Recent Updates in the Search for Astrophysical Neutrino Sources using the IceCube Detector

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IceCube
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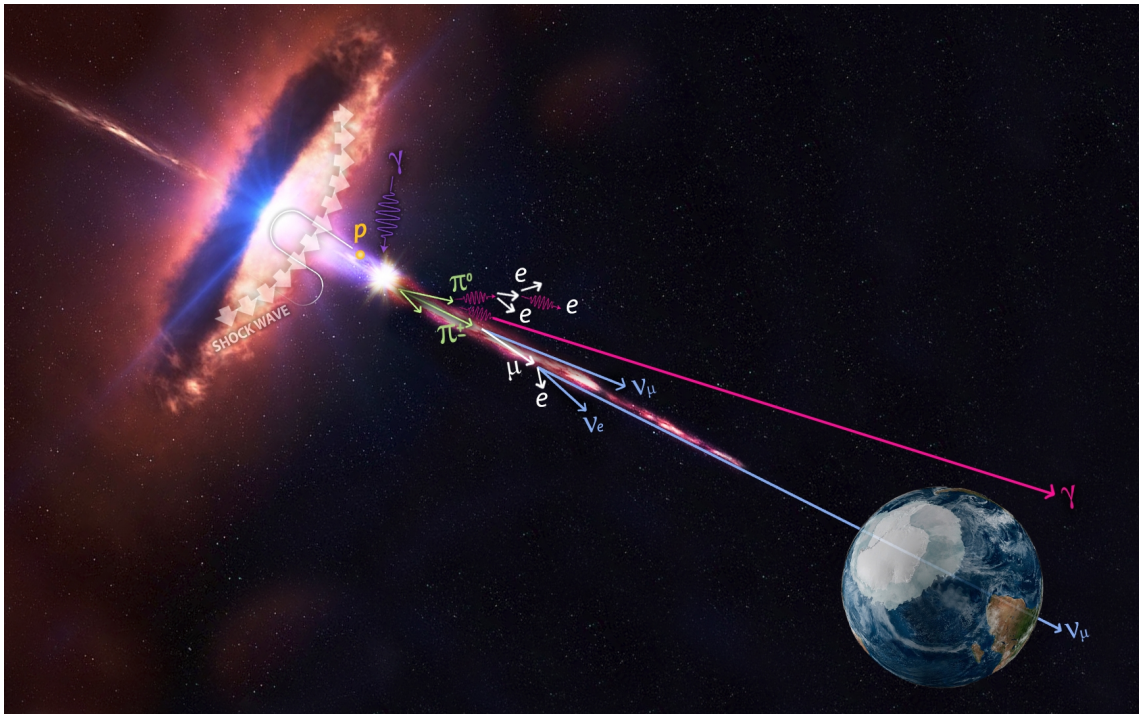
Messenger Particles

- **Protons / Cosmic Rays** : directly from the astrophysical sources.
- **Photons** : produced by CR interactions : Leptonic and Hadronic
- **Neutrinos** : produced only by Hadronic CR interactions.



Hadronic Interactions :

$$pp \Rightarrow \pi^0 \Rightarrow \gamma\,\gamma$$
$$pp \Rightarrow \pi^{\pm 1} \Rightarrow \mu^{\pm 1} + \nu_\mu$$
$$pp \Rightarrow \pi^{\pm 1} \Rightarrow \mu^{\pm 1} + \nu_\mu \Rightarrow \nu_\mu + e^{\pm 1} + \bar{\nu}_e + \nu_\mu$$

Other messenger particles are attenuated and/or **deviated** on their journey towards the earth.

Neutrinos travel unimpeded accross the universe so they can point **directly towards the source**.

