


Joint IceCube-Pierre Auger-Telescope Array point source analysis

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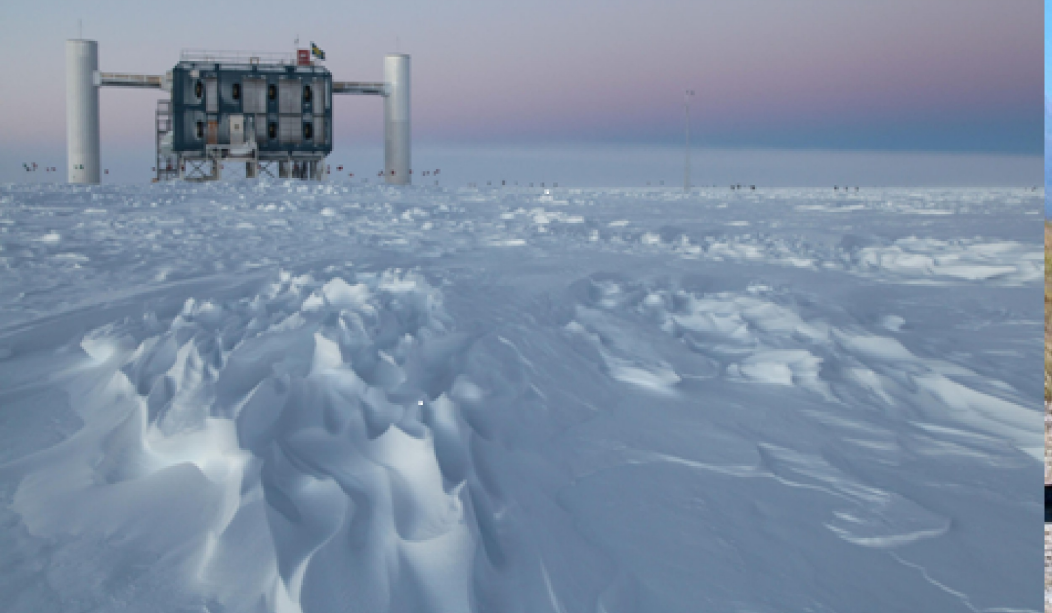
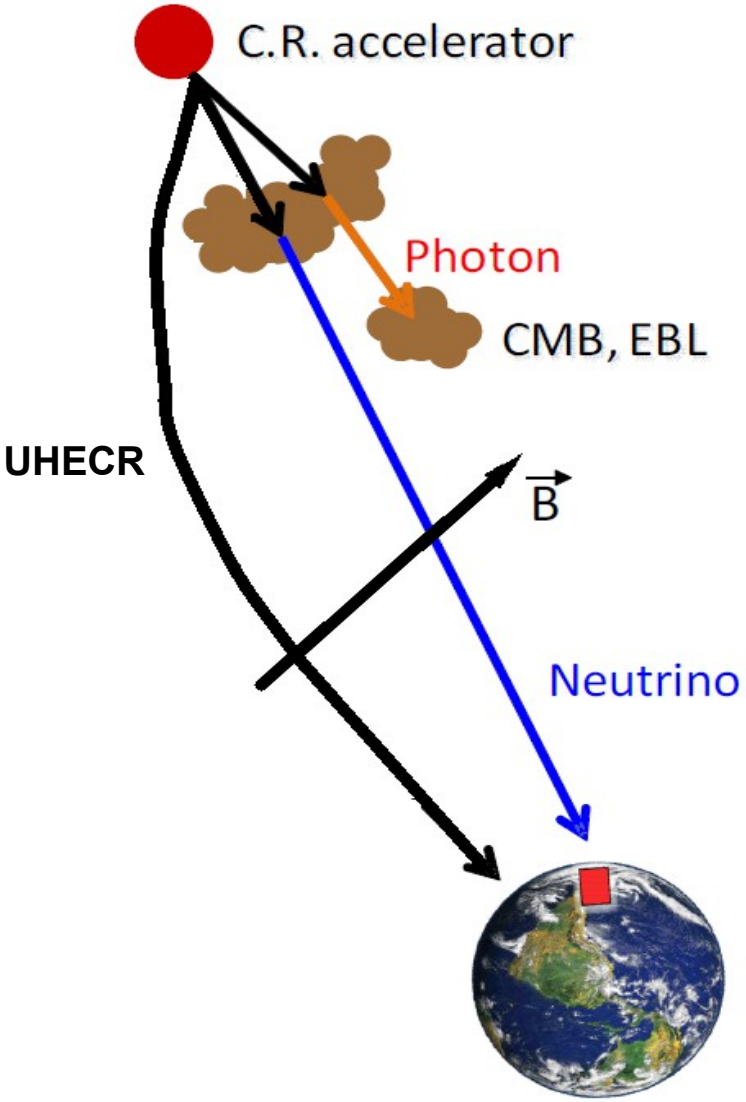
for the IceCube, Pierre Auger and Telescope Array Collaborations

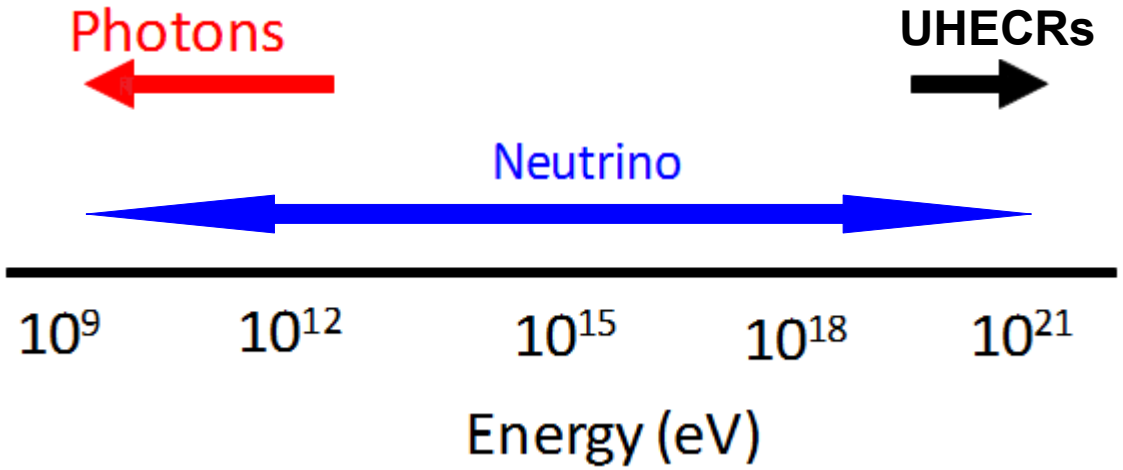



Multi-messenger astronomy

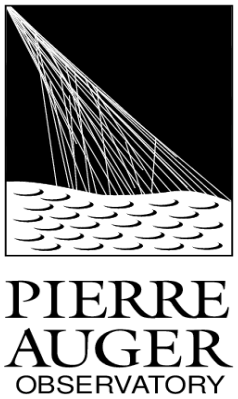


$$p + \gamma \xrightarrow[\text{or p...}]{} \pi^0 + p$$
$$\rightarrow \gamma + \gamma + p$$
$$\rightarrow \pi^+ + n$$
$$\rightarrow \mu^+ + \nu_\mu + n$$
$$\rightarrow e^+ + \bar{\nu}_\mu + \nu_e + \nu_\mu + n$$

Neutrinos



UHECR data set



- Period: 01/01/2004 to 31/03/2014.
- 231 events above 52 EeV.
- θ_{max} = 80°
- Angular resolution: 0.9°

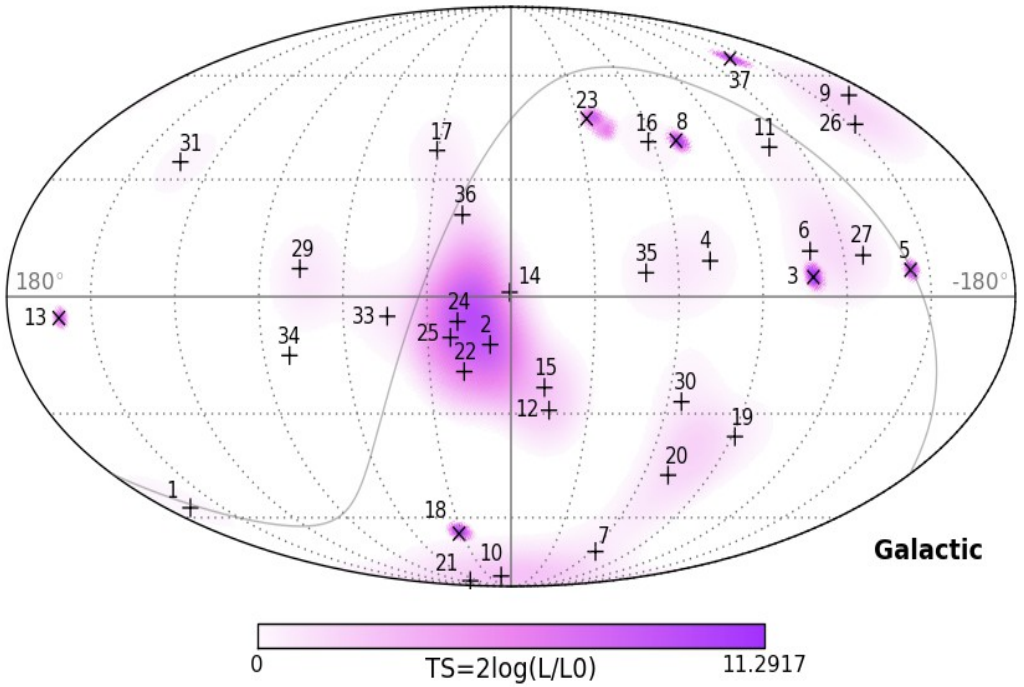
Data will be given to the working group soon.

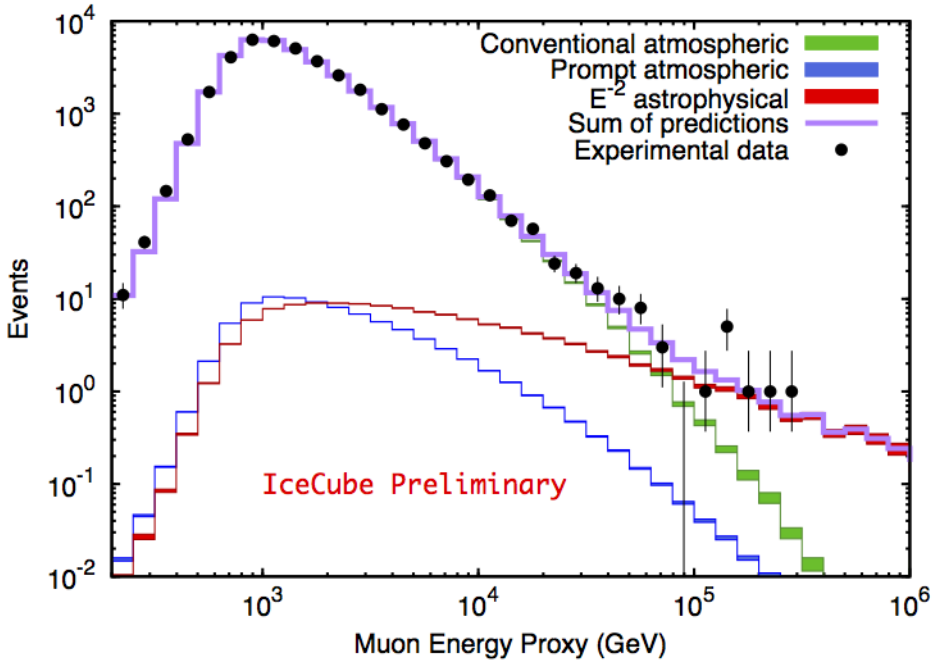
- Period: 11/05/2008 to 01/05/2014.
- 87 events above 57 EeV.
- θ_{max} = 55°
- Angular resolution: 1.5°

72 events are public (arXiv:1404.5890) + 1 year of data that will be provided to the working group.

Neutrino data sets

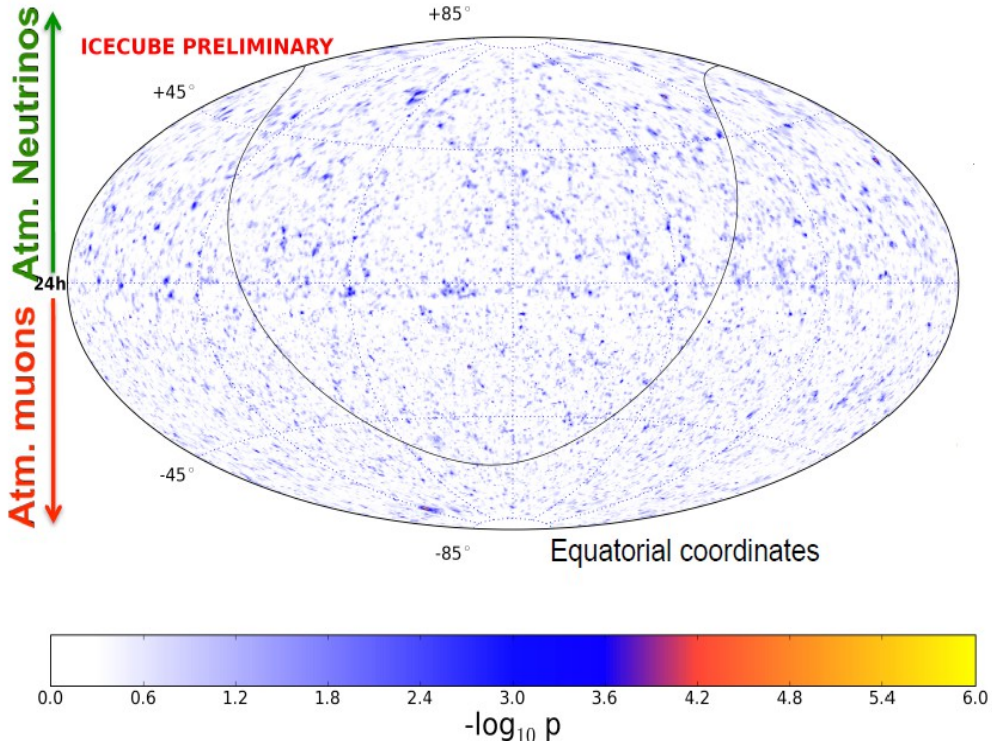
- 3-year HESE Cascades: 28 events (IC79+IC86-I+IC86-II)
- Golden sample of tracks: 3 of the HESE tracks plus 9 events with E_{dep} > 100 TeV from diffuse up-going analysis (IC79+IC86-I).

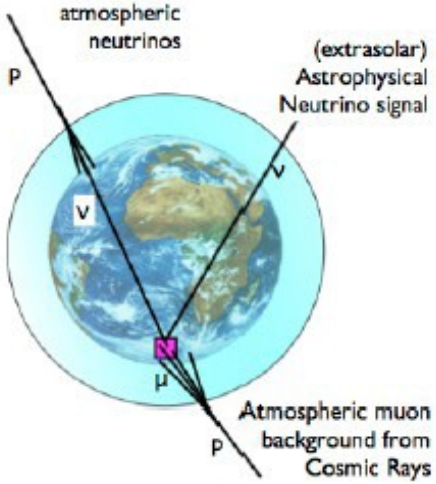




Neutrino data sets

• Point source sample: 4-year (IC40+IC59+IC79+IC86-I) sample of clean, through-going muons that could be associated with charged-current muon neutrino interactions (394,000 events).





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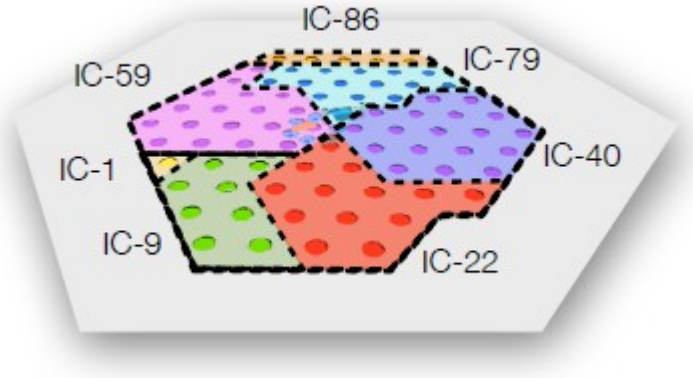
Analyses to be performed

1) Crosscorrelation method using the 3-year HESE sample (IC79+IC86-I+IC86-II) + high energy up-going tracks (IC79+IC86-I).

