Observations of the Anisotropy of Multi-TeV Cosmic Rays with HAWC and IceCube

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Overview

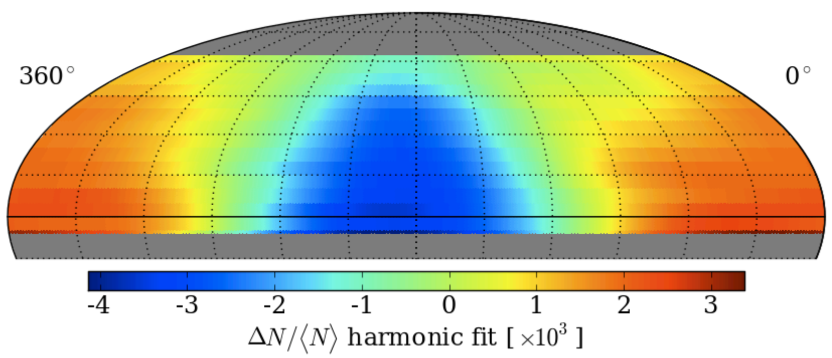
- Quick summary of cosmic-ray anisotropy.
- HAWC Observatory: analysis and results.
- IceCube Observatory: analysis and results.
- Joint analysis of data from IceCube and HAWC:
  - First all-sky cosmic-ray data set at 10 TeV.
  - Unbiased fit to dipole anisotropy of cosmic rays.
  - Sensitivity to diffusion of Galactic cosmic rays and the effects of the heliosphere on particles with 10 TV rigidity.

Cosmic Ray Anisotropy

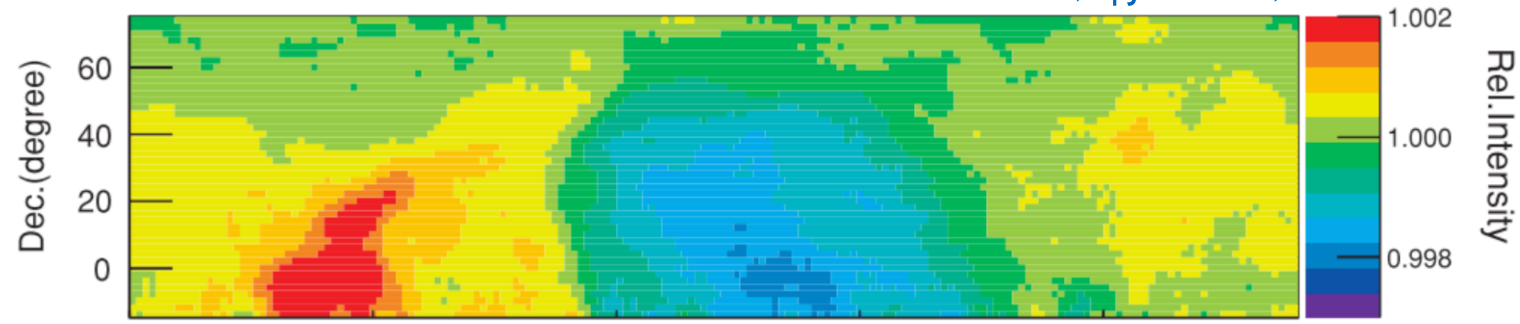
- Anisotropy in the arrival directions of cosmic rays has been observed by a number of underground and surface detectors.
- Total energy range covered: ~10 GeV to ~10 EeV.
- Large-scale structure
  - >60 degrees in extent, 10^{-3} relative intensity.
- Small-scale structure
  - <10 degrees in extent, 10^{-4} - 10^{-5} relative intensity.

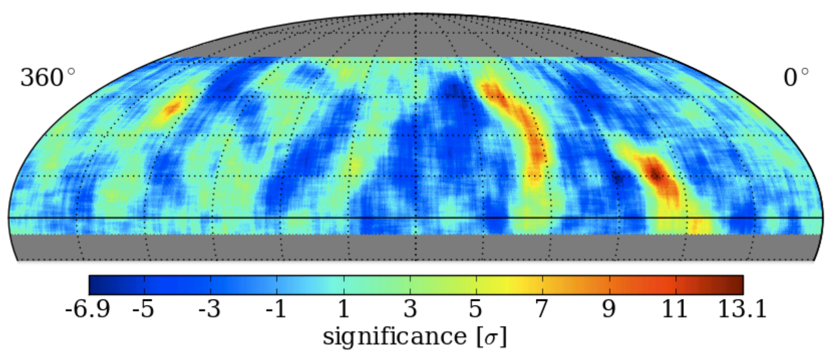
Anisotropy: Angular Scale

Milagro Collaboration, ApJ **698**:2121, 2009

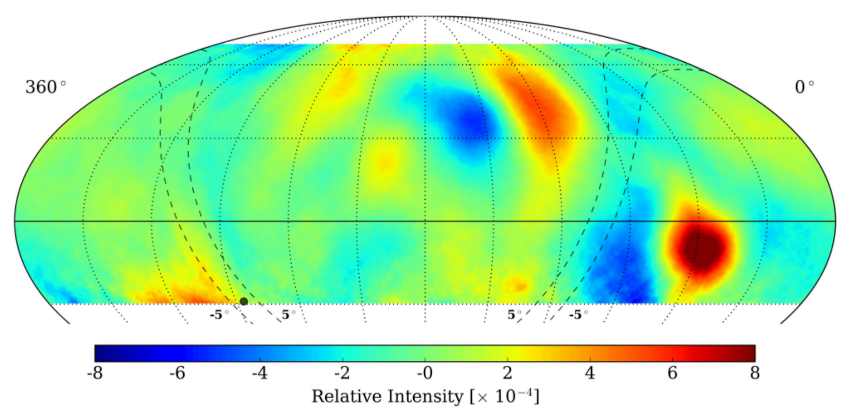


M. Amenomori et al., ApJ **711**:119, 2010

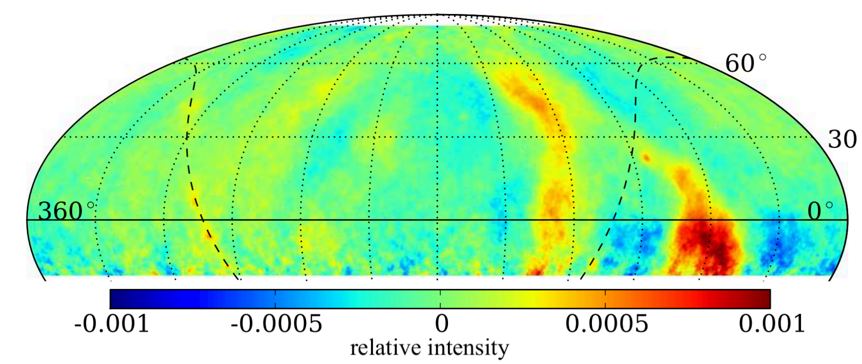




Milagro Collaboration, PRL **101**:221101, 2008

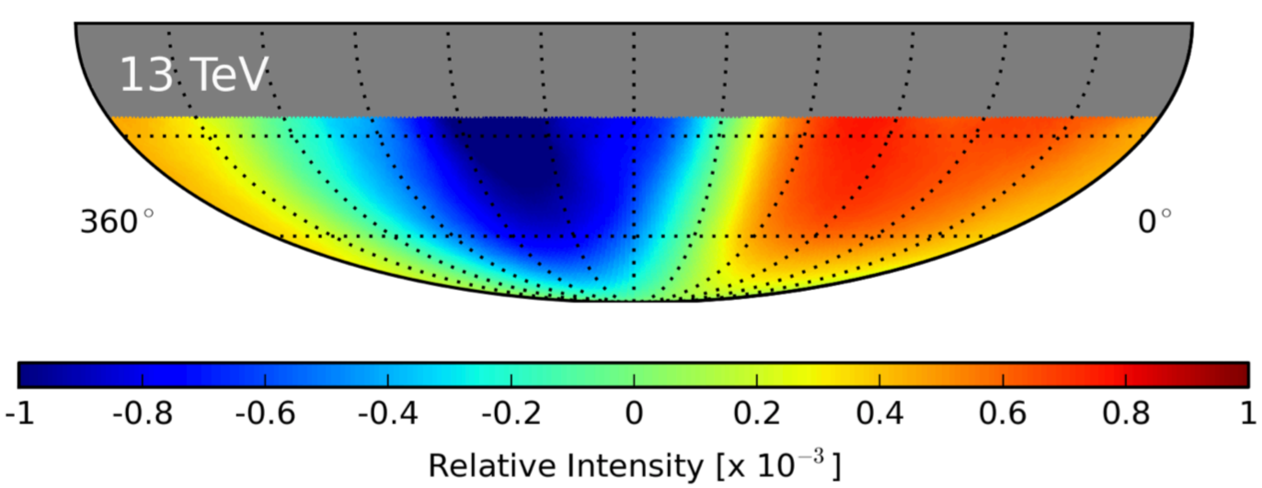


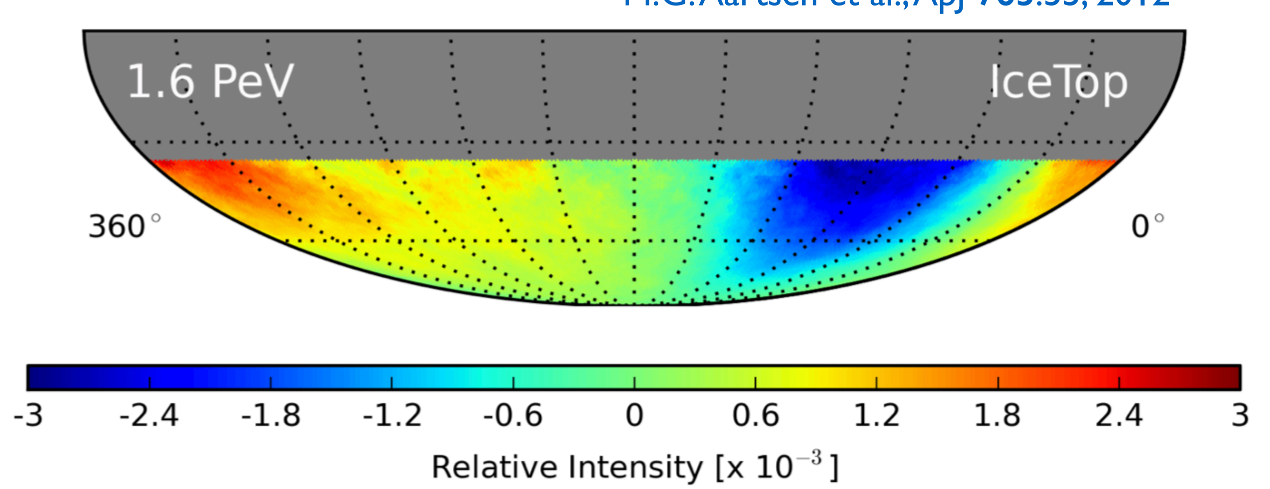
A.U. Abeysekara et al. ApJ **865**:57, 2018



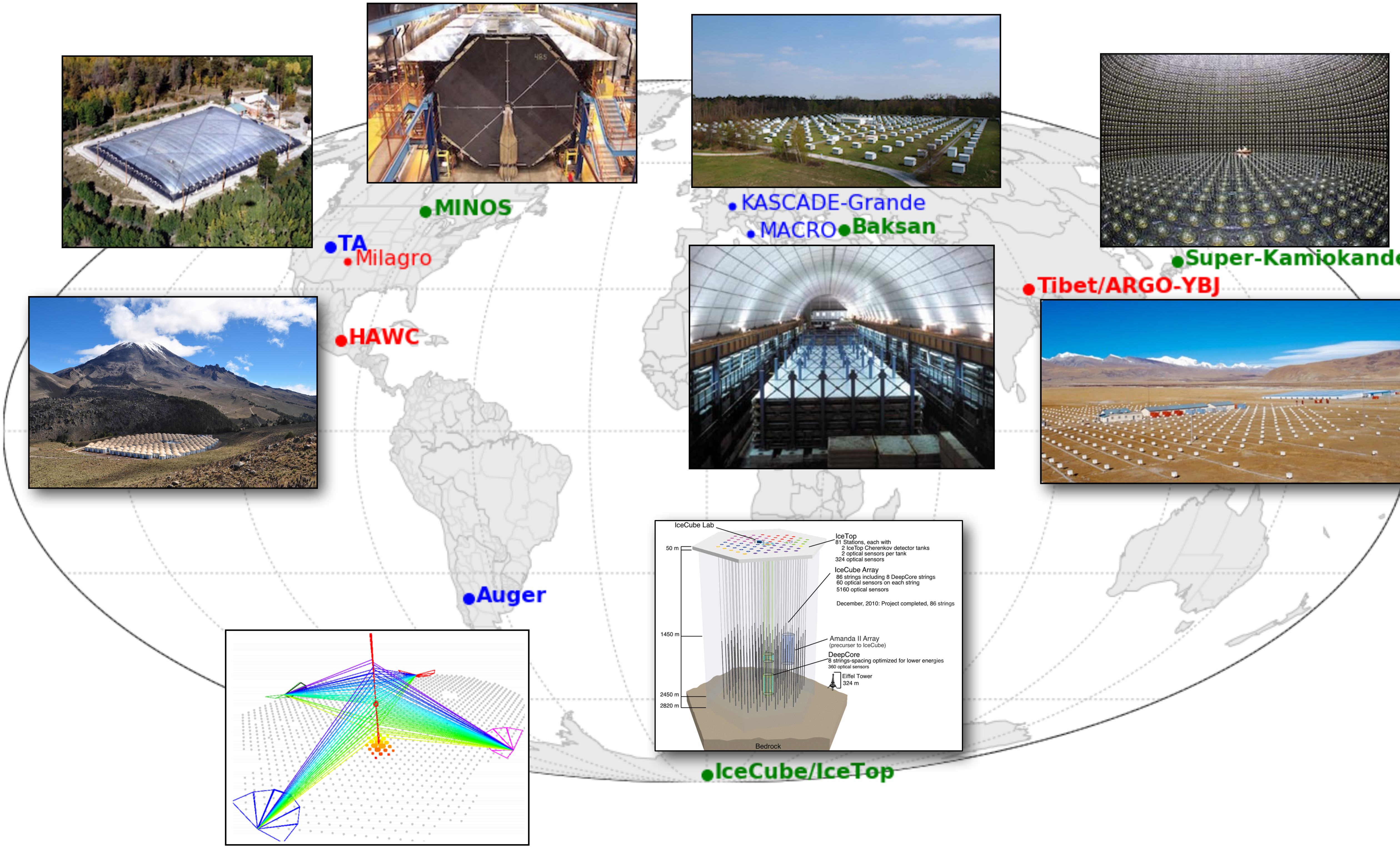
Bartoli et al., PRD **88**:082001, 2013

M.G. Aartsen et al., ApJ **765**:55, 2012





Anisotropy Measurements

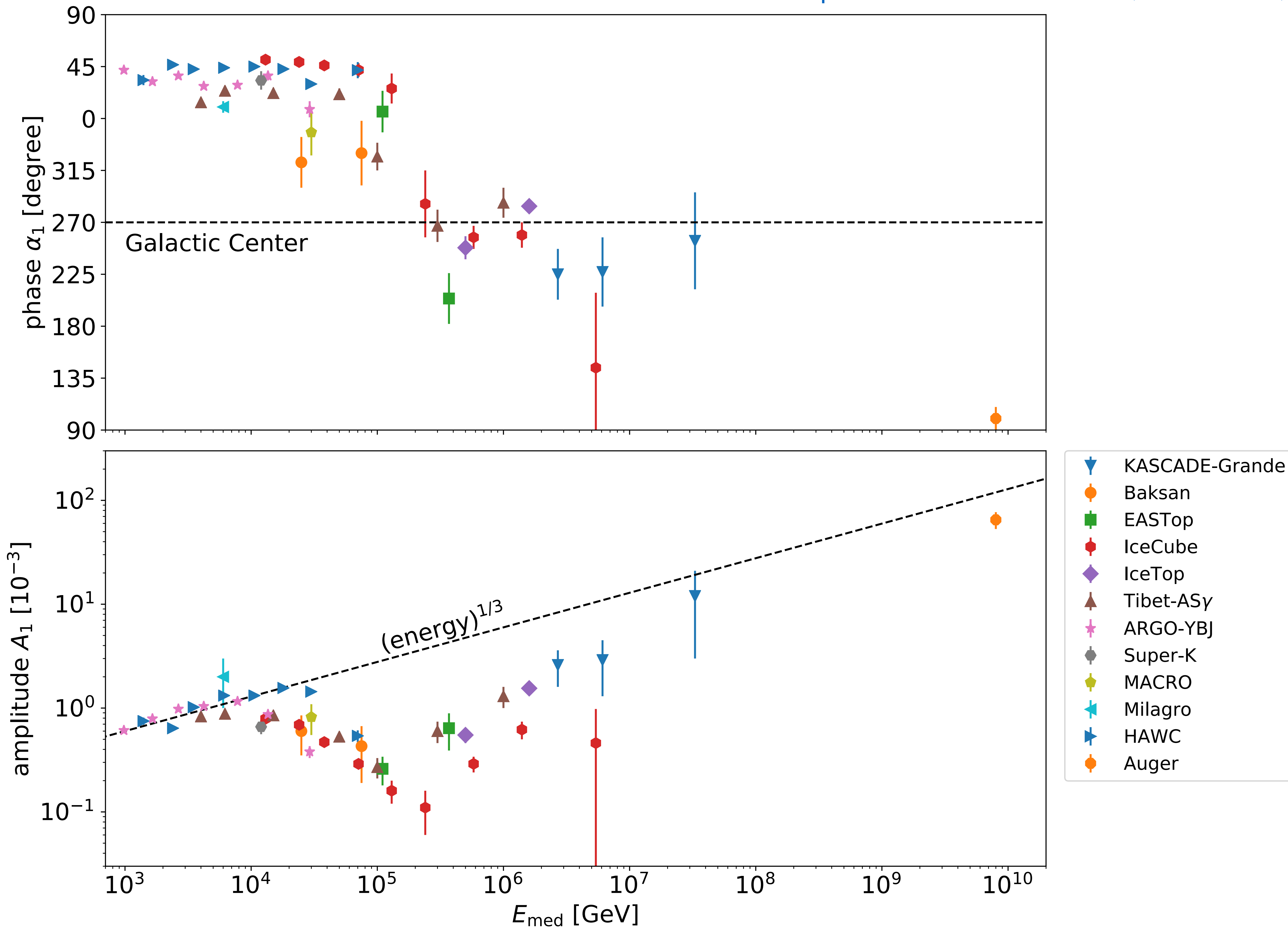


Massive Data Sets!

Detector	Altitude	Latitude	E_{median}	N_{events}	Coverage
Tibet ASγ	4300 m	30°S	~3 TeV	$\sim 4\times10^9$	Feb. 1997 - Nov. 2005
Milagro	2630 m	36°S	~1 TeV	$\sim 220\times10^9$	Jul. 2000 - Jul. 2007
ARGO-YBJ	4300 m	30°S	~1 TeV	$\sim 220\times10^9$	Nov. 2007 - May 2012
HAWC	**4100 m**	**19°N**	**~2 TeV**	$\sim 110\times10^9$	**Jun. 2013 -**
Auger	1400 m	35°S	~1 EeV	$\sim 0.001\times10^9$	Nov. 2004 -
IceCube	**—**	**90°S**	**~20 TeV**	$\sim 280\times10^9$	**May 2009 -**
IceTop	2835 m	90°S	~1.6 PeV	$\sim 0.23\times10^9$	May 2009 -

Dipole Energy Dependence

Adapted from Ahlers and Mertsch, PNPP **94**:184, 2017



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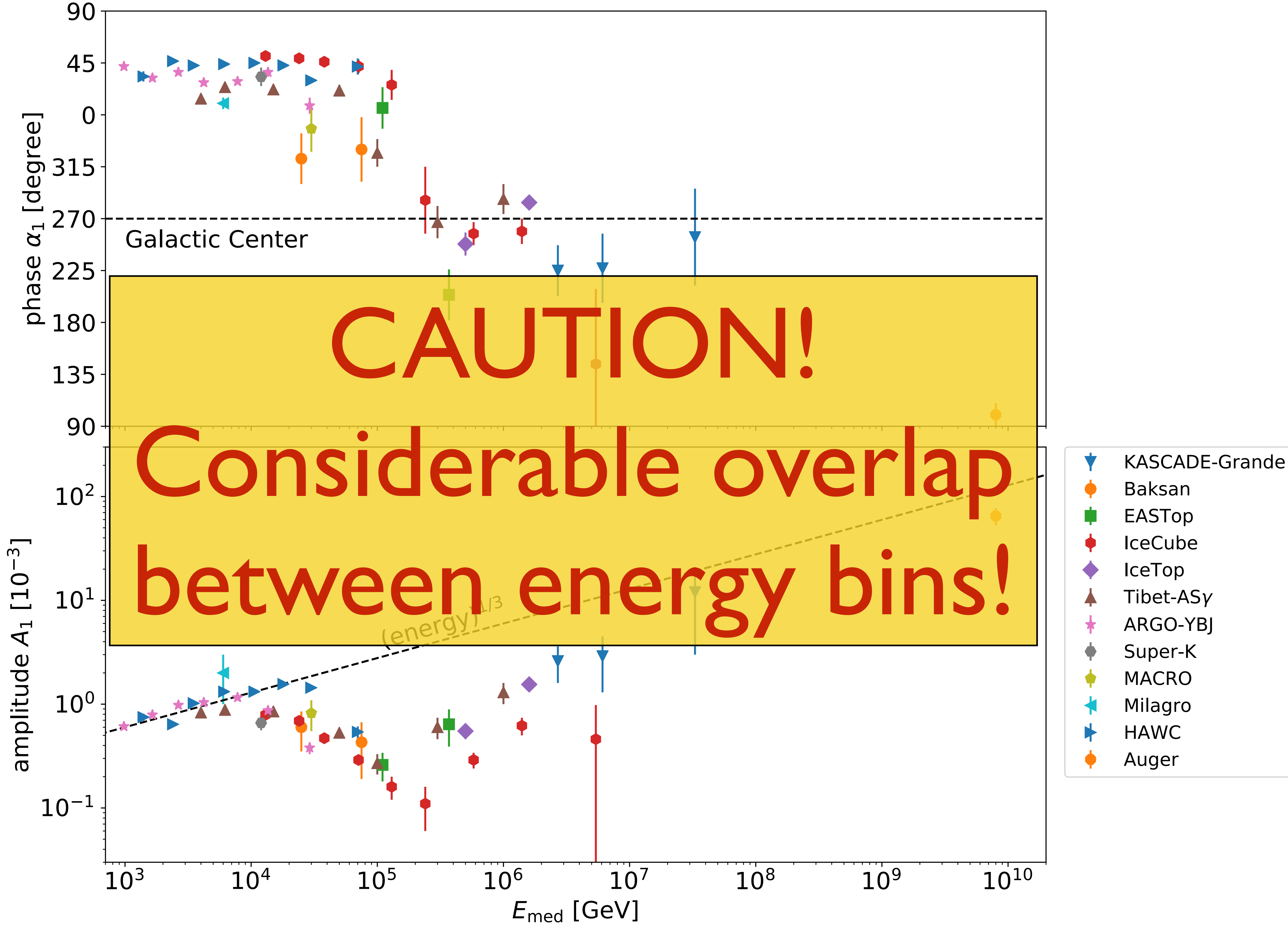


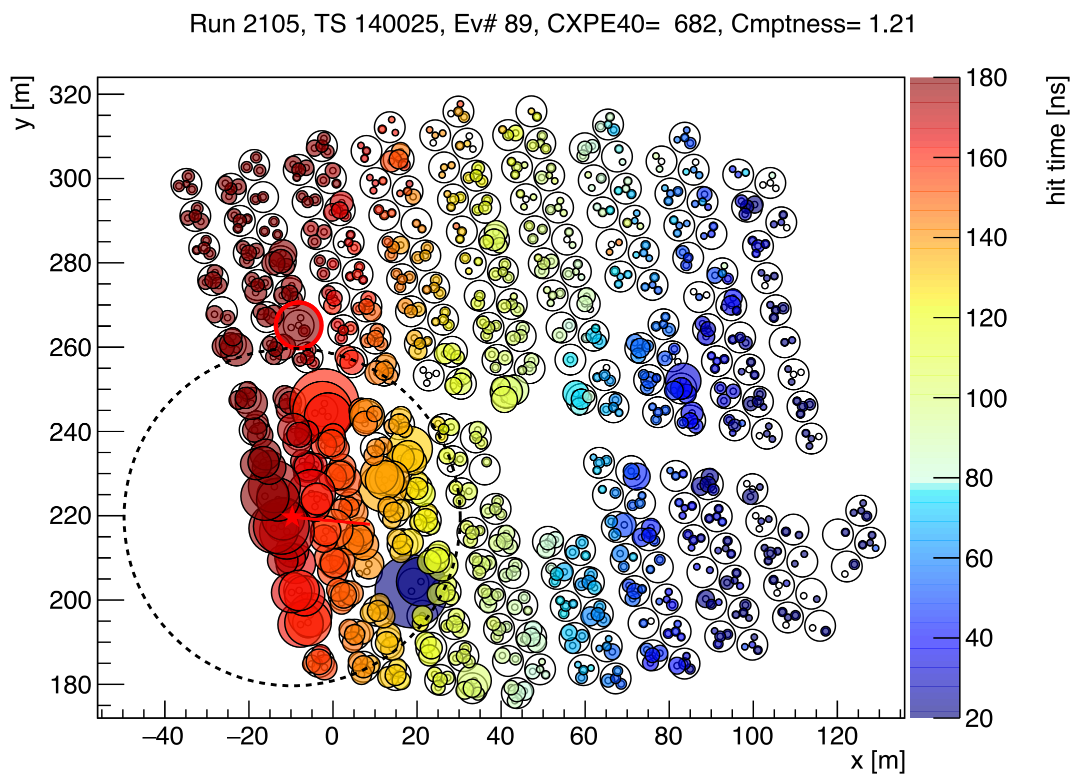
CAUTION!

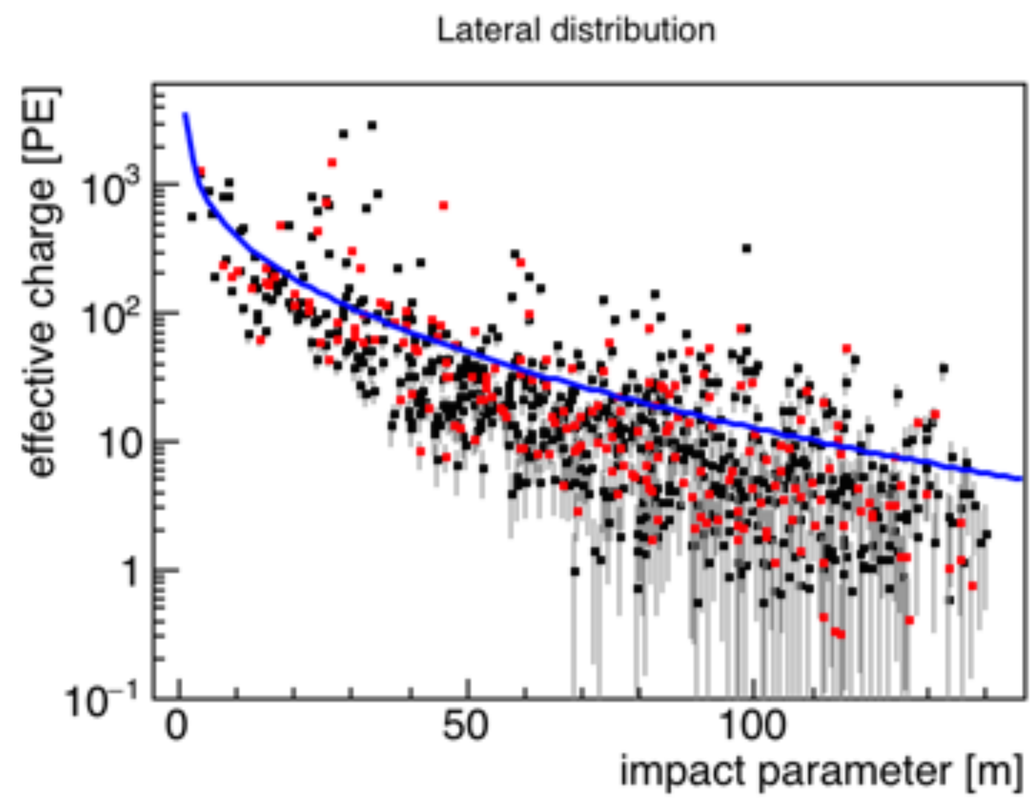
Considerable overlap between energy bins!

