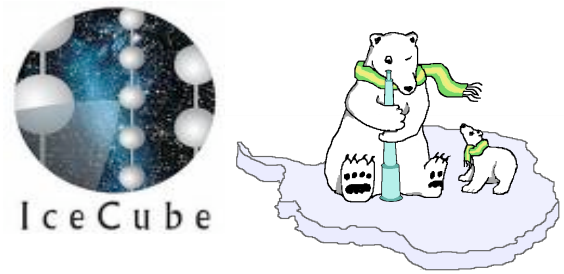


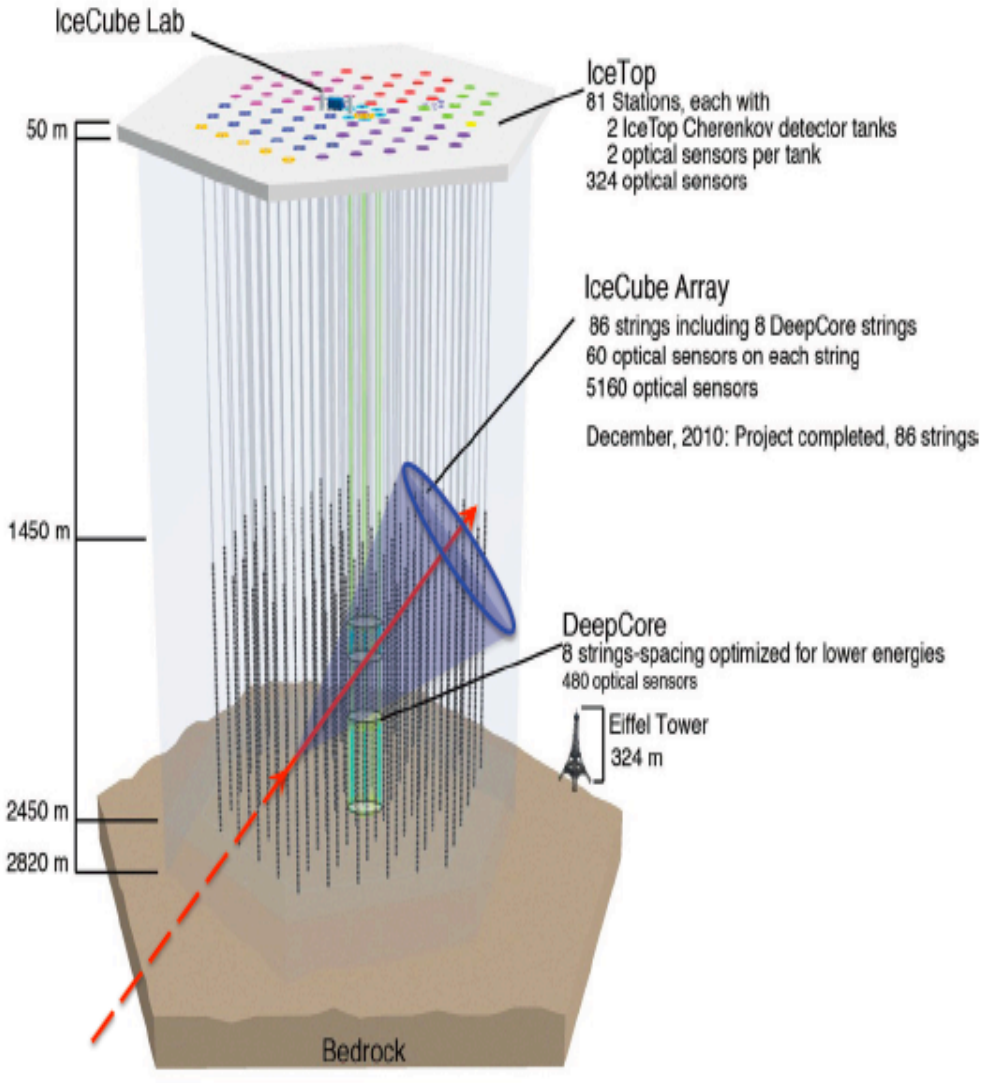
Evolution Of The Galactic Cosmic Rays Anisotropy Above 10^{14}eV

Rasha Abbasi

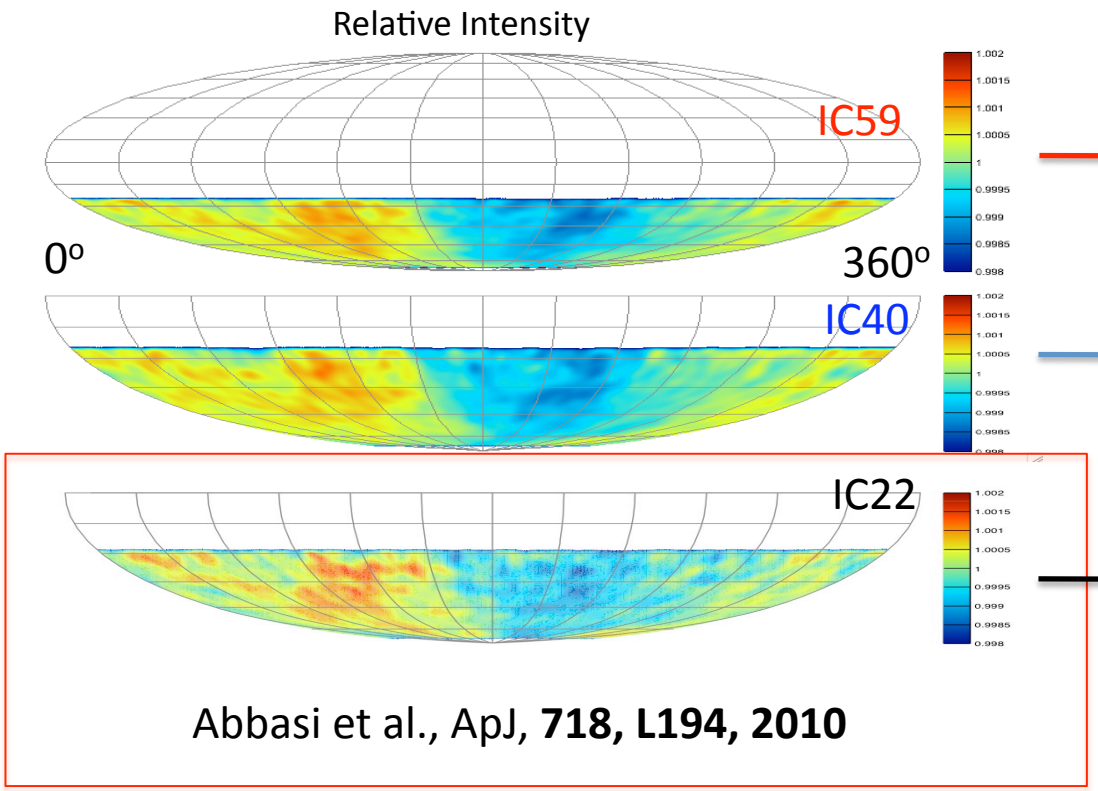
University of Wisconsin

The IceCube Neutrino Observatory

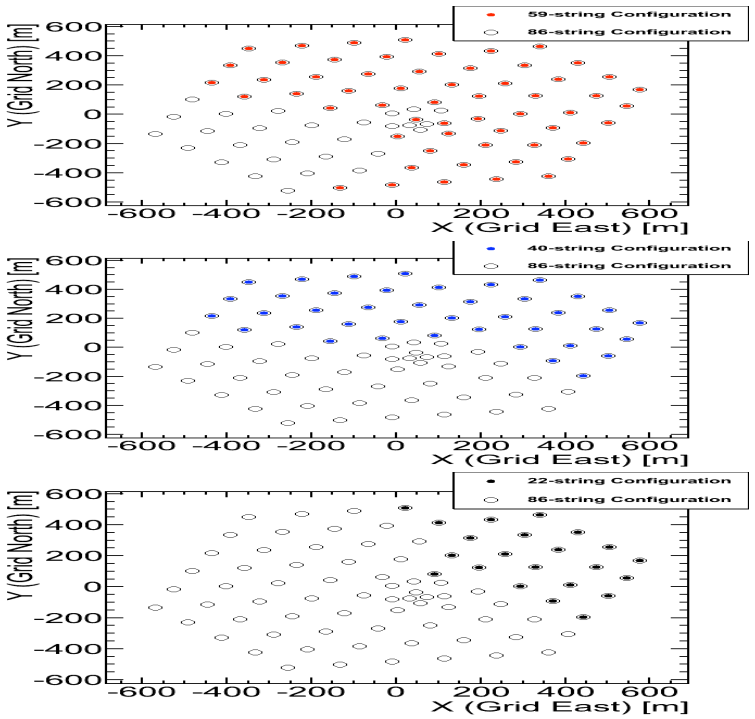
- IceCube detector is now complete and is taking data in the complete configuration 86-strings
- IceCube main goal is to detect astrophysical neutrinos using Cherenkov emission
- High statistics sample of downward going muon background are used to study high energy cosmic ray anisotropies at the 10^{-4} level and less.
- This analysis used the IceCube 59-strings configuration collected in from May 2009- May 2010.



Relative Intensity of Cosmic Rays (IC22, IC40 & IC59)



Abbasi et al., ApJ, **718, L194, 2010**

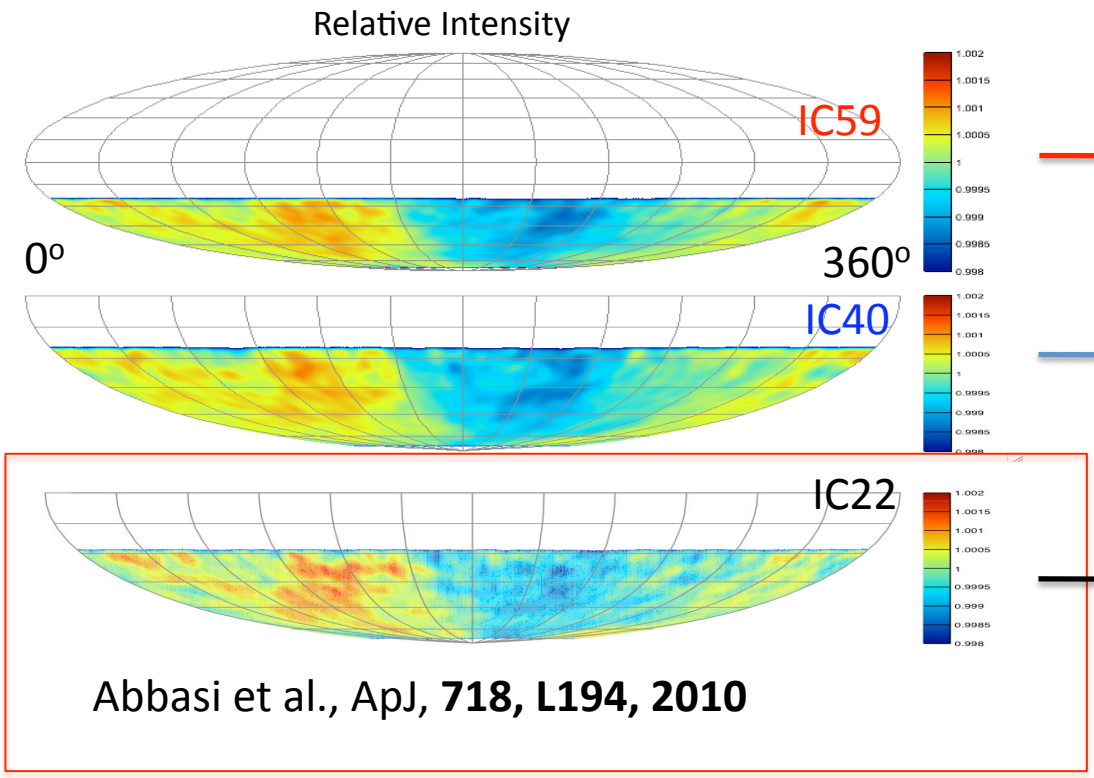


Relative Intensity: $\dfrac{N_i(\alpha,\delta)}{\langle N_i(\delta)\rangle\alpha}$

