ARGO-YBJ : status and highlights

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On behalf of the ARGO-YBJ Collaboration

Vulcano Workshop 2012 – May 30, 2012

Cosmic Ray Physics with ARGO-YBJ

ARGO-YBJ is facing the open problems in CR physics in different ways

- **Sky survey $-20^{o} \leq \delta \leq 80^{o}$ above 300 GeV (γ-sources $\rightarrow$ CR sources)**
- **High exposure for flaring activity (γ-sources, GRBs, solar flares)**
- **CR Energy Spectrum and Composiiton TeV → PeV**
- **Anisotropy in the CR arrival direction distribution**
- **Antimatter content: CR $\bar{p}/p$ flux ratio at TeV energies**
- **Solar and heliospheric physics**

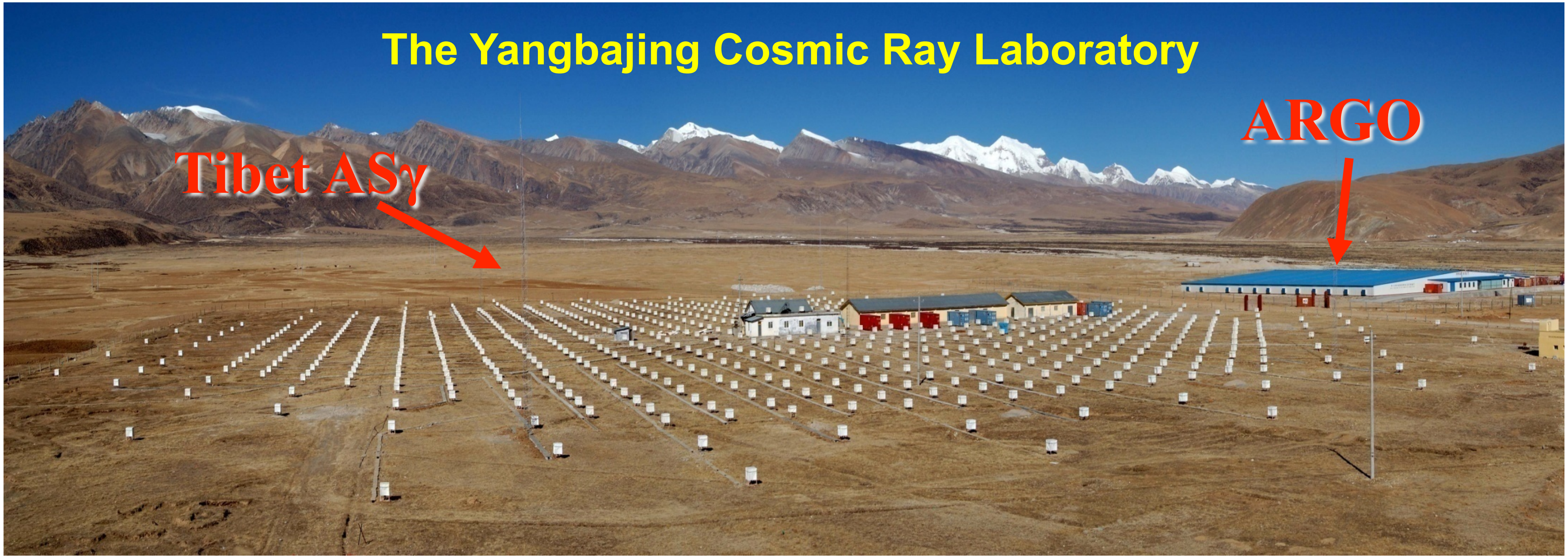
The ARGO-YBJ experiment

An unconventional EAS-array exploiting the full coverage approach at very high altitude to detect small air showers at an energy threshold of a few hundreds of GeV.

Longitude 90° 31’ 50” East
Latitude 30° 06’ 38” North

90 Km North from Lhasa (Tibet)

4300 m above the sea level
~ 600 g/cm^2



The basic concepts

…for an unconventional air shower detector

- ***HIGH ALTITUDE SITE***
  (YBJ - Tibet, 4300 m a.s.l, ~ 600 g/cm^2)

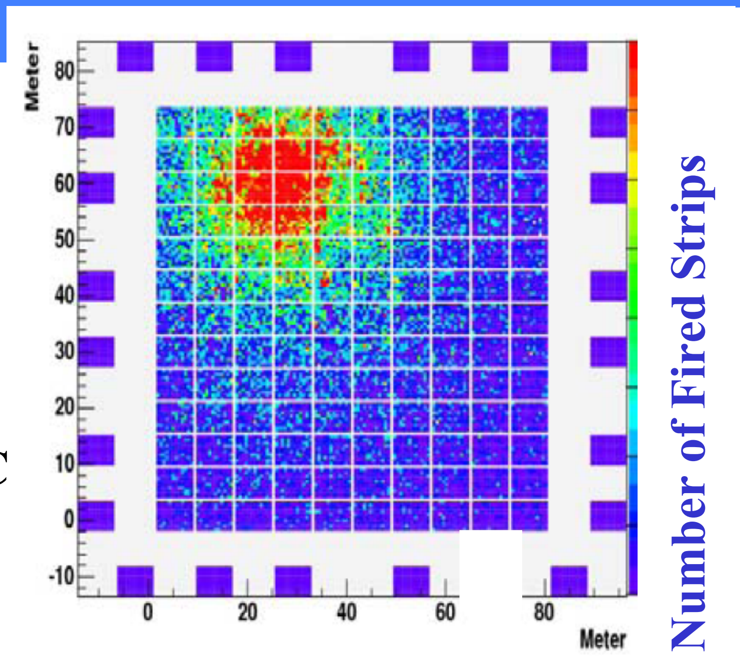
- ***FULL COVERAGE*** **(RPC technology, 92% covering factor)**

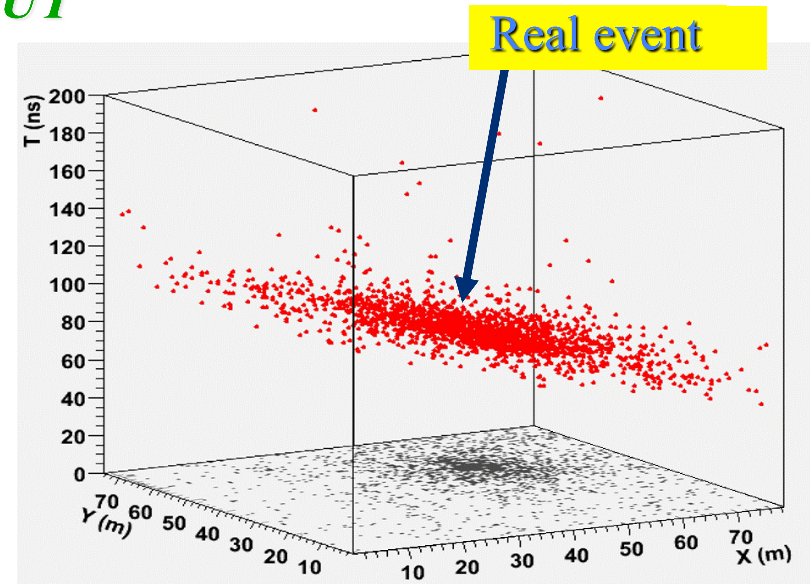
- ***HIGH SEGMENTATION OF THE READOUT***
  (small space-time pixels)

  Space pixels: 146,880 strips (7×62 cm^2)
  Time pixels: 18,360 pads (56×62 cm^2)

… in order to:

- **image the shower front**
- **get a energy threshold of a few hundreds of GeV**



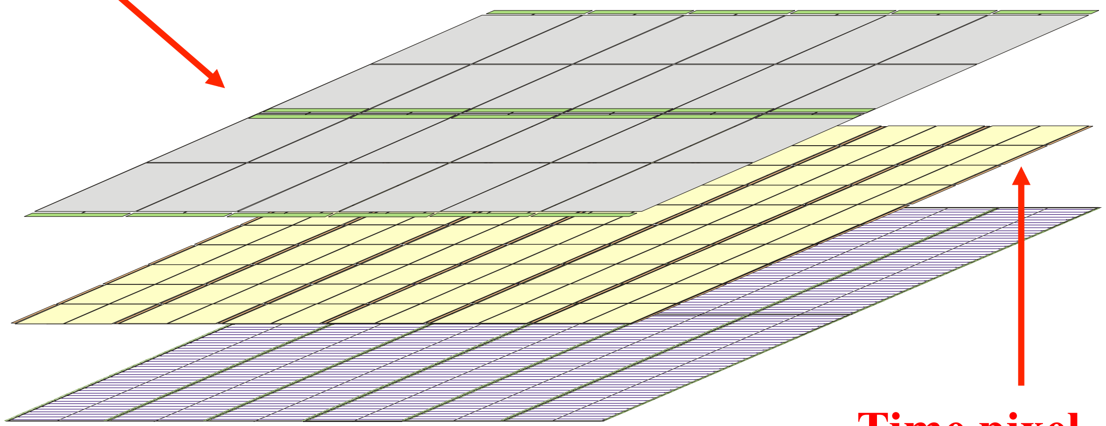


The basic concepts

…extending the dynamical range

- *ANALOG READ-OUT* → *PeV* (3672 1.40 × 1.25 m² "big pads")

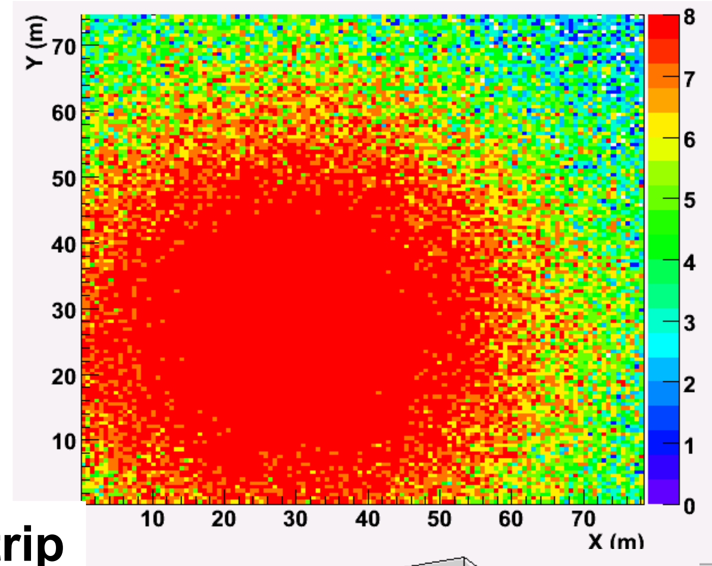
Big Pad for charge read-out

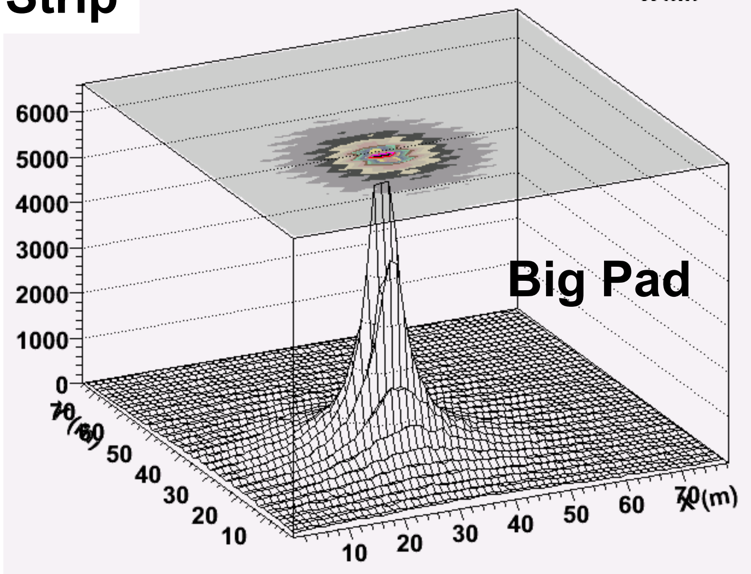


Time pixel
(56 × 62 cm²)
#18360

Space (digital) pixel
(6.7 × 62 cm²)
#146880

E ~ 1000 TeV



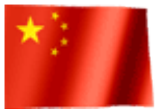


The ARGO-YBJ Collaboration

Collaboration Institutes:

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



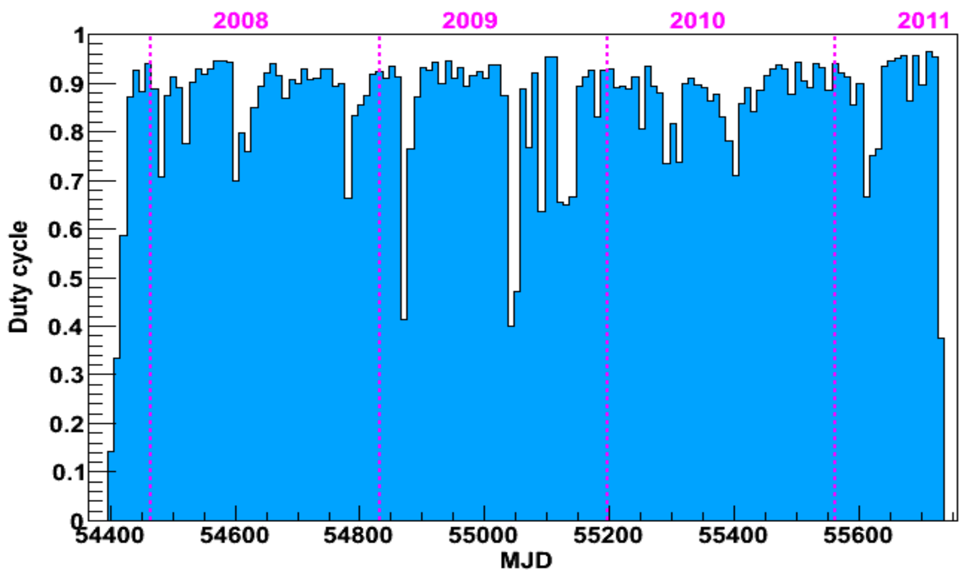


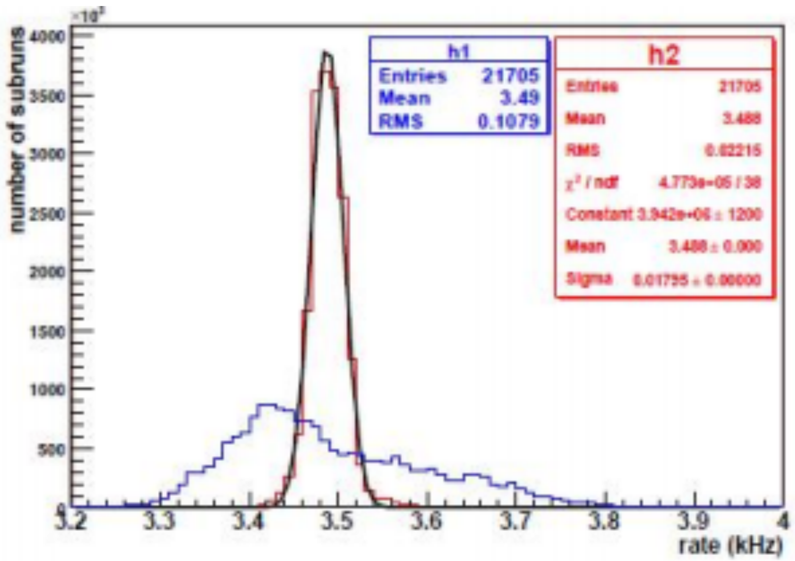

INAF/IASF, Palermo and INFN, Catania
INFN and Dpt. di Fisica Università, Lecce
INFN and Dpt. di Fisica Universita', Napoli
INFN and Dpt. di Fisica Universita', Pavia
INFN and Dpt di Fisica Università "Roma Tre", Roma
INFN and Dpt. di Fisica Univesità "Tor Vergata", Roma
INAF/IFSI and INFN, Torino

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

Current Status

- **In observation since July 2006 (commissioning phase)**
- **Stable data taking since November 2007**
- **The average duty cycle ~ 87%, dead time 4%**
- **Trigger rate ~3.5 kHz @ 20 pad threshold**
- **N. recorded events: ≈ $4 \cdot 10^{11}$ from 300 GeV to PeV**

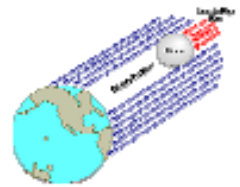




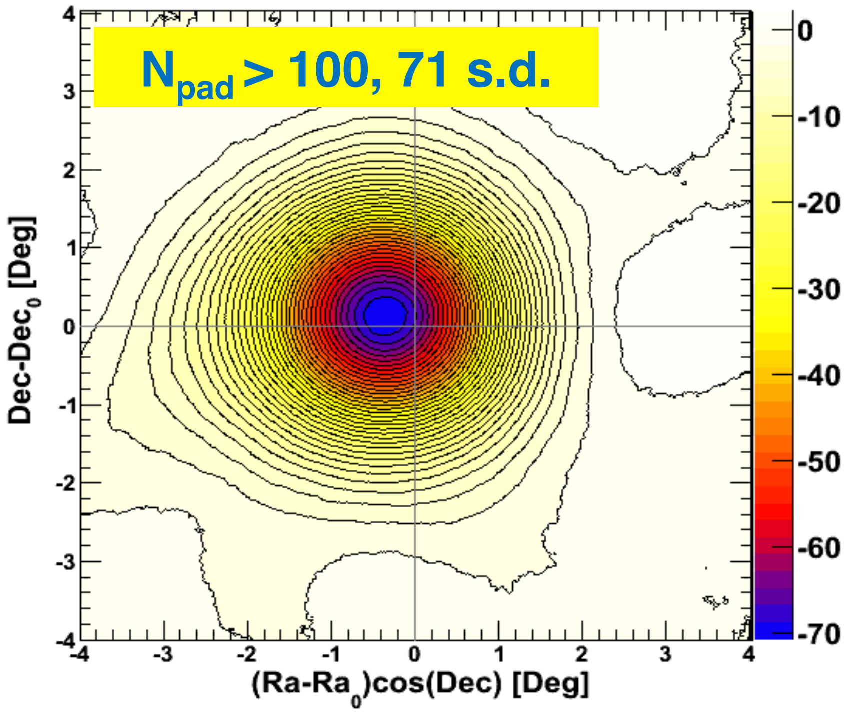
Intrinsic Trigger Rate stability 0.5%

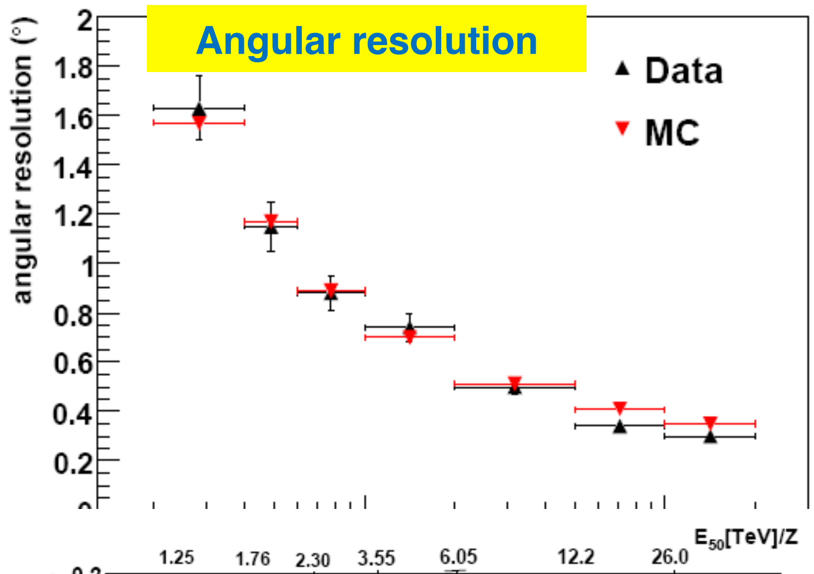
(after corrections for T/p effects)

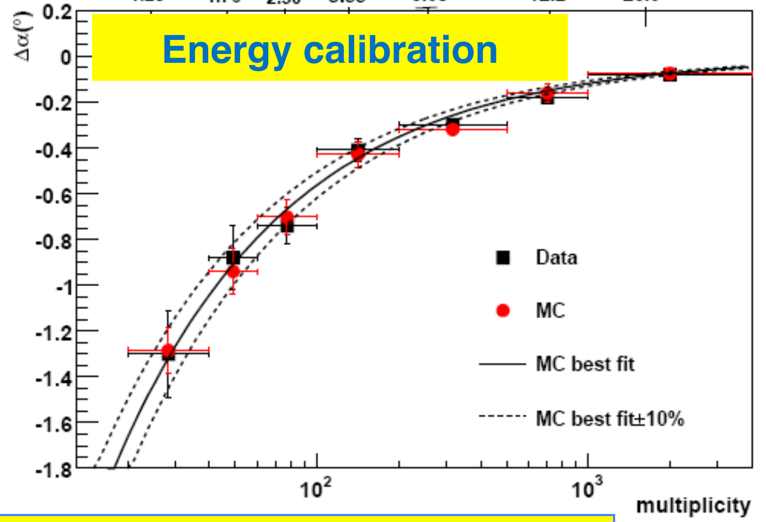
Moon shadow analysis



- **A tool to evaluate the detector performance**
  - ❖ Pointing accuracy
  - ❖ Angular resolution
  - ❖ Absolute energy calibration