HAWC Observatory

HAWC Observatory

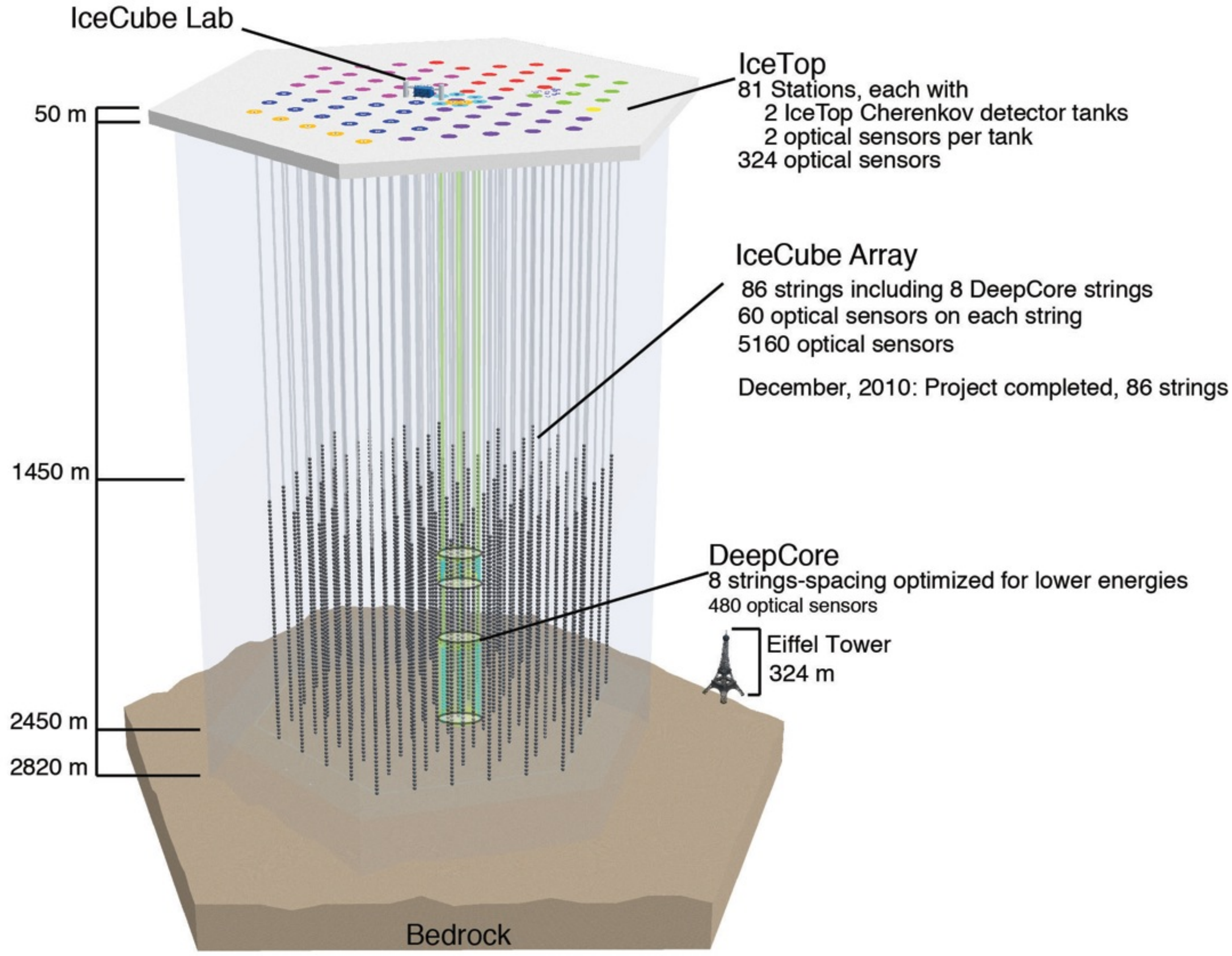
Cosmic Rays in HAWC



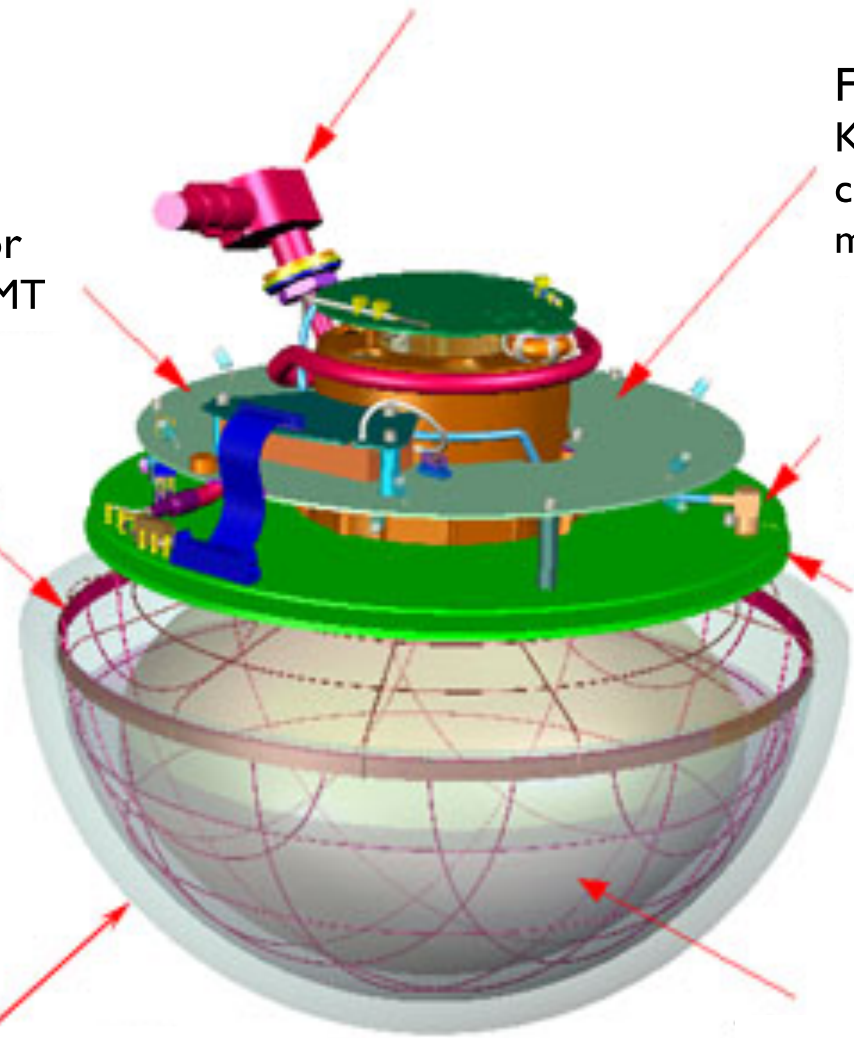


- Cosmic ray background: 25 kHz at trigger level.
- Cosmic ray showers produce "clumpy" deposits of charge at large distances from the shower core. Usually seek to remove these events from the data, but in the anisotropy analysis they are kept in favor of gamma rays.
- Median energy: 2 TeV; energy resolution ~50%; angular resolution ~1.5° to 0.3° (smaller than angular size of the Sun and Moon).

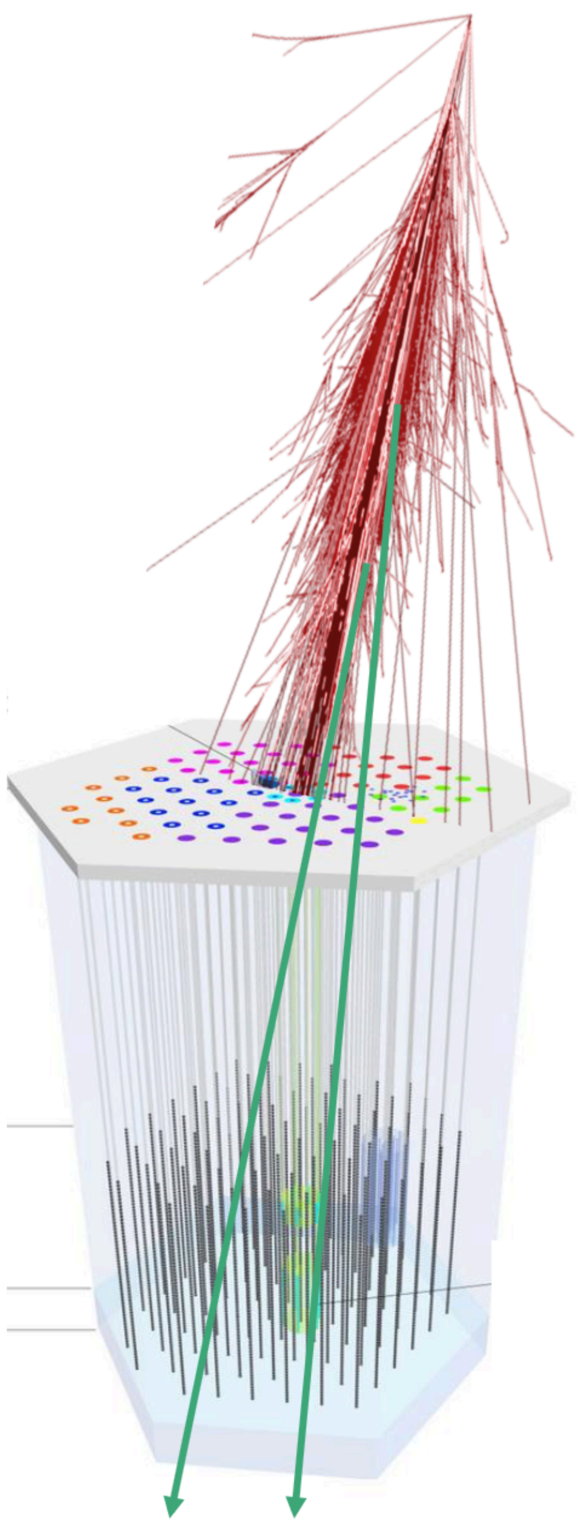
IceCube Observatory



IceCube Observatory



Cosmic Rays in IceCube

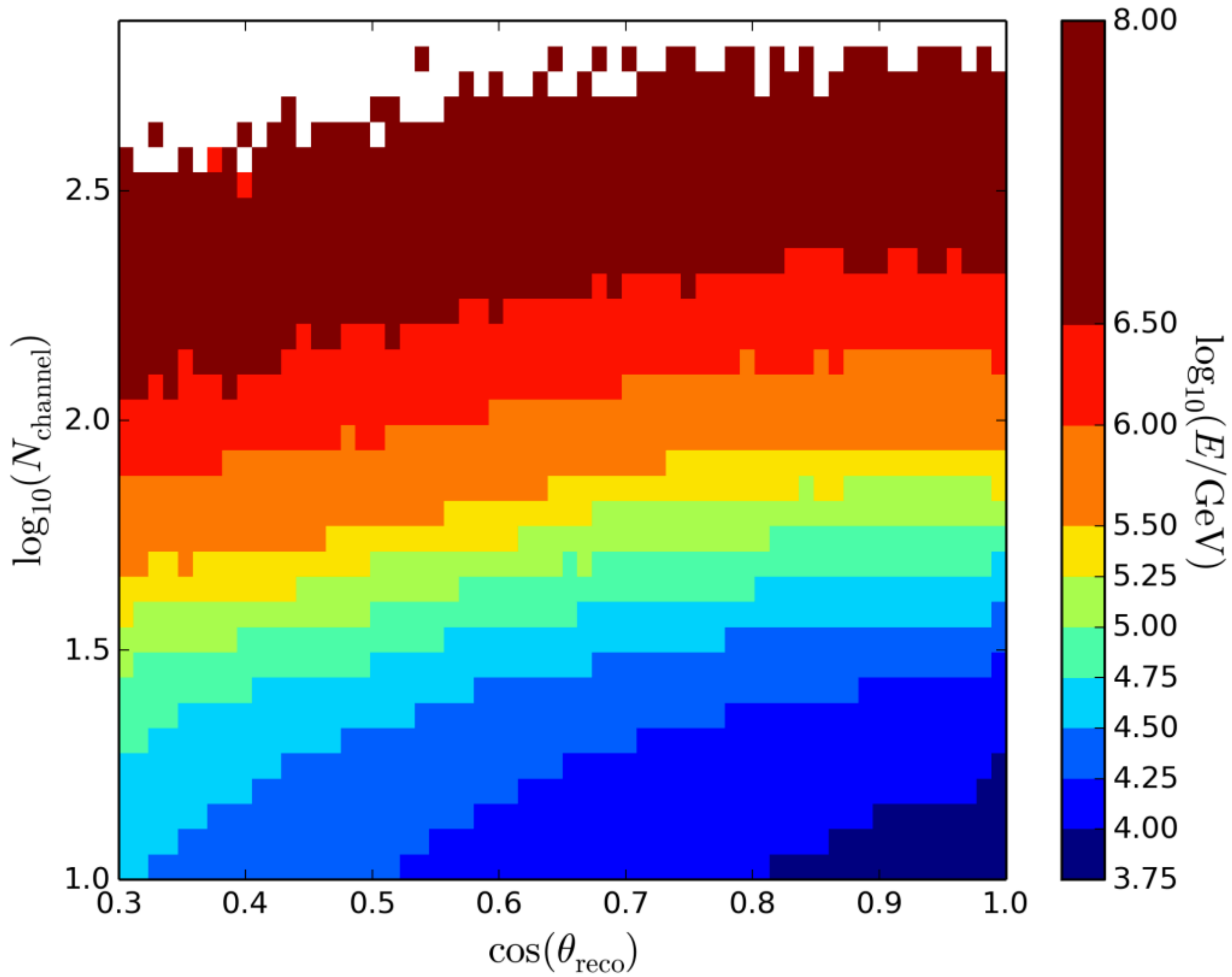


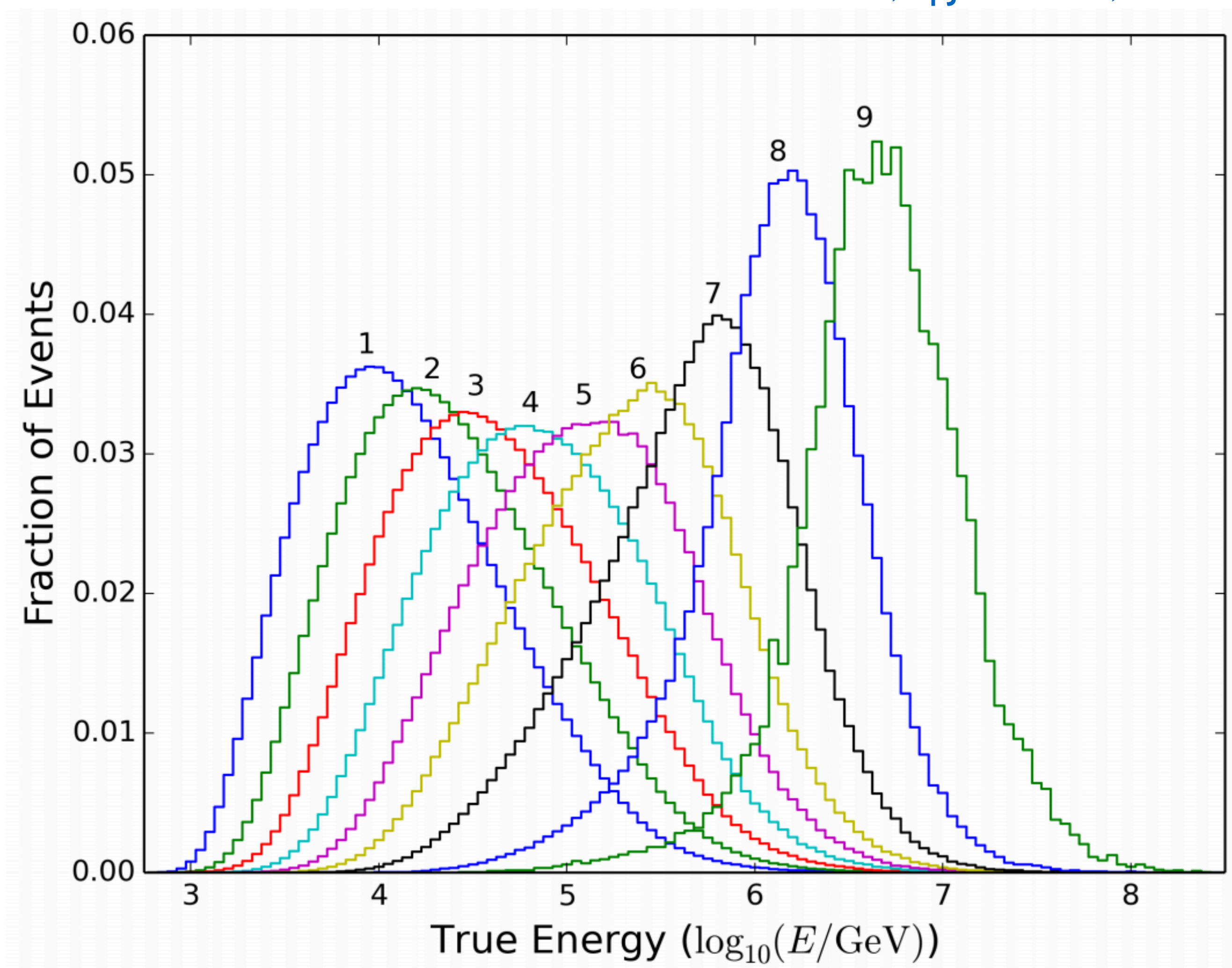
- IceCube detects down-going muons produced in air showers.
  - SMT rate: 2.5 kHz - 3 kHz.
  - Median angular resolution: 3°. Note: muon filter (neutrinos) is ~0.6°.
  - Energy resolution: ~100%.
  - Median energy: 20 TeV.
- Because of location at the South Pole, instantaneous FOV is equal to time-integrated FOV. Convenient for analysis.

Energy Resolution

- Cosmic-ray energy estimator in IceCube: number of triggered channels as a function of zenith angle.
- Events are binned in the 2D log(N_{ch})/cos θ plane and assigned to discrete energy bins.

IceCube Collab., ApJ **826**:220, 2016





Anisotropy Measurement

- To first order, the flux of cosmic rays at Earth is isotropic, so the anisotropy is a small deviation.
- Relative intensity:

$$\underbrace{\Phi(\mathbf{n})}_{\substack{\text{total}\\\text{flux}}} = \Phi_{\text{iso}} \cdot \underbrace{I(\mathbf{n})}_{\substack{\text{relative}\\\text{intensity}}}, \qquad \mathbf{n} = \begin{pmatrix} \cos\delta\cos\alpha \\ \cos\delta\sin\alpha \\ \sin\delta \end{pmatrix}.$$

- Anisotropy: $\delta I = I - 1 \ll 1.$
- Analysis: construct a data map Φ and a reference map Φ_{iso}, using the ratio to define relative intensity I.

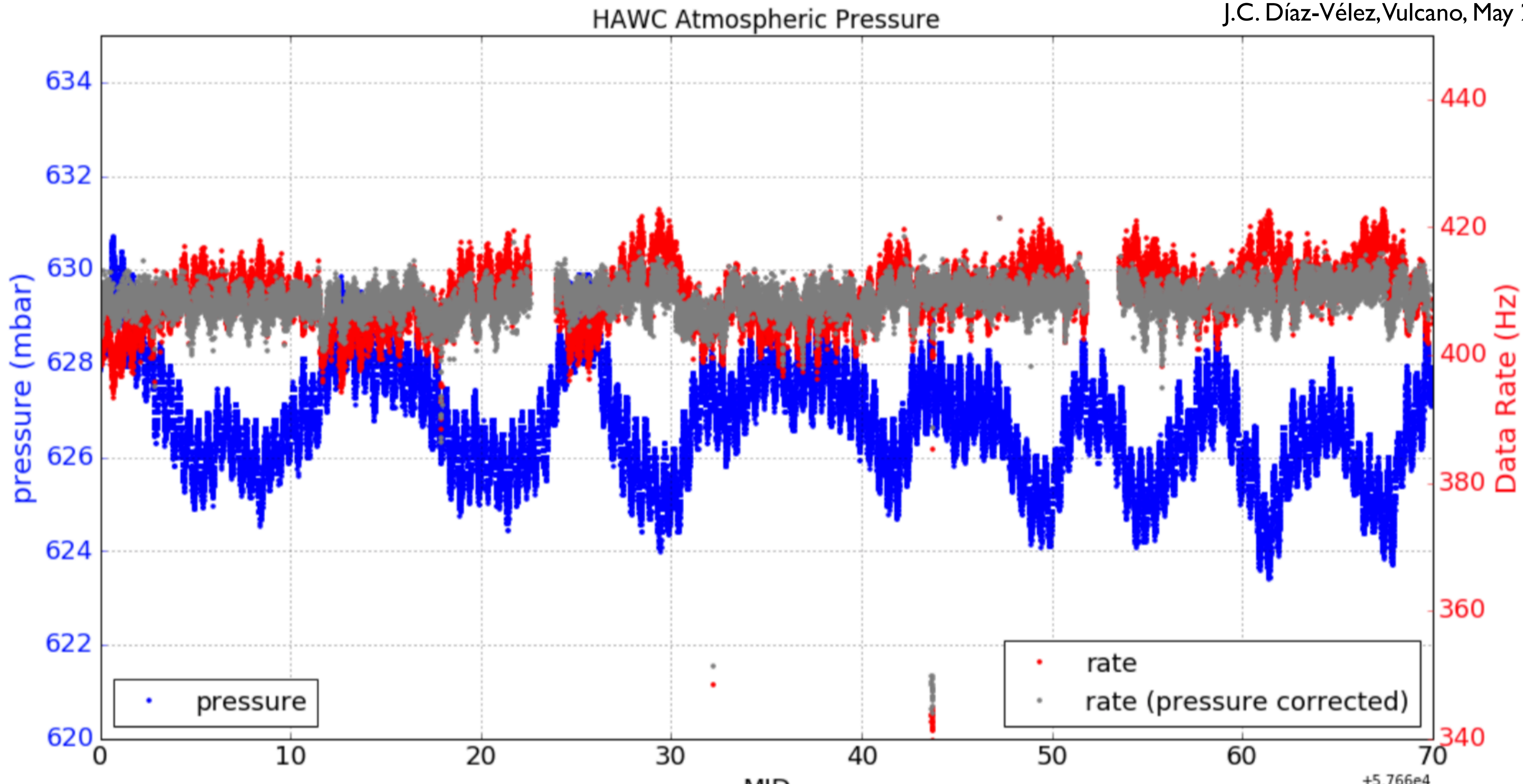
Reference Construction

- In practice both data + reference maps contain detector effects:
  - Seasonal and diurnal changes in the atmosphere and detector;
  - Planned and unplanned shutdowns resulting in nonuniform exposure to the sky.
- The reference map represents the detector "exposure" to an isotropic flux.
  - Reference not isotropic: Φ_{iso} folded through detector response.
- If all detector effects were known (including the state of the atmosphere) we could build up a realistic Monte Carlo to simulate the response to an isotropic flux.
  - Effect is $\sim 10^{-4}$; difficult to simulate with this level of accuracy.

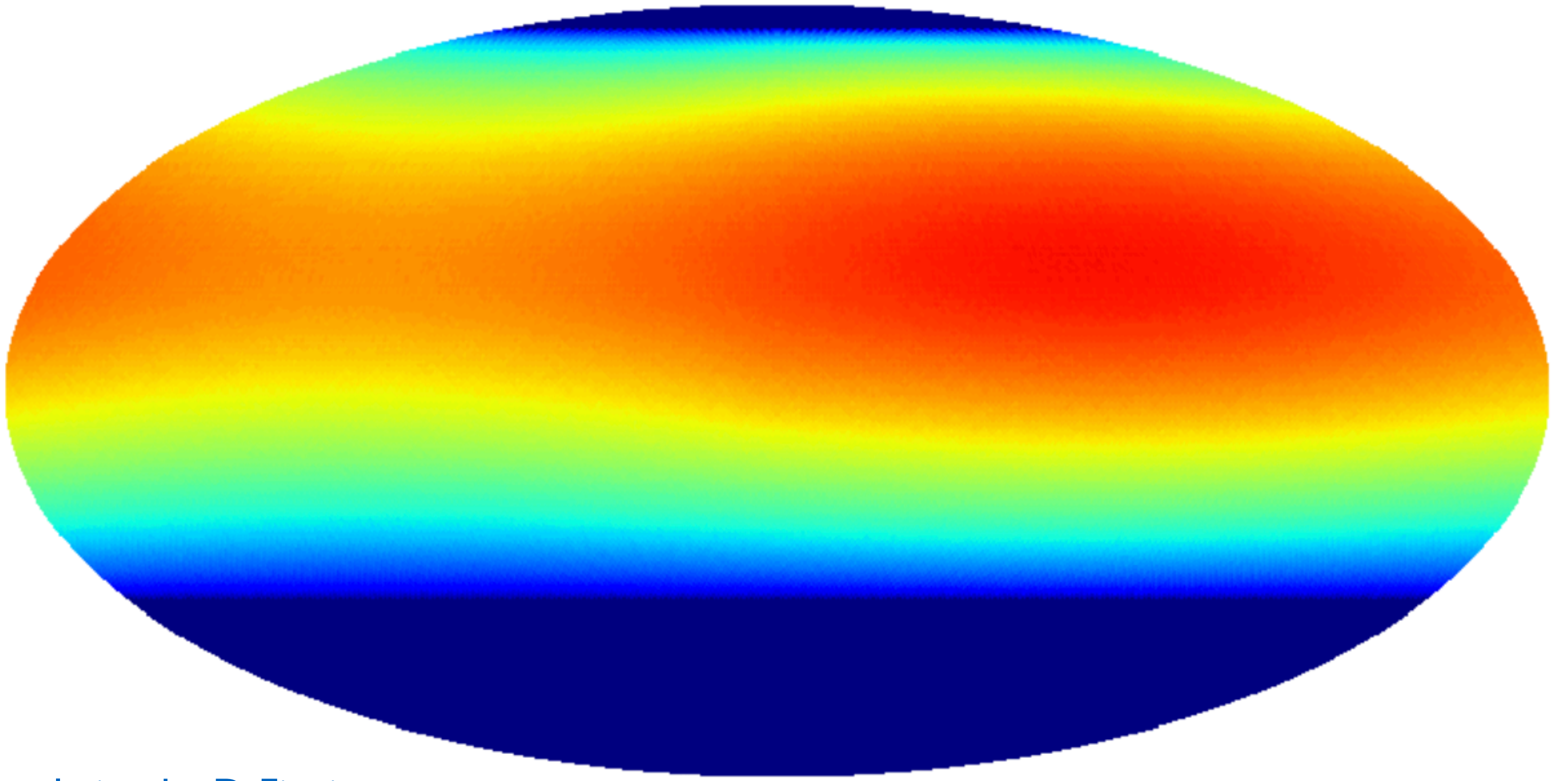
Systematics: Atmosphere

- Twice daily atmospheric tides at altitude are apparent in the HAWC event rate.
- Local measurements of pressure are used to zero out the effect.

