High-Energy Neutrino Astronomy in Ice and Water

Very brief overview of neutrino astronomy (and recent results from IceCube)

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TeV Neutrinos

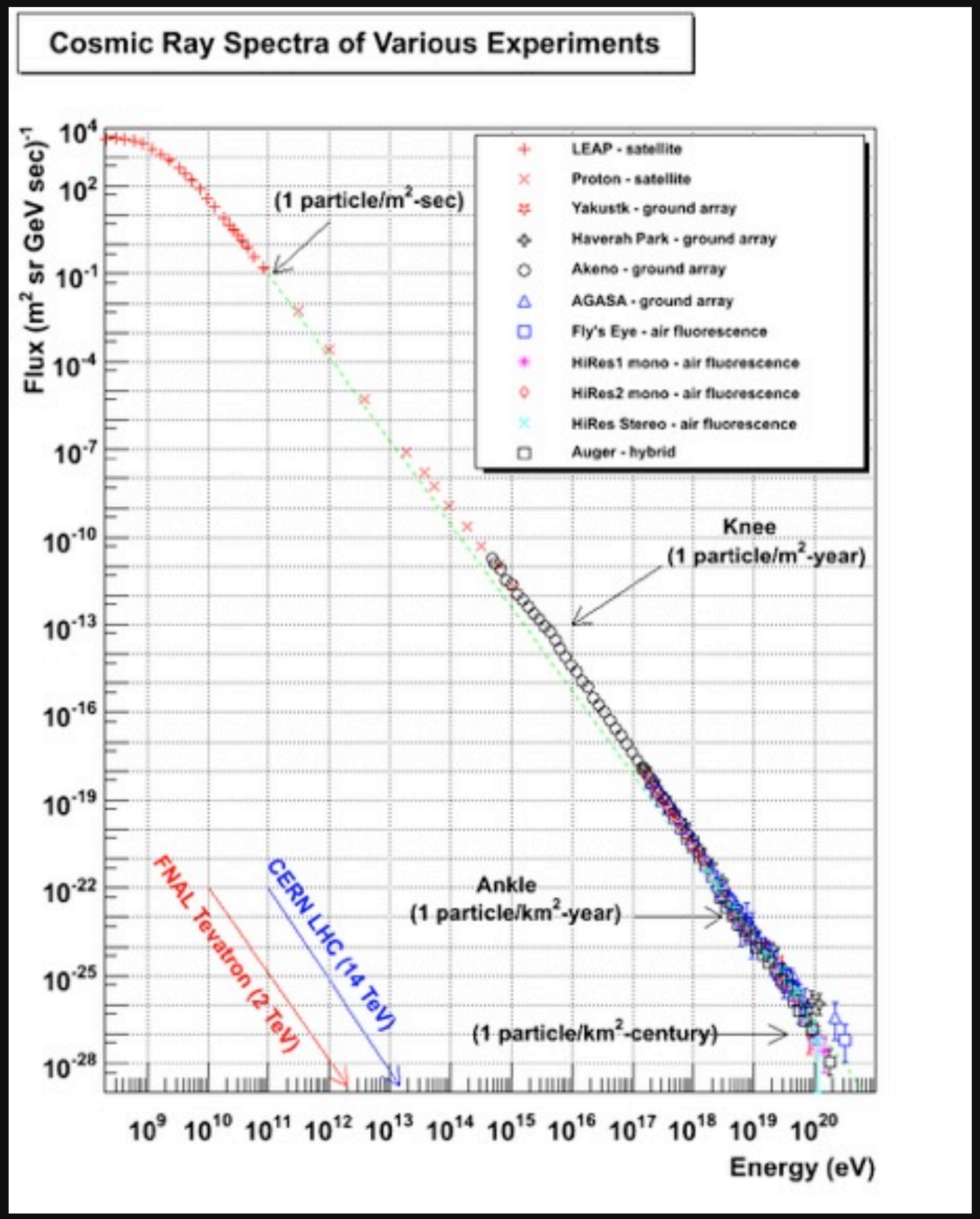
Observing astrophysical neutrinos allows conclusions about the acceleration mechanism

$$
\begin{aligned}
\mathrm{p} + \gamma \;&\rightarrow \pi^0 + \mathrm{p} \qquad (\gamma \text{ or p}, \ldots)\\
&\hookrightarrow \gamma + \gamma + \mathrm{p} \\
&\rightarrow \pi^+ + \mathrm{n} \\
&\hookrightarrow \mu^+ + \nu_\mu + \mathrm{n} \\
&\hookrightarrow \mathrm{e}^+ + \nu_{\bar{\mu}} + \nu_\mathrm{e} + \nu_\mu + \mathrm{n}
\end{aligned}
$$

TeV gamma rays ($\gamma + \gamma$)

Cosmic rays? (n)

TeV neutrinos (ν_μ; $\nu_{\bar{\mu}} + \nu_\mathrm{e}$)

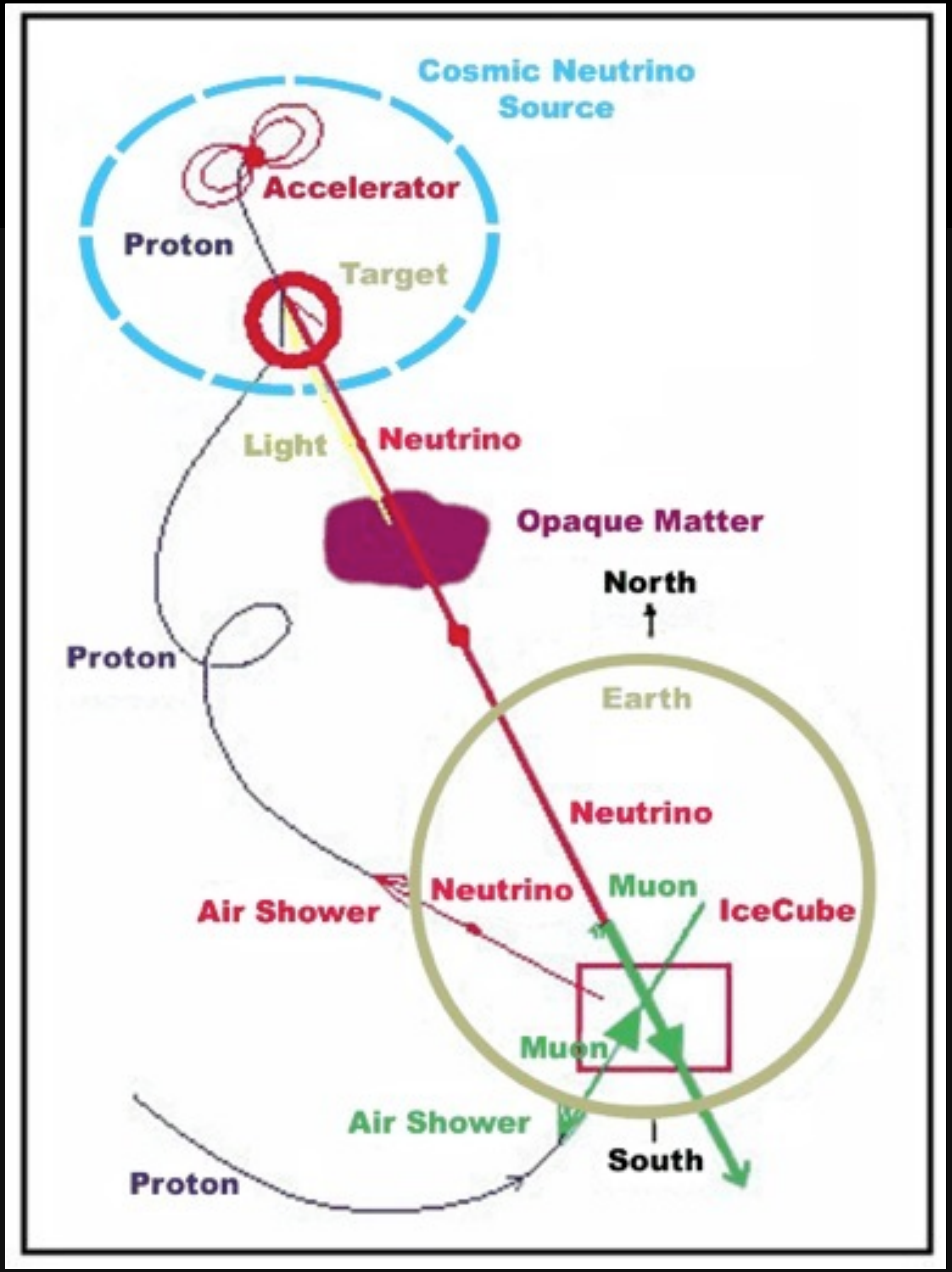


- **Neutrinos from cosmic ray interactions in:**
  - Atmosphere
  - Cosmic Microwave Background
  - Gamma Ray Bursts (Acceleration Sites)
  - Active Galactic Nuclei (Acceleration Sites)
  - ?

Why Neutrinos?

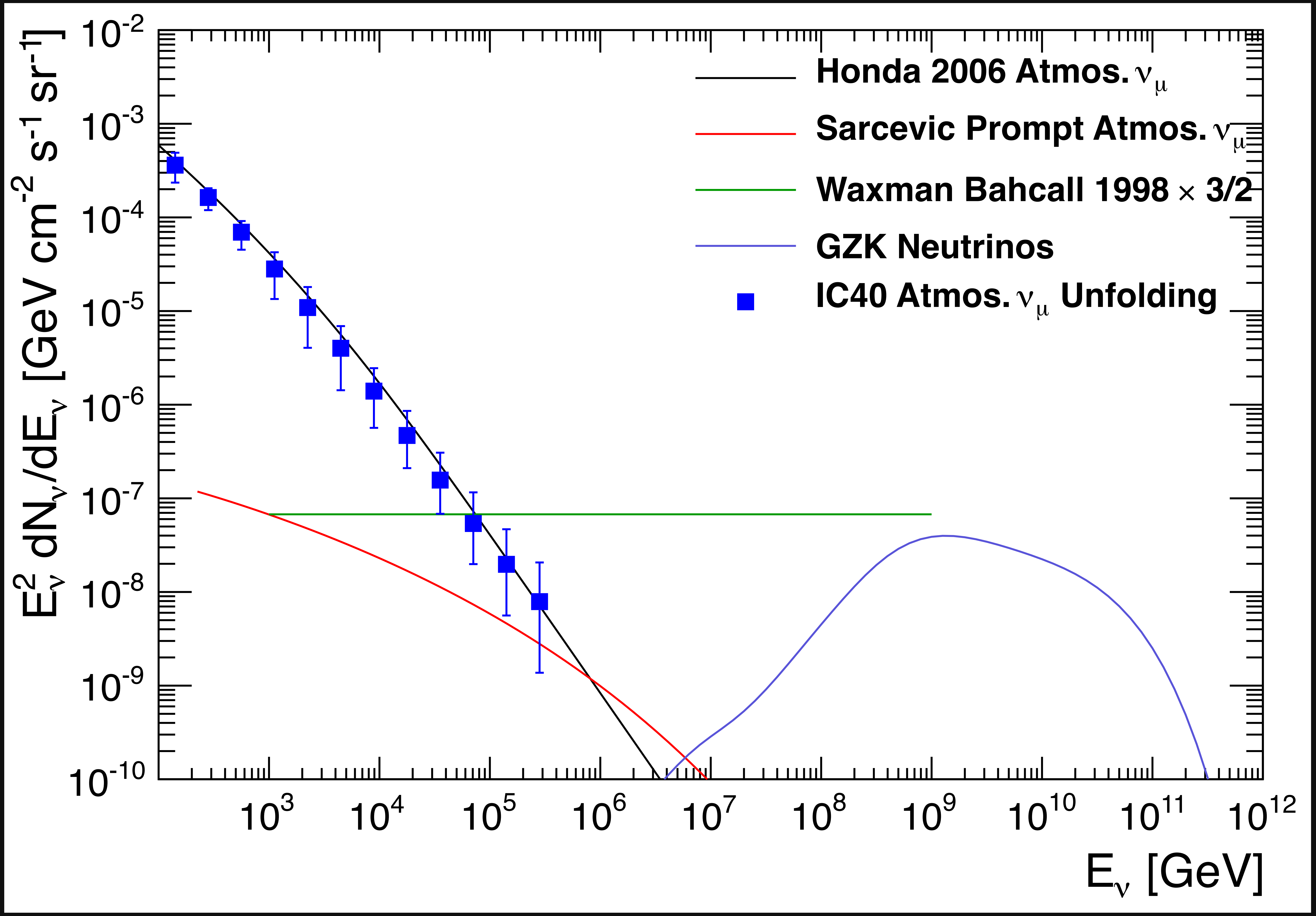
Neutrinos are ideal astrophysical messengers

- Travel in straight lines
- Very difficult to absorb in flight



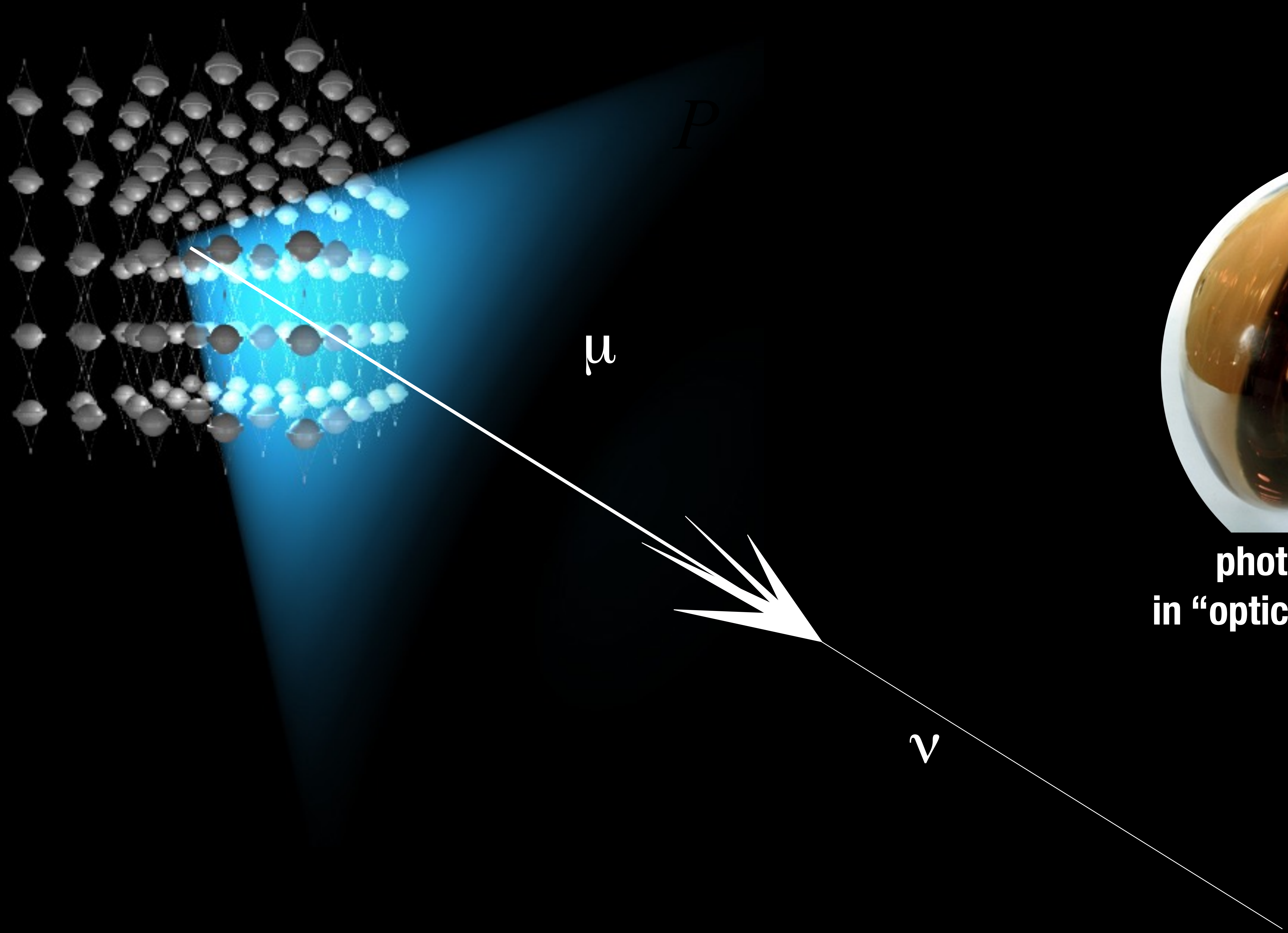
Interesting Neutrinos above 1 TeV

- **Atmospheric neutrinos (π/K)**
  - dominant < 100 TeV
- **Atmospheric neutrinos (charm)**
  - "prompt" ~ 100 TeV
- **Astrophysical neutrinos**
  - maybe dominant > 100 TeV
- **Cosmogenic neutrinos**
  - $>10^6$ TeV



Detection Principle

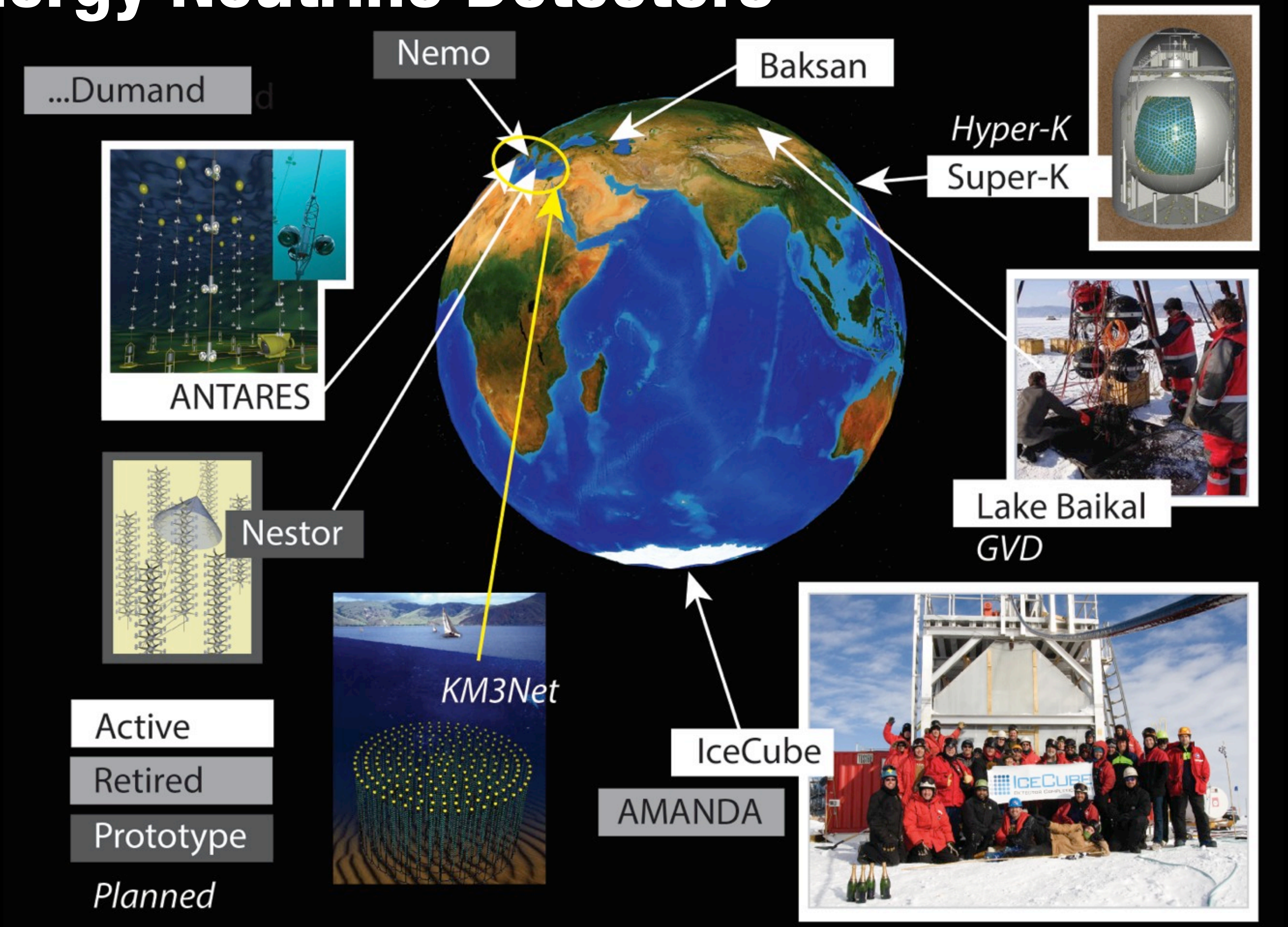
Observe Cherenkov light using a lattice of photomultipliers (PMTs) in an optically transparent medium



