# *Cosmic-ray physics with ARGO-YBJ*

**Roberto Iuppa**

**roberto.iuppa@roma2.infn.it**

***Università di Roma Tor Vergata***

***INFN – Sez. Roma  Tor Vergata***

**On behalf of the ARGO-YBJ Collaboration**

**IPA 2013**

**May, 13° 2013 – Madison (WI)**

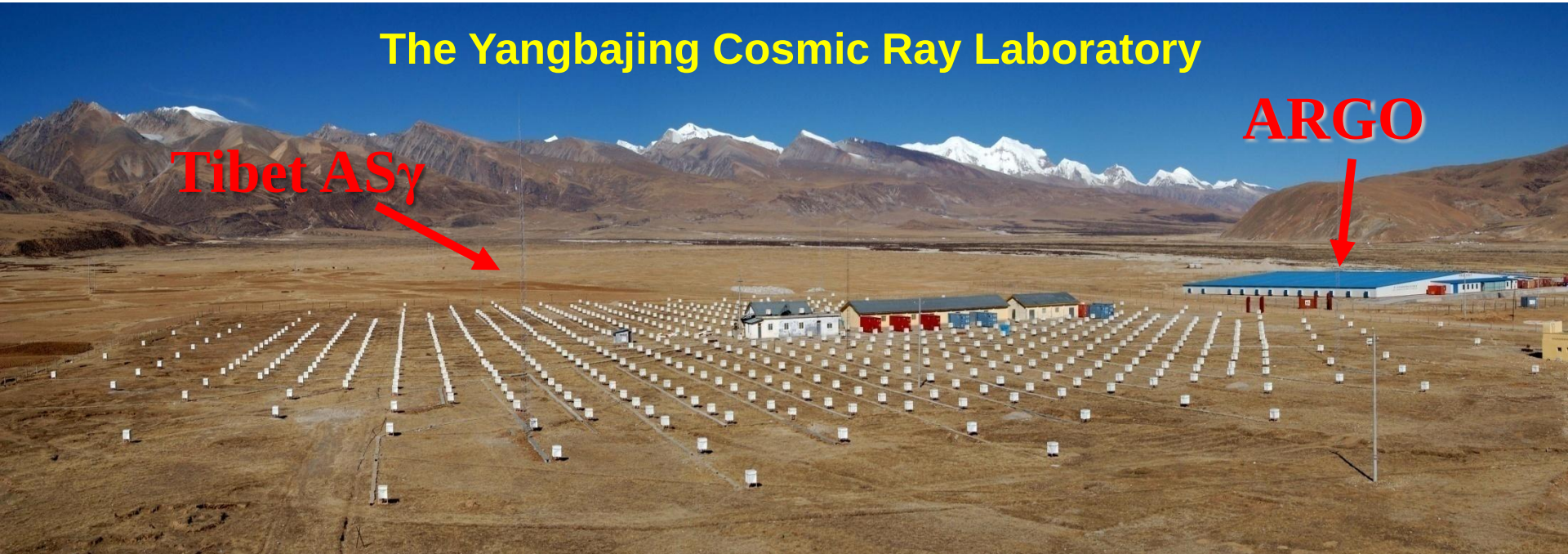
# *The ARGO-YBJ experiment*

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$^2$**



# *Highlights: γ-Ray Astronomy*

- First continuous sky survey of the northern hemisphere at TeV energies with a sensitivity of about 30% Crab flux
- Long term monitoring of Crab Nebula, Mrk421, Mrk501, MGRO J2031+41, MGRO J1908+06

  **ApJL 714 (2010) L208**
  **ApJ 734 (2011) 110**
  **ApJ 758 (2012) 2**
  **1 more ApJ in press**
- Observation of TeV gamma rays from the Cygnus region

  **ApJL 745 (2012) L22**
- Observation of the HESS J1841-55 region.

  **ApJ submitted**
- Search for high-energy gamma-ray emission from GRBs.

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

# *Highlights: Cosmic Ray Physics*

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

  **PRD 84 (2011) 022003**

- 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)**

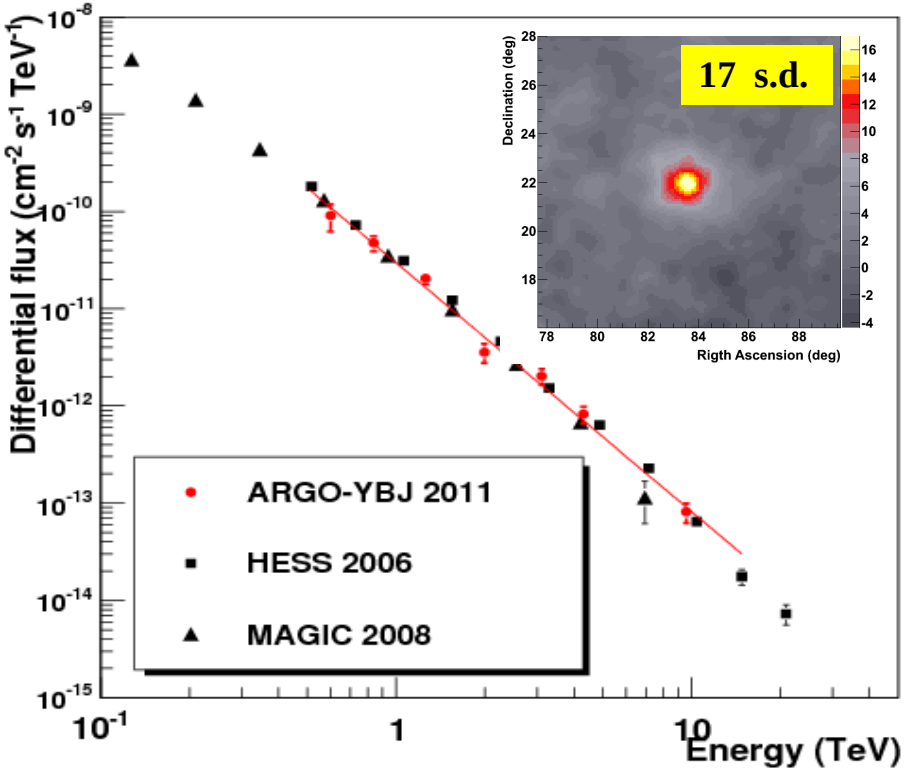
- First measurement/monitoring of the Interplanetary Magnetic Field by exploiting the "Sun shadow" effect.

