Cosmic Ray Astrophysics with The High Altitude Water Cherenkov (HAWC) TeV Gamma Ray Observatory at Mexico

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LABORATORIOS NACIONALES CONACYT
LABORATORIO NACIONAL HAWC DE RAYOS GAMMA
HAWC

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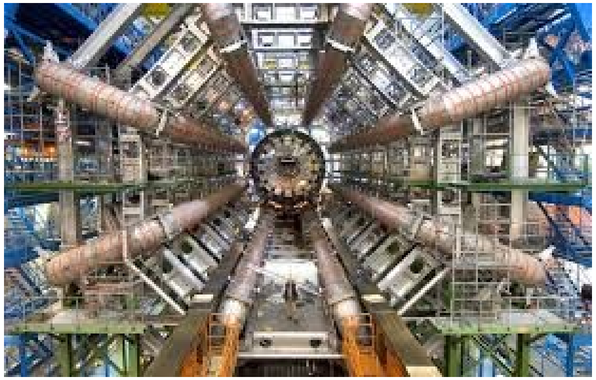
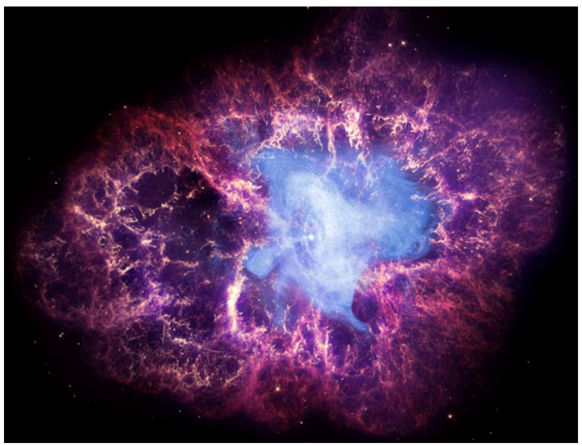
XLVII International Symposium on Multiparticle Dynamics (ISMD2017)

High Energy Physics
Particle Physics can be divided in:

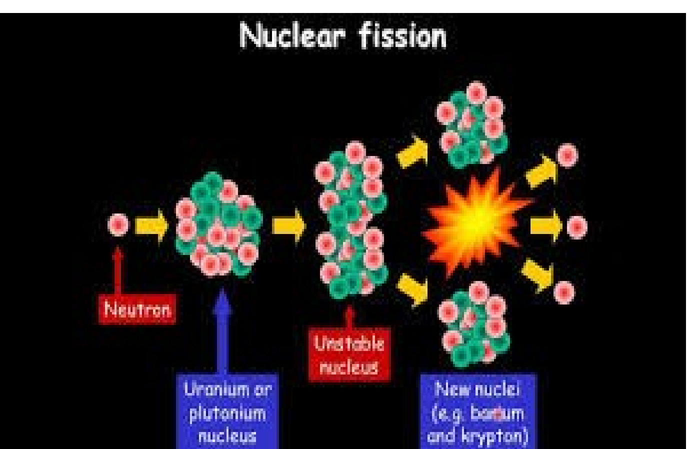
1.- ACCELERATOR PHYSICS



2.- ASTROPARTICLES



3.- NUCLEAR PHYSICS



Particle Accelerators: 1.- Artificial, and 2.- Natural: THE ENERGY IS THE KEY

-QUESTIONS TO ANSWER:

1.- ORIGIN (Where are they from?)

2.- IDENTITY (What are they?),

3.- ACCELERATION (How do they get their energy)

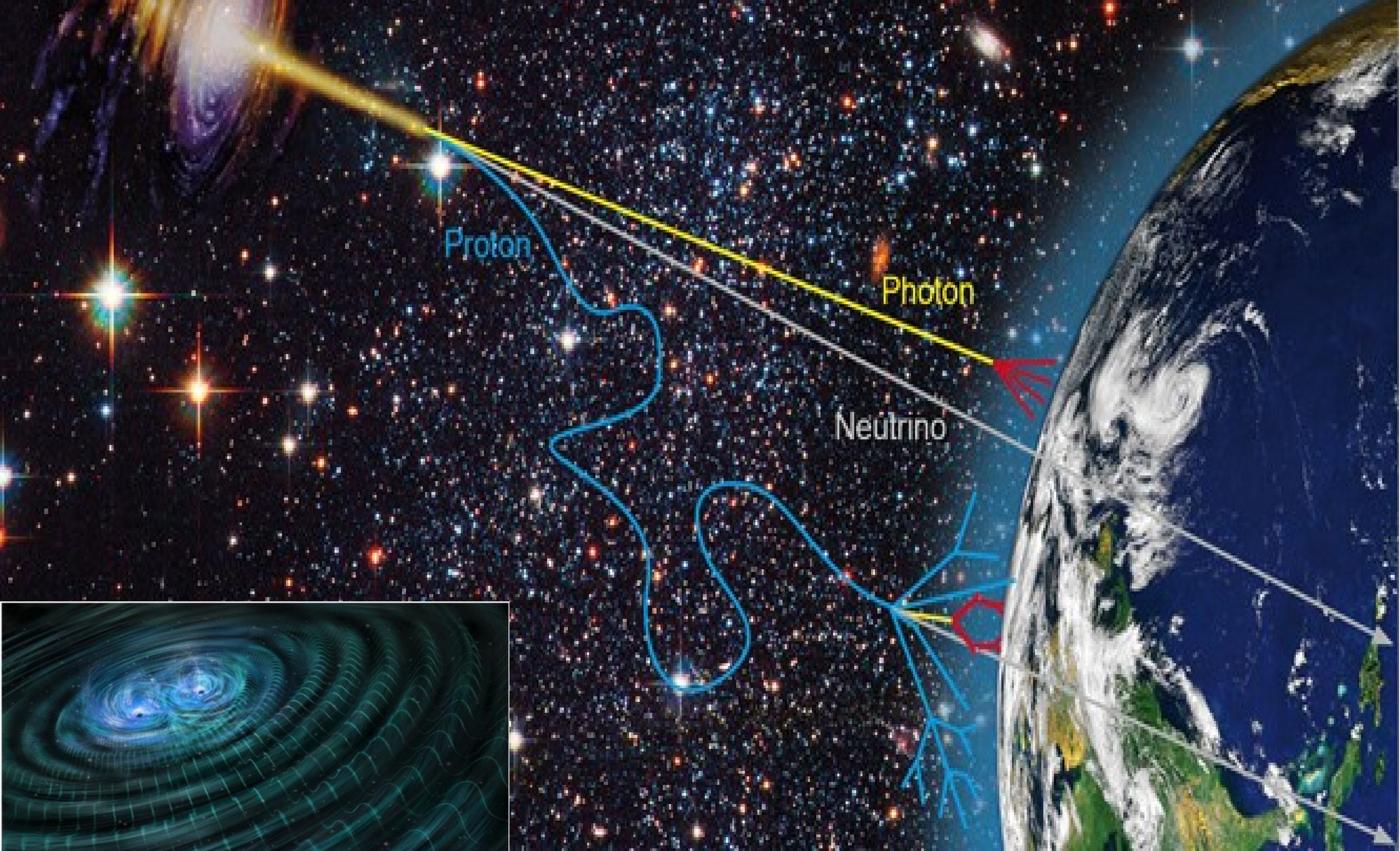
4.- PROPAGATION (What happend on their way)

