~2 times less sources

~400 AGNs @ >10 GeV (Fermi high-energy, 1FHL)



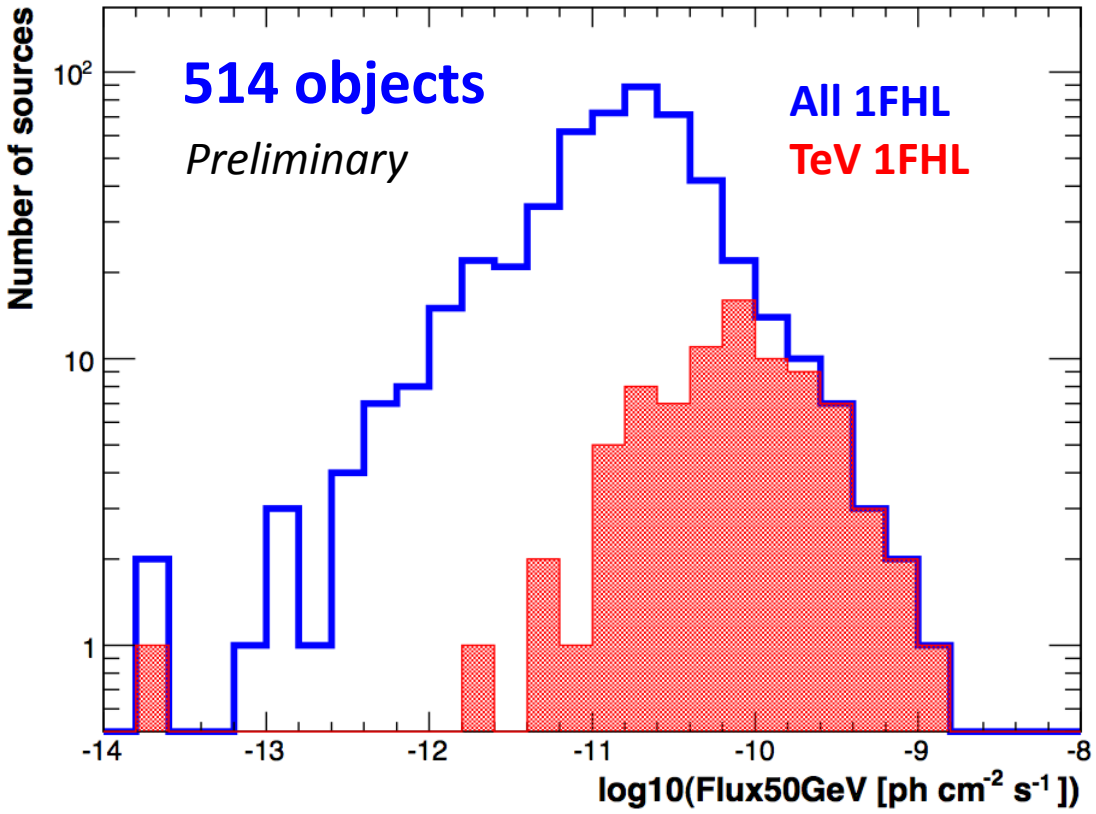
~10 times less sources above 100 GeV. Why ???

1) intrinsic turnovers or cutoffs
2) Extrinsic turnovers or cutoffs (EBL)
3) **Region not sufficiently explored with IACTs**
   IACTs have low duty cycles and small FoV
   → Difficult to make surveys over large areas
   (*HESS Galactic plane scan is special because of high source density)*

~50 AGNs @ >100 GeV (Cherenkov Telescopes)

