The high-energy cosmic-ray sky as seen by IceCube, IceTop, and AMANDA

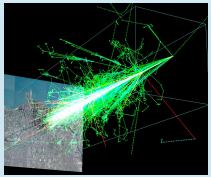
Marcos Santander

WIPAC, University of Wisconsin-Madison

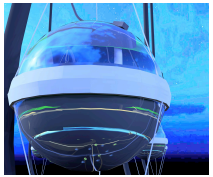
WIPAC
Wisconsin IceCube Particle Astrophysics Center

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

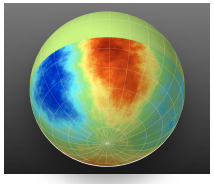
Outline



Cosmic rays
General introduction

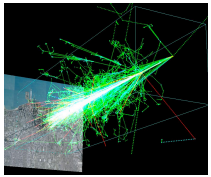


Cosmic-ray detectors
IceCube, IceTop, AMANDA



Anisotropy analysis
Angular scale, energy, time

Outline



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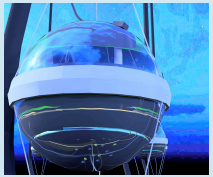

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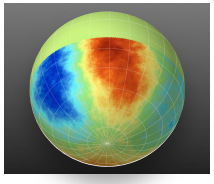

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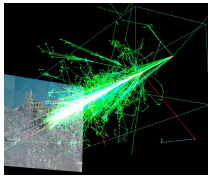

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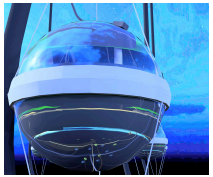

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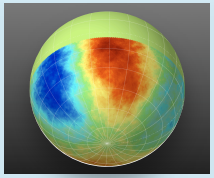
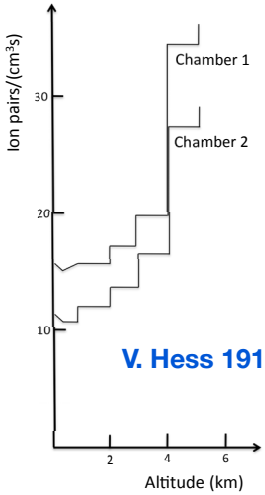


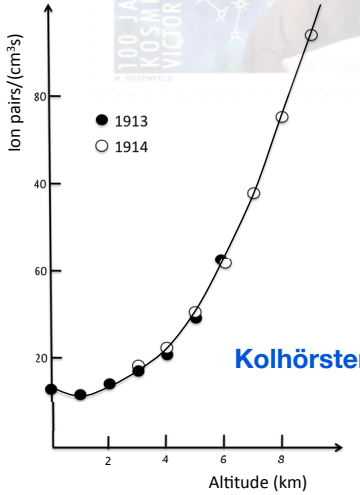
Anisotropy analysis
Angular scale, energy, time

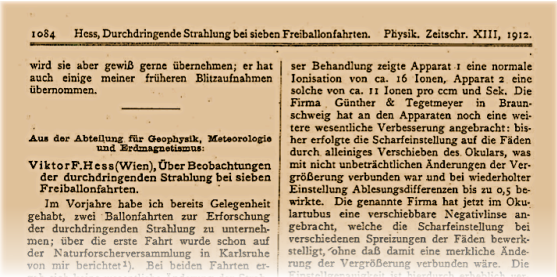
Discovery of cosmic rays

Victor F. Hess

Discovery **1912**
Nobel prize **1936**







1084 Hess, Durchdringende Strahlung bei sieben Freiballonfahrten. Physik. Zeitschr. XIII, 1912.

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Aus der Abteilung für Geophysik, Meteorologie und Erdmagnetismus:

Viktor F. Hess (Wien), Über Beobachtungen der durchdringenden Strahlung bei sieben Freiballonfahrten.

Im Vorjahre habe ich bereits Gelegenheit gehabt, zwei Ballonfahrten zur Erforschung der durchdringenden Strahlung zu unternehmen; über die erste Fahrt wurde schon auf der Naturforscherversammlung in Karlsruhe von mir berichtet[1]). Bei beiden Fahrten er-

ser Behandlung zeigte Apparat 1 eine normale Ionisation von ca. 16 Ionen, Apparat 2 eine solche von ca. 11 Ionen pro ccm und Sek. Die Firma Günther & Tegetmeyer in Braunschweig hat an den Apparaten noch eine weitere wesentliche Verbesserung angebracht: bisher erfolgte die Scharfeinstellung auf die Fäden durch alleiniges Verschieben des Okulars, was mit nicht unbeträchtlichen Änderungen der Vergrößerung verbunden war und bei wiederholter Einstellung Ablesungsdifferenzen bis zu 0,5 bewirkte. Die genannte Firma hat jetzt im Okulartubus eine verschiebbare Negativlinse angebracht, welche die Scharfeinstellung bei verschiedenen Spreizungen der Fäden bewerkstelligt, ohne daß damit eine merkliche Änderung der Vergrößerung verbunden wäre. Die

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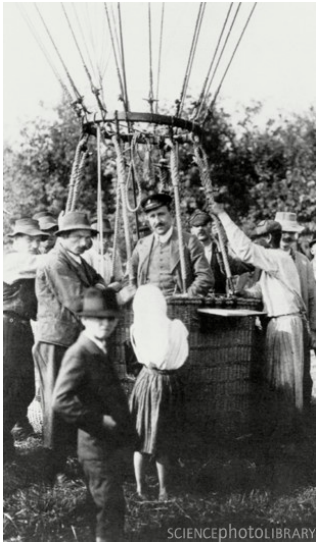

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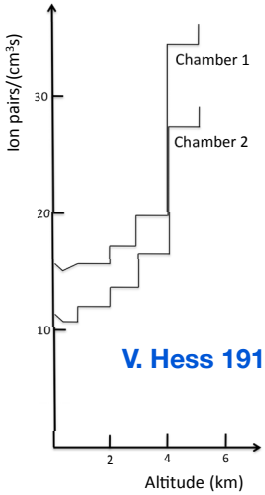

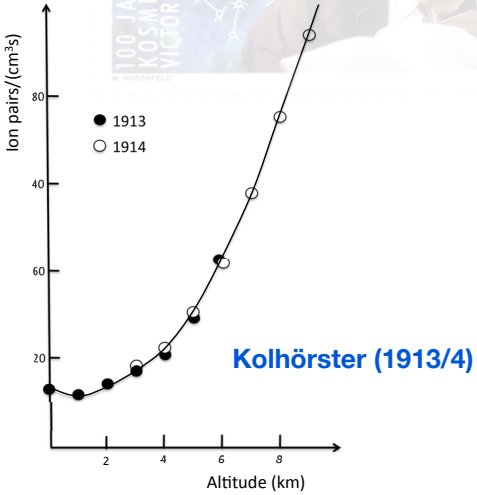

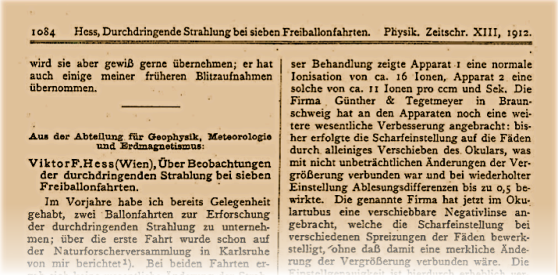

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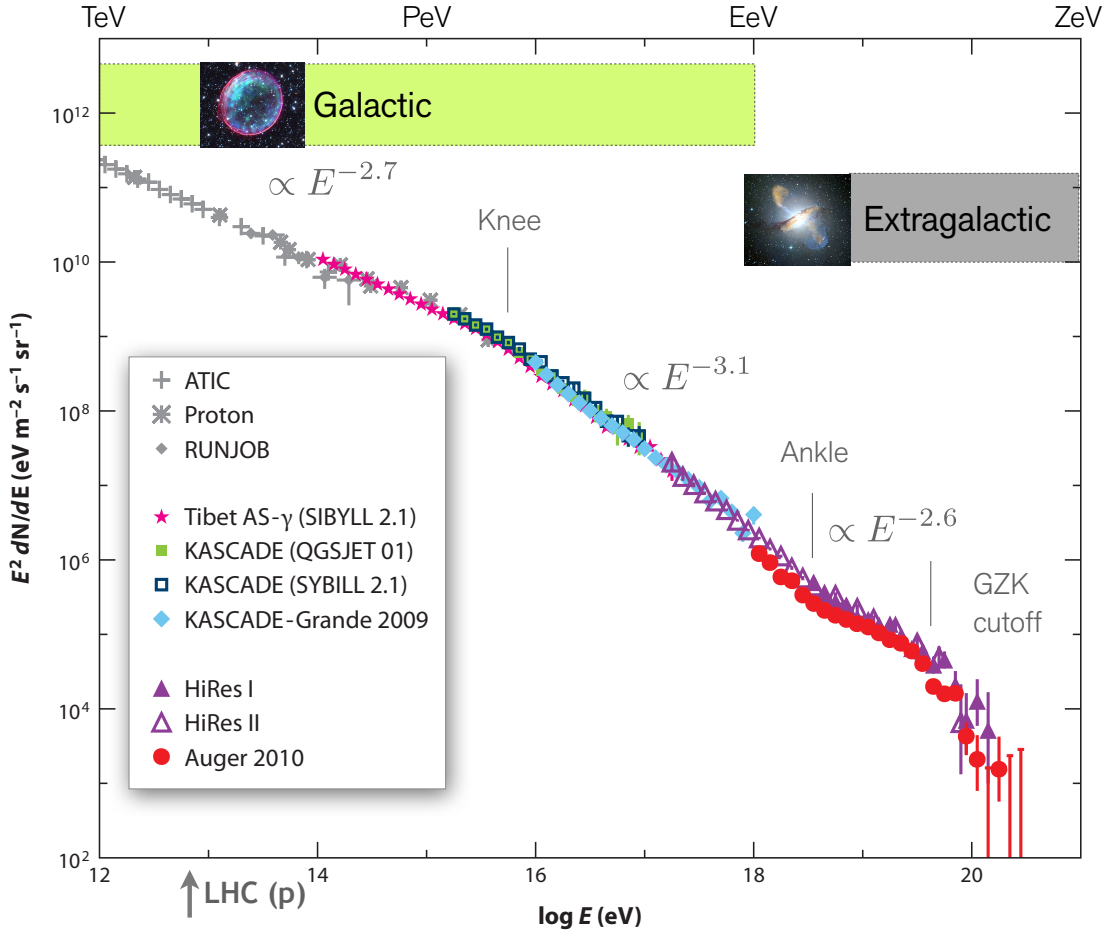
Energy spectrum



Cosmic-ray origin discovered?

New York Times (1923-Current file); Jan 20, 1985;
ProQuest Historical Newspapers: The New York Times (1851-2009)
pg. 1

Mystery of Cosmic Ray Origin May Be Solved

By WALTER SULLIVAN

Astronomers believe they have discovered several sources of cosmic rays, the penetrating radiation that bombards the Earth from all directions. The origin of these high-energy particles has been one of the most profound mysteries of the universe.

One of the sources, Cygnus X-3, a two-star system believed to lie on the outer fringes of the Milky Way, has been found to produce so much of the higher-energy cosmic rays that it could account for the galaxy's entire production of such rays.

A number of scientists who attended a recent meeting of the American Astronomical Society believe the discovery is a landmark in astrophysics.

Cosmic rays include the most powerful form of radiation known to science. In space, they consist primarily of high-energy protons, nuclei of hydrogen atoms, and when they strike the atmosphere they generate showers of secondary particles that reach the Earth.

The belief that a large portion of them originate in Cygnus X-3 is based on observations, both from space and from the ground, showing it to be a source of extremely energetic gamma rays.

Cygnus X-3 is assumed to be a pulsar, a fast rotating star of extreme density that circles and draws gas from a companion star. Interactions between the two apparently act as a giant particle accelerator of almost unbelievable

Continued on Page 22, Column 1

Cosmic-ray origin discovered?

New York Times (1923-Current file); Jan 14, 1933;
ProQuest Historical Newspapers: The New York Times (1851-2009)
pg. 1

Piccard Predicts Use of the Cosmic Ray To Run Motors, Light Cities, Drive Planes

Special to THE NEW YORK TIMES.

WASHINGTON, Jan. 13.—Cosmic rays may be the energy of the future, harnessed energy which will light cities, motivate industries and drive airplanes through the stratosphere at tremendous speeds, Professor Auguste Piccard, the Swiss physicist, who ascended ten miles in a balloon, told an audience in the Washington Auditorium tonight in his first lecture in this country, sponsored by the National Geographic Society. Coal will then become valueless, he said, and limitless power may be produced at almost no cost.

The energy contained in each cosmic ray is 1,000,000 times greater than that produced by the most violent reactions between molecules or atoms, and even radioactive reac-

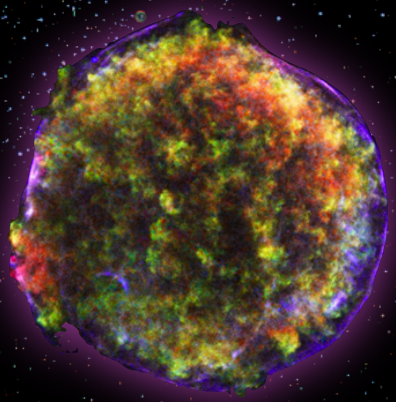
of generating cosmic rays, he went on.

"You see something of what this means for the engineer," he said. "Inasmuch as these reactions take place somewhere in the world, it is necessary to utilize them industrially.

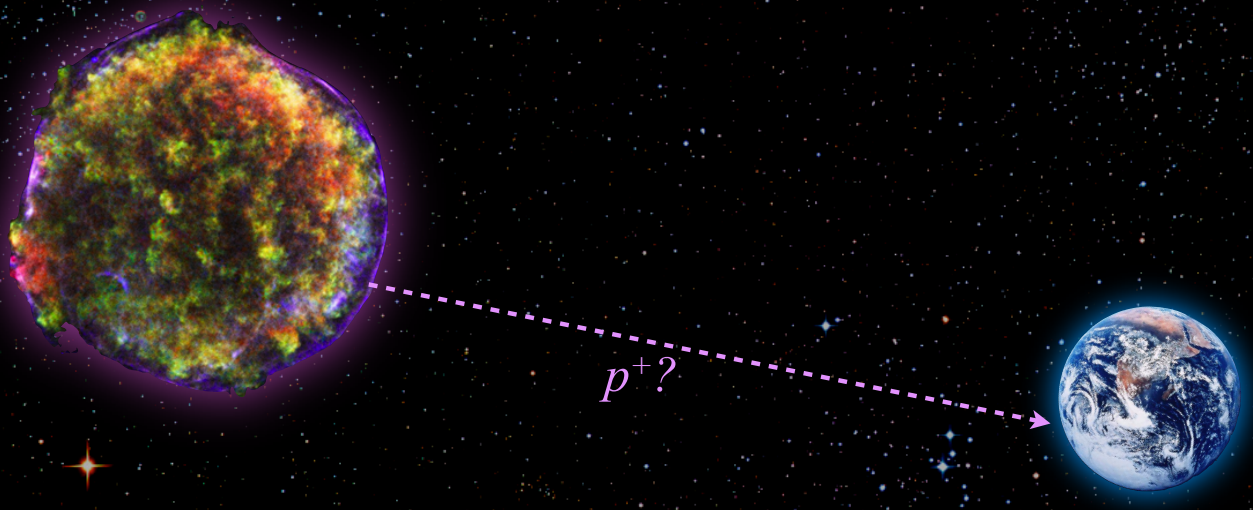
"The raw materials cost nothing —water, for example. The transformation of the atoms of three drops of water would produce enough cosmic rays and enough energy to light the whole city of Washington for a night.

"We must not expect modern science to find tomorrow the means of executing this transformation," Professor Piccard said. "The resultant crisis would be too violent for mankind; but later on, when

Cosmic-ray propagation



Cosmic-ray propagation



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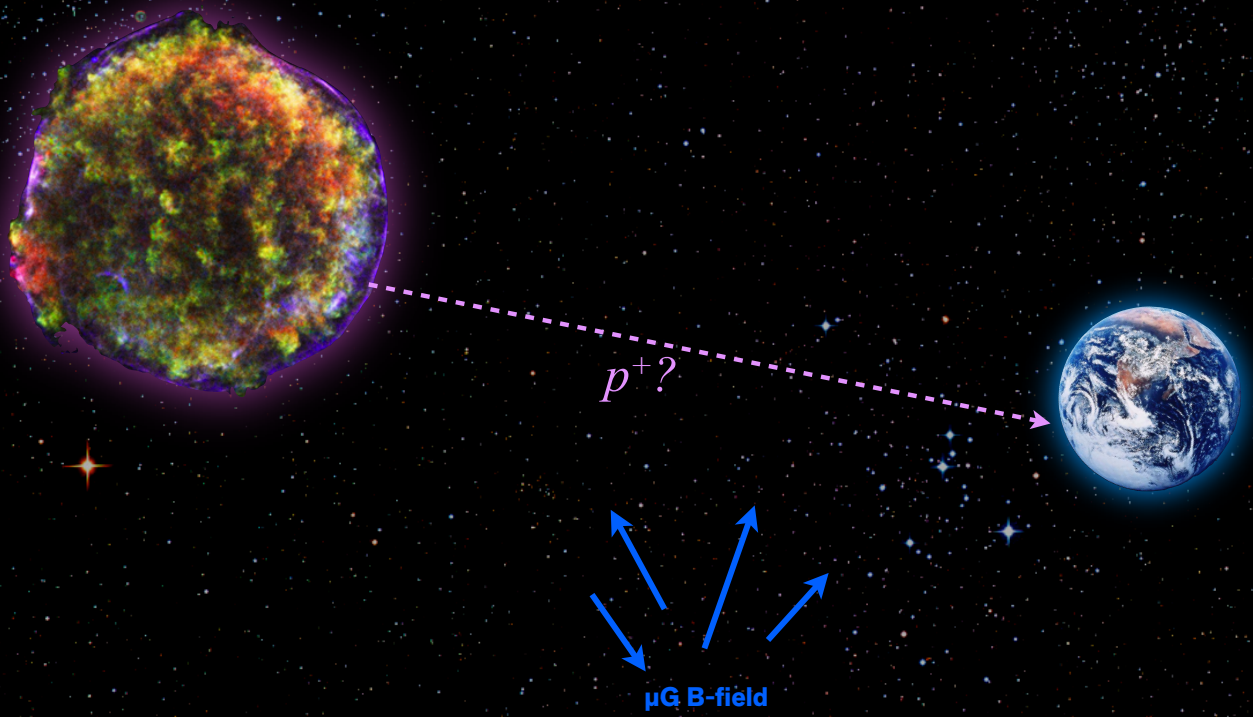

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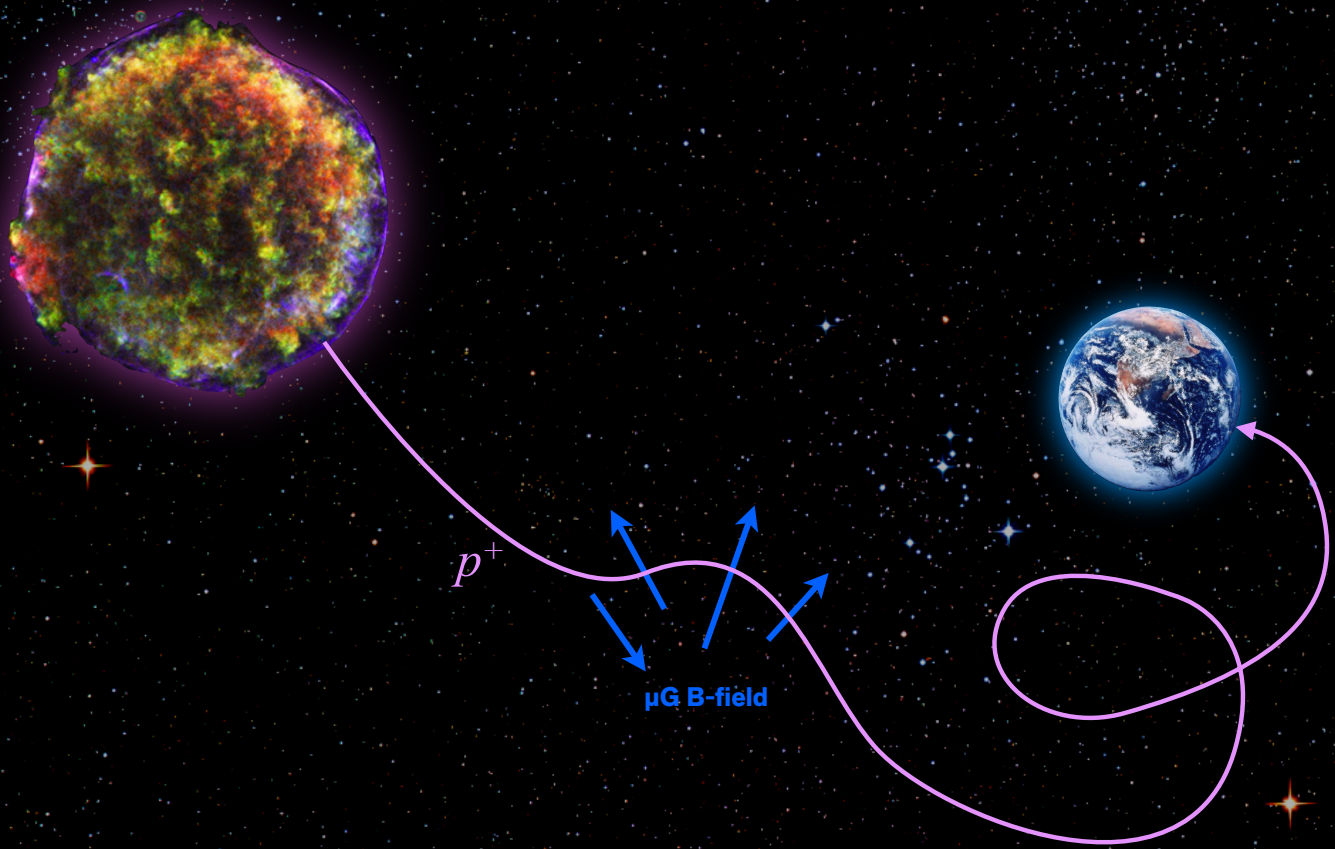

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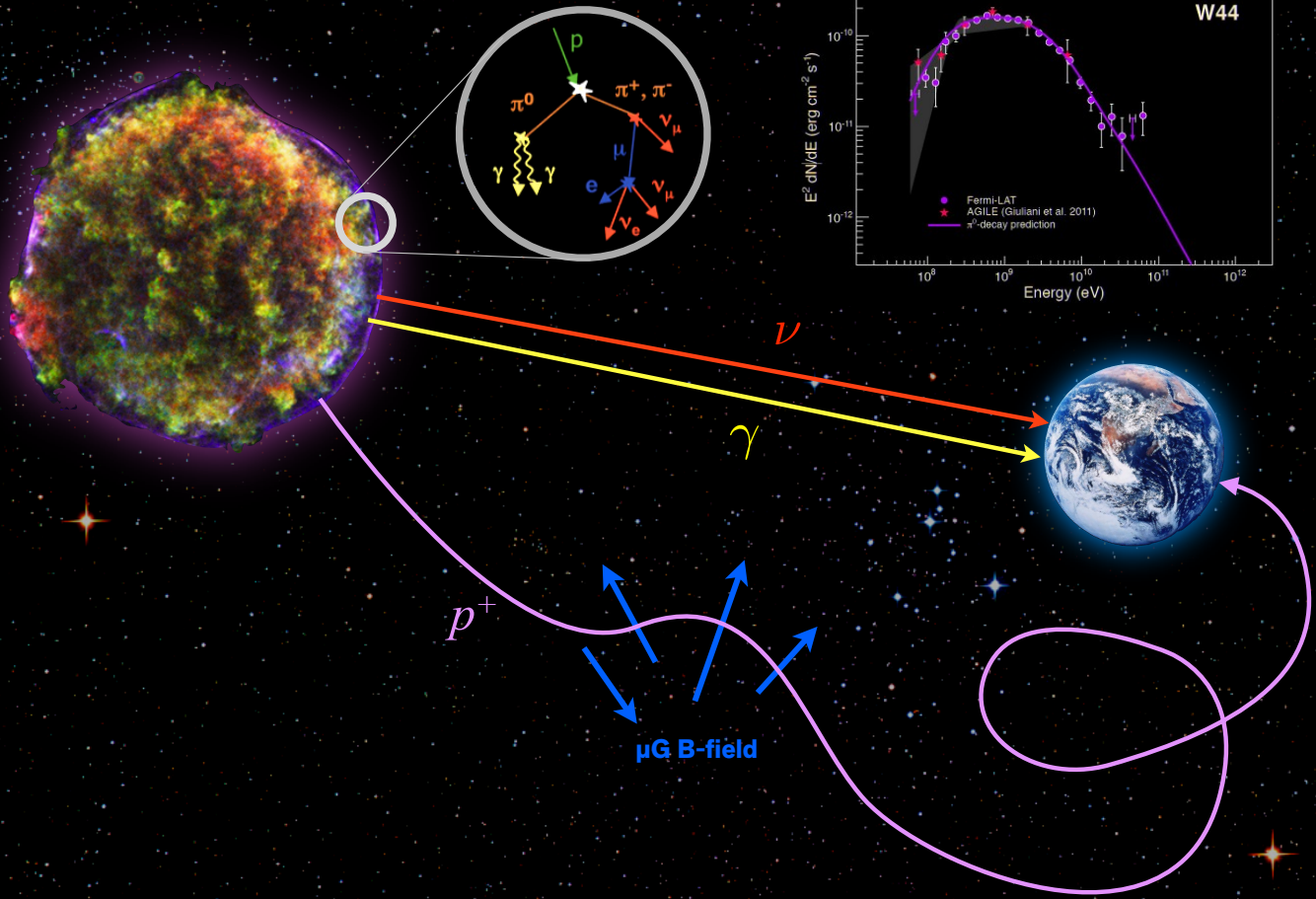


Cosmic-ray propagation

Diffusive cosmic ray propagation

$$\frac{\partial \mathcal{N}}{\partial t} = \nabla \cdot (D_i \nabla \mathcal{N}_i)$$ **Diffusion**

$$- \frac{\partial}{\partial E}[b_i(E)\mathcal{N}_i(E)]$$ Energy losses

$$- \nabla \cdot \mathbf{u}\, \mathcal{N}_i(E)$$ Convection

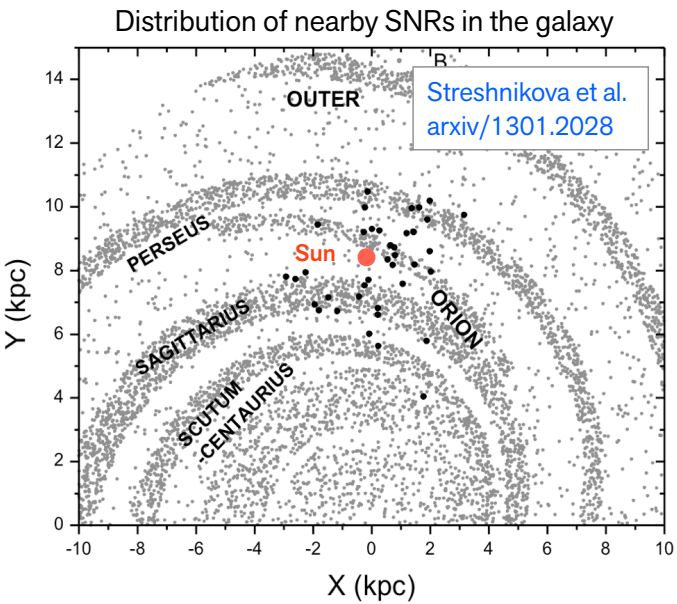
$$+ Q_i(E,t)$$ Source function

$$- p_i \mathcal{N}_i$$ Decay and collisions

$$+ \frac{v\ \rho}{m} \sum_{k \geq i} \int \frac{d\sigma_{i,k}(E,E')}{dE} \mathcal{N}_k(E') dE'$$ Spallation feed-down

- Parameters obtained from fitting secondary/primary ratios.

