Measuring High Energy Cosmic Rays and Neutrinos with IceCube

Particle Detection Workshop

Chiang Mai
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ICECUBE NEUTRINO OBSERVATORY
icecube.wisc.edu

"Trick" Question:

When can you **see** farther
– daytime or nighttime?

Answer

- At night of course!
- Then you can **see** the stars (and with a telescope nearly all the way back to the beginning of time as we know it).
- Notice that I avoid saying “to the edge of the universe” since the universe has no edge that we know of.

What Do We Mean By See

… actually I mean **see** as opposed to **detect**:

To **detect** an object, one needs to observe some signal from the object (either self generated or reflected).

To **see** an object the signal must carry information about the location of the object.

An Example to Think About

What would we know about the sun if the sky were always cloudy? We can detect the light and heat – but what could we say about the source?

We could clearly detect the moon – and some extra light that might be stars.

We could probably even conclude that the earth somehow revolves around the sun from the length of the solar day compared to the rotation rate of the earth.

But maybe not sunspots, solar flares, etc.?

We Could Do More

Just live with the fact that we cannot see features with “visible light” but instead observe in the infra-red or radio.

Also consider building airplanes or spacecraft to get above the clouds.

Then wouldn’t the stars be a wonderful, accidental discovery?

The Problem with Photons

We are getting closer to the real topic of my talk.

Photons are a marvelous probe of the Universe, but only at low energy.

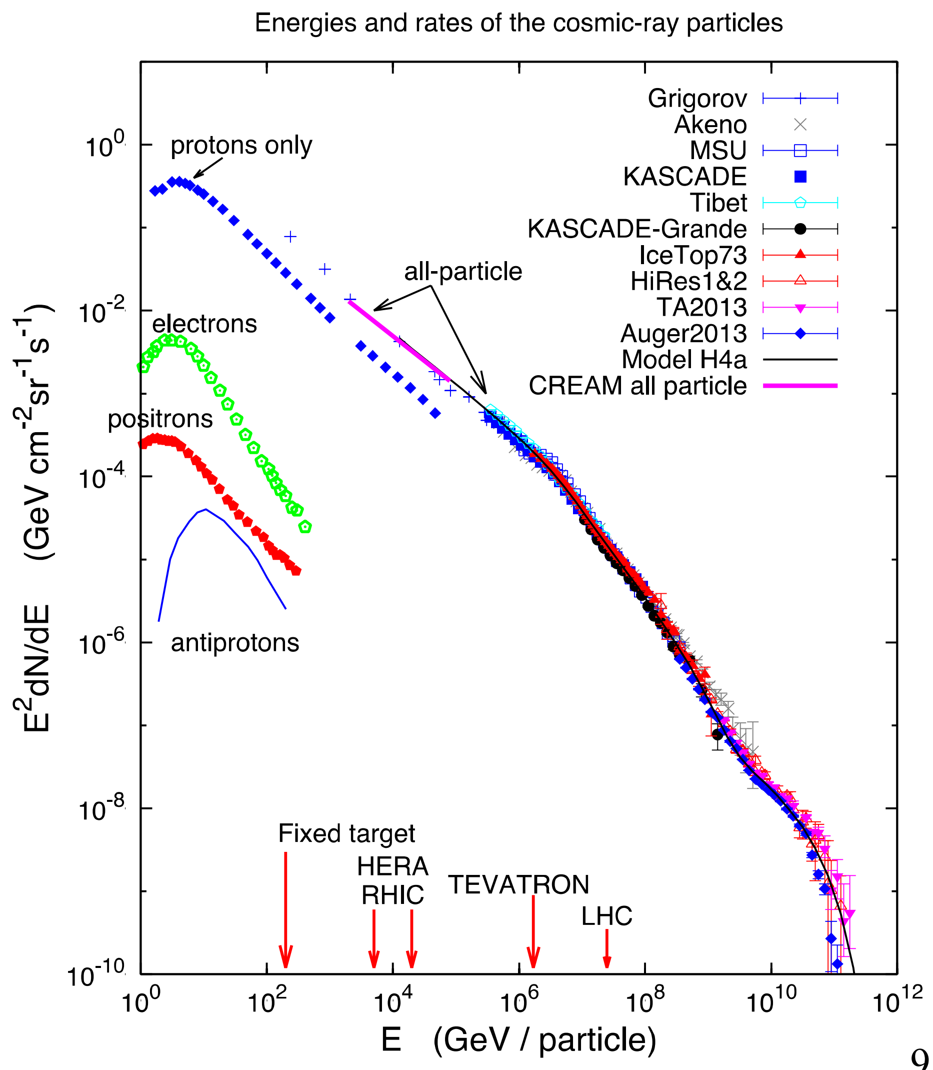
At really high energy the “clouds” of the cosmic background radiation stop the photons at distances “only” a little larger than the size of the galaxy.

However we **detect** things that are much more energetic, but we cannot **see** what is producing them.

Cosmic Rays

We detect individual particles that have energy of 10^{20} eV!

This is the kinetic energy energy of a baseball (or a computer mouse) thrown rather hard!

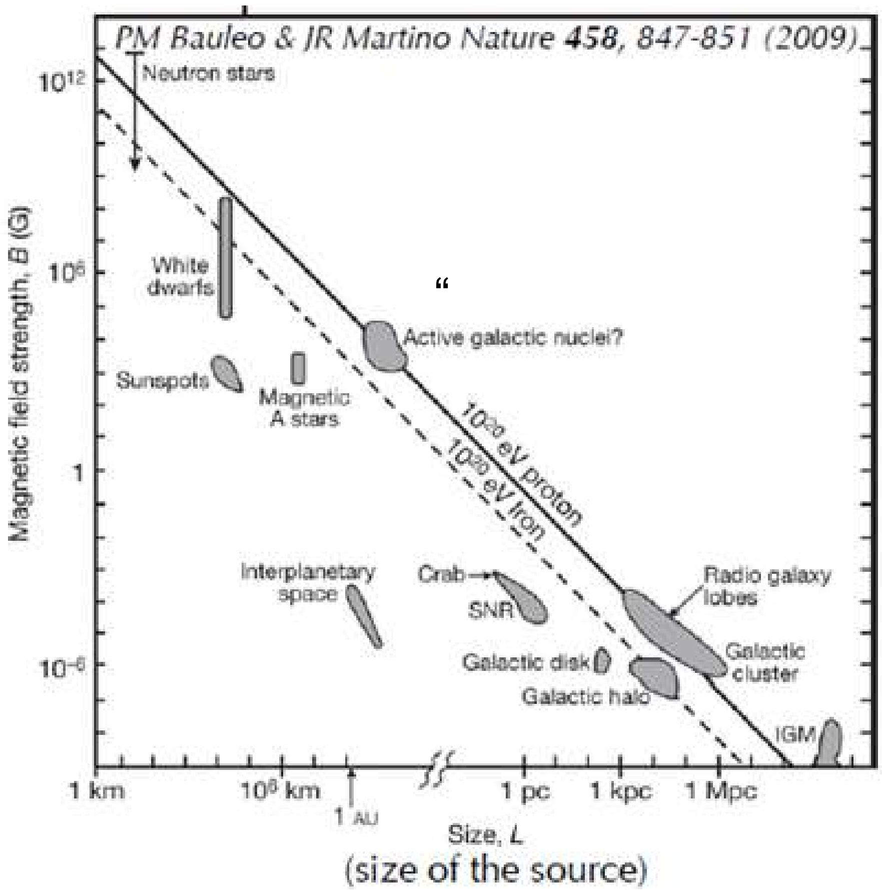


Where Do They Come From?

We really don't know!

Much like clouds diffuse sunlight, the magnetic fields in the Universe scramble the arrival directions of the particles so that only vague patterns remain.

Magnetic Confinement of Charged Particles



Possible sources can be identified with a so-called "Hillas Plot" of the magnetic field strength and size of the object.

Larmor Radius (r_L)

$$r_L(\text{cm}) = \frac{R\ (\text{Volt})}{300\ H\ (\text{Gauss})}$$

The rigidity is defined as

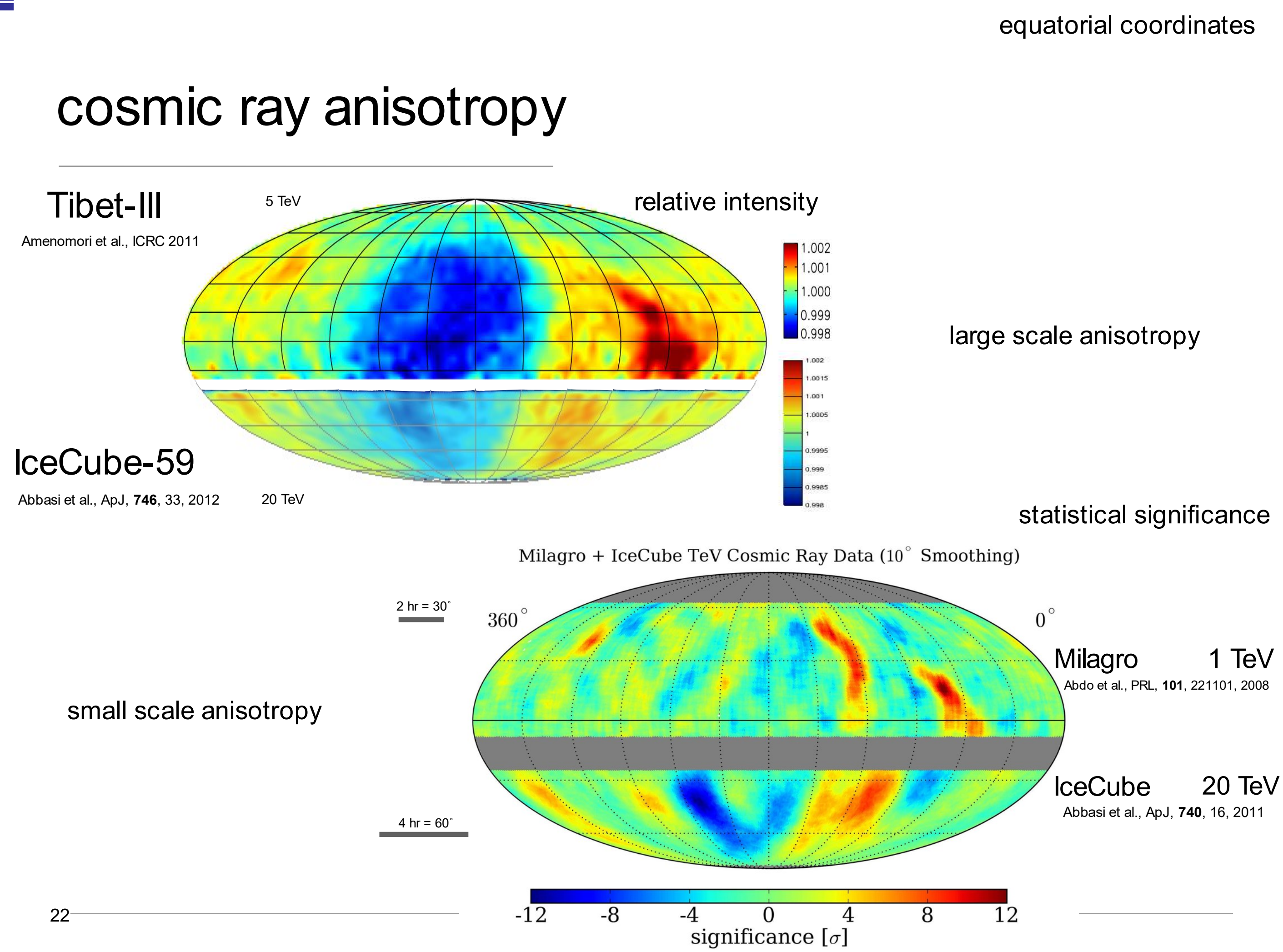
$$R = \frac{pc}{Ze} = \frac{A}{Z}\sqrt{E_k^2 + 2E_kE_0}$$