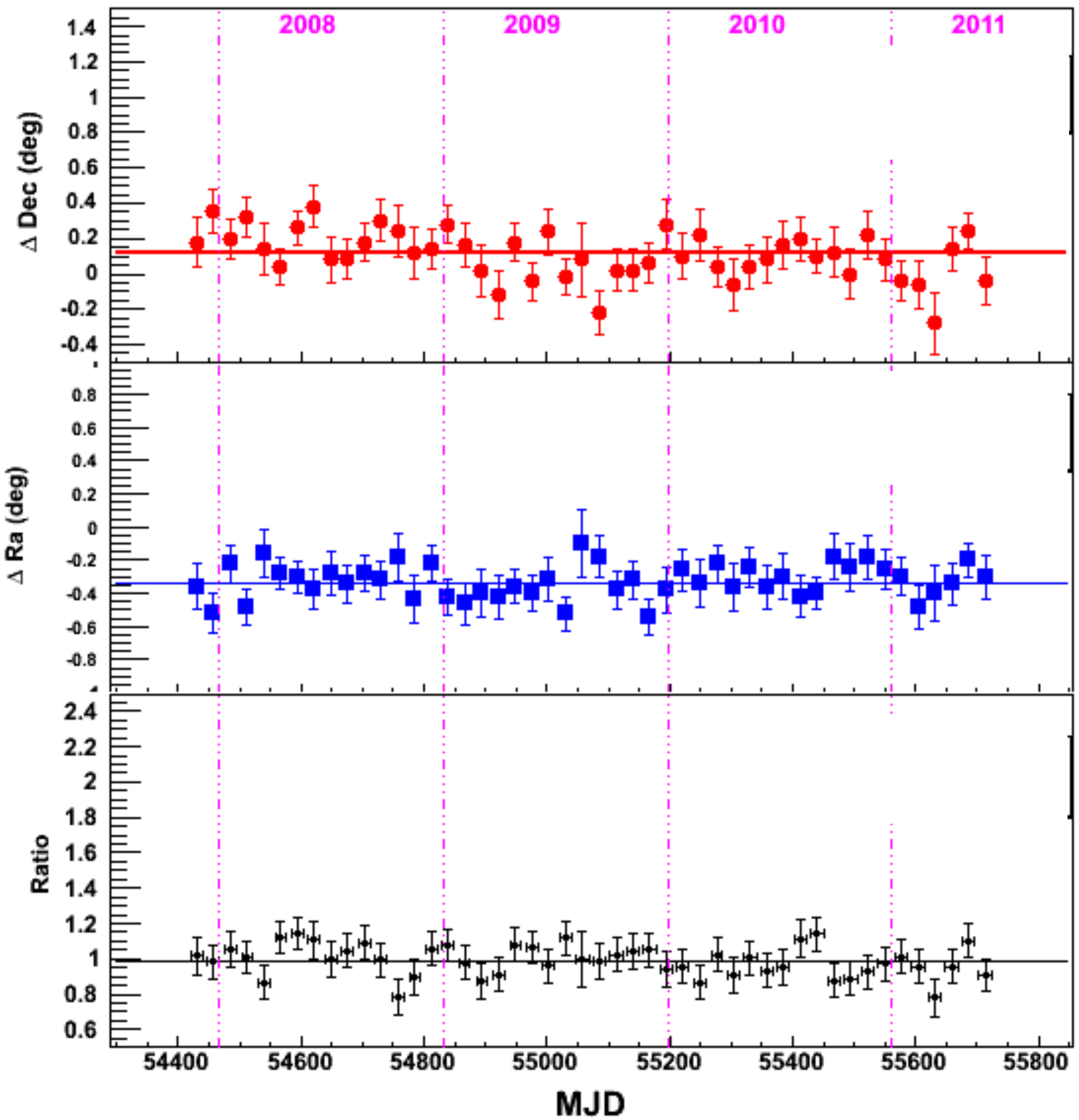


PRD 84 (2011) 022003
PRD 85 (2012) 022002

The energy scale uncertainty is estimated to be smaller than 13% in the energy range 1 – 30 (TeV/Z).

Long-term stability

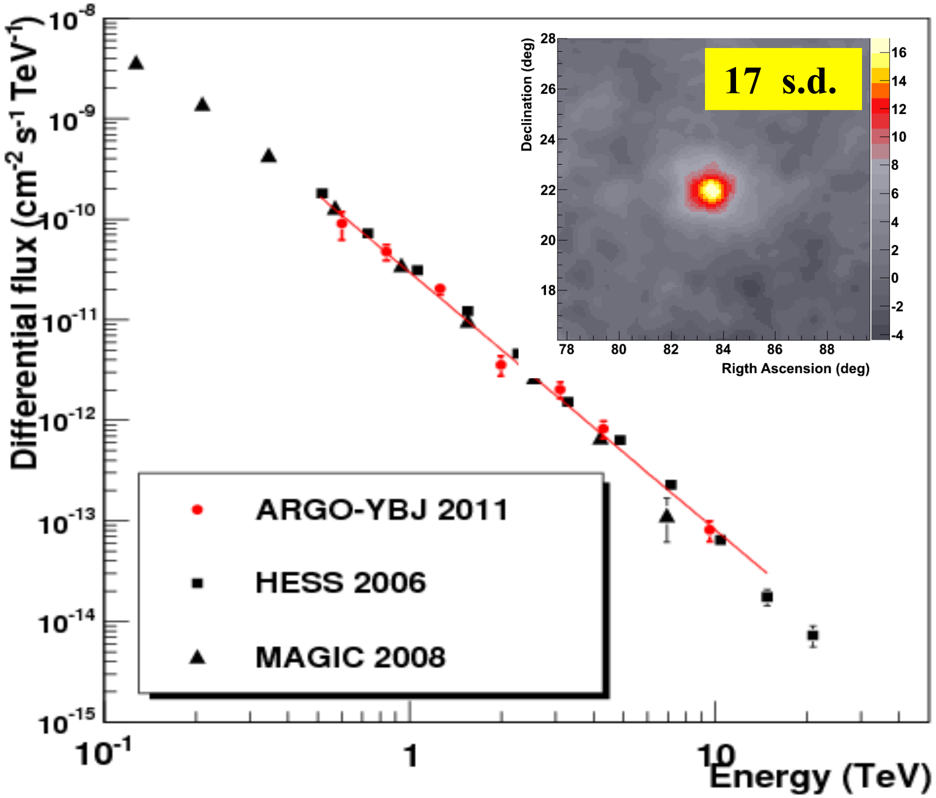
- N_{pad}>100: 10 s.d./month
- A tool to monitor the stability of the data and reconstruction
- Right figures: one point per month !
- Position stable at a level of 0.1°
- Angular resolution stable at a level of 10%

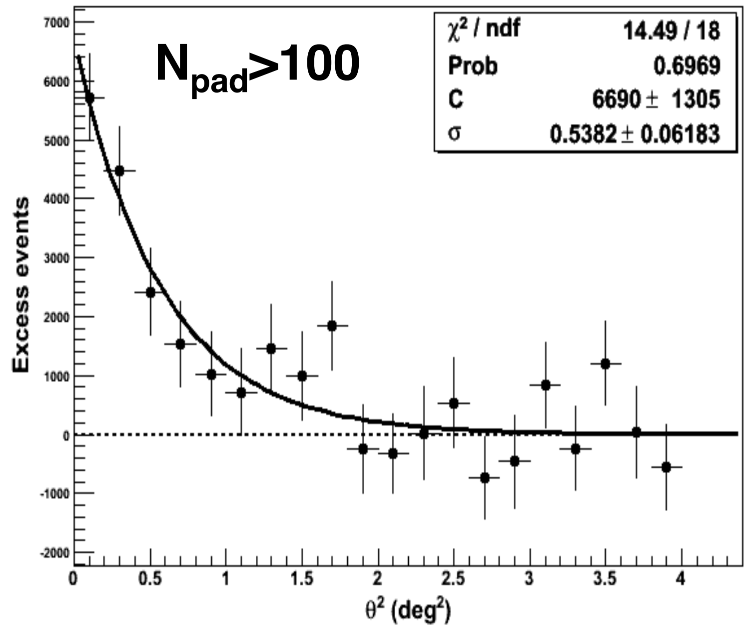


Crab Nebula

Average flux ~ 23 ±3 ev/hour - 84% from E_γ > 300 GeV

Current sensitivity: ~25% Crab flux





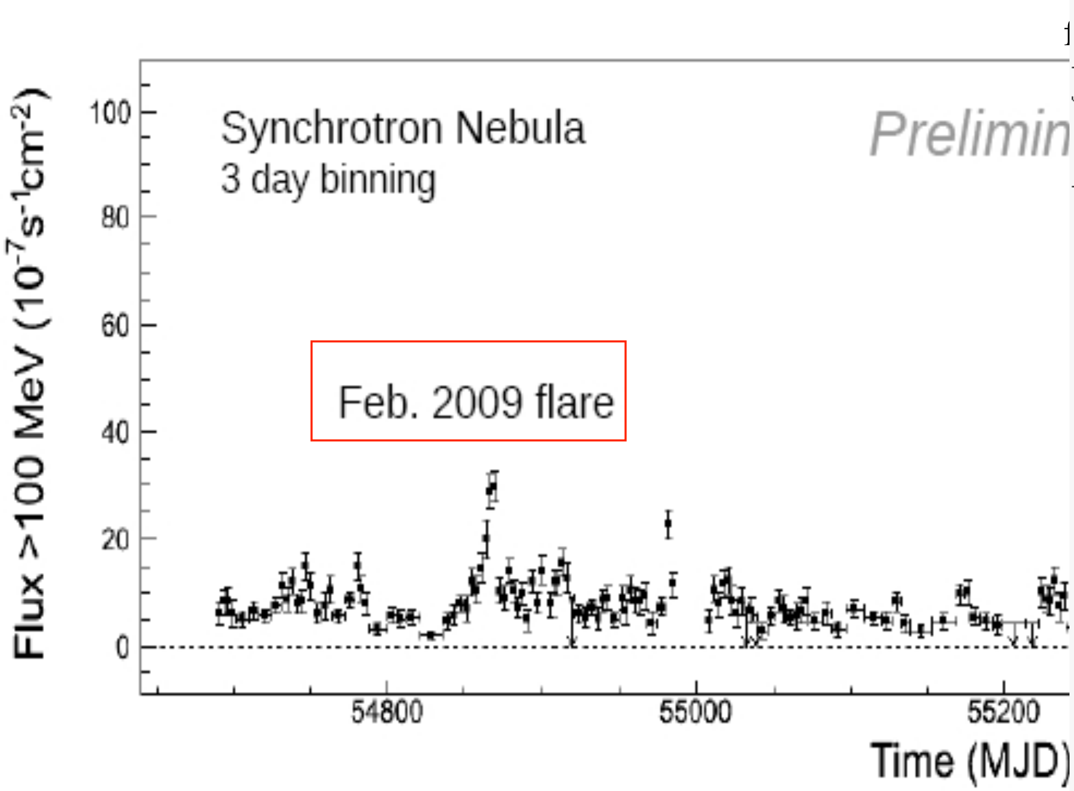
Measured PSF in agreement with MC

(0.5 – 10) TeV

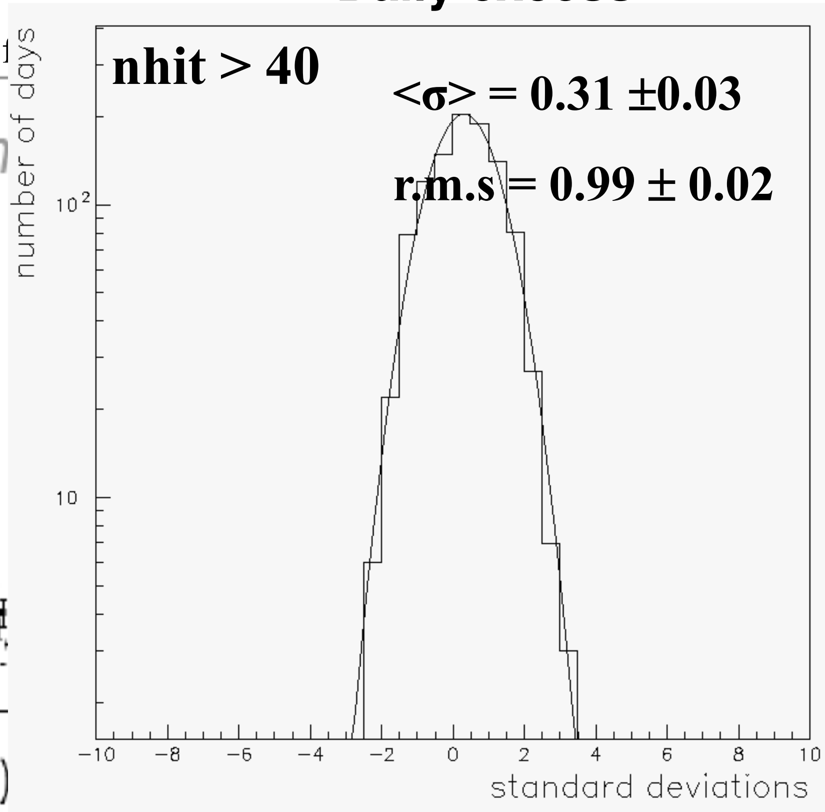
$$\frac{dN}{dE} = (3.0 \pm 0.3_{stat}) \cdot 10^{-11} \left(\frac{E}{1\,\mathrm{TeV}}\right)^{(-2.59 \pm 0.09_{stat})} \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{TeV}^{-1}$$

Crab Nebula is not a "standard candle"

3 flares during the ARGO-YBJ lifetime



Daily excess



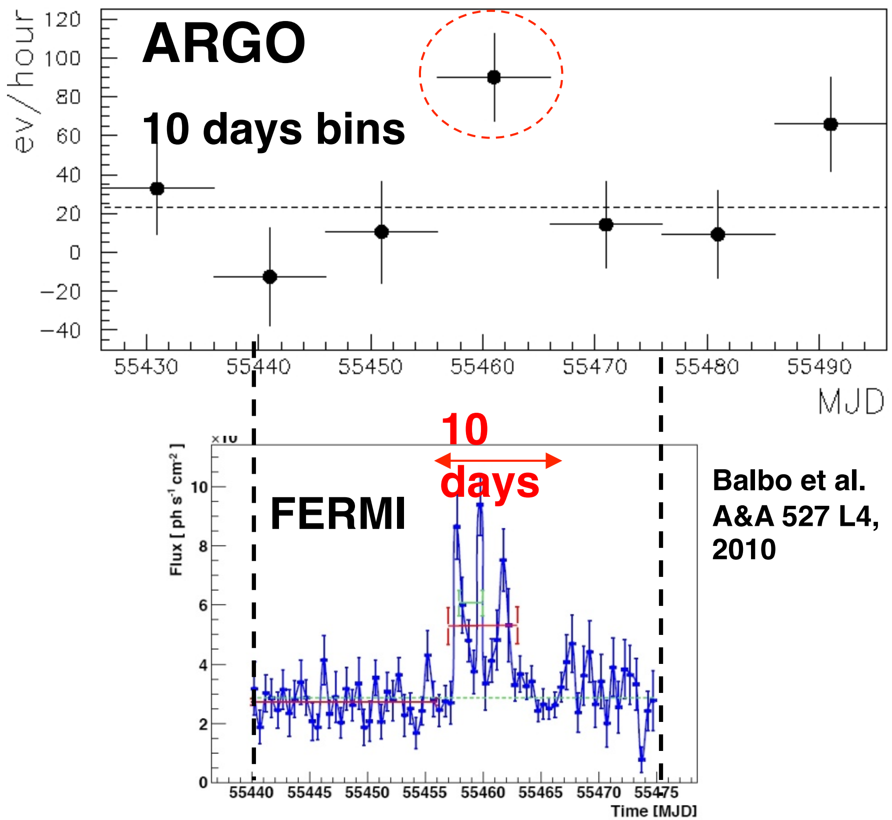
Significance distribution

One more check of the detector stability

Crab Nebula TeV flare ?

from transit 17/18 Sept. to transit 26/27 Sept.

- **AGILE discovered a flare at E > 100 MeV in 19th-21st September 2010 (ATel #2855)**
- **Fermi LAT confirmed (ATel #2861).**
- **TeV emission enhancement (~3 - 4 times) observed by ARGO-YBJ in ~54 h observation from 18th to 27th Sep. 2010 (ATel #2921).**
- **Not confirmed by MAGIC and VERITAS with observations from 17th to 20th Sep. 2010 (ATel #2967, 2968).**

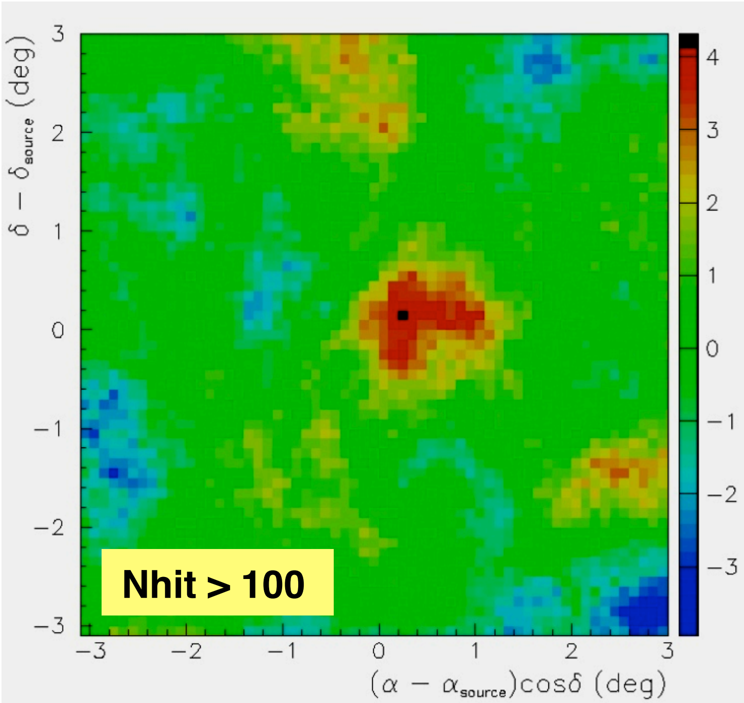


observed 4.1 s.d.

expected 1.0 s.d

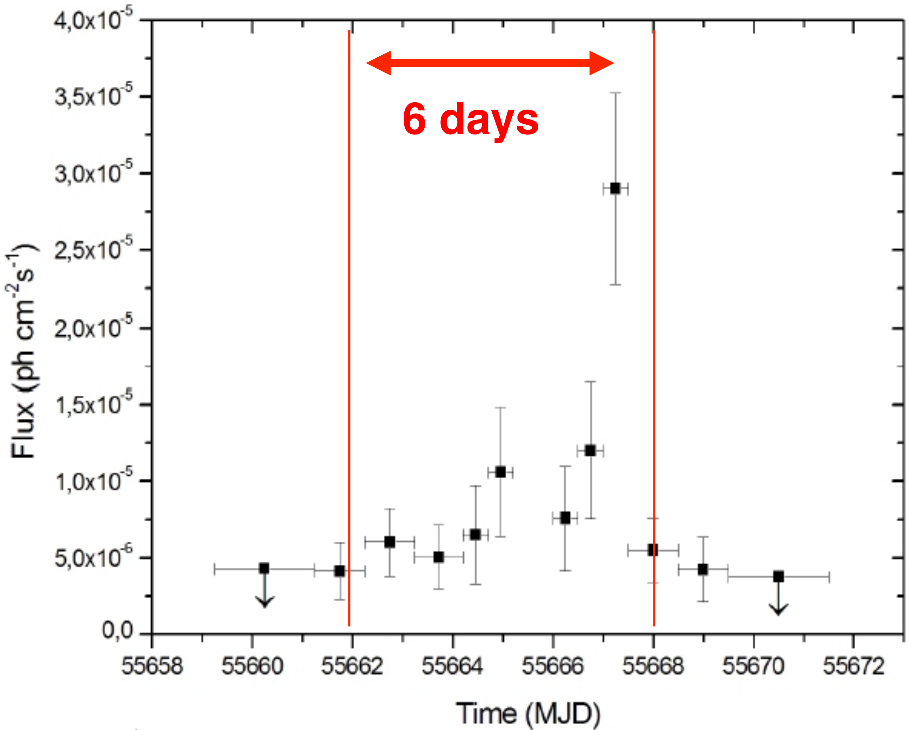
A new TeV Crab flare in April 2011 ?

