IceCube Point Sources Overview
UW Bootcamp

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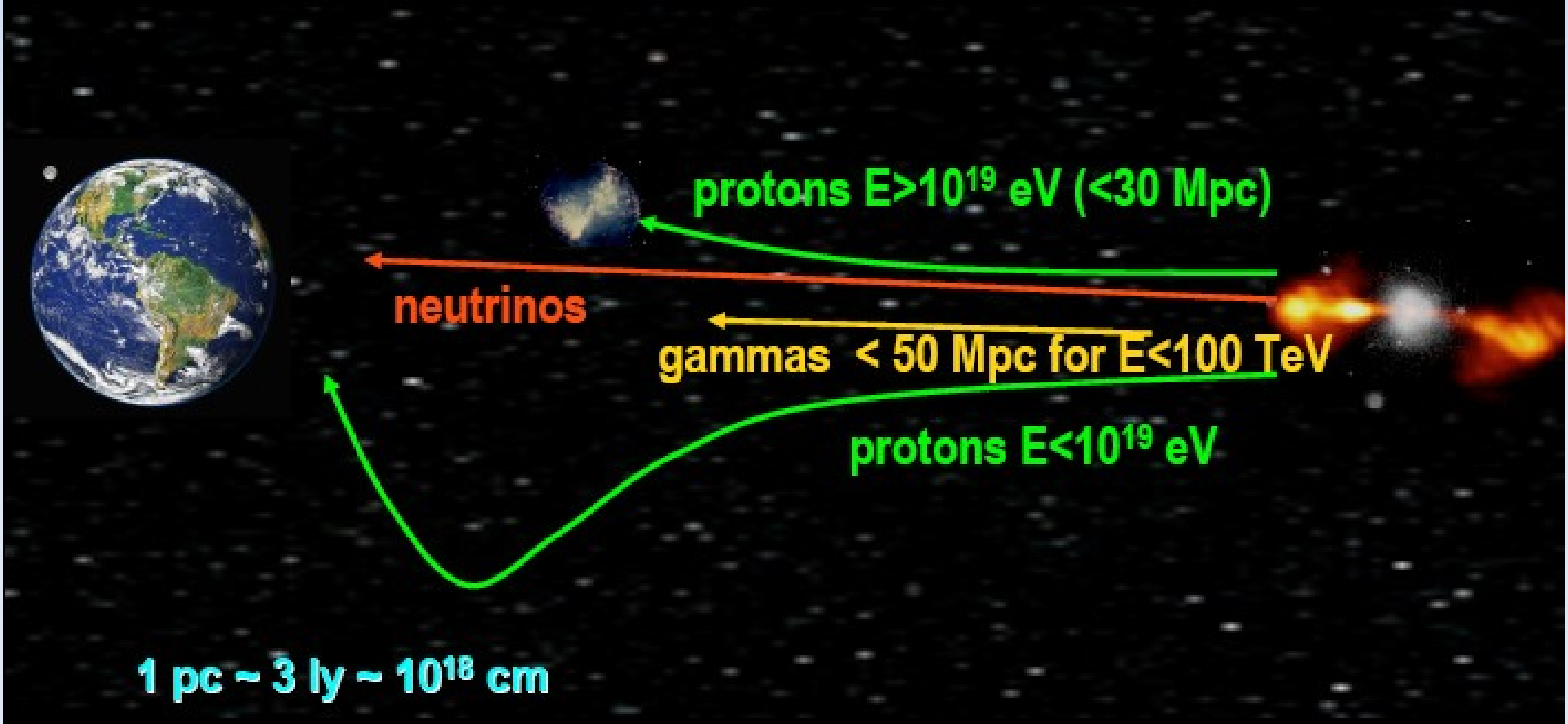
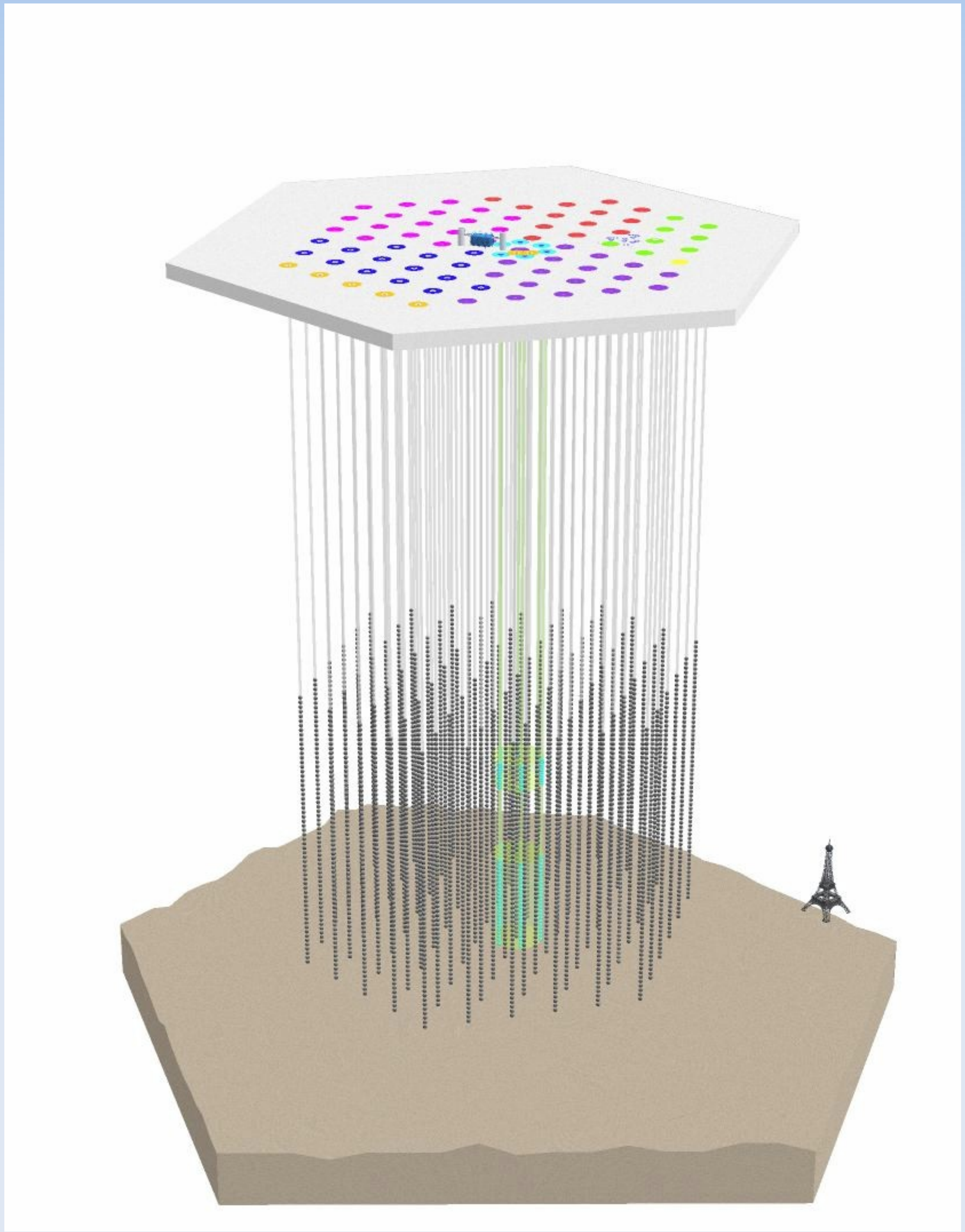
Messengers from the Universe

- Straight line propagation to point back to sources
- Small absorption in sources and during propagation



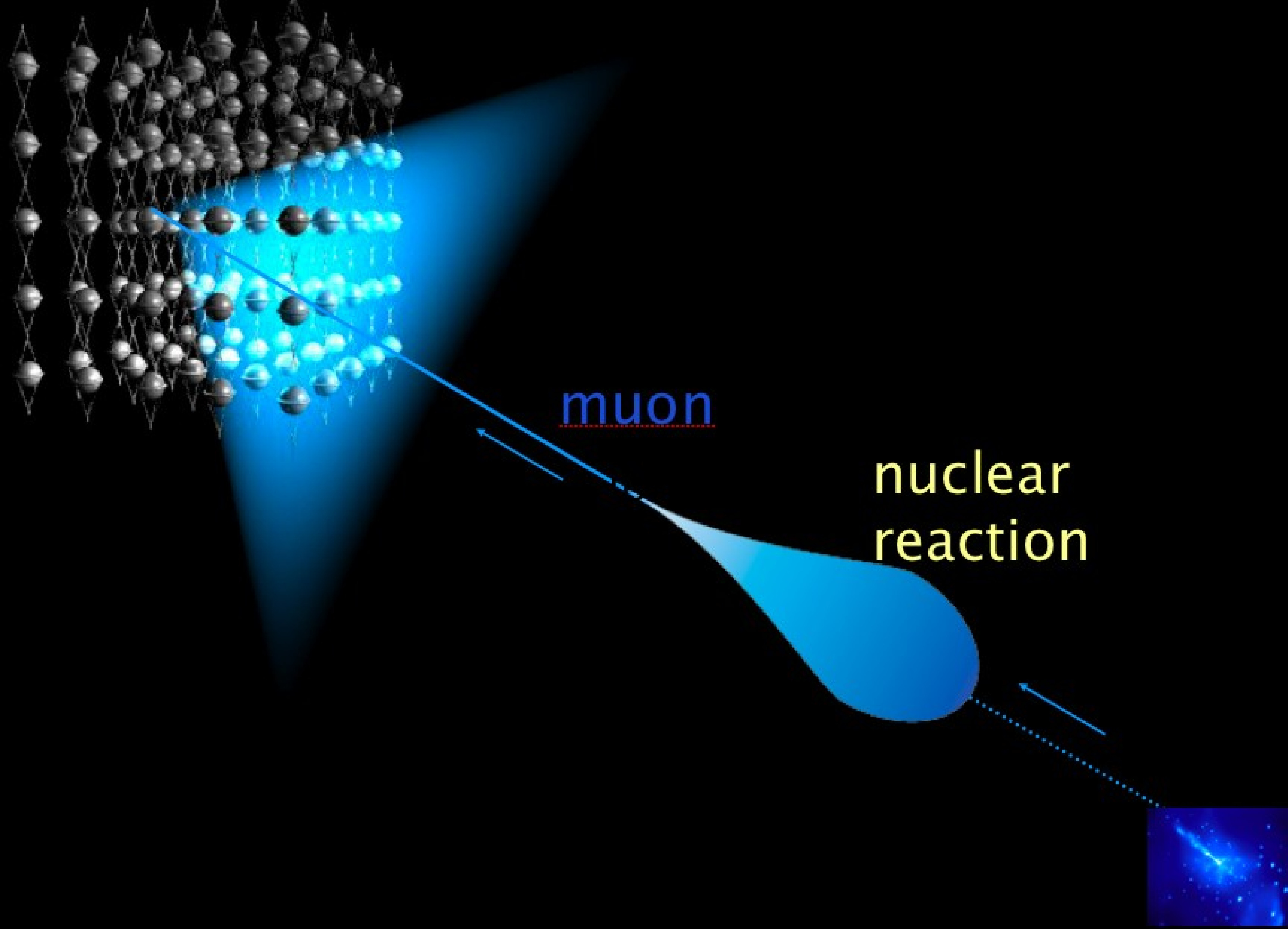


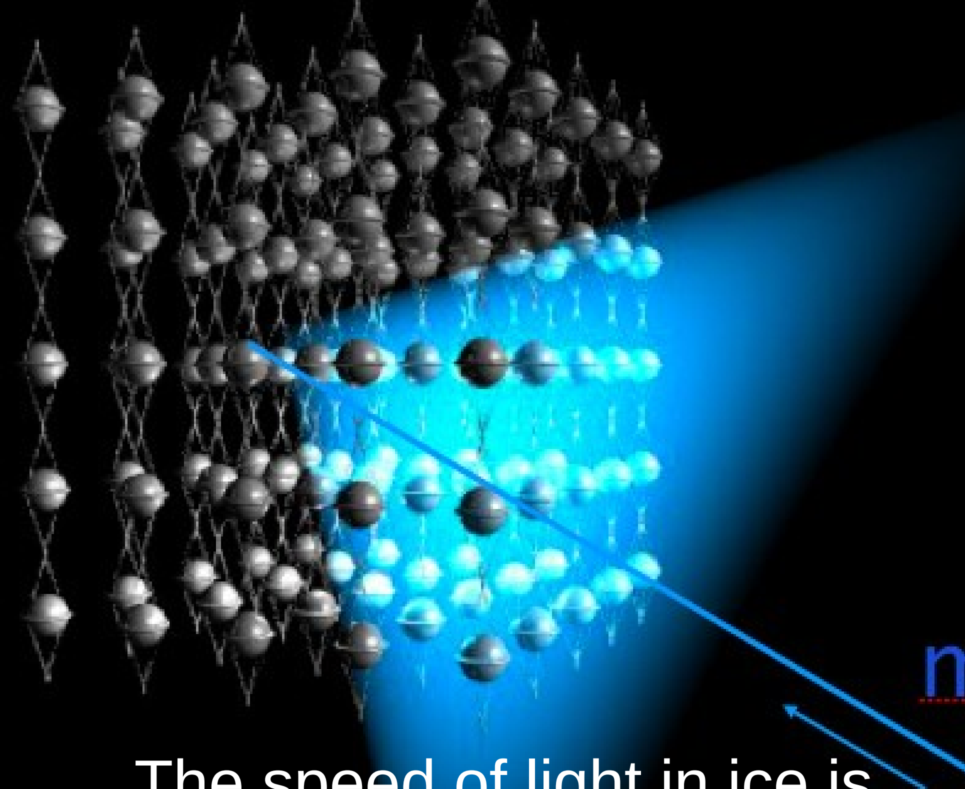
The idea behind IceCube is to have a huge amount of ice with embedded light detectors on 86 separate strings. The strings are instrumented between 1500 and 2500 meters below the surface of the glacier at the South Pole.

The DOM – Digital Optical Module

It consists of a large photomultiplier tube on the bottom half.

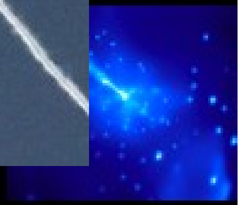
The top half has electronics to:
– read out the PMT signals with nanosecond precision
– relay signals to DOMs which are nearby
– send data to the surface
– control light sources used to test the detector


muon
nuclear
reaction



The speed of light in ice is about two-thirds of that in a vacuum.

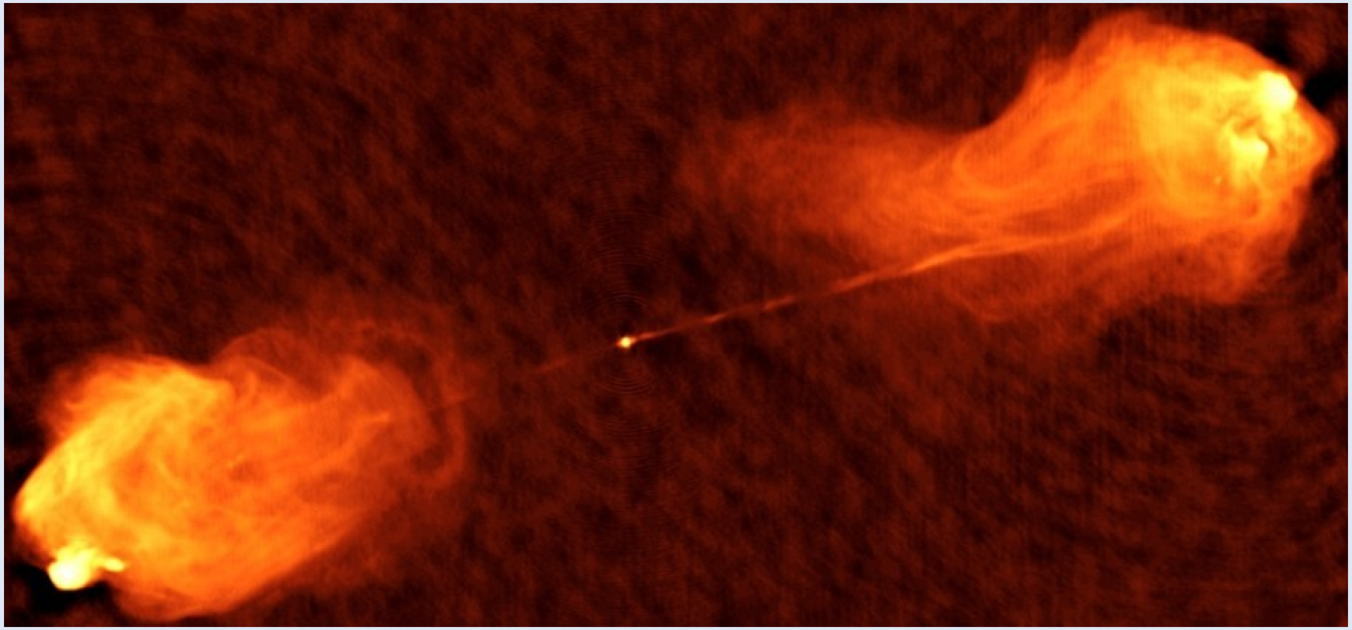
Since the muons created travel at nearly the speed of light in a vacuum it makes a cone of light – like the shock wave from a sonic boom of an airplane.

