Physics Results with the ARGO-YBJ Experiment

Tristano Di Girolamo

Università di Napoli "Federico II"

INFN – Sezione di Napoli

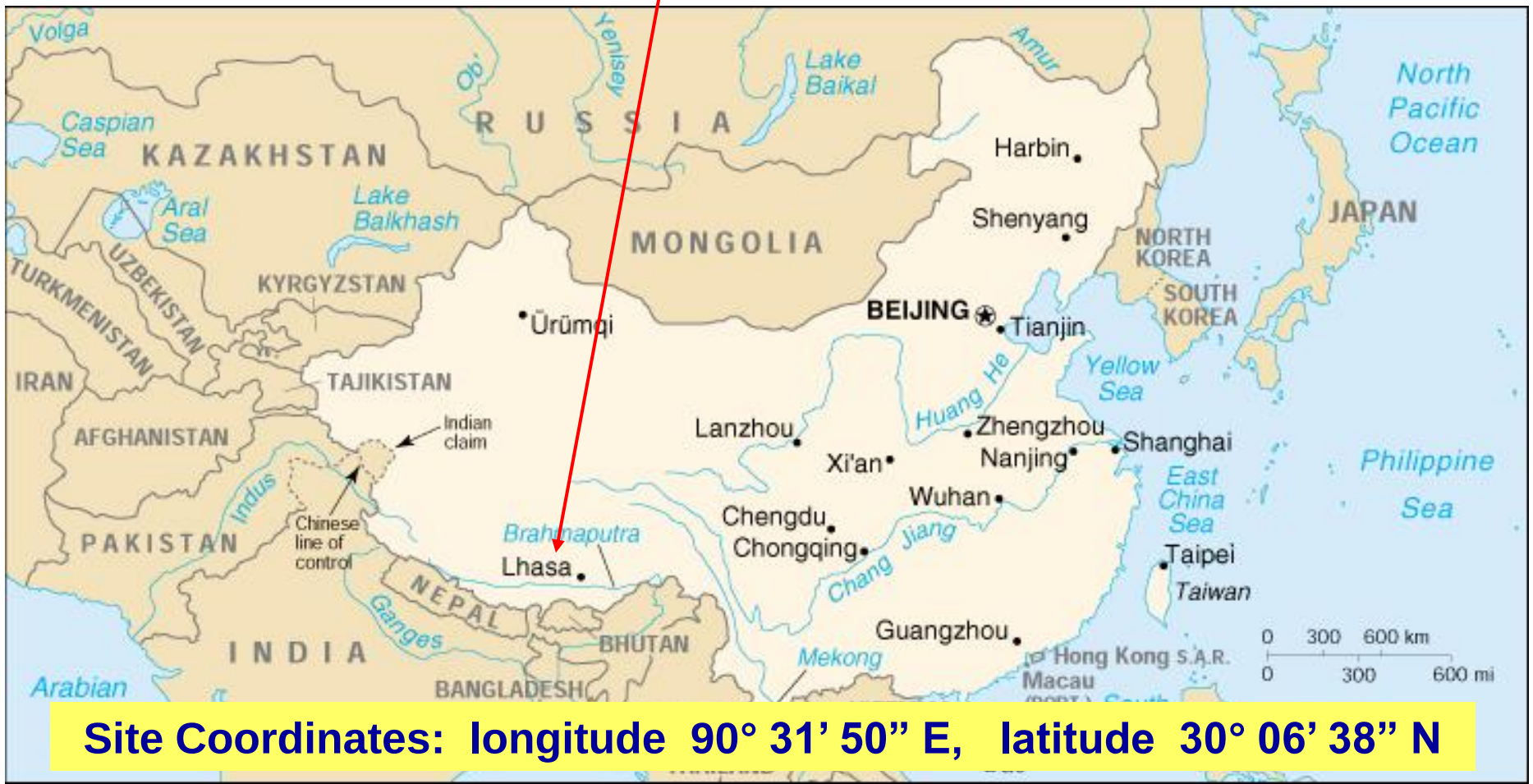
Napoli, 21 Febbraio 2013

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:

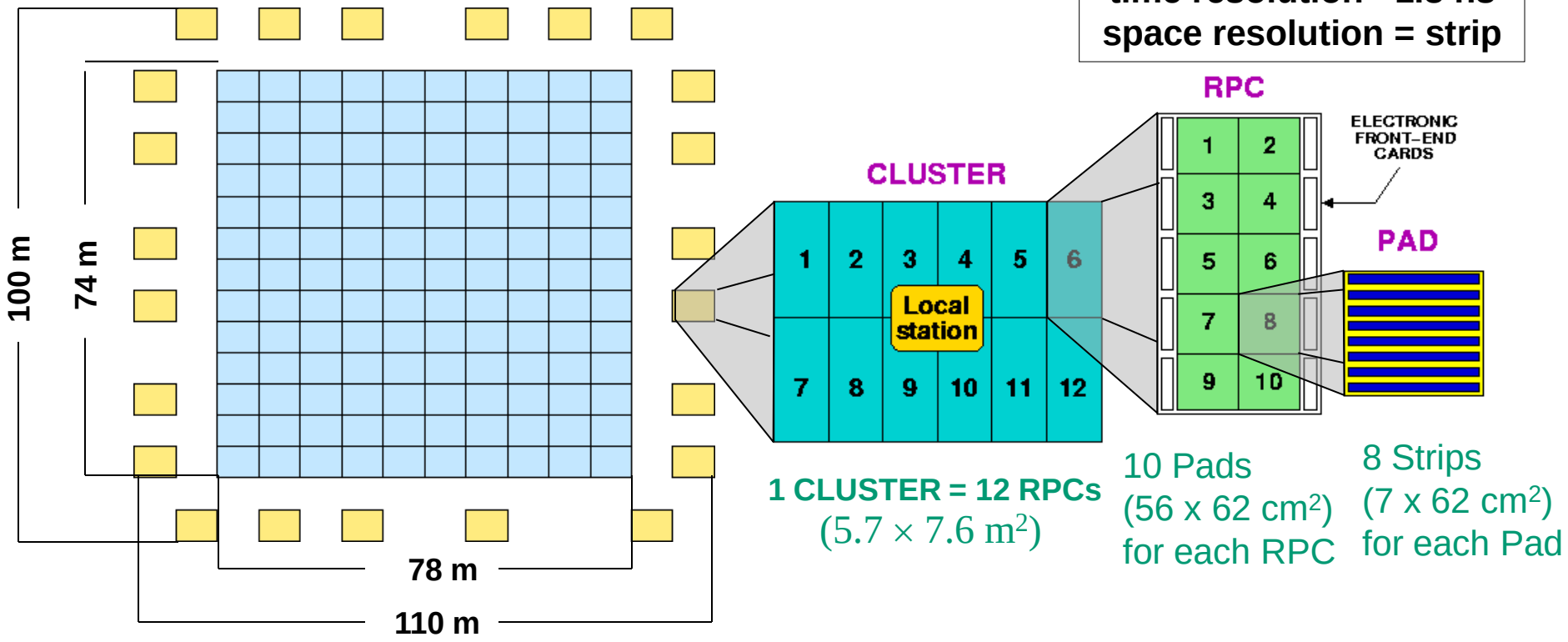
- ✓ **Chinese Academy of Science (CAS)**
- ✓ **Istituto Nazionale di Fisica Nucleare (INFN)**

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



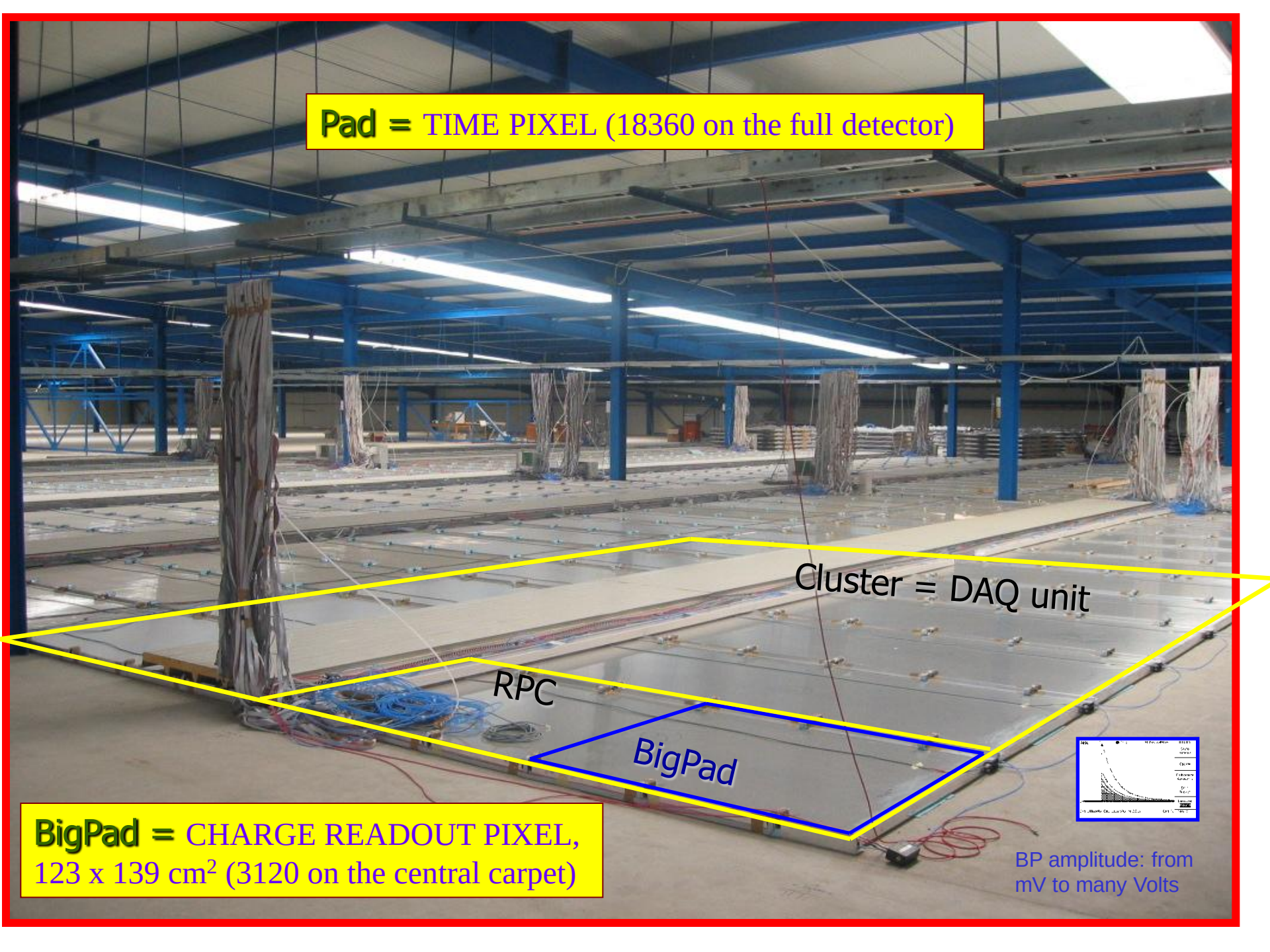
1 CLUSTER = 12 RPCs
(5.7 × 7.6 m^2)

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 (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)**

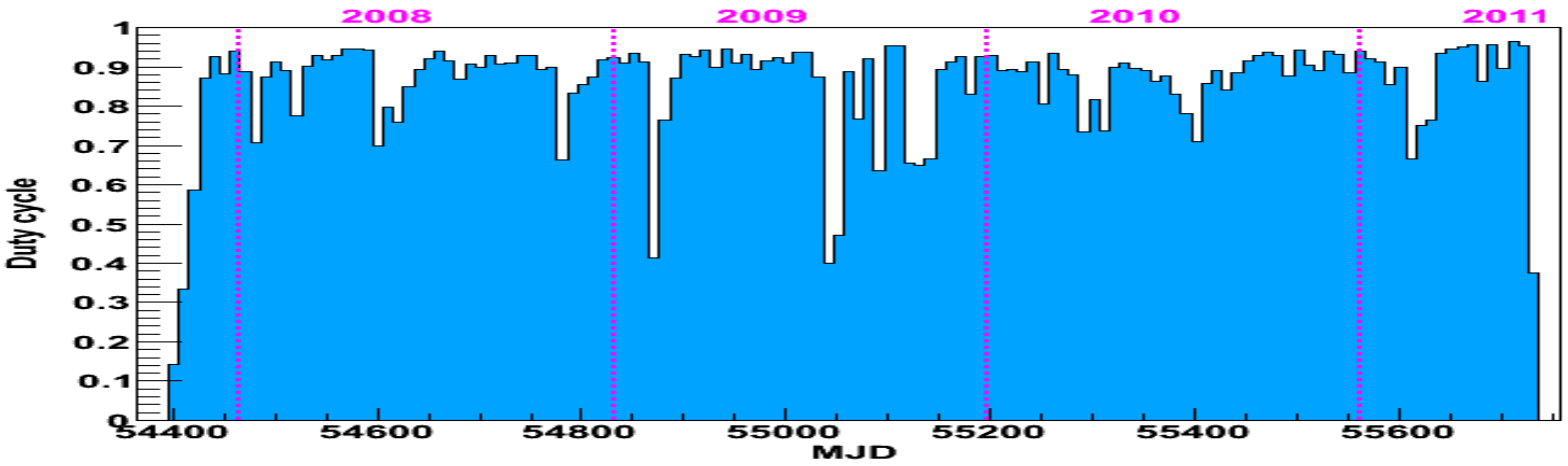

Pad = TIME PIXEL (18360 on the full detector)
Cluster = DAQ unit
RPC
BigPad
BigPad = CHARGE READOUT PIXEL,
123 x 139 cm² (3120 on the central carpet)
BP amplitude: from
mV to many Volts

Main steps

- 1996: ARGO proposal
- 1997-1998: ARGO Test
- 1998: ARGO-YBJ approved
- 2000: construction of the building at Yangbajing
- 2001: start of the installation of RPCs
- June 2006: commissioning of the central carpet
- October 2007: installation of the "guard ring"
- November 2007: start of data taking with the full detector
- January 2013: end of data taking

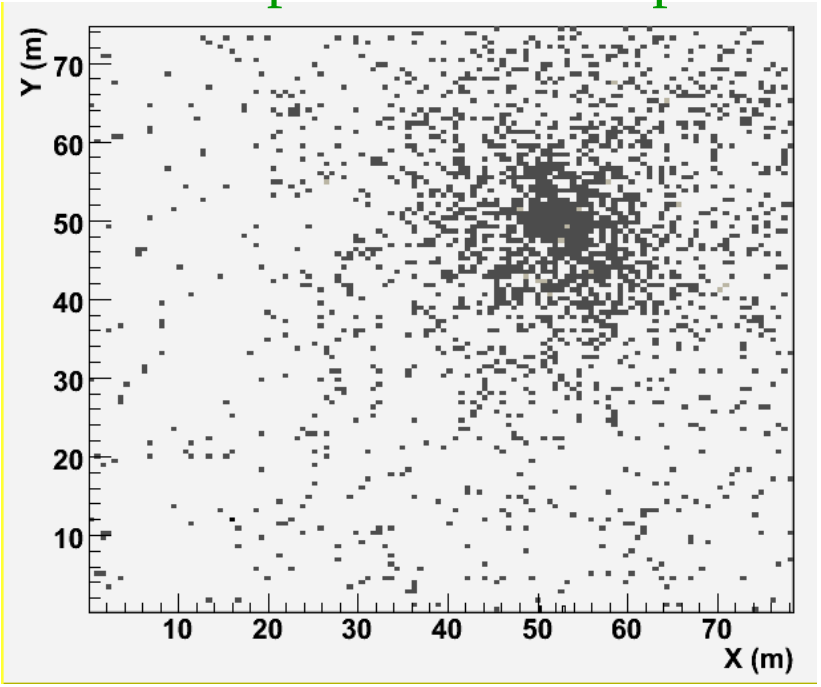
Status before end of data taking

- Operated since July 2006 (commissioning phase)
- Stable data taking since November 2007 with the final configuration
- Average duty cycle ~ 85%
- Trigger rate ~3.5 kHz with a 20 pad threshold in 420 ns
- > 5.0 x 10^{11} events collected
- Dead time: 4%
- 220 GB/day transferred to IHEP and CNAF data centres