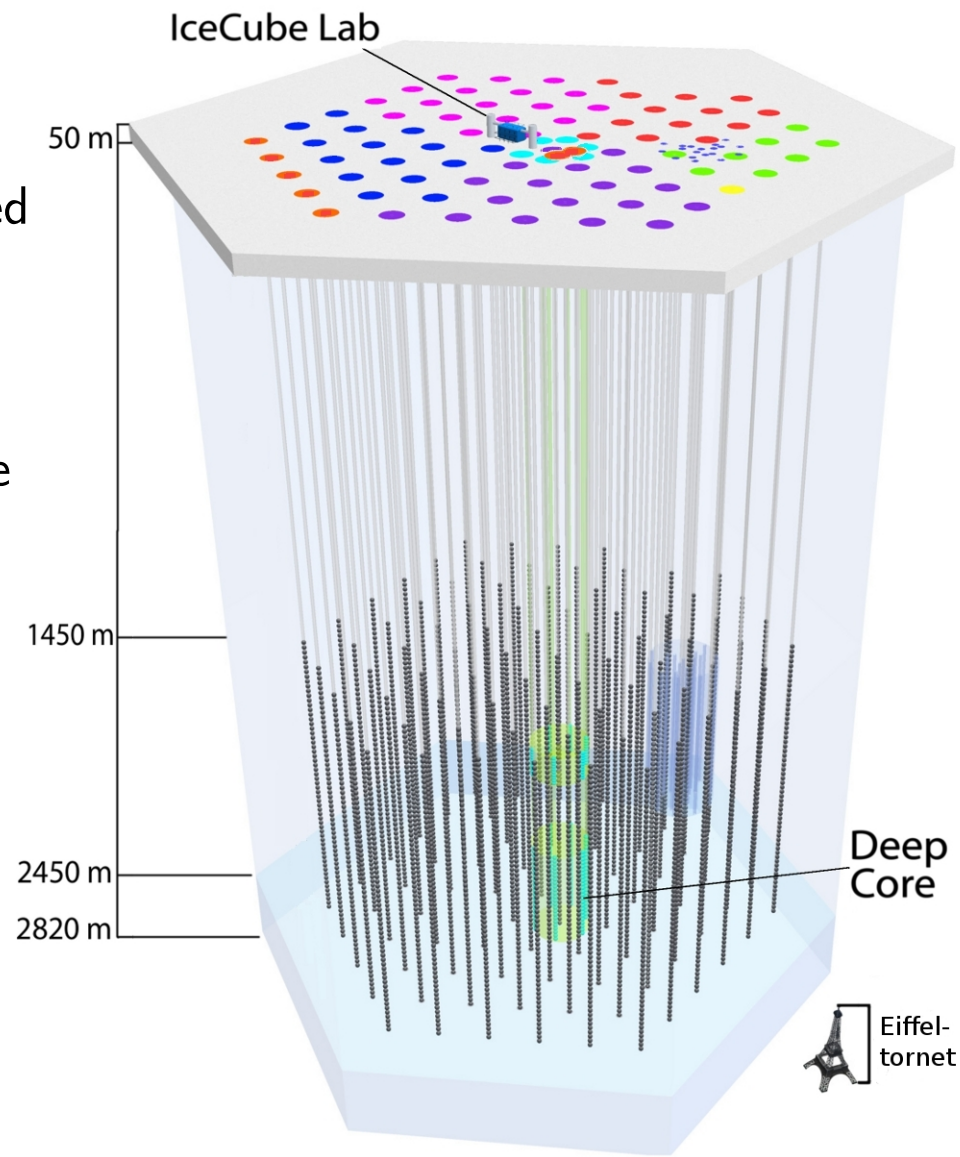
IceCube Detector

What Do We Detect ?

- Neutrinos interact in the ice producing charged leptons.
- Charged leptons then induce Cherenkov radiation during their propagation through the ice.

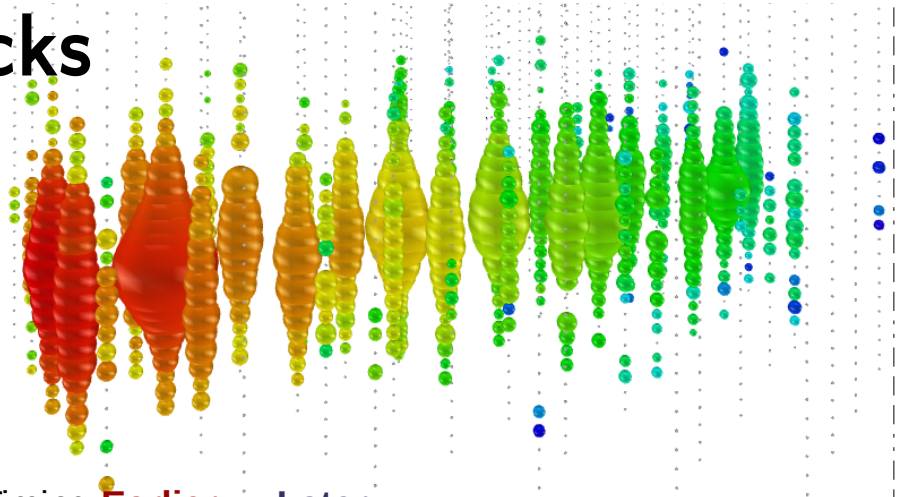
How ?

- 86 strings in cubic Km of Antarctic Ice over 1Km below the surface.
- Each string contains 60 Digital Optical Modules (DOMs) for observing Cherenkov Radiation in the ice.



IceCube Events

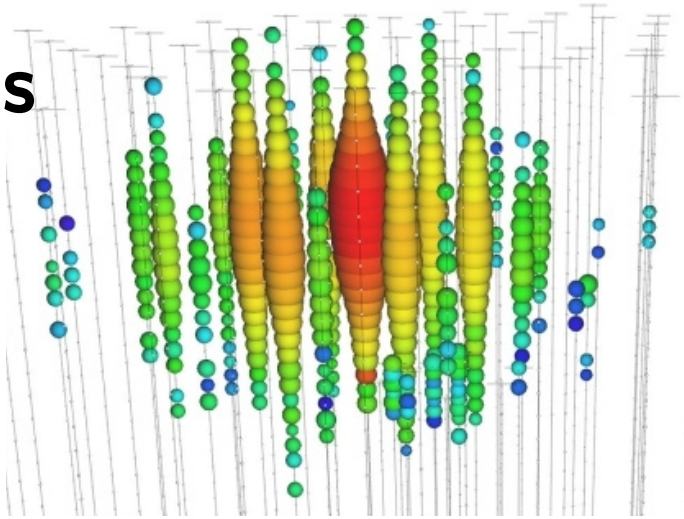
Tracks



Colour : Timing **Earlier** → **Later**
Size of dom : Energy deposited

- High Energy Muons propagate in the ice.
- From: Atmospheric Muons, and Charged Current ν_μ interactions.
- Angular Resolution $\sim 1^\circ$
- Poor Energy resolution