where p is the momentum, c is the speed of light, e is the electron charge, Z is the particle charge number, A is the mass number and kinetic and rest energy are per nucleon (if energy is in eV then rigidity is in Volts)

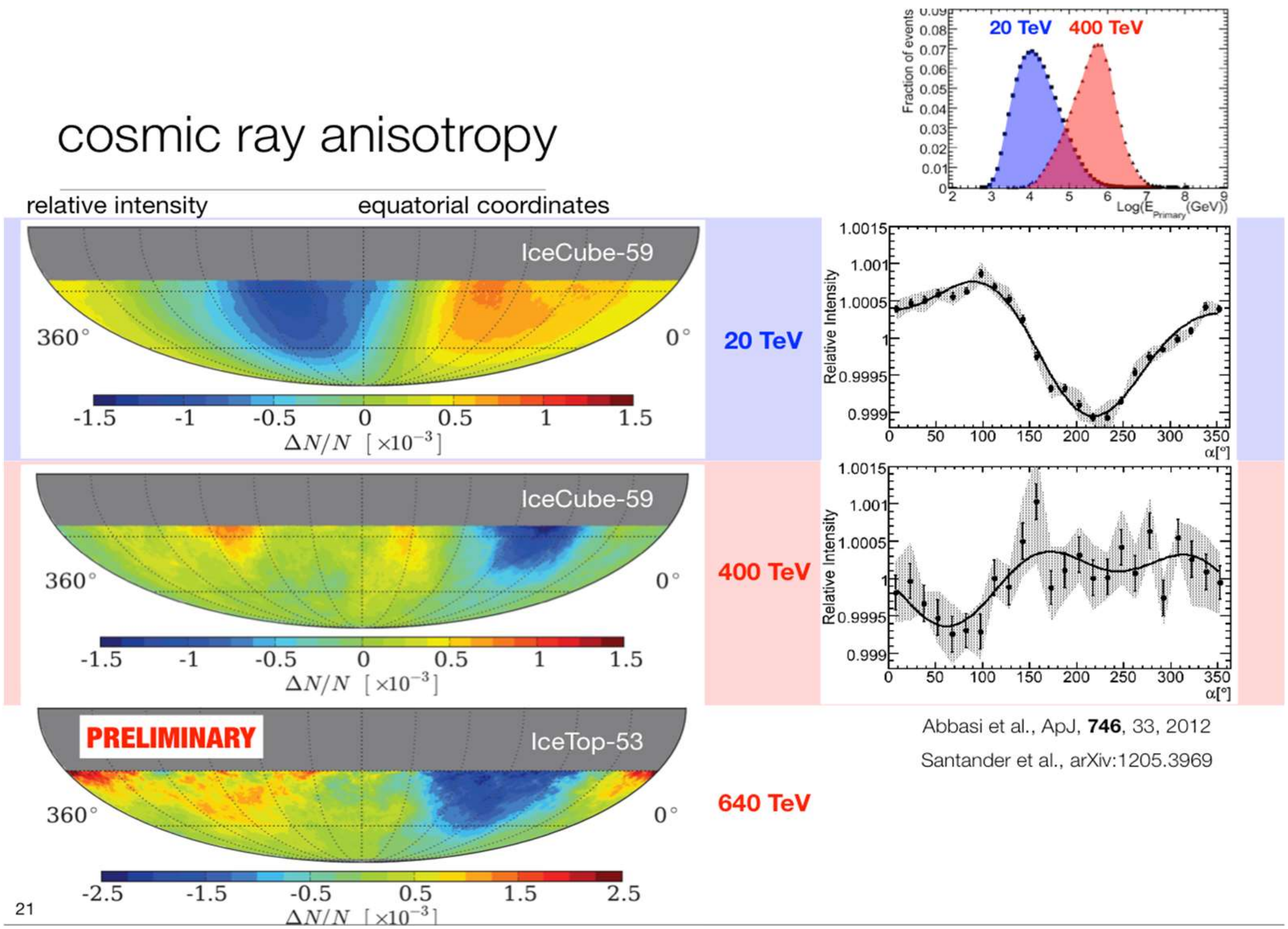
Example in the Heliosphere:

1 GV in 10^{-5} gauss ~ Earth-Moon distance ~ 0.01 AU

The Anisotropy is Tiny



The Anisotropy is Energy Dependent



Cosmic Ray Anisotropy

- These tiny but systematic anisotropies are unexplained. They probably have something to do with magnetic field structures close to the solar system.
- At lower energy, the much larger (and clearly time dependent) anisotropy created in by magnetic fields in the heliosphere forms the basis for a lot of Fhon's work.

Looking Through the Clouds

So is there any way to look through the clouds (cosmic microwave background and intergalactic magnetic field) to **see** the sources?

Why of course!

>>> Observe high energy neutrinos

What Are Neutrinos?

Yesterday, upon the stair,
I met a man who wasn't there.
He wasn't there again today,
I wish, I wish he'd go away...

"Antigonish" (1899) by William Hughes Mearns (1875–1965)

Little bundles of concentrated nothing …

Physics 131 (1965) from S.C. Wright

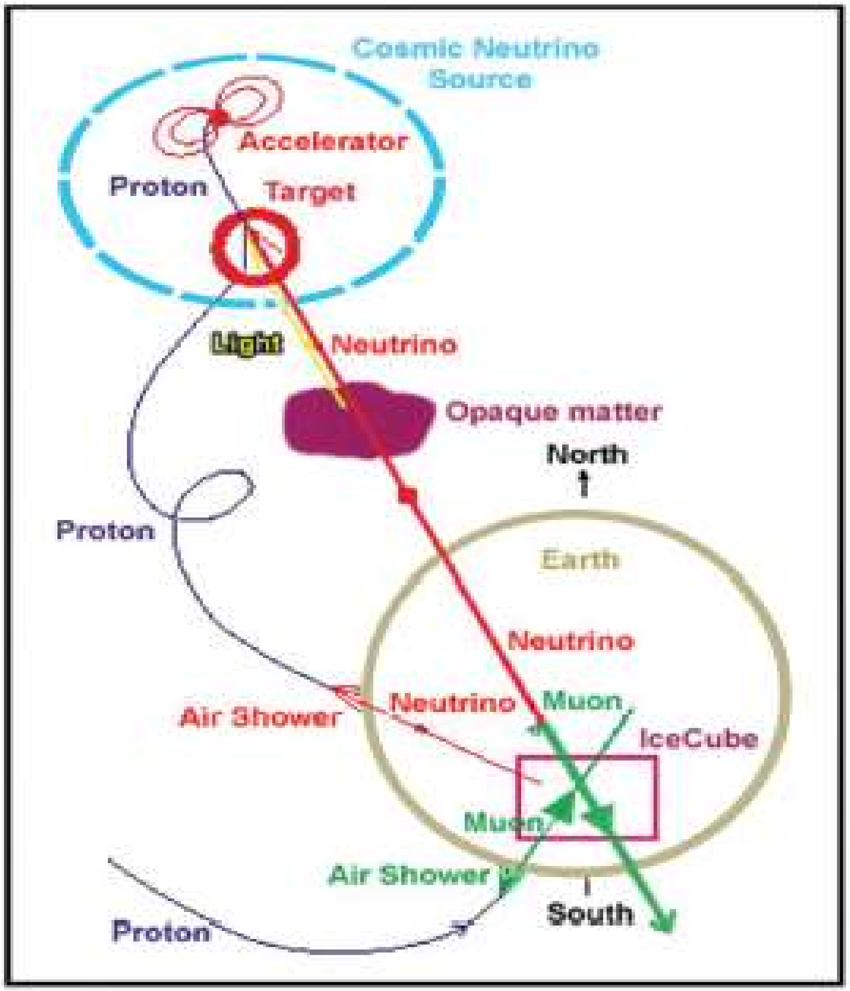
A Better(?) Explanation

- Neutrinos are electrons without charge. They are spin ½ fermions that only interact via the gravitational and weak forces.

- Hairy nose wombats are wombats with a hairy nose.

