# Recent Highlights from ARGO-YBJ

**G. Di Sciascio** on behalf of the ARGO-YBJ Collaboration
INFN Sezione Roma Tor Vergata

# Outline

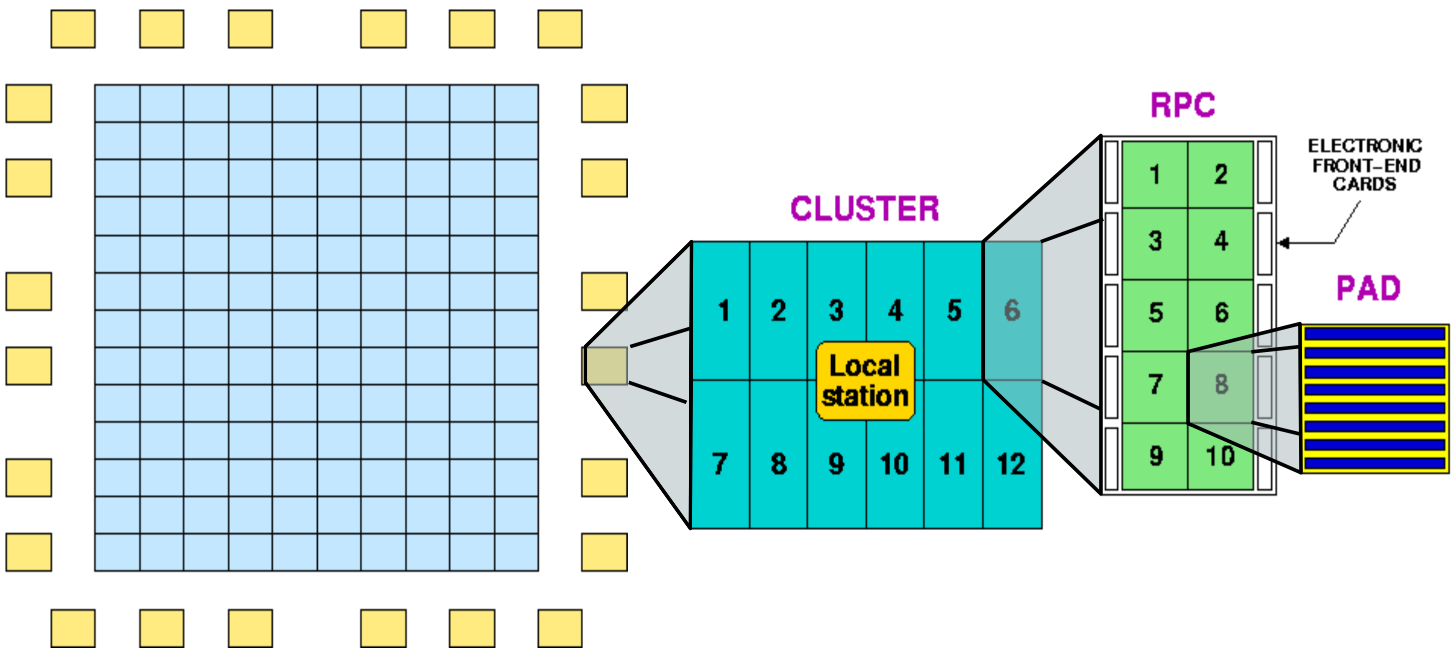
## ★Gamma-Ray Astronomy

- First Northern sky survey ($-10° < \delta < 70°$) at 0.25 Crab Units
- Study of extended sources

## ★Cosmic Ray Physics

- CR Light component (p+He) Energy Spectrum (2.5 - 800 TeV)
- Elemental composition approaching the knee
- CR Anisotropy at different angular scales

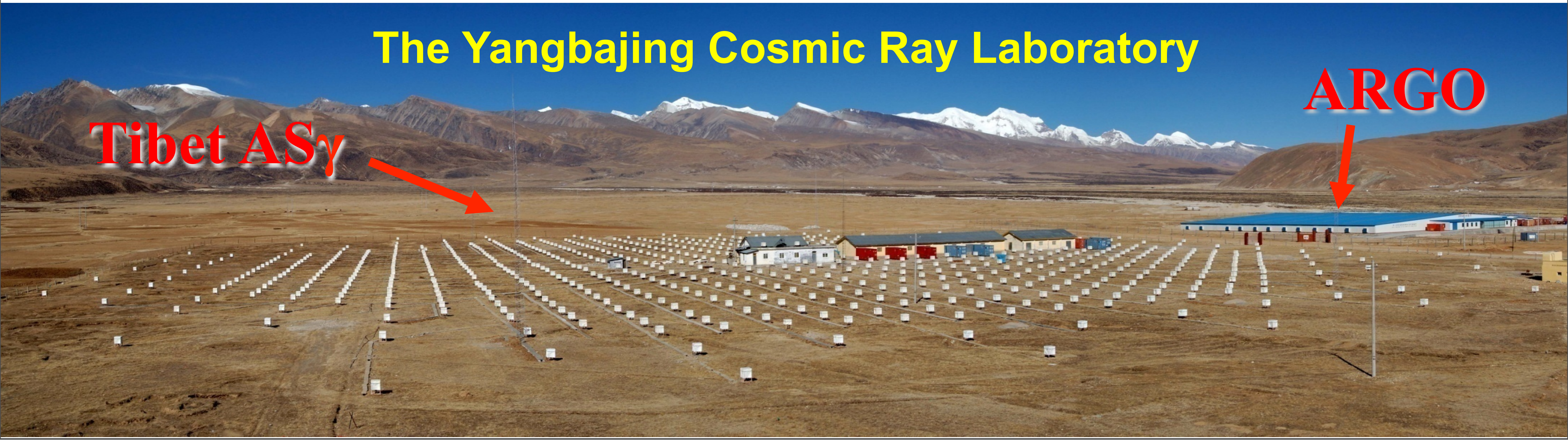
# The ARGO-YBJ experiment




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

**90 Km North from Lhasa (Tibet)**

**4300 m above the sea level**
**~ 600 g/cm²**



# The basic concepts

*…for an unconventional air shower detector*

❖ HIGH ALTITUDE SITE
(YBJ - Tibet 4300 m asl - 600 g/cm2)

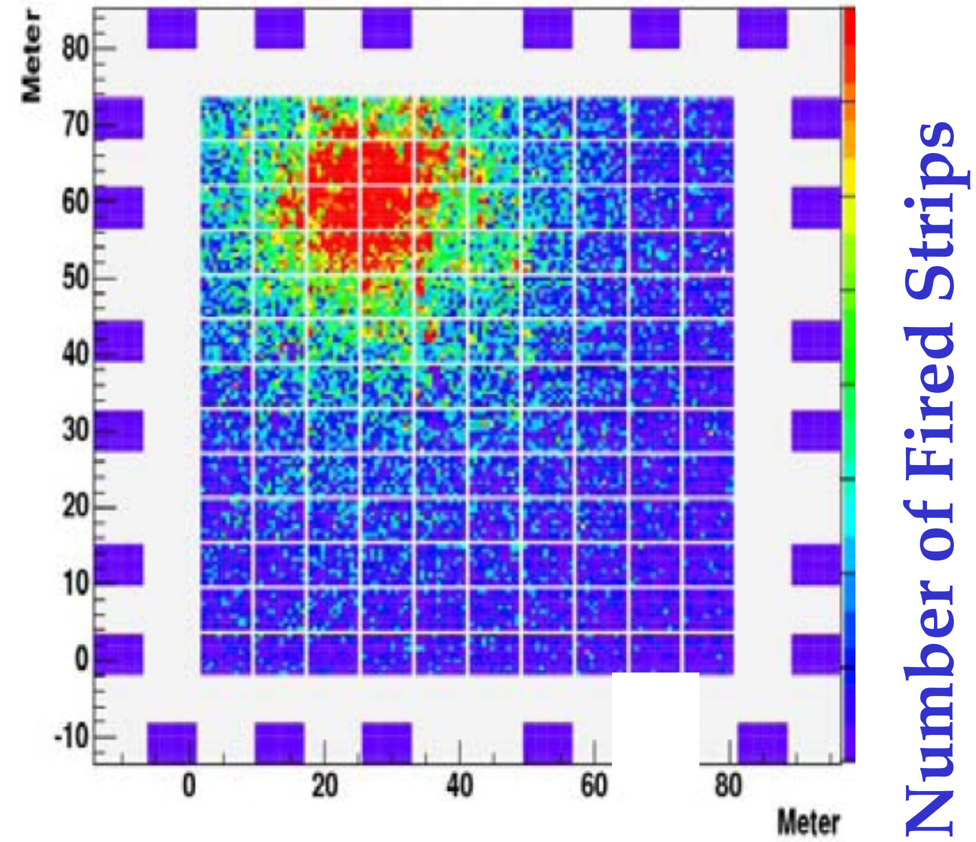
❖ FULL COVERAGE
(RPC technology, 92% covering factor)

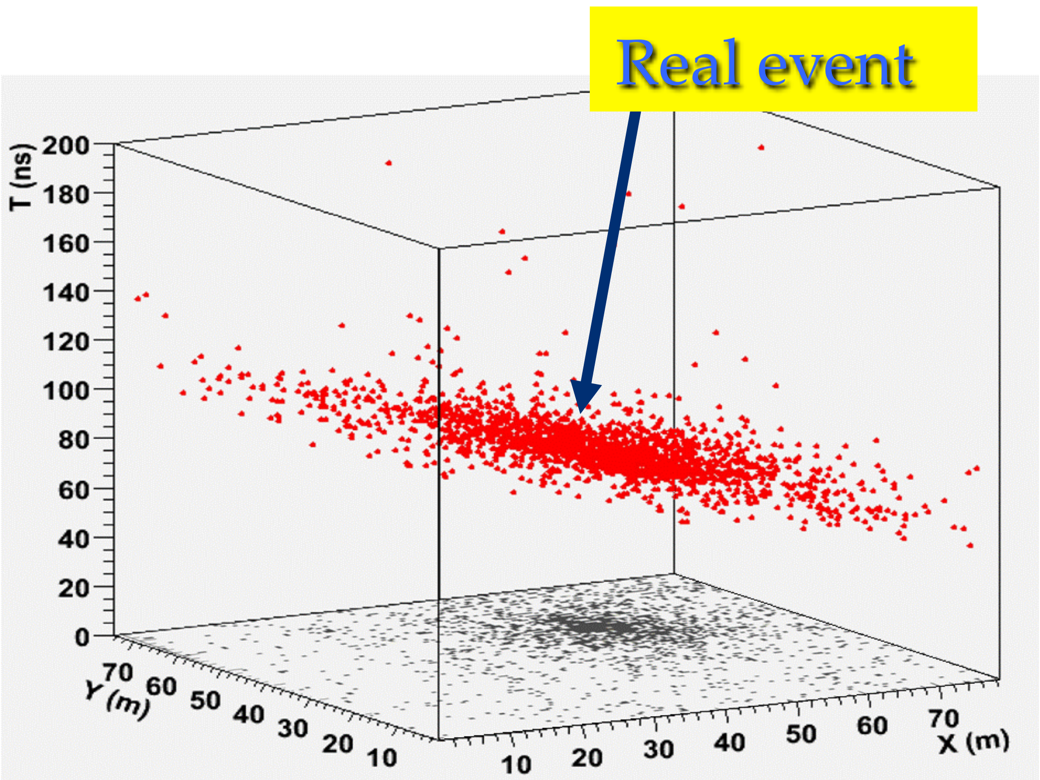
❖ HIGH SEGMENTATION OF THE READOUT
(small space-time pixels)

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 with unprecedented details
- get an energy threshold of a few hundreds of GeV

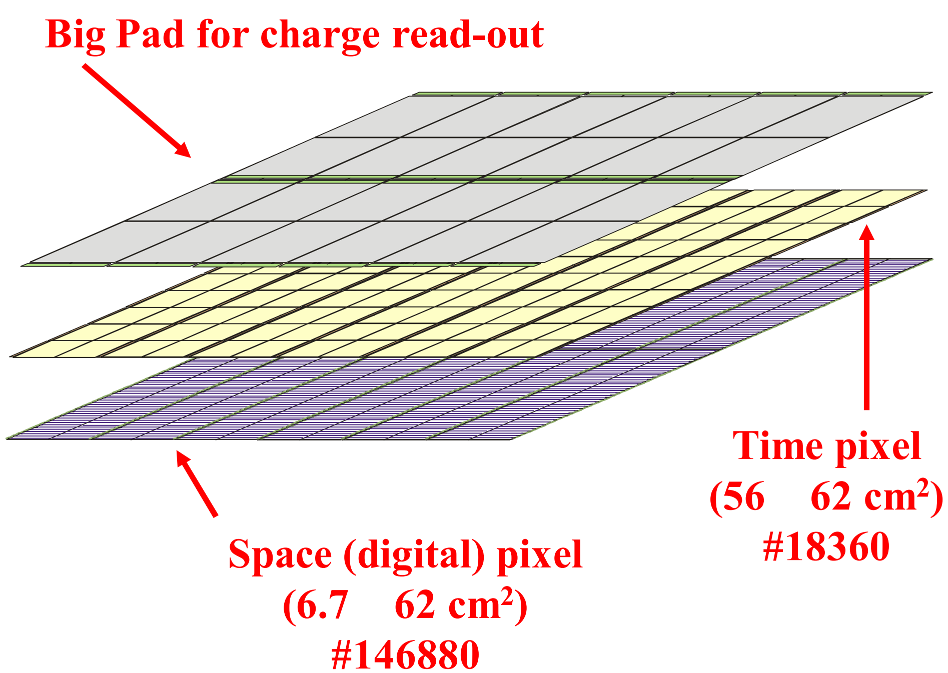


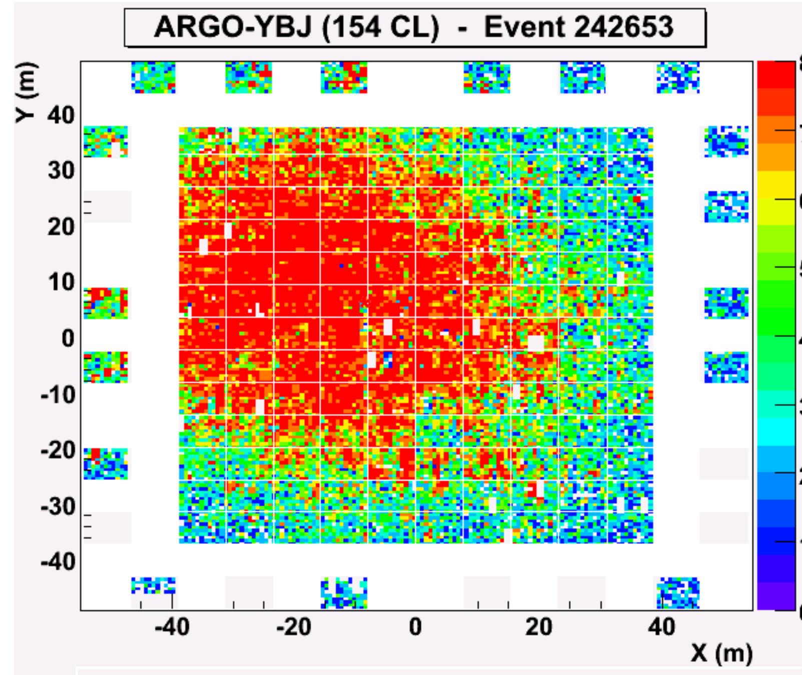



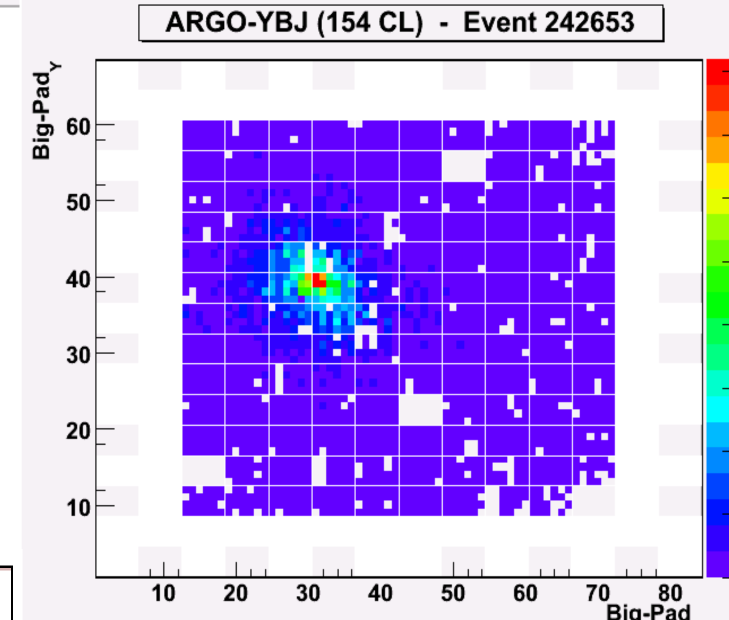
# The basic concepts

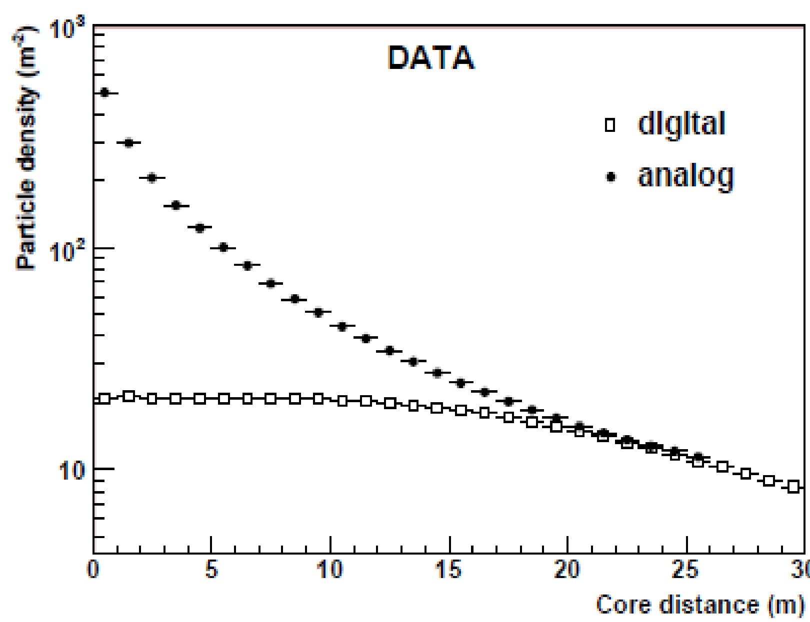
*...extending the dynamical range up to PeV*

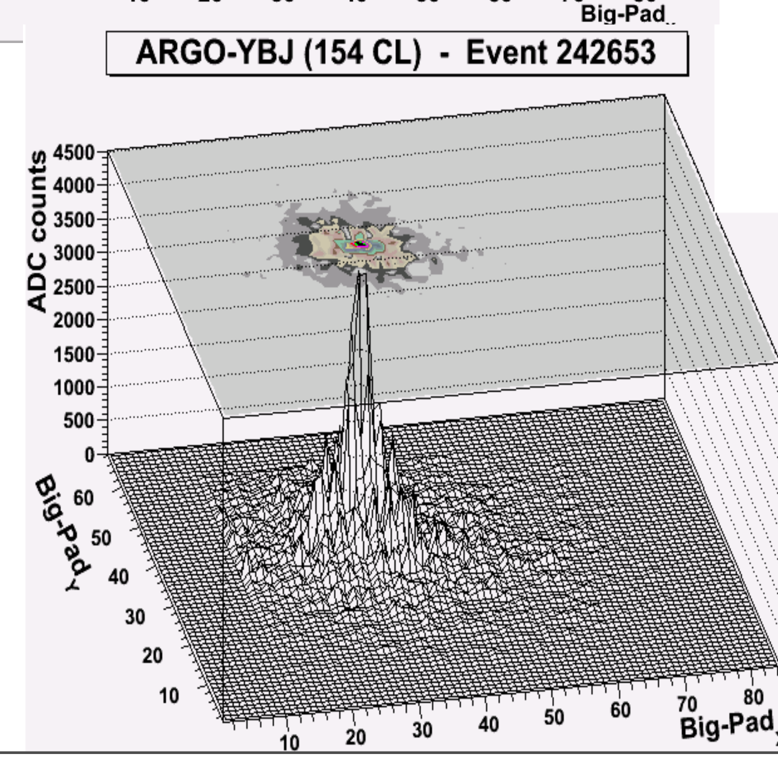
❖ ANALOG READOUT → PeV
(3672 1.40 × 1.25 $m^2$ "big pads")



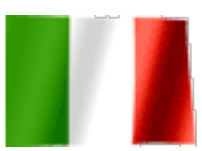



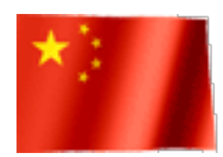




- Extend the covered energy range
- Access the LDF down to the shower core
- Sensitivity to primary mass
- Info/checks on Hadronic Interactions

# The ARGO-YBJ Collaboration

Collaboration Institutions:
- Chinese Academy of Sciences (CAS)
- Istituto Nazionale di Fisica Nucleare (INFN)

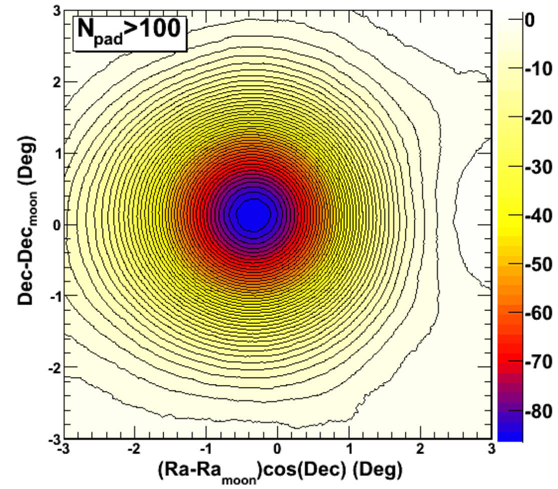


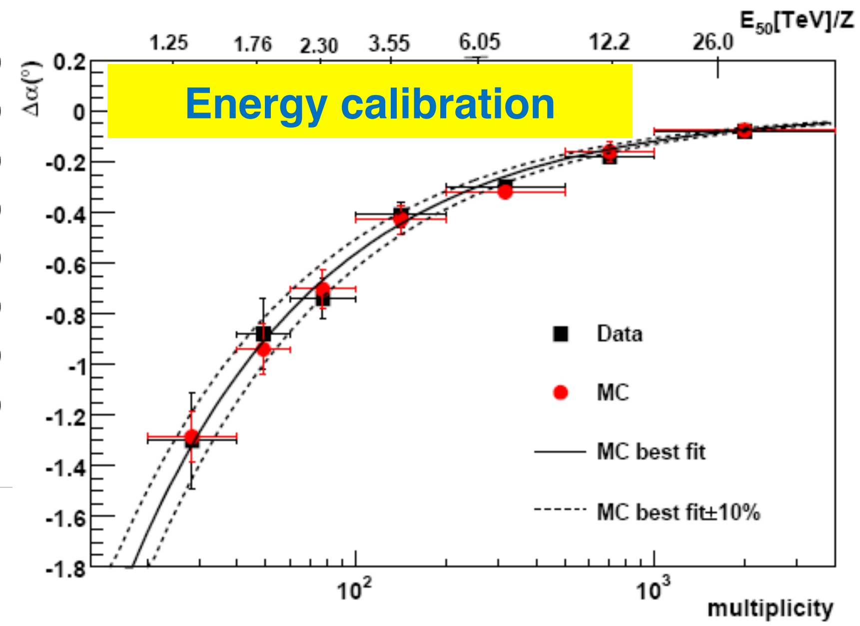



*INAF/IASF, Palermo and INFN, Catania*
*INFN and Dpt. di Fisica Università, Lecce*
*INFN and Dpt. di Fisica Universita', Napoli*
*INFN and Dpt. di Fisica Universita', Pavia*
*INFN and Dpt di Fisica Università "Roma Tre", Roma*
*INFN and Dpt. di Fisica Univesità "Tor Vergata", Roma*
*INAF/IFSI and INFN,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

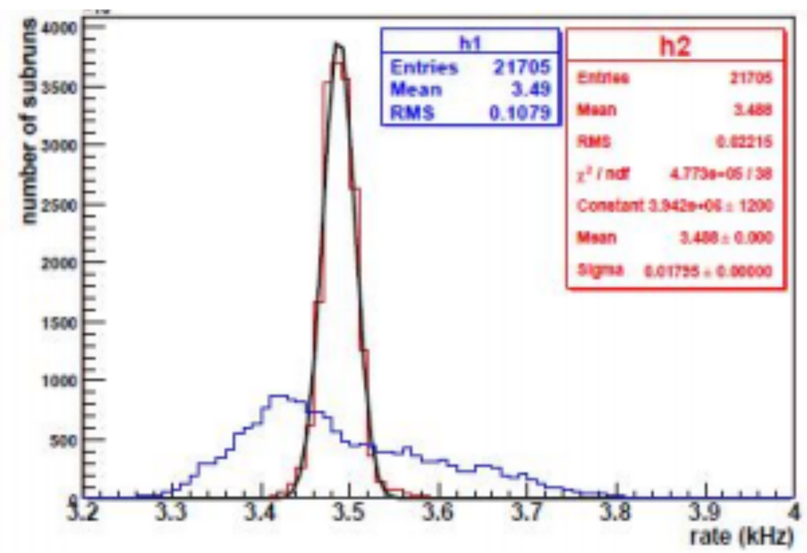
*IHEP, Beijing*
*Shandong University, Jinan*
*South West Jiaotong University, Chengdu*
*Tibet University, Lhasa*
*Yunnan University, Kunming*
*Hebei Normal University, Shijiazhuang*

# Status and performance

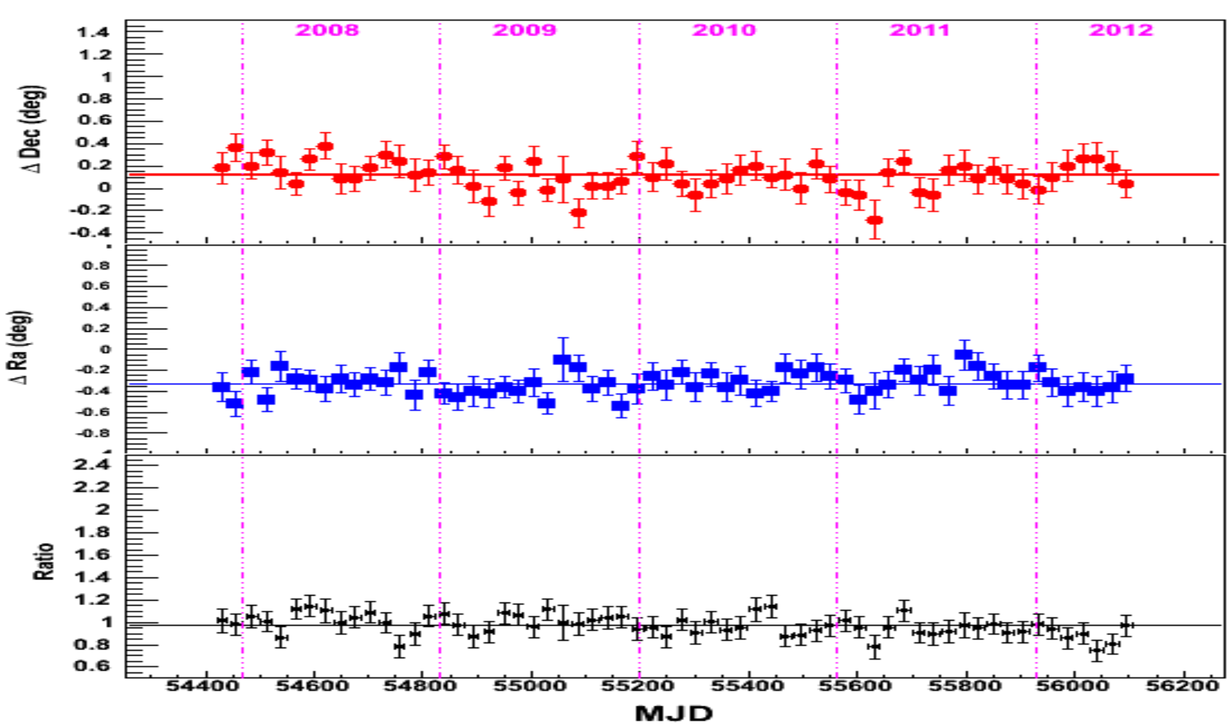


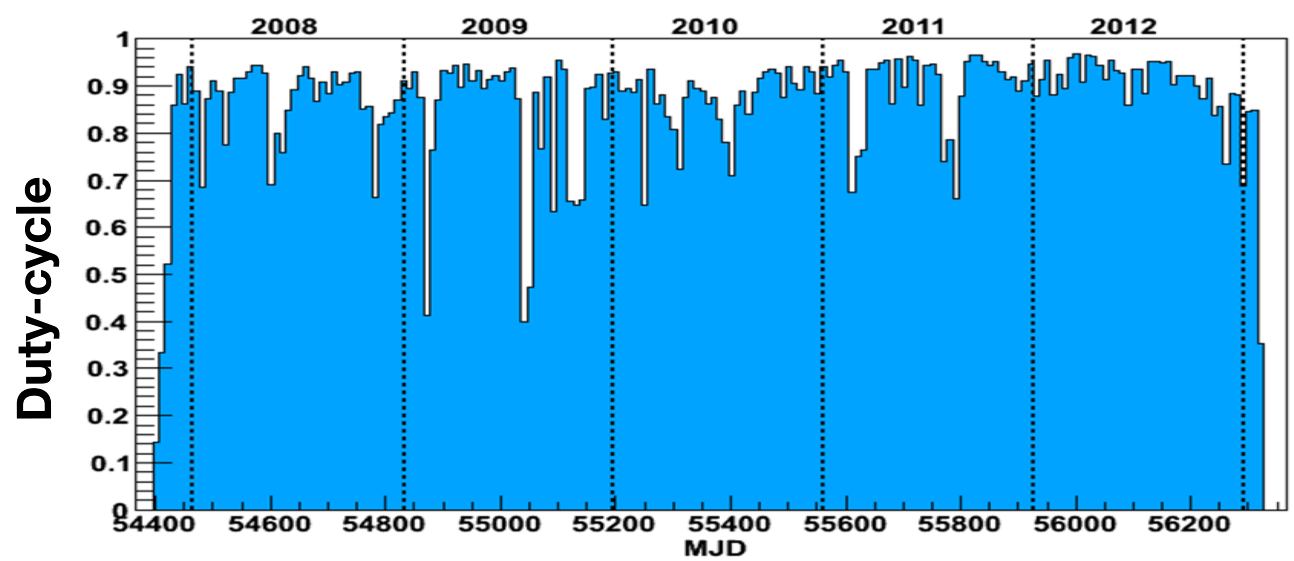




- In observation since July 2006 (commissioning phase)
- Stable data taking since November 2007
- End/Stop data taking: January 2013
- Average duty cycle ~87%
- Trigger rate ~3.5 kHz @ 20 pad threshold
- N. recorded events: ≈ $5\cdot10^{11}$ from 100 GeV to PeV
- 100 TB/year data




