Gamma Ray Astronomy with ARGO-YBJ

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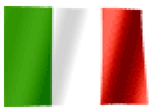
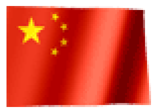
INFN – Sezione di Napoli

SciNeGHE, Lisboa, June 5, 2014

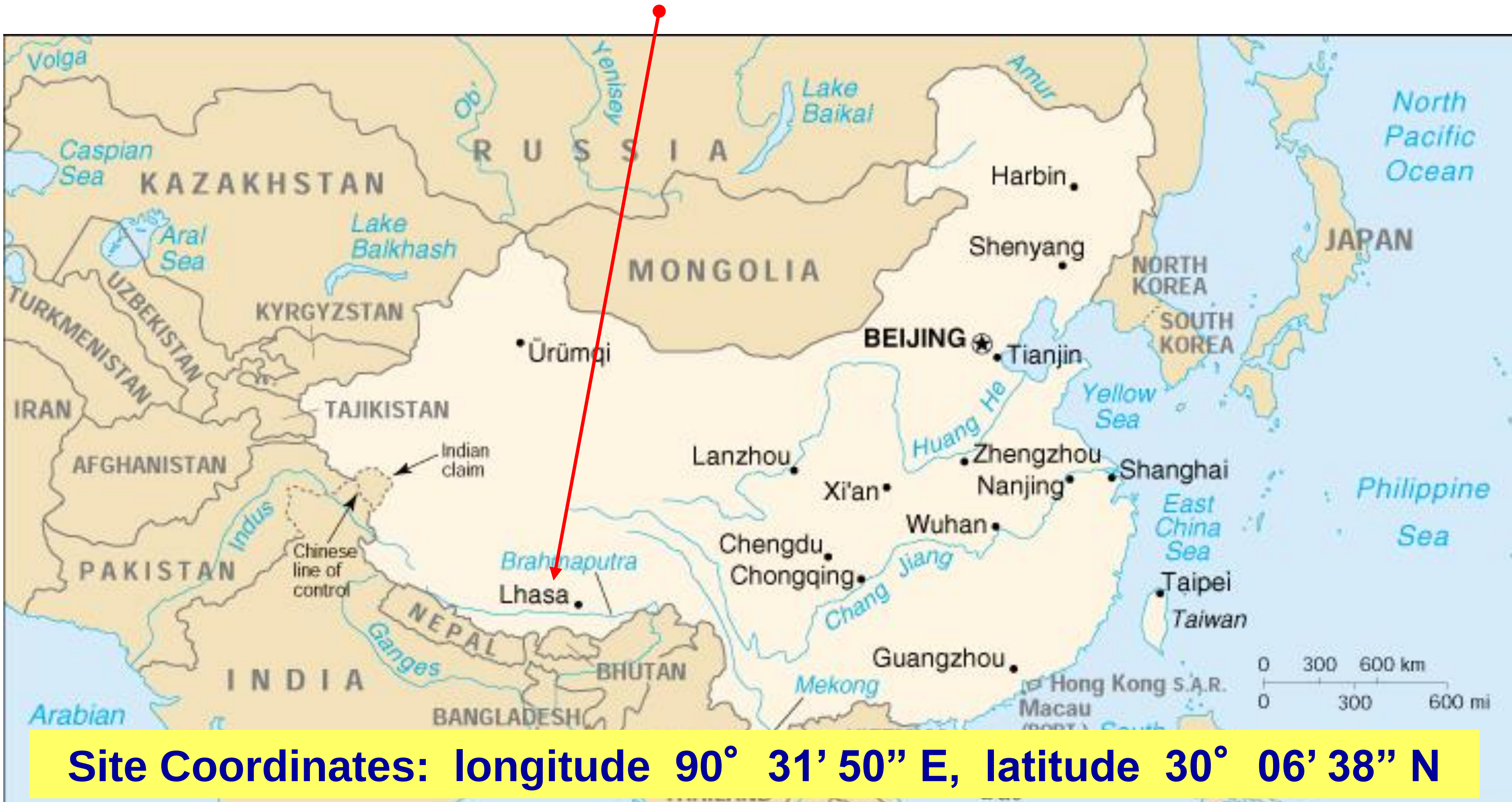
The ARGO-YBJ experiment

Collaboration between:

- **Istituto Nazionale di Fisica Nucleare (INFN) – Italy**
- **Chinese Academy of Science (CAS)**

Site: YangBaJing Cosmic Ray Laboratory (Tibet, P.R. of China), 4300 m a.s.l.

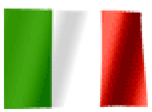


Site Coordinates: longitude 90° 31' 50" E, latitude 30° 06' 38" N

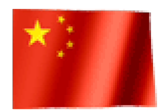
The ARGO-YBJ collaboration

Collaboration Institutes:

- ✓ Chinese Academy of Science (CAS)
- ✓ Istituto Nazionale di Fisica Nucleare (INFN)



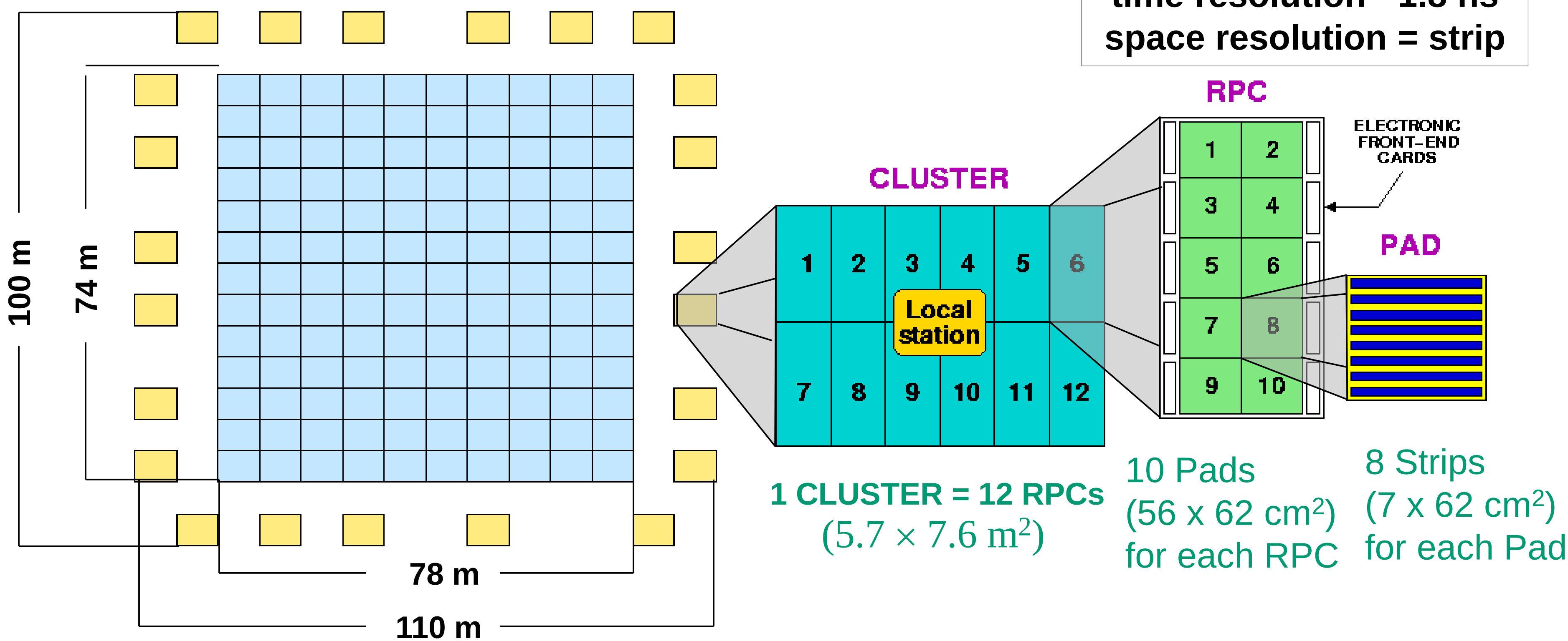
INFN and Dpt. di Fisica Università, Lecce
INFN and Dpt. di Fisica Universita’, Napoli
INFN and Dpt. di Fisica Universita’, Pavia
INFN and Dpt di Fisica Università “Roma Tre”, Roma
INFN and Dpt. di Fisica Univesità “Tor Vergata”, Roma
INAF/IFSI and INFN, Torino
INAF/IASF, Palermo and INFN, Catania



IHEP, Beijing
Shandong University, Jinan
South West Jiaotong University, Chengdu
Tibet University, Lhasa
Yunnan University, Kunming
Hebei Normal University, Shijiazhuang