2) Stacking method using the 3-year HESE sample (IC79+IC86-I+IC86-II) + high energy up-going tracks (IC79+IC86-I).

3) Stacking method using the 4-year IceCube point source sample (IC40+IC59+IC79+IC86-I).

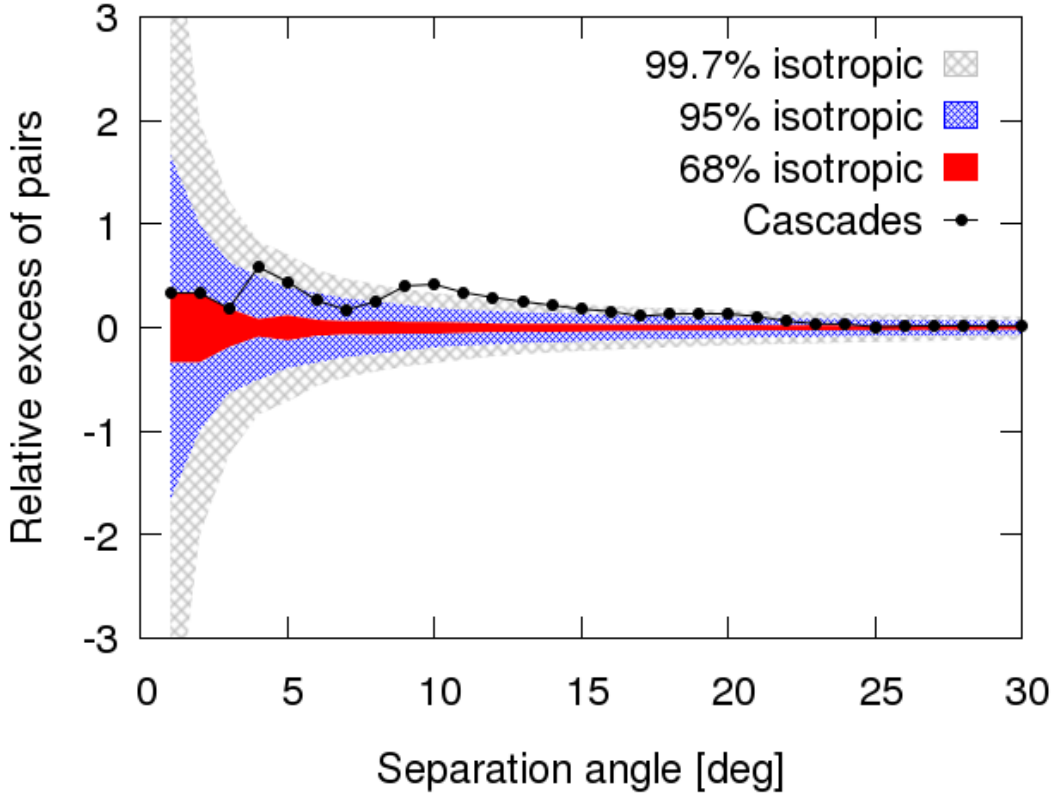


Crosscorrelation function

Compute the number of UHECR-neutrino pairs as a function of the angular separation in the data ($n_p(\alpha)$).

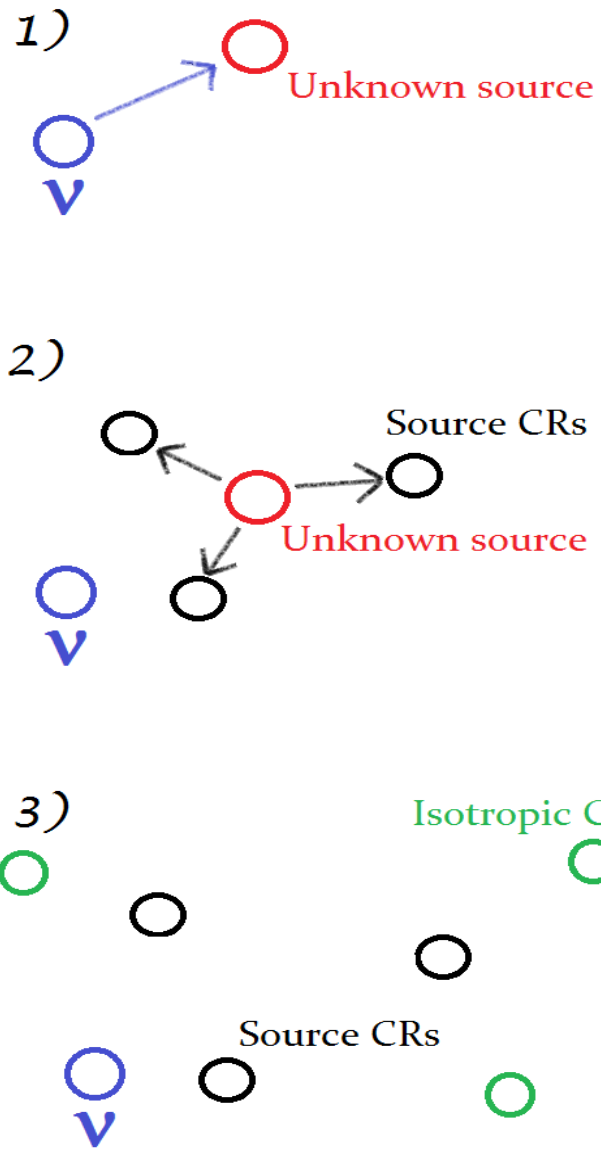
Note: the crosscorrelation method does not rely on any assumption about the magnetic deflections.

Example:



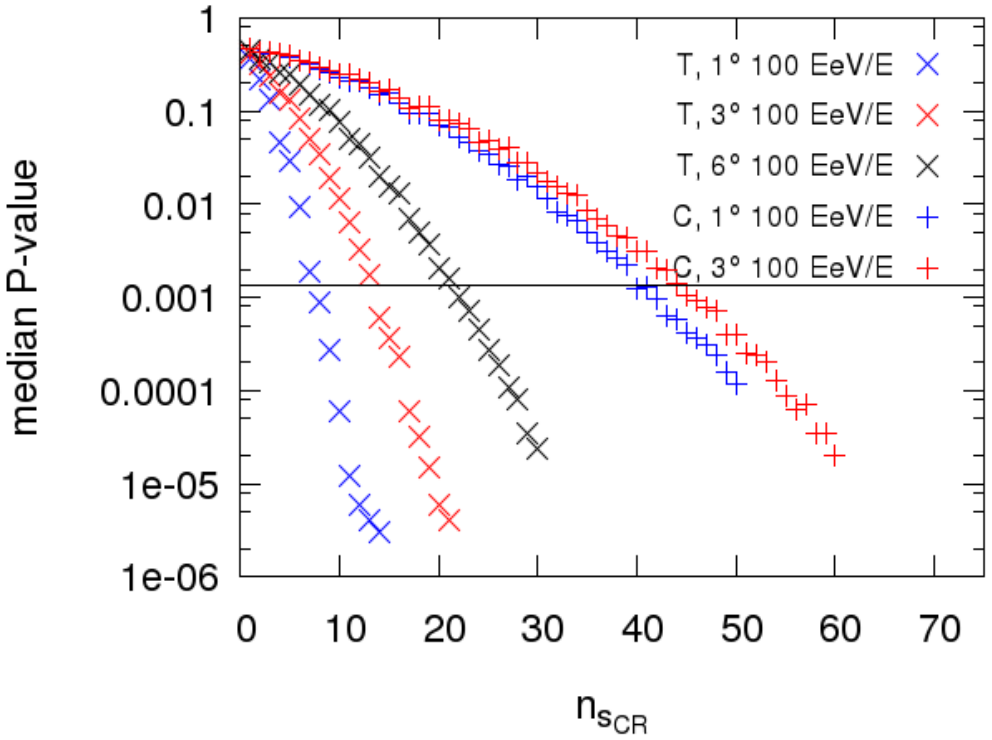
Crosscorrelation function
Sensitivity and discovery potential

1) Neutrino positions fixed. Unknown source positions: Gaussian smearing to the HESE positions with σ_{HESE} = 1°; 10° for tracks and cascades respectively.
2) n_{sCR} CR source events from these new source positions choosing randomly one of them each time (weighted by the exposure of Auger or TA) and adding a Gaussian smearing with $\sigma=(\sigma^2_{exp} + \sigma^2_{MD})^{1/2}$ where σ_{exp} = 0.9°or 1.5°, σ_{MD} = 1°;3°;6° 100 EeV/E_i.
3) Add 303 - n_{sCR} randomly distributed arrival directions of CRs weighted by the exposures of Auger and TA.



Crosscorrelation function

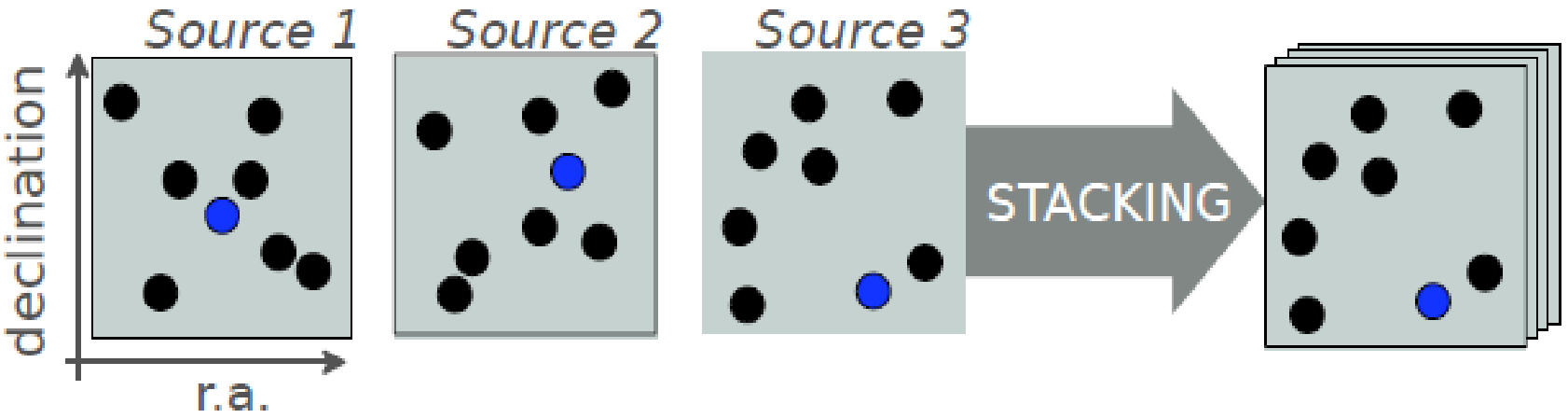
Sensitivity and discovery potential



Preliminary

σ_{MD}	Golden tracks		HESE Cascades	
	Sensit.	3σ Disc. Pot.	Sensit.	3σ Disc. Pot.
1° 100 EeV$/E_i$	3.7	7.9	17.9	40.2
3° 100 EeV$/E_i$	5.9	13.4	19.5	44.3
6° 100 EeV$/E_i$	9.4	21.4	-	-

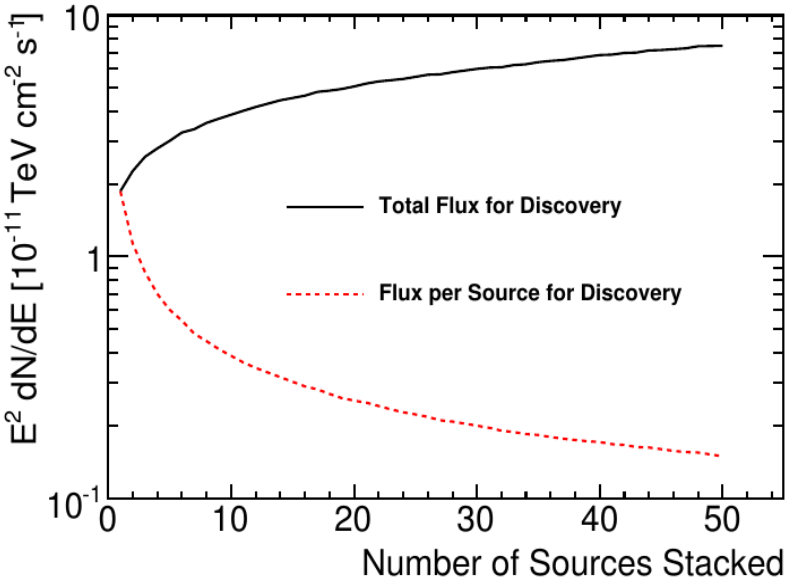
Stacking method



The discovery potential improves as more sources are stacked.

The “sources” are:
Analysis 2): the locations of neutrinos
Analysis 3): the locations of UHECRs

Example of improvement



Stacking with HESE and high energy tracks
Unbinned Maximum Likelihood

One fit parameter: the number of signal events n_{sCR}

$$\ln \mathcal{L} = \sum_{i=0}^{N_{\mathrm{Auger}}} \ln \left(\frac{n_{s_{CR}}}{N_{\mathrm{tot}}} S_i^{\mathrm{Auger}} + \frac{N_{\mathrm{tot}} - n_{s_{CR}}}{N_{\mathrm{tot}}} B_i^{\mathrm{Auger}} \right) +$$

$$\sum_{i=0}^{N_{\mathrm{TA}}} \ln \left(\frac{n_{s_{CR}}}{N_{\mathrm{tot}}} S_i^{\mathrm{TA}} + \frac{N_{\mathrm{tot}} - n_{s_{CR}}}{N_{\mathrm{tot}}} B_i^{\mathrm{TA}} \right)$$

$$N_{\mathrm{tot}} = N_{\mathrm{Auger}} + N_{\mathrm{TA}}$$

Signal PDF: the magnetic deflection plus the ν spatial PDFs have to be accounted for:

Background PDF: geometric exposure

$$S_i = \frac{1}{N_\nu} \sum_{j=0}^{N_\nu} \omega(\delta^j) S_i^j(ra_i, \delta_i, \sigma_{MD})$$

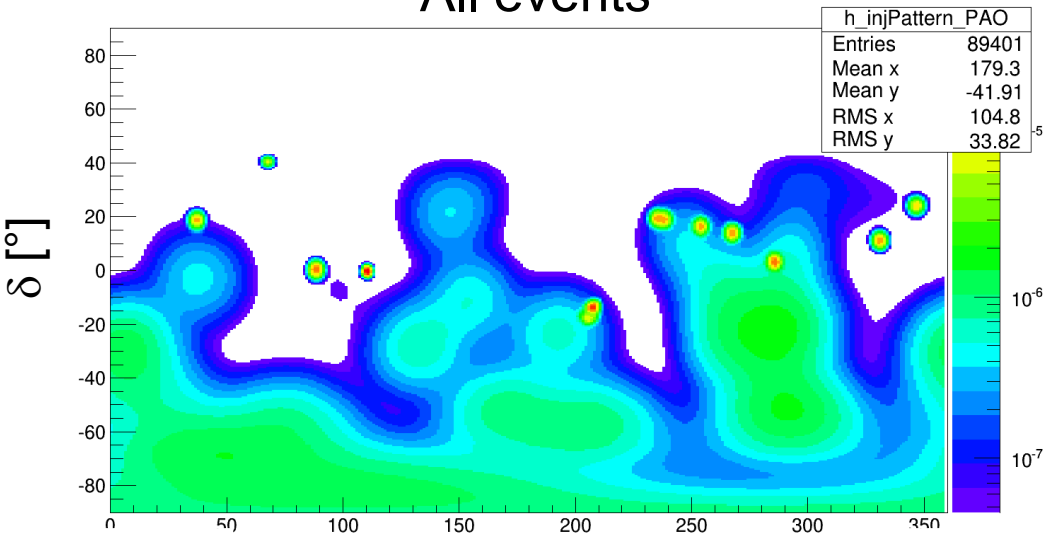
A PDF for a single CR and a single ν: takes into account the ν map and the magnetic deflection

The test statistic $TS = -2 \ln \left(\frac{\mathcal{L}(n_{s_{CR}})}{\mathcal{L}(n_{s_{CR}} = 0)} \right)$ should follow a χ^2 of 1 dof.

