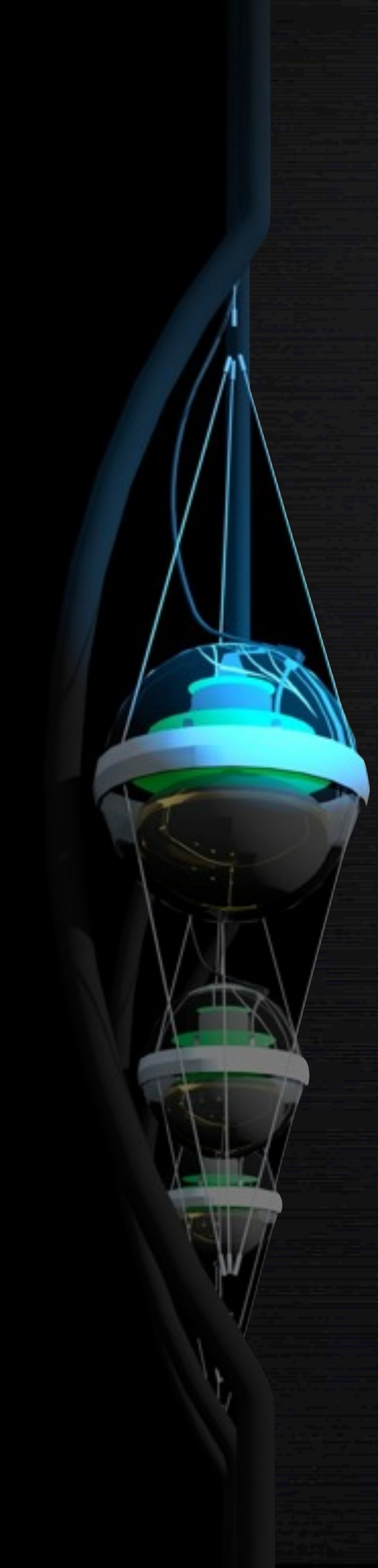
Evidence for Astrophysical Neutrinos with IceCube

Juan A. Aguilar

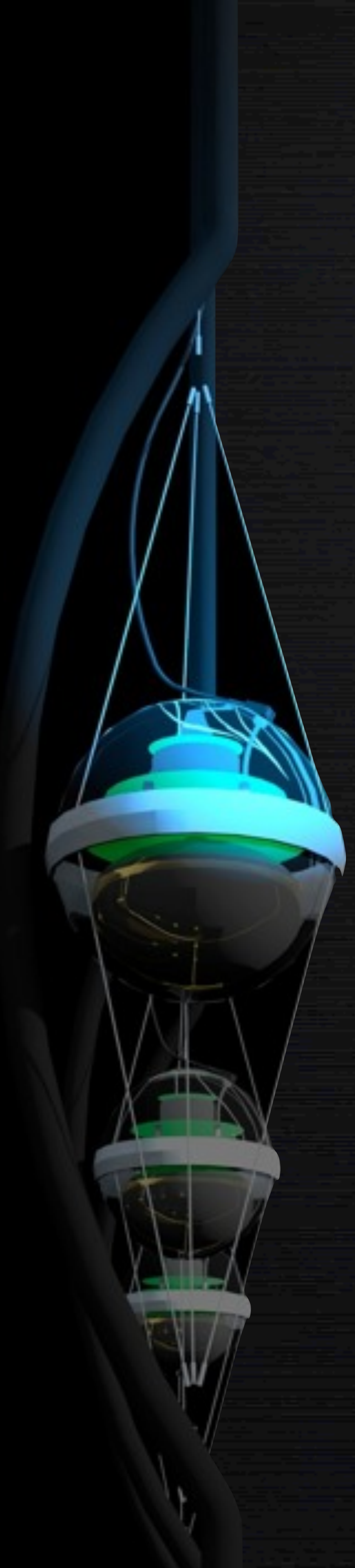
UNIVERSITÉ DE GENÈVE

IVICFA Friday's
Valencia, 25 October 2013



Outline

- Neutrino Astronomy
- The IceCube Observatory
- Search for point sources
- High energy contained events
  - Event Selection and Analysis
  - Results
- Conclusions