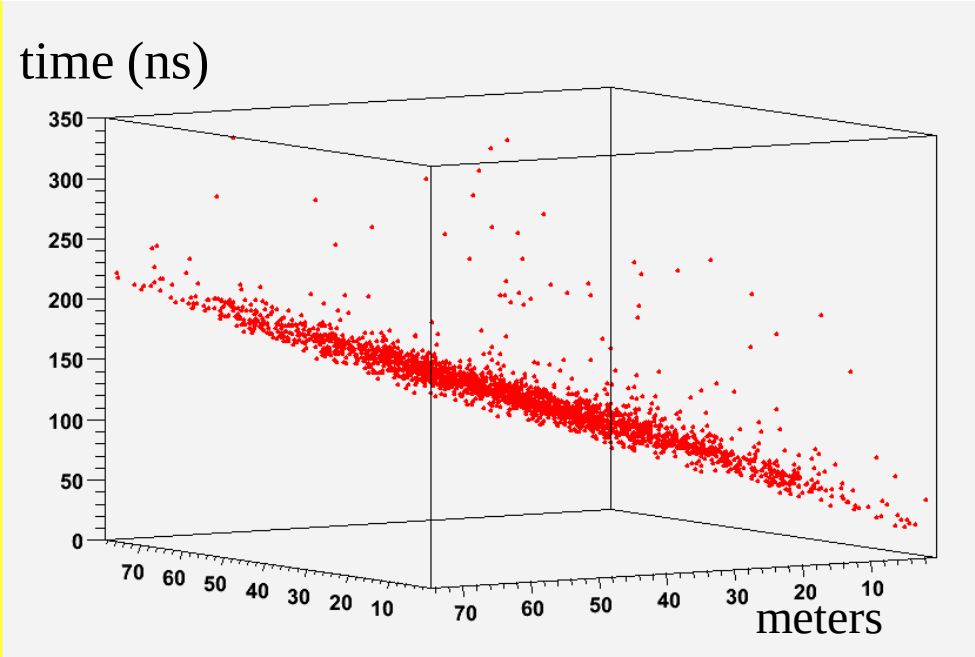


Shower reconstruction

Fired pads on the carpet



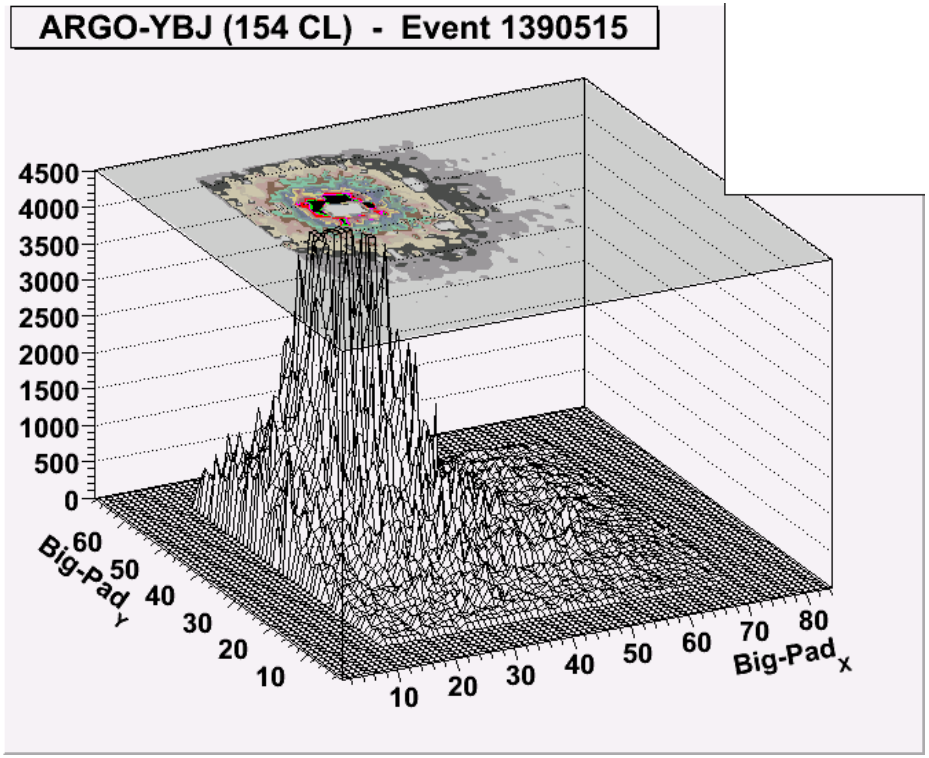
Arrival time vs. position

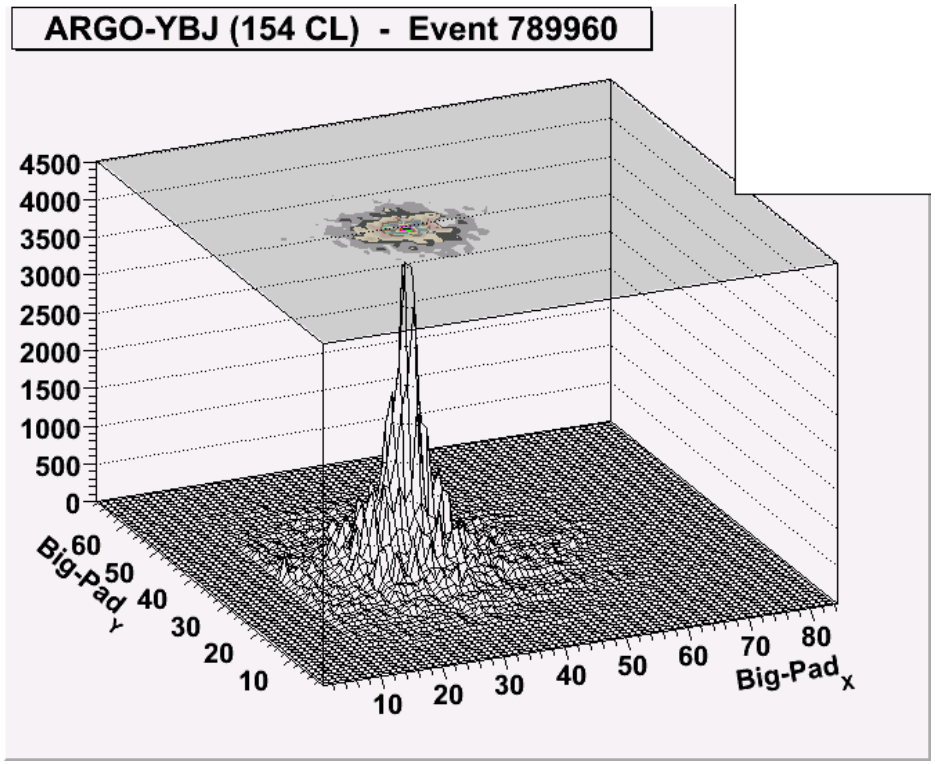


Measurement of the arrival direction:

- **Core reconstruction: Maximum Likelihood Method applied to the lateral density profile of the shower**
- **Fit of the shower front with a conical shape**

Showers observed with the charge readout





ARGO-YBJ: a multi-purpose experiment

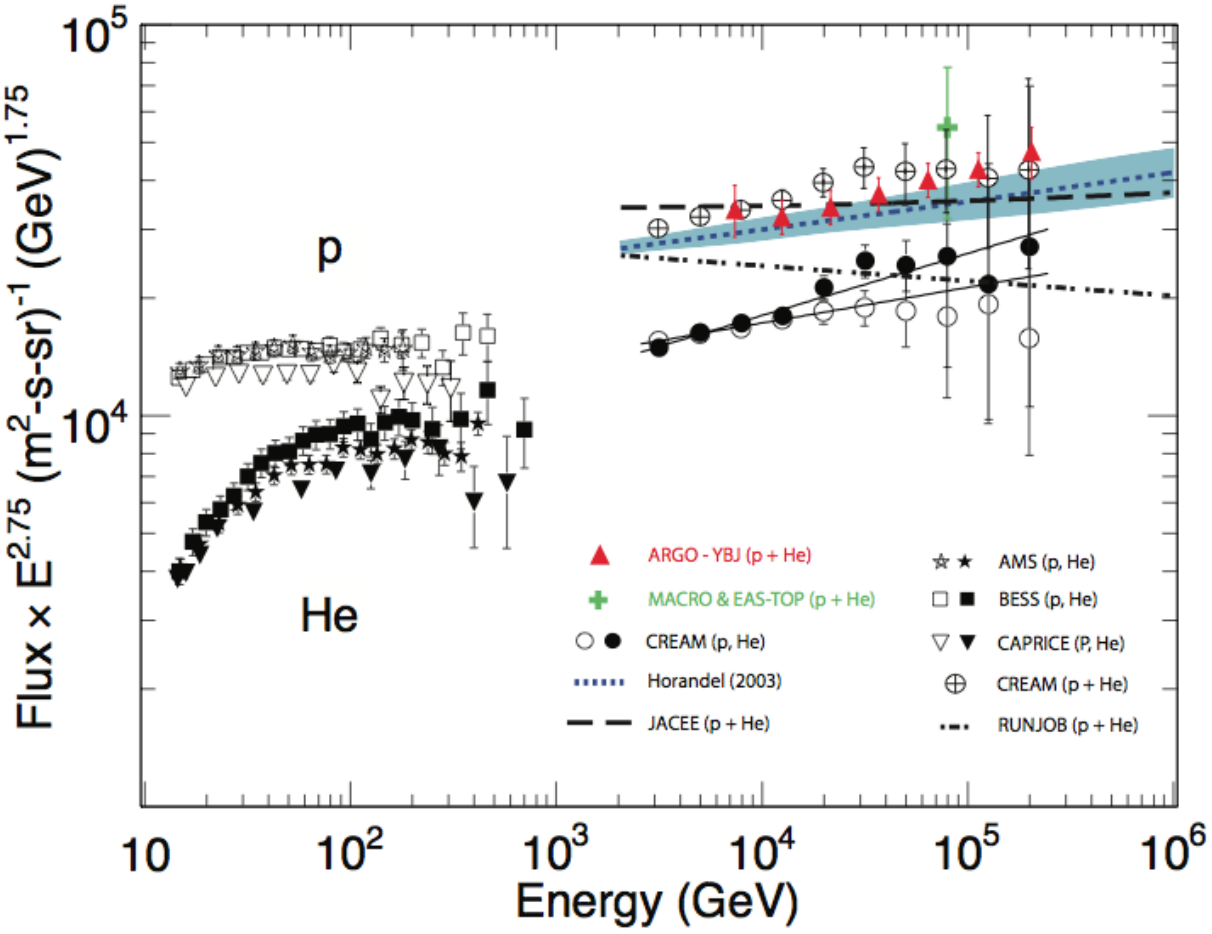
- CR physics from 1 TeV to 10^4 TeV { (p + He) spectrum; knee region; anisotropies
- Survey of the γ-ray sky in the band -10° ≤ decl. ≤ 70° and above 300 GeV
- High exposure for flaring activity (γ-ray sources, Gamma Ray Bursts, solar flares)
- CR $\bar{p}/p$ flux ratio at TeV energies
- Hadronic interactions (p-air and p-p cross sections)
- Solar and heliosphere physics

Cosmic Ray physics

- **Spectrum of the light component (5–200 TeV)**
- **Large and medium scale anisotropies**
- **Search for CR sources (γ-ray astronomy)**
- **The $\bar{p}$/p flux ratio**

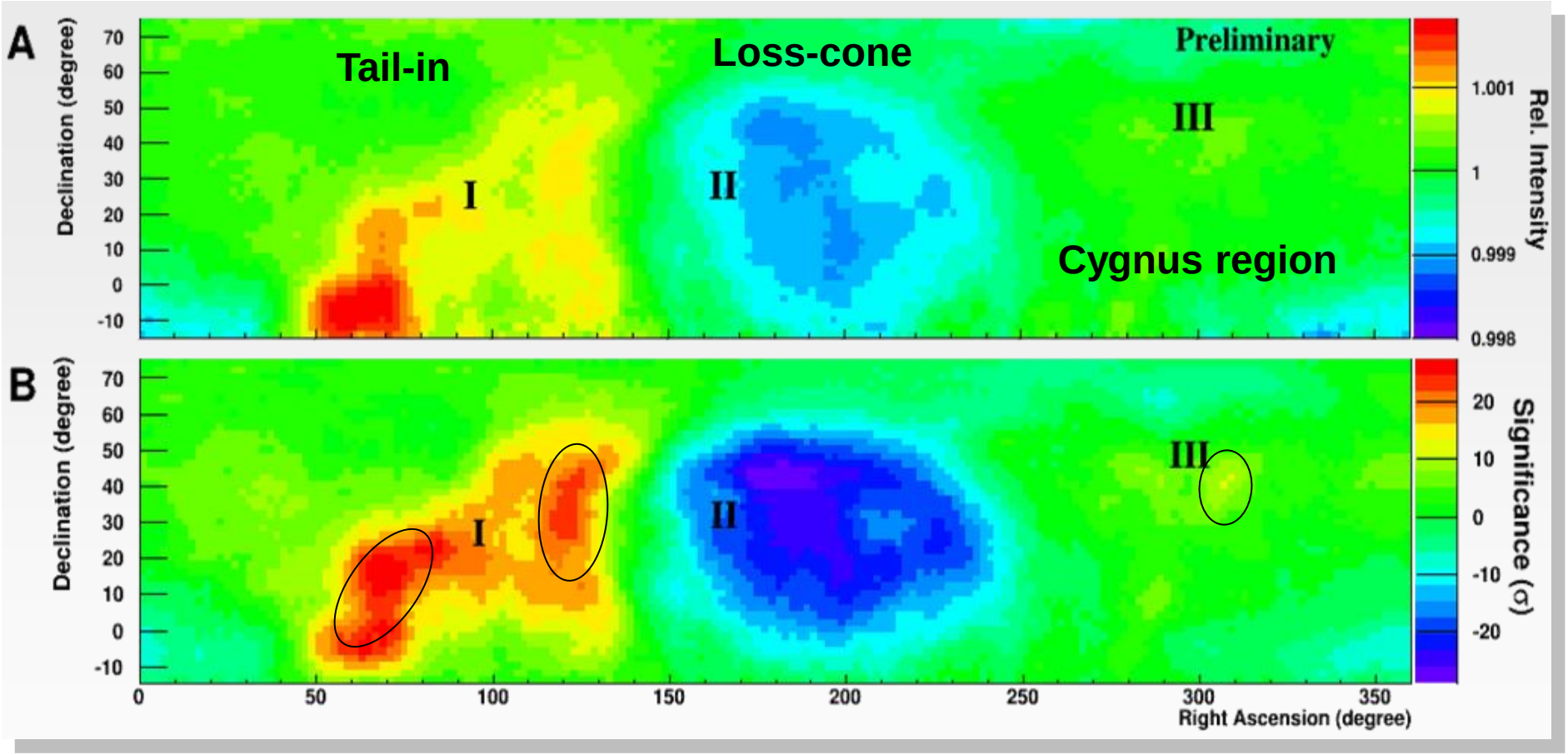
Spectrum of the light component

Phys. Rev. D 85 (2012) 092005

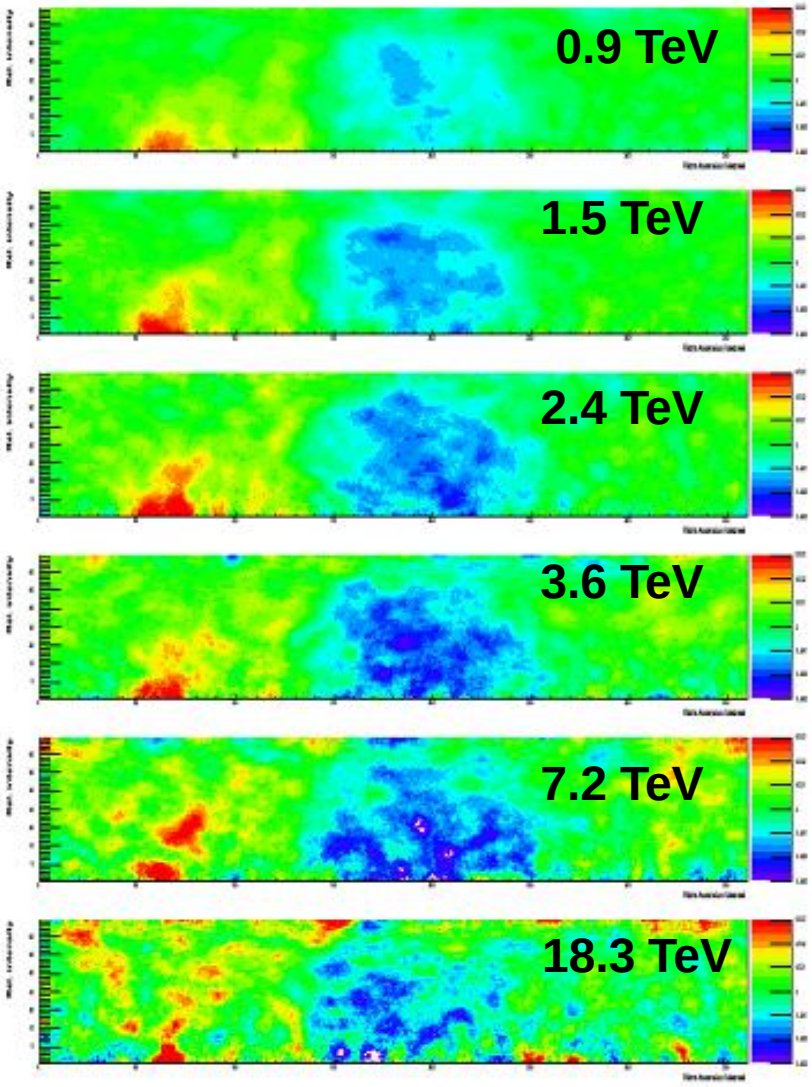


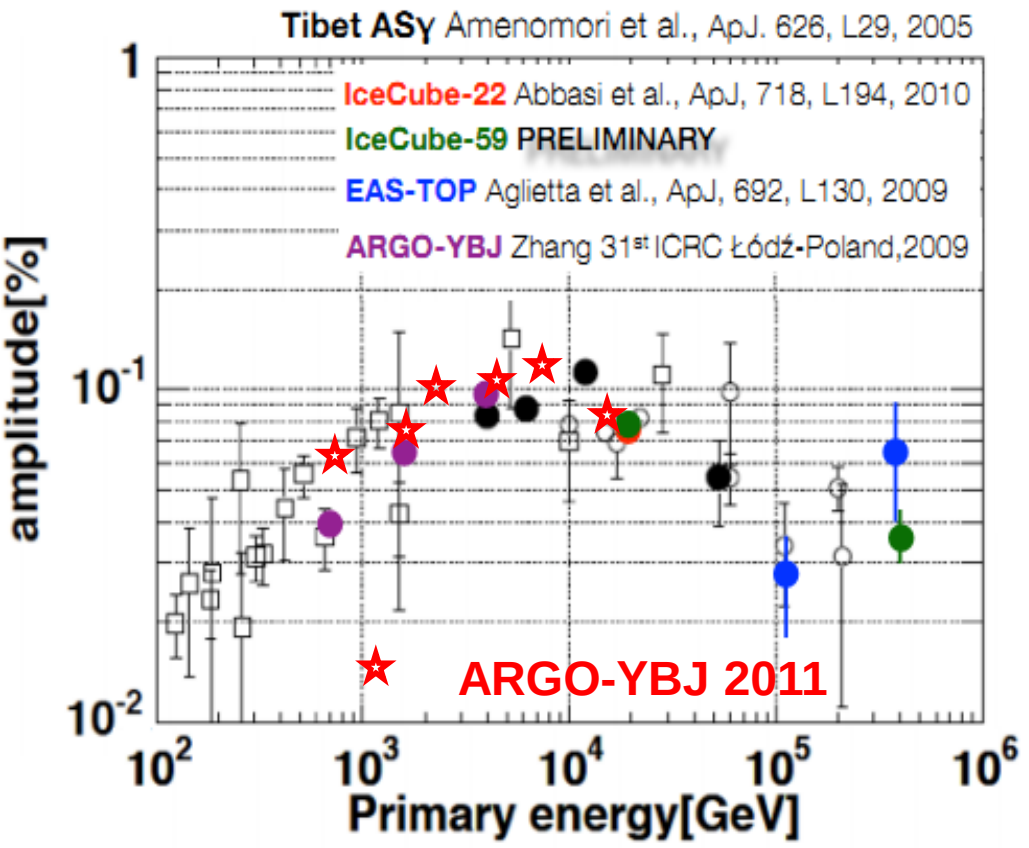
Unfolding the primary energy spectrum with a Bayesian approach

Large scale anisotropy



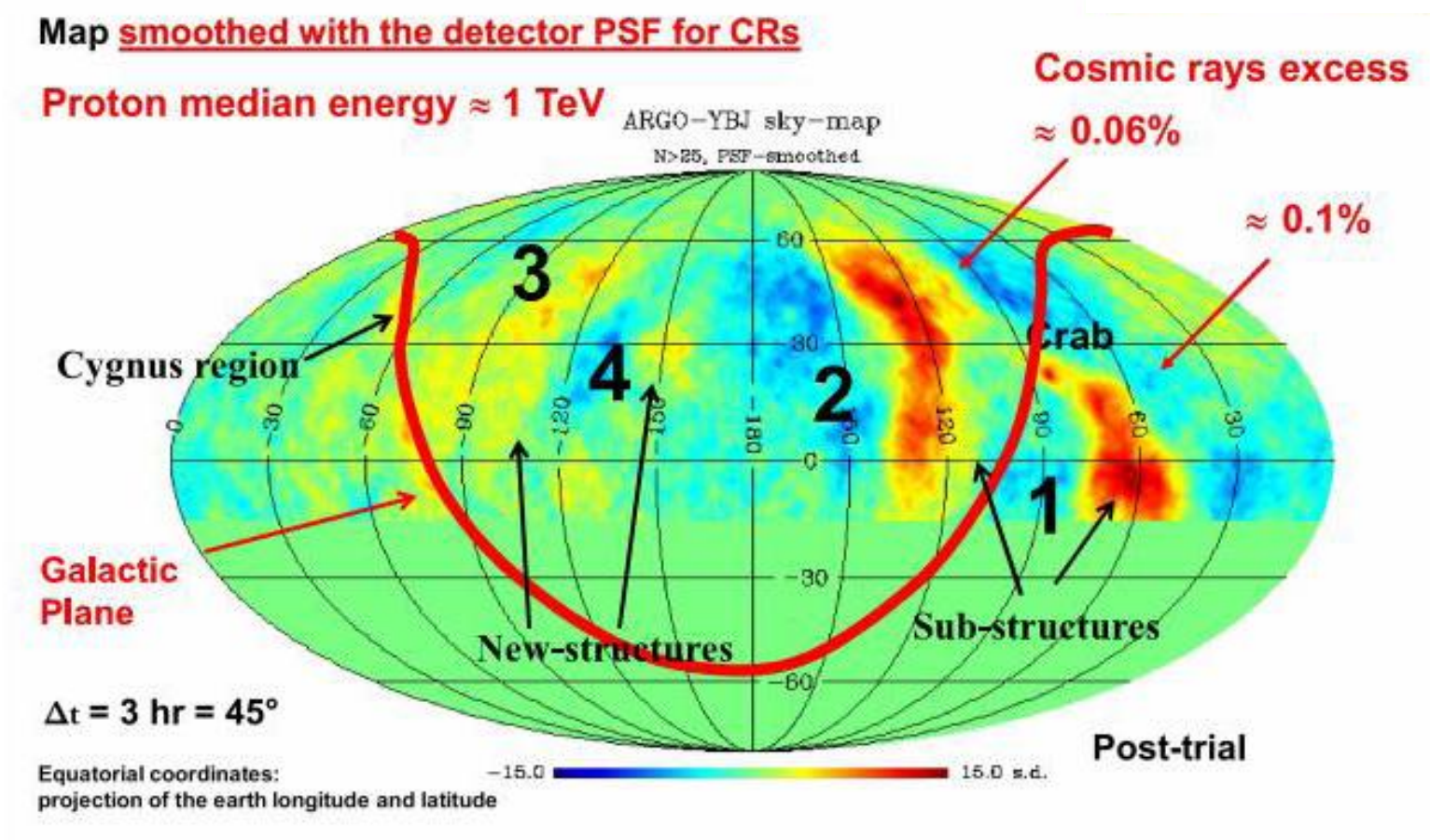
Large scale anisotropy vs. energy





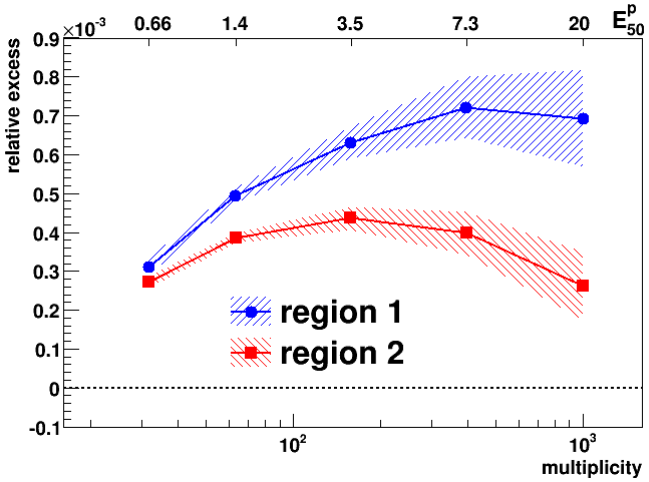
The tail-in broad structure appears to dissolve in smaller angular scale spots

