Completing & Improving the TeV Cosmic-Ray Sky with HAWC & IceCube

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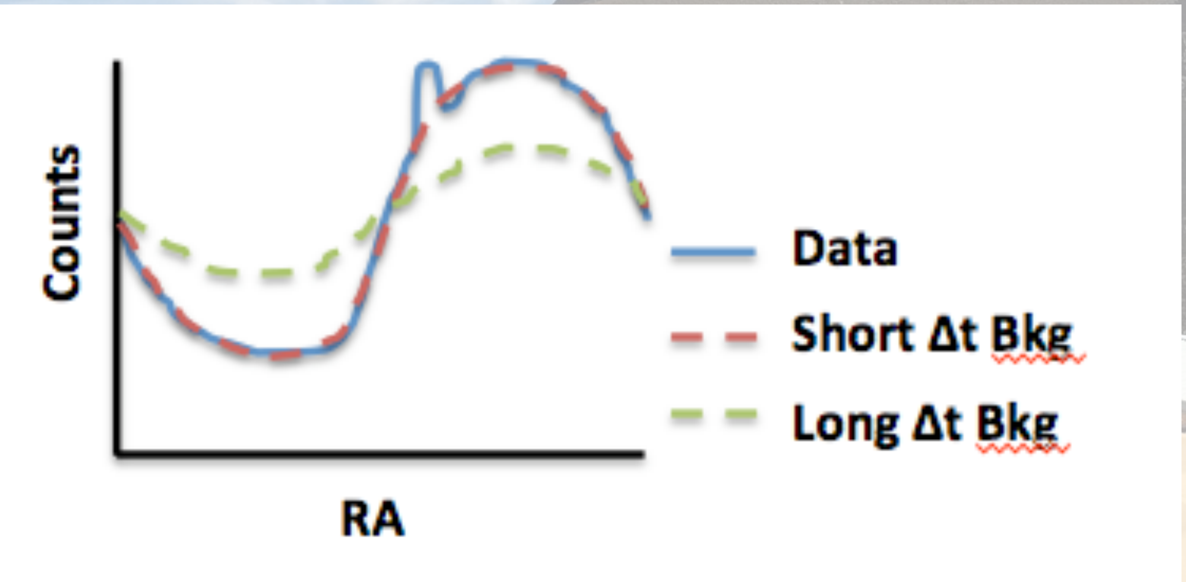
The TeV Cosmic-Ray Sky

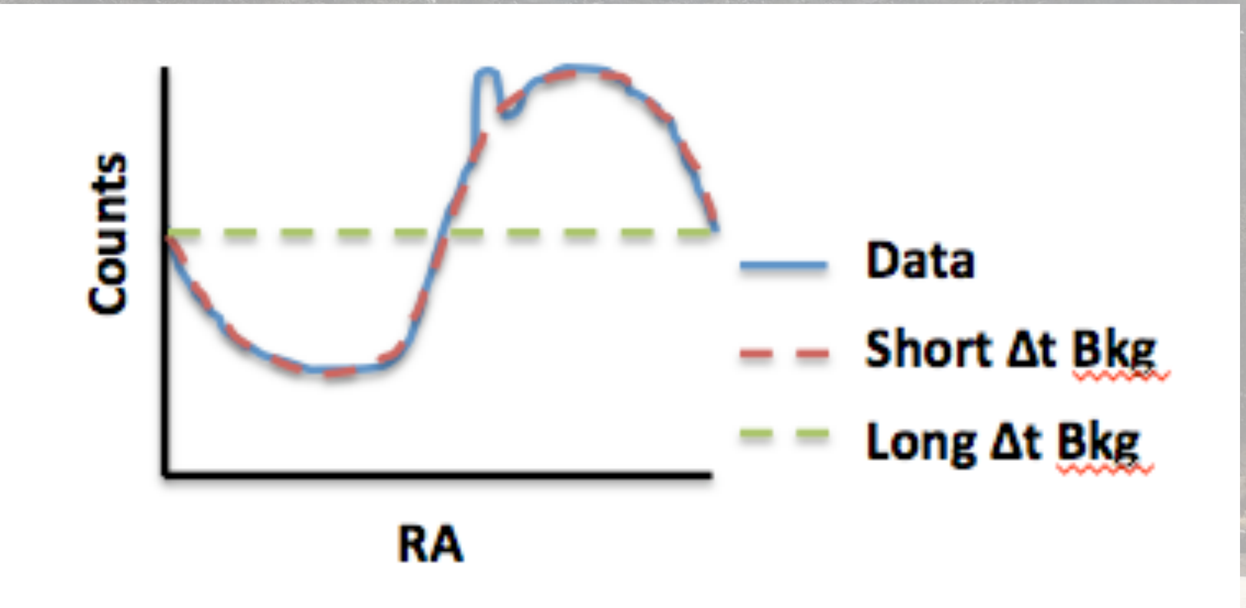
- Difficult to measure
  - Only ground-based detectors have detections
  - Background and weak signal are intertwined spatially
  - Ground detectors are currently limited to only measuring anisotropies in direction of Earth's rotation (RA)
- Hard to interpret
  - Need complete sky to properly measure
  - Missing anisotropy along Declination (m=0 modes)
  - Are deficits and excesses equally important?

- Recent Developments
  - Maximum-likelihood technique which uses direct integration to find unbiased background
  - Cosmic-ray energy estimation for ground detectors is evolving. Not just using number of hit detectors
  - Complete two-dimensional descriptions

