

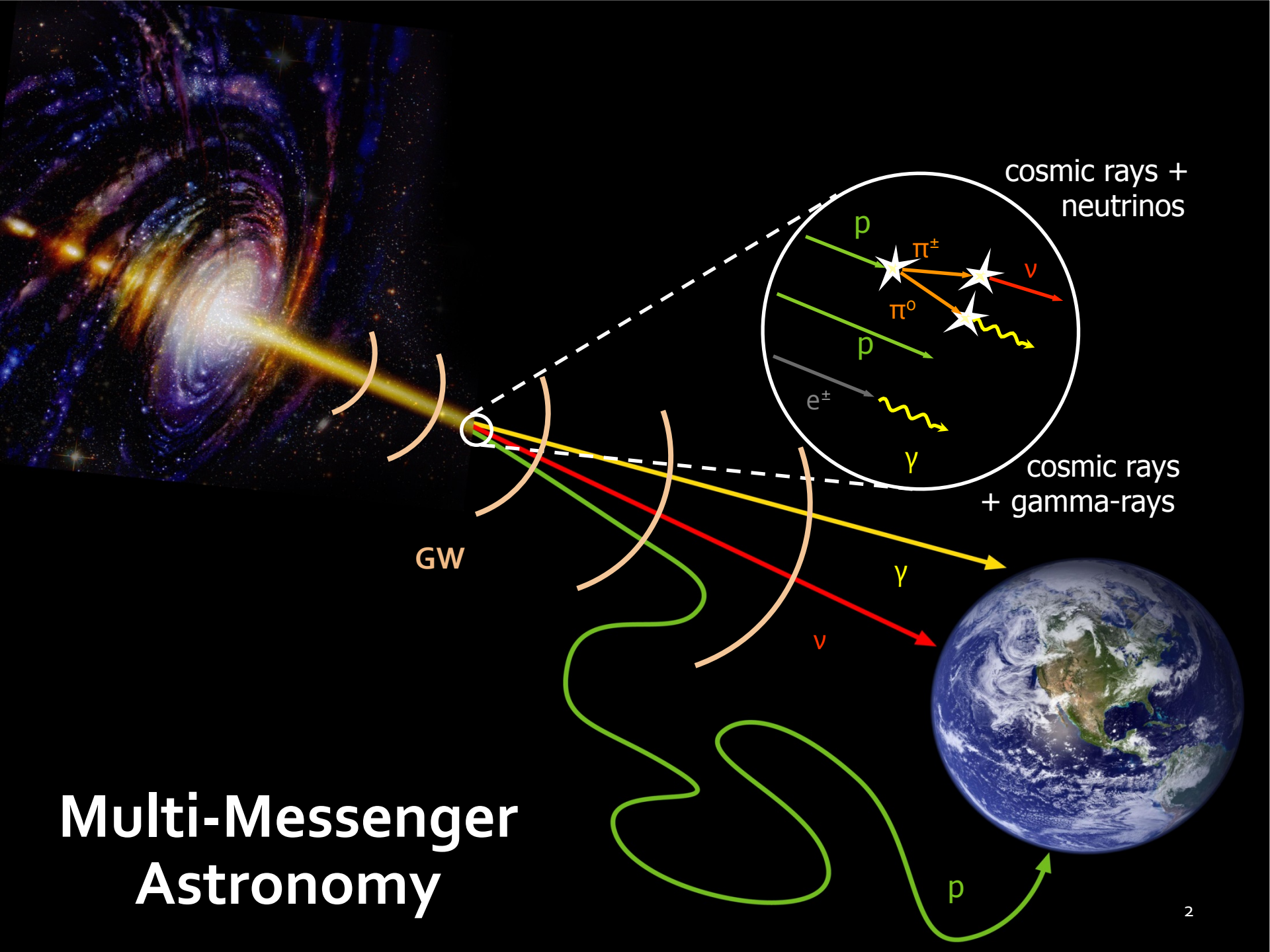
IberiCOS, Aranjuez, Spain, 30 March 2015

