Indirect Measurements of Cosmic Ray Anisotropy

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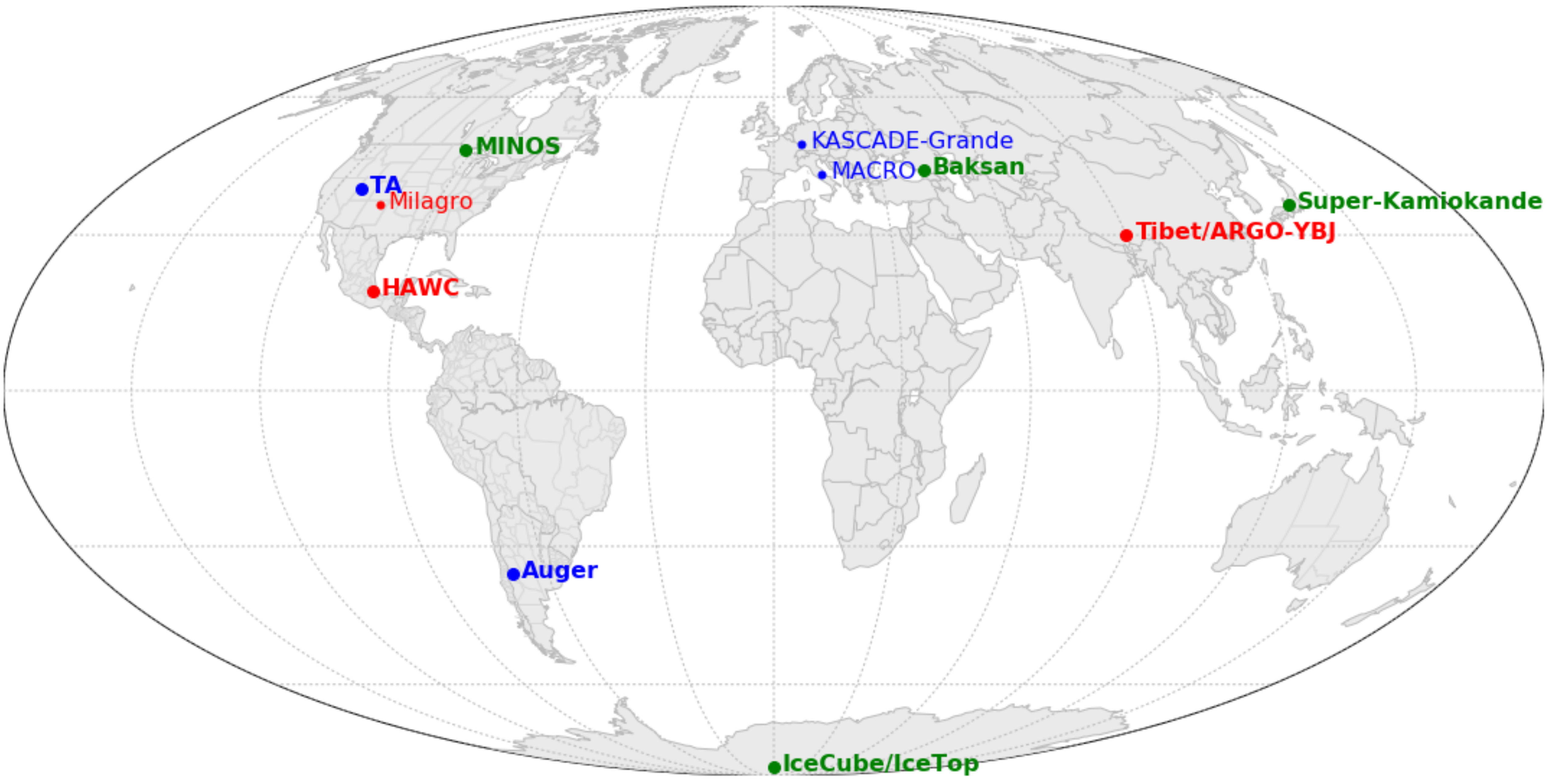
Cosmic Ray Anisotropy

- 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

Cosmic Ray Observatories



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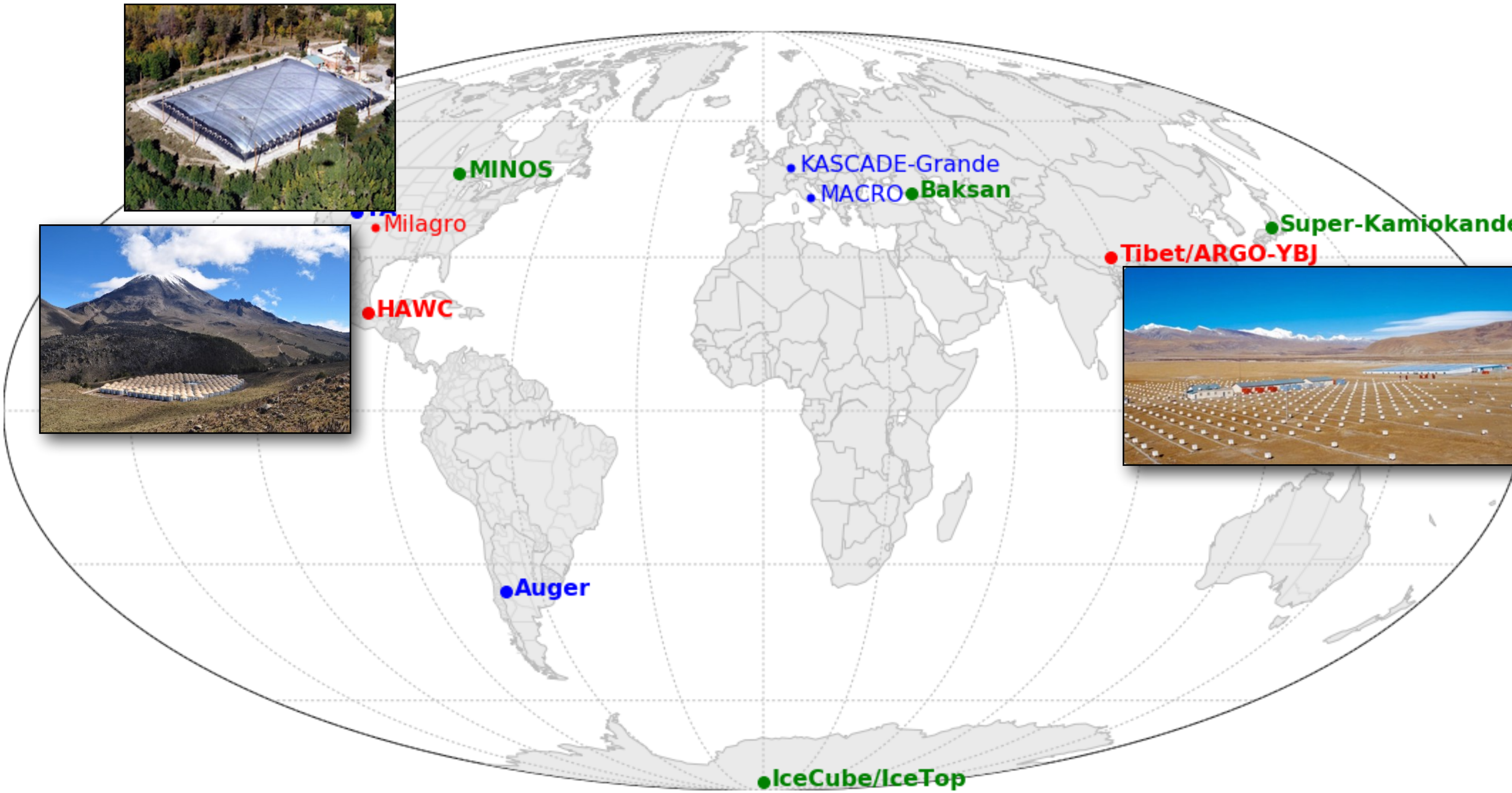

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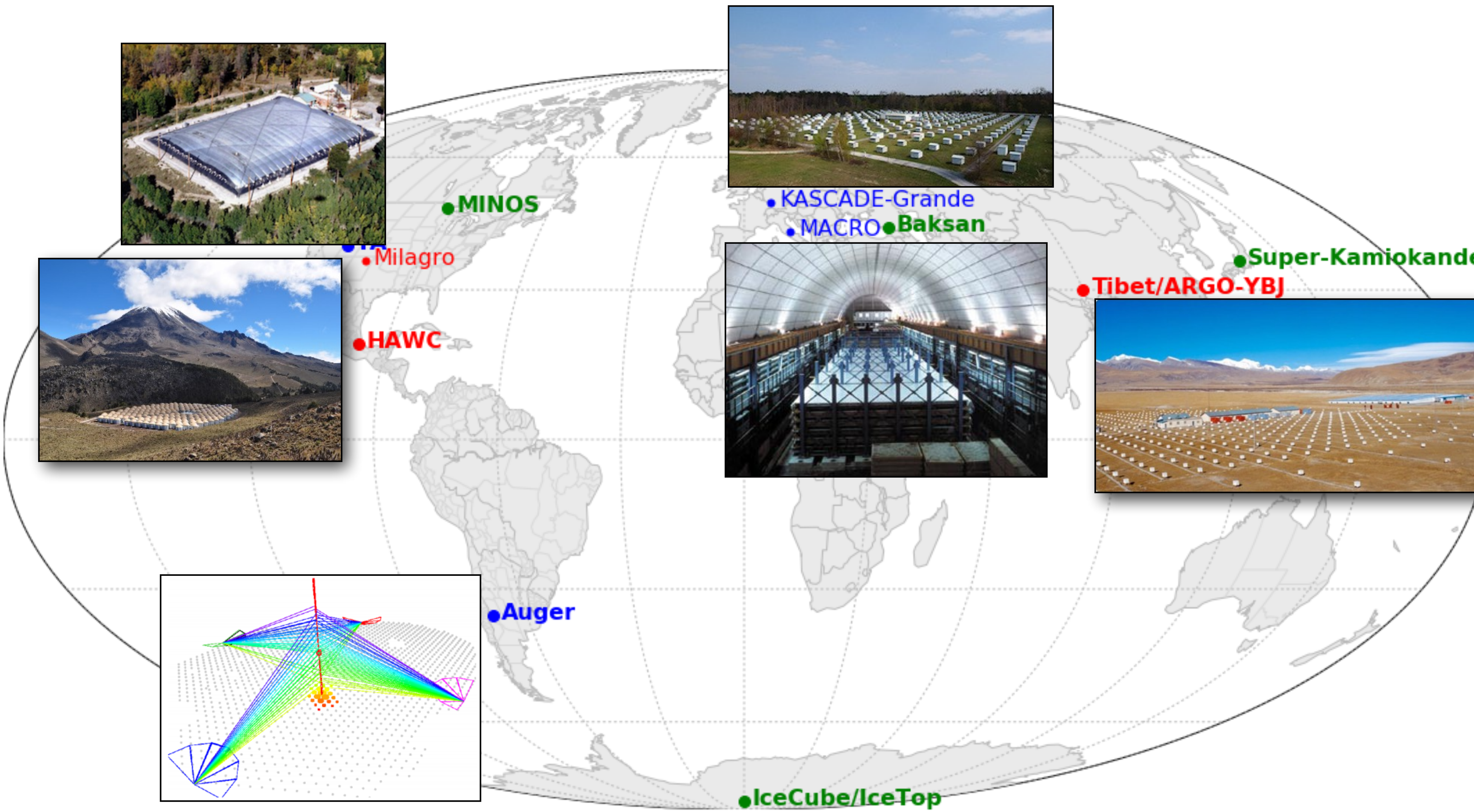

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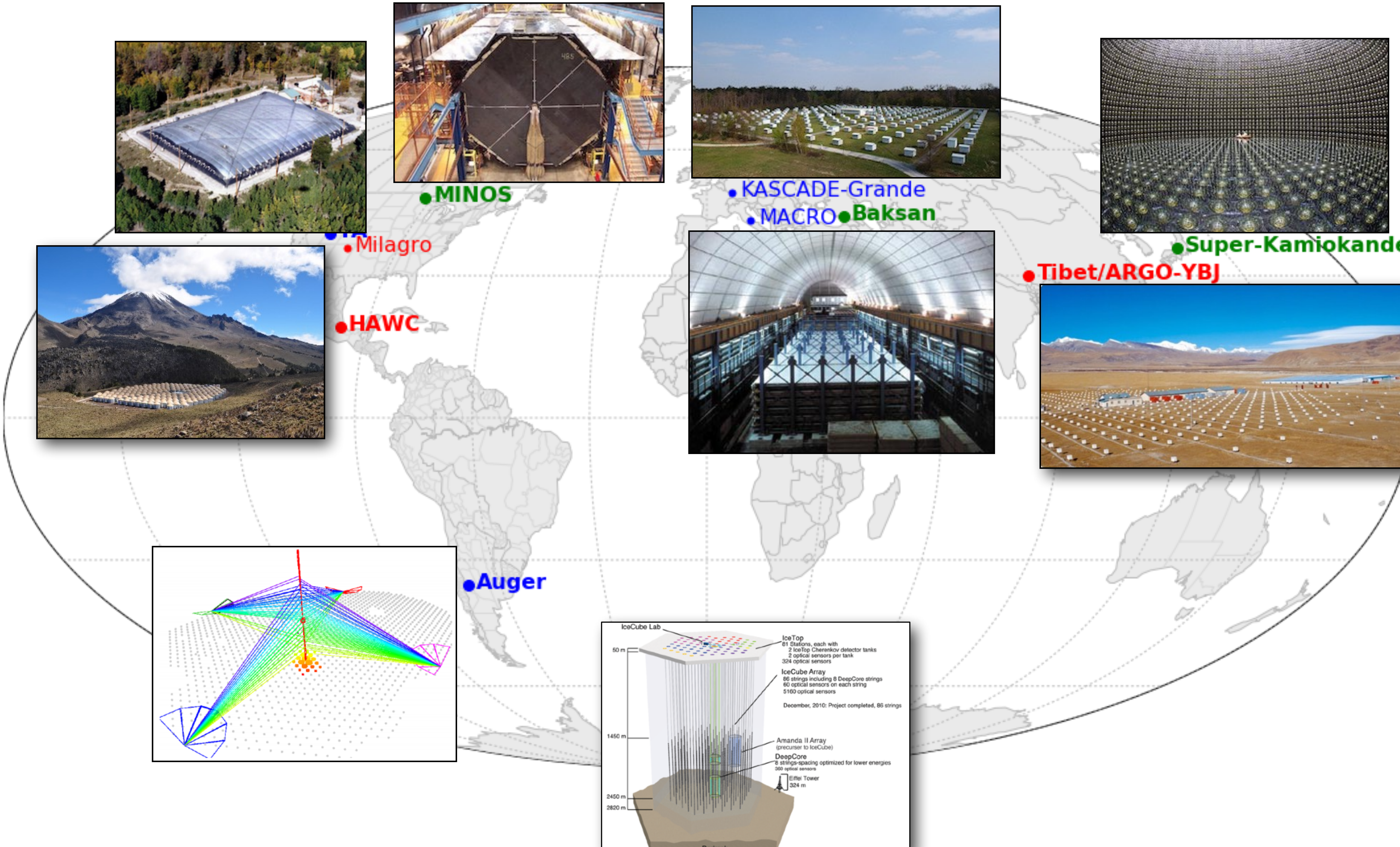
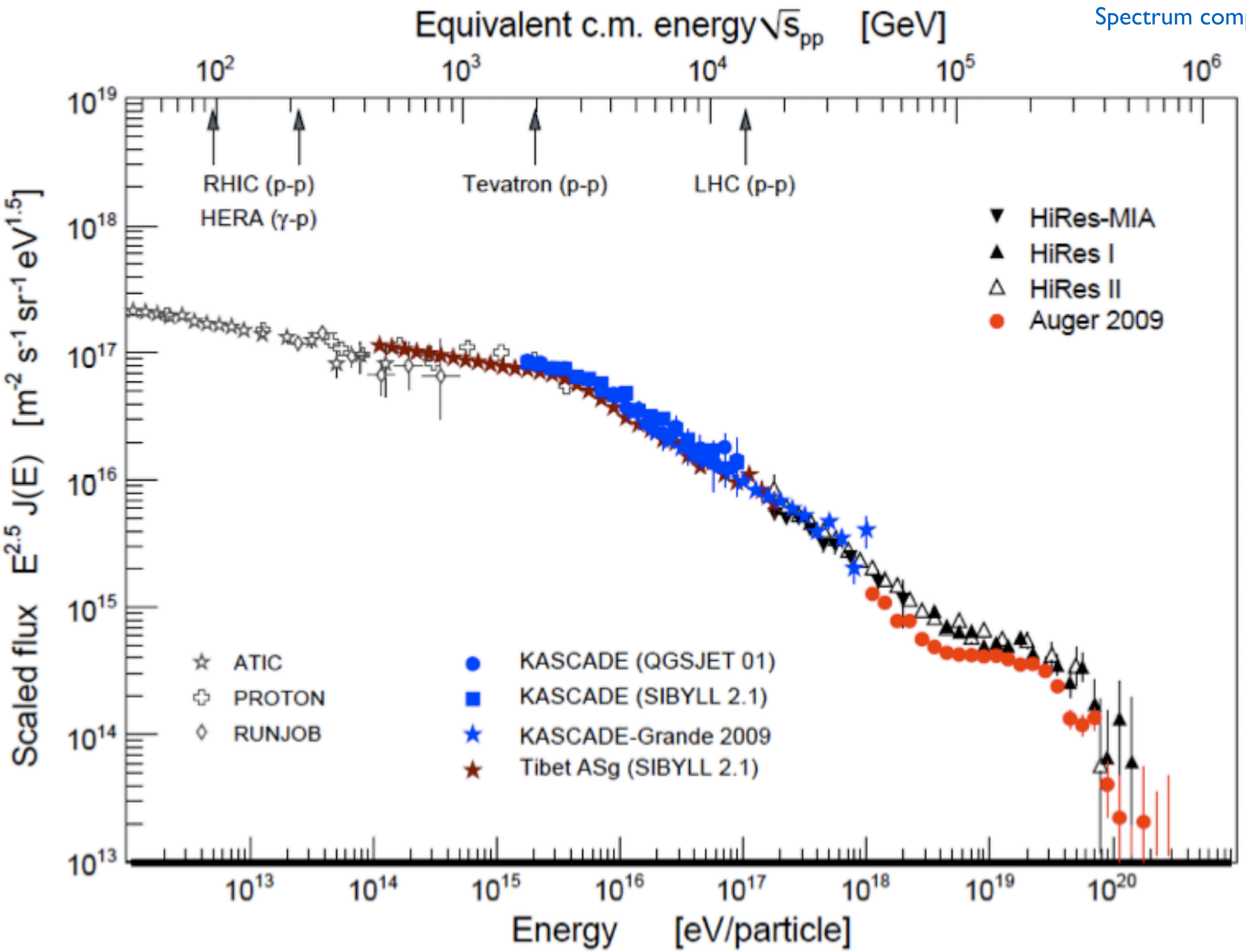


Energy Coverage

Spectrum compilation: R. Ulrich



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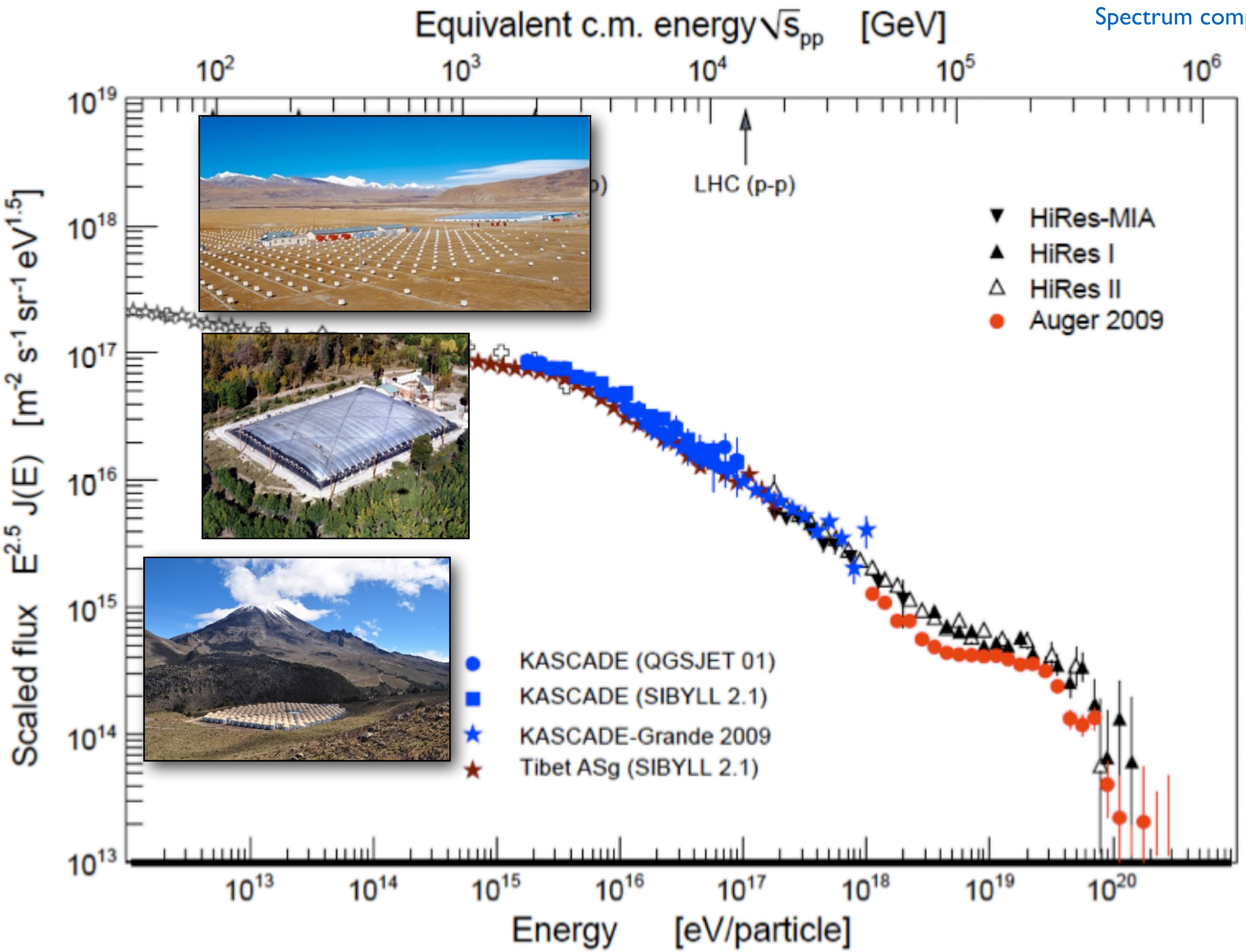

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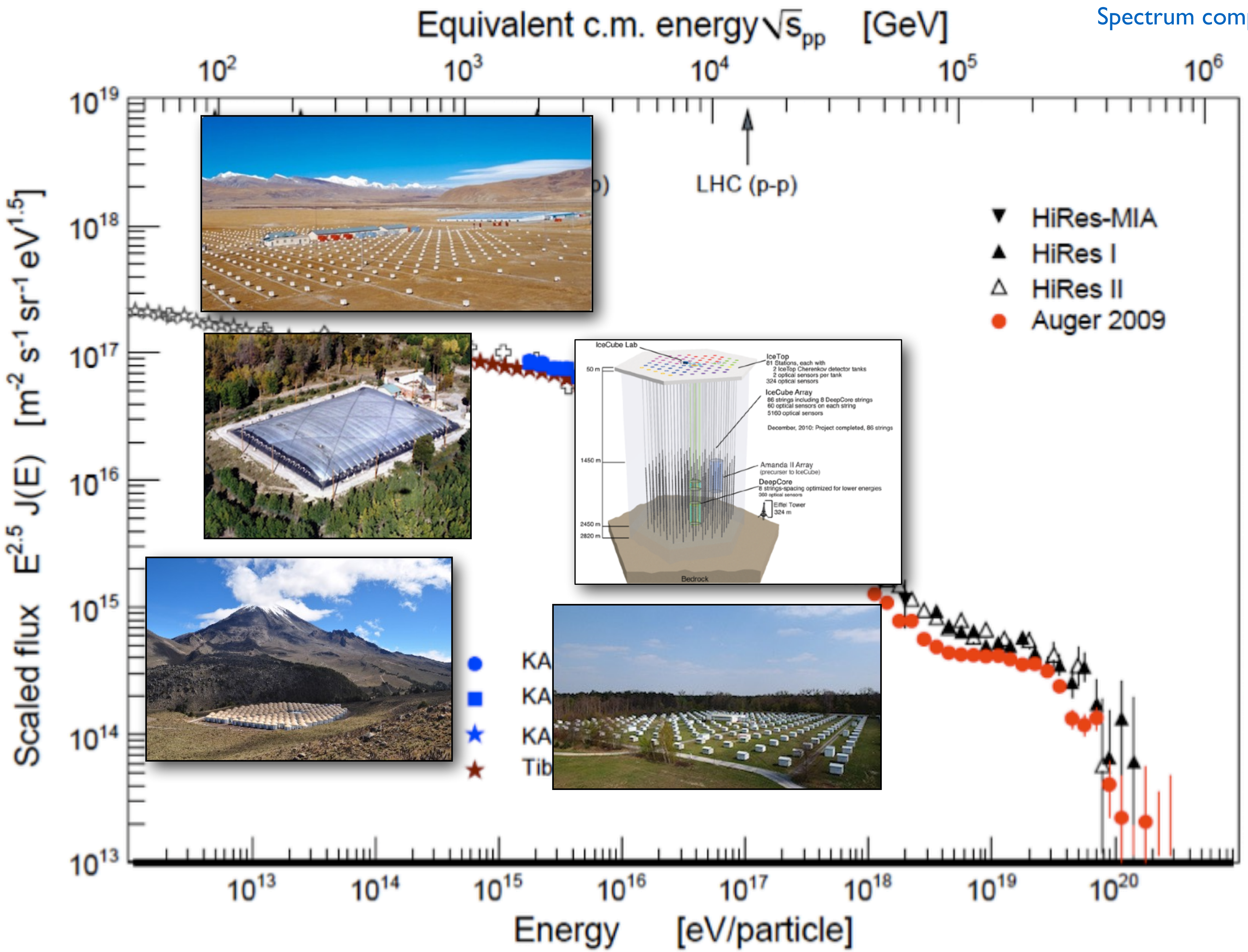