Unbiased Background Estimation

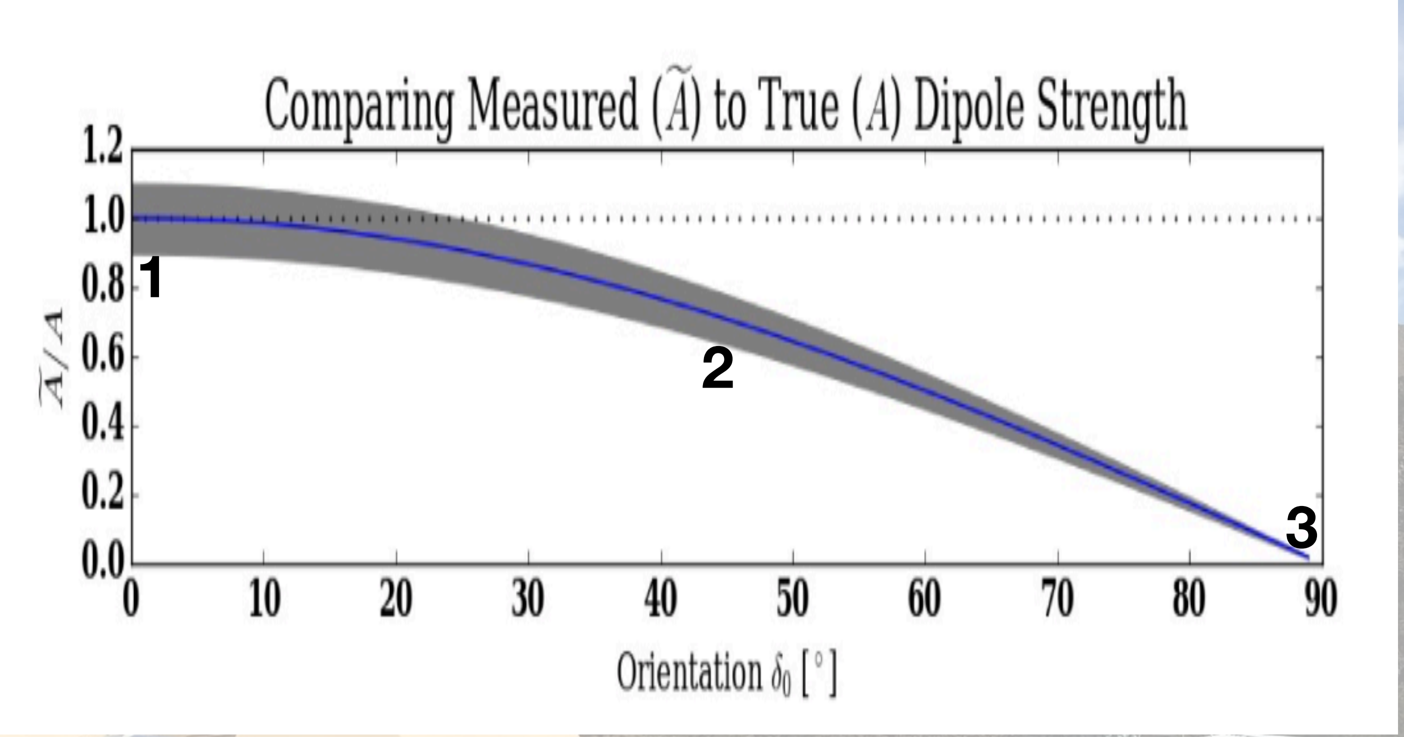
- For a detector with a constant acceptance as a function of time, the expected result of an isotropic flux would be … well … isotropic!
- Adding a dipolar signal to the isotropic flux will bias background estimation methods that are based upon data (e.g time-scrambling, direct integration) and over long periods (Long Δt).

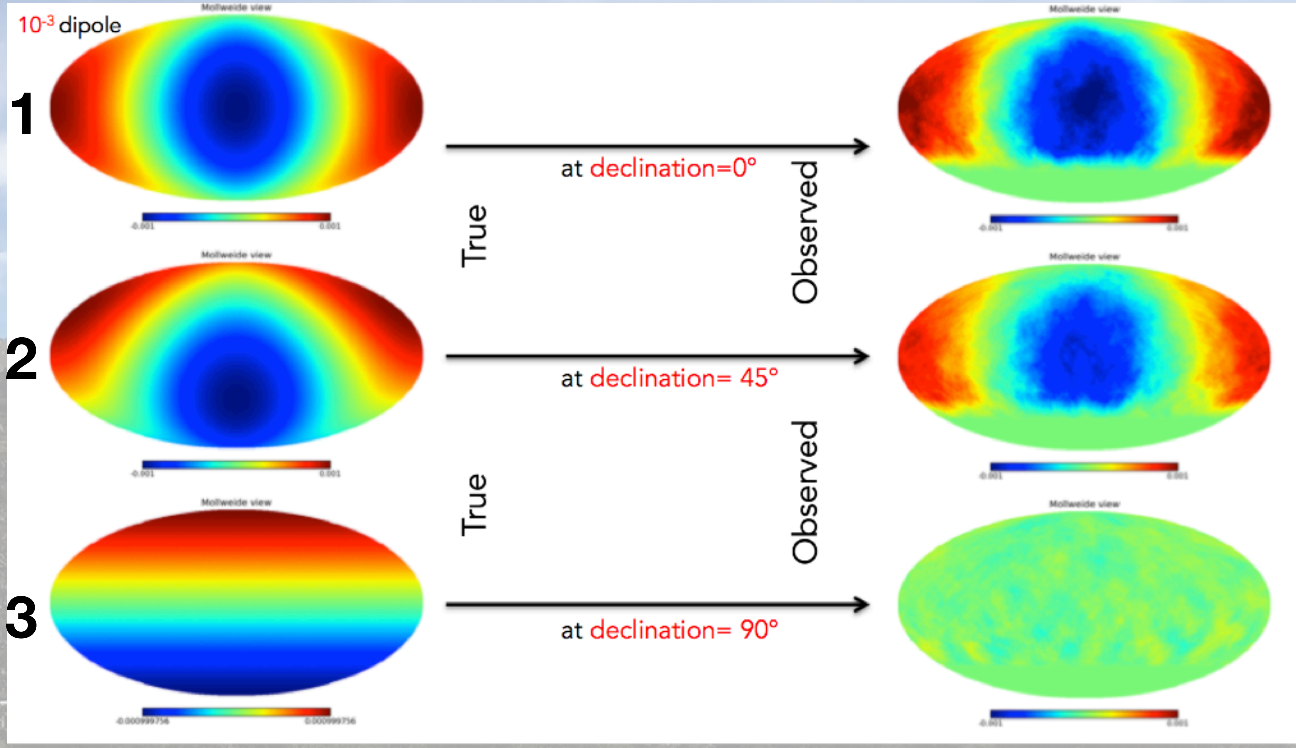




- With an iterative approach, this bias can be removed (right diagram) by fitting the detector response and anisotropy simultaneously.