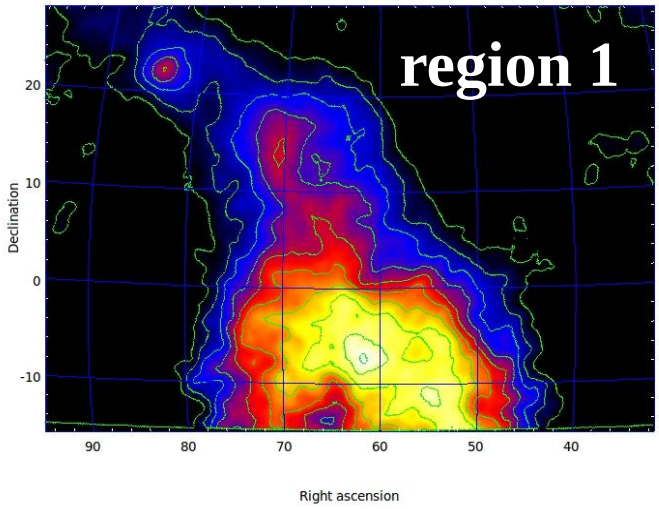
Medium Scale Anisotropy by ARGO-YBJ



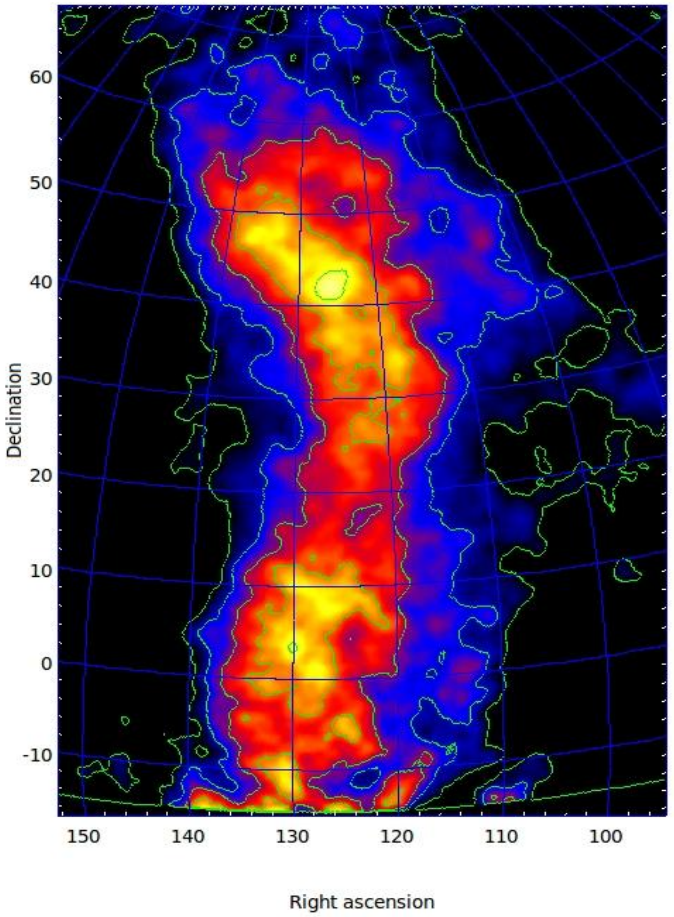
Energy spectrum

ARGO-YBJ





region 2



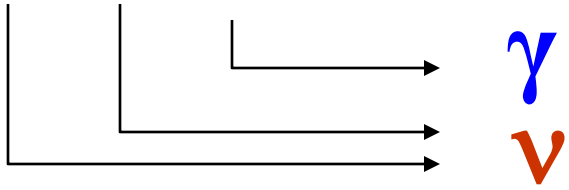
Medium scale anisotropy

Various explanations proposed:

- Diffusion from nearby sources
- Magnetic funnelling in local traps (mirrors)
- CR acceleration from magnetic reconnection in the heliospheric tail

Cosmic Rays and γ-ray astronomy

- Hadronic production:
  $p + p/\gamma \rightarrow n\,(\pi^+ + \pi^-) + m\pi^0 + \ldots$



- Electromagnetic production (Inverse Compton scattering):
  $e + \gamma \rightarrow e' + \gamma'$
  Synchrotron Self-Compton (SSC) model: photons radiated by high energy ($\approx 10^{15}$ eV) electrons and boosted by the same electrons

γ-rays point back to their sources (SNR, PWN, BS, AGN, GRB)

γ-ray astronomy

- **Sky map of the Northern hemisphere (-10° <δ<70°)**
- **Crab Nebula**
- **Mrk 421**
- **Mrk 501**
- **MGRO 1908+06**
- **Cygnus region**
- **HESS J1841-055**
- **Diffuse γ-rays on the Galactic plane**
- **Gamma Ray Bursts**

no γ/h discrimination has been applied so far in the data analysis

Sky survey

- ❖ KASCADE, EAS-TOP, CASA-MIA → E > 100 TeV
- ❖ MILAGRO, Tibet ASγ, ARGO-YBJ → E ≈ TeV
- ✓ ARGO-YBJ sensitivity (5 years of data taking) : 0.25 Crab Units
  With new reconstruction, γ/h discrimination → < 0.2 Crab Units
- ✓ MILAGRO sensitivity (7 years of data taking) : 0.30 Crab Units
  → discovery of 3 new sources
- ✓ HAWC (installation under way), LAWCA expected sensitivity:
  0.05 Crab Units (0.03 in 3 years of data taking)

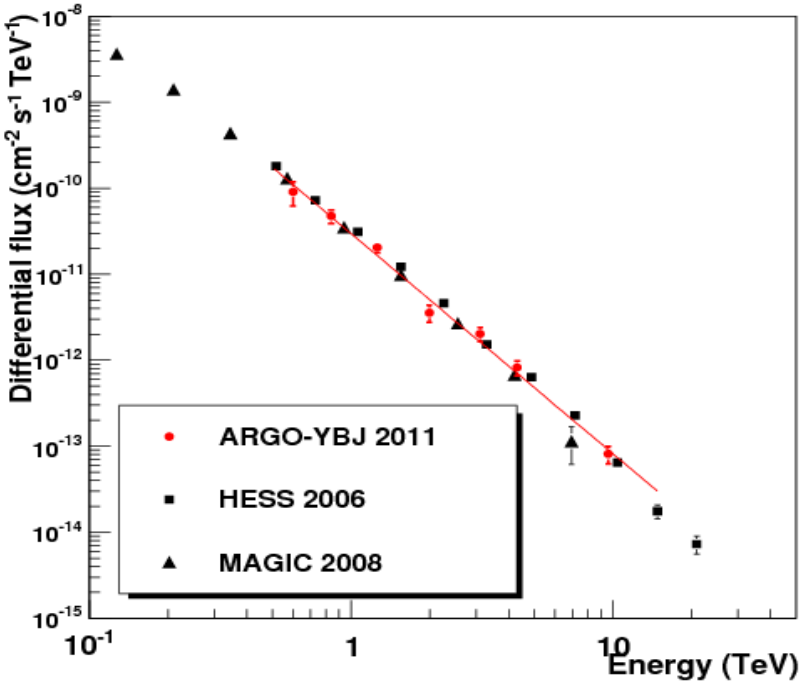
ARGO proposal (120m×120m + lead) ~ HAWC

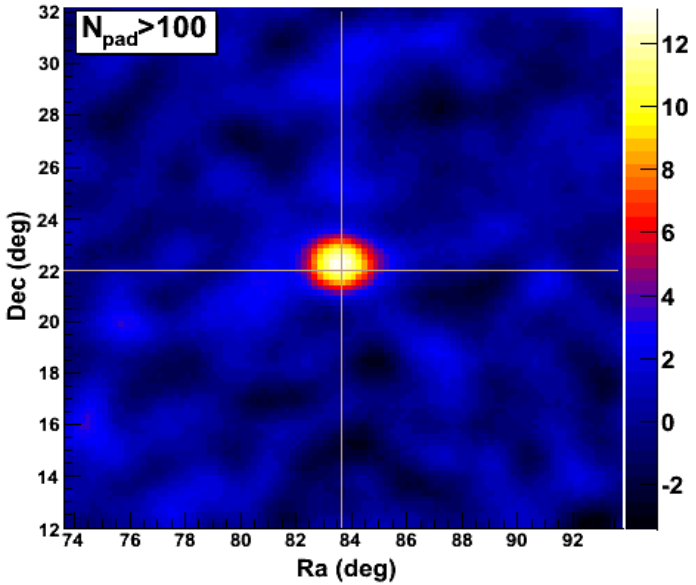
The ARGO-YBJ sky map will be released later this year

Crab Nebula

- Energy spectrum in 0.5–10 TeV in agreement with other experiments
- Measured Point Spread Function in agreement with MC simulations

$$dN/dE = (3.0 \pm 0.3) \cdot 10^{-11} \cdot E^{(-2.59 \pm 0.09)} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$$



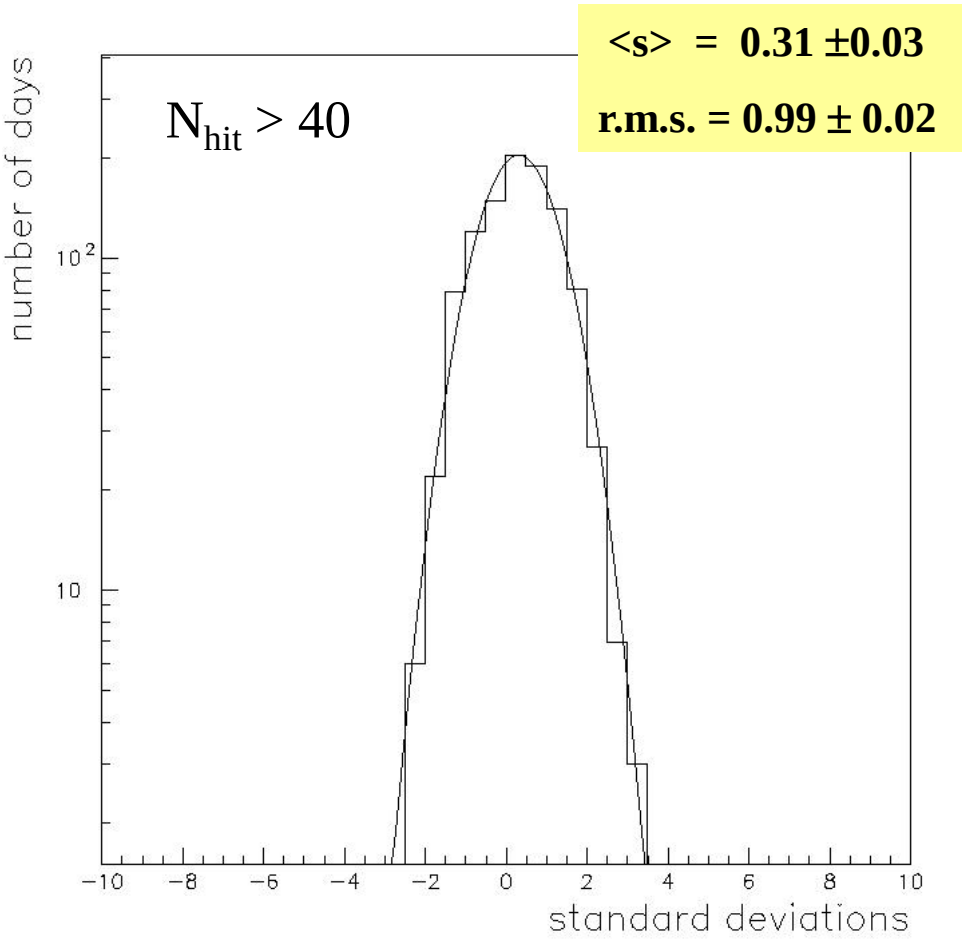


Crab event rate

Distribution of the daily excess significances in ~1000 days

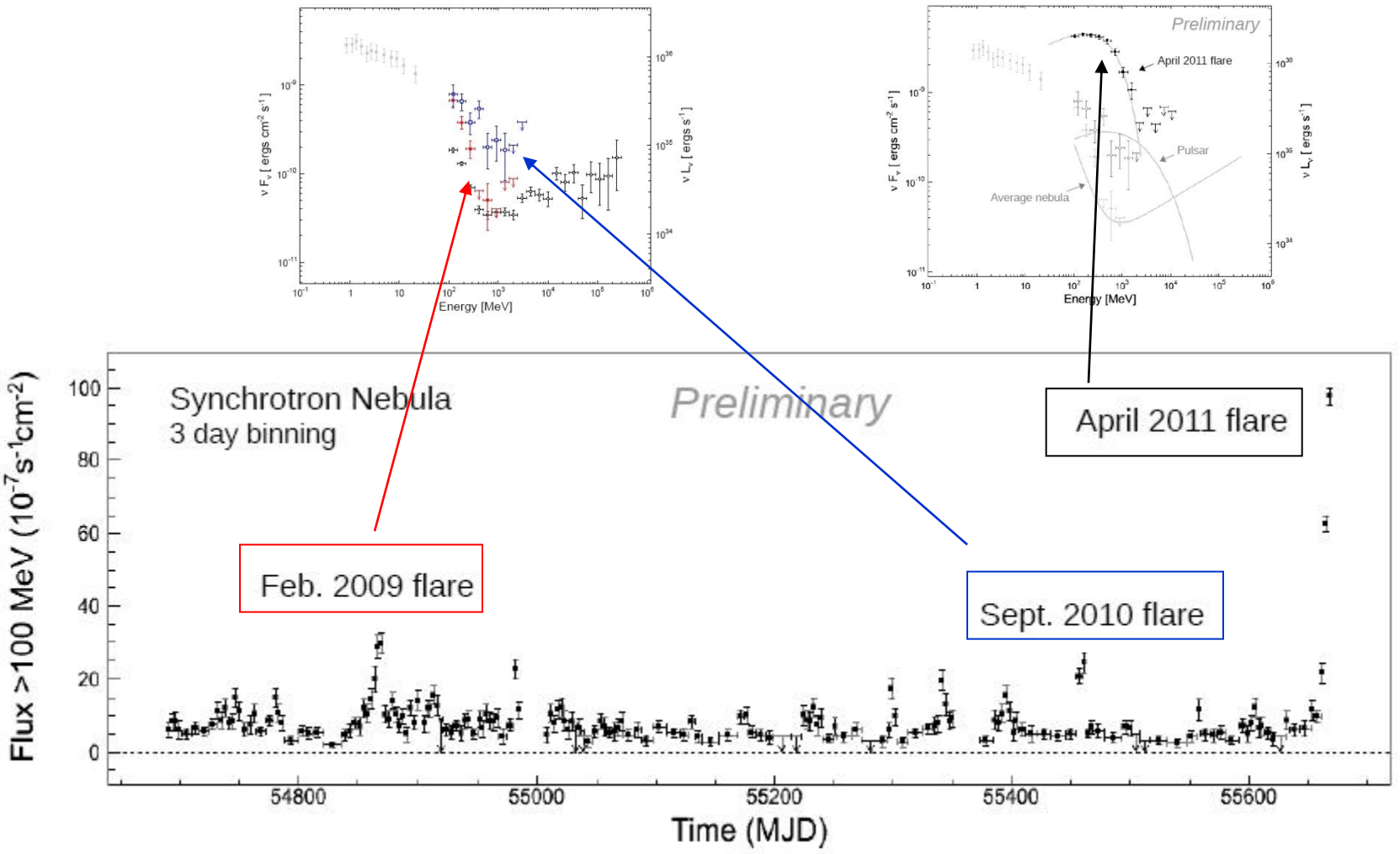
Average rate: ~ 23 ev/hour

84% with $E_\gamma > 300$ GeV



Another check of the detector stability

Crab Nebula no more a stable "candle"

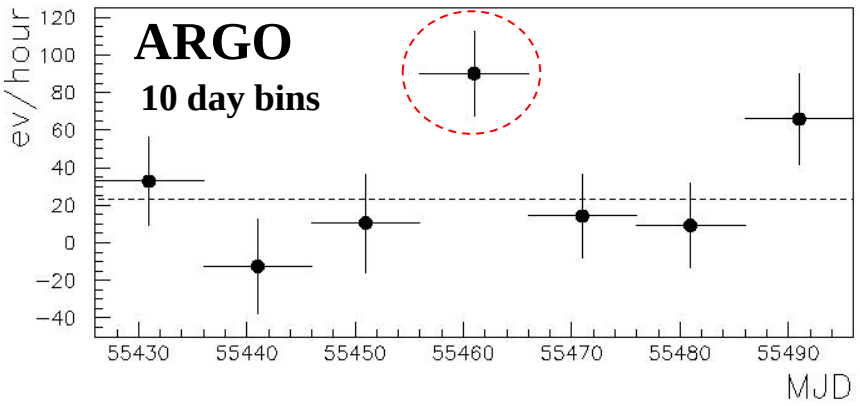


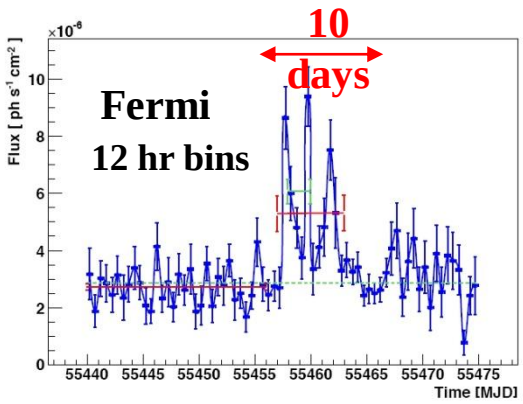
Fermi/LAT data (E > 100 MeV)

Crab Nebula TeV flare?

