HIGH ENERGY NEUTRINOS @ *ICECUBE*

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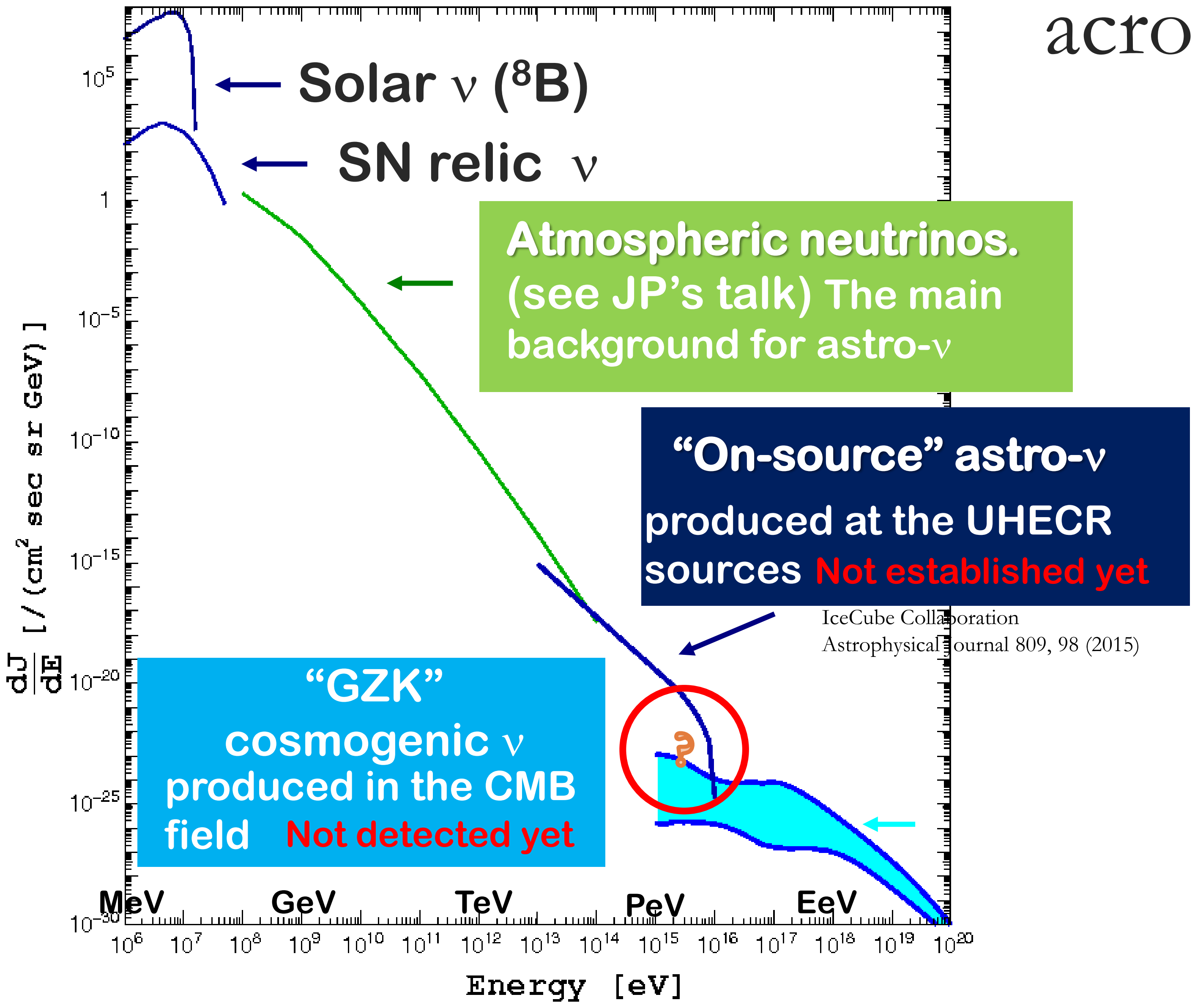
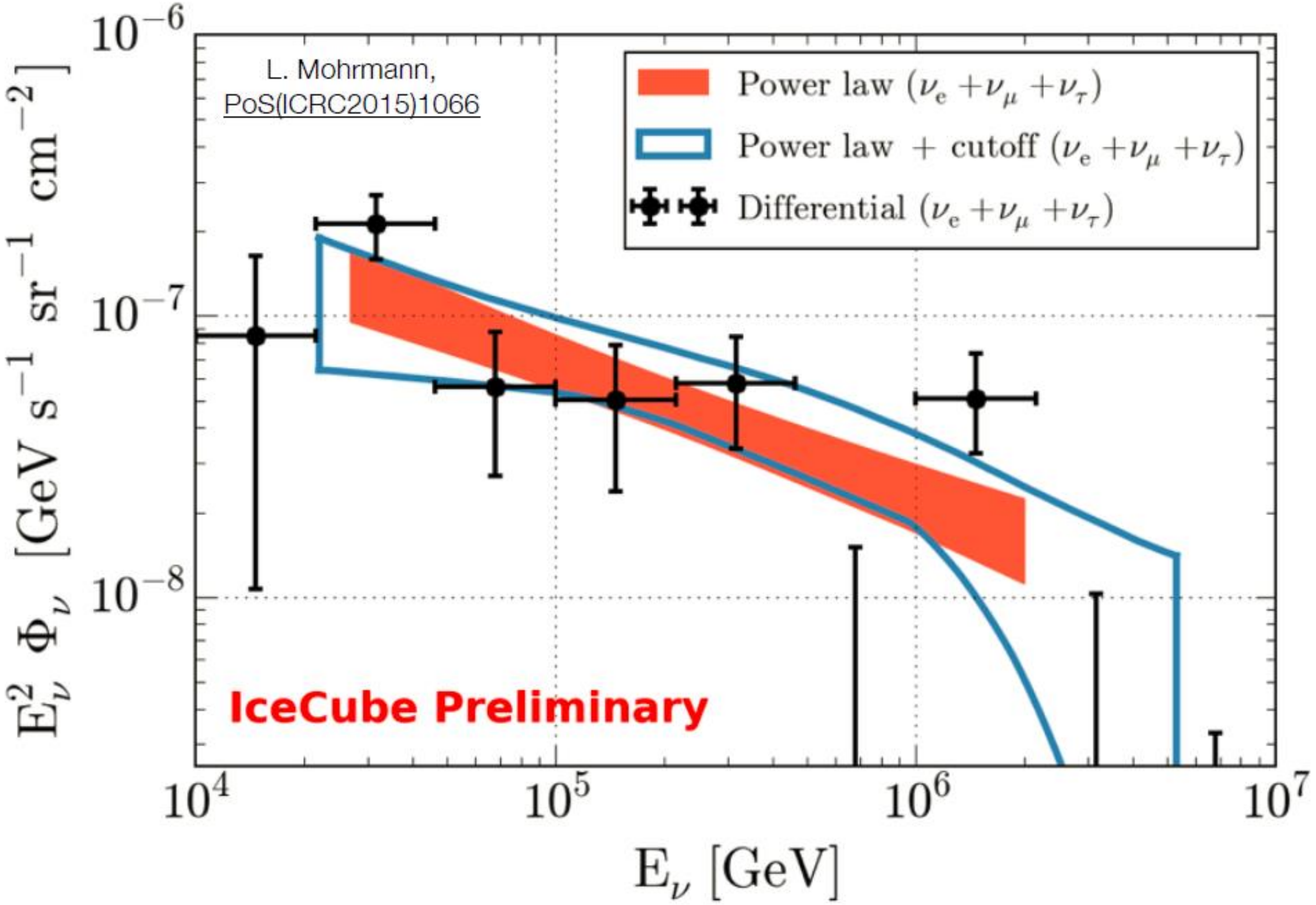
IceCube: Rich physics goals across 10 decades of energy

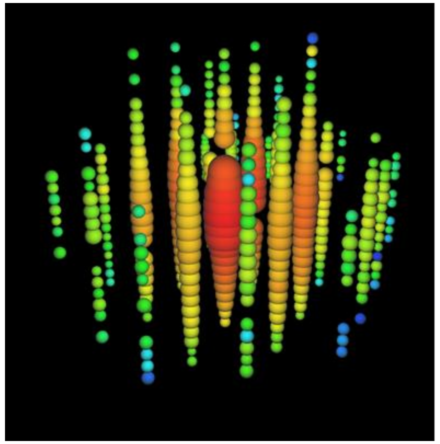


- Low energy neutrinos:
  - Neutrino oscillations
  - Indirect dark matter searches
- **High energy neutrinos**
  - Steady point source (arrival direction and correlation with cluster)
  - Transients (e.g. GRB) analyses
  - **Excess of diffuse neutrino flux over atmospheric neutrino background**
  - Charm production
  - **Ultra-high energy neutrinos (GZK)**
- Cosmic rays
  - Cosmic-ray composition
  - Anisotropy
  - Hadronic interaction models

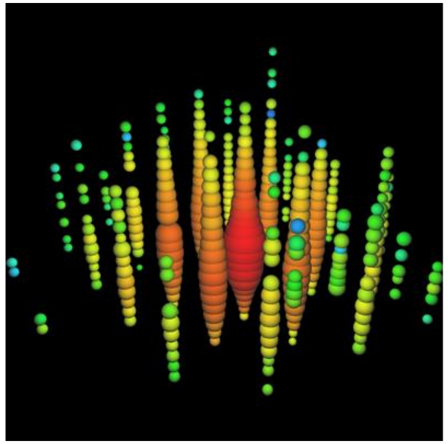
Astrophysical neutrinos observed – but we expect to see cosmogenic neutrinos with **even higher energy**

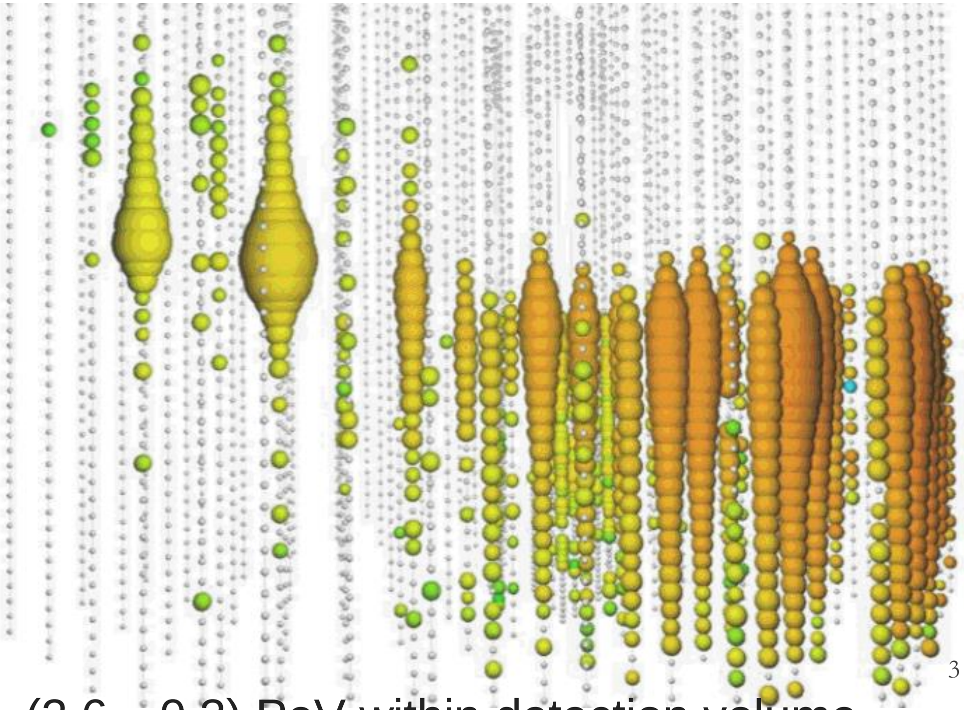


1.04 ± 0.16 PeV

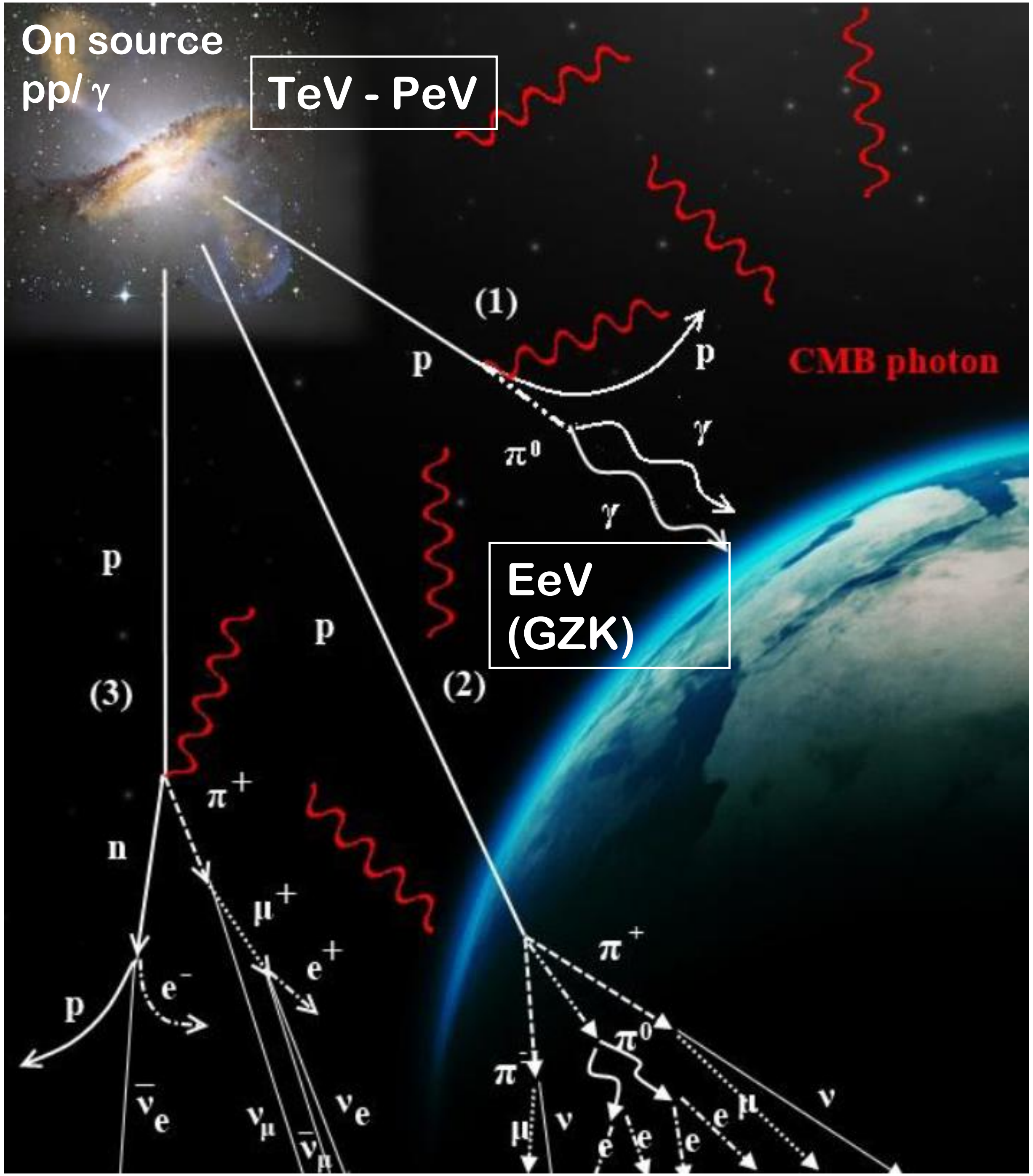


1.14 ± 0.17 PeV





(2.6 ± 0.3) PeV within detection volume



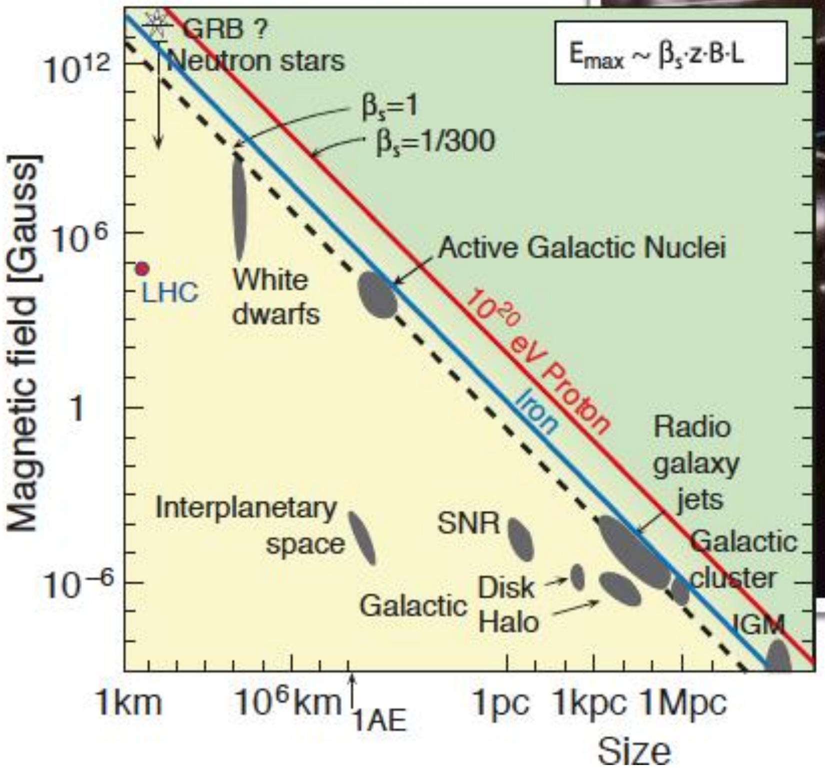
High energy neutrinos from deep Universe