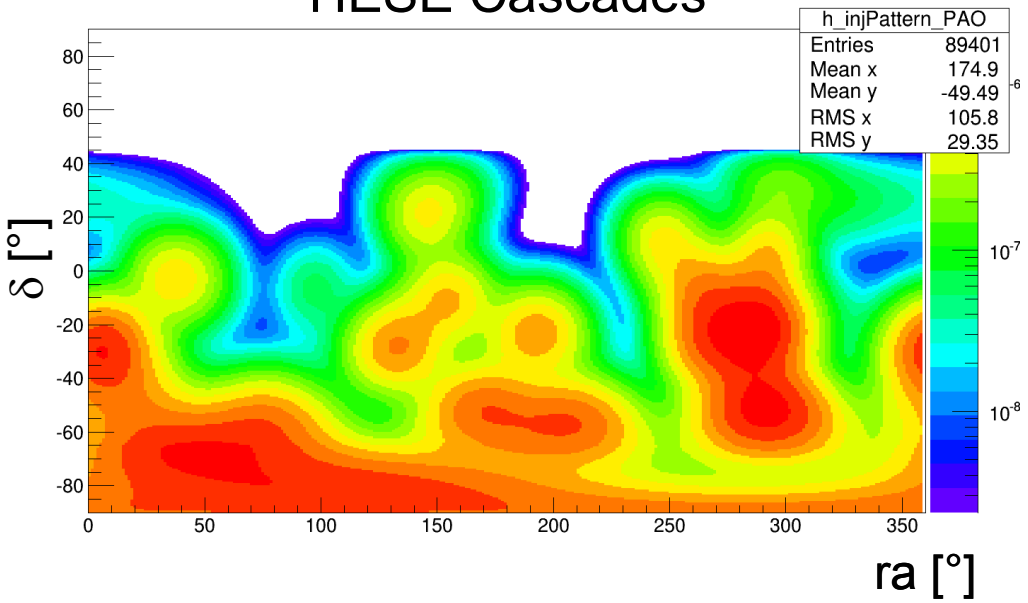
Stacking with HESE and high energy tracks

Spatial PDFs: example for Auger

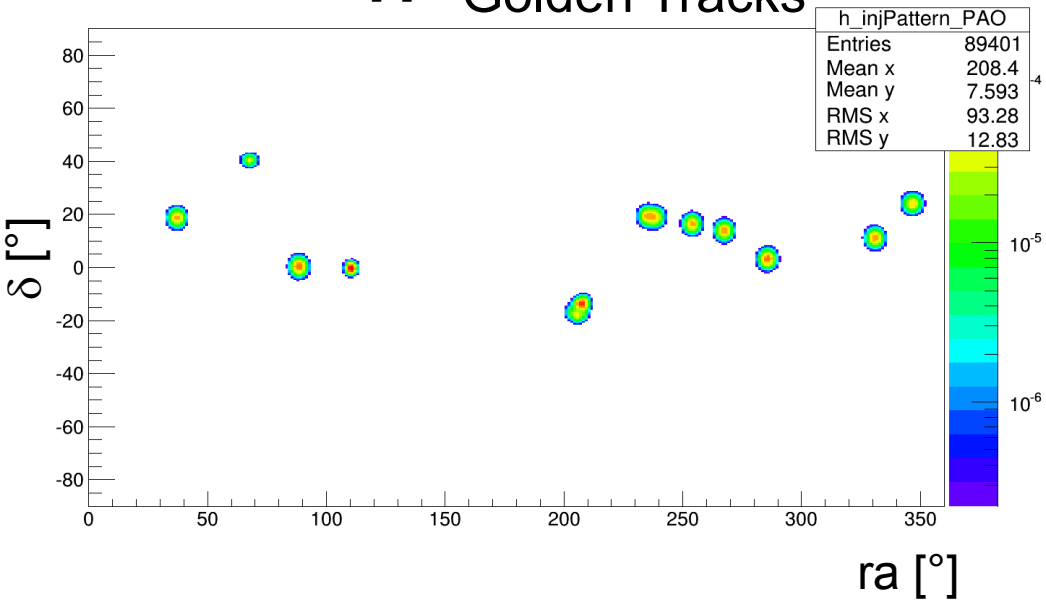
All events



HESE Cascades



Golden Tracks



Stacking with HESE and high energy tracks
Sensitivity and discovery potential

Preliminary

σ_{MD}	All events		
	Sensit.	3σ Disc. Pot.	5σ Disc. Pot.
1° 100 EeV/E_i	-	-	-
3° 100 EeV/E_i	-	33.3	63.8
6° 100 EeV/E_i	-	40.1	84.2

σ_{MD}	Golden tracks			HESE Cascades		
	Sensit.	3σ DP	5σ DP	Sensit.	3σ DP	5σ DP
1° 100 EeV/E_i	-	-	-	-	-	-
3° 100 EeV/E_i	-	5.1	14.2	-	89.5	132.6
6° 100 EeV/E_i	-	-	-	-	99.2	150

Stacking with the neutrino PS sample
Likelihood PS method

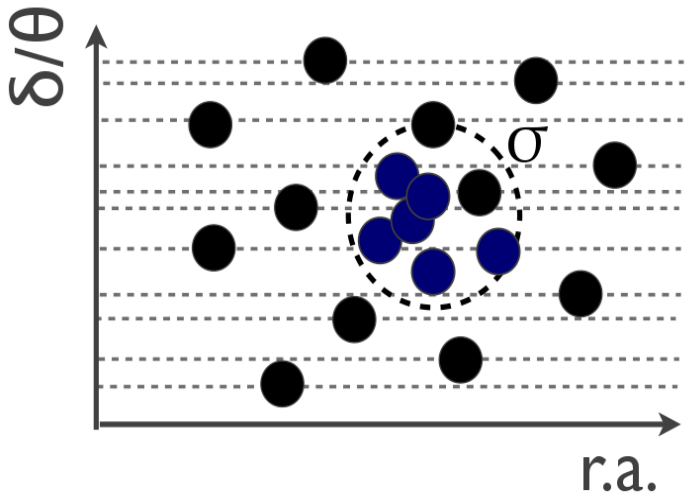
Maximize: γ (the neutrino spectral index)
and $n_{s\nu}$ (number of signal events)

$$\mathcal{L}(n_{s_\nu}, \gamma) = \prod_{i=1}^{N_\nu} \left(\frac{n_{s_\nu}}{N_\nu} S_i(\gamma) + \left(1 - \frac{n_{s_\nu}}{N_\nu}\right) B_i \right)$$

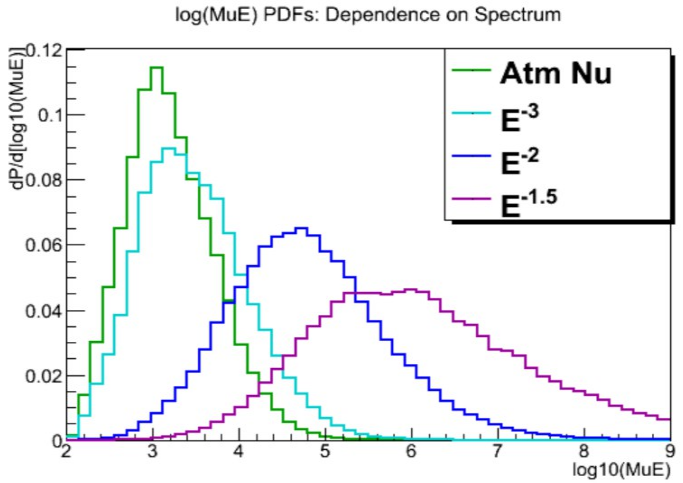
$$S_i = \frac{1}{2\pi\sigma_i^2} e^{-r_i^2/2\sigma_i^2} P(E_i|\gamma)$$

$$B_i = B(\theta_i) P_{atm}(E_i)$$

Spatial

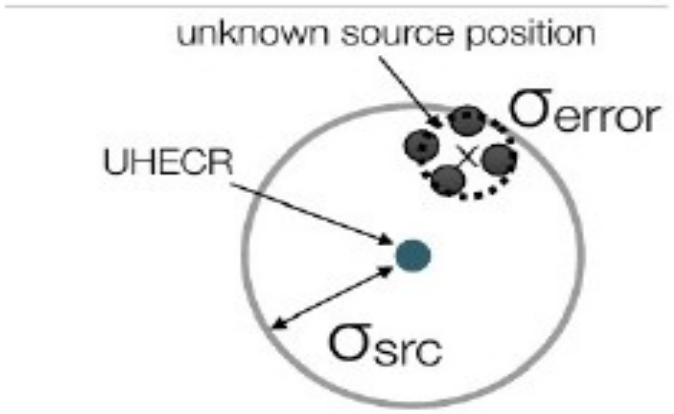


Energy



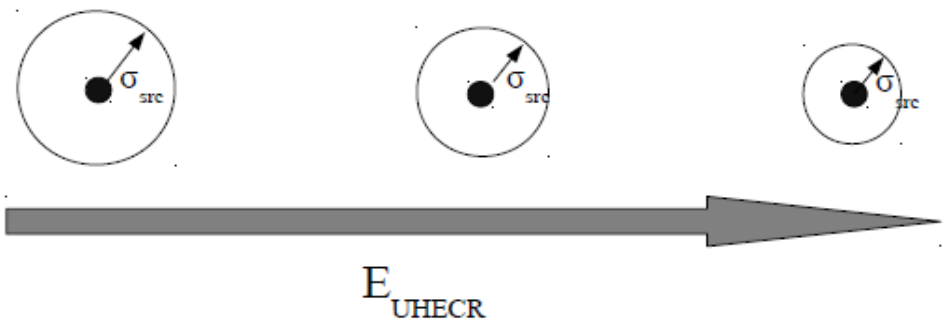
Stacking with the neutrino PS sample

We assume a spatial extension of:
$\sigma_{src} = D\ 100\ EeV/E_{UHECR}$ with D=1°,3°,6°



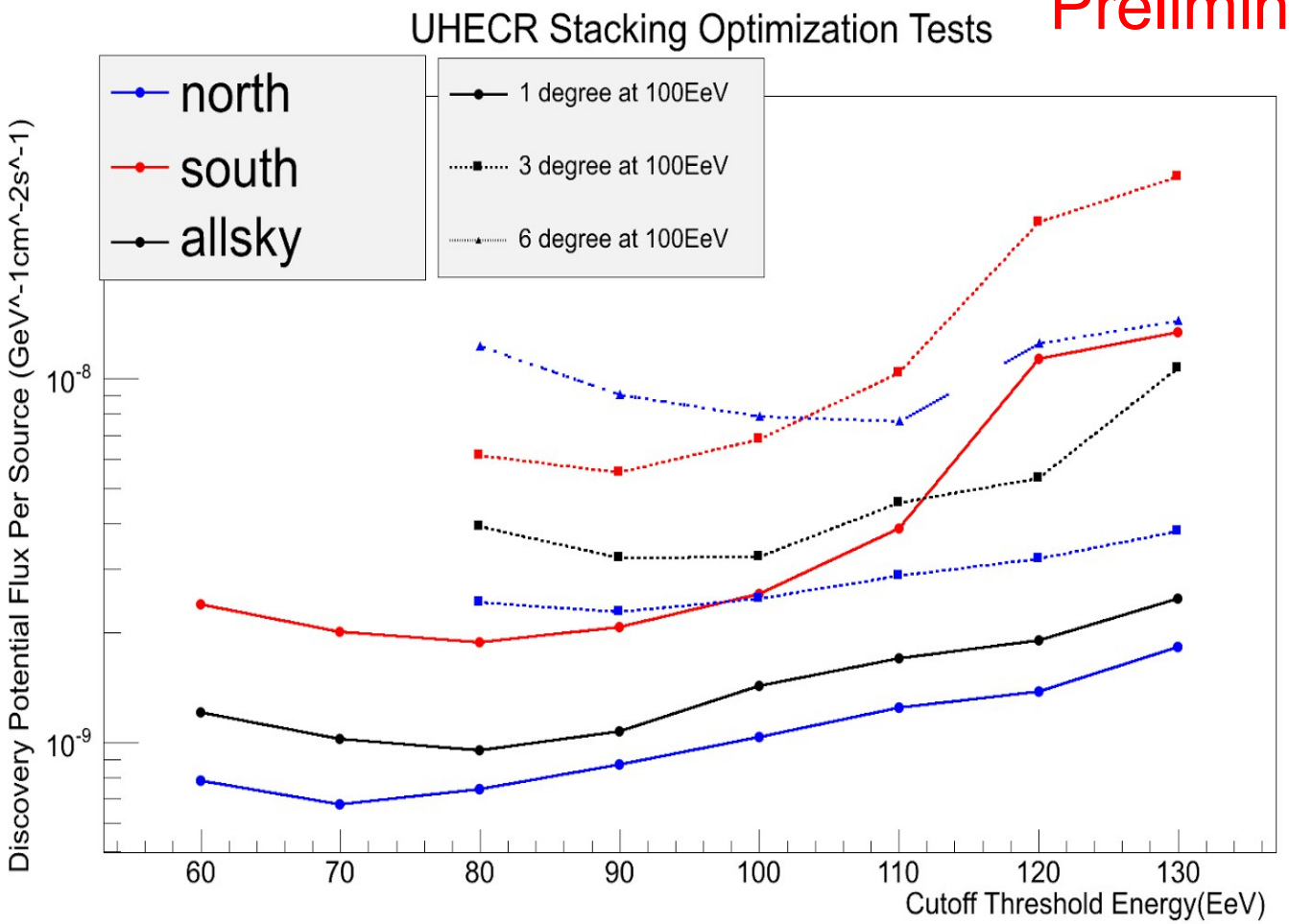
For calculating the discovery potentials we inject neutrinos from a point source displaced from the UHECR by the median deflection.

"Too many" UHECRs => the fraction of the sky covered is such that it becomes a diffuse analysis => Introduce a cut in the minimum UHECR energy, which is the optimal?



Stacking with the neutrino PS sample

Preliminary



Different energy thresholds according to the 3 different assumed magnetic deflections.

We will separate the analysis in two: one for the Northern hemisphere and one for the Southern hemisphere.

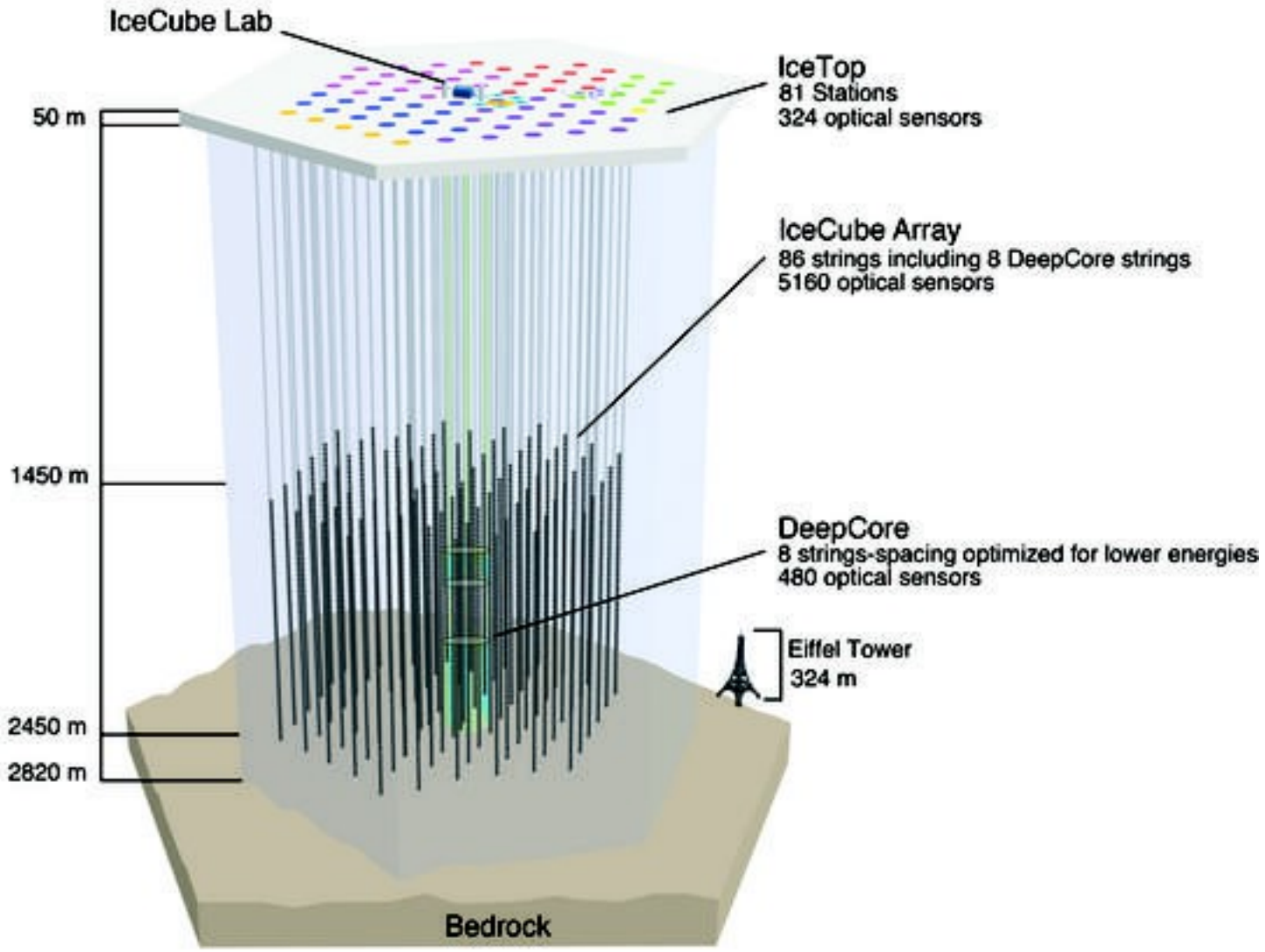
Conclusions

- First joint analysis between IceCube, Auger and TA.
- Sensitivity and discovery potentials are being computed for the chosen analyses.
- Stay tuned for the upcoming unblinding and results!