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

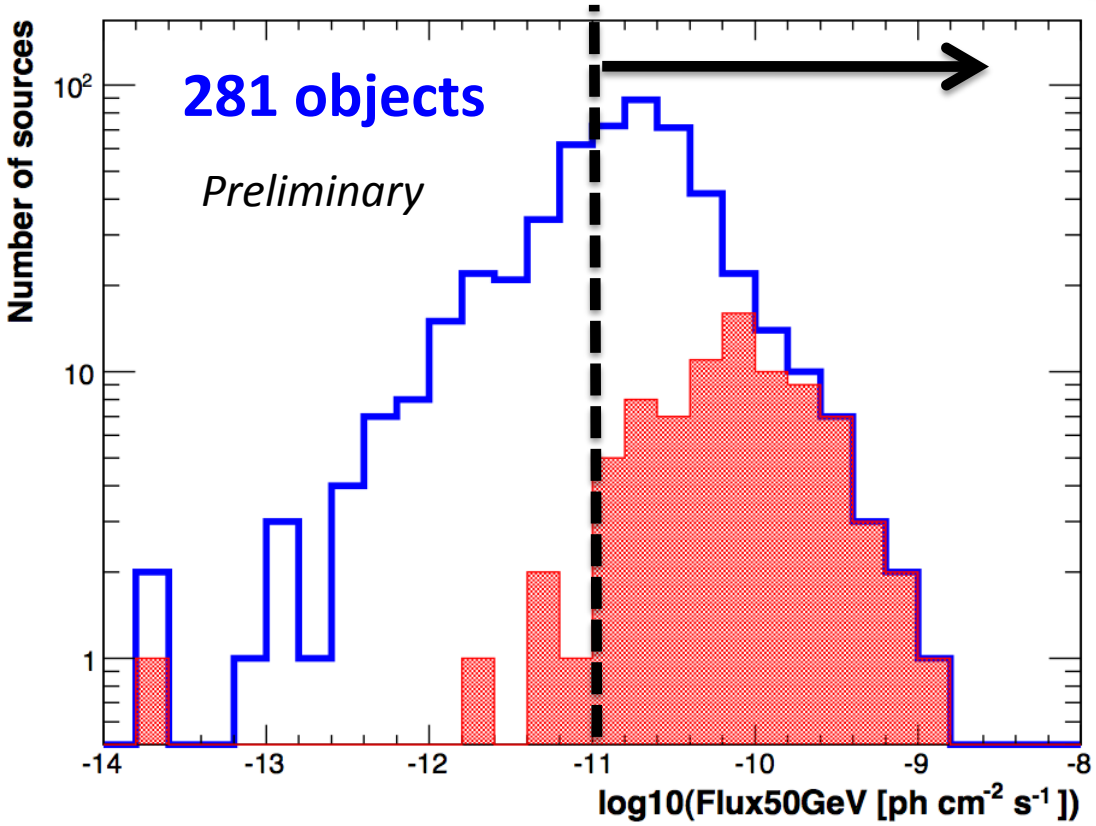
84 objects from the 1FHL list have been already detected with IACTs at VHE (→ TeV Src) http://tevcat.uchicago.edu/

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

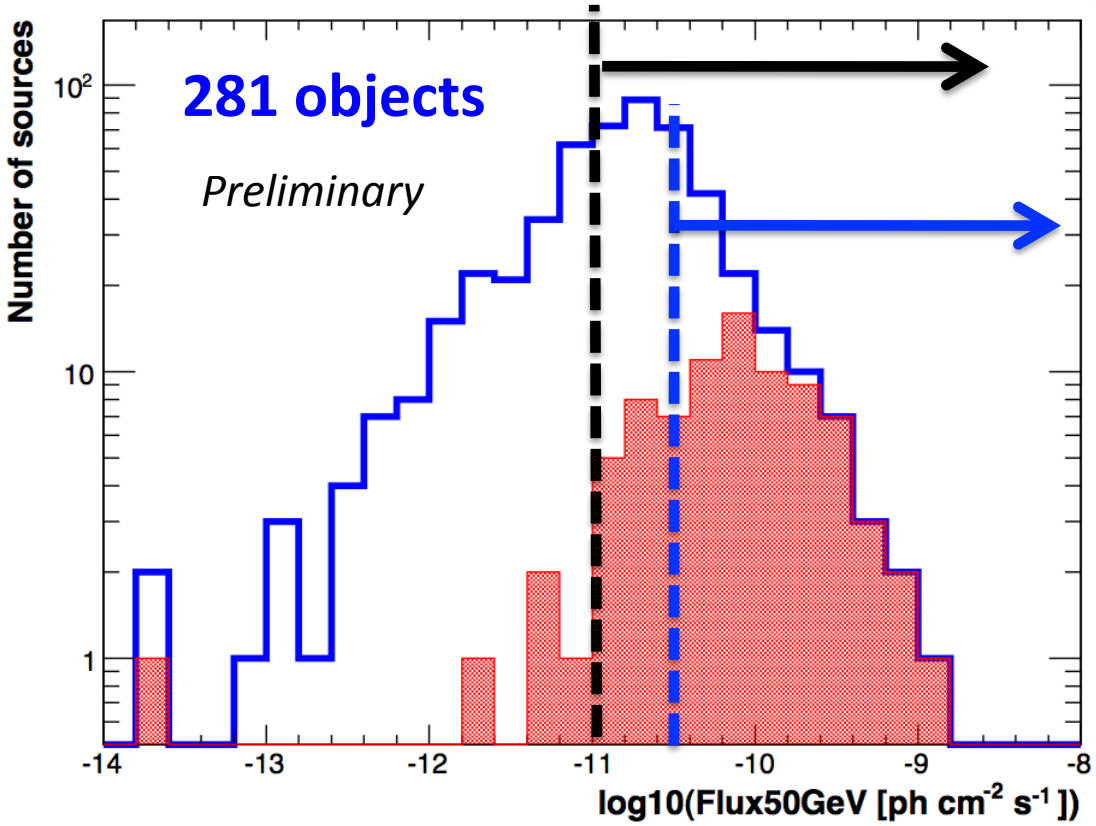
From the 84 TeV src in 1FHL, 69 objects survive the *TeV candidate selection cuts*

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*



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

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

Candidate TeV sources from FHL are being detected

Discovery of Very High Energy Gamma-Ray Emission from MS1221.8+2452 with the MAGIC telescopes