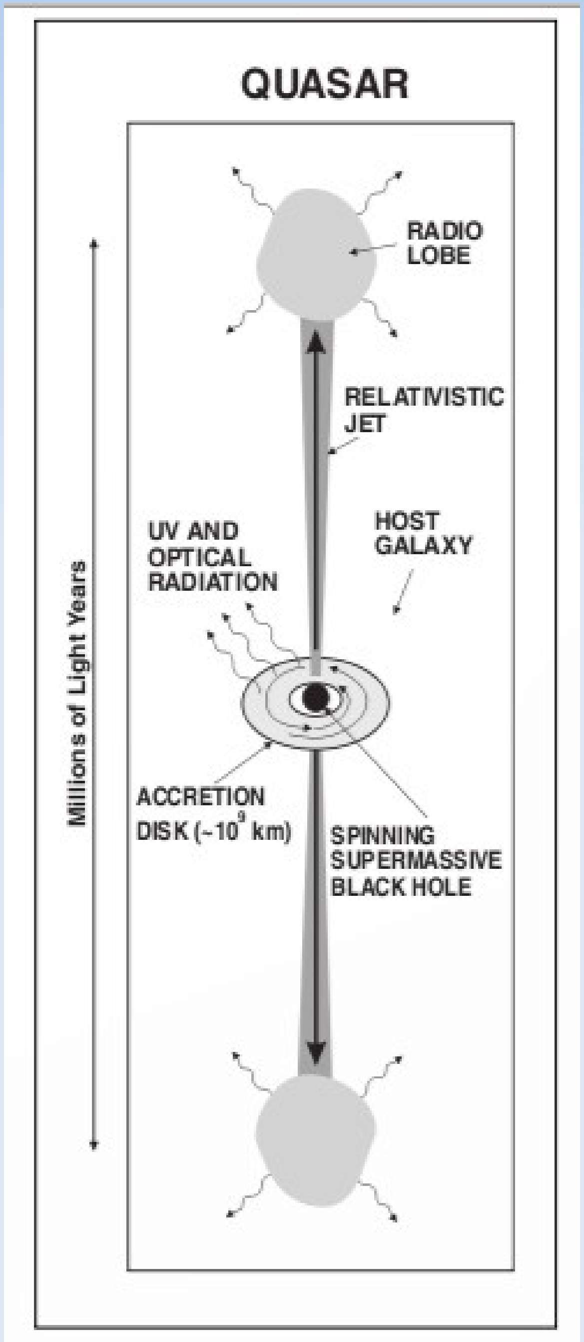


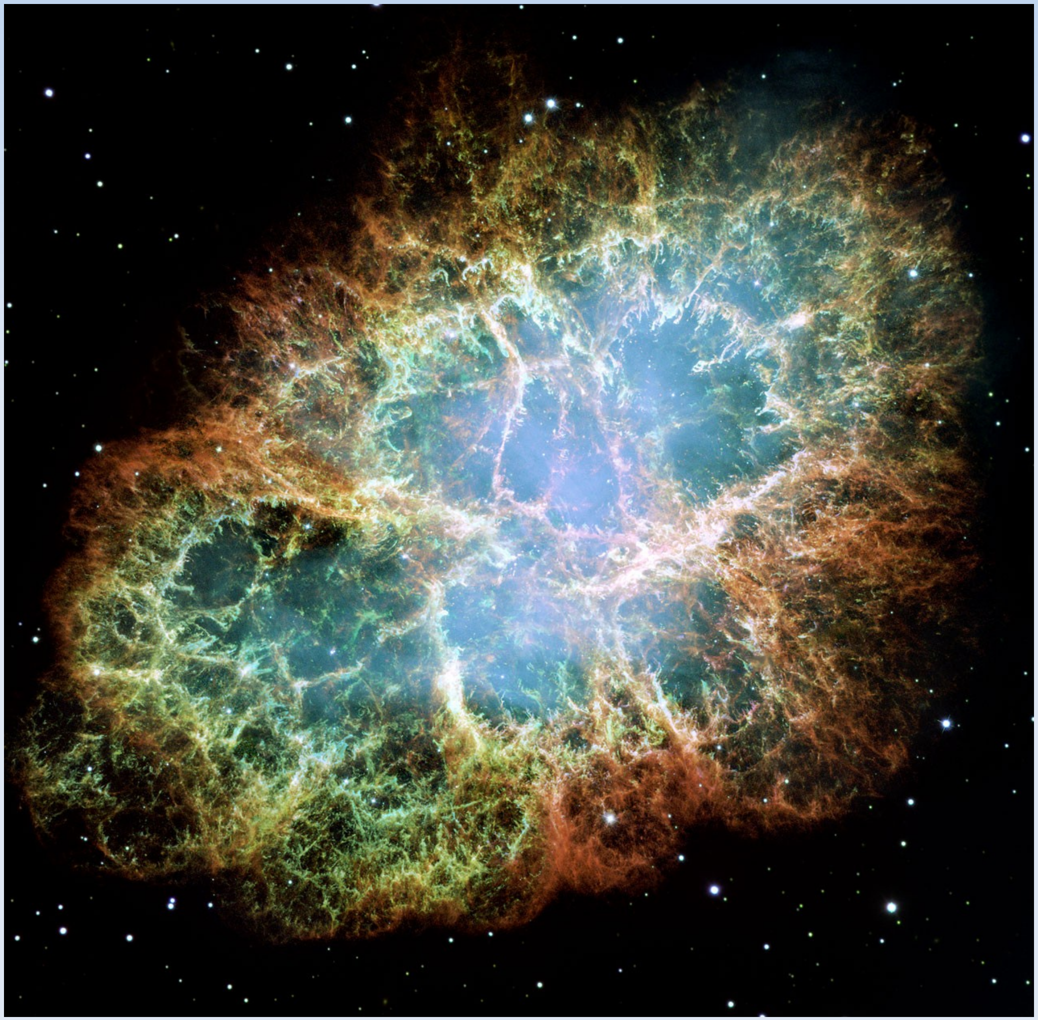
Types of objects we're looking for:

Quasars: a supermassive black hole in the center of a distant galaxy holds a disk of matter near it. Some of the matter falls in but most is accelerated in jets coming out of the galaxy.

In these jets particles can be accelerated to very high energies. We don't actually know yet how high the particles' energies can get!



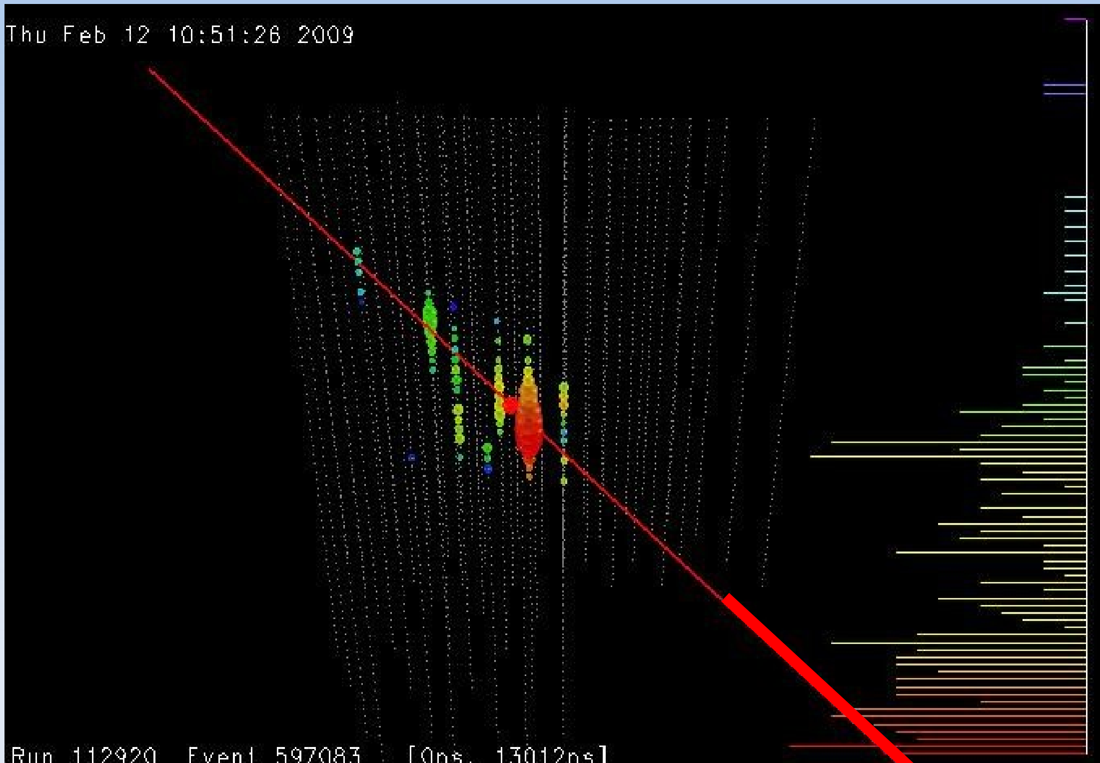




More types of objects we're looking for:

Supernovas or supernova remnants. When a star dies in a supernova its core turns into a giant mass of neutrons (emitting many neutrinos) and its outer shell is blasted off into space, making a nebula.

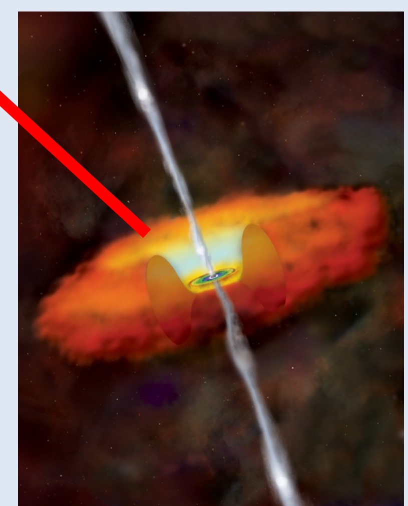
IceCube is also designed to see particles accelerated as the nebula expands into space.



So if neutrinos point back to where they were made, you

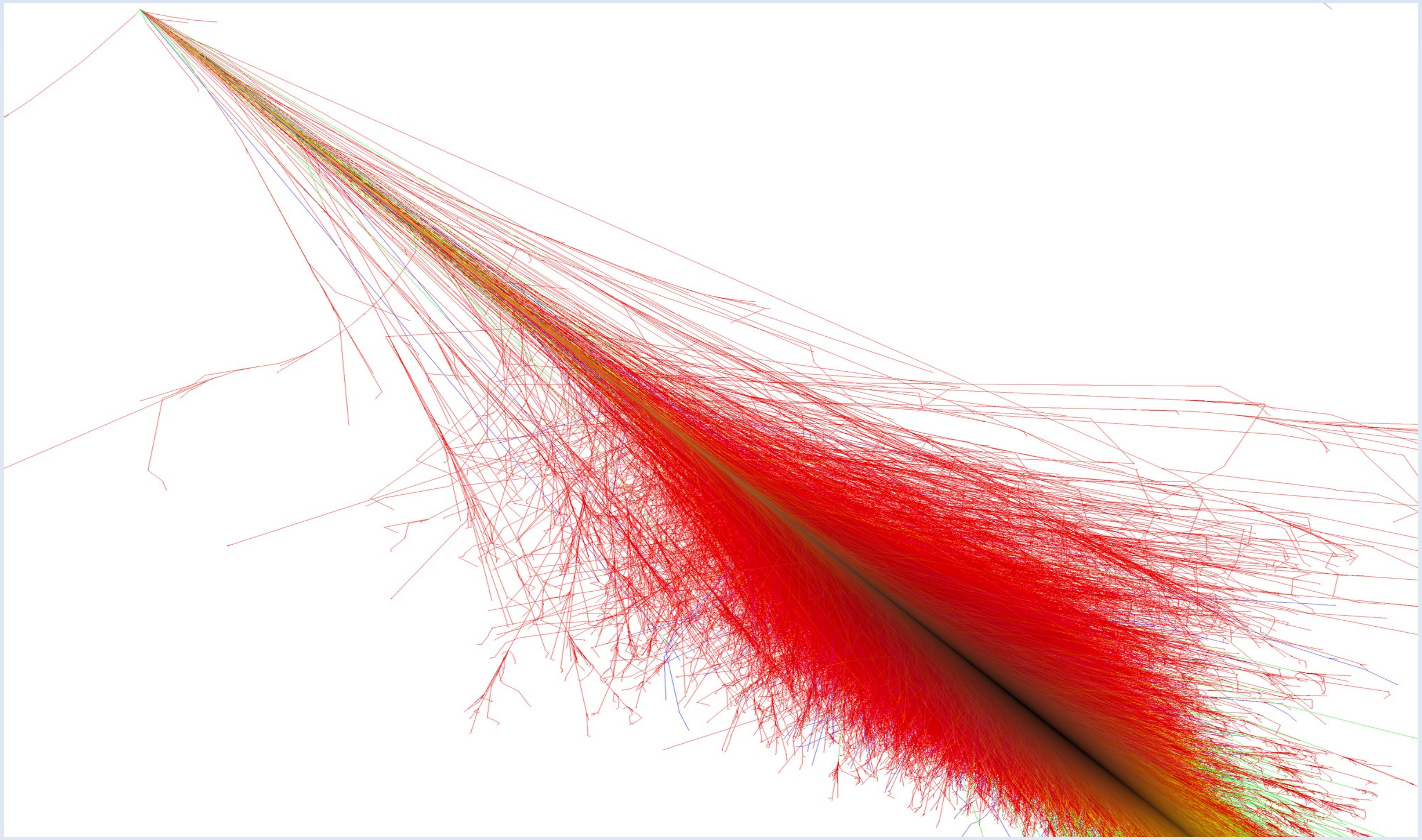
1) find a neutrino,
2) track it back, and
3) say SCIENCE!!!