Back up slides

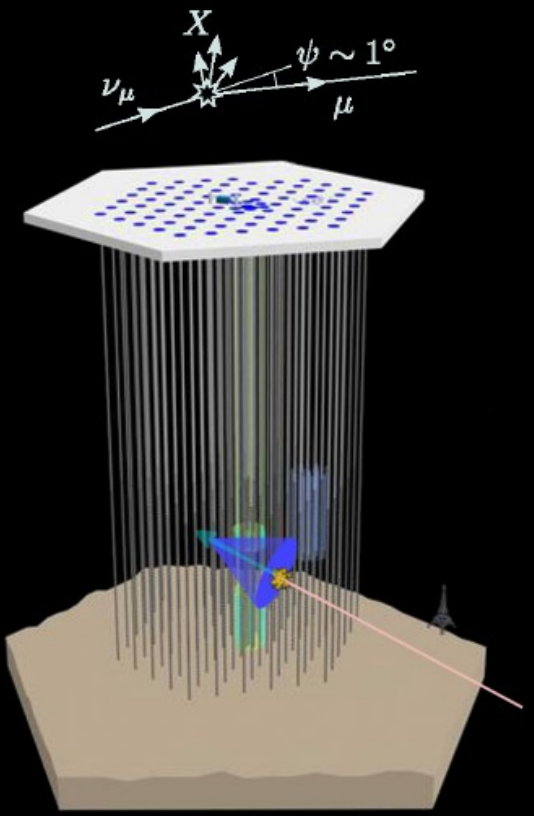
The IceCube Neutrino Telescope

- 1 km^3 volume
- 86 strings
- 5160 DOMs
- 17 m PMT-PMT spacing per string
- 125 m string spacing
- Completed in Dec. 2010

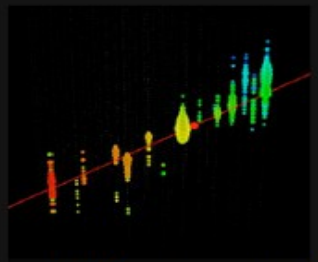


Detection Method

Neutrinos are detected by looking for Cherenkov radiation from secondary particles (muons, particle showers).



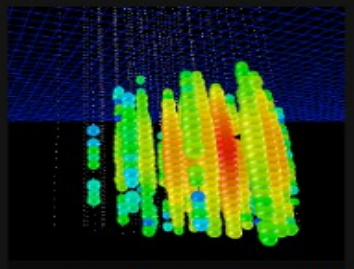
CC Muon Neutrino



$\nu_\mu + N \rightarrow \mu + X$

track (data)

Neutral Current /Electron Neutrino

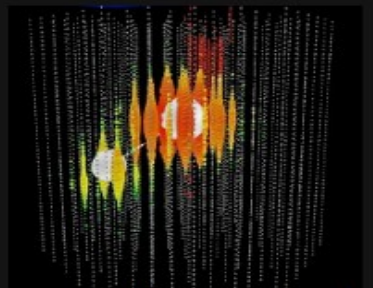


$\nu_e + N \rightarrow e + X$

$\nu_x + N \rightarrow \nu_x + X$

cascade (data)

CC Tau Neutrino



$\nu_\tau + N \rightarrow \tau + X$

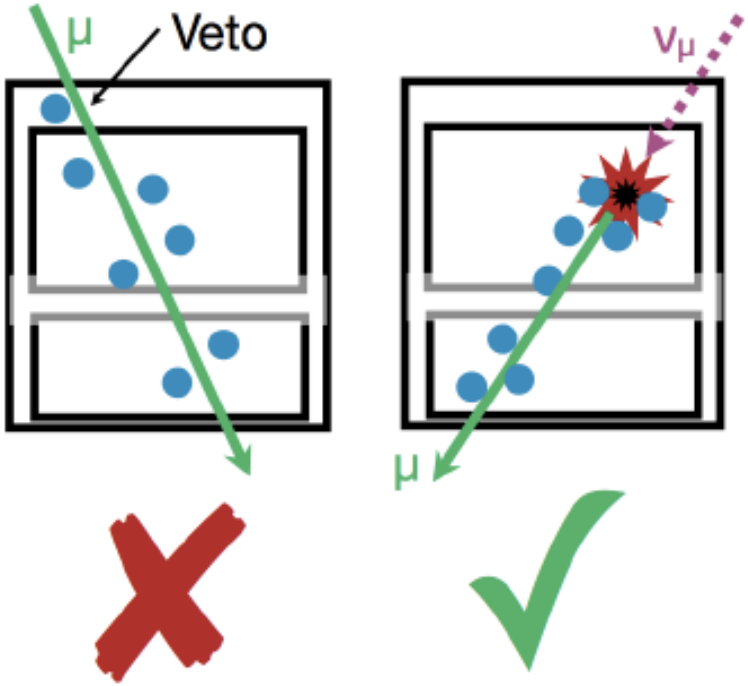
"double-bang" and other signatures (simulation)

HESE search

- Same dataset (“2 years” = 662 days).
- Containment at HE: (Q_{tot} > 6000 p.e.)
- Use atmospheric muon veto.
- Background:

*Atmospheric muons (mostly sneaking through the main dust layer): 6 ± 3.4 per 2 years (estimated from data using a tagging region).

*Atmospheric neutrinos: 4.6 + 3.7 – 1.2 events in 2 years (large uncertainties at high energies).



HESE search

28 observed events!

Background: $10.6^{+5}_{-3.6}$

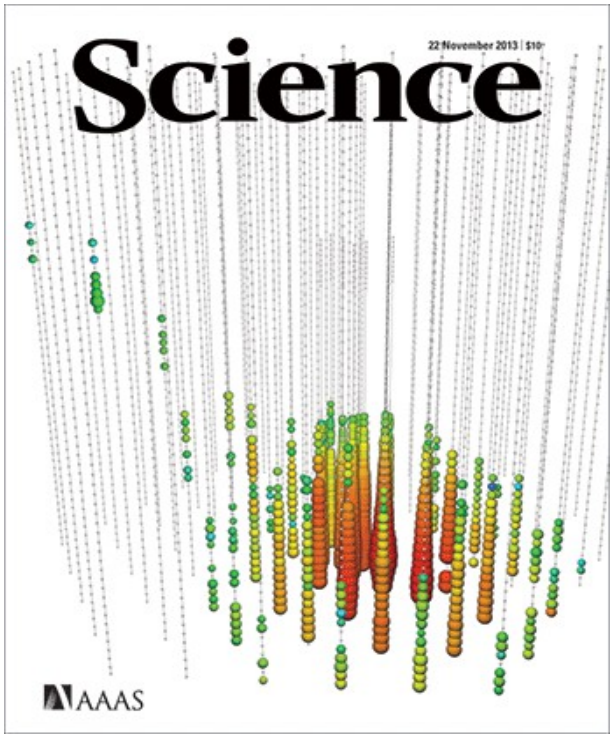
Significance:

3.3σ for 26 events,

combining with 2.8σ from PeV neutrinos:

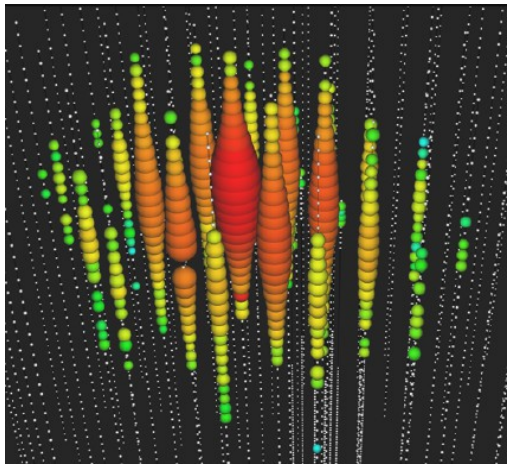
4.1σ for 28 events.

Science 342, 1242856 (2013)



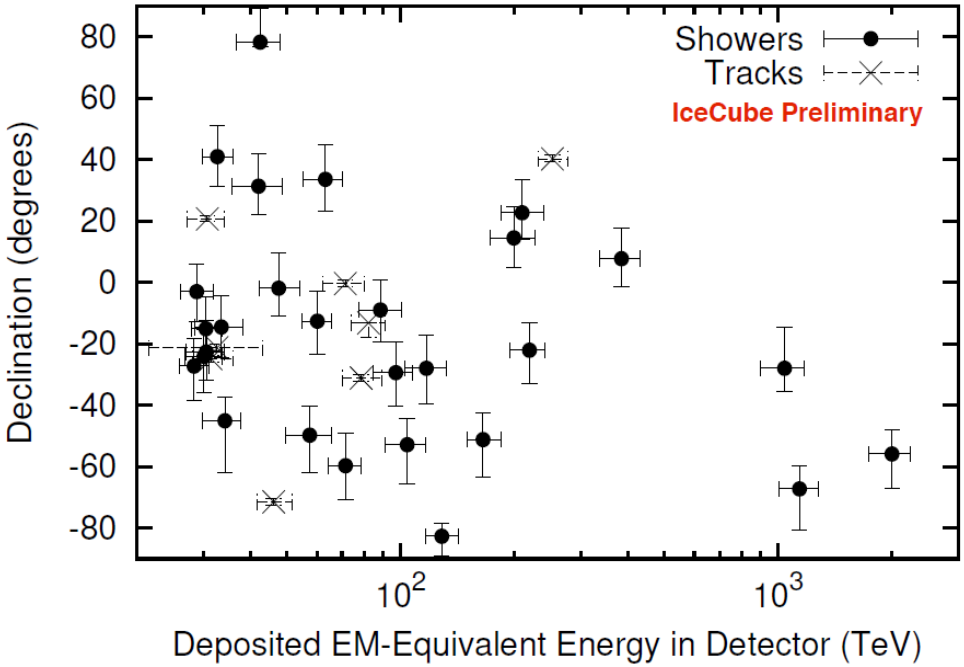
HESE search

Update: one more year of data
37 events observed in 3 years



Background:
$6.6\ ^{+5.9}_{-1.6}$ atm. neutrinos
8.4 ± 4.2 atm. muons

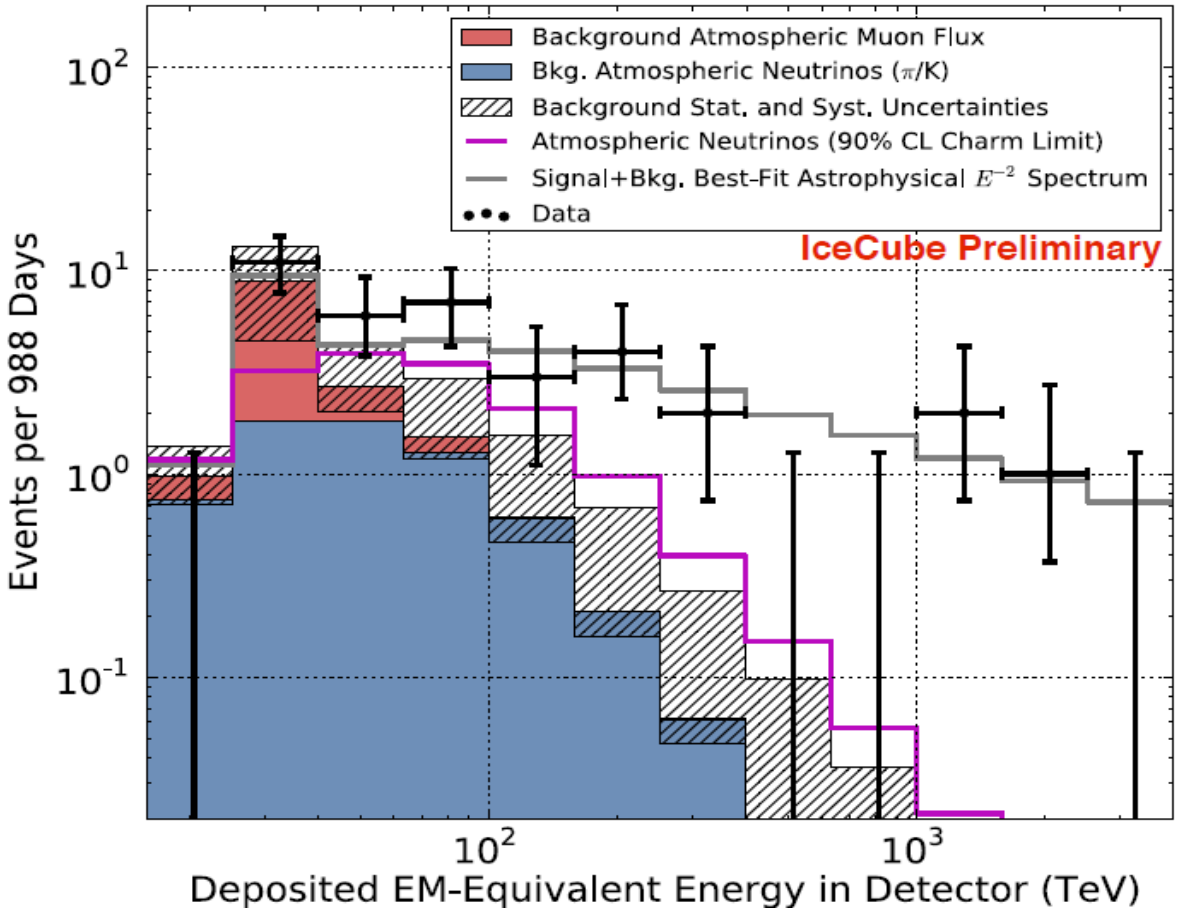
Preliminary significance (full likelihood fit of all components):
5.7σ
w.r.t reference background



PRL 113, 101101 (2014)

HESE search

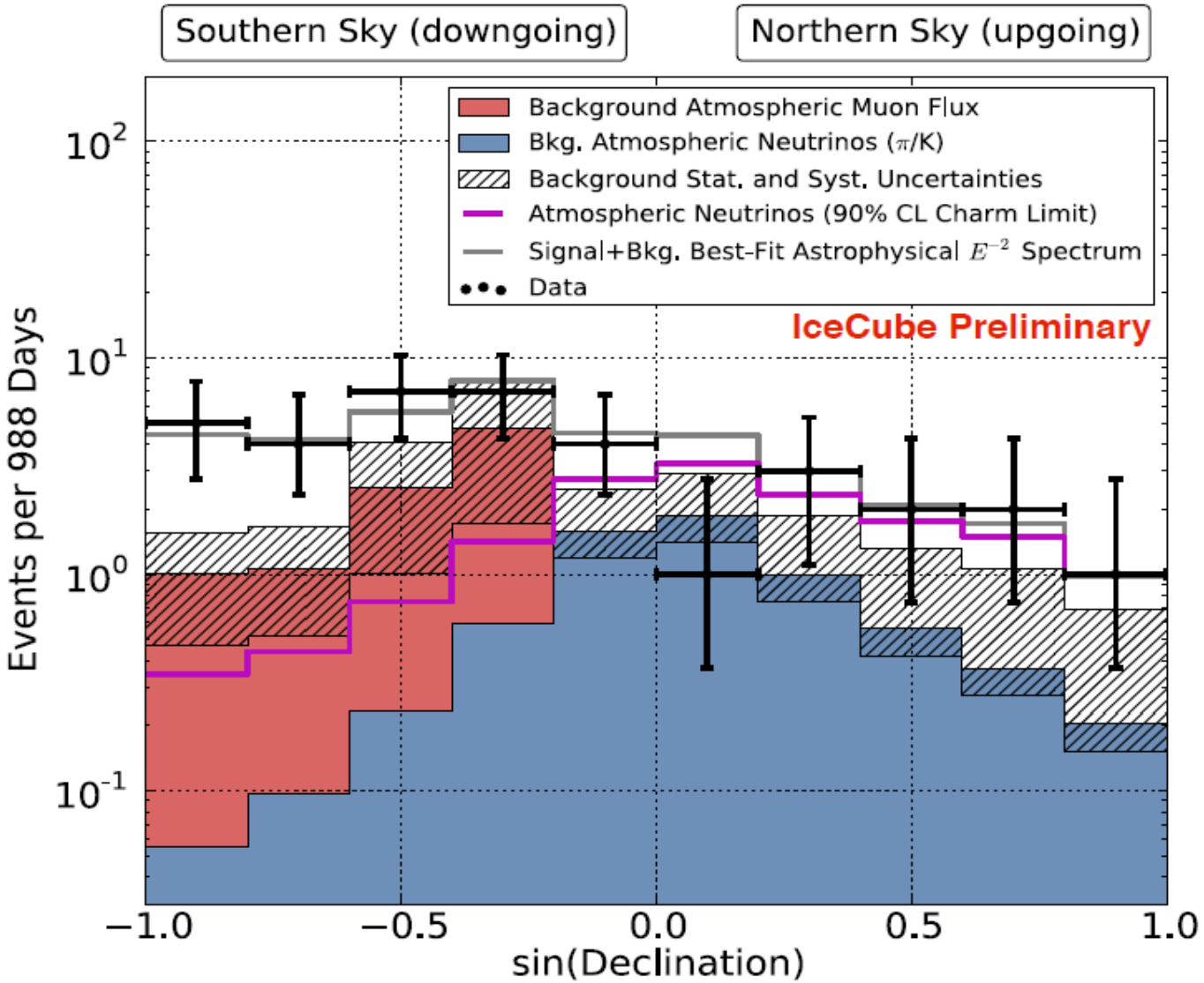
Energy spectrum:



- Harder than any expected atmospheric background.
- Compatible with benchmark E^{-2} astrophysical model.
- Potential cutoff at about few PeV
- Best fit: $(0.95 \pm 0.3)\ 10^{-8}$ E^{-2} GeV cm^{-2} s^{-1} sr^{-1} per flavor.

