Measurement of CR Spectrum and Anisotropy with ARGO-YBJ

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On behalf of the ARGO-YBJ Collaboration

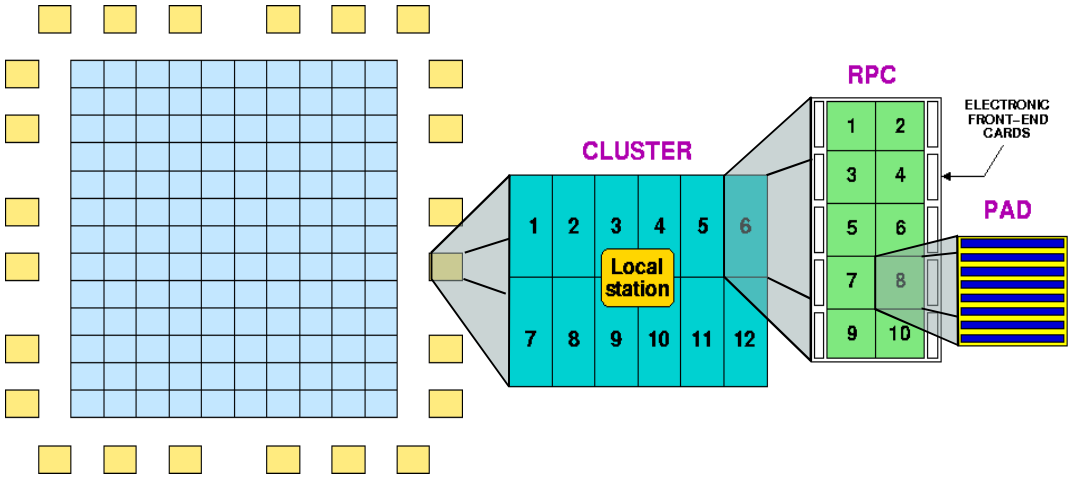
International Symposium on Very High Energy Cosmic Ray Interactions (ISVHECRI 2012)

Questions to the knee energy range

Overlap direct – indirect measurements ?	→	**Still missing**
Composition at the knee ?	→	**Still open**
Hadronic interaction models ?	→	**Still uncertain**
End of galactic spectrum ? **Transition galactic – xgalactic ?**	→	**Open**
Anisotropy ?	→	**Totally open**
Rigidity – dependent knee ?	→	**Probably established**

A. Haungs, 2011

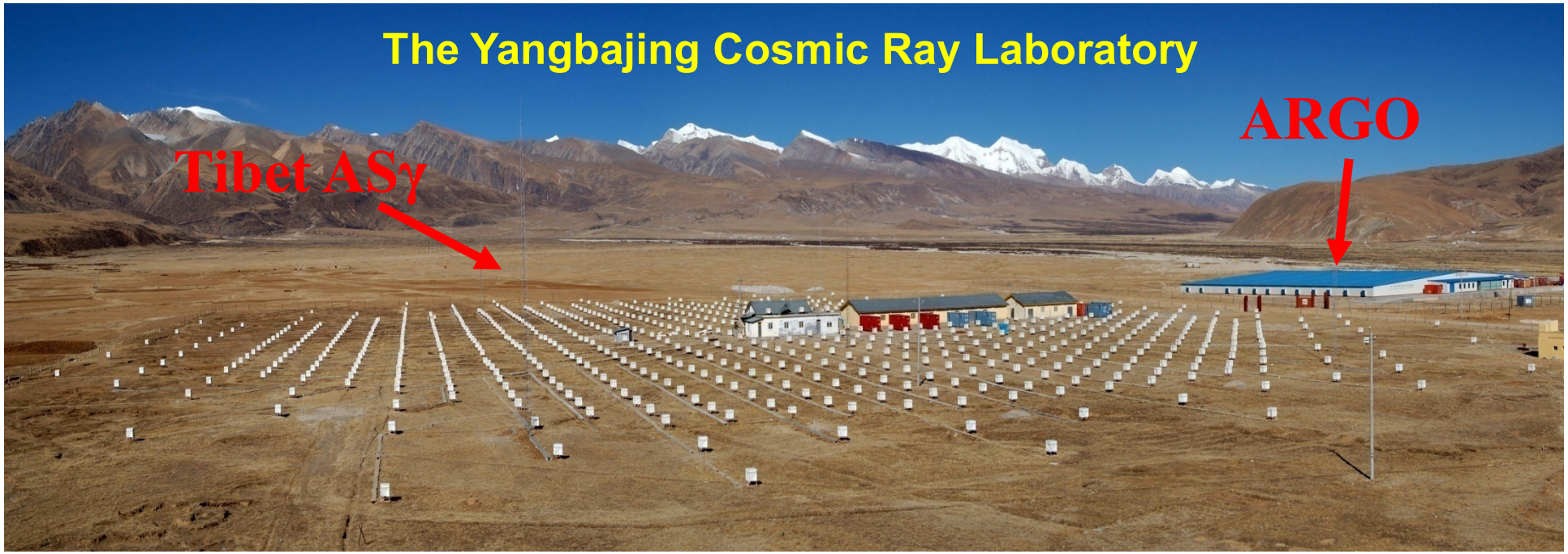
The ARGO-YBJ experiment



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)

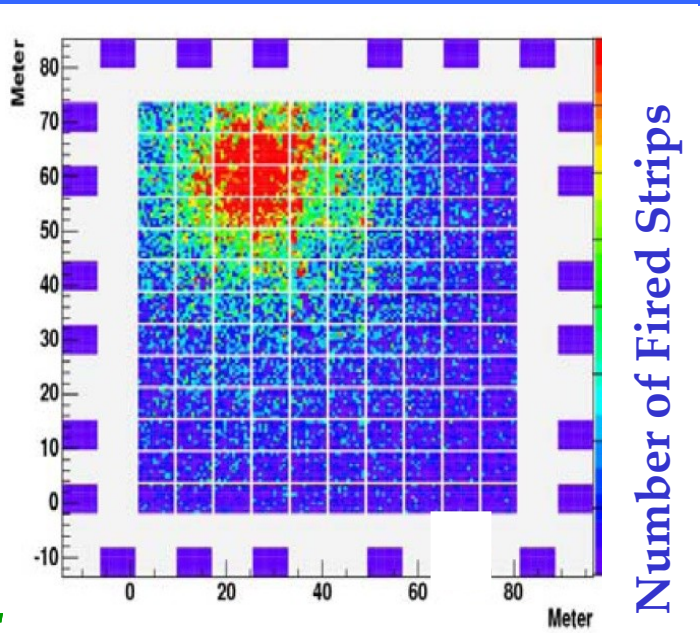
- ***FULL COVERAGE***
  (RPC technology, 92% covering factor)

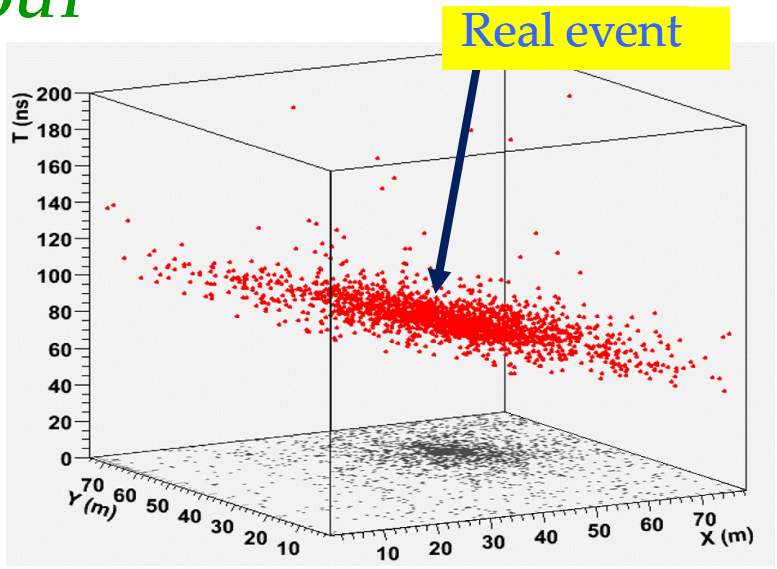
- ***HIGH SEGMENTATION OF THE READOUT***
  (small space-time pixels)

  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**



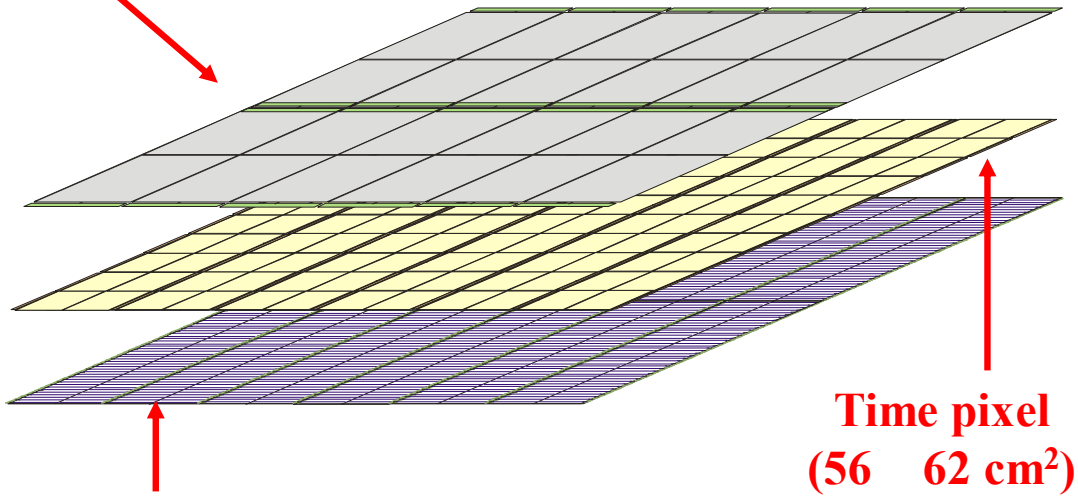


The basic concepts

…extending the dynamical range

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

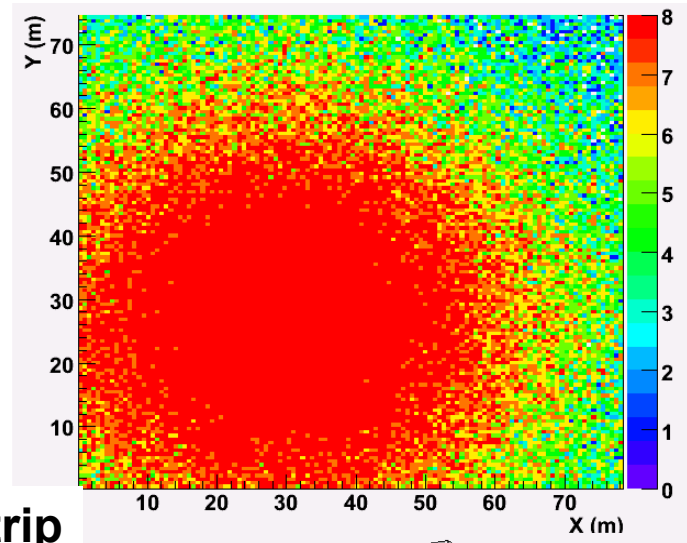
Big Pad for charge read-out



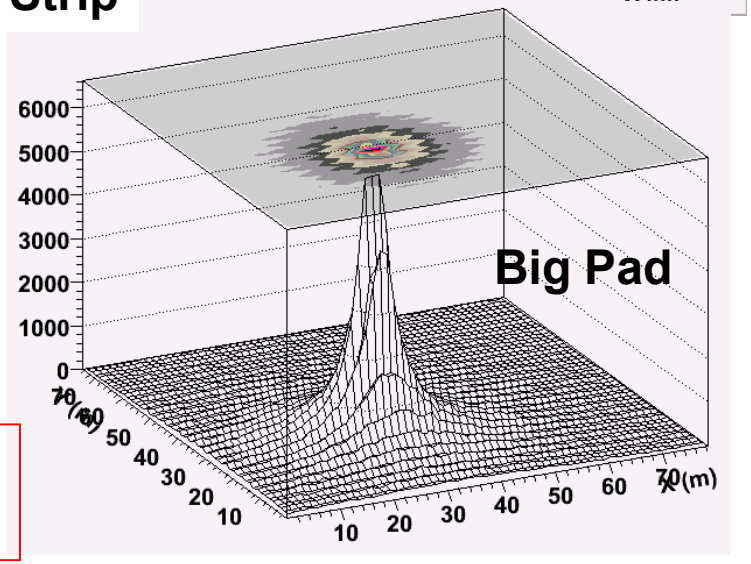
Space (digital) pixel
(6.7 62 cm²)
#146880

Time pixel
(56 62 cm²)
#18360

E ~ 1000 TeV



Strip

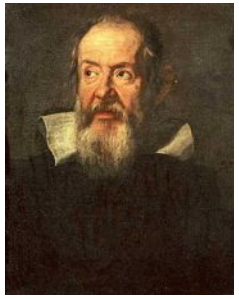


Monday, 13 Aug. 2012
14:40 talk by A. Surdo

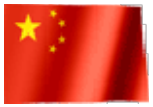
The ARGO-YBJ Collaboration

Collaboration Institutes:

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



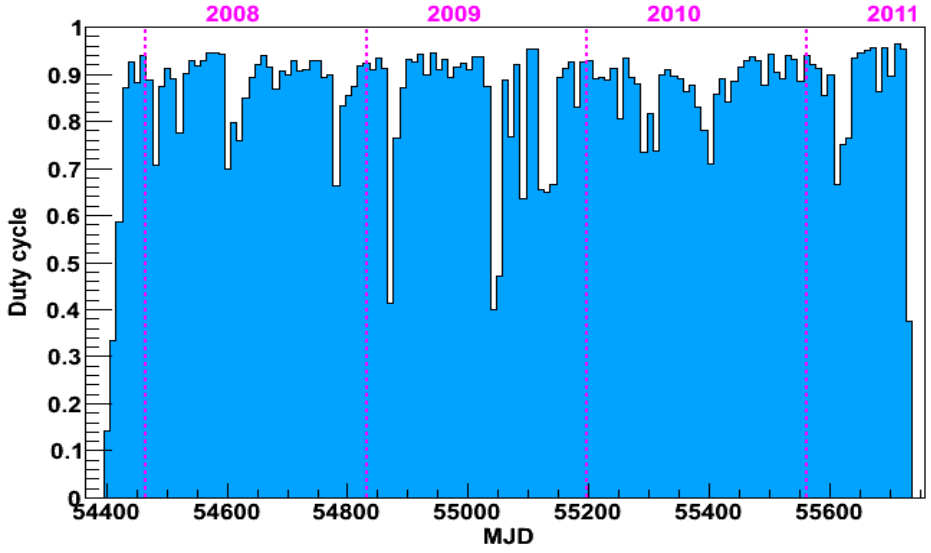
INAF/IASF, Palermo and INFN, Catania
INFN and Dpt. di Fisica Università, Lecce
INFN and Dpt. di Fisica Universita', Napoli
INFN and Dpt. di Fisica Universita', Pavia
INFN and Dpt di Fisica Università "Roma Tre", Roma
INFN and Dpt. di Fisica Univesità "Tor Vergata", Roma
INAF/IFSI and INFN, Torino

