Analysis of Cosmic-Ray Anisotropy
A HAWC and IceCube Collaboration

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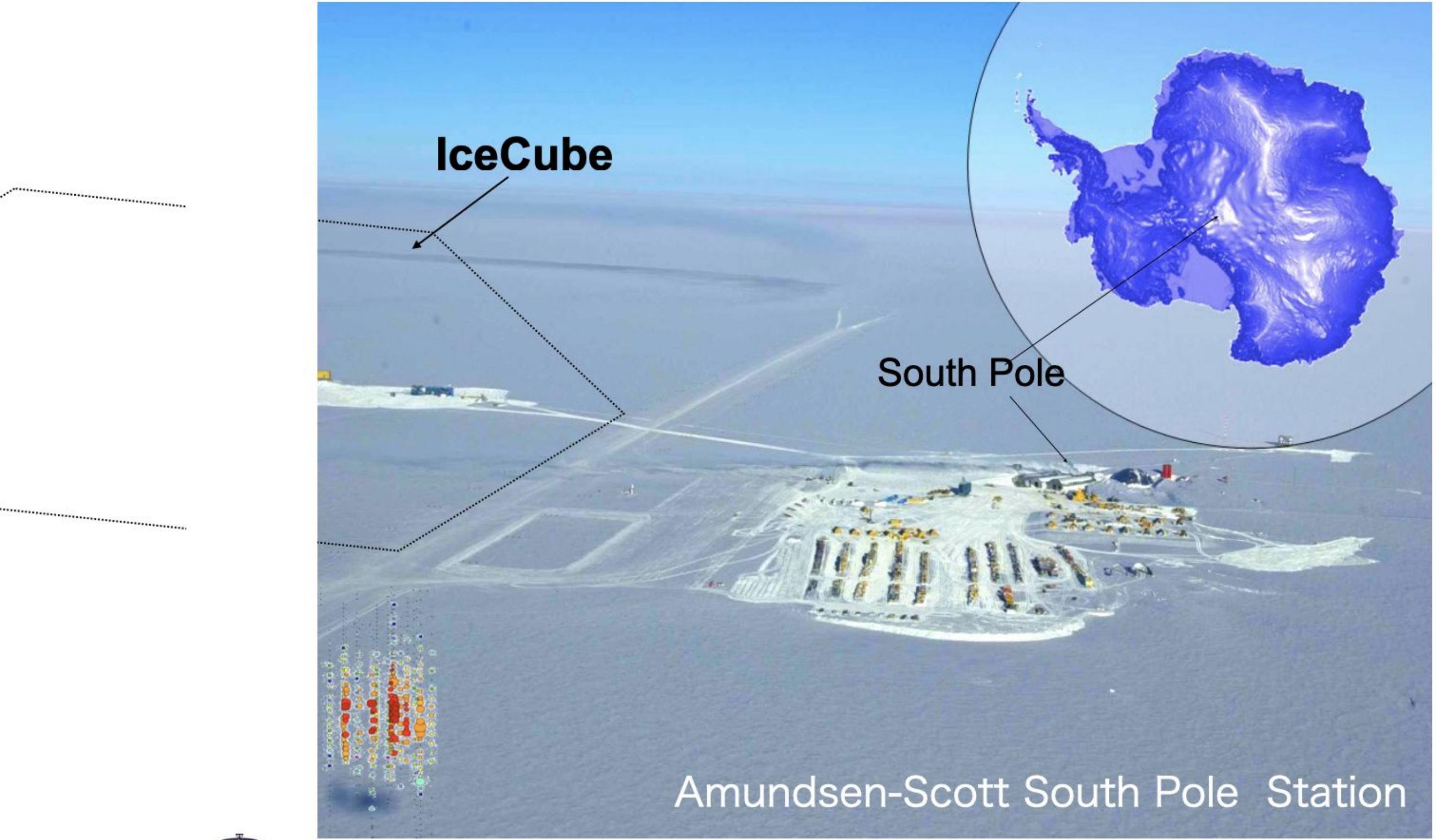
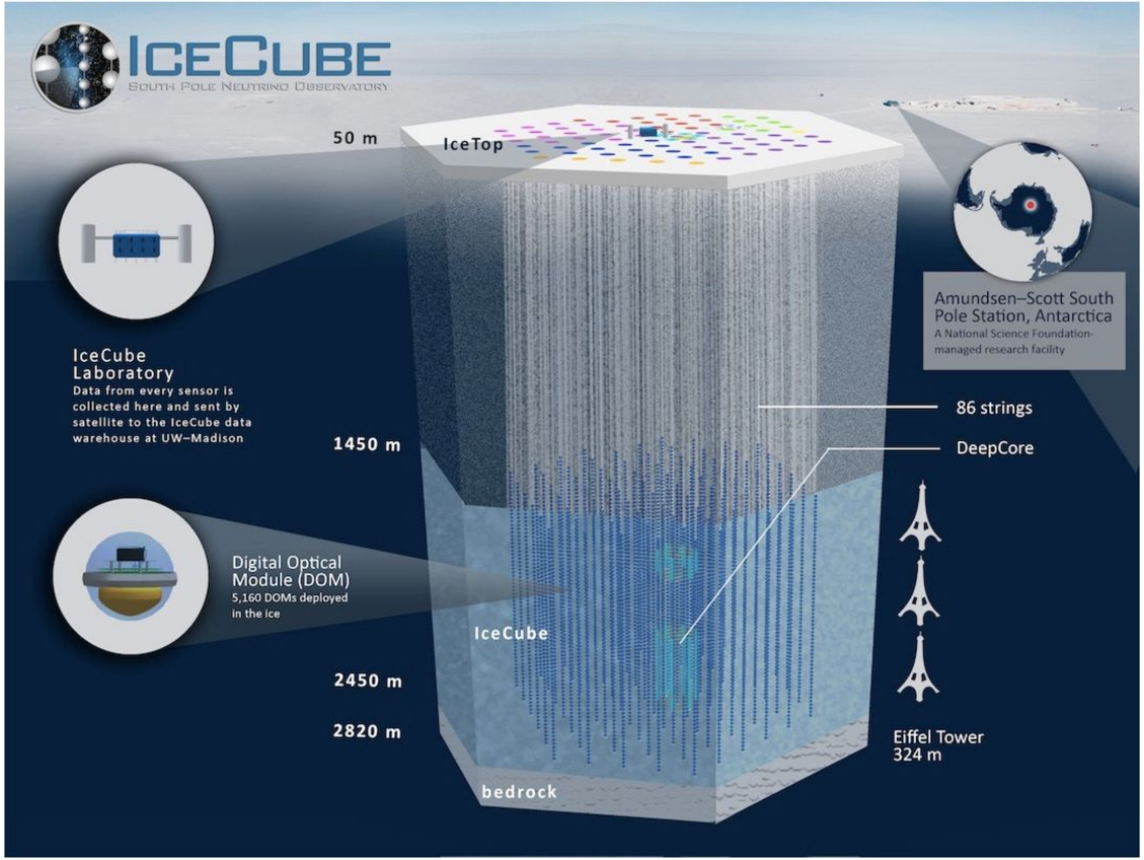
The IceCube Observatory