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



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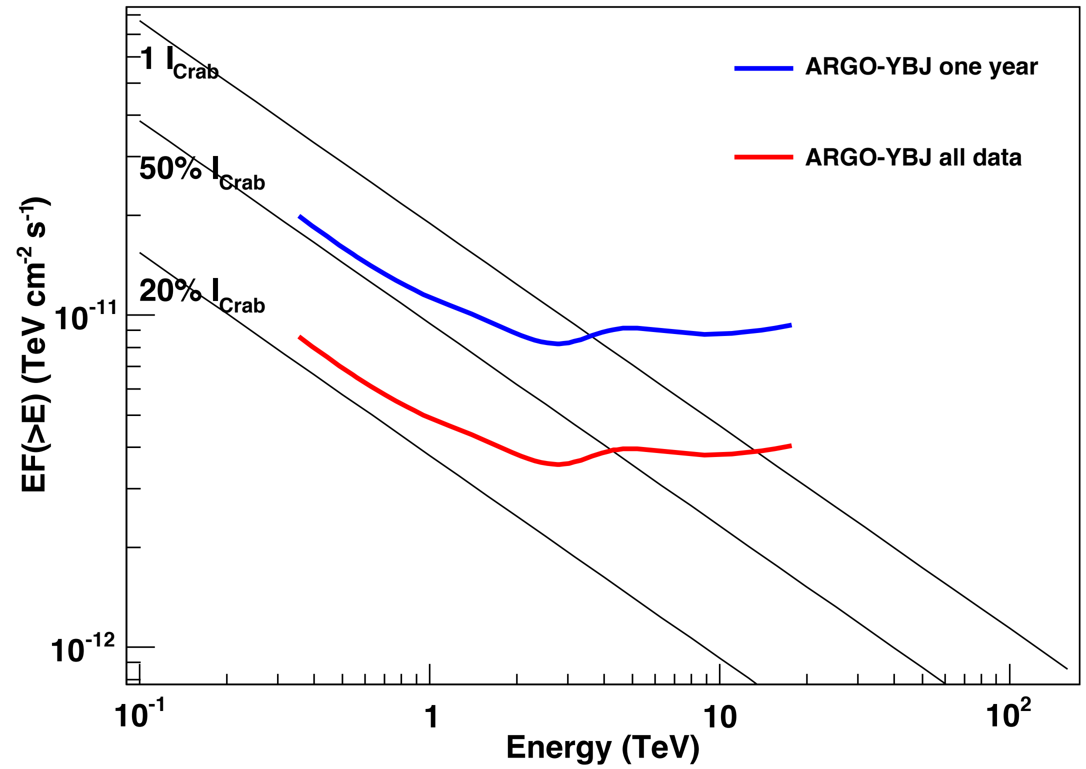
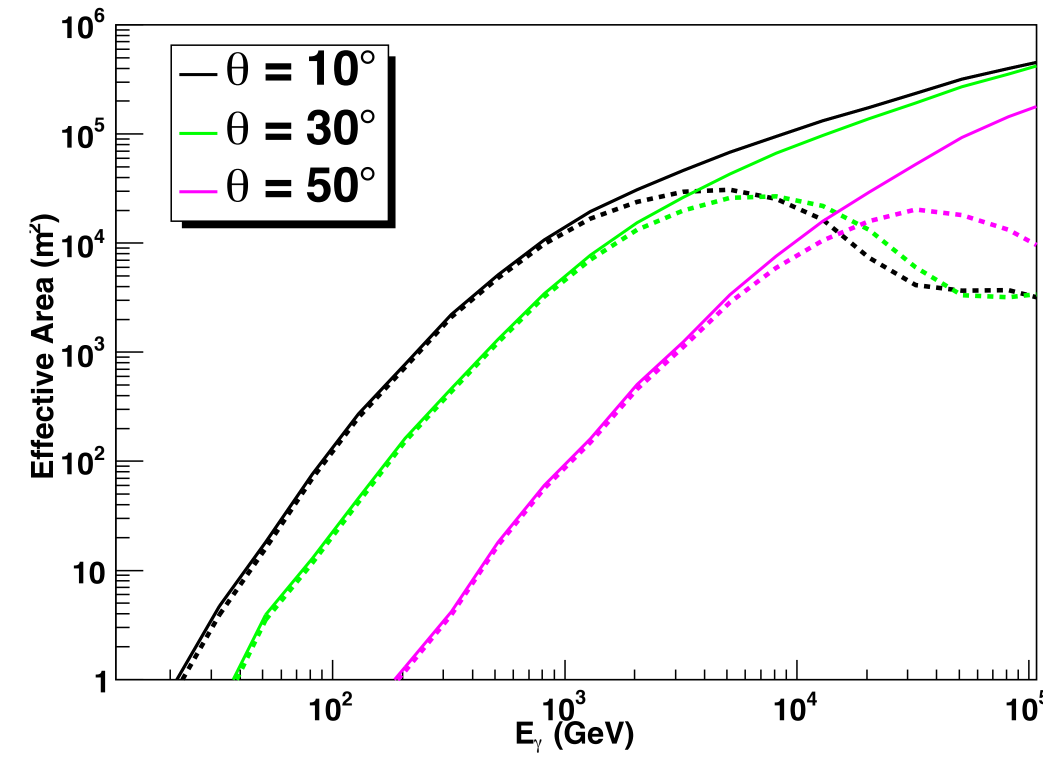
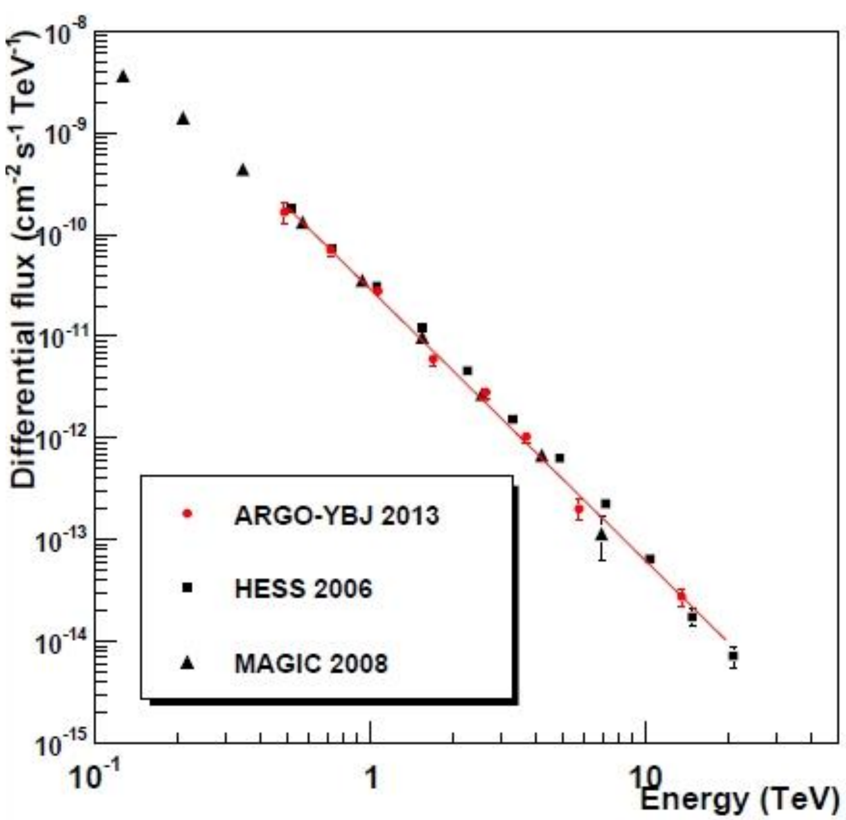
# Gamma-Ray Astronomy with ARGO-YBJ

- Energy threshold: few hundreds of GeV
  → Overlaps with Cherenkov detectors
- Large duty cycle: 86%
- Large field of view: ~2 sr
- Declination band from -10° to 70°
- Integrated sensitivity in 5 y at ~1 TeV:
  0.25 Crab for dec 15° - 45°



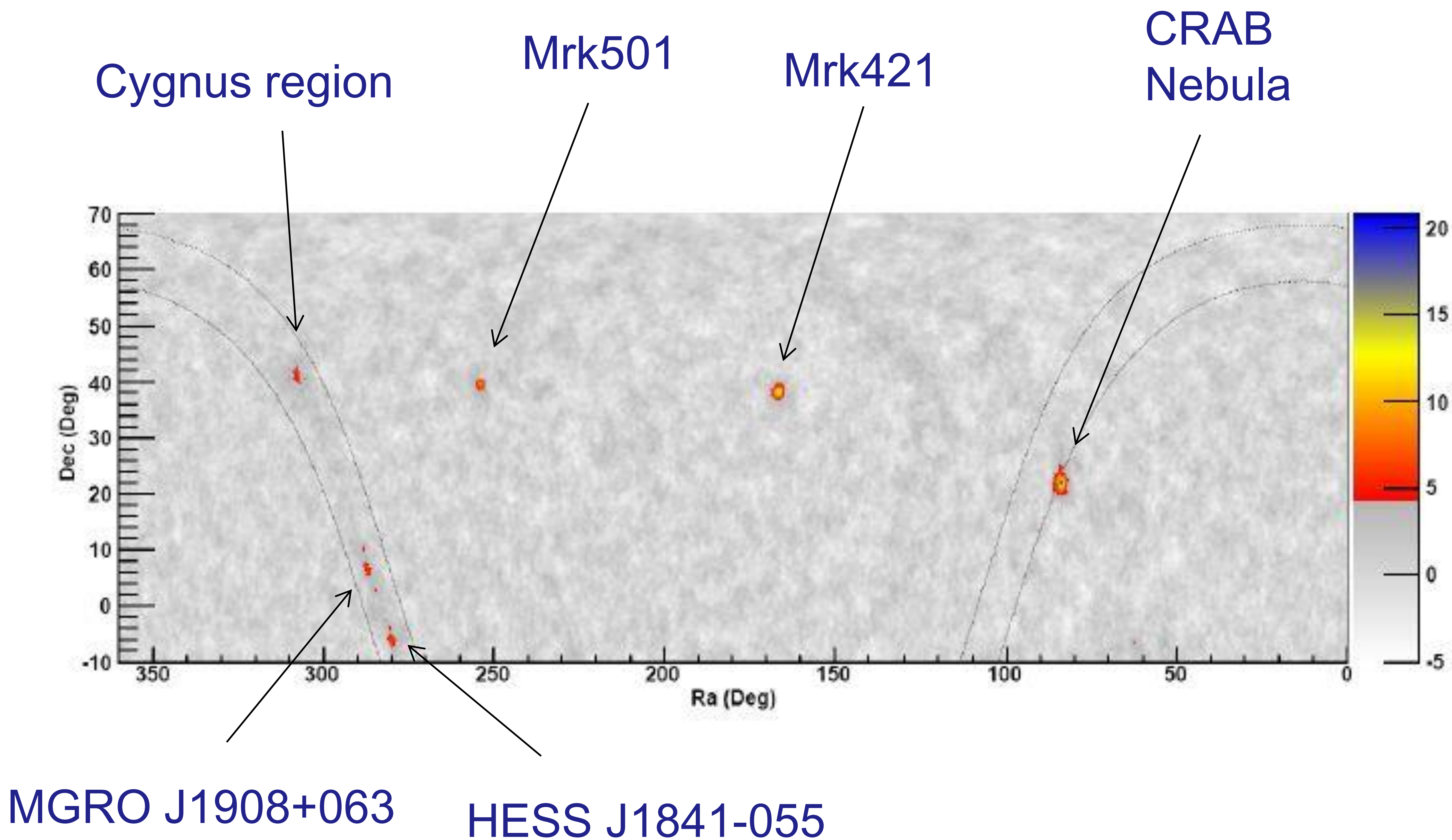

Crab Nebula 5 years data

$$\frac{dN}{dE} = (2.94 \pm 0.20_{stat}) \times 10^{-11} \left(\frac{E}{1\,\mathrm{TeV}}\right)^{(-2.67 \pm 0.06_{stat})} \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{TeV}^{-1}$$

(0.5 – 10) TeV

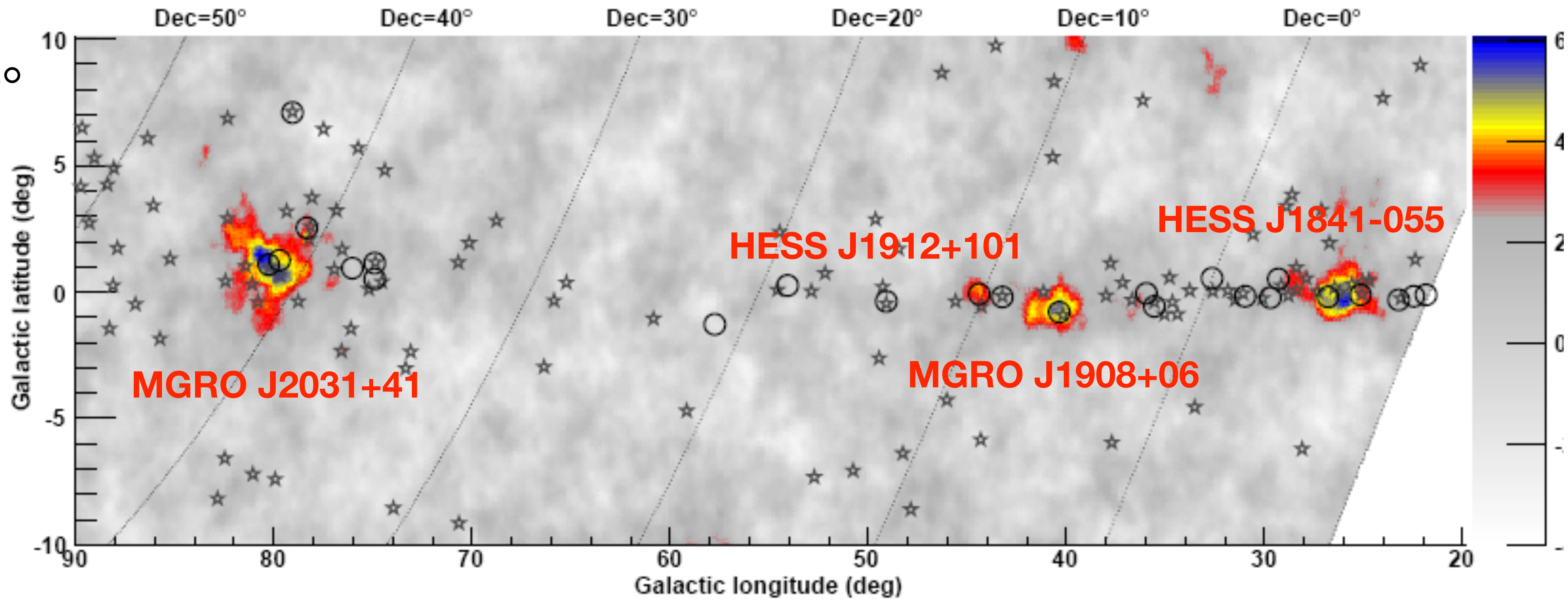
# ARGO-YBJ Sky Survey at 1 TeV

- Integrated sensitivity in 5 y at ~1 TeV: 0.25 Crab for dec 15° - 45°

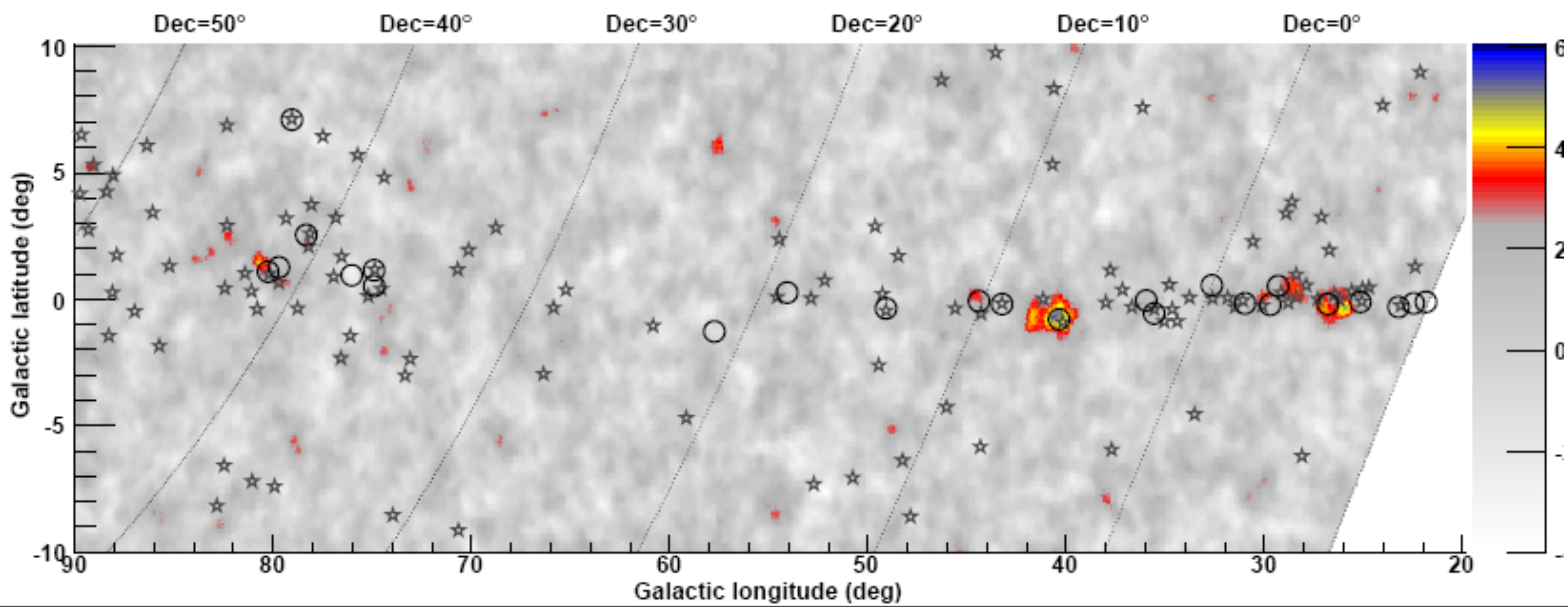


# ARGO-YBJ 5-years Survey of Inner Galactic Plane

$20° < l < 90°, |b| < 10°$




$E_{50} \approx 0.7$ TeV




$E_{50} \approx 1.8$ TeV

# Detected Sources

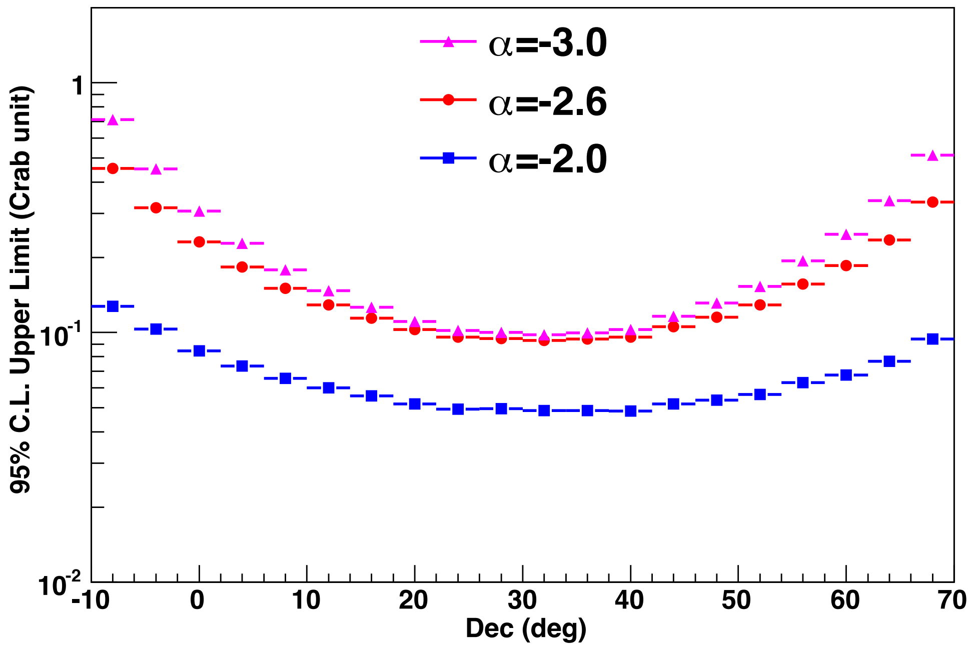



**Fig. 4**: Average 95% C.L. flux upper limit at energy above 500 GeV, averaged on the right ascension direction, as a function of declinations. Different curves indicate sources with different power-law spectral indices −2.0, −2.6 and −3.0. The Crab unit is $5.77\times10^{-11}$ $cm^{-2}$ $s^{-1}$ .

Table 2. Location of the excess regions

| ARGO-YBJ Name | Ra (deg) | Dec (deg) | l (deg) | b (deg) | S (s.d.) | Associated TeV Source |
|---|---|---|---|---|---|---|
| ARGO J0409−0627 | 62.35 | -6.45 | 198.51 | -38.73 | 4.8 | |
| ARGO J0535+2203 | 83.75 | 22.05 | 184.59 | -5.67 | 20.8 | Crab Nebula |
| ARGO J1105+3821 | 166.25 | 38.35 | 179.43 | 65.09 | 14.1 | Mrk 421 |
| ARGO J1654+3945 | 253.55 | 39.75 | 63.59 | 38.80 | 9.4 | Mrk 501 |
| ARGO J1839−0627 | 279.95 | -6.45 | 25.87 | -0.36 | 6.0 | HESS J1841−055 |
| ARGO J1907+0627 | 286.95 | 6.45 | 40.53 | -0.68 | 5.3 | HESS J1908+063 |
| ARGO J1910+0720 | 287.65 | 7.35 | 41.65 | -0.88 | 4.3 | |
| ARGO J1912+1026 | 288.05 | 10.45 | 44.59 | 0.20 | 4.2 | HESS J1912+101 |
| ARGO J2021+4038 | 305.25 | 40.65 | 78.34 | 2.28 | 4.3 | VER J2019+407 |
| ARGO J2031+4157 | 307.95 | 41.95 | 80.58 | 1.38 | 6.1 | MGRO J2031+41<br>TeV J2032+4130 |
| ARGO J1841-0332 | 280.25 | -3.55 | 28.58 | 0.70 | 4.2 | HESS J1843−033 |

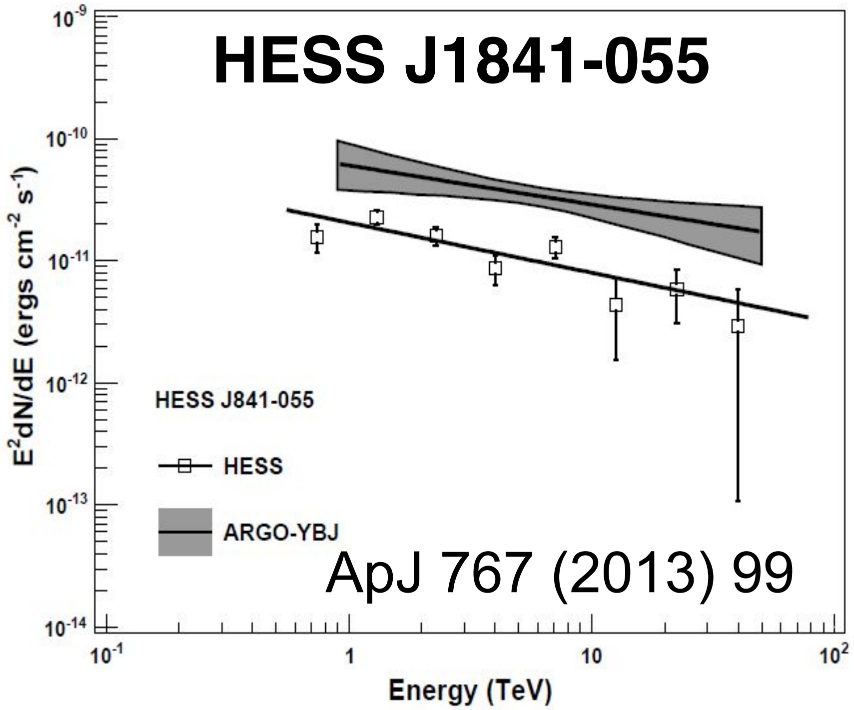
Paper submitted to ApJ

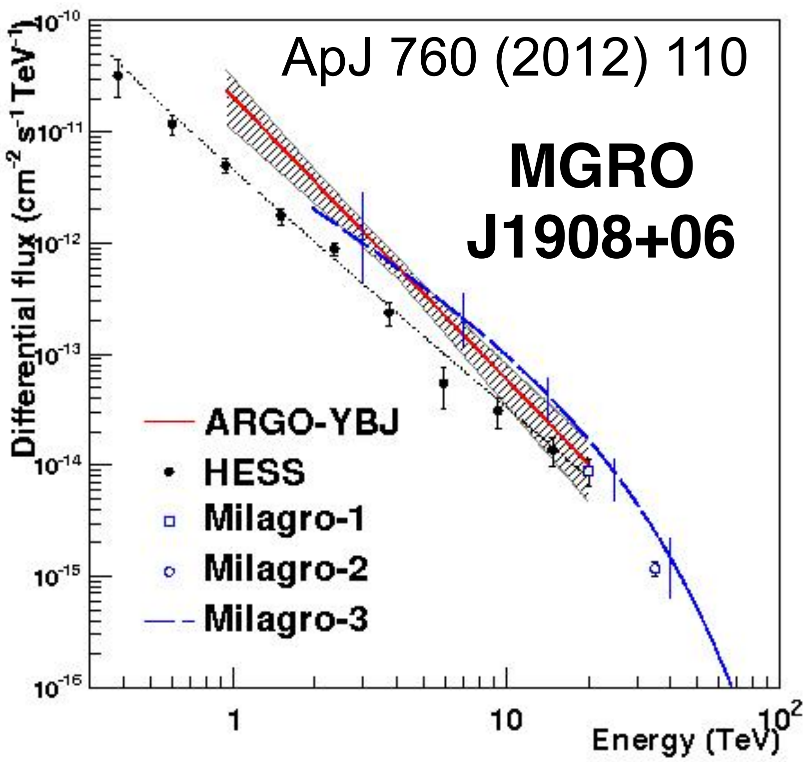
# Why gamma-ray extended sources ?