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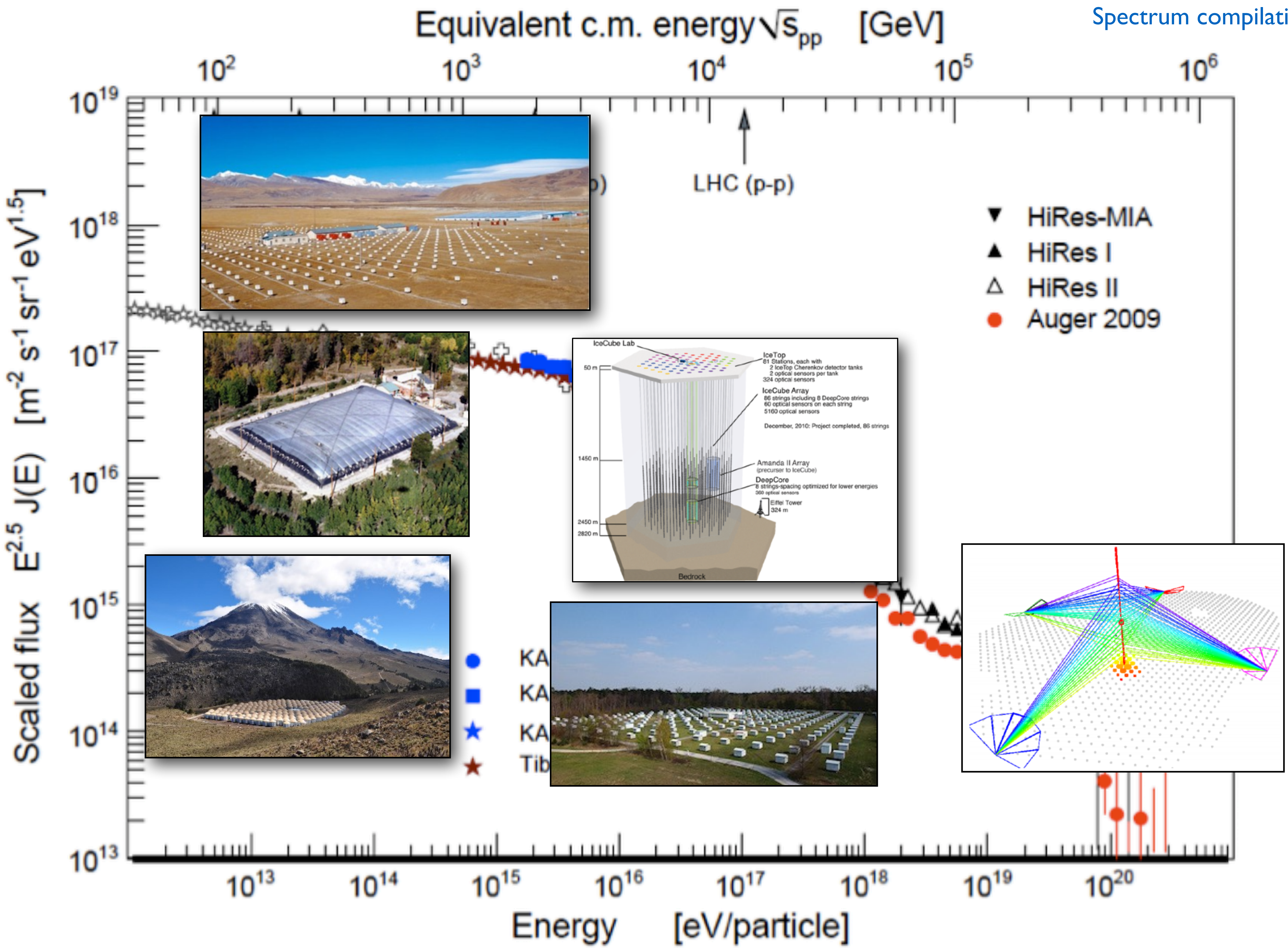

Large Data Sets

Detector	Altitude	Latitude	E_{median}	N_{events}	Run Date
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	$\sim 360\times10^9$	May 2009 -
IceTop	2835 m	90°S	~1.6 PeV	$\sim 0.23\times10^9$	May 2009 -

Detector Performance

- You'll notice that the largest CR datasets are being accumulated by gamma ray and neutrino detectors
- Not too surprising:
  - VHE gamma rays have low flux relative to cosmic-ray background
  - Neutrinos are tough to detect under the best of circumstances
  - Sensitive detectors need significant fiducial area/volume to achieve sufficient γ/ν statistics and also to reject the cosmic-ray background
- Lesson: if you want a really huge sample of cosmic rays, build a gamma-ray observatory

Example: HAWC

Photo by J. Goodman, Nov. 2016

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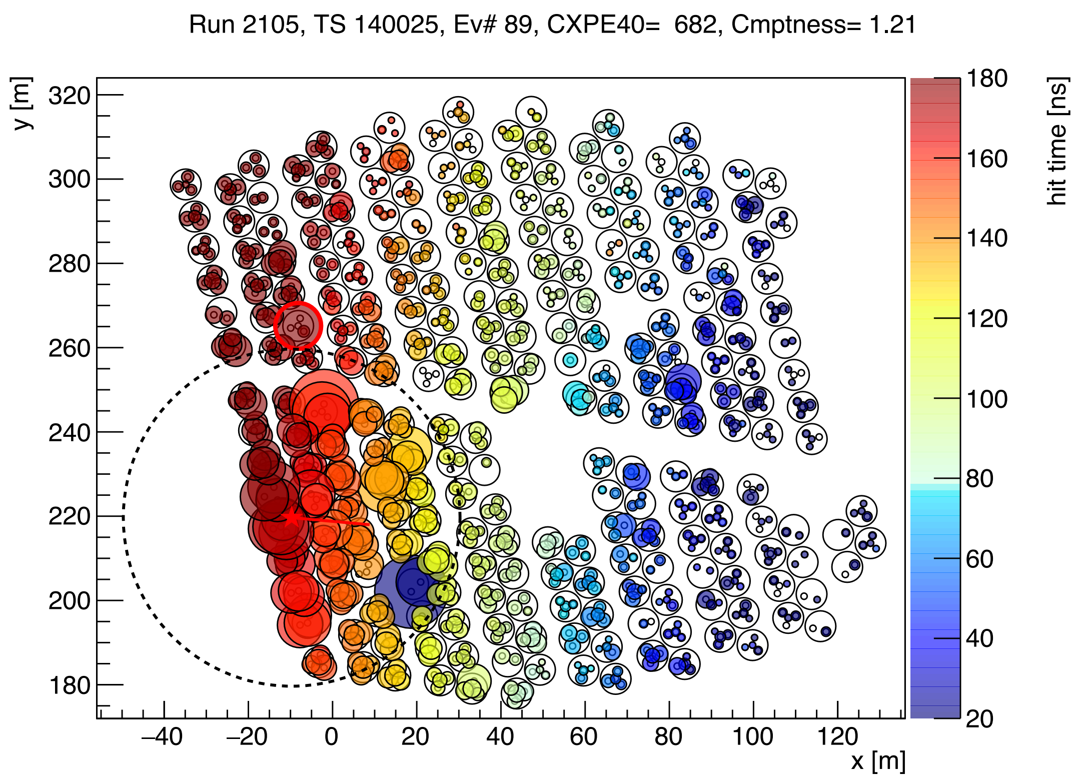
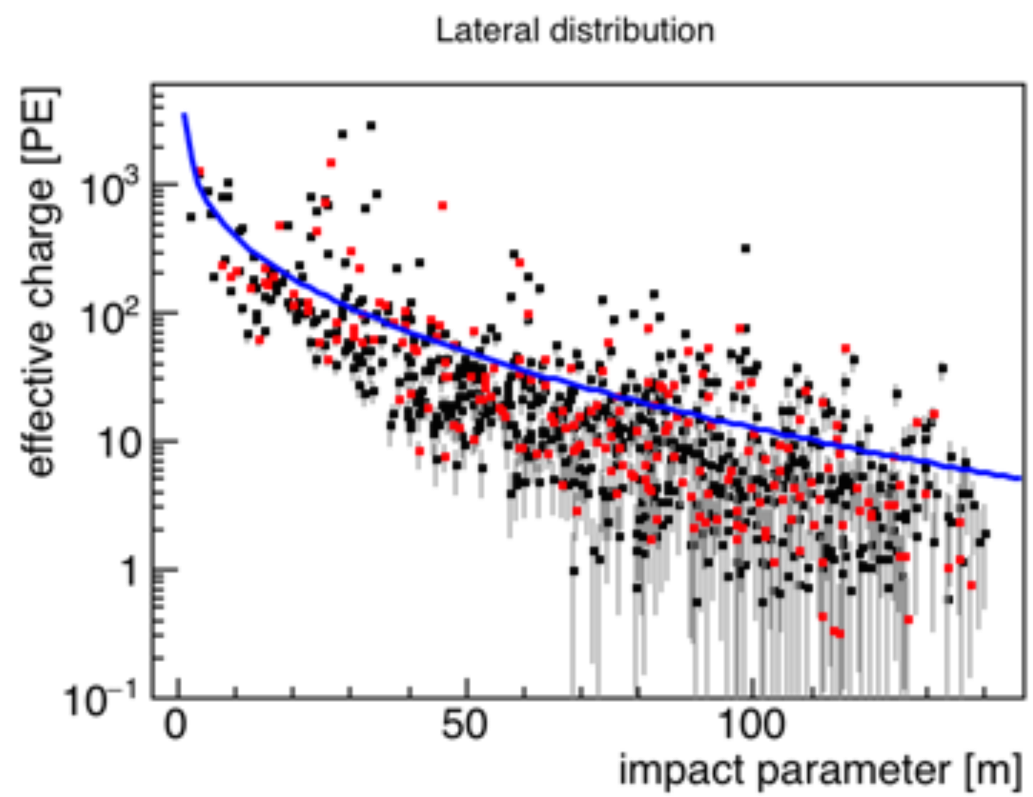
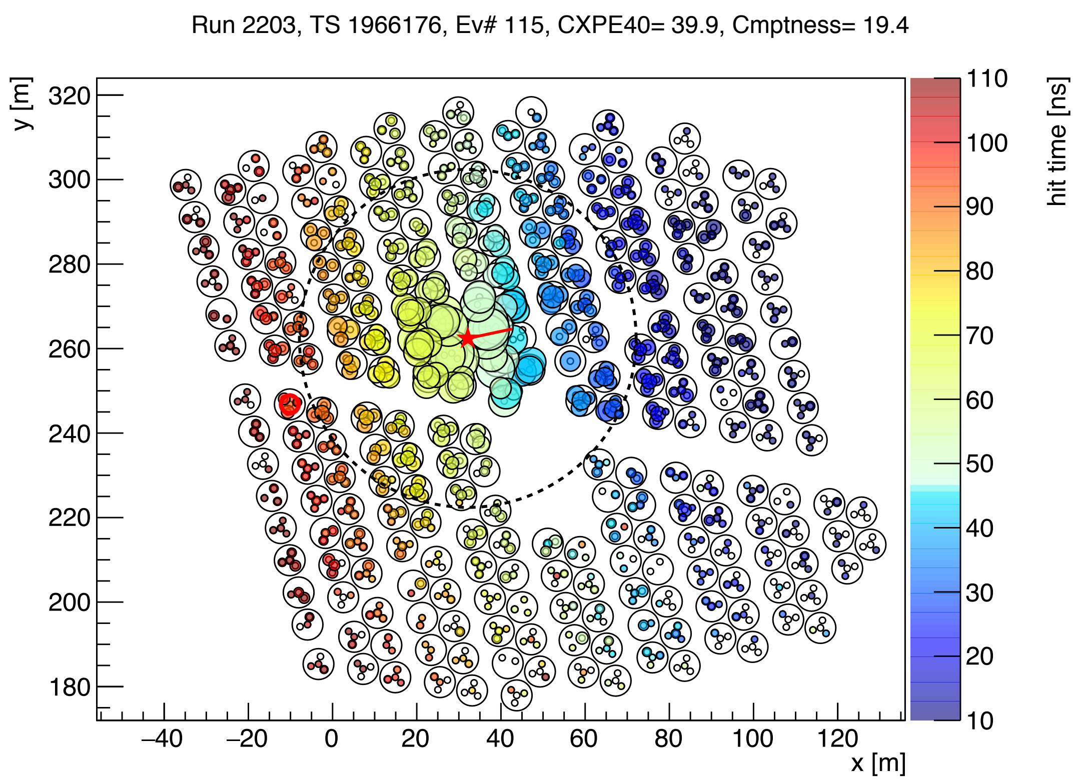
Cosmic Rays in HAWC

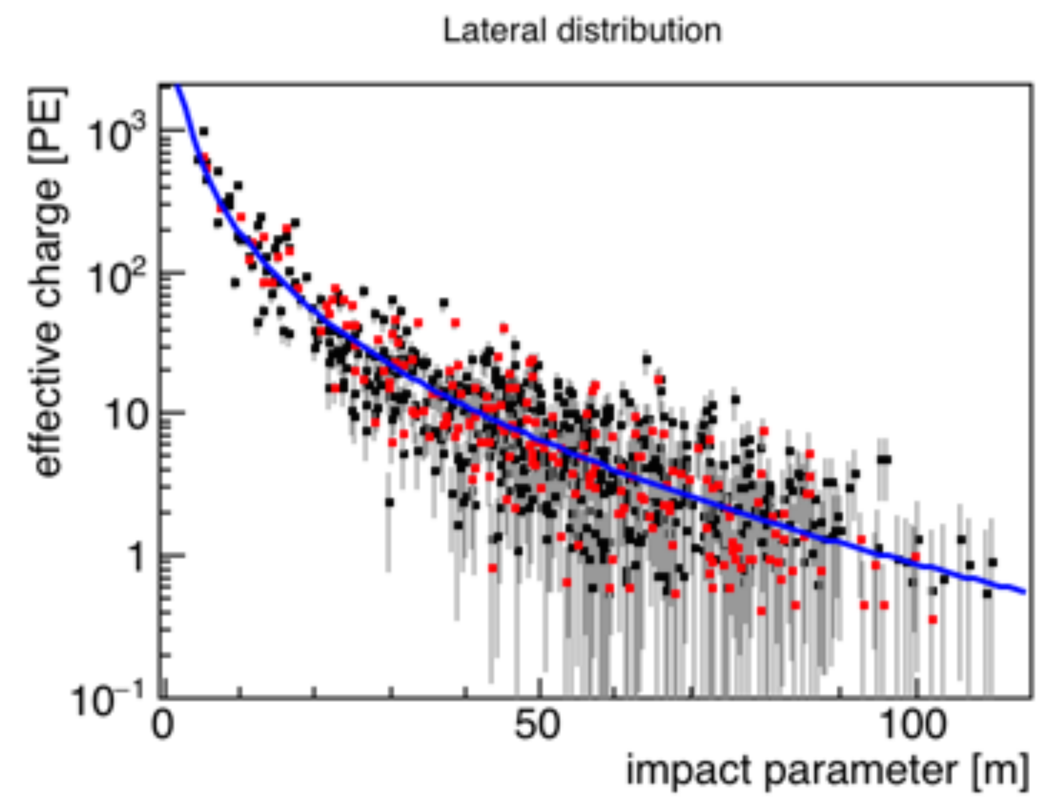




- Cosmic ray background: 25 kHz at trigger level
- Cosmic ray showers produce "clumpy" deposits of charge at large distances from the shower core
- Showers characterized by large variance in charge as a function of distance from shower core

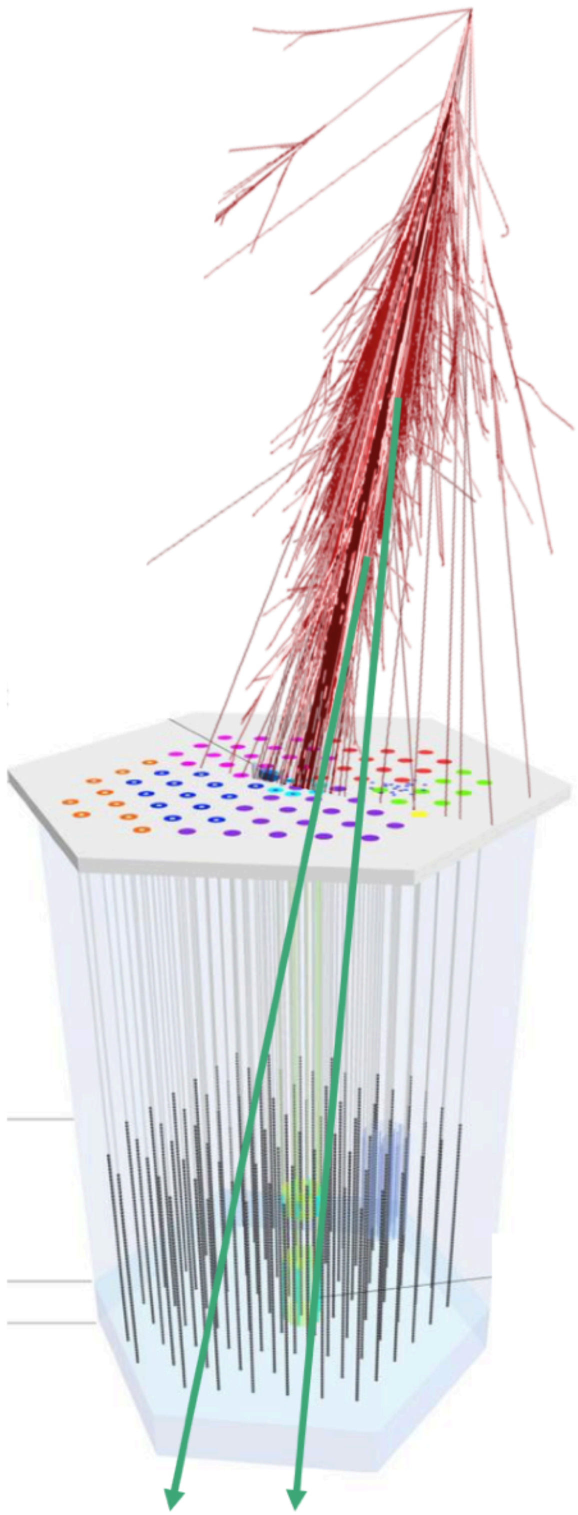
Cosmic Rays in HAWC





- Gamma ray signal: ~5 mHz from Crab Nebula
- Showers characterized by small variance in deposited charge vs distance from shower core
- 99.9% background suppression at 10 TeV

Example: IceCube



- IceCube detects down-going muons produced in air showers
  - SMT rate: 2.5 kHz - 3 kHz
  - Median angular resolution: 3°
  - Energy resolution: ~100%
  - Note that energy/angular resolution is *much better* for neutrino events
- Because of location at Pole, instantaneous FOV is equal to time-integrated FOV. Highly convenient…

Anisotropy Measurement

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

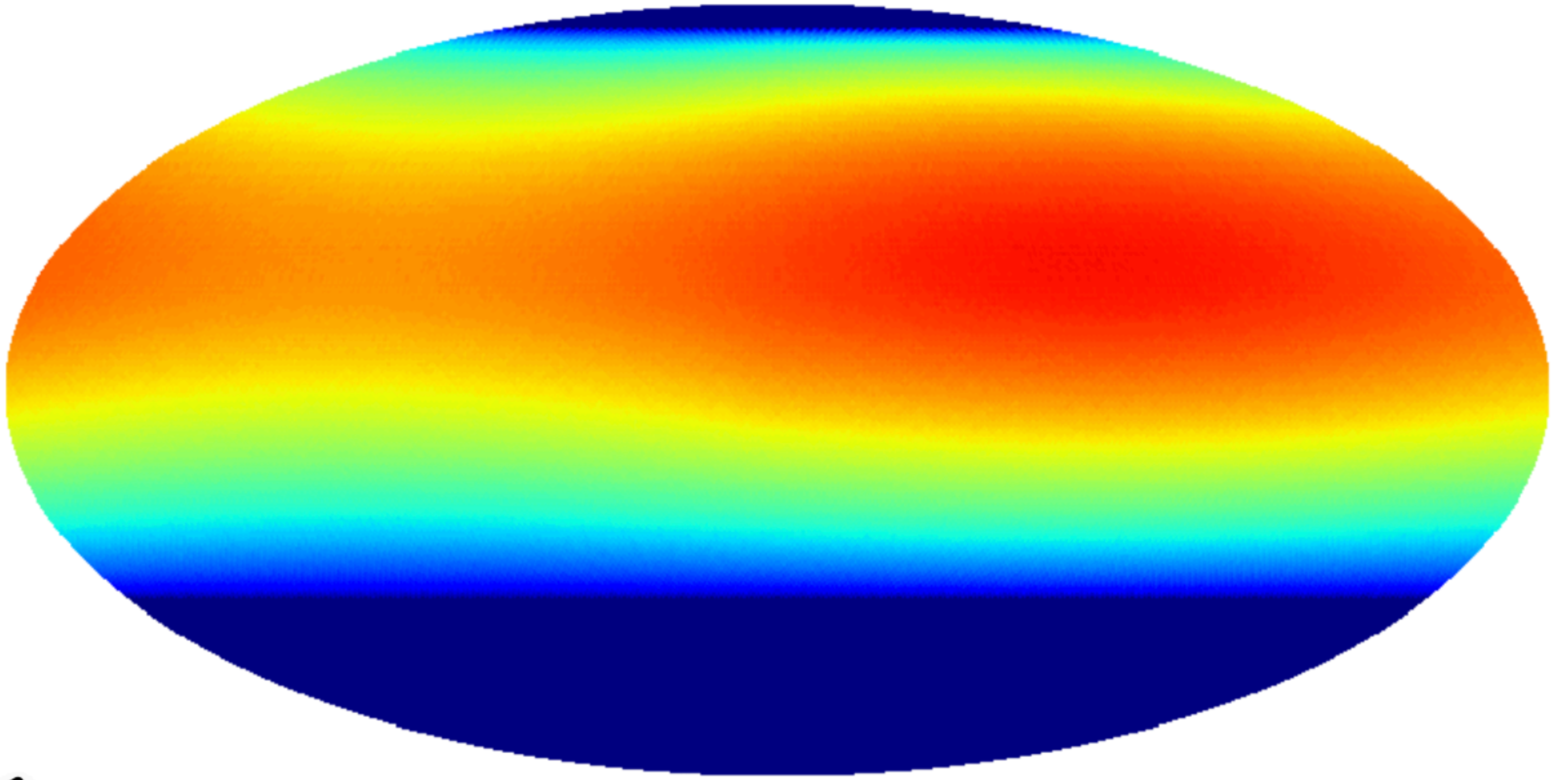
$$\mathbf{n} = \begin{pmatrix} \cos\delta\cos\alpha \\ \cos\delta\sin\alpha \\ \sin\delta \end{pmatrix}, \qquad \underbrace{\Phi(\mathbf{n})}_{\text{total flux}} = \Phi_{\text{iso}}\,\underbrace{I(\mathbf{n})}_{\text{rel. int.}}$$

- 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*

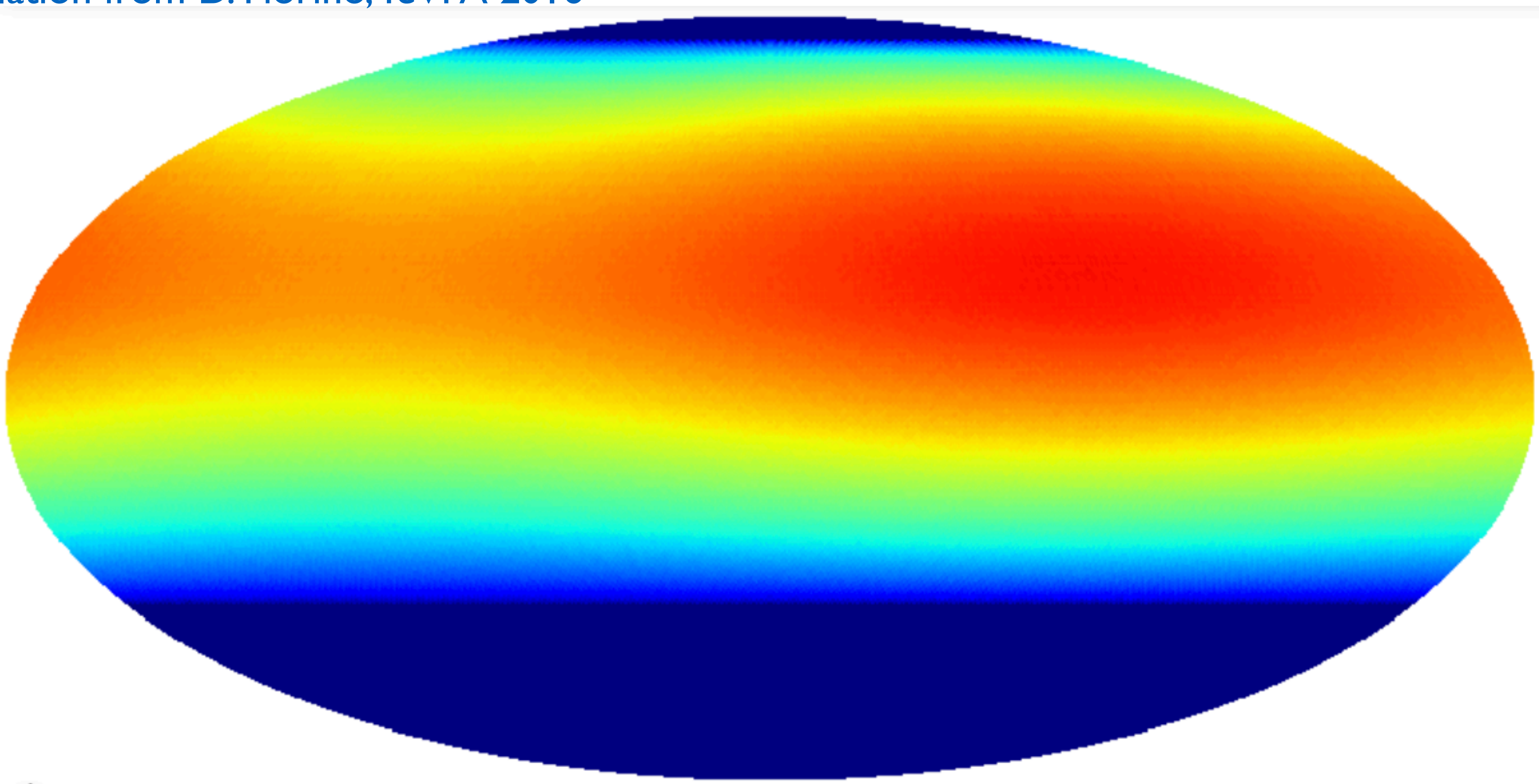
Reference Construction I

- 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" (language of Auger collaboration) 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