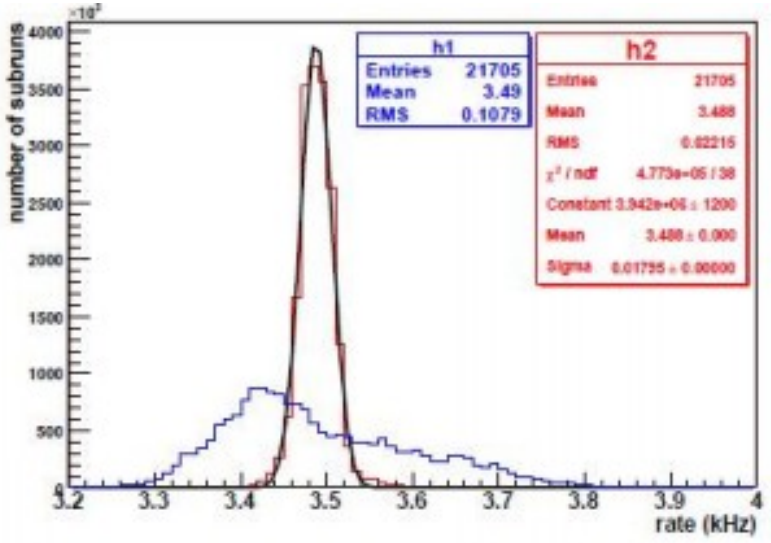


IHEP, Beijing
Shandong University, Jinan
South West Jiaotong University, Chengdu
Tibet University, Lhasa
Yunnan University, Kunming
Hebei Normal University, Shijiazhuang

Current Status

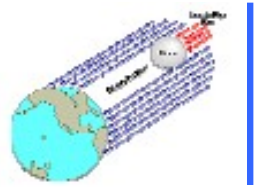
- **In observation since July 2006 (commissioning phase)**
- **Stable data taking since November 2007**
- **The average duty cycle ~ 87%, dead time 4%**
- **Trigger rate ~3.5 kHz @ 20 pad threshold**
- **N. recorded events: ≈ $4 \cdot 10^{11}$ from 300 GeV to PeV**



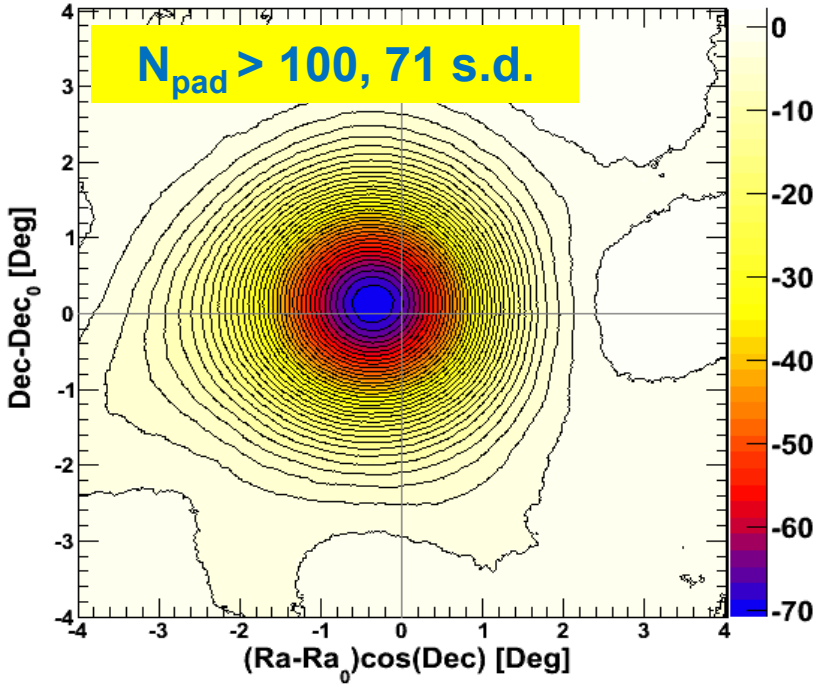


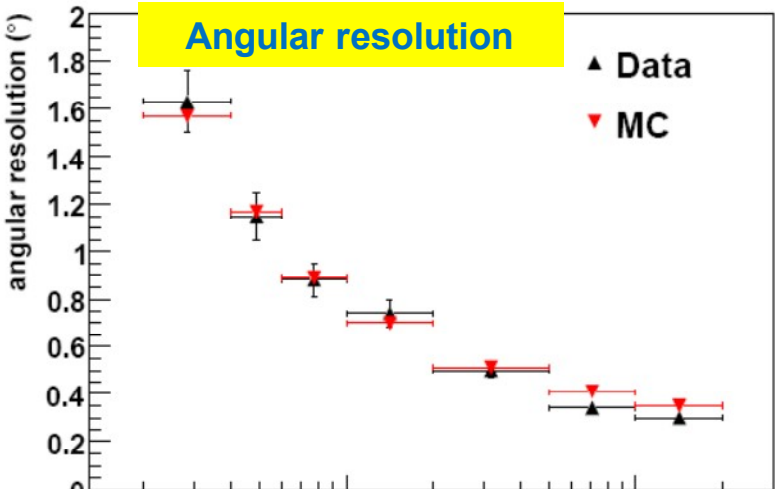
Intrinsic Trigger Rate stability 0.5%
(after corrections for T/p effects)

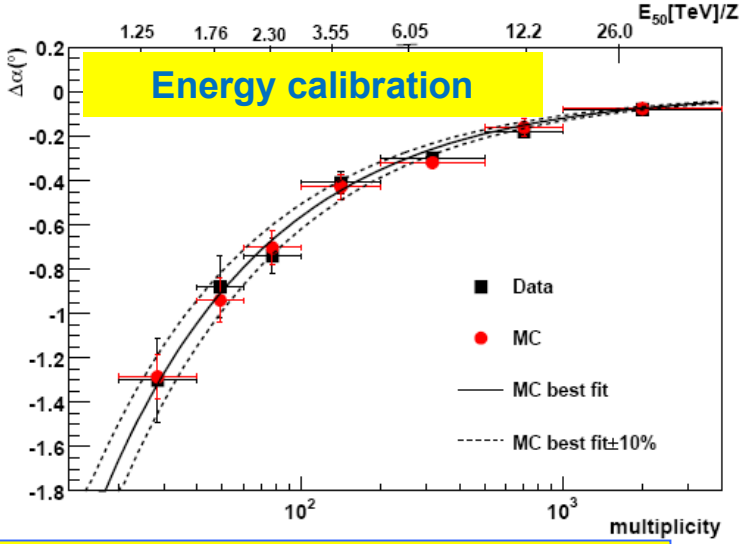
Moon shadow analysis



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



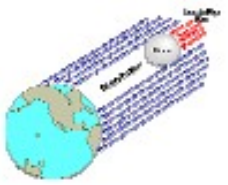




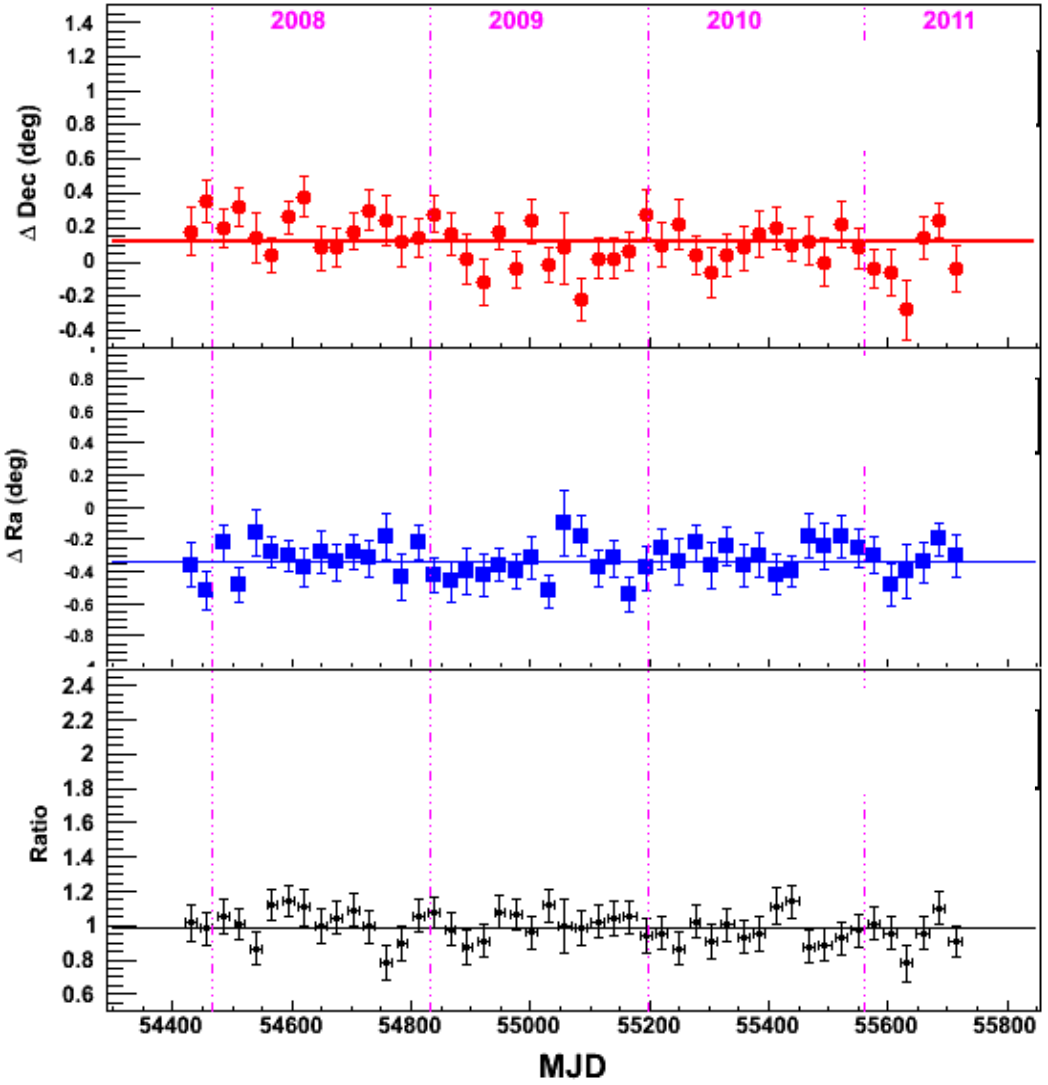
PRD 84 (2011) 022003
PRD 85 (2012) 022002

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%



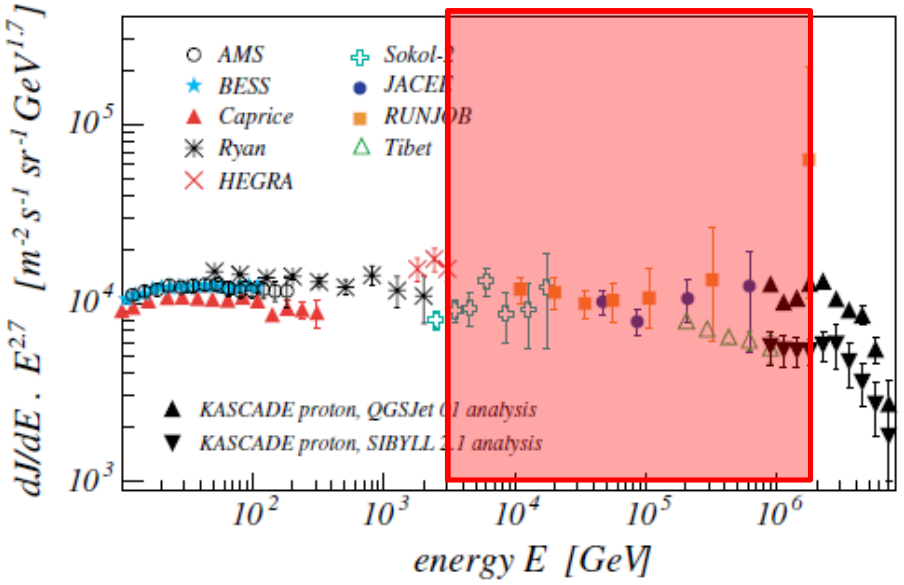
Overlapping the direct measurements

Measurements of the CR spectrum:

- **Balloons and satellites ≤ 100 TeV**
- **EAS-arrays energy threshold of ≈100 TeV**

The overlap direct – indirect measurements important to anchor the ground-based CR measurements in the UHE range still missing.

ARGO-YBJ is able to covers the energy range TeV → PeV.



Measurement of the CR primary spectrum

$$R(\Delta m) = \sum_i \int J_i(E) \cdot P_i(E;\Delta m) dE$$

- $\theta < 15$
- Core inside 40×40 m^2 area
- < 500 "dead" pads (over 15600) on the central carpet
- $\Delta p < 4\%$ in the YBJ site
- $m < 10^4$, contribution from heavy nuclei negligible

250 days ≈ 5 ·10^{11} events in 2009

Efficiency reconstruction >85%

Contamination from external events <15%

The expected rate

Different contributions calculated with CREAM spectra

Relative fractions (% of the total)

