Results from the ARGO-YBJ experiment at high altitude

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on behalf of the ARGO-YBJ collaboration

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SciNeGHE 2009

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The ARGO-YBJ Experiment

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
ZhengZhou University, ZhengZhou
Hong Kong University, Hong Kong

Outlook

- Introduction
- ARGO-YBJ detector features and performance
- γ-ray astronomy with ARGO-YBJ
- Cosmic-ray astronomy with ARGO-YBJ
- Conclusions

Basic concepts

for an unconventional air shower detector

- HIGH ALTITUDE SITE (YBJ, 4300 m a.s.l)
- FULL COVERAGE (RPC technology, 92%)
- HIGH SEGMENTATION → see next slides

… in order to:

✓ image the shower front

✓reach an energy threshold of a few hundreds of GeV


ARGO 实验厅

Current status

- Data taking since November 2007
- Duty cycle ~ 90%
- Trigger rate 3.6 kHz
- Dead time 4%
- 220 GB/day transferred to CNAF

Physical Goals

multi-purpose experiment

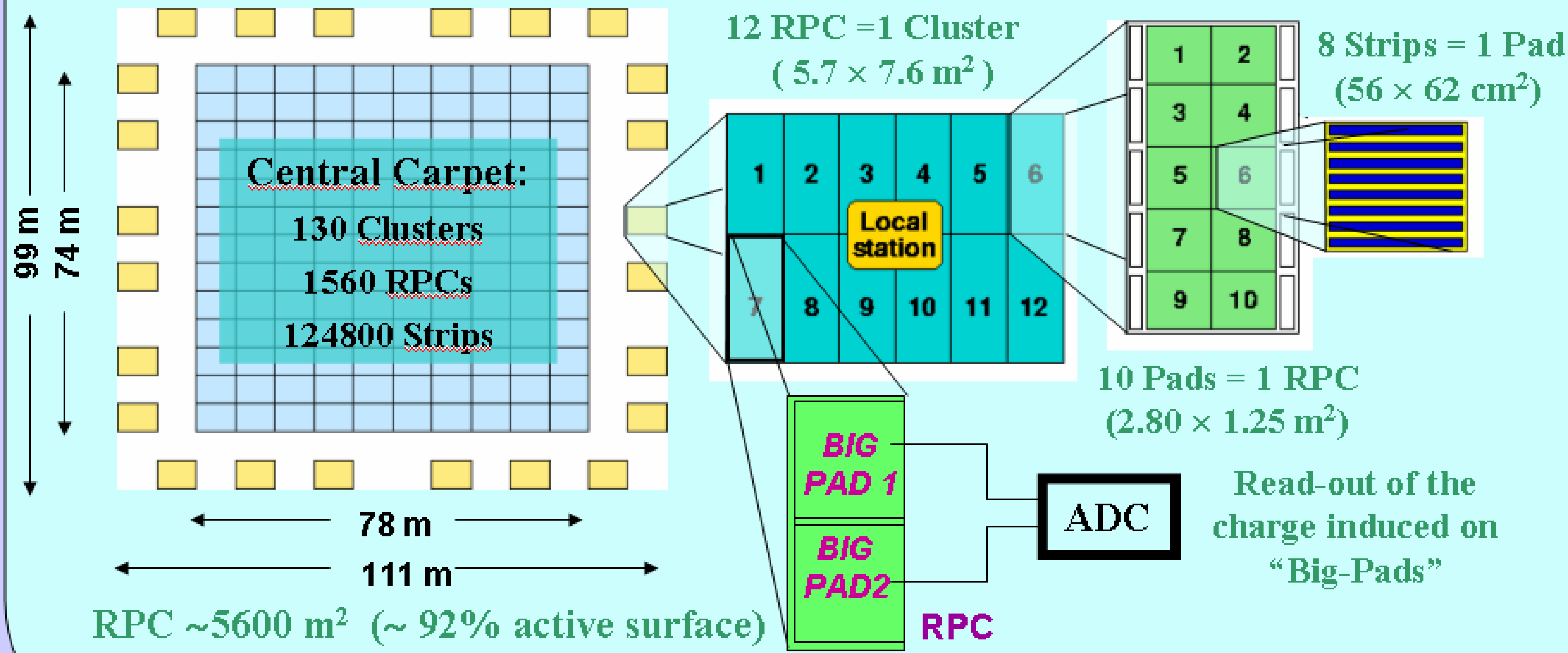
- Sky survey $-10° < \delta < 70°$ (γ-sources, anisotropies)
- High exposure for flaring activity (γ-sources, GRBs, solar flares)
- C.R. 1 TeV → 10^4 TeV
  - Helium spectrum
  - Proton "*knee*"
  - Knee region
- $\bar{p}/p$ at TeV energies
- hadronic interactions

by 2 operation modes:

- scaler mode (counting rate, > 1 GeV)
- shower mode (full reconstruction, > 300 GeV)

The ARGO-YBJ detector

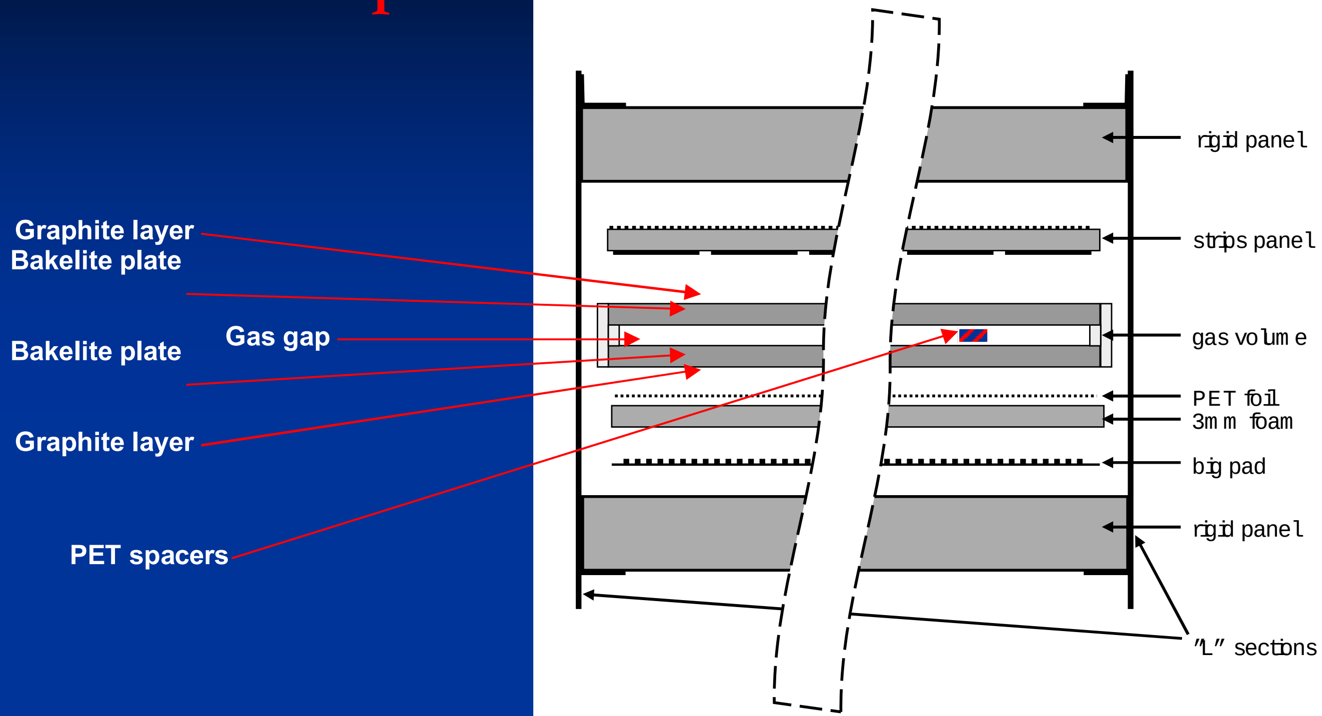
Gas Mixture: Ar/ Iso/TFE = 15/10/75



RPC ~5600 m² (~ 92% active surface)

• sampling guard-ring

The ARGO detector: operate



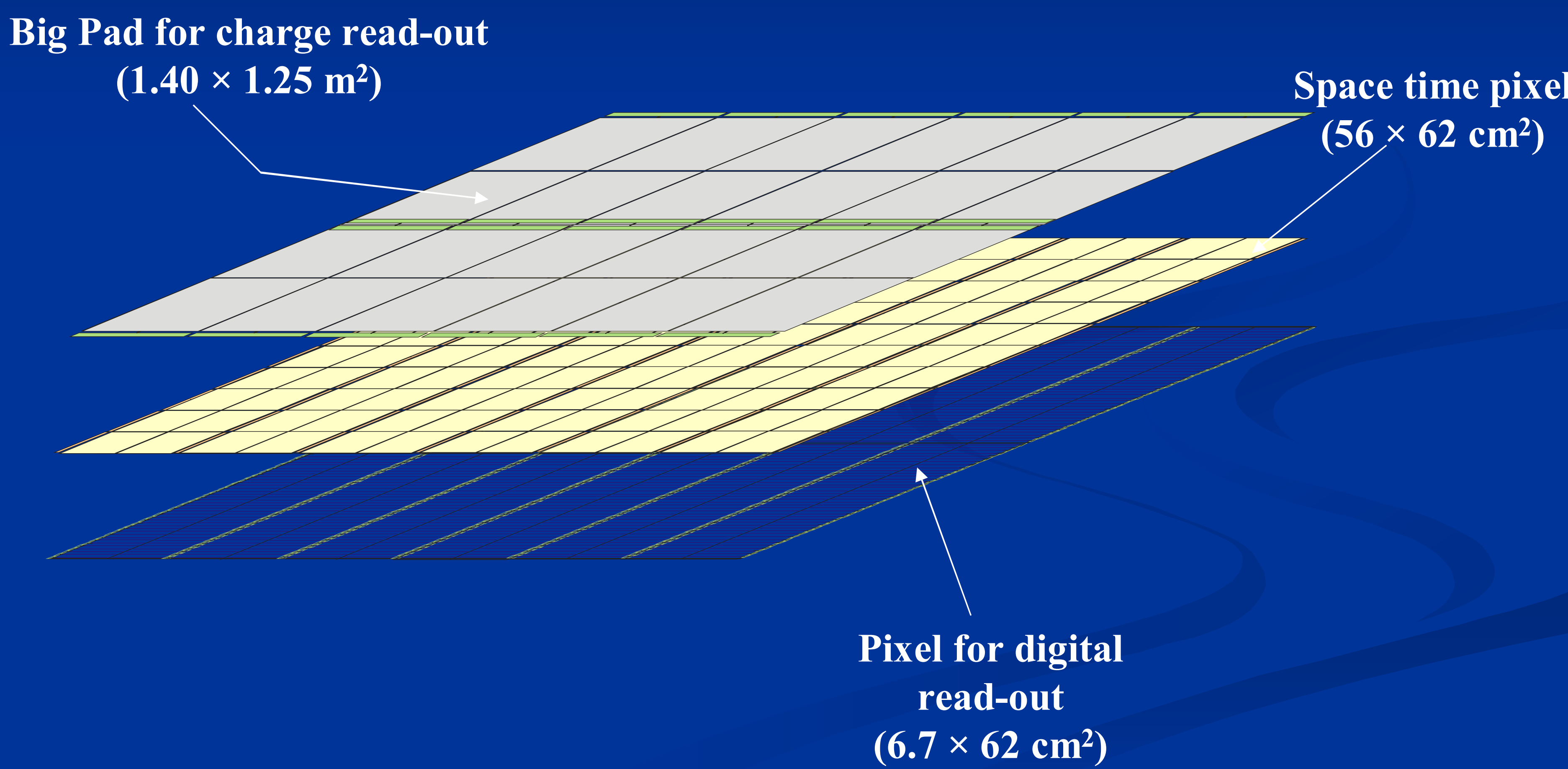
Gas mixture: Ar / i-C_4H_{10} / $C_2H_2F_4$ = 15/10/75

Operating voltage = 7.2 kV (10.2 kV at sea level)

Single RPC absorption current @ 7.2 kV = 3 - 4 μA

Single RPC count rate @ 7.2 kV = 4 kHz

Digital and analog read-out



Operation Modes

Shower Mode:

- Detection of *Extensive Air Showers* (direction, size, core …)
  Trigger : minimum number of fired pads within 420 ns
  $\geq$ 20 fired pads on the central carpet: rate ~3.6 kHz

  Aims:
  - cosmic-ray physics (above ~1 TeV)
  - VHE γ-astronomy (above ~300 GeV)

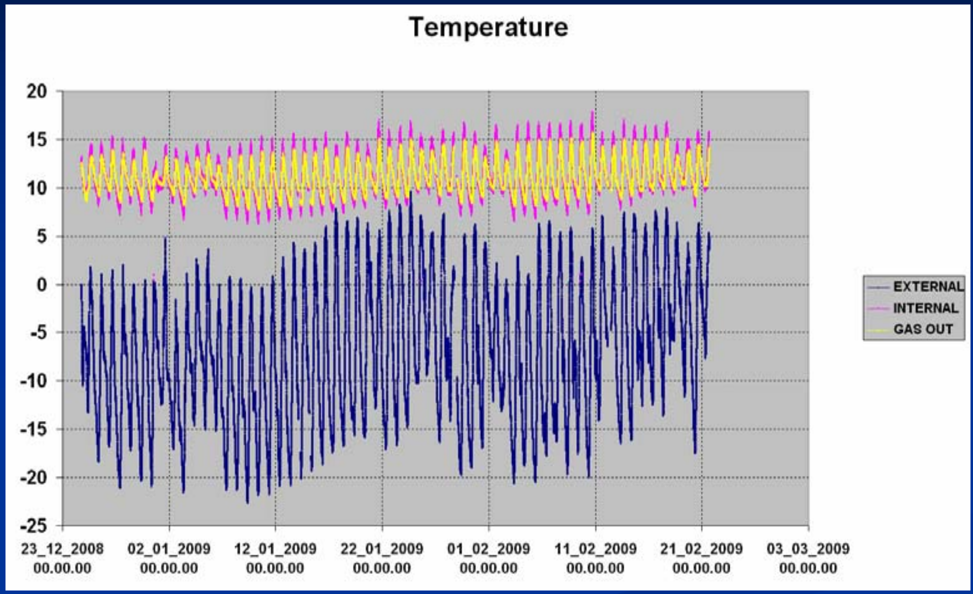
Scaler Mode:

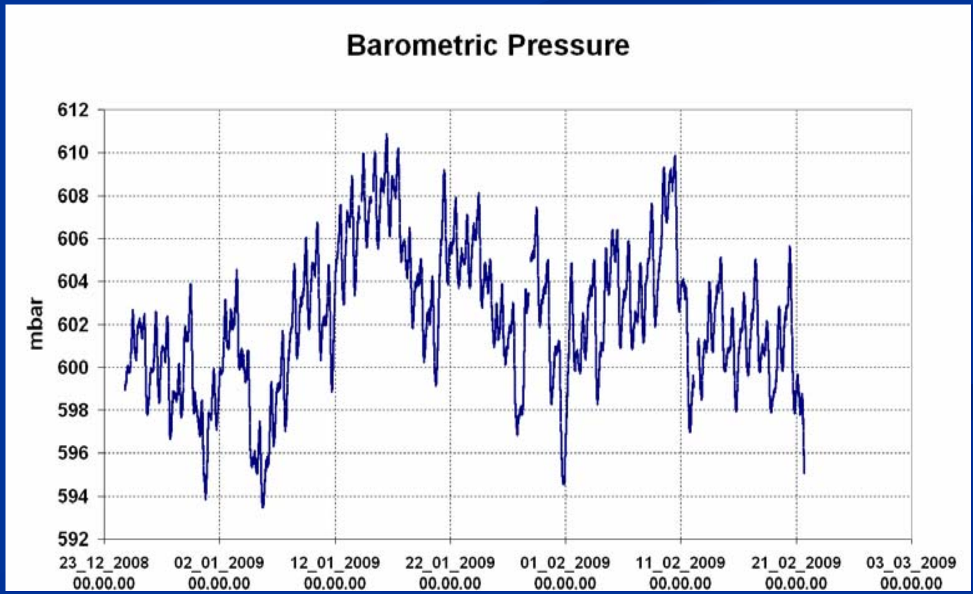
- Recording the counting rates ($\mathbf{N_{hit} \geq 1, \geq 2, \geq 3, \geq 4}$) for each cluster at fixed time intervals (every 0.5 s) lowers the energy threshold down to $\approx$1 GeV

  Aims:
  - flaring phenomena (high energy tail of GRBs, solar flares)
  - detector and environment monitor

Environmental Parameters

- All the parameters relevant to the detector operation are regularly monitored: temperature, pressure, etc.

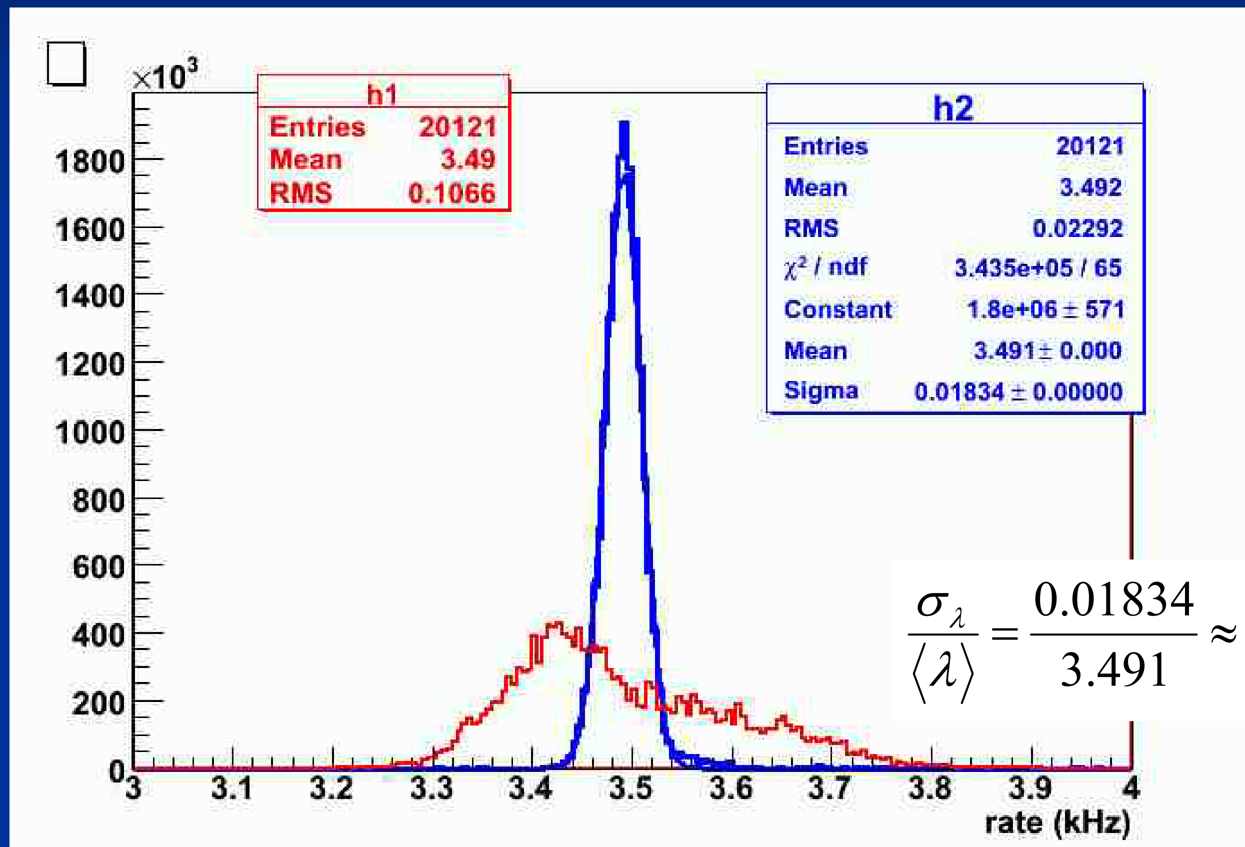




Detector stability

Accounting for the monitored changes in the atmospheric pressure the trigger rate is pretty stable, with relative fluctuation

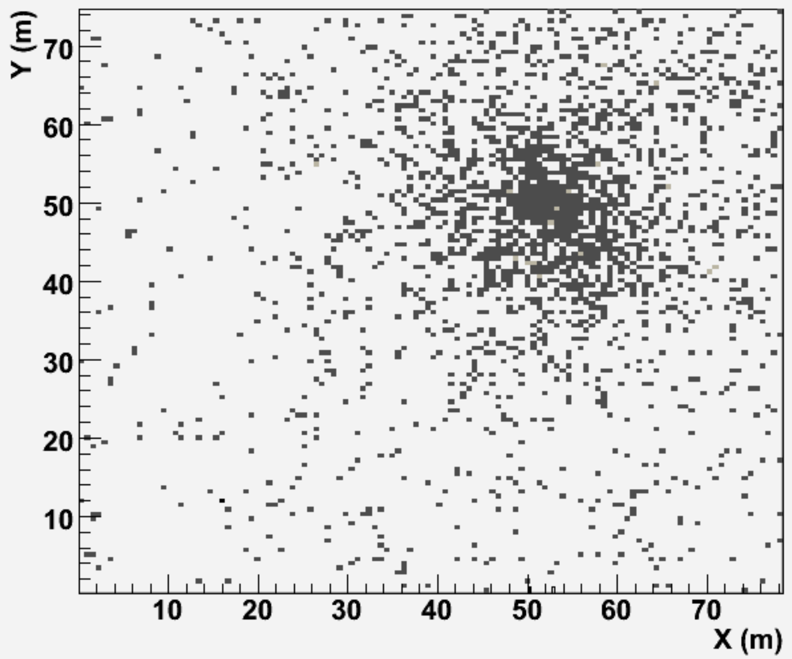
~ 0.5% @ 1σ



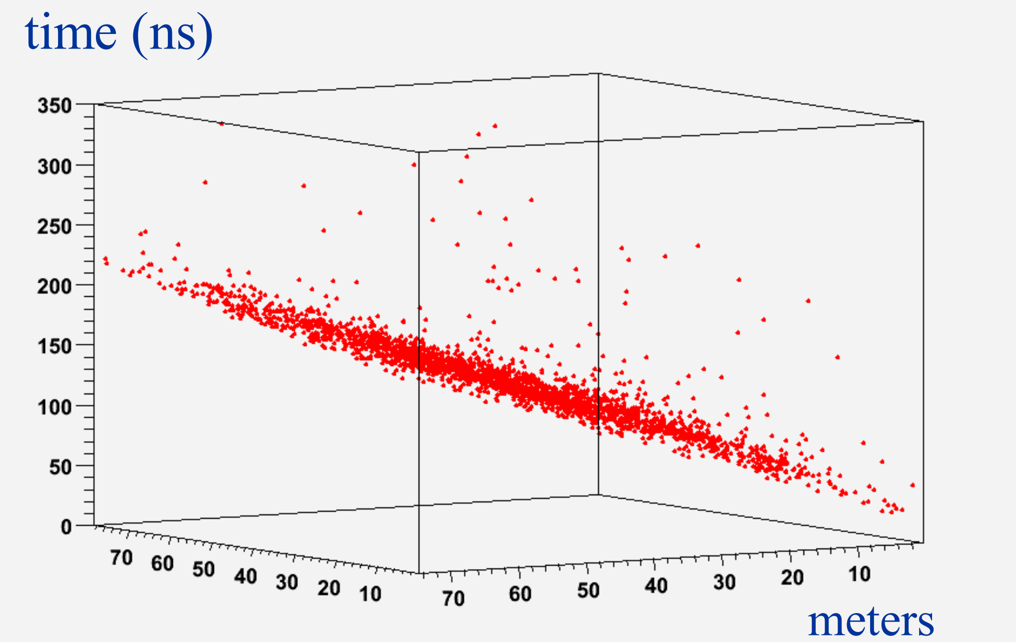
$$\frac{\sigma_\lambda}{\langle\lambda\rangle} = \frac{0.01834}{3.491} \approx 0.53\%$$

Shower reconstruction

Fired pads on the carpet



Arrival time vs position

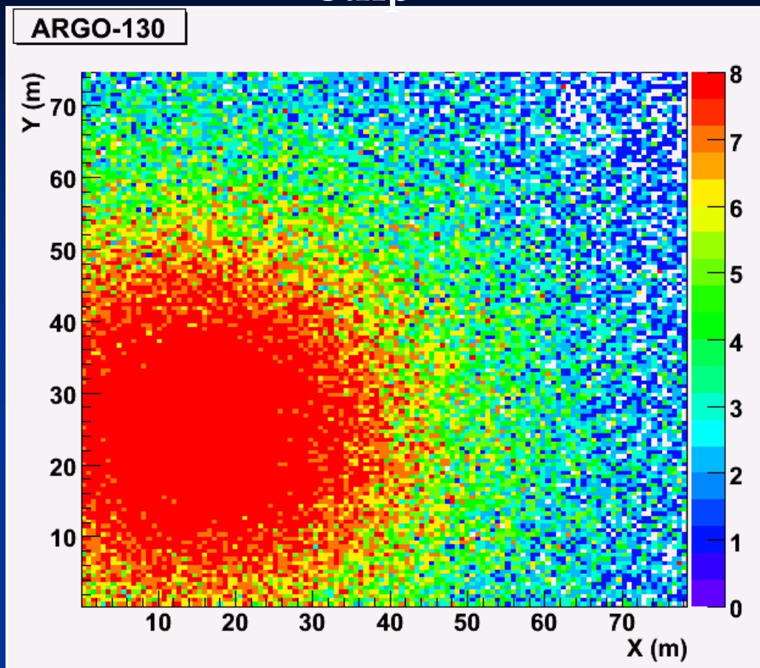


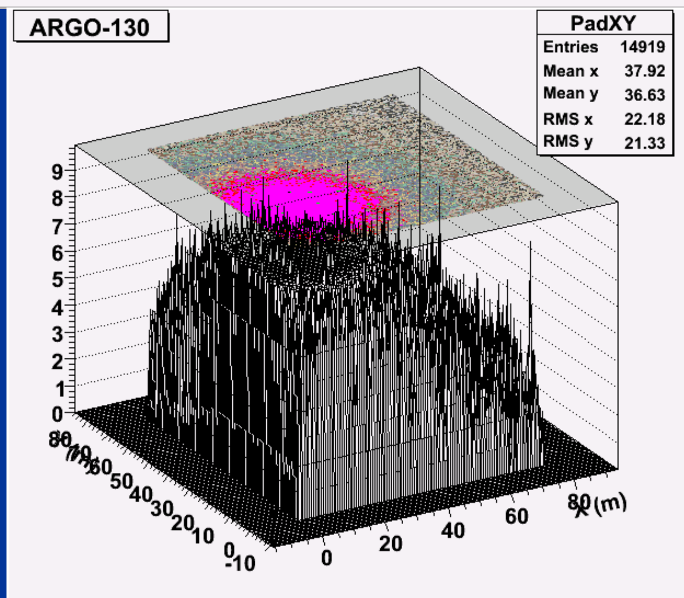
Arrival direction measurement:

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

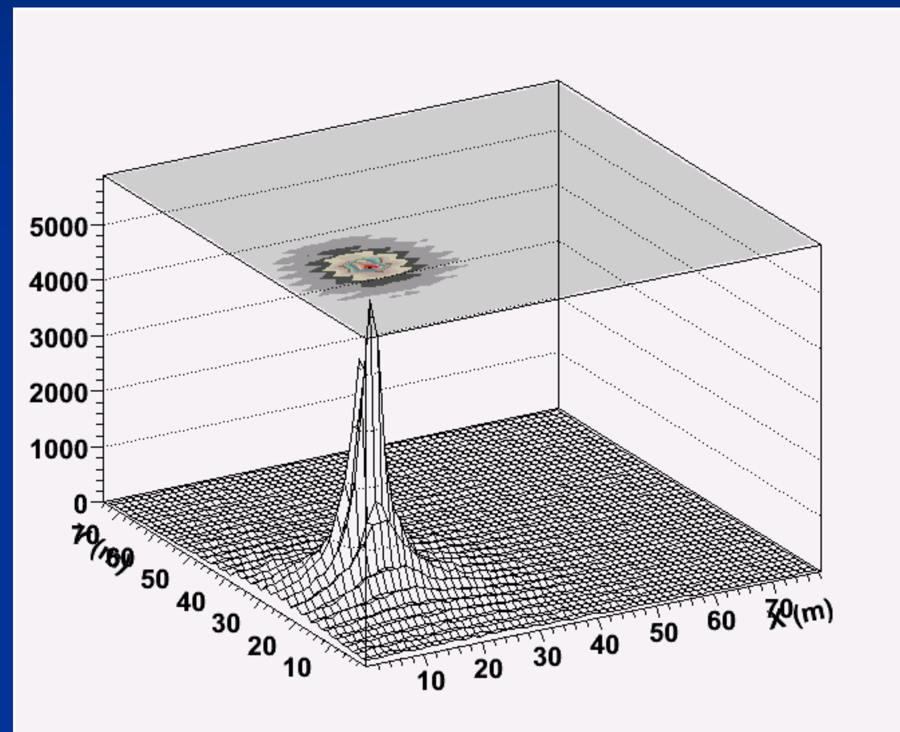
Analog readout

Strip





E ~ 1000 TeV



Big Pad

This will extend the dynamics of the detector up to and beyond 1 PeV

γ astronomy

- Crab
- Mrk 421
- Sky survey/galactic plane

no γ/h discrimination applied so far

Sources at > 3 σ

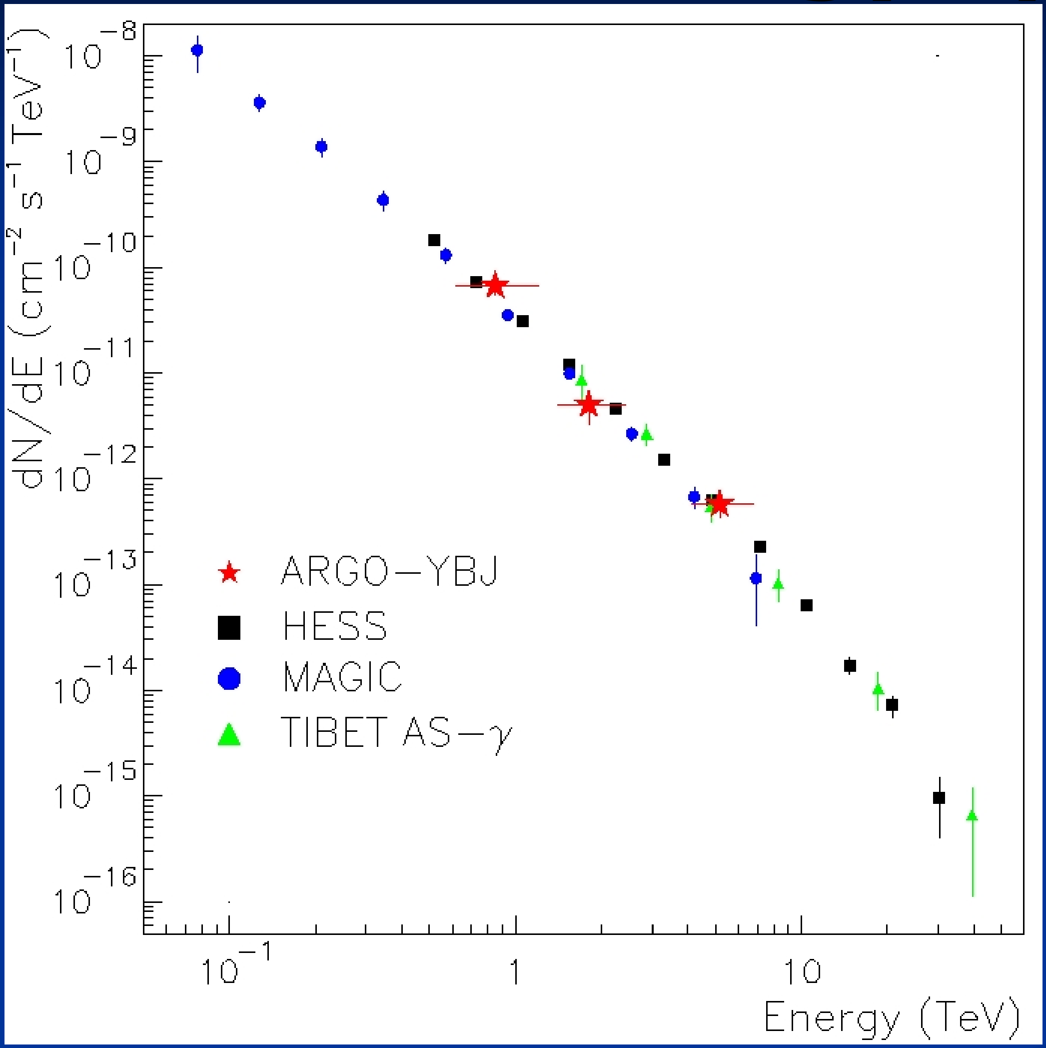
Galactic

- Crab 7.8 σ
- MGRO J2031+41 (LAT pulsar) 3.6 σ
- PSR J2021+4026 (LAT pulsar, gamma Cygni SNR) 3.5 σ
- HESS J1841-055 (unidentified) 3.2 σ

Extragalactic

- Mrk421 7.5 σ
- Blazar B3 0650+453 (FSRQ z=0.993) 3.2 σ

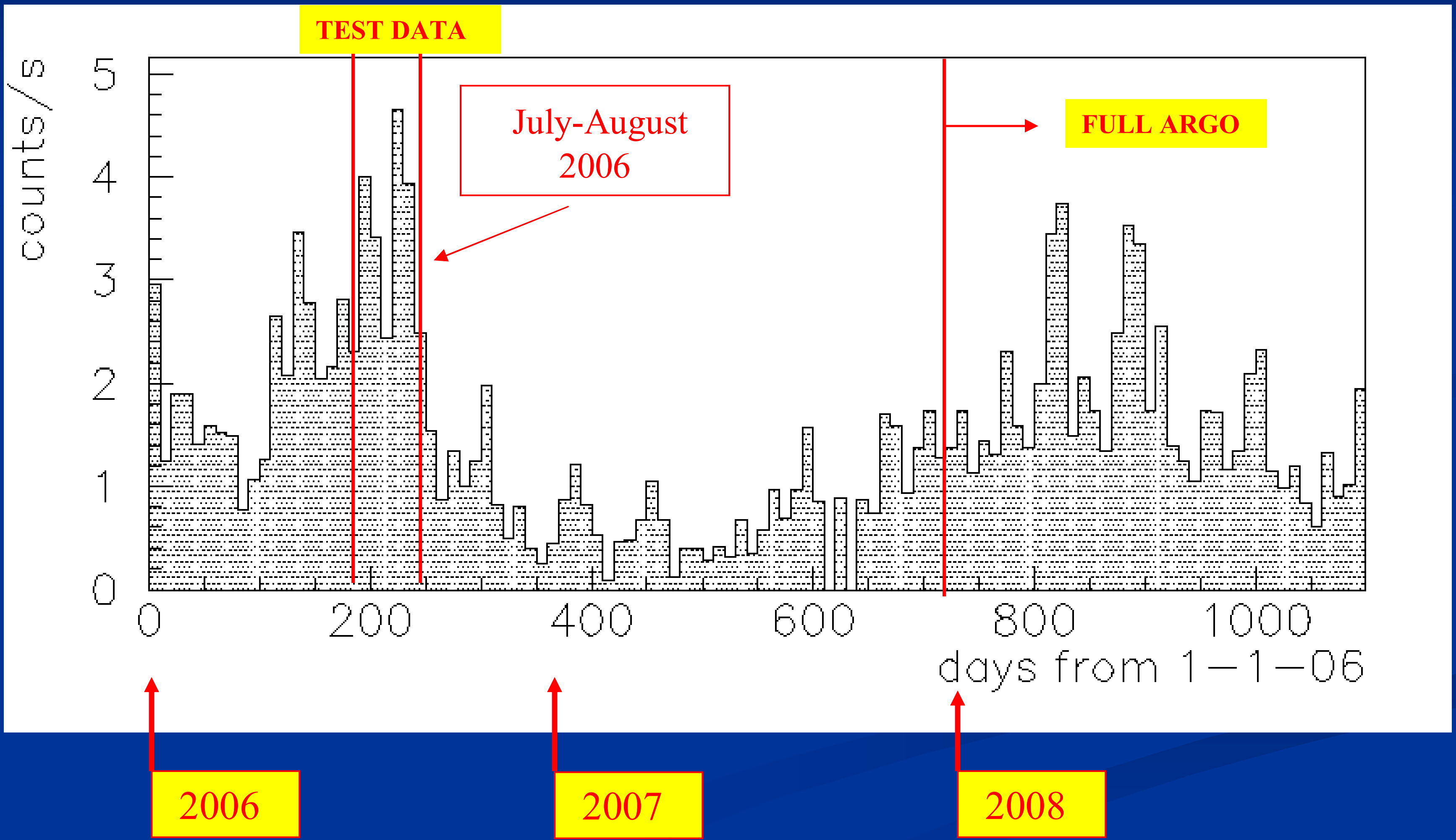
Crab energy spectrum



N_{PAD}	Events /day	E_{med} (TeV)
40 – 100	128 ± 24	0.85
100 – 300	17.9 ± 6.3	1.8
> 300	9.2 ± 2.3	5.2

$$dN/dE = (3.73 \pm 0.80)\cdot 10^{-11}\ E^{-2.67 \pm 0.25}\ \text{ev cm}^{-2}\ s^{-1}\ \text{TeV}^{-1}$$

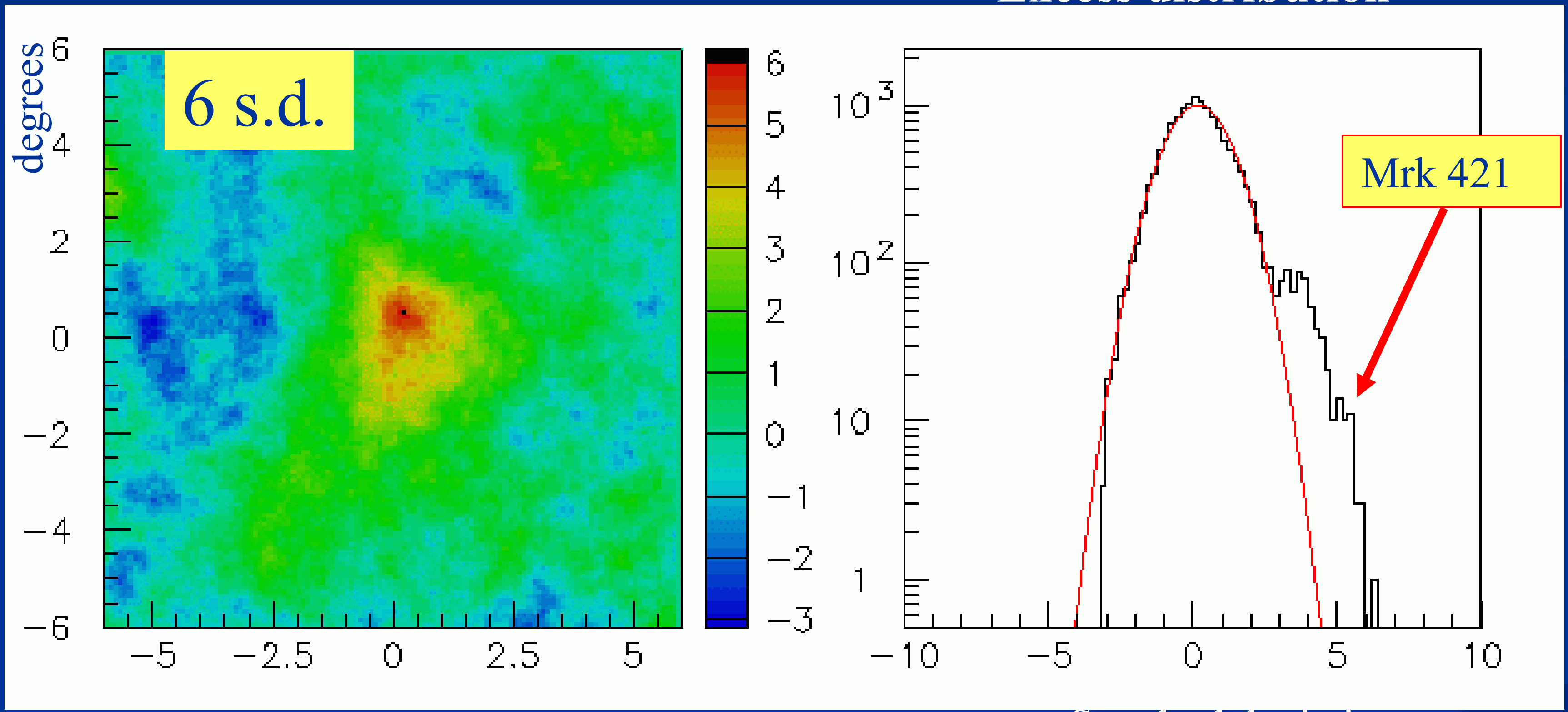
Mrk 421 X-rays ASM/RXTE



Mrk 421 - July-August 2006 (test data)

$N_{PAD} > 40$

Excess distribution



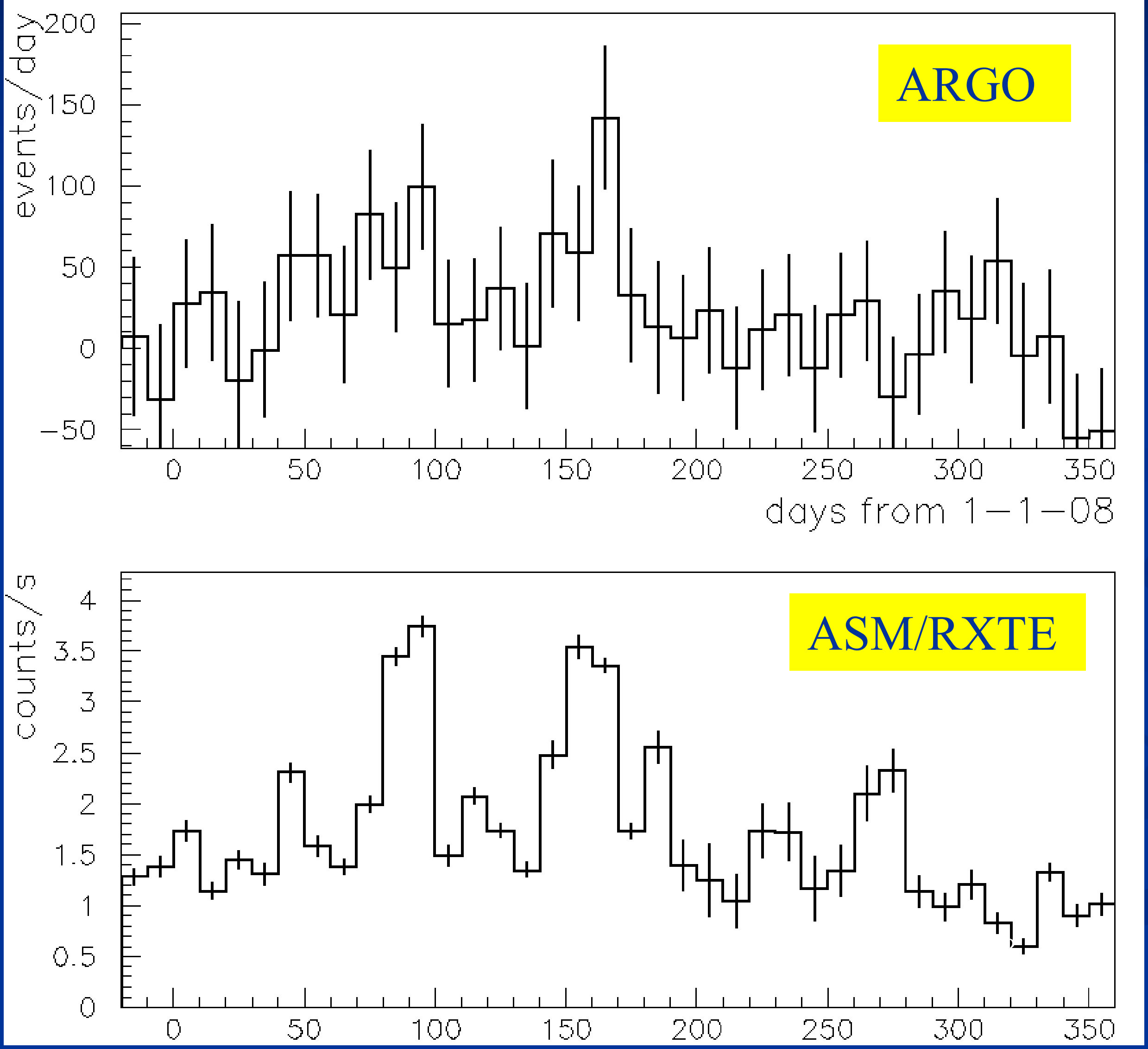
Standard deviations

obs. time ≈ 109 hours

Flux ≈ 3-4 Crab

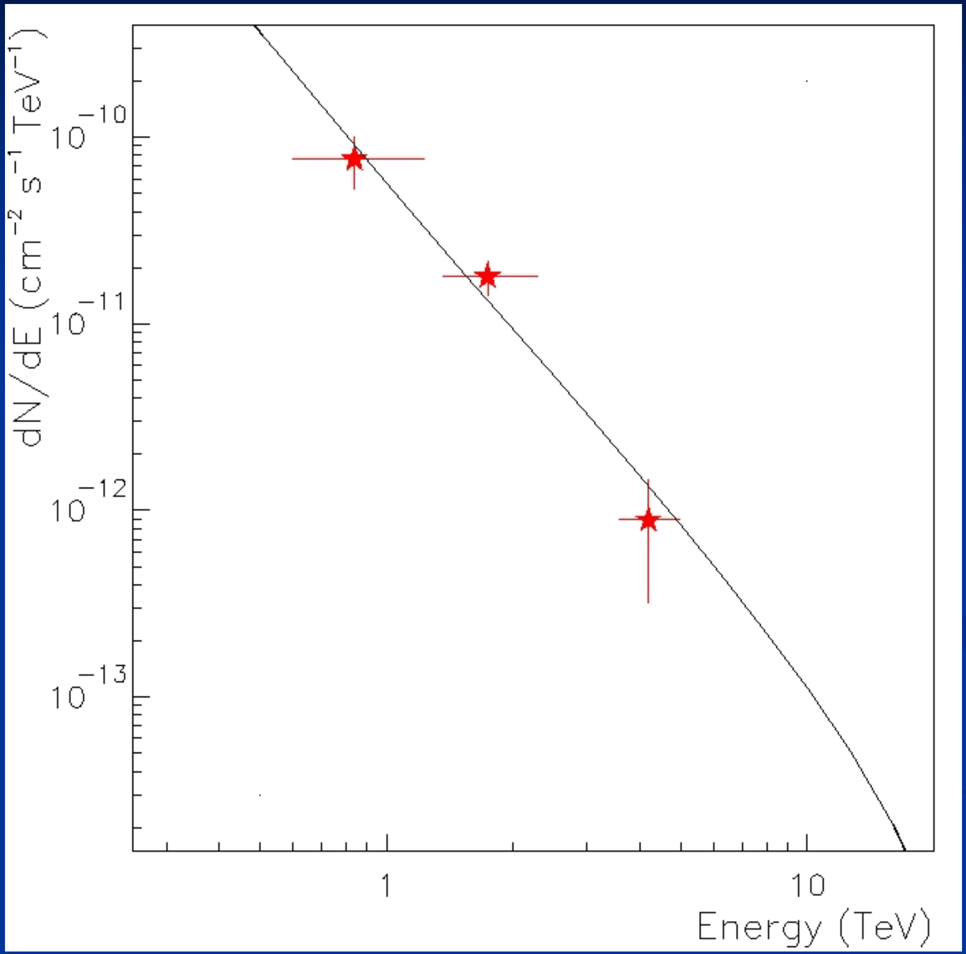
Mrk 421 - 2008

10 days average



$N_{PAD} > 100$

Mrk 421 spectrum (2008, days 41 – 180)



Integral flux (E > 1 TeV)

$(4.9 \pm 2.0) \cdot 10^{-11}$ ev cm $^{-2}$ s $^{-1}$

≈ 2 × Crab

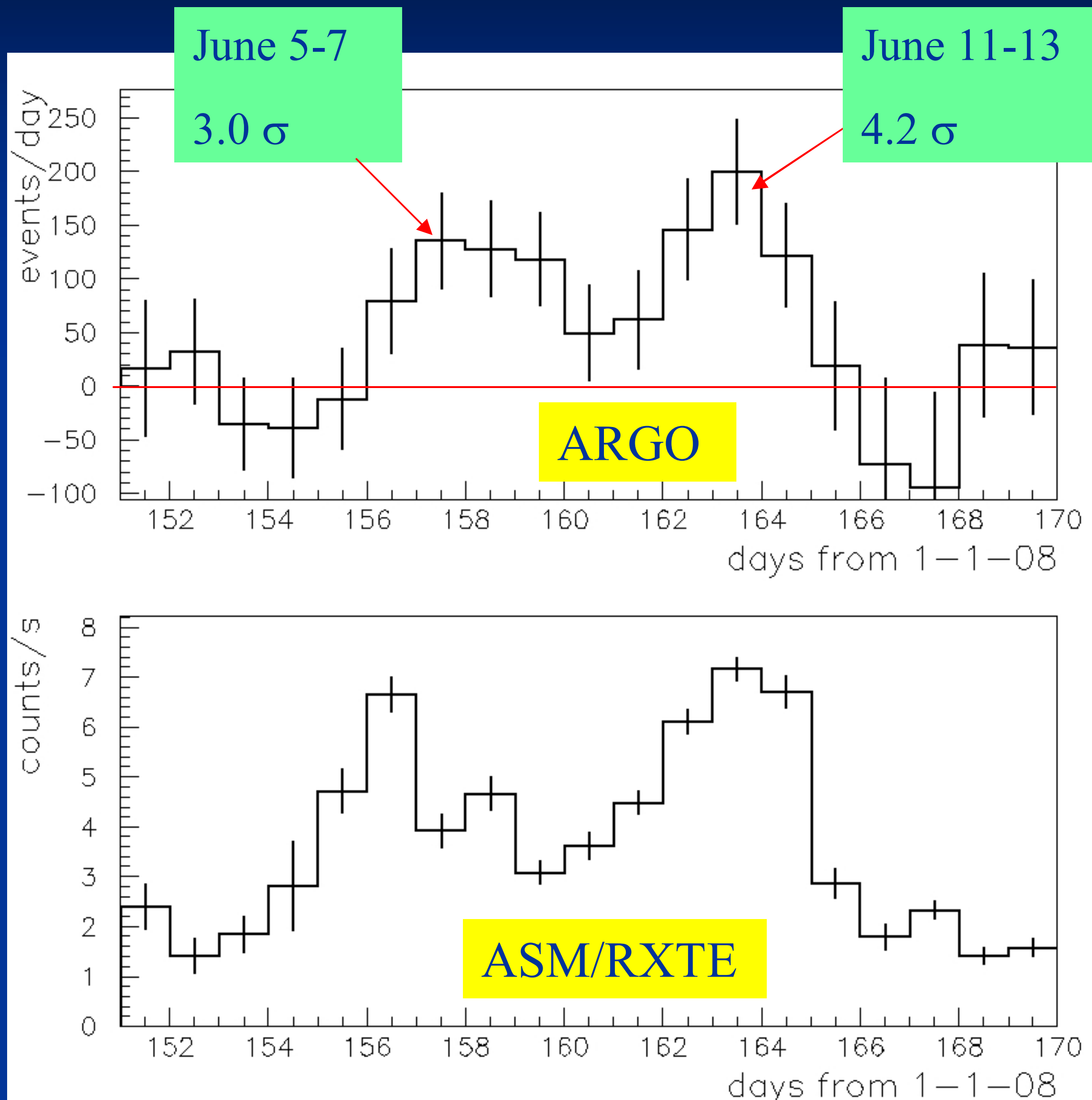
from: Primack et al.