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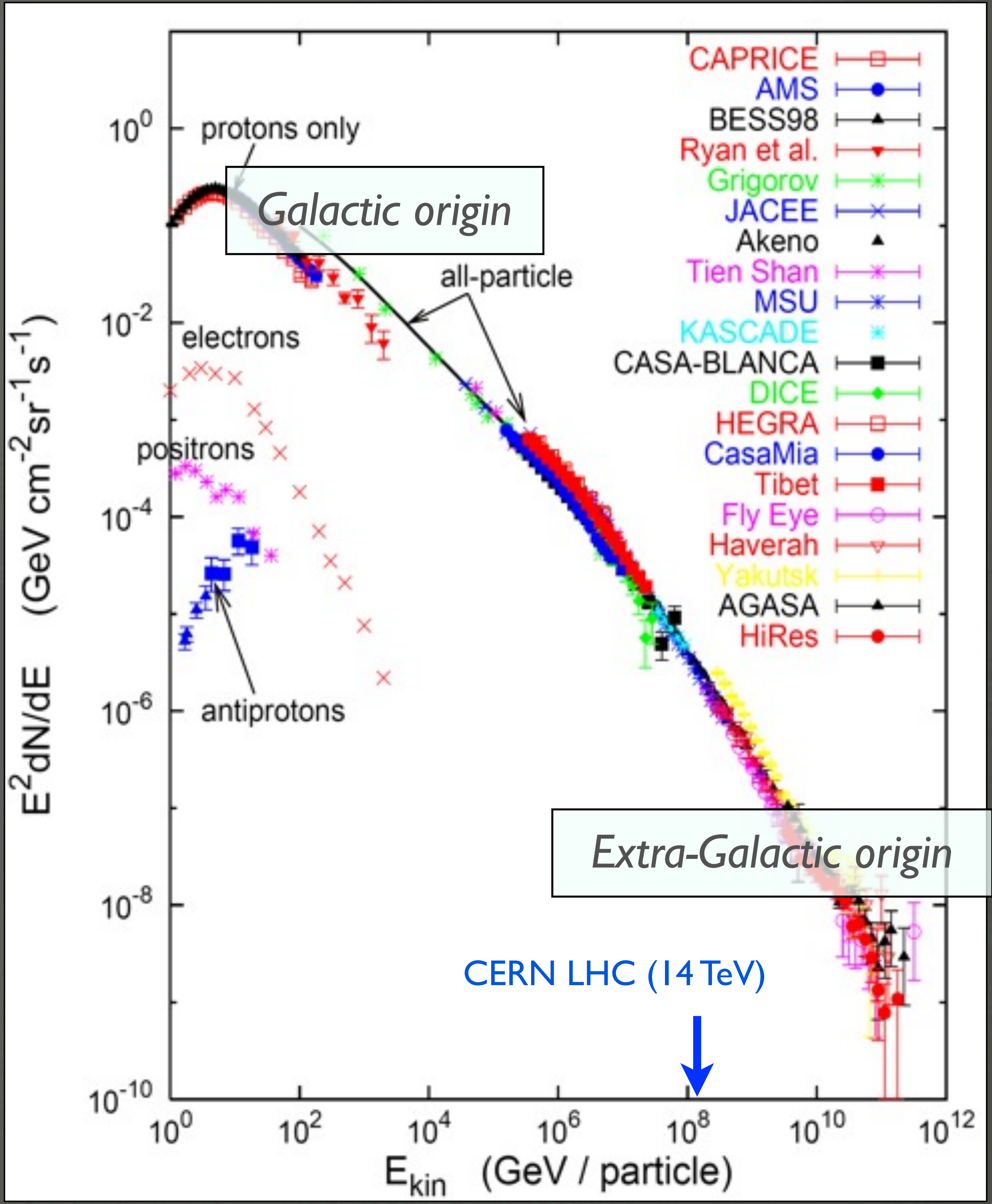
Cosmic Rays

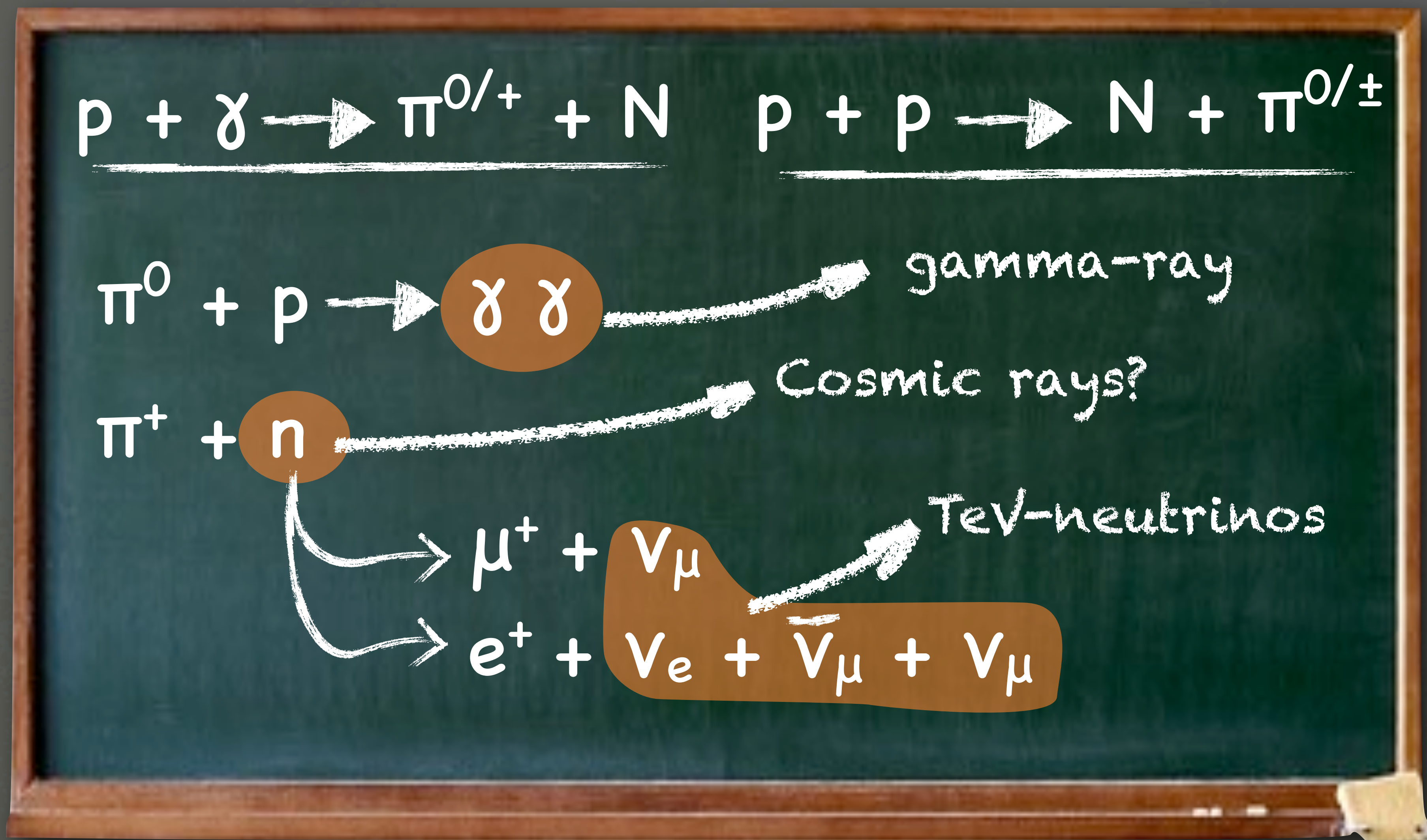
- Protons and nuclei hitting the Earth's atmosphere.
- Discovered by Victor Hess in **1912**
- Cosmic Rays spectrum spans 10 decades of energy. Origin still **unknown**.
  - Galactic CRs: Supernova remnants*?
  - Extra-Galactic CRs: AGNs, GRBs, magnetars?

