Observation of CR anisotropy with ARGO-YBJ

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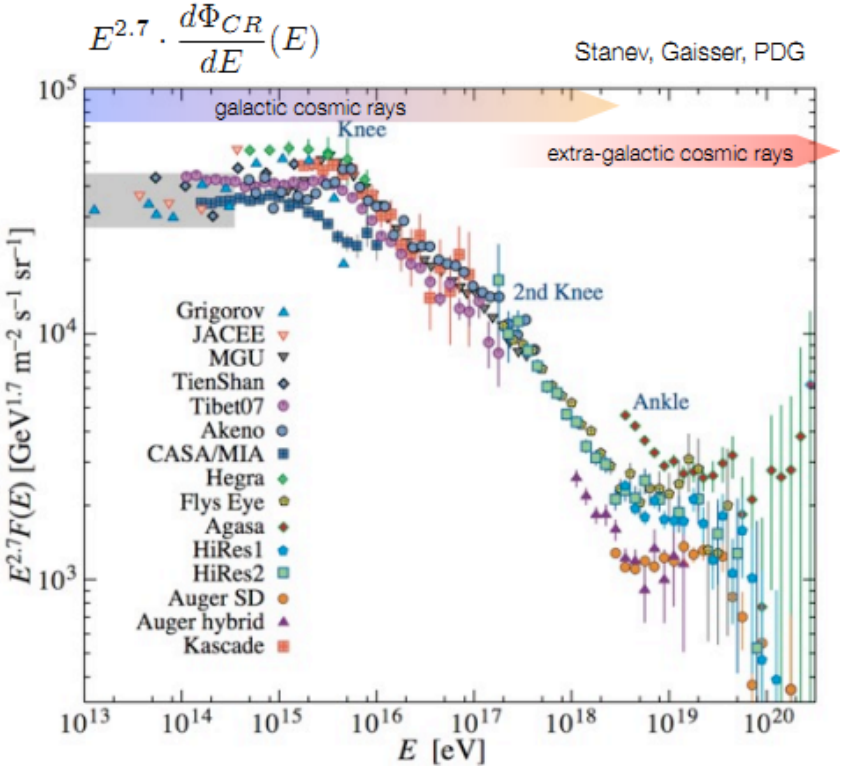
On behalf of the ARGO-YBJ Collaboration

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



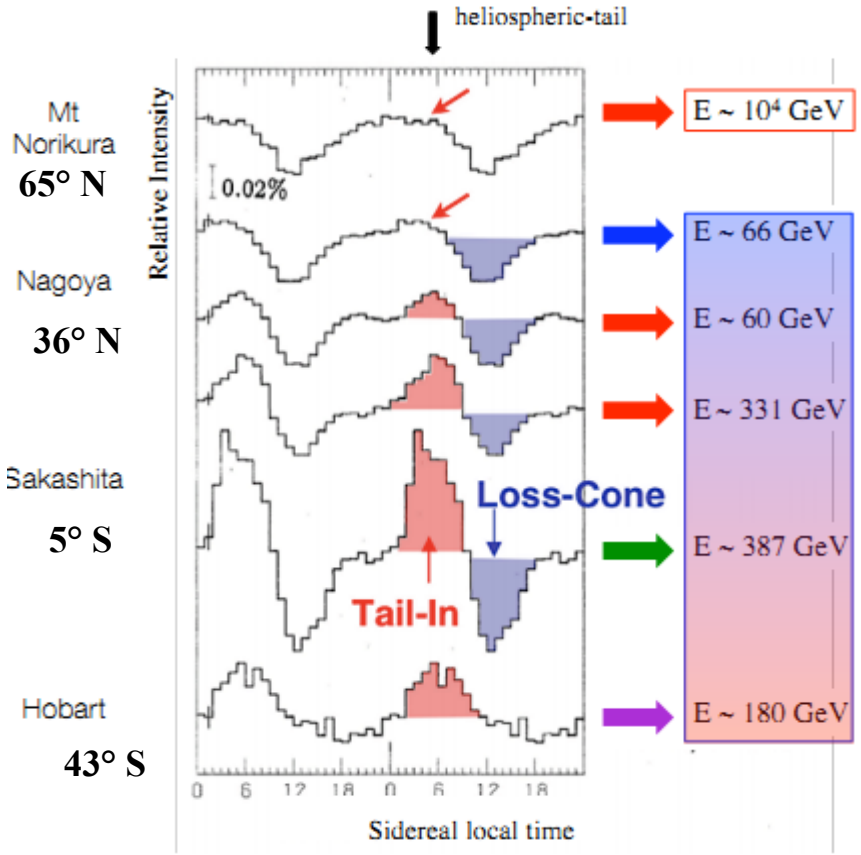
- Galactic CRs are expected to be highly isotropic scrambled by galactic magnetic field over very long time.

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

An-isotropy observed

- anisotropy of arrival direction of CRs 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



The knee of the CR spectrum

The study of the evolution of the anisotropy in the "knee" region can provide a test of diffusion models, and an insight for the discrimination between the possible explanations of the knee.

Possible reasons for the CR knee:

- Energy limits of the acceleration process at the sources, e.g. in SNRs believed to be the sources of galactic CRs.

- Change in the properties of CR propagation inside the Galaxy, described through diffusion models.

→ **Anisotropy change expected $\propto E^{\delta}$**

The measurement of the CR anisotropy is complementary to the study of their energy spectrum and chemical composition, to understand their origin and propagation.

Measuring the anisotropy

1. For each detected EAS, the direction is determined locating its Right Ascension α and Declination δ on the celestial sphere
2. EAS arrays have uniform exposure in α (thanks to Earth's rotation) but NOT in δ (fov limited by geographical position, zenith angle dependence of shower detection and reconstruction).

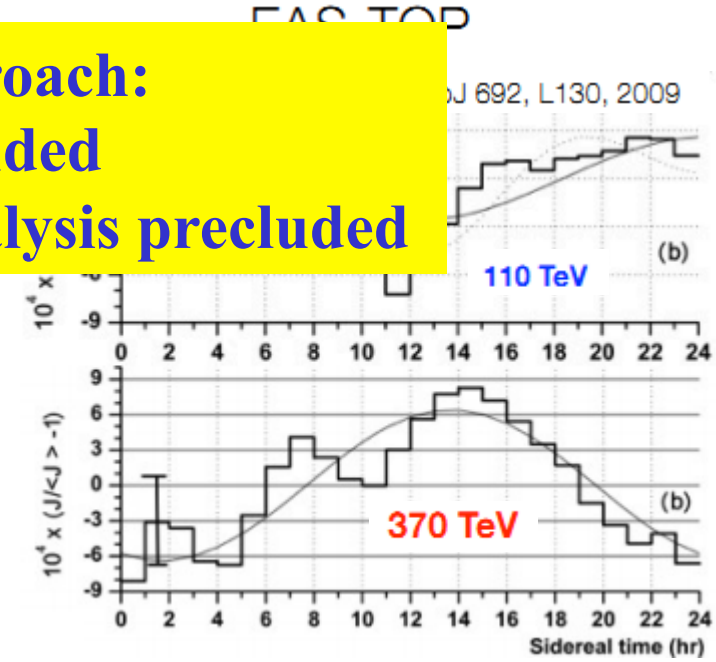
Usual tec

1 - Dimensional approach:

- ❑ **Morphological study precluded**
- ❑ **Angular scale structure analysis precluded**

1.analysi
analysis
declination band defined by the fov.

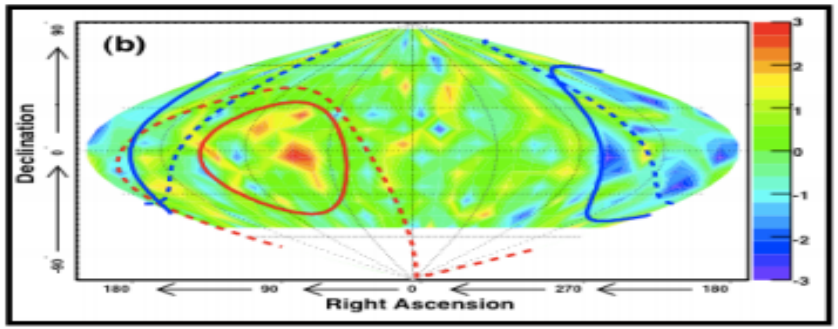
2.Rayleigh formalism gives amplitude A, phase ϕ (hour angle of the maximum intensity) and probability P for detecting a spurious amplitude due to fluctuations.



2D measurement of CR anisotropy

Super-K

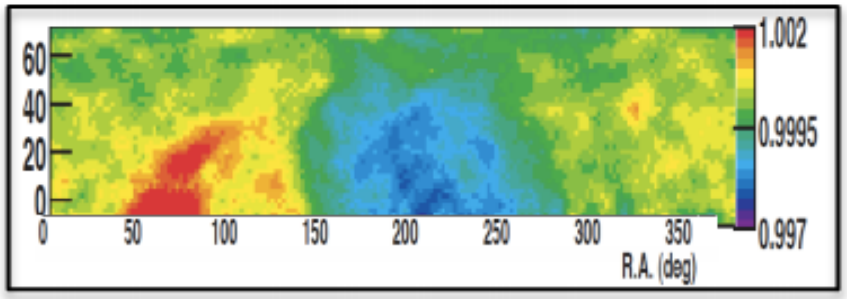
Guillian et al., arXiv:astro-ph/0508468



- 2.1×10^{8} events bet. 1996 – 2001
- Angular resolution < 2°
- Median energy ~ 10 TeV

Tibet Array

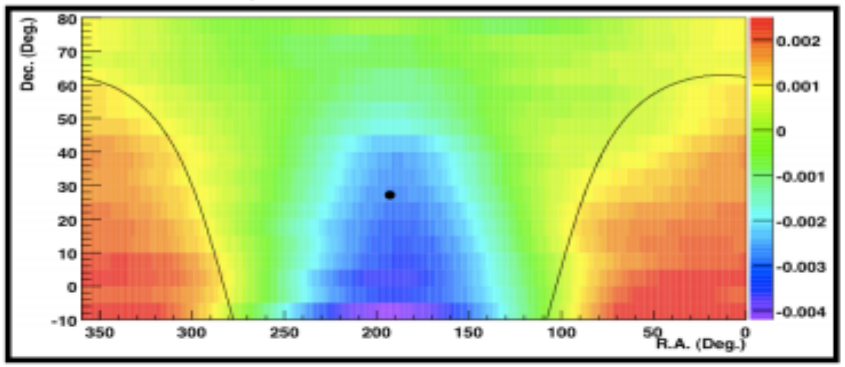
M. Amenomori et al., Science 314 (2006) 439



- 3.7×10^{10} events bet. 1997-2005
- Angular resolution < 1°
- Median energy ~ 6 TeV

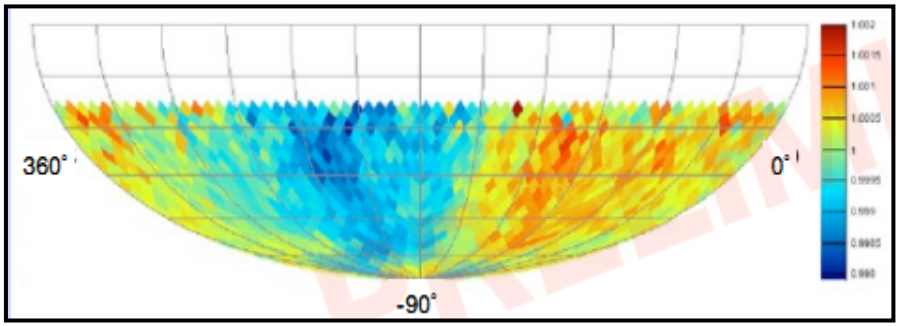
Milagro

Abdo et al., arXiv:0806.2293



- 9.6×10^{10} events bet. 2000-2007
- Angular resolution < 1°
- Median energy ~ 6 TeV

