The ARGO-YBJ Experiment

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

INFN - IHEP Meeting on Cosmic Ray Physics
LNGS, 16-17 Sept. 2013

Questions to the knee energy range

Cosmic Ray Sources ?	➡	**Still open**
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**

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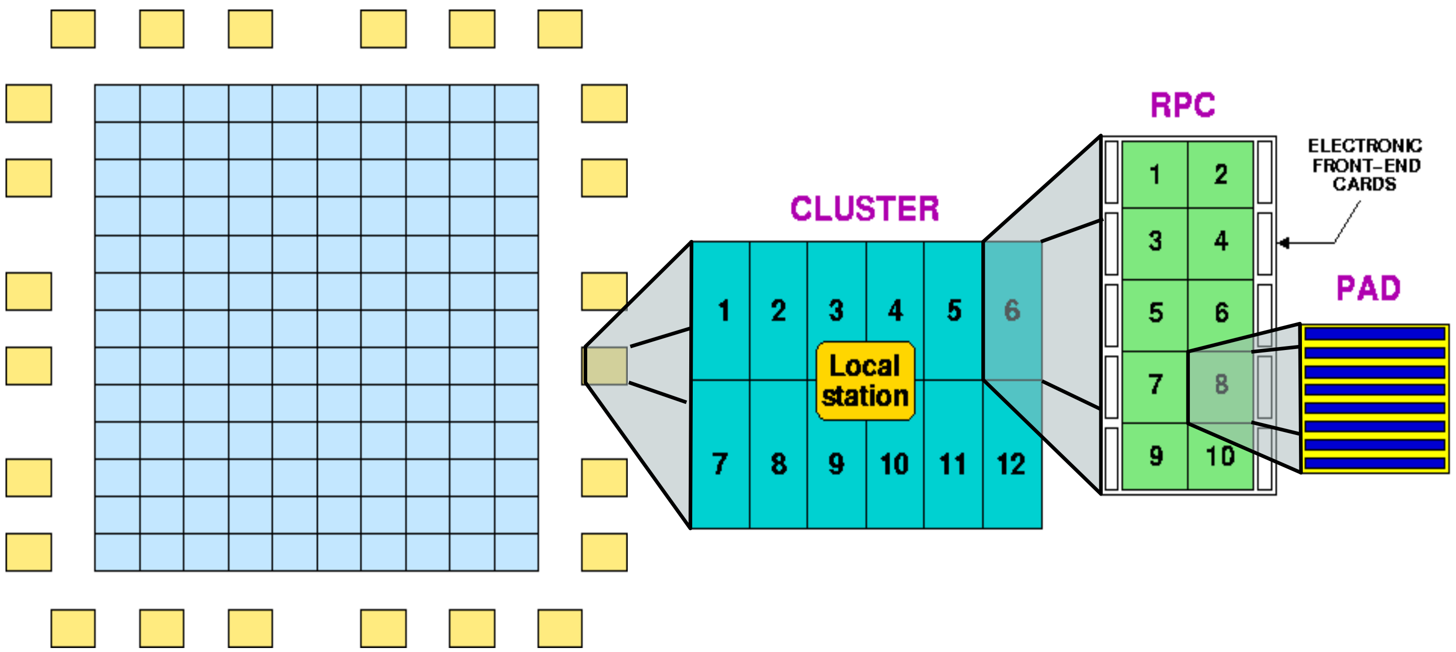
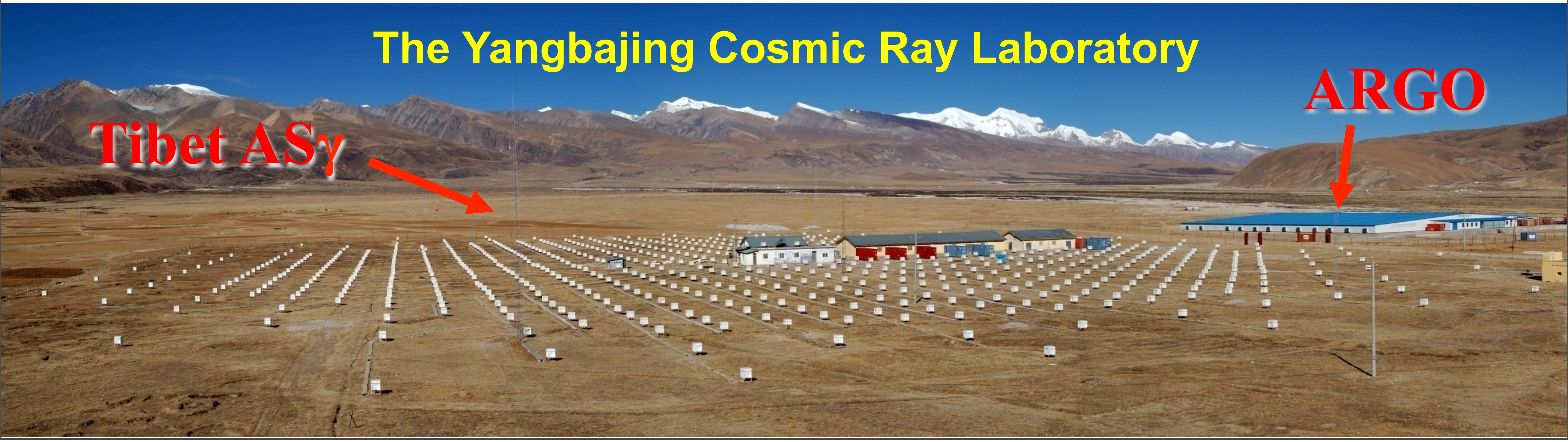
The ARGO-YBJ experiment



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 asl - 600 g/cm2)

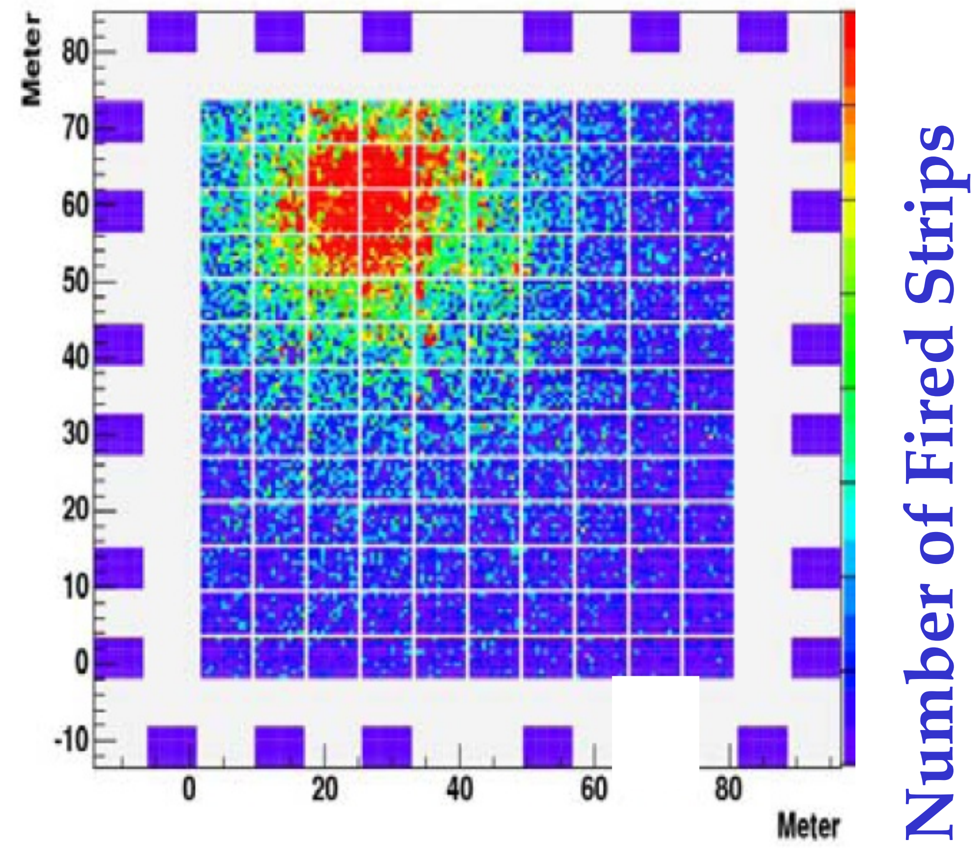
❖ FULL COVERAGE
(RPC technology, 92% covering factor)

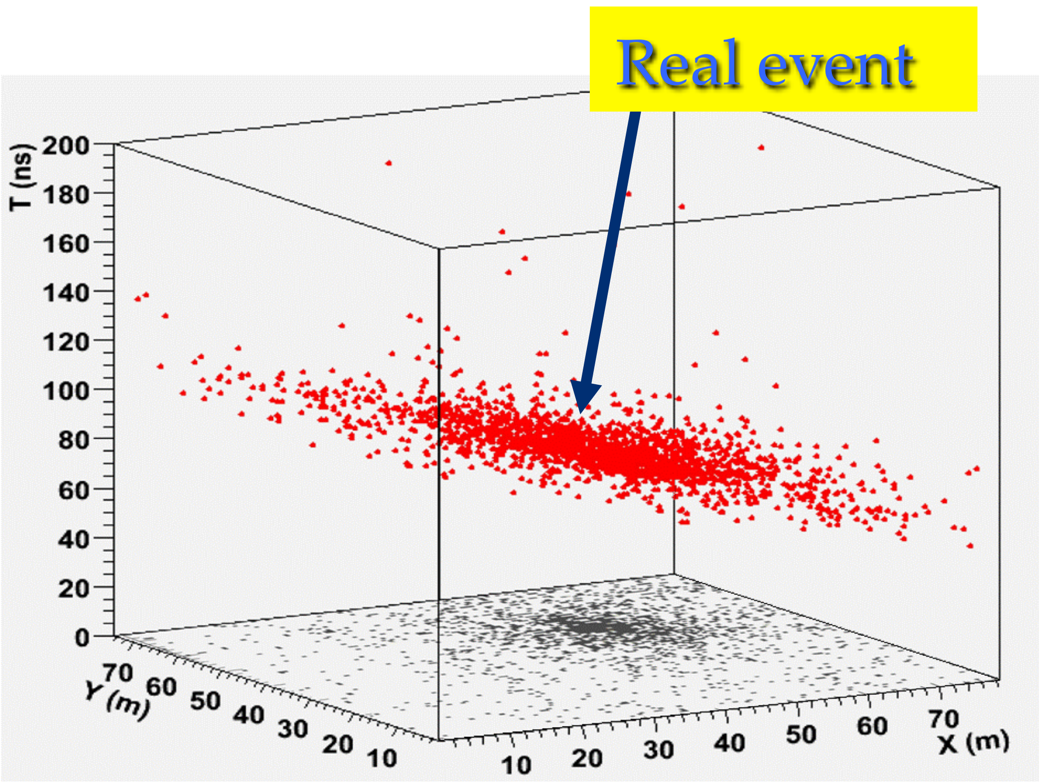
❖ HIGH SEGMENTATION OF THE READOUT
(small space-time pixels)

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



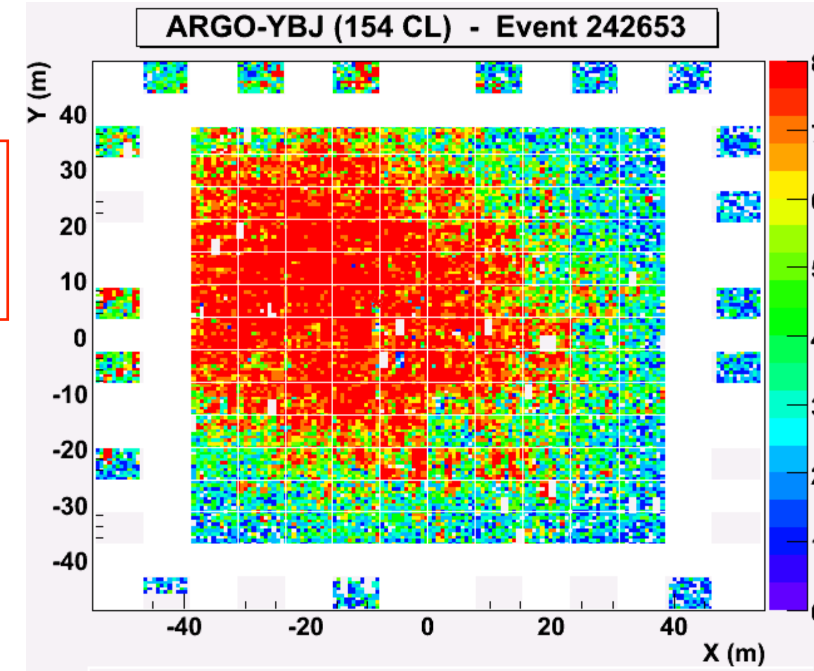


The basic concepts

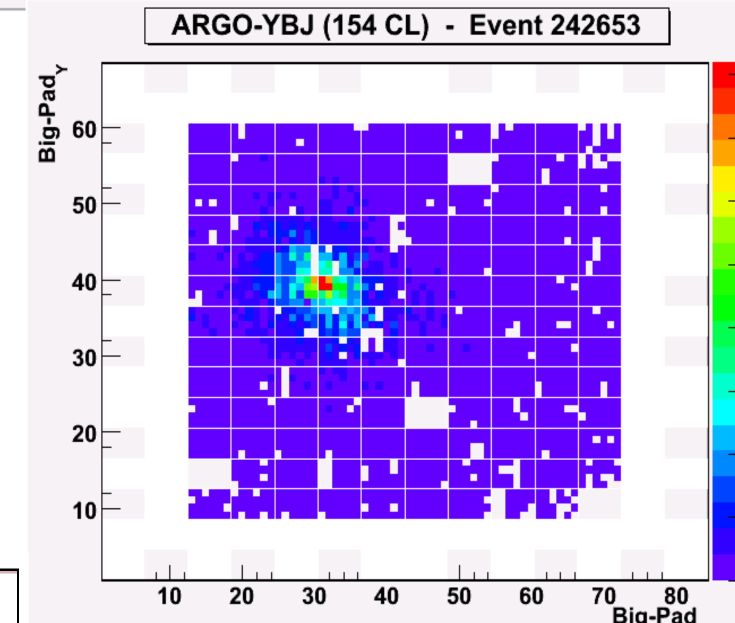
...extending the dynamical range up to PeV

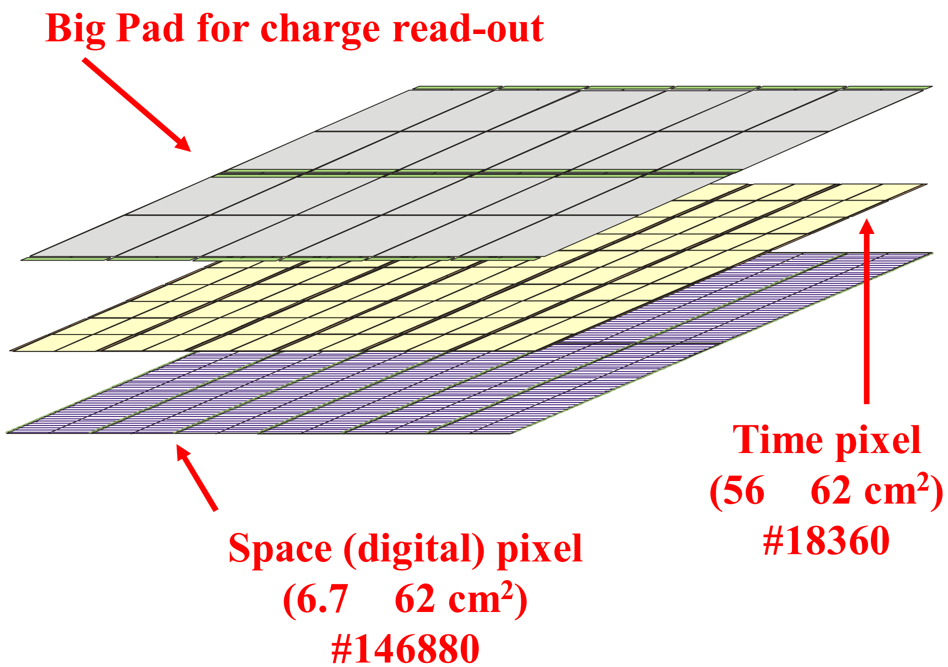
❖ ANALOG READOUT → PeV
(3672 1.40 × 1.25 m^2 “big pads”)

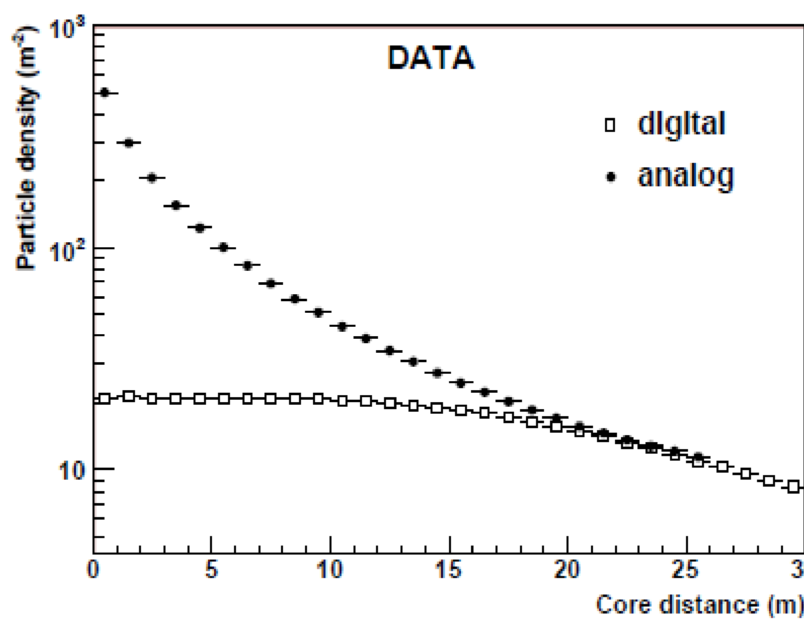
Strips (digital)

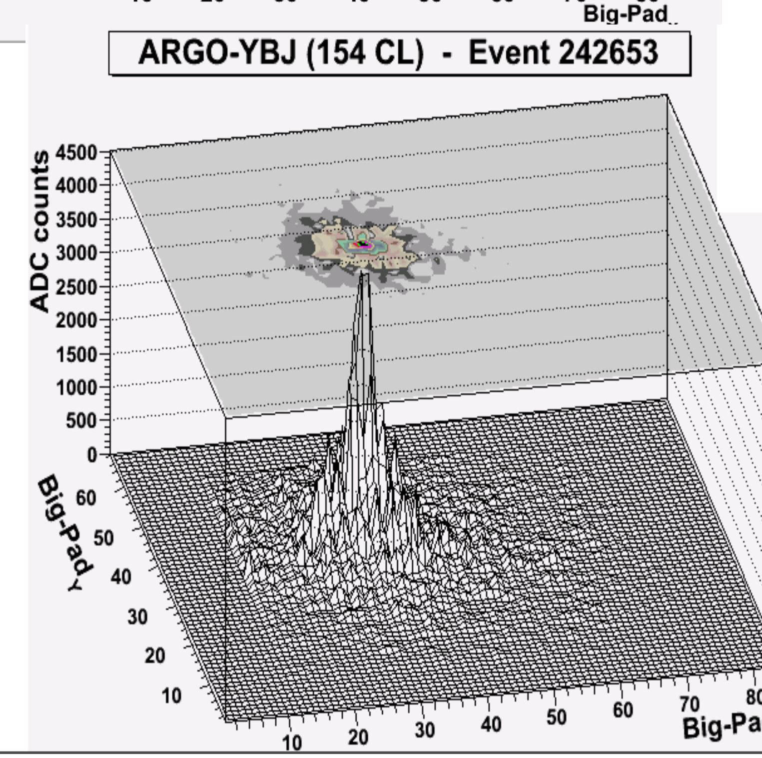


Big Pads (analog)





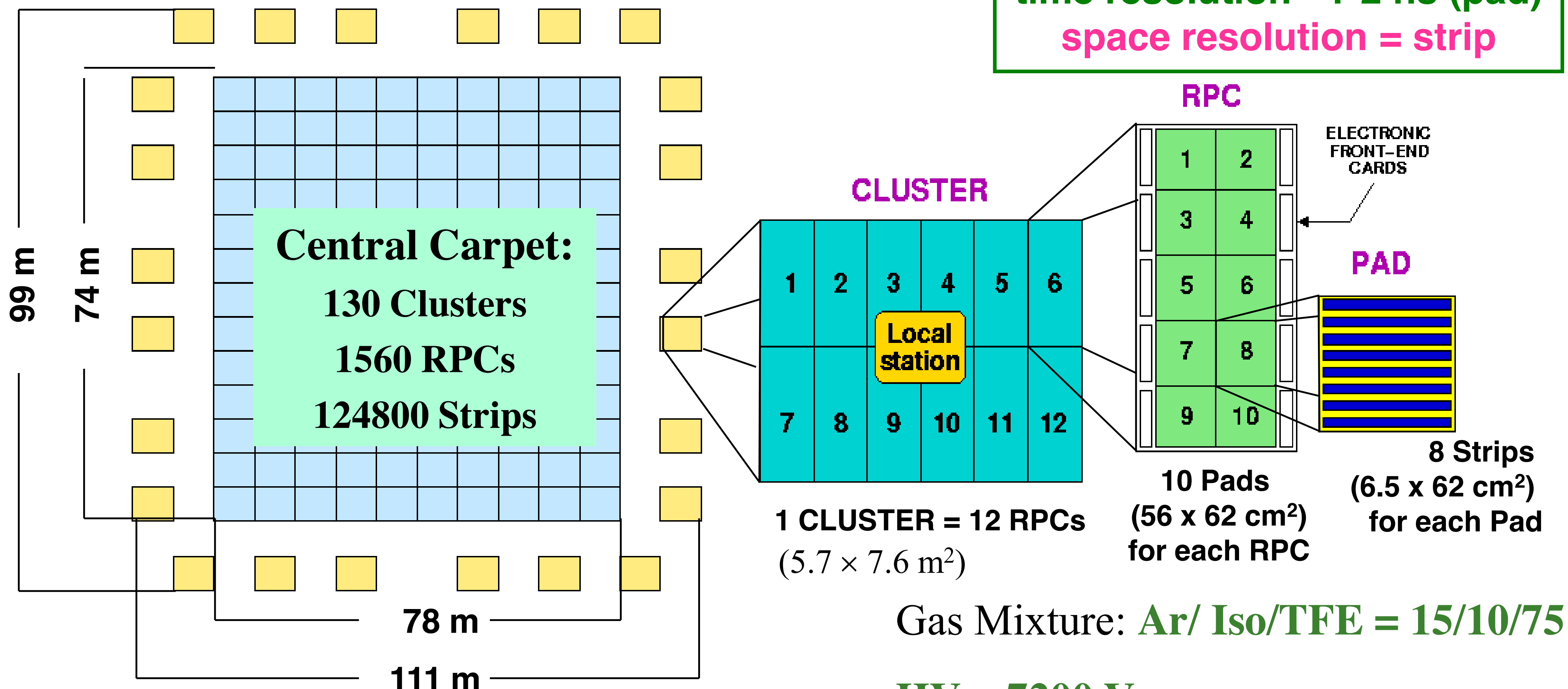




- Extend the covered energy range
- Access the LDF down to the shower core
- Sensitivity to primary mass
- Info/checks on Hadronic Interactions

The ARGO-YBJ layout

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



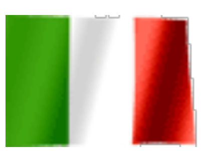
Gas Mixture: **Ar/ Iso/TFE = 15/10/75**

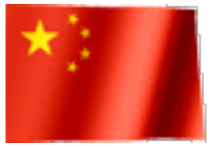
HV = 7200 V

Single layer of Resistive Plate Chambers (RPCs)
with a full coverage (92% active surface) of a large area (5600 m^2)
+ sampling guard ring (6700 m^2 in total)

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

The birth of an idea

Detection of small size air showers at high altitude: the expected performances of an RPC's carpet

B. D'Ettorre Piazzoli[(1)], G. Di Sciascio[(1)], E. Pompei[(2)], A. Surdo[(3)]

Experimental set-up

An RPC's carpet of $120 \times 120\ m^2$ has been considered with a 95% active area. Moreover a 95% efficiency has been take into account. Each RPC ($1 \times 2\ m^2$) is equipped with a read-out system of 3 cm wide, 50 cm long strips. Signals from the strips are OR-ed in order to get the time of the first particle hitting each $50 \times 50\ cm^2$ 'pad'. This time is smeared out with the detector response and assigned

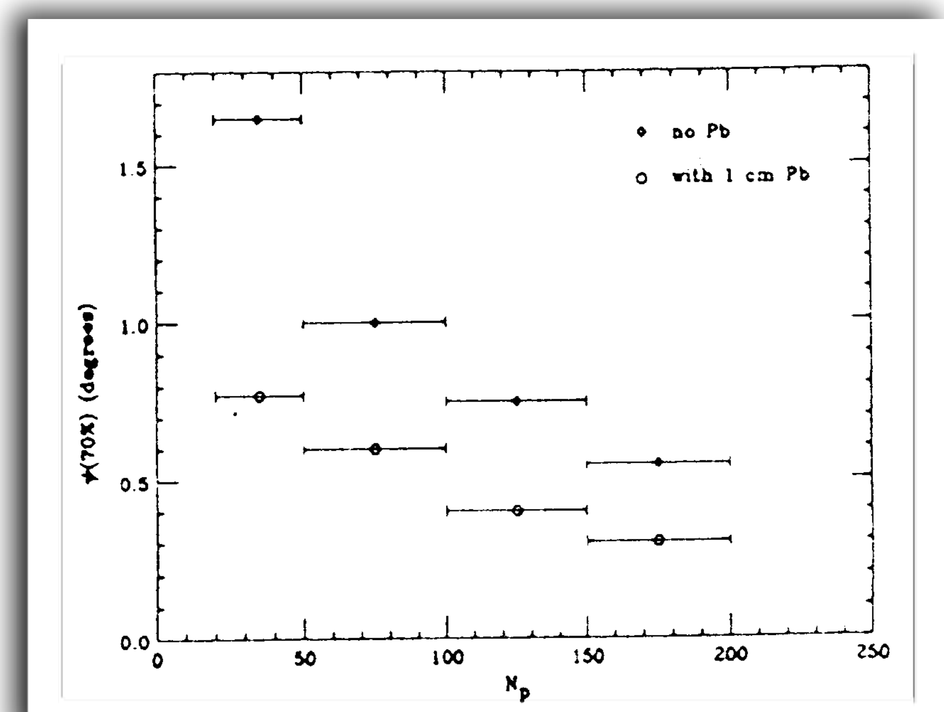
Conclusions

Preliminary calculations indicate that an RPC's carpet operating at high altitude could achieve excellent performances in detecting air showers initiated by photons of energy $\geq 300 GeV$. At this energy the minimum detectable integral flux at 4σ level in 1 yr of data taking is expected to be about $6 \cdot 10^{-11} \cdot \left(\frac{\psi(70\%)}{0.6^0}\right) \cdot \frac{1}{Q}\ cm^{-2} s^{-1}$, comparable to fluxes expected from extragalactic sources. Here Q is a rejection factor resulting

THE FIRST
INTERNATIONAL SYMPOSIUM
ON COSMIC RAY PHYSICS
IN TIBET

August 12—17, 1994 LHASA, CHINA

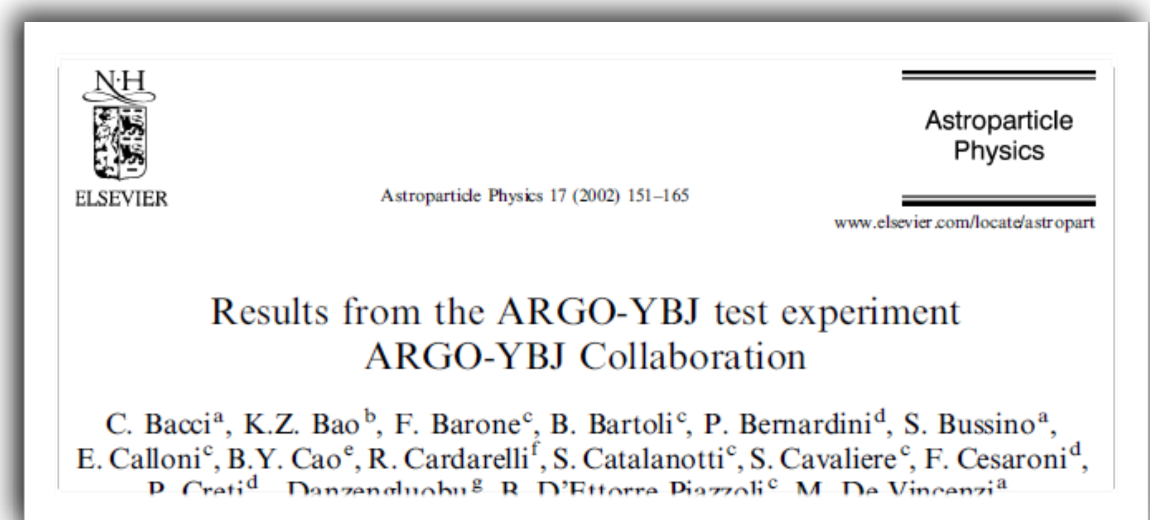
HAWC: ≈ $140 \times 140\ m^2$



The main stages

- ARGO proposal (1996)
- Approval of a successfull test in Tibet (ARGO-TEST, 1997-1998)
- Approval of the ARGO-YBJ experiment (1999)
- Inauguration of the ARGO-YBJ laboratory (June 2001)
- Central carpet in data taking (2006)
- Full layout in stable data taking (2007)

- End/Stop data taking: January 2013



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Astroparticle Physics 17 (2002) 151–165

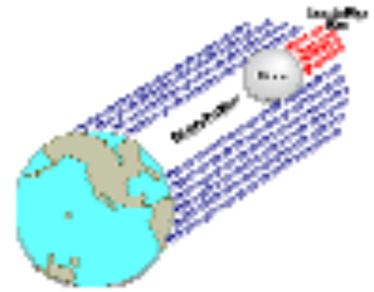
Astroparticle Physics

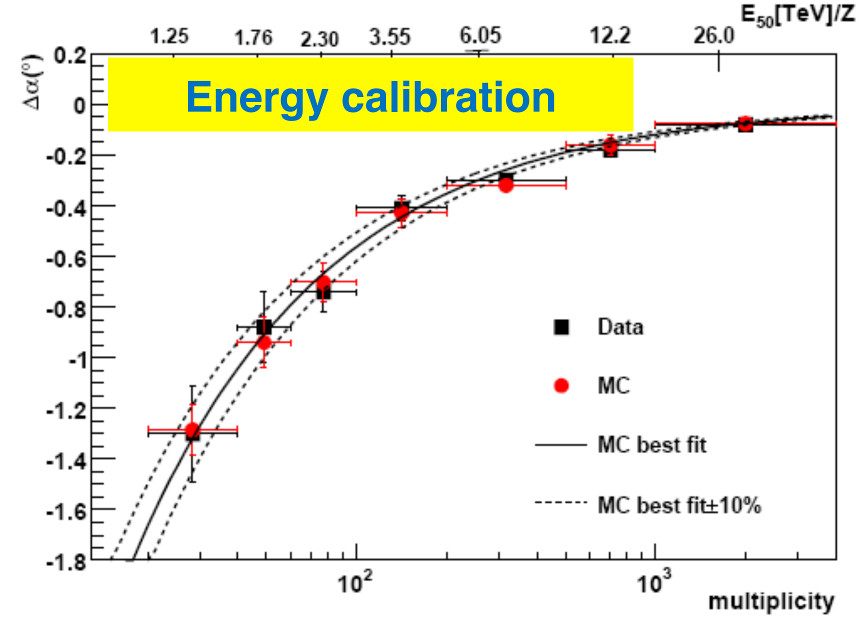
www.elsevier.com/locate/astropart

Results from the ARGO-YBJ test experiment
ARGO-YBJ Collaboration

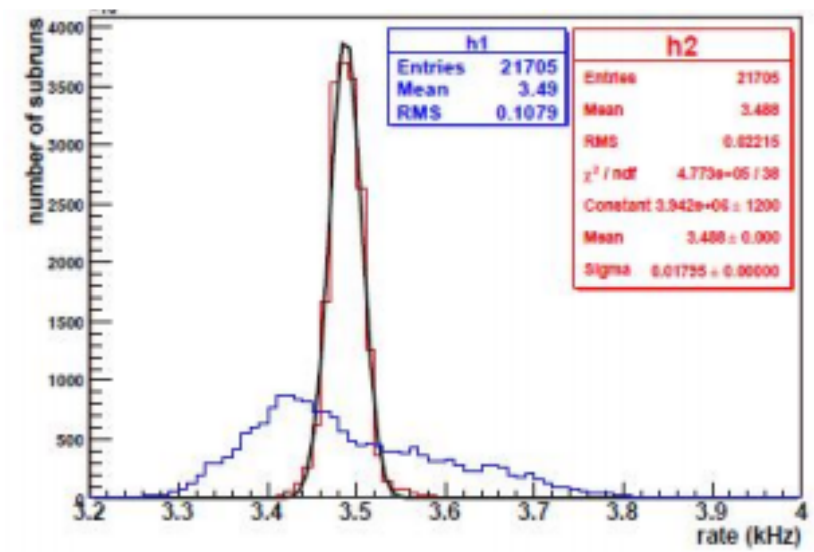
C. Bacci[a], K.Z. Bao[b], F. Barone[c], B. Bartoli[c], P. Bernardini[d], S. Bussino[a], E. Calloni[c], B.Y. Cao[e], R. Cardarelli[f], S. Catalanotti[c], S. Cavaliere[c], F. Cesaroni[d], P. Creti[d], Danzengluobu[g], B. D'Ettorre Piazzoli[c], M. De Vincenzi[a]

Status and performance

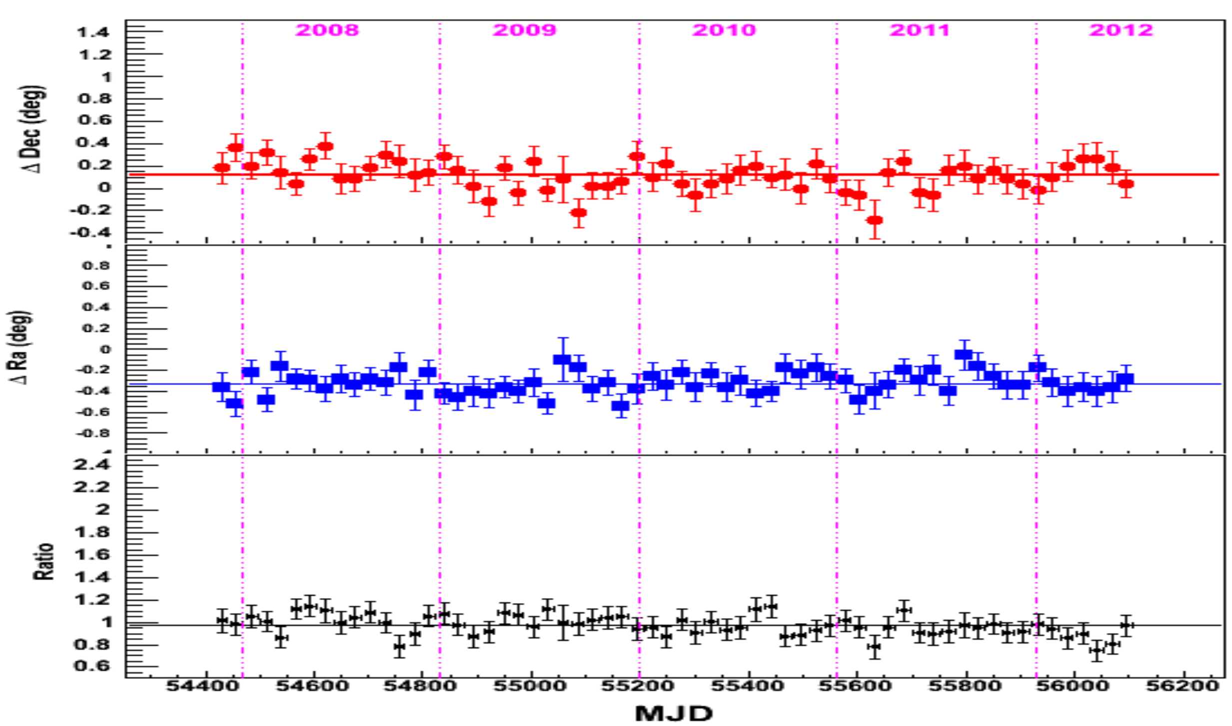


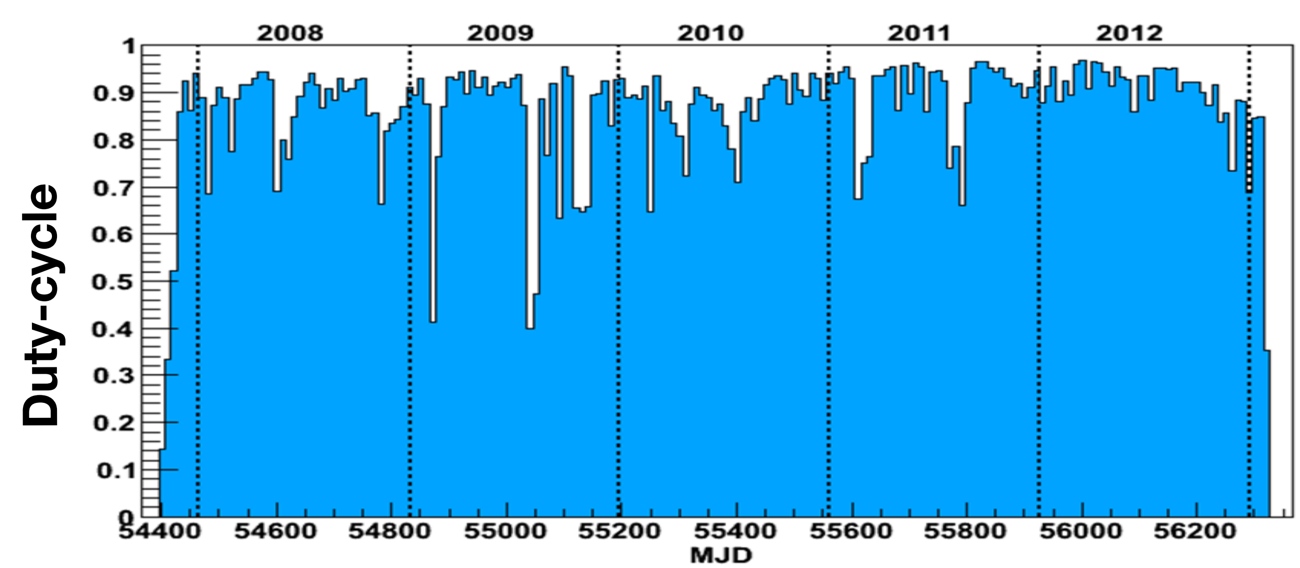


- In observation since July 2006 (commissioning phase)
- Stable data taking since November 2007
- End/Stop data taking: January 2013
- Average duty cycle ~87%
- Trigger rate ~3.5 kHz @ 20 pad threshold
- N. recorded events: ≈ $5 \cdot 10^{11}$ from 100 GeV to PeV
- 100 TB/year data



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

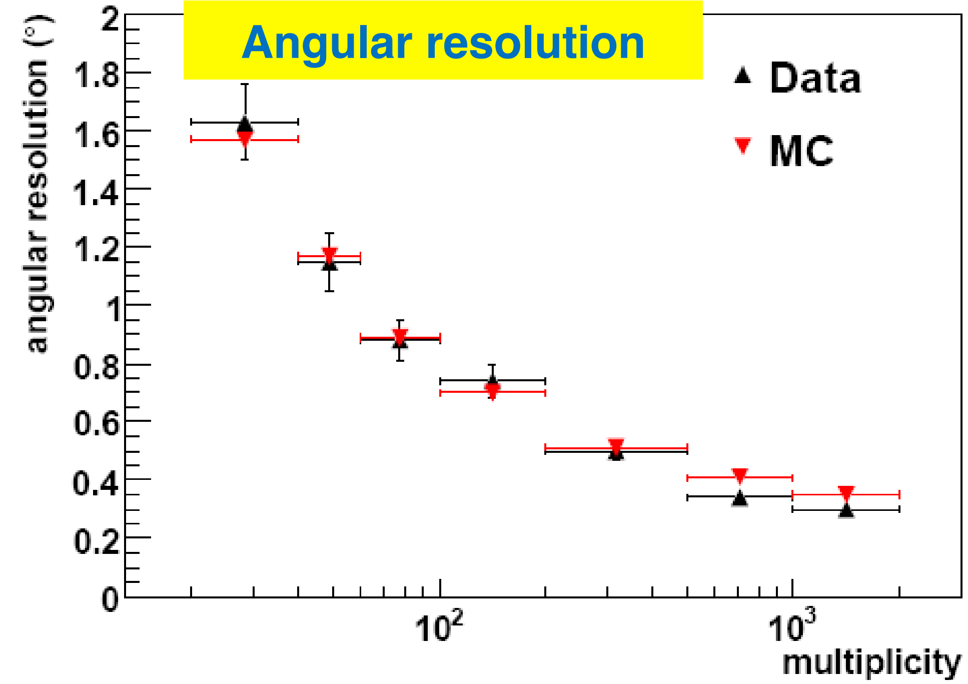


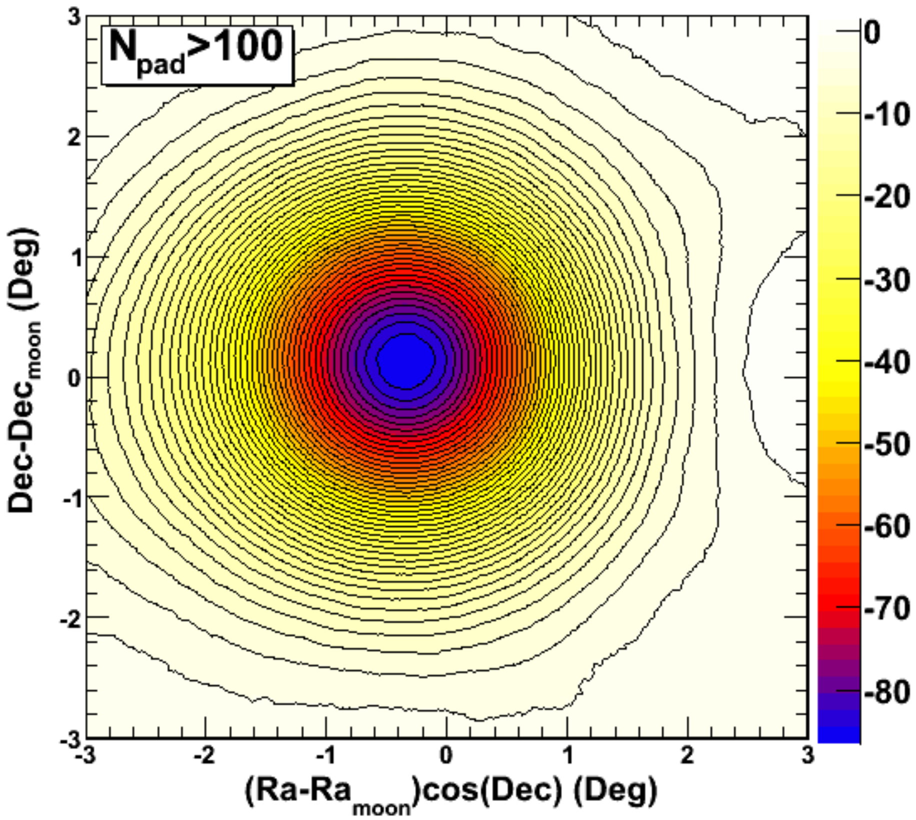


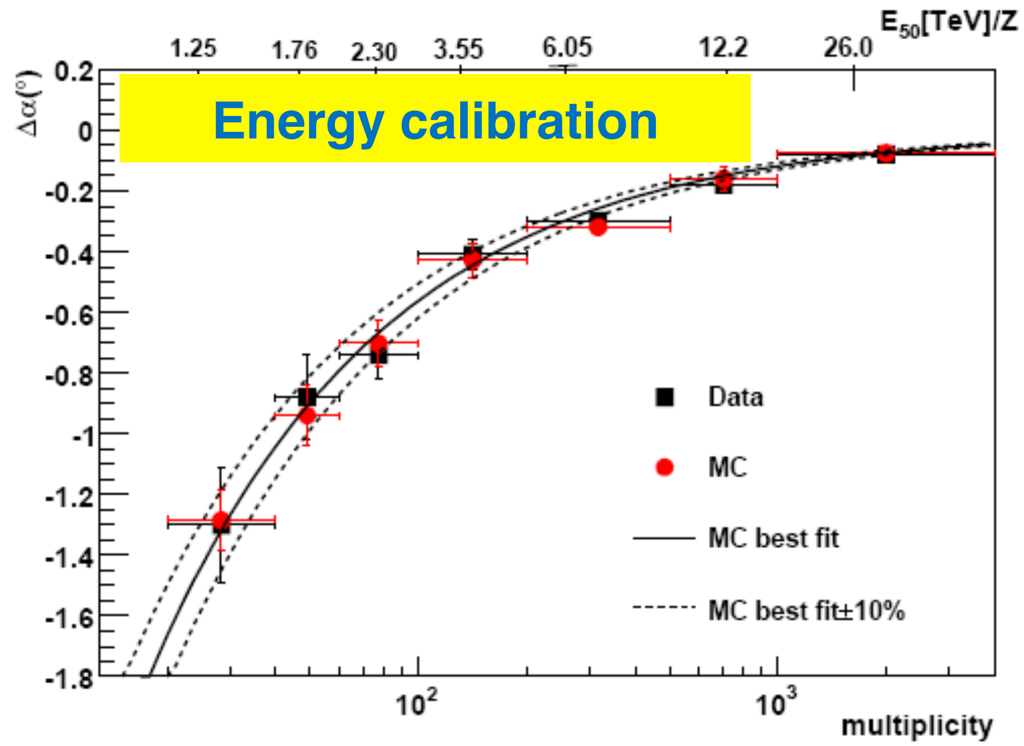
The *Moon shadow* analysis

★ 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).

Questions to the knee energy range

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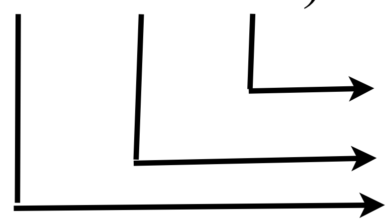
Cosmic Rays and γ-Ray Astronomy connection

★ Hadro-production (CR sources)

$$p + p/\gamma \Rightarrow n\ (\pi^{+} + \pi^{-} + \pi^{0}) + h$$



γ **Gamma-Ray Astronomy**

ν **Neutrino Astronomy**

CRs, photons and neutrinos strongly correlated

ONLY charged CRs observed at E > 10^{14} eV so far !