Astrophysical Sources of the IceCube Cosmic Neutrino Events

Soebur Razzaque

University of Johannesburg

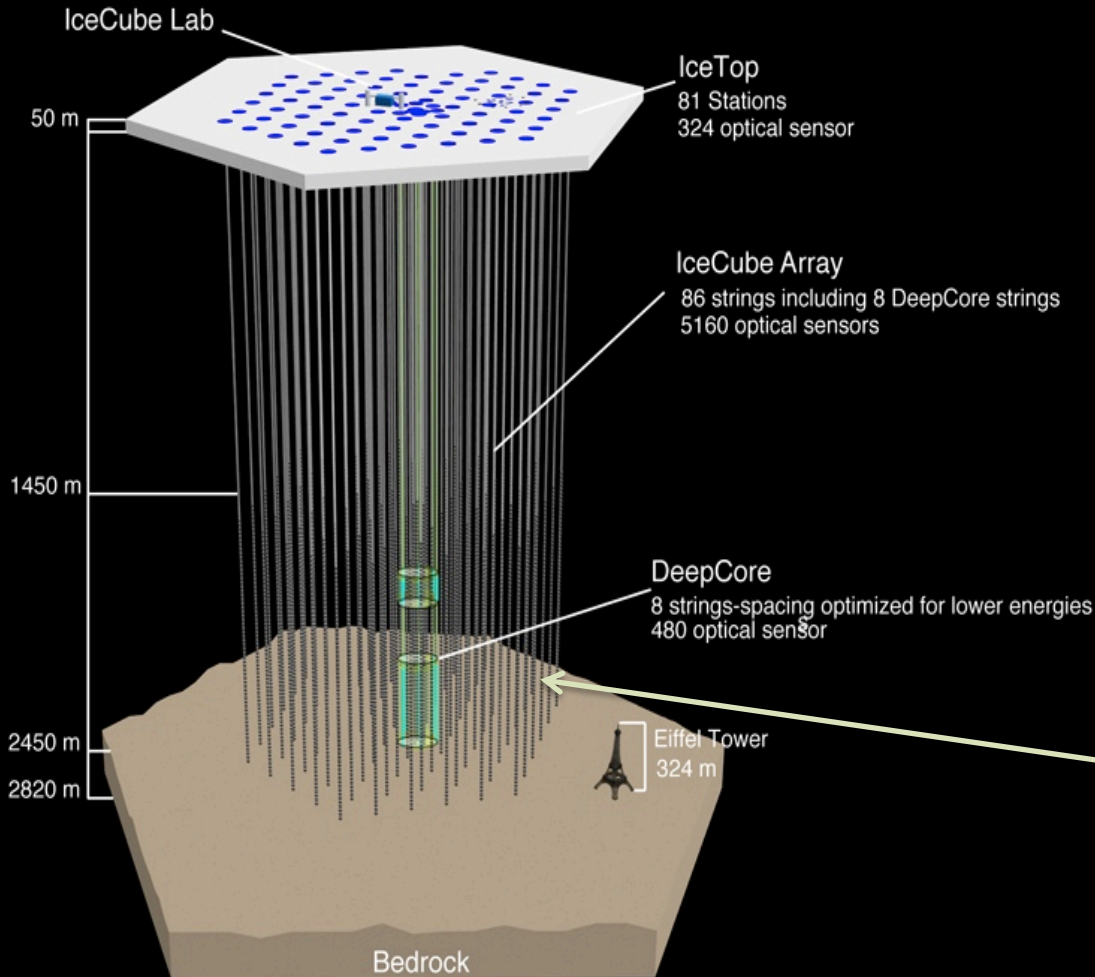
South Africa



Multi-Messenger Astronomy

IceCube Neutrino Observatory

1 km³ instrumented volume (1 Giga ton mass) of pure ice at the South Pole



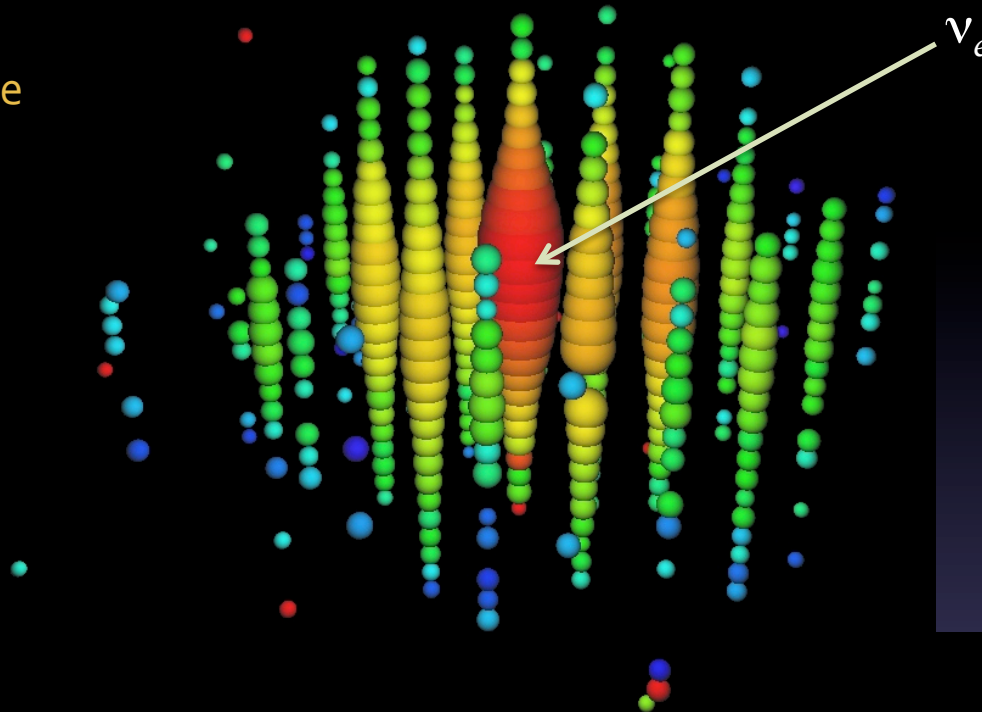
- Construction phase
Dec 2004 – Dec 2010
- 86 strings x 60 DOM
- IceTop air shower array
- IC86, >4 years running to date



Discovery of Cosmic ν 's by IceCube

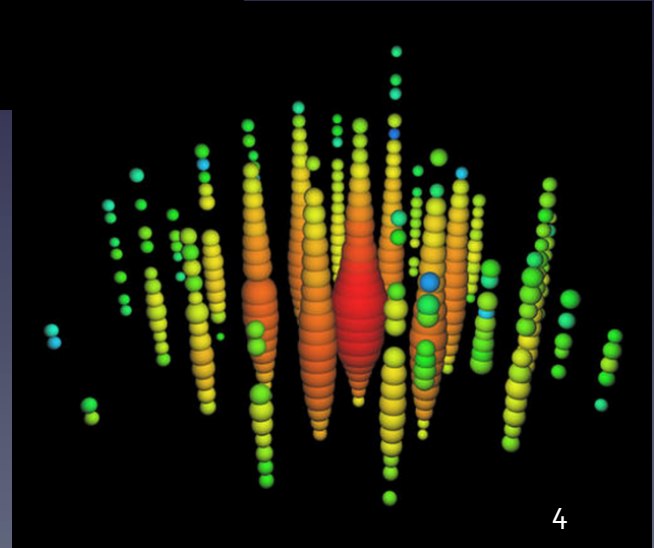
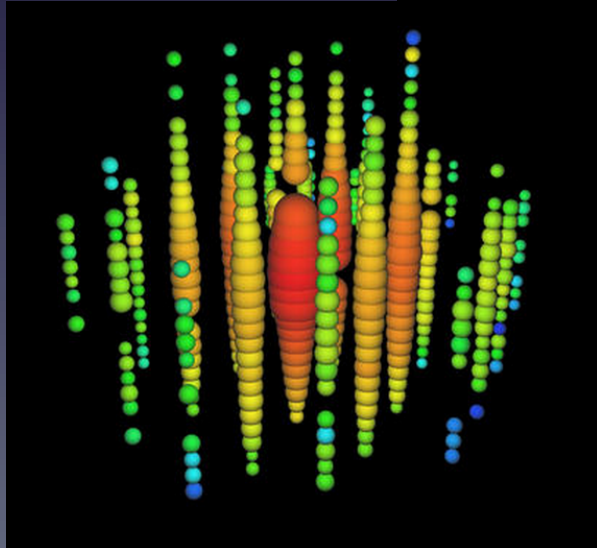
Event displays of
neutrino-induced particle
showers in IceCube