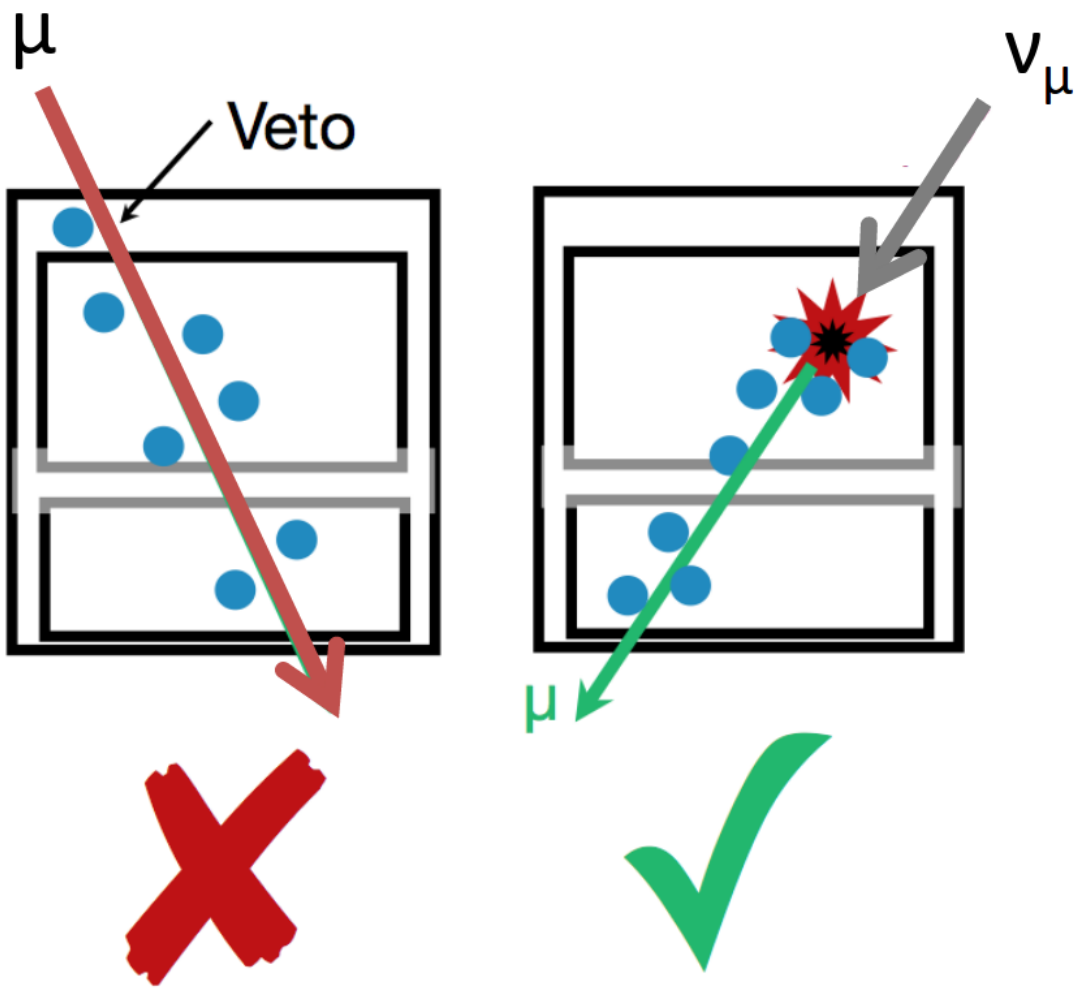
Cascades



IceCube BigBird event ~ 2 PeV

- Shower of charged particles in the ice
- From: ν_τ, ν_e, and Neutral Current ν_μ interactions.
- Angular Resolution $\sim 10^\circ$
- Good Energy Resolution

High Energy Starting Events



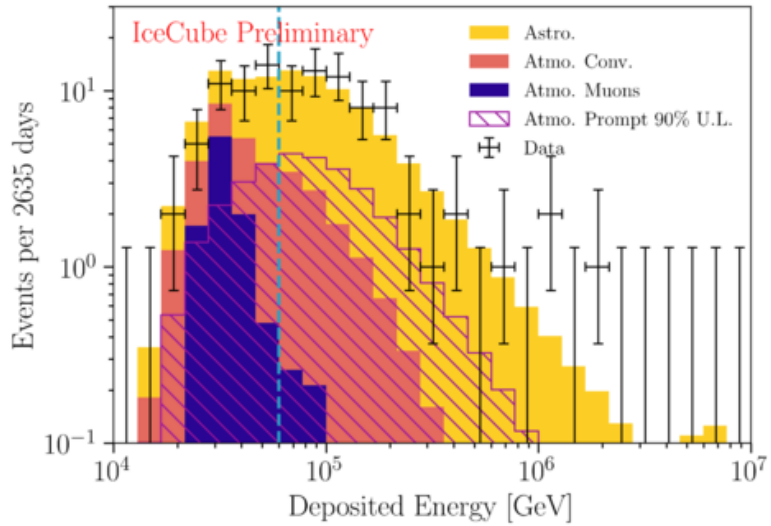
Massively reduce Muon background by demanding only events that start inside detector.

