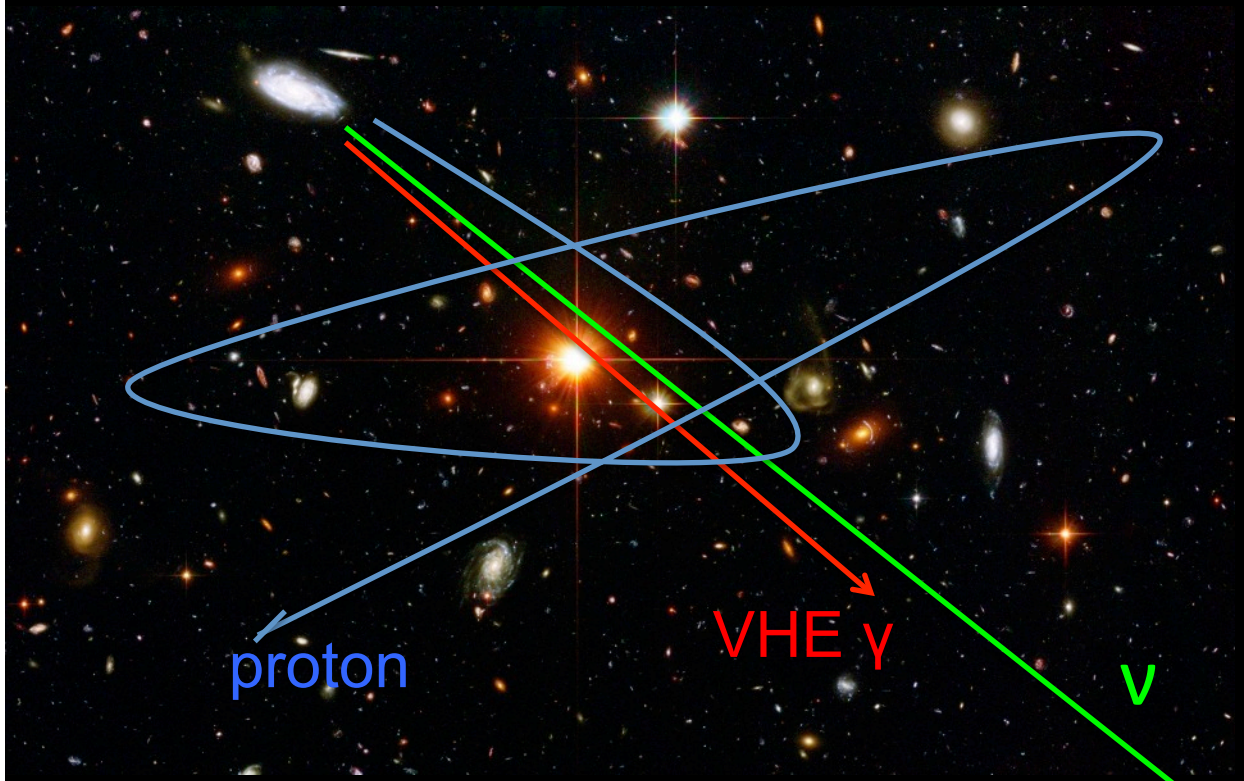
Evidence for high-energy extraterrestrial neutrinos at the IceCube detector

K. Mase, Chiba Univ.

Why neutrino?



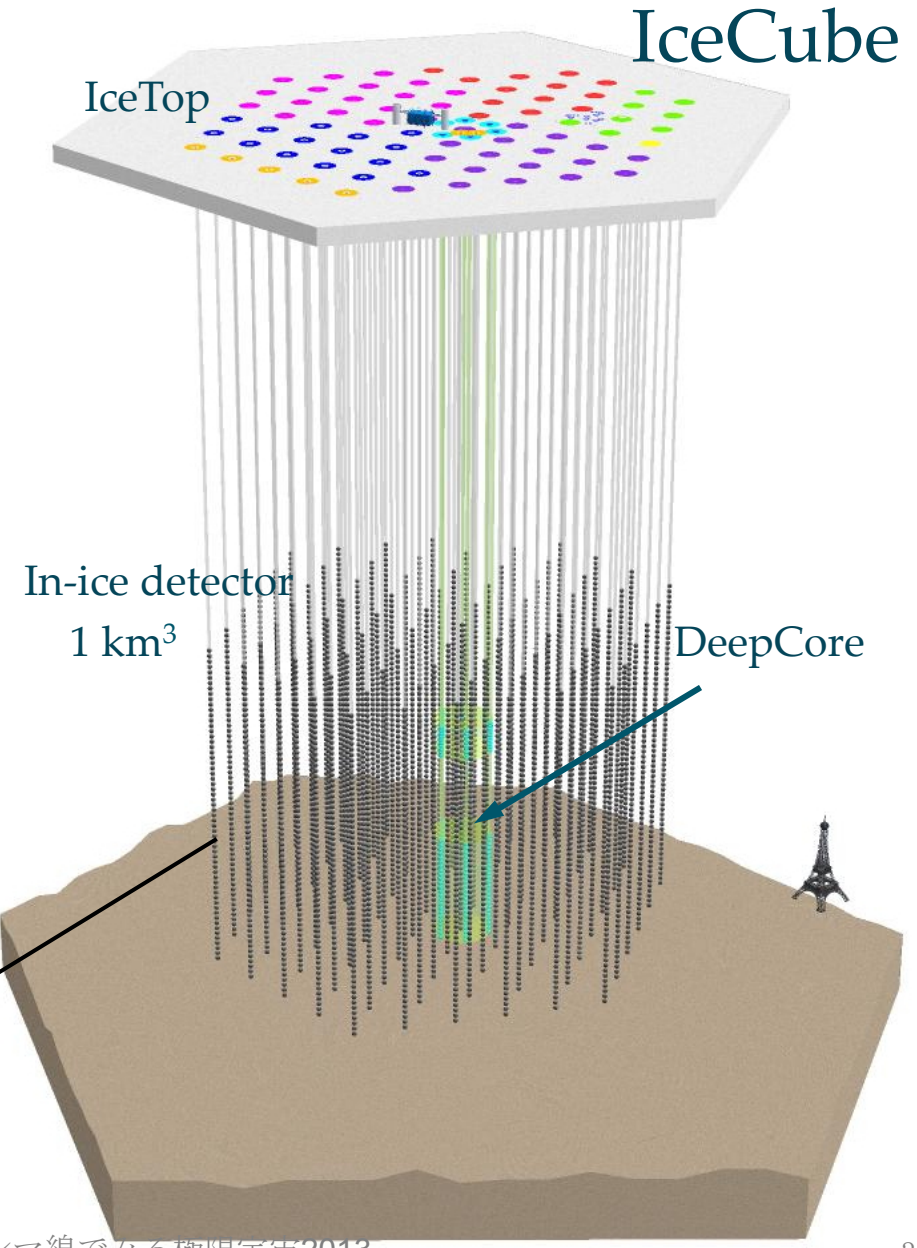
Neutrinos are rarely interacting particles

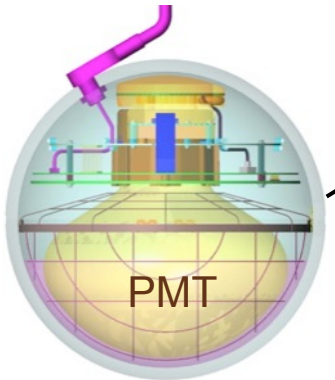
→ Arrive straight to the Earth from the deep Universe

Hadronic interaction → CR origin

The IceCube experiment

- Deployed in the Antarctic glacier
- In-ice + IceTop + DeepCore
- 86 strings (completed in 2010)
- ~ 5,000 photo-multiplier tubes (PMTs)
- Detector volume: ~ 1 km^3
- ATWD 300MSPS
  3 different gains (x16, x2, x0.25)
- FADC for long duration pulse
- Targets for cosmic high energy neutrinos
  (mainly >~ 100 GeV)

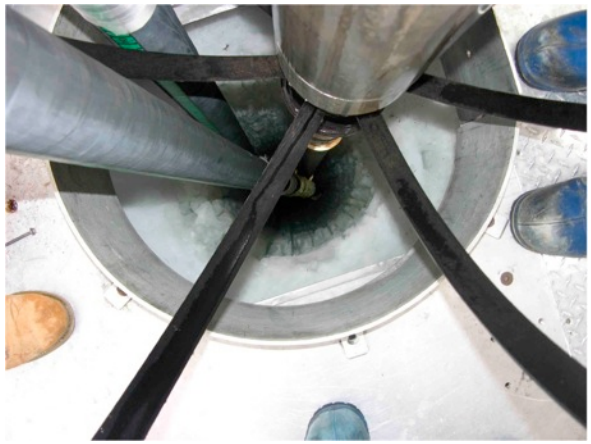


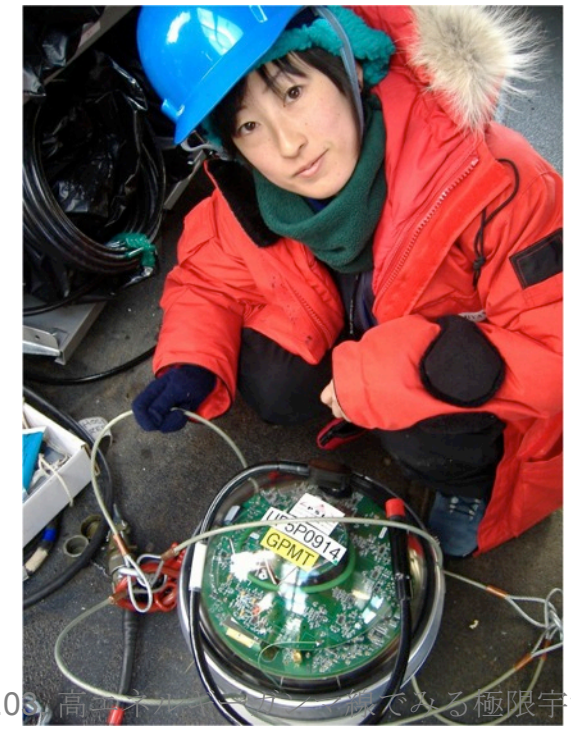


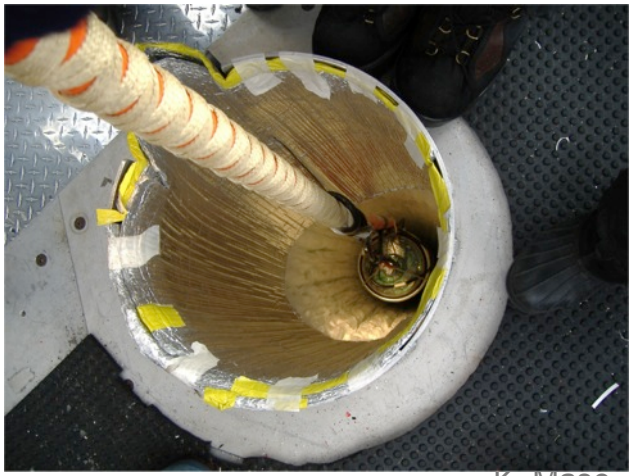
Digital Optical Module
(DOM)

41 institutes and ~280 physists

The deployment





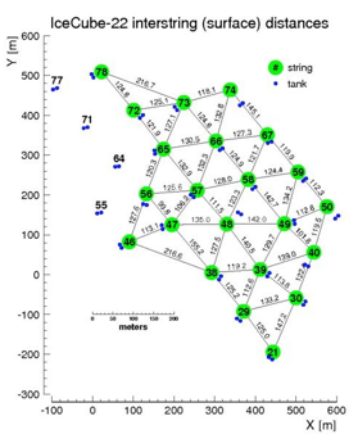


Use hot water to make a hole

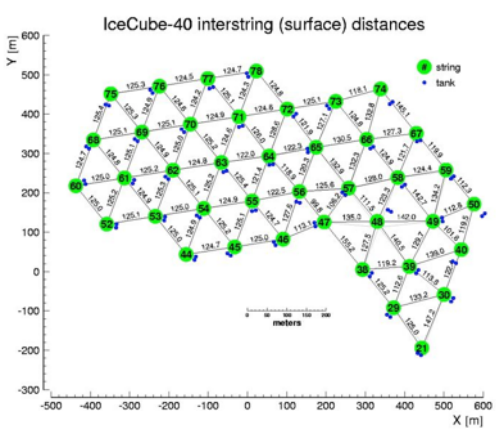
The construction

2004: project started
2006-2007: IC9
2007-2008: IC22
2008-2009: IC40
2009-2010: IC59
2010-2011: IC79
End of 2010: IceCube completed!
2011~: IC86

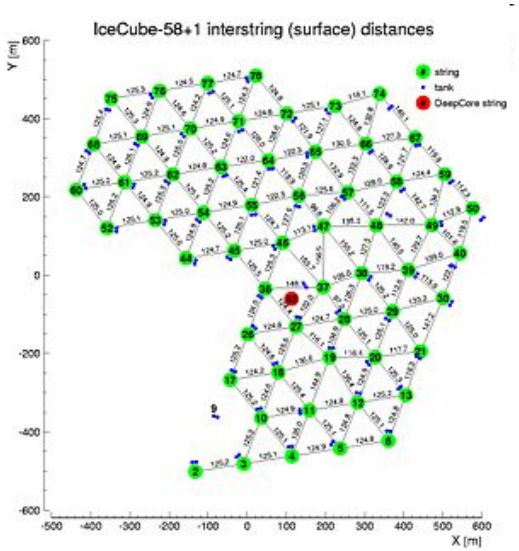
IC22 (2007-2008)



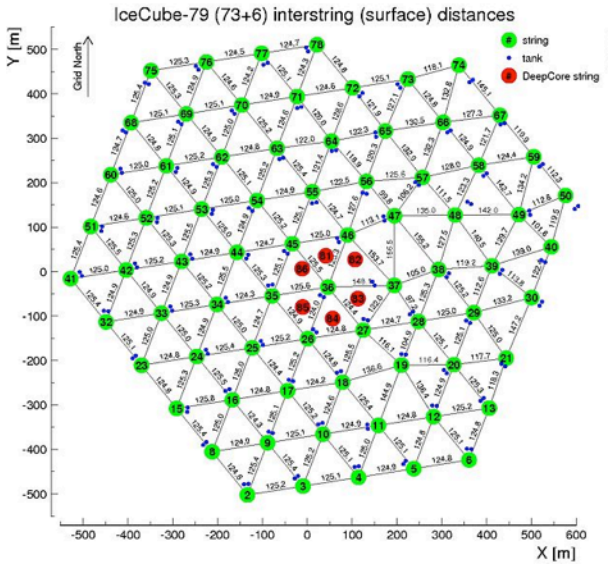
IC40 (2008-2009)



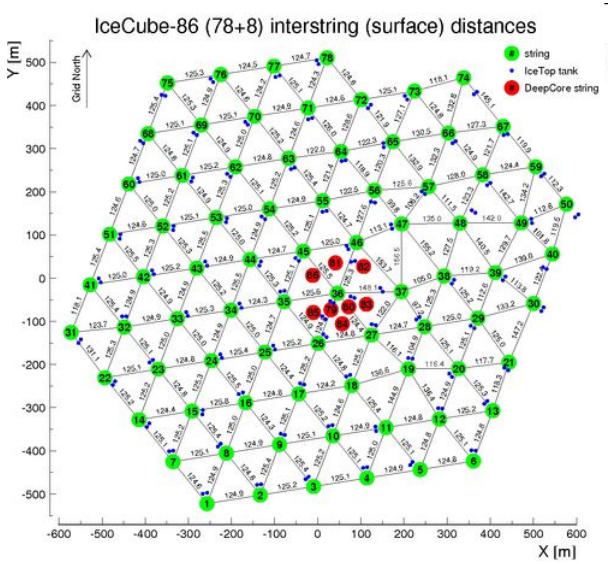
IC59 (2009-2010)



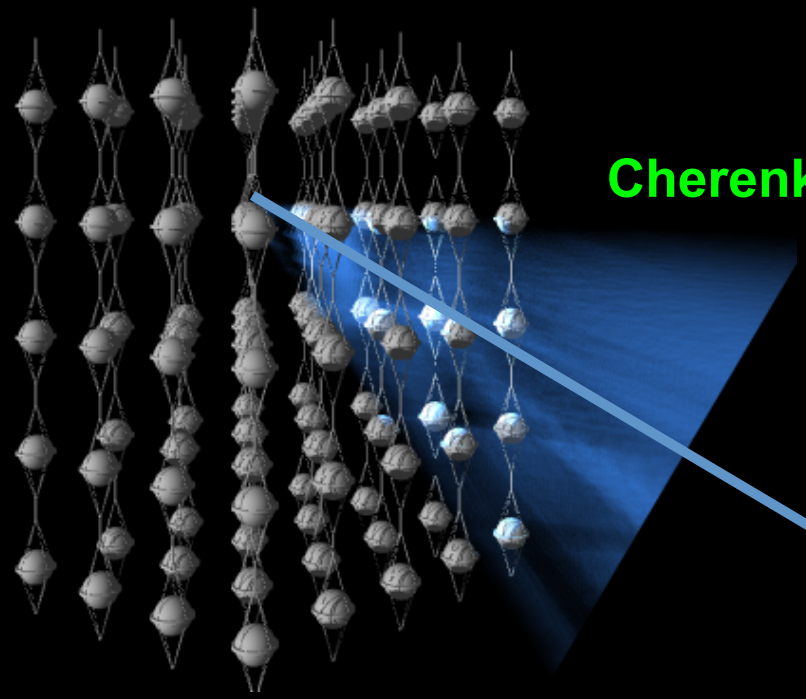
IC79 (2010-2011)



IC86 = complete IceCube (2011~)