HESE search

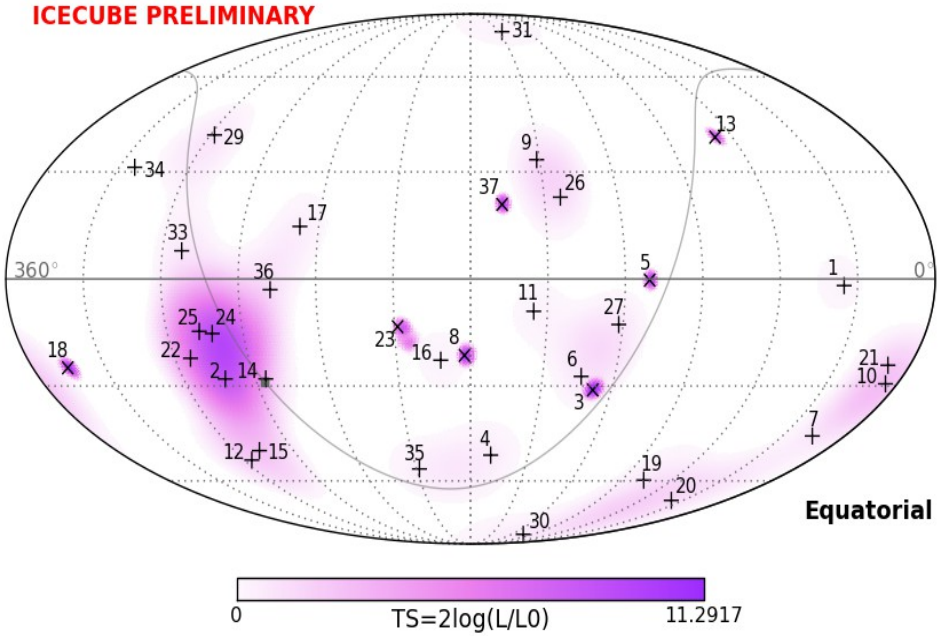
Declination distribution:

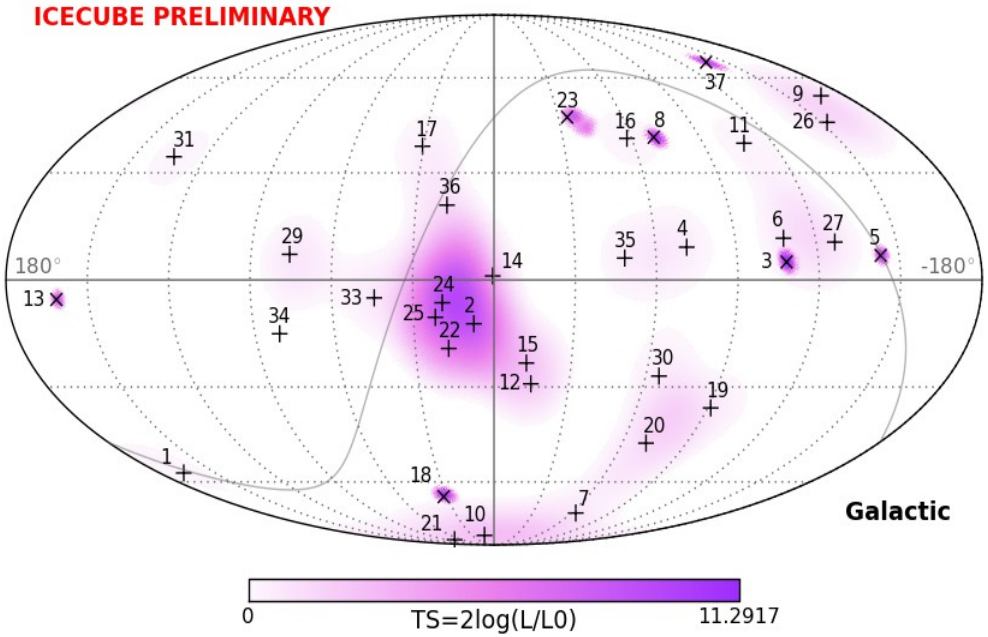


Events from Northern Hemisphere absorbed in Earth.

Compatible with isotropic flux.

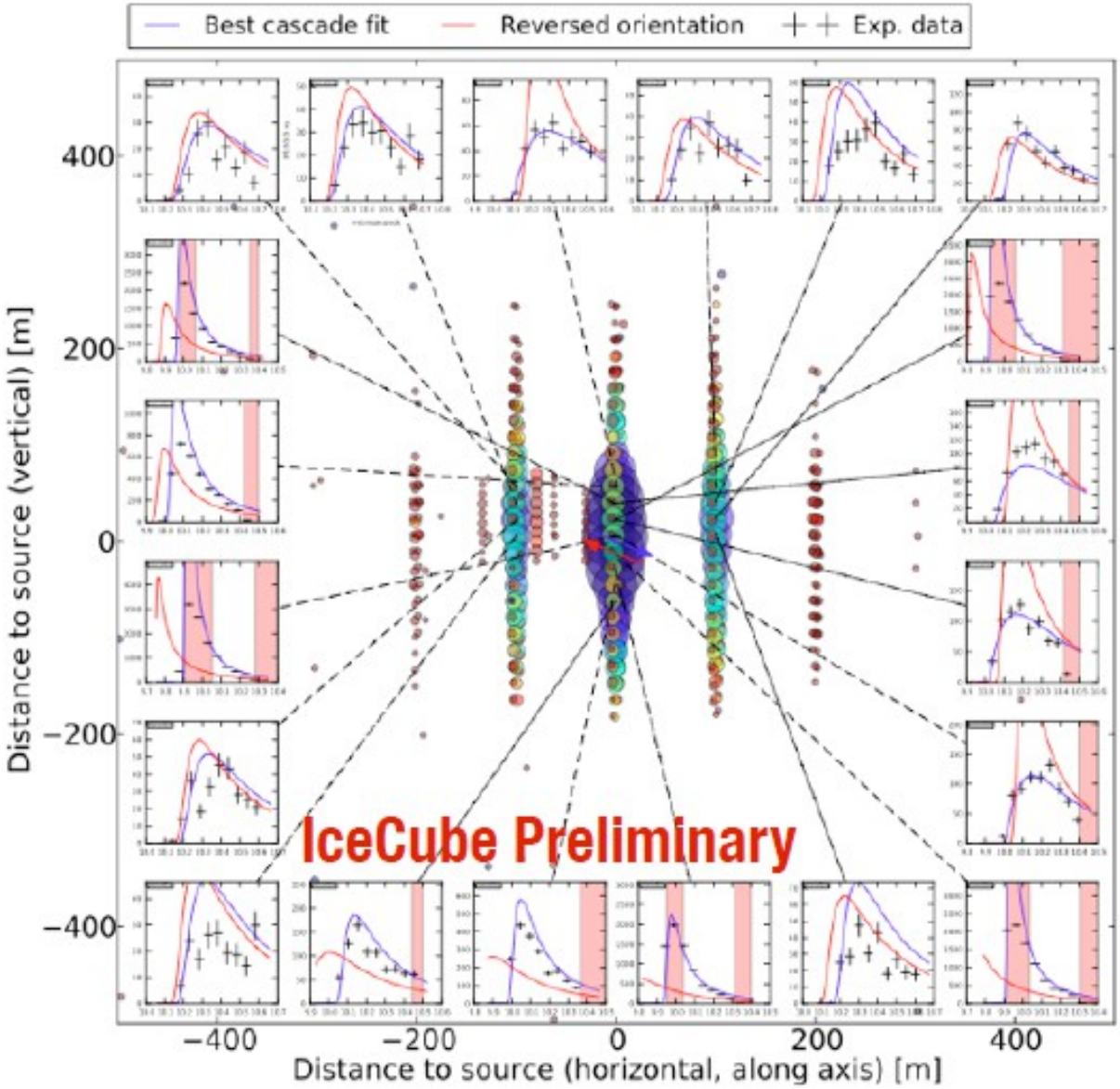
HESE search



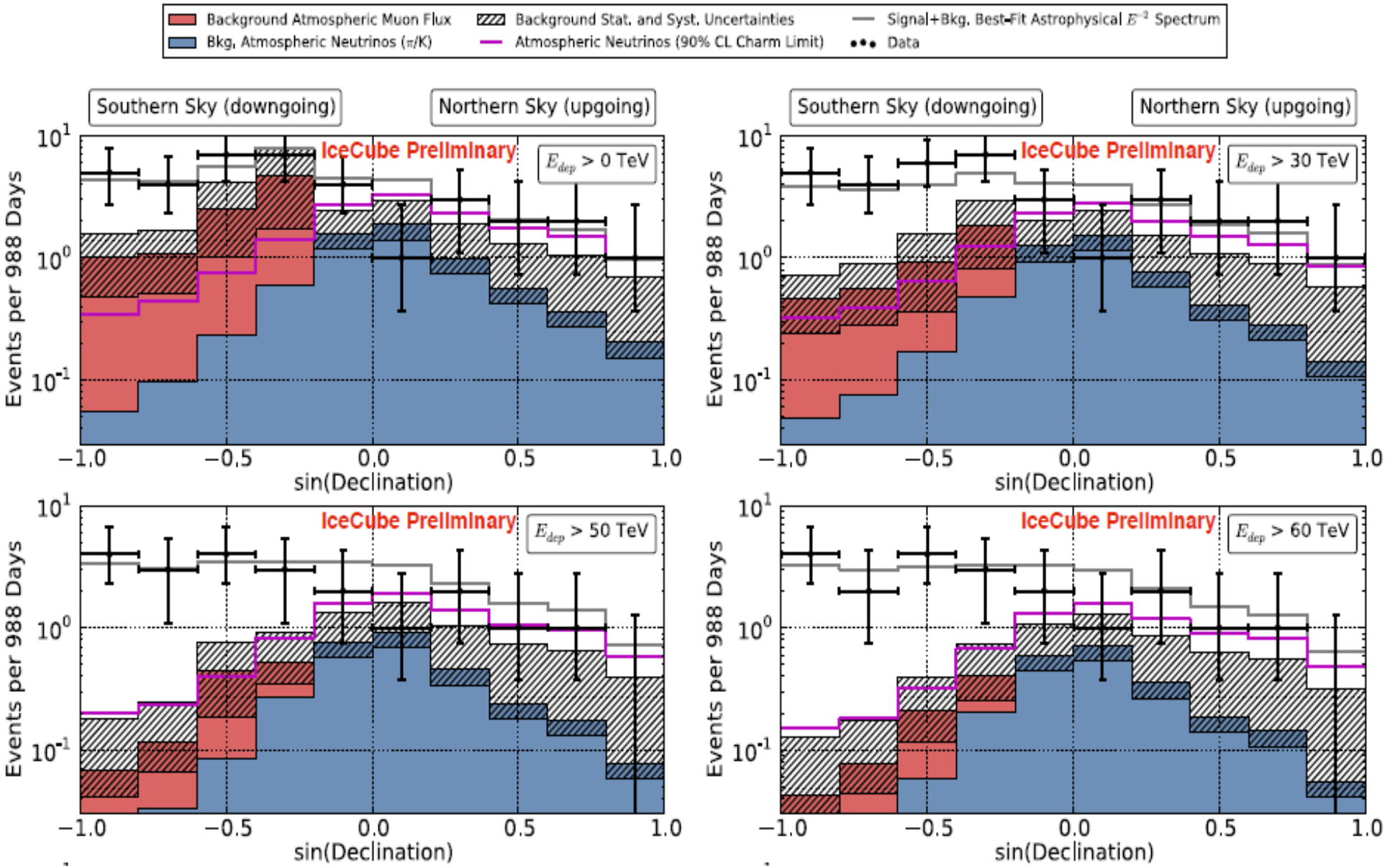


No significant clustering observed in position or time.
(cluster close to the GC has a P-value of 7%)