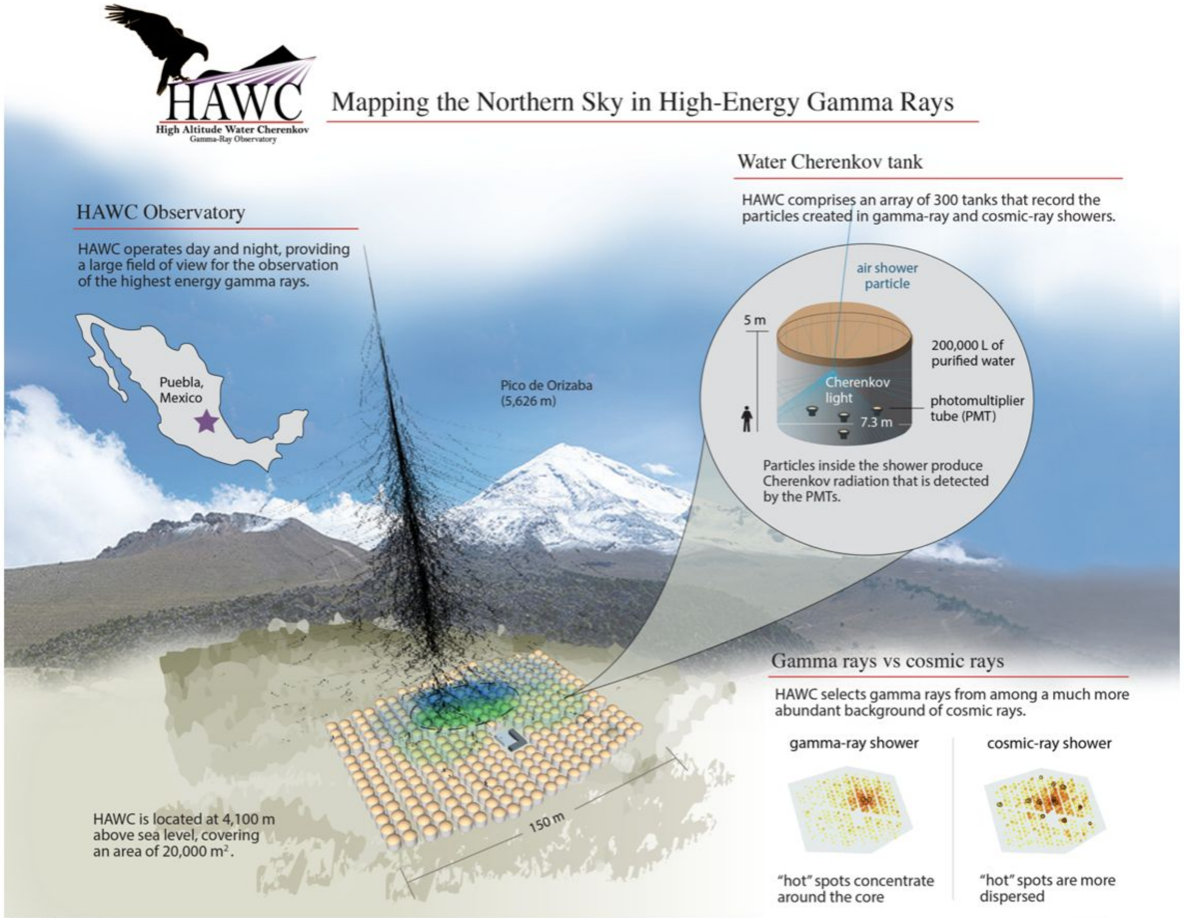


The IceCube Observatory

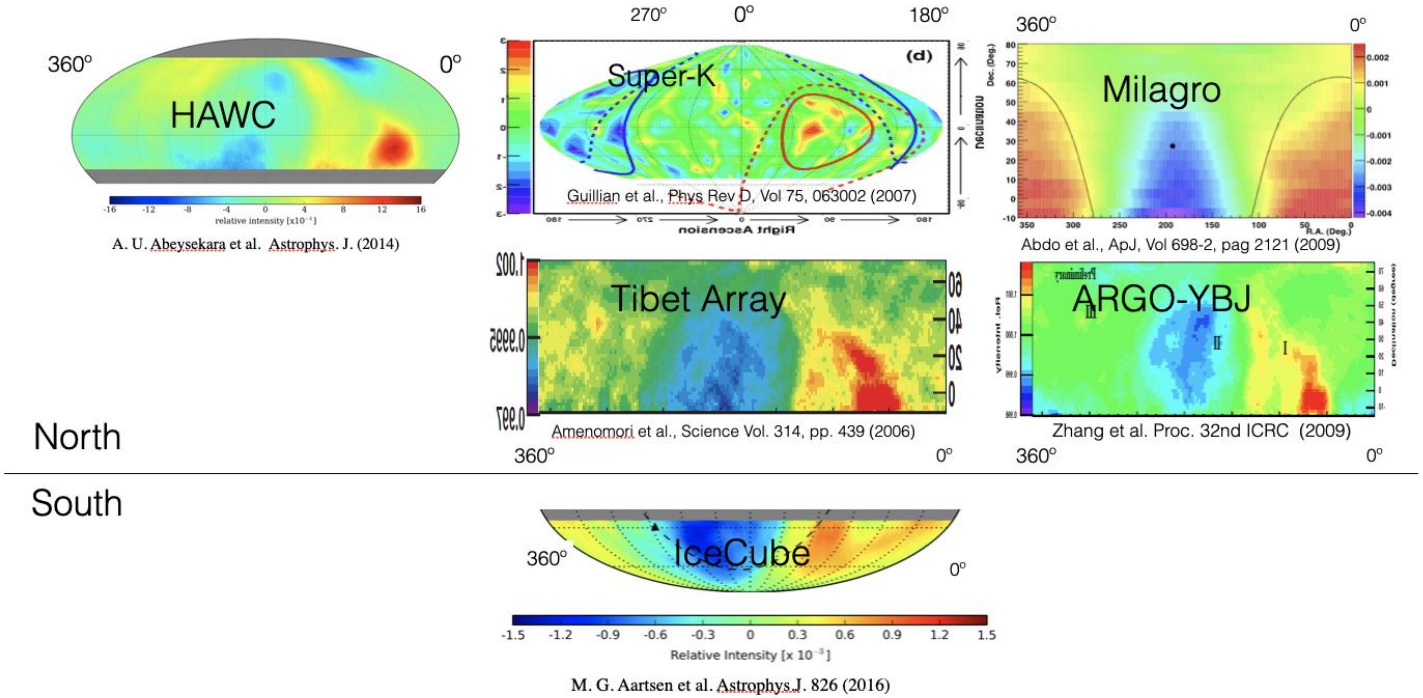


The HAWC Observatory

The HAWC Observatory



A large-scale ~TeV cosmic ray anisotropy at the level of 10^{-3} has been observed and measured over the last few decades as well as a small-scale structures of angular size from 10° to 30° with an amplitude of 10^{-4}.

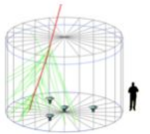


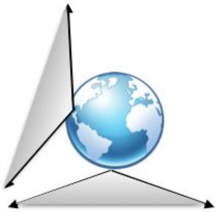
