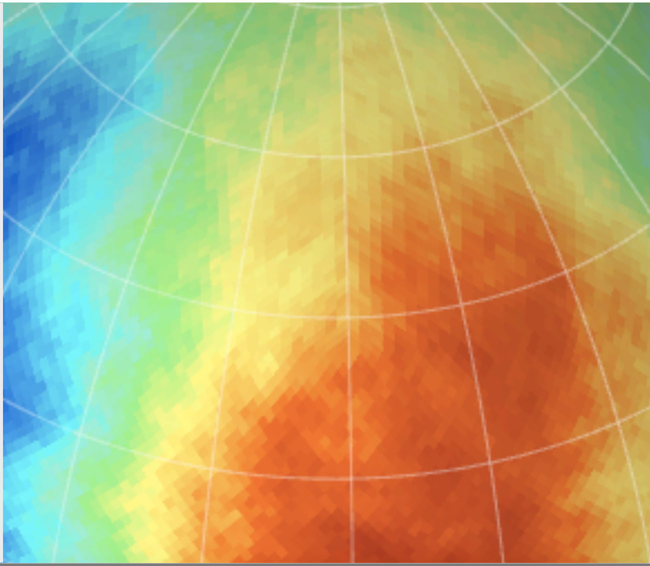
Study of cosmic-ray anisotropy with IceCube, IceTop, and AMANDA



Marcos Santander

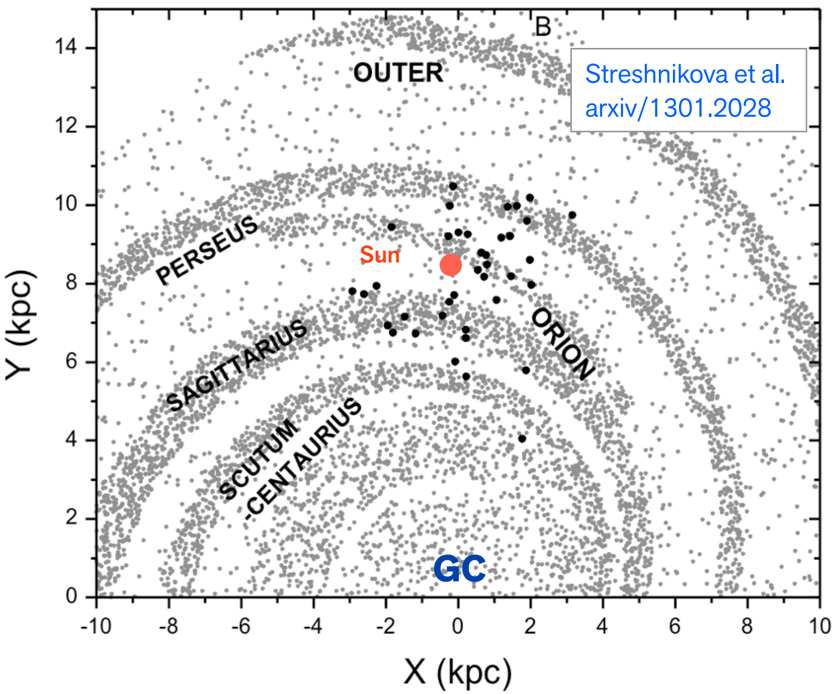
WIPAC, University of Wisconsin-Madison

WIPAC
Wisconsin IceCube Particle Astrophysics Center

Wisconsin
University of Wisconsin-Madison

Cosmic ray propagation and anisotropy

Distribution of nearby SNRs in the galaxy



Galactic cosmic rays

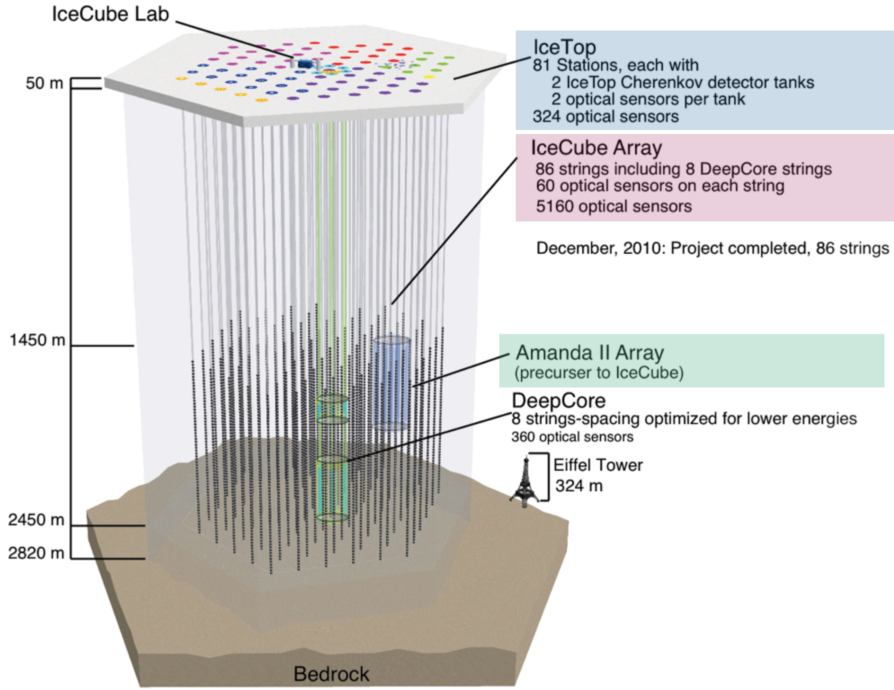
- Accelerated in SNRs
- Propagate diffusively

Consequences for anisotropy

- CR density gradients are visible as anisotropy.
- Anisotropy **amplitude ≤ 10^{-2}**.
- Amplitude **increases with energy**.
- **Dipole** shape.
- **Phase** should point towards the most significant source.

Small-amplitude anisotropy studies require large data sets (> 10^8 events)

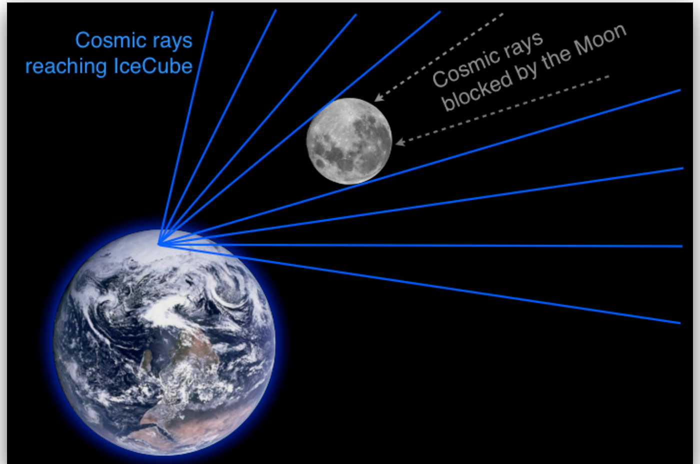
IceCube, IceTop, and AMANDA



- **IceTop**
  - CR rate ~ 10 Hz in IT81
  - ~ 3 x 10^8 CR events/year
  - sensitive to $\delta > 10^{-4}$ anisotropy
- **IceCube**
  - CR muon rate ~ 2 kHz in IC86
  - ~ 6 x 10^{10} CR events/year
  - sensitive $\delta > 10^{-5}$ anisotropy
- **AMANDA**
  - ~ 2 x 10^9 CR events/year
  - Data from 2000-2006

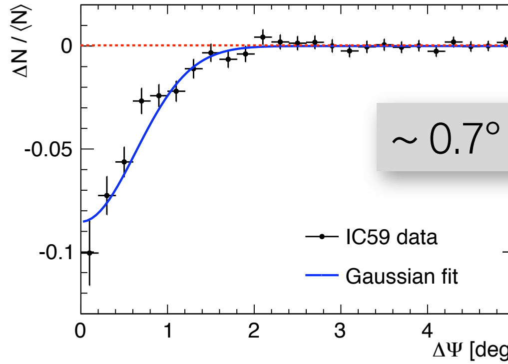
All three detectors have collected samples large enough to be sensitive to anisotropy <u>at and below the per-mille level</u>.

Angular resolution - Moon shadow



Resolution

Shadow profile vs. angular distance from the Moon



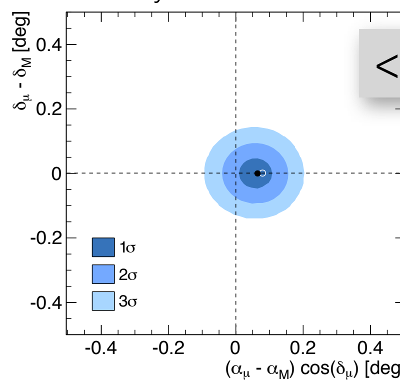
~ 0.7° resolution

- Moon blocks cosmic rays coming from its direction.
- Shadow observed in IC40, IC59, IC79, and IC86.
- Used to verify pointing, resolution.
- In IC59: deficit of ~ 8700 events (**13.9σ**)

Aartsen et al. (PRD accepted)
arxiv/1305.6811

Absolute pointing

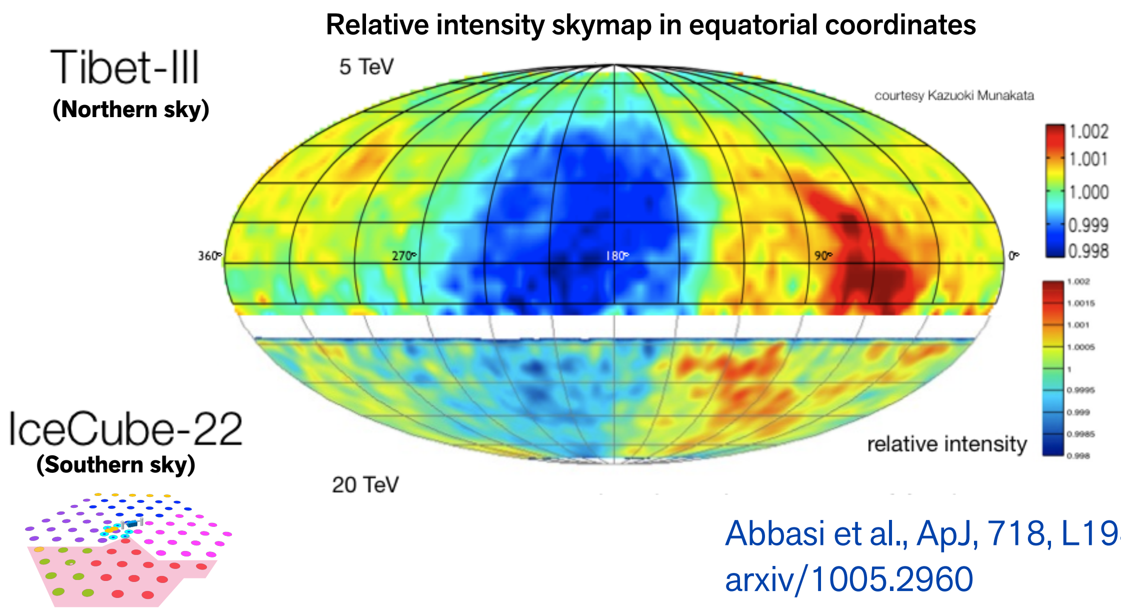
Most likely location of shadow center



< 0.1° pointing res.