AIP conf Proc 745, 23, 2005

Power law spectrum + EBL absorption :

$$dN/dE = (7.5 \pm 1.7) \cdot 10^{-11}\, E^{-2.51 \pm 0.29}\, e^{-\tau(E)} \ \text{ev cm}^{-2}\ \text{s}^{-1}\ \text{TeV}^{-1}$$

Mrk 421 - June 2008

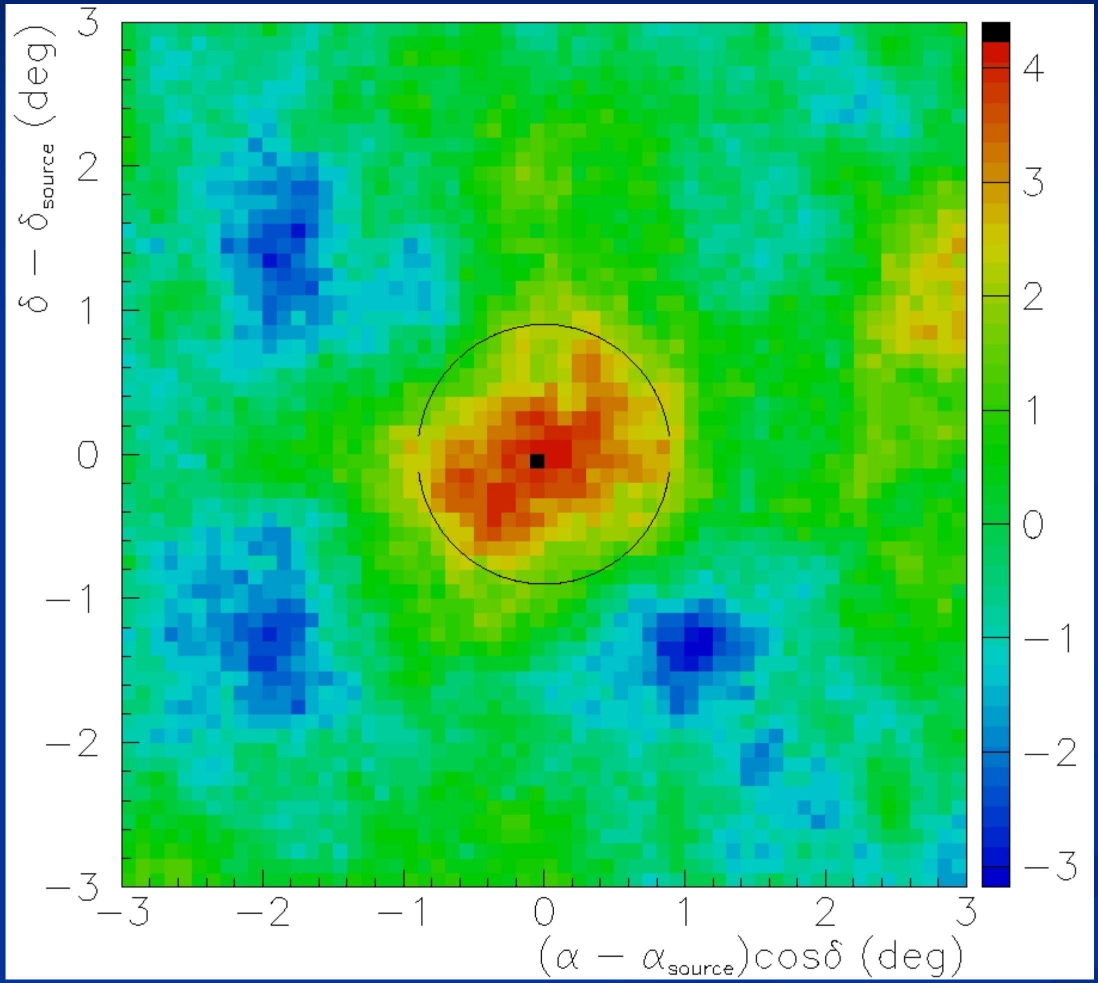


N_{PAD} > 100

3 days average

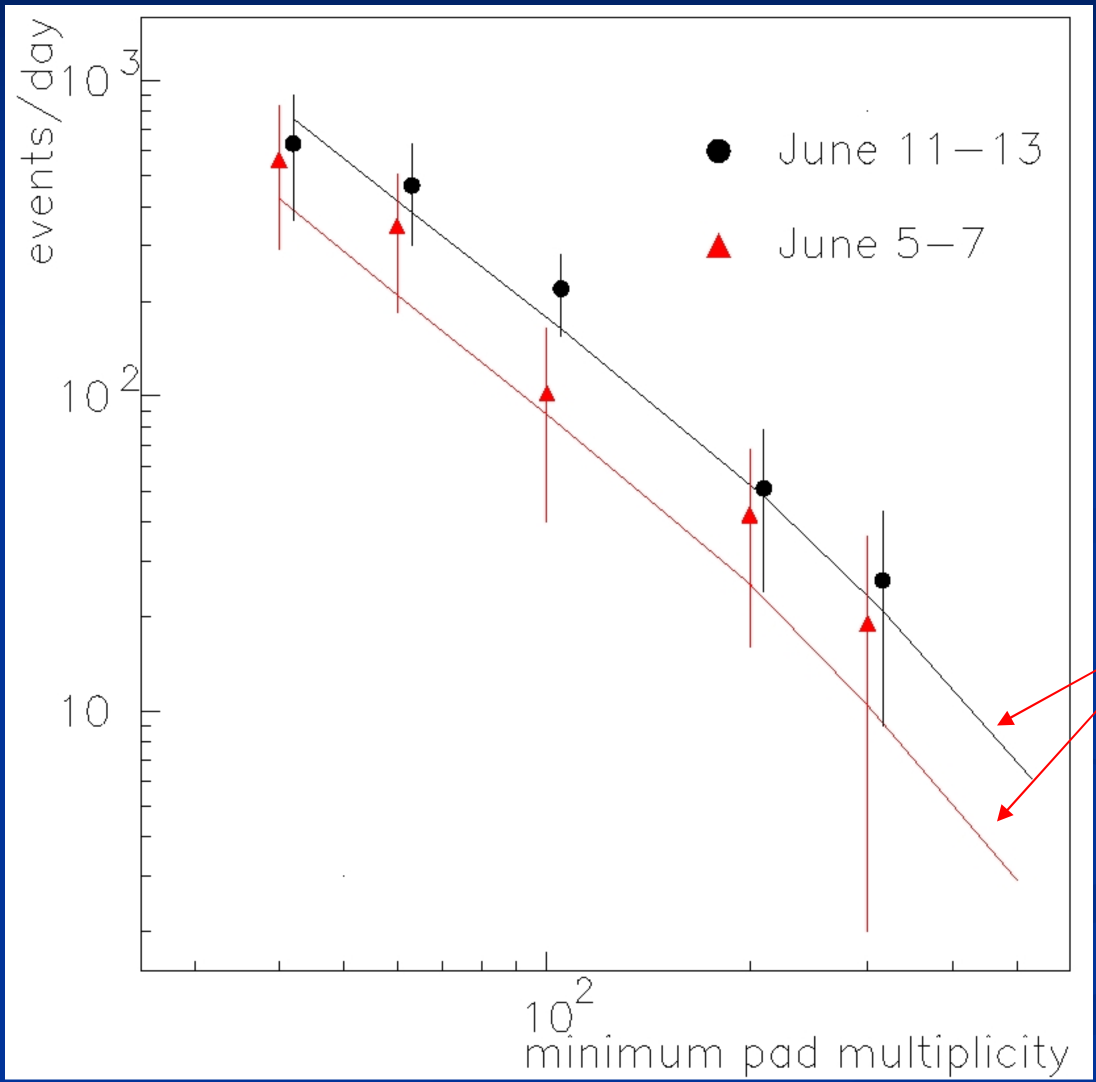
1 day average

June 11-13, 2008



4.2 σ

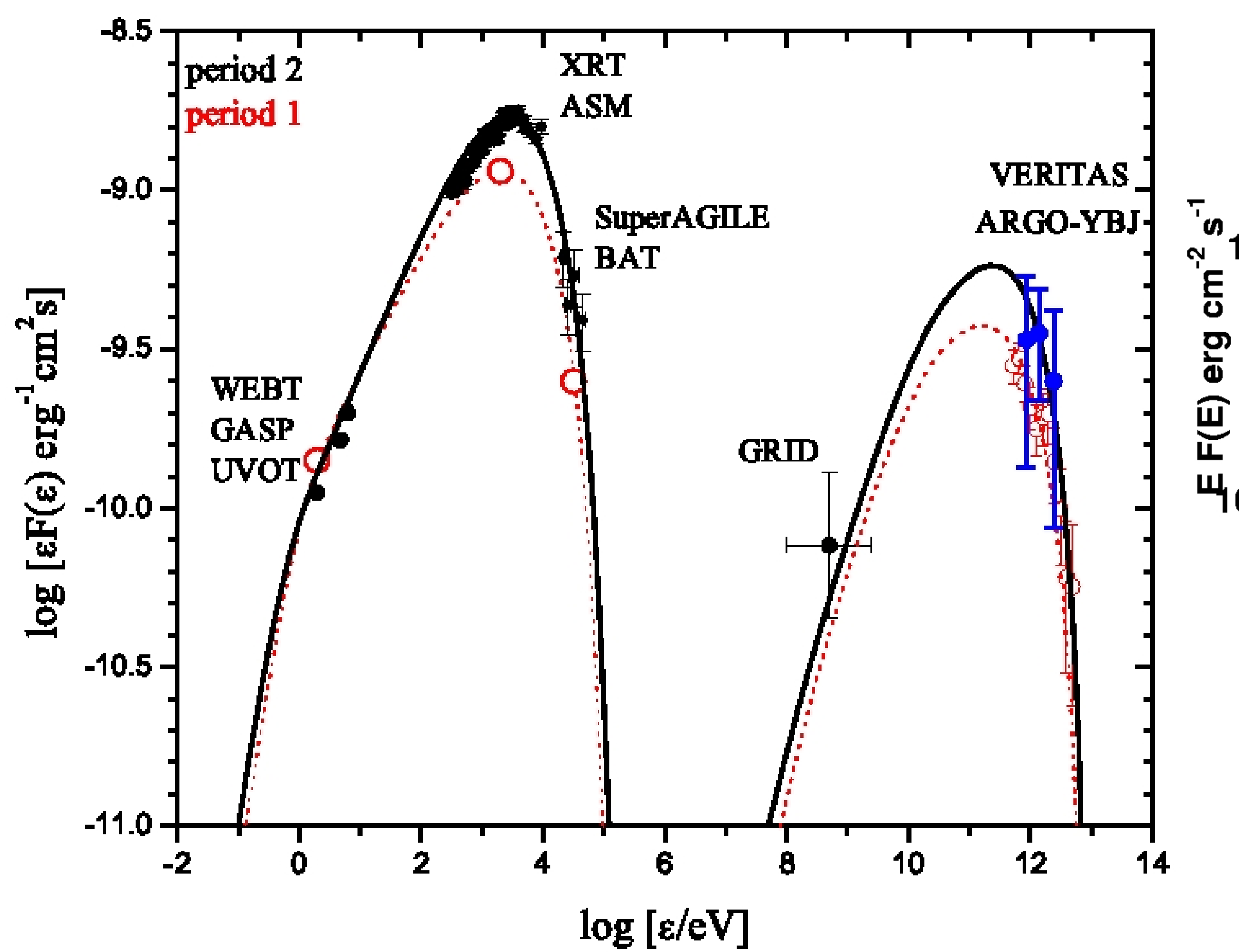
Event rate

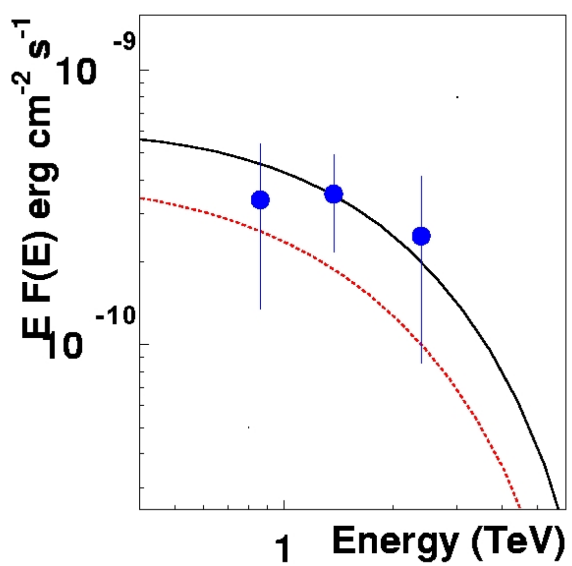


$N_{PAD} > 100$

Expected from theoretical SED

SED



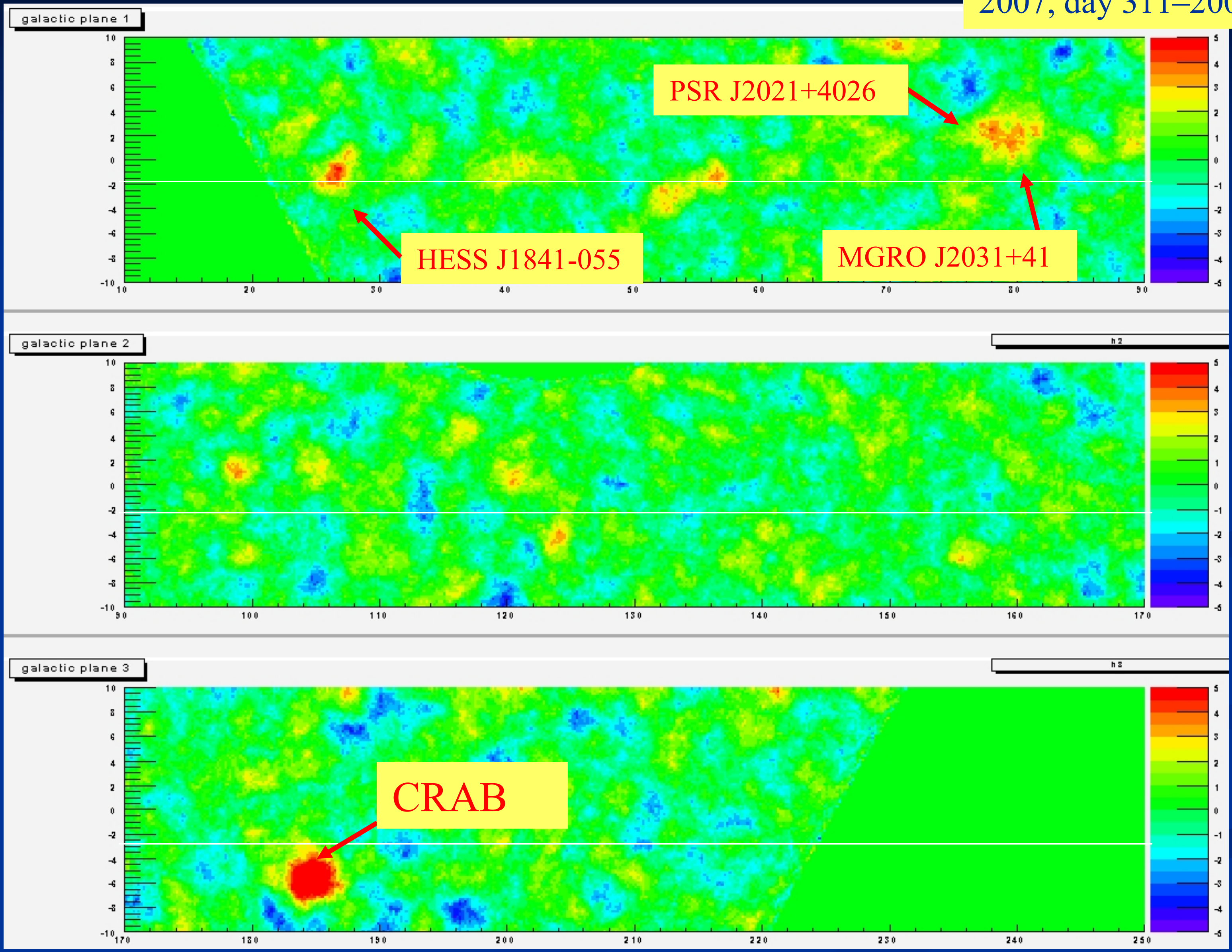


≈7 Crab units

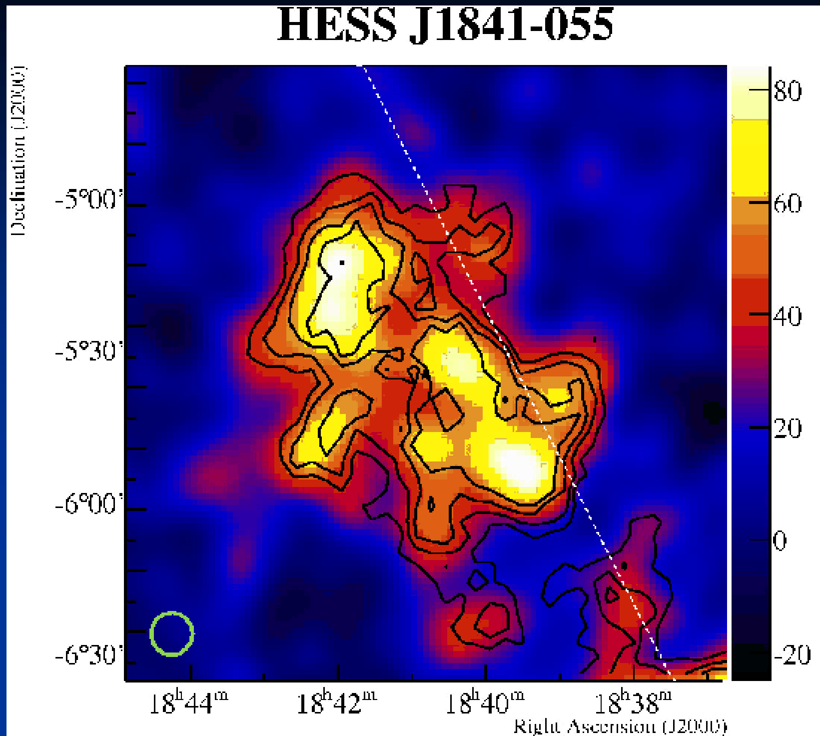
Galactic plane

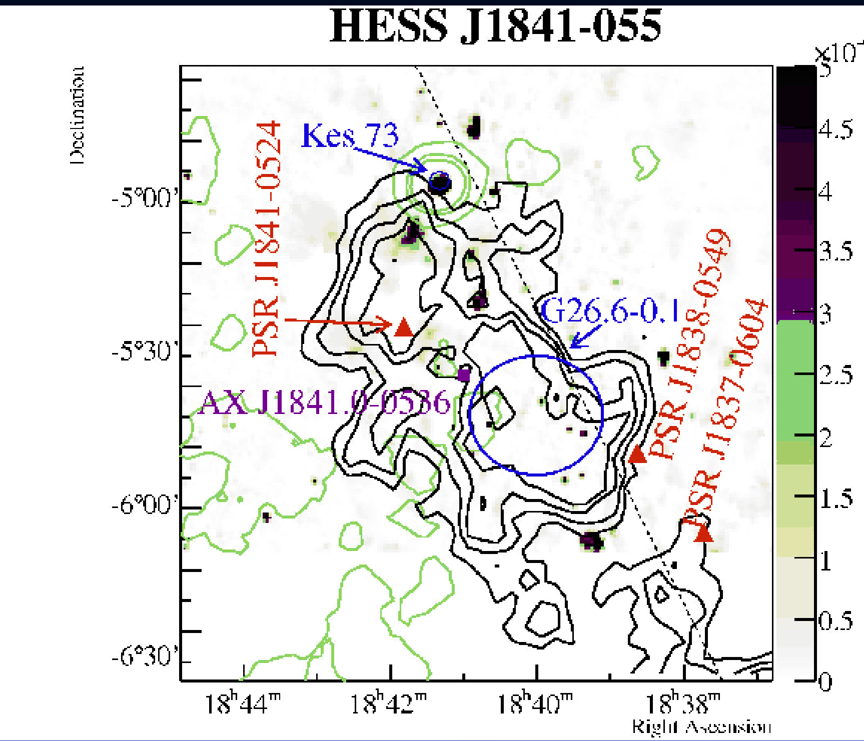
542 days

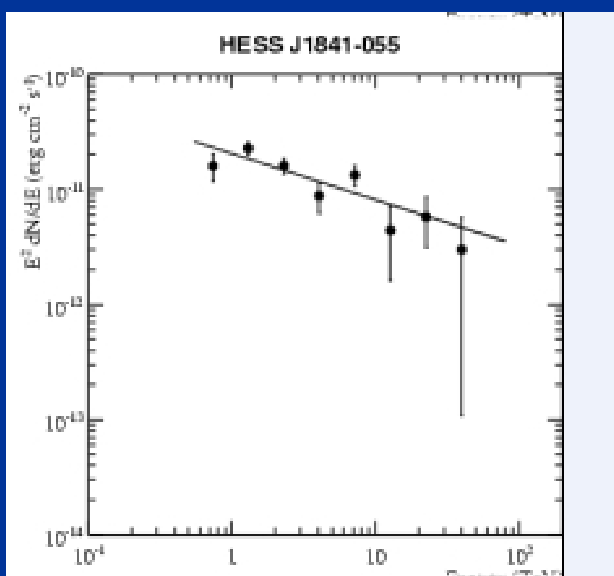
2007, day 311–2009, day 220



nhit > 40   Smoothing window radius = 1.3°







$T_{obs} = 10$ h   10.7 σ

Extension   0.8° □ 0.5°

$dN/dE = (1.28 \pm 0.13)\ 10^{-11}\ E^{-2.41}\ \gamma\ cm^{-2}\ s^{-1}\ TeV^{-1}$

for E = 0.5 – 80 TeV

~ 30% Crab

In ARGO: 8.5 ev/day

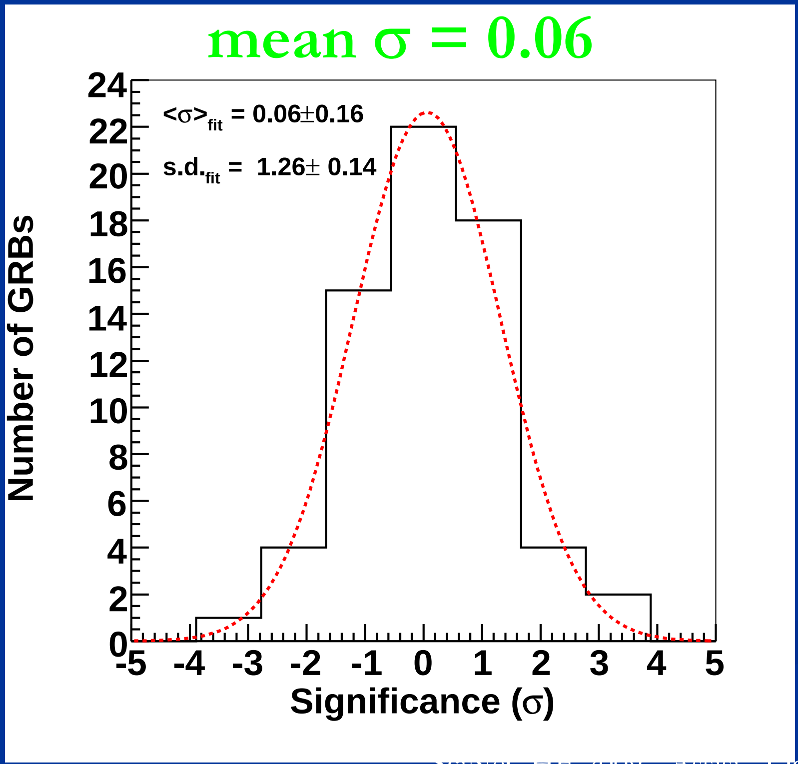
Aharonian et al., A&A 477, 353-363 (2008)

GRB

- Scaler mode 1-100 GeV
- Shower mode 10-1000 GeV
- Upper limits to the fluence
  ($\geq 10^{-5}$ erg/cm^2)
- Upper limits to the cutoff energy as a function of the spectral index (1-100 GeV)

GRB Sample (for ICRC09)

- Total number of GRBs analyzed: 66
- With known redshift: 11
- Long duration GRBs (> 2s): 58
- Short duration GRBs (≤ 2s): 8



The distribution of the statistical significances
is compared with a
standard normal distribution

Referenced Papers

1) Search for Gamma Ray Bursts with the ARGO-YBJ detector in scaler mode, Astrophysical Journal 699 (2009) 128

   → Upper limits to the fluence of 62 GRBs (9 with redshift z) in the energy range 1- 100 GeV

2) ARGO-YBJ constraints on very high energy emission from GRBs, Astroparticle Physics 32 (2009) 47

   → Upper limits to the fluence of 26 GRBs (6 with z) in the ranges 10 - 100 GeV and 10 - 1000 GeV

GRB090902B

- Detected by Fermi GBM at 11:05:08 UT (T_0) and zenith angle θ = 23.1° (uncertainty = 1.0°), with a duration T_{90} = 25 s

- Detected by Fermi LAT at 11:05:15 UT (uncertainty = 2.4 '):

  within 100 s $\rightarrow$ >30 events with E >1 GeV

  82 s after T_0 $\rightarrow$ photon with E = 33.4 GeV (record!)