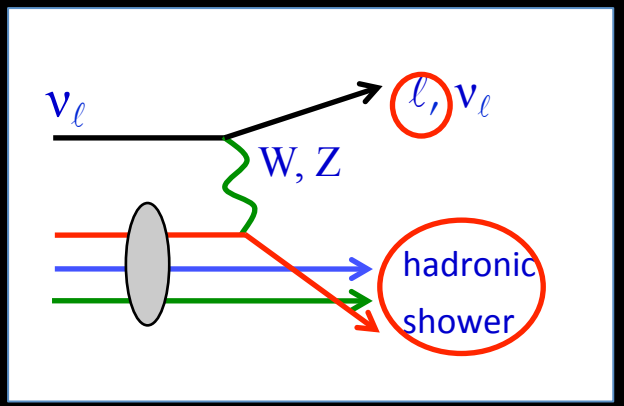


The detection principle



Cherenkov light

μ



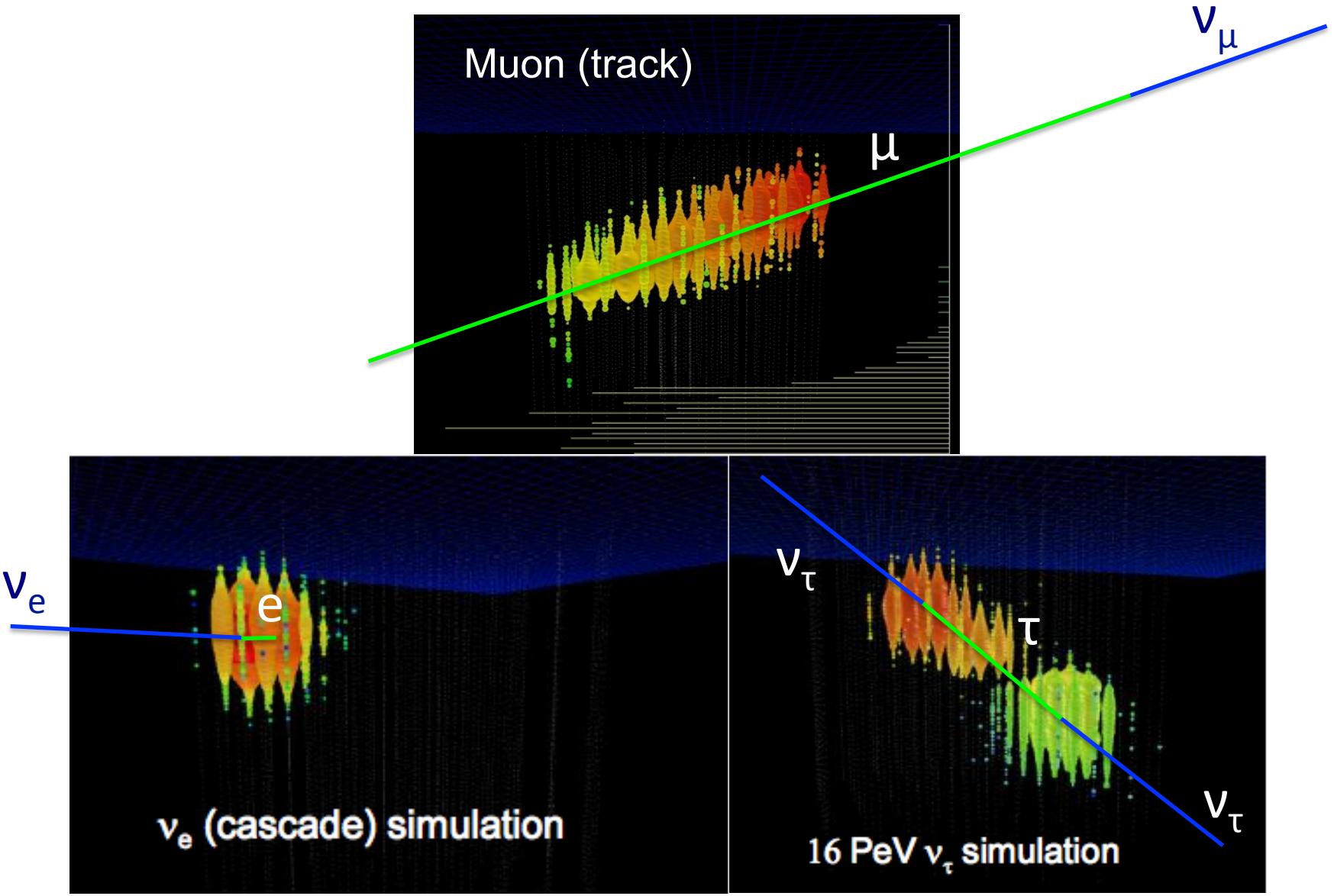
interaction

ν_μ

- A large volume
- transparent medium

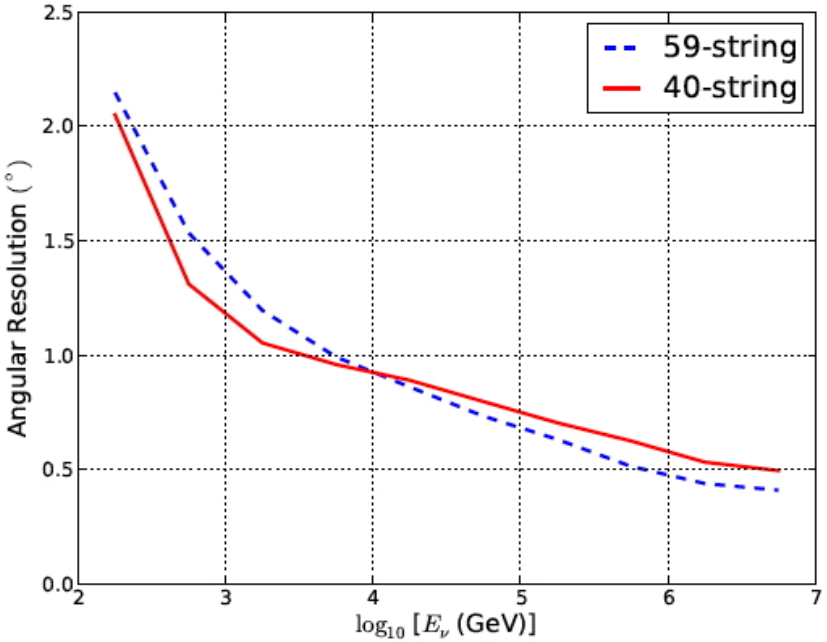
→ Antarctic glacier

Particle identification

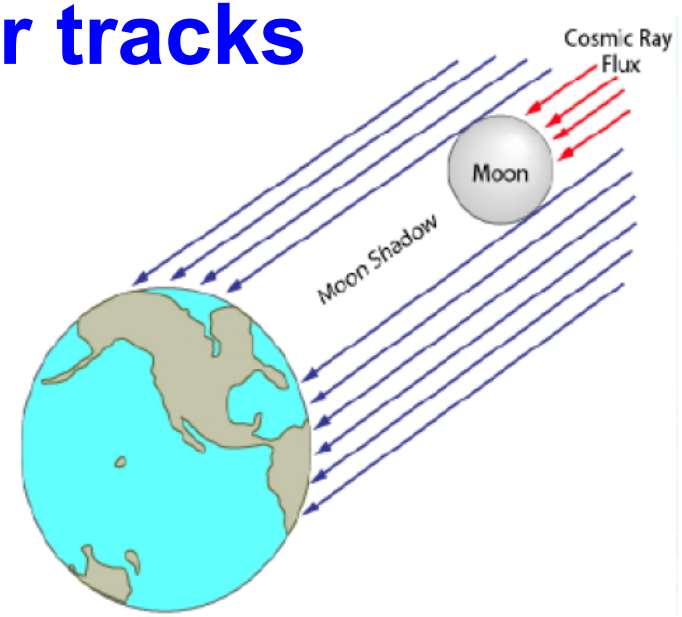


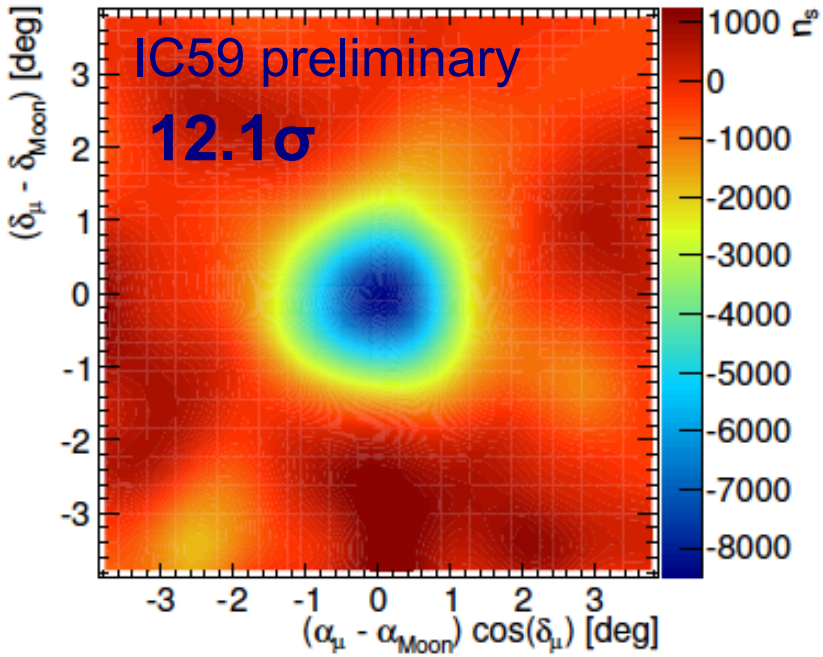
Neutral current events also generate cascades

The angular resolution for tracks



arXiv:1111.2741

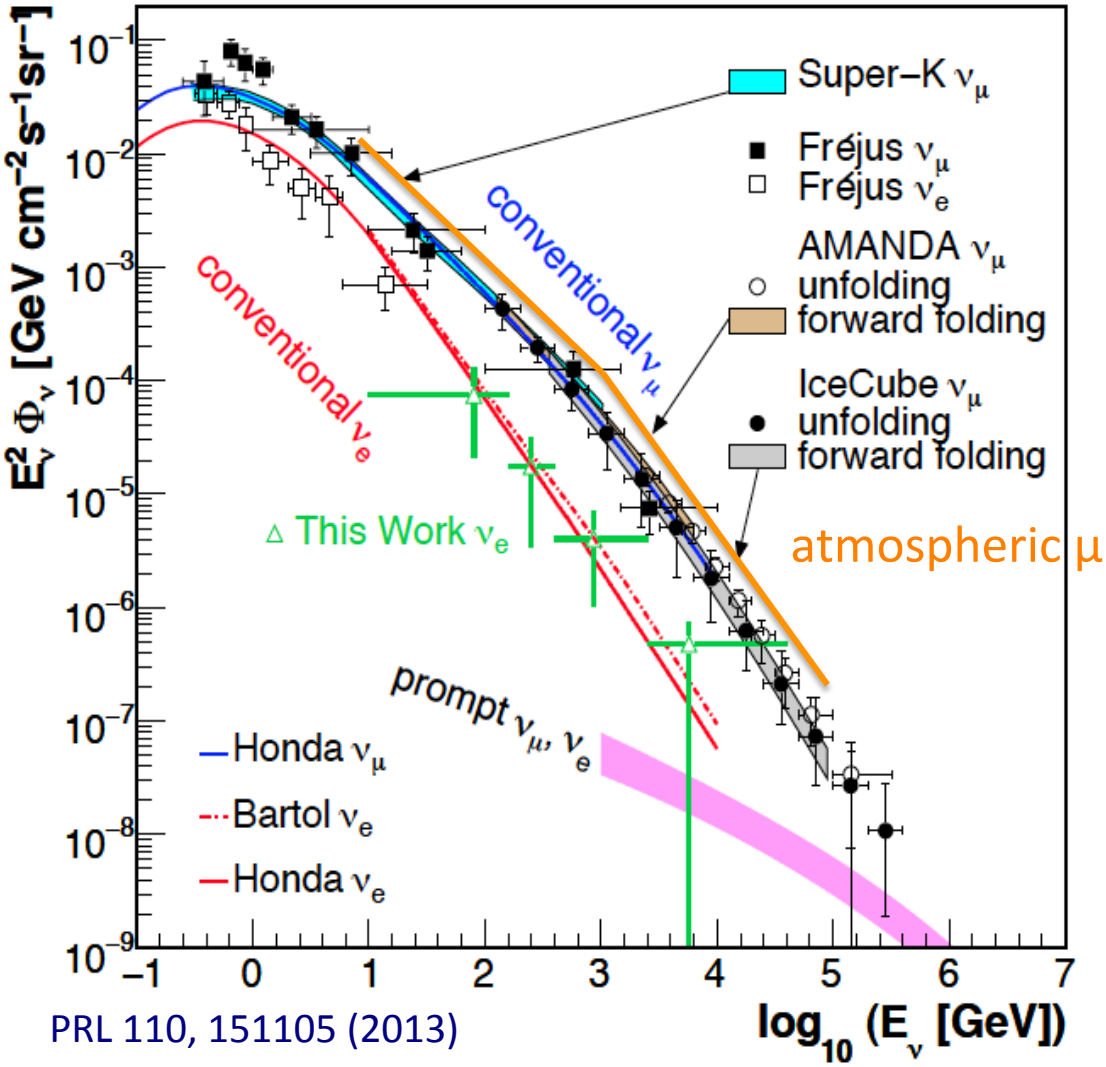




- Systematic angular shift < 0.2°
- Angular resolution < 1° (> 10 TeV)

Backgrounds

Energy spectra @ surface



PRL 110, 151105 (2013)

$$\frac{dN}{dE} \propto \frac{dN_{CR}}{dE} \frac{A}{1 + B\cos\theta \frac{E}{\varepsilon}}$$

θ: zenith angle, ε: critical energy

- atmospheric μ

$$\frac{dN_\mu}{dE} \propto E^{-3.7} \; (> \varepsilon_\pi = 115\, GeV)$$

- atmospheric ν

$$\frac{dN_\nu}{dE} \propto E^{-3.7} \; (> \varepsilon_\pi = 115\, GeV)$$

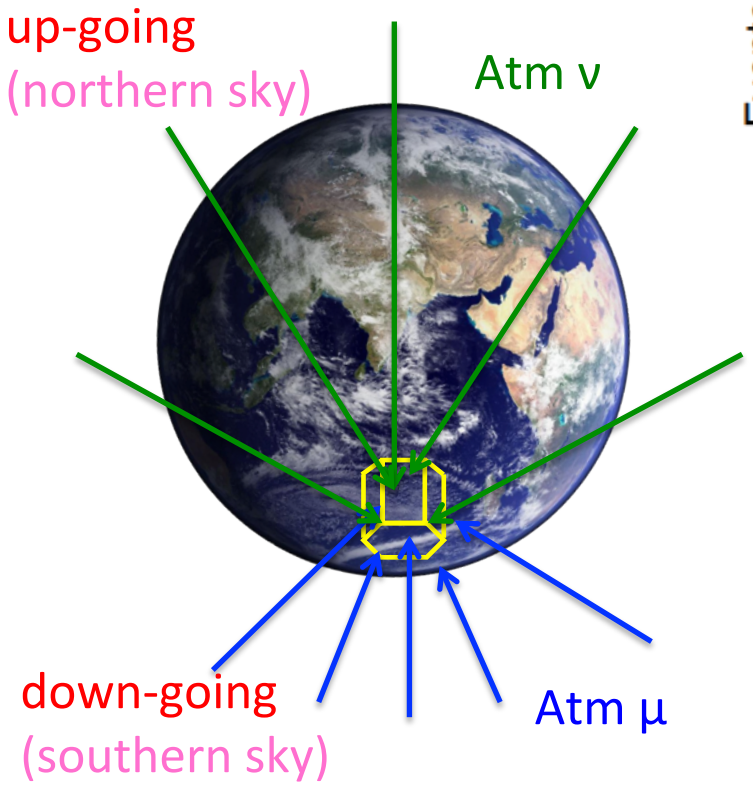
- prompt ν
  - decay from charmed particles

$$\frac{dN}{dE} \propto E^{-2.7} \; (< \varepsilon_{charm} = 10\, PeV)$$

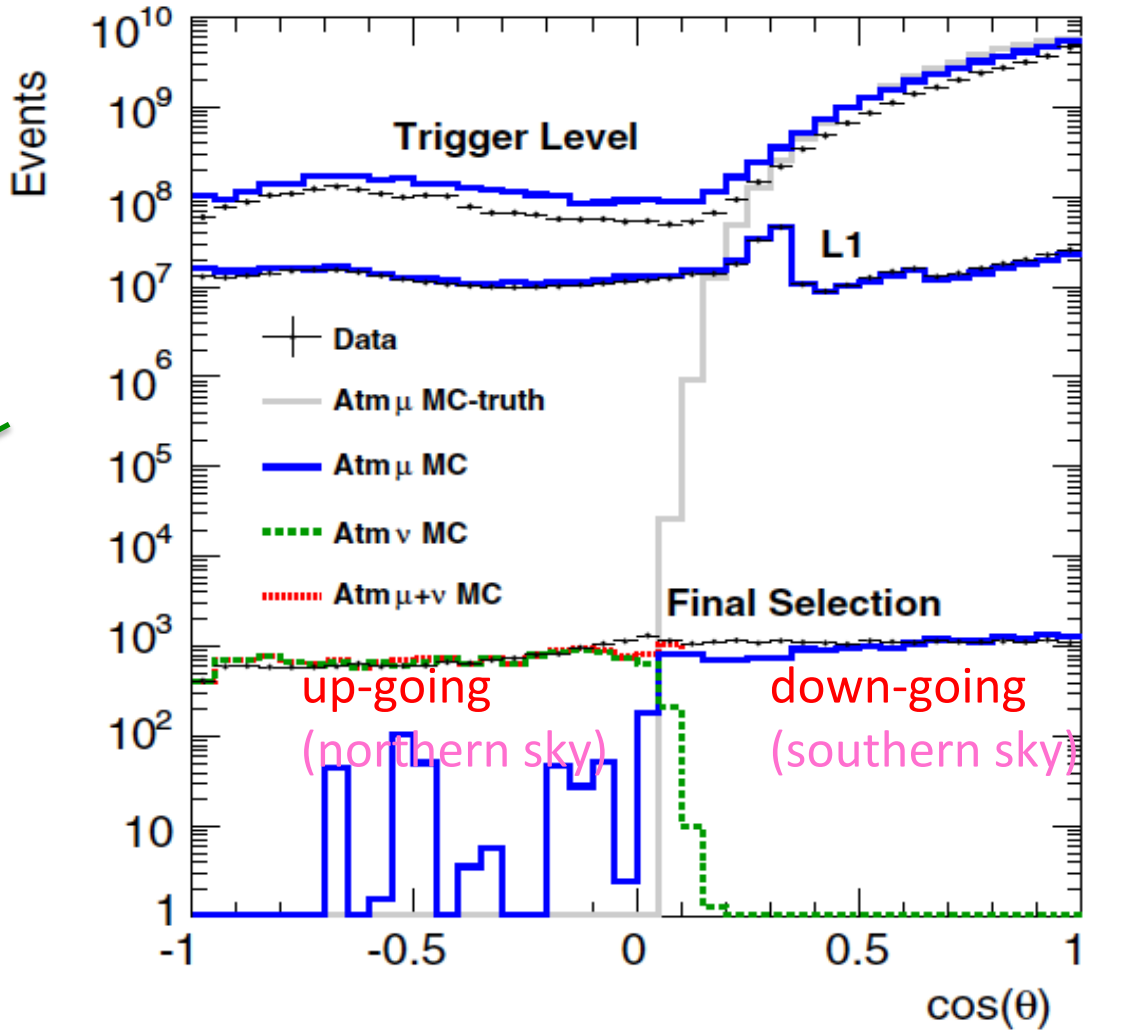
➢ Three main backgrounds: Atm μ, Atm ν, prompt ν (all CR originated)

Backgrounds (cont'd)

IC40 Point source analysis
ApJ, 732, 18 (2011)



Zenith angle distribution @ detector



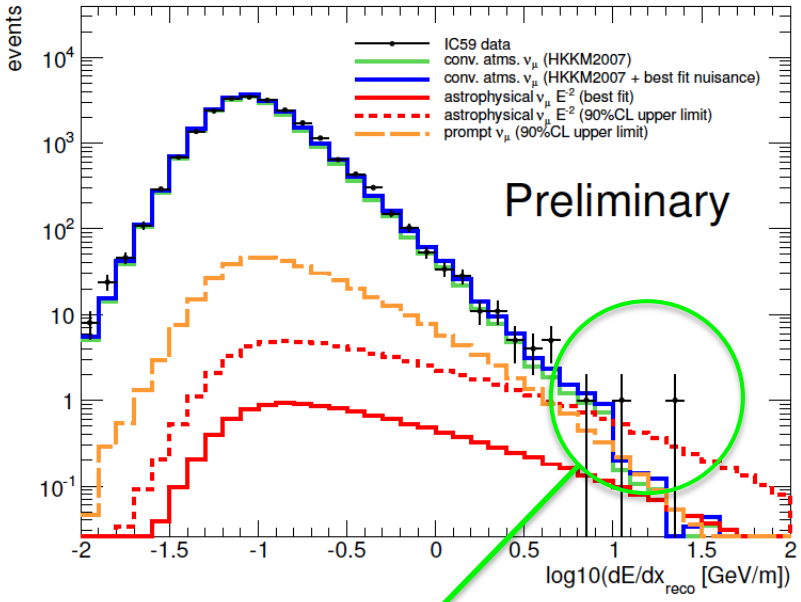
- Essentially energy and zenith angle information used for signal searches

Diffuse neutrino search

Idea to integrate weak neutrino flux
Search for diffuse muon neutrinos by using mainly energy information
Signal slope is harder than background slope

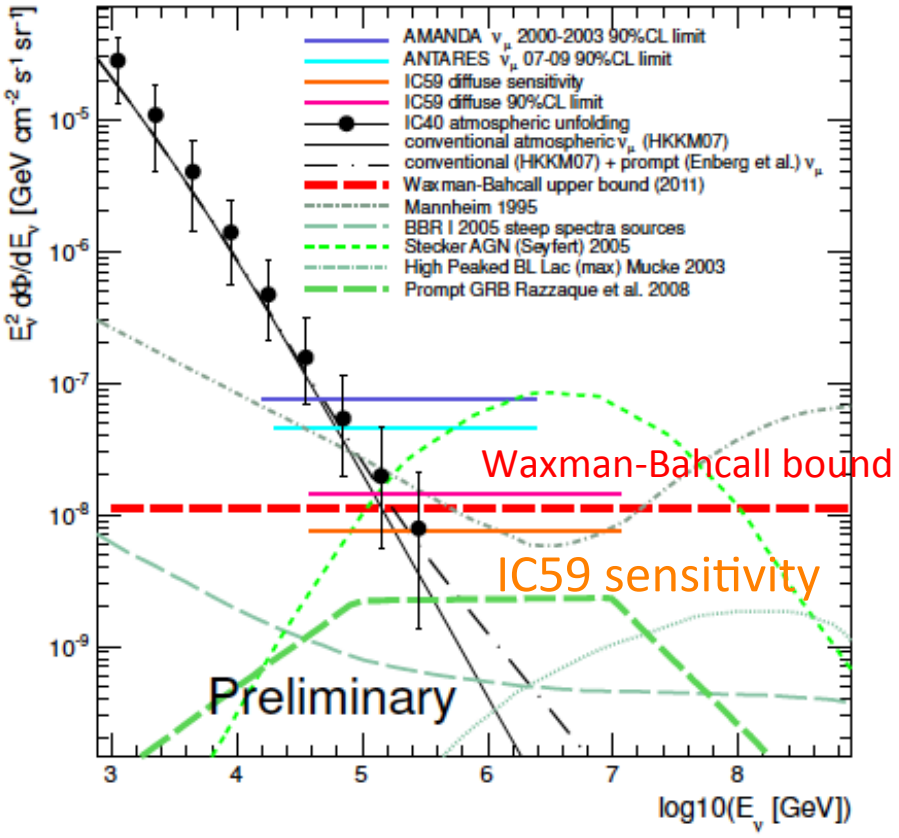
arXiv:1302.0127

IC59



Significance: 1.8σ

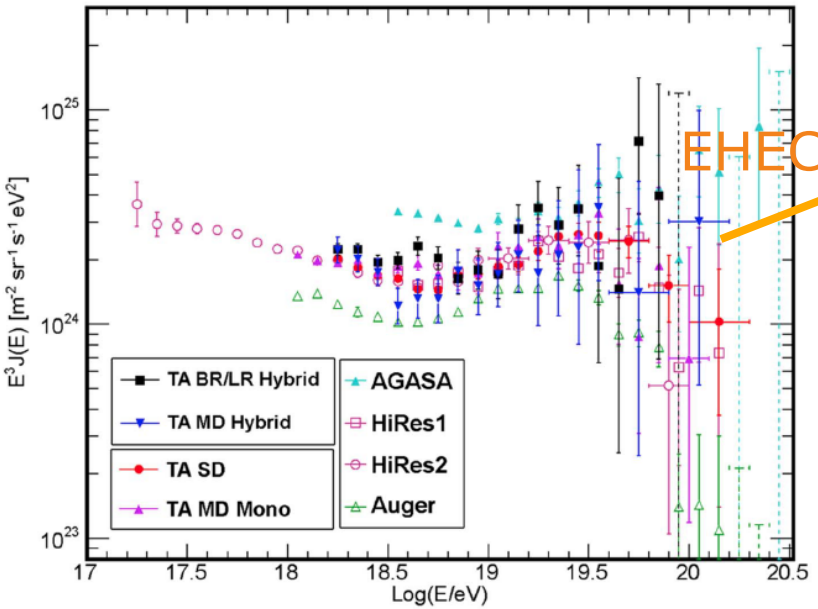
Sensitive: 30 TeV-10 PeV

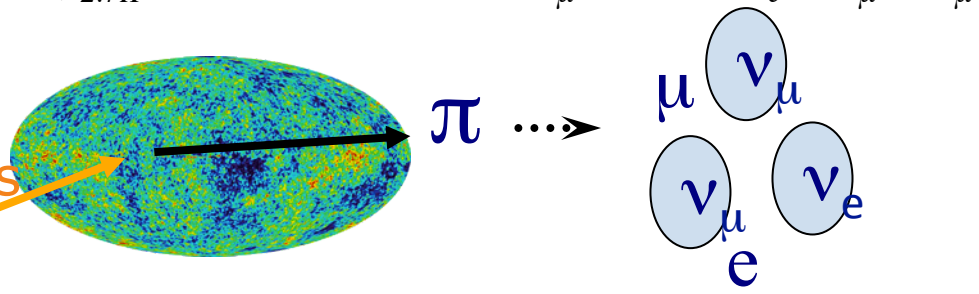


- Sensitivity is below Waxman-Bahcall bound
- Atmospheric neutrinos measured from 100 GeV - 300 TeV
  → Consistent with previous measurements

The extremely high energy (EHE) cosmogenic neutrino search

$$p\gamma_{2.7K} \rightarrow \pi^+ + X \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \overline{\nu}_\mu + \nu_\mu$$

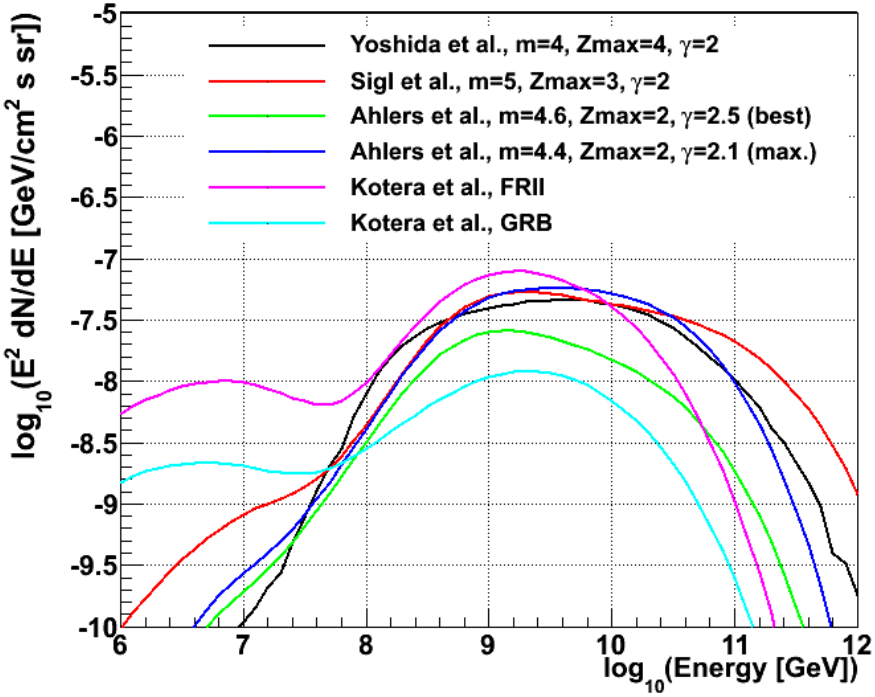




Shed light on the EHECR origin

- Source position
- Composition (proton/iron)?
- Source evolution / when the EHECR generation started