- HOW: By measuring their

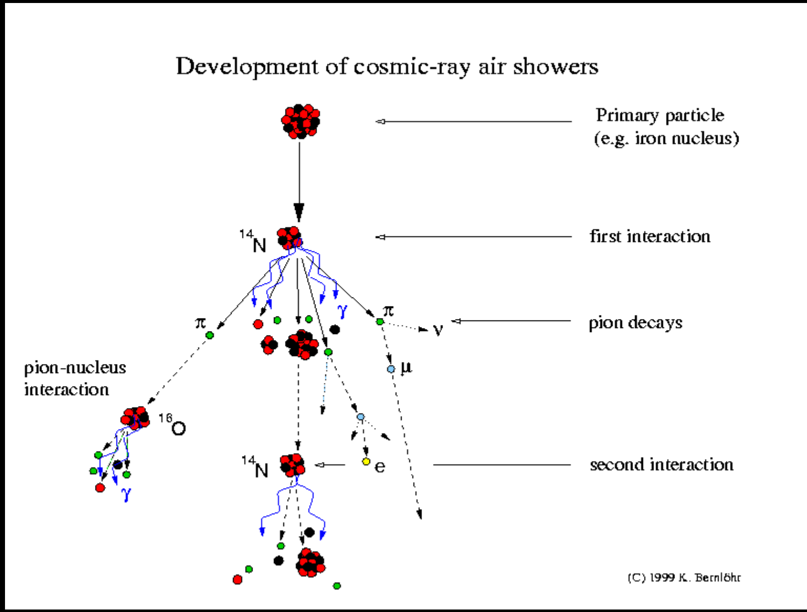
1.- ENERGY SPECTRUM
2.- COMPOSITION
3.- ARRIVAL DIRECTION

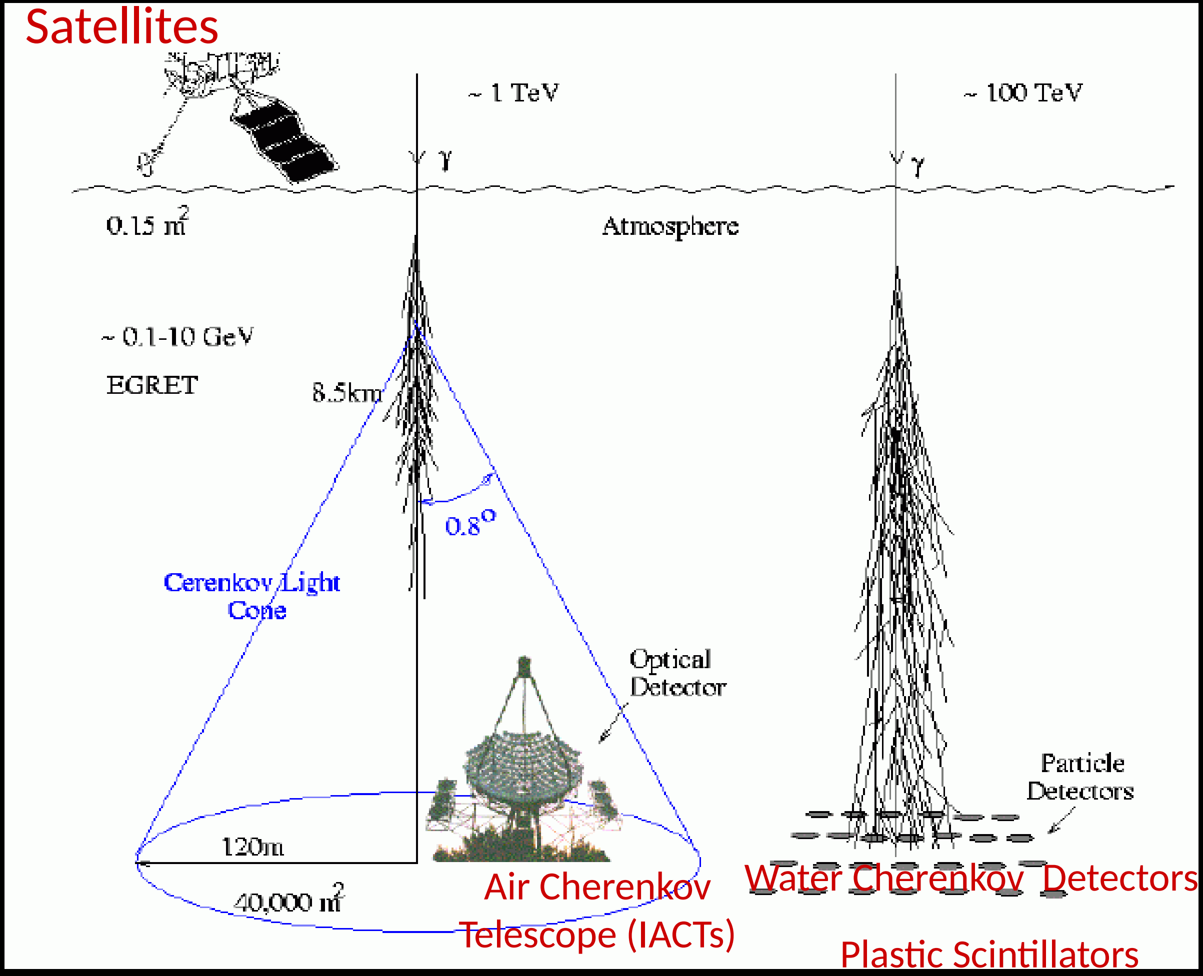
MULTIWAVELENGHT ASTRONOMY

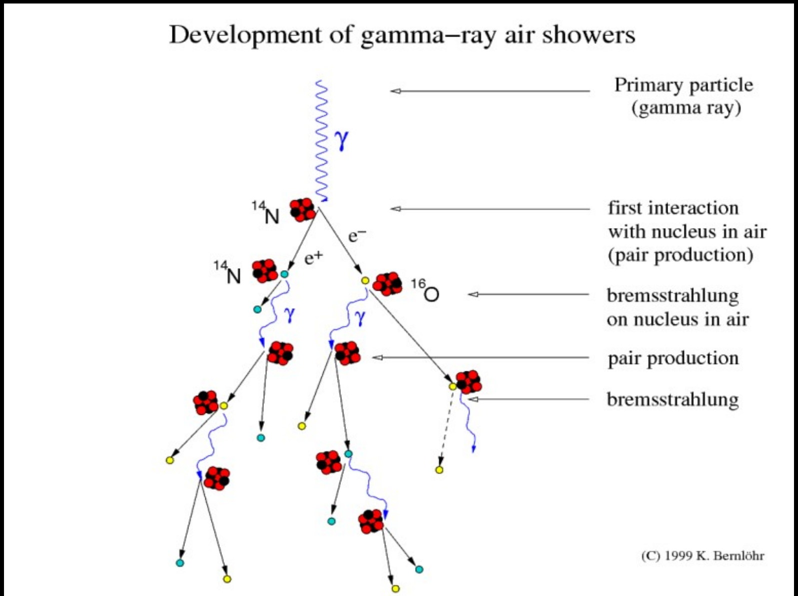
COSMIC RAYS, GAMMA RAYS, NEUTRINOS
Plus Gravitational Wave

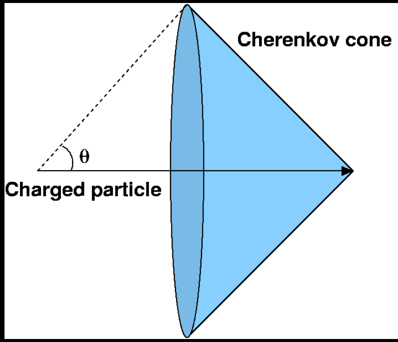


Astroparticles Observations (Detection)