Icecube - 59



- **34×10^{9} events**
- **Angular resolution ~ 3°**
- **Median energy ~20 TeV**

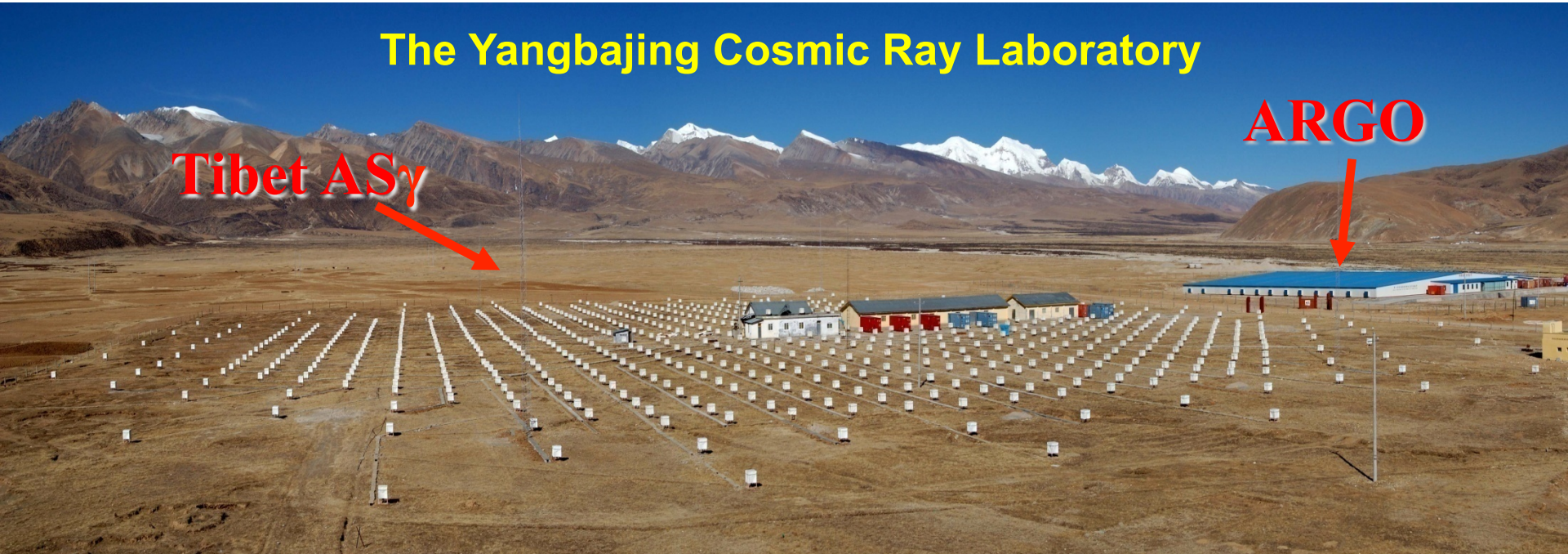
The ARGO-YBJ experiment

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



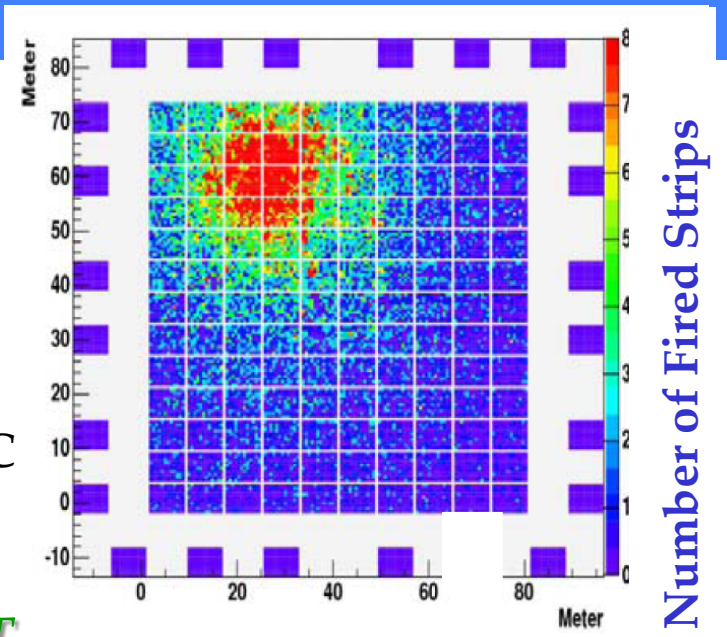
The basic concepts

…for an unconventional air shower detector

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

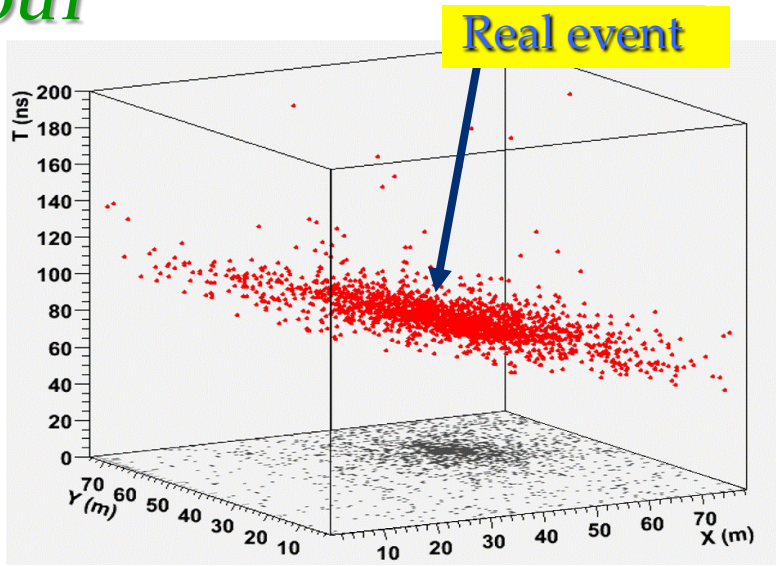
- ***FULL COVERAGE***
  technology, 92% covering factor)

(RPC



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

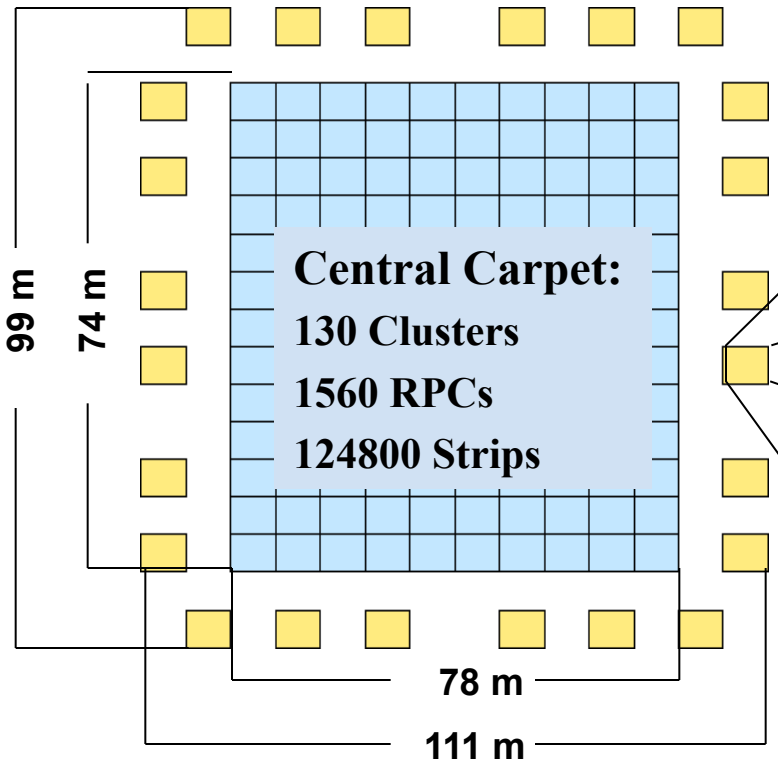
  Space pixels: 146,880 strips (7×62 cm^2)
  Time pixels: 18,360 pads (56×62 cm^2)



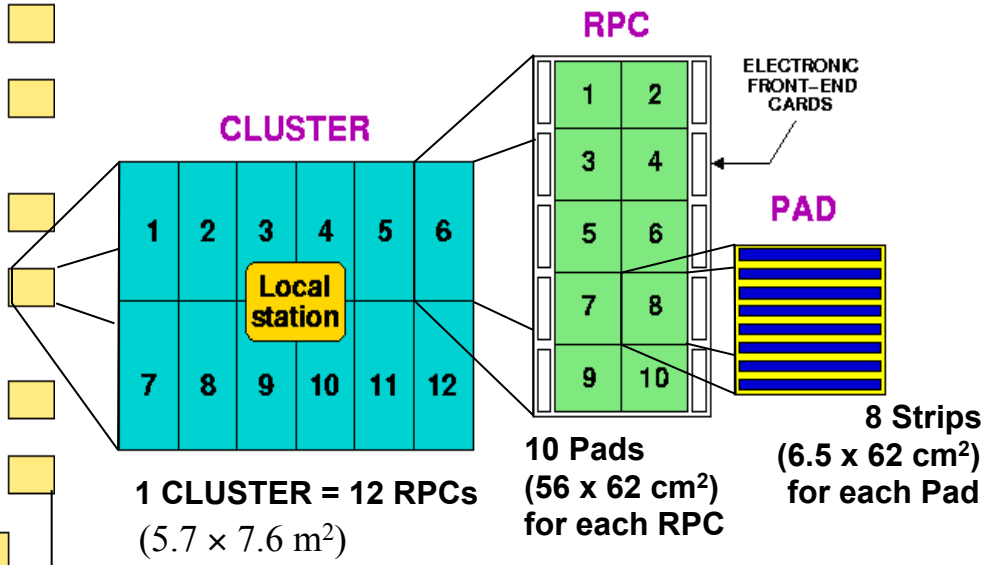
… in order to:

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

Experimental Hall & Detector Layout



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



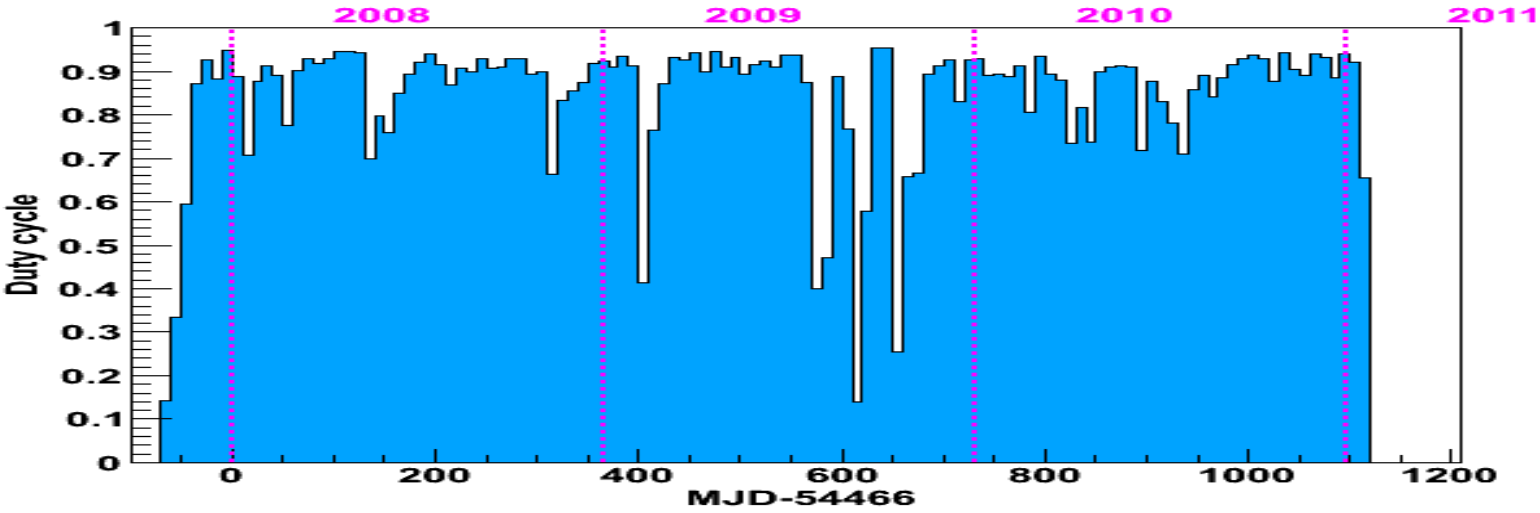
Gas Mixture: **Ar/ Iso/TFE = 15/10/75**

HV = 7200 V

Single layer of Resistive Plate Chambers (RPCs)
with a full coverage (92% active surface) of a large area (5600 m²)
+ sampling guard ring (6700 m² in total)

Current Status

- In observation since July 2006 (commissioning phase)
- Stable data taking since November 2007
- The **average duty cycle ~ 85%**
- **Trigger rate ~3.5 kHz** @ 20 pad threshold
- Dead time 4%
- 220 GB/day transferred to IHEP/CNAF data centers



ARGO-YBJ: a multi-purpose experiment

- Sky survey $-20^{o} \leq \delta \leq 80^{o}$ above 300 GeV (γ-sources)
- High exposure for flaring activity (γ-sources, GRBs, solar flares)
- CR physics 1 TeV → 10^4 TeV
  - (p + He) spectrum at low energies
  - Knee region
  - p-air and p-p cross sections
  - Anisotropies
  - Multicore events
- CR $\bar{p}/p$ flux ratio at TeV energies
- Solar and heliospheric physics

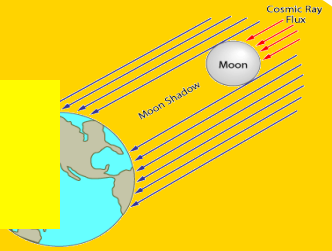
by 2 independent operational modes:

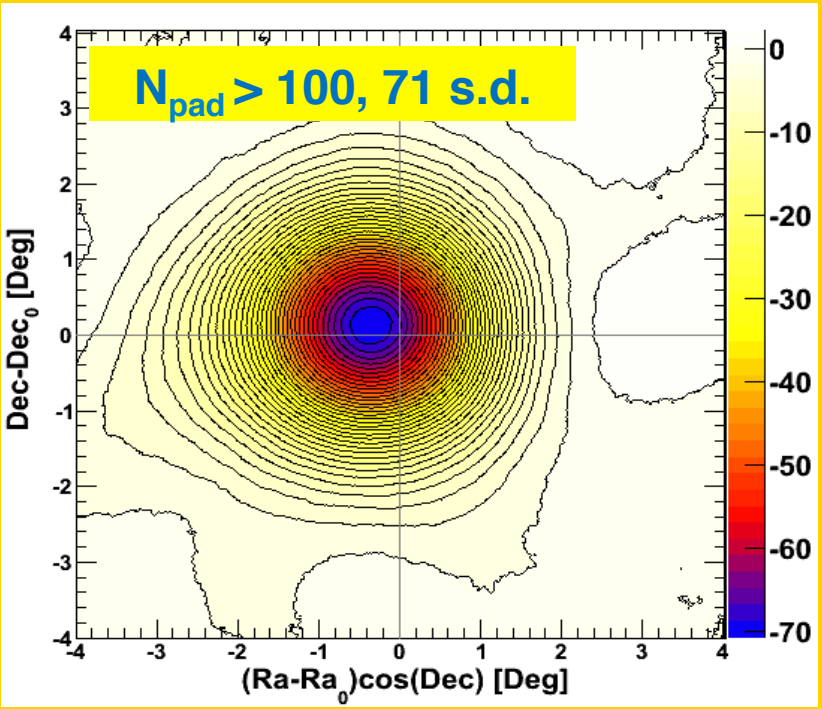
- ❖ **scaler mode** (counting rate, > 1 GeV)
- ❖ **shower mode** (full reconstruction, > 300 GeV)

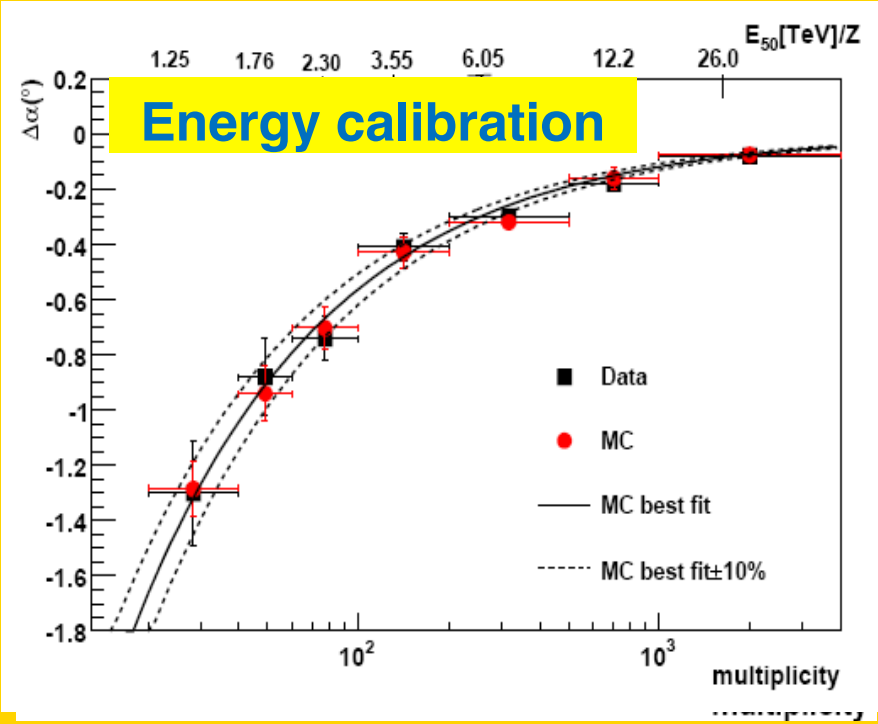
Moon shadow analysis (1)

- A tool to evaluate the performance of the detector

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

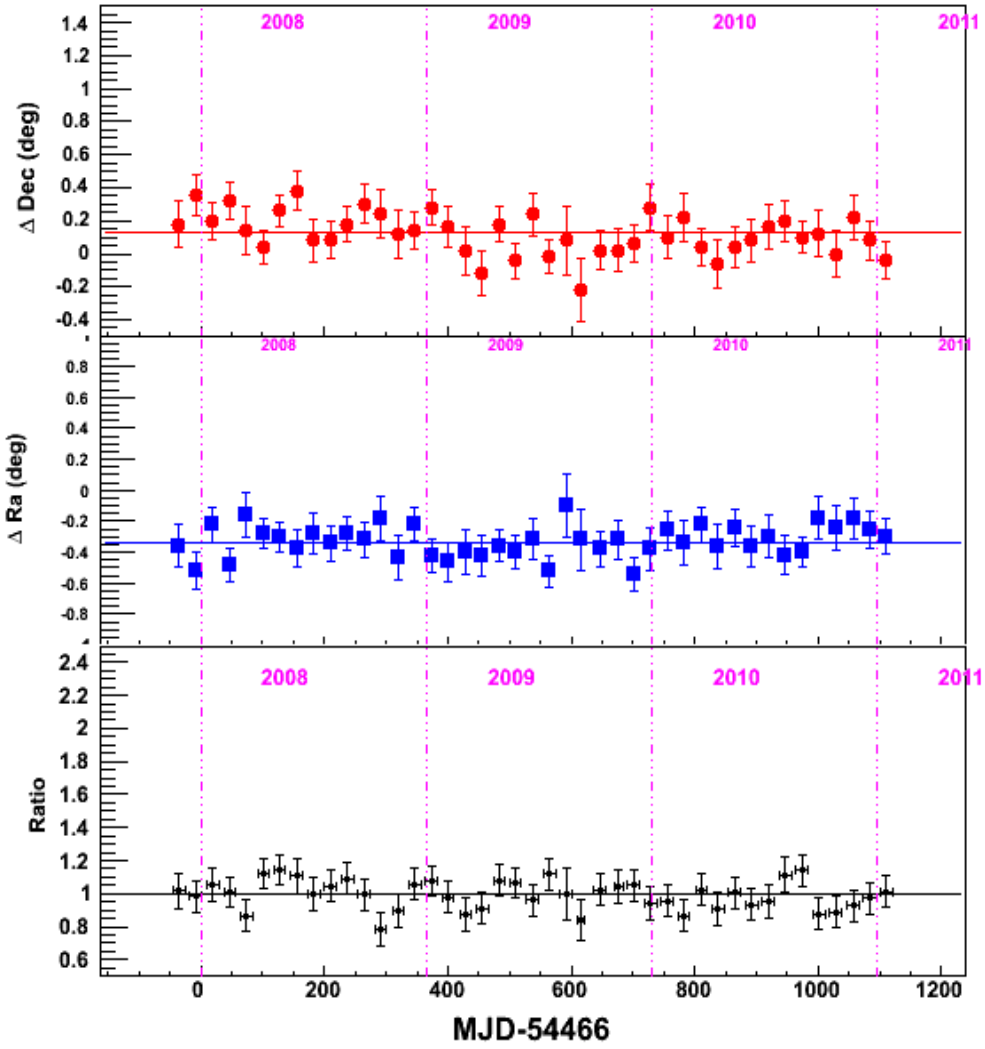






Moon shadow analysis (2)

- 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%



Data analysis

DATA SET:

3 years data: 2008 - 2010
N_{str} > 25, Zenith angle < 50°, $1.4 \cdot 10^{11}$ events

NO gamma/hadron discrimination technique applied.

Background estimation methods:

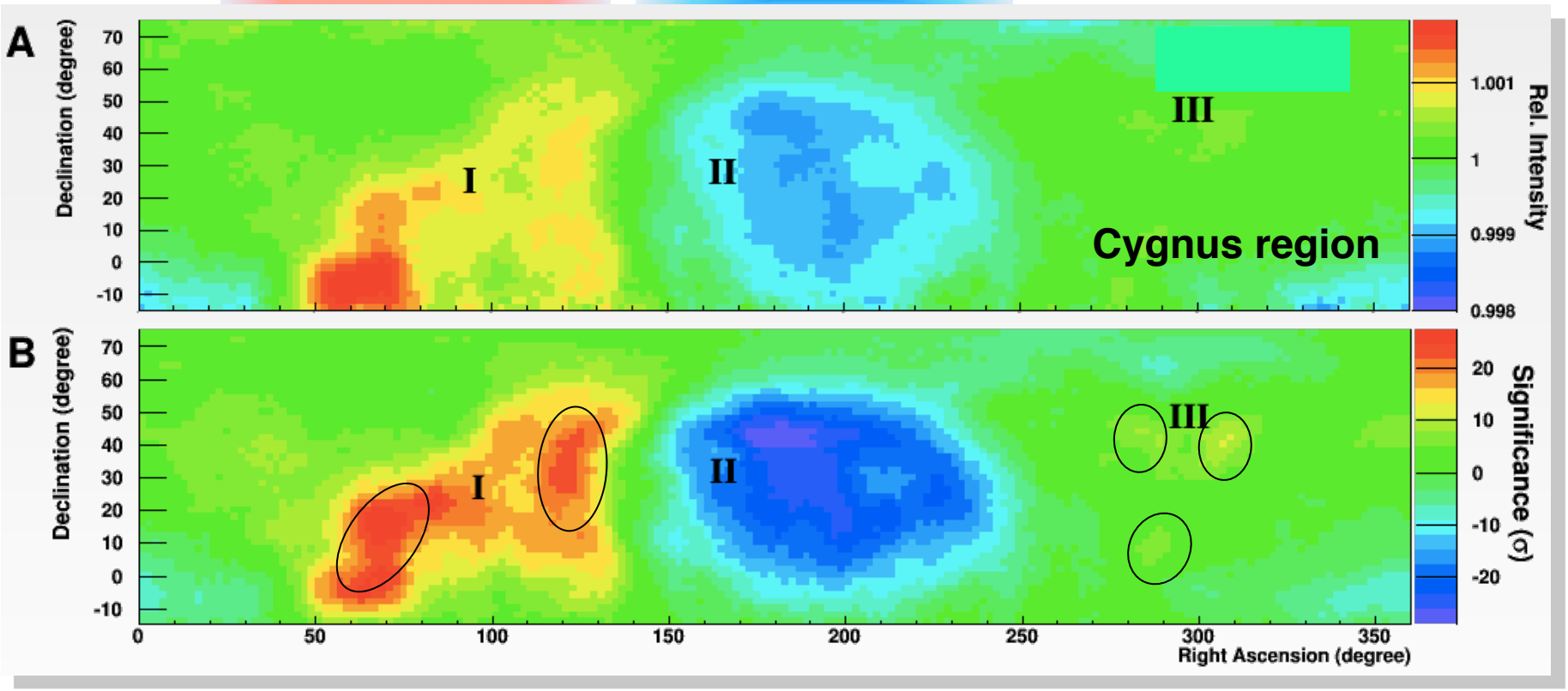
- **Up to 45°- wide structures:**
  - **Time swapping/scrambling (3 hrs, N_{off}/N_{on}=10)**
  - **Direct integration (3 hrs)**