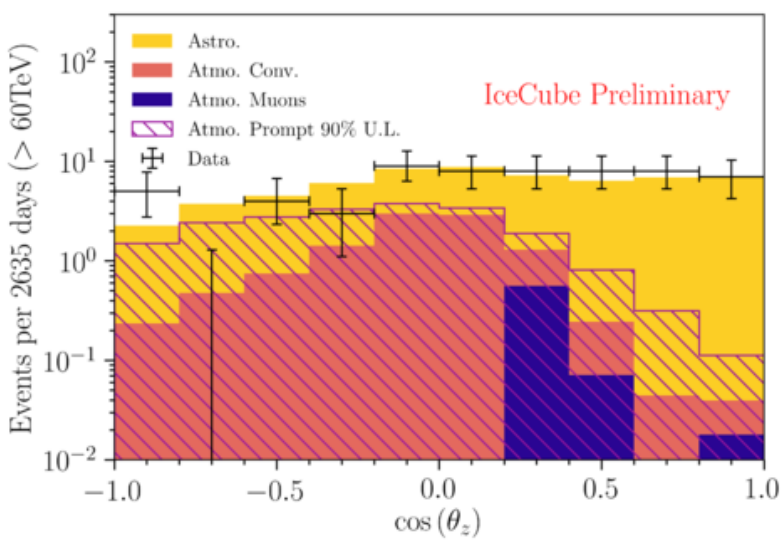
Also increase purity by strict energy threshold of 6000 photoelectrons observed. (approx 30TeV)

There is also an ***active veto*** which eliminates starting events in coincidence with muon tracks to remove obvious atmospheric ν_μ

HESE flux

IceCube observed an Astrophysical Neutrino Flux from High Energy Starting Events with 4 years of Data. We are now using 7 years of data :

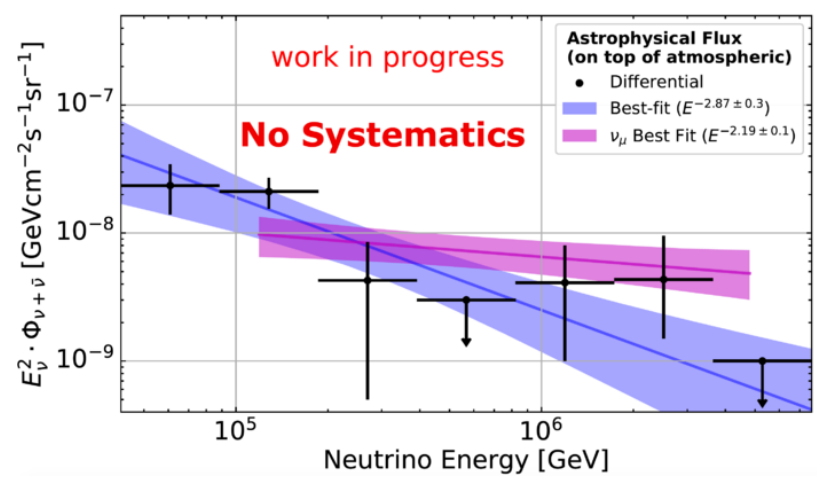




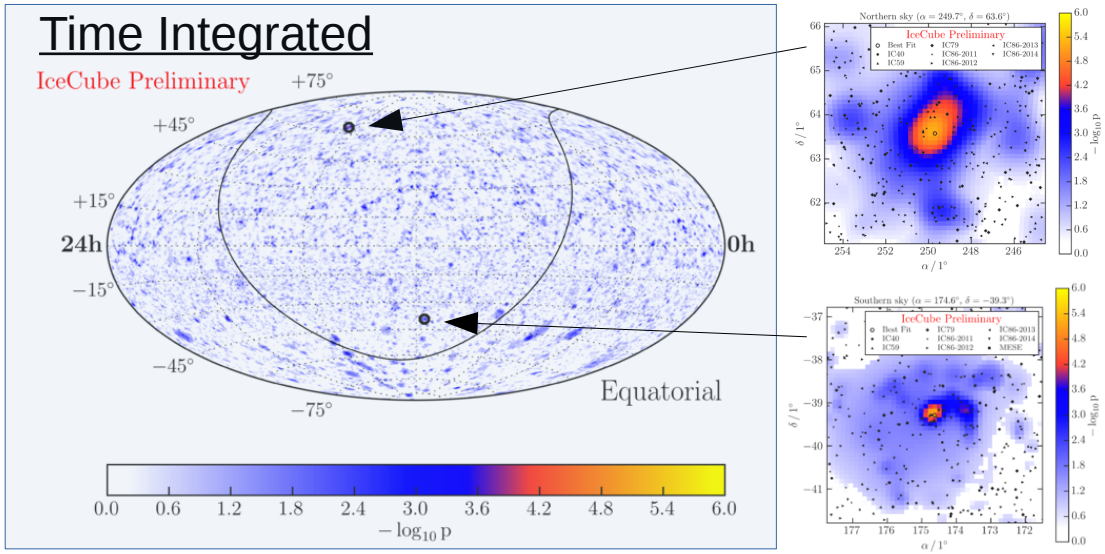
Now updated to 103 events out of which 60 have E>60 TeV at 75% astrophysical purity

$$\Phi_{\nu+\bar{\nu}} = 1.86^{+0.75}_{-0.65} \times \left[\frac{E_\nu}{100\,TeV}\right]^{-2.87\pm0.3}$$

Both this analysis and another with a different event selection fit the astrophysical flux at more than 5 σ.