photomultiplier tubes in "optical modules" ("OMs")

from ICRC 2013 plenary by F. Halzen

High-Energy Neutrino Detectors

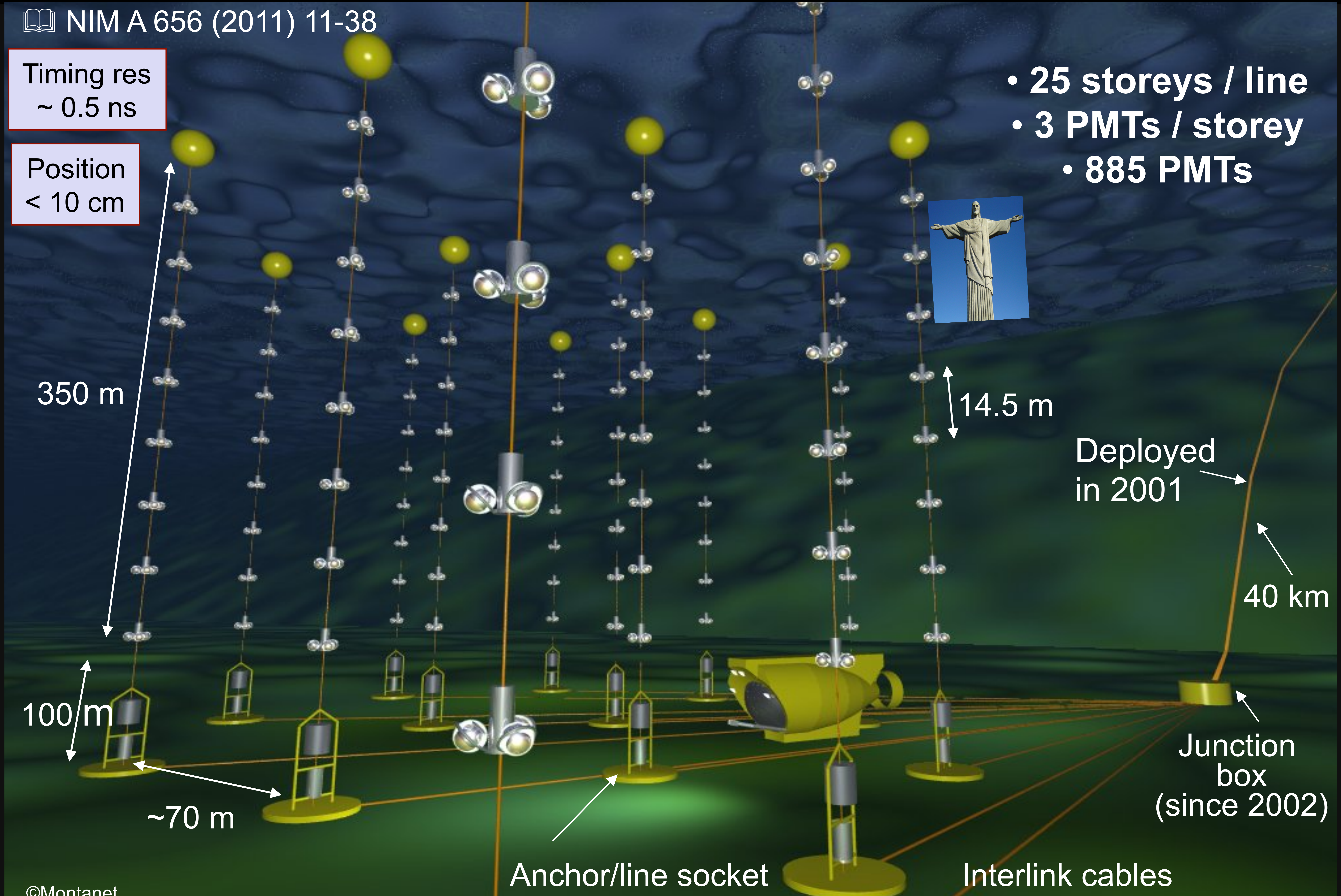


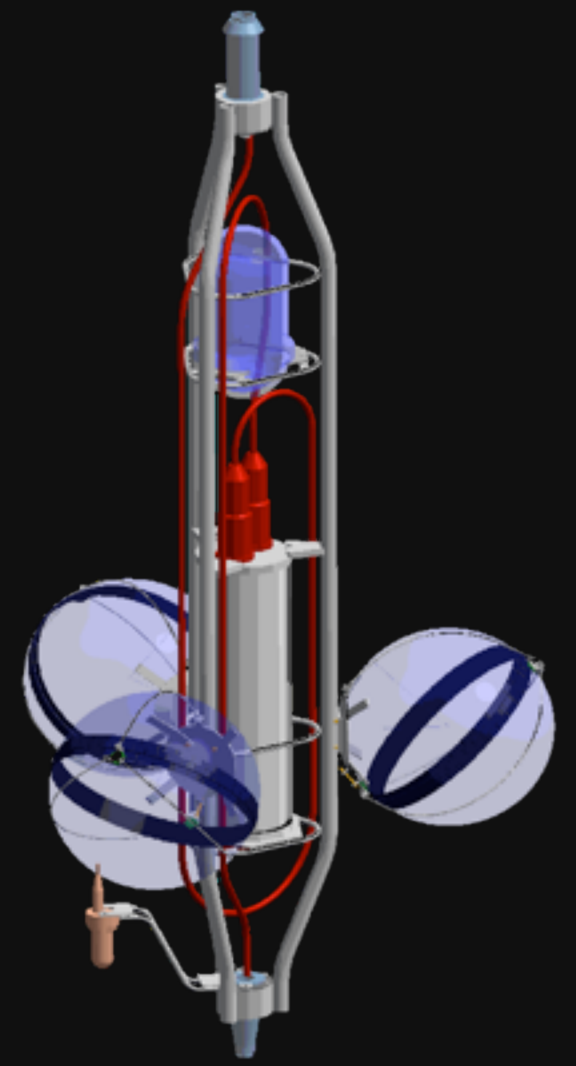
from ICRC 2013
plenary by F. Halzen

The ANTARES Neutrino Telescope

In the Mediterranean Sea (near Toulon, France)

Talk by A. Margiotta in this session!



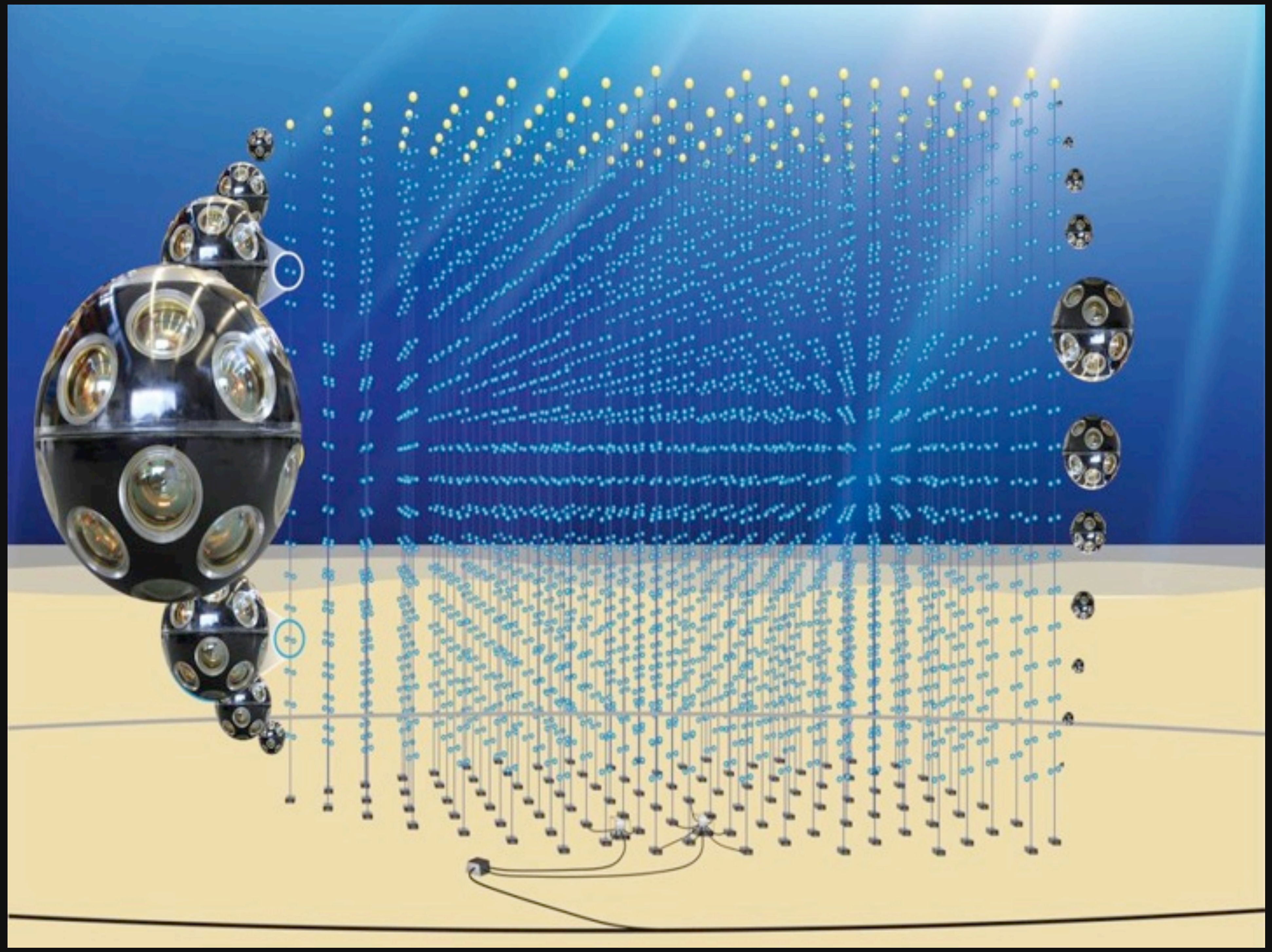


"storey" with 3 OMs

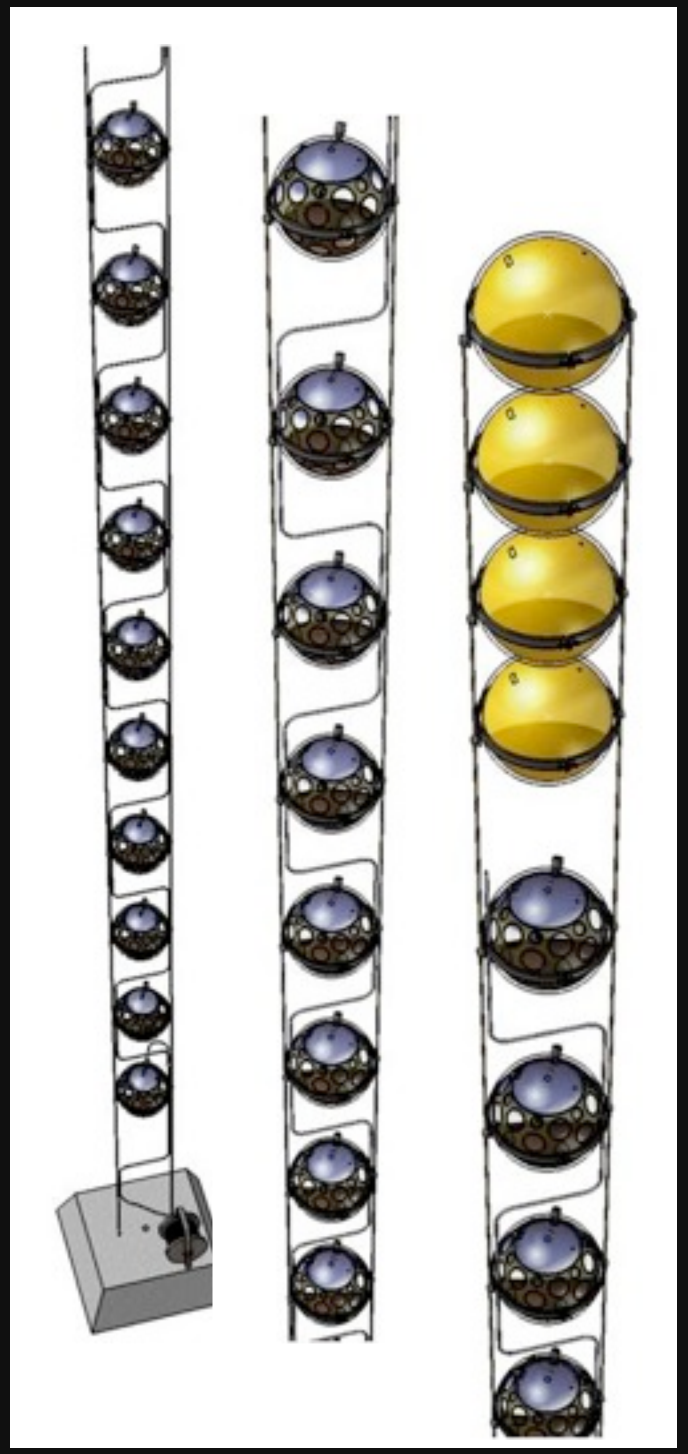
from ICRC 2013 plenary by A. Kouchner

The KM3NeT Neutrino Telescope

Multi-site installation in the Mediterranean Sea (France, Italy, Greece), instrumented in "building blocks", starting construction!



KM3NeT "building block"



string with OMs

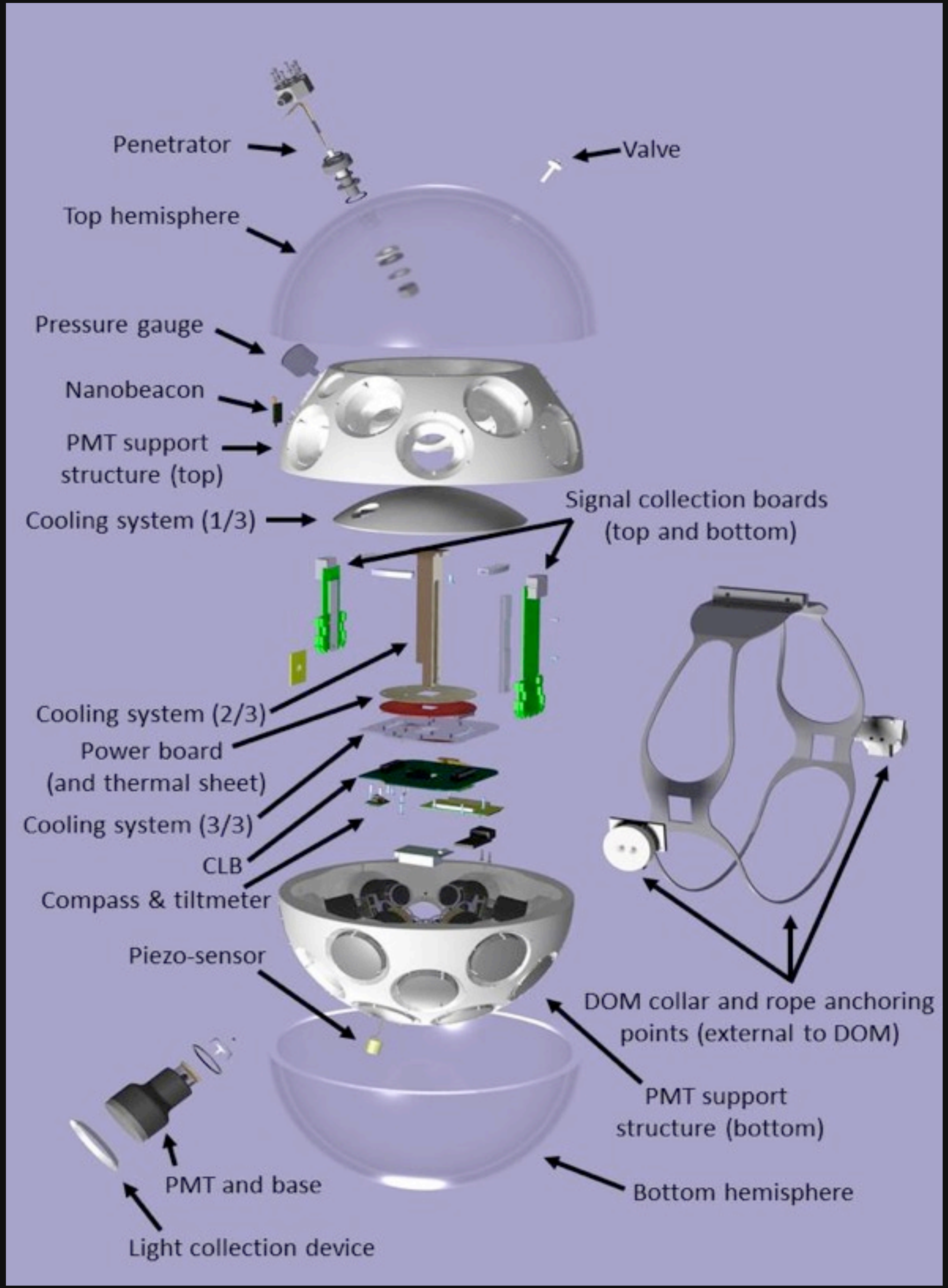
Multi-PMT digital optical module ("DOM")

from ICRC 2013
talk by P. Coyle

The KM3NeT Neutrino Telescope

Planned multi-site installation in the Mediterranean Sea (France, Italy, Greece), instrumented in “building blocks”

- **31 x 3” PMTs**
  - Hamamatsu, ETL, HZC
- **Light collection ring**
  - 20–40% gain in PC for free
- **Low power**
  - <10 W / DOM
- **FPGA readout**
  - sub-ns time stamping
  - time over threshold
- **Calibration**
  - LED & acoustic piezo
- **Optical fibre data transmission**
  - DWDM with 80 wavelengths
  - Gb/s readout



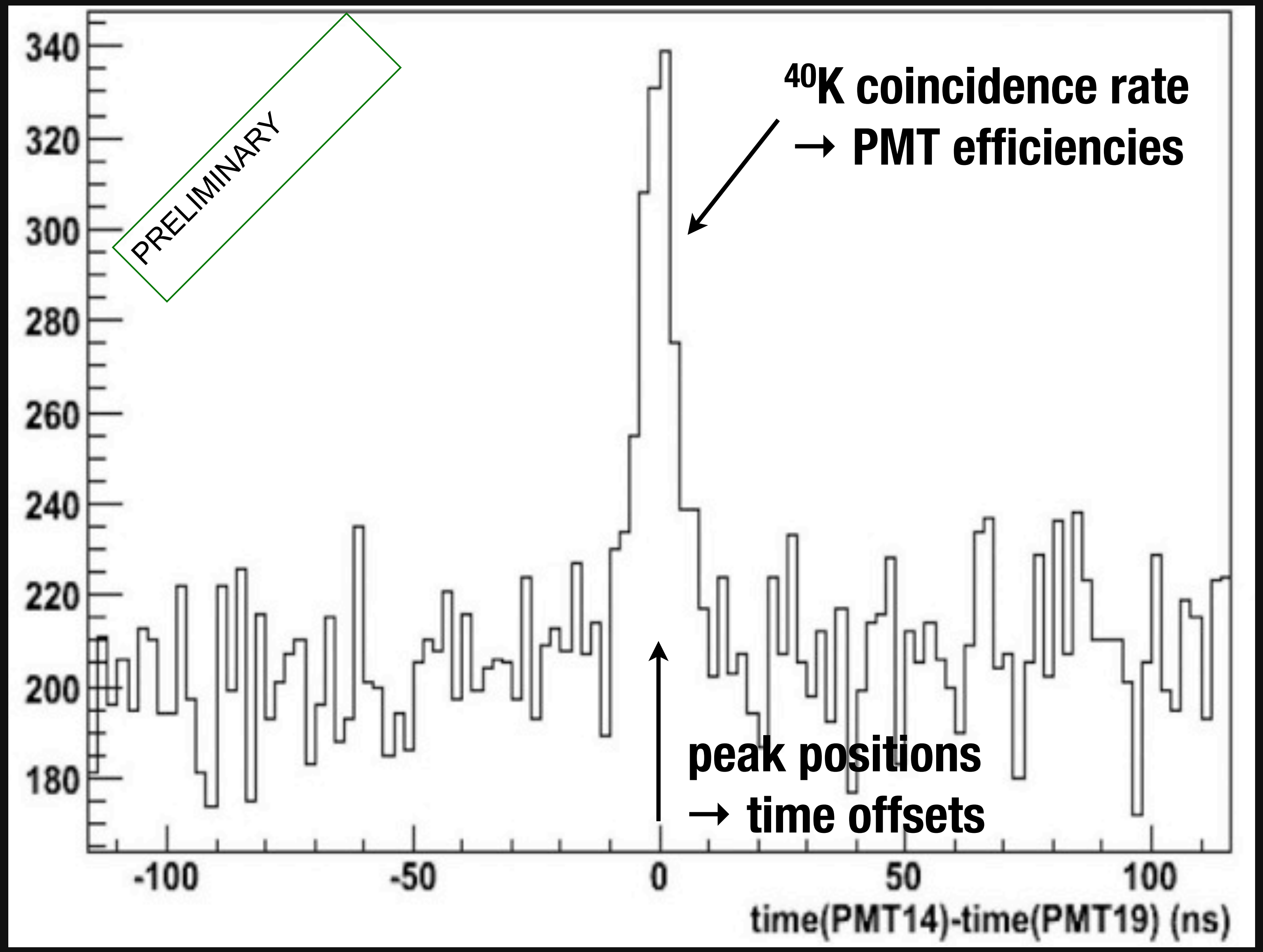
from ICRC 2013
talk by P. Coyle

The KM3NeT Neutrino Telescope

Planned multi-site installation in the Mediterranean Sea (France, Italy, Greece), instrumented in "building blocks"

test installation on ANTARES instrumentation string

Coincidence rate on 2 adjacent PMTs



use noise from ^{40}K decays as a calibration tool!