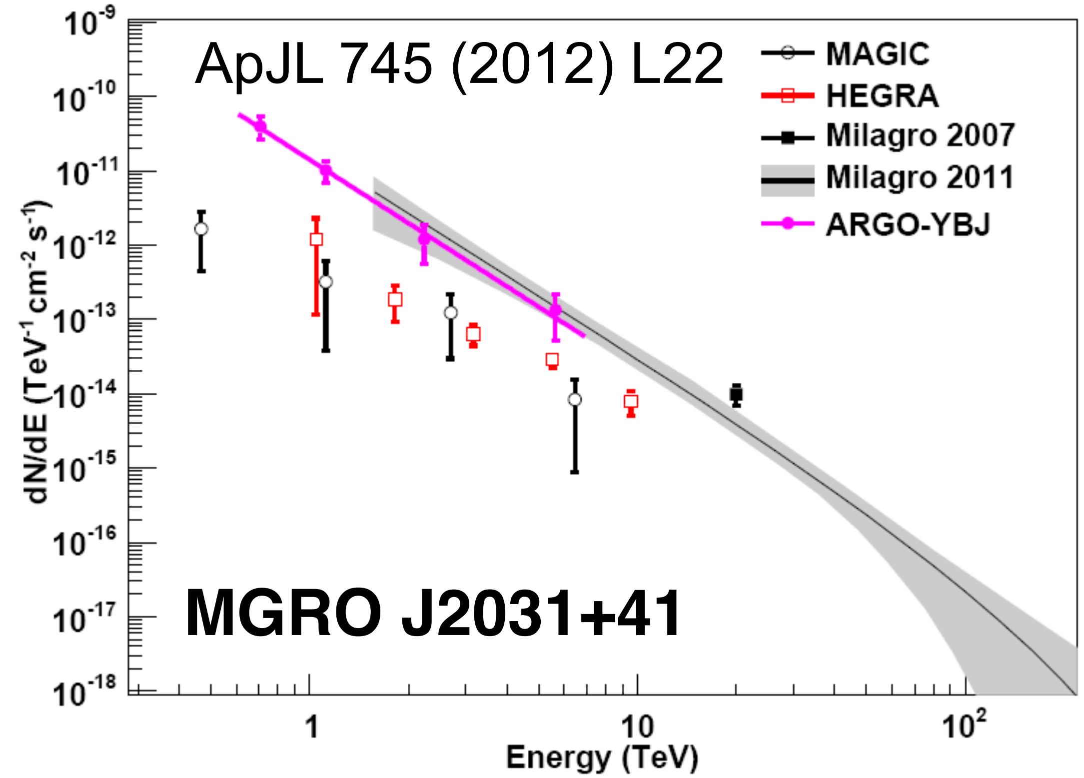
- TeV gamma-ray extended sources an important tool to investigate the sources of cosmic rays.
- The observed degree-scale extended emission could be produced by high-energy cosmic rays escaping from the source and diffusing in the interstellar medium. The gamma-ray emission should result from the interaction of these cosmic rays with the ISM particles.
- 80% of TeV galactic gamma ray sources are extended.
- Many of them are still unidentified.
- To study degree-scale sources we need instruments with a large field of view and able to correctly evaluate the cosmic ray background over a large solid angle
- Sensitivity to an extended source is relatively better for an EAS than an IACT because angular resolution is not as important

$$S_{\text{extended}} \approx S_{\text{point}} \frac{\sigma_{\text{source}}}{\sigma_{\text{detector}}}$$

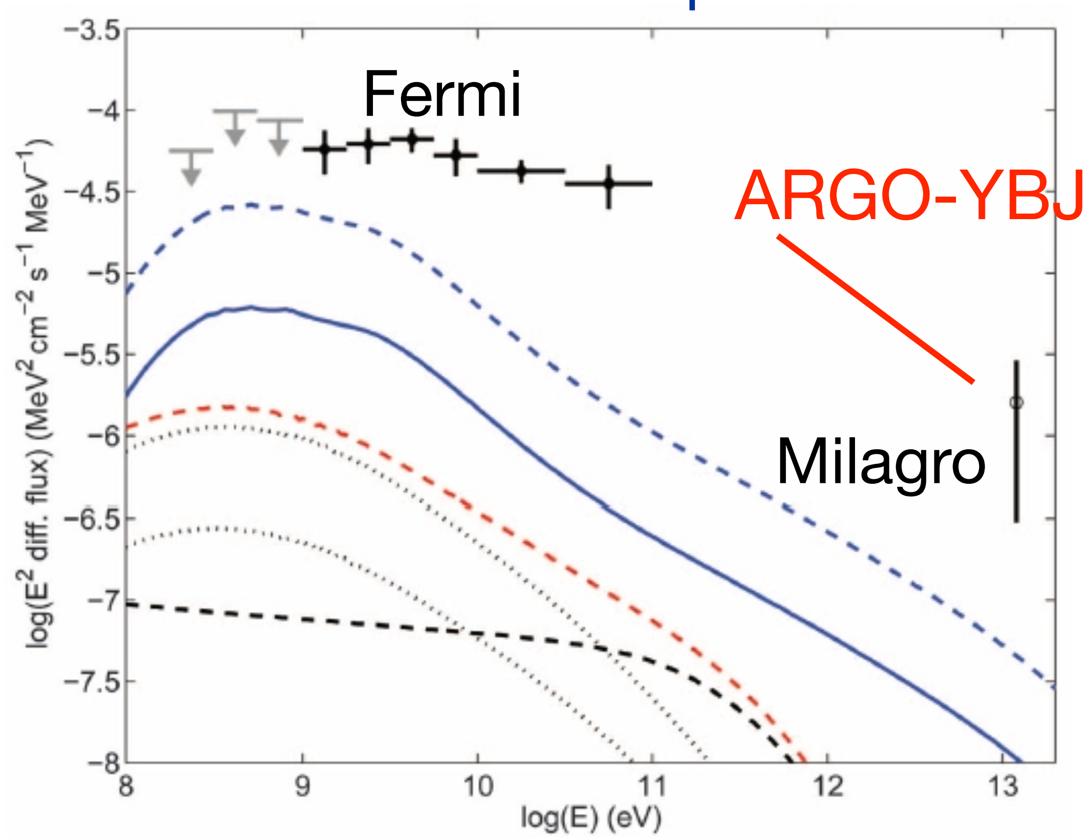
# Observation of extended sources with ARGO-YBJ



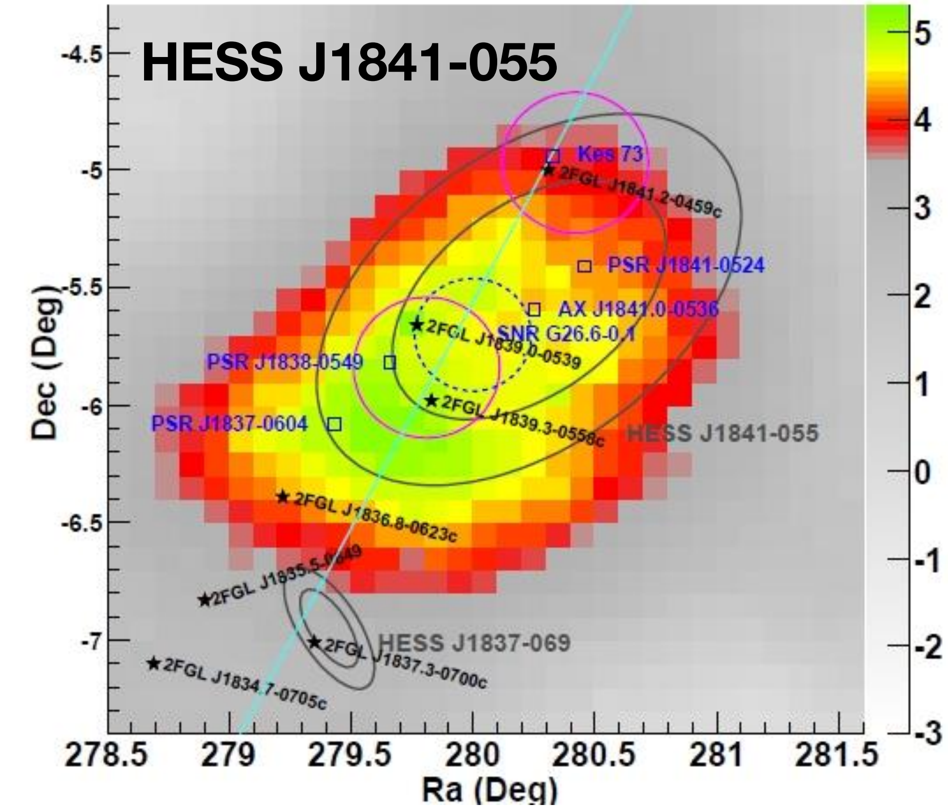




FERMI Cocoon spectrum



# Comments on extended sources

| | | |
|---|---|---|
| CRAB | point source | flux agrees with IACTs |
| MGRO J2031+41 | extended | flux ~ 10 X IACTs |
| MGRO J1908+06 | extended | flux ~ 4 X IACTs |
| HESS J1841-055 | extended | flux ~ 3 X IACTs |




ARGO-YBJ Coll., ApJ 767 (2013) 99

Systematic disagreement for extended sources !
ARGO-YBJ (and MILAGRO) measure higher fluxes

## Possible systematics in ARGO-YBJ

- CR background evaluation: checked with the distribution of the excesses (Gauss with s=1)
- Pointing accuracy (at 0.1° level checked with the Moon Shadow)
- Error in energy scale < 13%
- Contribution from the diffuse emission of the Galactic plane < 15%

**Overall systematics on the flux < 30%**

★The discrepancy could origin from the different techniques used in the background estimation for extended sources.

★Maybe the extended excess is due to the contribution of different sources

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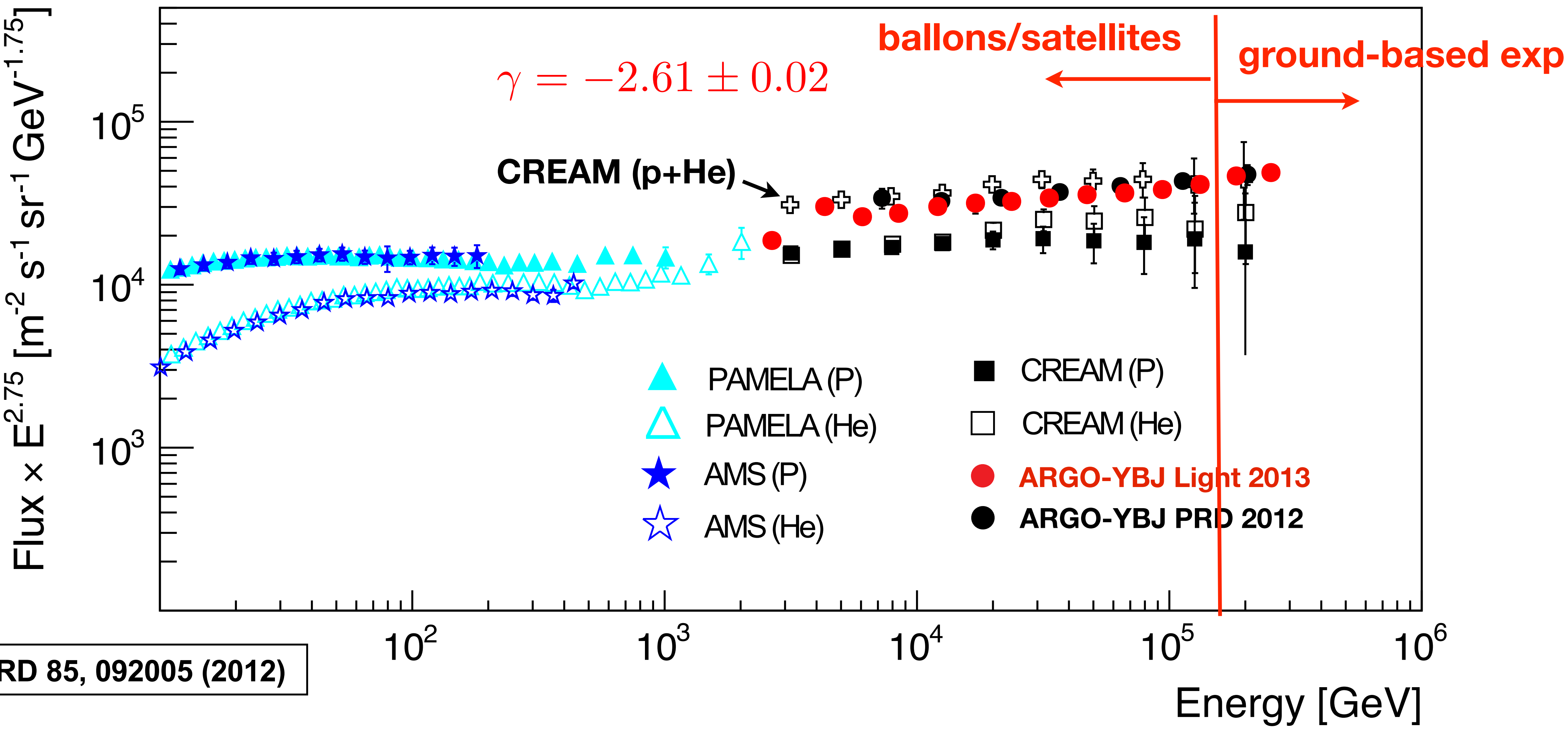
# The light-component spectrum (2.5 - 300 TeV)

Measurement of the light-component (p+He) CR spectrum in the energy region (2.5 – 300) TeV via a Bayesian unfolding procedure

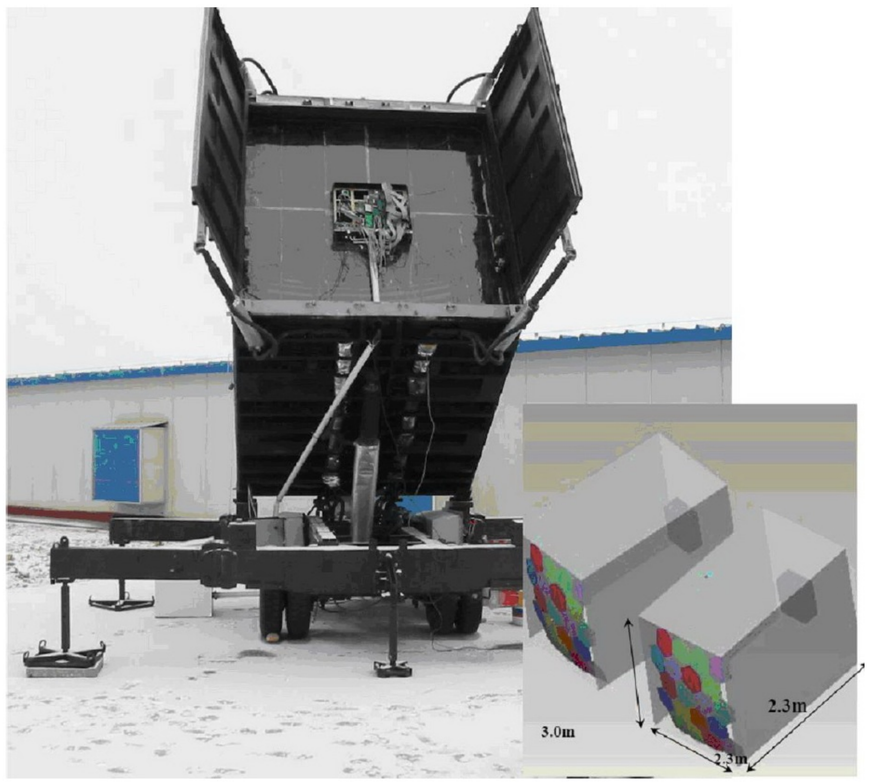



PRD 85, 092005 (2012)

*Direct and ground-based measurements overlap for a wide energy range thus making possible the cross-calibration of the experiments.*

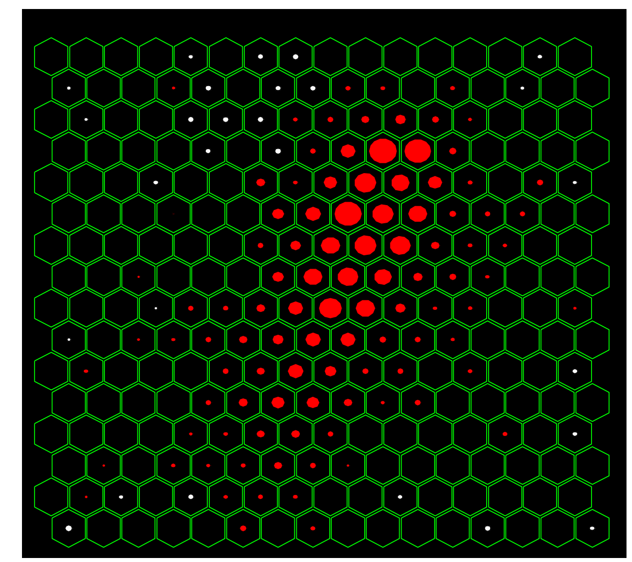
# WFCTA + ARGO-YBJ

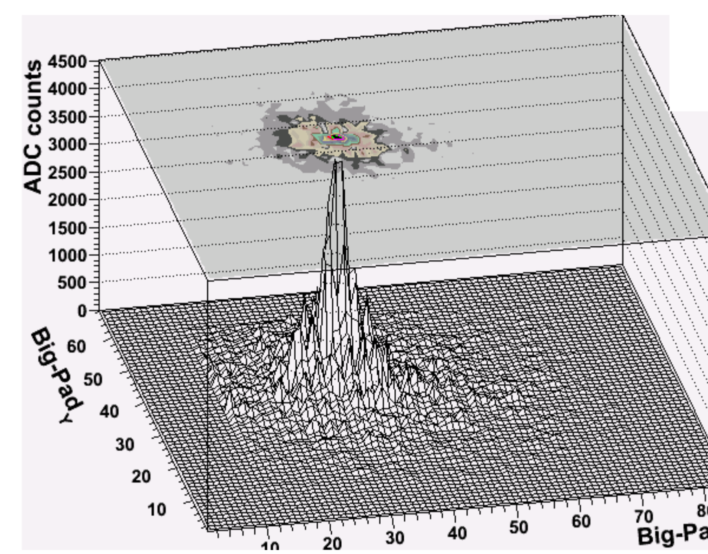
Hybrid measurement of the light-component (p+He) CR spectrum in the energy region (0.1 - 1) PeV


**Wide Field of View Cherenkov Telescope**

- **5 m² spherical mirror**
- **16 × 16 PMT array**
- **Pixel size 1°**
- **FOV: 14°× 16°**
- **Elevation angle: 60°**






✦ **ARGO-YBJ**: lateral distribution size in the core region ⇒ mass sensitive

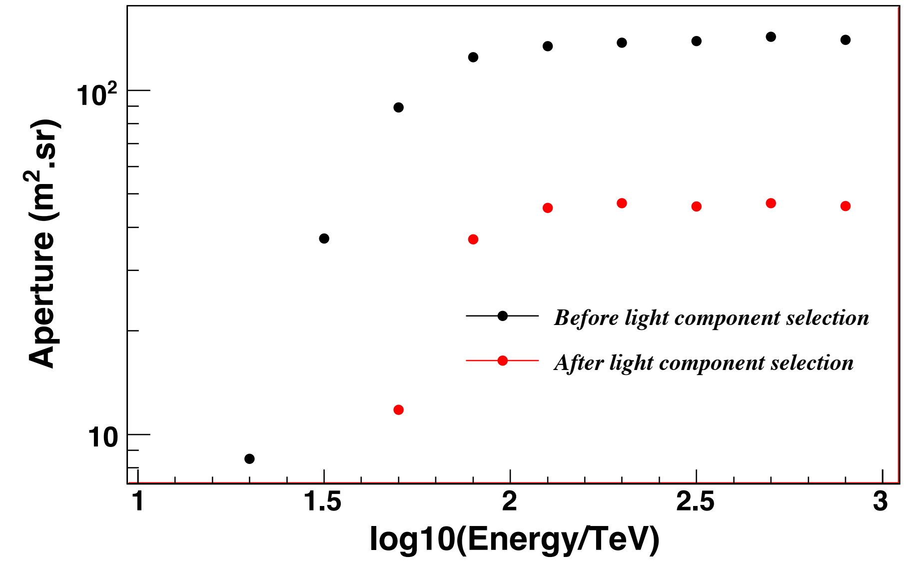
✦ **Cherenkov Telescope:** Hillas parameters ⇒ mass sensitive

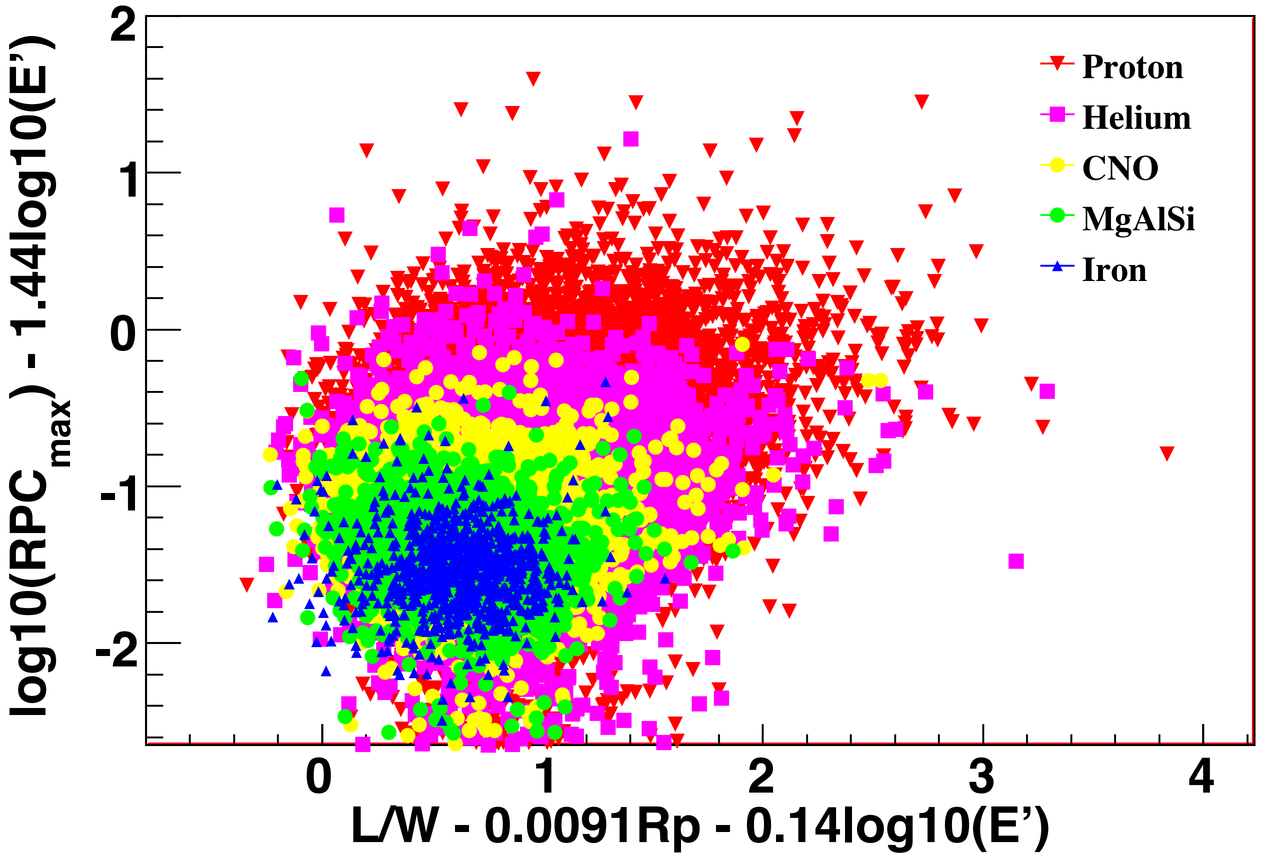
Energy ricontruction

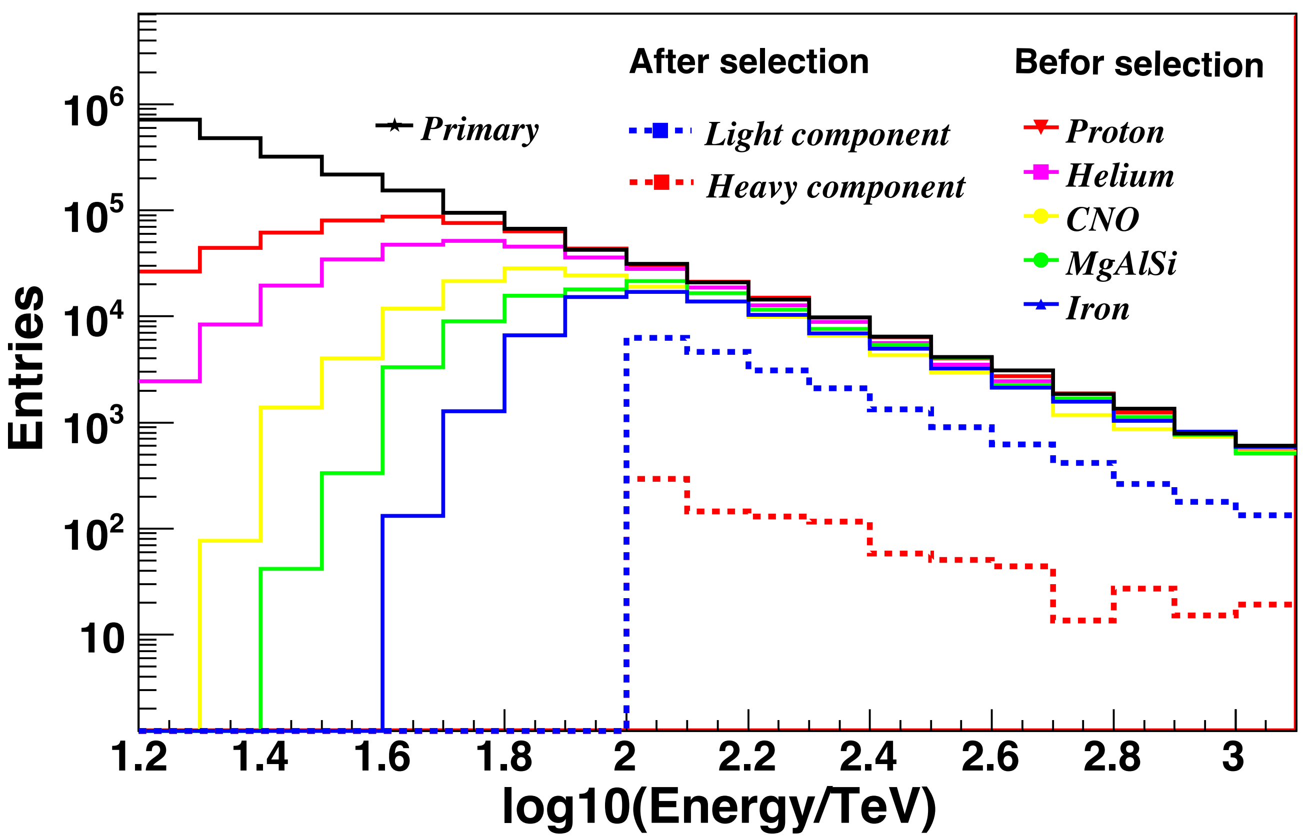
# Light-component (p+He) selection

- Contamination of heavier component < 5 %
- Energy resolution: ~25%
- Uncertainty : ~25% on flux

| | Proton | Helium | CNO | MgAlSi | Iron | SUM |
|---|---|---|---|---|---|---|
| The initial fractions | 20% | 20% | 20% | 20% | 20% | 100% |
| The fractions after composition selection | 69.1% | 25.8% | 3.8% | 1.1% | 0.2% | 100% |
| The selection efficiency | 51.0% | 19.1% | 2.7% | 0.8% | 0.1% | |