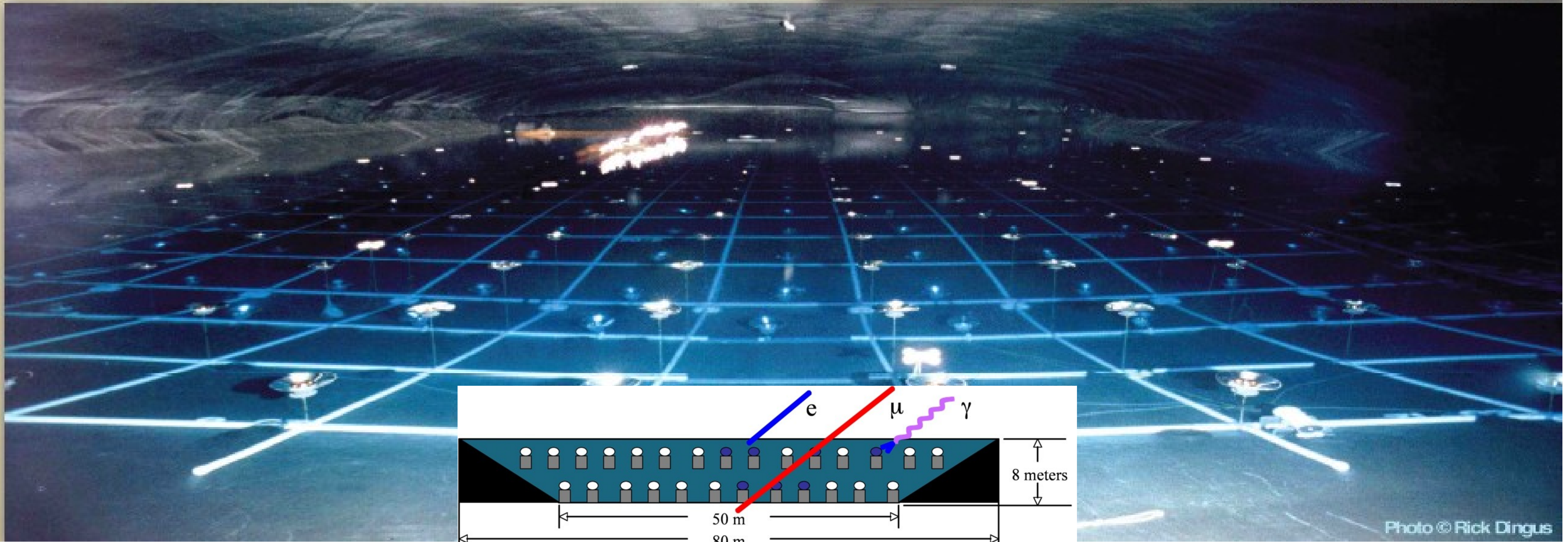




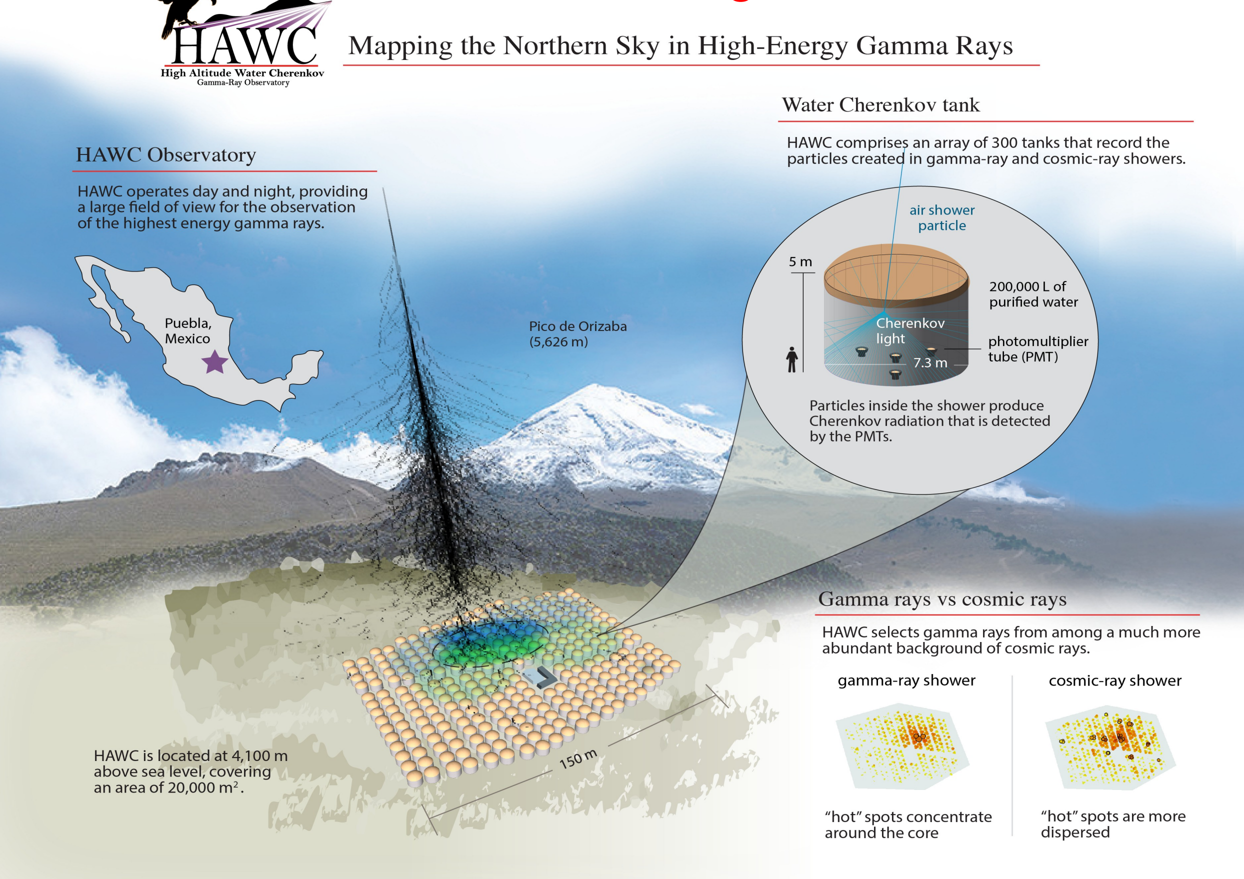
First generation of WCD

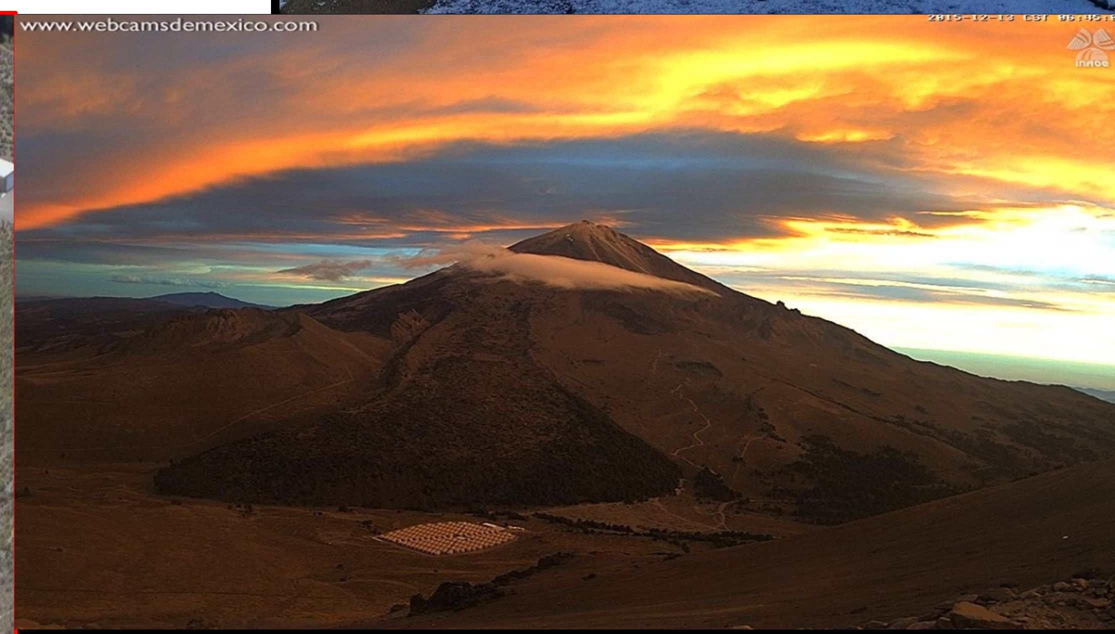
MILAGRO

- 2600m ASL (NM, USA)
- 2000-2008
- Water Cherenkov detector
- 898 PMTs
  - -450 top/273 bottom
  - -175 outriggers
- 40,000m^2 area
- 1700 Hz trigger rate
- 0.4°-0.9° resolution
- 2-40 TeV median energy



Second generation of WCD





Near Future Starting (on 2016):

HAWC outriggers

- Proposal for a sparse outrigger array to improve the sensitivity beyond 10 TeV $\Longrightarrow$ up to a factor of 4 in effective area.
- About 300 WCDs of 2,500 liters.
- Accurate core determination for showers off the main array.
- Funding by LANL and Mexico.