ATel #5038; *Juan Cortina (IFAE Barcelona) on behalf of the MAGIC collaboration*
on 2 May 2013; 19:25 UT
Credential Certification: Juan Cortina (cortina@ifae.es)

z=0.20

DISCOVERY OF VERY HIGH ENERGY GAMMA-RAY EMISSION FROM RBS 0723 WITH THE MAGIC TELESCOPES

z=0.20

ATel #5768; *Razmik Mirzoyan (Max-Planck-Institute for Physics, Munich, Germany)*
on 15 Jan 2014; 17:53 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Discovery of Very High Energy Gamma-Ray Emission from BL Lac object H1722+119 by the MAGIC Telescopes

z>0.17

ATel #5080; *Juan Cortina (IFAE Barcelona) on behalf of the MAGIC collaboration*
on 22 May 2013; 19:03 UT
Credential Certification: Juan Cortina (cortina@ifae.es)

Discovery of Very High Energy Gamma-Ray Emission from BL Lac object RX J1136.5+6737 by the MAGIC Telescopes

z=0.13

ATel #6062; *Razmik Mirzoyan (Max-Planck-Institute for Physics) on behalf of the MAGIC Collaboration*
on 11 Apr 2014; 11:11 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Discovery of 4+1 new VHE AGNs (with MAGIC) from the list of good TeV candidates from FHL

Crucial to monitor the gamma-ray activity

In some cases, e.g. for very distant AGNs, MAGIC observations are more efficient, when performed during the high-flux states of the objects. Fermi-LAT data can be used to trigger MAGIC observations.

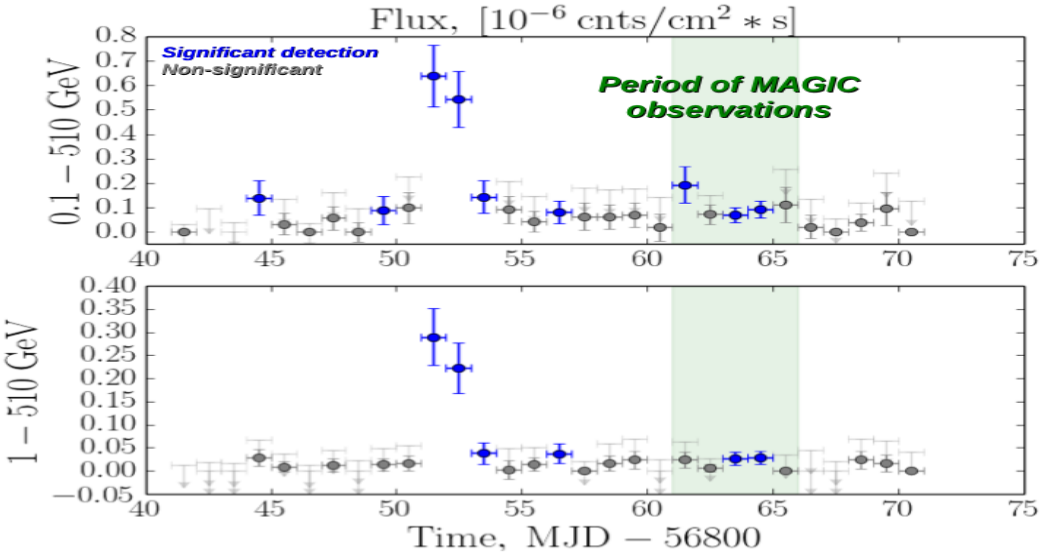
Within the Fermi-LAT collaboration there is a group of people that daily checks the sky and announces flaring events (through Astronomer telegrams and private communications).

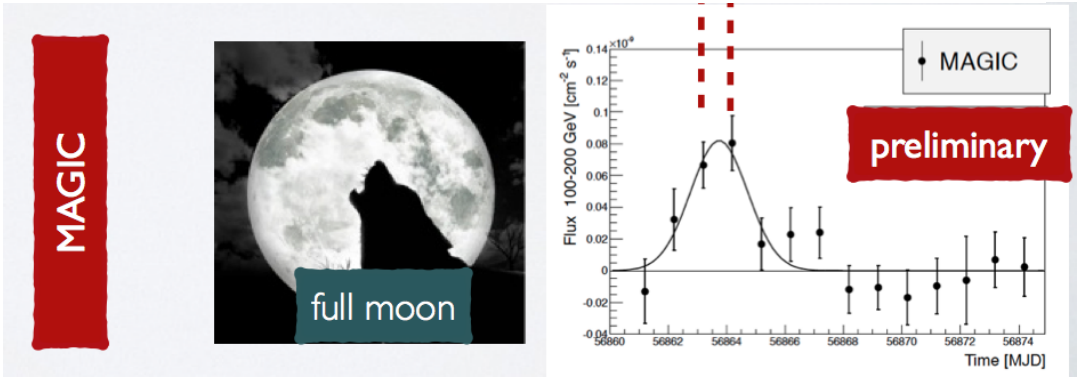
But to ensure that we will not miss the flares from the objects we are interested in, **Ievgen Vovk has set up a monitoring script here at MPP, that constantly checks the activity (at low and high energies) of a predefined list of sources**

Discovery of Very High Energy Gamma-Ray Emission From Gravitationally Lensed Blazar S3 0218+357 With the MAGIC Telescopes