[251-398] → few TeV

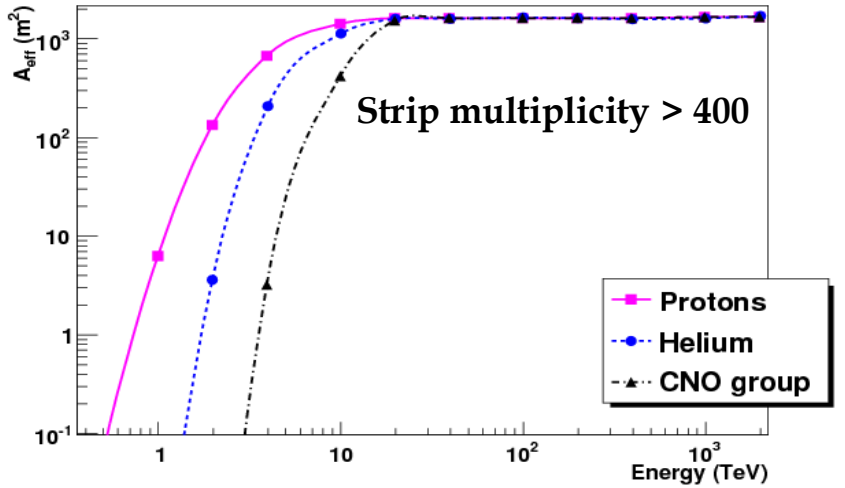
R_p / R_{He} / R_{CNO} / R_{Heavy}

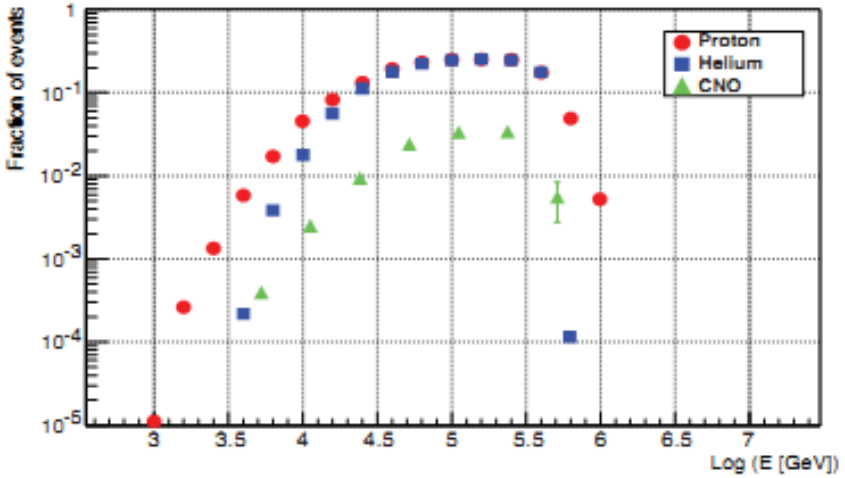
67.6 / 28.2 / 2.7 / 0.7 %

[6310-10000] → ≈ 100 TeV

R_P / R_{He} / R_{CNO} / R_{Heavy}

51.2 / 40.4 / 4.4 / 2.4 %

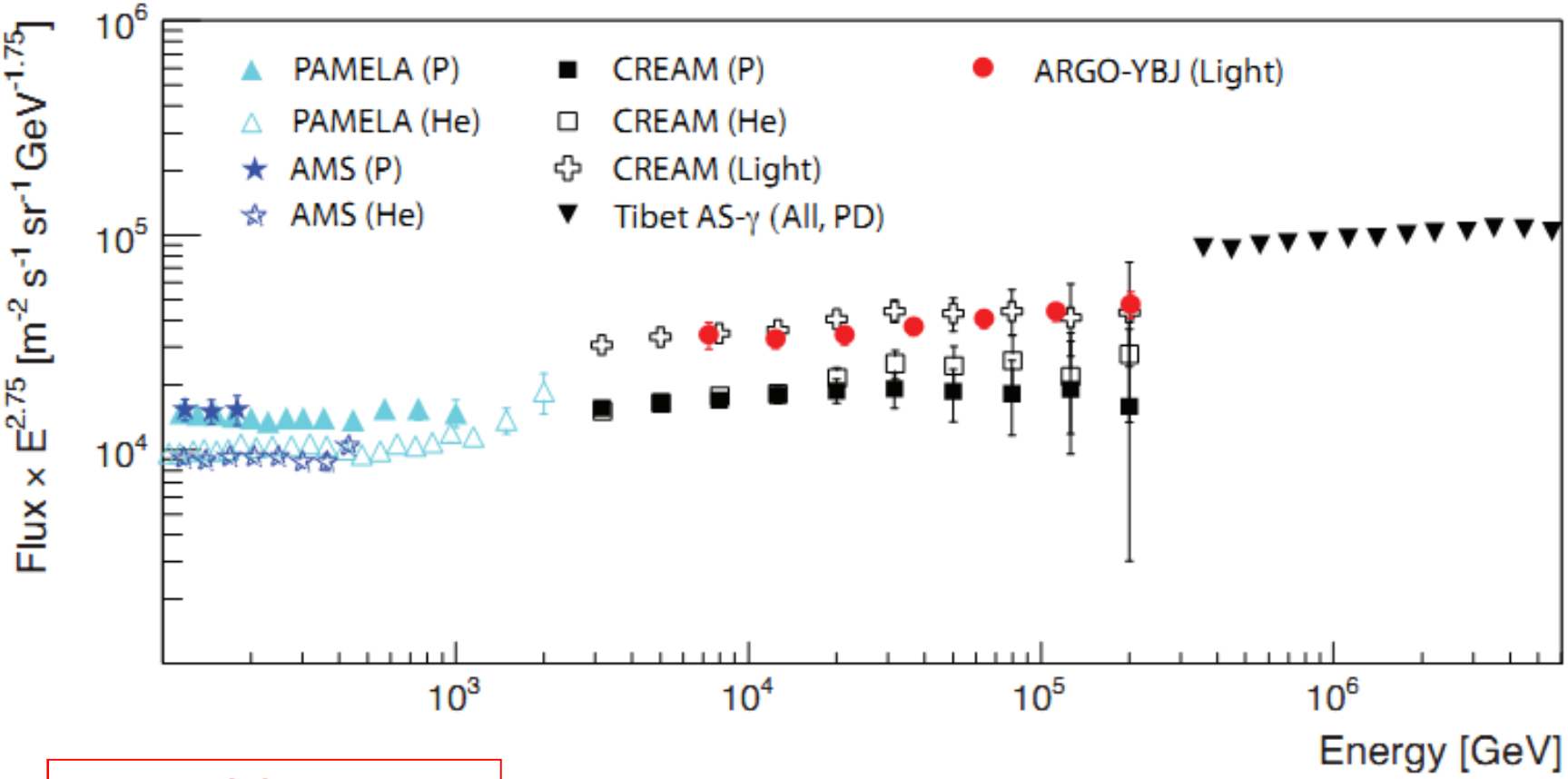




5. *The fraction of the simulated events selected by the cuts used in this analysis is shown as a function of the energy for proton induced events (red circles), helium induced events (blue squares) and CNO induced events (green triangles).*

Light-component (p+He) by ARGO-YBJ

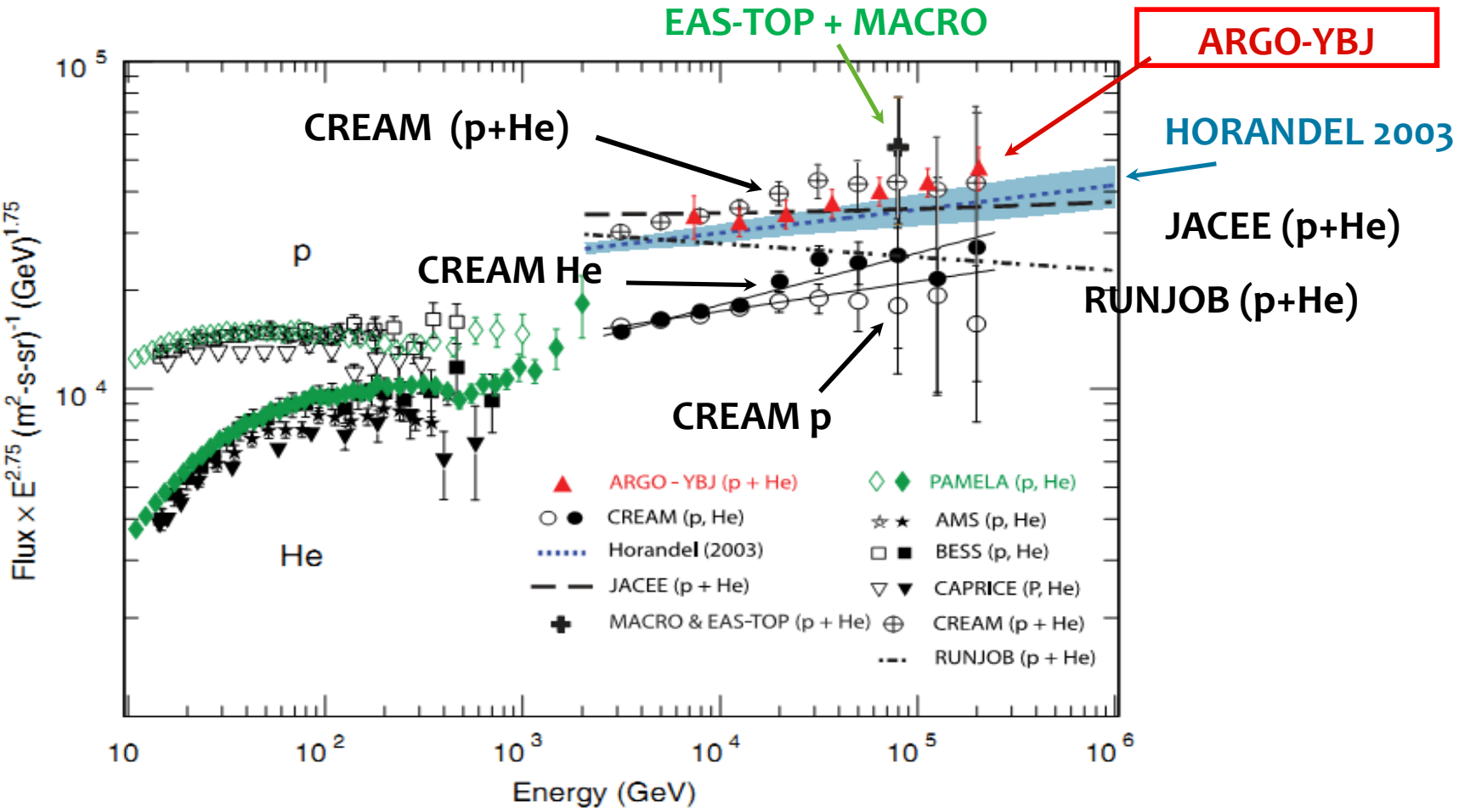
Measurement of the *light-component* (p+He) CR spectrum in the energy region (5 – 250) TeV via a Bayesian unfolding procedure



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

PRD 85, 092005 (2012)

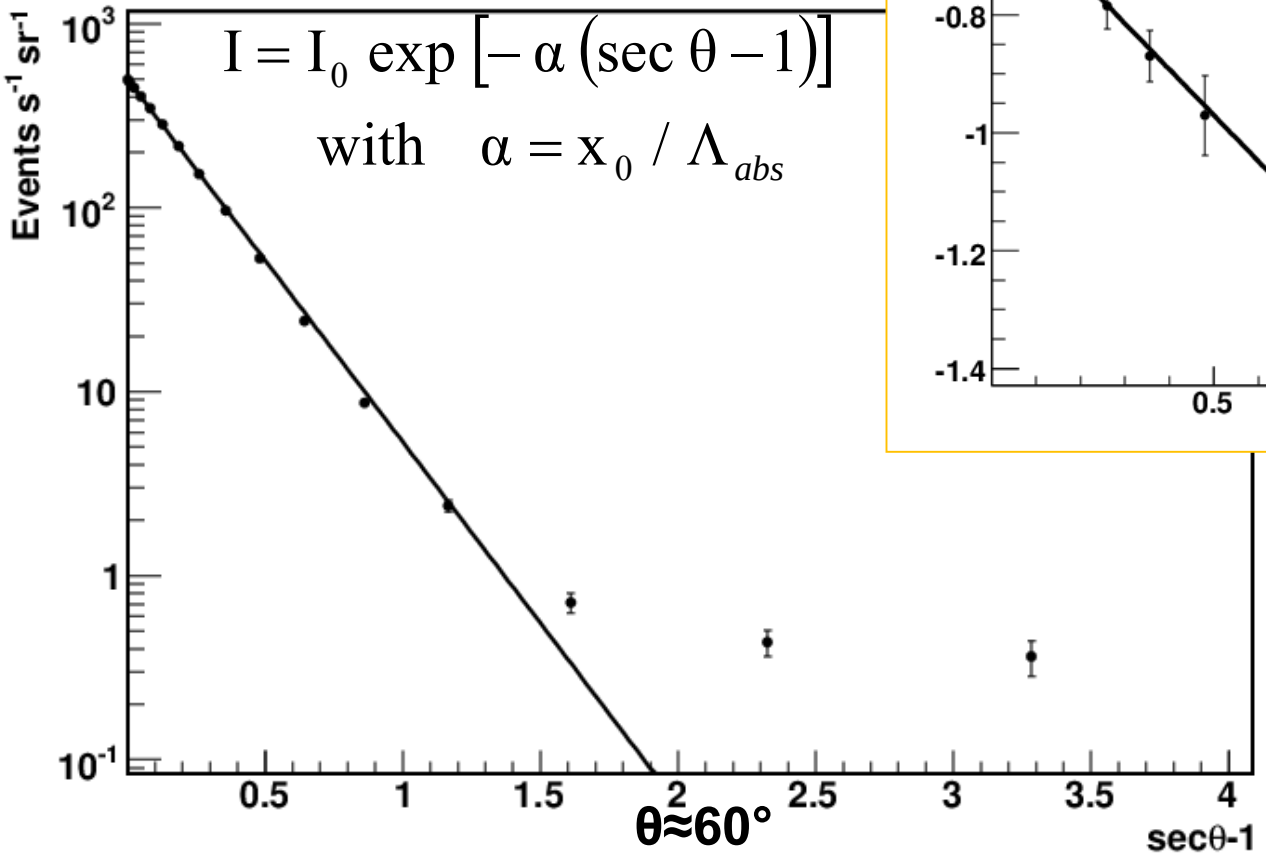
Light-component (p+He) Energy Spectrum



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.

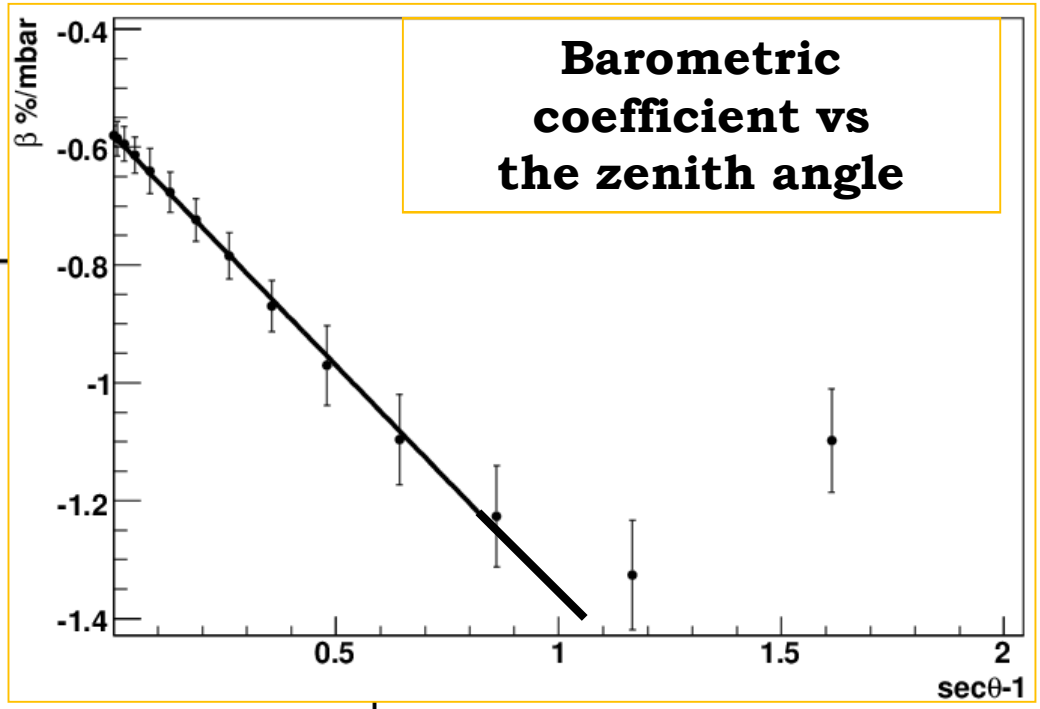
Rate as a function of the zenith angle

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



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

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



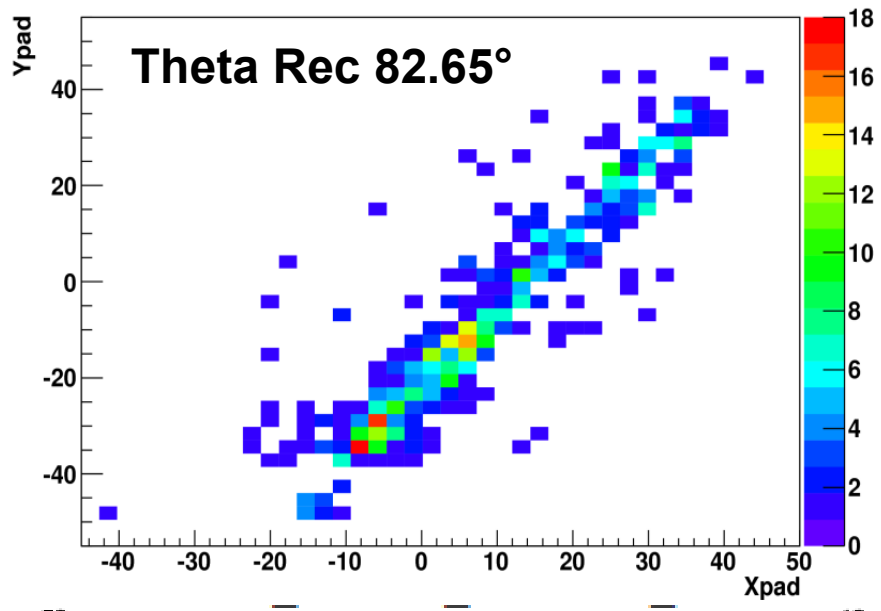
Barometric coefficient vs the zenith angle