Significance map in 6 days



AGILE light curve

E > 100 MeV



3.5 s.d.

expected 0.62

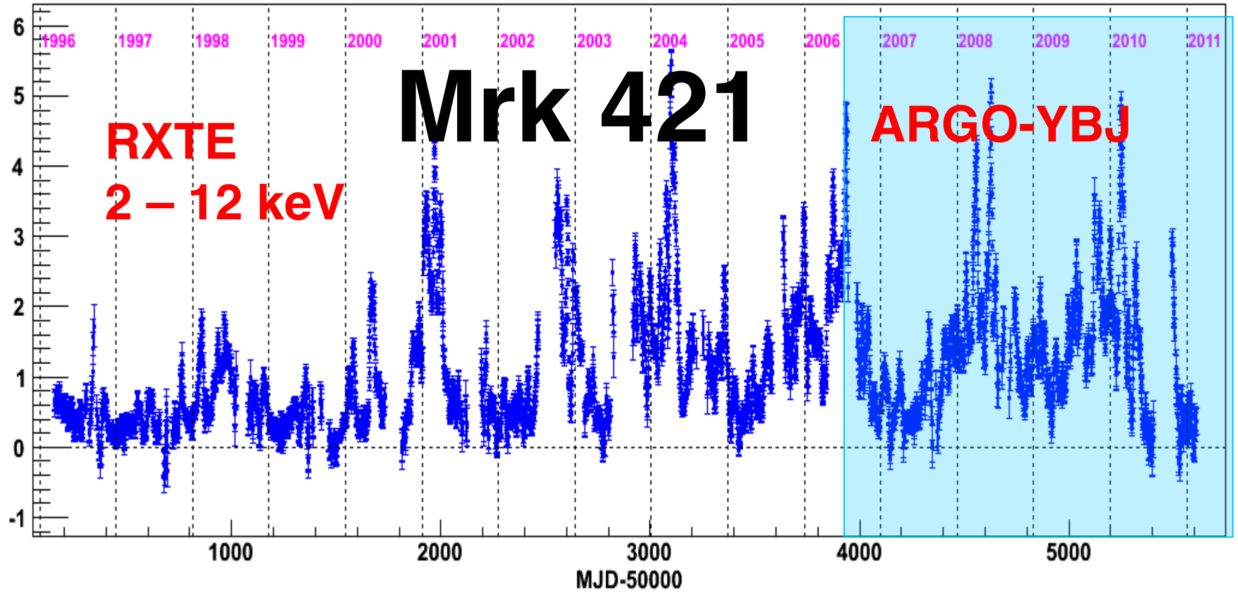
E ≈ 3 TeV

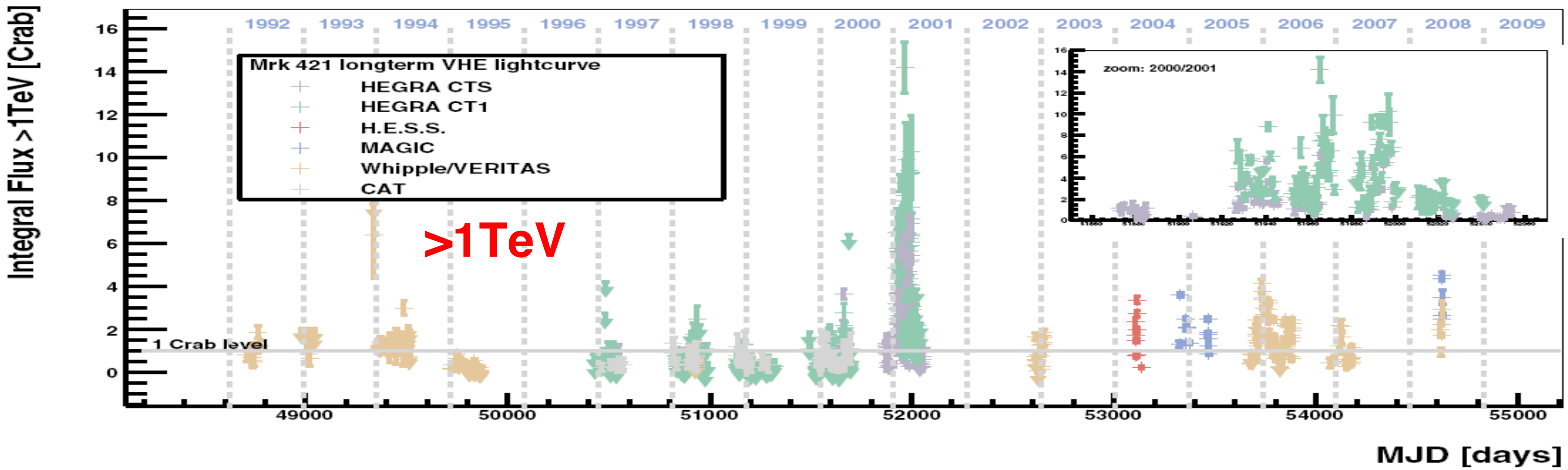
NO Cherenkov data available

- Marginal evidence (P≈ $2\cdot10^{-3}$) of a TeV flux increase correlated to MeV-GeV Crab flaring activity

AGN variability

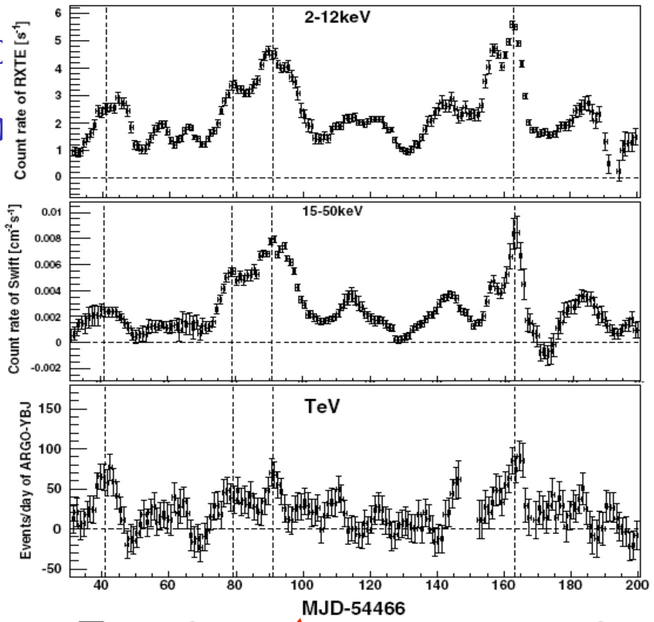
- AGNs are characterized by a strong flaring activity both in X-rays and in TeV γ–rays.
- Lack of continuous long-term monitoring at VHE.

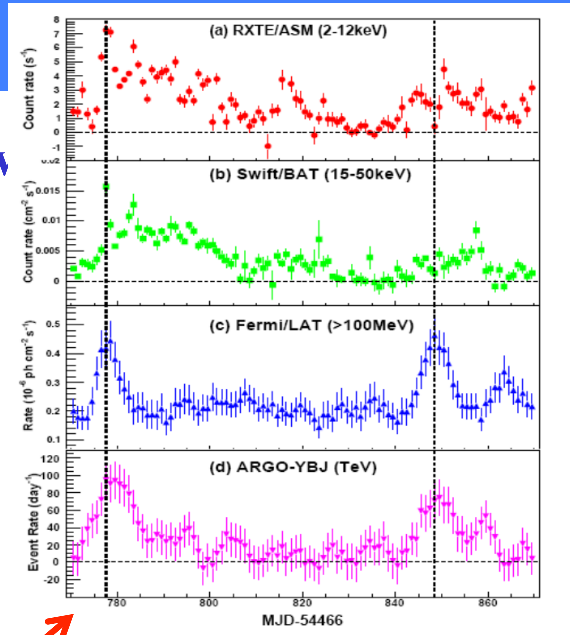




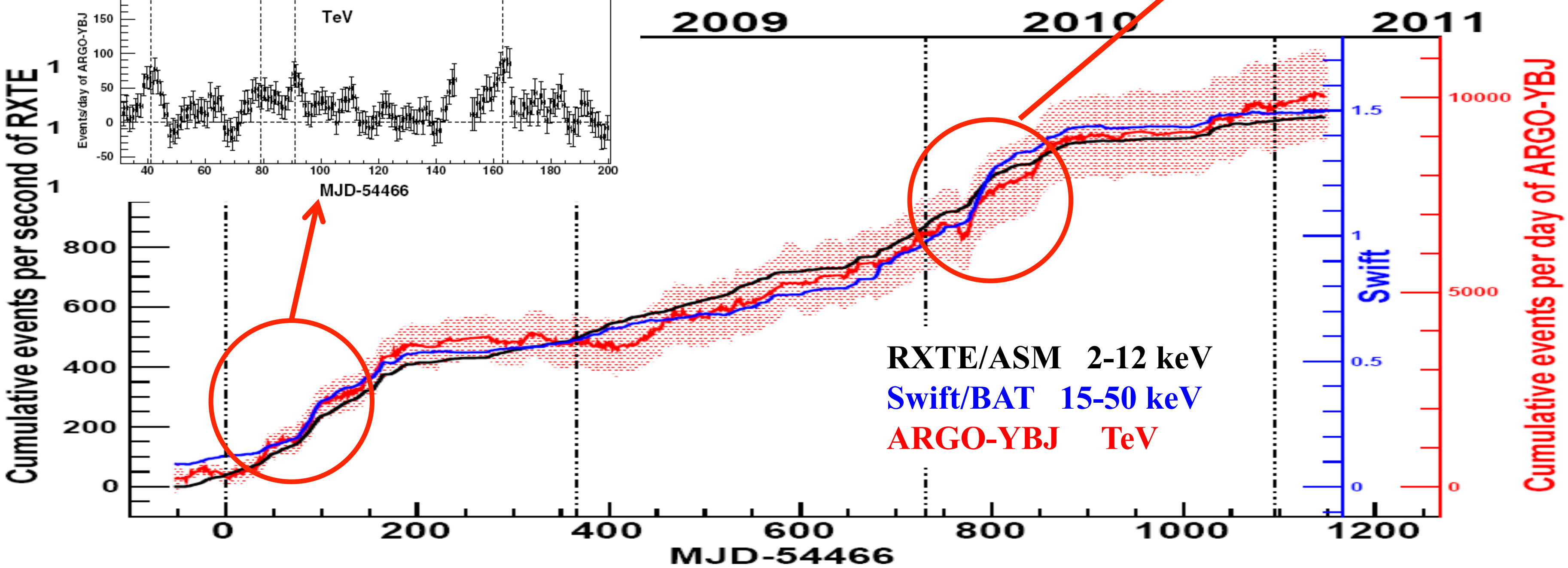
Mrk421 long-term monitoring

- ARGO-YBJ cumulative light curve (>TeV) compared with Sw data.
- Gc ray data.
- No t TeV energies



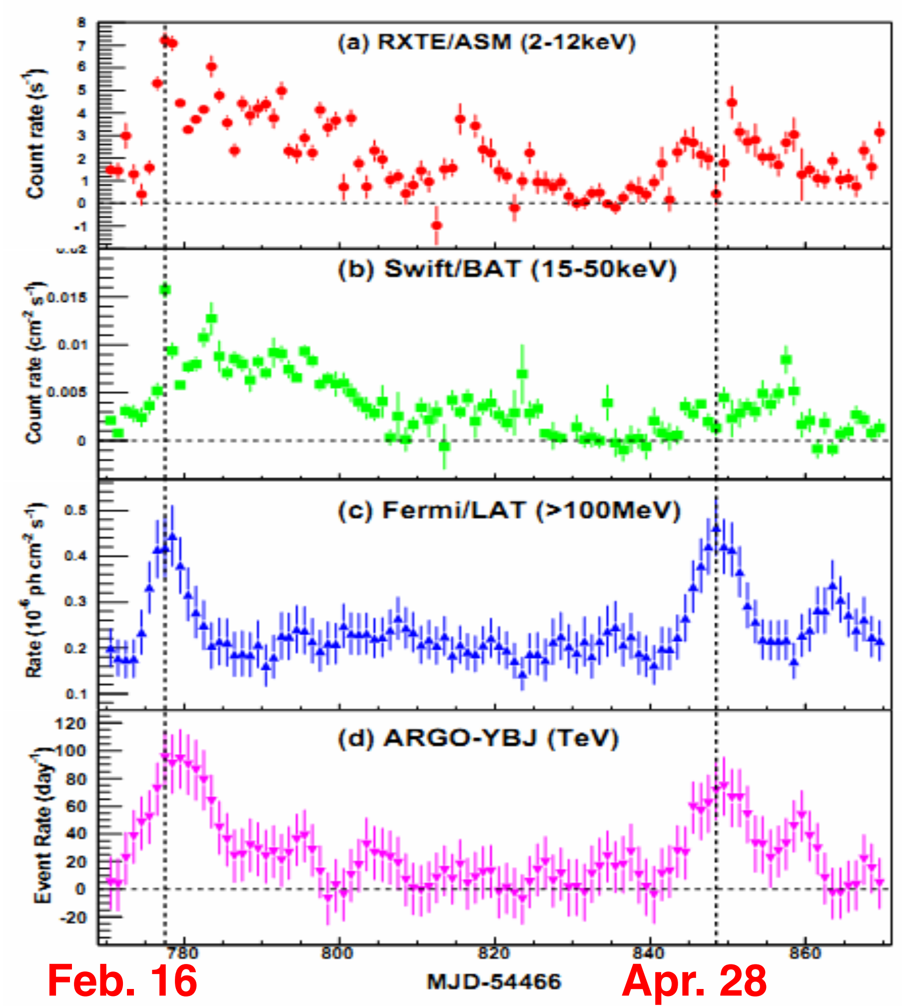


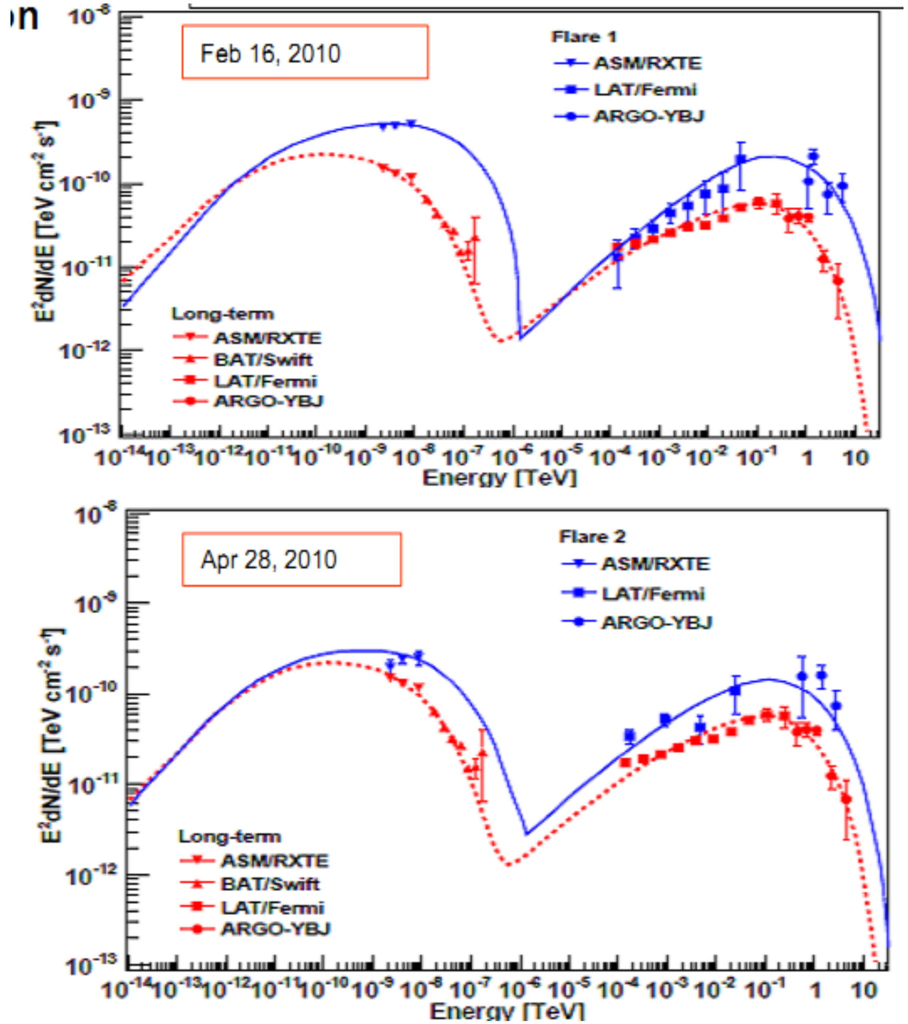
…ll., ApJ 734 (2011) 110



Mrk421 observations

- Both X-ray and TeV spectra are observed to harden as the flux increases
- Observations are compatible with a SSC model with flares being due to hardening of the electron injection spectrum