Recent observations of PeV neutrinos by Icecube

★ Electro-production (Inverse Compton)

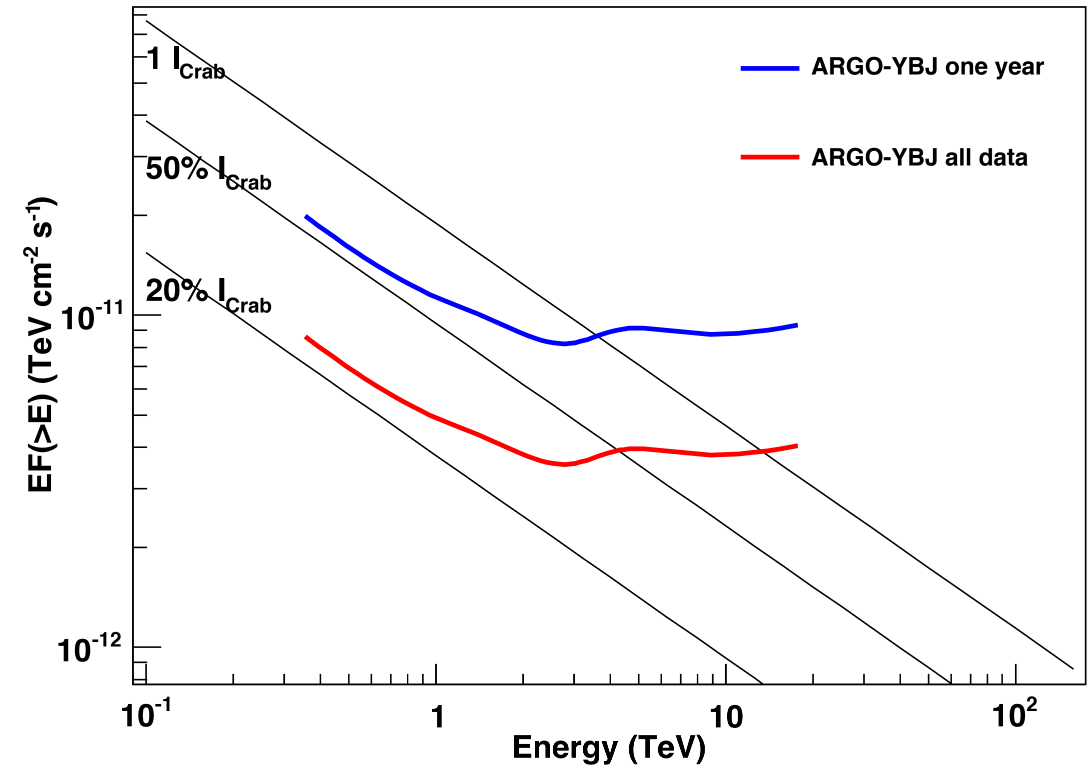
$$e + \gamma \Rightarrow e' + \gamma'$$

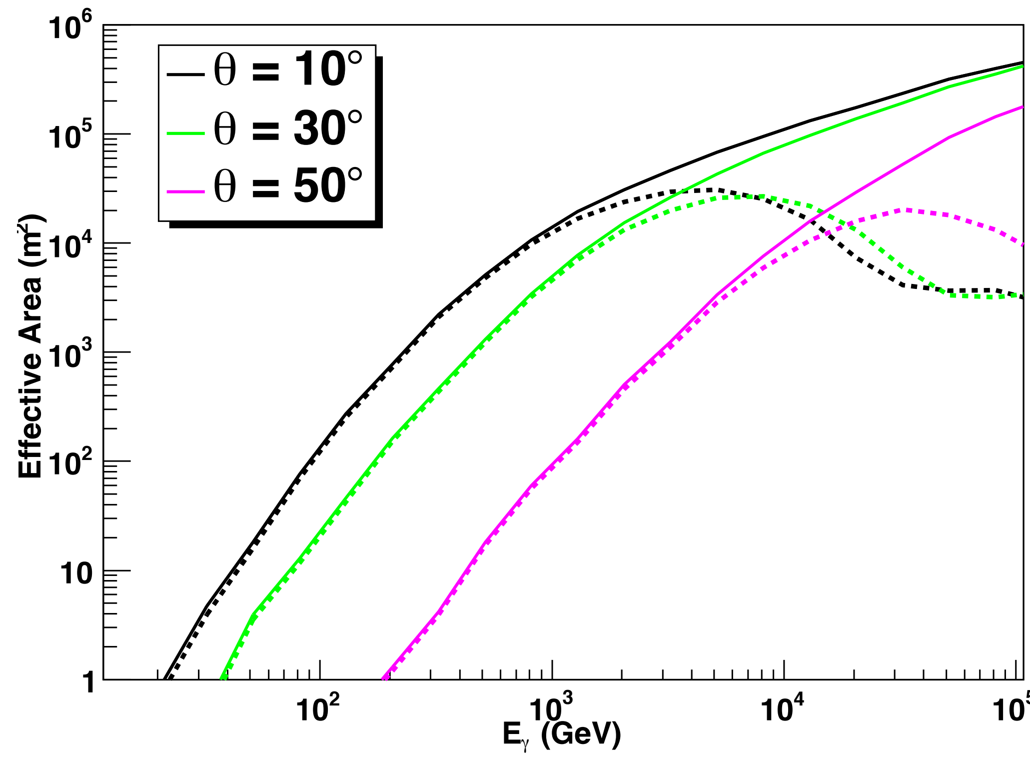
SSC model: photons radiated by high energy (10^{15} eV) electrons boosted by the same electrons

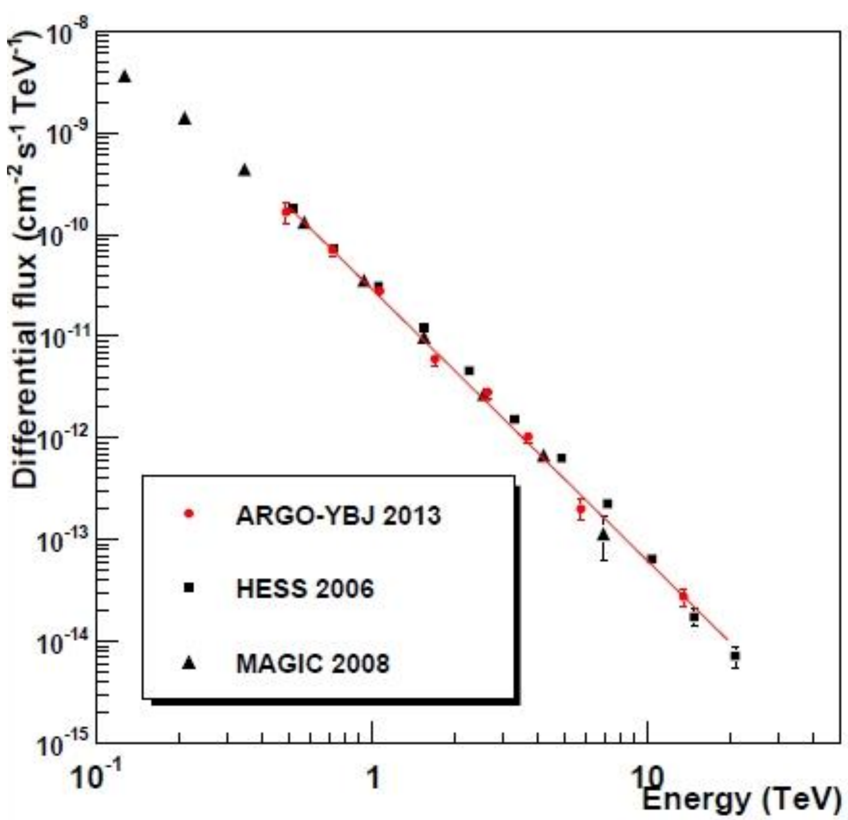
Gammas (and neutrinos) point back to their sources (SNR, PWN, BS, AGN ..)

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°







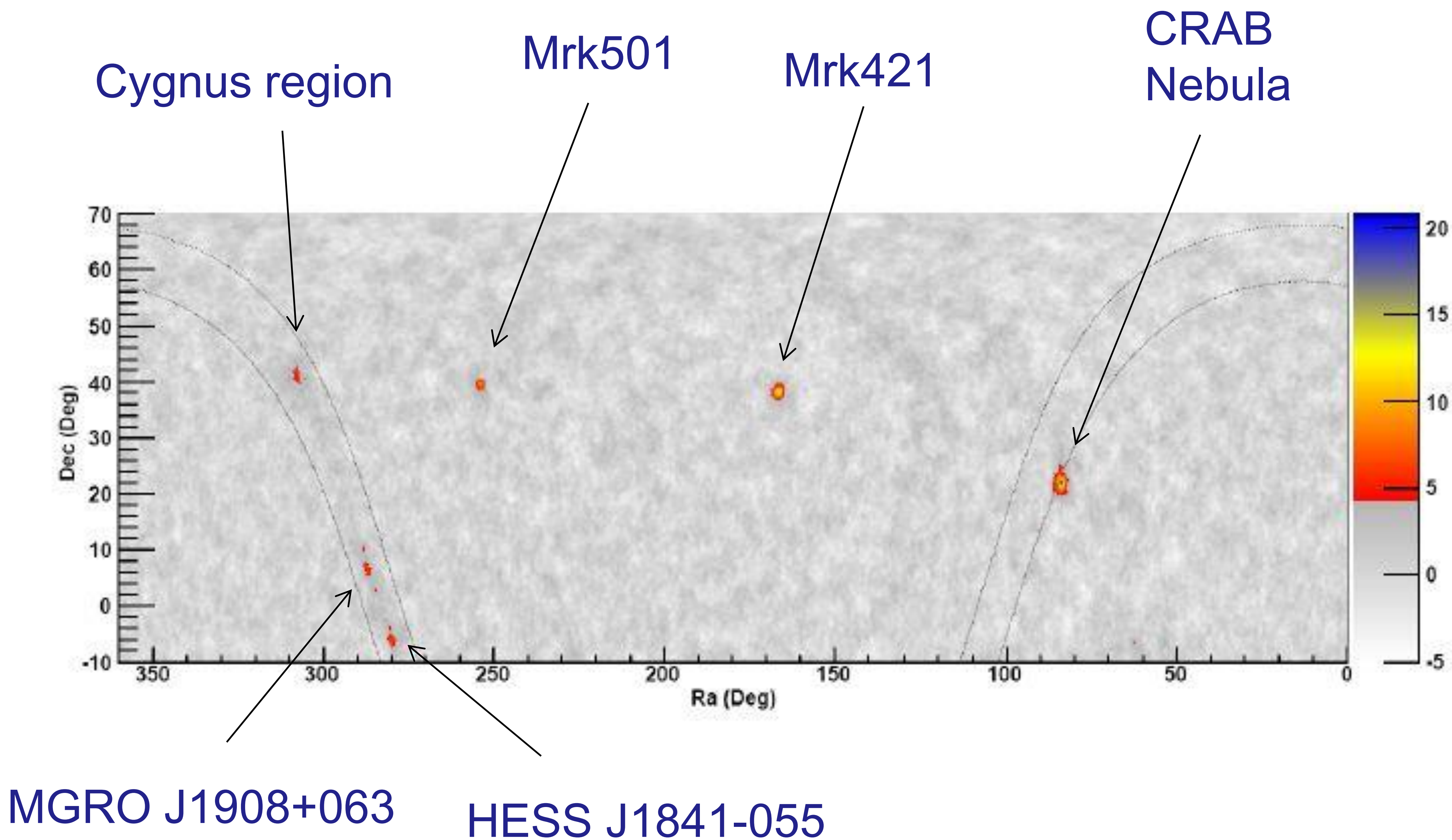
Crab Nebula 5 years data

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

(0.5 – 10) TeV

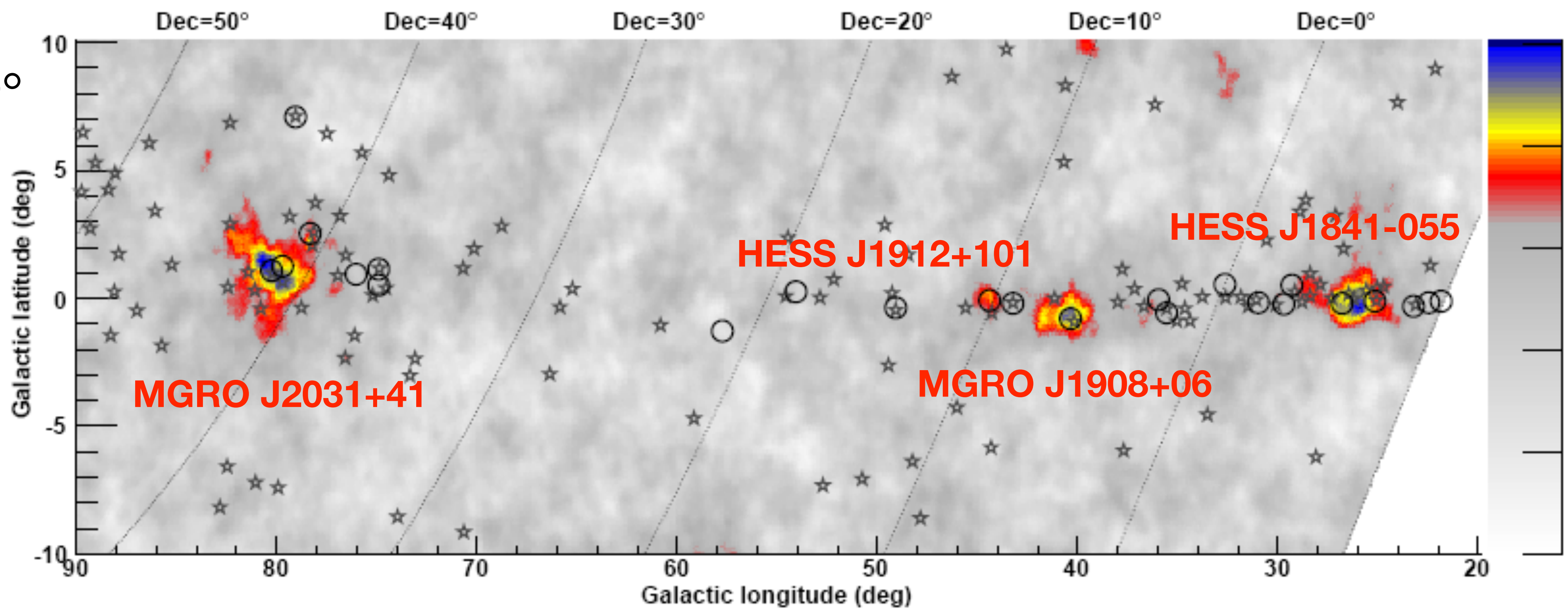
ARGO-YBJ Sky Survey at 1 TeV

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

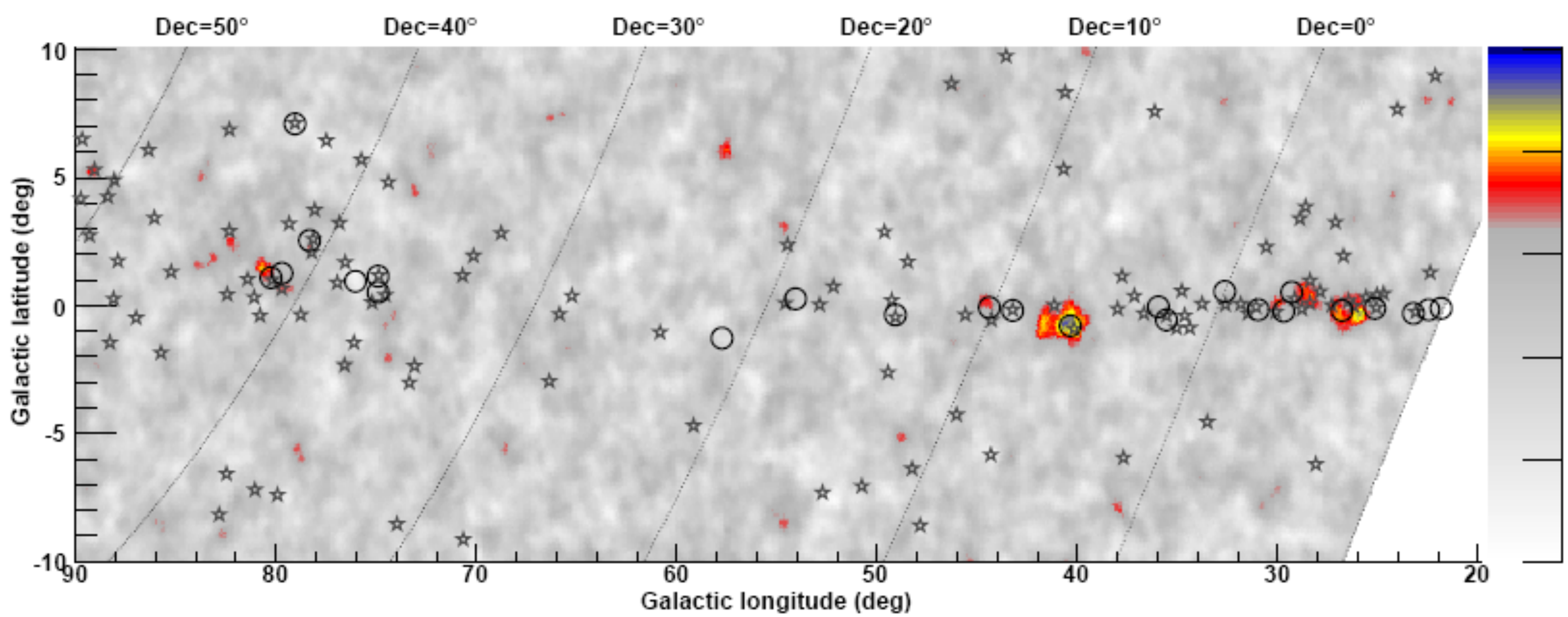


ARGO-YBJ 5-years Survey of Inner Galactic Plane

$20^\circ < l < 90^\circ, |b| < 10^\circ$



$E_{50} \approx 0.7$ TeV



$E_{50} \approx 1.8$ TeV

Detected Sources

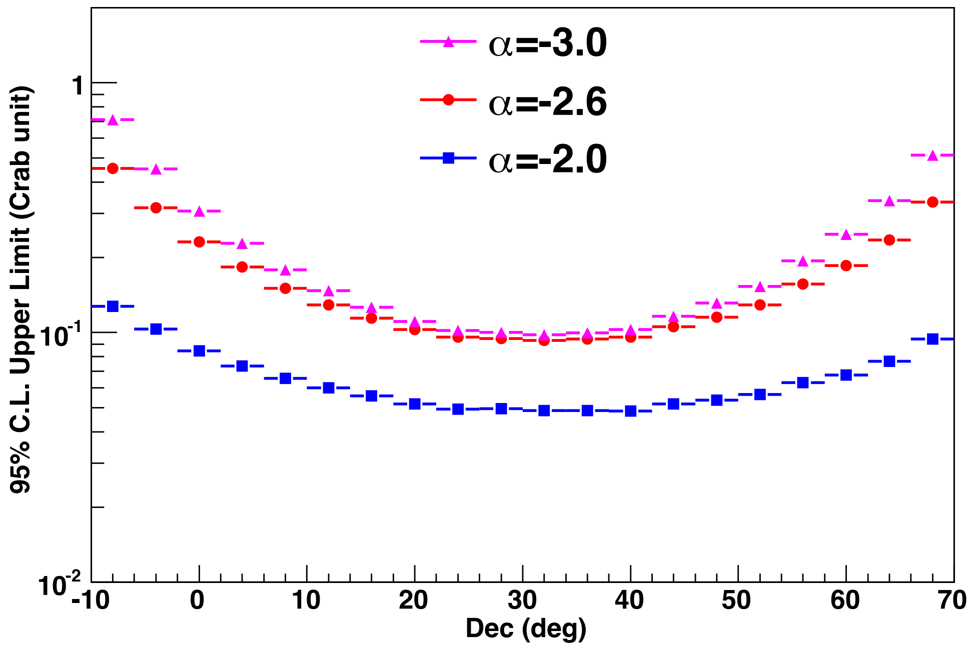


Fig. 4: Average 95% C.L. flux upper limit at energy above 500 GeV, averaged on the right ascension direction, as a function of declinations. Different curves indicate sources with different power-law spectral indices −2.0, −2.6 and −3.0. The Crab unit is 5.77×10^{-11} cm^{-2} s^{-1} .

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 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

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

The Cygnus Region

Very important region populated by many unidentified strong sources

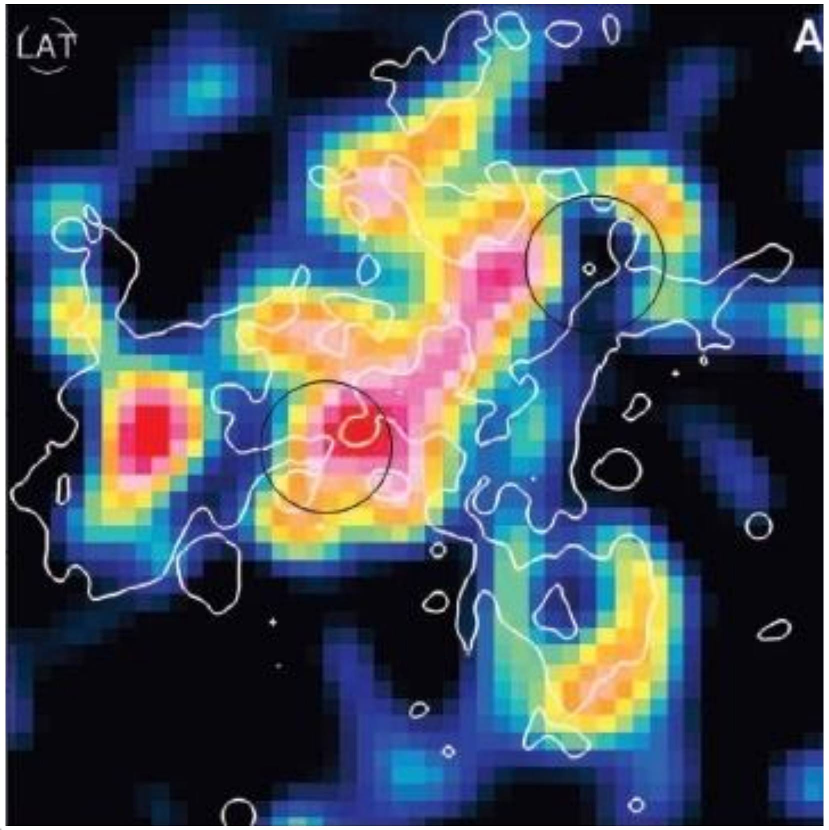
- The brightest diffuse γ-rays source in the northern hemisphere
- 9 supernova remnants
- >20 Wolf-Rayet starts
- 6 OB associations
- shocked gas

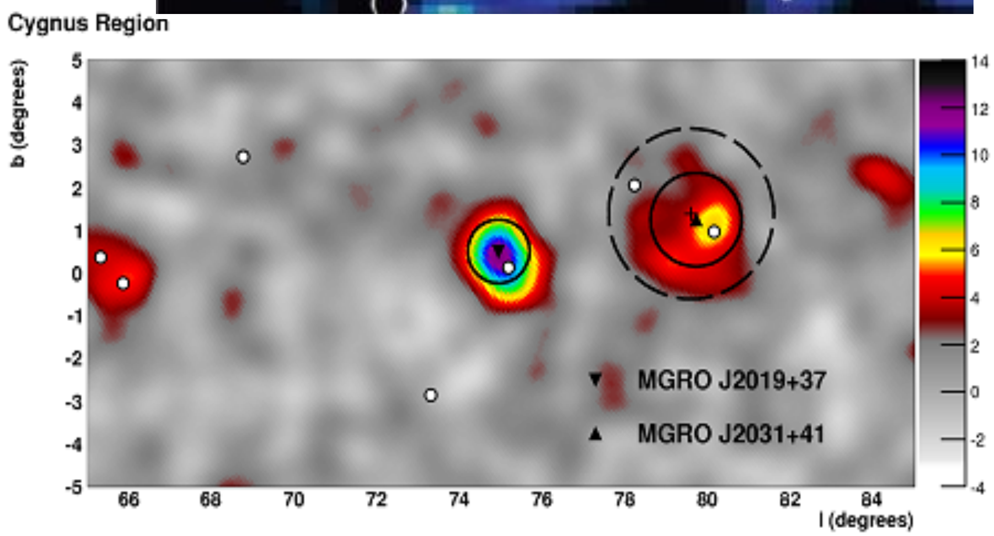
Natural site for cosmic-ray acceleration

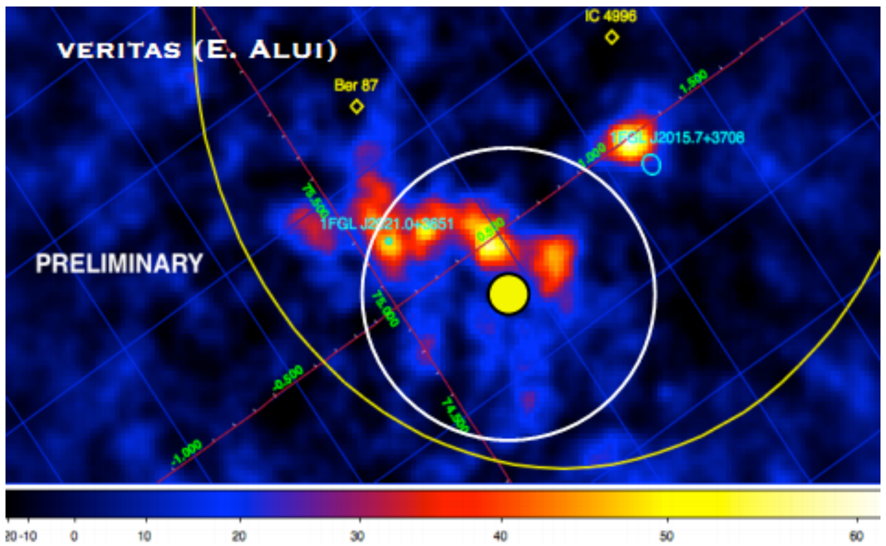
★ Fermi data (1-100 GeV):
A cocoon of freshly accelerated CRs ?

★ Milagro detected 2 sources at 20 TeV
✓ MGRO J2019+37 (12.4 σ)
✓ MGRO J2031+41 (7.6 σ)
Both consistent with Fermi source locations

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

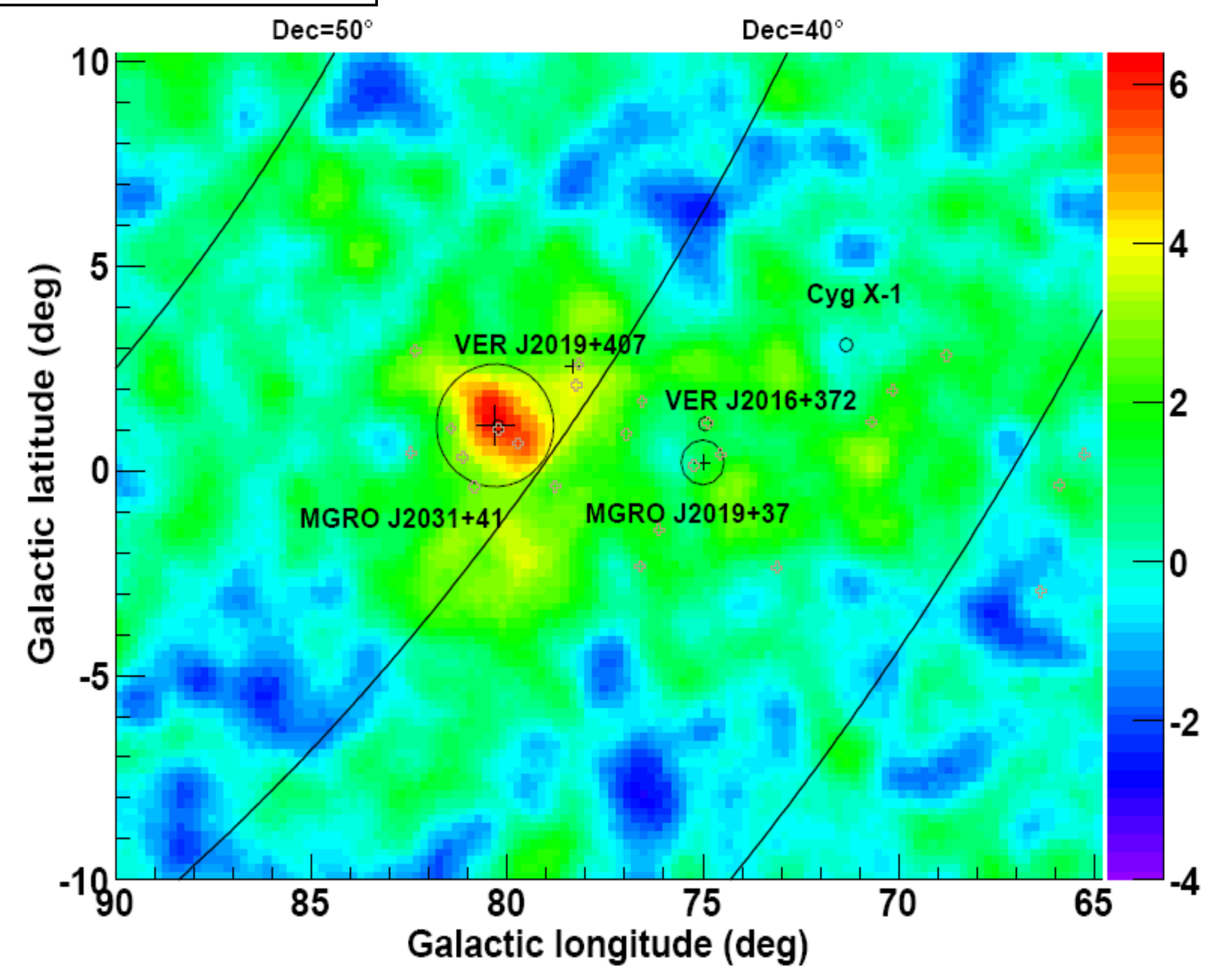


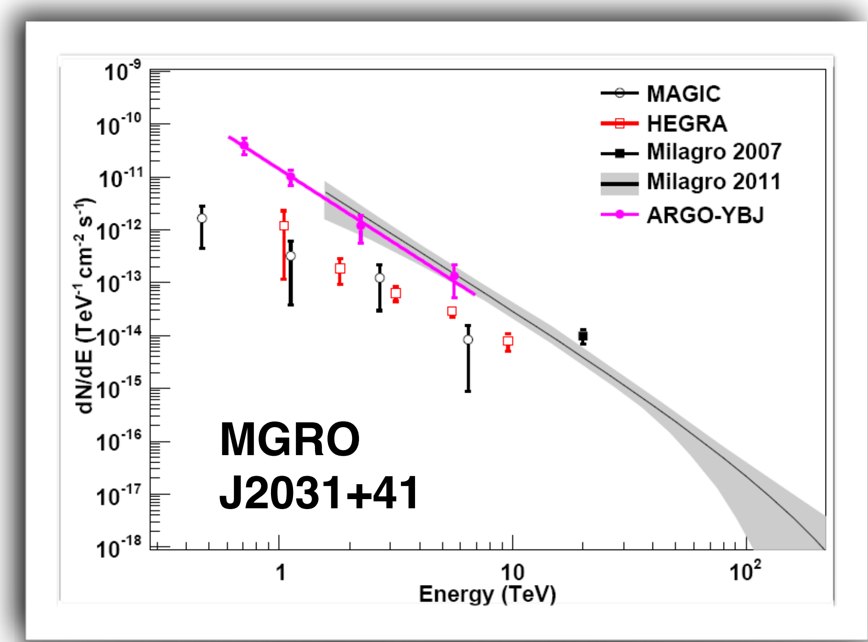


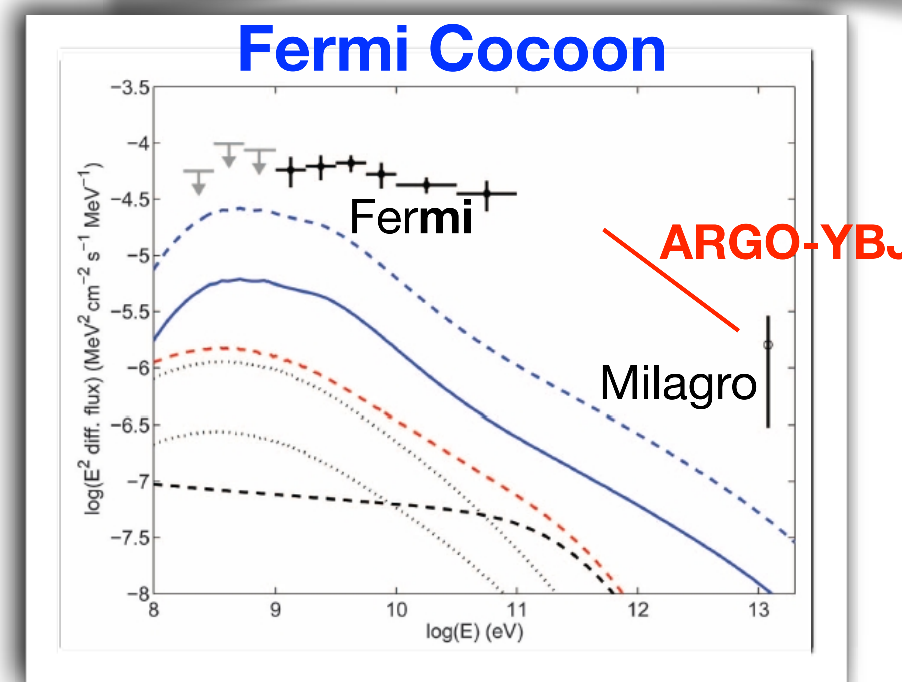


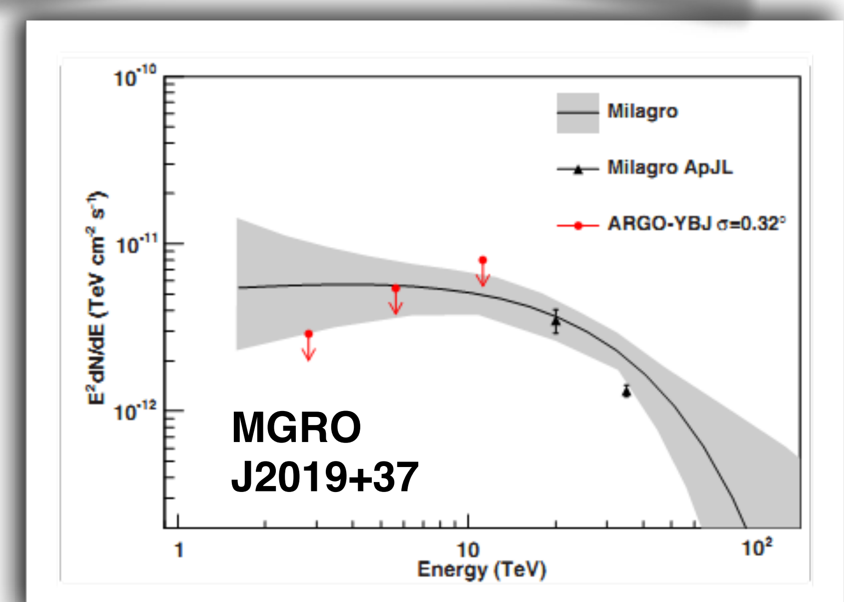
The Cygnus Region by ARGO-YBJ

ApJL 745 (2012) L22







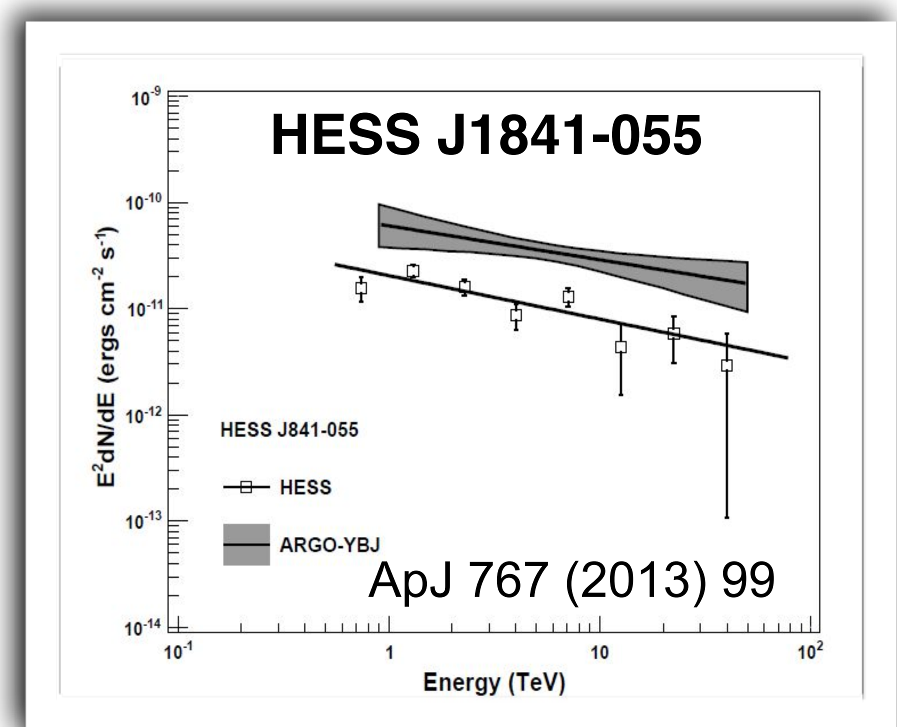


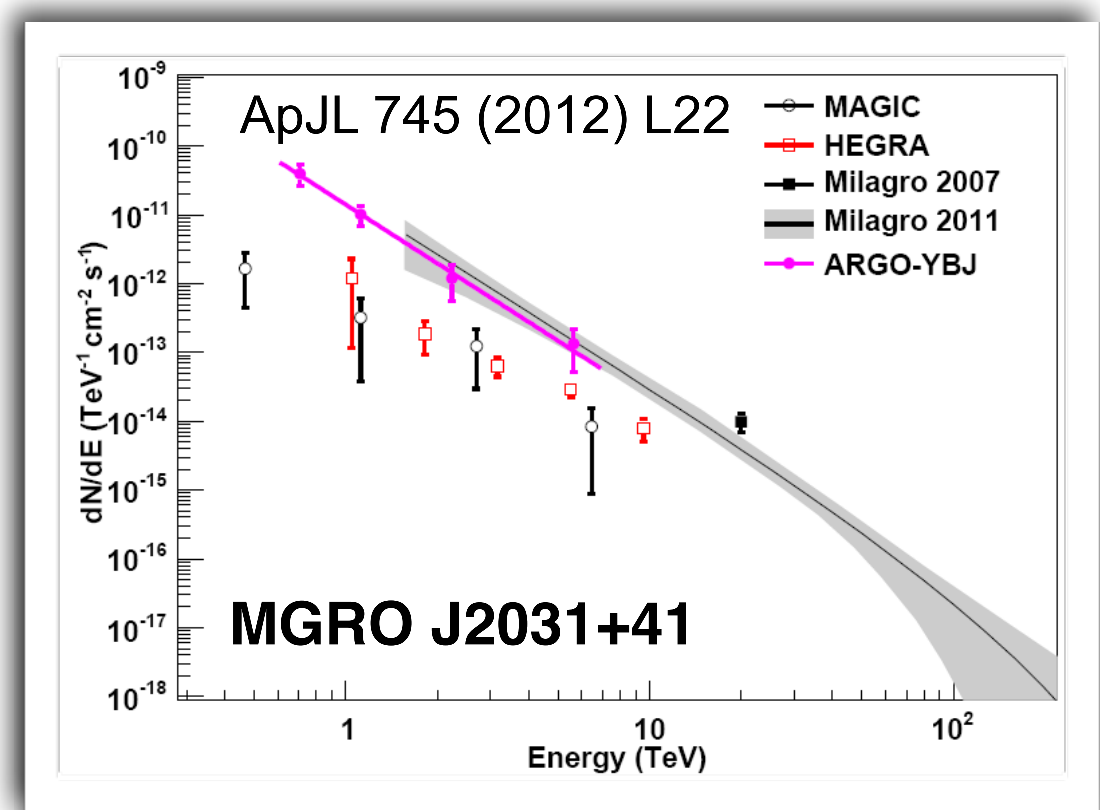
NO signal from the MGRO J2019+37 below 10 TeV

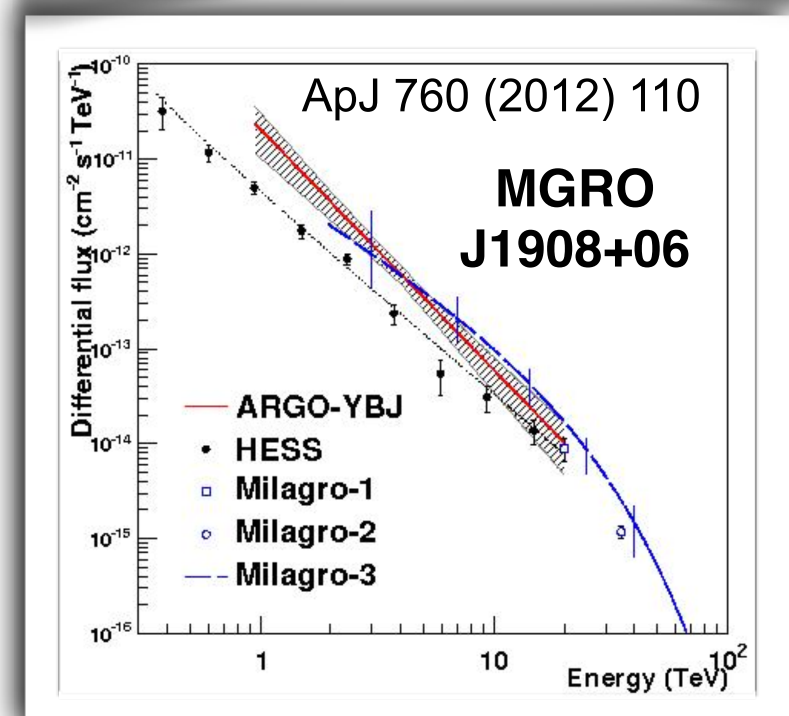
- ✓ Insufficient exposure above 5 TeV ?
- ✓ Variability ?