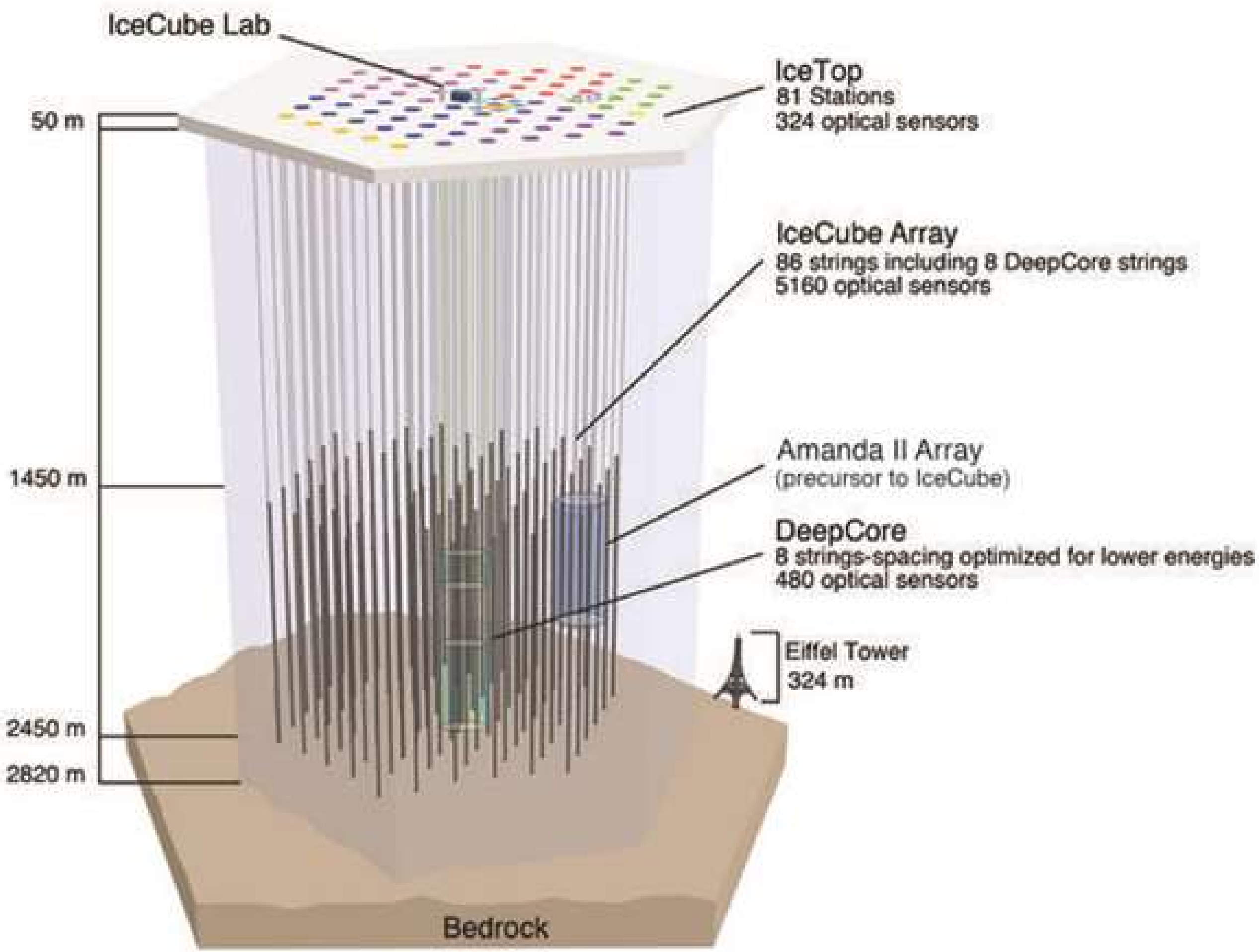
Photo: Eva Hejda

Cosmic Neutrinos: New Window On the Universe



- Cosmic neutrinos are expected to be produced in violent astrophysical sources such as supernovae, gamma ray bursts, and cataclysmic phenomena involving black holes and neutron stars.
- Unlike any other energetic particle, neutrinos can propagate across the known universe.
- Unaffected by magnetic fields they propagate in straight lines that extrapolate back to the point of production.

Ice Cube Concept

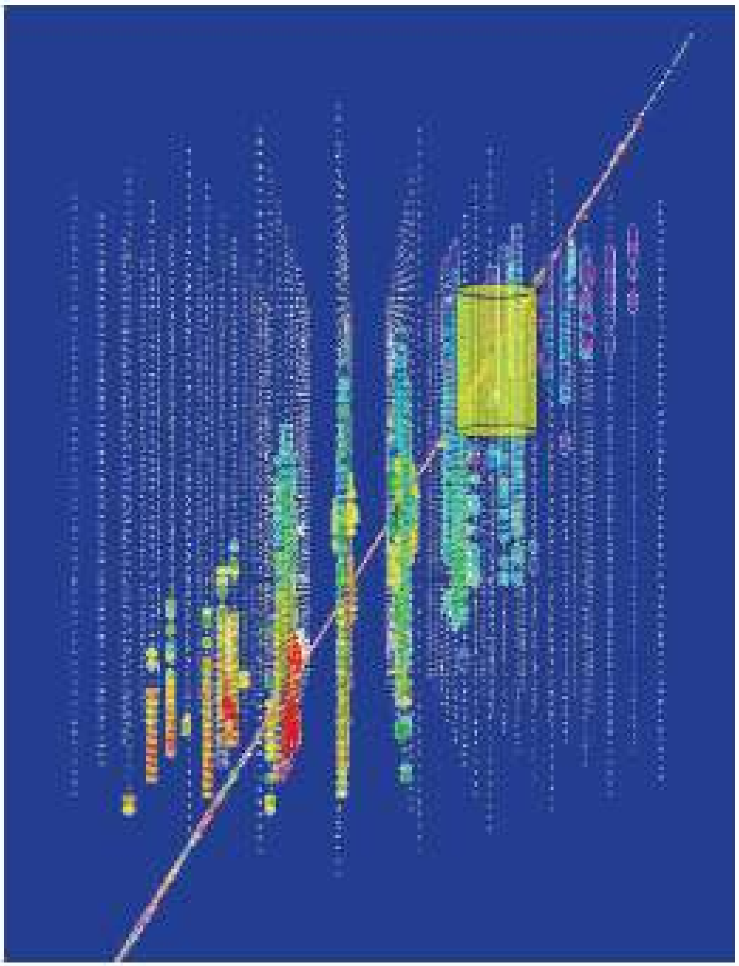


Trillions of neutrinos stream through your body every second, but none may leave a trace in your lifetime.

IceCube uses a large volume (one cubic kilometer) of ice at the South Pole to detect rare neutrino interactions.

Most often these interactions generate an energetic muon.

Ice Cube Concept



In the ultra-transparent ice, the muon radiates blue light that is detected by the optical sensors that comprise IceCube.

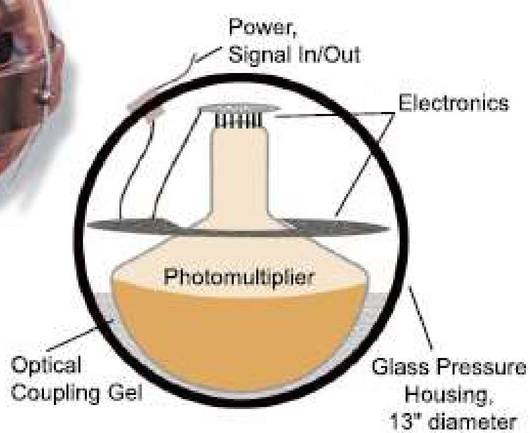
Muons follow the arrival direction of the original neutrino.

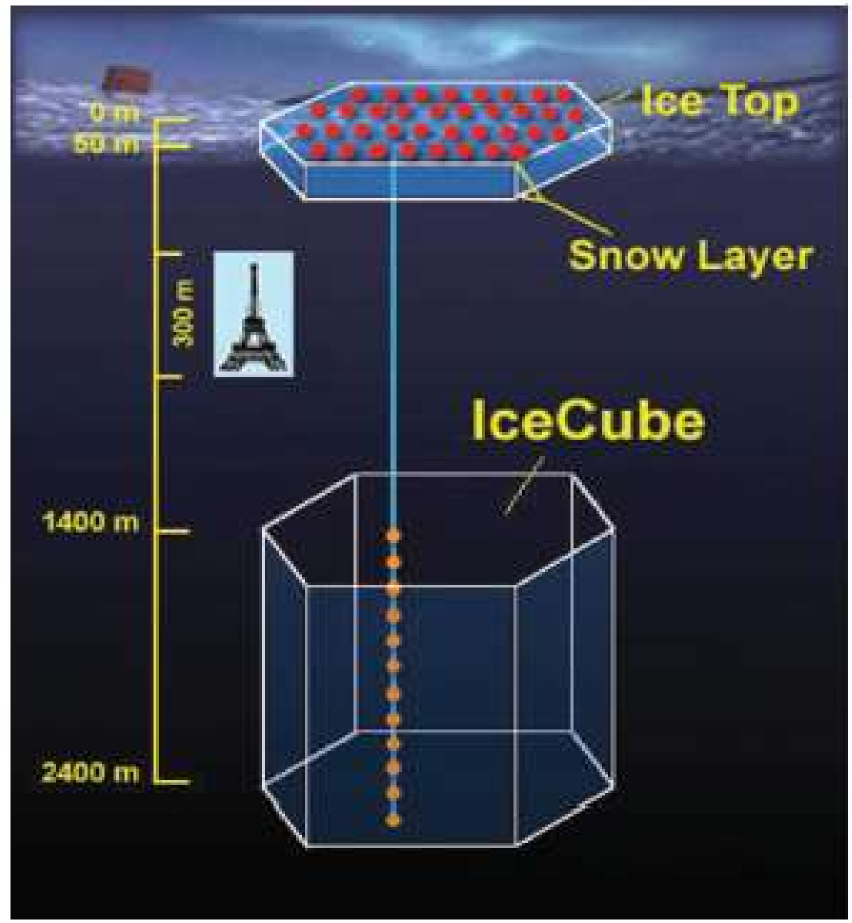
By measuring the arrival time and amount of light at each sensor the arrival direction of the neutrino is determined and the energy can be estimated.