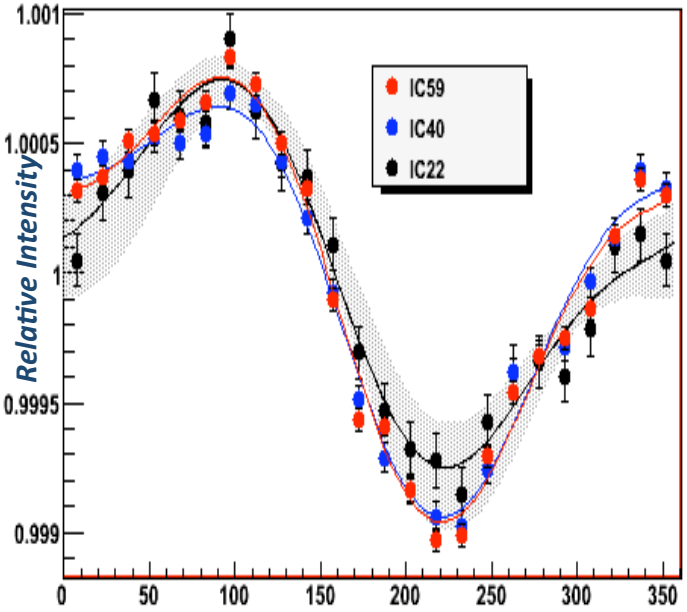
Relative intensity of the cosmic ray event rate in equatorial coordinates: for each declination belt of width 3°, the
plot shows the number of events relative to the average number of events in the belt.

Year	Rate (Hz)	Livetime (Days)	CR Median Energy (TeV)	Median Angular Resolution	Number of Events
2007-IC22	240	226	20	3°	~4×10^9
2008-IC40	780	324	20	3°	~19×10^9
2009-IC59	1200	324	20	3°	~32×10^9

Relative Intensity of Cosmic Rays (IC22, IC40 & IC59)



Abbasi et al., ApJ, **718, L194, 2010**



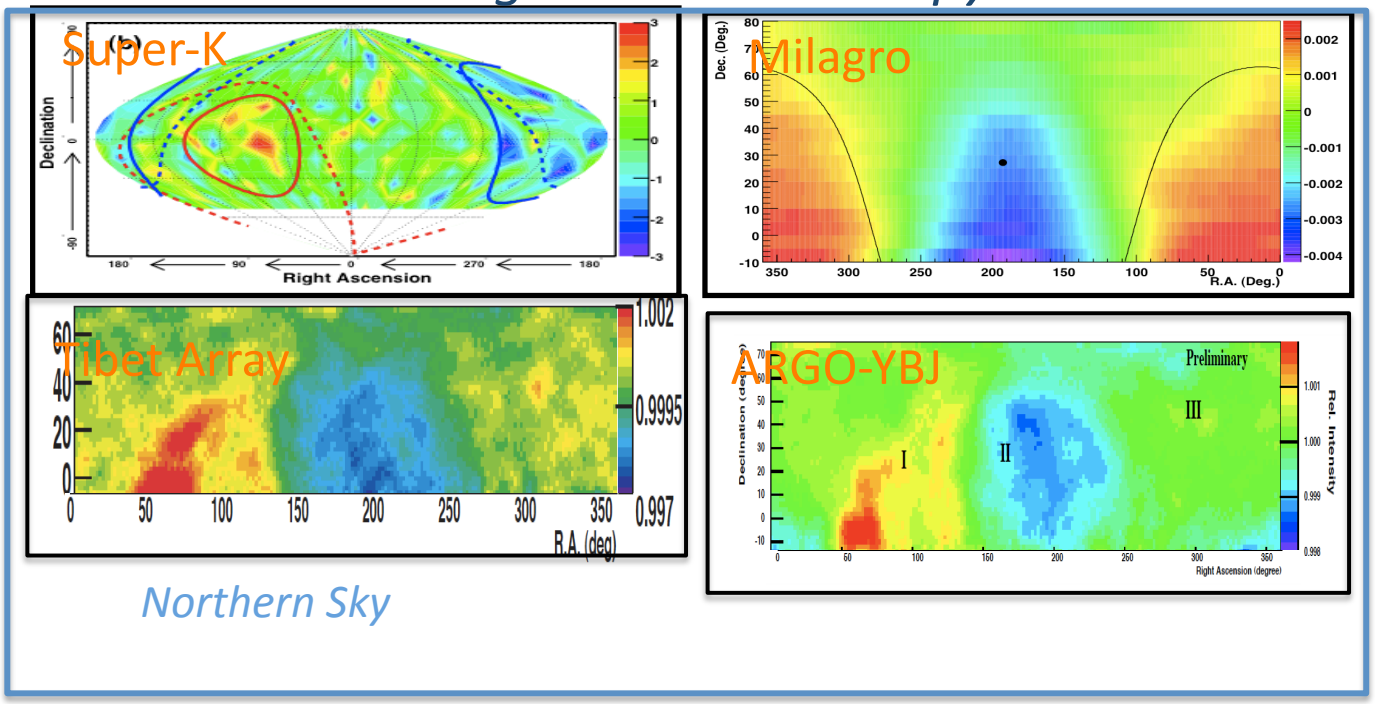
Relative Intensity: $\dfrac{N_i(\alpha,\delta)}{\langle N_i(\delta)\rangle\alpha}$

Relative intensity of the cosmic ray event rate in equatorial coordinates: for each declination belt of width 3°, the plot shows the number of events relative to the average number of events in the belt.

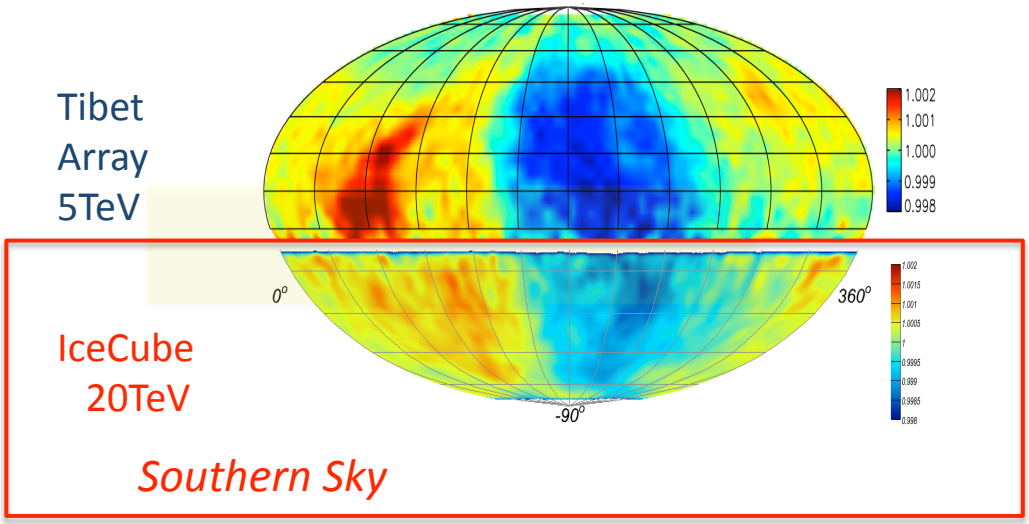
The 1-D projection of the equatorial relative intensity skymap is fitted to a first and second harmonic function of the form

$$\sum_{i=1}^{2} A_i \cos(i(\alpha - \phi_i)) + B$$

Large Scale Anisotropy and Past Results



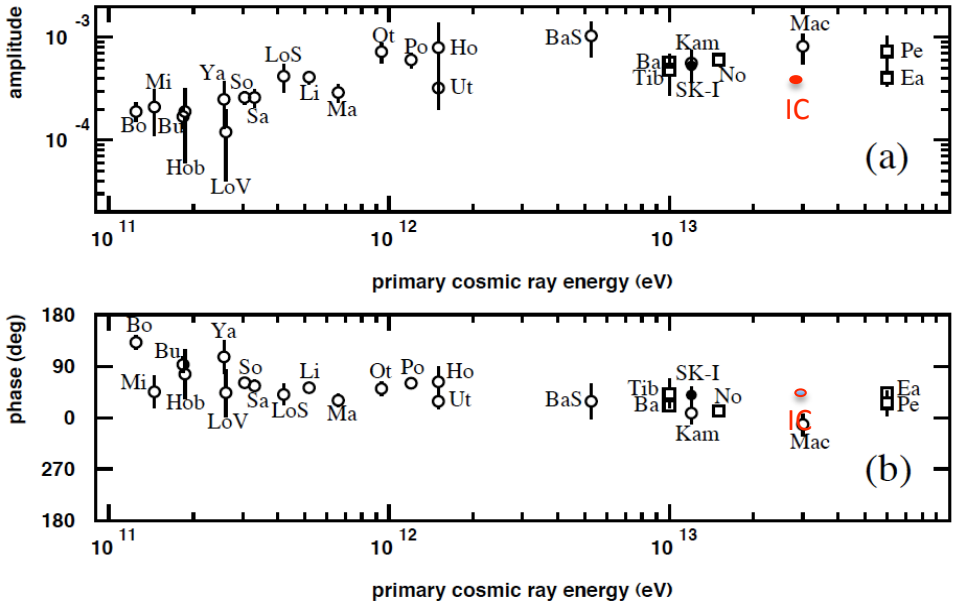
Northern Sky

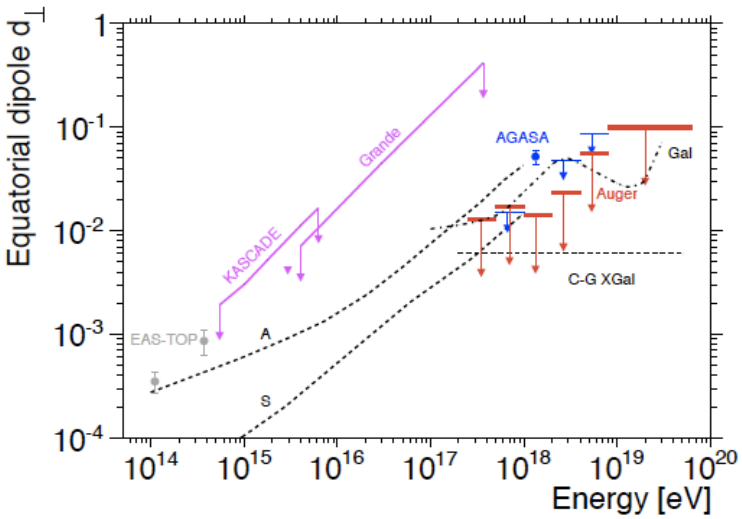


Southern Sky

- IceCube observed a large scale anisotropy at 10^{-3} level for the first time in the Southern Sky.
- *Large Scale Features appear to be a continuation of those observed in the Northern Hemisphere.*