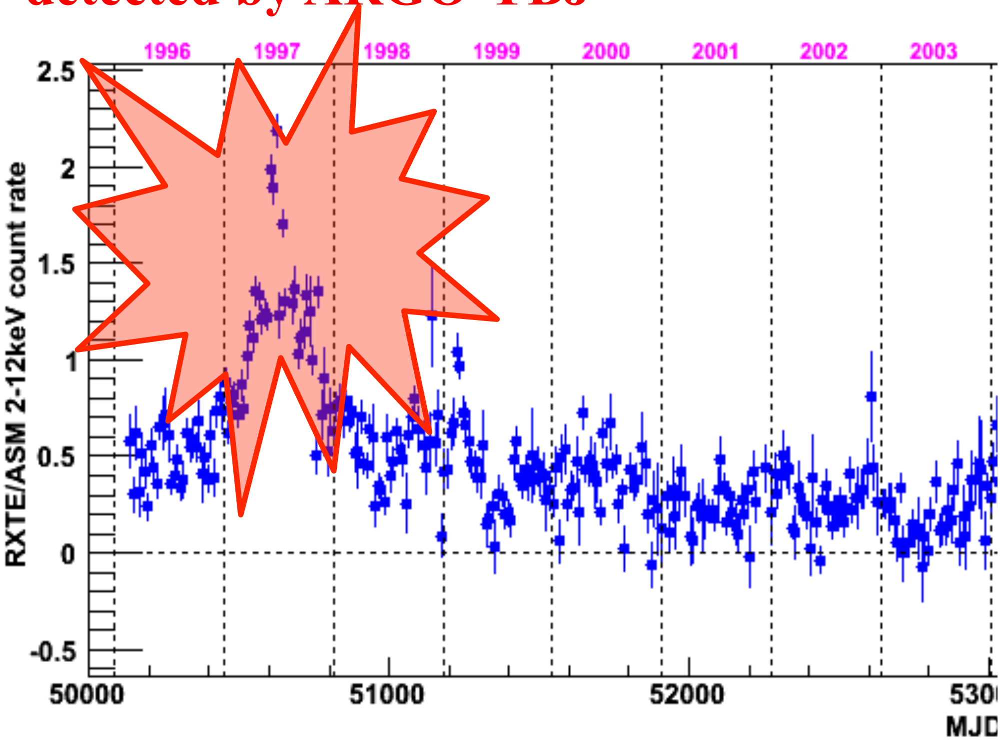


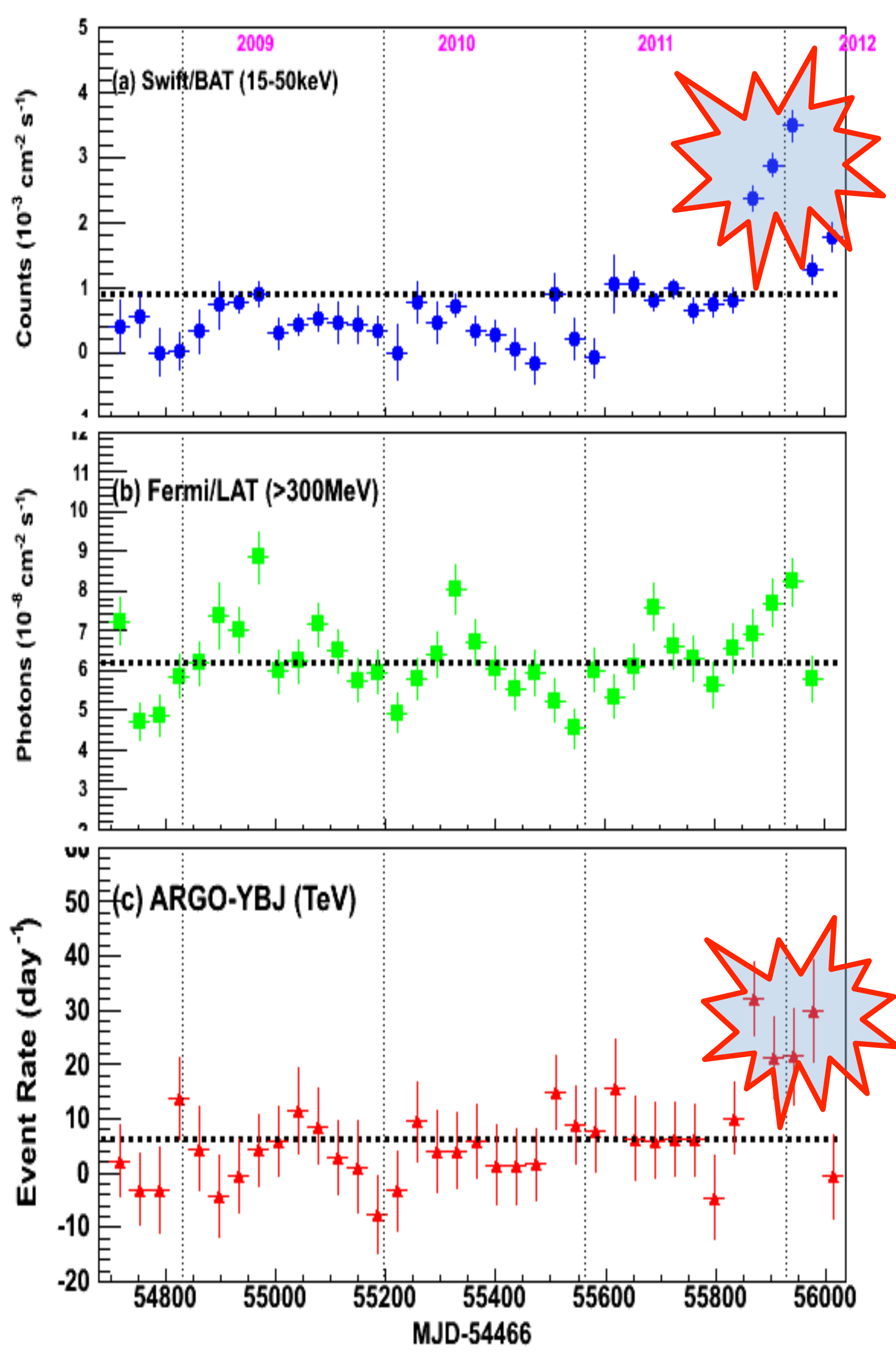
Mrk501

A strong X-ray flare in 1997 followed by a

New strong X-ray flare 14 years later: Oc

Flare associated to a strong TeV emission detected by ARGO-YBJ

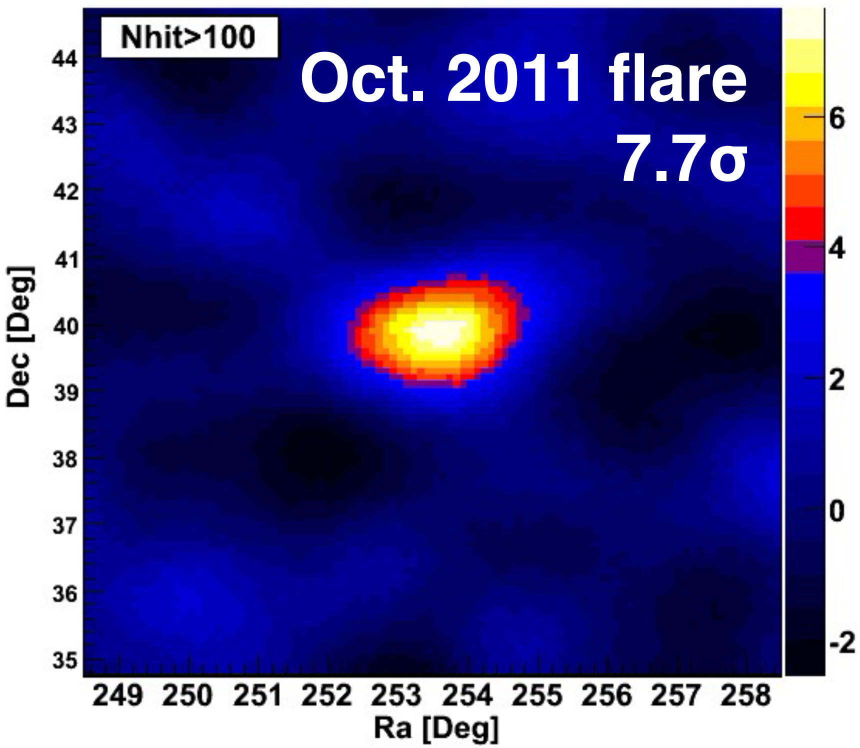


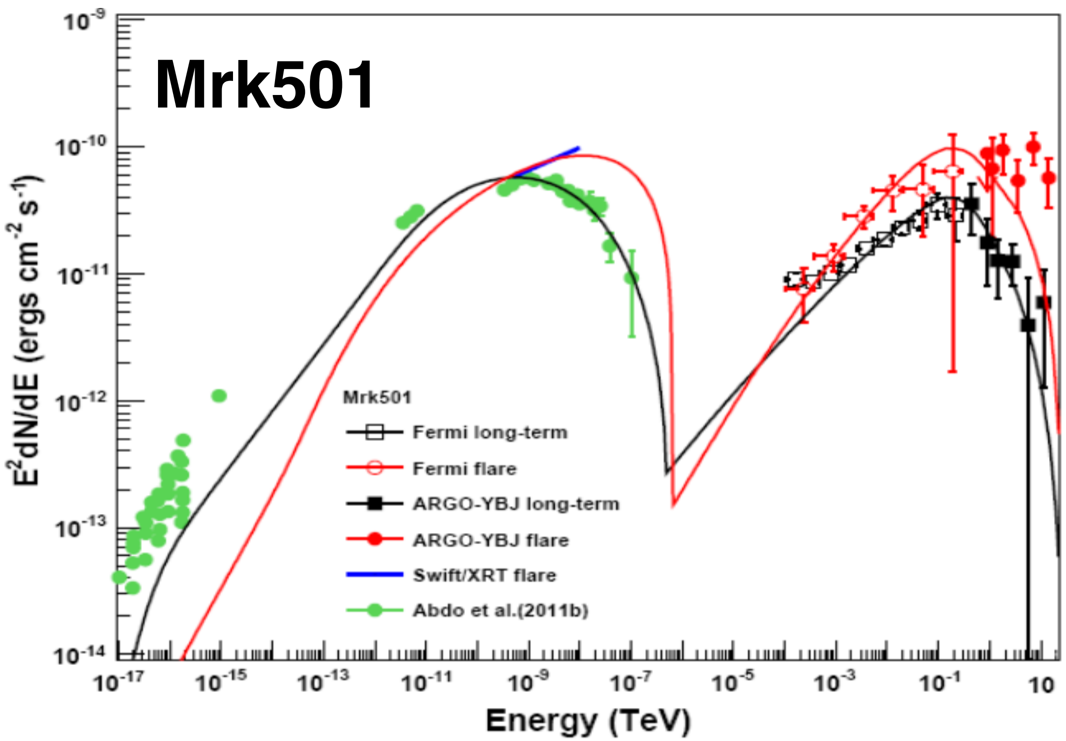


Mrk501 SED

ApJ in press

- ✓ For steady states, the SSC model is favored
- ✓ During flares, the spectrum is hardened. Simple SSC model is not favored
- ✓ Evolution is well observed

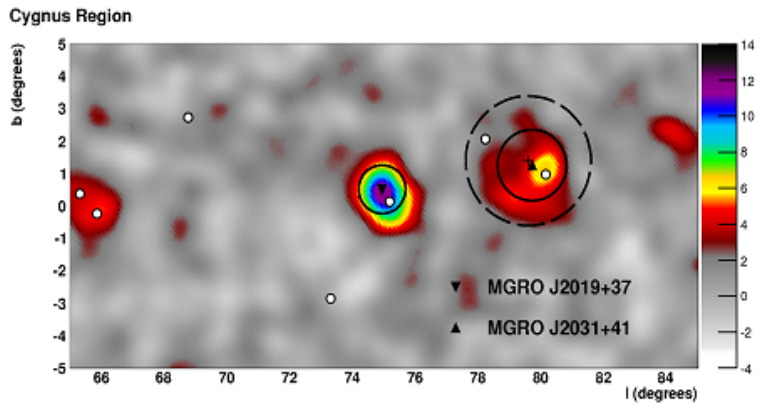




The Cygnus Region

Very important region populated by many unidentified strong sources.

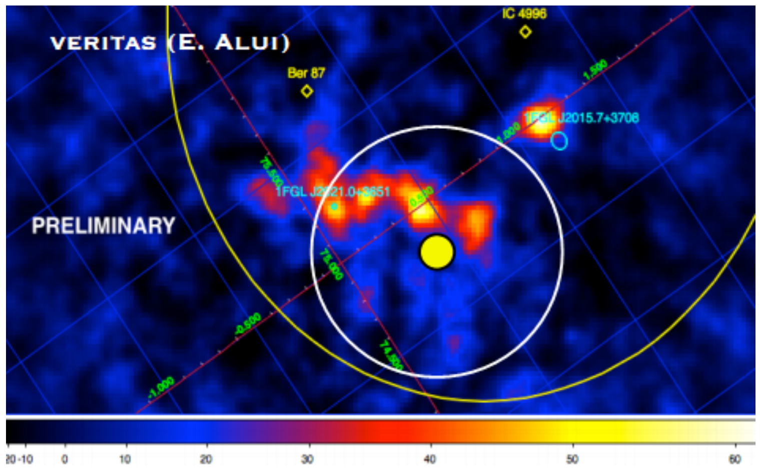
- The brightest diffuse γ-rays source in the northern hemisphere
- 9 supernova remnants
- >20 Wolf-Rayet starts
- 6 OB associations
- shocked gas
- *natural site for cosmic-ray acceleration*



- **Milagro detected 2 clear sources at 20 TeV**
  - MGRO J2019+37 (12.4 σ)
  - MGRO J2031+41 (7.6 σ)

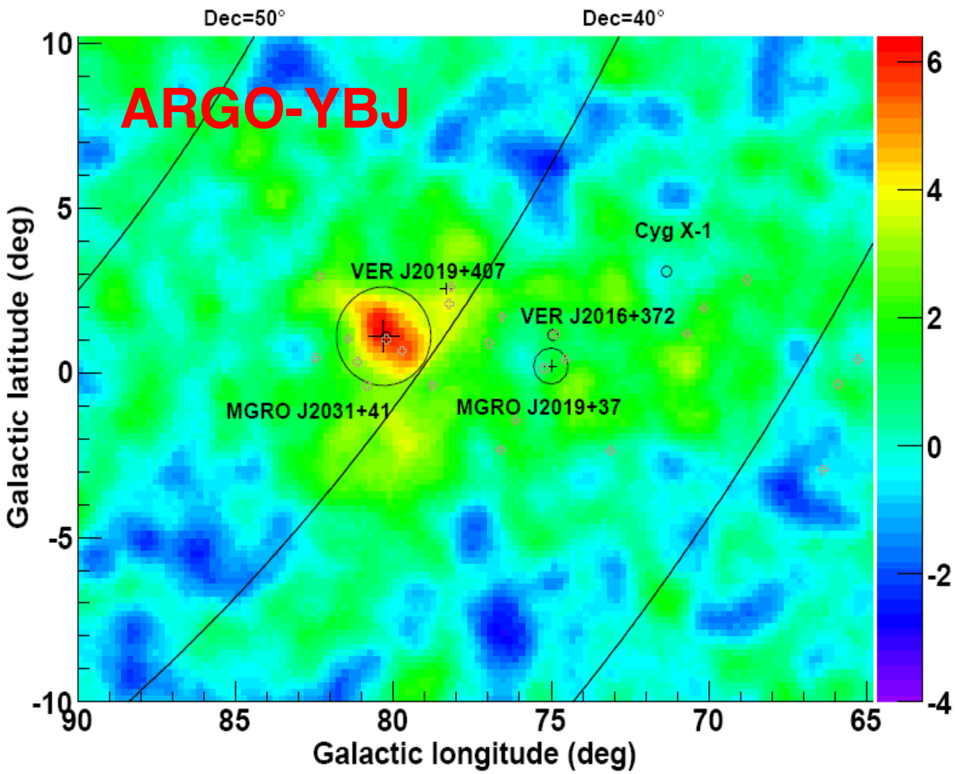
- **Both consistent with Fermi source locations**

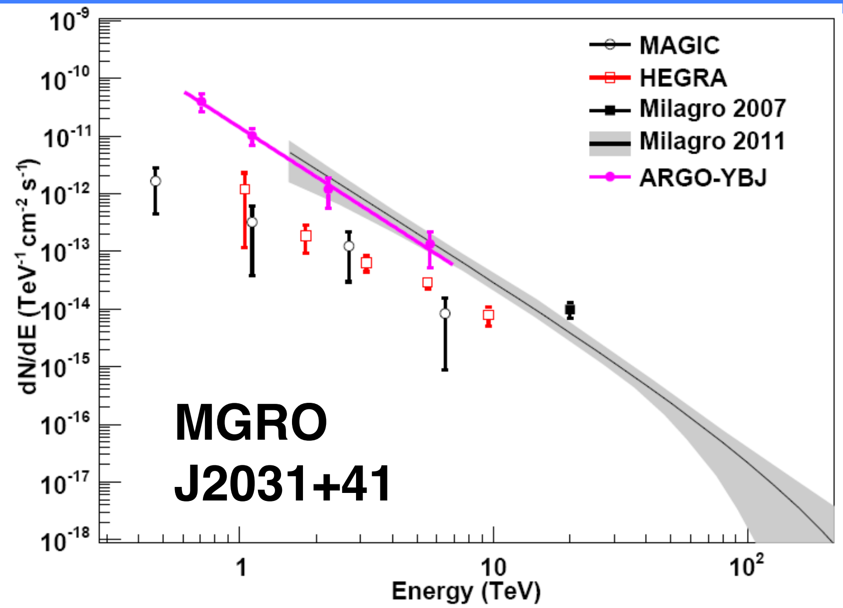
- **Complex emission observed by VERITAS consistent with location of MGRO J2019+37**



The Cygnus Region: ARGO-YBJ

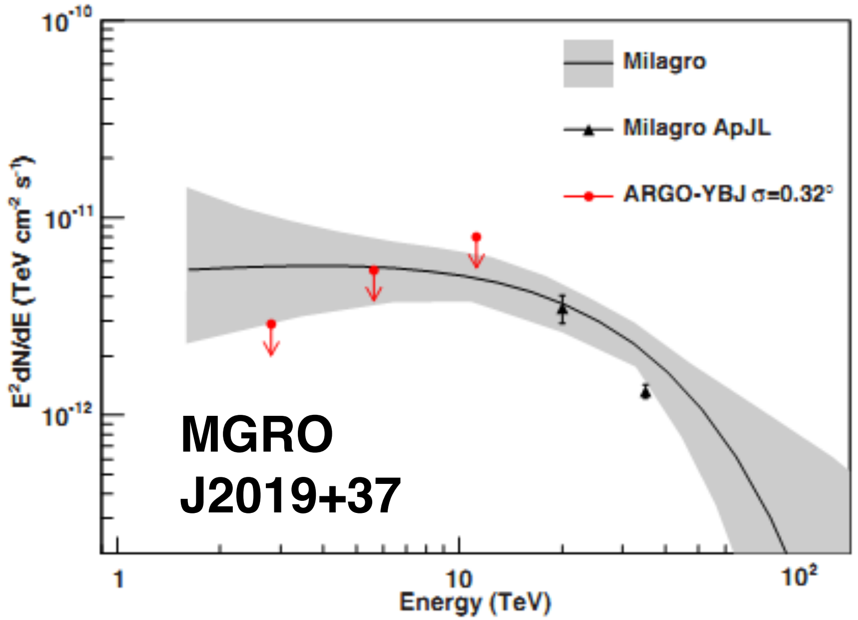
ApJL 745 (2012) L22



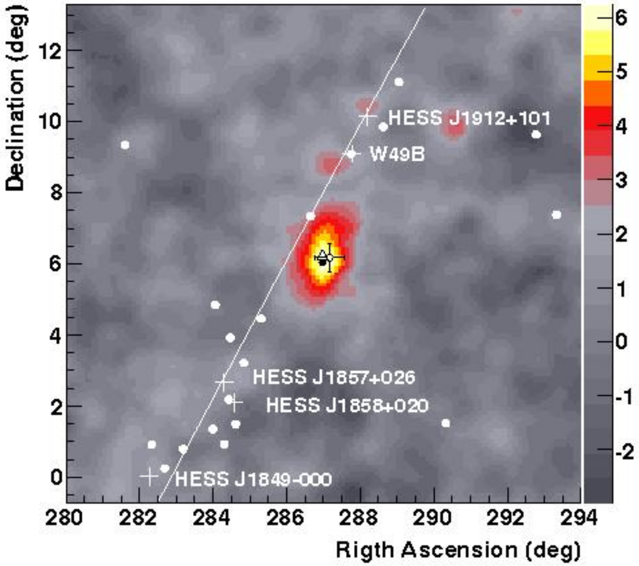


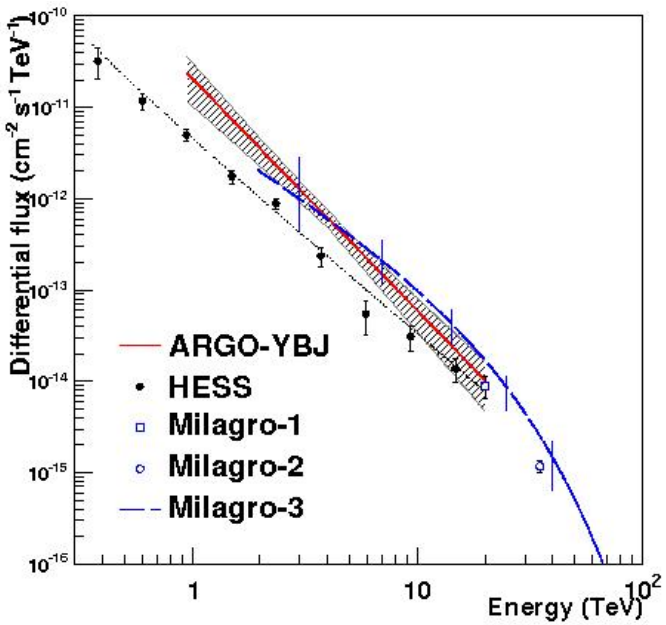
NO signal from the MGRO J2019+37 below 10 TeV

- ✓ **Insufficient exposure above 5 TeV ?**
- ✓ **Variability ?**



MGRO J1908+06





ApJ in press

6.2 s.d. excess above background

Extended source: gaussian profile with $\sigma = (0.49 \pm 0.22)°$ (HESS gives $0.34 \pm 0.04°$)

The large size supports the identification with the wind nebula associated of the Fermi pulsar PSR J1907+0602

Flux (between 1 and 20 TeV):
$dN/dE = (6.1 \pm 1.4) \times 10^{-13} (E/4TeV)^{-2.54\pm0.36}$ photons cm^{-2}s^{-1} TeV^{-1}

Flux in agreement with Milagro but a factor 2-3 larger than HESS at few TeV

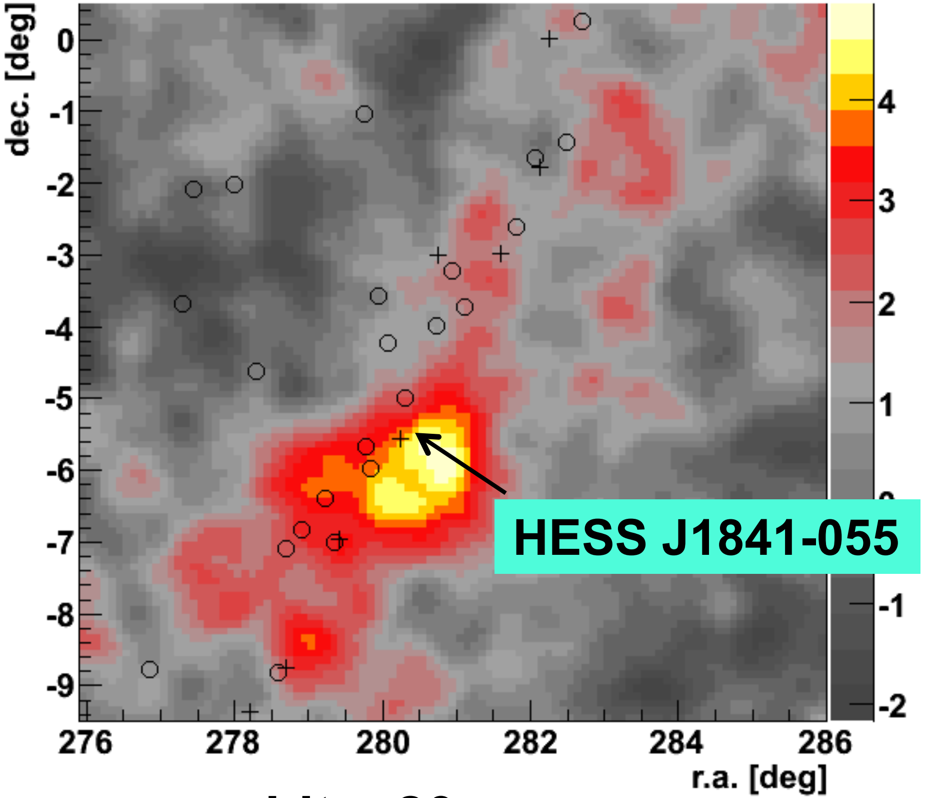
Complex source morphology ?
Diffuse galactic flux contamination ?
Flux variability ?