Detecting the Light

How does IceCube "see" a neutrino?

Like its predecessor, AMANDA, the basic component of IceCube is the sensor that transforms light into electrical signals. A sensor is a photomultiplier tube housed in a glass pressure vessel; IceCube will boast nearly 5000. The technology used in IceCube will be more advanced than that of AMANDA. IceCube will have "smart" sensors, meaning that each sensor will contain a computer chip connected through the internet to computers in scientists' offices! It is not too fanciful to think of the device as a cubic-kilometer, continuously sensing computer.

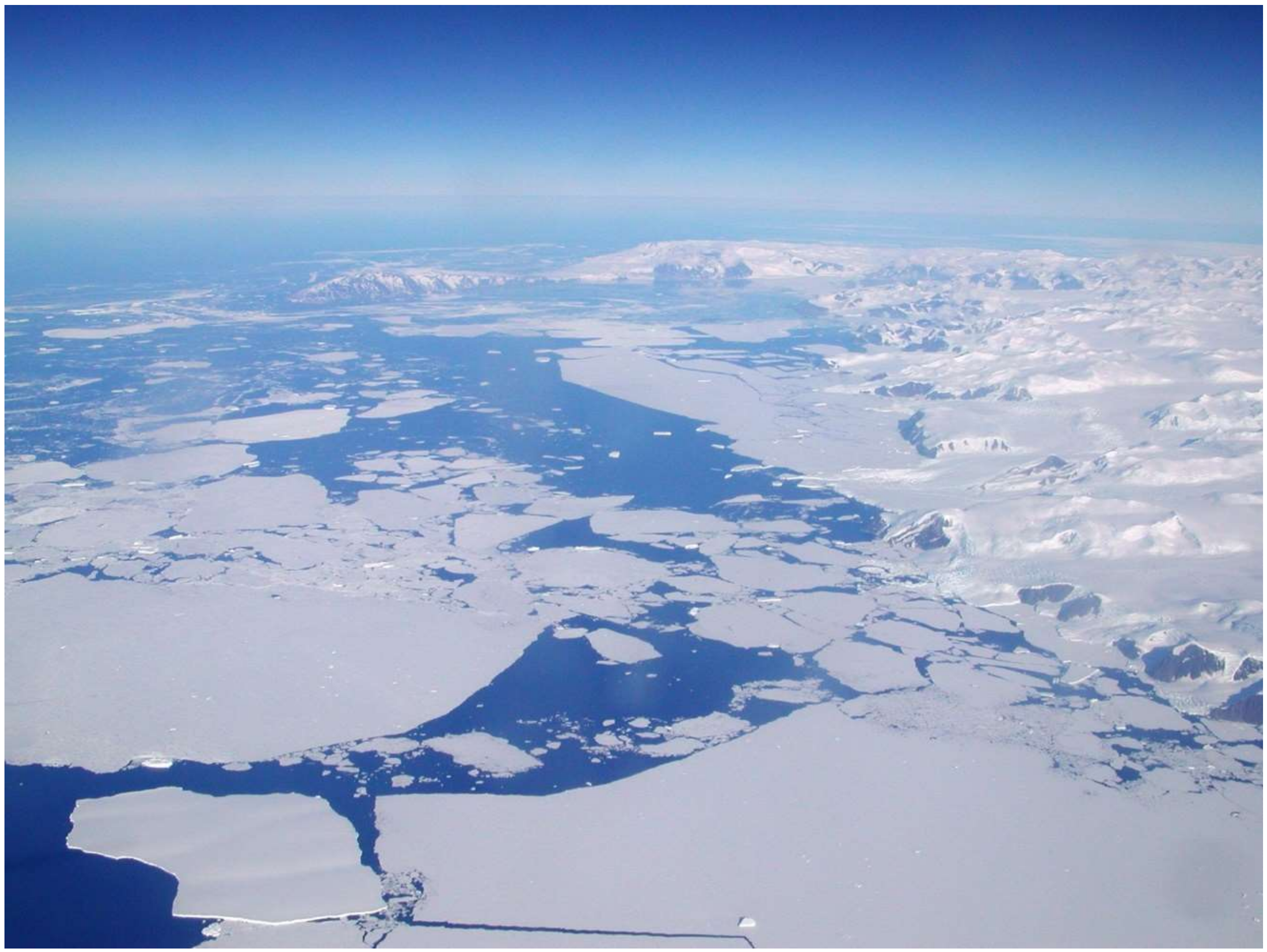




Getting to the South Pole: Christchurch NZ

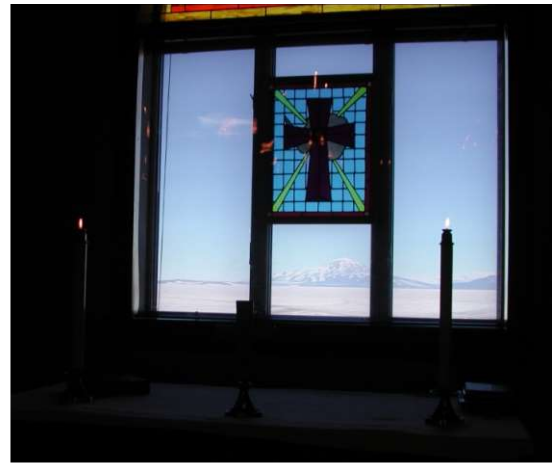
Journey South

Antarctica!



McMurdo (Continental Metropolis)

McMurdo
Scenery and Culture

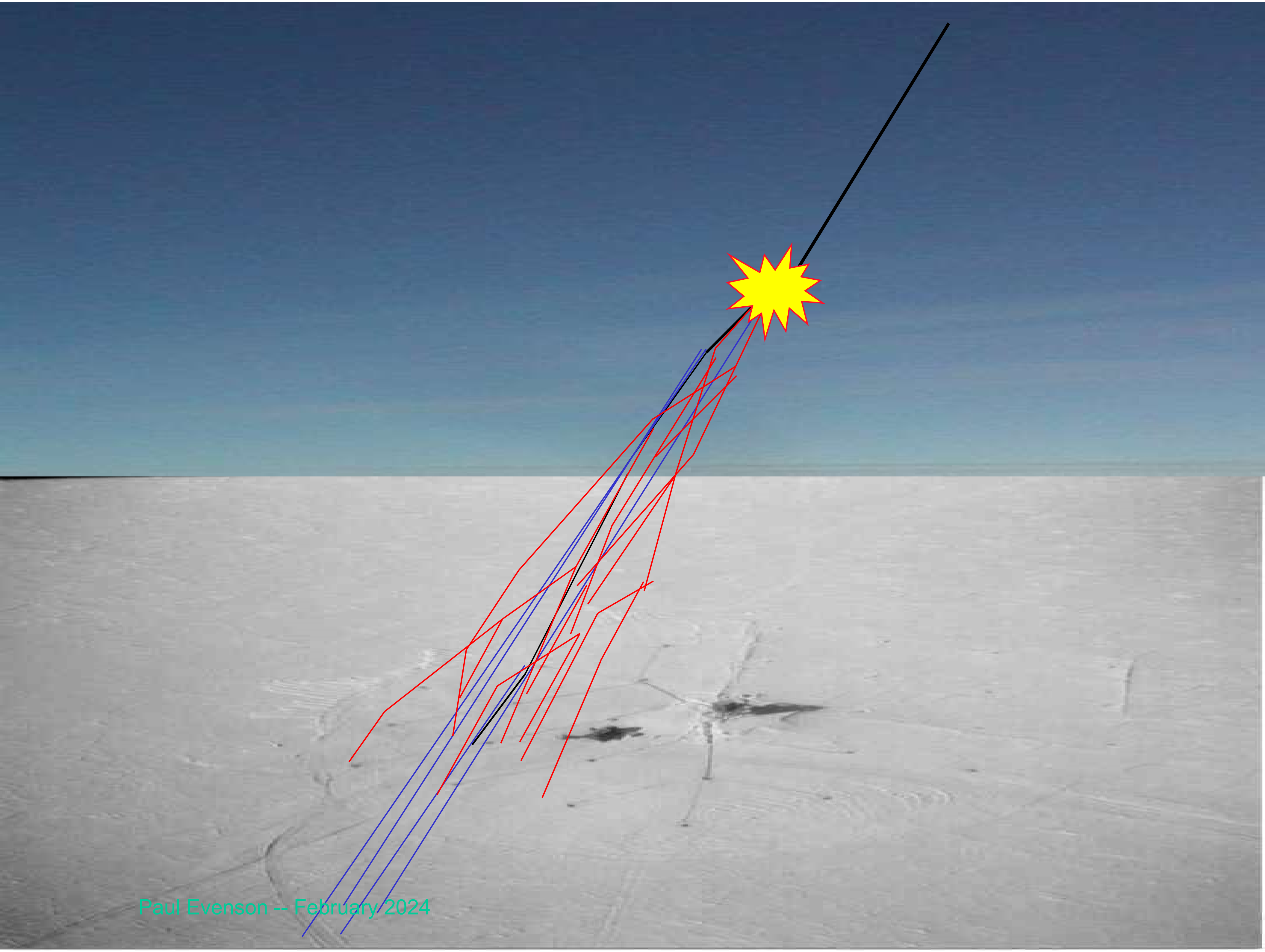


Ice Cube Construction

Hot Water Drilling

So What Do We See?