1.1 PeV
"Bert"
August 2011



2.0 PeV
"Big bird"
April 2014

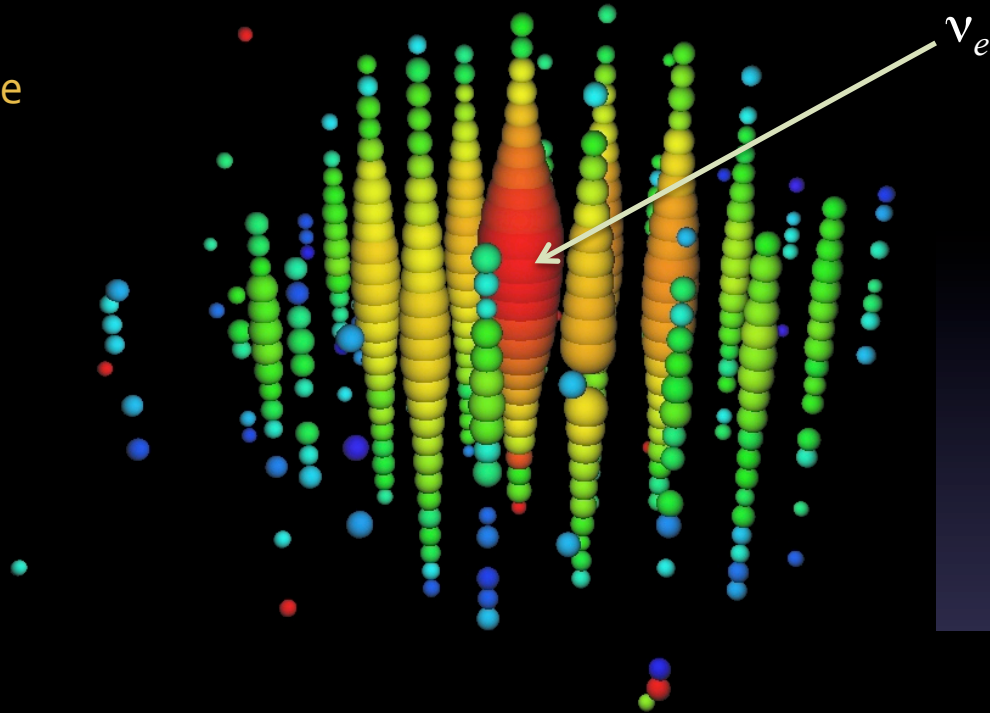
1.0 PeV
"Ernie"
January 2012



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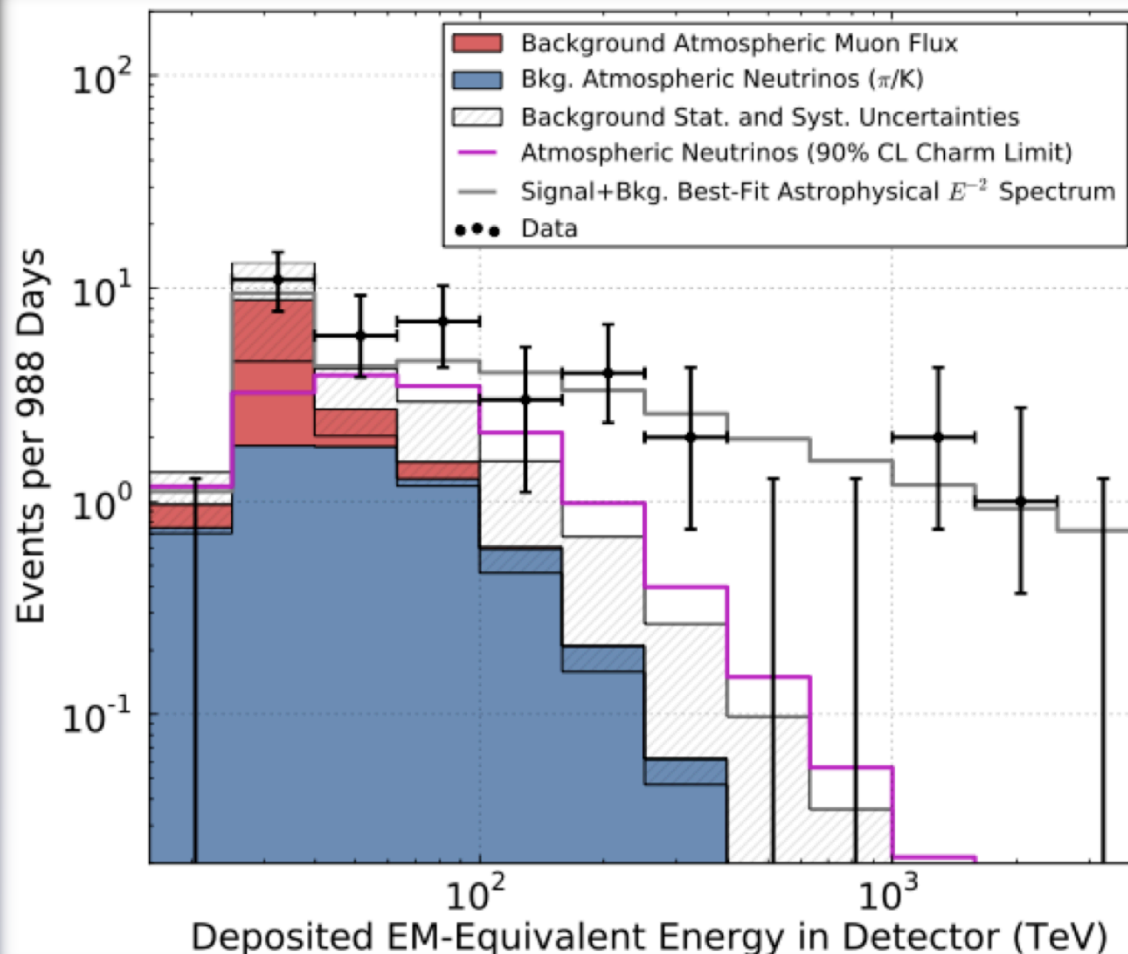
2.0 PeV
"Big bird"
April 2014

1.0 PeV
"Ernie"
January 2012

First detection of very
high-energy
neutrinos above
atmospheric neutrino
foreground

Atmospheric (ν , μ) + cosmic (ν)

Global fit of energy to a mixture of atmospheric and astrophysical E^{-2} ν flux
best fit flux: $E^2\Phi = 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ per neutrino flavor



Events in ~ 3 yr time
with energy > 30 TeV

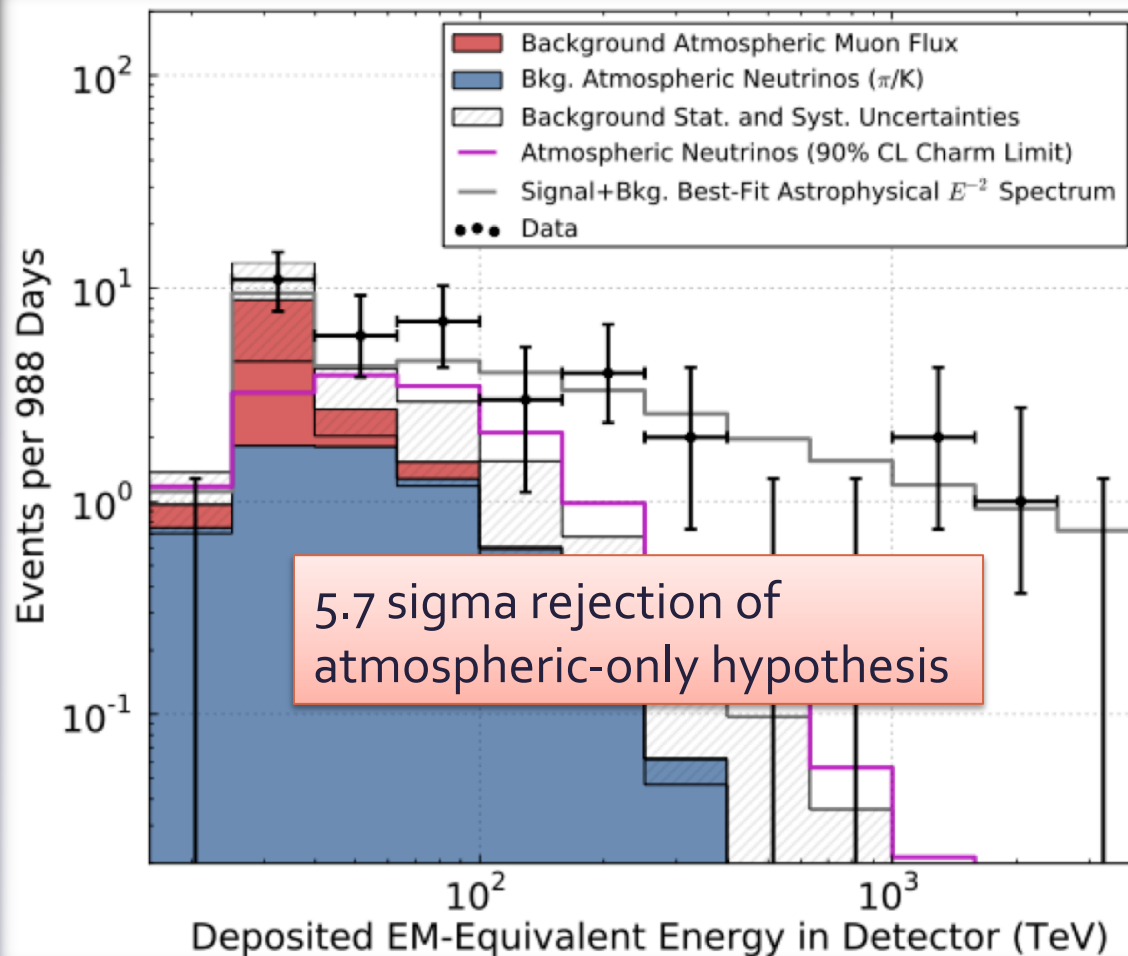
Total : 37

Expected
Atmospheric μ :
 8.4 ± 4.2

Expected
Atmospheric ν :
 $6.6 +5.9/-1.6$

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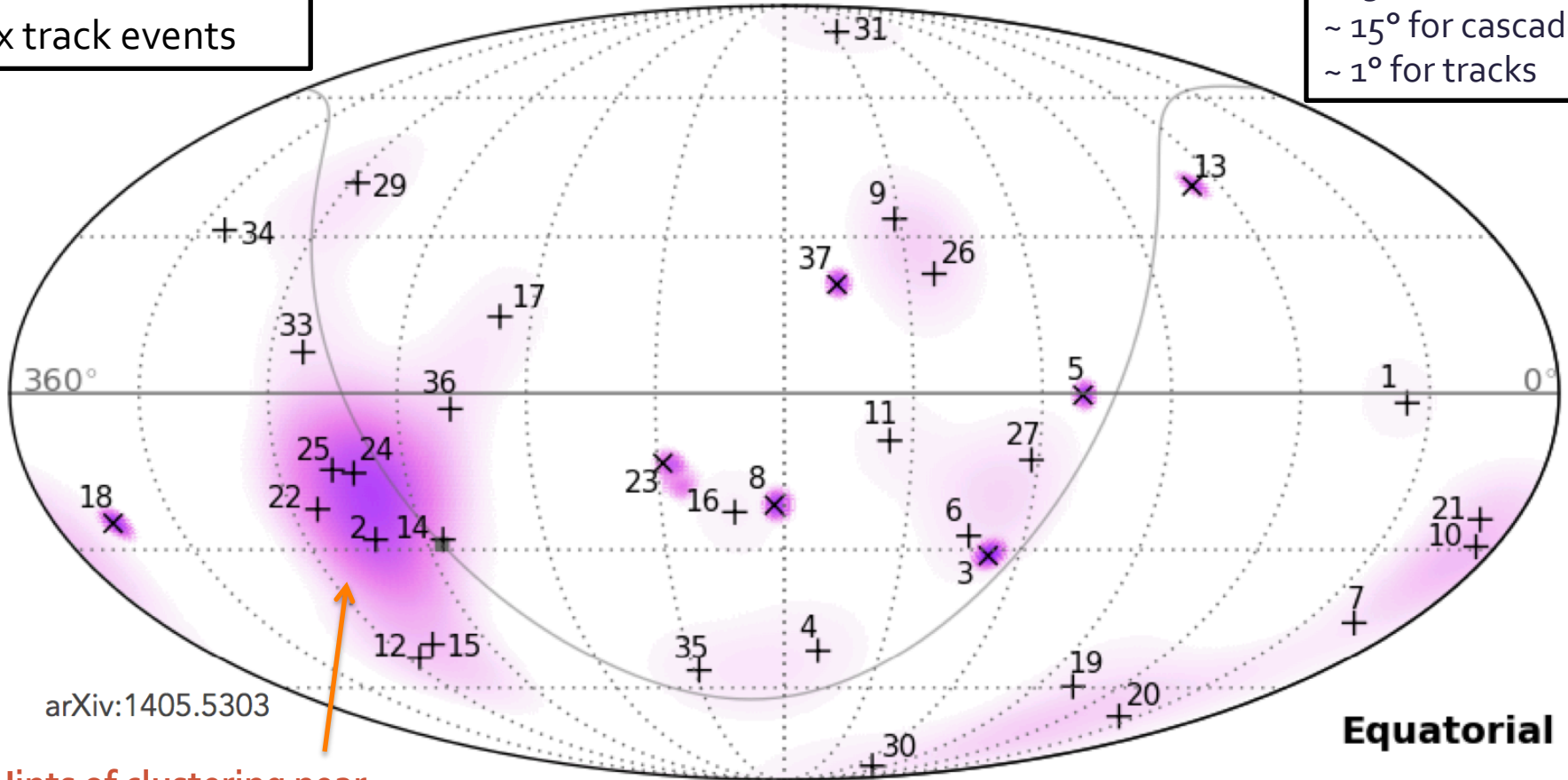
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 Atmospheric ν :
 $6.6 +5.9/-1.6$