- **AGILE discovered a flare at E > 100 MeV in Sept. 2010, 19-21 (ATel #2855) → Rossi Prize 2012**
- **Fermi/LAT confirmed this observation (ATel #2861)**
- **ARGO-YBJ observed a TeV enhancement (~3-4 times) in ~54 hr in Sept. 2010, 18-27 (ATel #2921)**
- **Cherenkov telescopes MAGIC and VERITAS did not confirm this TeV emission with observations in Sept. 2010, 17-20 (ATel #2967, 2968)**

Sept. 18 – 27

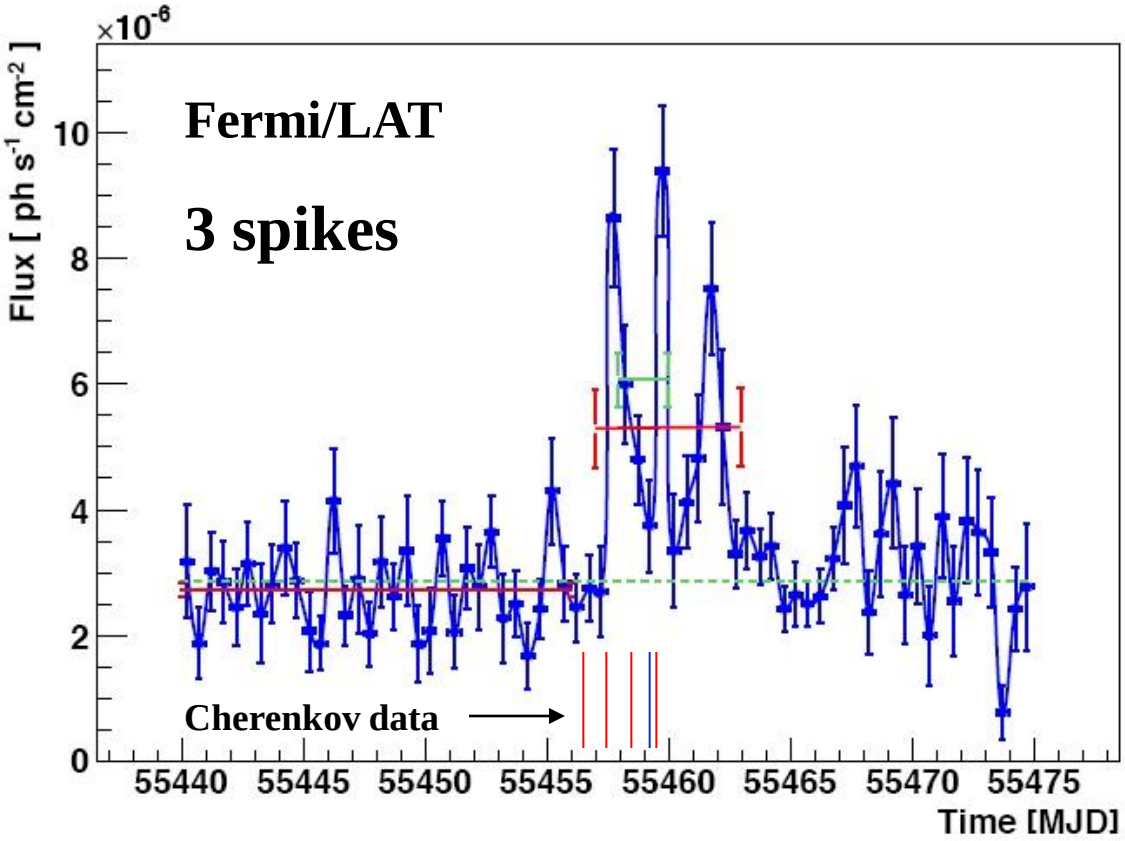




ARGO observed → 4.1 s.d.

ARGO expected → 1.0 s.d.

Crab: flare in September 2010



ARGO-YBJ during the 3 spikes:

→ **3.2 s.d.**

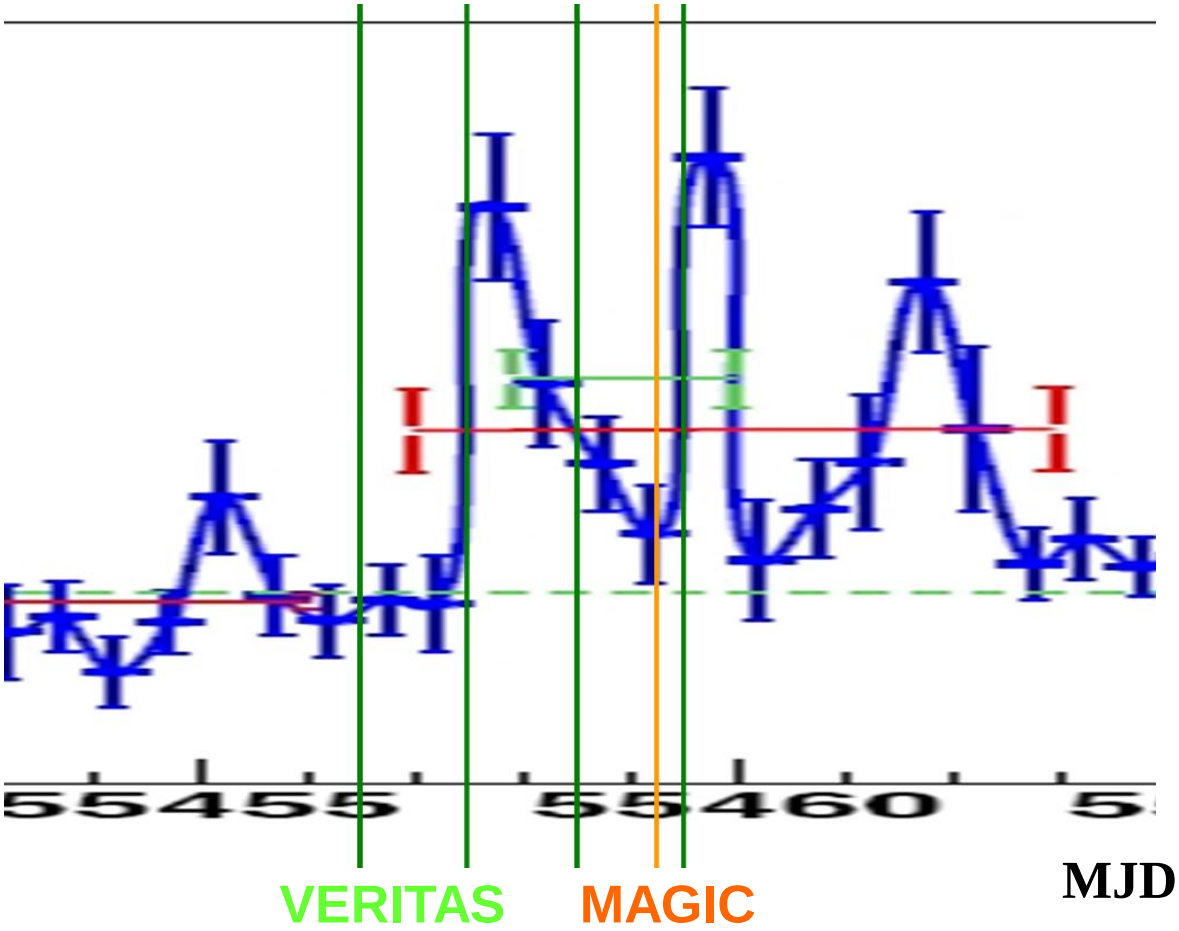
Expected signal: 0.55 s.d.

for events with $N_{hit} > 40$ (E ≈1 TeV)

Balbo et al. A&A 527 (2011) L4

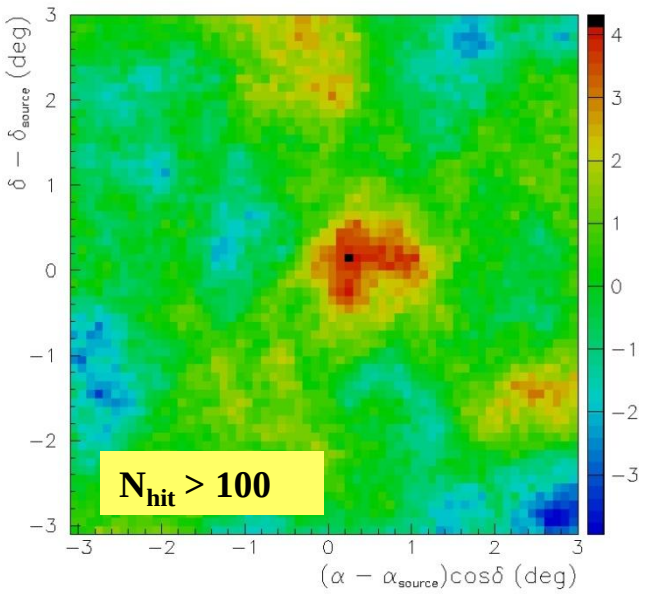
Fermi light curve and Cherenkov observations

Flare start: Sept. 18 at 6 UTC → end: Sept. 23 at 18 UTC



Crab: flare in April 2011

Significance map in 6 days



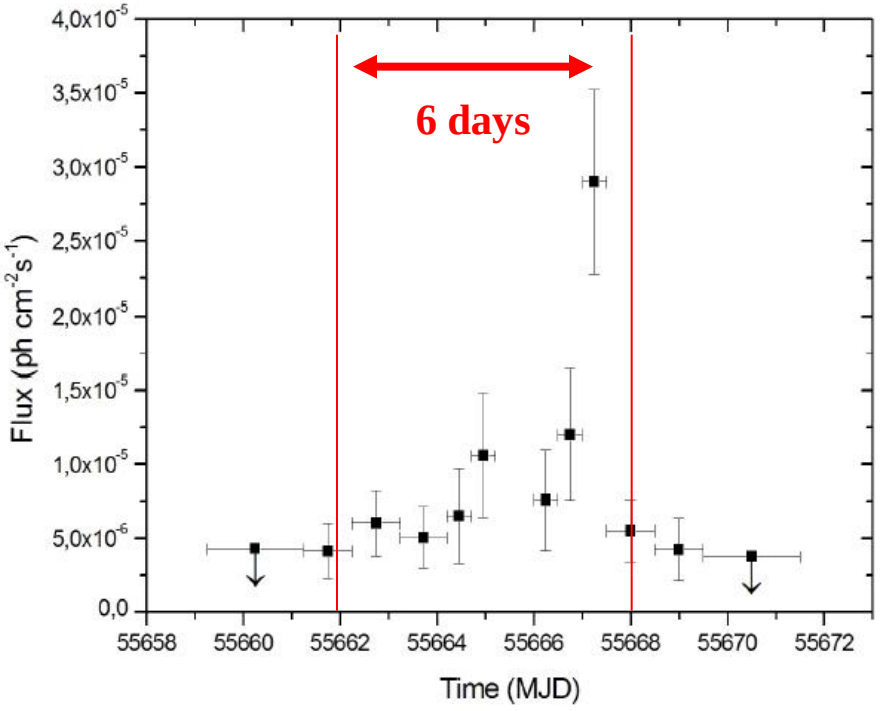
ARGO observed: 3.5 s.d.

ARGO expected: 0.62 s.d.

(E ≈ 3 TeV)

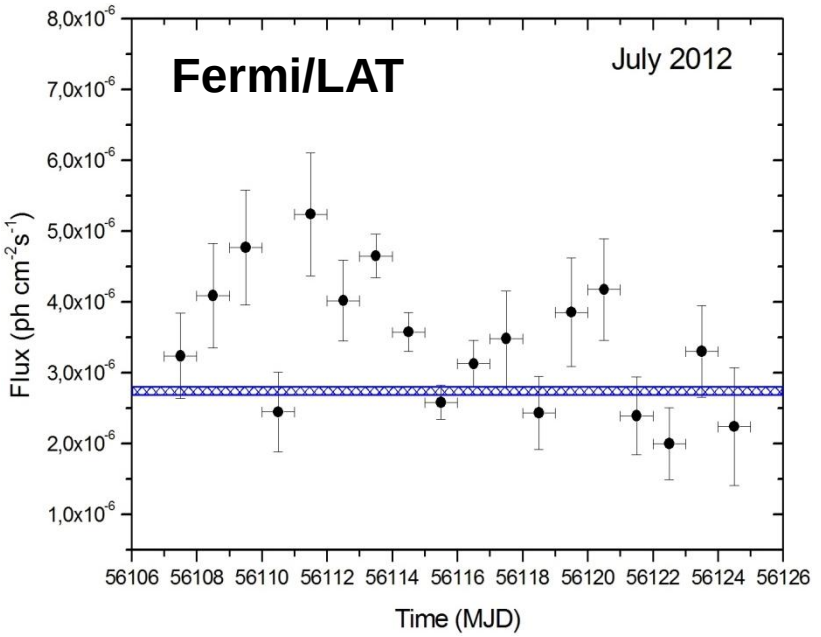
AGILE light curve

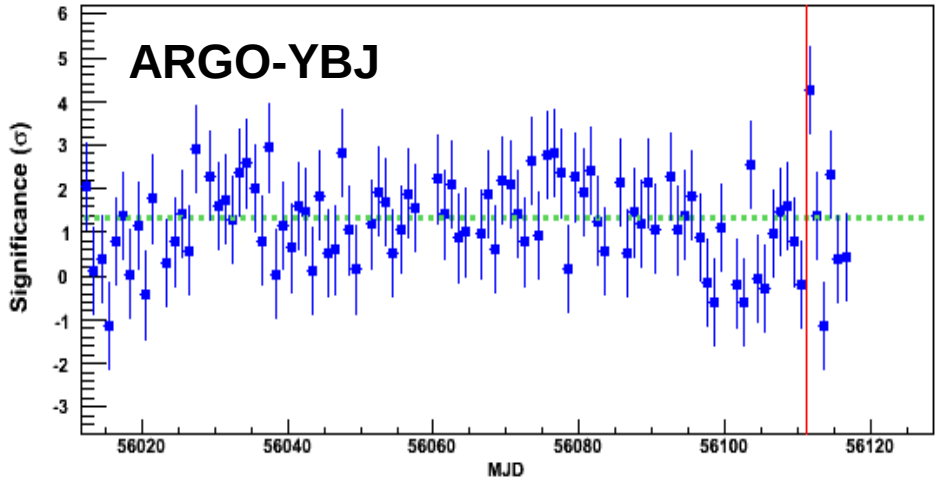
(E > 100 MeV)



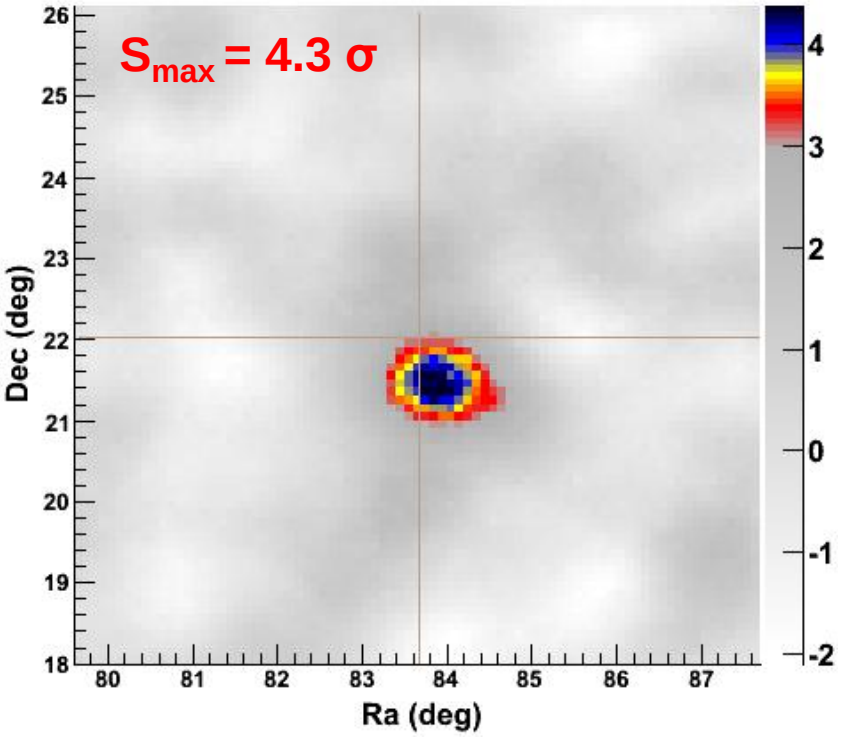
Crab Nebula: flare on July 3, 2012

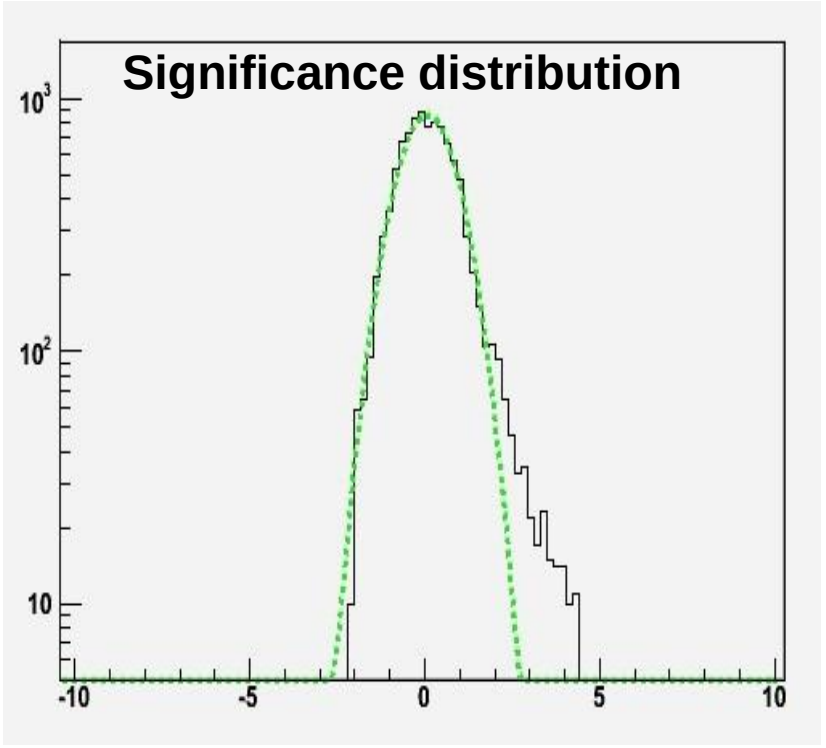
- Fermi/LAT observed a flare at E > 100 MeV on July 3, 2012 (MJD 56111) (ATel #4239)
- The daily-averaged emission doubled from $(2.4 \pm 0.5) \cdot 10^{-6}$ ph/cm^2/sec on July 2 to $(5.5 \pm 0.7) \cdot 10^{-6}$ ph/cm^2/sec on July 3, a factor 2 greater than the average flux of (2.75 ± 0.10) x 10^{-6} ph/cm^2/sec reported in the second Fermi/LAT catalog
- Possible TeV enhancement (≈ 8 times) observed by ARGO-YBJ only on July 3 (ATel #4258).