- **For larger scales: equi-zenith method**

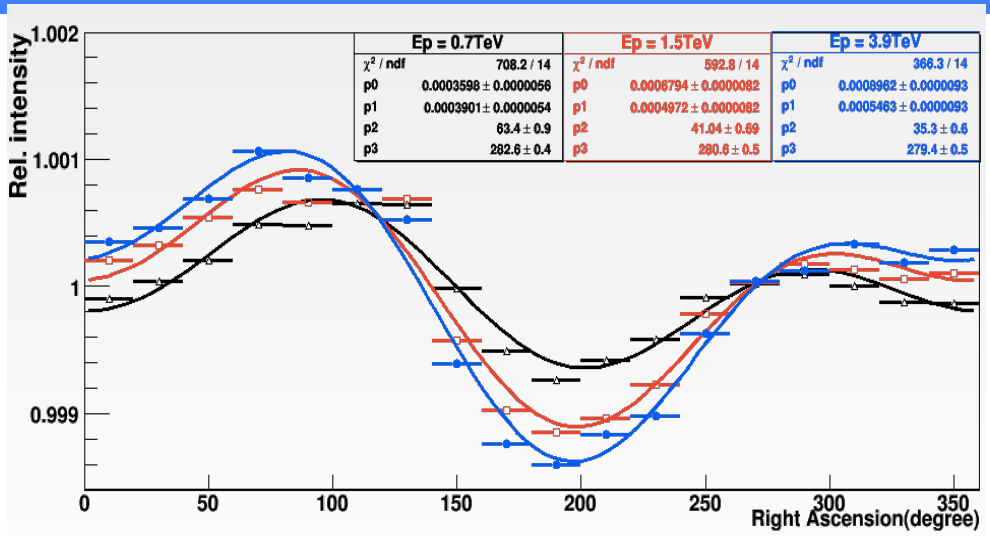
Large scale CR anisotropy

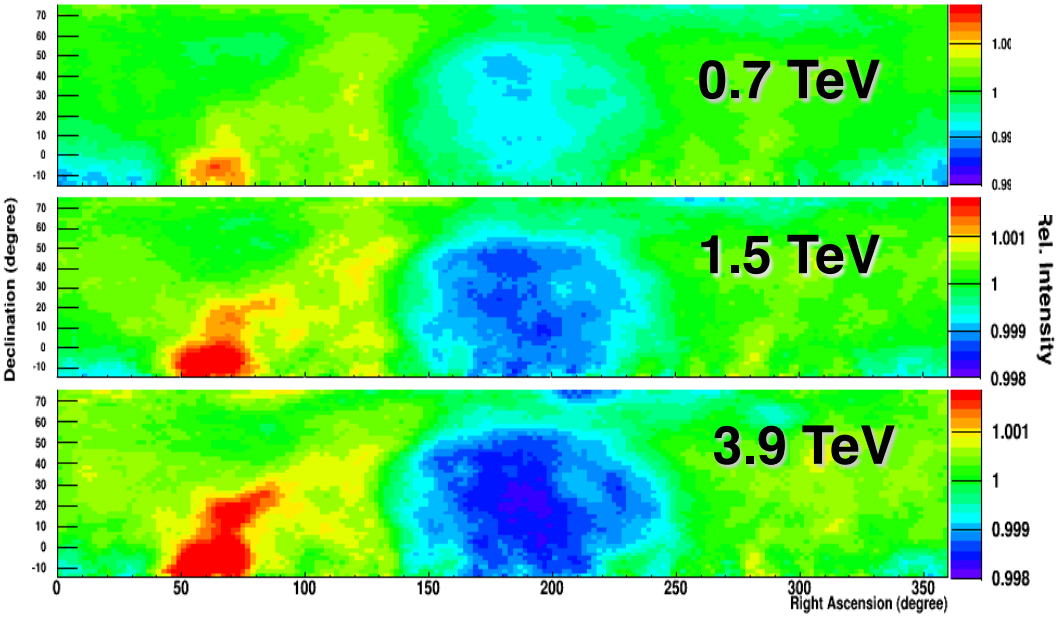
All-data sky-map. Analysis optimized to look at large scale anisotropies.

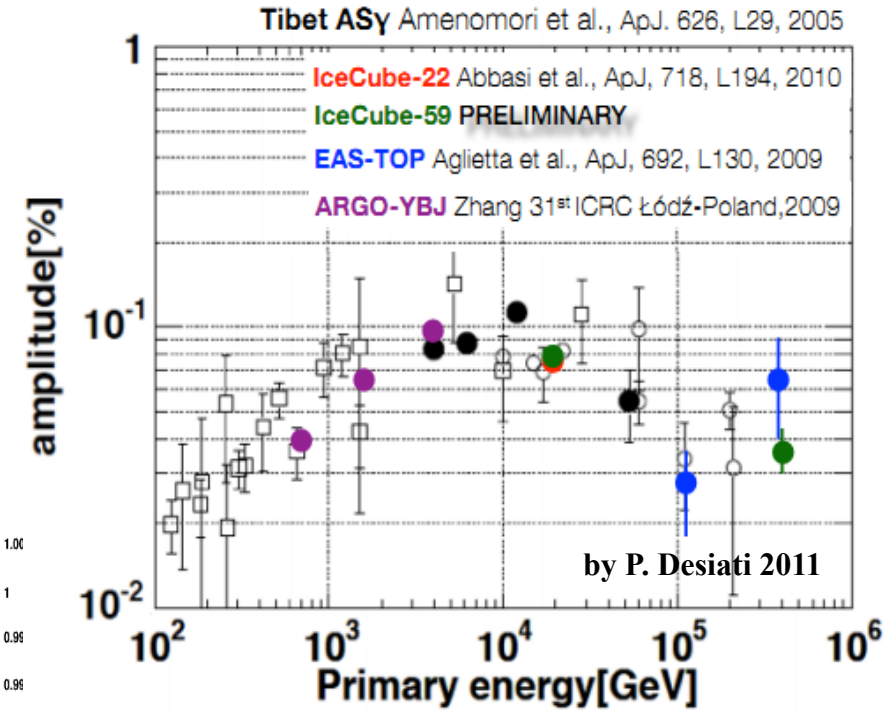
Tail-in excess region **Loss-cone deficit region**



CR anisotropy vs energy



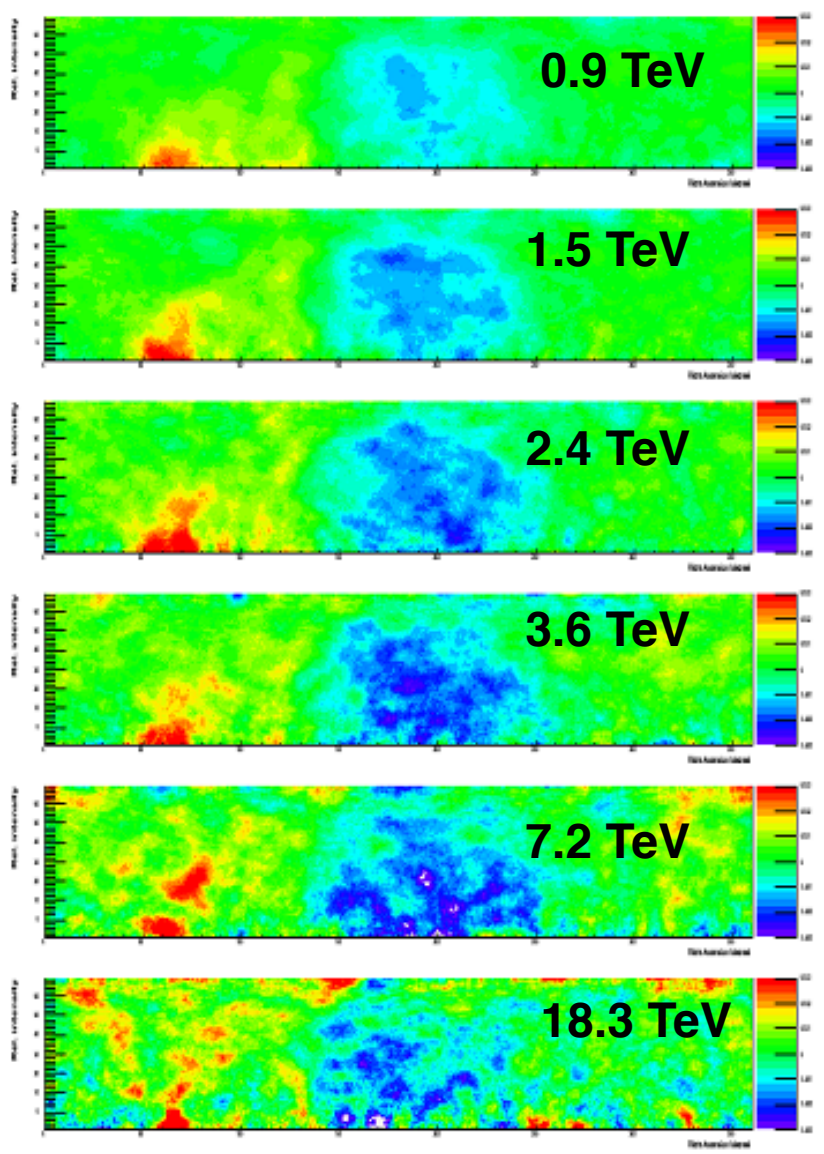


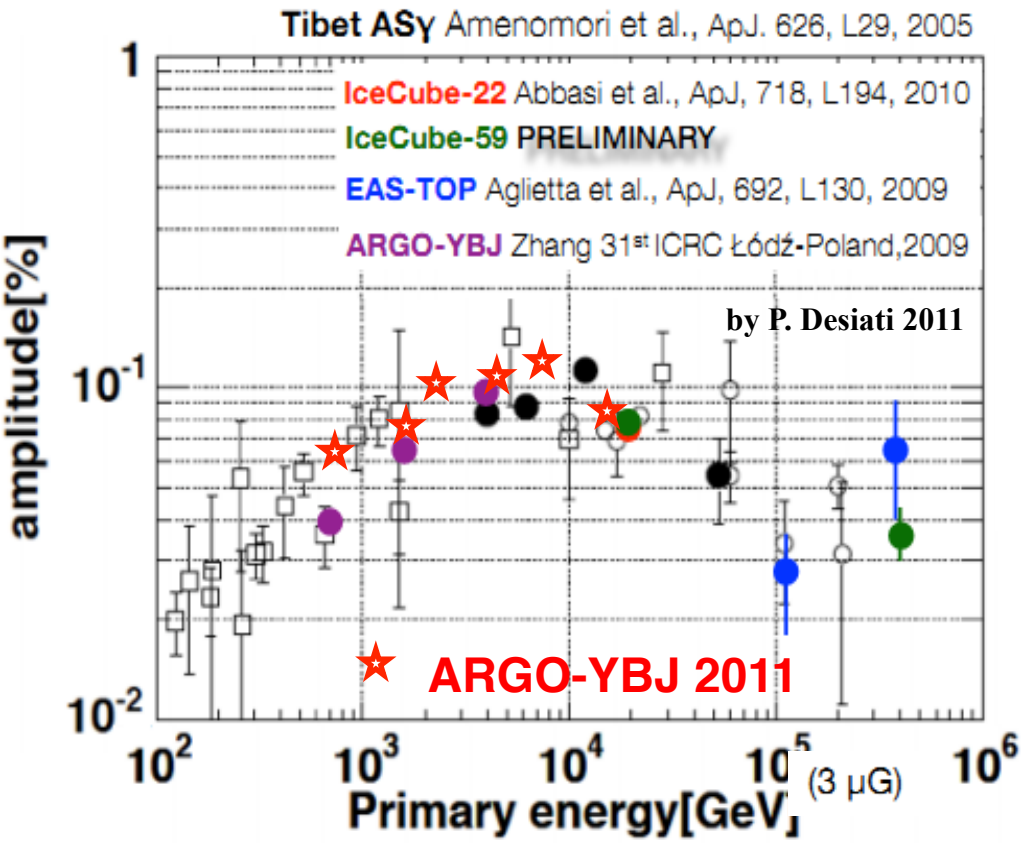


Fit function:

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

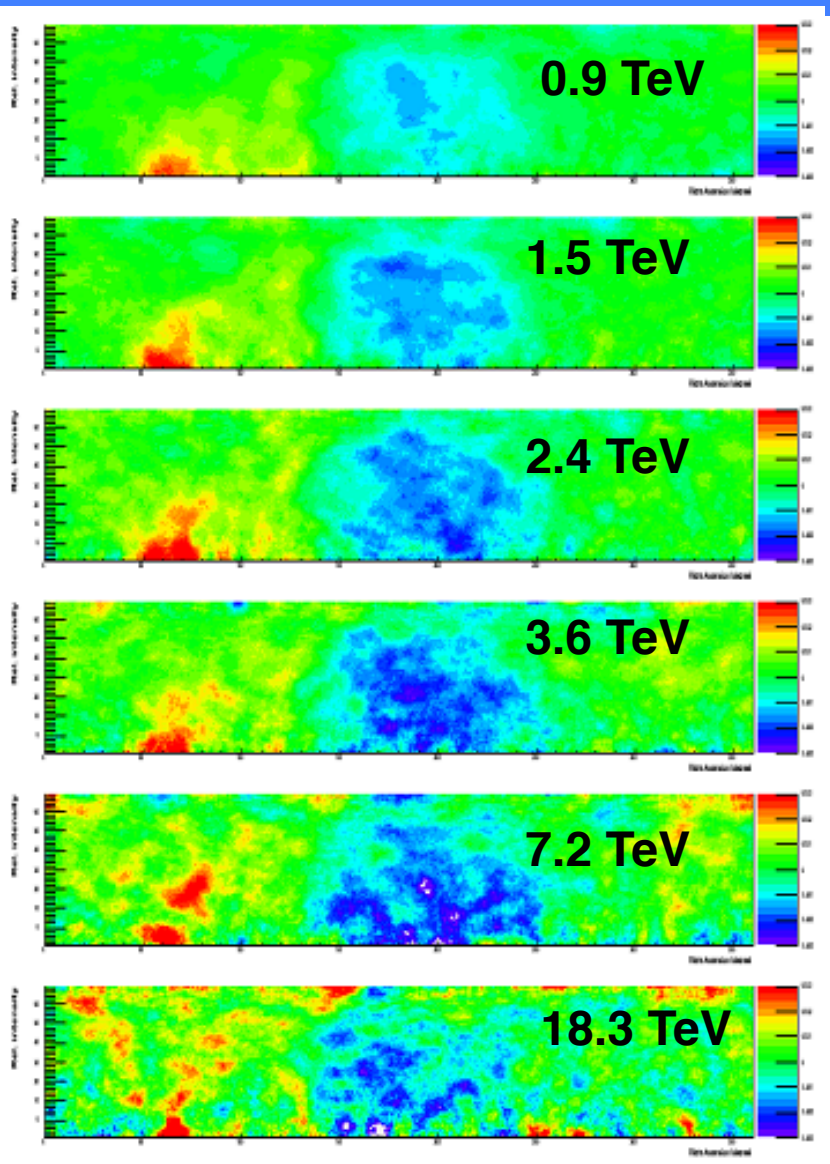
CR anisotropy vs energy



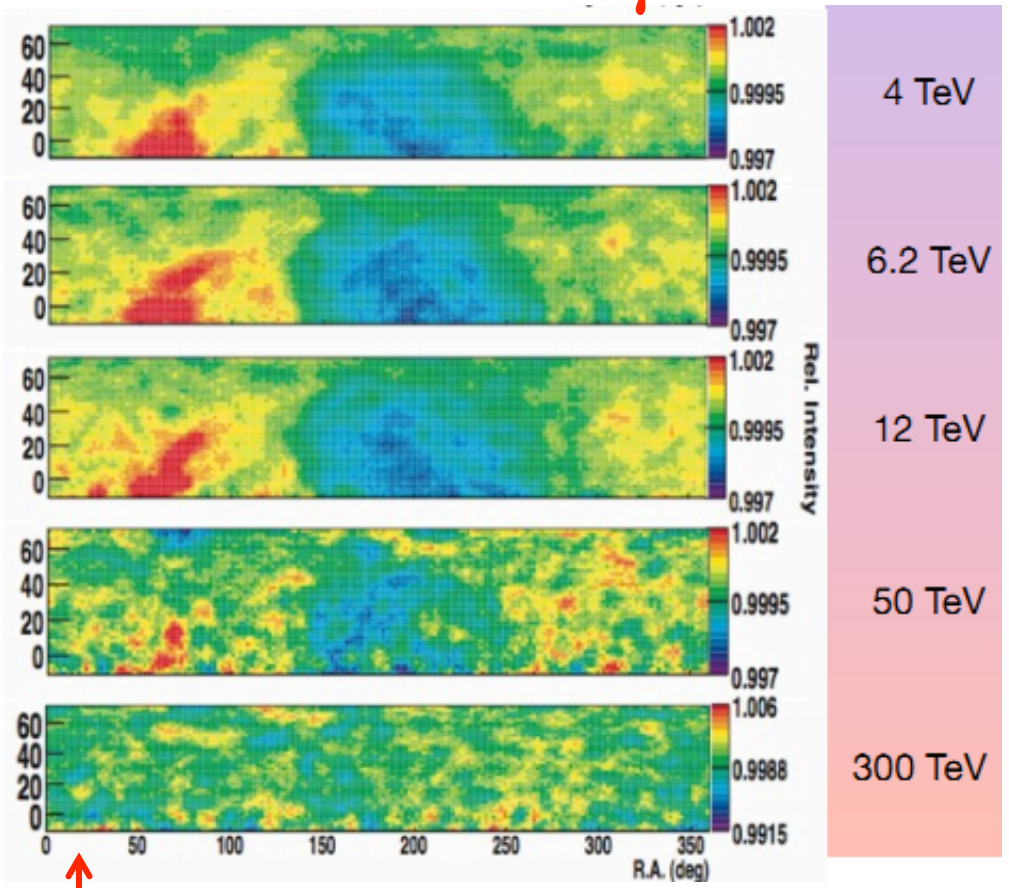


The tail-in broad structure appears to dissolve to smaller angular scale spots.

ARGO-YBJ and Tibet AS γ



Tibet ASγ



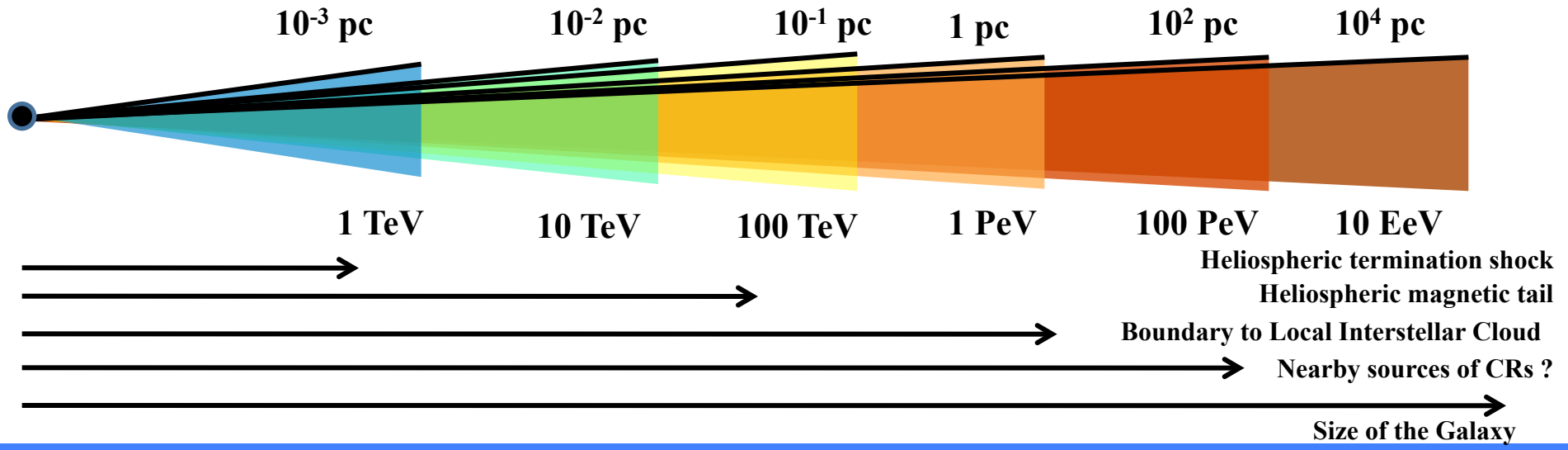
Anisotropy seems to disappear.

Possible Explanations

- **The origin of the large scale anisotropy in the CR arrival direction is still unknown.**
- **The structure of the local interstellar magnetic field is likely to have an important role.**

However, the combined study of the anisotropy energy and angular dependency, its time modulation, and angular scale structure seem to suggest that

- **the observation might be a combination of multiple superimposed effects, caused by phenomenologies at different distances from Earth.**



Tibet ASγ Model Fit to Data

Data

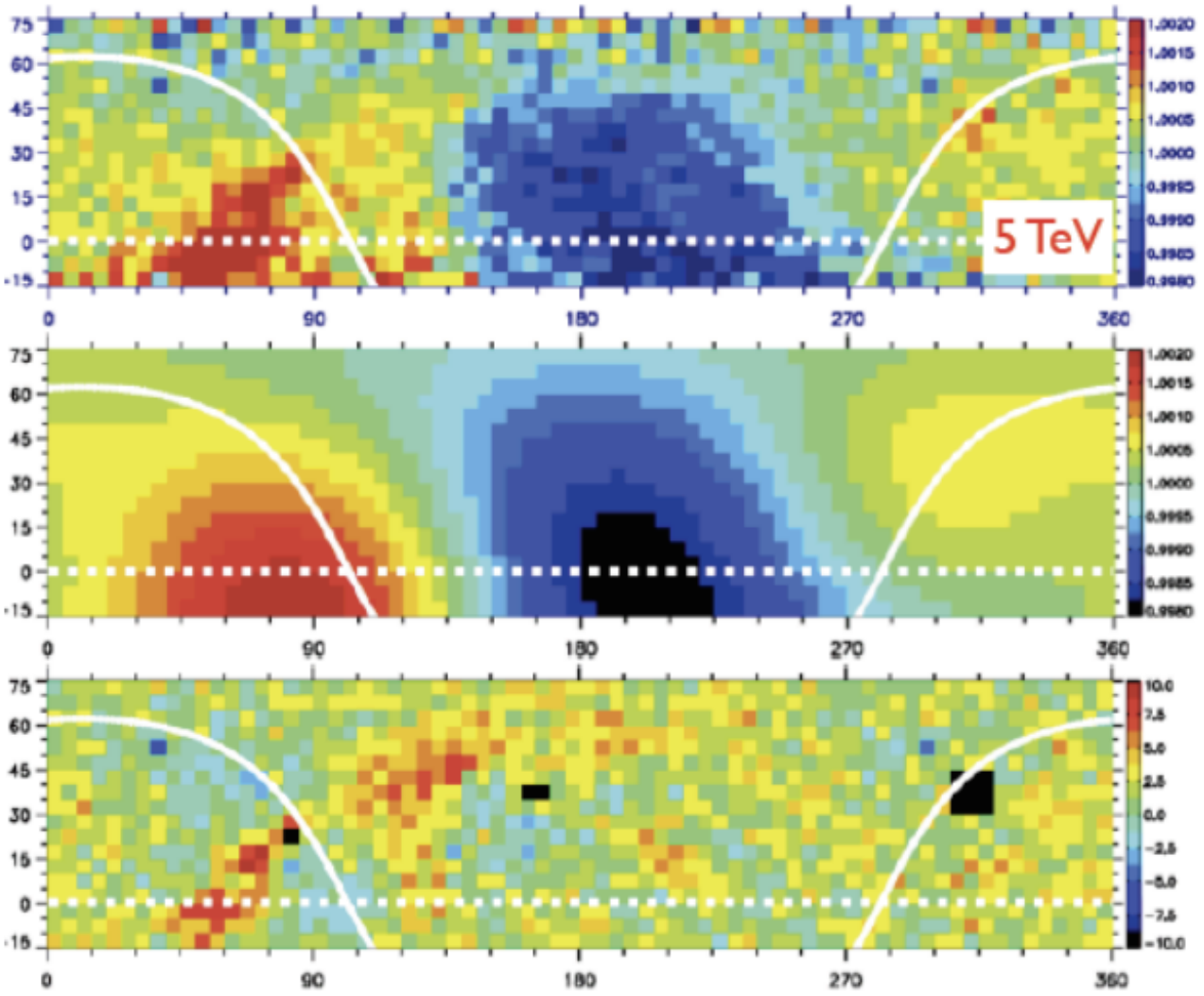
Model

uni-directional flow (dipole)

+

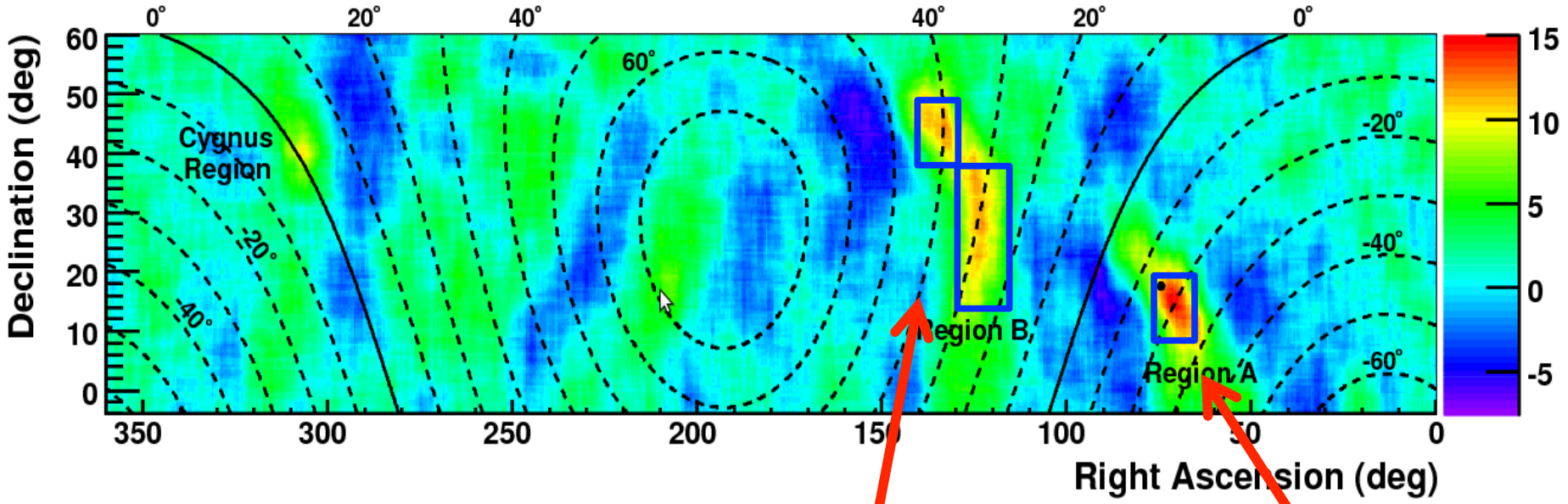
bi-directional flow (quadrupole)