Large Scale Anisotropy and Past Results

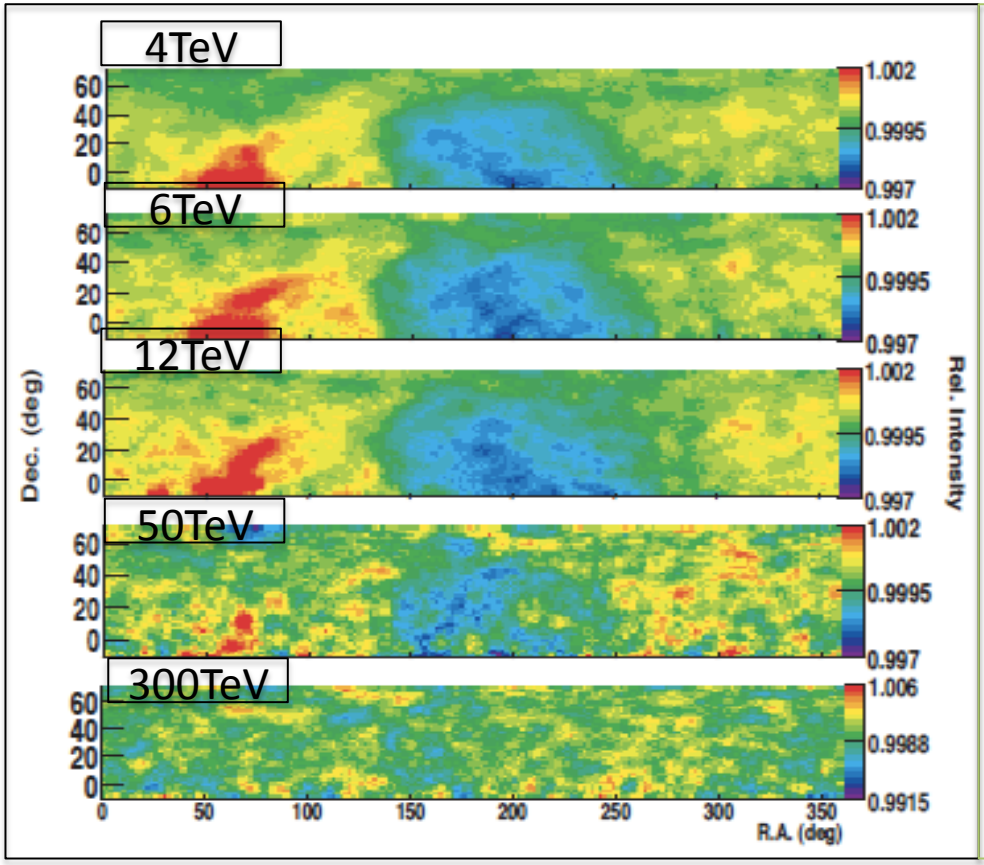




- Amplitude and phase is established experimentally between 10^{11}-10^{14}eV
- *Study of the anisotropy evolution in the energy region >10^{14} eV can provide an insight to the origin and propagation of cosmic rays.*