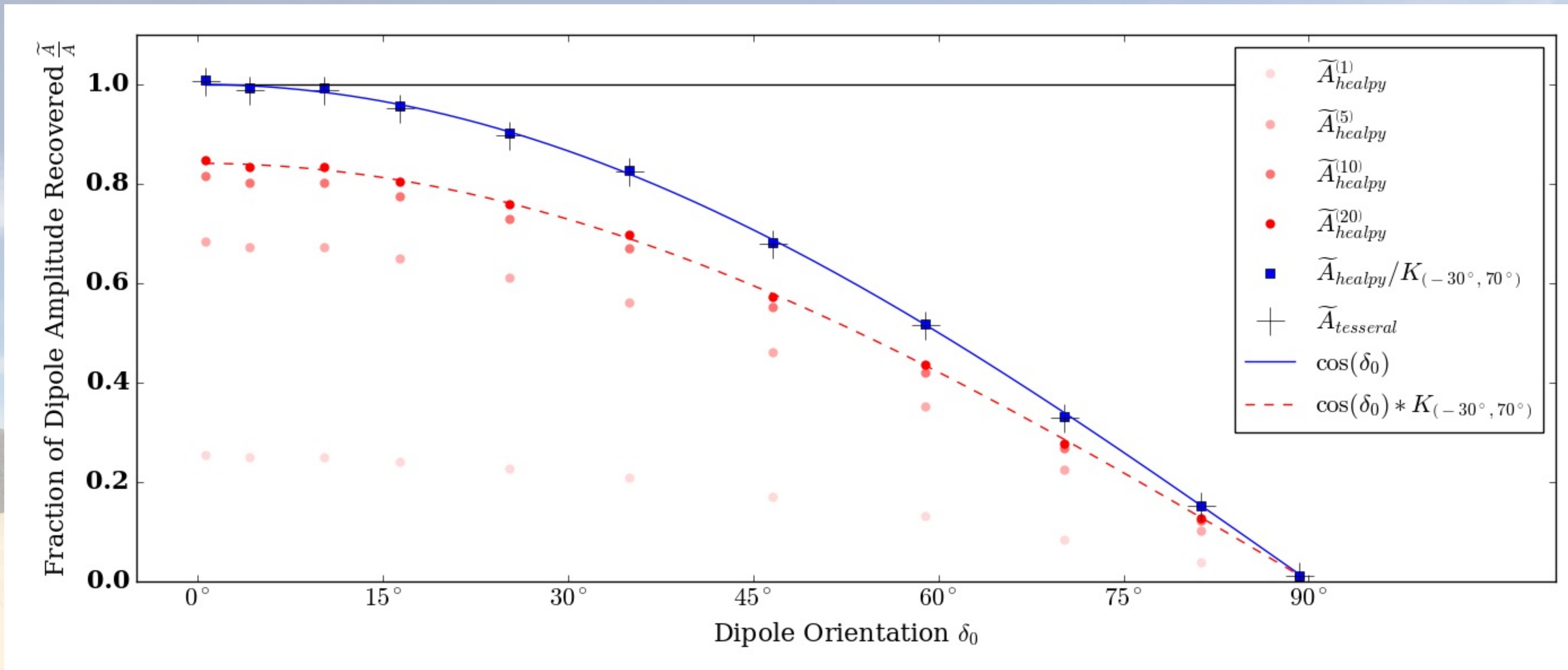
Limitations (Ground-based)





- Experiments are limited currently to measuring anisotropies in direction of Earth rotation (RA)
- For a pure dipole anisotropy, this greatly affects the measurable strength
- Measured strength goes to zero as the orientation goes to the poles (90°)

Unbiased Background / Limitations

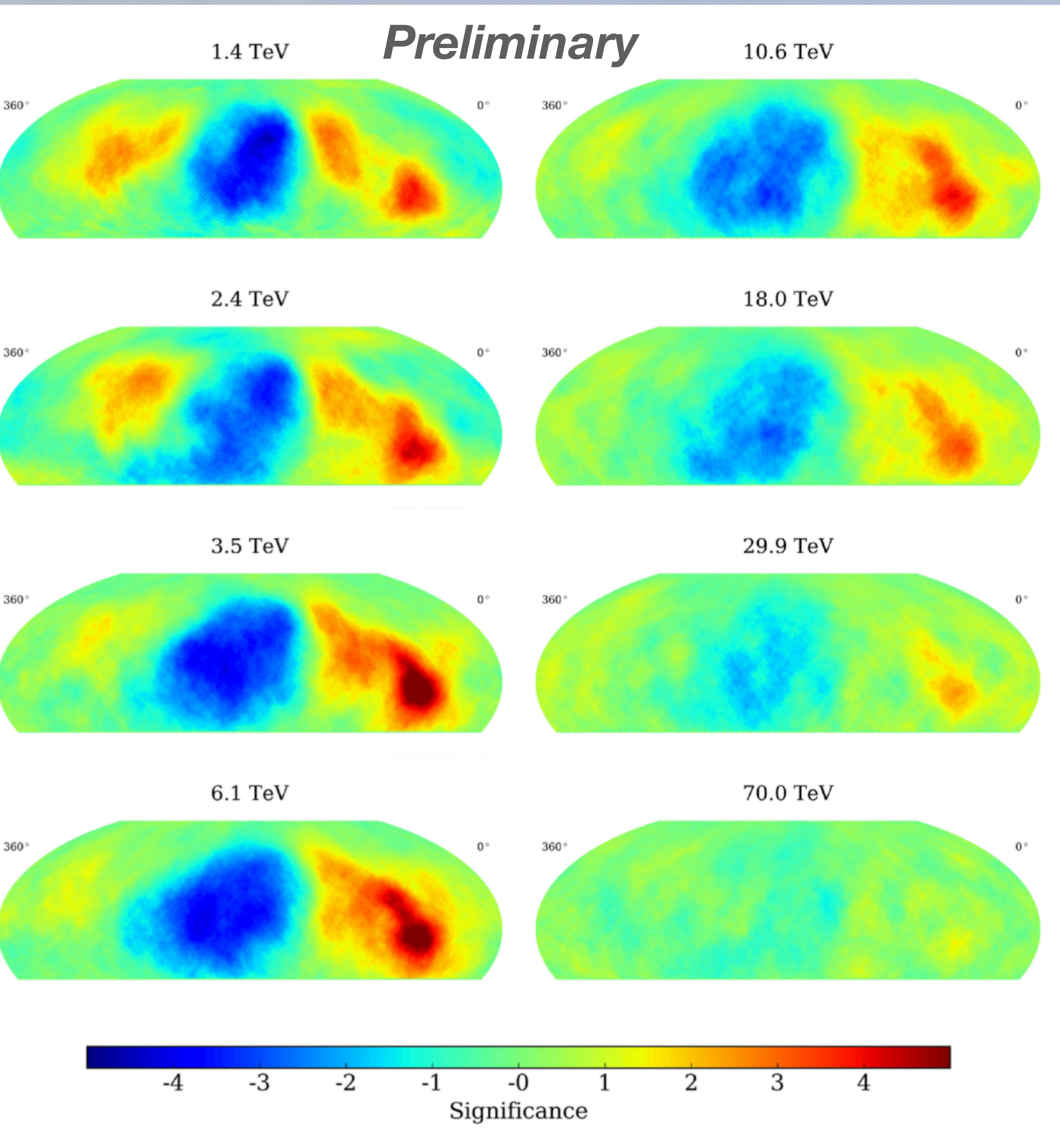


- Simulated dipole anisotropy reconstructed using method of (M. Ahlers et al. 2016)
- Blue line is the best one can do with ground-based instrument
- Red/blue points show fit from healpy software

- Method improves with iteration (light to dark red)
- healpy fit must be corrected because of limited sky coverage (blue)