Sky Map of Neutrino Events

No significant clustering probability

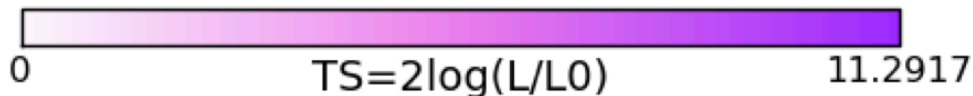
+ cascade events
x track events

angular resolution
~ 15° for cascades
~ 1° for tracks



arXiv:1405.5303

Hints of clustering near
the Galactic center
~8% probability



Equatorial

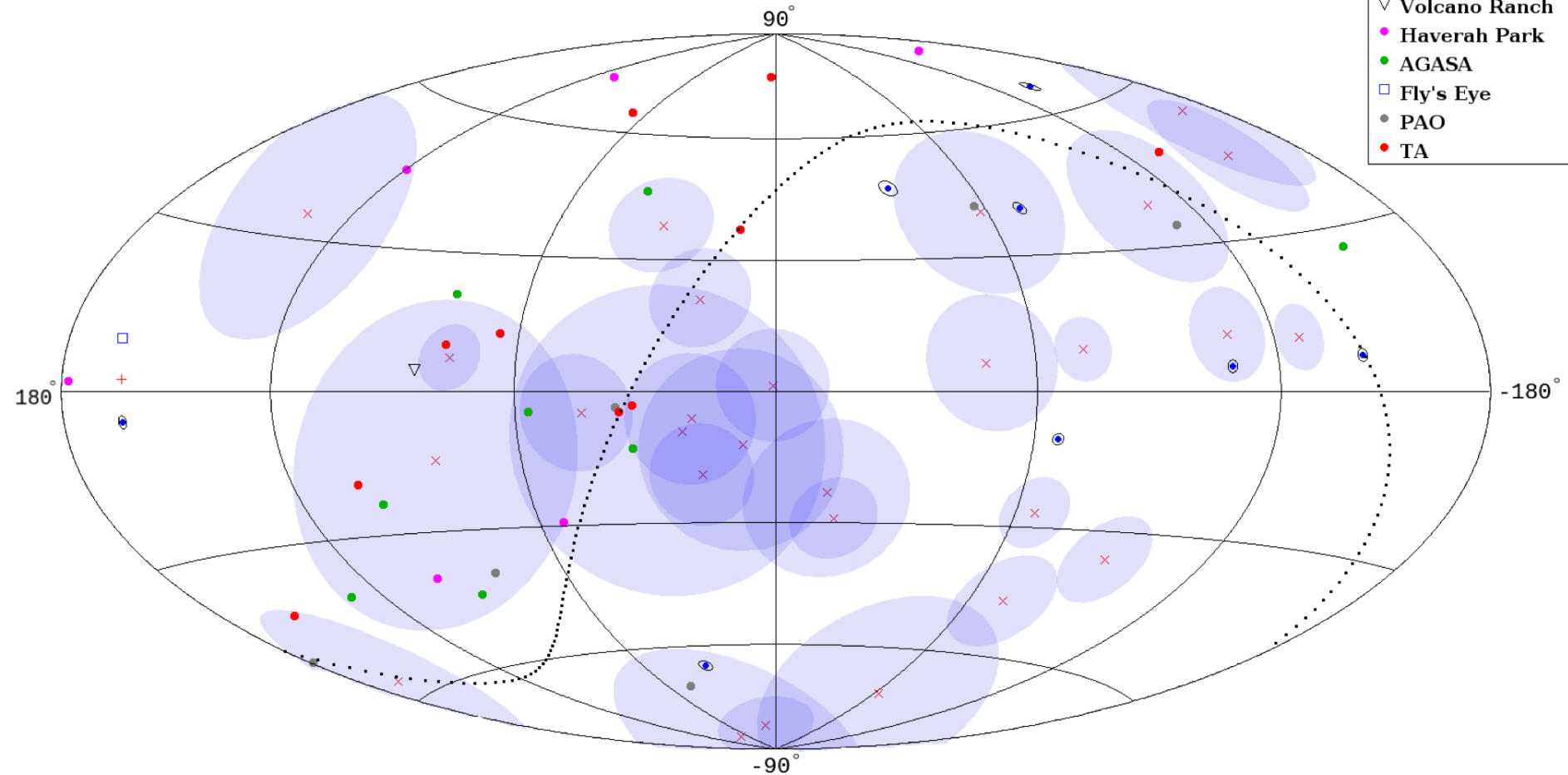
Cross-correlation Study

- Sources of ultrahigh-energy (≥ 80 EeV) cosmic rays are nearby
 - Within a 'GZK radius' of ~ 240 Mpc ($z \sim 0.06$)
- UHECRs deflect by an angle of the order of 1° in the Galactic and intergalactic magnetic field (assuming protons)
 - Can potentially point to their sources
 - Much better pointing resolution than the cascade ν events ($\sim 15^\circ$)
- Sources of UHECRs most likely accelerate particles over a wide energy range (Fermi acceleration mechanism)
 - Can potentially produce < 2 PeV neutrinos detected by IceCube