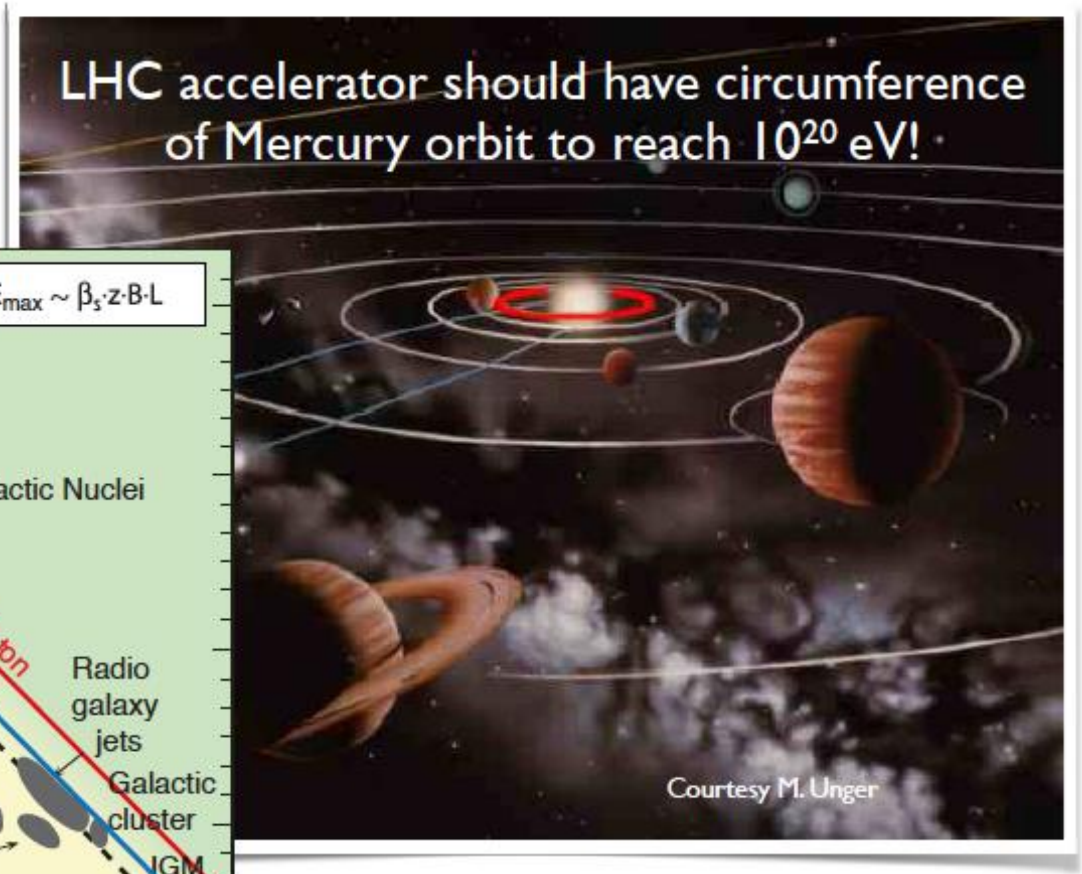
$$p + p \rightarrow p + p + \pi^{\pm/0}$$
$$p + \gamma \rightarrow n + \pi^{+}$$
$$\rightarrow p + \pi^{0}$$

- Nuclei (cosmic-rays): deflected
- Gamma-ray: can be absorbed
- ν: travel in straight lines and difficult to be absorbed

Approaching **Ultra High Energies…**

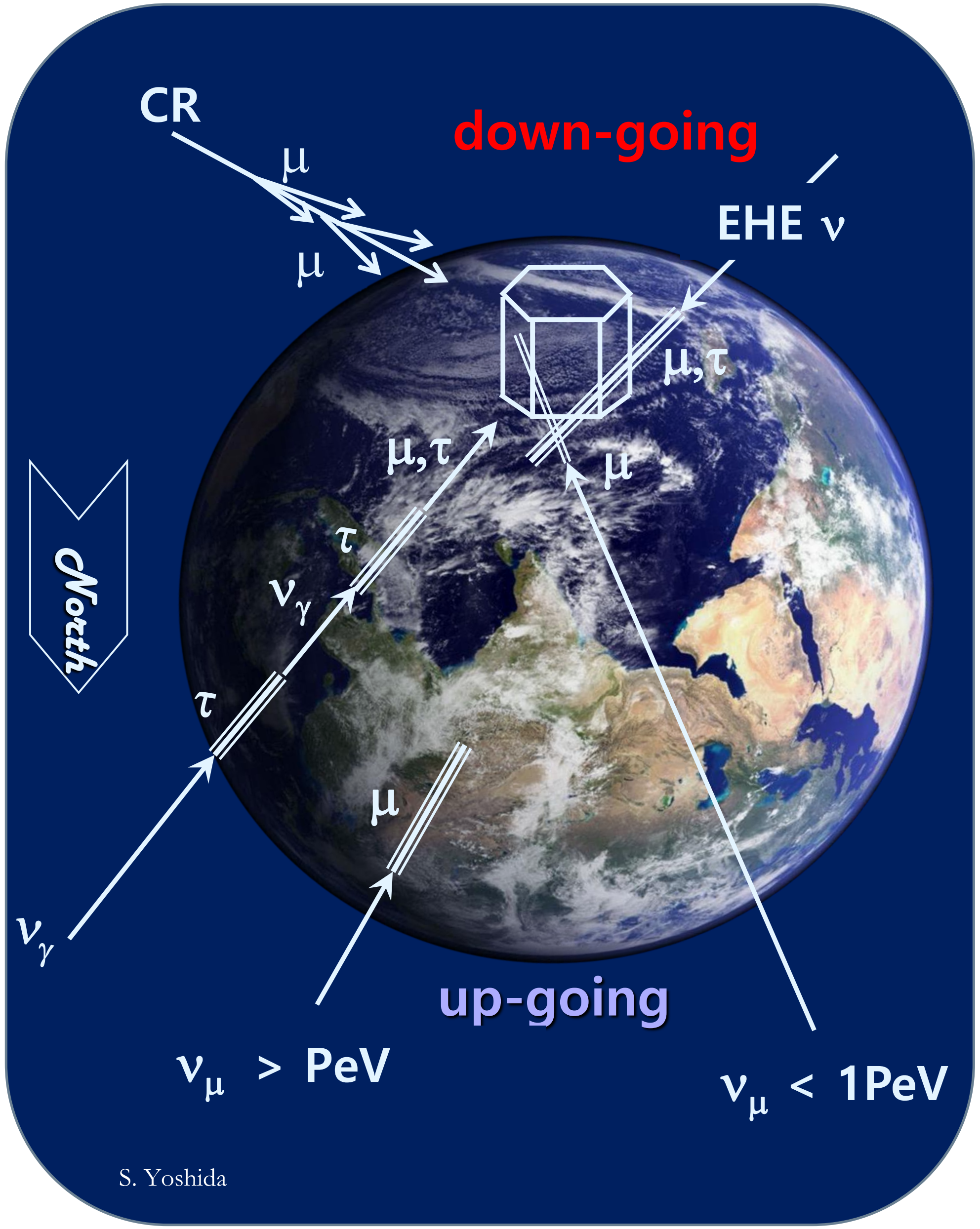
Hillas plot (1984)

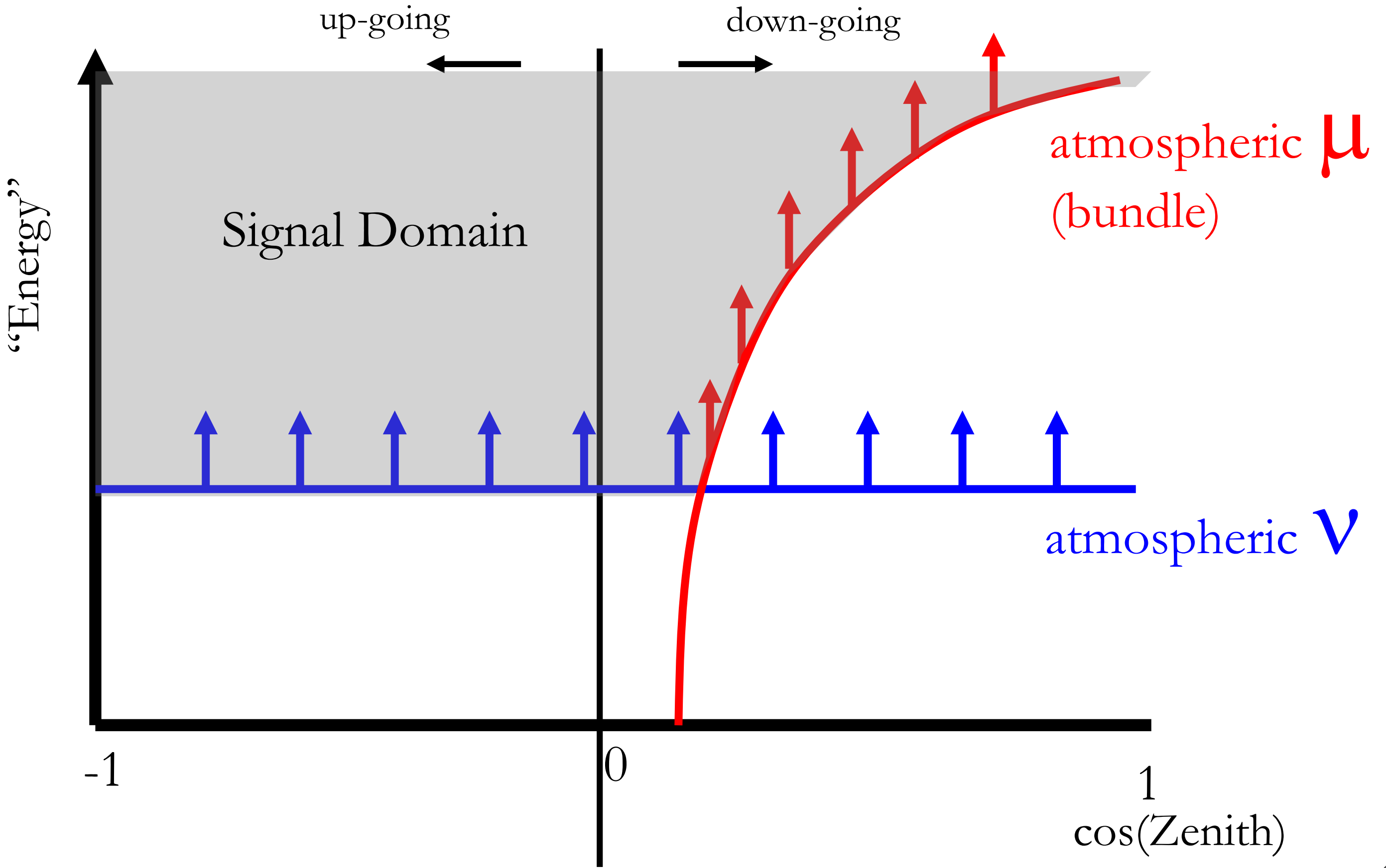




- We measure cosmic rays of energy **10^{20} eV**, but where are they from?
- What is the **mass composition** of the cosmic rays?
- How were they **accelerated** to such high energies?
- Neutrinos do not carry charge can **point back to the origin**.
- **Neutrinos are indirect test of mass composition and source models.**