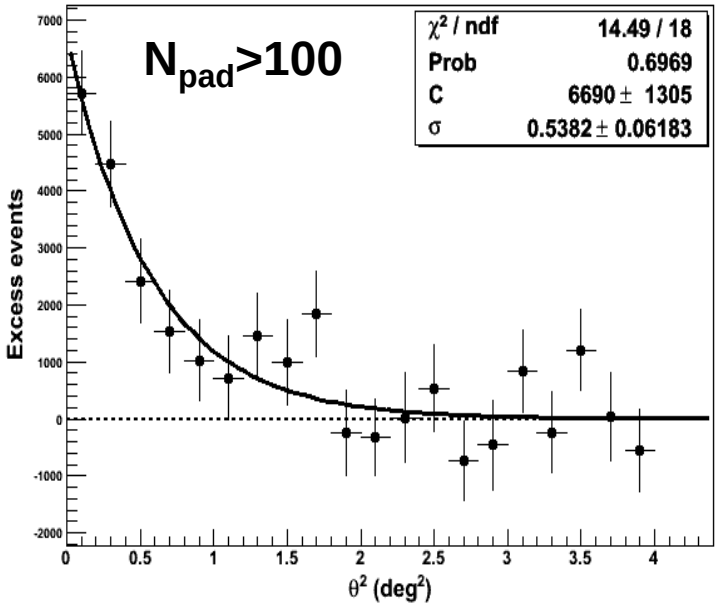
  **ApJ 729 (2011) 113**

# Crab Nebula

**Average flux ~ 23 ±3 ev/hour - 84% from $E_\gamma > 300$ GeV**

**Current sensitivity: ~25% Crab flux**




**Measured PSF in agreement with MC**

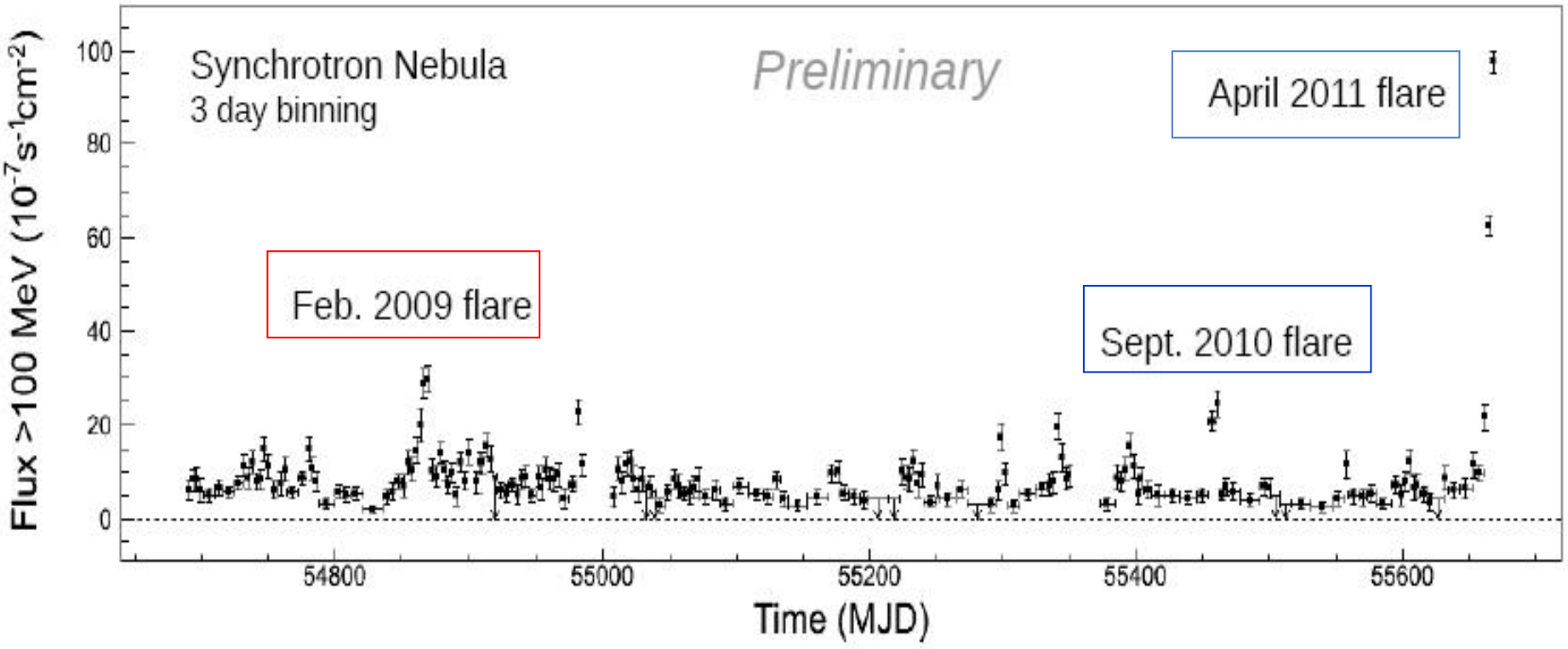
**(0.5 – 10) TeV**

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

# *Crab Nebula is not a "standard candle"*

**4 flares during the ARGO-YBJ lifetime**

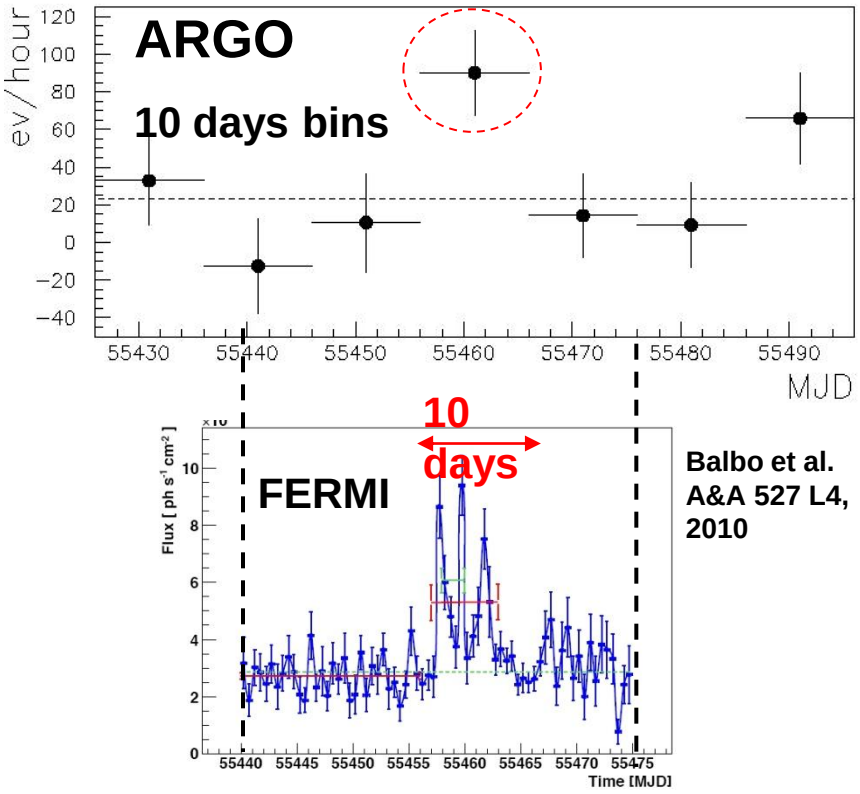
from Buehler slides – Fermi Symposium 2011



# *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).**

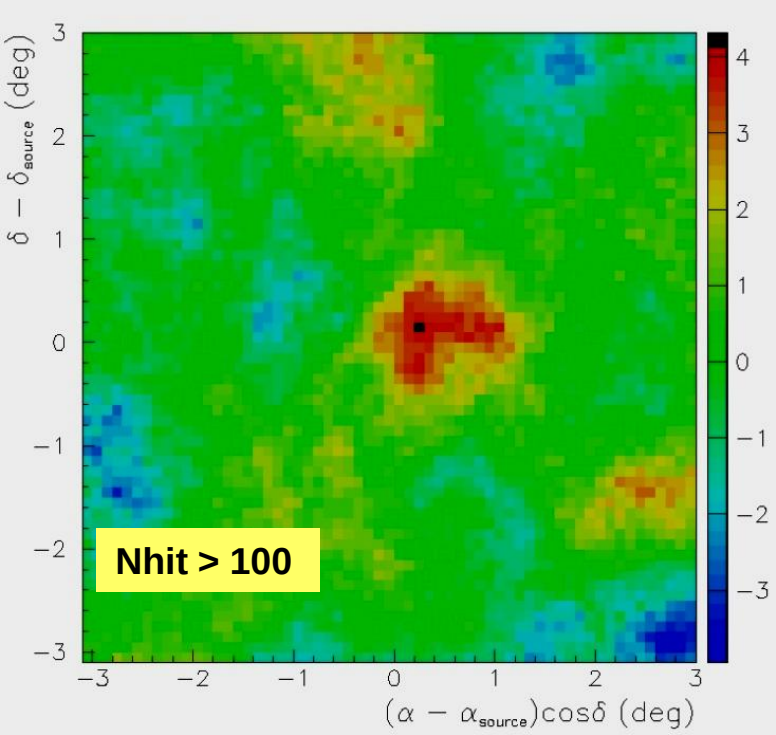



**observed 4.1 s.d.**

**expected 1.0 s.d**

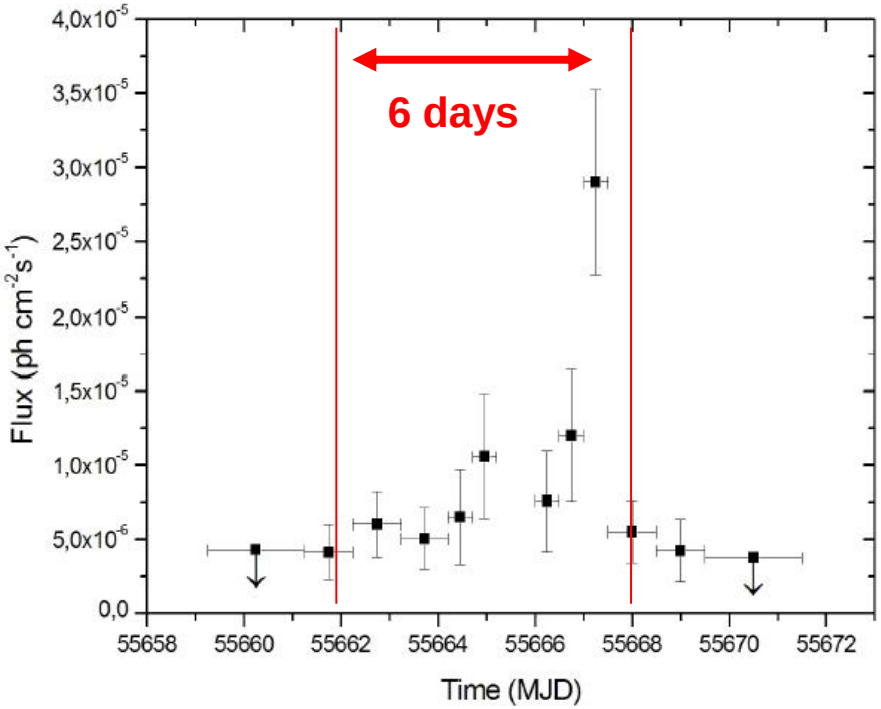
# A new TeV Crab flare in April 2011 ?