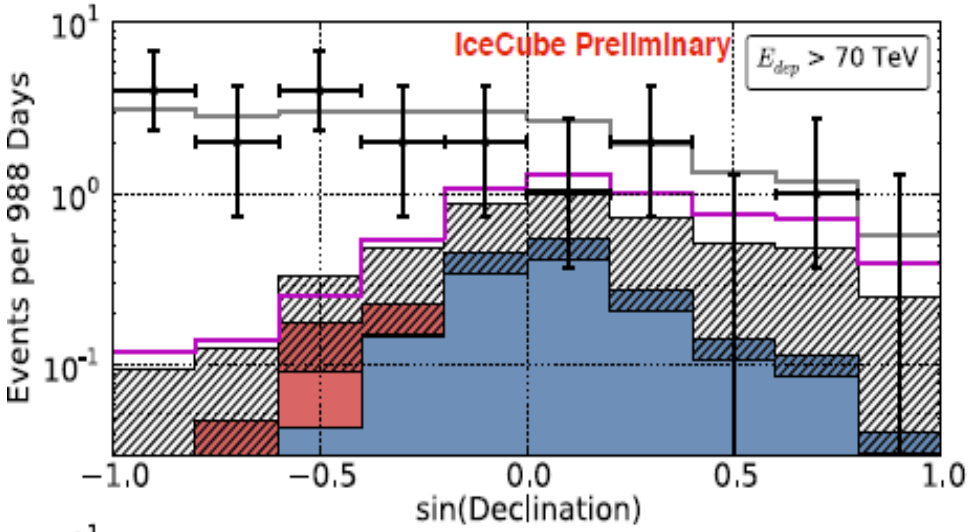
Cascade reconstruction

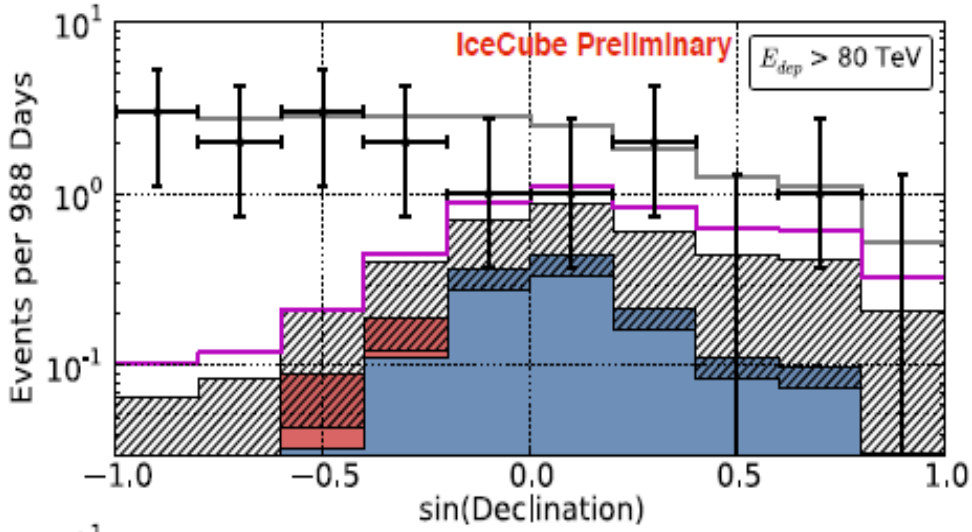


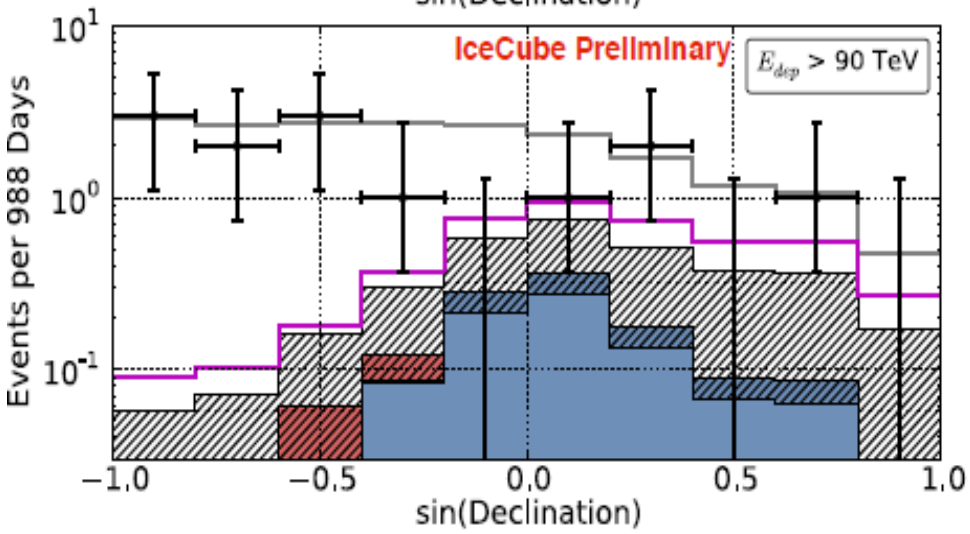
HESE zenith distribution

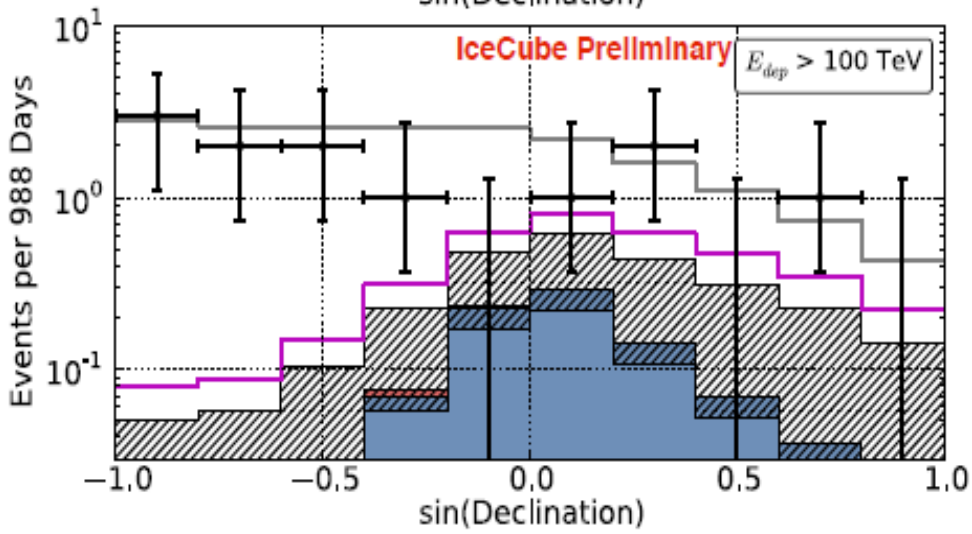


HESE zenith distribution

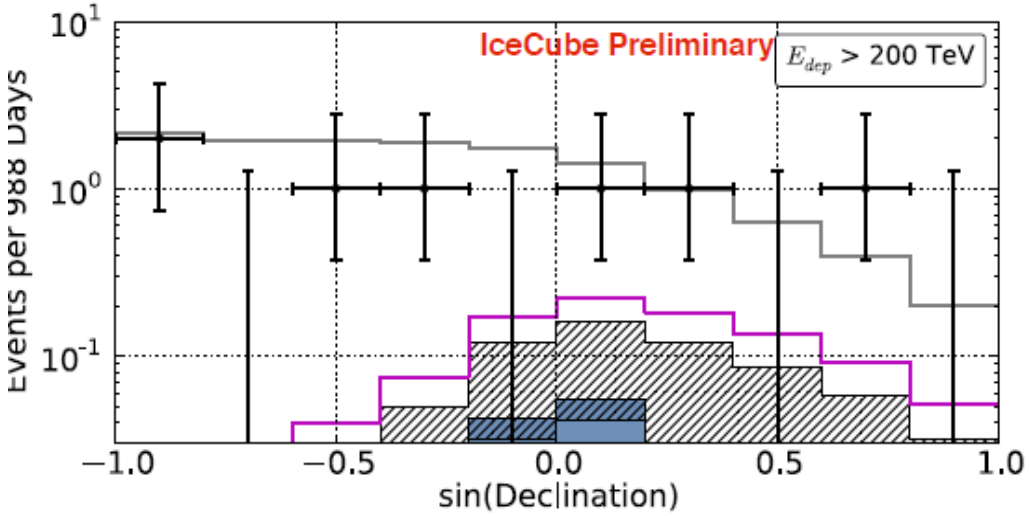


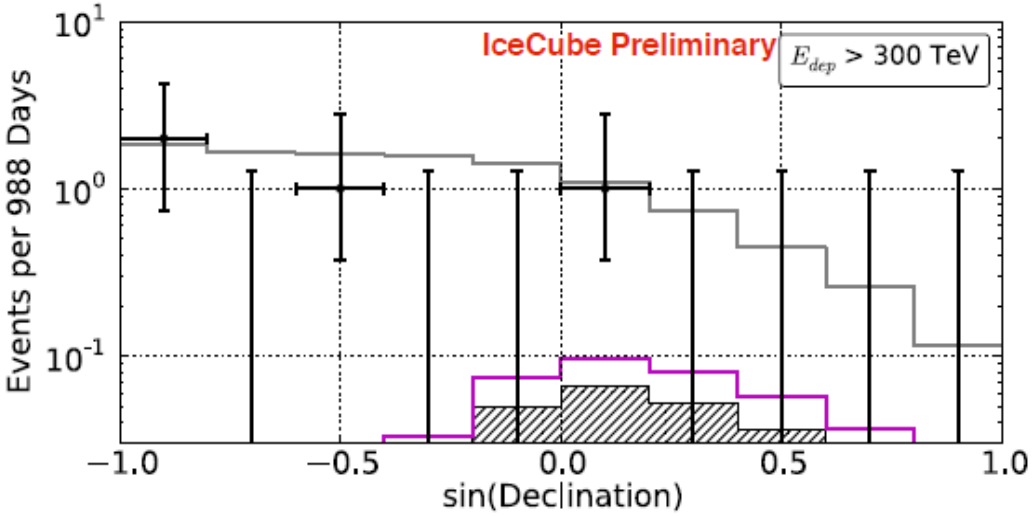




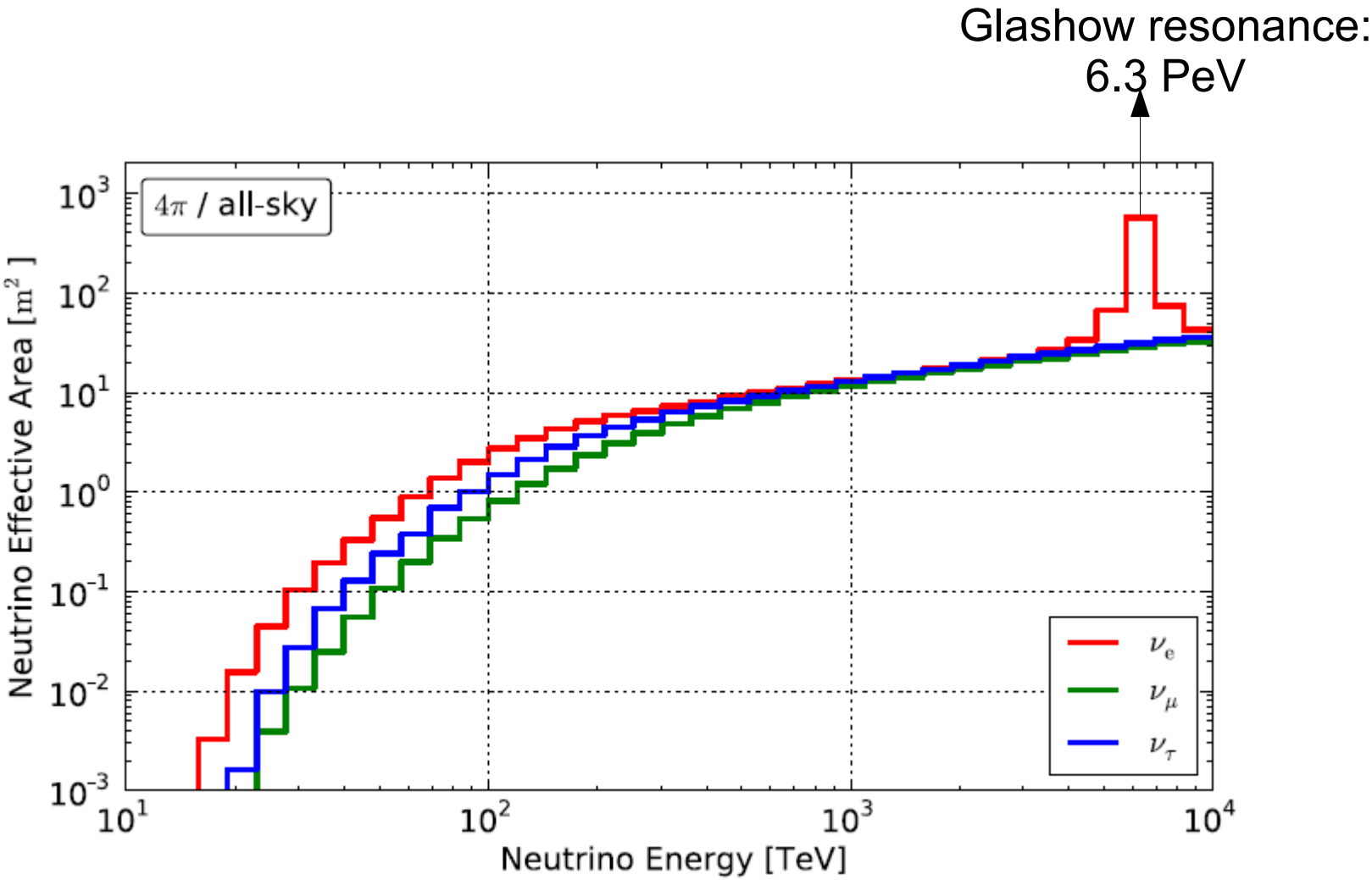


HESE zenith distribution

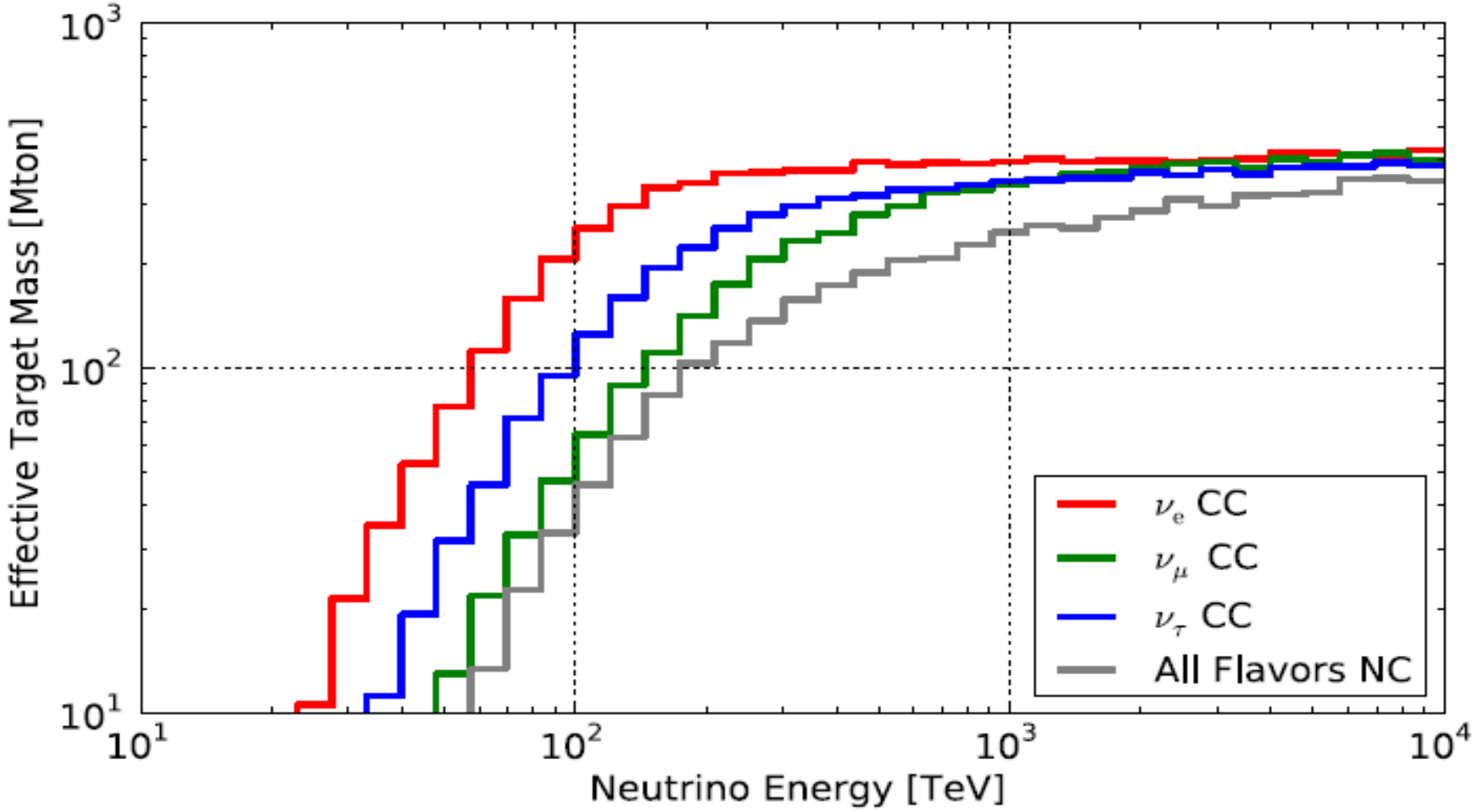




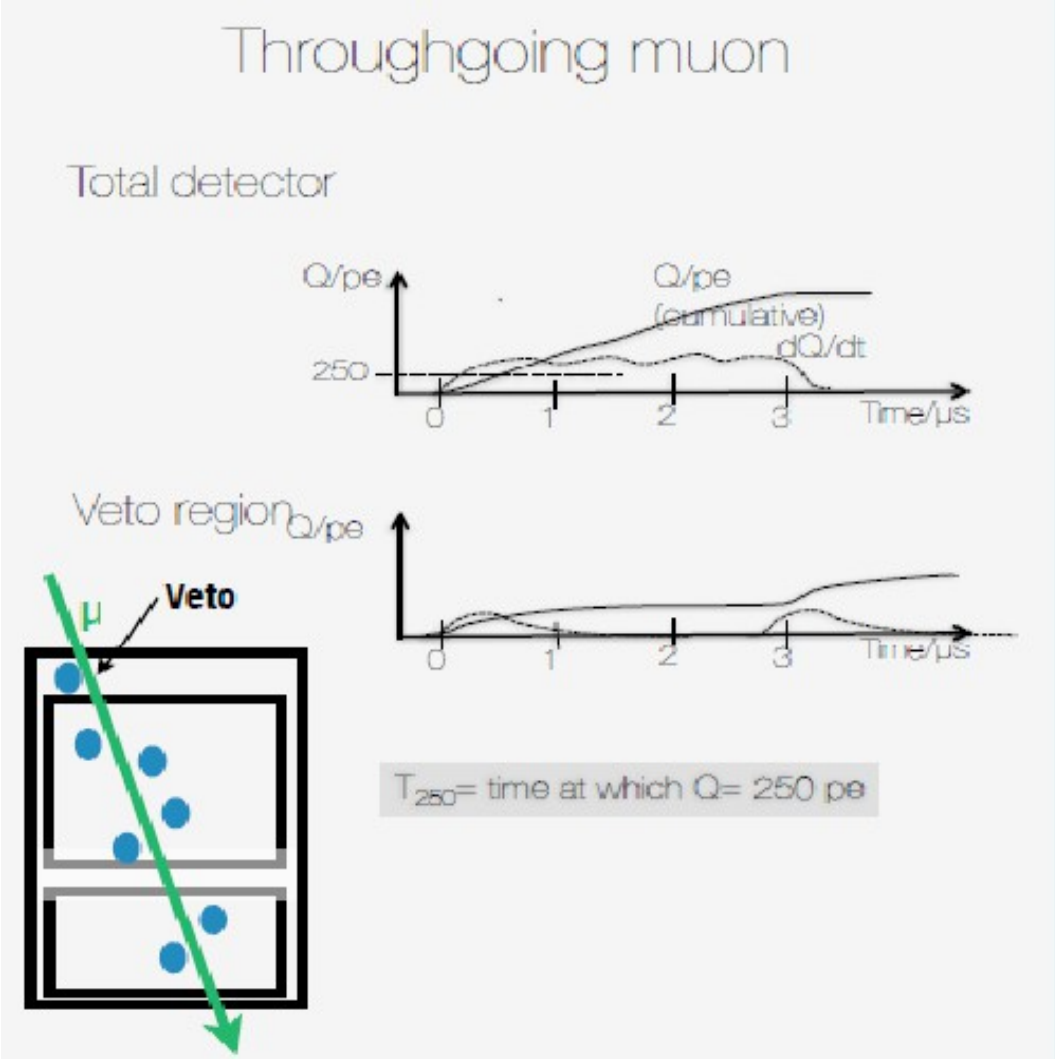
HESE effective area

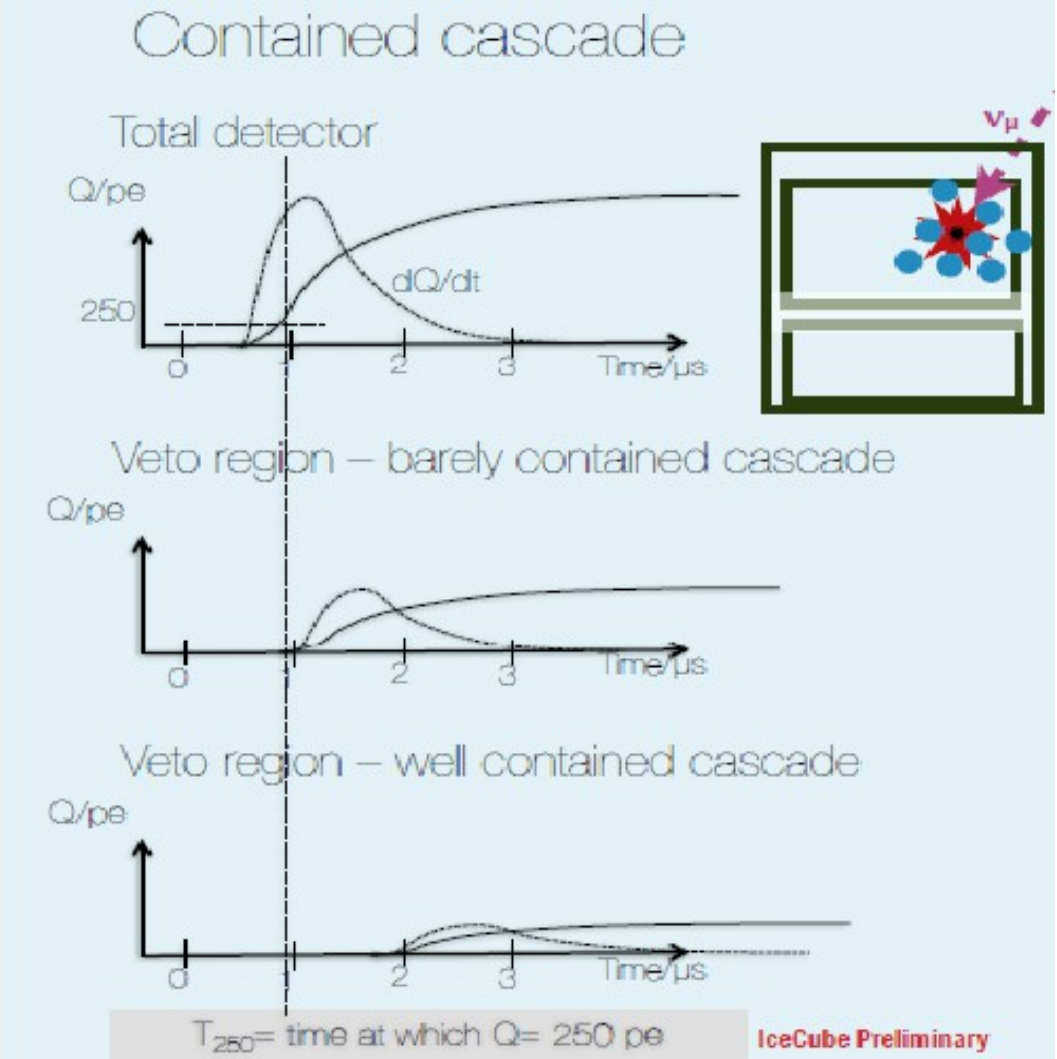