- Accounts for magnetic deflection effects

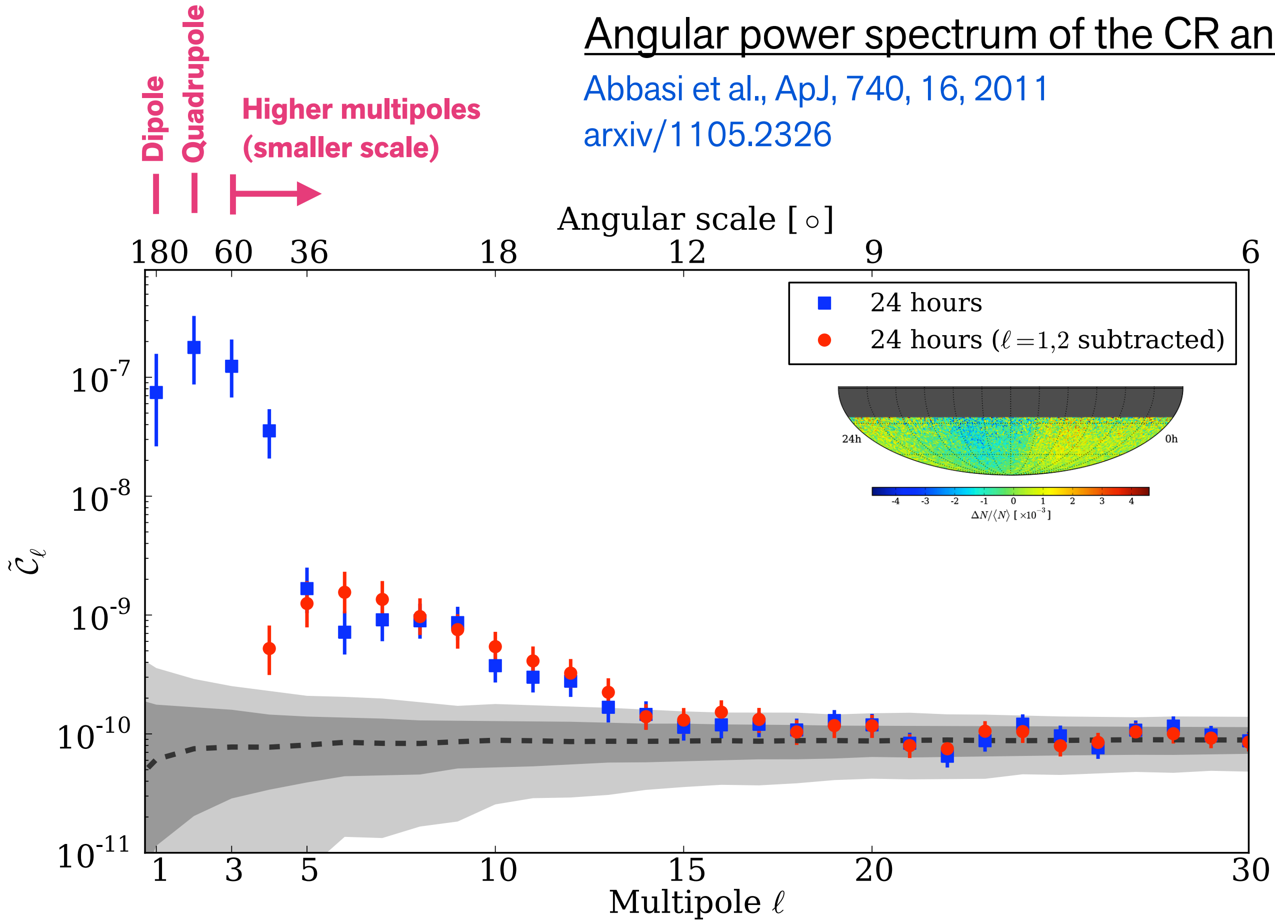
IceCube - Large scale anisotropy



Abbasi et al., ApJ, 718, L194, 2010
arxiv/1005.2960

- IC22 detector, 4 x 10^9 events, Median energy ~ 20 TeV
- First indication of large scale ~10^{-3} anisotropy observed in the South.
- Good match to observations in the North.

IceCube - Looking for smaller structure

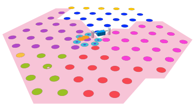


Angular power spectrum of the CR anisotropy

Abbasi et al., ApJ, 740, 16, 2011

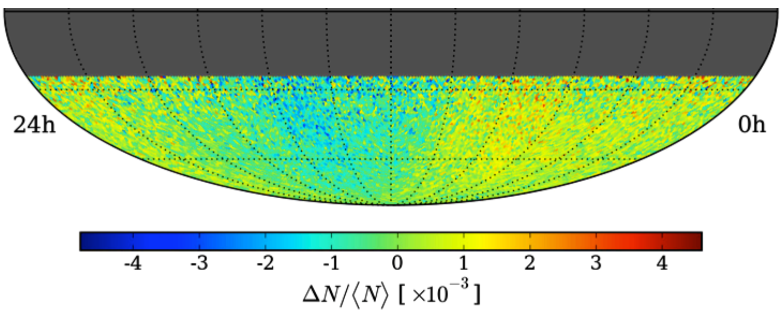
arxiv/1105.2326

IceCube - Small-scale anisotropy

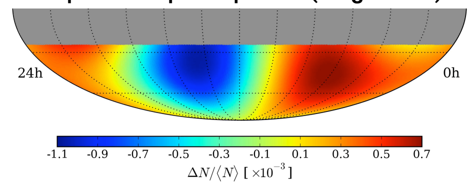


59-string detector

Input relative intensity map

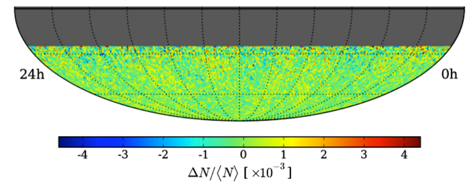


Dipole and quadrupole fit (Large scale)



+

Fit residuals (Small scale)

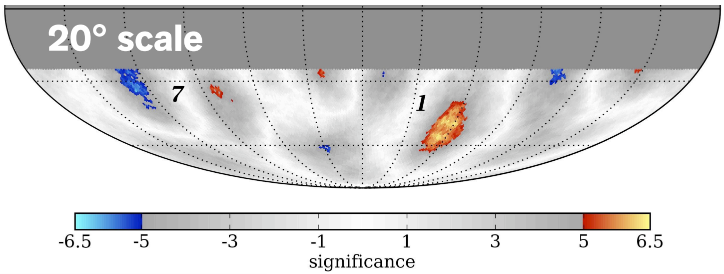


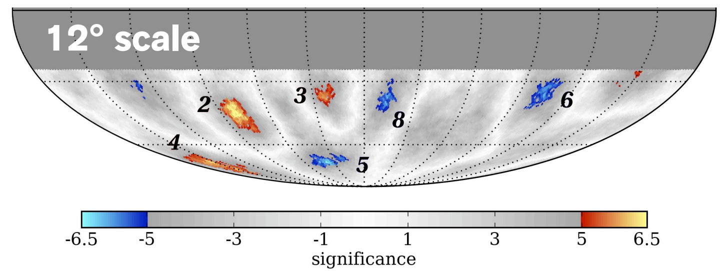
- Correlate pixels to increase sensitivity to different angular scales.

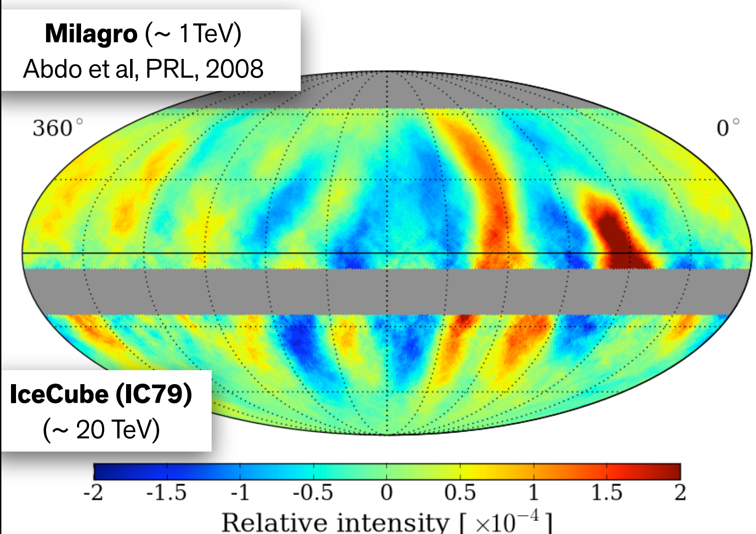
Abbasi et al., ApJ, 740, 16, 2011
arxiv/1105.2326

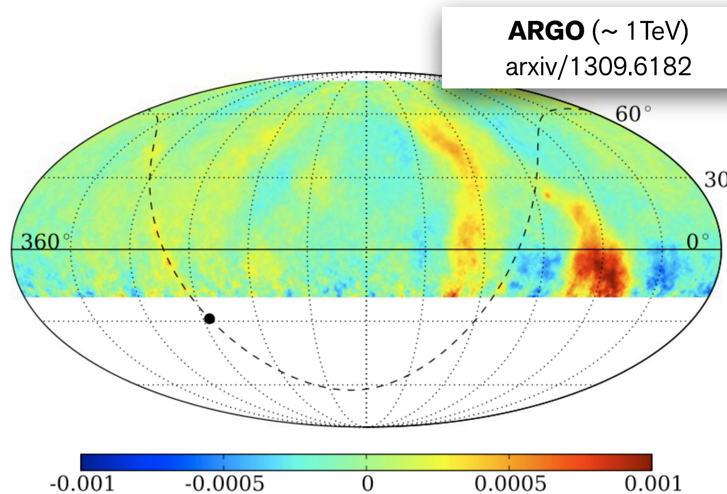
IceCube - Small-scale anisotropy

- Statistically significant structure with <u>typical sizes of 10°-20°</u>
  Abbasi et al., ApJ, 740, 16, 2011 arxiv/1105.2326