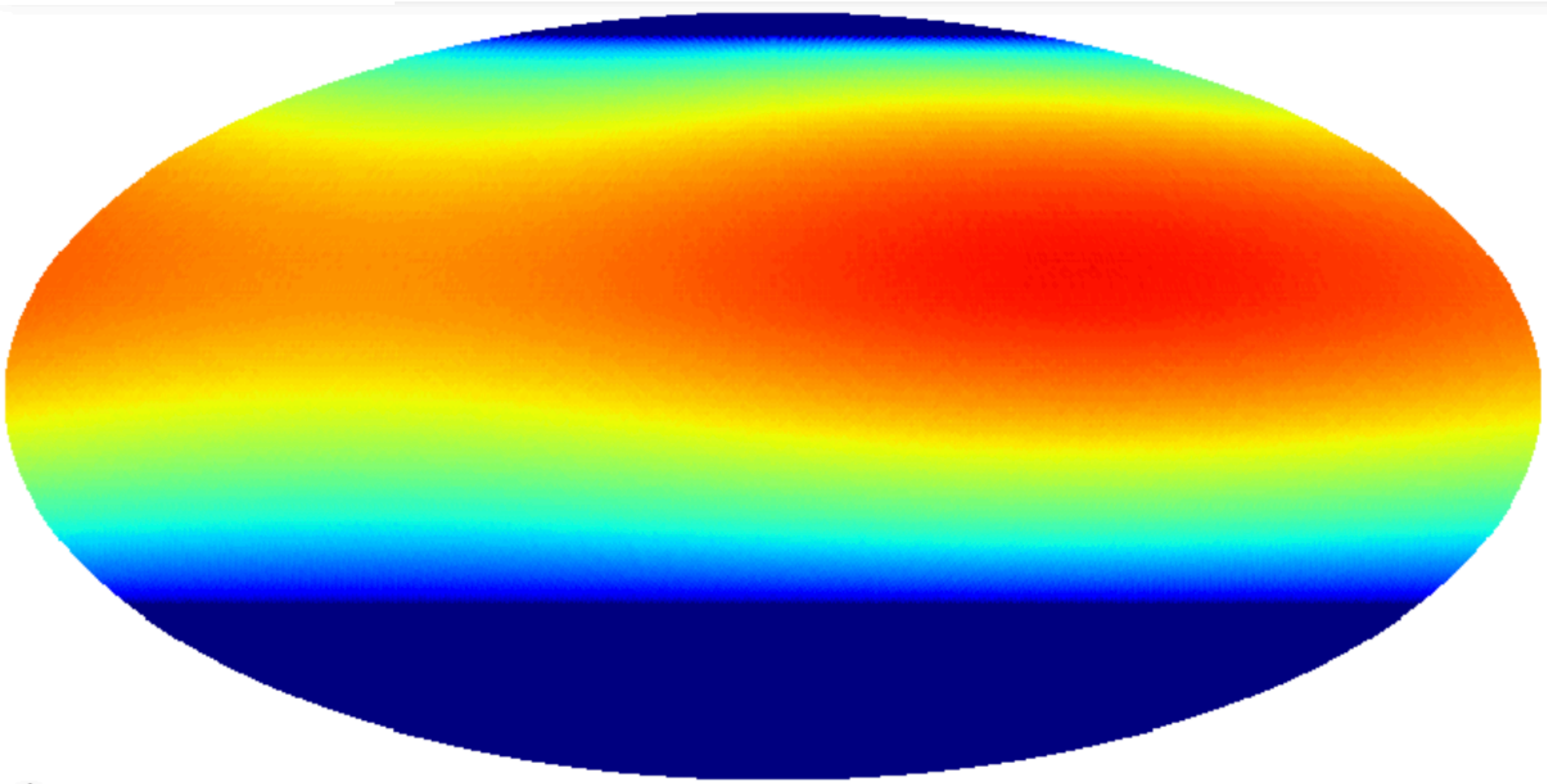
J.C. Díaz-Vélez, Vulcano, May 2018



Data and Reference Maps



Simulation by D. Fiorino

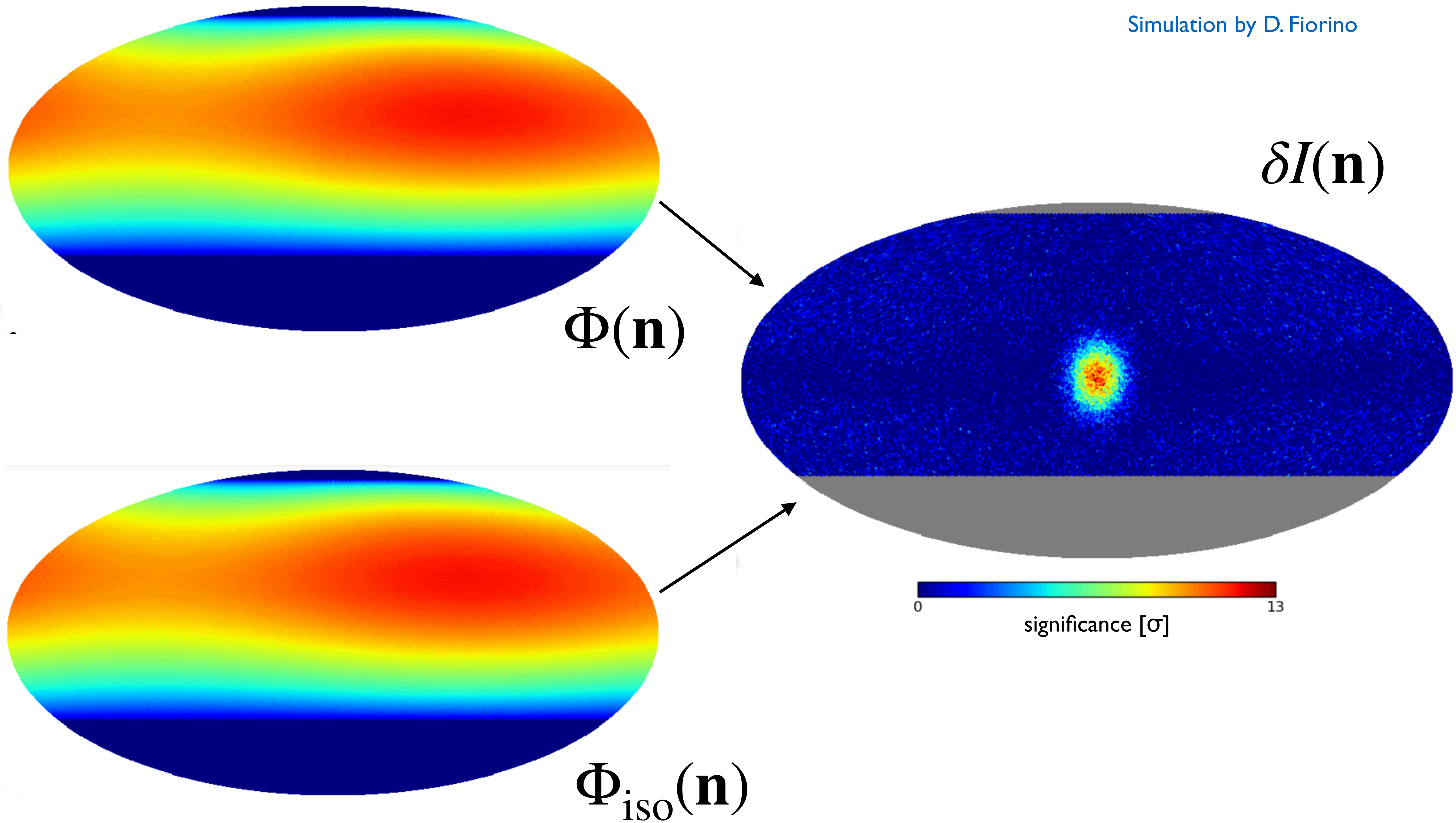


- "Data map:" event counts binned in HEALPix map. Bins usually much smaller than angular resolution.
- "Reference map:" estimate of expected counts from Φ_{iso}, after detector response.

Reference Construction

- Two approaches used:
  1. Time scrambling: generate fake events from the same time and local zenith angle distribution of the data.
     - Alexandreas et al., NIM A **328**:530, 1993.
  2. Direct integration: rate of events in small sidereal time bins Δt (e.g., 2 hr) is integrated against relative acceptance.
     - Atkins et al., ApJ **595**:803, 2003.
     - Note: Δt filters out features over $15^\circ \times (\Delta t\ /\ \mathrm{hr})$.
- Both methods build a detailed cumulative detector response from the data themselves.

Difference Map

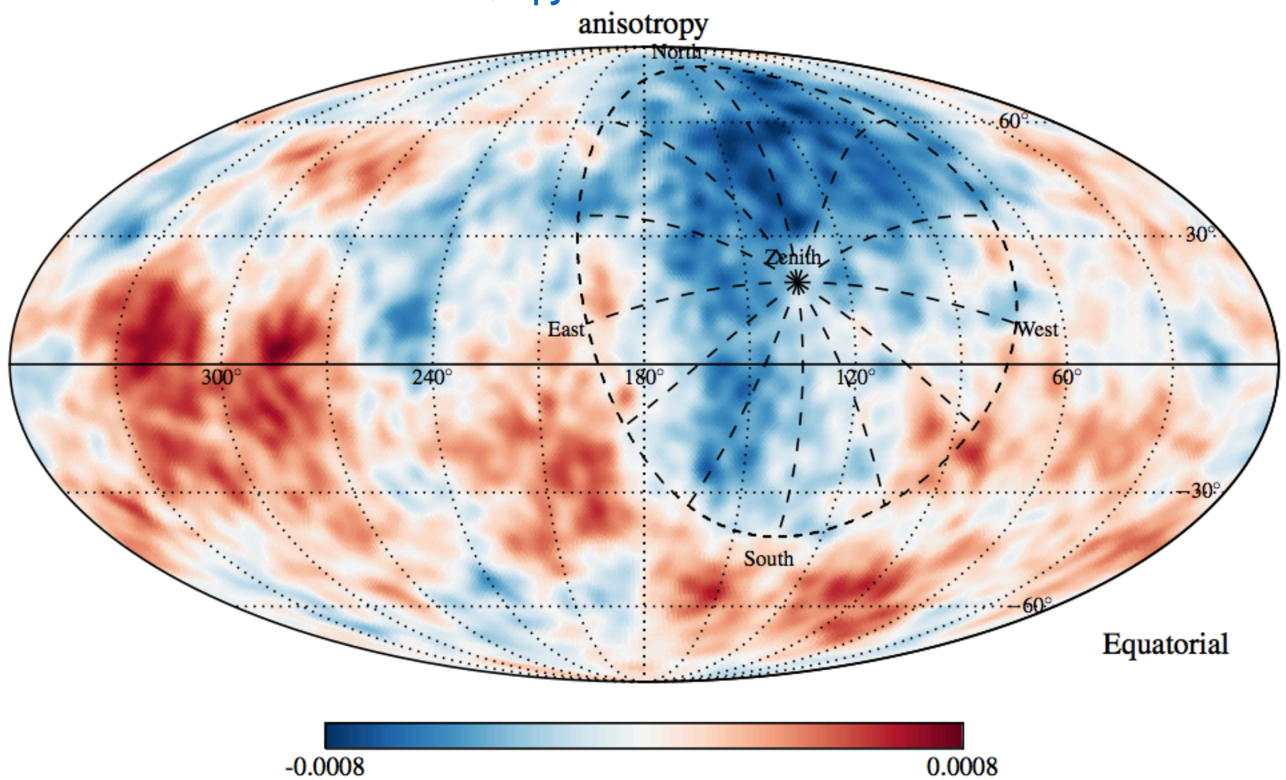


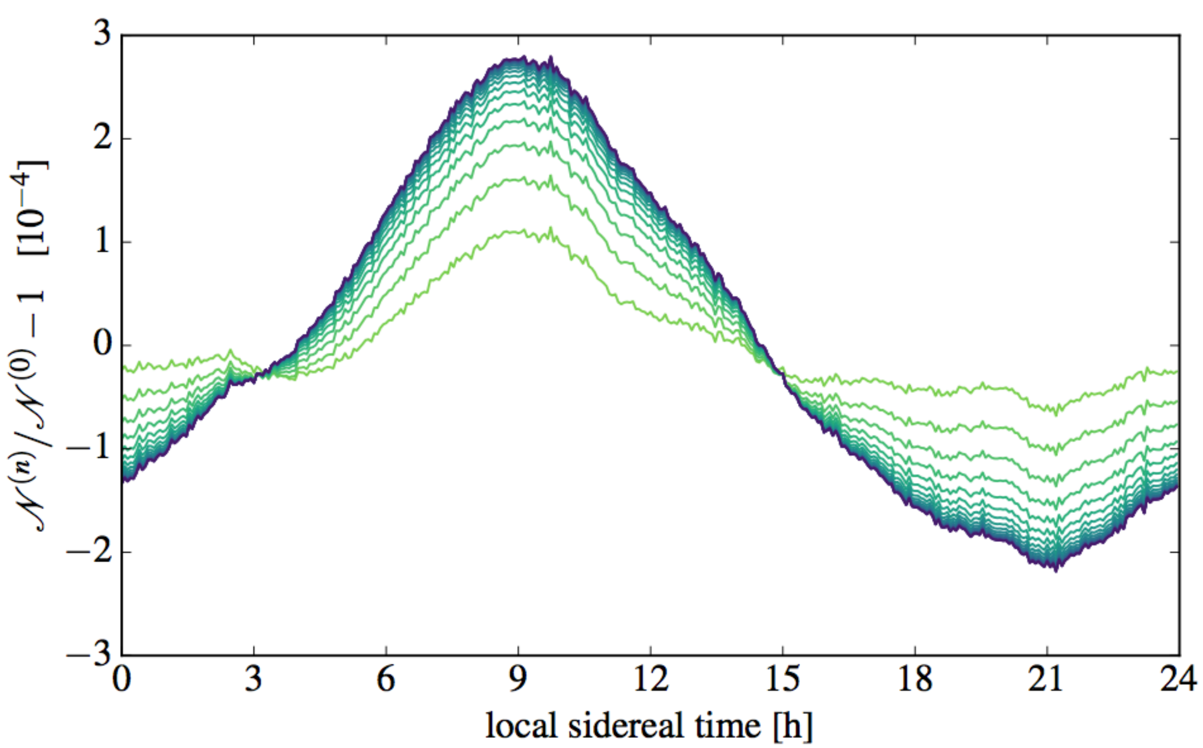
Mid-Latitude Attenuation

- An issue which affects detectors in the mid-latitudes — not IceCube+IceTop — is attenuation of large-scale structures.
  - Instantaneous exposure is much smaller than time-integrated exposure.
  - At any given time only part of a large-scale structure (>60°) can be observed, causing attenuation of estimated amplitude.
- Effect can be mitigated using iterative techniques:
  - E.g., Tibet-ASγ Collaboration, ApJ **633**:1005, 2005.
  - E.g., ARGO-YBJ Collaboration, ApJ **809**:90, 2015.
  - E.g., Ahlers et al., ApJ **823**:10, 2016.

Maximum Likelihood Iteration

Simulation from Ahlers et al., ApJ 2016



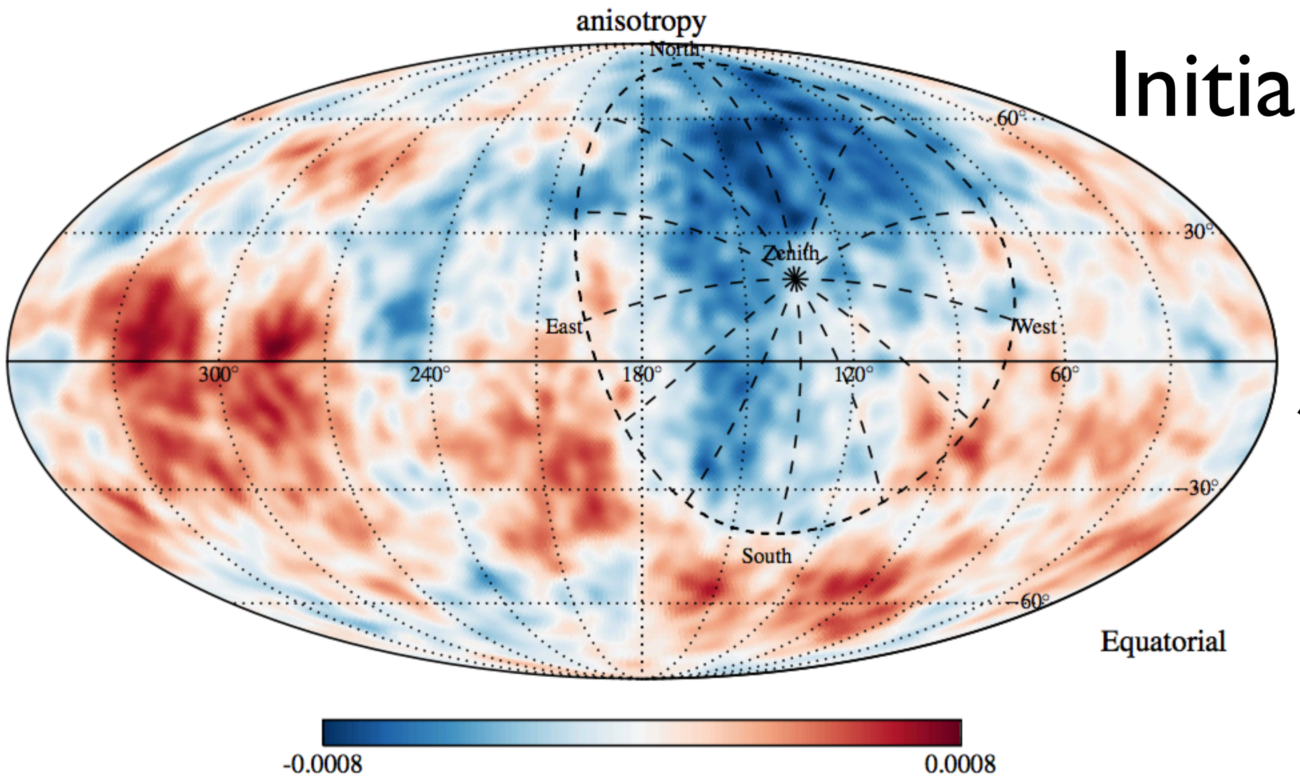


- HAWC instantaneous FOV is shown on a simulated sky map.
- When FOV is over a deficit, as in this case, the estimate for Φ_{iso} is too low.
- Maximum likelihood iteration compensates for effect by accounting for changes to relative acceptance and relative intensity.
- Typical convergence is <10 iterations.