ARGO-YBJ observation on July 3, 2012



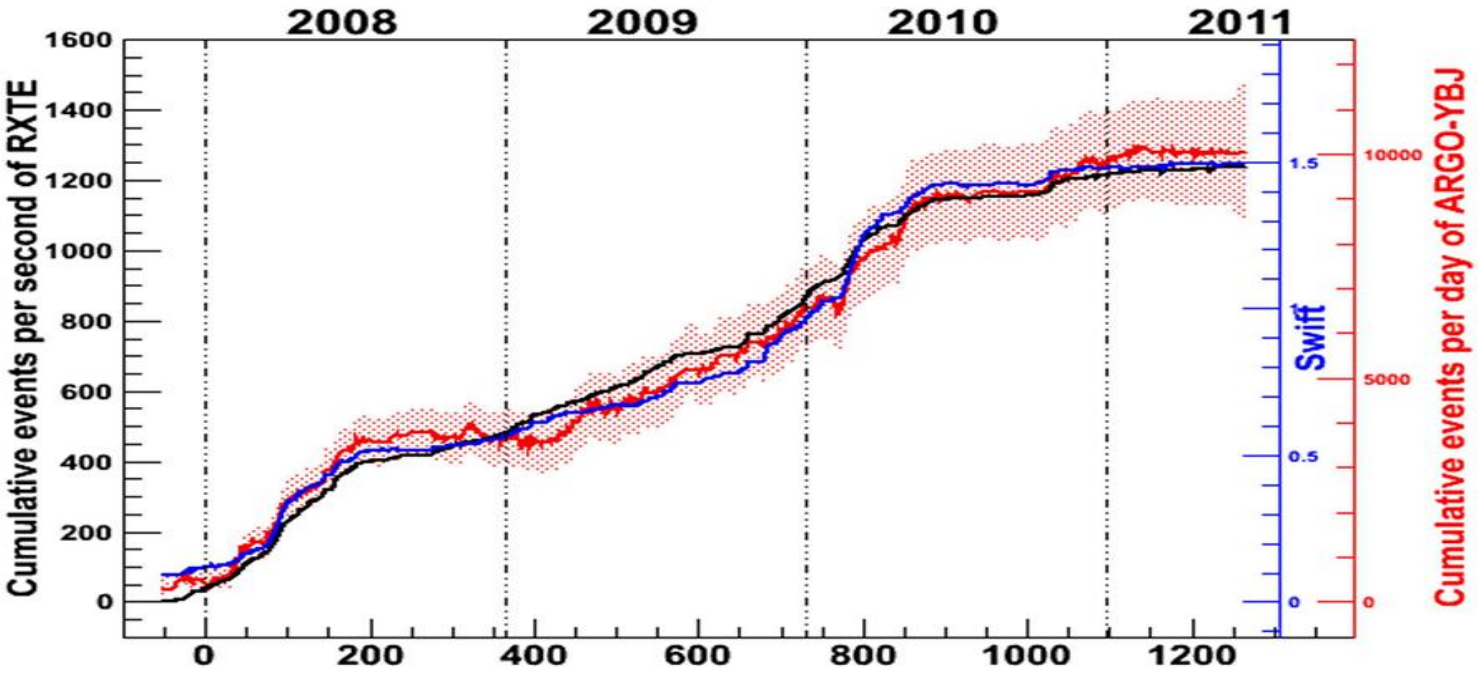


- ARGO-YBJ observed a 4.3 s.d. signal ~0.6 deg from the Crab nominal position but well inside its PSF
- The statistical significance at the Crab nominal position is 3.4 s.d.
- The expected significance of the steady flux is 0.33 s.d.
- The flaring flux should be a factor 8 – 10 higher

Long-term monitoring of Mrk421
ApJ 734 (2011) 110

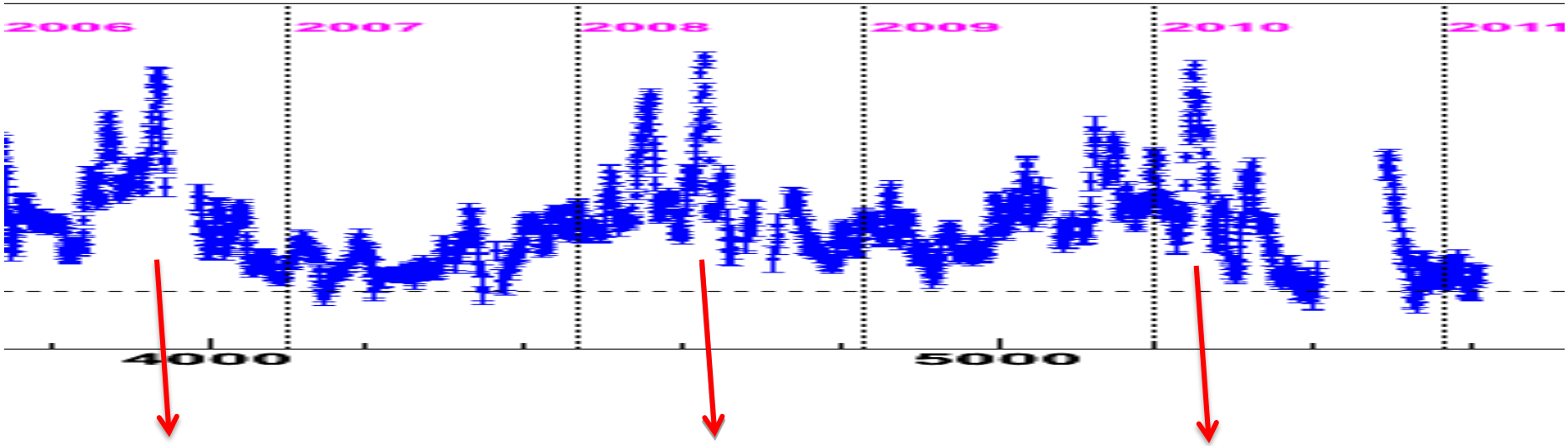
- ARGO-YBJ cumulative light curve compared with Swift/BAT and RXTE/ASM
- Good correlation between TeV and X-ray data
- Active and quiet periods are observed

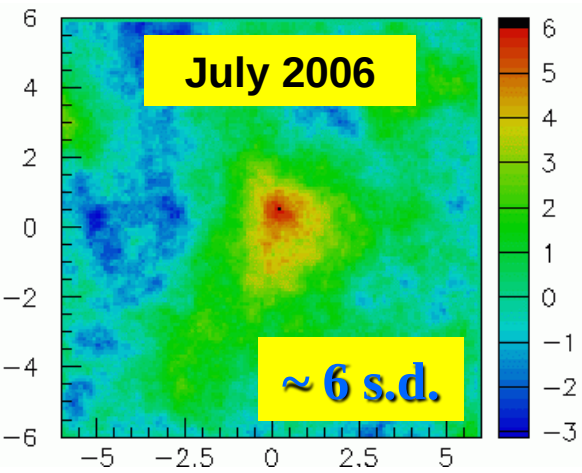
RXTE/ASM 2-12 keV
Swift/BAT 15-50 keV
ARGO-YBJ ≈ TeV

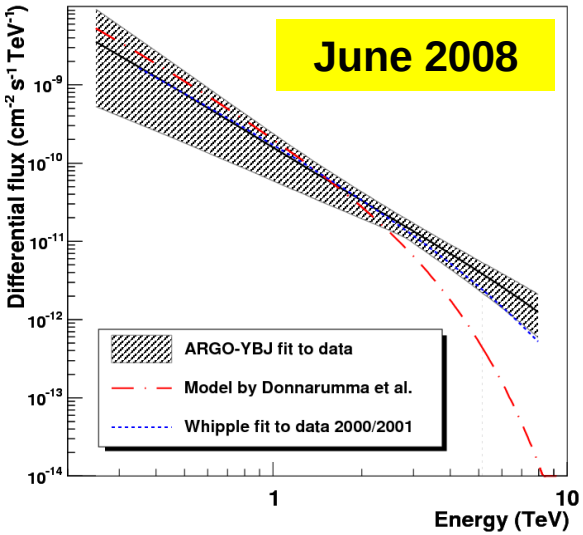


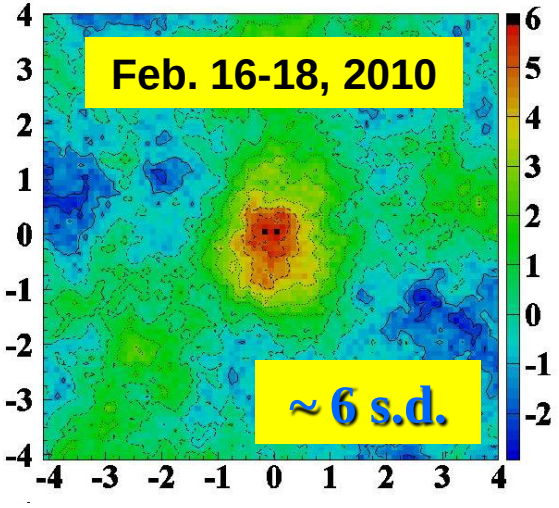
Mrk421: X-ray / TeV flares

RXTE, 2 – 12 keV





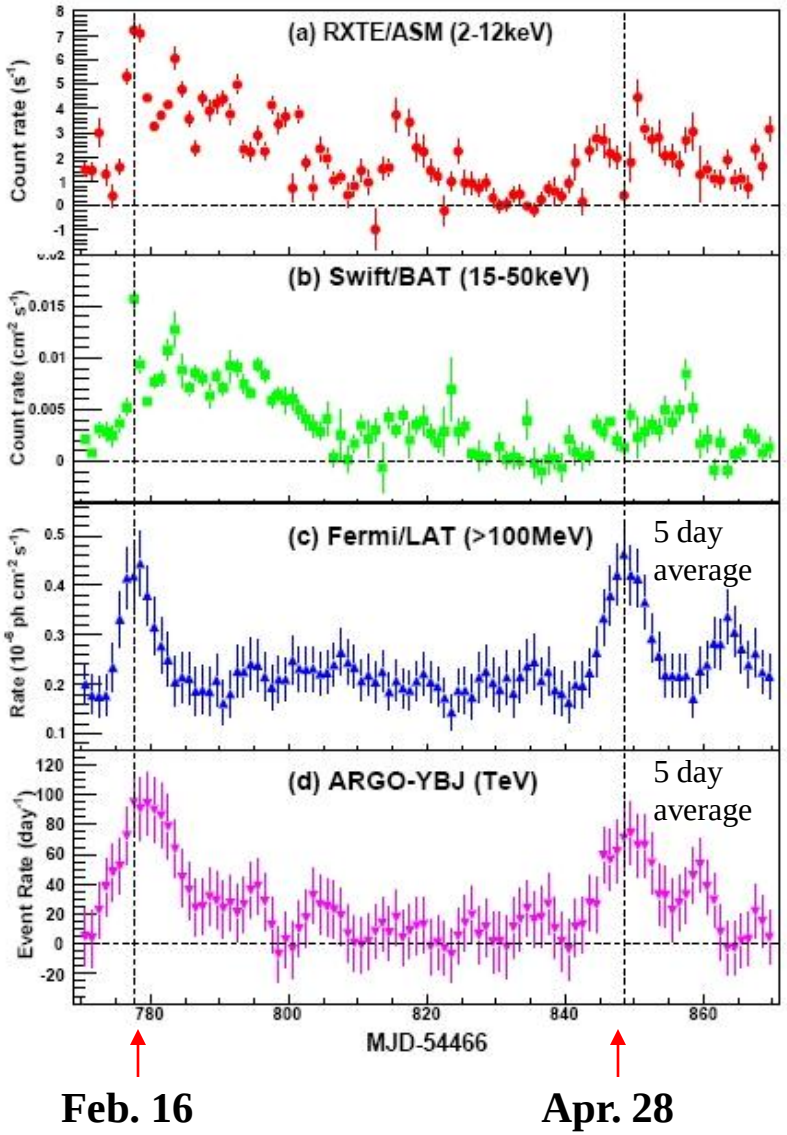




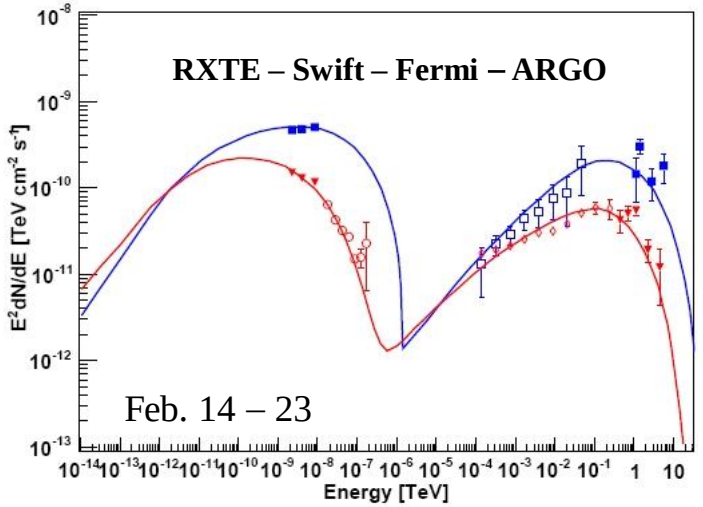
Aielli et al. ApJL 714 (2010) L208

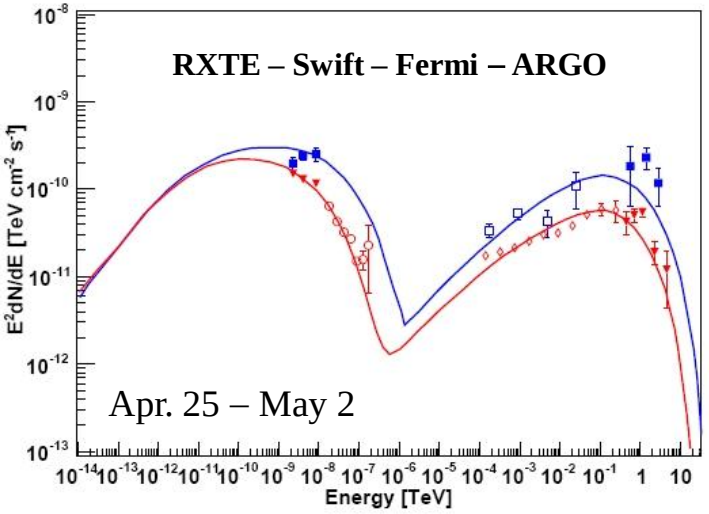
Mrk421: flares in 2010

Multiwavelength observation



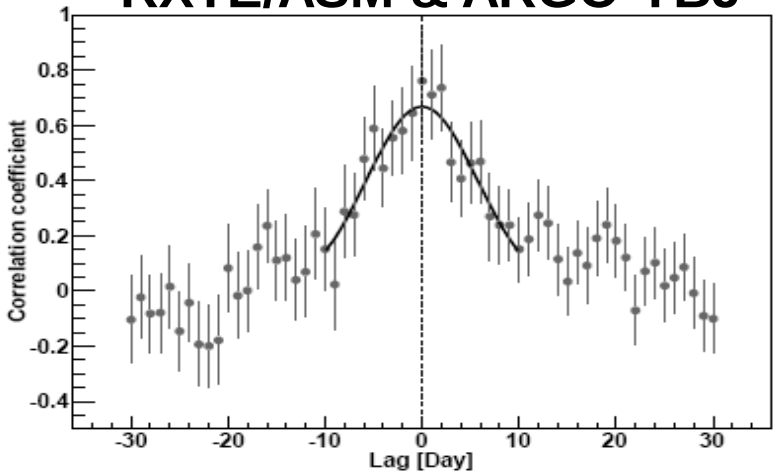
SSC model





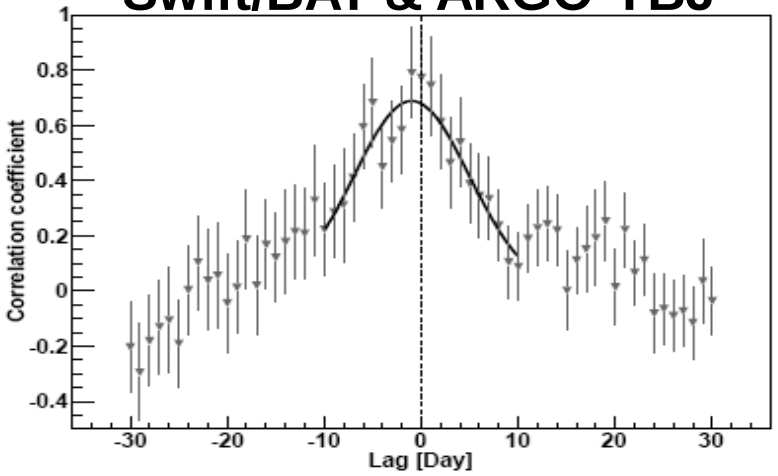
Mrk421: X-ray / TeV time lag

RXTE/ASM & ARGO-YBJ



0.108 ± 0.548

Swift/BAT & ARGO-YBJ



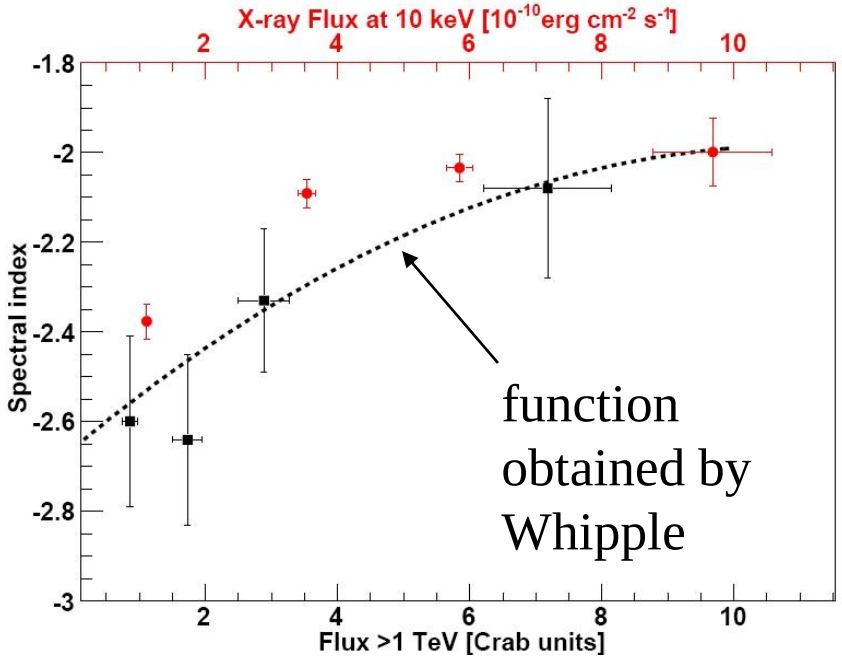
-0.647 ± 0.614

Positive values mean that TeV emission lags behind X-rays

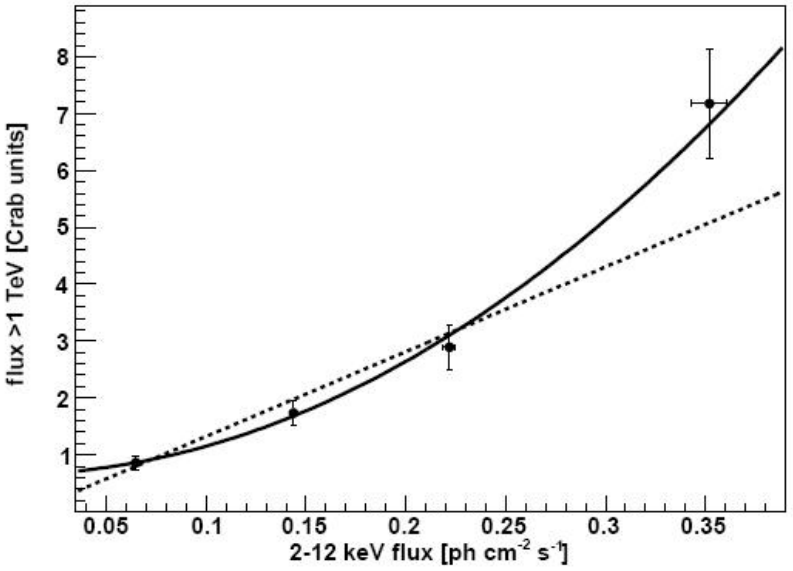
No significant time lag longer than 1 day is found