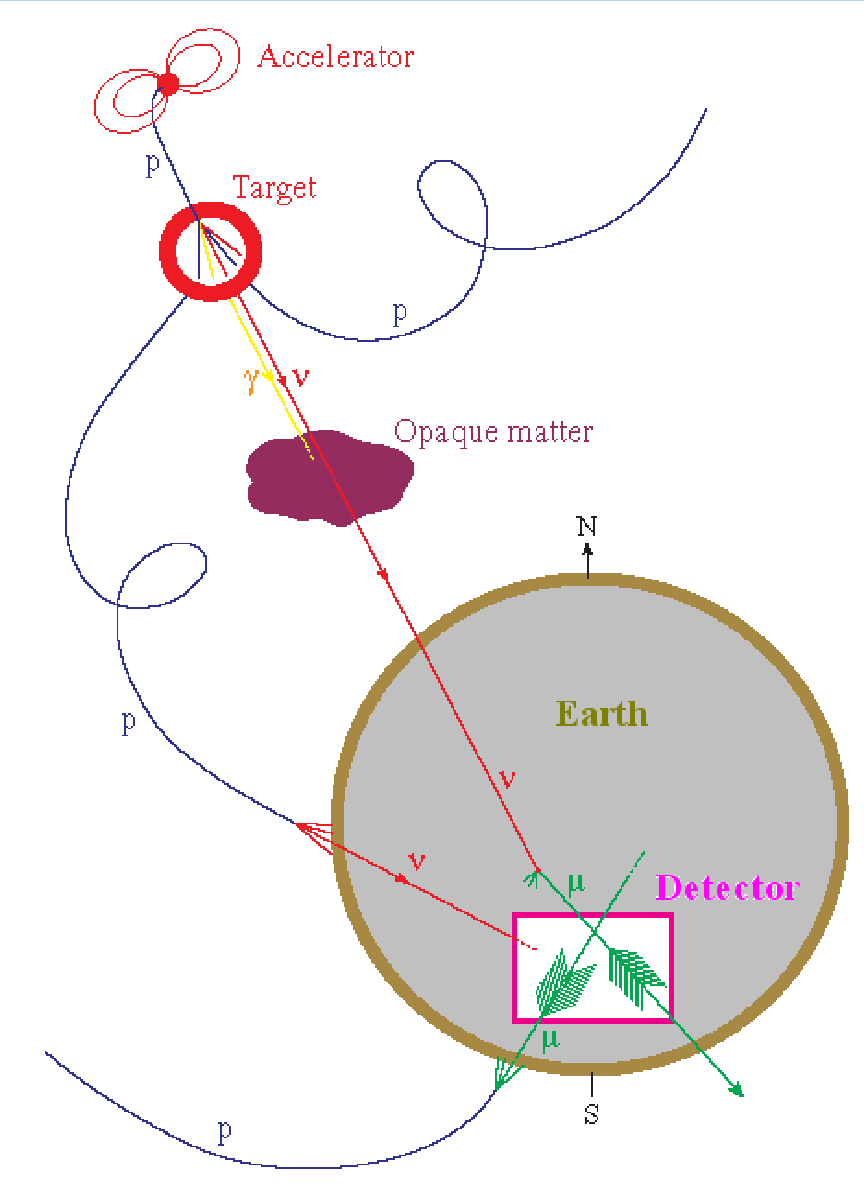
Right?



Most of the particles we see in IceCube are downgoing and created when Cosmic Rays (high energy nuclei travelling through space) collide with atoms in our atmosphere.

We see about 2,000 of these muons per second (1% are mis-reconstructed as up-going), and a muon created by a neutrino only every ten minutes.

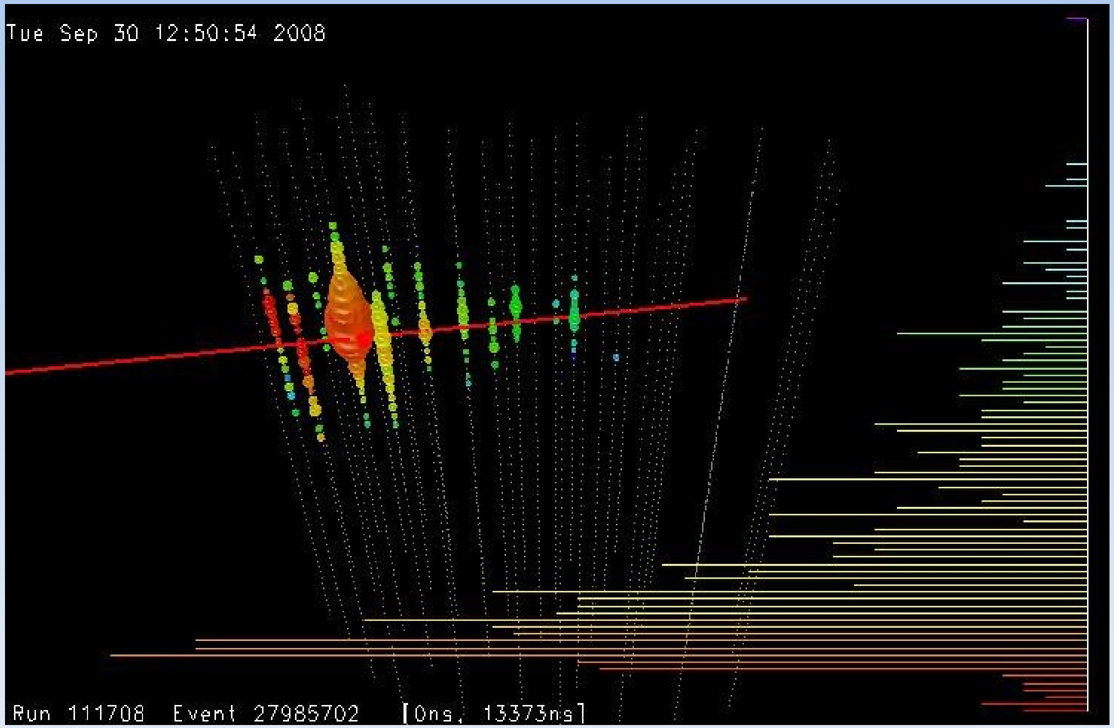


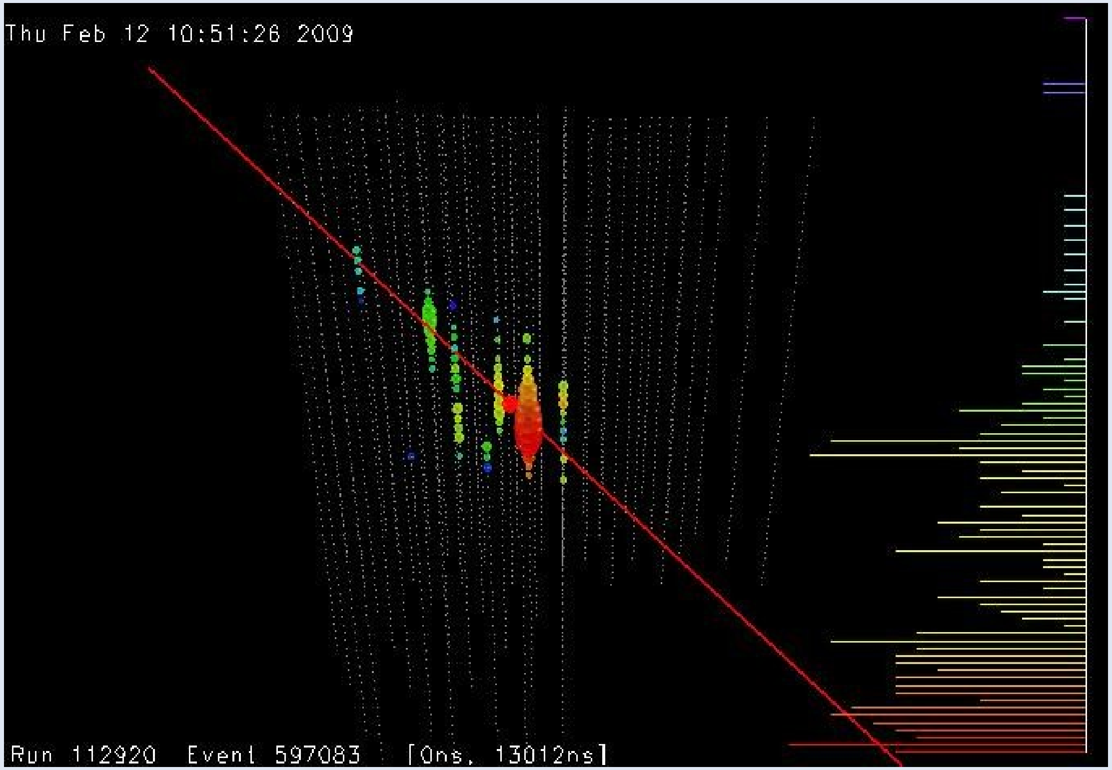


EVEN WORSE:

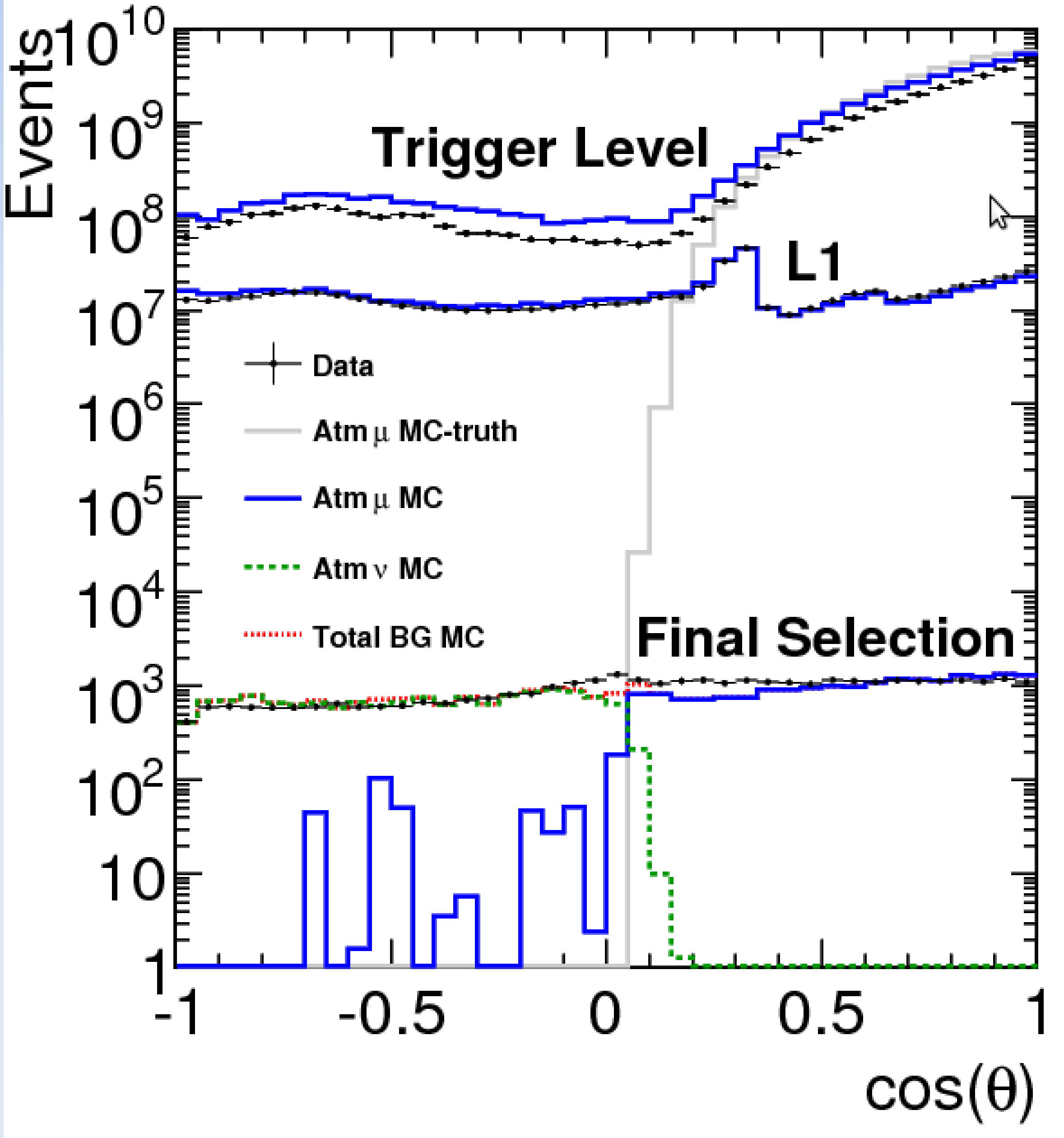
Whenever a cosmic ray hits the atmosphere and creates a muon, it also creates a muon neutrino. The neutrinos we see coming up through the Earth so far are compatible with only being from these atmospheric neutrinos.

They represent an irreducible background for point source analyses. :(





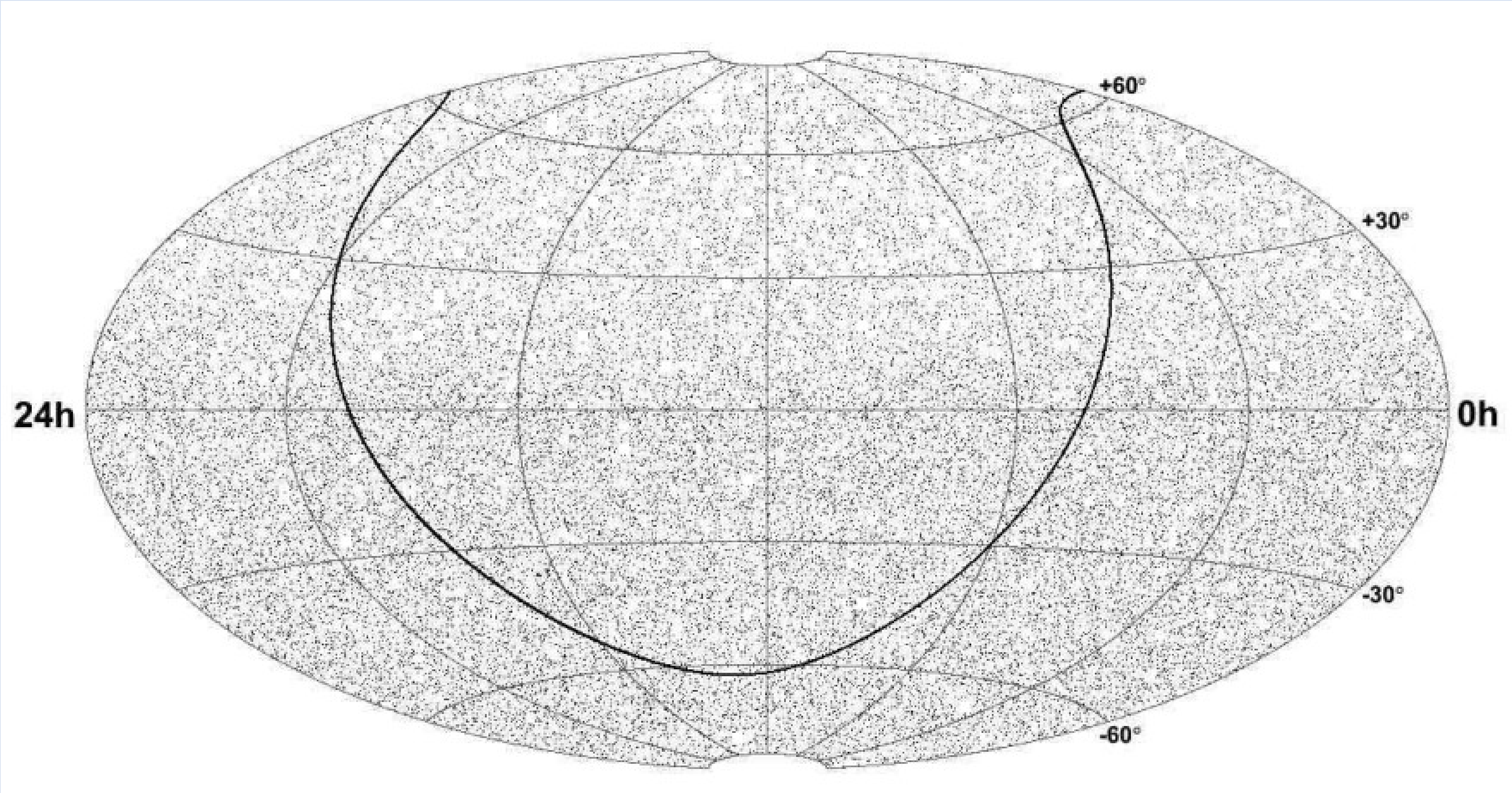
Since we see so many more events going down, we need to run tests to sort out the events which actually are upgoing instead of downgoing events which got a bad reconstruction. We also use events which are downgoing which have very high energies.