- Mostly high energy muons from cosmic rays interacting in the atmosphere…


Paul Evenson -- February 2024

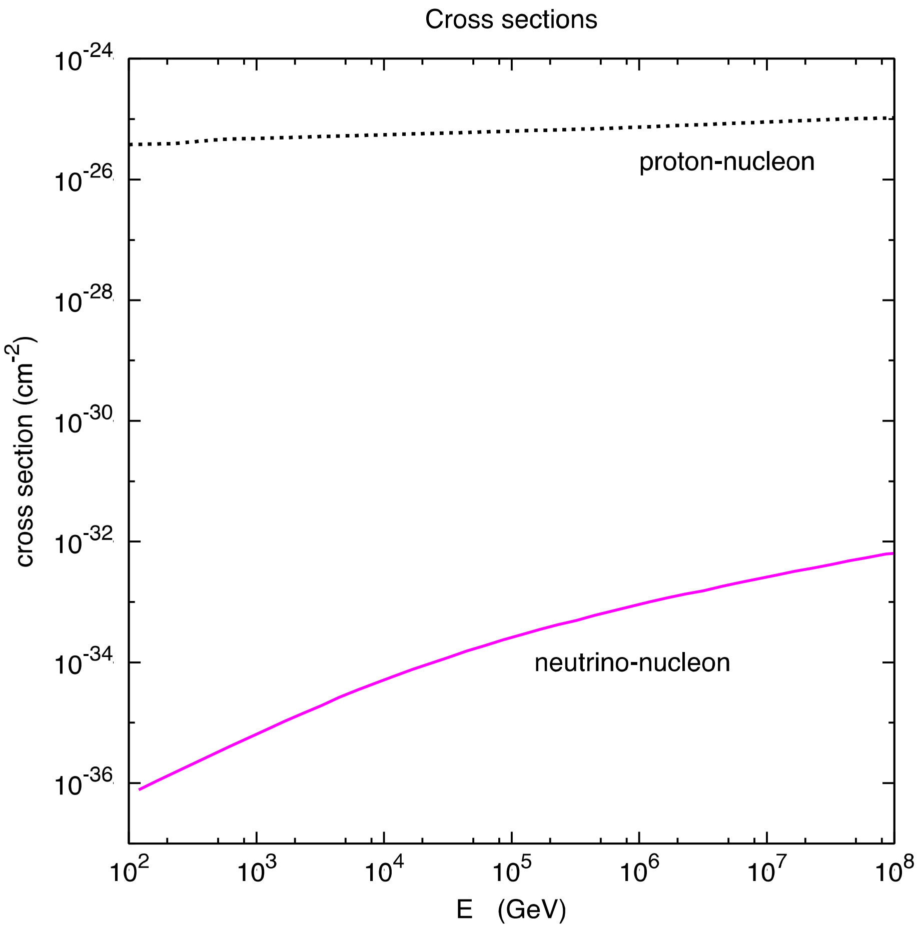
Main Source of Background

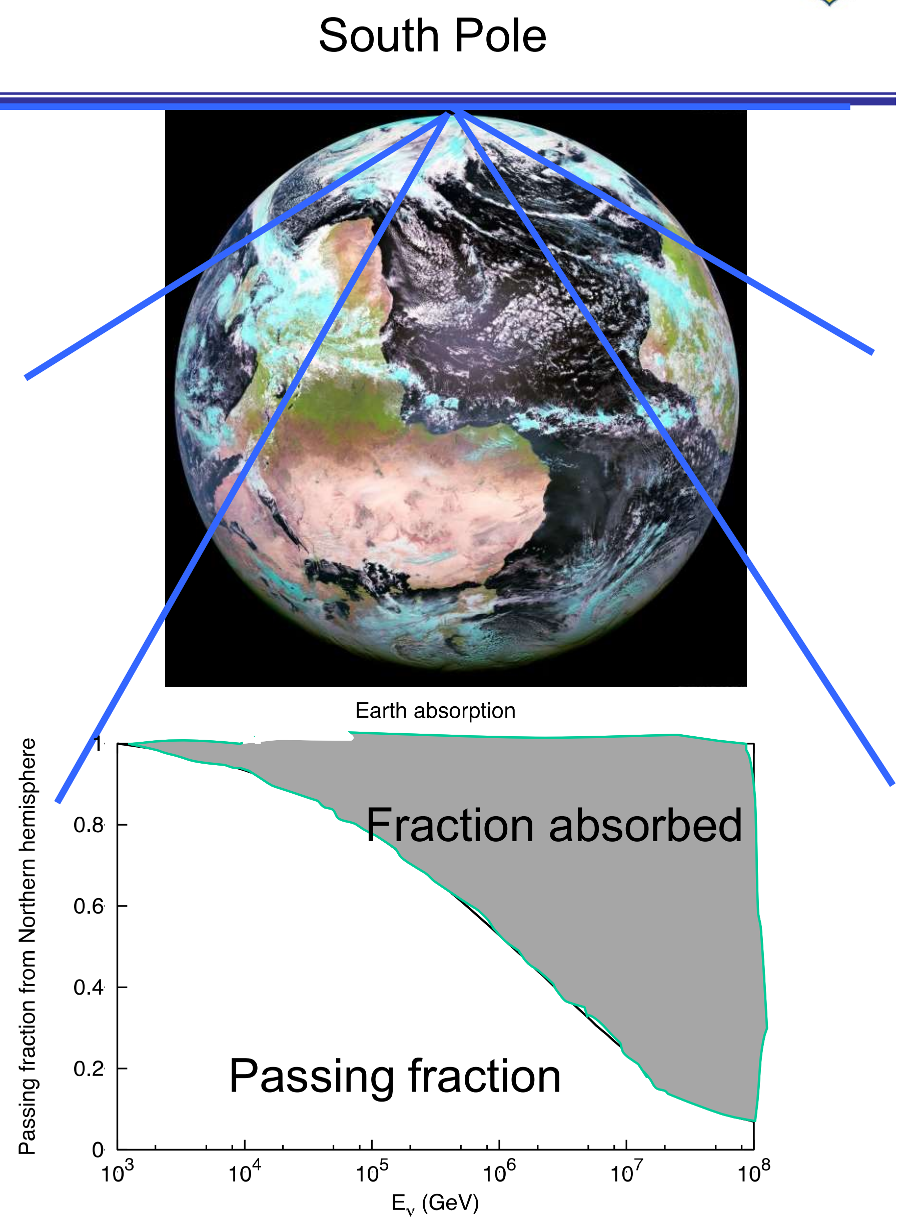
- About 2000 muons per second produce light in the detector.
- The real problem is that there are so many that often more than one at a time are passing through the detector.
- This produces all kinds of strange and hard to interpret events.

What About Neutrinos?

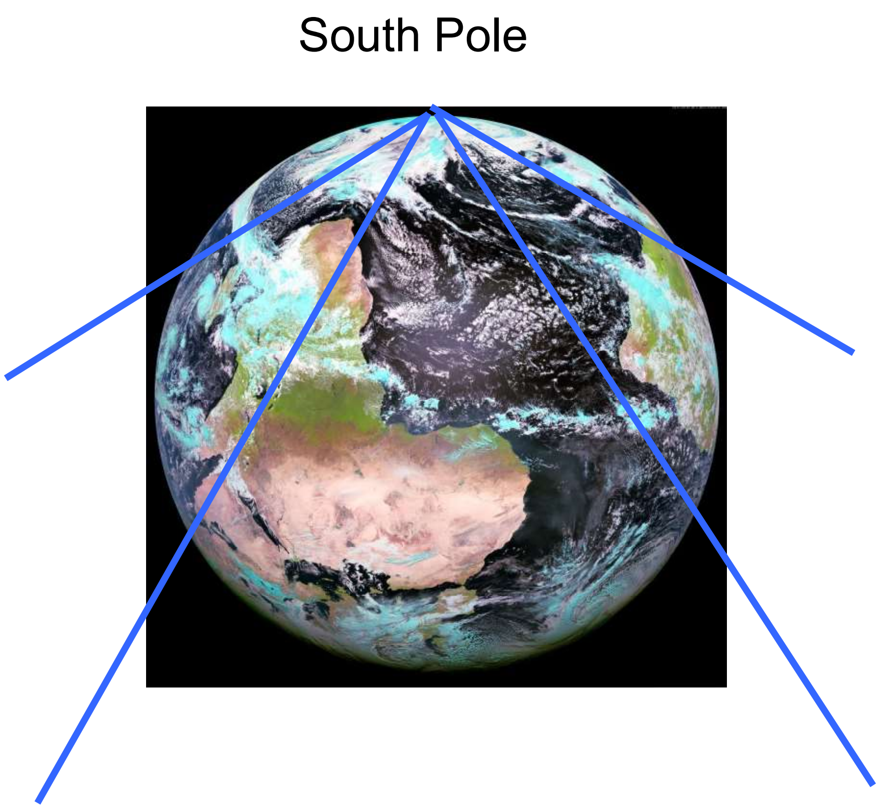
- We see lots of neutrinos, about a thousand per day.
- Most of these are produced in the atmosphere.
- We can study these to understand the “oscillation” of neutrinos.
- This is a variant of the “solar neutrino problem” but at very much higher energy