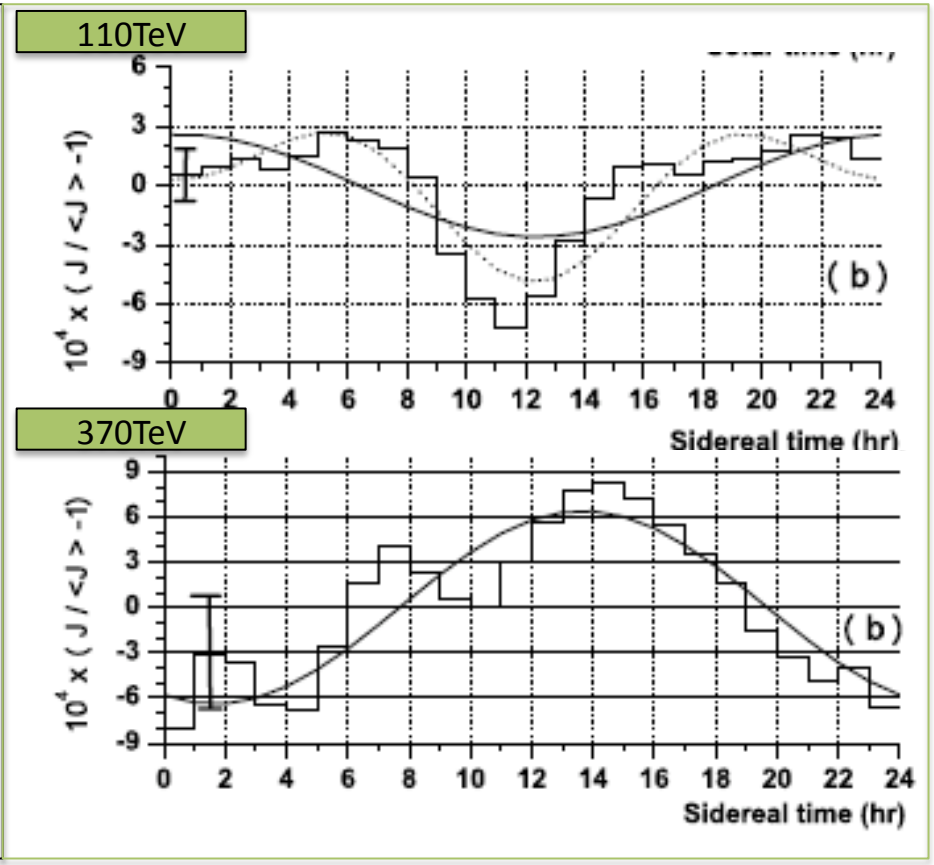
Large Scale Anisotropy and Past Results

Tibet Array



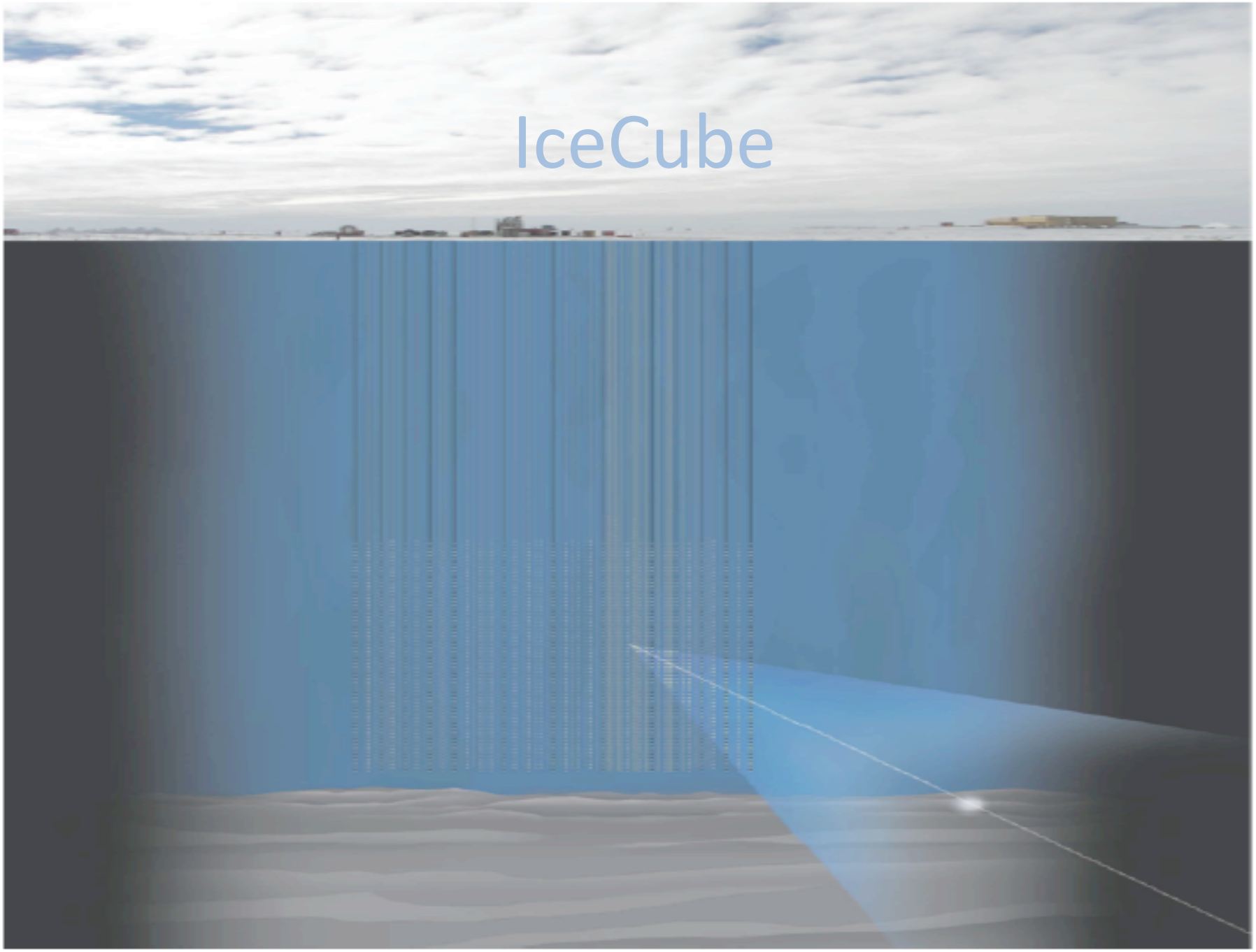
Science314:439-443,2006

EAS-TOP



arXiv:0901.2740

No Coherent Global Picture in the Northern Hemisphere

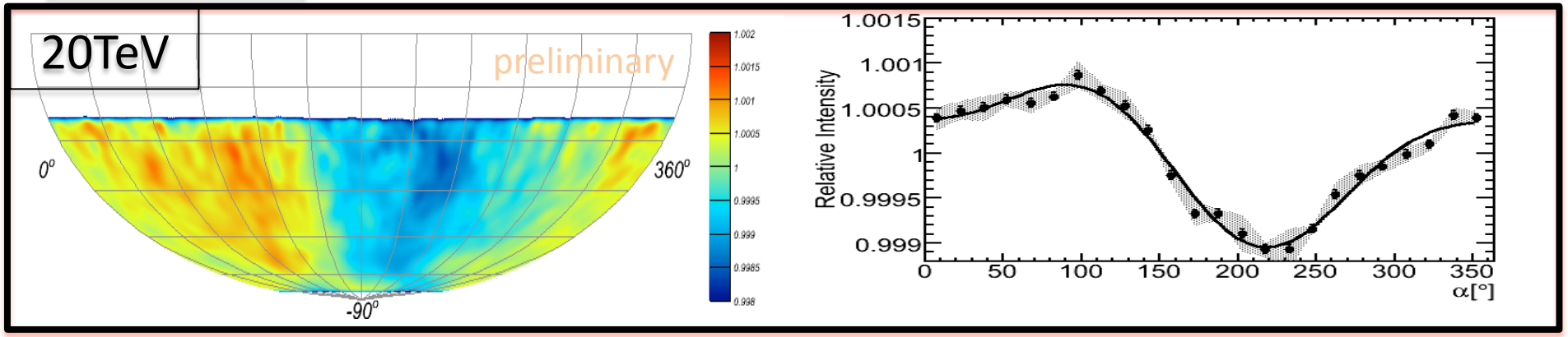

IceCube

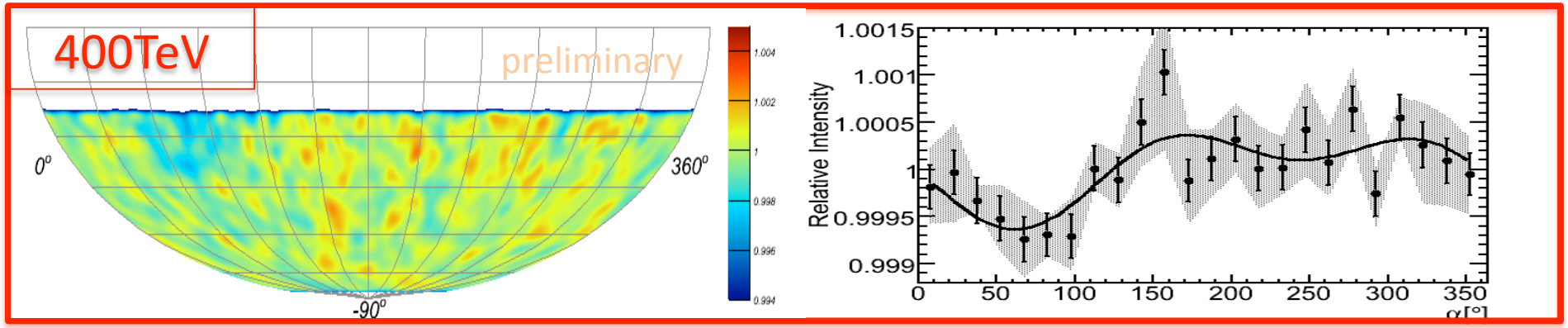
CR Energy Dependence (20TeV,400TeV)

Relative Intensity: $\frac{N_i(\alpha,\delta)}{\langle N_i(\delta)\rangle\alpha}$

equatorial coordinates

Relative Intensity maps





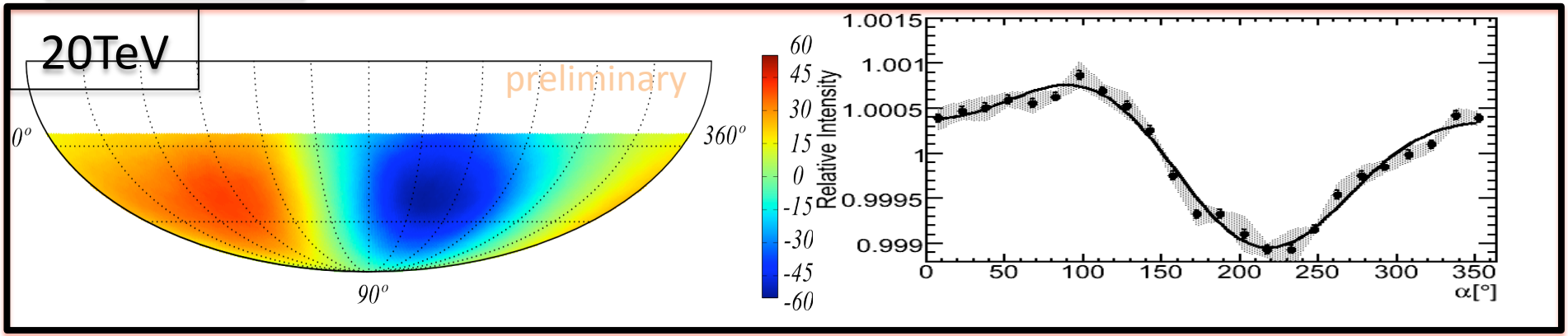
The anisotropy at 400 TeV shows a substantial difference w.r.t that observed at 20 TeV

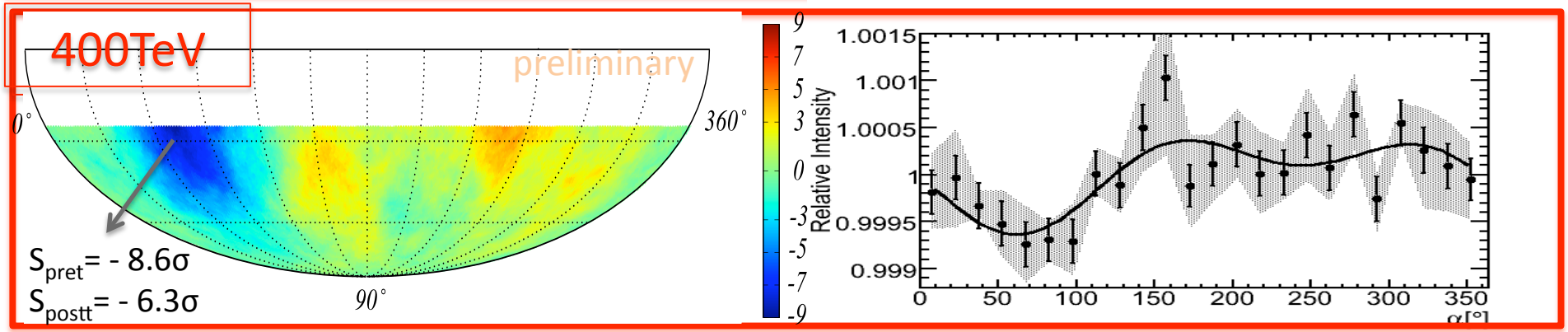
First Detection of Anisotropy at 400 TeV

Statistical Significance: $\sqrt{s}\left\{N_{on}\ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{on}}{N_{on}+N_{off}}\right)\right]+N_{off}\ln[(1-\alpha)\left(\frac{N_{off}}{N_{on}+N_{off}}\right)]\right\}^{1/2}$

equatorial coordinates

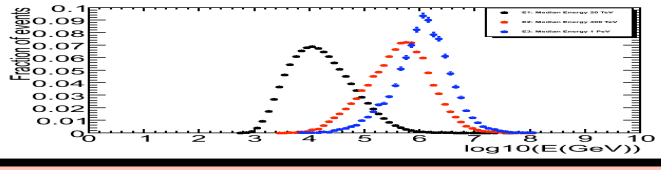
Statistical Significance Skymaps



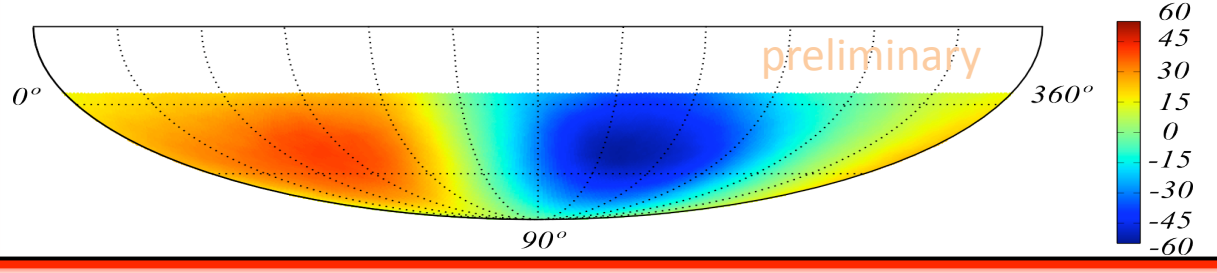


- Reference map is derived from data with time scrambling
- Scan from 1°-30° in smoothing radius to optimized for the highest significance regions
- Only a deficit at 21° Smoothing, (RA=73.1°,Dec=-25.3°), was identified as a significant structure.

A peak into the 1 PeV region

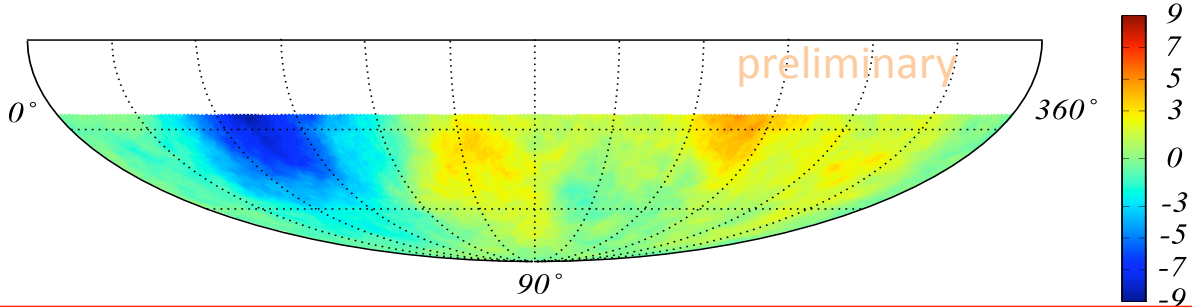


20 TeV



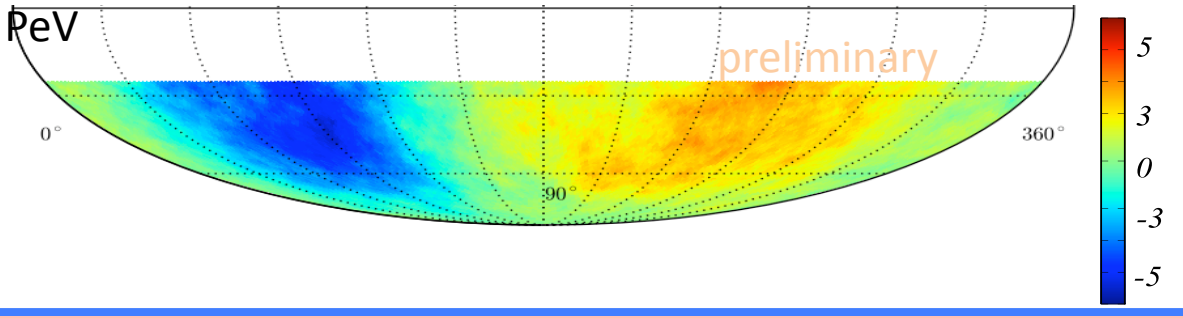
21 Billion events

400 TeV



580 Million events

1 PeV



137 Million events

- *No identified significant Anisotropy in the 1 PeV skymap*
- *The anisotropy is persistent with that observed at 400 TeV*
- *IC86 will enable us to understand the energy dependence with higher statistics closer to the knee region*

Summary

Summary

- *First significant observation of the anisotropy at 400 TeV in the Southern sky.*
- The result is supported by:
  - the observation of the solar dipole [See Poster by R.Abbasi HE1.1 Aug13-15]
  - the absence of the signal in the anti-sidereal time
  - data stability checks.
  - Persistence with observations from previous year.
- The origin of the anisotropy is unknown:
  - The result is not consistent with the CG assuming the galactic cosmic rays at rest with the galactic center.
  - Improved theoretical description of the diffusion processes of galactic cosmic rays closer to the knee.
  - Interstellar Magnetic field.
  - This anisotropy reveals a new feature of the Galactic cosmic ray distribution, which must be incorporated into theories of the origin and propagation of cosmic rays.

