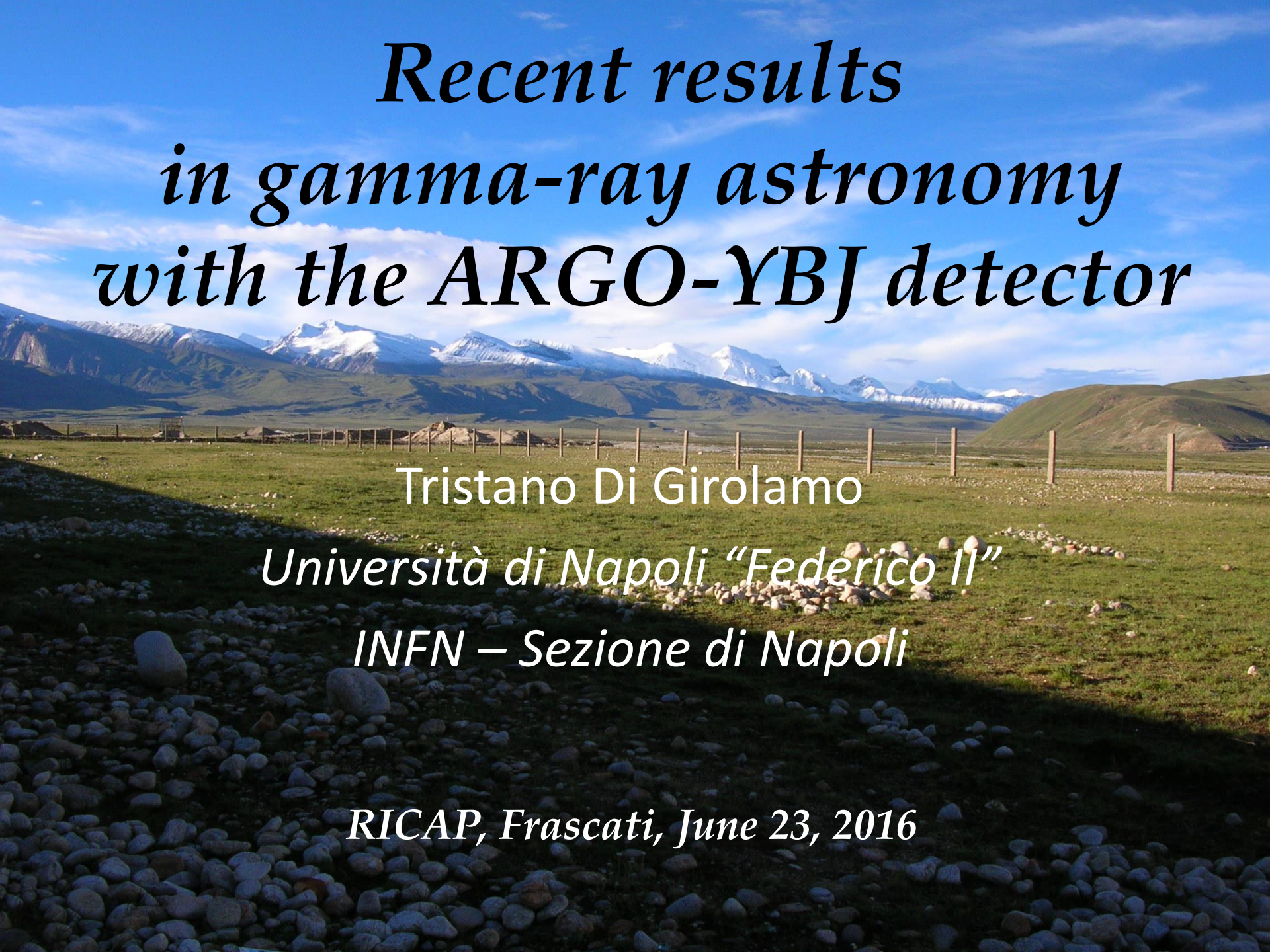


Recent results in gamma-ray astronomy with the ARGO-YBJ detector

Tristano Di Girolamo

Università di Napoli "Federico II"

INFN – Sezione di Napoli

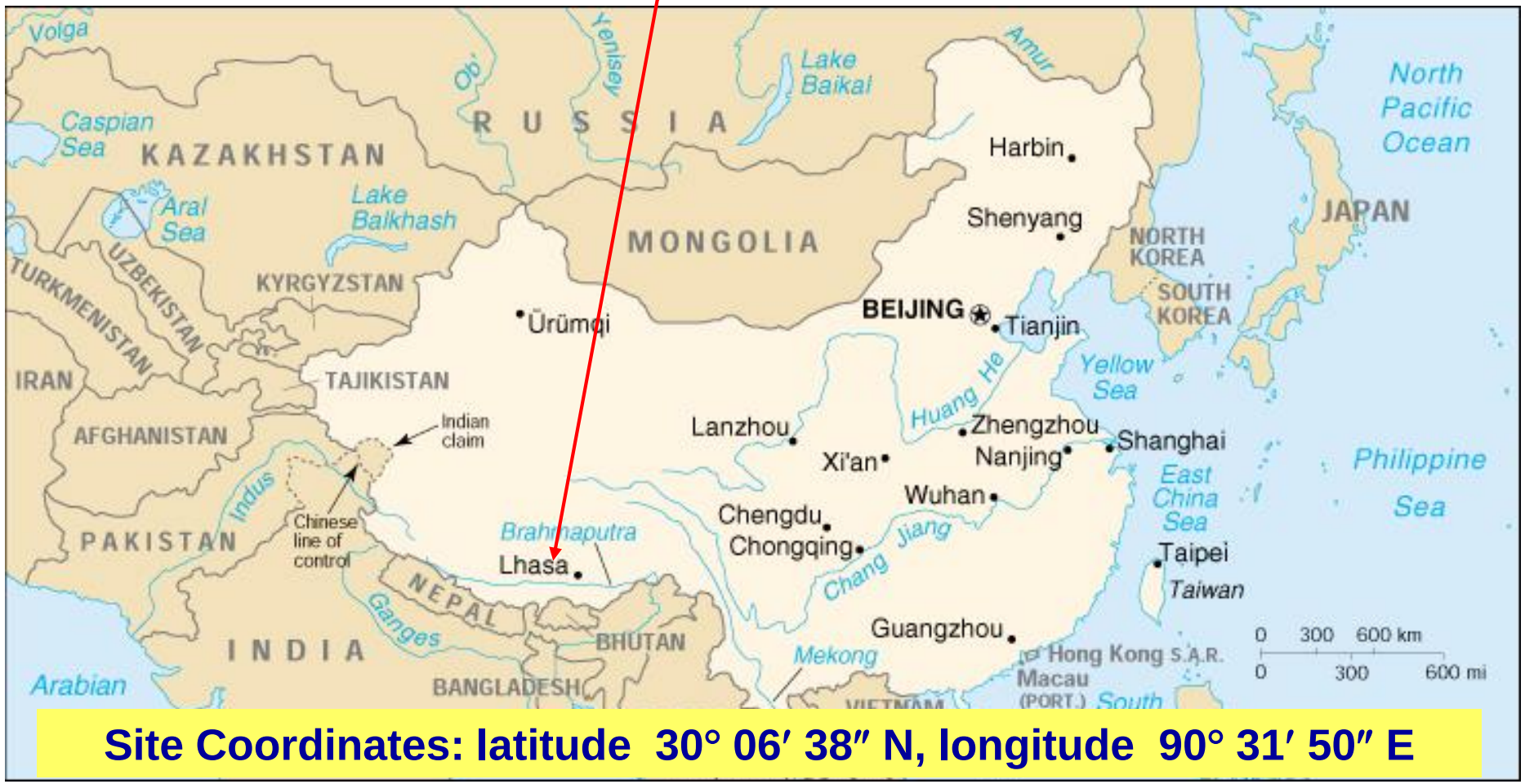
RICAP, Frascati, June 23, 2016

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: latitude 30° 06′ 38″ N, longitude 90° 31′ 50″ E