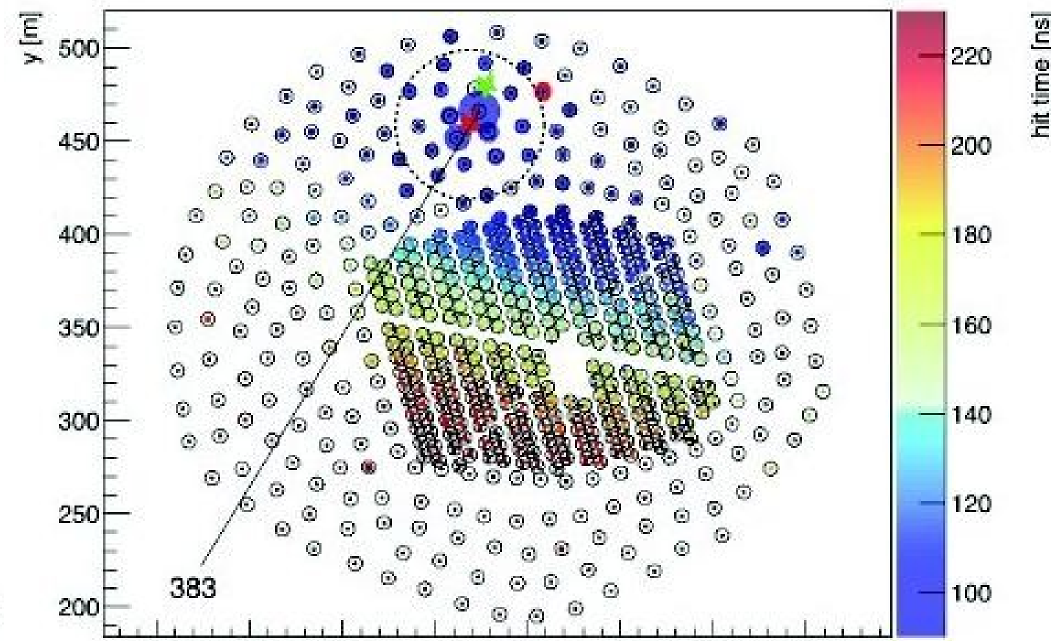
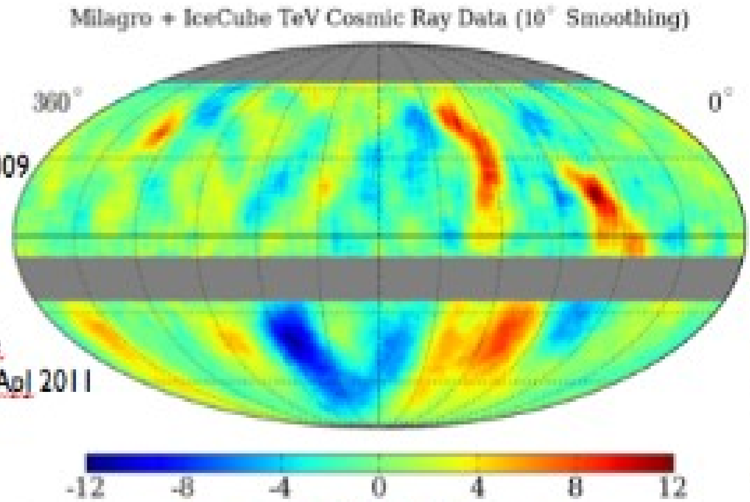


Photo Credit: Michael Schnider
(UCSC - HAWC)

Unexpected Anisotropy of 10 TeV Cosmic Rays; Gyroradius of 10TeV proton in 2μG field is 1000 AU

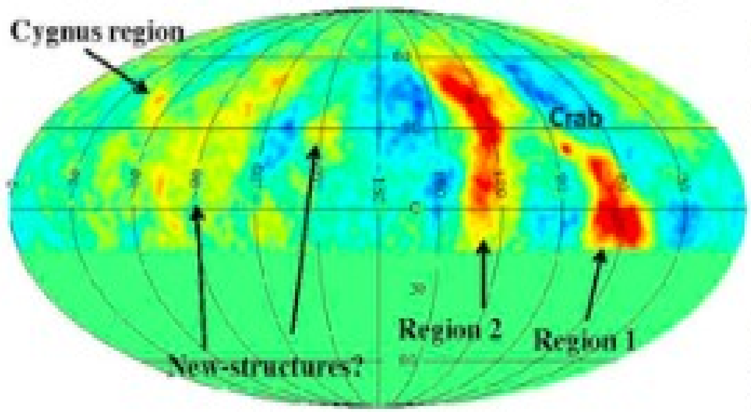
Milagro:
Abdo, et al. PRL, 2009

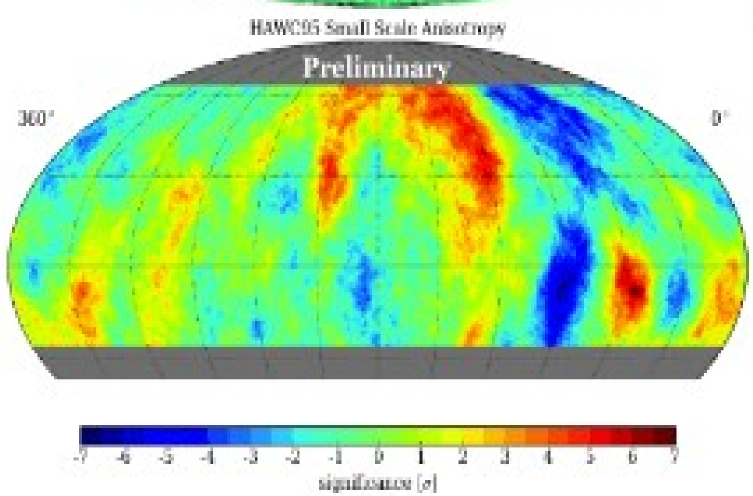


IceCube
R. Abbasi, et al., ApJ 2011

ARGO-YBJ

S. Vernetto et al., Proc. 31st ICRC, 2009





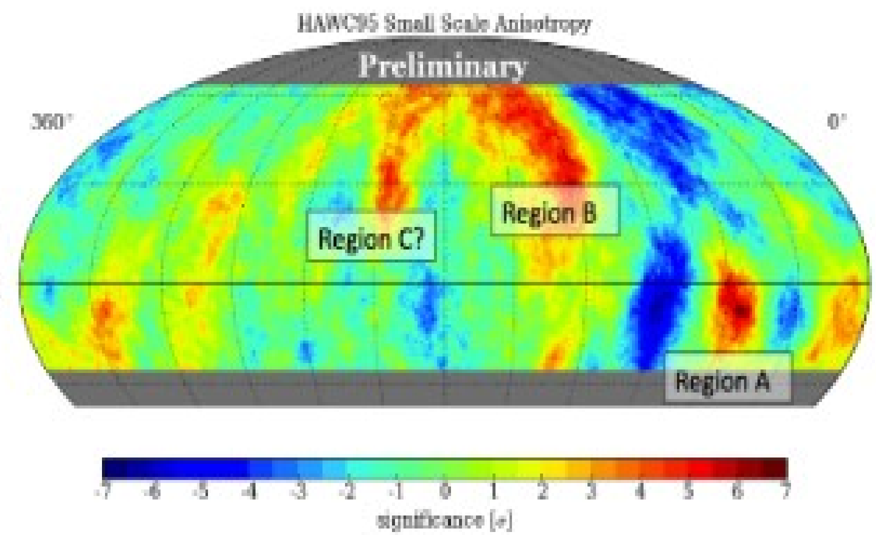
nCh ≥ 32

Direct integration

2hr ≥ dt ≥ 1hr

10° smoothing

Li/Ma signif.



Region A : 7.0 sigma
Region B: 5.5 sigma
Region C: 4.9 sigma

Pre-trial will be greater than 7 with another month of data.

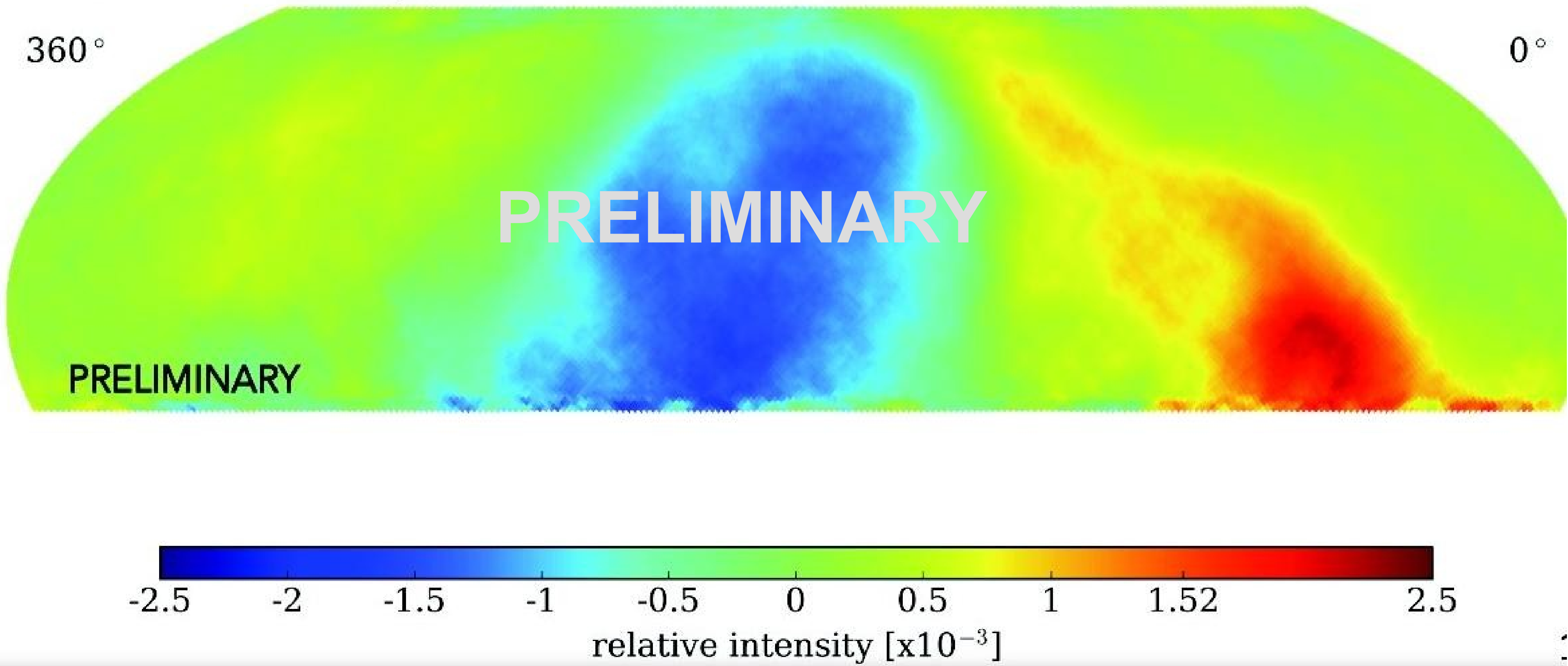
Find post-trial with random data sets.