UHECRs ($> 100 \text{ EeV}$) and Neutrinos

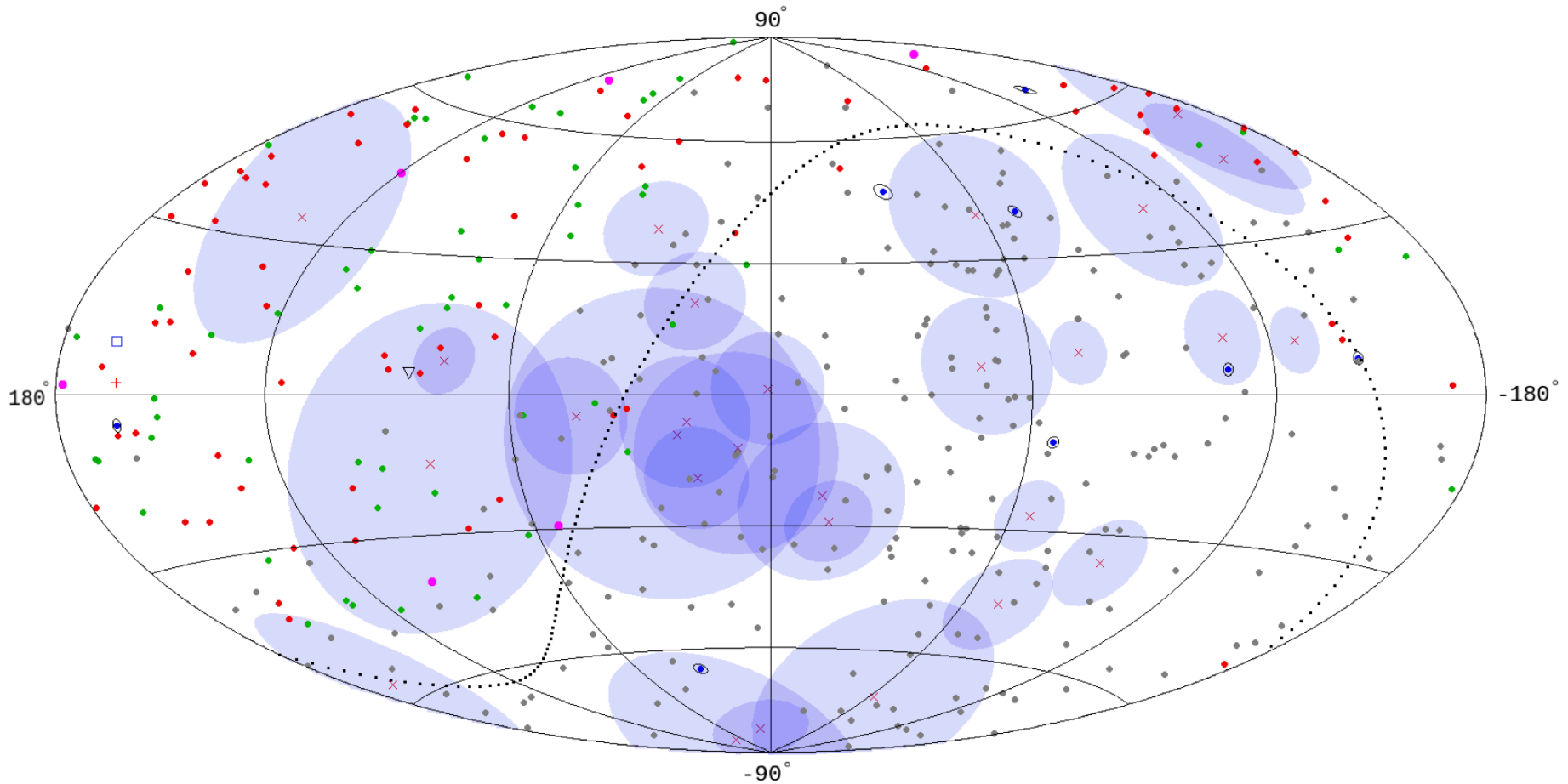
33 UHECRs and 35 Neutrinos

- Neutrino Shower
- Neutrino Tracks
- + Yakustak
- ▽ Volcano Ranch
- Haverah Park
- AGASA
- Fly's Eye
- PAO
- TA



UHECRs ($> 80 \text{ EeV}$) and Neutrinos

>60 UHECRs and 35 Neutrinos



Invariant Statistics

Unit vectors in the sky: $\hat{x} = (\sin \theta \cos \phi, \sin \theta \sin \phi, \cos \theta)^T$

Angular separation between events: $\gamma = \cos^{-1}(\hat{x}_{\text{neutrino}} \cdot \hat{x}_{\text{UHECR}})$

Statistic: $\delta\chi_i^2 = \min_j (\gamma_{ij}^2 / \delta\gamma_i^2)$ ≤ 1 is a 'good fit'

Angular resolution of ν event

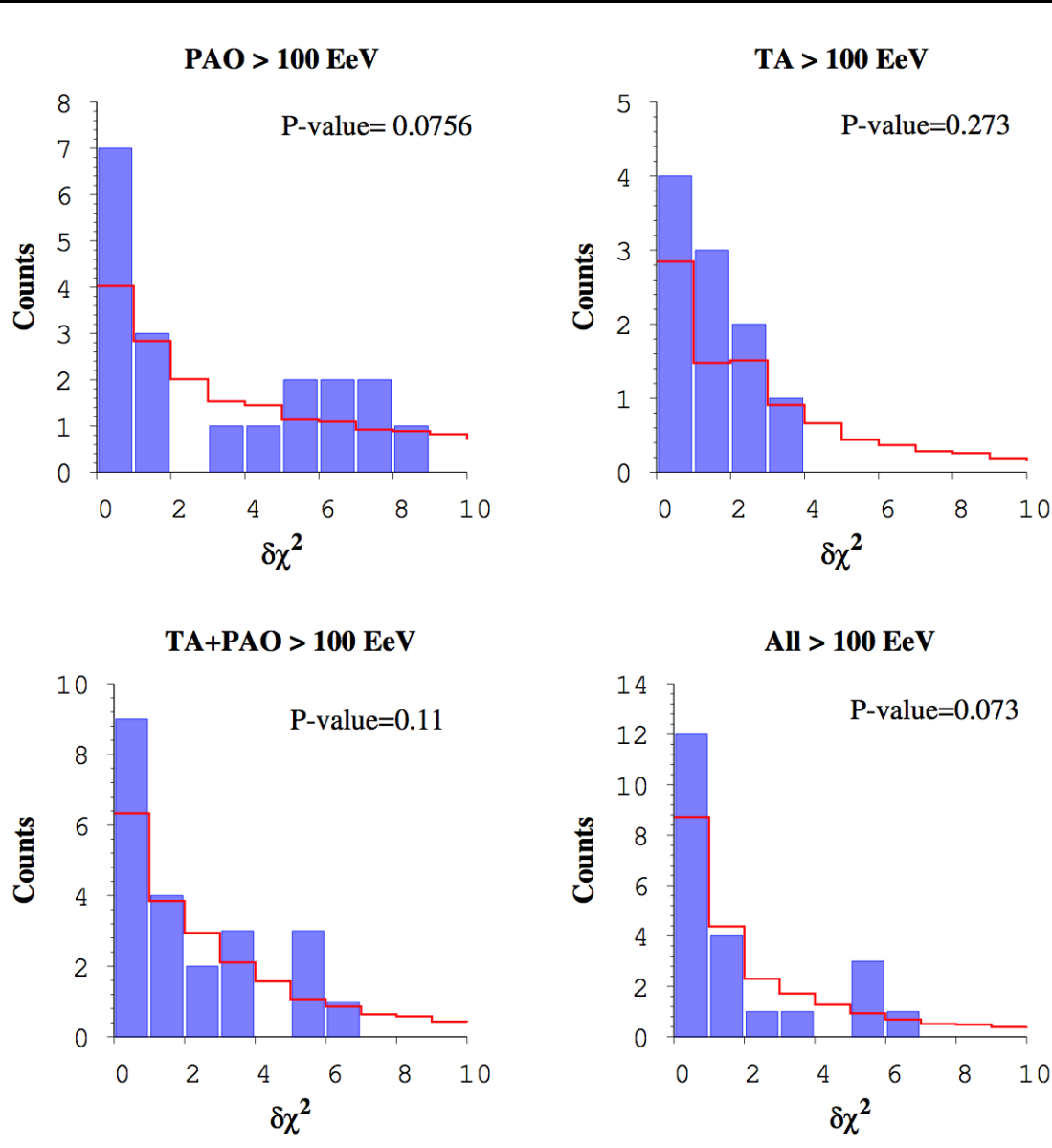
Minimize over all UHECRs

Keep ν direction fixed

Null distribution: Randomly vary UHECR directions and evaluate $\delta\chi^2$
(keeping detector-specific declination-dependence)
100,000 realizations