Integrated luminosity above 1 TeV ~ 1.8 times the Crab luminosity

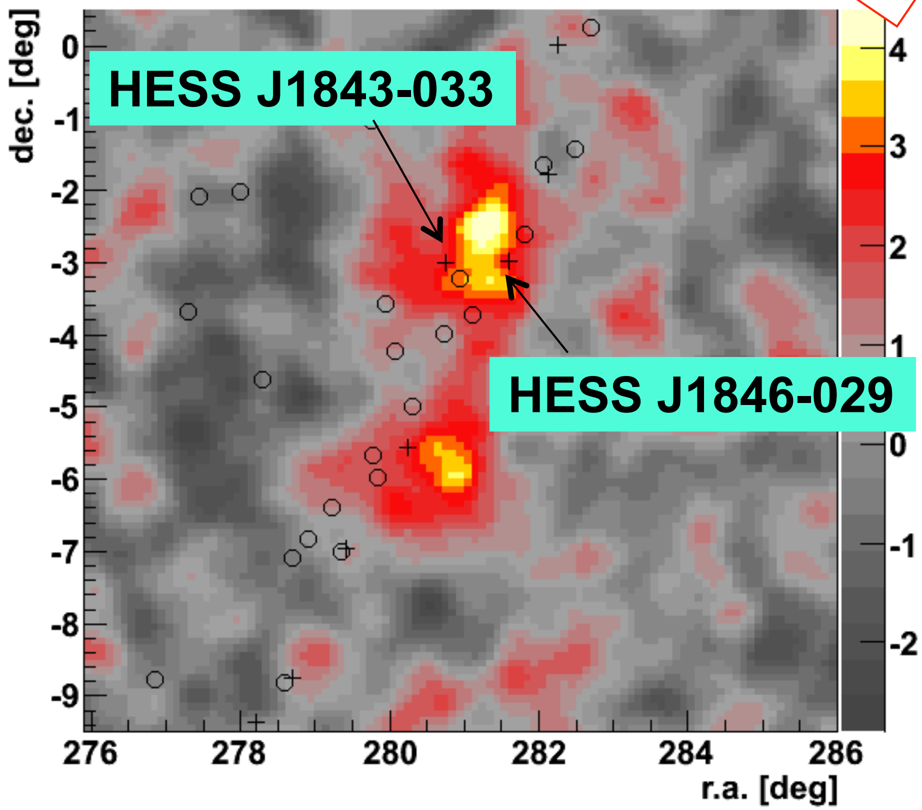
HESS J1841 Region

Preliminary

Evidence for TeV emission in the HESS J1841 region at about 4 s.d.



nhit > 20



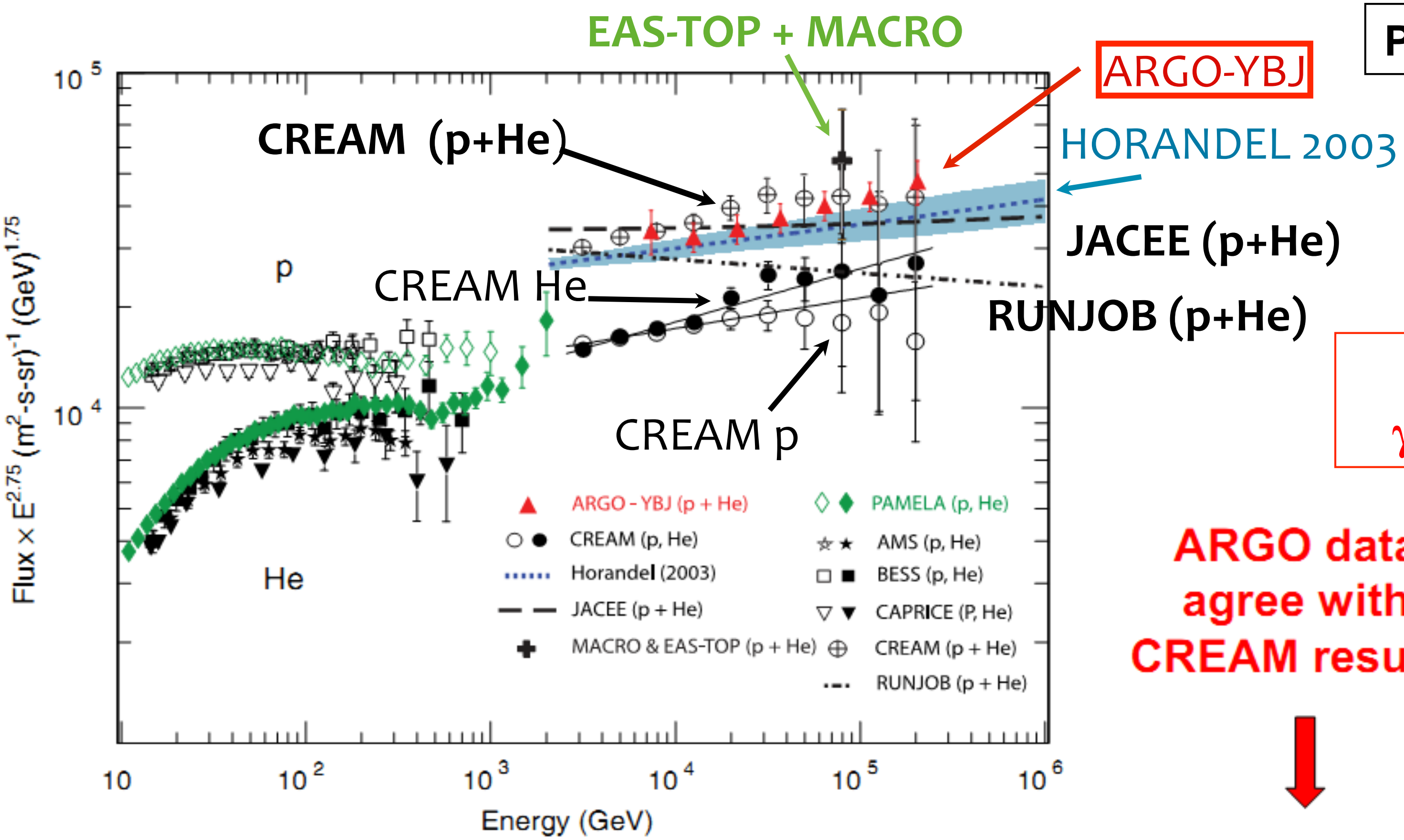
nhit > 100

Smoothing for point sources

Light-component (p+He) Energy Spectrum

Measurement of the *light-component* (p+He) spectrum of primary CRs in the energy region (5 – 250) TeV via a Bayesian unfolding procedure

PRD 85, 092005 (2012)



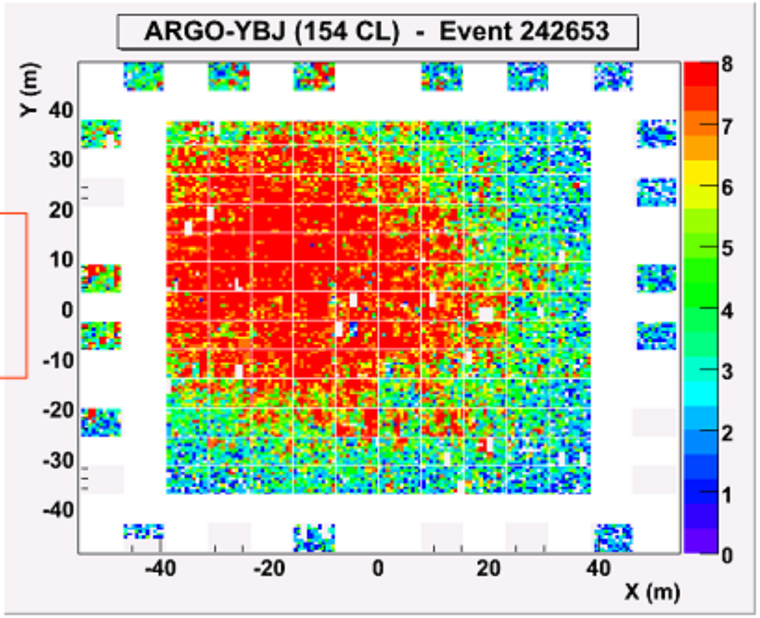
ARGO-YBJ:
$\gamma_{(p+He)} = 2.61 \pm 0.04$

ARGO data agree with CREAM results

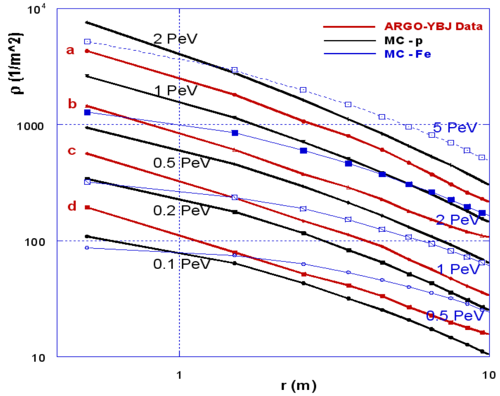
For the first time direct-indirect measurements of the CR spectrum overlaps for more than one energy decade, thus providing a solid 'anchorage' to the CR spectrum measurements at higher energies.

Analog Readout above 100 TeV

Strips (digital)

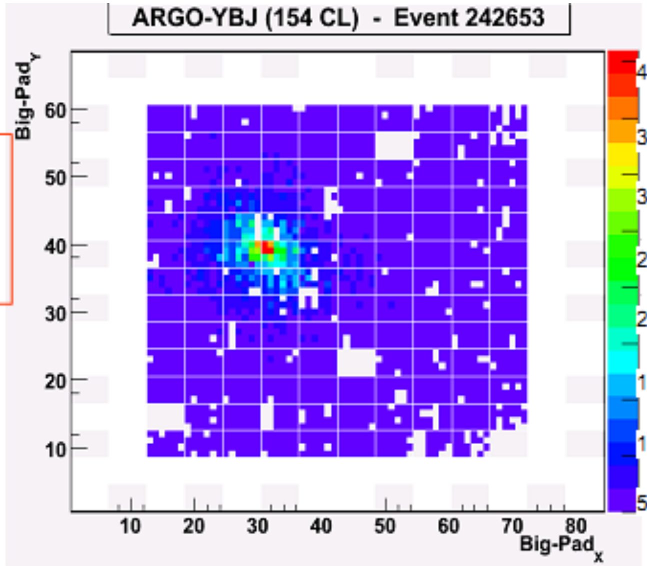


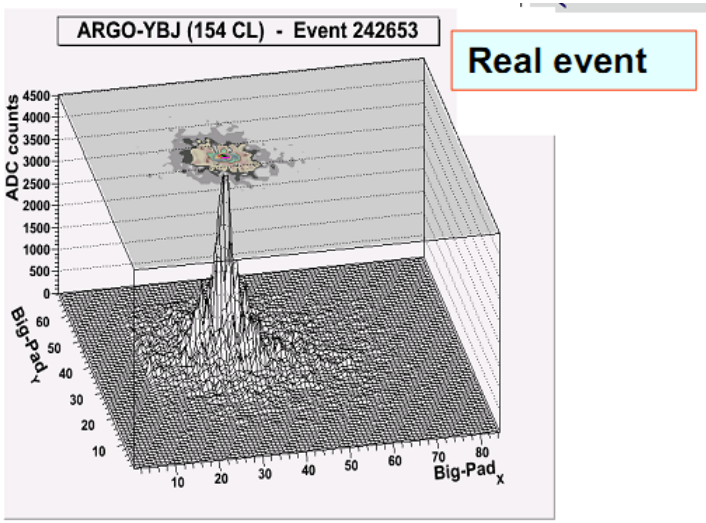
Lateral distributions:



ICRC2011, HE1.1 n.1028

BigPads (analog)

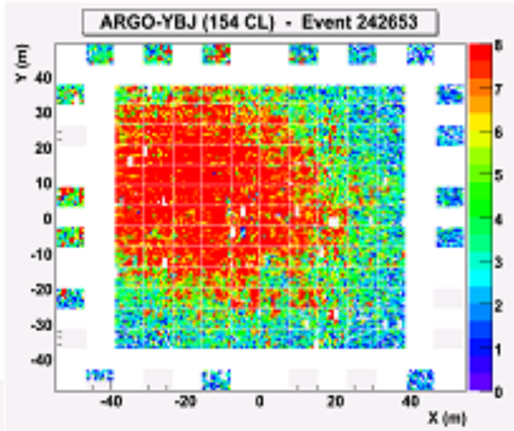


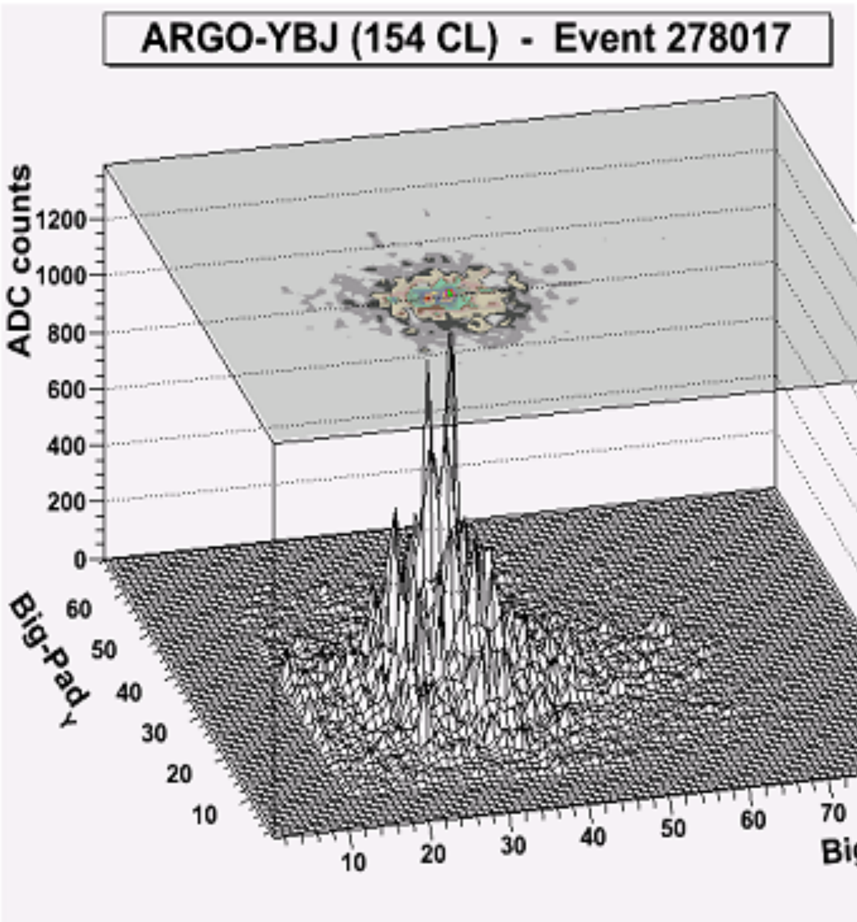


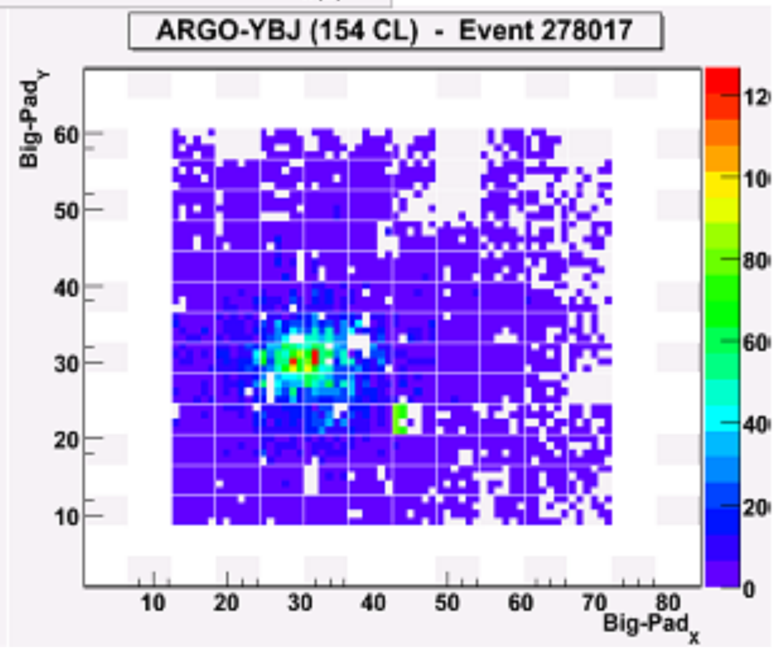
Multicore events with analog data

Preliminary results show the feasibility of these studies.

Analysis is in progress...