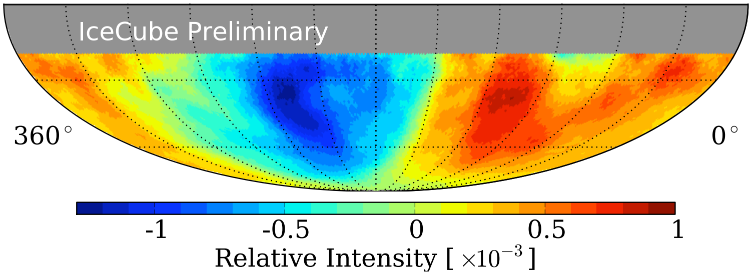


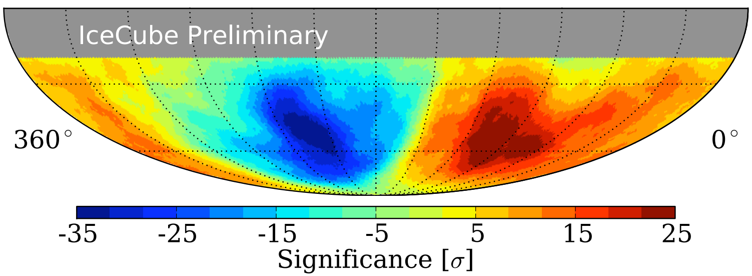


IceCube - Large-scale anisotropy

Preliminary

IC22-IC86 detector configurations (2007-2012)
5° scale

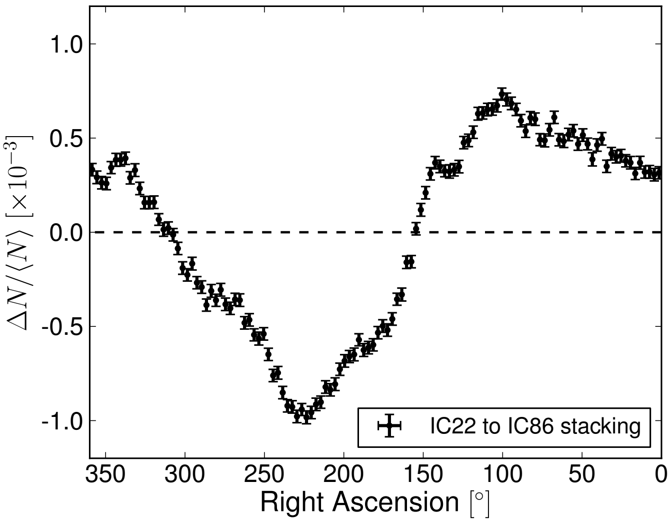




Update

- IC22-IC86: 1.5 x 10^{11} events.
- Significant structure at very small angular scales.

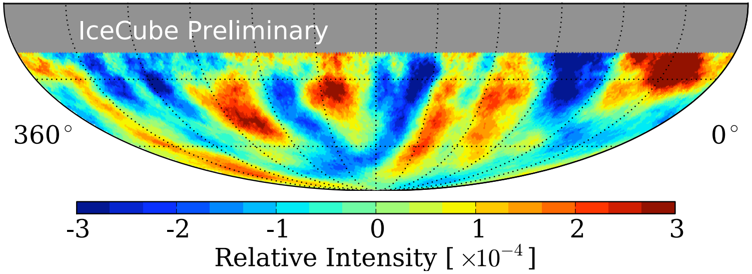
1D projection in right ascension

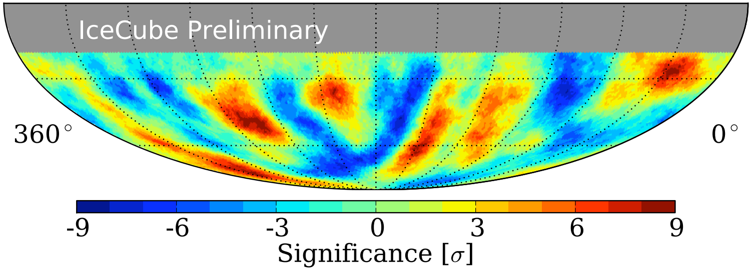


Preliminary

IC22-IC86 detector, **5° scale**

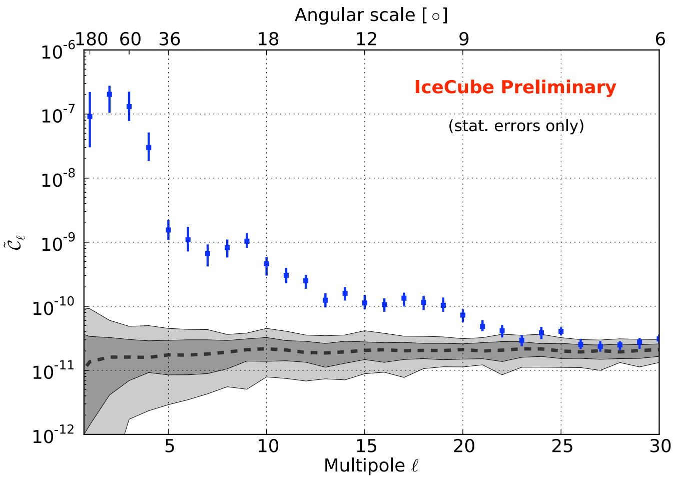
Large-scale subtracted (dipole and quadrupole)





Update

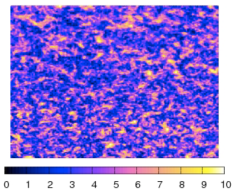
- Significant power in the spectrum for structures < 10°.



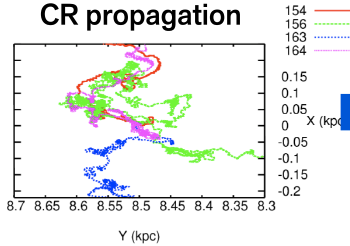
Origin of small-scale anisotropy

Propagation effects

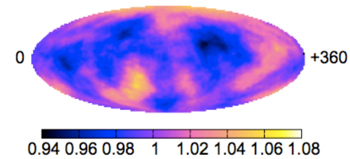
Turbulent GMF



CR propagation



Small-scale structure



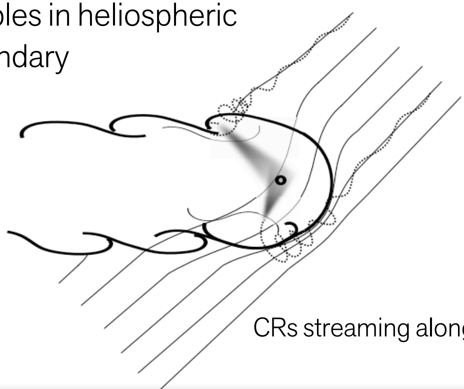
- Different energies probe different distances
- Connection between anisotropy and GMF turbulence

Giacinti & Sigl
arxiv/1111.2536

Heliospheric effects

Desiati & Lazarian
arxiv/1111.3075

Ripples in heliospheric boundary

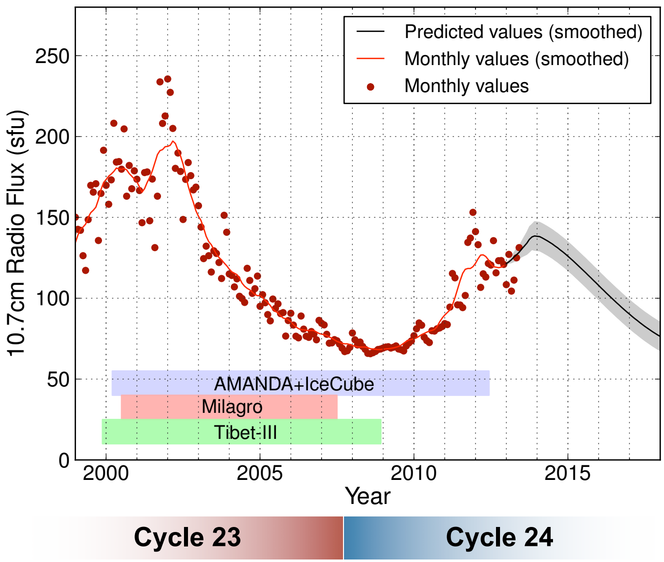


CRs streaming along LIMF

- CR scattering on ripples in the heliosphere boundary induce small-scale anisotropy.
- **Time dependence?**

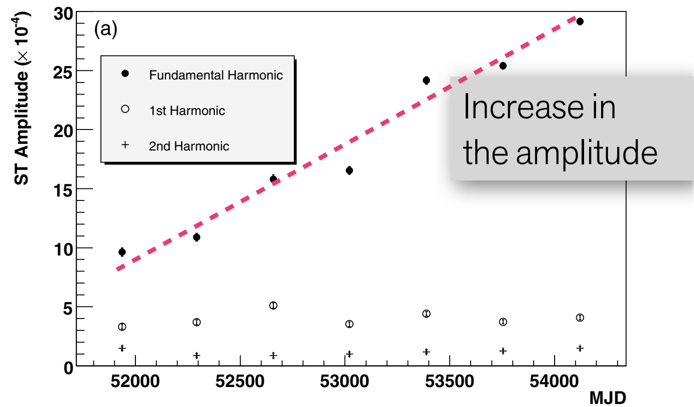
Time dependence study

Solar cycles #23 and #24



Milagro

(arxiv/0806.2293)



Tibet-III

(arxiv/1001.2646)