A number of observatories in the North and only IceCube in the southern hemisphere.

The IceCube and HAWC Data Sets

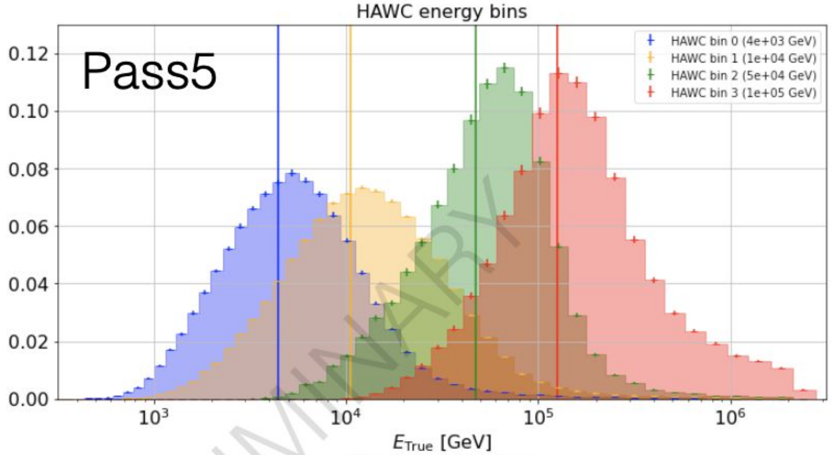
Individual experiments have provided partial sky coverage that limits the interpretation of the results. This first full-sky combined observation at the same energy is done with two observatories covering most of the celestial sphere.

	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° /68° , ~2 sr (8 sr observed)/24 h
Detector trigger rate	2.5 kHz	25 kHz