Cosmic-ray propagation



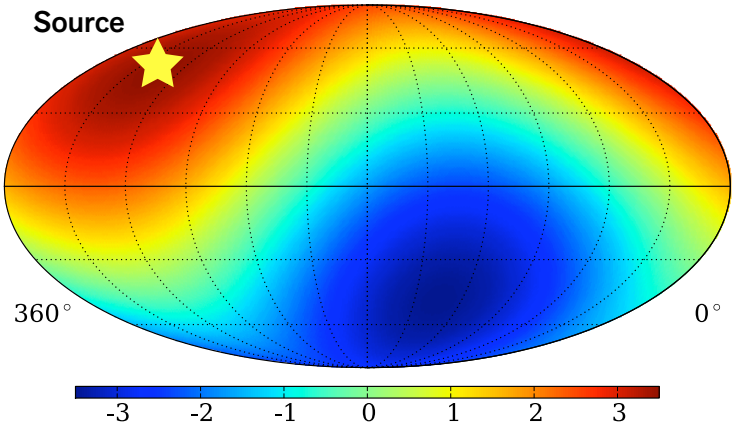
- SNRs accelerate cosmic rays.
- CRs propagate diffusively.
- Diffusion induces the presence of gradients.
- Gradients produce **anisotropy**.

Anisotropy amplitude

$$\delta(E) = \frac{3D(E)}{c}\frac{\nabla n(E)}{n(E)} \propto E^{\alpha}$$

Anisotropy from CR diffusion

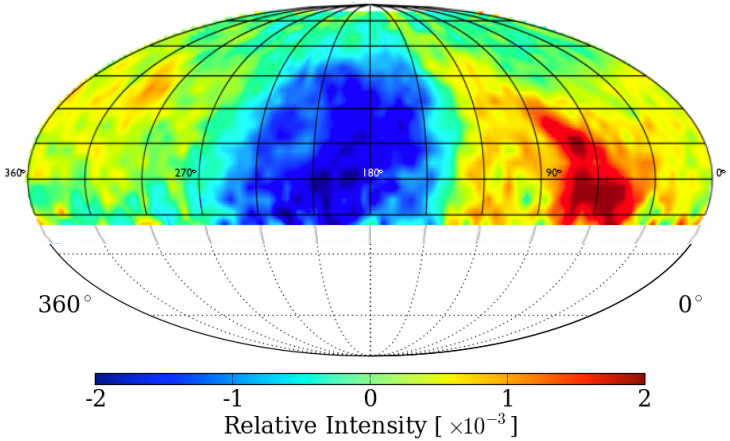
- Amplitude: 10^{-2} - 10^{-3} range
- Orientation: Depends on propagation geometry, mostly towards the relevant CR source(s).
- Shape: Dipole (large scale).



Relative intensity:
Fractional offset from isotropic level.

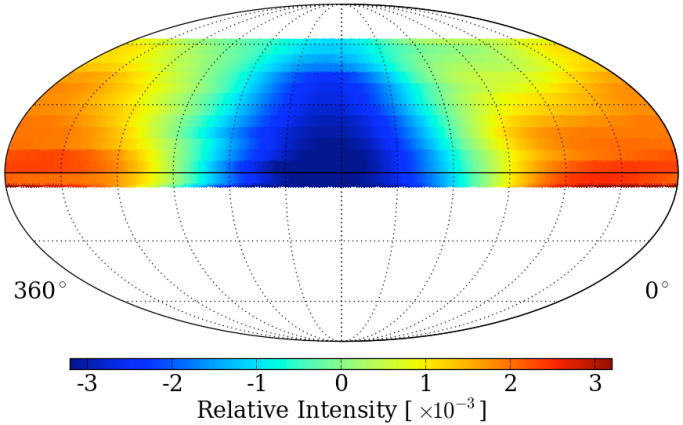
Large-scale anisotropy observations

Amenomori et al, astro-ph/0610671



Tibet-III

Abdo et al, arxiv/0806.2293

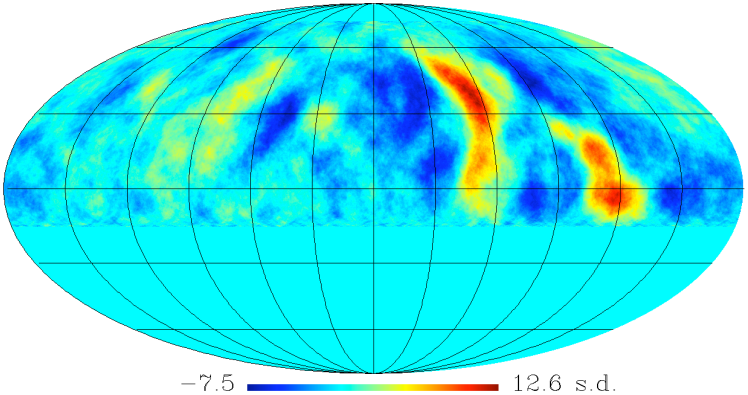


Milagro

- Several observations of **large-scale** anisotropy in the north (Tibet, Milagro, ARGO-YBJ, SuperK, HAWC) in the **1-10 TeV** energy range.
- **~10^{-3}** strength

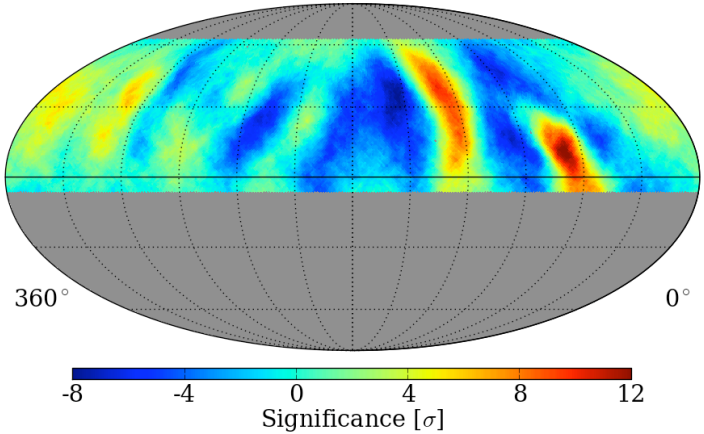
Small-scale anisotropy observations

Vernetto et al, Proc. of the ICRC 2009



ARGO-YBJ

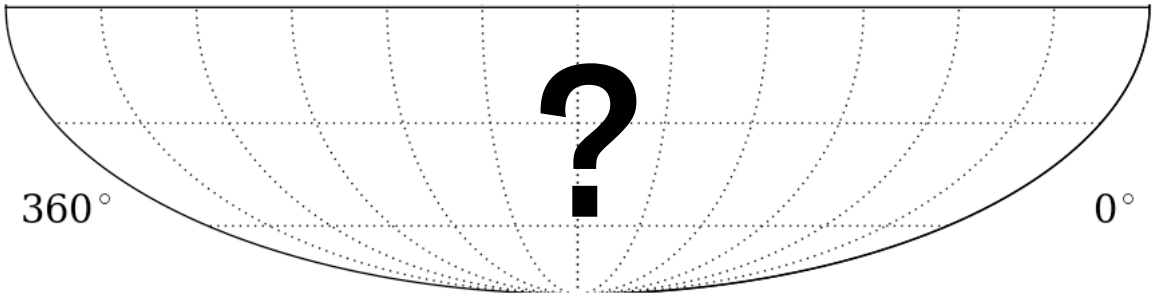
Abdo et al. arxiv/0801.3827



Milagro

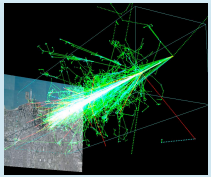
- Milagro, Tibet, ARGO-YBJ, and HAWC report small scale structures.
- **~10^{-4}** strength

Extending the observations to the south



- Detector sensitive to TeV cosmic rays.
- Weak anisotropy (10^{-3}) implies the need for large data sets (> 10^8-10^9 events) with good angular resolution.
- Stable detection conditions (few detector effects).

Outline



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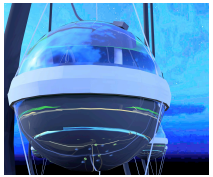

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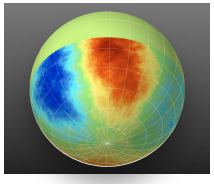

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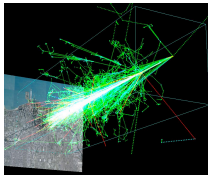

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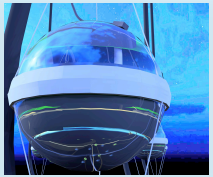

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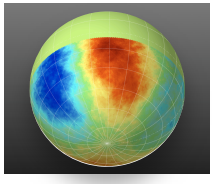

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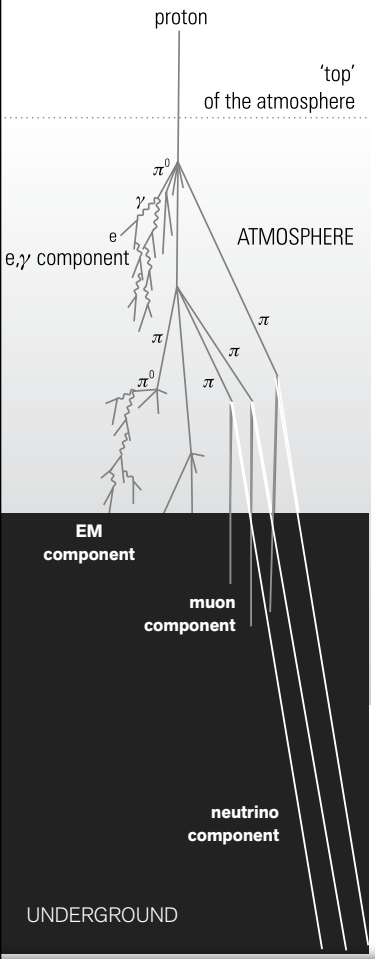
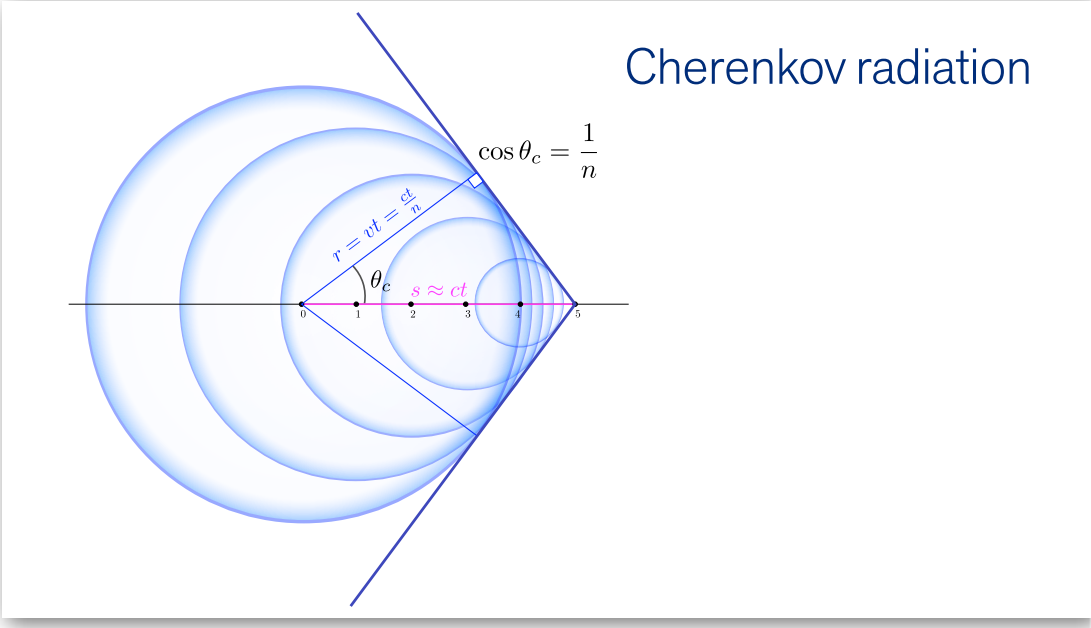
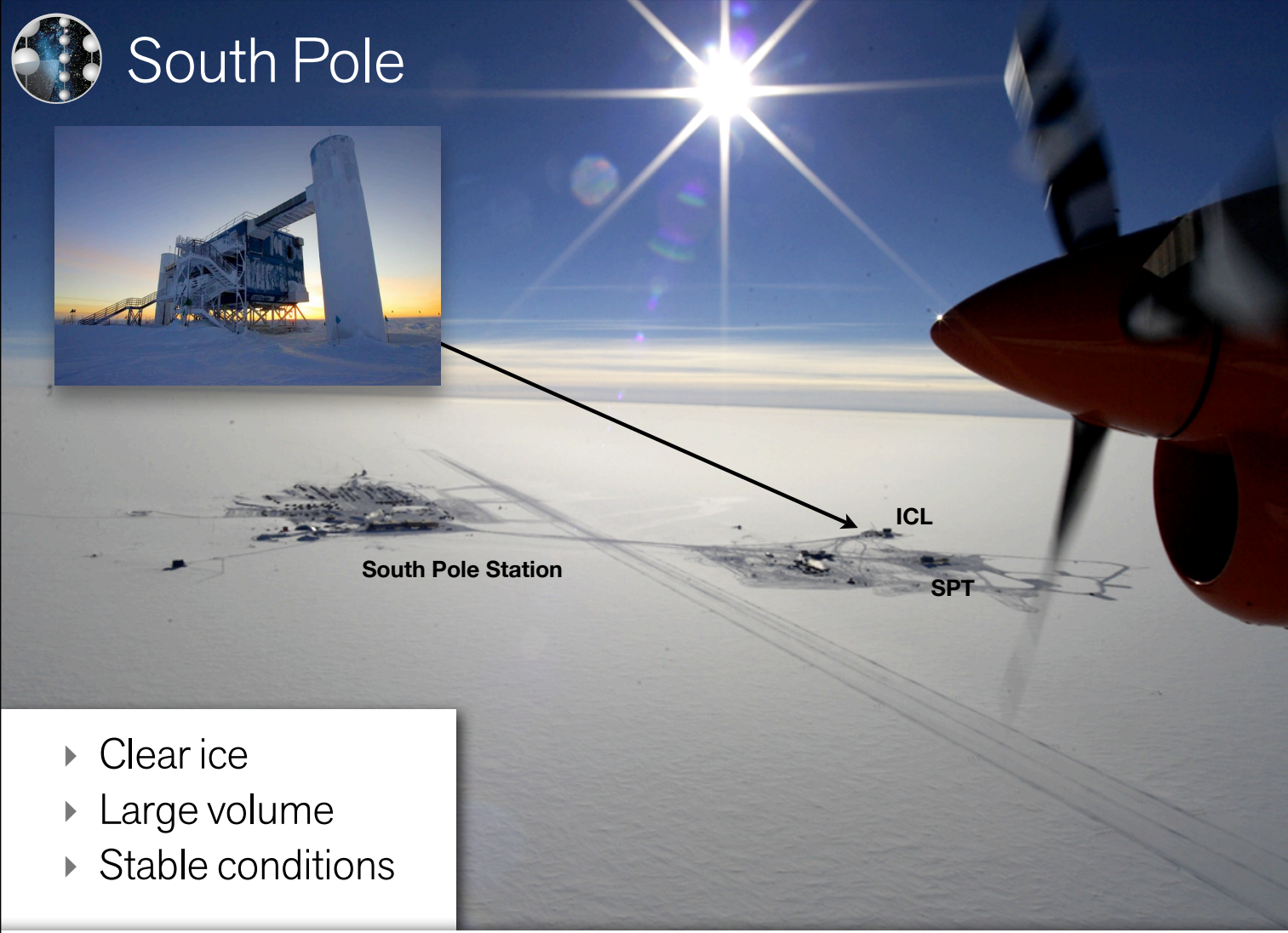
Cosmic-ray detectors





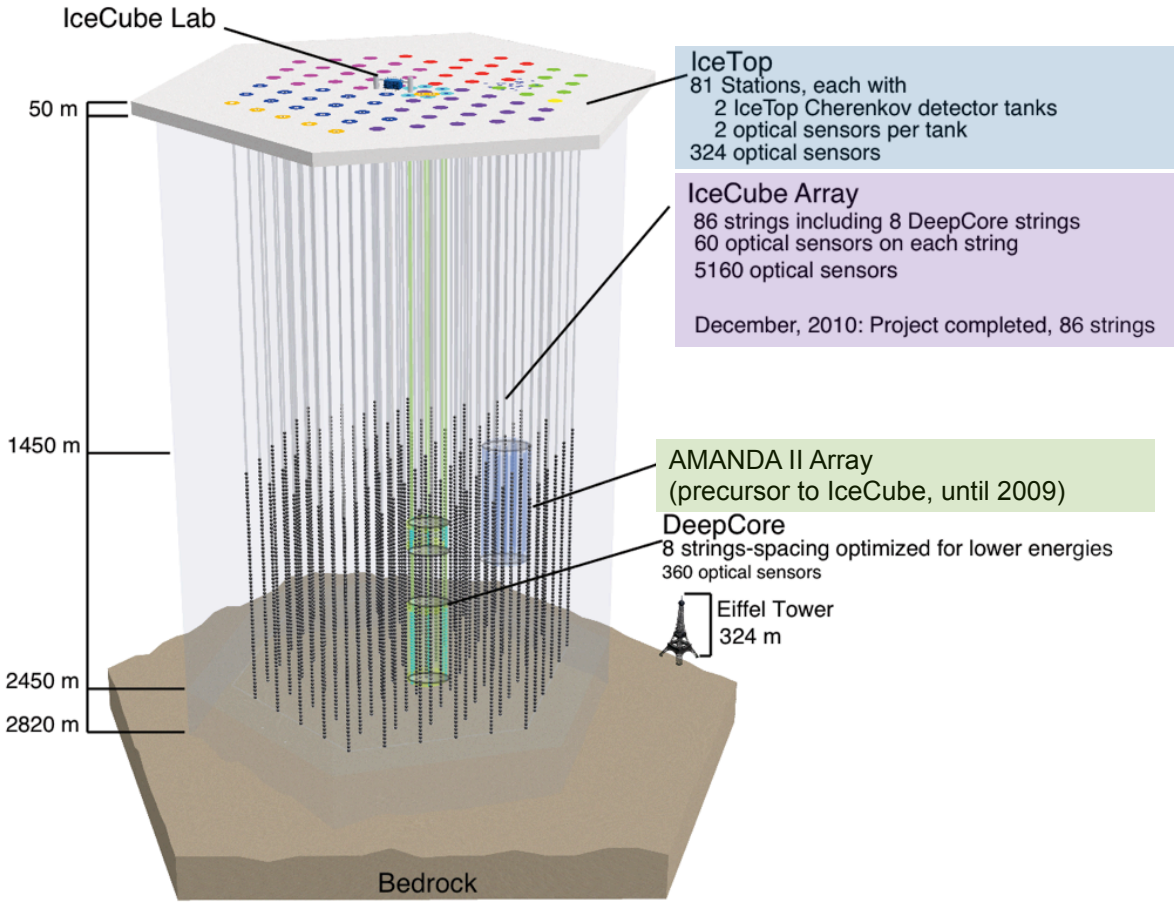
- Detect secondary particles in the air shower ($e^{\pm}$, muons).
- Energetic charged particles produce Cherenkov light in a refractive medium.
- If the medium is clear (i.e. low absorption and scattering) directions can be reconstructed.

South Pole



- Clear ice
- Large volume
- Stable conditions

IceCube, IceTop, and AMANDA



IceCube Collaboration

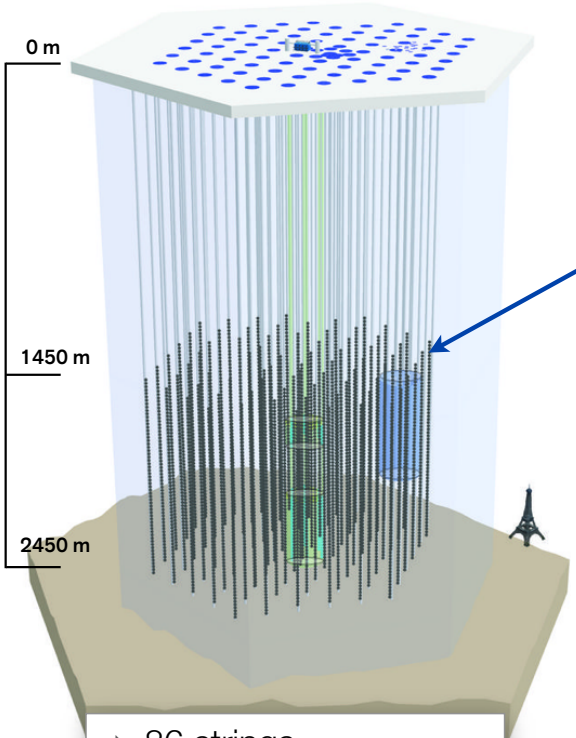
280 collaborators (approx.)