Data and Reference Maps



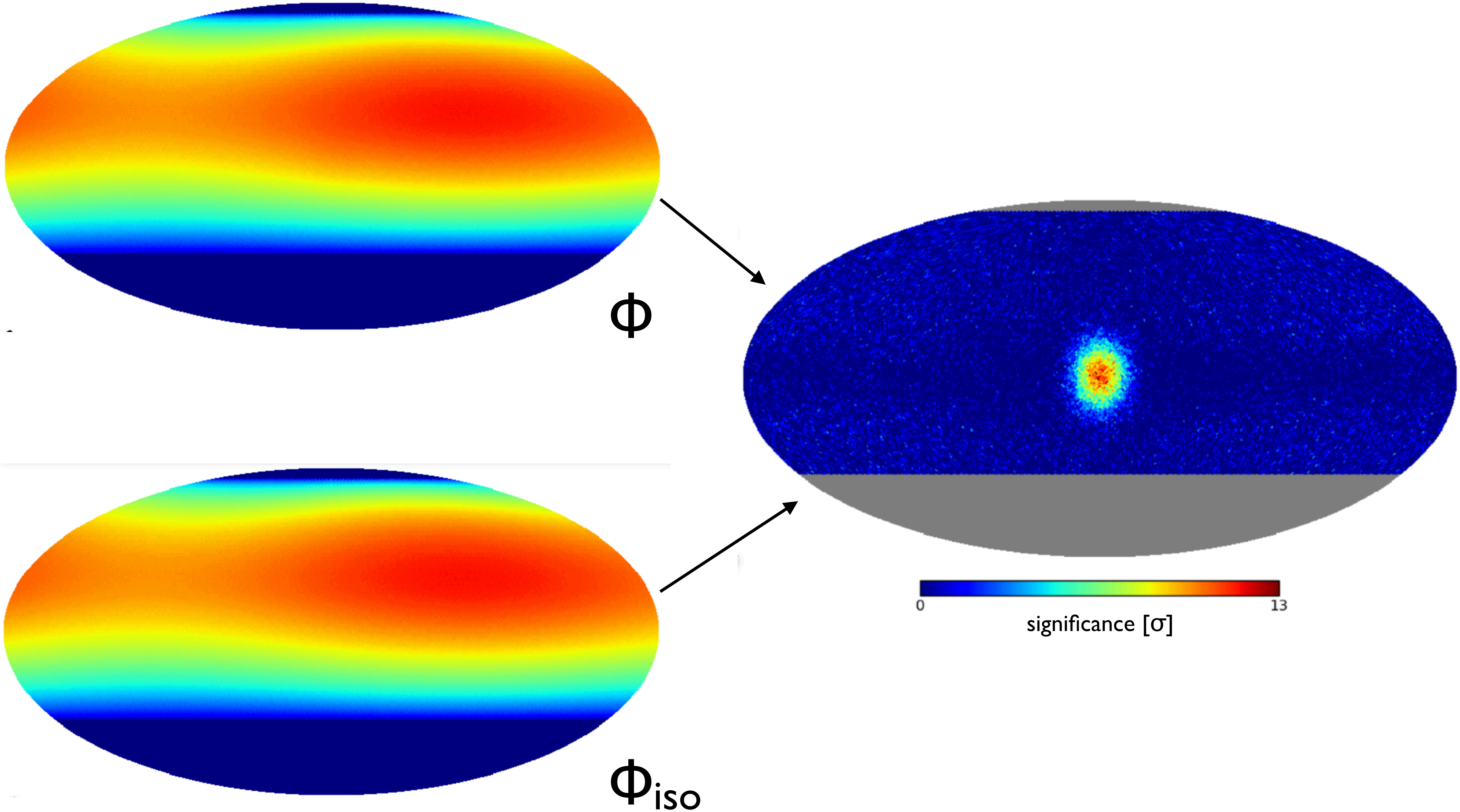
Simulation from D. Fiorino, TeVPA 2016



- "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

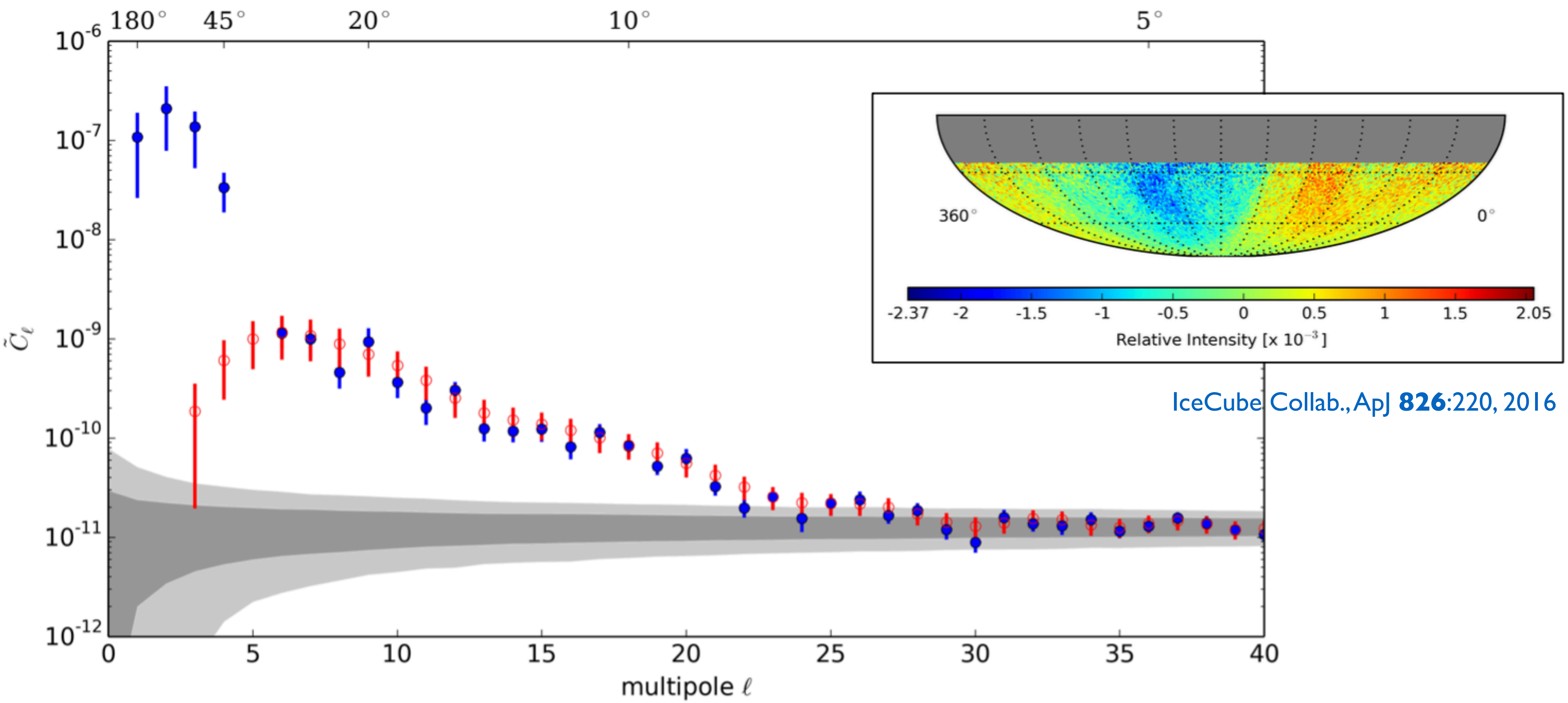
Difference Map

Simulation from D. Fiorino, TeVPA 2016



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 in random data sets



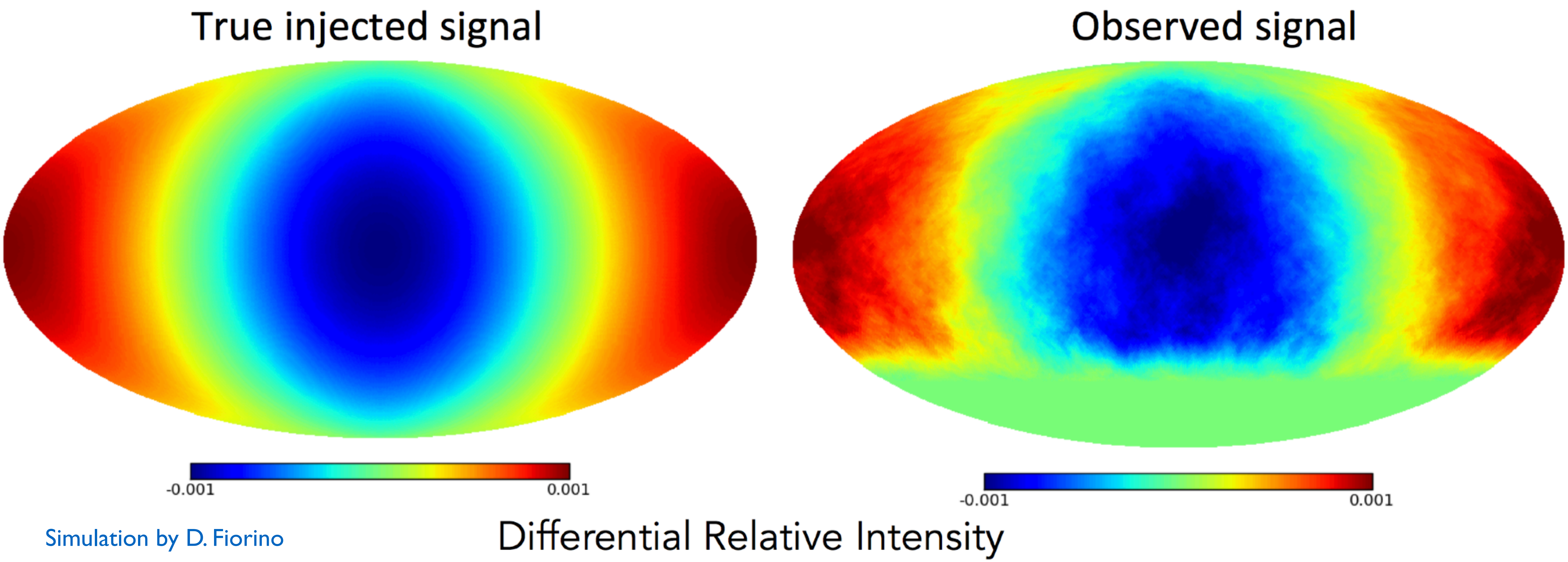
IceCube Collab., ApJ **826**:220, 2016

Reference Construction II

- 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 $15° \times (\Delta t$ / hr)
- Both methods build a detailed cumulative detector response from the data themselves

RA Projection Bias

- Reference map: equivalent to modifying RA of event within same Dec band
- Maps are re-normalized within each Dec band and show equal contribution from excesses and deficits, by definition
- Methods are sensitive to anisotropy along RA but not Dec, because we are working with declination strips. Structure is projected onto RA



Simulation by D. Fiorino

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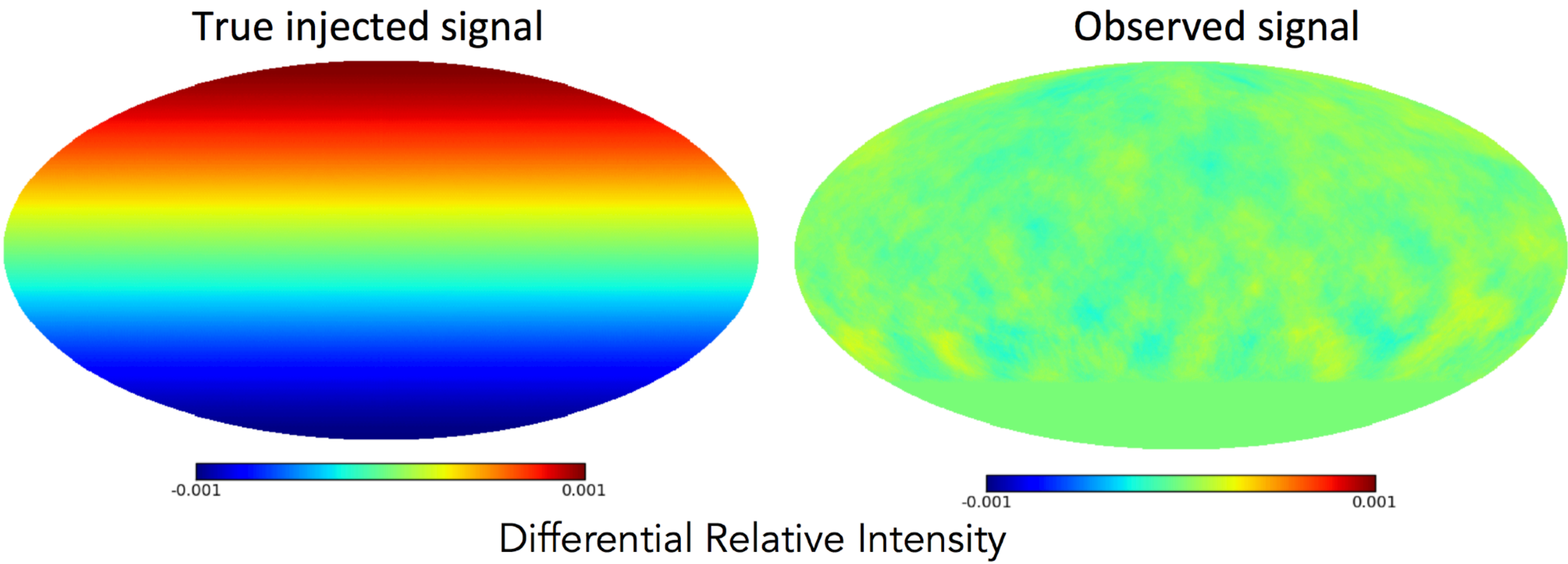

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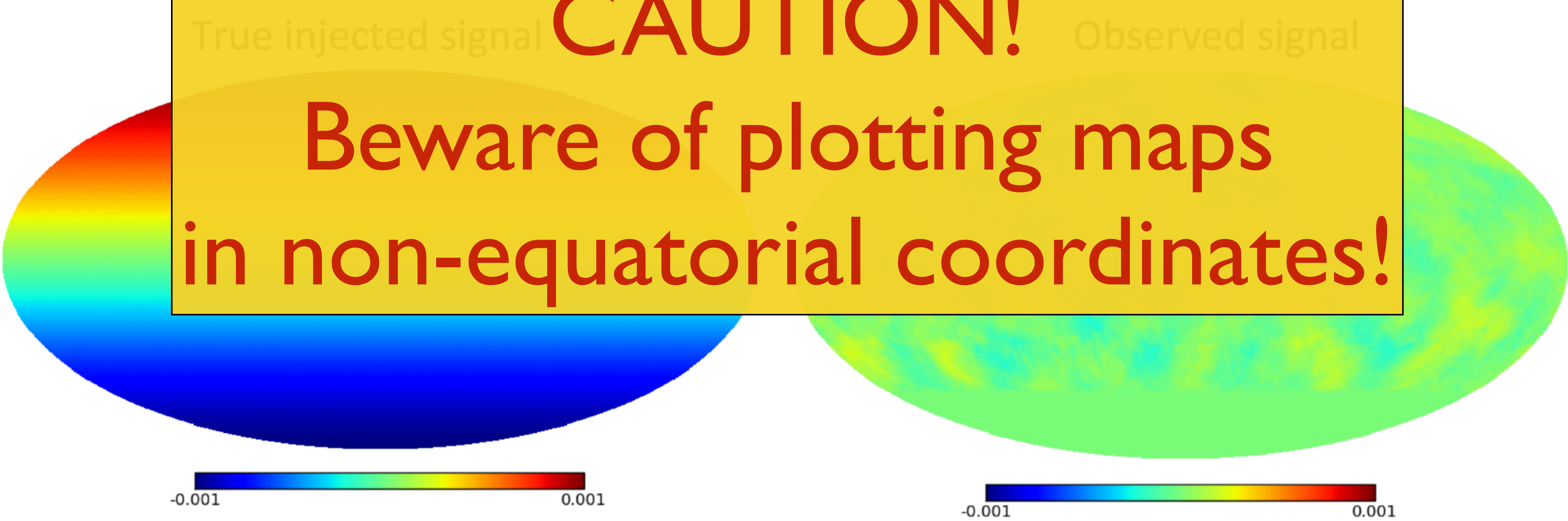
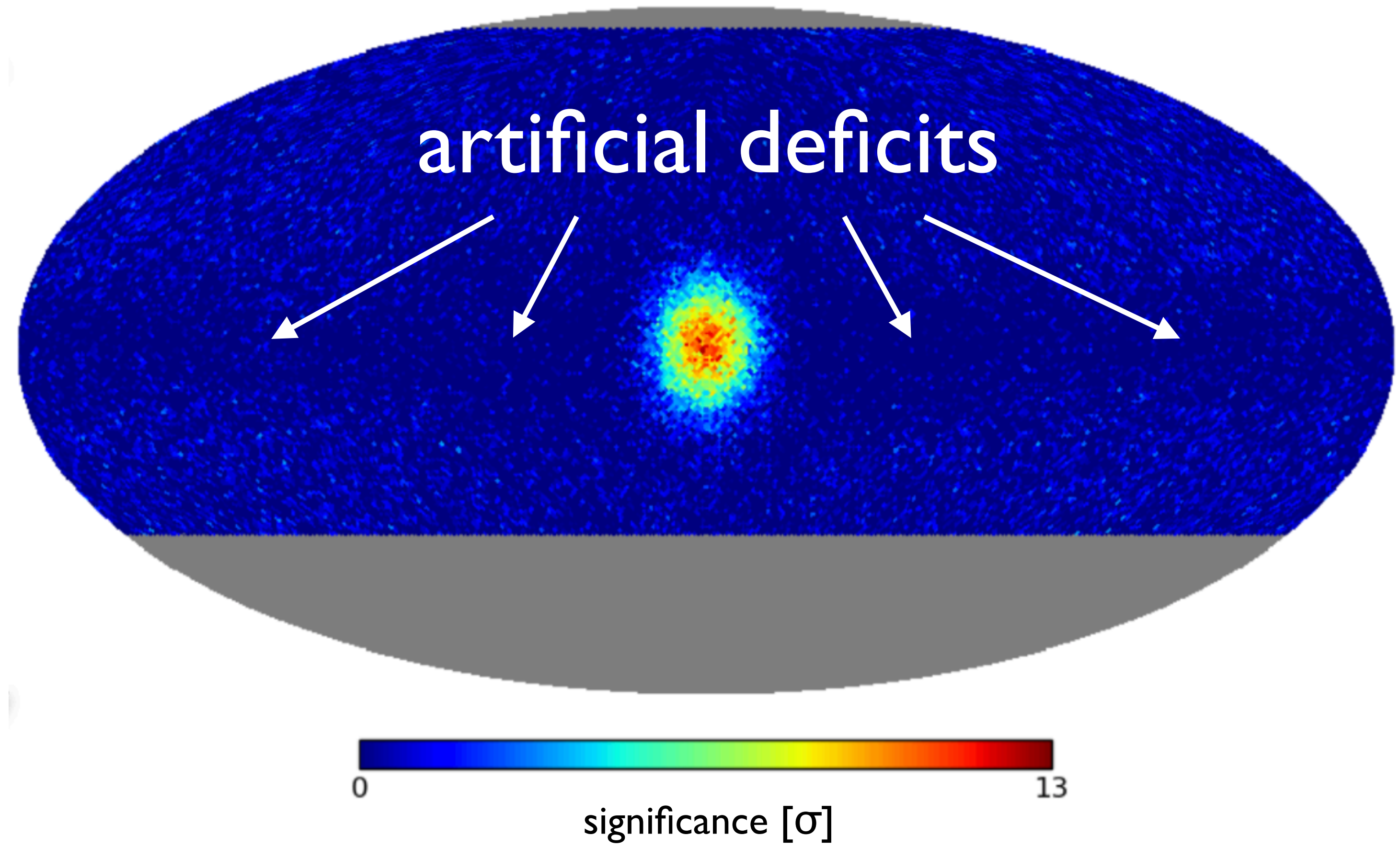
CAUTION!

Beware of plotting maps in non-equatorial coordinates!



Differential Relative Intensity

Strong Excess/Deficit Bias



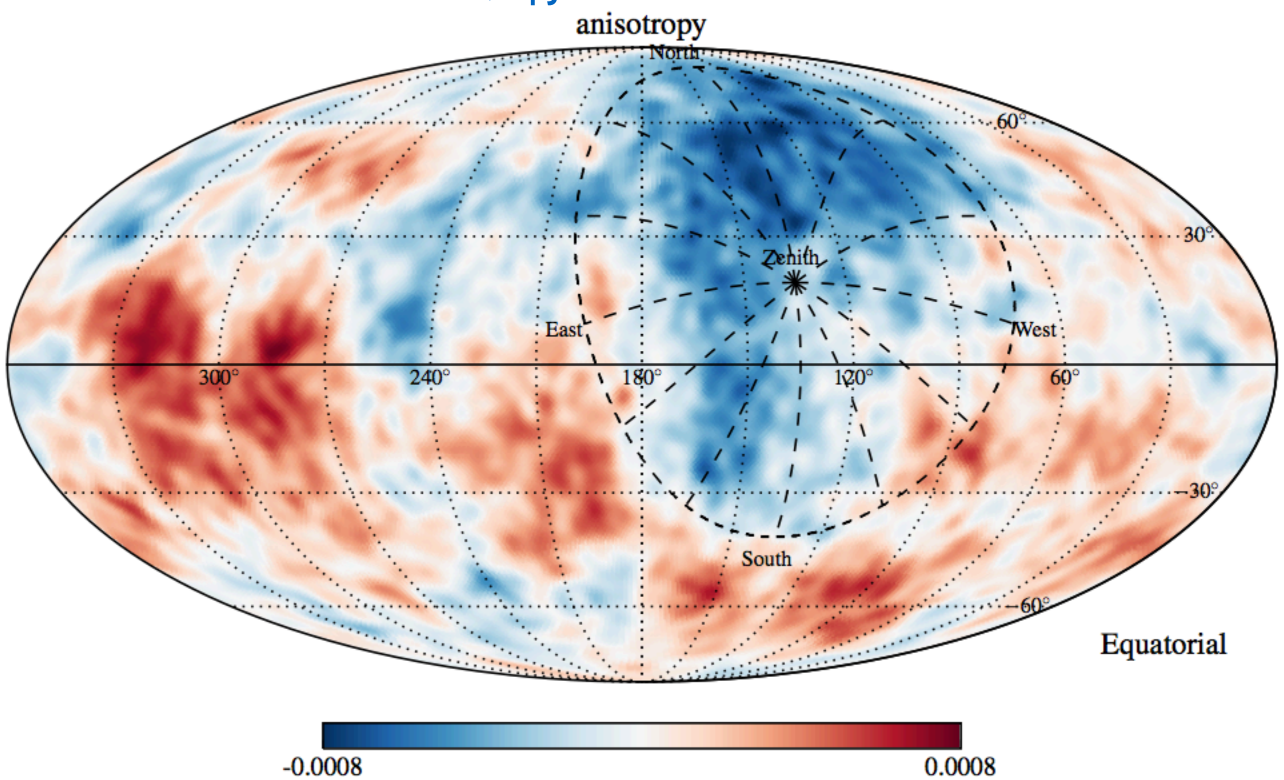
- Strong excesses (deficits) can produce artificial deficits (excesses) along bands of constant declination
- Easy to understand why: excesses and deficits lead to over/underestimation of background counts in declination strips
- Can be addressed by masking out regions of interest a posteriori