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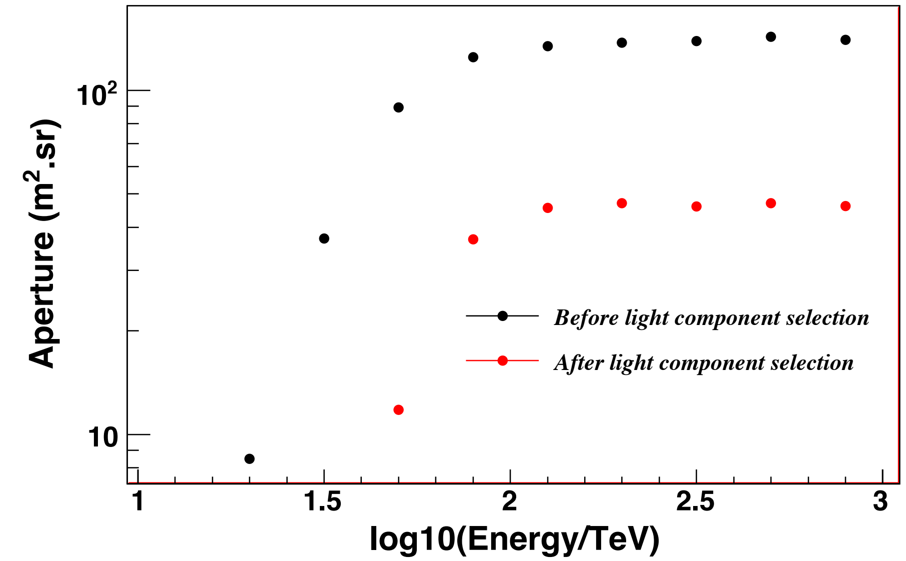
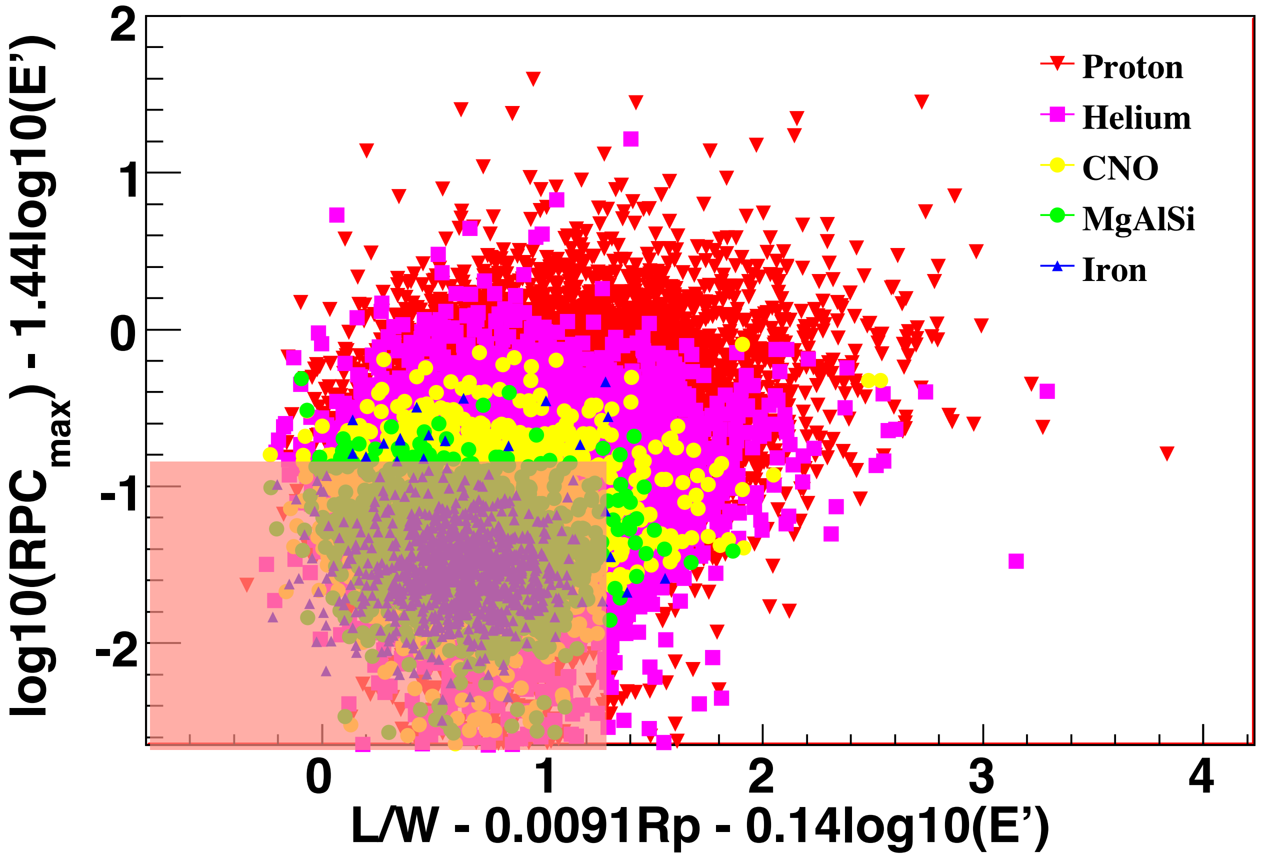
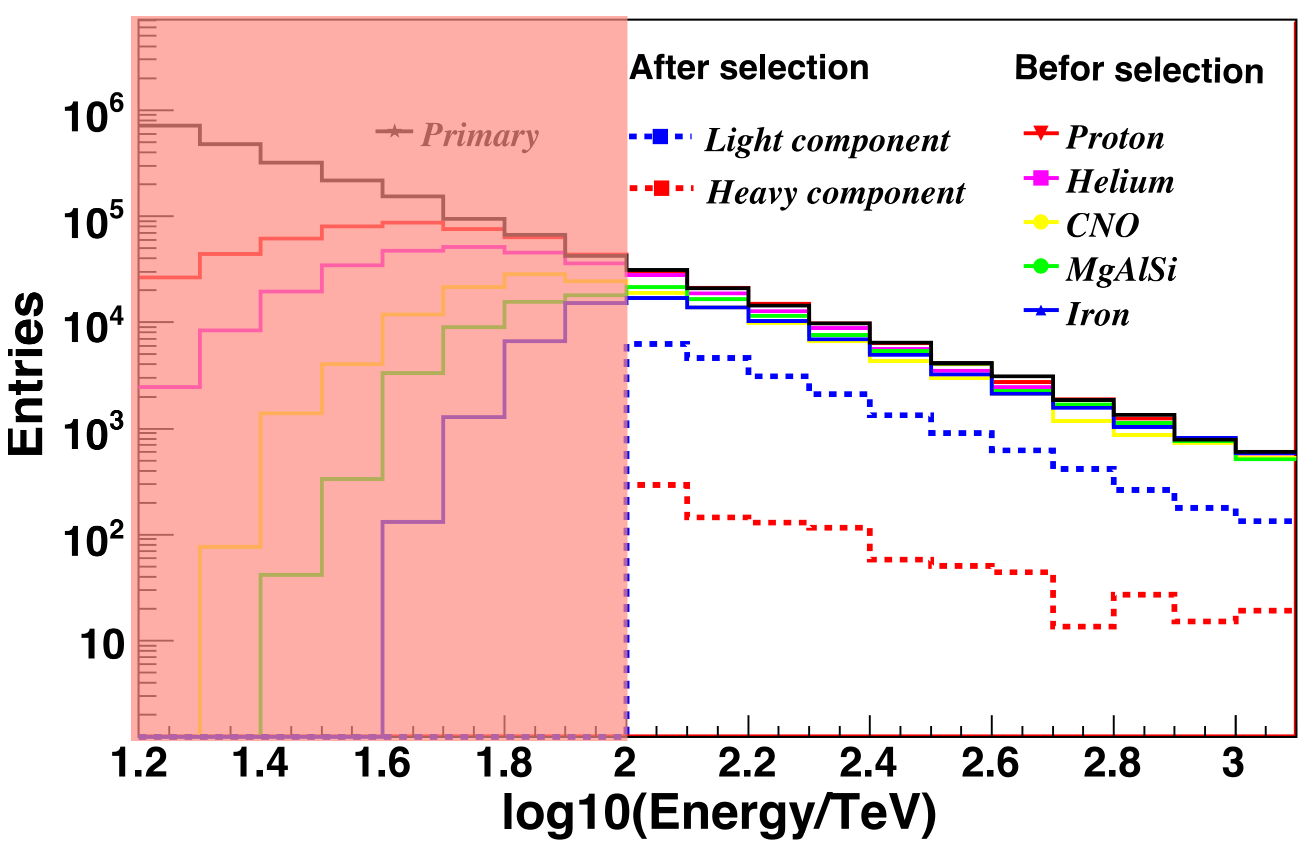
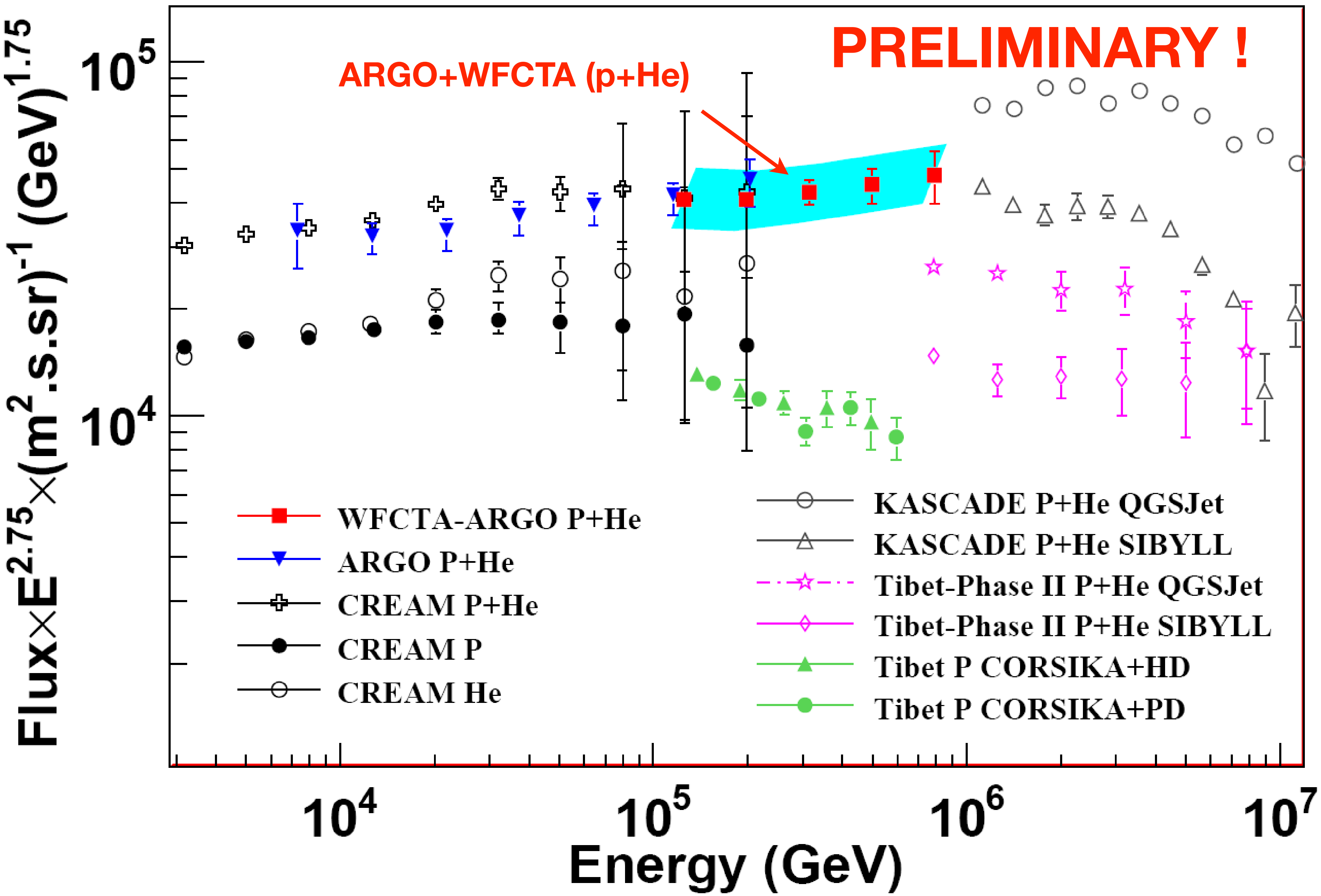


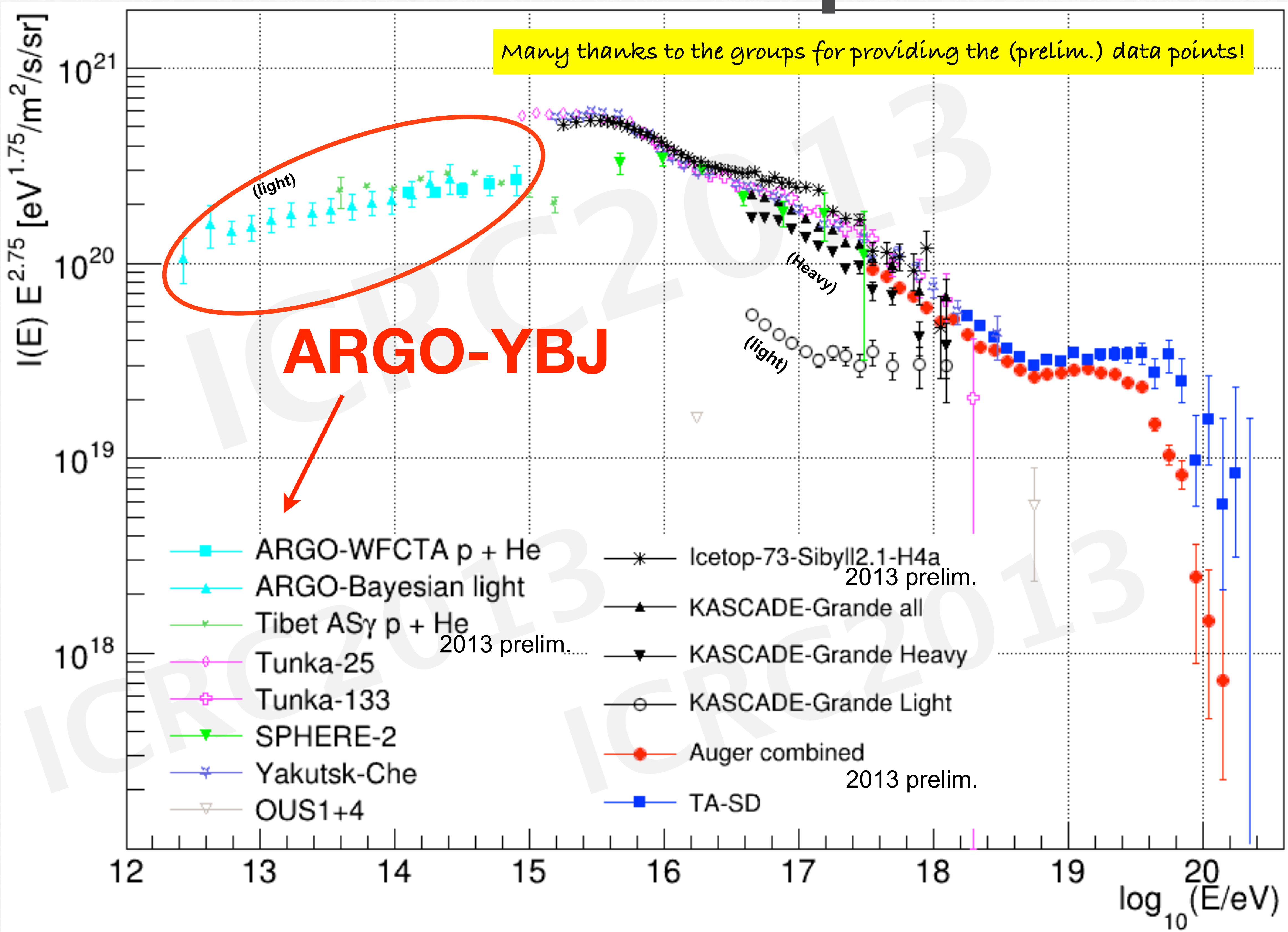



# The light-component spectrum (100 - 800) TeV

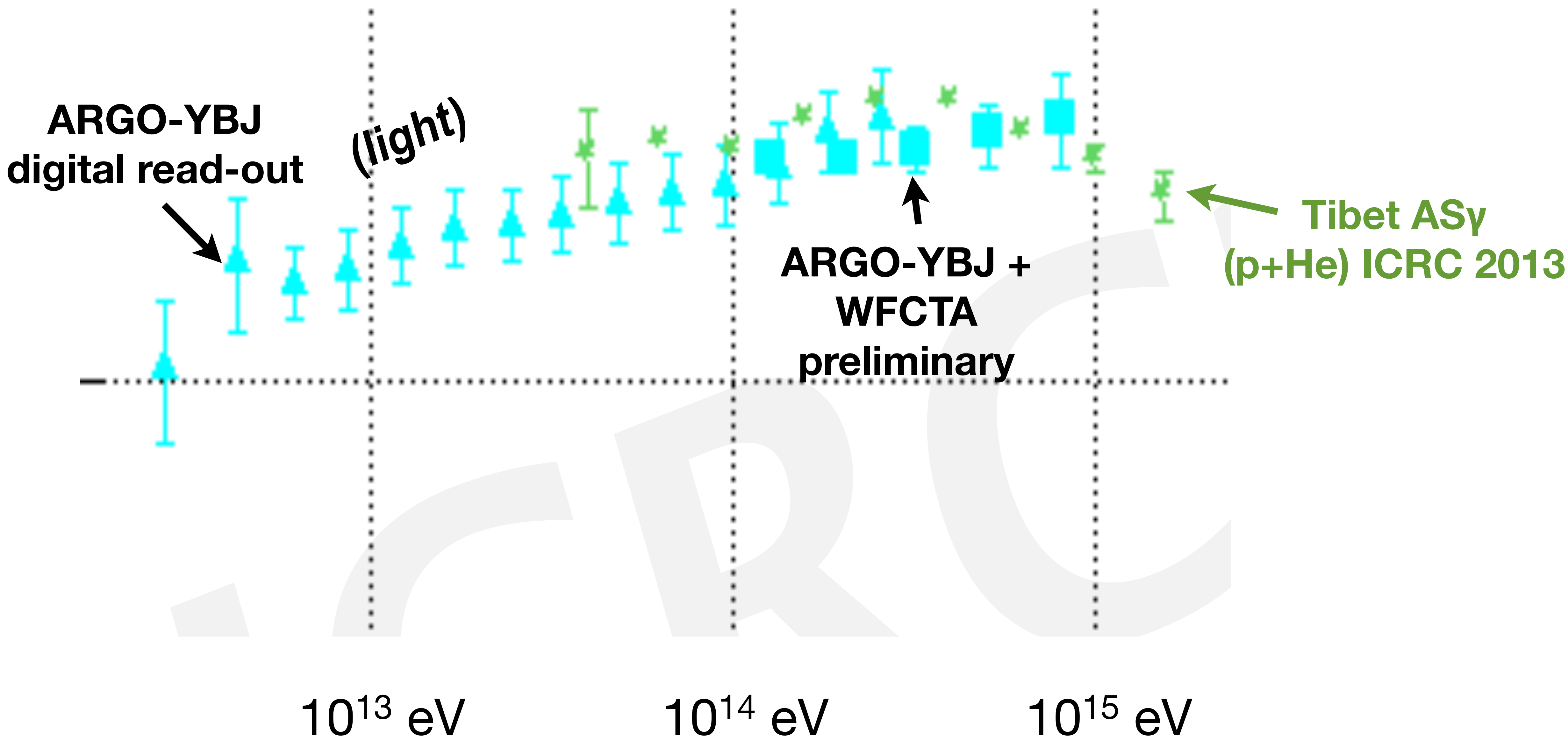
- Spectral index: γ = -2.69 ± 0.06  (ARGO: -2.61± 0.02)



# HE-CR: ICRC2013 Spectra



# ARGO-YBJ vs Tibet ASγ



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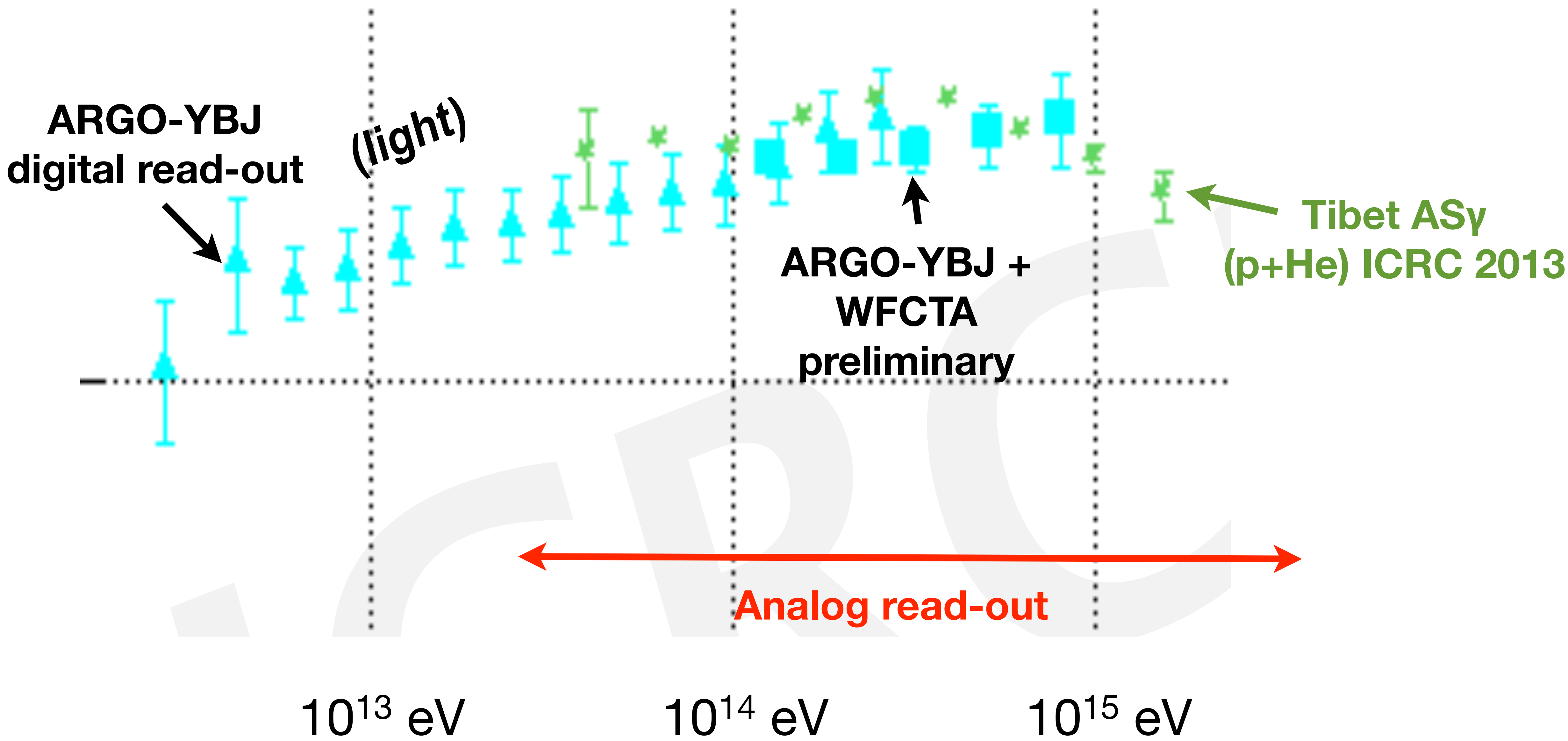


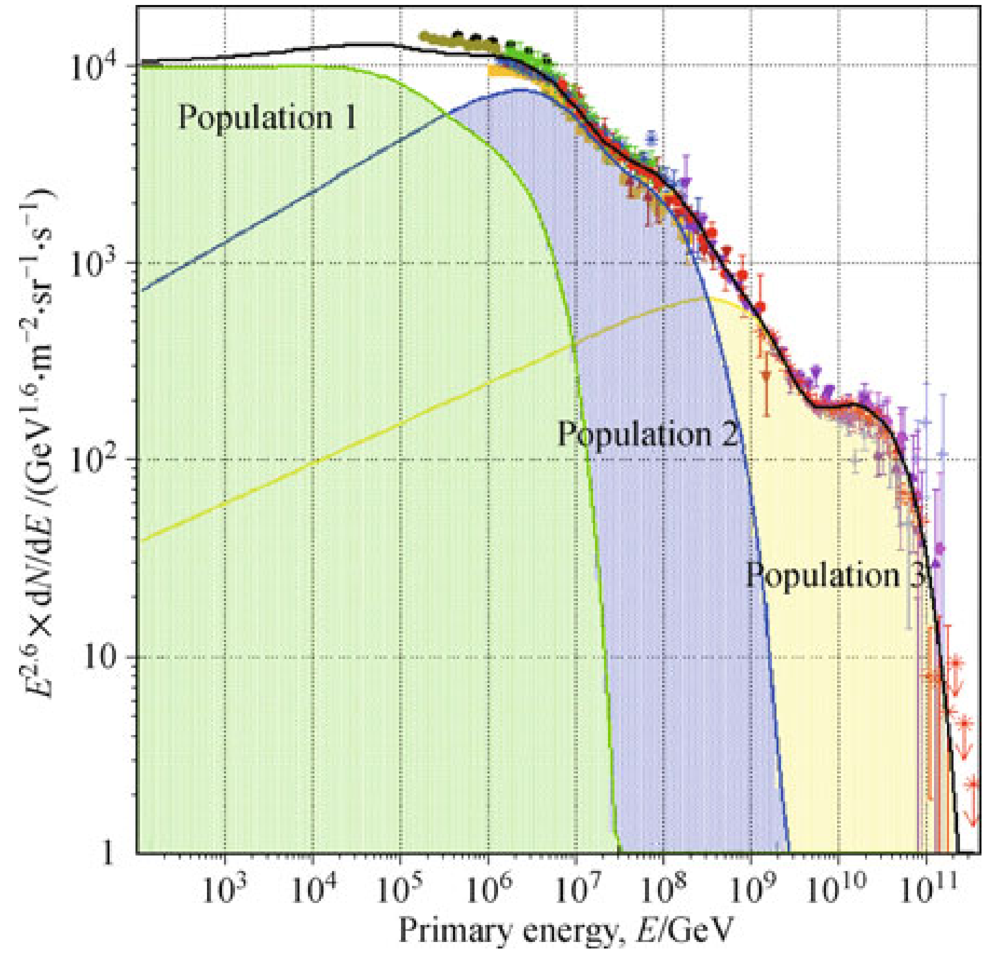

**Analysis with the analog read-out + Bayesian unfolding (50 TeV - few PeV) under way**

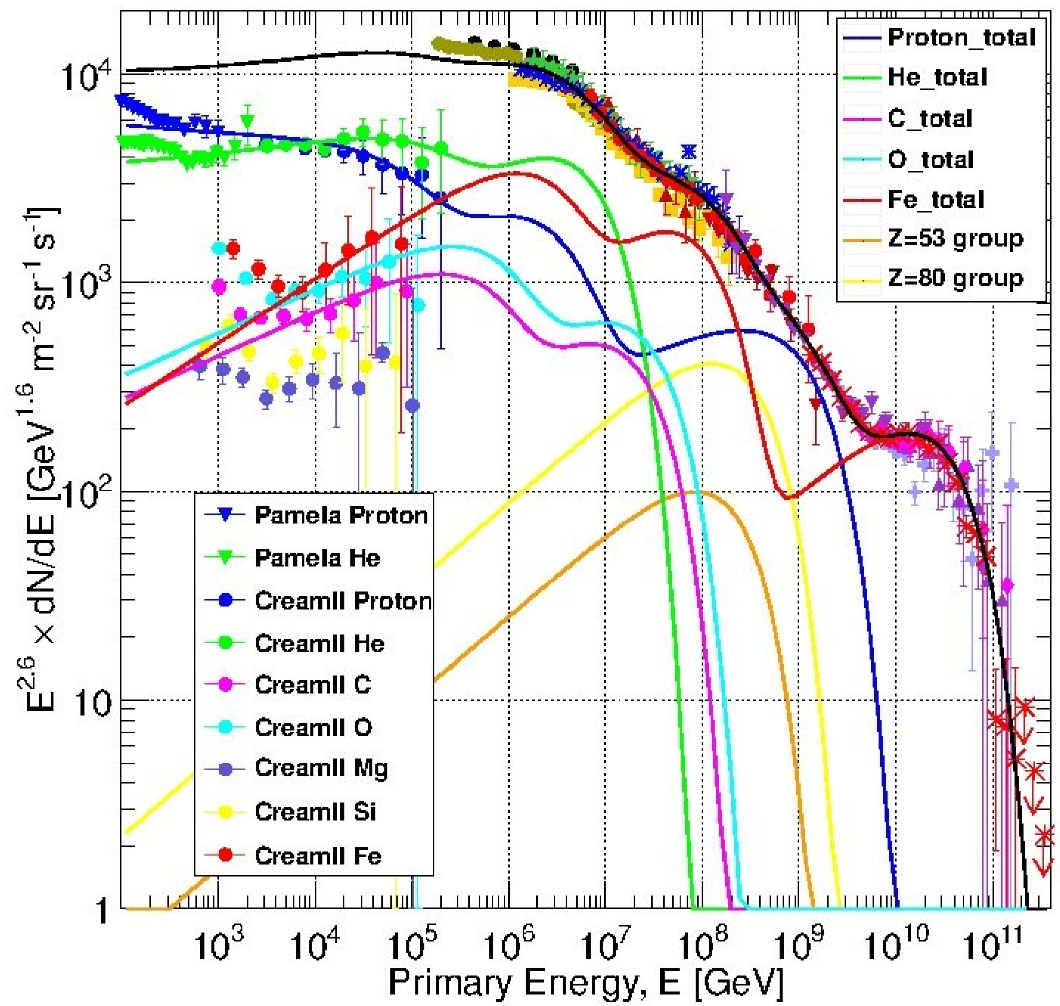
# The knee region

It is easy to re-implement the idea thinking of the 1961 paper of Bernard Peters stating that both cosmic ray acceleration and propagation in the Galaxy have to be discussed in terms of rigidity (R = p/Z). If a proton can be accelerated up to energy E_max then a nucleus of charge Z could achieve Z times higher energy.

We did use the Peters cycle trying to fit the shifted air shower spectra. There was no restriction on the number of *populations* of cosmic rays (presumably due to different types of sources) in the fit. The fitting procedure came up with four population where the fourth one describes the extragalactic cosmic rays. It is highly uncertain because the differences in the UHECR composition derived by HiRes (and TA) and Auger.