Mrk421: X-ray / TeV correlation

Spectral index vs. flux



TeV flux vs. X-ray flux



Both the X-ray and TeV spectra harden with increasing flux

The relation between TeV and X-ray fluxes is quadratic (SSC model)

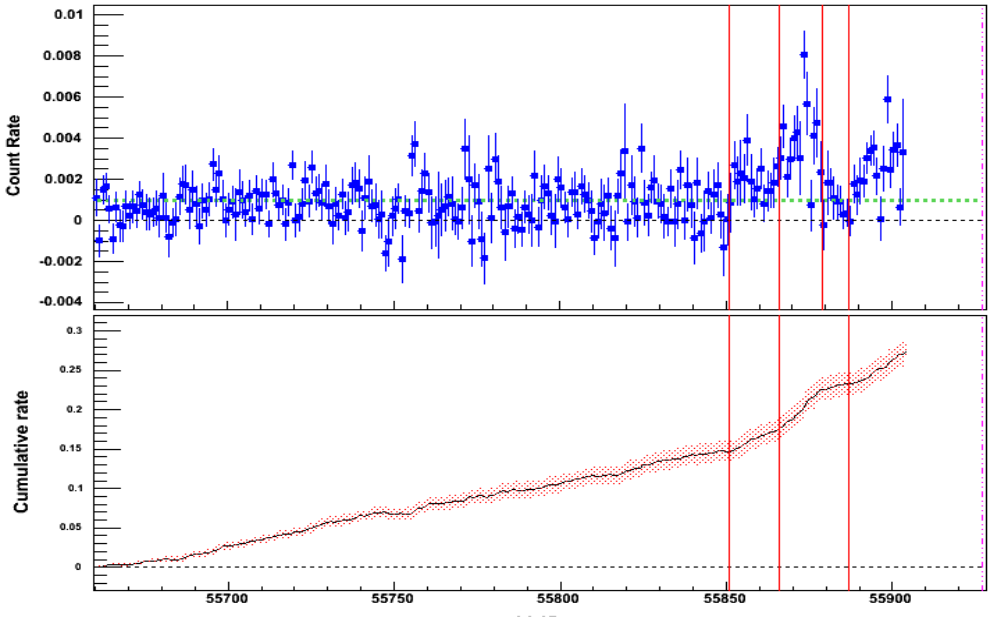
Mrk 501: long-term monitoring and flare
ApJ 758 (2012) 2

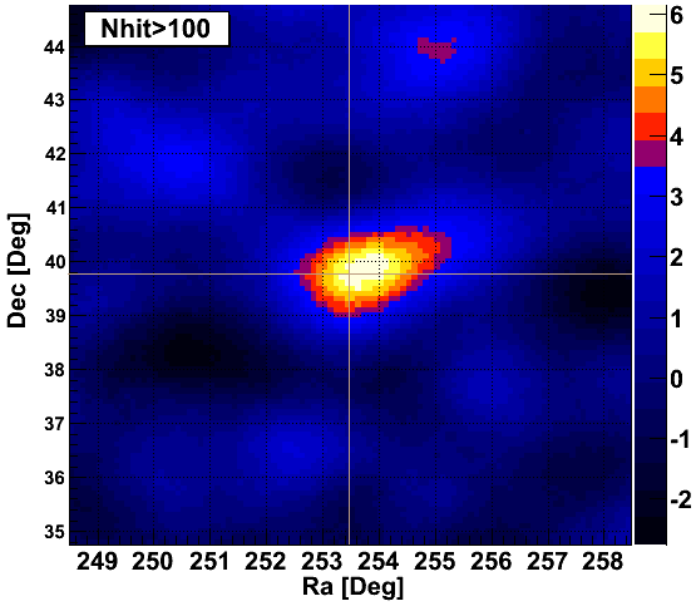
- Flare in 2011: days 290-325
- Large flare: October 2011 (304-317)

2011, days 290-325:

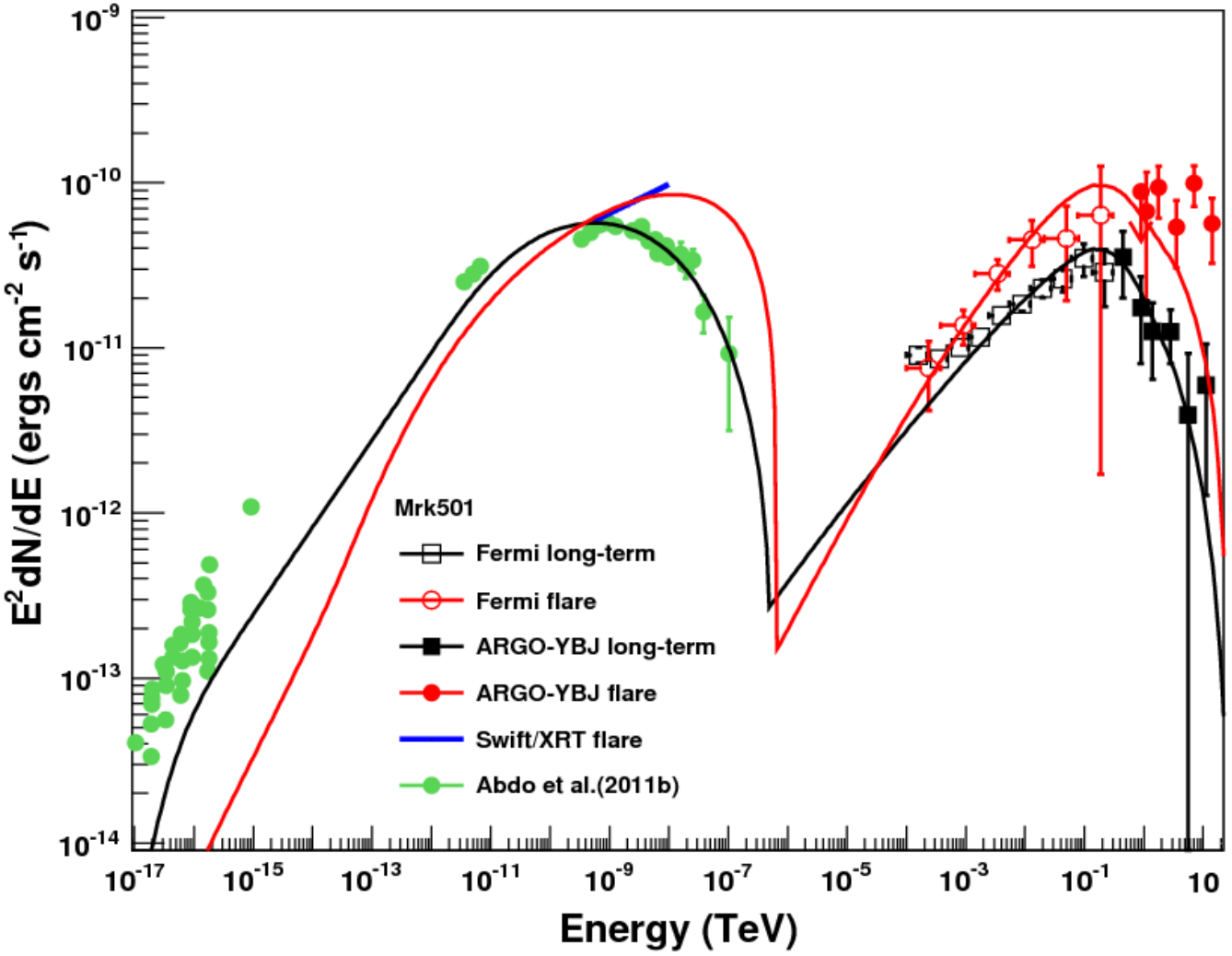
S_{max}= 6.14 s.d.

flux ~ 3 Crab Units





Mrk501: Spectral Energy Distribution

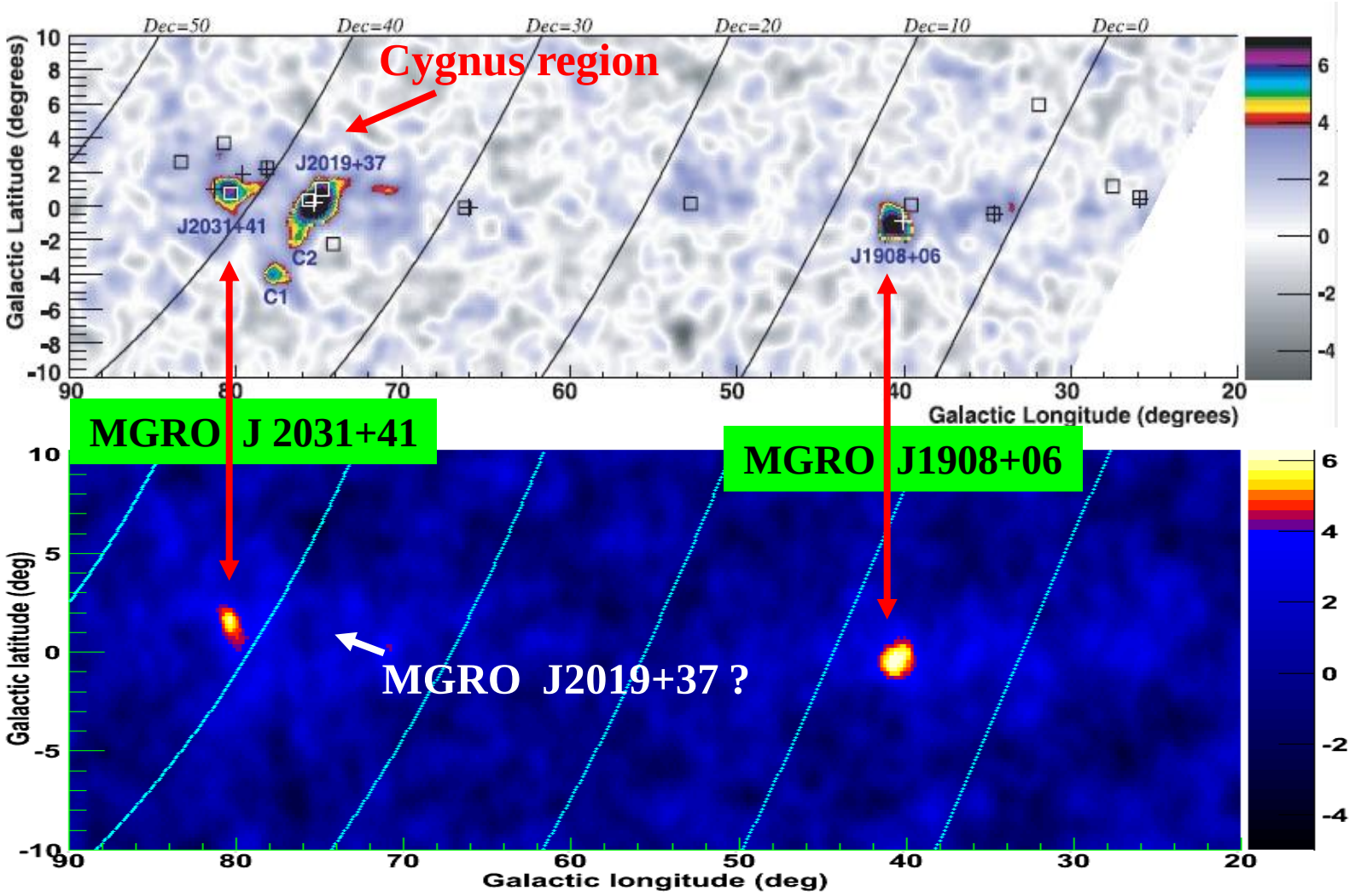


Simple SSC model unable to reproduce flaring emission at E > 8 TeV

Survey of the Galactic plane

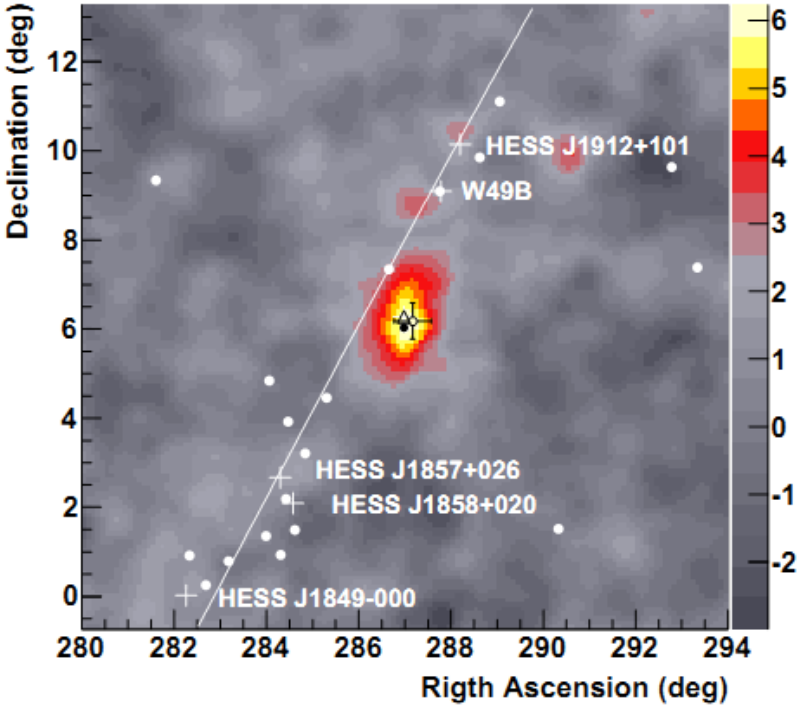
Milagro: E~20 TeV, 2000–2006

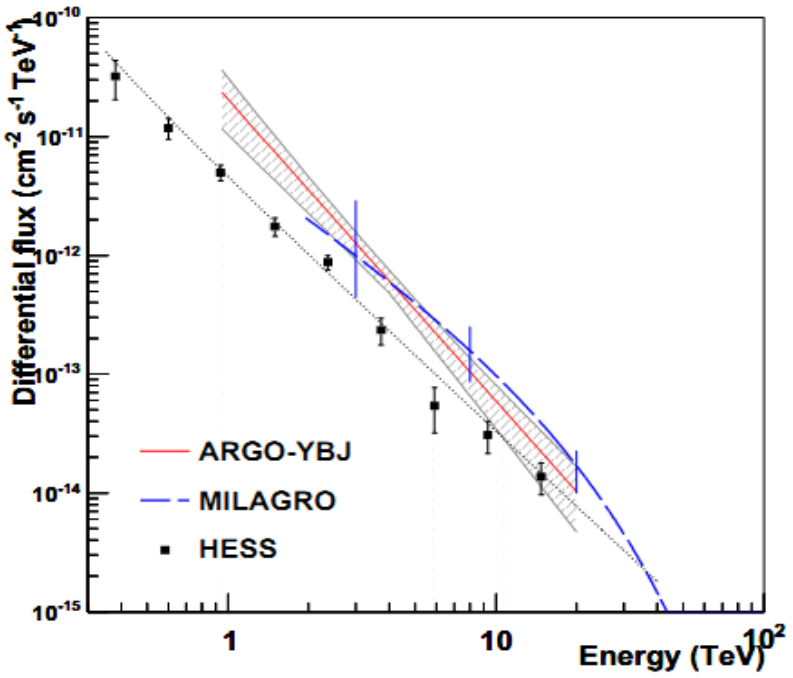
ARGO-YBJ: E~1 TeV, 2007–2011



MGRO J1908+06
ApJ 760 (2012) 110

- Pulsar Wind Nebula discovered by Milagro (≈ 8 s.d.) with a flux ≈ 0.8 Crab units
- Confirmed by HESS and VERITAS Cherenkov telescopes
- Observed by Tibet ASγ with significance 4.4 s.d. (2005)



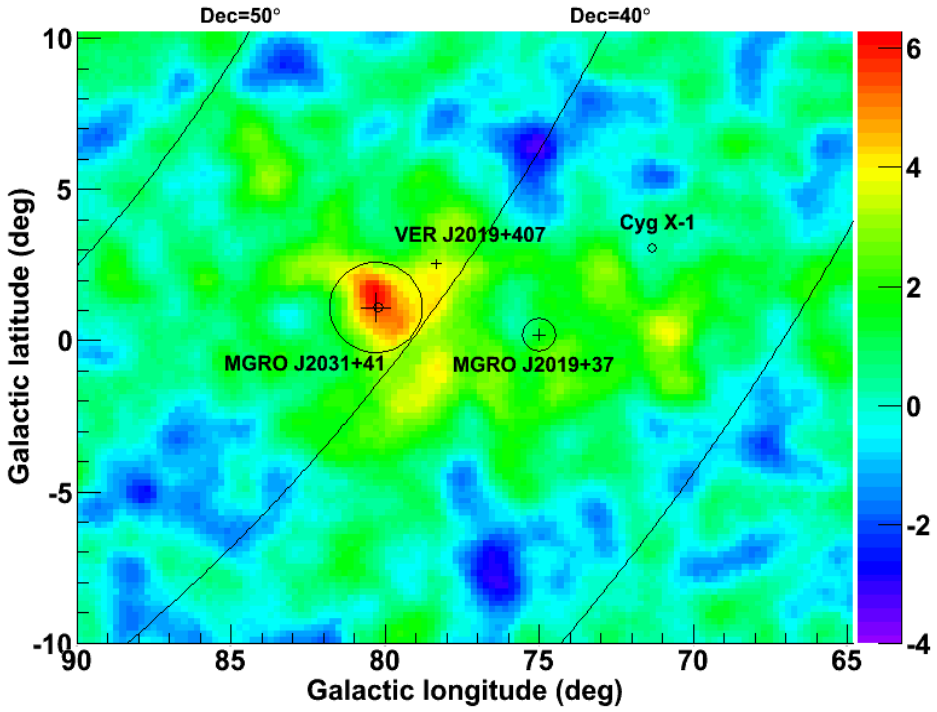


MGRO J1908+06: ARGO-YBJ results

- Measured intrinsic extension in agreement with HESS: $\sigma = 0.49^{o} \pm 0.22^{o}$
- Measured flux in agreement with that of Milagro, however 2–3 times the HESS flux
- Extended source stable during 11 years
- Luminosity (E > 1 TeV) ~ 2 L_{Crab}