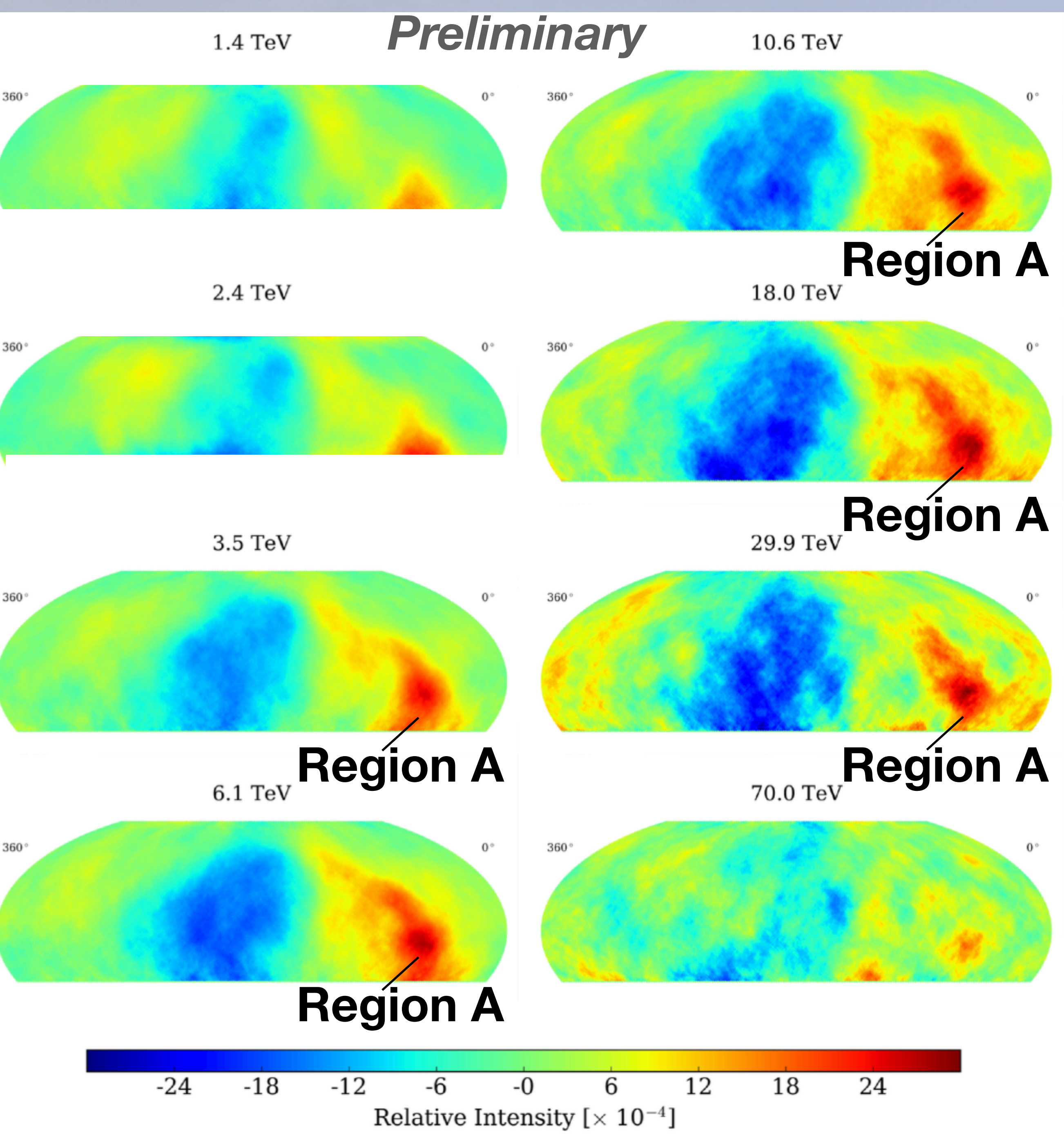
healpy: HEALPix + Python
HEALPix: sphere pixelation + sky map routines

HAWC Results



- Background method applied to 400 full, sidereal days of HAWC data
- Applied strong cut (2% pass) to reach unprecedented energy resolution for this measurement. Harsh cuts provide highly diagonalized mixing matrix (verified on CR spectrum/Moon shadow).
- Described using full 2D dipole fit (truncated)

Energy [TeV]	Amplitude [$\times 10^{-4}$]	Phase	$a_{1,1}$ [$\times 10^{-4}$]	$a_{1,-1}$ [$\times 10^{-4}$]
$1.4 \binom{-0.8}{+2.4}$	7.5 ± 0.6	$33.3° \pm 4.4°$	-18.1 ± 1.7	-11.9 ± 1.7
$2.4 \binom{-1.5}{+3.6}$	6.4 ± 0.3	$46.6° \pm 2.2°$	-12.7 ± 0.7	-13.5 ± 0.7
$3.5 \binom{-2.5}{+5.5}$	10.2 ± 0.2	$42.8° \pm 1.4°$	-21.6 ± 0.7	-20.1 ± 0.7
$6.1 \binom{-4.3}{+8.5}$	13.2 ± 0.3	$44.0° \pm 1.2°$	-27.5 ± 0.8	-26.6 ± 0.8
$10.6 \binom{-7.2}{+13.1}$	13.2 ± 0.4	$45.0° \pm 1.6°$	-27.1 ± 1.1	-27.1 ± 1.1
$18.0 \binom{-11.9}{+19.6}$	15.6 ± 0.5	$42.9° \pm 1.8°$	-33.0 ± 1.4	-30.7 ± 1.4
$29.9 \binom{-18.2}{+28.4}$	14.4 ± 0.7	$29.9° \pm 2.6°$	-36.2 ± 1.9	-20.8 ± 1.9
$70.0 \binom{-42.1}{+97.9}$	5.4 ± 0.7	$41.9° \pm 7.0°$	-11.7 ± 1.9	-10.4 ± 1.9



HAWC Results

- Non-dipolar structure is obviously present
    - Northward strengthening of 'Region A'
    - Strong quadrupole component at low energies
- Run out of statistics in last bin…