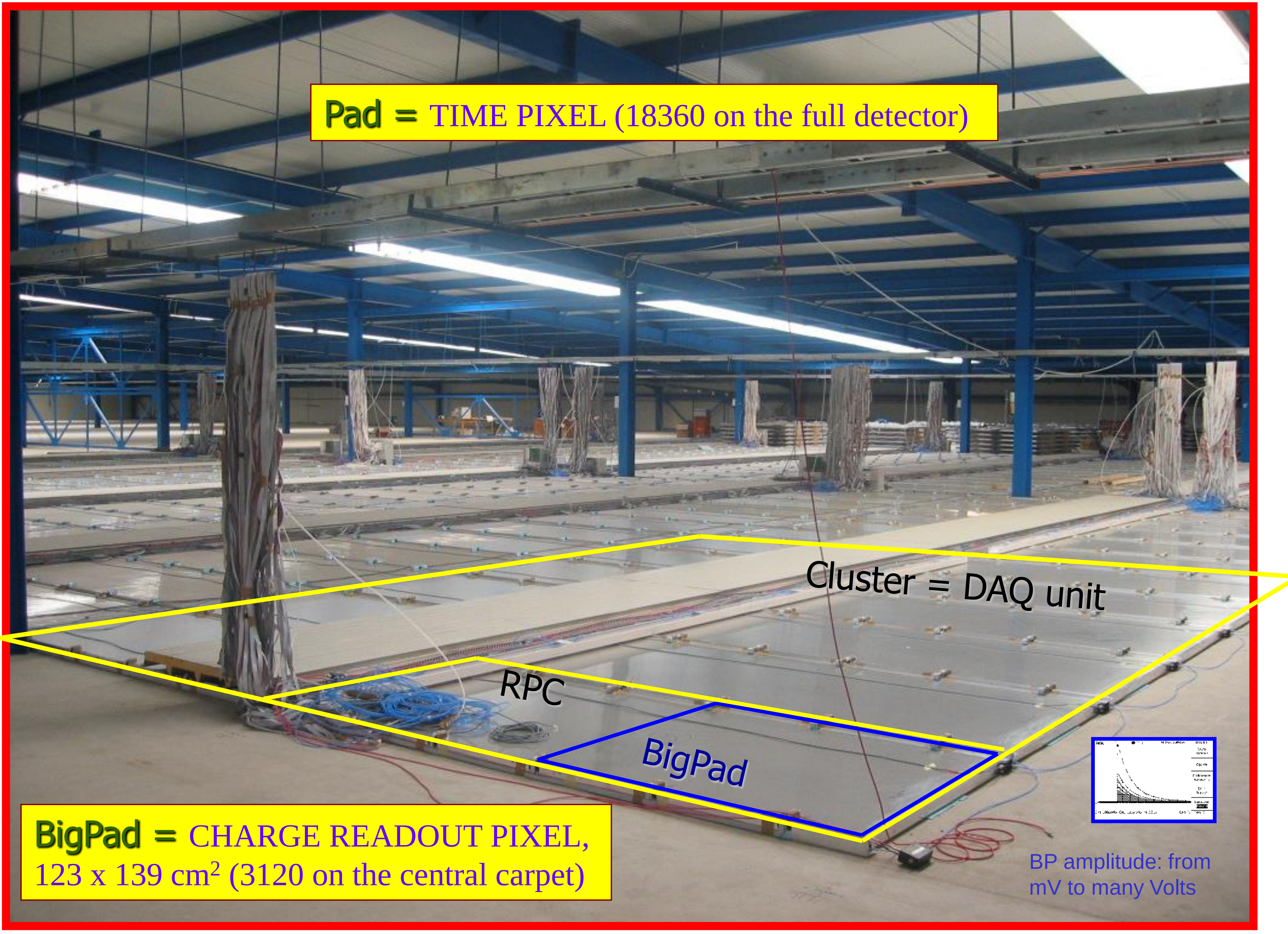
Detector layout

time resolution ~1.8 ns
space resolution = strip



Single layer of Resistive Plate Chambers (RPCs)
with a full coverage (93% active surface) of a large area (5600 m^2)
+ sampling guard ring (6700 m^2 in total)

⇒ detection of small showers (low energy threshold)


Pad = TIME PIXEL (18360 on the full detector)
Cluster = DAQ unit
RPC
BigPad
BigPad = CHARGE READOUT PIXEL, 123 x 139 cm2 (3120 on the central carpet)
BP amplitude: from mV to many Volts

ARGO-YBJ operation modes

The detector carpet is connected to two different DAQ systems, working independently:

Shower Mode:

for each event the location and timing of each detected particle is recorded, allowing the reconstruction of the lateral distribution and of the arrival direction

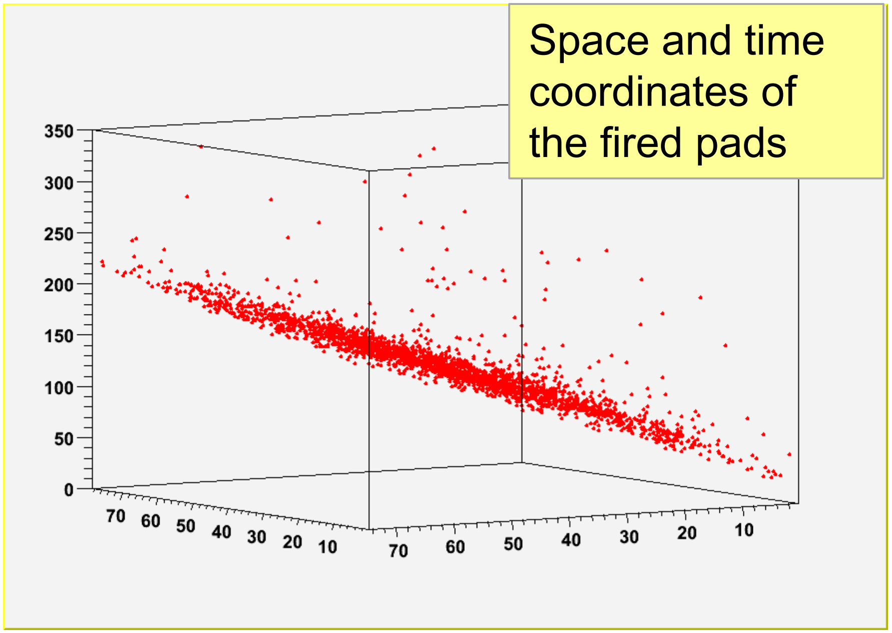
$\mathbf{E_{th} \approx 300\ GeV}$

Scaler Mode:

the counting rate of each CLUSTER is measured every 0.5 s, with no information on both the space distribution and the arrival direction of the detected particles

$\mathbf{E_{th} \approx 1\ GeV}$

Shower Data



- Trigger: $\geq$ 20 particles
- Trigger rate: ~3.5 kHz
- Duty cycle: > 86%
- Dead time: 4%

- Start of the installation of the RPCs in 2001
- Commissioning of the central carpet in June 2006
- Start of data taking with full detector in November 2007
- End of data taking in February 2013
- > 5 $\times 10^{11}$ events collected

ARGO-YBJ: a multi-purpose experiment

- CR physics from 1 TeV to 10^4 TeV
  - (p + He) spectrum
  - knee region
  - anisotropies
- Survey of the γ-ray sky in the band $-10° \leq$ decl. $\leq 70°$
- High exposure for flaring activity
  (γ-ray sources, Gamma Ray Bursts, solar flares)
- CR $\bar{p}/p$ flux ratio at TeV energies
- Hadronic interactions (p-air and p-p cross sections)
- Solar and heliosphere physics

Selected results in gamma-ray astronomy

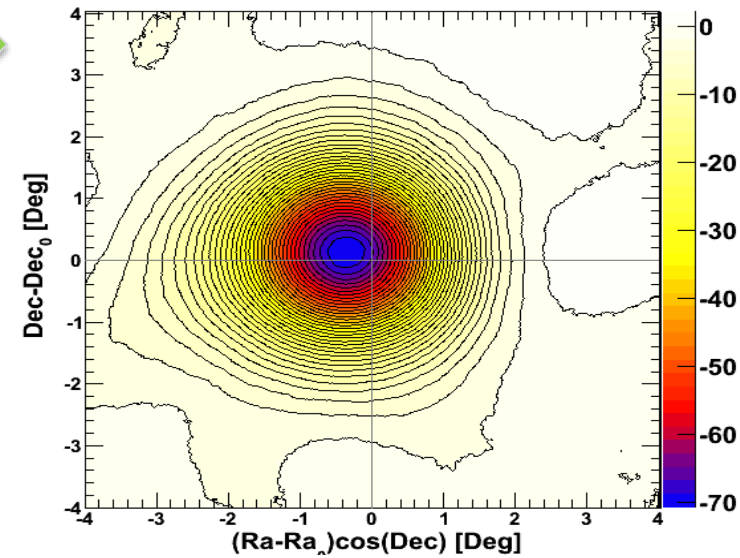
- **Sky survey of the Northern hemisphere** $(-10^\circ < \delta < 70^\circ)$
- **Crab Nebula**
- **Mrk 501**
- **Cygnus region**
- **Diffuse γ-rays from the Galactic plane**
- **Gamma Ray Bursts**