ATel #6349; *Razmik Mirzoyan (Max-Planck-Institute for Physics) On Behalf of the MAGIC Collaboration*
on 28 Jul 2014; 14:20 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

This one was ALSO in the list of good TeV candidates from FHL





The recent detection (by MAGIC) of the gravitationally lensed emission from the most distant (**z=0.94**) VHE blazar is the most spectacular of those detections

Candidate TeV sources from FHL are being detected

Surely there will be more VHE detections in the next years

Many detections will be possible due to a flaring state of the source (determined with Fermi-LAT or optical/X-ray)

→ Search for new VHE candidates done in 3D (RA,Dec, Time)

However, many observations with current IACTs will also lead to non-detections (upper limits) due to limited sensitivity and not-low-enough energy threshold. This will also be useful to understand better these sources

Large increase in number of sources expected with CTA-LST

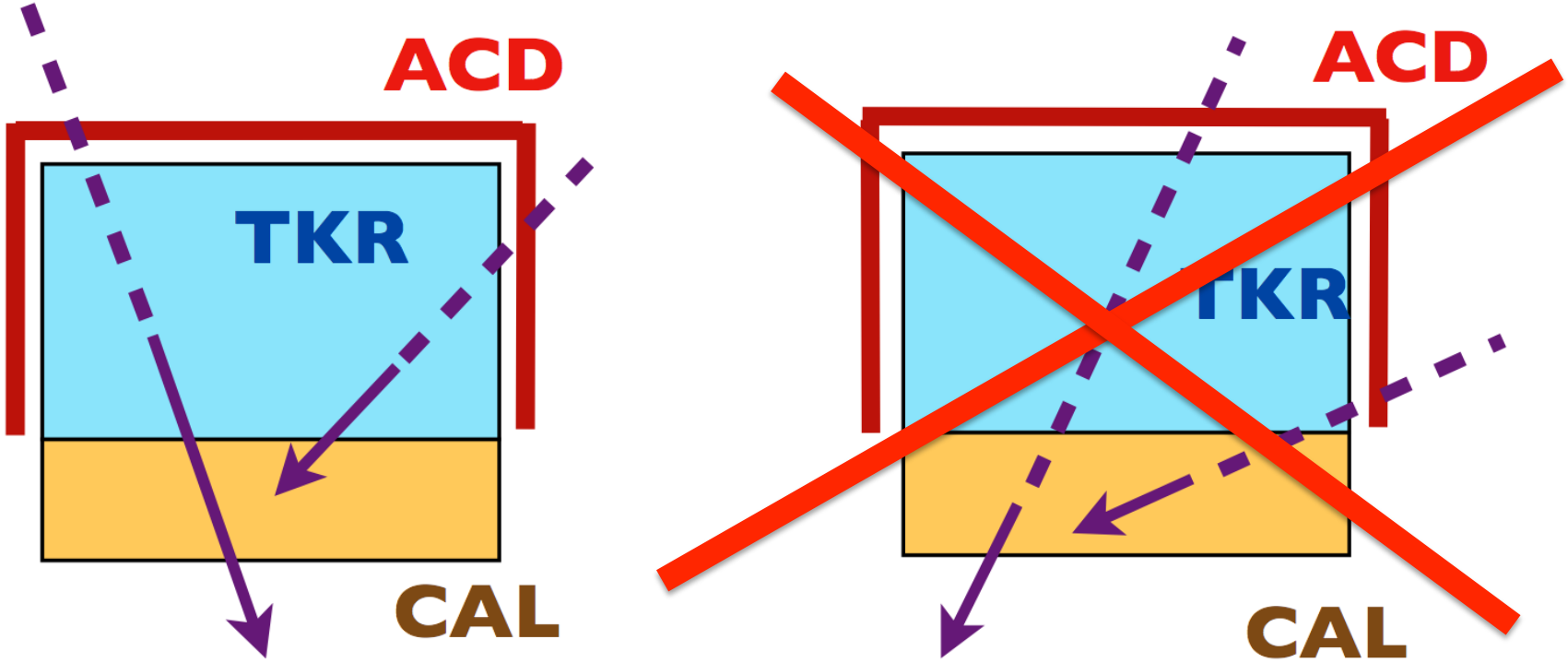
→ Energy threshold going down to 20 GeV

2.2 - Report on two topics

→ Fermi HE sky and search for new VHE sources

→ **Development of the Calorimeter-only event class**

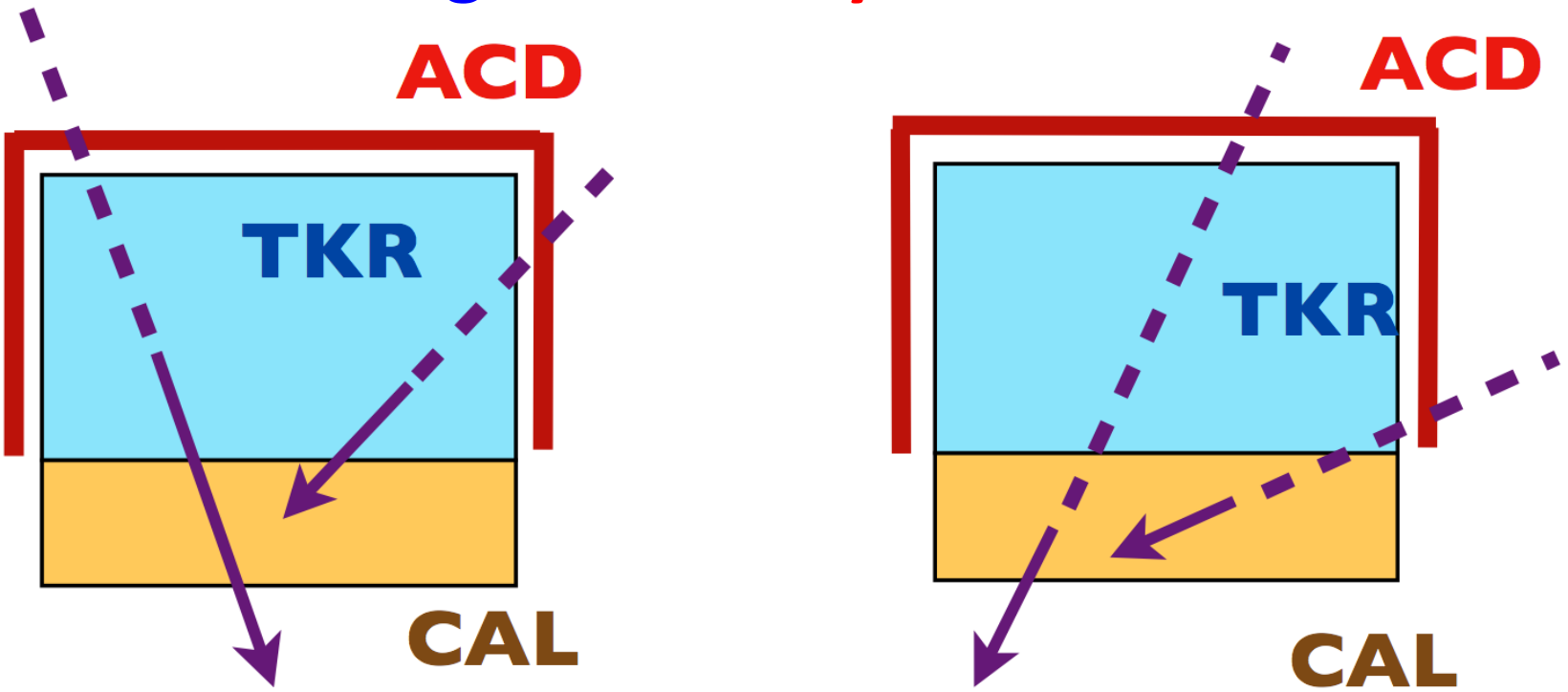
Further performance increase at the highest Fermi-LAT energies



Standard Fermi-LAT analysis requires information from the TKR

→**Many gamma-rays are discarded because they convert in the CAL**

Further performance increase at the highest Fermi-LAT energies: CalOnly Event Class



Standard Fermi-LAT analysis requires information from the TKR

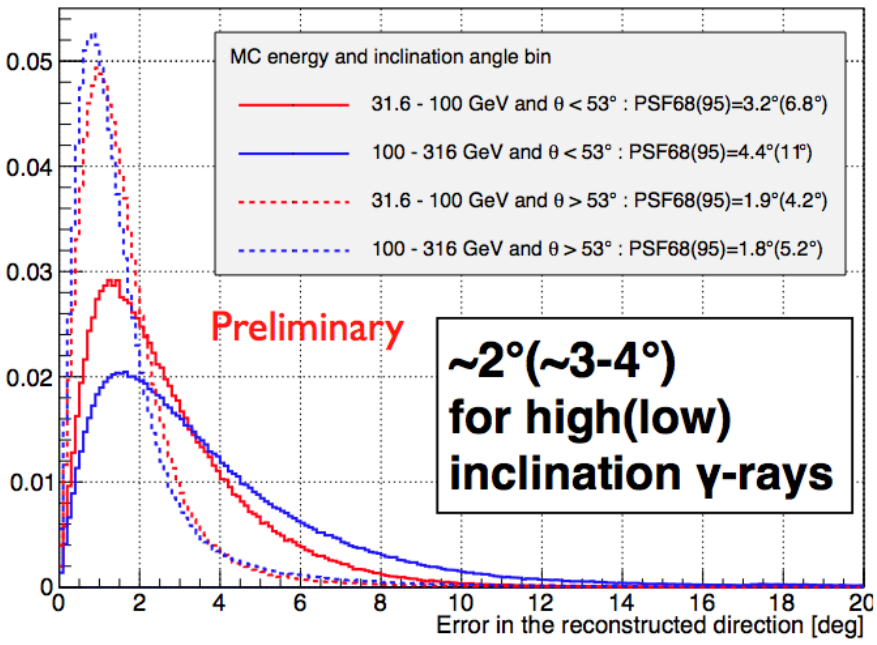
→**Many gamma-rays are discarded because they convert in the CAL**