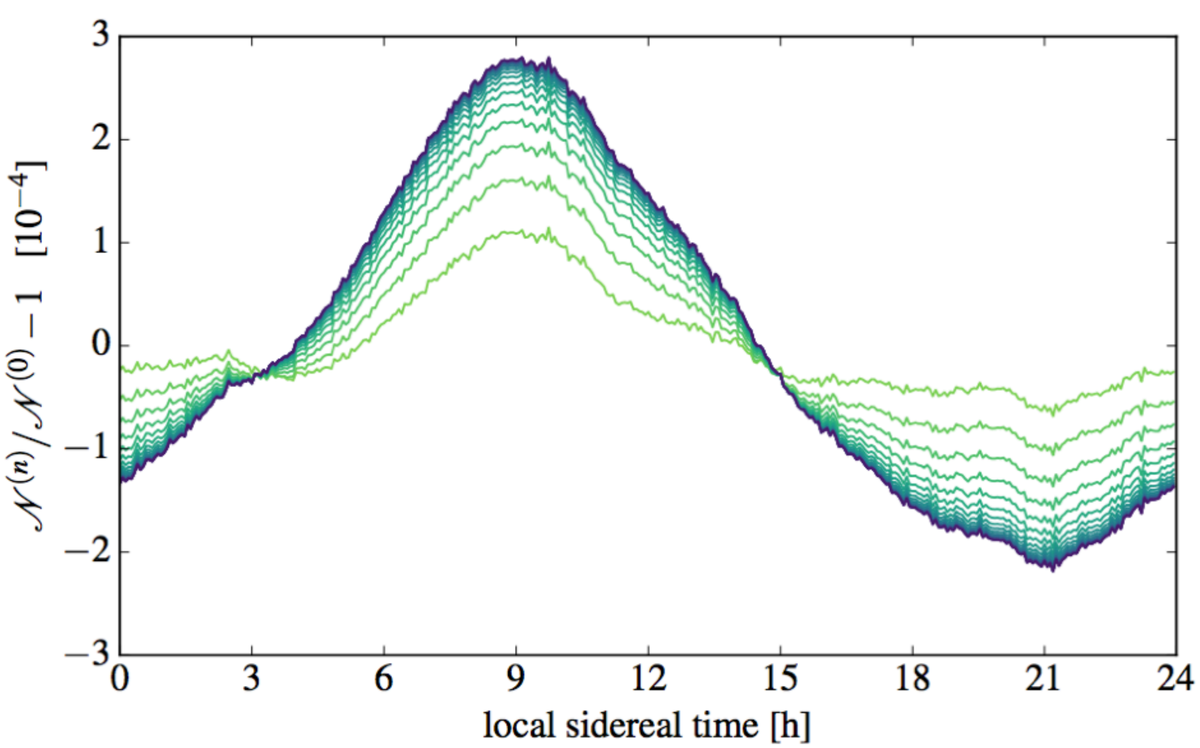
Mid-Latitude Attenuation

- An issue which affects detectors in the mid-latitudes (so 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:
  - Ahlers et al., ApJ **823**:10, 2016
  - See also Tibet-ASγ Collaboration, ApJ **633**:1005, 2005
  - See also ARGO-YBJ Collaboration, ApJ **809**:90, 2015

Maximum Likelihood Iteration

Simulation from Ahlers et al., ApJ 2016

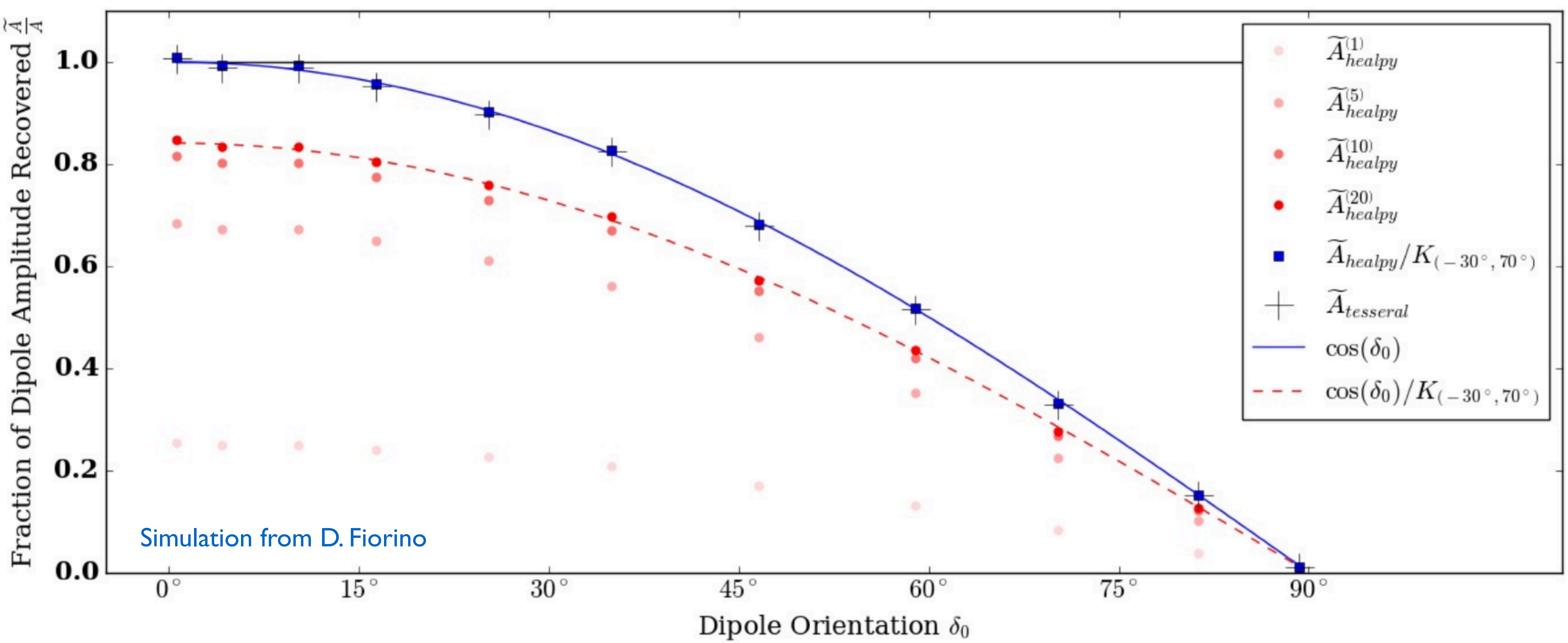




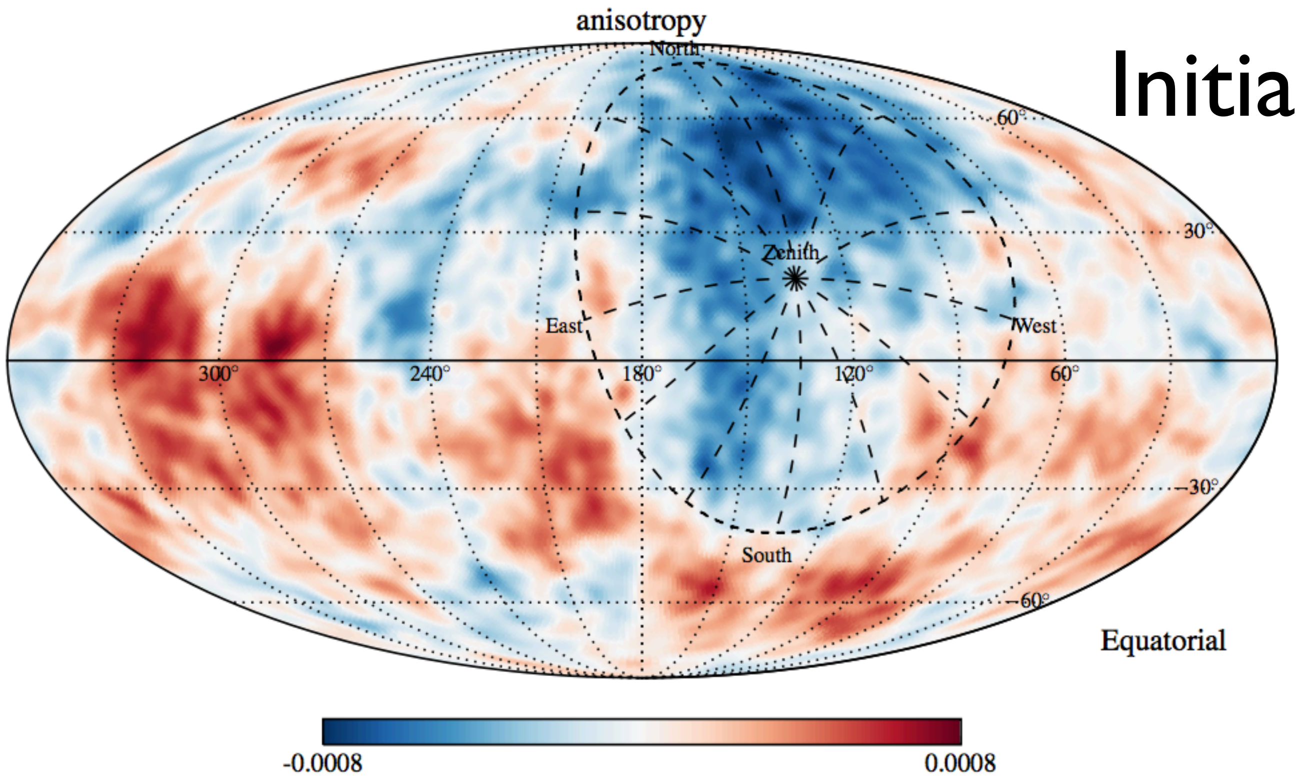
- HAWC instantaneous FOV is shown on a simulated sky map
- When FOV is over a deficit, as in this case, the estimate for Φ_{iso} is too low
- Maximum likelihood iteration compensates for effect. Typical convergence in <10 steps
- See presentation by J.-C. Diaz-Velez

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



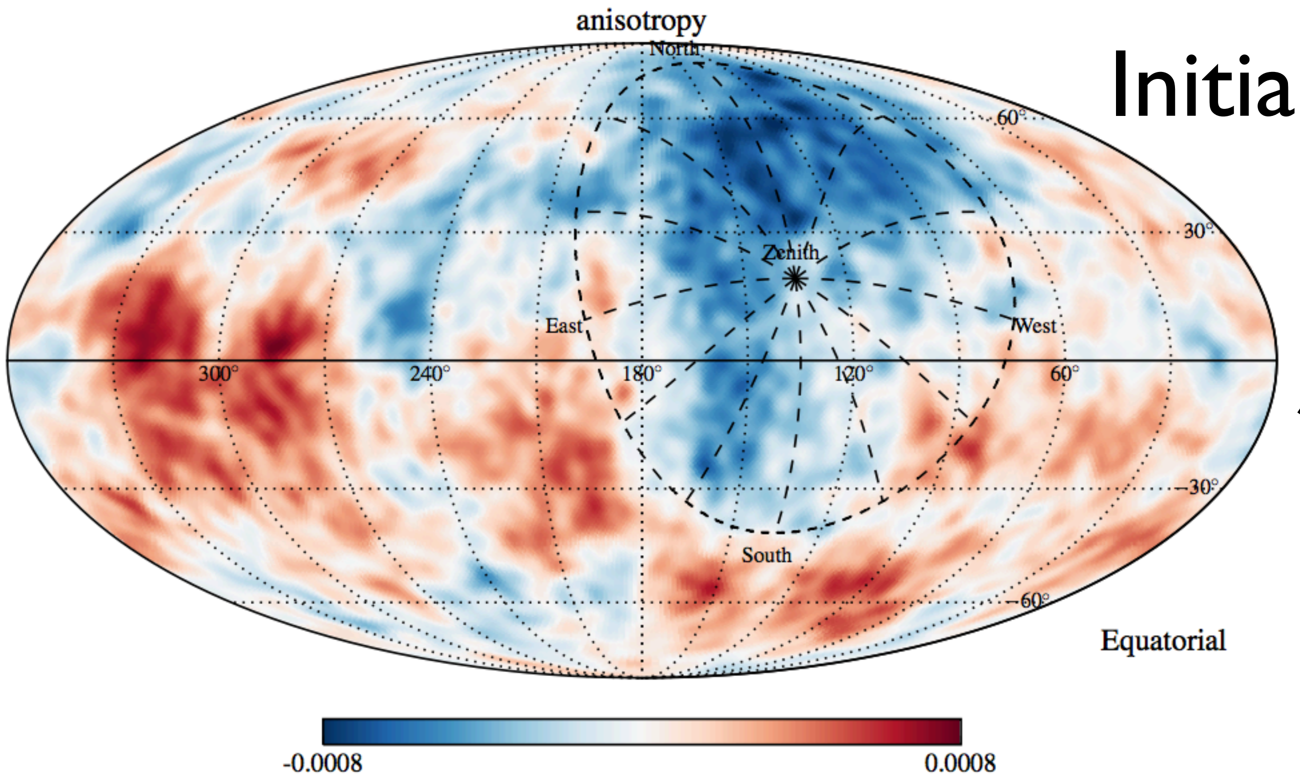
Iterations and Projection Bias



Initial anisotropy

Simulation from Ahlers et al., ApJ 2016

Iterations and Projection Bias



Initial anisotropy

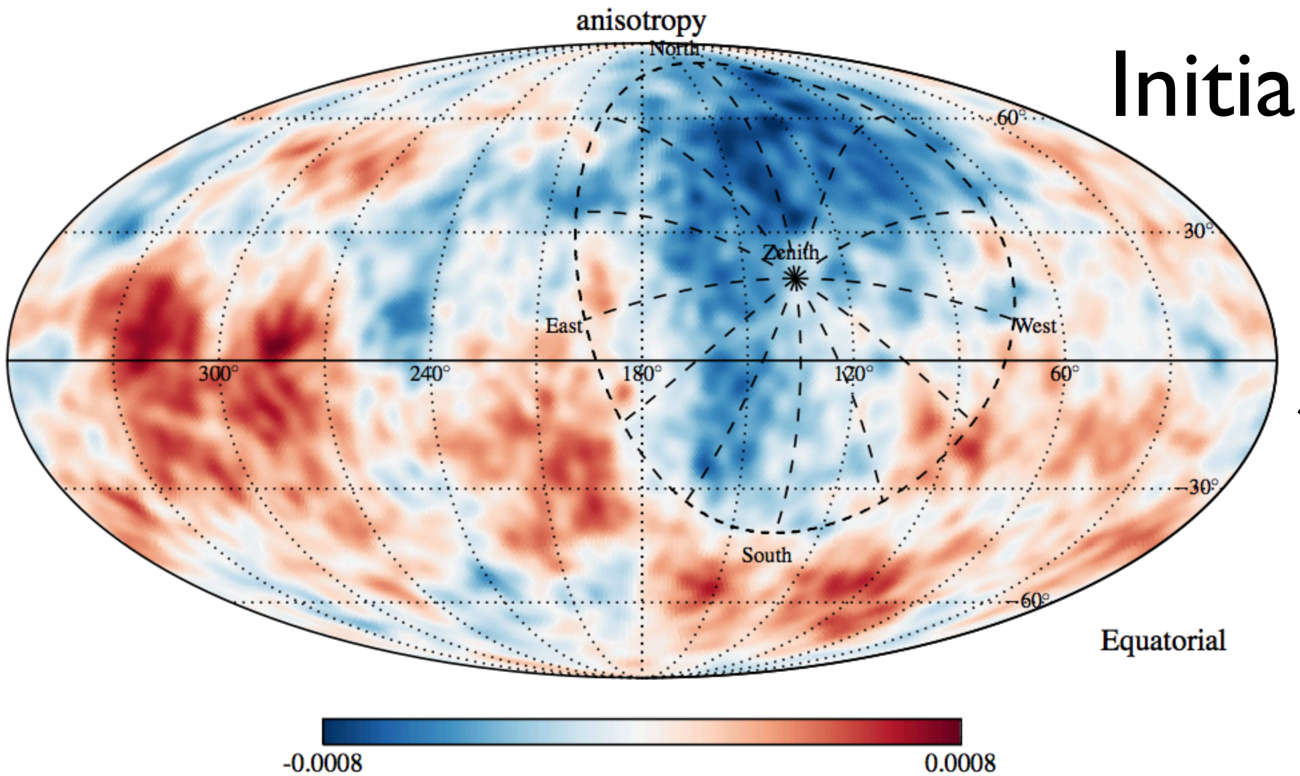
Simulation from Ahlers et al., ApJ 2016

Projection + smoothing

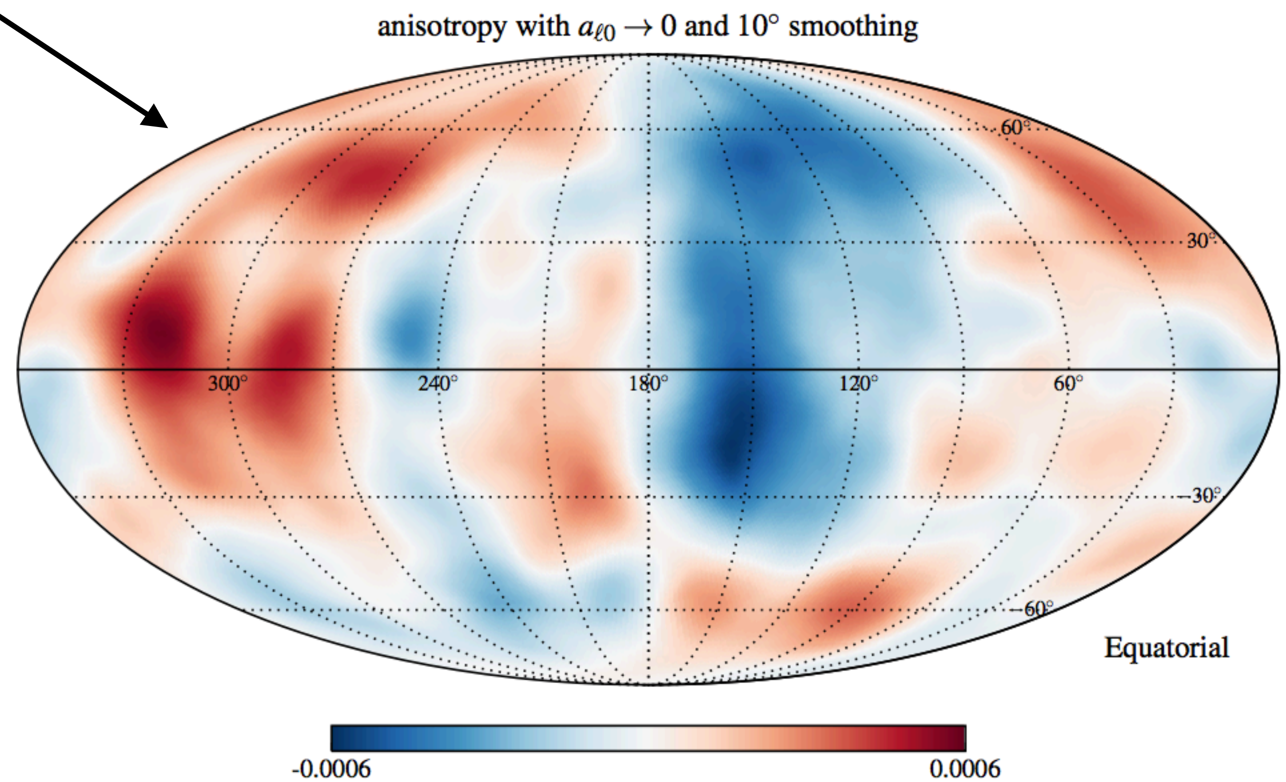
Iterations and Projection Bias

Initial anisotropy

Simulation from Ahlers et al., ApJ 2016



Projection + smoothing



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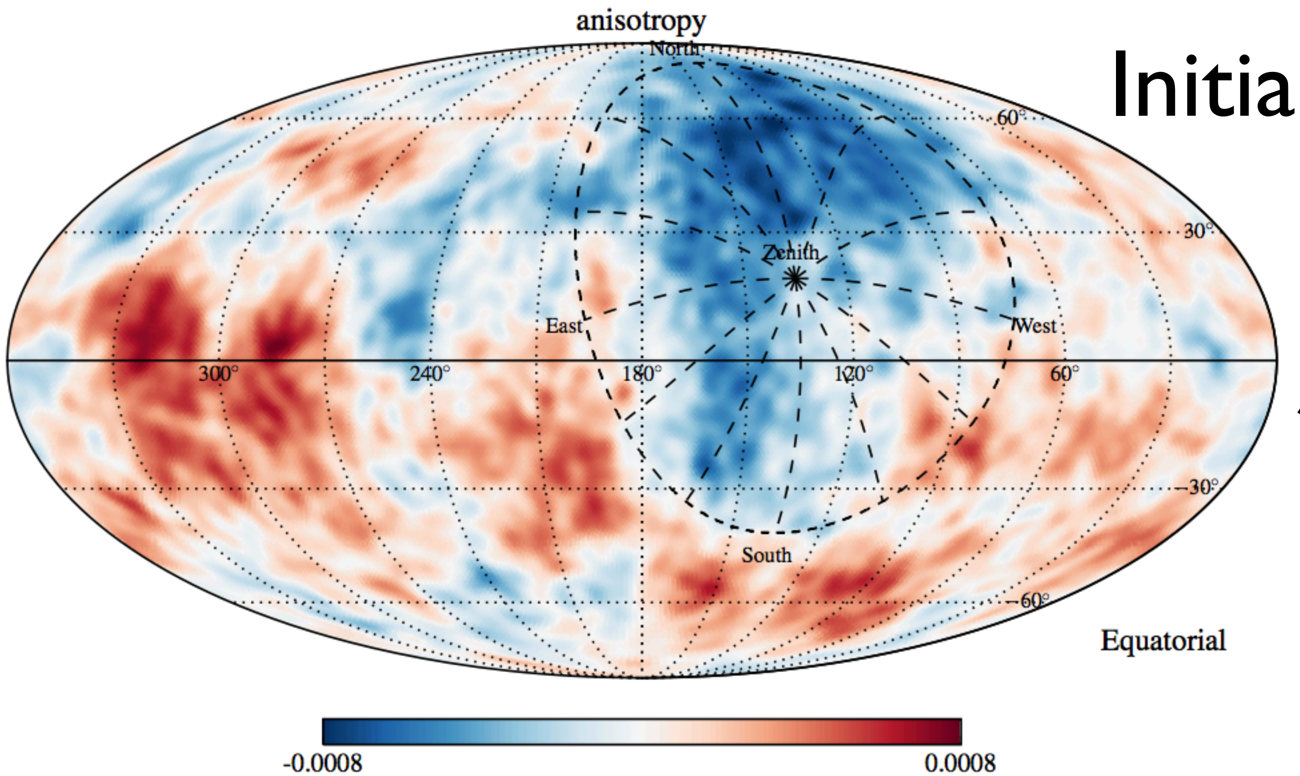

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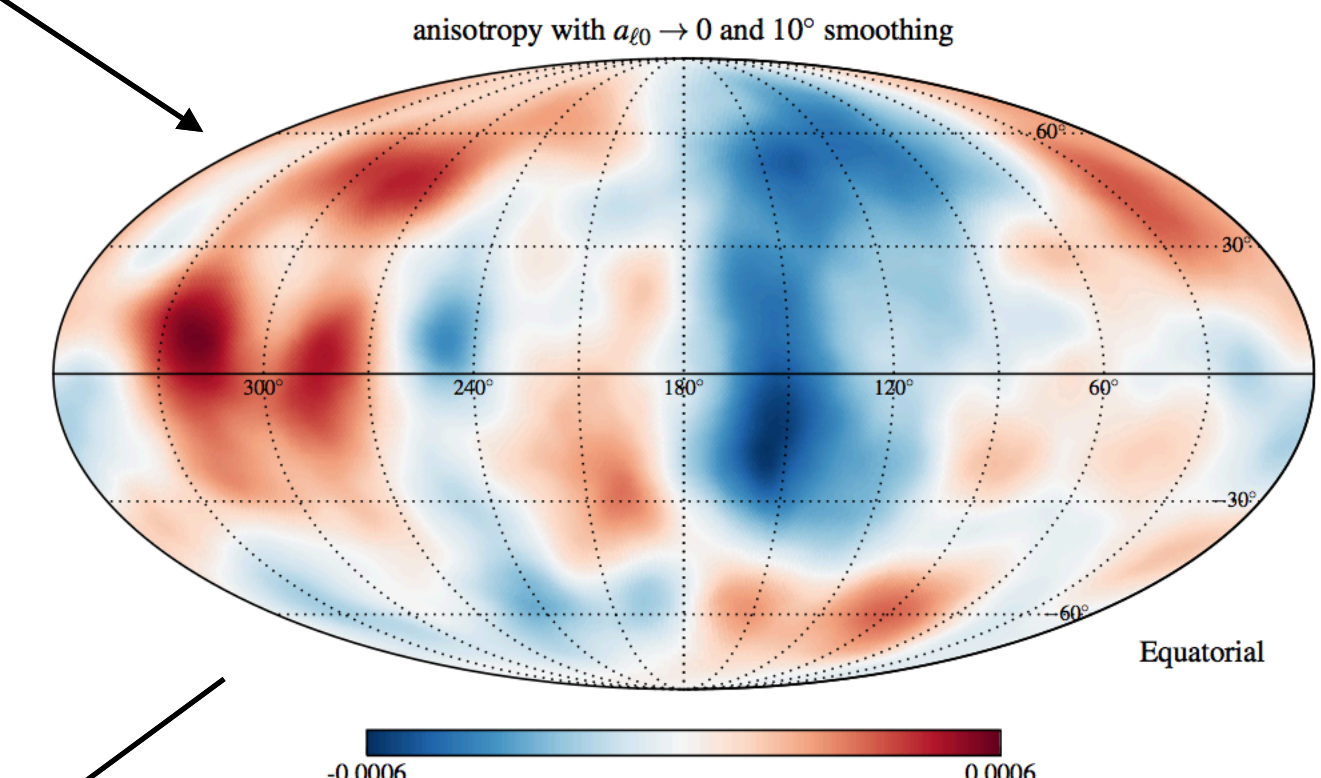
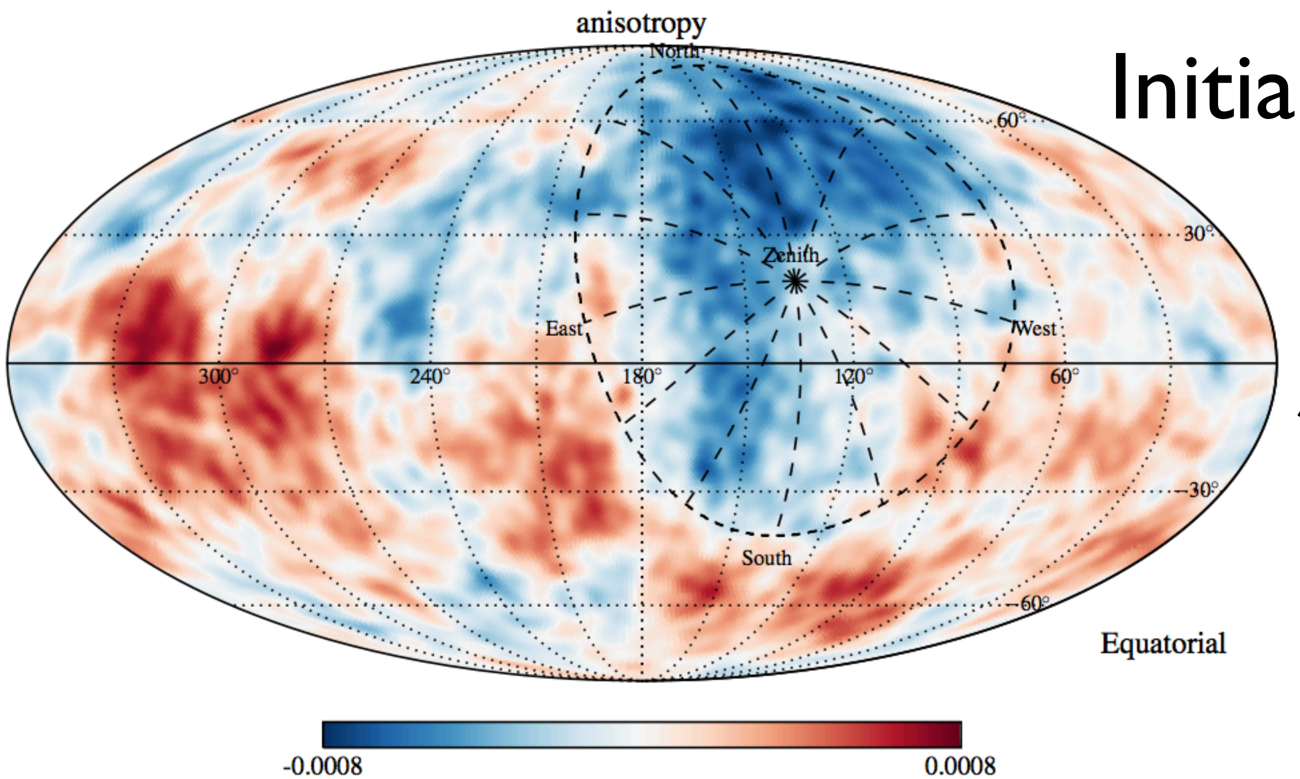