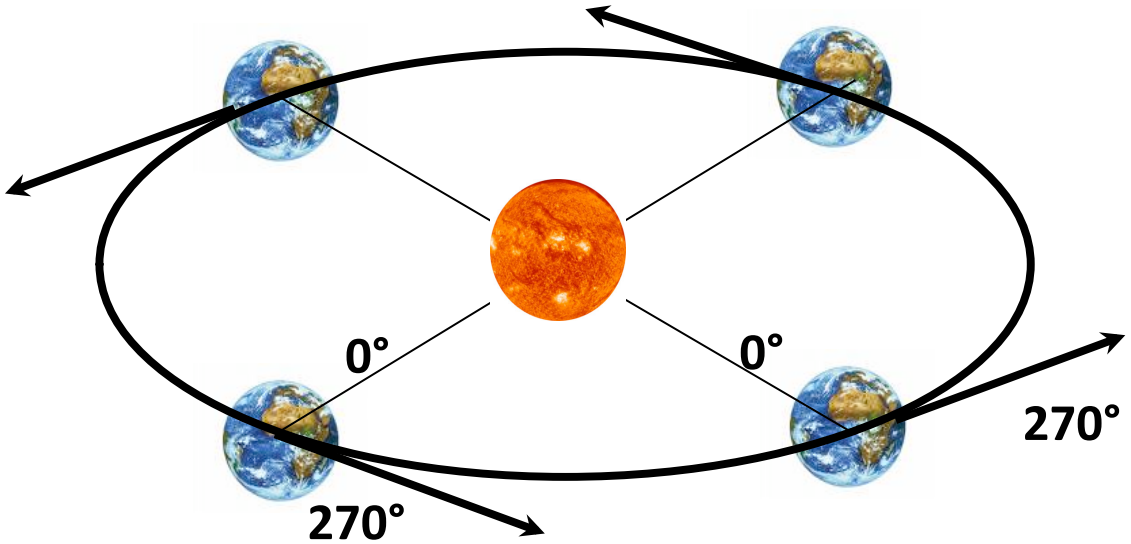
- *Paper in process for submission.*

Backup slides

Solar Diurnal Anisotropy

-This effect caused by Earth's motion around the Sun is apparent when the skymap is plotted with respect to the sun O(10^{-4}).

-The intensity of cosmic rays should be *higher* coming from the direction in which the observer is moving in causing a *dipole anisotropy*.



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

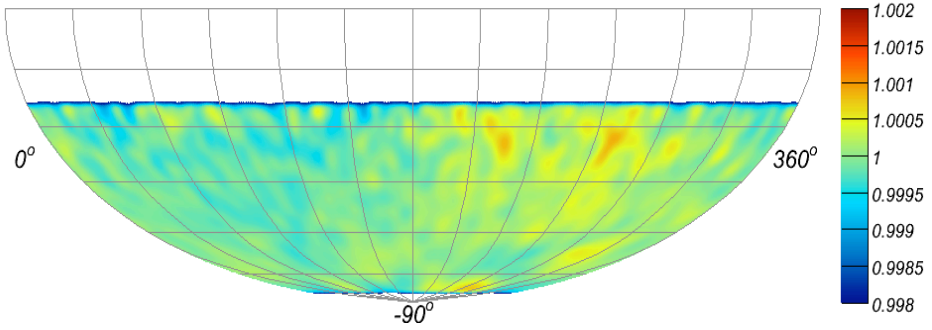
$\gamma = 2.7$ cosmic ray spectral index

$v = 29$ km/s speed

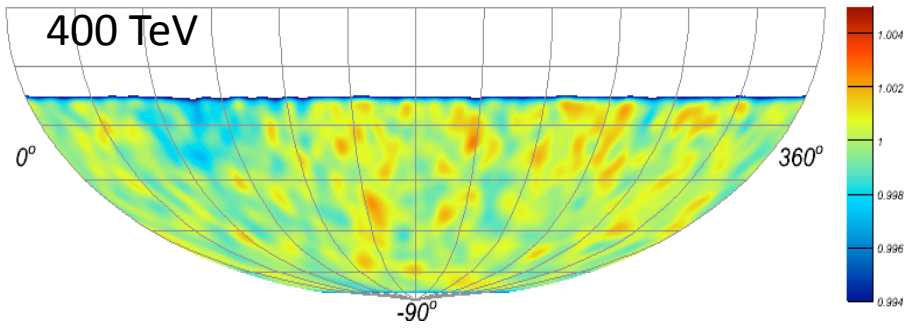
Solar Diurnal Anisotropy

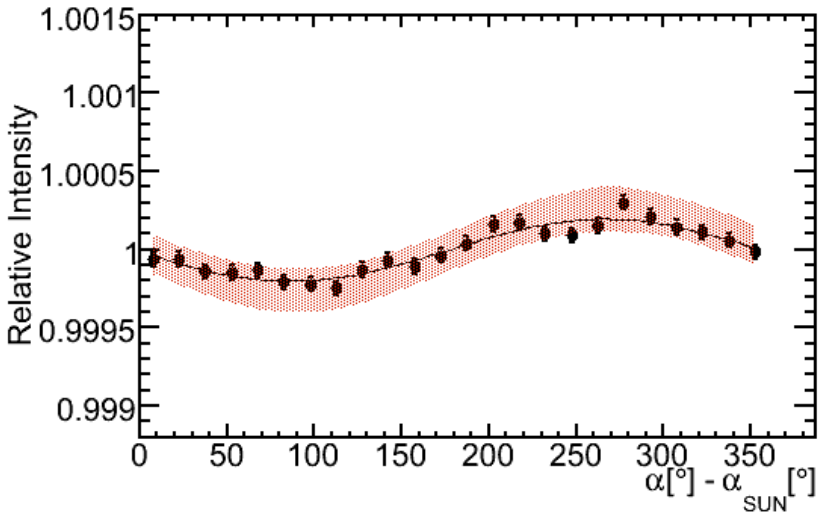
$$\frac{\Delta I}{\langle I \rangle} = (\gamma + 2)\ \frac{v}{c}\ \cos\vartheta$$