Energy [TeV]	Amplitude [$\times10^{-4}$]	Phase	$a_{1,1}$ [$\times10^{-4}$]	$a_{1,-1}$ [$\times10^{-4}$]
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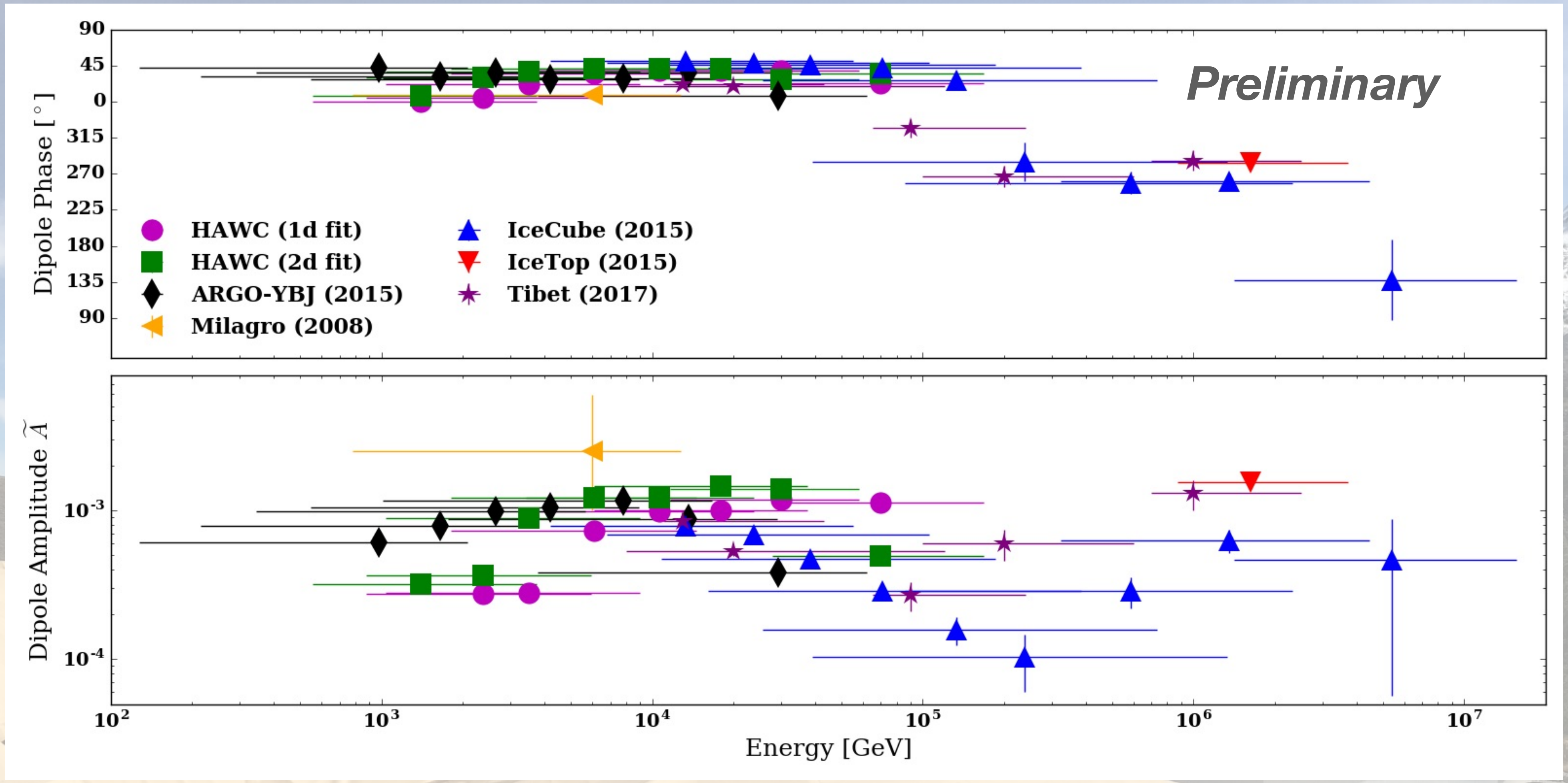
Comparison to other experiments

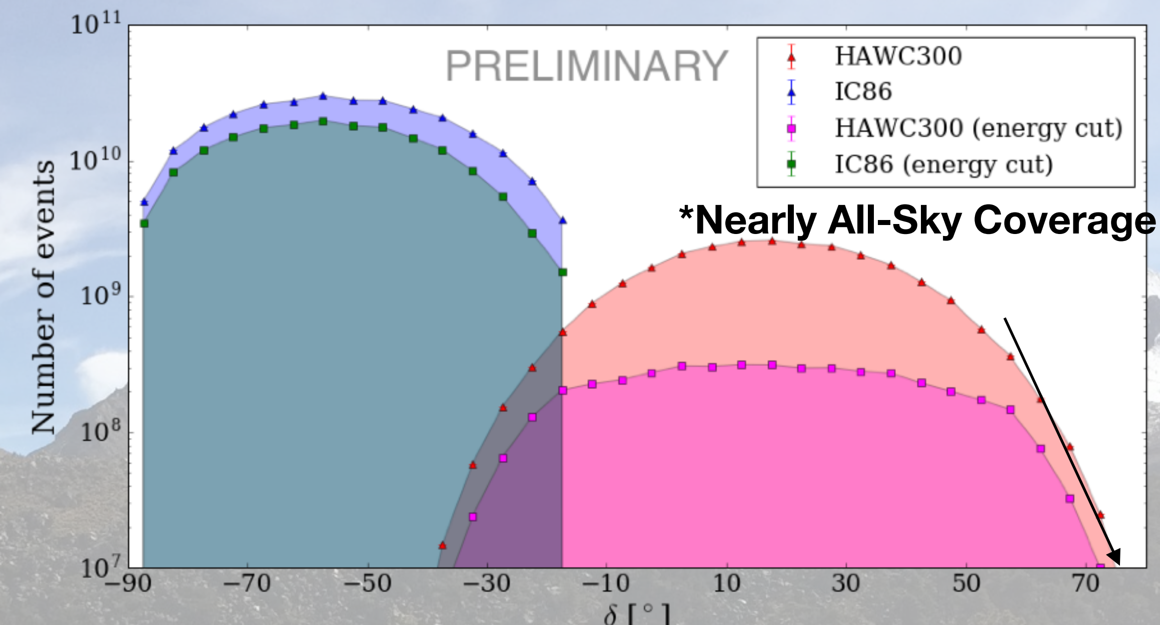


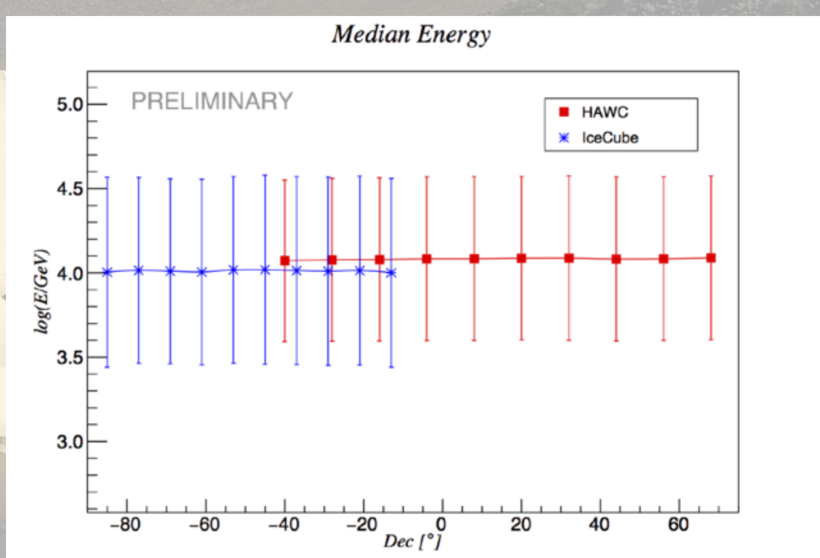
- Cause of Discrepancies?
  - Energy scale? ~10%
  - Use of 2D Fit?
  - CR composition sensitivity? (IceCube is underground…)