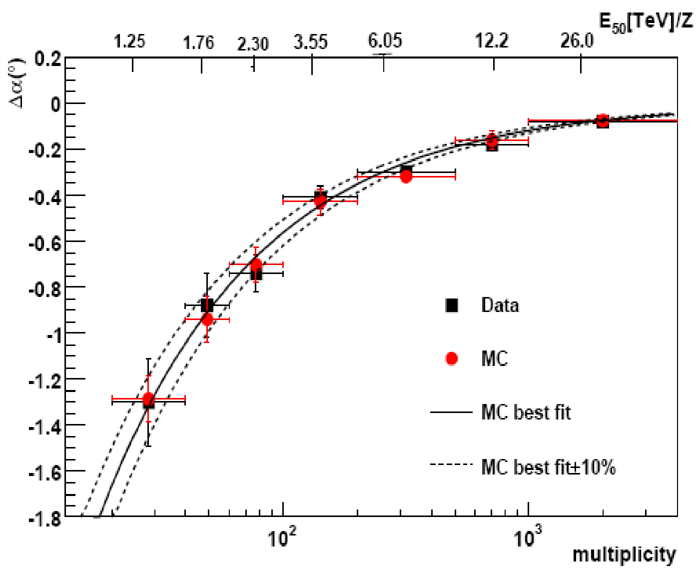
Analysis of the Moon shadow

Phys. Rev. D 84 (2011) 022003

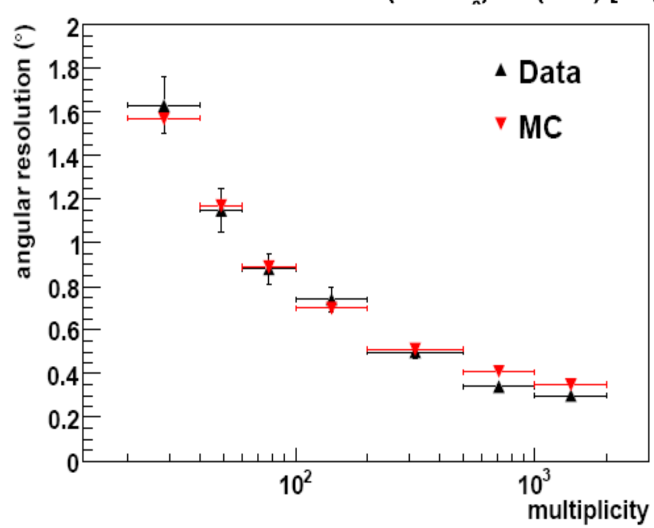
A natural tool to estimate the detector performance: $N_{pad} > 100$; 71 s.d.

- Pointing accuracy
- Angular resolution
- Absolute energy calibration





The energy scale uncertainty is estimated to be < 13% in the rigidity range 1 – 30 TeV/Z

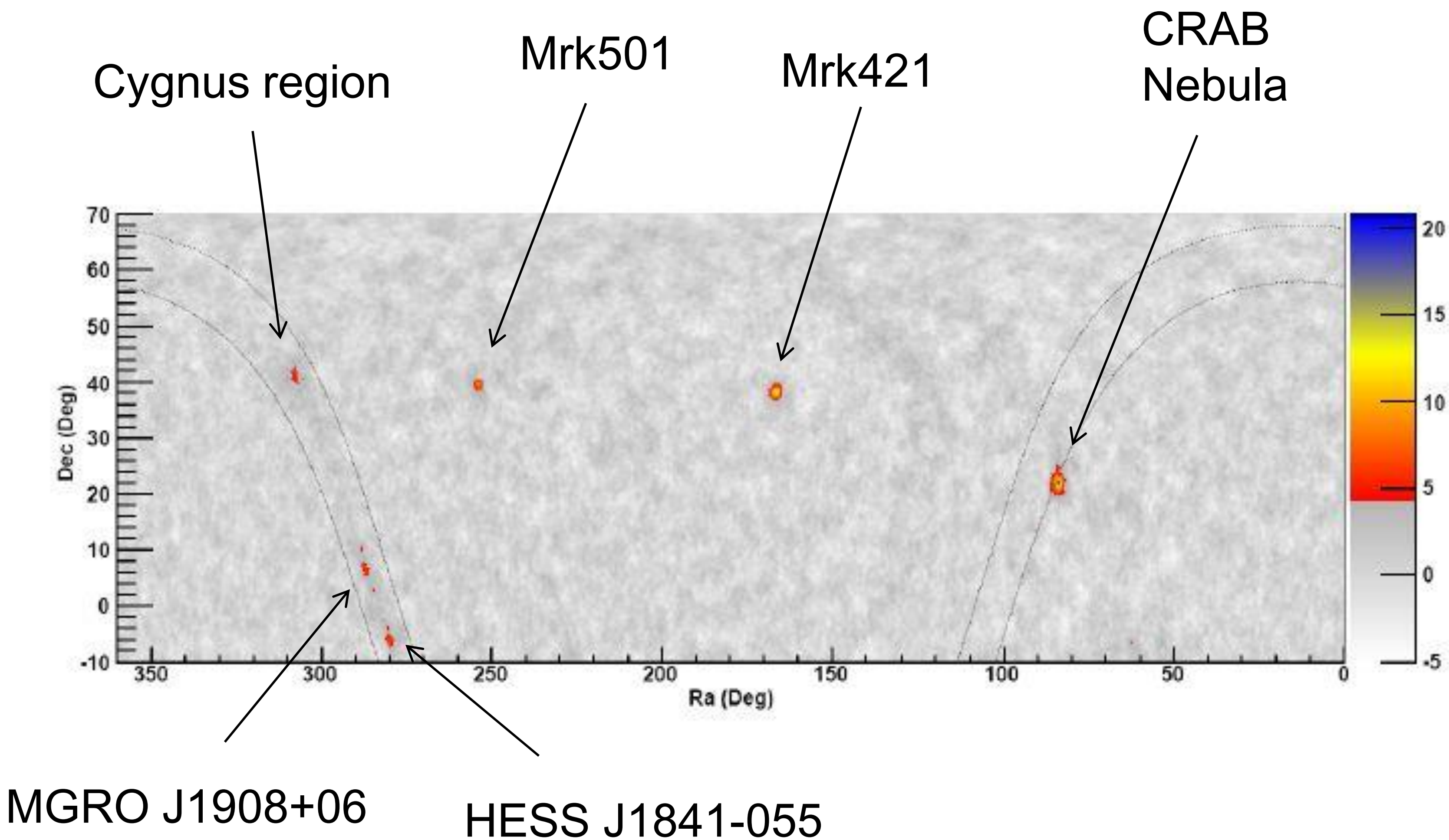


Angular resolution

Sky survey

ApJ 779 (2013) 27

ARGO-YBJ sensitivity (5 years of data taking) : 0.24 Crab units



6 sources with S > 5 s.d. + 5 hotspots with S > 4 s.d.