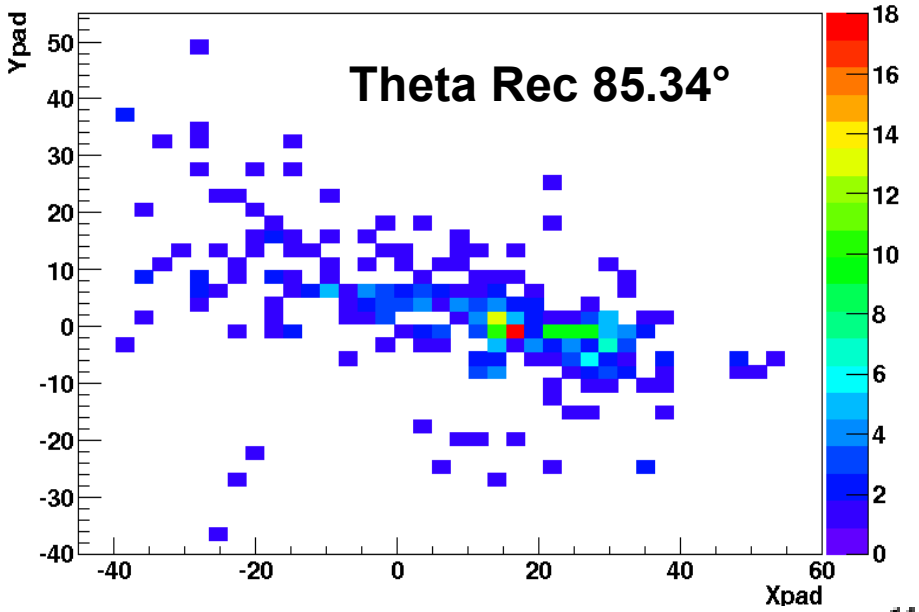
Fit: $I_0 = (165 \pm 9)$ s^{-1} sr^{-1}
$\alpha = 5.4 \pm 0.1$

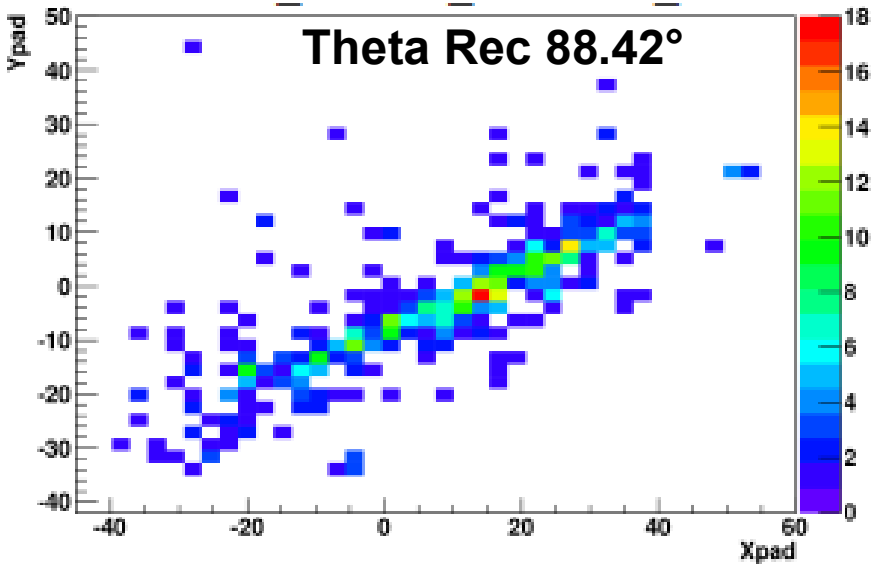
$\Lambda_{abs} = 108 + 2$ g/cm²

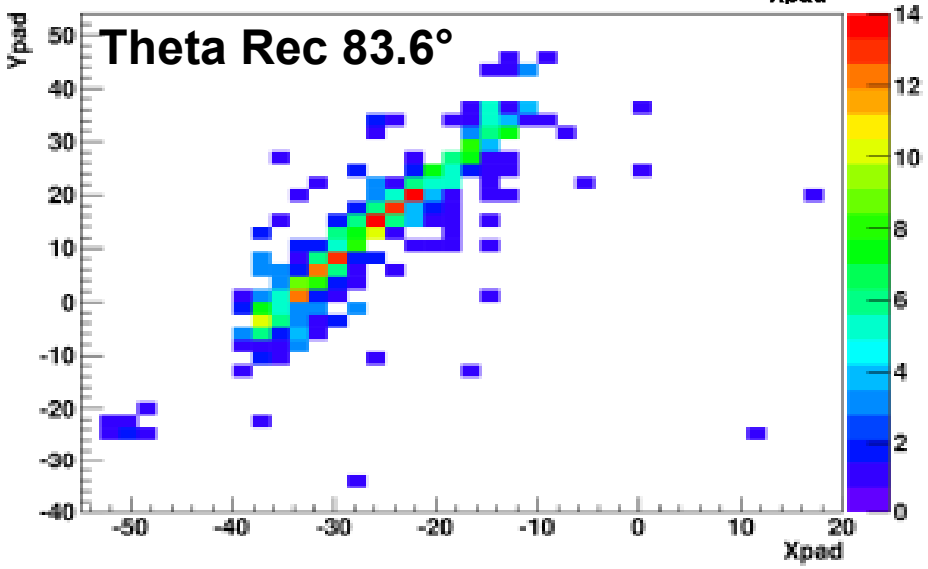
Λ_{abs} = absorption length
$\beta = \gamma/\lambda$

Horizontal Air Showers by ARGO-YBJ





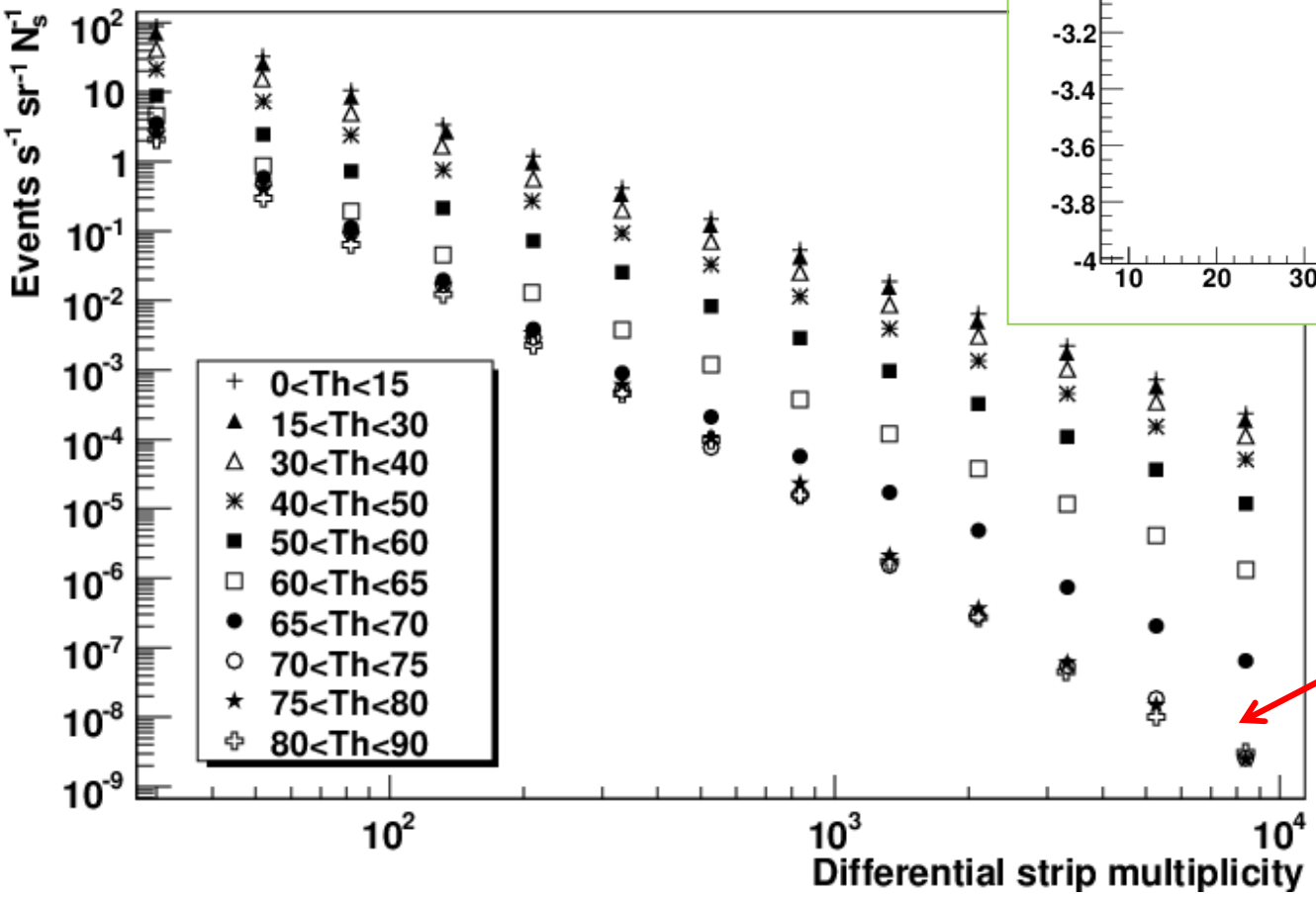


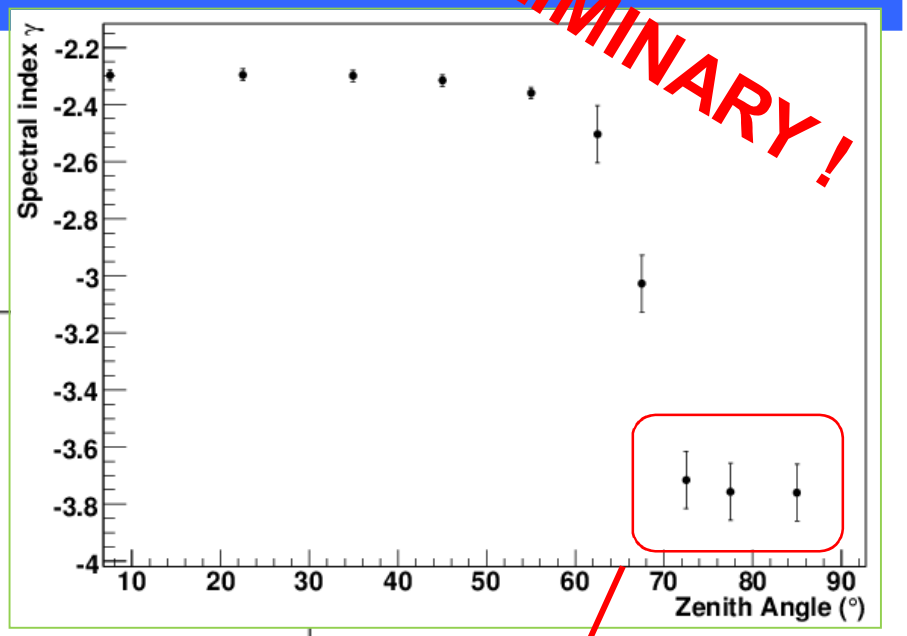


Measured Rate of HAS

PRELIMINARY !