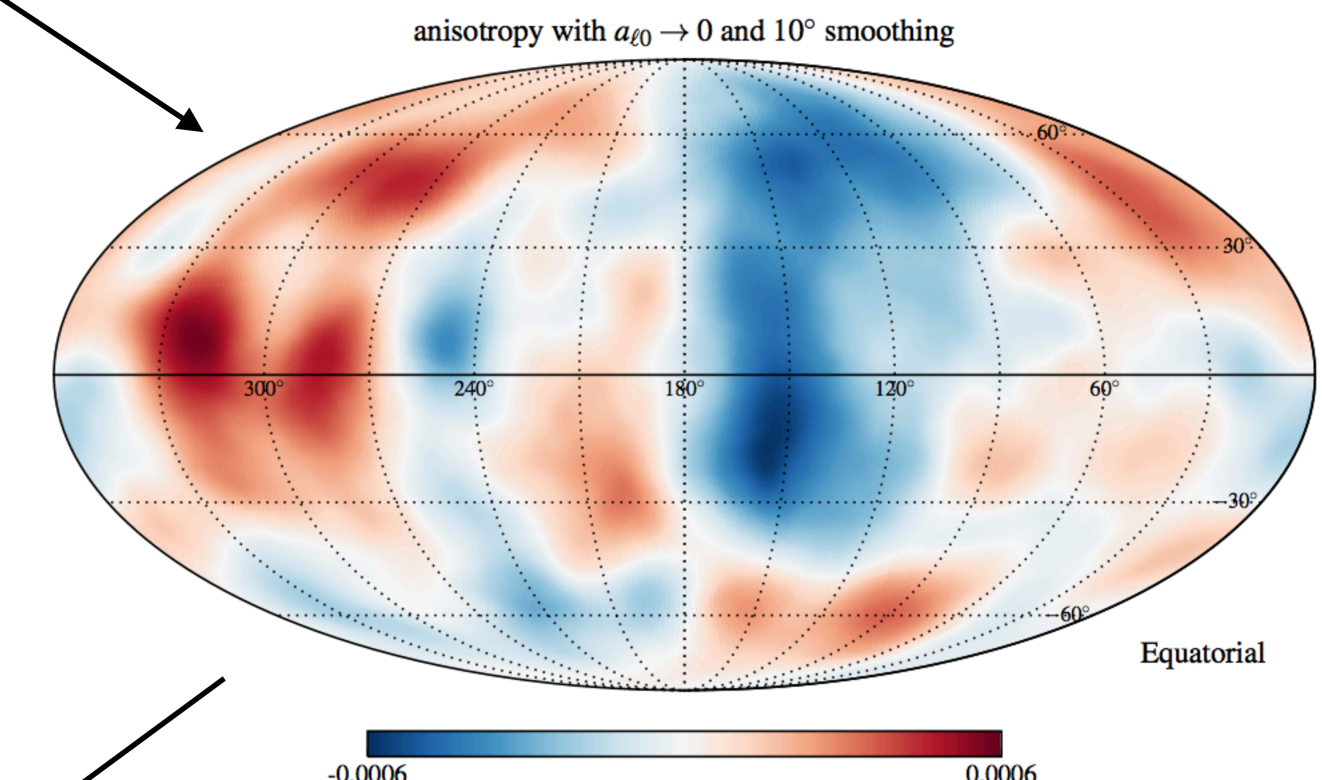
Iterative Map Construction

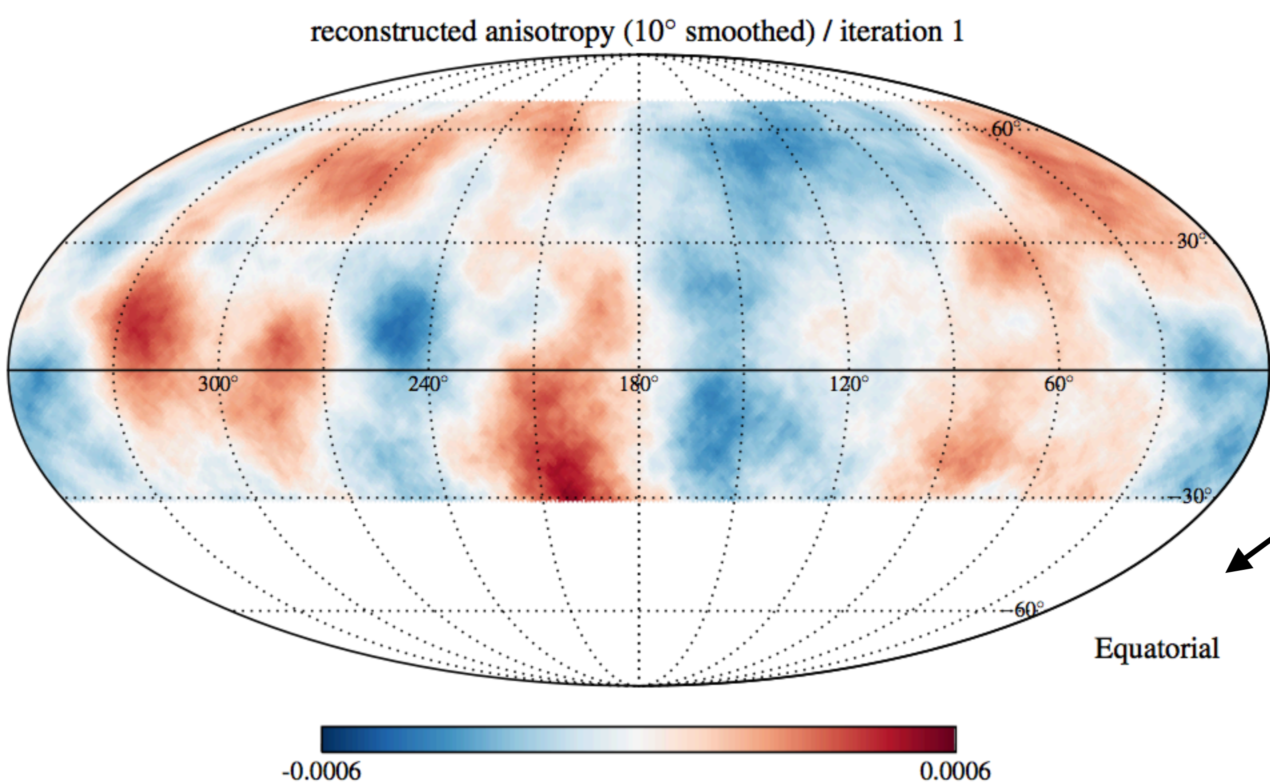
Initial anisotropy

Simulation from Ahlers et al., ApJ 2016



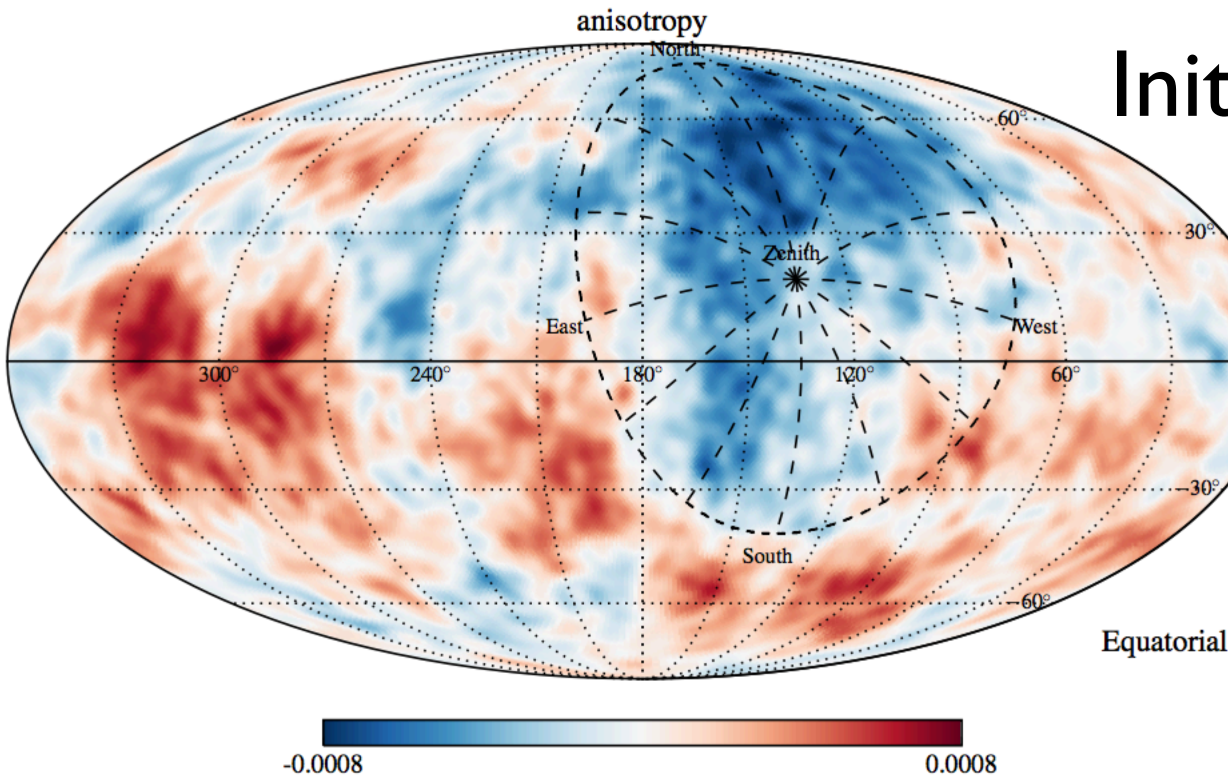
Projection + smoothing





Iterative ML reconstruction

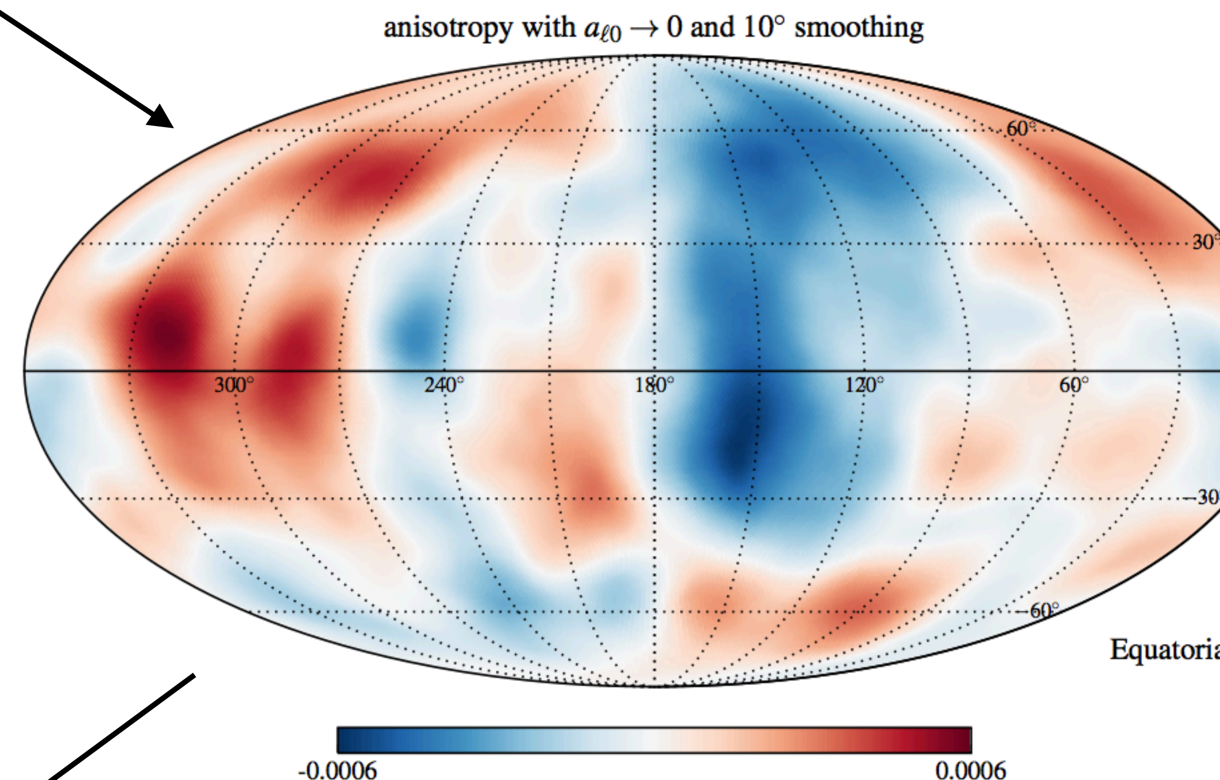
Iterative Map Construction

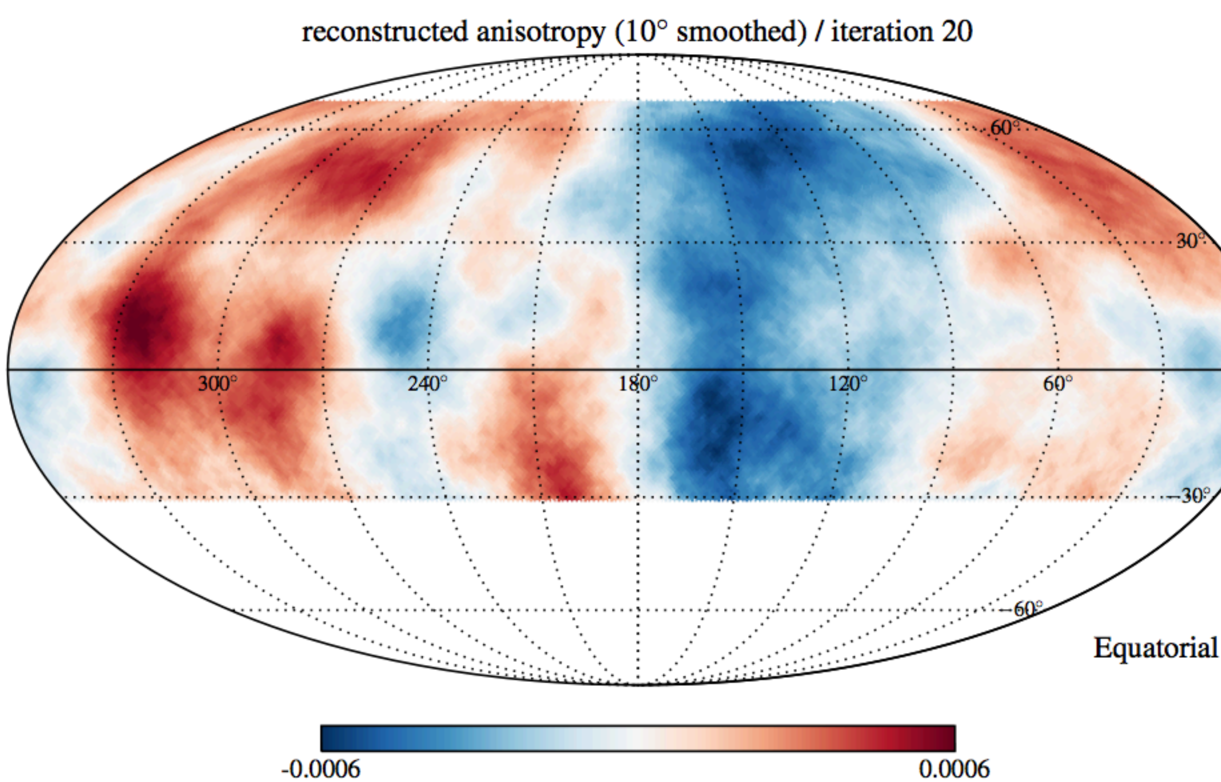


Initial anisotropy

Simulation from Ahlers et al., ApJ 2016

Projection + smoothing

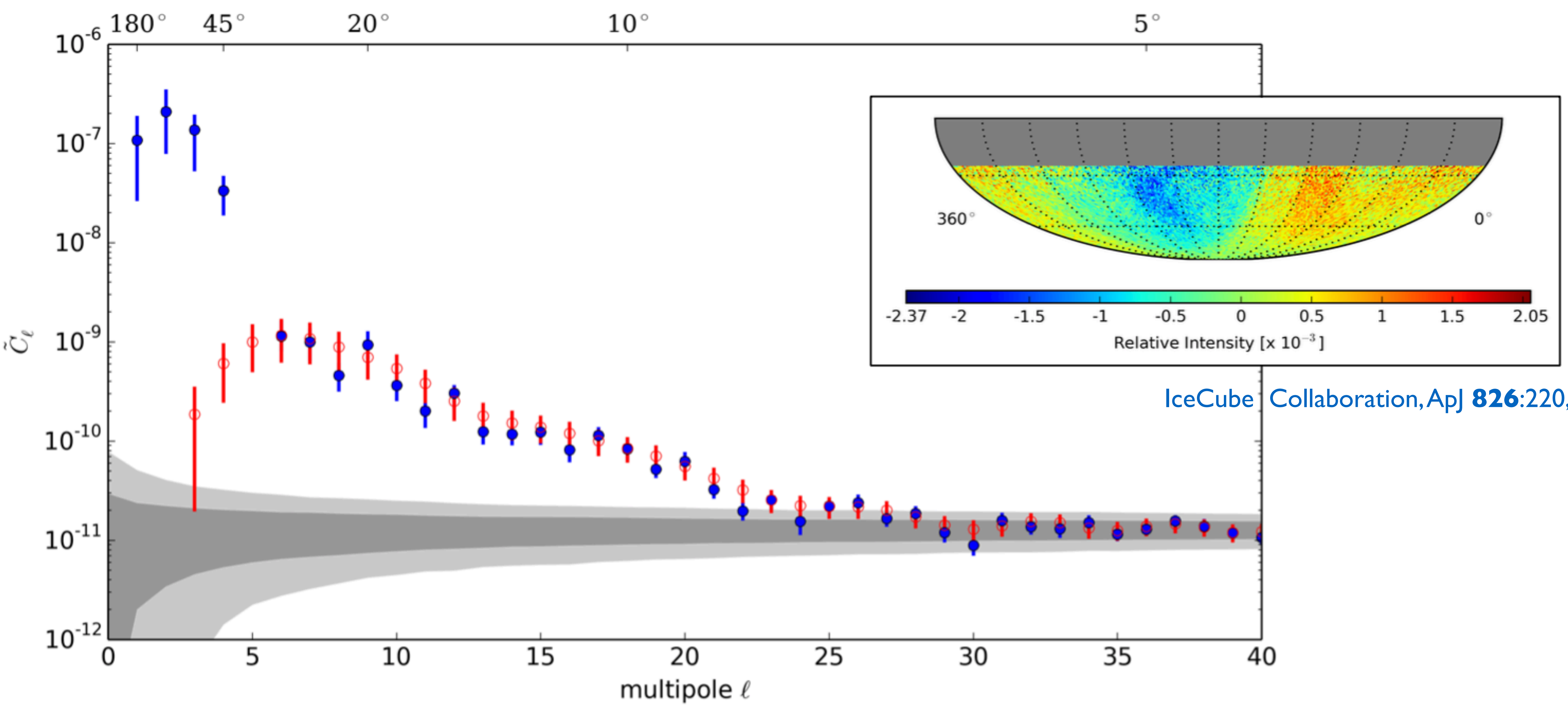




Iterative ML reconstruction

Angular Power Spectrum

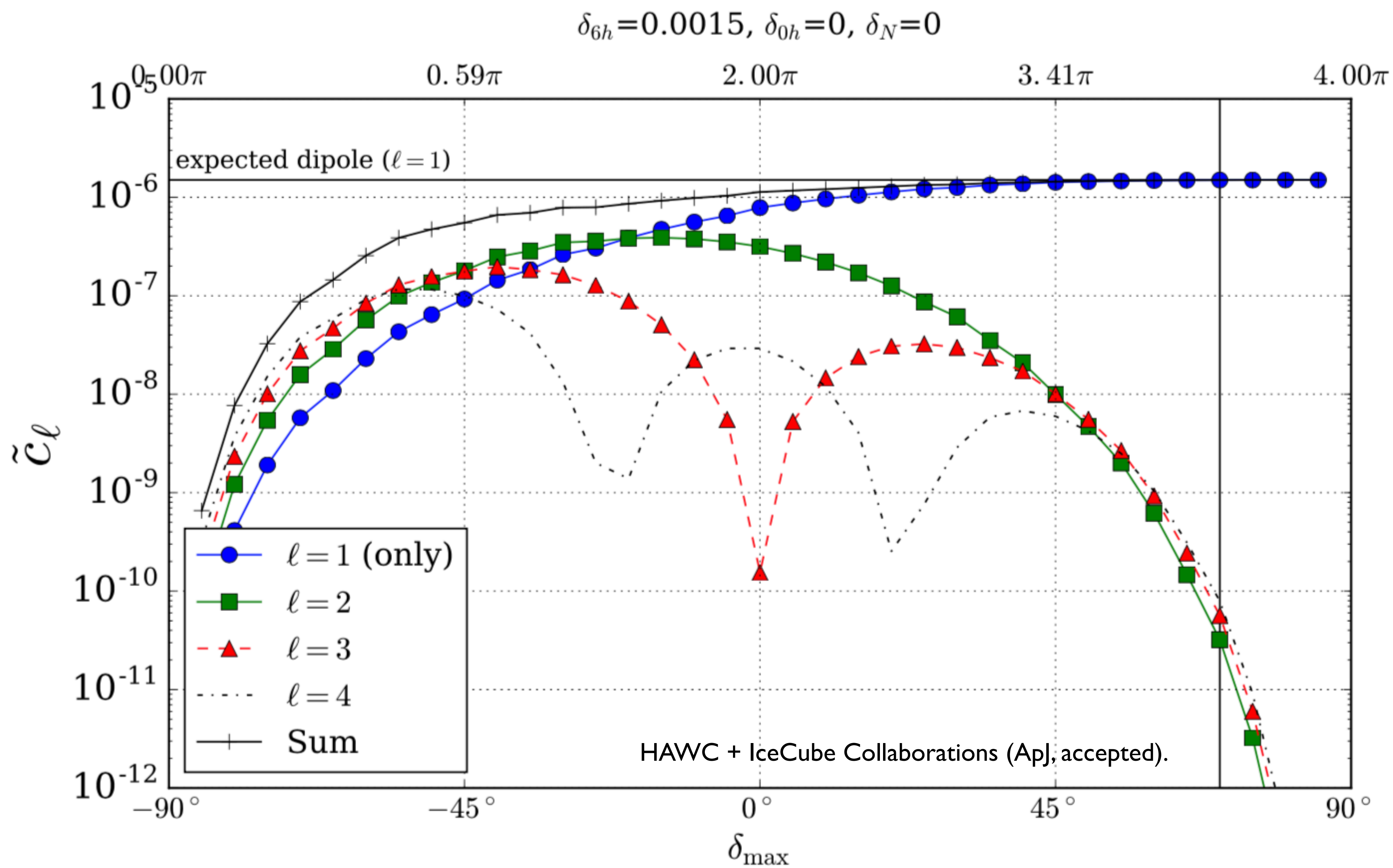
- Legendre expansion of anisotropy: study power on many angular scales.
- Below: IceCube-only power spectrum (blue), with dipole and quadrupole moments fit and subtracted (red). Gray bands indicate the typical power expected using realizations of random data sets.



IceCube Collaboration, ApJ **826**:220, 2016

Effect of Partial Coverage

- Partial sky coverage causes dipole power to "leak" into higher modes $\ell = 2,3,4,\ldots$



HAWC+IceCube Data

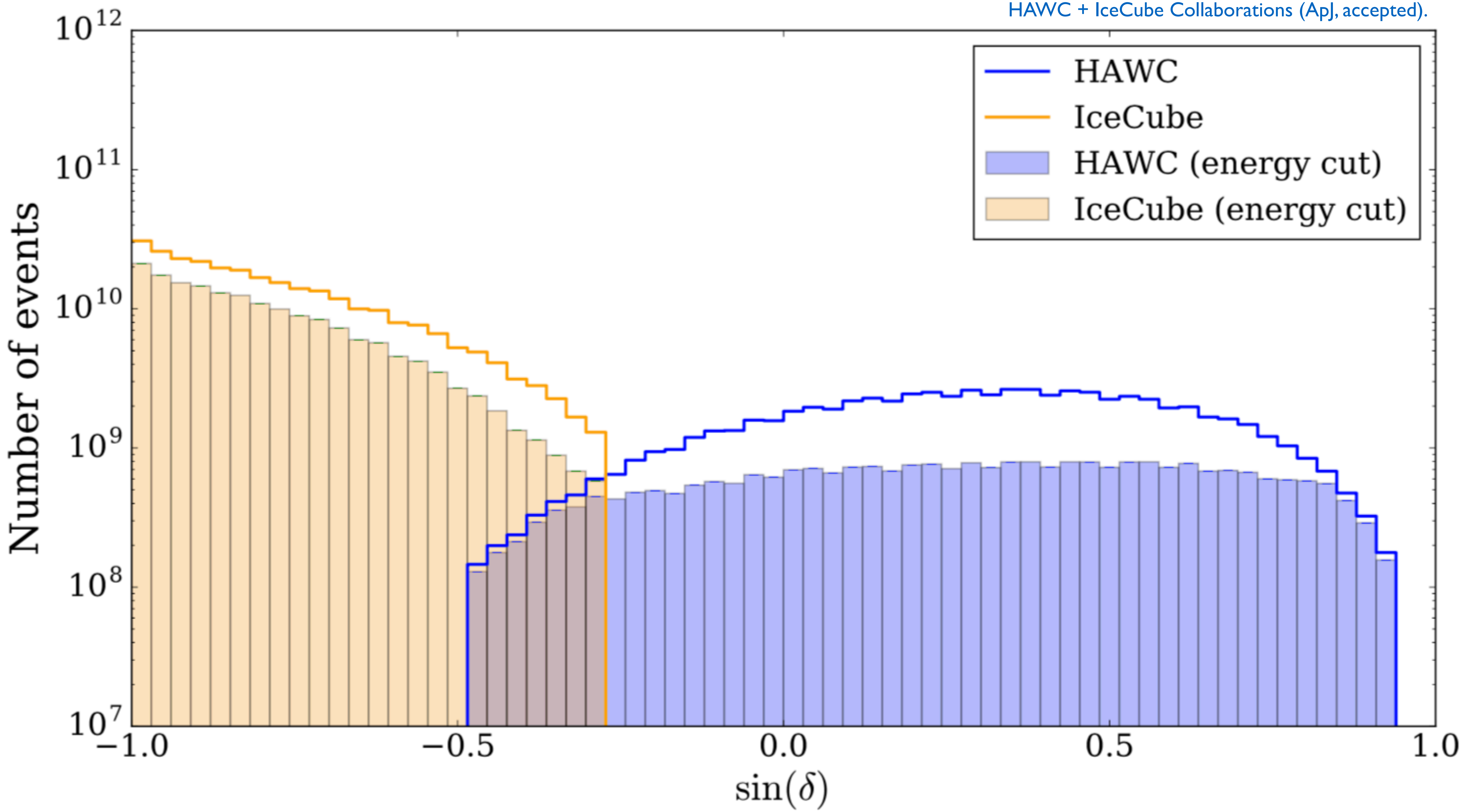
- It's clear that partial sky coverage limits our understanding of large-scale structure.
- With HAWC+IceCube, we can create an energy-matched data set with full-sky coverage.

	IceCube		*HAWC*	
Cuts	*quality*	*energy*	*quality*	*energy*
Med. Energy	20 TeV	10 TeV	2 TeV	10 TeV
Ang. res.	2°-3°	2°-6°	0.3°-1.5°	0.3°-1.5°
Events	2.3×10^{11}	1.7×10^{11}	7.1×10^{10}	2.8×10^{10}

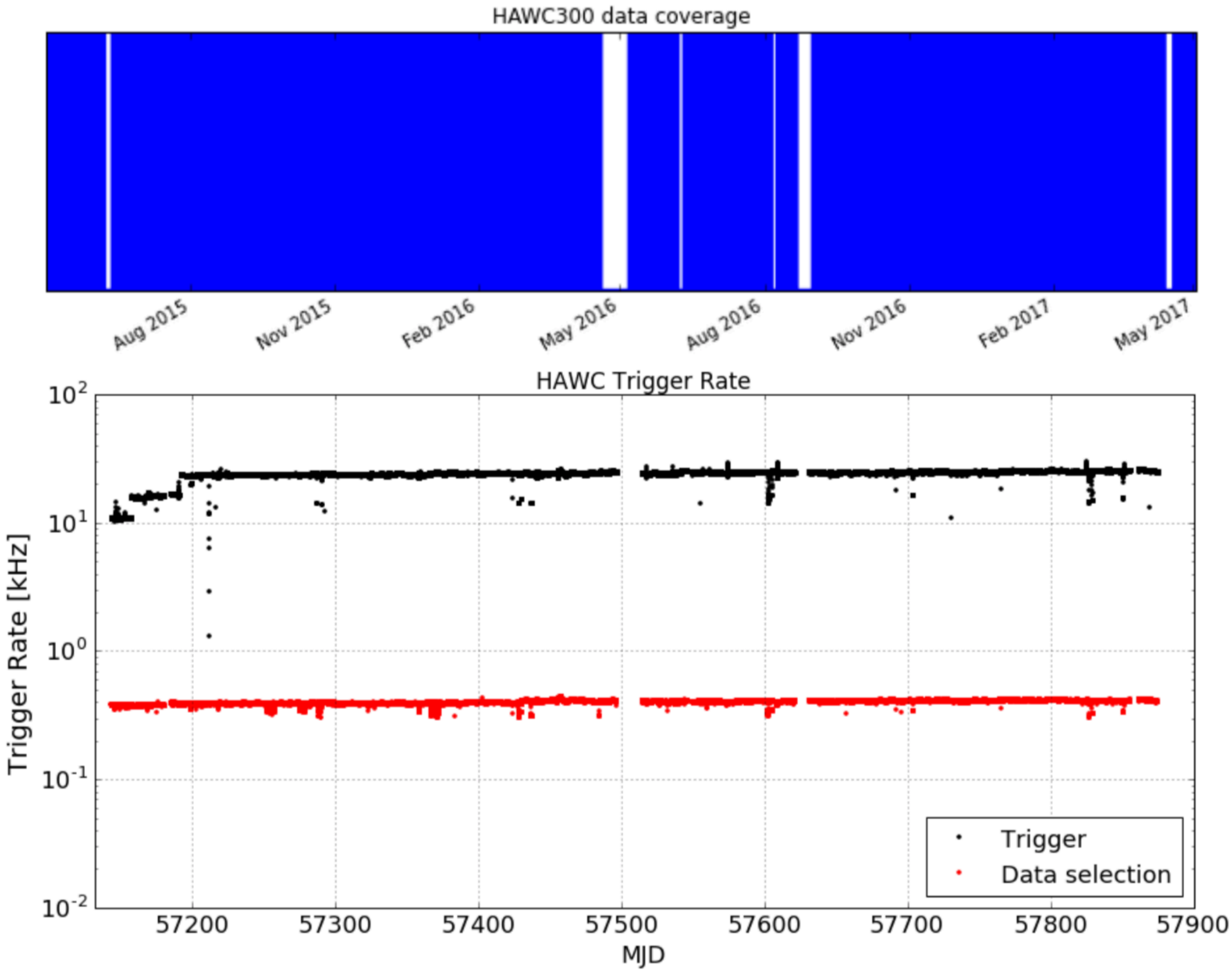
- Analysis by J.C. Díaz-Vélez and D. Fiorino (HAWC Collaboration), P. Desiati and M. Ahlers (IceCube Collaboration). ApJ 2019 (accepted).

HAWC+IceCube Data

HAWC + IceCube Collaborations (ApJ, accepted).



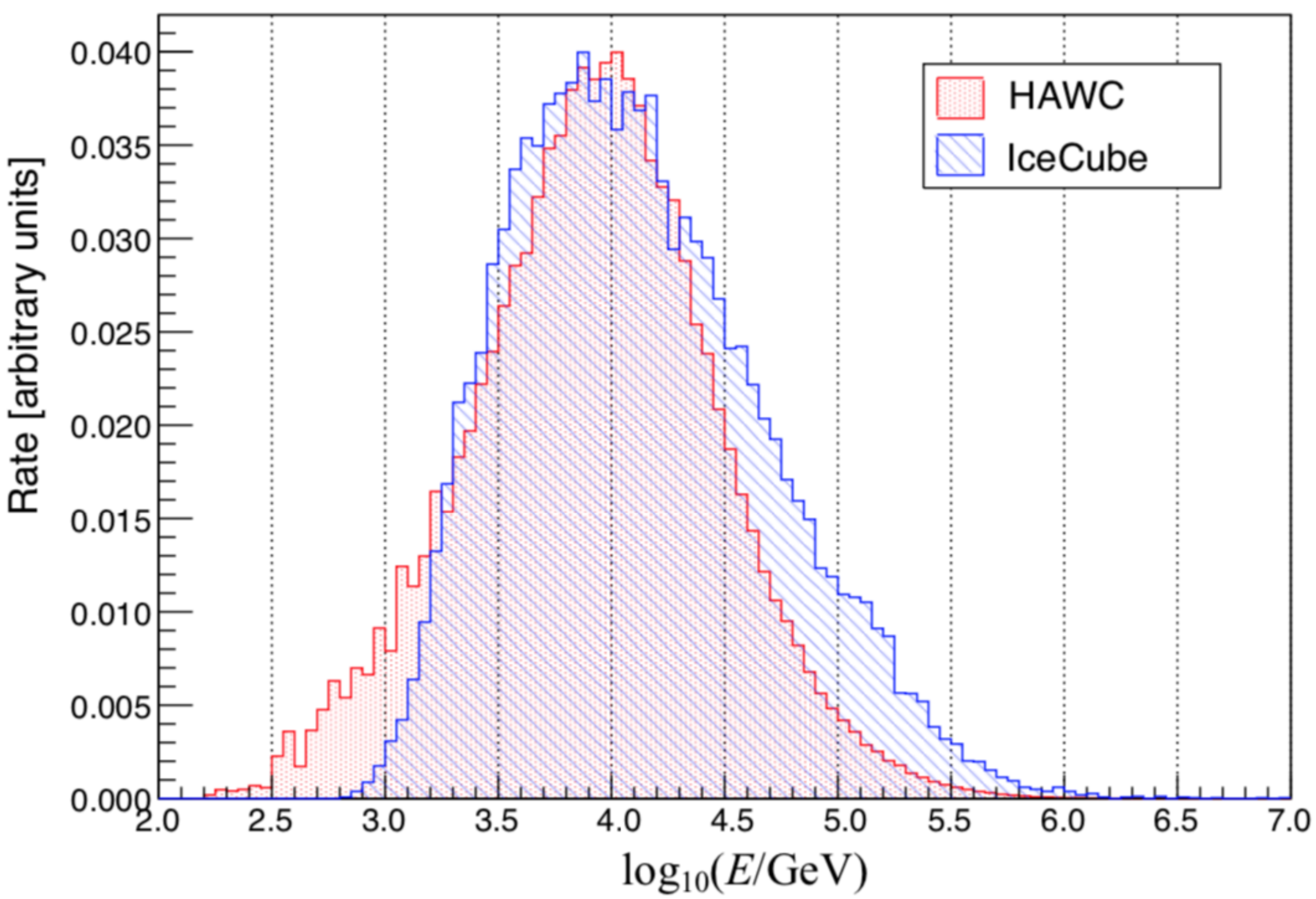
Quality Cuts: Run Selection

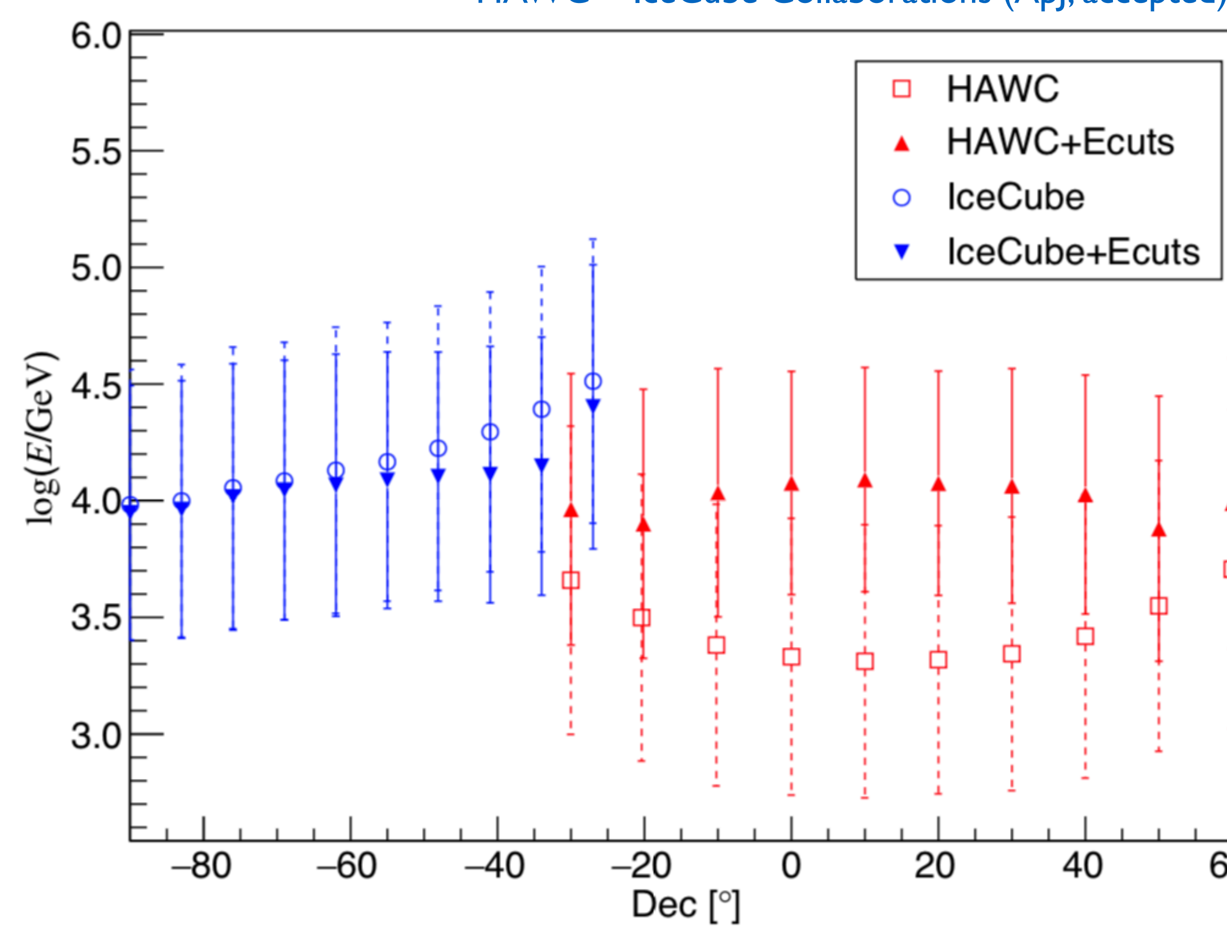


Energy Matching

- IceCube: 3-40 TeV (68%). HAWC: 2.5-30 TeV (68%).
- Composition is 95% p+He for both sets of cuts, assuming the Polygonato spectrum. Detector effects: the IceCube sample is more biased toward protons (75% of events) than HAWC (62% of events).

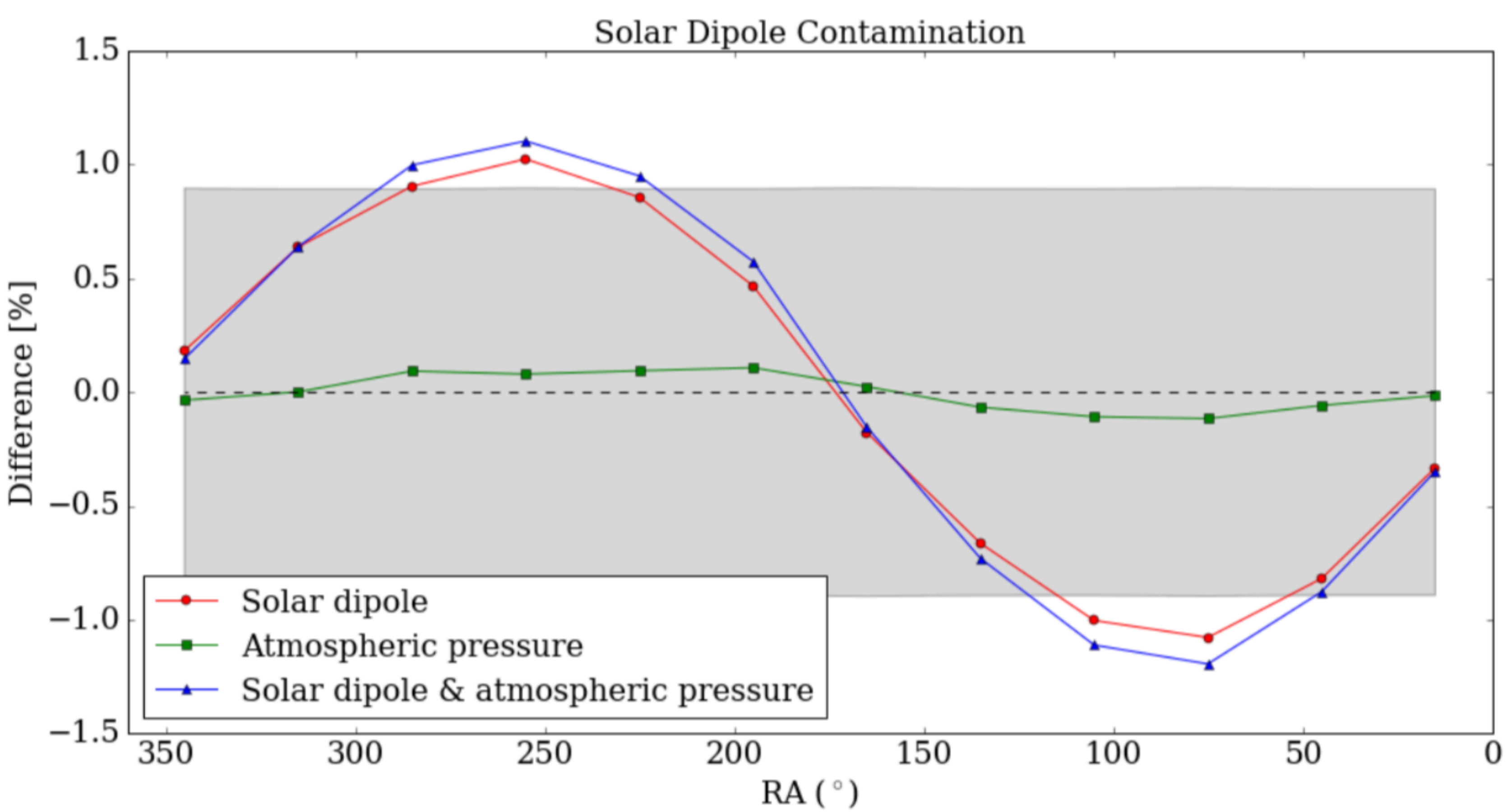
HAWC + IceCube Collaborations (ApJ, accepted).