from ICRC 2013
talk by P. Coyle

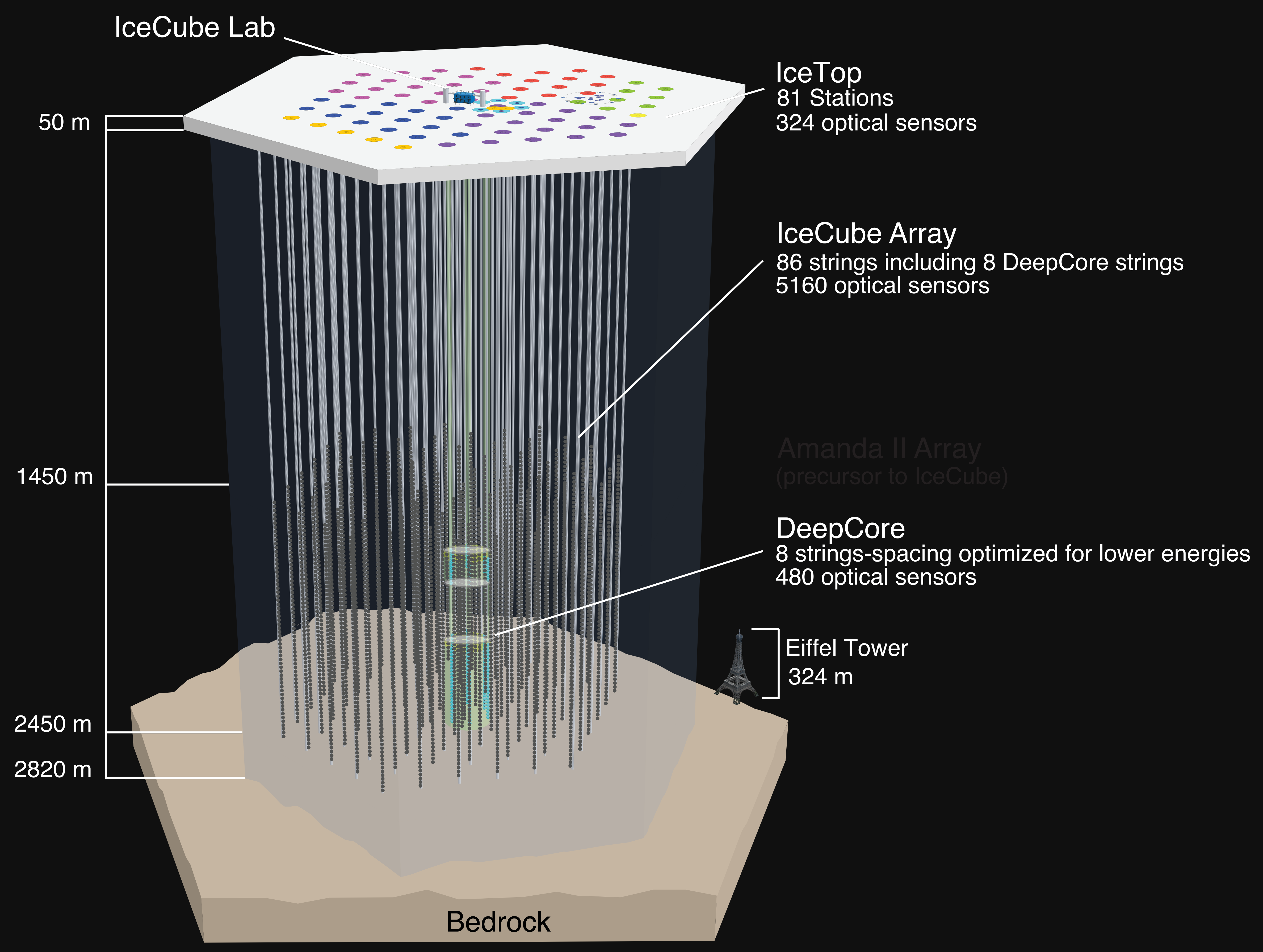
The KM3NeT Neutrino Telescope

String deployment by rolling up the string, deploying it to depth and the letting it unfurl

The IceCube Neutrino Observatory

Deployed in the deep glacial ice at the South Pole

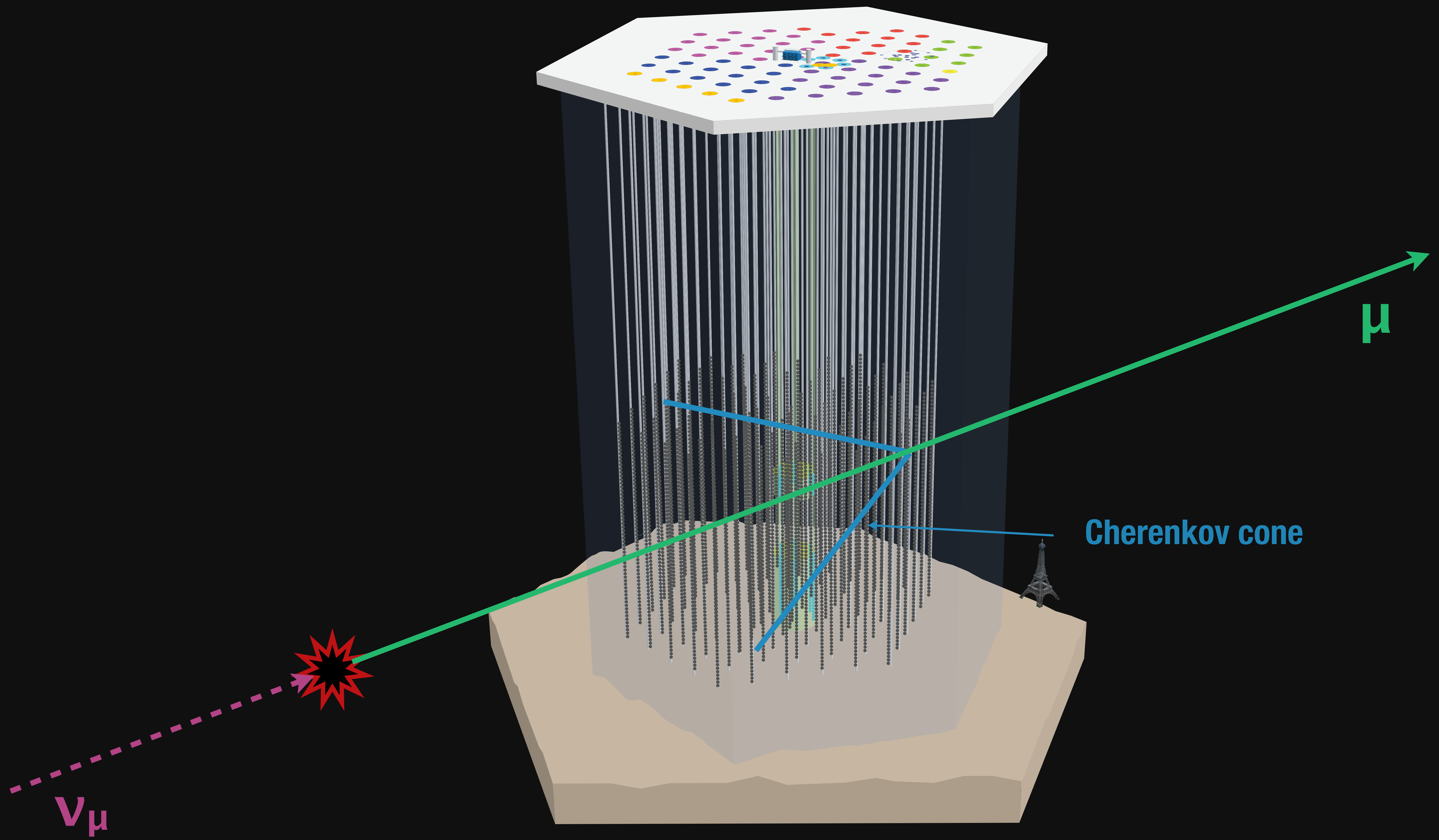
- **5160 DOMs (single-PMT)**
- **1 km^3 volume**
- **86 strings**
- **17 m PMT-PMT spacing per string**
- **125 m string spacing**
- **Completed 2010**



The IceCube Neutrino Observatory

The IceCube Neutrino Observatory

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



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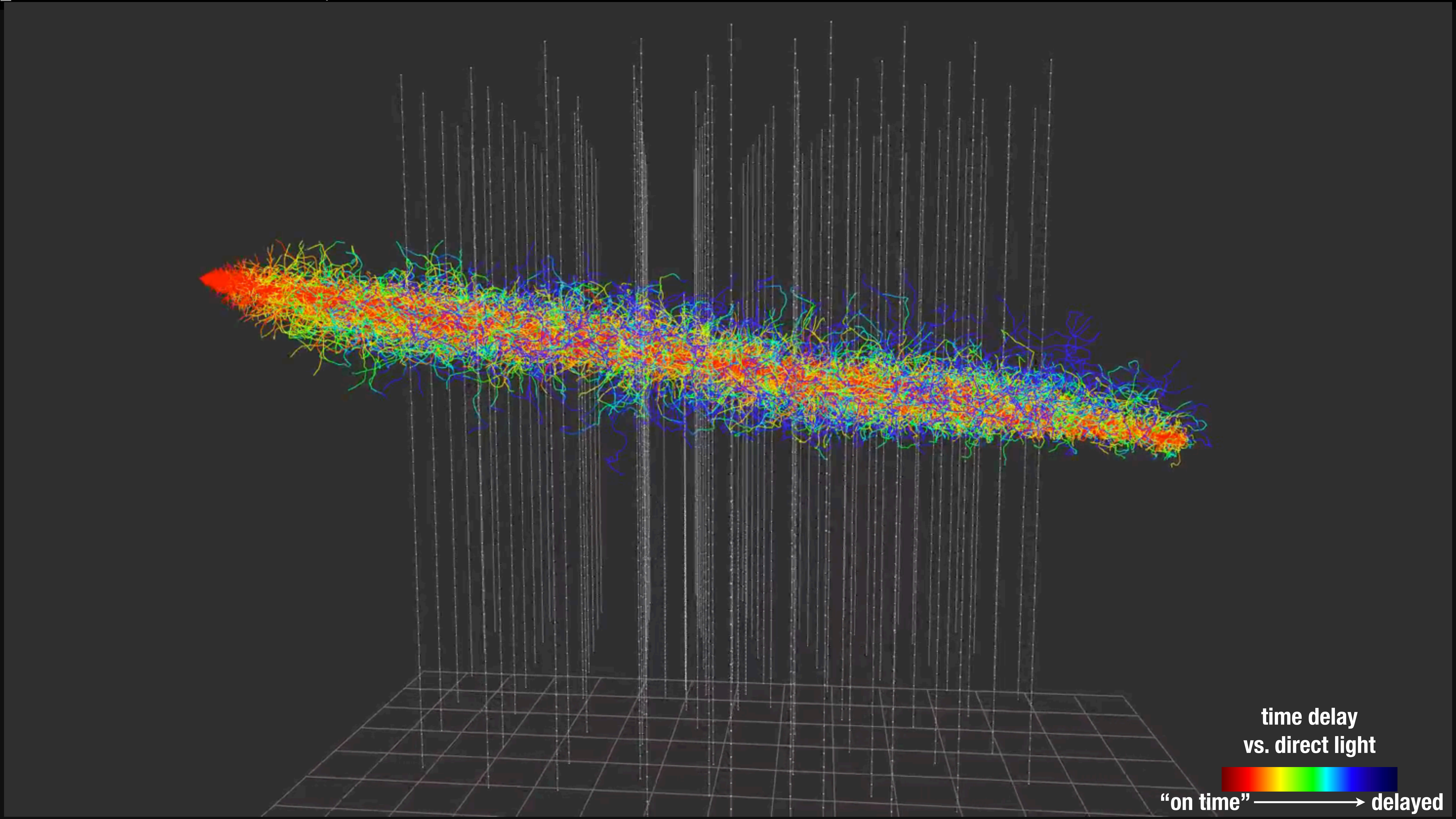
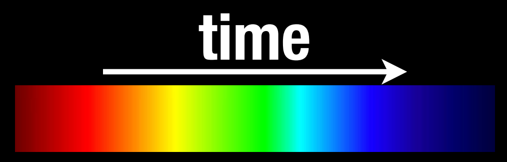
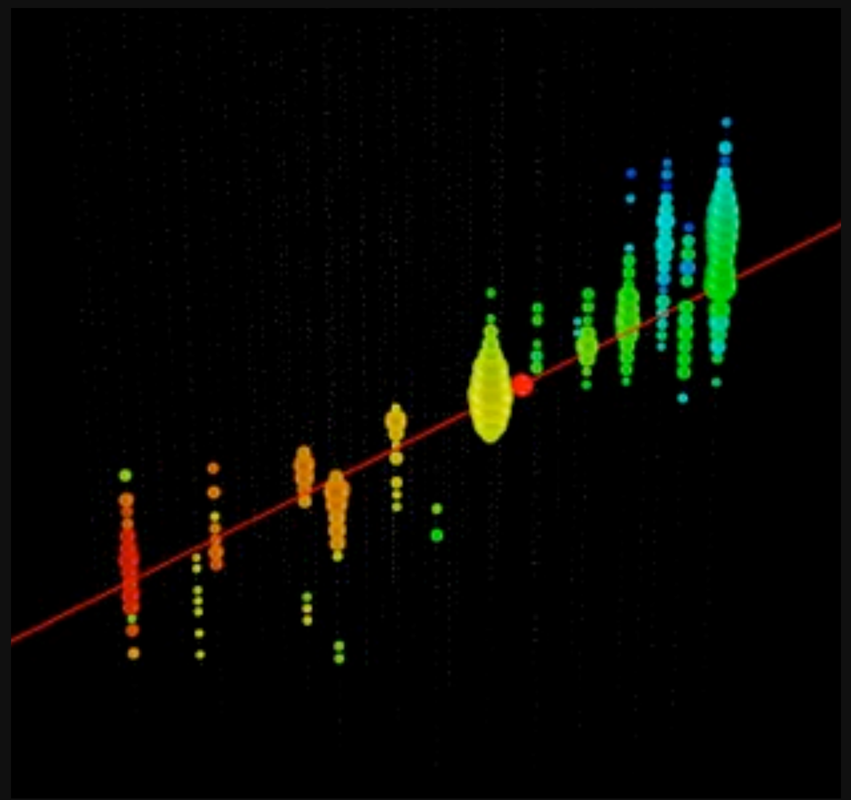


Neutrino Event Signatures

Signatures of signal events



CC Muon Neutrino

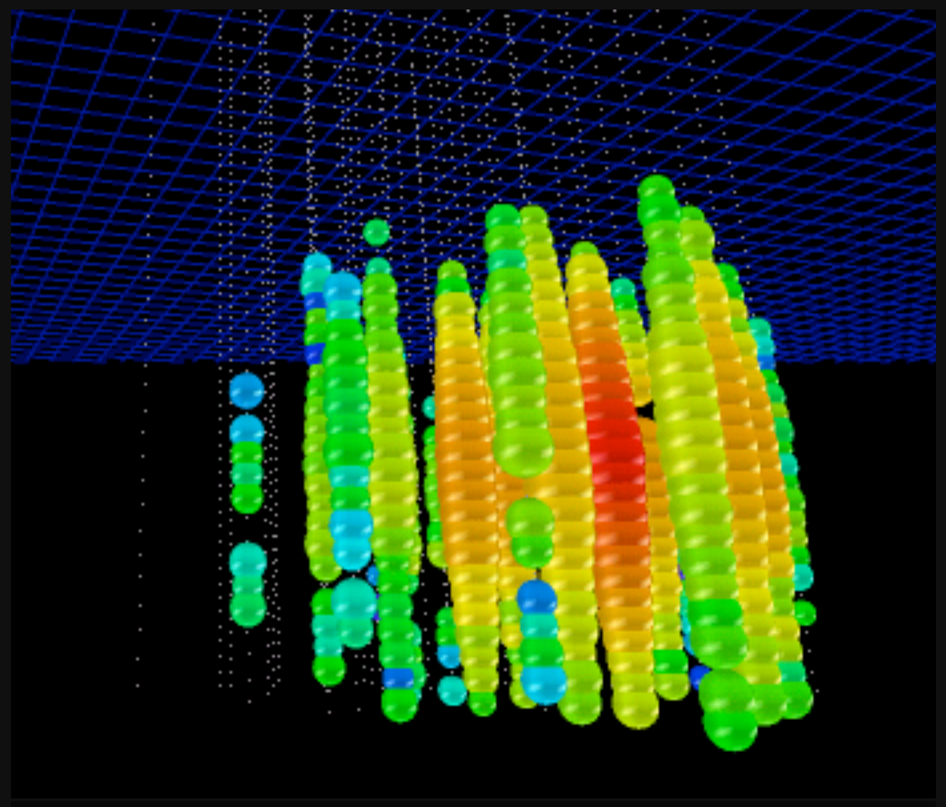


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
$< 1°$ angular resolution

Neutral Current /Electron Neutrino



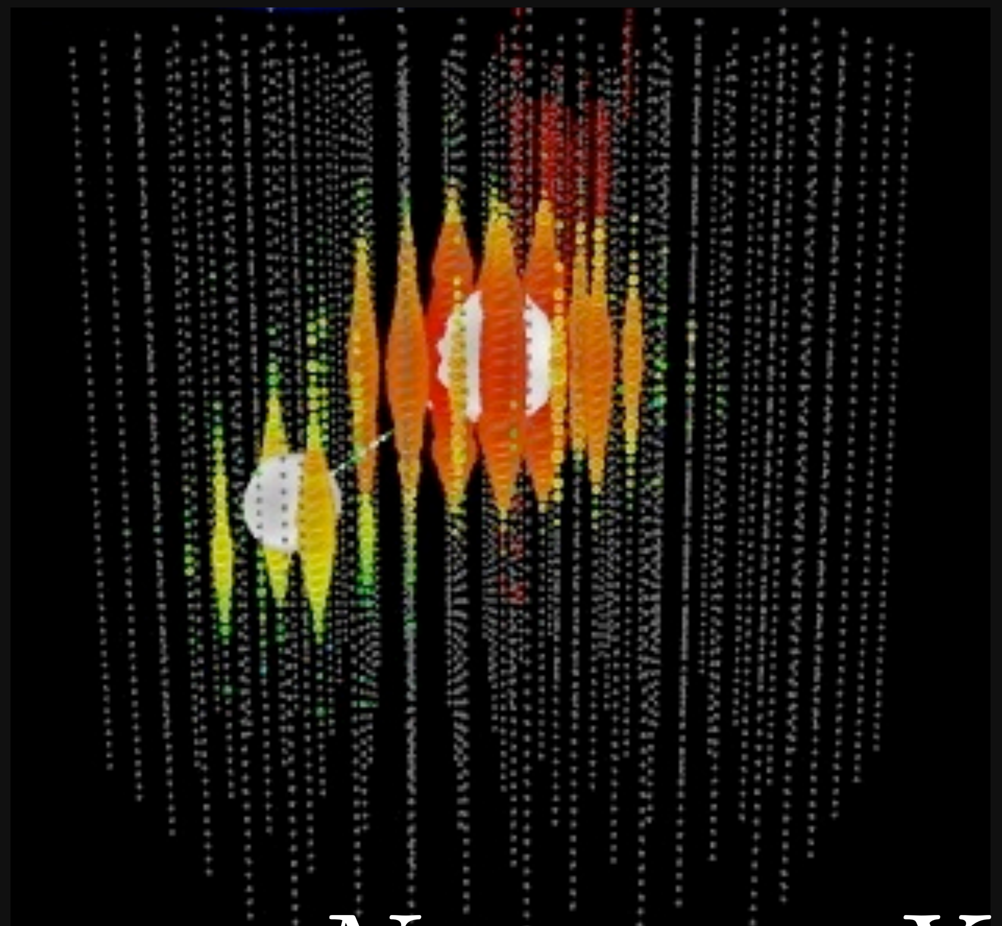
$$\nu_\mathrm{e} + N \rightarrow \mathrm{e} + X$$

$$\nu_\mathrm{x} + N \rightarrow \nu_\mathrm{x} + X$$

cascade (data)