**Science 15 Feb 2013: Fermi finds the hadronic acceleration*



The ν-γ connection

- Cosmic rays can interact on the accelerator sites: SNR, AGNs, GRBs,...

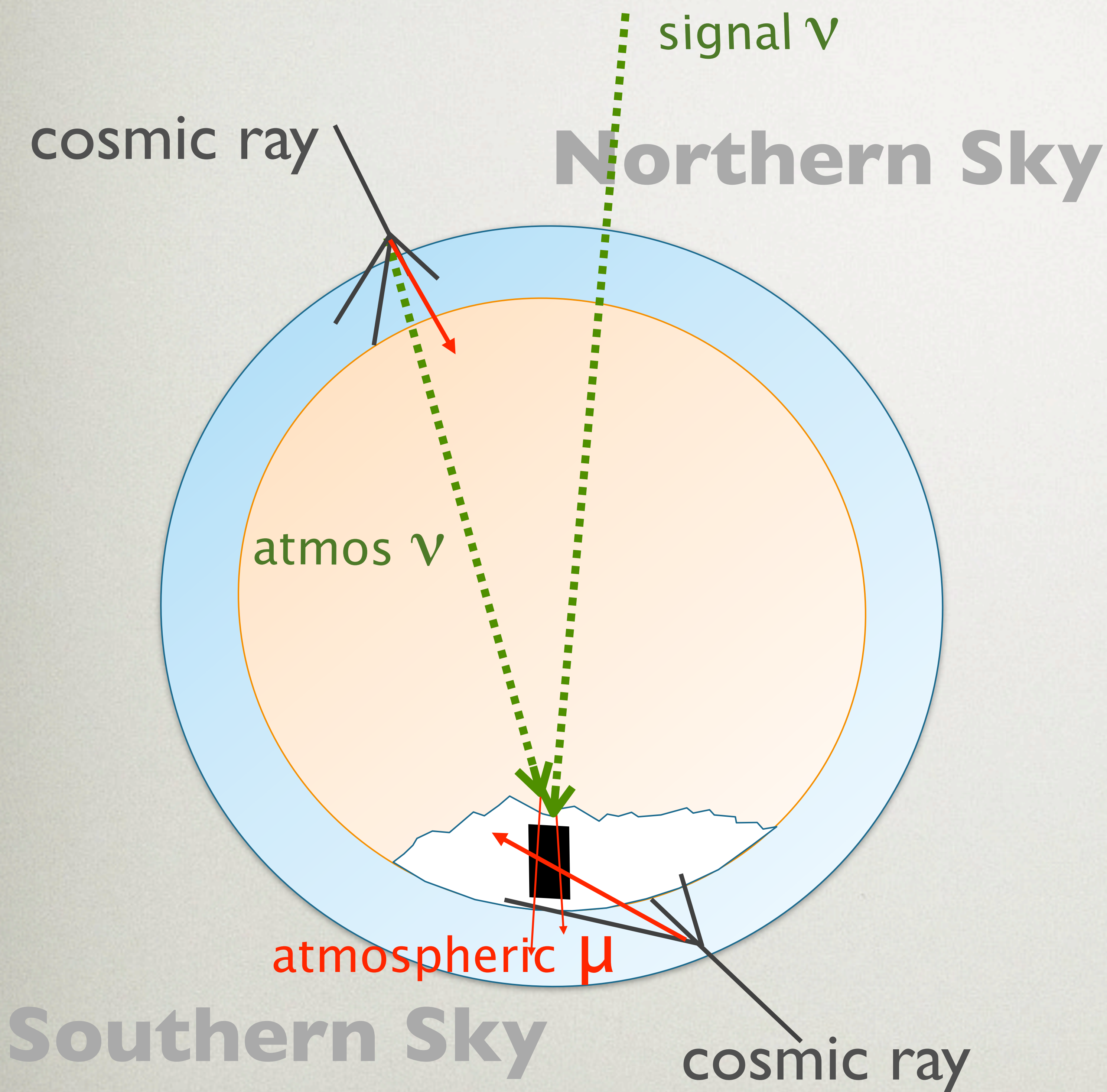


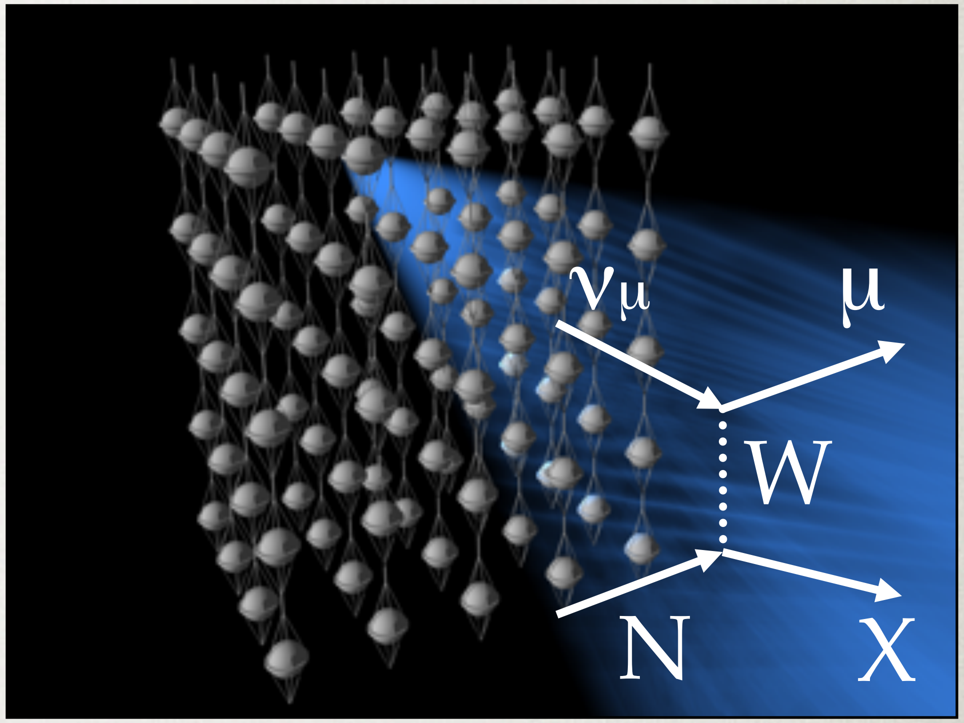
...or they can interact in known targets: Earth's atmosphere, Interstellar matter in Galactic plane, cosmic microwave background.