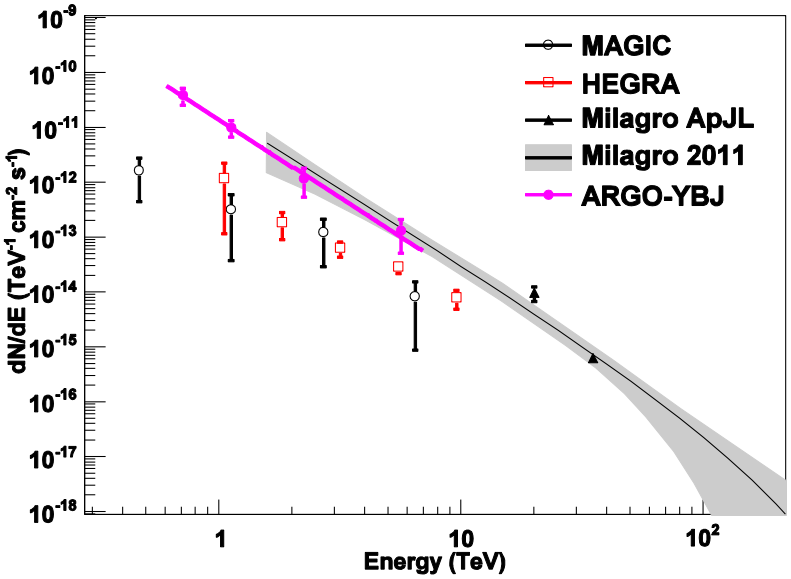
Cygnus region
ApJ 745 (2012) L22

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



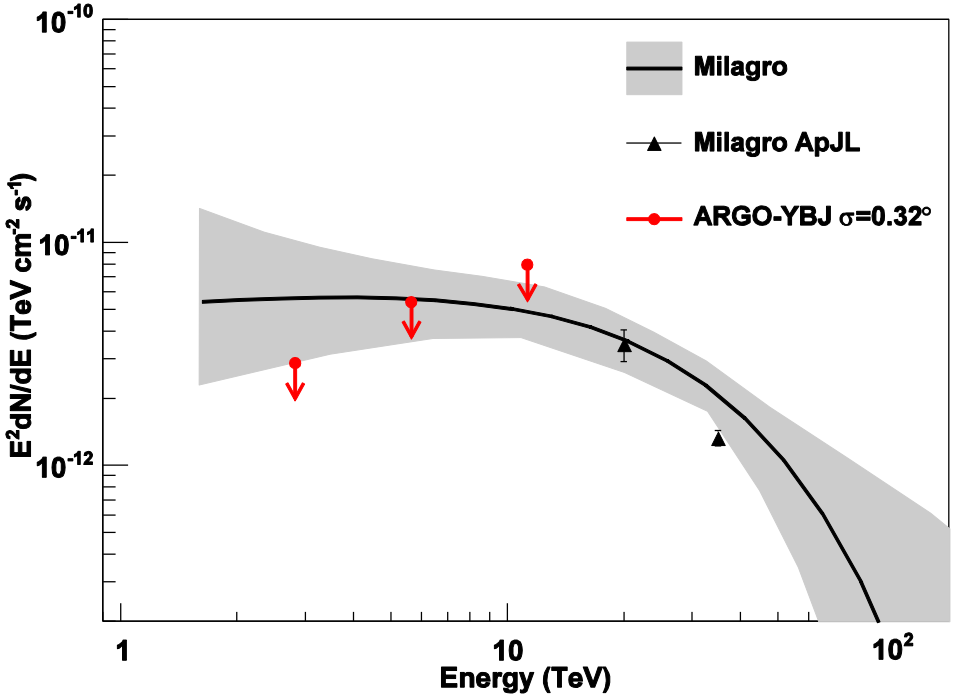
Cygnus region: MGRO J2031+41

- Extension $\sigma_{ext} = (0.2\ ^{+\ 0.4}_{-\ 0.2})^{\circ}$ consistent with HEGRA and MAGIC values ~ 0.1°
- Spectrum: $dN/dE \propto E^{-2.8 \pm 0.4}$ (assuming $\sigma_{ext} = 0.1°$)
- Flux (E > 1 TeV) ~ 0.3 Crab unit, about a factor 10 higher than HEGRA, Whipple and MAGIC results



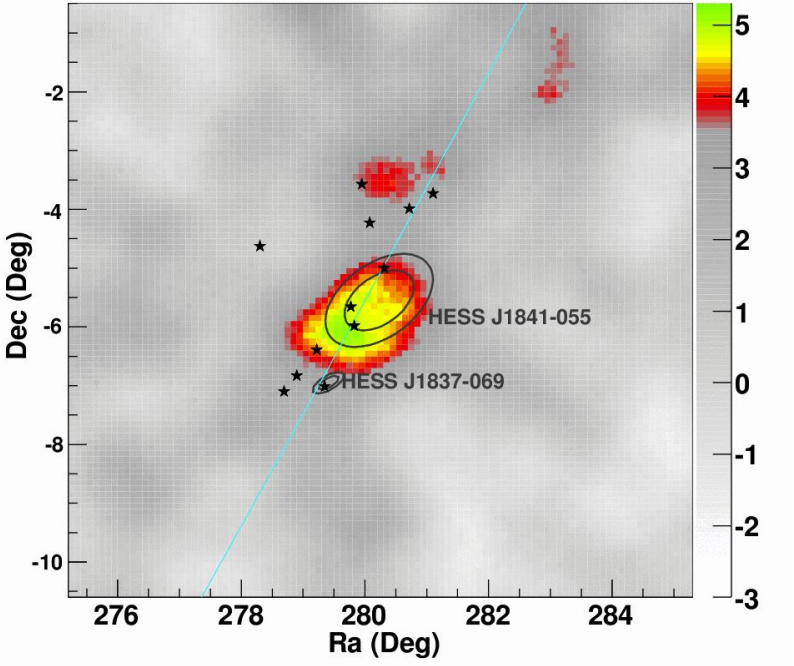
Cygnus region: MGRO J2019+37

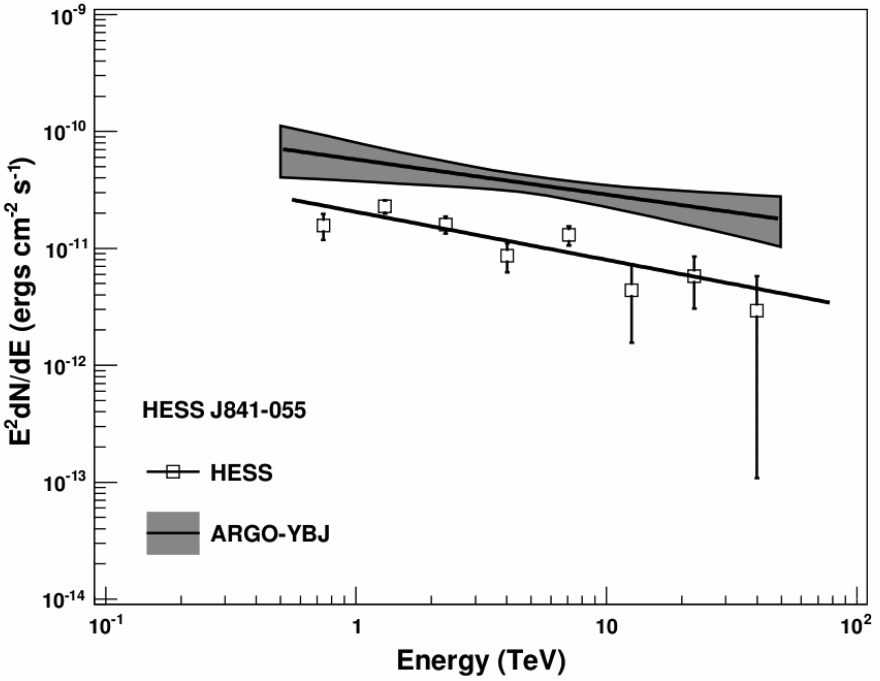
- The most intense Milagro source (12.4 s.d.) after the Crab
- Milagro spectrum: $dN/dE = 5.4\ 10^{-12} \cdot E^{-1.83} \exp(-E/22.4)$ cm^{-2} sec^{-1} TeV^{-1}
- Extension: $\sigma_{ext} = (0.32 \pm 0.12)°$



Several years of Δt (Milagro - ARGO) → global or local flux variability?

HESS J1841-055
Submitted to ApJ



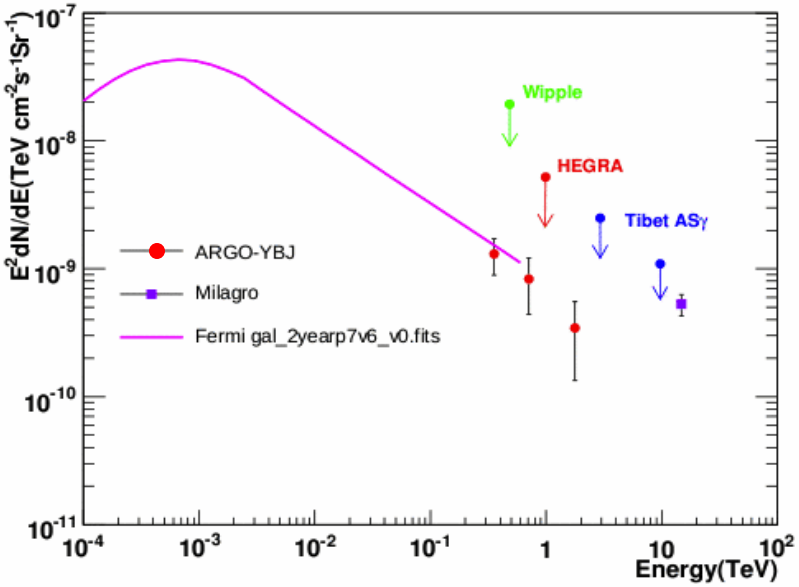


Extension: $\sigma_{ext} = (0.40\ ^{+\ 0.32}_{-\ 0.22})^\circ$

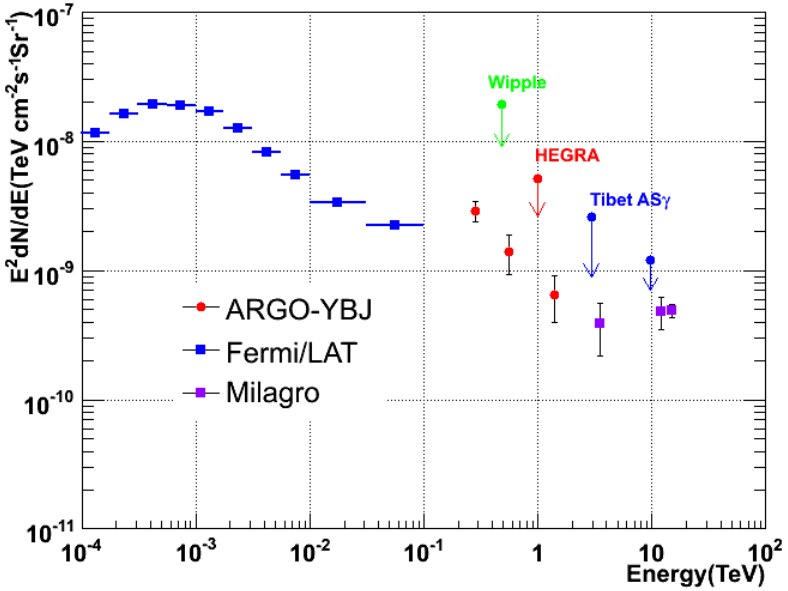
Flux (ARGO-YBJ) ~ 3 Flux (HESS)

Diffuse γ-rays in the inner Galactic plane

$25^\circ < l < 65^\circ$



$65^\circ < l < 85^\circ$
(Cygnus region)



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

Comments on extended sources

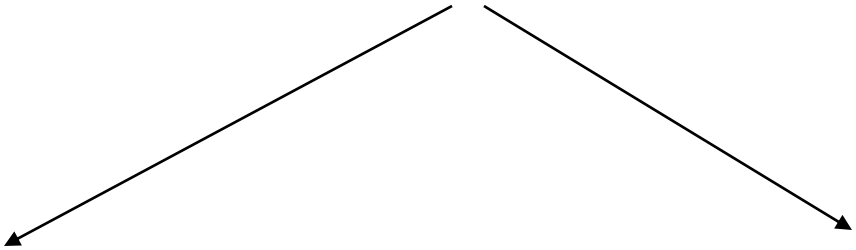
- As for Milagro, the fluxes measured in extended sources are significantly larger than those measured with Cherenkov telescopes

- A contribution is due to the Galactic diffuse emission and possible nearby sources, however it cannot explain the observed disagreement (being only ~ 10 %)
- The systematic error has been estimated to be < 30%
- Flux variations over the whole extended regions are difficult to be interpreted, but can not be completely excluded

- The discrepancy could origin from the different techniques used in the background estimation for extended sources

ARGO-YBJ scaler mode

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

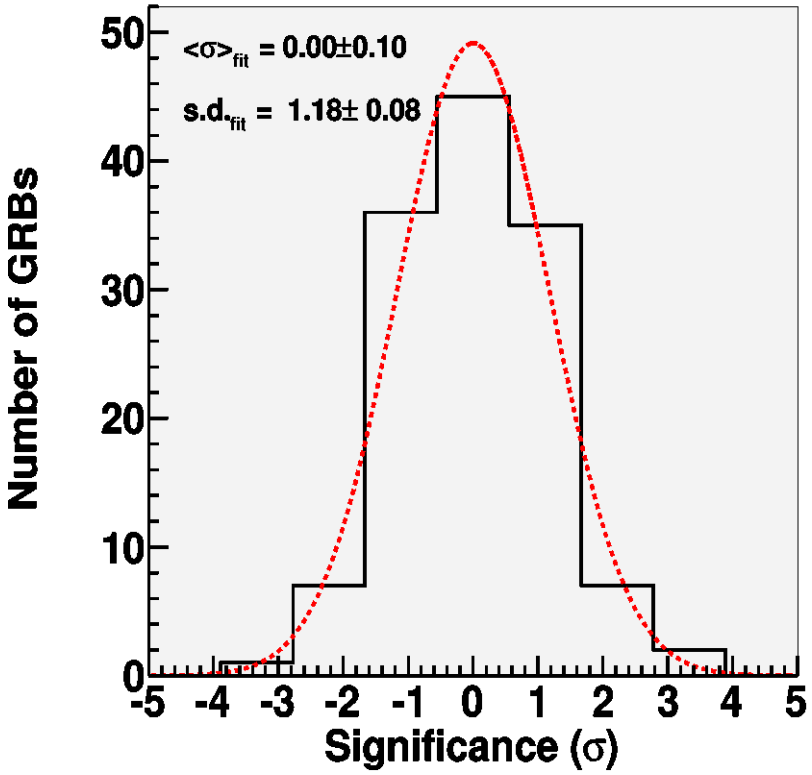
$E_{th} \approx 300$ GeV

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

Search for GRBs in the GeV-TeV range
ApJ 699 (2009) 1281



133 GRBs in the ARGO f.o.v. from Dec. 2004 to Aug. 2012
(largest sample at ground!)

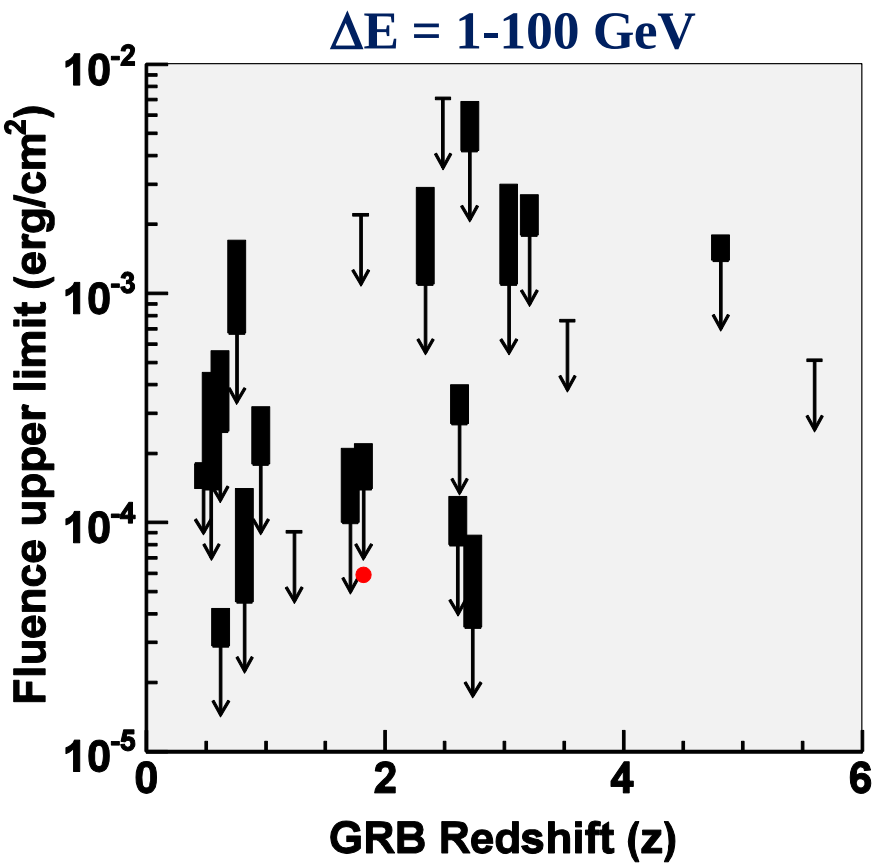
- **With known redshift: 22**
- **Discovered by Fermi/GBM: 26**
- **Detected by Fermi/LAT: 3**

- **Long duration GRBs (>2s): 117**
- **Short duration GRBs (≤2s): 16**

No evidence of coincident signal during the GRB T90 duration

In stacked analysis no evidence for any integral effect

Upper limits to GRB fluence



Fluence = Flux × ΔT

Sample of 22 GRBs with known redshift

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

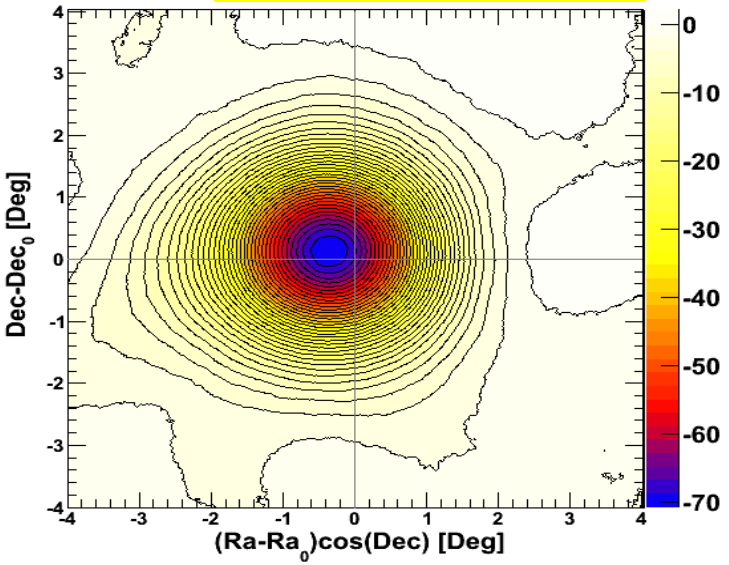
Fluence upper limits (99% c.l.) obtained with differential spectral indexes ranging from the value measured by satellites to 2.5

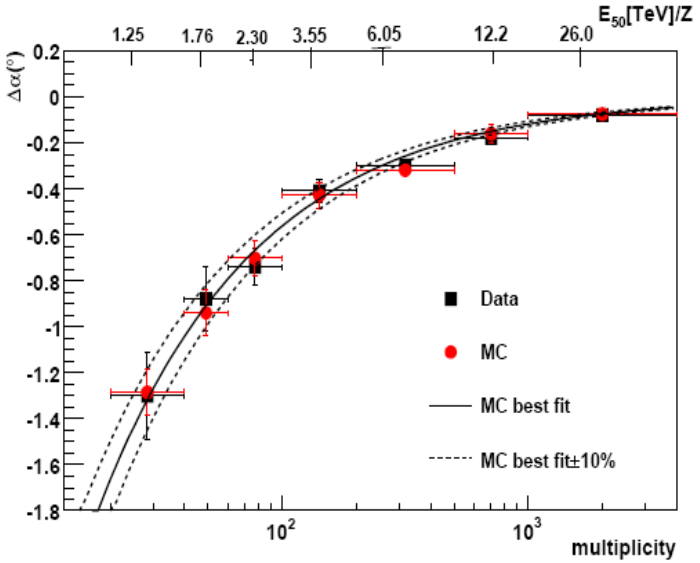
Analysis of the Moon shadow
Phys. Rev. D 84 (2011) 022003

A natural tool to estimate the detector performance:

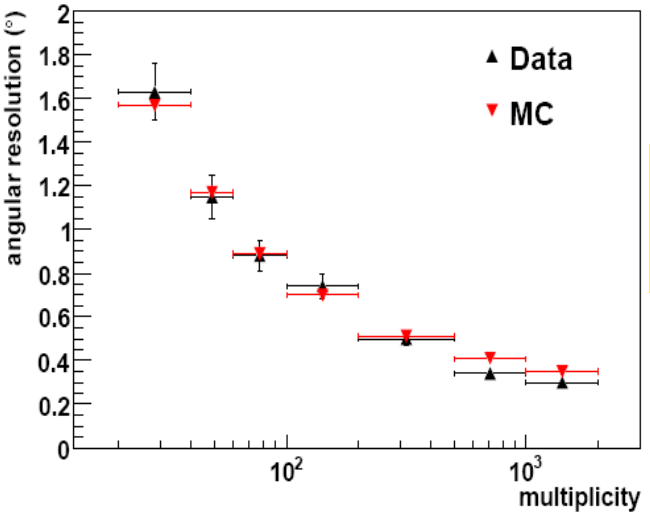
$N_{hit} > 100$, 71 s.d.