$\approx \pm 15\%$ deposited energy resolution
$\approx 10°$ angular resolution
(at energies $\gtrapprox 100$ TeV)

CC Tau Neutrino



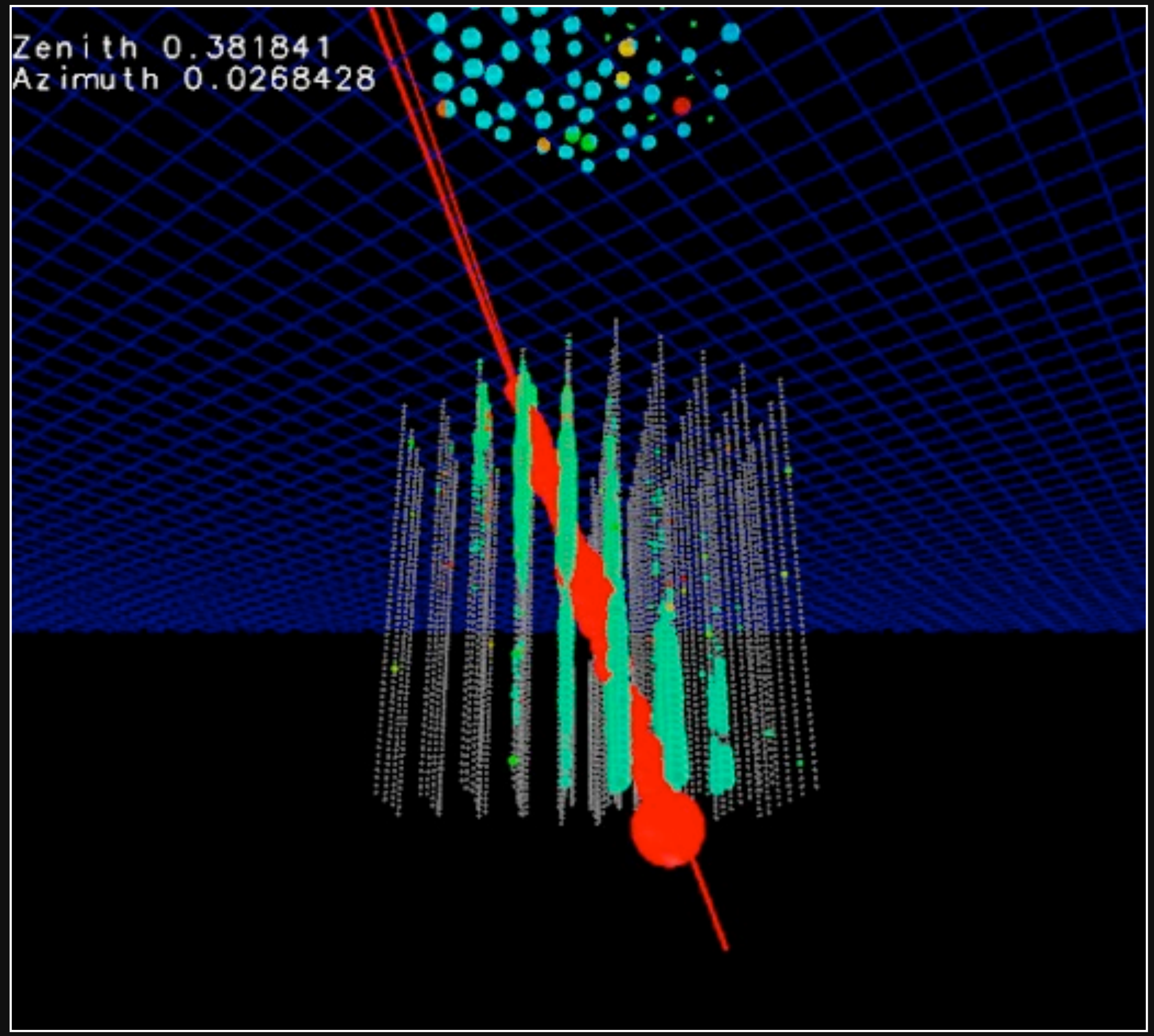
$$\nu_\tau + N \rightarrow \tau + X$$

"double-bang" and other signatures
(simulation)

(not observed yet)

Backgrounds and Systematics

- **Backgrounds:**
  - Cosmic Ray Muons
  - Atmospheric Neutrinos
- **Largest Uncertainties:**
  - Optical Properties of Ice
  - Energy Scale Calibration
  - Neutral current / ν_e degeneracy



A bundle of muons from a CR interaction in the atmosphere
(also observed in the "IceTop" surface array)

Studying Neutrinos

Many possible analyses!

- **High-energy:**
  - Point-source searches looking for clustering in the sky
  - Diffuse fluxes above the atmospheric neutrino background
  - Gamma-ray bursts searches (many models excluded by IceCube: Nature 484 (2012))
  - Ultra-high energy “GZK” neutrinos from proton interactions on the CMB
- **Low energy:**
  - Neutrino oscillations with IceCube and ANTARES
- **Others:**
  - Dark Matter / WIMPs, ...

The High-Energy Tail

Searching for a signal above the atmospheric neutrino background

Signals and Backgrounds

Signal

- Dominated by showers (~80% per volume) from oscillations
- High energy (benchmark spectrum is typically E^{-2})
- Mostly in the Southern Sky due to absorption of high-energy neutrinos in the Earth

Background

- Track-like events from Cosmic Ray muons and atmospheric ν_μ
- Soft spectrum ($E^{-3.7}$ - $E^{-2.7}$)
- Muons in the Southern Sky, neutrinos in from the North

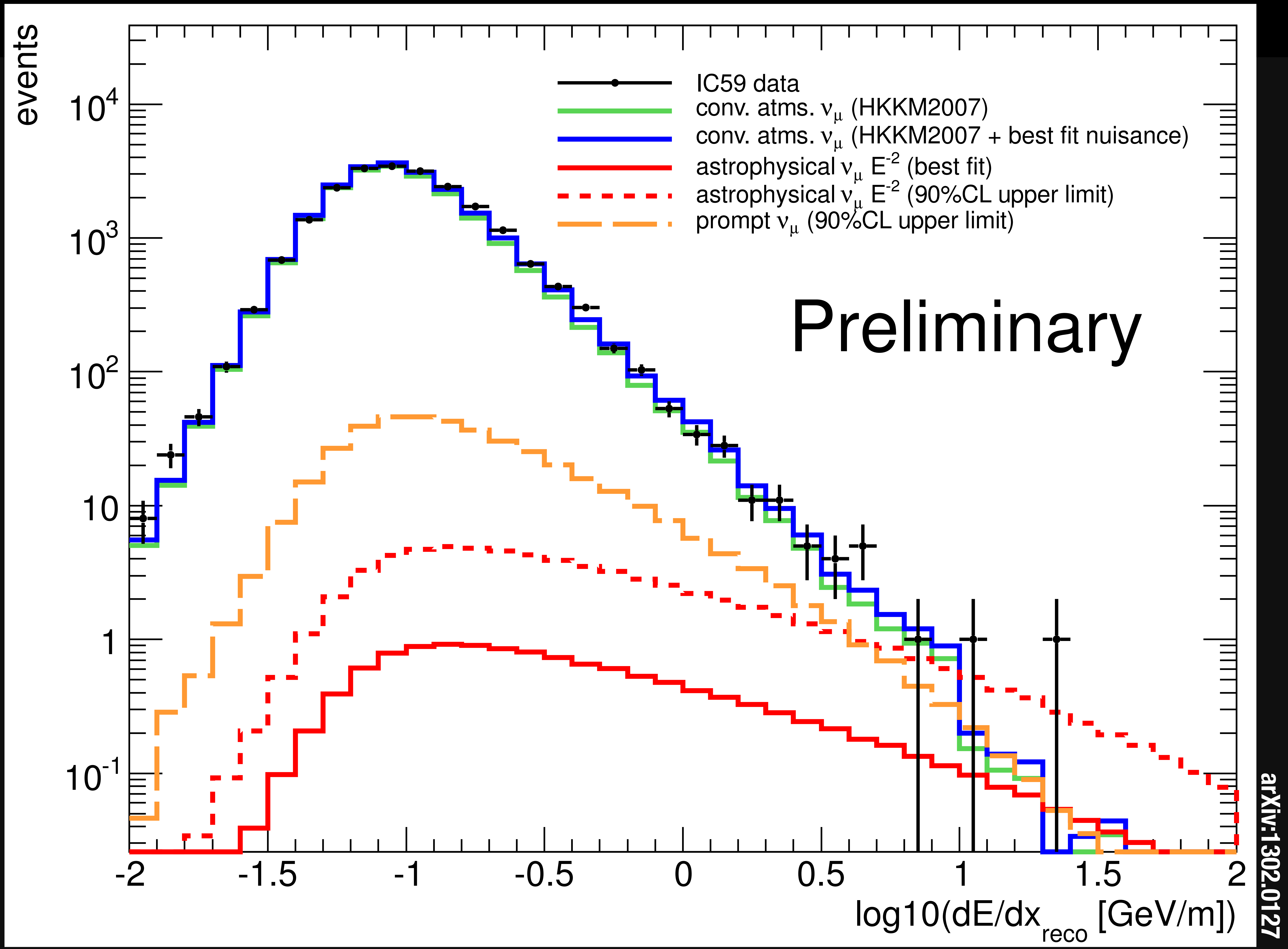
Observables

Different observables probe different properties

- **Spectral slope**
  - separate extraterrestrial flux from atmospheric, accelerator properties
- **Position of possible cutoff in energy**
  - accelerator properties, maybe different population of sources above/below CR knee?
- **Flavor composition**
  - physics of production process, discrimination against backgrounds
- **Zenith distribution**
  - comparison to backgrounds
- **Full arrival direction**
  - source locations once significant clustering is observed (skymap!)

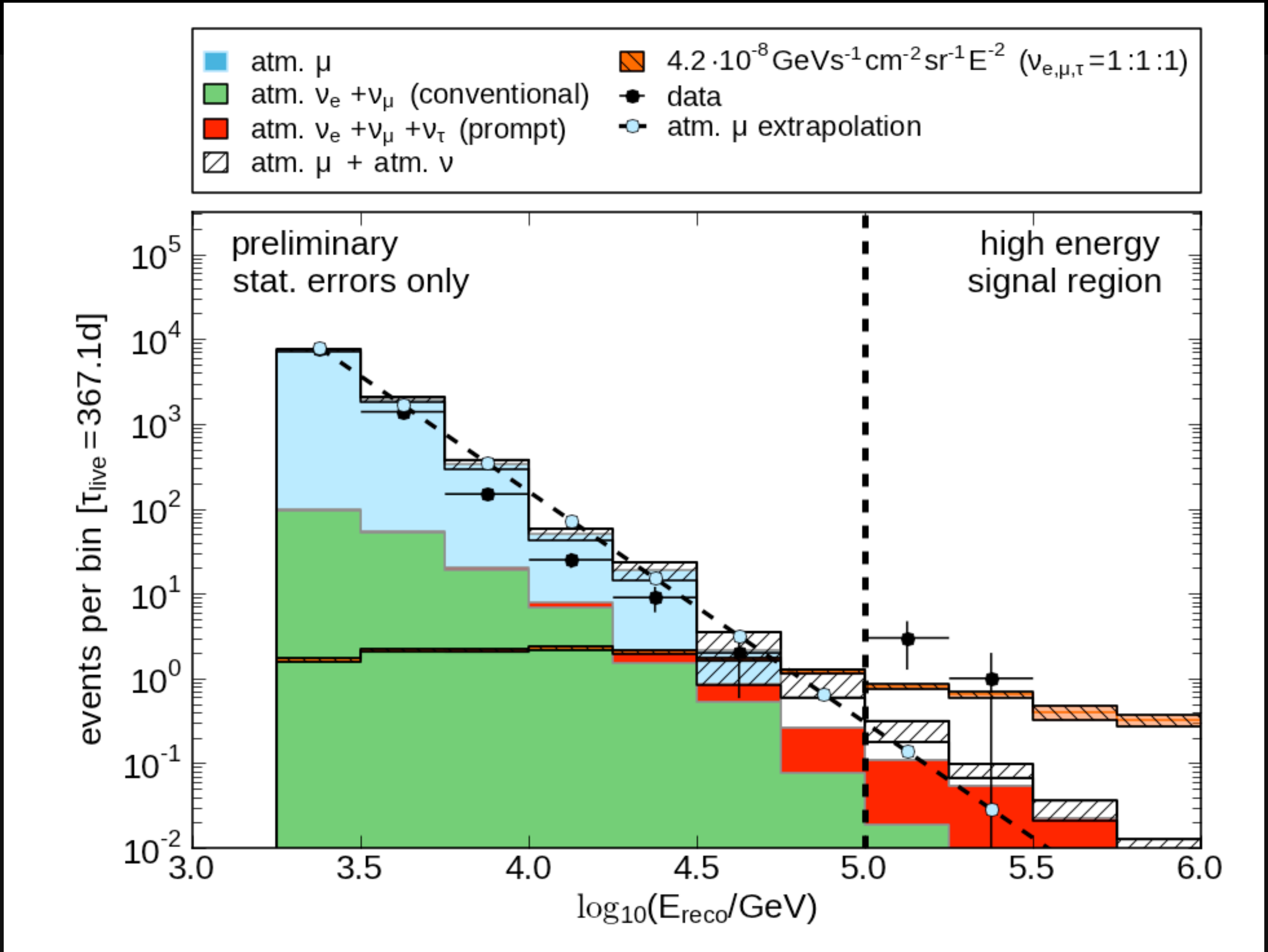
Hint in upgoing muons

Study using the "IC59" partial detector during construction: 1.8σ



Another Hint in Shower

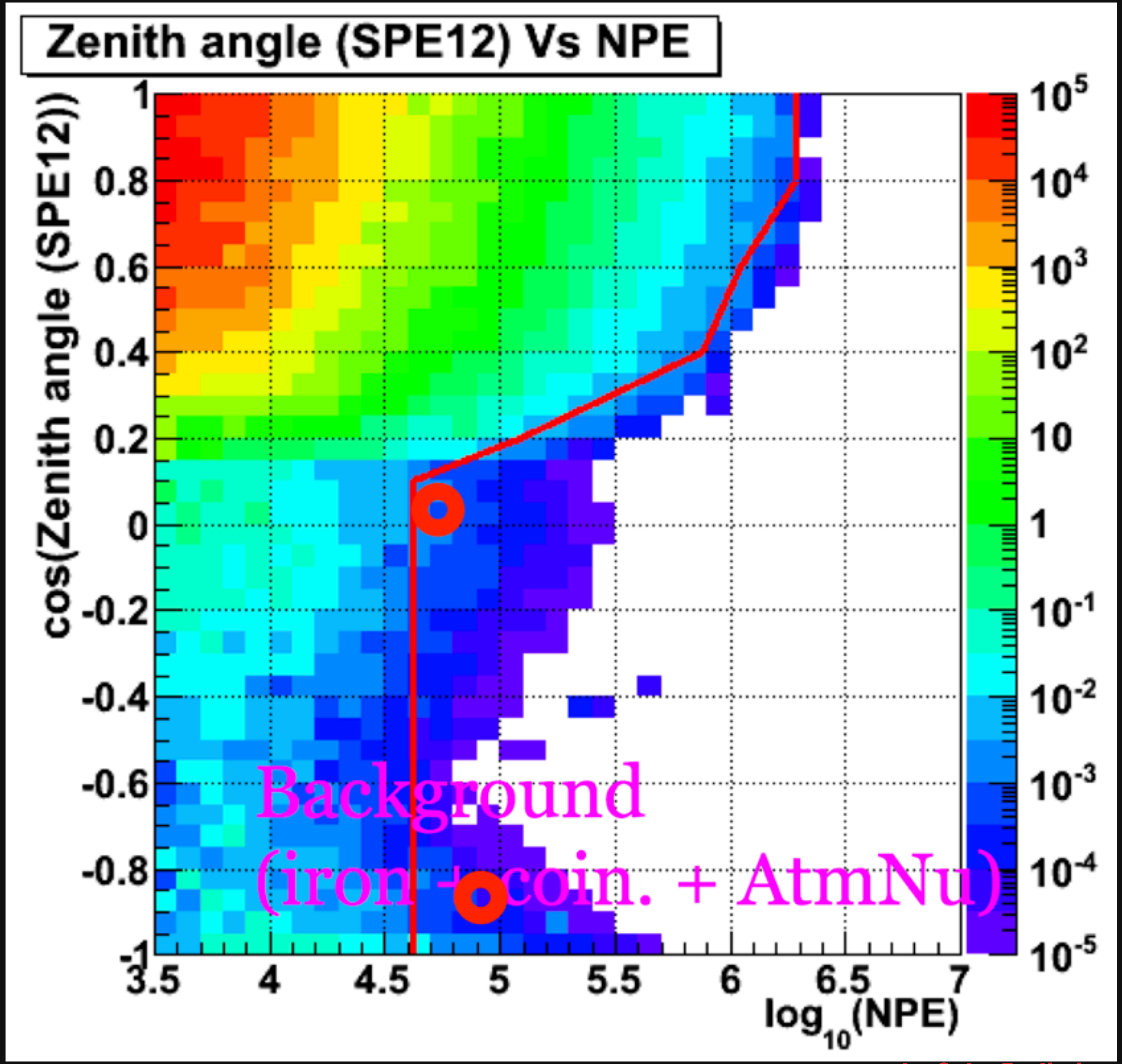
Study using the "IC40" partial detector during construction: 2.4σ



GZK Neutrino Analysis

Simple search to look for extremely high energies (10^9 GeV) neutrinos from proton interactions on the CMB