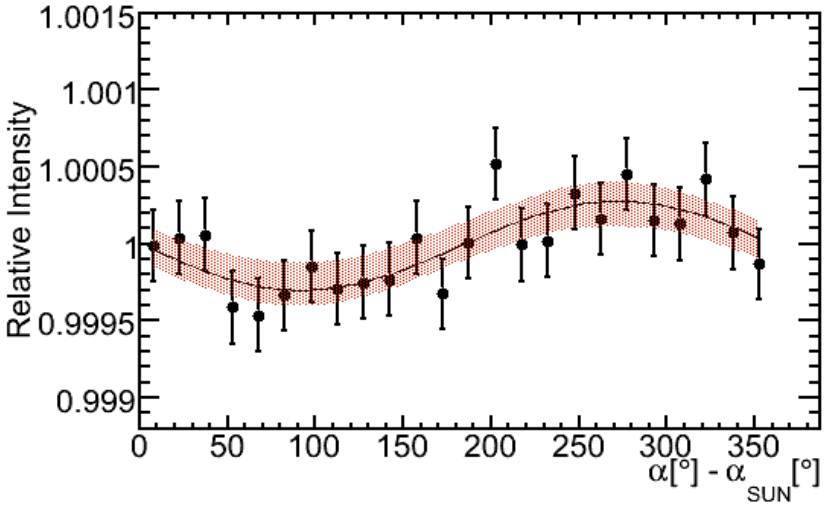
20 TeV



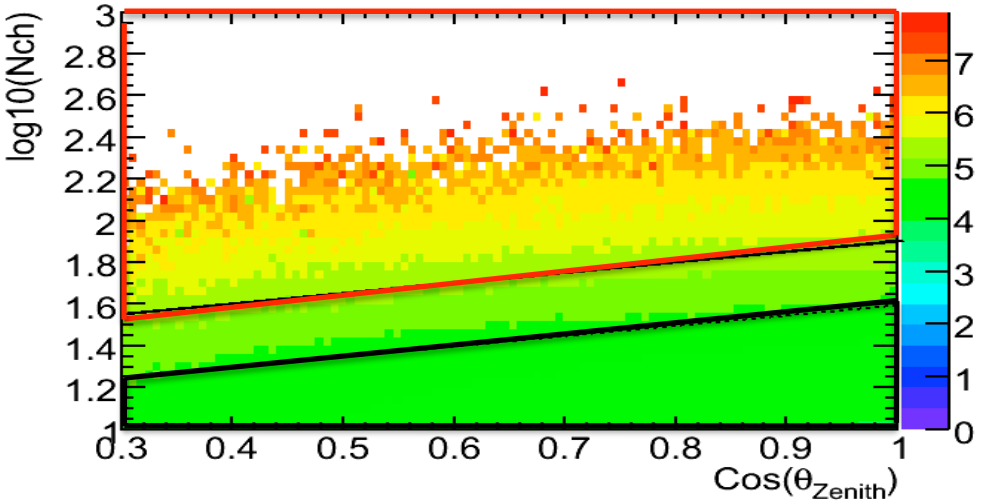
400 TeV

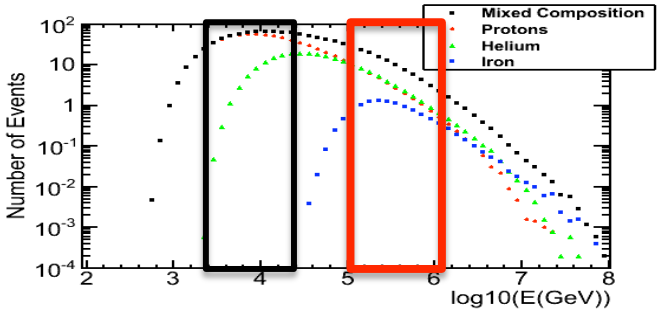


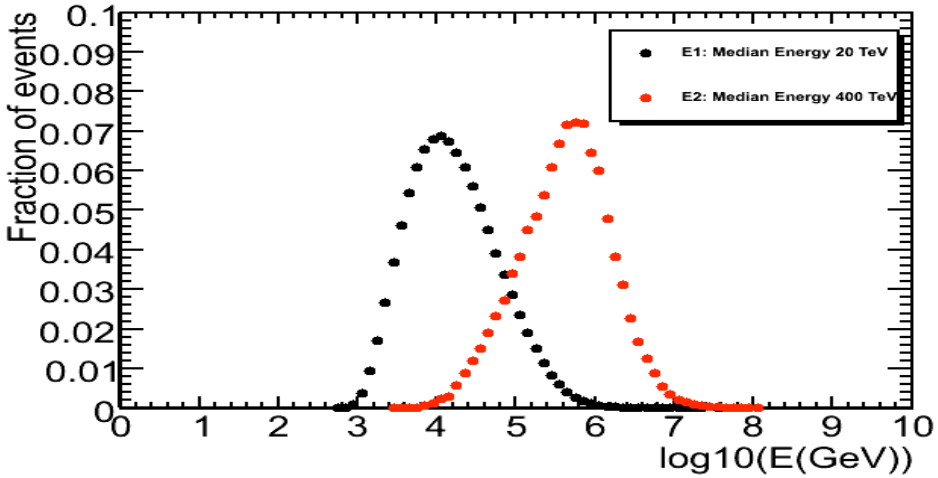




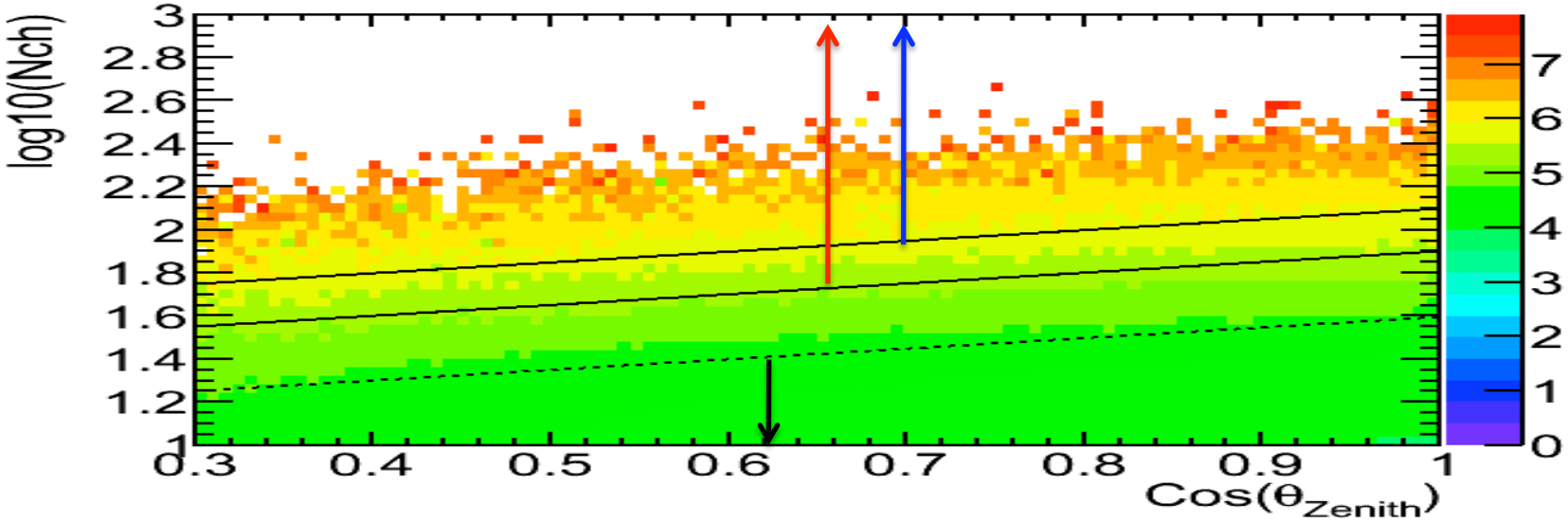
CR Energy Event selection (20TeV,400TeV)

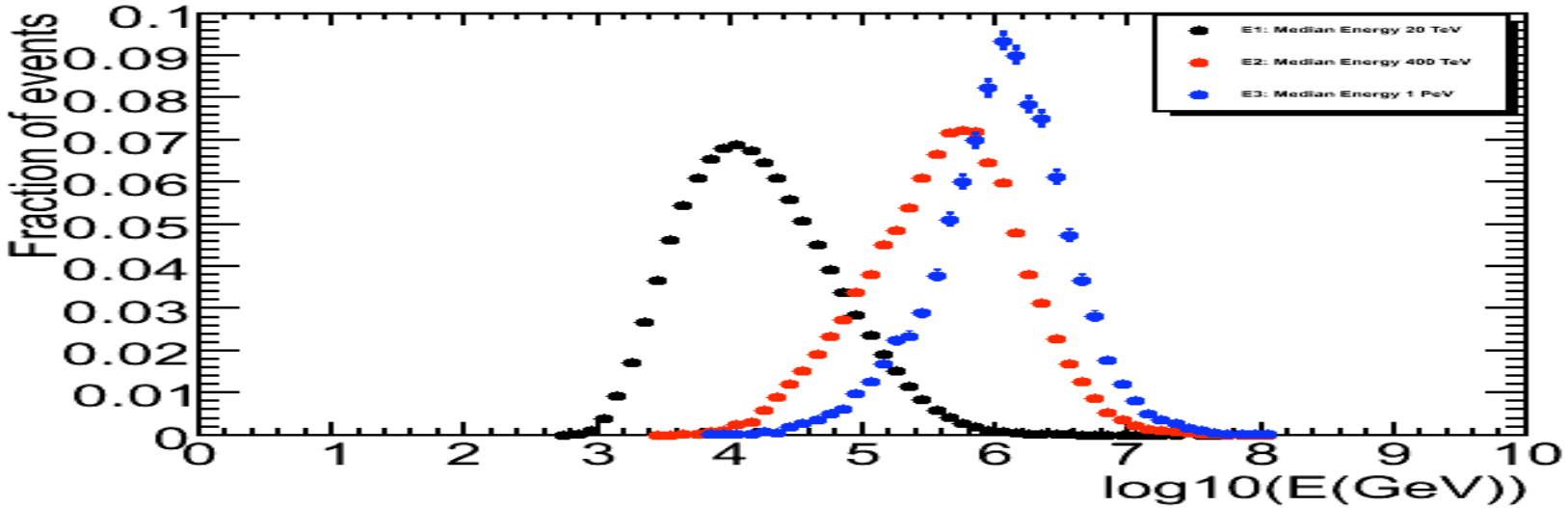






Anisotropy Energy Dependence (10TeV,400TeV,1PeV)