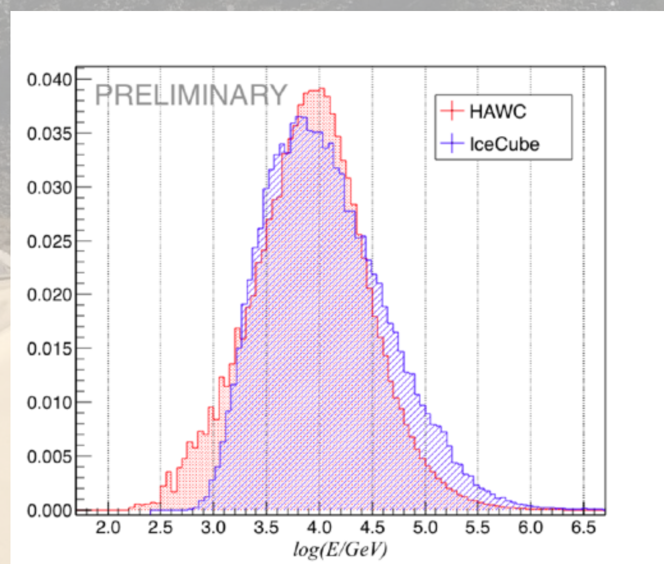
- Compares favorable with other experiments when considering uncertainty in energy

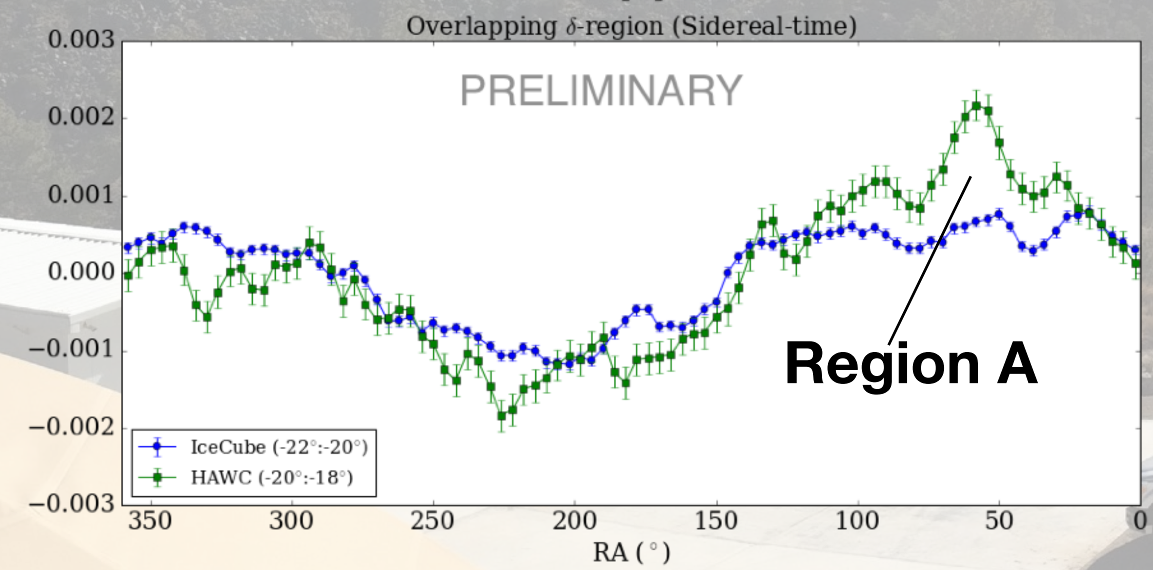
1st Ever All-Sky* TeV Cosmic-Ray Map

- Combining data from HAWC (North) and IceCube (South) gives almost full sky coverage
- Data is energy-matched to be meaningful
- Same method as with HAWC-only data