All flavor sensitive, Energy > 1 PeV



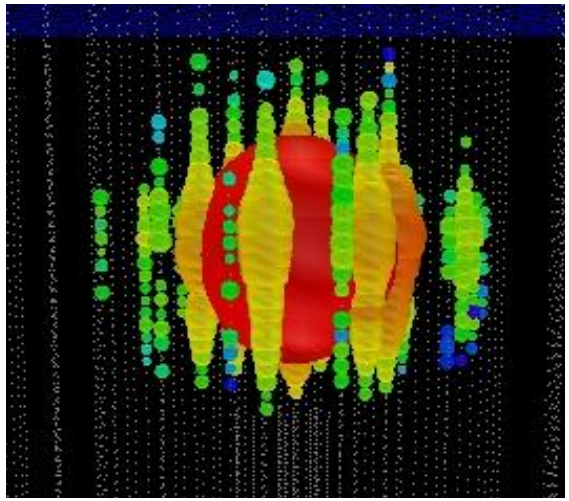
Two cascade like events found in 2011-2012 data

May, 2011 - May, 2012 (350.9 days), IC86 configuration

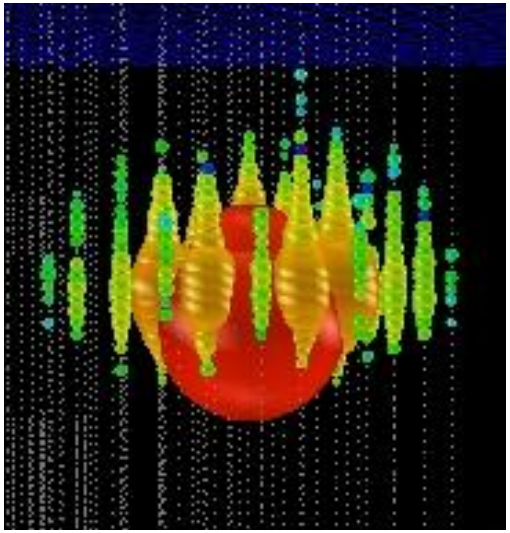
PRL 111, 021103 (2013)

Either CC interaction of ν_e or NC interaction of any flavor ν

"Bert"
Aug., 9th, 2011
Run 118545
-Event 63733662
NPE: 7.0 x 10^4
NDOM: 354
1.04±0.16 PeV



"Ernie"
Jan, 3rd, 2012
Run 119316
-Event 36556705
NPE: 9.6 x 10^4
NDOM: 312
1.14±0.17 PeV

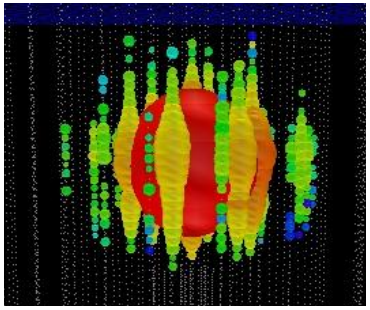


	event rate in 615.9 days
Atmospheric muons	0.038 ± 0.004
conventional atmospheric neutrinos	0.012 ± 0.001
prompt neutrinos*	0.033 ± 0.001
total background	**0.082 ± 0.004**

Significance: 2.8σ

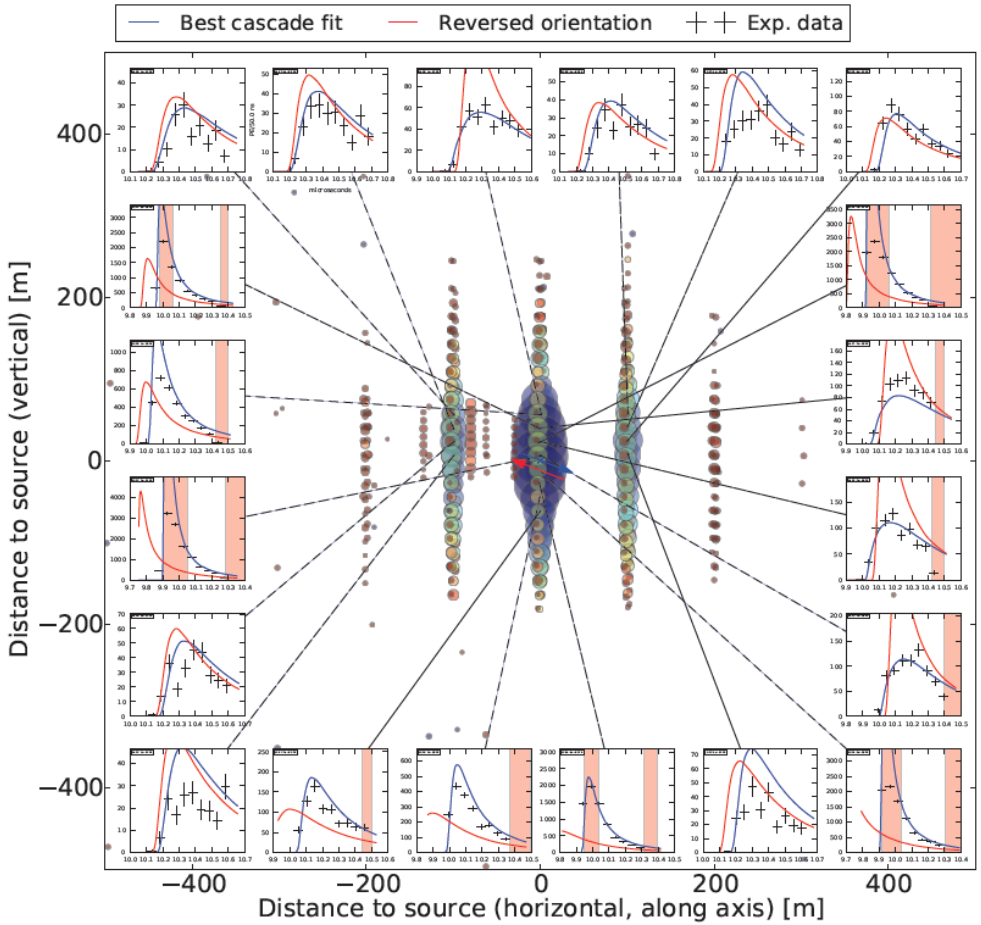
* R. Enberg, M.H. Reno, and I. Sarcevic. PRD78, 043005 (2008).

The deposited energy and geometry reconstruction



Aug. ("Bert")

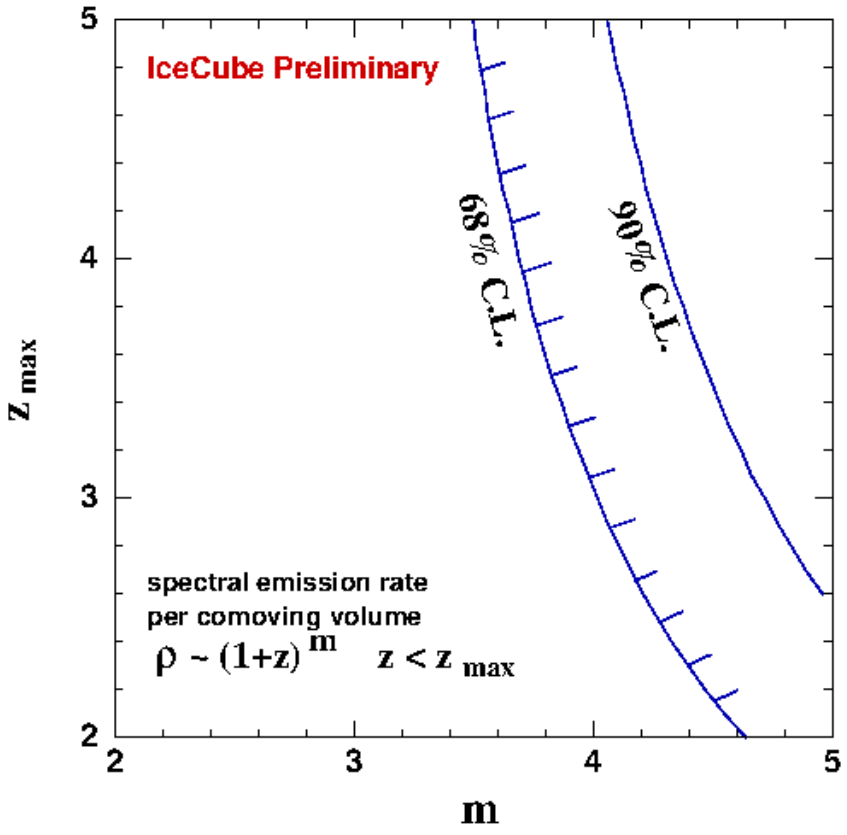
1.04±0.16 PeV



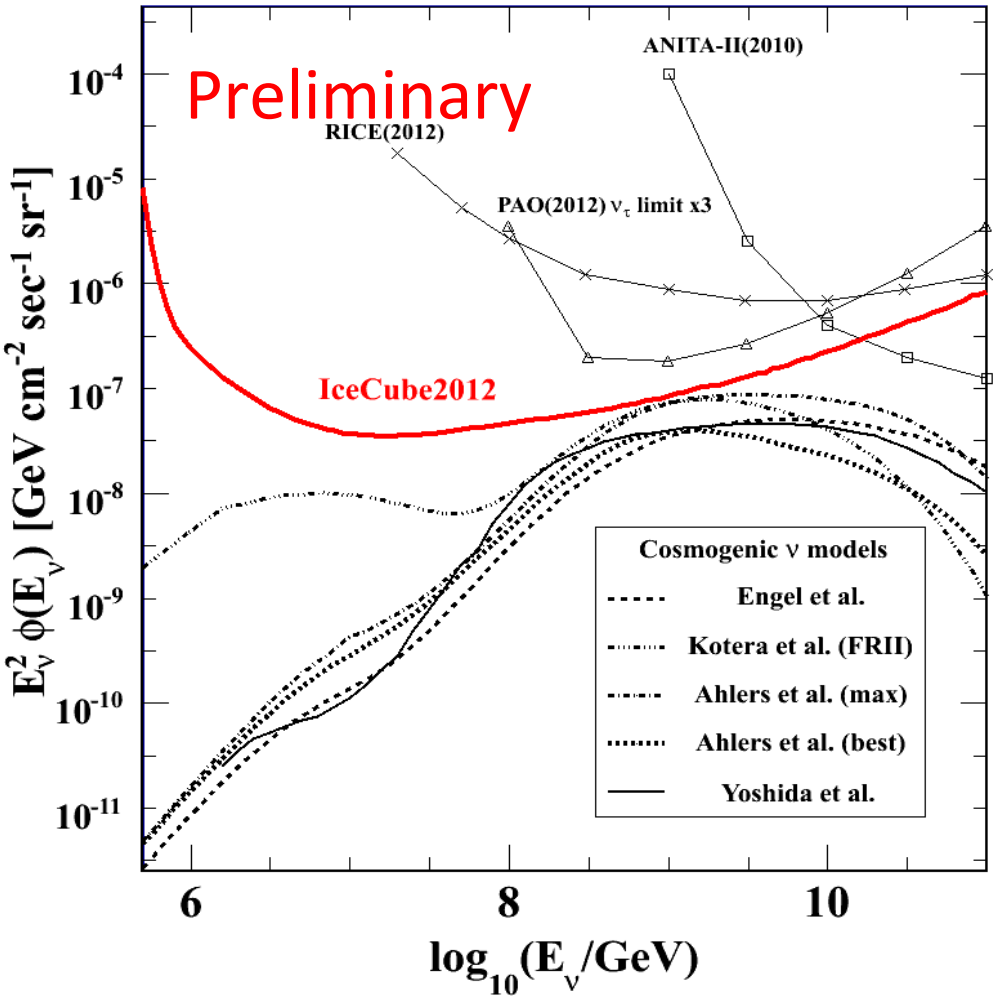
- Energy based on total charge
- Energy resolution ~15%
- Energy resolution for these specific events
- Including systematics (ice + DOM eff.)

- Shower size ~10 m < detector spacing 17 m
- Shower development information is somewhat kept
- Direct photon (forward): sharp wf
- Scattered photon (backward): wide wf
- Angular resolution: 10°-15°

Limits



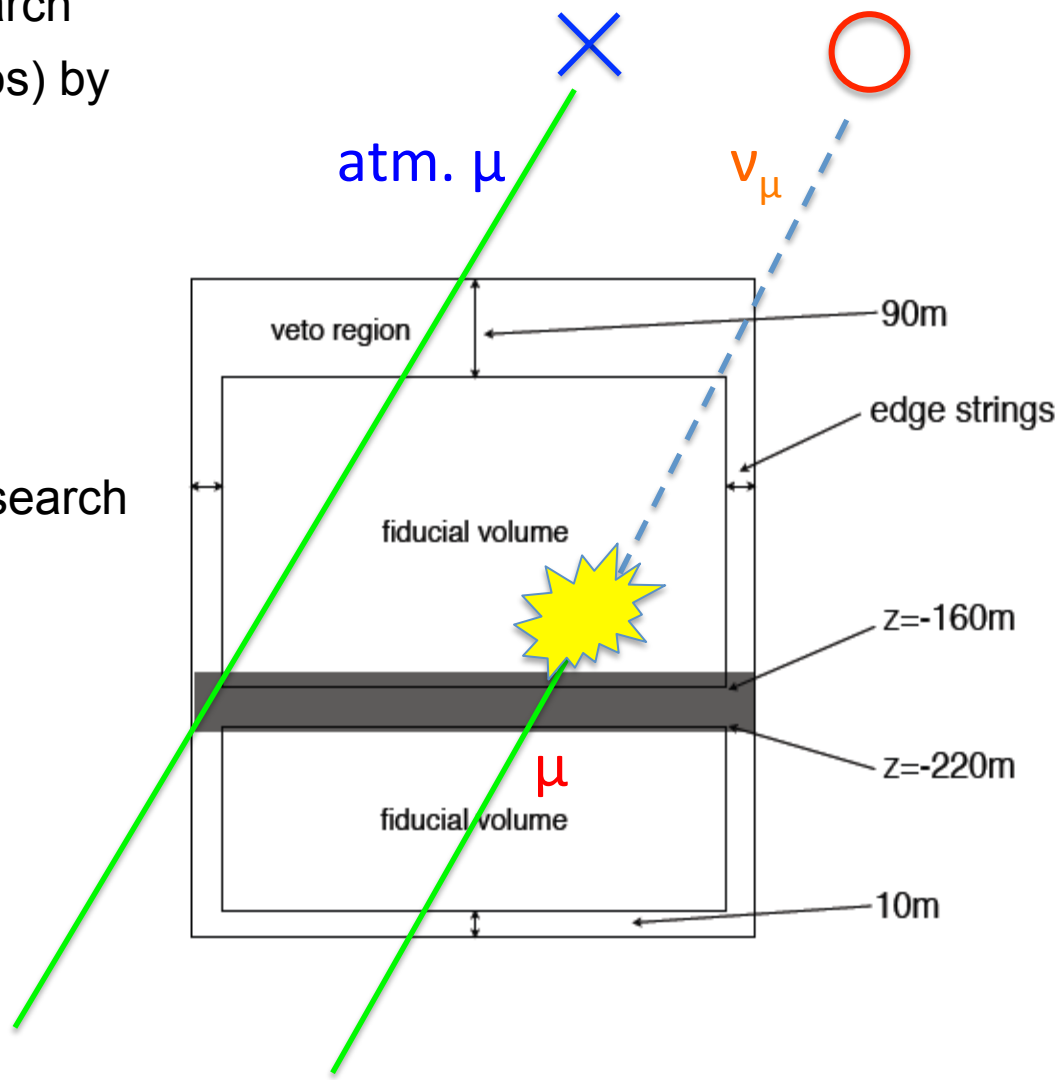
high evolution models (m>4) are mostly ruled out such as FRII



differential limit per one energy decade

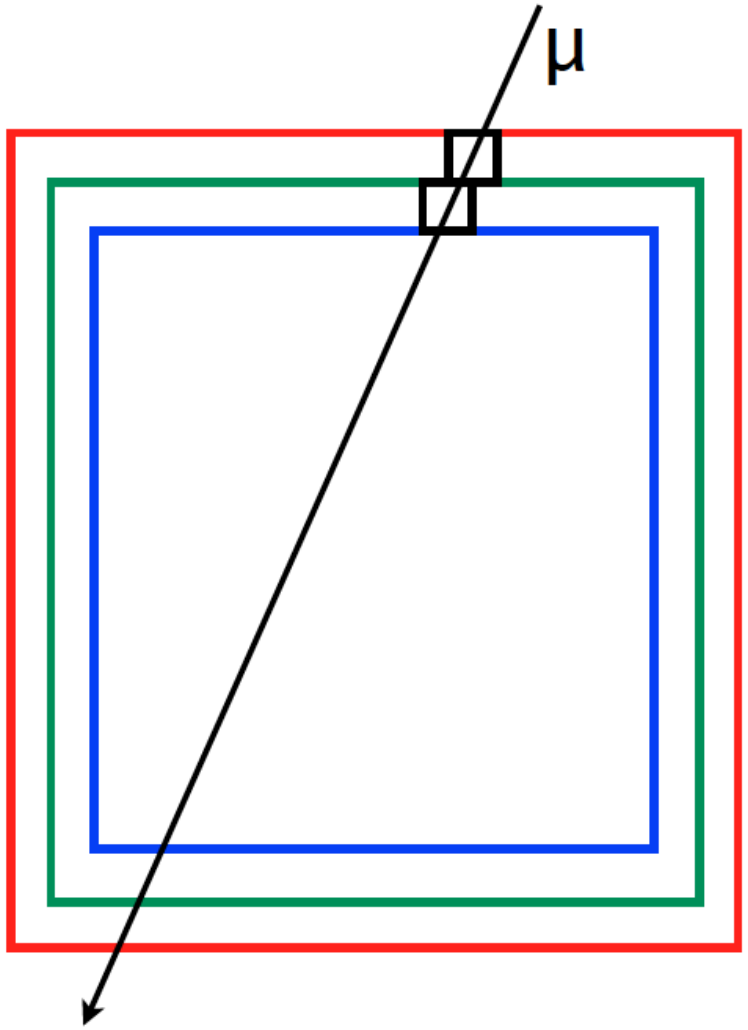
High energy starting event (HESE) search

- Follow-up of the EHE neutrino search
- Search contained events (neutrinos) by using outer layers as veto
- Reduce backgrounds
- 420 Mton fiducial mass
- All flavor
- > 60 TeV
- 3 times better than EHE neutrino search @ 1 PeV
- livetime: 662 days (2 years)



Atmospheric muon background

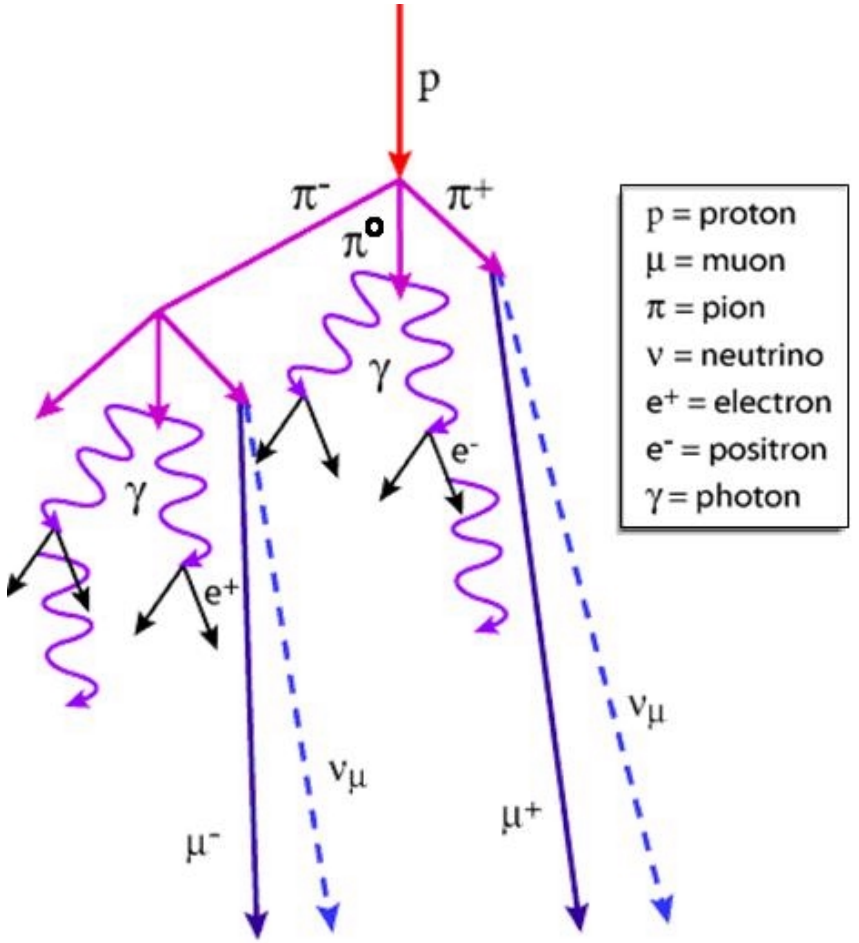
- Dominant down-going background
- Estimated by using data
- Second veto layer introduced
- veto power: at least 3 orders of magnitude
- Removes also 70% of down-going atmospheric neutrino background (southern sky)
- 3 muon events passed the inner layer → 6.0 ± 3.4 events / 2 years with geometrical volume correction