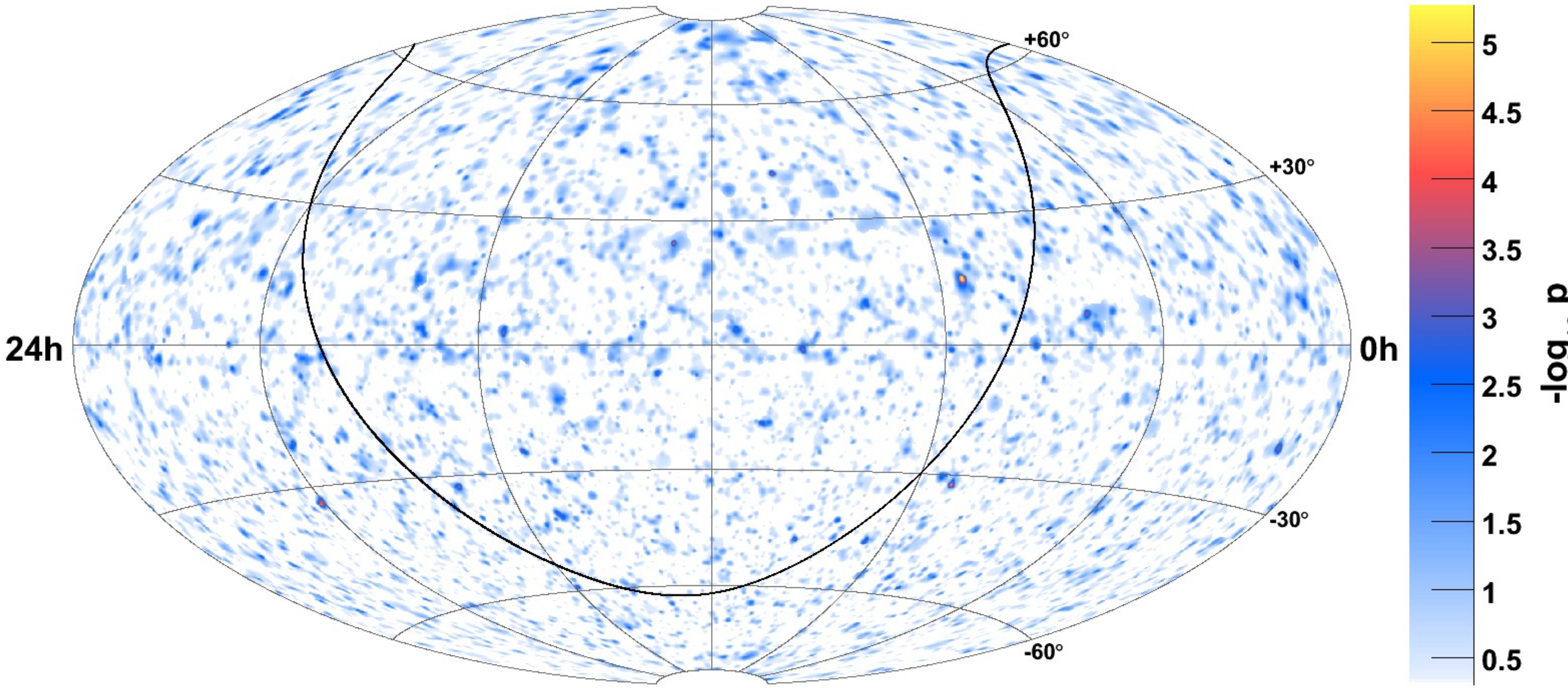
This is everything that triggers IceCube.

This is what we keep for point source analysis

We do reconstructions on our events, and put them together as an event sample, which we use to test different hypotheses. Each dot on this map represents a particle seen by IceCube.



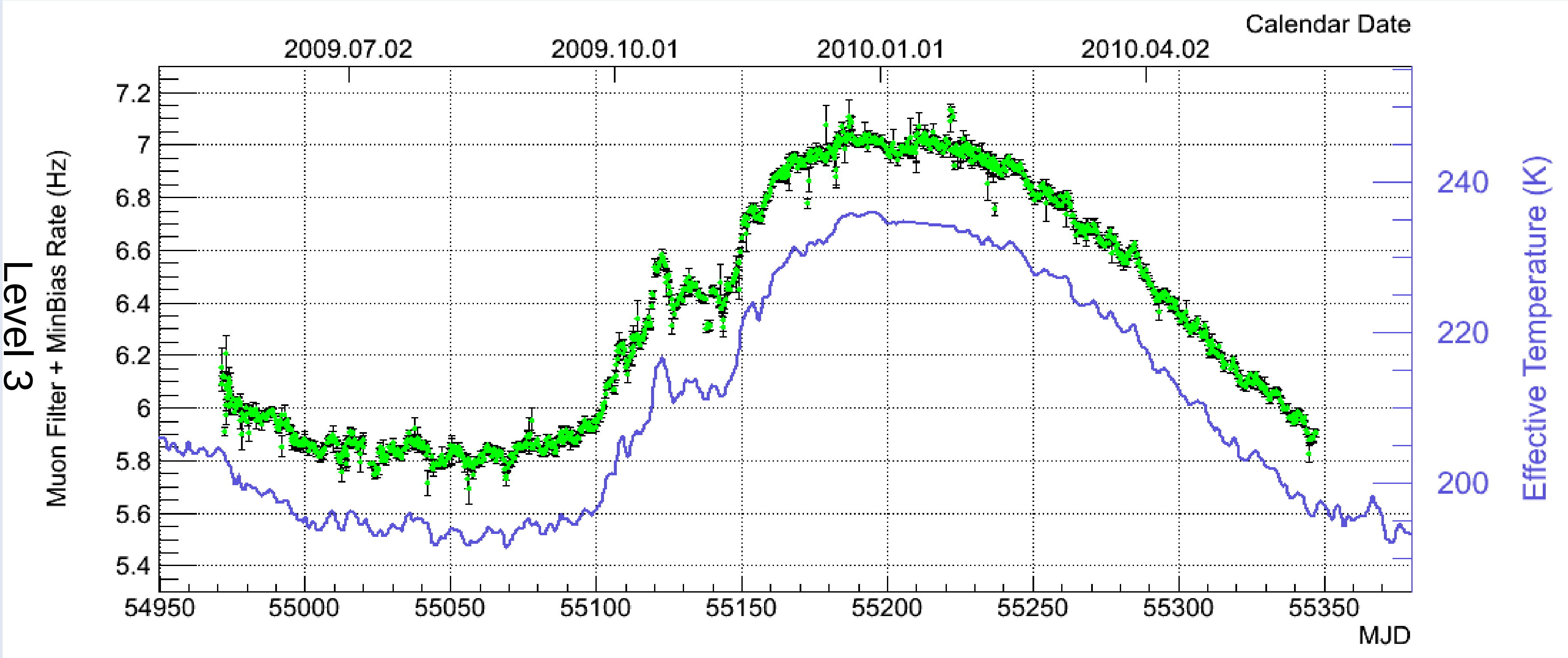
Here is what the sky looks like in neutrinos with half the detector deployed. Unfortunately nothing stands out. We didn't see anything that was proof of neutrinos coming from an object in space.

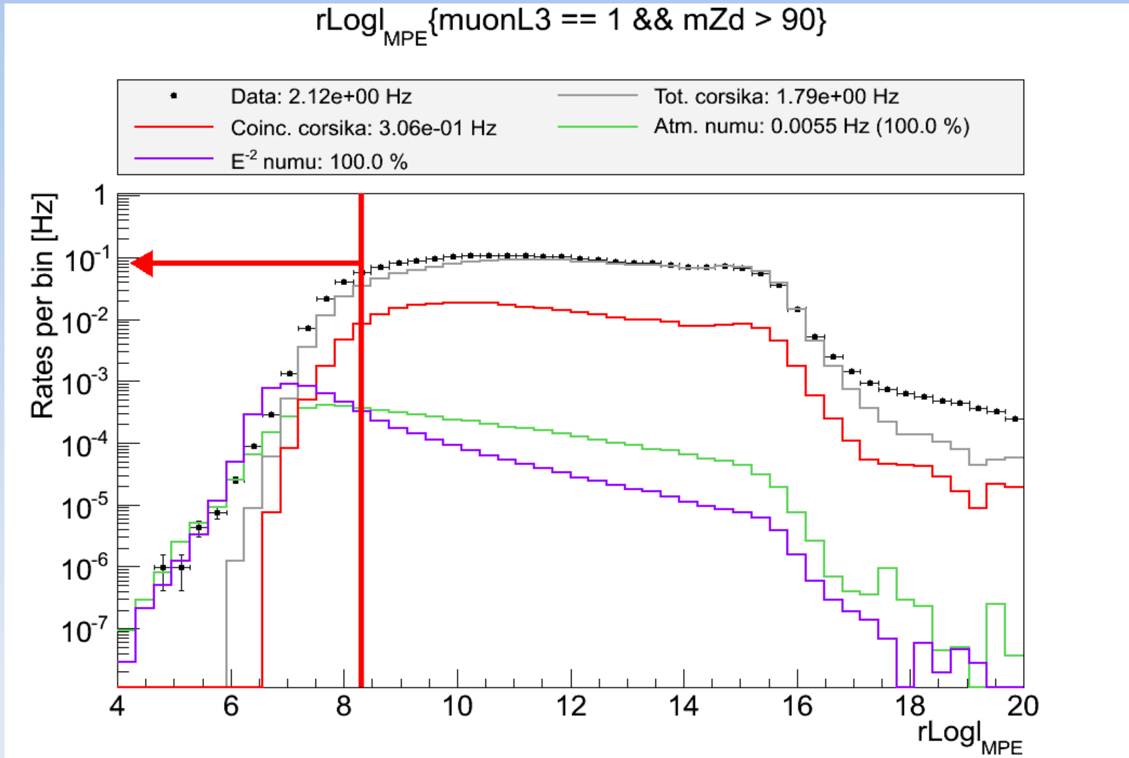


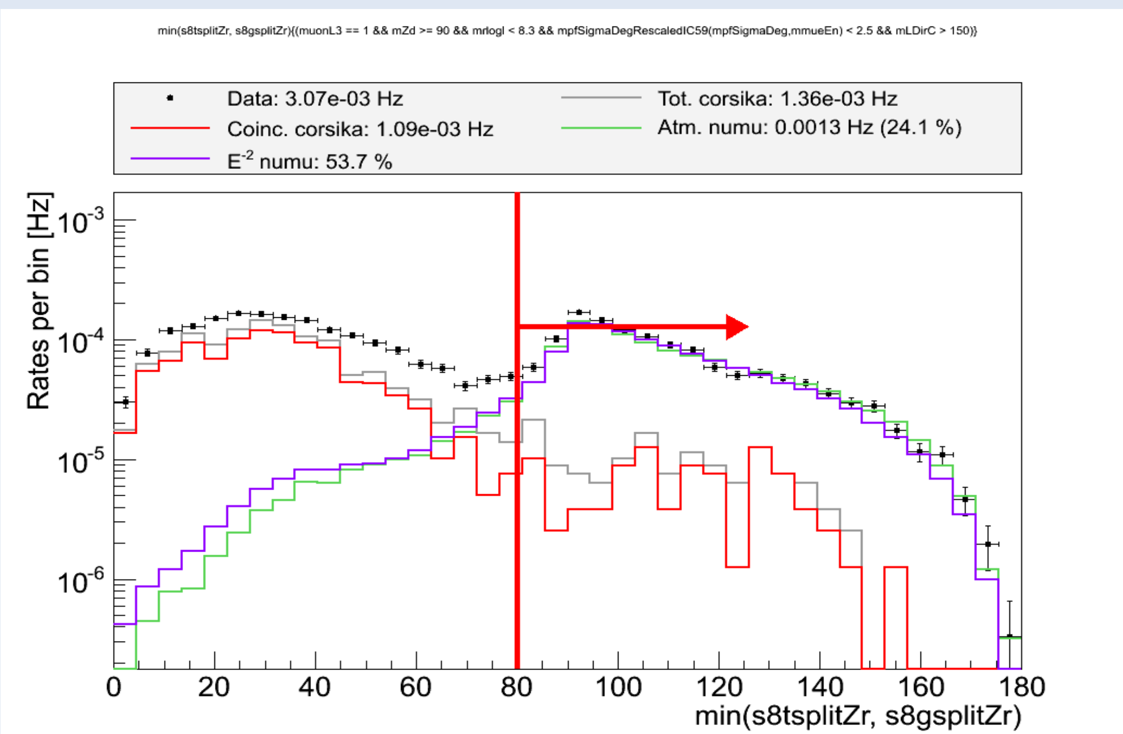
IC59 Data Sample

- May 20, 2009 to May 31, 2010
- 348 days of livetime out of 375 days running
- 93% of data used in analysis

For comparison, IC40 had 375 days of livetime with 92% of data used in analysis.







We get to the final event level by cutting on things like the track quality (top) and reconstructions splitting up the events (bottom).

Likelihood Method!

$$L(\mathbf{x}_s, \gamma, n_s) = \prod P_i(|\mathbf{x}_i - \mathbf{x}_s|, E_i, \gamma, n_s)$$

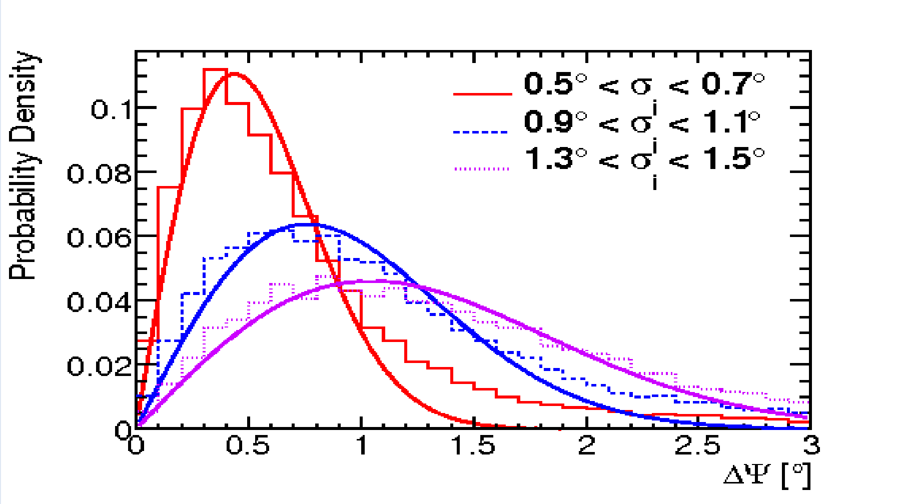
Likelihood Function

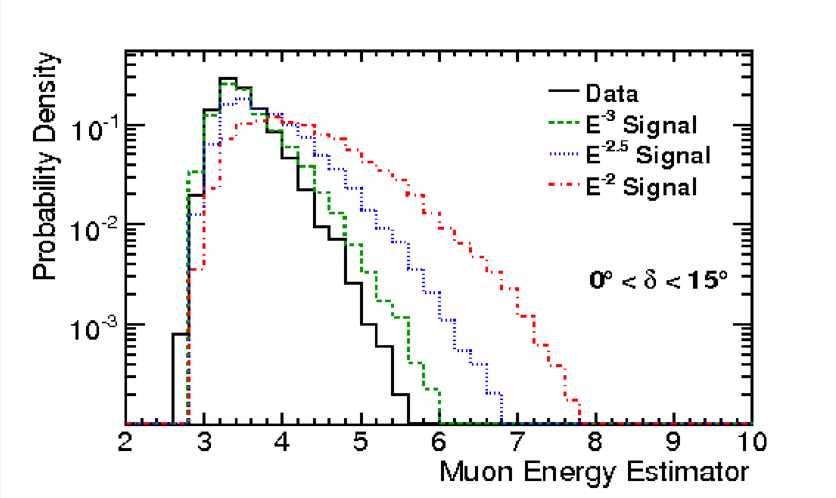
Individual event probability

$$P_i(|\mathbf{x}_i - \mathbf{x}_s|, E_i, \gamma, n_s) = \frac{n_s}{n_{\text{tot}}} S_i(|\mathbf{x}_i - \mathbf{x}_s|, E_i, \gamma) + \left(1 - \frac{n_s}{n_{\text{tot}}}\right) B(\mathbf{x}_i, E_i)$$