Frequentists' approach to evaluate p -value

Cross-correlation Results, >100 EeV

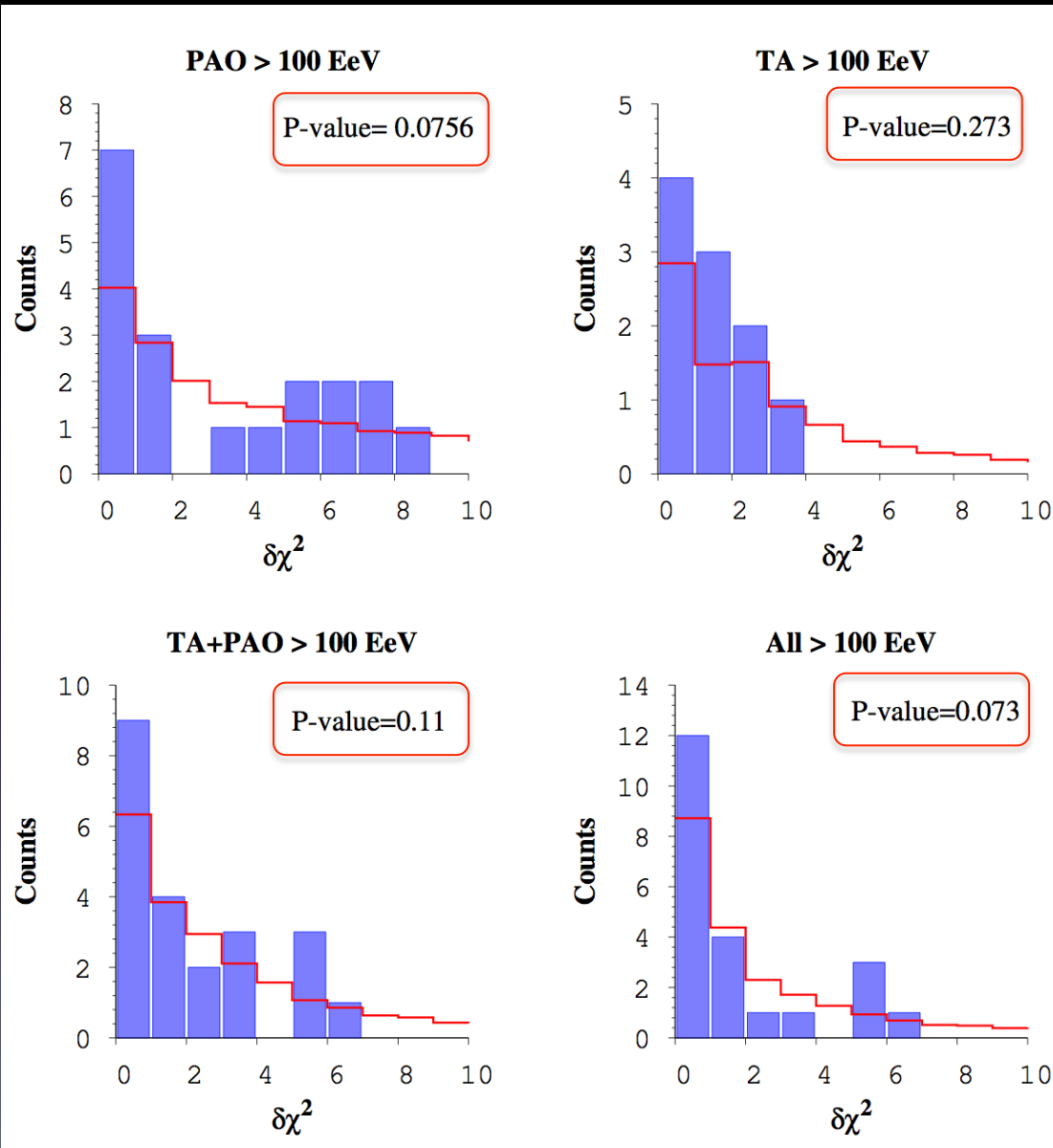


Small hint of correlation between UHECRs and cosmic neutrino data

Dominated by PAO data

Preliminary ...

Cross-correlation Results, >100 EeV

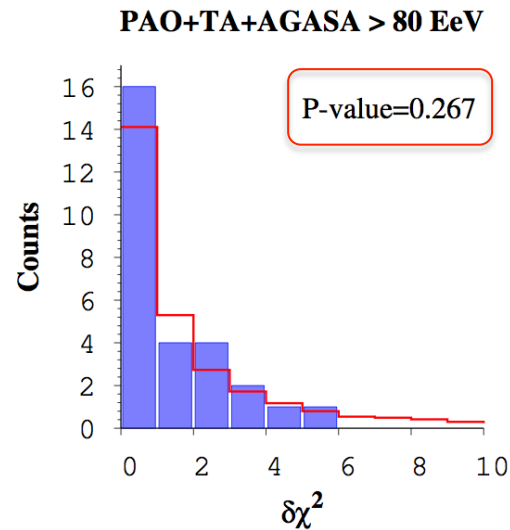
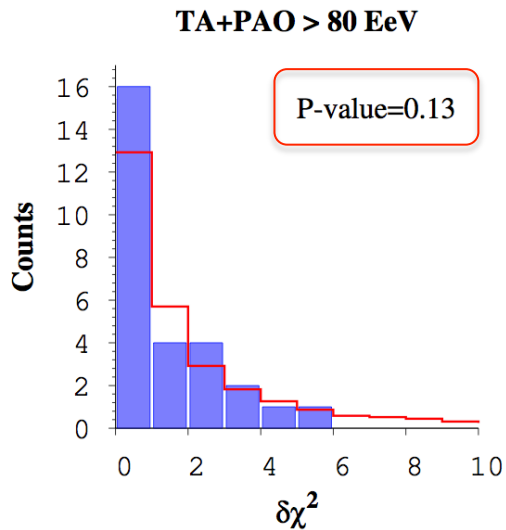
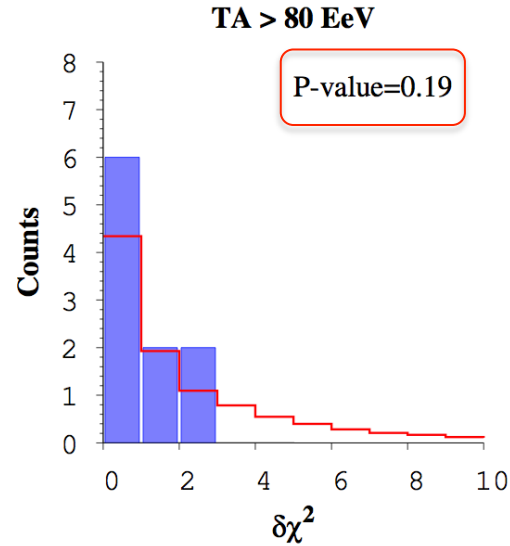
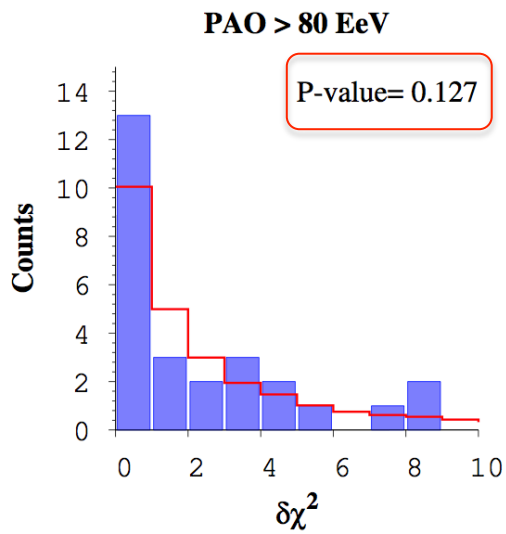


Small hint of correlation between UHECRs and cosmic neutrino data

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Preliminary ...

Cross-correlation Results, >80 EeV



Significance decreases with decrease of UHECRs' energy

Preliminary ...

Source search around UHECR directions

Neutrino Event #	UHECR			<i>Swift</i> X-ray Source Catalog [21]			
	RA	Dec	Experiment	Name	z	Type	
1	45.6	-1.7	PAO	NGC 1142	0.0289	Sy2	
				NGC 1194	0.0136	Sy1	
				MCG +00-09-042	0.0238	Sy2	
				NGC 1068	0.0038	Sy2	
11	150.1	-10.3	PAO	2MASX J10084862-0954510	0.0573	Sy1.8	
17	241.5	23	AGASA	2MASX J16311554+2352577	0.0590	Sy2	
29, 34	295.6	43.52	TA	2MASX J19471938+4449425	0.0539	Sy2	
				ABELL 2319	0.0557	GC	
				Cygnus A	0.0561	Sy2	
21	352.6	-20.2	PAO	PKS 2331-240	0.0477	Sy2	
2, 24, 25	294.5	-5.8	AGASA	2MASX J19373299-0613046	0.0103	Sy1.5	
				34	340.6	12	PAO
	349.0	12.3	AGASA	MCG +02-57-002	0.0290	Sy1.5	
				UGC 12237	0.0283	Sy2	
				NGC 7479	0.0079	Sy2/Liner	
				2MASX J23272195+1524375	0.0457	Sy1	
				NGC 7469	0.0163	Sy1.2	
	352.6	-20.2	Haverah Park	NGC 7679	0.0171	Sy2	

Neutrino Event #	UHECR			Kühr Radio Source Catalog [22]		
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34	340.6	12	PAO	NGC 7385	0.0255	GC

Table 4. Sources correlated with UHECRs and neutrino events simultaneously.