Abeysekara et al., HAWC Collaboration
The Astrophysical Journal, Volume 796, Issue 2, article id. 108, 11 pp. (2014)

HAWC

241 stable sidereal days ~ 3 TeV
more restrictive cuts to cut on energy
19 billion events
10° smoothing to show correlations

Large-scale anisotropy

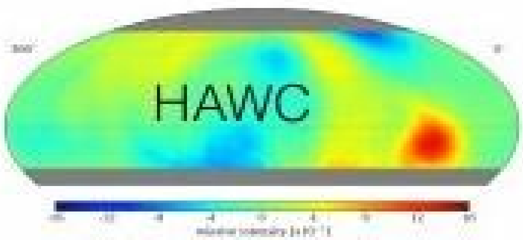


Dan Fiorino, UW, USA, Ph. D. Thesis, 2016

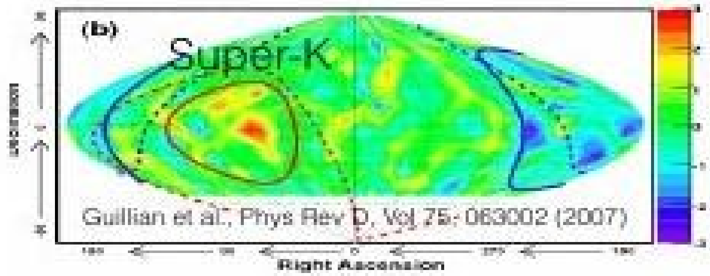
JC—Diaz Velez, CUVALLES UdeG+UW, MEX+USA, Ph. D. Thesis, 2017

Credit:: UW and The HAWC Collaboration

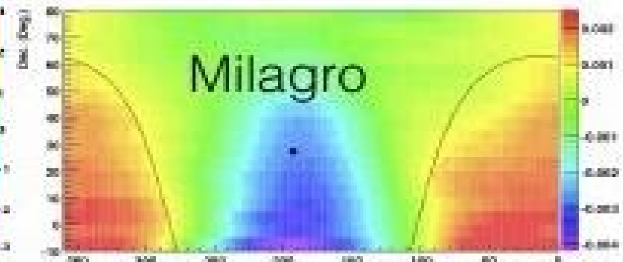
Over the last few decades, several studies have measured a large scale anisotropy at 10^{-3} level and a small-scale structure with an amplitude of 10^{-4} and angular size from 10° to 30°.



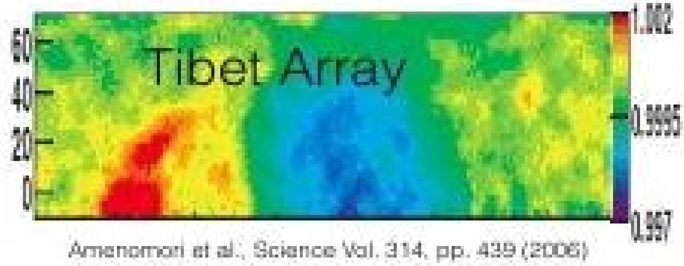
A. U. Abeysekara et al. Astrophys. J. (2014)



Guillian et al., Phys Rev D, Vol 75, 063002 (2007)



Abdo et al., ApJ, Vol 698-2, pag 2121 (2009)

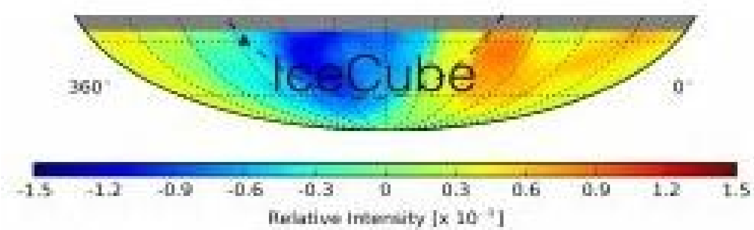


Amenomori et al., Science Vol. 314, pp. 439 (2006)

Zhang et al. Proc. 32nd ICRC (2009)

North

South



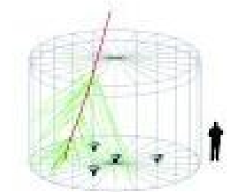
M. G. Aartsen et al. Astrophys.J. 826 (2016)

Large-scale features in South appear to be a continuation of those observed in the Northern Hemisphere.

Data Sets

Individual experiments have provided partial sky coverage that limits the interpretation of the results. This first full-sky combined observation at the same energy is done with two observatories covering most of the celestial sphere.

	IceCube		HAWC	
Hemisphere	Southern		Northern	
Latitude	-90°		19°	
Detection method	muons produced by CR		air showers produced by CR and γ	
Field of view	-90°/-20°, ~4 sr (same sky over 24h)		-30° /64° , ~2 sr (8 sr observed)/24 h	
Livetime	5 years		269 days over a period of 336.36 days	
Detector trigger rate	2.5 kHz		25 kHz	
	quality cuts	energy cuts	quality cuts	energy cuts
Median primary energy	20 TeV	10 TeV	2 TeV	10 TeV
Energy resolution (logE/GeV)	0.5	0.5	0.2	0.2
Approx. angular resolution	2-3°	2-6°	0.3-1.5°	0.3-1.5°
Number of events	2.8×10^{11}	1.7×10^{11}	2.6×10^{10}	4.4×10^{9}



Data selected for analysis come from 5 years of the complete IceCube array, as well as 1 year of HAWC in its final configuration of 300 tanks. Only continuous sidereal days* of data were chosen for these analyses in order to reduce the bias of uneven exposure along right ascension.

Diaz-Velez Ph. D. Thesis, CUValles, Universidad de Guadalajara; arxiv:1708/03005 (ICRC 2017)

IC86 2011-2015

- Data duration:
  - 5 continuous years
  - 2011/05/13 to 2016/05/20.
- Reconstructed a South Pole with fast but not very precise algorithms before being transmitted.
- Select long tracks with better angular reconstruction.
- Reconstructed energy < 32 TeV.

Data Cuts

- $\log_{10}(E_{reco}) < 4.5$ (32 TeV)
- rlogl* < 15
- ldir_c** > 200 $\cos(\theta_{zenith})$
- ndir_c*** > 9 $\cos(\theta_{zenith})$

*Reduced log-likelihood of the track reconstruction fit.
**Length of track in direct (on-time) PE hits.
***Number of direct (on-time) PE hits.