Background PDF
from scrambled data:

$$B(\mathbf{x}_i, E_i) = P_{BkgDec}(\mathbf{x}_i)\, P_{BkgMue}(\delta_i, E_i)$$



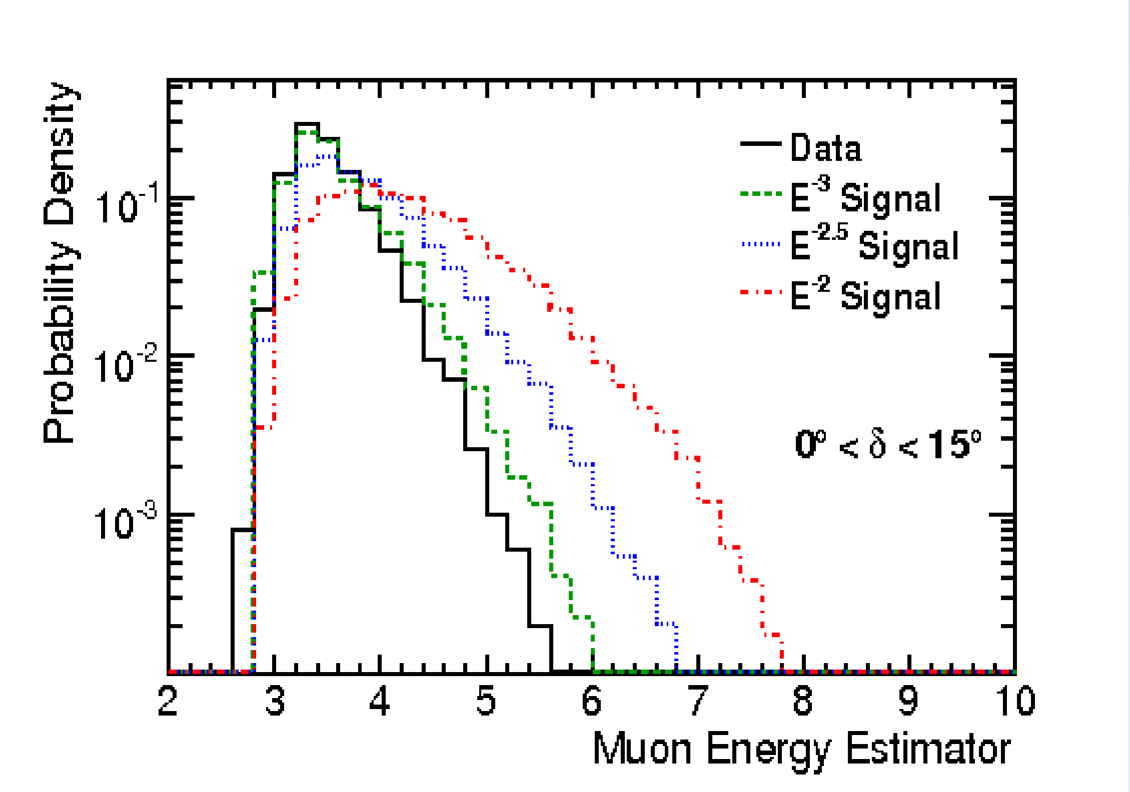


J. Braun et al. Astrop. Phys. 33 (2010) 175.;

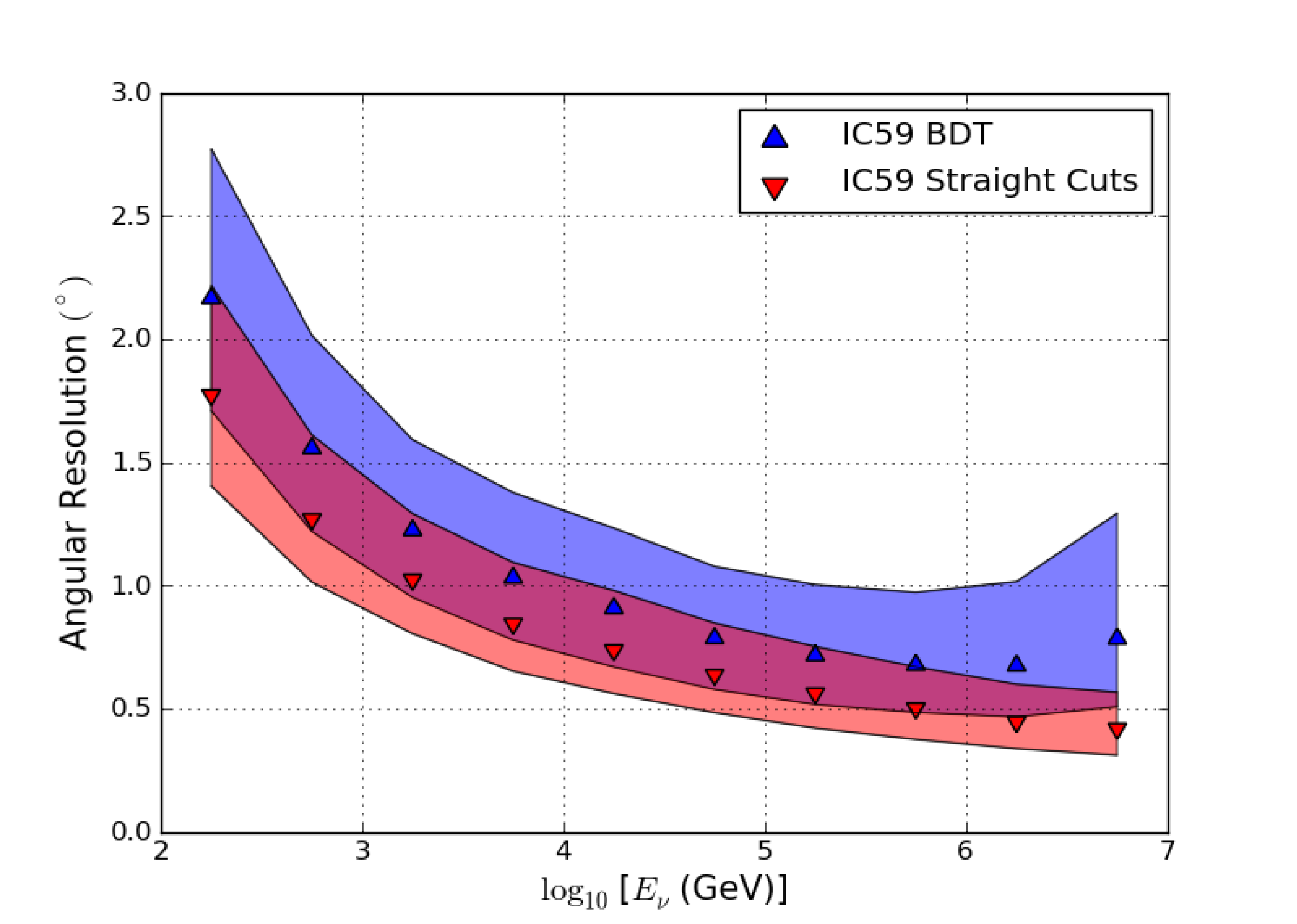
J. Braun et al. Astropart. Phys. 29 (2008) 299 and arXiv:0801.1604

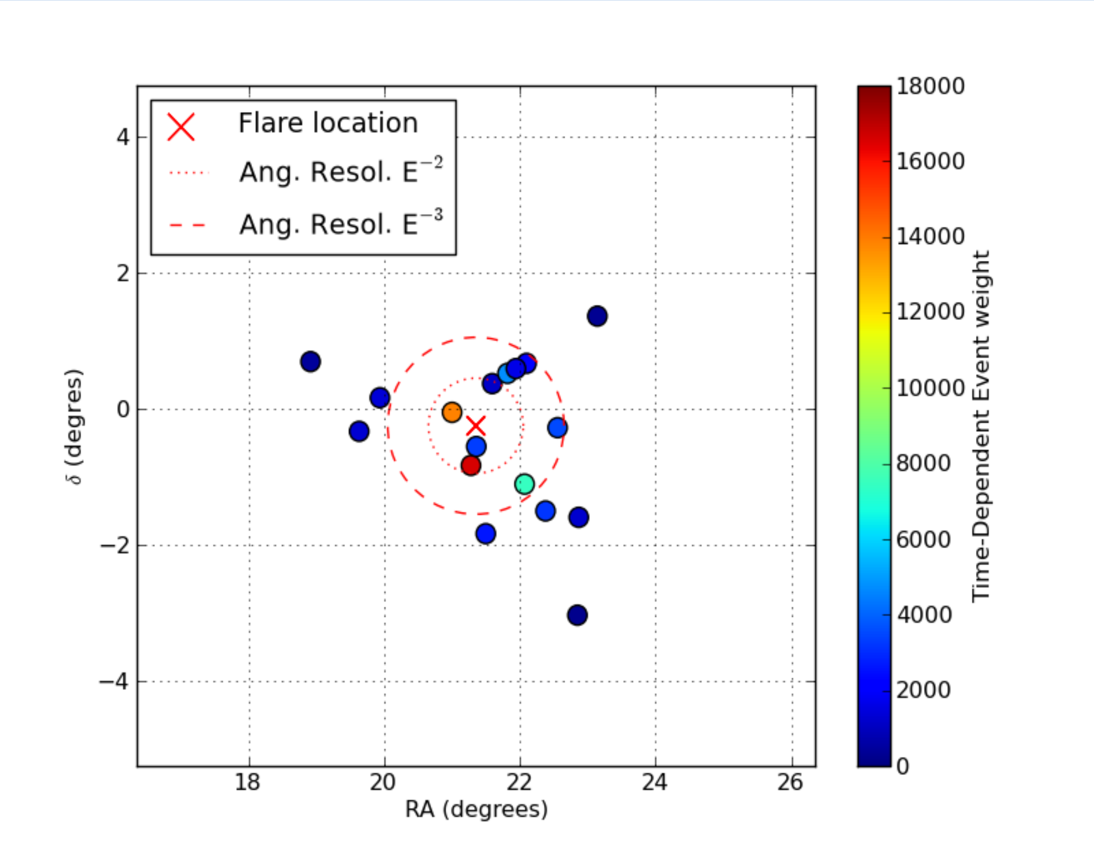
The atmospheric neutrinos have a characteristic energy spectrum, most events are between 1 and 10 TeV.

We expect astrophysical sources to have different characteristic spectra, so we expect more events above 30 TeV. This has a big improvement on the discovery potential.



The angular resolution depends on the energy of the event, it also depends on what cuts you use to get to the final sample.





Each event gets an estimate of the reconstruction error. Events we select typically have an error of less than 1 deg.

The plot shows the ratios of the signal-ness to the background-ness of several interesting events.

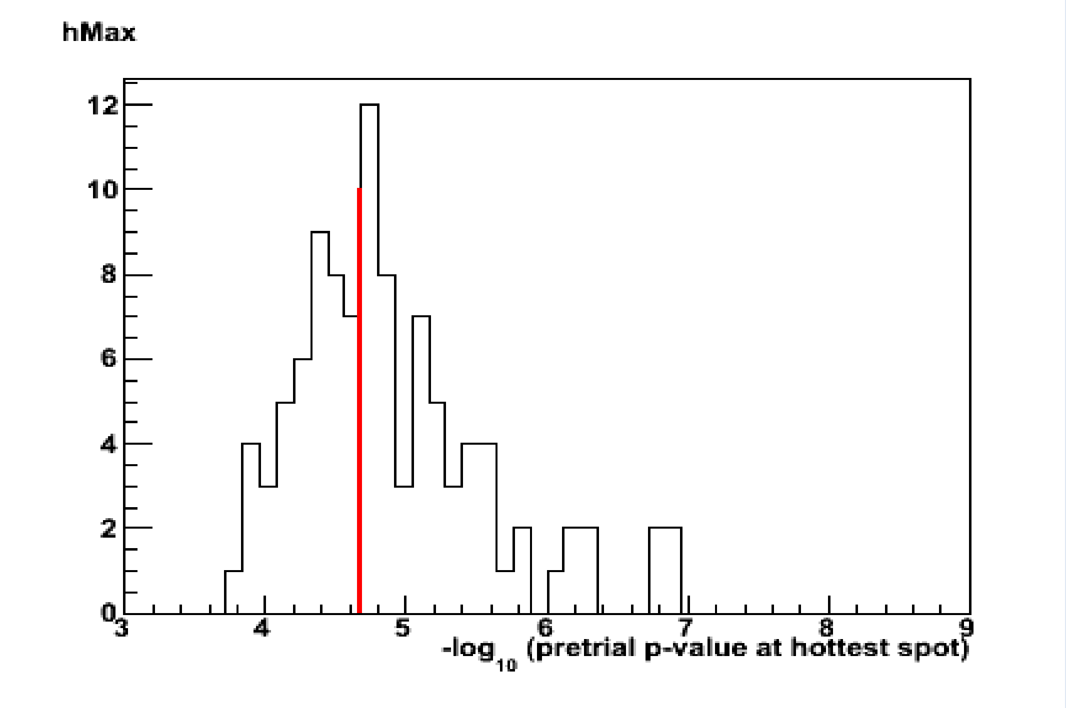
We use a method to estimate how many events over background and how signal-like those events are to get a p-value.

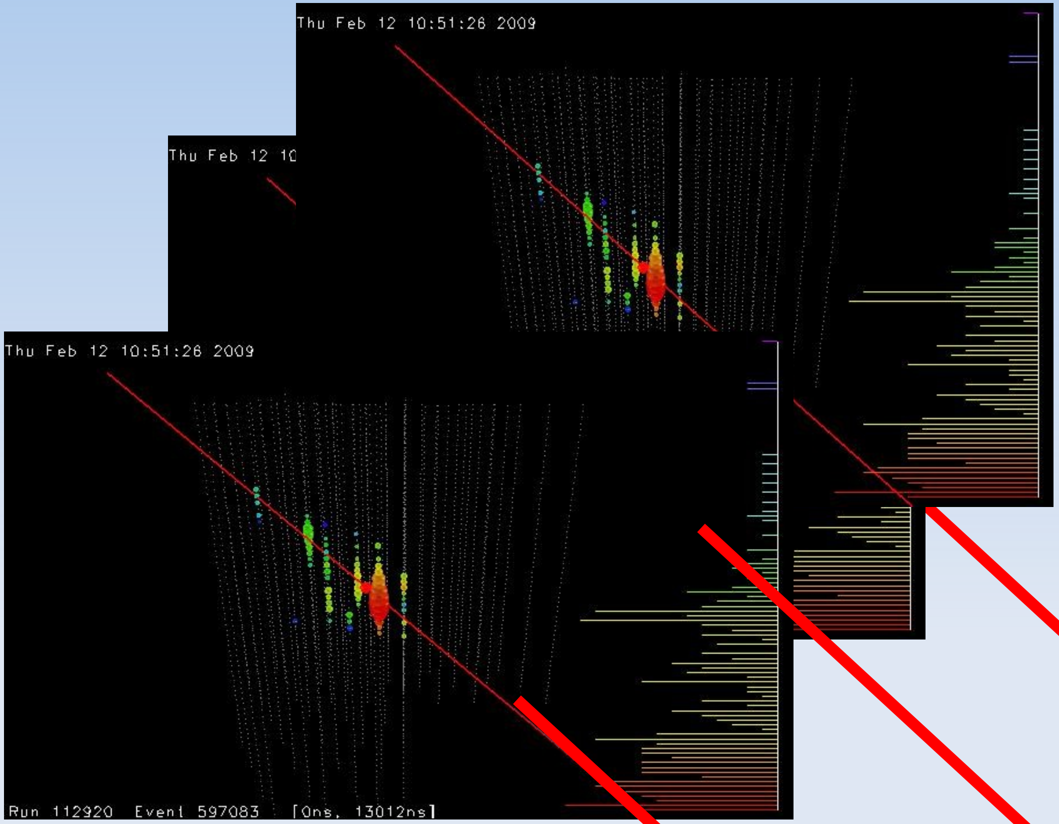
$$P_i(|\mathbf{x}_i - \mathbf{x}_s|, E_i, \gamma, n_s) = \frac{n_s}{n_{\text{tot}}} S_i(|\mathbf{x}_i - \mathbf{x}_s|, E_i, \gamma) + \left(1 - \frac{n_s}{n_{\text{tot}}}\right) B(\mathbf{x}_i, E_i)$$

The p-value is calculated by taking the data, scrambling it in time and right ascension to get a sample which has no real correlations. The p-value is the fraction of scrambled datasets which get a more signal-like result.