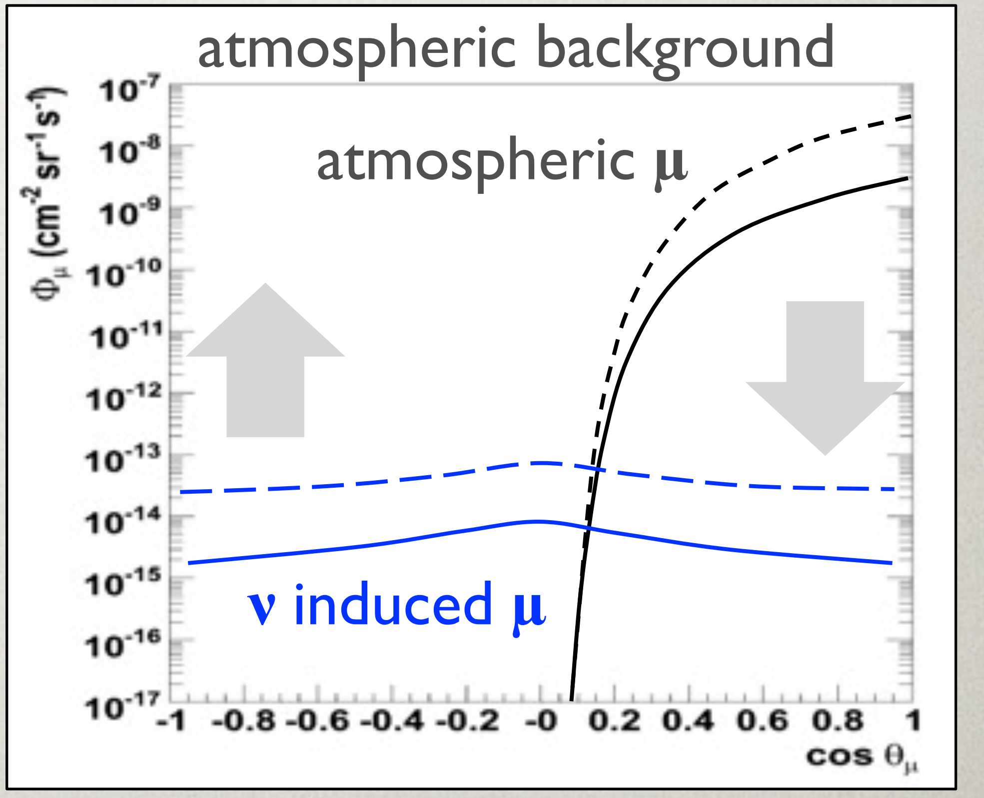
Why neutrinos?

- ***Protons*** are deviated by magnetic fields ($E_p < 10^{19}$ eV) and very energetic protons travel distances of a few Mpc.
- ***Neutrons*** reach distances of ~kpc at very high energy.
- ***Photons*** interact with the EBL (~100 Mpc) and CMB (~10 kpc).
- ***Neutrinos*** are ***neutral***, ***stable*** and ***weakly interacting*** particles.