  ➡ extended emission at GeV energies

  (common feature of high energy emission?)

- Scaler data analysis

GRB090902B: Upper Limit

- The spectrum obtained with both GBM and LAT data is well fitted by a Band function + underlying single power law

- Fluences of the Band component: $F = 3.74 \cdot 10^{-4}$ erg/cm^2
  Fluence of the whole GBM + LAT emission:
  $F(8 \text{ keV}–30 \text{ GeV}) = 4.86 \cdot 10^{-4}$ erg/cm^2

- Extrapolated fluence, considering absorption in EBL ($z = 1.8$):
  $F(1–100 \text{ GeV}) = 5.9 \cdot 10^{-5}$ erg/cm^2

- Upper limit to fluence during T_{90}, considering absorption:
  $F(1–100 \text{ GeV}) = 1.4 \cdot 10^{-4}$ erg/cm^2

- Upper limit to the cutoff energy, without absorption in EBL:
  $E_{cut} = 130$ GeV

Cosmic Rays

- Medium scale anisotropies
- Moon shadow and the anti-p/p ratio
- Proton-air cross section

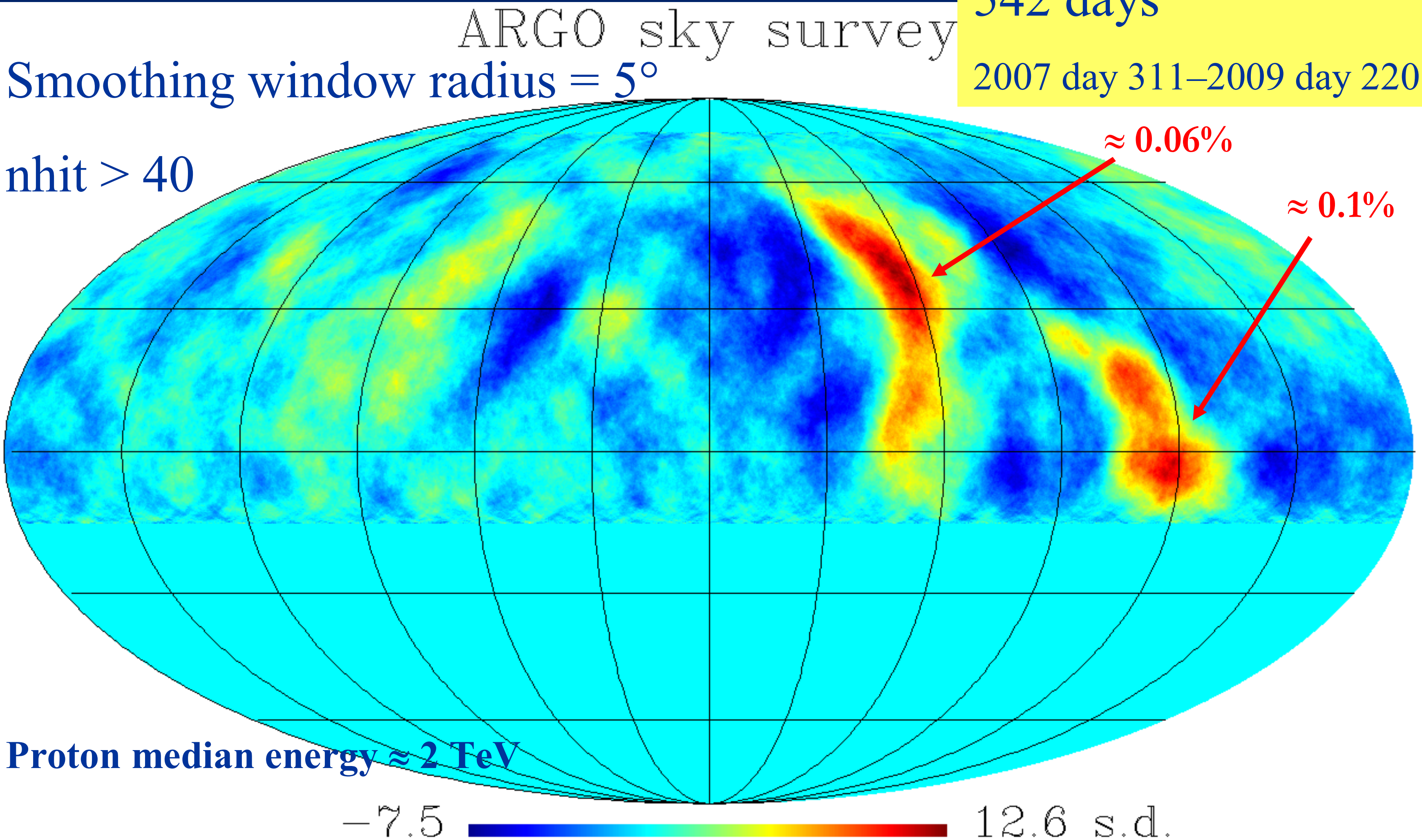
Medium scale anisotropy (preliminary)

542 days

2007 day 311–2009 day 220

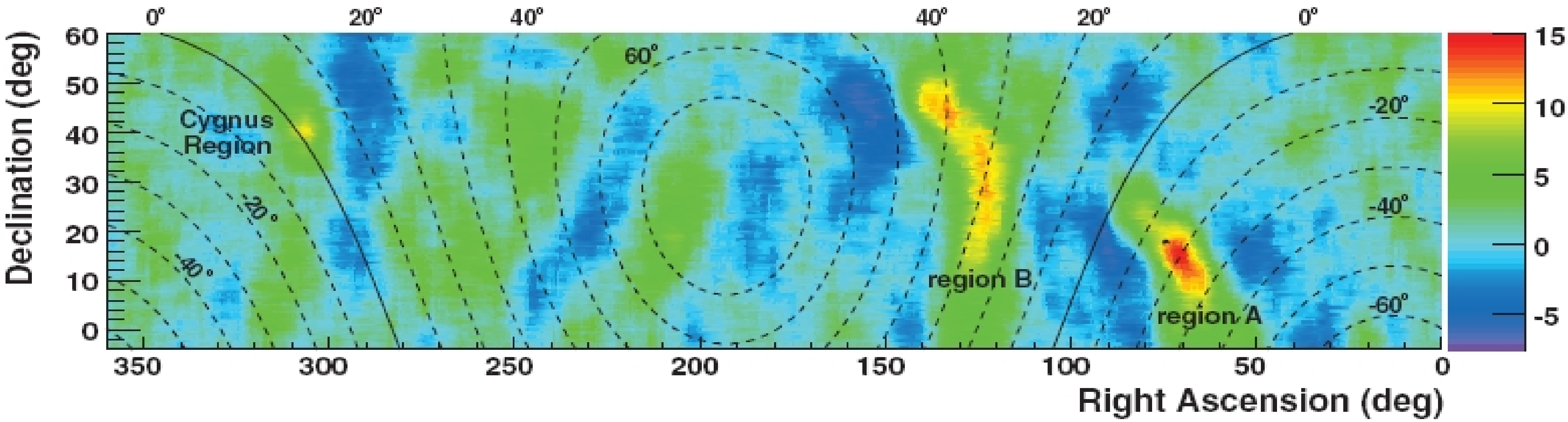
Smoothing window radius = 5°

nhit > 40

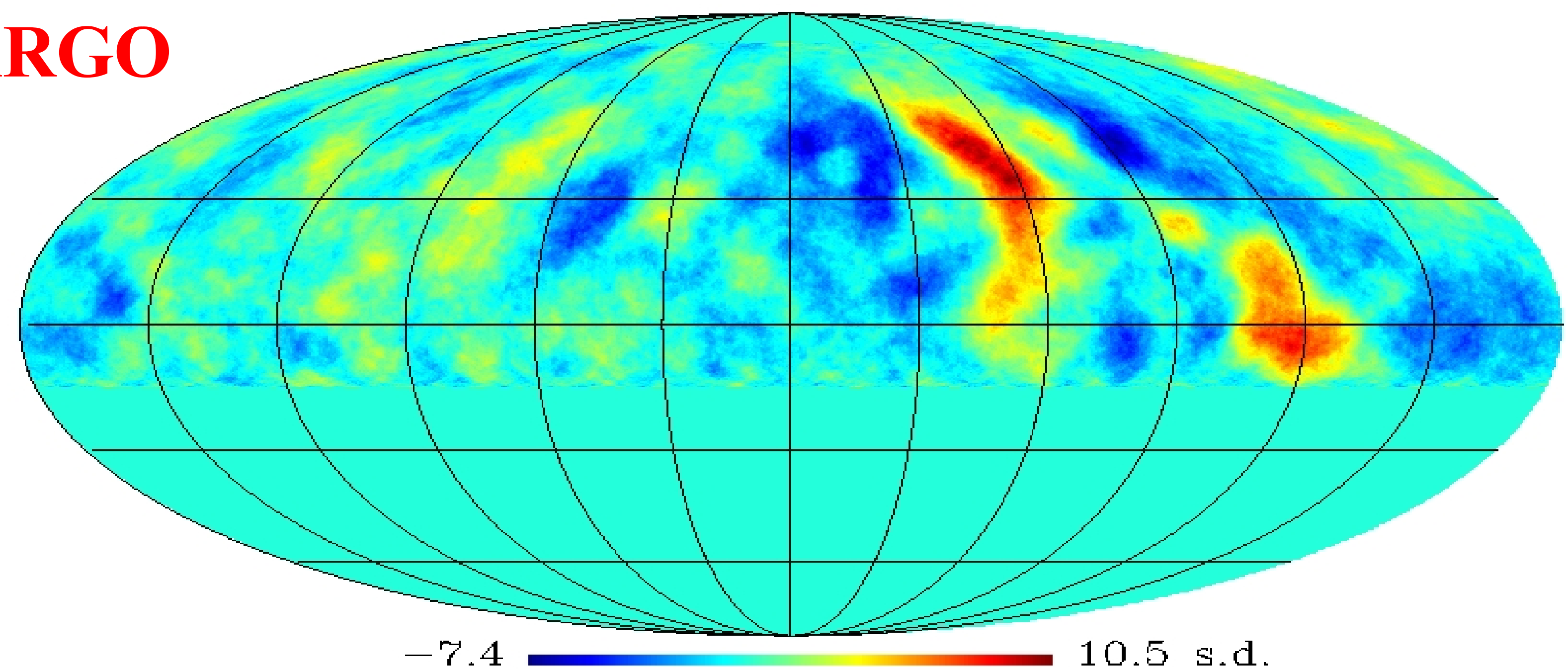


Proton median energy ≈ 2 TeV

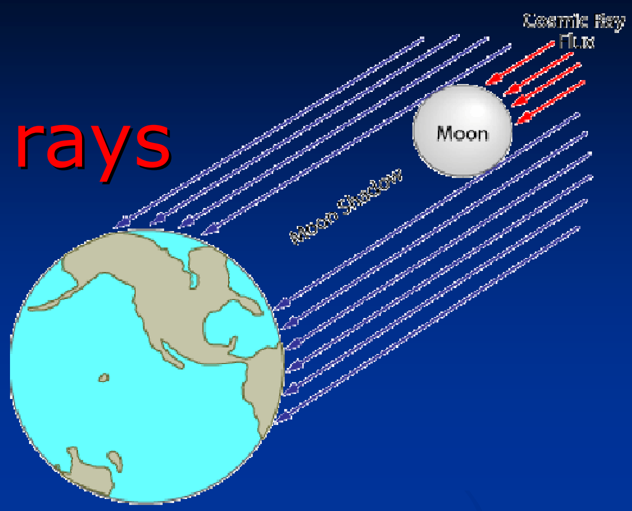
MILAGRO



ARGO



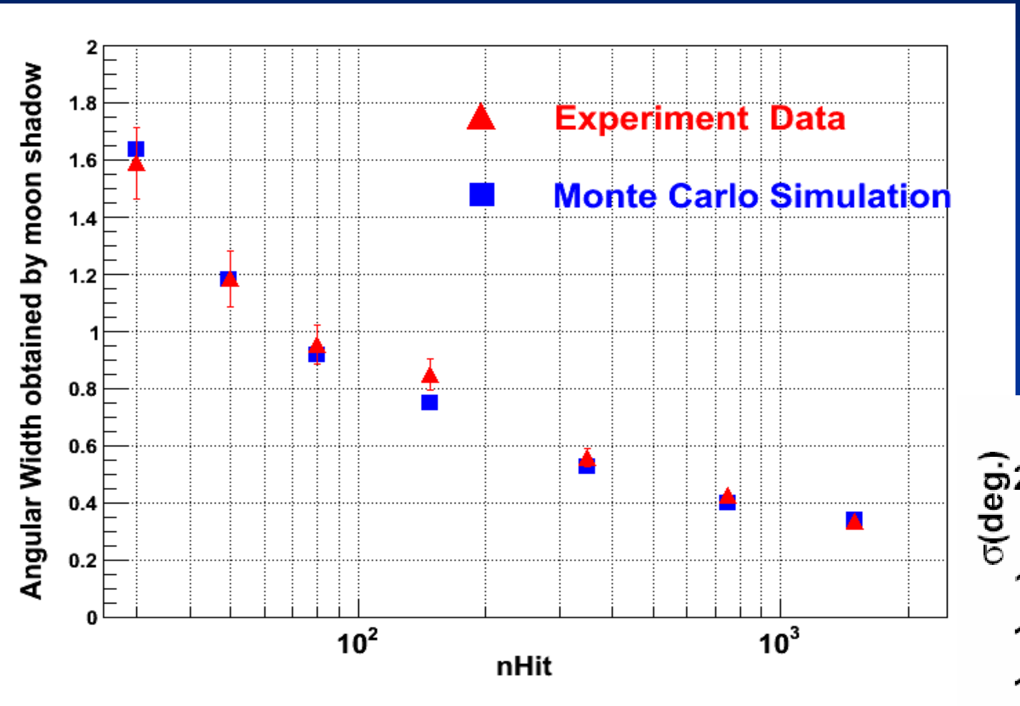
The Moon shadow on cosmic rays



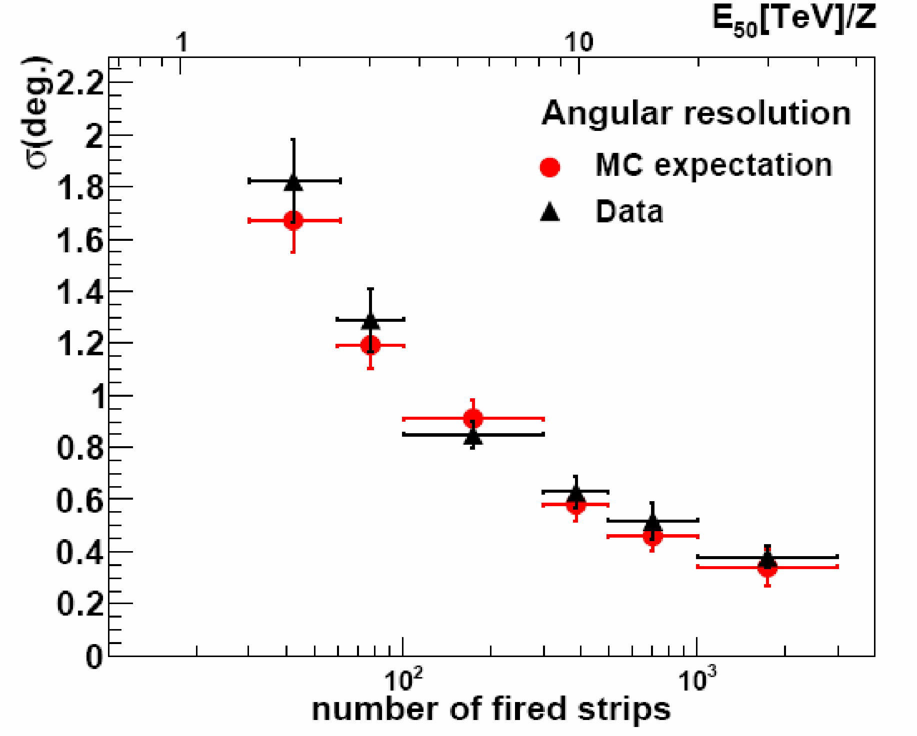
- Size of the deficit $\Rightarrow$ angular resolution
- Position $\Rightarrow$ pointing accuracy
- West displacement $\Rightarrow$ Energy calibration

Geomagnetic bending $\approx$ 1.57° × Z / E (TeV)

The angular width in the N-S direction using the Moon shadow



$$RMS \simeq \sigma \sqrt{1 + \left(\frac{R}{2\sigma}\right)^2}$$

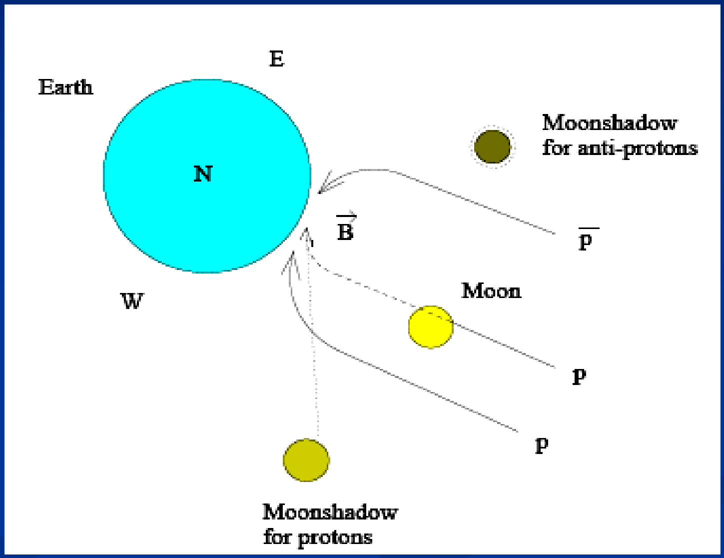


Based on the Robust method reconstruction

The Earth-Moon system as a spectrometer

The Moon shadow can be used <u>to put limits on the antiparticle flux</u>.

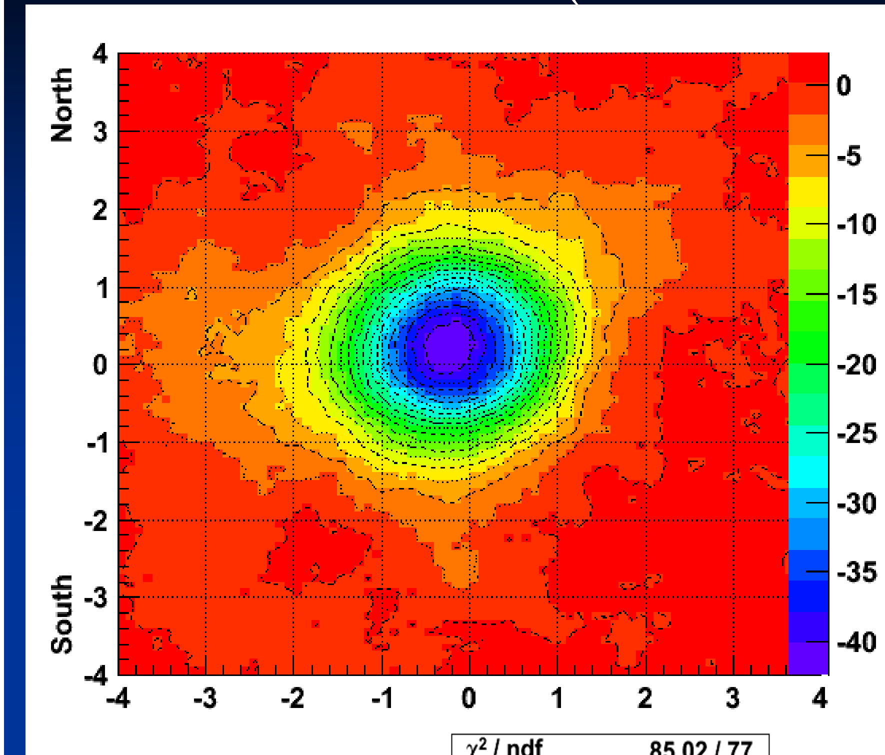
In fact, if protons are deflected towards the West, antiprotons are deflected towards the East.

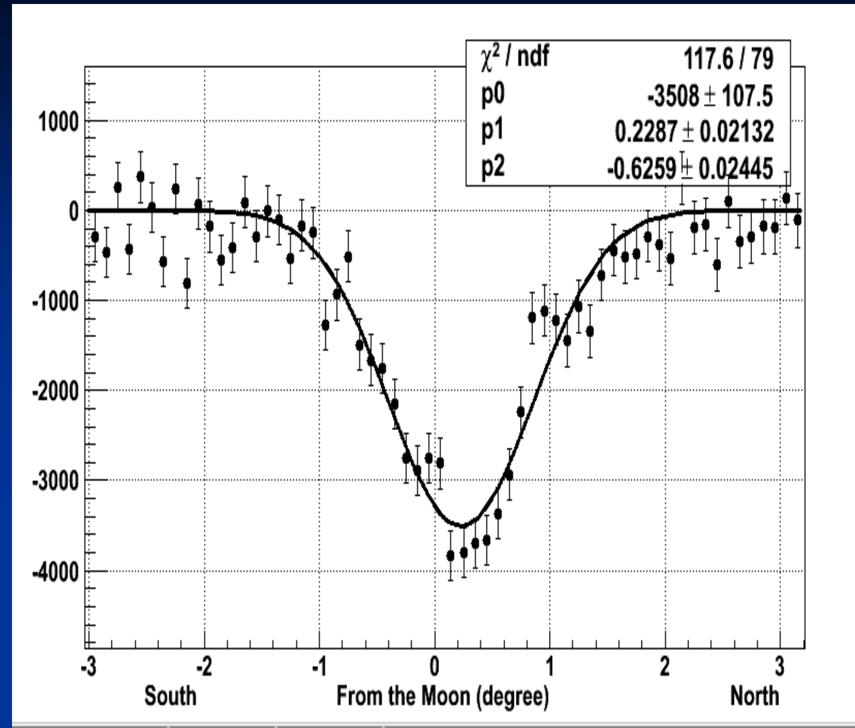


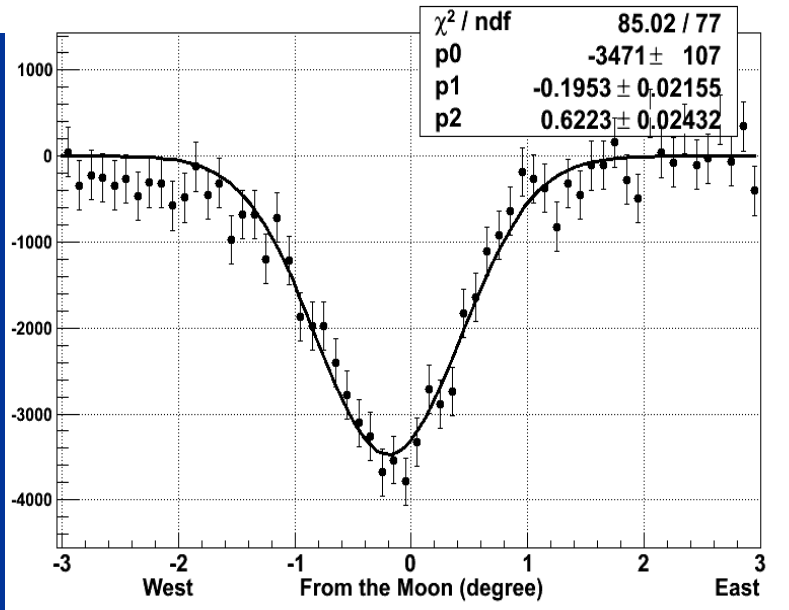
If the displacement is large and the angular resolution is small enough, we can distinguish between the 2 shadows.