We say we will only claim a detection is for 5σ confidence level (p=2.87e-7)

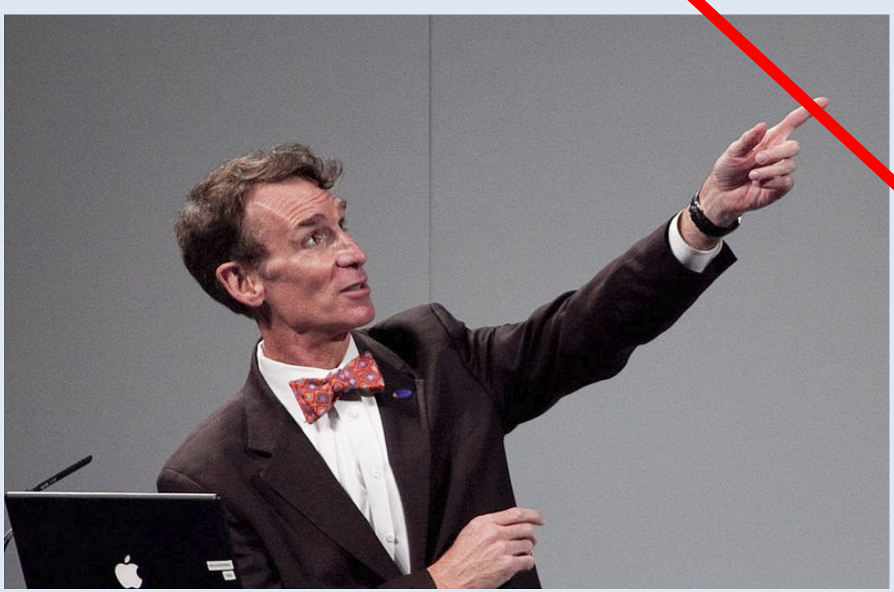
We say our upper limit is what we need inject to a scrambled map to get a better p-value than we saw in data 90% of the times you try.

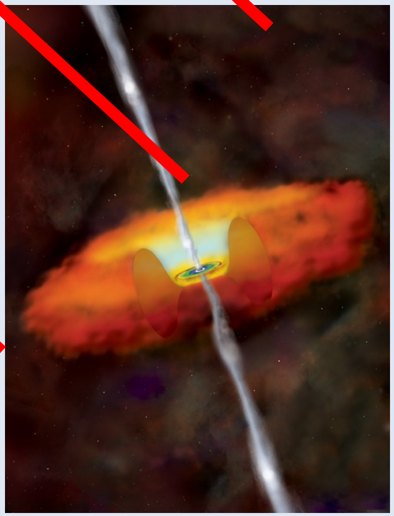




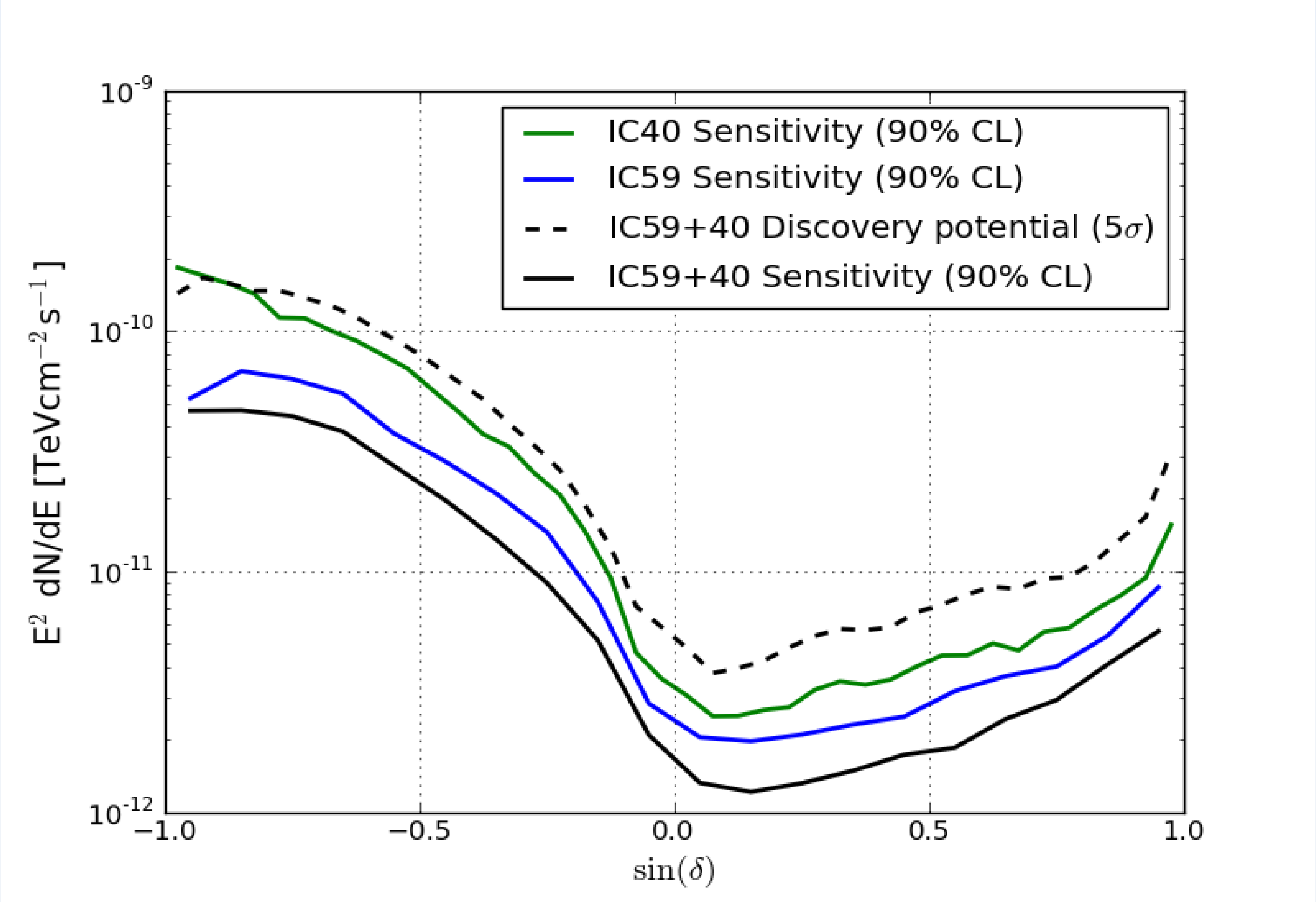
So what we really are trying to do is:

1) find 10-20 neutrinos,
2) track them back to the same point on the sky, and
3) say SCIENCE!!!





Here's an idea of what the power of the analysis looks like. Sources with a flux above the solid black line will look warm, those with a flux above the dotted line ought to be detected.



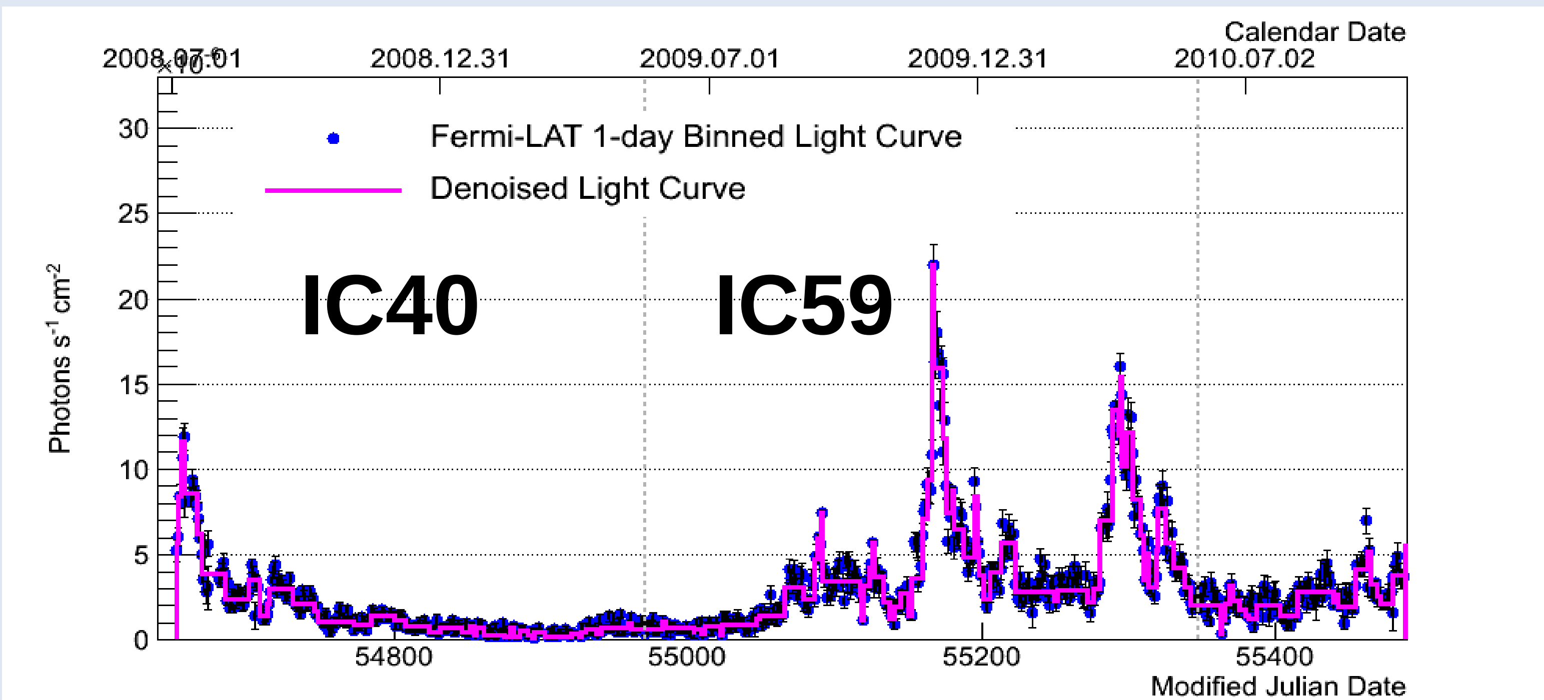
There are ways to try to do better:

Use time information of events and sources,
Look for events from multiple expected sources,

Time-dependent analyses

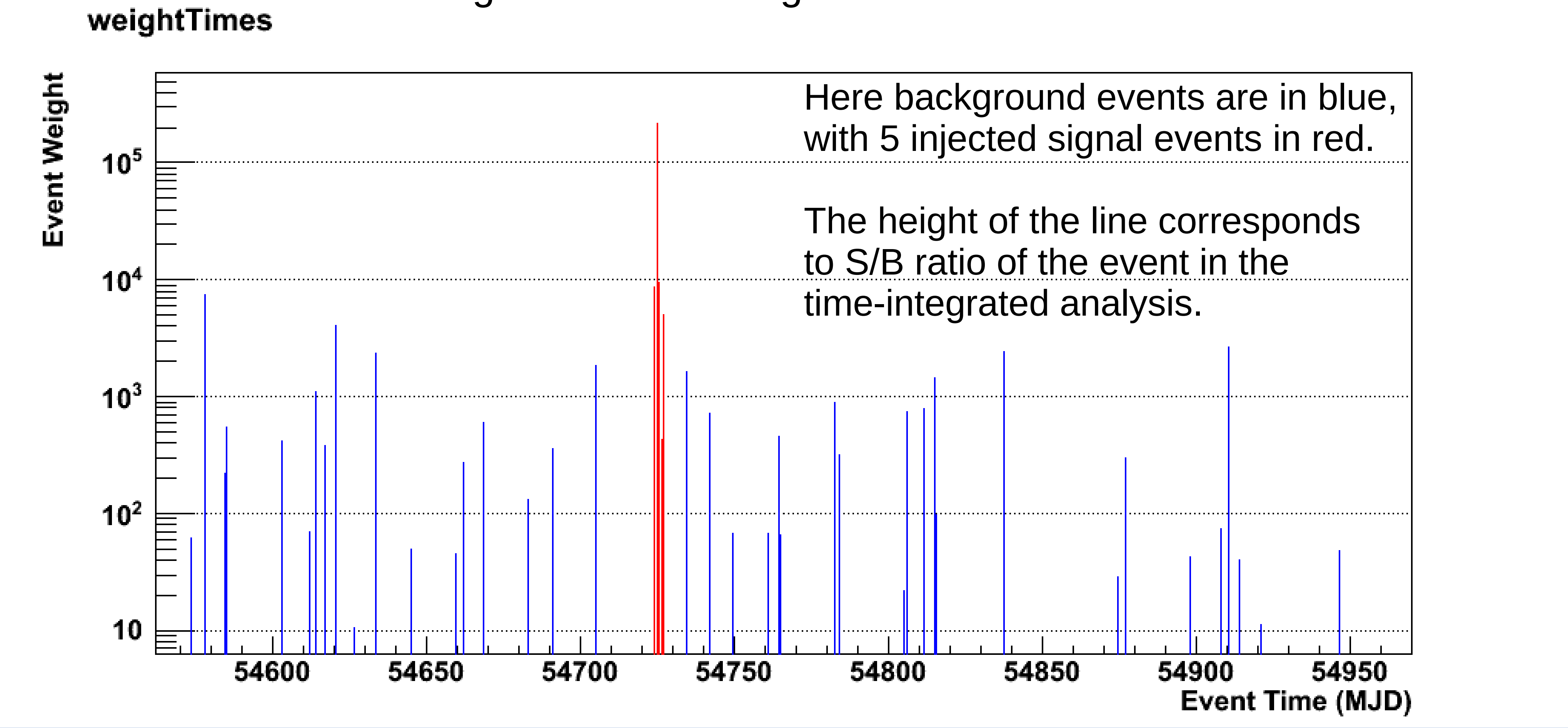
As in IC40, we propose to use lightcurves from Fermi to test for flaring behavior. The lightcurve is used to test for neutrino emission in coincidence with photon flares.

We propose to use the lightcurves from both IC40 and IC59 to test for flaring behavior from 23 sources. The blazar 3C 454.3 lightcurve is shown below.



We know of transient astrophysical phenomena with timescales of milliseconds-seconds (GRB) to minutes-days (AGN flares, SN afterglow). Observations in photons give us candidates to test for correlations in triggered searches, but these observations are not always continuous depending on the energy range tested.

We have an interest in performing a general search which covers many orders of magnitude of flare duration to find occurrences undetected or undetectable with photon emission. We fit for the best mean and sigma of a Gaussian in time to find the strongest flare from a given source location.