At the highest energies (>20-30 GeV), CAL could be sufficient to reconstruct the event and recover a fraction of these “lost” gammas

→**Calorimeter-only (CalOnly) event class**

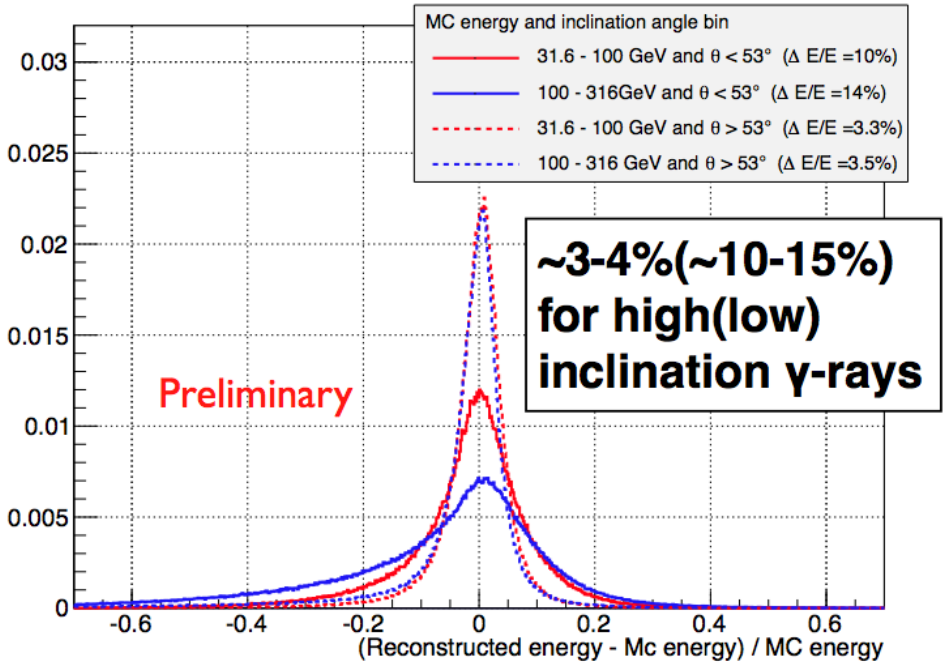
Reconstruction of a CalOnly gamma-ray event

Angular resolution



Normalized histograms of the distances between reconstructed and MC direction of CalOnly events in 2 inclination angle x 2 energy bins

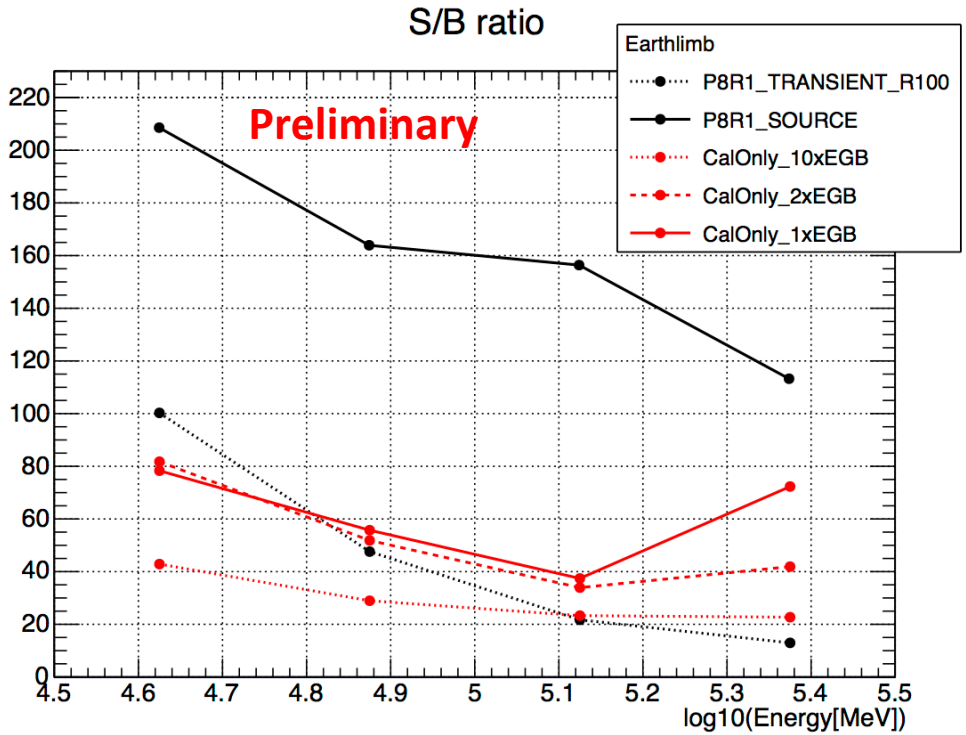
Energy resolution



Normalized histograms of the dispersions in the reconstructed energy of MC CalOnly events in 2 inclination angles x 2 energy bins