41 institutions

12 countries

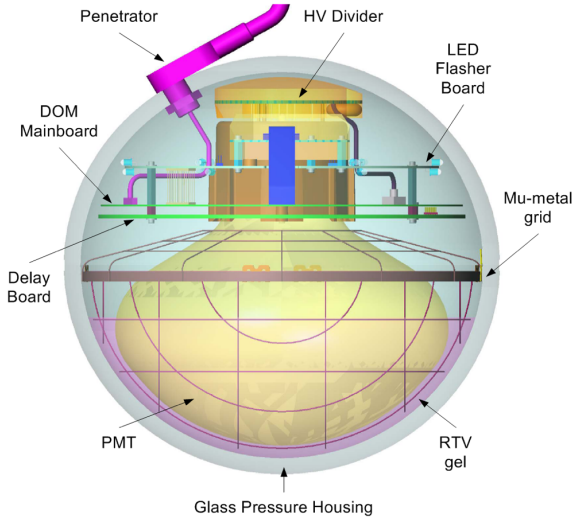
http://icecube.wisc.edu

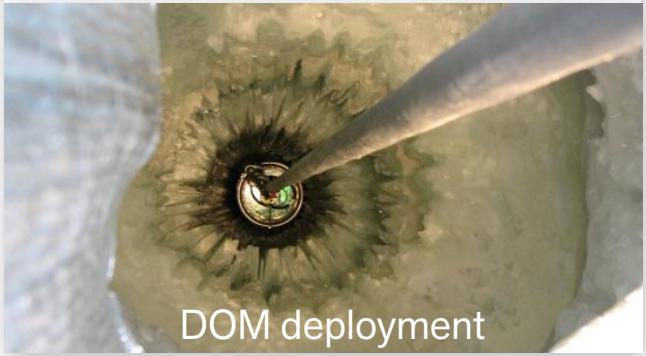
IceCube



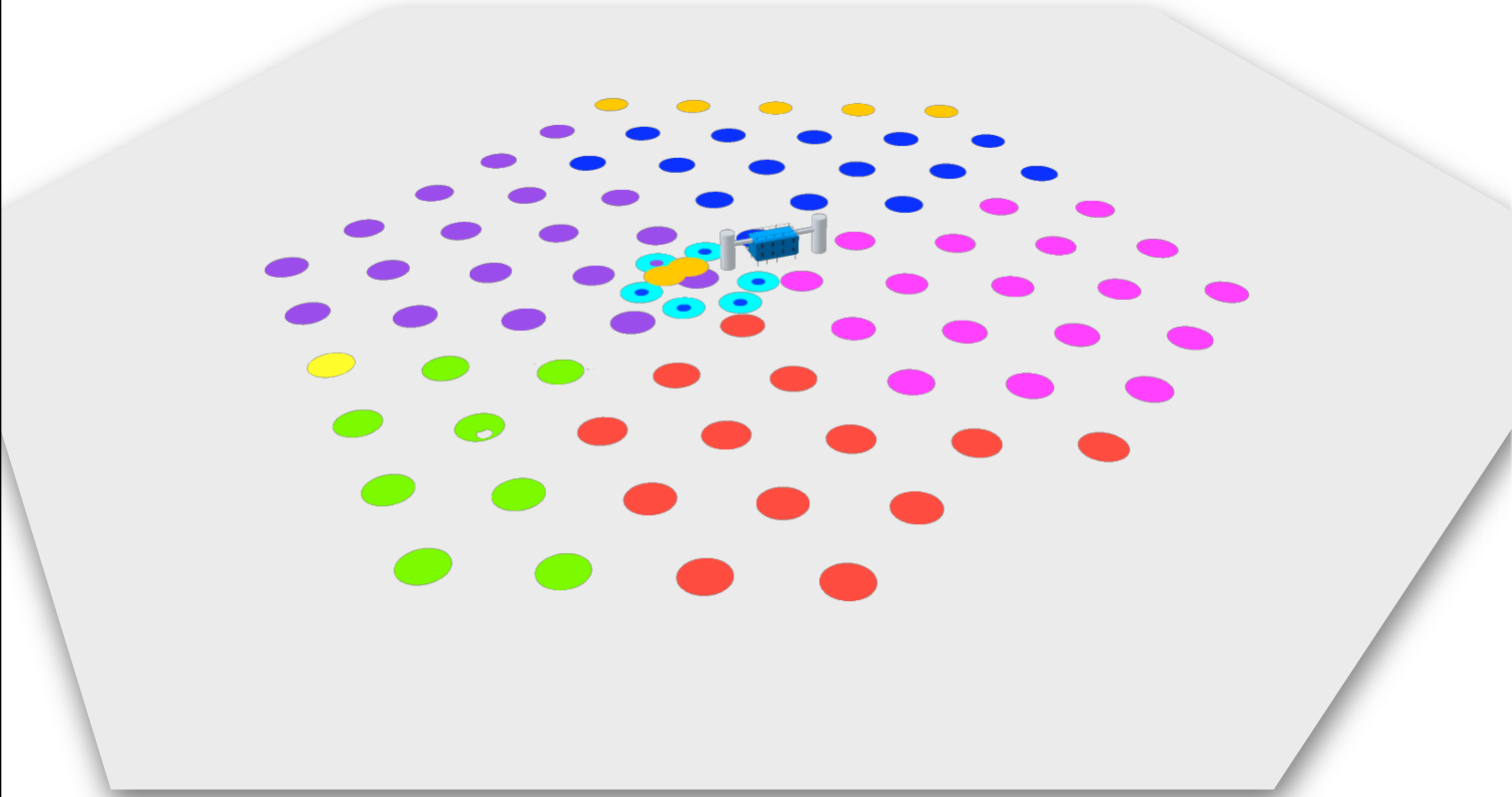
- 86 strings
- 5160 DOMs
- 17 m vertical spacing
- 125 m between strings

Digital Optical Module (DOM)