**Significance map in 6 days**




**AGILE light curve**

**E > 100 MeV**




**3.5 s.d.**

**expected 0.62**

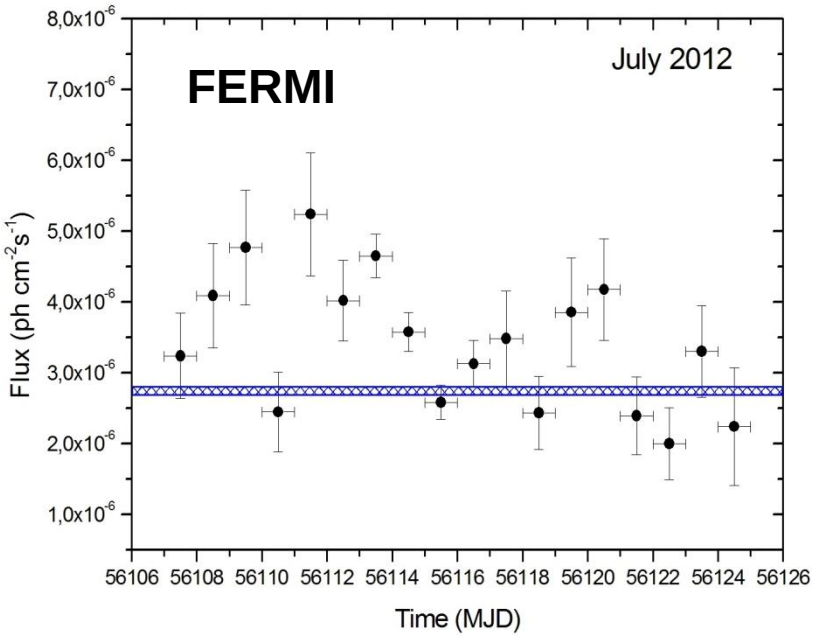
**NO Cherenkov data available**

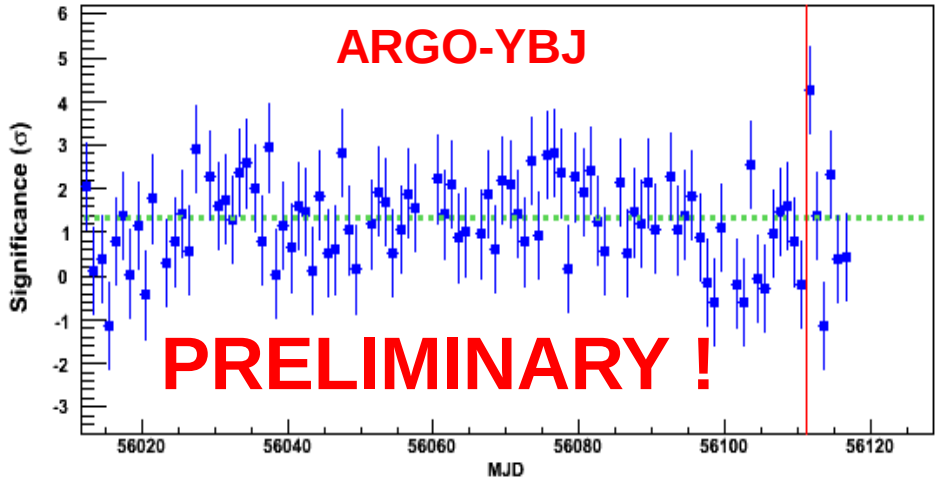
**E ≈ 3 TeV**

# *Crab Nebula 3rd July 2012 flare*

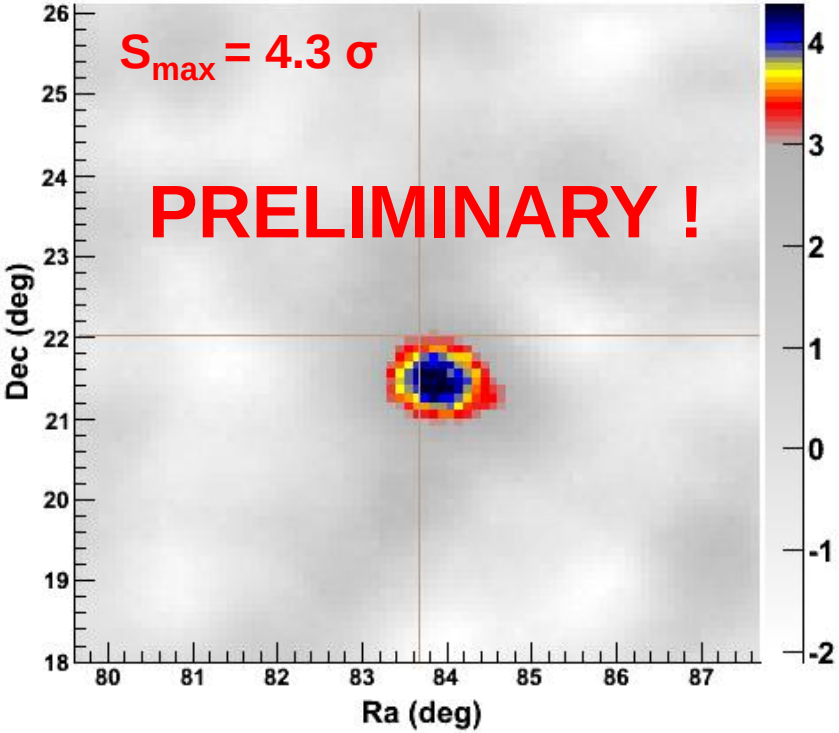
- **FERMI observed a flare at E > 100 MeV in 3rd July 2012 (MJD 16111) (Atel #4239)**
- **The daily-averaged emission doubled from (2.4 ±0.5) x $10^{-6}$ ph/cm$^2$ / sec on July 2nd to (5.5±0.7) x $10^{-6}$ ph/cm$^2$/sec on July 3rd, a factor of 2 greater than the average flux of (2.75±0.10) x $10^{-6}$ ph/cm$^2$/sec reported in the second Fermi LAT catalog.**
- **Possible TeV emission enhancement (≈ 8 times) observed by ARGO-YBJ in 3rd July only (ATel #4258).**

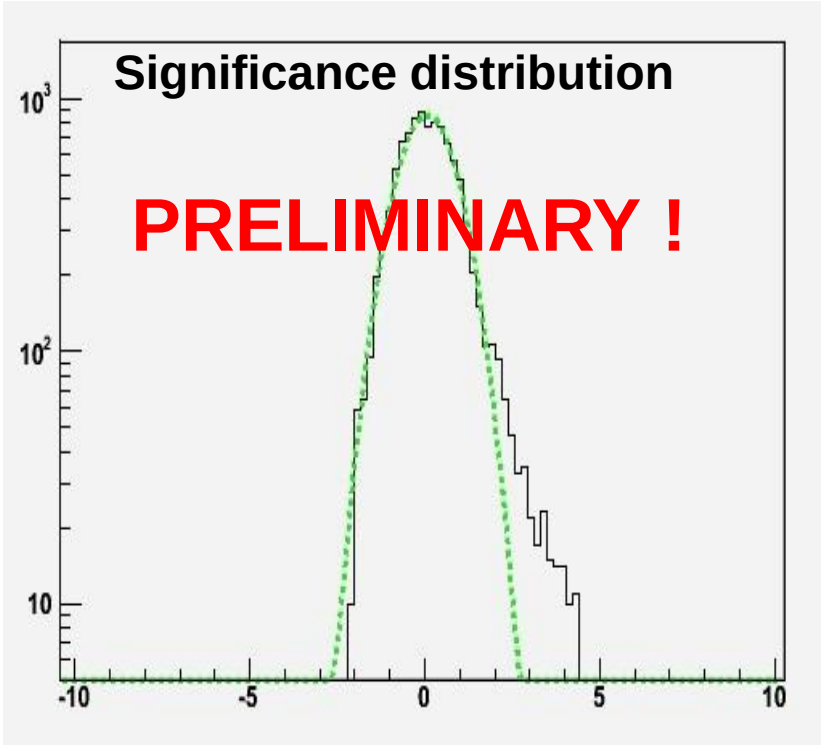
  **NO Cherenkov data available**



# ARGO-YBJ observation: 3rd July 2012




- We observed a 4.3 s.d. signal ≈ 0.6 deg apart from the Crab nominal position but well inside the ARGO-YBJ PSF.
- The statistical significance at the nominal position is 3.4 s.d.
- The expected steady flux is 0.33 s.d.
- The corresponding flux should be enhanced by a factor of 8 – 10 !

# *Max significance within 0.6 deg around Crab*

- **We found 1 day out of 1543 with statistical significance greater than that on day July 3rd, 2012**
- **The probability to find an event with maximum significance greater than 4.3 σ around the Crab region is 1/1543 = 6.5 × $10^{-4}$.**
- **The post-trial chance probability is ≈ $10^{-3}$**

## CONCLUSIONS

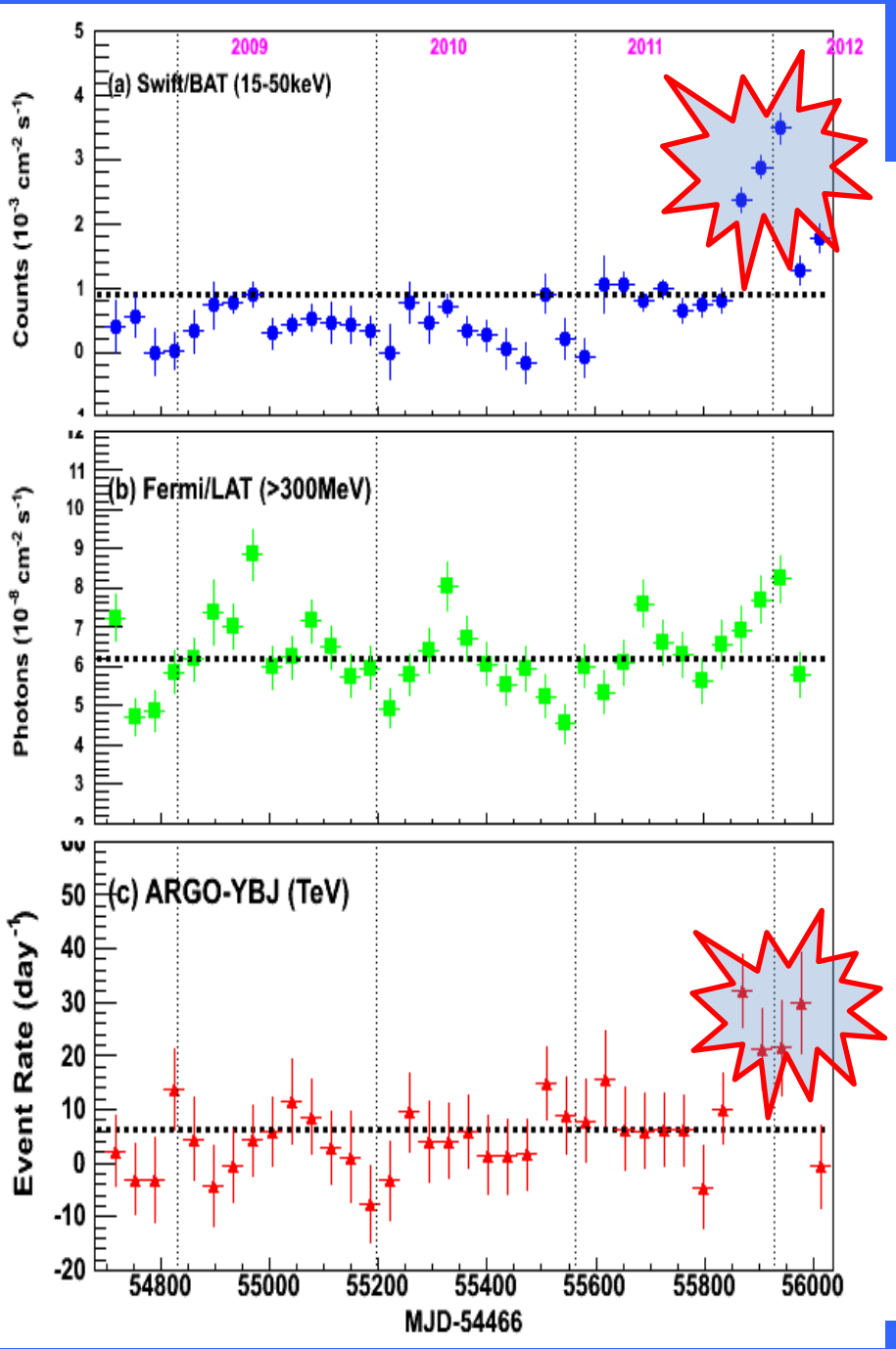
- **We observed marginal evidence (P≈ $2 \cdot 10^{-3}$ ) of 3 (out 4) TeV flux increases correlated to MeV-GeV Crab flaring activity.**