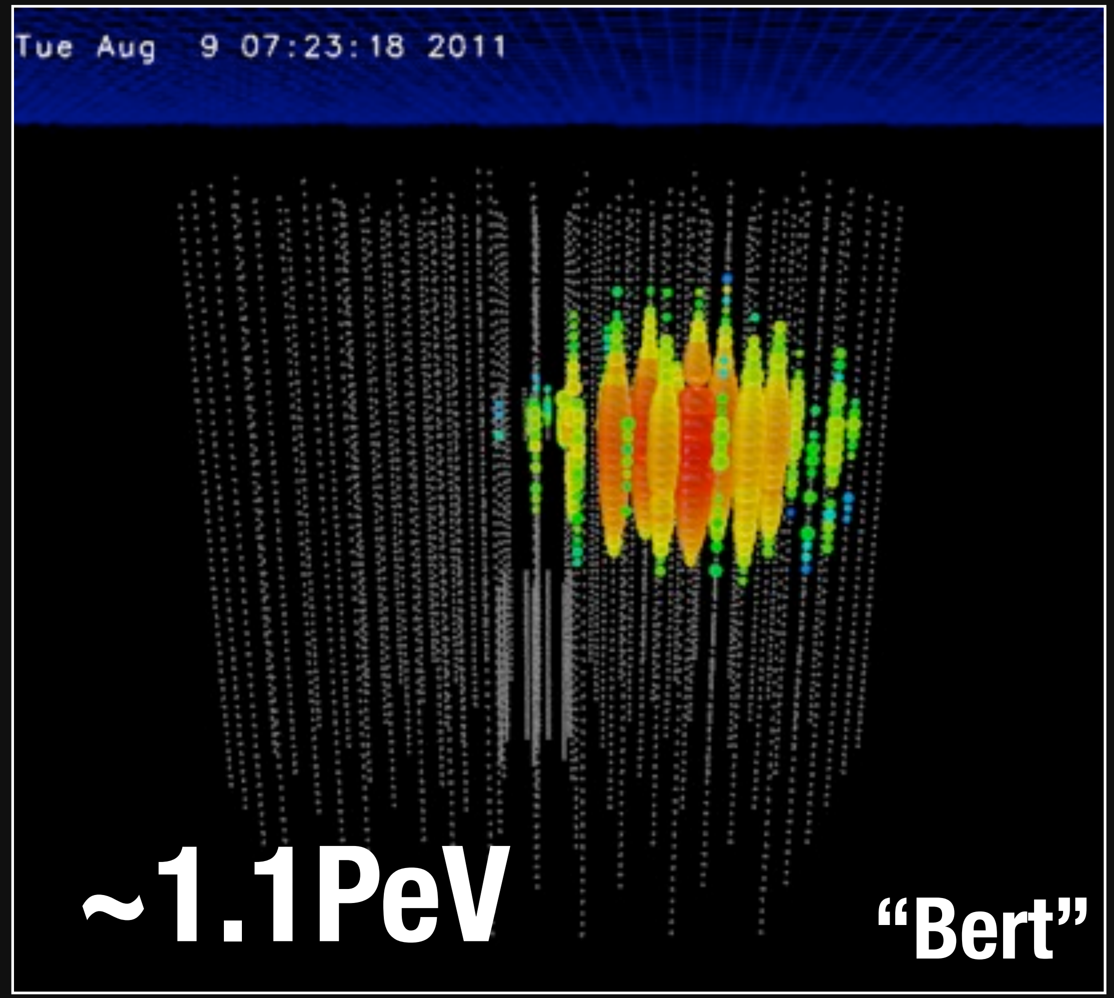
- **Upgoing muons**
  - Always neutrinos
  - Background: atm. neutrinos
  - High threshold (1 PeV)
- **Downgoing muons (VHE)**
  - Cosmic Ray muon background
  - Very high threshold (100 PeV)

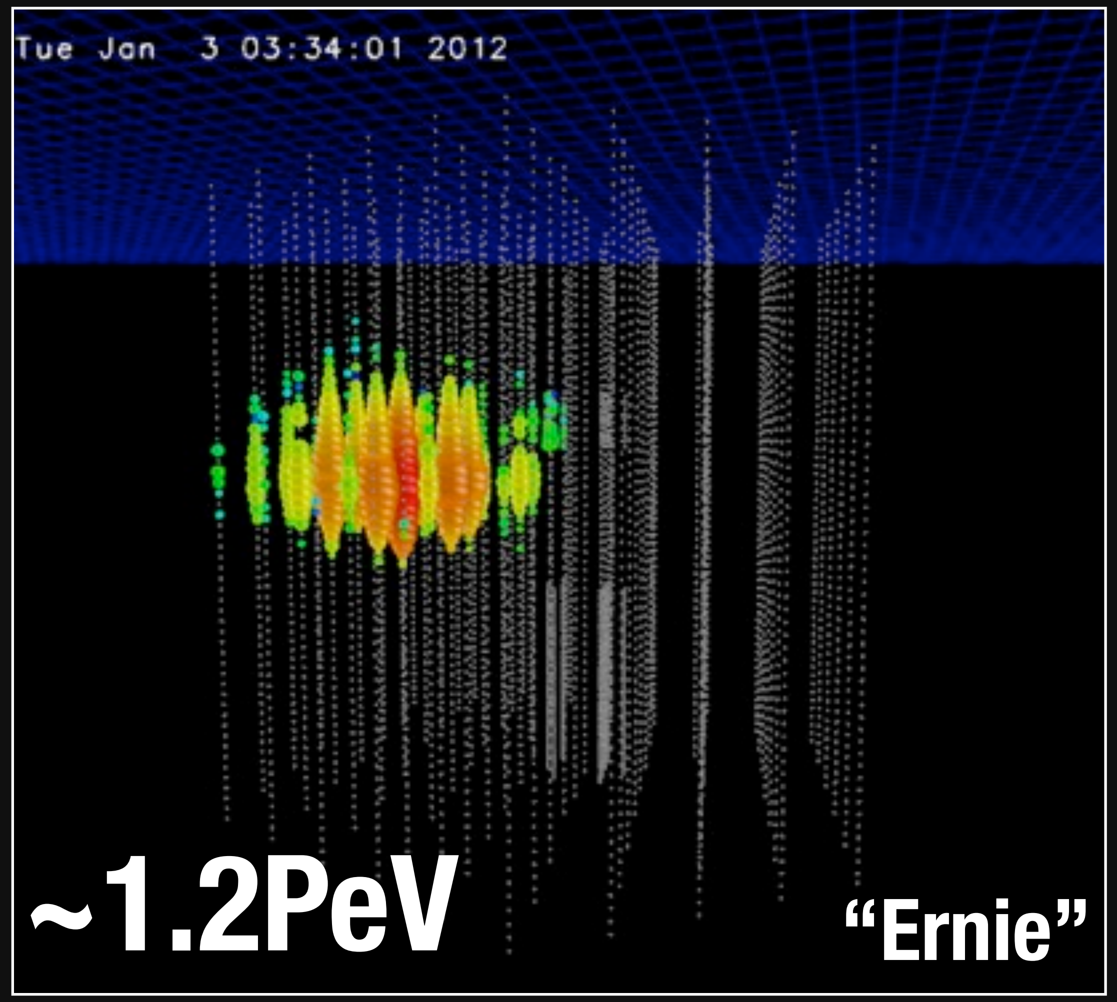


Results

Appearance of ~1 PeV cascades as an at-threshold background

- **Two very interesting events in IceCube (between May 2010 and May 2012)**
  - shown at Neutrino '12
  - 2.8σ excess over expected background in GZK analysis
  - paper published in PRL 111 (2013) 021103
- **There should be more**
  - GZK analysis is only sensitive to very specific event topologies at these energies





Things We Know

- At least two PeV neutrinos in a 2-year dataset
- Events are downgoing
- Seems not to be GZK (too low in energy)
- Higher than expected for atmospheric background
- Spectrum seems not to extend to much higher energies
  - unbroken E^{-2} would have made 8-9 more above 1 PeV

Things We Wanted to Learn

- Isolated events or tail of spectrum?
- Spectral slope/cutoff
- Flavor composition
- Where do they come from?
- Astrophysical or air shower physics (e.g. charm)?
- Need more statistics to answer all of these!

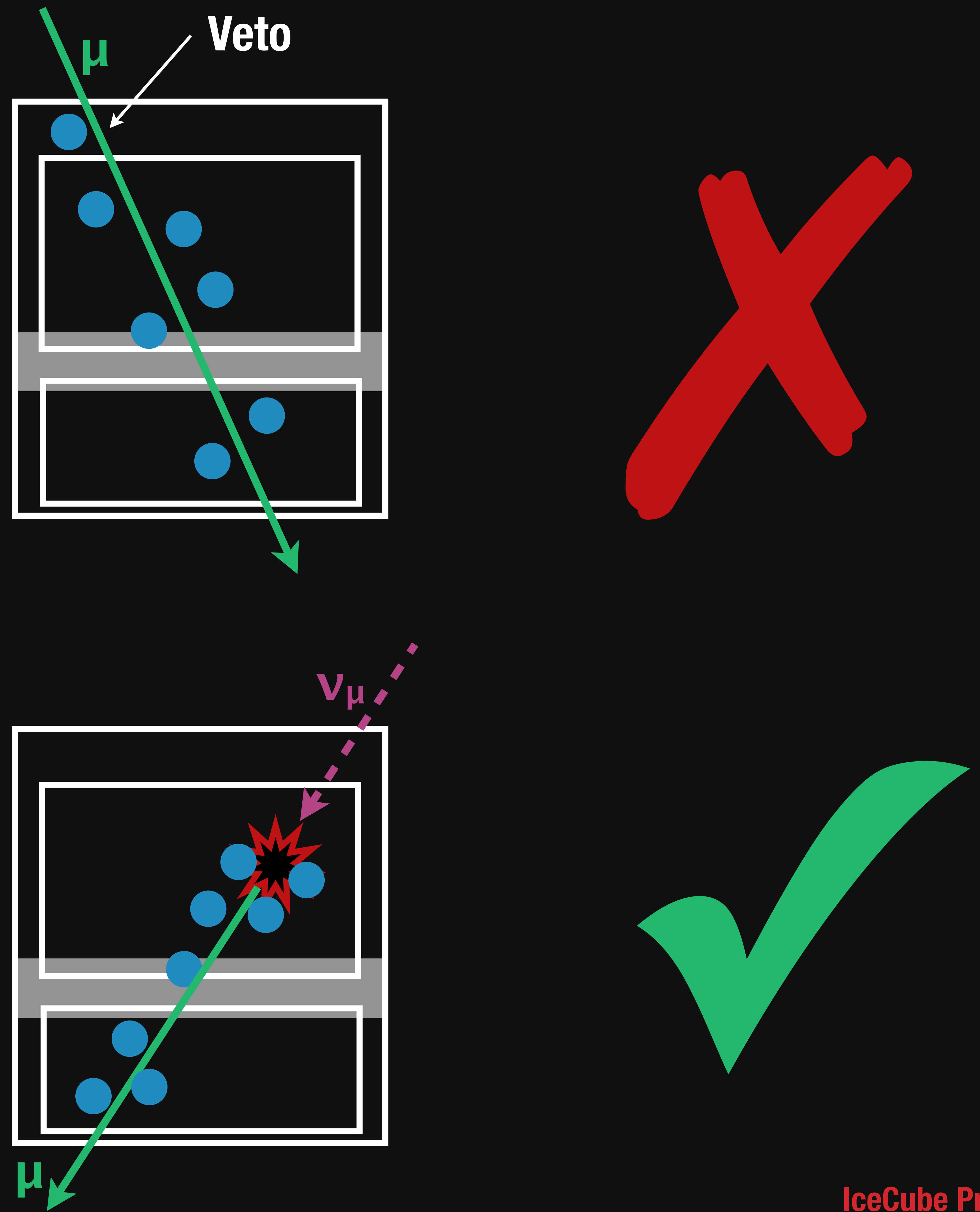
High-Energy Contained Vertex Search

How we found more...

Follow-up Analysis

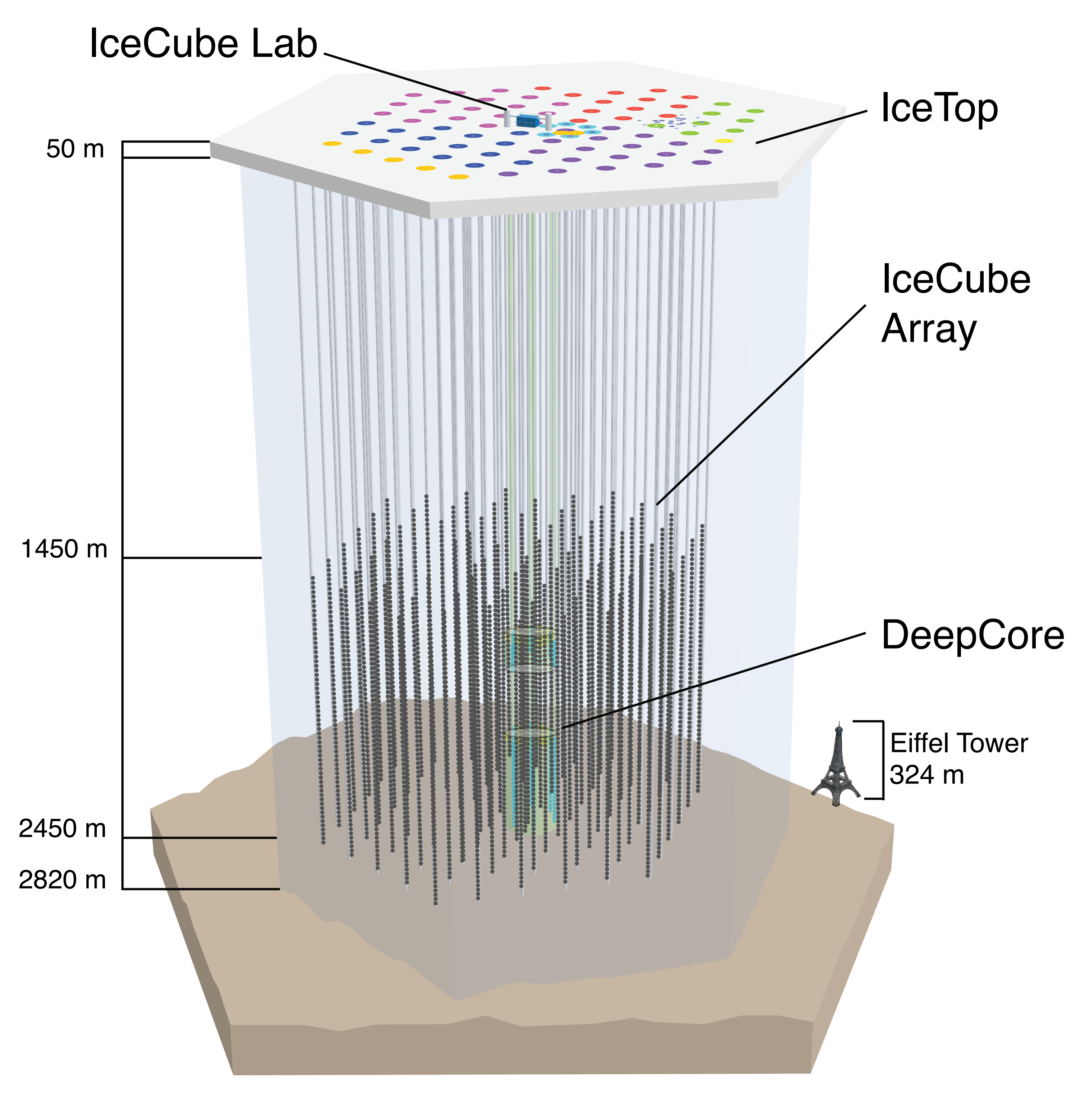
Specifically designed to find these contained events
Analysis of dataset taken from May 2010 to May 2012 (662 days of livetime)

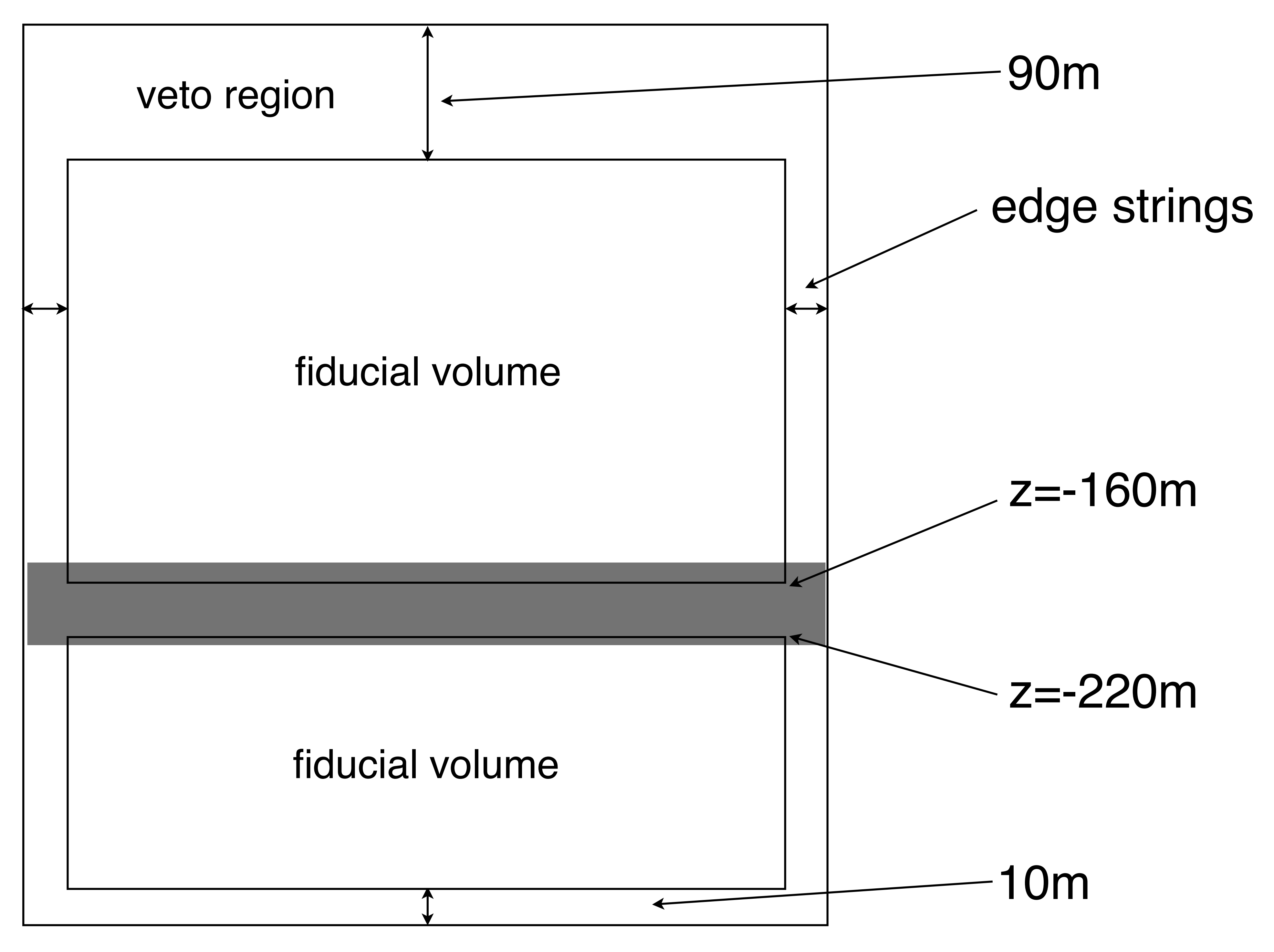
- **Explicit contained search at high energies (cut: Q_{tot}>6000)**
- **400 Mton effective fiducial mass**
- **Use atmospheric muon veto**
- **Sensitive to all flavors in region above 60TeV**
- **Three times as sensitive at 1 PeV**
- **Estimate background from data**