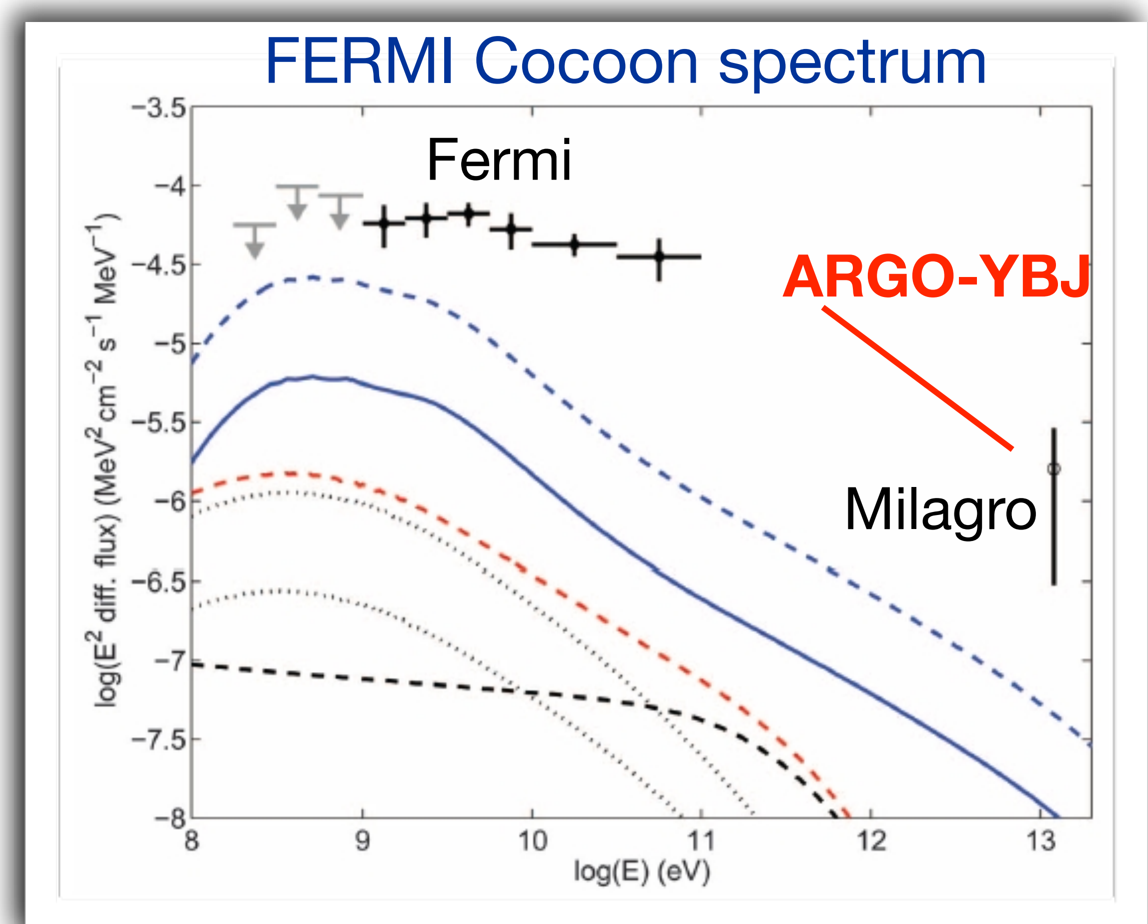
G. Di Sciascio, Meeting INFN/IHEP, LNGS Italy, Sept. 16-17, 2013

Observation of extended sources with ARGO-YBJ





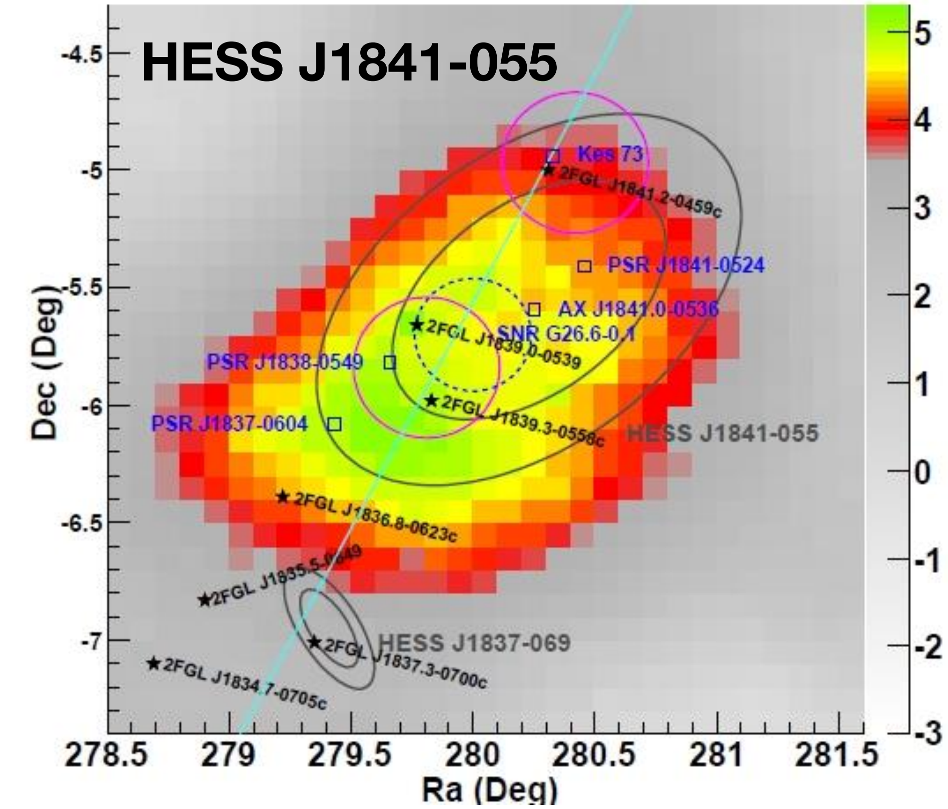




Measured extensions consistent with IACTs

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

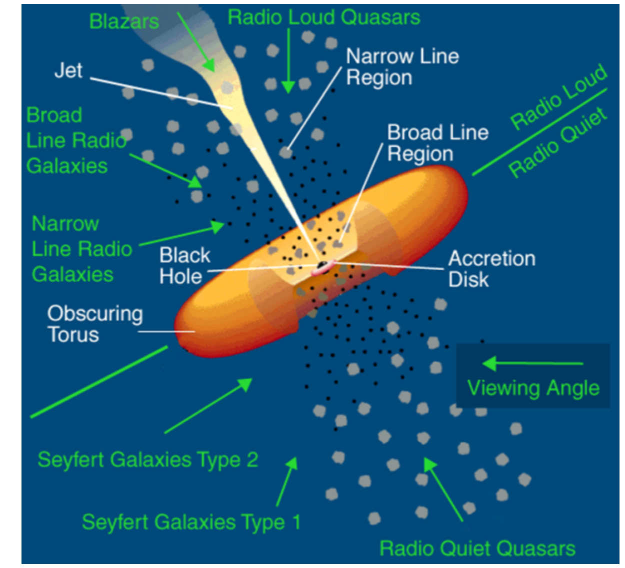
Possible systematics in ARGO-YBJ

- 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%

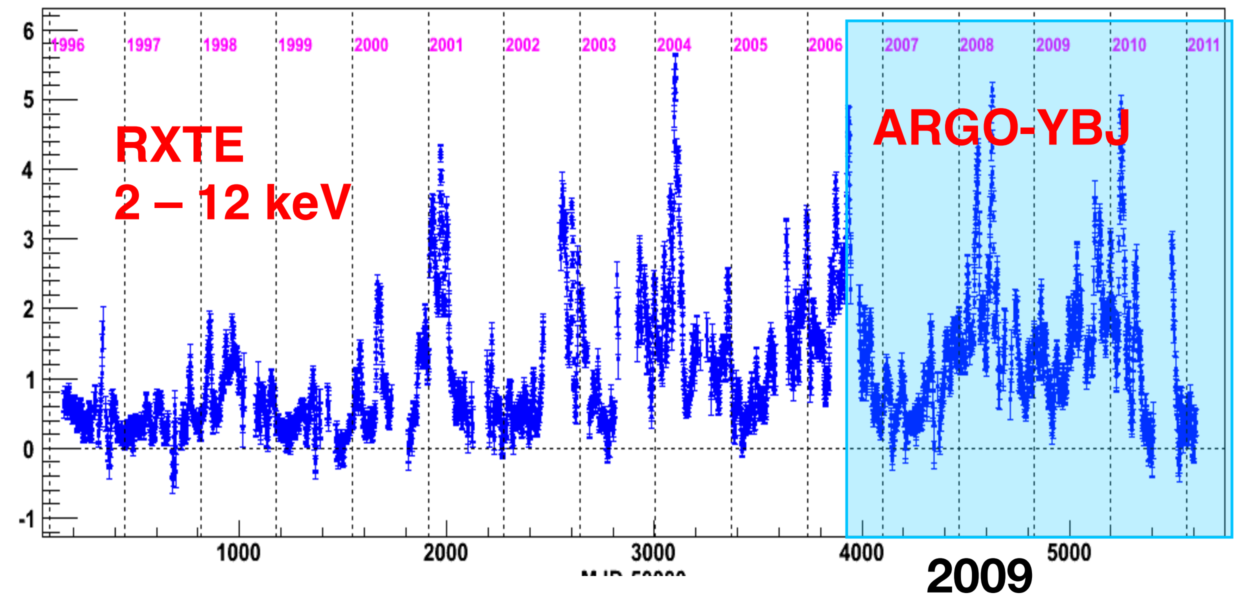
Overall systematics on the flux < 30%

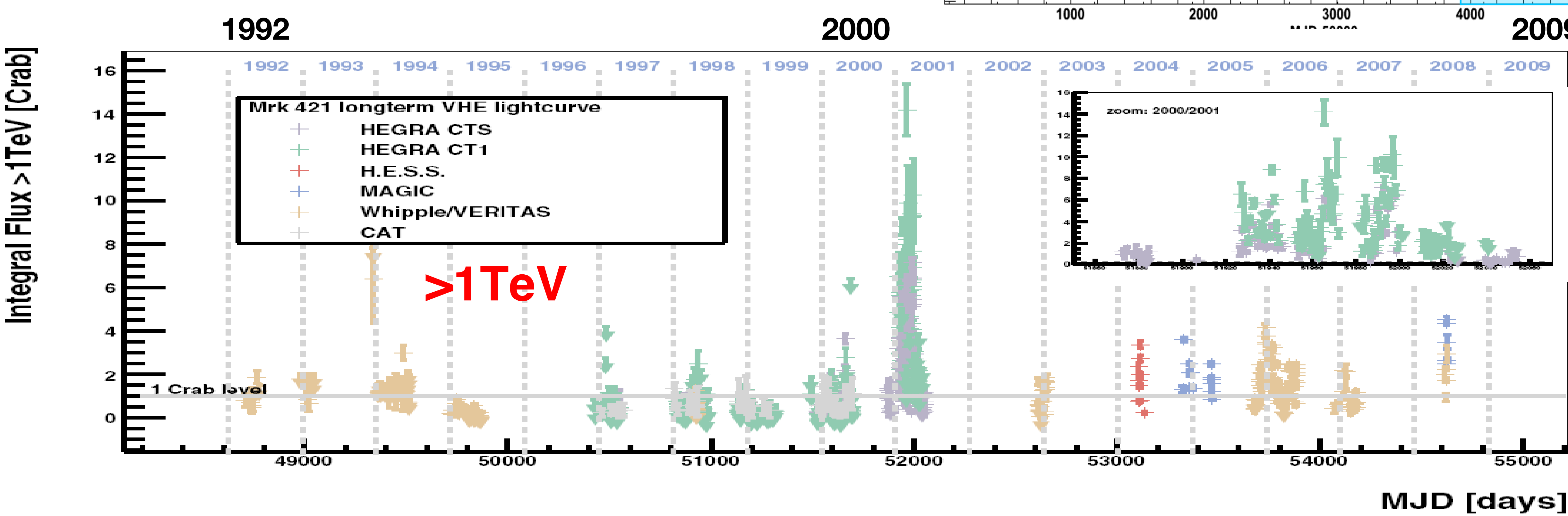
★The discrepancy could origin from the different techniques used in the background estimation for extended sources.
★Maybe the extended excess is due to the contribution of different sources

The flaring sky: AGN variability



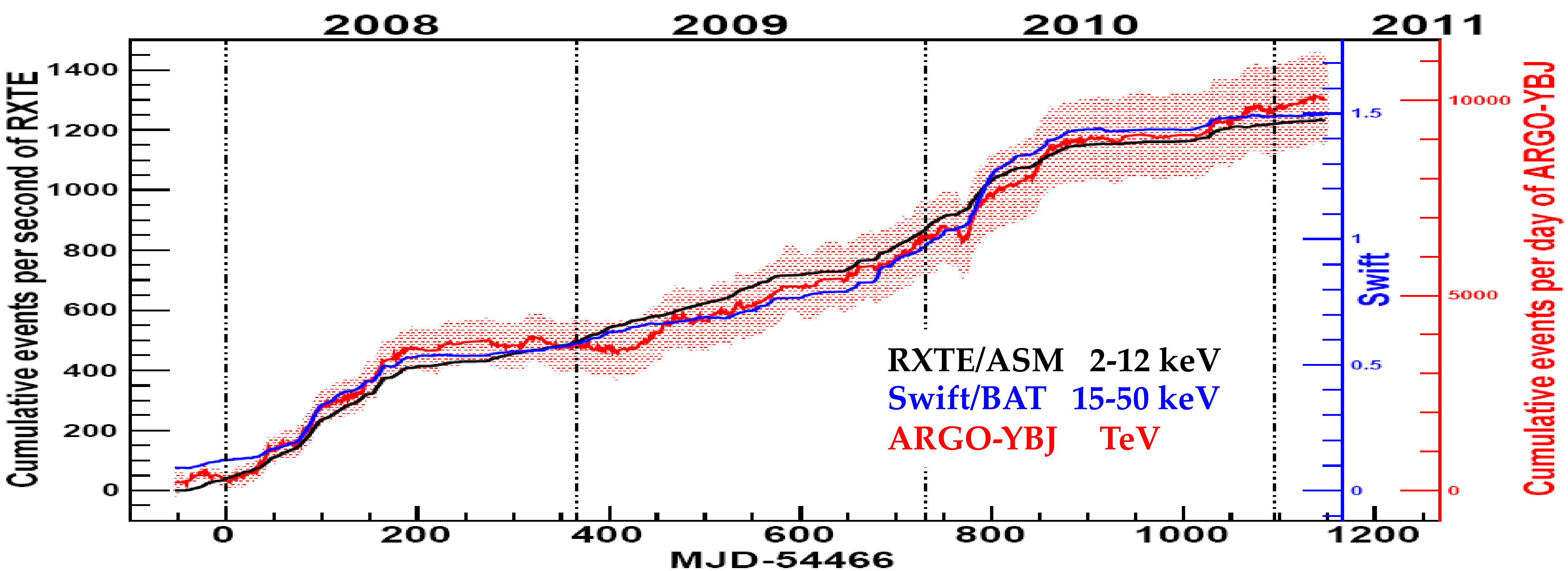
- **AGNs are characterized by a strong flaring activity both in X-rays and in TeV γ–rays.**
- **Lack of continuous long-term monitoring at VHE.**





Mrk421 long-term monitoring

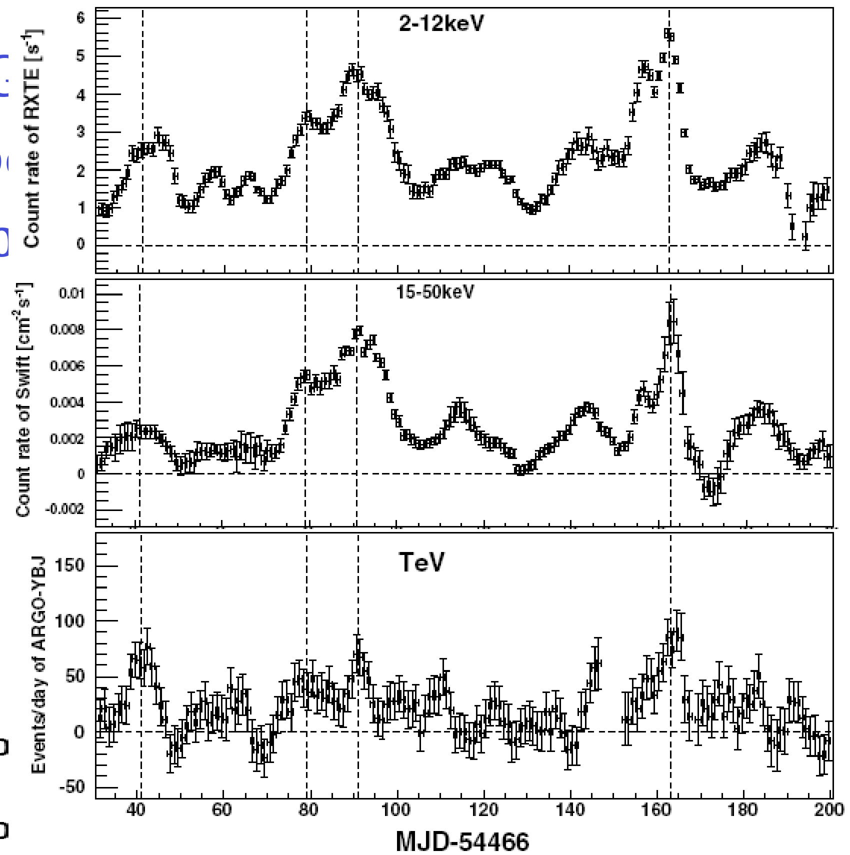
- ARGO-YBJ cumulative light curve (>TeV) compared with Swift and Rossi/RXTE data.
- Good correlation between TeV/X-ray data.
- No other continuous observation at TeV energies

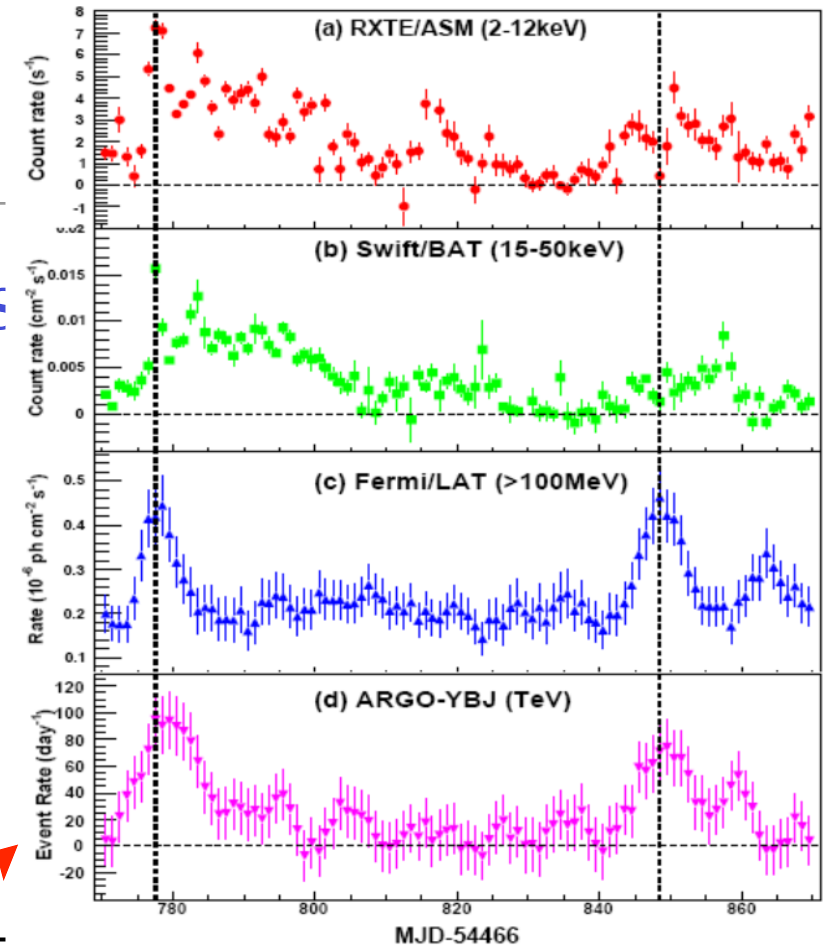


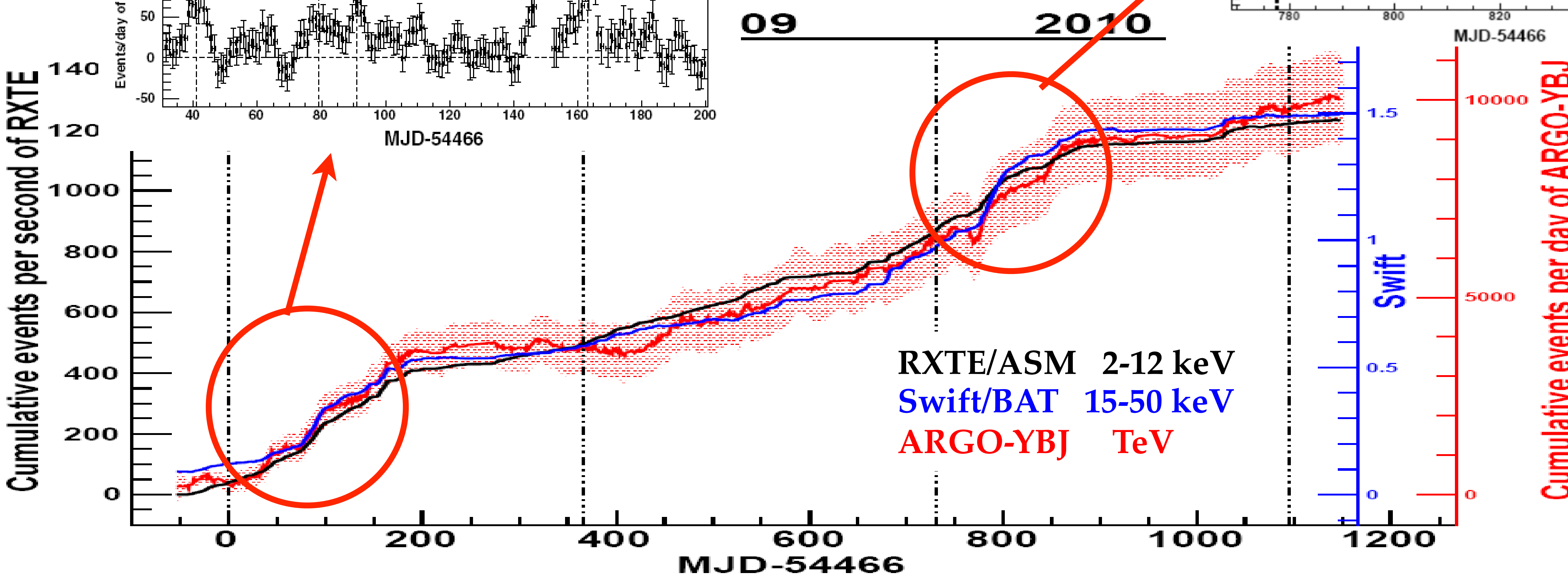
ARGO-YBJ coll., ApJ 734 (2011) 110

Mrk421 long-term monitoring

- ARG... TeV) compared with S
- Goo... data.
- No c... eV energies



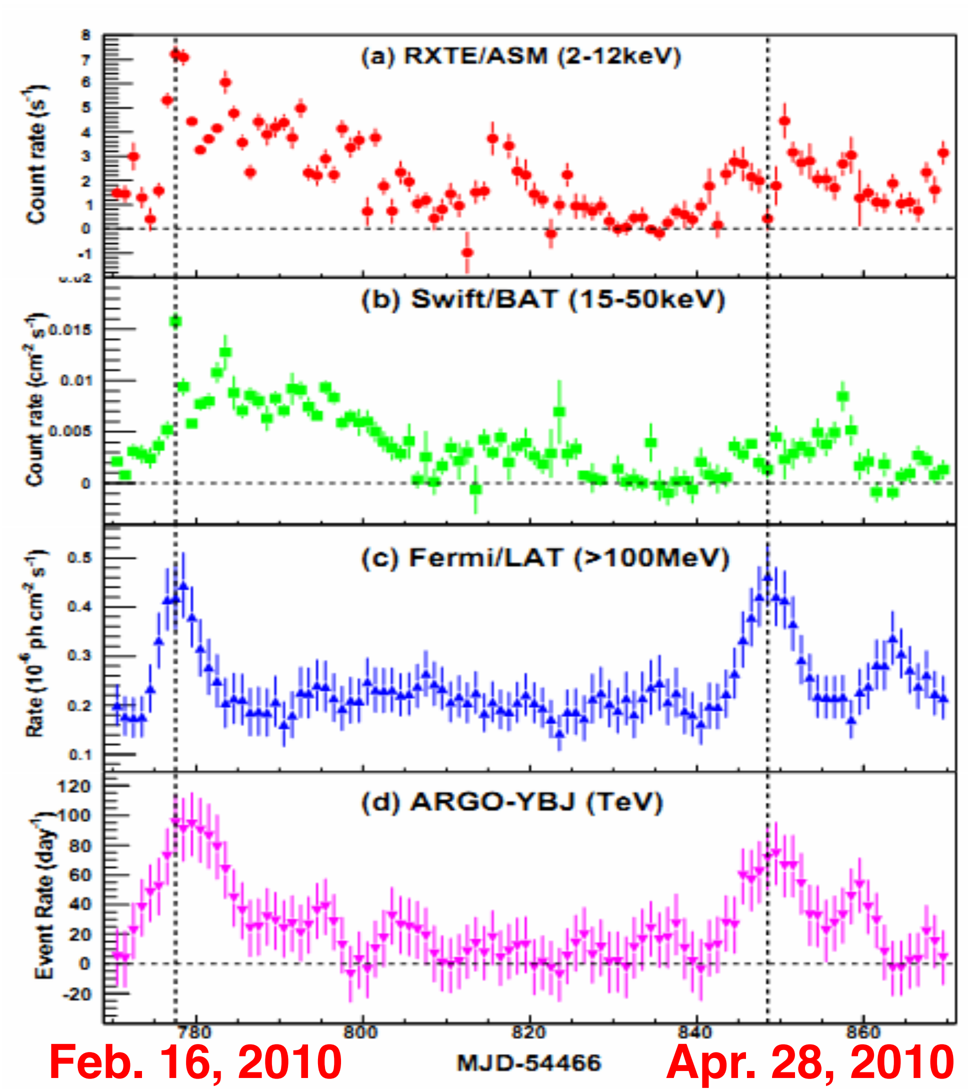


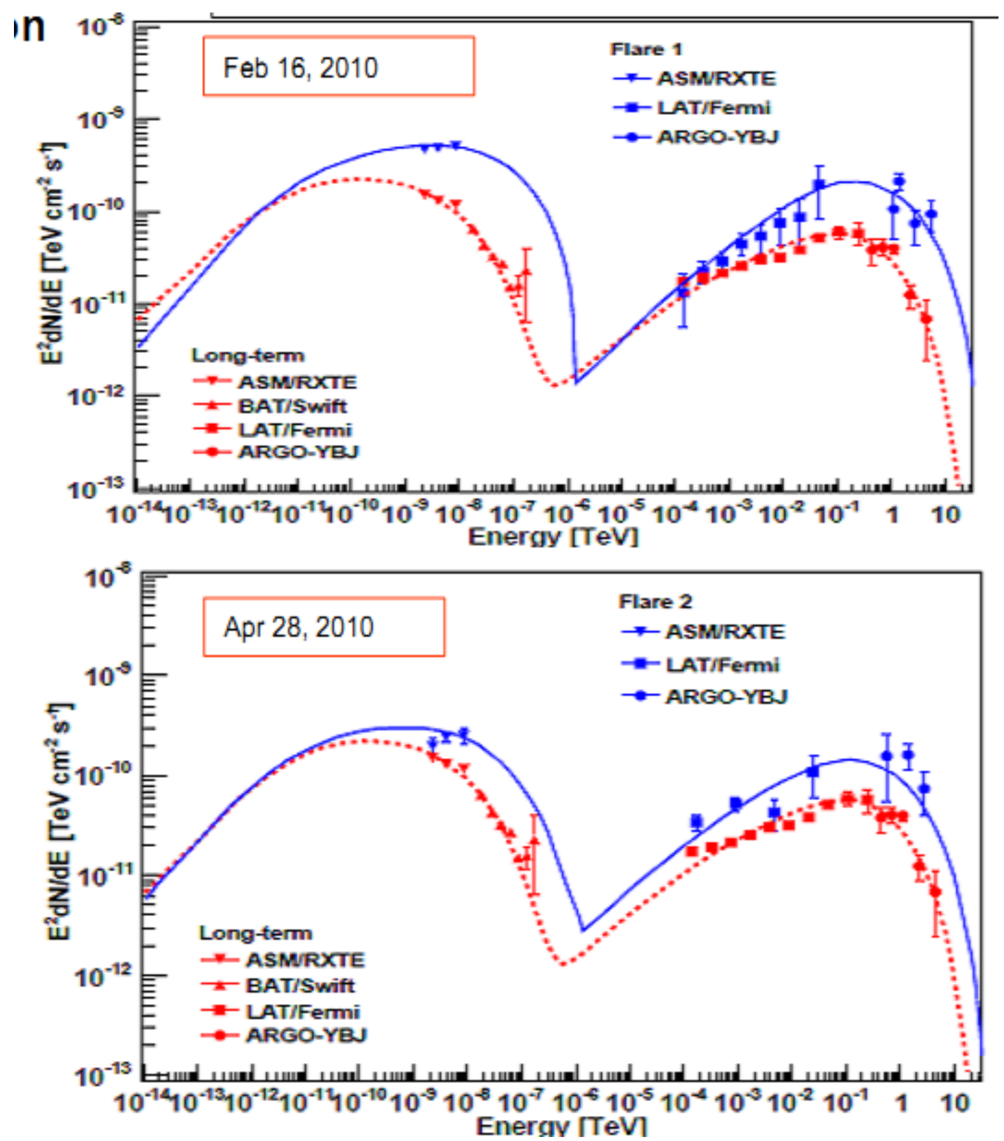


ARGO-YBJ coll., ApJ 734 (2011) 110

Mrk 421 SED: electromagnetic scenario

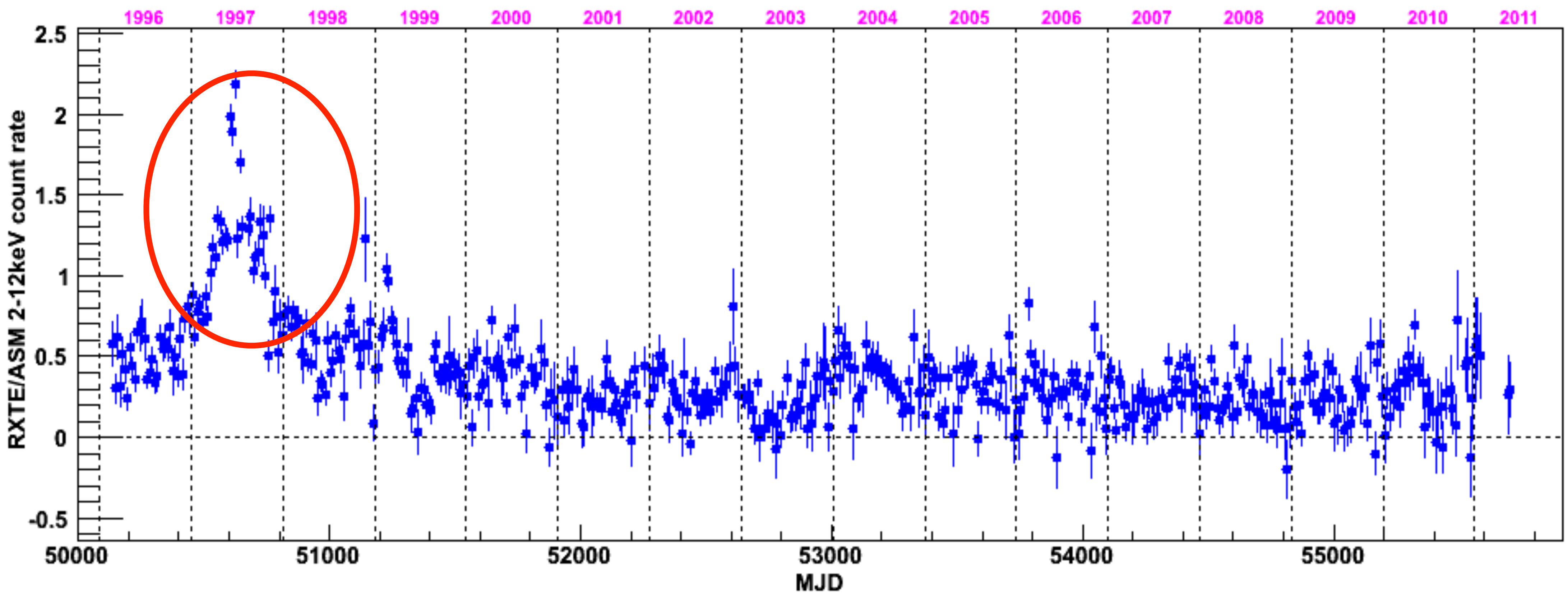
- ★ Both X-ray and TeV spectra are observed to harden as the flux increases
- ★ Observations are compatible with a SSC model with flares being due to hardening of the electron injection spectrum





Mrk 501

A strong X-ray flare in 1997 followed by a long “quiet” period

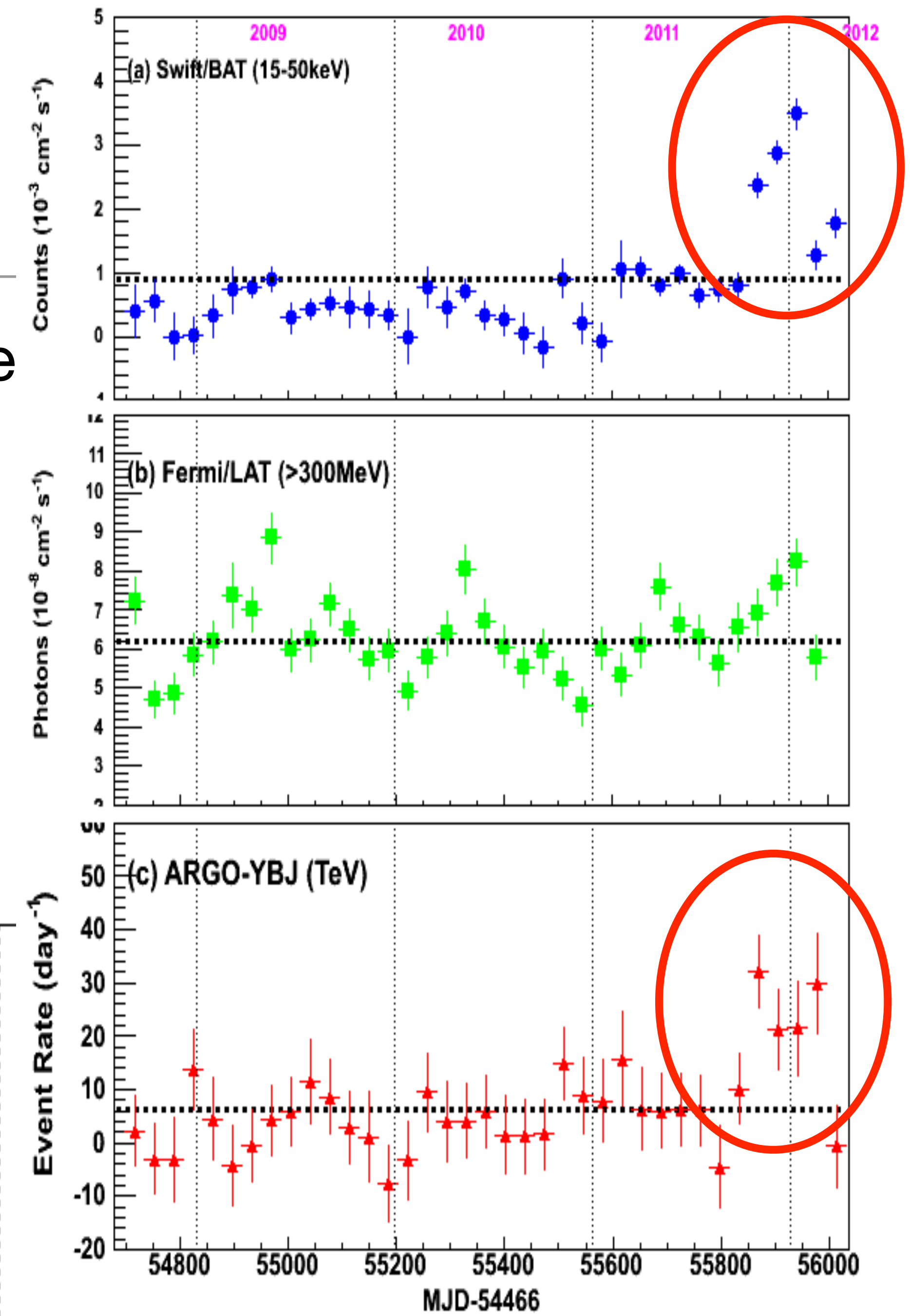


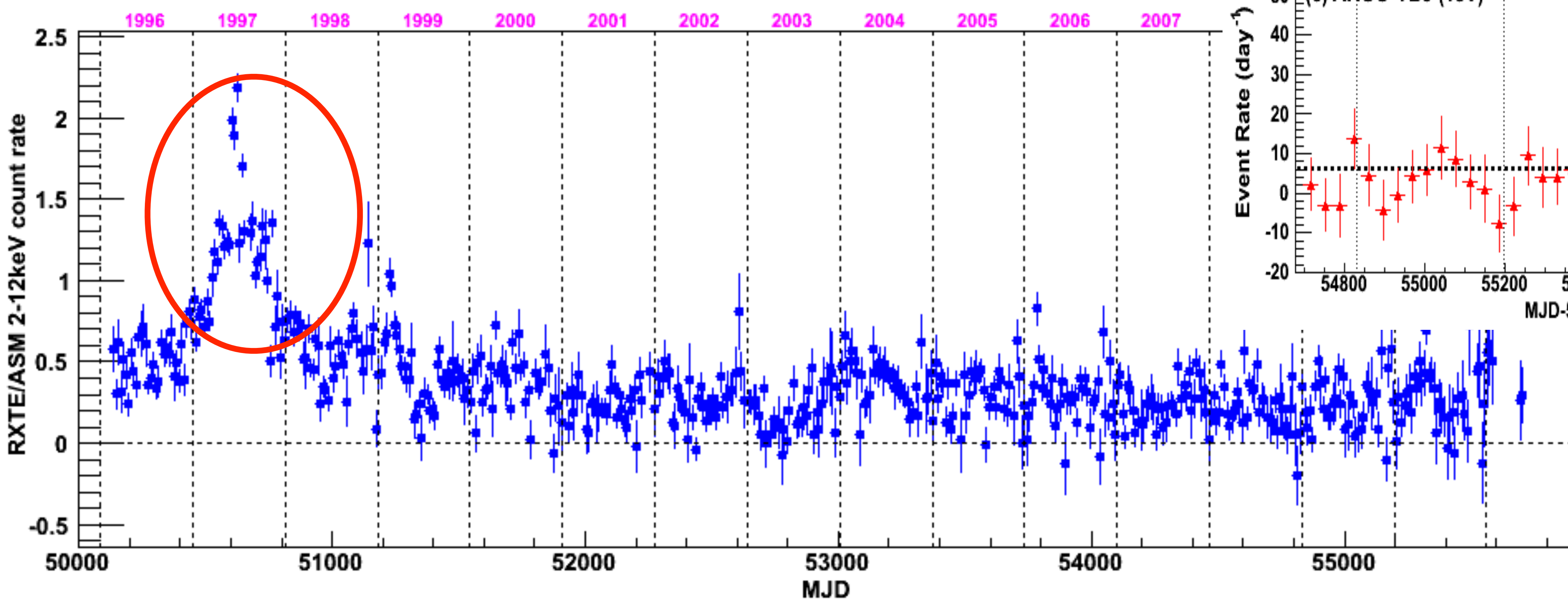
Mrk 501

A strong X-ray flare in 1997 followed by a long “quiet” pe

★ New strong X-ray flare took place 14 years later: Oct 2011

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





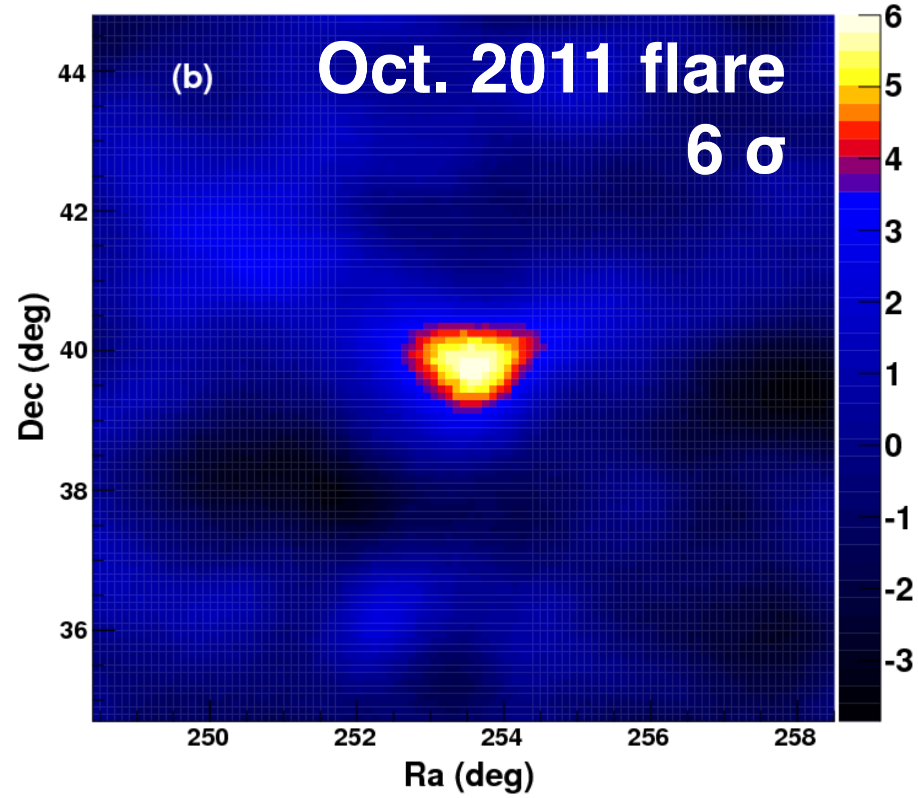
Mrk 501 Spectral Energy Distribution

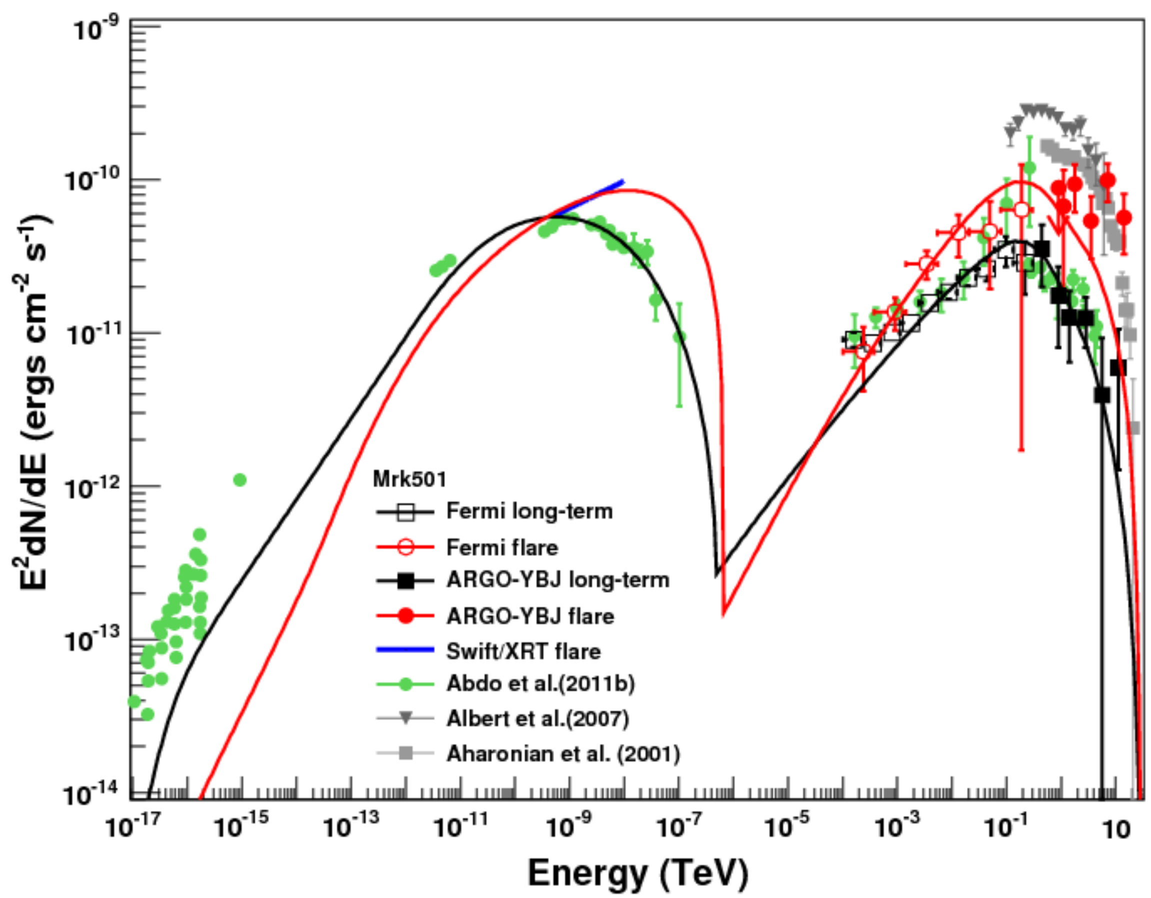
★ During the flare flux > 1 TeV a factor 6.6 above the steady emission

★ For steady state, the SSC model is favored

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

ApJ 758 (2012) 2





Questions to the knee energy range

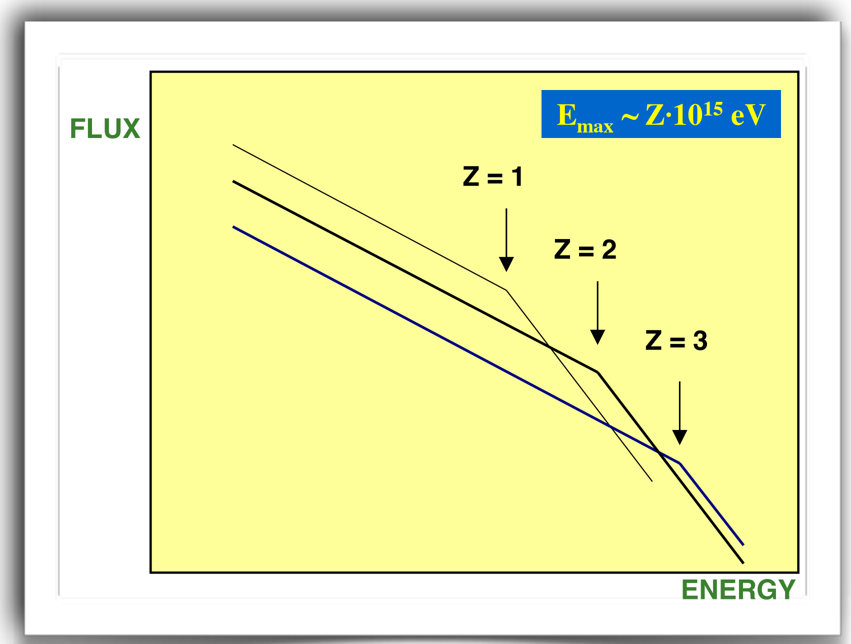
Cosmic Ray Sources ?	→	**Still open**
Overlap direct – indirect measurements ?	→	**Still missing**
Composition at the knee ?	→	**Still open**
Hadronic interaction models ?	→	**Still uncertain**
End of galactic spectrum ? **Transition galactic – xgalactic ?**	→	**Open**
Anisotropy ?	→	**Totally open**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

Approaching the knee

How well do we know the structure of the primary spectrum around the knee (10^{14} – 10^{16} eV) ?

The standard model:

- Knee attributed to light (proton) component
- Rigidity-dependent structure (Peters cycle): cut-offs at energies proportional to the nuclear charge
  $E_Z = Z \cdot 4.5$ PeV
- The sum of the flux of all elements with their individual cut-offs makes up the all-particle spectrum.
- Not only does the spectrum become steeper due to such a cutoff but also heavier.



E_{max}(iron) = 26 · E_{max}(proton)

But

with increasing altitude the proton component no more dominant at knee

Increasing the altitude

- Knee attributed to light component since shower detected at sea level are mainly due to protons !?