# *Mrk 501: l.t. monitor.*

**A strong X-ray flare in 1997 followed by a long "quiet" period**

**New strong X-ray flare 14 years later: Oct 2011**

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

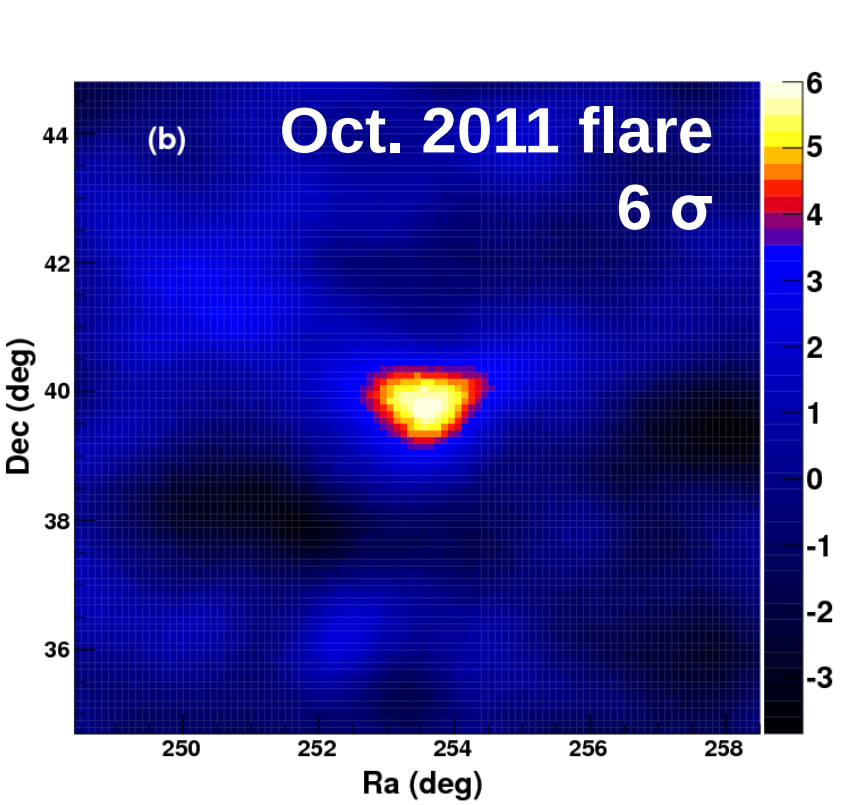


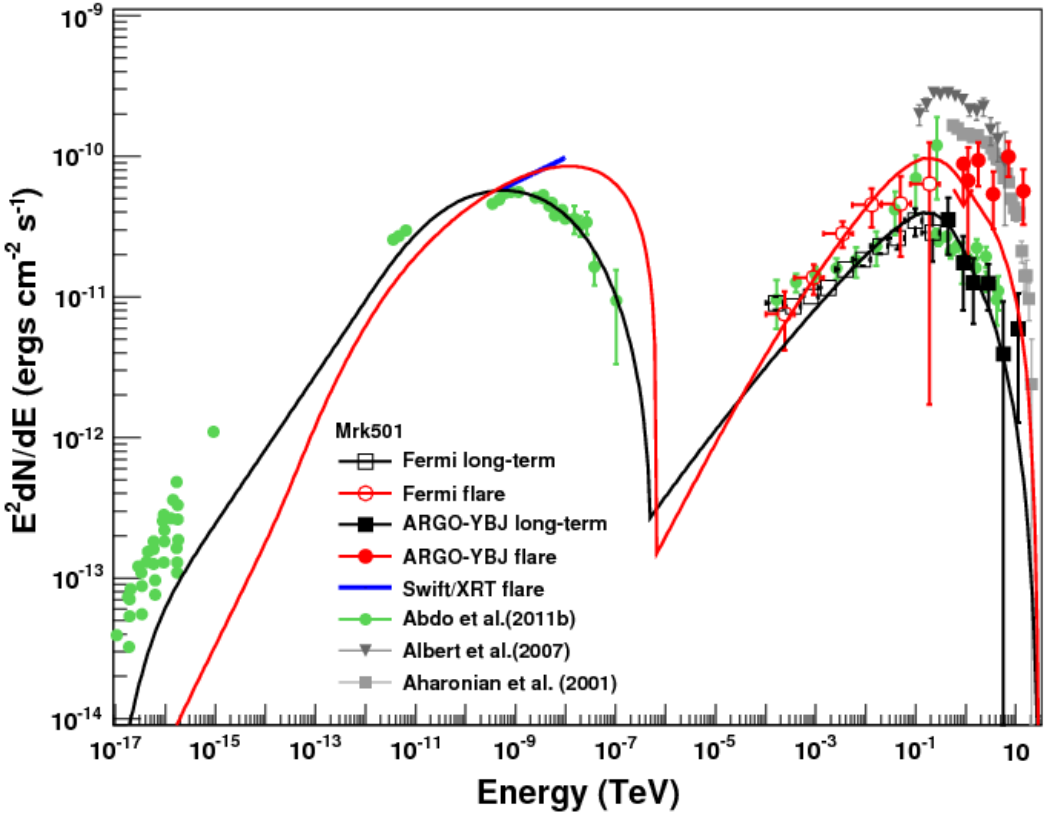
# Mrk 501: SED

- ✓ During the flare flux > 1 TeV a factor 6.6 above the steady emission
- ✓ For steady state, the SSC model is favored

ApJ 758 (2012) 2

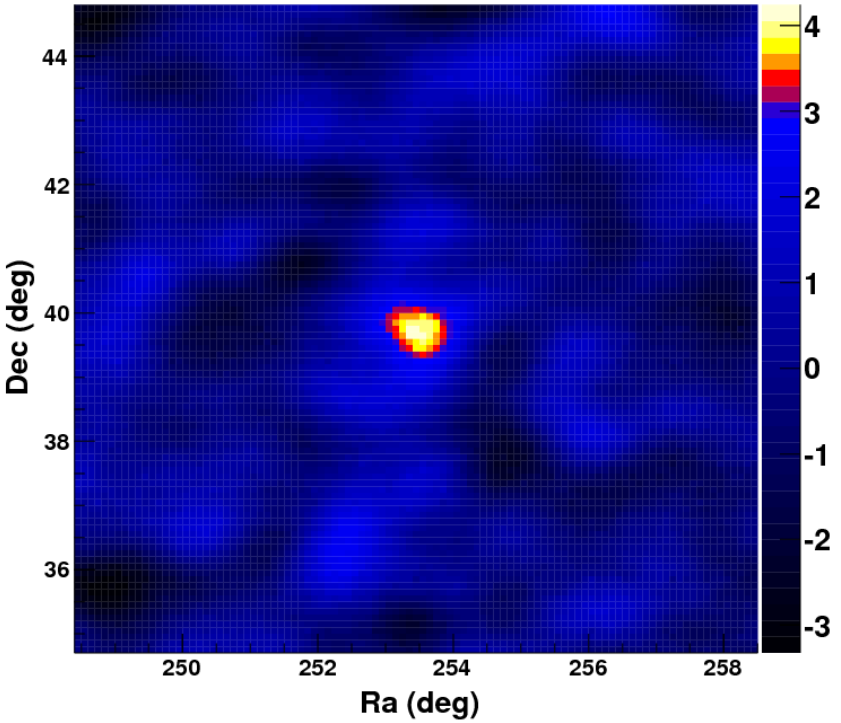
- ✓ During flare, the spectrum is hardened. Simple SSC model is not favored

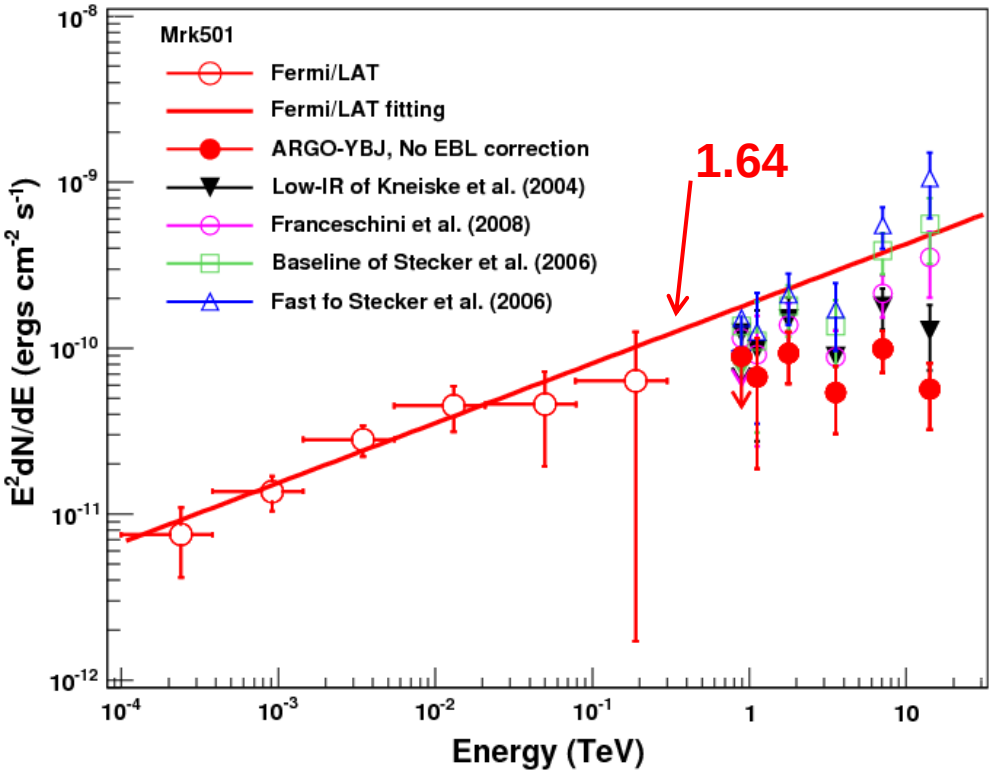


# *Mrk 501 and EBL*

**During the Oct 2011 flare ARGO-YBJ observed γ-rays > 8 TeV, which has not happened since the 1997 flare → it is possibile to test different EBL models assuming a minimum intrinsic photon spectral index (Fermi at GeV).**



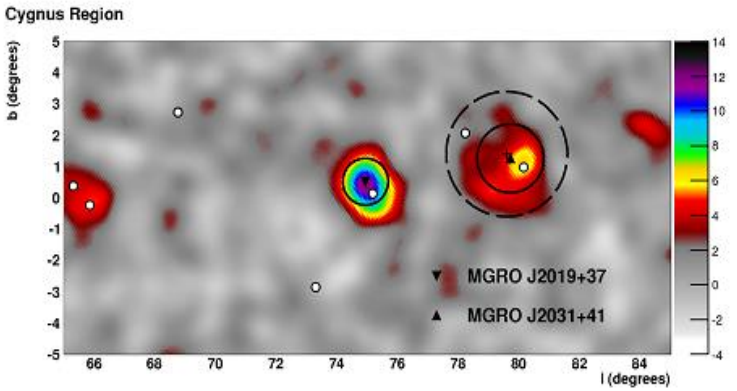




**The spectral shape in GeV/TeV favors the "low-IR" EBL model of Kneiske et al. (2004).**

# The Cygnus Region

**Very important region populated by many unidentified strong sources.**

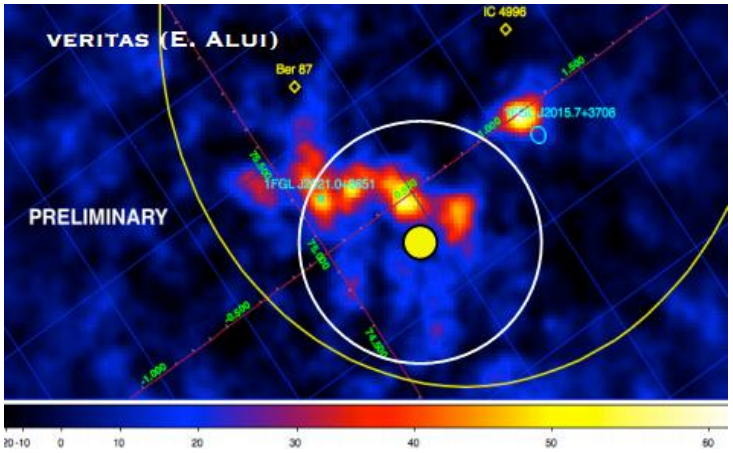
- **The brightest diffuse γ-rays source in the northern hemisphere**
- **9 supernova remnants**
- **>20 Wolf-Rayet starts**
- **6 OB associations**
- **shocked gas**
- ***natural site for cosmic-ray acceleration***