Residual skymap



M. Amenomori *et. al.* ICRC 2007 Proceedings

Medium scale anisotropy by Milagro



Phys.Rev.Lett.101:221101,2008

RA: 117°-131° | 131°-141°
Dec: 15°-40° | 40°-50°

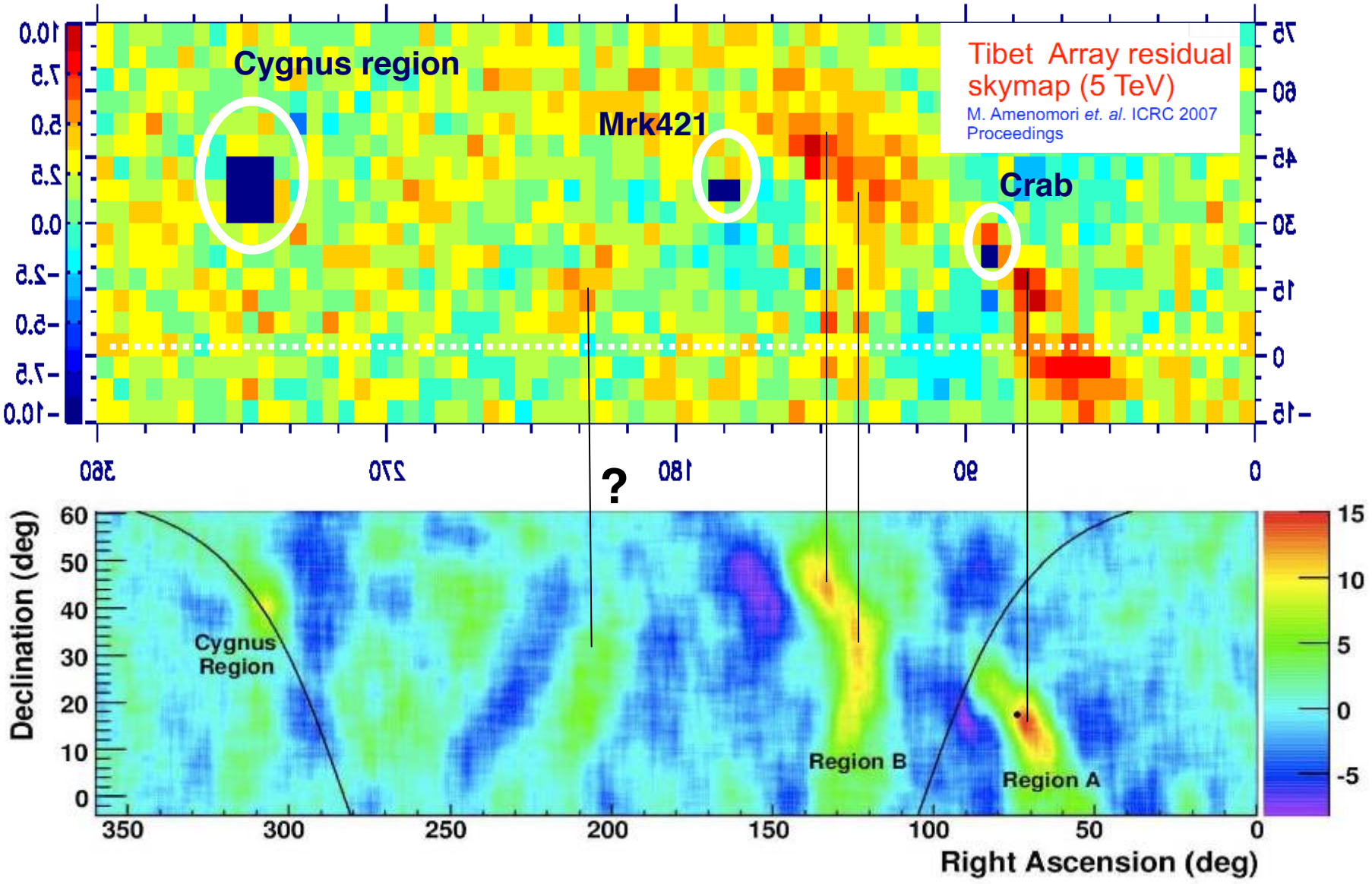
RA: 66°-76°
Dec: 10°-20°

Region B
12.4 s.d.
Fractional excess:
$4\ 10^{-4}$

Region A
15 s.d.
Fractional excess:
$6\ 10^{-4}$

Smoothing radius 10°

Tibet ASγ and Milagro



ARGO-YBJ observation

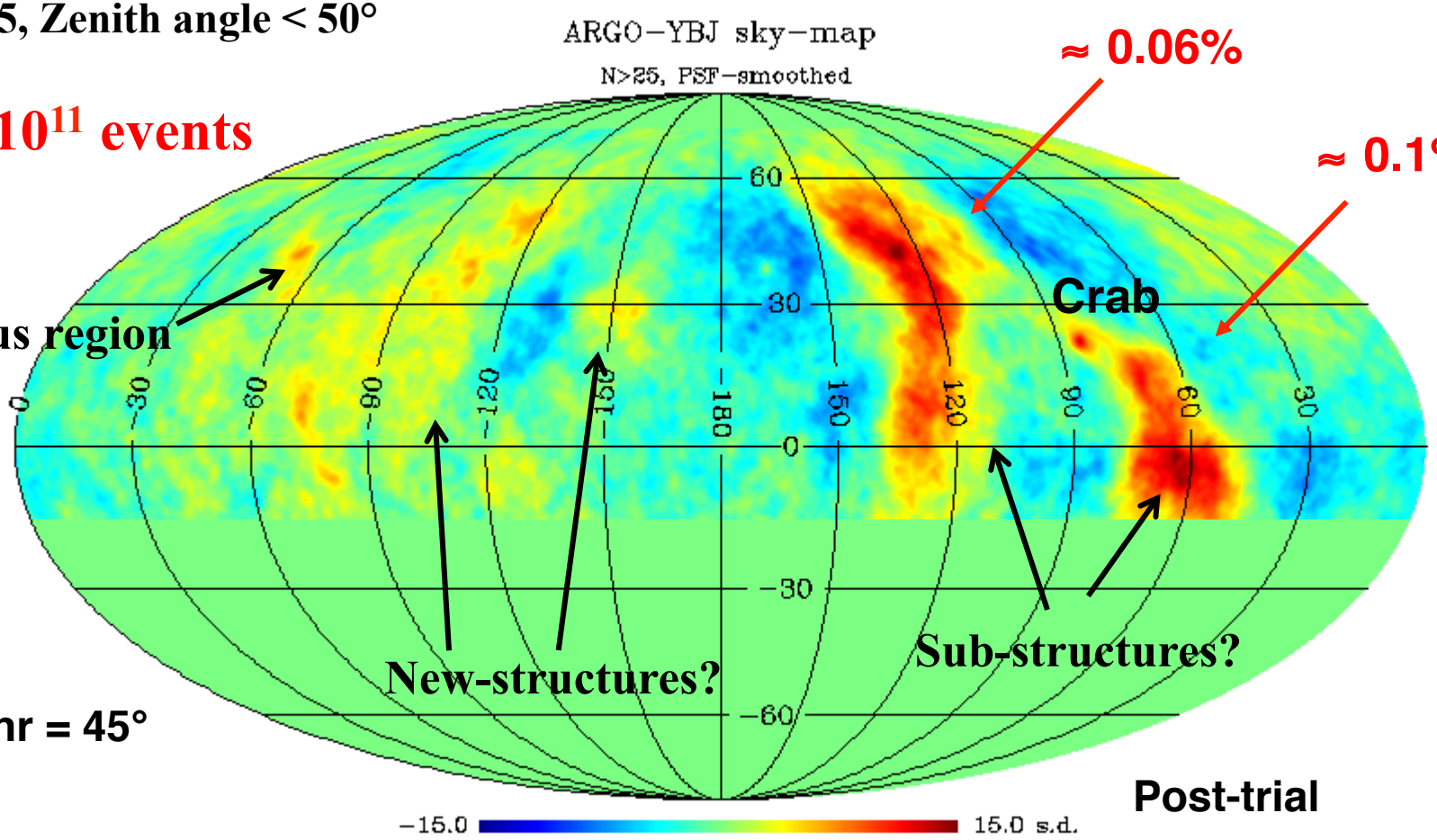
3 years data: 2008 - 2010
N_{str} > 25, Zenith angle < 50°

$1.4 \cdot 10^{11}$ events

Cosmic rays excess

≈ 0.06%

≈ 0.1%



Crab

Cygnus region

New-structures?

Sub-structures?

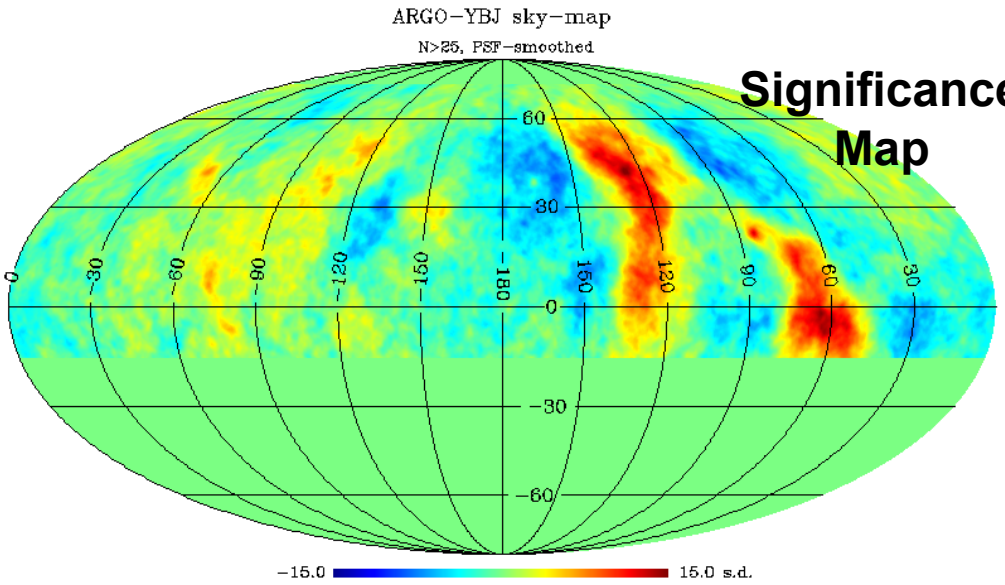
Δ t =3 hr = 45°

Post-trial

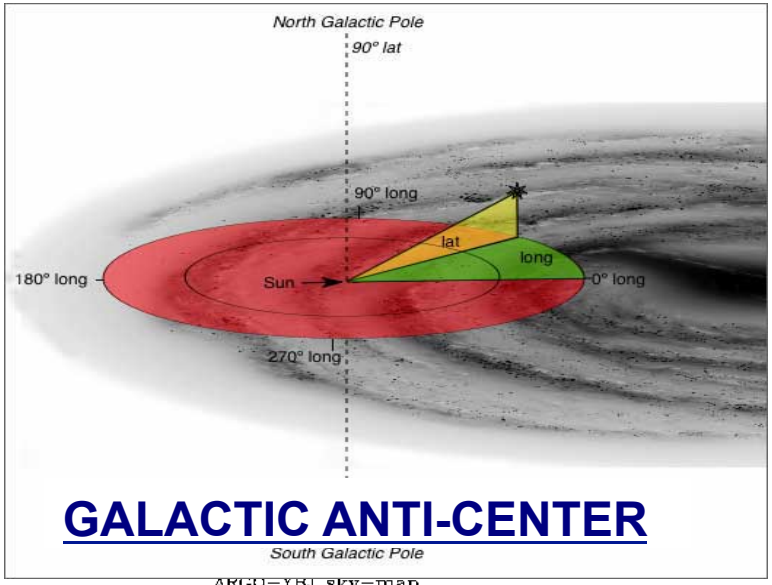
Equatorial coordinates:
projection of the earth longitude and latitude