Upward ν in IceCube



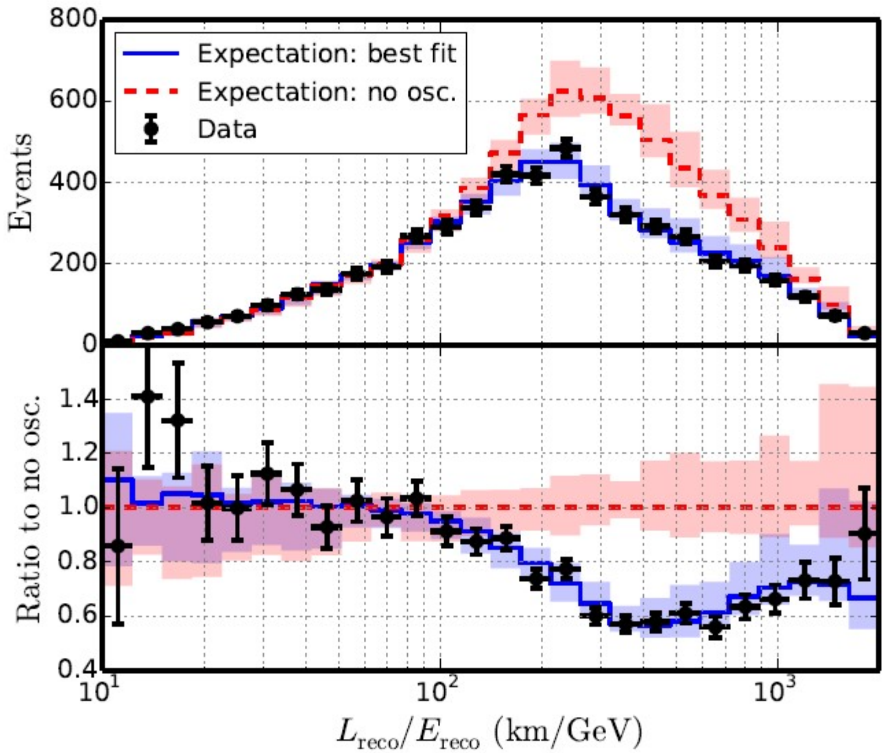


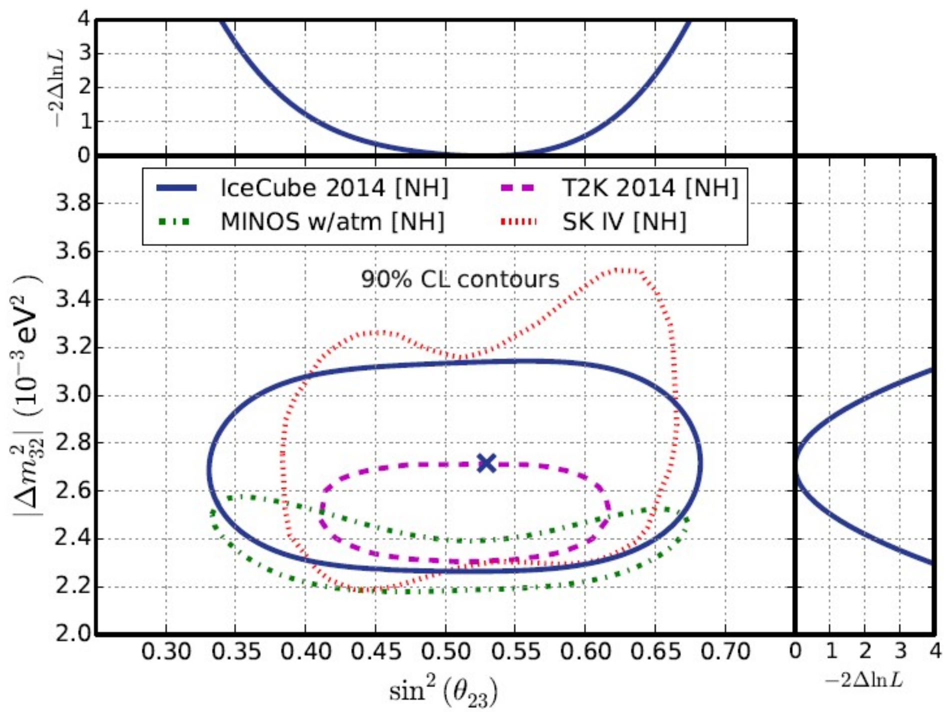
Observing Neutrino Oscillations



The oscillation length scales with energy because of Lorentz time dilation, so a good parameter to organize data is L_{reco}/E_{reco}. L_{reco} is the "reconstructed" distance from the detector through the Earth to the atmosphere while E_{reco} is the "reconstructed" energy.

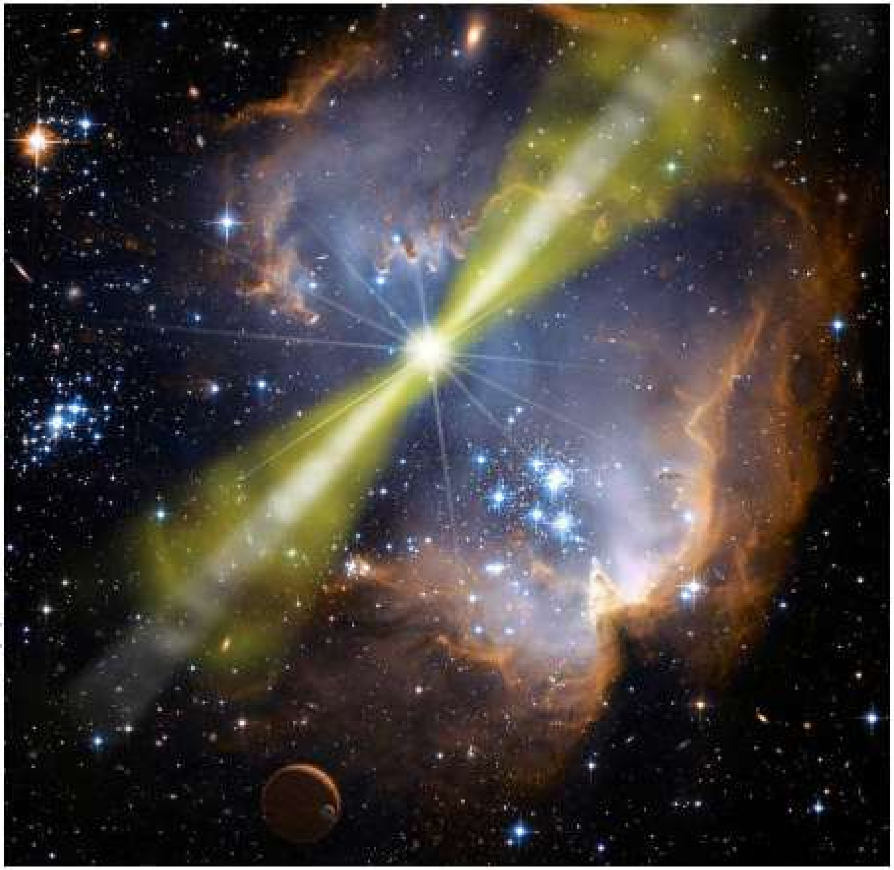
Oscillation Parameters





By modeling the observations an “allowed region” in the oscillation parameters is determined.

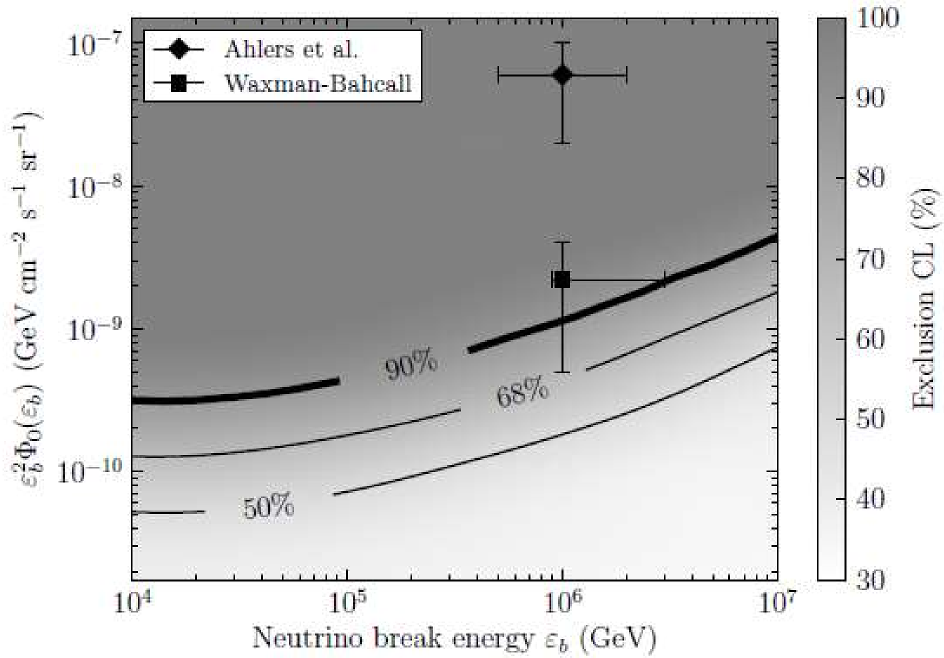
Gamma Ray Bursts



Artist's illustration of a bright gamma-ray burst occurring in a star-forming region. Image: NASA/Swift/Mary Pat Hrybyk-Keith and John Jones

Gamma-ray bursts (GRBs) were once the most promising candidate source of ultra-high-energy cosmic rays (UHECRs). They release extremely large amounts of energy in short periods of time, so if they could accelerate protons as they do electrons, then GRBs could account for most of the observed UHECRs.

The man who wasn't there…



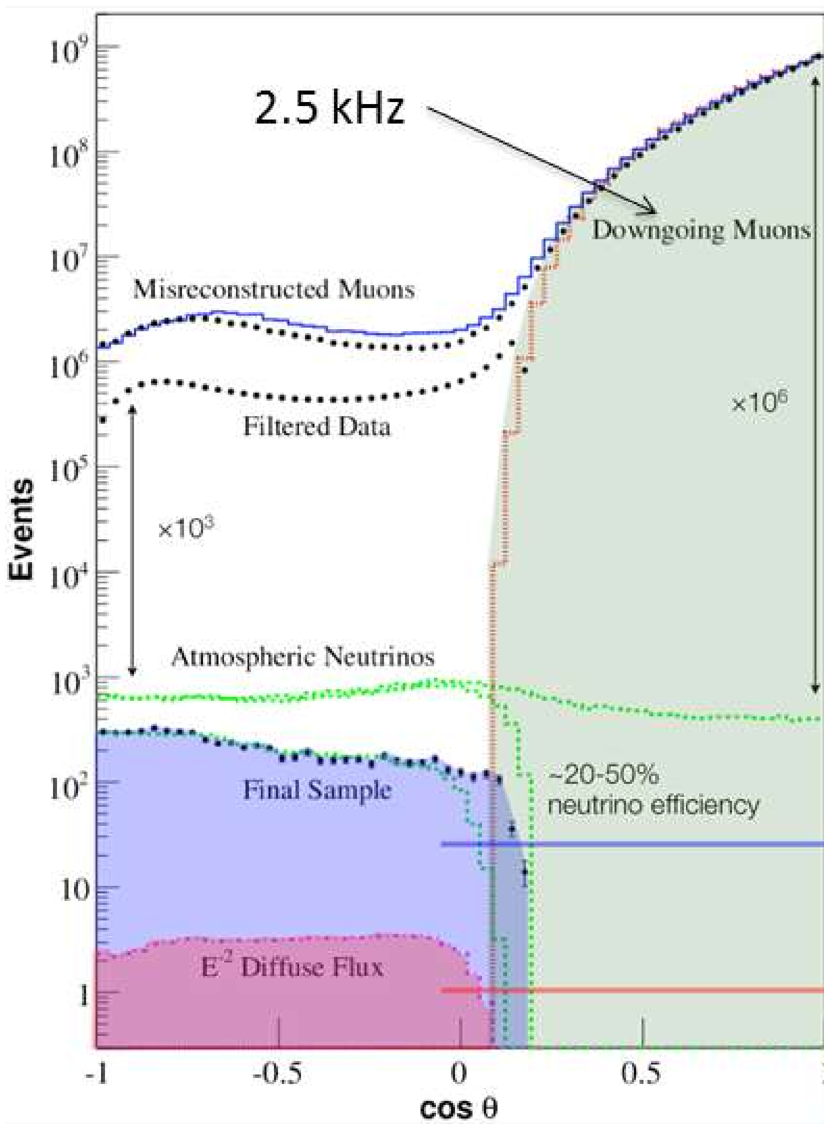
IceCube has looked for a neutrino signature in coincidence with over 500 GRBs observed during the data-taking period from April 2008 to May 2012. A single low-significance neutrino was found, confirming previous results by the collaboration. However, this data sample was much larger, including the first data from the completed detector and allowing still more stringent limits on GRB neutrino production.