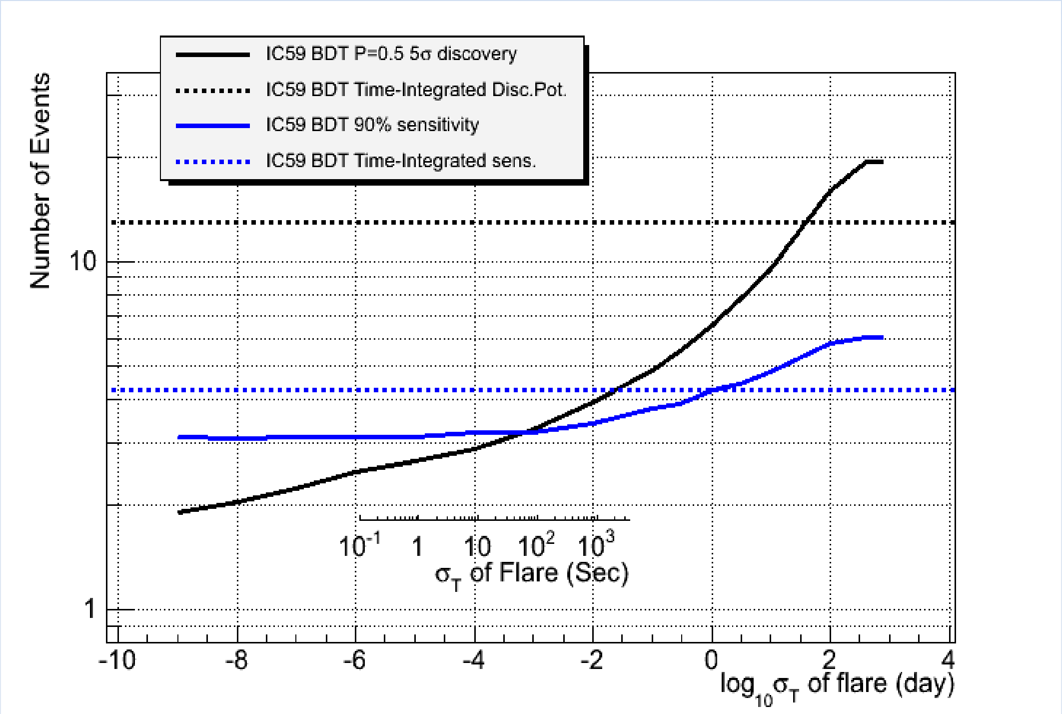


Untriggered flare search

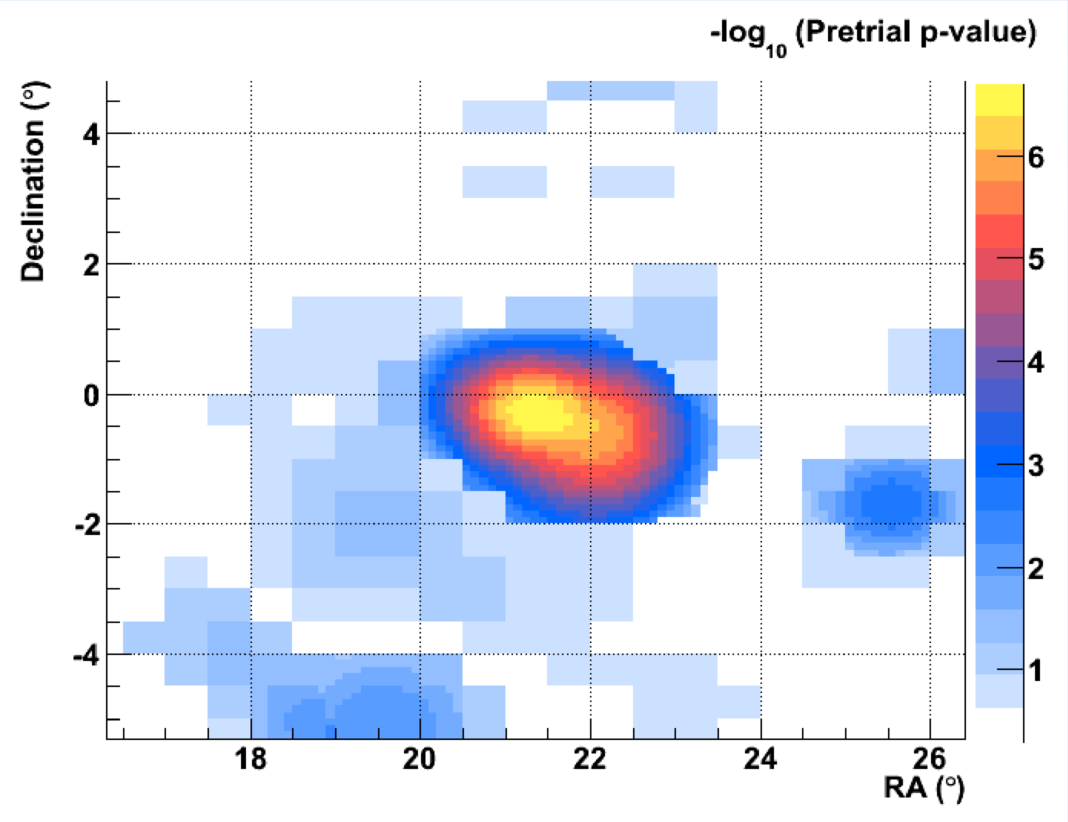
This search is not triggered by observations from other experiments, and is capable of finding clusters from GRB to AGN flare timescales.

For flares of one second this is a factor of four improvement in discovery potential with respect to the time-integrated method.

We propose to perform the search on IC59 sample only since it was already applied to IC40.



Hottest Spot



Here is a zoom-in on the warmest flare location.

The method of making the maps initially samples a 0.5x0.5 deg grid, then a fine 0.1x0.1 deg grid for locations which were overfluctuations.

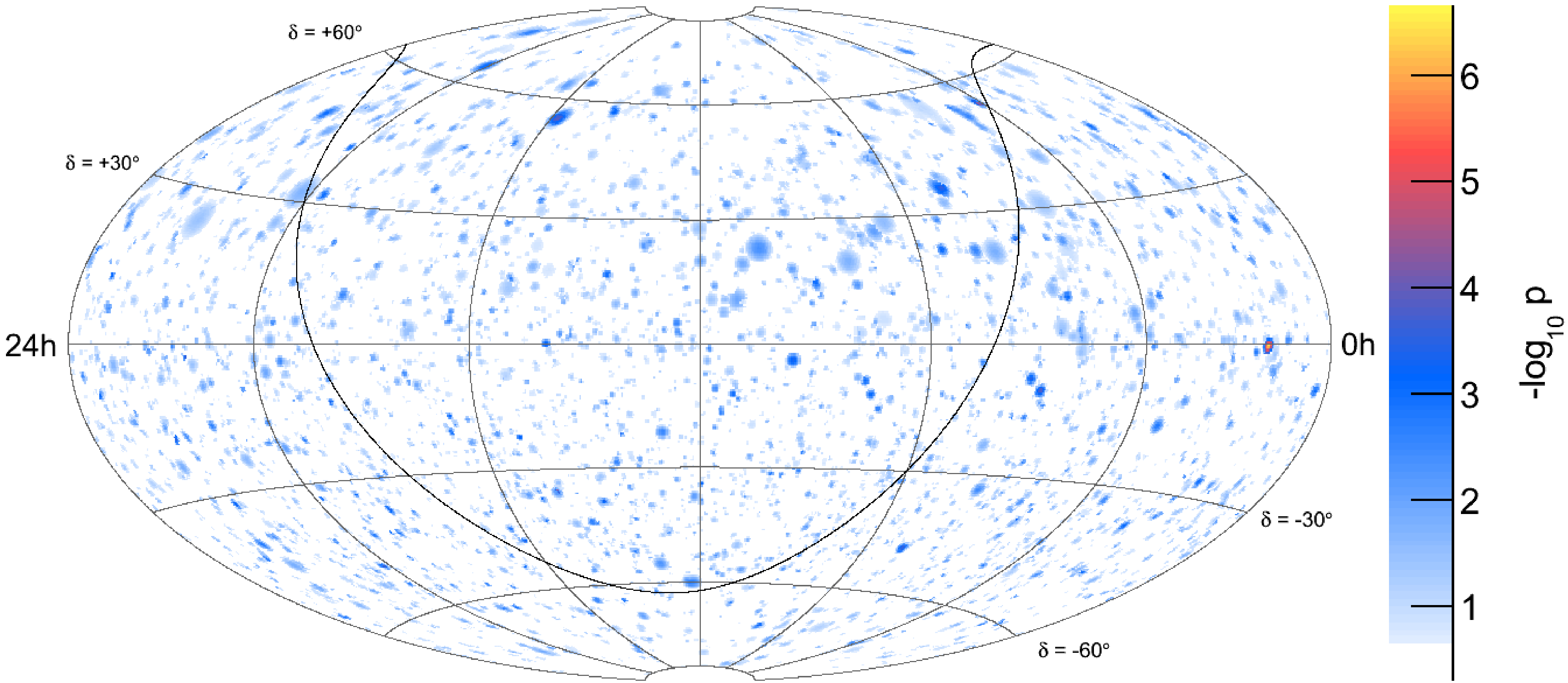
IceCube point source searches:

Look for an excess of events from a particular spot on the sky.

The excess has to come on top of an irreducible background sample at a statistically-significant level.

If you don't see a source, you can set limits on what you would have seen.

IC59 Flare Unblinded Skymap



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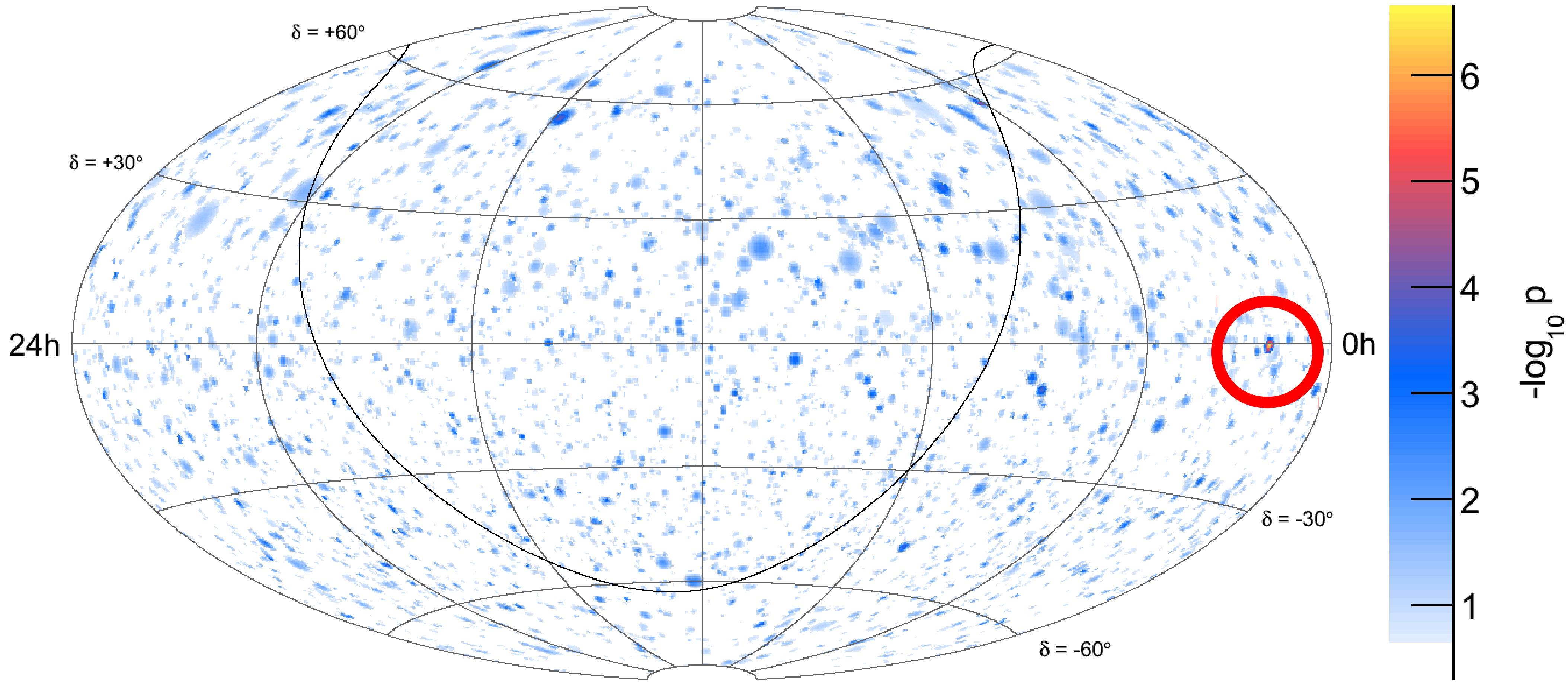
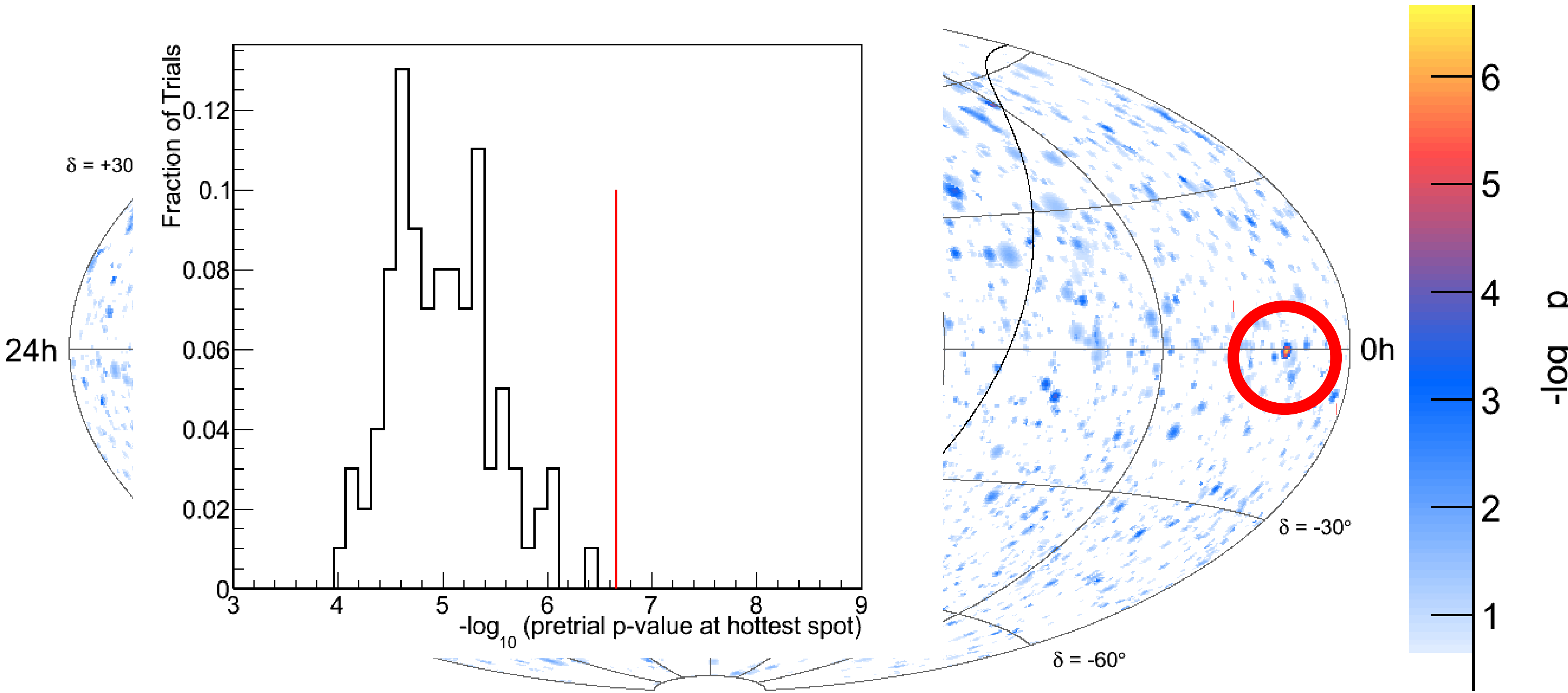


The strongest fluctuation is from RA=21.35, dec=-0.25), the method finds an excess of 14.5 events, spectrum of E^-3.9, a mean of MJD 55259 and Gaussian width of 5.5 days (or a FWHM of 13 days).