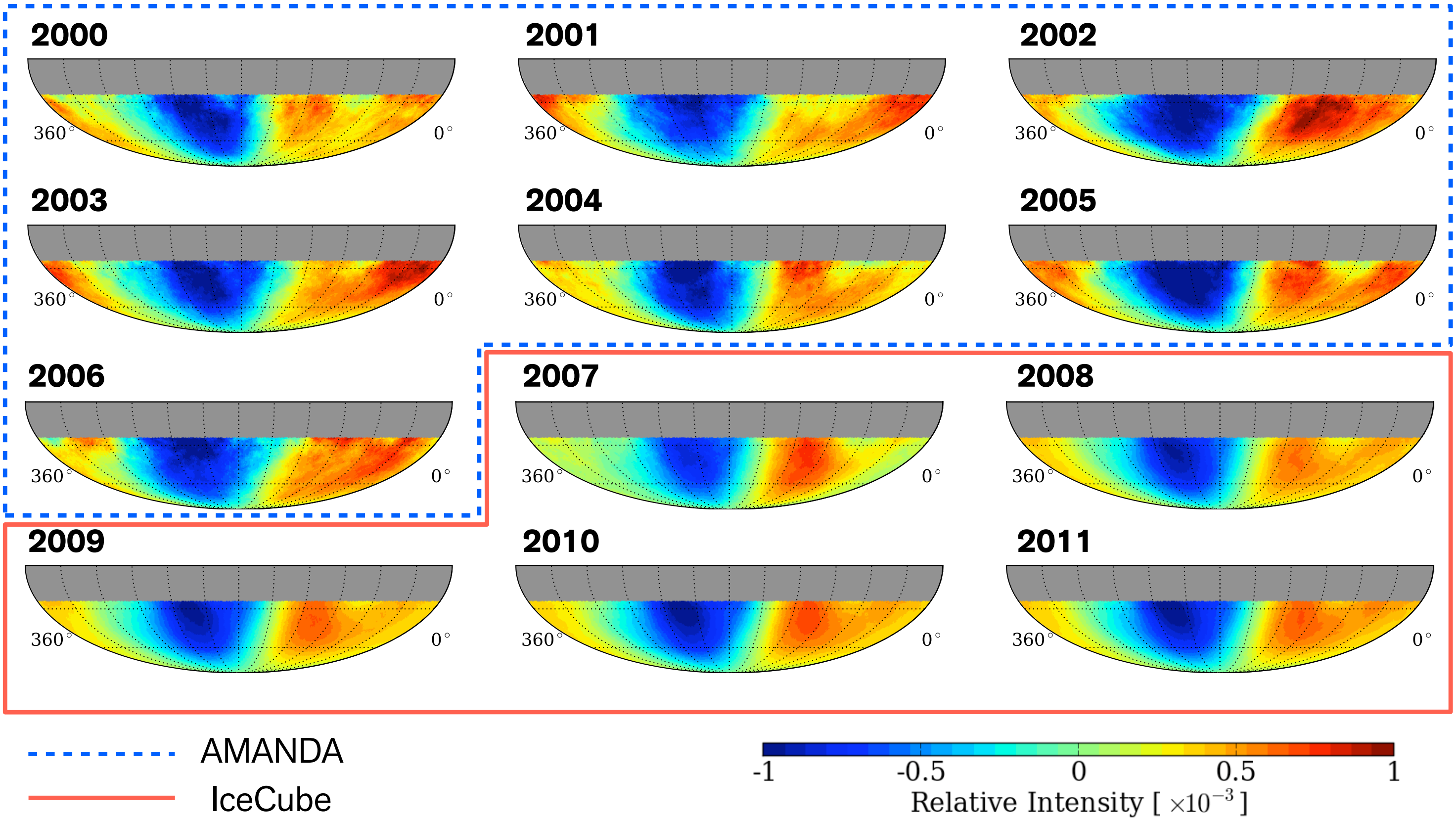
No significant change

- Use AMANDA+IceCube (160 billion events, 20 TeV, 12 years combined)
- Analyze each year separately, compare.

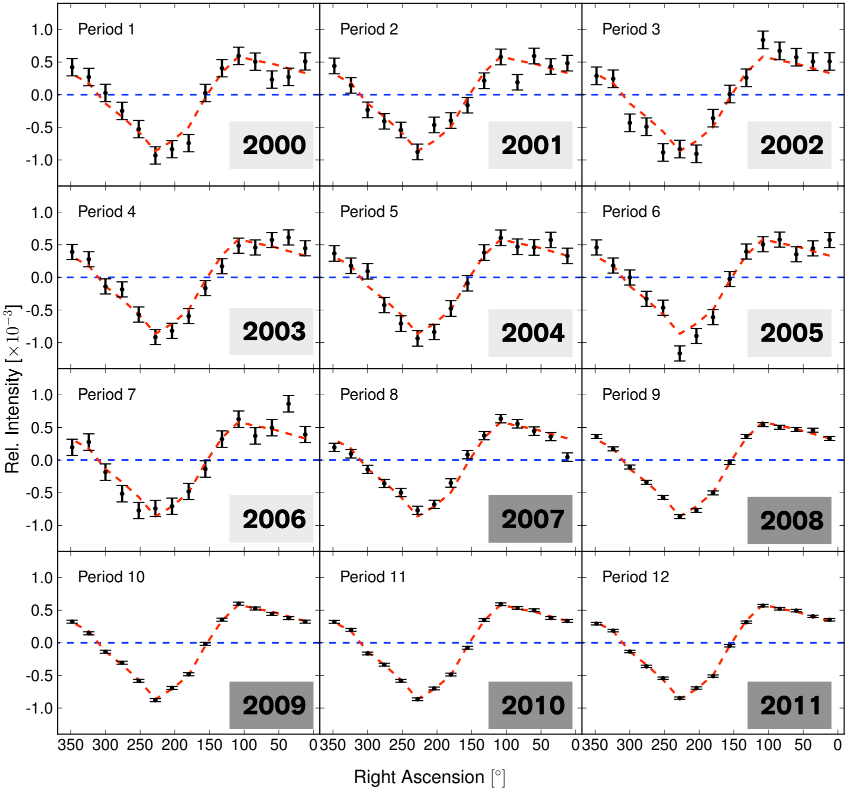
Large-scale anisotropy

Relative intensity maps

Preliminary



Right-ascension projections



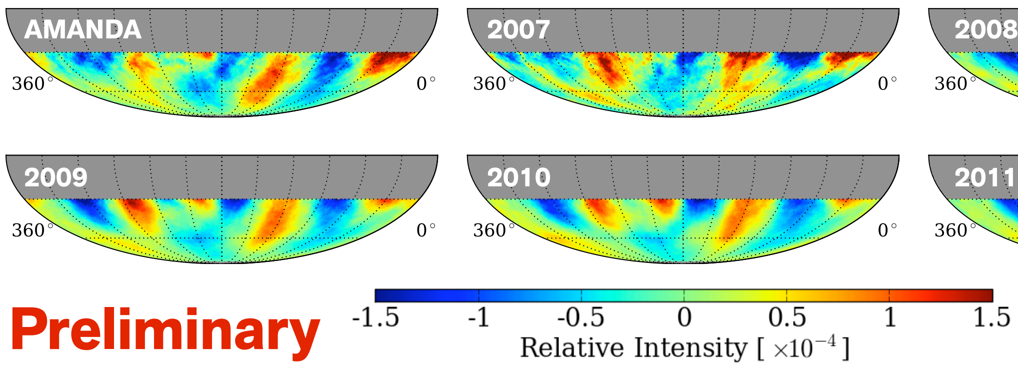
Preliminary

Detector	Year	χ^2/dof	p-value
AM-II	2000	11.3/15	0.73
AM-II	2001	16.6/15	0.34
AM-II	2002	26.0/15	0.04
AM-II	2003	19.3/15	0.20
AM-II	2004	14.3/15	0.50
AM-II	2005	21.0/15	0.14
AM-II	2006	24.4/15	0.06
IC22	2007	45.2/15	7×10^{-5}
IC40	2008	12.8/15	0.62
IC59	2009	11.1/15	0.75
IC79	2010	6.5/15	0.97
IC86	2011	8.9/15	0.88

Preliminary studies show a deviation for Period 8.
Systematic studies in progress.

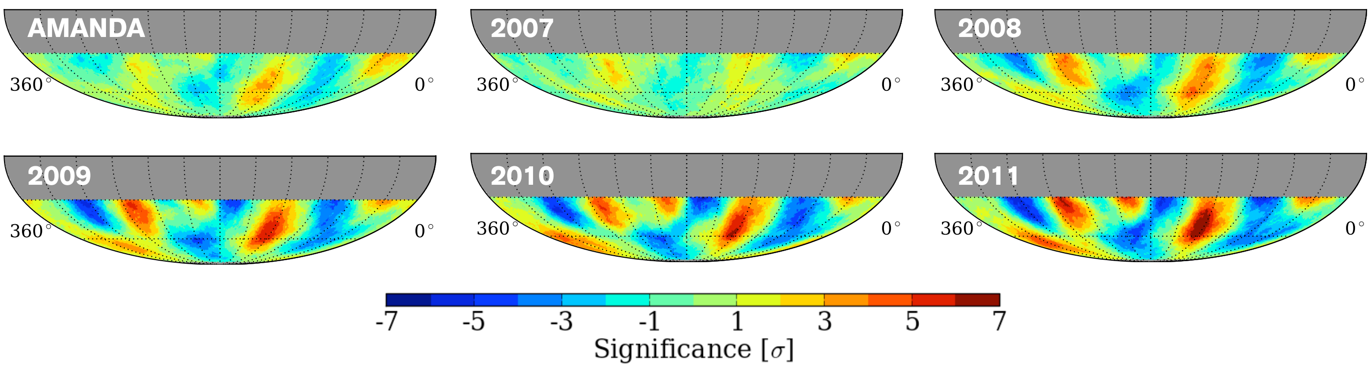
Residual maps after large-scale (dipole and quadrupole) subtraction, 20° smoothing

Rel. Intensity

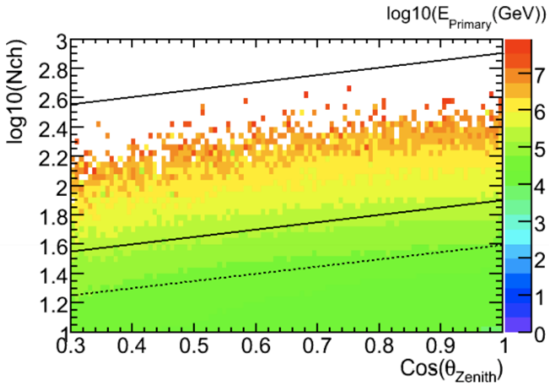


Preliminary

Significance



Anisotropy at higher energies

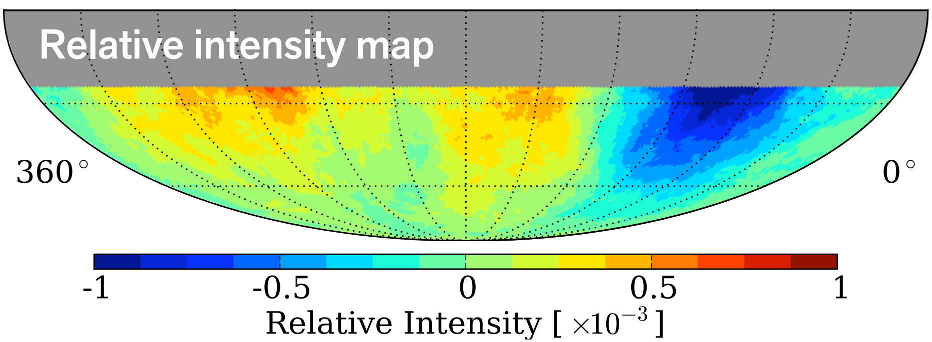


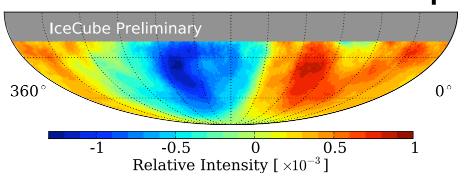
IceCube

- Cut on zenith angle and #DOMs
- Final sample: **6.1 x 10^8 events**

Abbasi et al., 2012 ApJ 746 33
arxiv/1109.1017

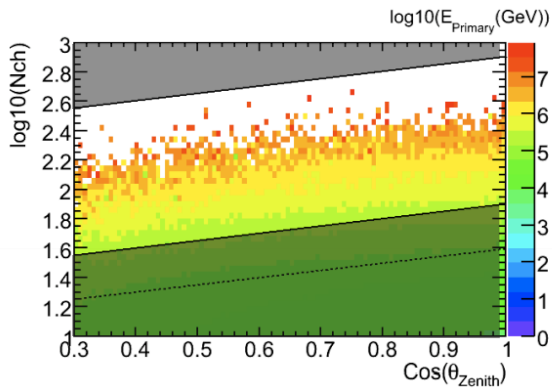
20 TeV map





- **400 TeV** median energy, anisotropy at **10^{-3}** level, size ~ **20°**, significance **6.3σ**