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

Data (2006 + 2007 + 2008)





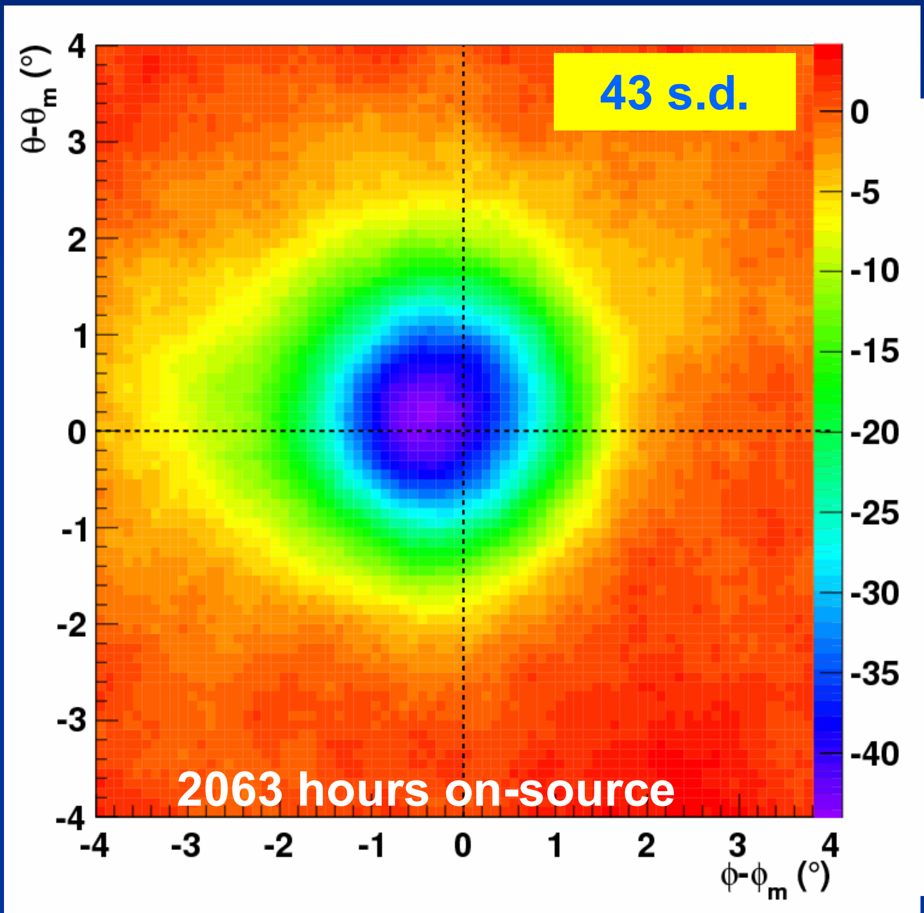


n Pad > 100

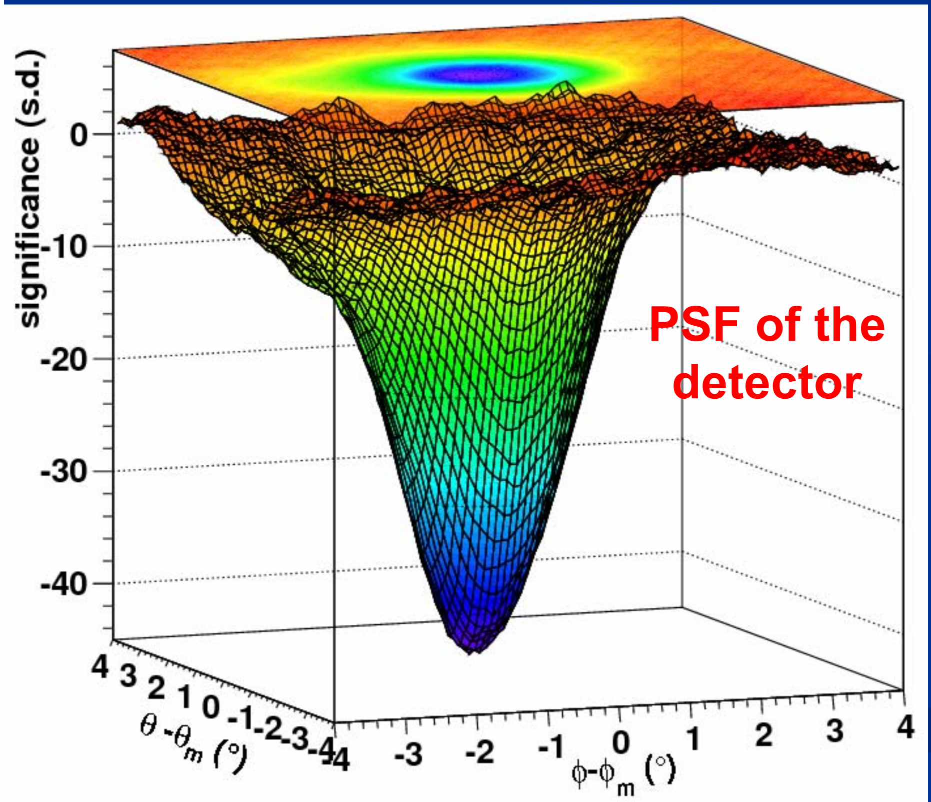
Significance: ~ 43 σ

□ 9 standard deviations /month

Moon shadow: all data (2006+2007+2008)



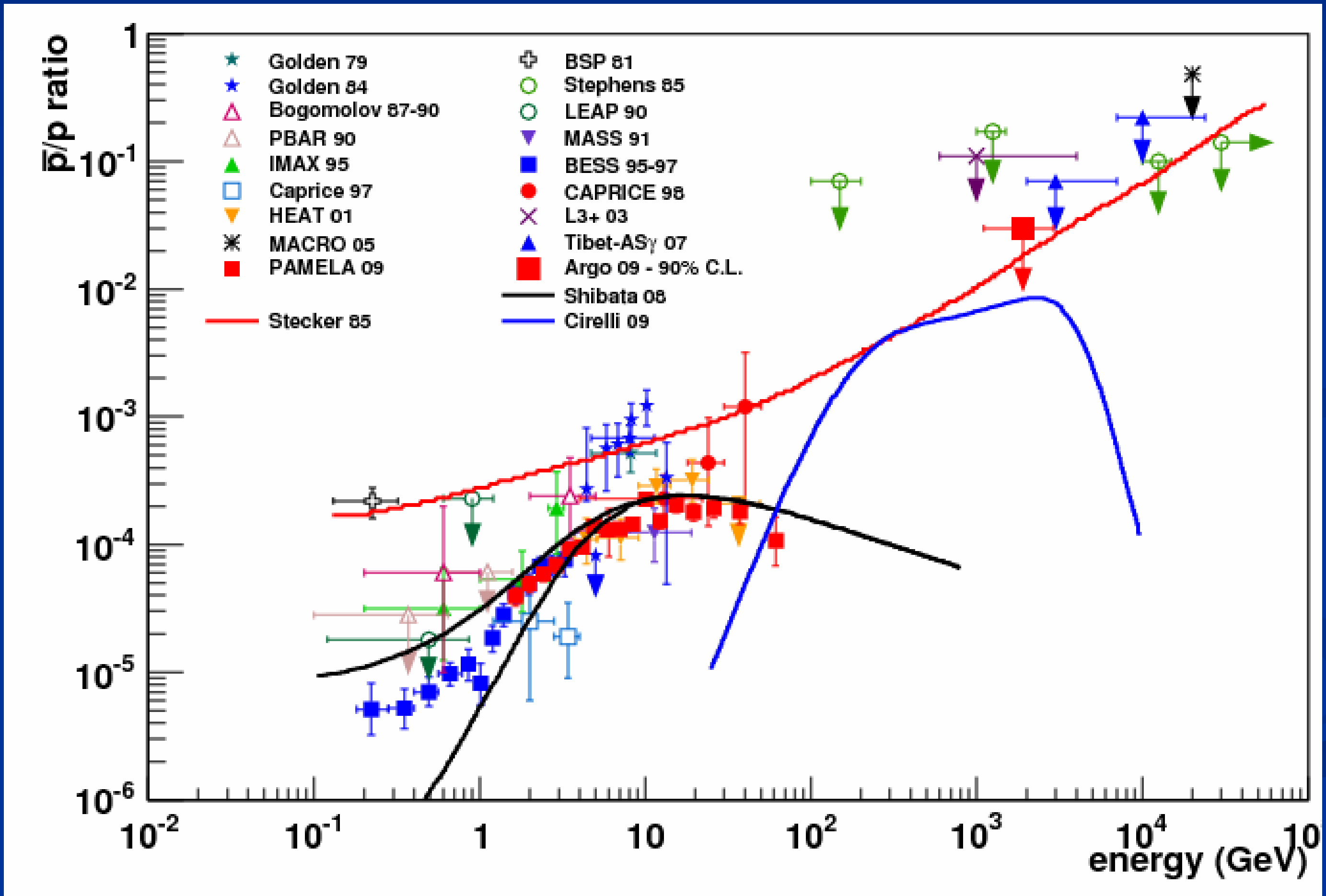
N > 60 θ < 50°



≈ 9 standard deviations / month

Antiproton/proton ratio at TeV energies

G. Di Sciascio et al.
ICRC 2009
arXiv:0907.1164



Proton-air cross section measurement
(to be published soon on PR D)

Use the shower frequency vs (sec θ -1)

$$I(\theta) = I(0)\cdot e^{-\frac{h_o}{\Lambda}(\sec\theta - 1)}$$

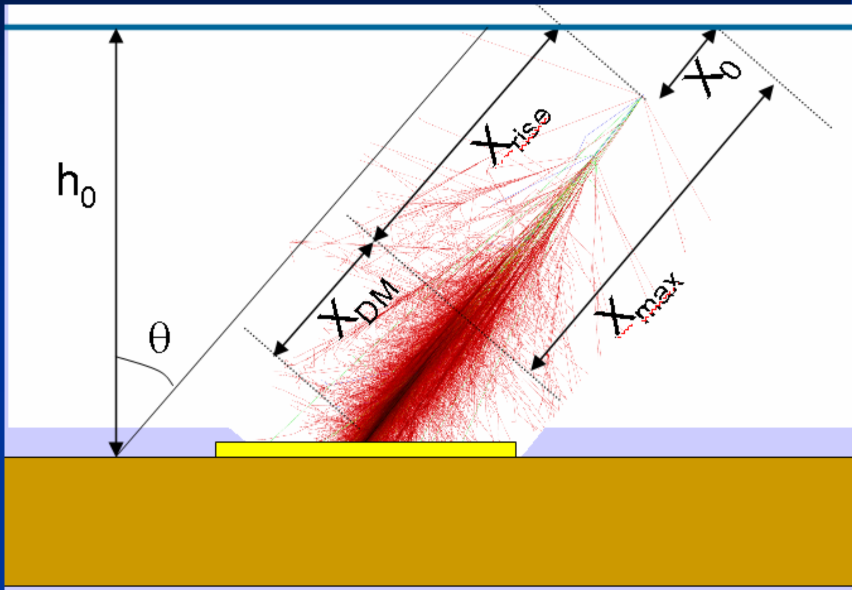
for fixed energy and shower age.

The lenght Λ differs from the p interaction lenght mainly because of collision inelasticity, shower fluctuations and detector resolution.

It has been shown that **Λ = k λ_{int}**, where **k** is determined by simulations and depends on:

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

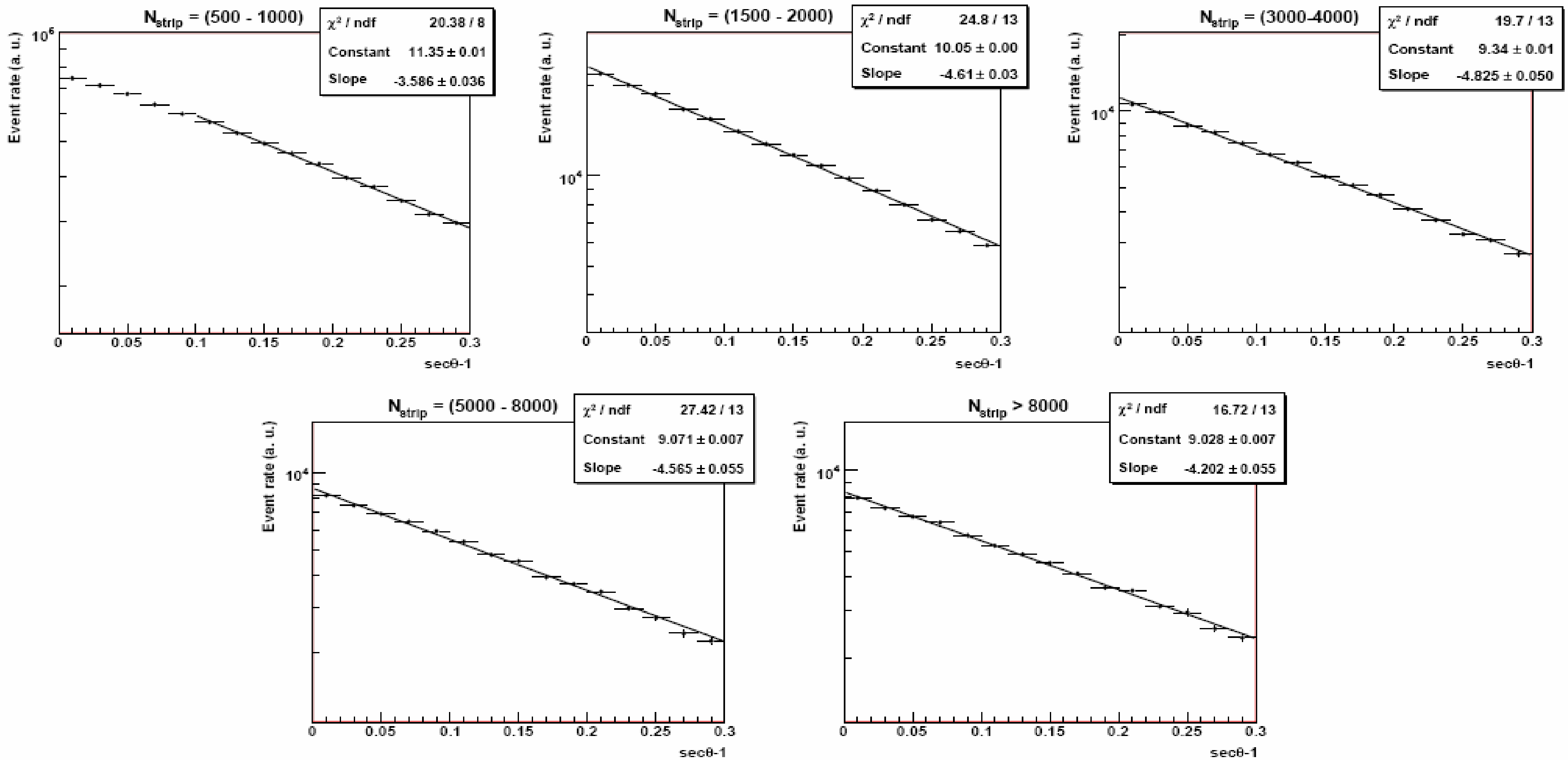
Then: **$\sigma_{p\text{-}Air}$ (mb) = 2.4 · 10^4 / λ_{int}(g/cm^2)**



Take care of shower fluctuations

- **Constrain** $X_{DO} = X_{det} - X_0$ or
  $X_{DM} = X_{det} - X_{max}$
- **Select** deep showers (large X_{max}, i.e. small X_{DM})
- **Exploit** the detector features (space-time pattern) and location (depth).

Experimental data



Clear exponential behaviour

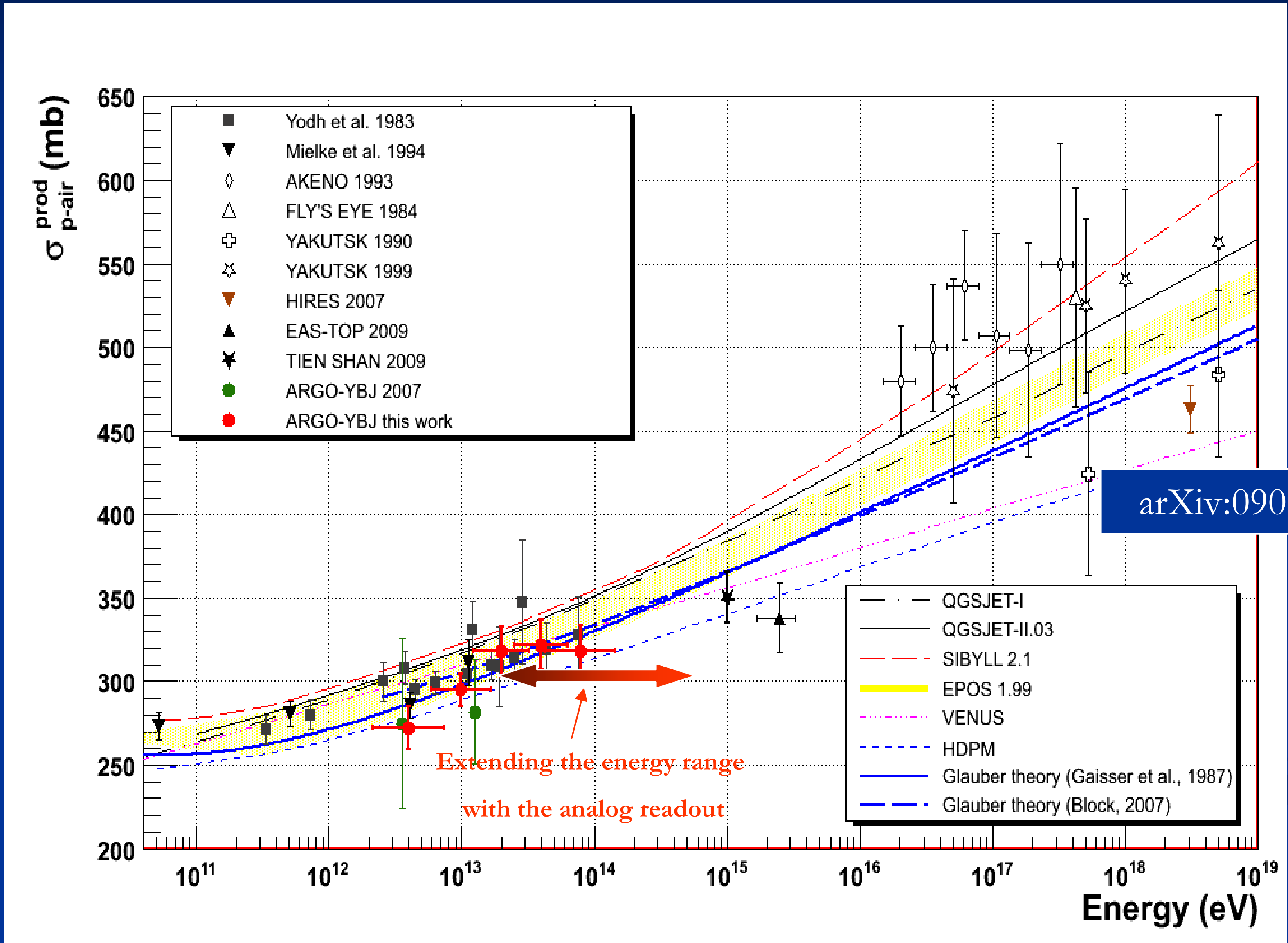
Full consistency with MC simulation at each selection step

Weather effects, namely the atmospheric pressure dependence on time, have been shown to be at the level of less than 1 %

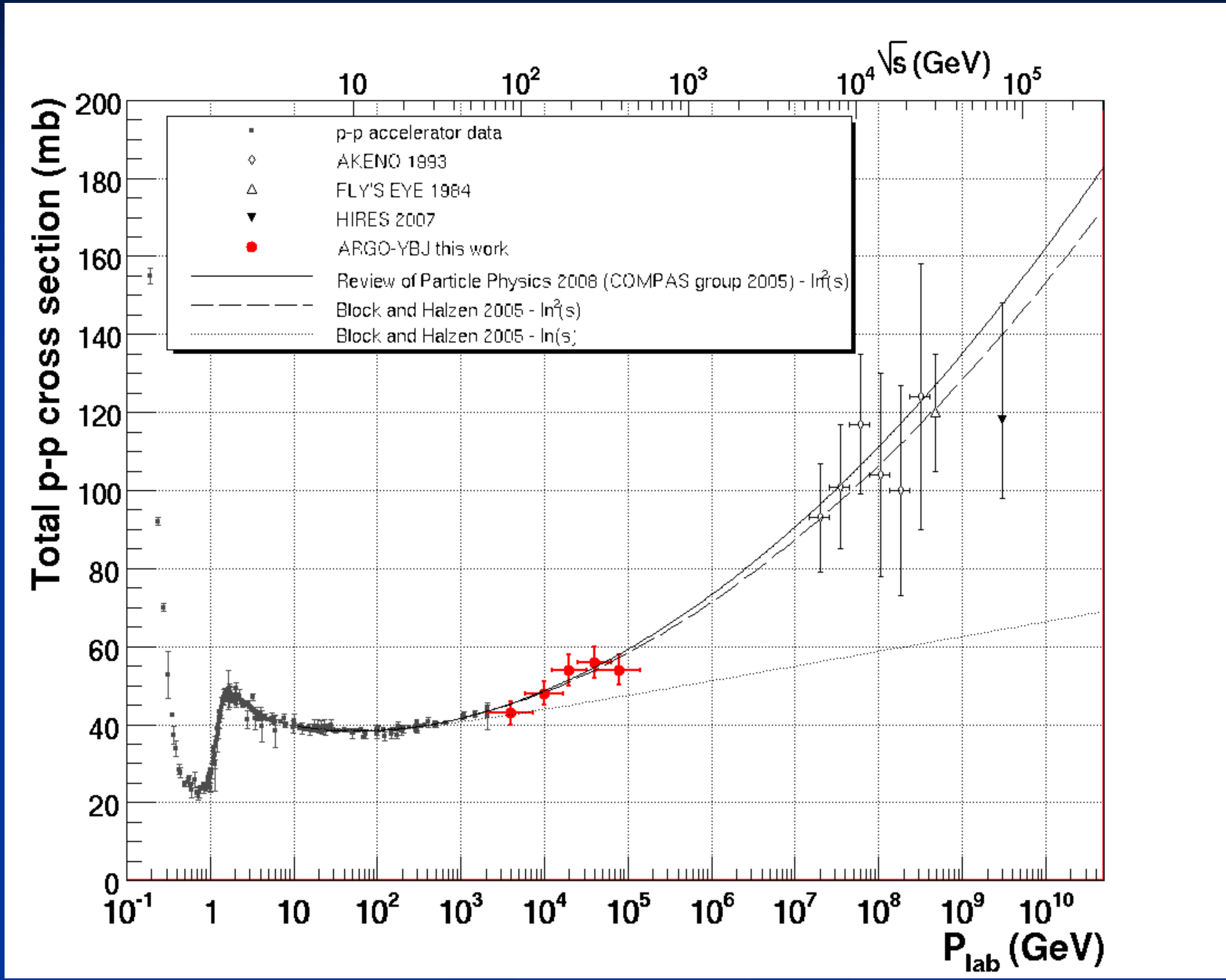
h_0^{MC} = 606.7 g/cm² (4300m a.s.l. standard atm.)

h_0^{MC} / h_0 = 0.988 ± 0.007

The proton-air cross section



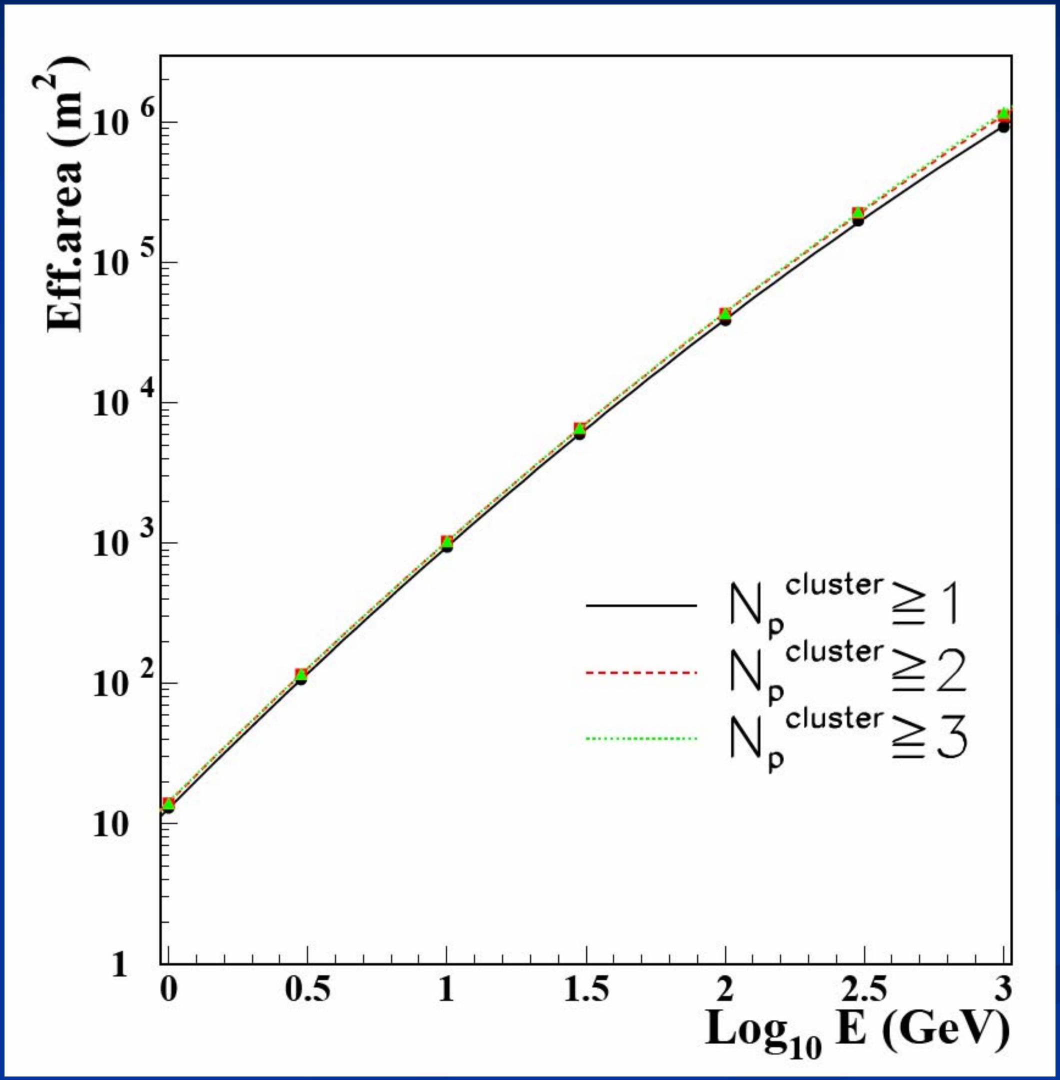
arXiv:0904.4198


p-p accelerator data
AKENO 1993
FLY'S EYE 1984
HIRES 2007
ARGO-YBJ this work
Review of Particle Physics 2008 (COMPAS group 2005) - ln²(s)
Block and Halzen 2005 - ln²(s)
Block and Halzen 2005 - ln(s)
Total p-p cross section (mb)
$\sqrt{s}$ (GeV)
P_{lab} (GeV)