- 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

$\bar{p}$ / p flux ratio at TeV energies

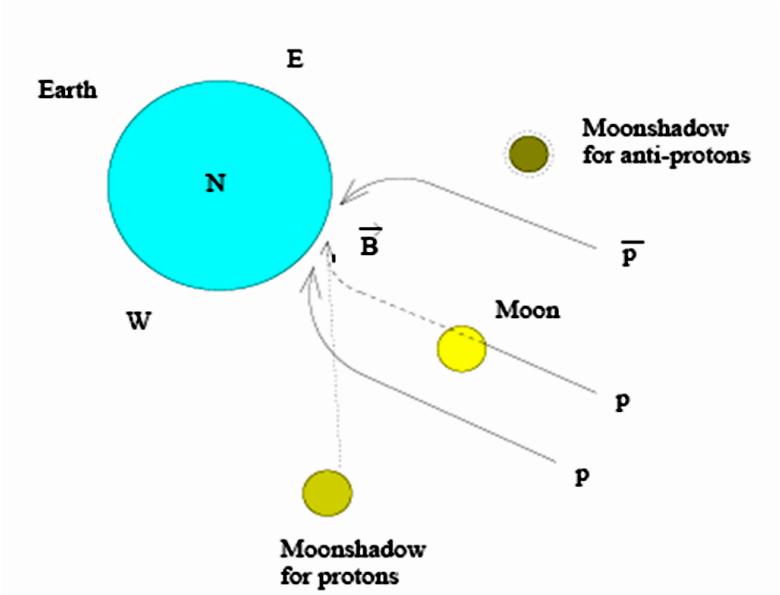
Phys. Rev. D 85 (2012) 022002

Using the data of the Moon shadow, limits on the antiproton flux can be derived: protons are deflected towards East by the geomagnetic field, while antiprotons are deflected towards West

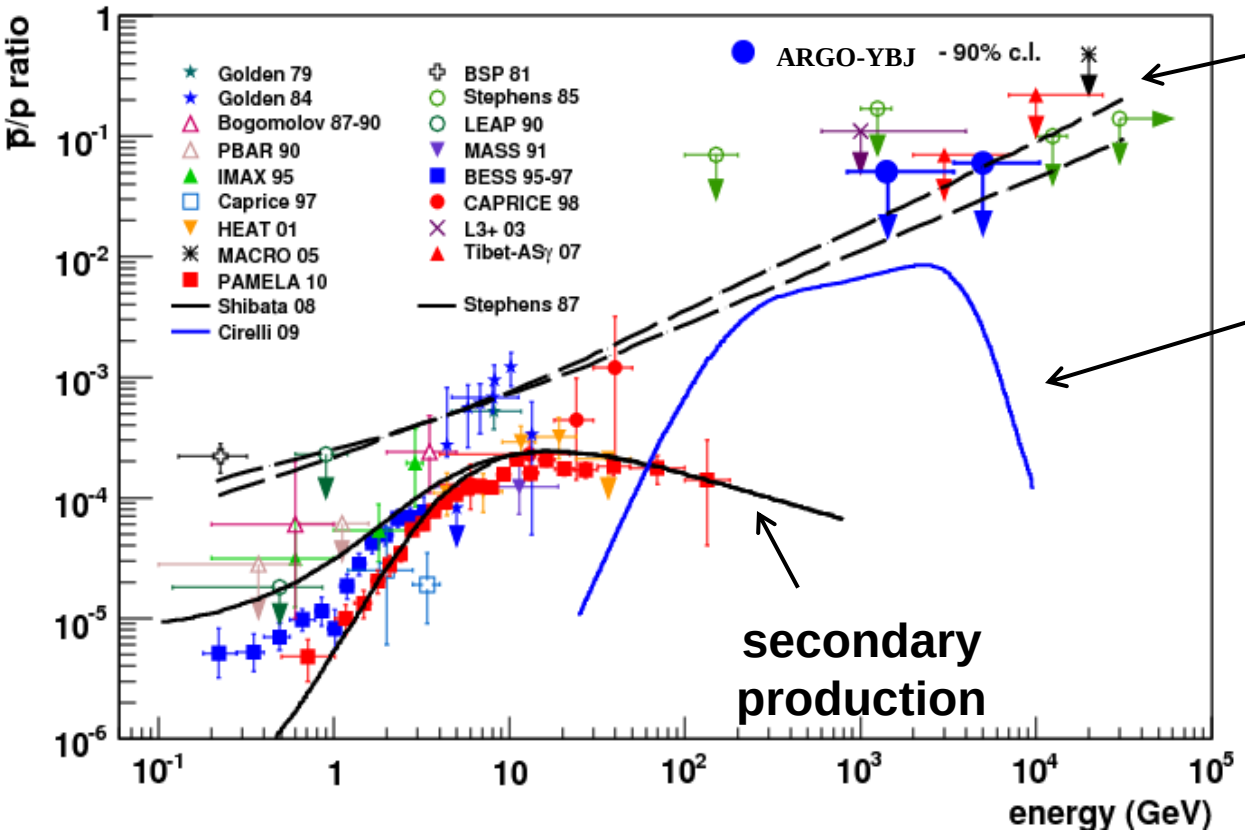
→ two symmetrical shadows are expected

If the displacement is large and the angular resolution good enough, we can distinguish between the two separate shadows

If no event deficit on the antimatter side is observed, an upper limit on the antiproton content can be determined



Upper limits on the $\bar{p}$ / p flux ratio



contribution from antimatter galaxies for two values of the diffusion coefficient

annihilation of heavy dark matter

5% at 1.4 TeV (90% c.l.)
6% at 5 TeV (90% c.l.)

lowest limits available at these energies until now

In the TeV energy region the p fraction in CRs is ≈70%

Measurement of the proton-air cross section
Phys. Rev. D 80 (2009) 092004

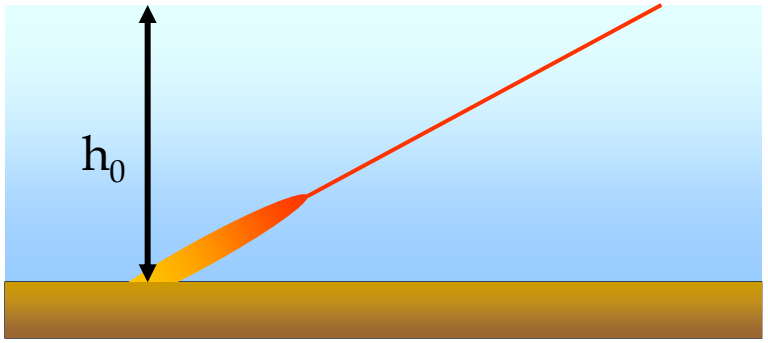
Technique: measurement of the shower rate at fixed energies as a function of the zenith angle θ:

$$I(\theta) = I(0)\ \exp[-(h_0/\Lambda)(\sec\theta - 1)]$$

where Λ is not the p interaction length because of inelasticity, shower fluctuations and detector resolution, however: $\Lambda = k\,\lambda_{int}$

where k is determined by MC simulations and depends on:

- hadronic interactions
- detector features and location (atm. depth)
- actual set of experimental observables
- analysis cuts
- energy threshold



$I(\theta)$

↓ Data

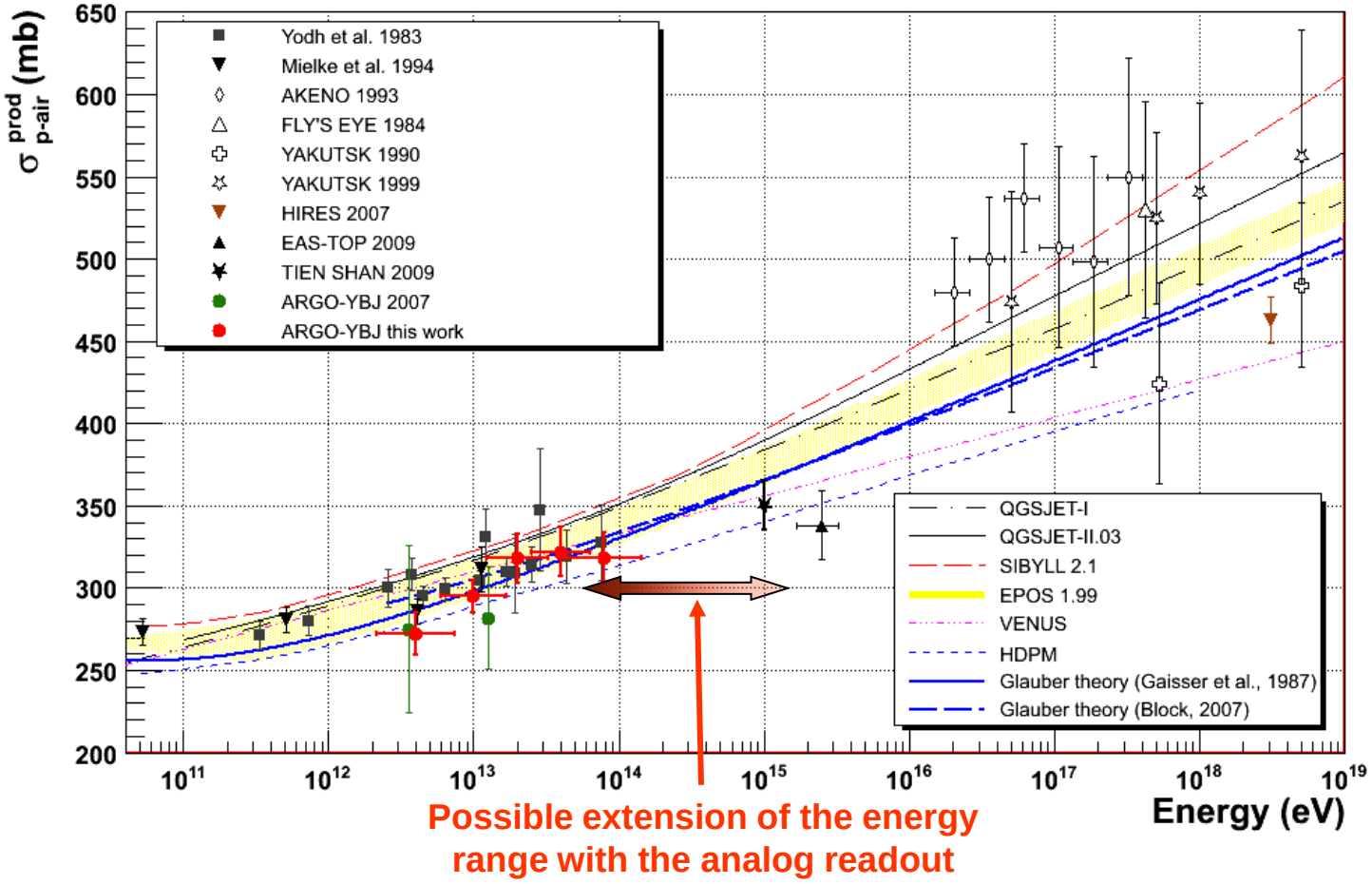
Λ

↓ MC

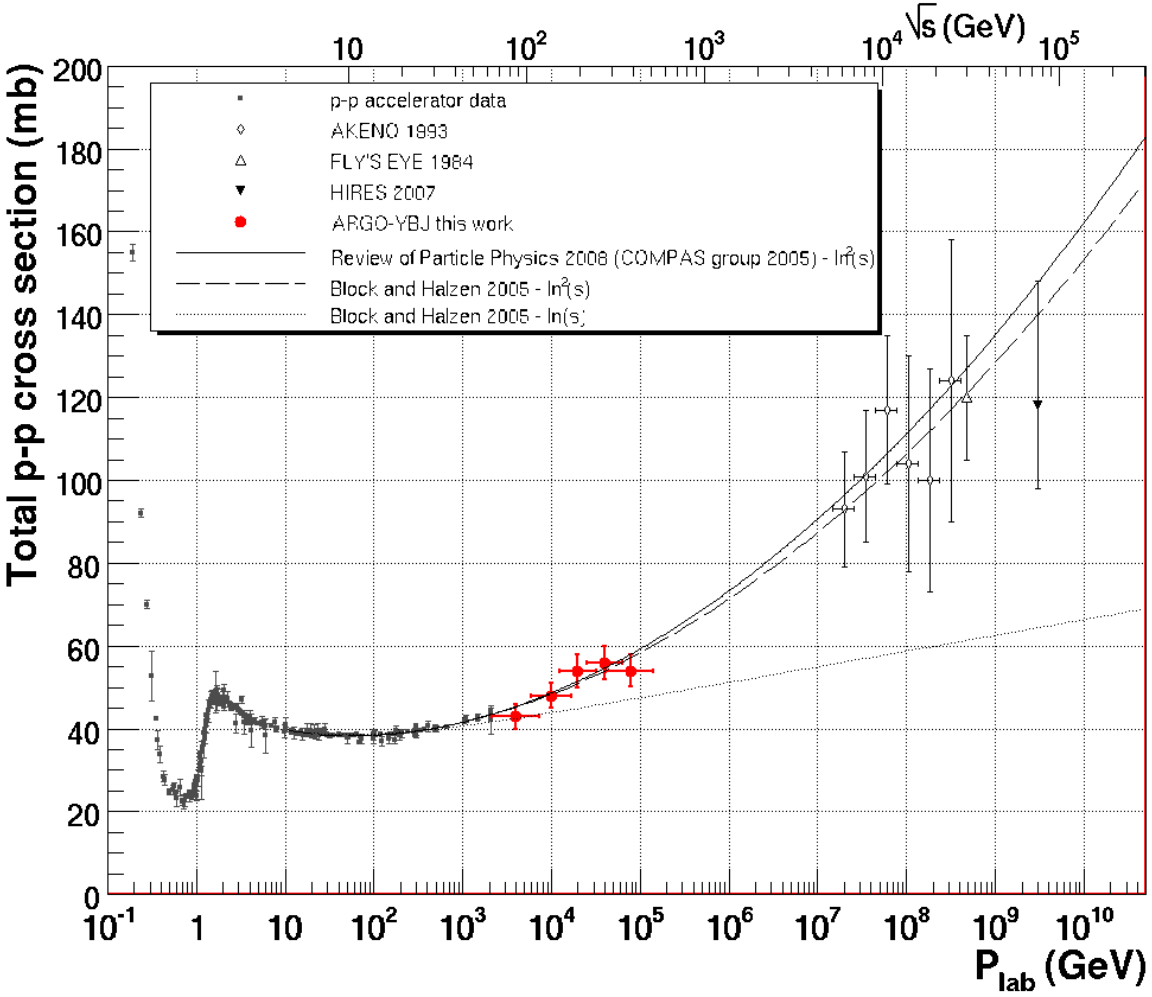
λ_{int}

$$\sigma_{p\text{-}air}\ (mb) = 2.4 \cdot 10^4 / \lambda_{int}\ (g/cm^2)$$

The proton-air cross section

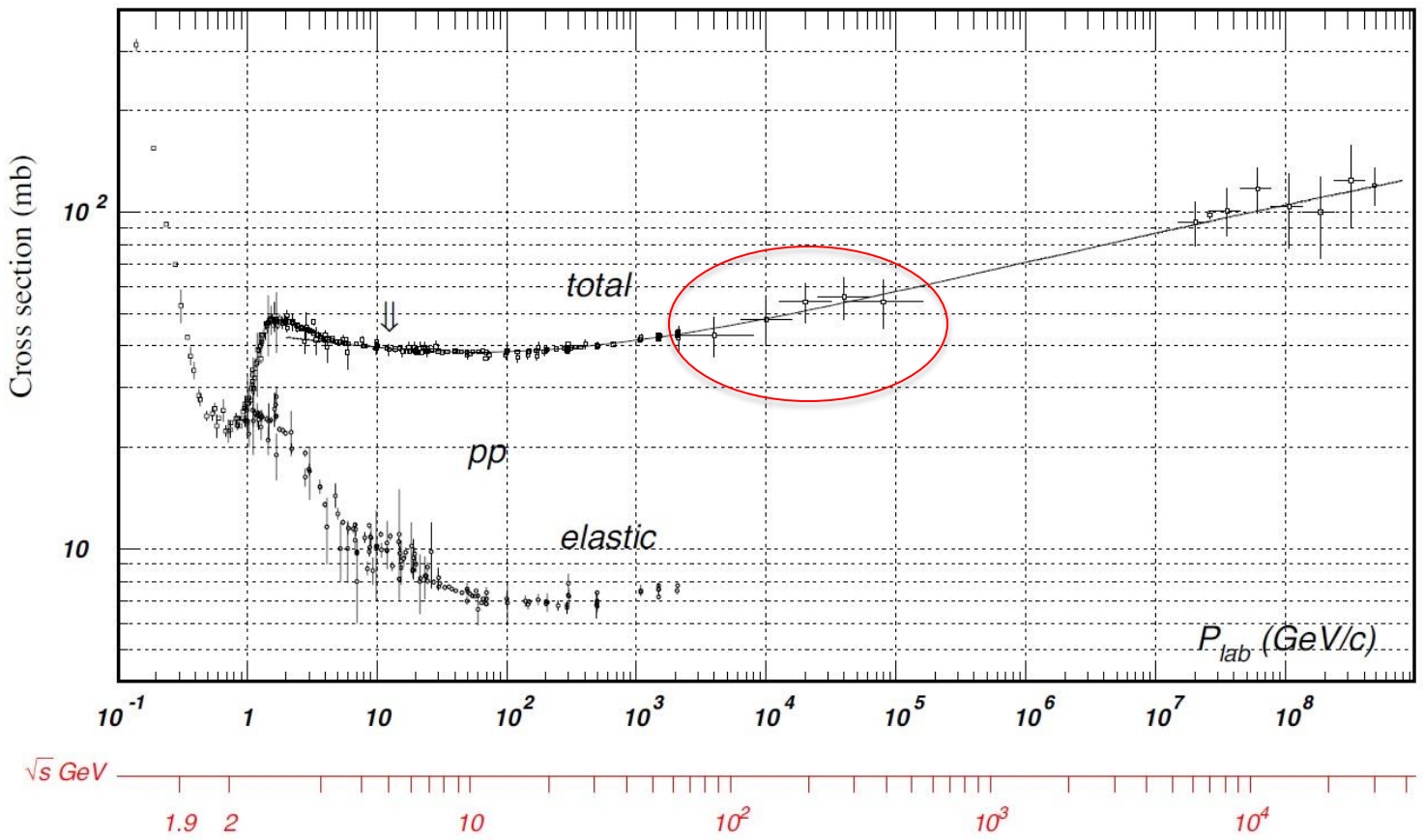


The proton-proton cross section



Obtained from $\sigma_{p\text{-}air}$ via the Glauber theory

Citation in the Review of Particle Physics 2012



Analyses in progress or planned

1. **Data reprocessing with γ/h discrimination in order to update the current results of the sky survey**

2. **Study of the knee region (E ≈ PeV) in the CR spectrum with the analog readout**

3. **Study of the CR anisotropy at all angular scales with a new analysis technique ("needlet-based"), also in collaboration with IceCube**

4. **Analysis of horizontal air showers (θ ≥ 70°)**

5. **Search for γ-ray emission from dark matter particles in galaxy clusters**

6. **Monitoring of the Interplanetary Magnetic Field around the maximum of the solar cycle**