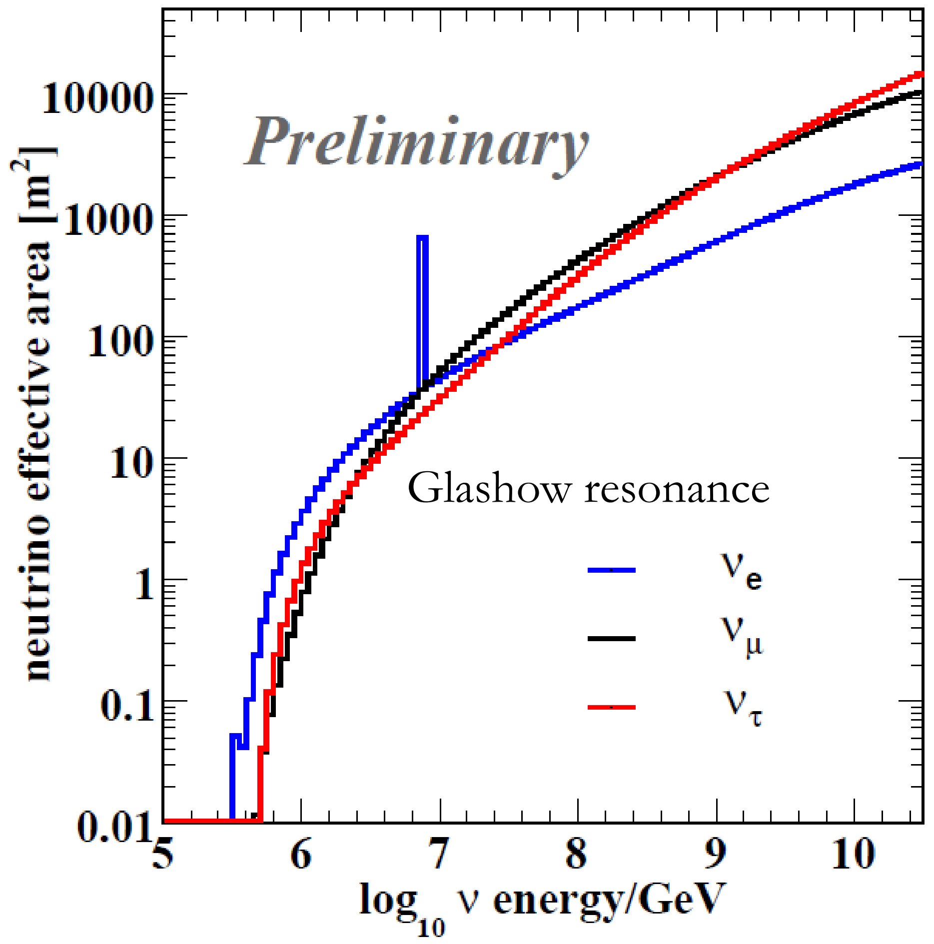
Signatures of UHE neutrinos

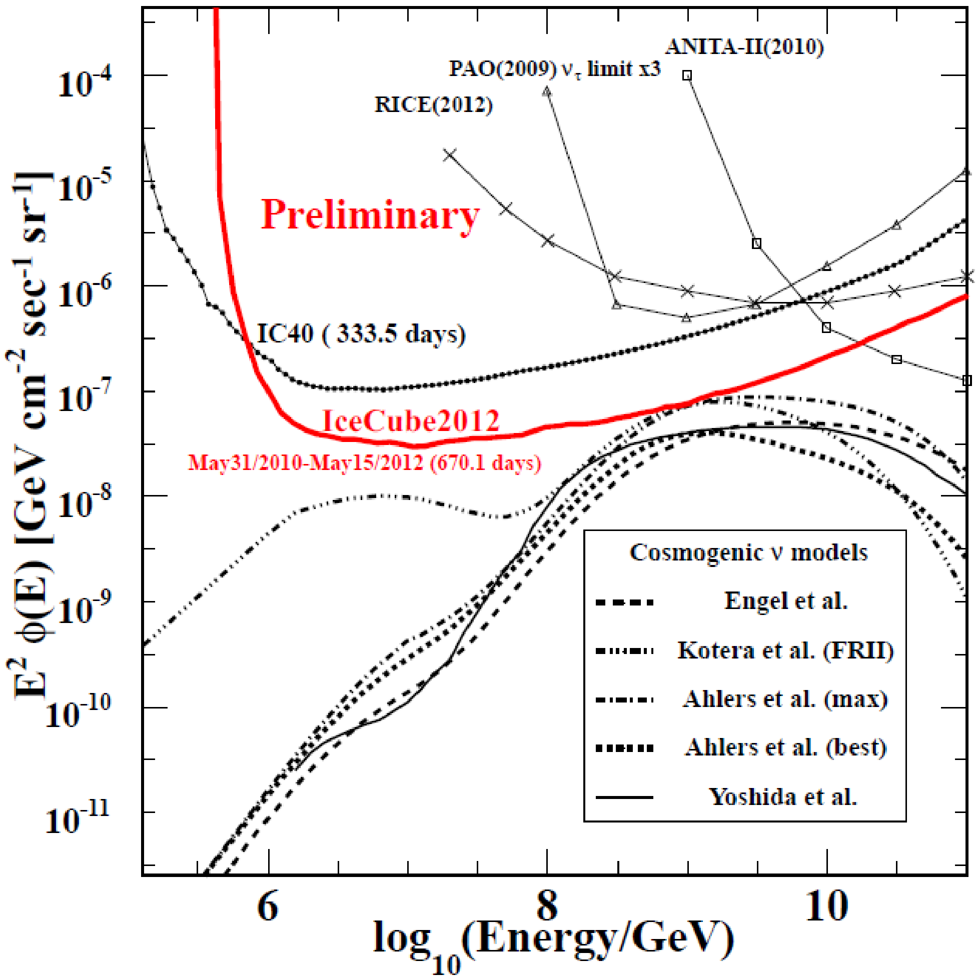




Fix cuts before unblinding data

Simple cut and counts 2012 results





- PeV-ish region: Electron neutrinos (cascades)
- EeV-ish region: Muon/Tau neutrinos

A. Ishihara for IceCube Collaboration, Nuclear Physics B Proceedings Supplement 00 (2012) 1–6

Time for an update (7yrs data) change to ***Poisson-binned likelihood ratio*** method

- 1D →2D: The effect (signature) of the detected events is automatically taken into account
- In case we find candidates -
  - Are they **background**
  - Are they **GZK** neutrinos
  - A part of sub PeV cosmic neutrino bulk? (**E^{-2}** spectrum ? Cut-off?)
  - **Upper limit**?
  - How can they constrain the known **GZK models**? (not included in this talk)

- Search results in publication process

Binned-Poisson likelihood ratio method

Observed prediction

$$L\,(\kappa) = \prod_{i=1}^{N} Poisson\,(n_i, \mu_i(\kappa))$$

Floating parameter

$L(H_0) = L(\kappa_0)$ Null hypnosis

$L(H_1) = L^{max}(\kappa)$ Alternative hypnosis

$$'llh' = \ln \Lambda = \ln \frac{L(H_1)}{L(H_0)}$$

Is it background?

We have **2D** variable set for distinguishing signal and background

Use both parameters cos(θ) and reconstructed energy

Number of events

BG + κ GZK+a Astro

Floating parameter

$$\lambda \begin{cases} = 0 & : H_0 \quad \text{BG only} \\ \geq 0 & : H_1 \quad \text{With GZK/Astro} \end{cases}$$

$$L = \prod_j Poisson(k_{jk}, \mu_{jk})$$

log NPE (energy) cos(θ)

‘2D pdf’ for signal and background

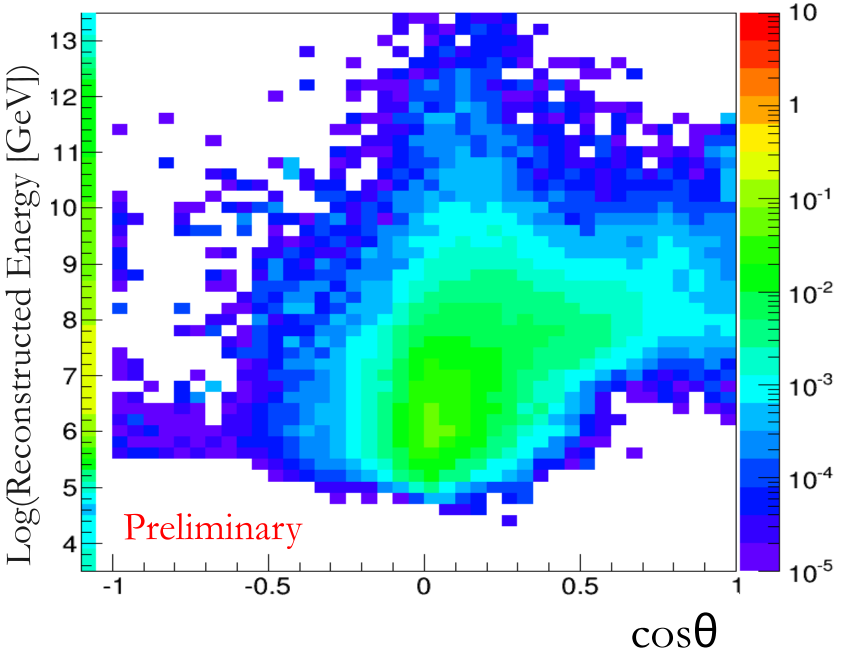
$$\mu_{jk}^{\mathrm{BG}} = \frac{d\log N_{\mathrm{BG}}}{d\log \mathrm{NPE}\, d\cos\theta}(\log \mathrm{NPE}^j, \cos\theta^k)\, d\log \mathrm{NPE}\, d\cos\theta^k,$$

$$N^{\mathrm{BG}} = \sum_{jk} \mu_{jk}^{\mathrm{BG}}.$$

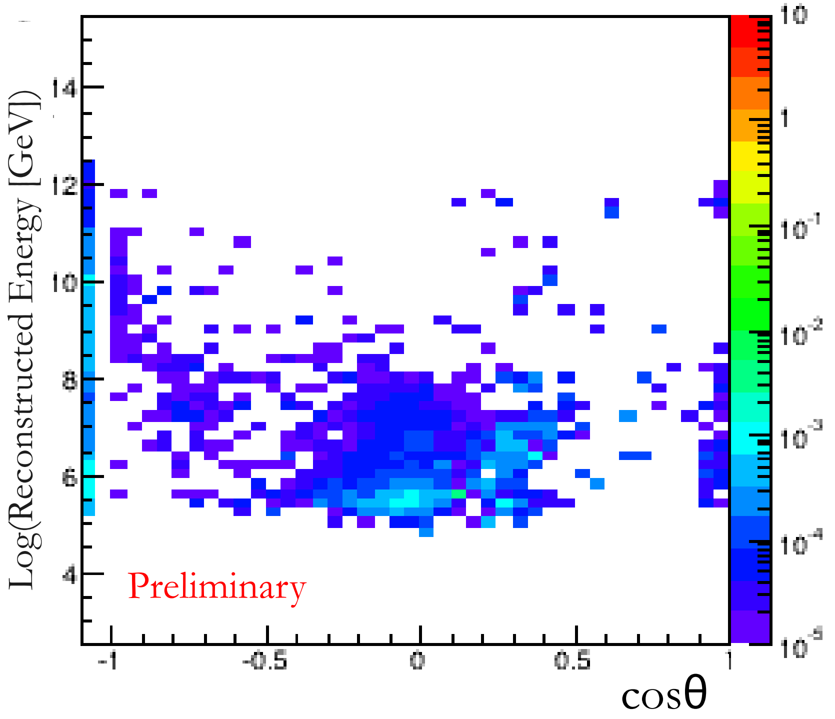
$$\mu_{jk}^{\mathrm{GZK}} = \frac{d\log N_{\mathrm{GZK}}}{d\log \mathrm{NPE}\, d\cos\theta}(\log \mathrm{NPE}^j, \cos\theta^k)\, d\log \mathrm{NPE}\, d\cos\theta^k,$$

$$N^{\mathrm{GZK}} = \sum_{jk} \mu_{jk}^{\mathrm{GZK}}.$$

N^{BG}~$O(0.01) - O(0.1)$. Same level as signal



ν Signal



Atmospheric background

Constructing likelihood ratio

$$\lambda \begin{cases} = 0 & : H_0 \quad \text{BG only} \\ \geq 0 & : H_1 \quad \text{with GZK} \end{cases}$$

$$L_0 = \prod_{jk} Poisson(k_{jk}, \mu_{jk}^{\mathrm{BG}})$$

$$L_1 = \prod_{jk} Poisson(k_{jk}, \mu_{jk}^{\mathrm{BG}} + \lambda^{\max}\mu_{jk}^{\mathrm{GZK}})$$

$\lambda^{\max}$ maximizes L_1 for H_1.

$$\Lambda \equiv \frac{L_1}{L_0} = \frac{\prod_{jk} Poisson(k_{jk}, \mu_{jk}^{\mathrm{BG}} + \lambda^{\max}\mu_{jk}^{\mathrm{GZK}})}{\prod_{jk} Poisson(k_{jk}, \mu_{jk}^{\mathrm{BG}})}$$

$$x^2 \equiv \ln \Lambda$$

Side note: physics meaning of $\lambda^{\max}$

$$L_1 = \exp^{-(N^{\mathrm{BG}} + \lambda^{\max} N^{\mathrm{GZK}})} \prod_i^N (\mu_i^{\mathrm{BG}} + \lambda^{\max}\mu_i^{\mathrm{GZK}}).$$

The $\lambda^{\max}$ is obtained by requesting $d\ln L_1 / d\lambda^{\max} = 0$

$$-N^{\mathrm{GZK}} + \sum_i^N \frac{1}{\left(\frac{\mu_i^{\mathrm{BG}}}{\mu_i^{\mathrm{GZK}}}\right) + \lambda^{\max}} = 0$$

$$\mu_i^{\mathrm{BG}} / \mu_i^{\mathrm{GZK}} \ll \lambda^{\max}$$

$$\lambda^{\max} \sim \frac{N}{N^{\mathrm{GZK}}}$$

Normalisation factor!

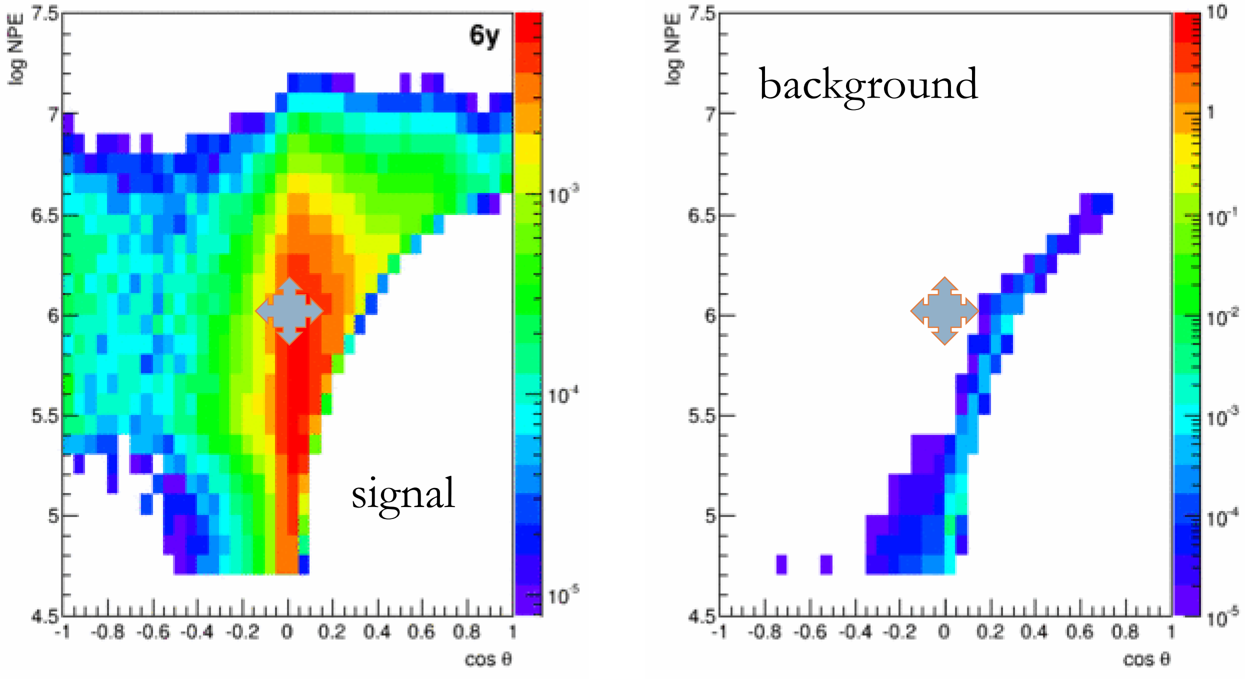
P-values from **likelihood ratio** vs **cut-and-count** (I)

- Three examples:
  - 1 detection at signal-rich & poor-bg region
  - 1 detection at signal-rich & bg-rich region
  - 1 detection at edge of signal cuts