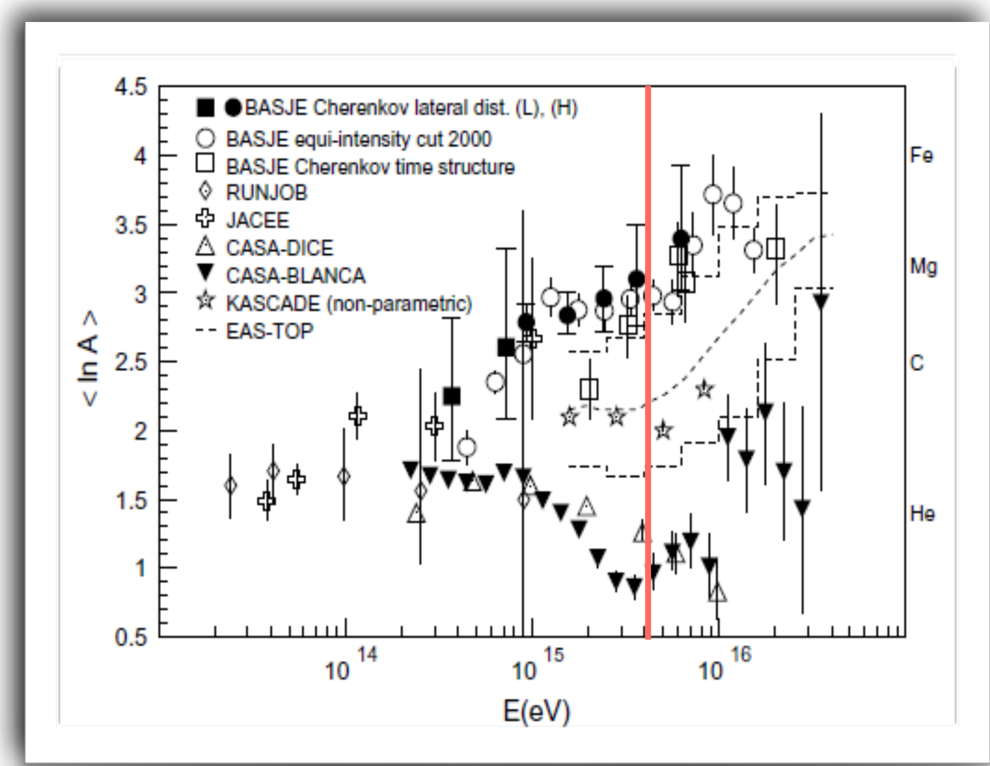
BASJE-MAS (5200 m asl): MgSi - Fe

Tibet ASγ (4300 m asl): MgSi - Fe

EAS-TOP (200 m asl): He - CNO

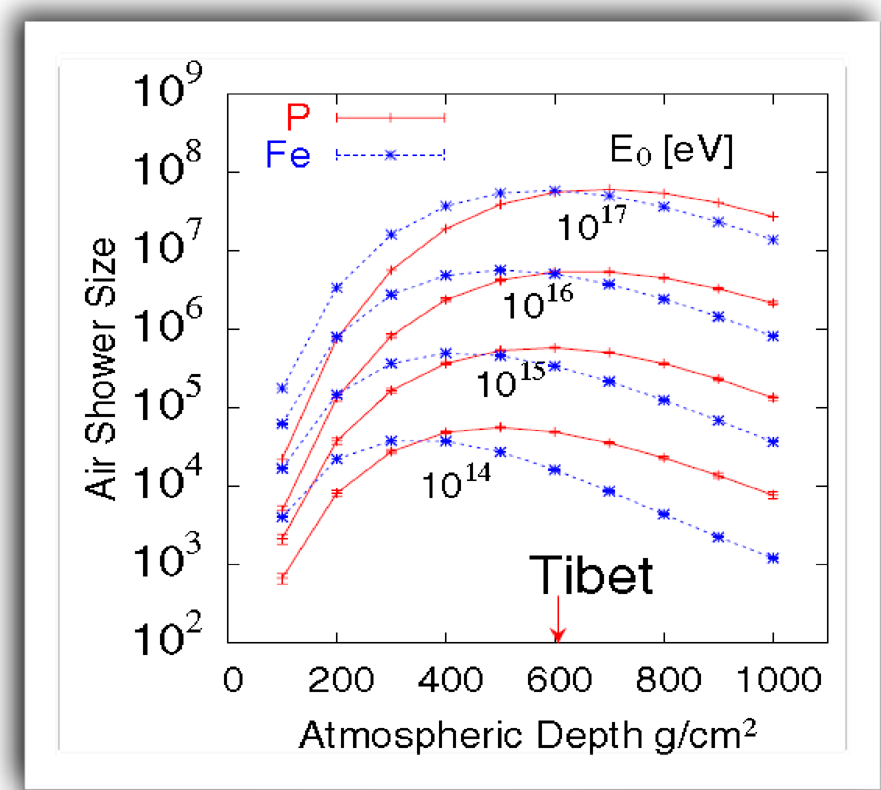
KASCADE (sea level): p - He

altitude
mass



Same efficiency to all masses in the knee region at 4000 m asl:

p and Fe produce showers with similar size



Cross-calibration

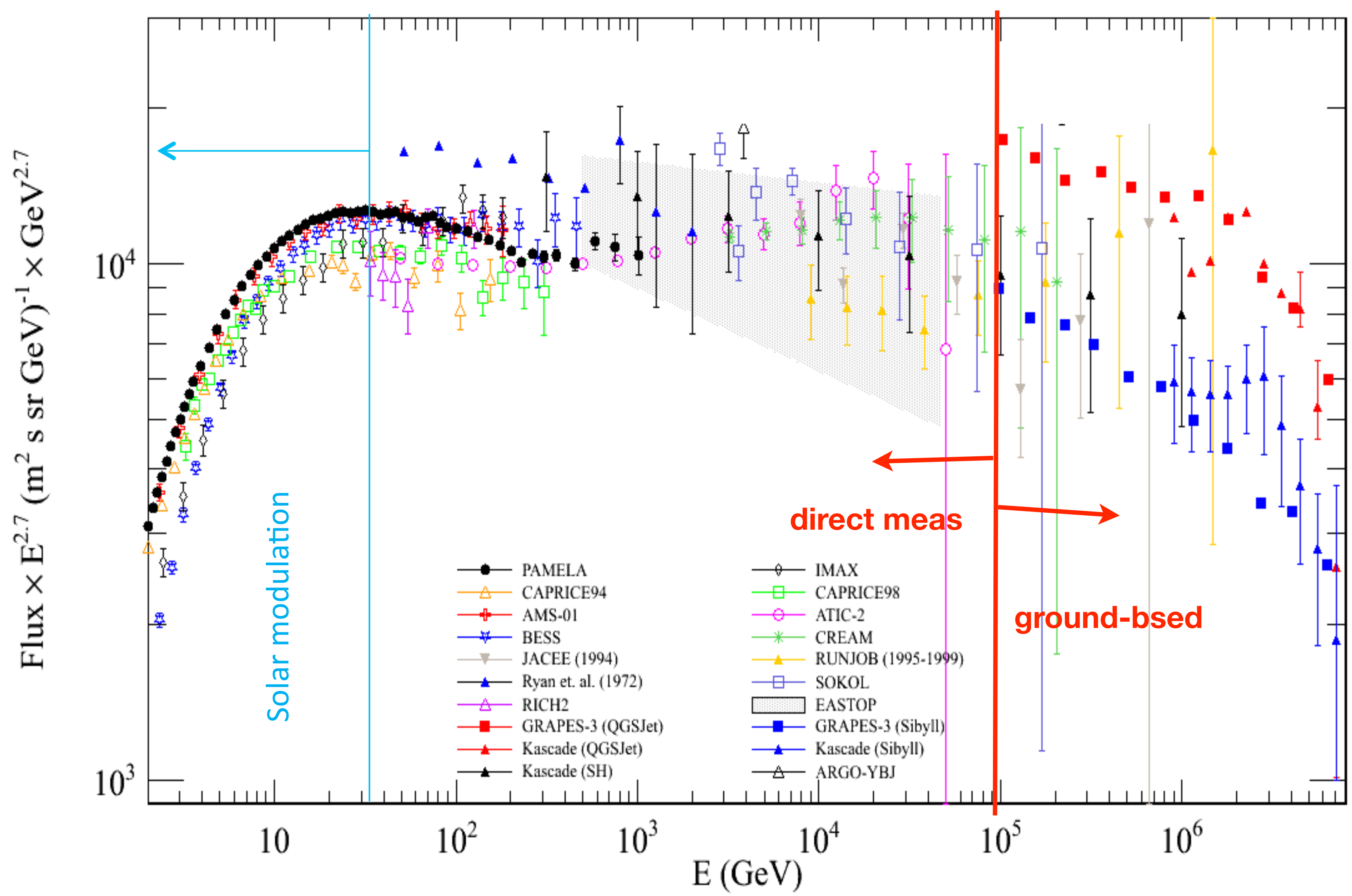
"The calibration of the ground arrays by an overlap with direct measurements is a crucial goal to pursue, not only to understand the origin of the knee but also to describe correctly the transition from galactic to extragalactic cosmic rays. The two problems are tightly related to each other".

ICRC 2007 Rapporteur Talk

...but also to reconcile different measurements

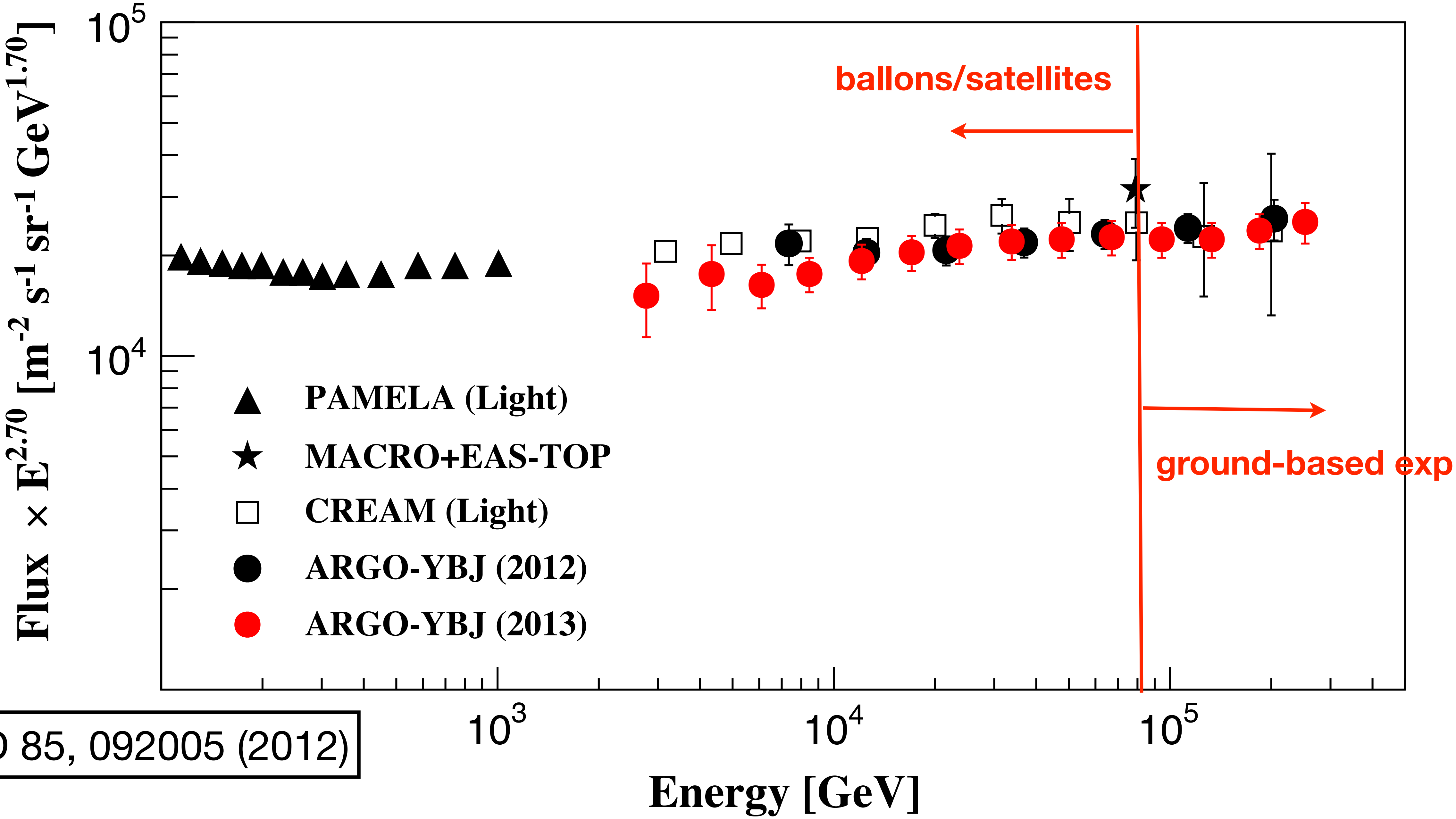
proton: the key component

proton spectrum



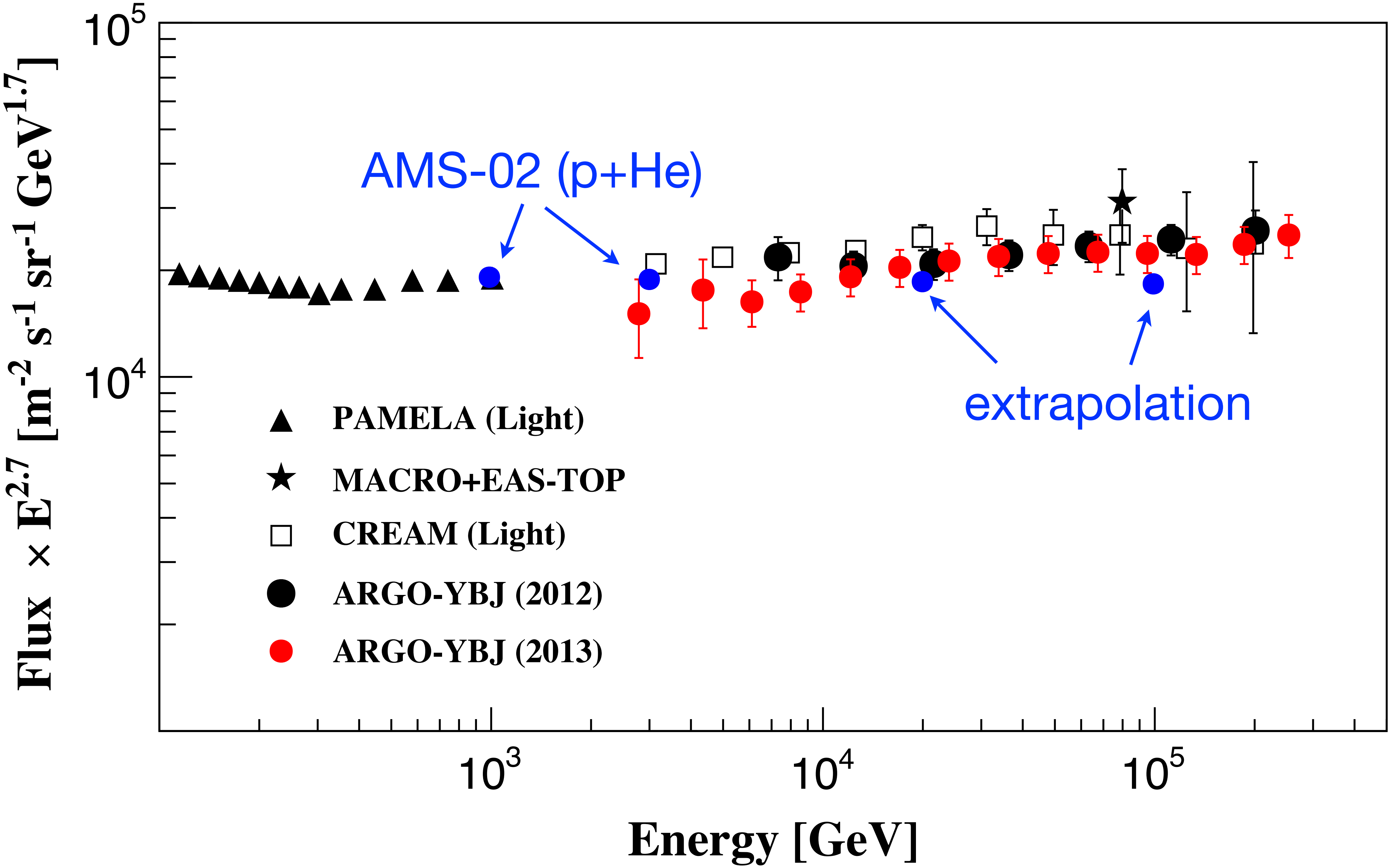
The light-component spectrum (2.5 - 300 TeV)

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)

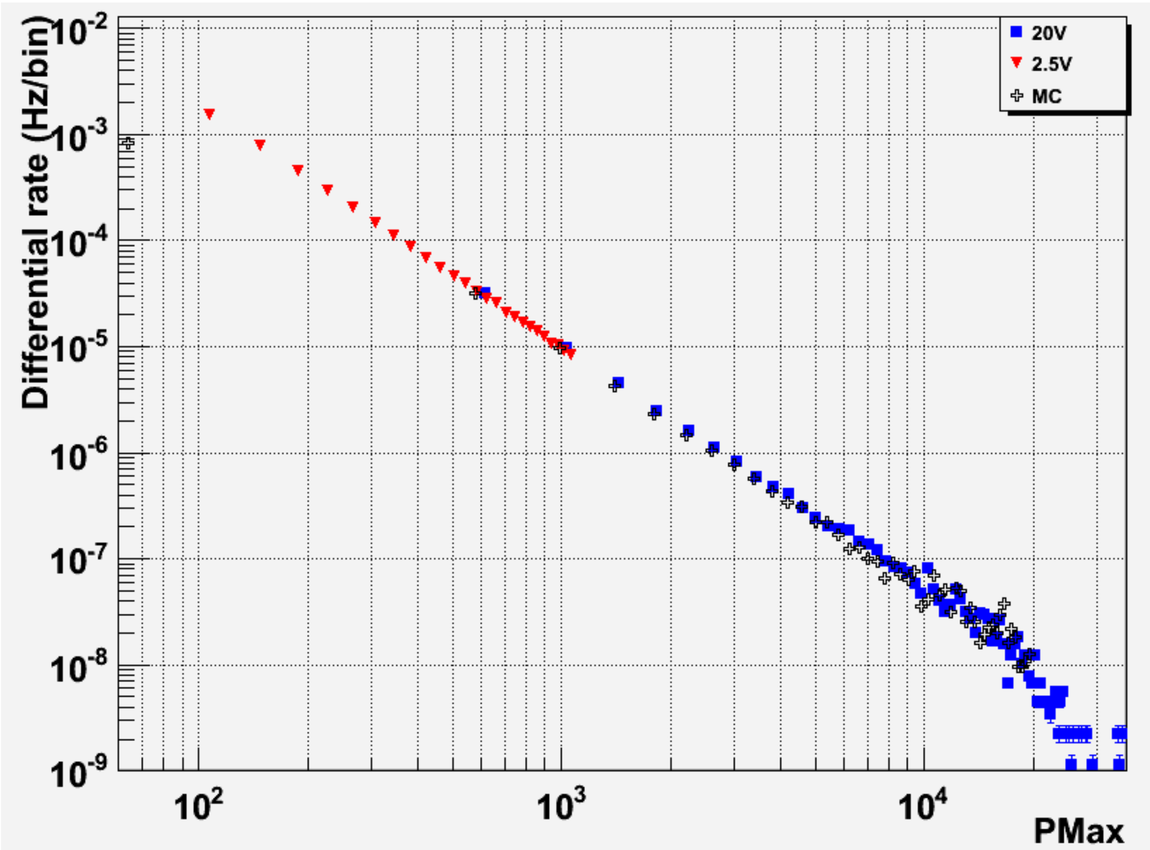
ARGO-YBJ and AMS-02



The RPC analog read-out

Readout of the charge signal on 1.39 × 1.23 m^2 “big pads” (two / RPC)

Shower maximum distribution

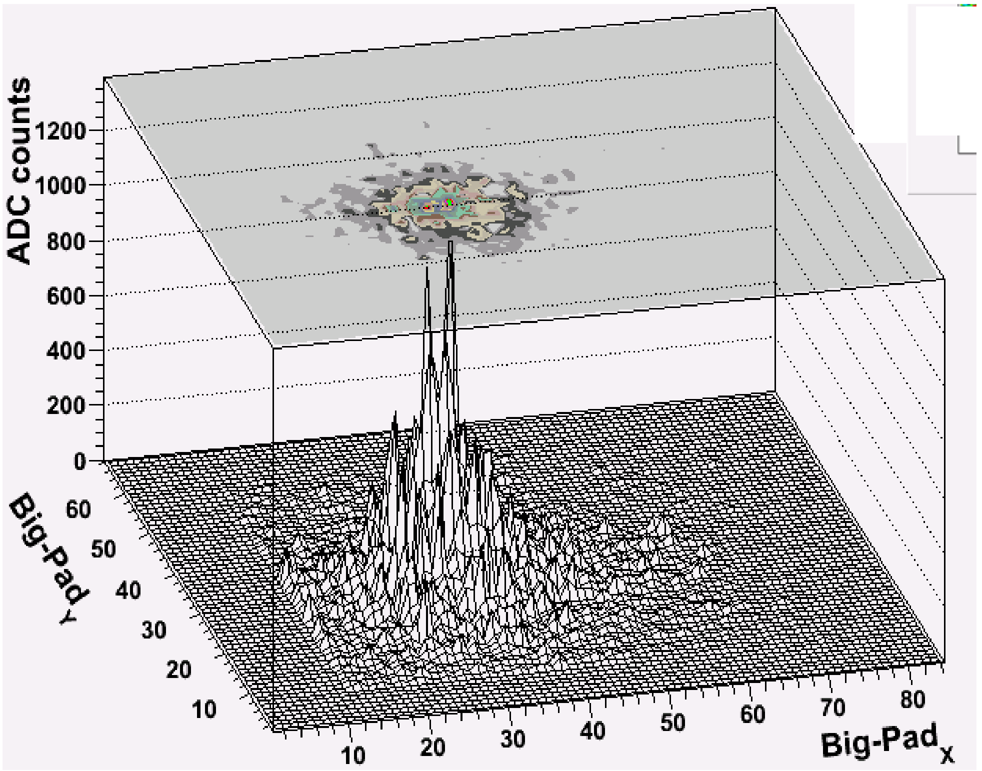


Different gain scales used to cover a wide range in particle density:

$$\rho_{max-strip} \approx 20 \text{ particles/m}^2$$

$$\rho_{max-analog} \approx 10^4 \text{ particles/m}^2$$

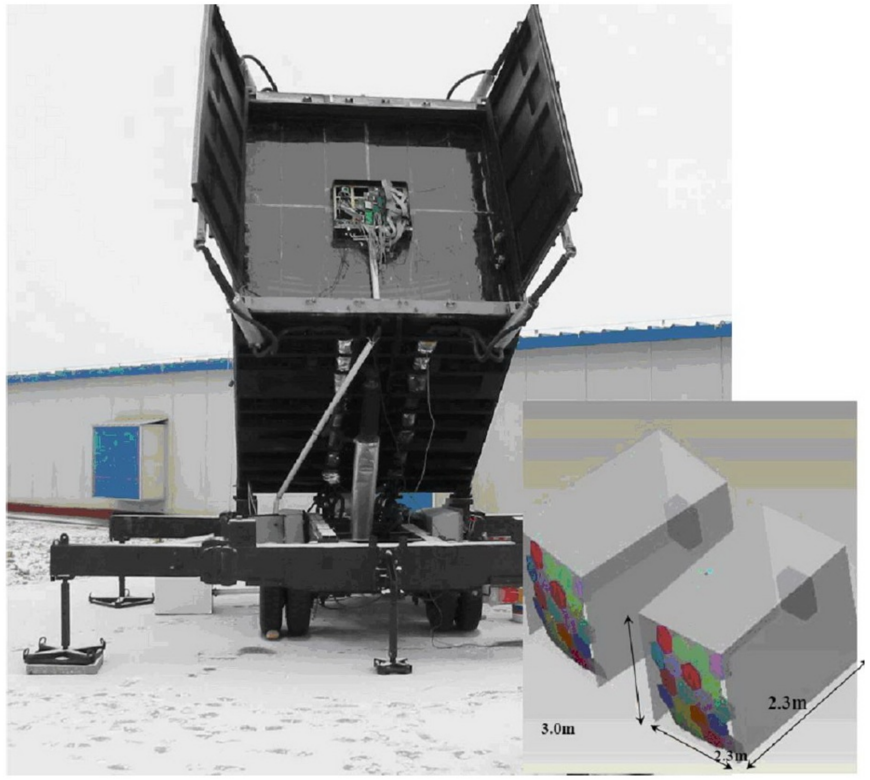
Intrinsic limit at about one particle per cm^2, due to space charge effects of the streamer discharge: the so called dead zone.



Analysis under way

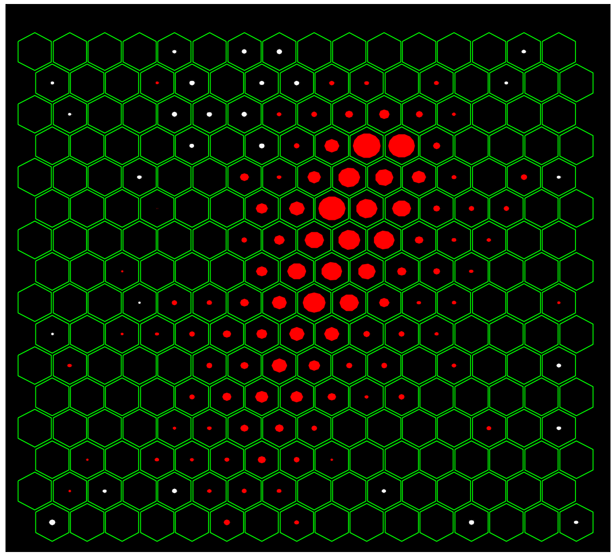
WFCTA + ARGO-YBJ

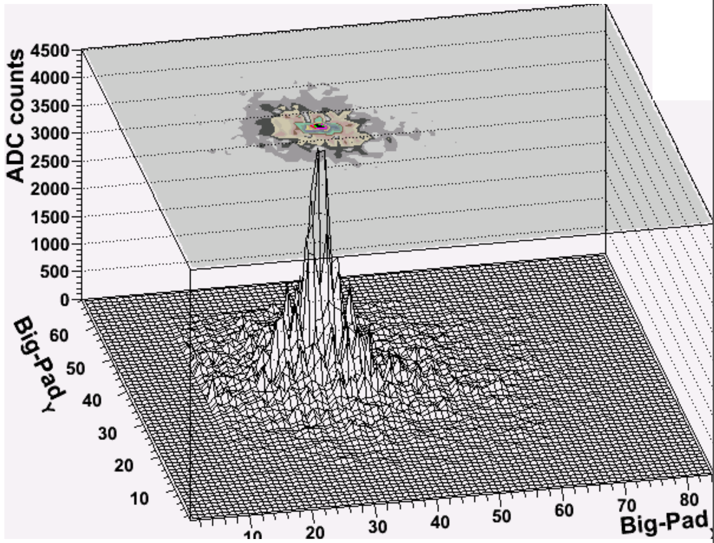
Hybrid measurement of the light-component (p+He) CR spectrum in the energy region (0.1 - 1) PeV



Wide Field of View Cherenkov Telescope

- **5 m^2 spherical mirror**
- **16 × 16 PMT array**
- **Pixel size 1°**
- **FOV: 14°× 16°**
- **Elevation angle: 60°**





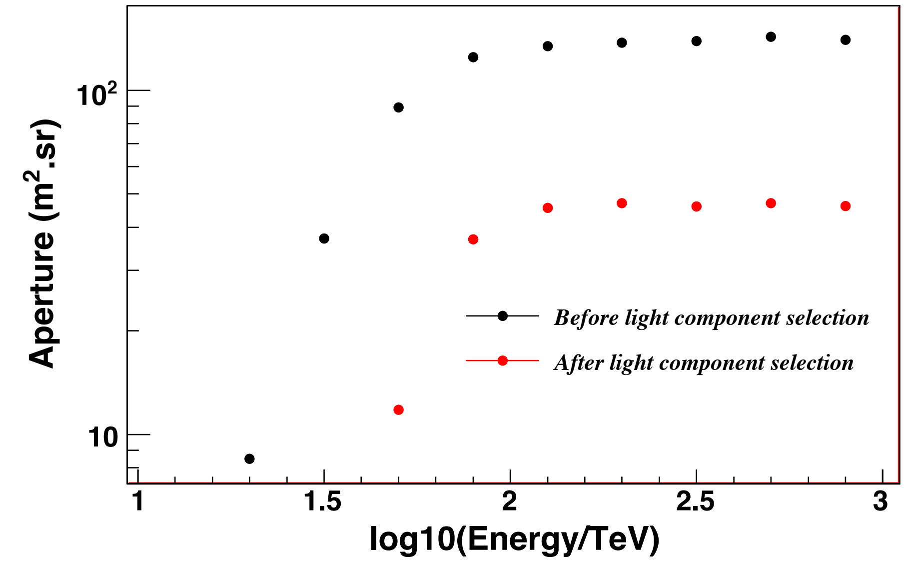
- **ARGO-YBJ**: lateral distribution size in the core region ⇒ mass sensitive
- **Cherenkov Telescope:** Hillas parameters ⇒ mass sensitive

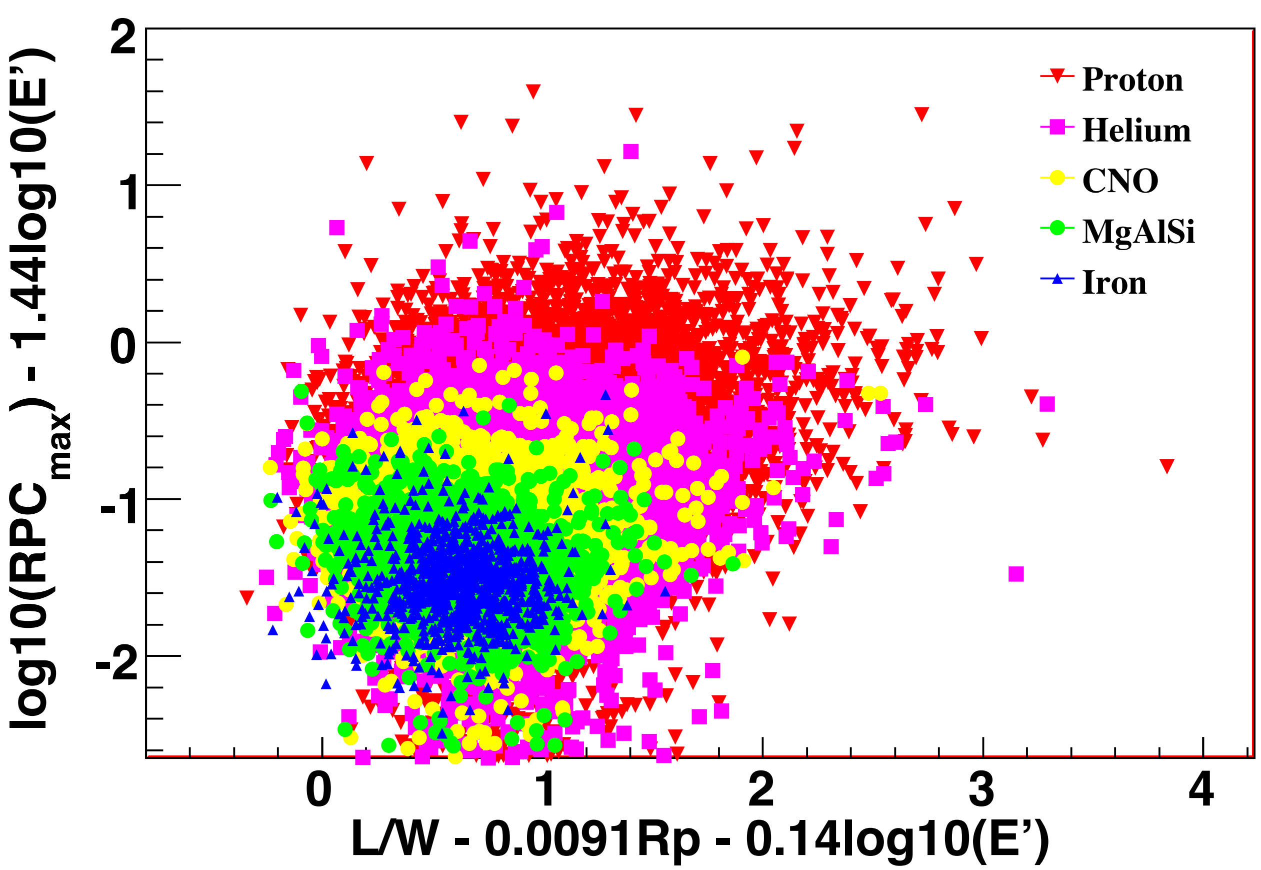
  Energy ricontruction

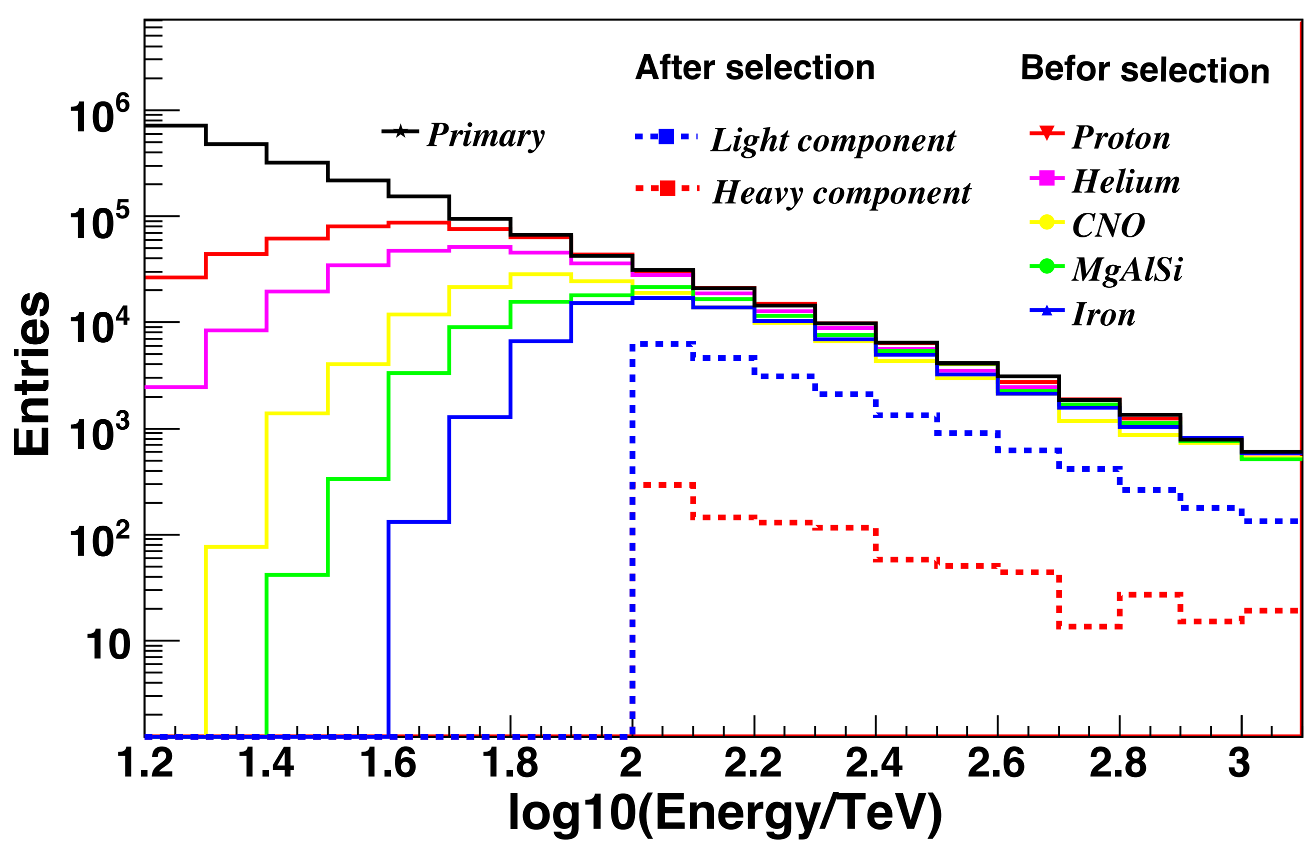
Light-component (p+He) selection

- 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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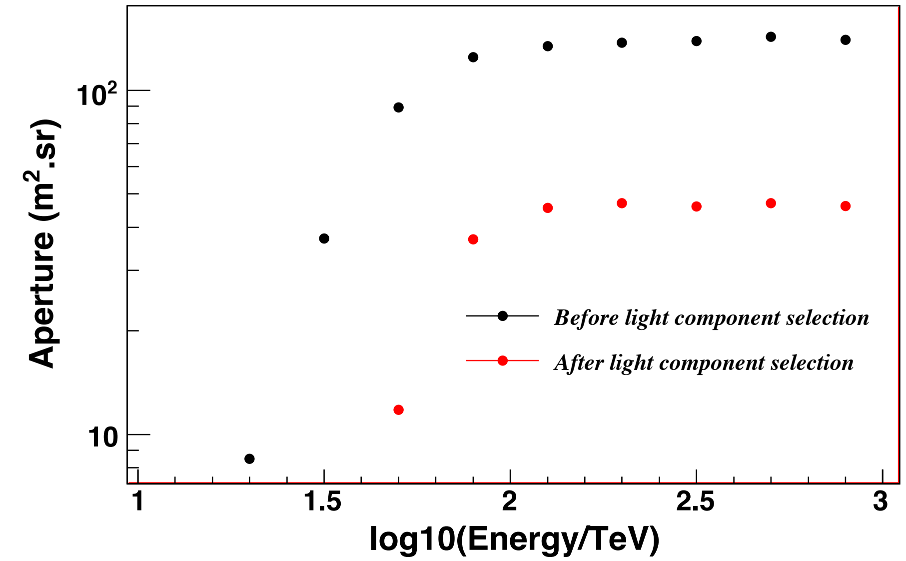
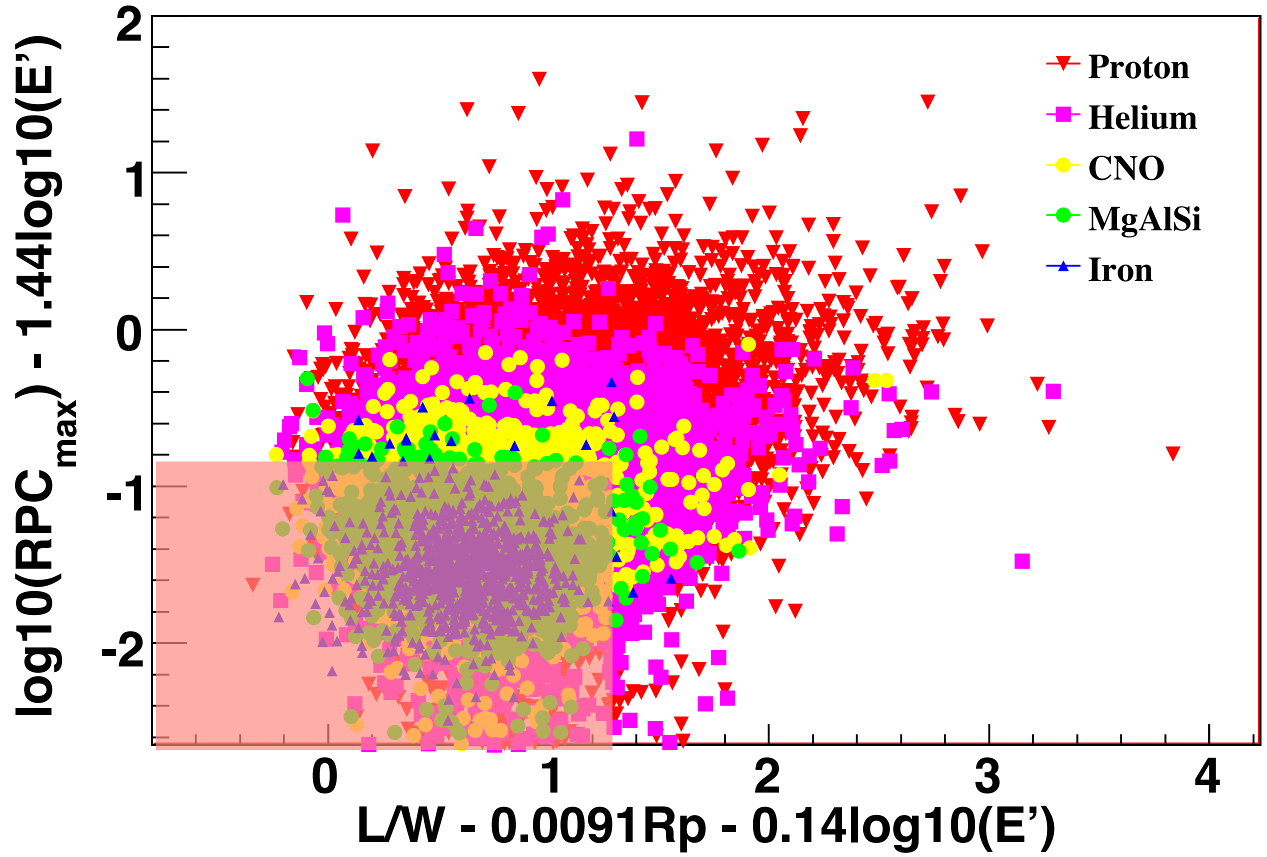
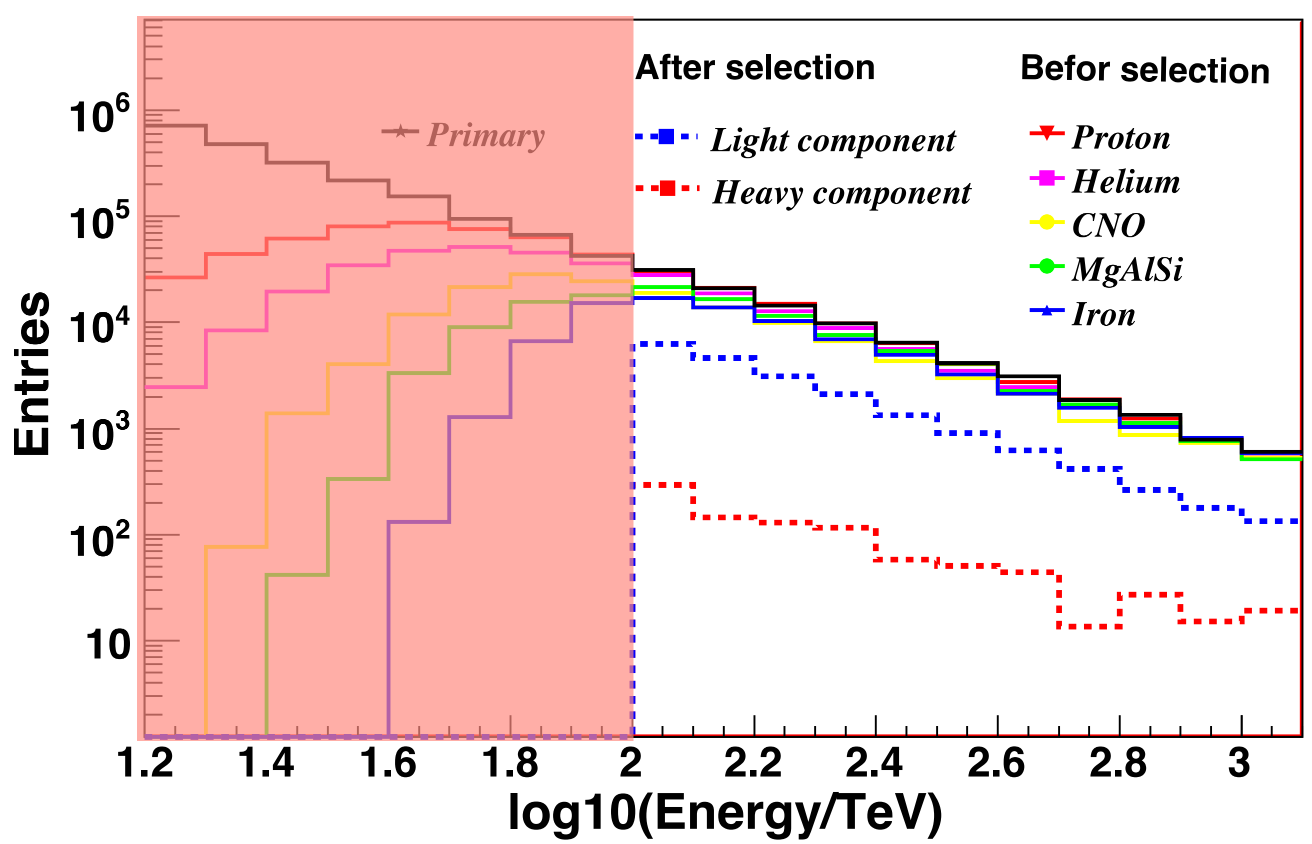
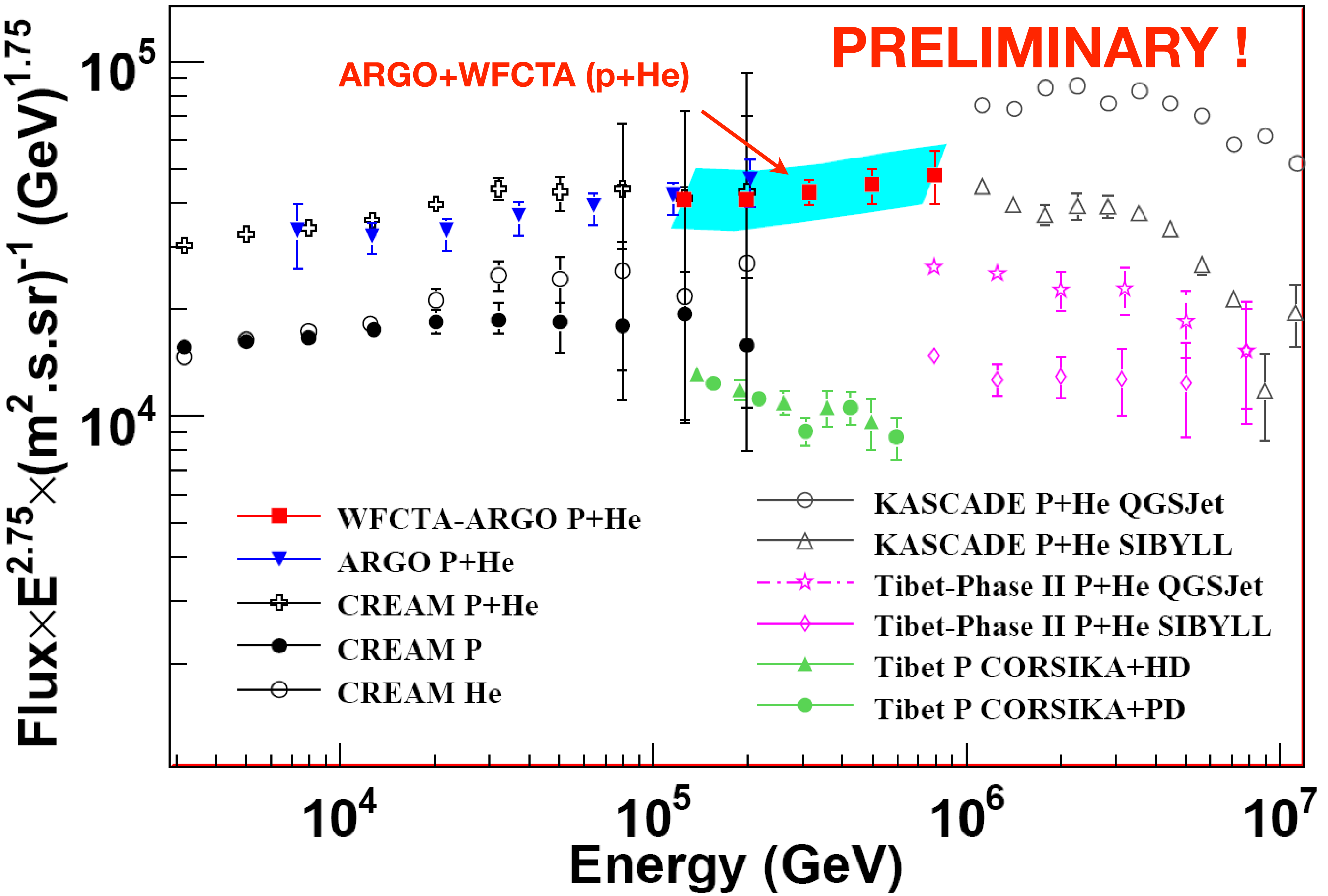