HAWC300

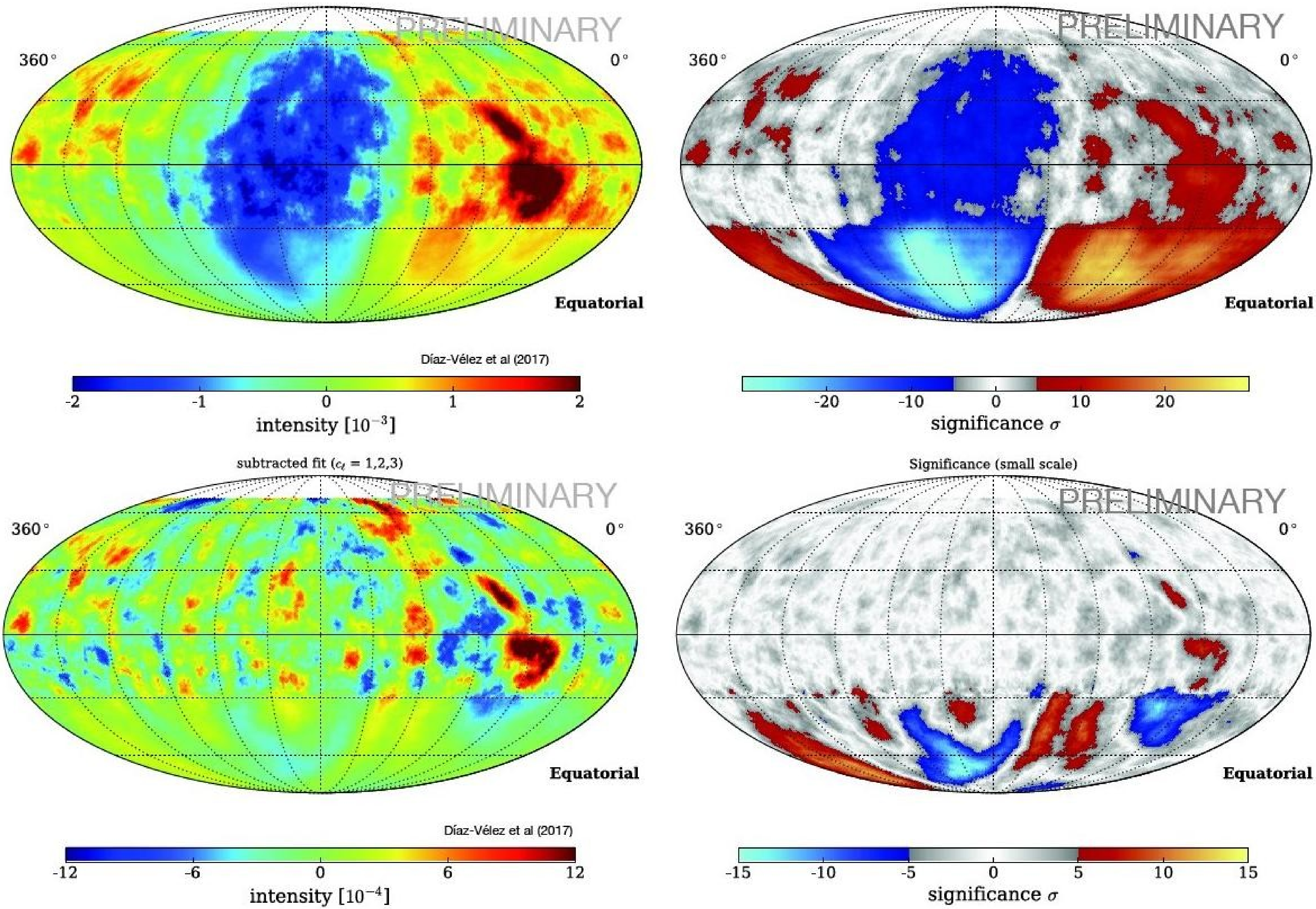
- Data duration:
  - 269.0 cont. day periods
  - (336.36) total days
  - 2015/04/21 to 2016/04/19.
- Combine short runs:
  - time gaps < 20 min.
- Select high quality reconstructions.
- Eliminate γ-ray candidate events
- Reconstructed energy > 10 TeV.

Data Cuts

- $\log_{10}(E_{reco}) >= 4.0$ (10 TeV)
- nHit* >= 75
- $0 \leq \theta_{zenith} < 1.0$ (57.3°)
- CxPE40XnCh** > 40
- PINC*** > 1.6

*Number of PE hits.
**Number of channels beyond 40m from the reconstructed core.
***Gamma/Hadron separation (smoothness of shower).

Diaz-Velez Ph. D. Thesis, CUValles, Universidad de Guadalajara; arxiv:1708/03005 (ICRC 2017)



(A) https://arxiv.org/abs/1708.03005 (B)

Take on mind that:

1.- For a relative intensity measurement, we need to have a background estimation (where variations exist)

2.- The ammount of cosmic rays arriving to detectors is not uniform (more sensitivity to other directions. Also variations on the atmosphere on time affect detectors sensitivity).

https://arxiv.org/abs/1708.03005

Take on mind that:

3.- The latter means we need to make an estimation of the number of cosmic rays that can be detected on every direction considering isotropy and estimate true variations (anisotropy)

LIKELIHOOD ANALYSIS TO DO A FIT THROUGH AN ITERATIVE ALGORITHM.

Where every iteraction provides a better estimation and so on until converge to a correct result.

https://arxiv.org/abs/1708.03005

Take on mind that:

4.- We need also to make a spectral analisis (like fourier transformation) to get an indication of the precence of several signals at different angular scales (as function of space), instead reveals the amplitude of signals at different frequencies (as function of time).

Here data combination is more important even that in the multipolar fit, because if we only have partial covering of sky, there is interference at diferent angular scales: Amplitude underestimation or overestimation on the phase at differents scales.

5.- We have anisotripies at large and small scales

https://arxiv.org/abs/1708.03005

METHODOLOGY

Data map:

Reference map: sensitivity of the detector considering an CRs isotropic flux (iterative maximum likelihood analysis)

Compare both, Data and reference map to determine if any "true" anisotropy is observed.

This comparasion is done using two maps:

Relative Intensity and statiscal signifance map

https://arxiv.org/abs/1708.03005

METHODOLOGY

Data (D) map: Considering local coordinates of each detected cosmic ray, and the time of each detection (transformation to celestial coordinates):

Reference (R) map (Healpix; Gorzky et al. 2005): From data map but considering that the detection time (t) is randomized on a Delta t window: The contribution of the anisotropy is erased, but keeping the angular sensitivity of the detectors and fluctuations from weather variables (Pressure and temperature).

https://arxiv.org/abs/1708.03005

Determination of the anisotropy in terms of the relative intensity for each pixel i considering number of events on i (D and R maps)

$$\delta I_i = \frac{\Delta N_i}{\langle N \rangle_i} = \frac{N_i - \langle N_i \rangle}{\langle N_i \rangle} ,$$

Significanse using T. P. Li and Y. Q Ma method (1983) that consider statistical fluctuations on D and R.

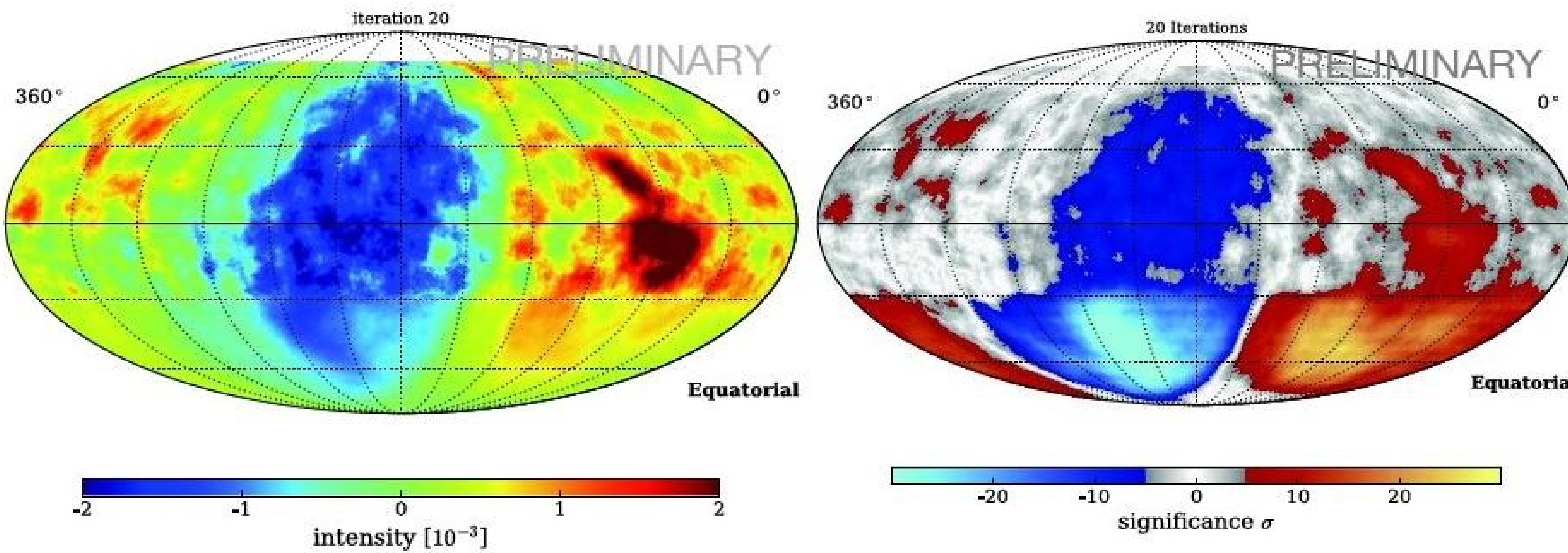
$$s_i = \sqrt{2}\left\{N_i \log\left[\frac{1+\alpha}{\alpha}\left(\frac{N_i}{N_i+N_o}\right)\right] + N_o \log\left[(1+\alpha)\left(\frac{N_o}{N_i+N_o}\right)\right]\right\}^{1/2}$$