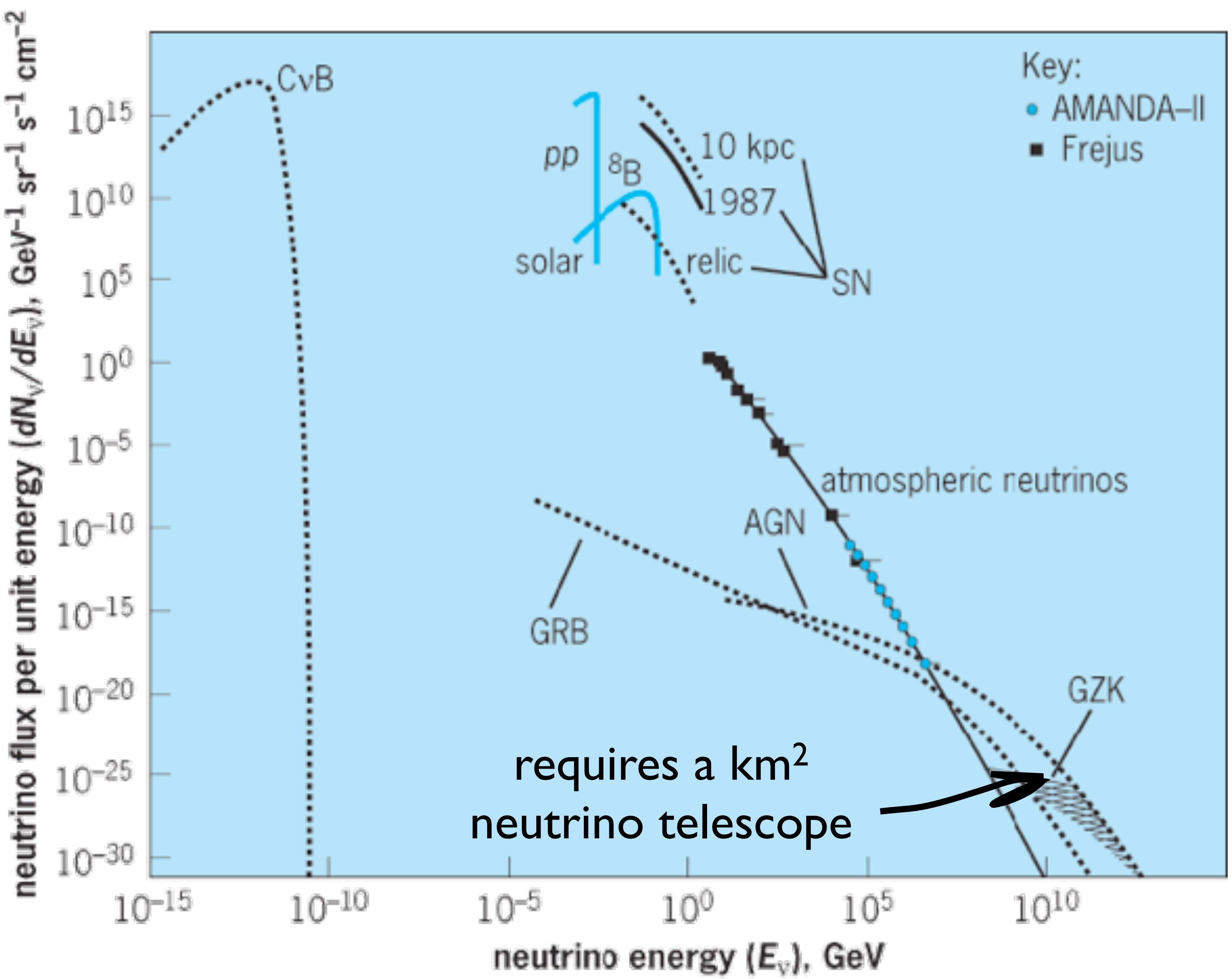
Detection principle



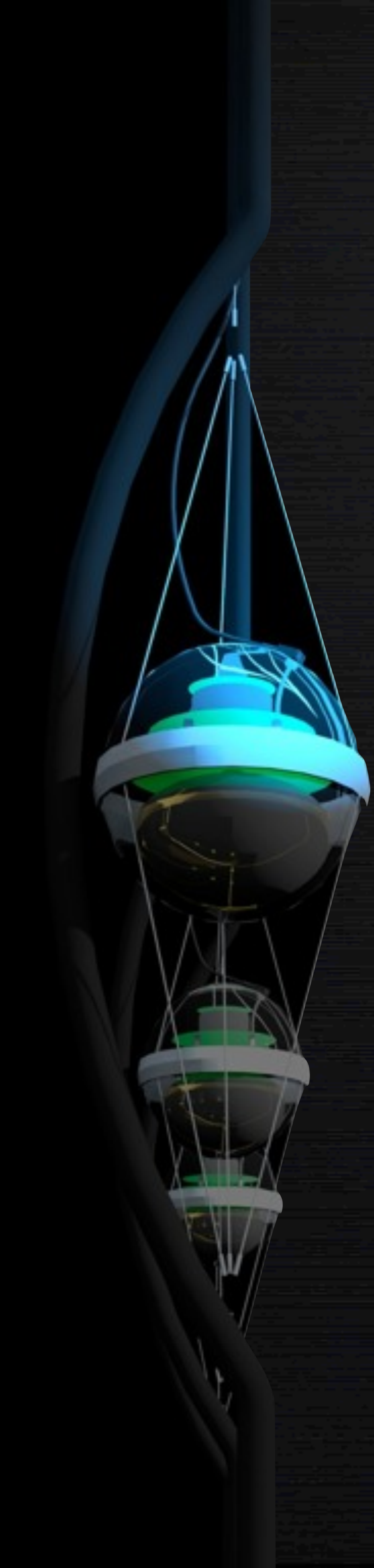




The Neutrino Sky



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



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