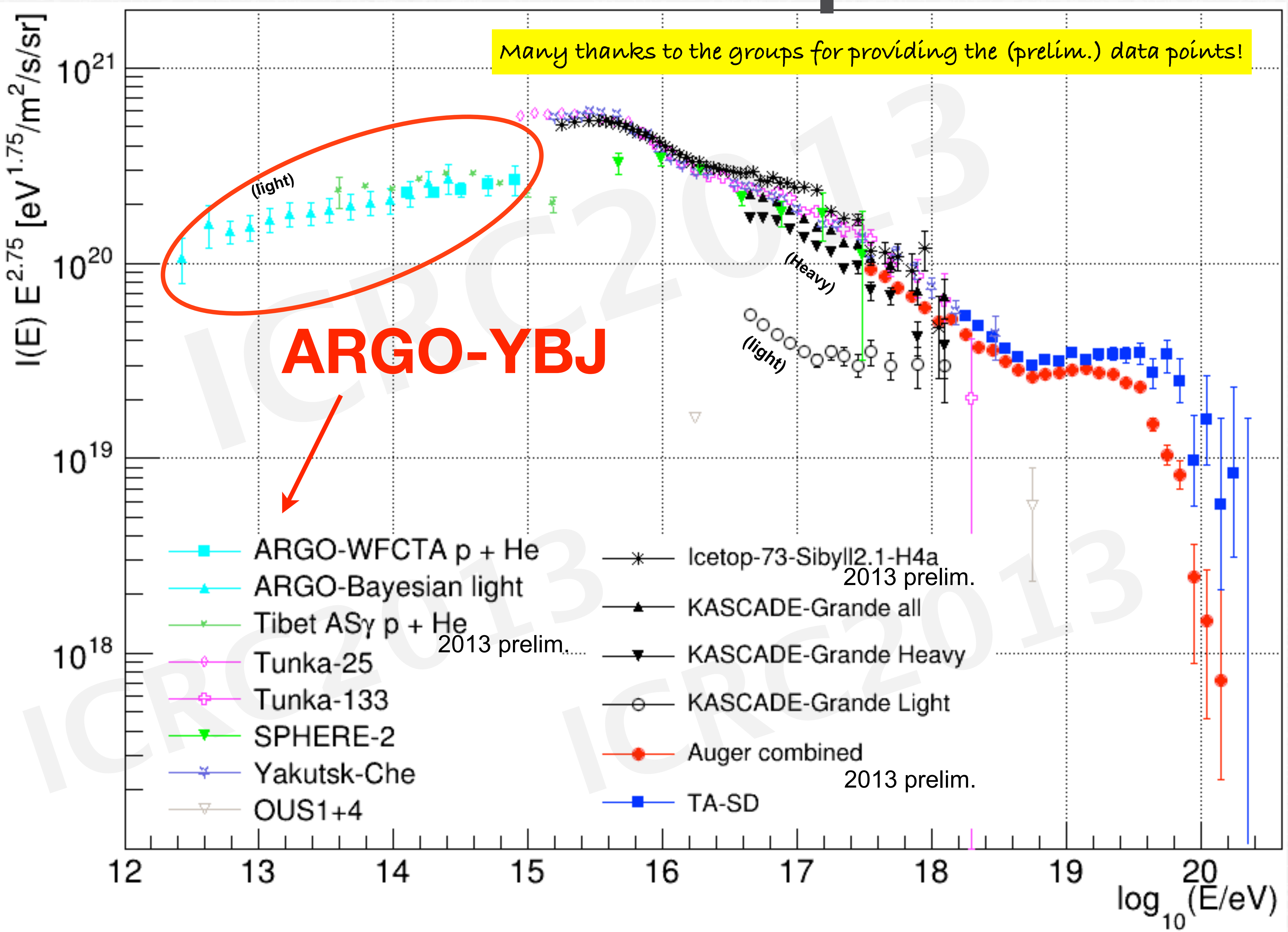


The light-component spectrum (100 - 800) TeV

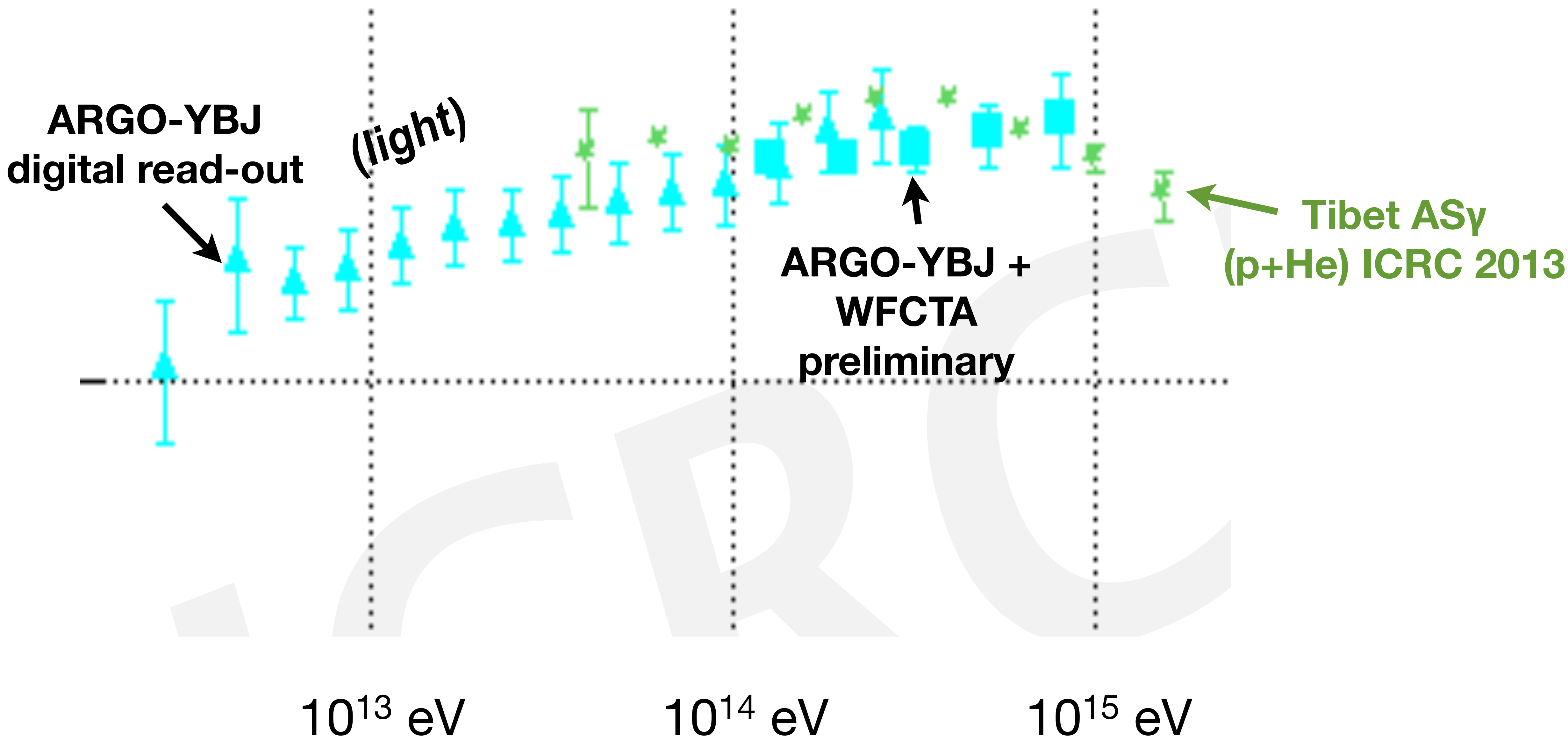
- Spectral index: γ = -2.69 ± 0.06 (ARGO: -2.61± 0.02)



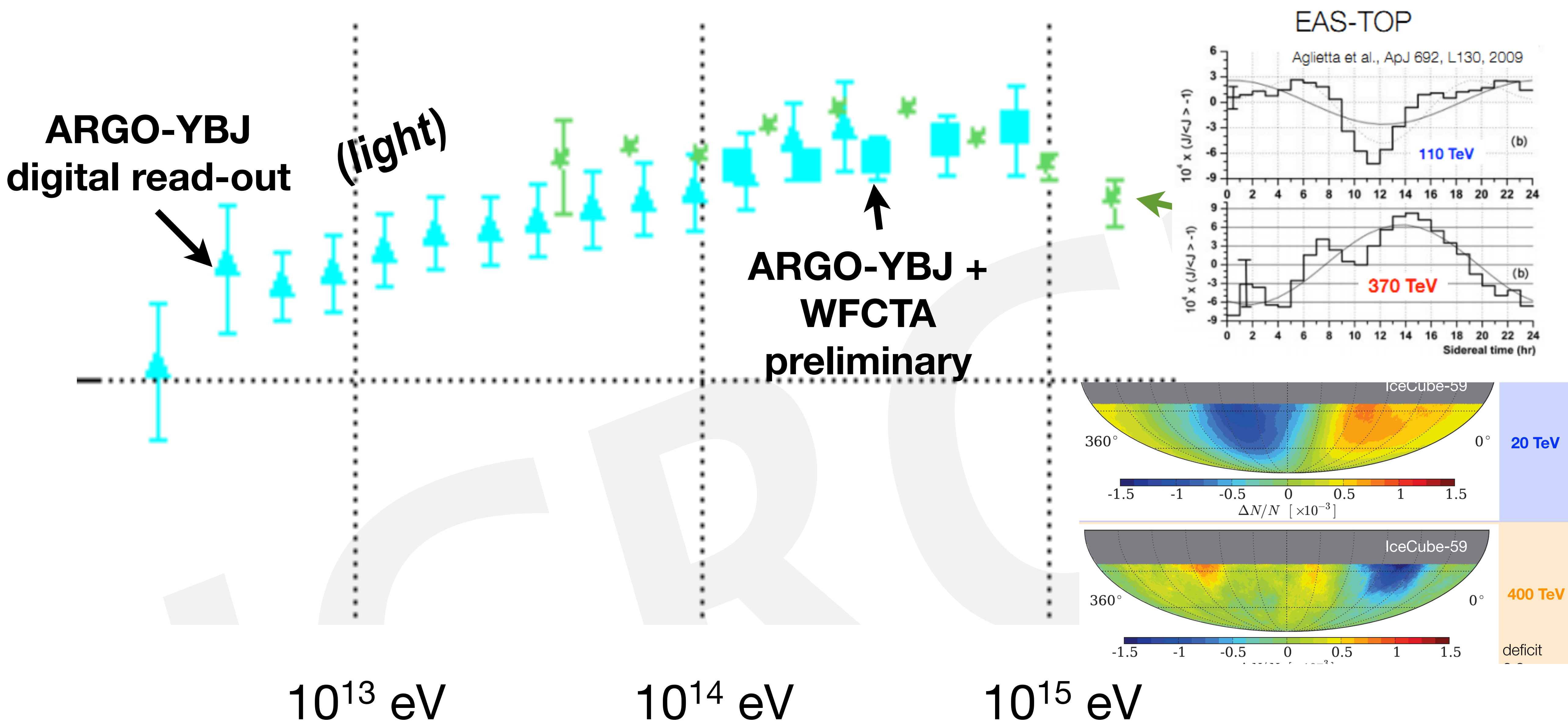
HE-CR: ICRC2013 Spectra



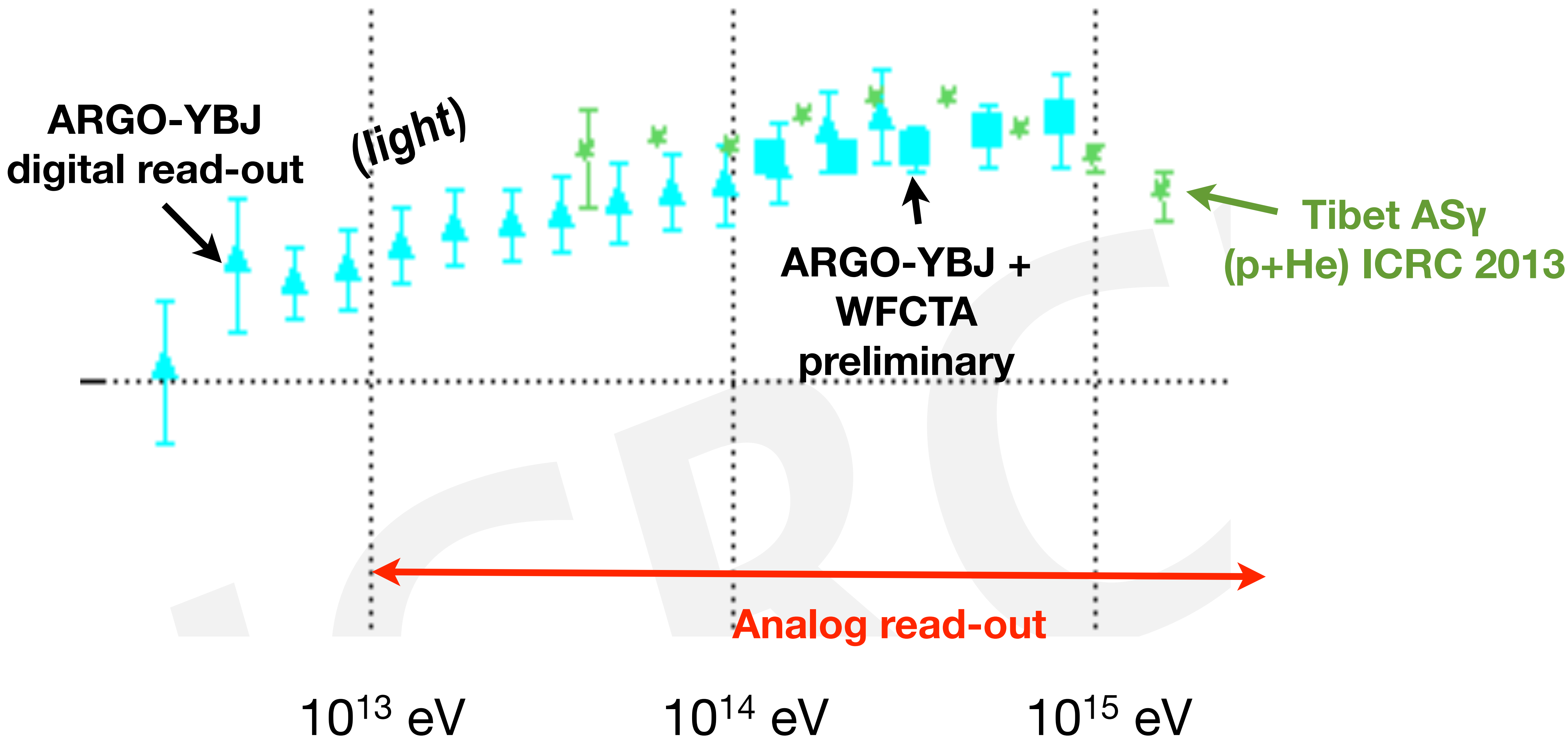
ARGO-YBJ vs Tibet ASγ



ARGO-YBJ vs Tibet ASγ



ARGO-YBJ vs Tibet ASγ



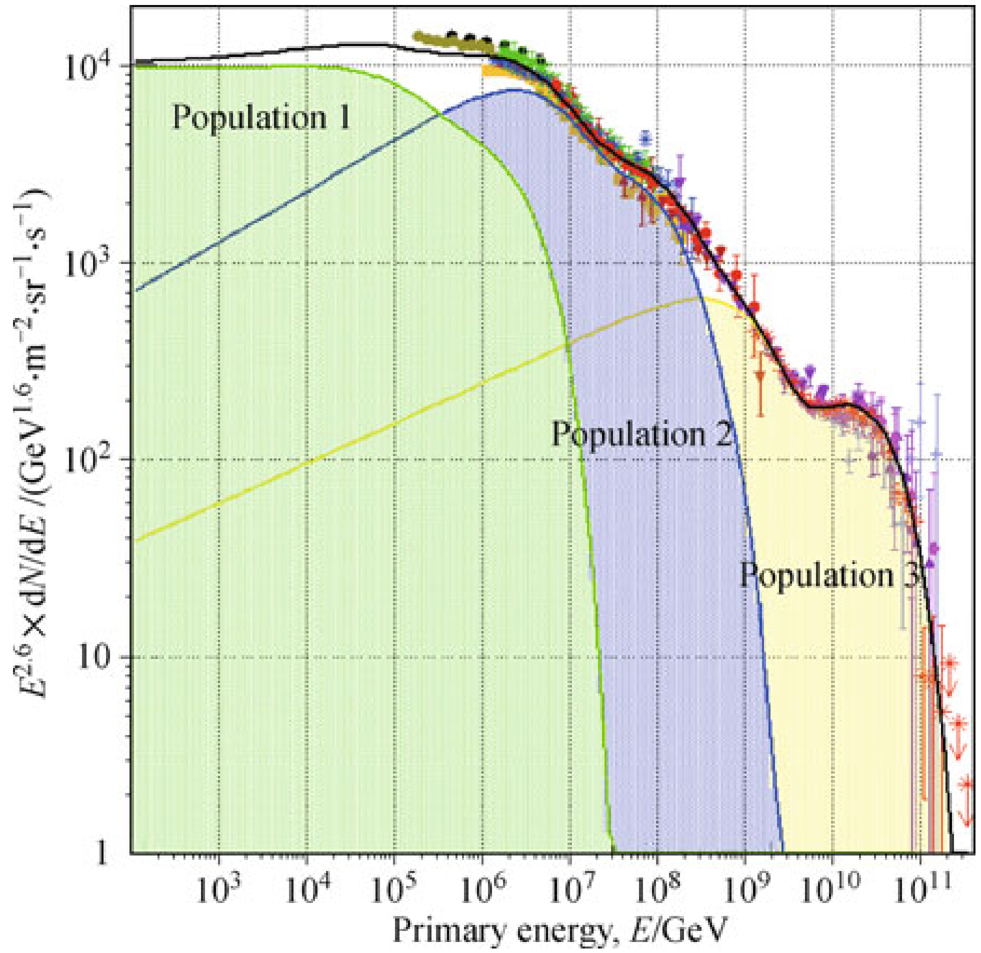
Analysis with the analog read-out + Bayesian unfolding (10 TeV - few PeV) under way

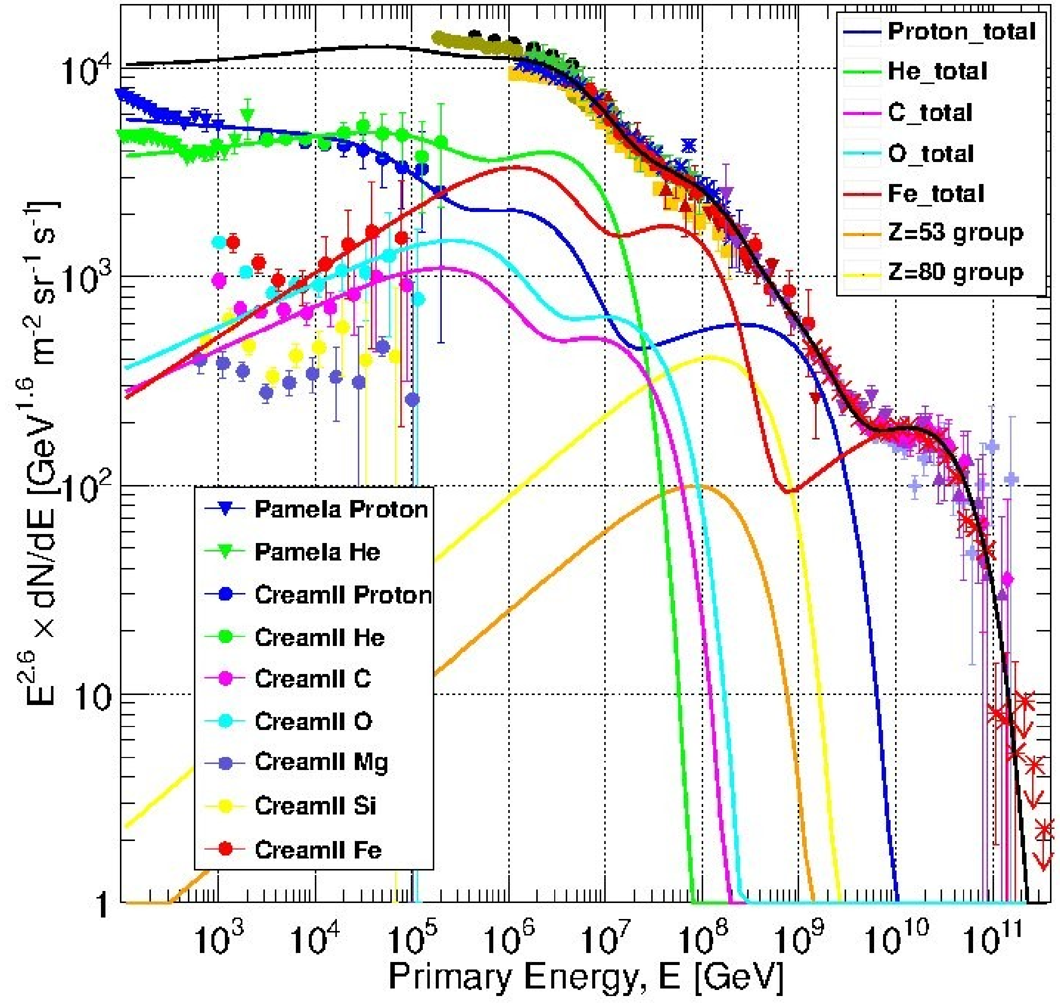
The knee region

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



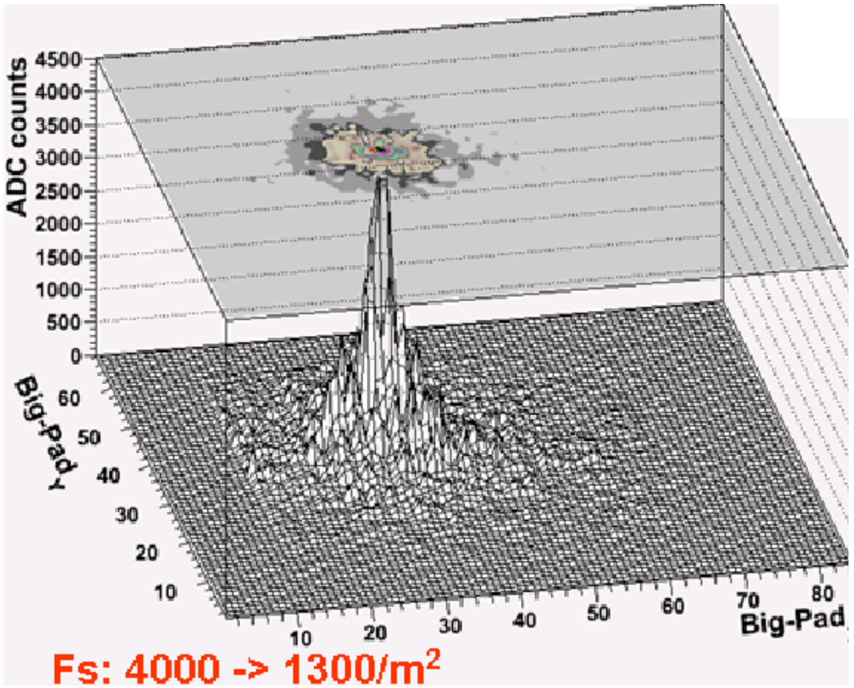


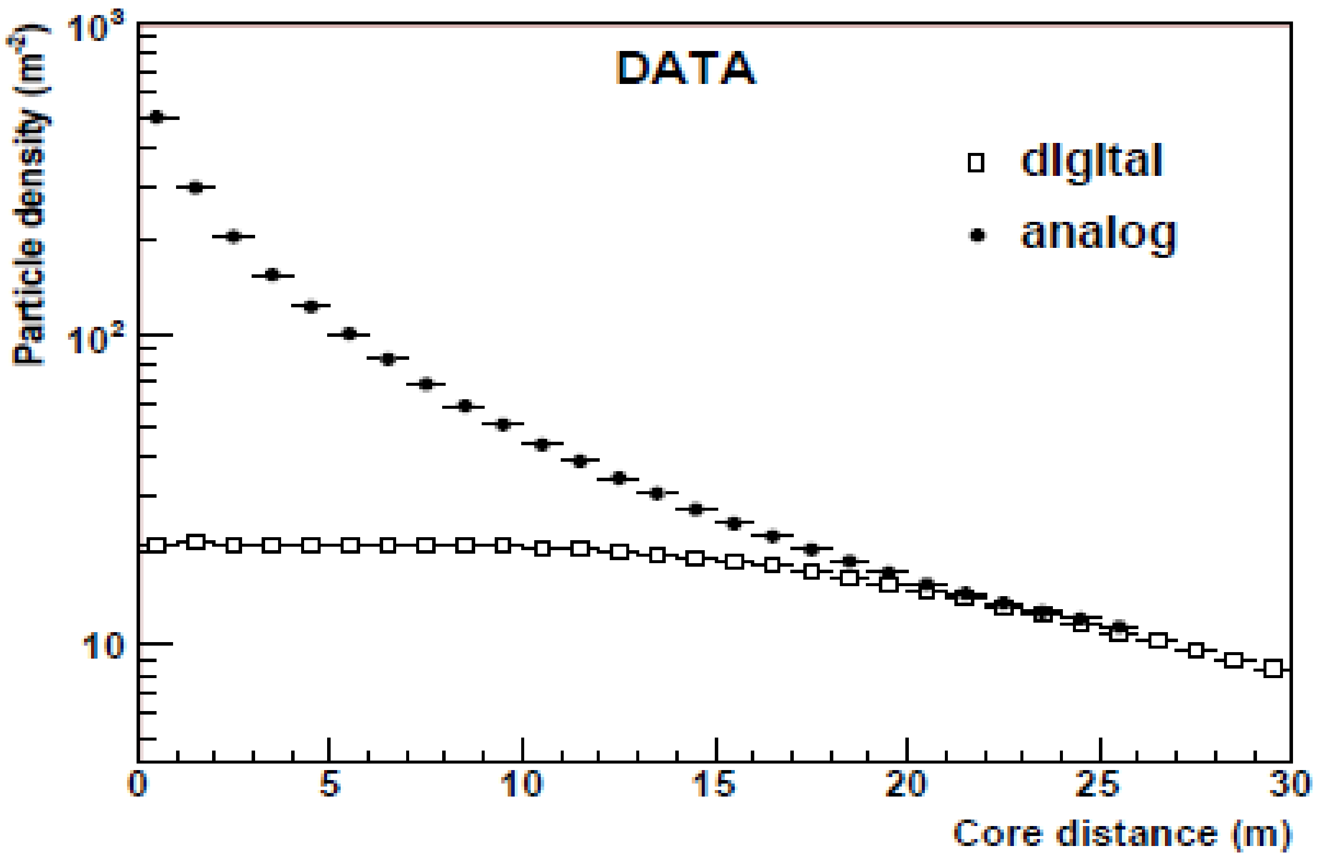
Measurement of heavy (Fe) component evolutoin approaching the knee crucial

LDF and shower age

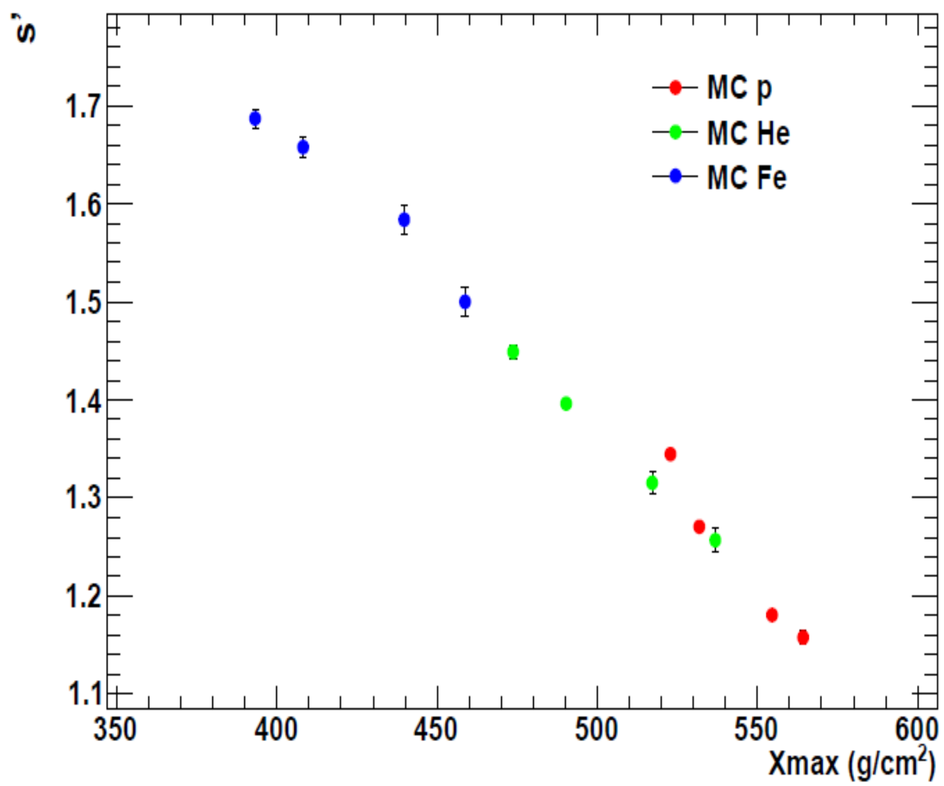
With the analog data we can study the LDF without saturation near the core. Well fitted by modified NKG function.

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





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

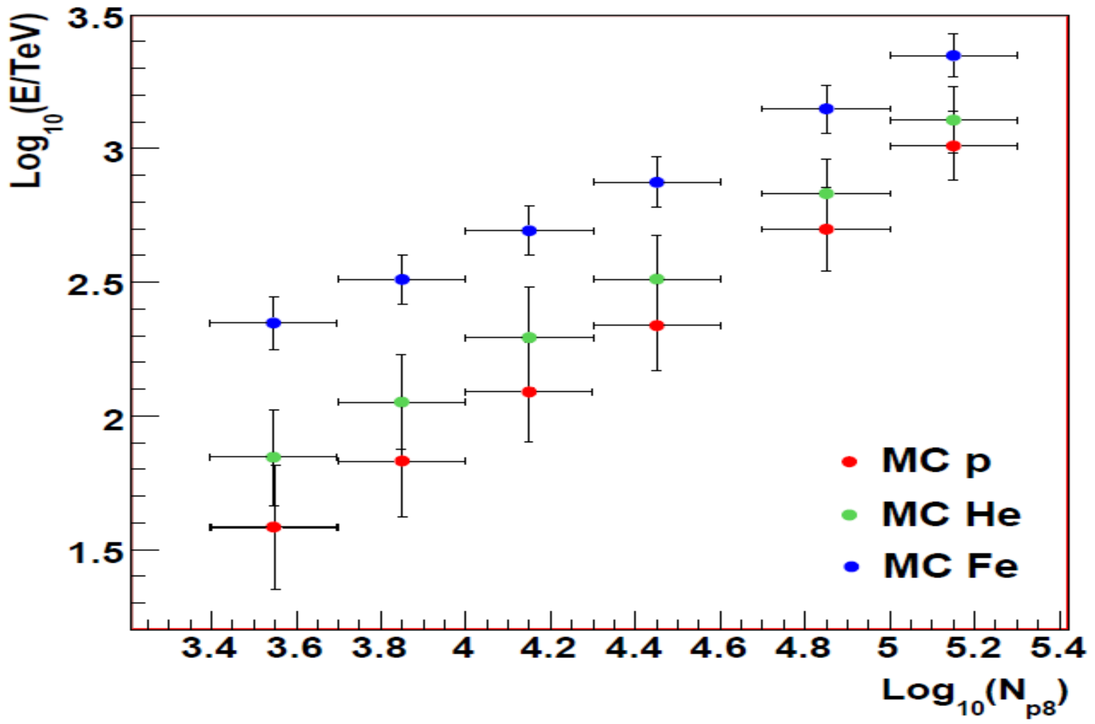


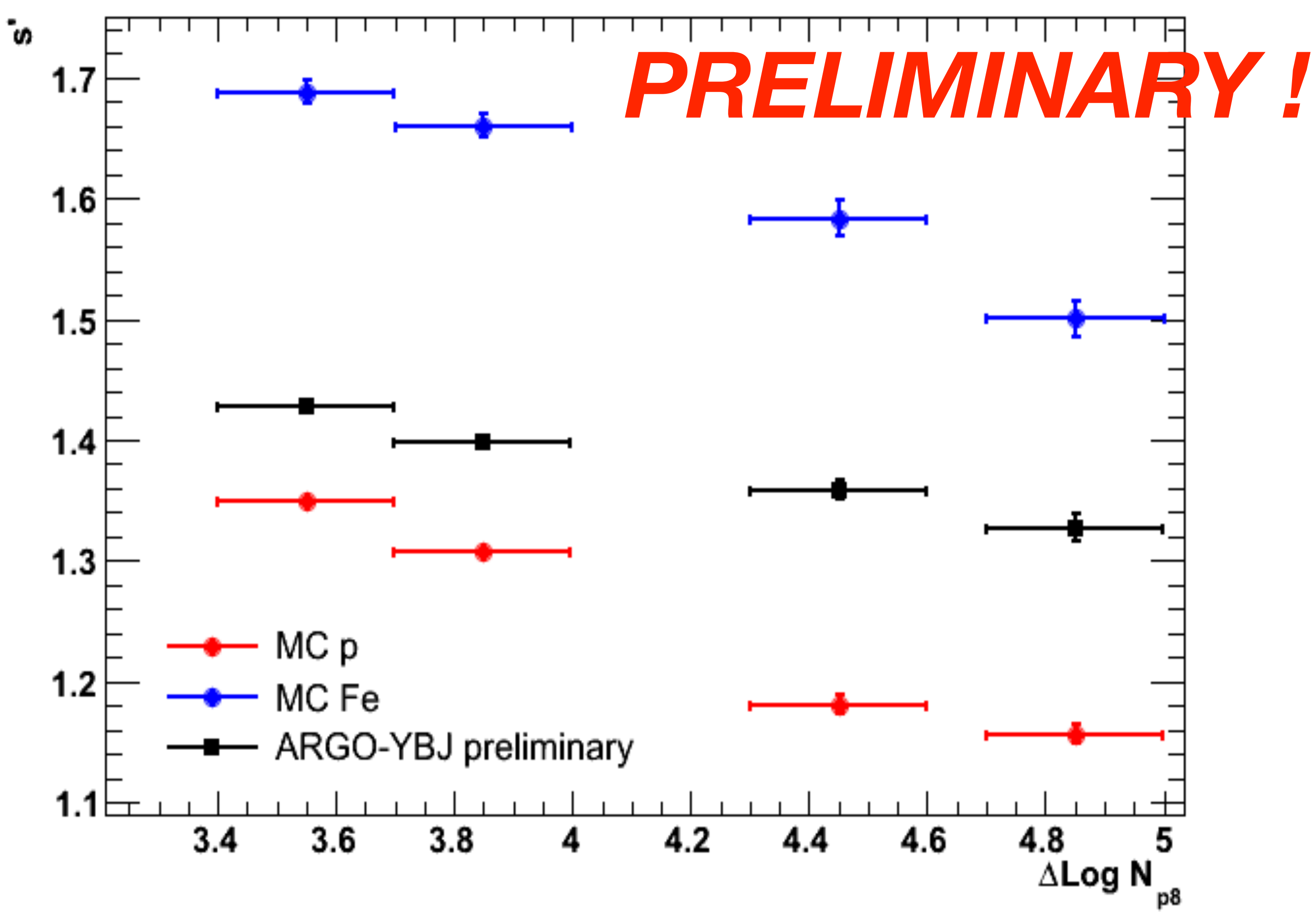
The s' parameter is correlated to the X_{max} position, whatever the primary is.

Shower age and primary mass

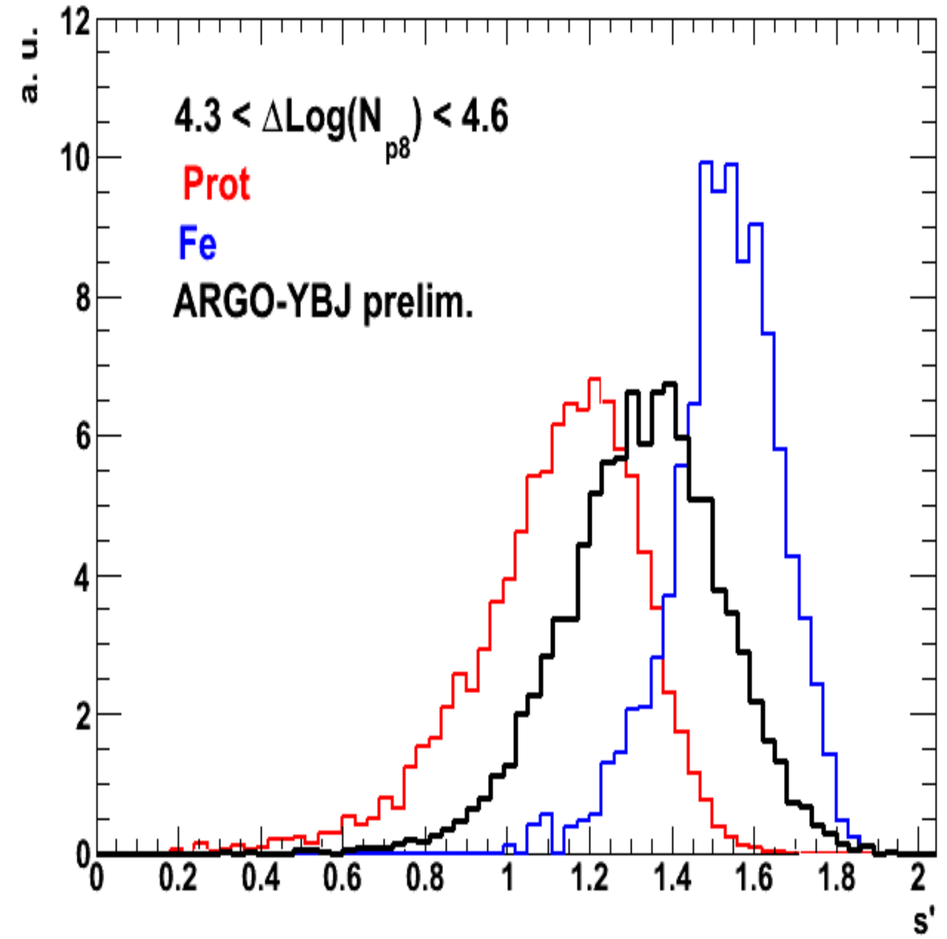
Np8 (number of particles within 8 m from the core):

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



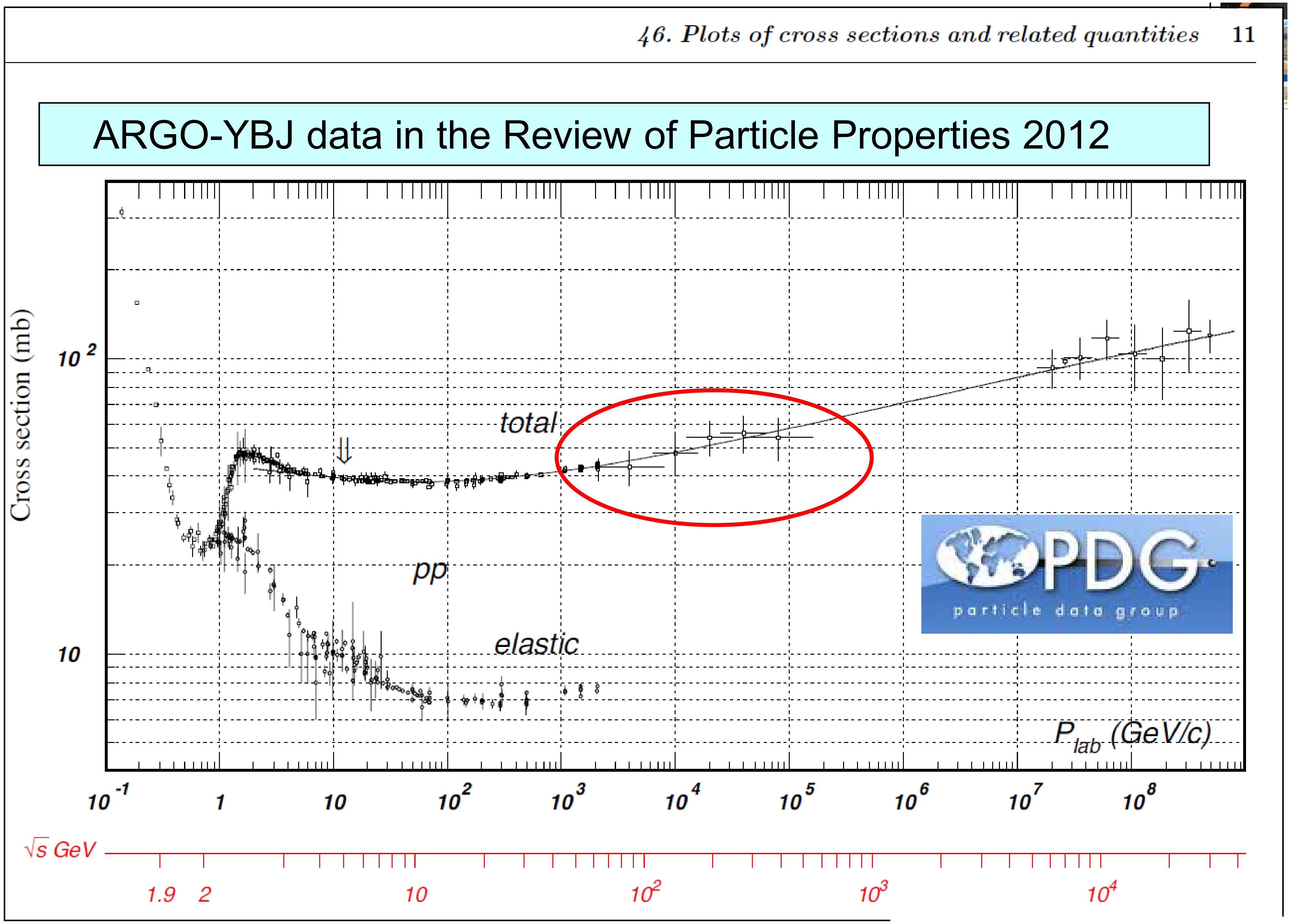


From event-wise LDF fits



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

The total p-p cross section



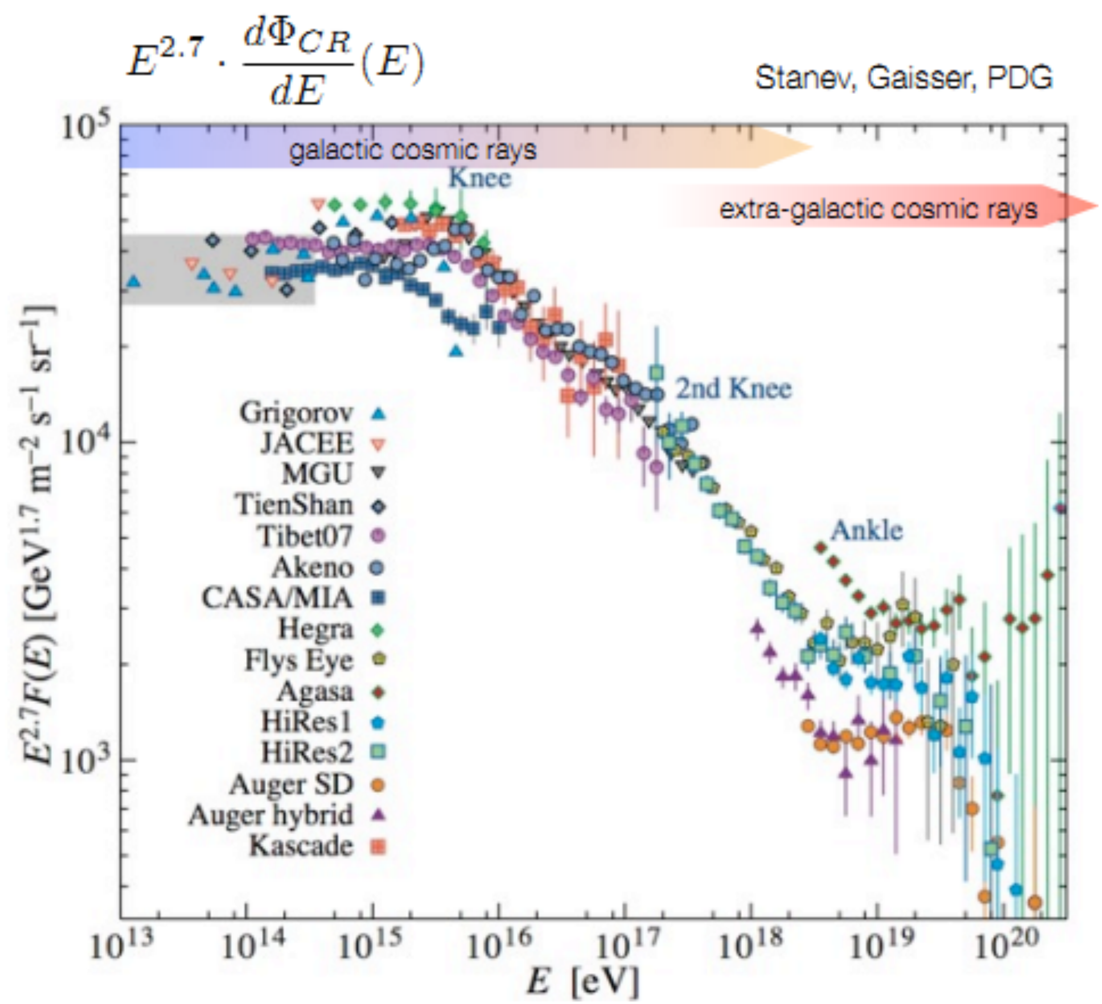
ARGO-YBJ Coll., Phys. Rev D 80, 092004 (2009)

Questions to the knee energy range

Cosmic Ray Sources ?	➡	**Still open**
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**

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

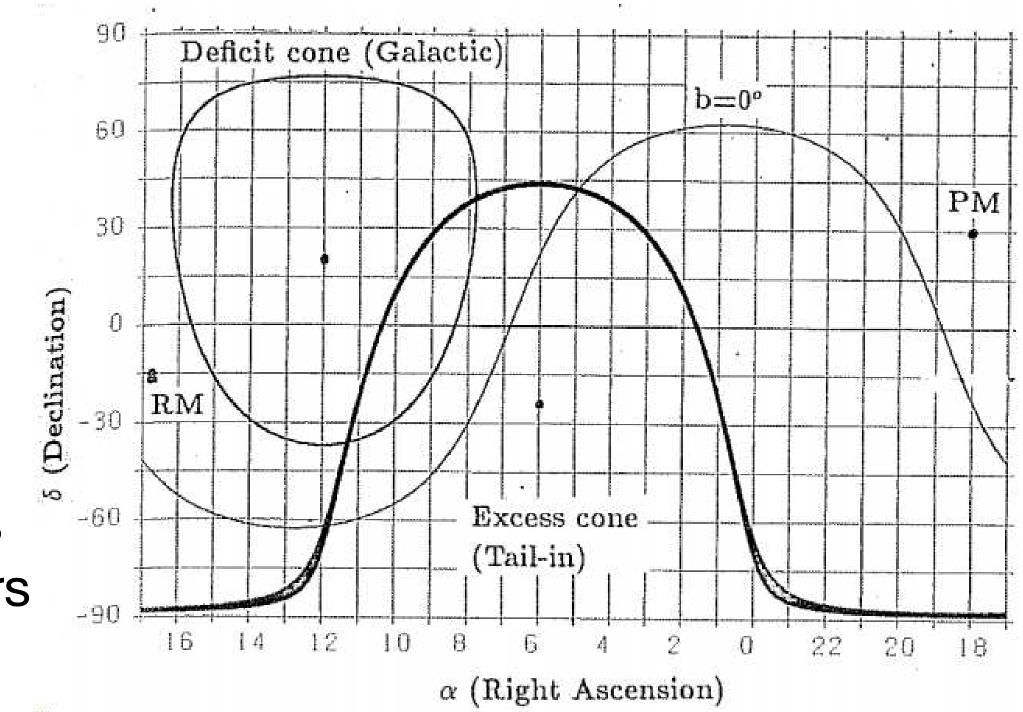


Galactic CRs are expected to be highly isotropic
scrambled by galactic magnetic field over very long time.