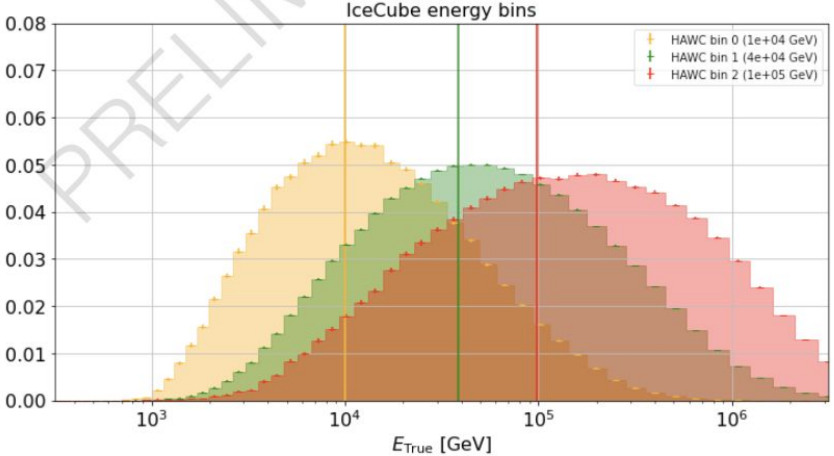




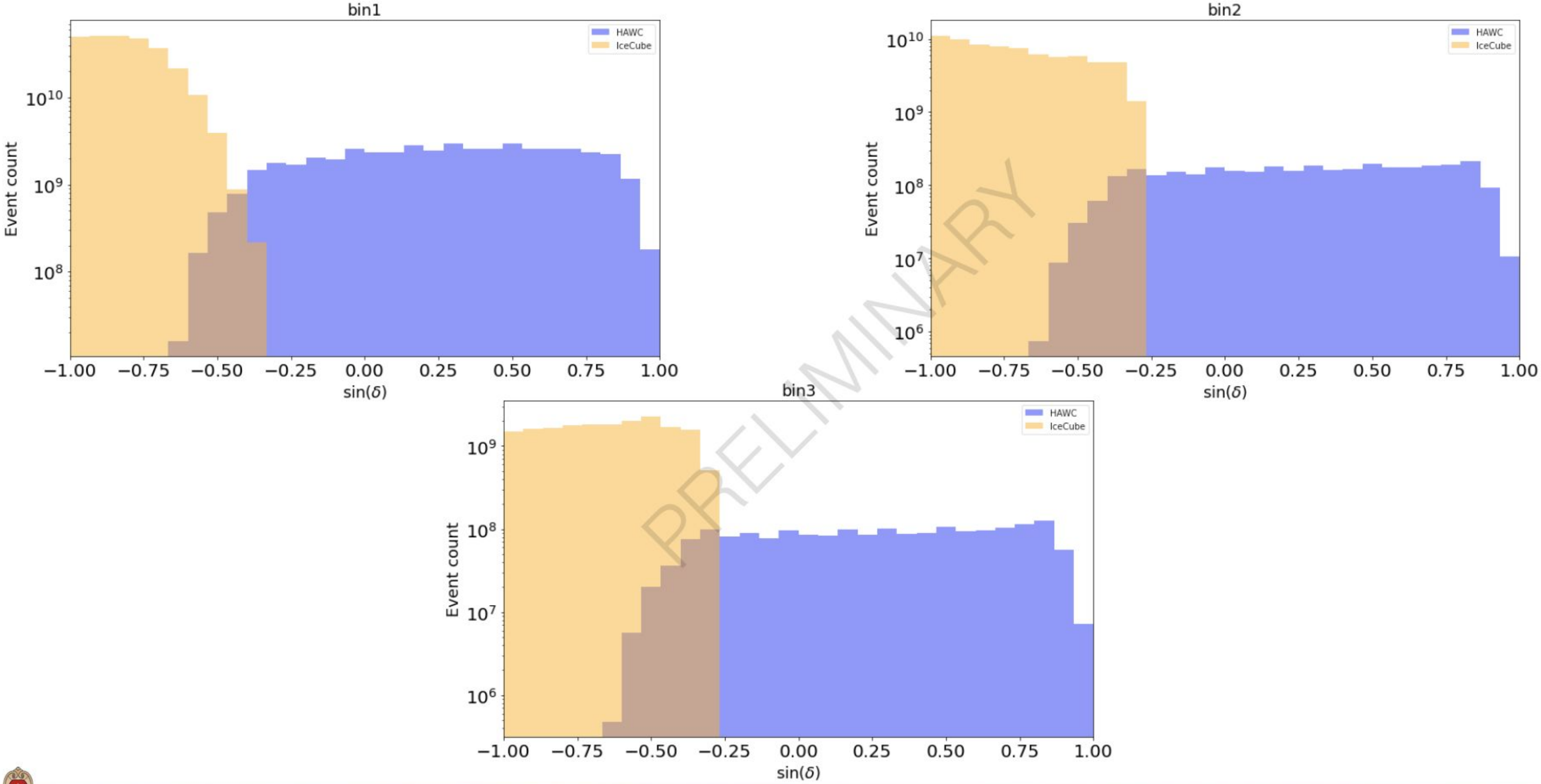
E_med=4.46 (-2.01, +9.95)
E_med=10.5 (-4.15, +27.1)
E_med=47.6 (-20.2, +91.8)
E_med=126 (-56.8, +307)



E_med=10 (-3.31, +37.3)
E_med=38.5 (-9.23, +185)
E_med=98.2 (-18.2, +557)

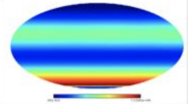


Overlap Region

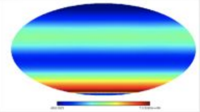


Method for measuring CR anisotropy

1 Build a binned data map using the equatorial coordinates of the events



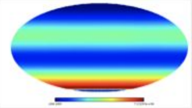
2 Construct a “reference” map by integrating acceptance over 24 hours.