T. Stanev Ricap 2013

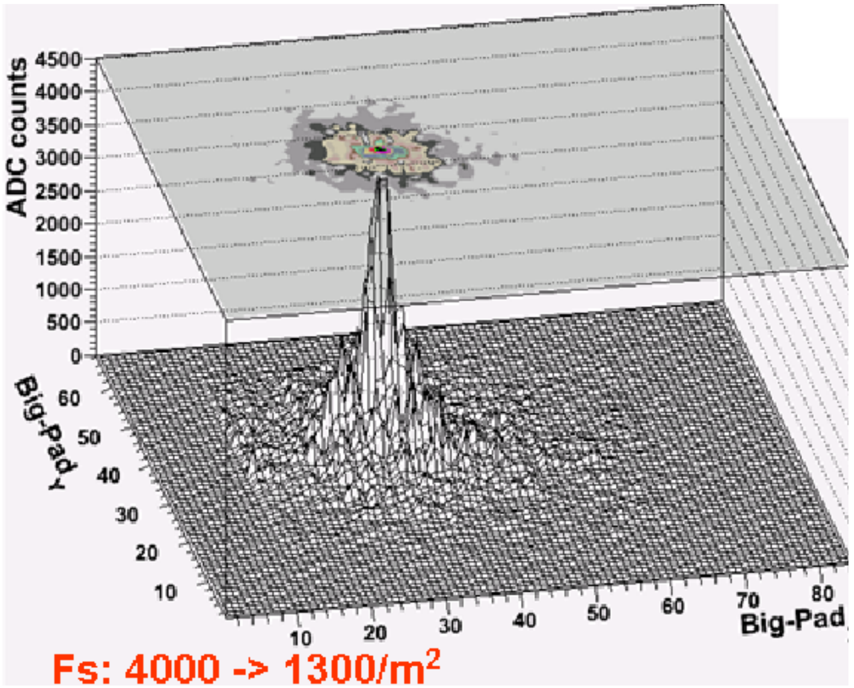


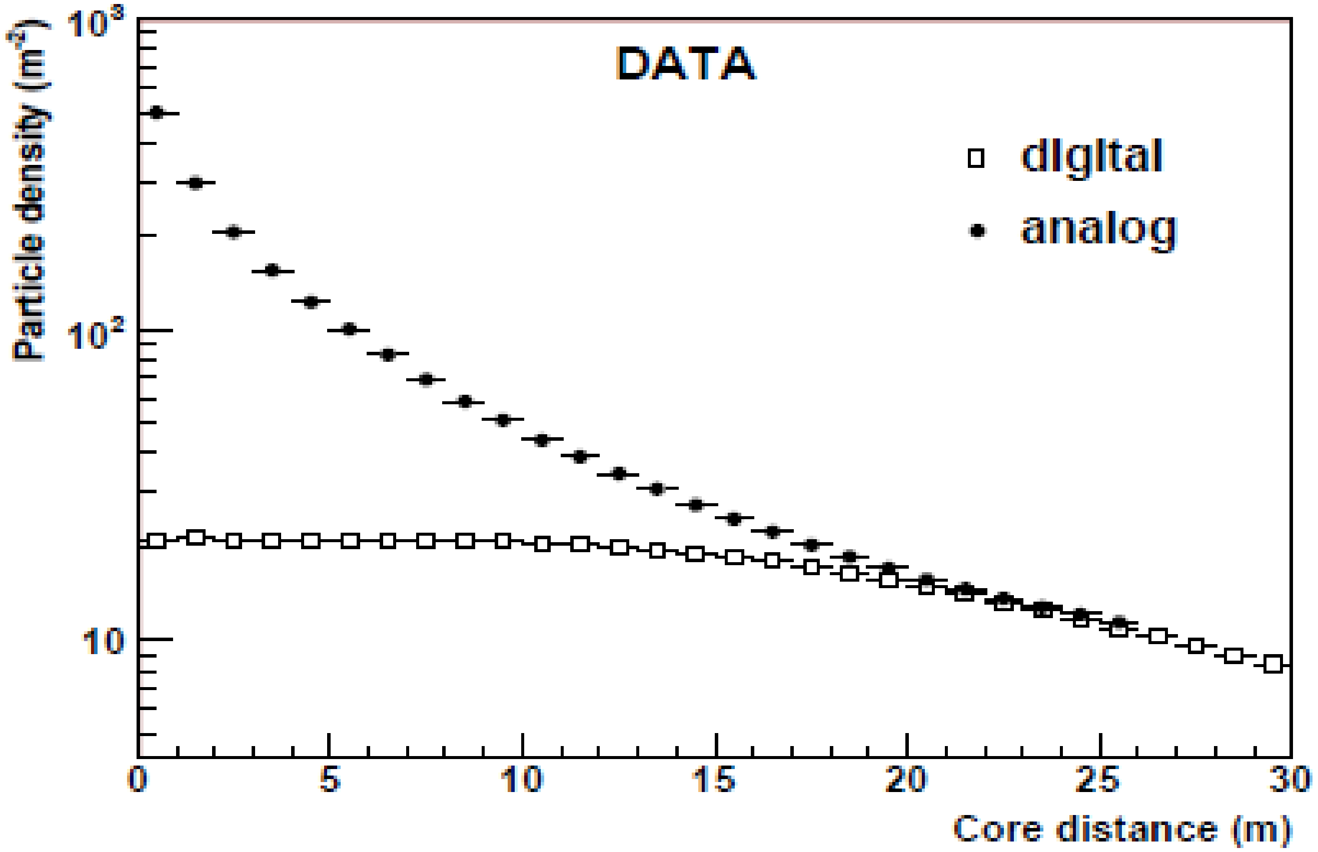



# LDF and shower age

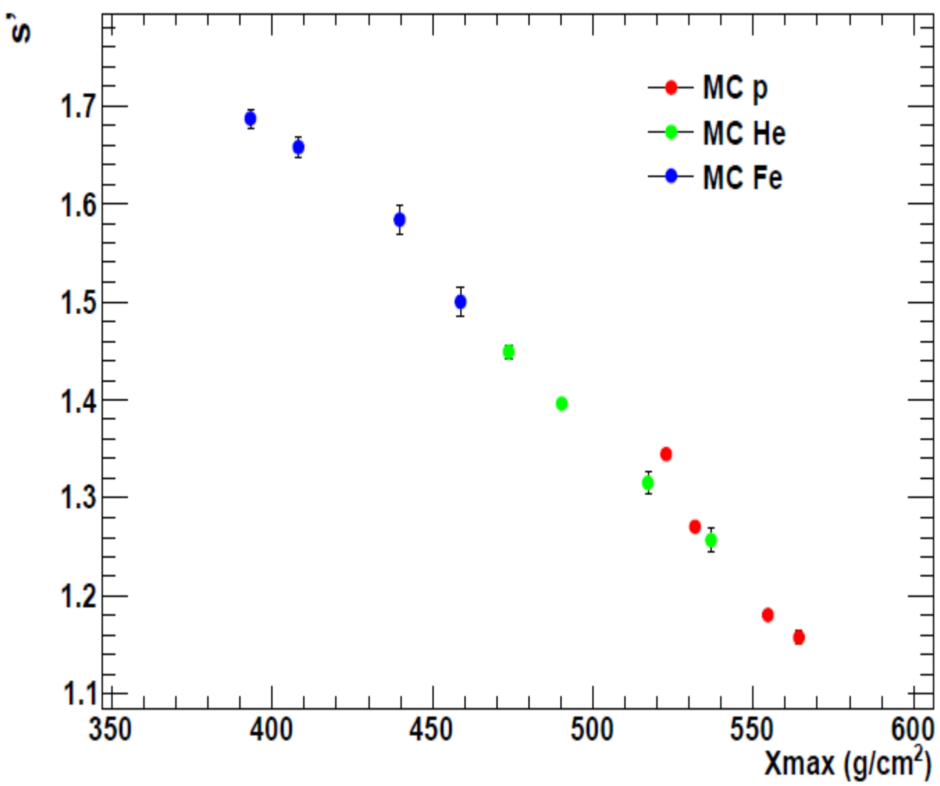
With the analog data we can study the LDF without saturation near the core. Well fitted by modified NKG function.

$$\rho'_{NKG} = A \cdot \left(\frac{r}{r_M}\right)^{s'-2} \cdot \left(1 + \frac{r}{r_M}\right)^{s'-4.5}$$




The LDF slope s' is related to the shower age independently on the primary mass

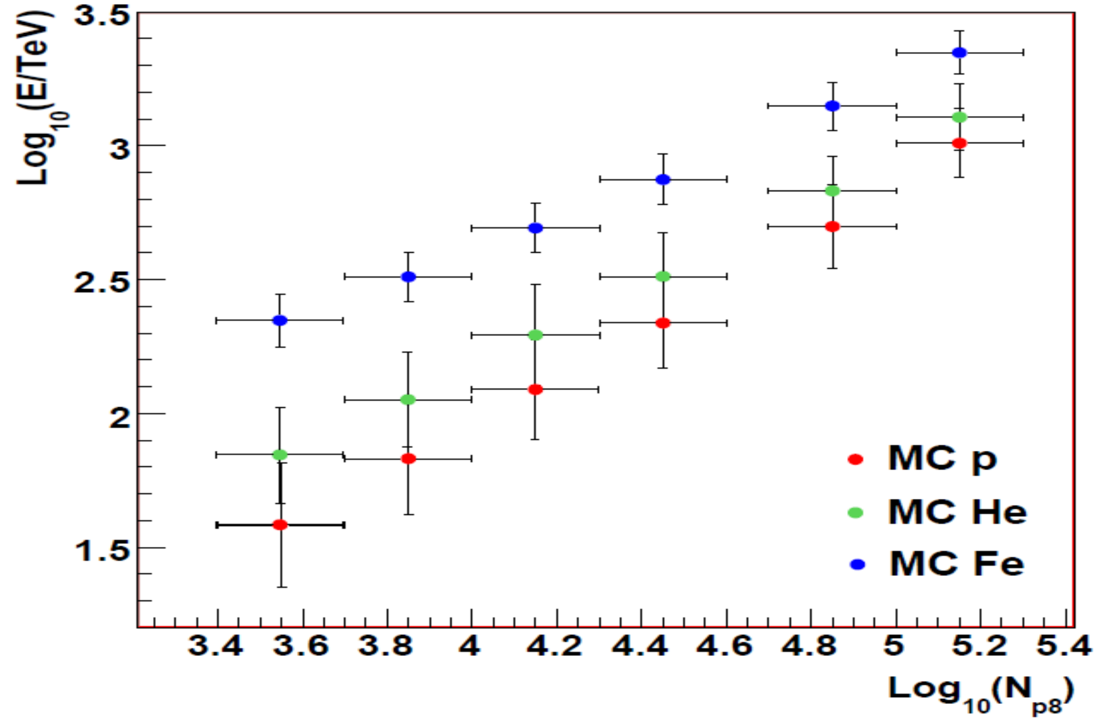



The s' parameter is correlated to the $X_{max}$ position, whatever the primary is.

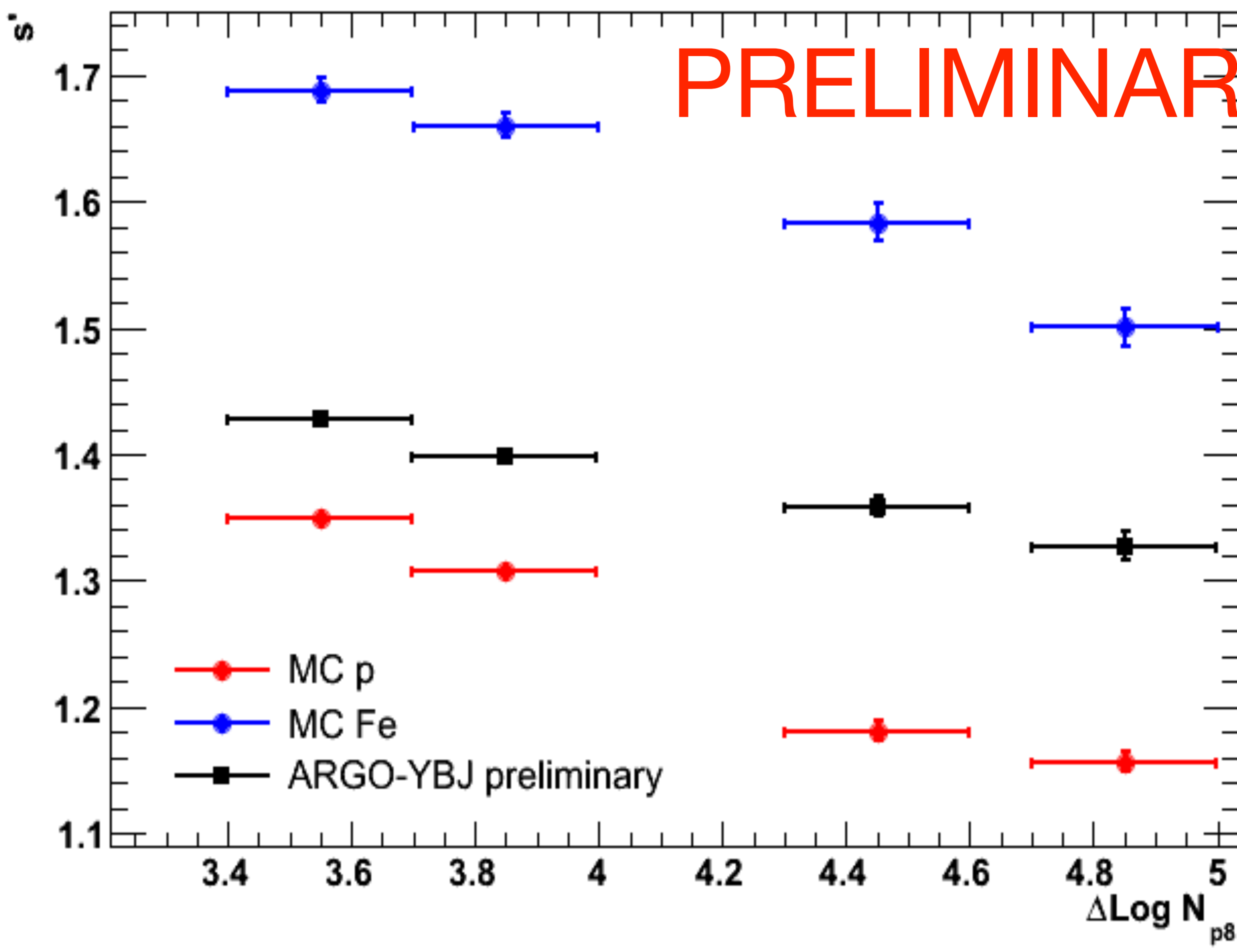
# Shower age and primary mass

Np8 (number of particles within 8 m from the core):

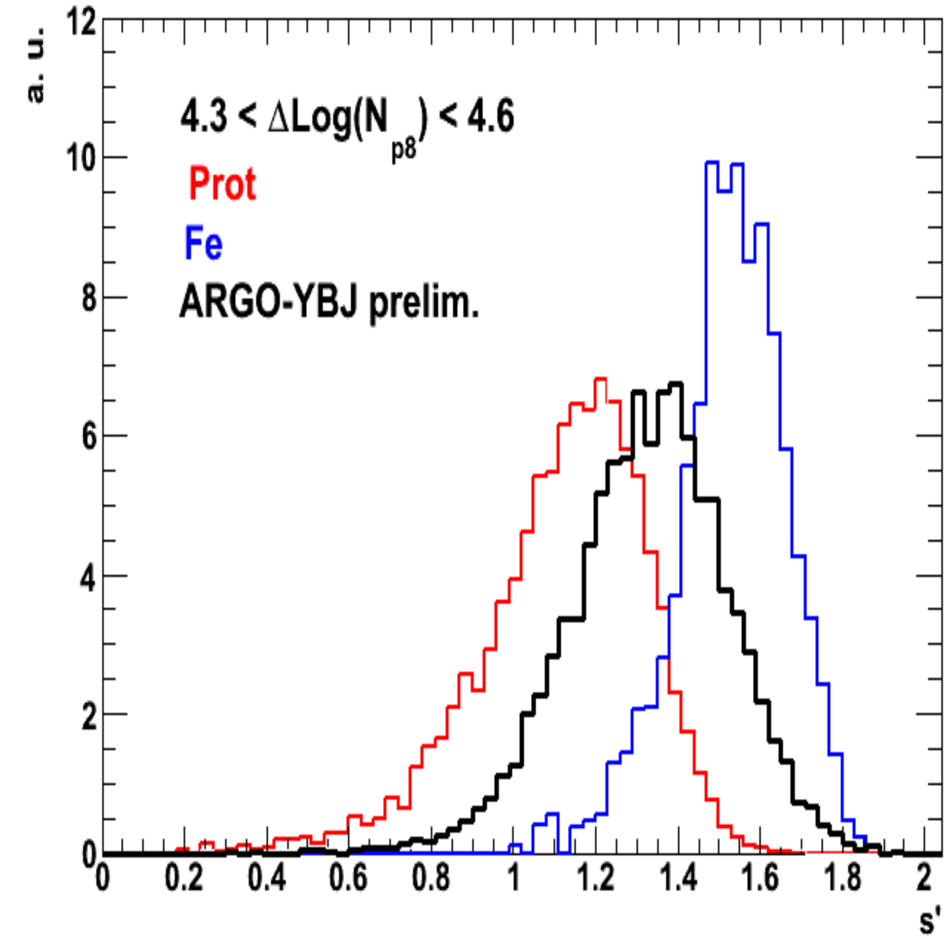
- well correlated with primary energy
- not biased by finite detector size effects
- weakly affected by shower fluctuations




PRELIMINARY !



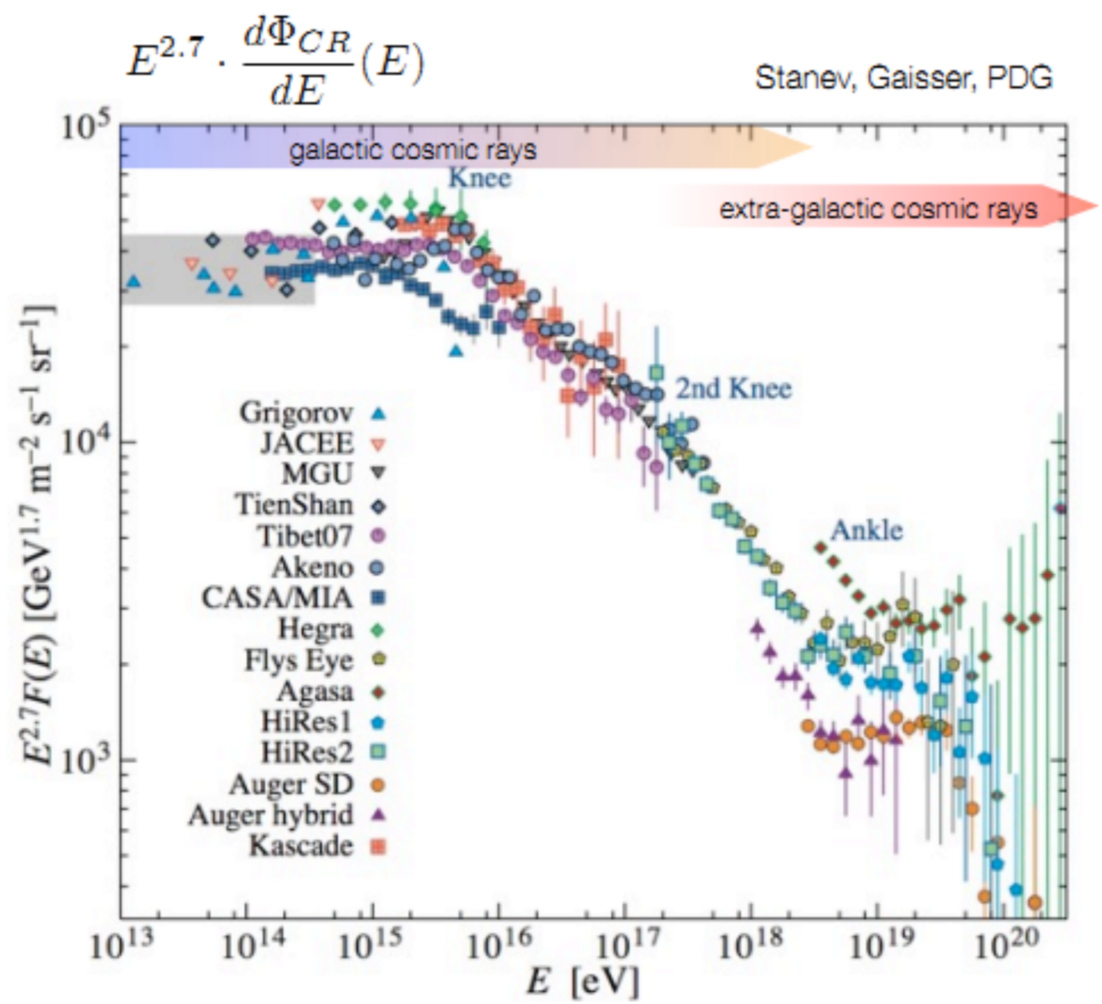

From event-wise LDF fits




⇒ Possibility to get hints on (a) shower age and (b) primary mass

# Cosmic Ray Isotropy

- CRs below $10^{17}$ 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

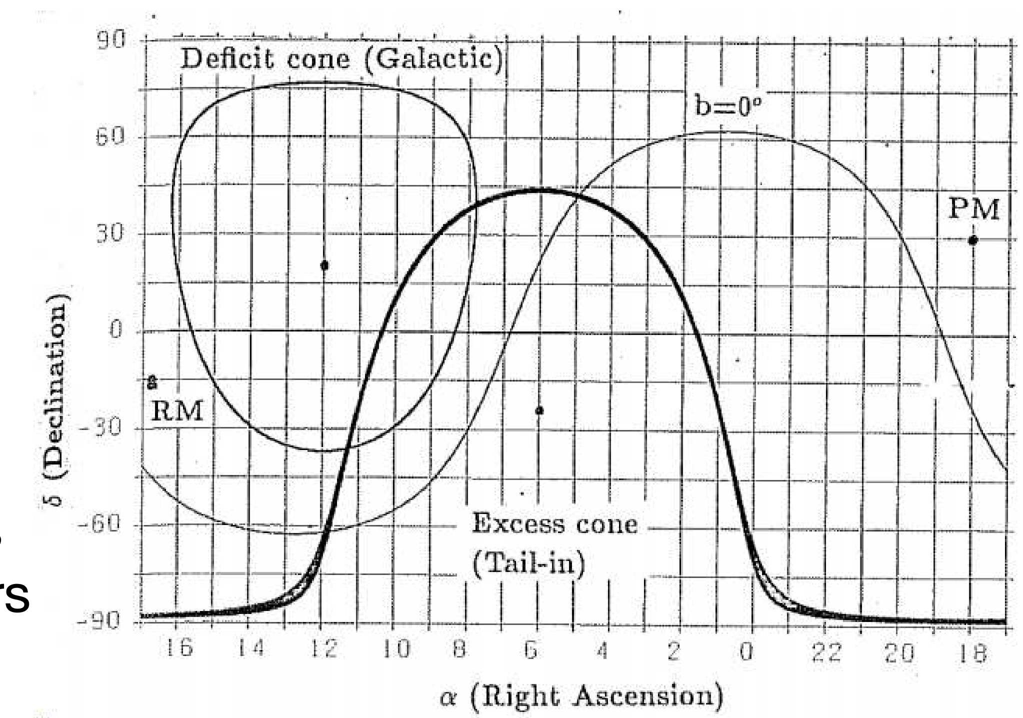



**Galactic CRs are expected to be highly isotropic**
scrambled by galactic magnetic field over very long time.

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

# Measuring the anisotropy

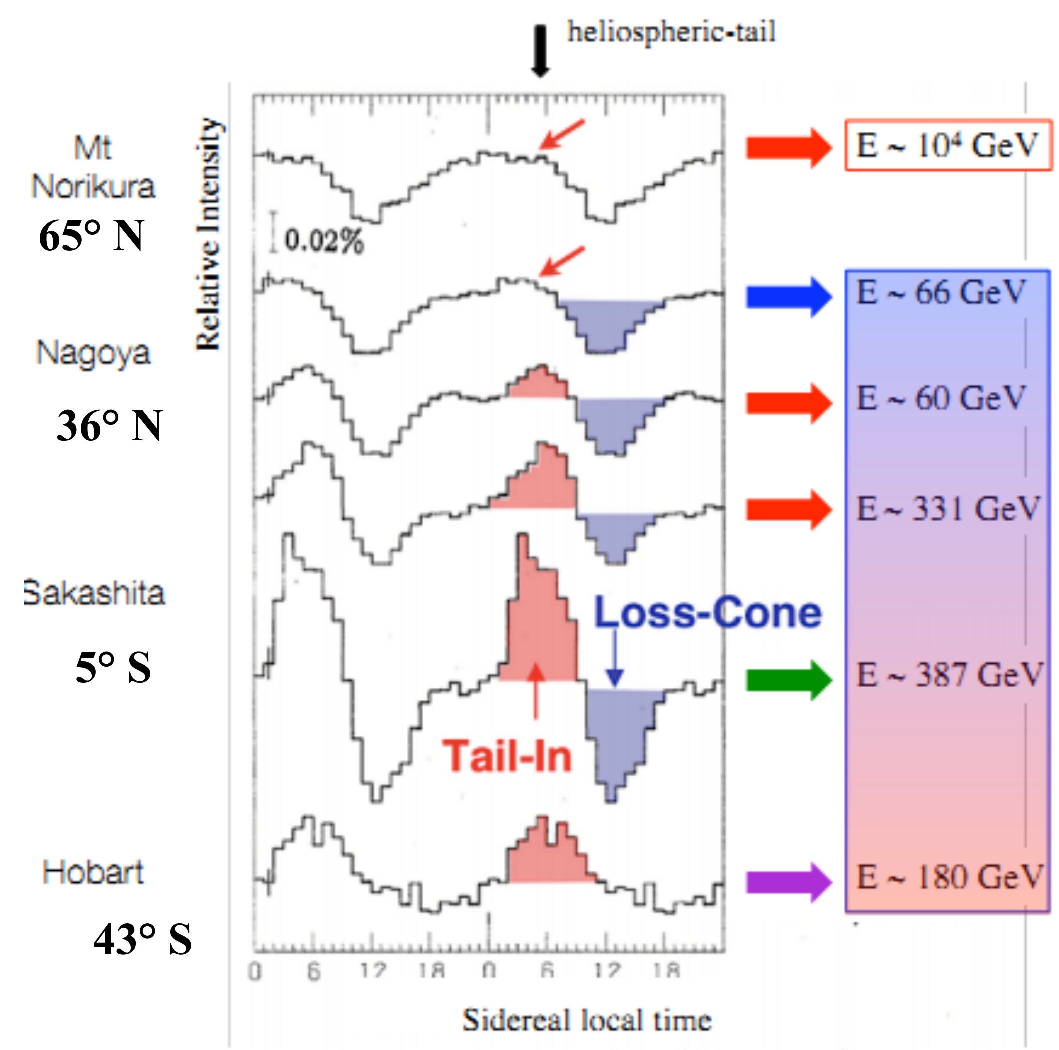
★ anisotropy of arrival direction of CRs clearly observed since 80's
★ 10's GeV - 100's TeV in μ detector, surface arrays and ν detectors
★ observed anisotropy of about $10^{-3}$ - $10^{-4}$




The earliest "map" of the large scale anisotropy

In 1998 Nagashima, Fujimoto, and Jacklyn reported the first comprehensive observation of a large angular scale anisotropy in the sub-TeV CRs arrival direction by combining data from different experiments in the northern and southern hemispheres.