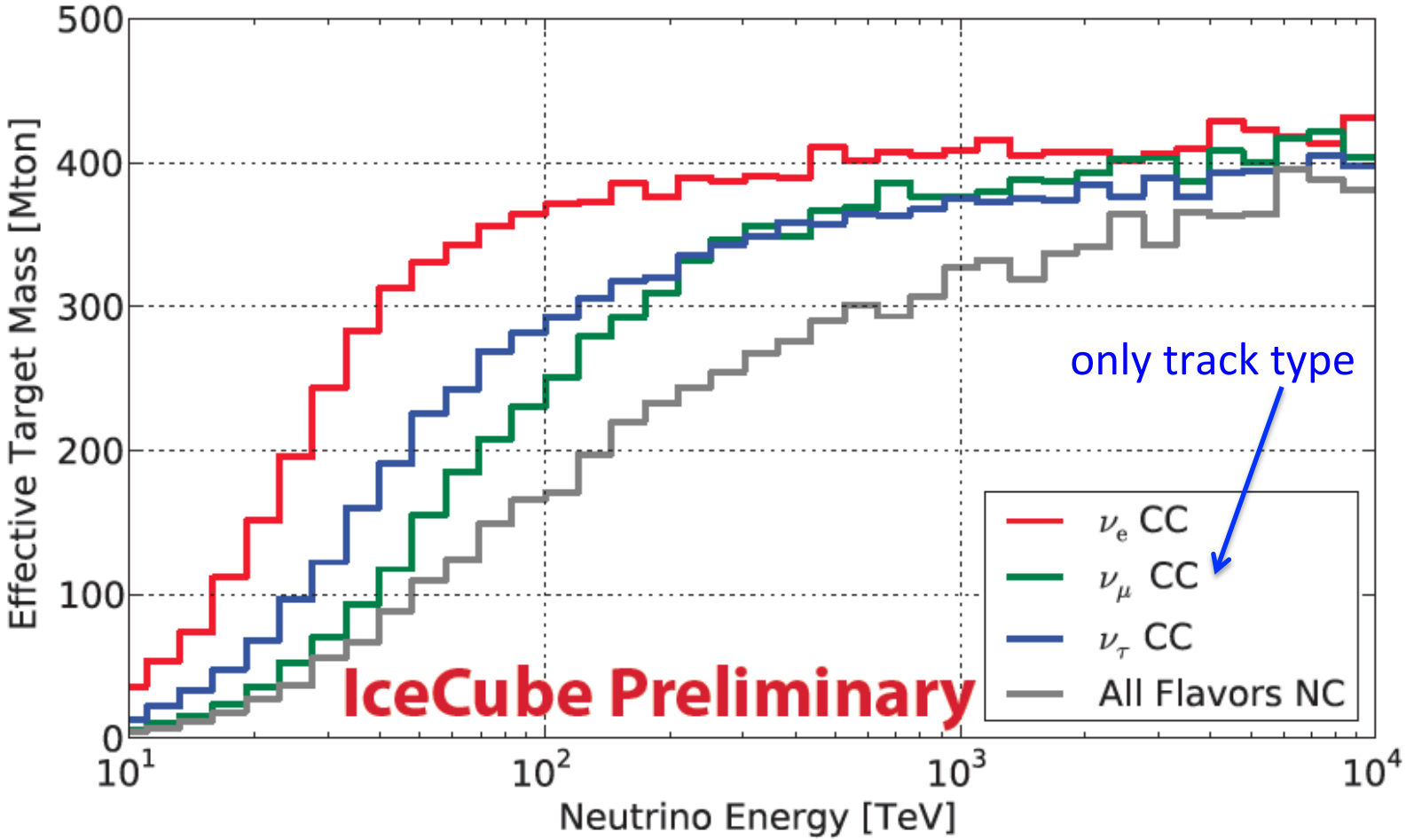
Atmospheric neutrino background

- Low rate at PeV energy (0.1 event/year)
- Reduced by 70% by the muon veto
- Uncertainty ~30% from CR composition and hadronic interaction
- Large uncertainty from unmeasured charm contribution Enberg et al. (2008) employed (NLO perturbative QCD)

  -> 3.4 events
- Estimated bg rate: $4.6^{+3.7}_{-1.2}$ events / 2 years



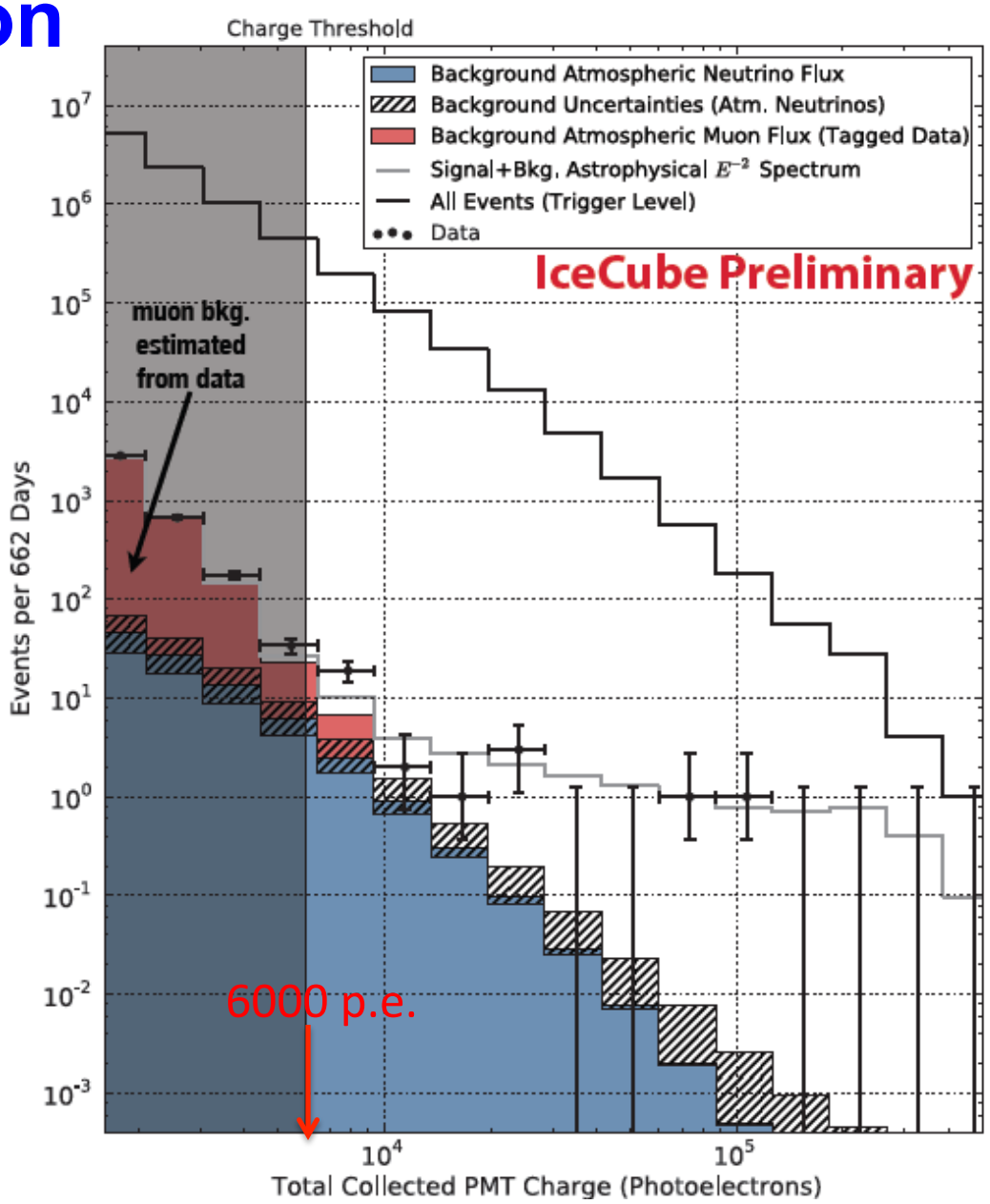
Effective volume



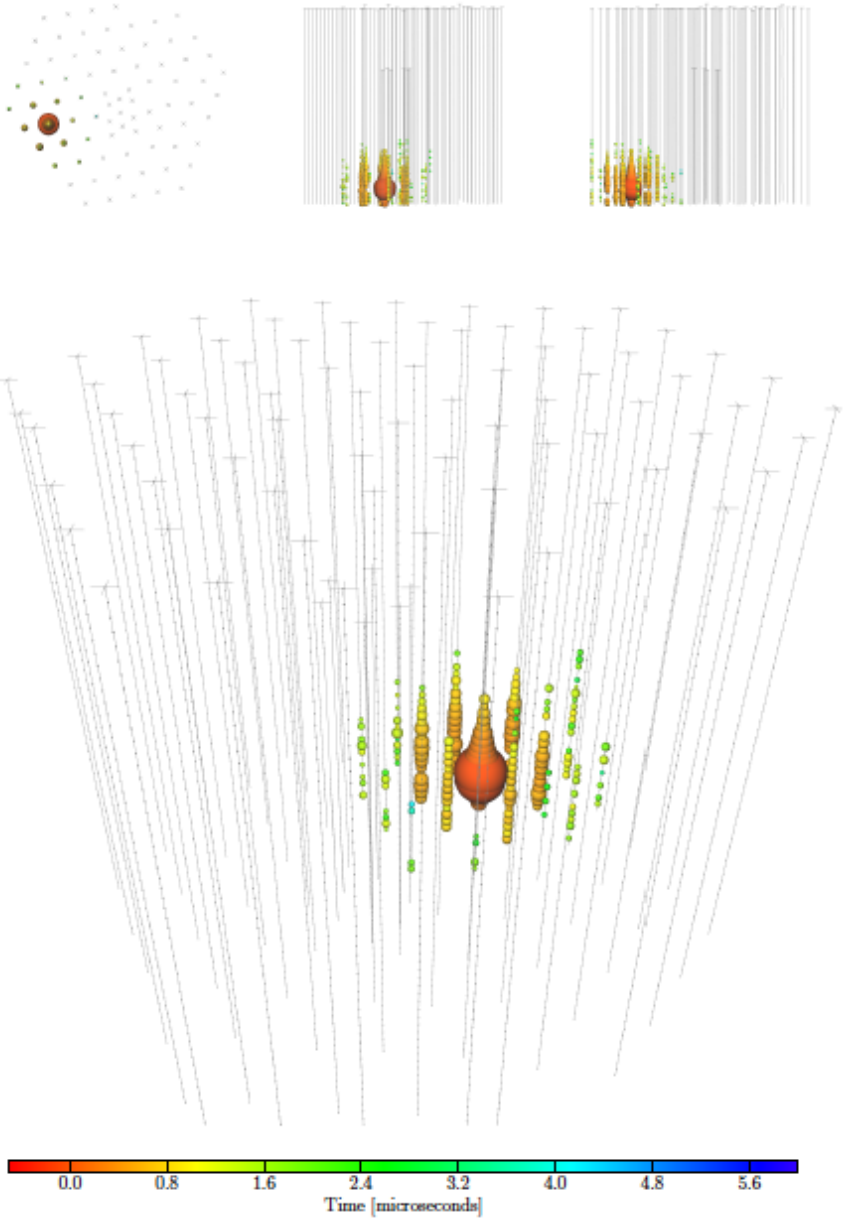
This analysis is more sensitive to cascade events

Charge distribution

- 28 events observed above selection criteria
- Total bg: $10.6^{+4.5}_{-3.9}$
- Significance: 3.3σ (HESE analysis alone wo two PeV events)
- Including EHE result (2.8 σ): 4.1σ
- A posteriori (including two PeV events): 4.8σ
- Atmospheric muons are largely reduced
- Data and MC agree well at low charge



Event samples



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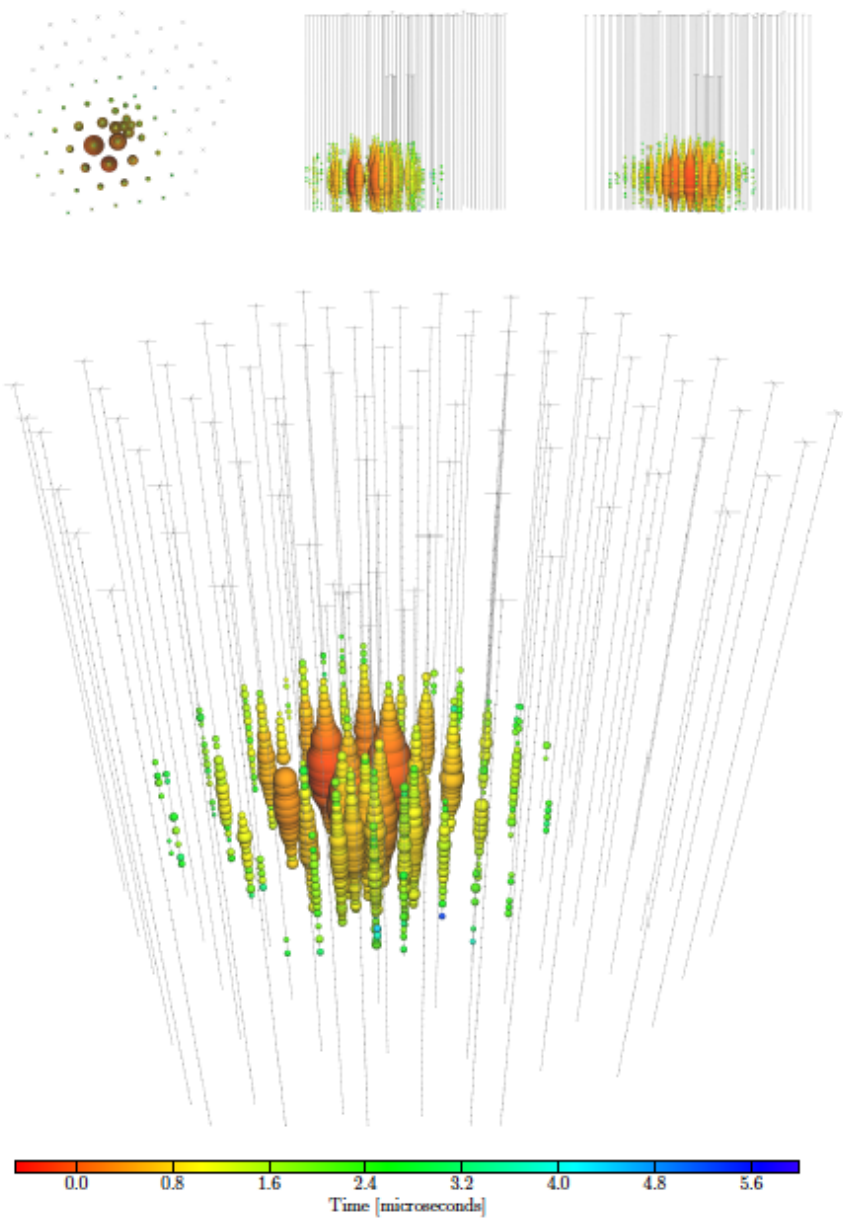
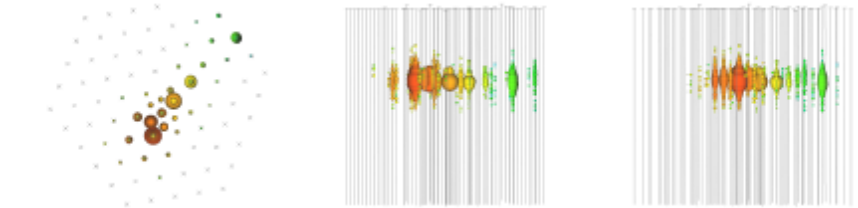
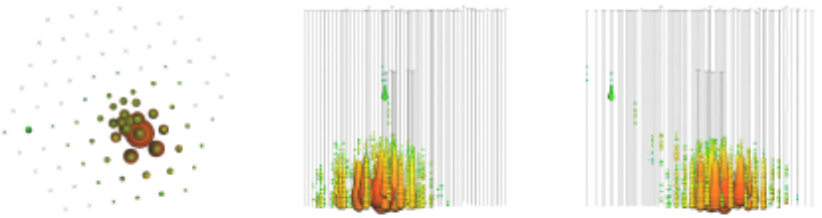
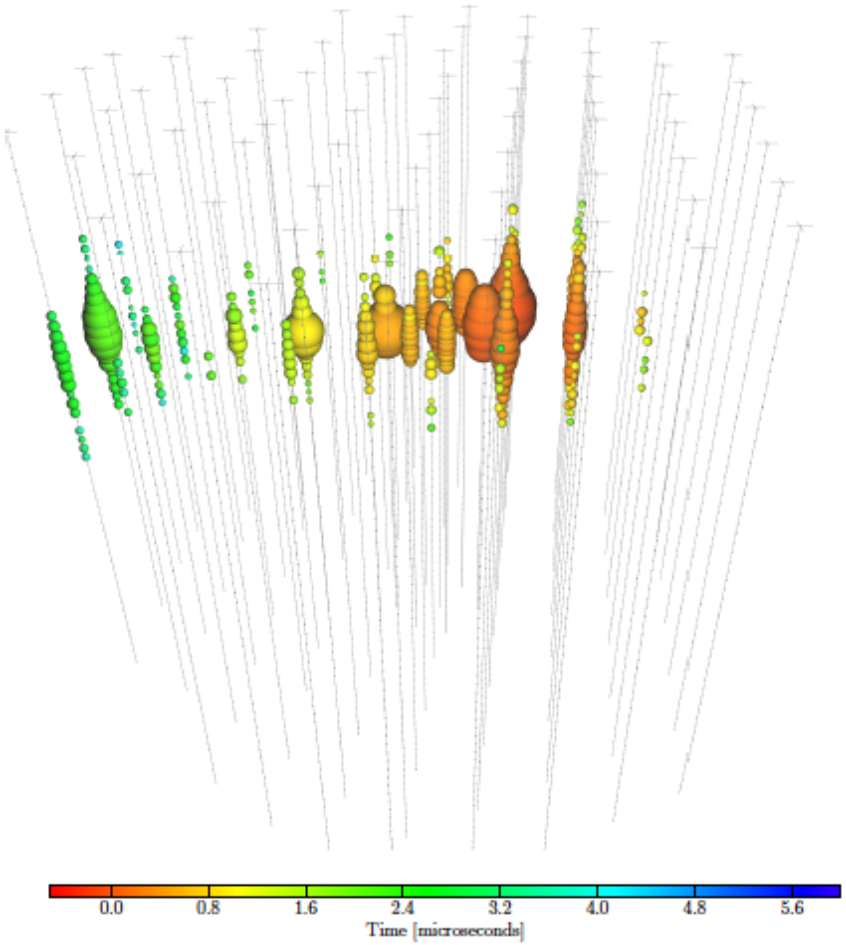
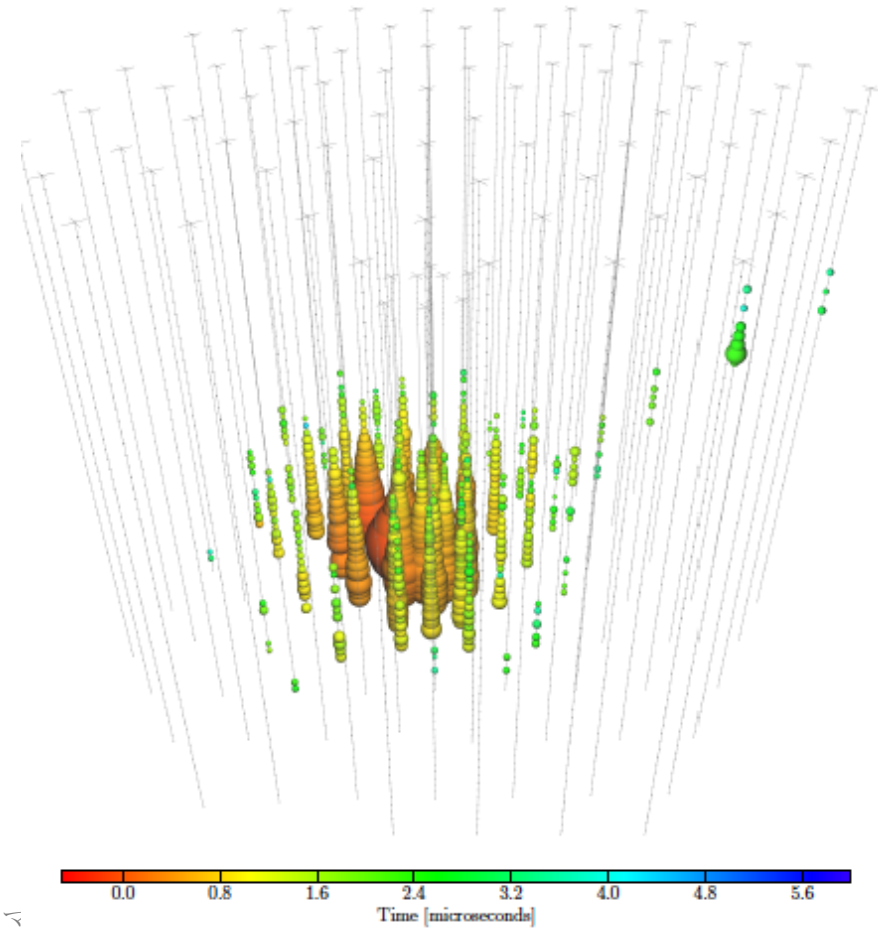