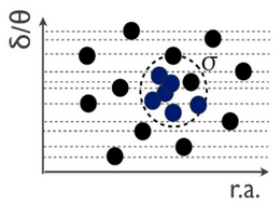
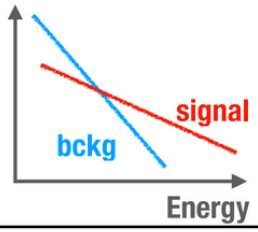
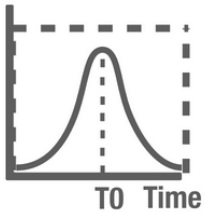


Untriggered - Sky Scan



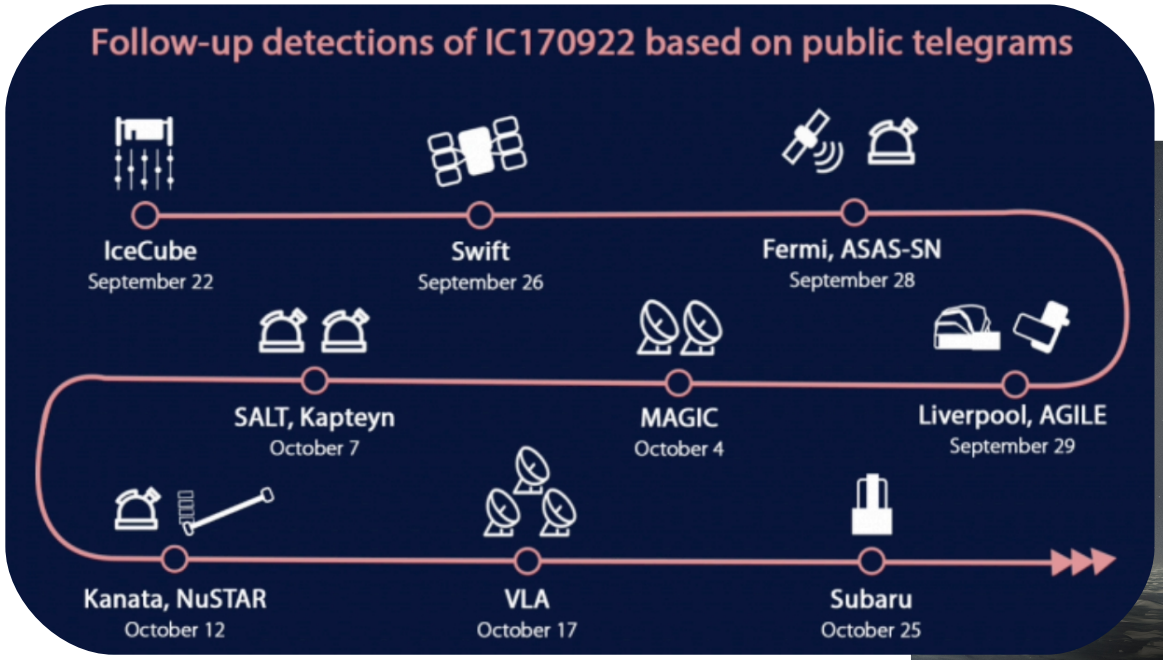
https://arxiv.org/abs/1609.04981

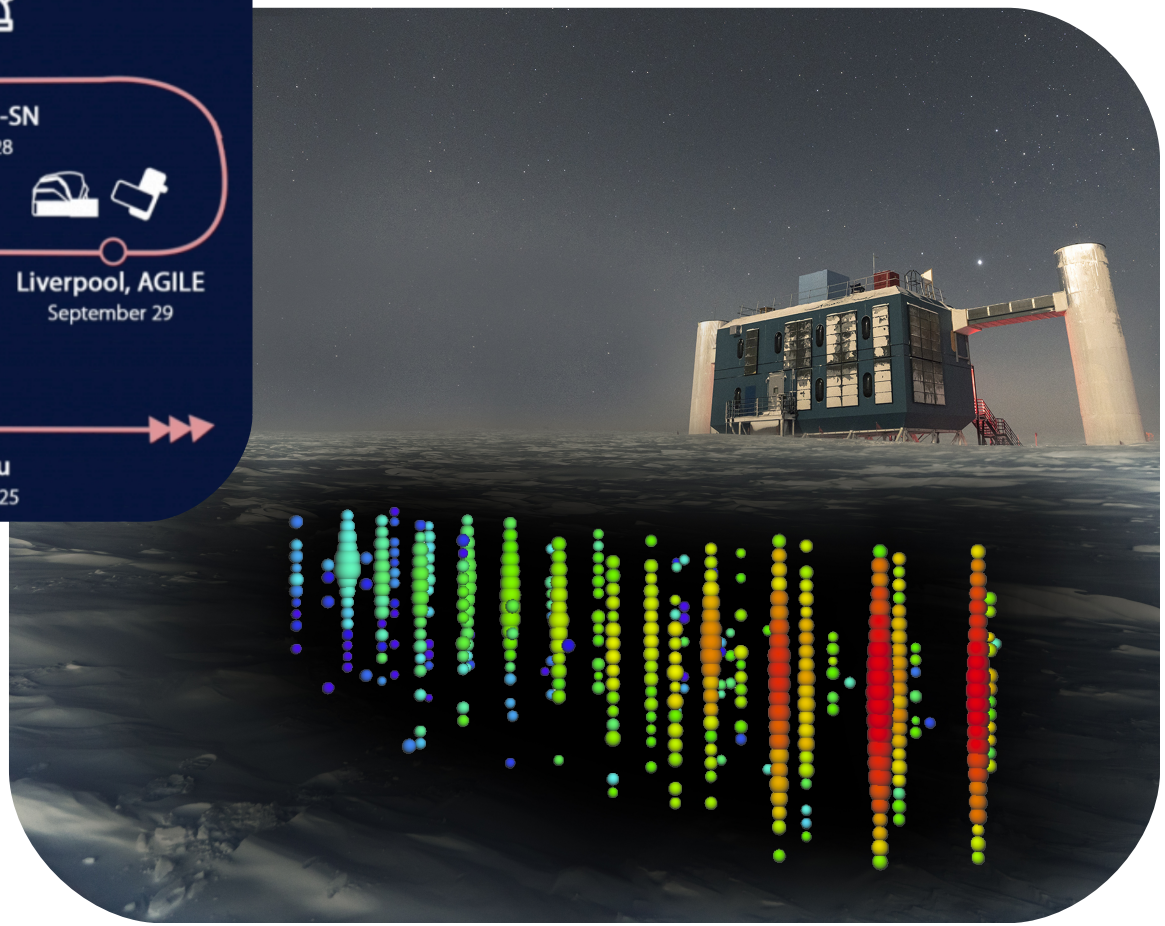
- Without using any prior knowledge of when or when we expect to find our neutrino sources.
- Scan the entire sky and evaluate the likelihood of signal over background at each point.
- The position with the highest test statistic value in each hemisphere is taken as the hottest spot.
- The final pvalue is calculated by comparing this test-statistic with those of many background generated hotspots.