- 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



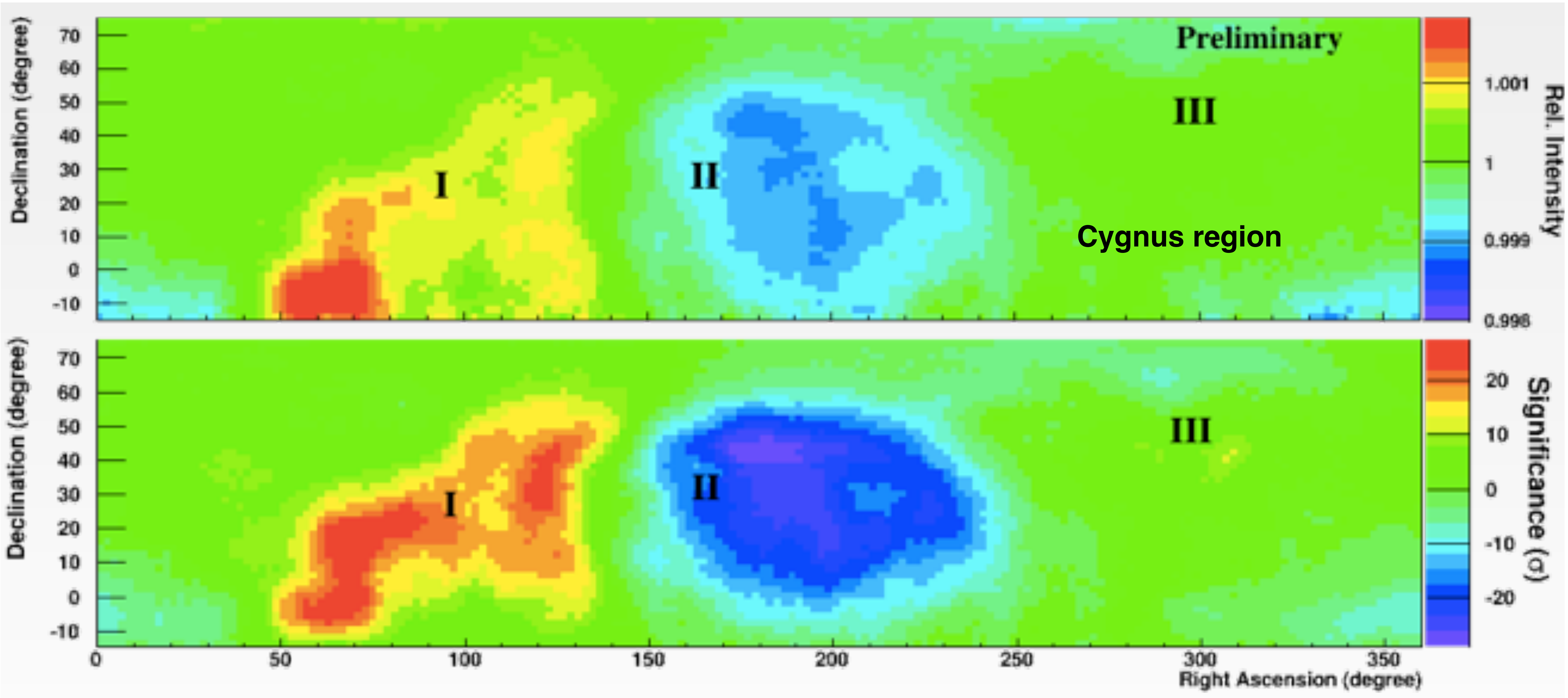

by Nagashima 1998

# Large scale anisotropy by ARGO-YBJ

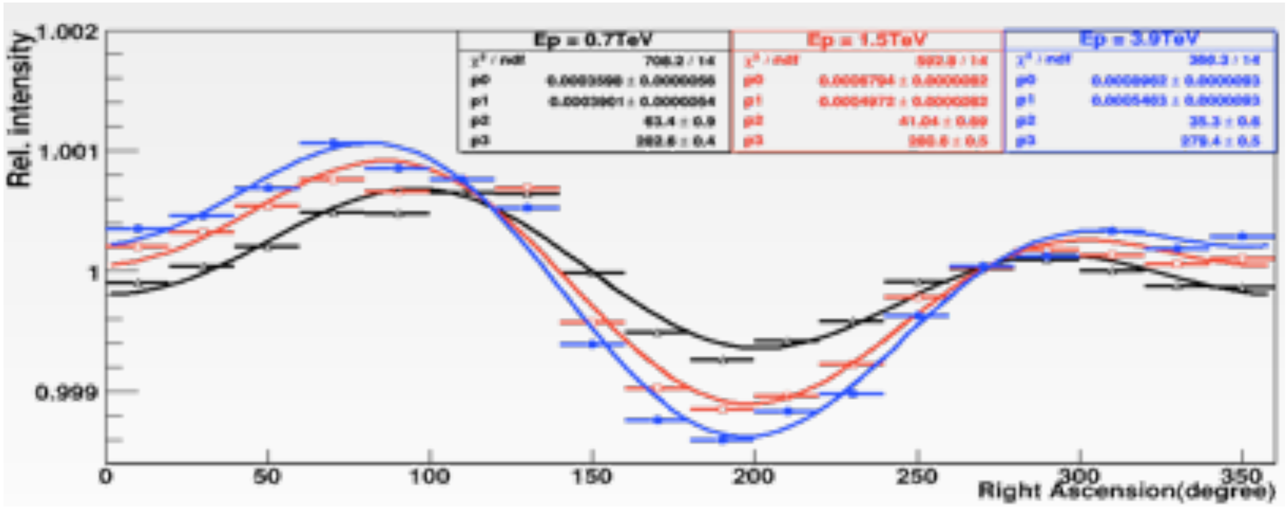
2 years data: 2008- 2009, E ≈ 1 TeV, $3.6 \times 10^{10}$ events

**Final analysis under way**

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

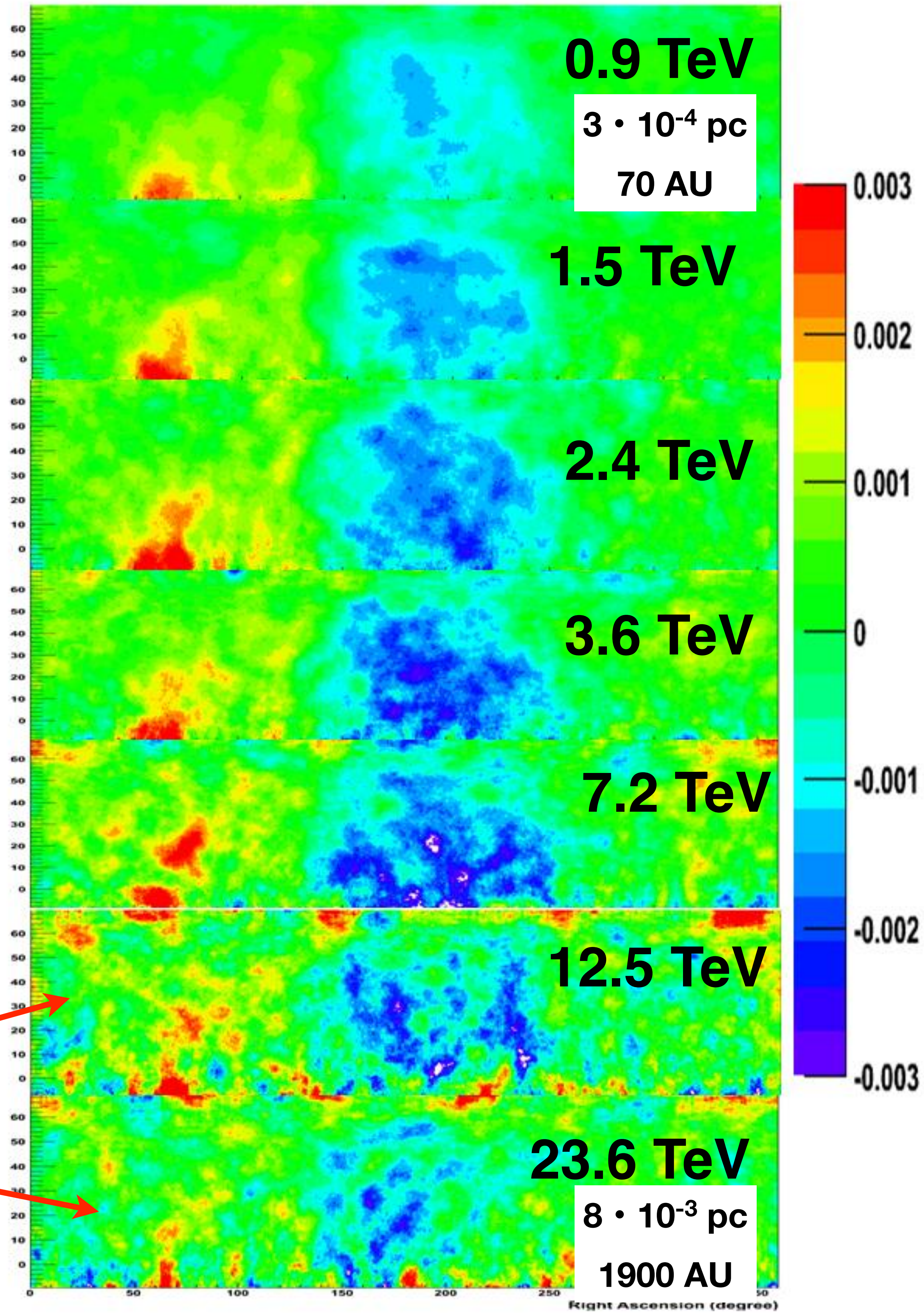


# Anisotropy vs energy




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

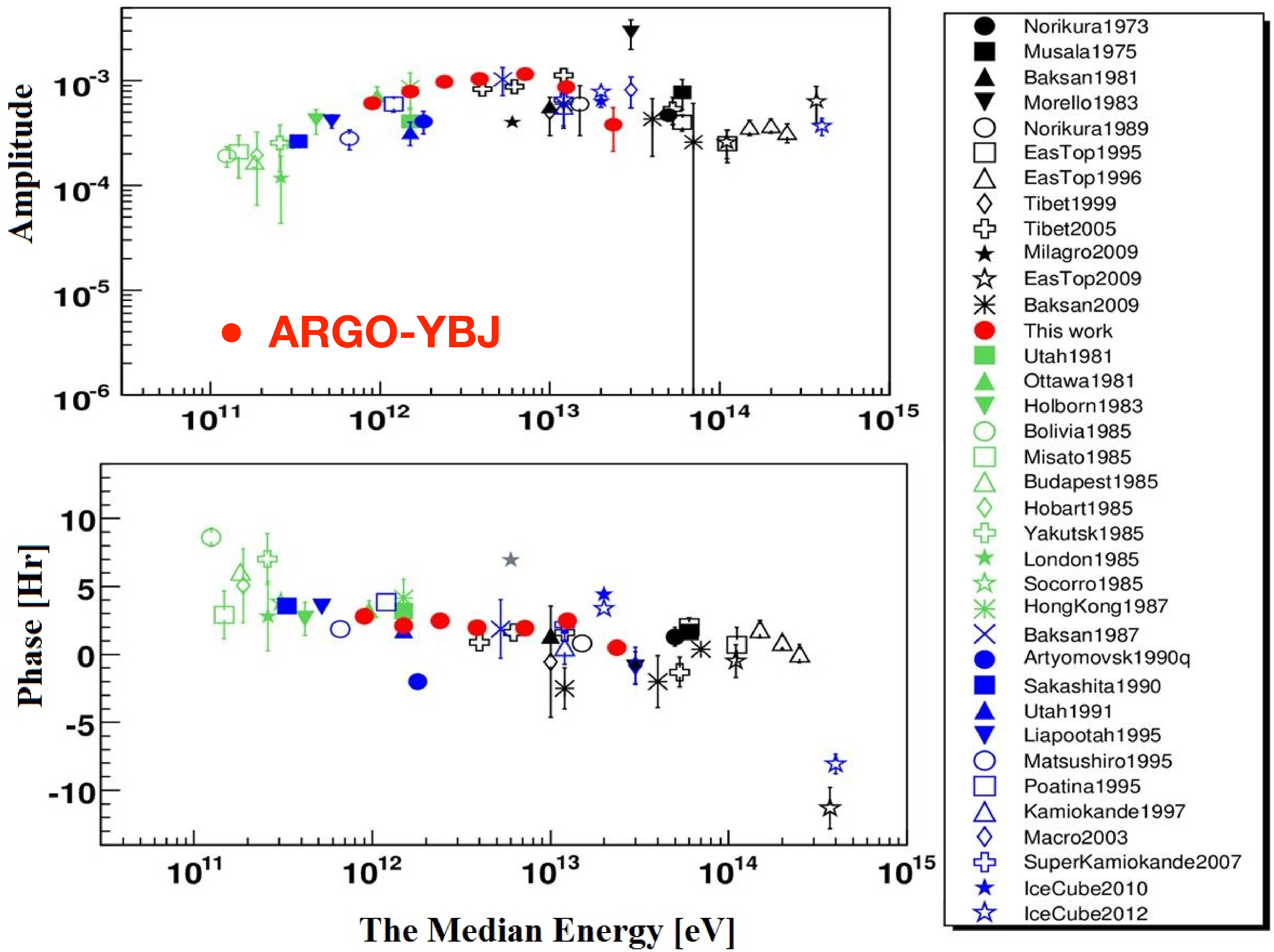
The tail-in broad structure appears to dissolve to smaller angular scale spots



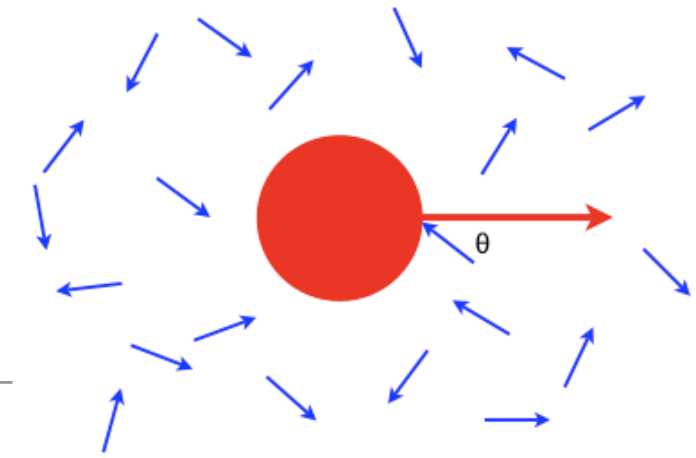
# Amplitude and phase of the first harmonic

ARGO-YBJ results in good agrrement with other experiments.

Analysis with the full statistics under way to extend the measurement up to the 100 TeV energy region



# x-check: 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 (CR "gas"), he sees a current of particles from the direction opposite to that of its own motion

A benchmark for the reliability of the detector and the analysis method. In fact, all the features (period, amplitude and phase) of the signal are predictable without uncertainty, due to the exquisitely kinetic nature of the effect.

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

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

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)

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

$$\varphi(\exp) : 6hr$$

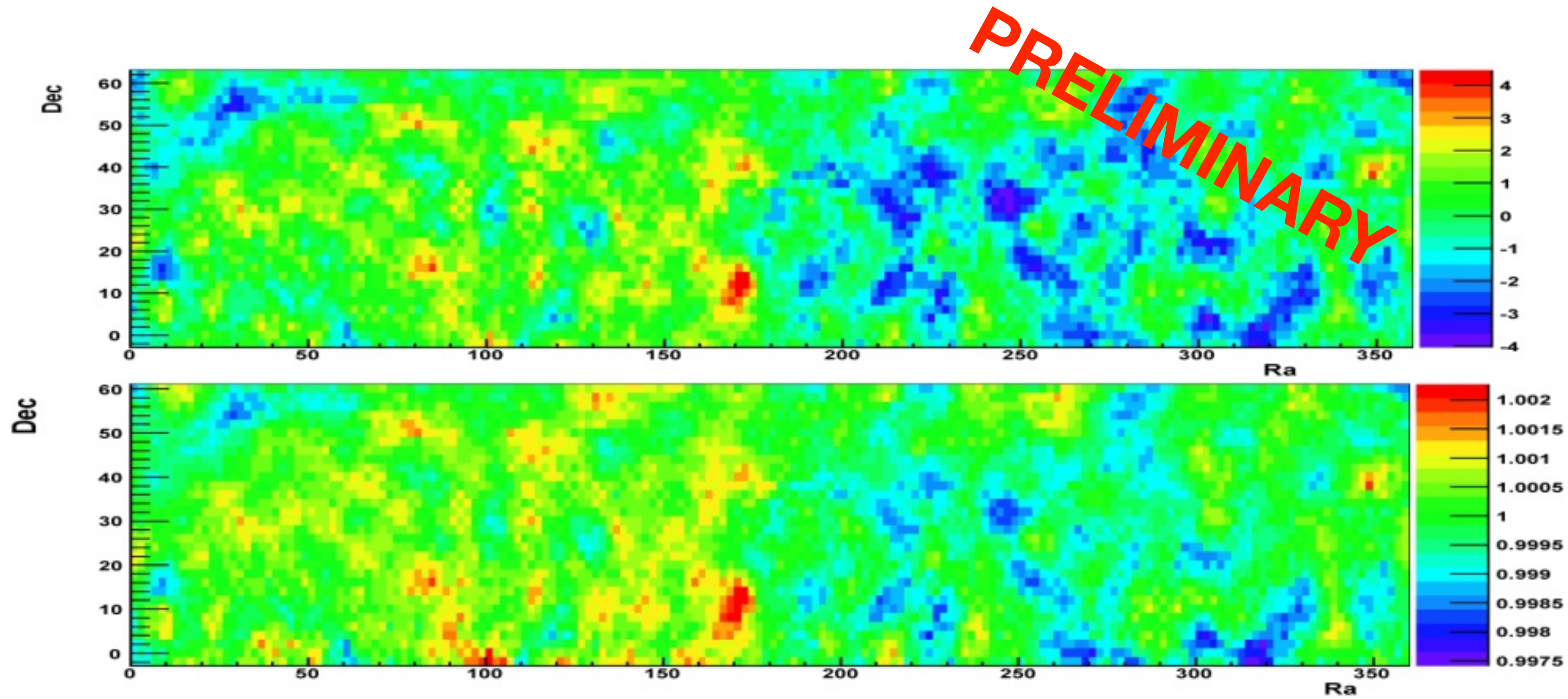
The first clear observation of the SCG effect with an EAS array was reported by EAS-TOP (LNGS) in 1996 at about $10^{14}$ eV.

# Compton-Getting effect by ARGO-YBJ

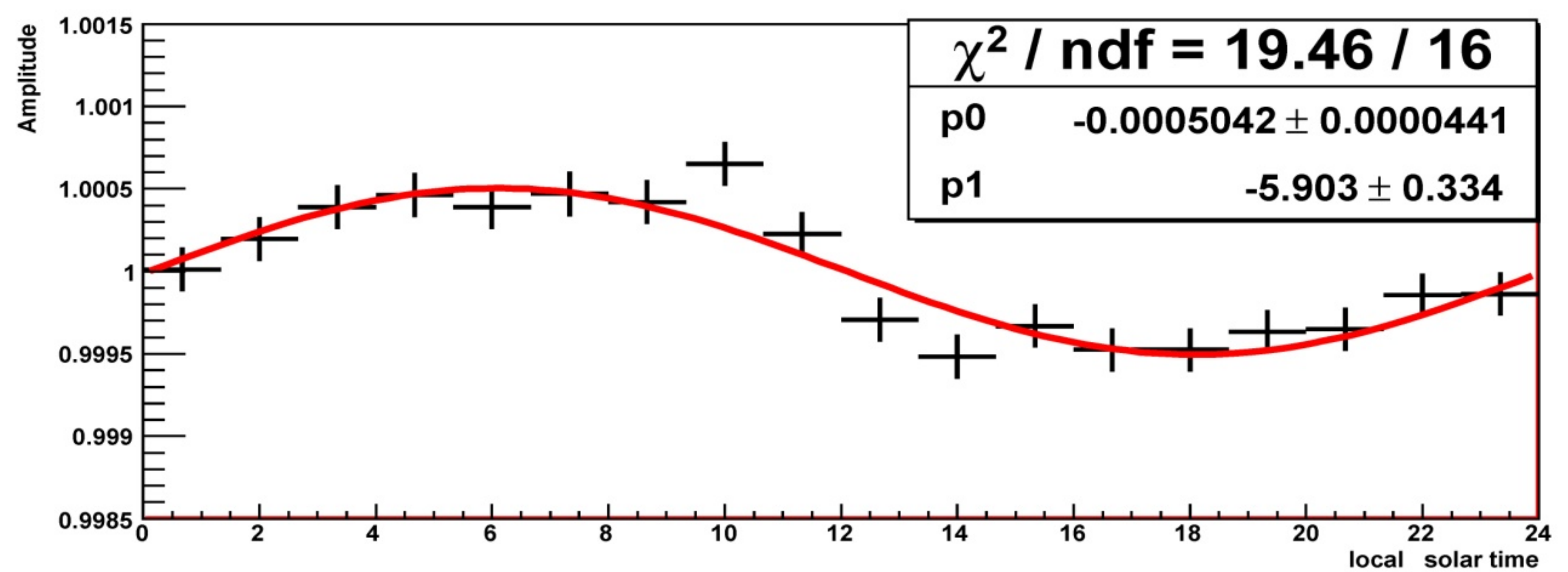
Solare Time (UT)
2008 – 2009 data

**Nhit 500 → ≈ 8 TeV**

to avoid solar effects
on low energy CRs




Evidence for an additional new anisotropy component at lower energy (solar effects ?) under study



# *Medium/Small* Scale Anisotropy

Data: November 8, 2007 - May 20, 2012
$\approx 3.70 \times 10^{11}$ events

dec. region $\delta \sim -20^{\circ} \div 80^{\circ}$

Map smoothed with the detected PSF for CRs

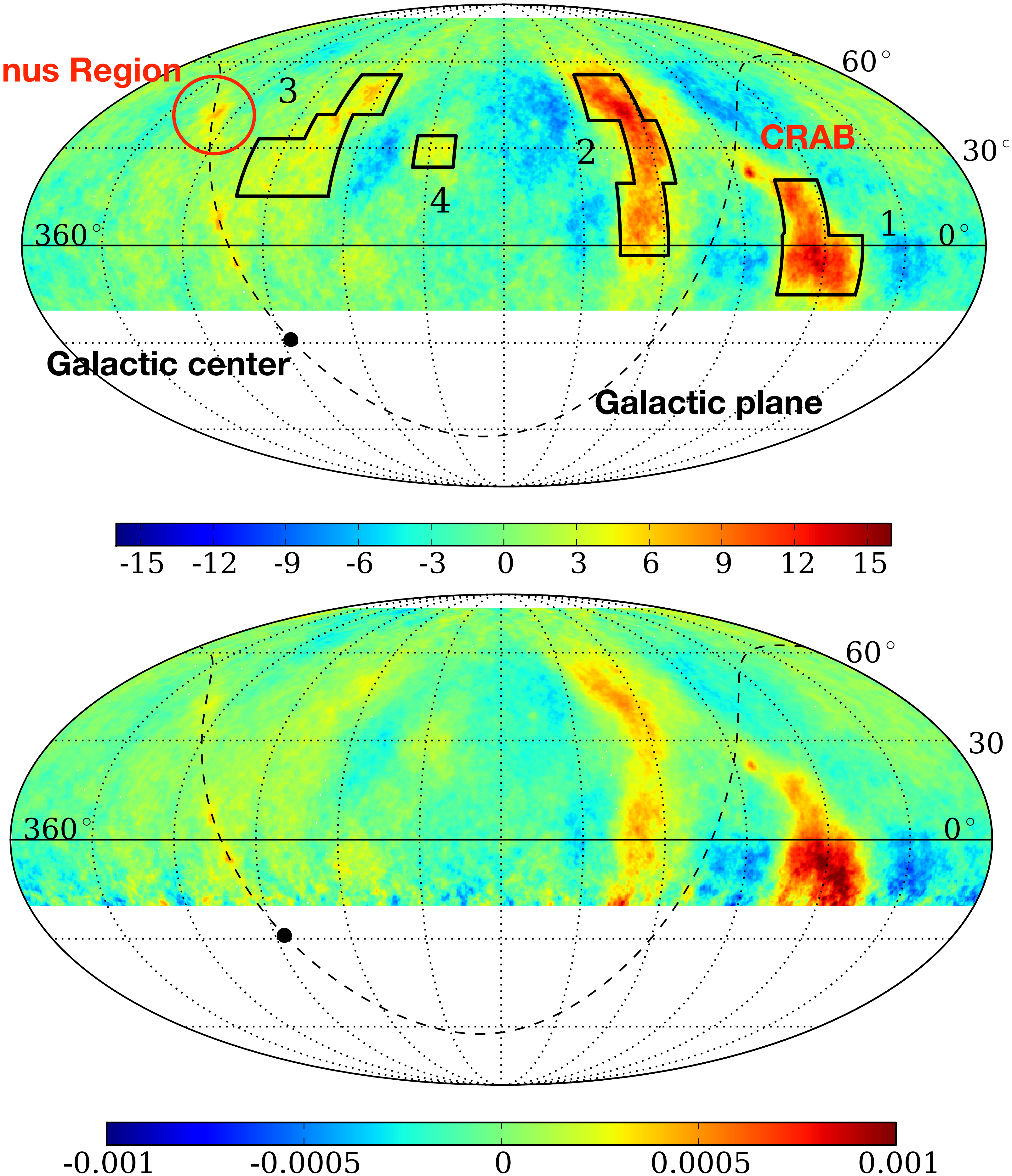
**Proton median energy ≈ 1 TeV**

**CRs excess ≈ 0.1 %**
**with significincance up to 15 s.d.**

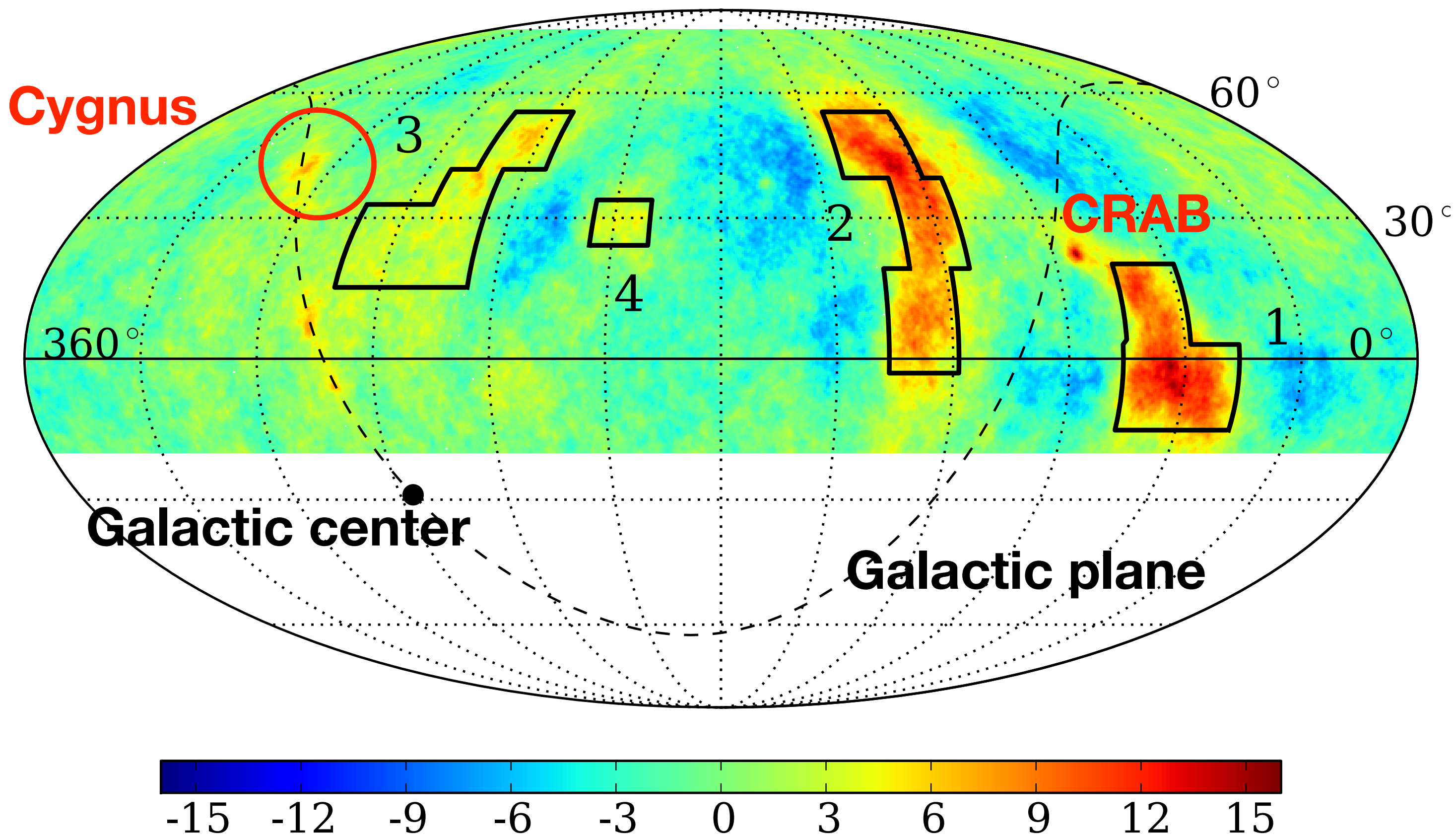
| **Strip-multiplicity interval** | **number of events** | | $\mathbf{E_p^{50}}$ [TeV] |
|---|---|---|---|
| 25 – 40 | $1.1409 \times 10^{11}$ | (38%) | 0.66 |
| 40 – 100 | $1.4317 \times 10^{11}$ | (48%) | 1.4 |
| 100 – 250 | $3.088 \times 10^{10}$ | (10%) | 3.5 |
| 250 – 630 | $8.86 \times 10^{9}$ | (3%) | 7.3 |
| more than 630 | $3.52 \times 10^{9}$ | (1%) | 20 |

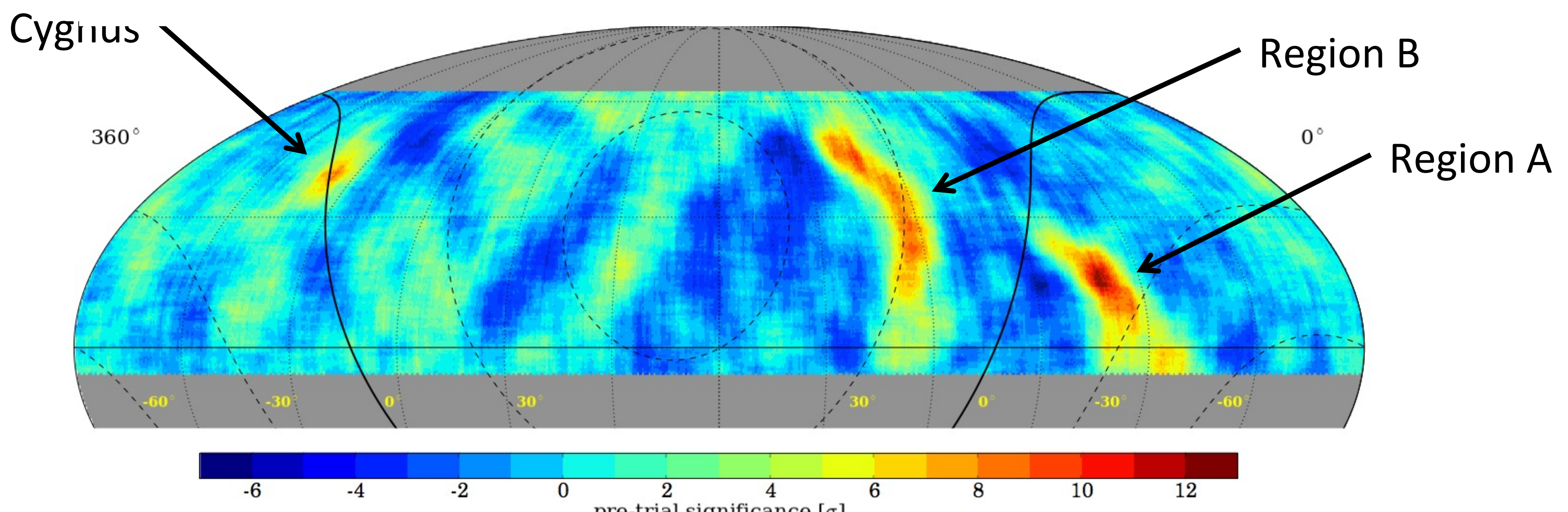
TABLE I: Multiplicity intervals used in the analysis. The central columns report the number of events collected. The right column shows the corresponding isotropic CR proton median energy.