Time-scrambling: $(\theta, \phi, t) \rightarrow (\alpha, \delta) \quad (\theta, \phi, t') \rightarrow (\alpha', \delta')$

LLH: $\mathcal{L}(n|I, \mathcal{N}, \mathcal{A}) = \prod_{\tau i} \frac{(\mu_{\tau i})^{n_{\tau i}} e^{-\mu_{\tau i}}}{n_{\tau i}!}$ M. Ahlers *et al* 2016 *ApJ* **823** 10

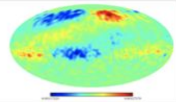
3 Correlate pixels to increase sensitivity to different angular scales



Relative Intensity

$$\delta I(\alpha, \delta)_i = \frac{N(\alpha, \delta)_i - \langle N \rangle(\alpha, \delta)_i}{\langle N \rangle(\alpha, \delta)_i}$$

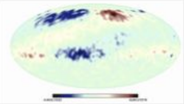
4 Calculate relative differences between data and reference with significance.



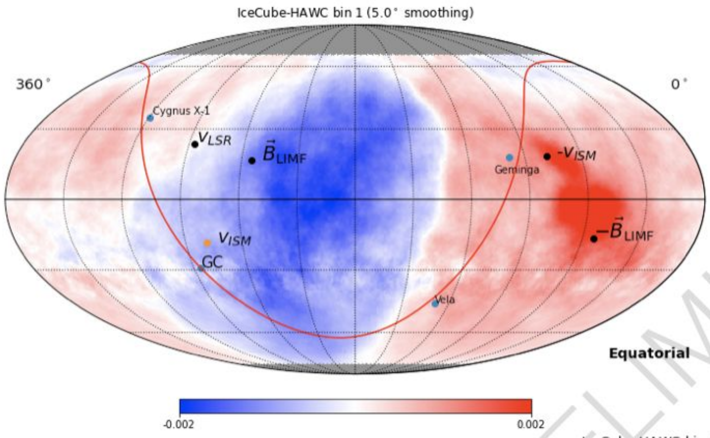
$$s_i = \sqrt{2}\left\{N_i \log\left[\frac{1+\alpha}{\alpha}\left(\frac{N_i}{N_i + N_o}\right)\right] + N_o \log\left[(1+\alpha)\left(\frac{N_o}{N_i + N_o}\right)\right]\right\}^{1/2}$$

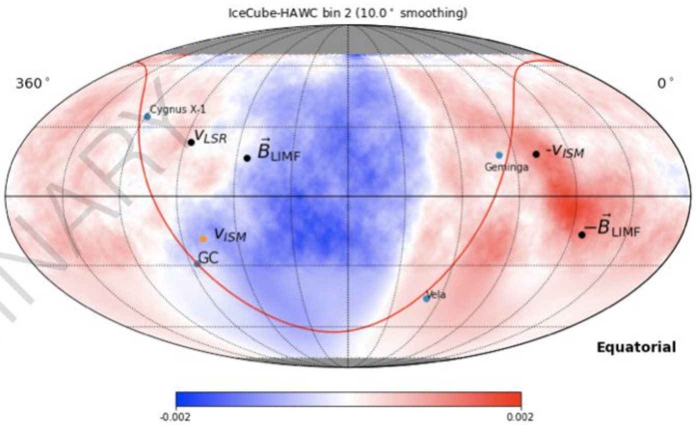
Li, T. P. & Ma, Y. Q. 1983, *ApJ* **272**

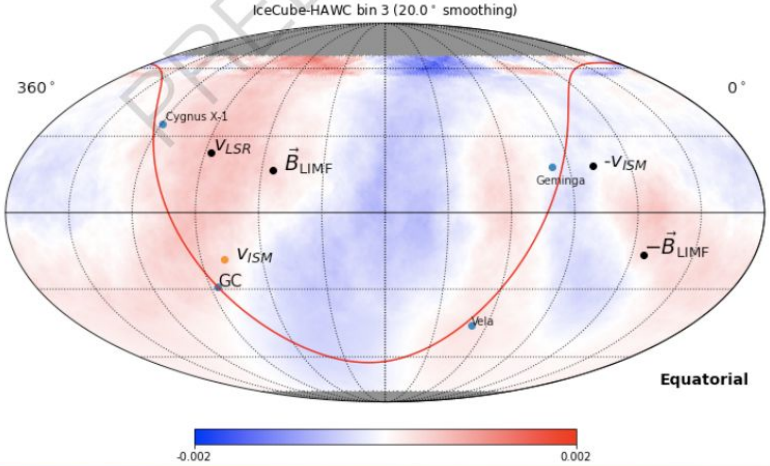
5 Calculate statistical significance for each pixel