Anisotropy at higher energies



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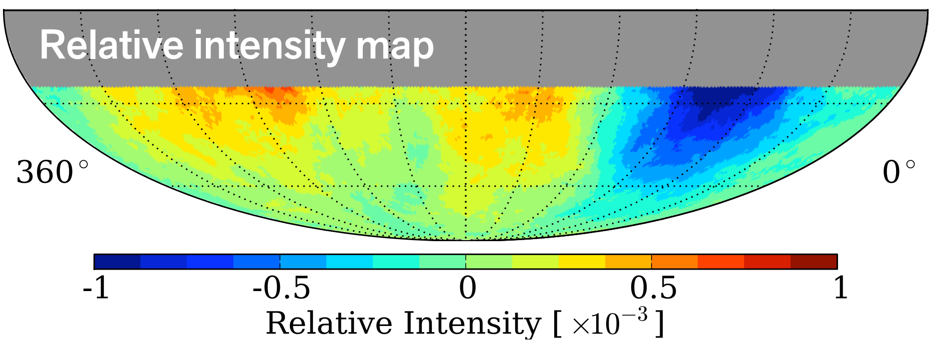

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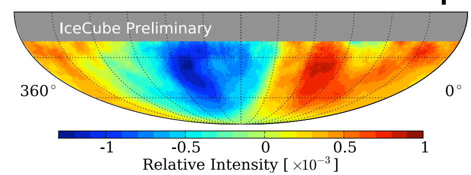

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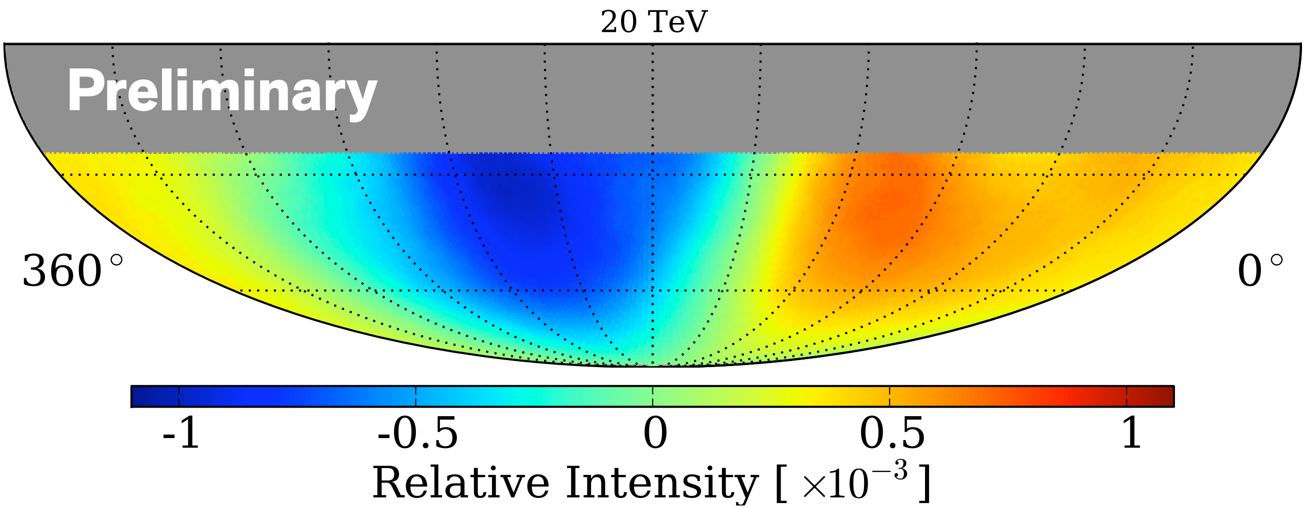
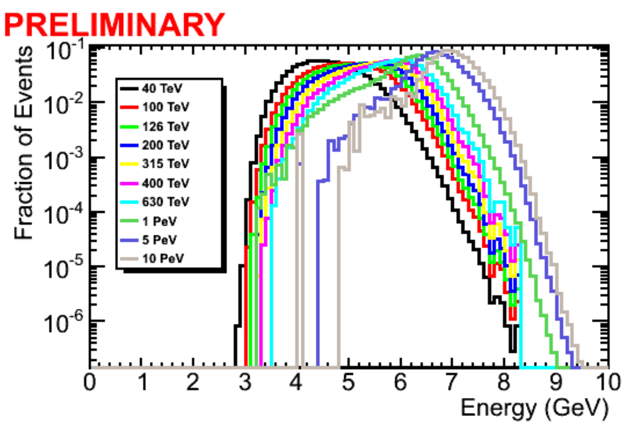
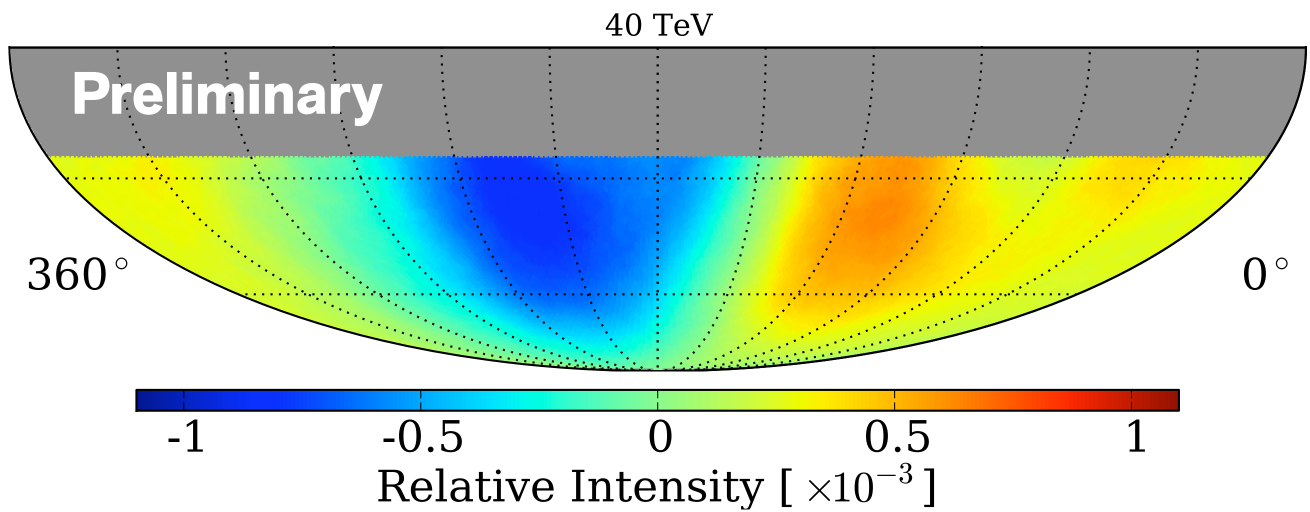
Transition between 20 and 630 TeV

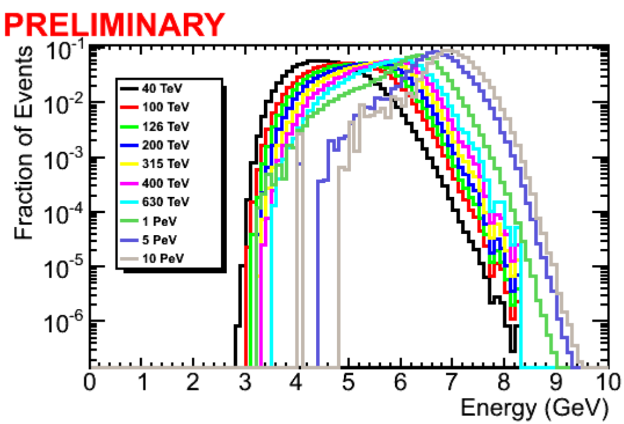




- **Note:** Very wide energy distributions. Statistically correlated maps.

Transition between 20 and 630 TeV





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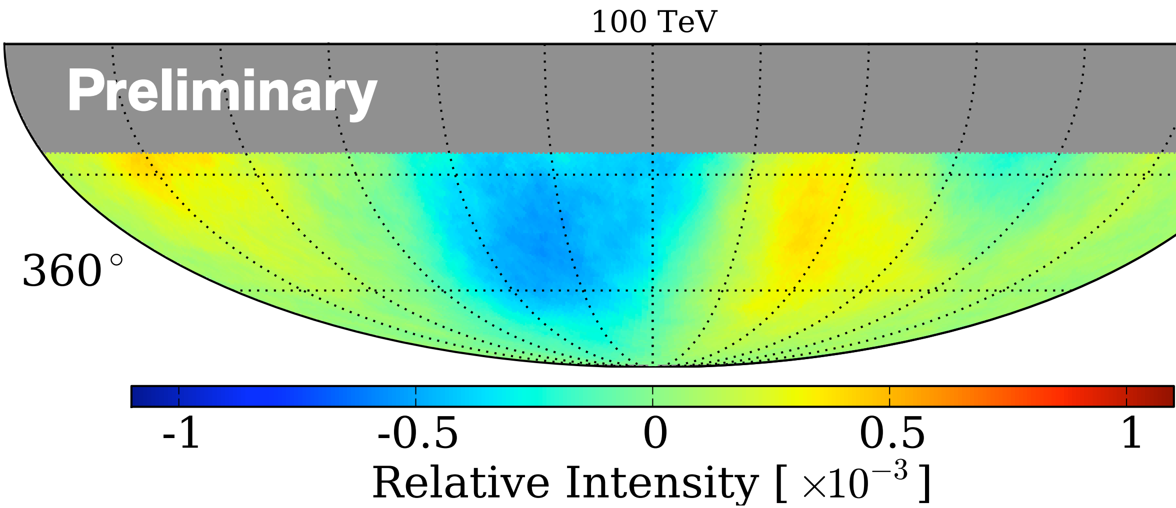