PRD in press

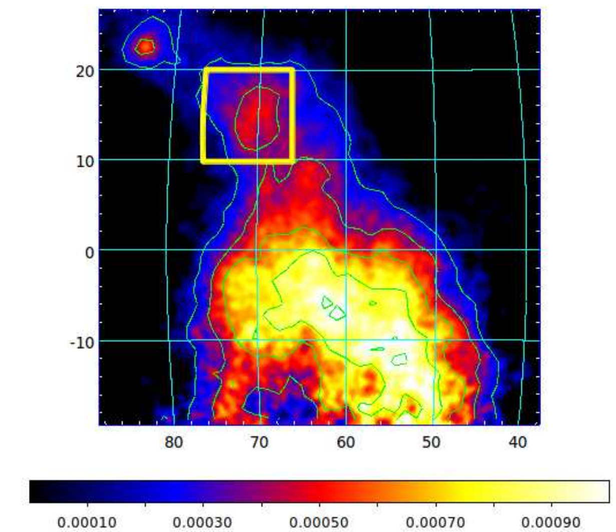


# Comparison to Milagro Sky Map

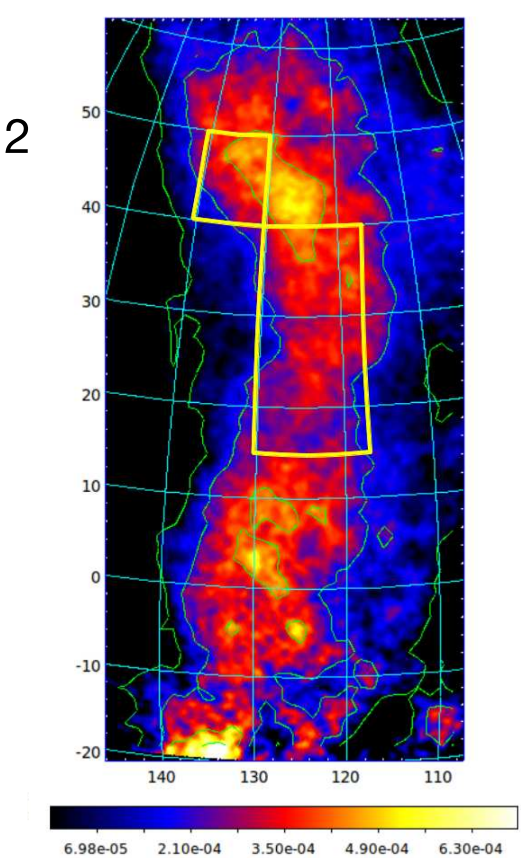



Region 1

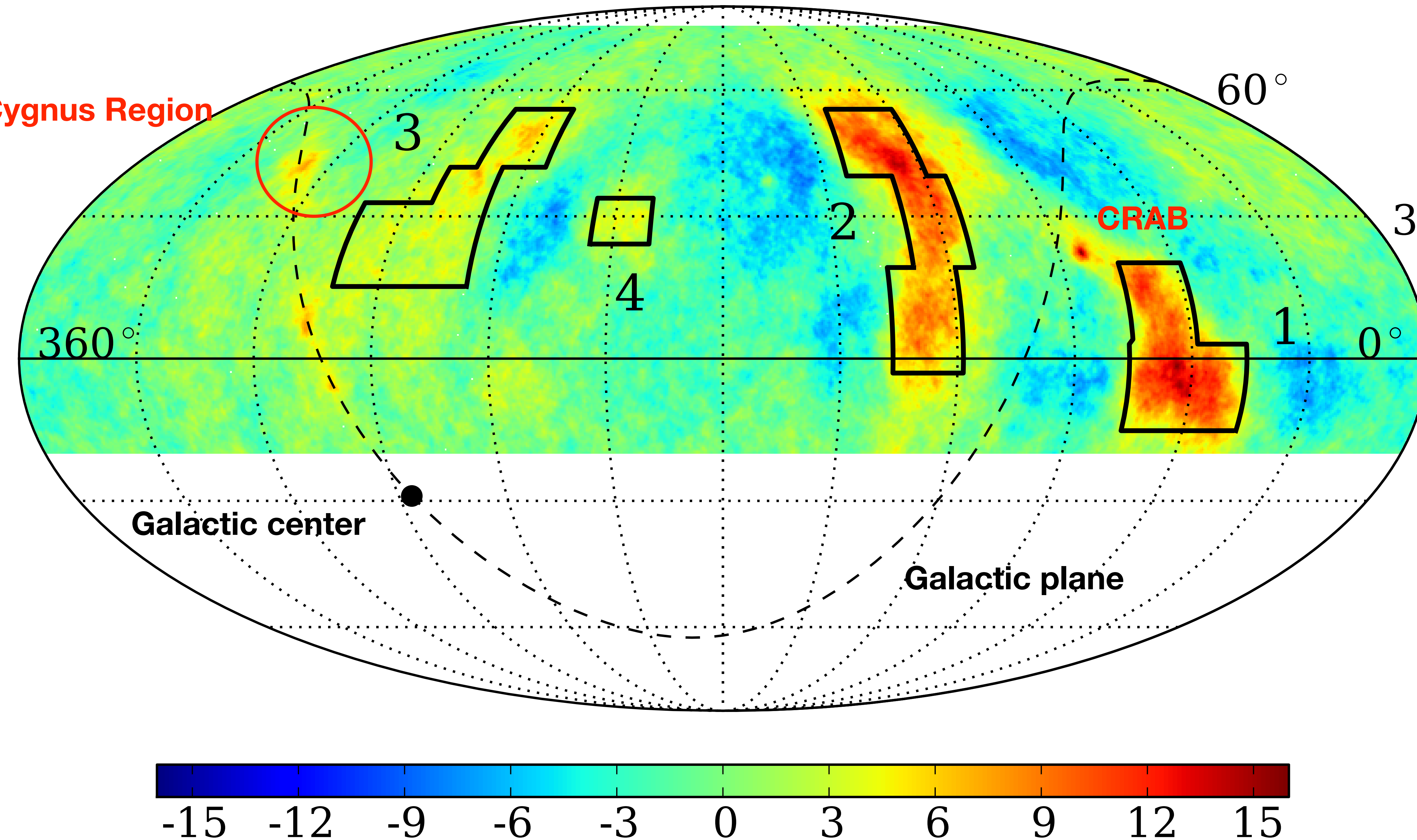



Region 2

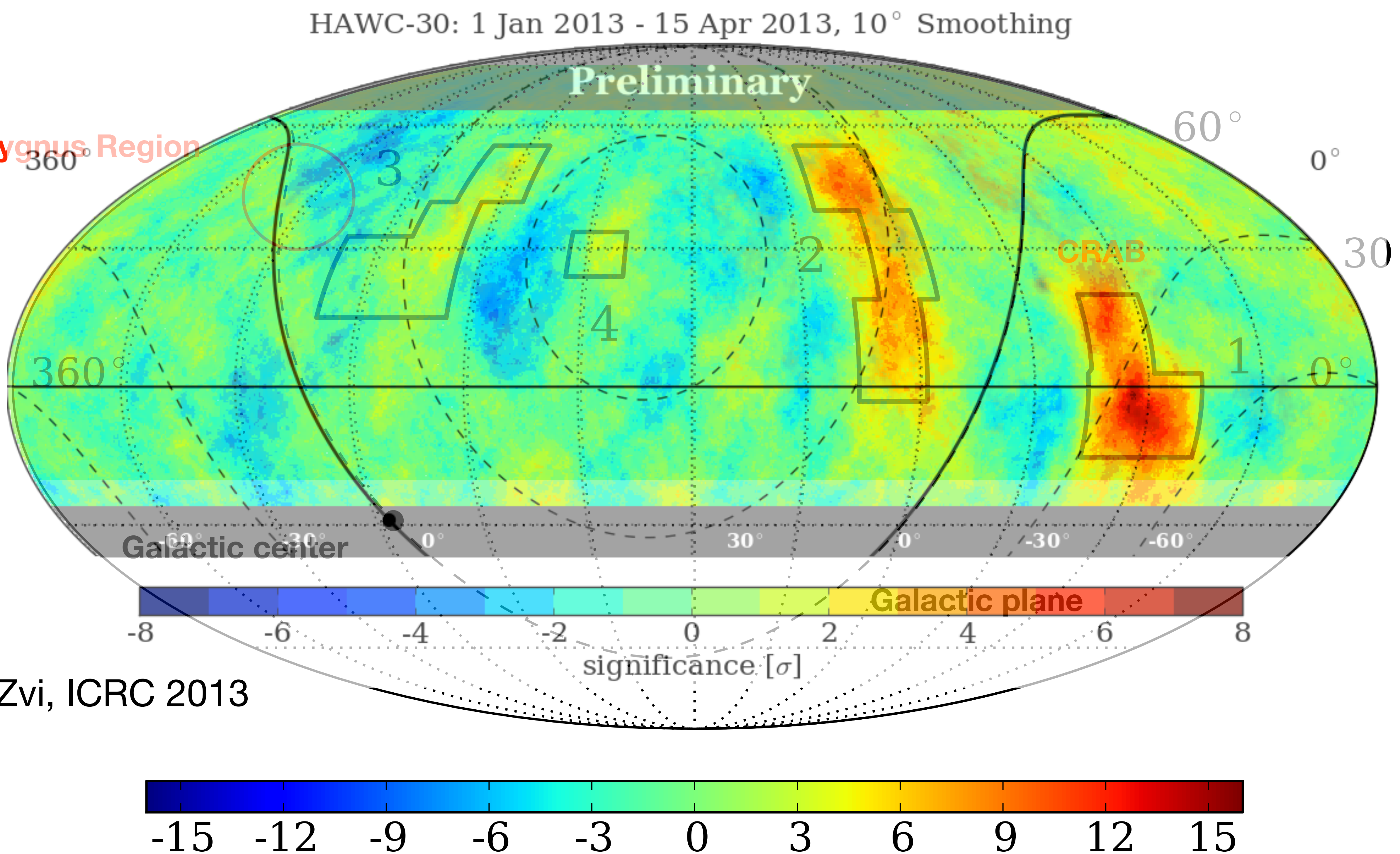



A. Abdo et al., PRL **101**:221101, 2008

# Comparison to HAWC Sky Map

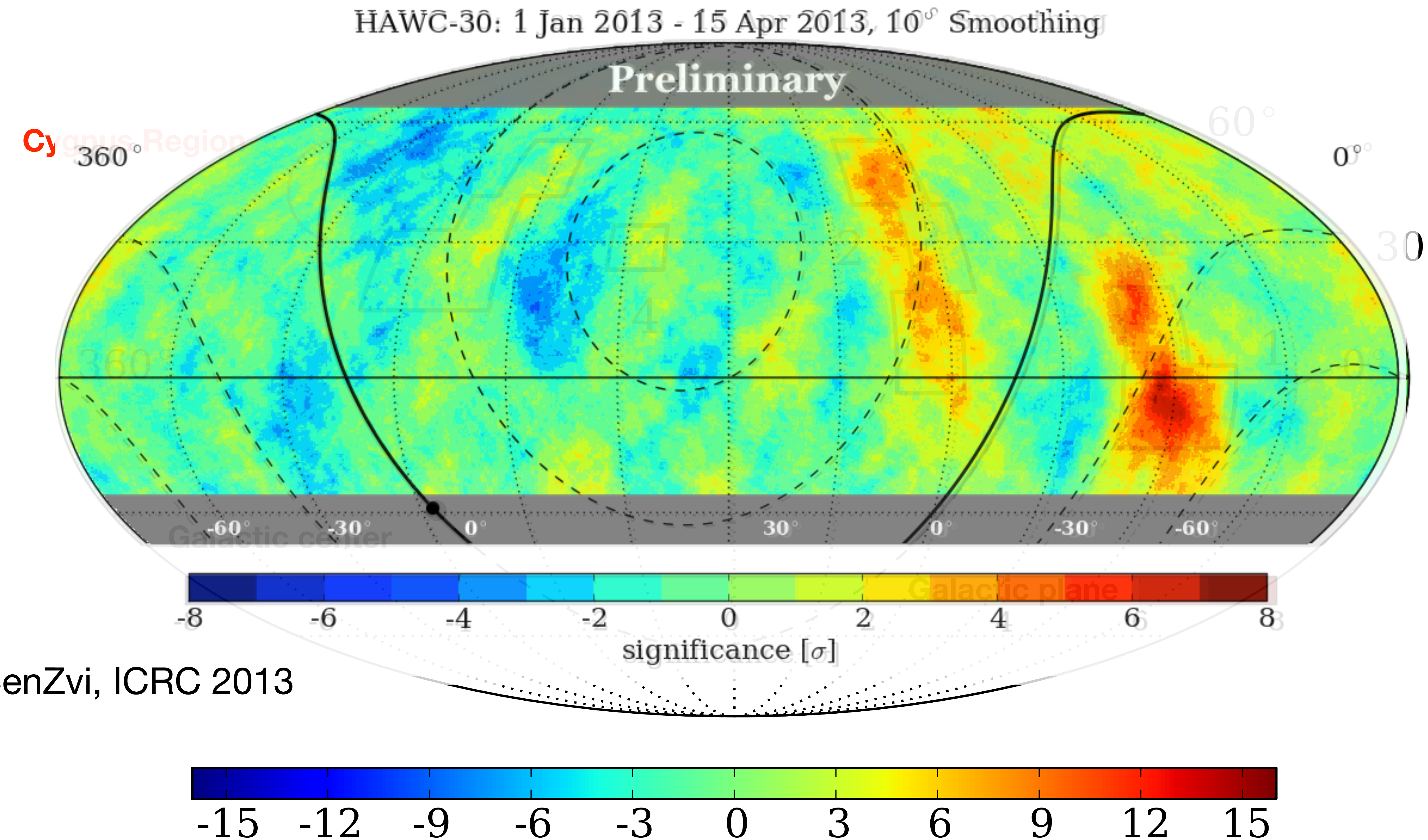


# Comparison to HAWC Sky Map



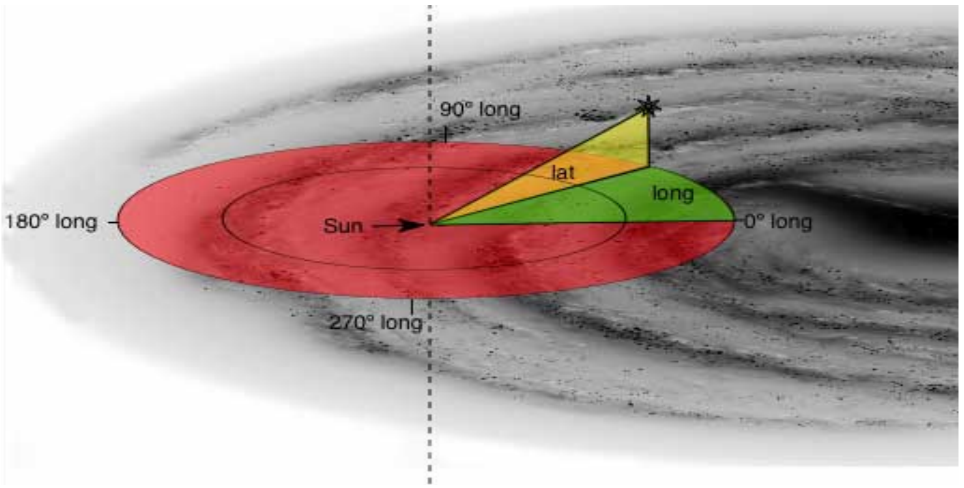

S. BenZvi, ICRC 2013

# Comparison to HAWC Sky Map

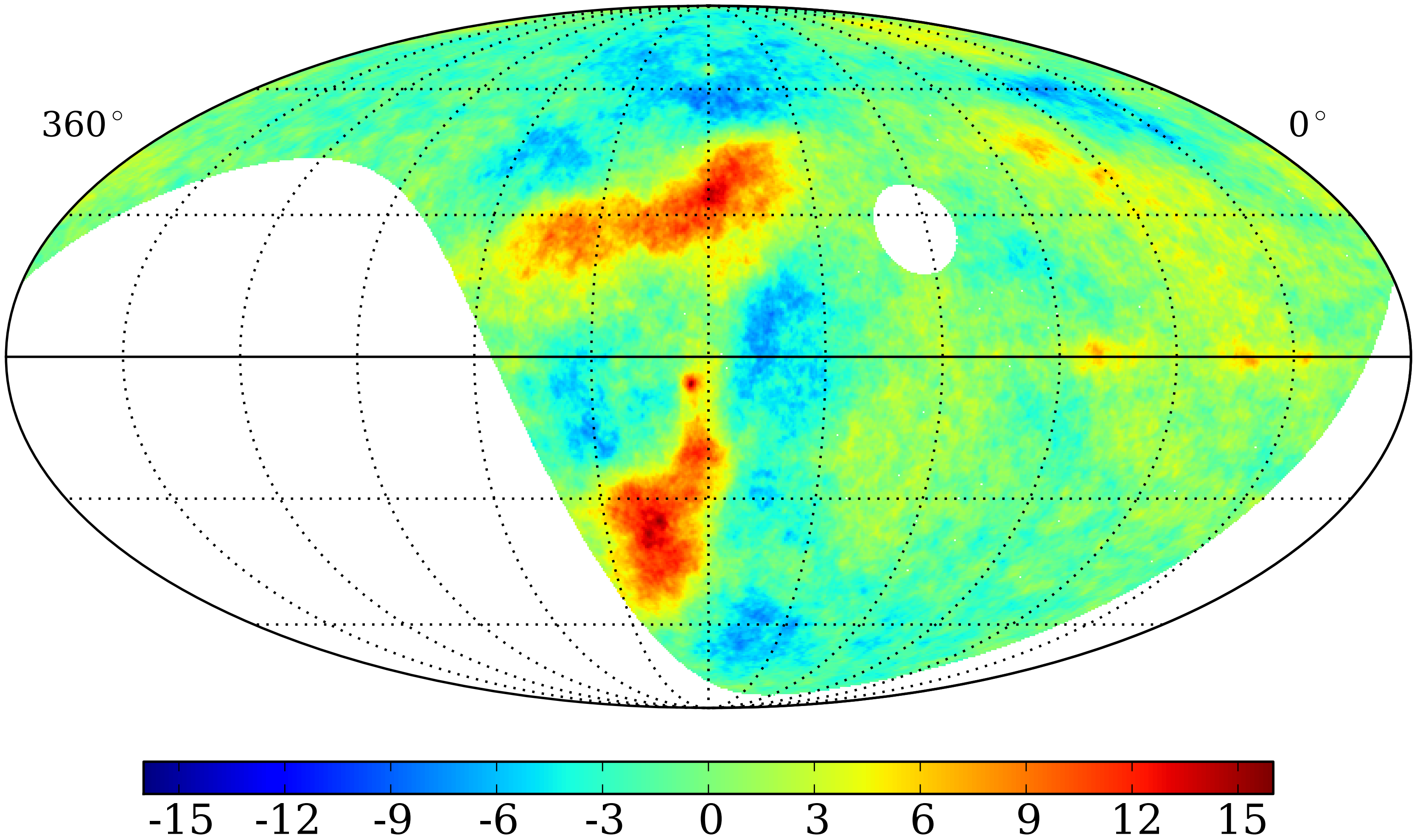



S. BenZvi, ICRC 2013

# MSA in galactic coordinates




The map center points towards the galactic Anti-Center.




The regions 1 and 2 are distributed symmetrically with respect to the Galactic plane and have longitude centered around the galactic Anti-Center.

The new detected hot spots do not lie on the galactic plane and one of them is very close to the galactic north pole.

In spite of the fact that the bulk of SNR, pulsars and other potential CR sources are in the Inner Galaxy surrounding the Galactic Centre, the excess of CR is observed in the opposite, Anti-Centre direction.
The fact that the observed excesses are in the Northern and in the Southern Galactic Hemispheres, favors the conclusion that the CR at TeV energies originate in sources whose directions span a large range of Galactic latitudes.

# Conclusions

The ARGO-YBJ detector exploiting the full coverage approach and the high segmentation of the readout is imaging the front of atmospheric showers with unprecedented resolution and detail.

The digital and analog readout are allowing a deep study of the CR physics in the wide TeV - PeV energy range.

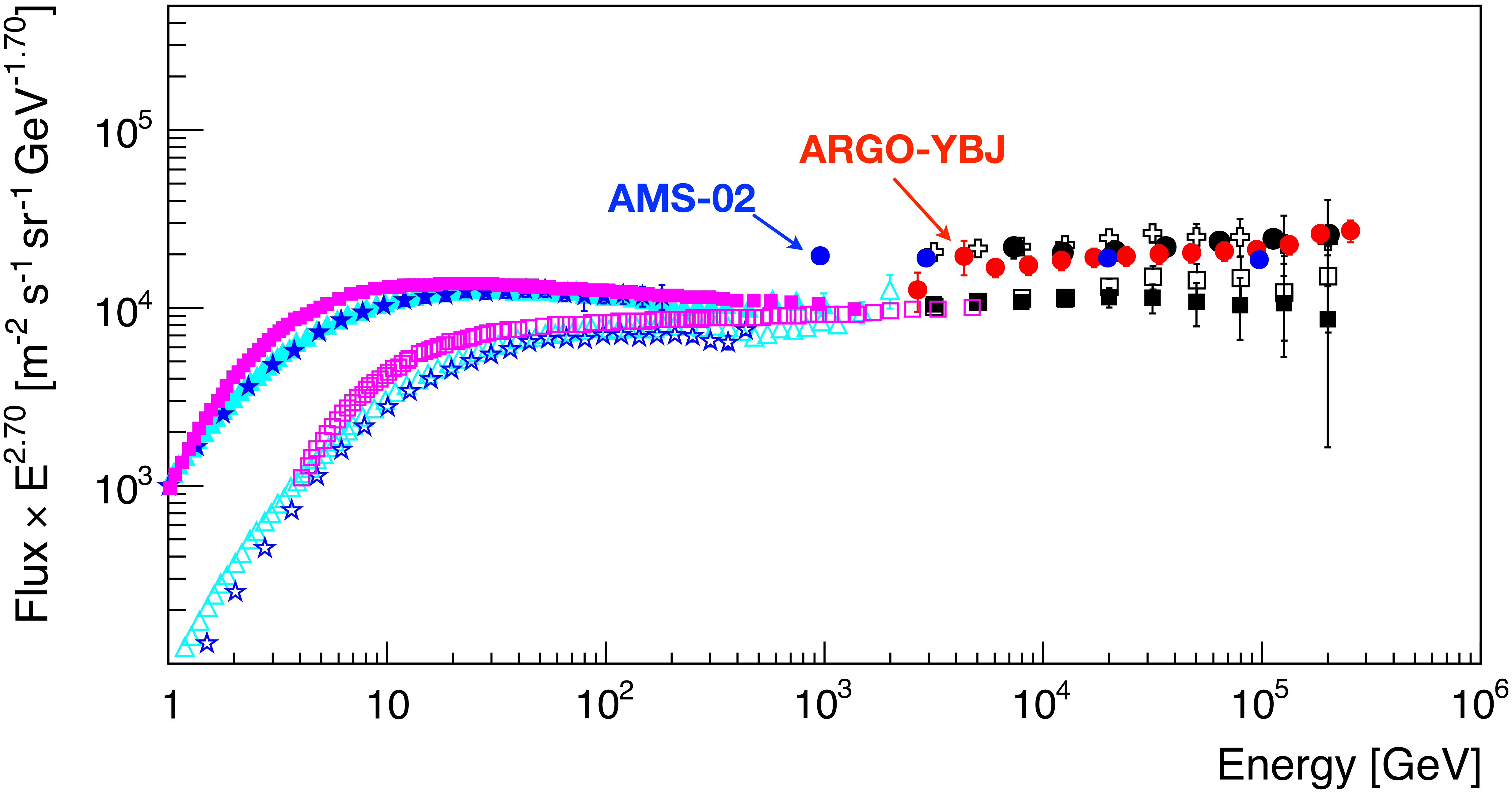
A number of interesting results have been obtained

- First Northern sky survey (-10° < $\delta$ < 70°) at 0.25 Crab Units.
- Observed TeV gamma-ray emission from 6 sources above 5 s.d.
- Detailed study of flaring and extedend TeV gamma-ray sources

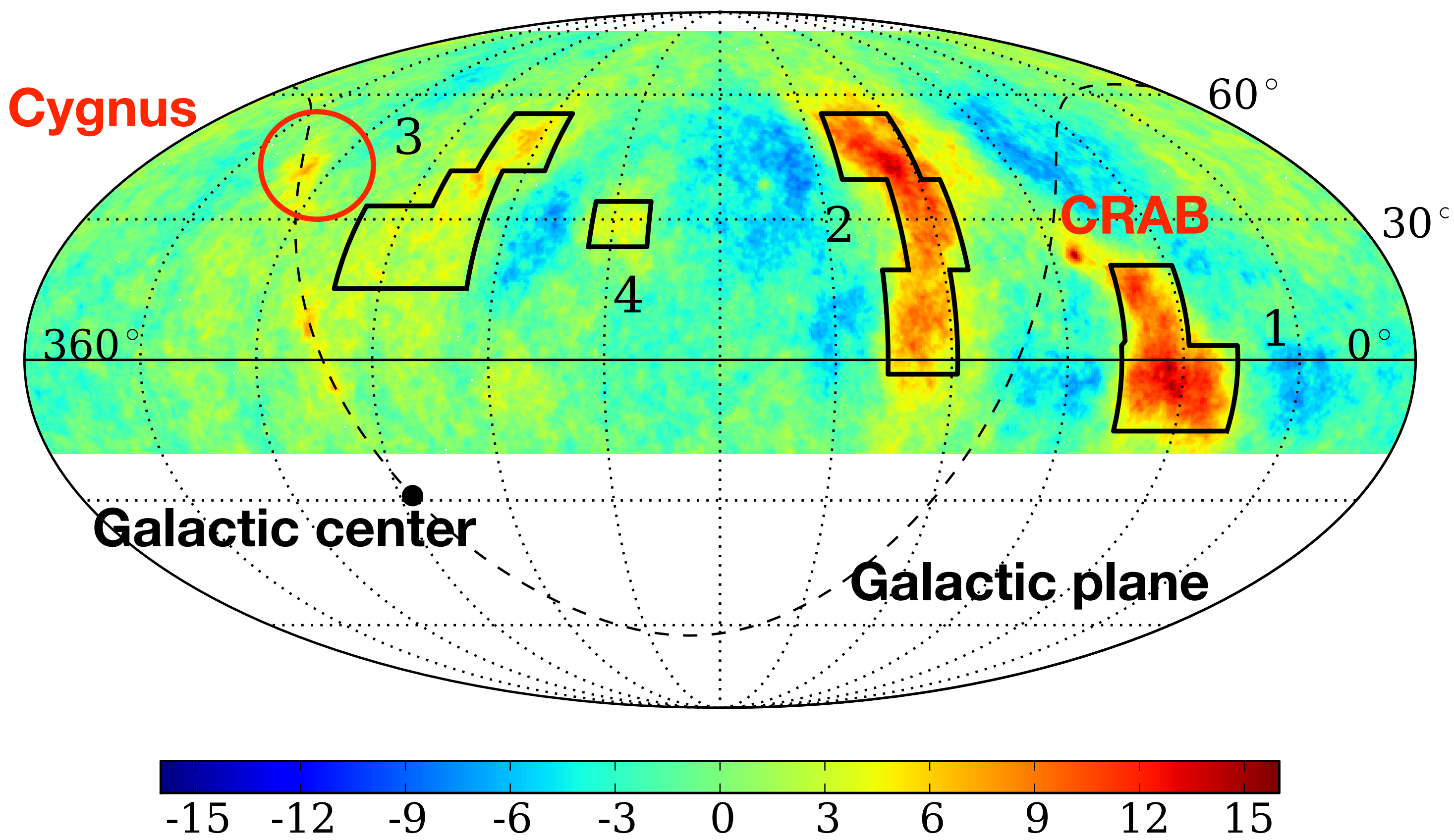
- Measurement of CR light component energy spectrum up to PeV
- Study of EAS phenomenology up to PeV
- Study of the CR anisotropy at different angular scales
- Measurement of the CR antip/p flux ratio in TeV energy range
- Measurement of the p-air and p-p cross sections up to 100 TeV