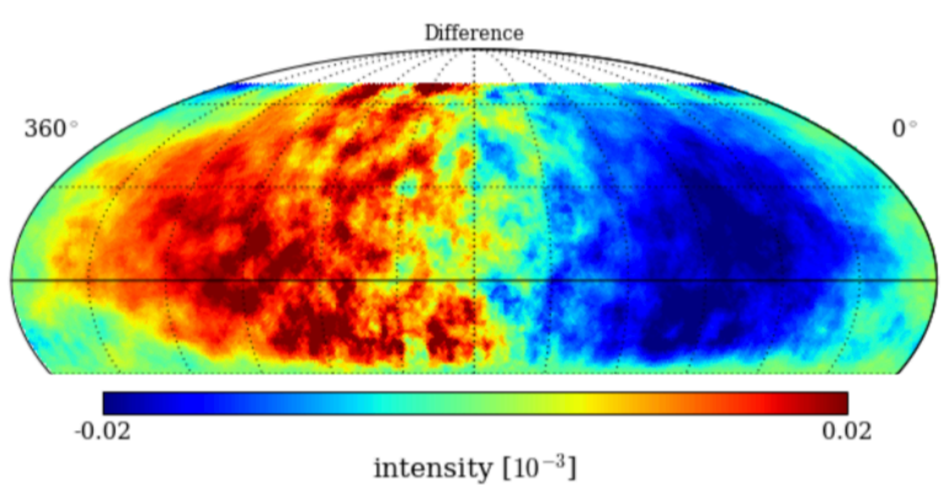




Systematics: Solar Dipole

- Dipole in cosmic-ray arrival direction due to Earth's relative motion about the Sun. Produces contaminating side-lobes in the sidereal anisotropy.
- Effect is ~10^{-5}, smaller than statistical uncertainties in the data.



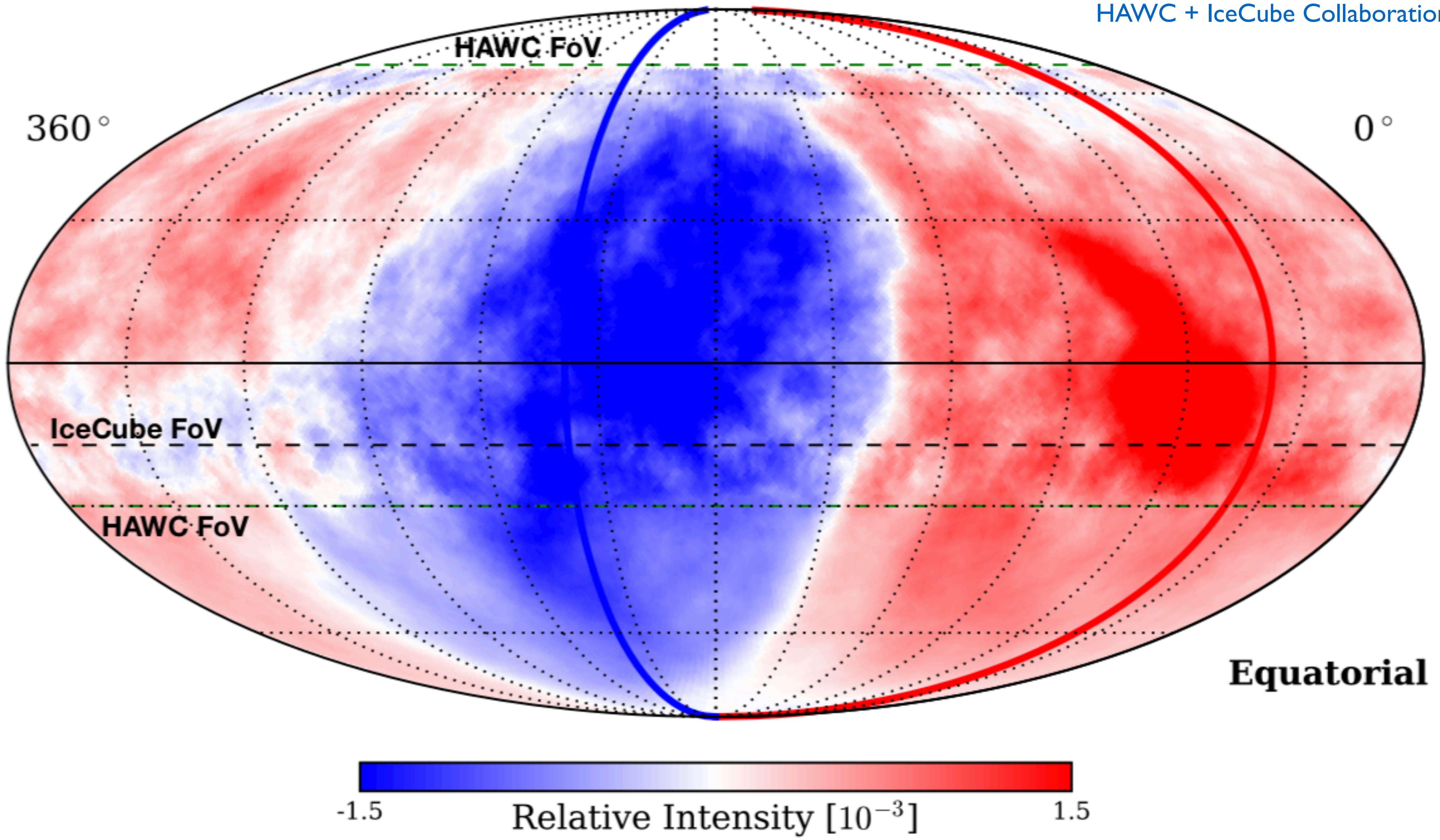


$$\delta I = (\gamma + 2)\frac{v}{c}\cos\theta_v$$

All-Sky Anisotropy

- Relative intensity and significance of the energy-matched full-sky data set (5° smoothing).

HAWC + IceCube Collaborations (ApJ, accepted).



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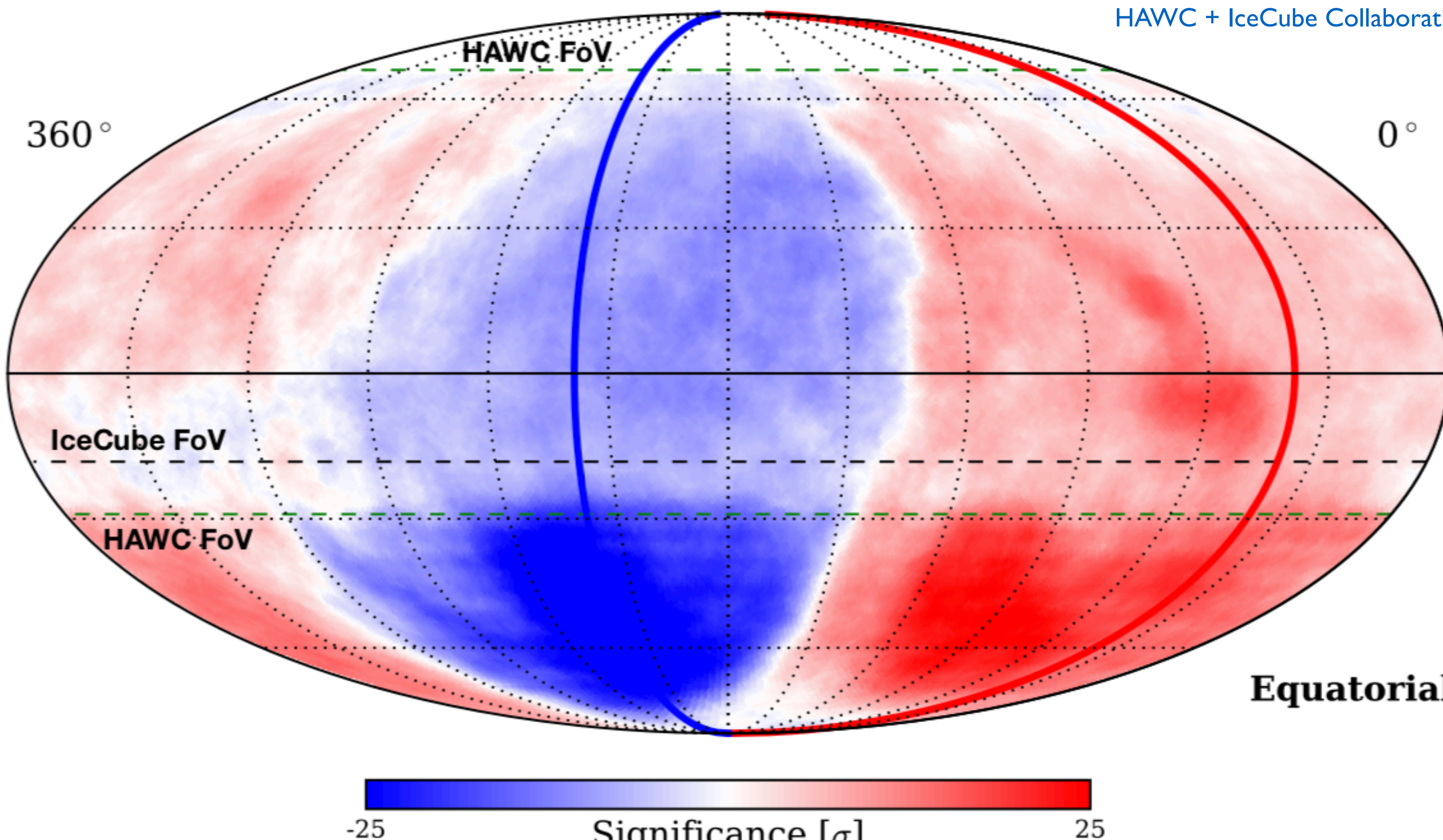

Small-Scale Structure

- Relative intensity and significance after subtraction of fits to structure with $\ell \leq 3$.

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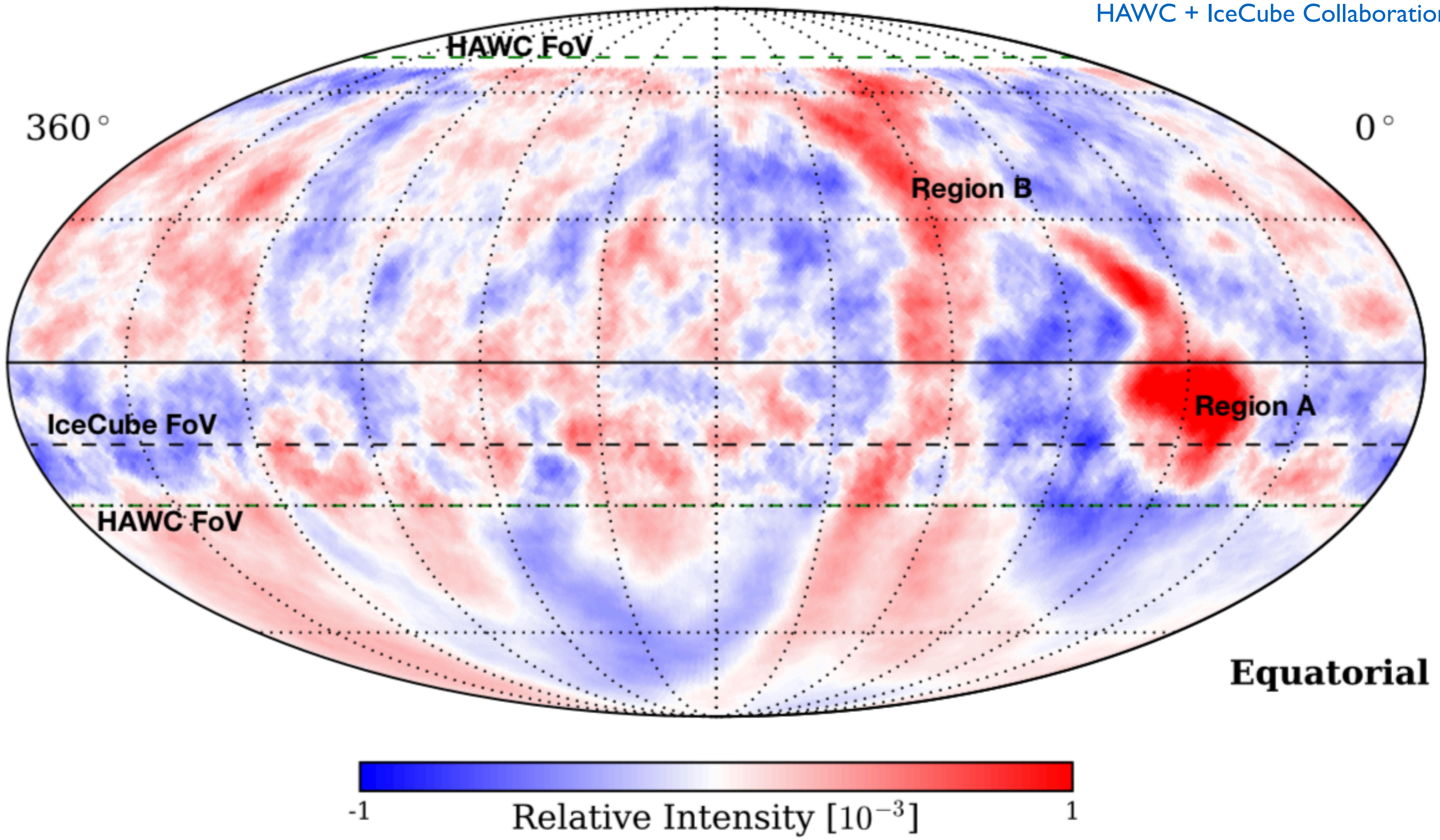

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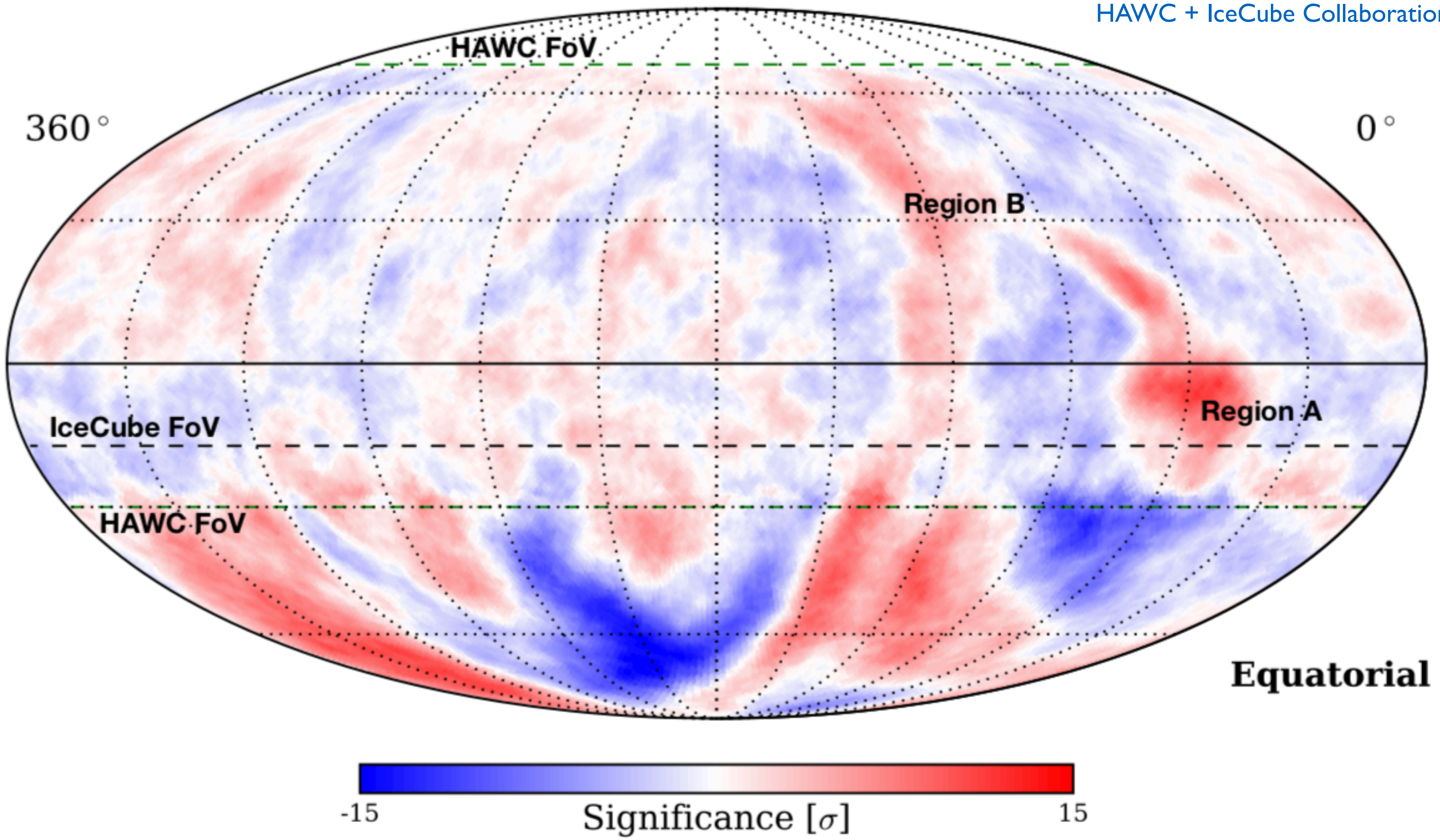
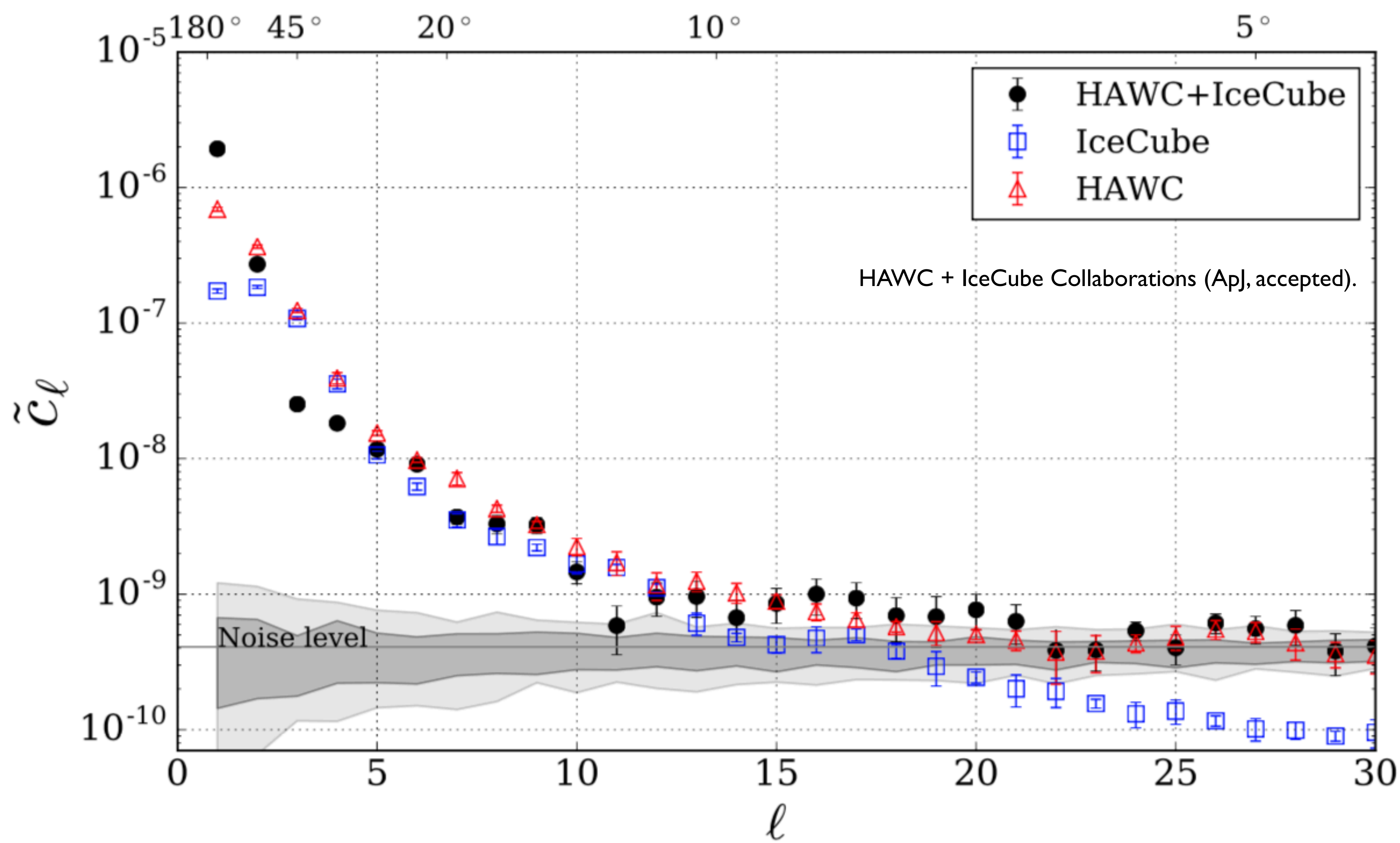


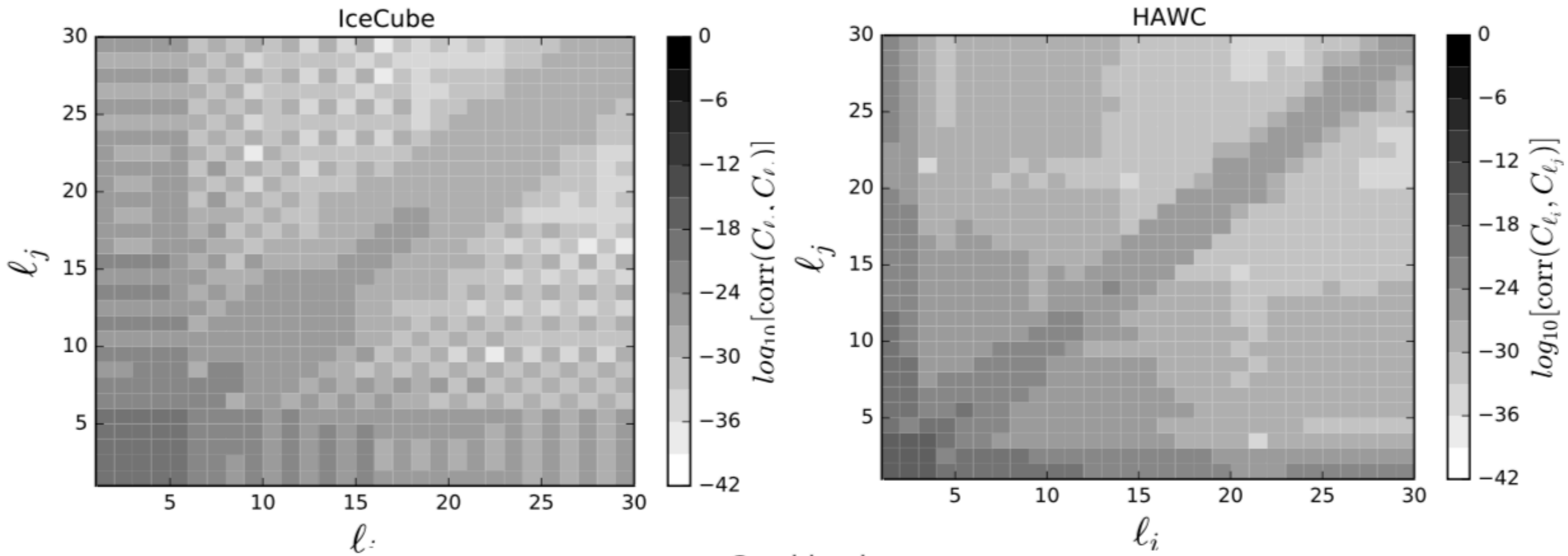
Combined Power Spectrum

- Note significant increase in power in modes $\ell \leq 3$.

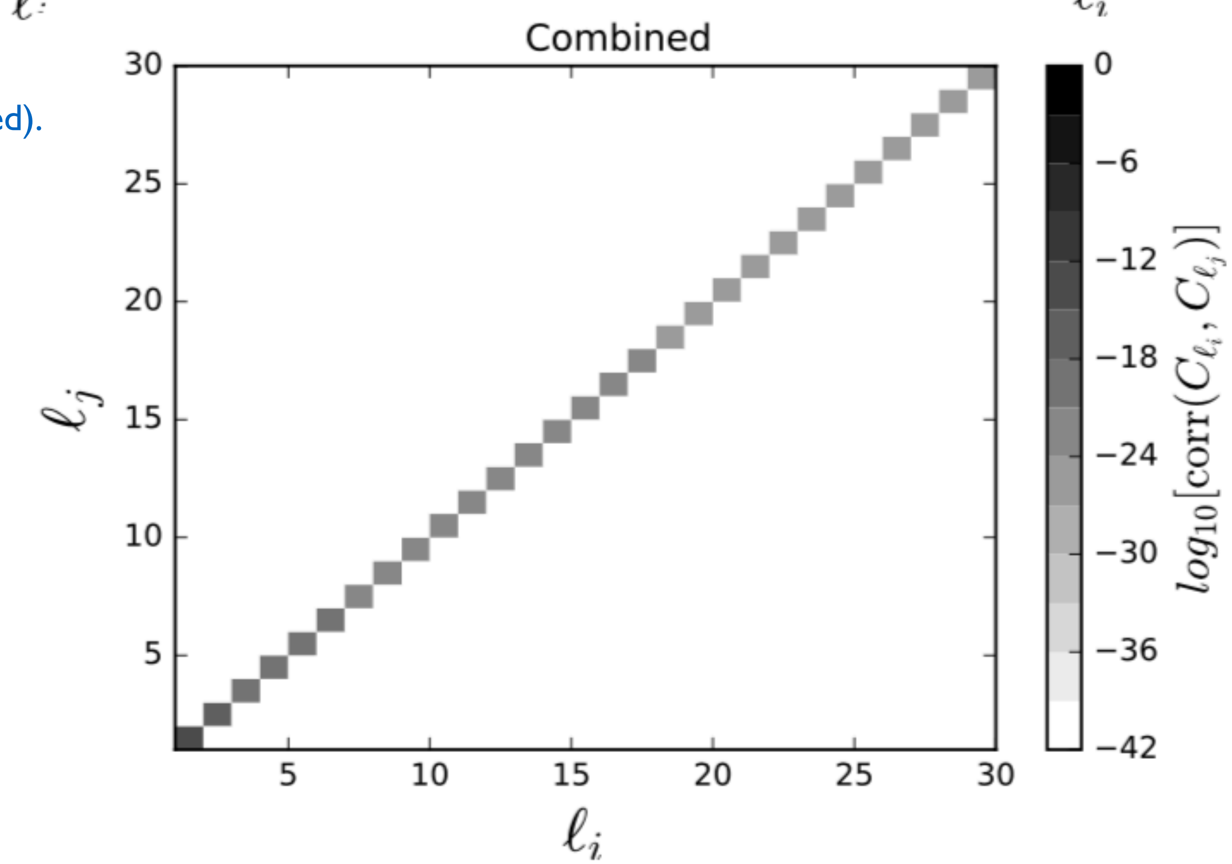


HAWC + IceCube Collaborations (ApJ, accepted).