Background 1 - Atmospheric Muons

Mostly incoming atmospheric muons sneaking in through the main dust layer



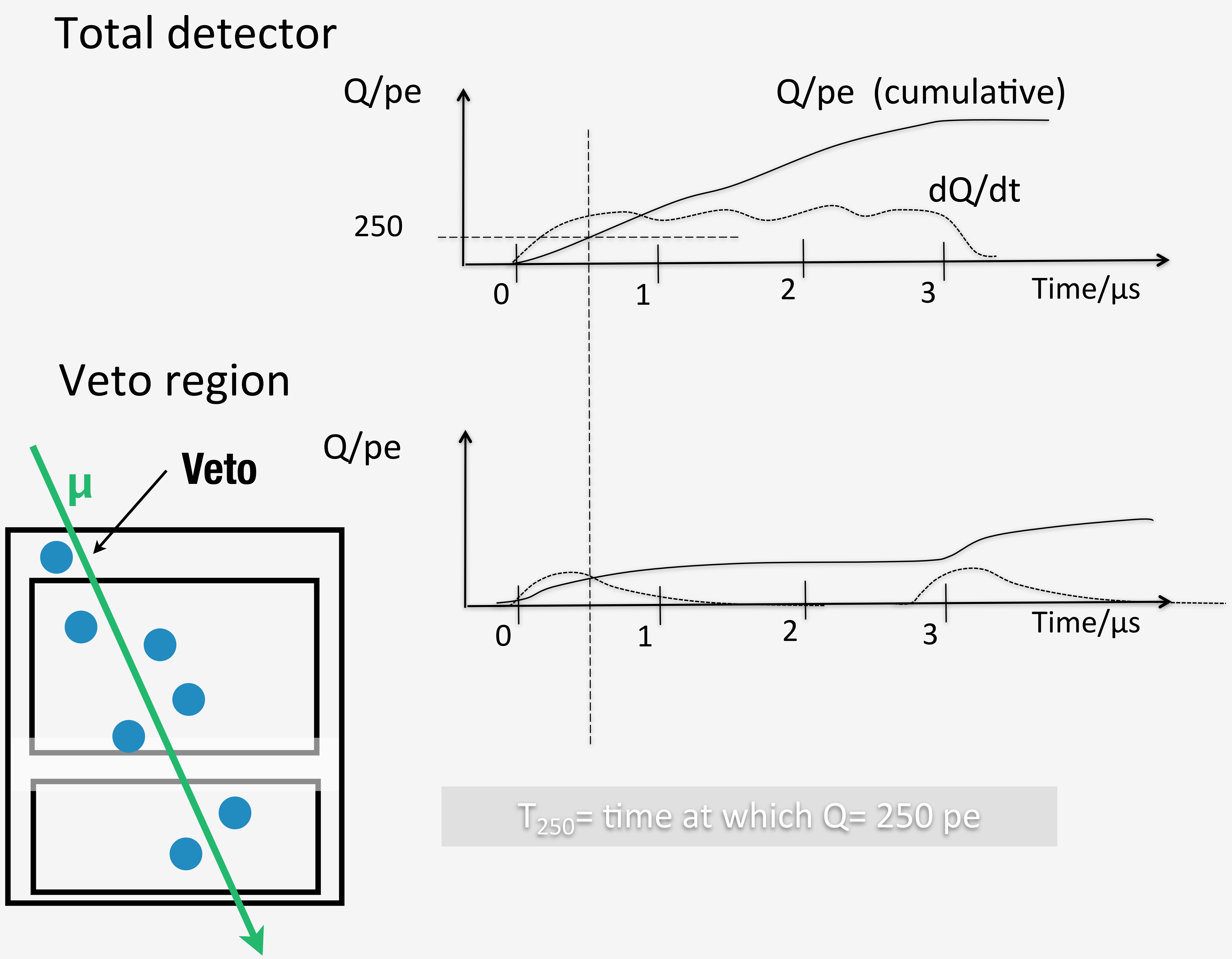


- Reject incoming muons when “early charge” in veto region
- Control sample available: tag muons with part of the detector - known bkg.
- 6±3.4 muons per 2 years (662 days)

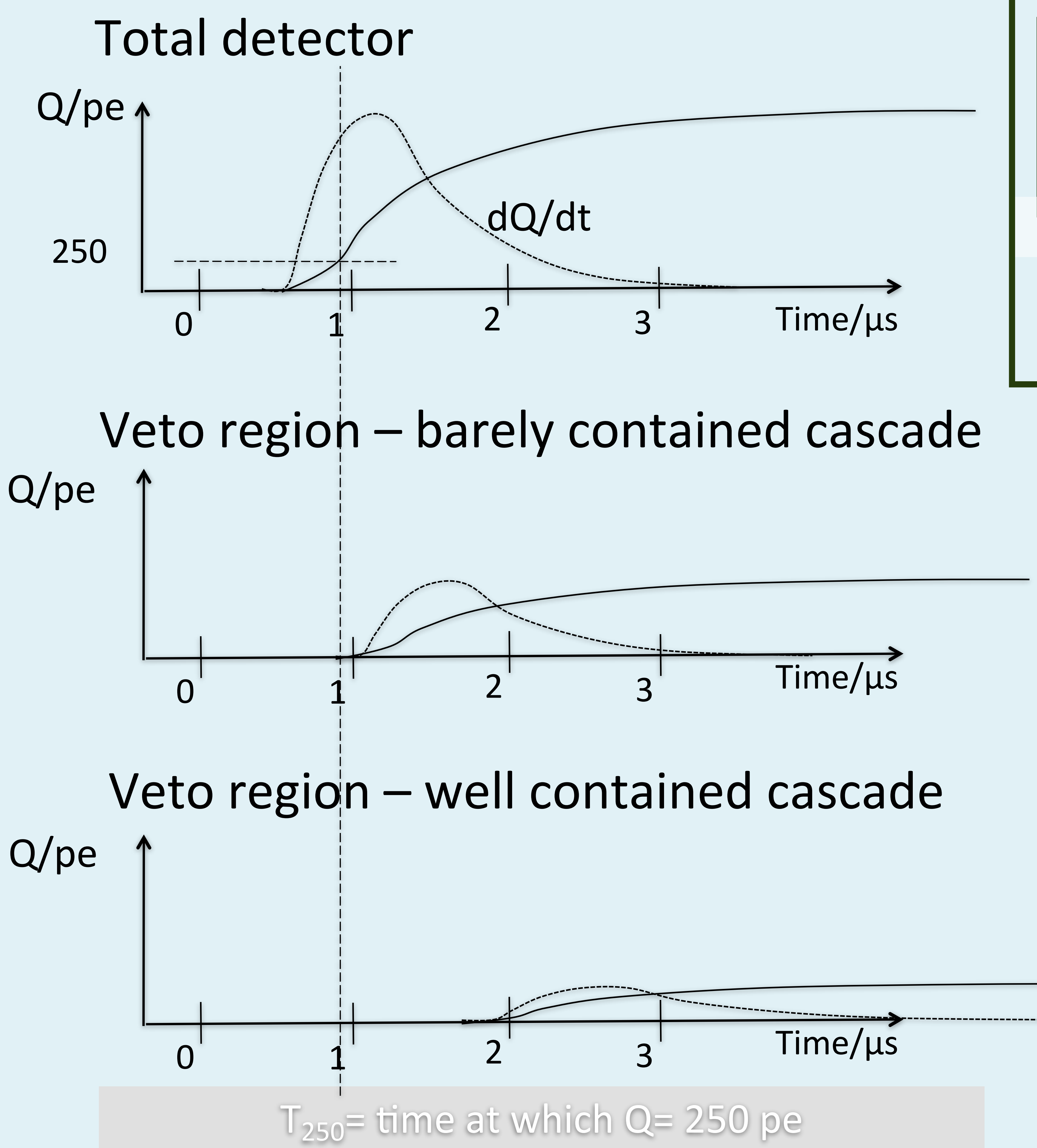
Background 1 - Atmospheric Muons

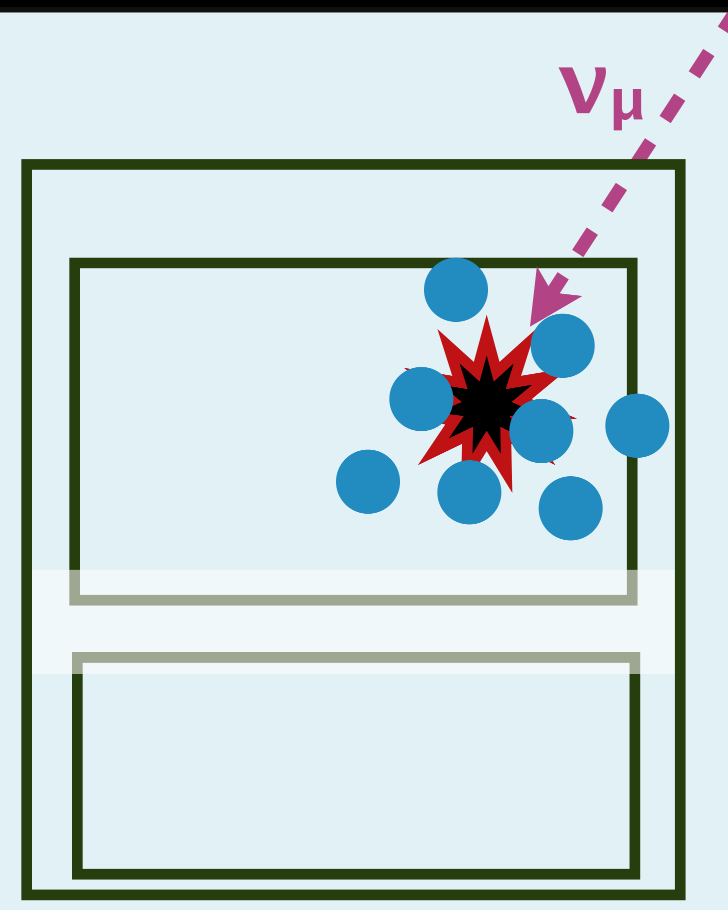
What's "early charge"?

Throughgoing muon



Contained cascade



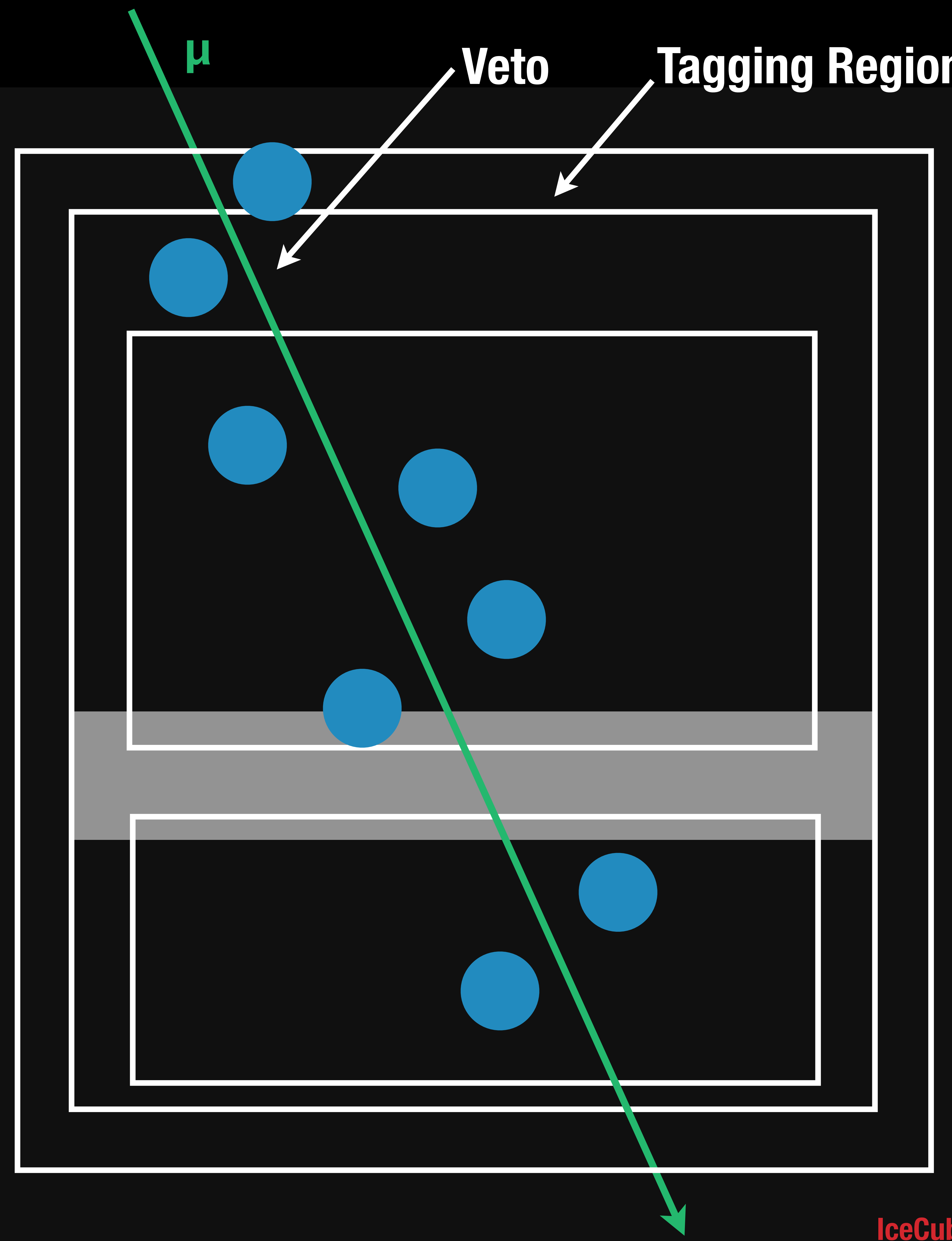


IceCube Preliminary

Estimating Muon Background From Data

Use known background from atmospheric muons tagged in an outer layer to estimate the veto efficiency

- Add one layer of DOMs on the outside to tag known background events
  - Then use these events to evaluate the veto efficiency
- Avoids systematics from simulation assumptions/models!
- Can be validated at charges below our cut (6000 p.e.) where background dominates



IceCube Preliminary

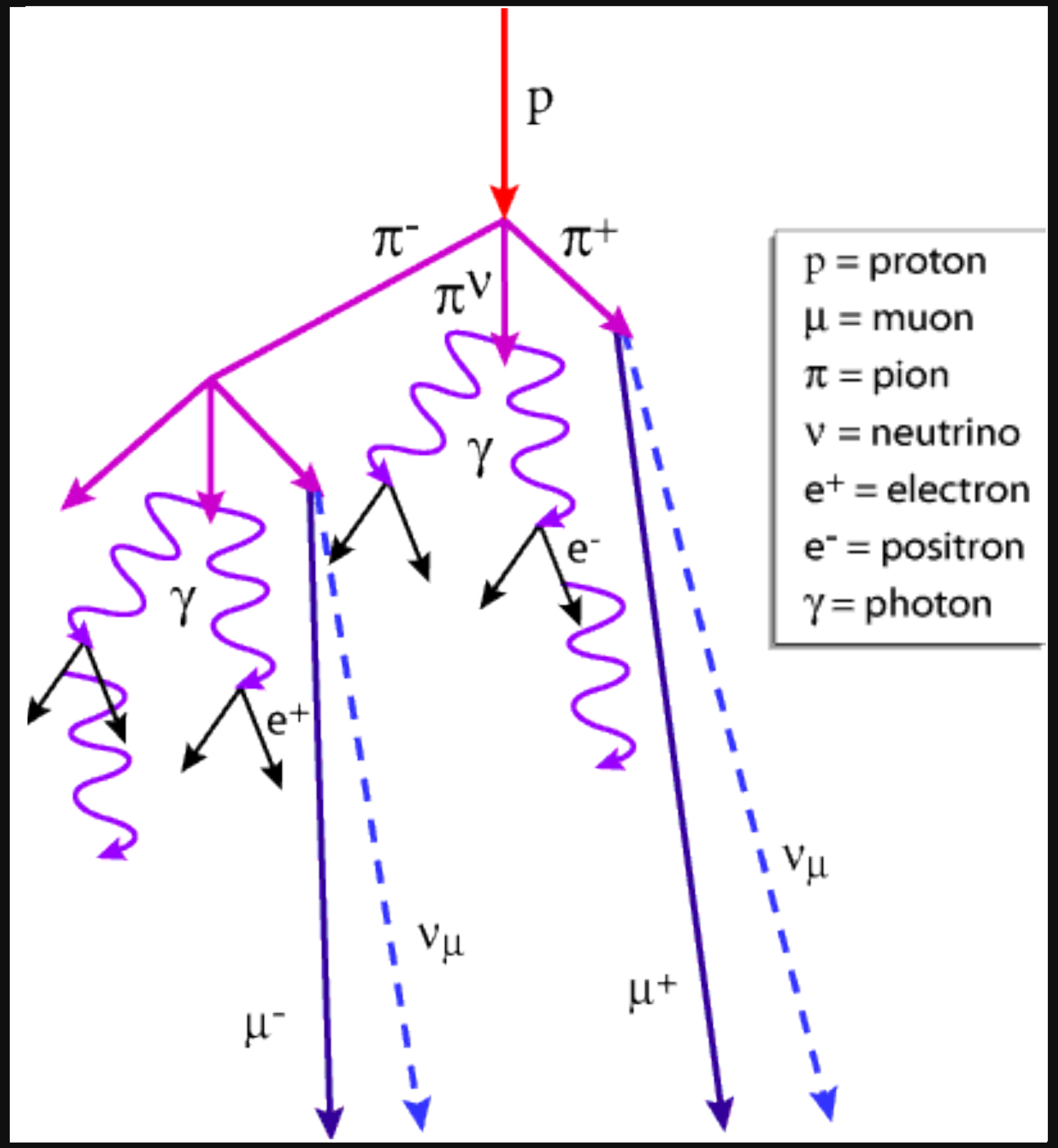
Background 2 - Atmospheric Neutrinos

Very low at PeV energies

- Typically separated by energy
- Very low at PeV energies (order of 0.1 events/year)
- Large uncertainties in spectrum at high energies
- $4.6^{+3.7}_{-1.2}$ events in two years (662 days)
- Rate accounts for events vetoed by accompanying muon from the same air shower in the Southern Sky
- Baseline model: Enberg et al. (updated with cosmic-ray Knee model)

Vetoing Atmospheric Neutrinos

- Atmospheric neutrinos are made in air showers
- For downgoing neutrinos, the muons will likely not have ranged out at IceCube
- Downgoing events that start in the detector are extremely unlikely to be atmospheric



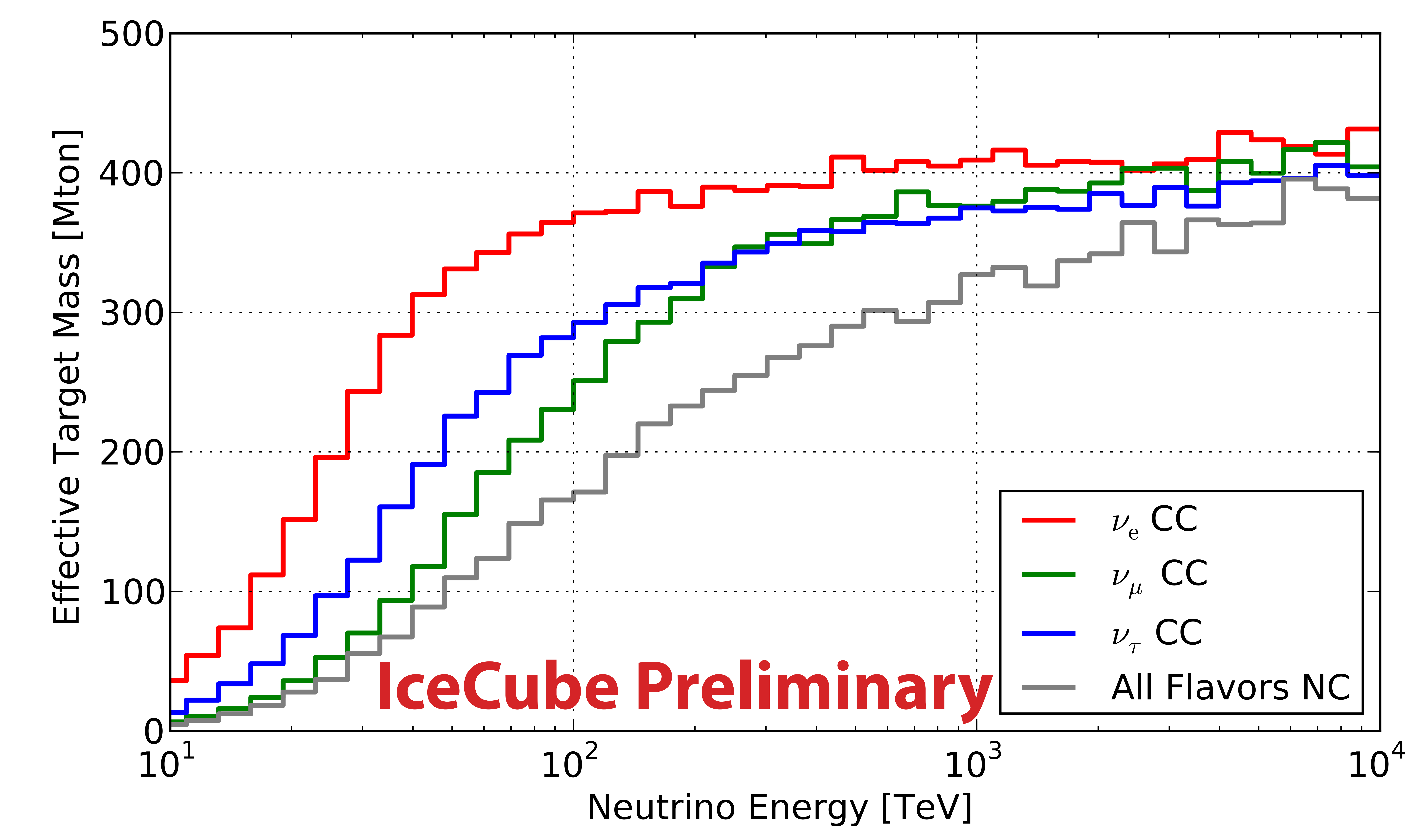
Schönert et al., arXiv:0812.4308

- Note: optimal use requires *minimal* overburden to have the highest possible rate of cosmic ray muons!