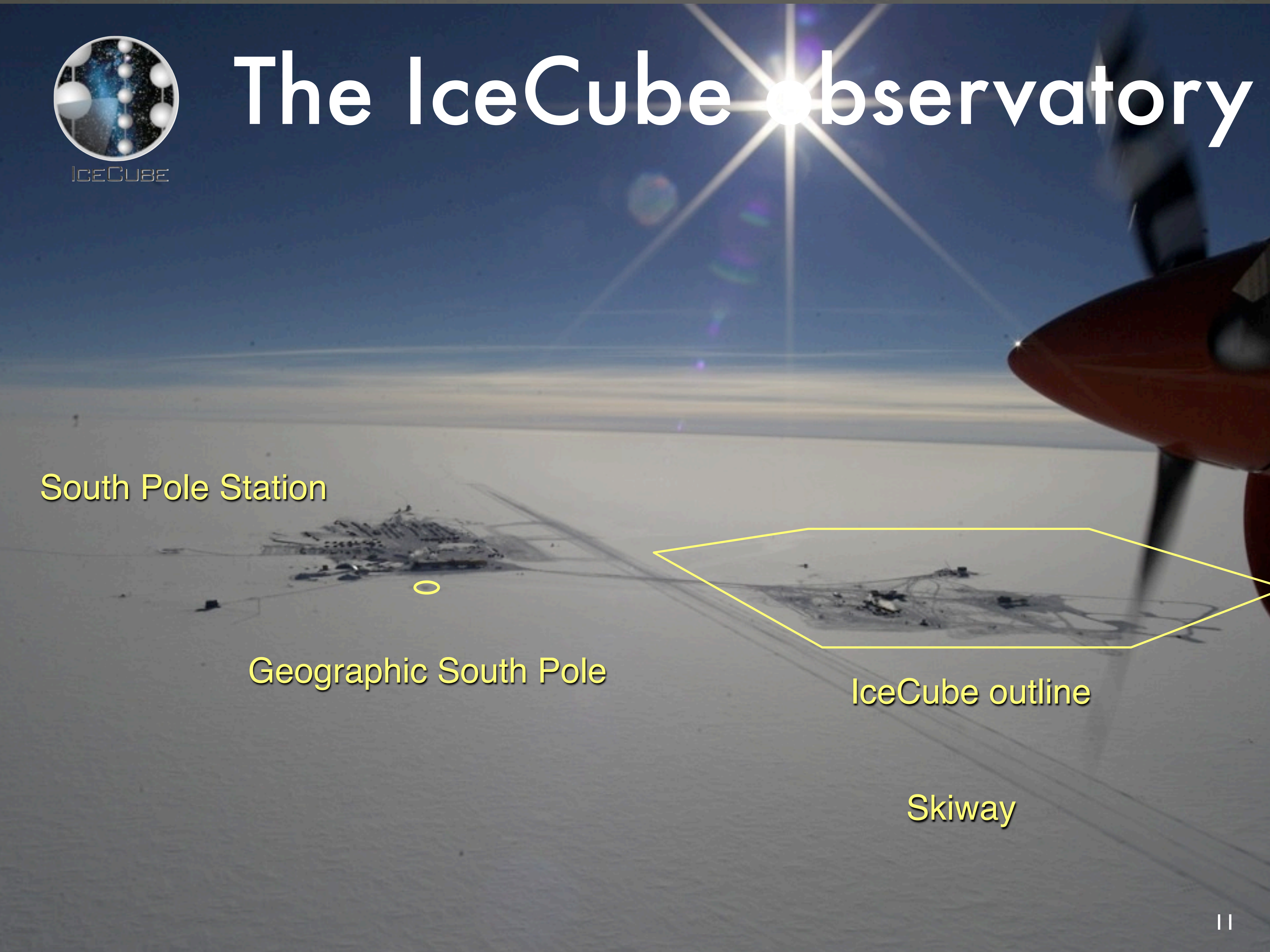
The IceCube Collaboration

10 countries, 40 institutions, ~260 collaborators

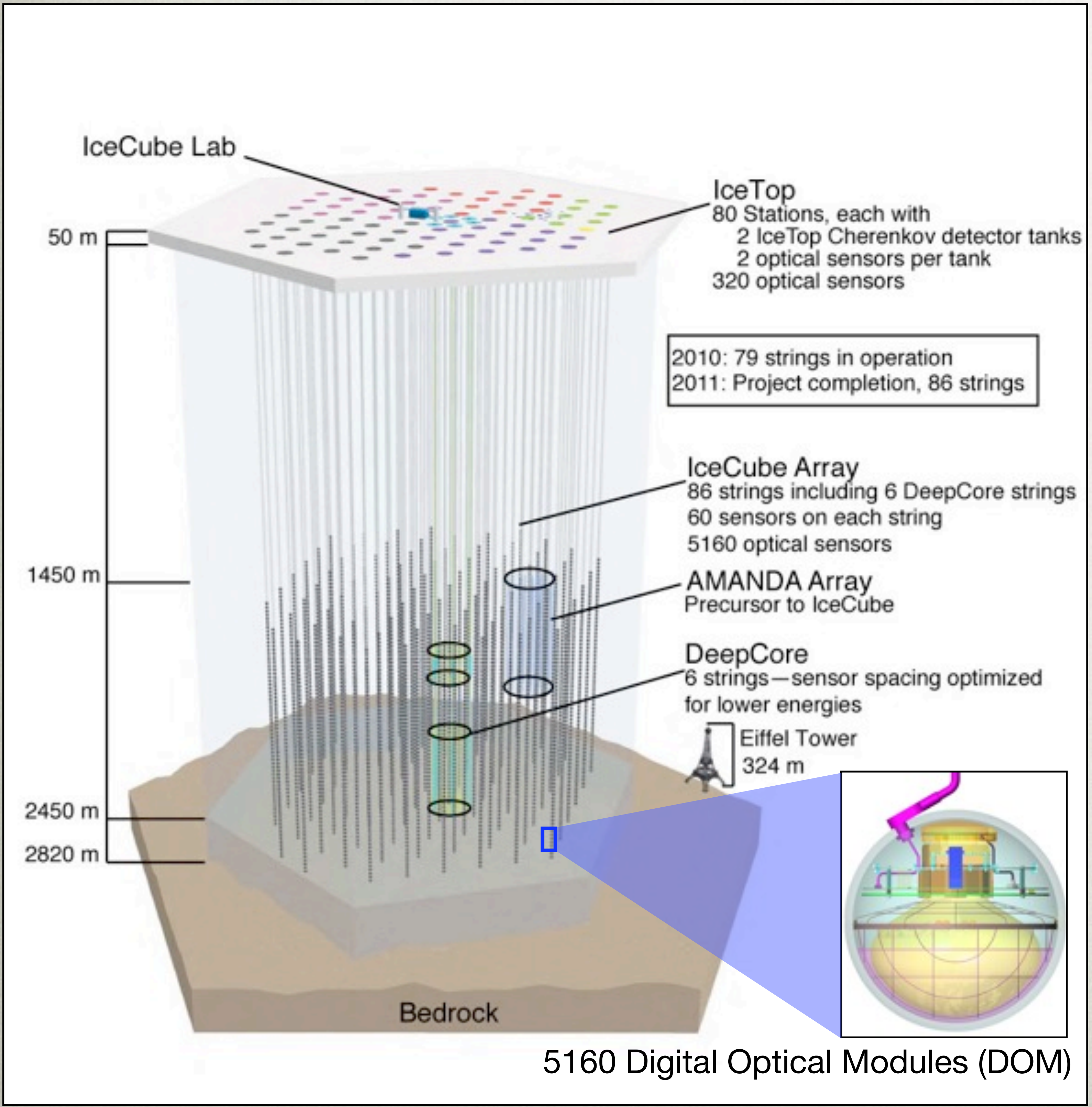
International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