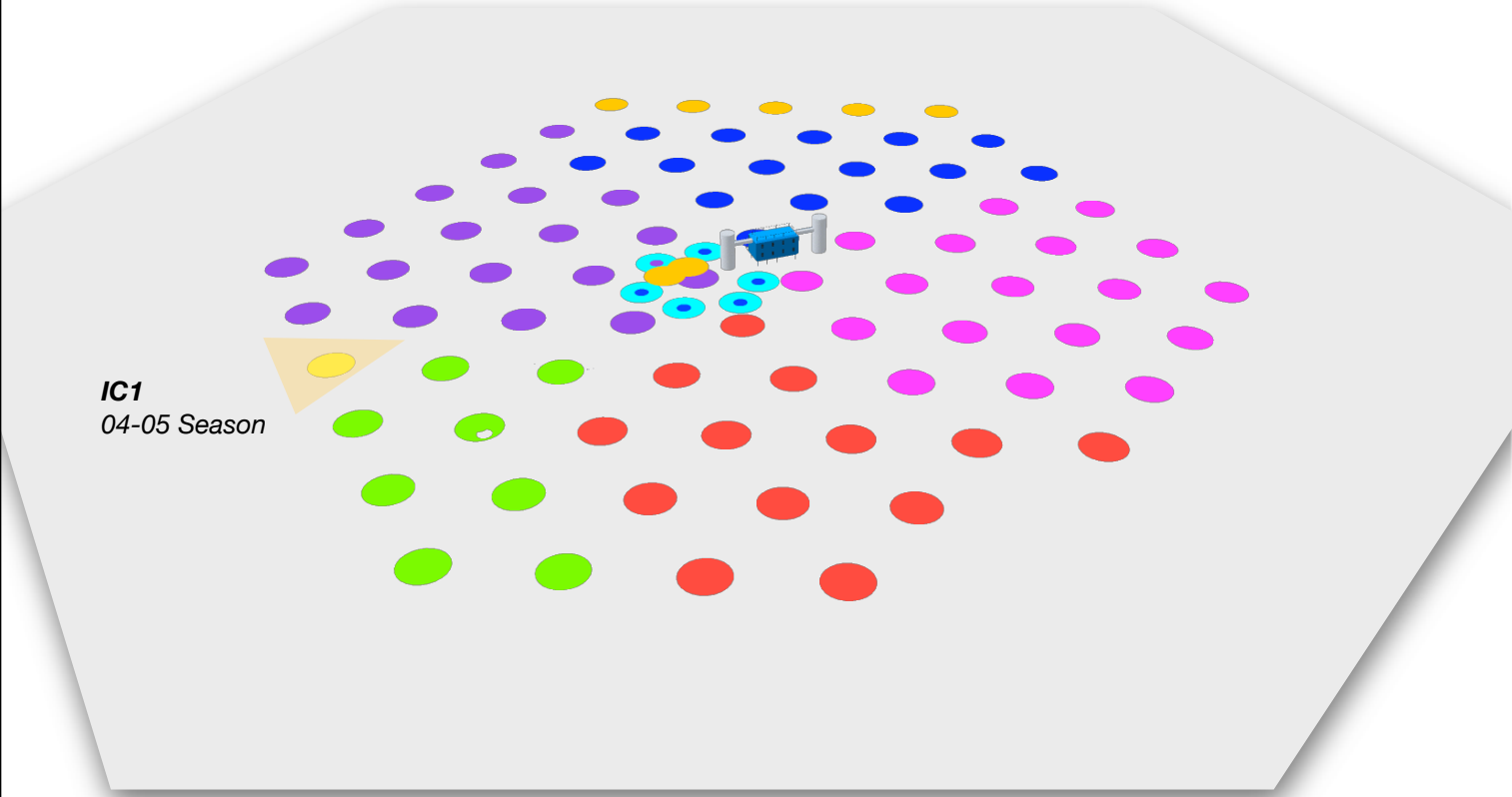




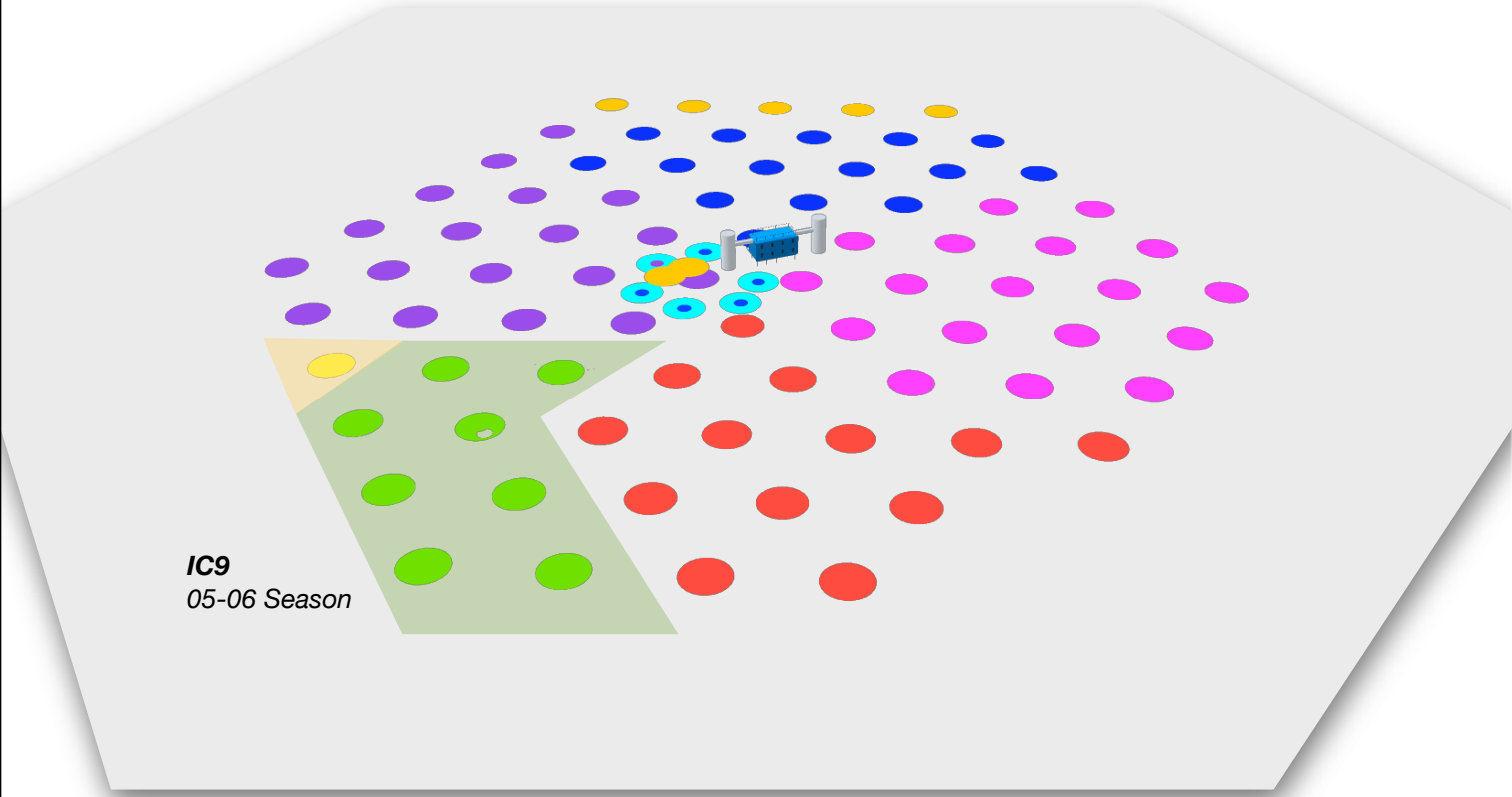
IceCube configurations



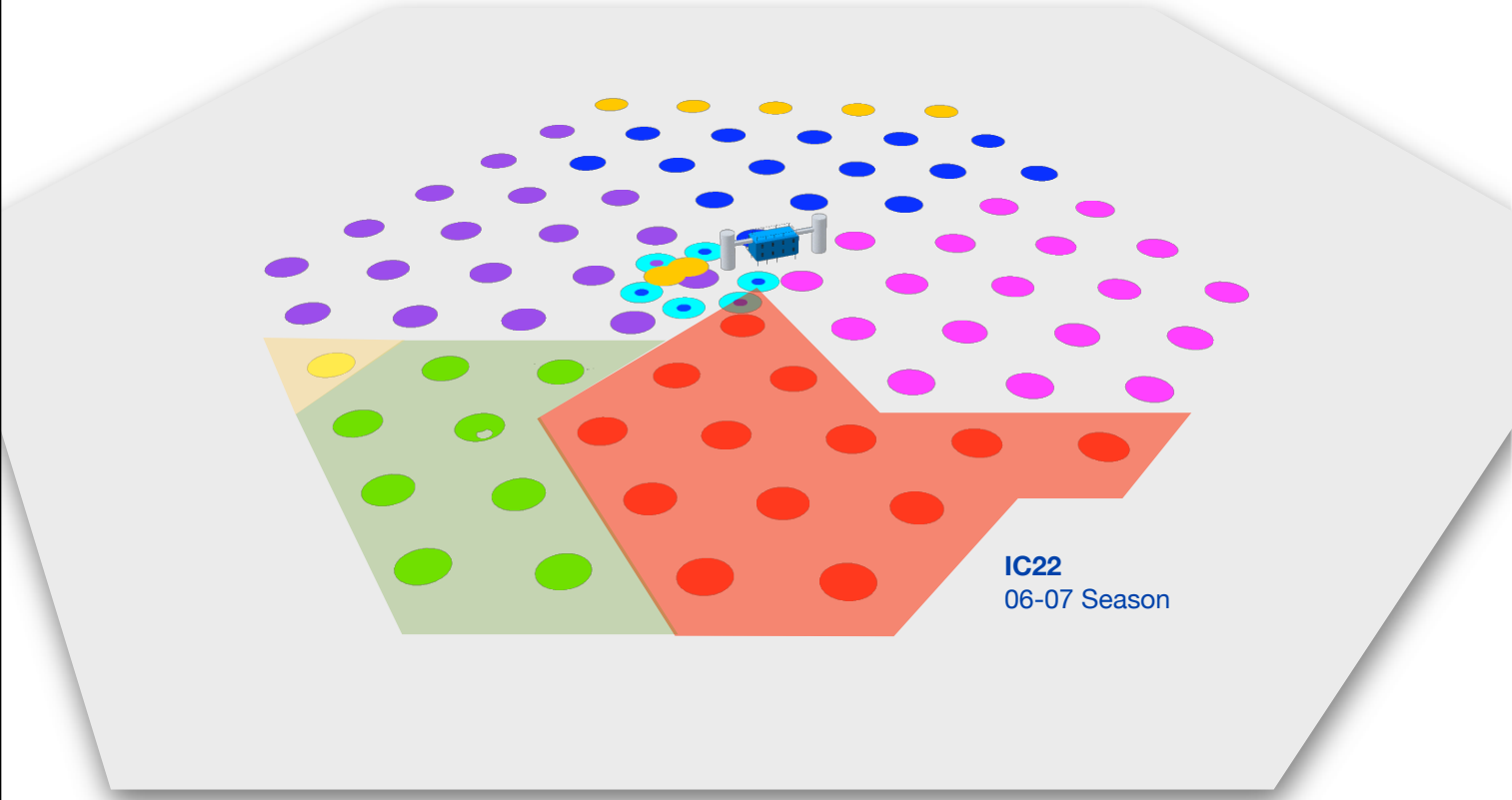
IceCube configurations



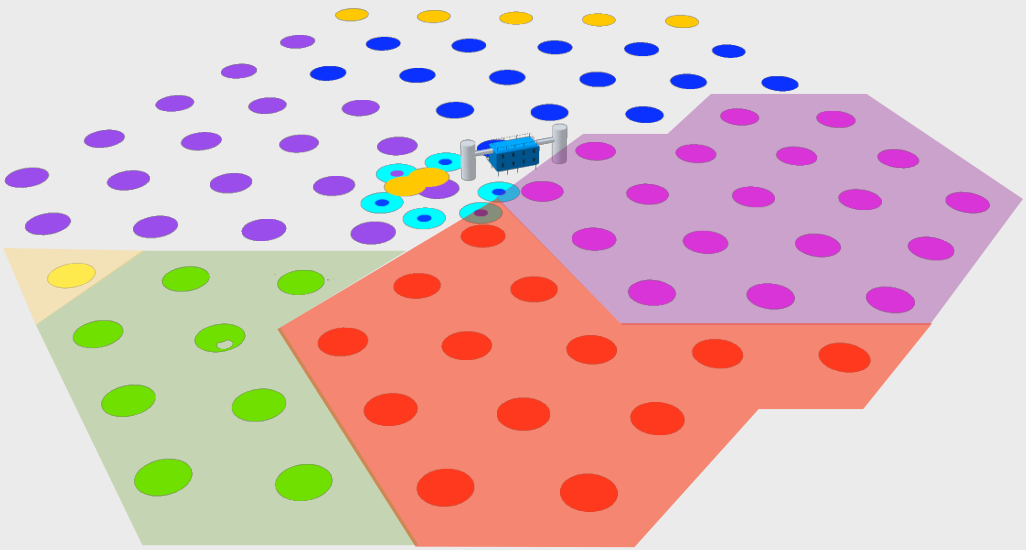
IceCube configurations



IceCube configurations

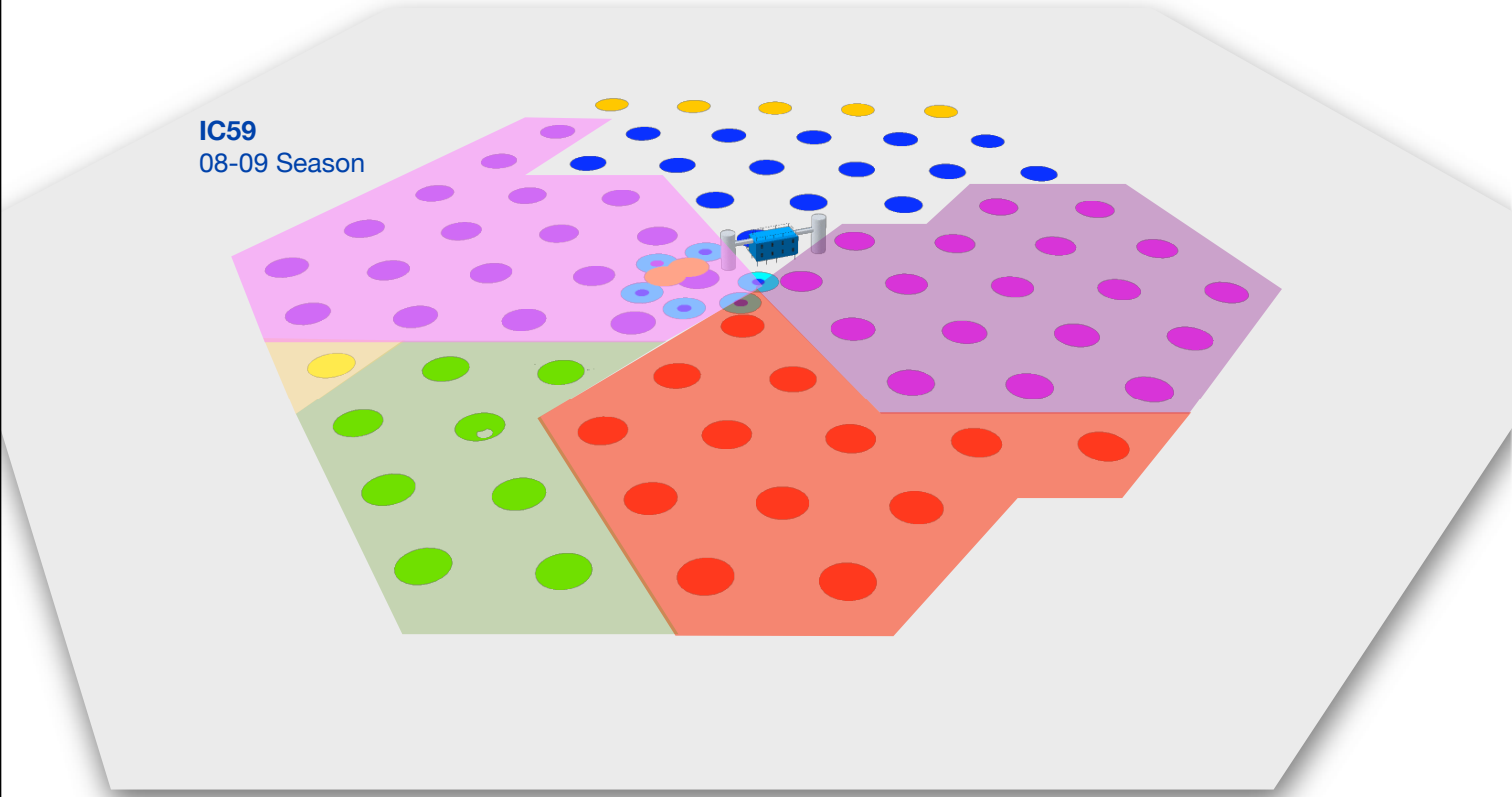


IceCube configurations

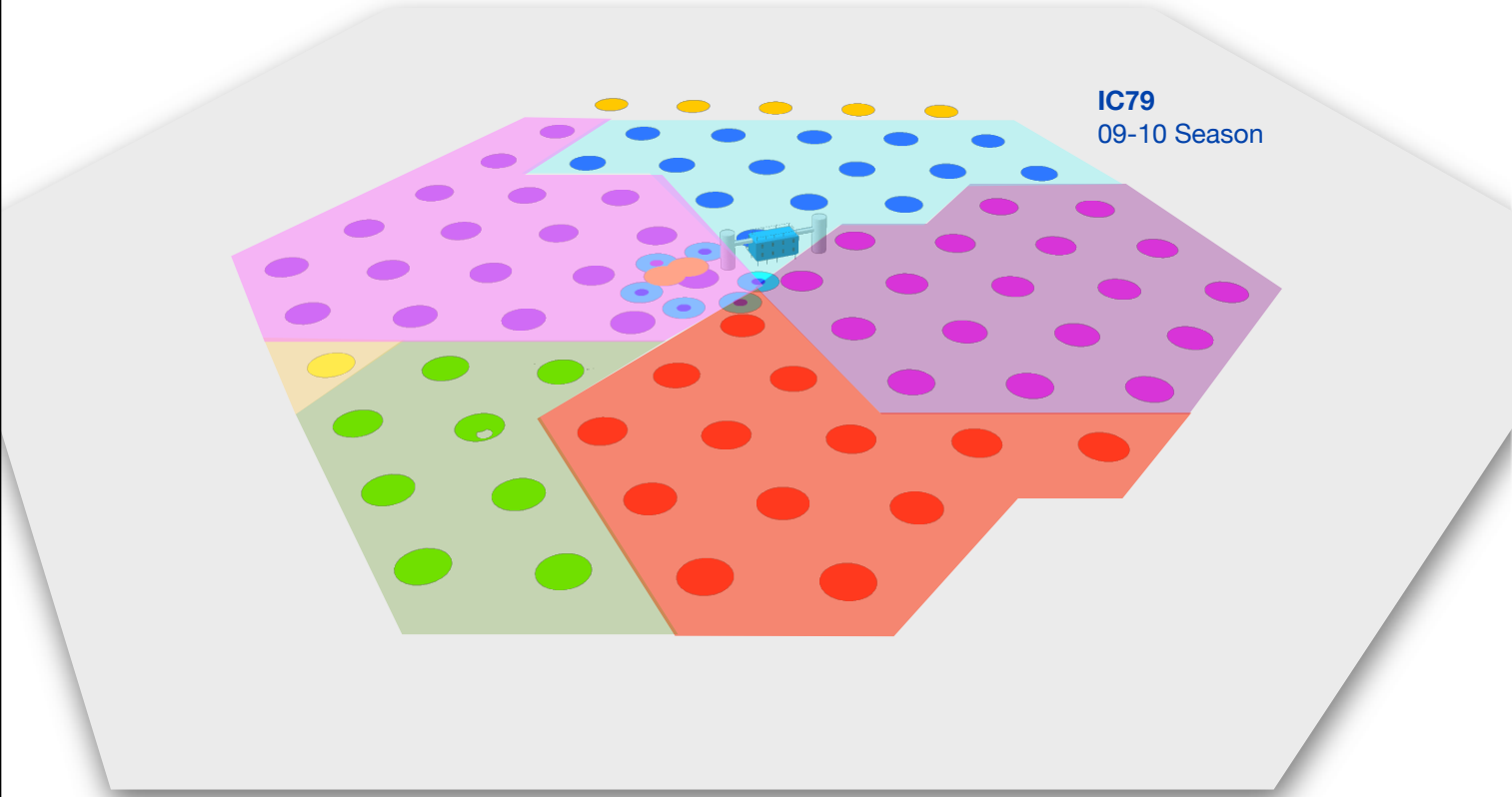


IC40
07-08 Season

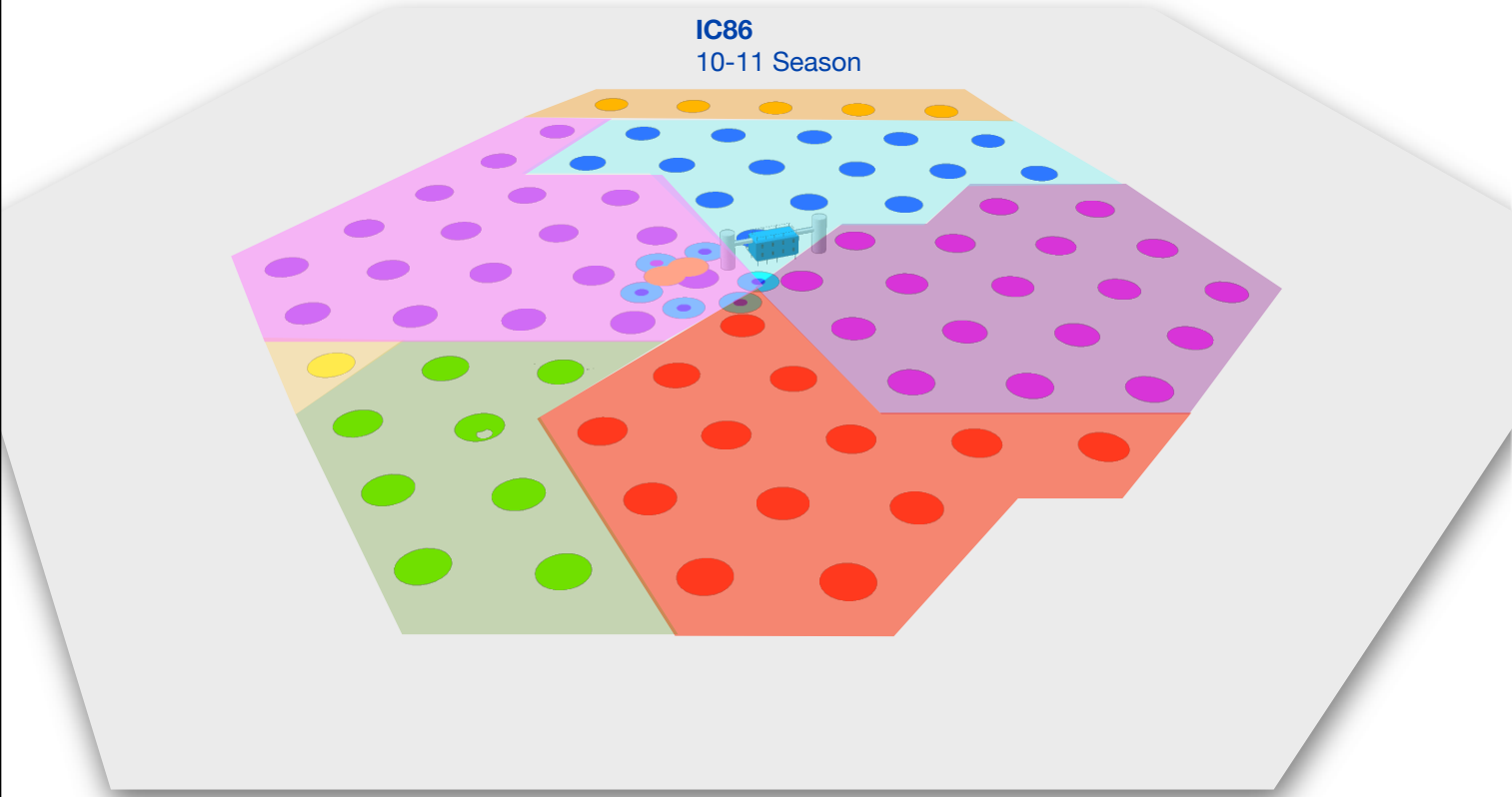
IceCube configurations



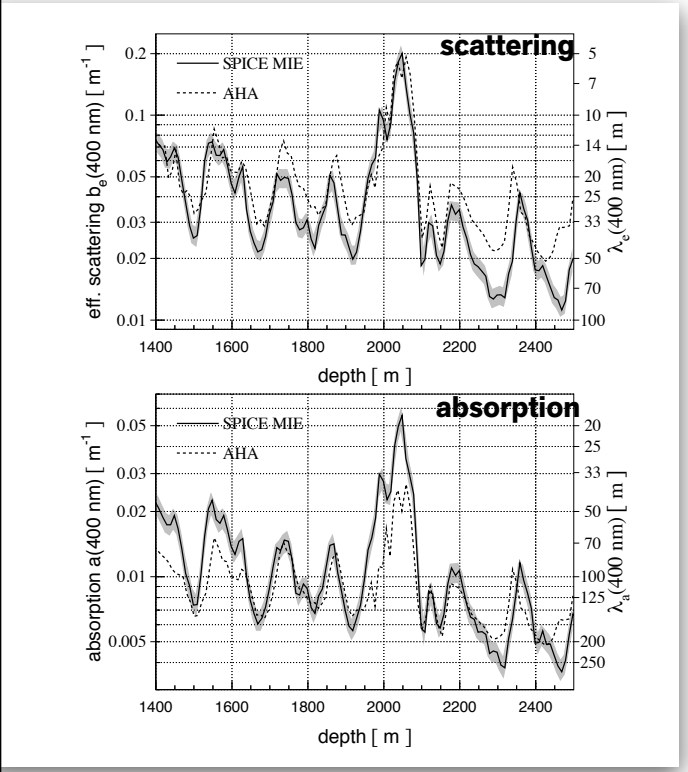
IceCube configurations

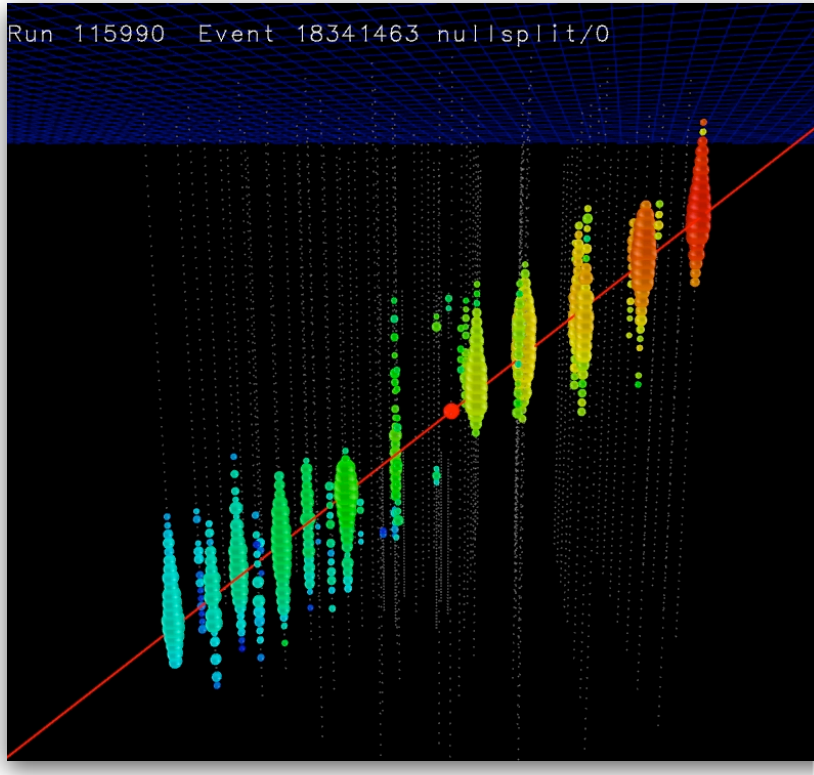


IceCube configurations



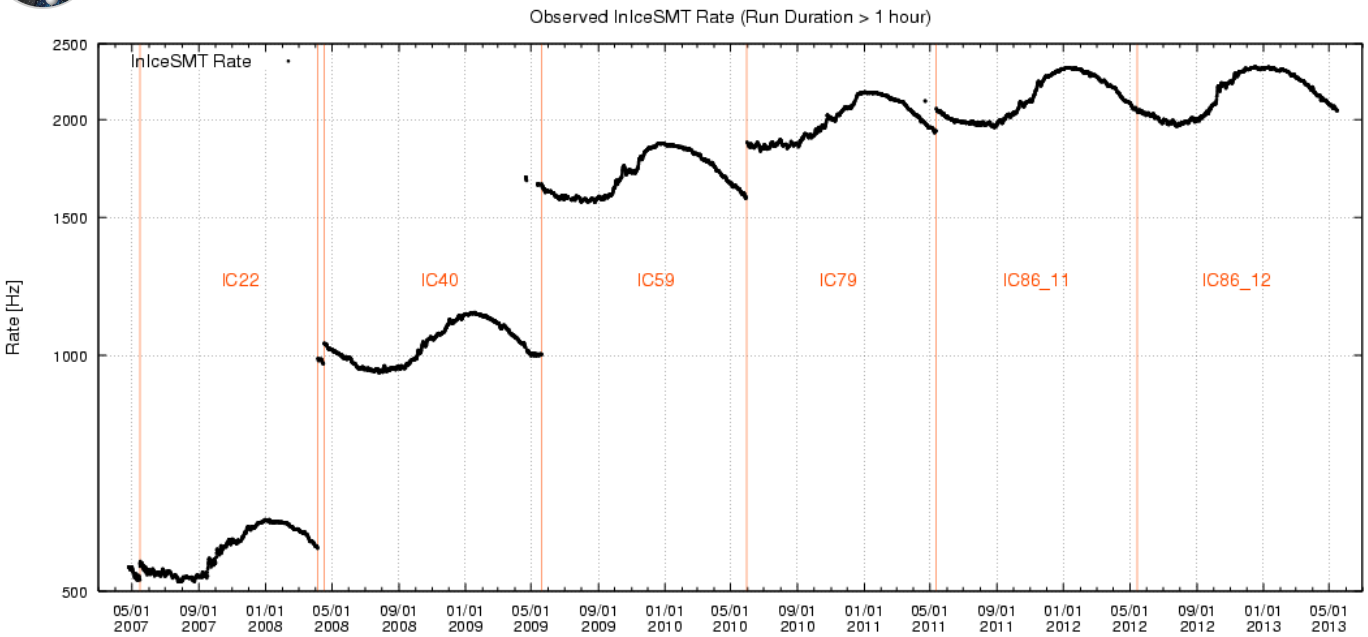
Light propagation in ice





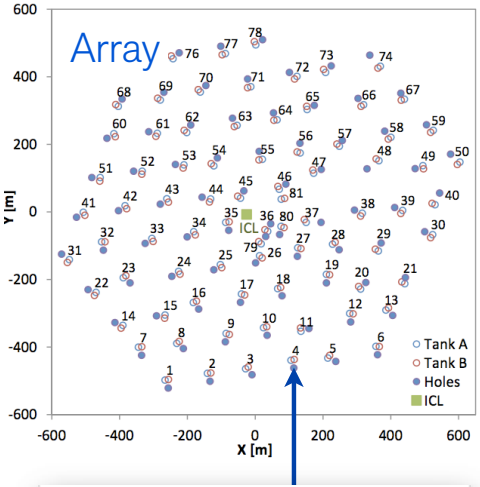
Cosmic ray event in IceCube

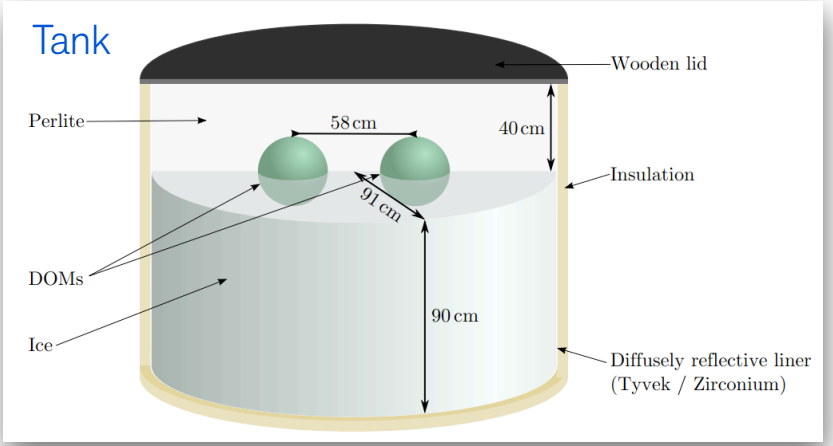
Event rate



- Compressed format retains reco info for all events passing simple majority trigger (8 DOMs hit within 5 μs).
- 1 kHz ~ 30 billion events / year. ~20 TeV CR median energy.
- Angular resolution ~ 3°.

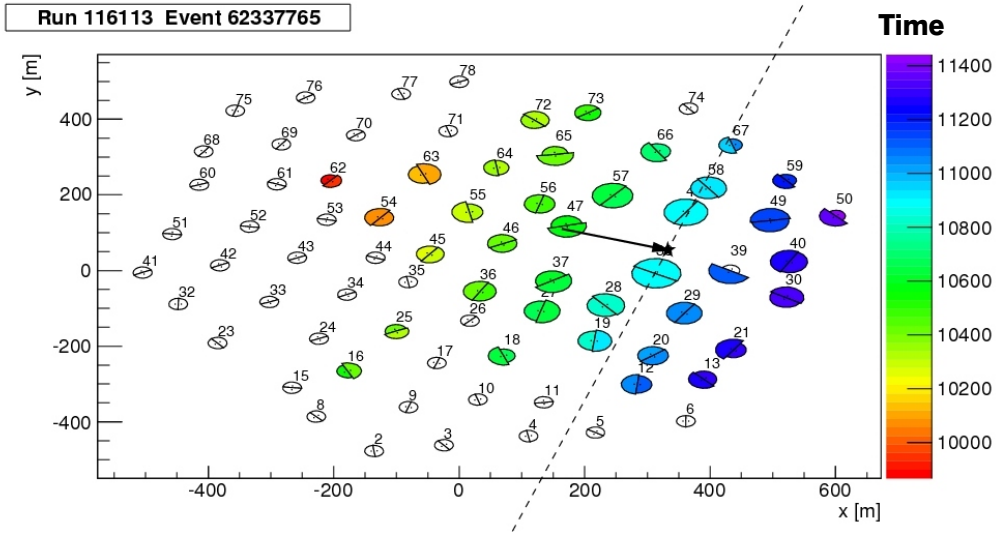
IceTop





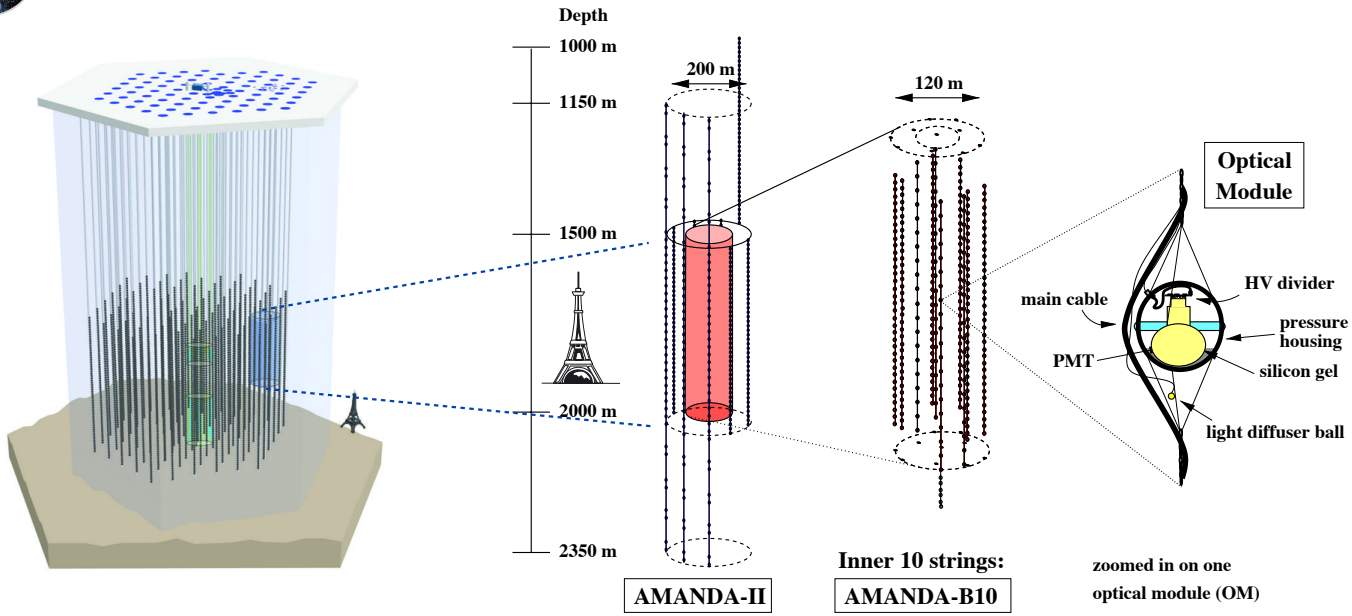
- **81 stations** (2 tanks/station, 2 DOMs/tank).
- High-gain & low-gain DOMs
- High-gain DOMs operated in local coincidence (hits within +/- 1 μs of each-other)
- Trigger**:** ≥ 6 coincident DOMs within 5 μs (at least 2 stations)

Event reconstruction



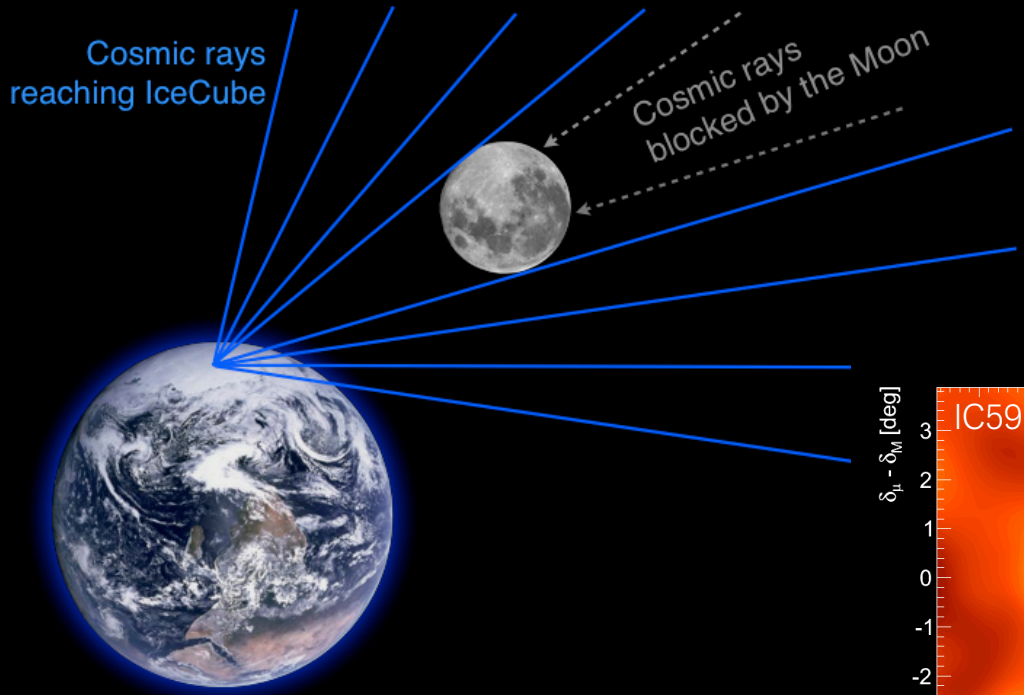
- ~ 10 Hz trigger rate (~ 300 million events / year).
- ~ 400 TeV CR median energy.
- Shower plane approximation:
  - ~ 3° angular resolution.

AMANDA



- 677 optical modules in 19 strings.
- AMANDA-II operated between 2000 and 2009.
- Trigger: 24 OMs within 2.5 μs. ~ 5° resolution and 10 TeV median CR energy.
- ~ 2 billion CR events / year (~ 60 Hz).

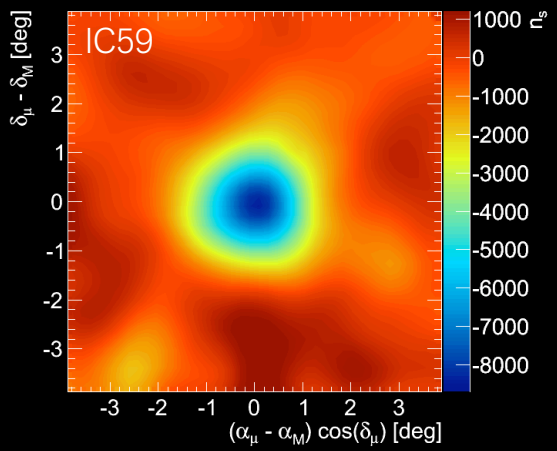
Angular resolution - Moon shadow



CR Moon shadow

Verification of the angular pointing of IceCube

Aartsen et al. (PRD accepted)
arxiv/1305.6811

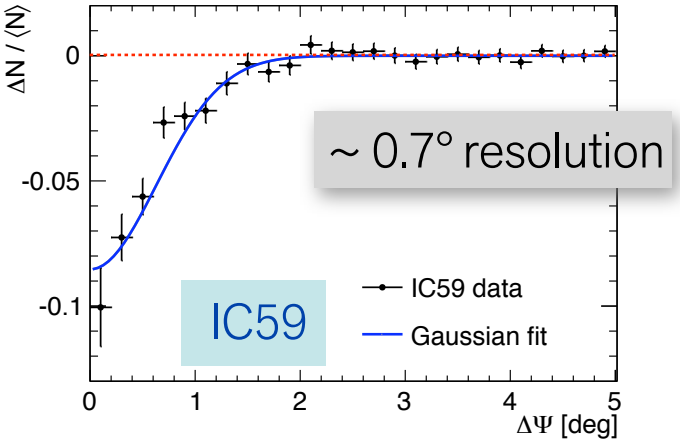


Angular resolution

Aartsen et al. (PRD accepted)
arxiv/1305.6811

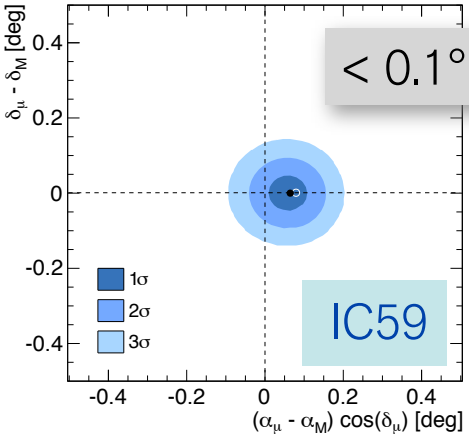
Resolution

Shadow profile vs. angular distance from the Moon



Absolute pointing

Most likely location of shadow center

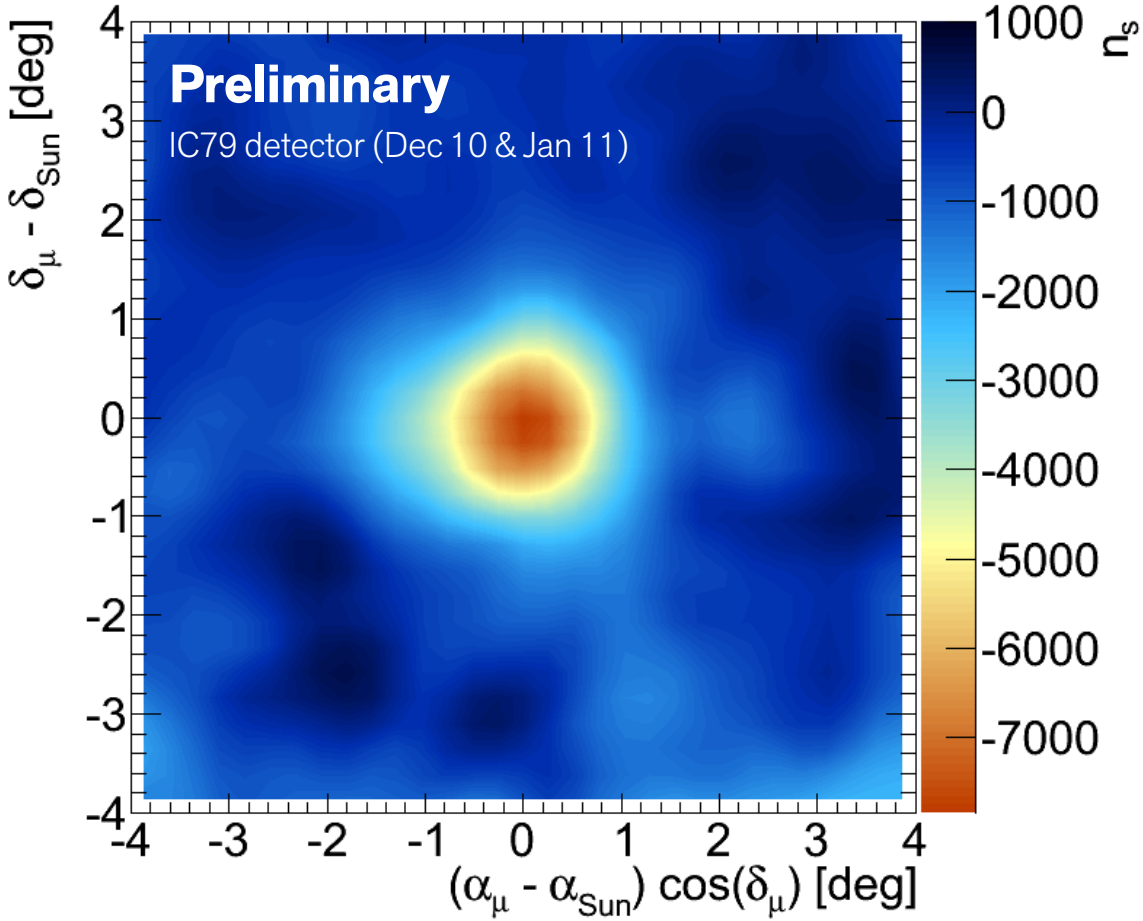


< 0.1° pointing res.