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

Measuring the anisotropy

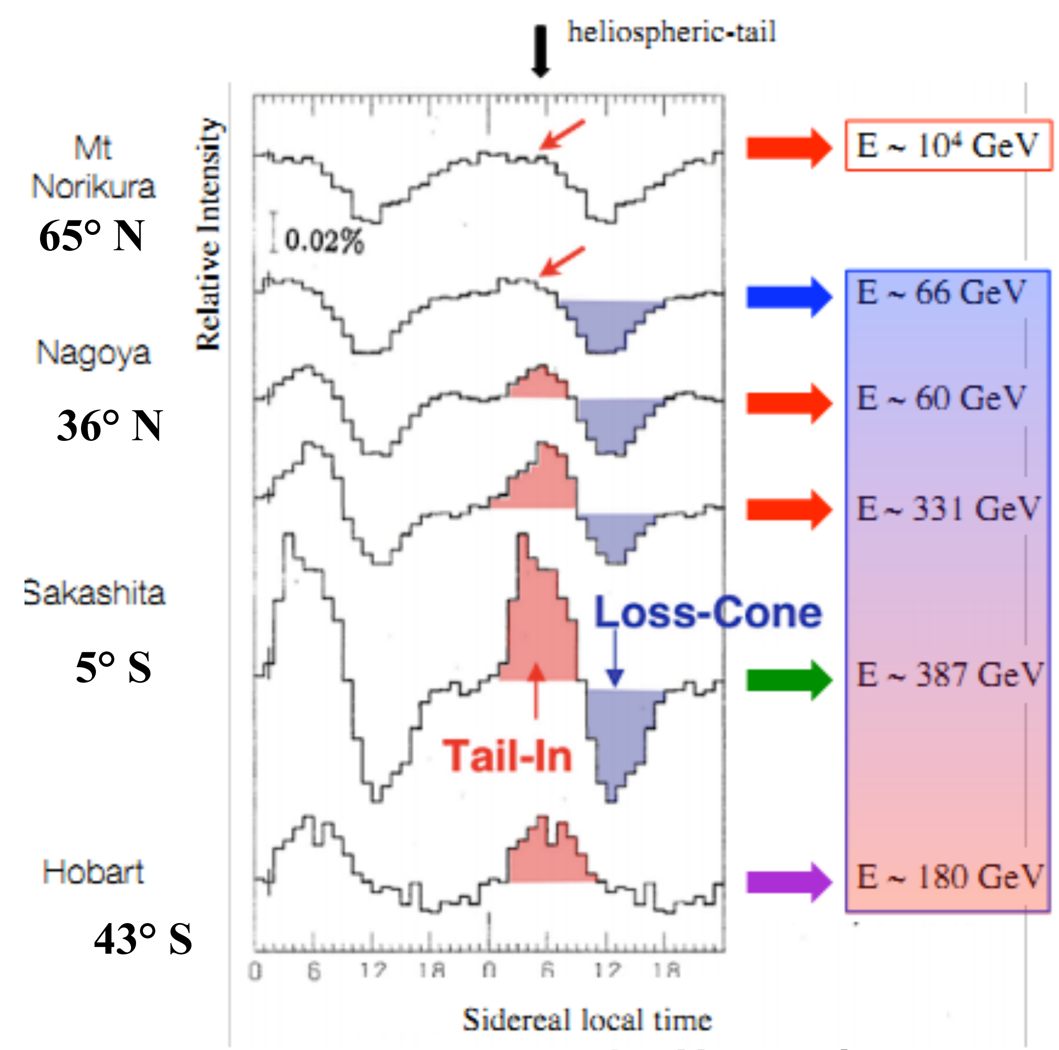
★ anisotropy of arrival direction of CRs clearly observed since 80's
★ 10's GeV - 100's TeV in μ detector, surface arrays and ν detectors
★ observed anisotropy of about 10^{-3} - 10^{-4}



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



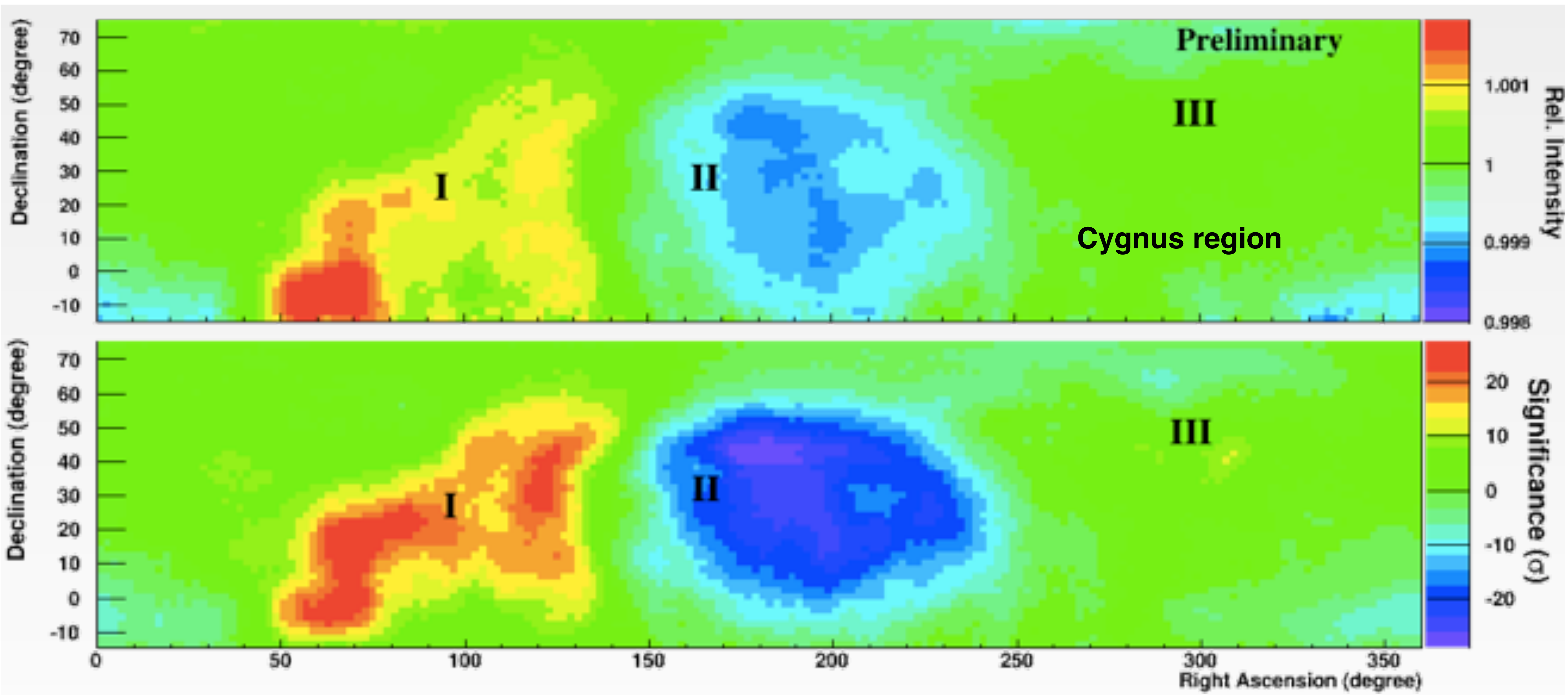
by Nagashima 1998

Large scale anisotropy by ARGO-YBJ

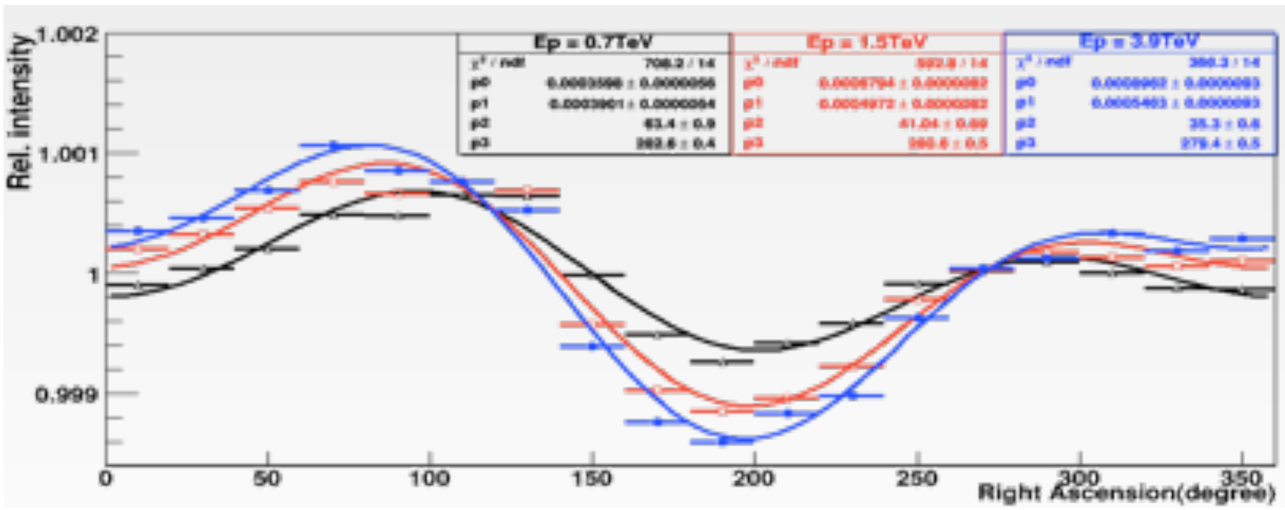
2 years data: 2008- 2009, E ≈ 1 TeV, 3.6×10^{10} events

Final analysis under way

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

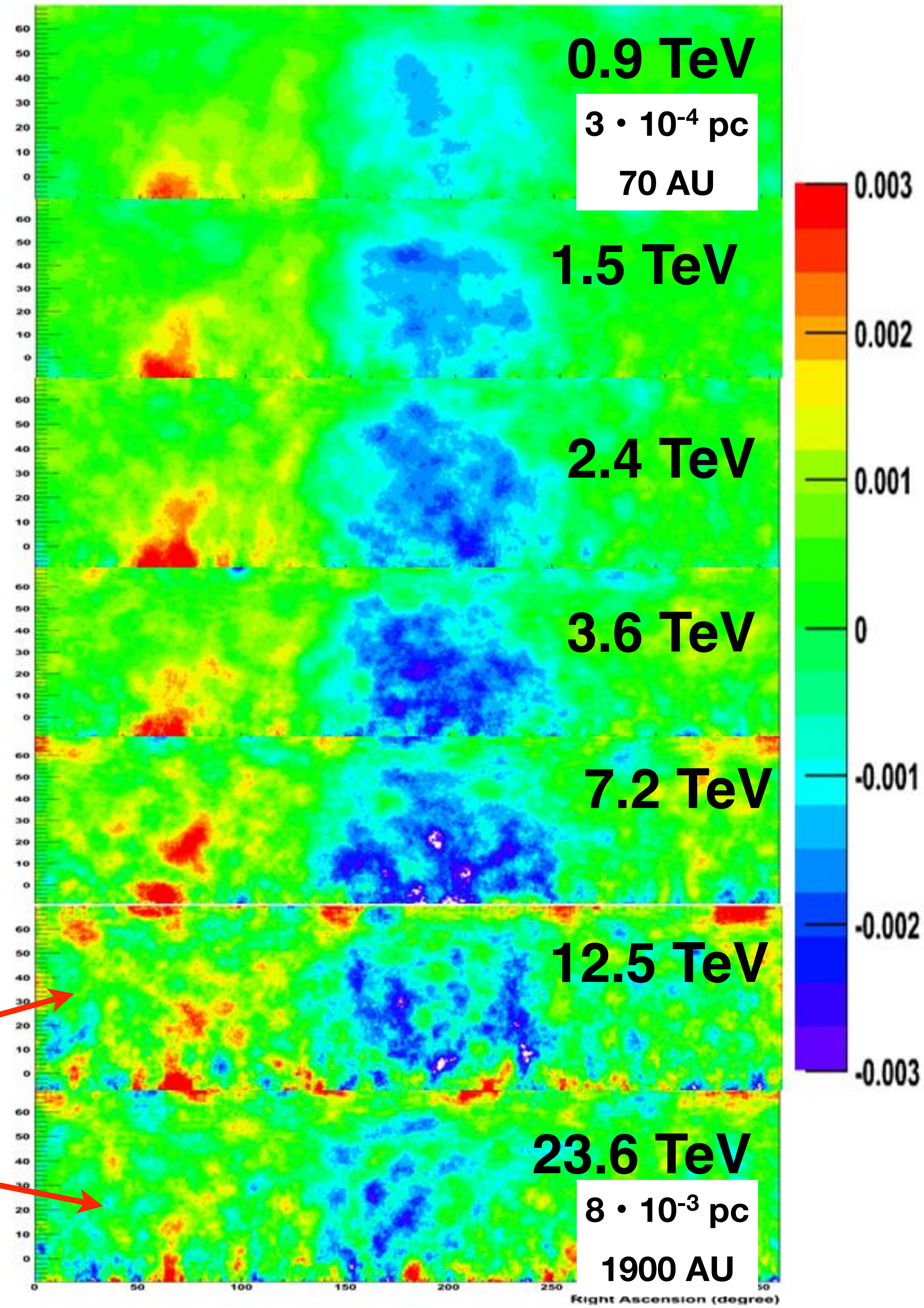


Anisotropy vs energy



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

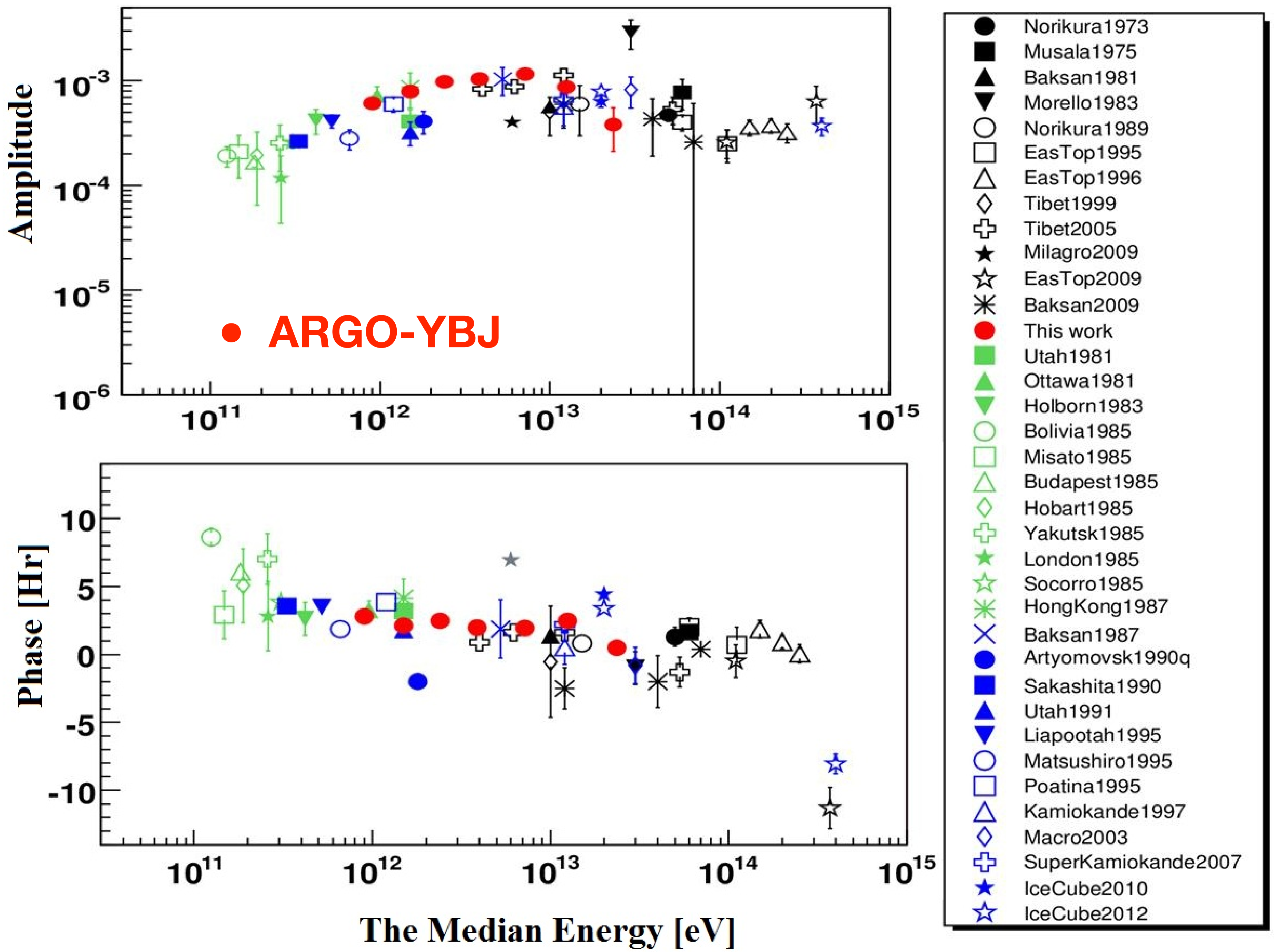
The tail-in broad structure appears to dissolve to smaller angular scale spots



Amplitude and phase of the first harmonic

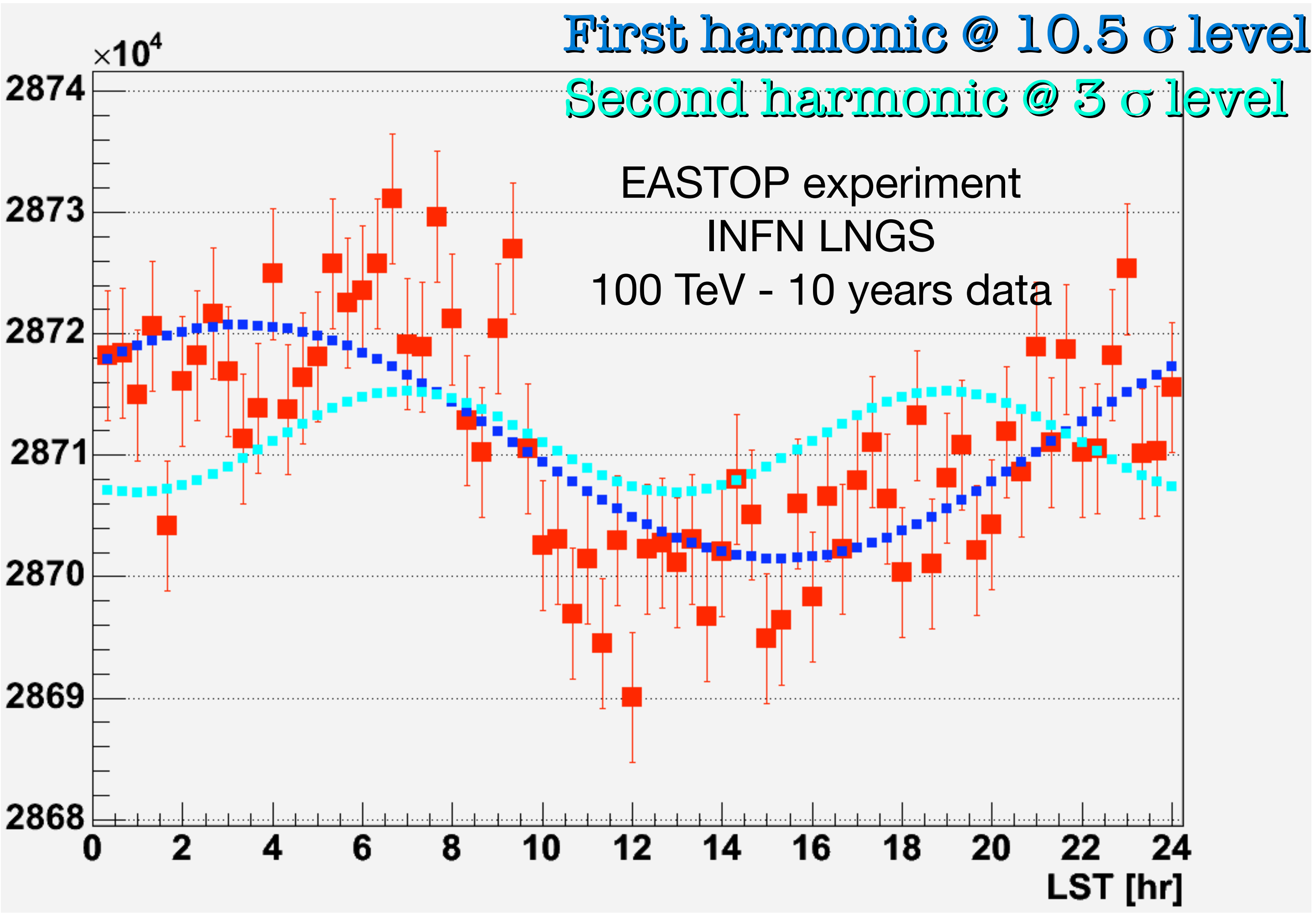
ARGO-YBJ results in good agrrement with other experiments.

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



What CR anisotropy tell us ?

The CR arrival distribution in sidereal time was never found to be purely dipolar,



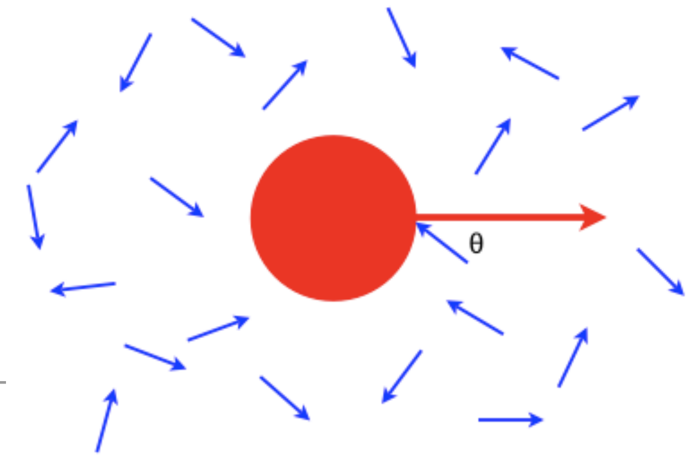
The use of 2 harmonics means that the spatial distribution of CR intensity has a rather complicated structure

No simple kinetic nature of the anisotropy
(CG effect)

The origin of the Large Scale Anisotropy is still unknown

The CR plasma is supposed to co-move with the solar system and the origin of the observed anisotropy is probably related to “harder” effects, to be searched for in unknown features of the local ISM, either for the magnetic field and the closest CR sources.

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.

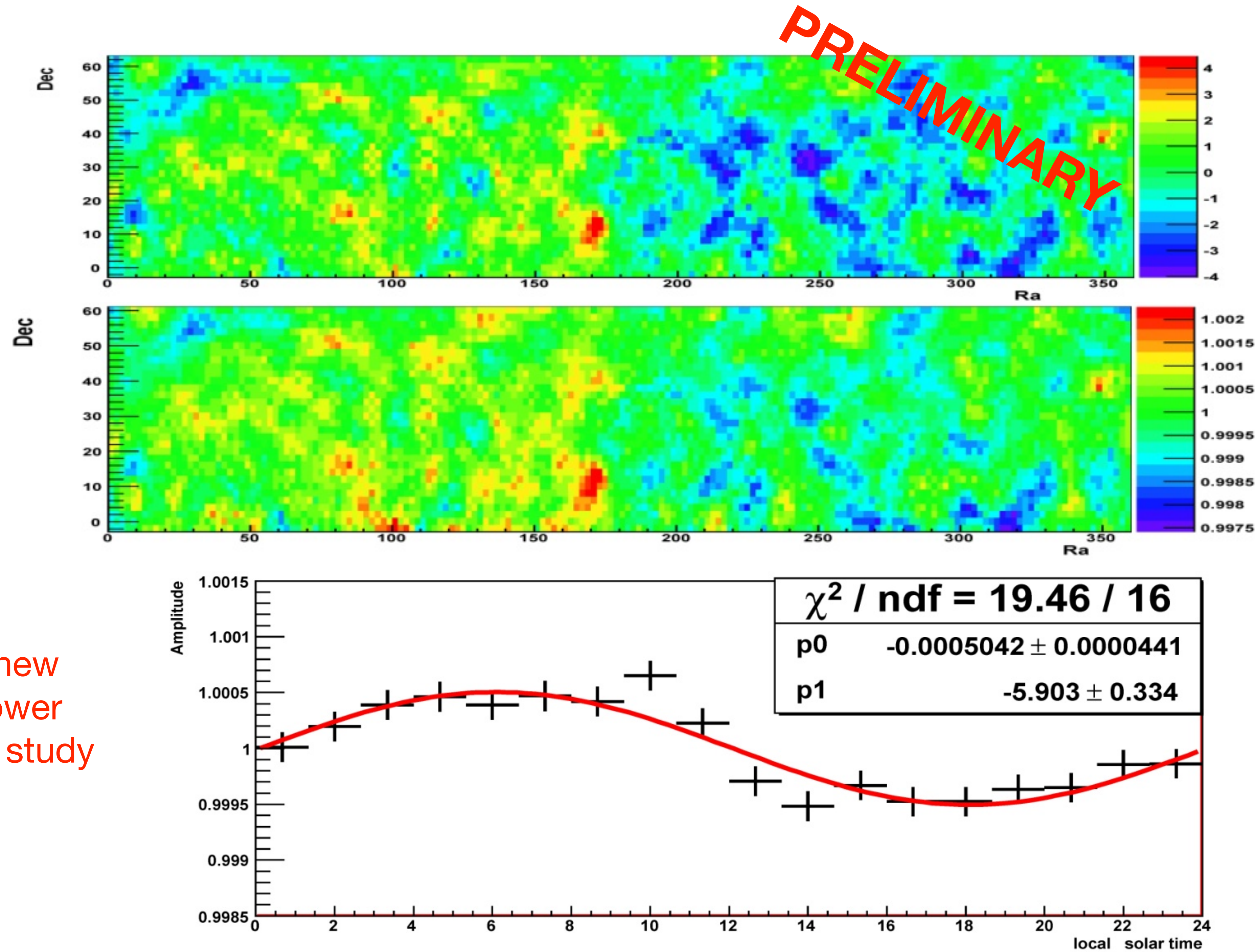
Compton-Getting effect by ARGO-YBJ

Solare Time (UT)
2008 – 2009 data

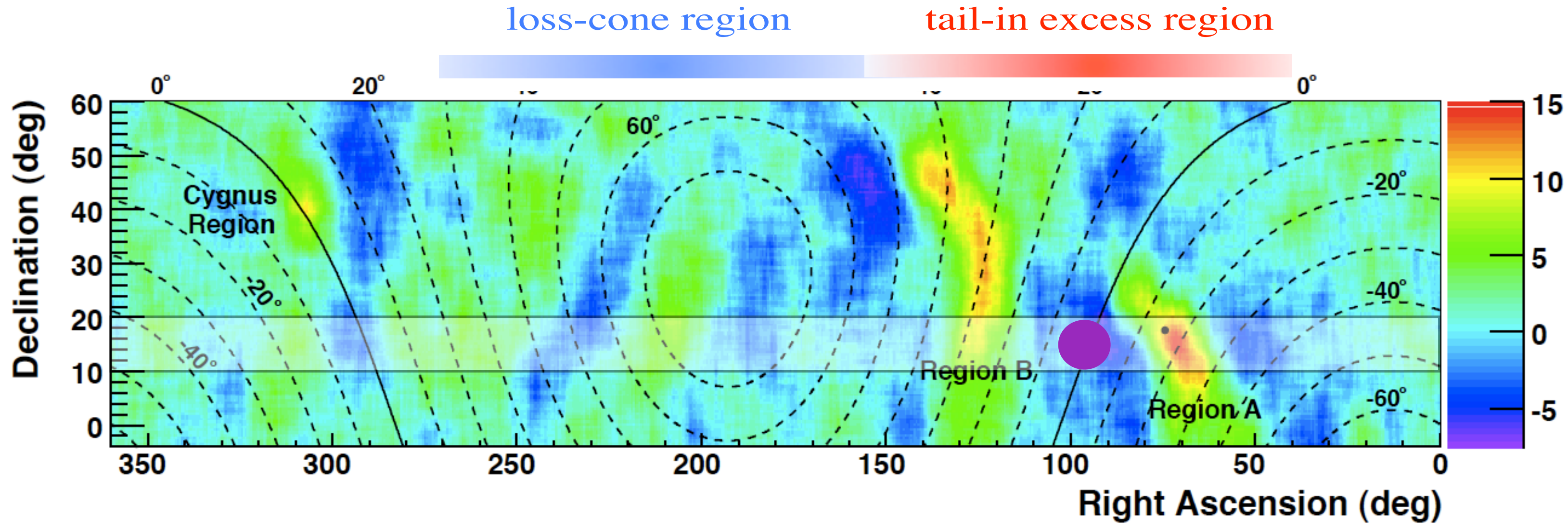
Nhit 500 → ≈ 8 TeV

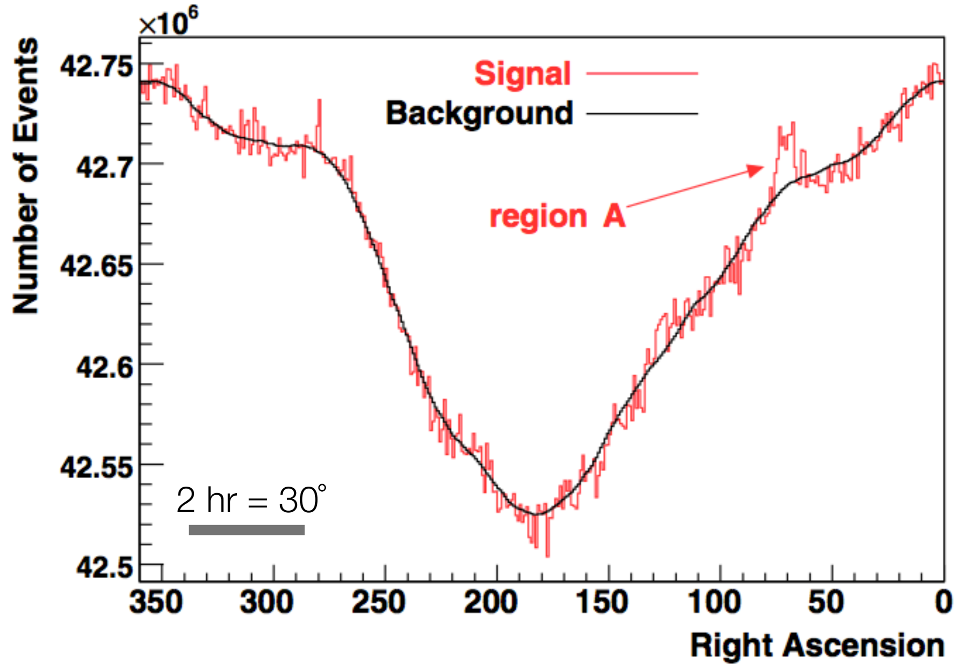
to avoid solar effects
on low energy CRs

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



medium/small scale anisotropy





Abdo et al., Phys.Rev.Lett.**101** (2008) 221101

Milagro

$2.2 \cdot 10^{11}$ events
median CR energy ~ 1 TeV = 10^{12} eV
average angular resolution < 1°

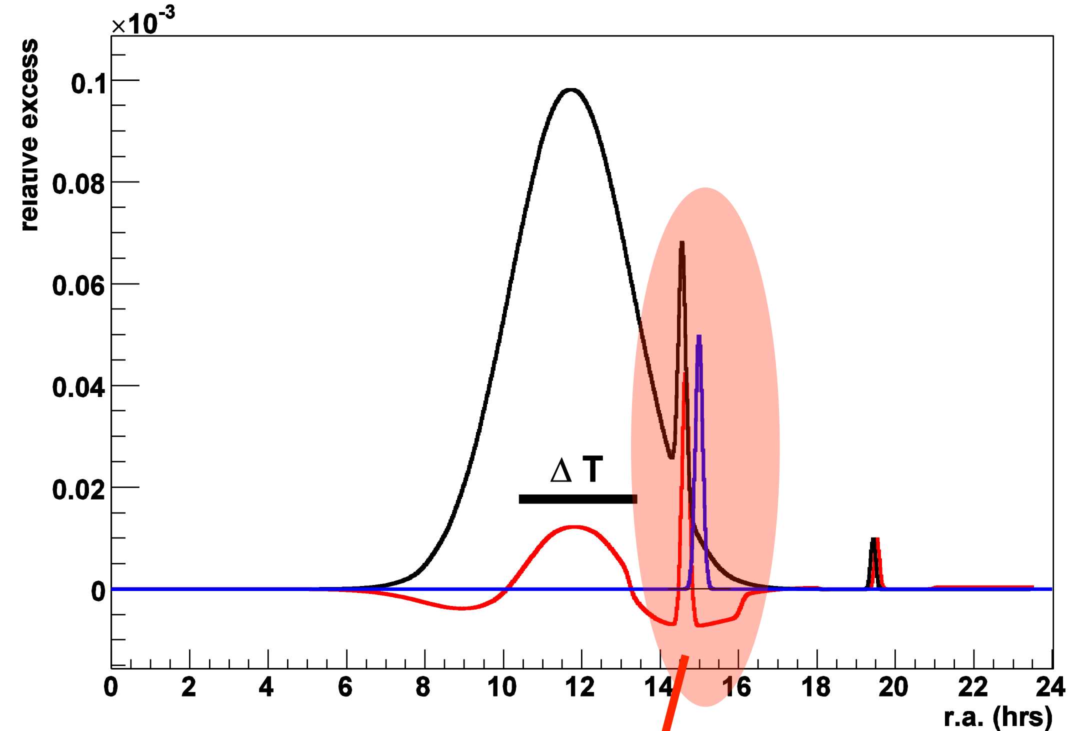
2hr time window
10° smoothing

- filter all angular features > 30°
- technique used in γ-ray searches

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.

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

Medium Scale Anisotropy



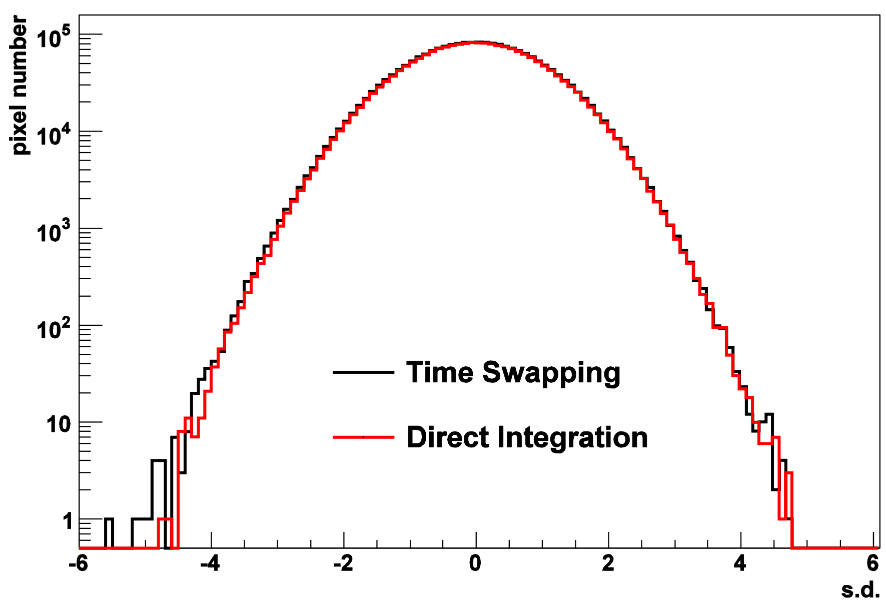
How to focus on medium scale structures ?

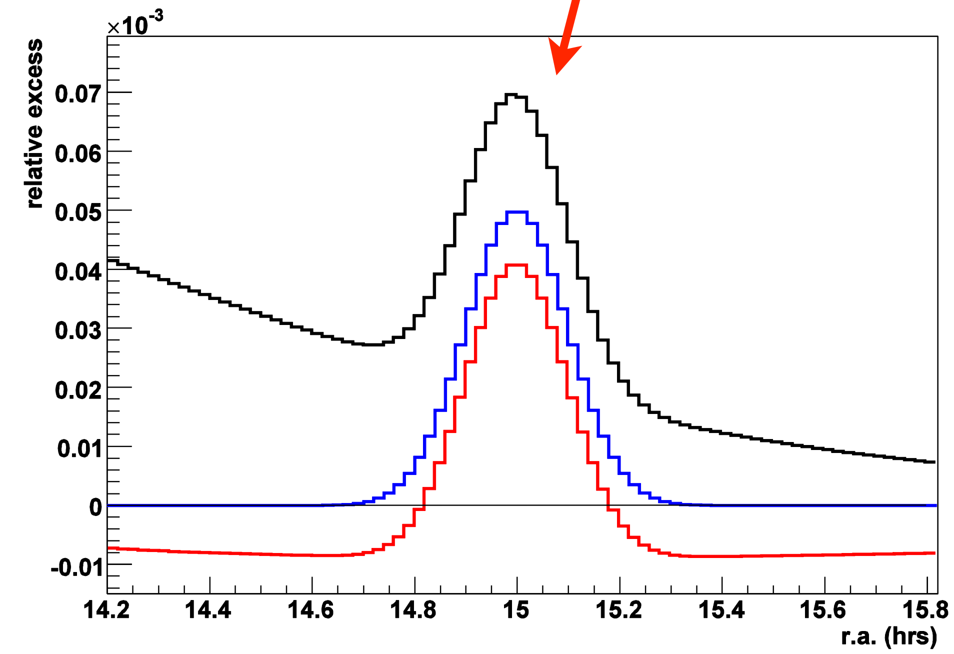
Traditional background estimation methods:

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

(consistent each other within 0.3 s.d.)

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

Medium/Small Scale Anisotropy

Data: November 8, 2007 - May 20, 2012

≈ 3.70×10^{11} events

dec. region δ ~ -20°÷ 80°

Map smoothed with the detected PSF for CRs

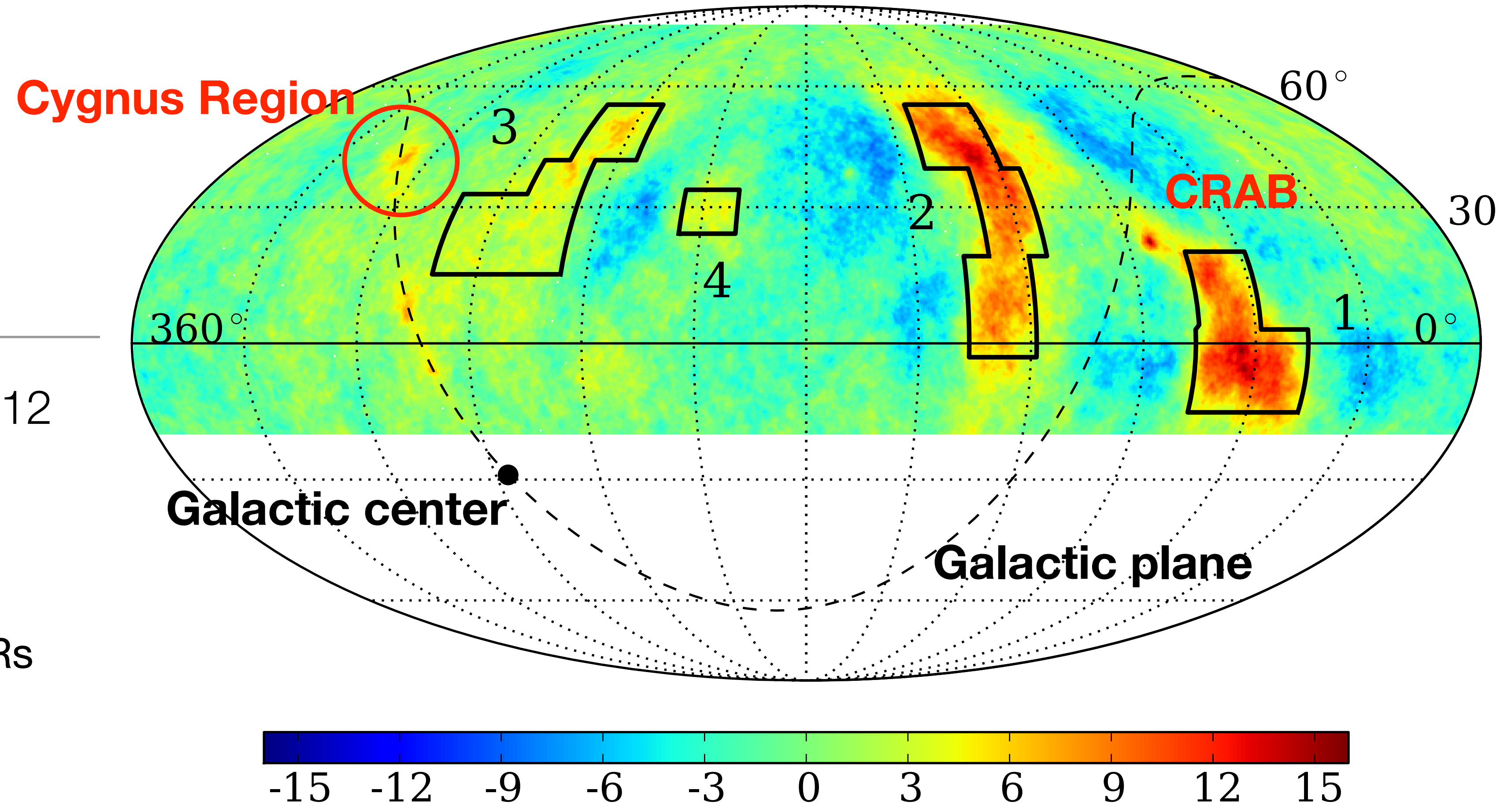
Proton median energy ≈ 1 TeV

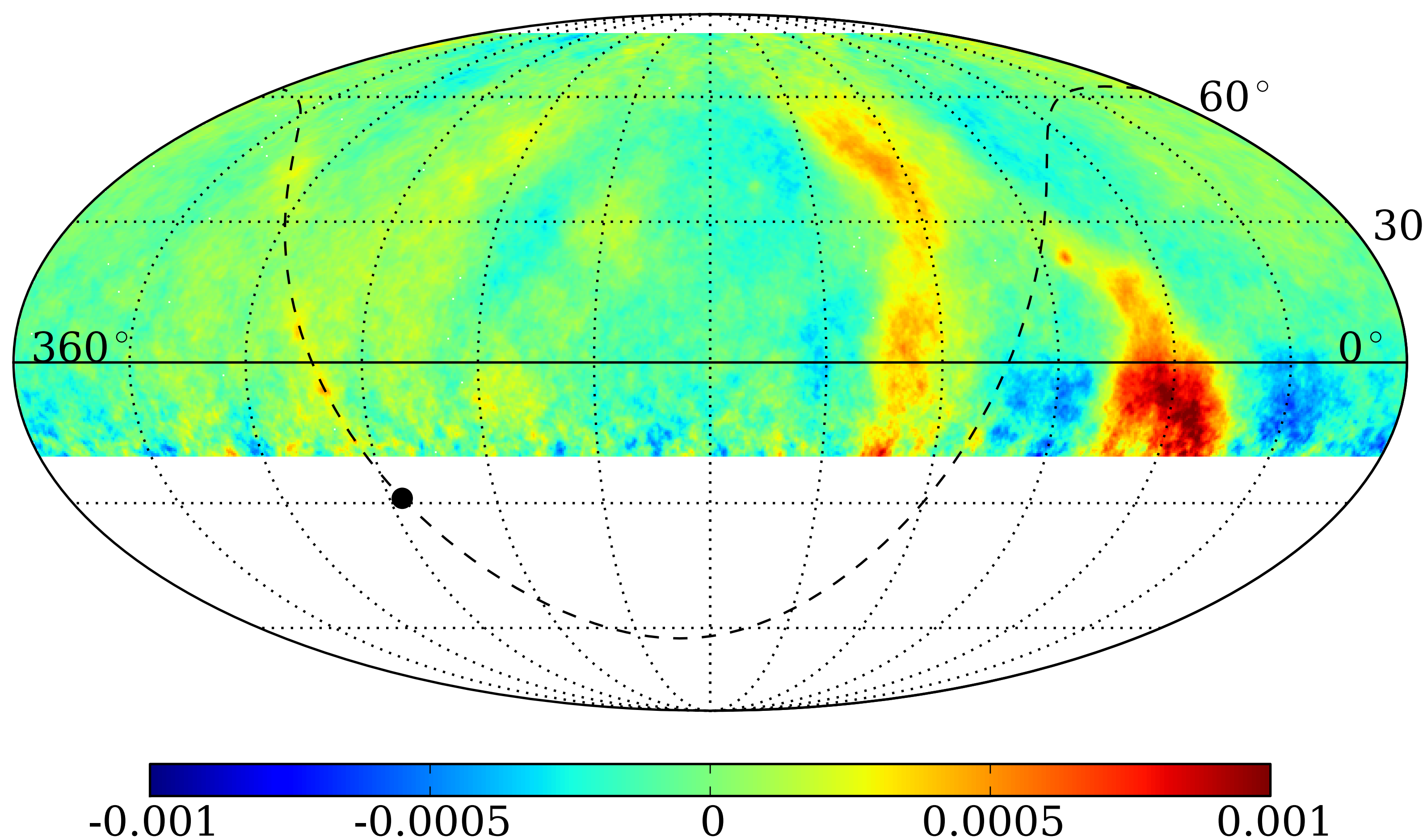
CRs excess ≈ 0.1 %
with signifincance up to 15 s.d.