UHECRs (>100 EeV) must be correlated with one or more ν events

Search within a 3° error circle around UHECR directions

Use X-ray, gamma-ray, radio source catalogues ($z < 0.06$)

Preliminary ...

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Preliminary ...

Sources are dominantly weak AGNs (Syfert galaxies)

Summary

✧ Neutrinos are messengers of energetic cosmic events

- ✧ Identify the location of particle acceleration, probe emission mechanism, constrain source environment

✧ Birth of neutrino astronomy (~2013)

- ✧ > 5 sigma detection of cosmic neutrinos by IceCube
- ✧ Large angular error prohibits direct identification of point sources

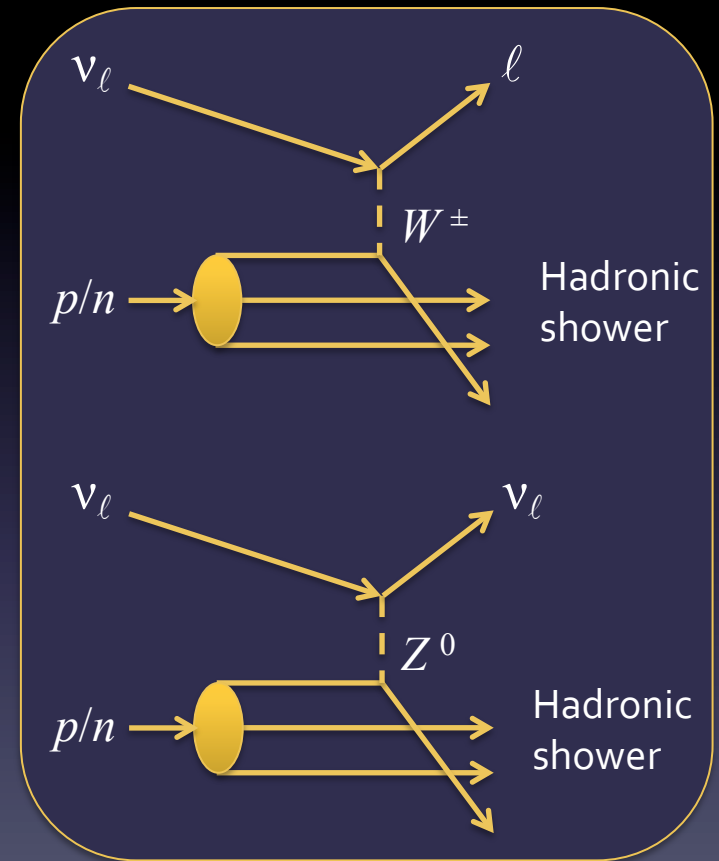
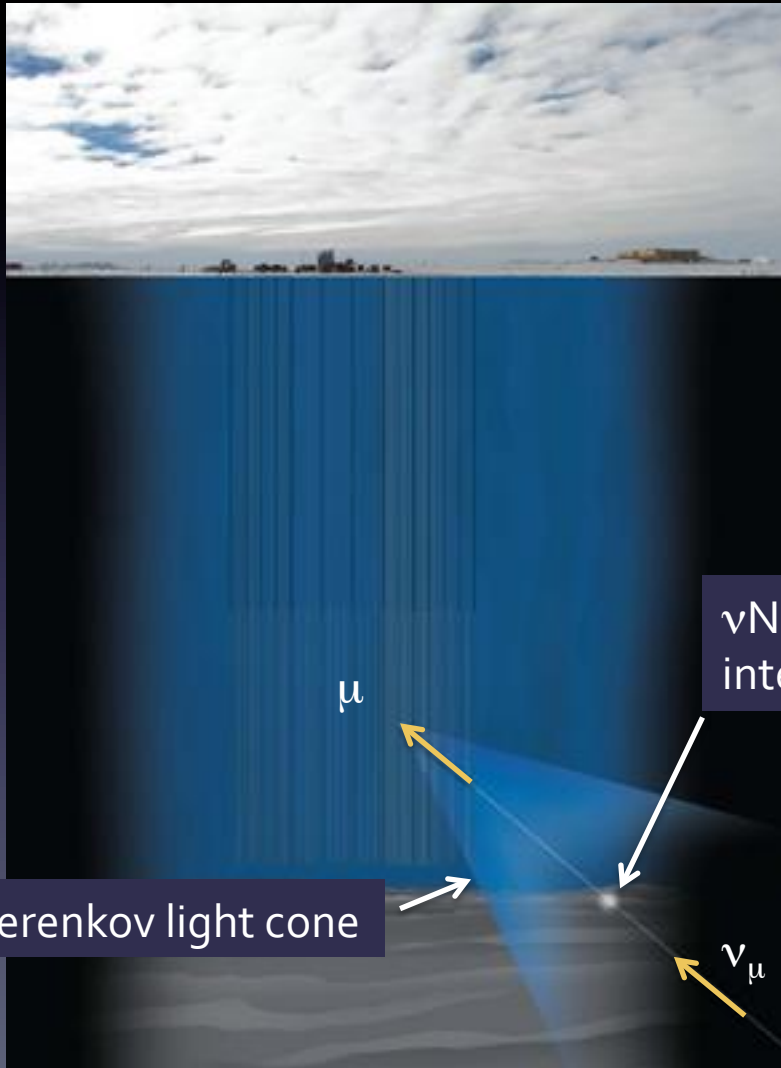
✧ Extragalactic neutrino sources

- ✧ Some hints of correlation between UHECRs with energy > 100 EeV and cosmic neutrinos detected by IceCube
- ✧ UHECRs which are correlated with neutrinos point to the directions of Active Galactic Nuclei which are bright in X-rays and/or radio

Neutrino Detection Principle

IceCube array

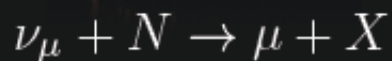
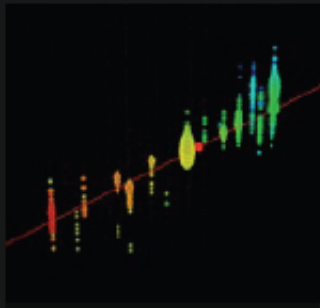
νN charge/neutral current (CC/NC) interactions



~ 80% of ν energy to secondary lepton

Neutrino Flavor Identification

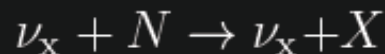
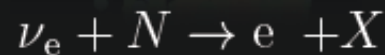
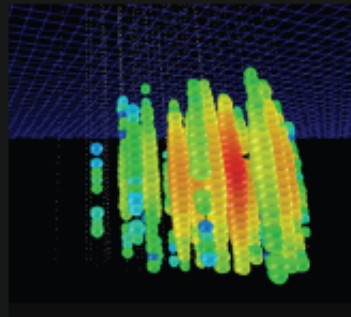
CC Muon Neutrino



track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution

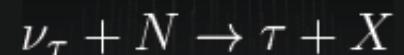
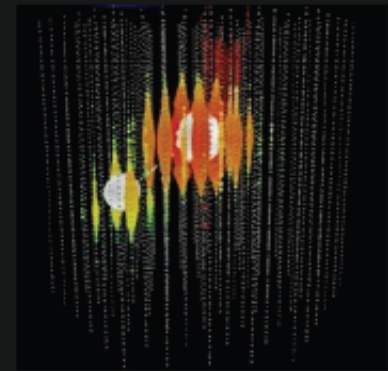
Neutral Current / Electron Neutrino



cascade (data)

$\approx \pm 15\%$ deposited energy resolution
 $\approx 10^{\circ}$ angular resolution
(at energies ≈ 100 TeV)