List of detected and candidate sources

Table 2
Location of the Excess Regions

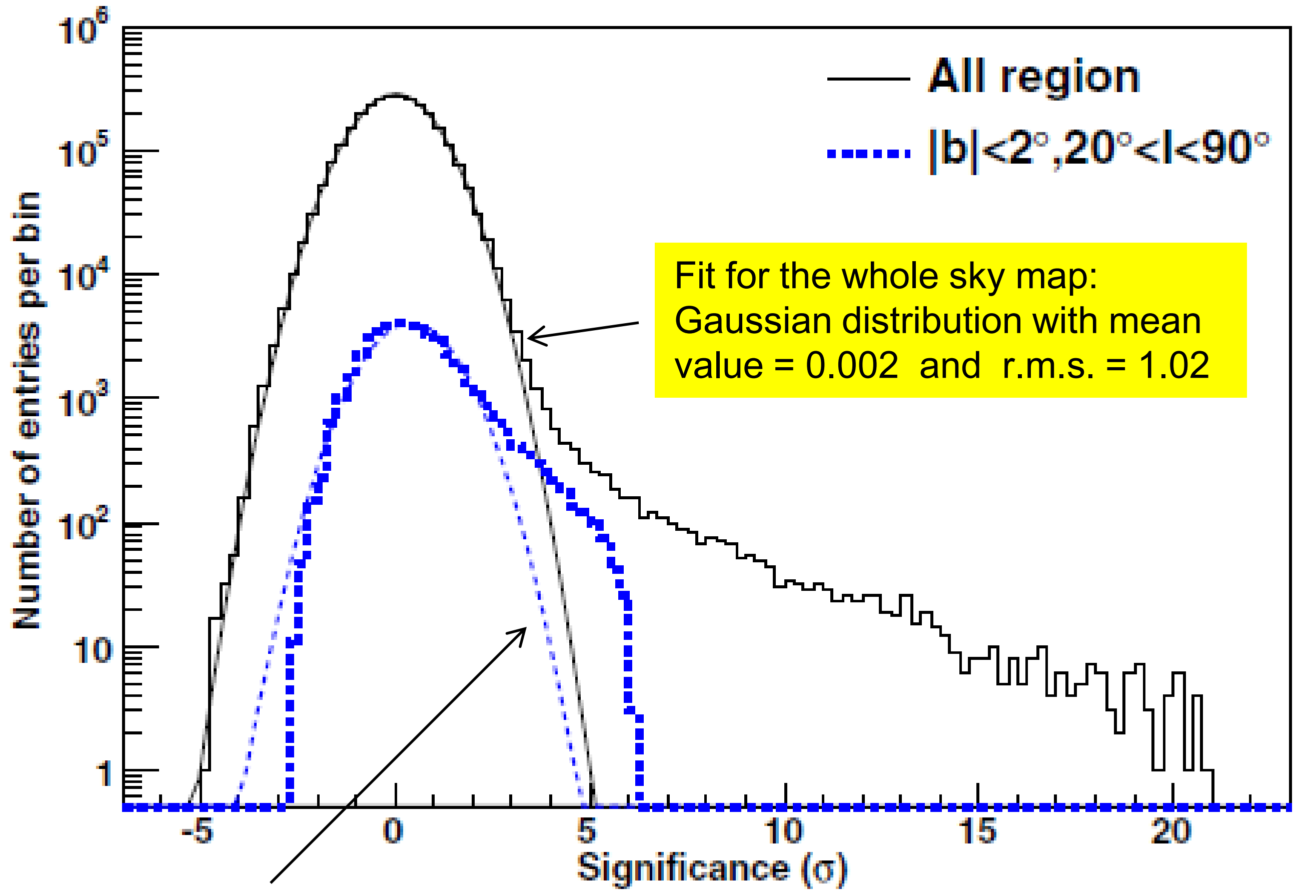
$N_{pad} \geq 20$

ARGO-YBJ Name	R.A.[a] (deg)	Decl.[a] (deg)	l (deg)	b (deg)	S (s.d.)	Associated TeV Source
ARGO J0409−0627	62.35	−6.45	198.51	−38.73	4.8	
ARGO J0535+2203	83.75	22.05	184.59	−5.67	20.8	Crab Nebula
ARGO J1105+3821	166.25	38.35	179.43	65.09	14.1	Mrk 421
ARGO J1654+3945	253.55	39.75	63.59	38.80	9.4	Mrk 501
ARGO J1839−0627	279.95	−6.45	25.87	−0.36	6.0	HESS J1841−055
ARGO J1907+0627	286.95	6.45	40.53	−0.68	5.3	HESS J1908+063
ARGO J1910+0720	287.65	7.35	41.65	−0.88	4.3	
ARGO J1912+1026	288.05	10.45	44.59	0.20	4.2	HESS J1912+101
ARGO J2021+4038	305.25	40.65	78.34	2.28	4.3	VER J2019+407
ARGO J2031+4157	307.95	41.95	80.58	1.38	6.1	MGRO J2031+41
						TeV J2032+4130
ARGO J1841−0332	280.25	−3.55	28.58	0.70	4.2	HESS J1843−033

$N_{pad} \geq 100$

Note. [a] R.A. and decl. are celestial coordinates in J2000 epoch.

Distribution of Significances



Fit for the whole sky map:
Gaussian distribution with mean
value = 0.002 and r.m.s. = 1.02

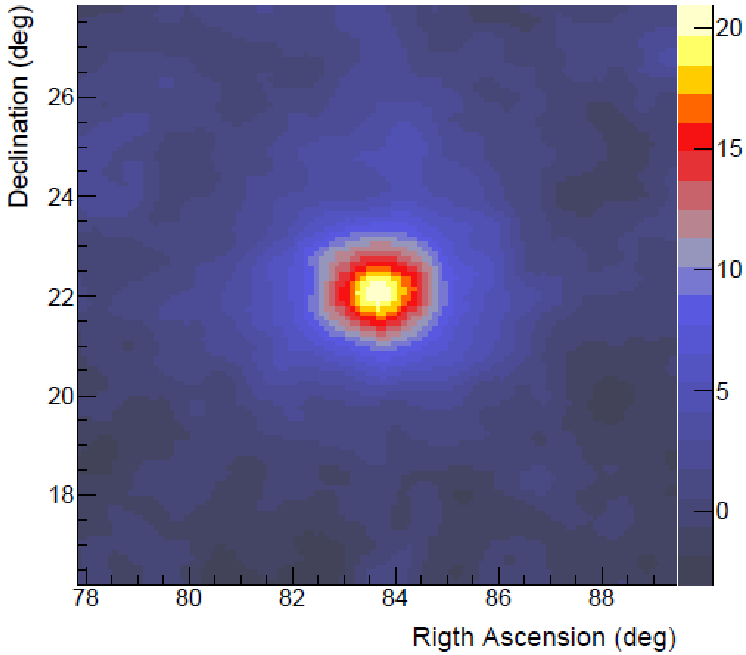
Fit for the inner Galactic plane:
Gaussian distribution with mean
value = 0.40 and r.m.s. = 1.04

Crab Nebula

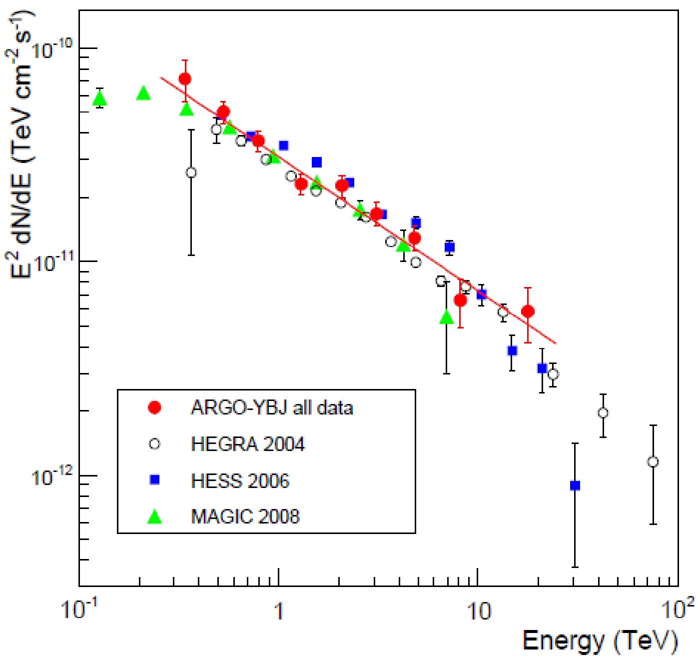
Paper in preparation

- **Measured Point Spread Function in agreement with MC simulations**
- **Energy spectrum in 0.3–20 TeV in agreement with other experiments**

$$dN/dE = (5.2 \pm 0.2)\cdot 10^{-12}\cdot (E/2\ \mathrm{TeV})^{(-2.63 \pm 0.05)}\ \mathrm{cm^{-2}\,s^{-1}\,TeV^{-1}}$$