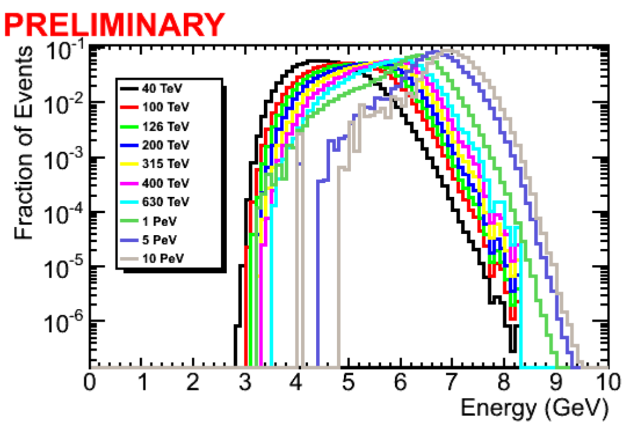

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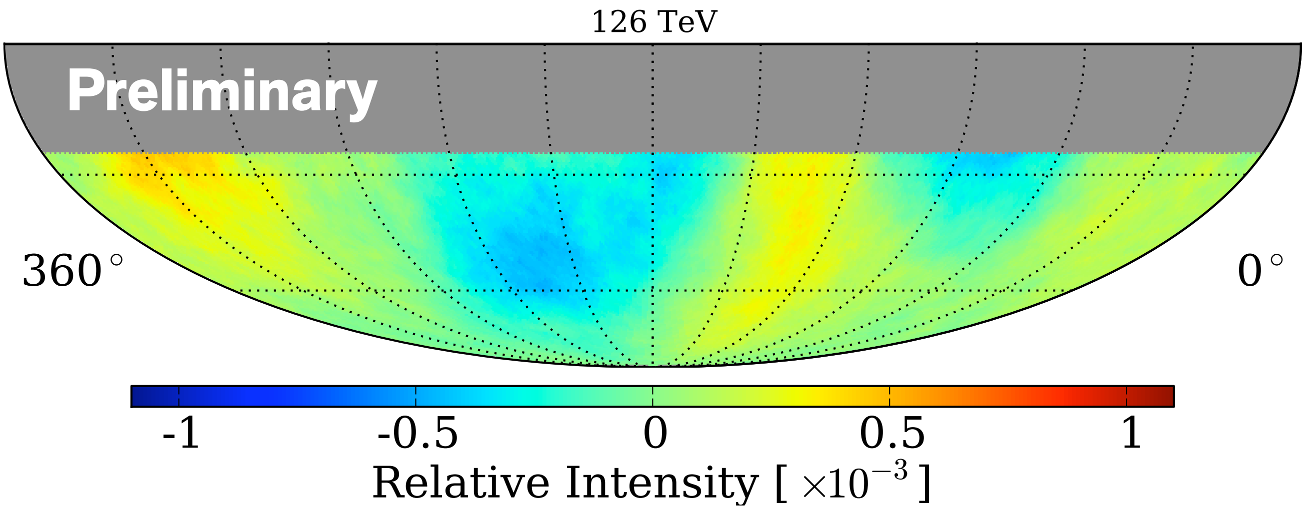

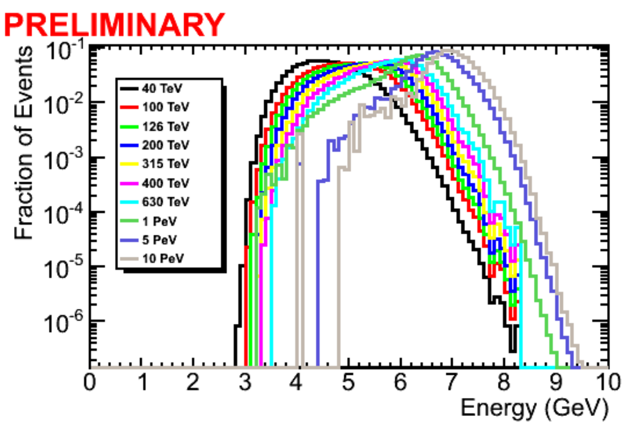

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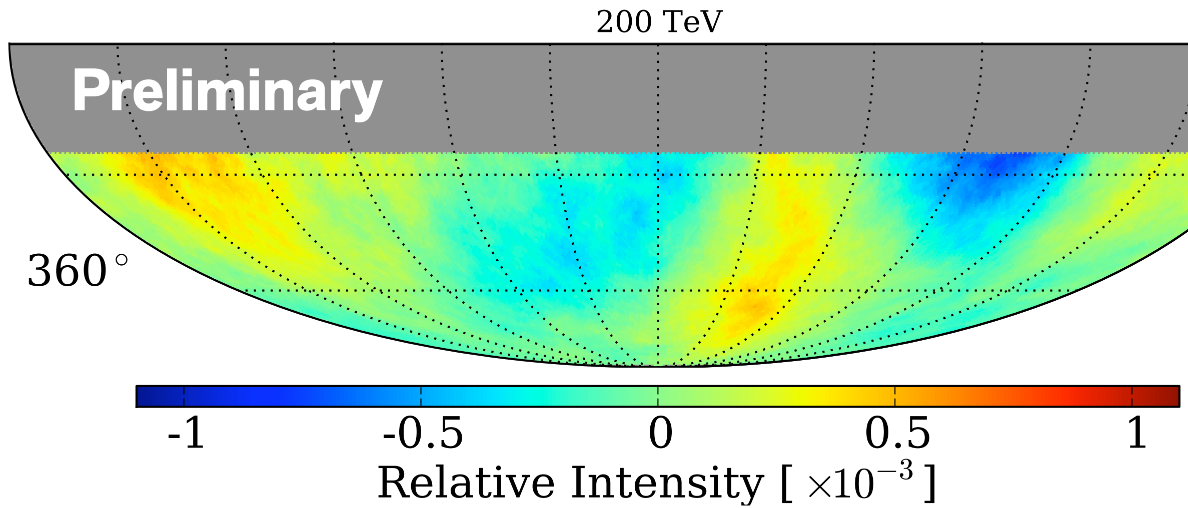

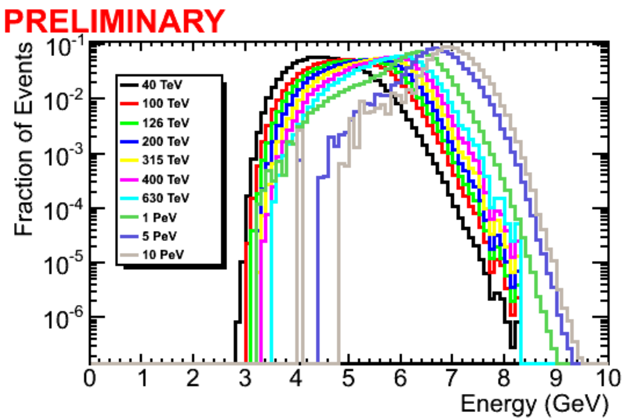

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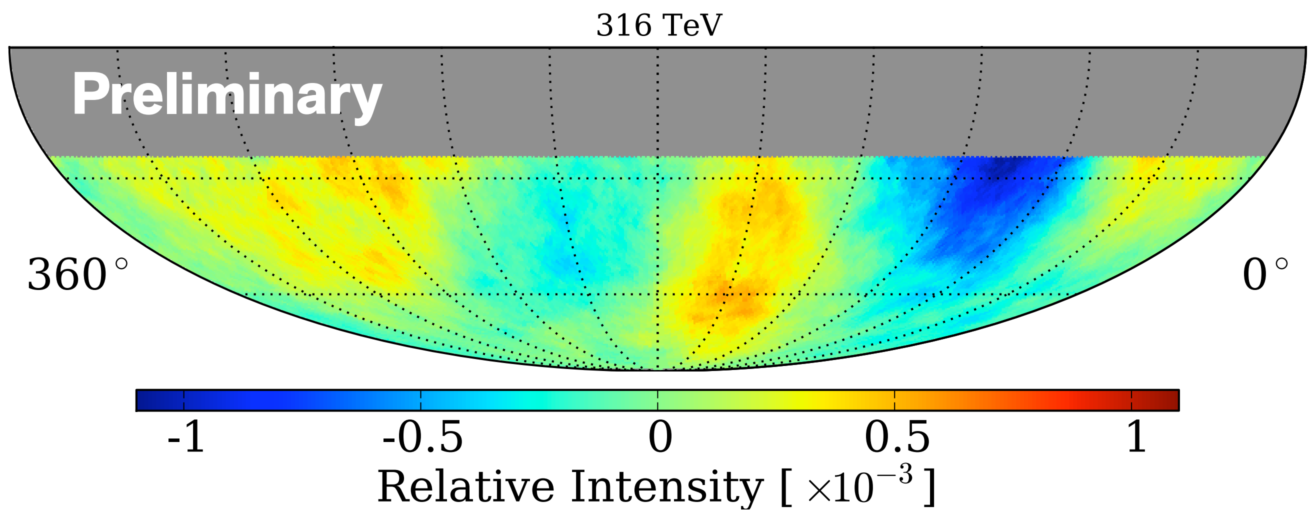

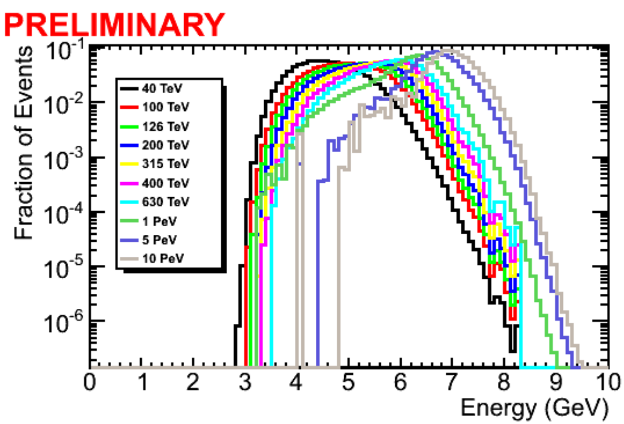

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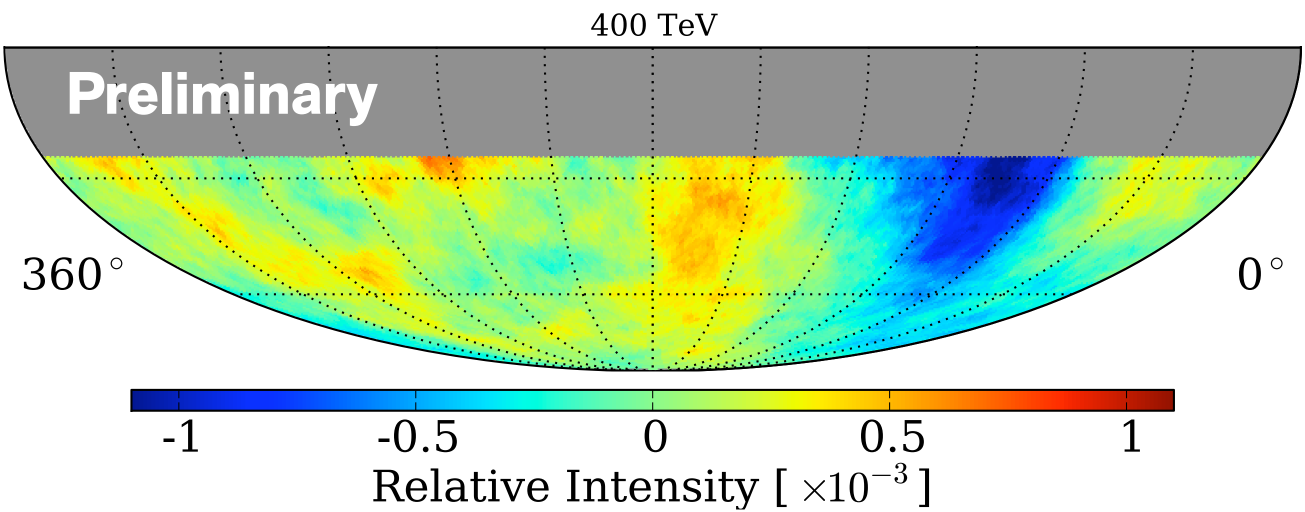