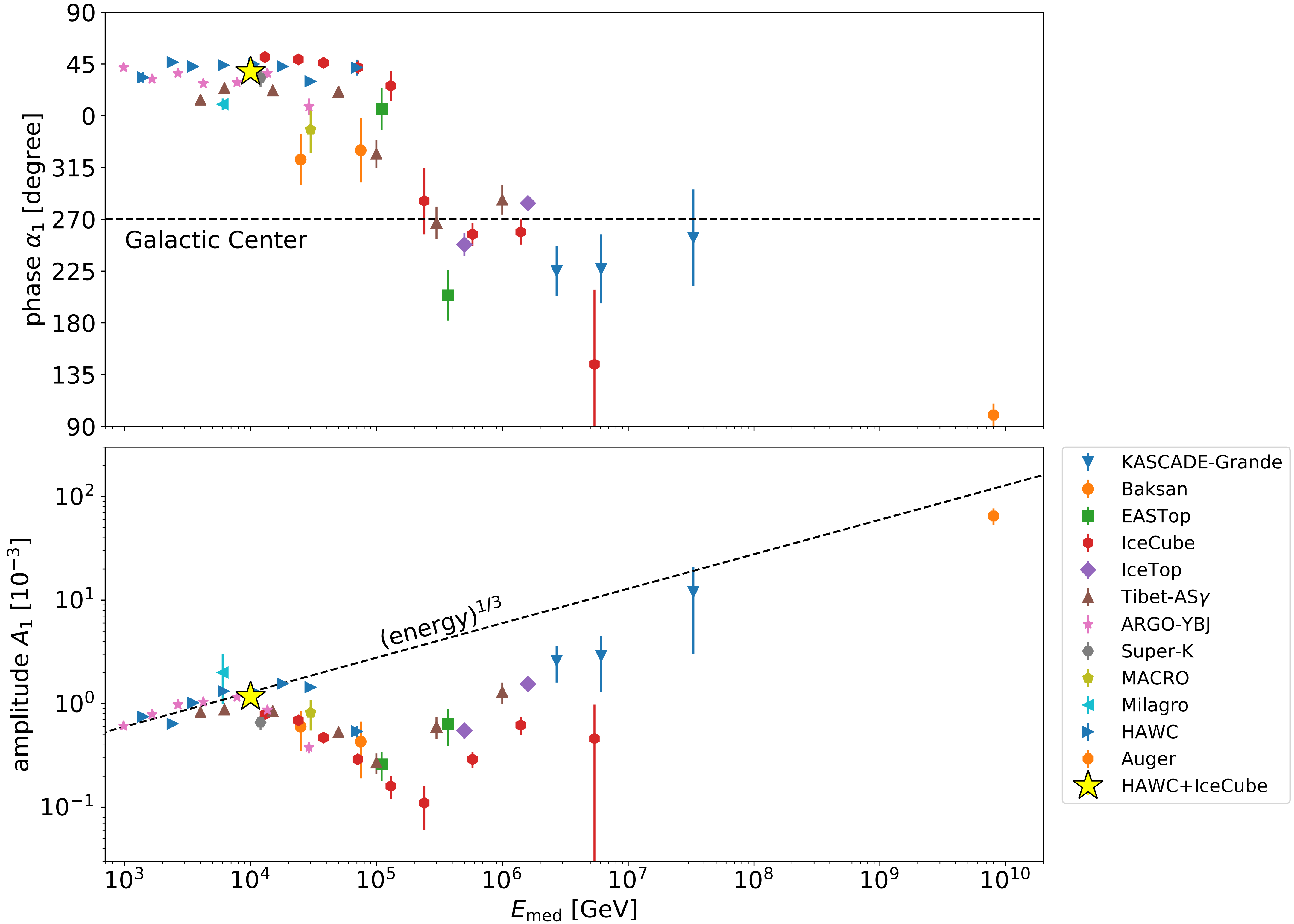
Mode-Mode Correlations



HAWC + IceCube Collaborations (ApJ, accepted).

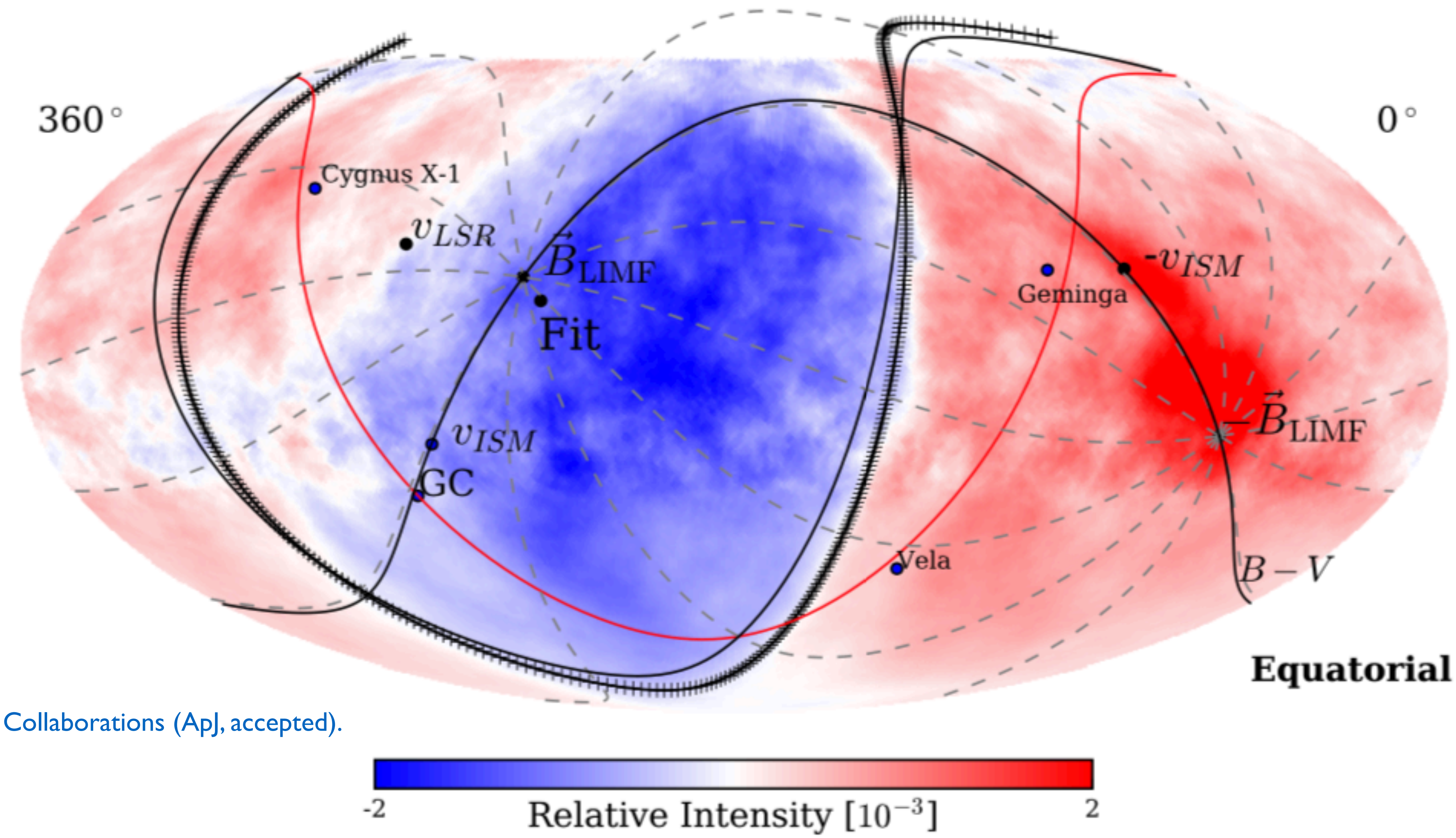


All-Sky Dipole Fit



Potential Origin

- Could features be a combination of diffusion and heliospheric effects?
- 10 TV cosmic ray has a Larmor radius of 700 AU (assume 3 μG field).



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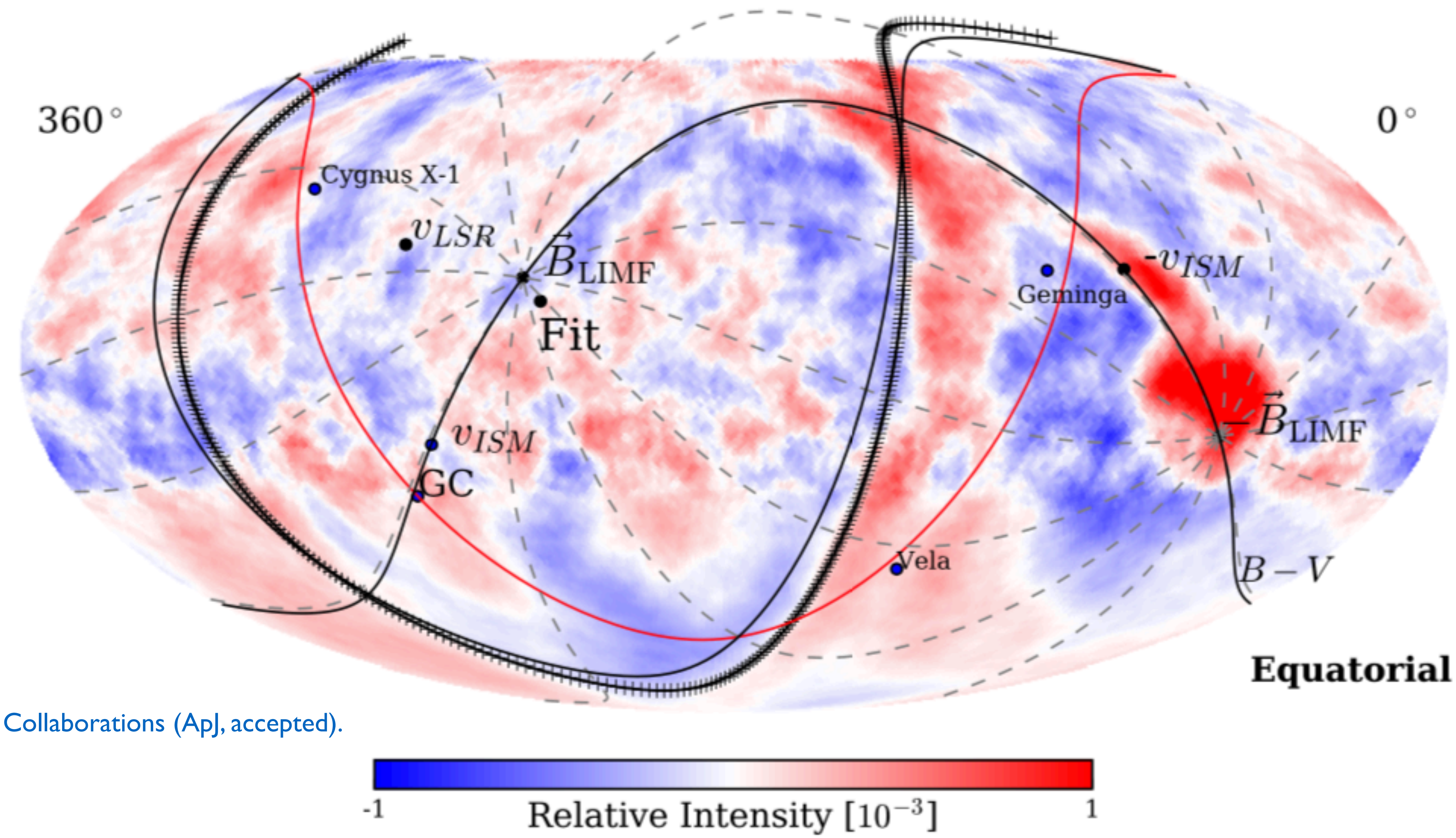
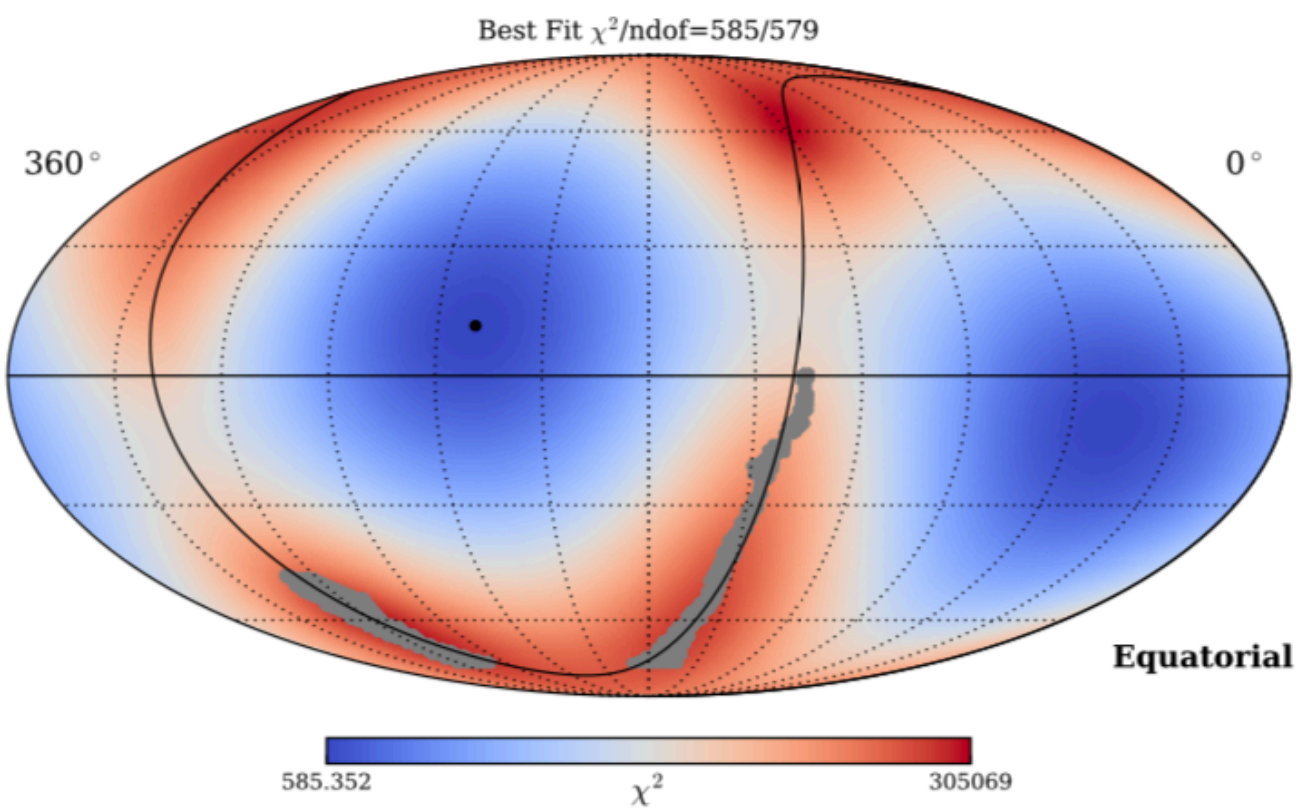


HAWC + IceCube Collaborations (ApJ, accepted).

Constraints on LIMF

- Dipole alignment: similar to B_{LIMF} direction from IBEX measurements of energetic neutral atoms and polarization measurements of stars with 40 pc of Earth.
- Could be reasonable. Expect diffusion to be anisotropic with fastest propagation along the magnetic field lines.



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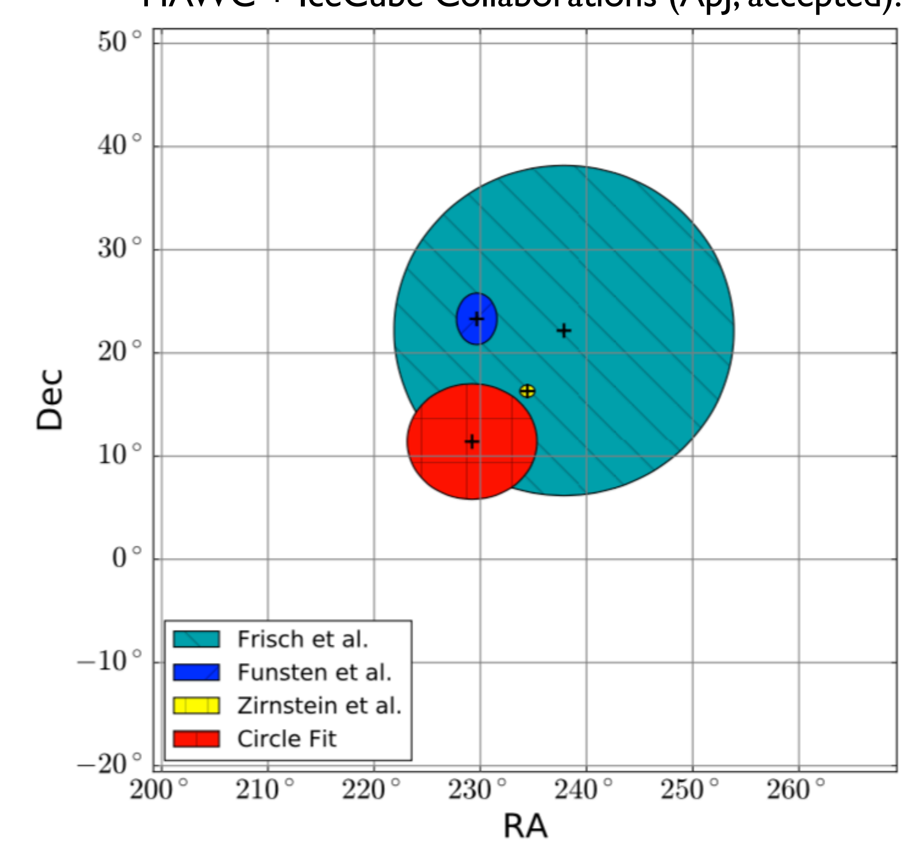


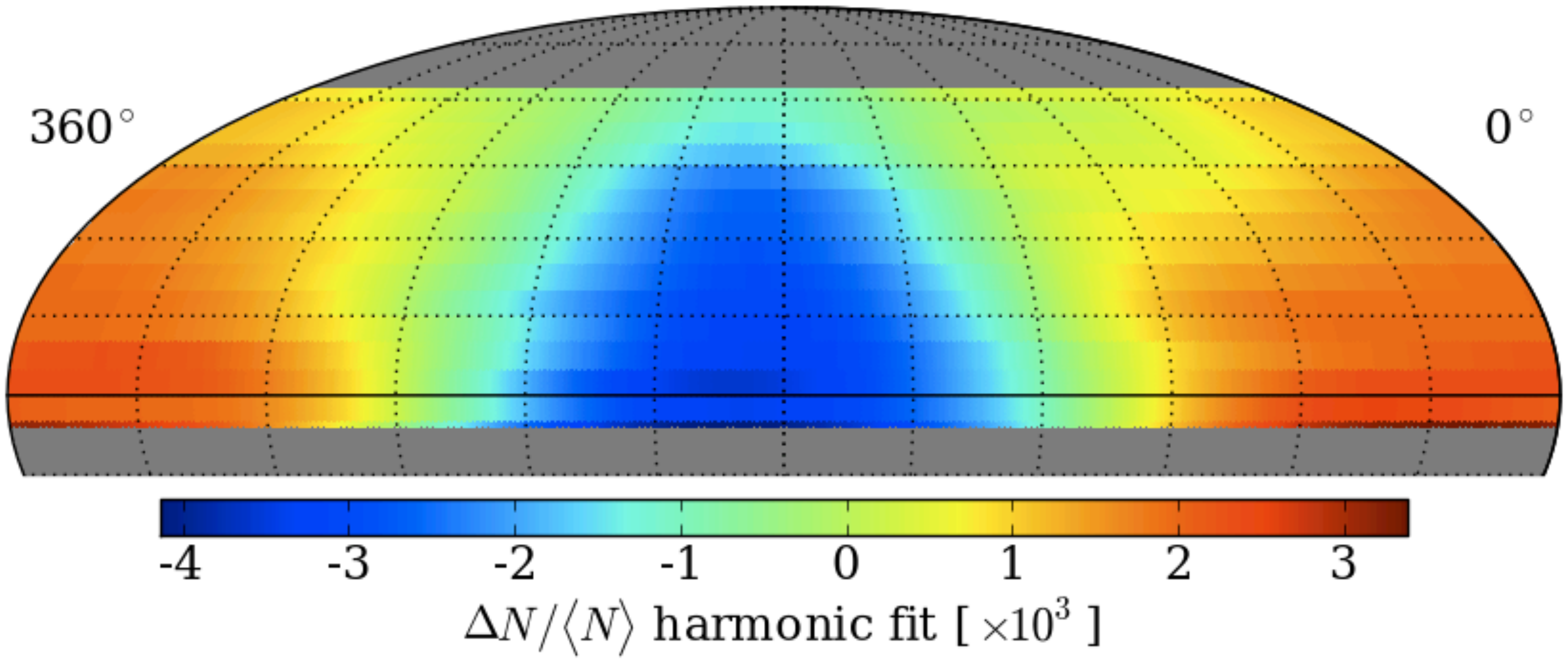
Conclusions

- HAWC and IceCube have a combined cosmic-ray data set that will soon approach 10^{12} events.
- Construction of an energy-matched data sample for the first time.
  - 10 TeV data set covering almost the entire sky, 95% light cosmic rays in both HAWC and IceCube subsets.
  - First all-sky fit to cosmic ray dipole at this energy. Significant reduction of partial-coverage bias in dipole fit.
  - Strong hints of correspondence between large-scale structure and the local interstellar magnetic field.
- Future work: extend analysis to different energy ranges. New high-energy reach possible with HAWC outrigger extension. Excellent science for LHAASO and future observatories.

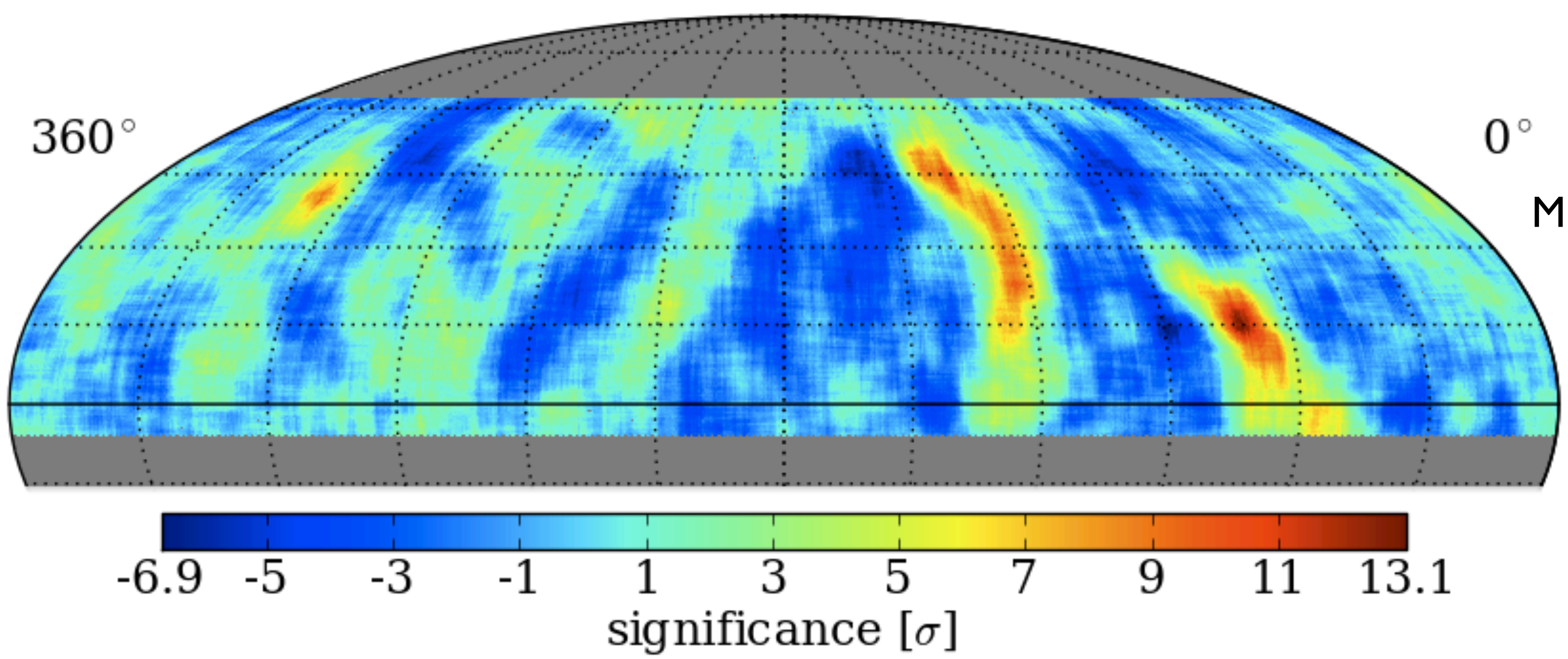
Outline of Current Results

- Relative intensity ranges from 10^{-3} on large angular scales to 10^{-5} on small scales.
- The large-scale anisotropy is not described by a simple dipole, though the dipole component is often shown when comparing across experiments.
- The anisotropy is energy dependent
  - Shift in phase of LS structure >100 TeV.
  - Small-scale excesses seem to have hard spectrum w.r.t. isotropic background. Cut off >10 TeV.
- At the few percent level, the anisotropy is time-independent going back almost 20 years.

Anisotropy: Milagro



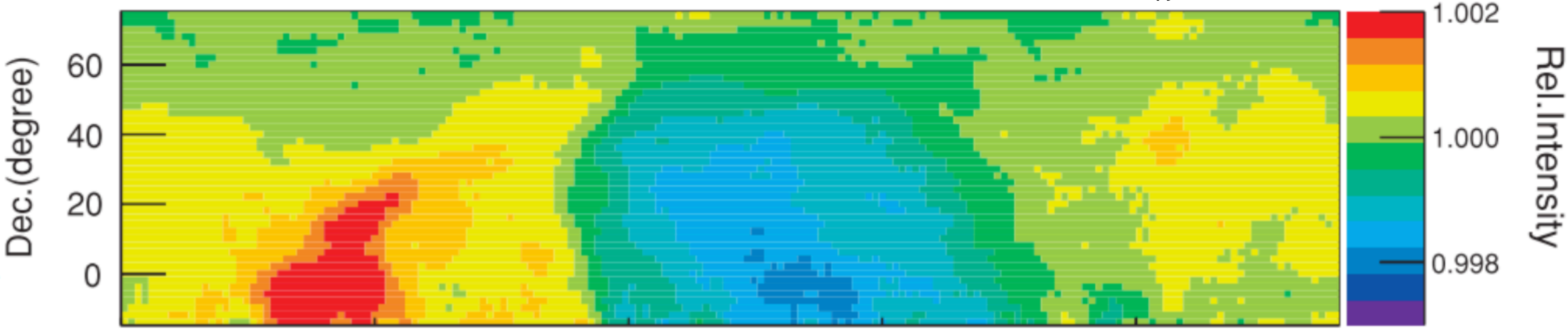
Milagro Collaboration, ApJ **698**:2121, 2009

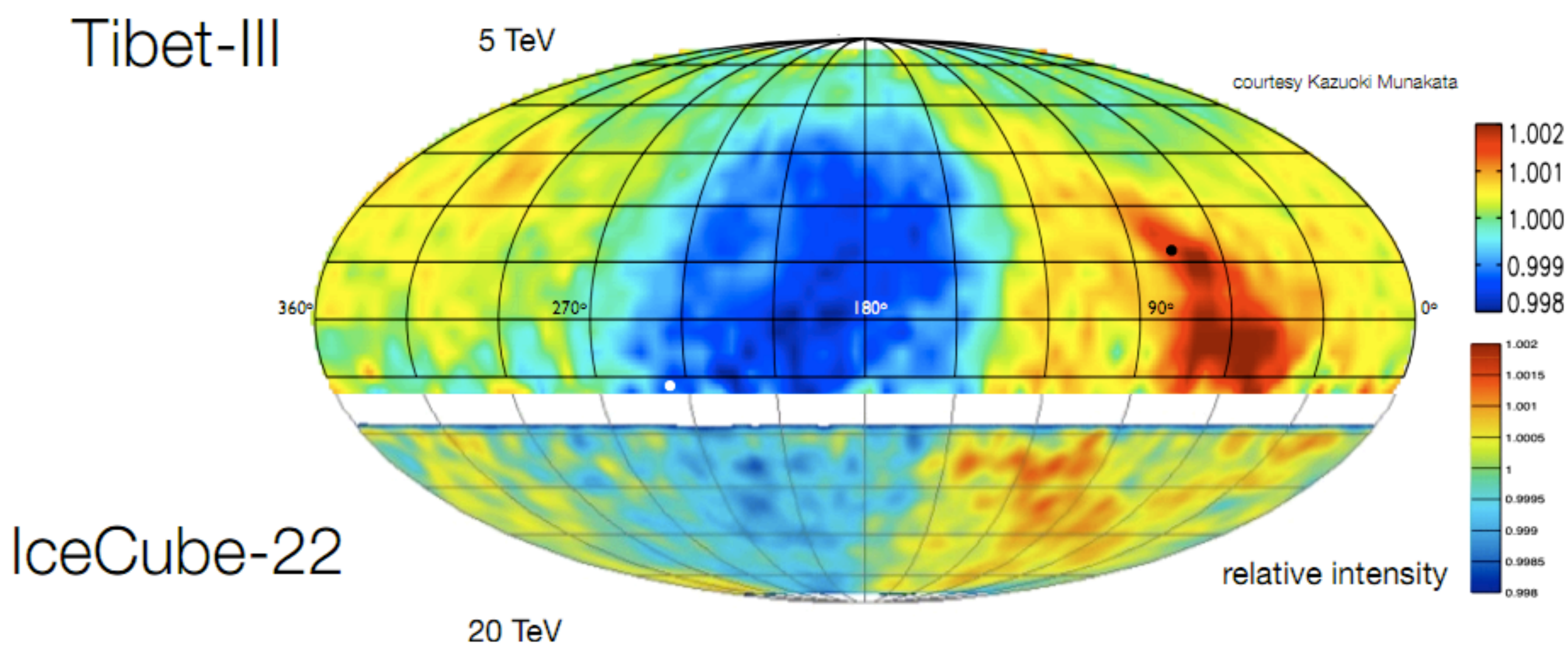


Milagro Collaboration, PRL **101**:221101, 2008

Anisotropy: Tibet

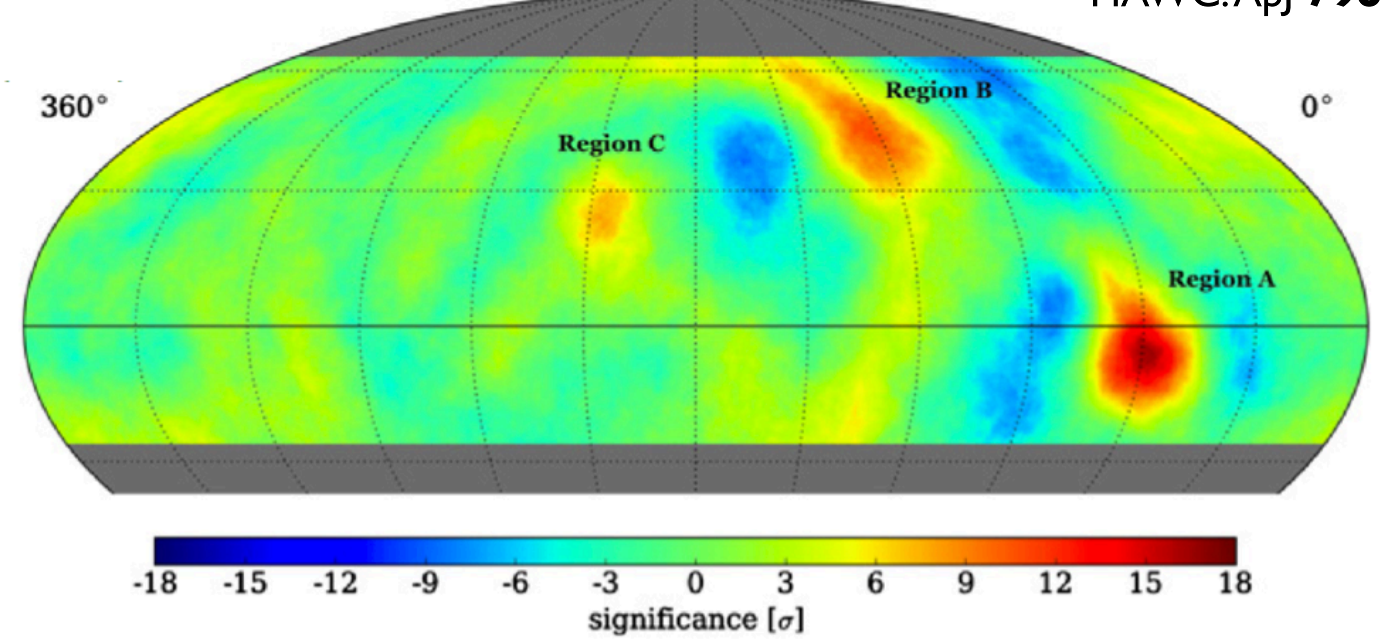
M. Amenomori et al., ApJ **711**:119, 2010