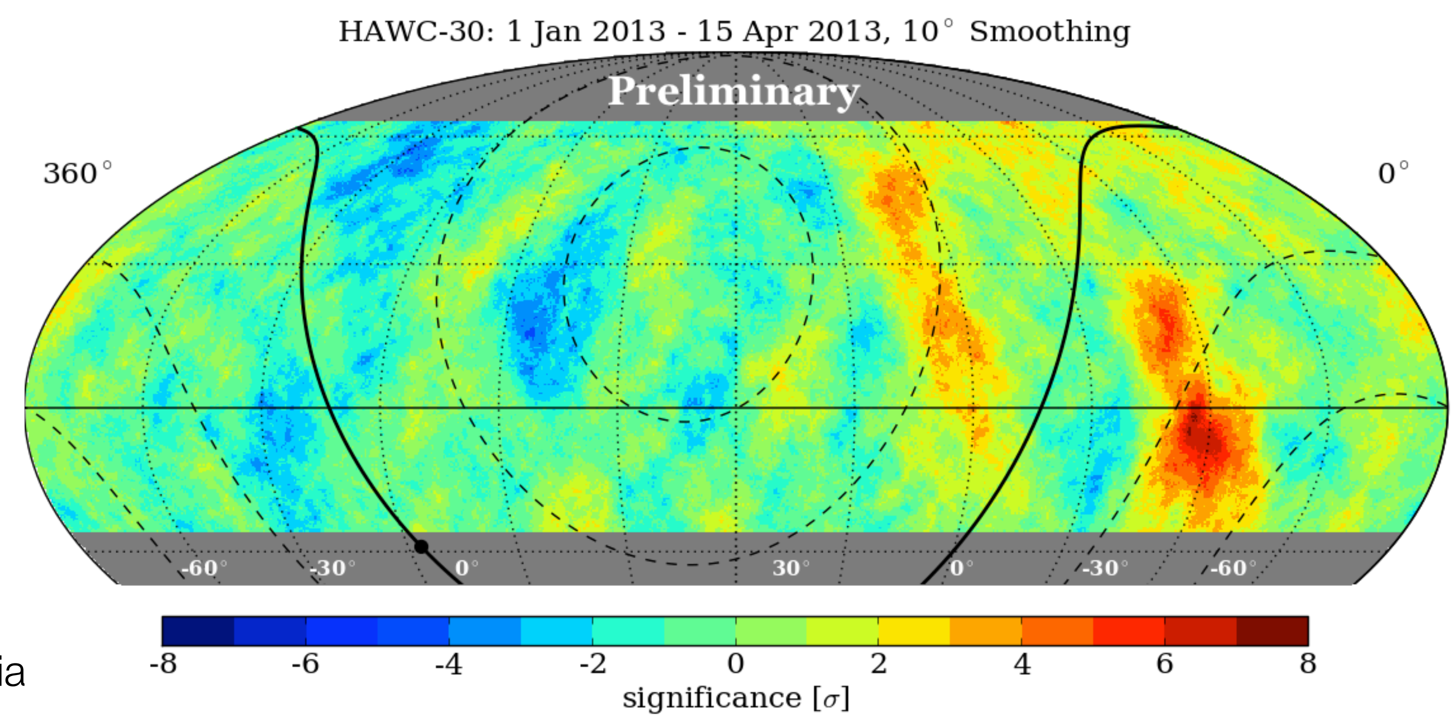
- Detailed study of the Sun shadow in correlation with the solar activity

# ARGO-YBJ and AMS-02



# Comparison to HAWC Sky Map




S. BenZvi, ICRC 2013

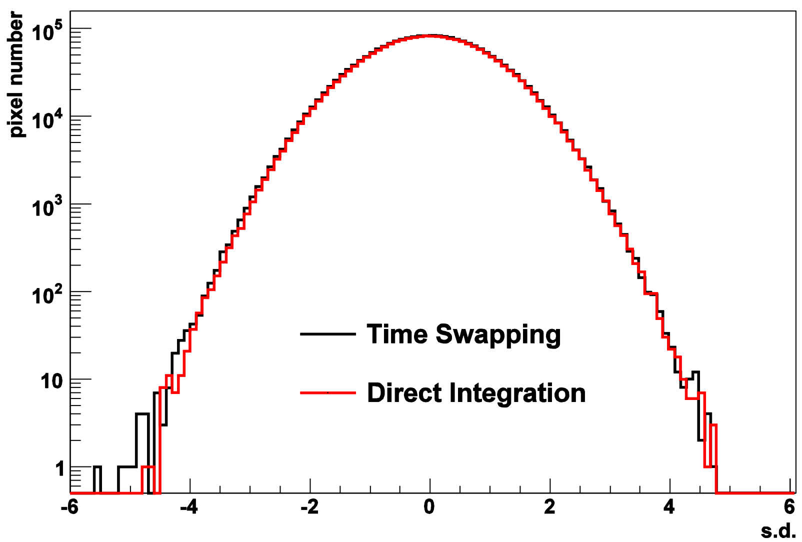
# *Medium/Small* Scale Anisotropy

How to focus on *medium/small* scale structures ?

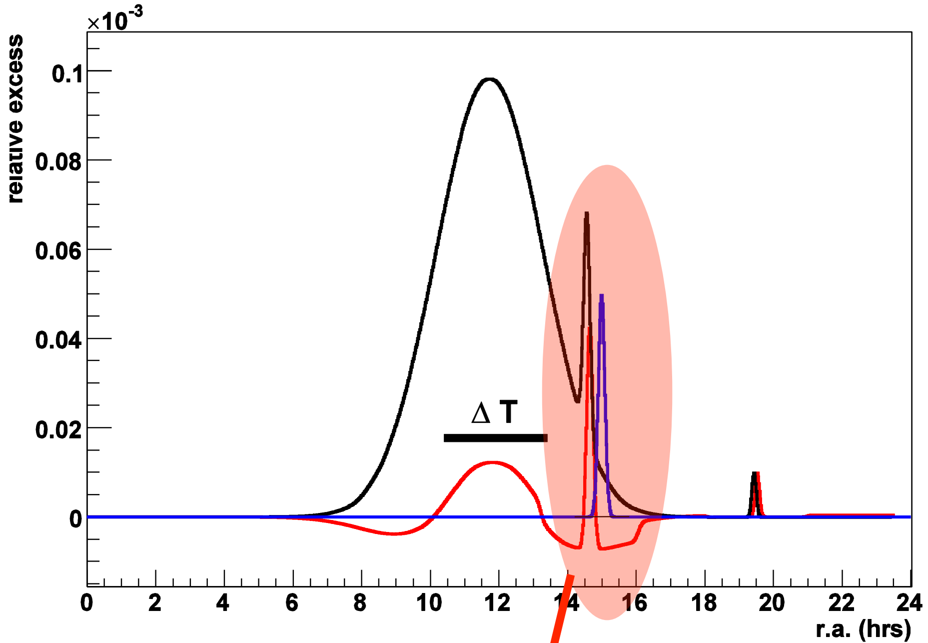
*Traditional background estimation methods:*

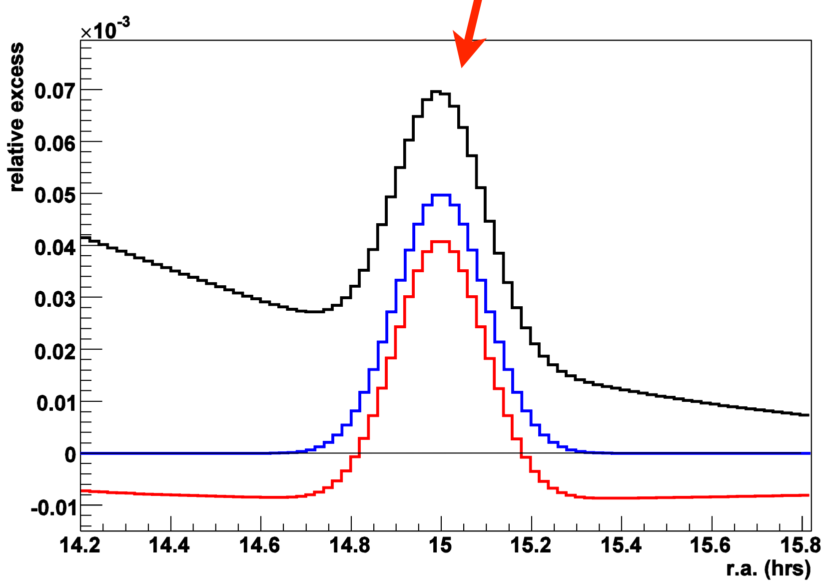
- Time swapping/scrambling (3 hrs,)
- Direct integration (3 hrs)

(consistent each other within 0.3 s.d.)




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



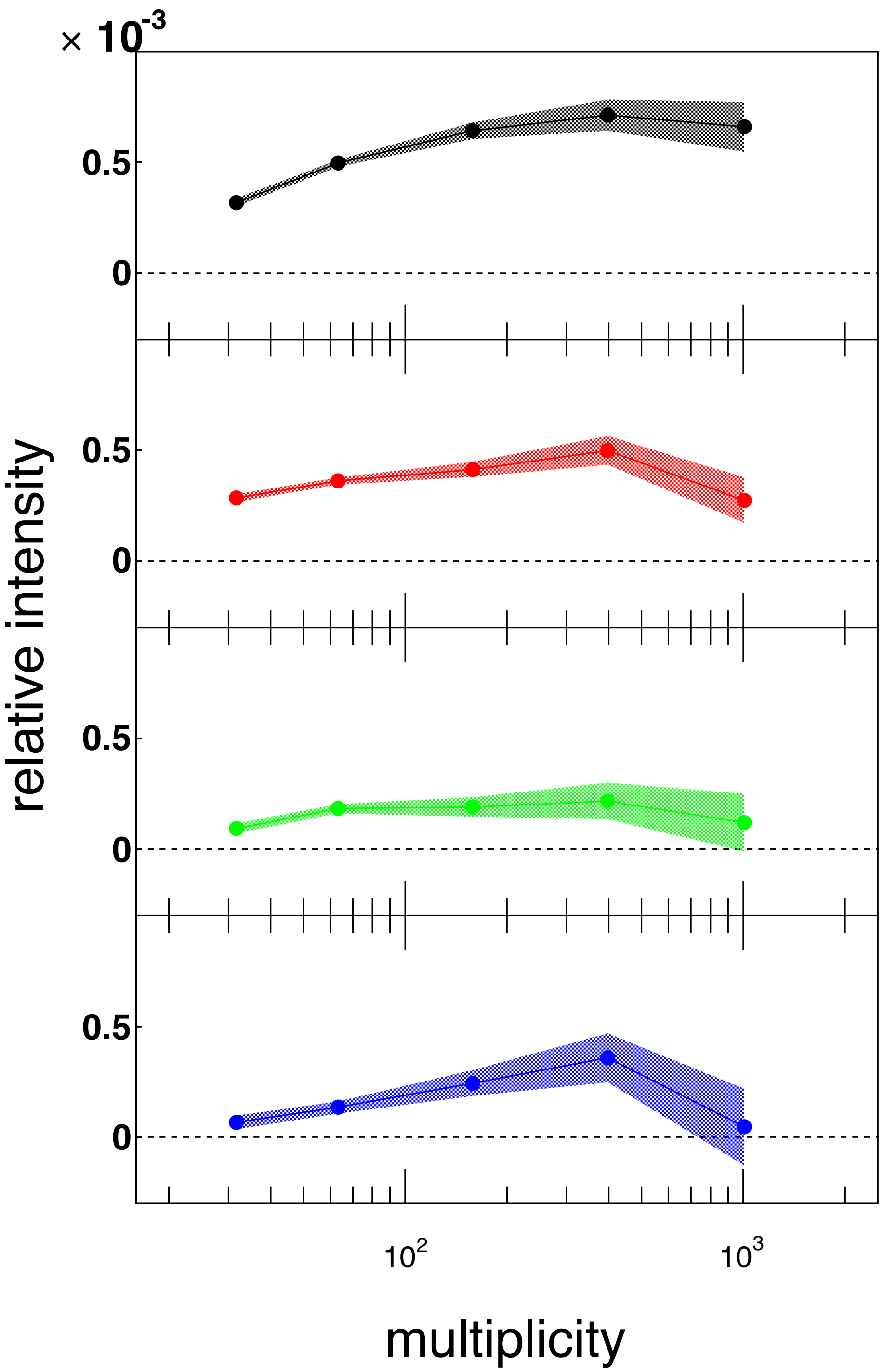

every feature larger than ΔT is brought to zero (apart from the peak)

First systematic study of the time average-based methods

R. Iuppa and G. Di Sciascio, ApJ **766** (2013) 96

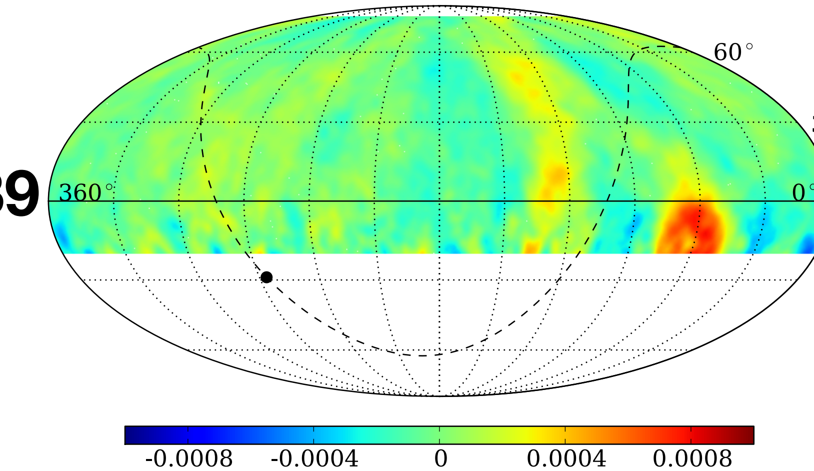
The observation of a possible small angular scale anisotropy region contained inside a larger one relies on the capability for suppressing the anisotropic structures at larger scales without, simultaneously, introducing effects of the analysis on smaller scales.

# MSA vs energy

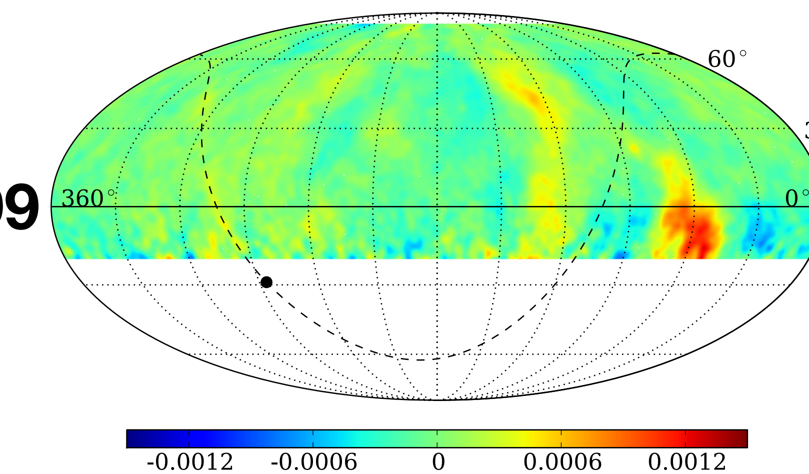



The size spectra look quite harder than the CR isotropic flux

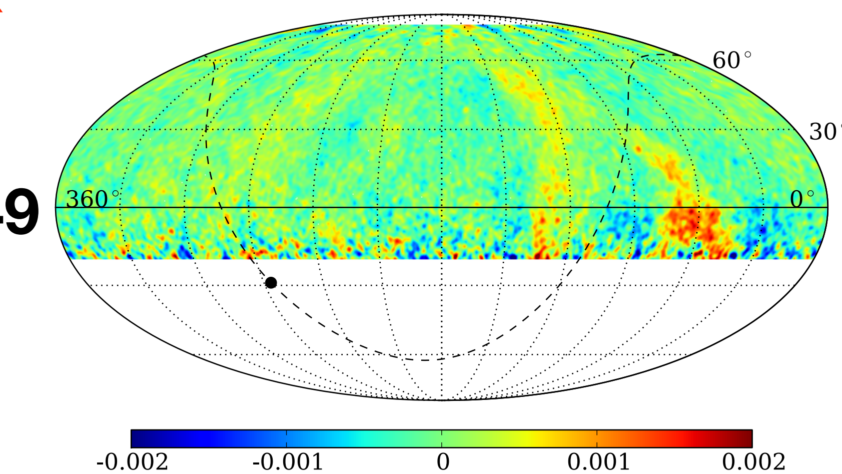
N = 25 - 39



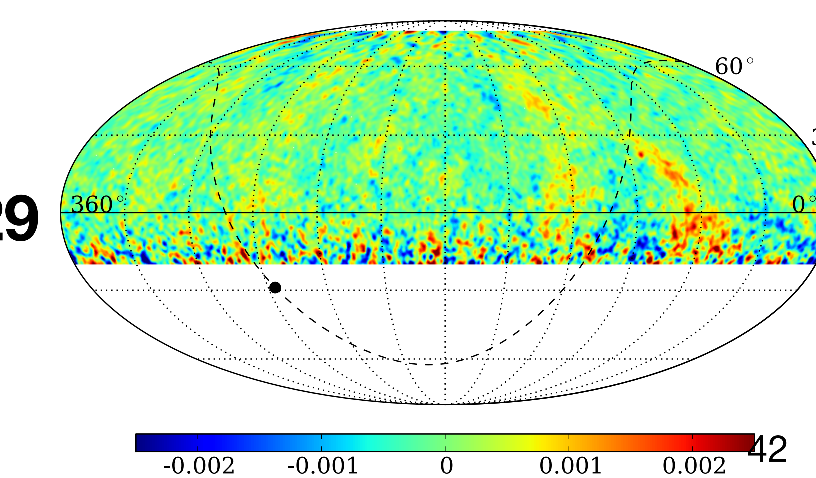

40 - 99



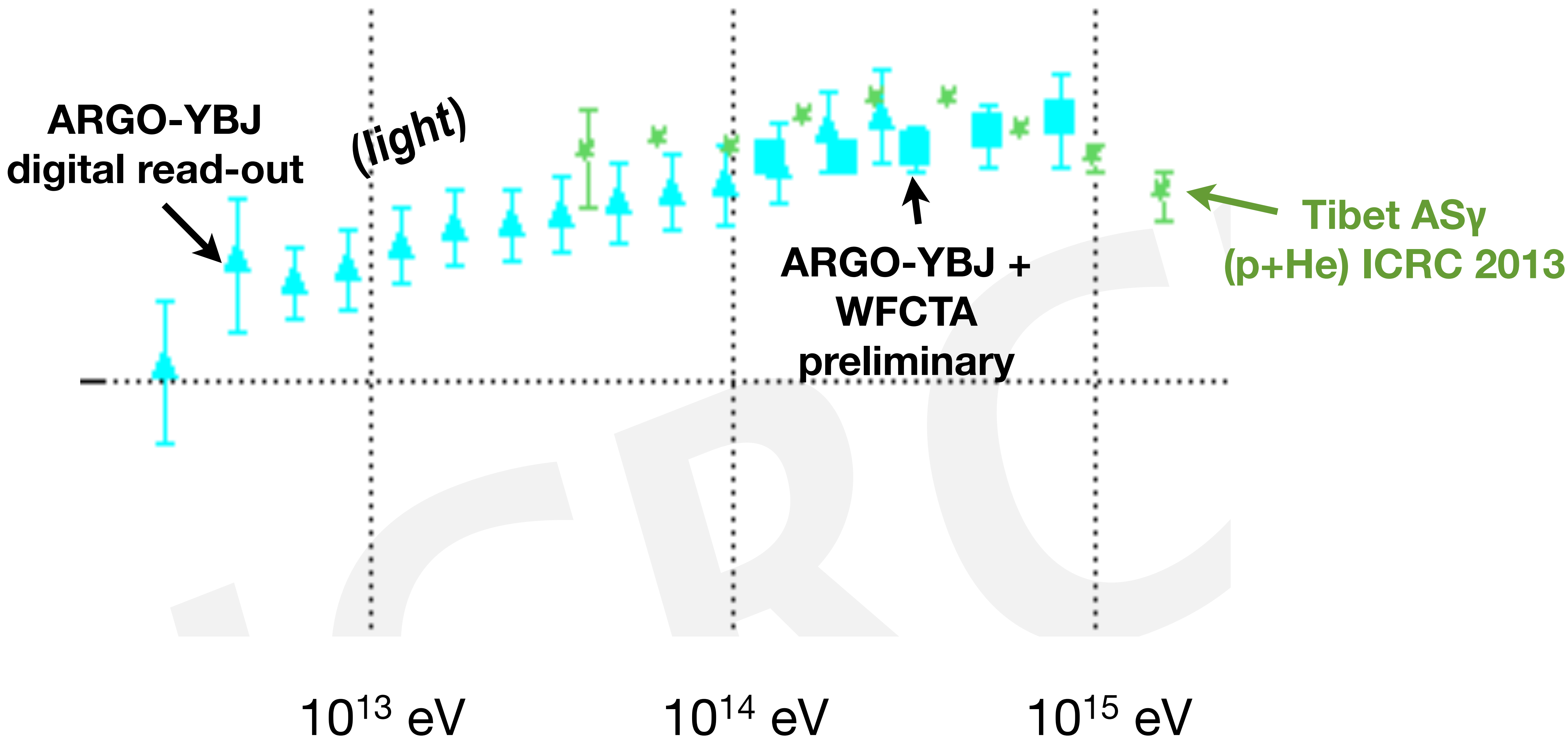

100 - 249




250 - 629



# ARGO-YBJ vs Tibet ASγ



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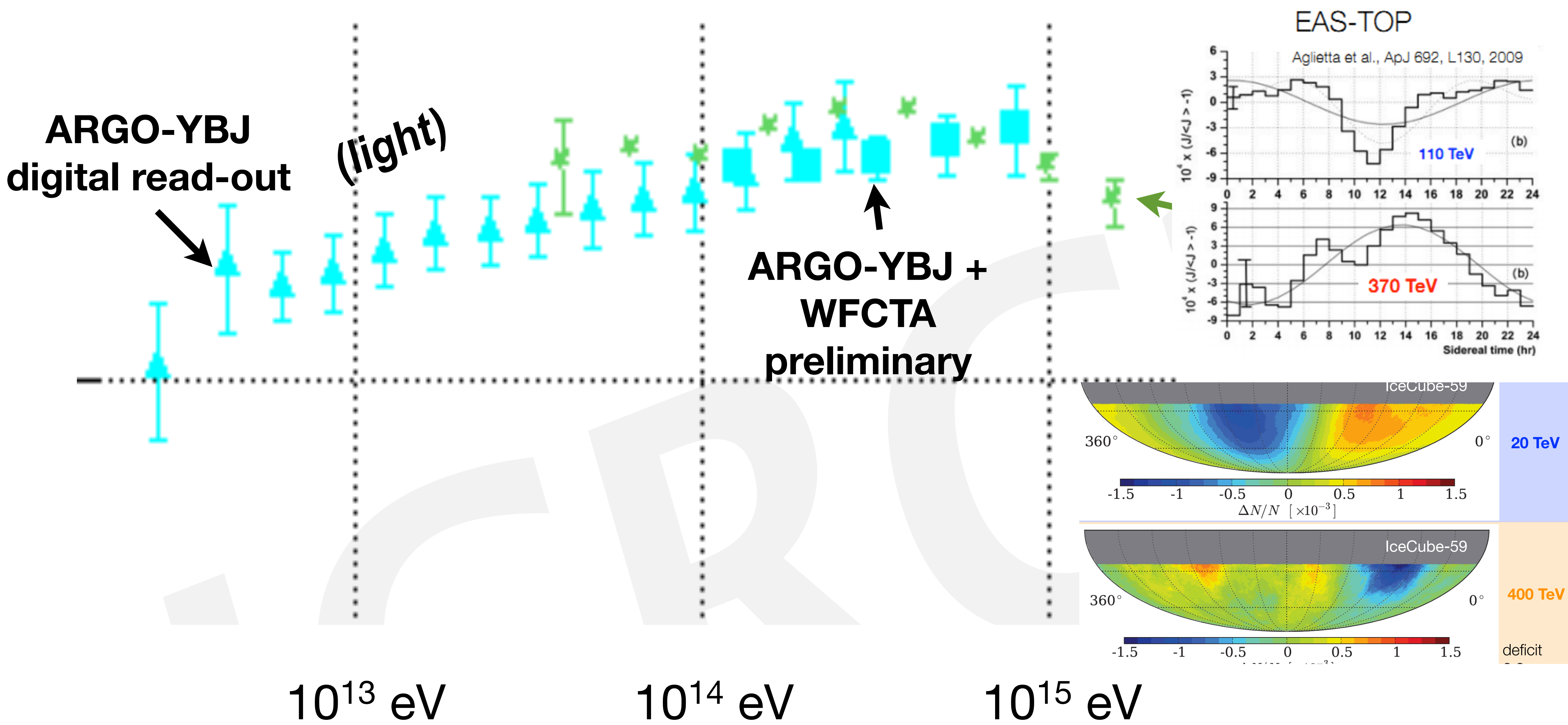
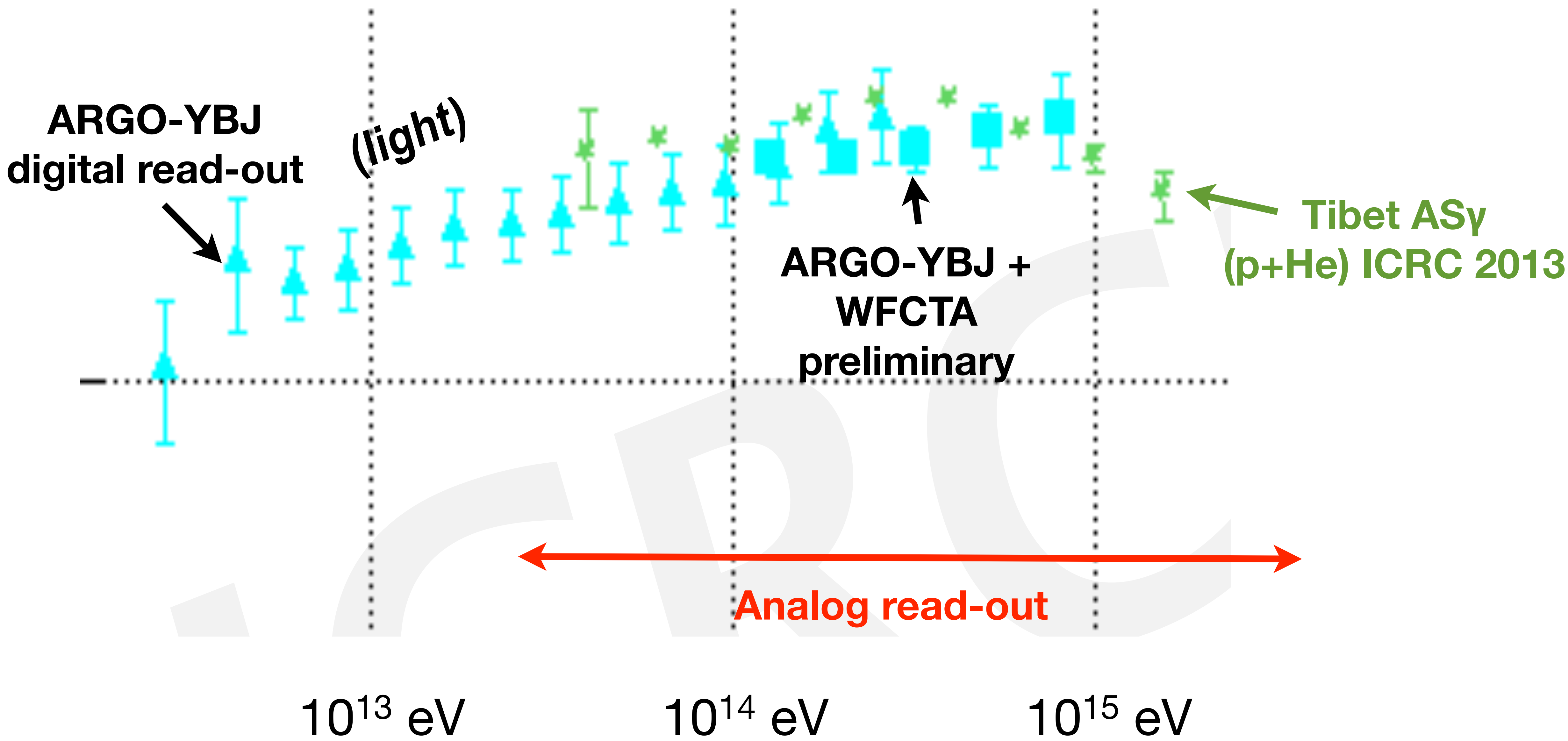


# ARGO-YBJ vs Tibet ASγ




**Analysis with the analog read-out + Bayesian unfolding (50 TeV - few PeV) under way**