The ARGO-YBJ collaboration

Collaboration Institutes:

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

Galileo Galilei

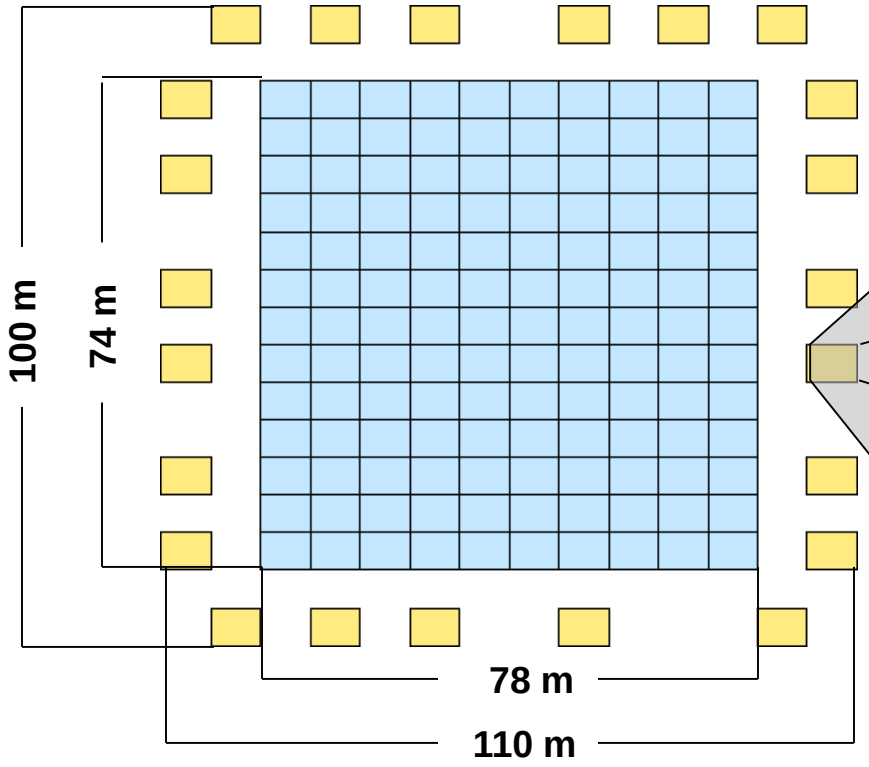
INFN and Dpt. di Fisica Università, Lecce
INFN and Dpt. di Fisica Università, Napoli
INFN and Dpt. di Fisica Università, Pavia
INFN and Dpt. di Fisica Università "Roma Tre", Roma
INFN and Dpt. di Fisica Univesità "Tor Vergata", Roma
INAF/IFSI and INFN, Torino
INAF/IASF, Palermo and INFN, Catania

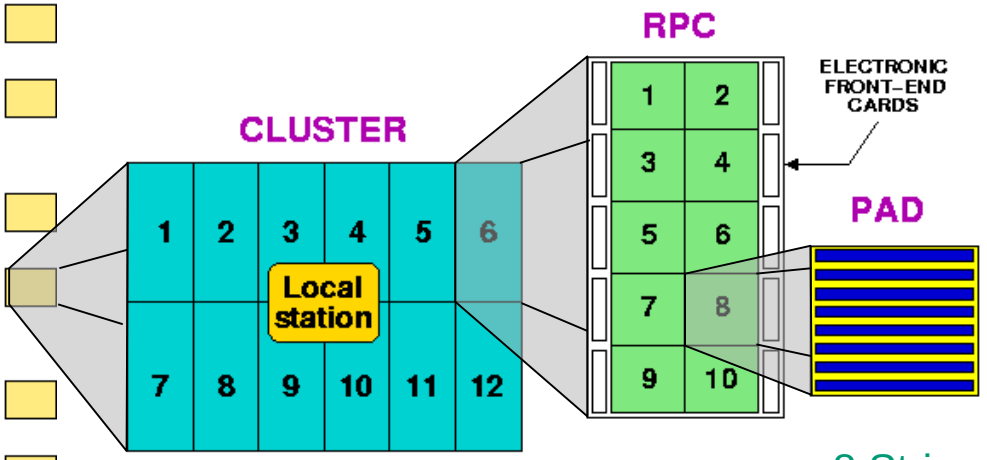
Xu Guangqi

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





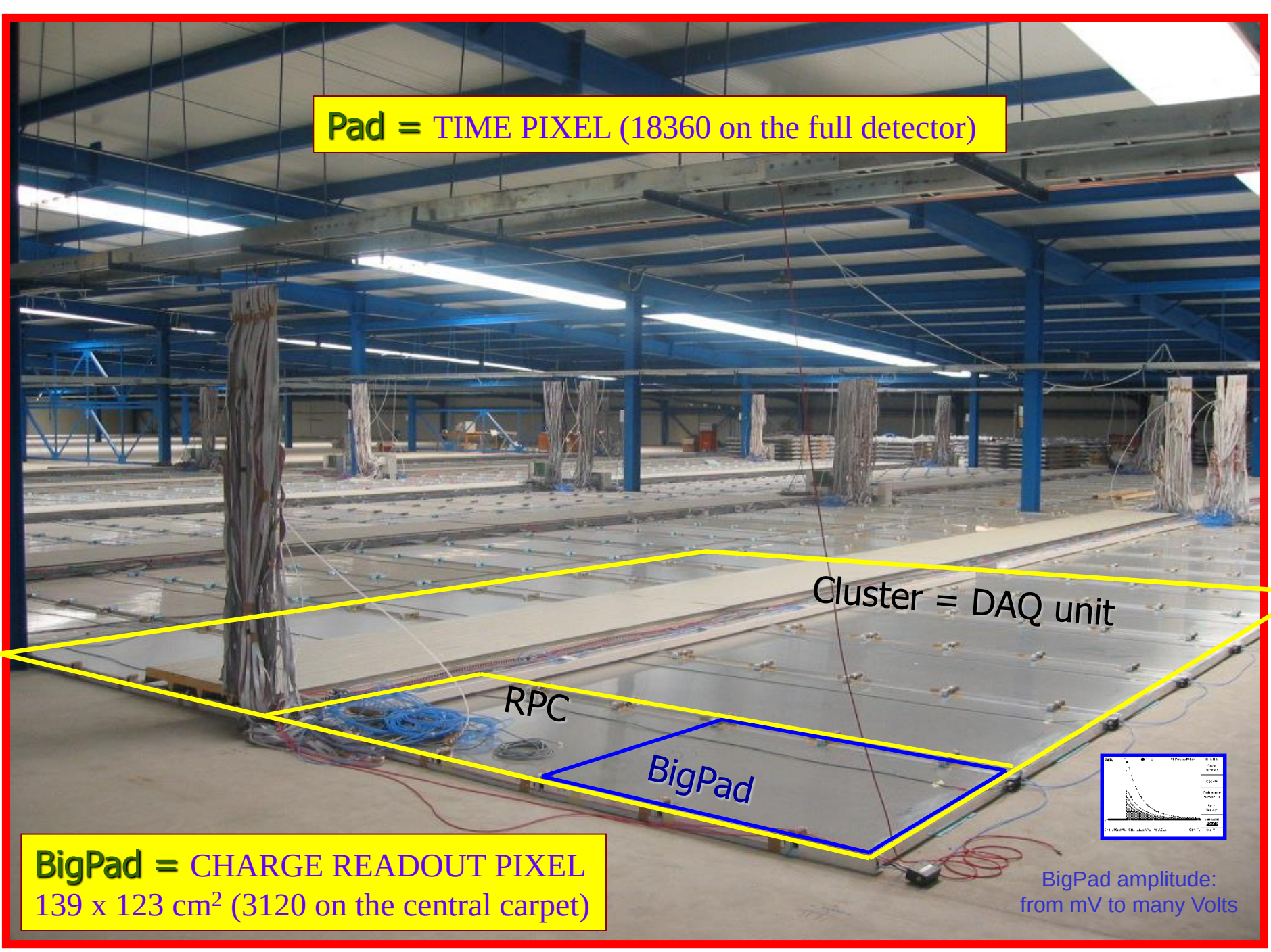
1 CLUSTER = 12 RPCs
(5.7 × 7.6 m^2)