Strip multiplicity for different zenith angles

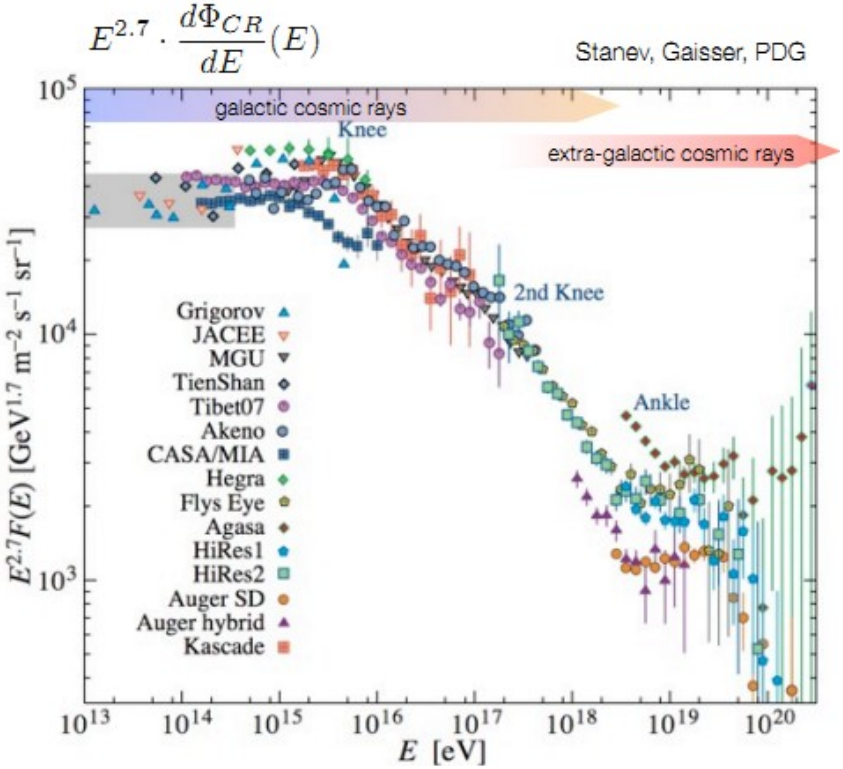




$\gamma \approx -3.70$ spectral index muons in EAS

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**



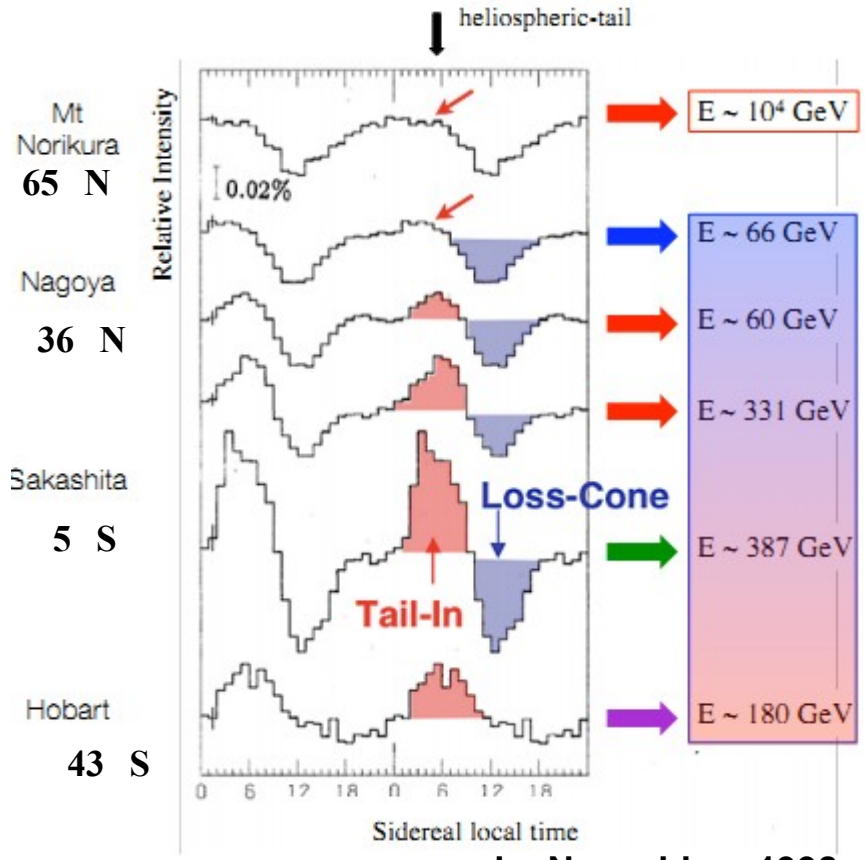
- **Galactic CRs are expected to be highly isotropic scrambled by galactic magnetic field over very long time.**

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

An-isotropy observed

- anisotropy of arrival direction of CRs clearly observed since 80's
- 10's GeV - 100's TeV in μ detector, surface arrays and ν detectors
- observed anisotropy of about 10^{-3} - 10^{-4}

- Tail-in feature directed towards the heliospheric tail peak located at RA ~ 6h (~90°) .
- Amplitude and phase change with latitude
- North-South asymmetry
- Tail-in modulated in time: max in Dec. and min in June



by Nagashima 1998

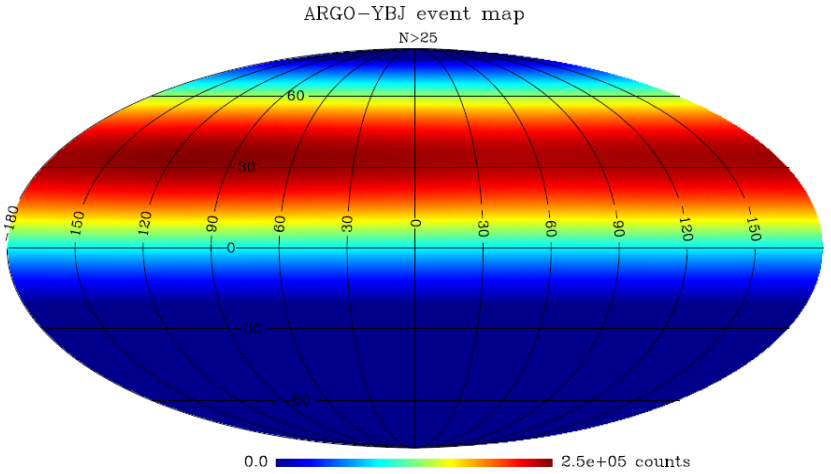
Anisotropy data analysis

DATA SET:

Nov. 2007 - May 2011 data (~1300 days)

N_{str} > 25, Zenith angle < 50°, $3 \cdot 10^{11}$ events

No selection cuts applied.



Equatorial coordinates
The color scale gives the bin content.

Exposure estimation:

Crucial, as any mis-intepretation of the sky exposure may mimic a fake anisotropy.

Challenging: signals are as intense as 10^{-3} - 10^{-4} with respect of the average flux → the exposure has to be estimated with accuracy equal or better.

For larger scales: Equi-zenith angle method

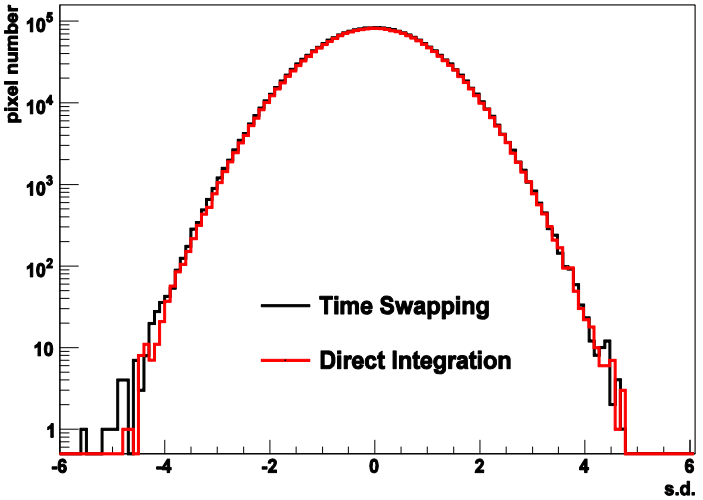
Medium Scale Anisotropy

How to focus on medium scale structures ?

Traditional background estimation methods:

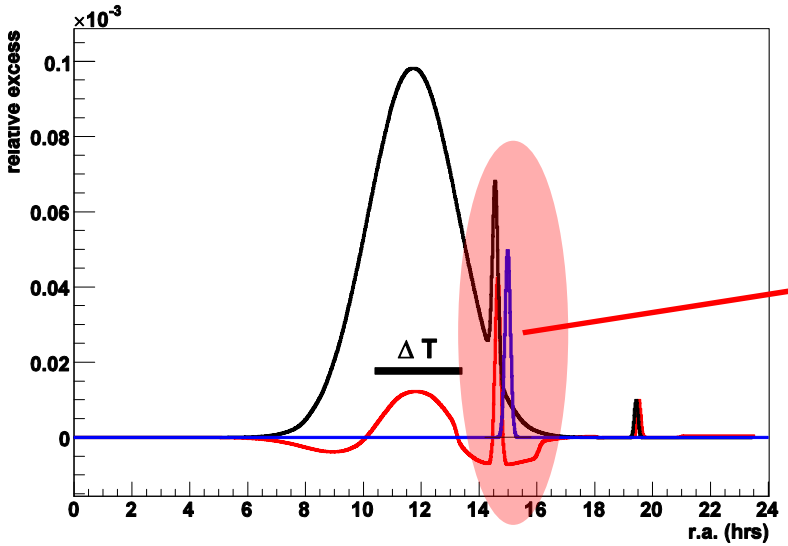
- Time swapping/scrambling (3 hrs,)
- Direct integration (3 hrs)

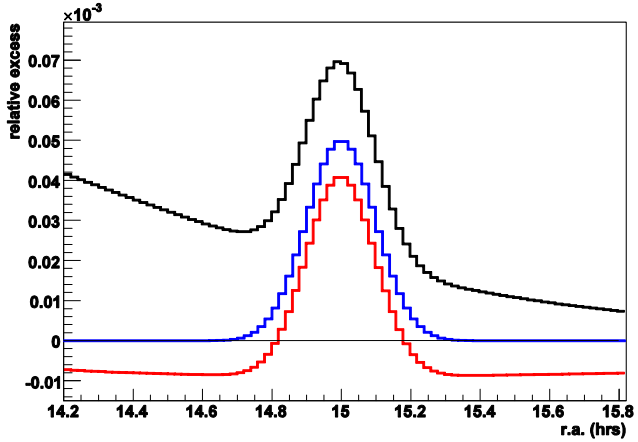
(consistent each other within 0.3 s.d.)



First systematic study of the time average-based methods.

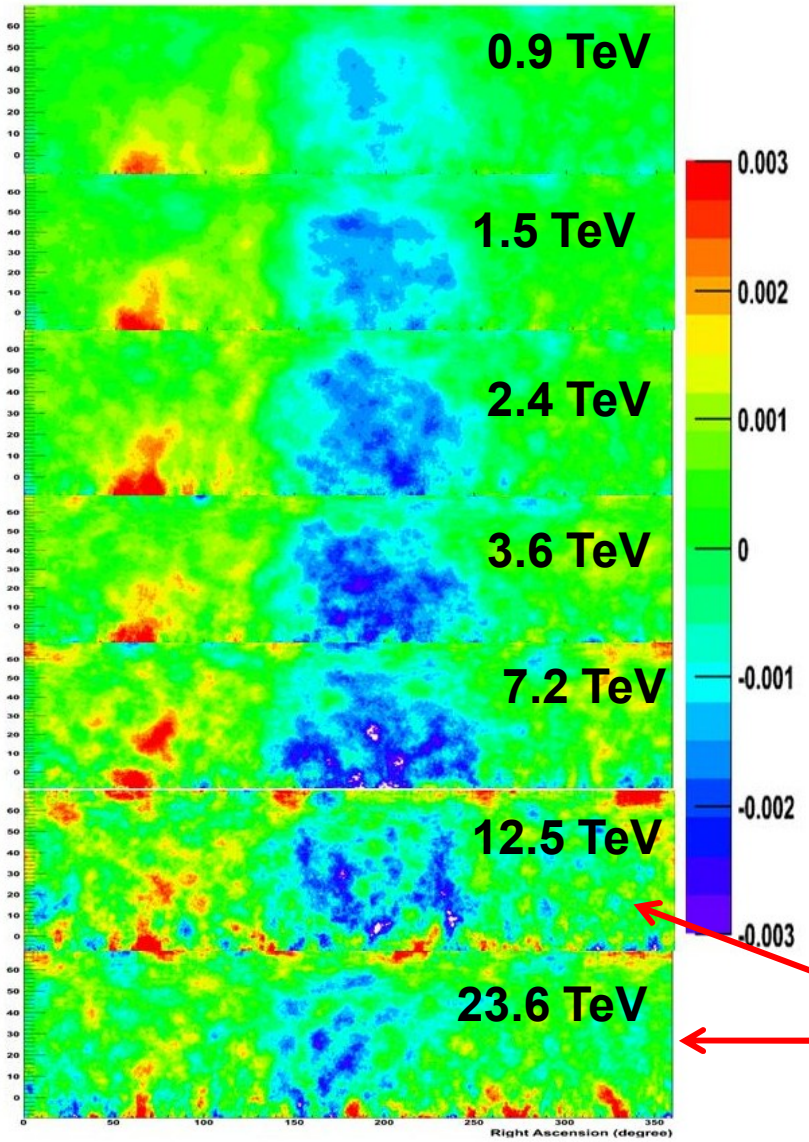
An effective high-pass filter for structures narrower than 3 hrs × 15°/hrs = 45° in R.A.
(35° safety-limit)

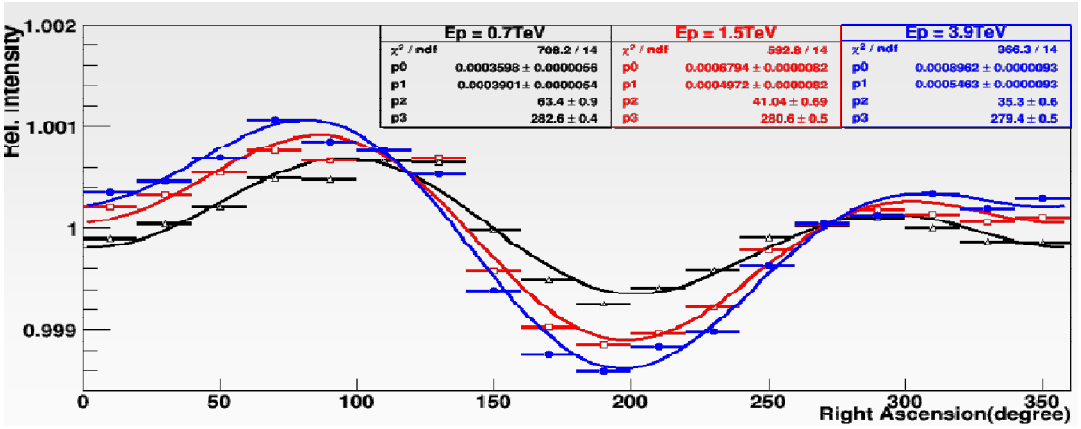




every feature larger than ΔT is brought to zero (apart from the peak)