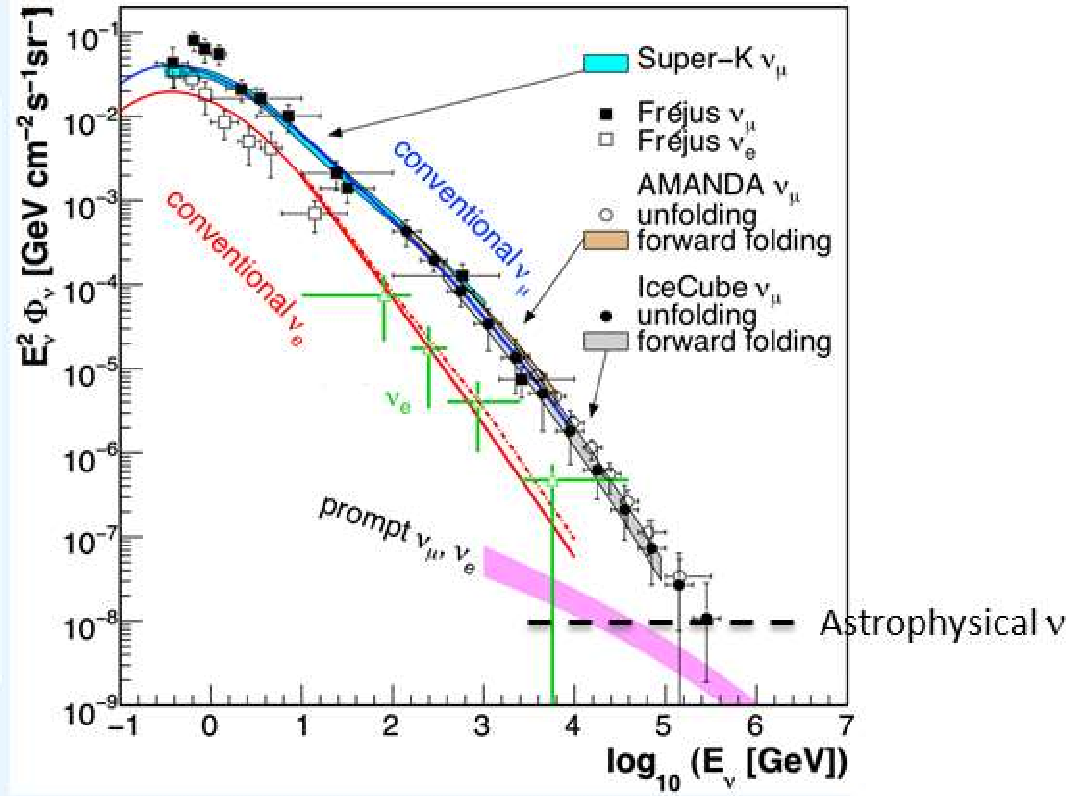
The figure shows the constraint on generic doubly-broken power law neutrino flux models as a function of burst break energy ε_b and normalization Φ_0. The model by Ahlers et al. (2011) assumes that only neutrons escape from the GRB fireball to contribute to the UHECR flux. The Waxman-Bahcall model (1997), which allows all protons to escape the fireball, has been updated to account for more recent measurements of the UHECR flux (Katz et al. 2009) and typical gamma break energy (Goldstein et al. 2012)

Search Strategies for Astrophysical Neutrinos

1. Look for a hard, high-energy component above the atmospheric background
   – Upward ν_μ induced muons
     • Highest rate
   – Events starting in the detector
     • Lower rate, but
     • Atmospheric ν background is lower
2. Look for excess of events in the ν_μ skymap

Needle in a Hay Stack!





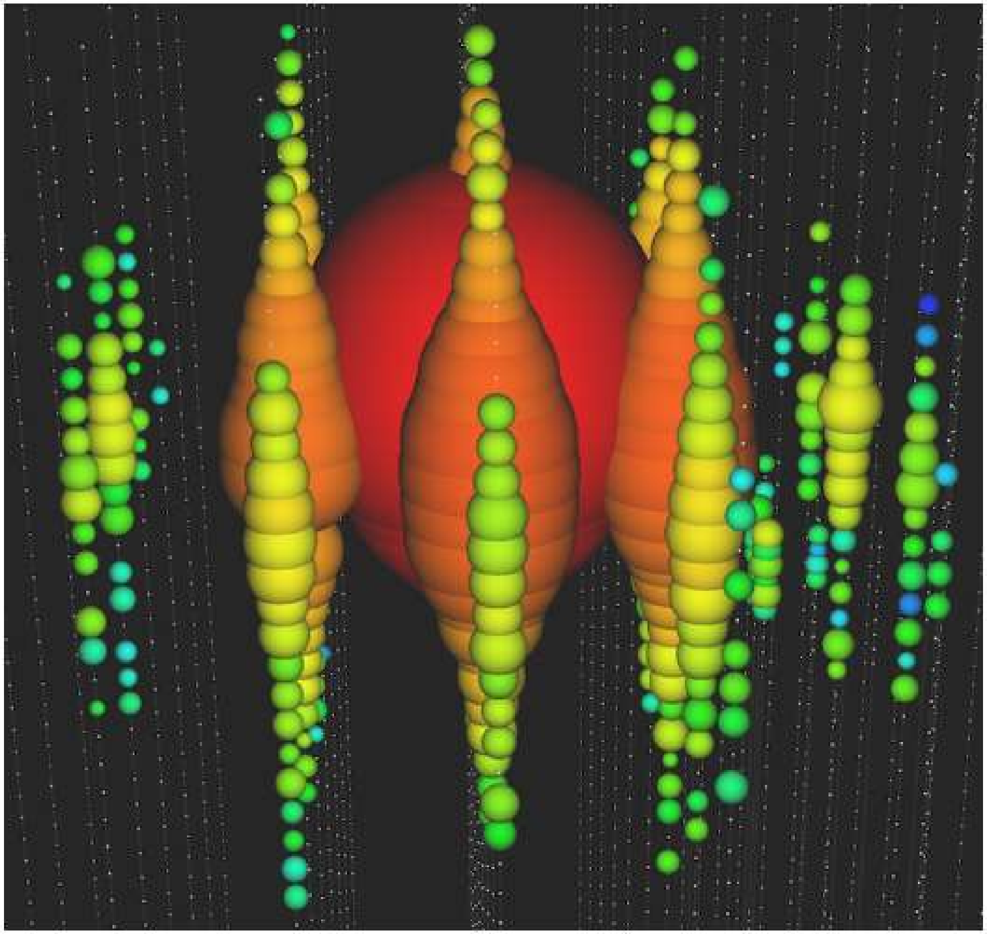
atmospheric neutrinos
~ 1 per million

extra-terrestrial neutrinos
~ 1 per billion

But Are There Cosmic Neutrinos?

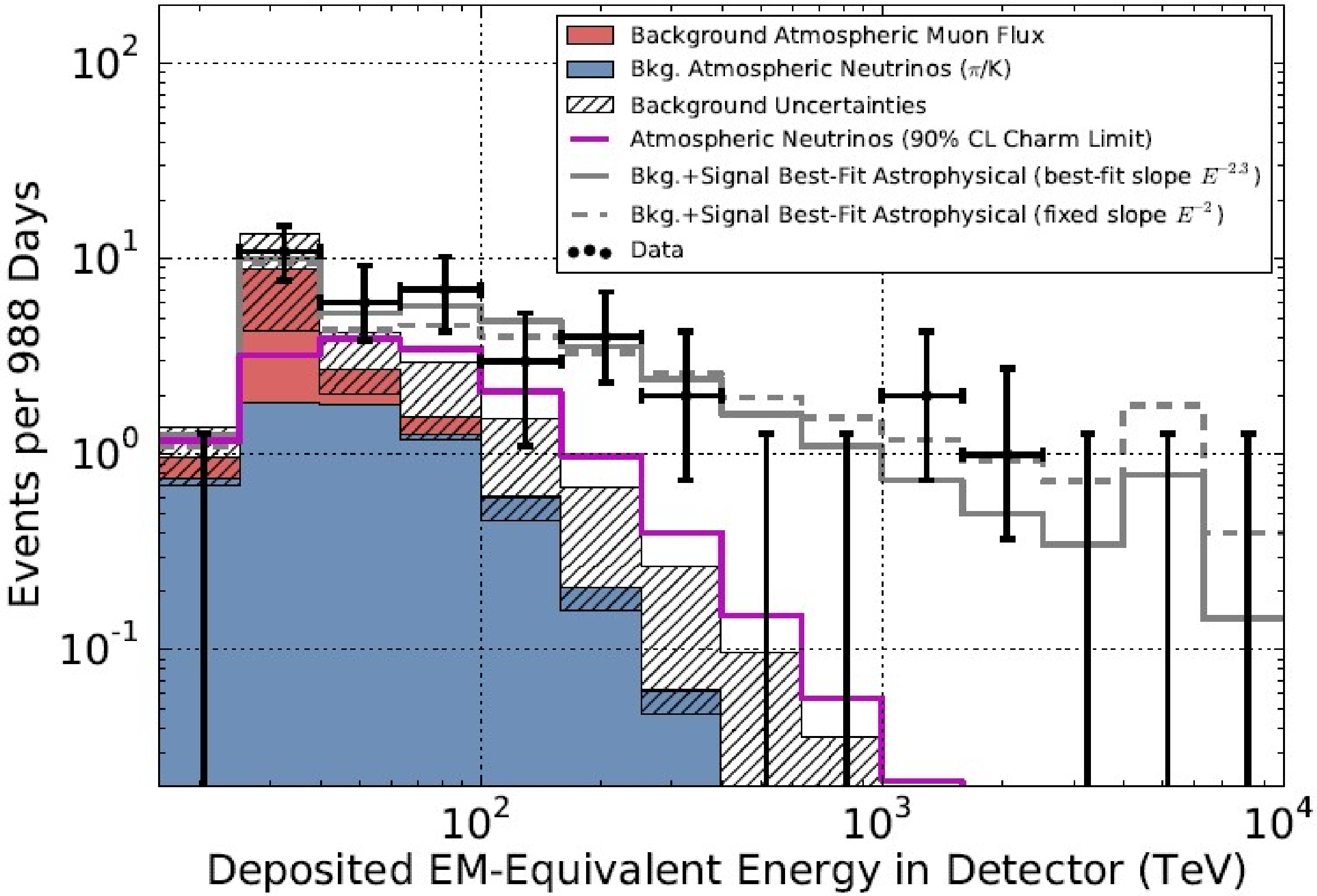
- YES!
- We have at least 28 events that look like cosmic neutrinos (of which an estimated 12 are still some kind of background)
- Twelve year of work, $300 million tax dollars, but by golly it looks like we see something!