10 Pads
(56 x 62 cm^2)
for each RPC

8 Strips
(7 x 62 cm^2)
for each Pad

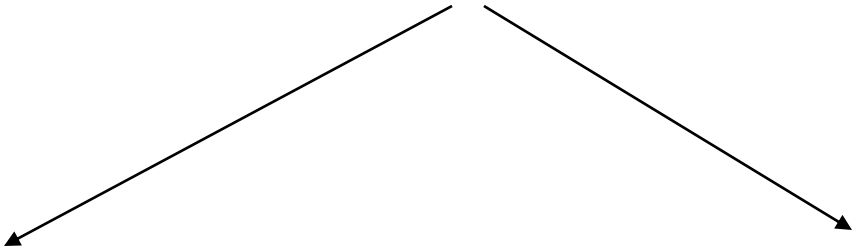
Single layer of Resistive Plate Chambers (RPCs)
with a full coverage (92% active surface) of a large area (5600 m^2)
+ sampling guard ring (6600 m^2 in total)

⇒ **detection of small showers (low energy threshold)**


Pad = TIME PIXEL (18360 on the full detector)
Cluster = DAQ unit
RPC
BigPad
BigPad = CHARGE READOUT PIXEL
139 x 123 cm^2 (3120 on the central carpet)
BigPad amplitude:
from mV to many Volts

ARGO-YBJ operation modes

The detector carpet was 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

$E_{th} \approx 300$ GeV

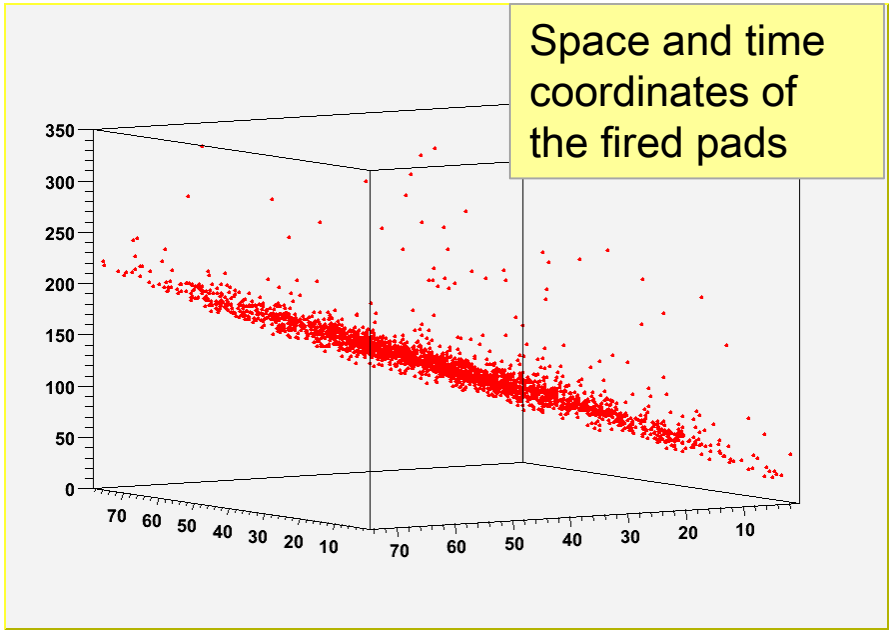
Scaler Mode:

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

$E_{th} \approx 1$ GeV

Shower Data

- Trigger: $\geq$ 20 fired pads
- 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 PeV
  - (p + He) spectrum
  - knee region
  - anisotropies
- Survey of the γ-ray sky in the band $-10° \leq \text{decl.} \leq 70°$
- 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

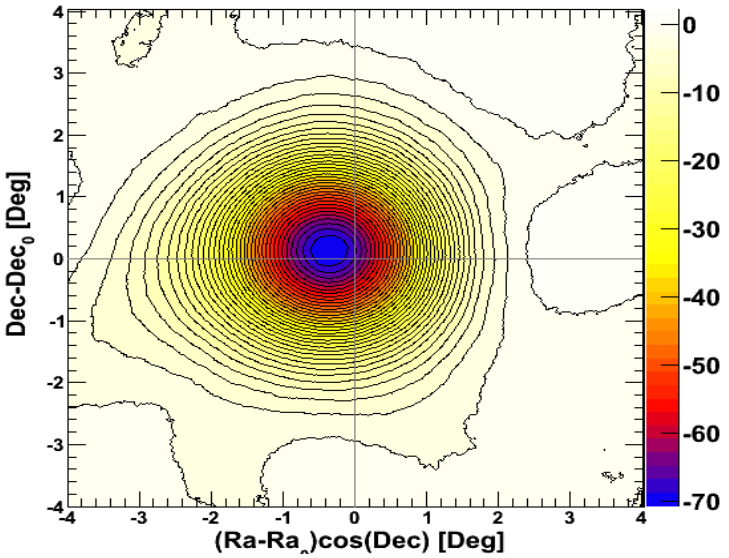
Analysis of the Moon shadow

Phys. Rev. D 84 (2011) 022003

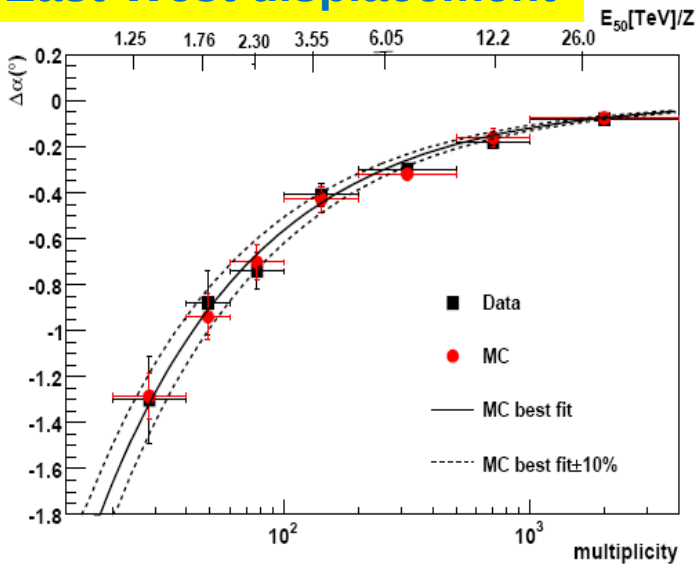
An important tool to determine the detector performance:

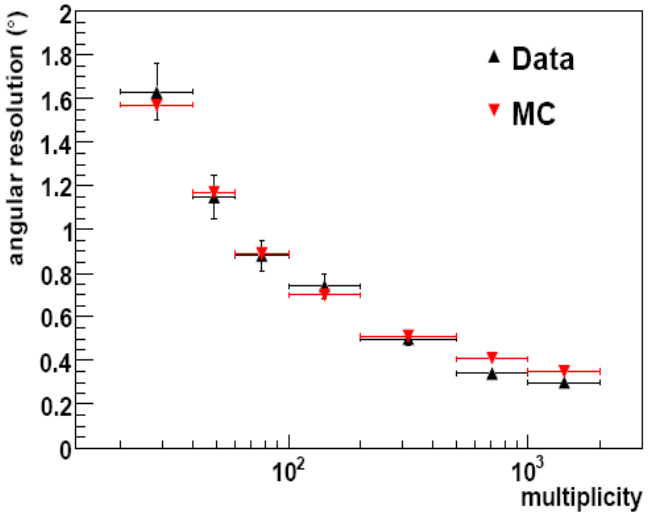
- Pointing accuracy
- Angular resolution
- Absolute energy calibration

$N_{pad} > 100$; 71 s.d.



East-West displacement





Angular resolution

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

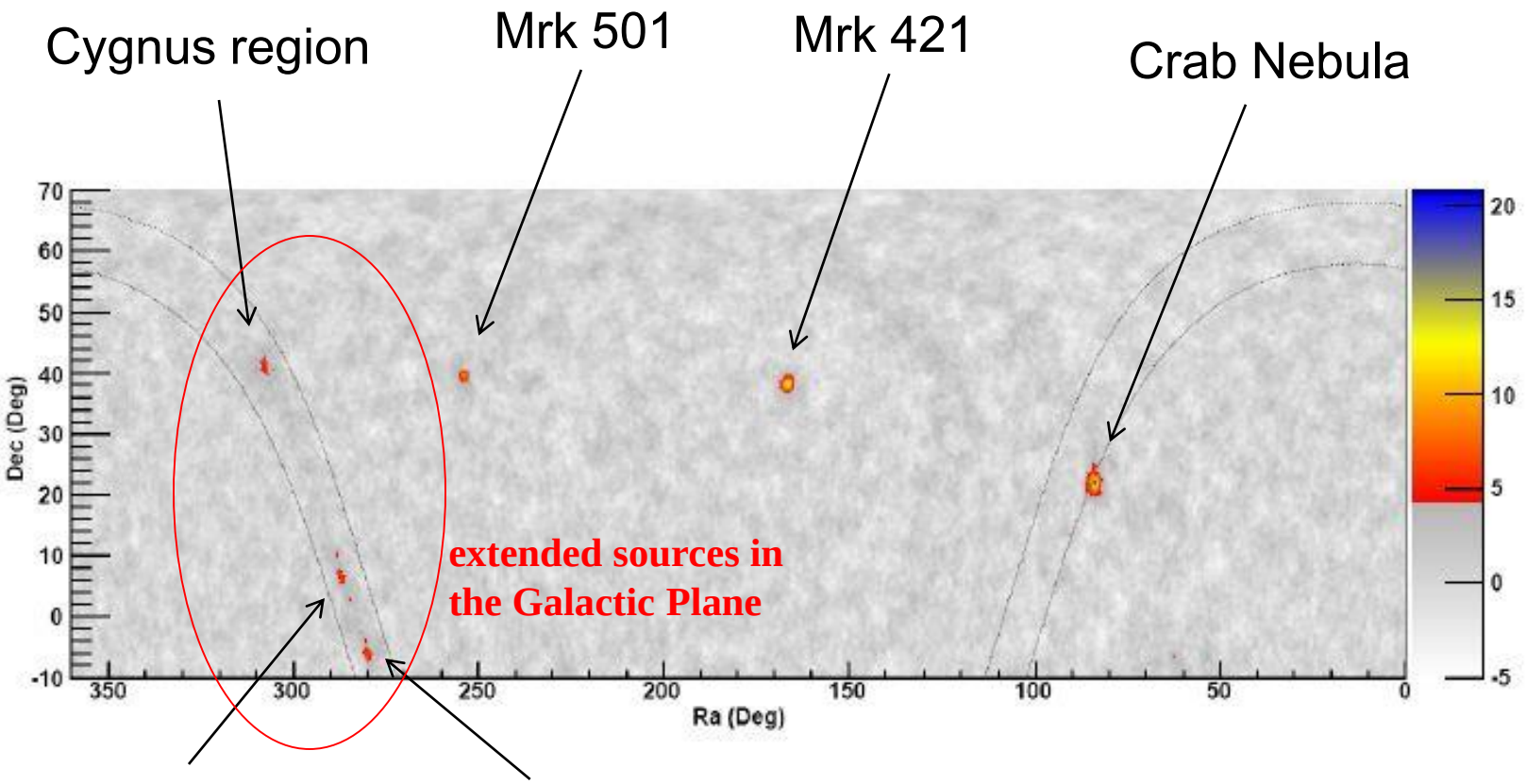
Recent results in gamma-ray astronomy

- Sky survey of the Northern hemisphere ($-10° < \delta < 70°$)
- Crab Nebula during 5 years of observations
- Multiwavelength observations of the blazar Mrk 421
- TeV counterpart of the Cygnus Cocoon
- Diffuse γ-rays from the Galactic plane
- Gamma Ray Bursts

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

$N_{pad} \geq 100$

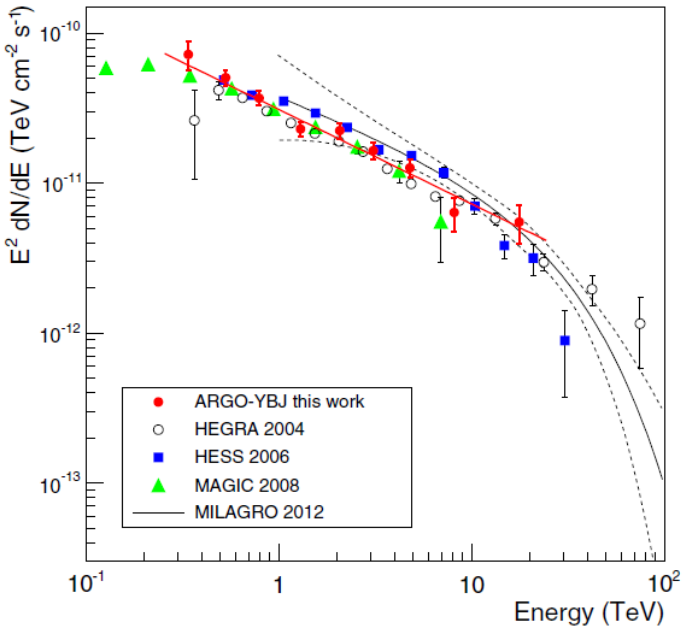
Note. [a] R.A. and decl. are celestial coordinates in J2000 epoch.