HESE effective volume



HESE
Atmospheric muon background





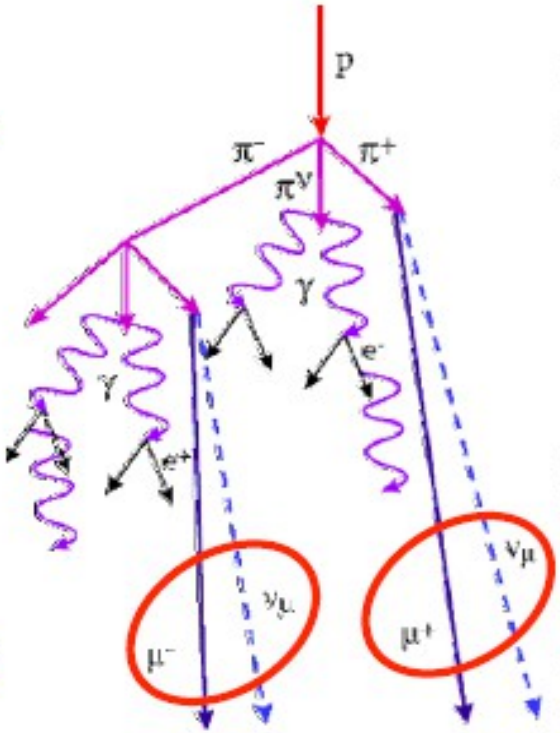
HESE

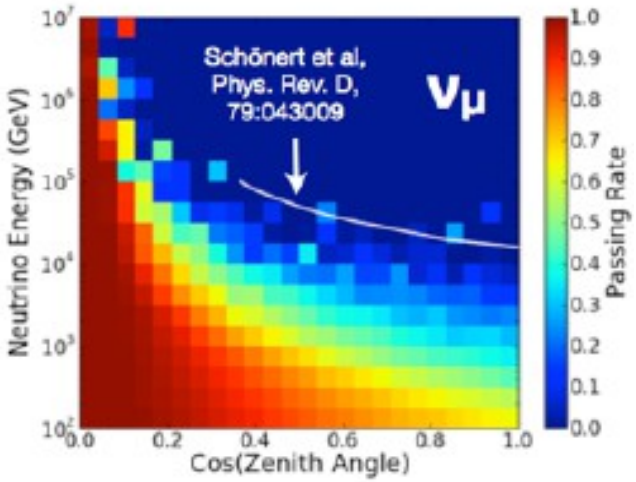
- atmospheric muons
  - estimated from data (tag events on outer layer)

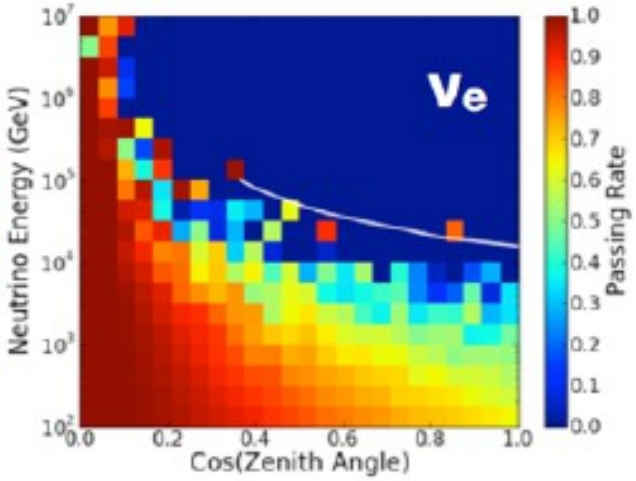
6 ± 3.4 μ's

- atmospheric neutrinos
  - reject events with accompanied muons for > 60 TeV (**self-veto**)

$4.6\ ^{+3.7}_{-1.2}$ ν's



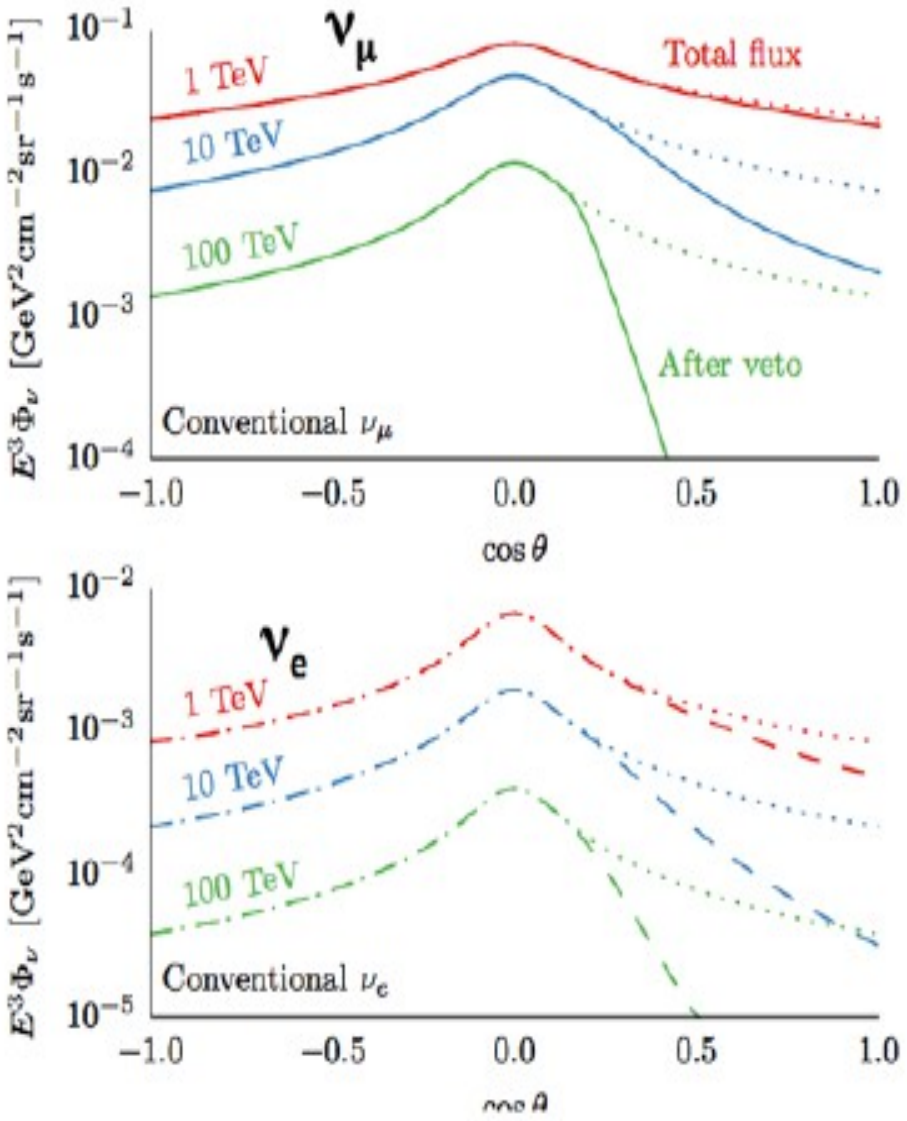


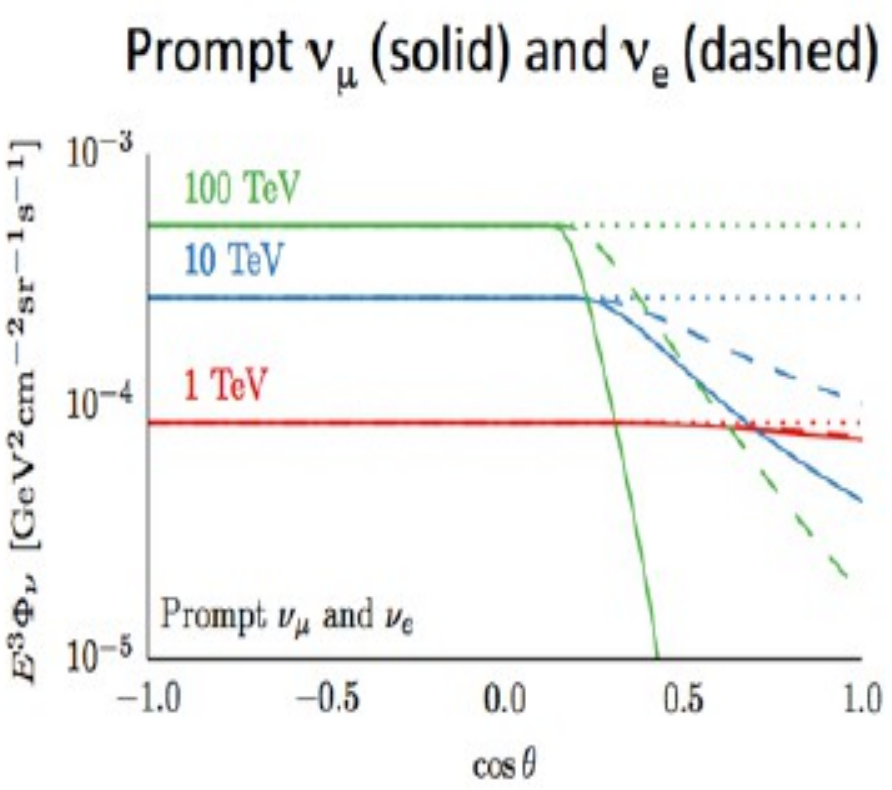


Plots courtesy of K. Jero (UW-Madison)

(P. Desiati)