Iterative ML reconstruction

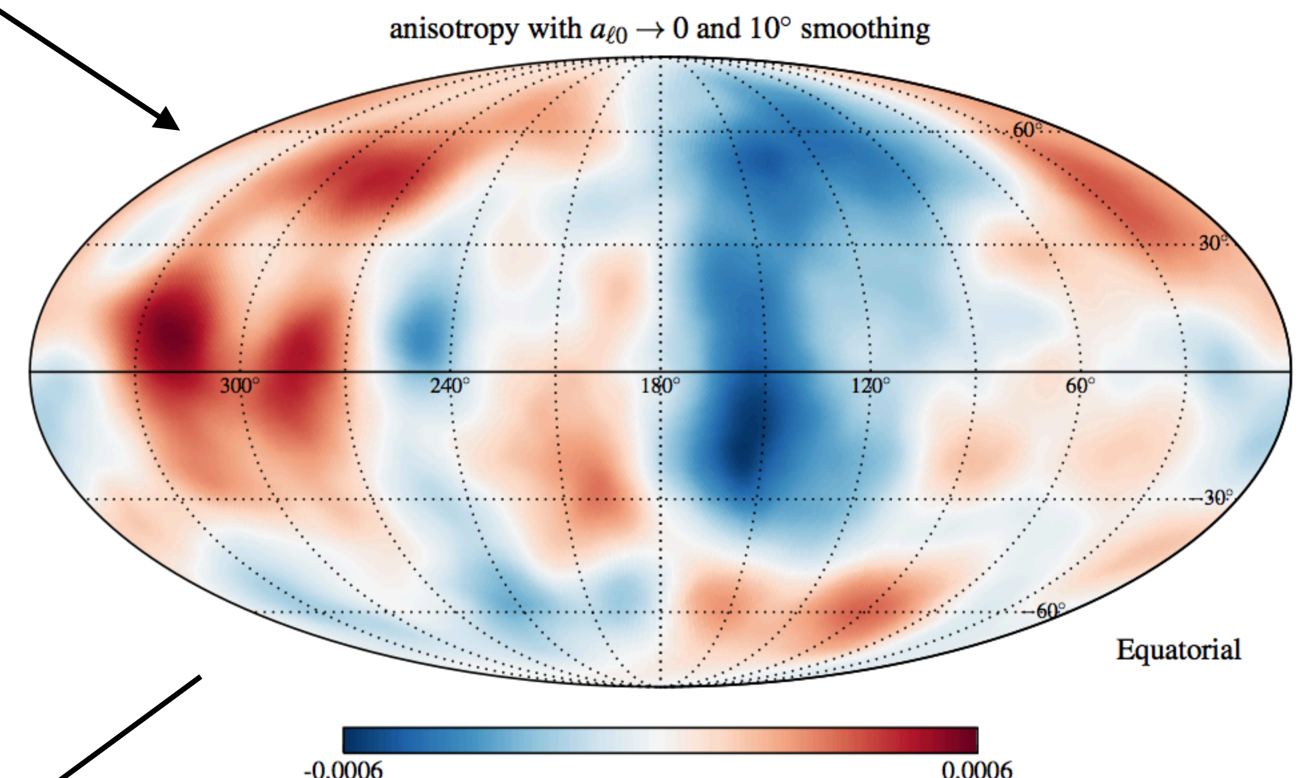
Iterations and Projection Bias

Initial anisotropy

Simulation from Ahlers et al., ApJ 2016



Projection + smoothing



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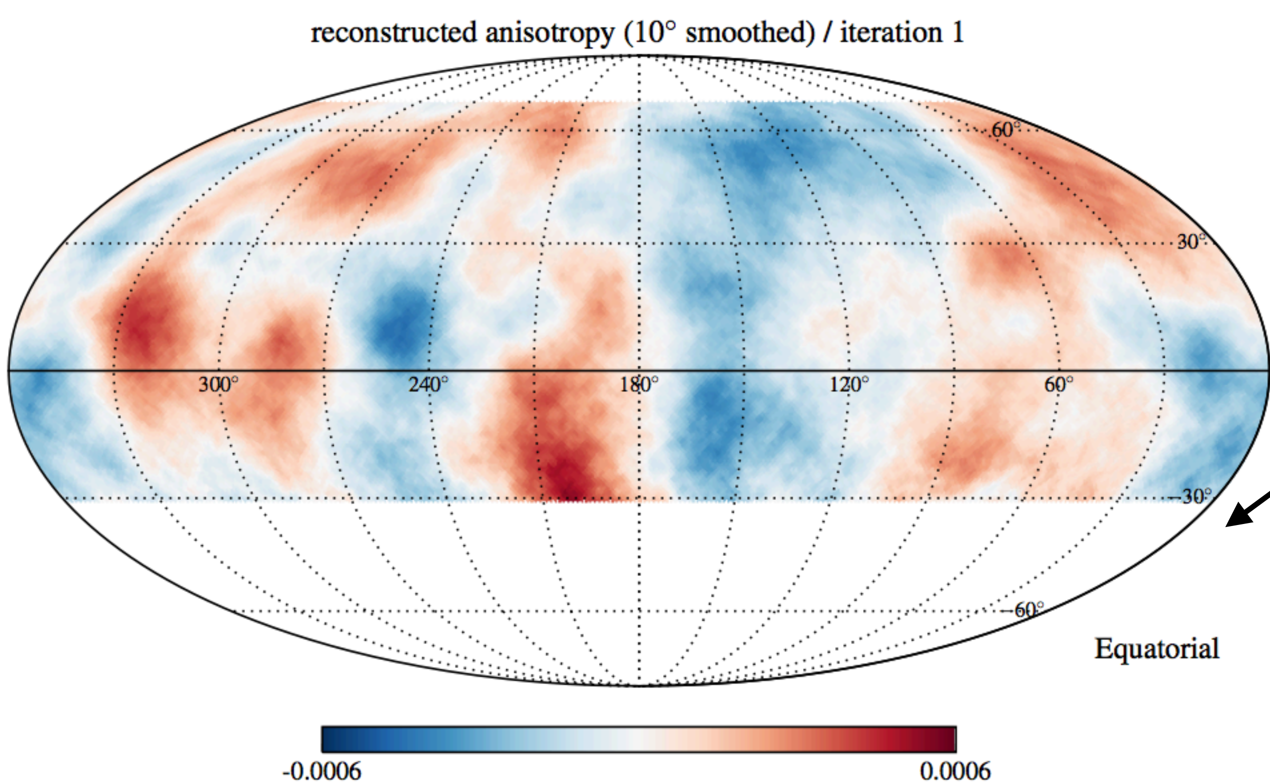

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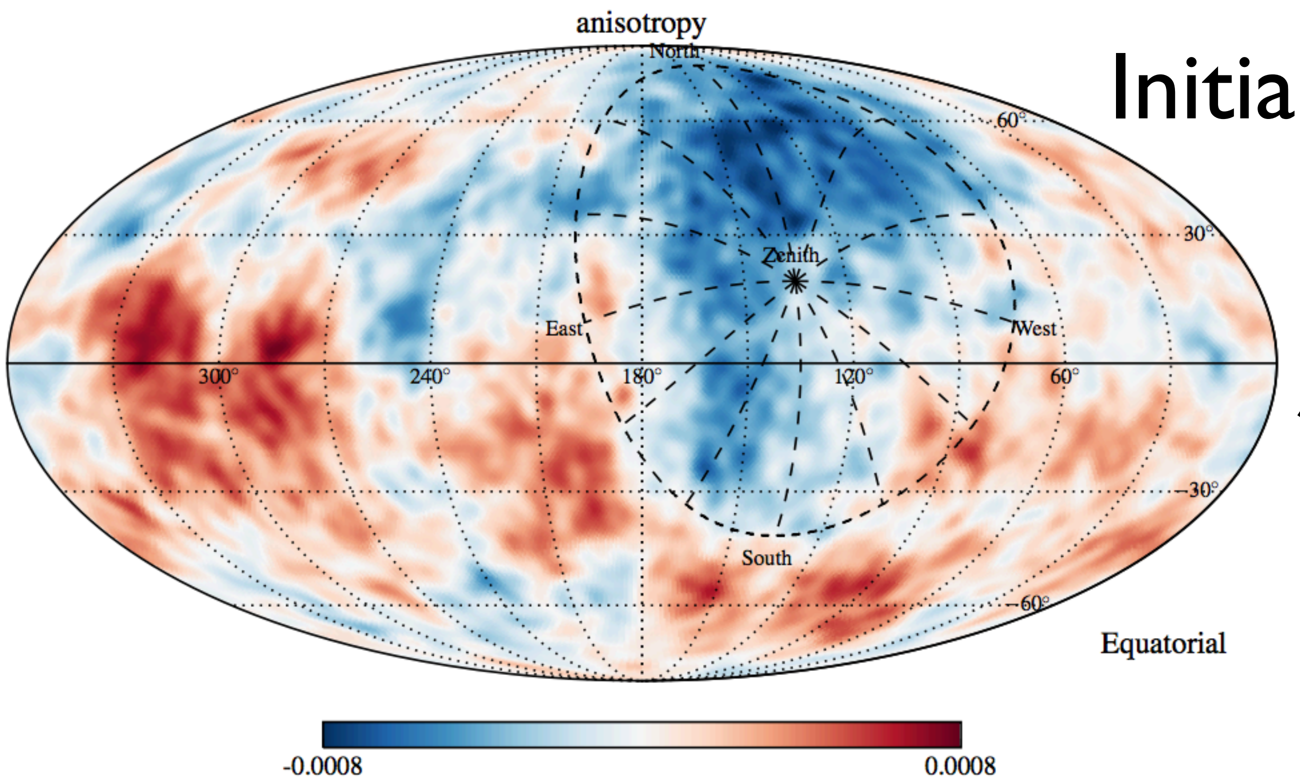

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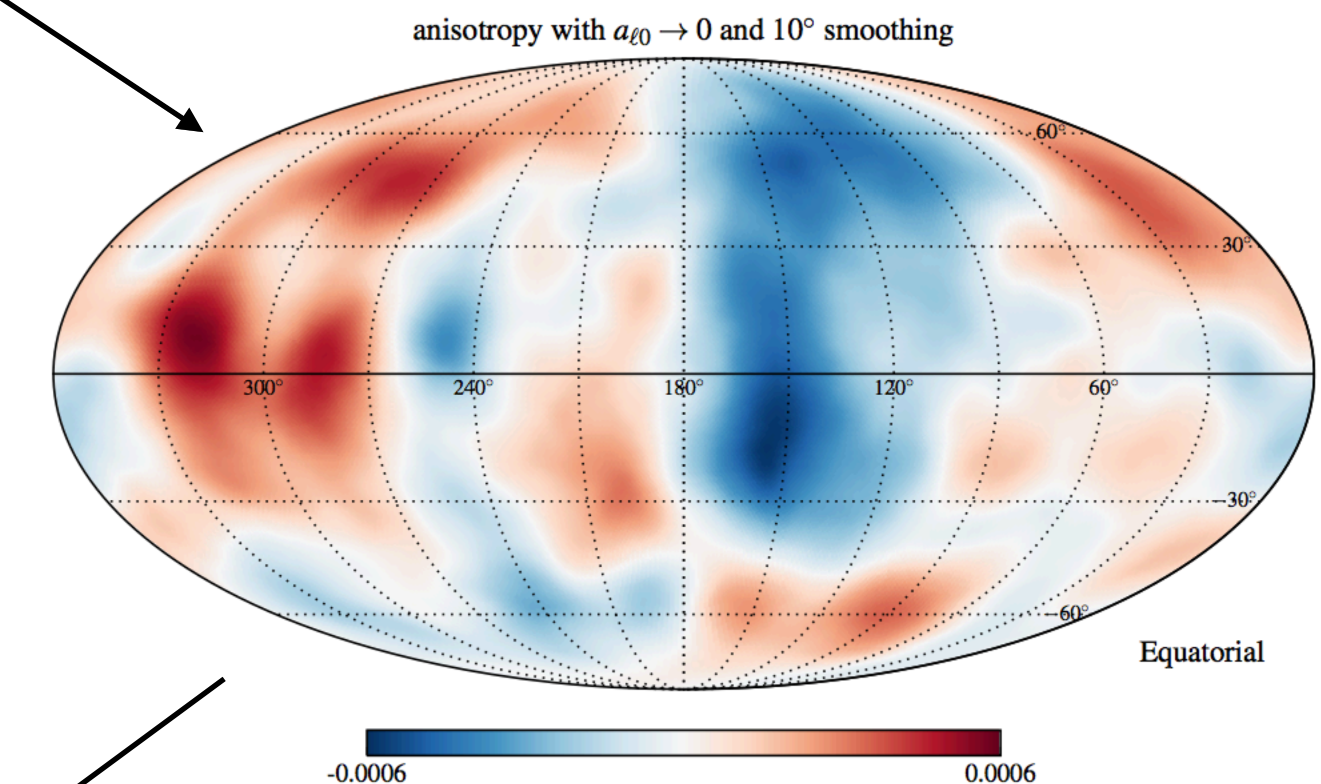
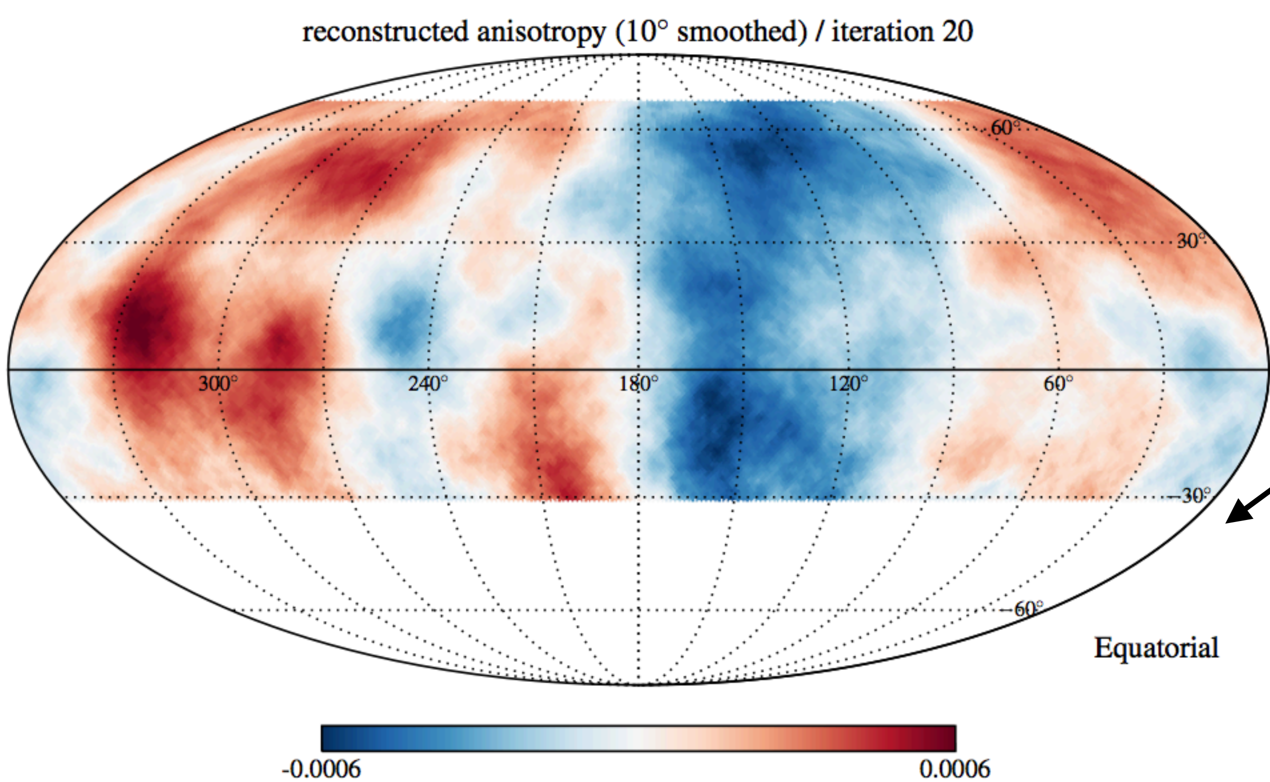


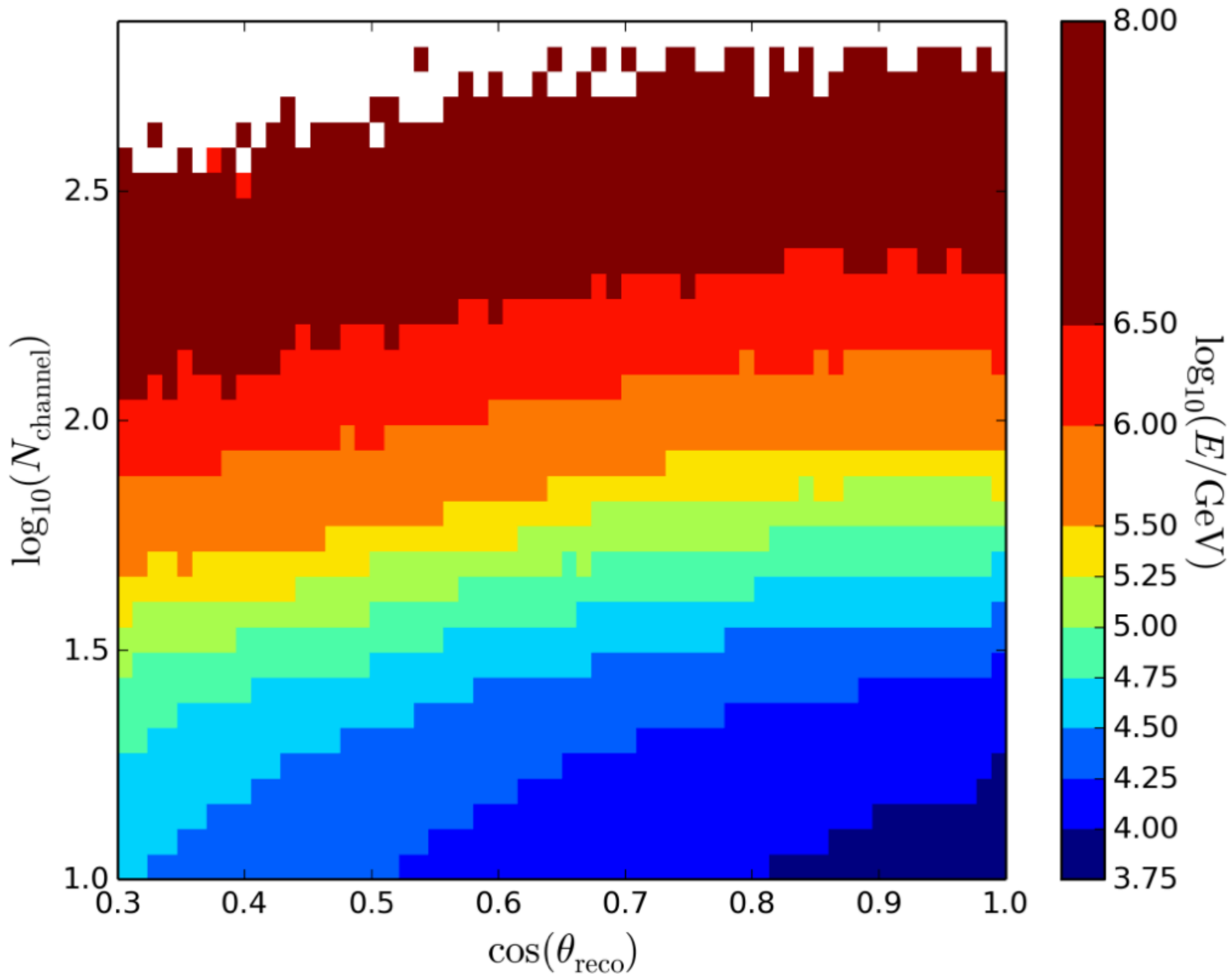


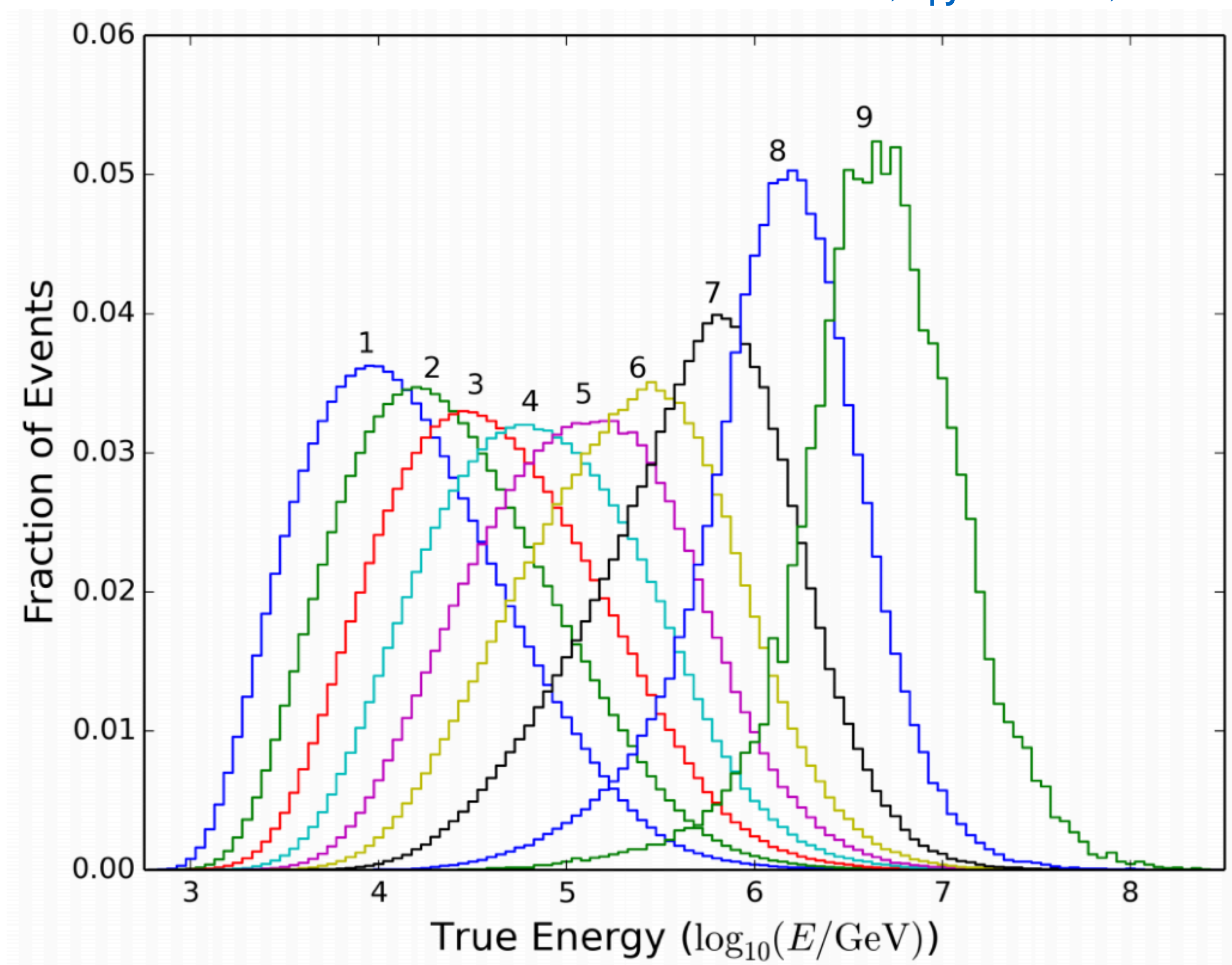
Iterative ML reconstruction

Energy Estimators

- Another point of caution: the experiments with high statistics tend to have relatively poor energy resolution. For example:

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

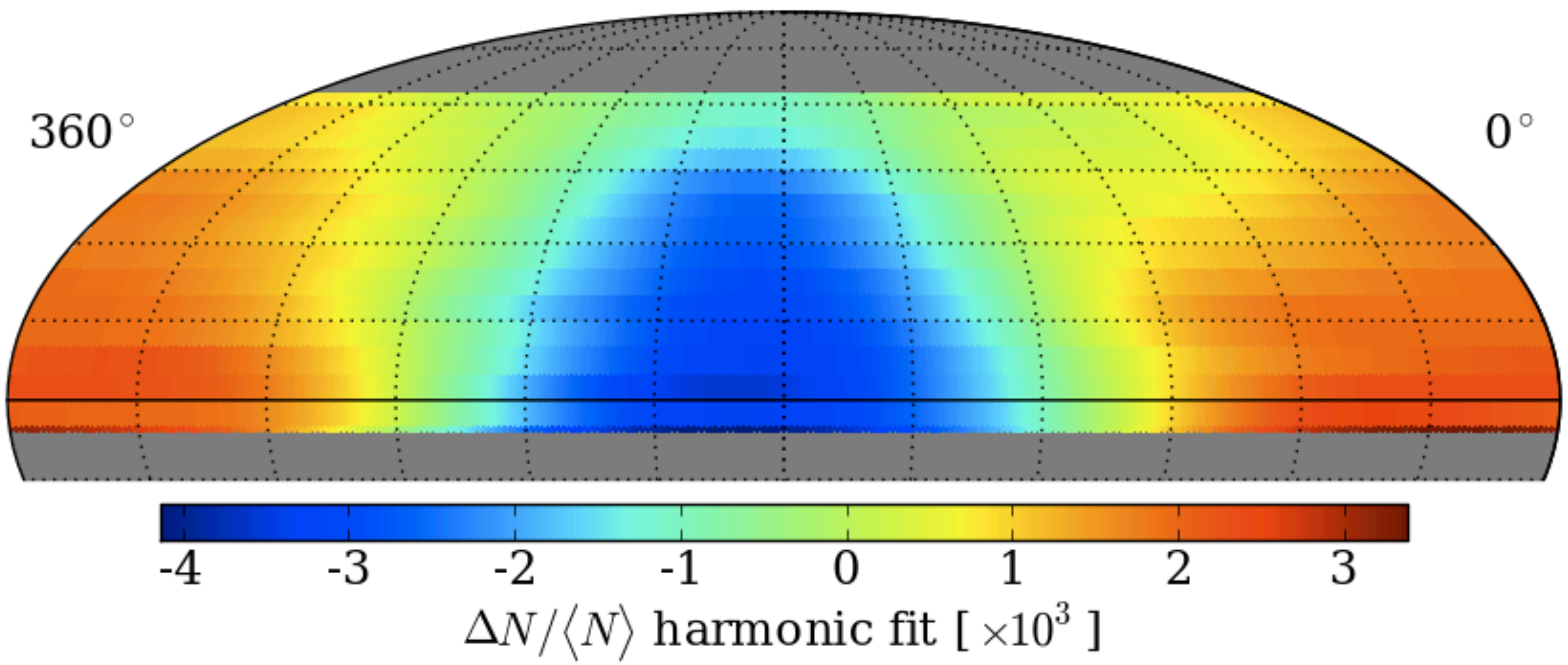




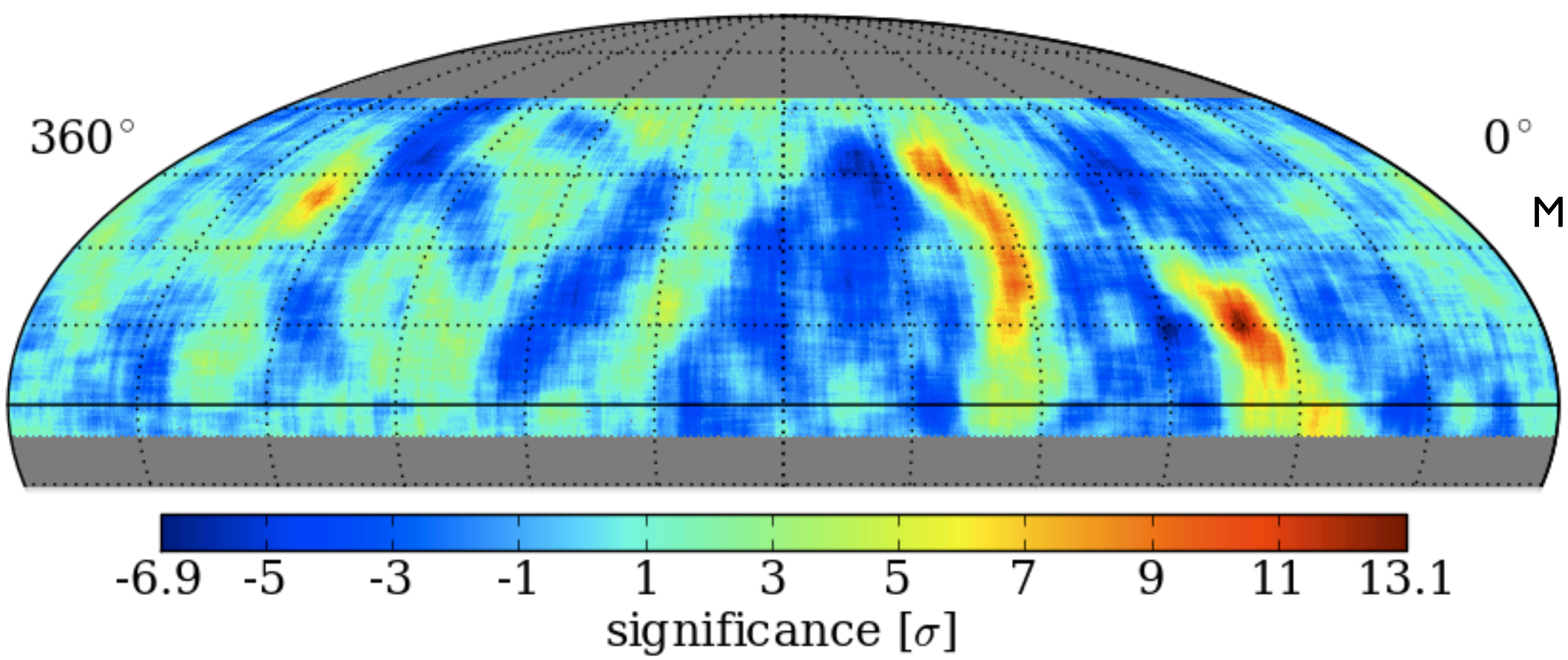
Outline of Current Results

- 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



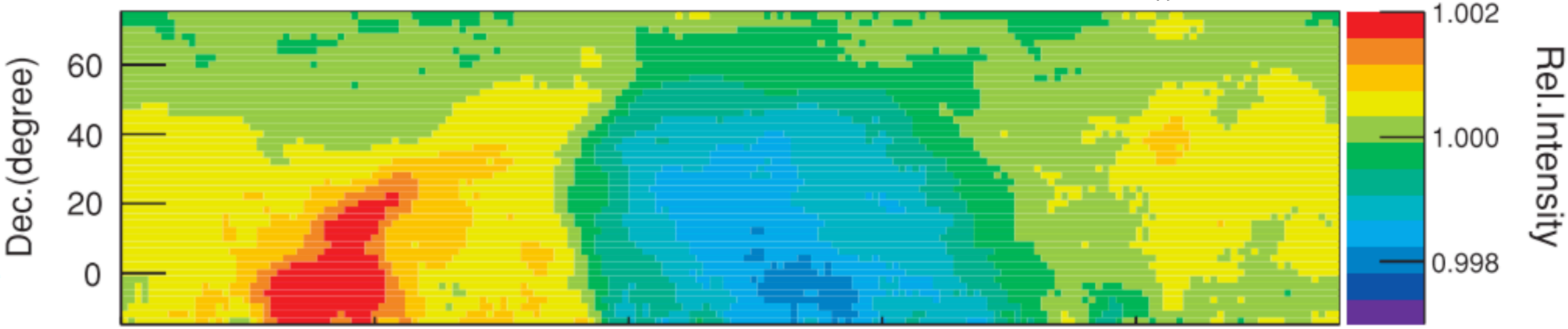
Milagro Collaboration, ApJ **698**:2121, 2009

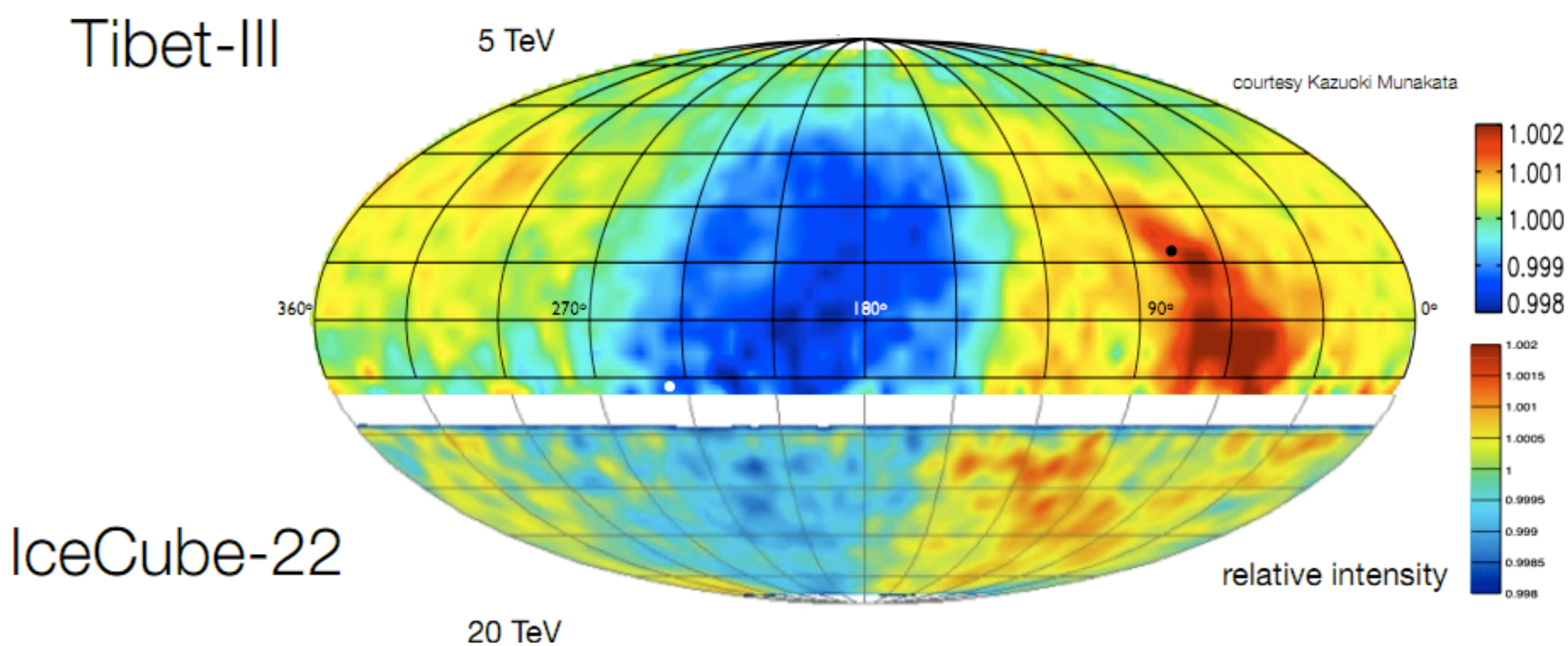


Milagro Collaboration, PRL **101**:221101, 2008

Anisotropy: Tibet

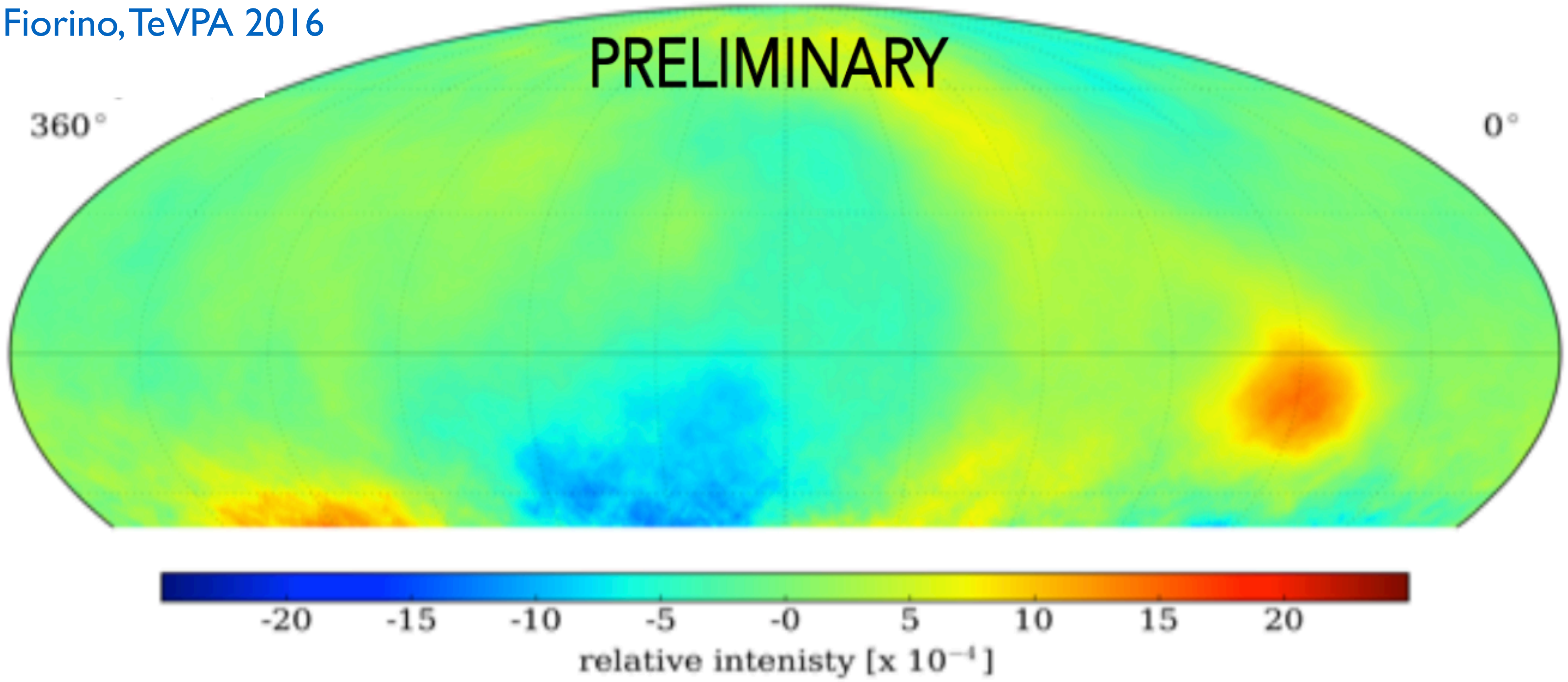
M. Amenomori et al., ApJ **711**:119, 2010

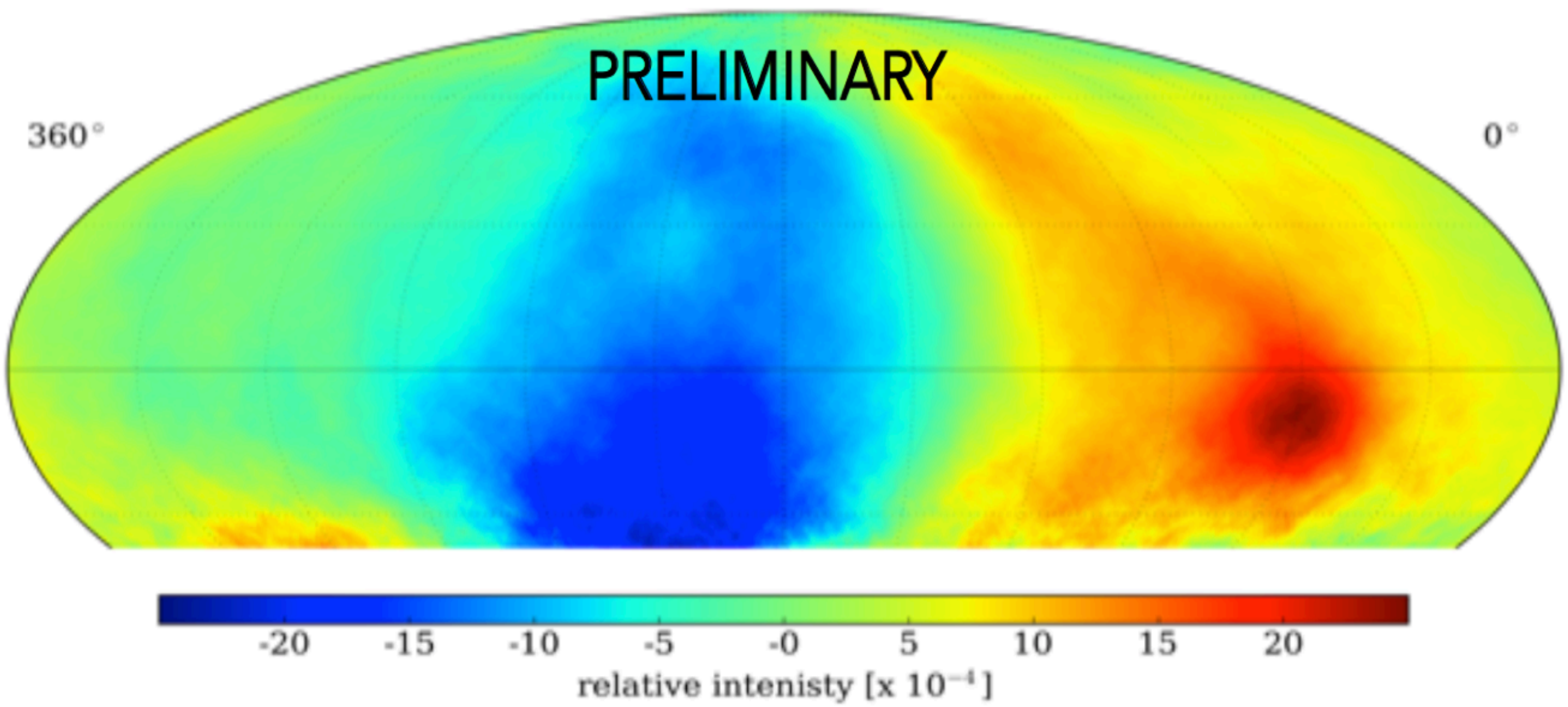




Anisotropy: HAWC

D. Fiorino, TeVPA 2016

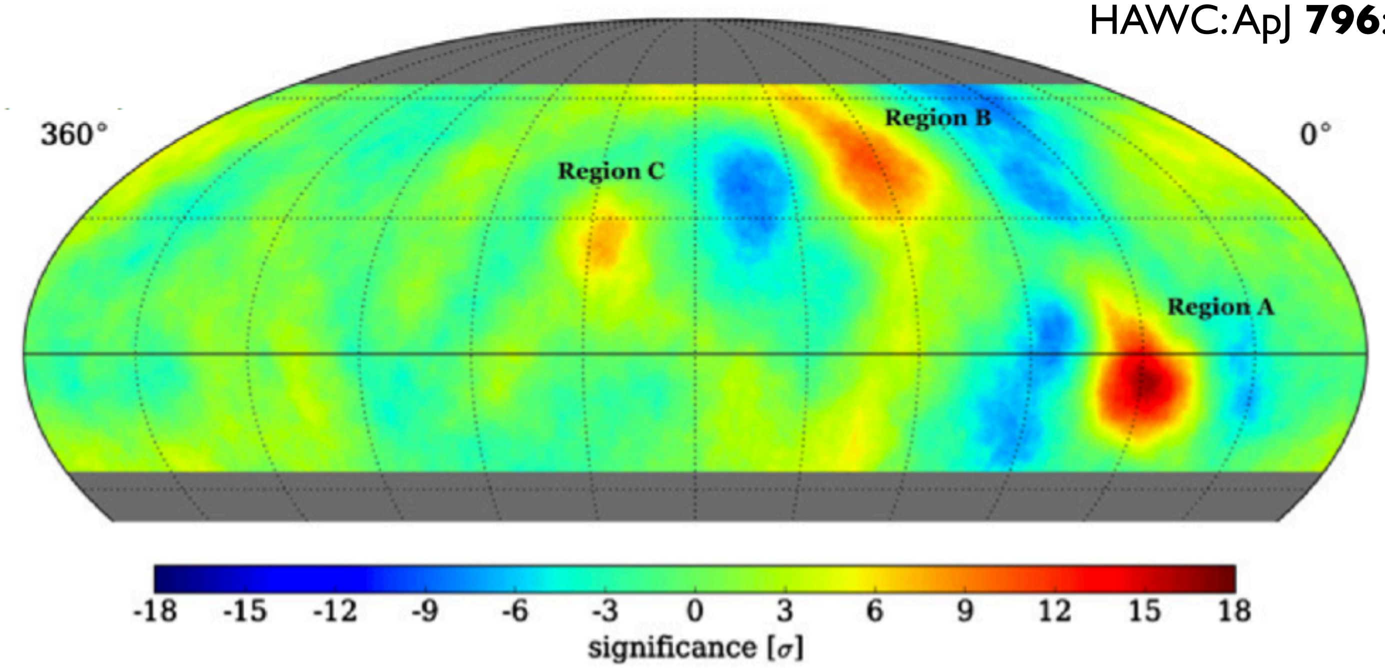




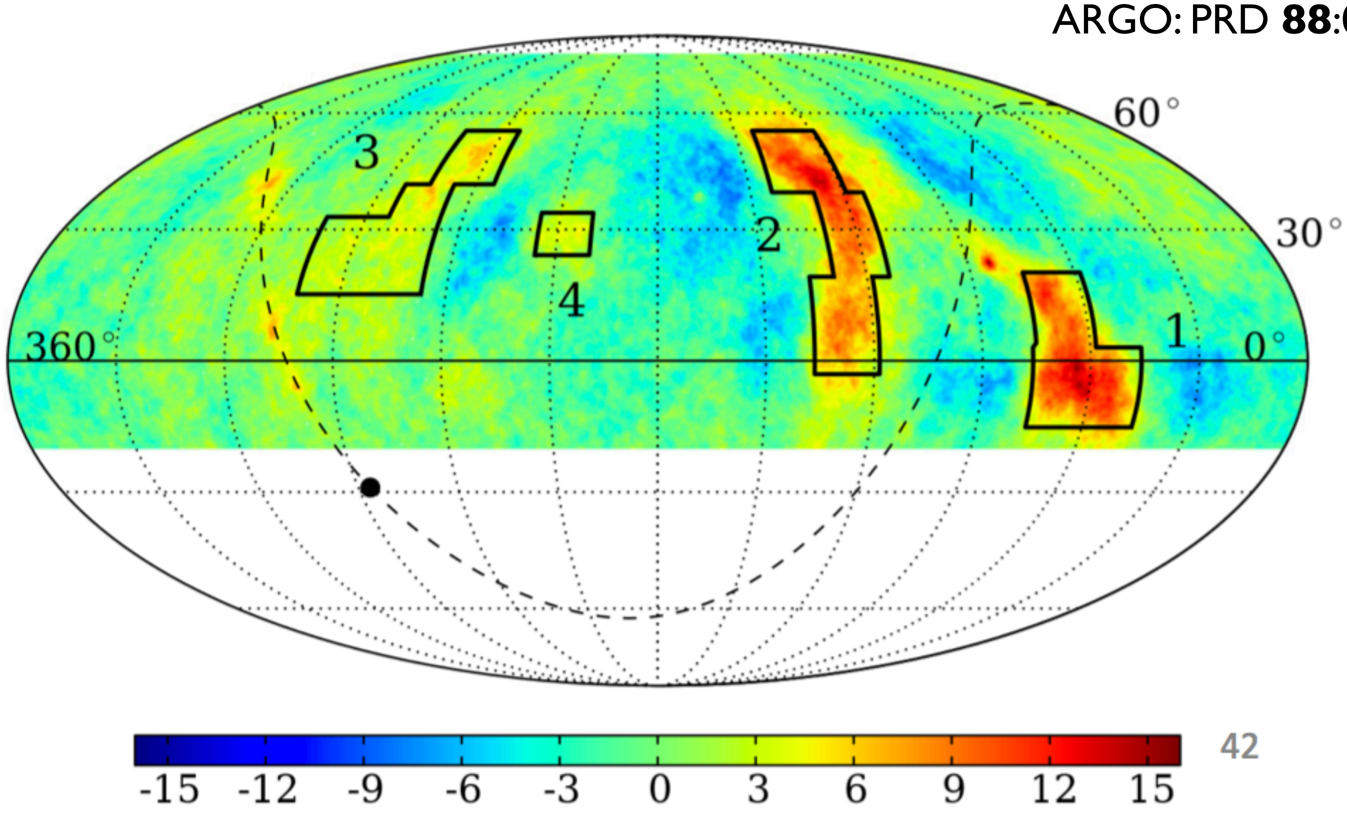
- Data: HAWC-100
- Top: direct integration without iterations
- Bottom: direct integration after 10 iterations
- Factor 2x enhancement in measured flux