No = <Ni> / alpha; alpha = 1 / n

https://arxiv.org/abs/1708.03005

Relative Intensity

Significance Map



- Relative intensity and significance maps after 20 iterations smoothed over 5deg radius.
- First full-sky combined observation at same energy with two observatories covering most of the celestial sphere.
- Significance of features in the northern sky is lower than previously published HAWC results due to decreased statistics from energy cuts.

https://arxiv.org/abs/1708.03005

Diaz-Velez Ph. D. Thesis, CUValles, Universidad de Guadalajara; arxiv:1708/03005 (ICRC 2017)

Iterative maximum likelihood method

Ahlers, BenZvi, Desiati, Díaz-Vélez, Fiorino, Westerhoff (arXiv:1601.07877)

The likelihood of observing n cosmic rays is given by the product of Poisson probabilities

$$\mathcal{L}(n|I,\mathcal{N},\mathcal{A}) = \prod_{\tau i} \frac{(\mu_{\tau i})^{n_{\tau i}} e^{-\mu_{\tau i}}}{n_{\tau i}!}$$

$$\mu_{\tau i} \simeq I_{\tau i}\mathcal{N}_\tau\mathcal{A}_i$$

relative intensity

relative acceptance

expected number of events from isotropic background

The number of cosmic rays expected from this location in asidereal time interval Δτ with central value τ.

Maximize the likelihood ratio via null hypothesis in $\mathcal{N}$, $\mathcal{A}$ y I

The likelihood ratio of signal over null hypothesis in N , A, and I.

$$\lambda = \frac{\mathcal{L}(n|I,\mathcal{N},\mathcal{A})}{\mathcal{L}(n|I^{(0)},\mathcal{N}^{(0)},\mathcal{A}^{(0)})}$$

maximum values ($I^\star$,$\mathcal{N}^\star$,$\mathcal{A}^\star$) must follow

$$I^\star_a = \sum_\tau n_{\tau a} \Big/ \sum_\kappa \mathcal{A}^\star_{\kappa a}\mathcal{N}^\star_\kappa\,,$$

$$\mathcal{N}^\star_\tau = \sum_i n_{\tau i} \Big/ \sum_j \mathcal{A}^\star_j I^\star_{\tau j}\,,$$

$$\mathcal{A}^\star_i = \sum_\tau n_{\tau i} \Big/ \sum_\kappa \mathcal{N}^\star_\kappa I^\star_{\kappa i}\,,$$

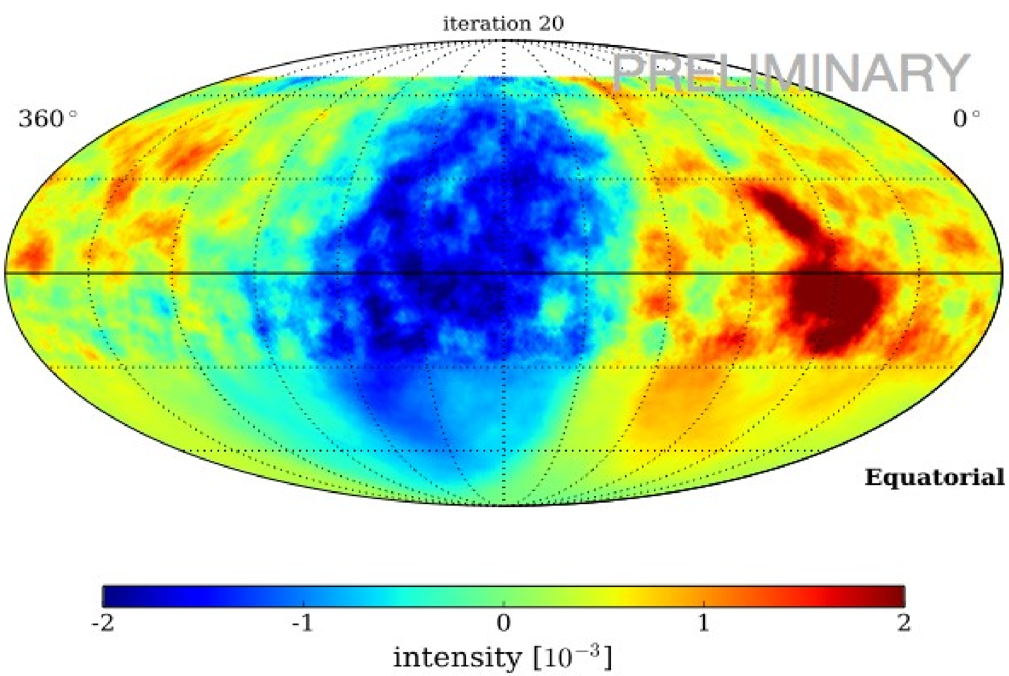
which can be solved iteratively.

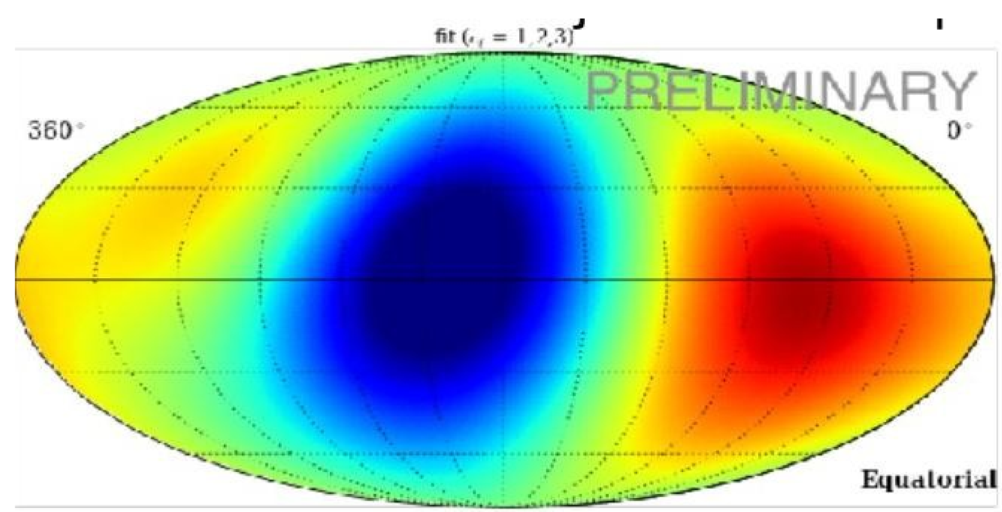
Best method to recover the total amplitude of the anisotropies at large scales projected on the equatorial plane

Diaz-Velez Ph. D. Thesis, CUValles, Universidad de Guadalajara; arxiv:1708/03005 (ICRC 2017)

Multipolar Fit: dipolar and cuadrupolar moment substractions from the data, and study the residuals (Santadner 2013; Ph. D. Thesis, UW-Madison; Smoot and Lubin 1979).