- Pseudo experiments
  - obtained by MC simulations which repeats replica experiments with sampling observed event number distribution following the likelihood function of null hypothesis L_0. Then the p-value is calculated by the probability that x^2 is greater than the observed log likelihood ratio x^2_{obs} under H_0:

$$p = Pr(x^2 > x^2_{\mathrm{obs}}).$$

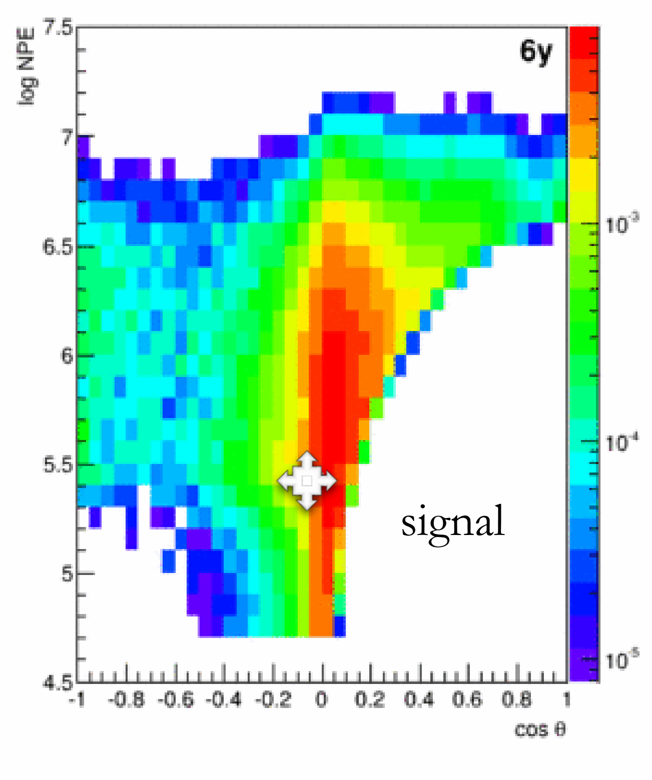
case 1

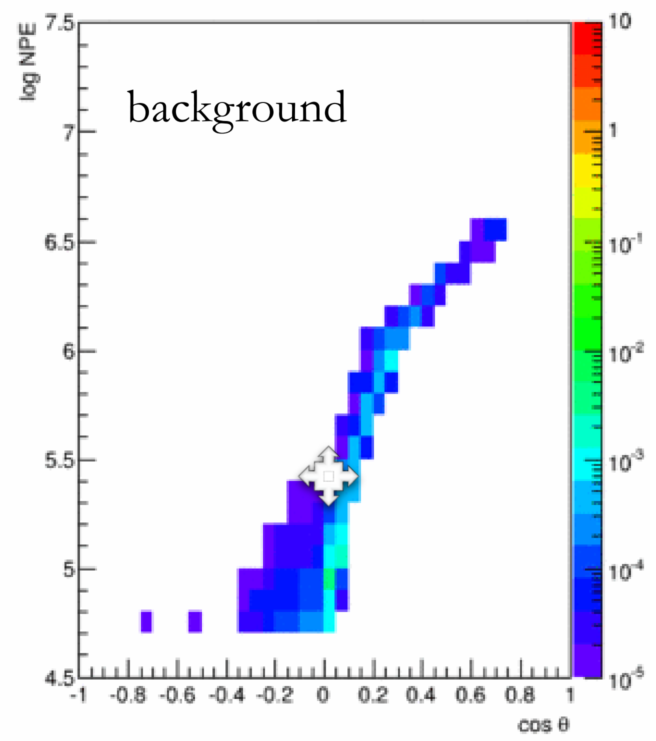


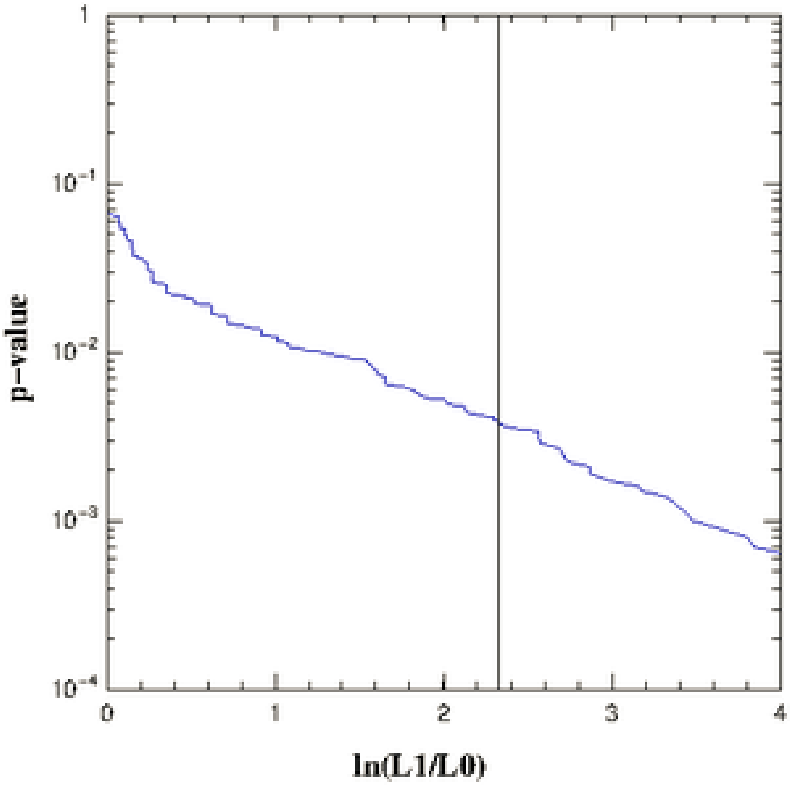
log(NPE)	cos(zenith)	p-value by the likelihood ratio	p-value by the cut-and-count
6.05	-0.025	3.00×10^{-5}	1.61×10^{-1} (1.01σ - BG=0.176, obs=1)

P-values from likelihood ratio vs cut-and-count (II)

case 2



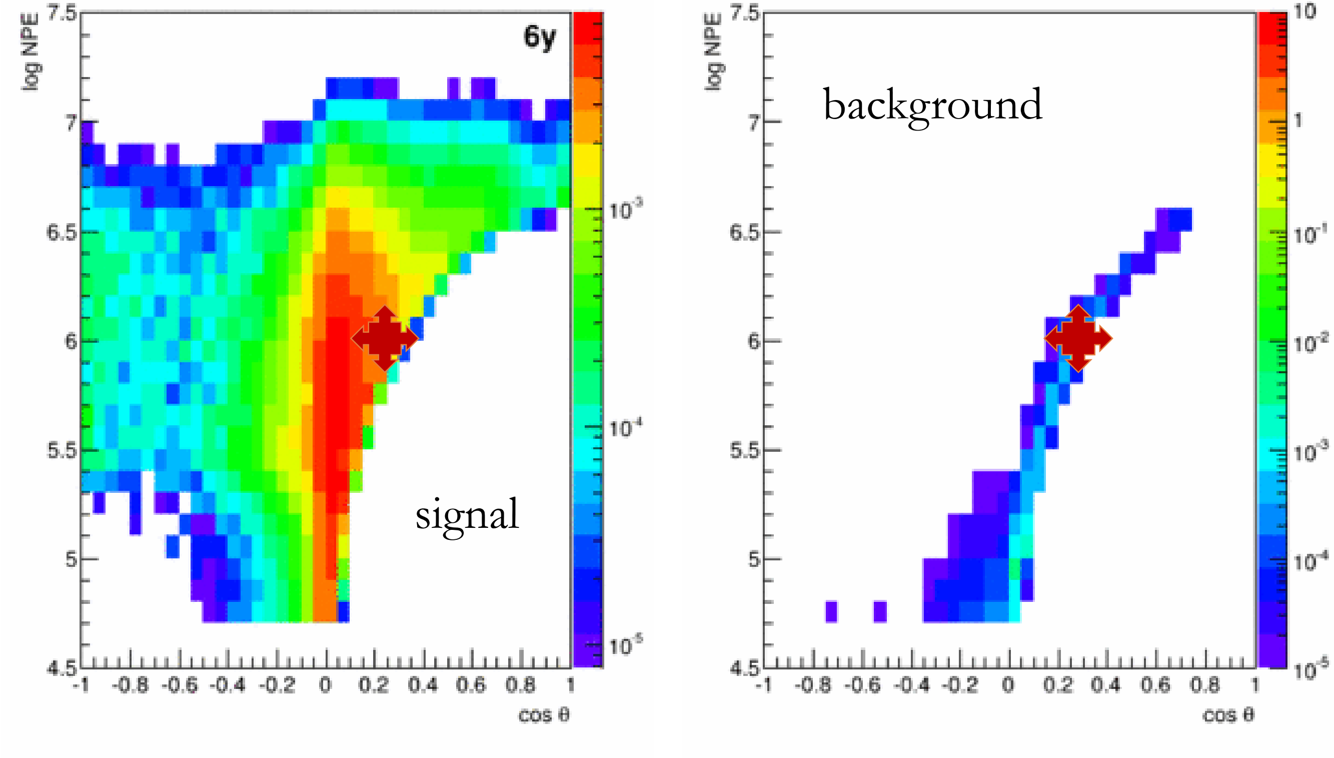


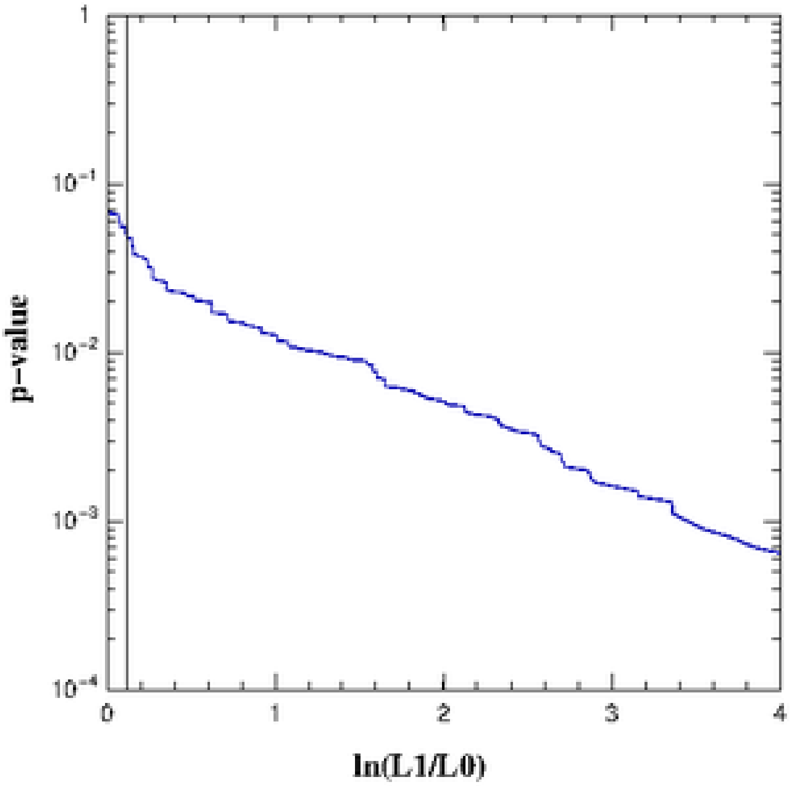


log(NPE)	cos(zenith)	p-value by the likelihood ratio	p-value by the cut-and-count
5.45	-0.025	3.96×10^{-3}	1.61×10^{-1} (1.01σ - BG=0.176, obs=1)

P-values from **likelihood ratio** vs **cut-and-count** (III)

case 3





log(NPE)	cos(zenith)	p-value by the likelihood ratio	p-value by the cut-and-count
5.95	0.275	5.10×10^{-2}	1.61×10^{-1} (1.01σ - BG=0.176, obs=1)

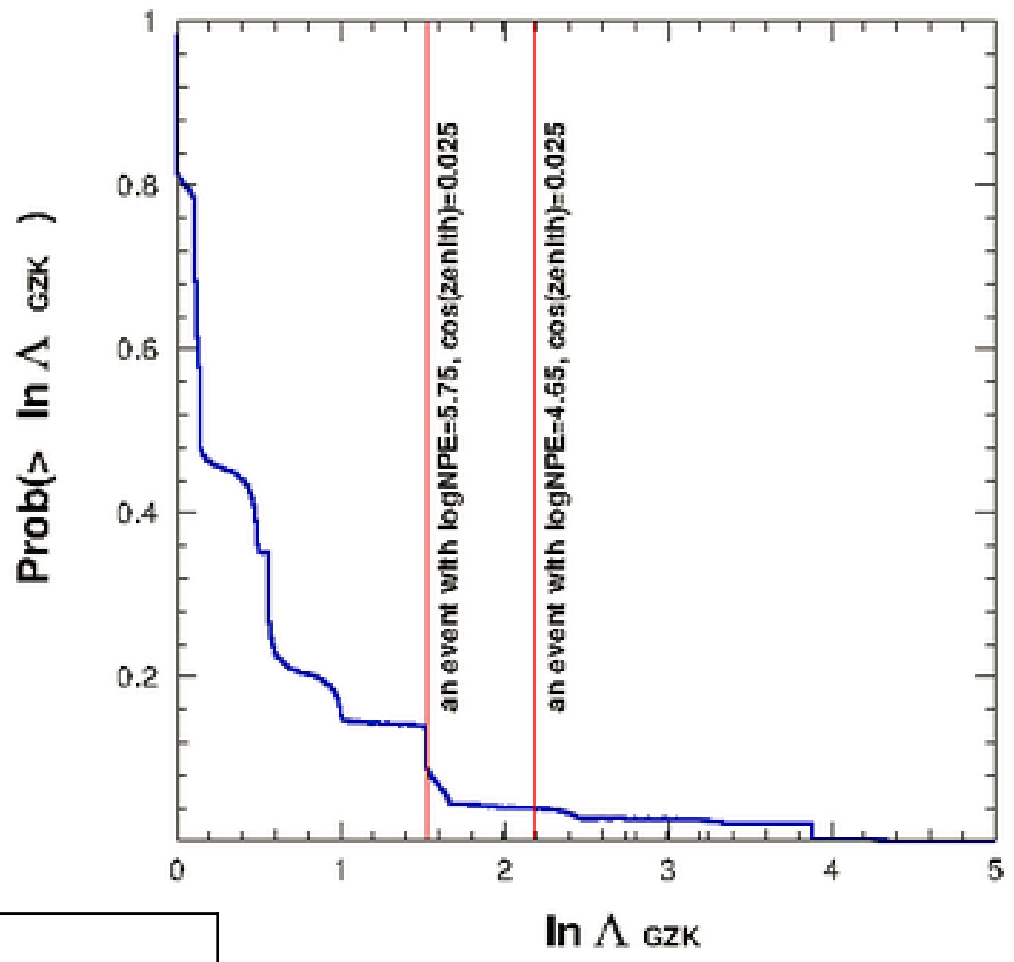
Testing GZK models

- Previous Cut and count (IceCube Collaboration. Phys. Rev. Lett. **111**, 021103)

$$N^{\mathrm{GZK}} = \sum_{jk} \mu_{jk}^{\mathrm{GZK}}.$$

$$\begin{array}{ll} \mu_{jk} = \mu_{jk}^{\mathrm{GZK}} & : H_0 \\ \mu_{jk} = \lambda_{\mathrm{GZK}} \mu_{jk}^{\mathrm{GZK}}, \lambda_{\mathrm{GZK}} \neq 1 & : H_1 \end{array}$$

$$\Lambda_{\mathrm{GZK}} \equiv \frac{L_1}{L_0} = \frac{\prod_{jk} Poisson(k_{jk}, \mu_{jk}^{\mathrm{BG}} + \lambda_{\mathrm{GZK}}^{\max} \mu_{jk}^{\mathrm{GZK}})}{\prod_{jk} Poisson(k_{jk}, \mu_{jk}^{\mathrm{BG}} + \mu_{jk}^{\mathrm{GZK}})}.$$



The p-values for the GZK models - when we see a single event				
	log(NPE)	cos(zenith)	p-value GZK Ahler Best - exp.# of events 3.88	p-value GZK Ahler max - exp.# of events 7.81
Case A	5.75	0.025	0.11 (ref. simple poisson 0.10)	4.2×10^{-3} (ref. simple poisson 3.6×10^{-3})
Case B	4.65	0.025	0.040 (ref. simple poisson 0.10)	7.5×10^{-4} (ref. simple poisson 3.6×10^{-3})