Conclusions

- excellent detector performance
- smooth running of the experiment with good parameters
  - duty cycle: 90%
  - trigger rate: 3.6 kHz
  - dead time: 4%
  - minimum shower size: 20 particles
  - Total integrated events > 2×10^{11}
- imaging of the shower front successfully implemented
- analysis to be extended beyond 100 TeV
- studies to improve the reconstruction and sensitivity in progress
- many relevant results on the road

Effective area for γ-ray detection in ARGO-YBJ



flare of MRK421 from optical to TeV energies

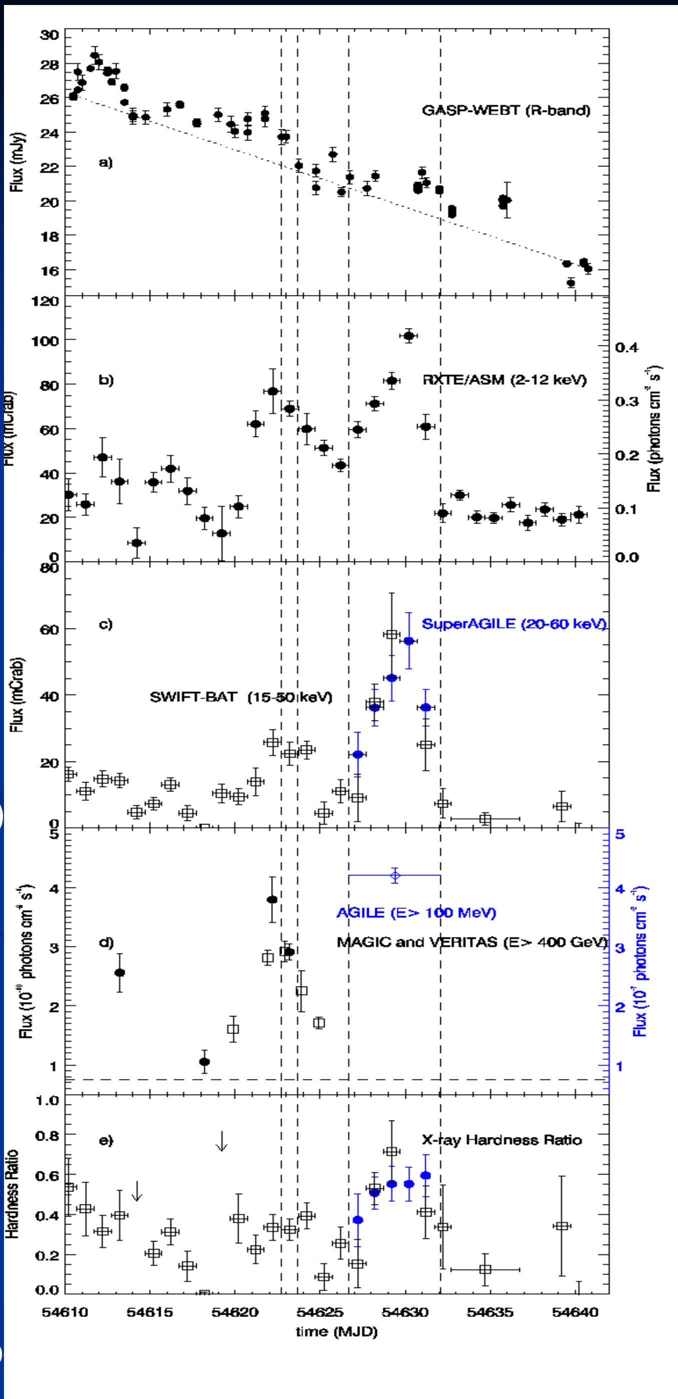
Donnarumma et al. ApJ 691 L13 (2009)

data from:

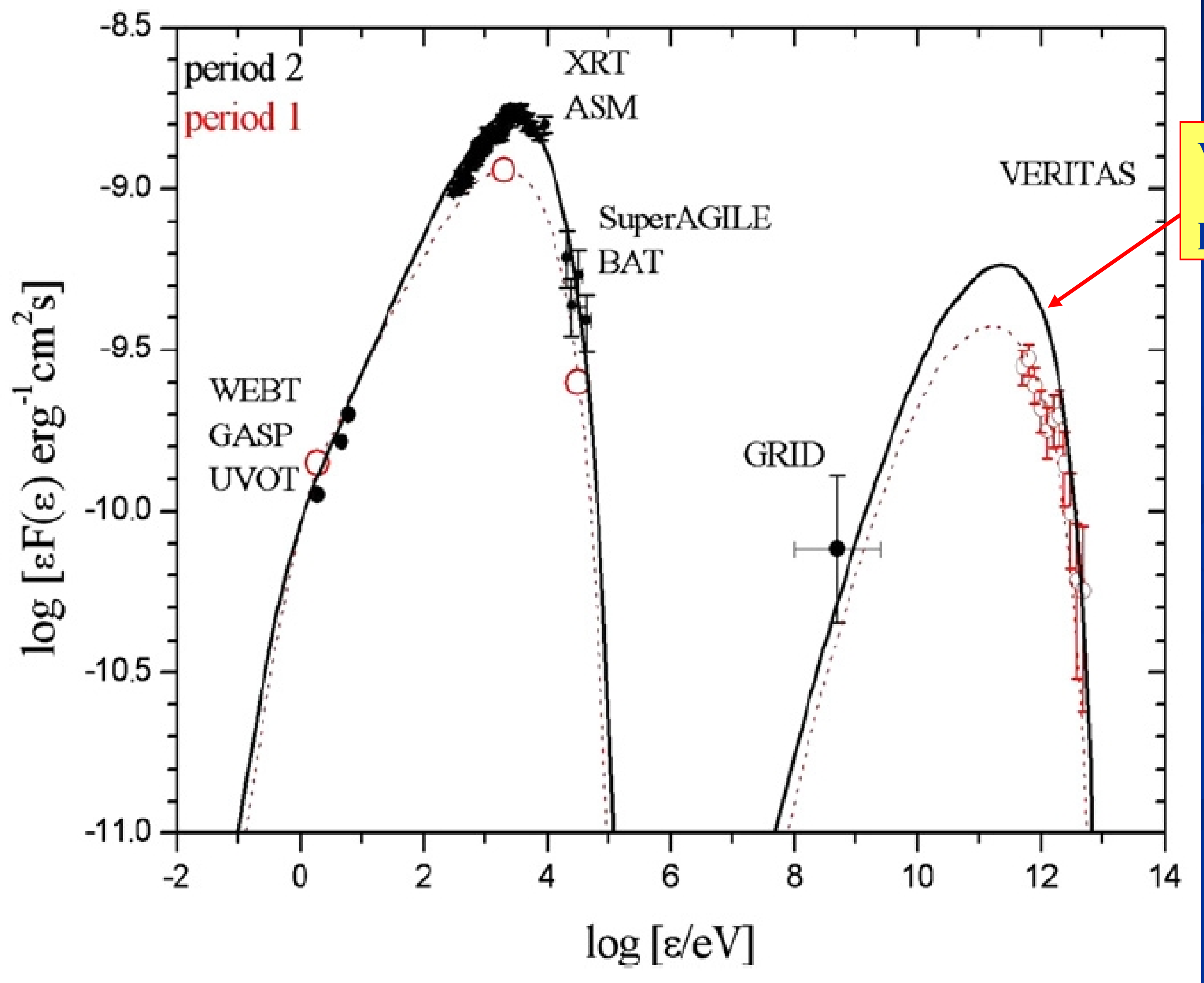
- GASP-WEBT (R-band; May 24 to June 23)
- SWIFT (UVOT & XRT; June 12-13)
- AGILE (E > 100 MeV; June 9-15)
- MAGIC and VERITAS (E> 400 GeV; May 27 - June 8)

complemented by publicly-available data from RossiXTE/ASM (2-12 keV) and Swift/BAT (15-50 keV).

No VHE data after June 8



SEDs for June 2008 flares

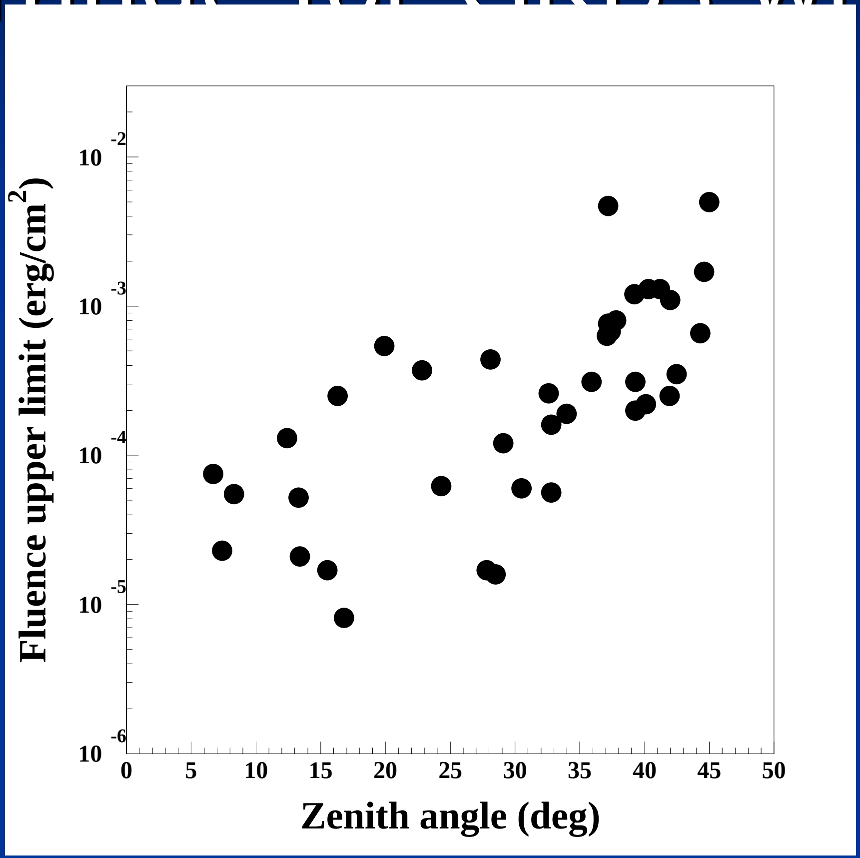


VHE predicted flux

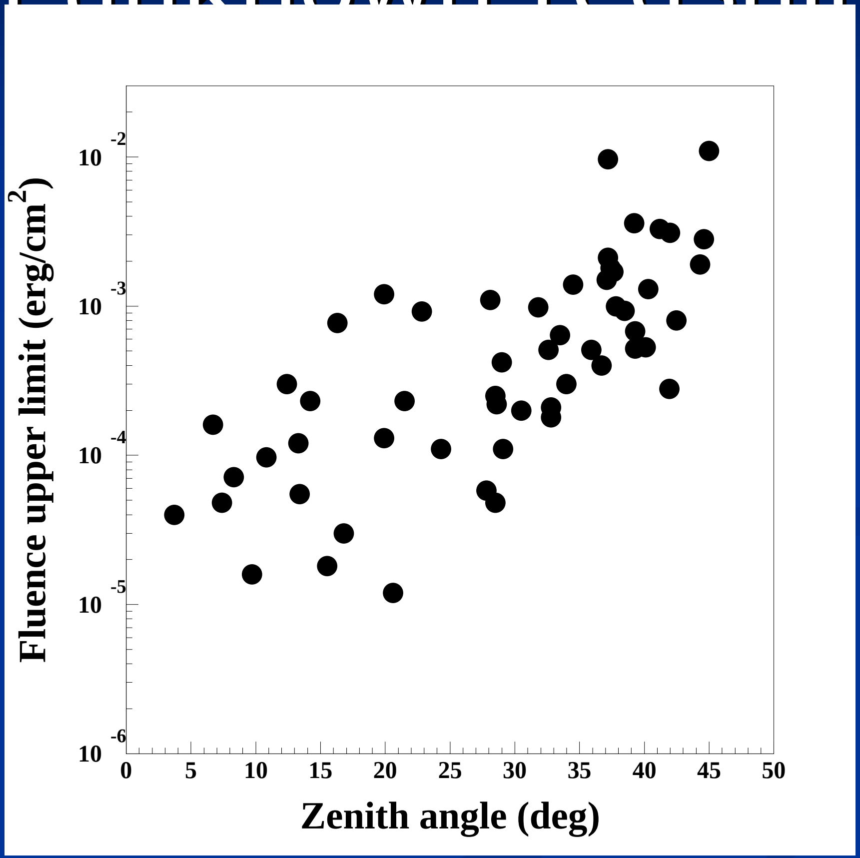
- The **total proton-proton cross section**, in an energy region so far **unexplored by particle accelerators**, has been inferred by using the Glauber theory. The result favours the $\log^2(s)$ asymptotic behaviour.

- The analysis will be extended to larger energies (**up to the PeV region**), by using the analog RPC readout, now being implemented

Fluence Upper Limits in the 1–100 GeV range for GRBs with unknown redshift



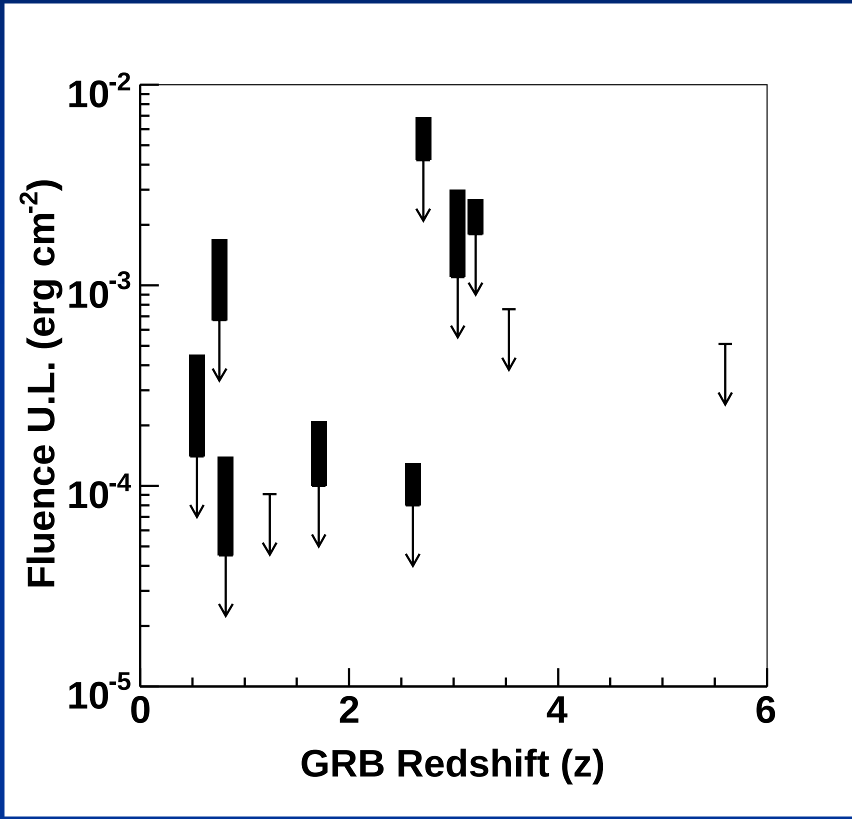
Fluence upper limits (99% c.l.) obtained extrapolating the keV power law spectra measured by satellites



Fluence upper limits (99% c.l.) obtained assuming a differential spectral index 2.5

z = 1 is assumed to consider extragalactic absorption (Kneiske et al. 2004)

Fluence Upper Limits in the 1–100 GeV range for GRBs with known redshift



Fluence upper limits (99% c.l.) obtained with differential spectral indexes ranging from the value measured by satellites to 2.5
(only this latter case is considered for Cutoff Power Law spectra)

Conclusions

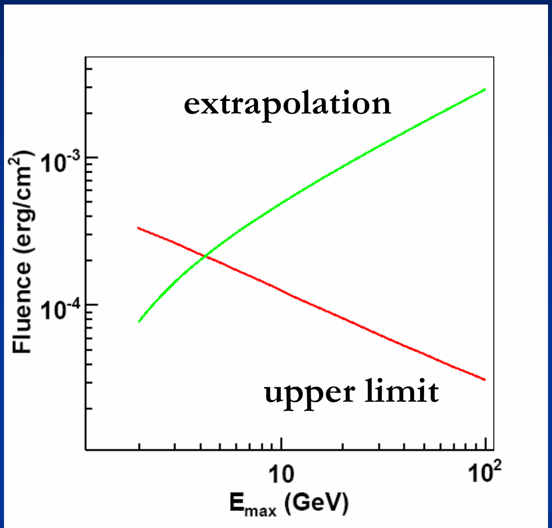
ARGO-YBJ has been taking data since Nov 2007
with duty cycle > 90%

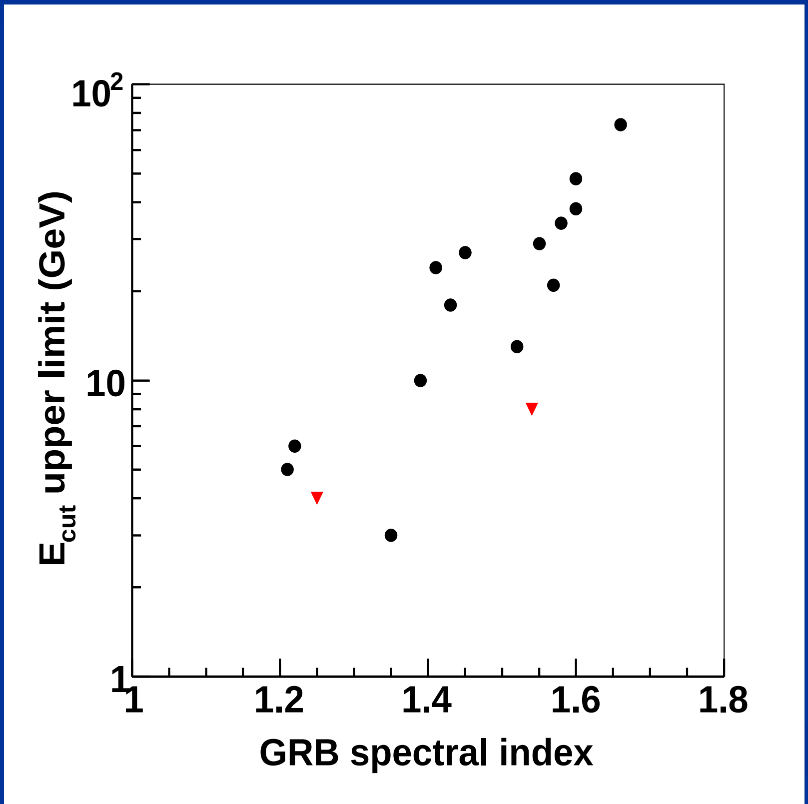
Results from the first year data :

- Angular resolution as expected
- Crab Nebula spectrum in agreement with other experiments
- Mrk421: - flare observed in 2006 with ARGO test data
  - monitored during all 2008
  - VHE flux correlated with X rays
  - observed flare in June in only 3 days
- Studies to increase the sensitivity are in progress
- Confirmation of the Milagro cosmic rays hotspots
- Sky survey going on

Upper Limits to the Cutoff Energy

An upper limit on the GRB cutoff energy is given by the intersection of the fluence upper limit, as a function of the cutoff energy, with the extrapolation of the fluence measured by satellites





The spectra of these GRBs do not extend beyond E_{cut} (with the index measured by satellites) with a 99% c.l.

(red triangles represent GRBs with known redshift)

Sky Survey

Search independent of satellite detections

In EAS-TOP a search for clusters of N shower events in □t $\leq$ 10 s in a circular window with radius $\alpha = 2.2\times\sigma_{res}$ was carried out, where σ_{res} was the detector angular resolution. The statistical significance of these clusters was then obtained from comparison with Poisson probability.

Possible search also for signals from evaporation of Primordial Black Holes (M □10^{15} g) on short timescales □t (Whipple → 1, 3 and 5 s).

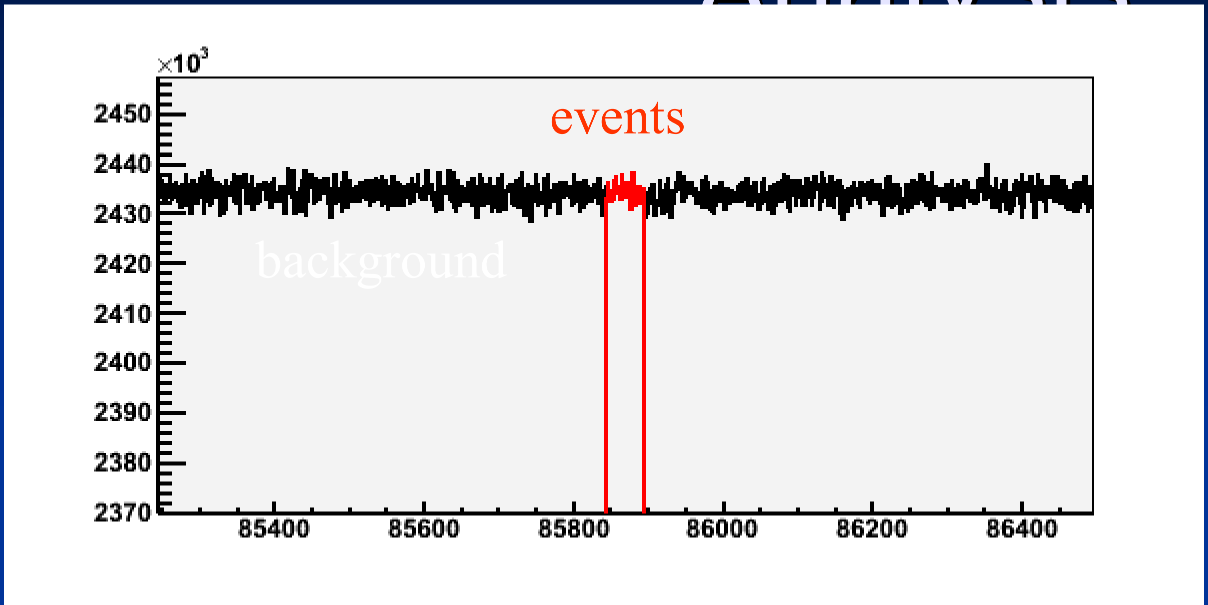
Absorption in the Extragalactic Background Light (EBL)

- GRB paper in single mode → model of Kneiske et al. (2004)
- Paper on Mrk421 → model of Primack et al. (2005)
- GRB paper in shower mode → model of Franceschini et al. (2008)

GRBs observed by LAT on Fermi

GRB	SAT	□T (s)	□ (°)	z	□
080825C	Fermi	22	56.2	~	2.34
080916C	Fermi	66	95.2	4.35	2.26
081024B	Fermi	□0.4	104	~	1.24
081215A	Fermi	7.7	35.9	~	2.066
090217	Fermi	32.8	109	~	CPL
090323	Fermi	□150	74.1	3.57	CPL
090328A	Fermi	□80	158	0.736	2.05
090510A	Swift	0.3	57.4	0.903	0.98
090626	Fermi	70	111	~	Band
090902B	Fermi	25	23.1	□1.822	1.94

GRB090902B: Scaler Data Analysis



□300 s around T90
(bins of □t = 0.5 s)

127 “good” clusters

Search on different timescales □t

T90 = 25 s → □ = 1.12
□t = 90 s (extended emission) → □ $\simeq$ 0.50
□t = T_0+6 □ T_0+26 s (maximum density of >1 GeV events) → □ = 1.16
□t = T_0+82 □ T_0+83 s (time of the 33 GeV photon) → □ = 0.74

GRB090902B: Upper Limit

- The spectrum obtained with both GBM and LAT data is well fitted by a Band function + underlying single power law

- Fluences of the Band component: F = 3.74□1$\tilde{0}^4$ erg/cm^2
  Fluence of the whole GBM + LAT emission:
  F(8 ke$\tilde{V}$30 GeV) = 4.86□1$\tilde{0}^4$ erg/cm^2

- Extrapolated fluence, considering absorption in EBL (z =1.8):
  F($\tilde{1}$100 GeV) = 5.9□1$\tilde{0}^5$ erg/cm^2

- Upper limit to fluence during T90, considering absorption:
  F($\tilde{1}$100 GeV) = 1.4□1$\tilde{0}^4$ erg/cm^2

- Upper limit to the cutoff energy, without absorption in EBL:
  E_{cut} = 130 GeV

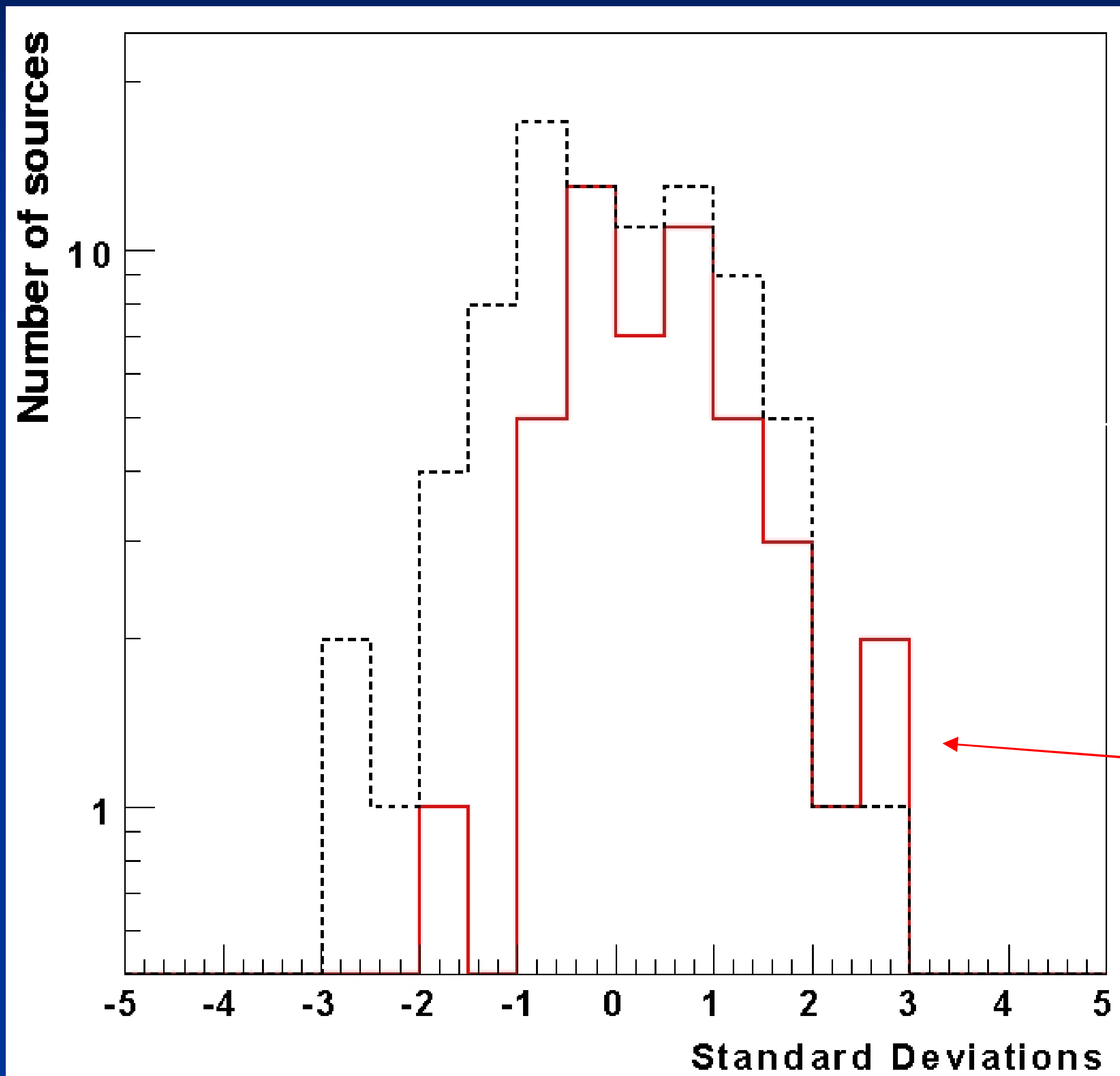
Other gamma rays sources….