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

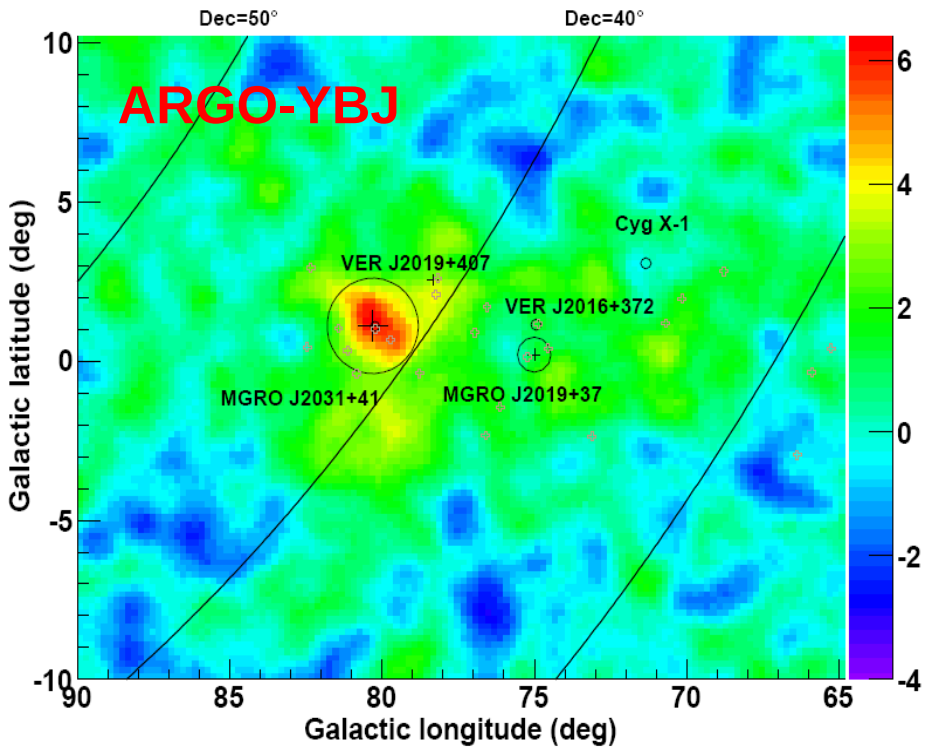
- **Both consistent with Fermi source locations**

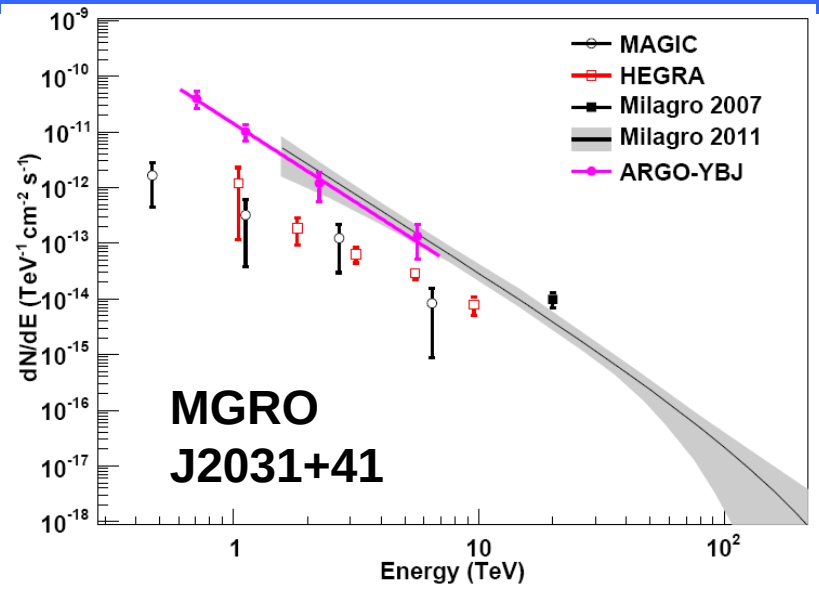
- **Complex emission observed by VERITAS consistent with location of MGRO J2019+37**

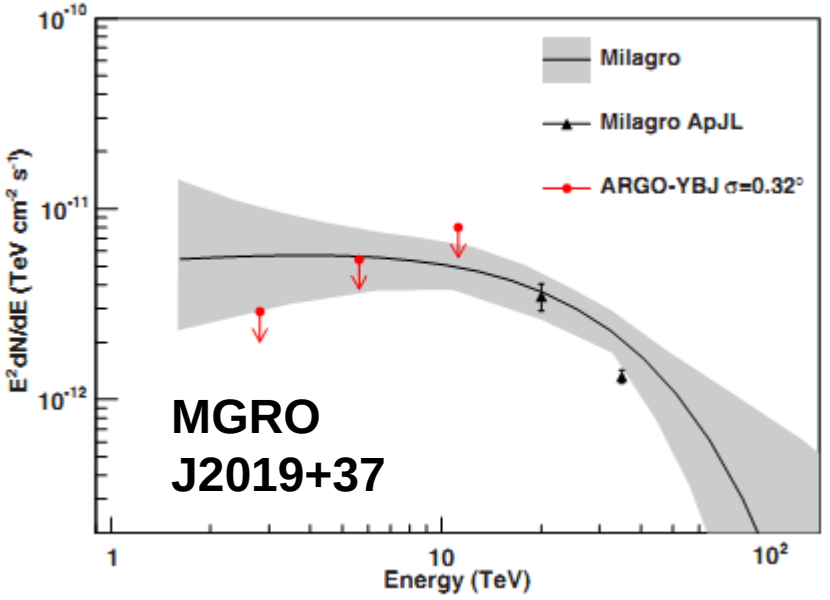


# The Cygnus Region: ARGO-YBJ

**ApJL 745 (2012) L22**



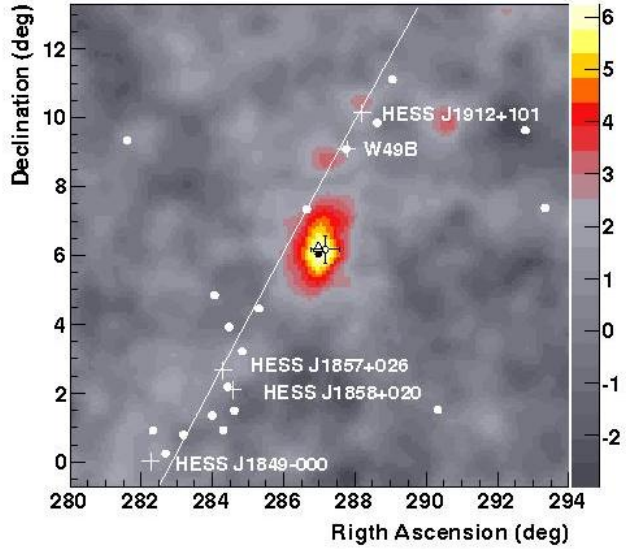



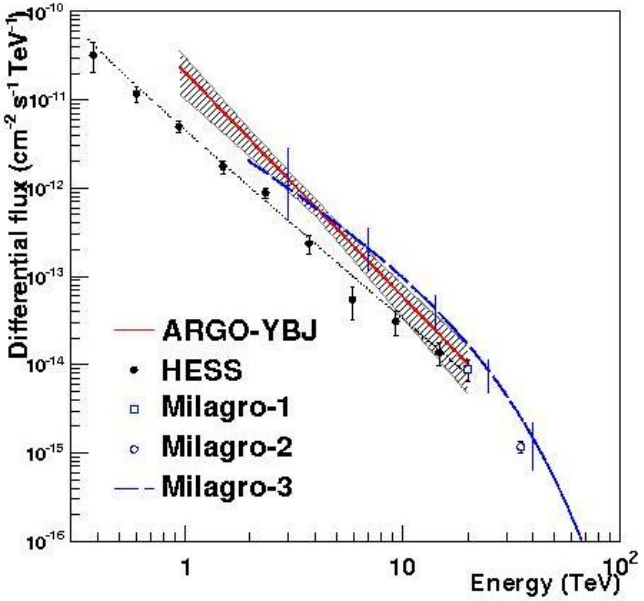




**NO signal from the MGRO J2019+37 below 10 TeV**

- ✓ **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**

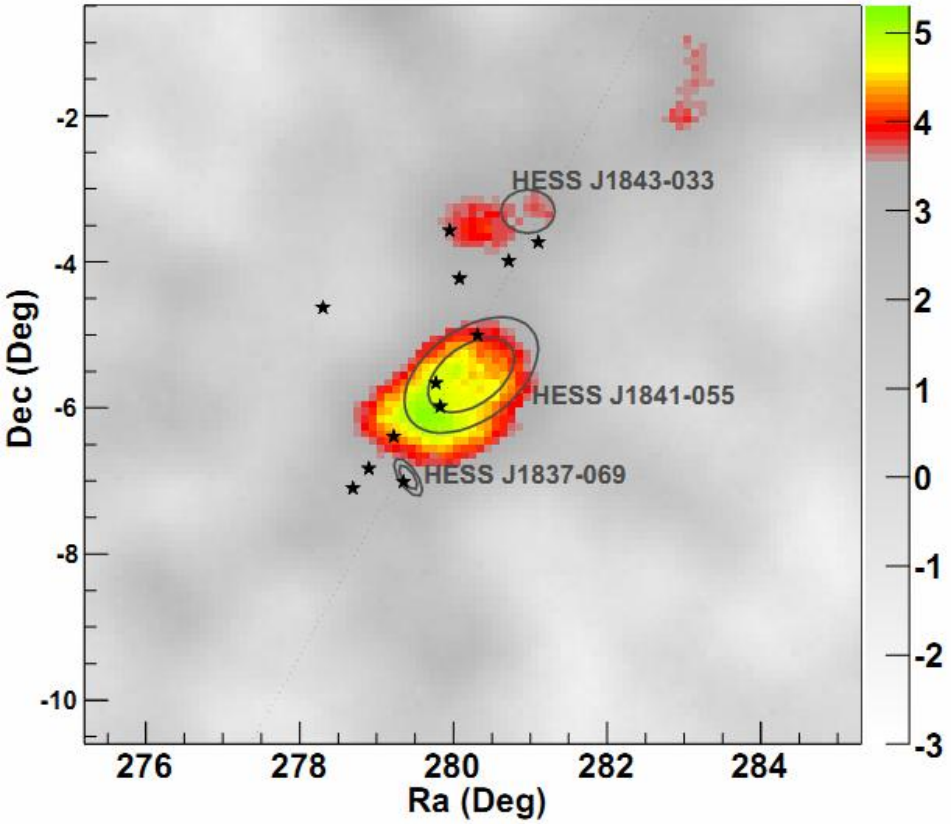
**Complex source morphology ?**
**Diffuse galactic flux contamination ?**
**Flux variability ?**