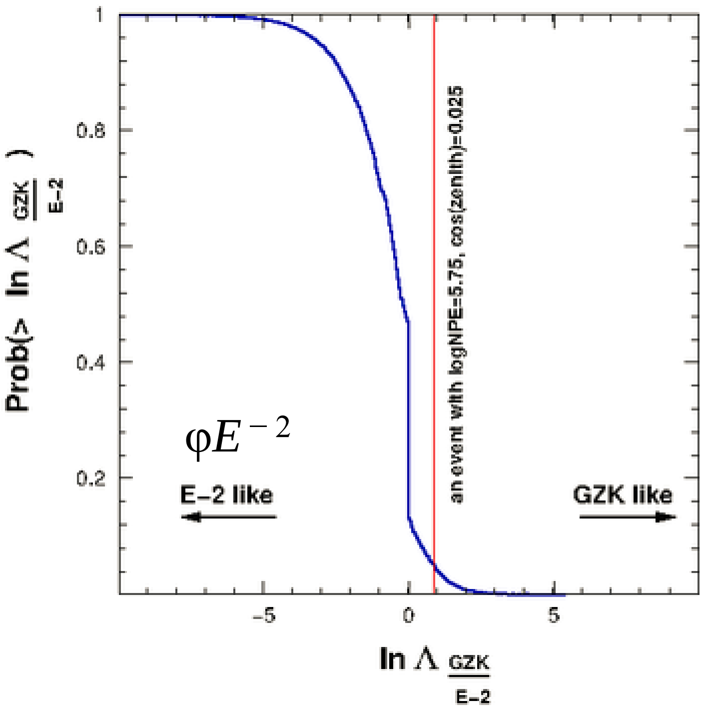
Case A
an event at (logNPE=5.75, cos(zenith)=0.025) - "GZK-like"
Case B
an event at (logNPE=4.65, cos(zenith)=0.025) - "astro-like"

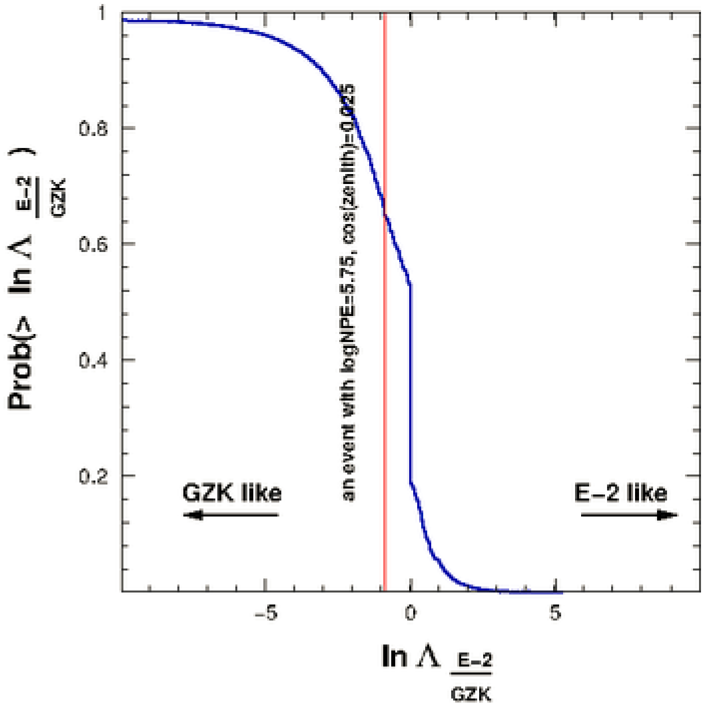
Is it the tail of the power-law neutrino flux?

$$\mu_{jk} = \lambda_{\mathrm{GZK}} \times \mu_{jk}^{\mathrm{GZK}} \quad : H_1$$
$$\mu_{jk} = \lambda_{\mathrm{E}^{-2}} \times \mu_{jk}^{\mathrm{E}^{-2}} \quad : H_0$$

For GZK hypothesis (H_1), we take a *typical* GZK model (say, Ahler best), and float the normalization.

$$\Lambda_{\mathrm{GZK/E}^{-2}} \equiv \frac{L_1}{L_0} = \frac{\prod_{jk} Poisson(k_{jk}, \mu_{jk}^{\mathrm{BG}} + \lambda_{\mathrm{GZK}}^{\max}\mu_{jk}^{\mathrm{GZK}})}{\prod_{jk} Poisson(k_{jk}, \mu_{jk}^{\mathrm{BG}} + \lambda_{\mathrm{E}^{-2}}^{\max}\mu_{jk}^{\mathrm{E}^{-2}})}.$$





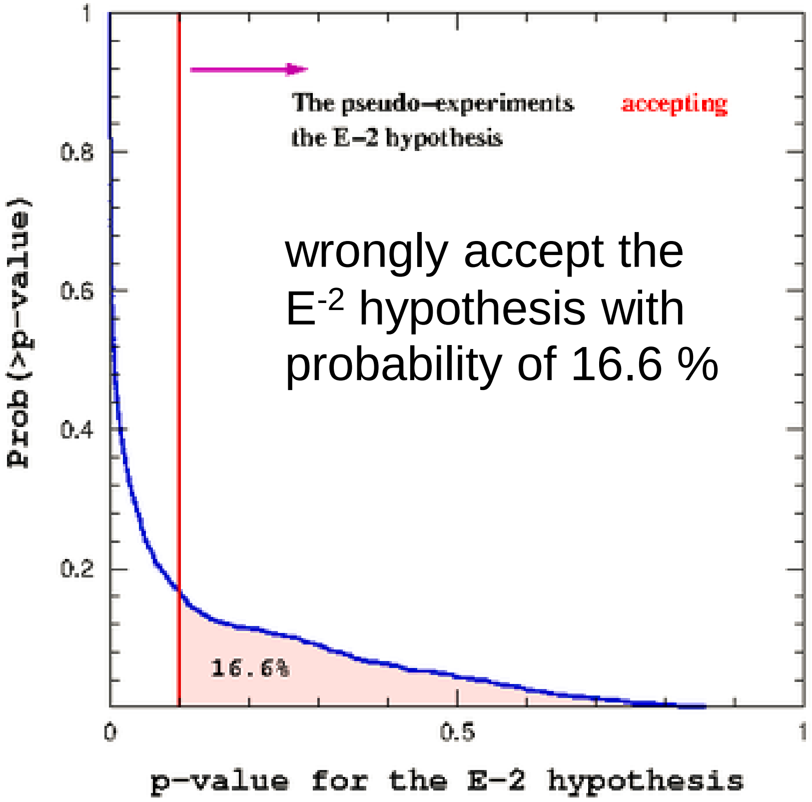
test of E-2 Vs GZK	$x^2 \equiv \ln \Lambda_{\mathrm{GZK/E}^{-2}}$		$x^2 \equiv \ln \Lambda_{\mathrm{E}^{-2}/\mathrm{GZK}}$	
	log(NPE)	cos(zenith)	p-value for GZK	p-value for E^{-2}
case A (a GZK-like event detection)	5.75	0.025	0.66	0.051
case B (a low NPE event detection)	4.65	0.025	0.0852	0.63

reject the E^{-2} hypothesis by 95 % C.L.

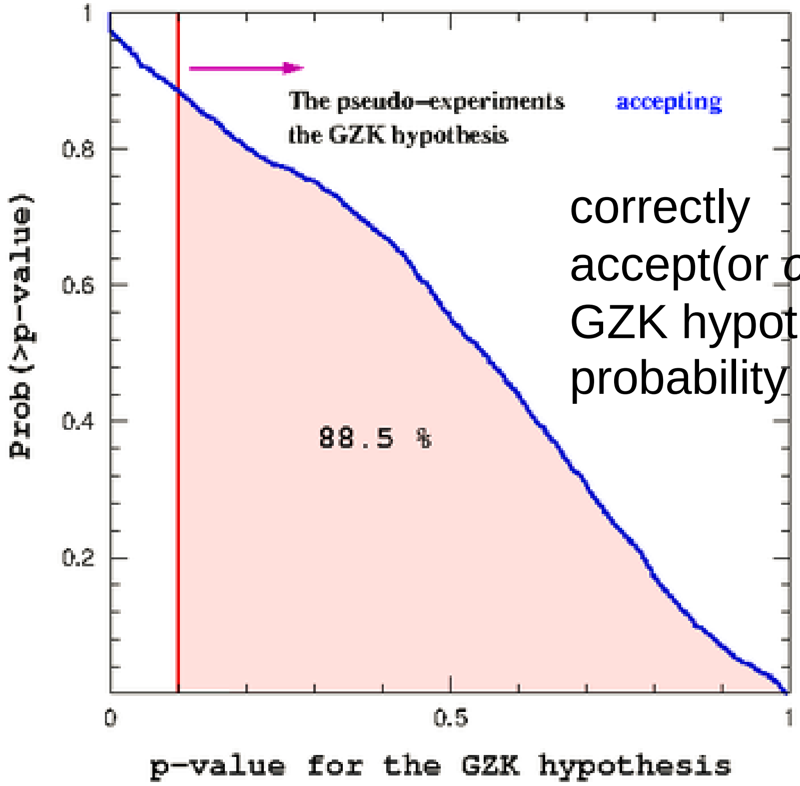
reject GZK hypothesis by ~ 90 % C.L.

how likely we will not be mistaken? ($\Lambda_{GZK/E^{-2}}$)

replacing an event-basis case study by events generated by a pseudo-experiment of a GZK model. expected total number of events is 3.88. capability of confirming GZK (or rejecting E^{-2}-like) when we detect a few events.



wrongly accept the E^{-2} hypothesis with probability of 16.6 %



correctly accept(or *confirm*) the GZK hypothesis with probability of 88.5 %

if we carry out the present IceCube EHE search 100 times, 83 our of 100 measurements yields the event detection that rejects the E^{-2} hypothesis at more than 90% C.L..

The model independent differential limit

$$\phi(E_\nu) = \frac{J_0}{\Delta \log E_\nu} \frac{1}{\ln 10} E_\nu^{-1}, \qquad \log E_\nu \in (\log E_\nu - \frac{1}{2}\Delta \log E_\nu, \log E_\nu + \frac{1}{2}\Delta \log E_\nu)$$

J_0, the normalization factor of the log differential spectrum, is considered as a free parameter. Build the likelihood ratio

$$\Lambda \equiv \frac{L_1}{L_0} = \frac{\prod_{jk} Poisson(k_{jk}, \mu_{jk}^{\mathrm{BG}} + \mu_{jk}^{J^{\max}})}{\prod_{jk} Poisson(k_{jk}, \mu_{jk}^{\mathrm{BG}} + \mu_{jk}^{J_0})}$$

where $J^{\max}$ maximises the likelihood and calculate the distribution of $x^2 = \ln\Lambda$ by running replica experiments. Repeat these steps with varying J_0 and search for the upperlimit J_0^{90}

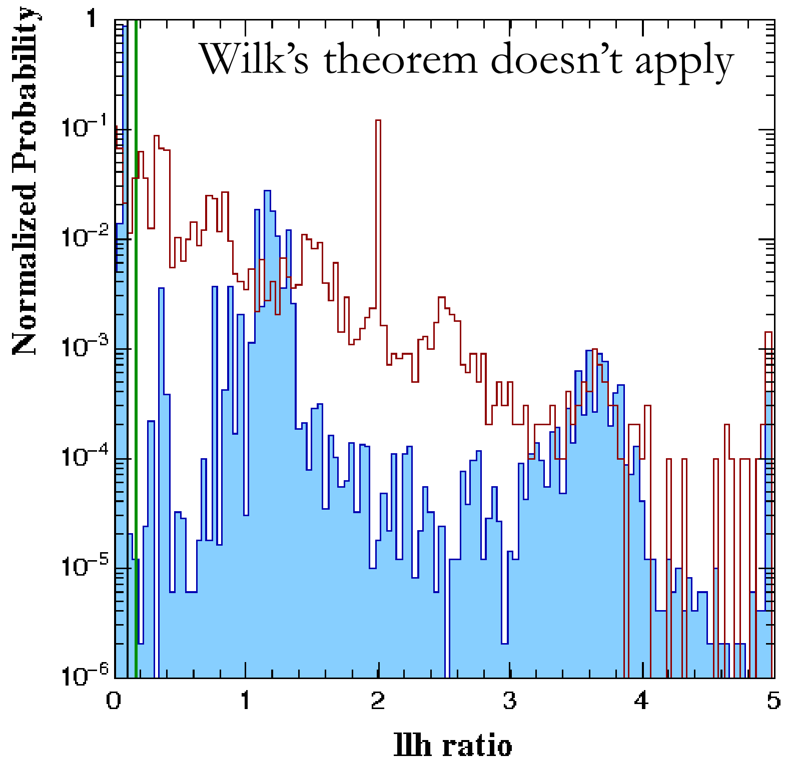
$$p = Pr(x^2 > x^2_{\mathrm{obs}}) = 0.1.$$

differential upper limit of flux at 90 % C.L for a given neutrino energy of E_ν.

Few thoughts on the Poisson-binned likelihood ratio

- Pros:
  - Automatically taking into account full info available
  - Can be used for fitting when there are small number of events
- Cons:
  - Computationally expensive
  - How to decide on binning?
- Aware:
  - Possible nuisance parameter. E.g. cut-off energy of falling spectrum, which adds more work for computation.
- **Questions**:
  - Is there existing package to accelerate the calculation?
  - Is it possible to calculate p-value or confidence level **without running pseudo-experiments**. In the Poisson domain where many bins are null observed, the PDF of likelihood ratio are different from $\chi 2$ distribution based on Wilk's theorem.