115 Fermi Lat sources

44 TeV sources

⇨ 135 sources

135 Fermi LAT + TeV sources



Excesses distribution

86 extragalactic

Mean value = -0.02□0.12

49 galactic

Mean value = 0.45□0.14

The Moon Shadow

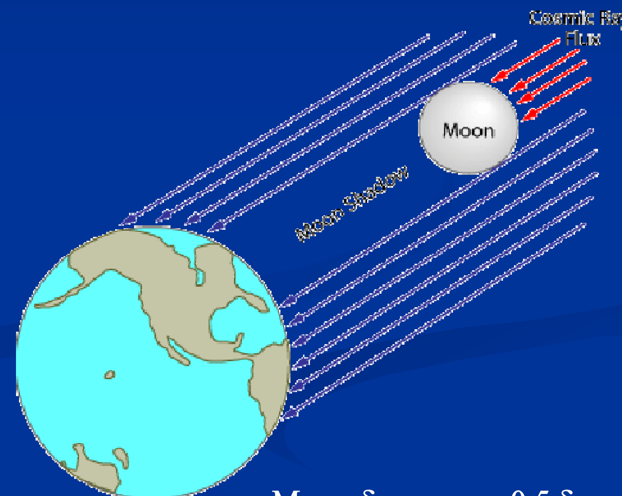
Χοσμιχ ραψσ αρε ηαμπερεδ βψ τηε Μοον

Δεφιχιτ οφ χοσμιχ ραψσ ιν τηε διρεχτιον οφ τηε Μοον

- Σιζε οφ τηε δεφιχιτ → Ανγυλαρ Ρεσολυτιον
- Ποσιτιον οφ τηε δεφιχιτ → Ποιντινγ Ερροր

Γεομαγνετιχ Φιελδ: ποσιτιϖελψ χηαργεδ παρτιχλεσ δεφλεχτεδ τοωαρδσ τηε Ωεστ ανδ νεγατιϖελψ χηαργεδ παρτιχλεσ τοωαρδσ τηε Εαστ. → Ιον σπεχτρομετερ

$$\Delta\vartheta \approx \frac{1.6^0 \cdot Z}{E(TeV)}$$

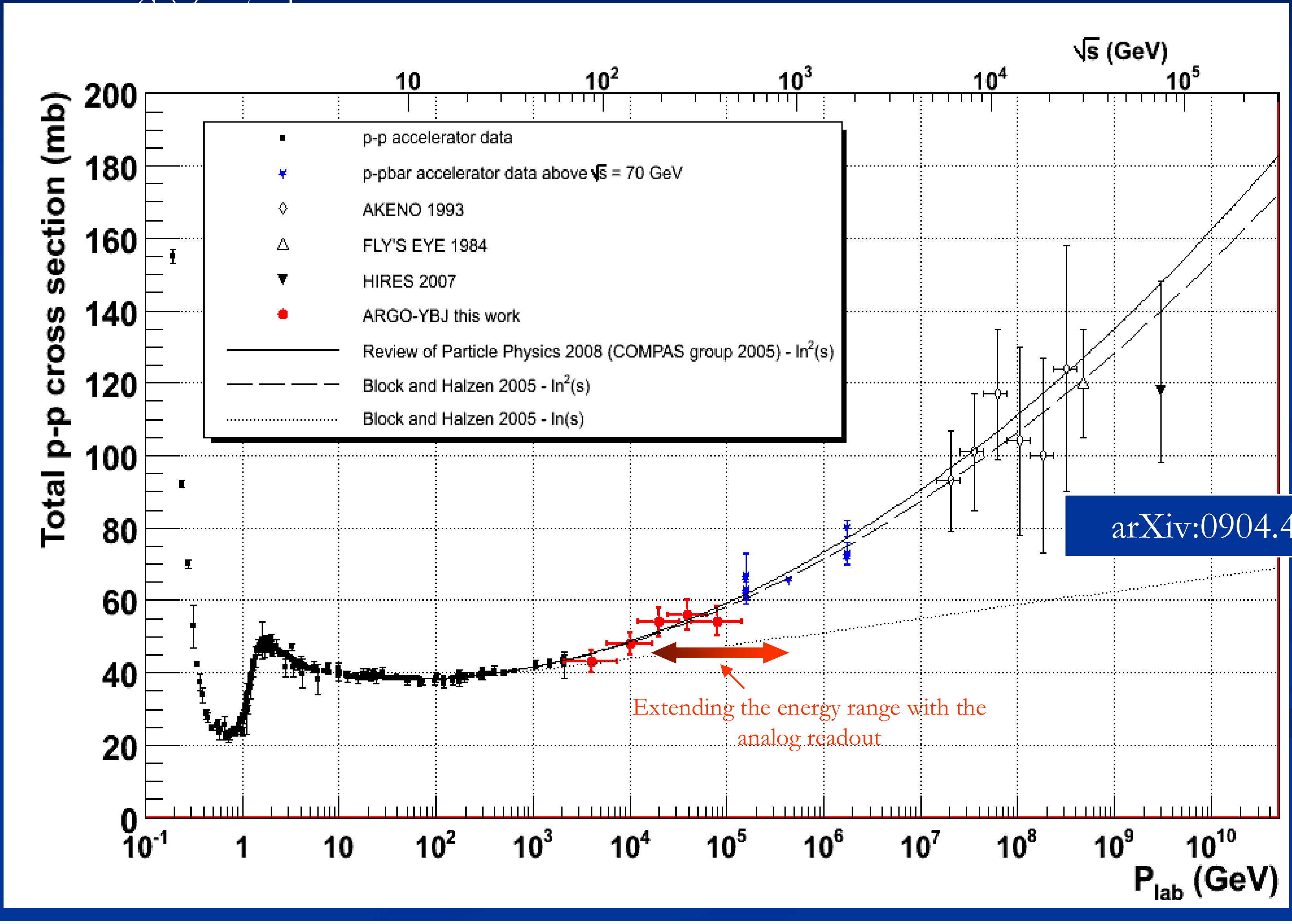


Μοον διαμετερ ~0.5 δεγ

Τηε οβσερϖατιον οφ τηε Μοον σηαδοω χαν προϖιδε α διρεχτ χηεχκ οφ τηε ρελατιον βετωεεν σιζε ανδ πριμαρψ ενεργψ → Ενεργψ χαλιβρατιον

section

- No p-p (and pbar-p) accelerator data available at these energies
- The log^2(s) asymptotic behaviour is favoured