Significance map for $N_{pad} > 20$



Spectrum multiplied by E^2

Crab event rate

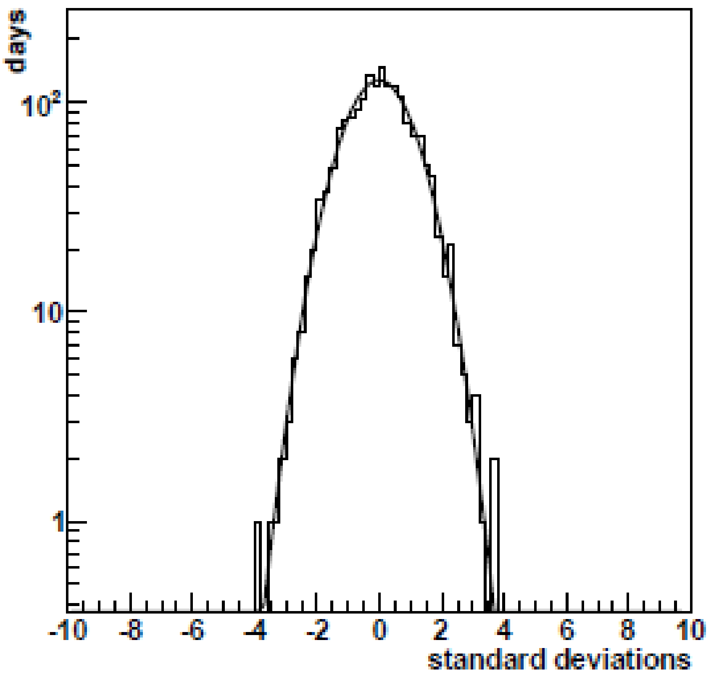
$N_{pad} \geq 40$

$\langle s \rangle$ = -0.014 ±0.026

r.m.s. = 1.086 ± 0.019

Distribution of the daily excess significances in ~1800 days

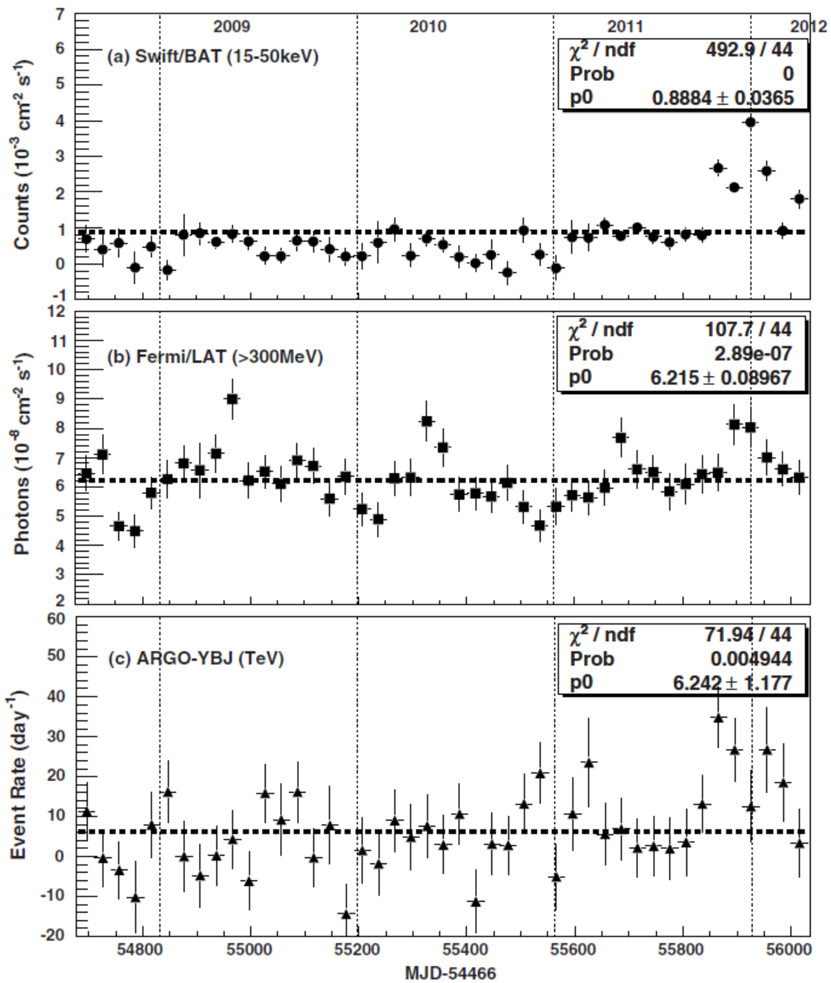
Average rate: 16.5 ev/hour



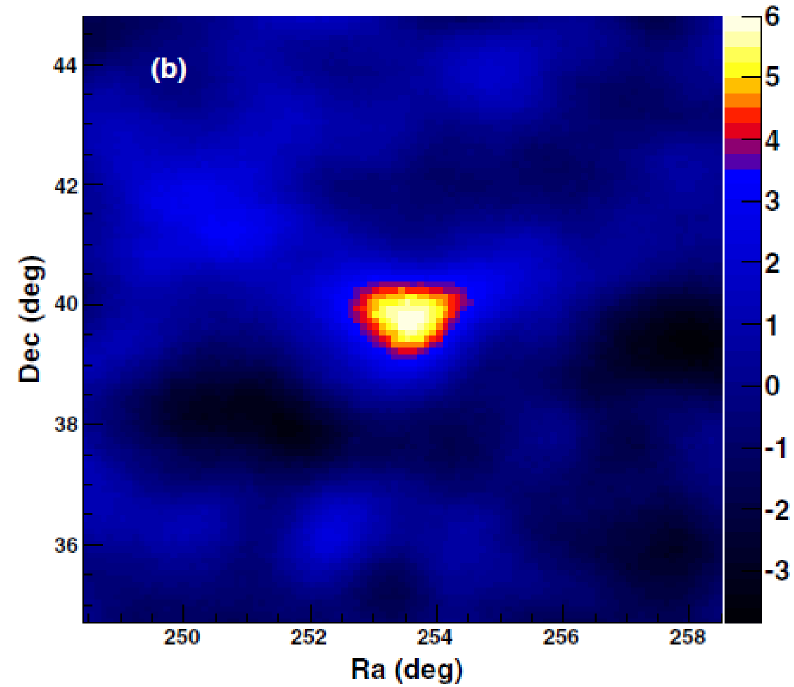
Alternative check of the detector stability

Mrk 501: long-term monitoring and flare

ApJ 758 (2012) 2 (similar paper for Mrk 421 in ApJ 734 (2011) 110)



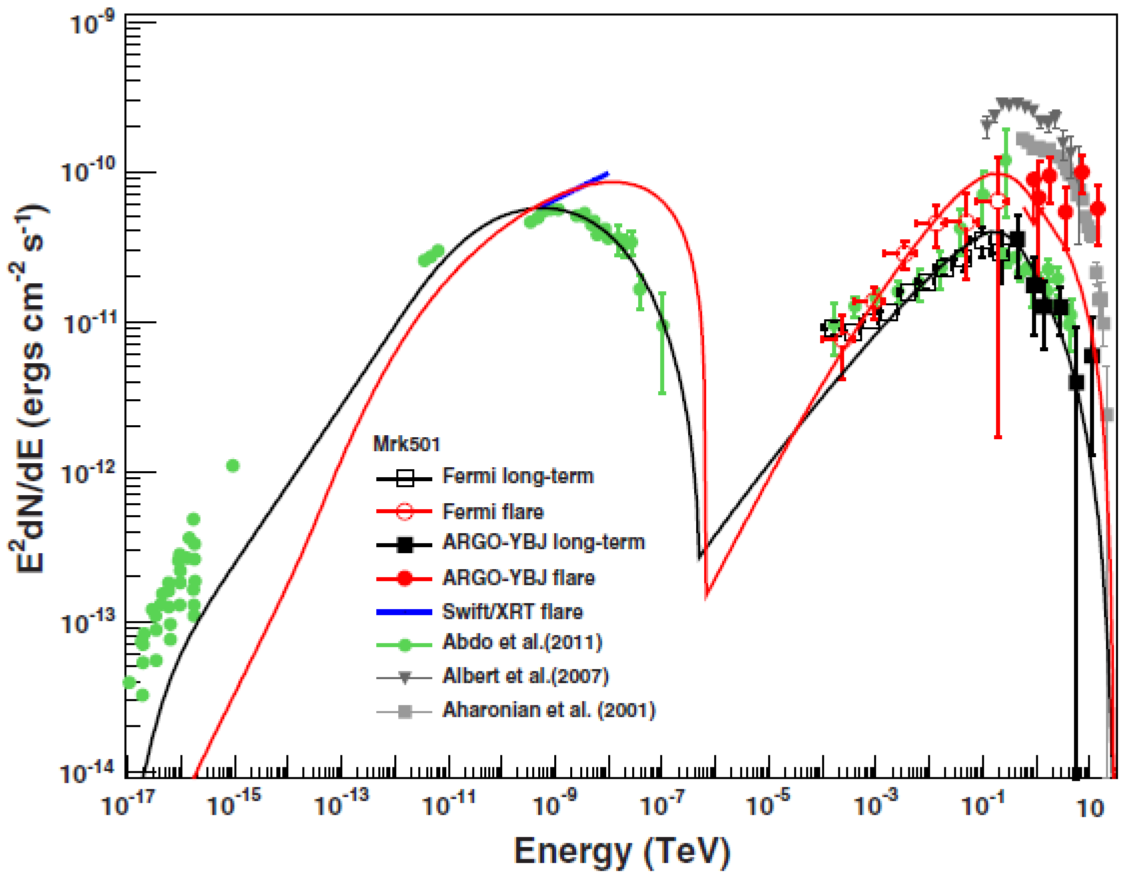
Largest flare in 2011, from October 17 to November 22: TeV flux ~ 2 Crab units, ~ 6.6 the long-term steady state



bins with 30 days

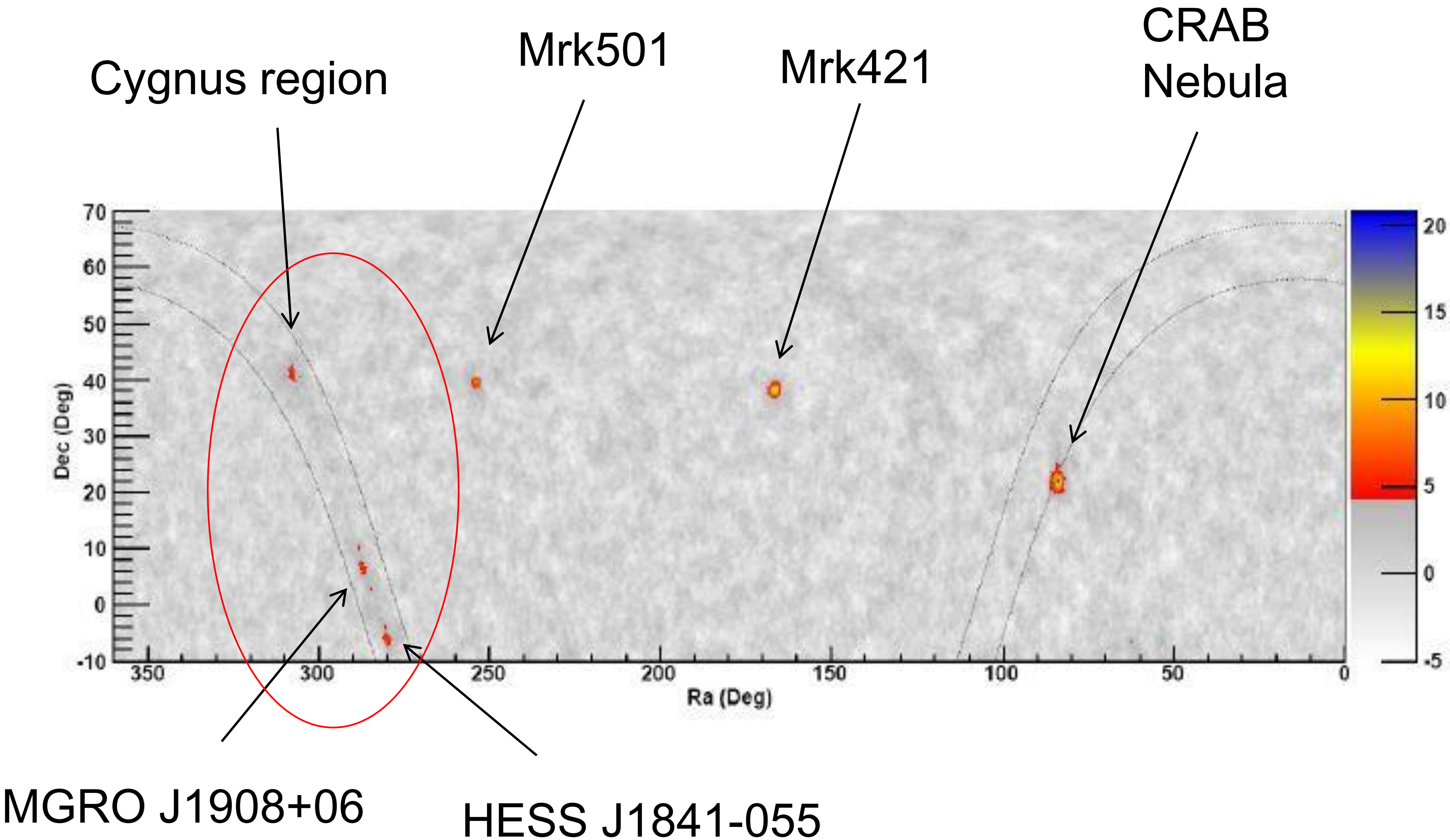
$N_{pad} \geq 60$; $S_{max} = 6.1$ s.d.