The IceCube observatory



IceCube in-ice telescope



20 years of construction from AMANDA to IceCube

IceCube phases:

IceCube 1 (2004-5)

•
•
•

IceCube 40 (2008-9)

IceCube 59 (2009-10)

IceCube 79 (2010-11)

Completion with 86 strings in December 2010.

IceCube 86-I (2011-12)

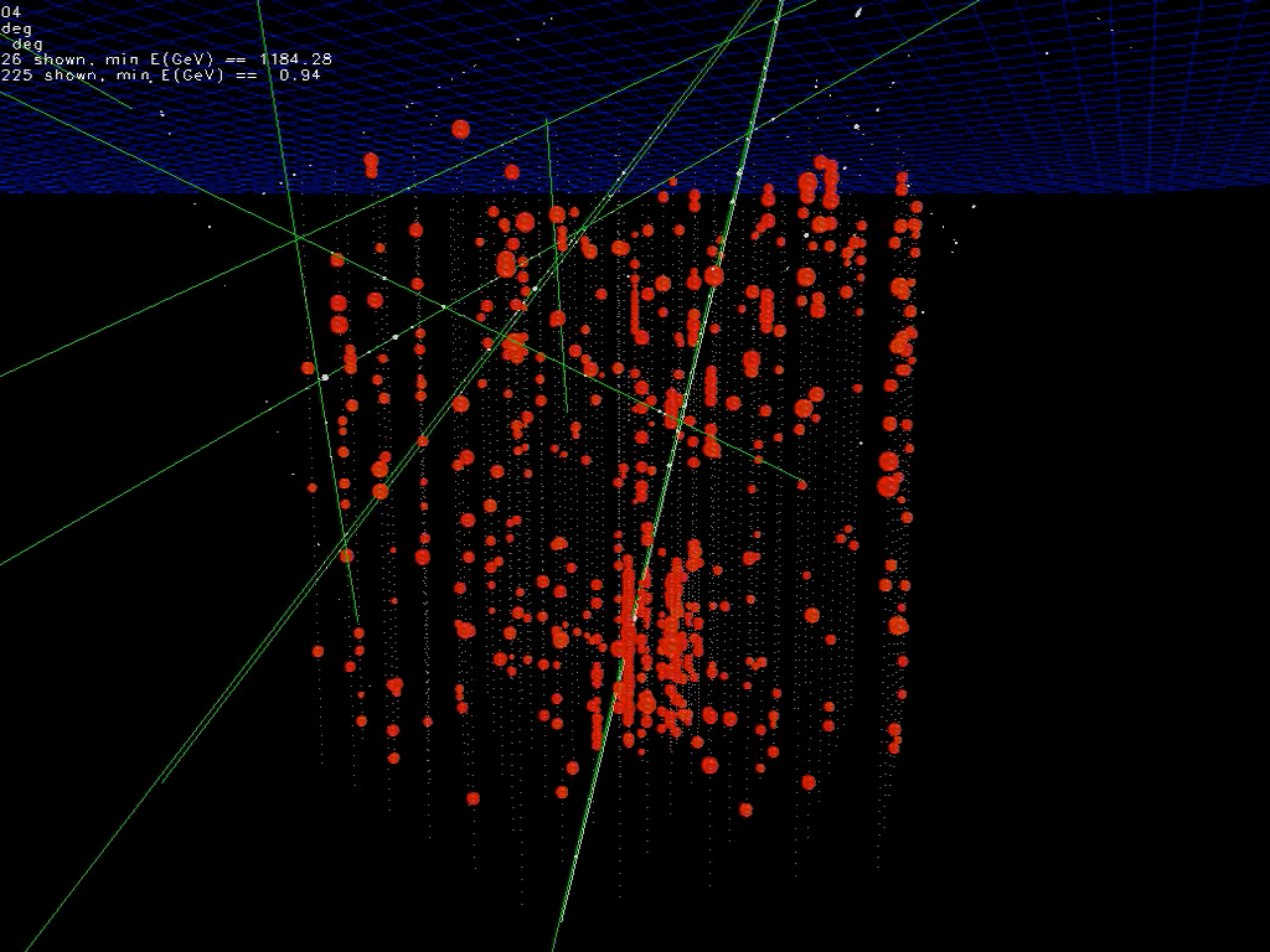
•
•
•

IceCube is running with high uptime …

2 winter-over scientist ensure high uptime of **~99%**
Rates: 3 kHz of muons (trigger); >200 atmospheric neutrinos/day (final sample)
Hardware very stable.