Event samples









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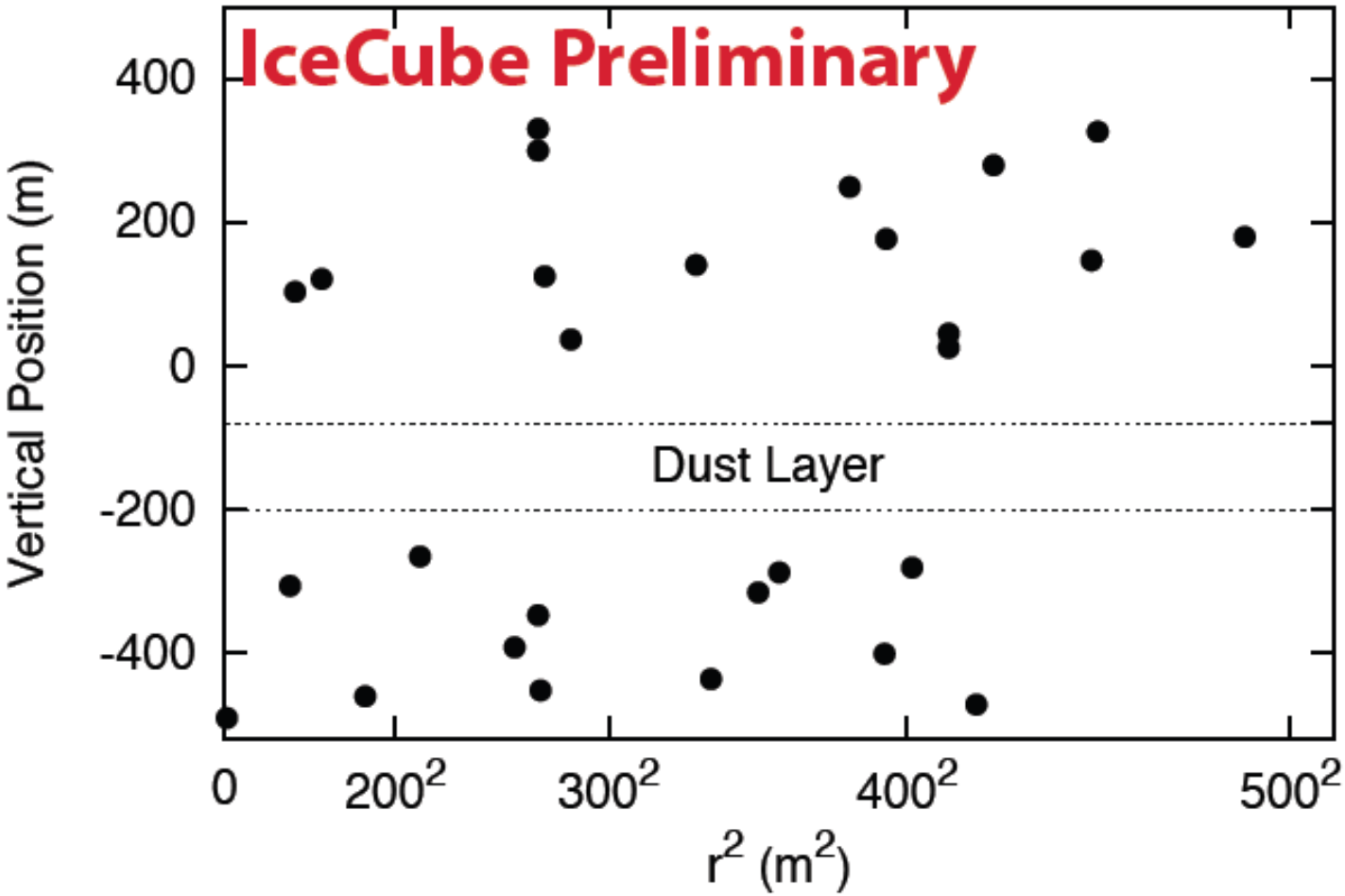
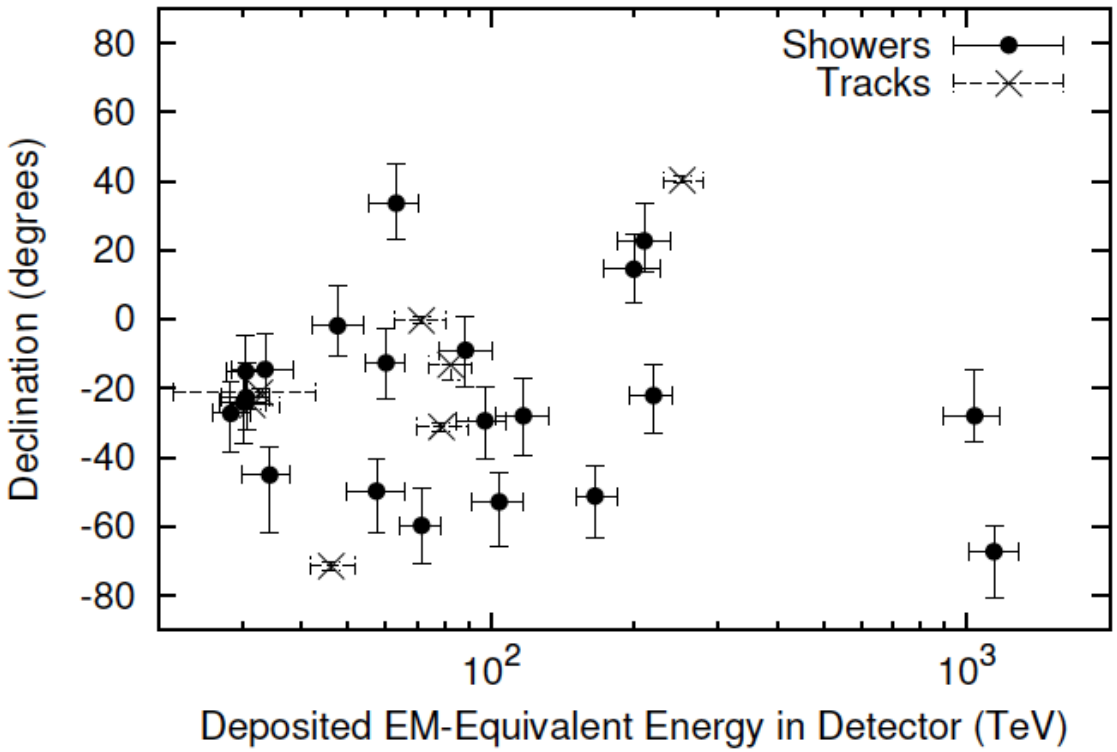
Coordinate of the first detected light

- Uniformly distributed



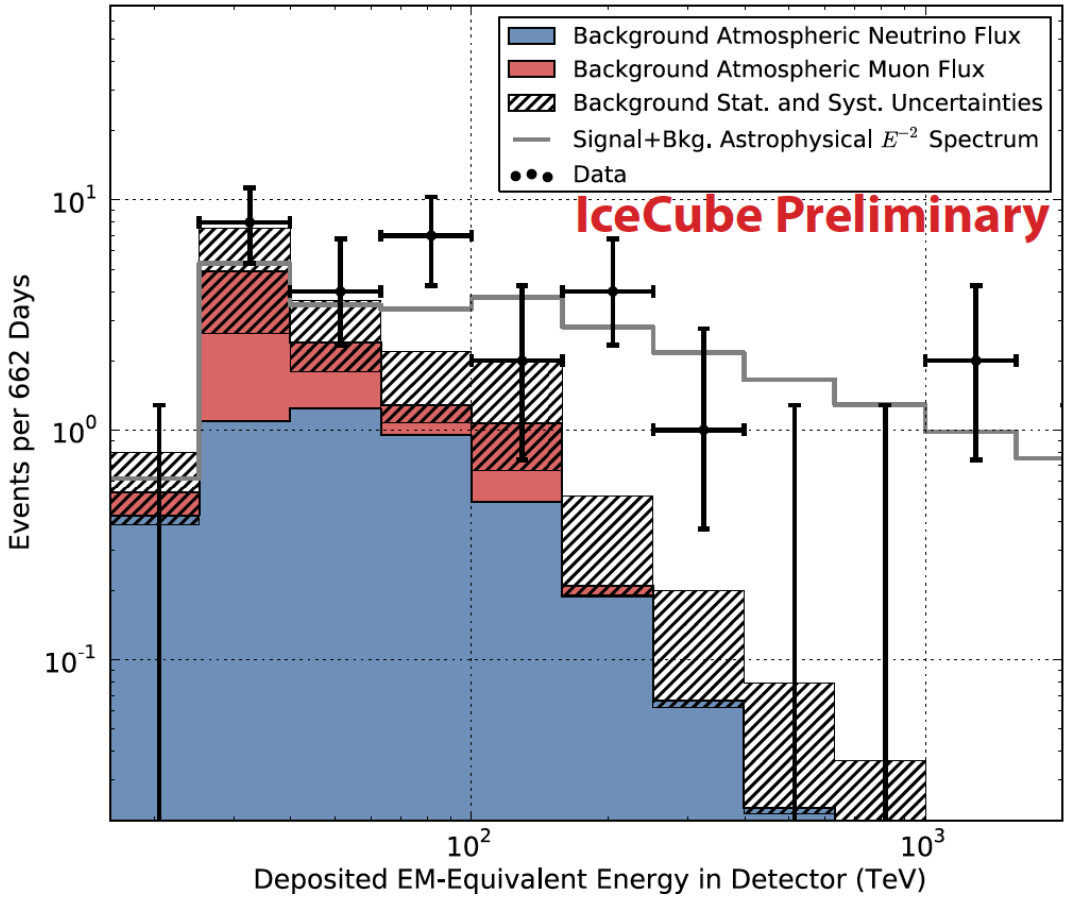
Declination vs deposited energy

- 21 showers vs 7 tracks
  Suggesting signals.
- In case of conventional atmospheric:
  track : cascade = 2:1
- Most of events come from southern sky because events from north are absorbed by the Earth
- Excess in south is not due to atm. ν since they are reduced in south by our muon veto
- low energy 4 tracks look atmospheric origin (consistent with the prediction of 6±3.4)
- Neutrino energy for track events can be very high compared to the deposited energy



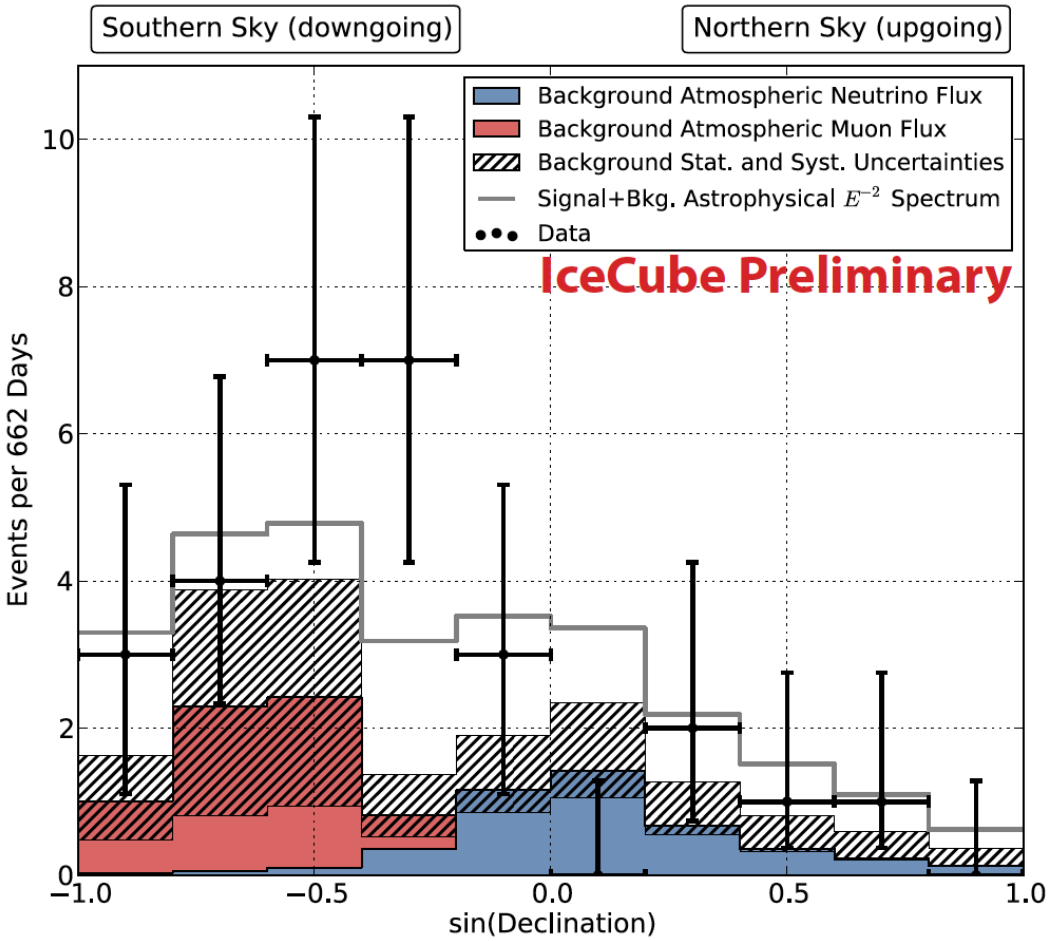
Deposited energy distribution

- Energy spectrum harder than that of backgrounds
- Data fits well with the prediction at low energy
- $E^2\phi = 3.6 \pm 1.2 \times 10^{-8}$ GeV/cm^2/s/sr (3 flavours)
- Best fit: $E^{-2.2\pm0.4}$
- Cut-off energy above 2 PeV is preferable



Zenith angle distribution

- Compatible with isotropic flux
- Events absorbed by the Earth from northern sky
- atm. ν is reduced in south due to the muon veto
- Excess in southern sky is not significant



Sky map and the significance

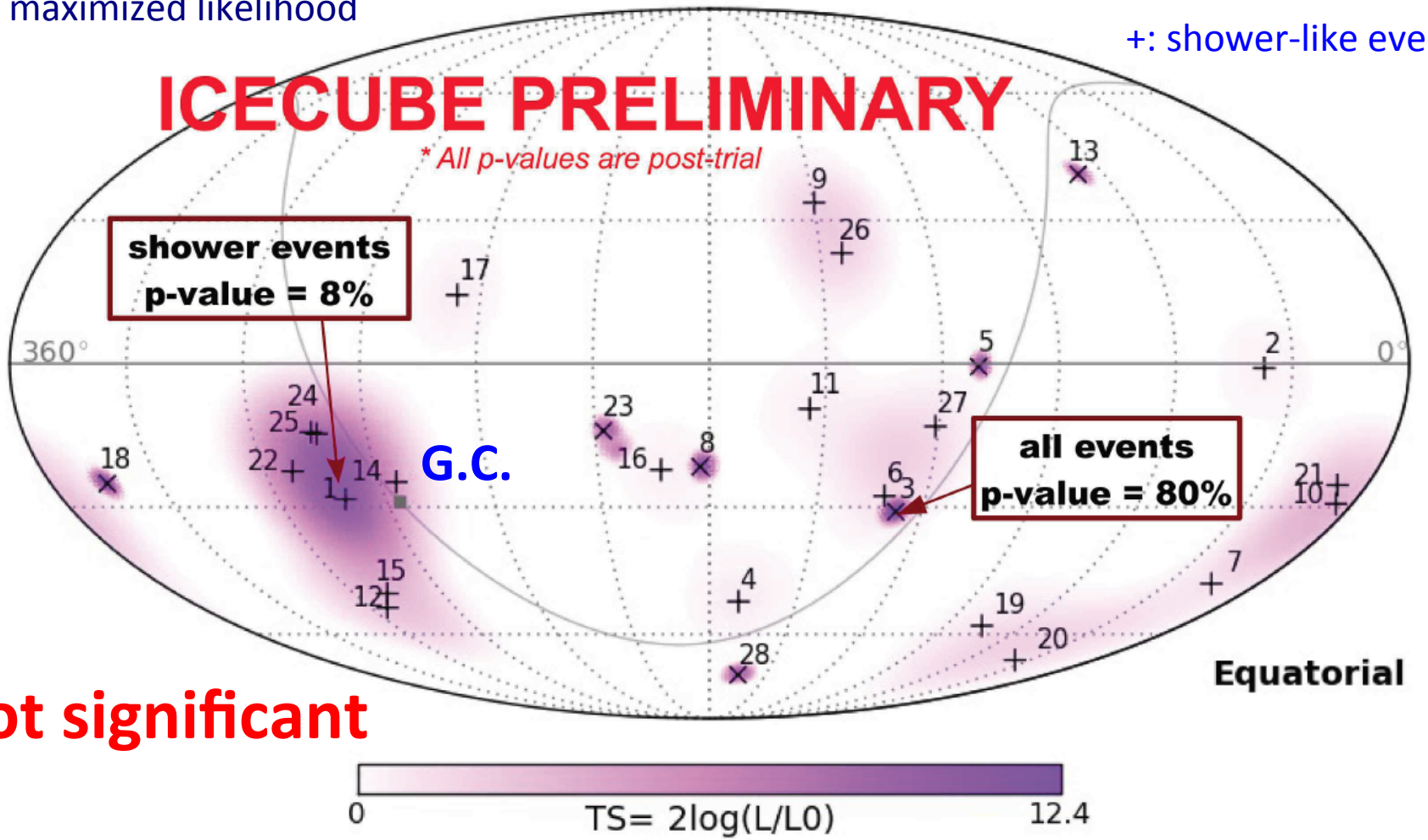
Test null hypothesis against the most likely

L0: null hypothesis

L: maximized likelihood

x: track-like events

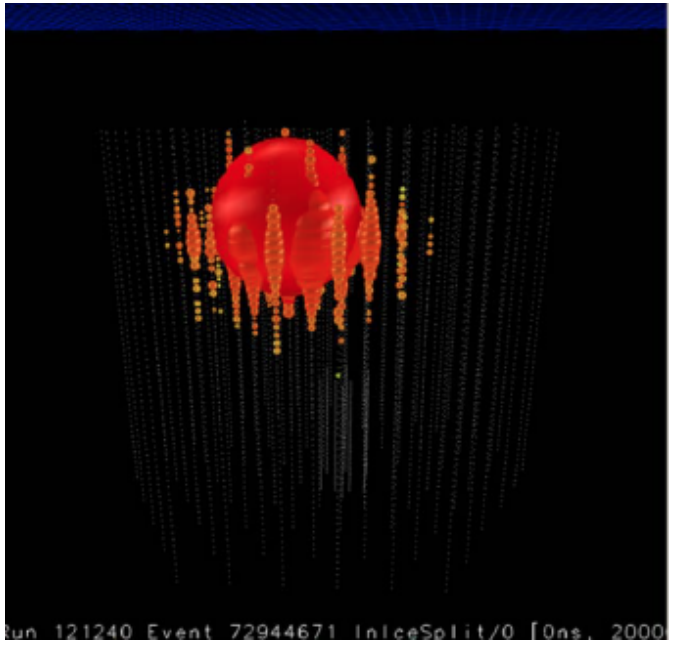
+: shower-like events

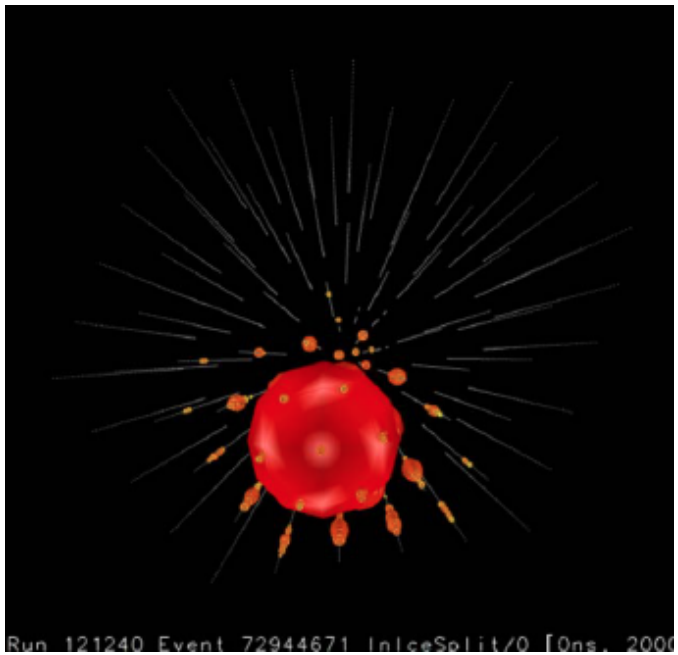


Not significant

Big Bird

- Another high energy event found in the 2012 test sample
- 378 hit DOMs





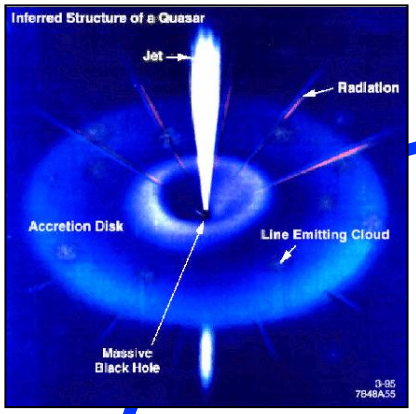
❑ Summary

- IceCube completed end of 2010 and performing as expected
- Two PeV neutrinos were firstly observed in 2012
- The significance is 2.8σ
- 26 additional neutrino candidates observed by a follow-up search for high energy starting events
- The significance is 4.1σ (combining with the EHE result)
- **We have started to see other than backgrounds!**
- **More events are coming!**

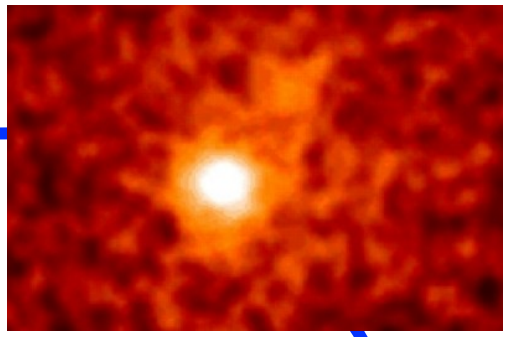
backups

Target objects

Explore the universe with neutrinos



■ AGNs



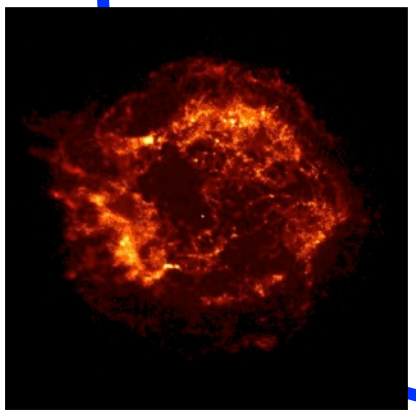
■ GRBs

talk by M. Ahlers

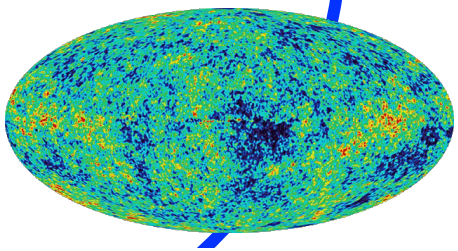
■ Cosmic ray origin

■ Dark Matter

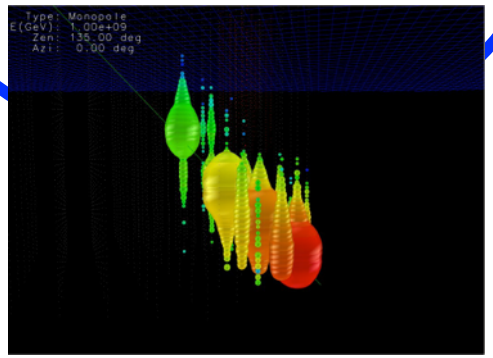
■ Particle physics



■ Supernova



■ Cosmogenic neutrinos



■ Exiotic
(monopole etc…)

The South Pole

The South Pole

IceCube

1 km

Point source search

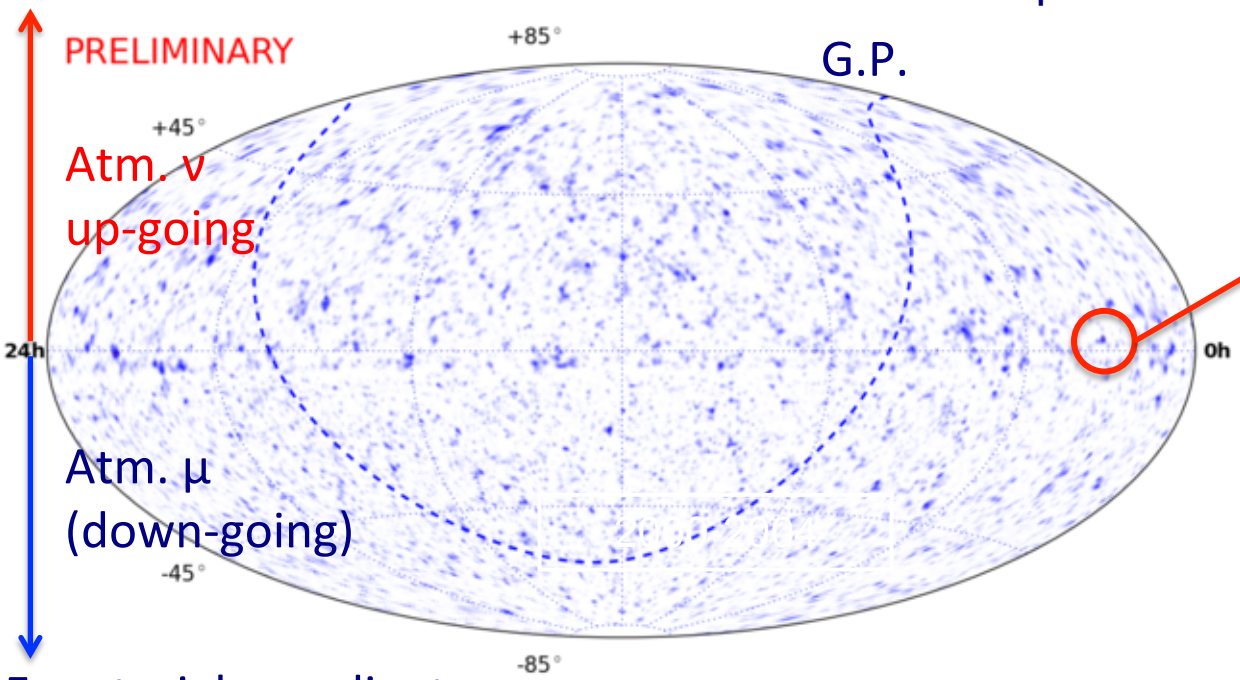
Sensitive: > ~1 TeV

Search for muon neutrinos by using mainly the directions

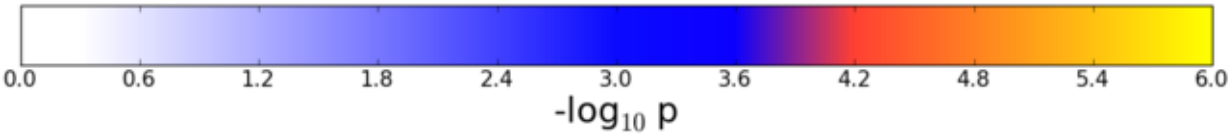
IC40 (375 days) + IC59 (348 days) + IC79 (316 days)

Test null hypothesis of no signal against one with signals

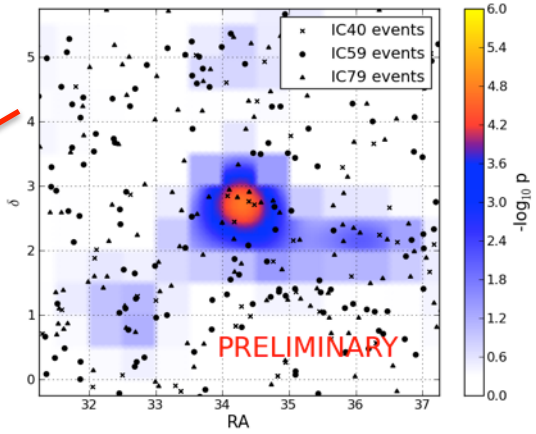
108317 ν + 146018 μ



Equatorial coordinate



RA: 34.25 deg.
Dec: 2.75 deg.