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

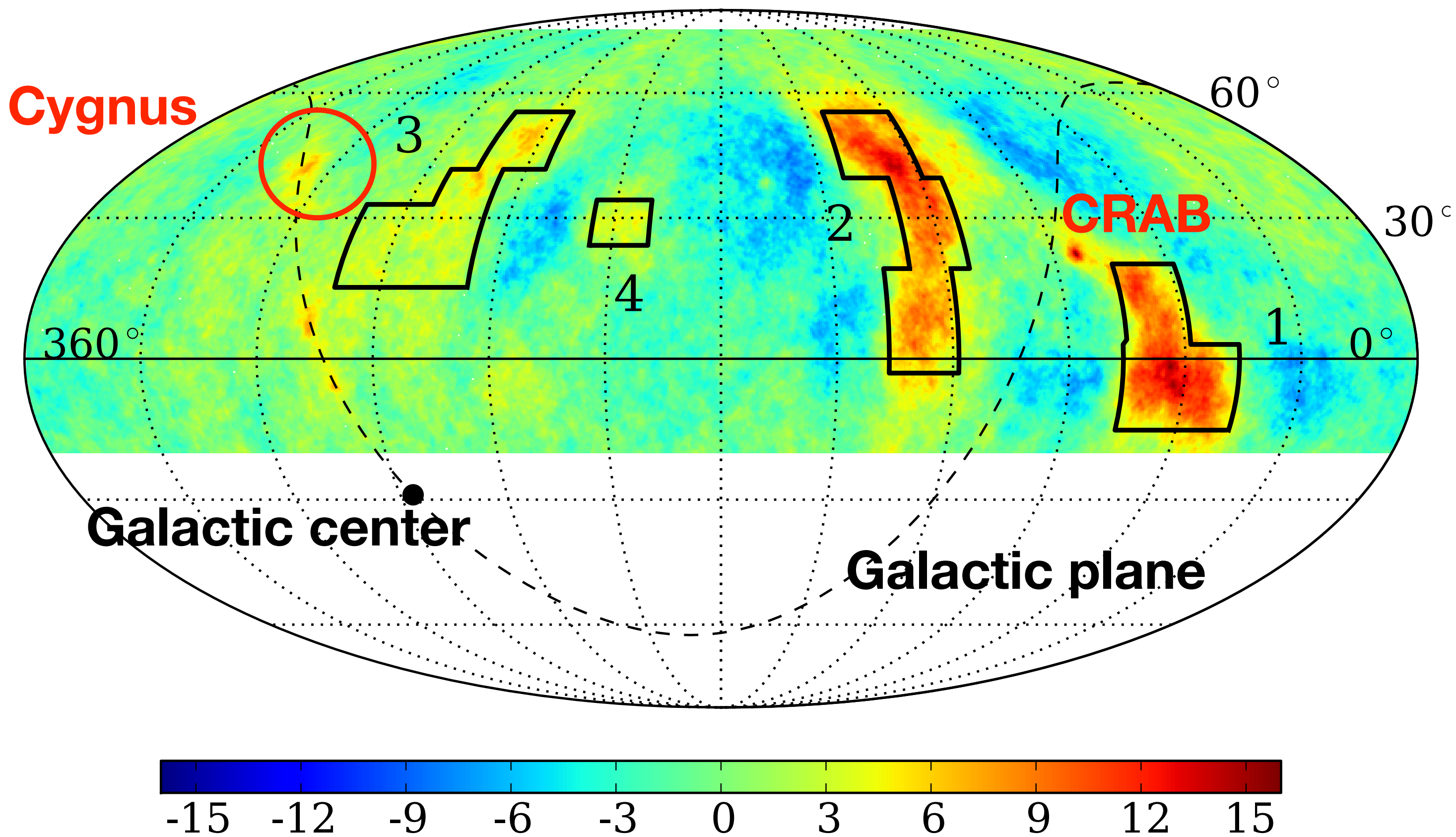
TABLE I: Multiplicity intervals used in the analysis. The central columns report the number of events collected. The right column shows the corresponding isotropic CR proton median energy.

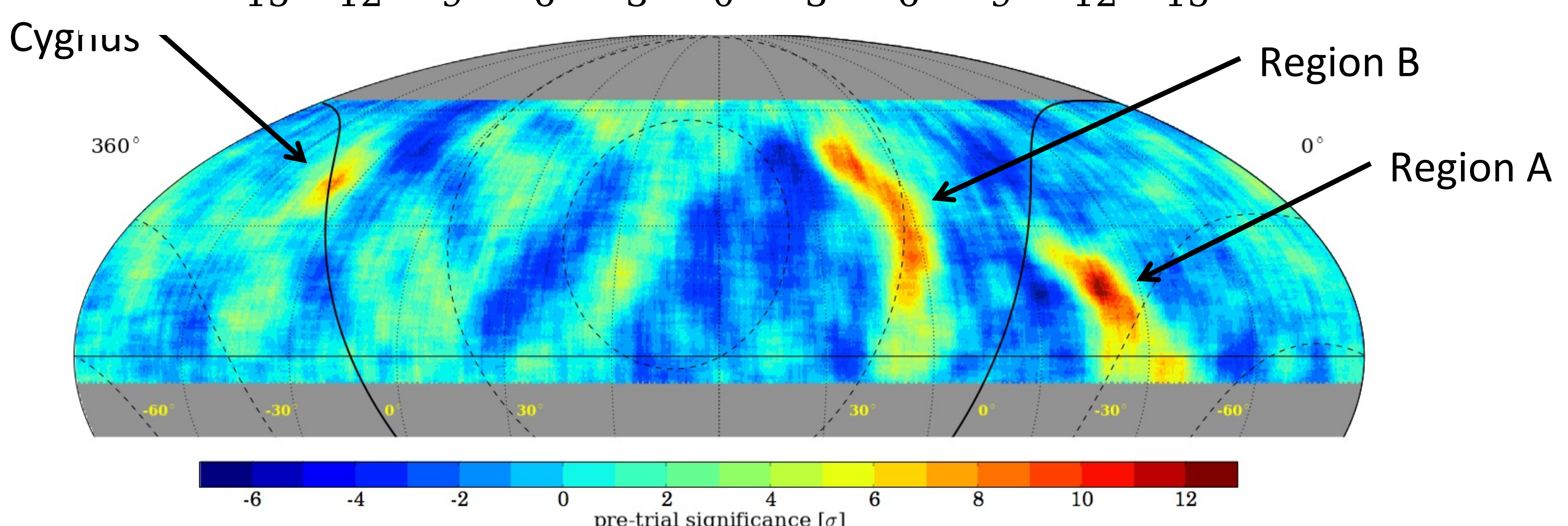
PRD in press





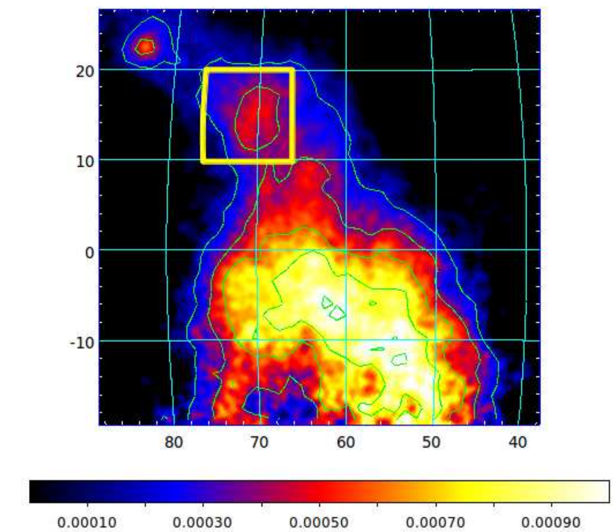
Comparison to Milagro Sky Map



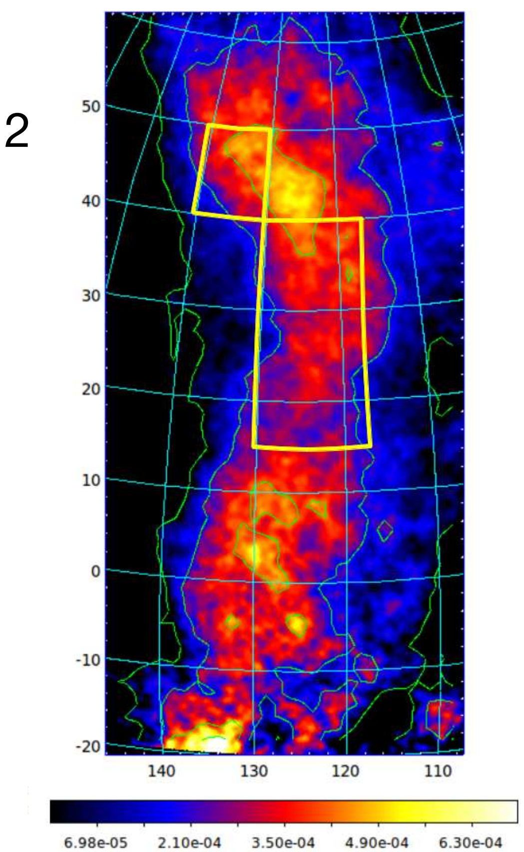


A. Abdo et al., PRL **101**:221101, 2008

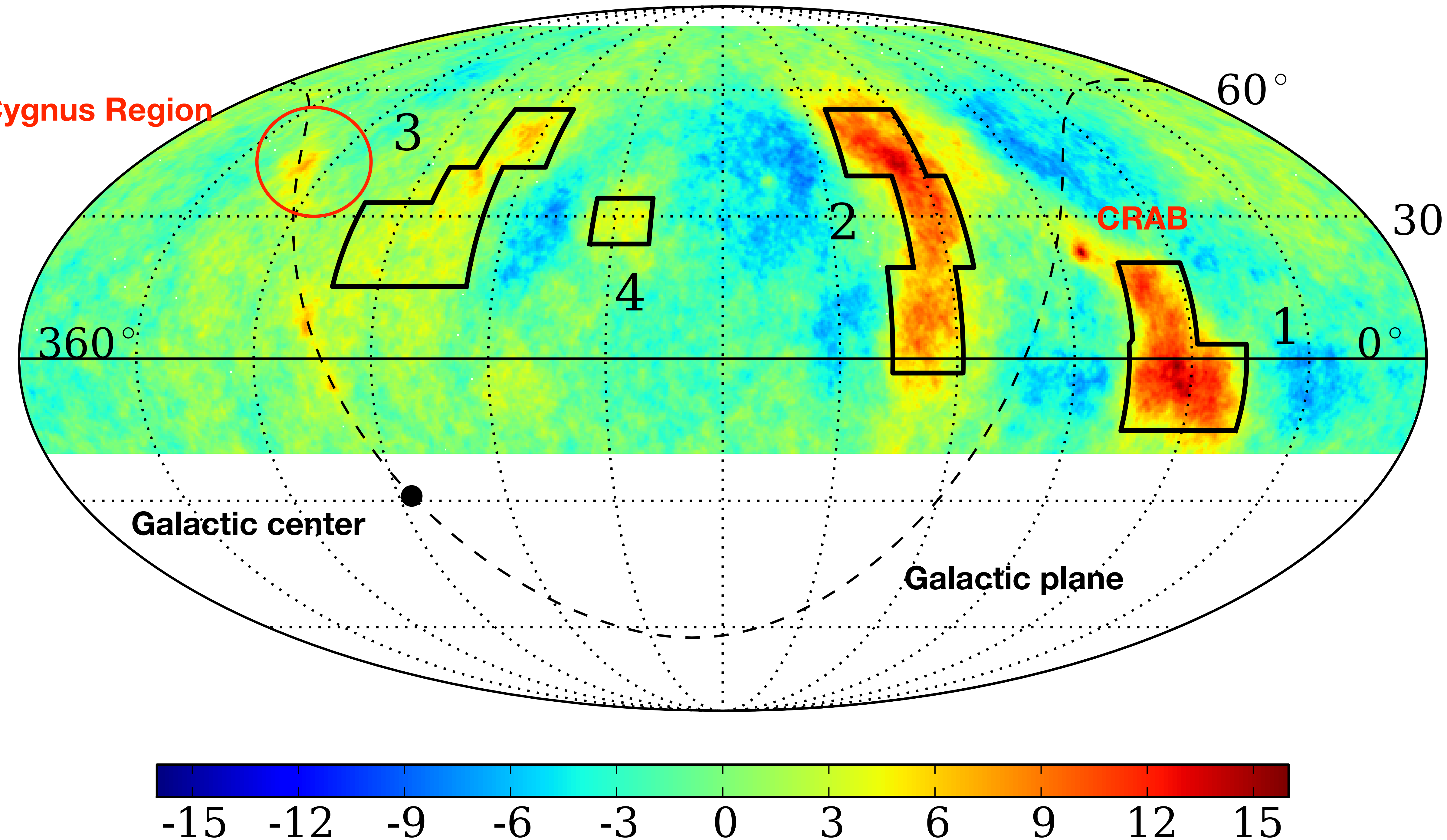
Region 1



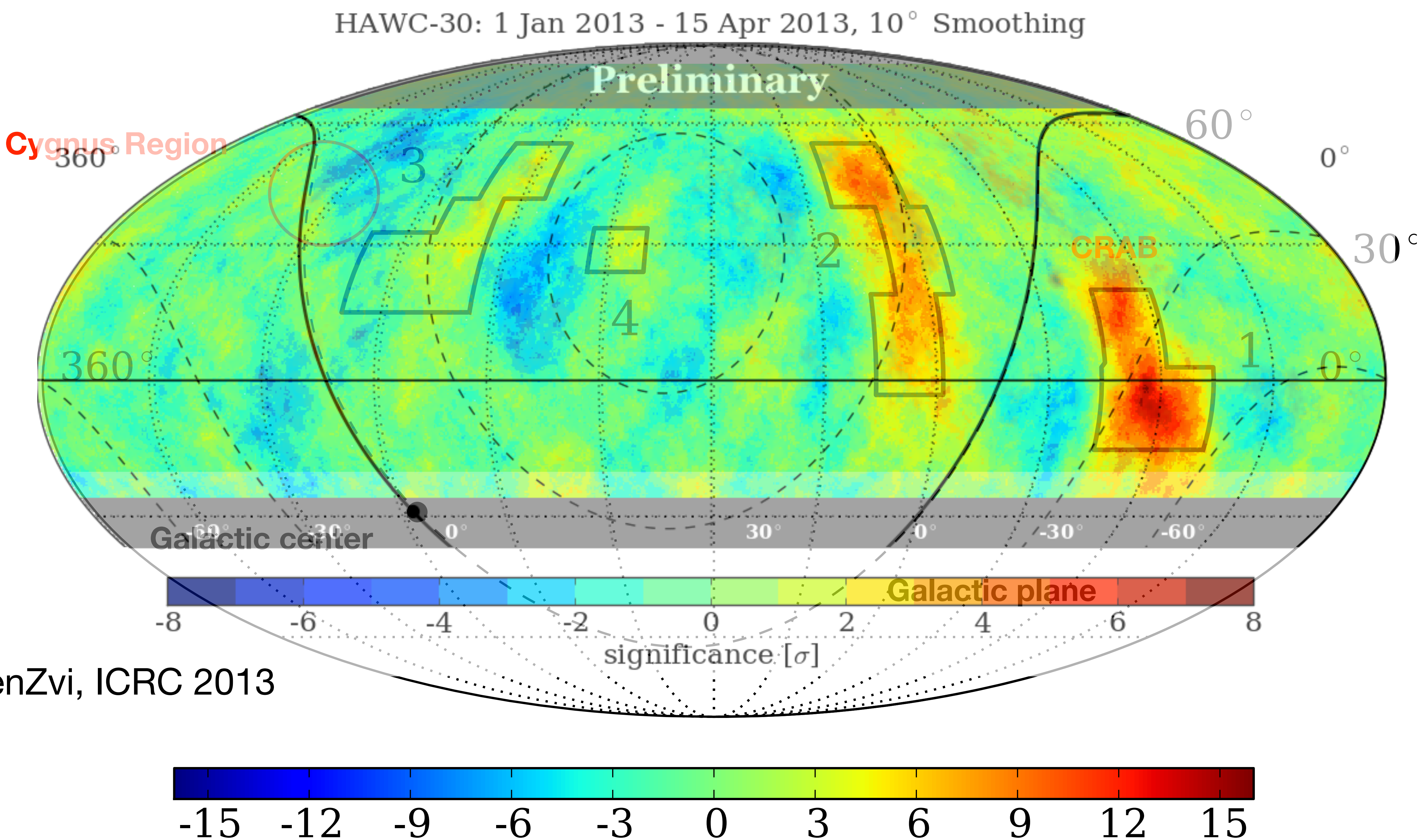
Region 2



Comparison to HAWC Sky Map

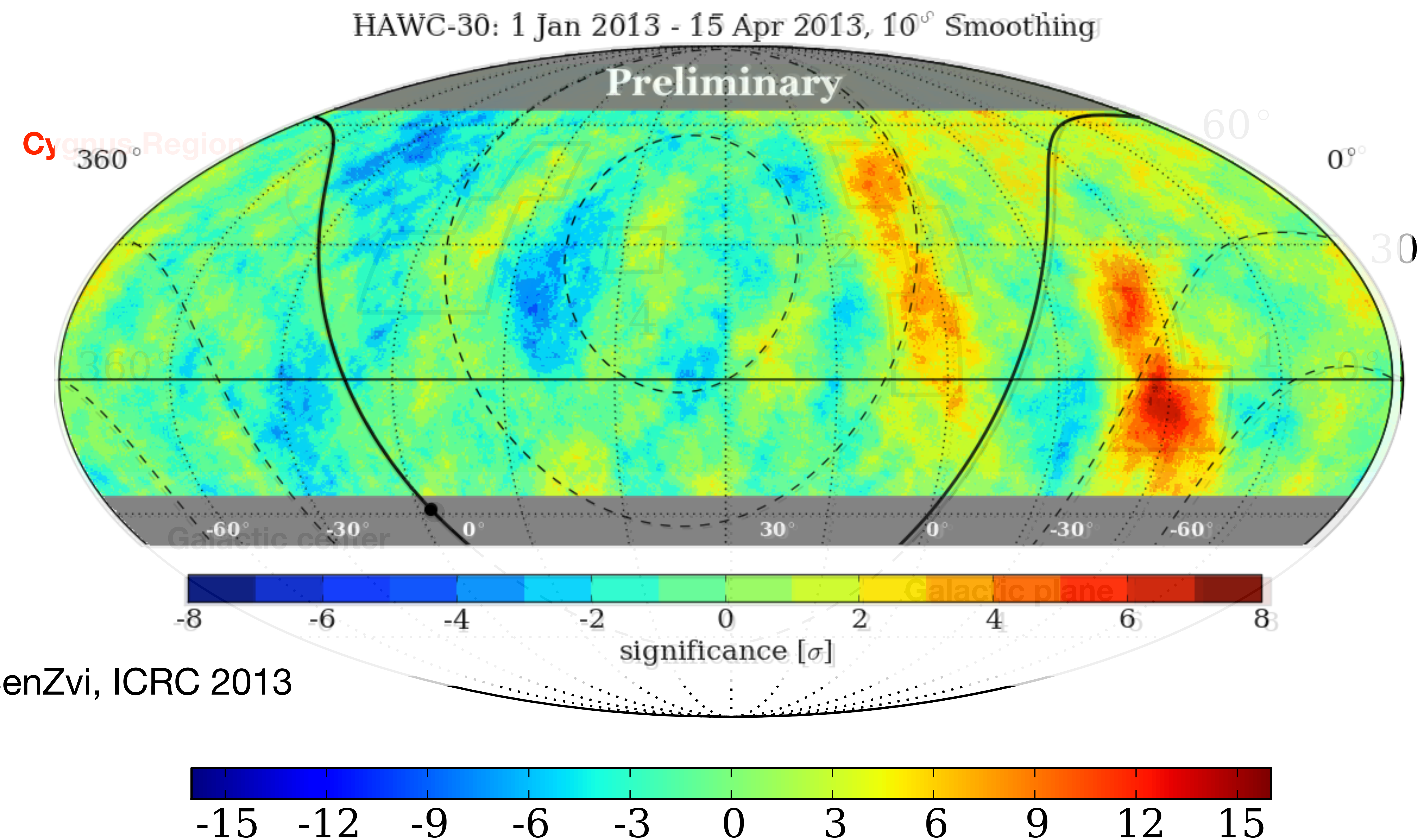


Comparison to HAWC Sky Map



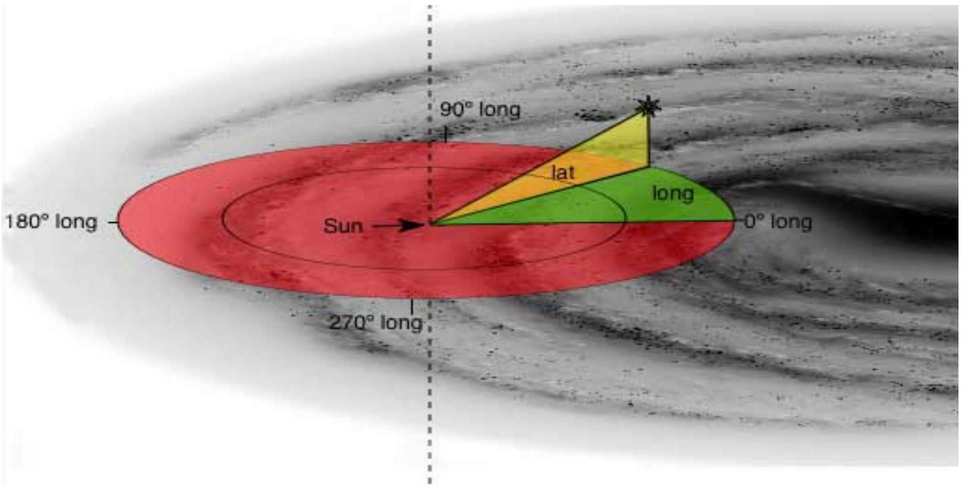
S. BenZvi, ICRC 2013

Comparison to HAWC Sky Map

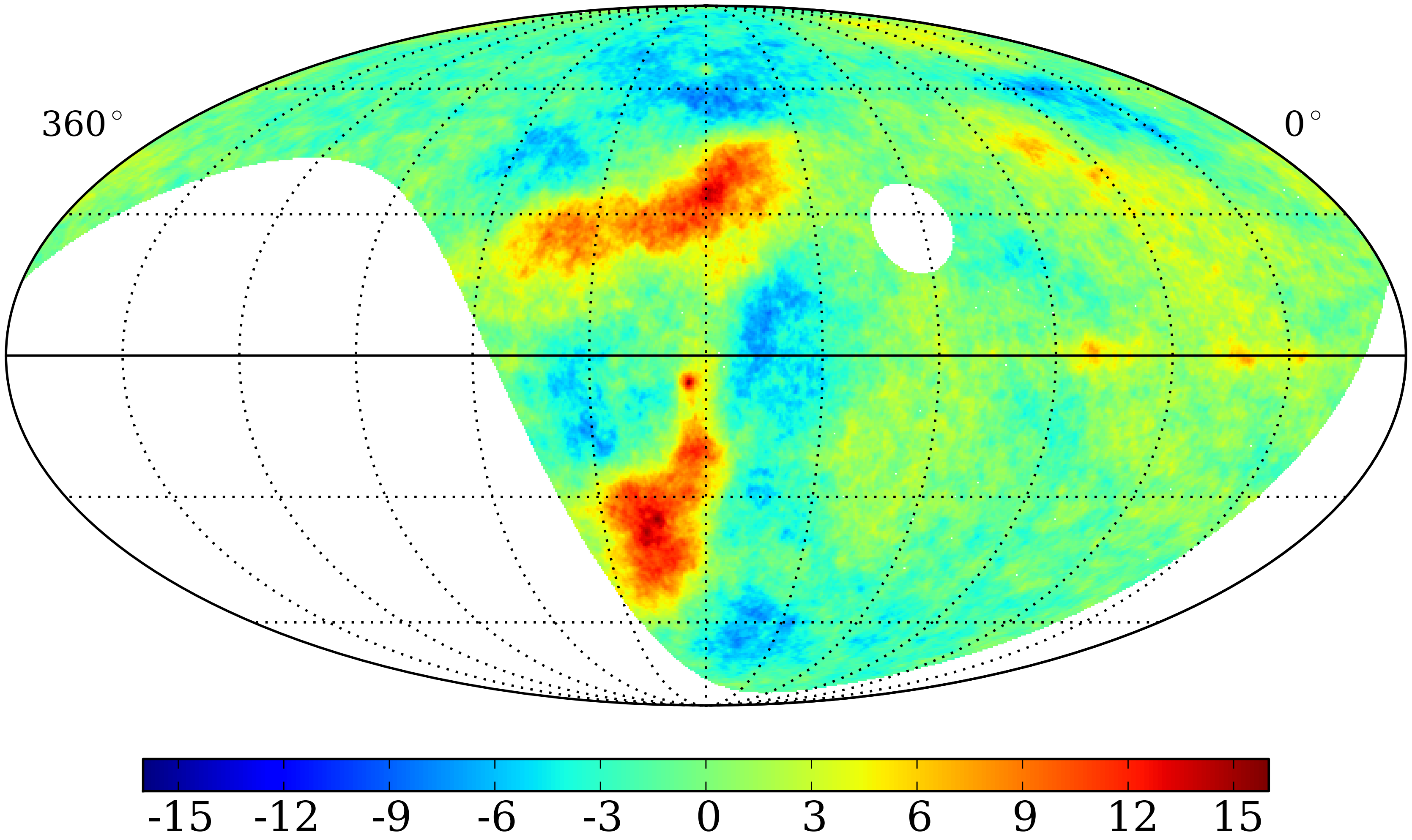


S. BenZvi, ICRC 2013

MSA in galactic coordinates



The map center points towards the galactic Anti-Center.

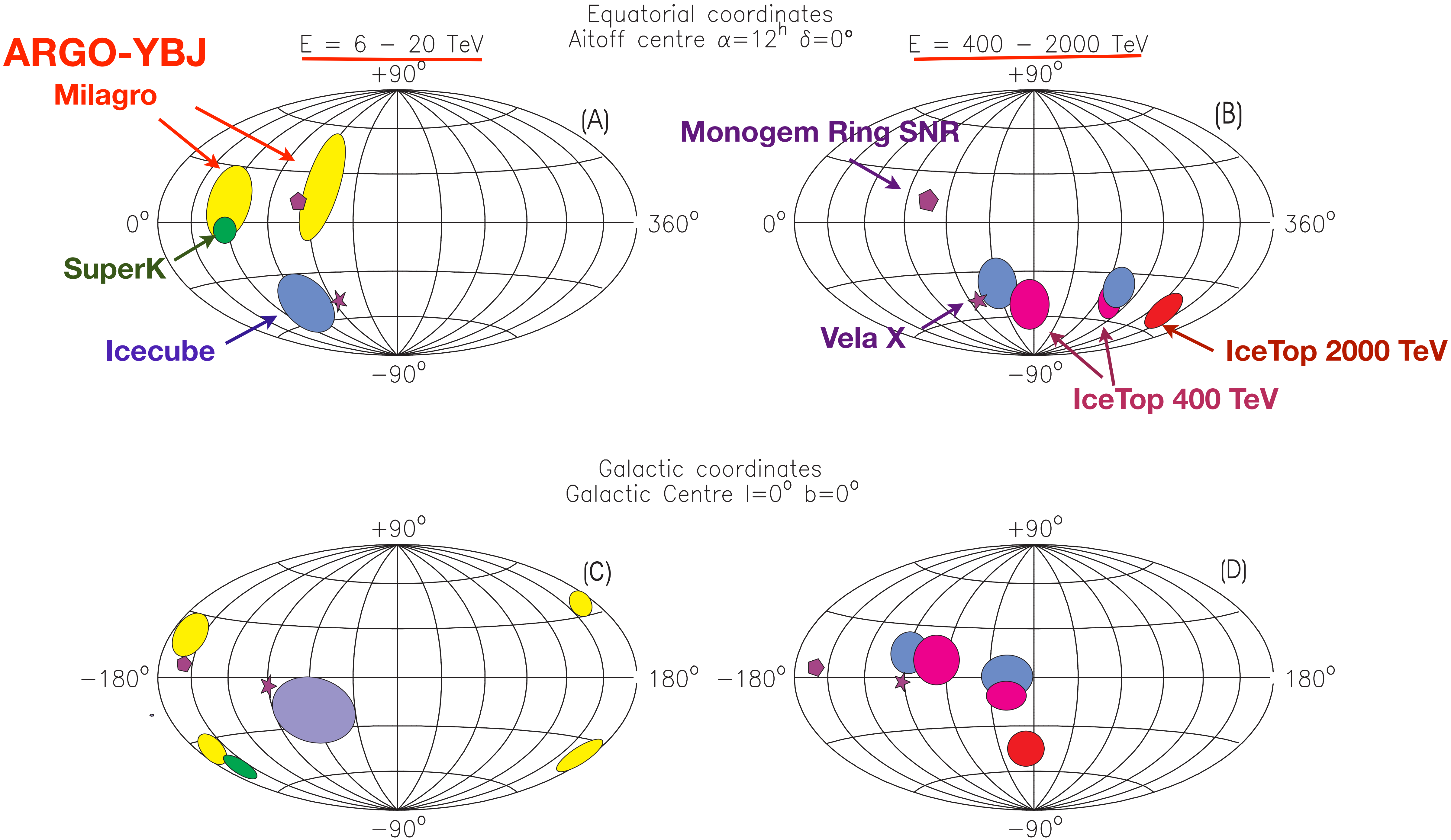


The regions 1 and 2 are distributed symmetrically with respect to the Galactic plane and have longitude centered around the galactic Anti-Center.

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

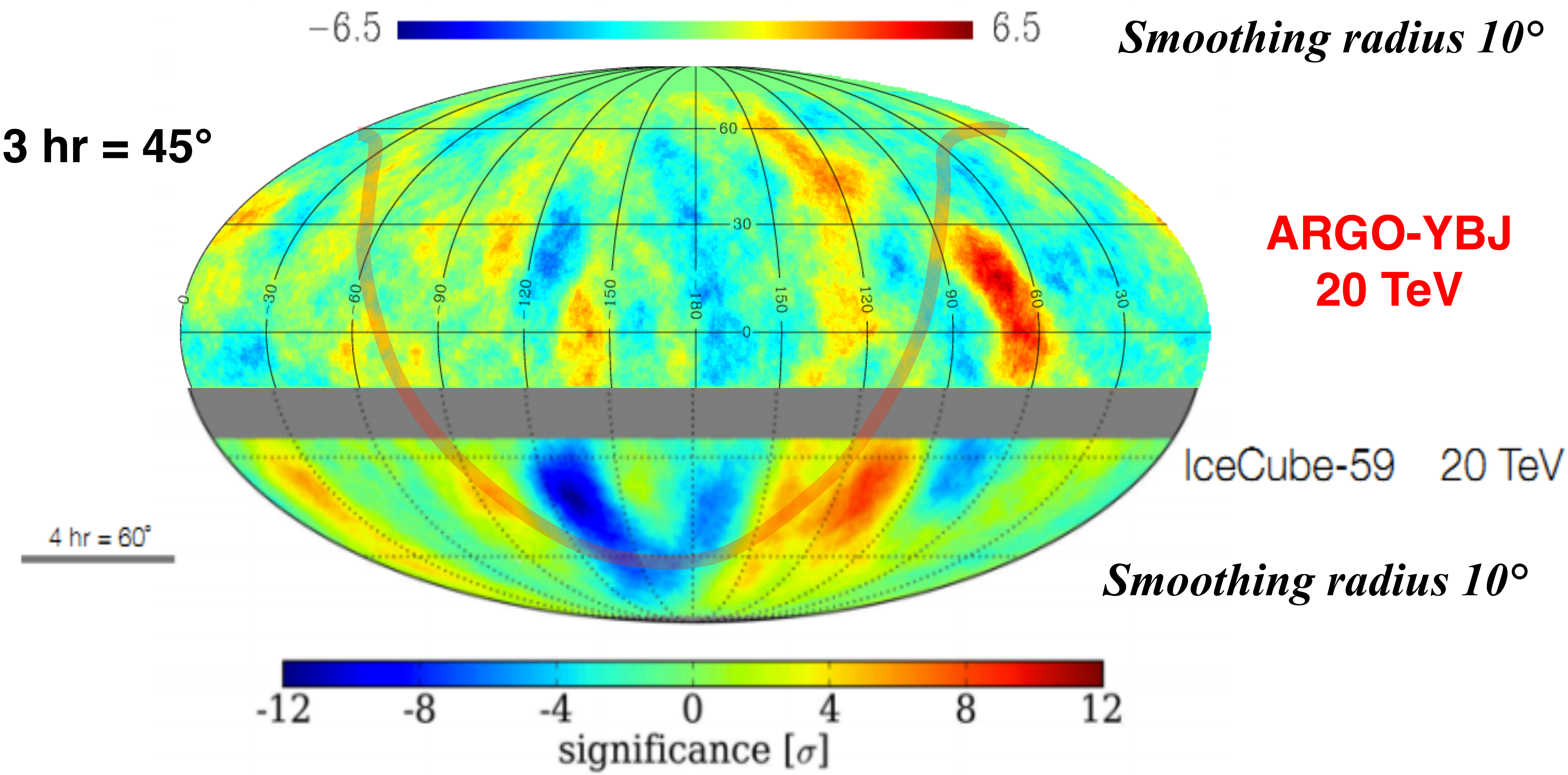
In spite of the fact that the bulk of SNR, pulsars and other potential CR sources are in the Inner Galaxy surrounding the Galactic Centre, the excess of CR is observed in the opposite, Anti-Centre direction.
The fact that the observed excesses are in the Northern and in the Southern Galactic Hemispheres,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

Comparison with other observations



by A. Erlykin and A. Wolfendale, 2013

Outlook to the future: towards a complete TeV CR sky-map



Towards a complete TeV CR sky-map

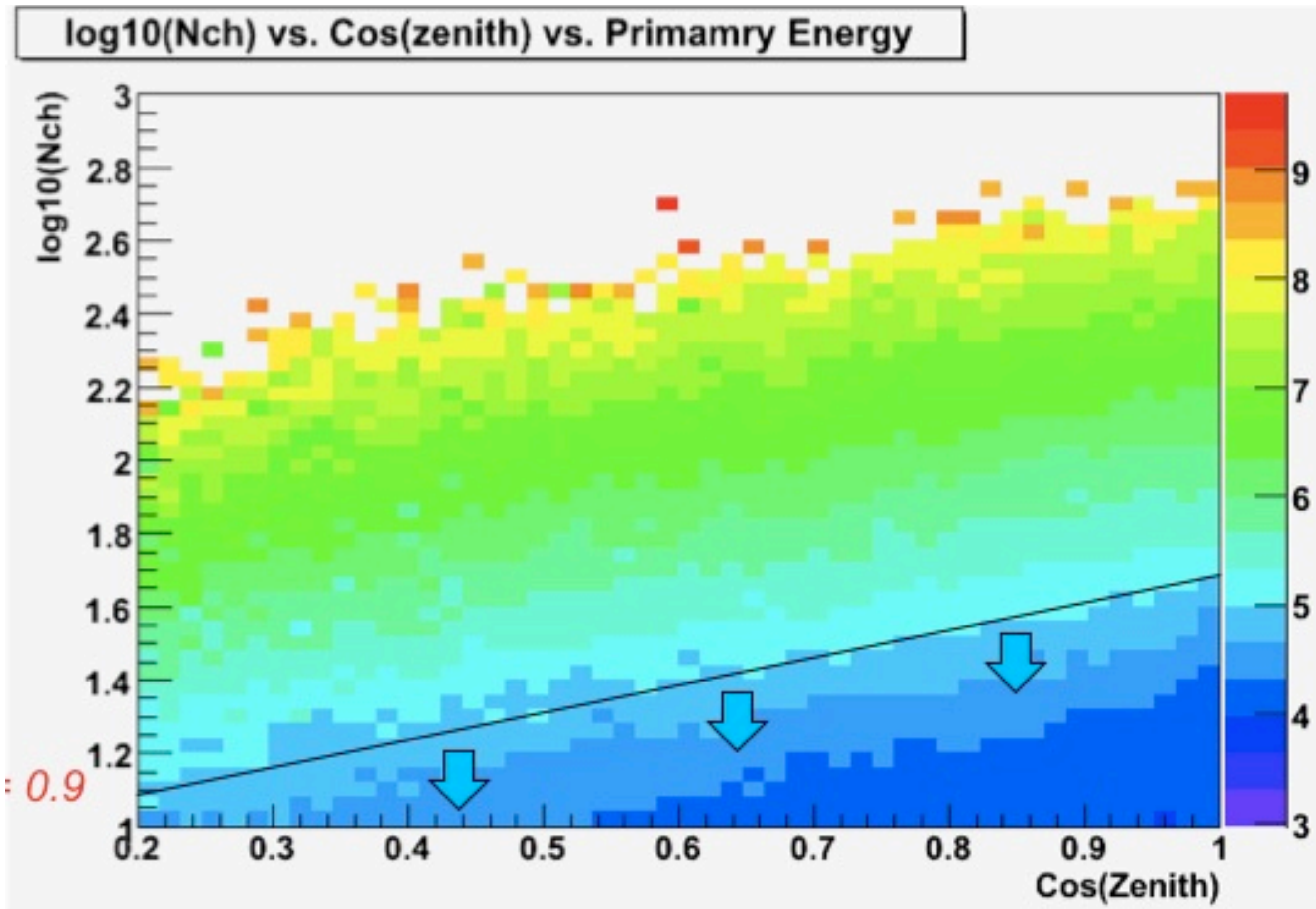
A joint analysis of concurrent data recorded by different experiments in both hemispheres should be a high priority to clarify the observations.

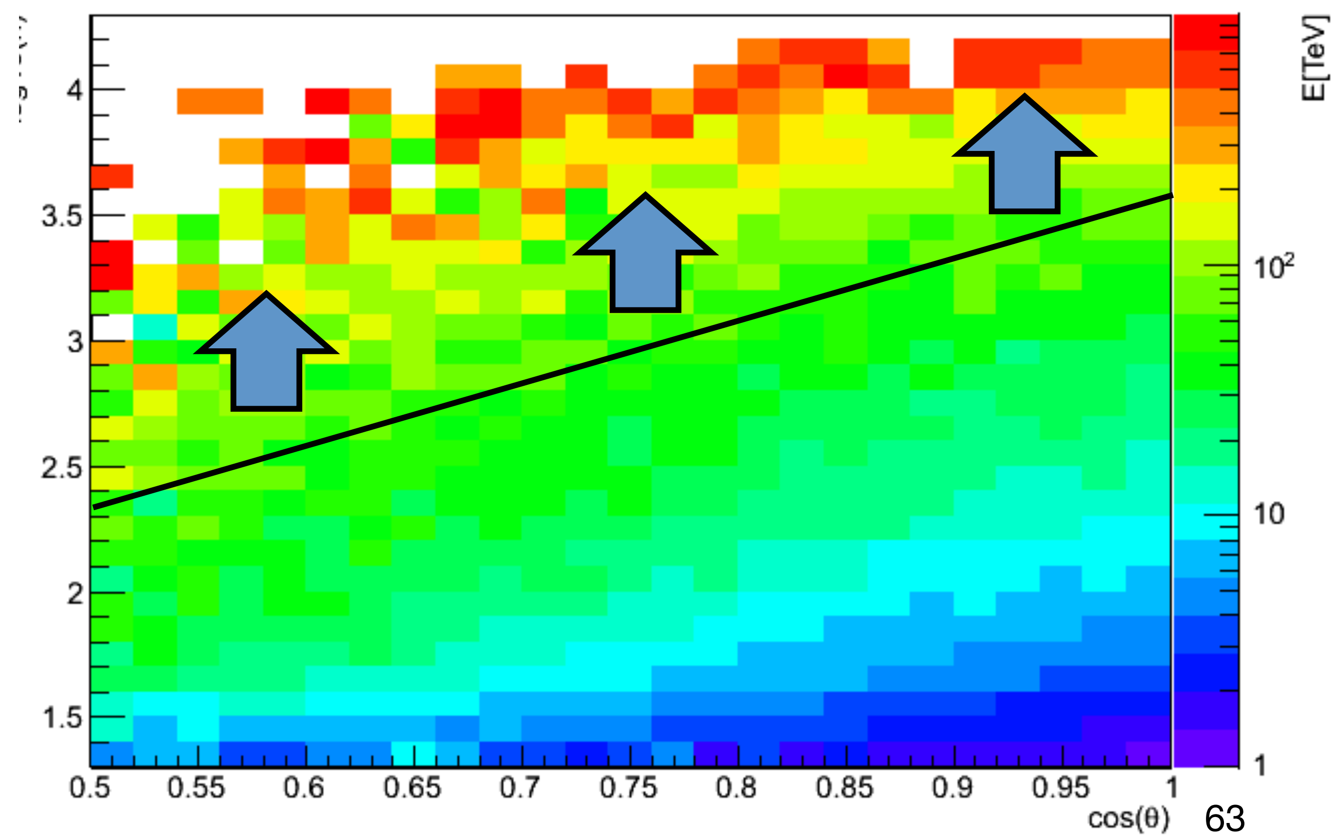
1. Unprecedented high precision of the low-multiple phase as a function of the declination
2. Demonstration of the existence of two distinct components, with different physical meaning: large scale probably due to a composition of the interstellar magnetic field and the interplanetary one. Medium and small scales structures may be a direct measurement of the interplanetary magnetic field turbulences
3. Deepening of the elemental composition of anisotropy regions

Joint analysis very difficult:

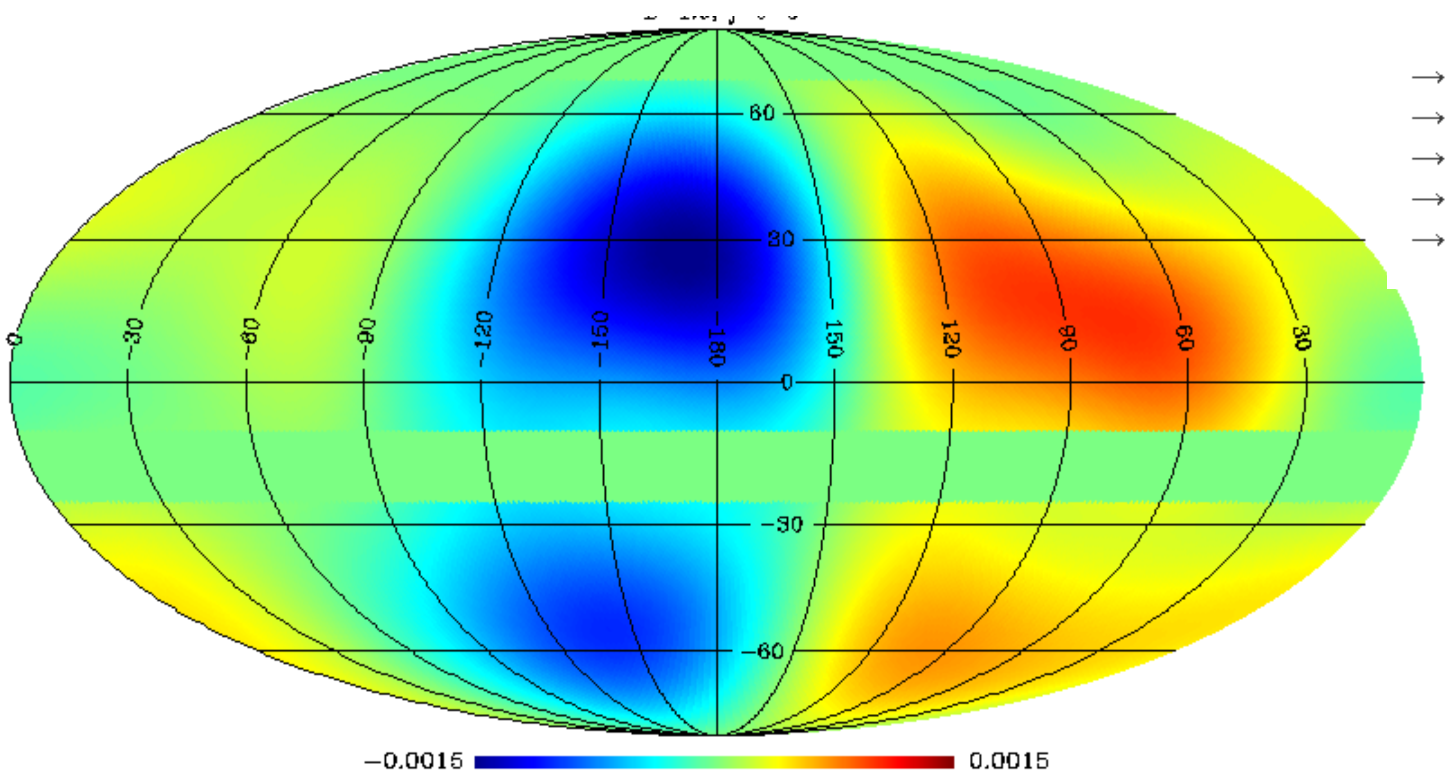
1. Energy inter-calibration
2. Mass composition (hard to be accounted for)
3. Angular resolution (not relevant)

ARGO-YBJ and ICECUBE: energy calibration





ARGO-YBJ + ICECUBE



→ Declination belt: -30°/-20°
→ ARGO-YBJ N>250, ICECUBE "data-set 20 TeV"
→ ARGO-YBJ 7.6e6 events; Icecube 1.2e10 events
→ Background methods: EZ iteration-method (ARGO) VS TS 24 hrs (Icecube)
→ Periods: ARGO-YBJ November 2007-September 2012; IC_40_59_79_86

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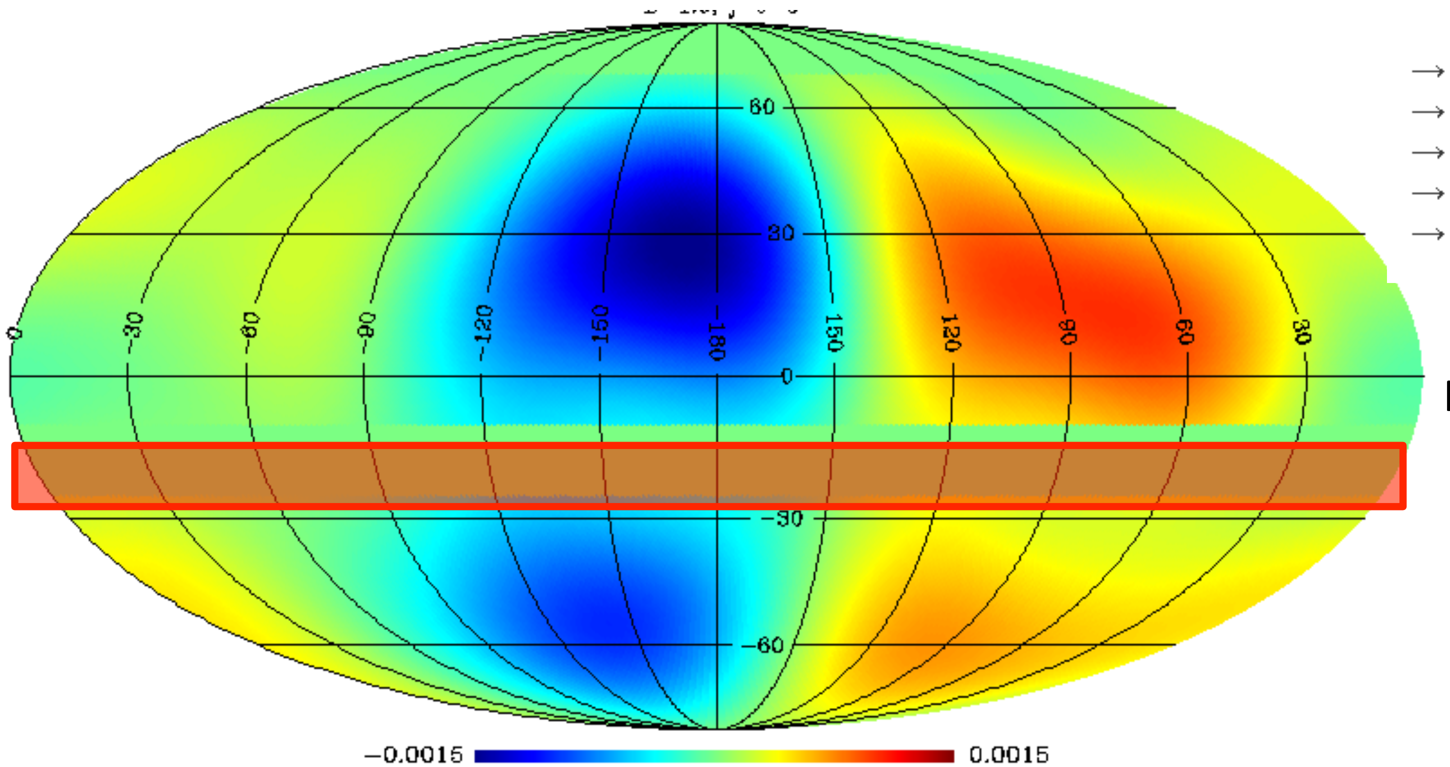