Crab Nebula

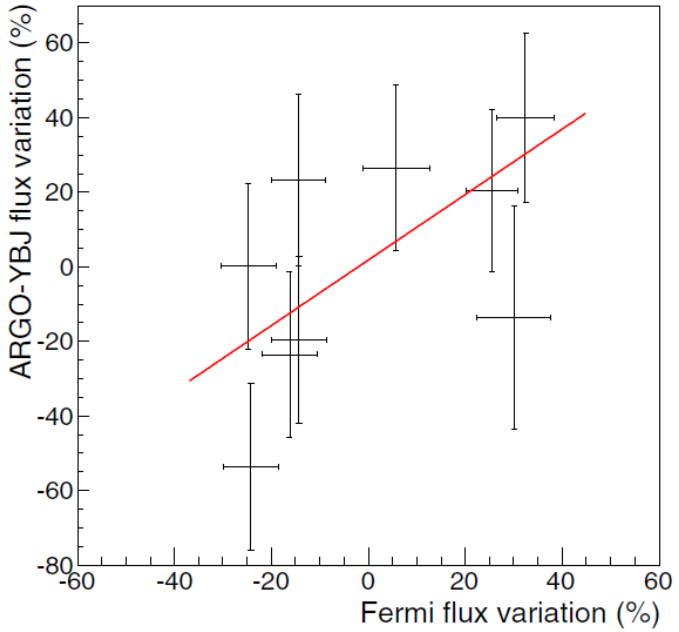
ApJ 798 (2015) 119

- **Energy spectrum in 0.3–20 TeV in agreement with other experiments**
- **Light curve over five years compatible with a steady emission (p=0.07)**

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



Spectrum multiplied by E^2



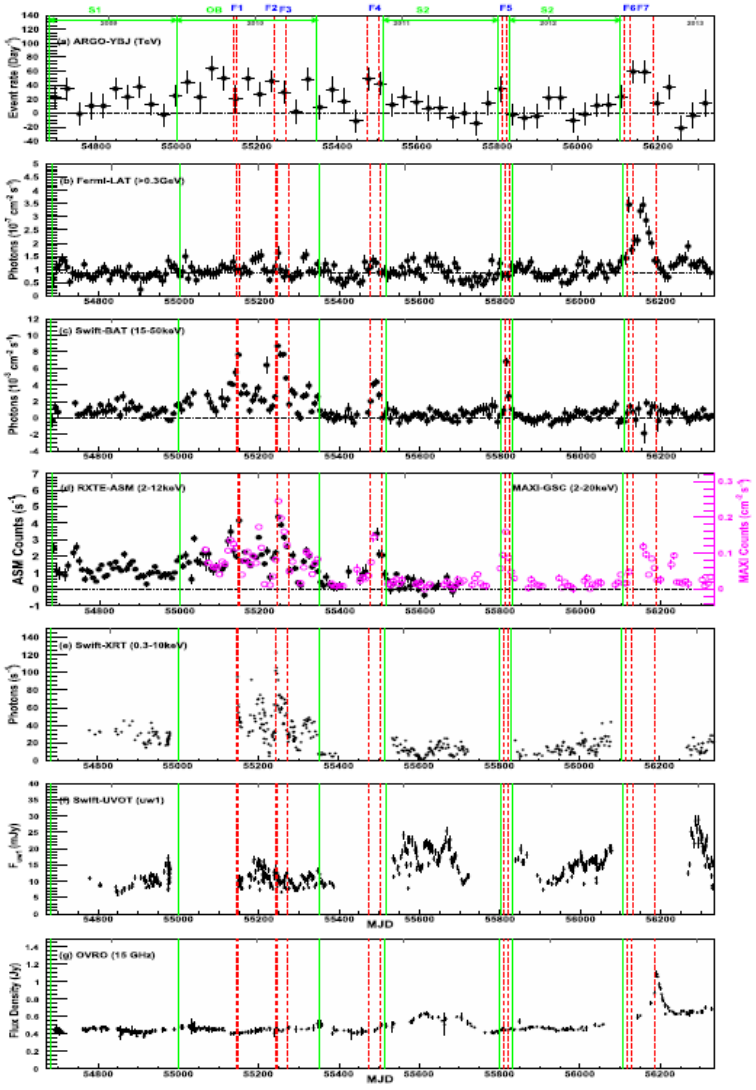
Percentage variations with respect to average values

Pearson correlation coefficient for a correlated analysis with Fermi/LAT data over ~4.5 yr of common observing time (bins of 200 days):

$r = 0.56 \pm 0.22$

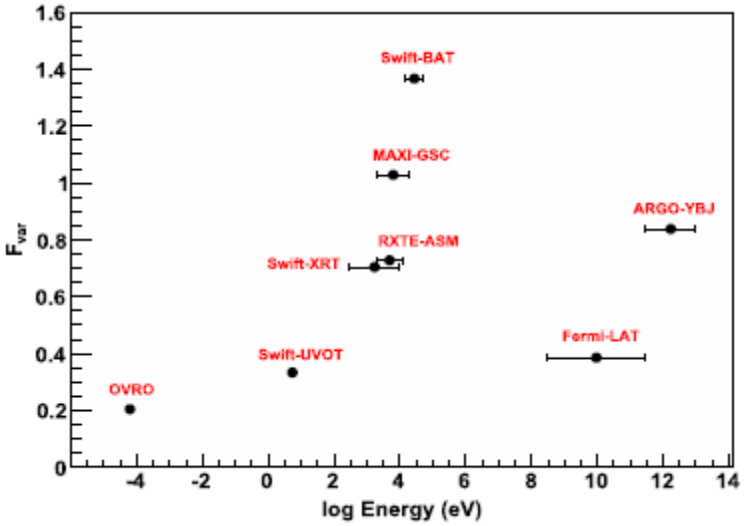
Mrk 421: long-term observations

ApJS 222 (2016) 6 (similar paper for Mrk 501 in ApJ 758 (2012) 2)



ARGO-YBJ bins with 30 days

Normalized variability amplitude F_{var} for different energy bands:



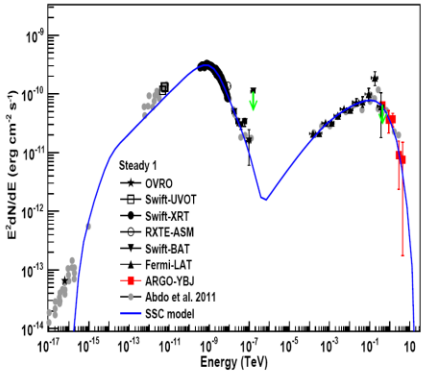
$F_{var} = (\sigma_{tot}^2 - \sigma_{err}^2)^{0.5} / < F >$

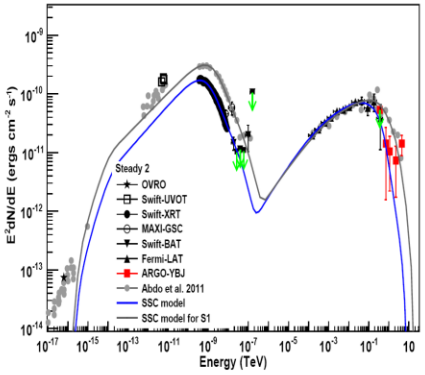
σ_{tot} = flux standard deviation;

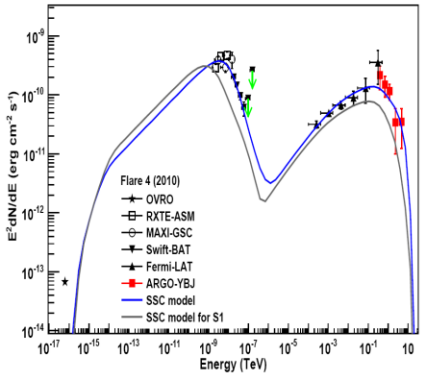
σ_{err} = flux mean error; $< F >$ = mean flux

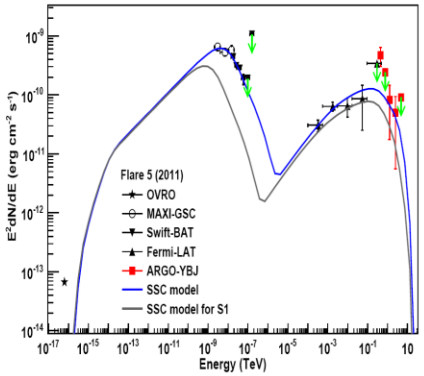
TeV flux clearly correlated with X-ray flux, partially with GeV flux

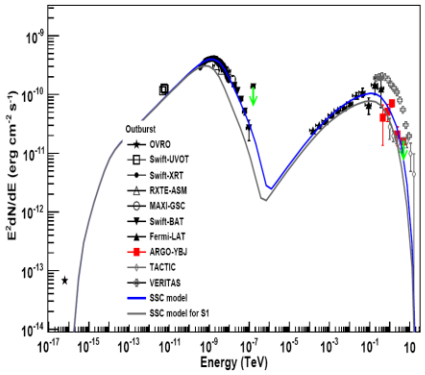
Mrk 421: Spectral Energy Distribution

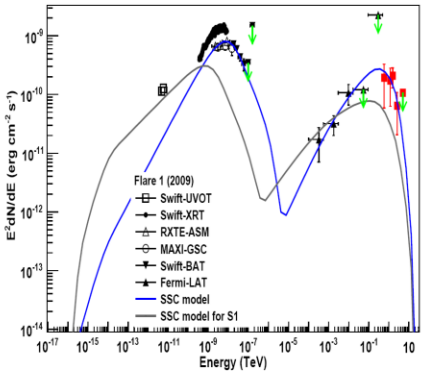


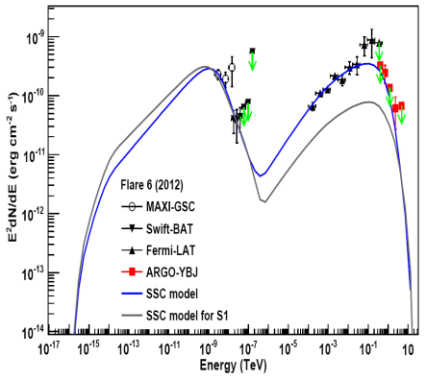


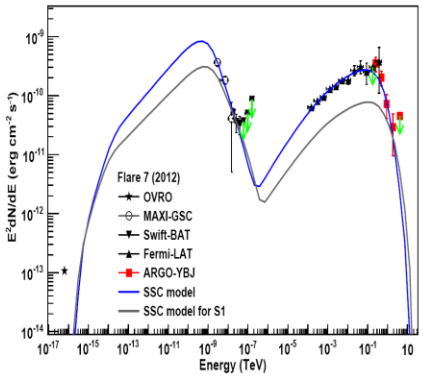


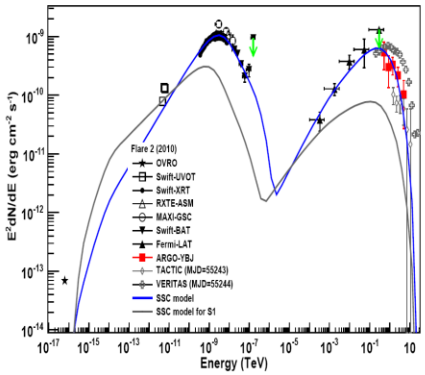


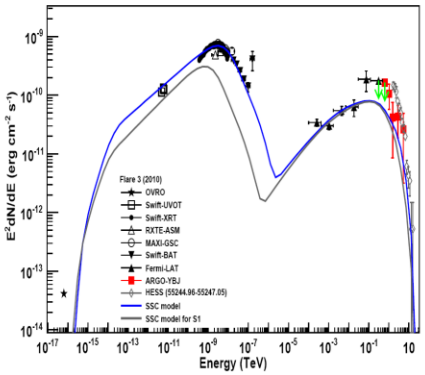












Simple one-zone SSC model adopted

SEDs classified in 3 different groups:

in 2/3 electrons are injected with power law index p ~ 2.2 (as in relativistic diffuse shocks);

in flares 1 and 2 the spectrum is harder (p~1.8)

Variations of states due to:

environment properties

acceleration process

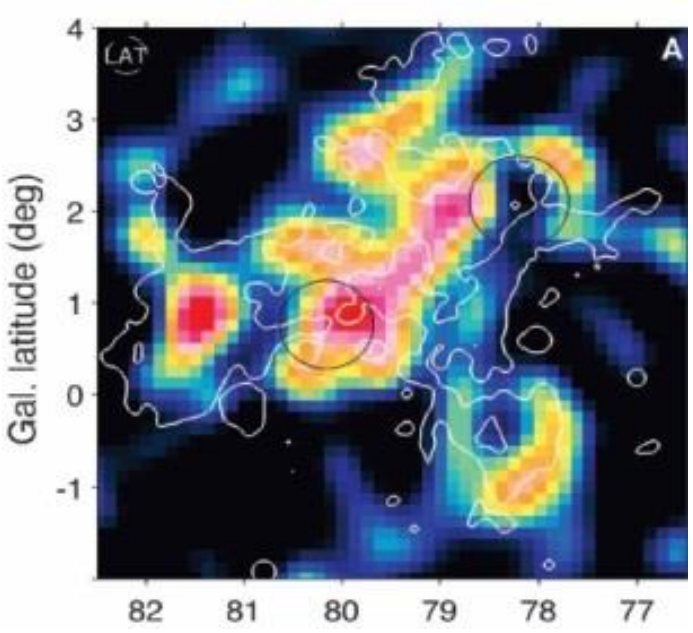
ARGO J2031+4157 as the Cygnus Cocoon

ApJ 790 (2014) 152

A cocoon of freshly accelerated cosmic rays

The Fermi / LAT view

in the 10-100 GeV band:

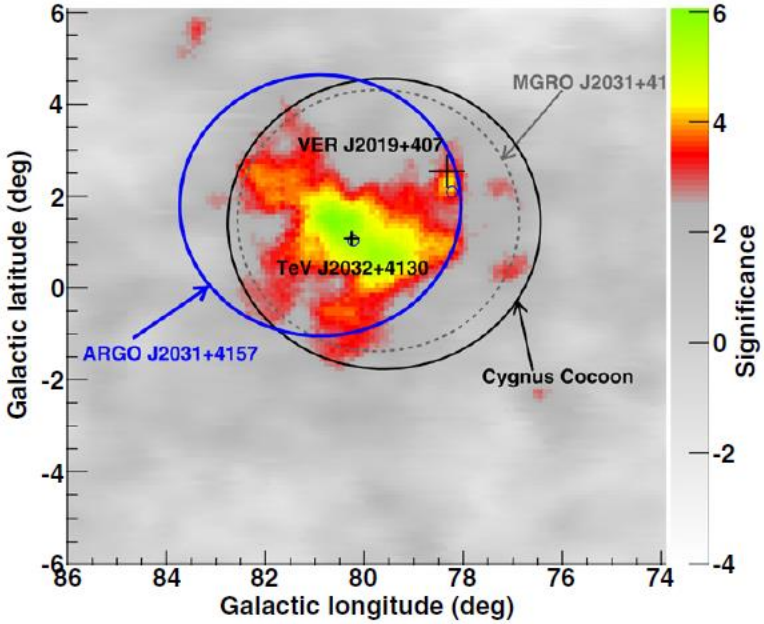


Ackermann et al. (2011)
measured size: (2.0 ± 0.2)°

The ARGO-YBJ view

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

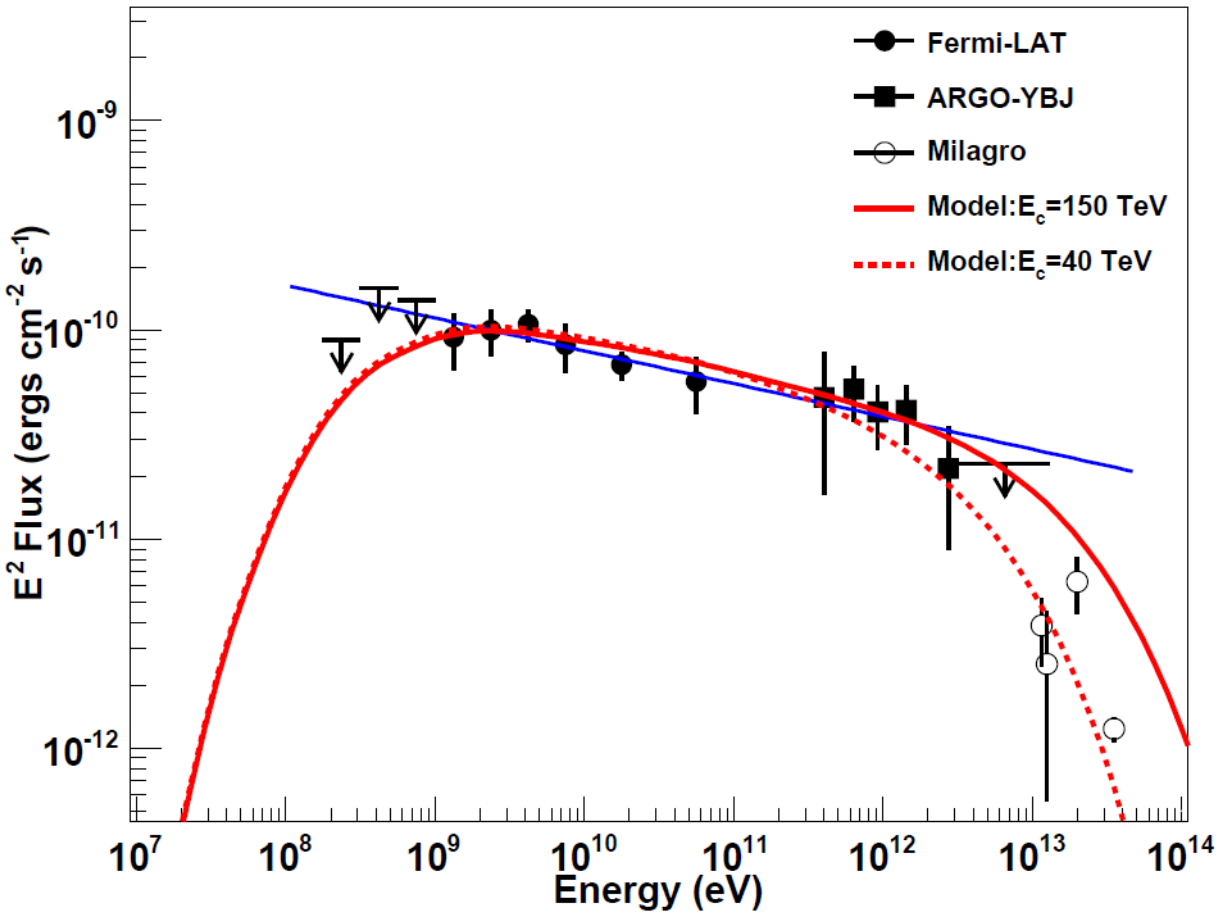
after reanalysis with the full data:



S_{max} = 6.1 s.d.

$\sigma_{ext} = (1.8 \pm 0.5)°$

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 fit model was assumed with a power law and a cutoff energy E_c

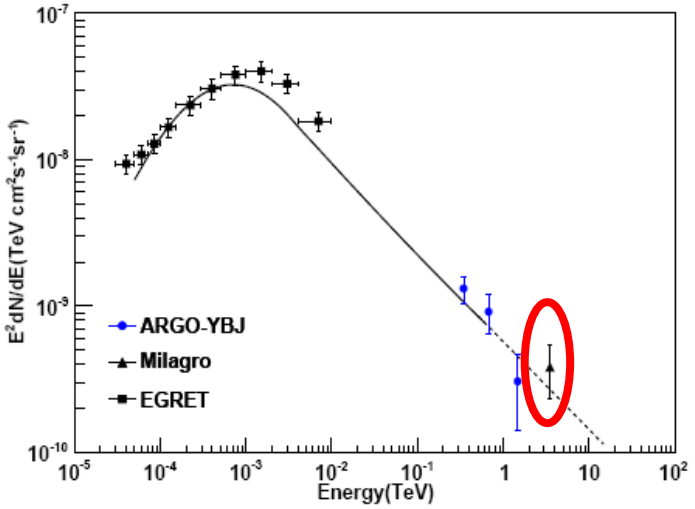
Spectrum of ARGO J2031+4157: $dN/dE \propto E^{-2.6\pm0.3}$