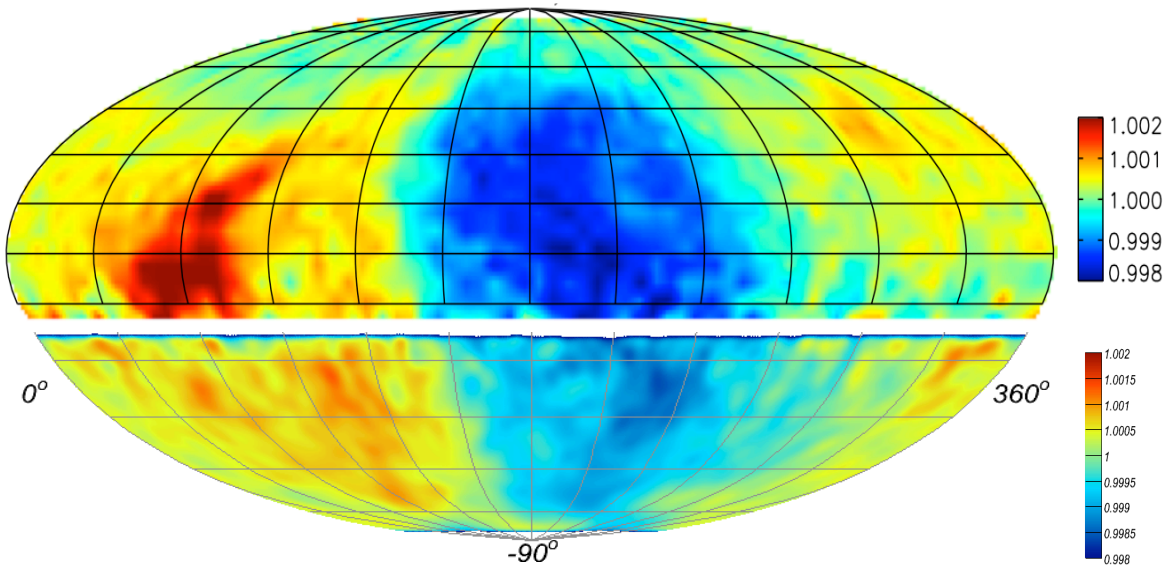




Large Scale Anisotropy and Past Results

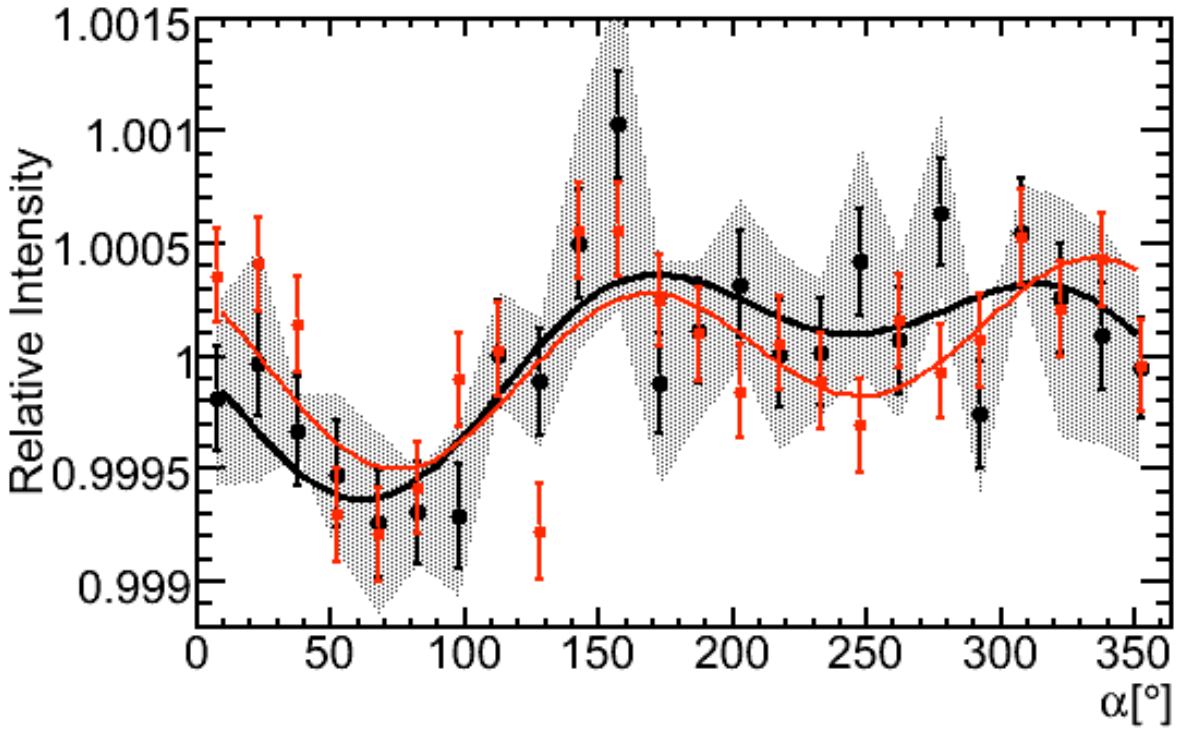
Tibet Array
5TeV

IceCube
20TeV

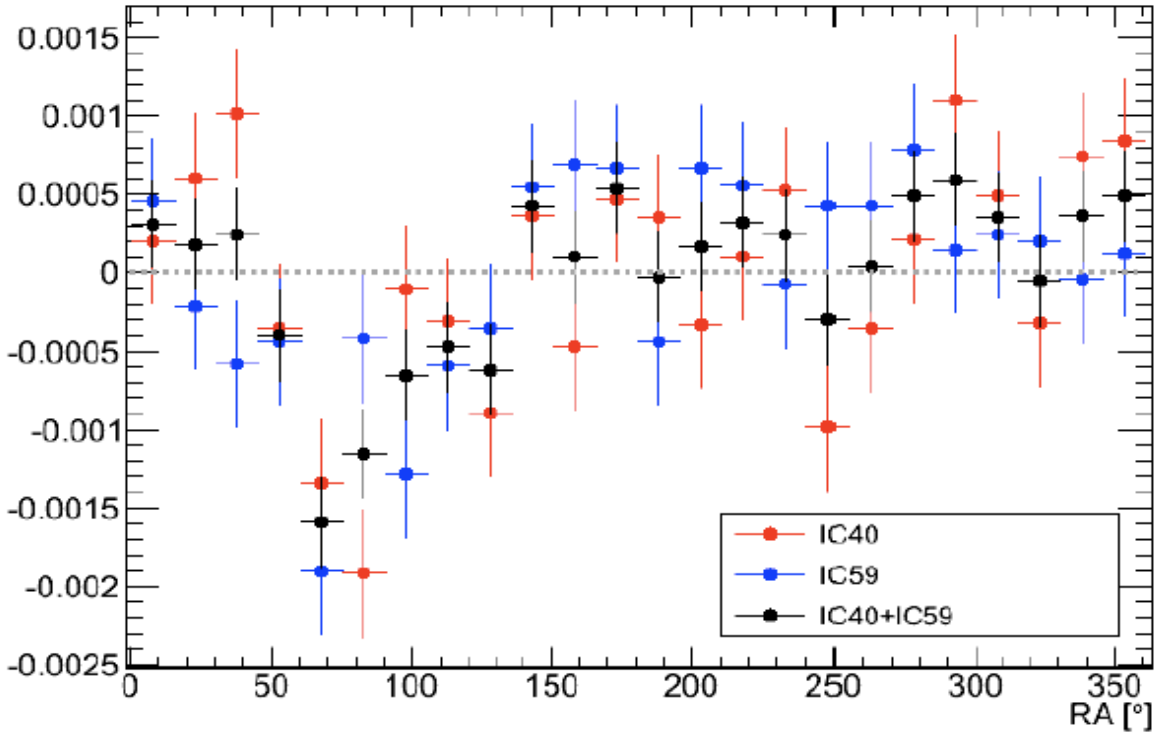


- *Large Scale Features appear to be a continuation of those observed in the Northern Hemisphere.*
- *The anisotropy is not a pure dipole and is not consistent with the Compton Getting effect assuming the galactic cosmic rays at rest with the galactic center.*

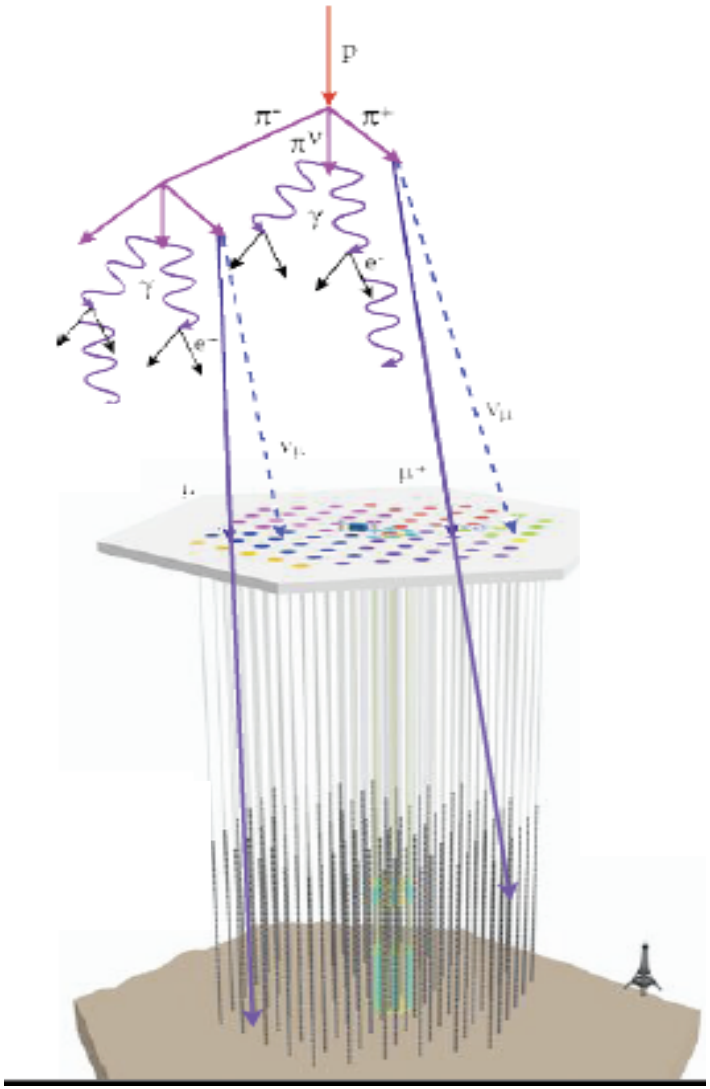
Relative Intensity 1D projection 400 TeV Cosmic Rays (IC59 & IC40)



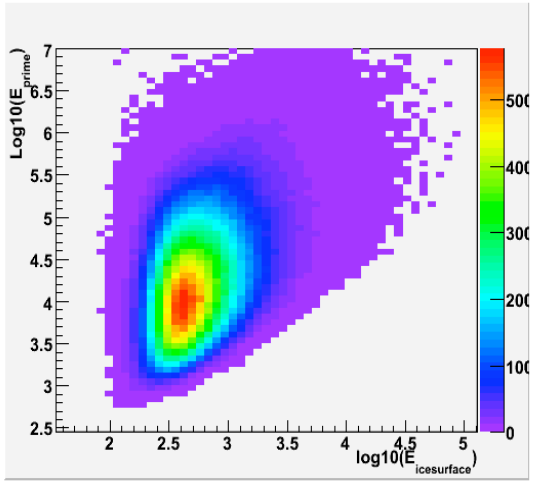
Relative Intensity 1D projection 1 PeV Cosmic Rays

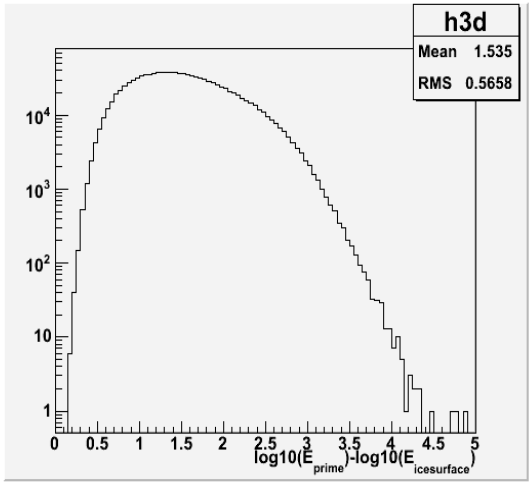


Cosmic Ray Energy estimation

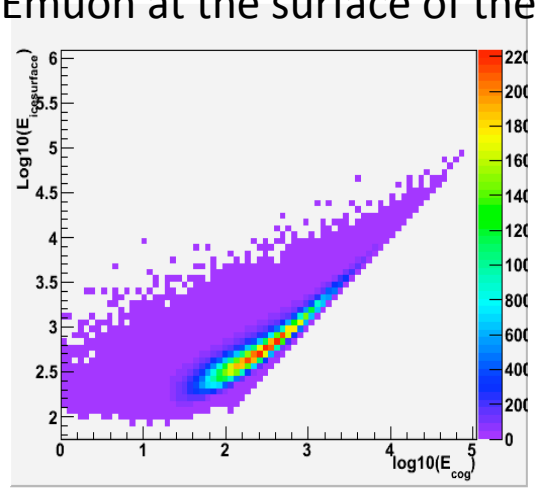


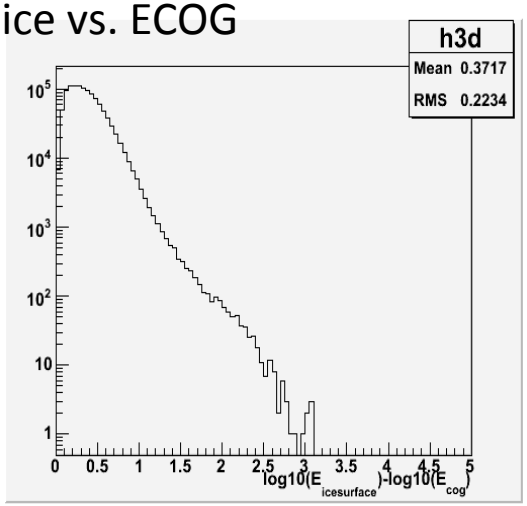
Eprime vs. Emuon at the surface of the ice





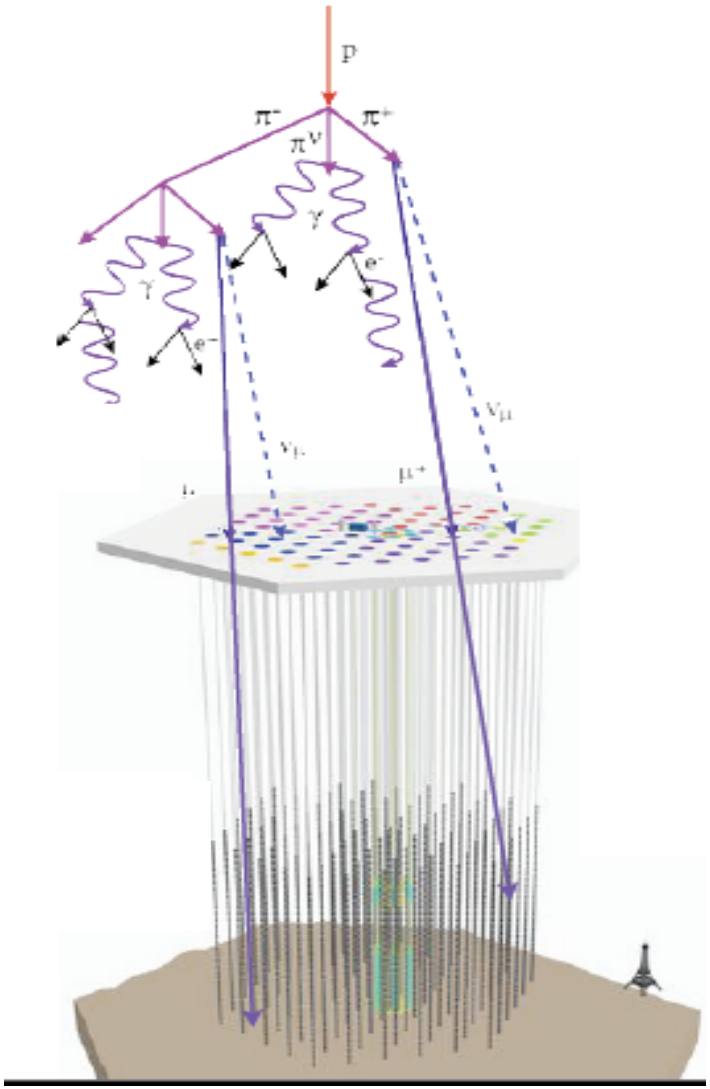
Emuon at the surface of the ice vs. ECOG