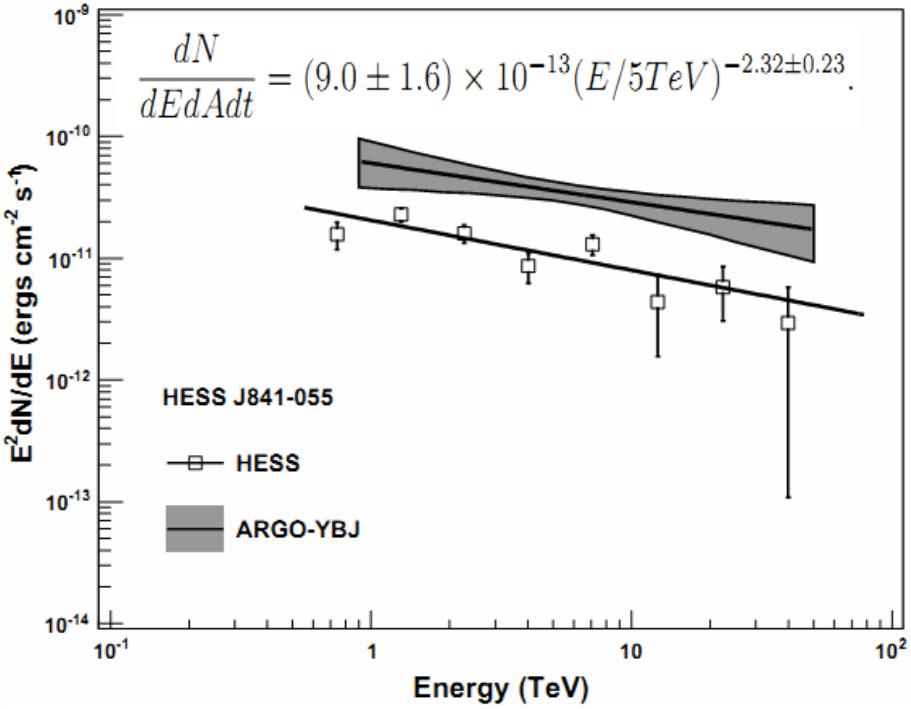
**Integrated luminosity above 1 TeV**
**~ 1.8 times the Crab luminosity**

# HESS J1841-055 region

**ARGO-YBJ observed TeV emission in the HESS J1841 region at about 5 s.d.**

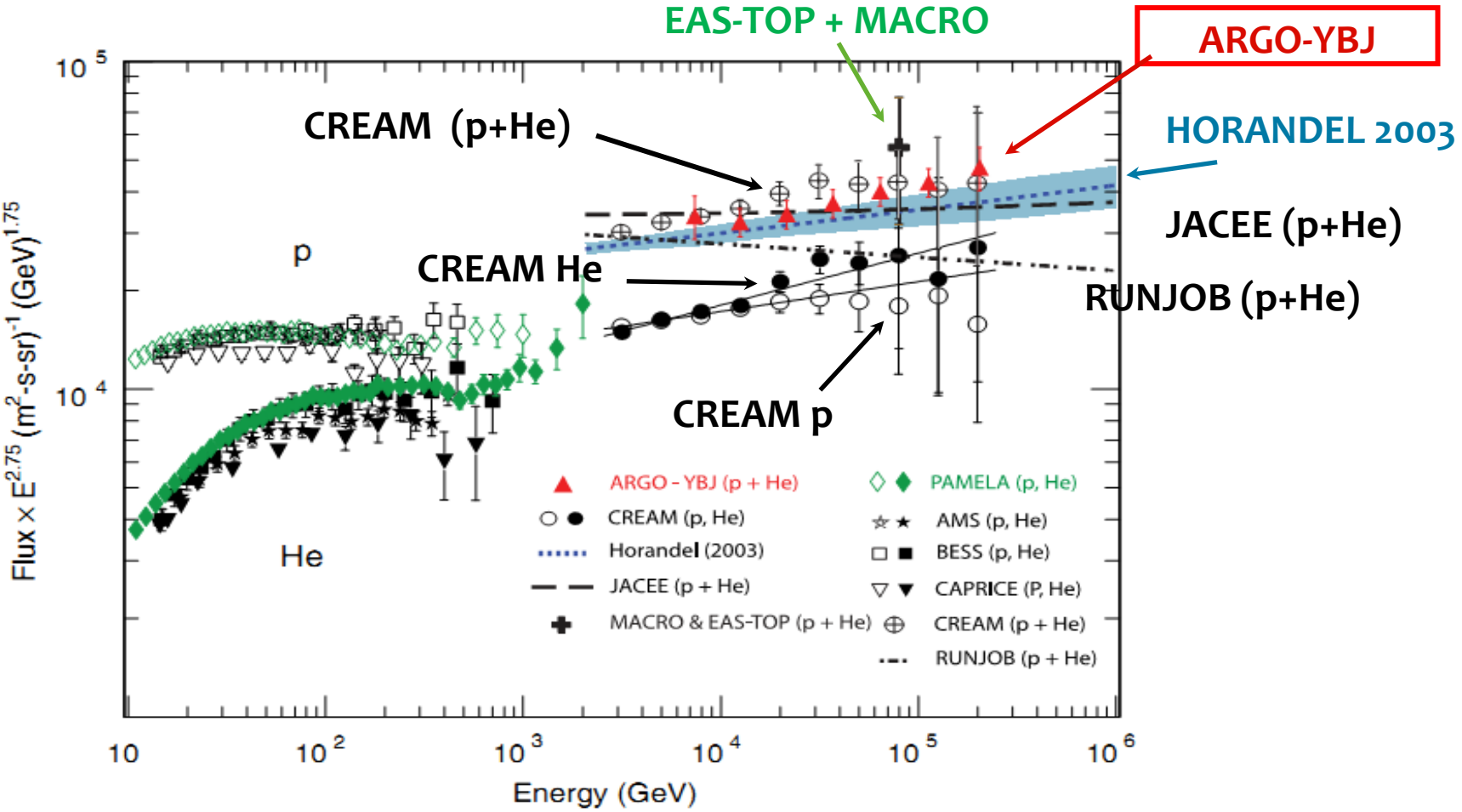
**Extended source: gaussian profile with σ = (0.49± 0.22)°**



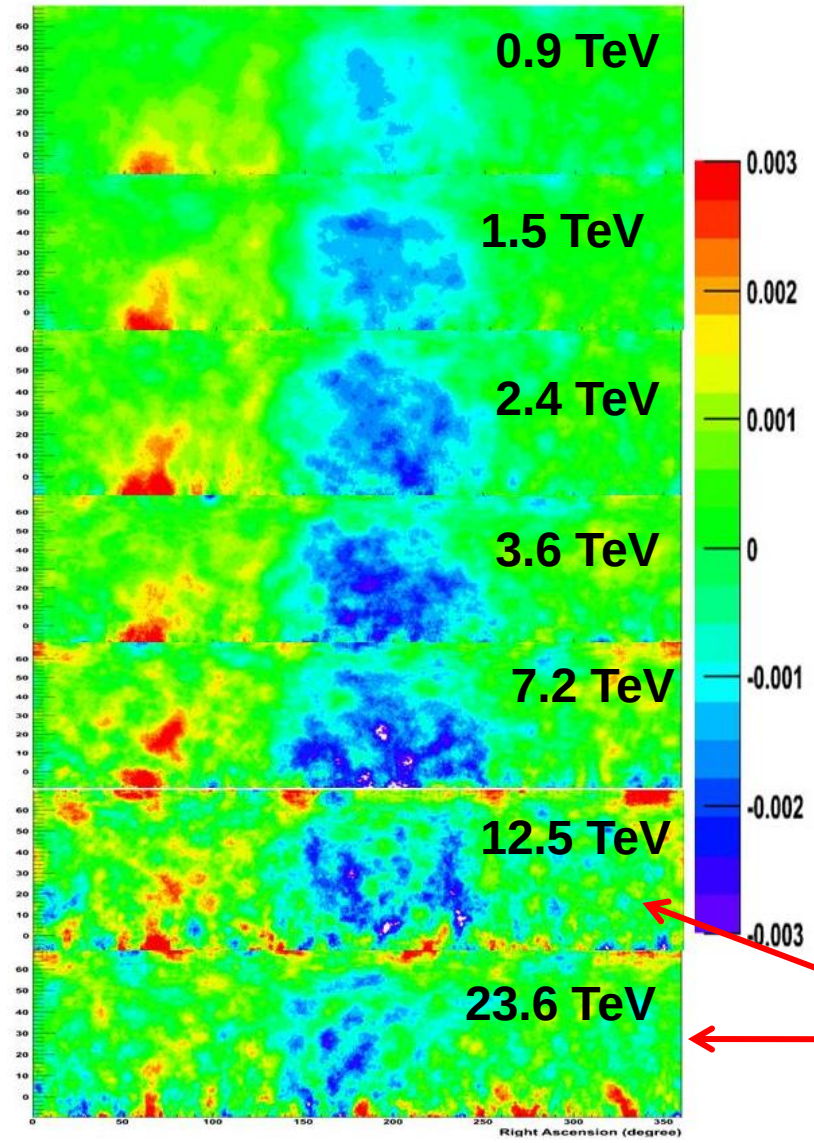

**The integral flux > 1 TeV is 1.28 ± 0.40 Crab unit, which is 3.2 ± 1.0 times the flux determined by H.E.S.S. , i.e. 0.40 Crab unit.**

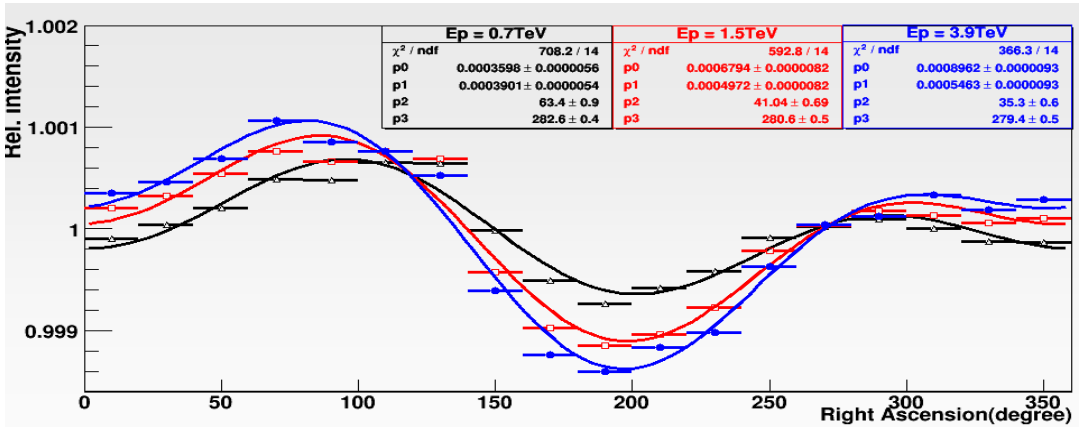
# Light-component (p+He) Energy Spectrum