Combined IceCube-HAWC

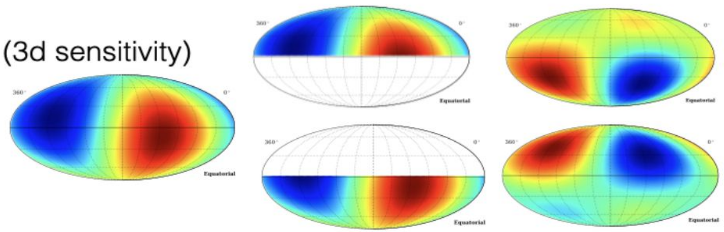






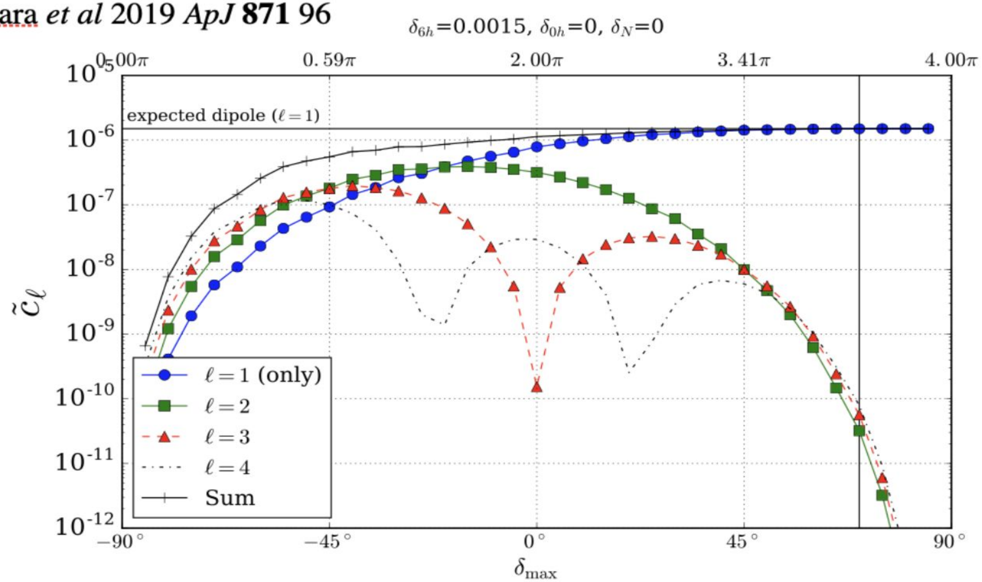
Partial sky-coverage

Pure dipole (3d sensitivity)

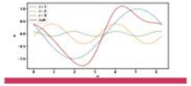


Multipole components are subject to crosstalk caused by partial sky coverage since there is a degeneracy between different ℓ-modes.
A purely dipole can result in an artificial quadrupole due to partial sky coverage.

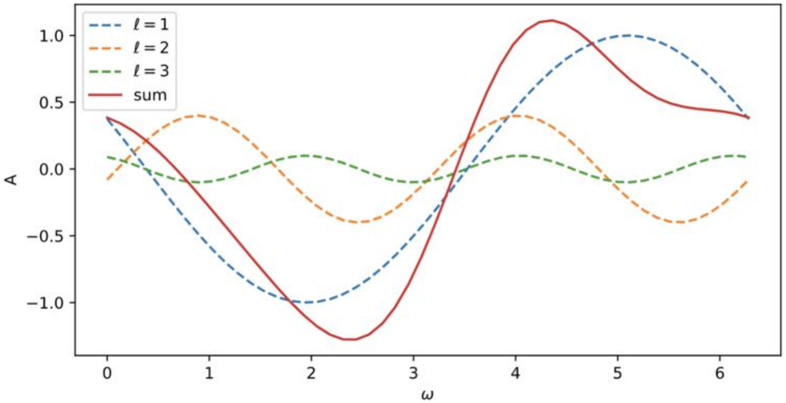
A. U. Abeysekara *et al* 2019 *ApJ* **871** 96