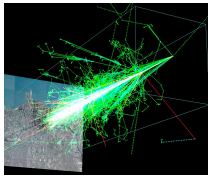
Accounts for magnetic deflection effects

- Validation for point-source neutrino searches
- Detector with good resolution and angular pointing for anisotropy studies.

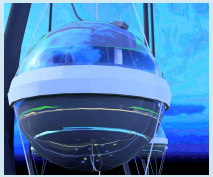
Sun shadow


Preliminary
IC79 detector (Dec 10 & Jan 11)
$\delta_\mu - \delta_{Sun}$ [deg]
$(\alpha_\mu - \alpha_{Sun}) \cos(\delta_\mu)$ [deg]
n_s
4
3
2
1
0
-1
-2
-3
-4
1000
0
-1000
-2000
-3000
-4000
-5000
-6000
-7000

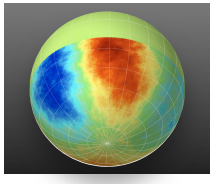
Outline



Cosmic rays
General introduction

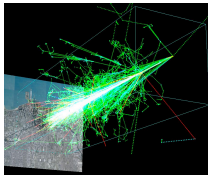


Cosmic-ray detectors
IceCube, IceTop, AMANDA

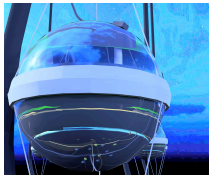


Anisotropy analysis
Angular scale, energy, time

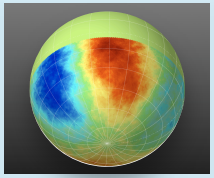
Outline



Cosmic rays
General introduction

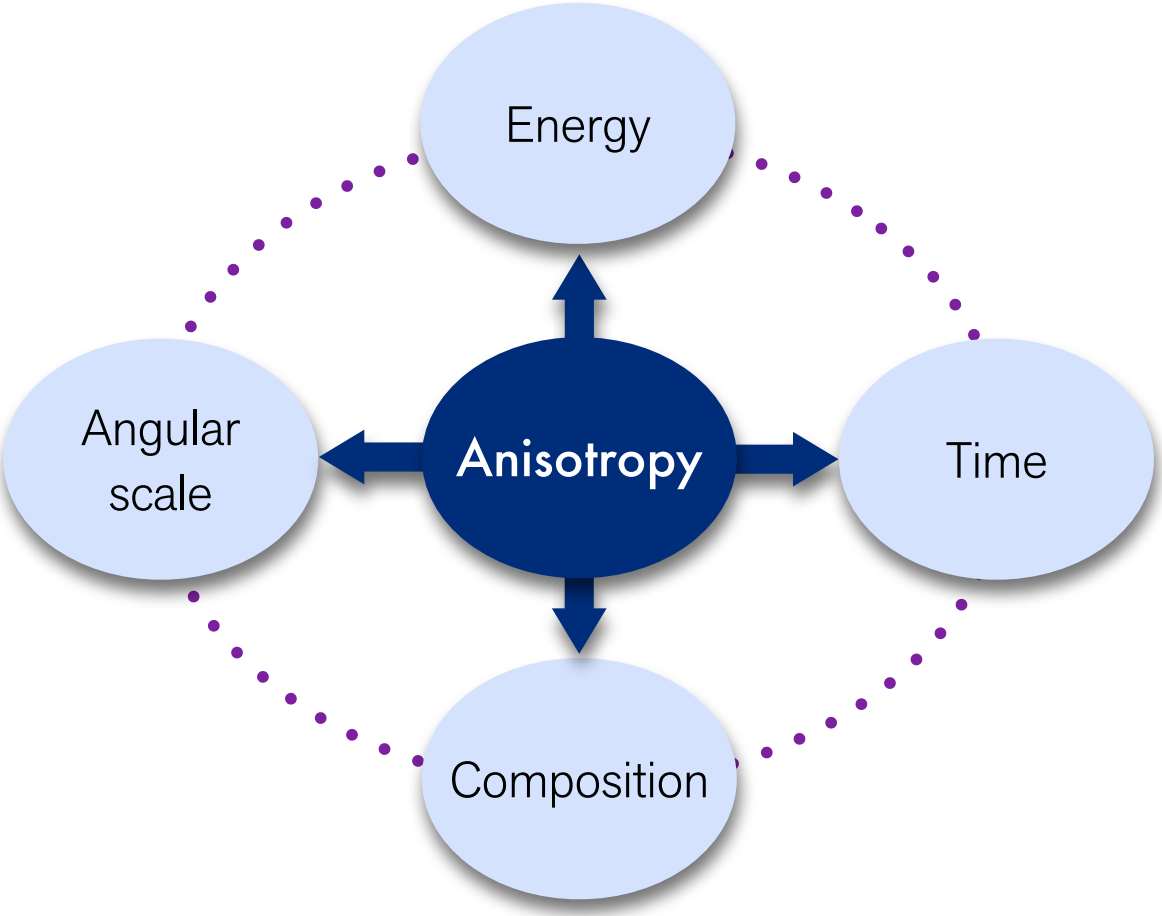


Cosmic-ray detectors
IceCube, IceTop, AMANDA

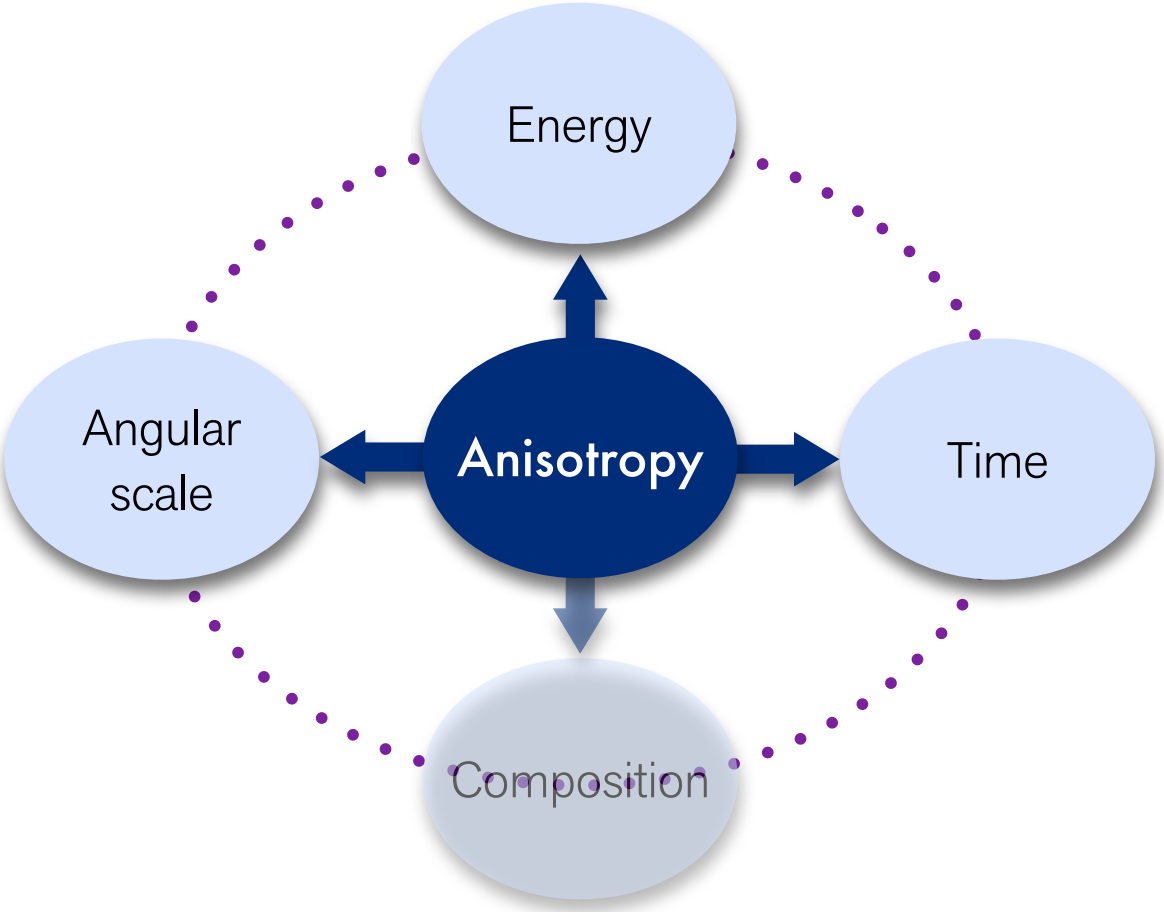


Anisotropy analysis
Angular scale, energy, time

Anisotropy studies

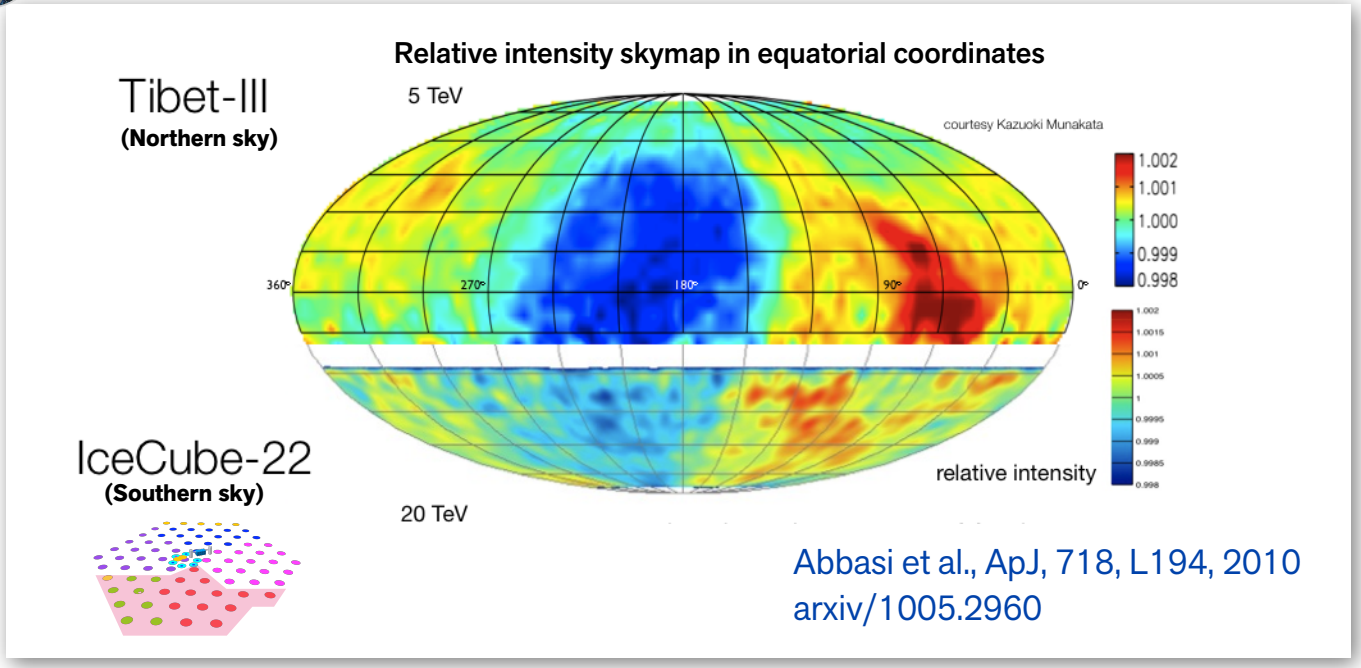


Anisotropy studies



Anisotropy as a function of angular scale

IceCube - Large scale anisotropy



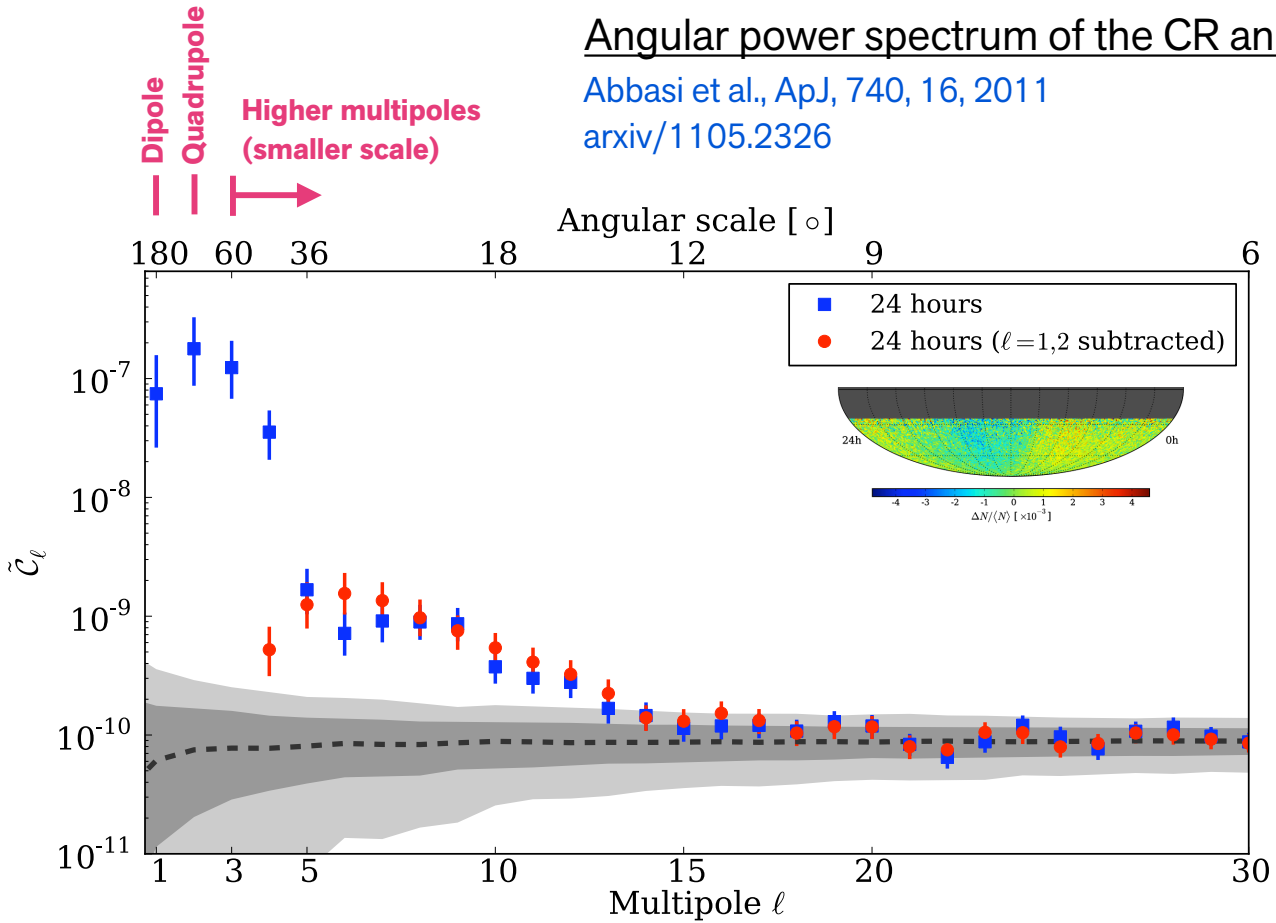
Abbasi et al., ApJ, 718, L194, 2010
arxiv/1005.2960

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

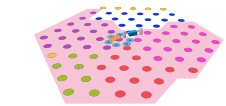
IceCube - Looking for smaller structure

<u>Angular power spectrum of the CR anisotropy</u>

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

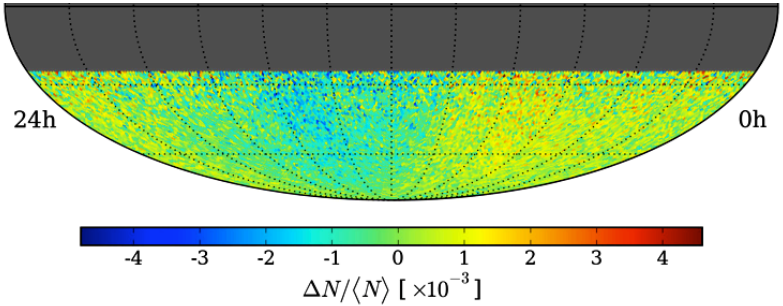


IceCube - Small-scale anisotropy

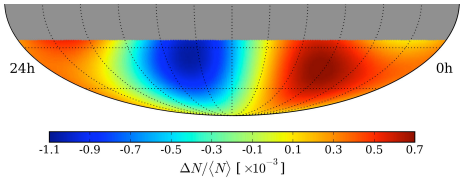


59-string detector

Input relative intensity map

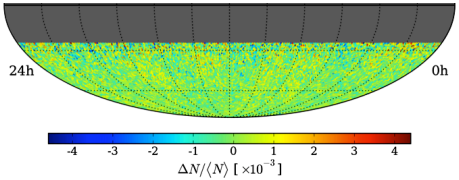


Dipole and quadrupole fit (Large scale)



+

Fit residuals (Small scale)

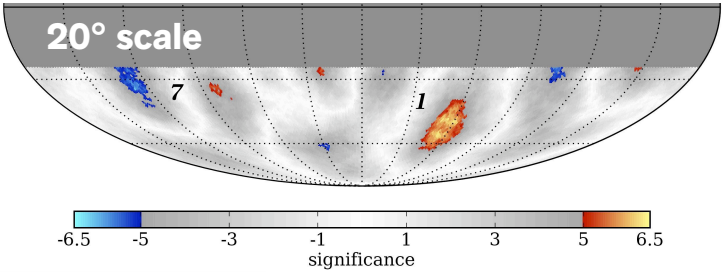


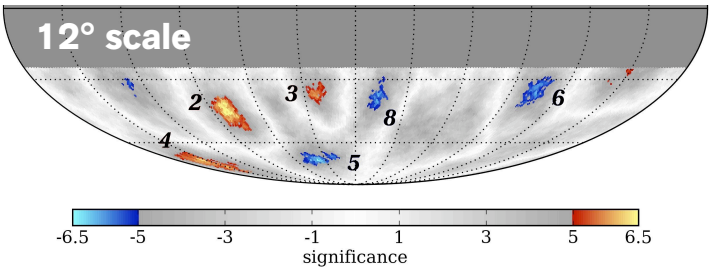
- Correlate pixels to increase sensitivity to different angular scales.