$$\delta I(\alpha,\delta) = m_0 + p_x \cos\delta\cos\alpha + p_y \cos\delta\sin\alpha + p_z \sin\delta$$
$$+ \frac{1}{2}Q_1(3\cos^2\delta - 1) + Q_2 \sin 2\delta\cos\alpha + Q_3 \sin 2\delta \sin\alpha$$
$$+ Q_4 \cos^2\delta\cos 2\alpha + Q_5 \cos^2\delta \sin 2\alpha\ .$$





https://arxiv.org/abs/1708.03005

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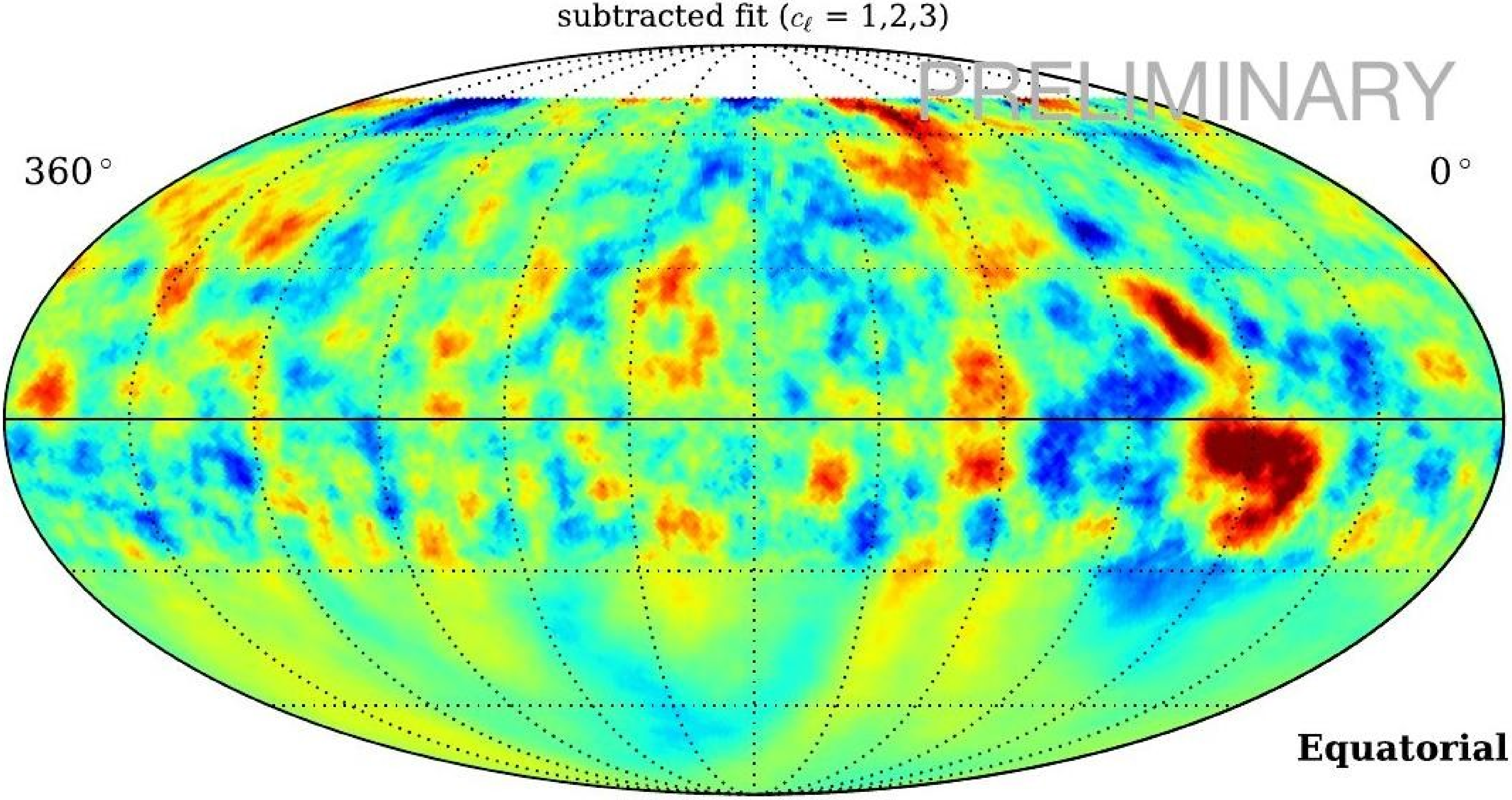
Relative Intensity after substraction of the multipolar fit.



Fit substraction to reveal the caracteristics of small angular scales anisotropies that are embeeded with the larg angular scales anisotropies. Data here is important ti verify independent maps.

https://arxiv.org/abs/1708.03005

Diaz-Velez Ph. D. Thesis, CUValles, Universidad de Guadalajara; arxiv:1708/03005 (ICRC 2017)

Summary

- This IceCube-HAWC study is the first (nearly) full-sky cosmic ray arrival direction distribution analysis with combined data from observatories in the North and South at the same primary energy of 10 TeV and is a key to probe into the origin of the CRA observations.
- Iterative maximum-likelihood reconstruction method simultaneously fits CR anisotropies and detector acceptance.
- Provides an optimal anisotropy reconstruction and the recovery of the dipole anisotropy for ground-based observatories located in middle latitudes.
- Ground-based observatories are generally insensitive to cosmic-ray anisotropy variations that are symmetric in RA, i.e. only vary across declination bands (i. e. dipole only observed as a projection onto celestial equator).
- Nearly full-sky coverage gives better fit of phase and amplitude of horizontal component of the dipole anisotropy.
- Significant small-scale structure is largely consistent with previous individual measurements.
- Currently analyzing an additional year of HAWC data which will double the statistics in the northern hemisphere.

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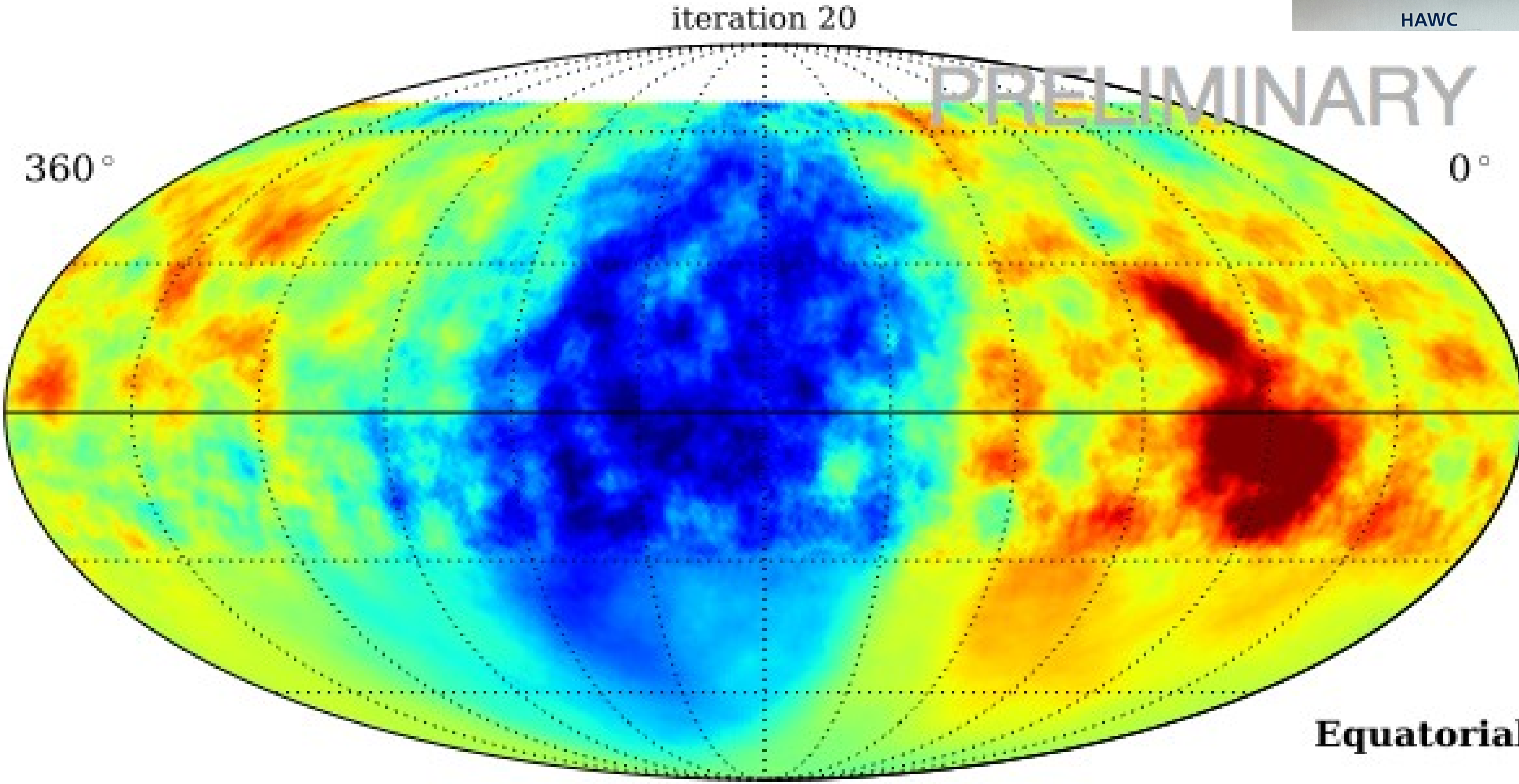
Muchas Gracias !!!



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