Mrk501: Spectral Energy Distribution



A simple one-zone SSC model is unable to reproduce the flaring emission at E > 8 TeV, while the long-term data are well fitted

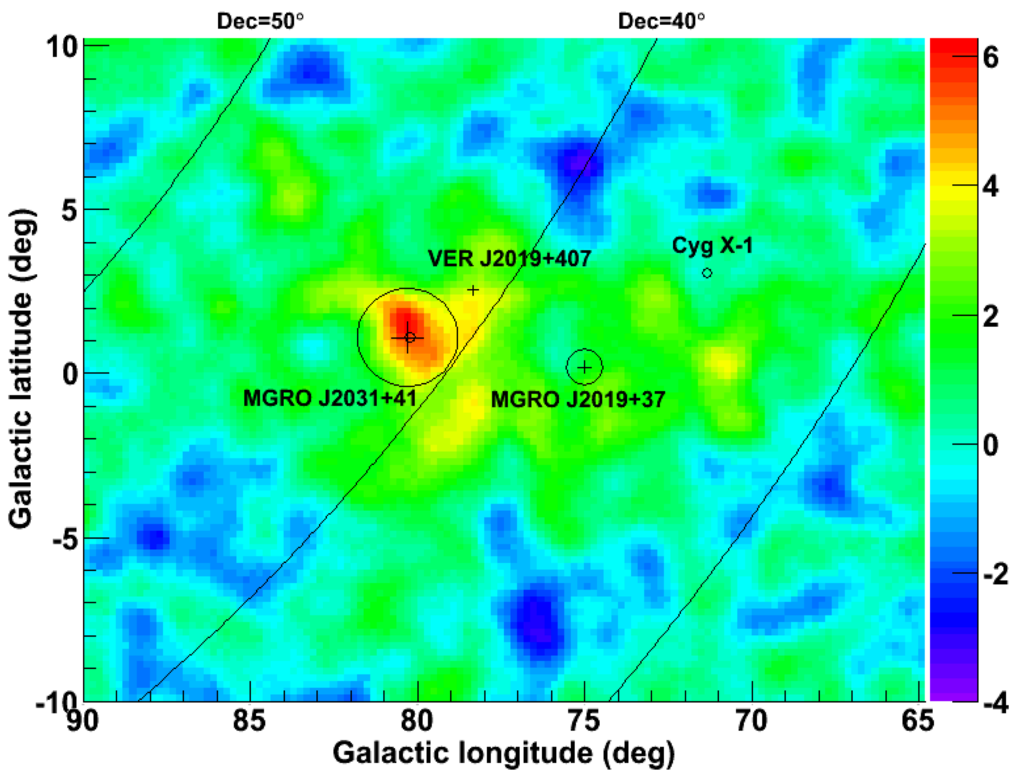
Extended Sources in the Galactic Plane



Cygnus region

ApJ 745 (2012) L22

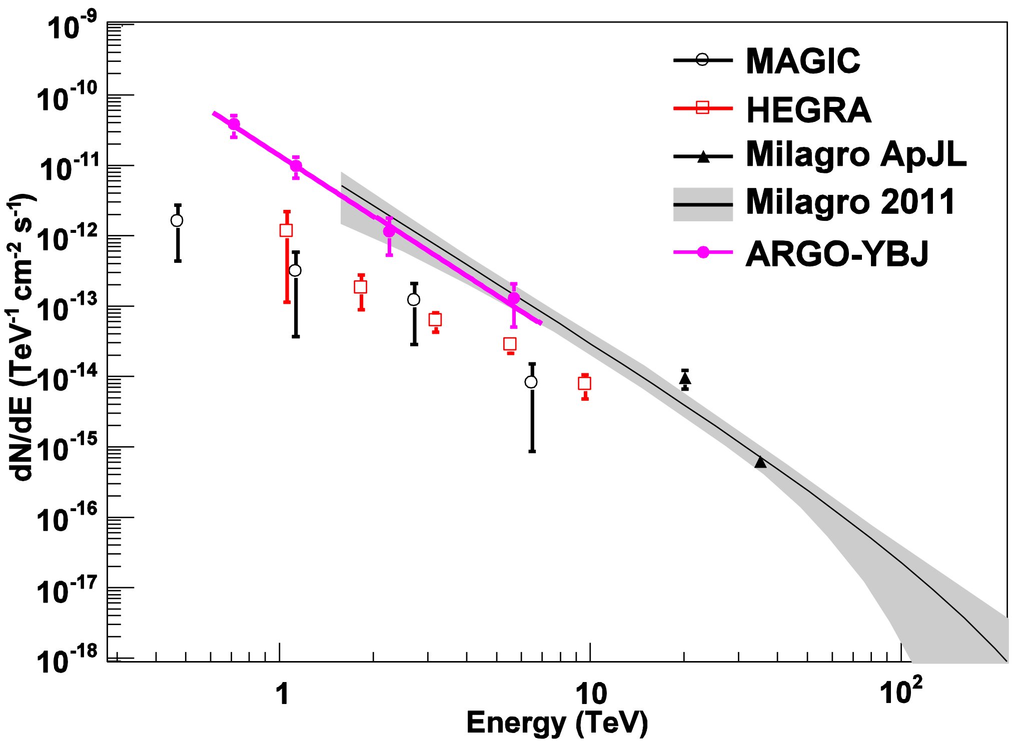
- MGRO J2031+41/TeV J2032 +4130 → **6.4 s.d.**
- No significant signal from MGRO J2019+37 **(< 3.0 s.d.)**



Cygnus region: MGRO J2031+41

- Extension $\sigma_{ext} = (0.2^{+0.4}_{-0.2})^{\circ}$ consistent with HEGRA and MAGIC $\sigma_{ext} \sim 0.1°$
- Spectrum: $dN/dE \propto E^{-2.83 \pm 0.37}$ (assuming $\sigma_{ext} = 0.1°$)
- Flux (E > 1 TeV) ~ 0.3 Crab unit, in agreement with Milagro

  but about a factor 10 higher than HEGRA and MAGIC results



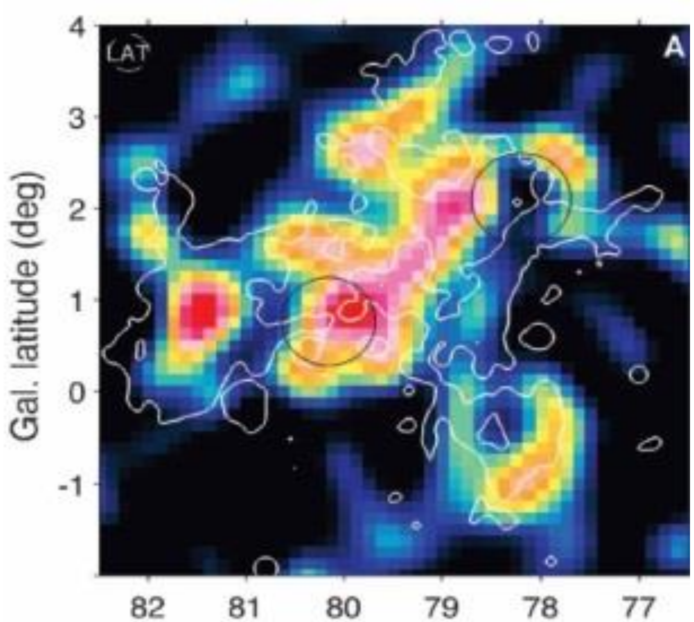
ARGO J2031+4157 as the Cygnus Cocoon

Paper submitted

A cocoon of freshly accelerated cosmic rays

The Fermi / LAT view

in the 10-100 GeV band:

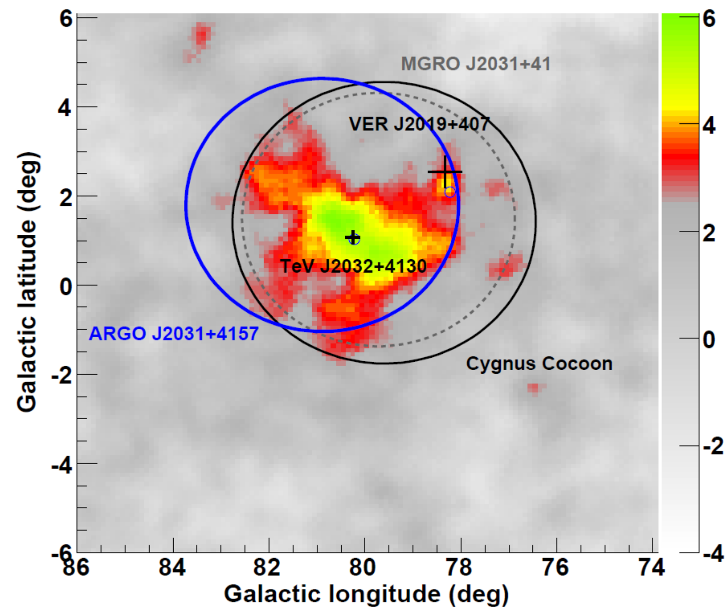


Ackermann et al.,
Science 334 (2011) 1103

The ARGO-YBJ view

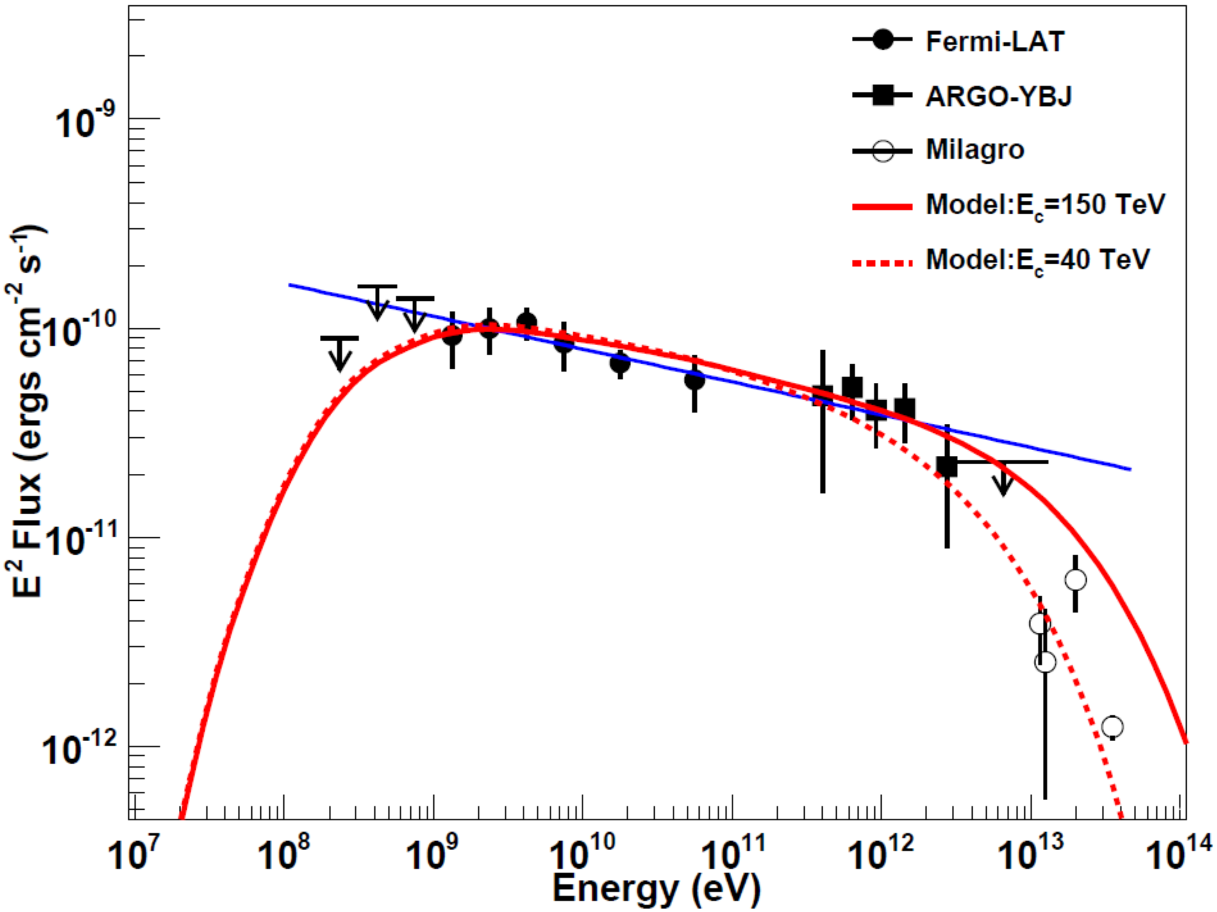
at TeV energies ($N_{pad} \geq 20$)

after reanalysis with the full data:



S_{max} = 6.1 s.d.
σ_{ext} = 1.8°±0.5°

Spectrum of the Cygnus Cocoon



Milagro data refer to MGRO J2031+41, at 12 TeV also corrected for the extrapolation of TeV J2032+4130

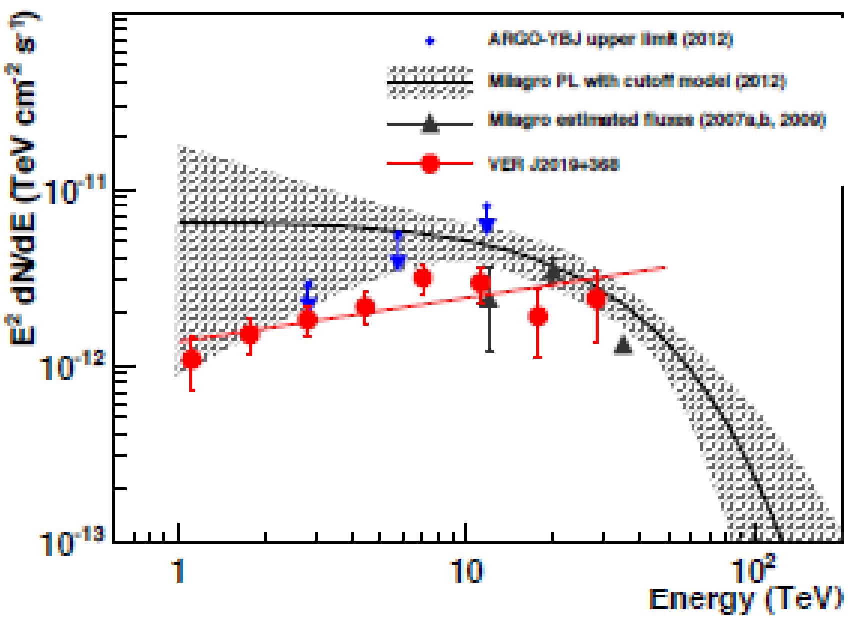
A pure hadronic model was assumed with a power law and a cutoff energy E_c

Spectrum of ARGO J2031+4157: dN/dE $\propto$ $E^{-2.62\pm0.27}$

Combined LAT&ARGO spectrum: dN/dE $\propto$ $E^{-2.16\pm0.04}$

Cygnus region: MGRO J2019+37

- The most intense Milagro source (12.4 s.d.) after the Crab
- Milagro spectrum: $dN/dE = 5.4\ 10^{-12} \cdot E^{-1.83} \exp(-E/22.4)\ \ cm^{-2}\ sec^{-1}\ TeV^{-1}$
- Extension: $\sigma_{ext} = (0.32 \pm 0.12)^{\circ}$
- VERITAS recently (arXiv:1404.1841) resolved it in two different sources: the faint point-like VER J2016+371 and the extended (~ 1°) VER J2019+368



VER J2019+368 likely contributes to the bulk of the emission observed by Milagro and coincides with the PSR J2021+3651 and the star formation HII region Sh2-104

A few years of Δt (Milagro - ARGO) → flux variability of the components?

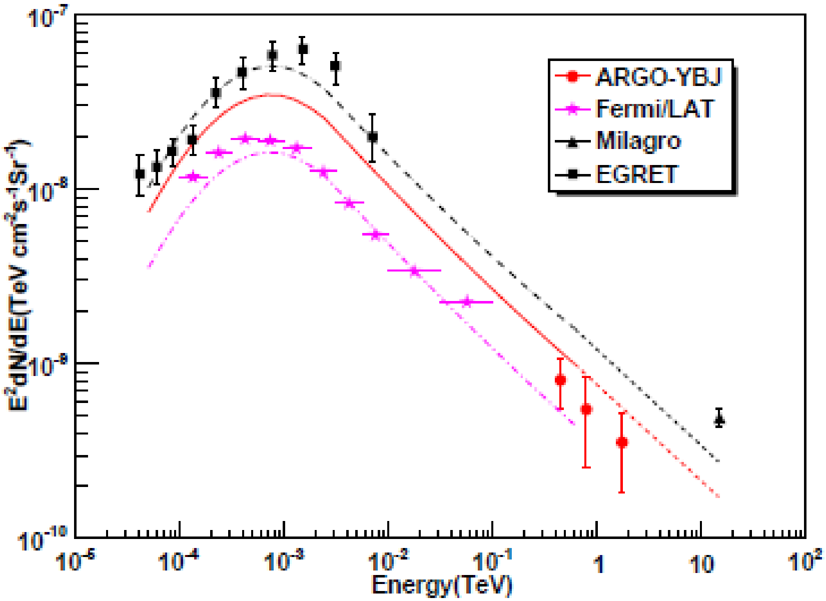
Comments on extended sources

- Considering also the ARGO-YBJ results for MGRO J1908+06 (ApJ 760 (2012) 110) and HESS J1841-055 (ApJ 767 (2013) 99), as for the air shower array Milagro, the fluxes measured in extended sources are systematically larger than those measured with Cherenkov telescopes
- A contribution is due to the diffuse emission from the Galactic plane, however it cannot explain the observed disagreement, being < 15 %
- The overall systematic error on the flux has been estimated to be < 30%