Effective Volume / Target Mass

Fully efficient above 100 TeV for CC electron neutrinos

About 400 Mton effective target mass



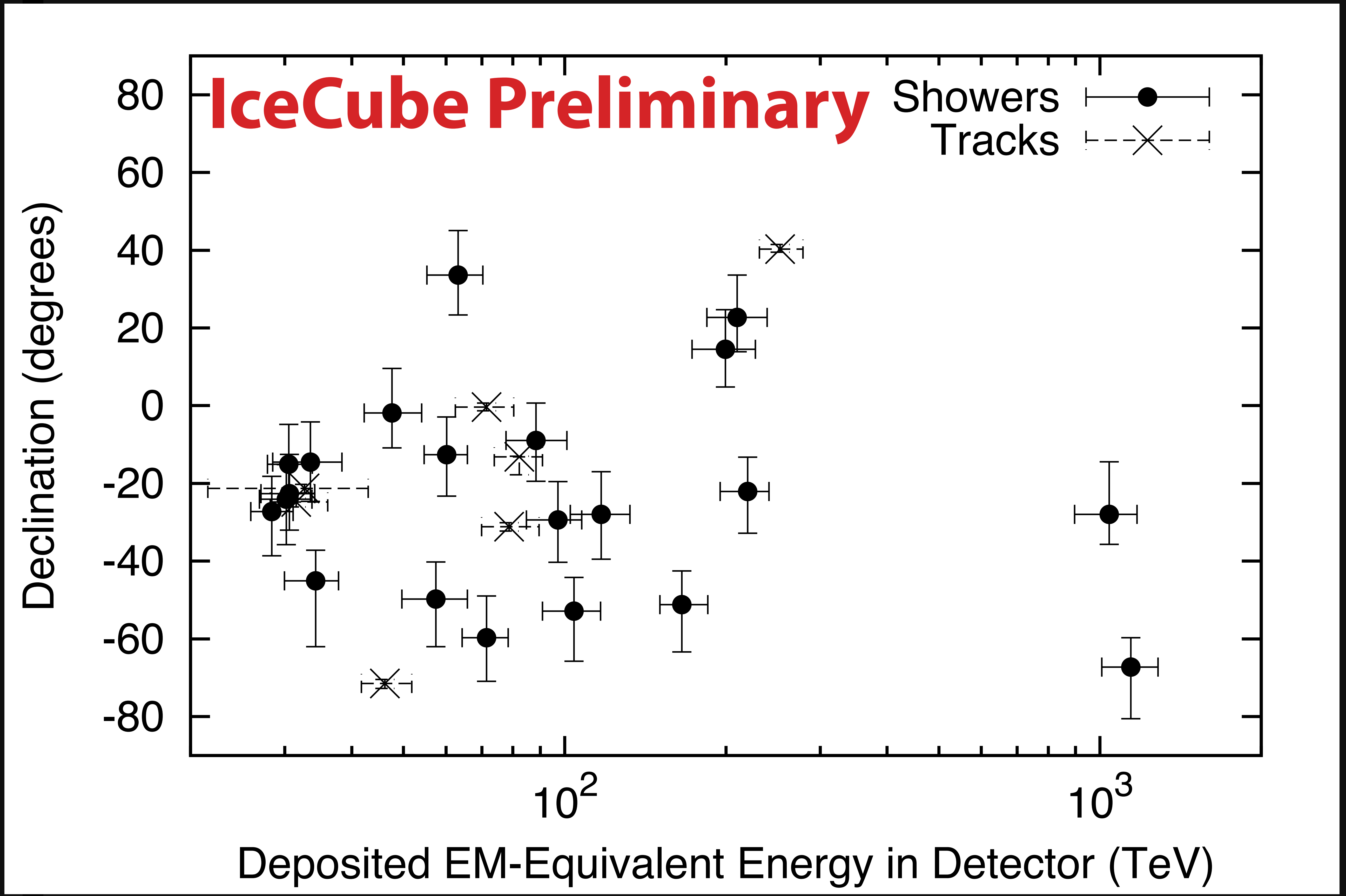
What Did We Find?

26 more events!

What Did We Find?

26 more events in the 2 years of IceCube data (2010/2011 season: "IC79"&"IC86")

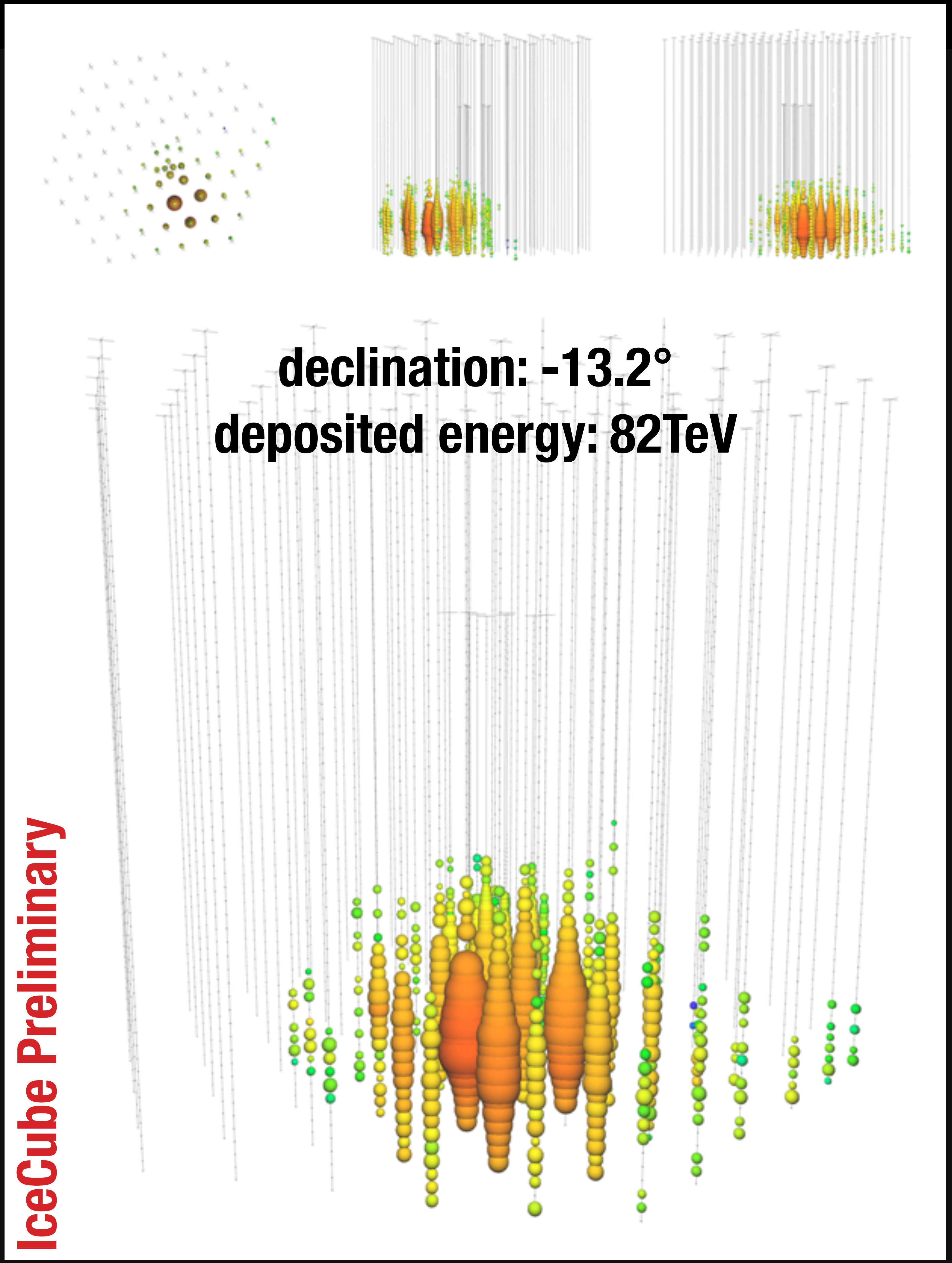
- **28 events observed!**
  - 26 new events in addition to the two 1 PeV events!
- **Track events (x) can have much higher neutrino energies than deposited energies**
  - also true on a smaller scale for shower events for all signatures except charged-current ν_e
- **Background: $10.6^{+5.0}_{-3.6}$**
  - (or 12.1±3.4 for reference neutrino background model)

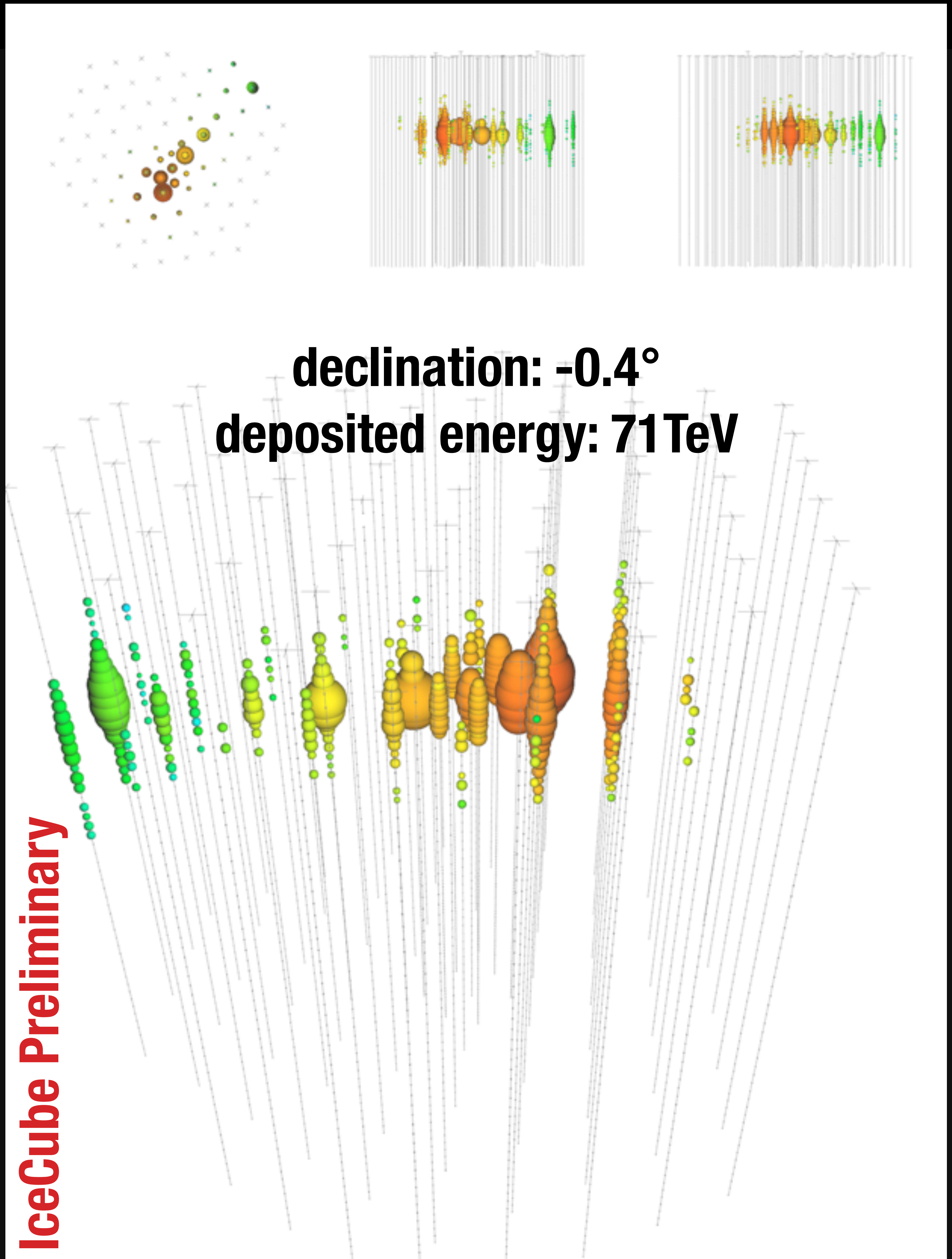


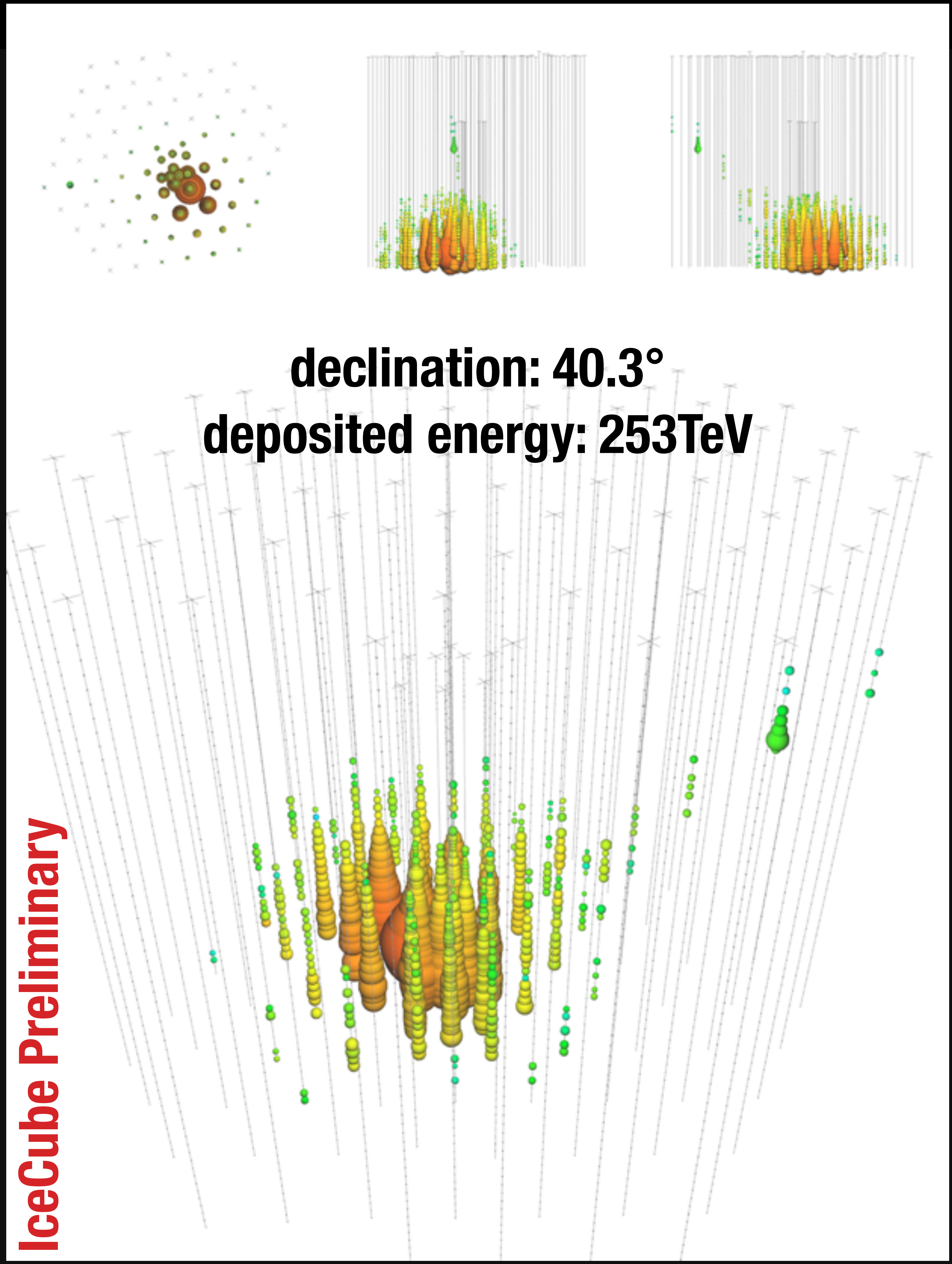
(preliminary significance w.r.t. reference bkg. model: 3.3σ for 26 events; 4.1σ for 28 events)

What Did We Find?

Some examples



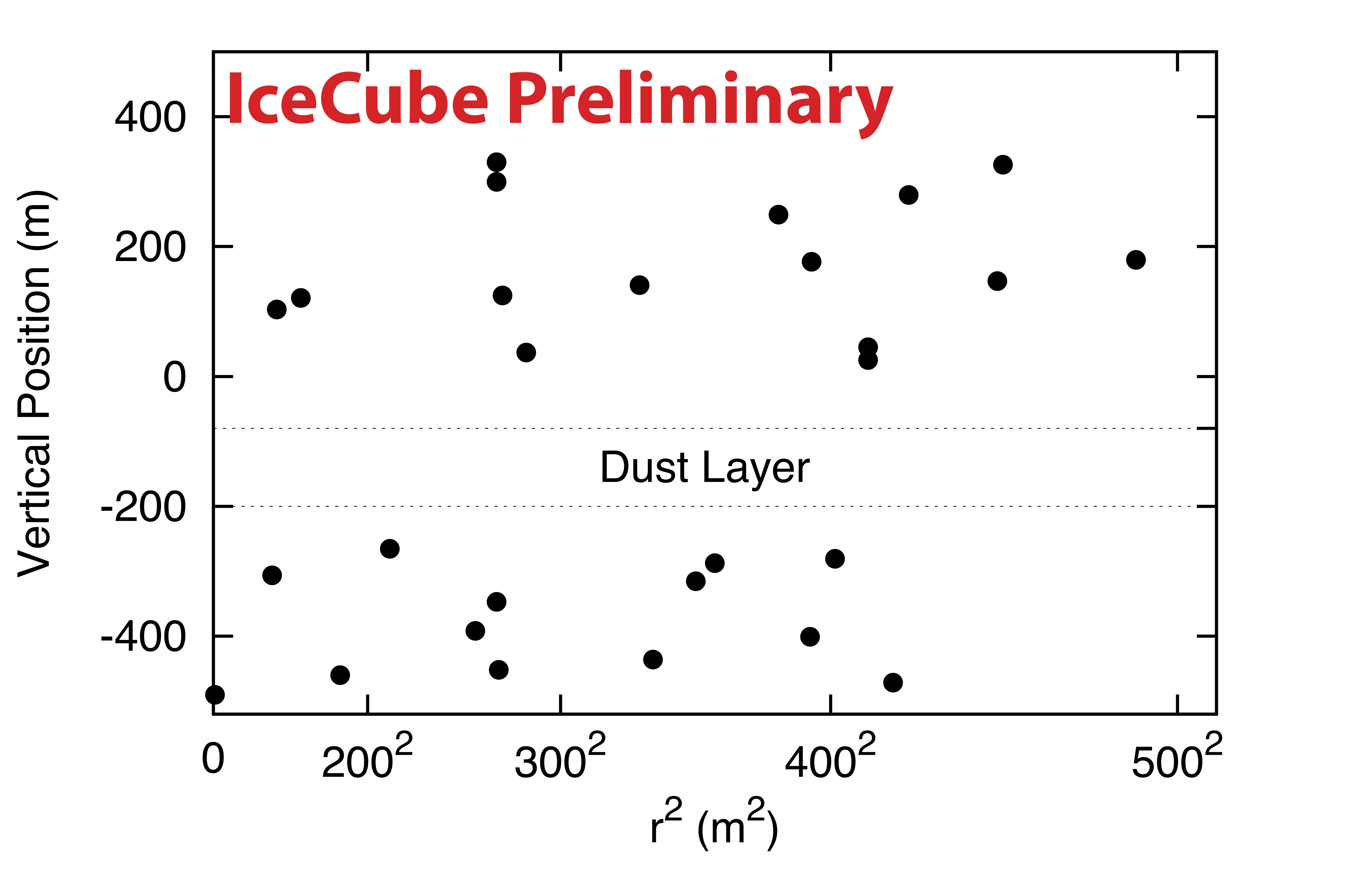




Event Distribution in Detector

Uniform in fiducial volume

- Backgrounds from atm. muons would pile up preferentially at the detector boundary
- No such effect is observed!