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

Diffuse γ-rays from the Galactic plane

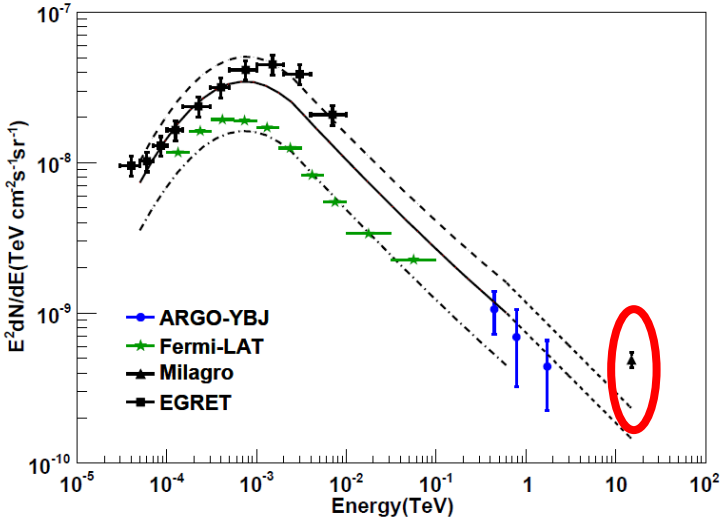
ApJ 806 (2015) 20

Galactic region 40°< l < 100° ; |b| < 5°



The line indicates the energy spectrum expected from the Fermi/LAT template (with spectral index -2.6).
The fit to ARGO-YBJ data gives an index –2.90 ± 0.31.

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

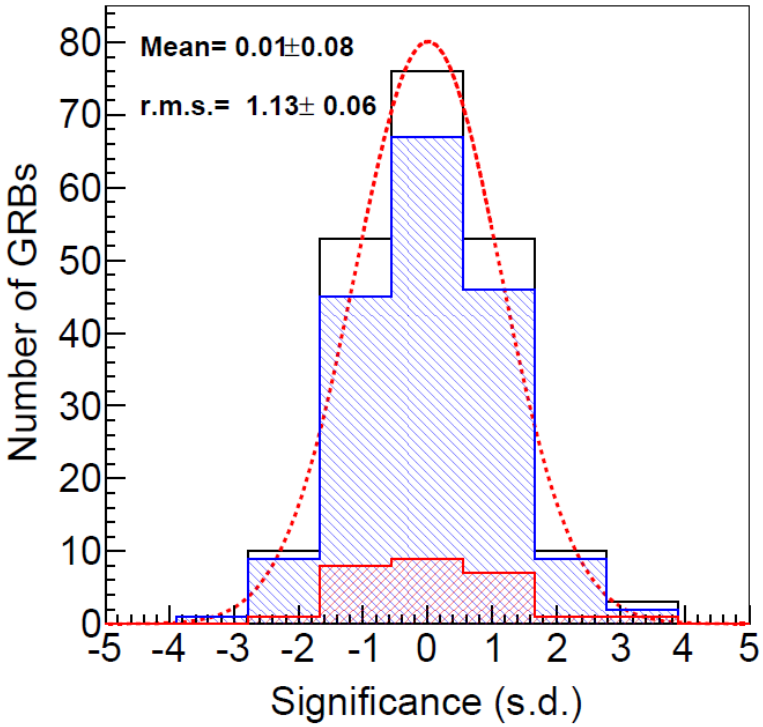


The different lines indicate the energy spectra expected from the Fermi/LAT template (with spectral index -2.6) in the different sky regions investigated by the detectors.
The fit to ARGO-YBJ data gives an index –2.65 ± 0.44.

The sub-TeV diffuse flux does not show any excess corresponding to that found by Milagro at higher energies ("TeV excess").
The difference may be mainly due to the Cygnus Cocoon, not yet discovered at the time of the Milagro measurement.
The harder spectrum in the Cygnus region may suggest the presence of young cosmic rays coming from a nearby source.

Search for GRBs in scaler mode

ApJ 794 (2014) 82



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

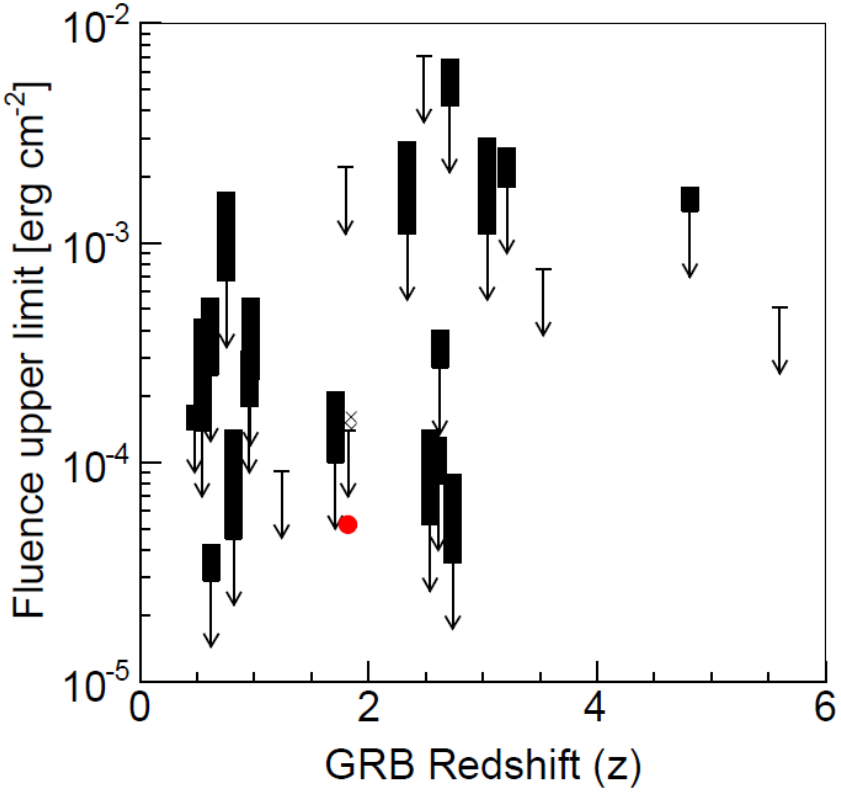
- With known redshift: 24
- Discovered by Fermi/GBM: 90 (including its 2nd GRB catalog)
- Detected by Fermi/LAT: 4

- 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

ΔE = 1–100 GeV



Sample of the 24 GRBs with known redshift

The Kneiske et al. (2004) model is adopted to take into account the absorption of γ-rays in the extragalactic background light

The red dot shows the extrapolated fluence of GRB090902B as observed by Fermi/LAT (factor ~3 lower than expected sensitivity)

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

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 units
- The Crab Nebula light curve over five years is compatible with a steady emission and its spectrum is in agreement with other experiments
- Continuous long-term observations for multiwavelength studies of the flaring sources Mrk 421 and Mrk 501
- Identification of the TeV counterpart of the Cygnus Cocoon
- Detection of diffuse γ-rays from the Galactic plane, with no excess observed at sub-TeV energies corresponding to that found by Milagro at higher energies
- 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 at high energies