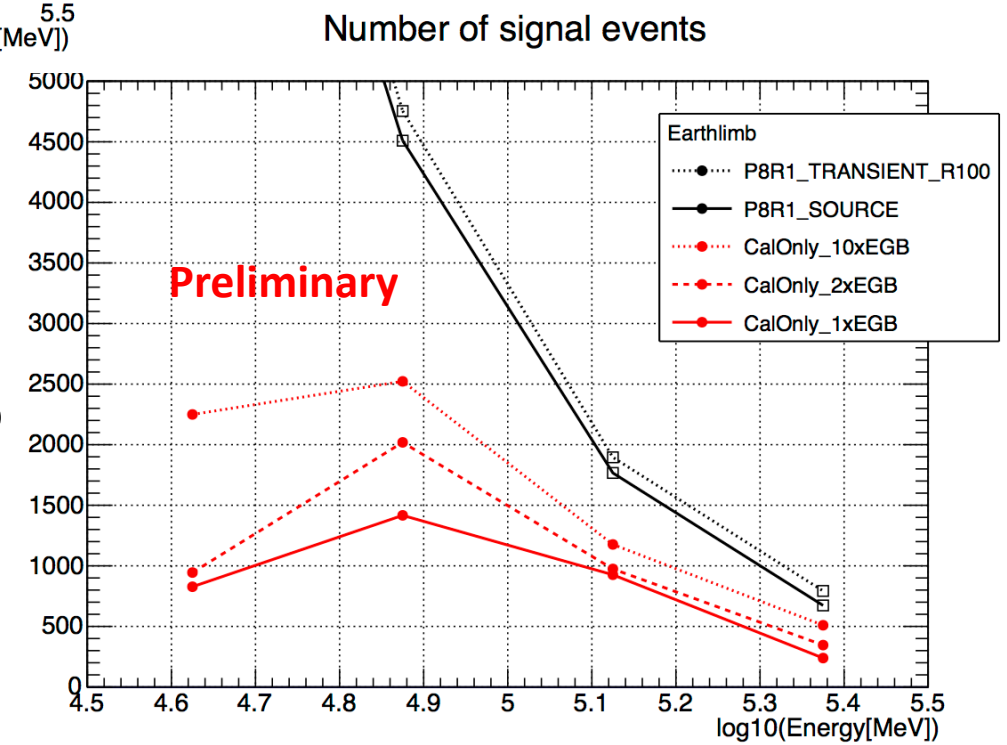
Energy resolution is excellent, but angular resolution is one order of magnitude worse than when TKR information is available

→ No problem for source confusion, but could be problematic for the signal/background separation



Performance evaluated with Earth Limb gamma rays

Signal/Background ratio for the CalOnly events (with different cuts) is lower than that for SOURCE, but comparable to the TRANSIENT class



The CalOnly event PRELIMINARY class may bring 30-60% additional events (with respect to the standard SORUCE class) at the highest energies

Further performance increase at the highest Fermi-LAT energies: CalOnly Event Class

Potentially could increase acceptance by ~30-60% (larger bkg), where the performance is photon statistics limited.

Real performance Needs to be checked with regular gamma-ray sources (Mrk421, Mrk501…)
And analysis is not yet final…

Such event class could potentially be used in a later improvement of 2nd Fermi High-Energy LAT catalog (2FHL), or for 3FHL

Particularly, the CalOnly event class may impact the LAT science output in two areas:

→Search for line-signals potentially coming from Dark Matter annihilation (because of the larger number of events and the excellent energy resolution for the large-incident angle events)

→Study of transient events like GRBs and AGN flares (because of the larger number of events and the valuable increase in the temporal coverage of the sources

Hopefully ready to be used by the end of 2015

3 – Conclusions

Fermi-LAT, in scientific operation since August 2008

→ scanning the full sky every 3 hours with sensitivity 30 better than EGRET

Fermi-LAT provides a large leap in capabilities,

→ Many "expected" results, but also many unexpected !!

→ **New data provides new challenges to the theoreticians**

This large amount of high quality and novel experimental observations translated into a high publication rate: **~500 papers in 6 years (~7 papers/month)**

3 – Conclusions

Fermi-LAT, in scientific operation since August 2008

→ scanning the full sky every 3 hours with sensitivity 30 better than EGRET

Fermi-LAT provides a large leap in capabilities,

→ Many "expected" results, but also many unexpected !!

→ **New data provides new challenges to the theoreticians**

This large amount of high quality and novel experimental observations translated into a high publication rate**: ~500 papers in 6 years (~7 papers/month)**

MPP Fermi-related activities:

Fermi-LAT operations and data analysis (sometimes in the framework of ISOC)

→ Systematic monitoring of the technical performance of LAT

→ Development of Calorimeter-only analysis

→ MAGIC-Fermi Cross-calibration

Science related topics great synergy with MAGIC

→ Active Galactic Nuclei (most of the current activity)