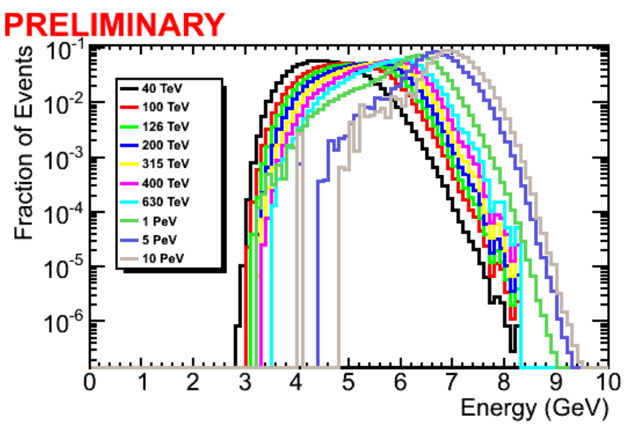

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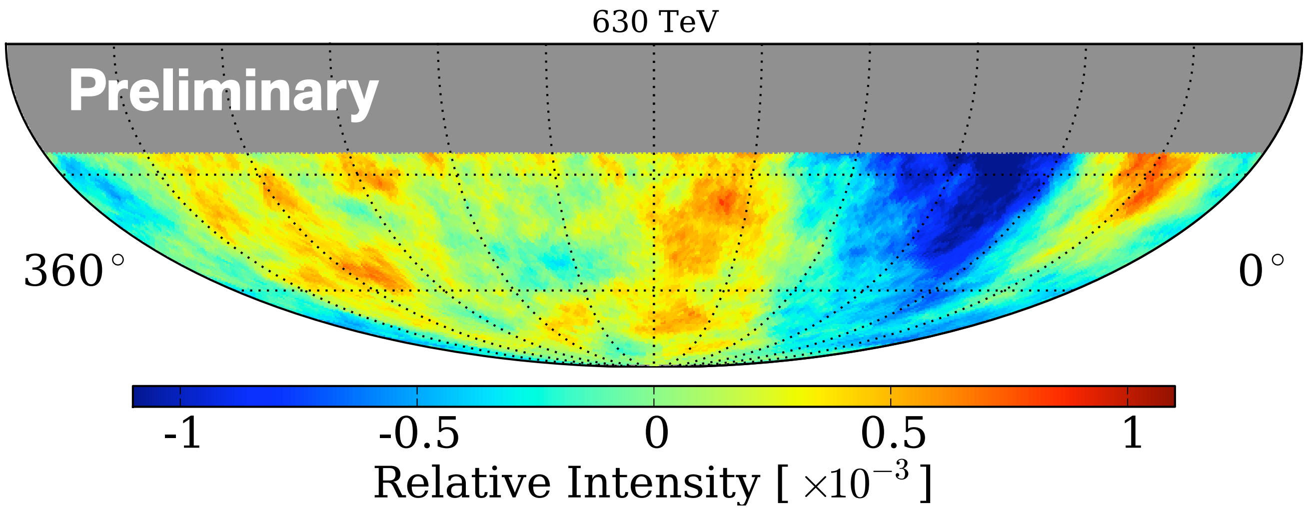

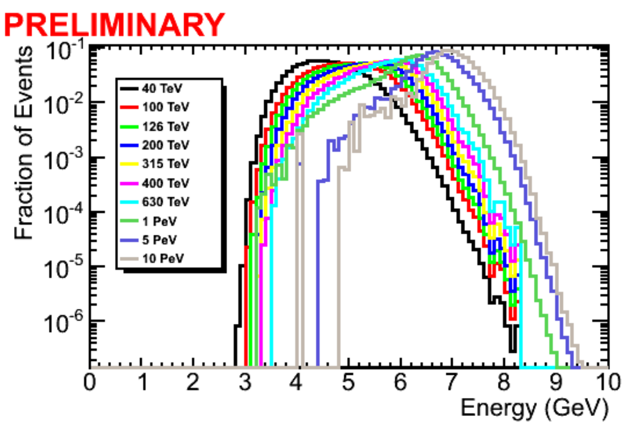

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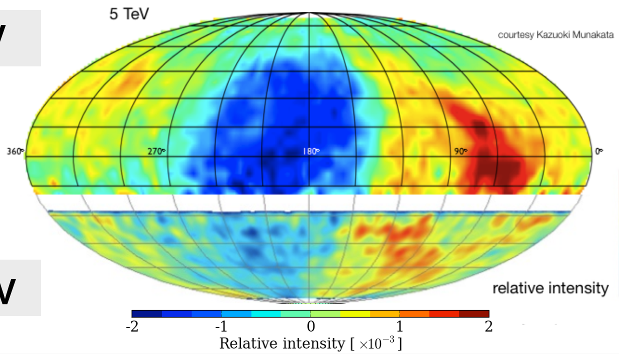
Comparison between different energies

5 TeV

20 TeV



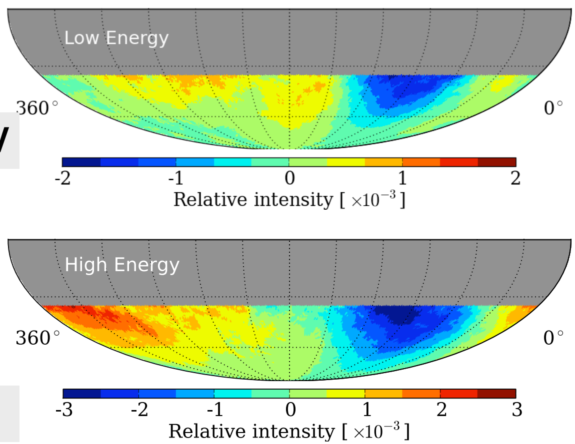
- The anisotropy changes position
- Similar peak-to-peak strength
- Smaller characteristic size at high energies

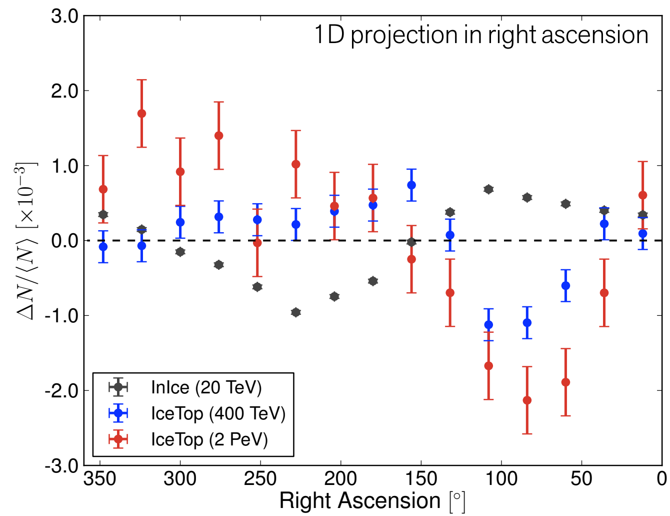
Aarsten et al., 2013 ApJ 765 55
arxiv/1210.5278

IceTop

400 TeV

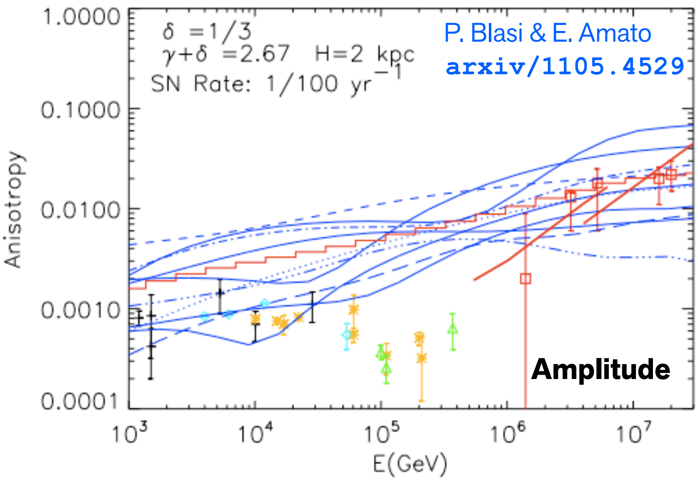
2 PeV

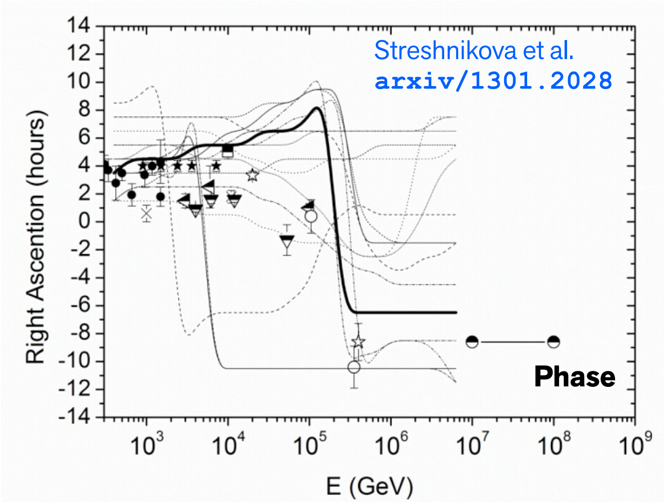




Interpretation of energy dependence

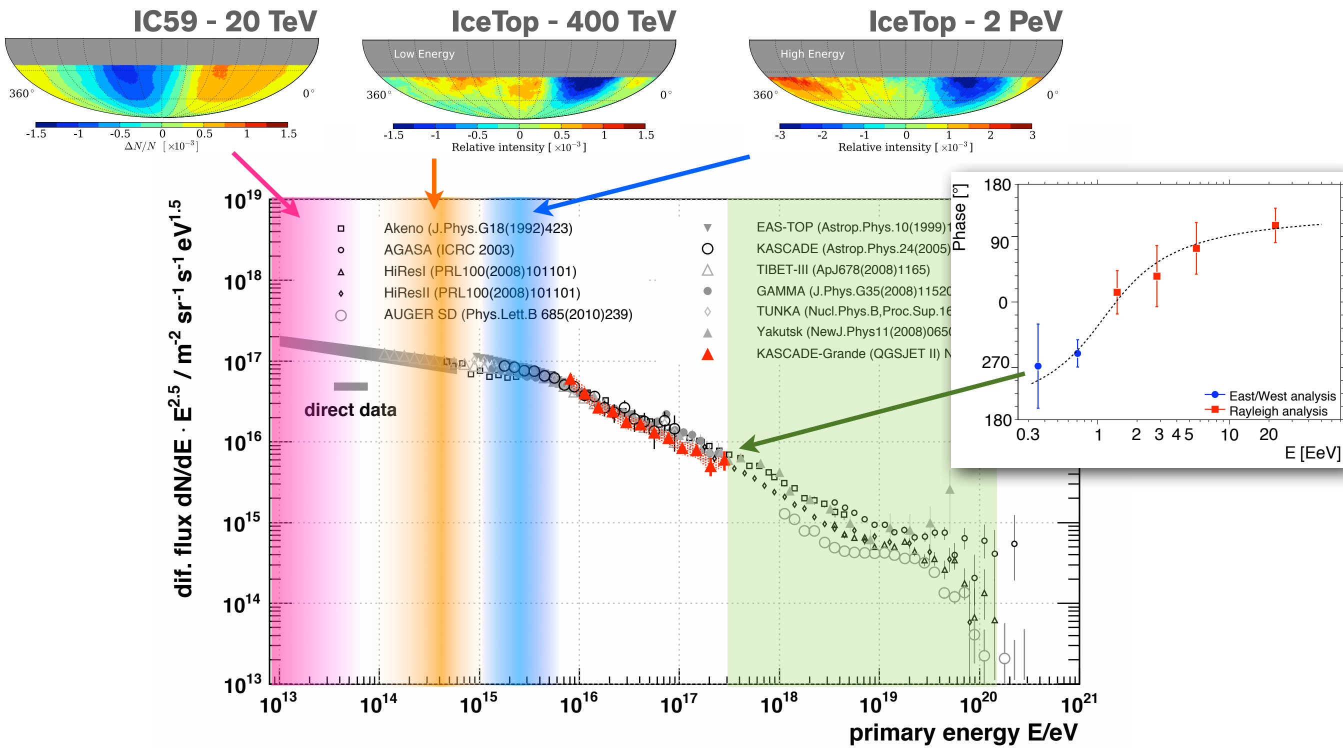
Similar to Erlykin & Wolfendale (2006)





- Anisotropy arises from discrete distribution of sources
- Phase changes according to galaxy parameters and location of nearby sources
- Strength increases with energy (diffusion coefficient)
- *Problem*: anisotropy not dipolar, not strong enough.