CC Tau Neutrino



“double-bang” and other
signatures (simulation)

(not observed yet)

Atmospheric Neutrinos

Cosmic ray interactions in the earth's atmosphere

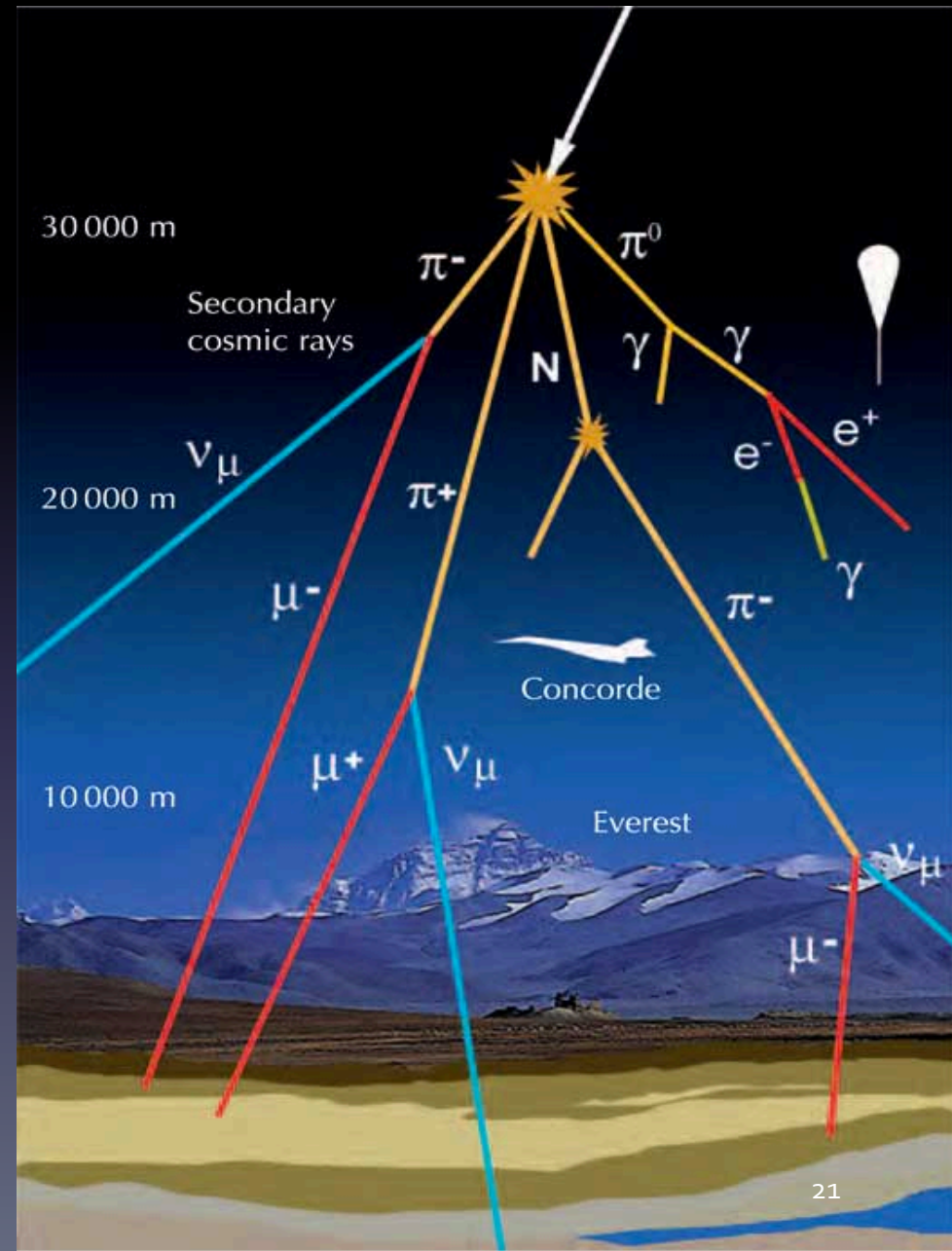
Foreground to the astrophysical neutrino signal

Cosmic-ray spectrum $\sim E^{-2.7}$

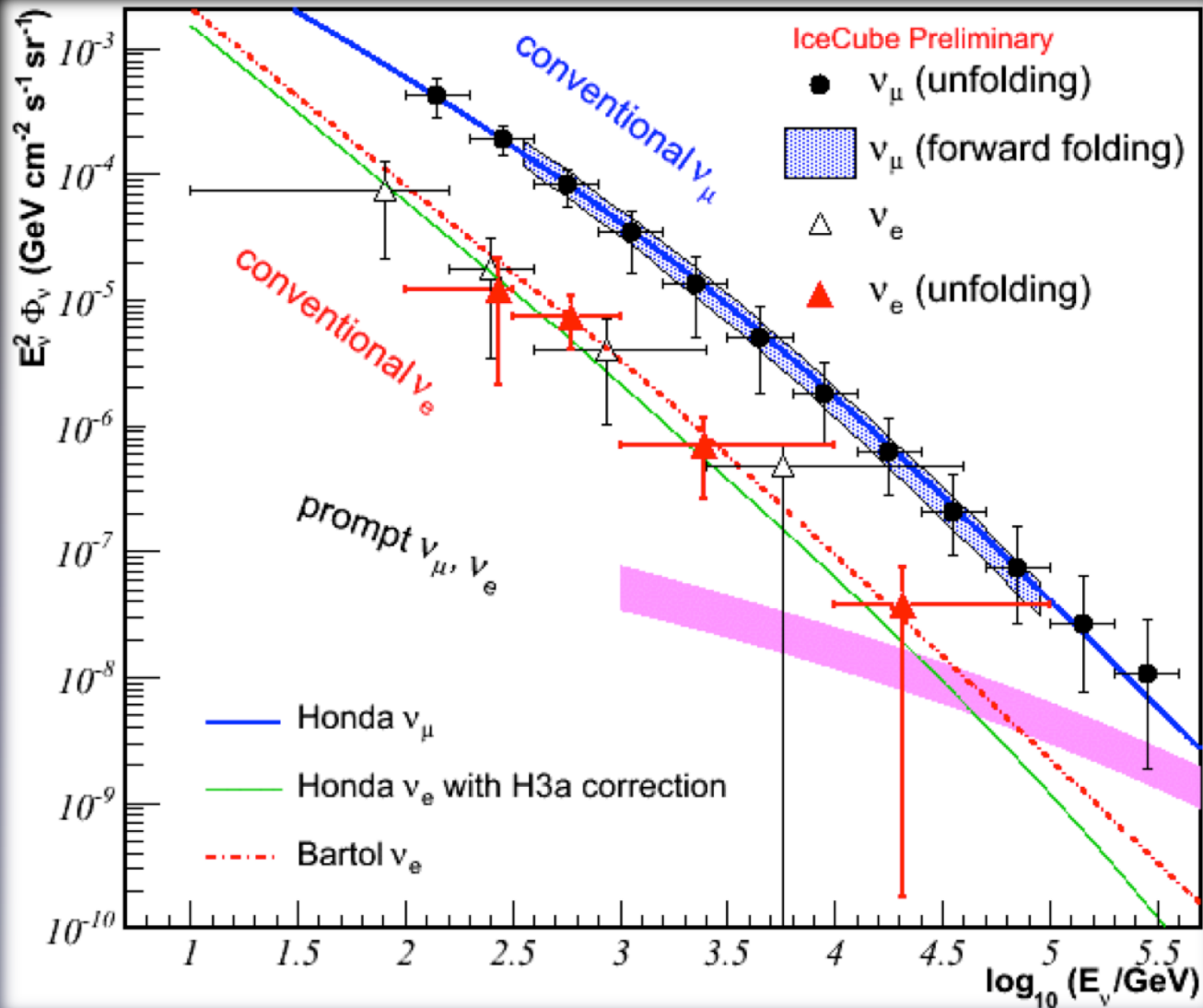
Conventional (π/K decay)

ν spectrum $\sim E^{-2.7} - E^{-3.7}$

Prompt ν spectrum (from short-lived charm meson decays) $\sim E^{-2.7}$



Atmospheric Neutrino Flux



Diffuse Flux of Cosmic Neutrinos