Proton median energy ≈ 1 TeV

The small scale anisotropy PSF-smoothed

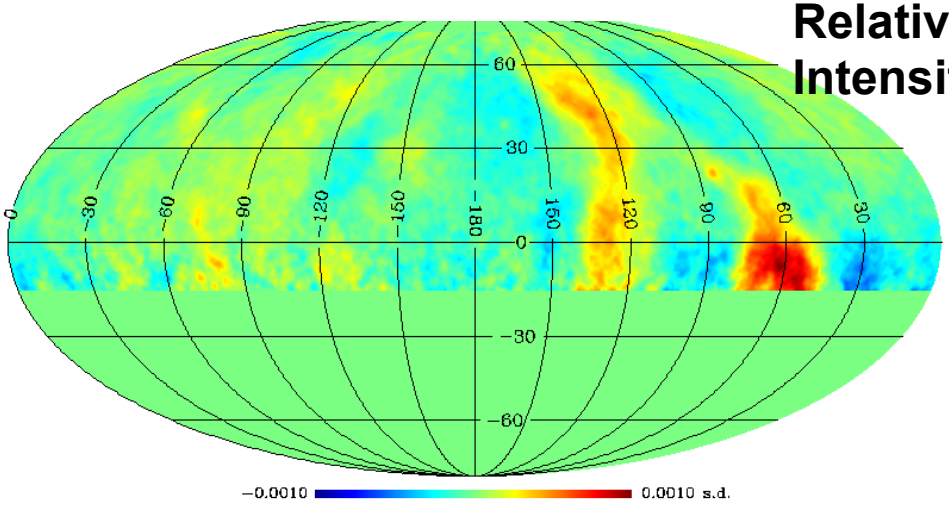


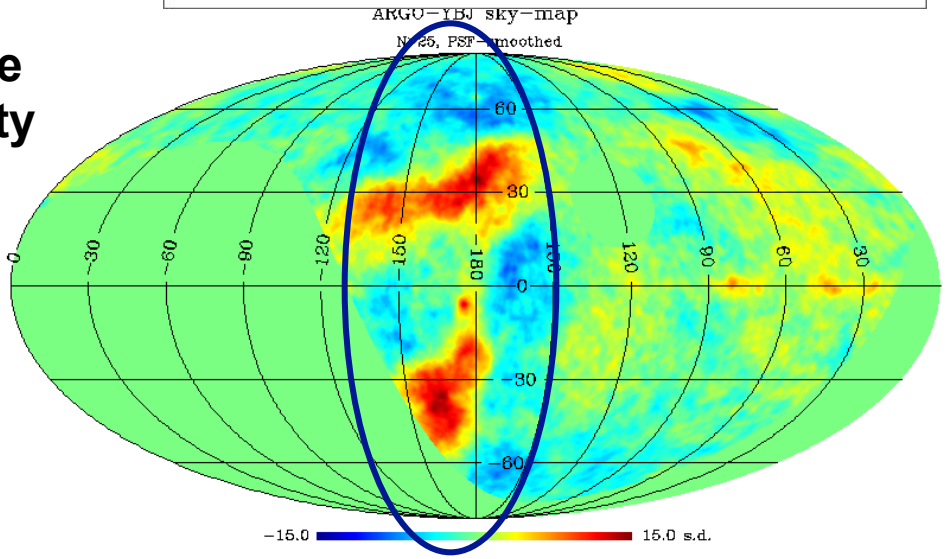
Significance Map



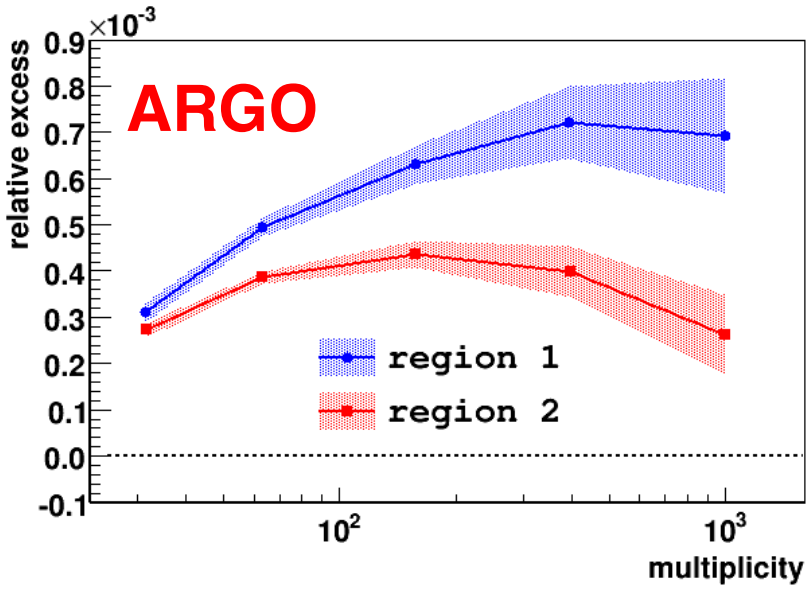
GALACTIC ANTI-CENTER

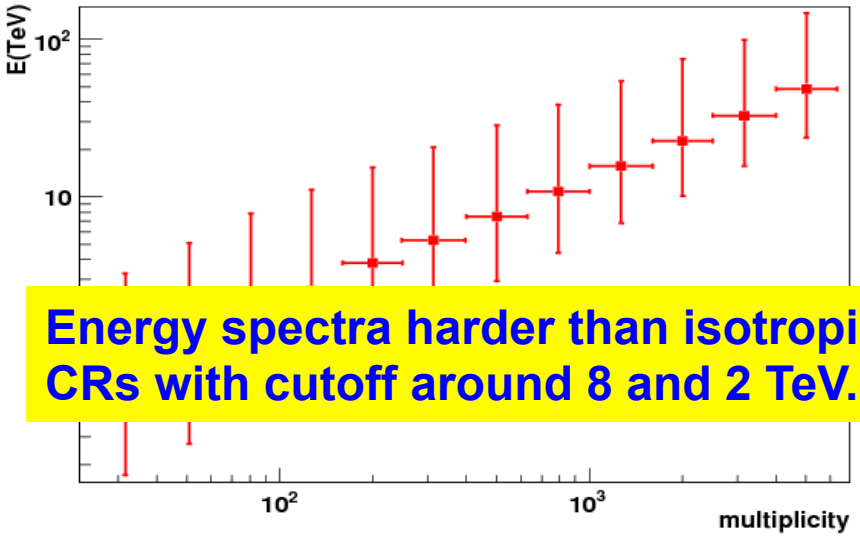
Relative Intensity





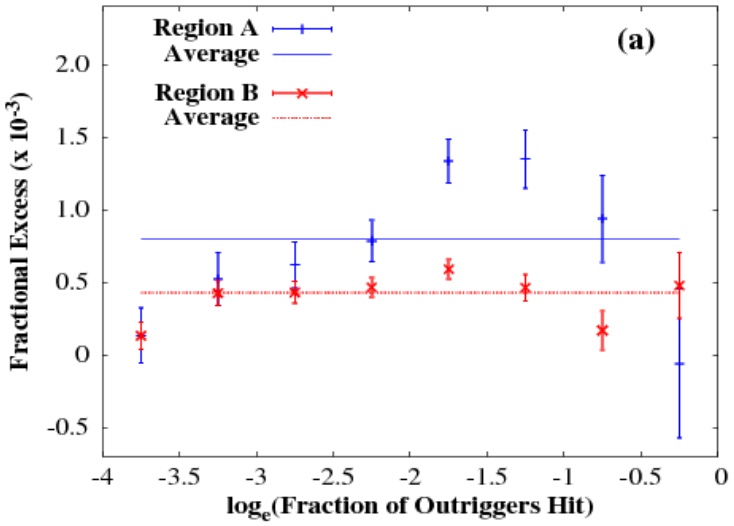
Energy spectrum

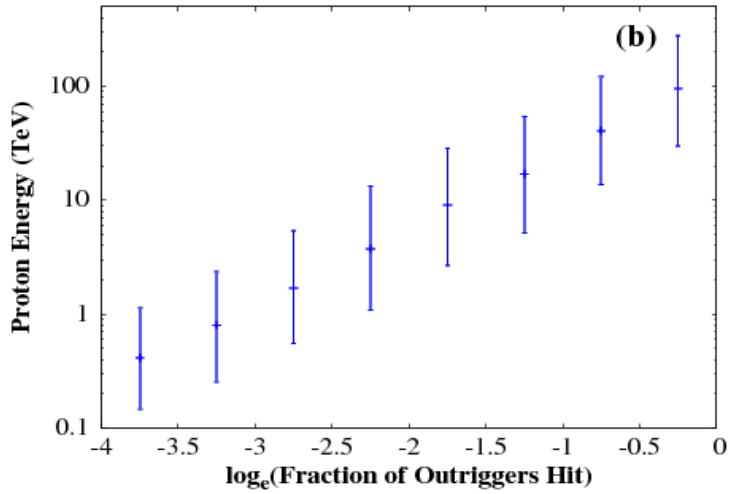




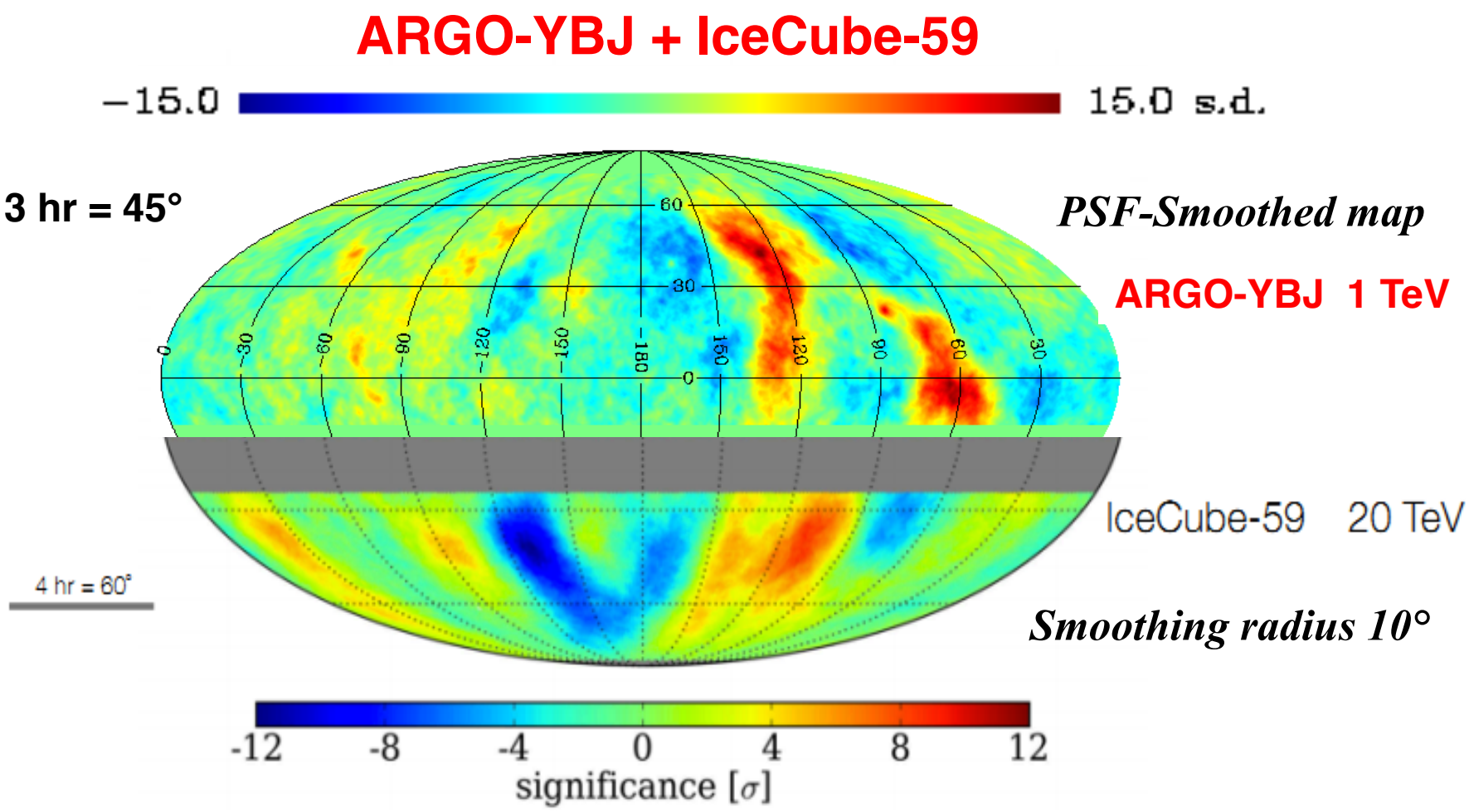
Energy spectra harder than isotropic CRs with cutoff around 8 and 2 TeV.