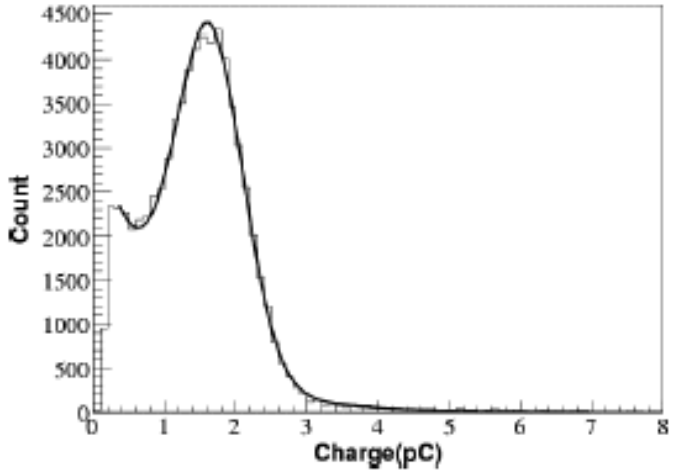
post-trial after scrambling data

→ P-value: 56.8%

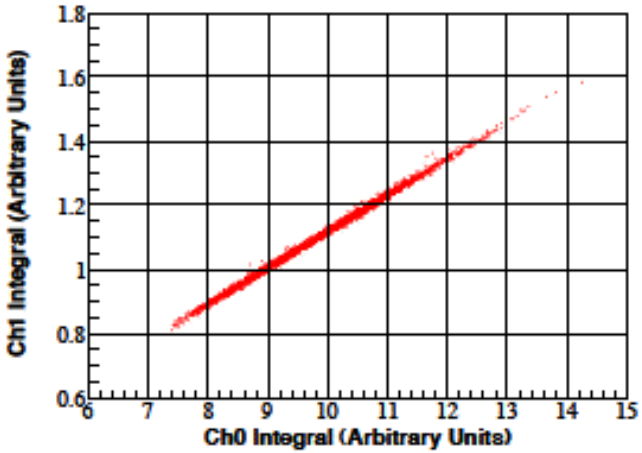
Not significant

The detector performance check

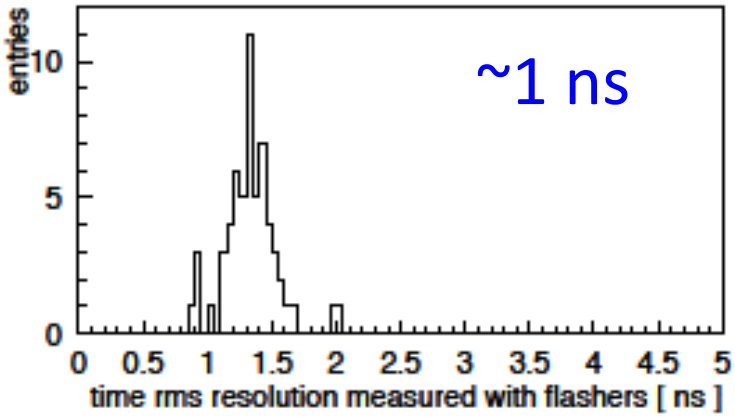
1 p.e. distribution



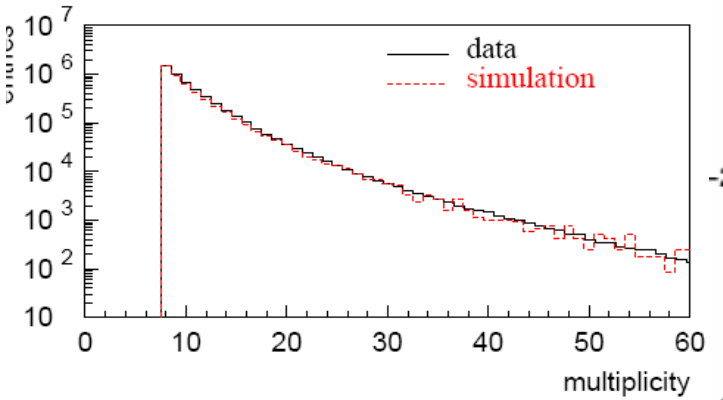
Gain check

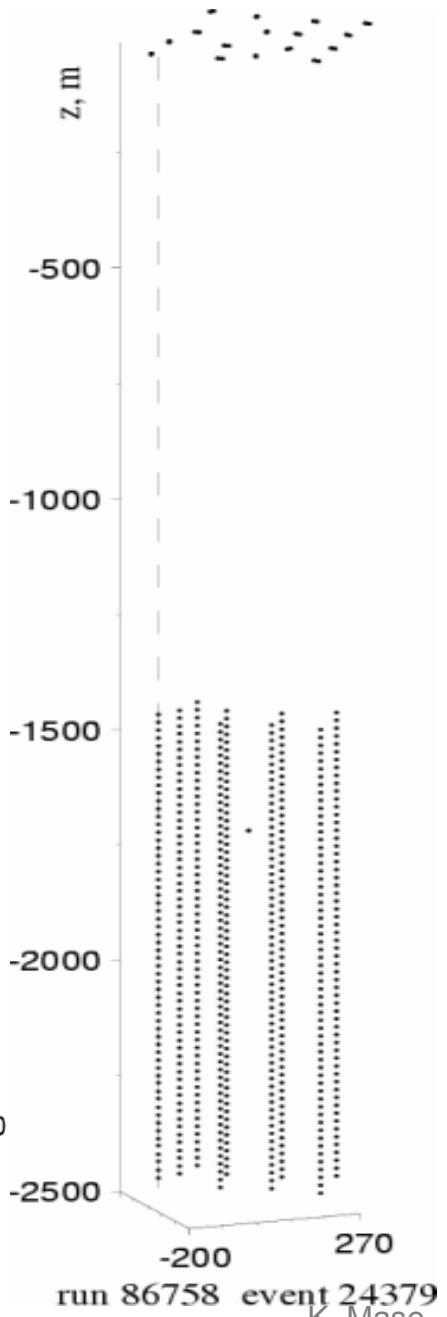


Time resolution



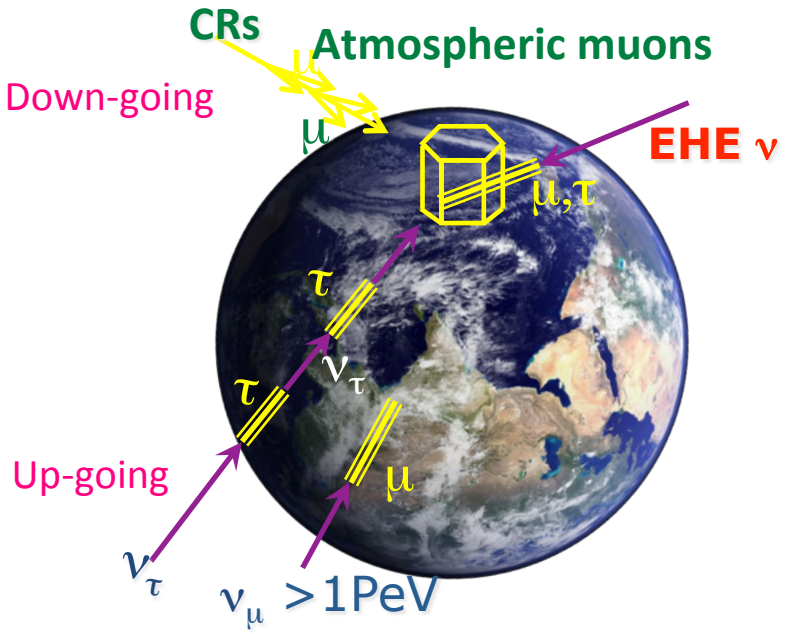
Multiplicity distribution





A. Achterberg et al., Astropart. Phys., 26, 3, 155-173 (2006)

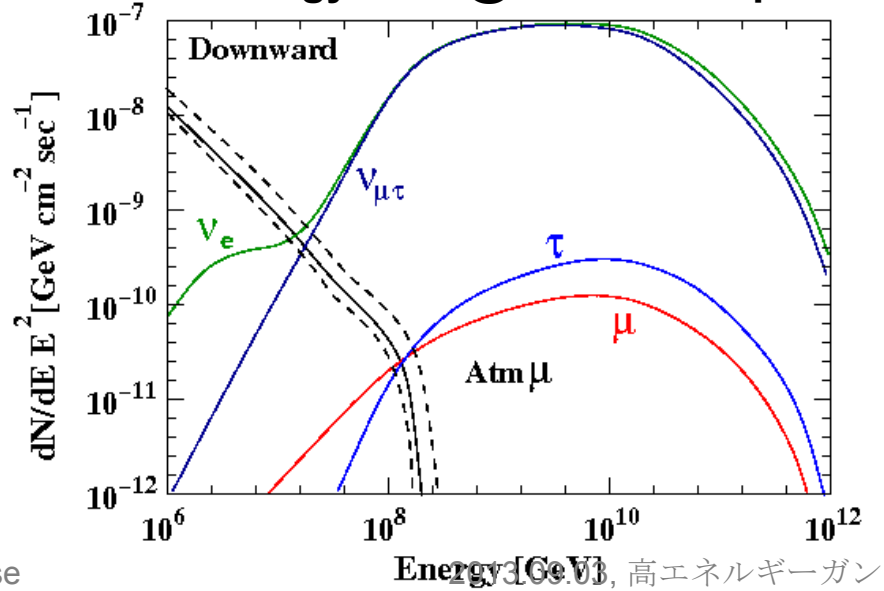
The detection principle



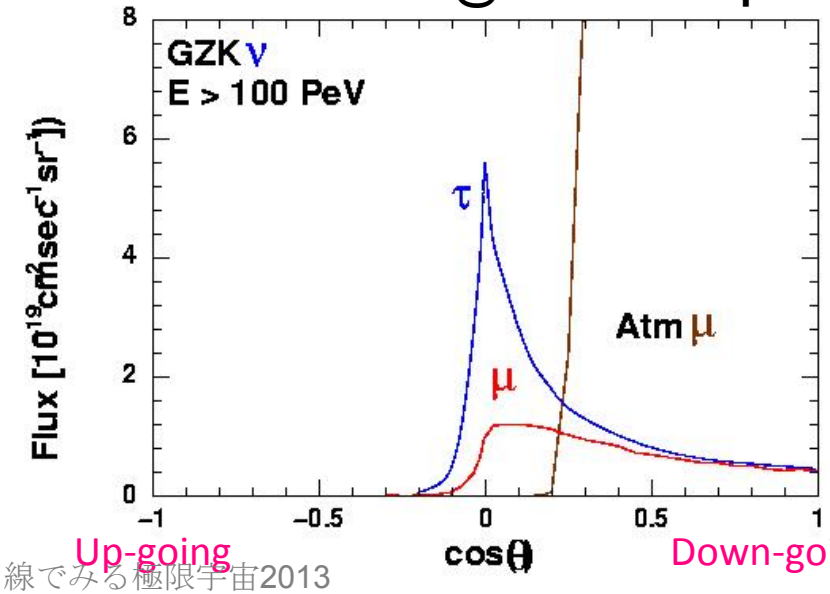
- **EHE neutrino signal (all flavor)**
  - Horizontal (opaque to the earth)
  - High energy (> 10^8 GeV)
- **Atmospheric muon background**
  - Down-going
  - Low energy (the energy spectrum is steep (~$E^{-3.7}$))

Yoshida et al PRD **69** 103004 (2004)

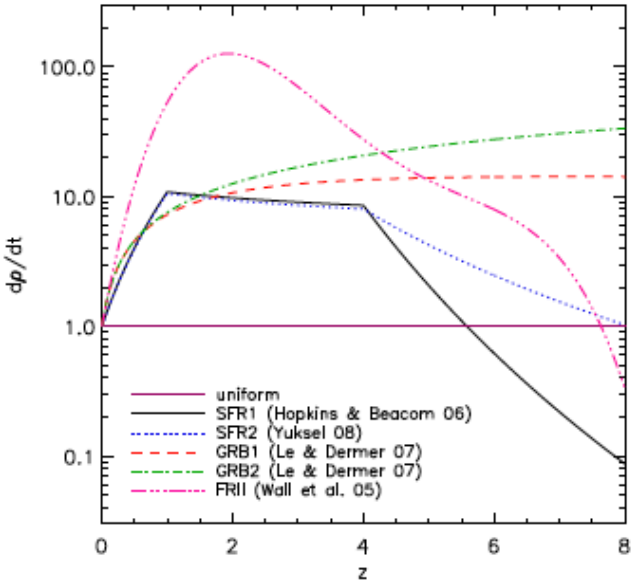
Energy Dist. @ IceCube Depth



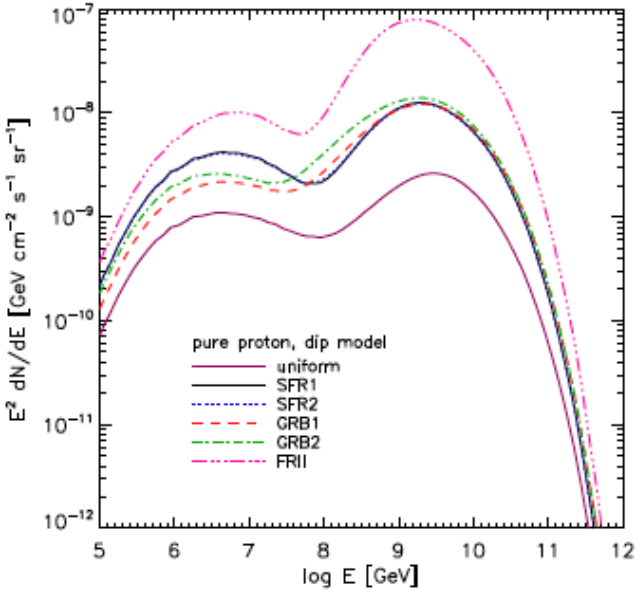
Zenith Dist. @ IceCube Depth

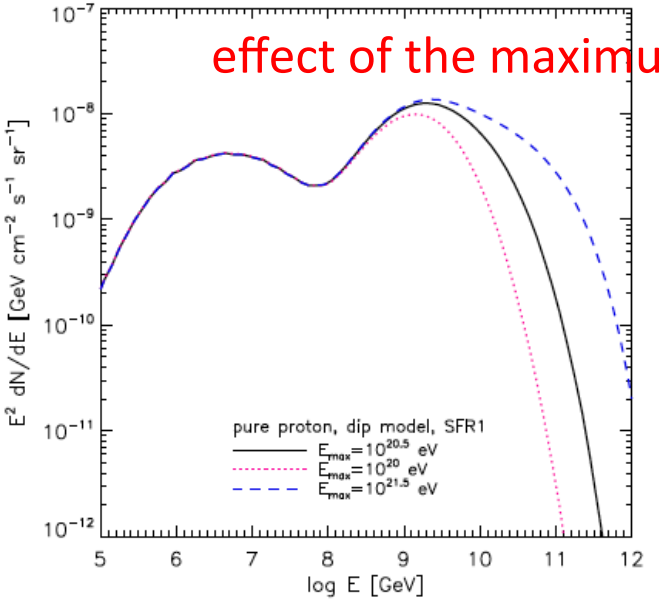


❑ Effect of source evolution and maximum energy on neutrino flux



effect of the source evolution





effect of the maximum energy

neutrino flux depend on the source evolution and maximum energy

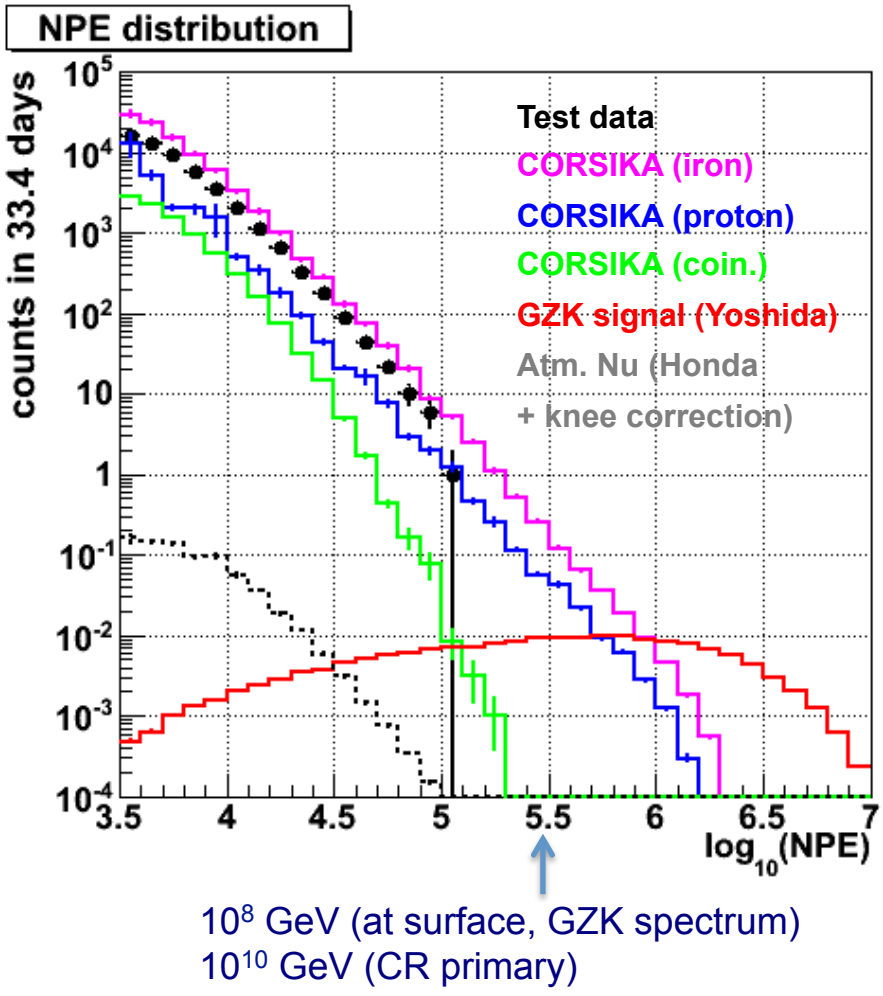
-> constraint on the parameters

Kotera et al., JCAP 10 (2010) 013

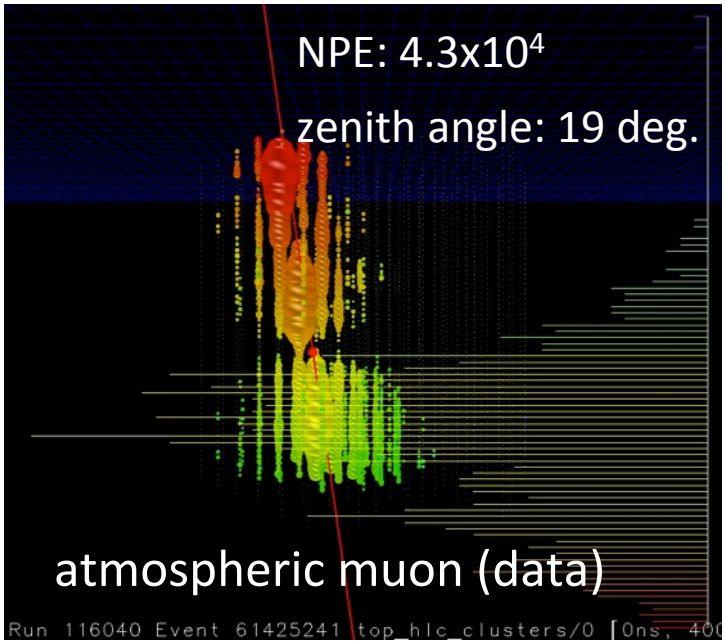
❑ Offline filter level

NPE > $10^{3.5}$ && NDOM > 300 && Coincidence cleaning

33.4 days	Obs. data	GZK signal	proton	iron	Coin.	Atm. nu
all	(5.23±0.02)x10^4	0.174±0.001	(2.53±0.51)x10^4	(9.10±0.52)x10^4	(8.74±0.08)x10^3	0.769±0.032



10^8 GeV (at surface, GZK spectrum)
10^{10} GeV (CR primary)