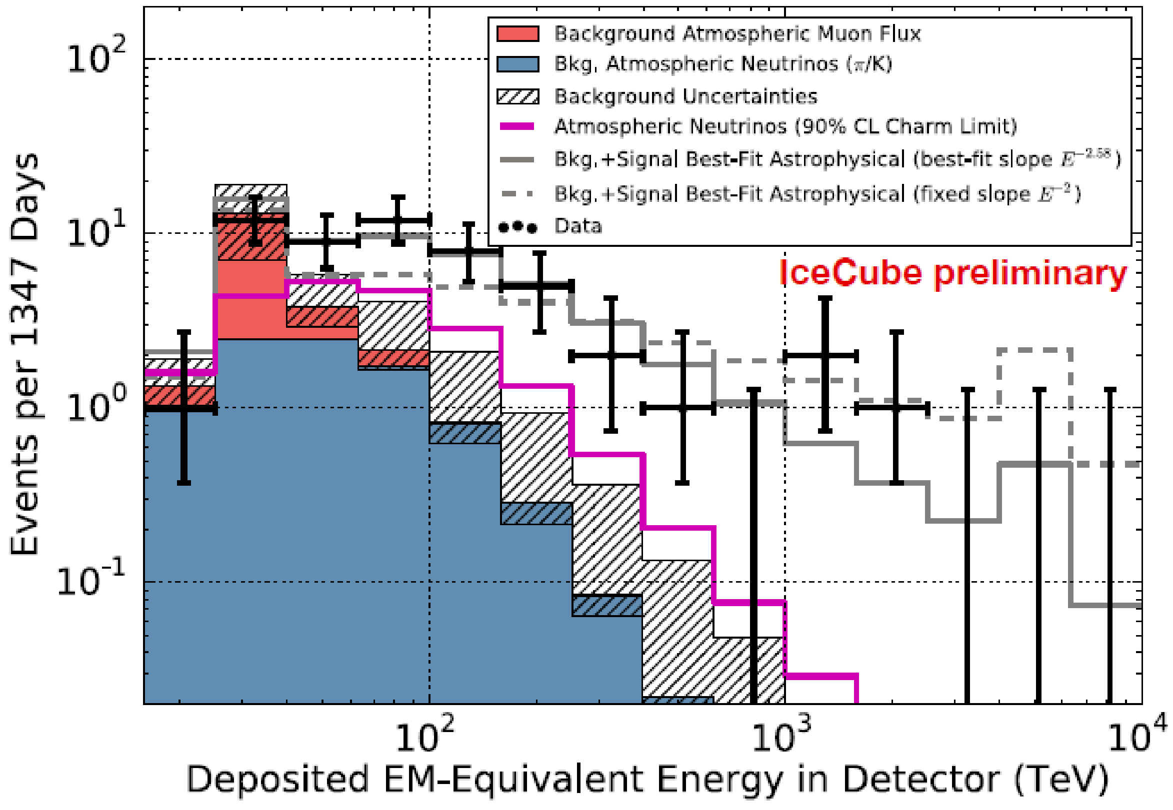
Example of llh distribution



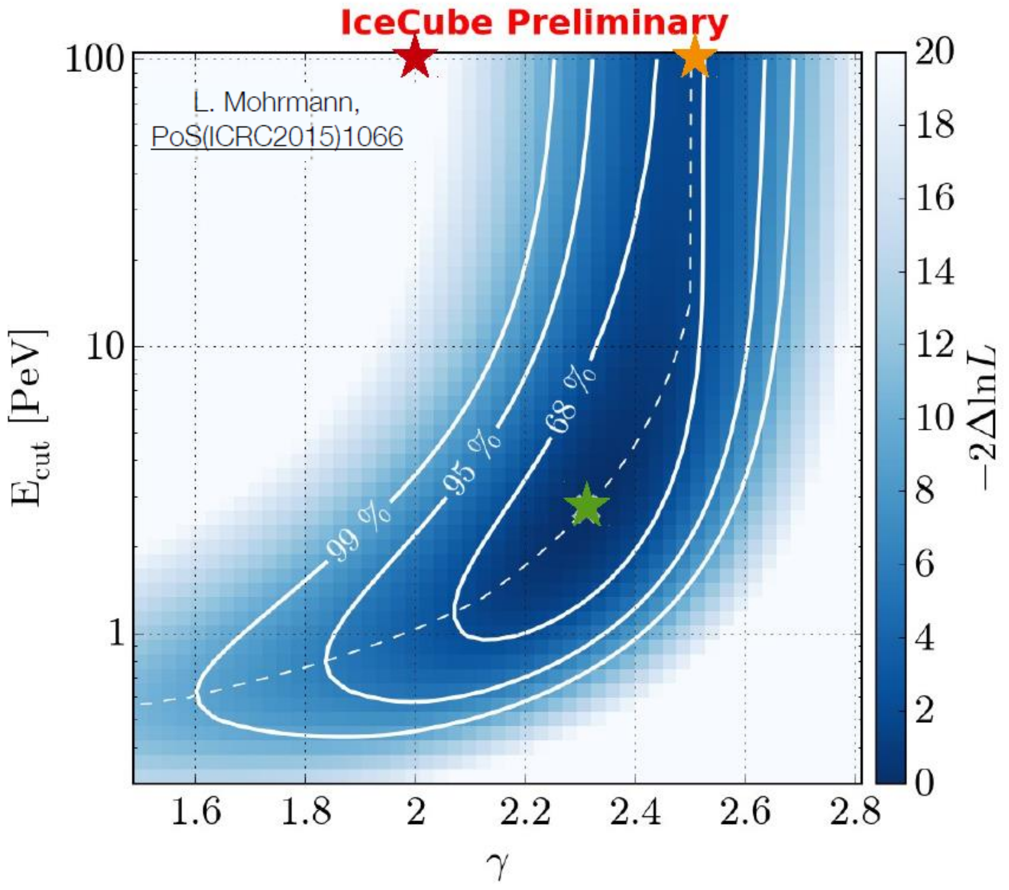
A new search – Is there a cut-off?

$$\Phi_\nu = \phi \times \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-\gamma}$$

$$\Phi_\nu = \phi \times \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-\gamma} \times \exp(-E/E_{\mathrm{cut}})$$



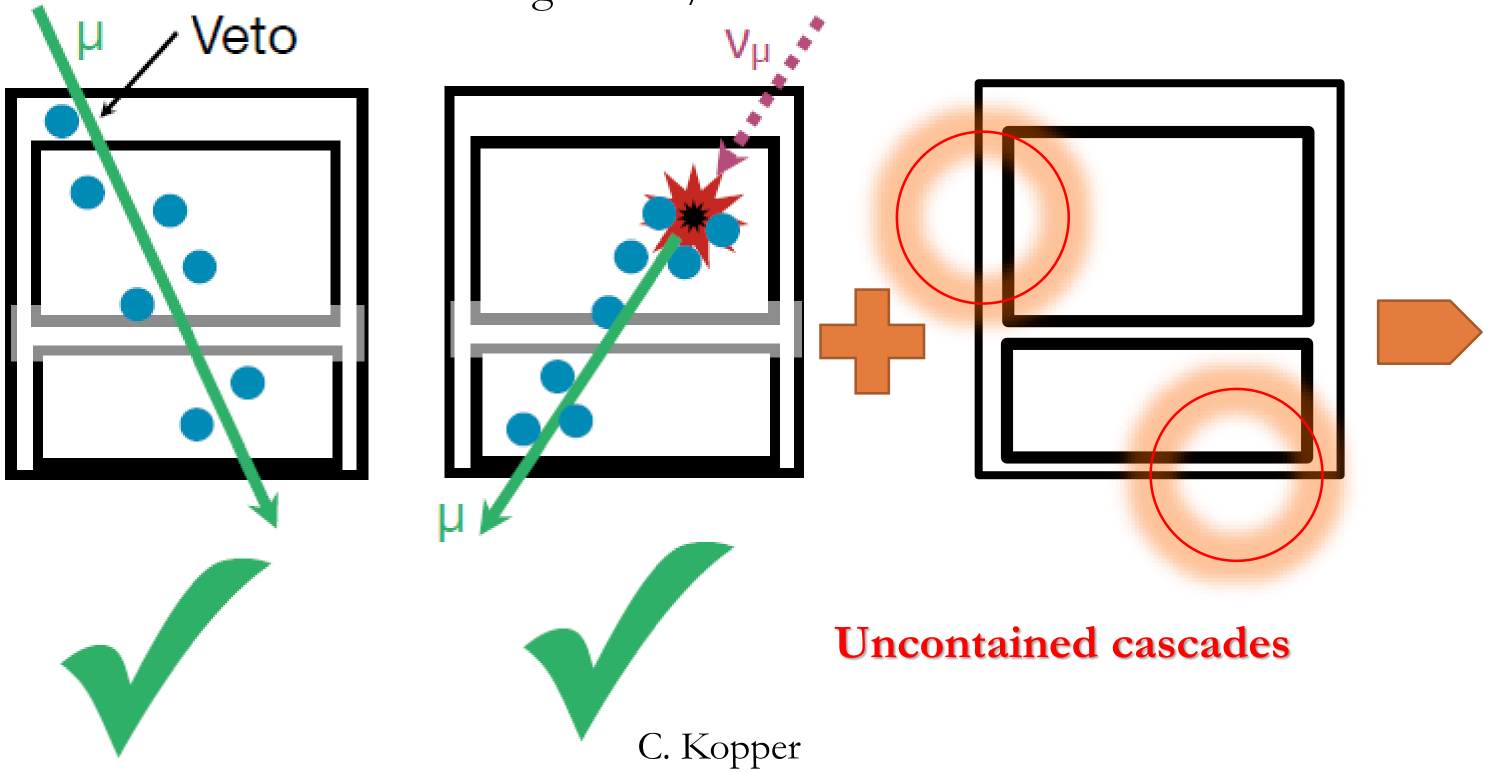
C. Kopper et al, PoS(ICRC2015)1081



Multi-flavour approach

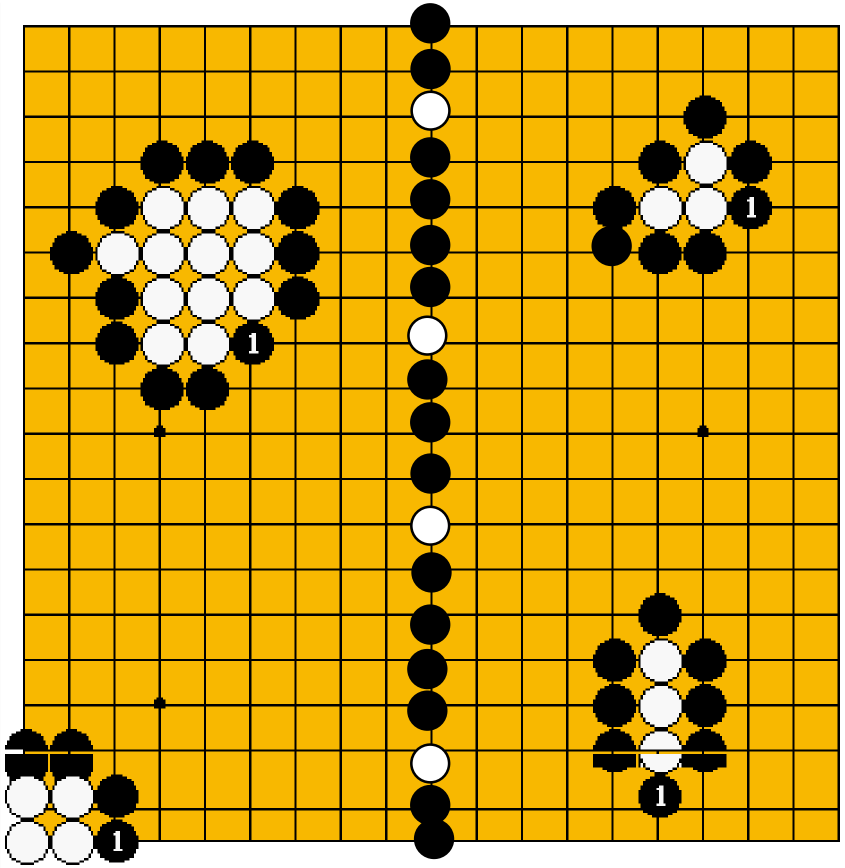
Through-going tracks

starting tracks / cascade



Uncontained cascades

C. Kopper

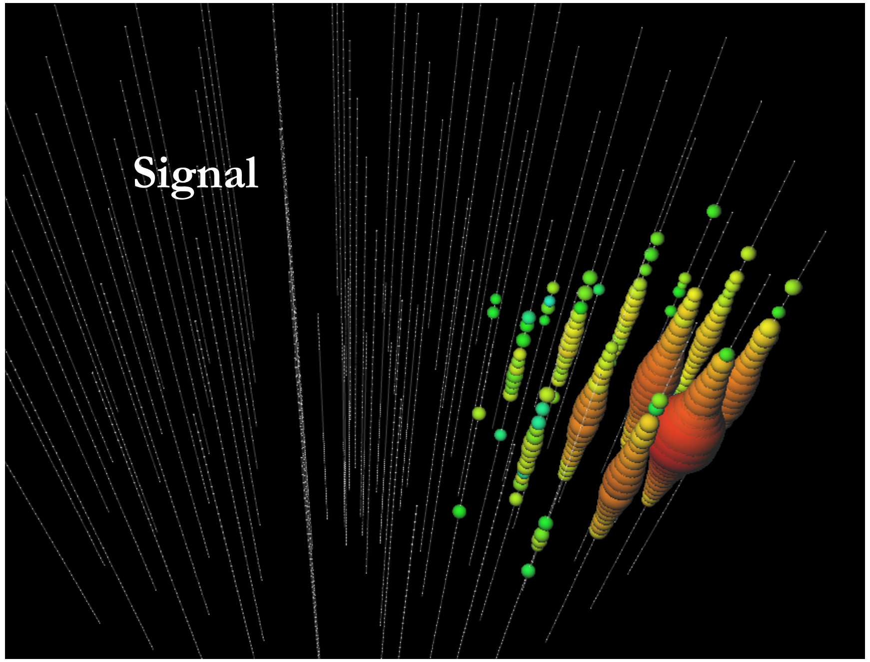


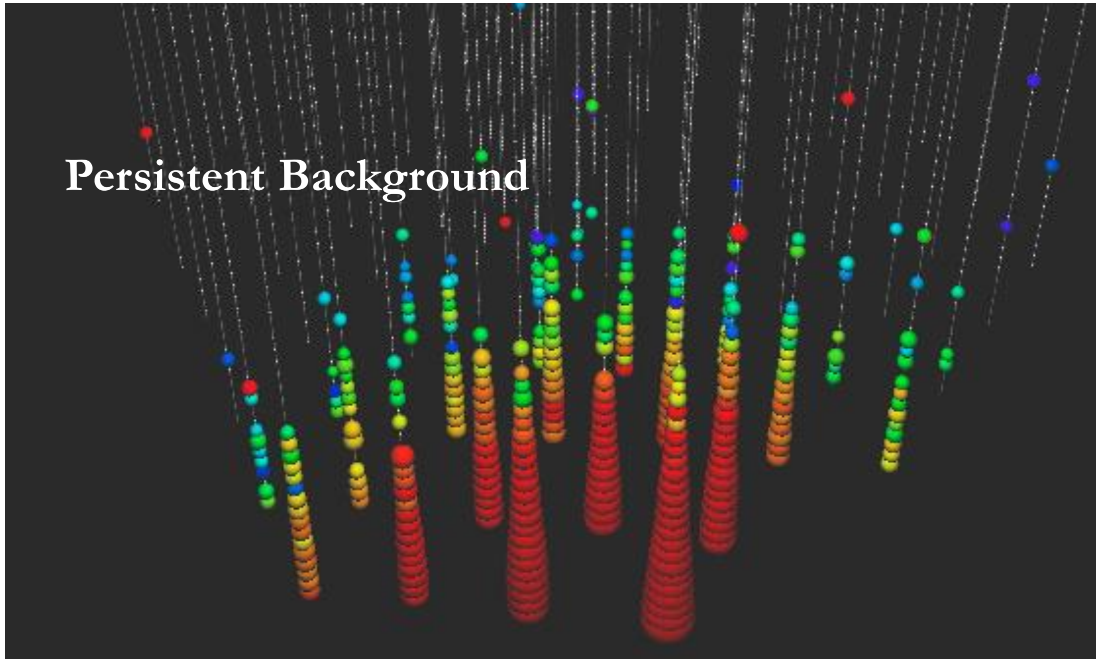
IceCube-Go

Using Boosted Decision Tree for classification

- Regarding **blinding/unblinded** analysis:
  - Should we use data for training?
    - Pros: no systematics due to modelling / unknown physics
    - Cons: not enough statistics from burn-samples
      mis-labelling

- Regarding **event reconstruction**:
  - How to improve partially contained cascades reconstruction? (at the moment likelihood-based reconstruction method using time-space and signal info)
    - Good news: forward spectrum   Bad news: larger energy bias (use BDT regression for corrections?)