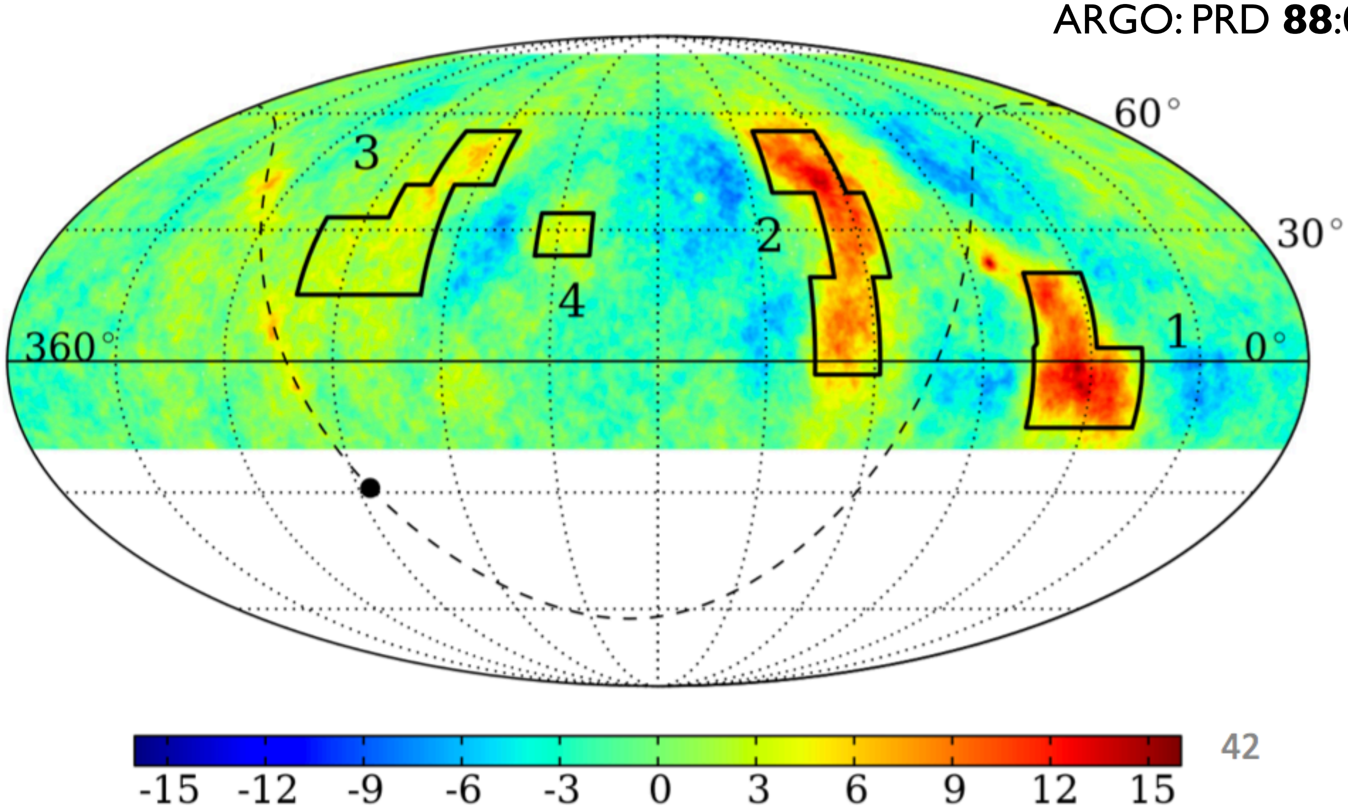


Small-Scale Structure

HAWC: ApJ **796**:108, 2014

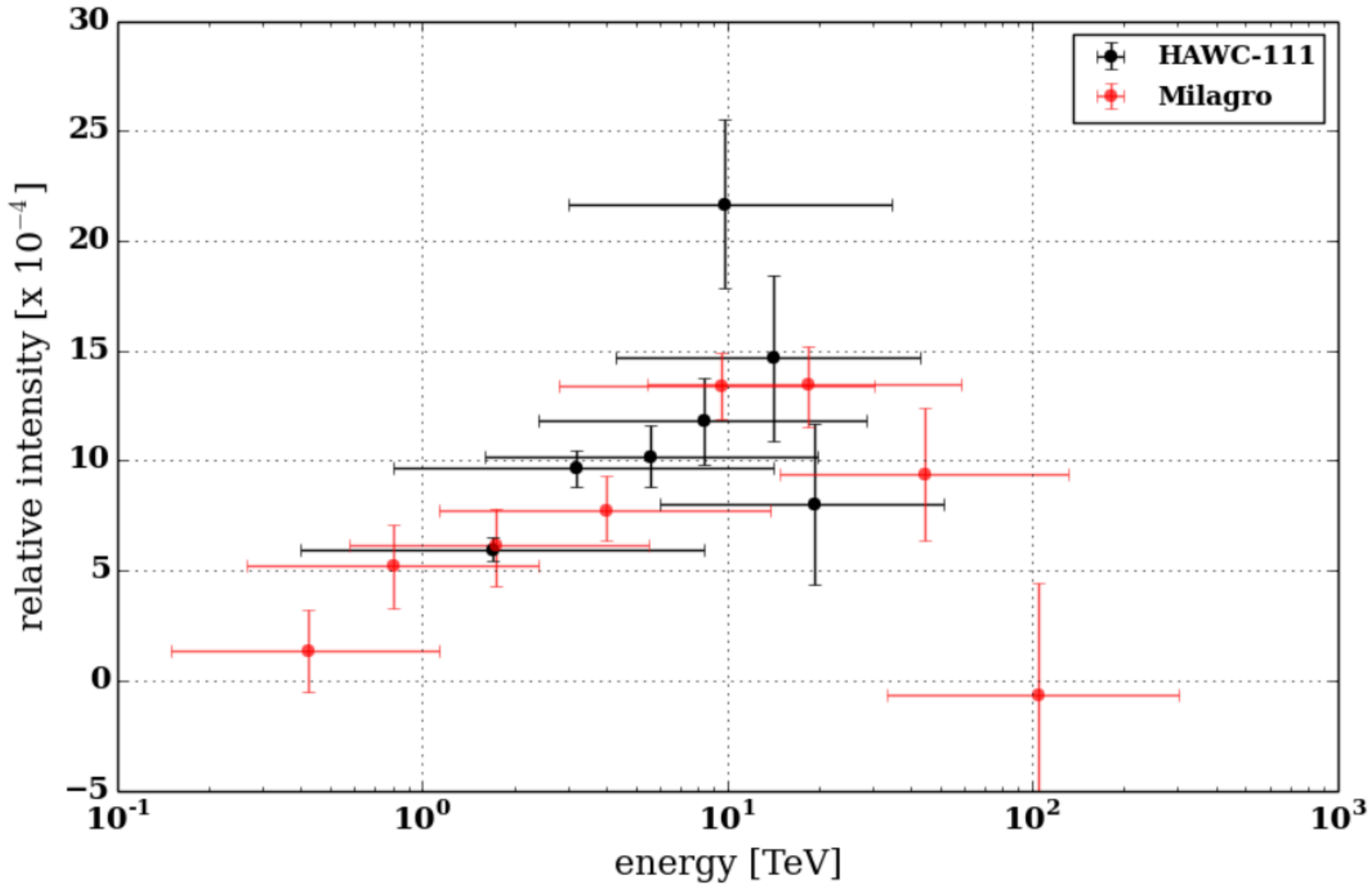


ARGO: PRD **88**:082001, 2013



- Close correspondence between several regions in the data from HAWC and ARGO-YBJ
- Region A/1: hard CR spectrum with a cutoff around 10 TeV

Region A



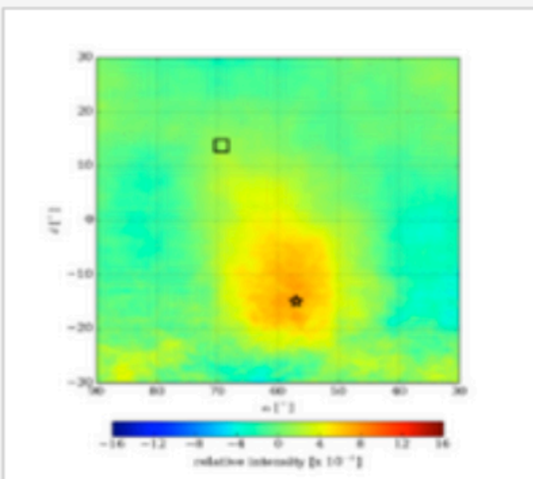
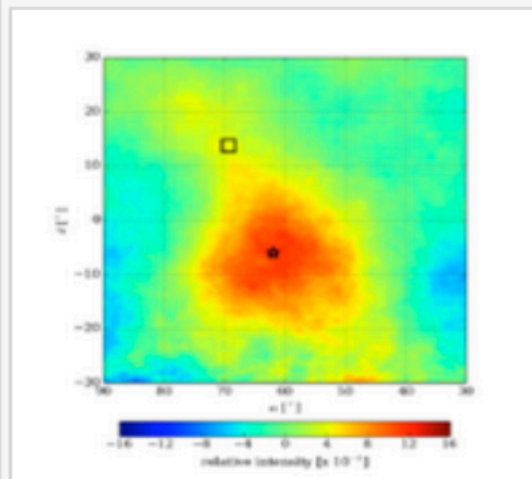
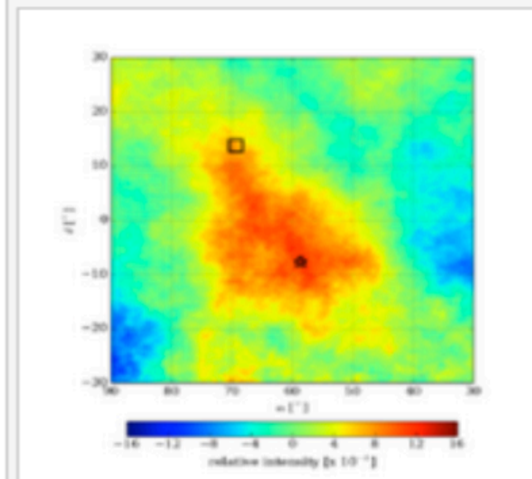
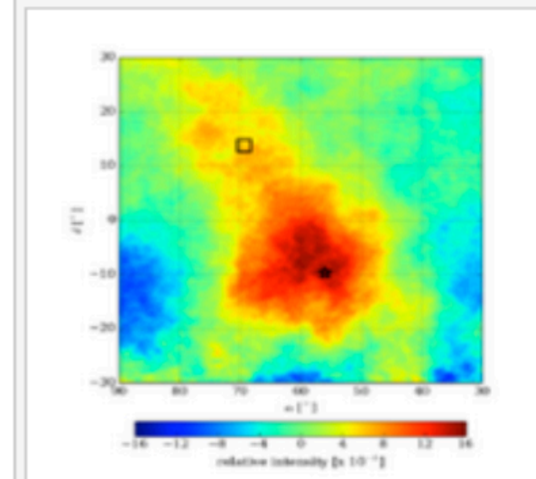
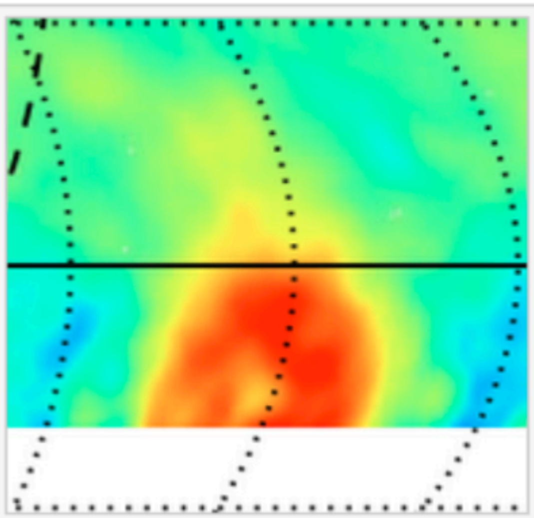
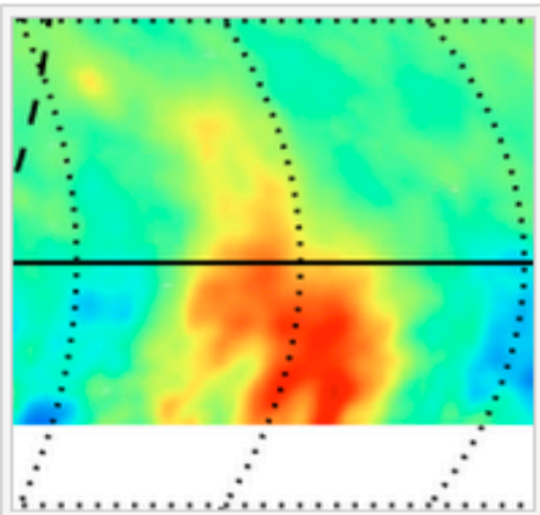
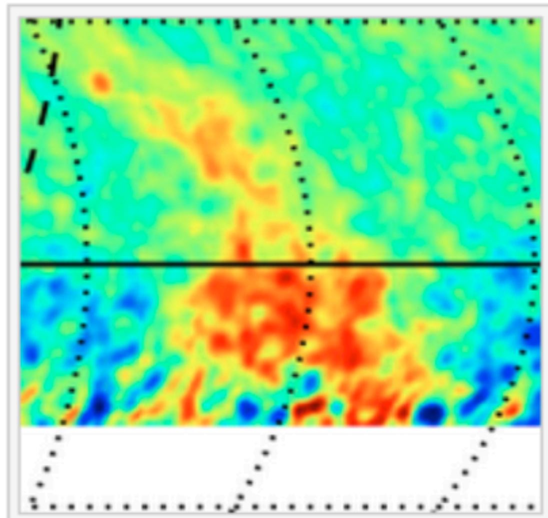
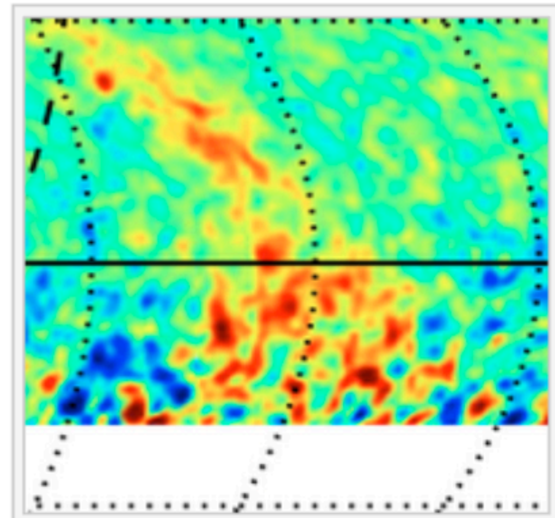
Milagro:
PRL **101**:221101, 2008

HAWC-111:
ApJ **796**:108, 2014

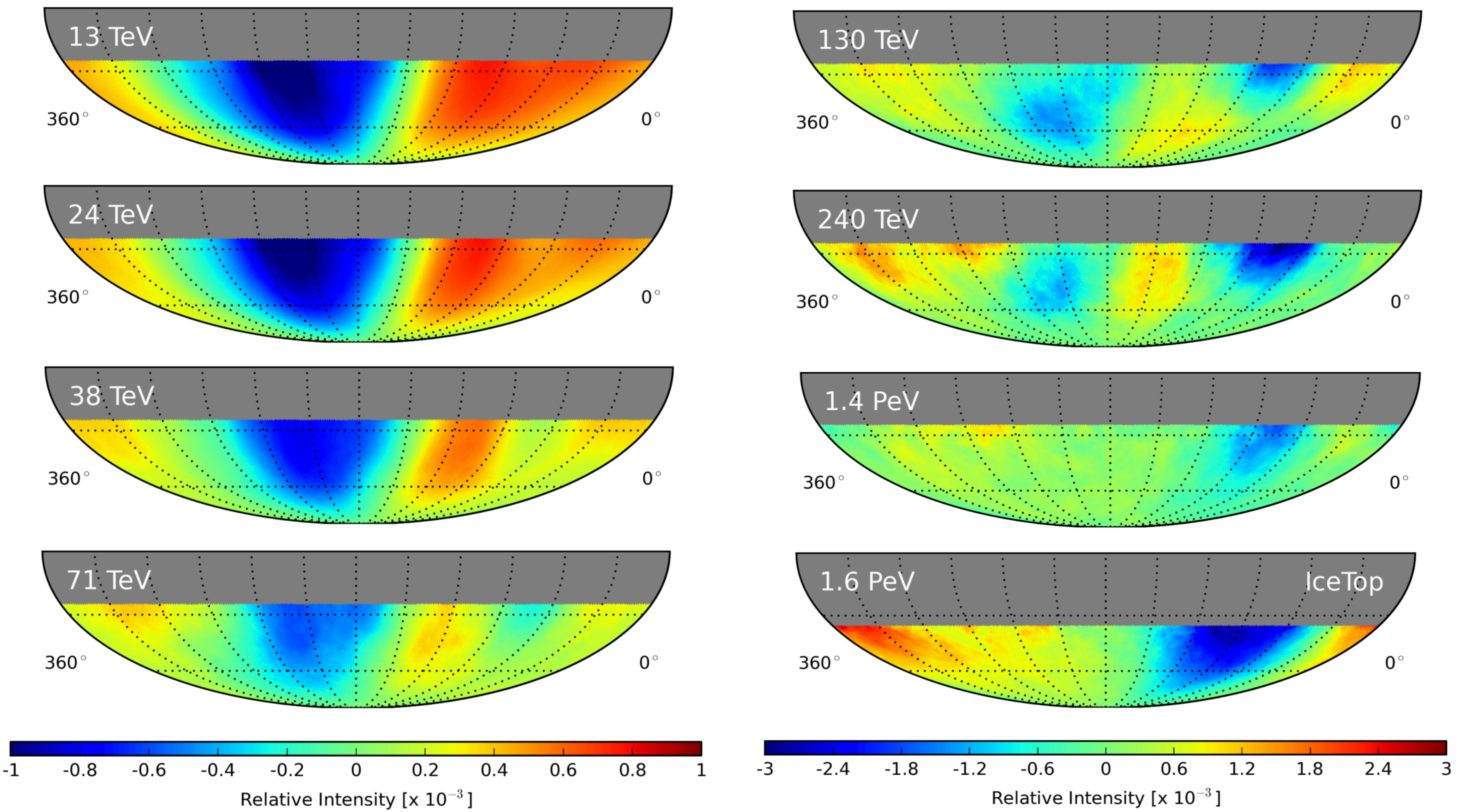
- Pseudo-spectrum of region A using energy proxy bins
- Milagro and HAWC observe a hard spectrum w.r.t. isotropic flux; 4σ effect after trials

Region A: HAWC + ARGO

D. Fiorino, TeVPA 2016

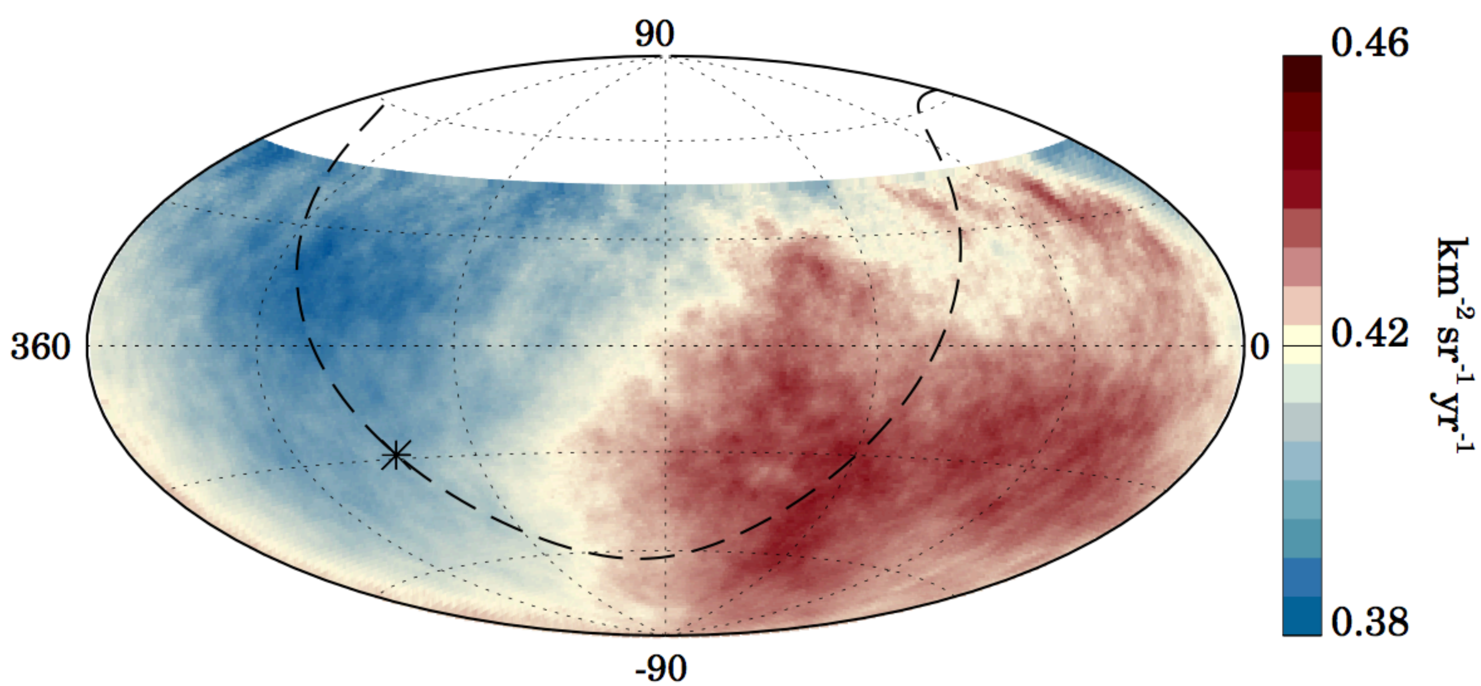
	0	1	2	3
HAWC	 Bin0: 1.7 (+6.6/-1.3) TeV Milagro Hotspot (square) HAWC Hotspot (star)	 Bin1: 3.2 (+10.9/-2.4) TeV Milagro Hotspot (square) HAWC Hotspot (star)	 Bin2: 5.6 (+14.2/-3.9) TeV Milagro Hotspot (square) HAWC Hotspot (star)	 Bins3-6: 14.1 (+28.7/-9.9) TeV Milagro Hotspot (square) HAWC Hotspot (star)
ARGO	 Bin0: 25-39 hits ≈ 0.66 TeV	 Bin1: 40-99 hits ≈ 1.4 TeV	 Bin2: 100-249 hits ≈ 3.5 TeV	 Bin3: 250-629 hits ≈ 7.3 TeV

Energy Dependence: IceCube

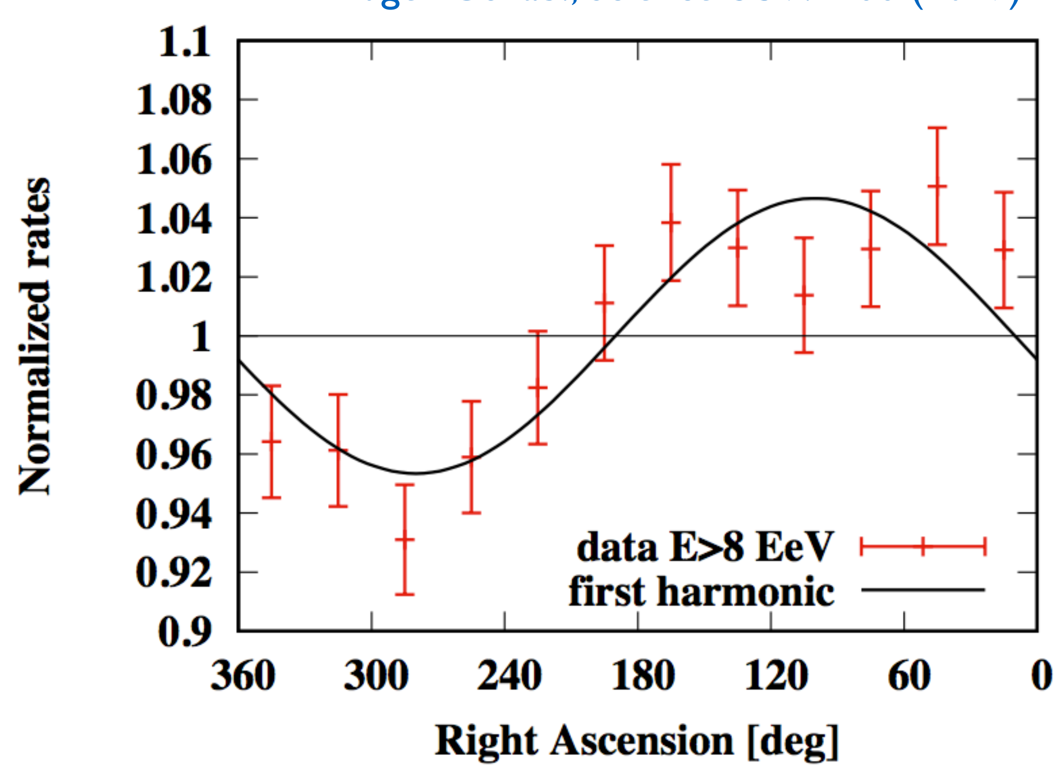


Large Scale Anisotropy: Auger

- Observation of anisotropy at >5σ level above 8 EeV by Auger.
- At this energy the Larmor radius of a proton is large enough that Galactic sources should stand out.
- No obvious Galactic correlation observed.