Method	Spatial PDF	Energy PDF	Time PDF	Test Statistics
Time-integrated			not applicable	$TS = 2\log(\mathcal{L}(\Phi_{100},\gamma)/\mathcal{L}(\Phi_{100}=0))$
Time-dependent	same	same		$TS = 2\log\left[\frac{T_W}{T} \times \frac{\mathcal{L}(\Phi_{100},\gamma,T_0,T_W)}{\mathcal{L}(\Phi_{100}=0)}\right]$

More info in poster of Stephanie Bron

TXS 0506+560 – Flaring Blazar Evidence

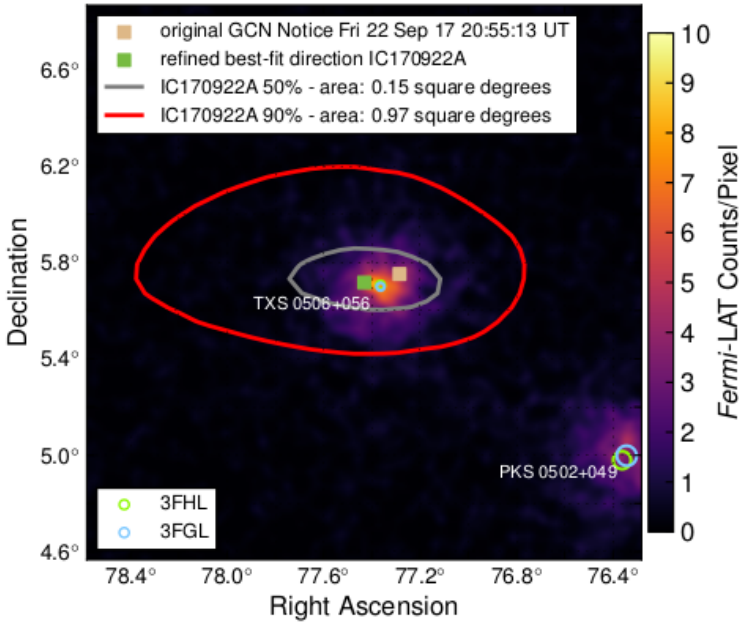


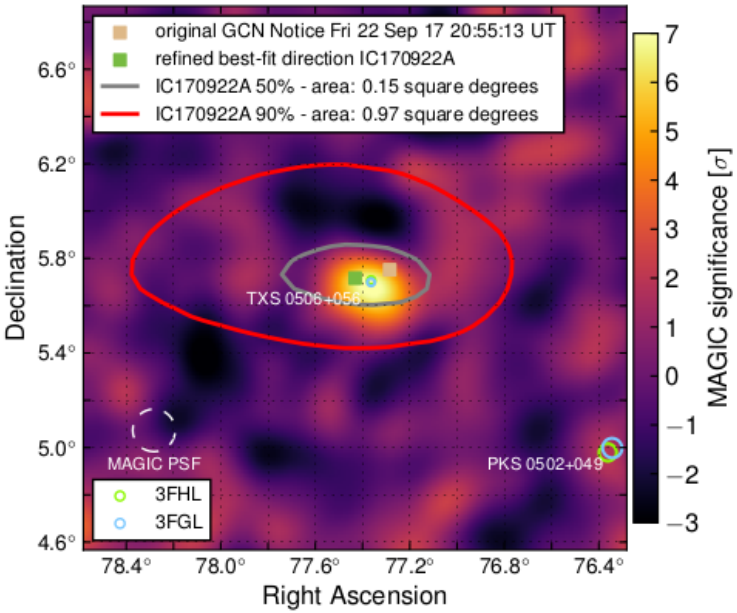


- IceCube High Energy events trigger alerts.
- Initial direction and energy reconstructions are sent to other telescopes.
- In September one of these alerts was observed in spatial and temporal cooincidence with a flaring blazar in Gamma.