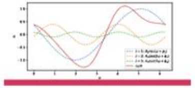


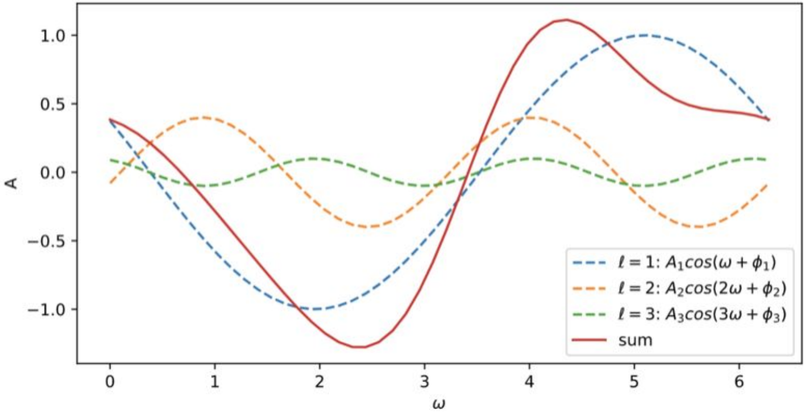
WISCONSIN ICECUBE PARTICLE ASTROPHYSICS CENTER



How the dipole, quadrupole, and the octopole are estimated

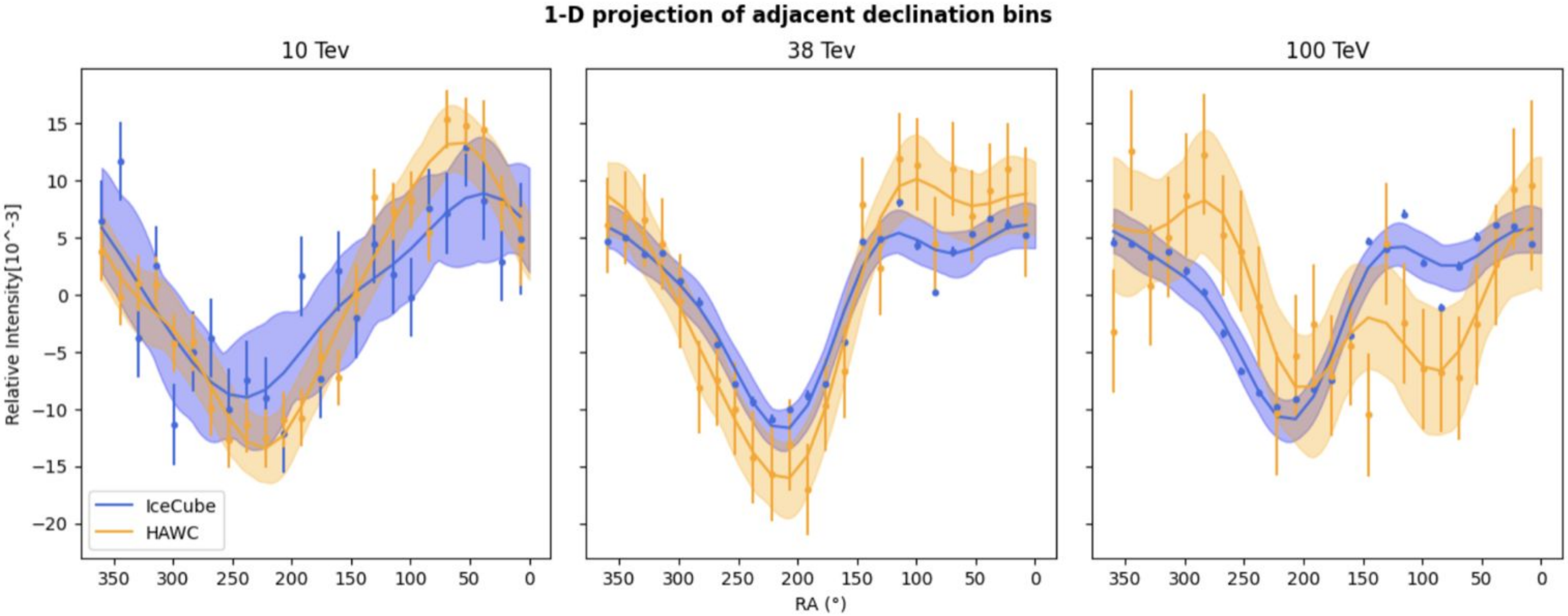






Overlapping Region

- Plotting it in a graph format helps us find the statistical compatibility of the two relative intensities
- We used the Chi squared test to find this compatibility
- Bins 2 & 3 had a value of 1.06 and 1.89 respectively.



Thank you