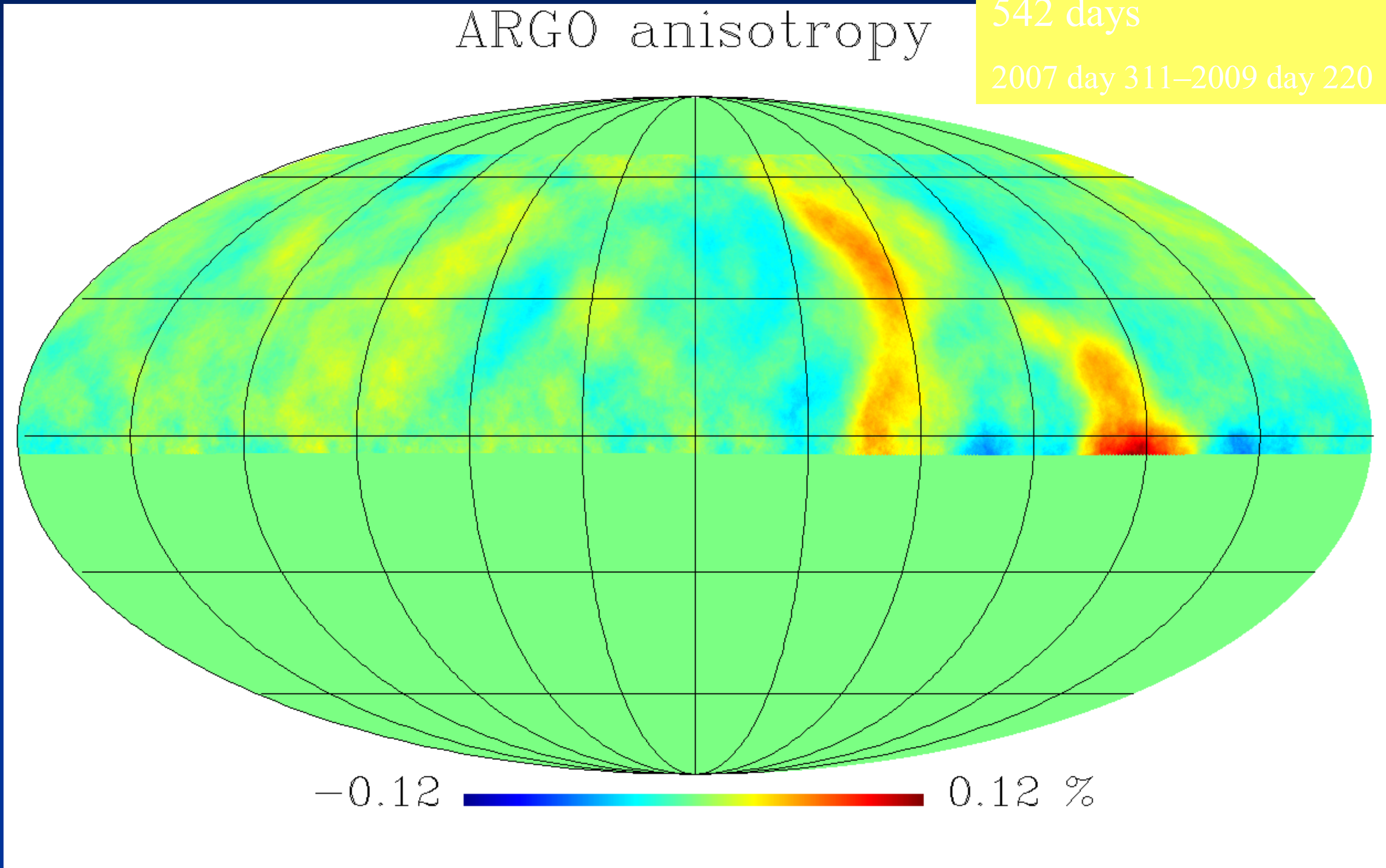


arXiv:0904.4198

Percent variation

542 days

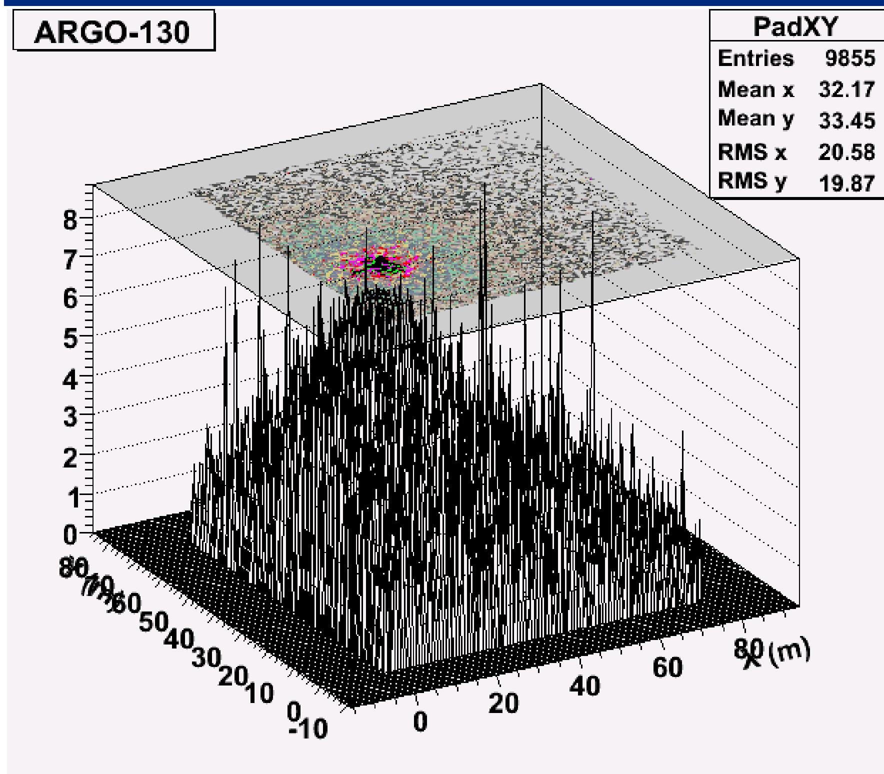
2007 day 311–2009 day 220



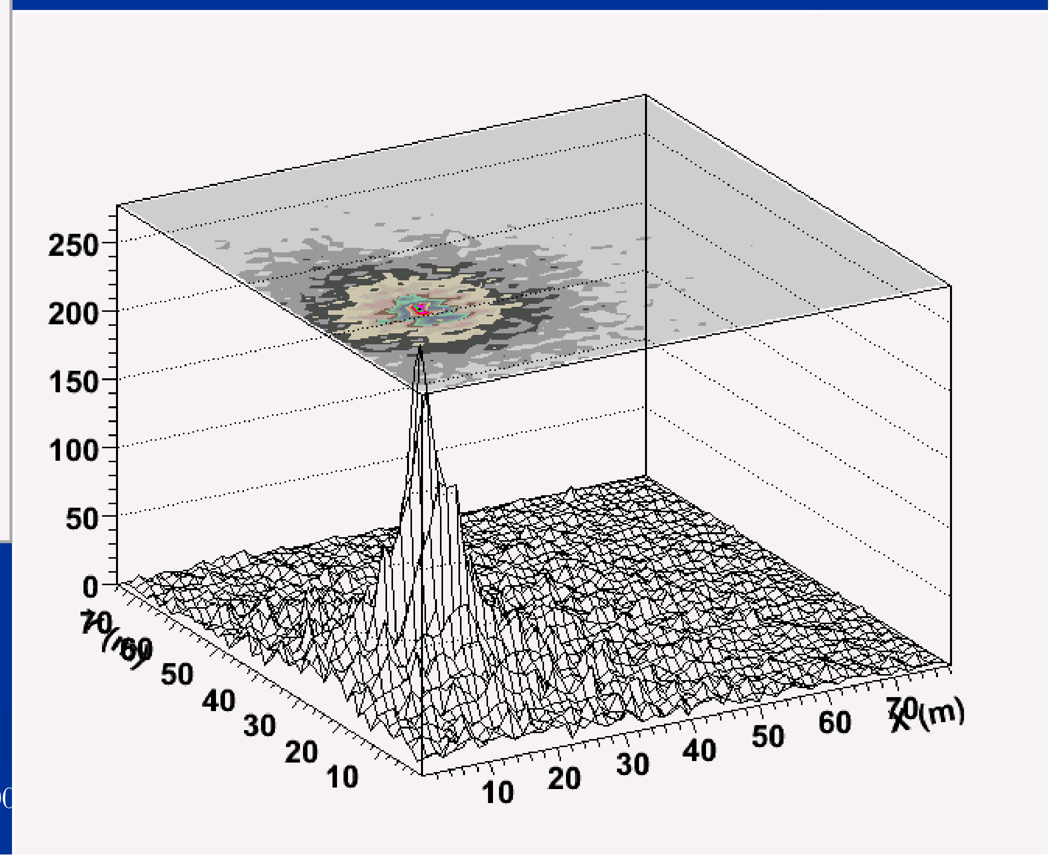
MX Εϖεντ δισπλαψ

Strip

E □ 100 TeV

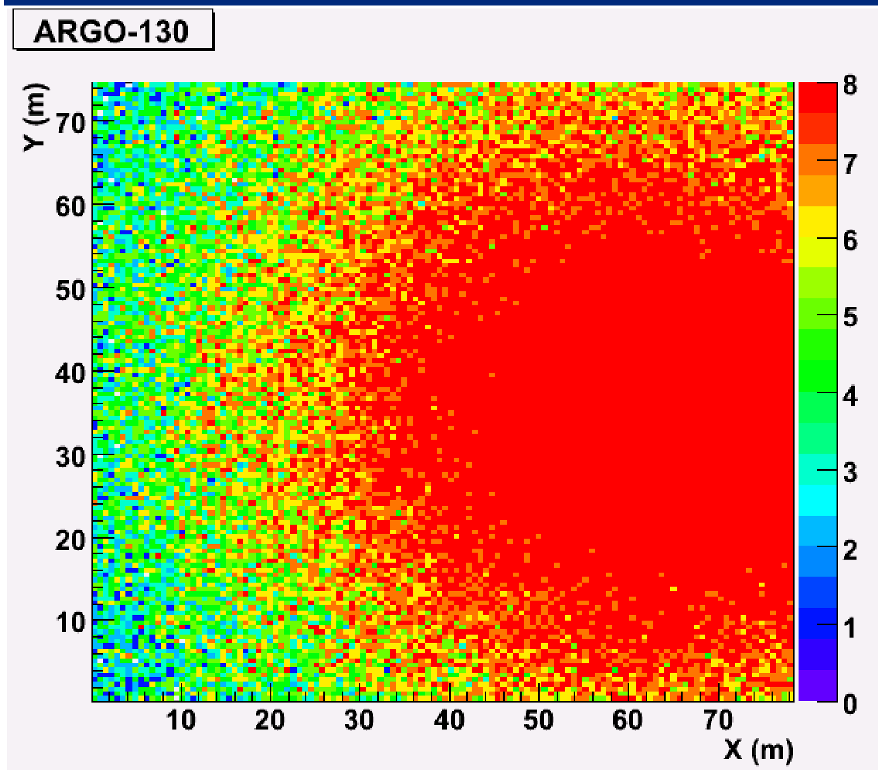


Big Pad

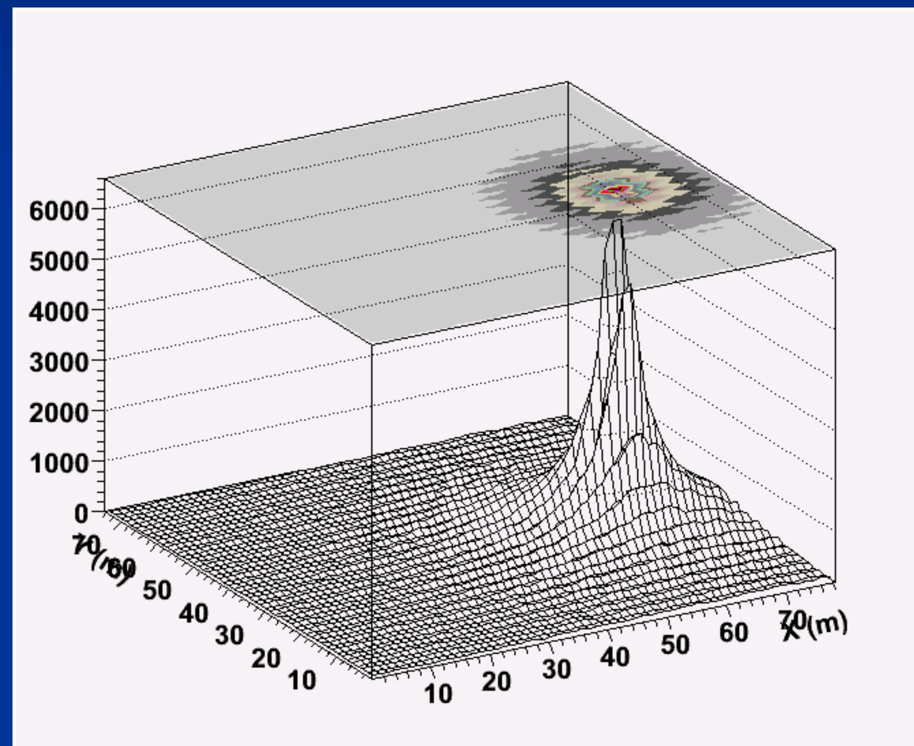


E 1000 TeV

Strip

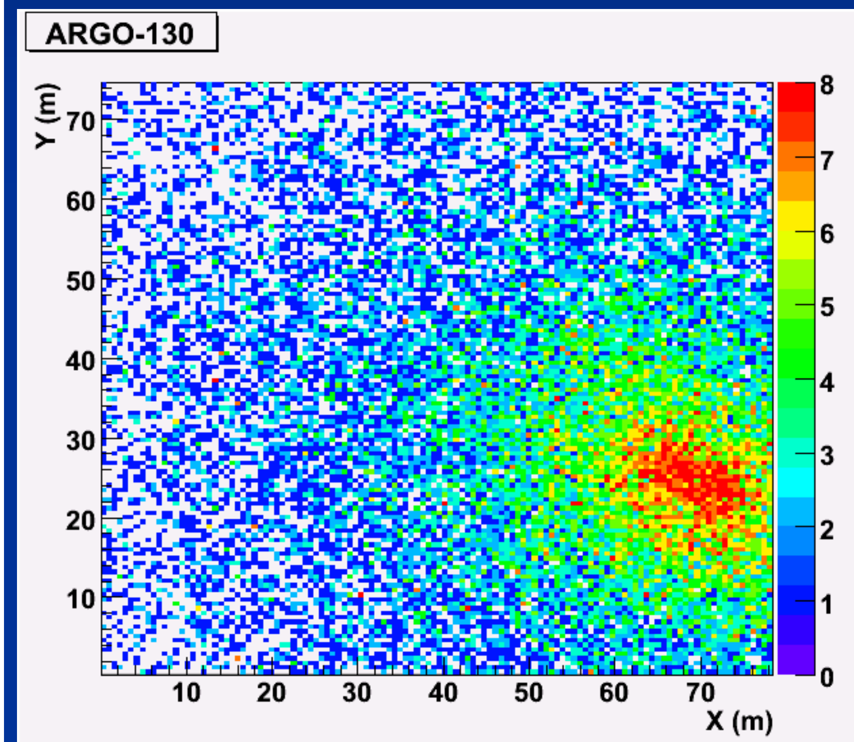


Big Pad

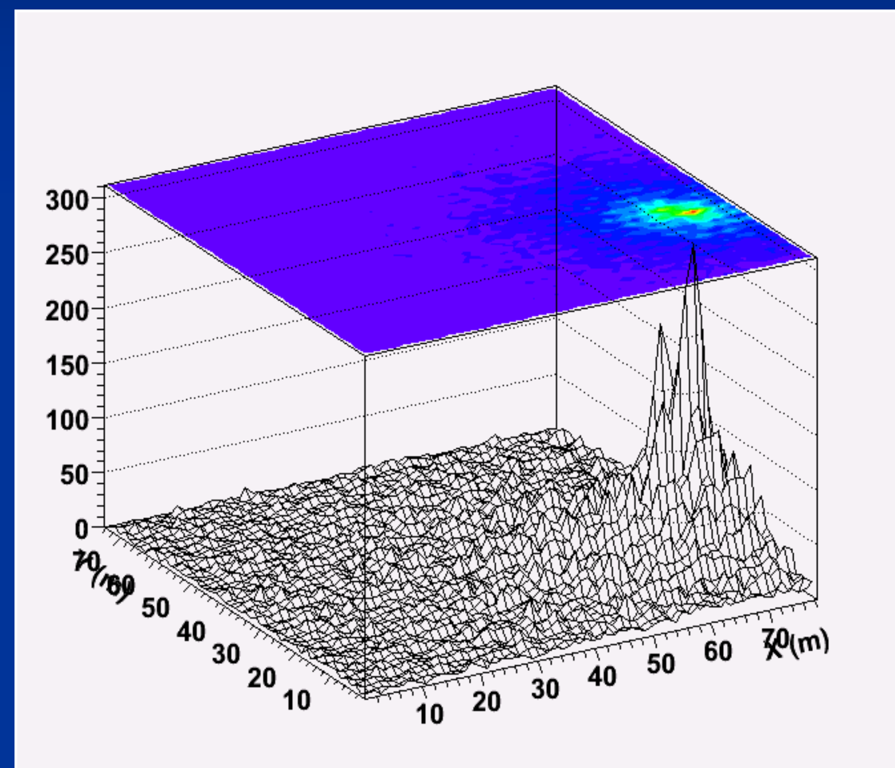


E □ 100 TeV

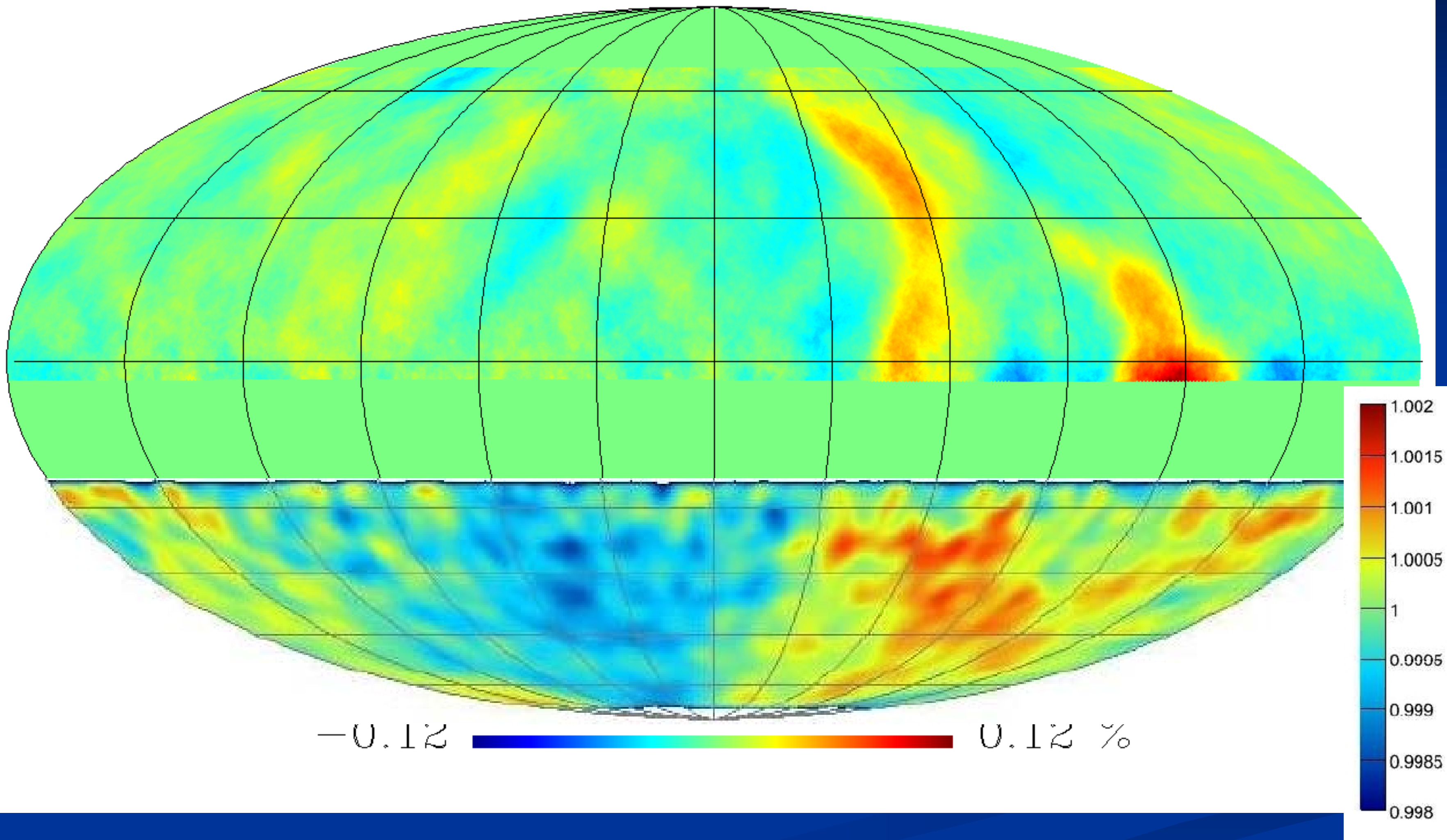
Strip

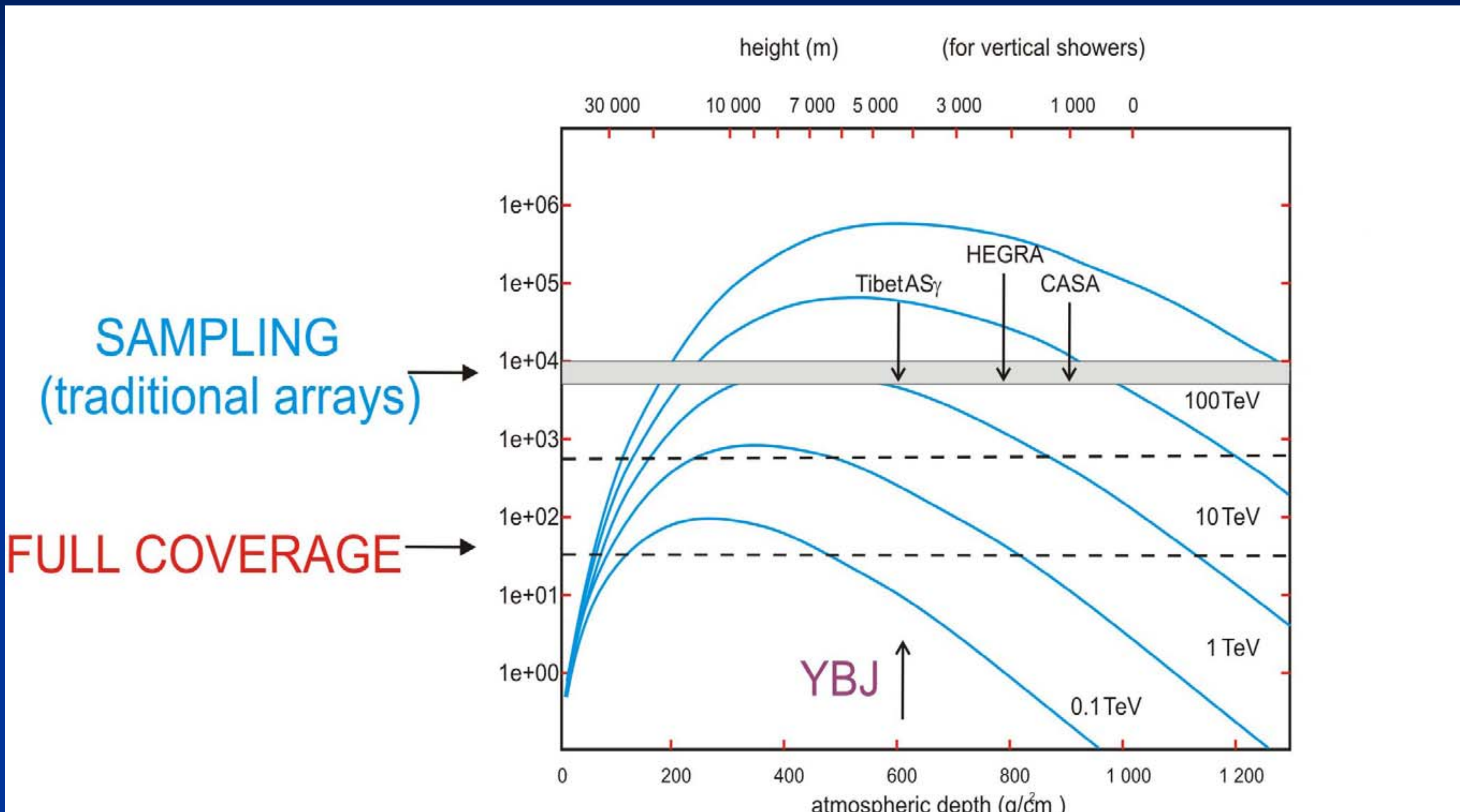


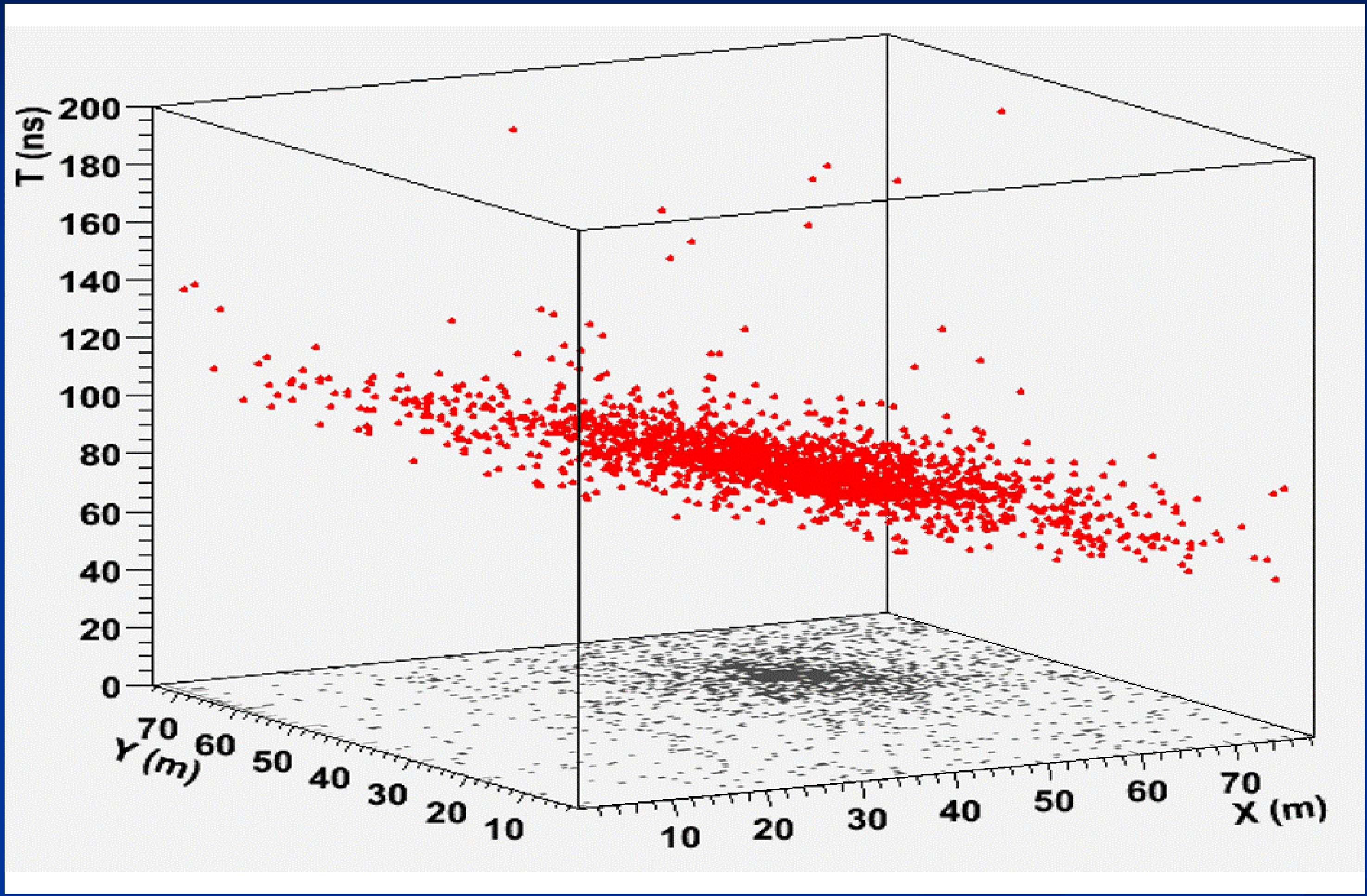
Big Pad



ARGO & ICECUBE muons

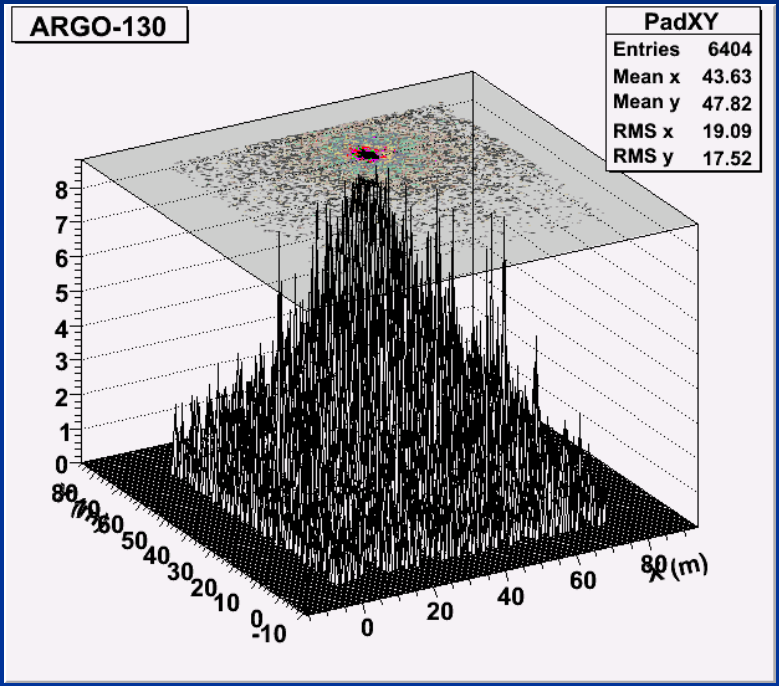


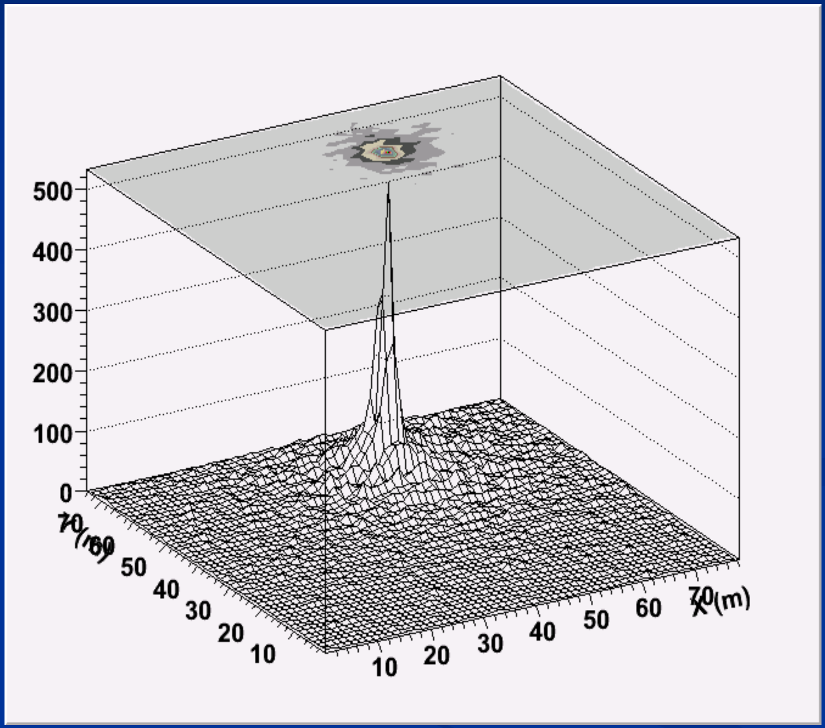

SAMPLING
(traditional arrays)
FULL COVERAGE
height (m)
(for vertical showers)
30 000
10 000
7 000
5 000
3 000
1 000
0
1e+06
1e+05
1e+04
1e+03
1e+02
1e+01
1e+00
HEGRA
TibetASγ
CASA
100 TeV
10 TeV
1 TeV
0.1 TeV
YBJ
0
200
400
600
800
1 000
1 200
atmospheric depth (g/cm²)



T (ns)
200
180
160
140
120
100
80
60
40
20
0
Y (m)
70
60
50
40
30
20
10
X (m)
10
20
30
40
50
60
70

E ~ 100 TeV

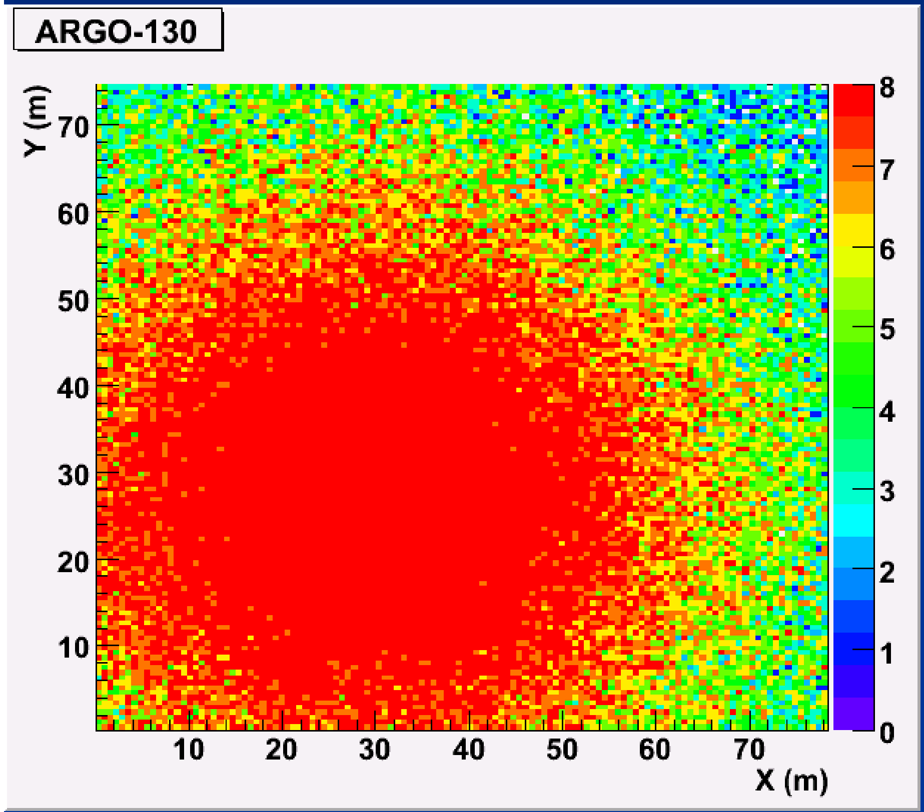


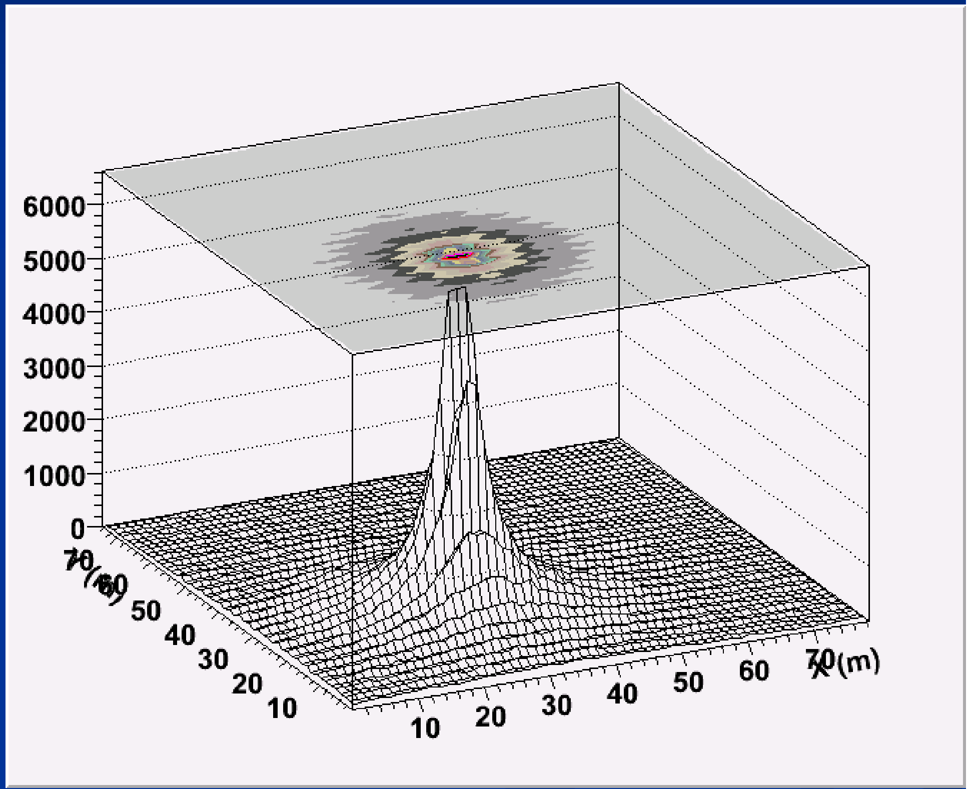


Strip

Big Pad

E ~ 1000 TeV

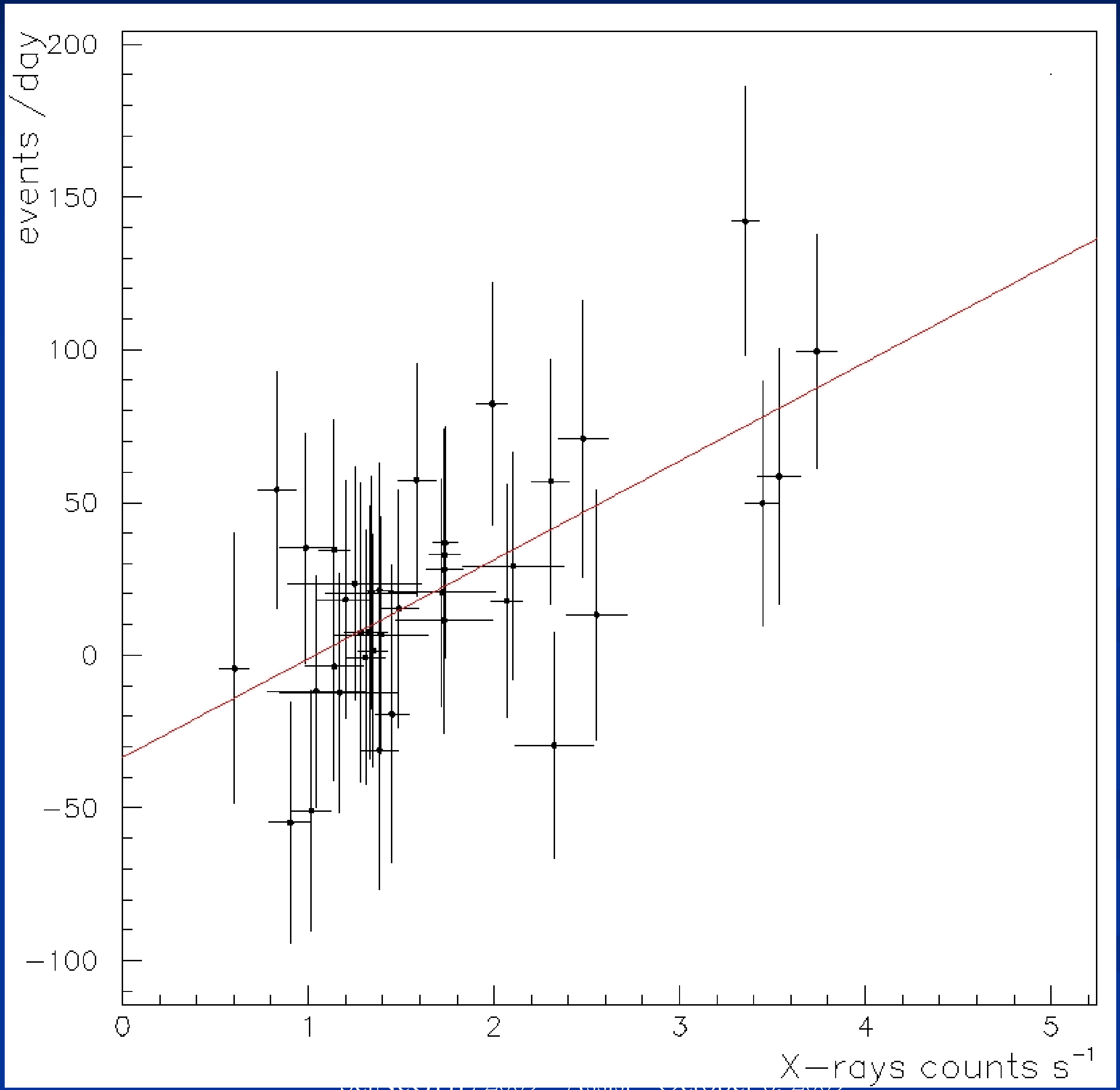




Strip

Big Pad

Gamma Rays vs X-rays in 2008



10 days average