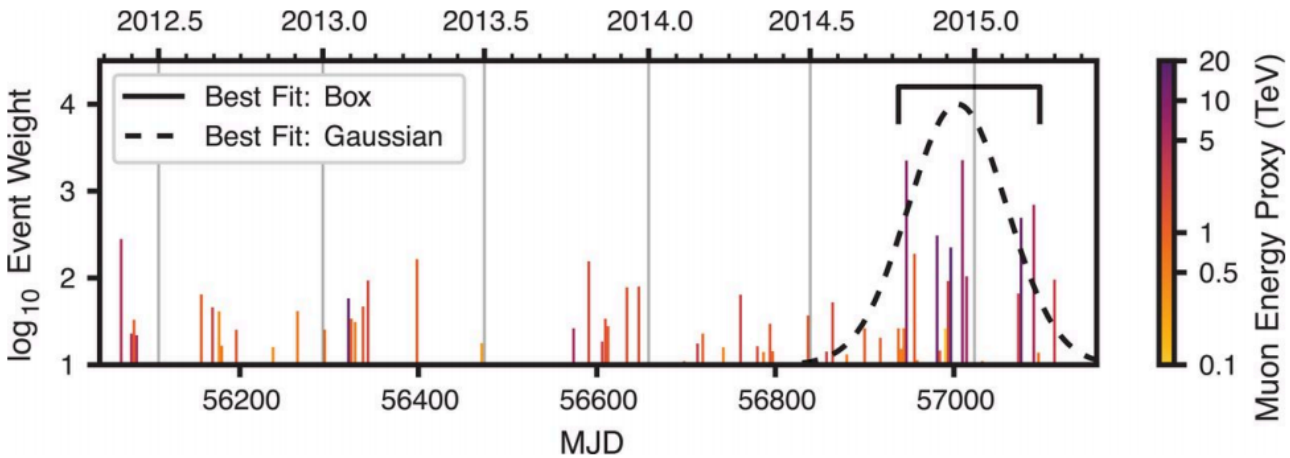
Motivated TXS Analyses

- We can observe the spatial correlation between IceCube alert and Gamma source seen by Fermi and Magic.
- Given the Neutrino alert was seen in coincidence with a flaring Gamma ray source, this motivated further analyses in the direction of the TXS source.
- The main checks done used not just the data around the time of alert but 6 <u>independent</u> periods of data spanning from 2008 up till ~ 1 month after the alert (October 2017)