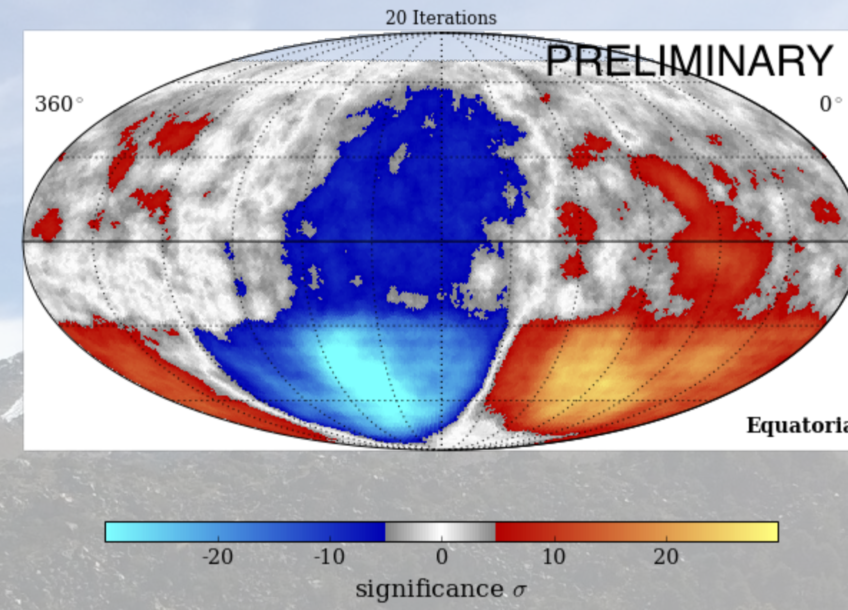


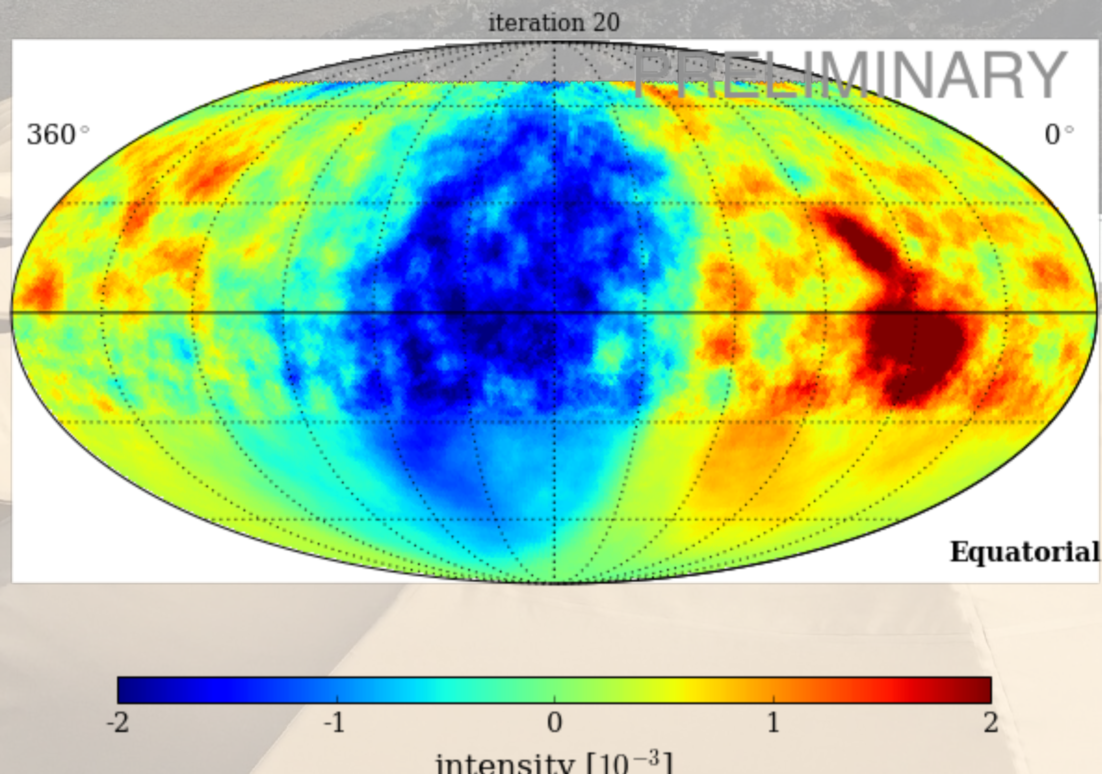


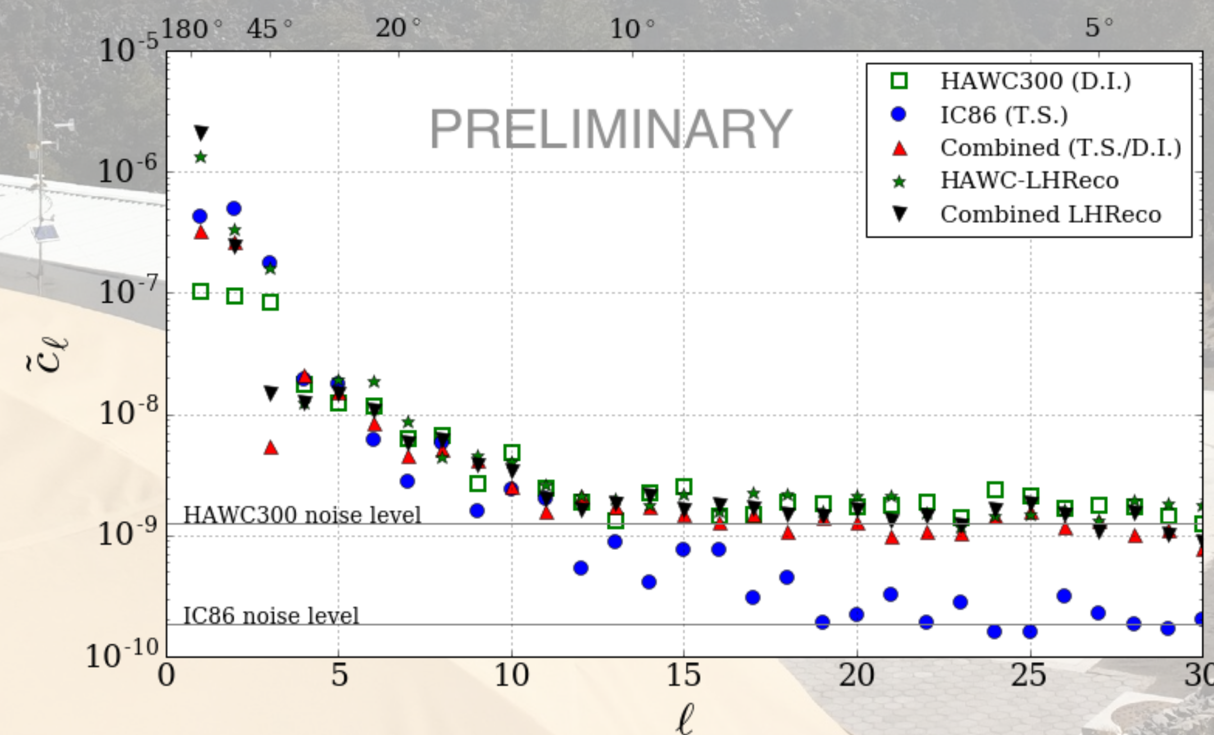
plots taken from: ICRC 2017 Contribution by Diaz Velez, J.C., et al. (PoS 539)
<u>‘Combined Analysis of Cosmic-Ray Anisotropy with 2 IceCube and HAWC’</u>

1st Ever All-Sky* TeV Cosmic-Ray Map

- Dipolar feature connects well,
- Region A does not continue South at these energies
- IceCube features are more significant (more data)
- Combined map has more power in the dipole due to better sky coverage (most of this comes from the HAWC data)