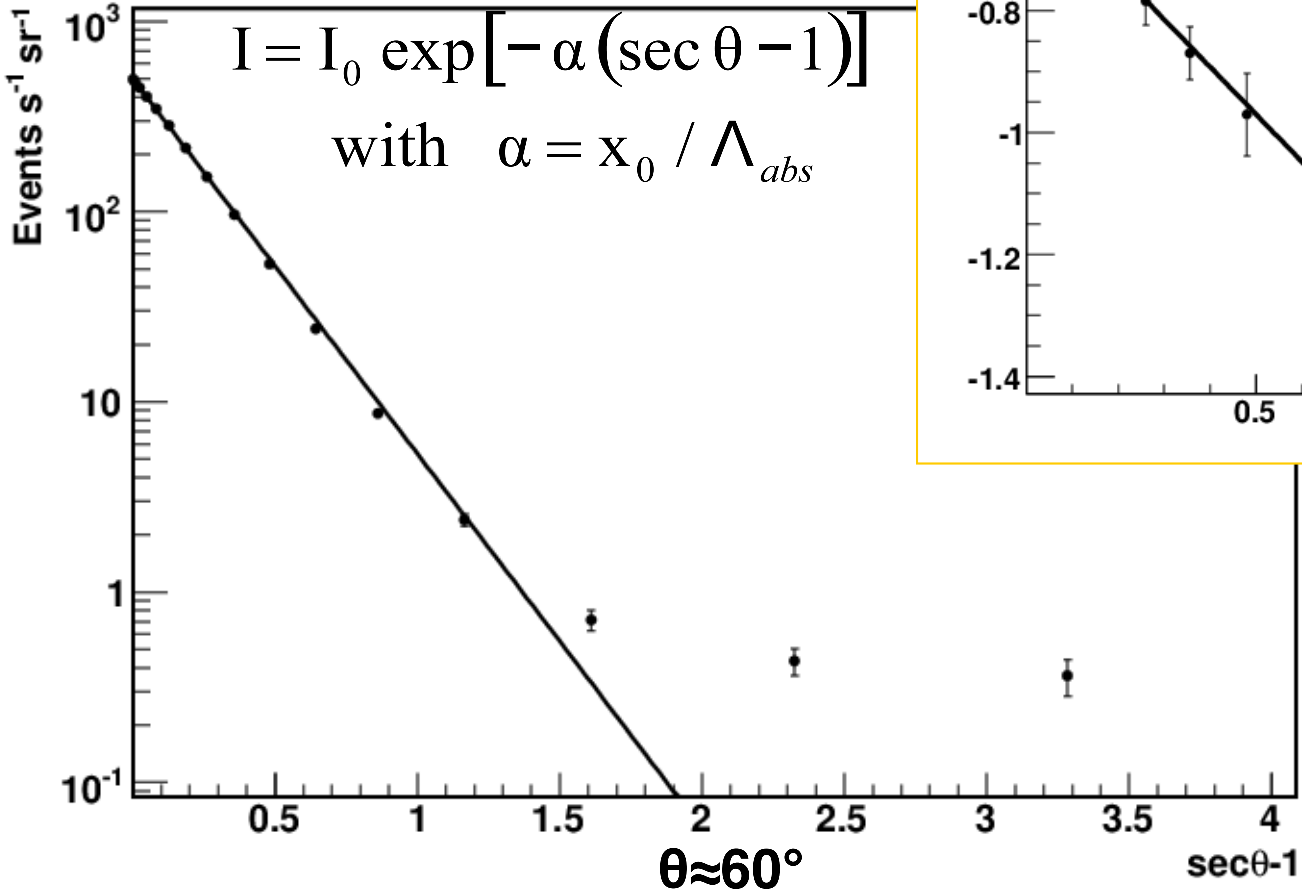


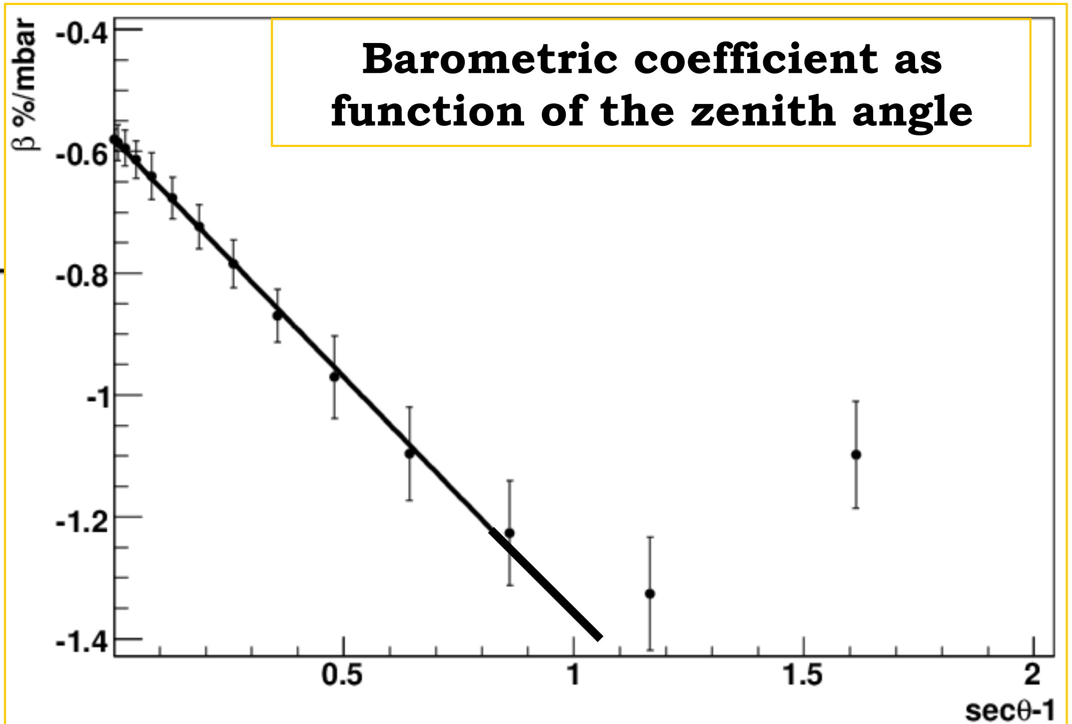
Rate Vs zenith angle

YBJ altitude – 606 g/cm²
θ>70° - 1248 g/cm²
θ>80° - 2458 g/cm²

$$I = I_0 \exp\left[-\alpha\left(\sec\theta - 1\right)\right]$$

$$\text{with} \quad \alpha = x_0 / \Lambda_{abs}$$





Fit: $I_0 = (165 \pm 9)\ s^{-1}\ sr^{-1}$

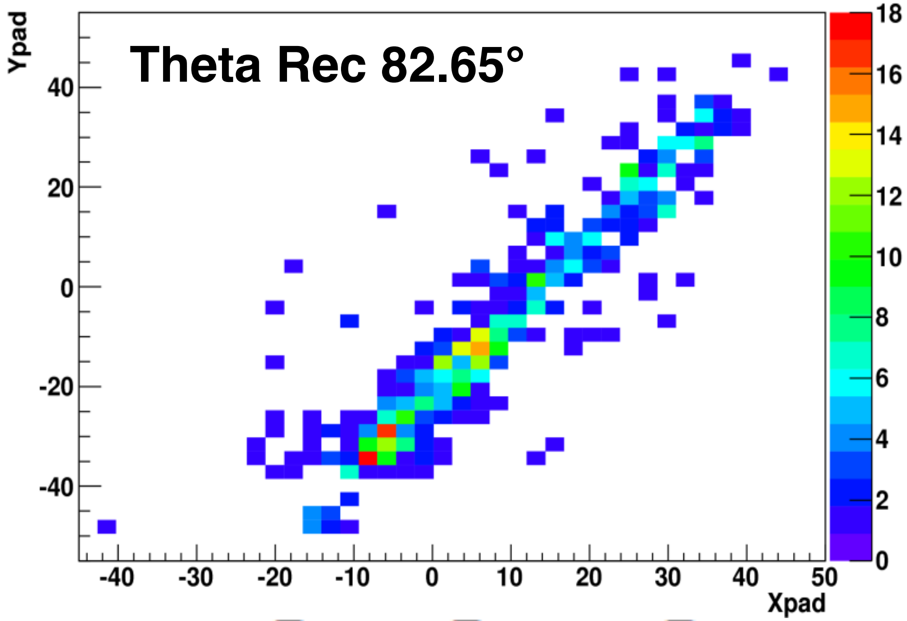
$\alpha = 5.4 \pm 0.1$

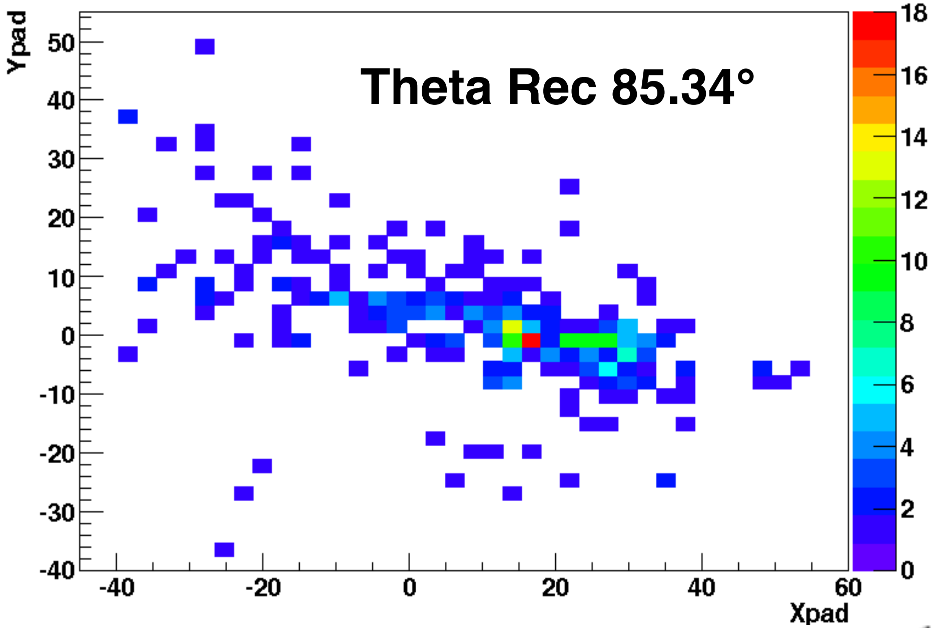
$\Lambda_{abs} = 108 + 2\ g/cm^2$

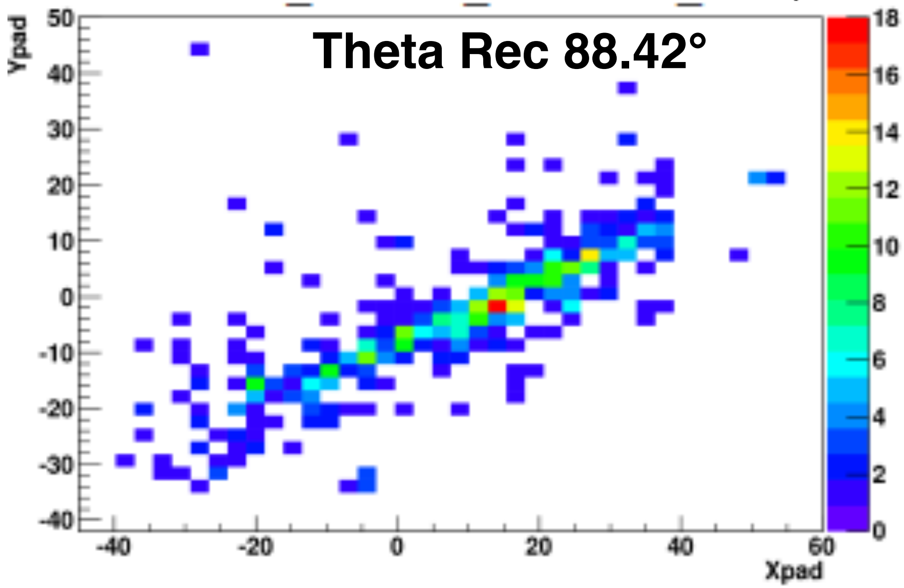
Λ_{abs} = absorption length

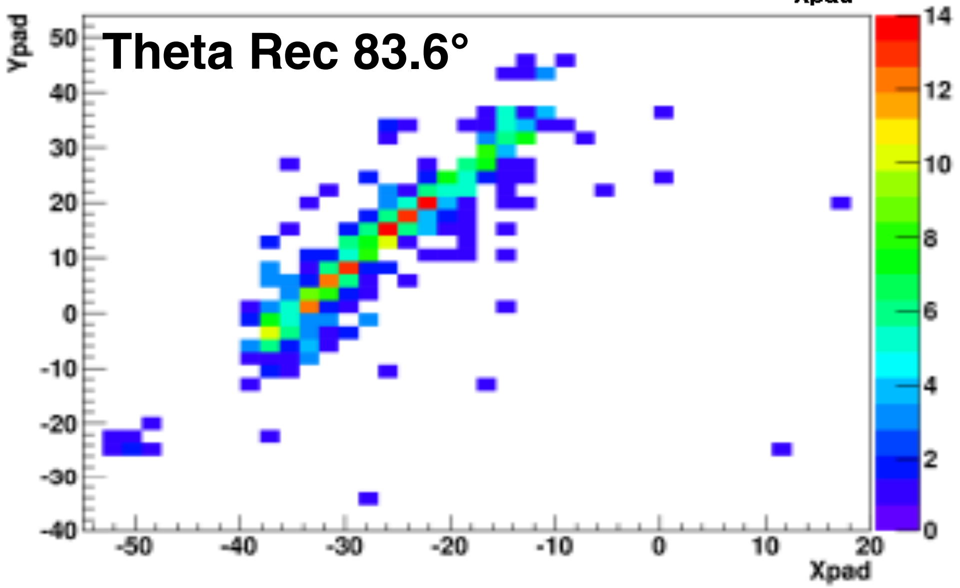
$\beta = \gamma/\lambda$

Horizontal Air Showers by ARGO-YBJ



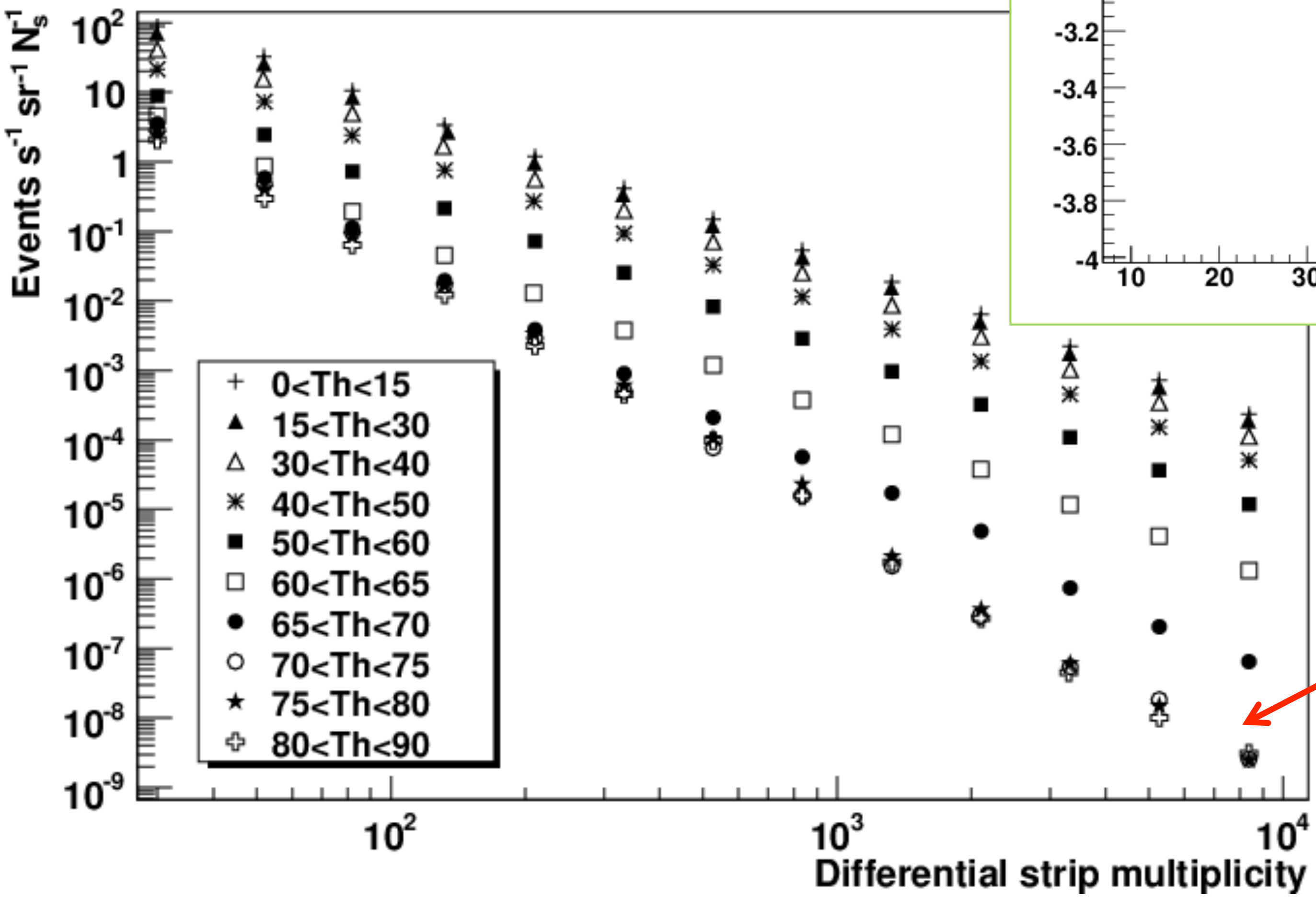


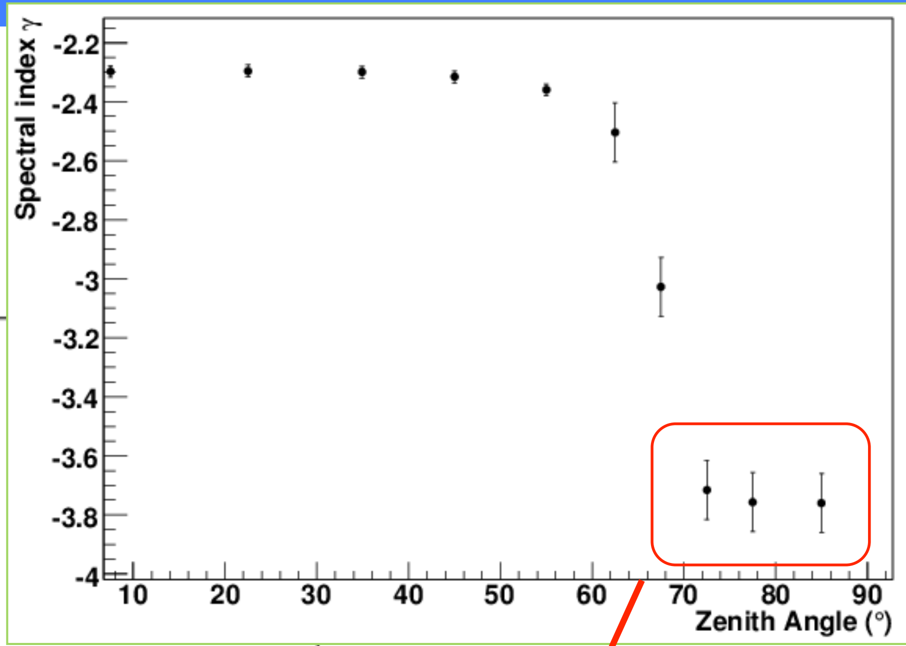




Size Spectrum of HAS

Strip multiplicity for different zenith angles





$\gamma = -3.60$

Spectral index

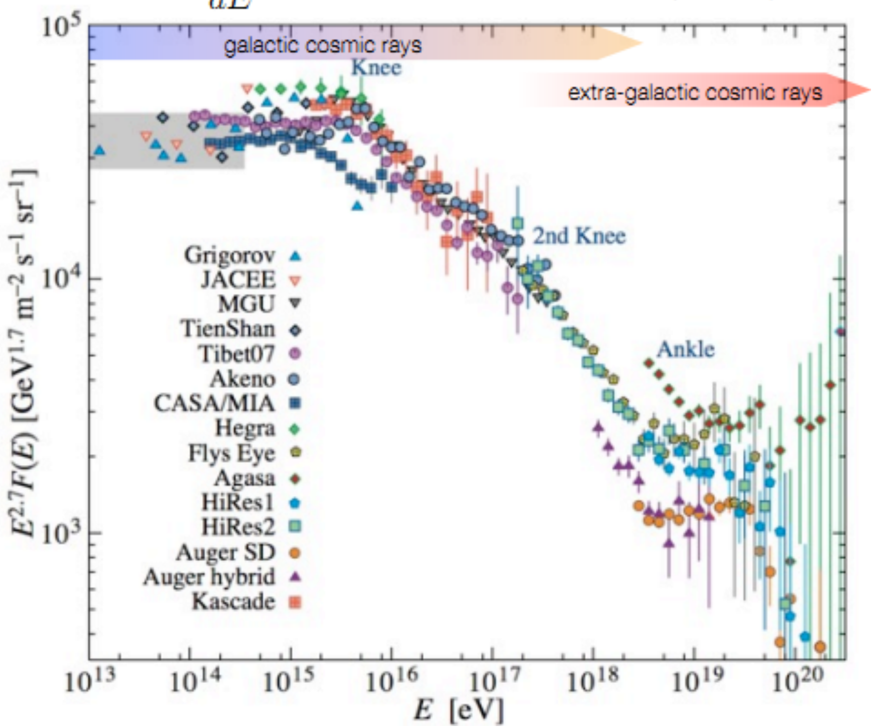
Mu in EAS

Cosmic Ray Isotropy

- CRs below 10^{18} eV are predominantly galactic.
- The bulk of CR is produced by shock acceleration in SN explosions.
- Diffusion of accelerated CRs through non-uniform, non-homogeneous ISM.
- At 1 TeV, B ~ 1 μG, Gyro-Radius ~ 200AU, 0.001pc

⬇

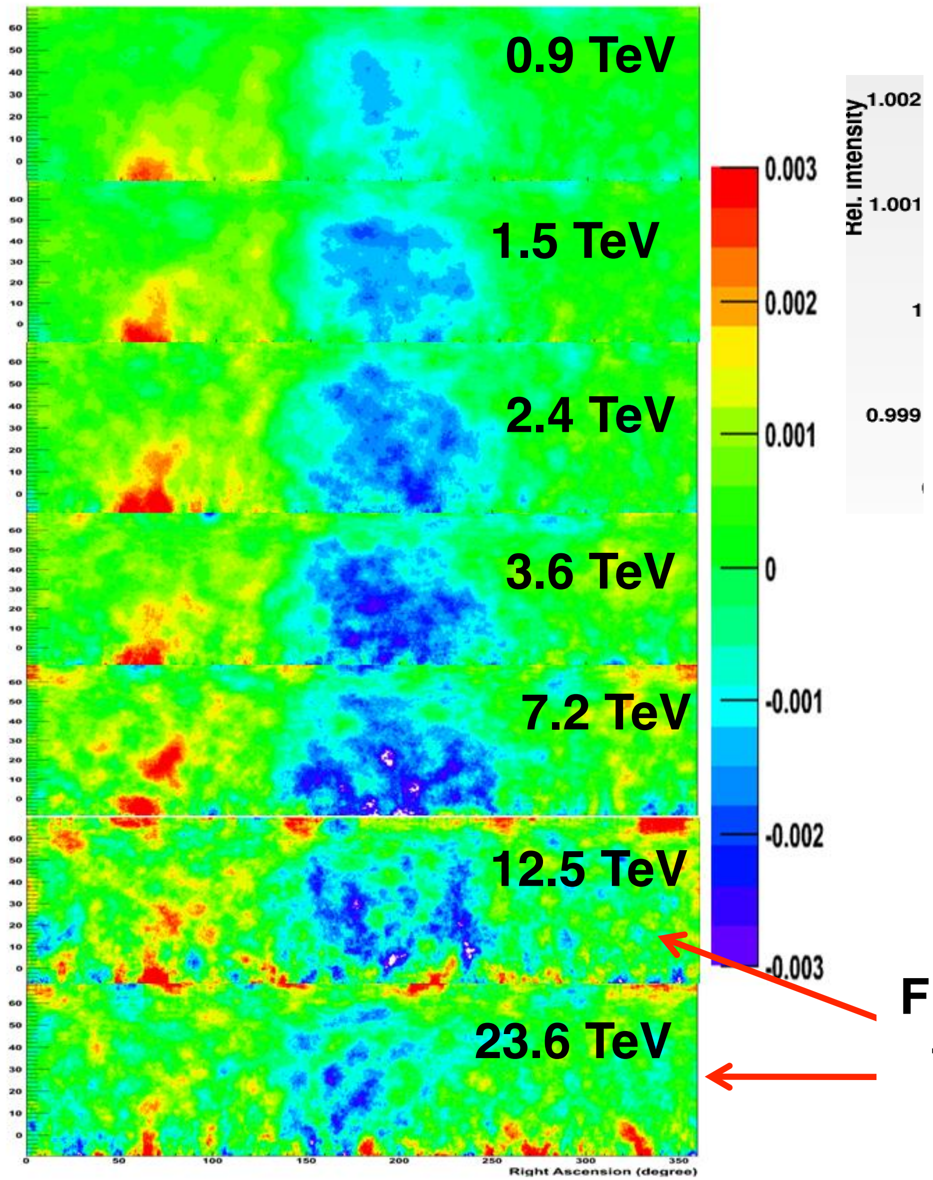
- **Galactic CRs are expected to be highly isotropic** scrambled by galactic magnetic field over very long time.