Large Scale CR anisotropy vs Energy



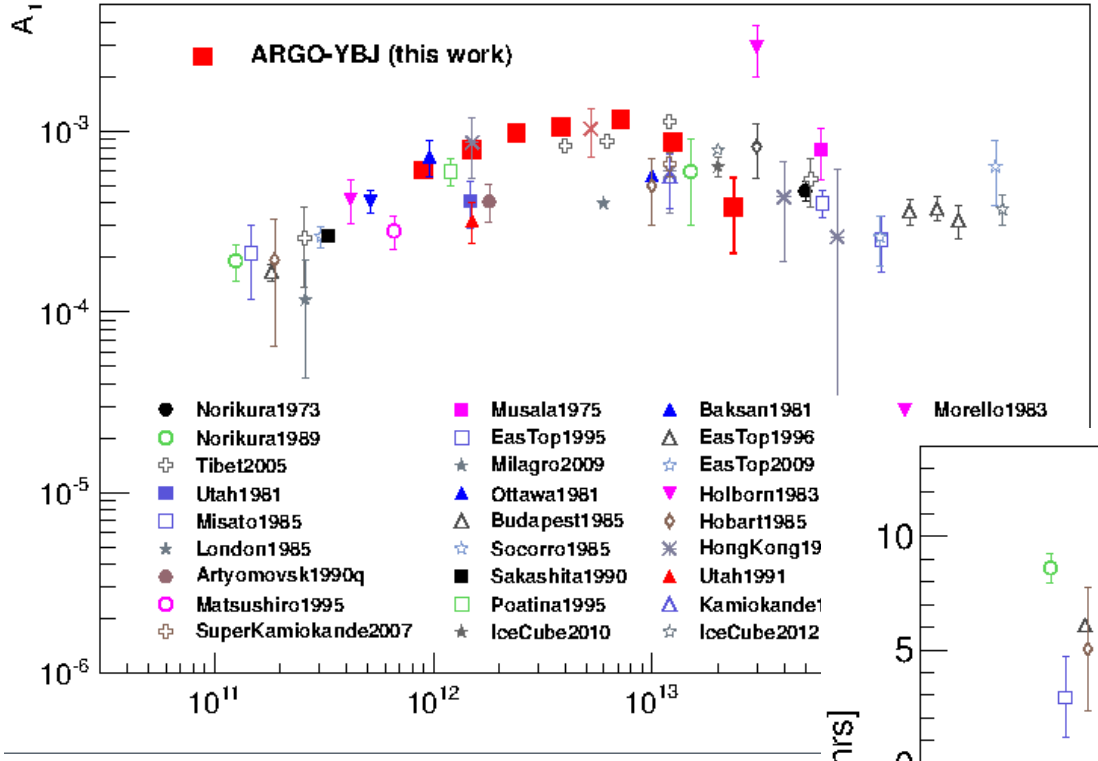


$$1 + A_1 cos(2\pi(x - \phi_1)/360) + A_2 cos(2\pi(x - \phi_2)/180)$$

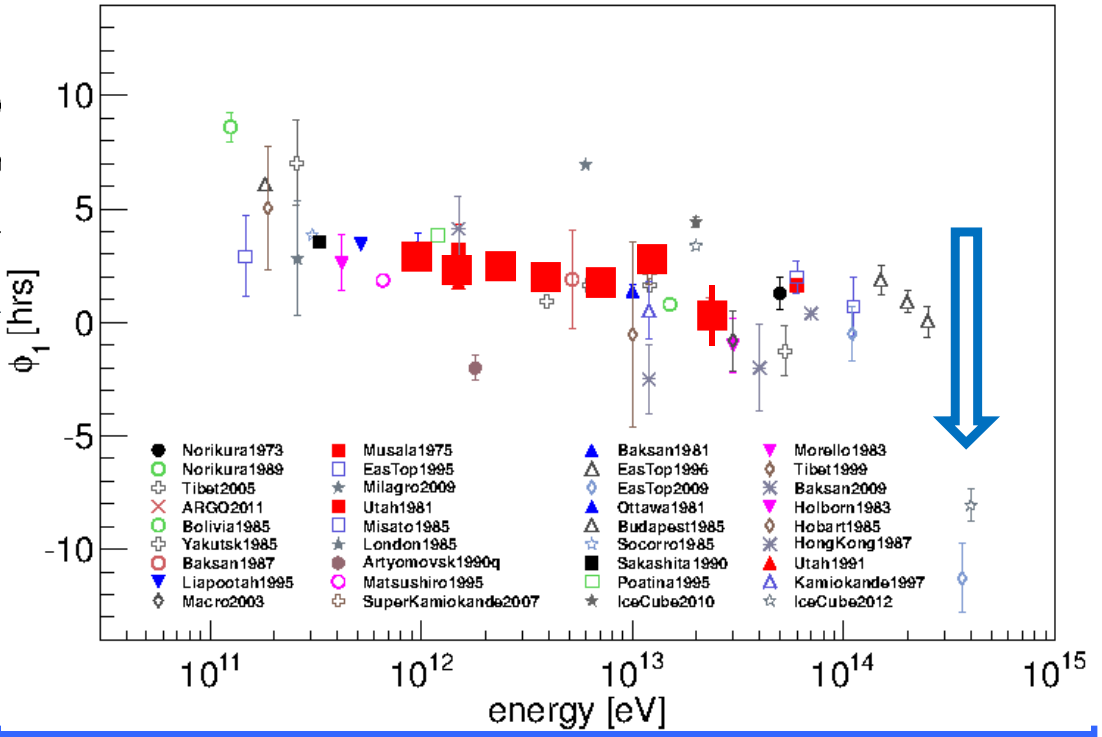
First measurement with an EAS array in an energy region so far investigated only by underground muon detectors

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

x-check: the Compton-Getting effect

- **Expected CR anisotropy due to Earth's orbital motion around the Sun: when an observer (CR detector) moves through a gas which is isotropic in the rest frame (cosmic ray "gas"), he sees a current of particles from the direction opposite to that of its own motion.**

$$\frac{\Delta I}{\langle I \rangle} = (\gamma + 2)\frac{v}{c}\cos\vartheta$$

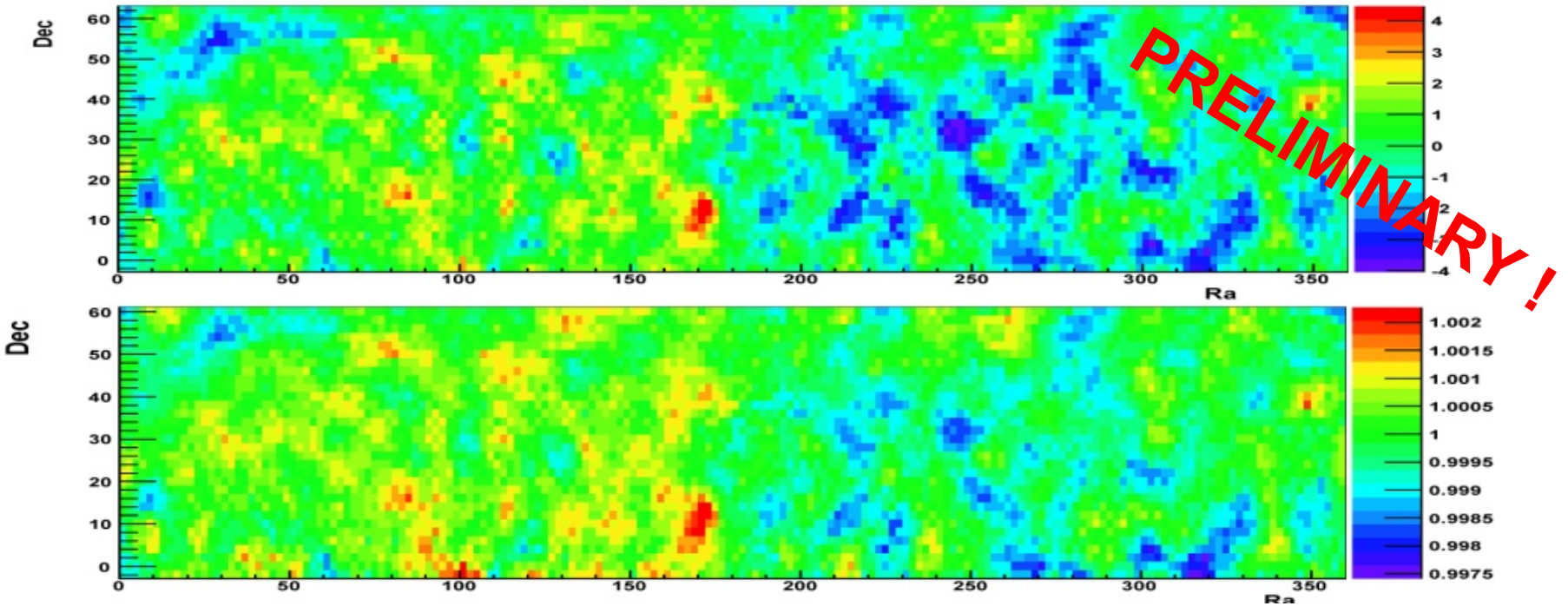
I = CR intensity
γ = power-law index of CR spectrum (2.7)
v = detector velocity ≈ 30 km/s
θ = angle between detector motion and CR arrival direction

$$\frac{\Delta I}{\langle I \rangle}(\text{exp}) : \ 0.047\%$$

$$\varphi(\text{exp}) : \ 6hr$$

A detector on the Earth moving around the Sun scans various directions in space while the Earth spins.
Maximum at 6 hr solar time (when the detector is sensitive to a direction parallel to the Earth's orbit)

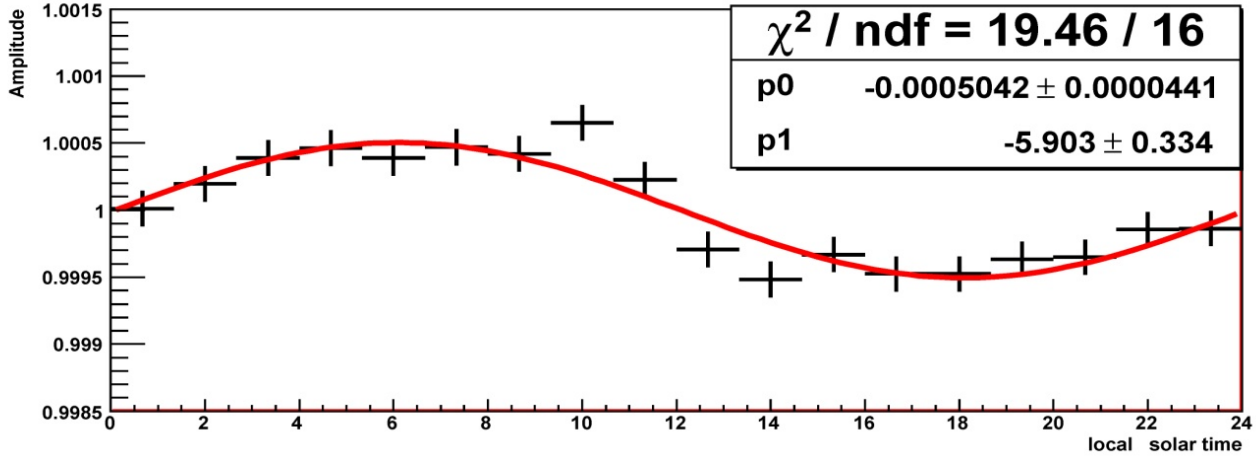
Compton-Getting effect in solar time (UT)



2008 – 2009

Nhit ≥ 500 → ≈ 8 TeV

to avoid solar effects on low energy CRs



Medium Scale Anisotropy by ARGO-YBJ

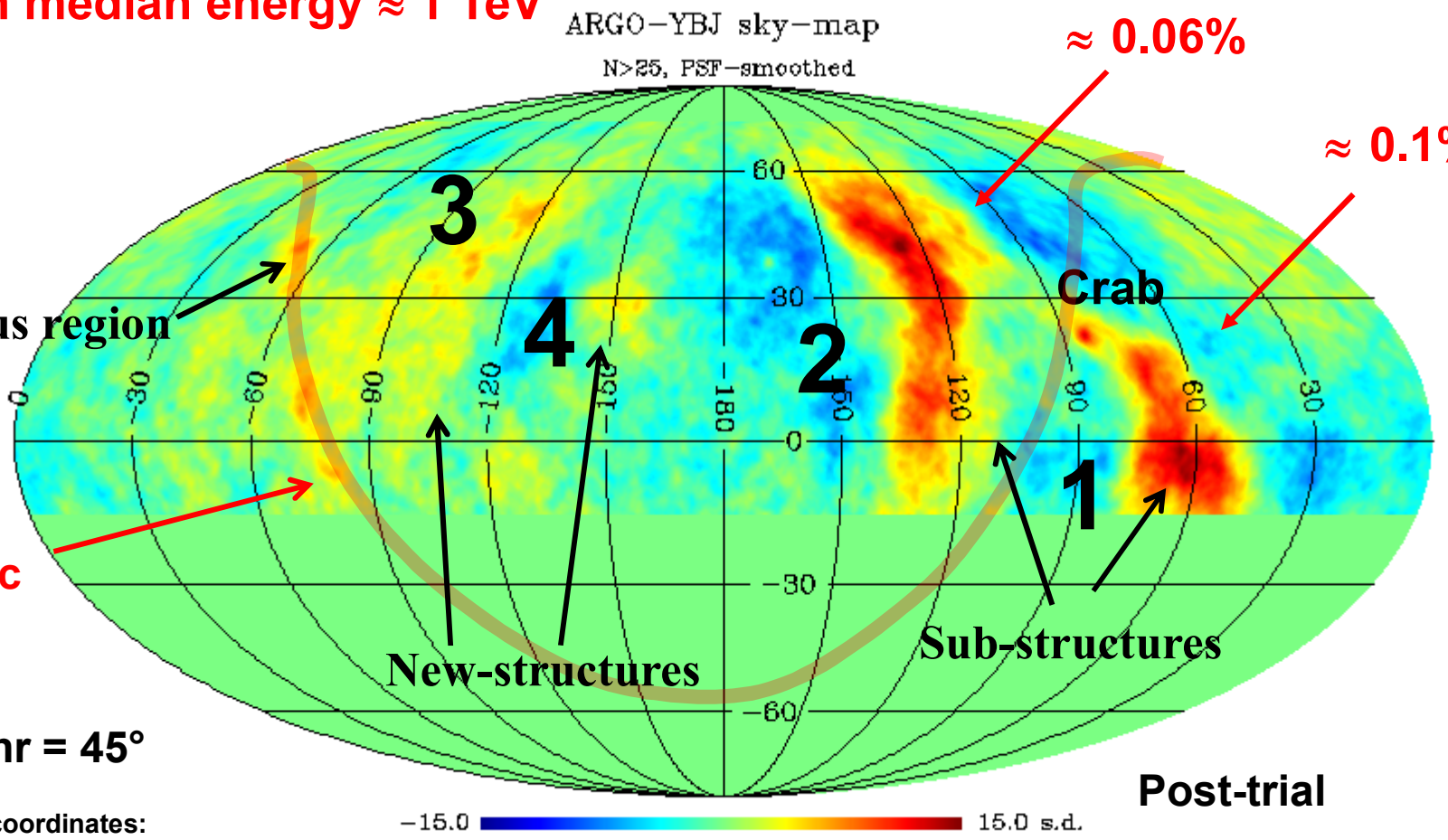
Map smoothed with the detector PSF for CRs