Diffuse γ-rays from the Galactic plane

Paper in preparation

Cygnus region: 65° < l < 85° ; |b| < 5°



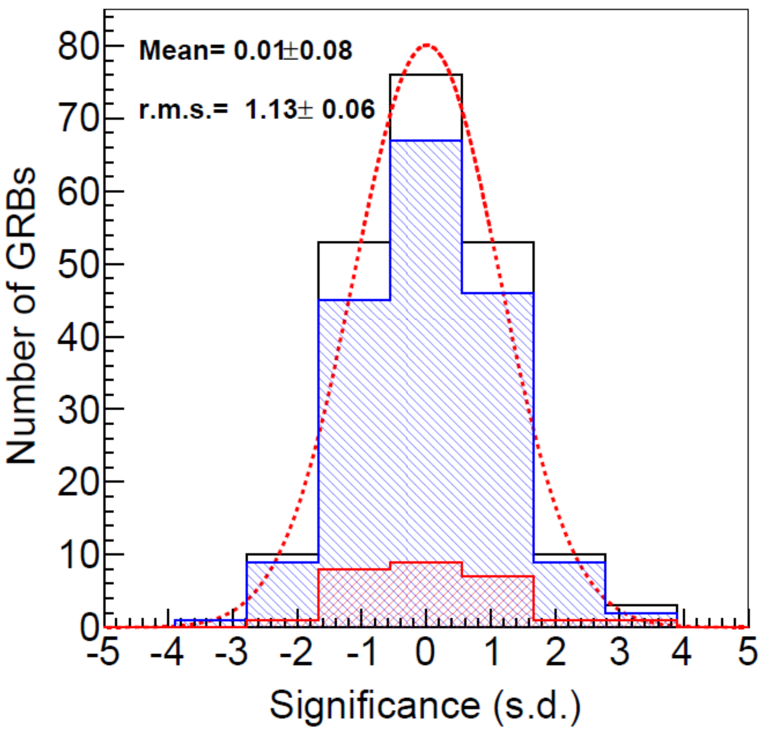
The different lines indicate the energy spectra expected from the Fermi/LAT template (with spectral index -2.6) in the different sky regions investigated by the detectors

The TeV diffuse flux in the Cygnus region does not show a strong excess like that reported by Milagro at 15 TeV

The difference may be due to the Cygnus Cocoon, not yet discovered at the time of the Milagro measurement

Search for GRBs in scaler mode

ApJ 699 (2009) 1281 + new paper submitted



206 GRBs in the ARGO f.o.v. from Dec. 2004 to Jan. 2013 (largest sample from ground!)

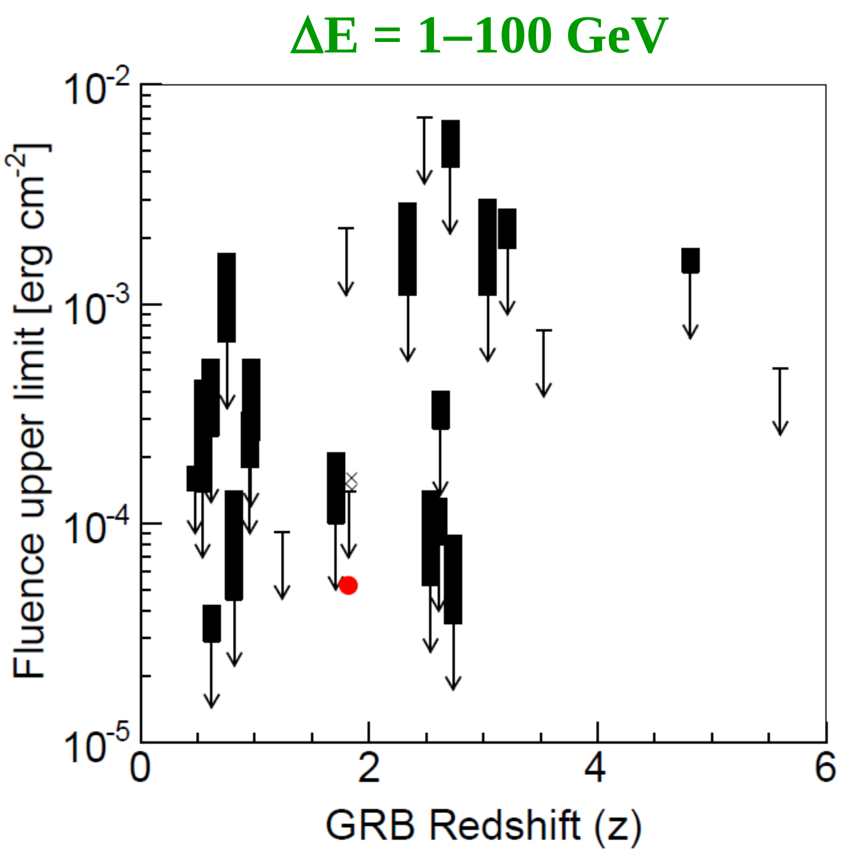
- **With known redshift: 24**
- **Discovered by Fermi/GBM: 90 (including its 2nd GRB catalog)**
- **Detected by Fermi/LAT: 4**

- Long duration GRBs (> 2s): 179
- Short duration GRBs (≤ 2s): 27

- No evidence of coincident signal during the GRB T90 duration

- In stacked analyses (time and phase) no evidence of any integral effect

Upper limits to GRB fluence



Sample of the 24 GRBs with known redshift

The Kneiske et al. (2004) model is adopted to take into account the extragalactic absorption

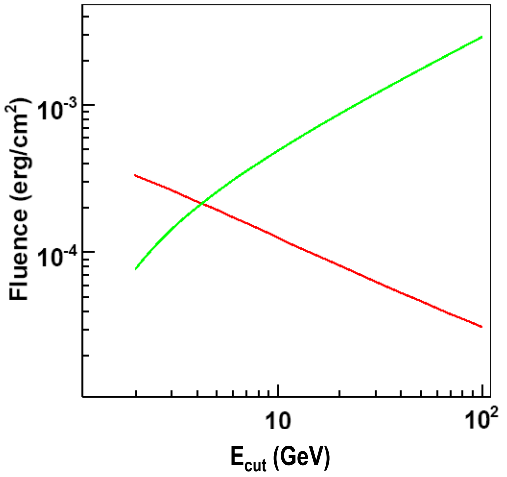
The red dot shows the extrapolated fluence of GRB090902B as observed by Fermi/LAT

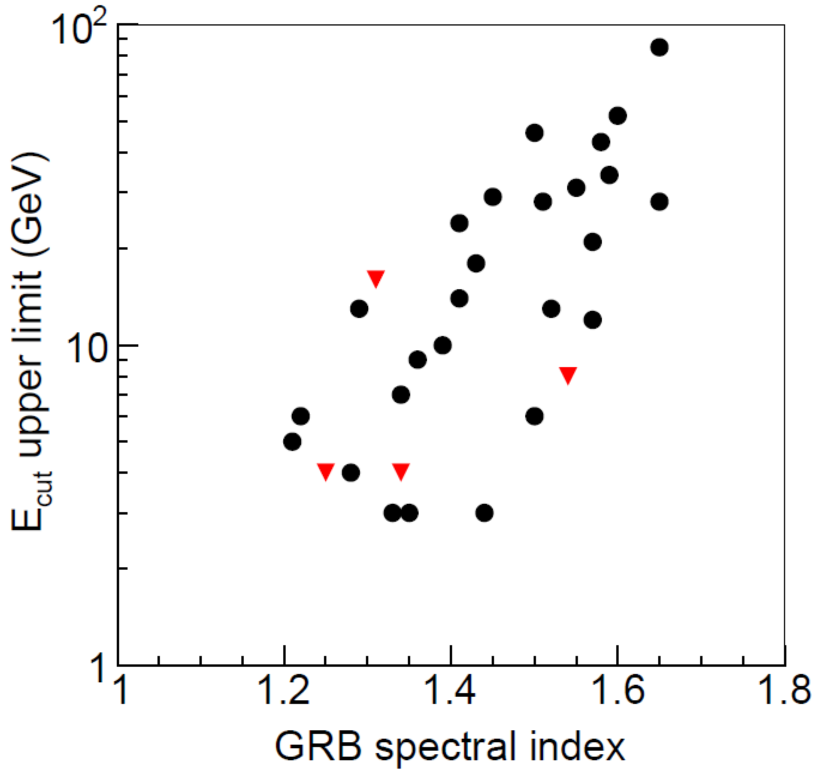
Fluence upper limits (at 99% c.l.) obtained with differential spectral indexes ranging from the value measured by satellites to -2.5

For GRB090902B the LAT index was used with E_{max} = 30–100 GeV

Upper limits to GRB cutoff energy

An upper limit to the GRB cutoff energy E_{cut} is given by the intersection of the fluence upper limit, as a function of E_{cut}, with the extrapolation to $\Delta E = 1$ GeV–E_{cut} of the fluence measured by satellites





The spectra of these GRBs do not extend beyond E_{cut} (with the index measured by satellites) at a 99% c.l.
Red triangles represent GRBs with known redshift, while z = 2 and z = 0.6 are assumed for the other long and short GRBs, respectively

Summary

- **6 sources detected and 5 source candidates in the sky survey of the Northern hemisphere ($-10° < \delta < 70°$) with a sensitivity of 0.24 Crab**
- **The Crab Nebula spectrum is in agreement with other experiments**
- **Continuous long-term monitoring of the flaring sources Mrk 421 and Mrk 501**
- **The fluxes of the extended sources MGRO J2031+41, MGRO J1908+06 and HESS J1841-055 are in agreement with those measured by Milagro but larger than those measured by Cherenkov telescopes**
- **Detection of diffuse γ-rays from the Galactic plane**
- **Upper limits to the emission in the 1–100 GeV range for a sample of 206 Gamma Ray Bursts, the largest ever investigated with a ground-based detector**