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

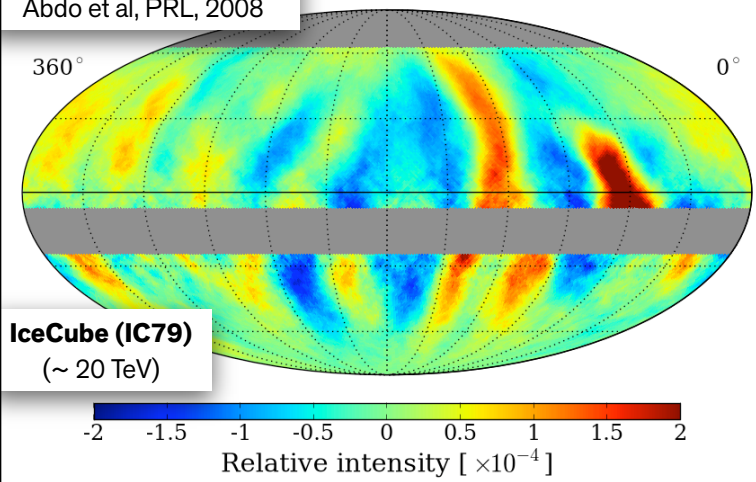
IceCube - Small-scale anisotropy

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



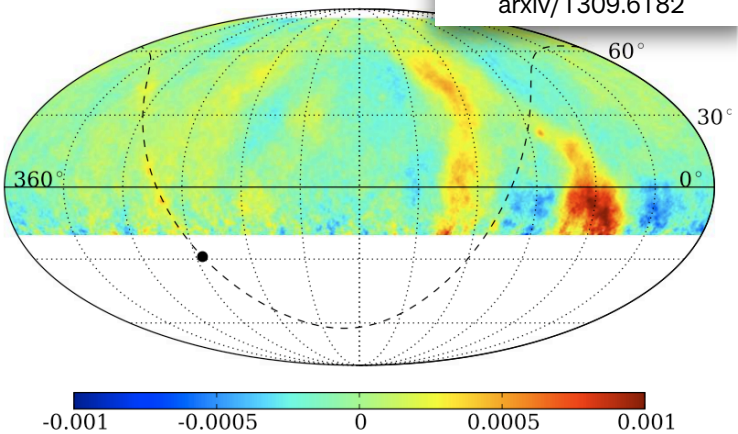


Milagro (~ 1TeV)
Abdo et al, PRL, 2008



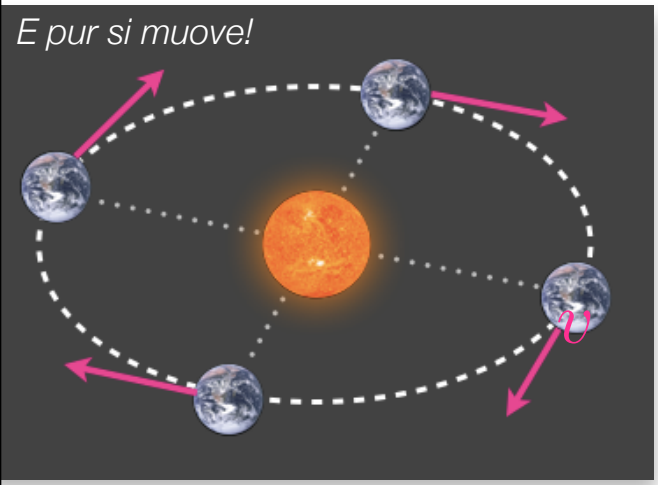
IceCube (IC79)
(~ 20 TeV)

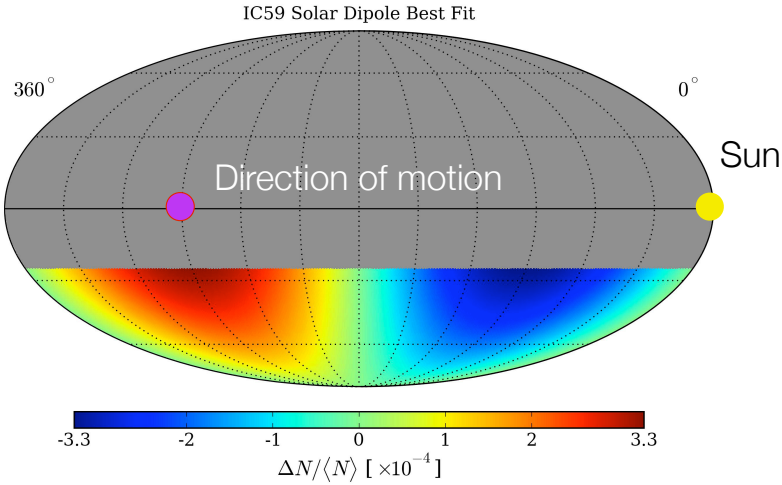
ARGO (~ 1TeV)
arxiv/1309.6182



Solar dipole

Compton-Getting dipole *Physical Review* **47** (11): 817–821, 1935





Coefficient	Fit Value ($\times 10^{-4}$)
m_0	-0.029 ± 0.058
p_x	0.017 ± 0.142
p_y	-3.661 ± 0.142
p_z	-0.027 ± 0.072

$\chi^2/\mathrm{ndf} = 14206.8/14192 \qquad \Pr(\chi^2|\mathrm{ndf}) = 0.416$

$$(3.66 \pm 0.14_{\mathrm{stat}} \pm 0.99_{\mathrm{sys}}) \times 10^{-4}$$

2.67 29.8 km/s

$$\frac{\Delta I}{I} = (\gamma + 2)\frac{v}{c}\cos\theta$$

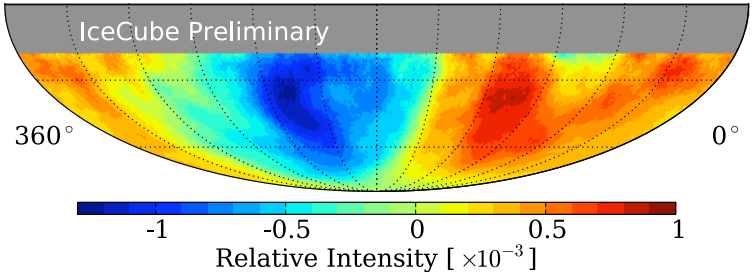
$$\sim 4.7 \times 10^{-4}$$

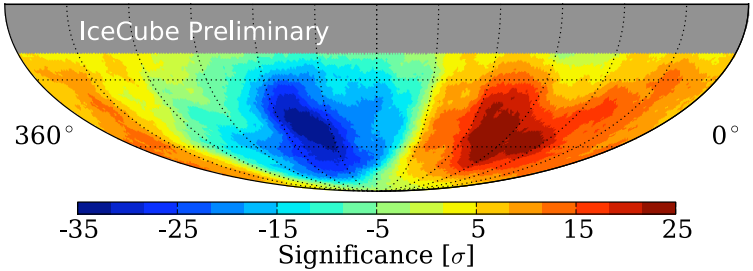
IceCube - Large-scale anisotropy

Preliminary

IC22-IC86 detector configurations (2007-2012)

5° scale





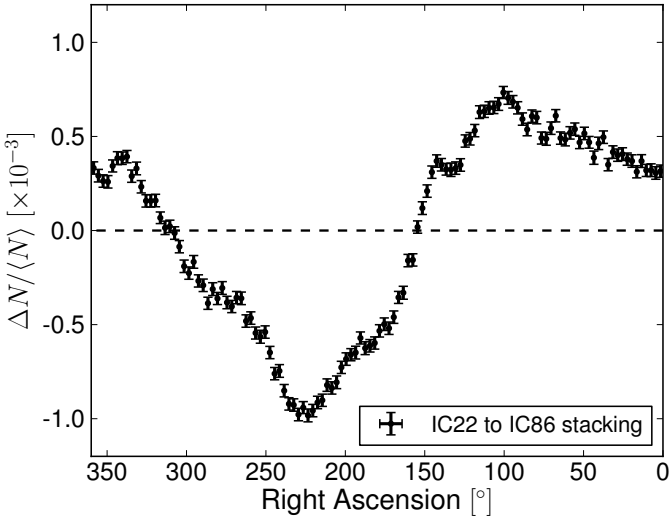
Santander et al. (0382 - ICRC 2013)

arxiv/1309.7006

Update

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

1D projection in right ascension

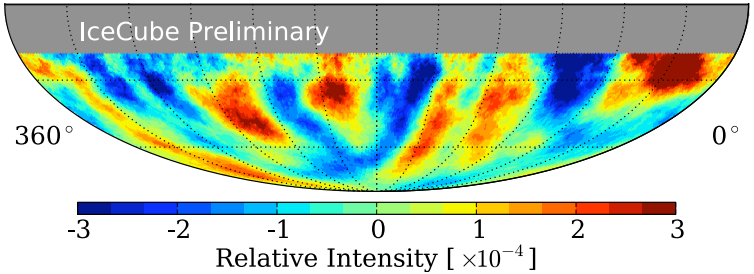


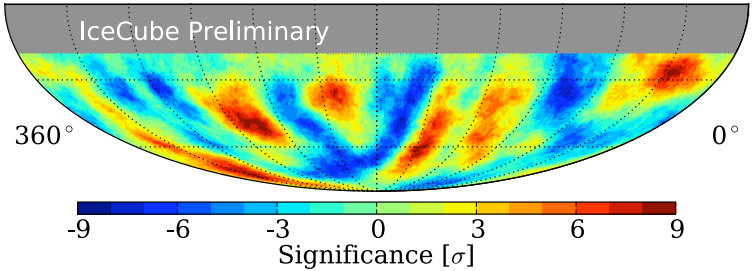
IceCube - Small-scale anisotropy

Preliminary

IC22-IC86 detector, **5° scale**

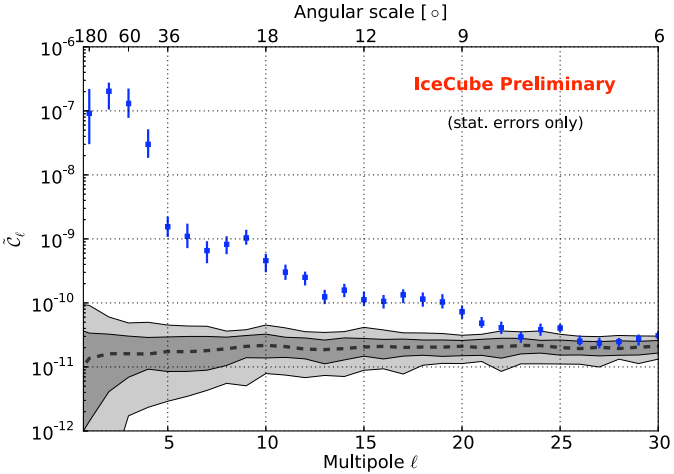
Large-scale subtracted (dipole and quadrupole)





Update

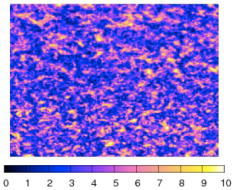
- Significant power in the spectrum for structures < 10°.



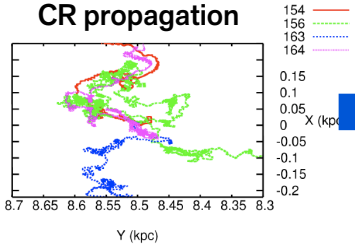
Origin of small-scale anisotropy

Propagation effects

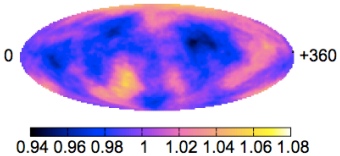
Turbulent GMF



CR propagation



Small-scale structure



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

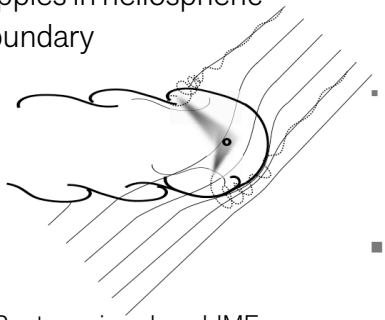
Giacinti & Sigl
arxiv/1111.2536

Heliospheric effects

Desiati & Lazarian
arxiv/1111.3075

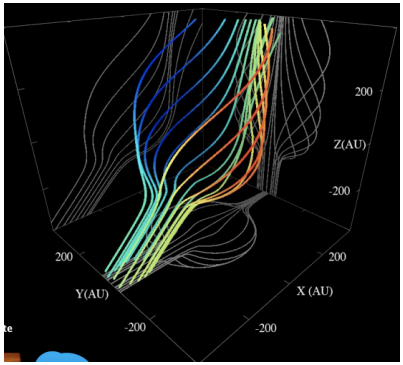
Schwadron et al.
Science 28, 343, 2014

Ripples in heliospheric boundary



CRs streaming along LIMF

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

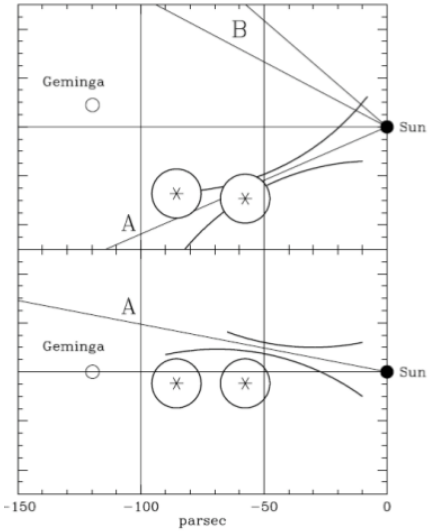


Origin of small-scale anisotropy

Non-standard magnetic fields and diffusion mechanisms

Geminga? (155 pc)

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



Non-standard diffusion and propagation models

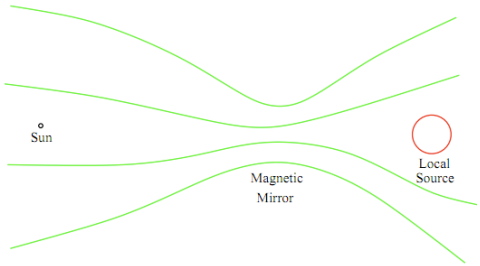
Malkov et al ApJ 721, 750 (2010)

Electric fields in the heliosphere

Drury arxiv/1305.6752 (ICRC 2013)

Magnetic mirroring and funneling from nearby source

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

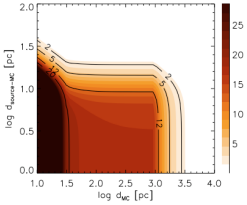


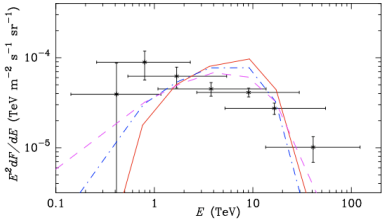
Large-scale cascading

Ahlers arxiv/1310.5712

Strangelets from NS

Kotera et al arxiv/1303.1186





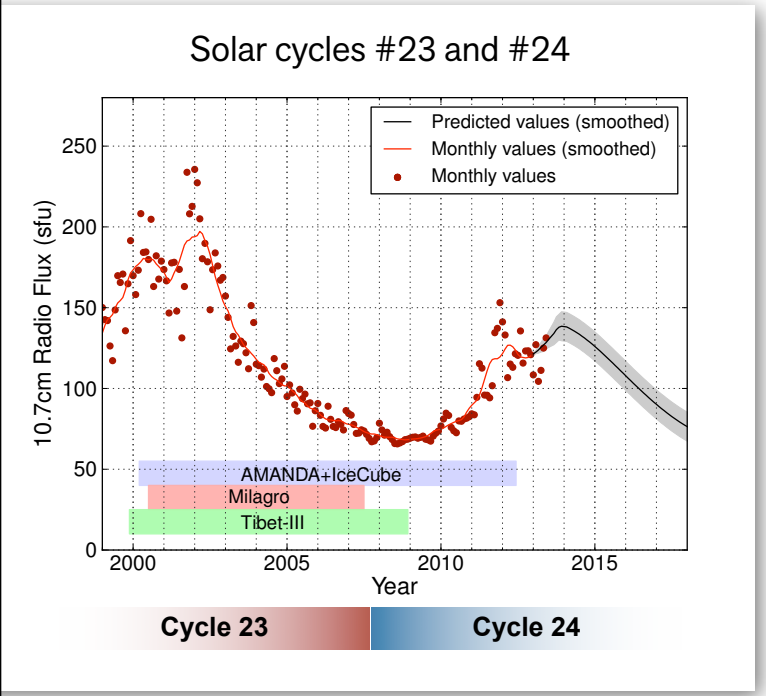
Dark matter annihilation

J.P. Harding arxiv/1307.6537

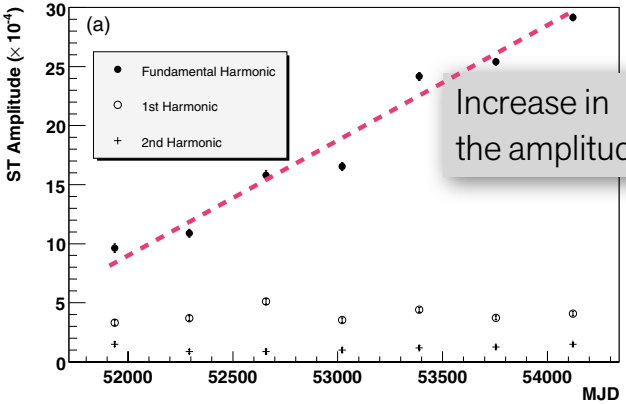
Anisotropy as a function of time

Time dependence study

Santander et al. (0411 - ICRC 2013)
arxiv/1309.7006



Milagro (arxiv/0806.2293)



Tibet-III (arxiv/1001.2646)

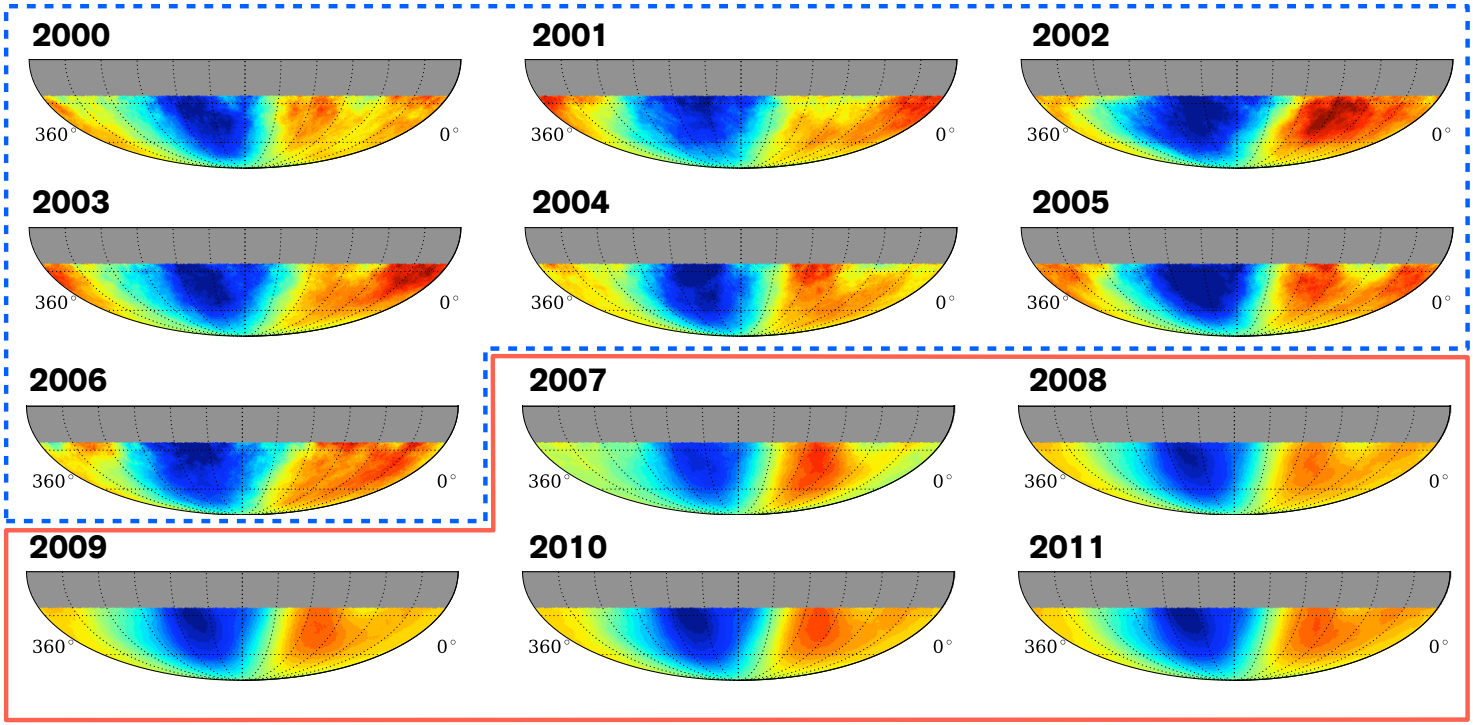
No significant change

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

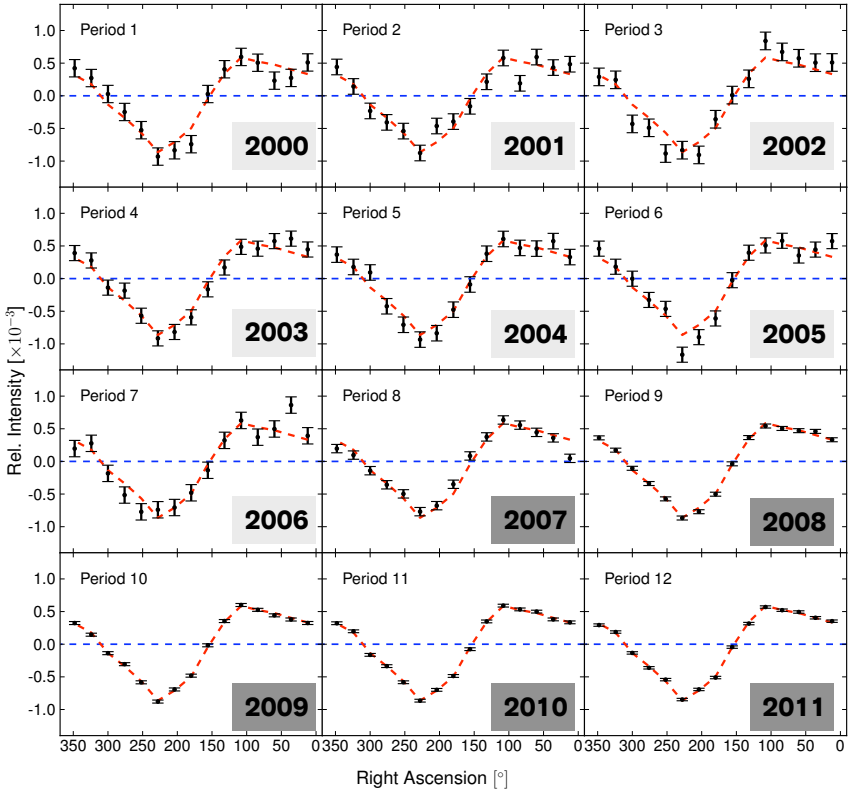
Large-scale anisotropy

Relative intensity maps

Preliminary



Right-ascension projections



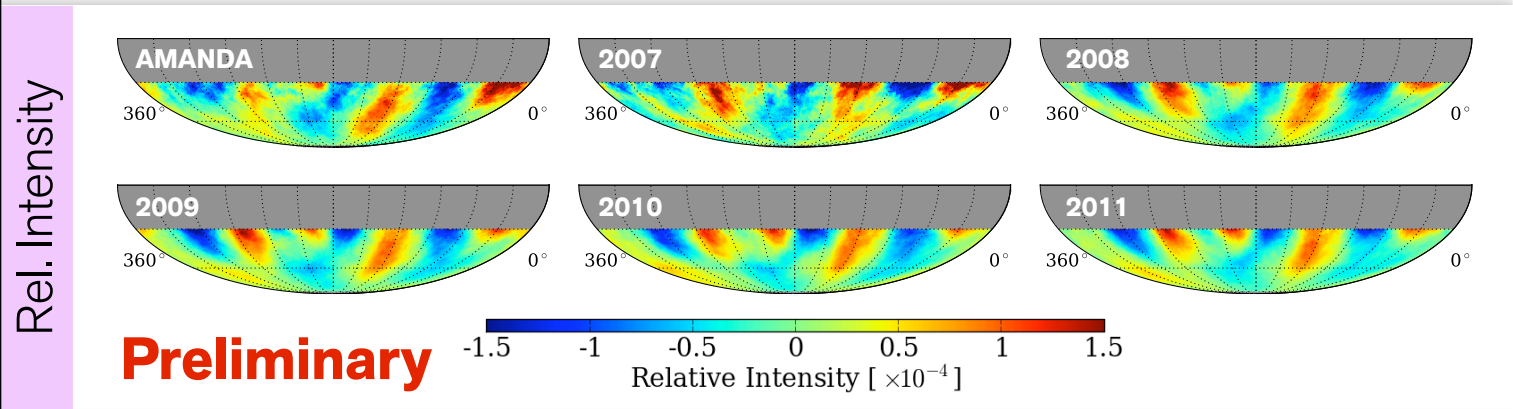
Preliminary

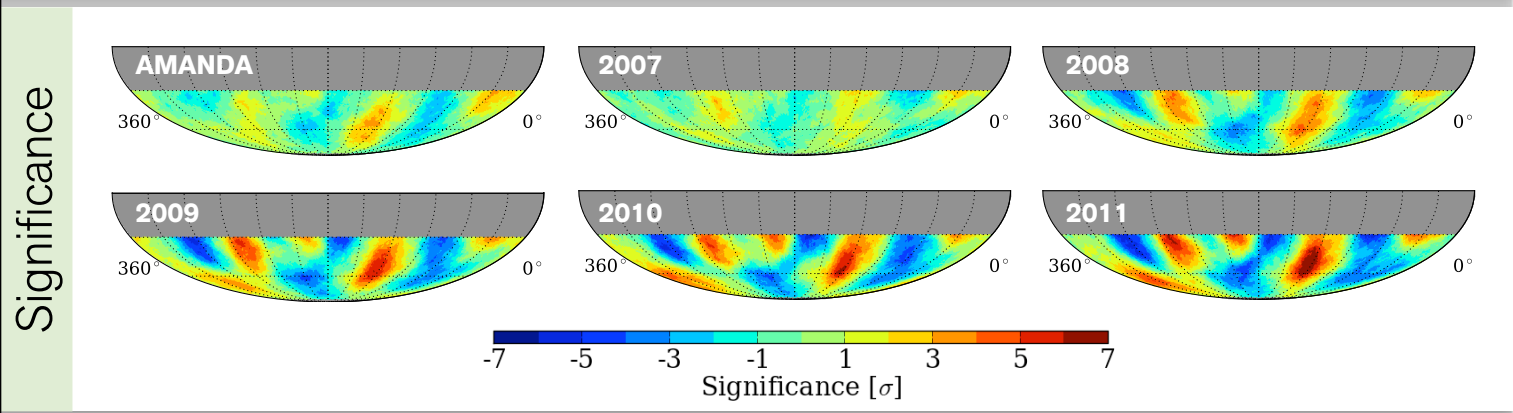
Detector	Year	χ^2/dof	p-value
AM-II	2000	11.3/15	0.73
AM-II	2001	16.6/15	0.34
AM-II	2002	26.0/15	0.04
AM-II	2003	19.3/15	0.20
AM-II	2004	14.3/15	0.50
AM-II	2005	21.0/15	0.14
AM-II	2006	24.4/15	0.06
IC22	2007	45.2/15	7×10^{-5}
IC40	2008	12.8/15	0.62
IC59	2009	11.1/15	0.75
IC79	2010	6.5/15	0.97
IC86	2011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

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

Small-scale anisotropy

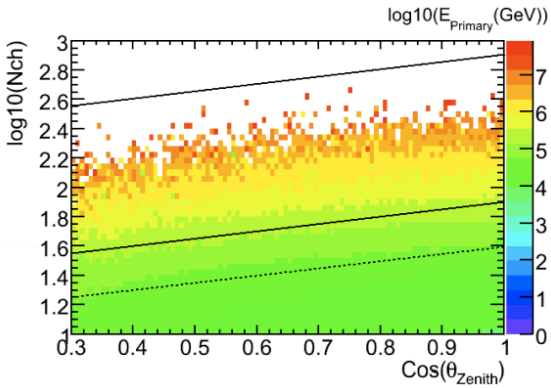
Residual maps after large-scale (dipole and quadrupole) subtraction, 20° smoothing