A "Typical" Event



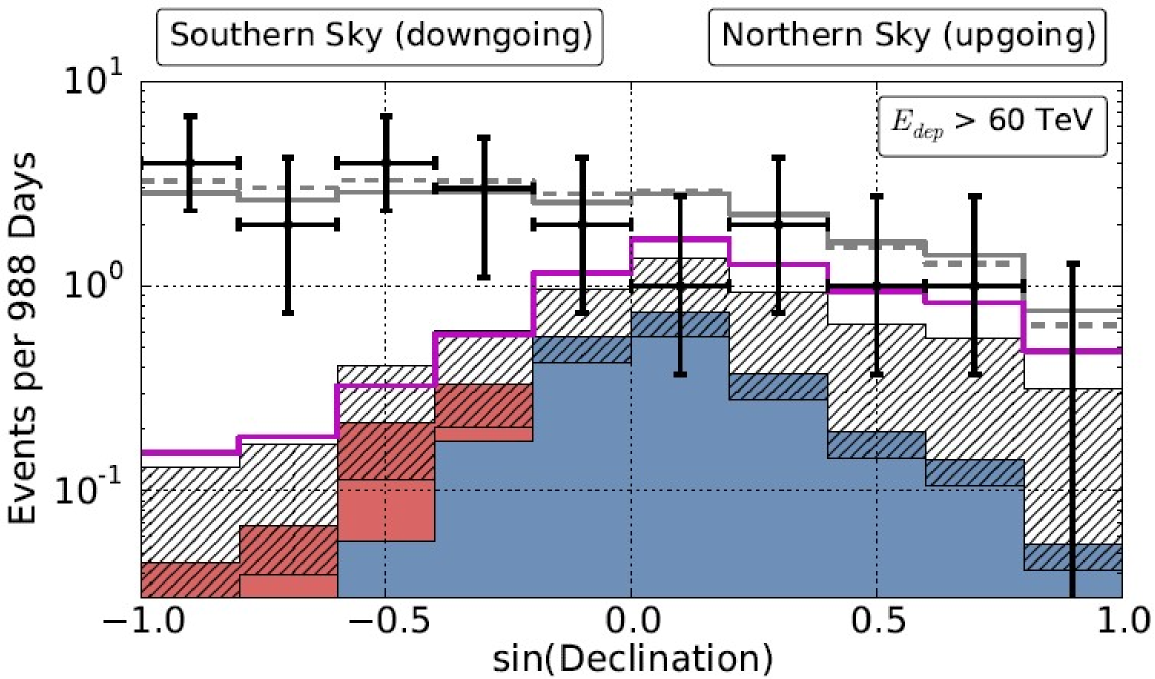
This 2-PeV neutrino event was detected by IceCube on Tuesday, December 4, 2012. It was dubbed "Big Bird." Image: IceCube Collaboration.

Energy Spectrum



Deposited energies of observed events with predictions. The hashed region shows uncertainties on the sum of all backgrounds. Muons (red) are computed from simulation to overcome statistical limitations in our background measurement and scaled to match the total measured background rate. Atmospheric neutrinos and uncertainties thereon are derived from previous measurements of both the π/K and charm components of the atmospheric ν_τ spectrum. A gap larger than the one between 400 and 1000 TeV appears in 43% of realizations of the best-fit continuous spectrum.

Zenith Angle Distribution



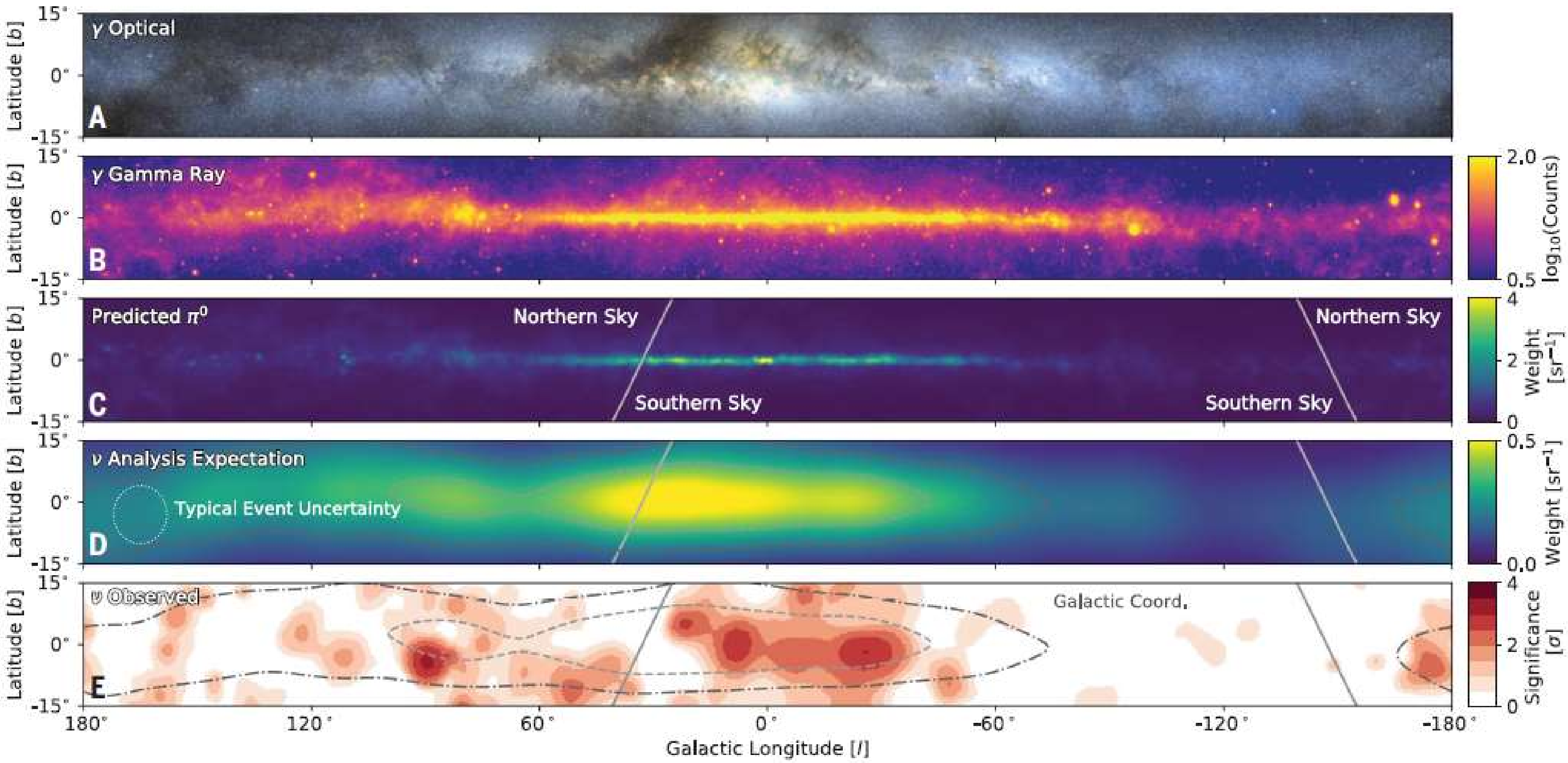
Arrival angles of events with E_{dep} > 60TeV (as used

in our fit) above the majority of the cosmic ray muon background. The increasing opacity of the Earth to high energy neutrinos is visible at the right of the plot.

Vetoing atmospheric neutrinos by muons from their parent air showers depresses the atmospheric neutrino background on the left.

The data are described well by the expected backgrounds and a hard astrophysical isotropic neutrino flux (gray lines).

Plane of the Milky Way Galaxy in Photons and Neutrinos.



IceCube Collaboration, Science 380, 1338–1343 (2023) 30 June 2023

Summary

IceCube is the world's largest neutrino detector, encompassing a cubic kilometer of ice.

IceCube searches for neutrinos from the most violent astrophysical sources: events like exploding stars, gamma-ray bursts, and cataclysmic phenomena involving black holes and neutron stars.

The IceCube telescope is a powerful tool to search for dark matter and could reveal the physical processes associated with the enigmatic origin of the highest energy particles in nature.

In addition, exploring the background of neutrinos produced in the atmosphere, IceCube studies the neutrinos themselves; their energies (10 GeV to 10 PeV) far exceed those produced by accelerator beams.