Anisotropy vs. energy



- Anisotropy changes in position, size
- Above 400 TeV, increase in amplitude approaching the knee.

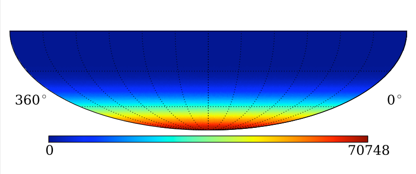
Conclusions

- Anisotropy observed with *IceCube*, *IceTop*, and *AMANDA*
- Anisotropy studied as a function of **angular scale**, **energy**, and **time**. Composition studies starting.
- Wide angular scale range (**10°-180°**)
- Strength in the **10^{-4}-10^{-3}** range
- Different energies: **20 TeV to 2 PeV**
- 20 TeV anisotropy matches that observed in the North
- Change in shape, orientation from 20 to 400 TeV, larger amplitude at 2 PeV
- No significant time variability over 12 years.

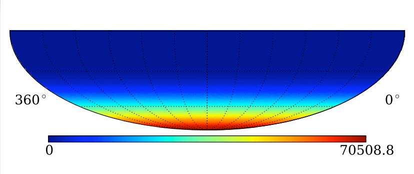
Backup slides

Method to search for CR anisotropy

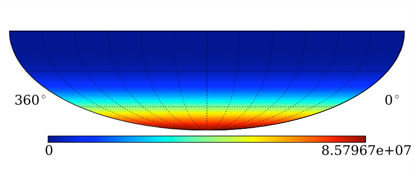
1 Build a binned data map using the equatorial coordinates of the events



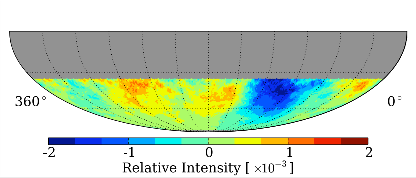
2 Construct a “reference” map by time scrambling over 24 hours.



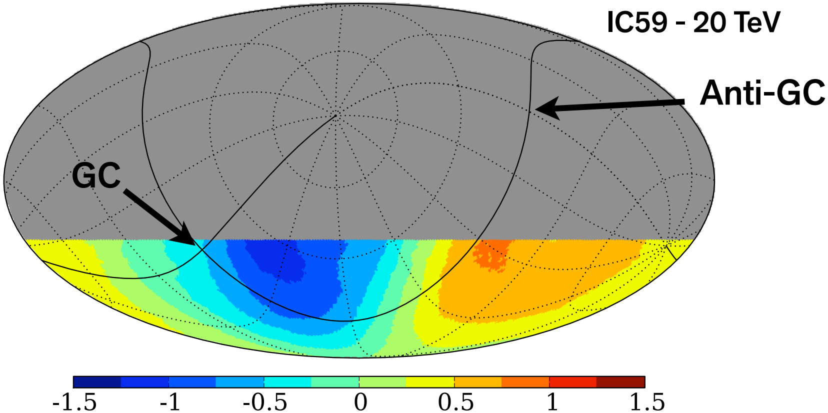
3 Correlate pixels to increase sensitivity to different angular scales



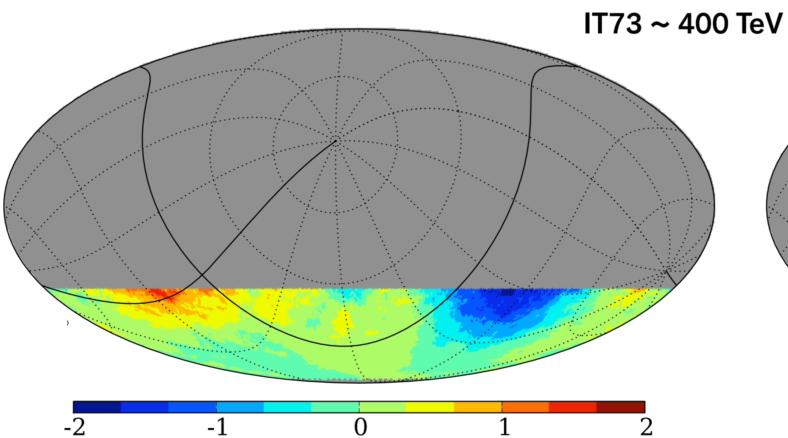
4 Calculate relative differences between data and reference with significance.

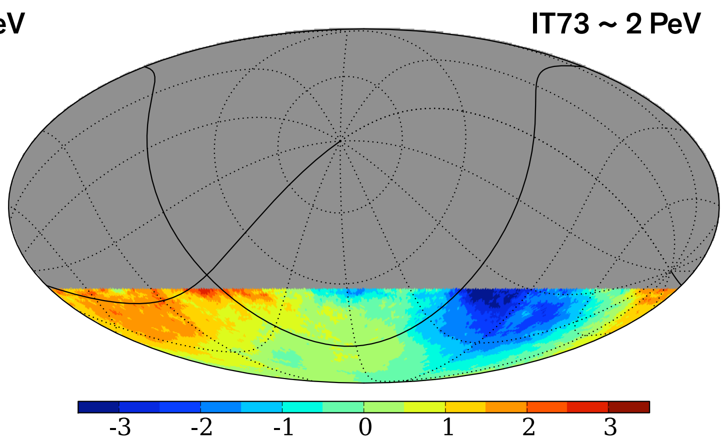


Anisotropy in galactic grid

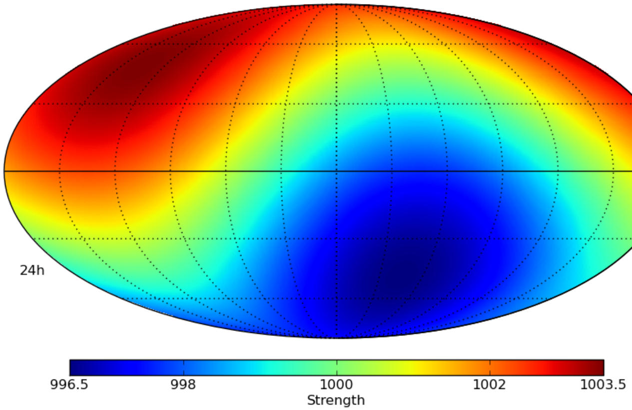


- All amplitudes x 10^{-3}
- Caveat: The background estimation technique could introduce features in the equatorial frame that do not translate to the galactic frame.





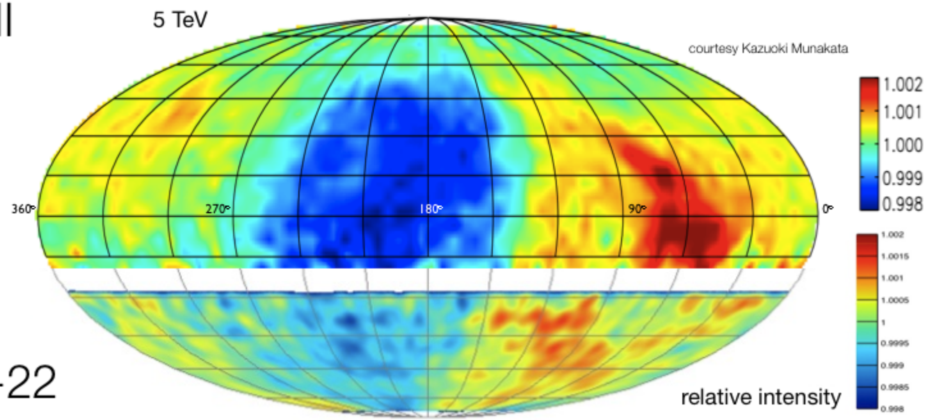
Compton-Getting effect



Expected C-G dipole

Tibet-III

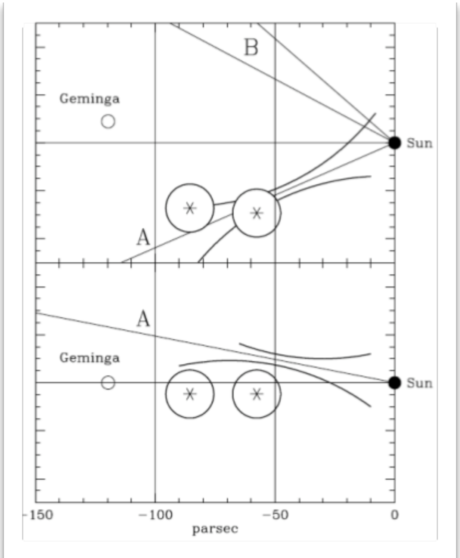
5 TeV



IceCube-22

20 TeV

Possible sources for Milagro hotspots

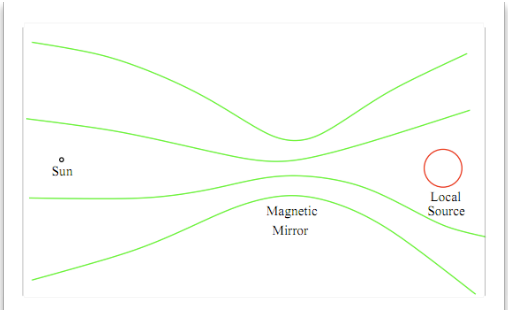


- Non-standard magnetic fields and diffusion mechanisms
- Geminga? (155 pc)

Salvati and Sacco. A&A 485, 527-529 (2008)

- CR beams

Malkov, M. A., Diamond, P. H., Drury, L. O. C., & Sagdeev, R. Z. 2010, Astrophys. J., 721, 750



- Magnetic mirroring and funneling from nearby source

Drury and Aharonian. Astropart. Phys. 29 420-423 (2008)