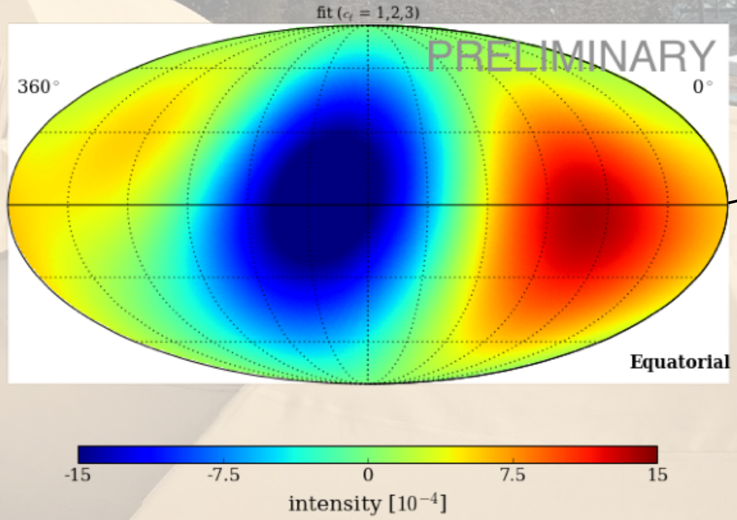


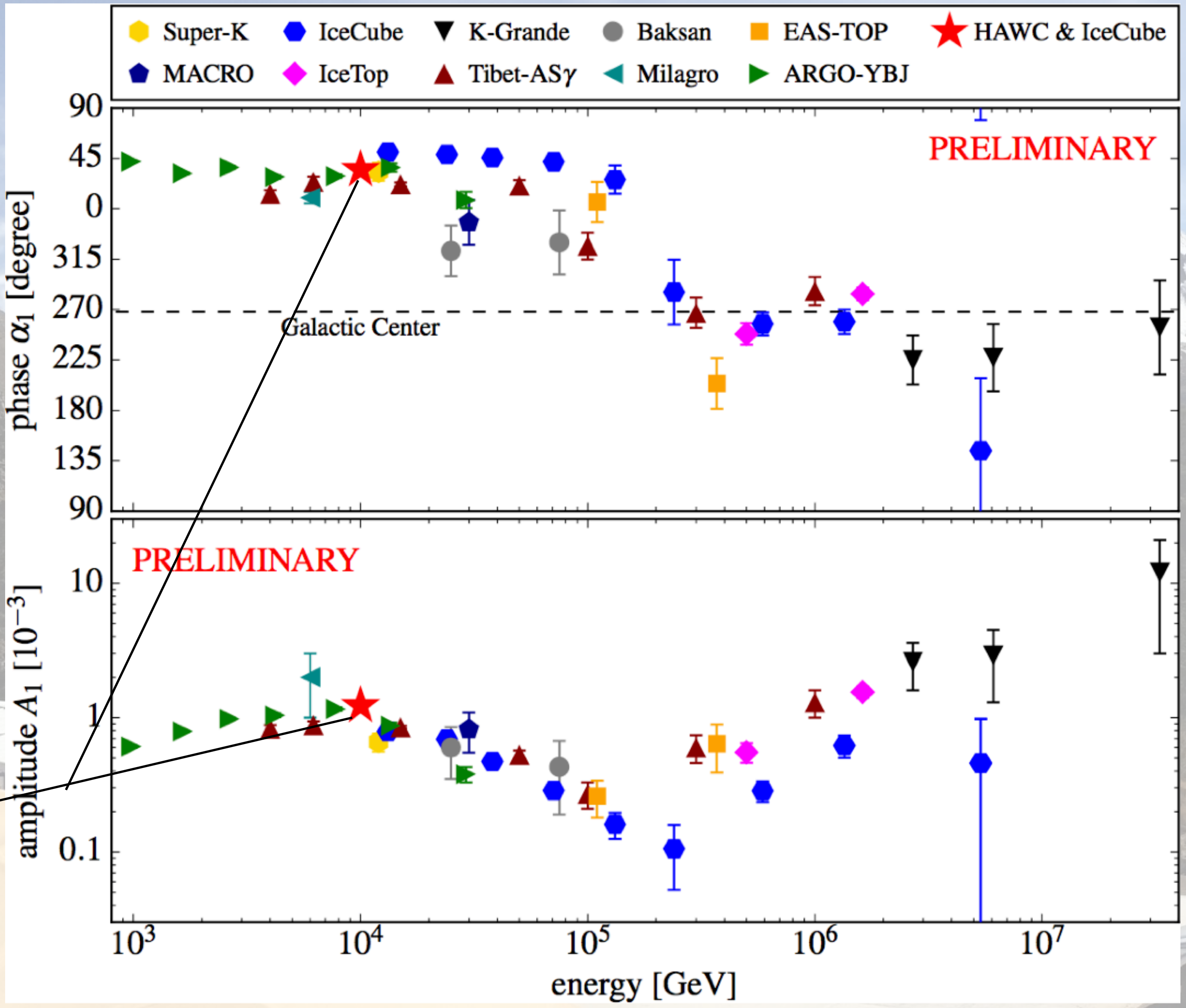


1st Ever All-Sky* TeV Cosmic-Ray Map

- Combined map is then fit with truncated spherical harmonic series (l ≤ 3)

- Dipole amplitude and phase can be compared against other experiments

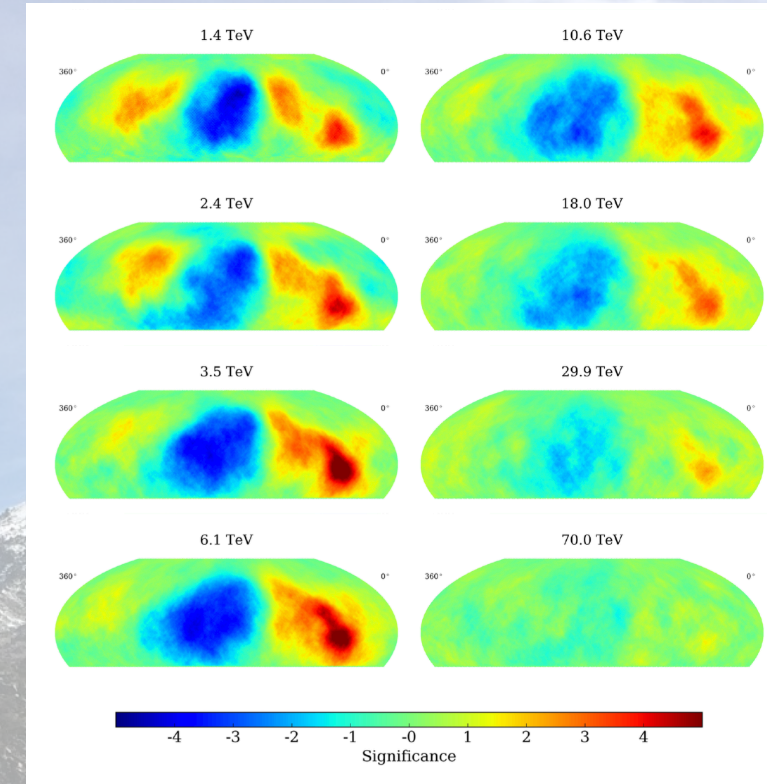


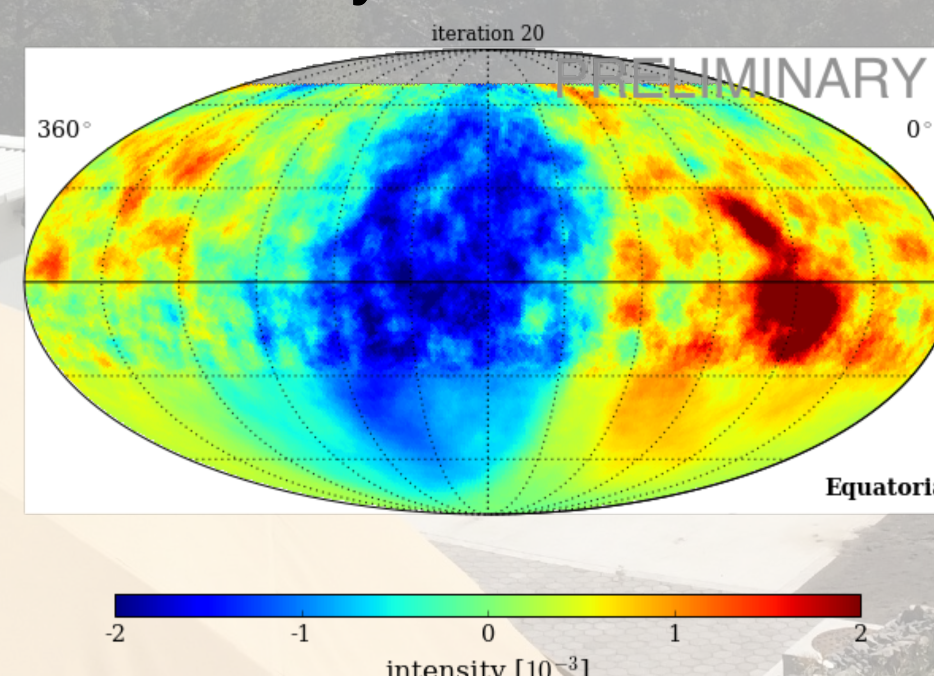


adopted from M. Ahlers et al. ArXiv:1612.01873

Summary

- Our descriptions of the TeV Sky are improving!
    - Background techniques are mature
    - Energy estimation is maturing
- Results are being reported with full two-dimensionality
- A full-sky* picture is available!





Combined Sky Map
Large-scale Removed (right)