Goal: Applying Binned-Poisson likelihood ratio method for fitting

- Three free parameters – normalisation, cut-off energy and spectrum index
- Possibly adding the fourth parameter for charm fraction

$$\mu_{jk} = \lambda_{E^{-\gamma}} \times E^{-\gamma} \quad \text{:H0}$$

$$\mu_{jk} = \lambda_{E_{cut}} \times E^{-\gamma} \times e^{-E/E_{cut}} \quad \text{:H1}$$

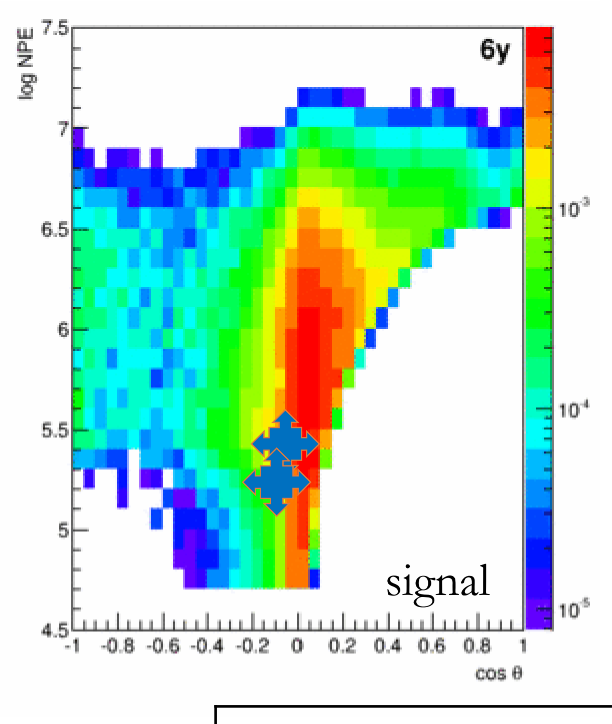
$$\Lambda_{\frac{E_{cut}}{E^{-\gamma}}} = \frac{L_1}{L_0} = \frac{\prod_{jk} Poisson(k_{jk}, \mu_{jk}^{cut})}{\prod_{jk} Poisson(k_{jk}, \mu_{jk}^{power\ law})}$$

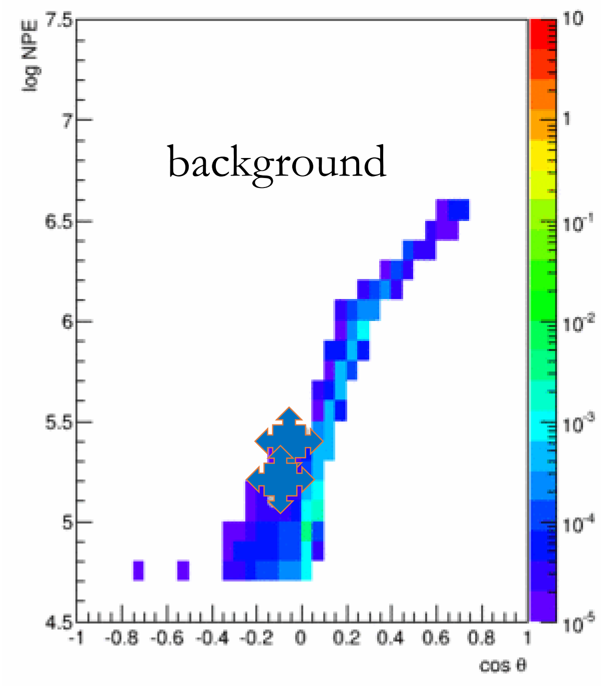
- Loop over each bin to find maximum H_1 and H_0
- Find contours for 90% c.d.l.

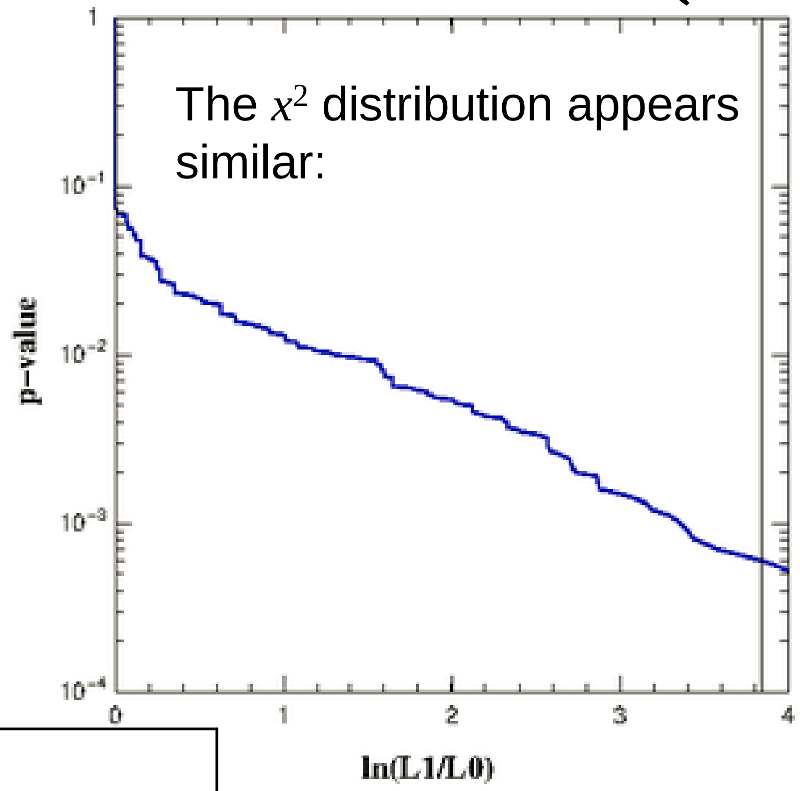
Conclusions

- IceCube is sensitive to 10 decades of energy and has rich topics in both particle physics and astrophysics
- A binned-Poisson likelihood ratio method has been discussed for applications of testing GZK / background / GZK models etc.
- The method improves the robustness of the test depending on the feature of candidates.
- It is computationally heavy
- The same technique is planed to be used for testing if there is a cut-off at the 1 – 10 PeV region.
- Looking for suggestions on how to slim the procedure for calculating confident bands.

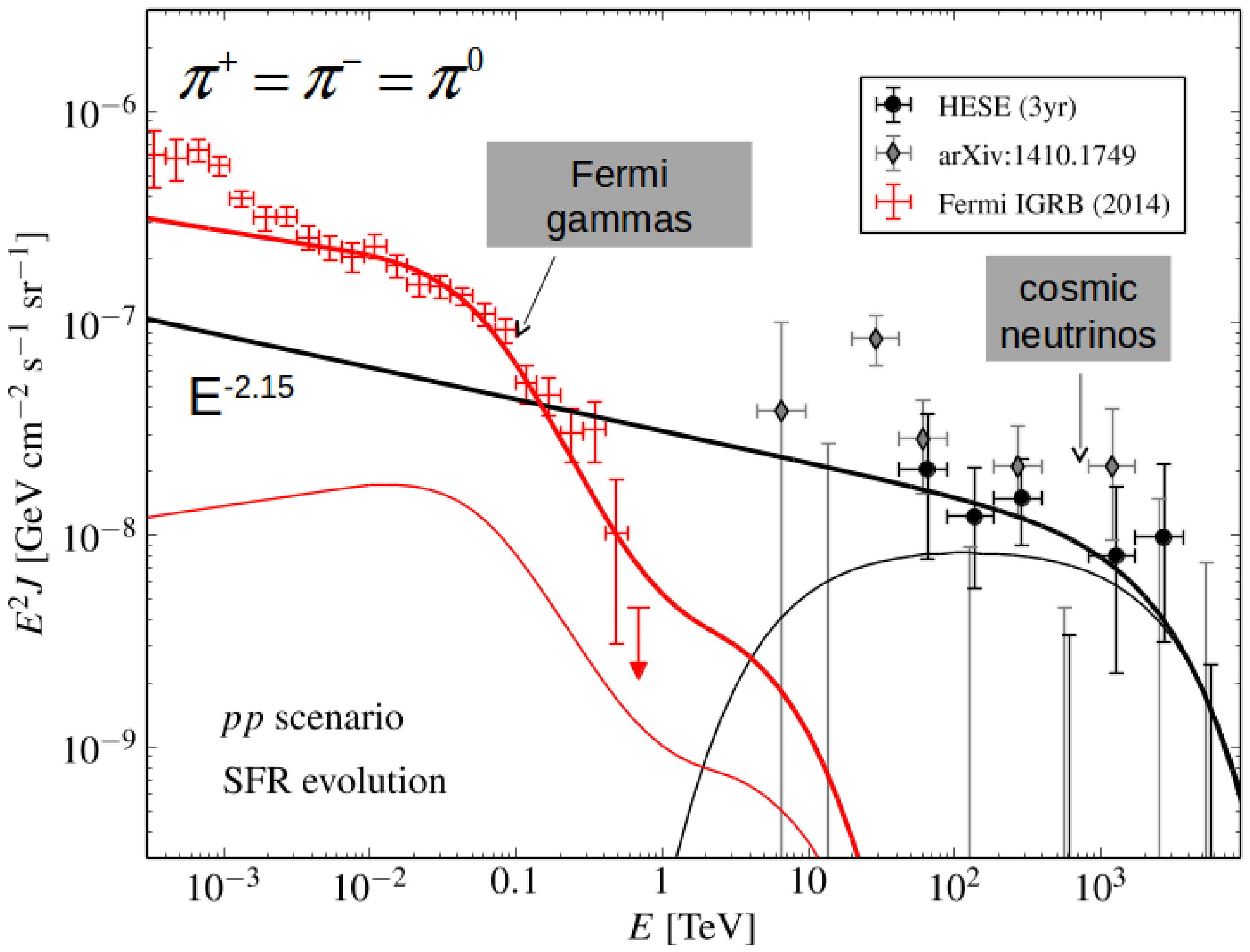
P-values from likelihood ratio vs cut-and-count (IV)





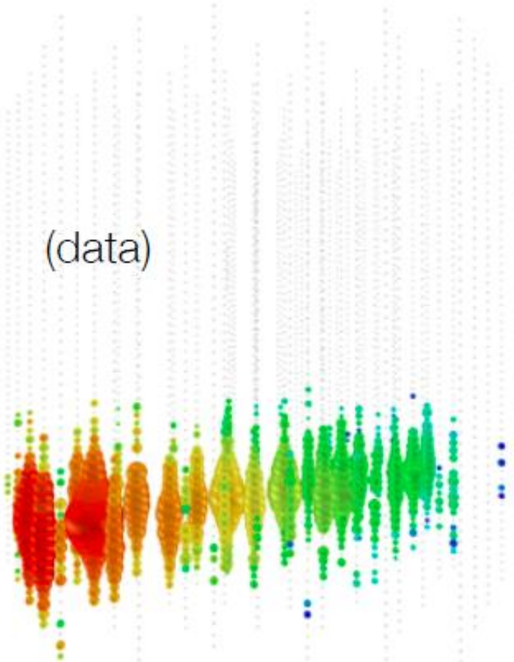
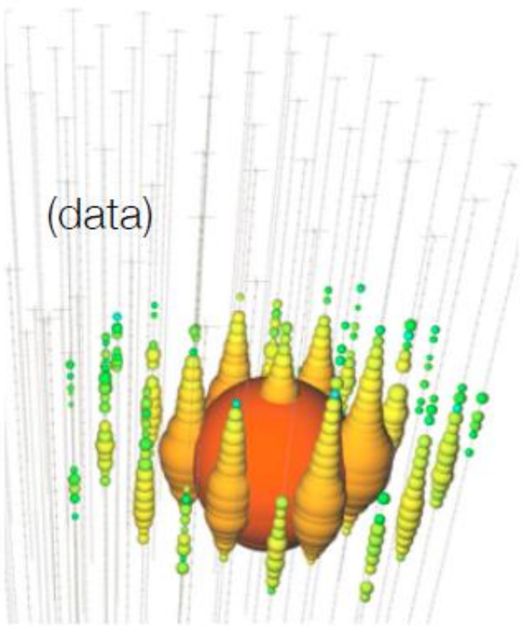
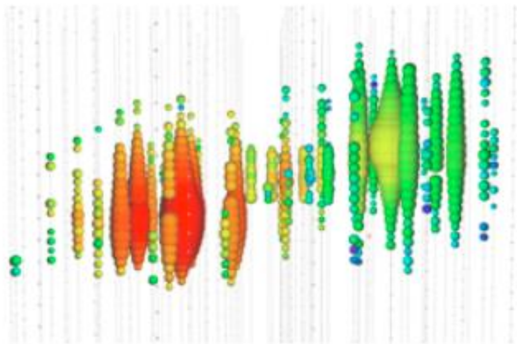


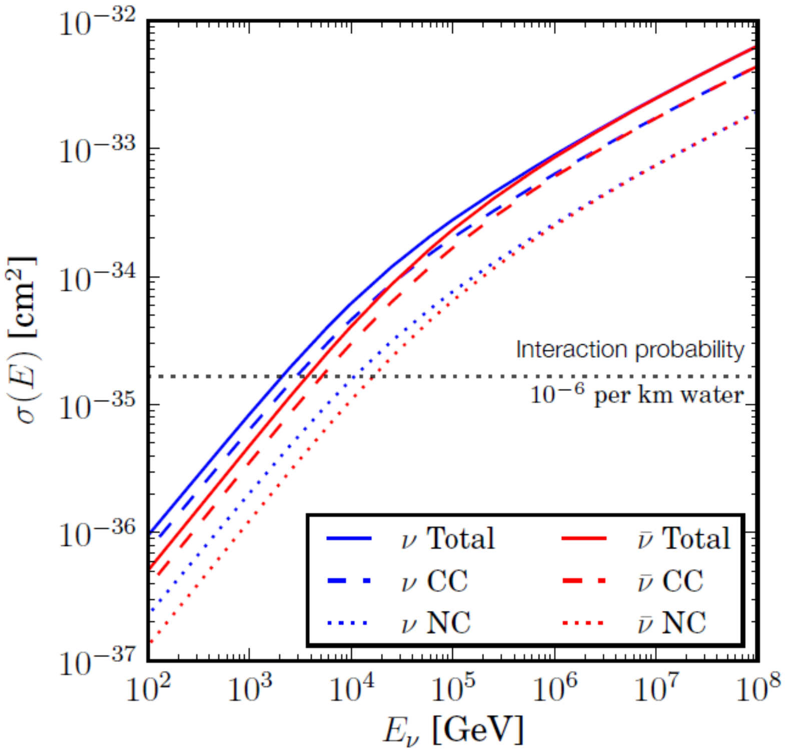
log(NPE)	cos(zenith)
5.45	-0.025
5.25	-0.125
p-value by the likelihood ratio	p-value by the cut-and-count
6.30 x 10^{-4}	1.378 x 10^{-2} (2.2σ - BG=0.176, obs=2)



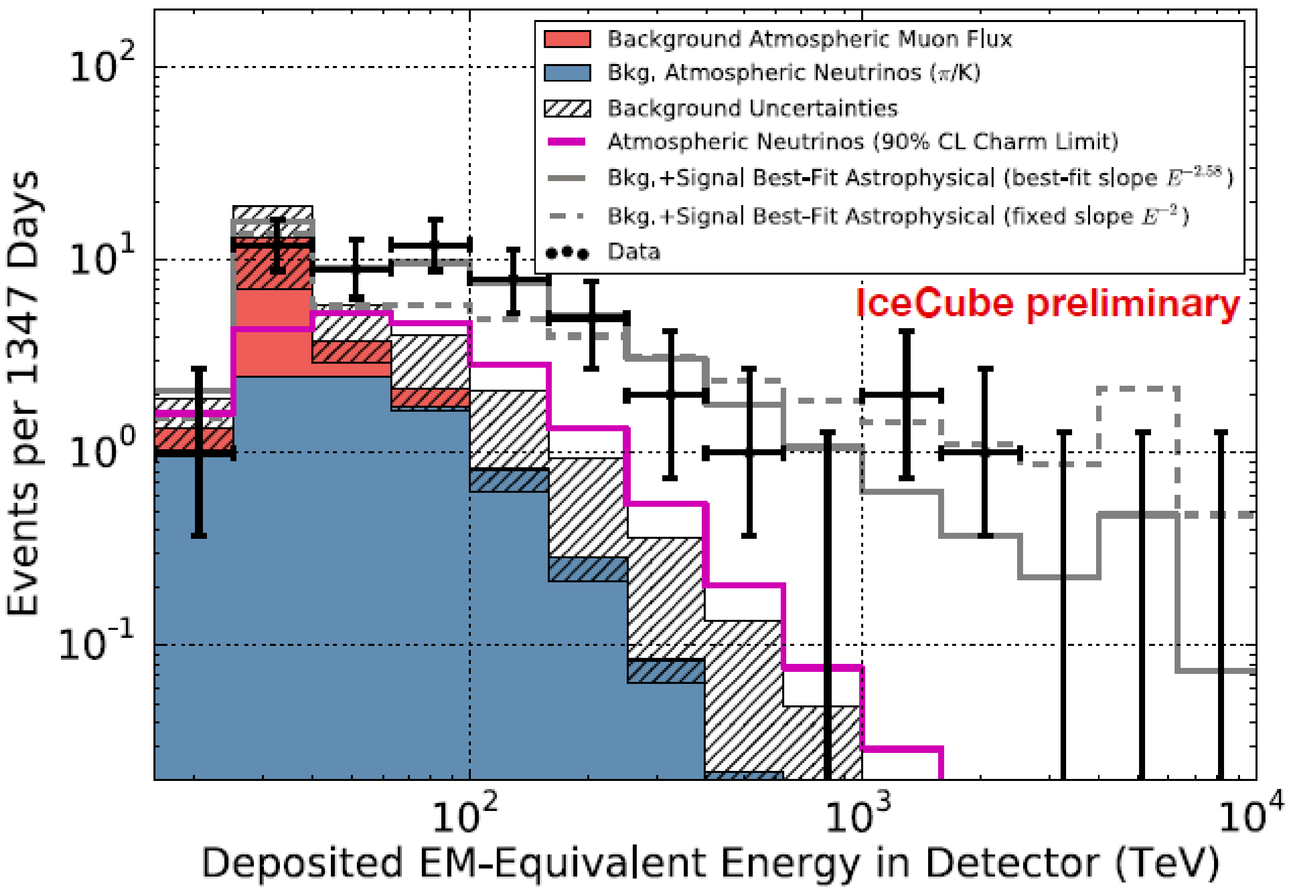
Experiment in pure ice

- Introduction see the morning talk from JP.
- This helps light to travel far, so we could have larger detectors and yet still sensitive to 100 TeV. ?