Small-Scale Structure

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

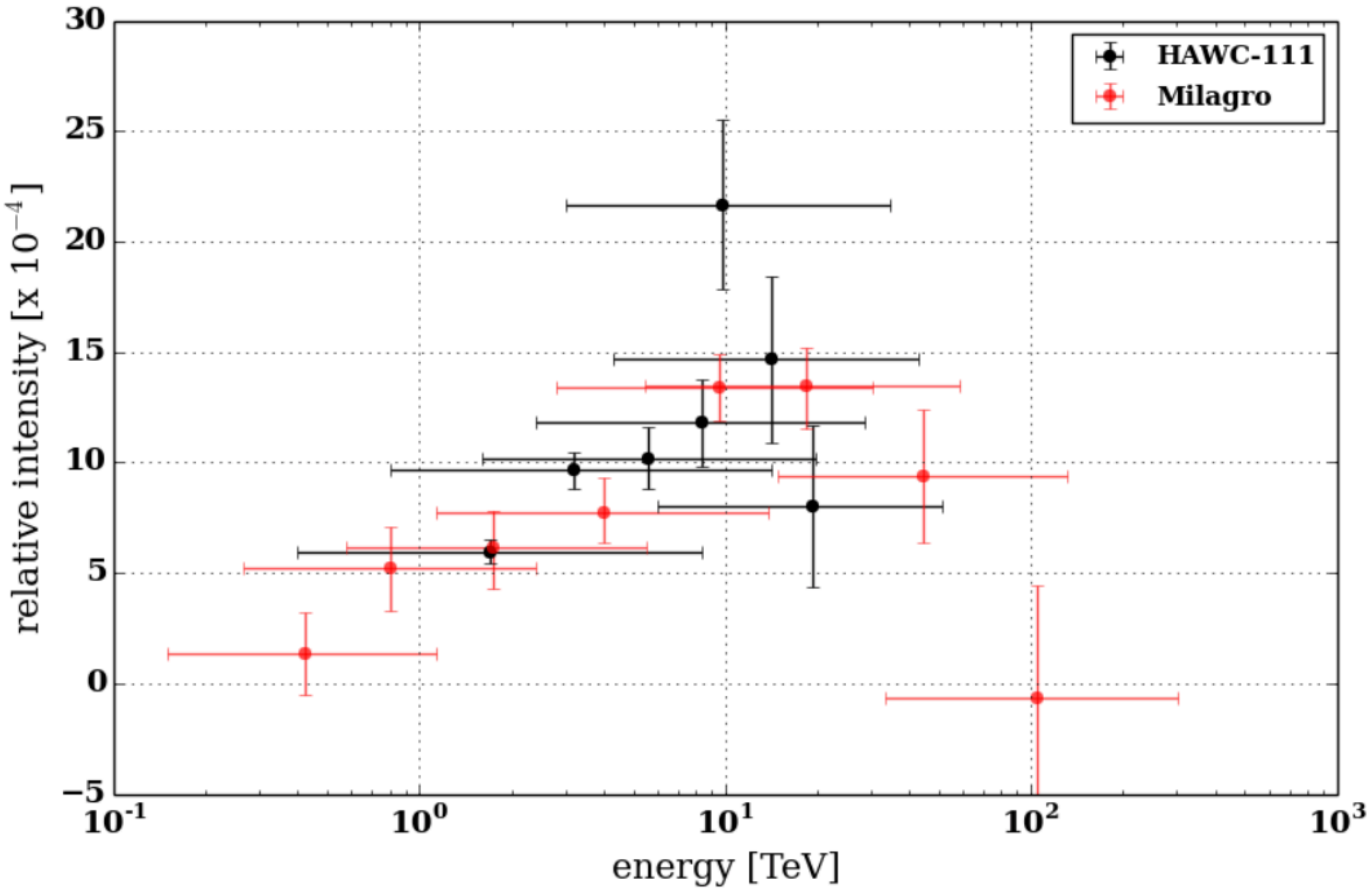


ARGO: PRD **88**:082001, 2013



- 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



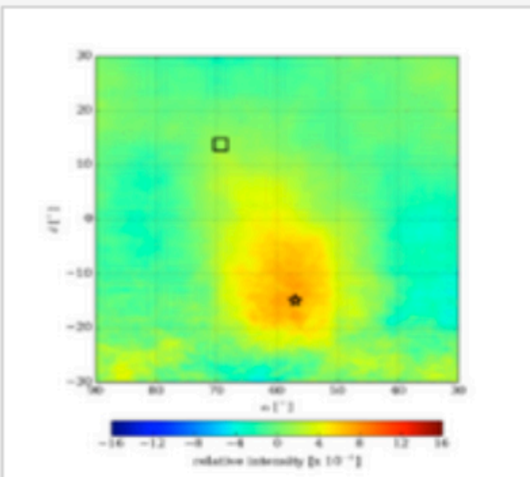
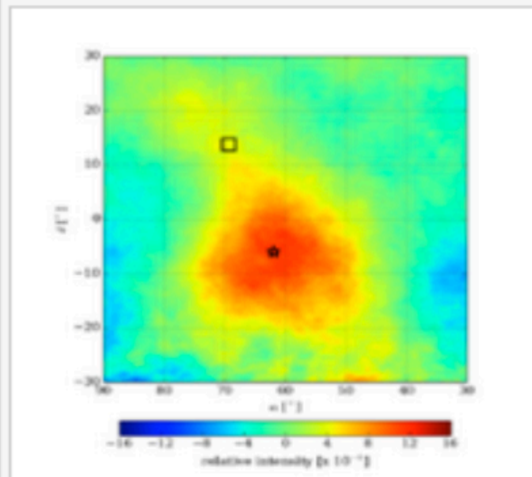
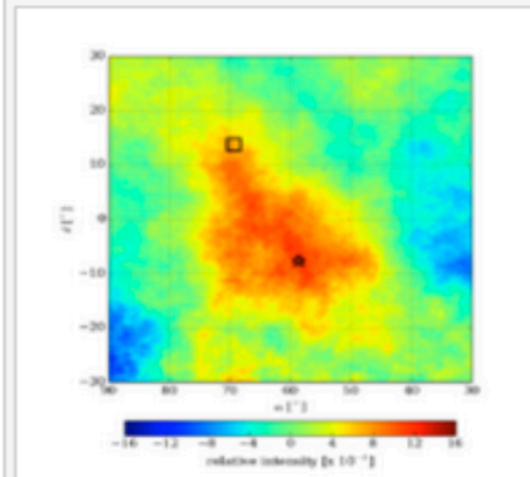
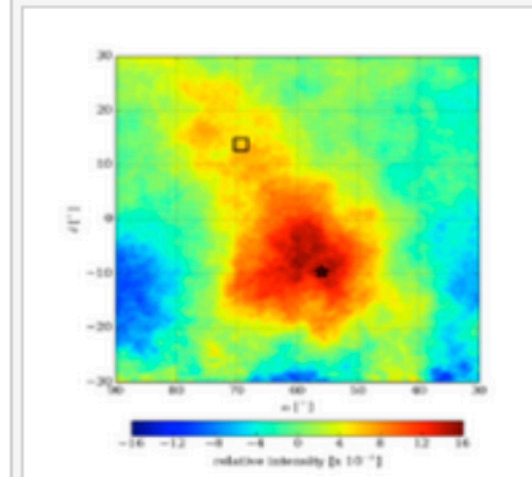
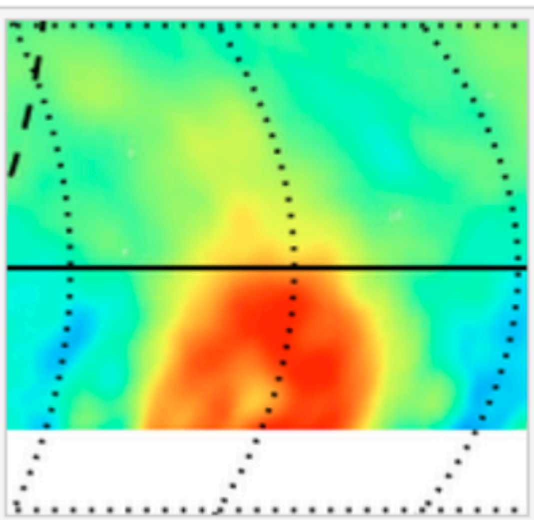
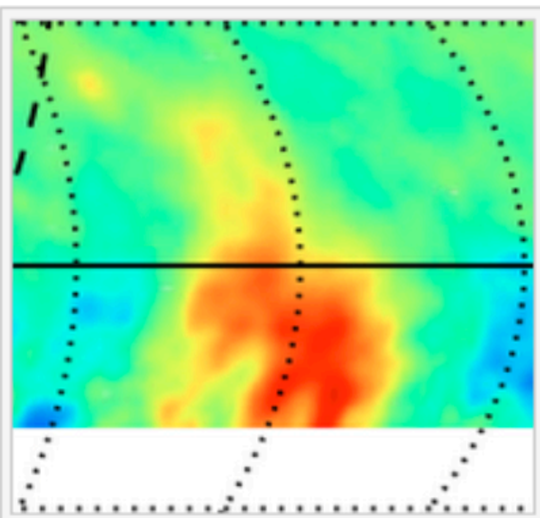
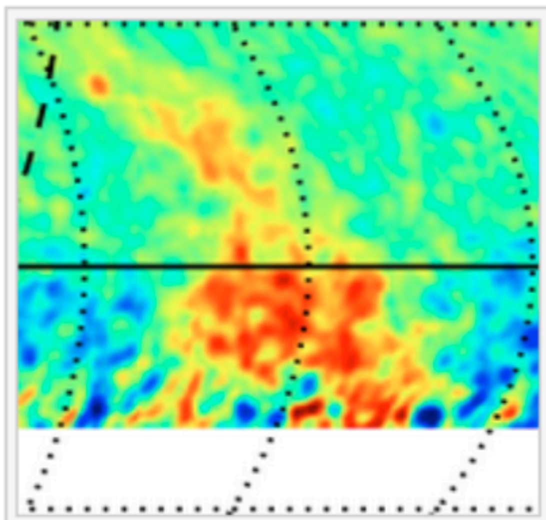
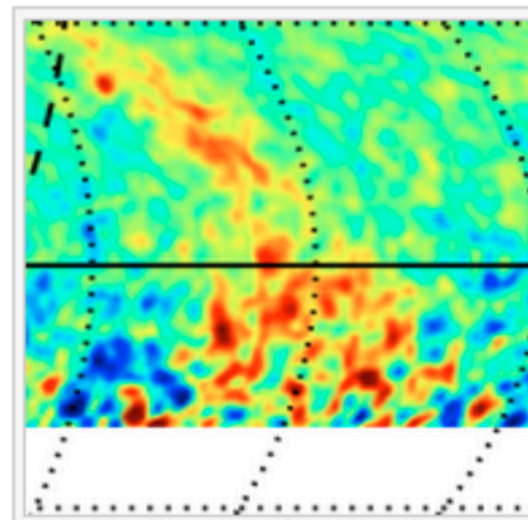
Milagro:
PRL **101**:221101, 2008

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

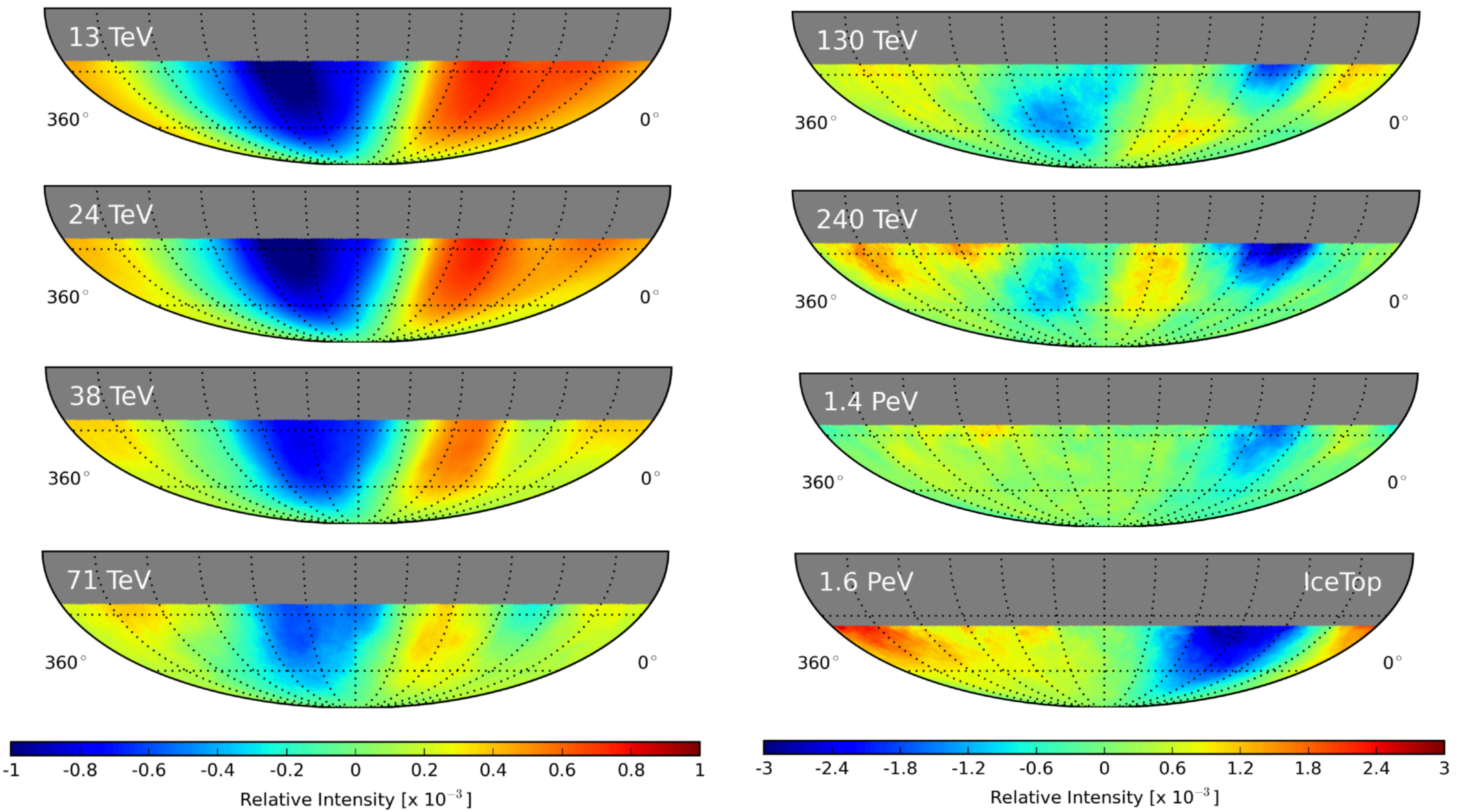
- Pseudo-spectrum of region A using energy proxy bins
- Milagro and HAWC observe a hard spectrum w.r.t. isotropic flux; 4σ effect after trials

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

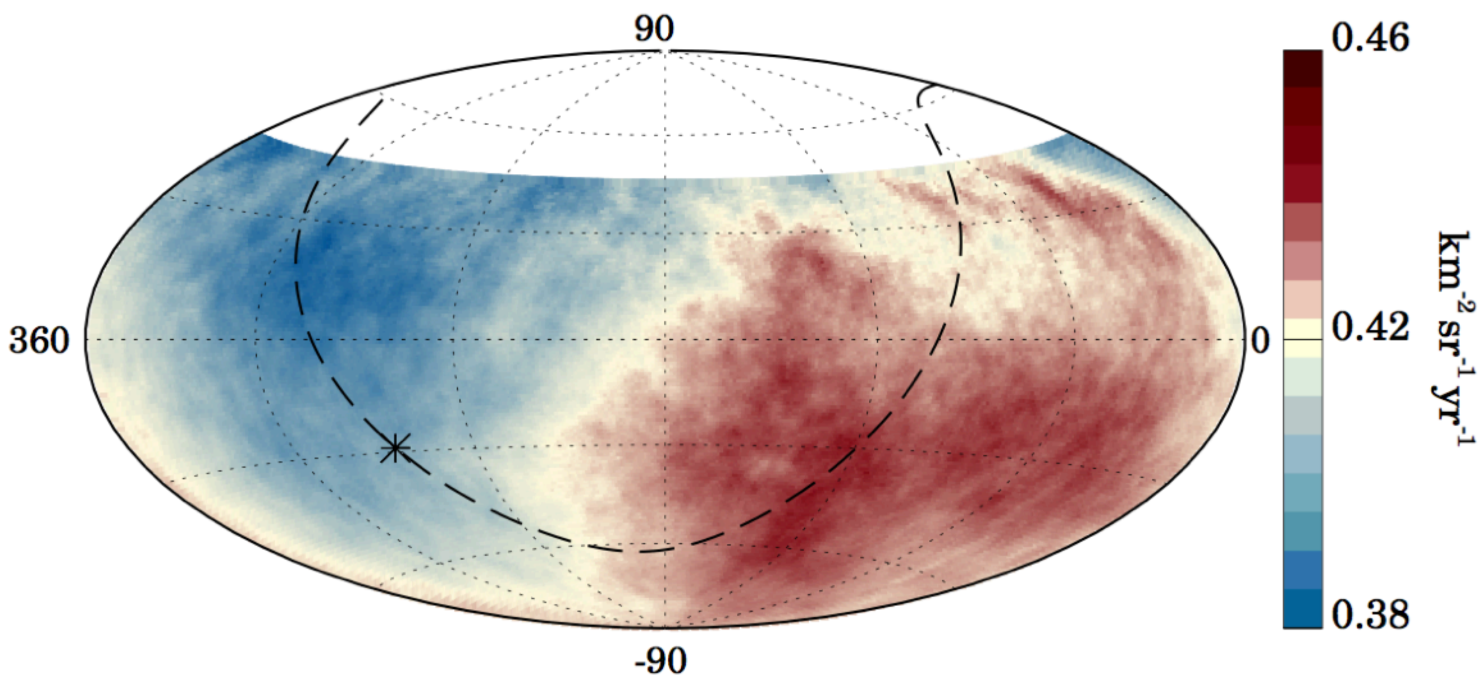
Energy Dependence: IceCube

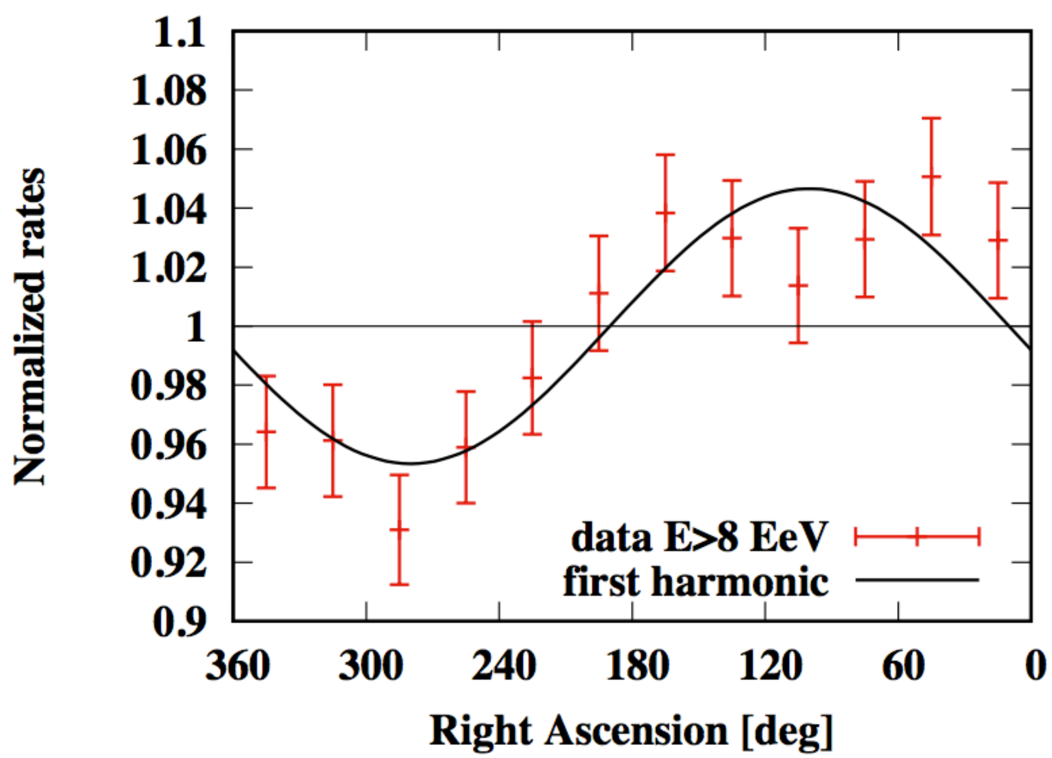


Large Scale Anisotropy: Auger

- Recent big news: 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

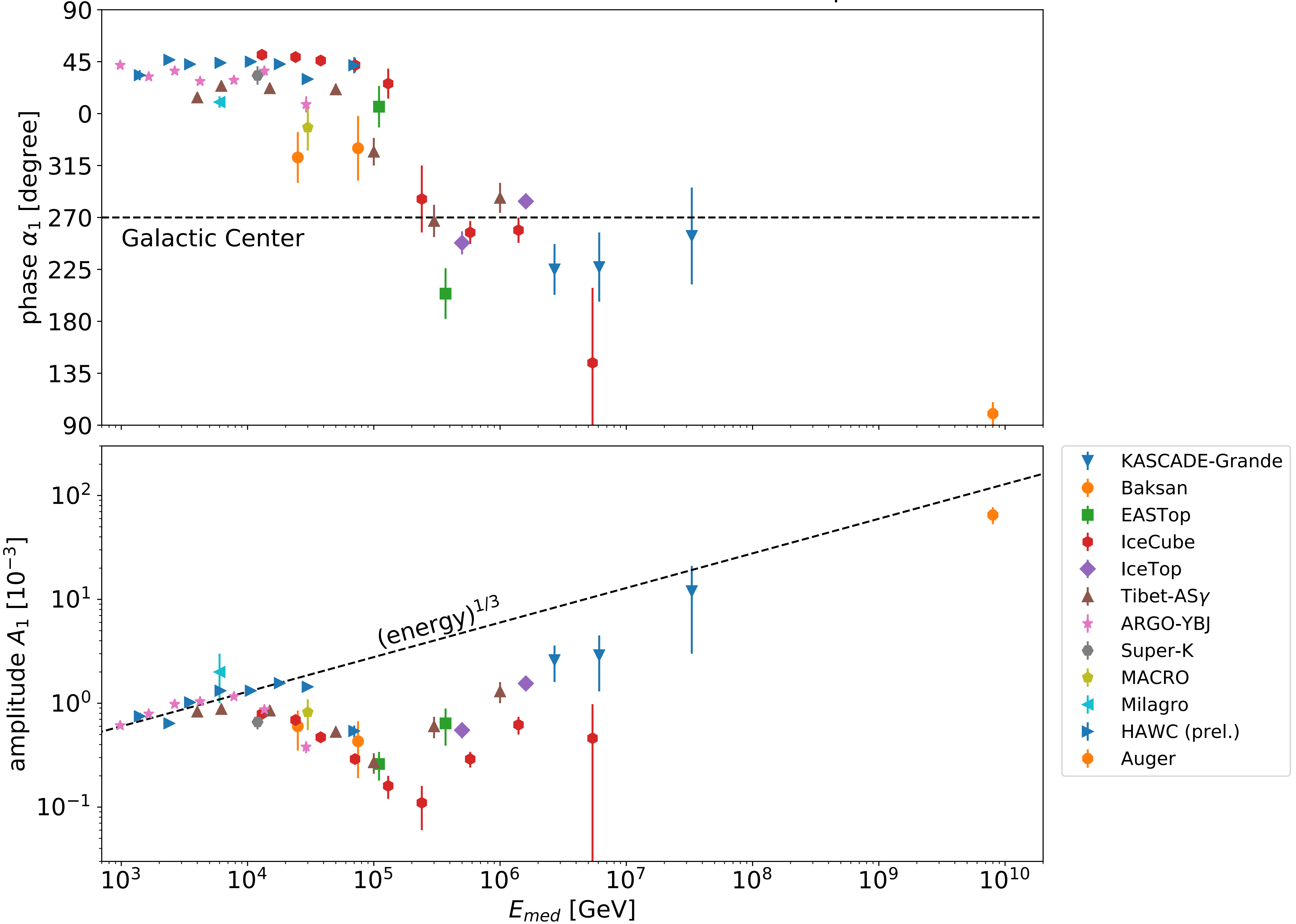
Auger Collab., Science **357**:1266 (2017)