Anisotropy as a function of energy

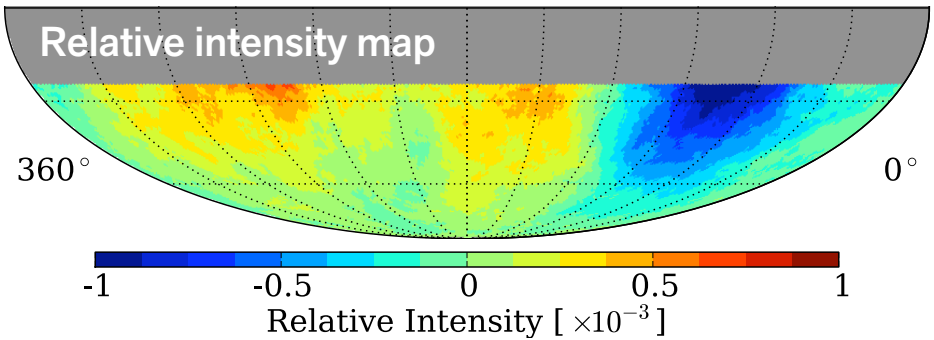
Anisotropy at higher energies



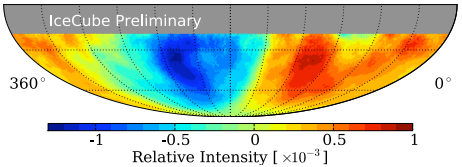
IceCube

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

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

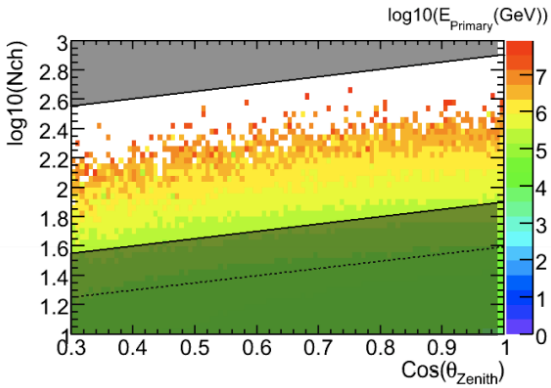


20 TeV map



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

Anisotropy at higher energies



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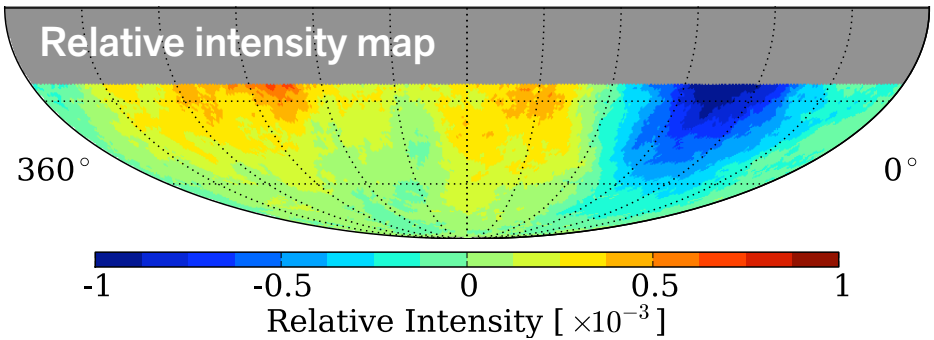

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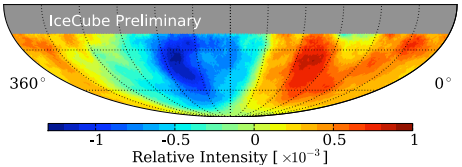
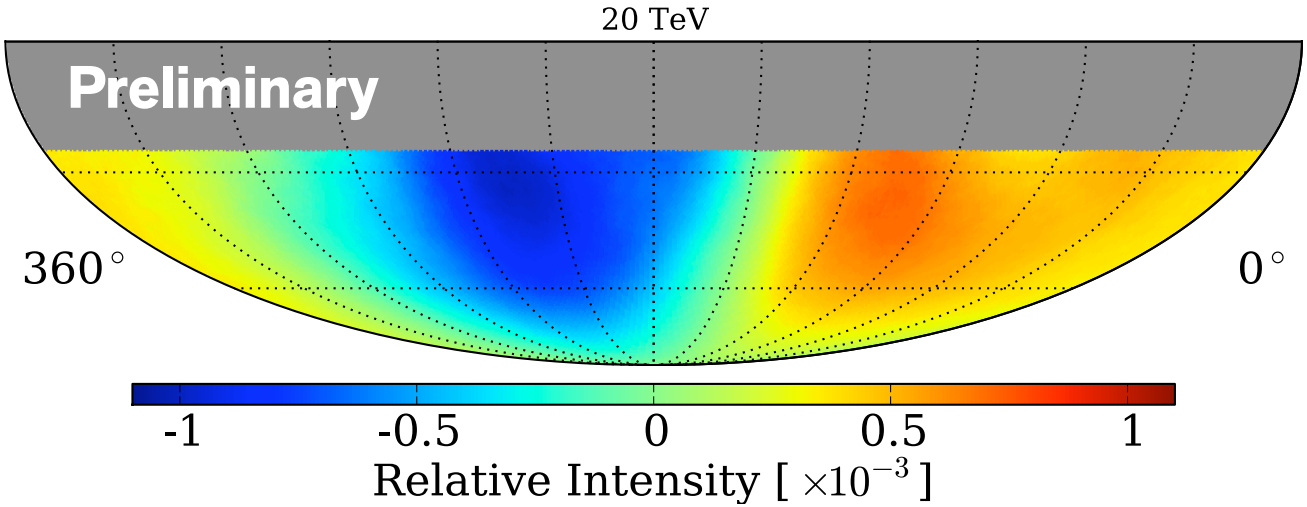
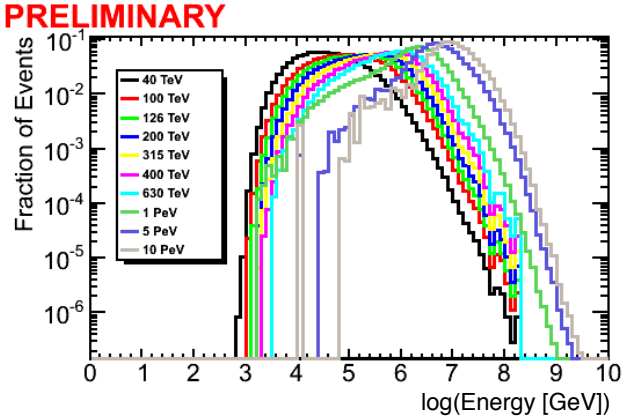


- **400 TeV** median energy, anisotropy at **10^{-3}** level, size ~ **20°**, significance **6.3σ**

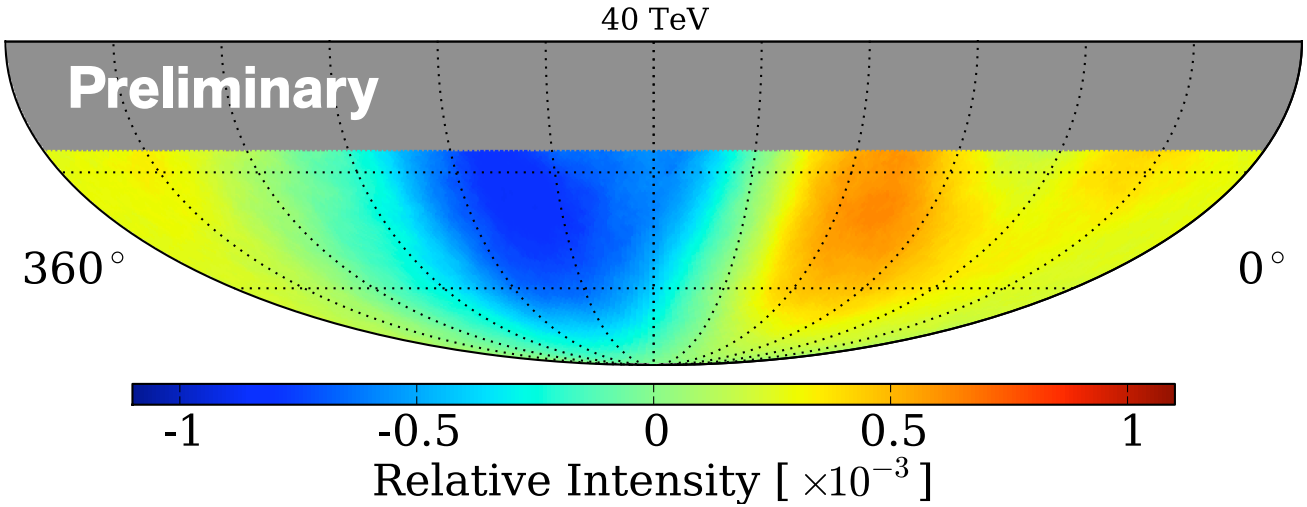
Transition between 20 and 630 TeV

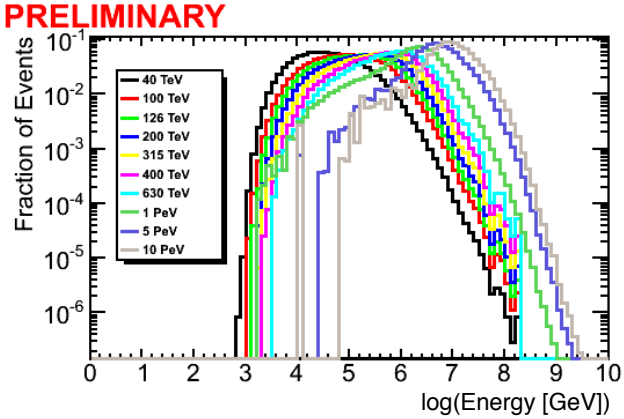




- **Note:** Very wide energy distributions. Statistically correlated maps.

Transition between 20 and 630 TeV





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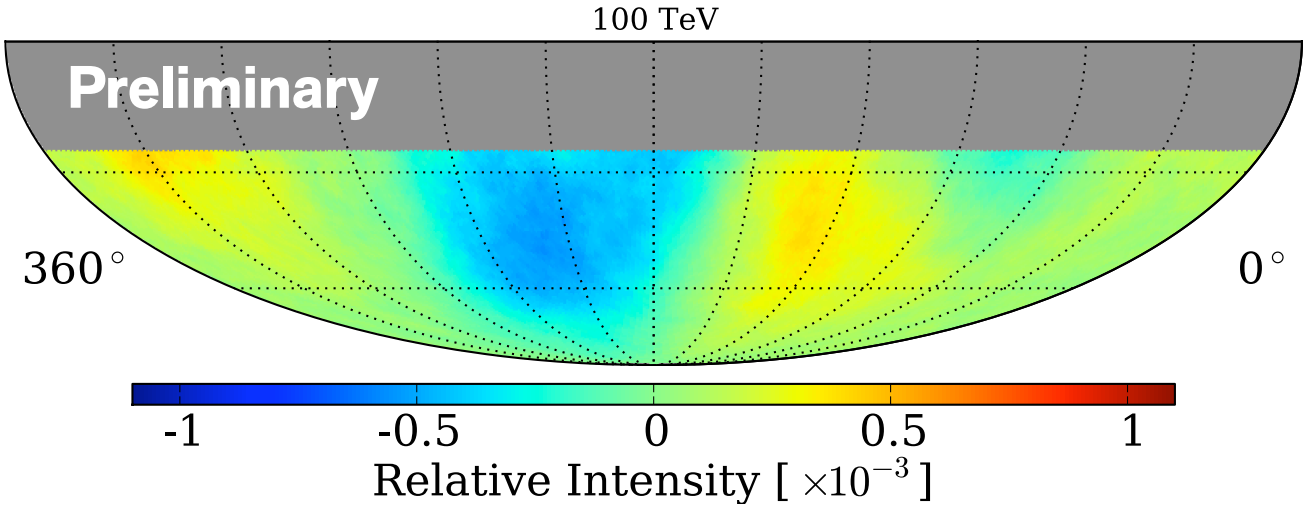

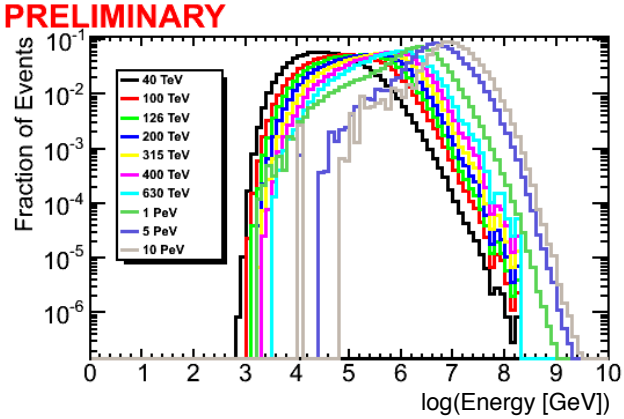

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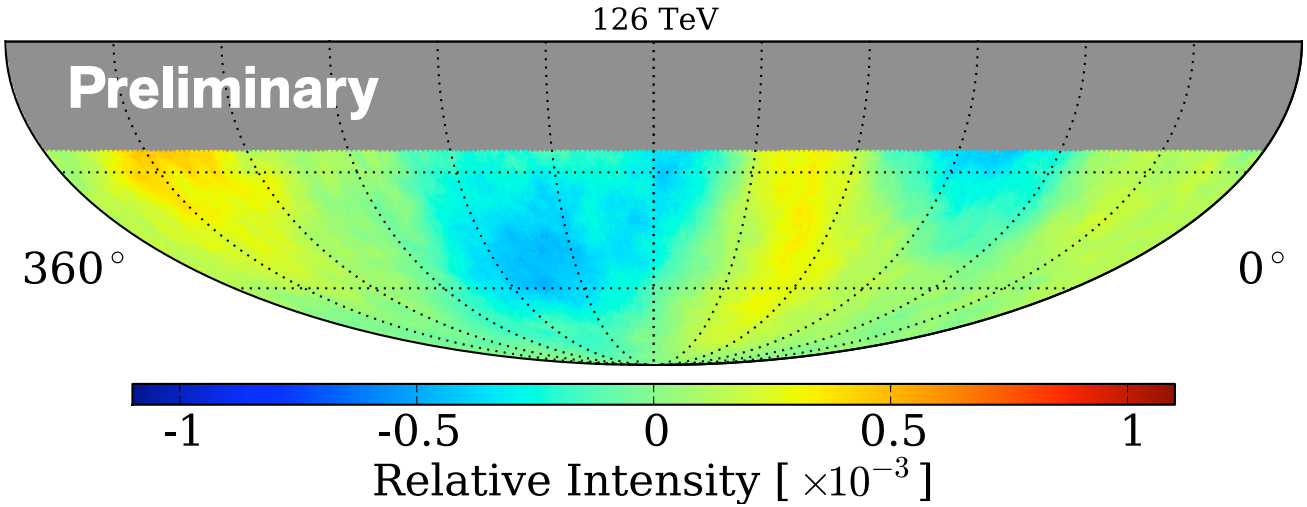

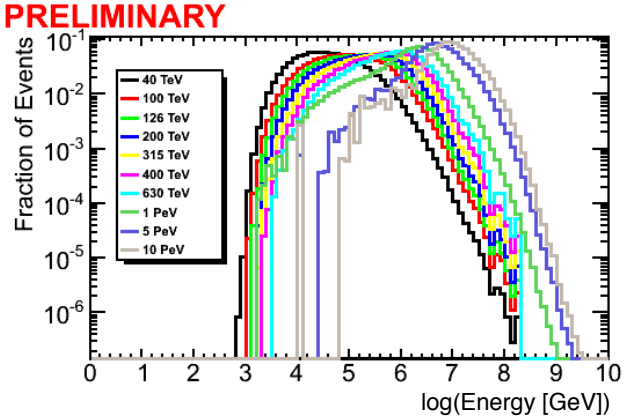

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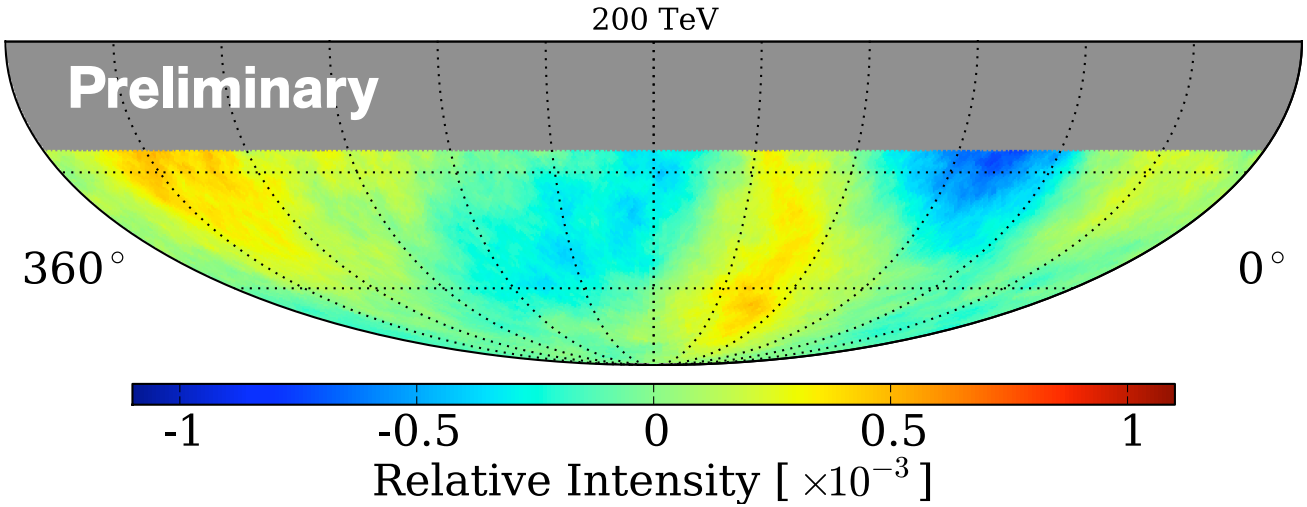

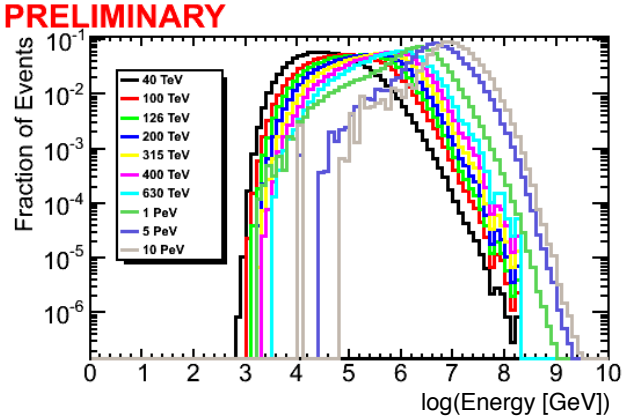

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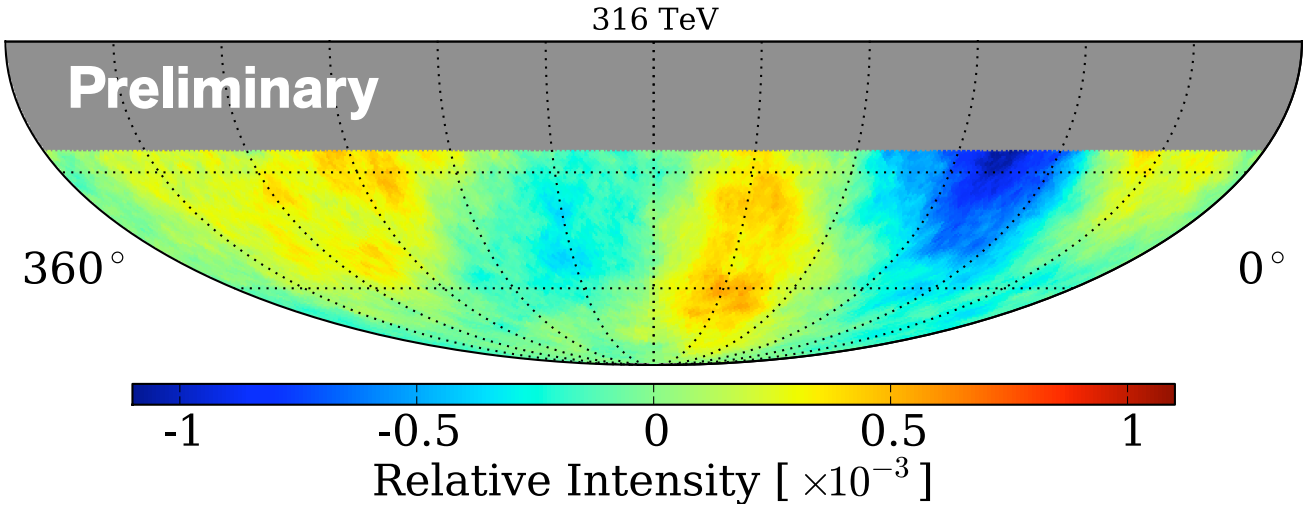

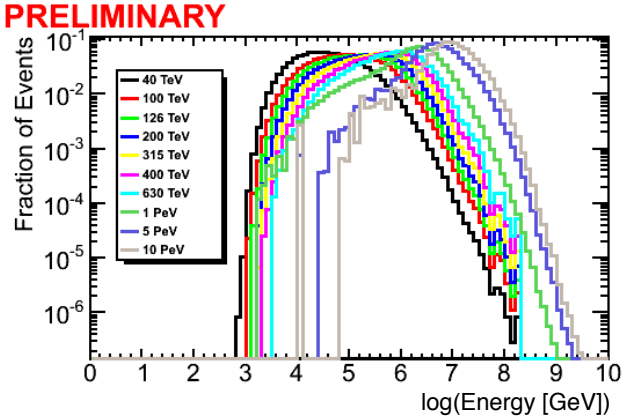

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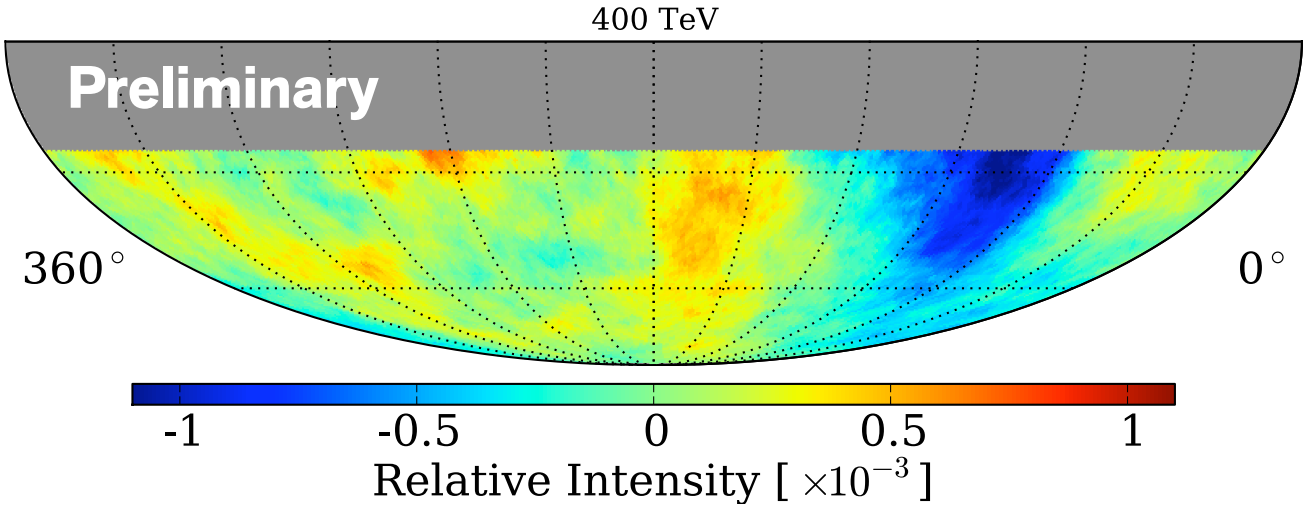