Proton median energy ≈ 1 TeV

Cosmic rays excess

≈ 0.06%

≈ 0.1%

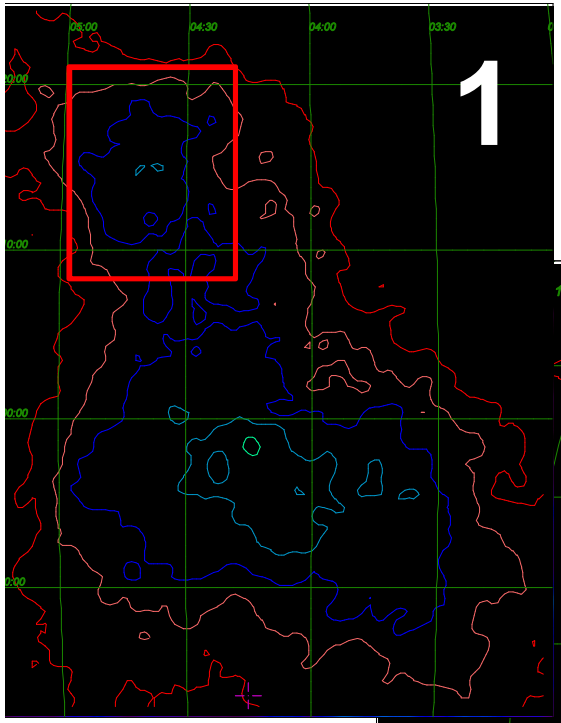


Δt = 3 hr = 45°

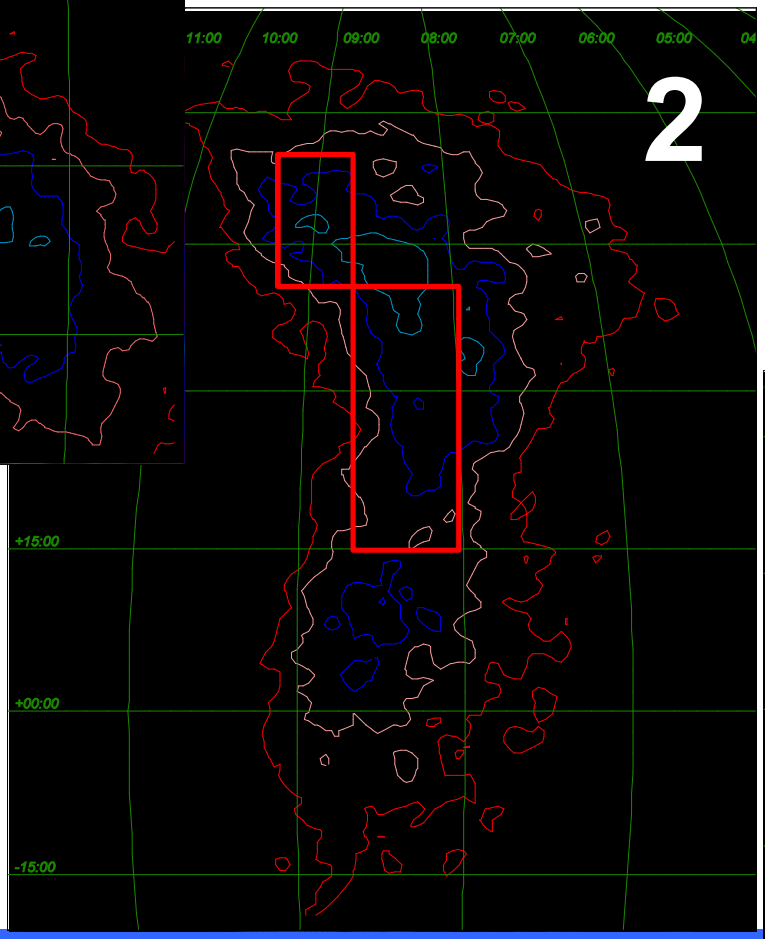
Post-trial

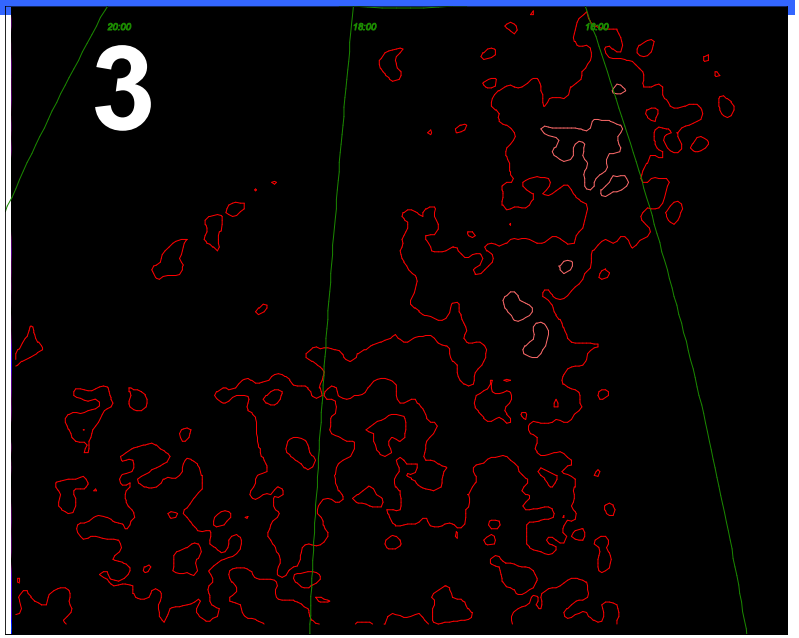
Equatorial coordinates:
projection of the earth longitude and latitude

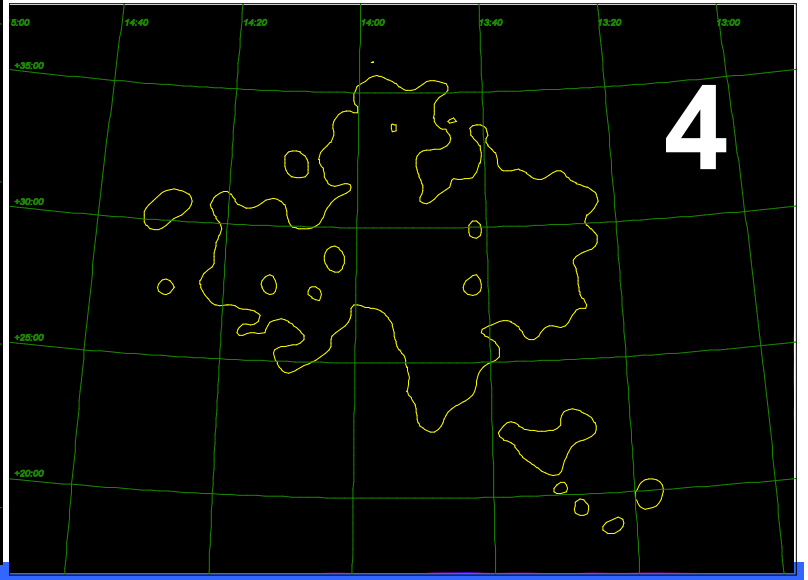
Medium Scale Anisotropy morphology



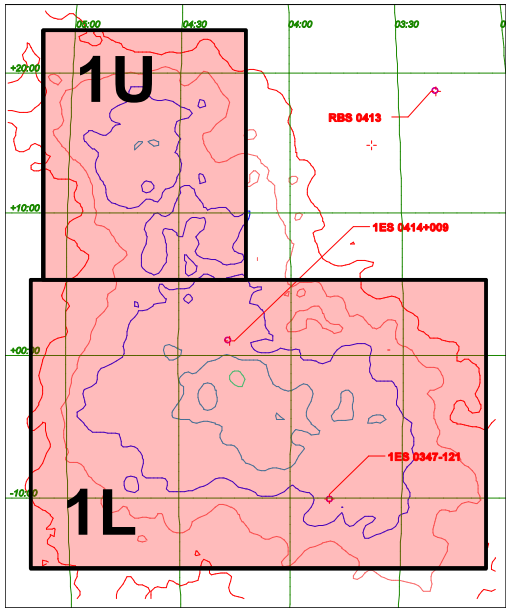
MILAGRO missed an important part of the MSA

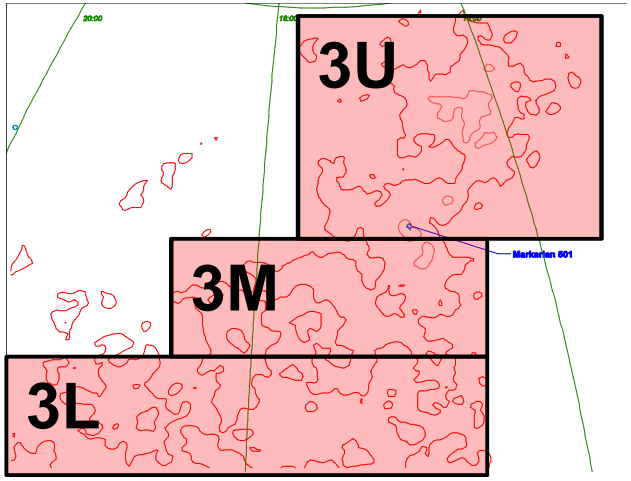






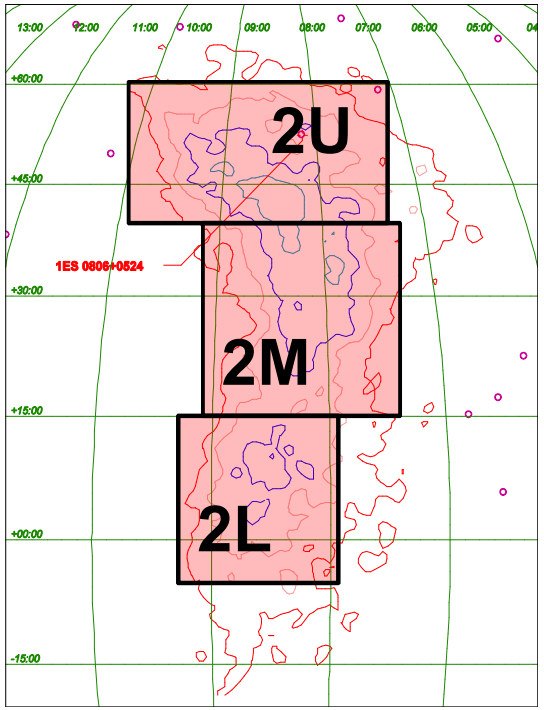
Region parametrizations

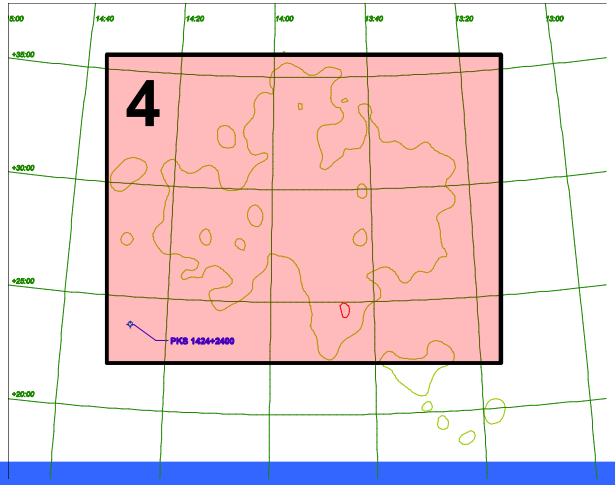




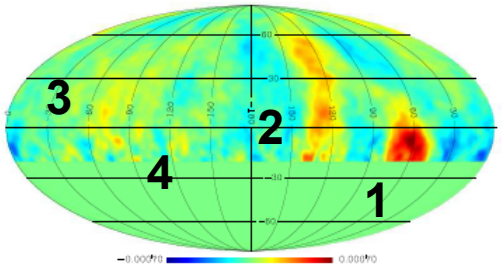
Complex morphology requires **composite parameterization.** For the sake of simplicity, r.a.-dec. boxes were used.

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

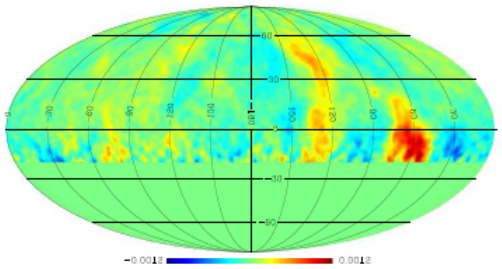




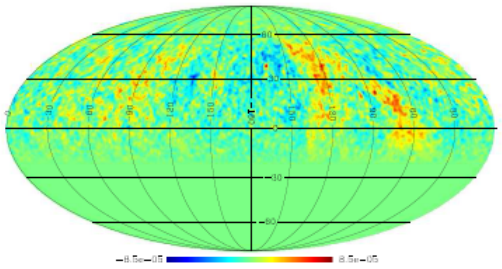
Energy Spectrum in the MSA regions



(a)

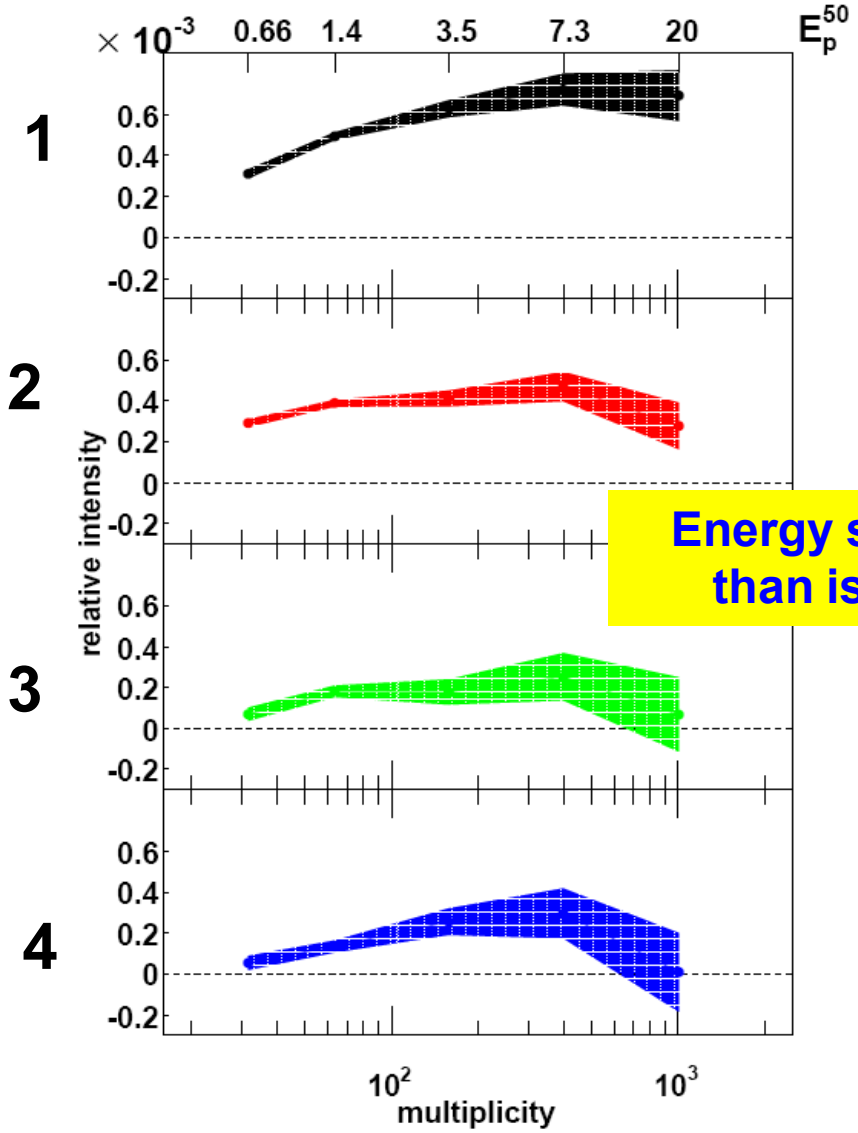


(b)



(c)