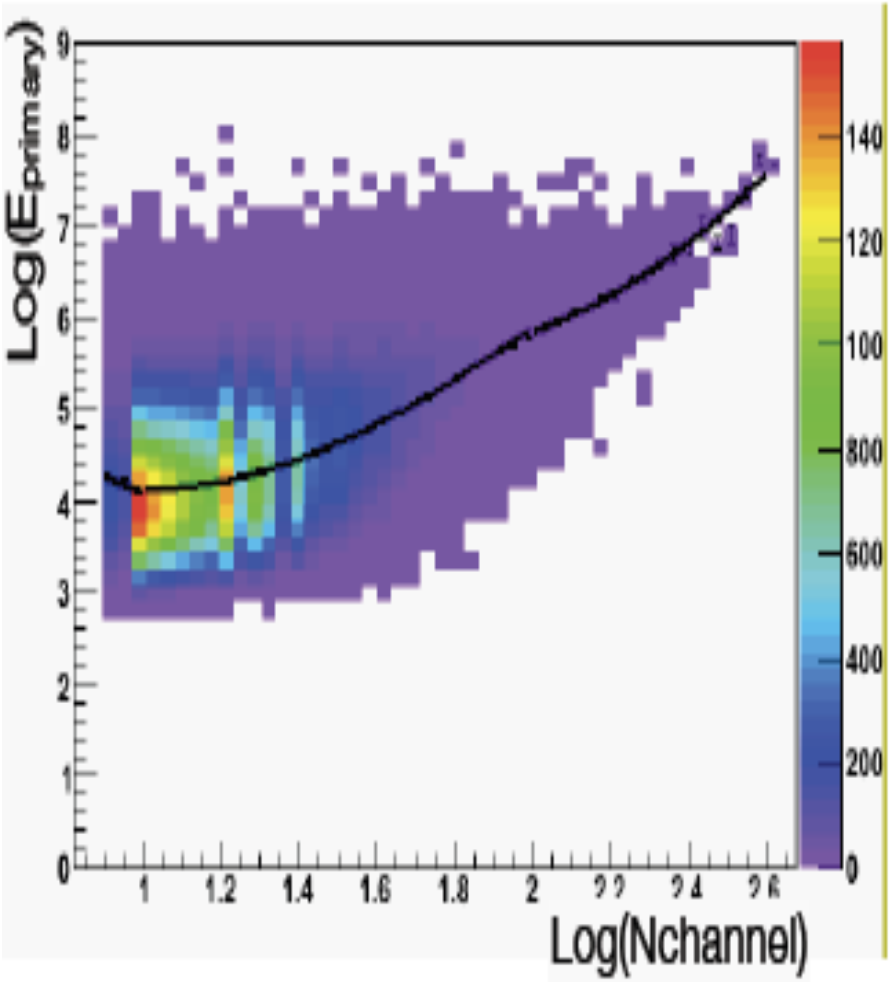




Energy resolution is dominated by energy losses in the EAS

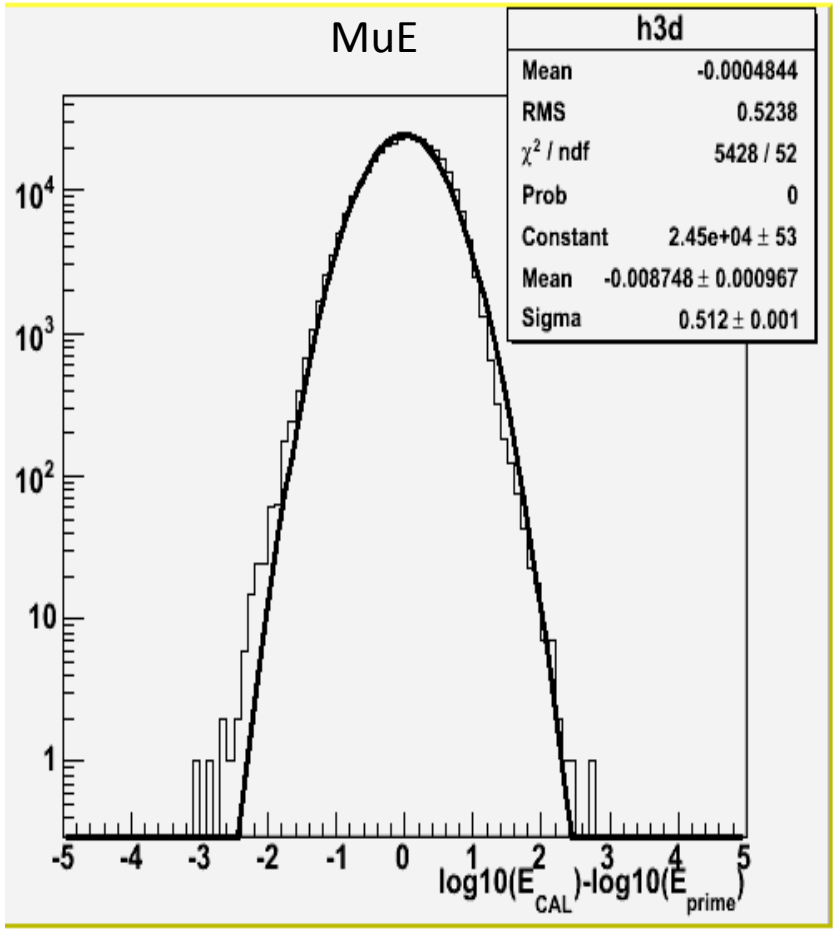
Cosmic Ray Energy estimation

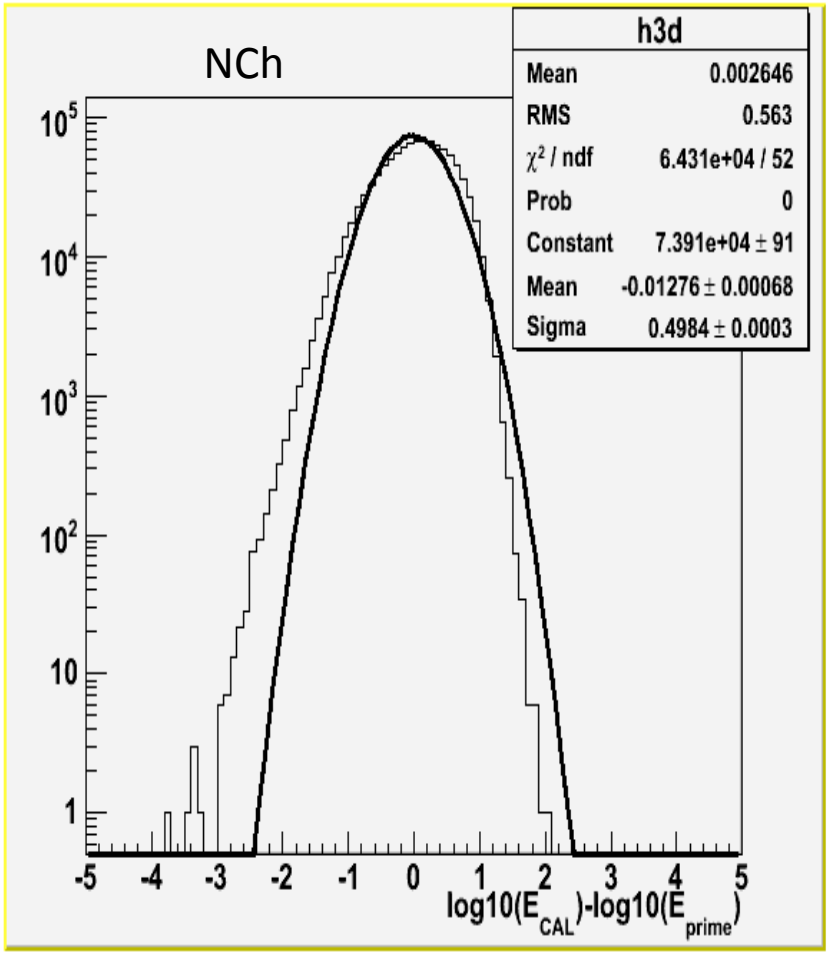




Energy resolution is dominated by energy losses in the EAS

Primary Cosmic Ray Particle Energy Resolution



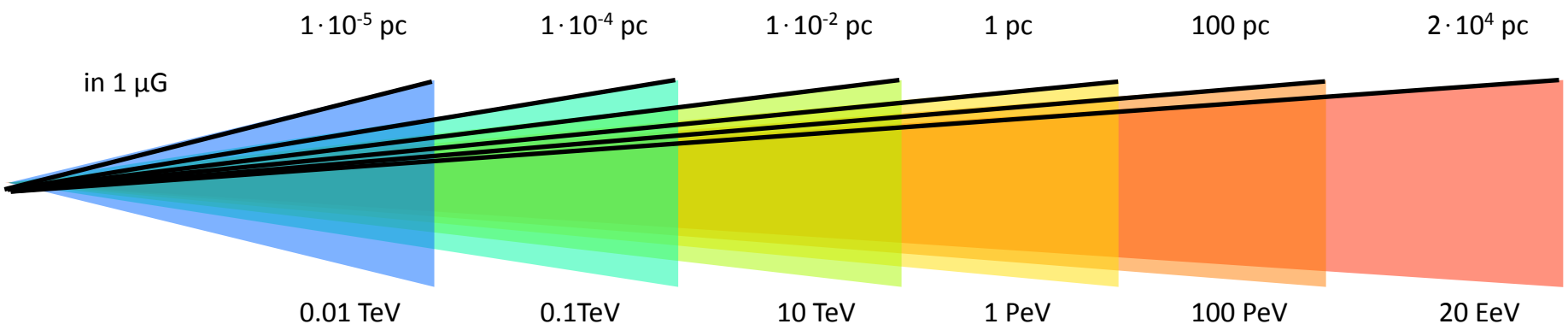


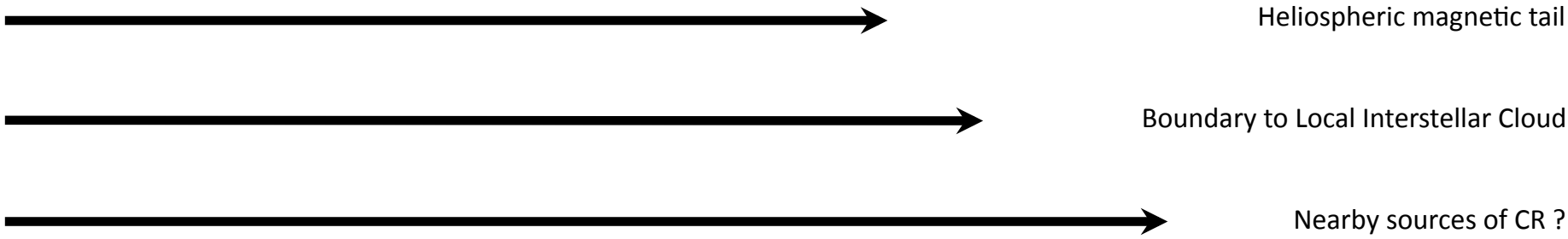
Although MuE may seem a better parameter to estimate energy. A similar energy Resolution is obtained with nchannel while keeping more number of events.

Origin of the anisotropy?

- Feature connected to the diffusion of cosmic rays in the interstellar magnetic field.

$$\frac{R_g^{CR}}{pc} = \frac{1.1 \cdot 10^{-3}}{|Z|} \left(\frac{p_\perp^{CR}}{TeV/c} \right) \left(\frac{\mu G}{B_{IS}} \right)$$





- References for explanations