→ Pulsars

→ Gamma Ray Bursts

Backup

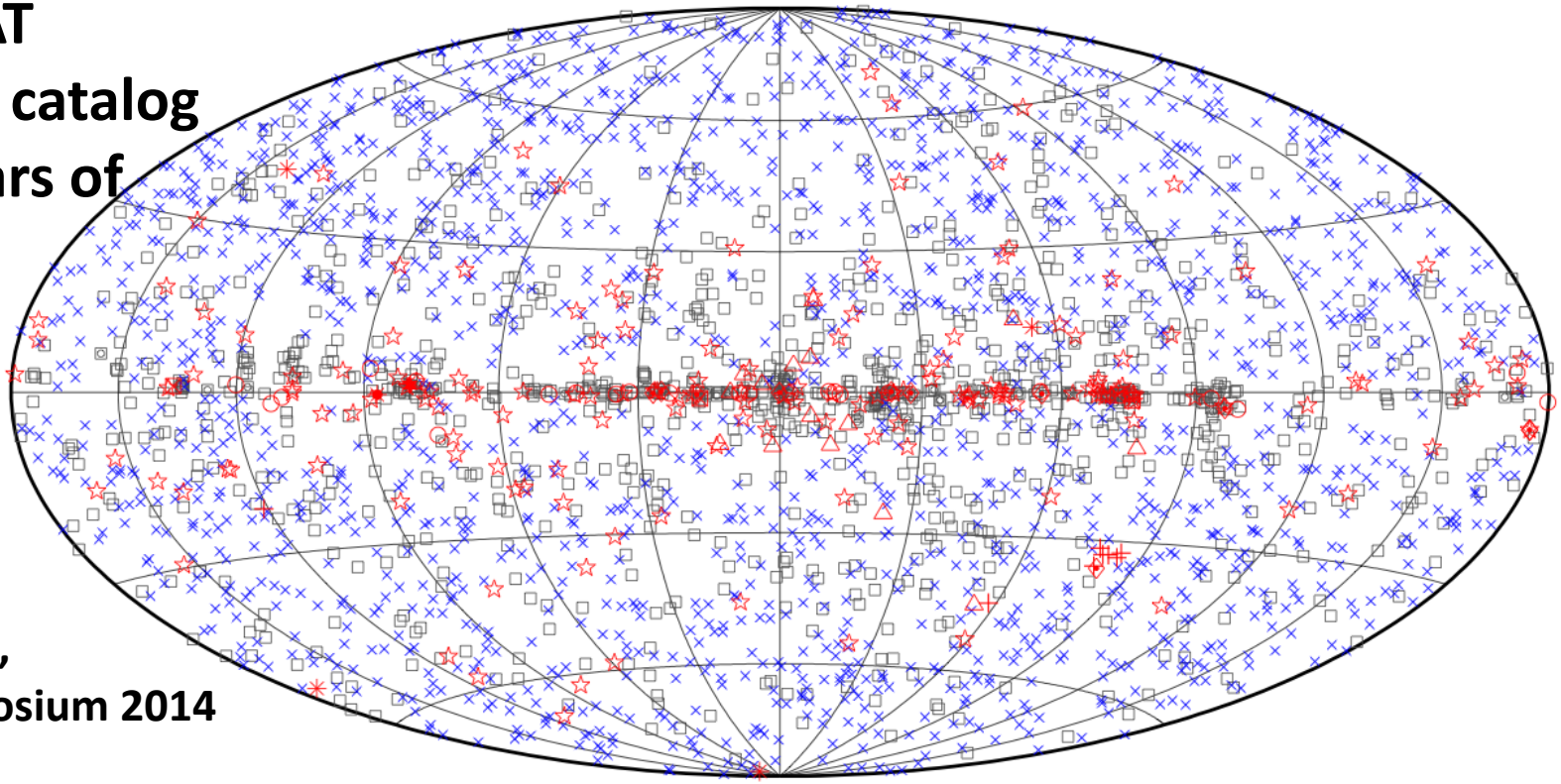
Gamma-ray astronomy with the Fermi-LAT instrument

David Paneque

MPP Project Review 2014

3rd Fermi-LAT Gamma-ray catalog (3FGL, 4 years of operation)

3033 sources



Cavazutti et al .,
5th Fermi symposium 2014

No association	Possible association with SNR or PWN		AGN
Pulsar	Globular cluster	Starburst Galaxy	PWN
Binary	Galaxy	SNR	Nova
Star–forming region			

Since 2009, we have a close collaboration between Fermi-LAT and Cherenkov Telescopes to increase the number of VHE AGNs

1) We identify VHE AGN candidates using Fermi-LAT data

2) Cherenkov telescopes observe some of these objects

- Detection of the source or upper limits (both are useful)

Often IACT observations are triggered by an enhanced activity in LAT, or by enhanced activity in optical/X-ray in a VHE candidate source

In the last 5 years (since 2009):

IACTs discovered 34 new VHE AGNs, most of them following information from Fermi-LAT (TeV candidates and/or flaring LAT sources)

The total number of reported VHE AGNs is now 58 (after ~25 years of operation with IACTs, see TeVCat for details)

→ **In last 5 years we have increased the known VHE extragalactic sky by 142%(=34/(58-34)), and Fermi-LAT played a crucial role**

→ *Important to increase the census of VHE AGNs and improve population studies*