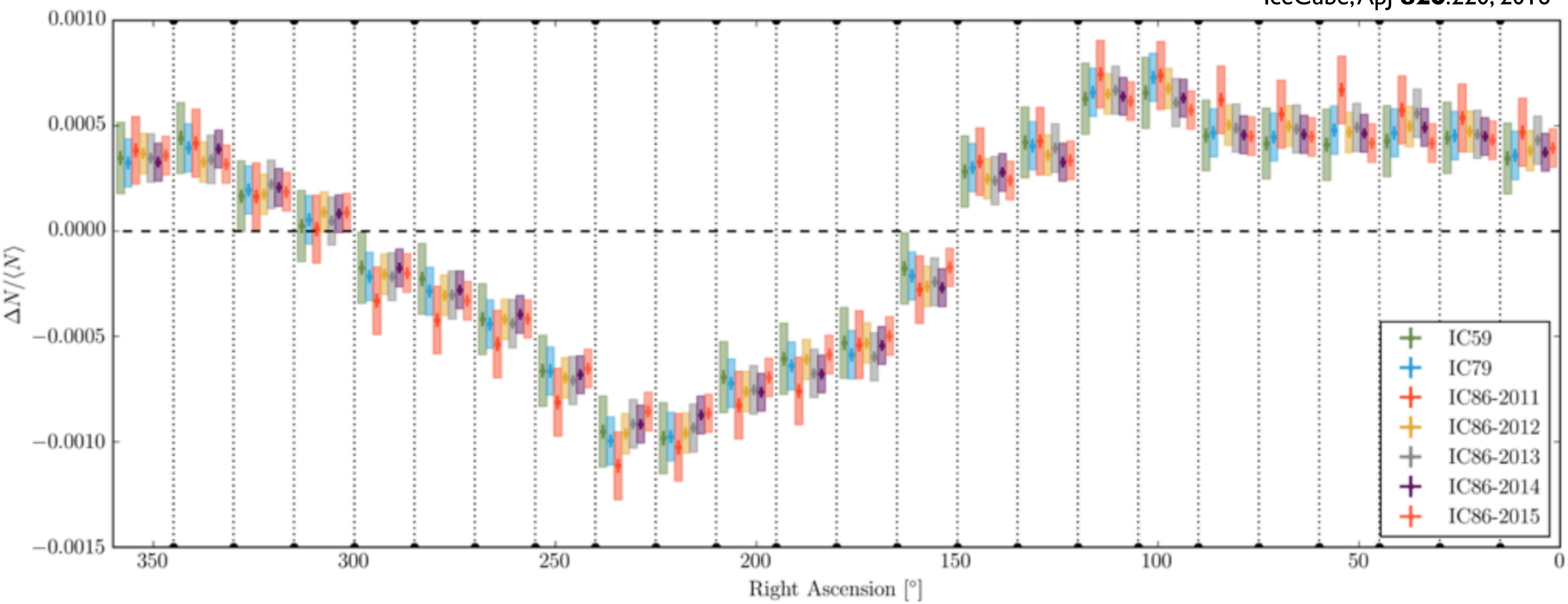
Auger Collab., Science **357**:1266 (2017)



Time Dependence

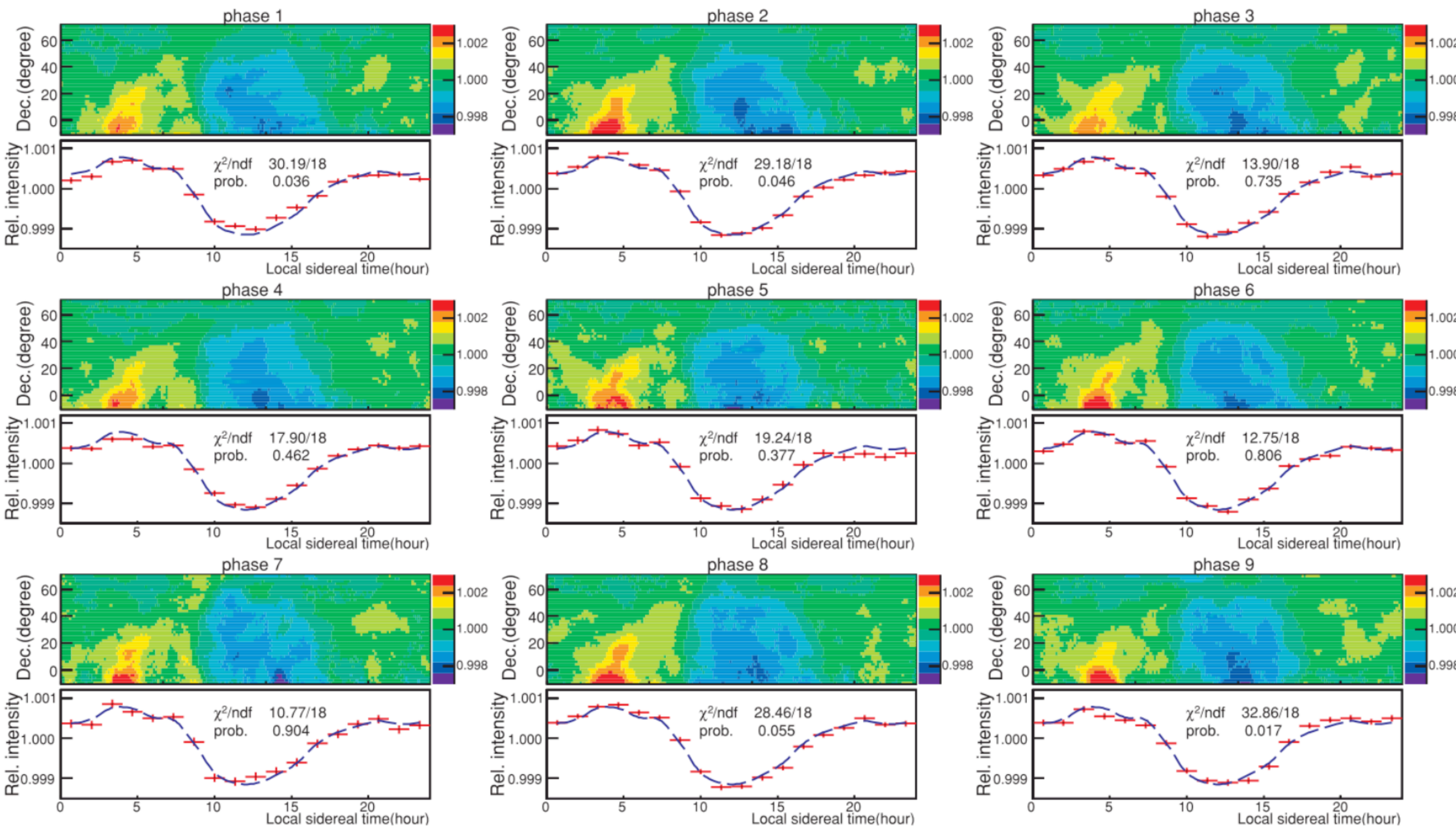
- Solar cycle 23 (Jun 1996 - Jan 2008) covered by AMANDA. No time dependence observed (arXiv:1309.7006)
- Solar cycle 24 (Jan 2008, max Apr 2014) covered by IceCube. No time dependence observed

IceCube, ApJ **826**:220, 2016



Time Dependence

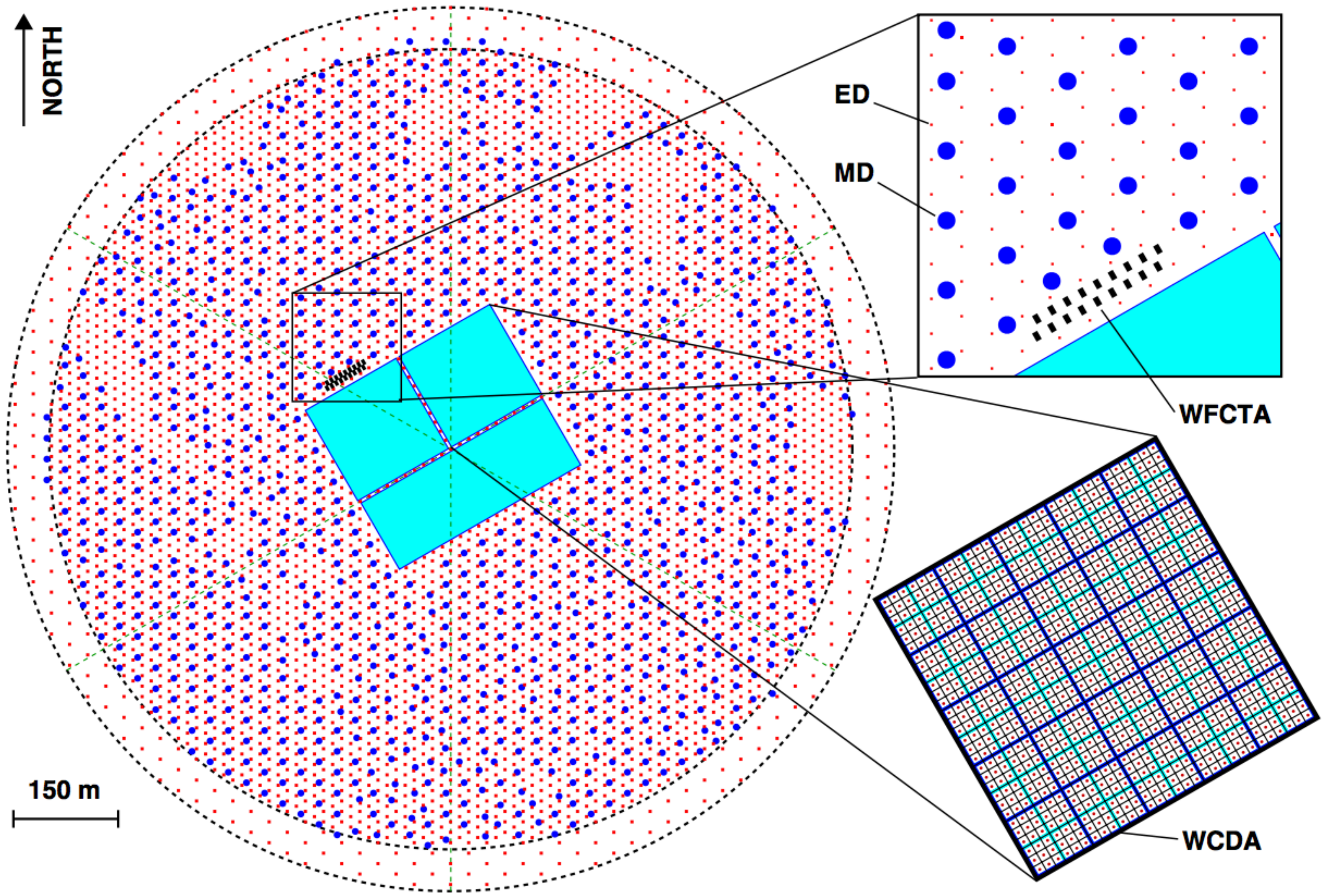
- Cycle 23 also covered by Tibet-ASγ (Nov. 1999 - Dec. 2008). No time dependence observed



Future Detectors

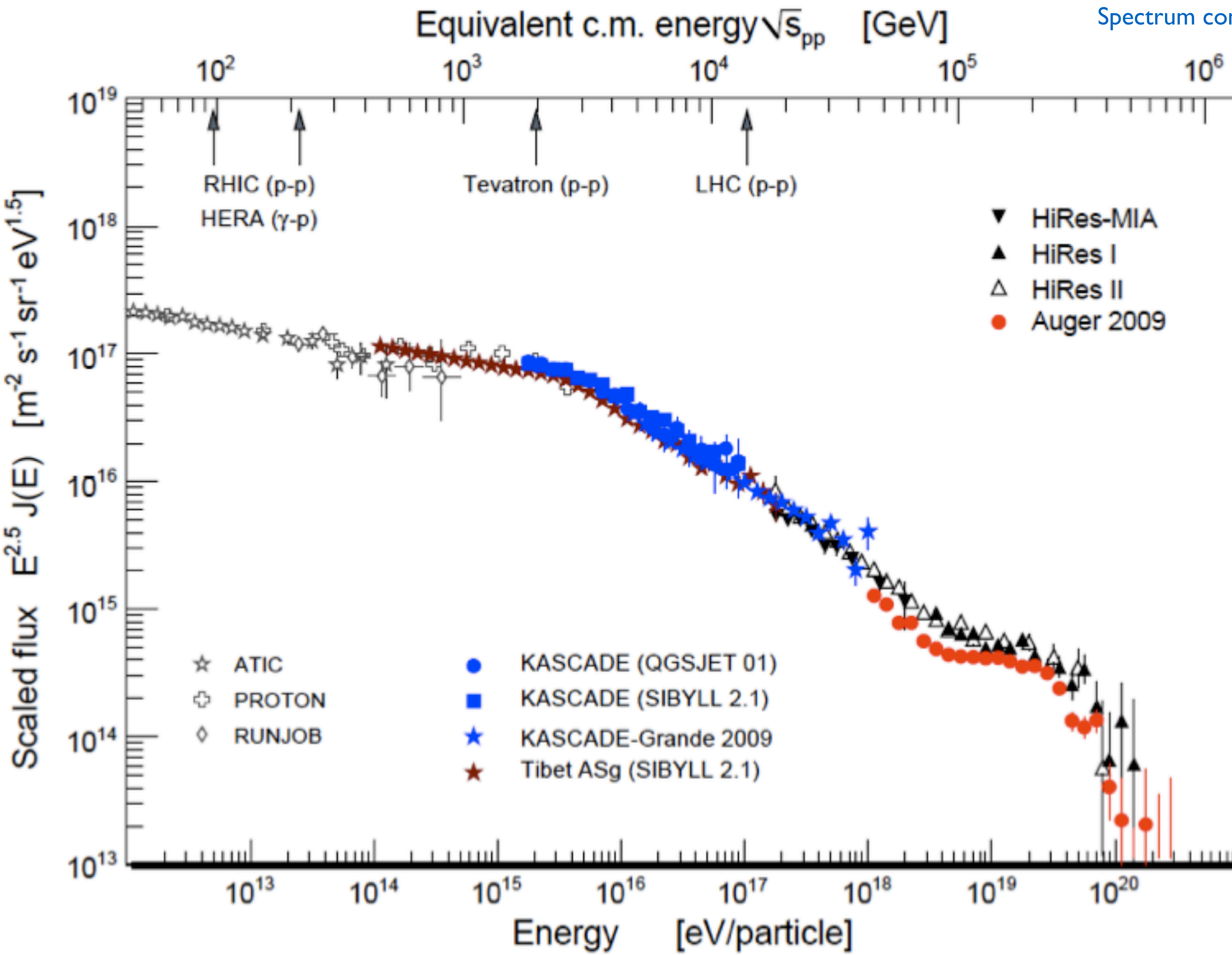
- LHAASO: nested set of detectors to cover 1 TeV to 0.1 EeV in range, close to IceCube+IceTop range

From G. Di Sciascio, ISVHECRI 2016



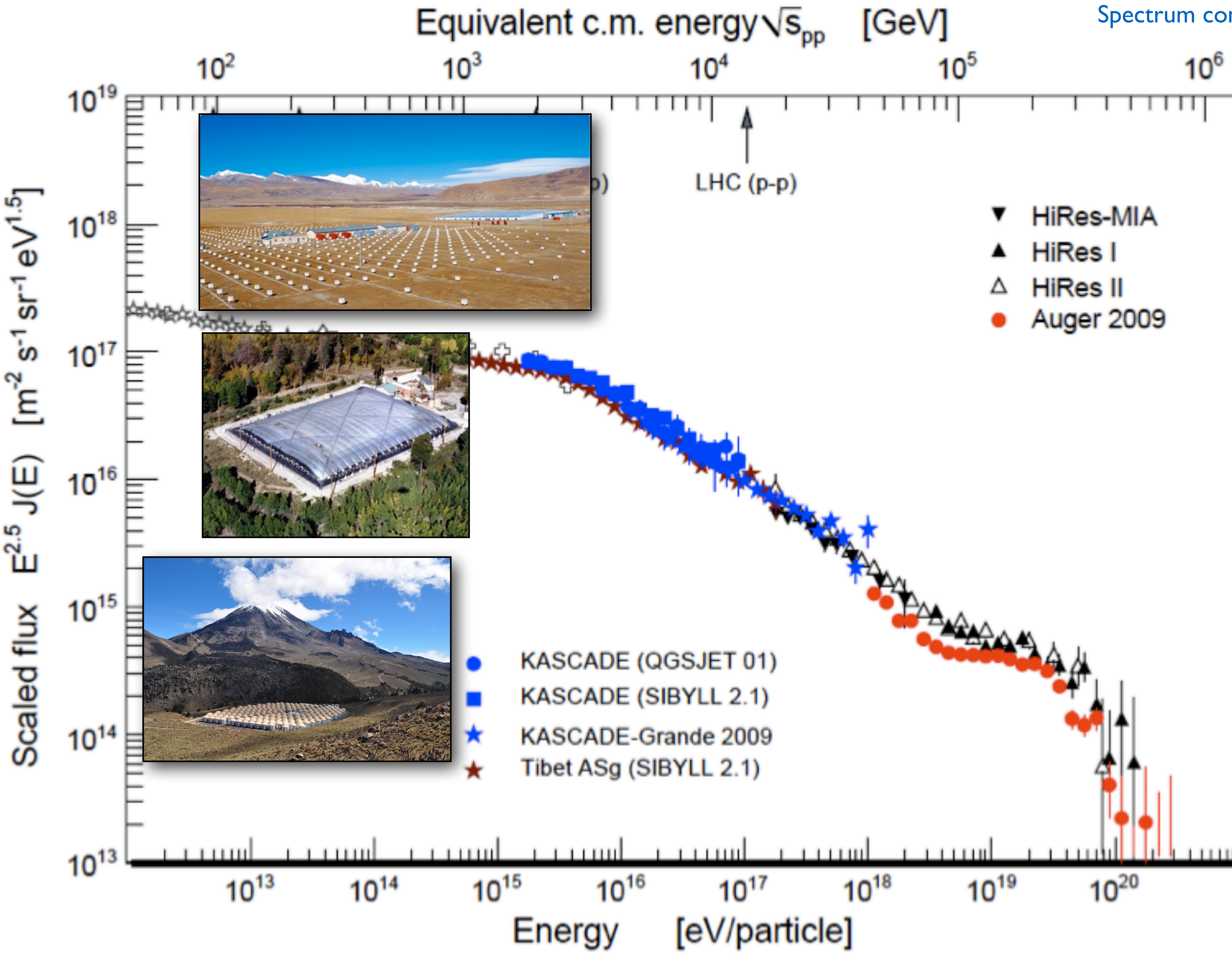
Energy Coverage

Spectrum compilation: R. Ulrich



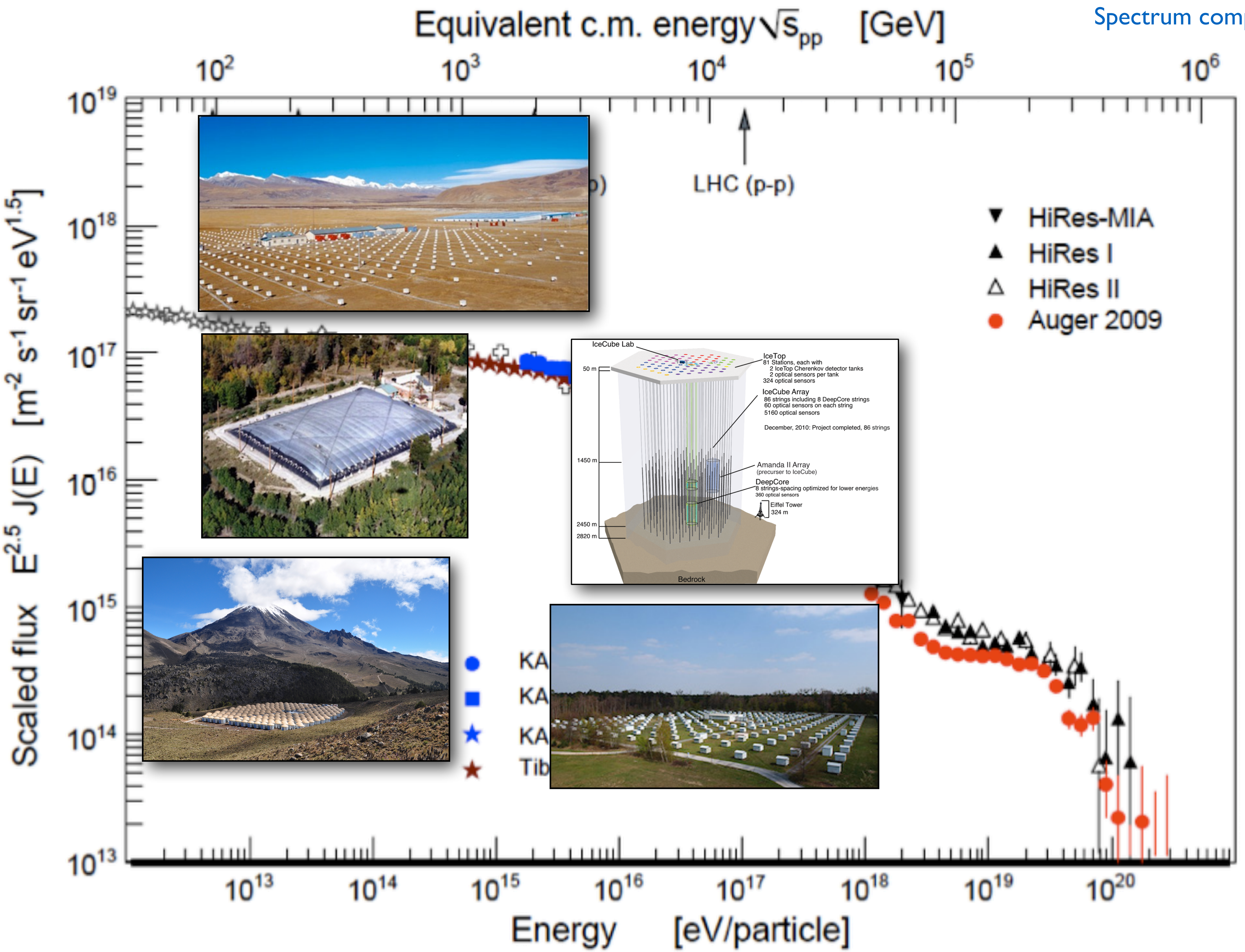
Energy Coverage

Spectrum compilation: R. Ulrich



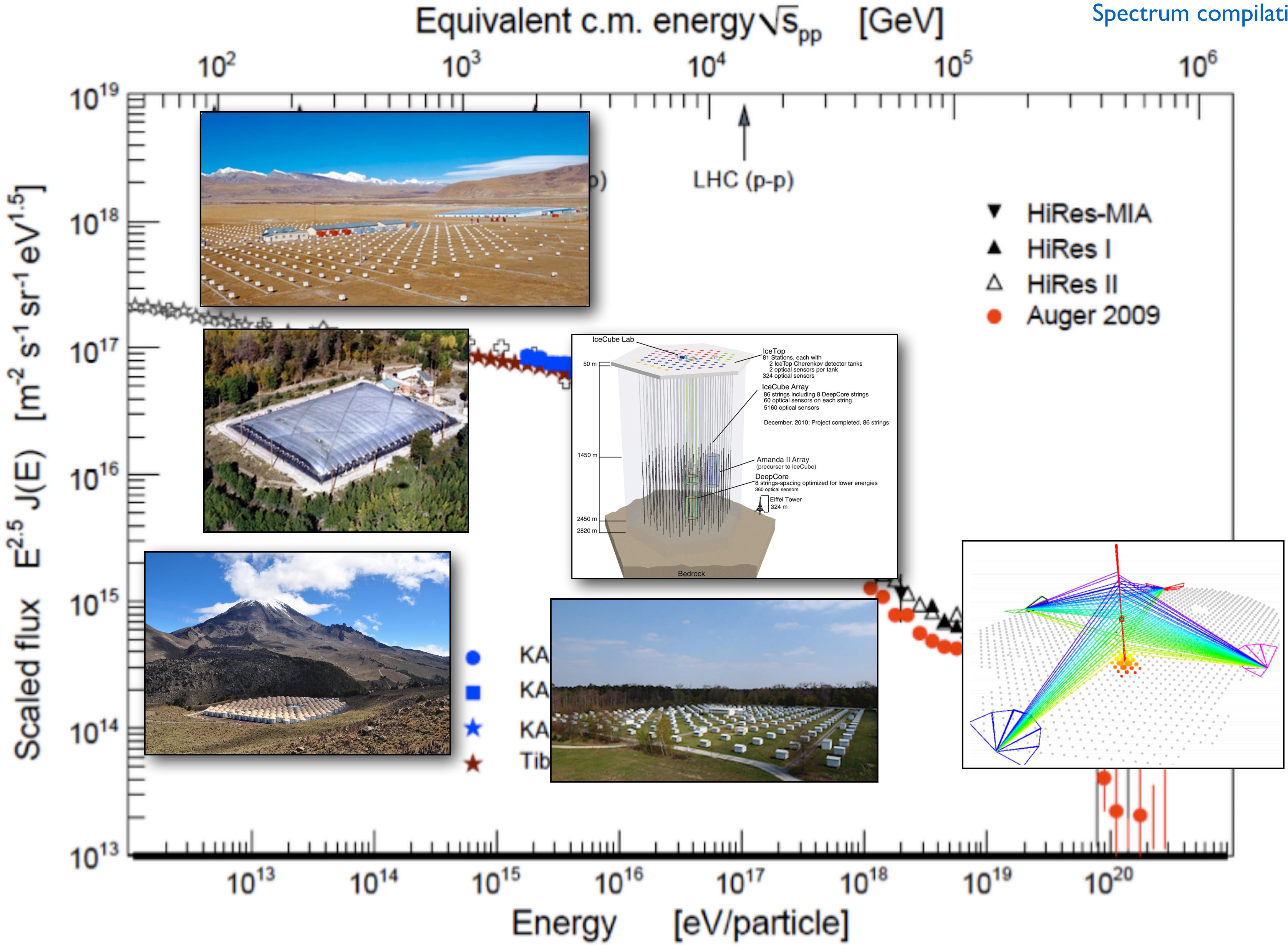
Energy Coverage

Spectrum compilation: R. Ulrich

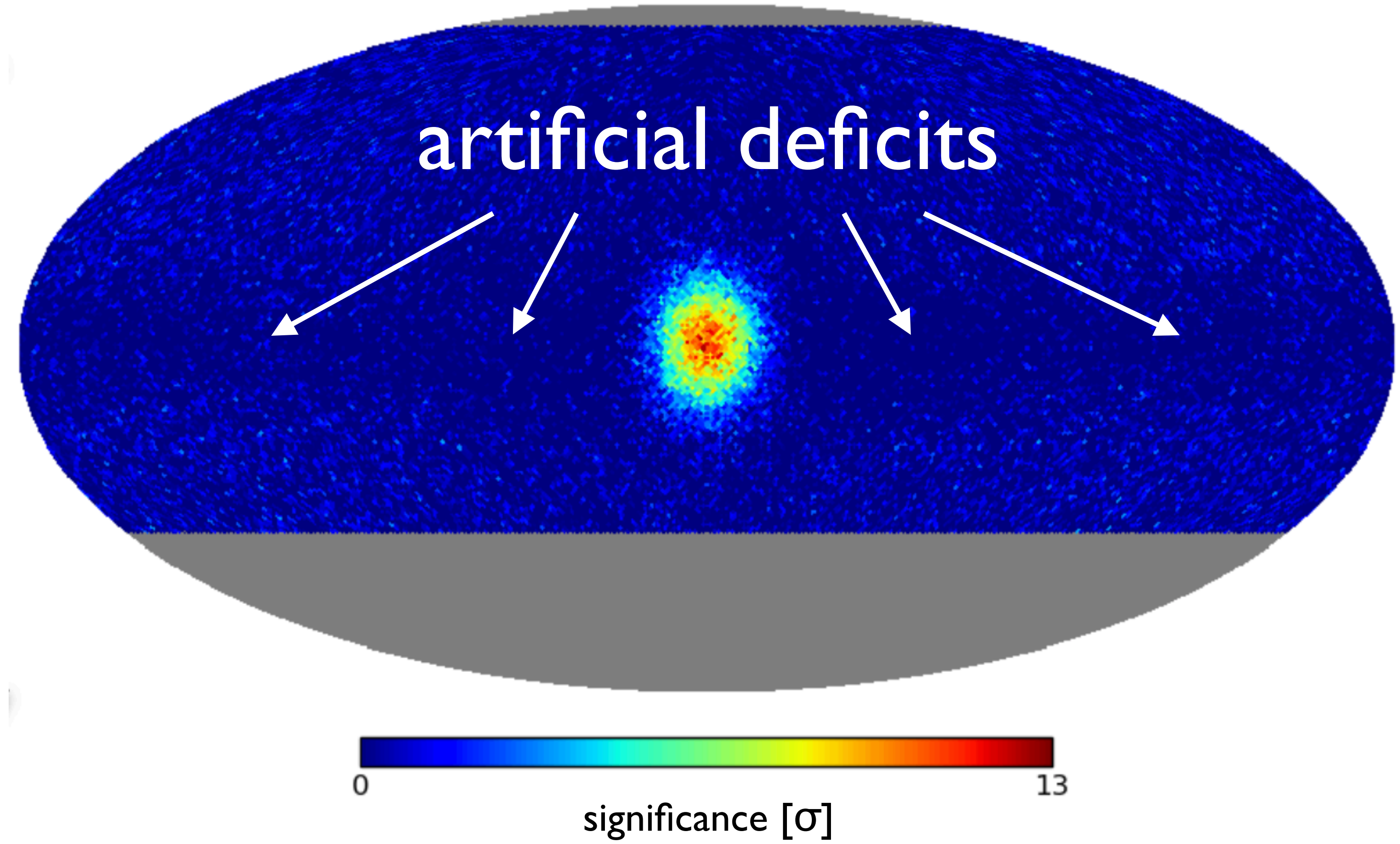


Energy Coverage

Spectrum compilation: R. Ulrich



Strong Excess/Deficit Bias



- Strong excesses (deficits) can produce artificial deficits (excesses) along bands of constant declination.
- Easy to understand why: excesses and deficits lead to over/underestimation of background counts in declination strips.
- Can be addressed by masking out regions of interest a posteriori.

Persistence of Projection Bias

- Below: fits to a simulated dipole in a HAWC-like detector.
- Various amplitude reconstructions are tried, and the iterative ML procedure improves the fraction of the recovered dipole signal.
- Note the projection effect, seen as the decrease in the recovered dipole strength as a function of its orientation in declination.