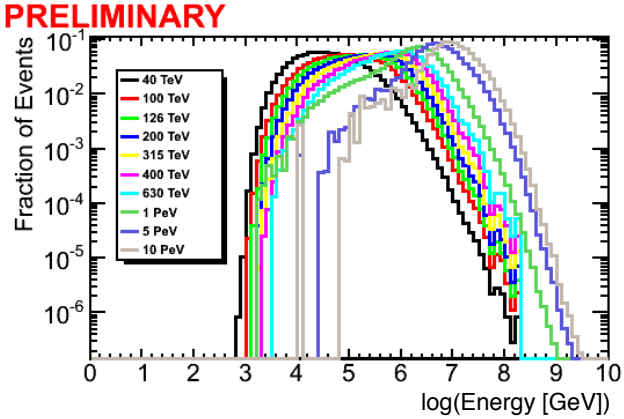

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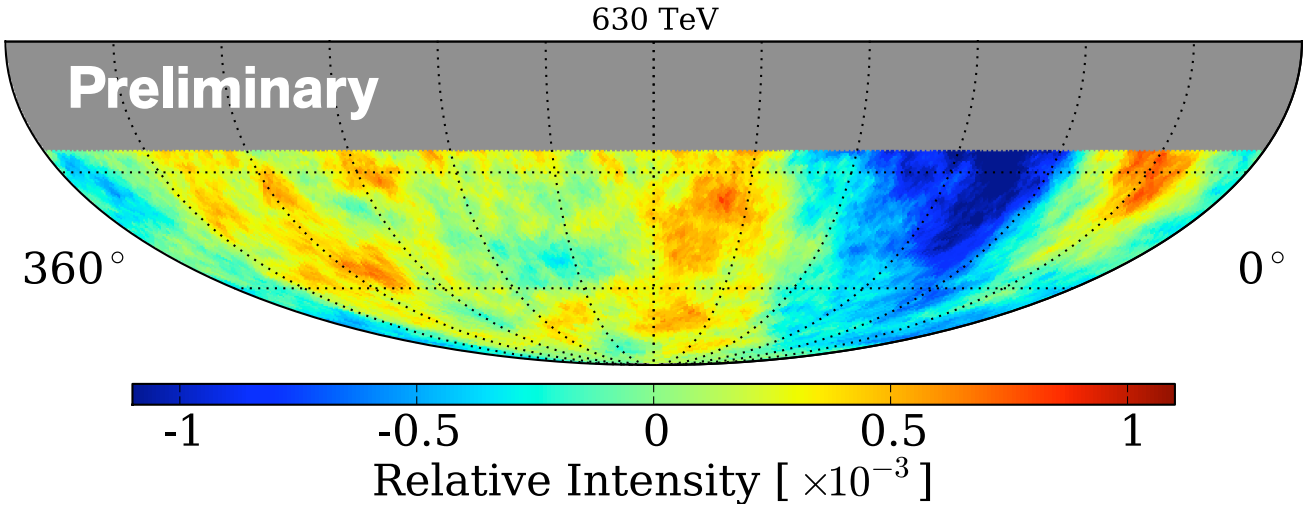

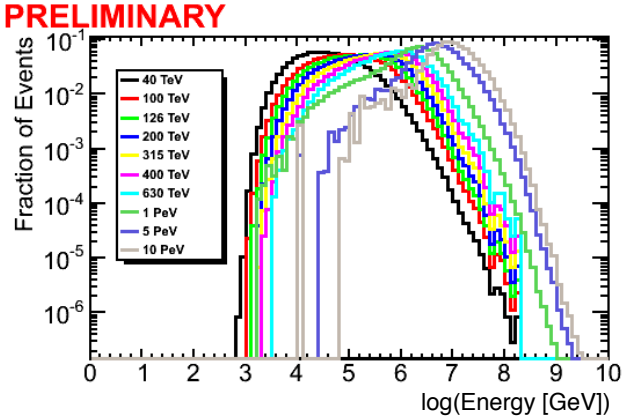

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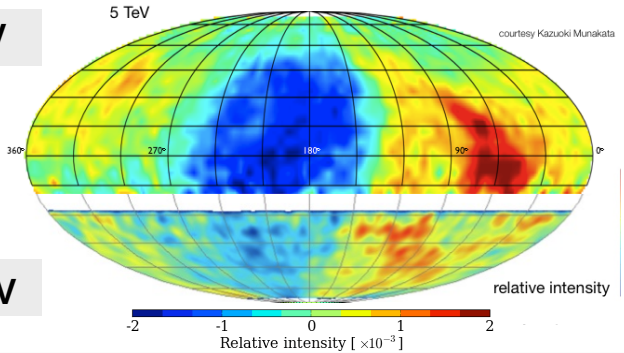
Comparison between different energies

5 TeV

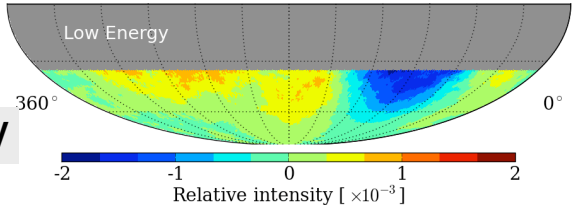
20 TeV



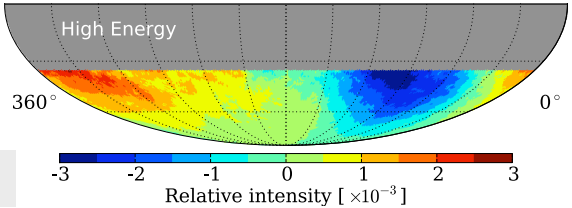
- The anisotropy changes position
- Similar peak-to-peak strength
- Smaller characteristic size at high energies

IceTop

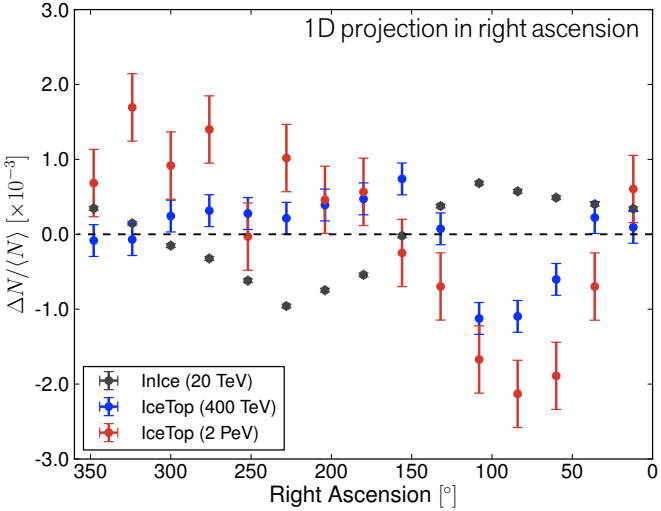
400 TeV



2 PeV

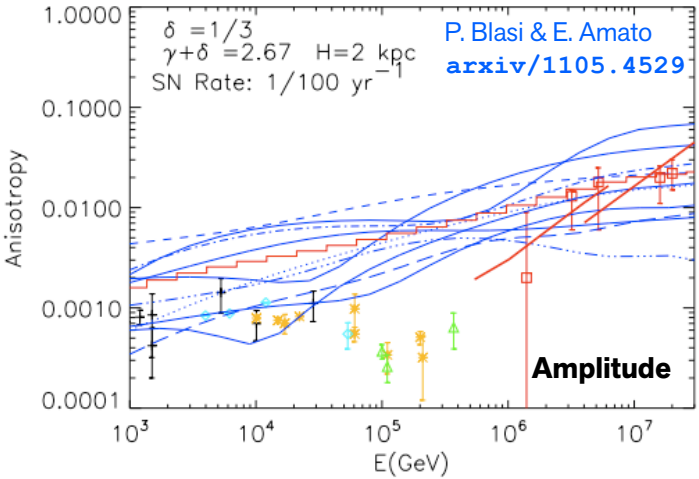


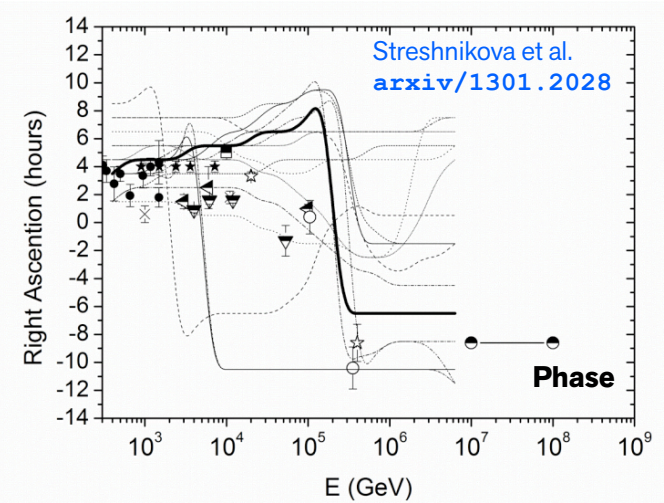
Aarsten et al., 2013 ApJ 765 55
arxiv/1210.5278



Interpretation of energy dependence

Similar to Erlykin & Wolfendale (2006)

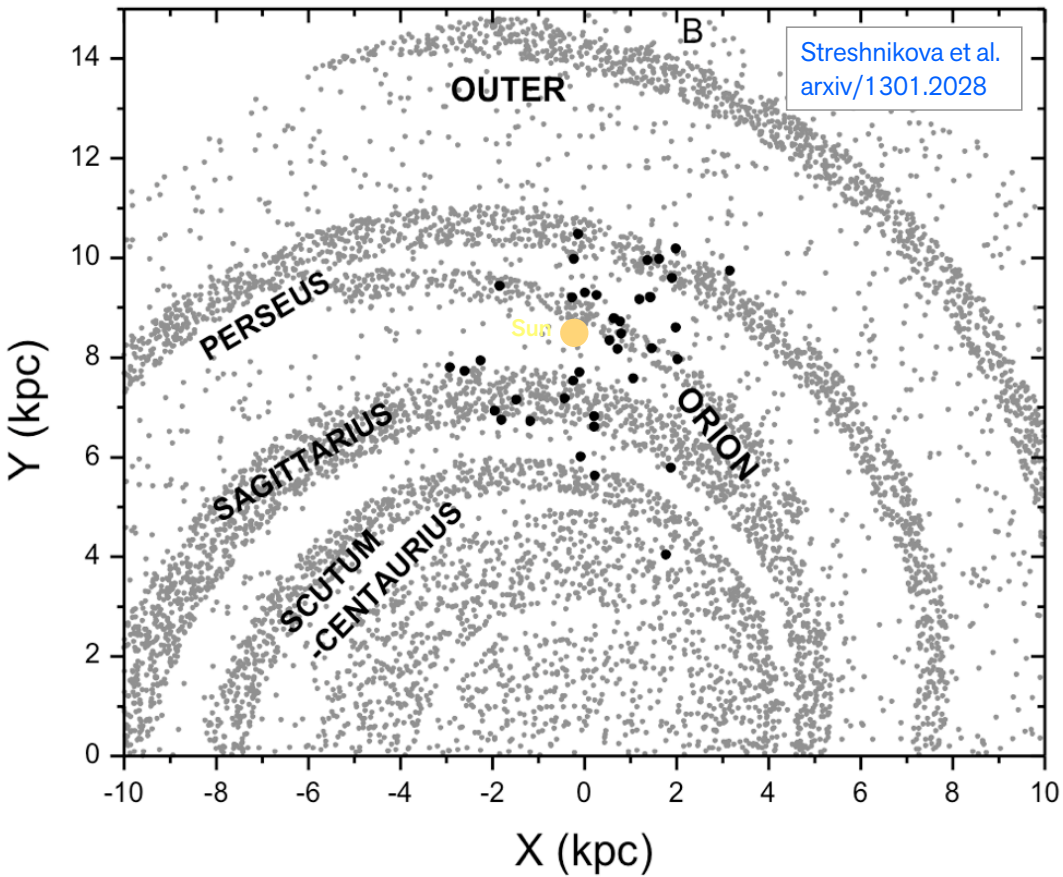




- Anisotropy arises from discrete distribution of sources
- Phase changes according to galaxy parameters and location of nearby sources
- Strength increases with energy (diffusion coefficient)
- *Problem*: anisotropy not dipolar, not strong enough.

Galactic CR sources

Distribution of nearby SNRs in the galaxy



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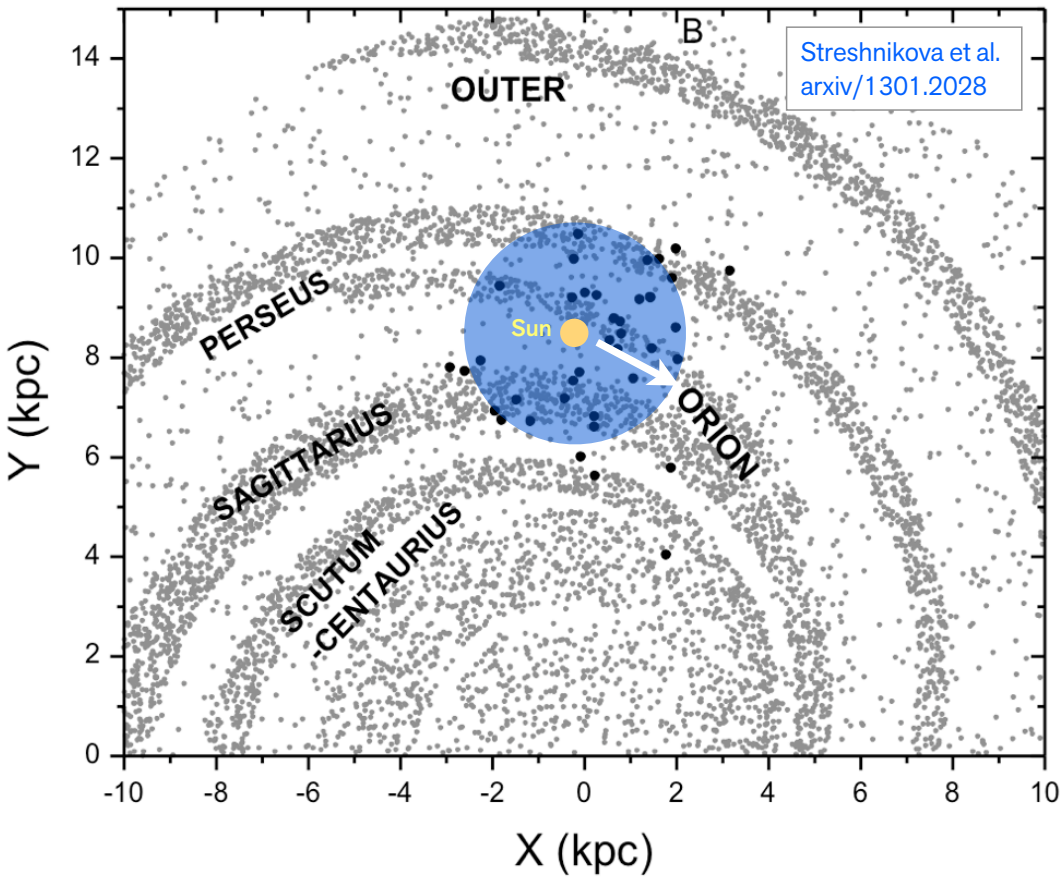

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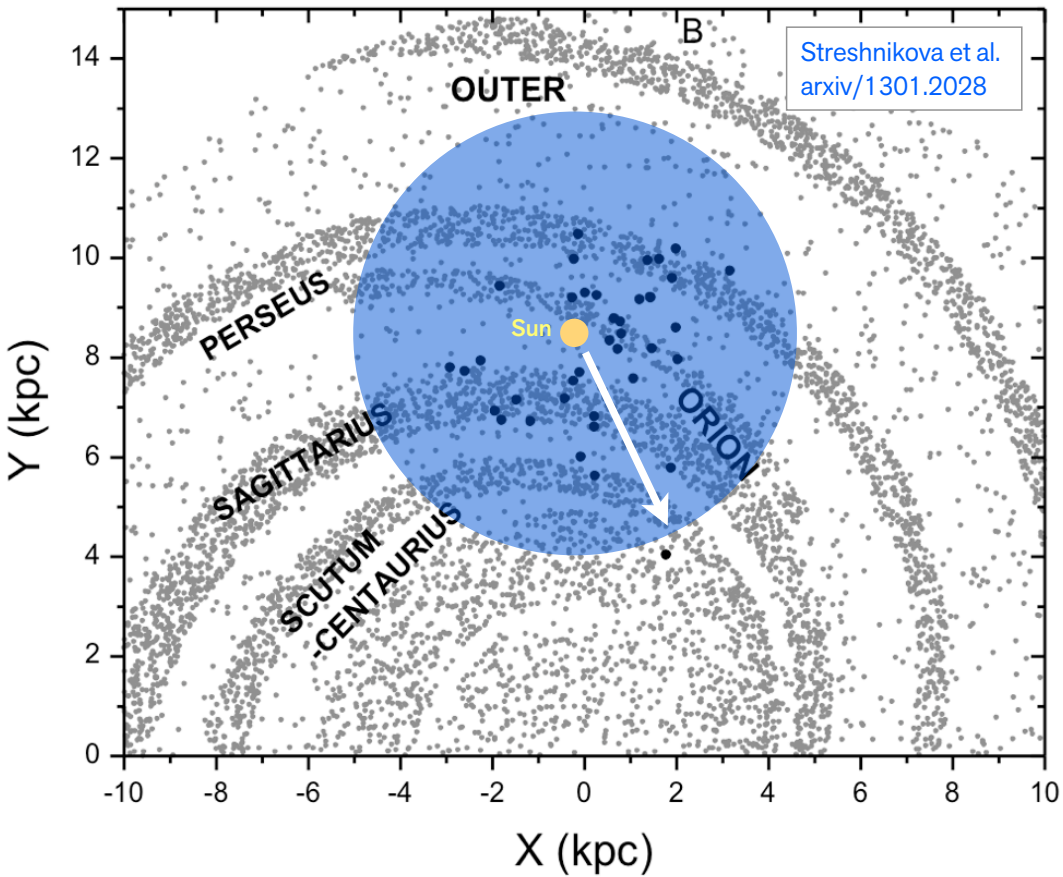

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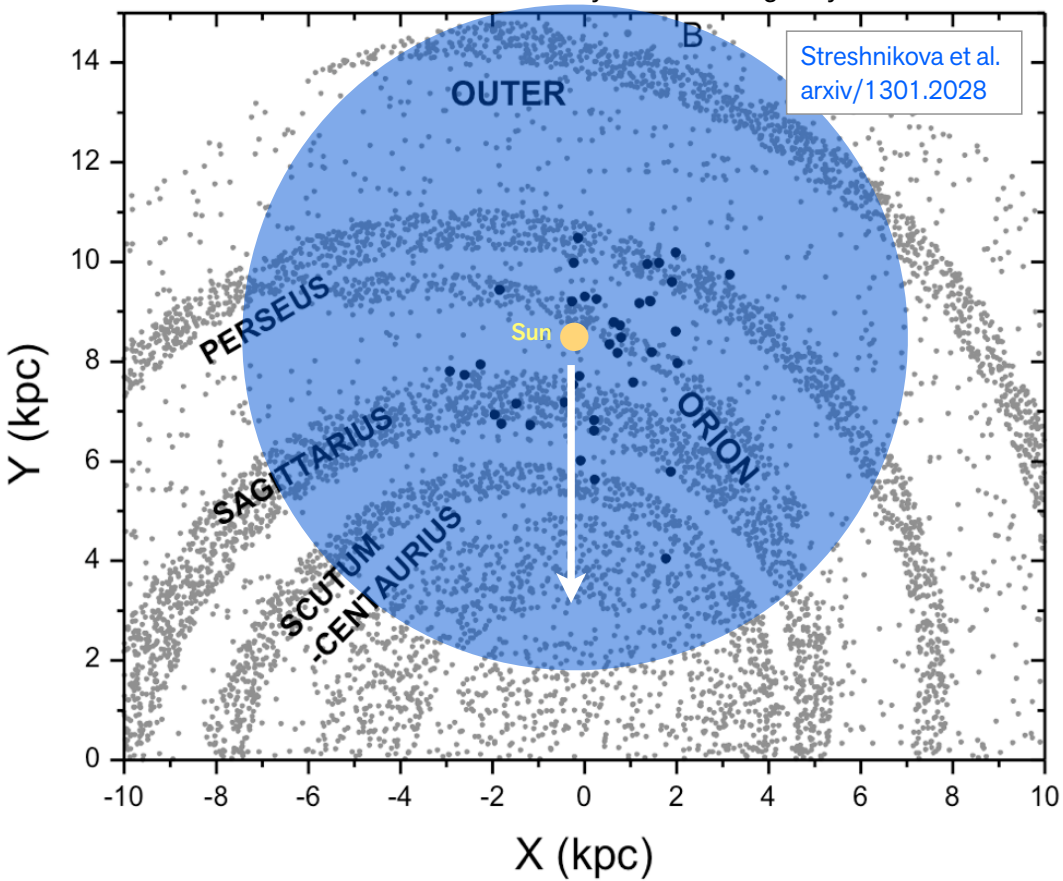
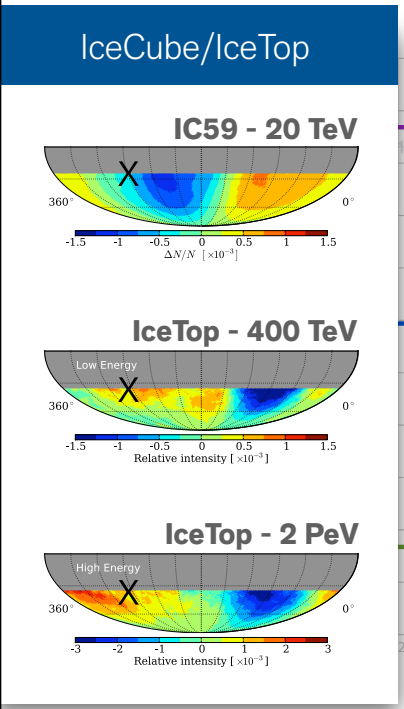
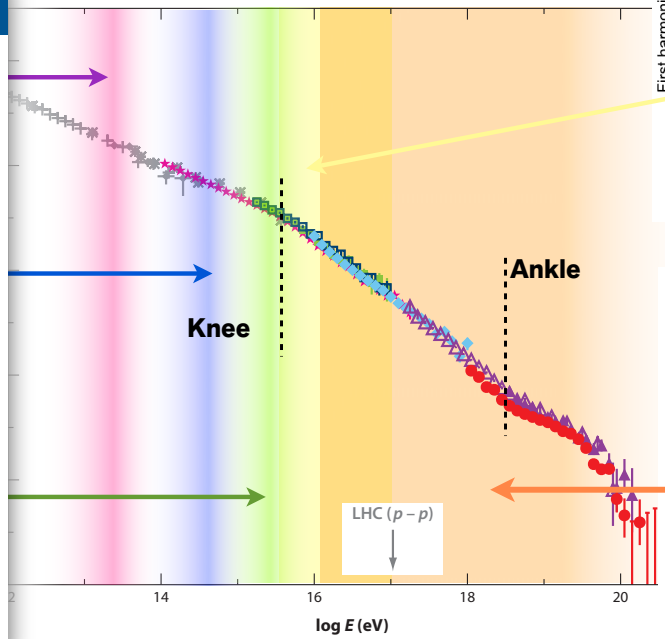
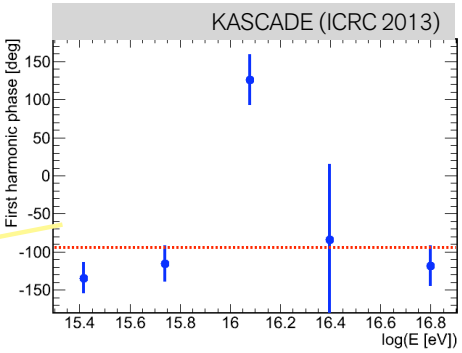
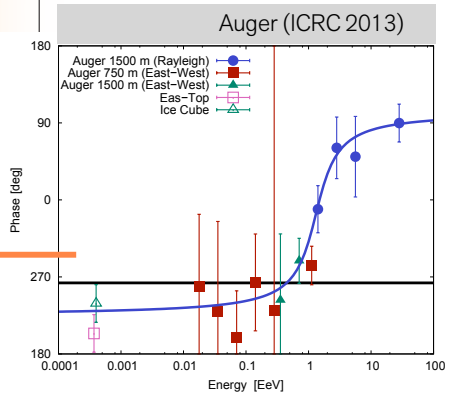


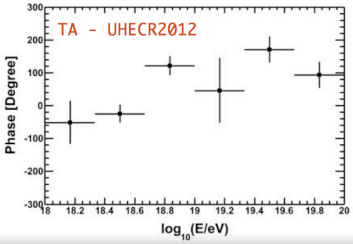
Anisotropy vs. energy











- Anisotropy changes in amplitude, size @ 400 TeV.
- Phase seems to shift towards the galactic center region at high energies.

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.

The future

- Anisotropy as a function of composition.
- Anisotropy above the knee.
- CR spectra for different parts of the sky.

- Work on the theory side is needed.