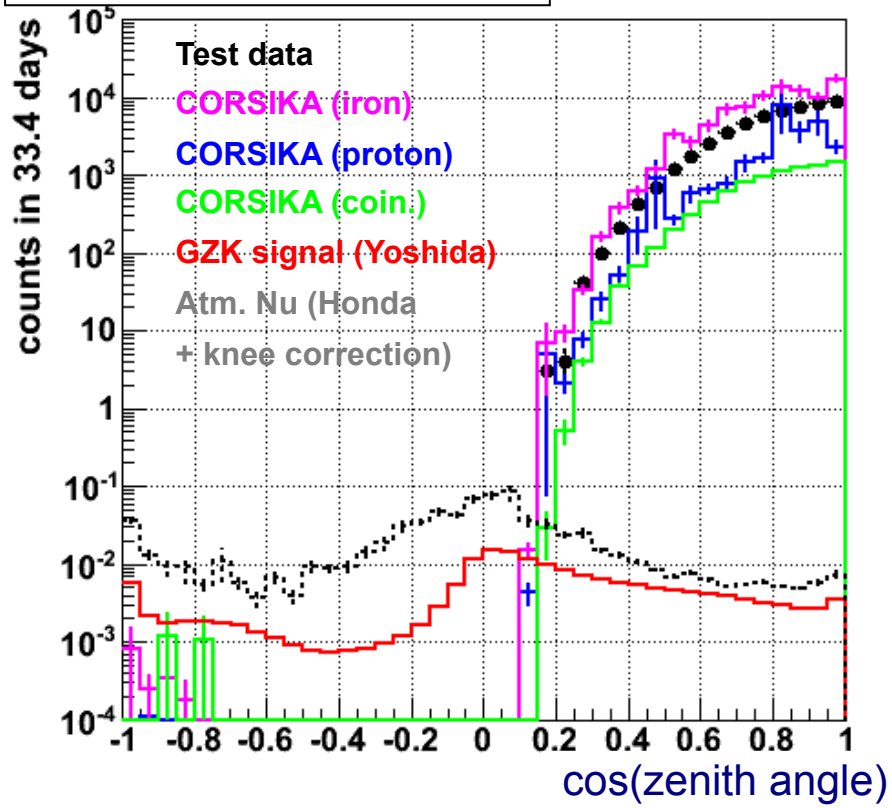
reasonable MC/data agreement
Dominated by atmospheric muons

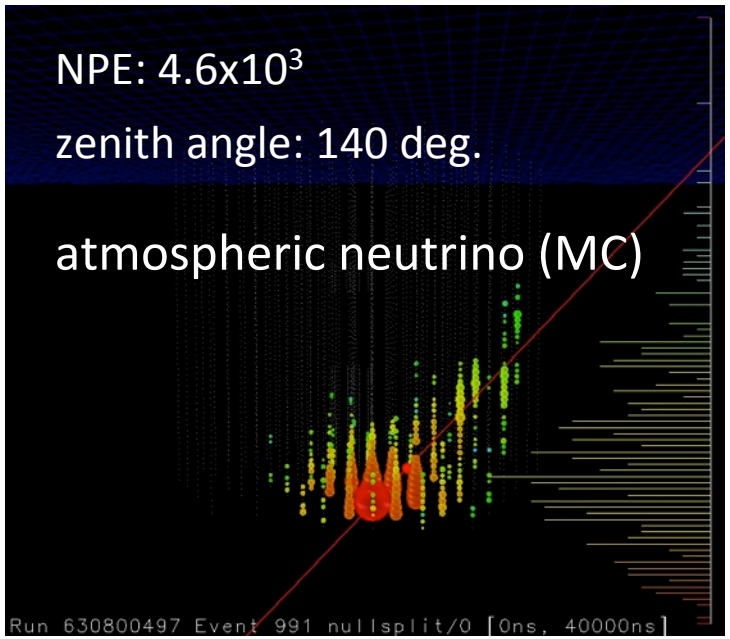
❑ Final filter level

with precise reconstruction algorithms && further coincidence cleaning

33.4 days	Obs. data	GZK signal	proton	iron	Coin.	Atm. nu
all	$(5.22\pm0.02)\times10^{4}$	0.170 ± 0.001	$(2.53\pm0.51)\times10^{4}$	$(9.10\pm0.52)\times10^{4}$	$(8.72\pm0.08)\times10^{3}$	0.769 ± 0.032
Below horizon	0 ± 0	0.0459 ± 0.0004	$(2.25\pm0.94)\times10^{-4}$	$(1.61\pm0.80)\times10^{-3}$	$(2.35\pm1.63)\times10^{-3}$	0.383 ± 0.017

Zenith angle distribution



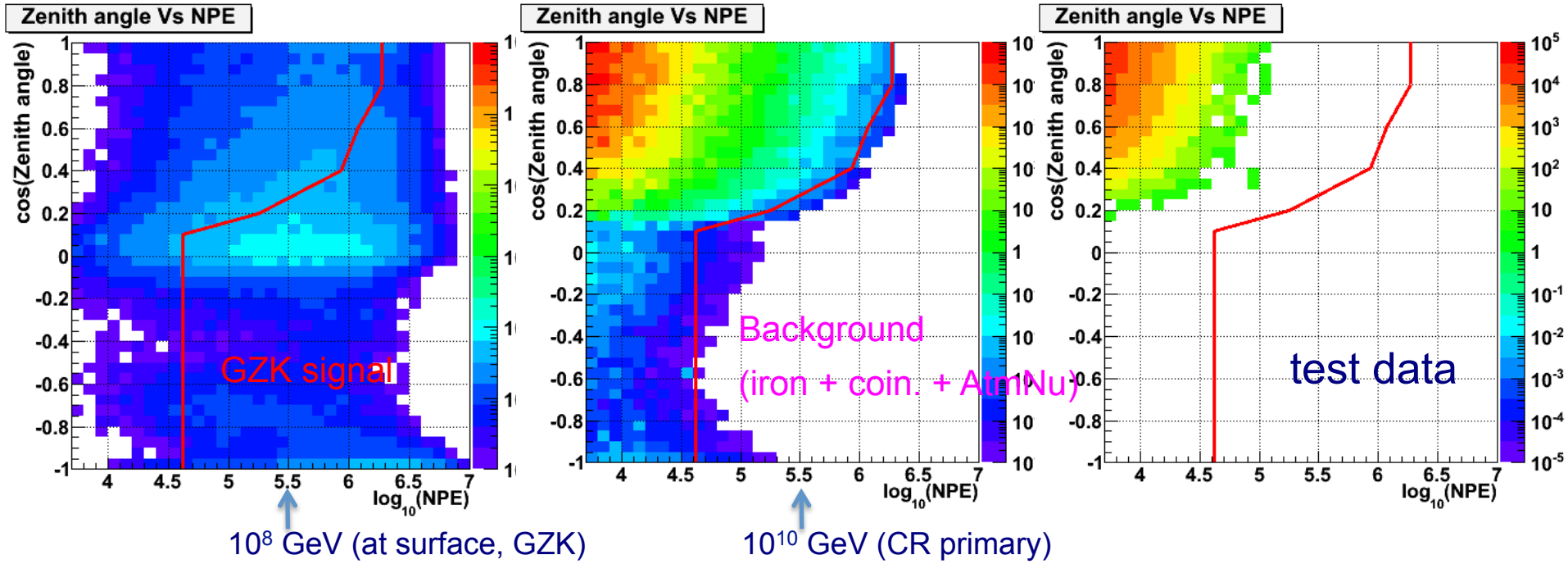


- mis-reconstructd events are cleaned
- atmospheric neutrinos also come from horizon, but low energy

Final selection criteria

Model discovery potential method used (4 sigma)

Iron + coin. + atm. nu is used for the background to be conservative

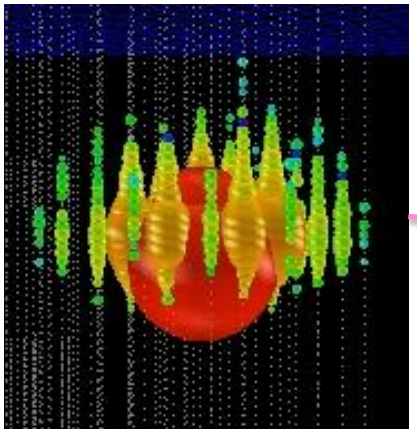


319.2 days	Obs. data	GZK signal	proton	iron	Coin.	Atm. nu
all	0±0	**0.978±0.005**	$(6.77\pm1.29)\times10^{-3}$	$(3.31\pm0.25)\times10^{-2}$	0±0	$(1.59\pm0.10)\times10^{-2}$
Below horizon	0±0	0.0363±0.003	$(7.88\pm6.08)\times10^{-4}$	$(1.92\pm1.09)\times10^{-3}$	0±0	$(1.29\pm0.09)\times10^{-2}$

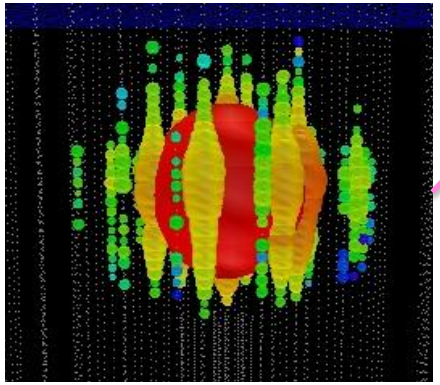
* 0.57 per 333 days for IC40

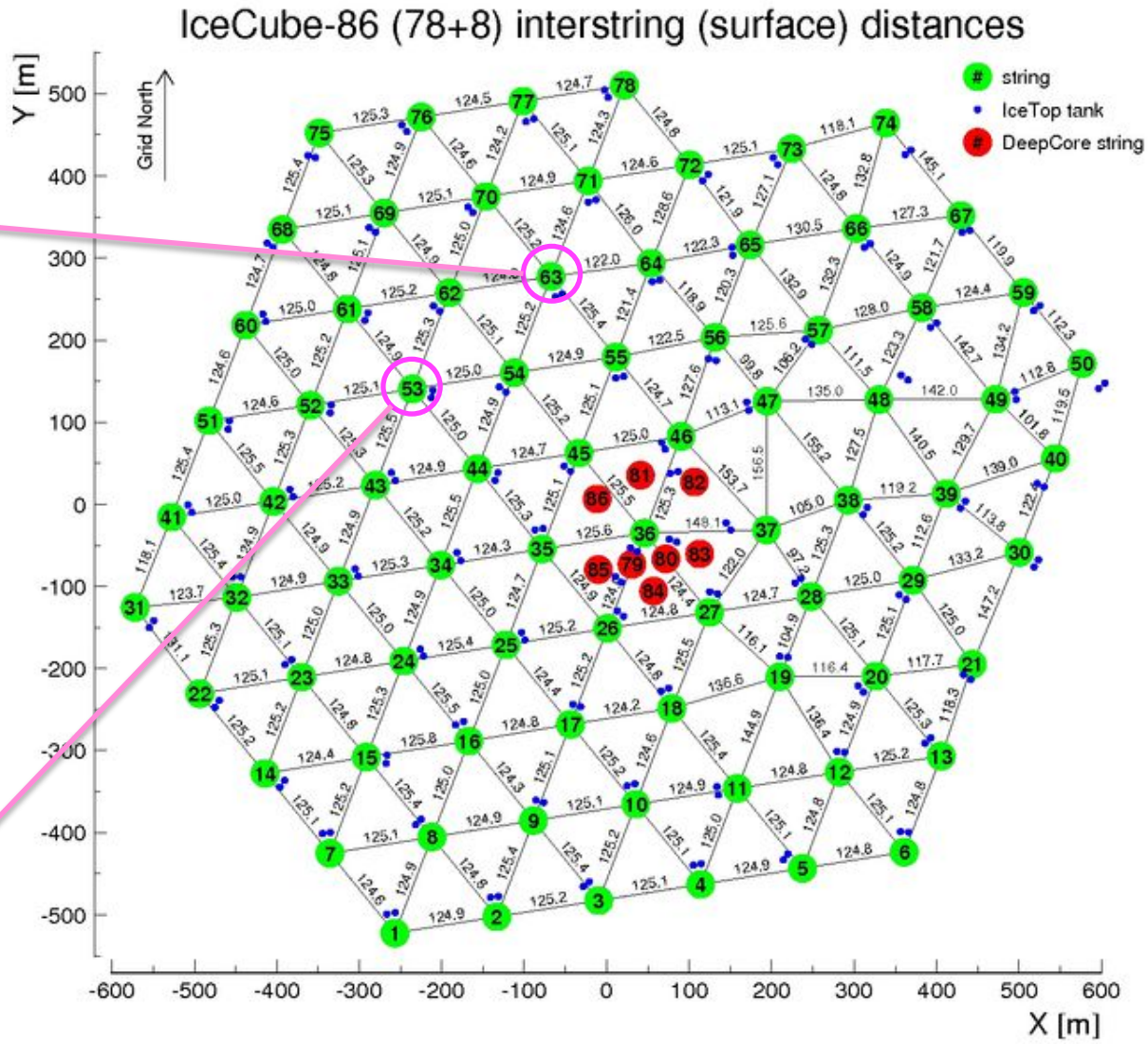
The brightest string positions

Ernie



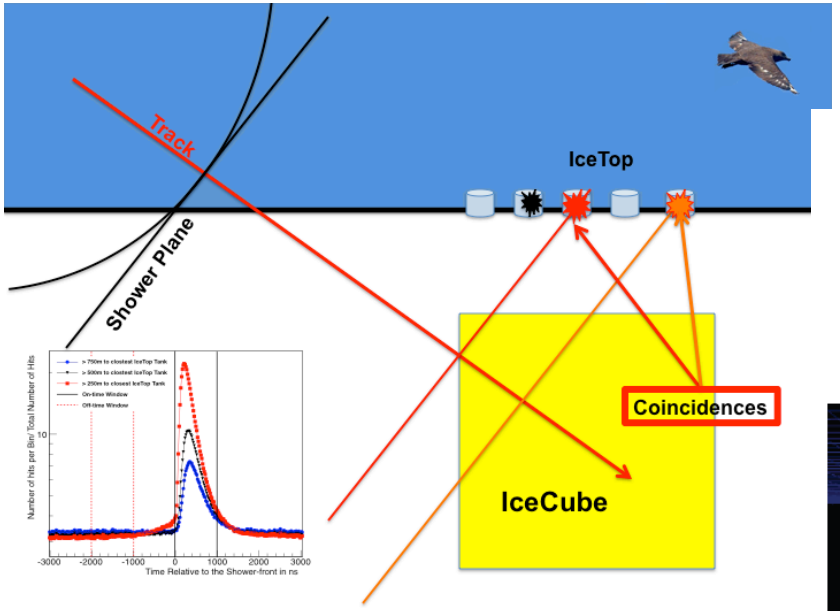
Bert

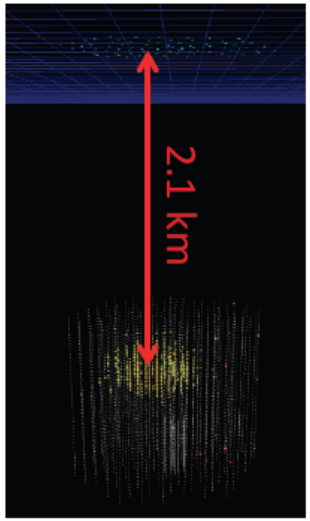




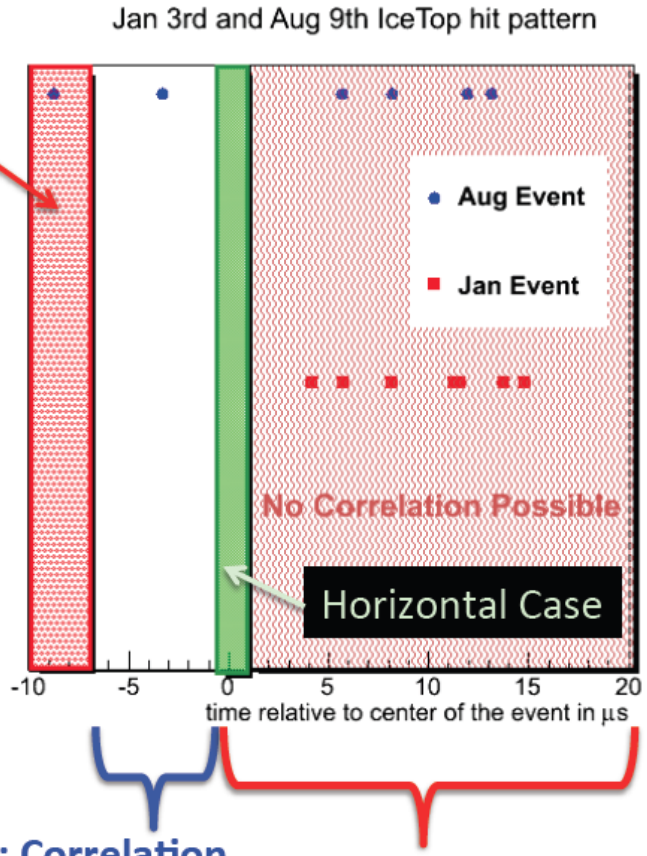
Well contained

❑ IceTop (surface array) veto information





Geometrical not possible as Cascades 2 .1km deep



- IceTop veto information was checked
- hits search in allowed 8µs time window
- 0 and 1 hit observed against 2.1 noise hits

-> No CR shower

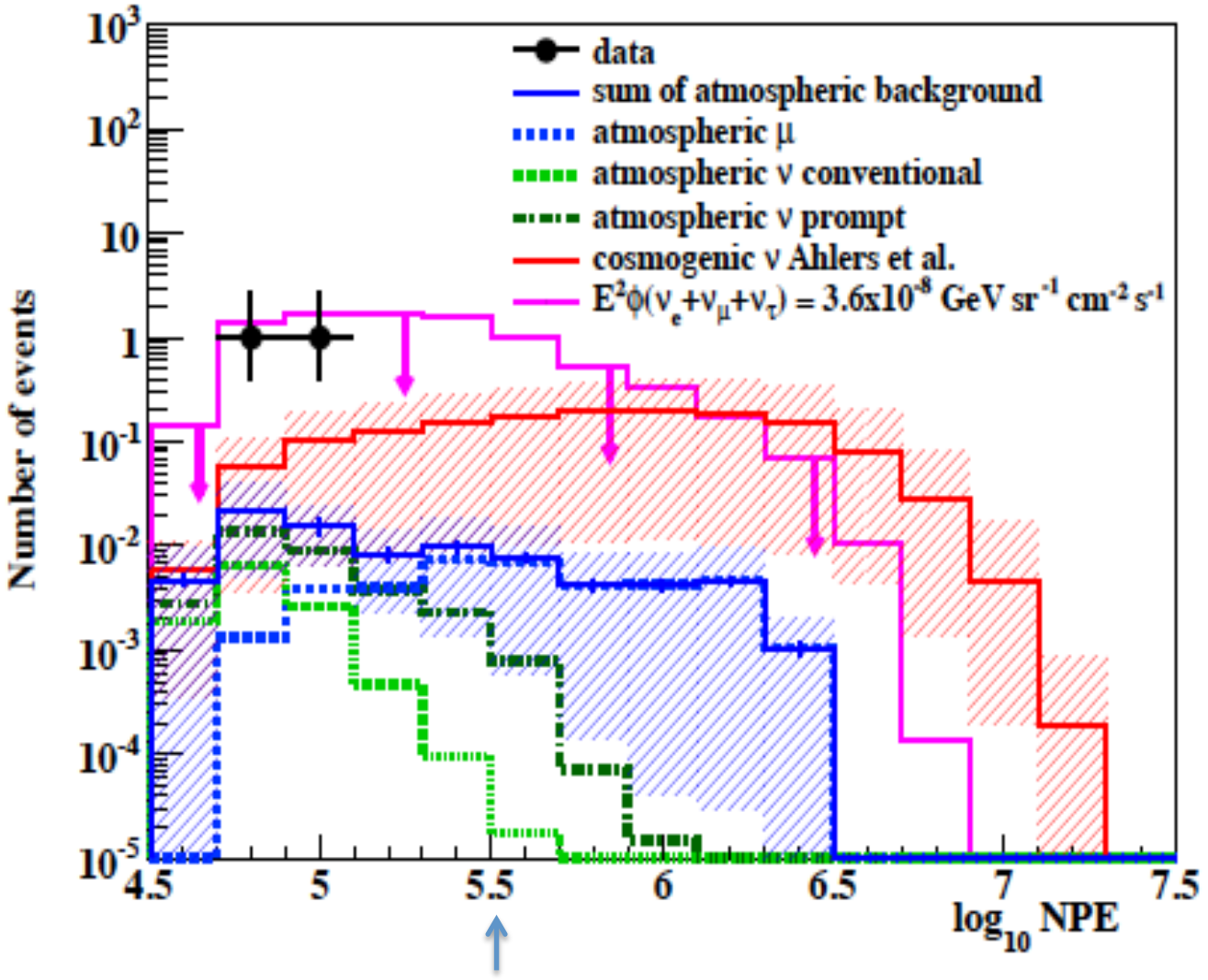
Before first Hit: Correlation possible

After the Event no Down-going correlation possible

NPE distribution at final level

IC79/86 combined (615.9 days)

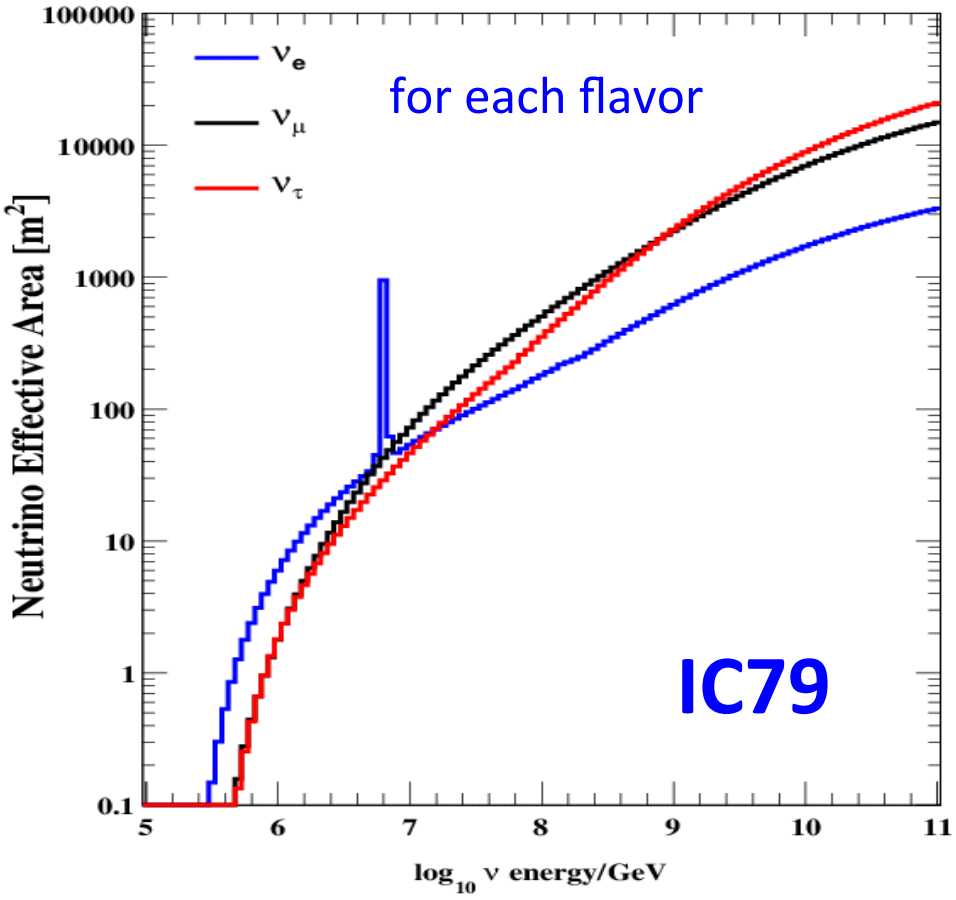
PRL 111, 021103 (2013)