MILAGRO 2008

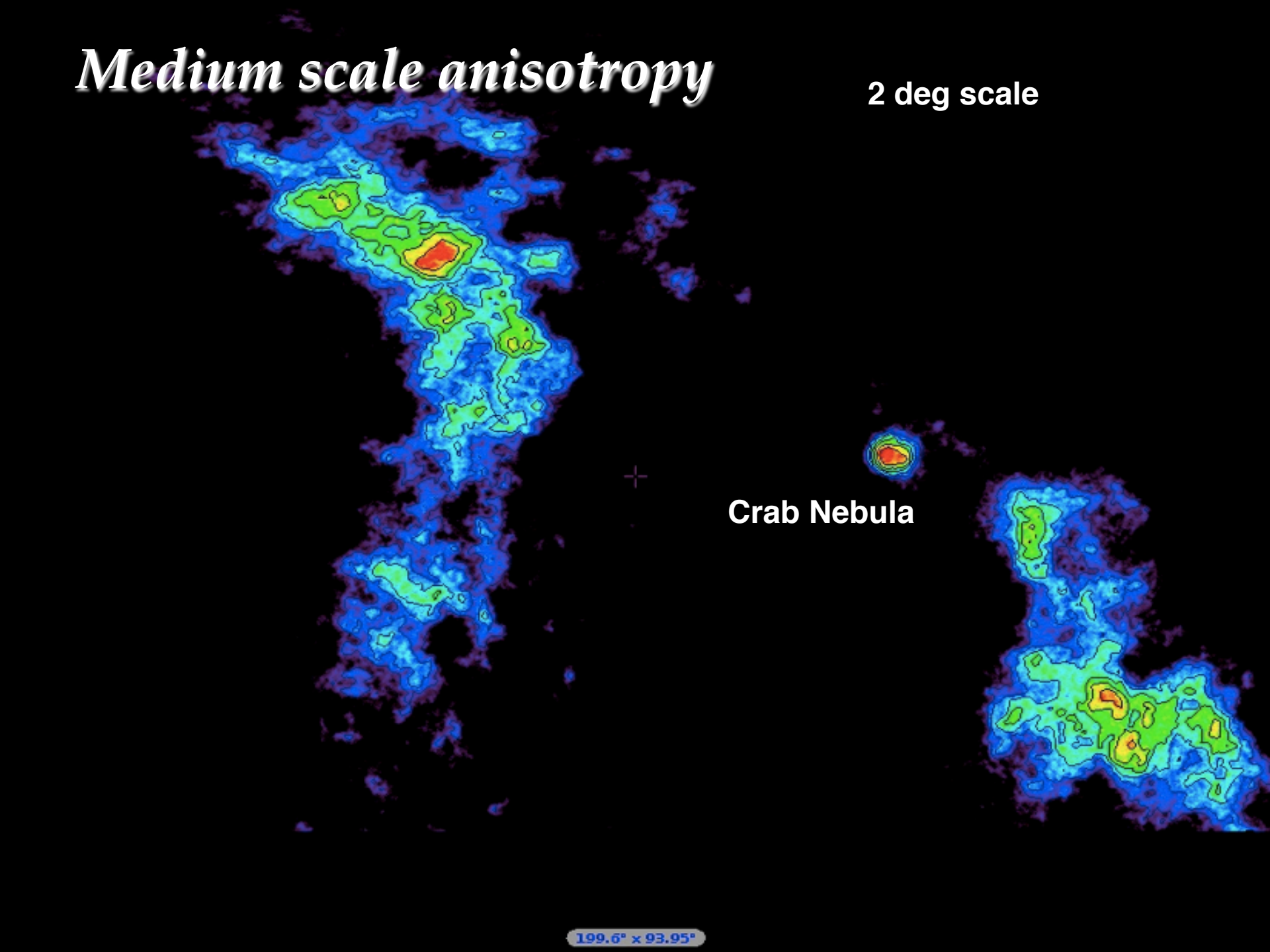




Complete CR map of the entire TeV sky



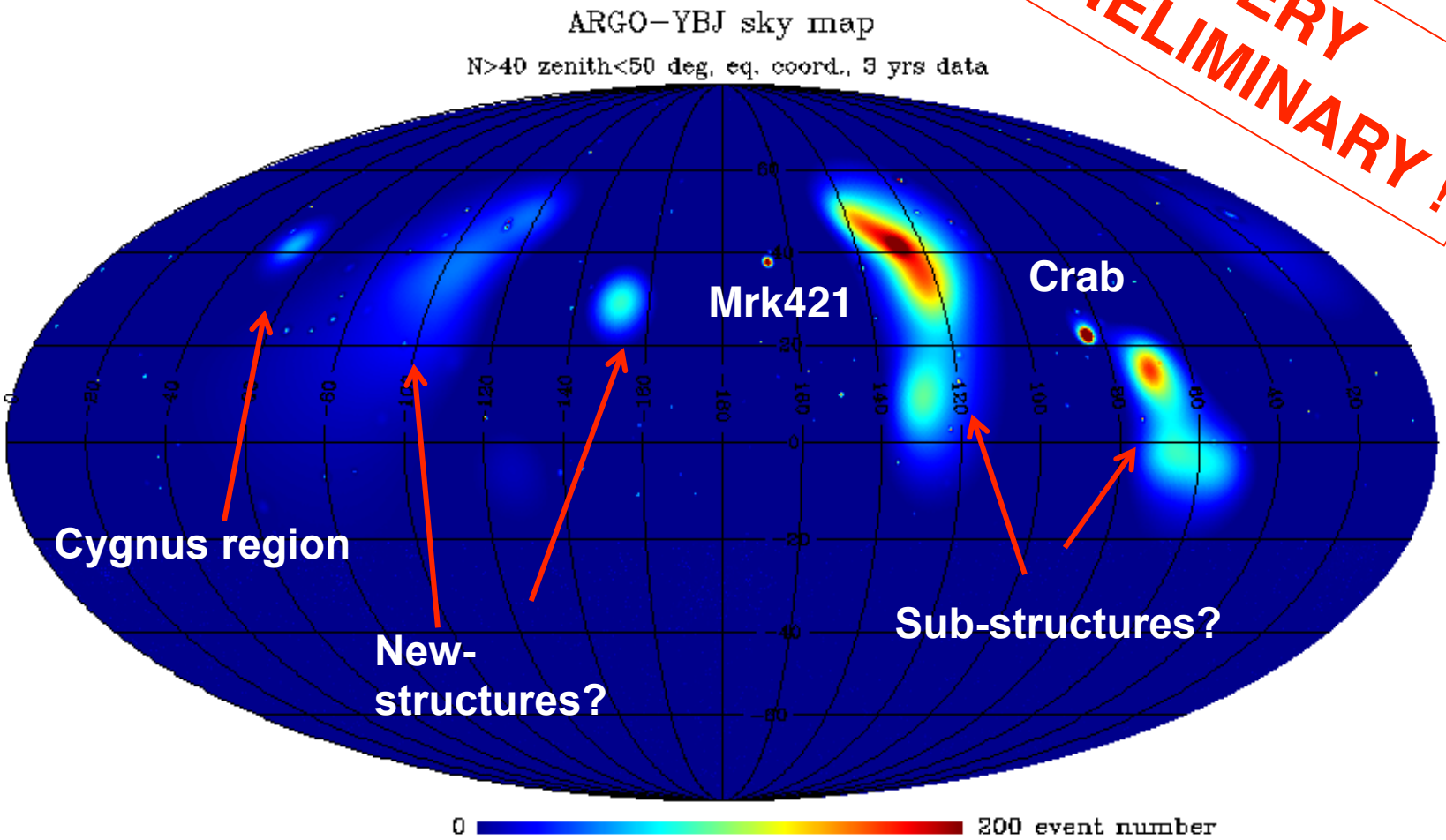
Medium scale anisotropy



A new approach: Needlet-based analysis

Focus on >4 s.d. significant regions

VERY PRELIMINARY !



Equatorial coordinates:
projection of the earth longitude and latitude

Origin/Explanation of the "hot-spots"

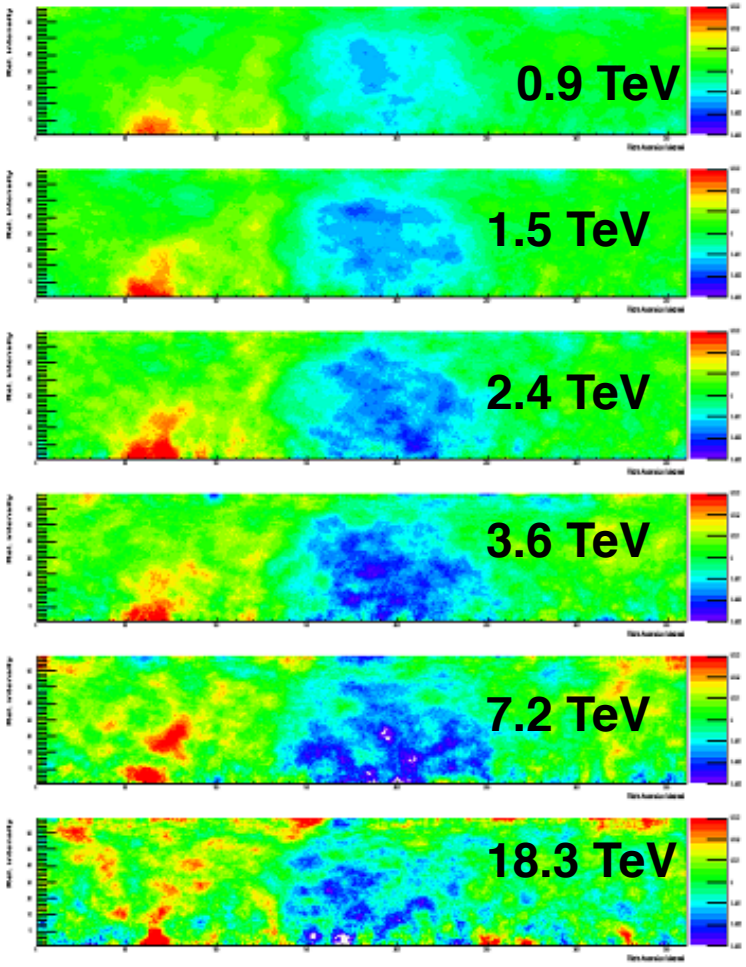
- **There is currently no explanation for these local enhancements in the CR flux.**

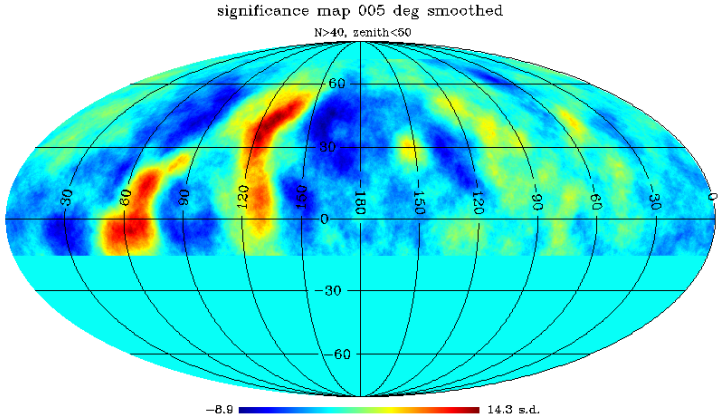
- **Composition:**
  - **Not photons or electrons (Milagro)**
  - **Neutrons from a star? Unlikely → 10 TeV neutrons decay in 0.1pc → much closer than the nearest star.**
  - **Gyro-radius of a 10 TeV proton in a 2μG magnetic field is only ~0.005pc (1000 AU).**
    - **Magnetic field must connect us to the source and be coherent out to it (>=100pc).**
- **Tips:**
    - **Connection to heliosphere ? Region A coincides with the direction of the heliotail.**
    - **The direction of both regions is nearly perpendicular to the expected Galactic magnetic field direction.**
- **Multiple explanations were proposed:**

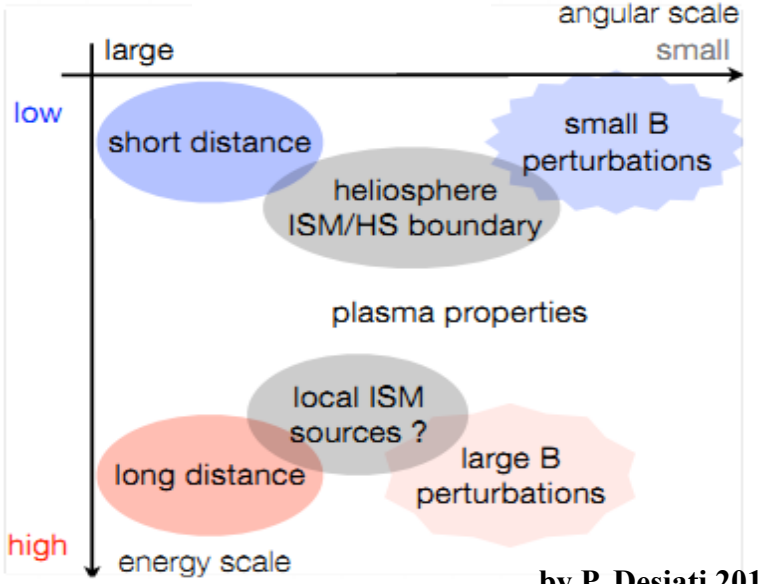
Salvati & Sacco, A&A 485 (2008) 527
Drury & Aharonian, Astrop. Phys. 29 (2008) 420.
K. Munakata ,AIP Conf Proc Vol 932, page 283
Salvati, A&A 513 (2010) A28
Lazarian & Desiati , ApJ 722 (2010) 188.

Energy and angular scale

The correlation of energy and angular scale of the anisotropy might provide a hint on the distance scale of the cause.







by P. Desiati 2011

Conclusions

- **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 20 TeV is in agreement with other experiments and provides useful data to constrain diffusion models.**
- **The observation of an intermediate scale anisotropy showed evidence of several new features still uninvestigated.**
- **Deeper analysis with new techniques is under way.**
- **The possibility that a young nearby SN might have produced an anisotropic feature over the isotropic intensity of old CRs provides the possibility that the origin of CRs might be discovered through the study of their anisotropy.**