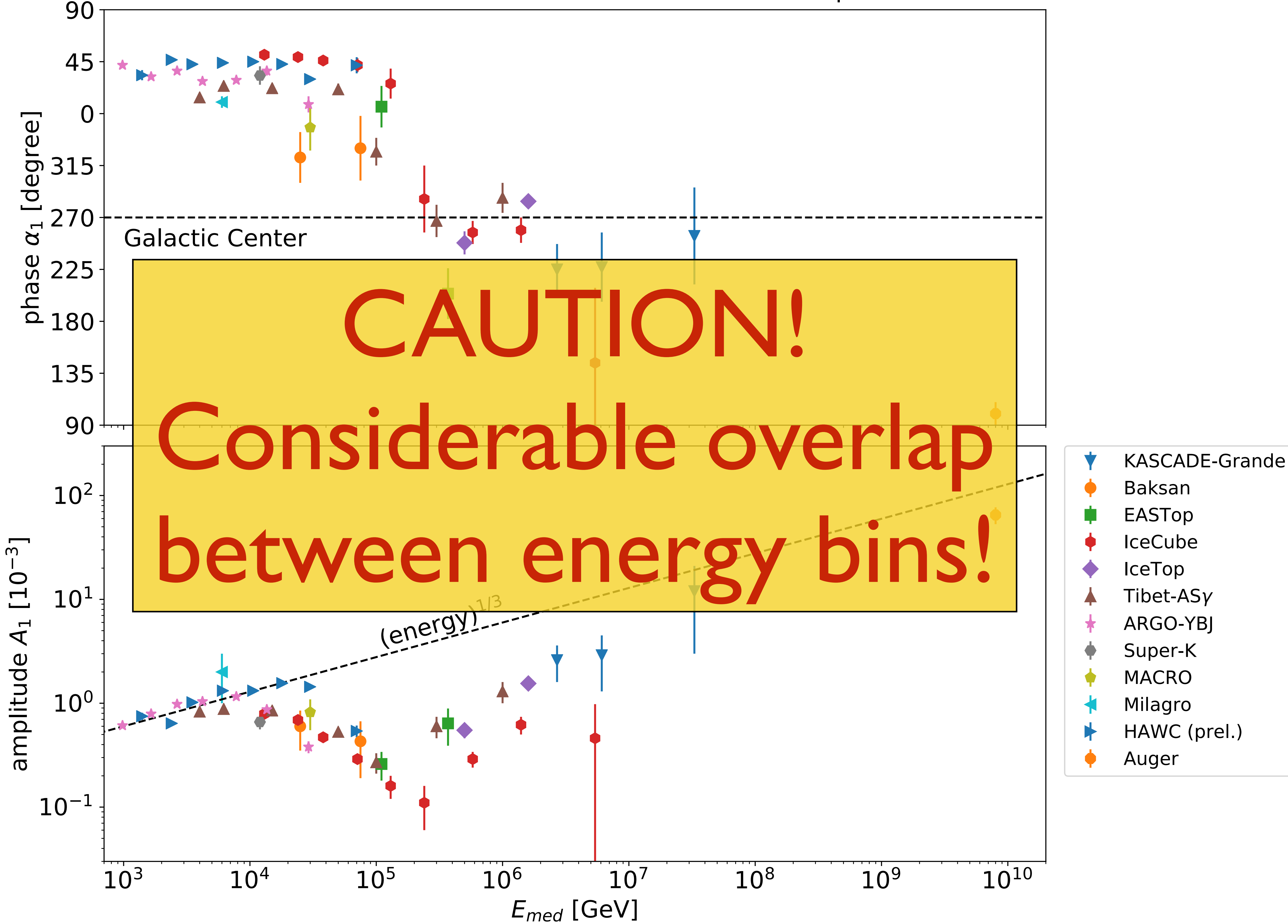
Energy Dependence

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



Energy Dependence

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



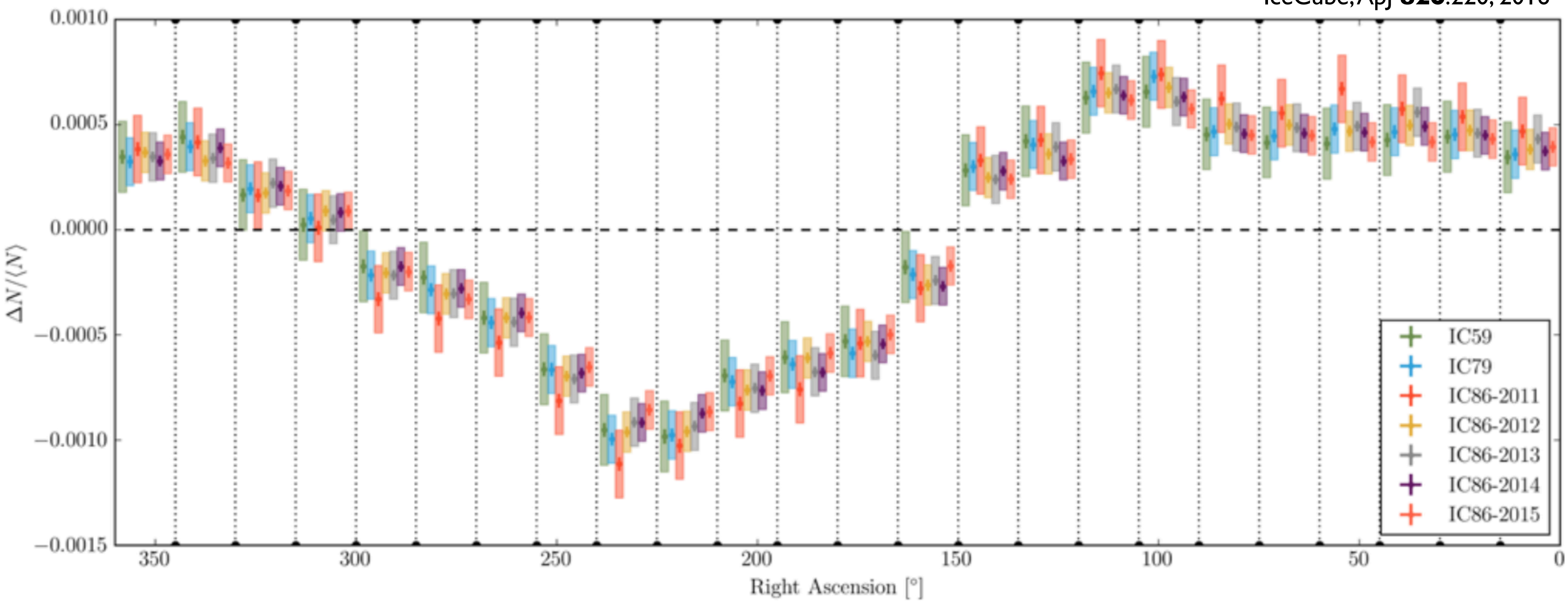
CAUTION!

Considerable overlap between energy bins!

Time Dependence

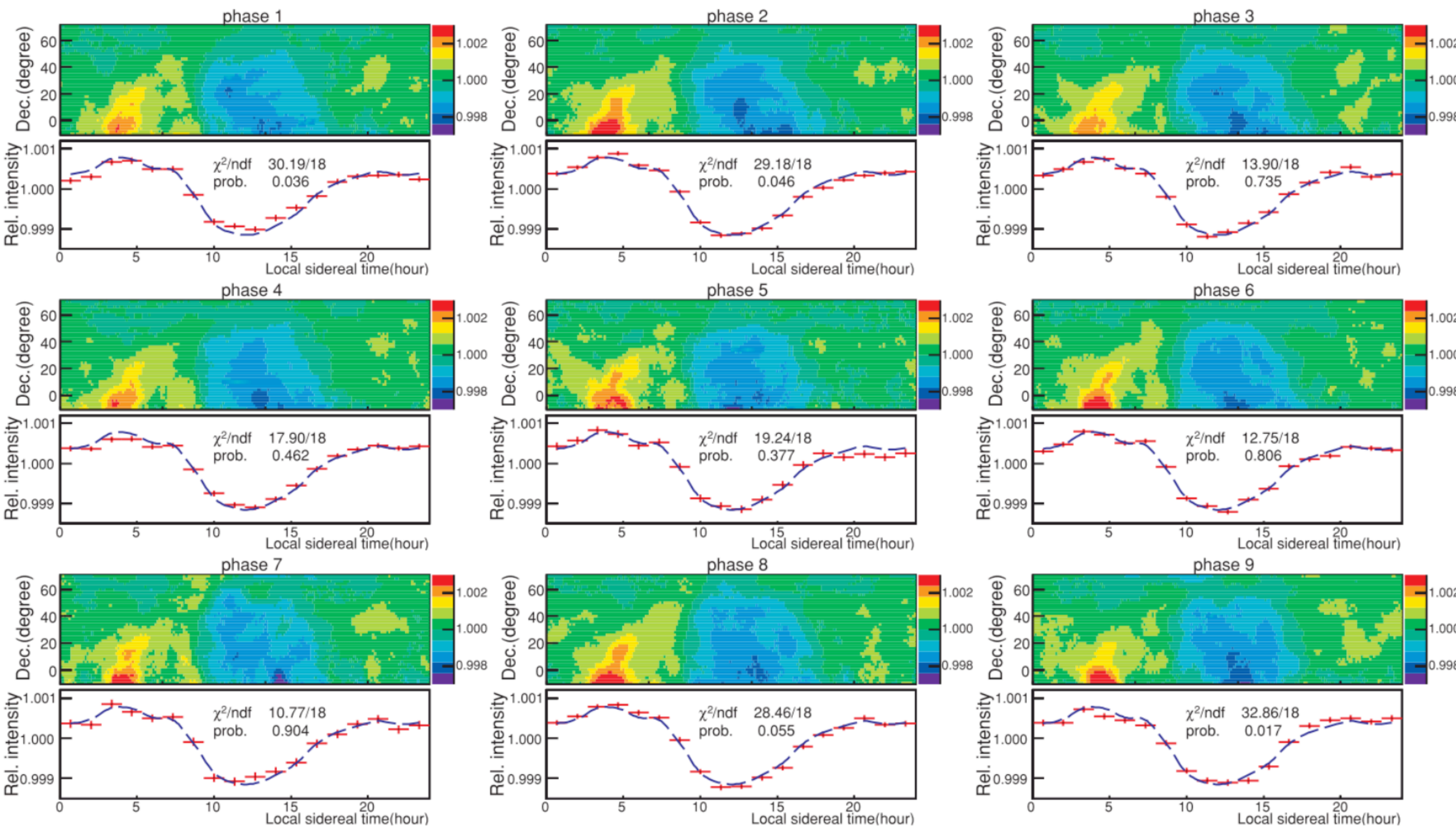
- Solar cycle 23 (Jun 1996 - Jan 2008) covered by AMANDA. No time dependence observed (arXiv:1309.7006)
- Solar cycle 24 (Jan 2008, max Apr 2014) covered by IceCube. No time dependence observed

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



Time Dependence

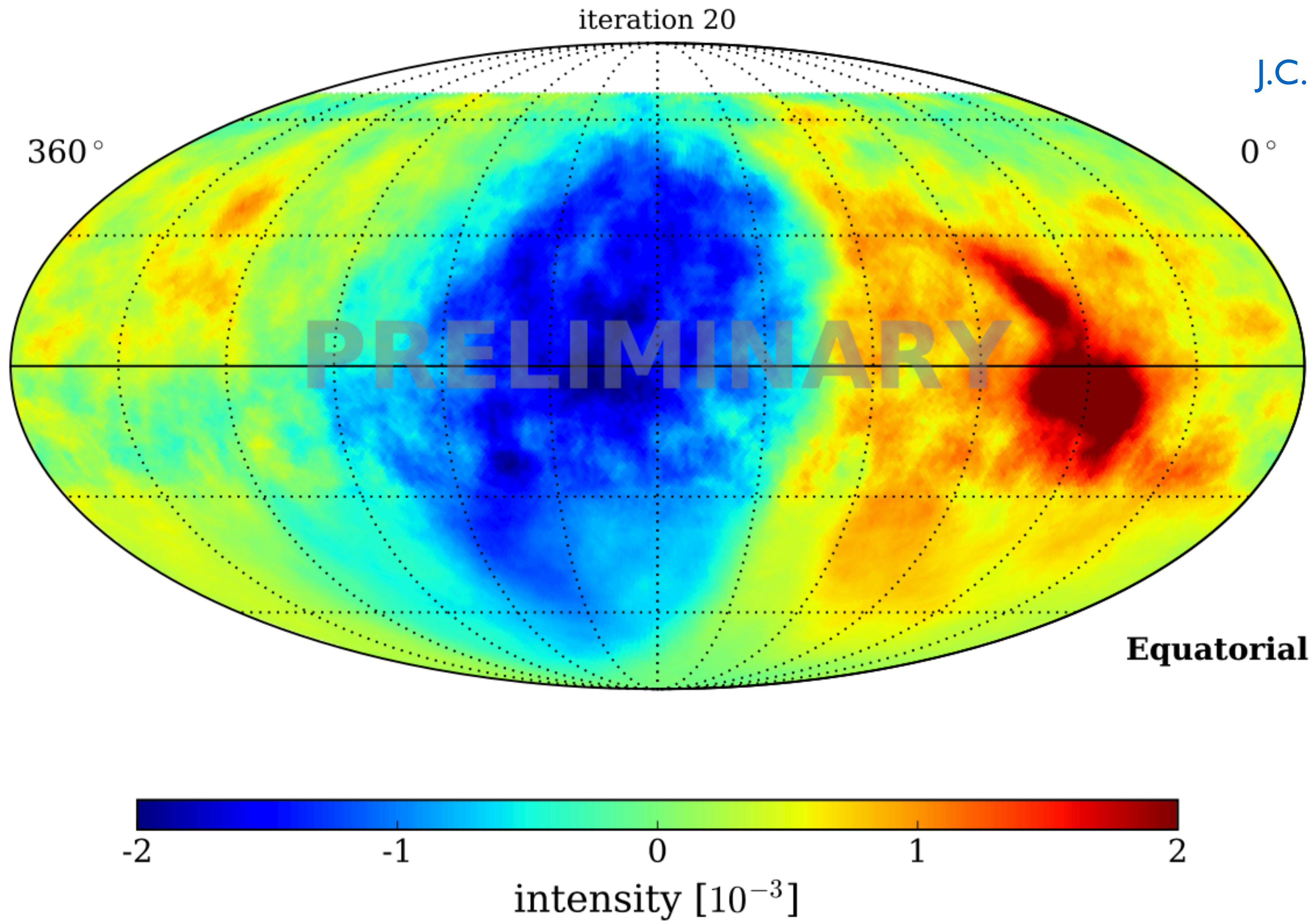
- Cycle 23 also covered by Tibet-ASγ (Nov. 1999 - Dec. 2008). No time dependence observed



All-Sky Coverage

- Next step is an energy-matched analysis between HAWC and IceCube:

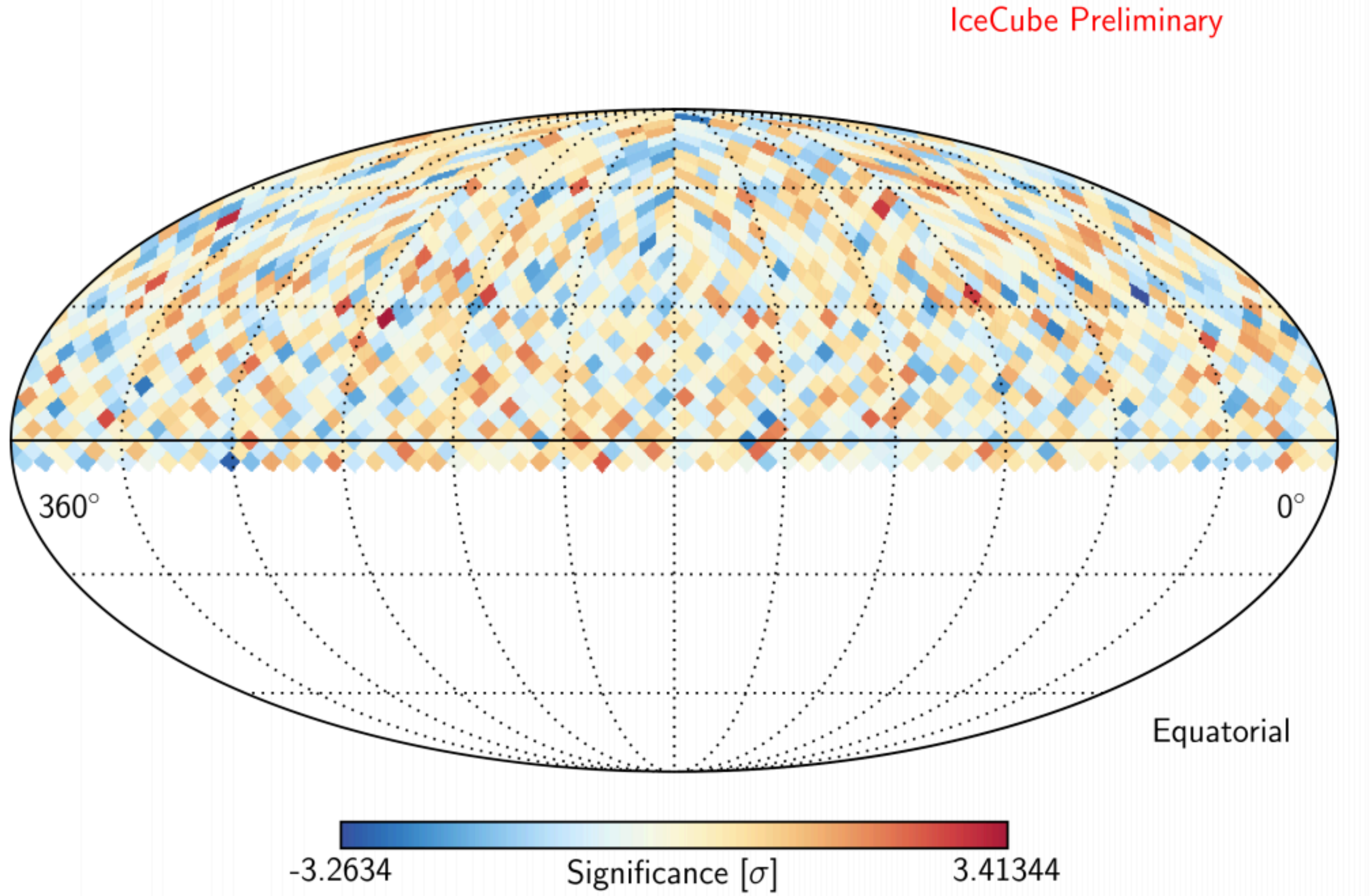
J.C. Diaz-Velez, CRA 2017



- Advantage: reduced crosstalk between angular modes

All-Sky Coverage

- Another approach: look for imprint of CR anisotropy in atmospheric neutrinos from 10-100 TeV cosmic rays

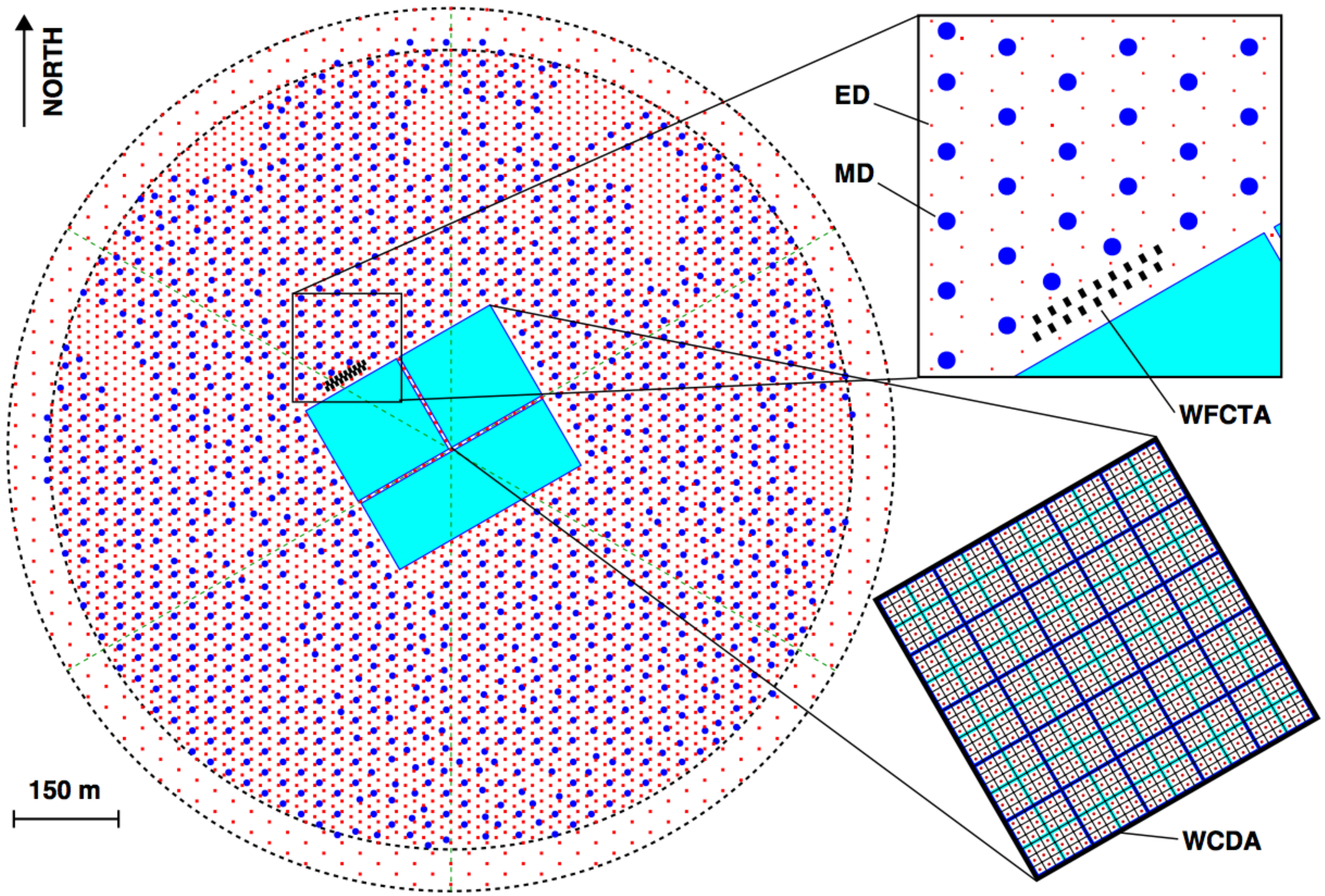


- Advantage: try to use IceCube as a single 4π detector

Future Detectors

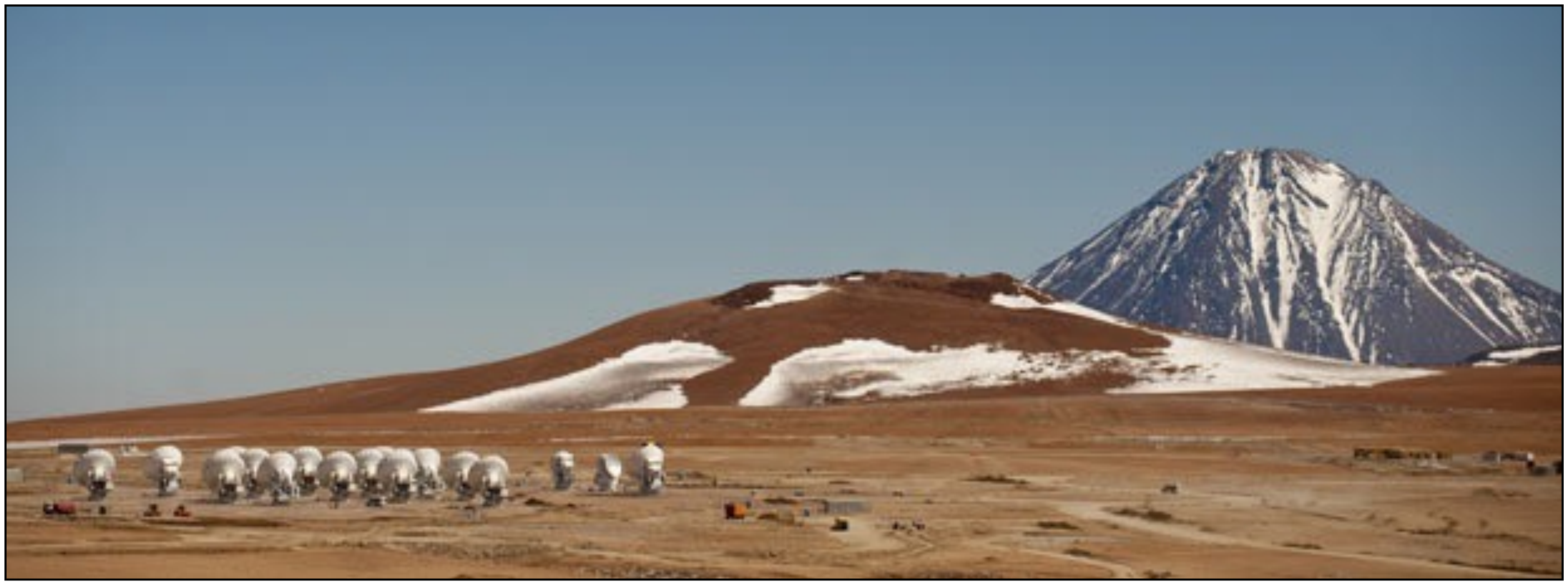
- LHAASO: nested set of detectors to cover 1 TeV to 0.1 EeV in range, close to IceCube+IceTop range

From G. Di Sciascio, ISVHECRI 2016



Southern Gamma-Ray Survey Observatory

- A high altitude site (4800-5000 m a.s.l.) in the Southern Hemisphere is under discussion



- Goals: improved sensitivity <1 TeV, exposure to Galactic Center, about 8 sr daily sky coverage, early warning system for CTA
- Workshop in Buenos Aires on Dec. 11-12: https://events.icecube.wisc.edu/conferenceDisplay.py?confId=96

Summary

- The anisotropy in CR arrival directions has been observed by many indirect detectors for nearly 20 years. Characteristics:
  - Scale ranges from dipole and quadrupole structures to about the angular resolution of instruments
  - Relative intensity ranges from 10^{-3} to 10^{-5}
  - It is energy dependent but not time dependent
  - Energy ranges from ~1 TeV to >1 EeV now that Auger has observed large-scale structure!

Summary (cont.)

- Beware of biases in analysis techniques which affect all ground-based experiments; in particular the RA projection effect
- Outlook:
  - Analyses are now extending to full sky coverage (IceCube + HAWC) and with high-energy reach (IceTop, Auger)
  - Comparisons from LHAASO will be available in a few years