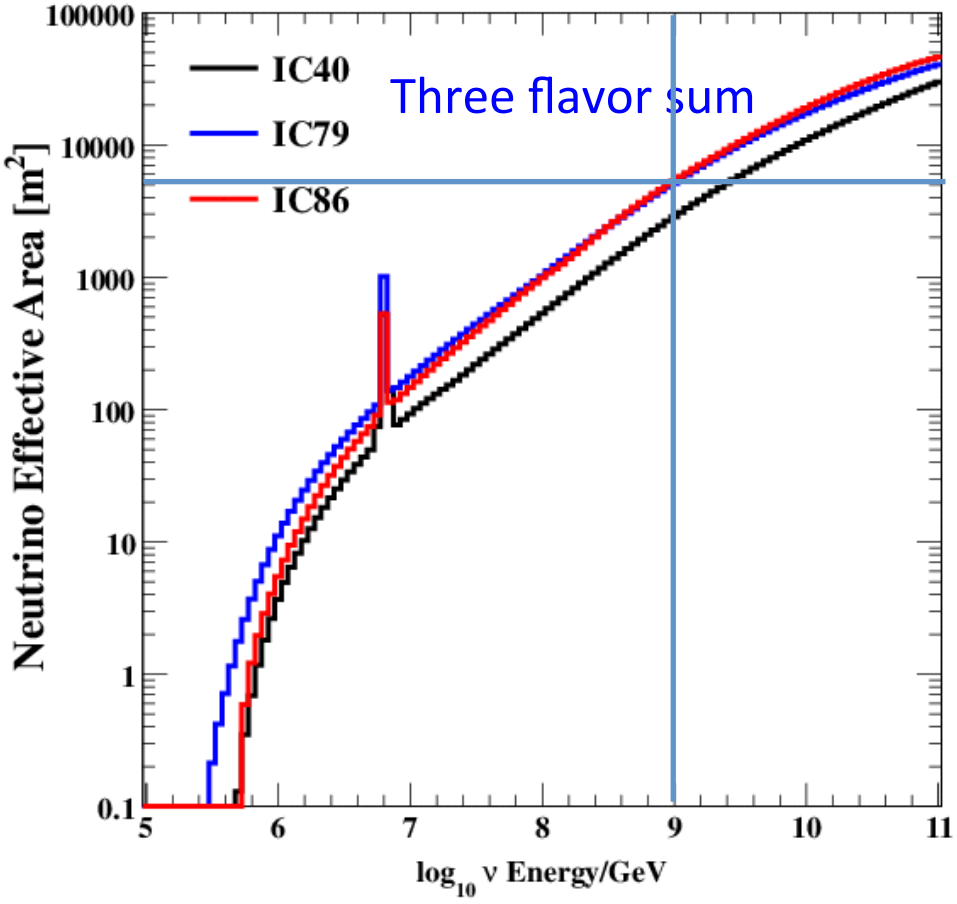


corresponds to ~10^8 GeV neutrinos at surface with a cosmogenic neutrino spectrum

Effective area

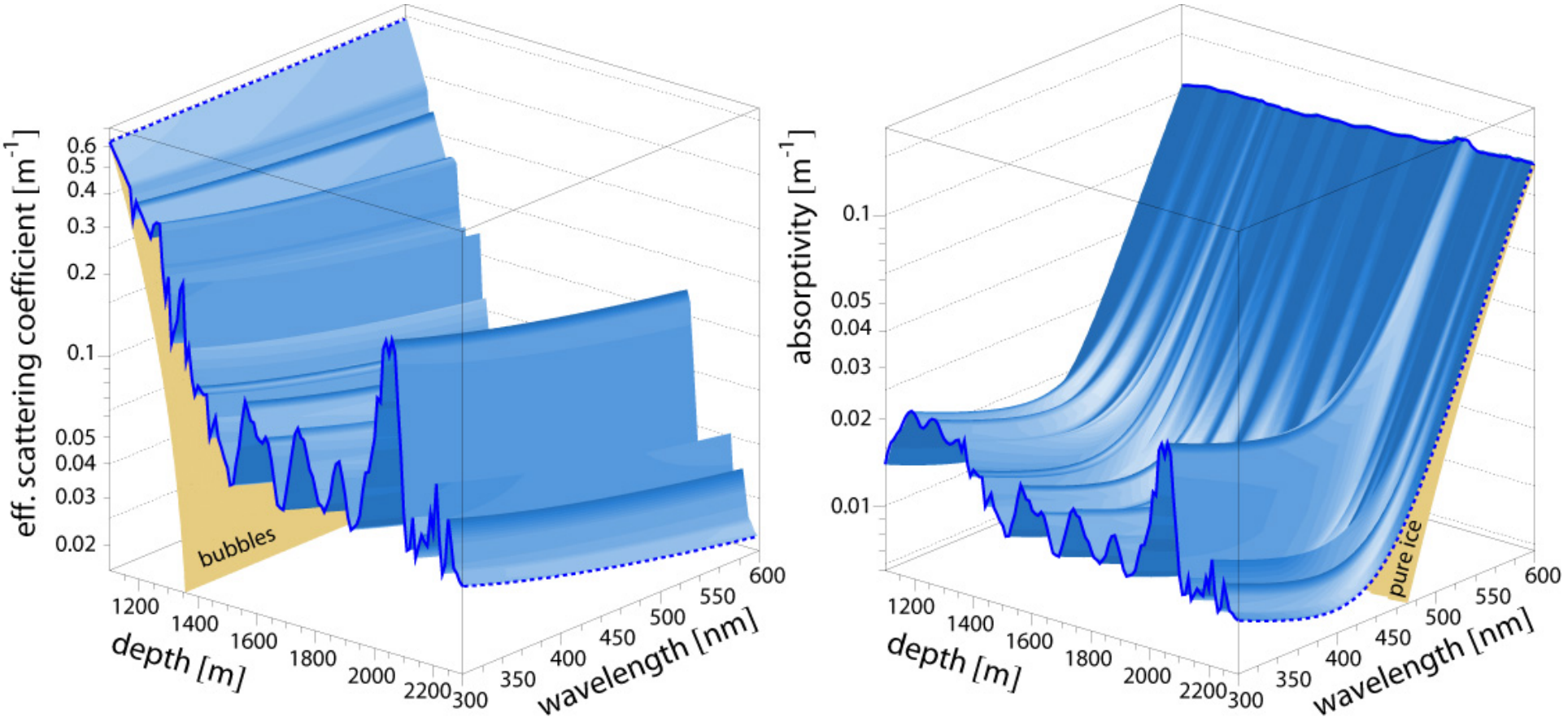
$A_{IC79} \approx A_{IC86} \approx 2 \times A_{IC40}$





- Increases with energy
- ~5000 m^2 @ EeV

The ice property



Average optical parameters:

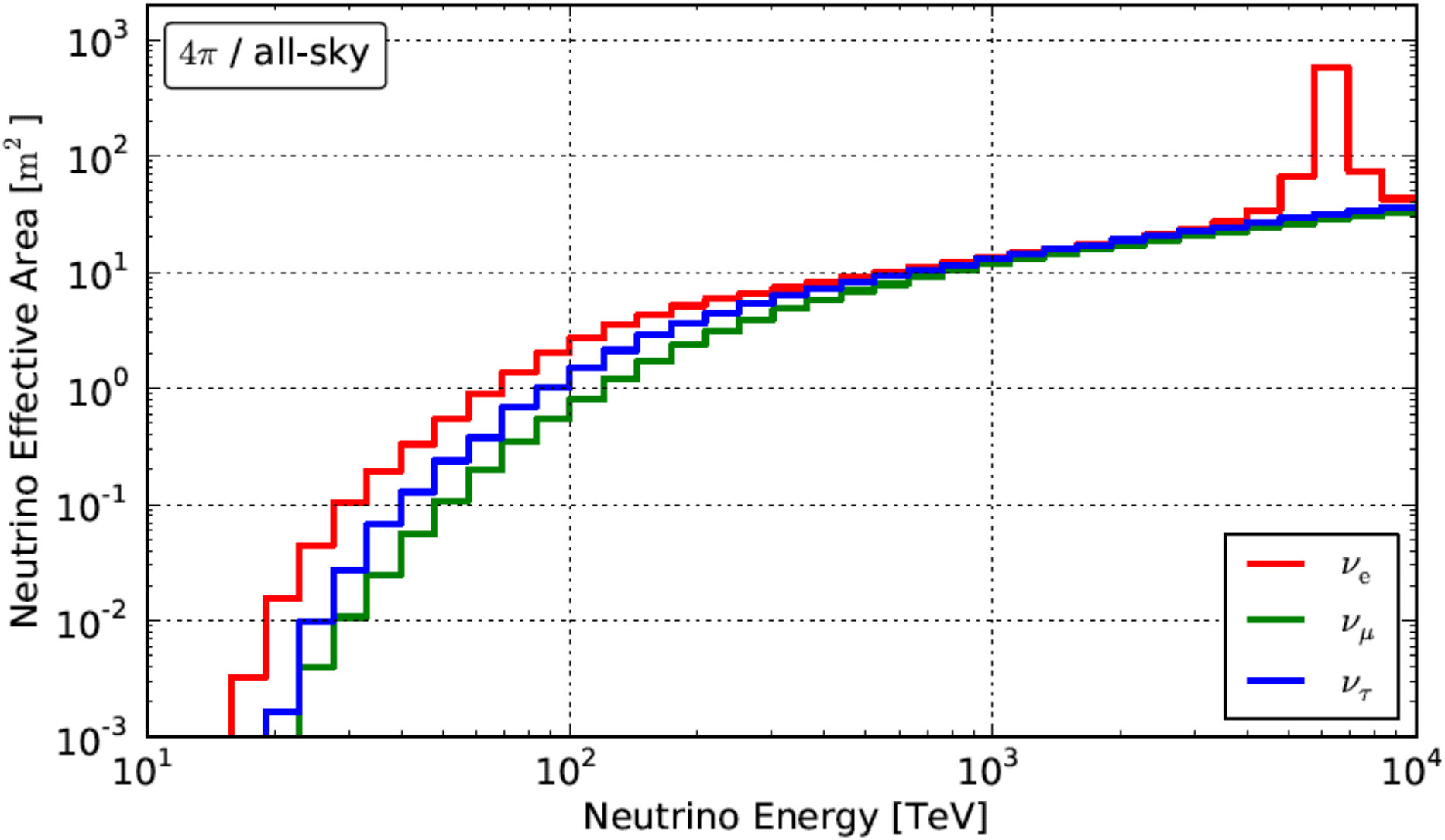
λ_{abs} ~ 110 m @ 400 nm

λ_{scat} ~ 20 m @ 400 nm

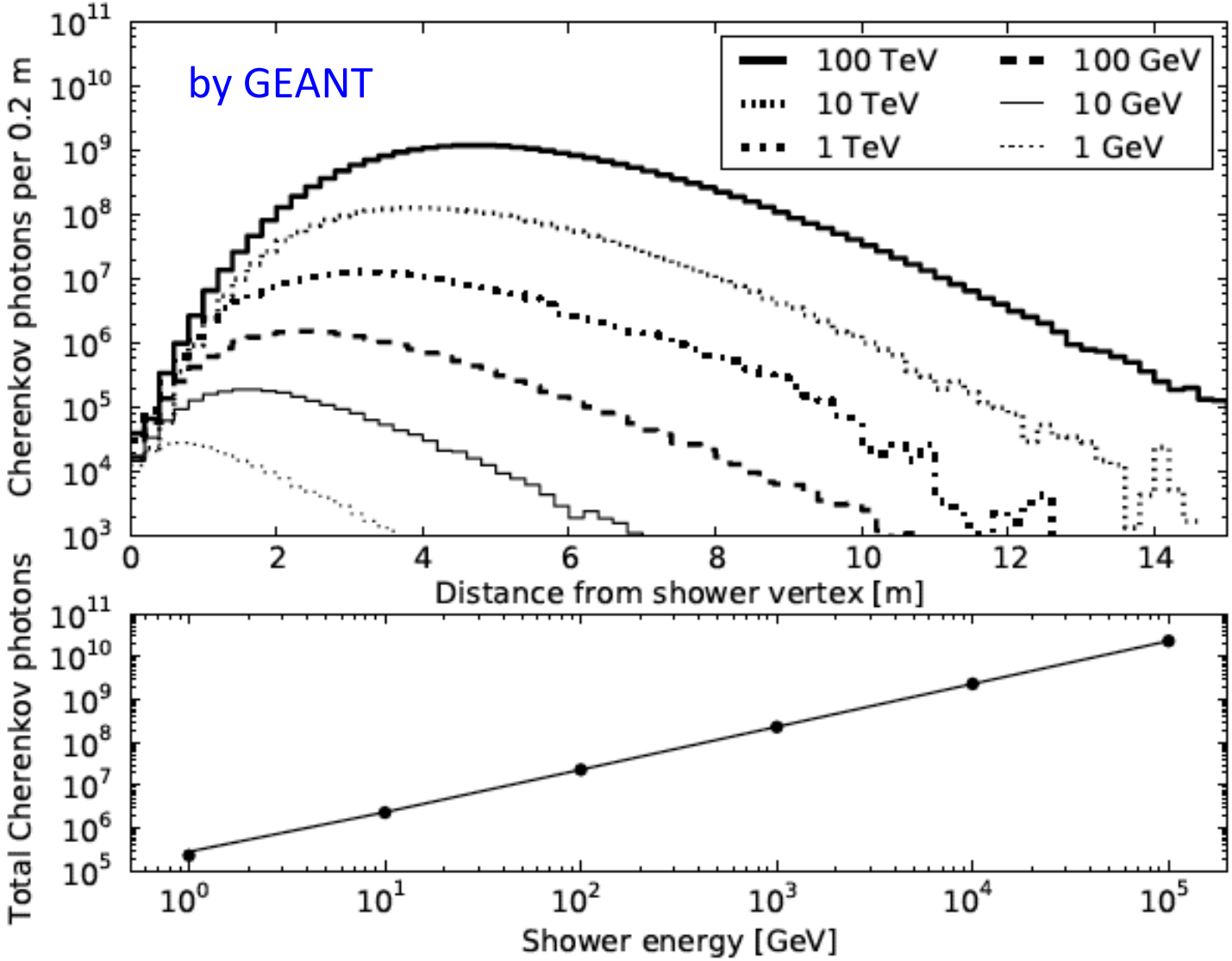
Clear depth dependence

→ taken into account in simulation

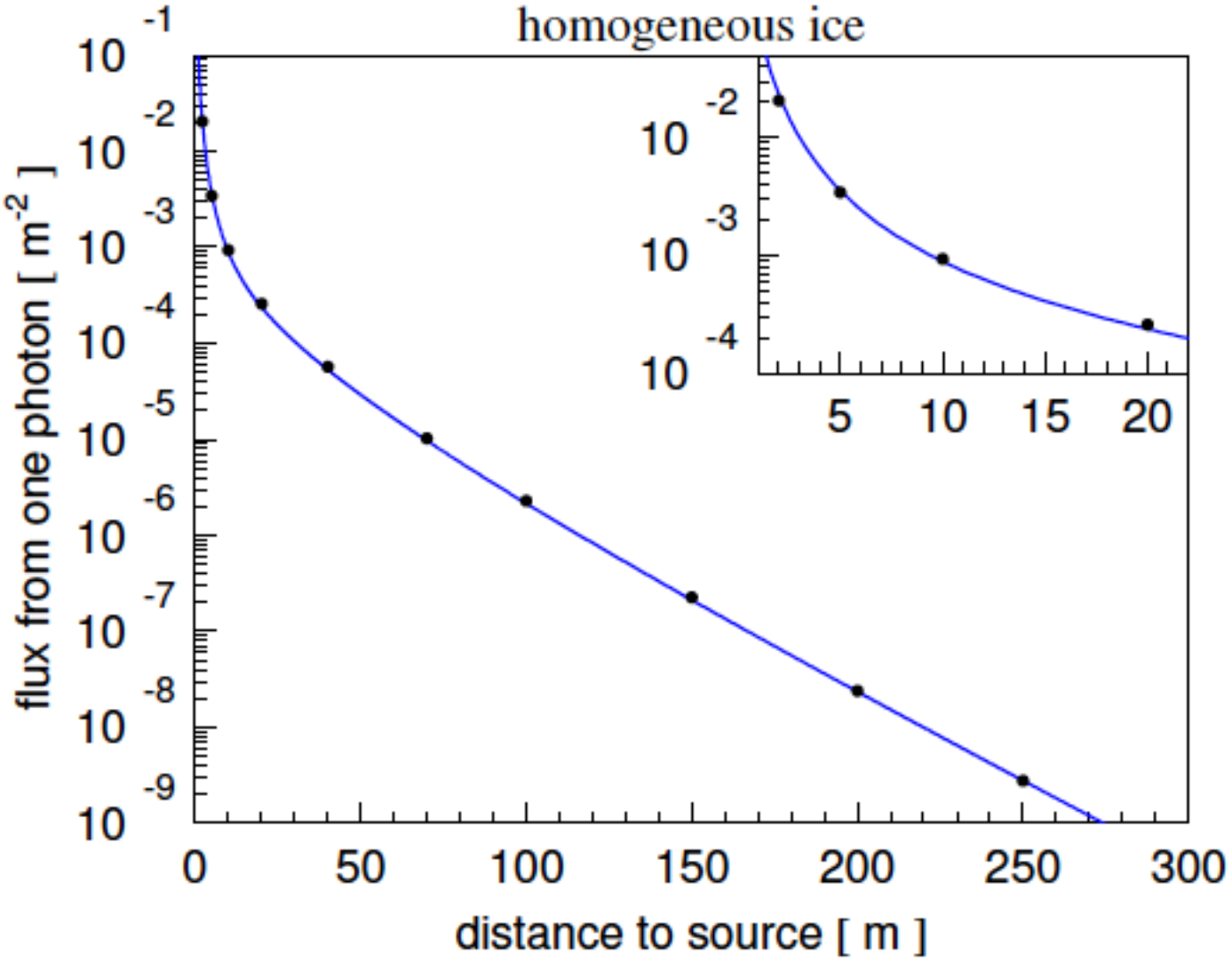
Effective area (HESE)

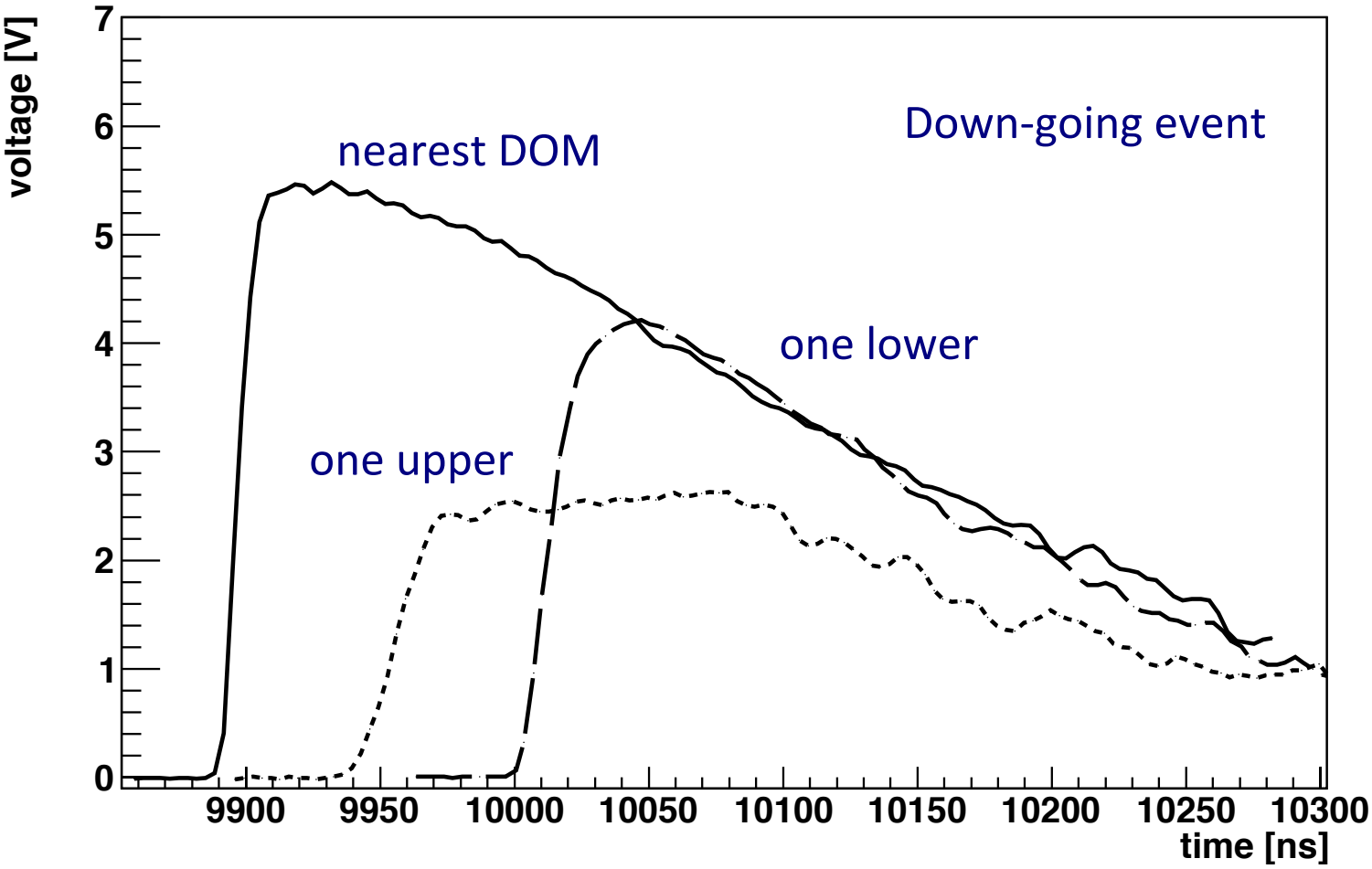


Longitudinal shower development in ice



Light yield vs. distance for a point-like source




voltage [V]
7
6
5
4
3
2
1
0
9900
9950
10000
10050
10100
10150
10200
10250
10300
time [ns]
Down-going event
nearest DOM
one lower
one upper