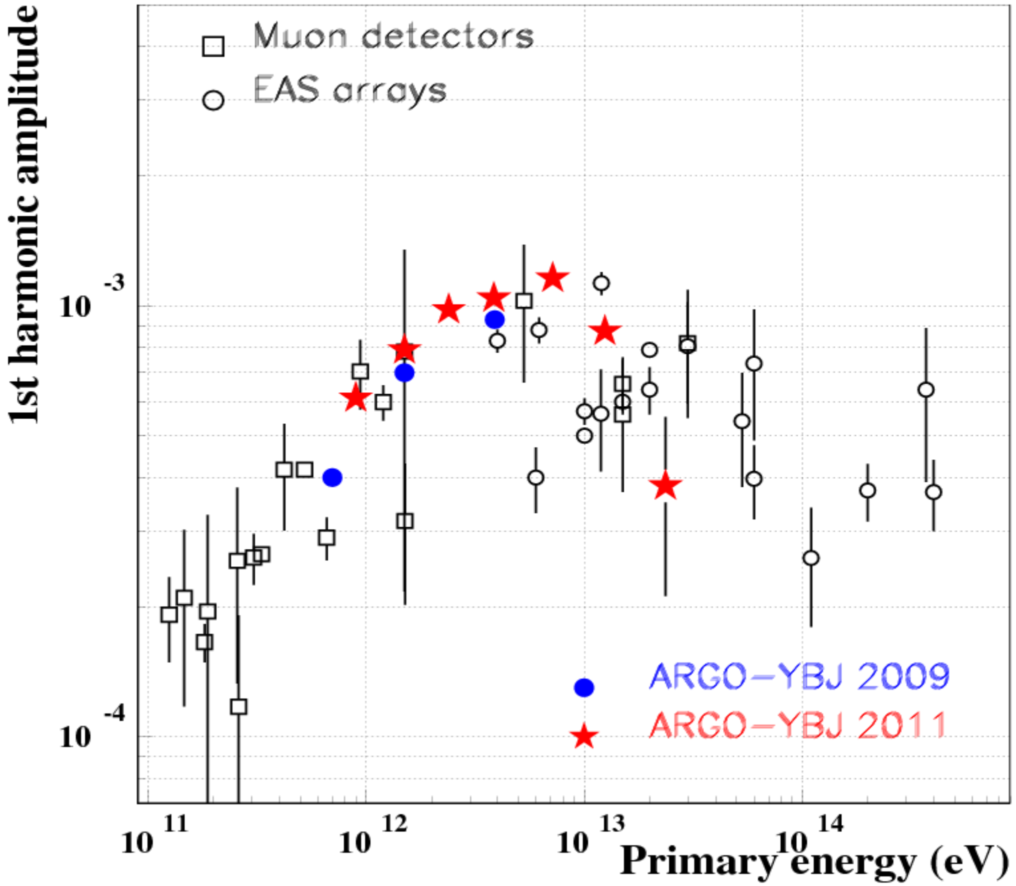


$$E^{2.7} \cdot \frac{d\Phi_{CR}}{dE}(E)$$

$$R_{gyro} \approx 1\text{kpc}\,\frac{1}{z}\,\frac{E}{10^{18}\,\text{eV}}\,\frac{\mu G}{B}$$

Large Scale CR anisotropy vs Energy



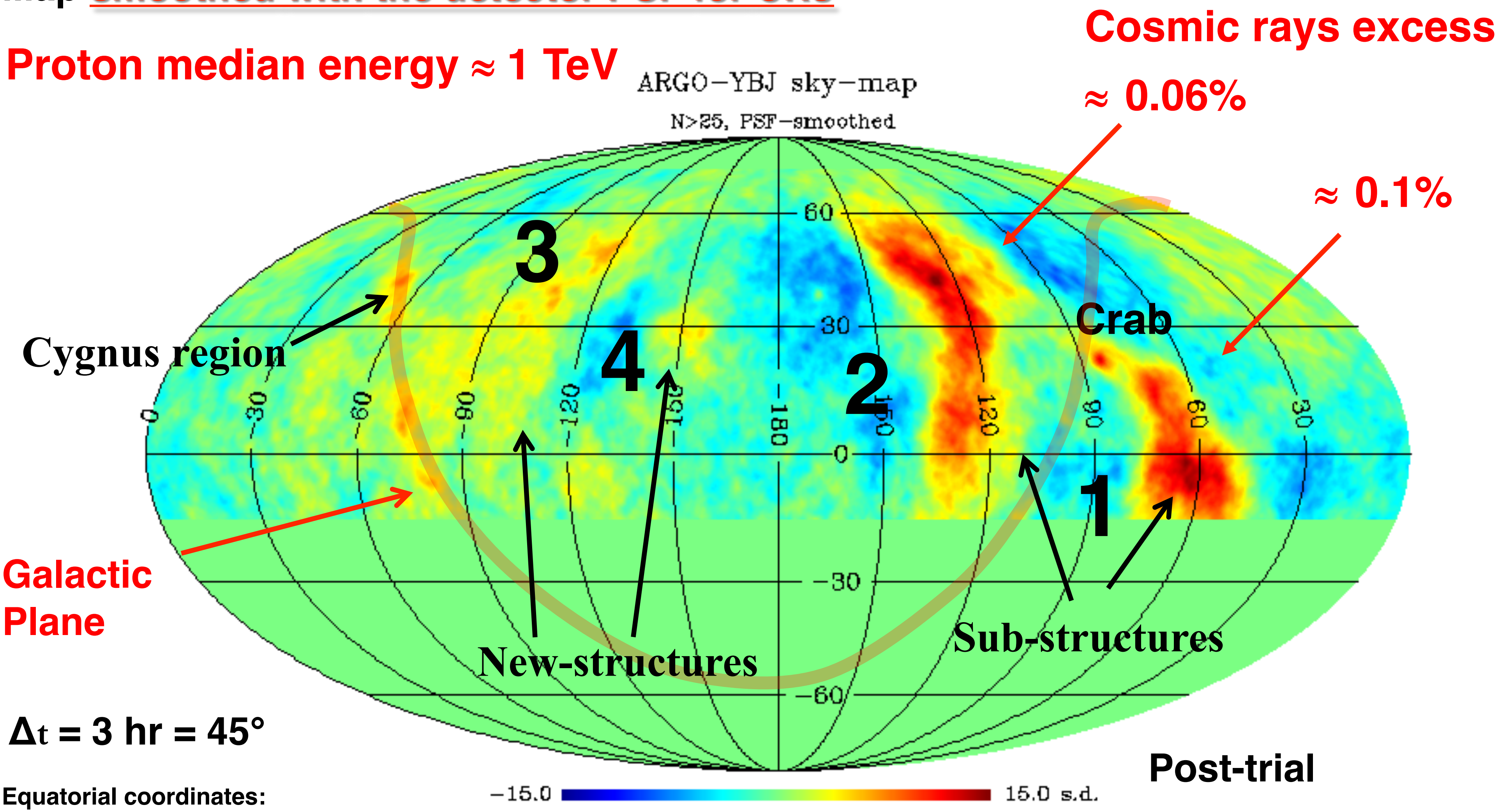


First measurement with an EAS array below the TeV energy region so far investigated only by underground muon detectors

Medium Scale Anisotropy by ARGO-YBJ

Map smoothed with the detector PSF for CRs

Proton median energy ≈ 1 TeV

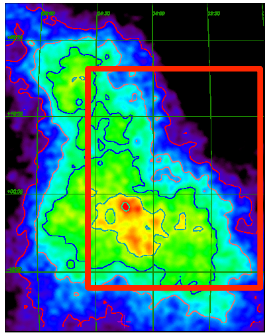


Δt = 3 hr = 45°

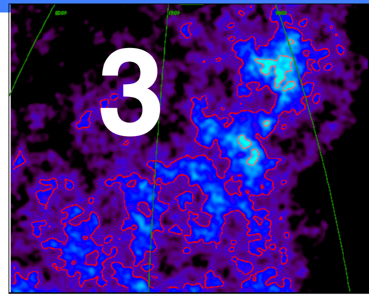
Post-trial

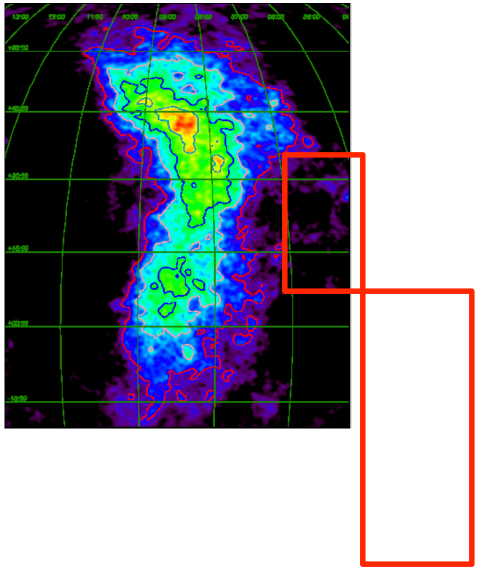
Equatorial coordinates:
projection of the earth longitude and latitude

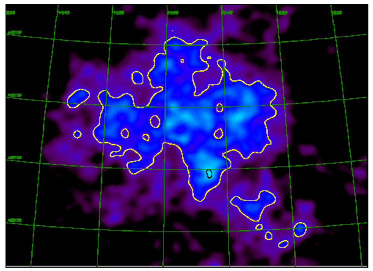
Medium Scale Anisotropy morphology



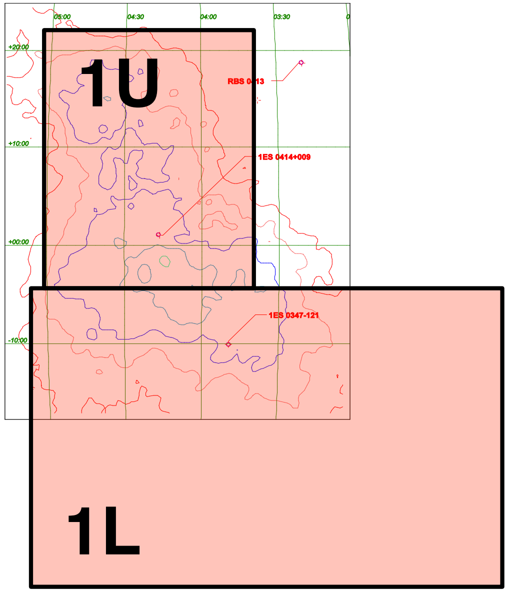
MILAGRO missed
an important part
of the MSA



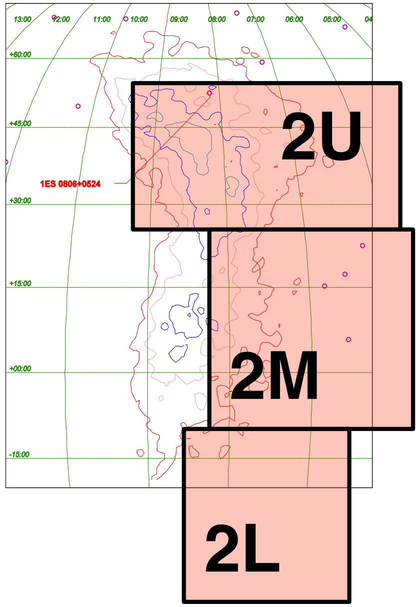


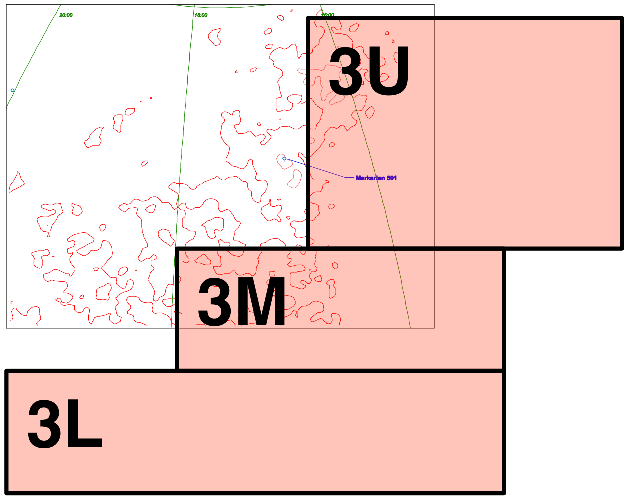


Region parametrizations

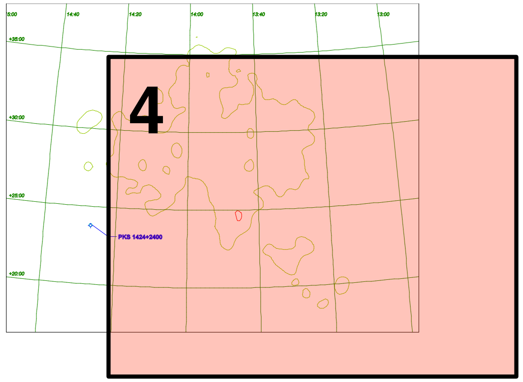


Complex morphology requires **composite parameterization.** For the sake of simplicity, r.a.-dec. boxes were used.

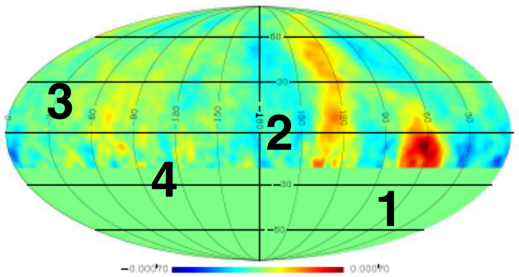




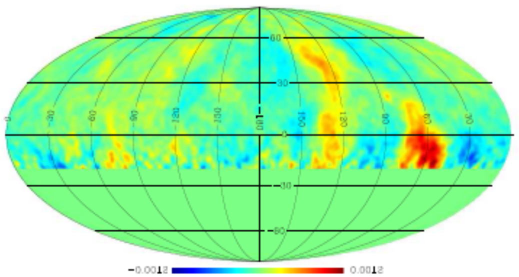
No known TeV gamma-ray sources are known which can account for the observed (extended) excess



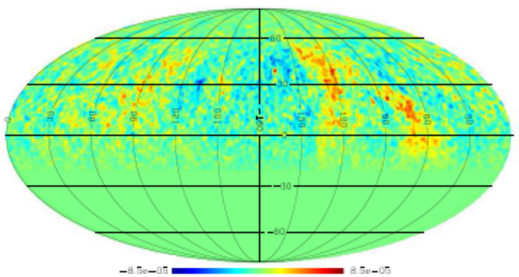
Energy Spectrum



(a)

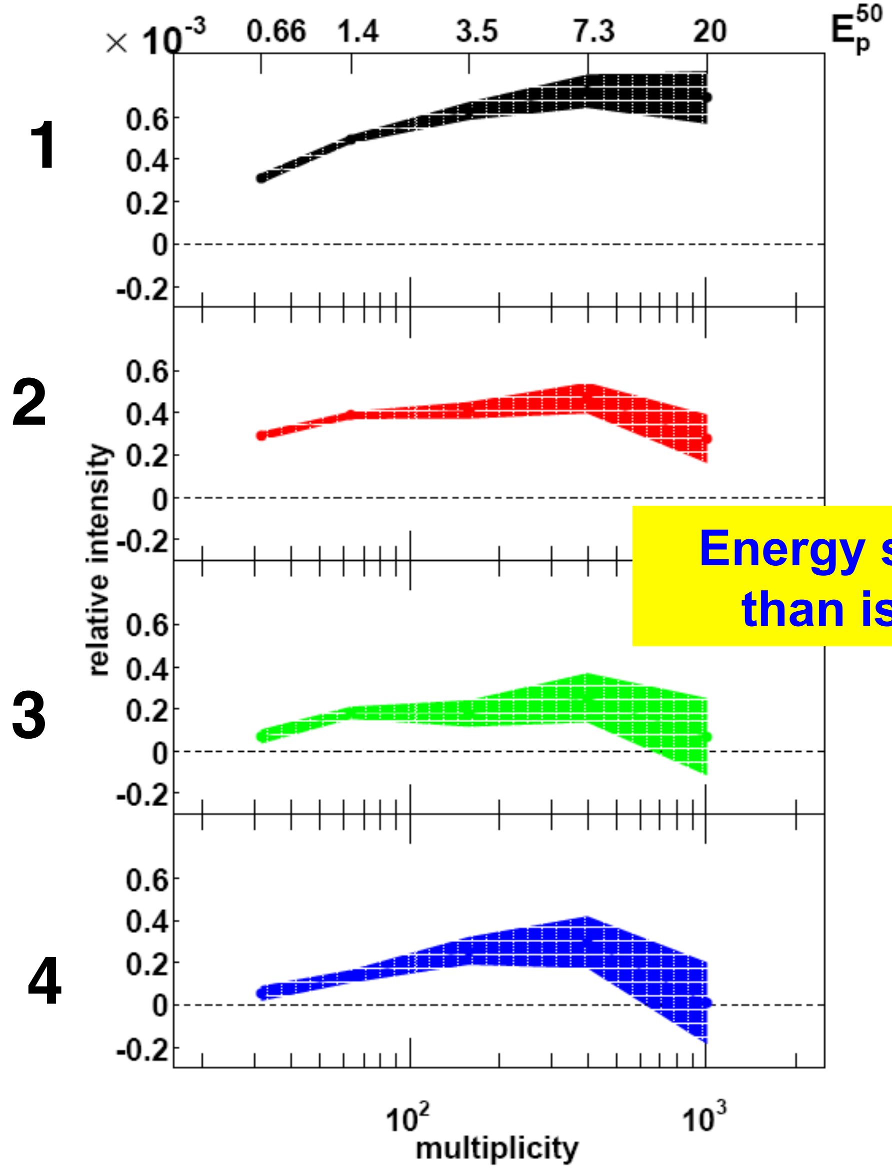


(b)



(c)