HESE
Down-going self-veto

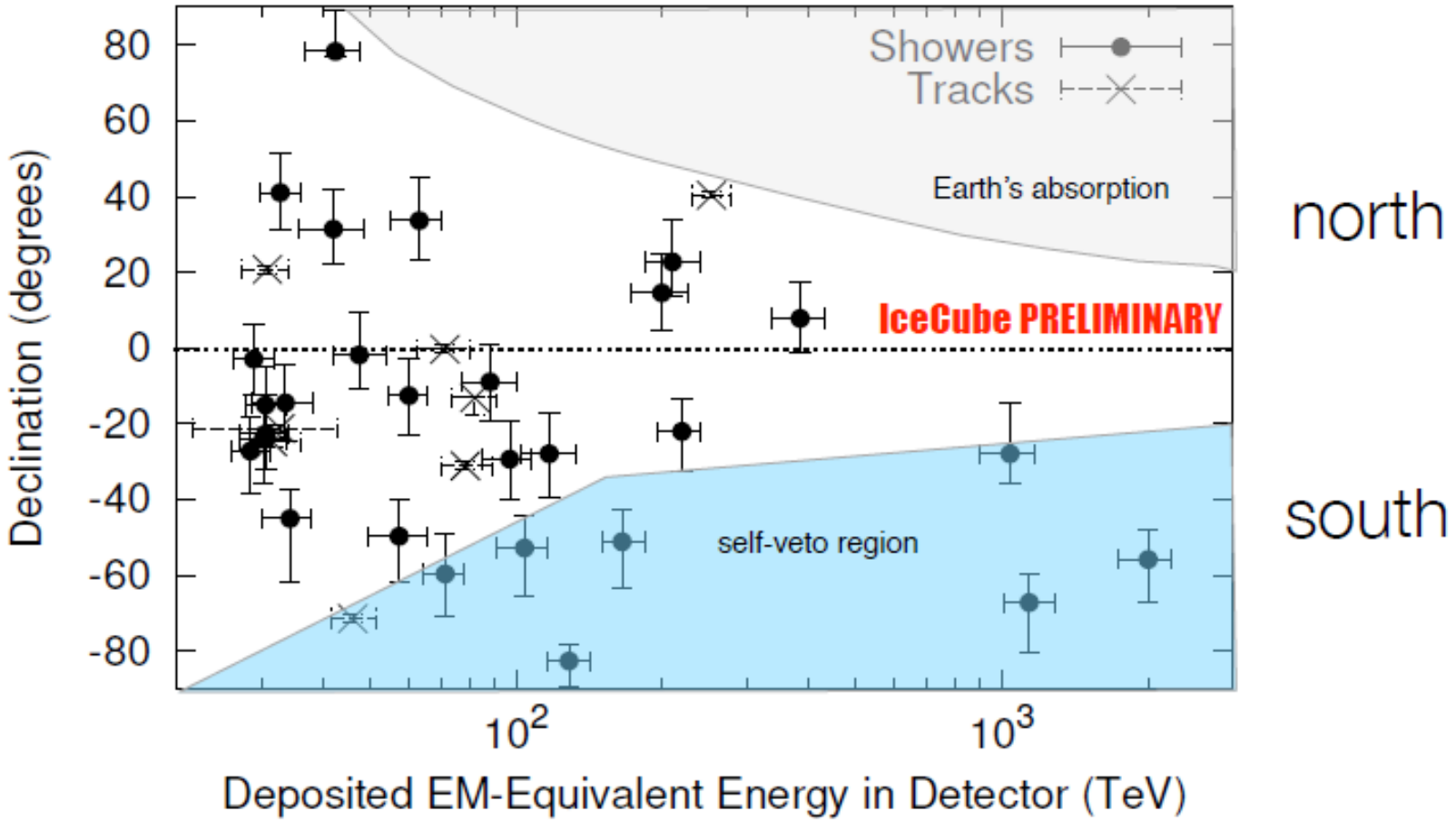




Gaisser, Jero, Karle, van Santen,
Phys. Rev. D, 90:023009 (2014)

(P. Desiati)

HESE

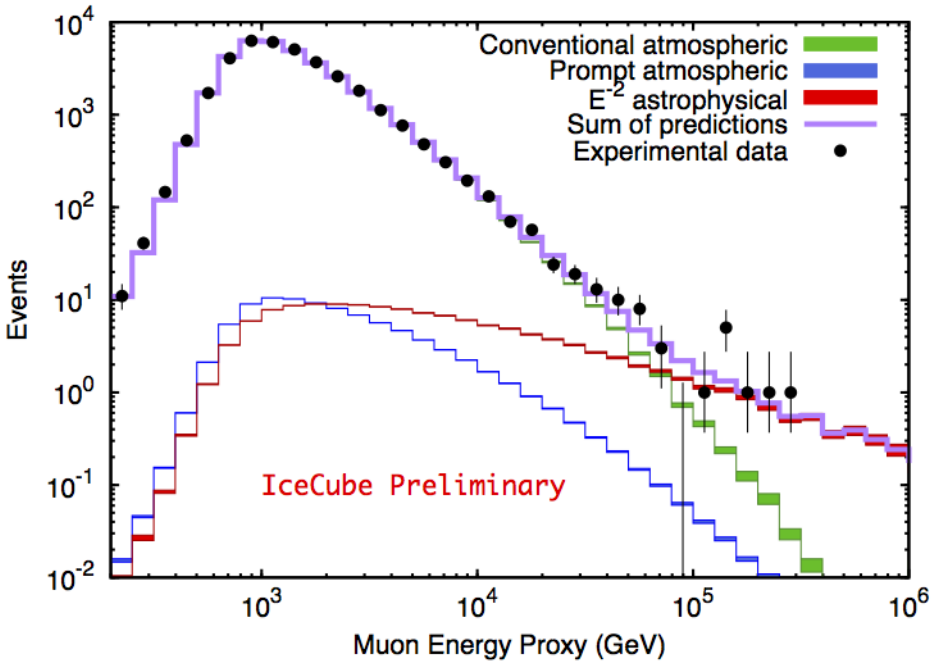


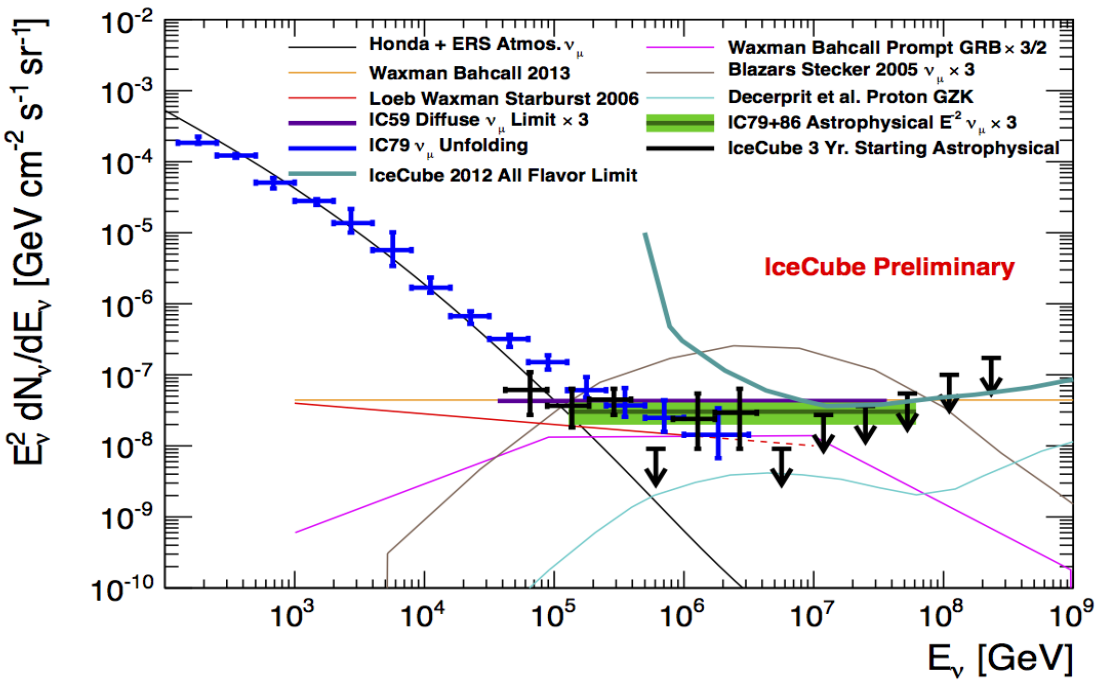
(P. Desiati)

Diffuse muon neutrinos

IceCube Preliminary

IC79+IC86-I data, only considering up-going events

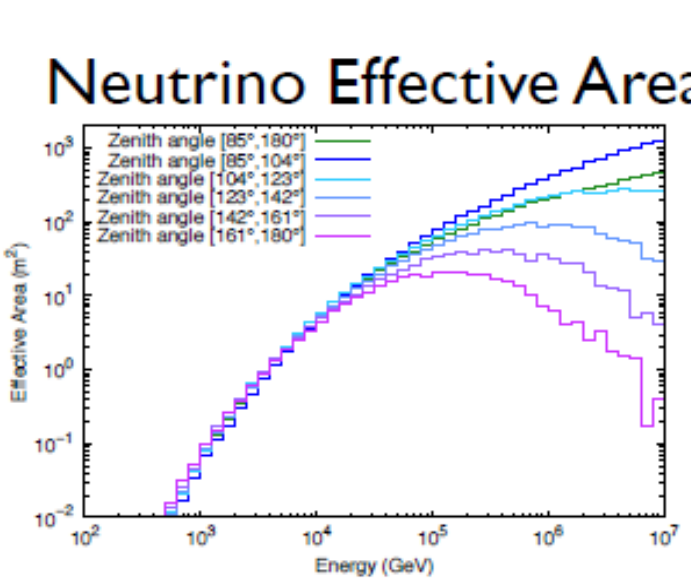


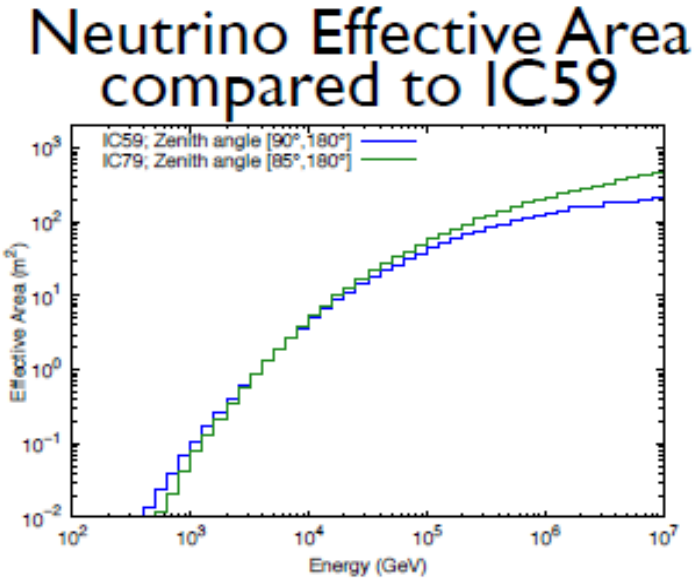


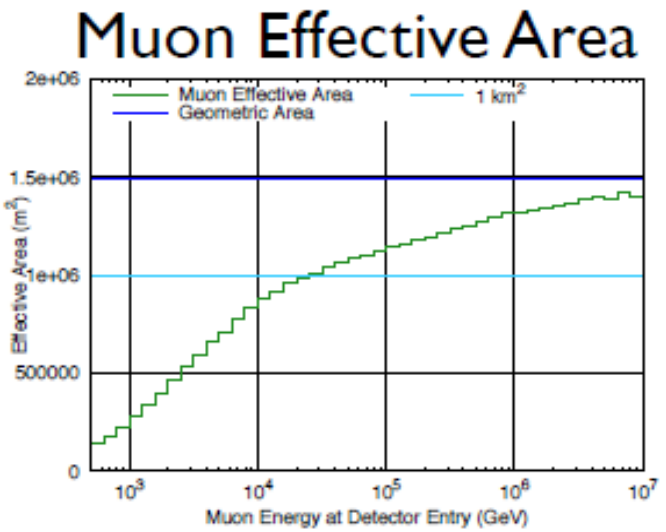
Evidence for a cosmic neutrino flux found at levels of around 10^{-8} E^{-2} GeV cm^{-2} s^{-1} sr^{-1} per flavor with a significance of 3.9σ over atmospheric expectation.

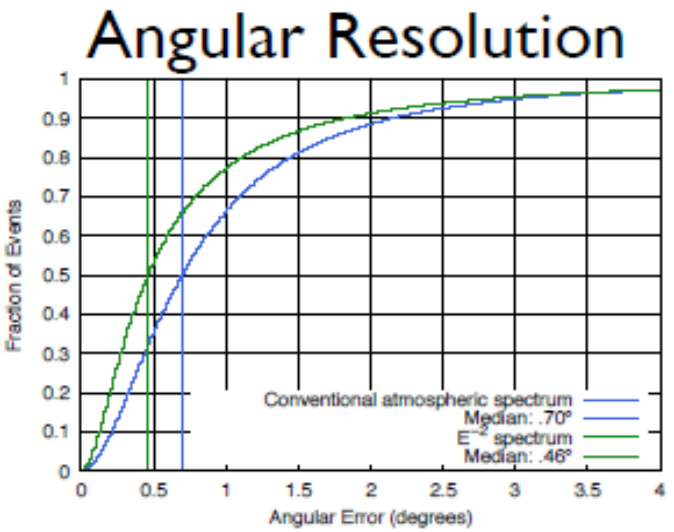
$$E^2 \phi(E) = (0.96 \pm 0.35)\ 10^{-8}\ \text{GeV cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$

Diffuse muon neutrinos

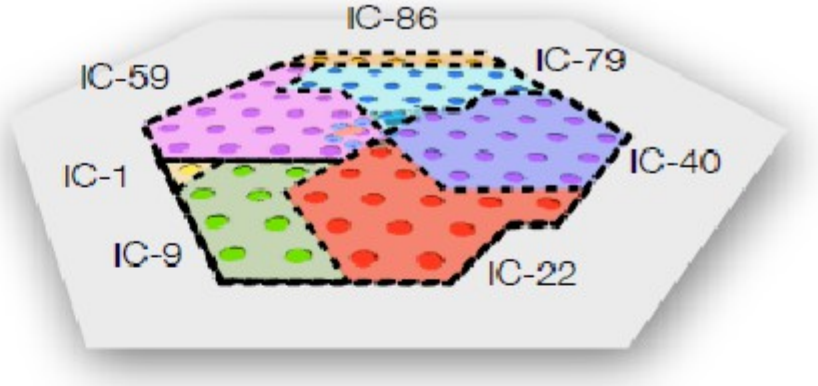






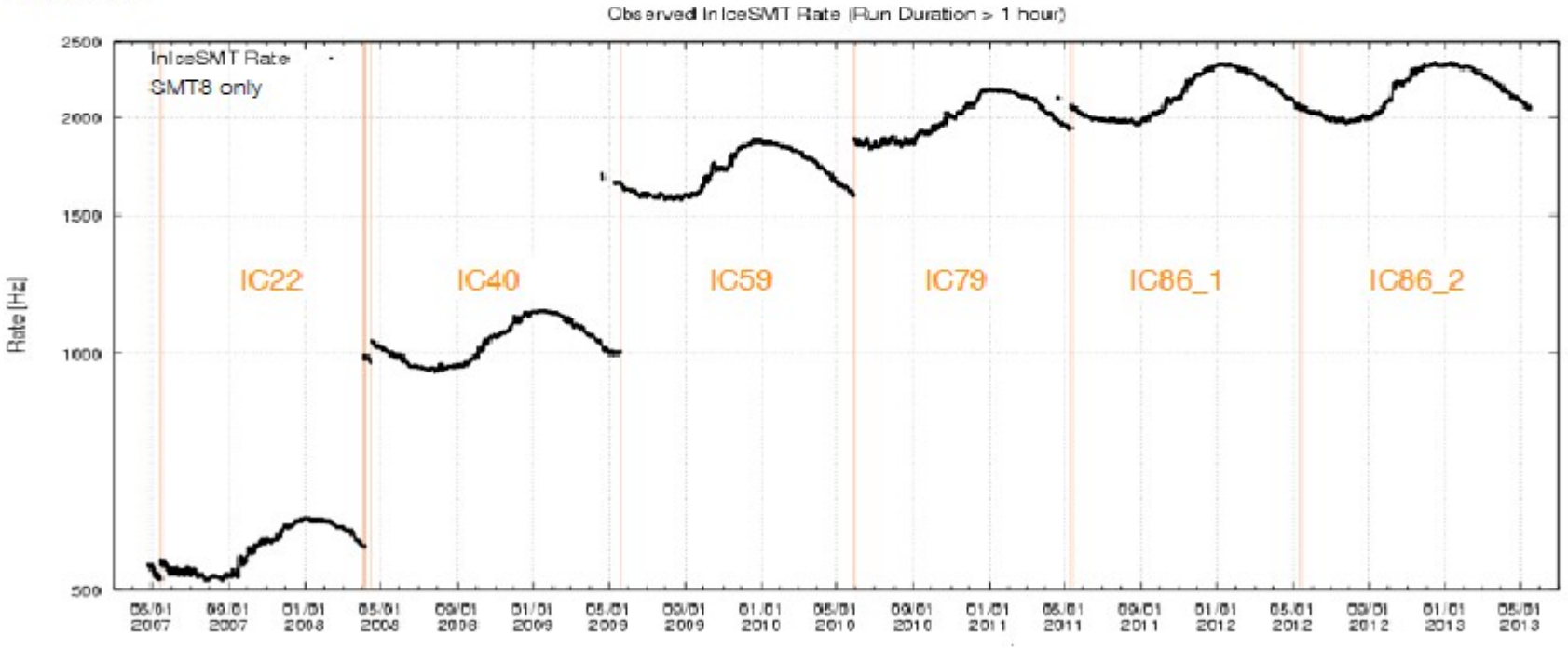


Event collection



Strings	Year	μ rate	number of ν
IC22	2007	500 Hz	~20 / day
IC40	2008	1100 Hz	~40 / day
IC59	2009	1700 Hz	~70 / day
IC79	2010	2000 Hz	>100 /day
IC86-1,2,3	2011+	2200 Hz	~200 / day

(*) SMT8 rate



(P. Desiati)