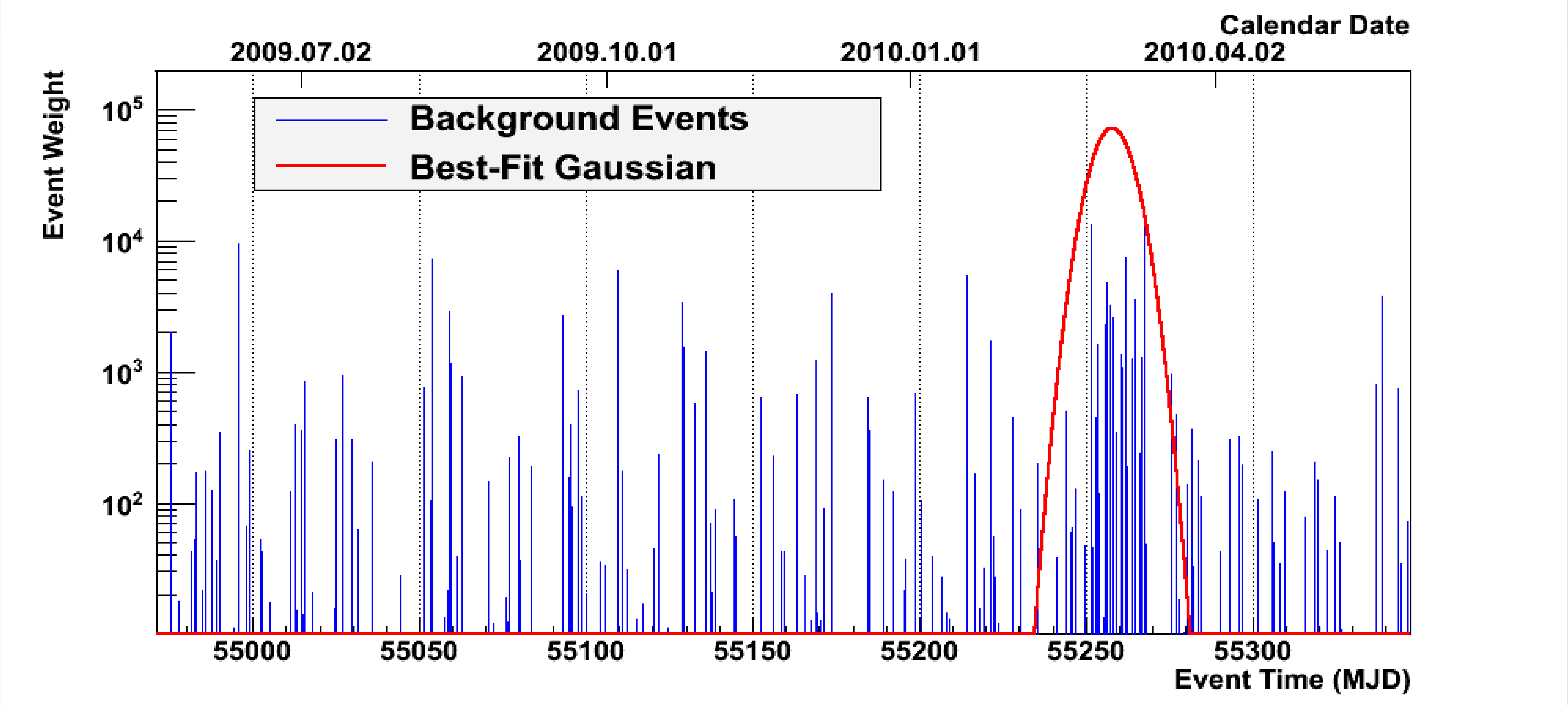
IC59 Flare Unblinded Skymap



The -log10(pretrial p-value) for data is 6.69. The skymaps take a very long time to run, and the unblinded result is more significant than the 100 scrambled skymaps generated so far, so the final p-value is likely less than 1%. More scrambled trials are on the cluster.

Here we see the time-integrated weights of the events at the strongest flare locaton.

The cluster stands out fairly well. The events are fairly low energy, and a weight of 1e4 means they are typically less than ~1deg from the spot tested.



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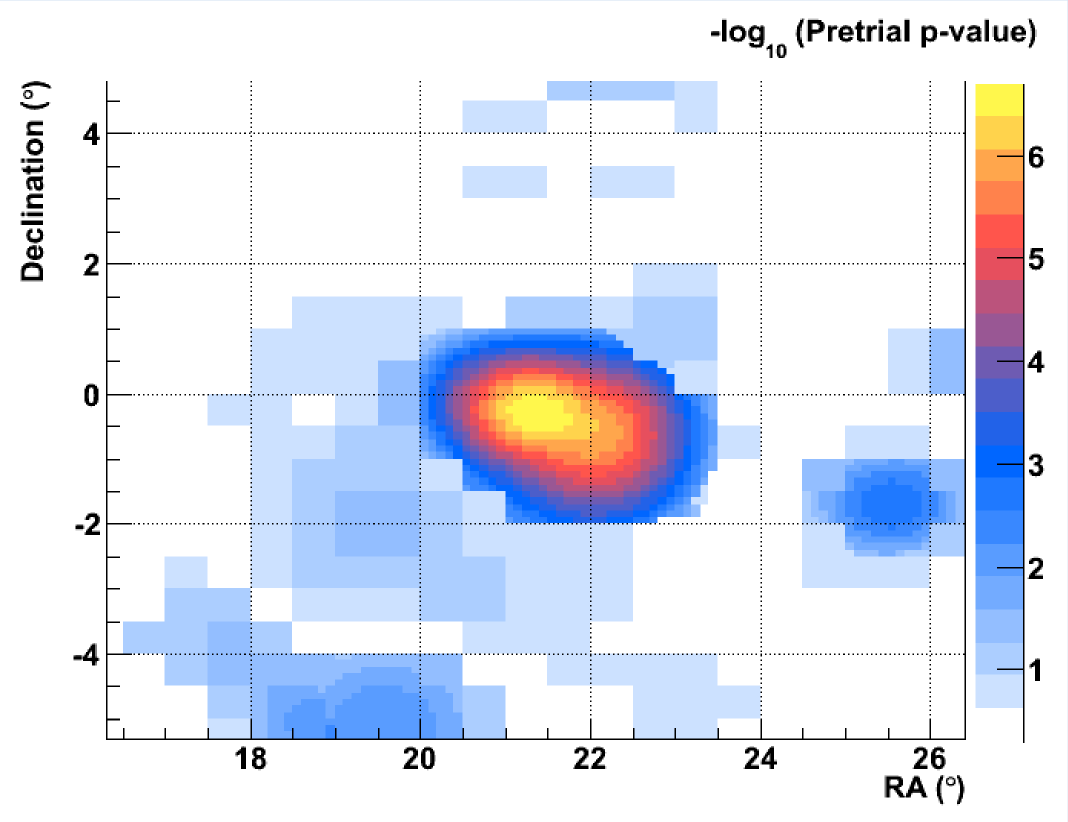

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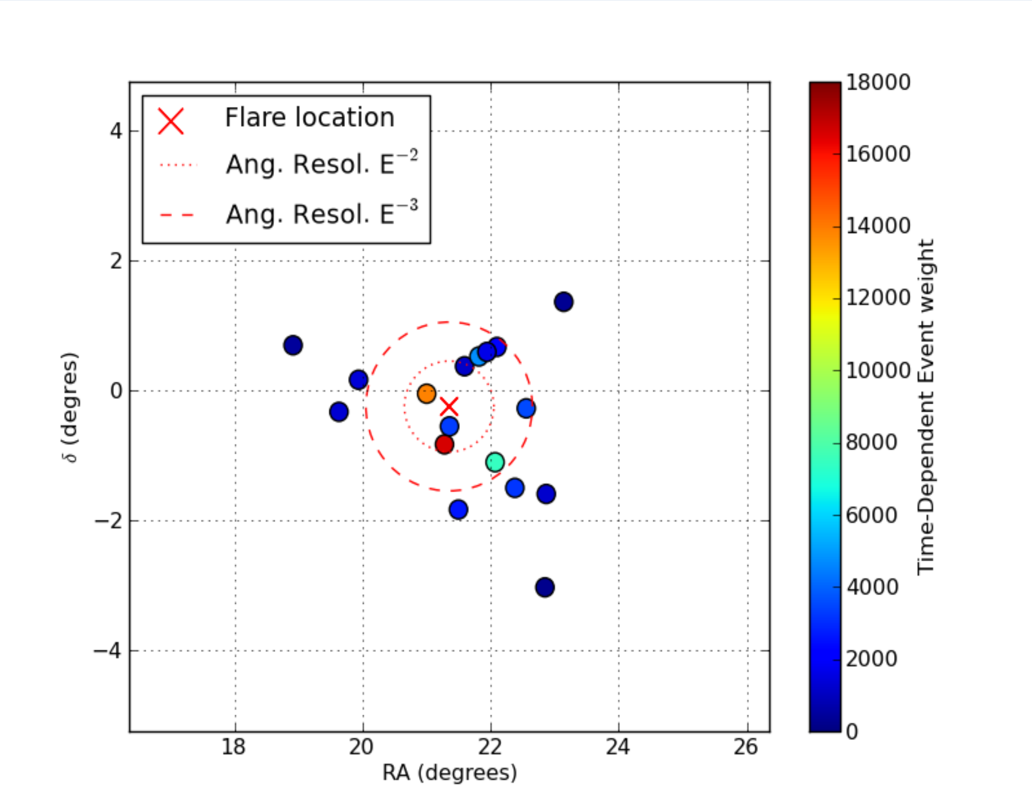
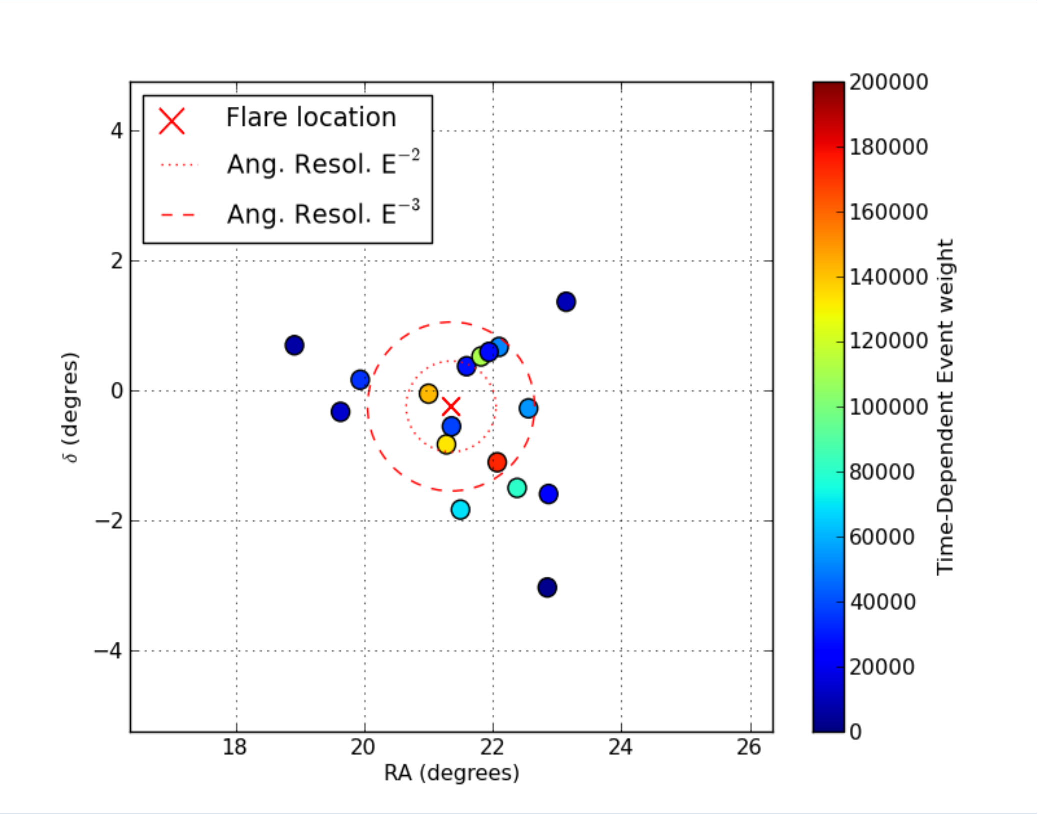
The method of making the maps initially samples a 0.5x0.5 deg grid, then a fine 0.1x0.1 deg grid for locations which were overfluctuations.

Distribution of events

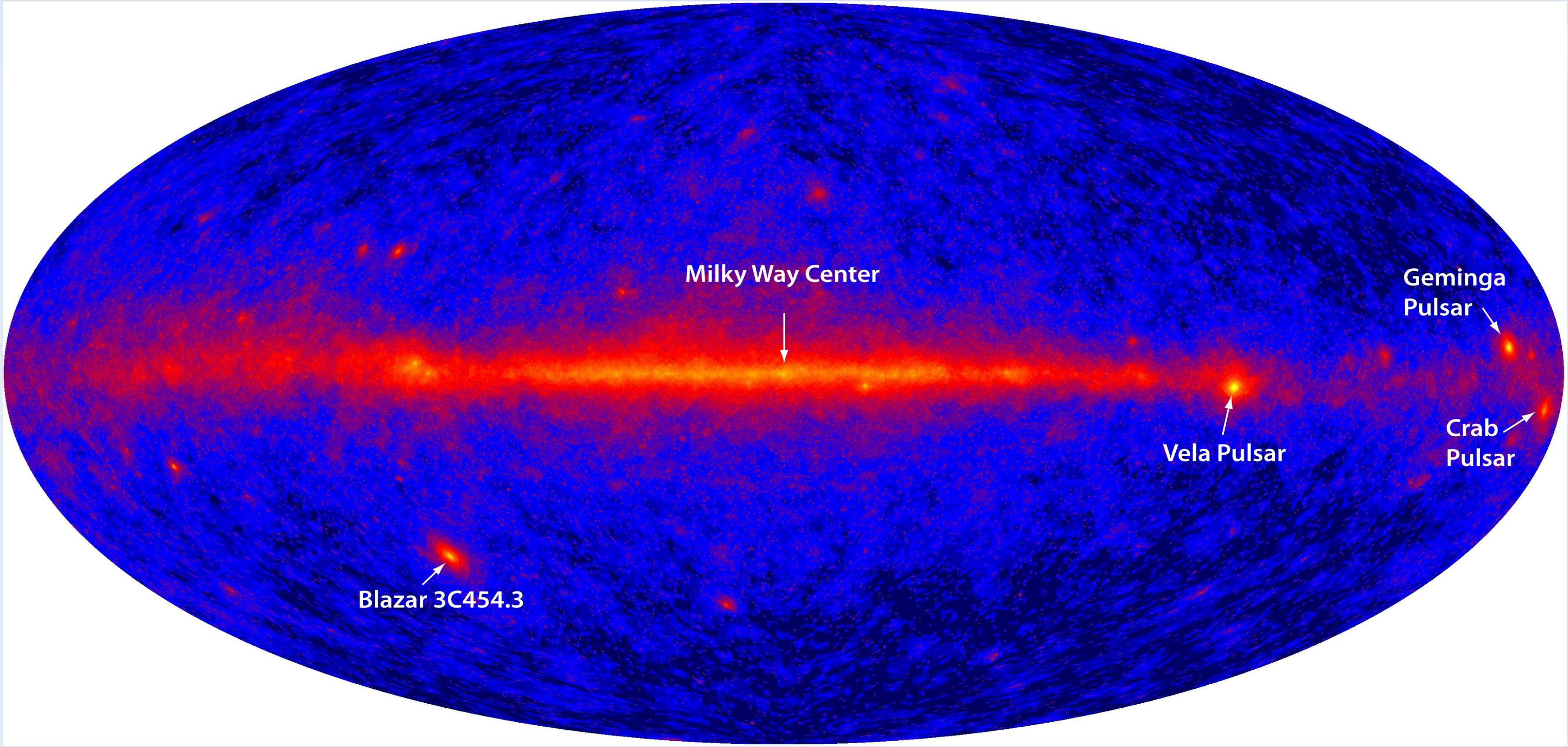
Below we have the weights with no time term (ie using space and energy only) and including the time Pdf (right). The events shown are the 19 most significant events.





The sky in gamma rays

Most of what we see is from our own galaxy, from clouds of gas and remnants of supernovae. We can also see a few quasars which have their jets pointed toward the Earth.



Local Coordinate Effects

We have the local coordinate functions for IC40 and IC59.

The effect of the 'long end' vs the 'short end' from IC40 is mostly smoothed out.

Effects from events reconstructed along lines of strings is still evident.