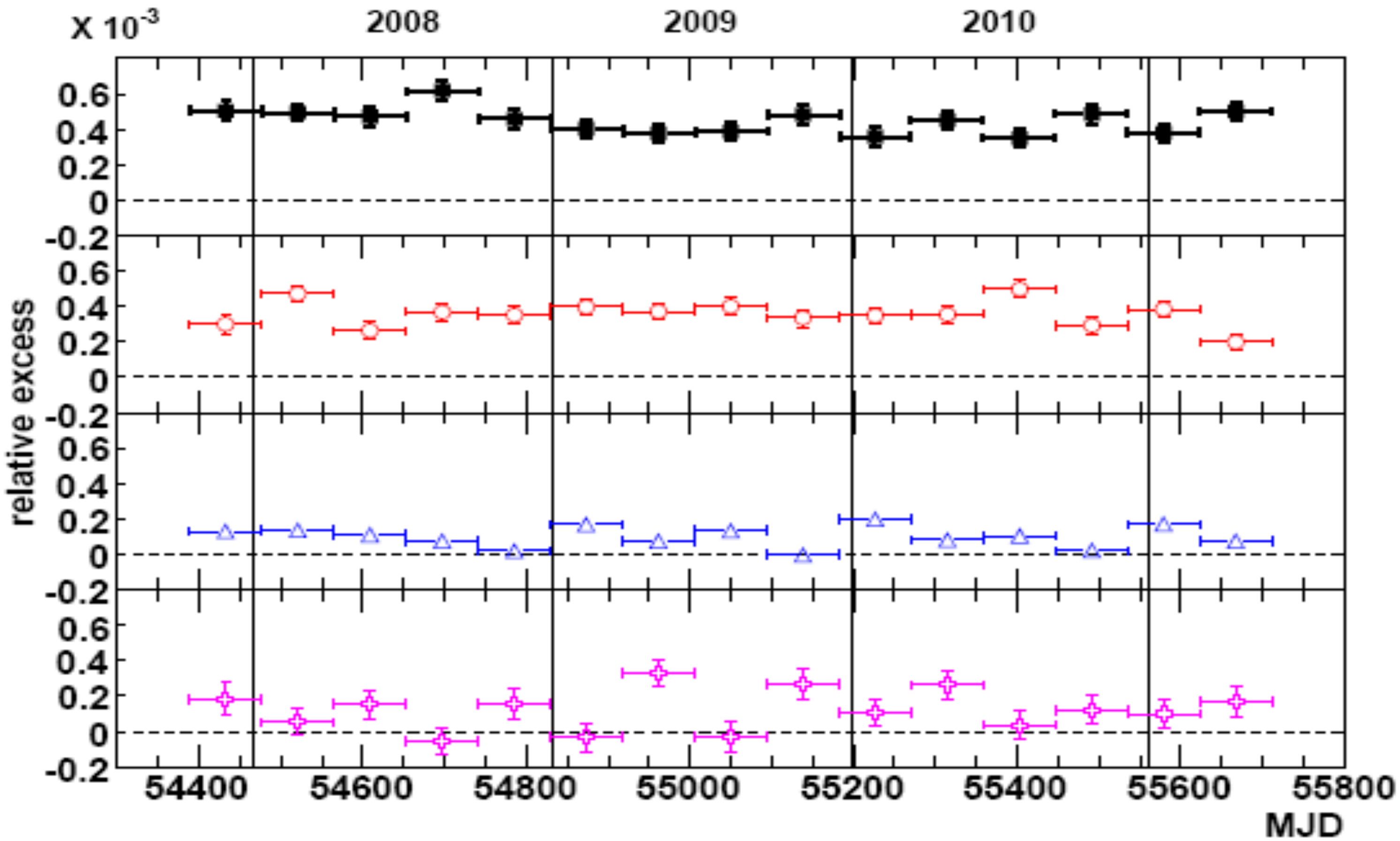
First three multiplicity intervals as a reference



Energy spectra harder than isotropic CRs

Intensity as a function of the Time

Milagro reported indications for time dependence: the fractional excess was lowest in the summer and highest in the winter



NO evidence for time dependence observed by ARGO-YBJ in the last 3 years

LAWCA: Large Area Water Cerenkov Array

"Low Energy Branch" of LHAASO under construction at YangBajing

Sensitivity similar to HAWC: 5% Crab flux above few TeV

Water pool: 205m×110m, 41×22=902 units (5m×5m each) separated by curtains. Water depth: 4m

A prototype at IHEP (see **Nucl.Instrum.Meth.A644:11-17,2011**)

Conclusions - 1

- Detector performance studied with the most detailed analysis of the "Moon shadow" effect.

  PRD 84 (2011) 022003

- First continuous sky survey of the northern hemisphere at TeV energies with a sensitivity of about 25% Crab flux

- Long term monitoring of Crab Nebula, Mrk421, Mrk501, MGRO J2031+41, MGRO J1908+06

  ApJL 714 (2010) L208
  ApJ 734 (2011) 110
  2 more ApJ in press

- Observation of TeV gamma rays from the Cygnus region

  ApJL 745 (2012) L22

- Search for high-energy gamma-ray emission from GRBs.

  Astrop. Phys. 30 (2008) 85
  ApJ 699 (2009) 1281
  Astrop. Phys. 32 (2009) 47.

Conclusions - 2

- First measurement of the p-air and p-p cross sections at center-of-mass energies between 70 and 500 GeV, where no accelerator data are available.

  PRD 80 (2009) 092004

- Lowest limits set to the antip/p CR flux ratio at TeV energies by exploiting the Moon shadow analysis

  PRD 85, 022002 (2012)

- First ground-based measurement of the CR primary light component (p+He) energy spectrum in the range TeV – 200 TeV so far investigated only by balloons/satellites.

  PRD 85, 092005 (2012)

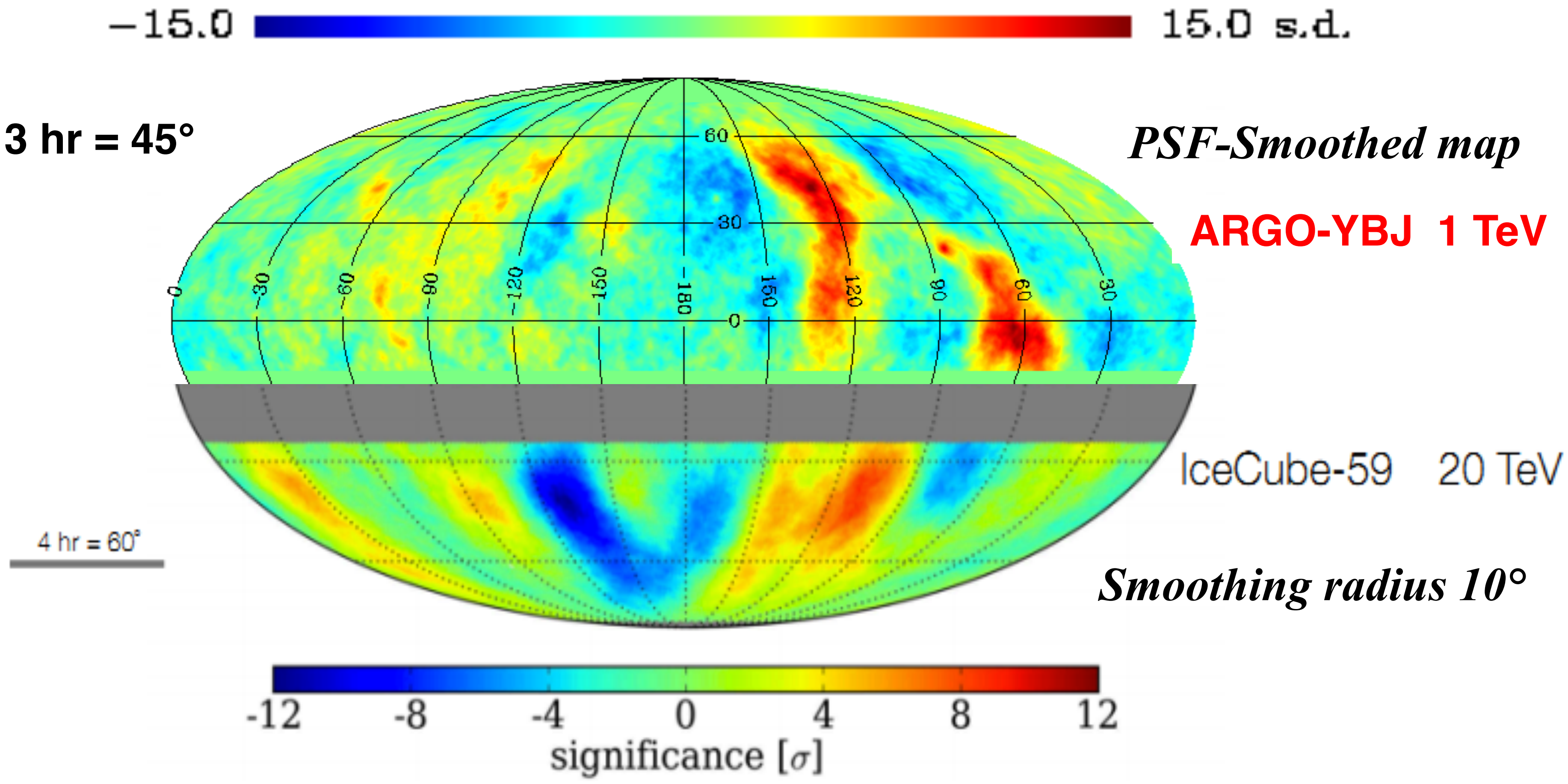
- First measurement/monitoring of the Interplanetary Magnetic Field by exploiting the “Sun shadow” effect.

  ApJ 729 (2011) 113

More stuff…

Complete CR map of the entire TeV sky

ARGO-YBJ + IceCube-59



Anisotropy data analysis

DATA SET:

November 2007 - May 2011 data (~1300 days)

N_{str} > 25, Zenith angle < 45°, 2.2 · 10^{11} events

NO gamma/hadron discrimination technique applied.

Background estimation methods:

- **Equi-zenith angle method**

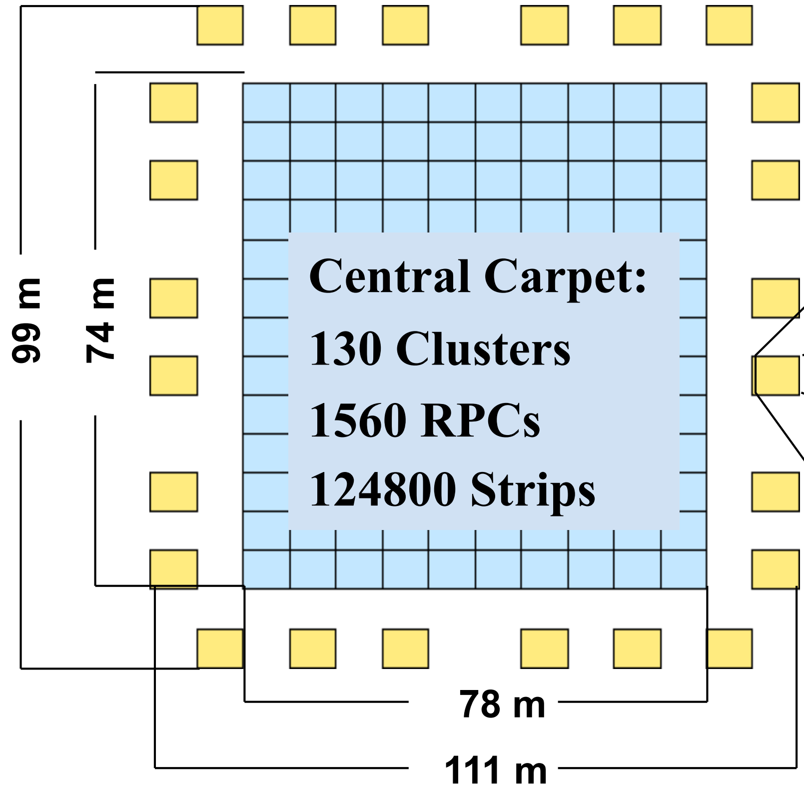
- **Up to 45°- wide structures:**
  - **Time swapping/scrambling (3 hrs, N_{off}/N_{on}=10)**
  - **Direct integration (3 hrs)**

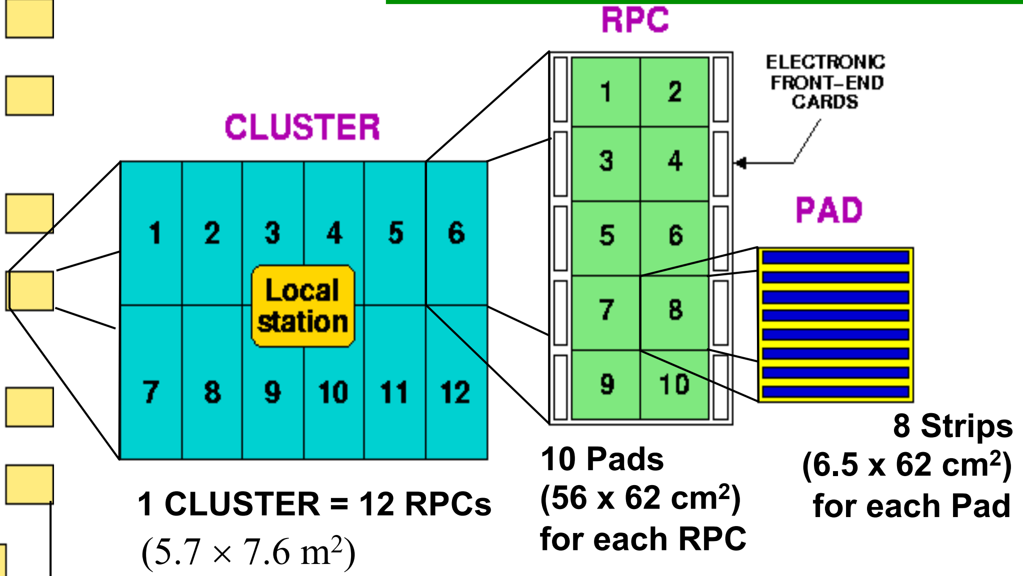
  (consistent each other within 0.3 s.d.)

An effective high-pass filter for structures narrower than 3 hrs × 15°/hrs = 45° in R.A.

Detector layout

time resolution ~1-2 ns (pad)
space resolution = strip



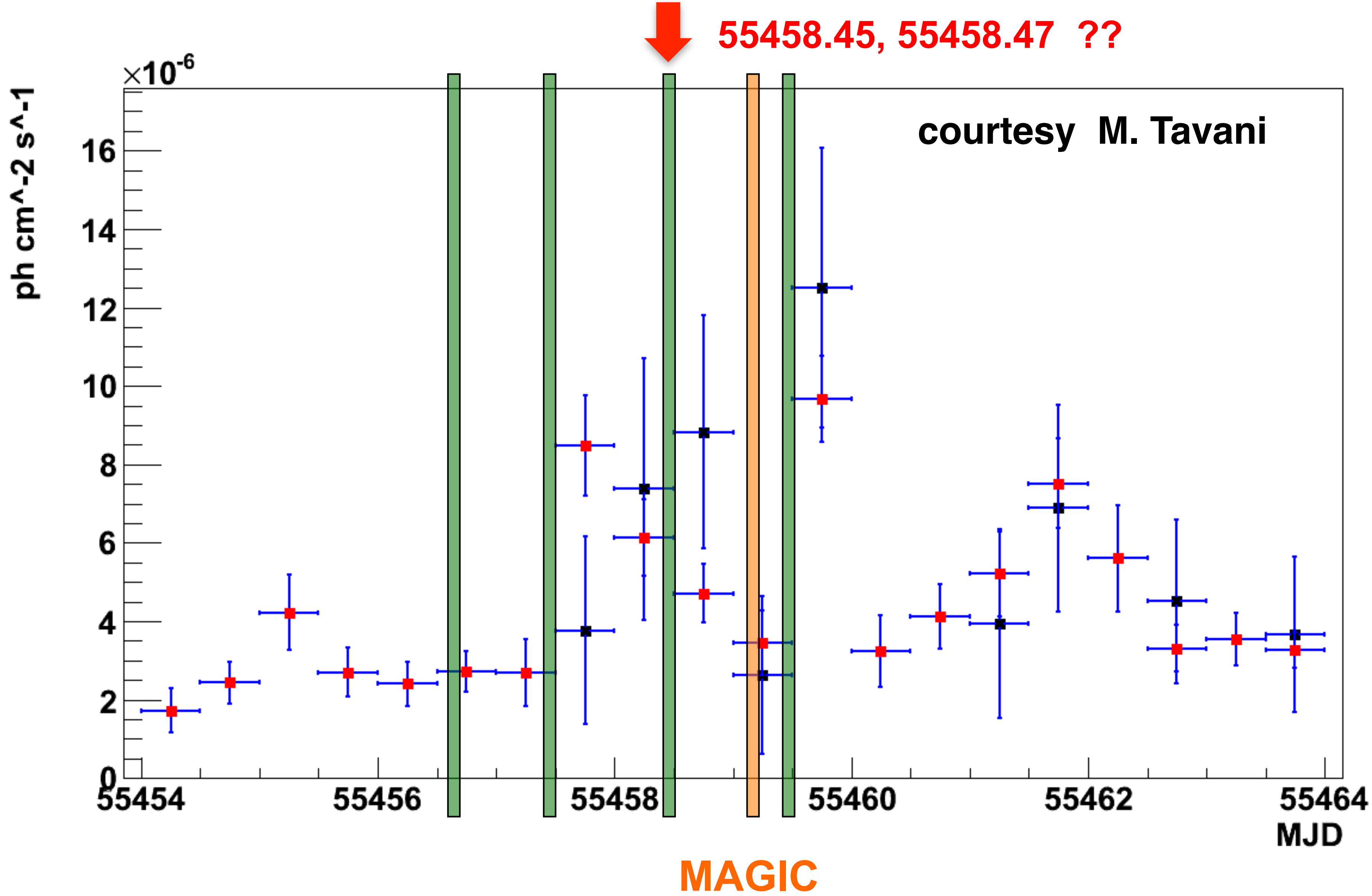


Gas Mixture: Ar/ Iso/TFE = 15/10/75

HV = 7200 V

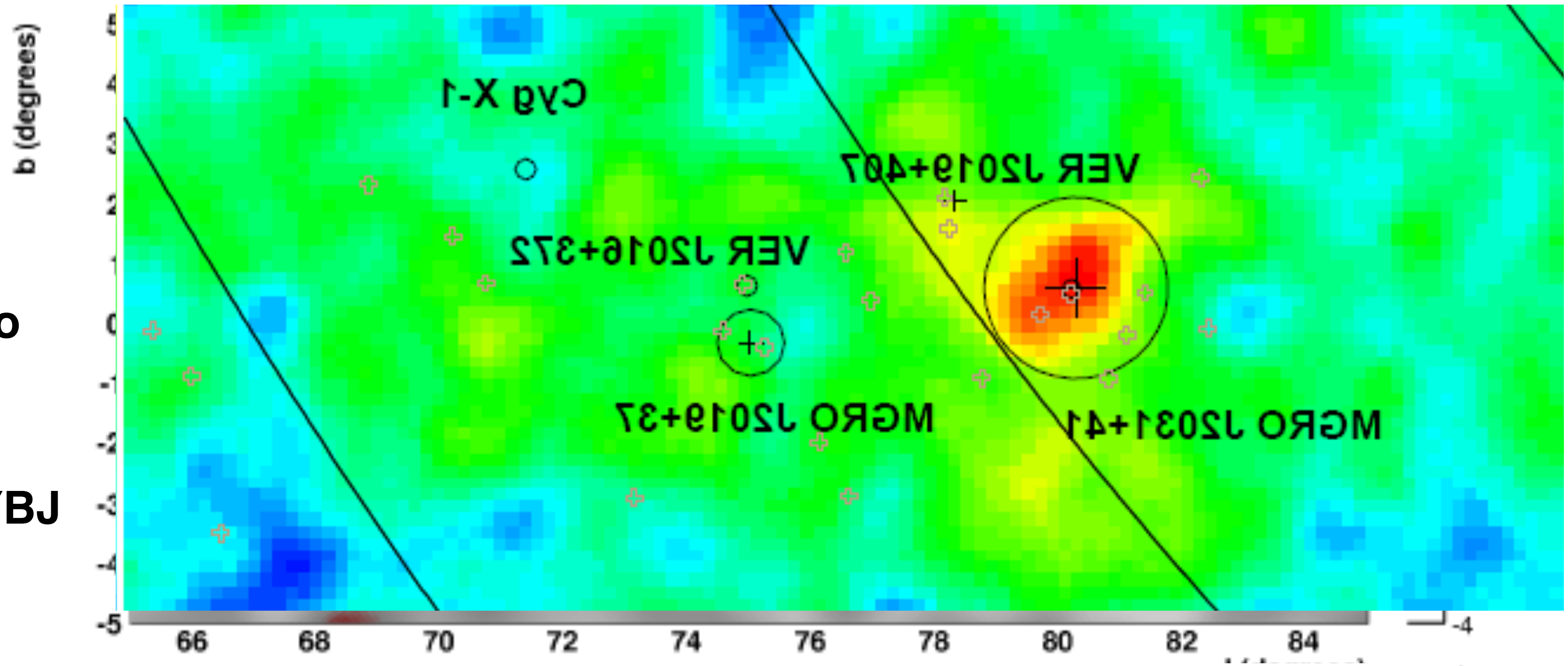
Single layer of Resistive Plate Chambers (RPCs)
with a full coverage (92% active surface) of a large area (5600 m^2)
+ sampling guard ring (6700 m^2 in total)

Fermi/Agile 12 hr light curves and Č observations



Milagro

ARGO-YBJ



FERMI above 10 GeV