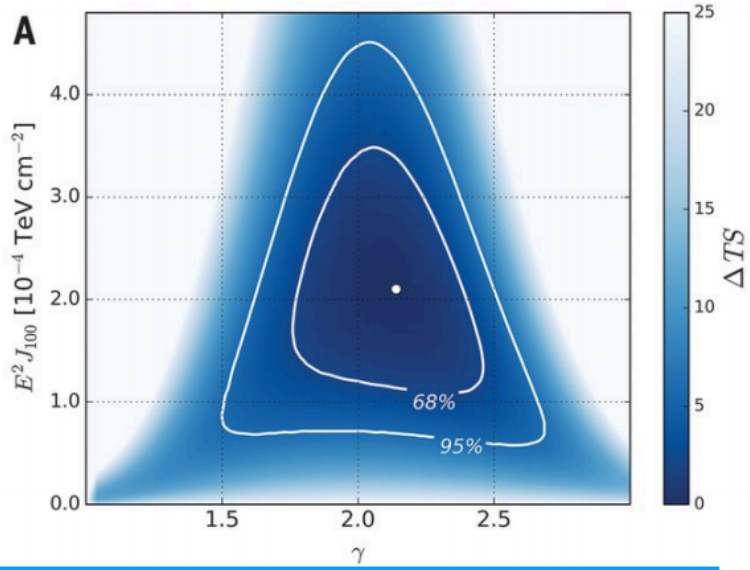




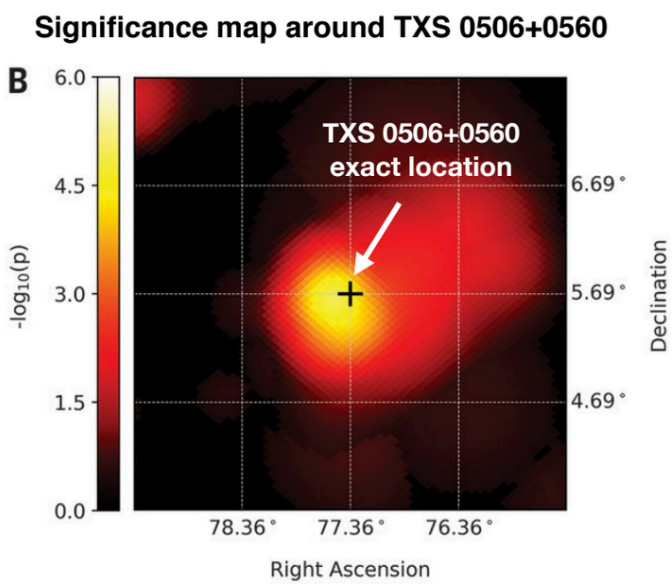
Time Dependent Results



Spatial and Energy dependant event weights assuming γ = 2.1

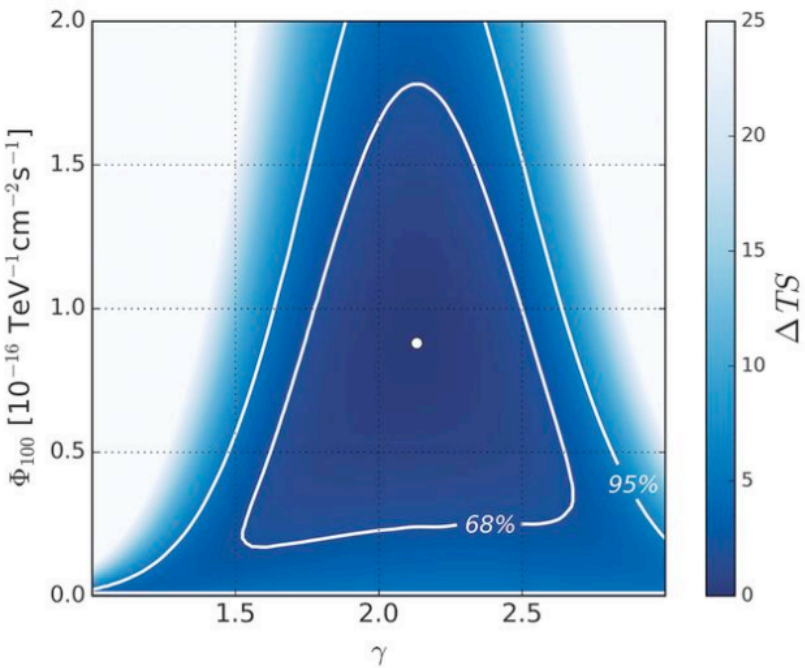


Fluence: E^2J_{100} = 2.1 +0.9/ -0. 7 10^{-4} TeV cm^{-2} at 100 TeV
spectral index γ = 2.1 ± 0.2



- These searches resulted in finding an earlier flare at the TXS location with an excess of 13 ± 5 neutrino events in 2015 relative to background.
- The flare in 2015 is found by 2 seperate analyses at ~ 3.5 σ.
- The flares which are fitted in the other time periods are considered not significant.

Time Integrated Results



- Integrating over the entire livetime of the detector at TXS 0506+0560 for the same data selection gives a significance of 4.1σ.
- Once the final period (2015-2017)containing the EHE event is removed this falls to 2.1 σ.
- However both periods fit a spectral index in agreement with that of the time-dependant search of 2.0+/- 0.3 and 2.1 ± 0.3 respectively.

Summary

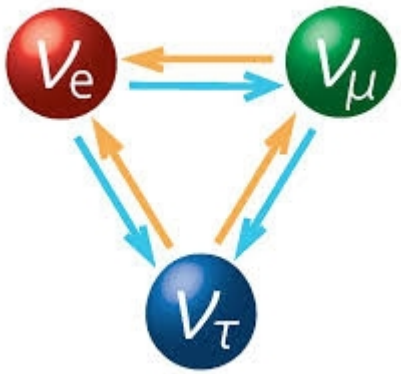
- IceCube Triggers are able to notify other telescopes within minutes of a high energy neutrino event via multimessenger programs.
- This system found a coincidence between an IceCube event and a flaring gamma source in September 2017.
- This motivated archival searches across over 9yrs of full sky data in the direction of TXS0506+560
- This search identified a flare fitting 13 ± 5 astrophysical neutrinos in a period of 5 months.
- **TXS 0506+0560 is the first known object to provide evidence in the understanding of the neutrino-gamma ray relationship in blazars.**

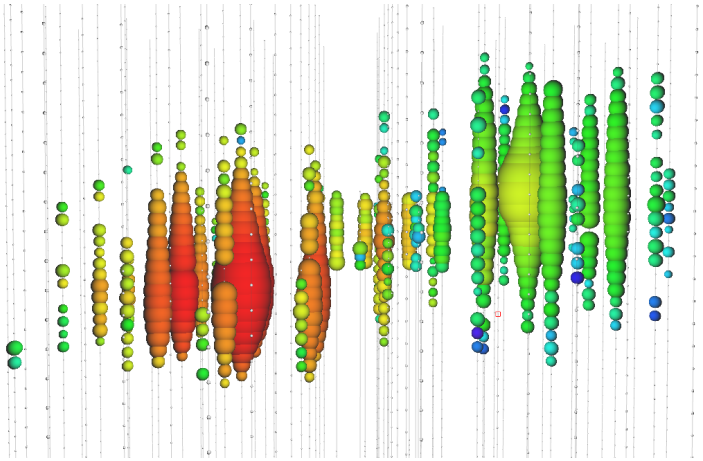

Thank you for
Listening !

Backup

HESE Flavor Composition

- We expect flavour ratio at source to come from hadronic decay : $\nu_e : \nu_\mu : \nu_\tau = 1:2:0$
- The neutrinos oscillate on their journey towards earth. We expect to observe : $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$
- ν_τ events in particular could be differentiated as a double cascade where the resulting τau has enough energy to travel an observable distance before decaying into a shower. This is known as a double cascade.
- Previous fits with 6 years of HESE were consistent with $\nu_\tau = 0$





Simulated double cascade in IceCube

Flavour Results

- Two double cascade cadidate events have been identified
- In one of these two events, the observed light arrival time favors the double cascade hypothesis
- Double cascades can arise from atmospheric and astrophysical backgrounds
- Further study of the tauness of double cascade events is ongoing, as well as independent double pulse analyses
- Best fit flavor composition is 0.35:0.45:0.20 but zero τ cannot be excluded