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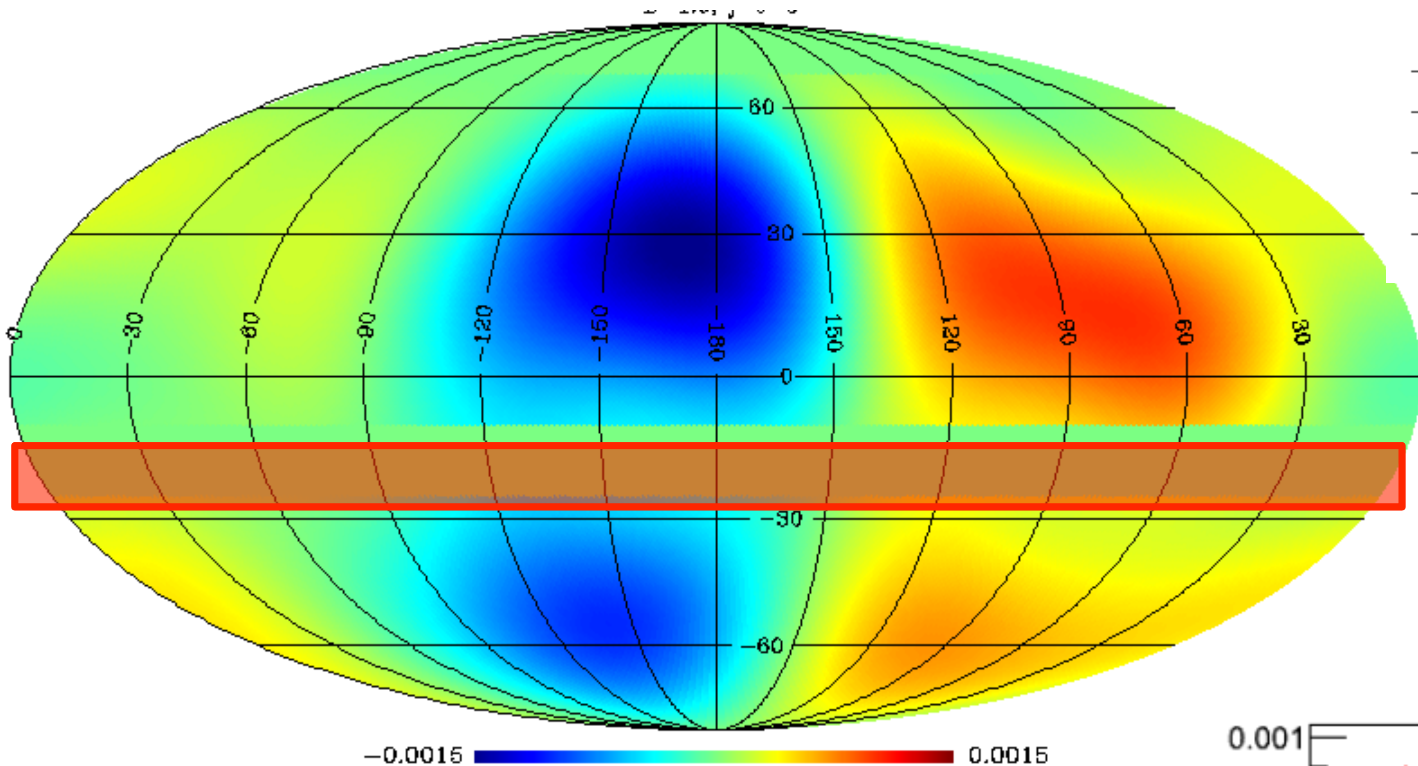
ROI: declination band -30°/-20° (for intercalibration purposes)

Fast 1D analysis run for ARGO

ARGO-YBJ + ICECUBE



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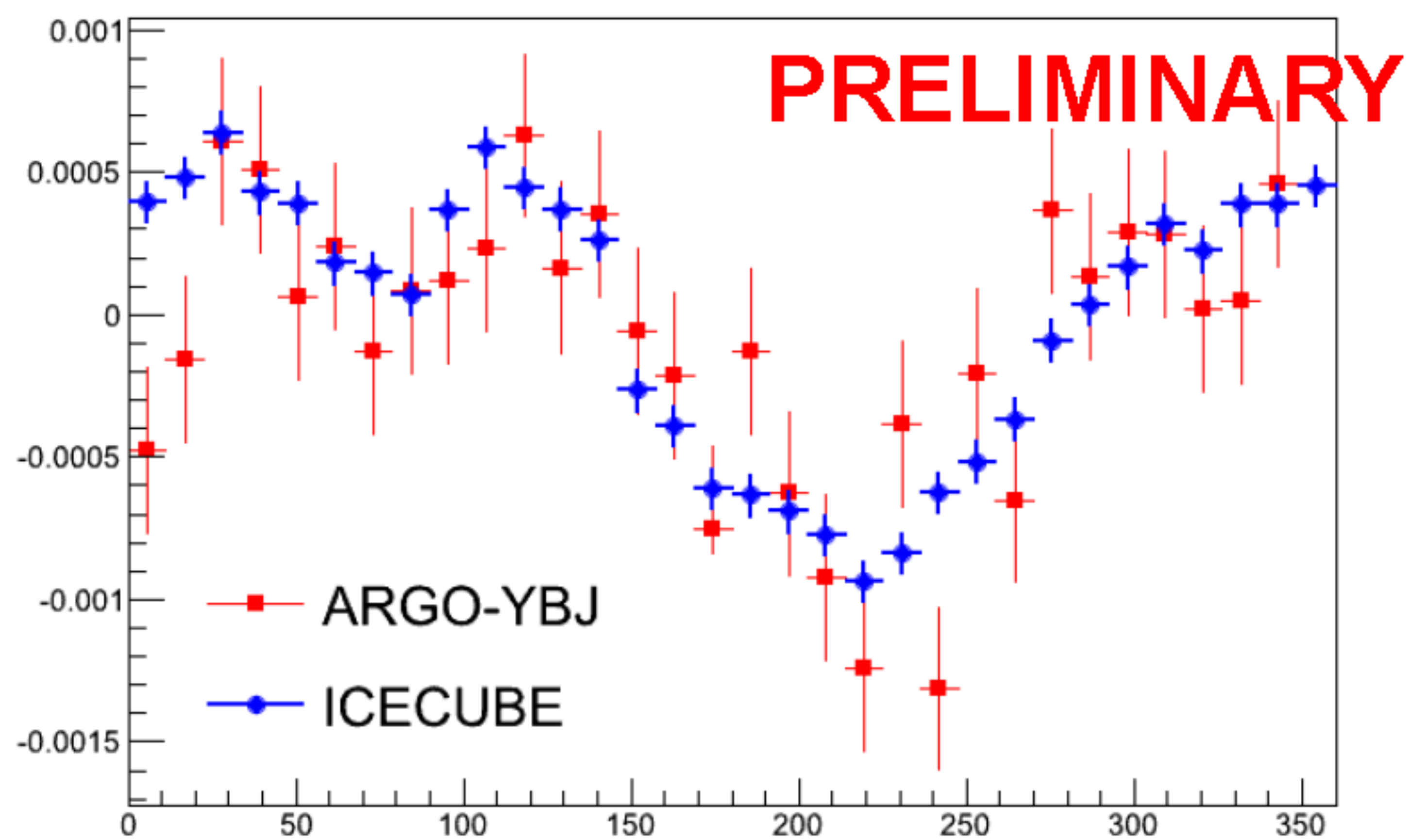
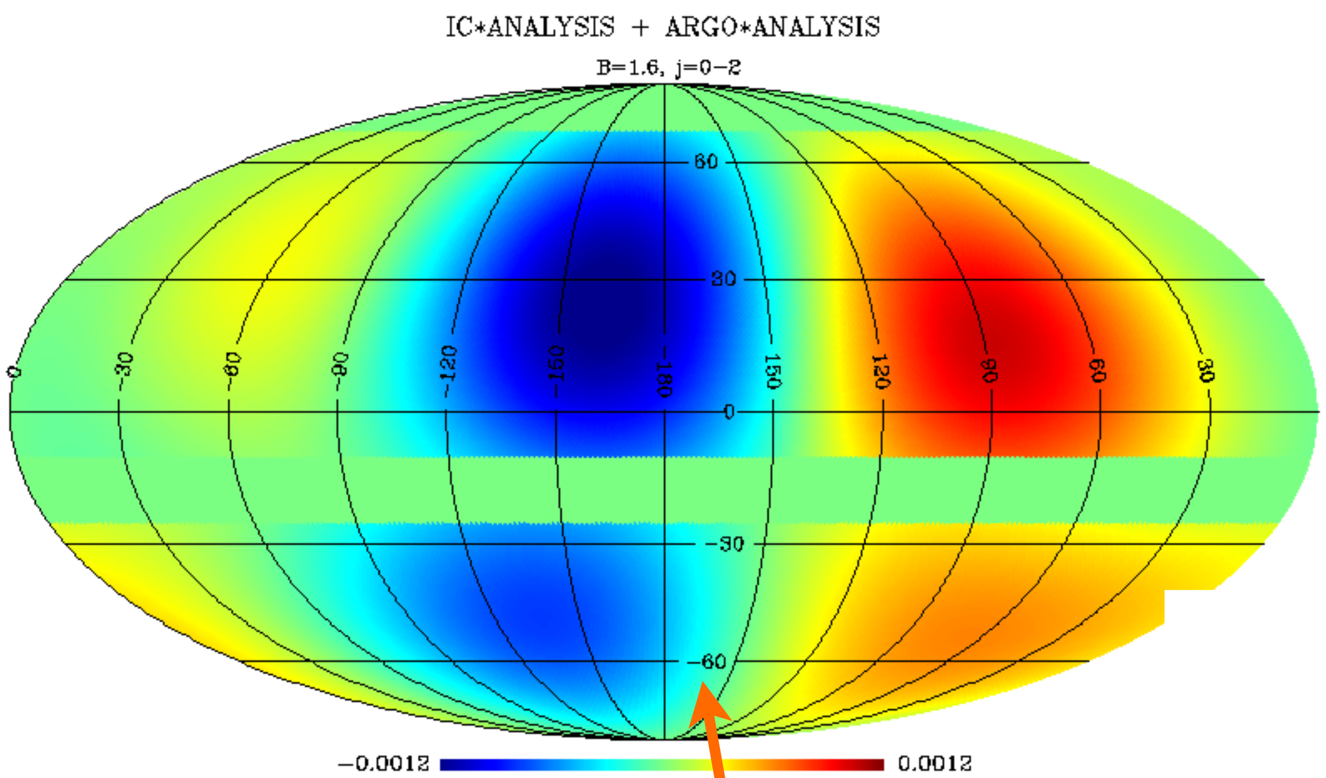
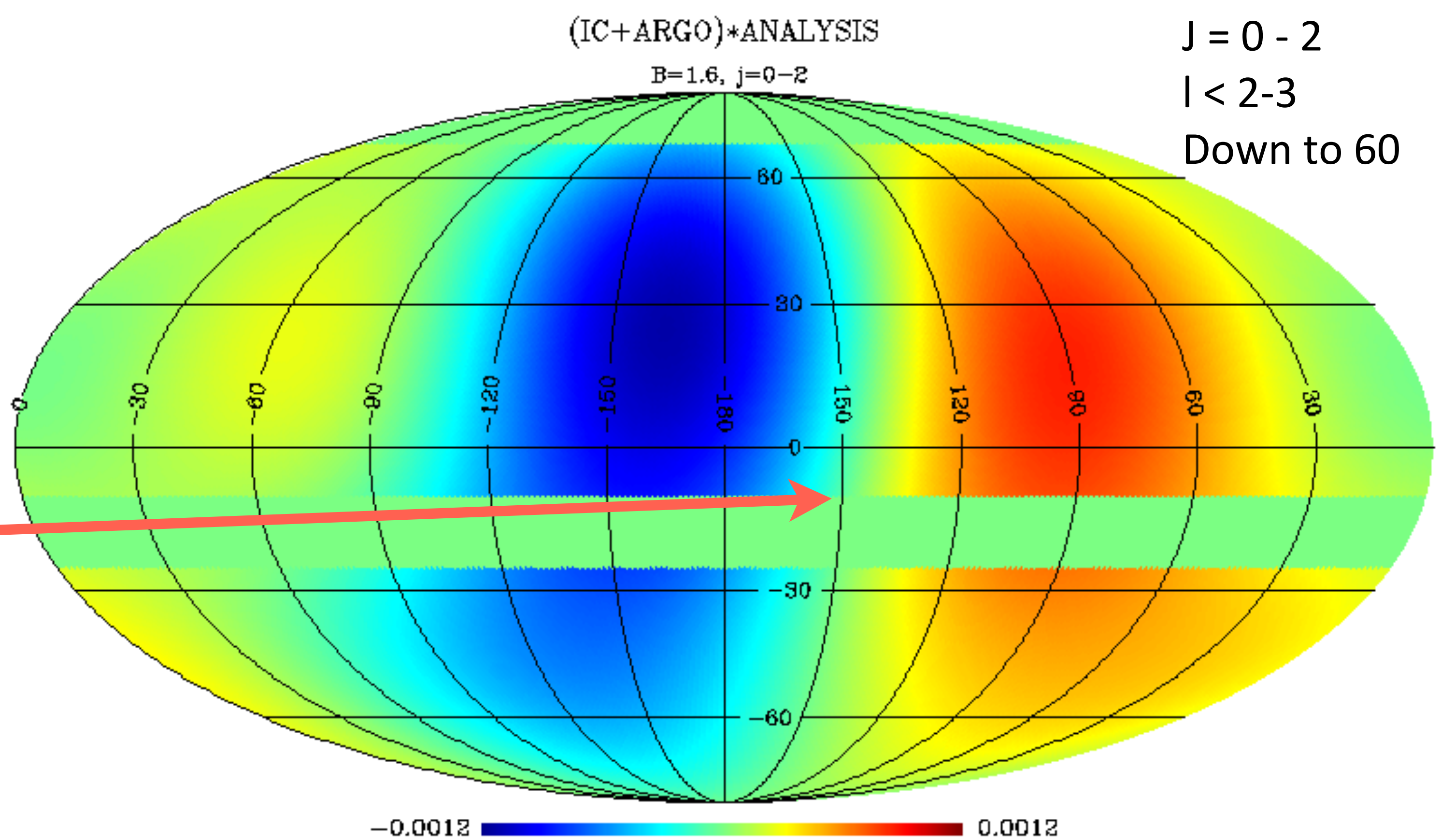


Thanks to R. Iuppa
Icecube Associate Member

Joint analysis ARGO-YBJ with ICECUBE



Very Preliminary results analysis under way



J = 0 - 2
l < 2-3
Down to 60

Well-defined edge. Common analysis may strongly reduce the uncertainty on the phase of the anisotropy

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

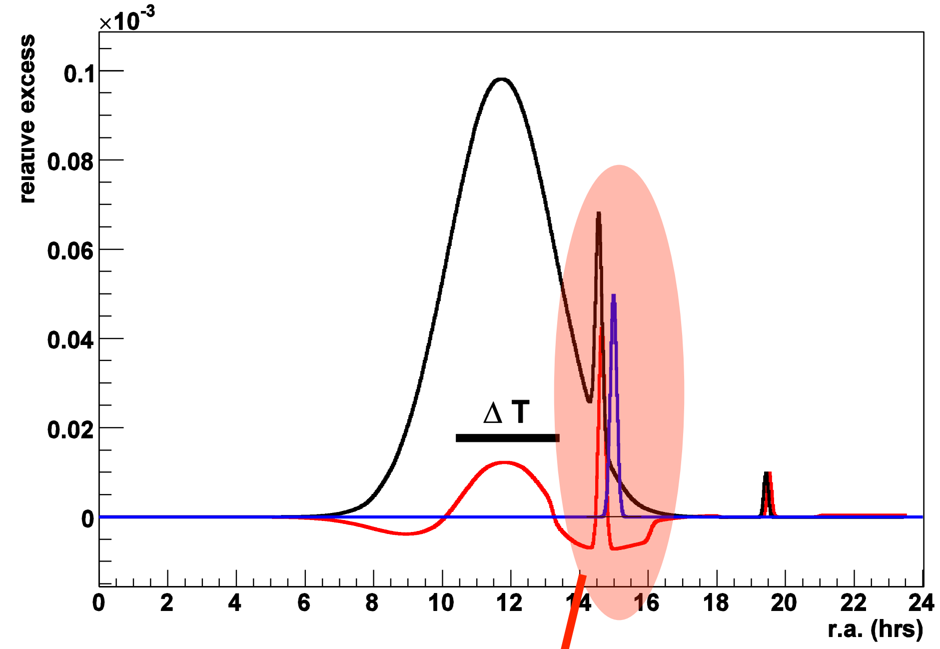
- Measurement of CR light component energy spectrum up to PeV
- Study of EAS phenomenology up to PeV
- Study of the CR anisotropy at different angular scales
- Measurement of the CR antip/p flux ratio in TeV energy range
- Measurement of the p-air and p-p cross sections up to 100 TeV

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

Acknowledgements

...to INFN, IHEP, CAS and all friends who worked hard in these years to tranform an idea in an experiment

Medium/Small Scale Anisotropy



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

Traditional background estimation methods:

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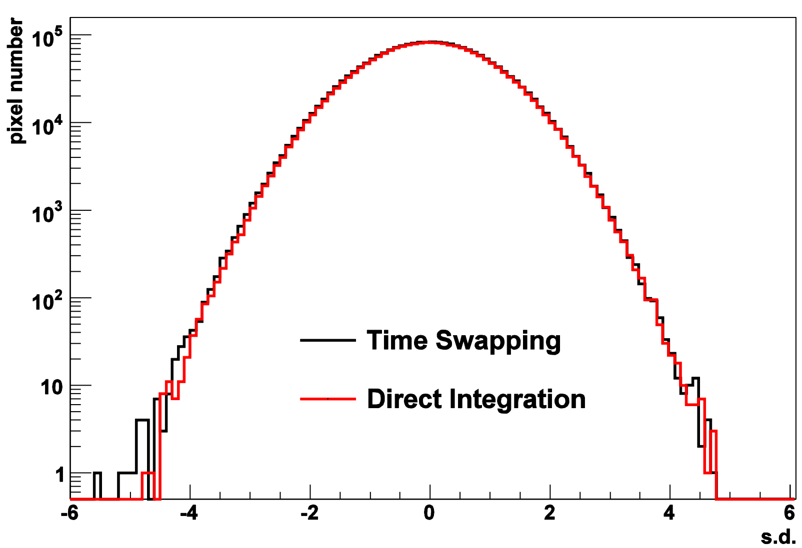
- Direct integration (3 hrs)

(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.
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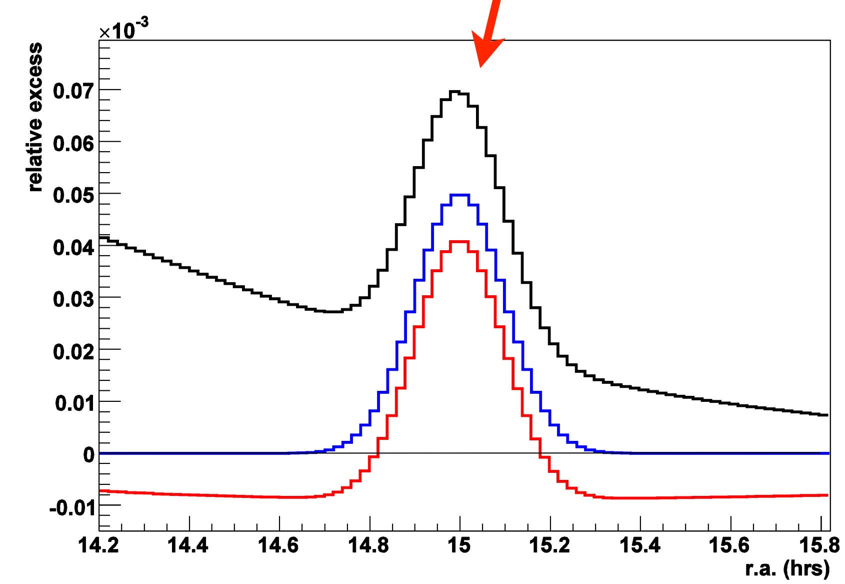


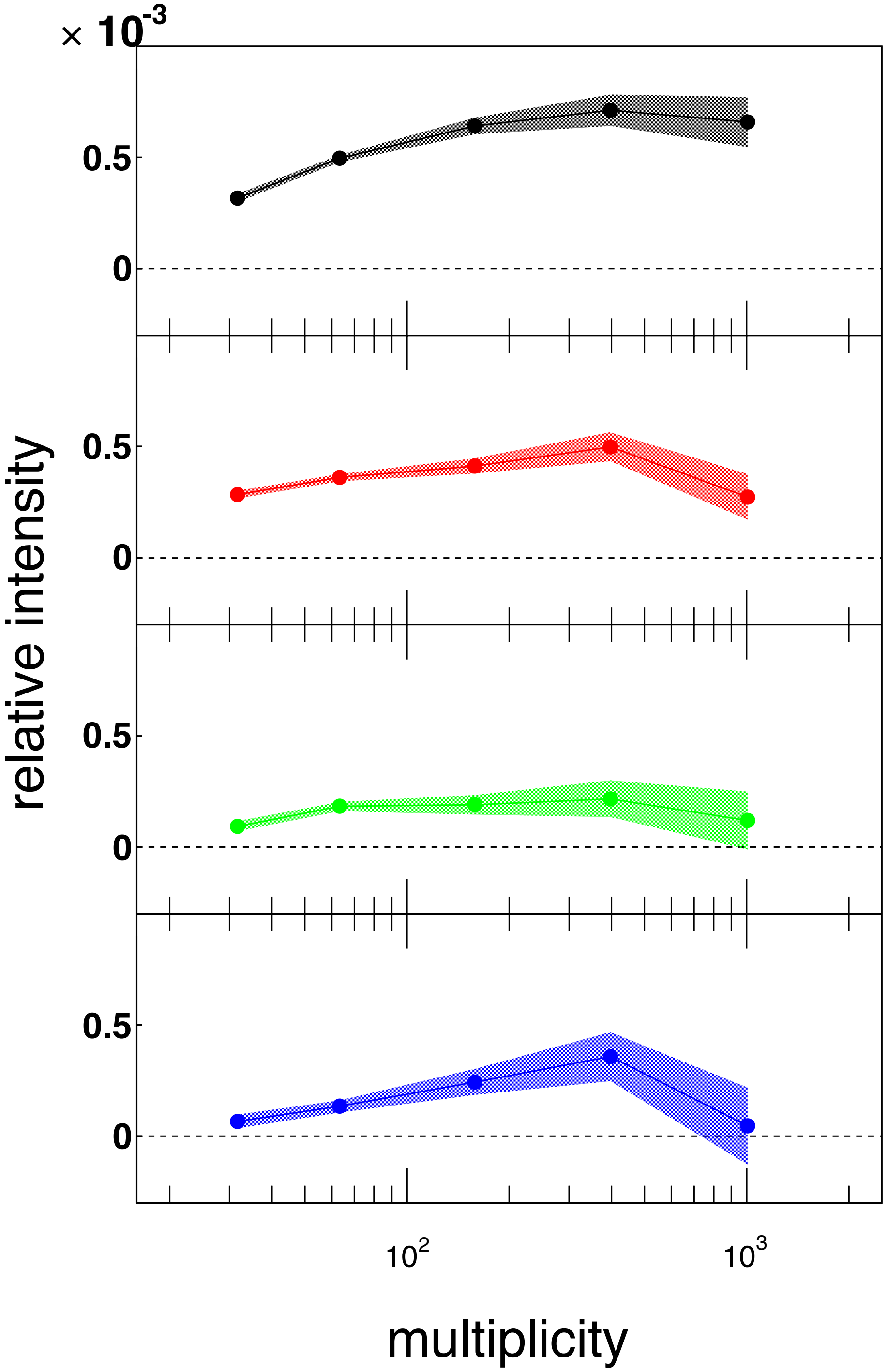
every feature larger than ΔT is brought to zero
(apart from the peak)

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



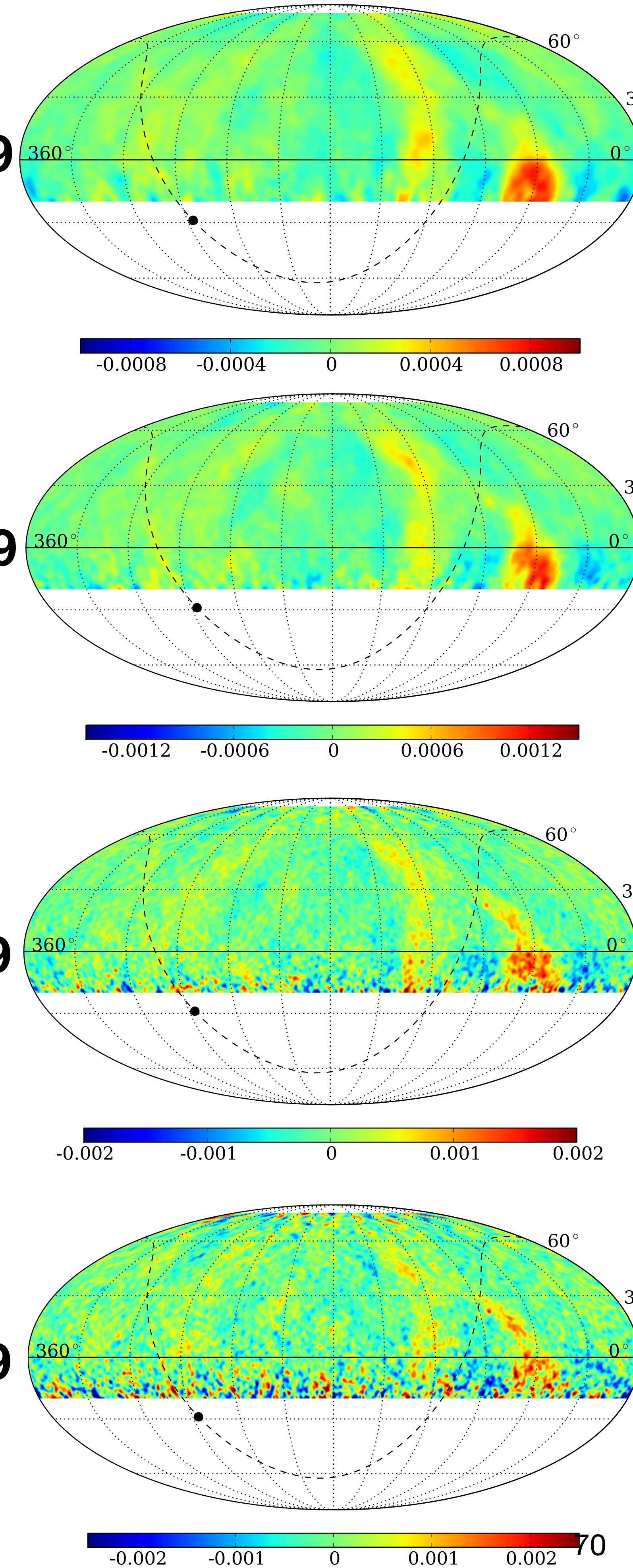
The size spectra look quite harder than the CR isotropic flux

N = 25 - 39

40 - 99

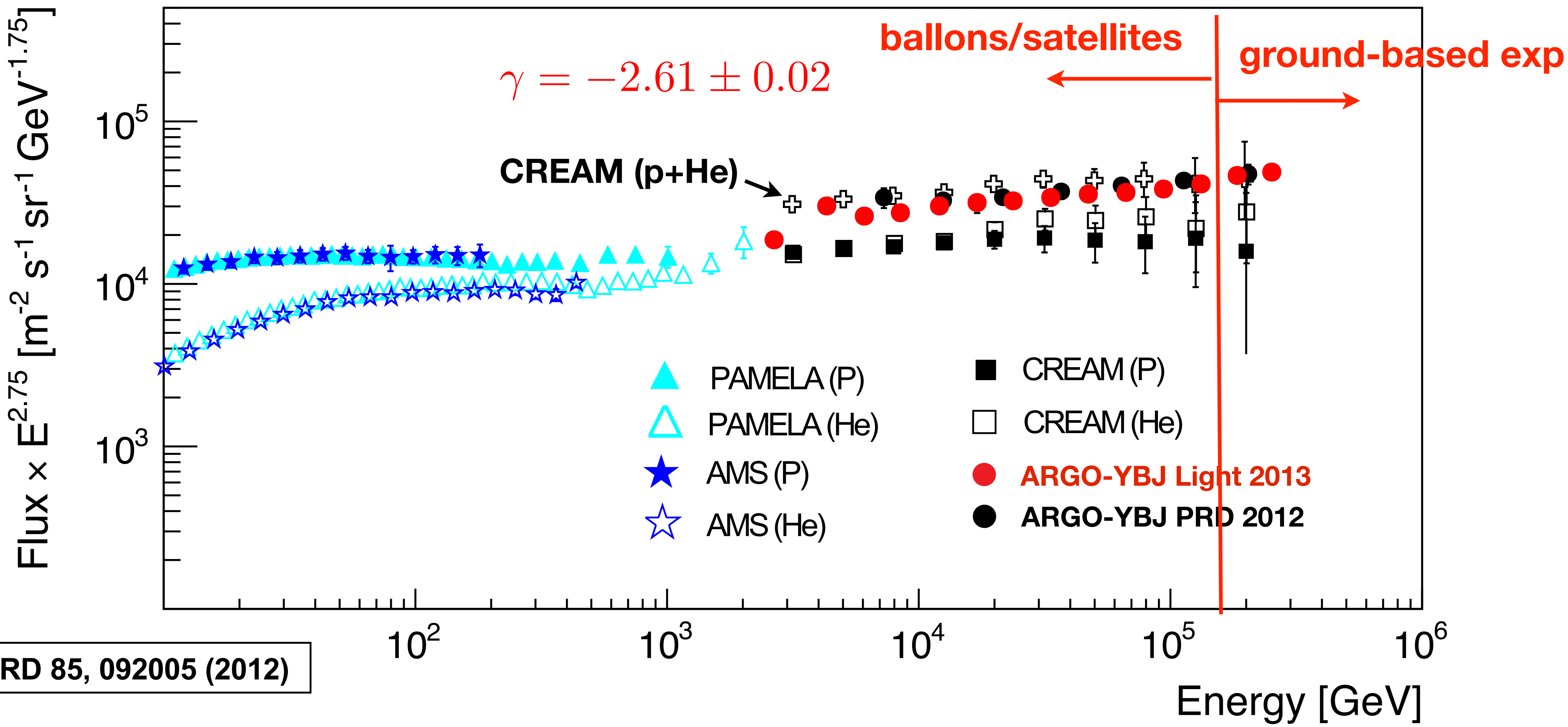
100 - 249

250 - 629



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.

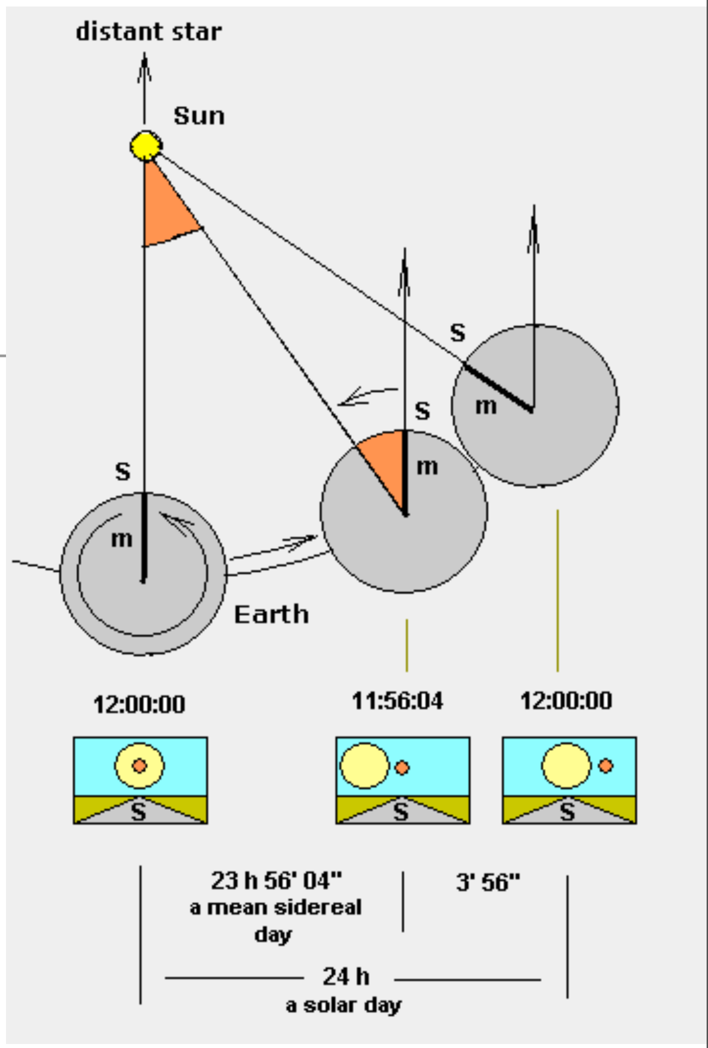
Solar vs Sidereal day

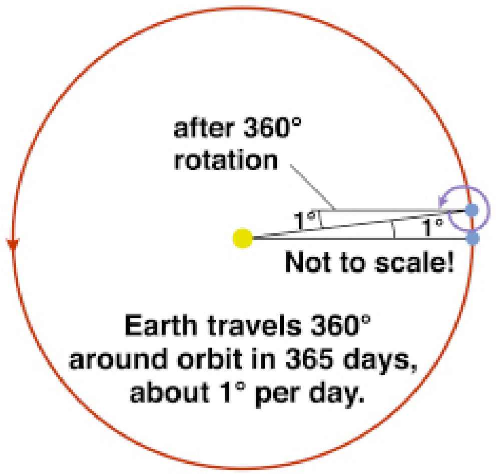
★ Sidereal day – time it takes a star at the meridian to return to the meridian. 23 hours 56 min 4 sec

★ Solar day – time it takes the Sun at meridian (noon) to return to the meridian. noon to noon or 24 hours

Why the 4-minute difference?

as it rotates, the Earth also orbits the Sun. Earth must rotate an extra degree (4 min) each day...for any observer on Earth to be at noon again

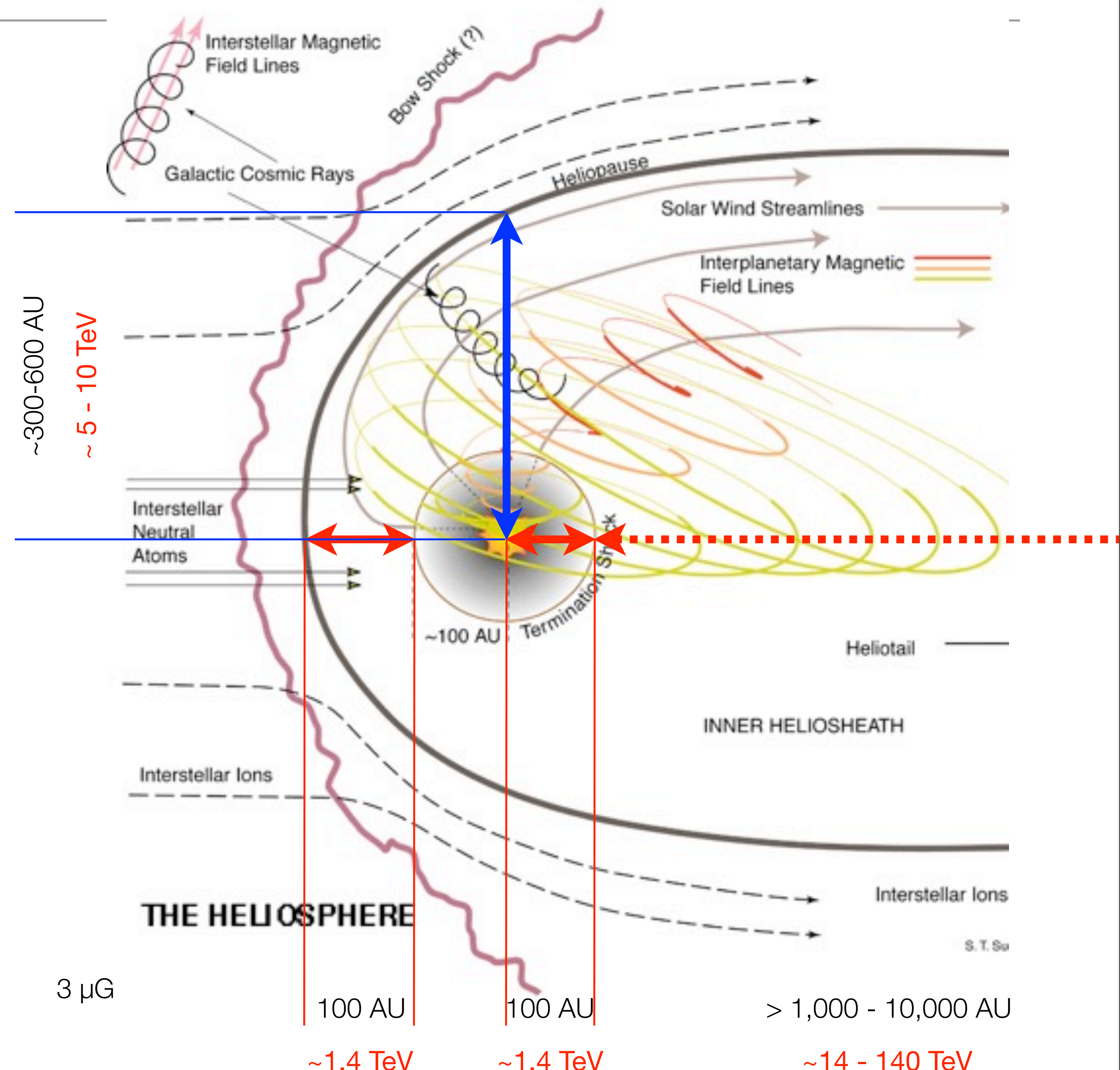




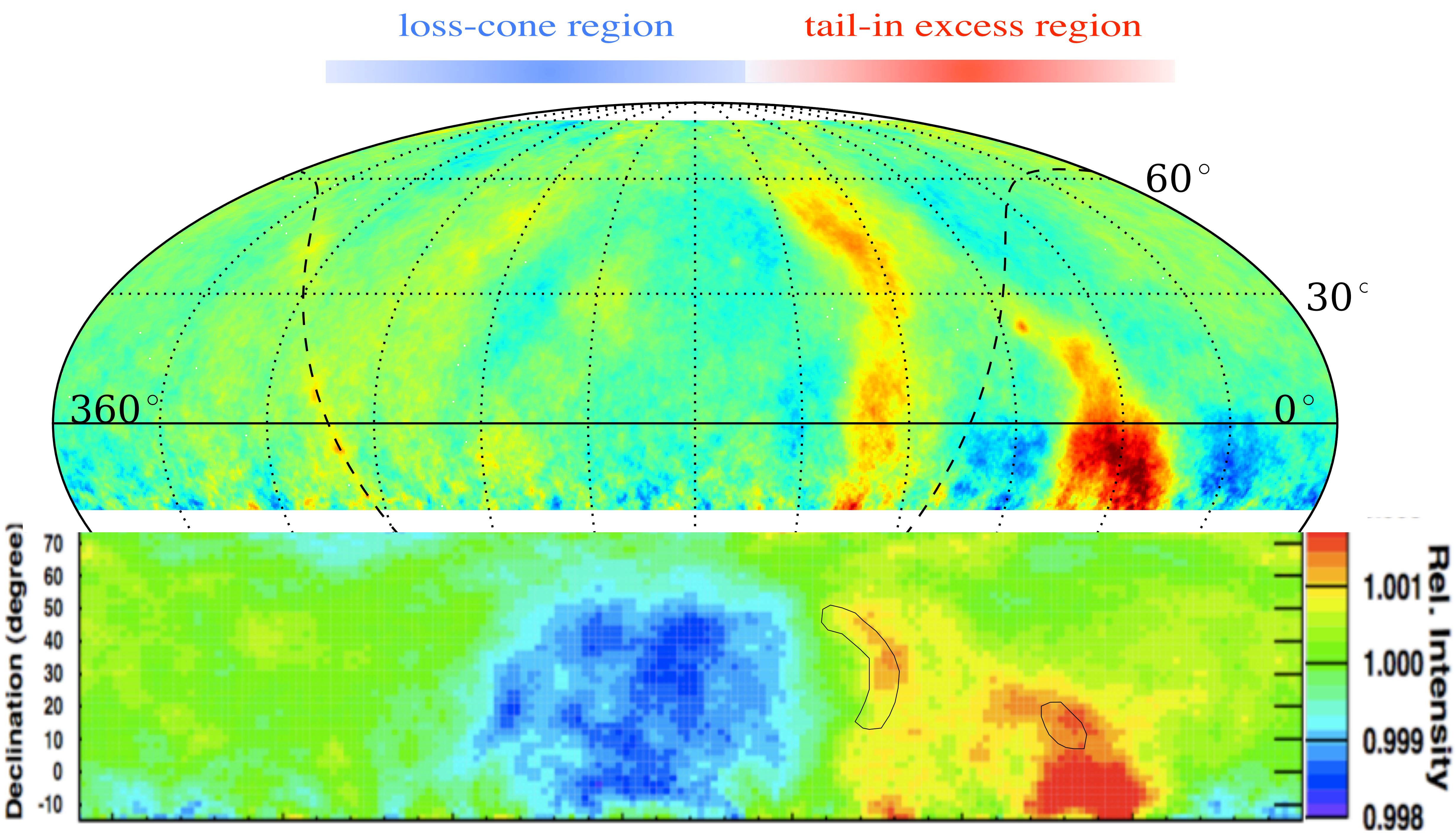
scale : 100-10,000 AU
0.0005-0.05 pc

Heliosphere

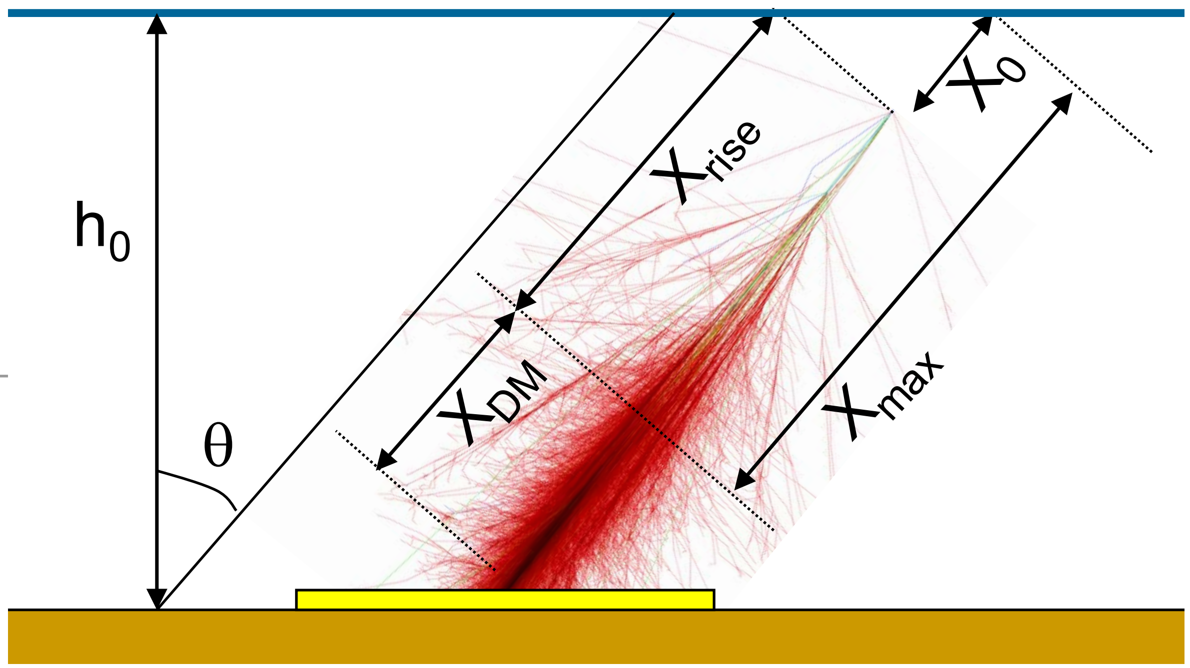
- solar system moves wrt IS medium at 26 km/s
- solar wind diverts interstellar plasma at 400-800 km/s
- termination shock @ solar pressure ~ interstellar pressure : ~ 100 AU
- solar and interstellar medium (& magnetic field) separated by heliopause : ~ 150-200 AU
- heliotail size up to ~ 10,000 AU ?



Angular scale of CR anisotropy



Measurement of the p-air cross section



Use the shower frequency vs (secθ -1)

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

for fixed energy and shower age.

The lenght Λ is connected to the p interaction lenght by the ralation **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)**

- **Constrain** $X_{DM} = X_{det} - X_{max}$
- **Select** deep showers (large X_{max}, i.e. small X_{DM}) to access exponential tail and reduce shower fluctuations → cut on Rs_{70} (strip concentration parameter)
- **Exploit** detector features (space-time pattern) and location (depth).

ARGO-YBJ Coll., Phys. Rev D 80, 092004 (2009)