**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.**

# Large Scale CR anisotropy vs Energy



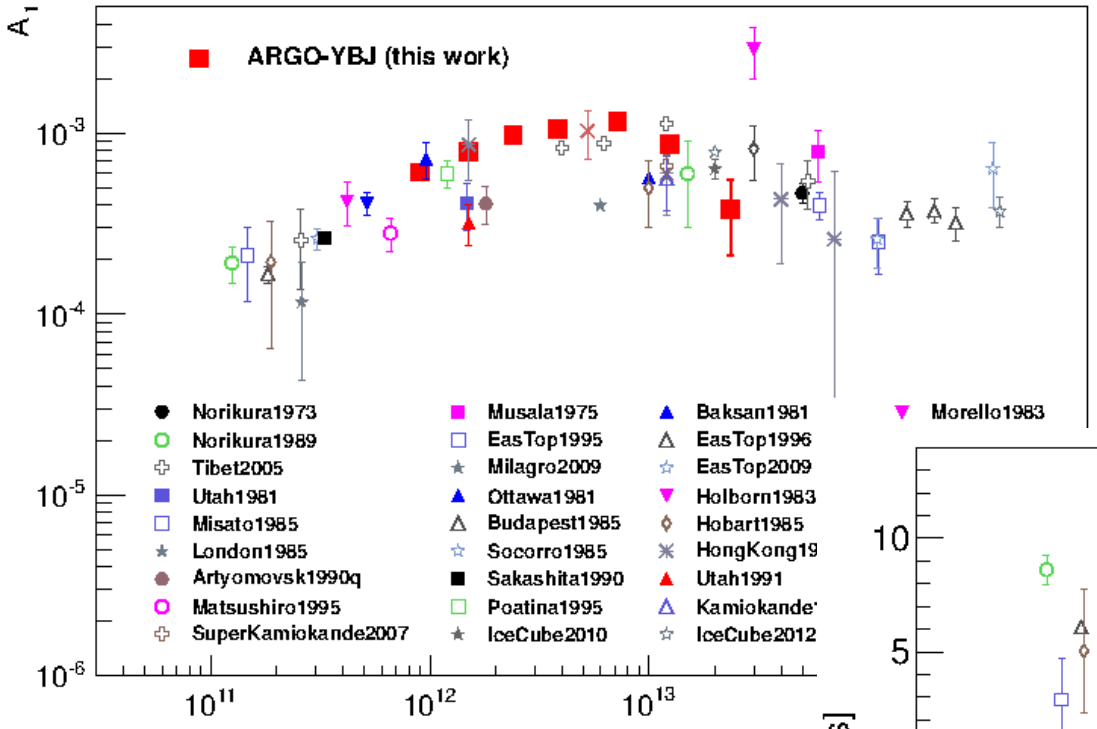




$$1 + A_1 cos(2\pi(x - \phi_1)/360) + A_2 cos(2\pi(x - \phi_2)/180)$$

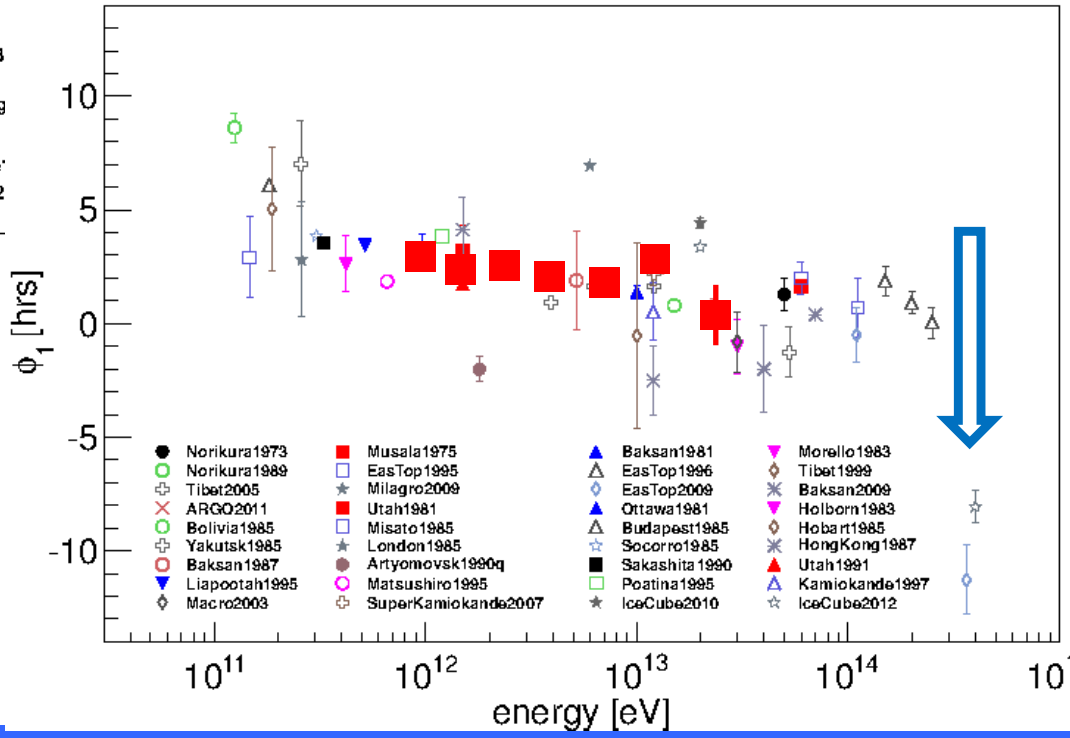
**First measurement with an EAS array in an energy region so far investigated only by underground muon detectors**

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

# 1st harmonics amplitude and phase




**Measurement covering either the rise and the fall of the signal**




**Uniform phase decrease**

# Medium Scale Anisotropy by ARGO-YBJ

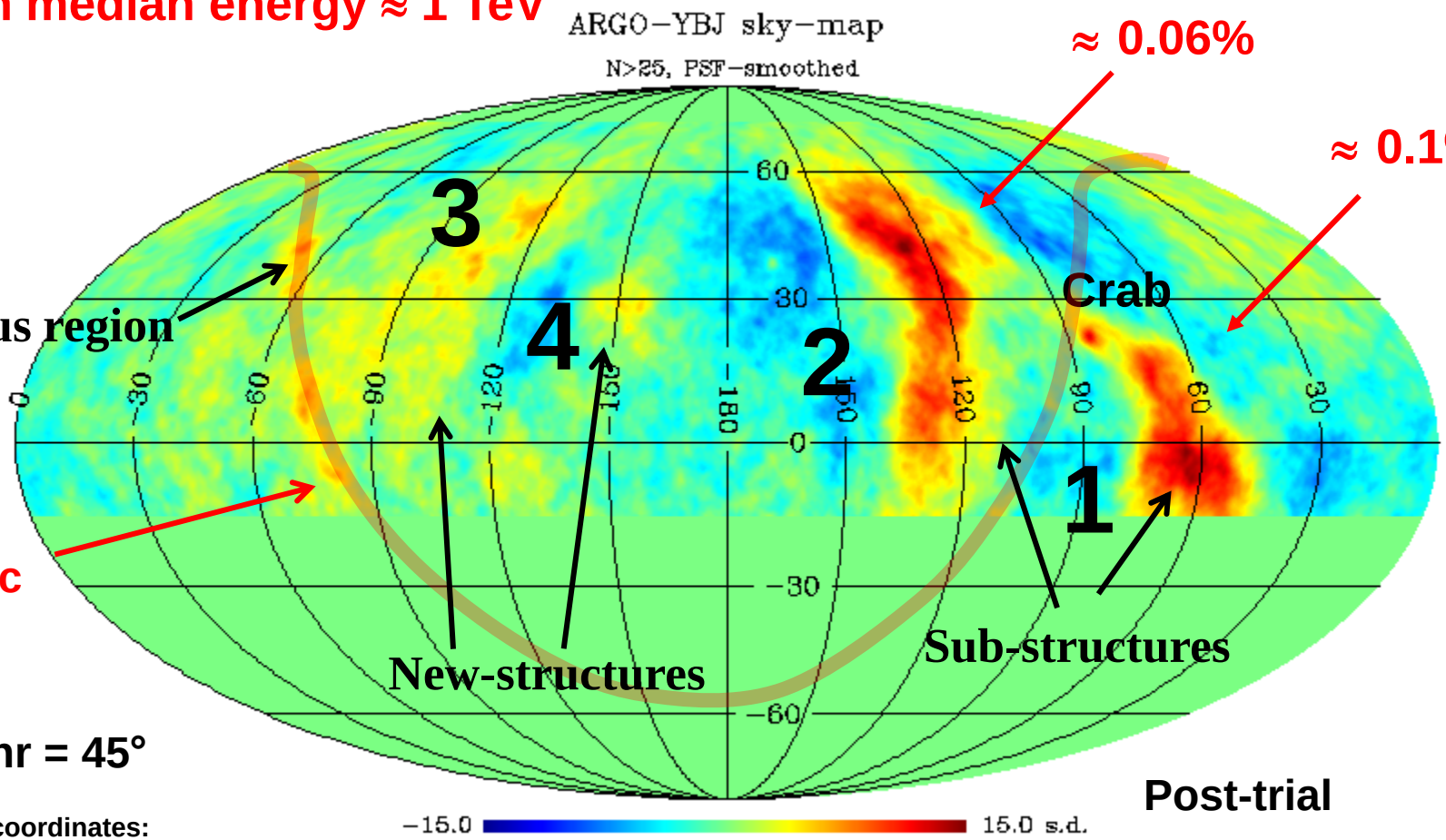
**Map smoothed with the detector PSF for CRs**

**Proton median energy ≈ 1 TeV**

**Cosmic rays excess**

**≈ 0.06%**

**≈ 0.1%**




**$\Delta t$ = 3 hr = 45°**

**Post-trial**

**Equatorial coordinates:**
**projection of the earth longitude and latitude**

# *Conclusions*

- **First Northern sky map (> $10^5$ pixels, -10° < δ < 70° ) at 0.3 Crab Units.**
- **Evidence of 3 TeV Crab flares in correlation with AGILE/Fermi data.**
- Long term monitoring of Crab Nebula, Mrk421, Mrk501, MGRO J2031+41, MGRO J1908+06, HESS J1841-55. Observation of different glares in correlation with RXTE/ASM , SWIFT/BAT and Fermi data.
- **Extended sources fluxes >> fluxes measured by Cerenkov Telescopes**
- Study of the largest sample of GRBs investigated by a ground-based detector. Fluence upper limits down to $\approx 10^{-5}$ erg/cm$^2$ in the 1–100 GeV energy range
- 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.
- **Observation of 4 regions of medium scale CR anisotropy.**

# *Backup*

# The basic concepts

*…for an unconventional air shower detector*

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

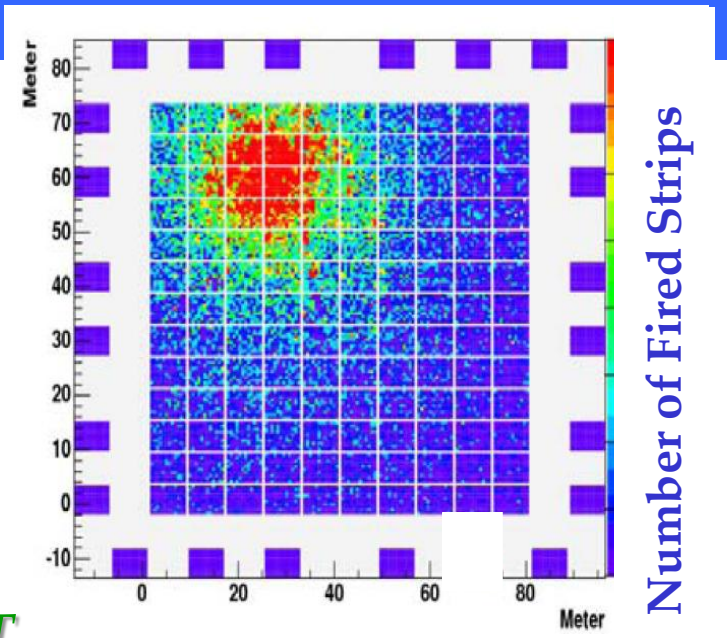
- ***FULL COVERAGE***
  **(RPC technology, 92% covering factor)**