Systematic Studies and Cross-Checks

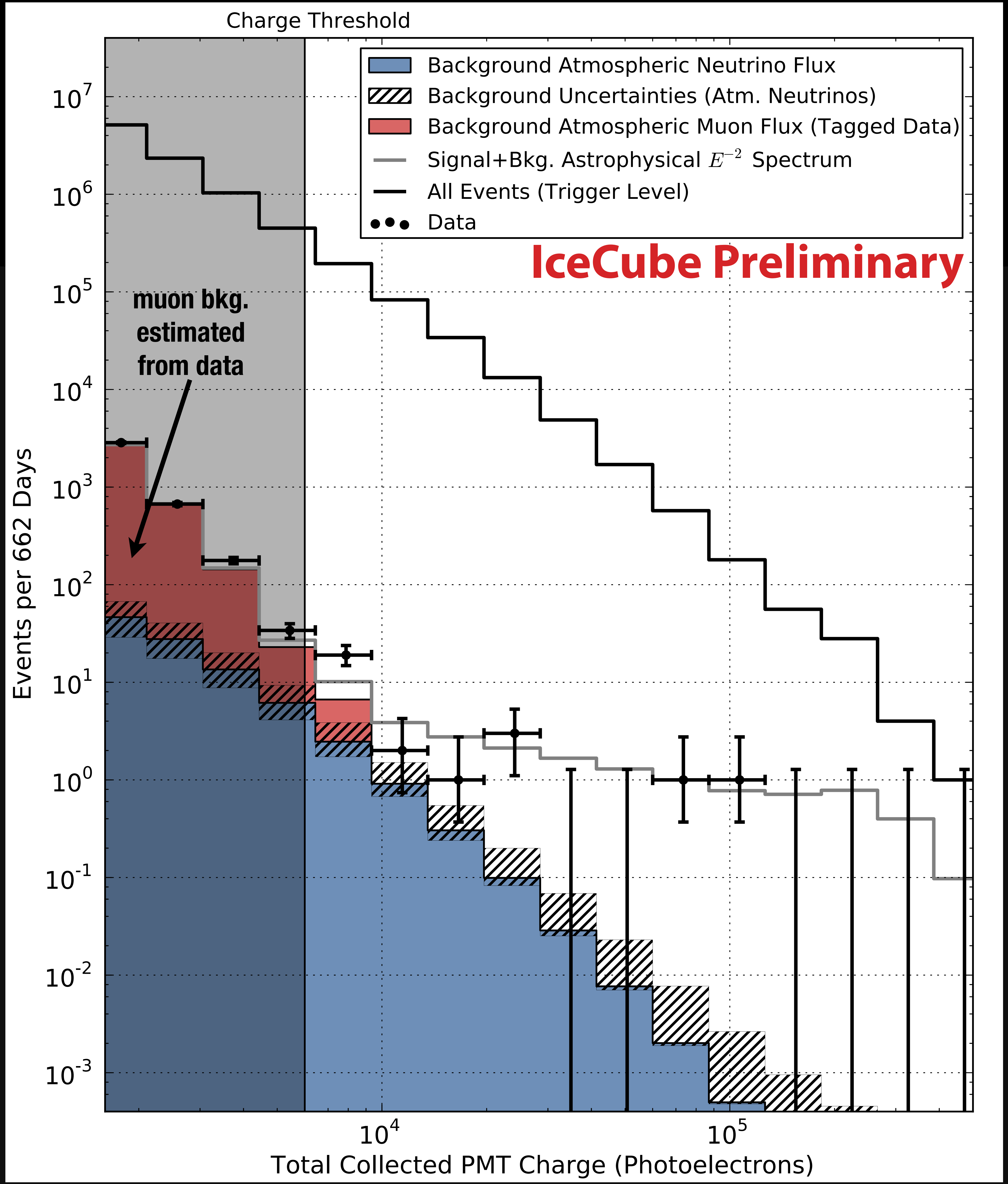
- **Systematics were checked using an extensive per-event re-simulation**
  - varied the ice model and energy scale within uncertainties for each iteration and repeated analysis
- **Different fit methods applied to the events show consistent results**

- **Tracks:**
  - good angular resolution (<1deg)
  - inherently worse resolution on energy due to leaving muon
- **Showers:**
  - larger uncertainties on angle (about 10°-15°)
  - good resolution on deposited energy (might not be total energy for NC and ν_τ)

IceCube Preliminary

Charge Distribution

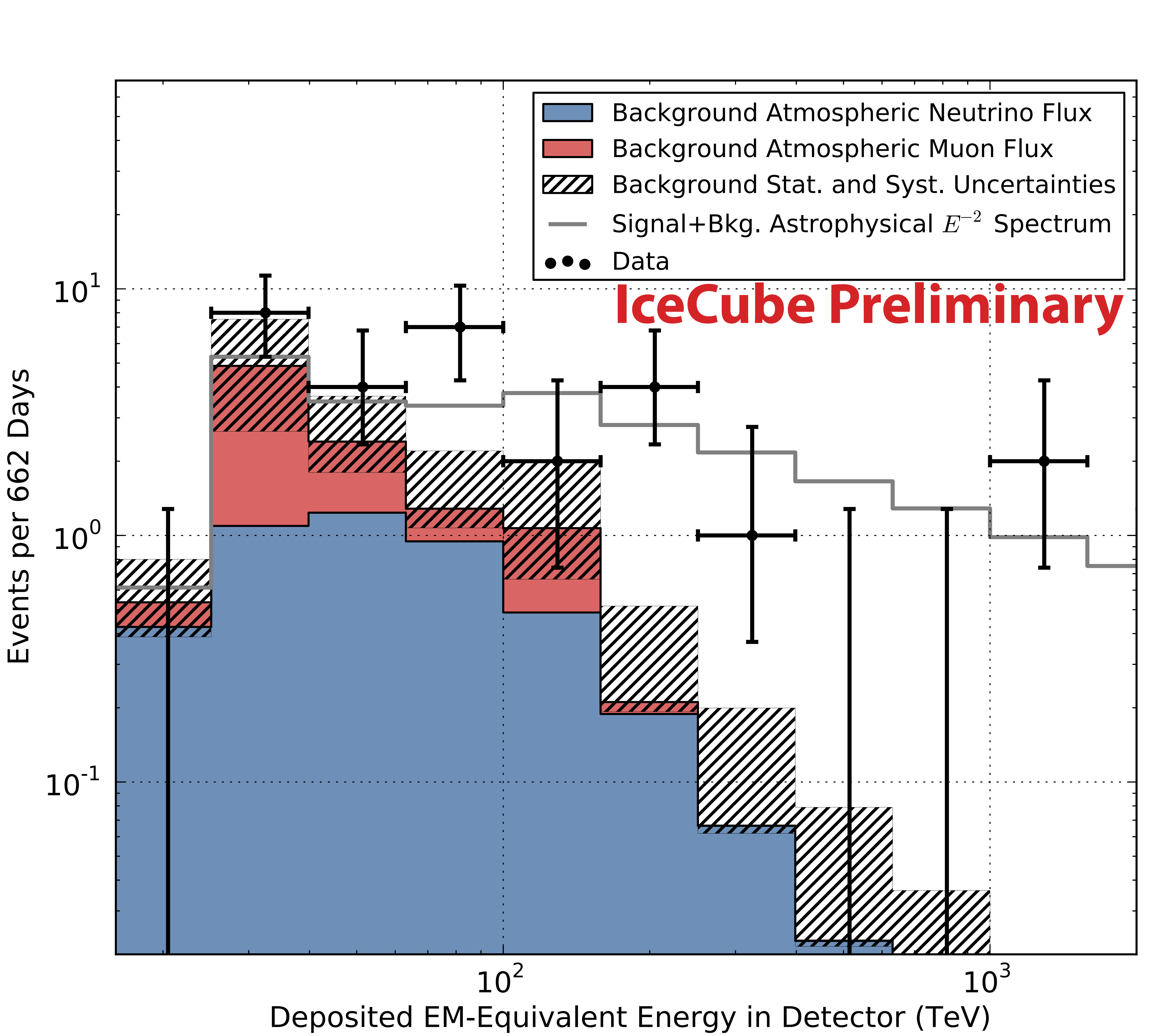
- Fits well to tagged background estimate from atmospheric muon data (red) below charge threshold (Q_{tot}>6000)
- Hatched region includes uncertainties from conventional and charm atmospheric neutrino flux (blue)



Energy Spectrum

Compatible with benchmark E^{-2} astrophysical model

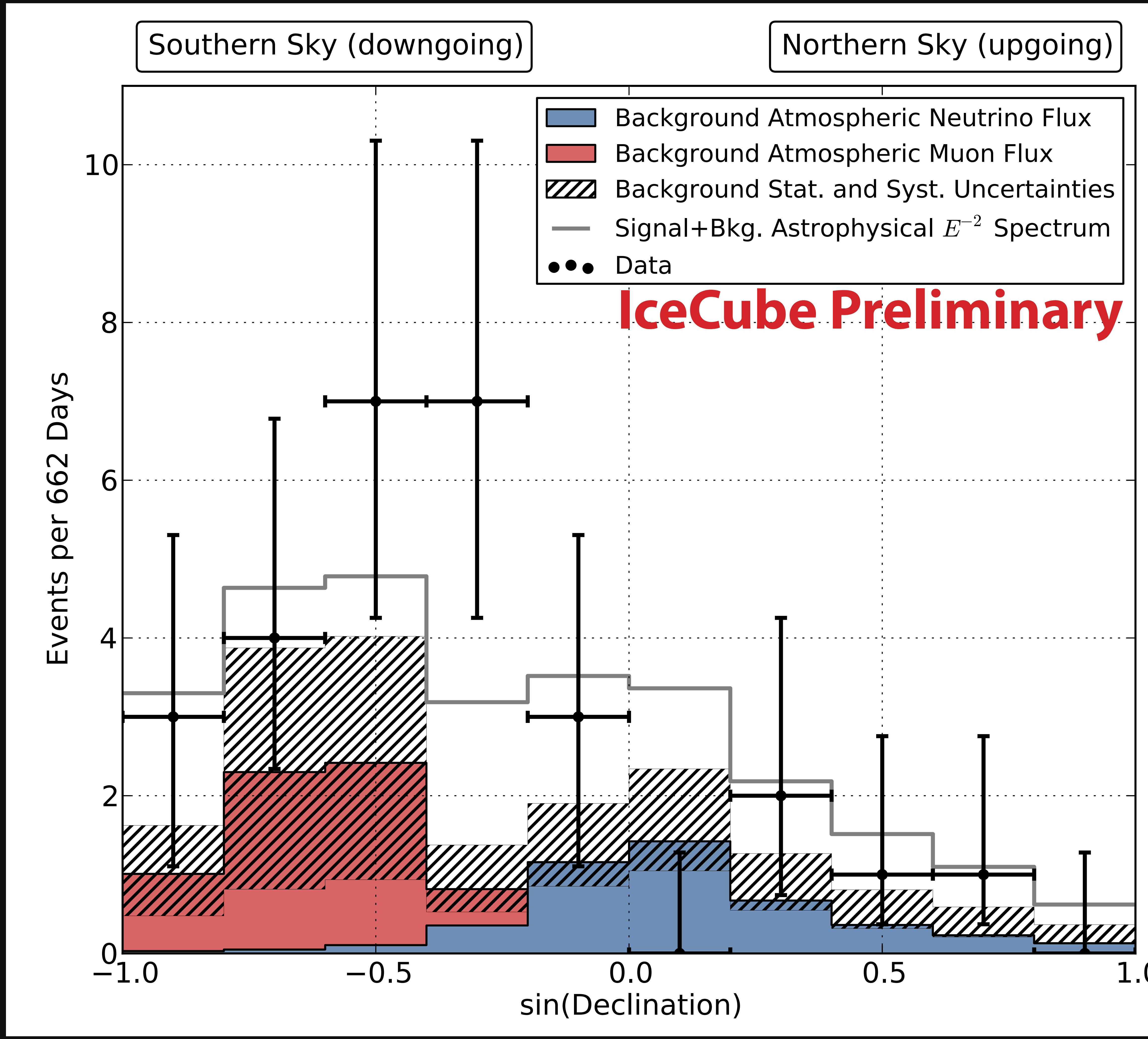
- **Harder than any expected atmospheric background**
- **Merges well into background at low energies**
- **Potential cutoff at about 2-5 PeV**
  - at $1.6^{+1.5}_{-0.4}$ PeV when fitting a hard cutoff
- **Best fit:**
  - $1.2 \pm 0.4\ 10^{-8}$ GeV^{-1} cm^{-2} s^{-1} sr^{-1}



Declination Distribution

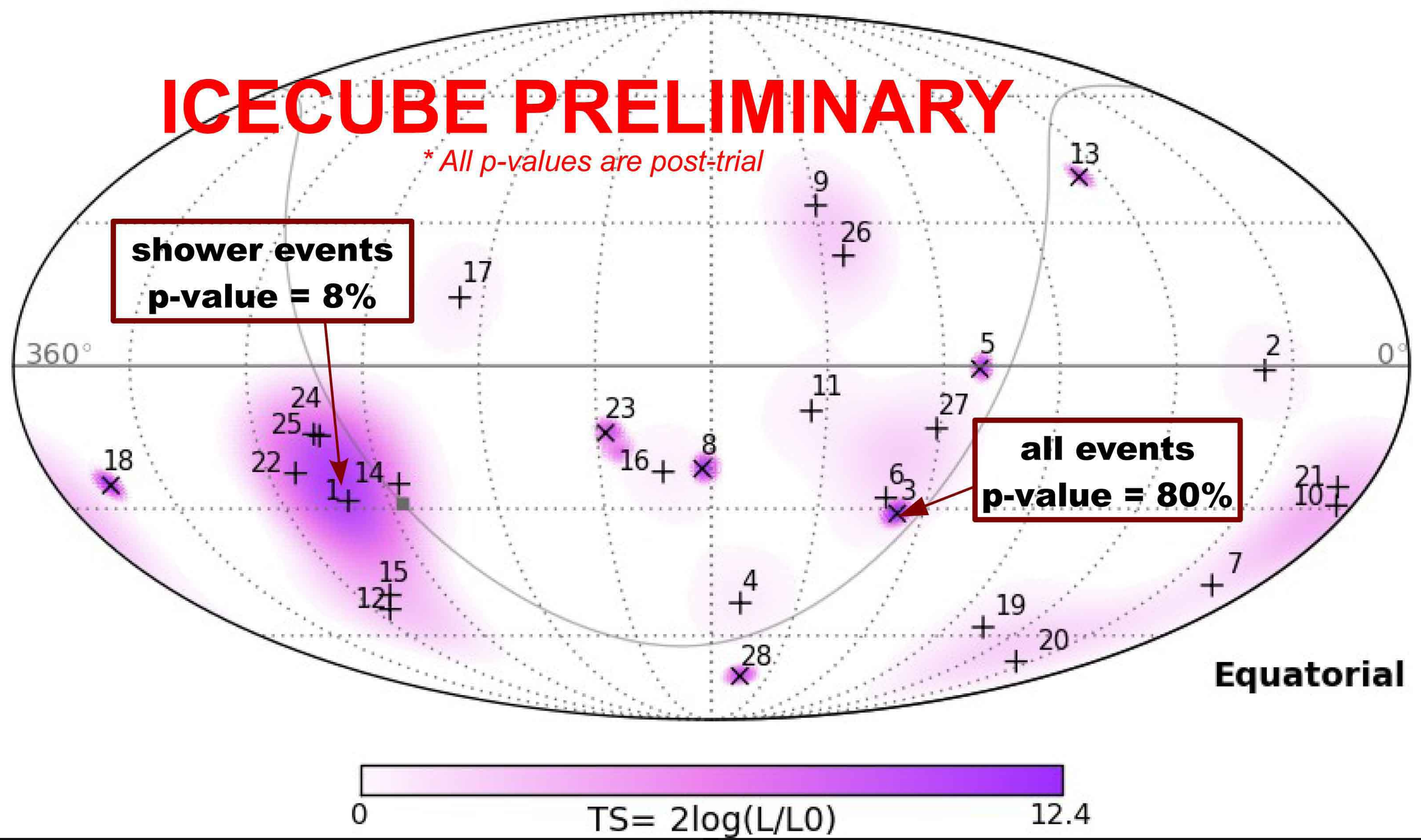
Or: “Zenith Distribution” because we are at the South Pole

- Compatible with isotropic flux
- Events absorbed in Earth from Northern Hemisphere
- Minor excess in south compared to isotropic, but not significant



Skymap / Clustering

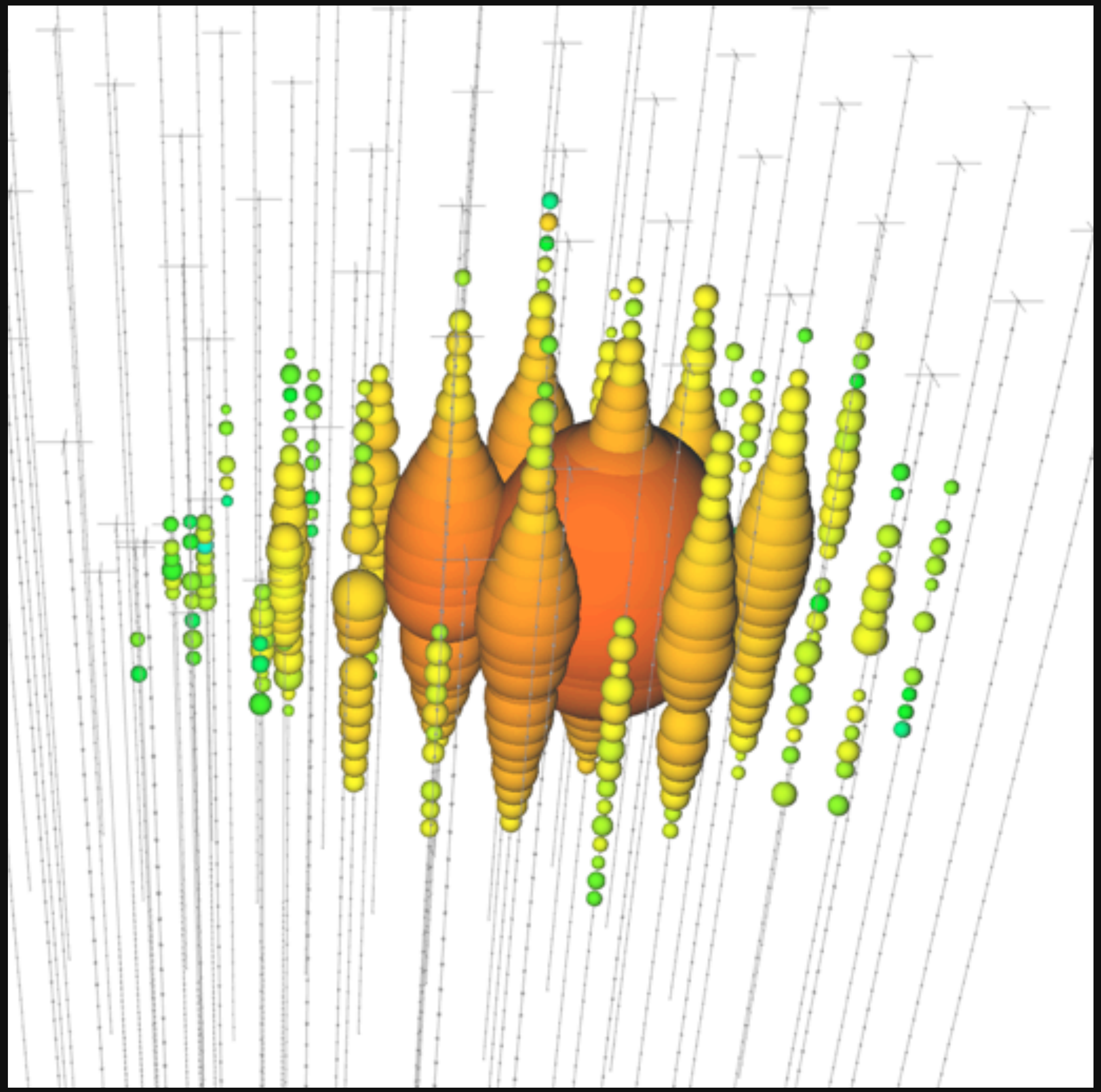
No significant clustering observed



Conclusions

Stay tuned!

- 28 events with energies above ≈ 50 TeV found in two years of IceCube data (2010 & 2011)
- Increasing evidence for high-energy component beyond the atmospheric spectrum
- Inconsistent at 4.1σ with standard background assumptions
- Less clear what it is - compatible with astrophysical explanations
- More data coming soon!



IceCube Preliminary