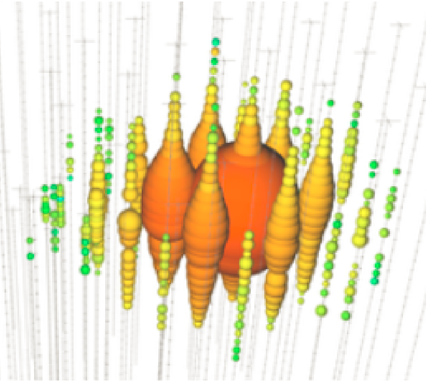
Charged-current ν_μ	Neutral-current / ν_e	Charged-current ν_τ
		
Up-going track	**Isolated energy deposition (cascade) with no track**	**“Double-bang”**
Factor of ~2 energy resolution < 1 degree angular resolution	15% deposited energy resolution 10 degree angular resolution (above 100 TeV)	(none observed yet: τ decay length is 50 m/PeV)

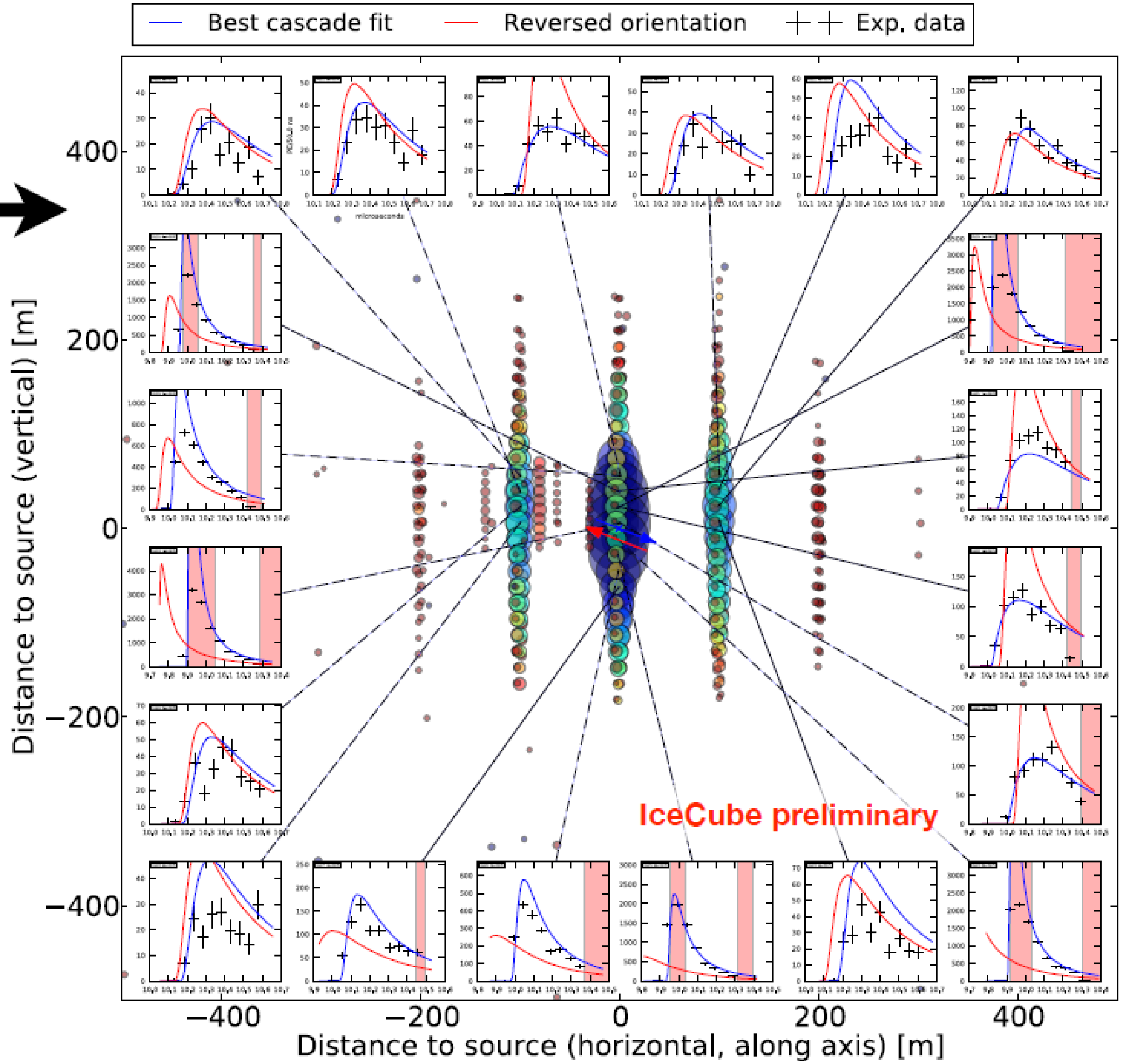


Deposited energy



C. Kopper et al, PoS(ICRC2015)1081





Best cascade fit
Reversed orientation
Exp. data
IceCube preliminary
Distance to source (vertical) [m]
Distance to source (horizontal, along axis) [m]
400
200
0
−200
−400

Test Including energy PDF of the two events

Use the Kolmogorov-Smirnov statistics

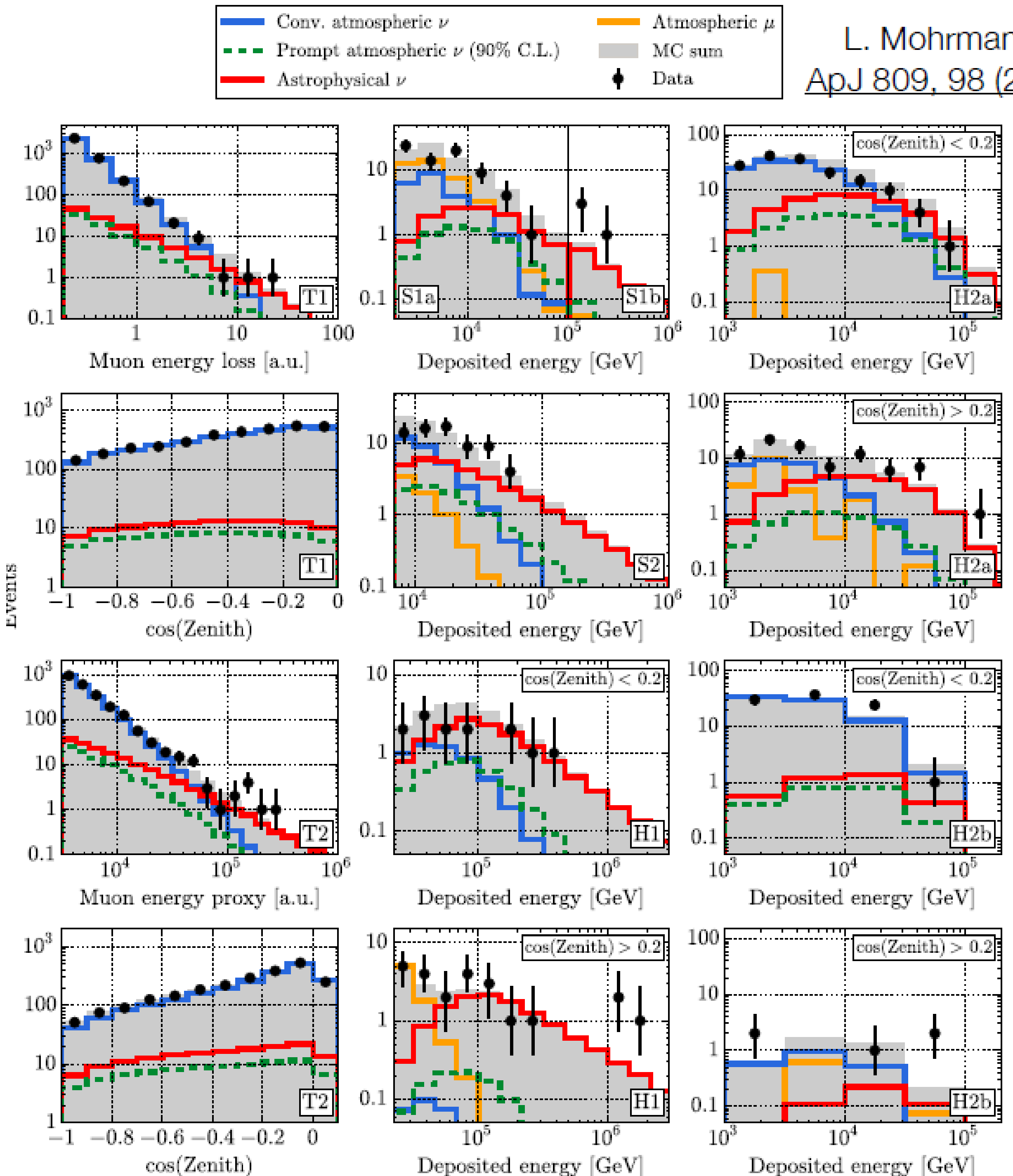
p-value =

$$\int d\log E_{Bert}\, \rho_{Bert}(\log E_{Bert}) \int d\log E_{Ernie}\, \rho_{Erine}(\log E_{Ernie})\, P_{KS}(\log E_{Bert}, \log E_{Ernie})$$

p-values are found to be 4~8x10^{-2} dependent on the models

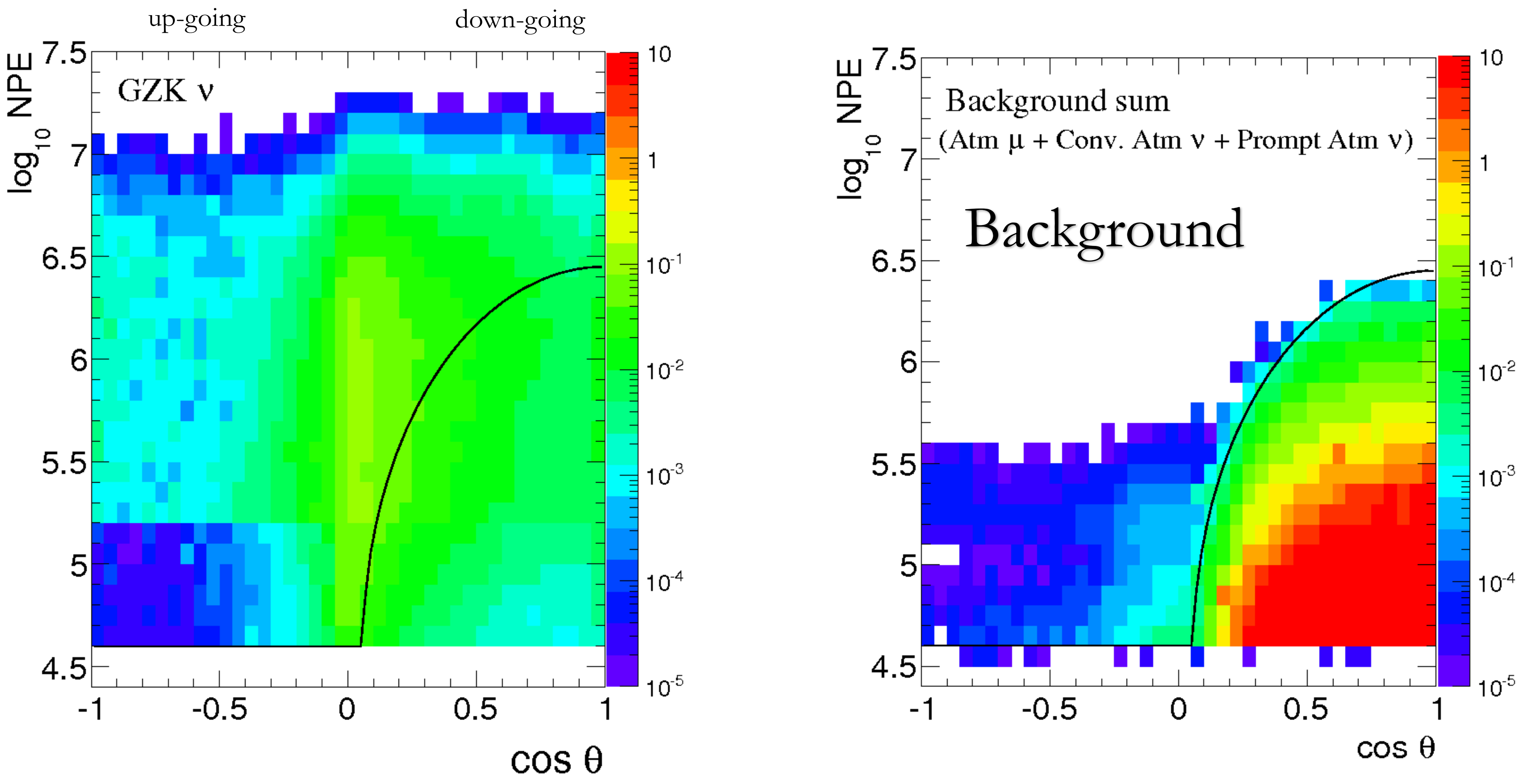
- >90% CL the two events can not be explained by cosmogenic neutrinos

- Let us leave the question of “then what are they?” to dedicated follow up analyses
- Here, we focus on the fact that **we have not seen the cosmogneic neutrinos flux so far with IceCube**



L. Mohrmann, ApJ 809, 98 (2015)

Event selection for GZK neutrinos



◦ Simple cuts on zenith angle and Number of PhotoElectrons (NPE, as energy proxy)