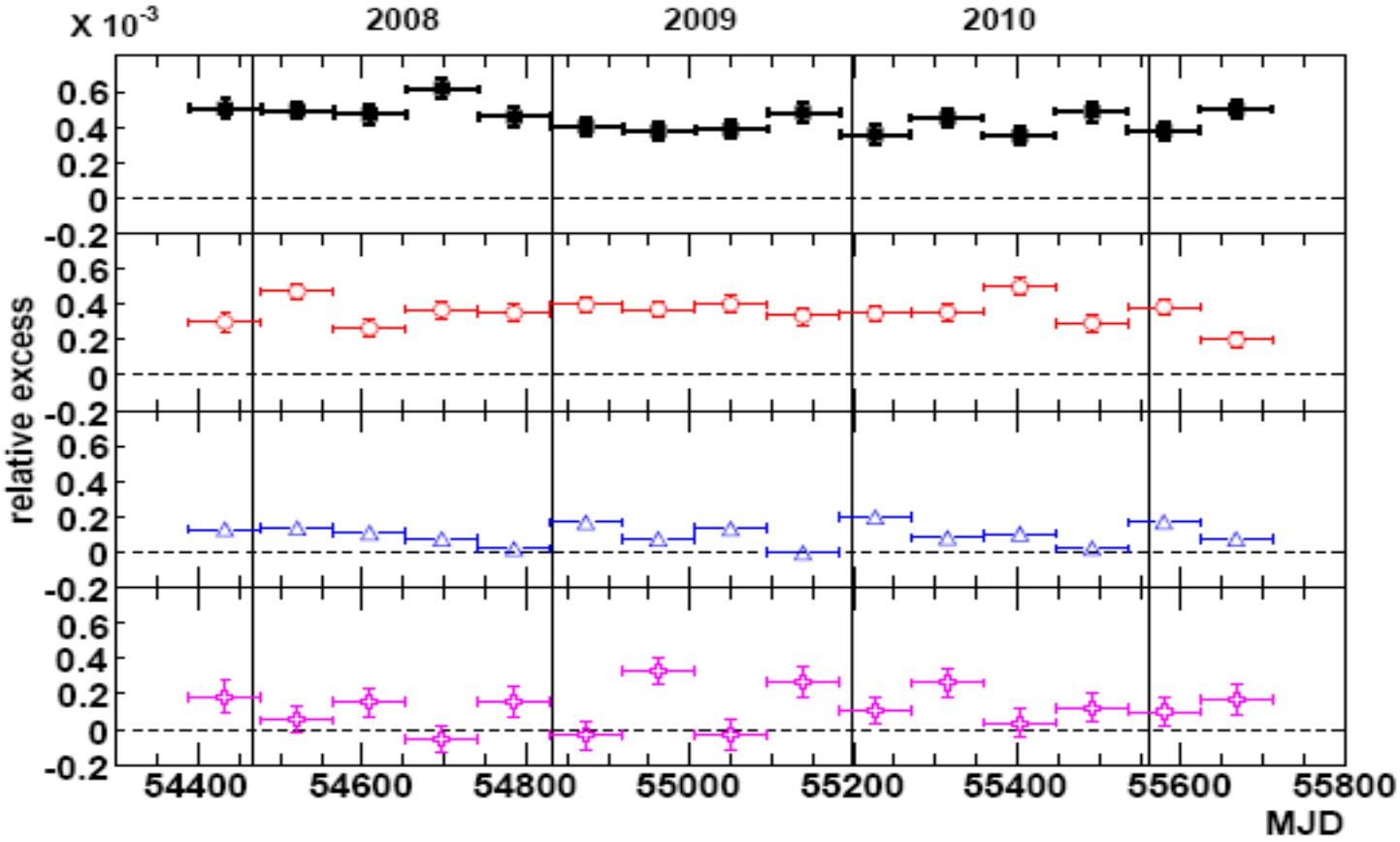
First three multiplicity intervals as a reference



Energy spectra harder than isotropic CRs

Intensity as a function of the Time

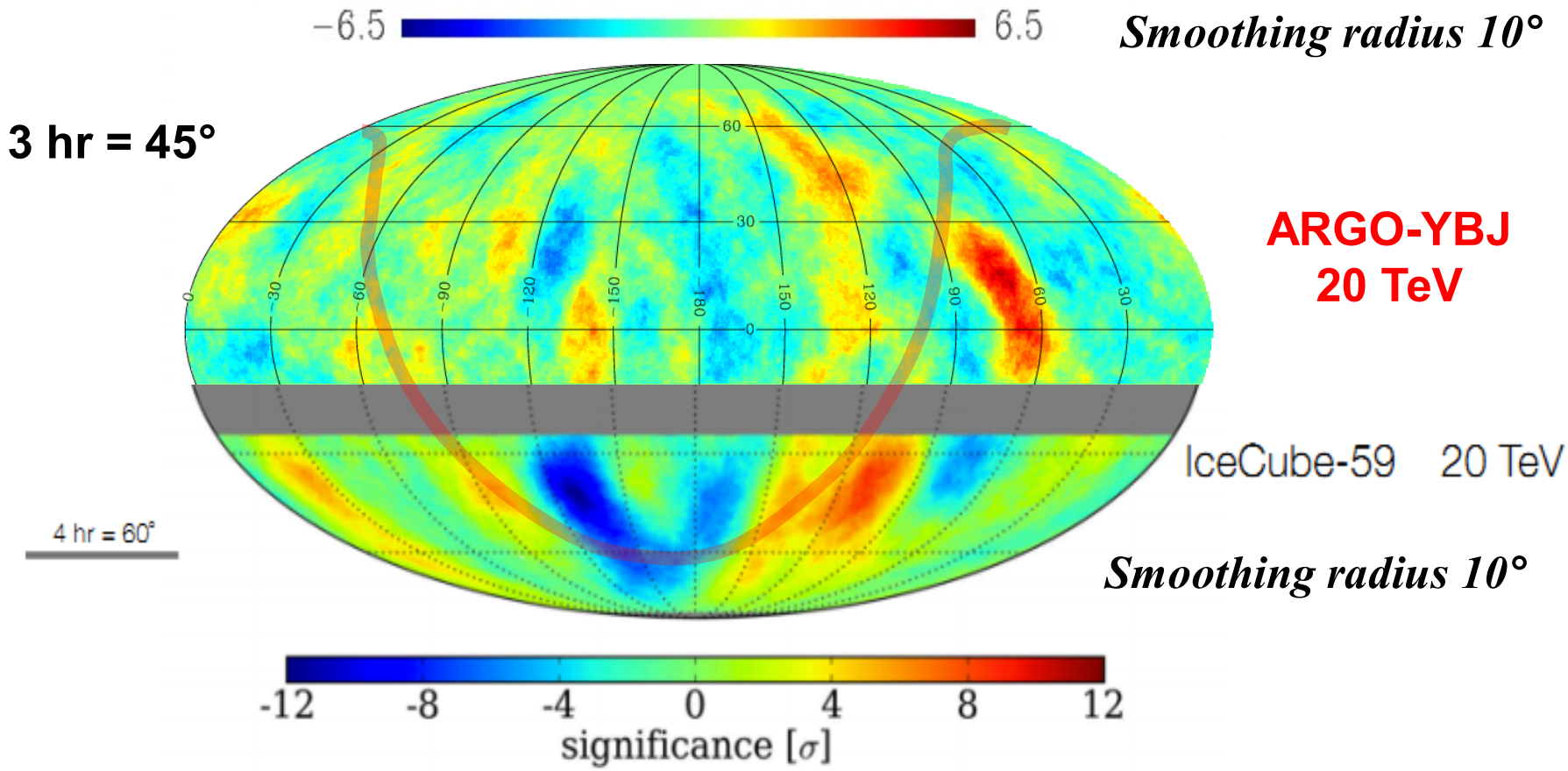
Milagro reported indications for time dependence: the fractional excess was lowest in the summer and highest in the winter



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

Complete CR map of the entire TeV sky

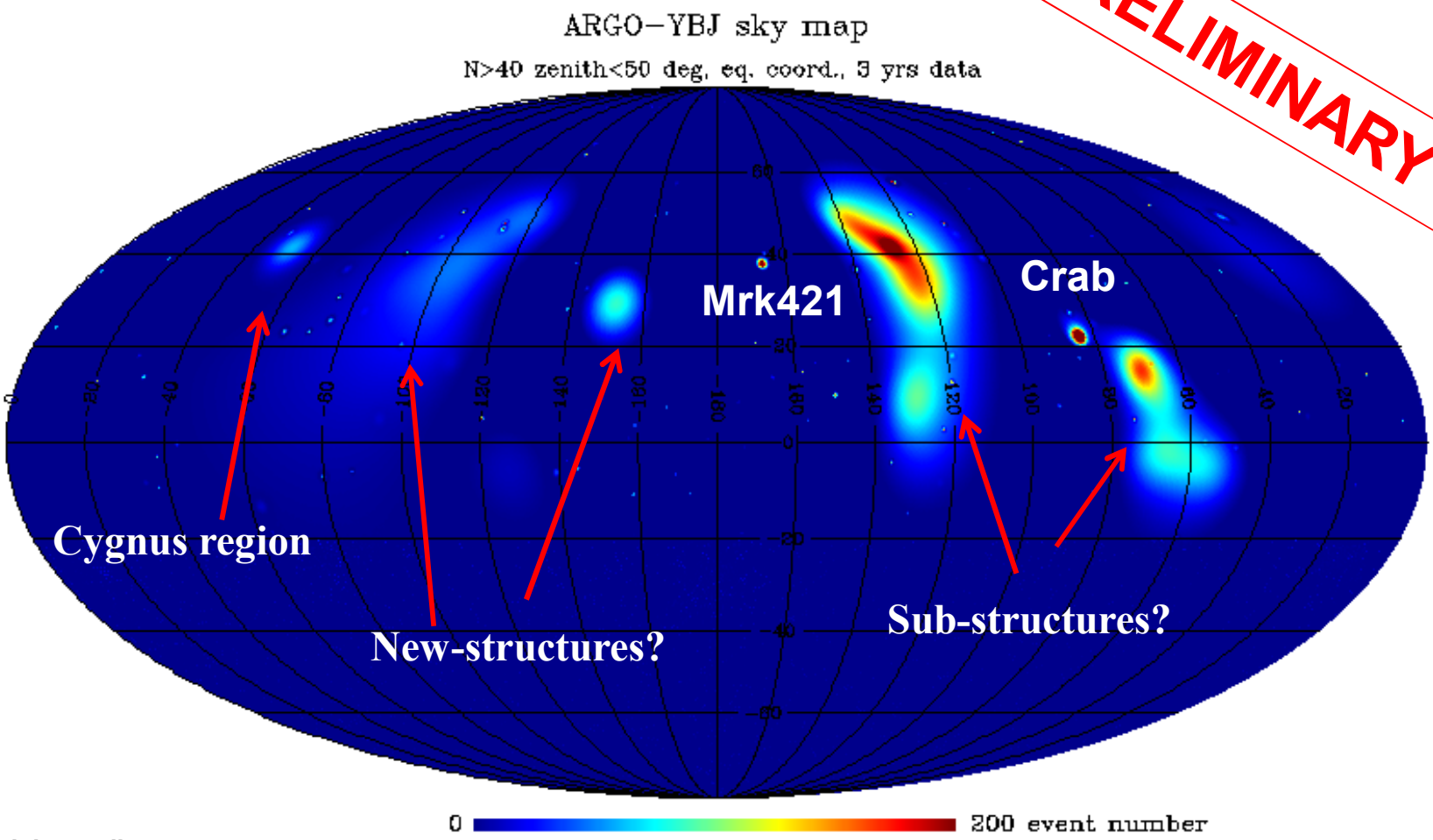
ARGO-YBJ + IceCube-59



A new approach: Needlet-based analysis

Focus on >4 s.d. significant regions

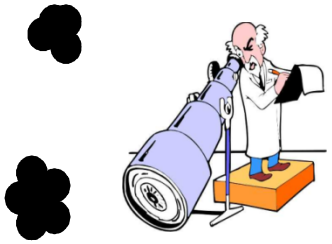
PRELIMINARY !



Equatorial coordinates:
projection of the earth longitude and latitude

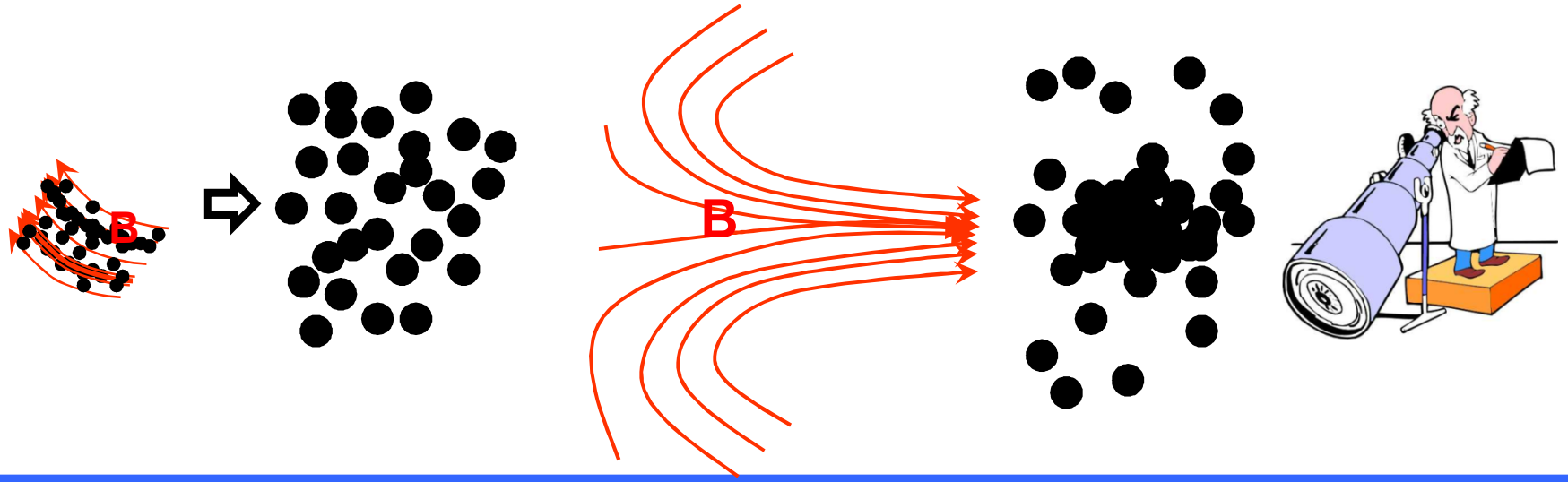
What the observation of MSA might suggest

- there are sources nearby.



- the galactic magnetic field is not what we imagine:
  - the role of the Solar wind as well as the magnetic field in the solar system may be non-negligible.
  - there might be local (or non-local) magnetic field structures focusing CRs up to the Solar System.
  - the chaotic component of the magnetic field may overwhelm the regular one.

- any combination of the two facts above.



Conclusions

- **With ARGO-YBJ 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 measurements at higher energies.**
- **ARGO-YBJ observed either the large scale and the intermediate scale CR anisotropies with high statistical significance.**
- **The observation of the large scale CR anisotropy up to about 25 TeV is in agreement with other experiments.**
- **The observation of an intermediate scale anisotropy shows evidence of several new features still uninvestigated.**
- **Deeper analysis with new techniques is under way.**