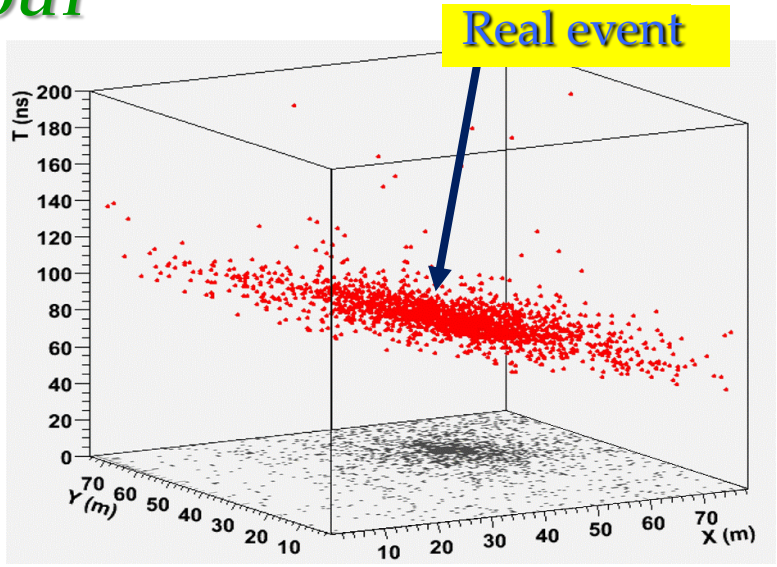
- ***HIGH SEGMENTATION OF THE READOUT***
  **(small space-time pixels)**

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

**… in order to:**

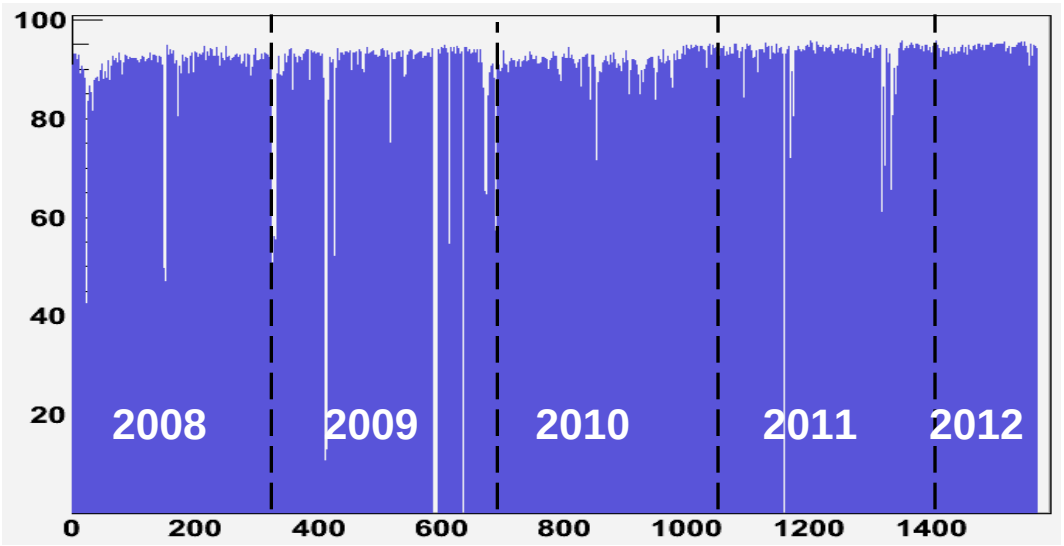
- **image the shower front**
- **get a energy threshold of a few hundreds of GeV**

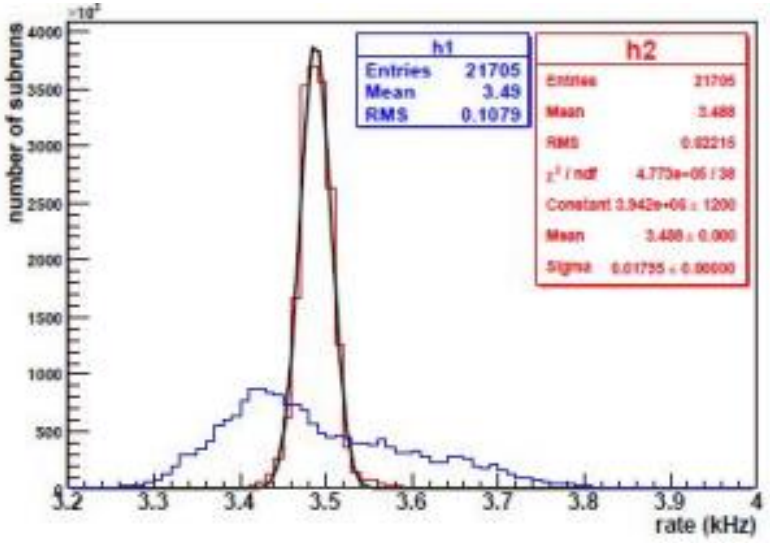


# Current Status

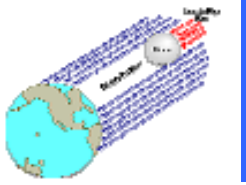
- In observation since July 2006 (commissioning phase)
- Stable data taking since November 2007
- The average duty cycle ~ 87%, dead time 4%
- Trigger rate ~3.5 kHz @ 20 pad threshold
- N. recorded events: ≈ $4 \cdot 10^{11}$ from 300 GeV to PeV



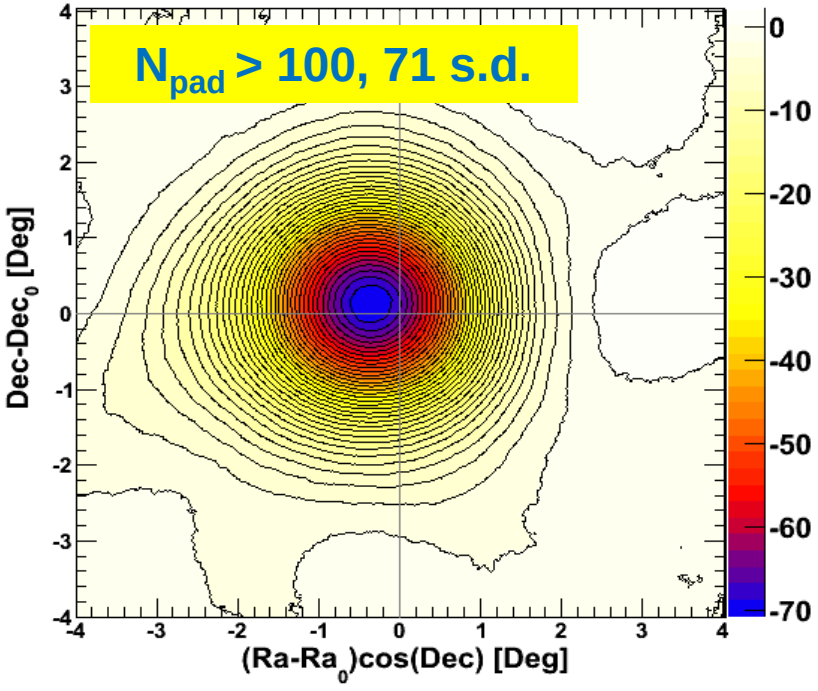



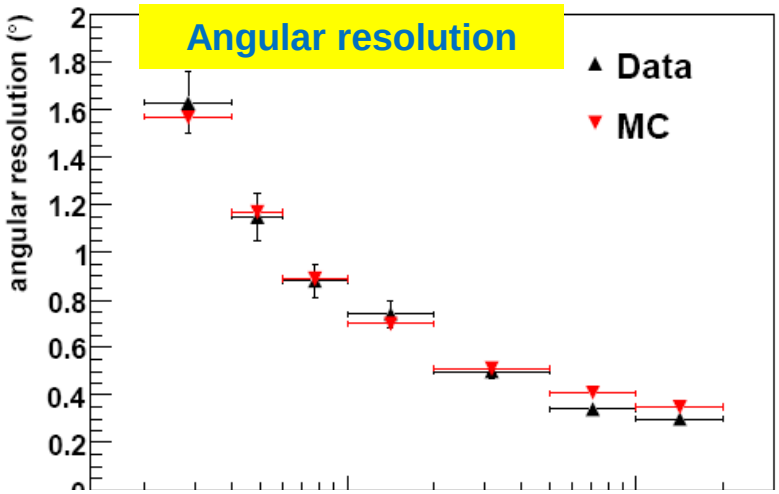

**Intrinsic Trigger Rate stability 0.5%**
(after corrections for T/p effects)

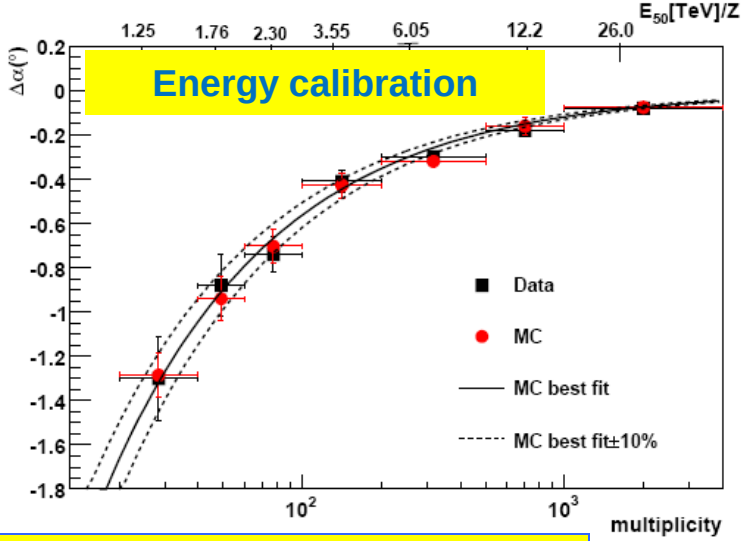
# Moon shadow analysis



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



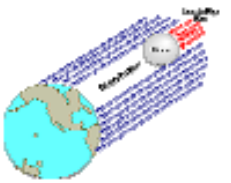




PRD 84 (2011) 022003
PRD 85 (2012) 022002

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%