DOM performance

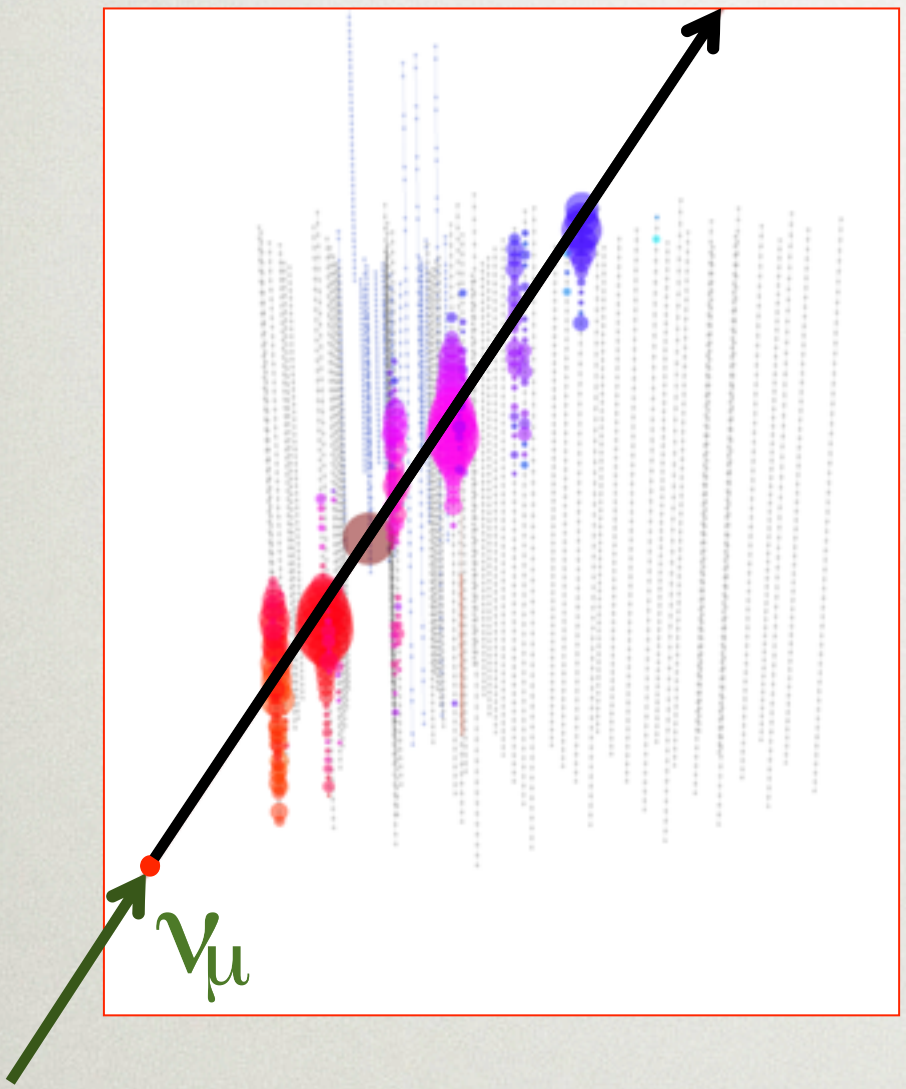
- 99.1% (5435) DOMs have survived installation.
- Failure rate: 2/year.
- After 15 years operation (2025) we expect 97.2% +/- 0.4% of the detector operational.


04
deg
deg
26 shown, min E(GeV) == 1184.28
225 shown, min E(GeV) == 0.94


04
deg
deg
26 shown, min E(GeV) == 1184.28
225 shown, min E(GeV) == 0.94
you looked at 10 ms of data!

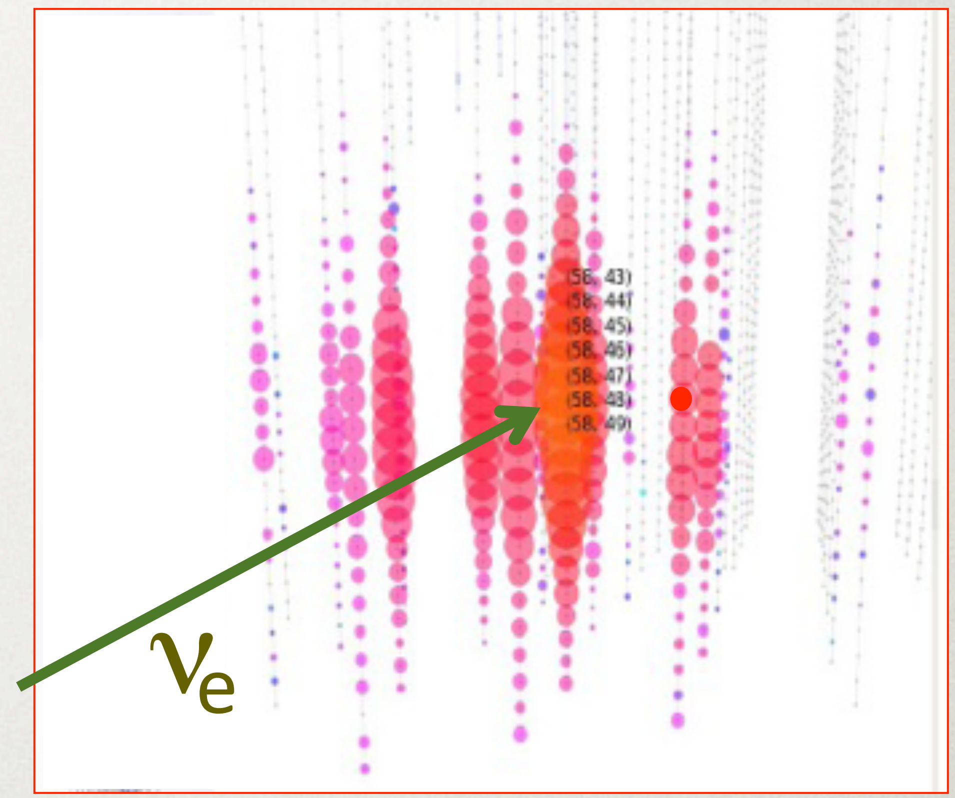
Detection Methods

through-going muons



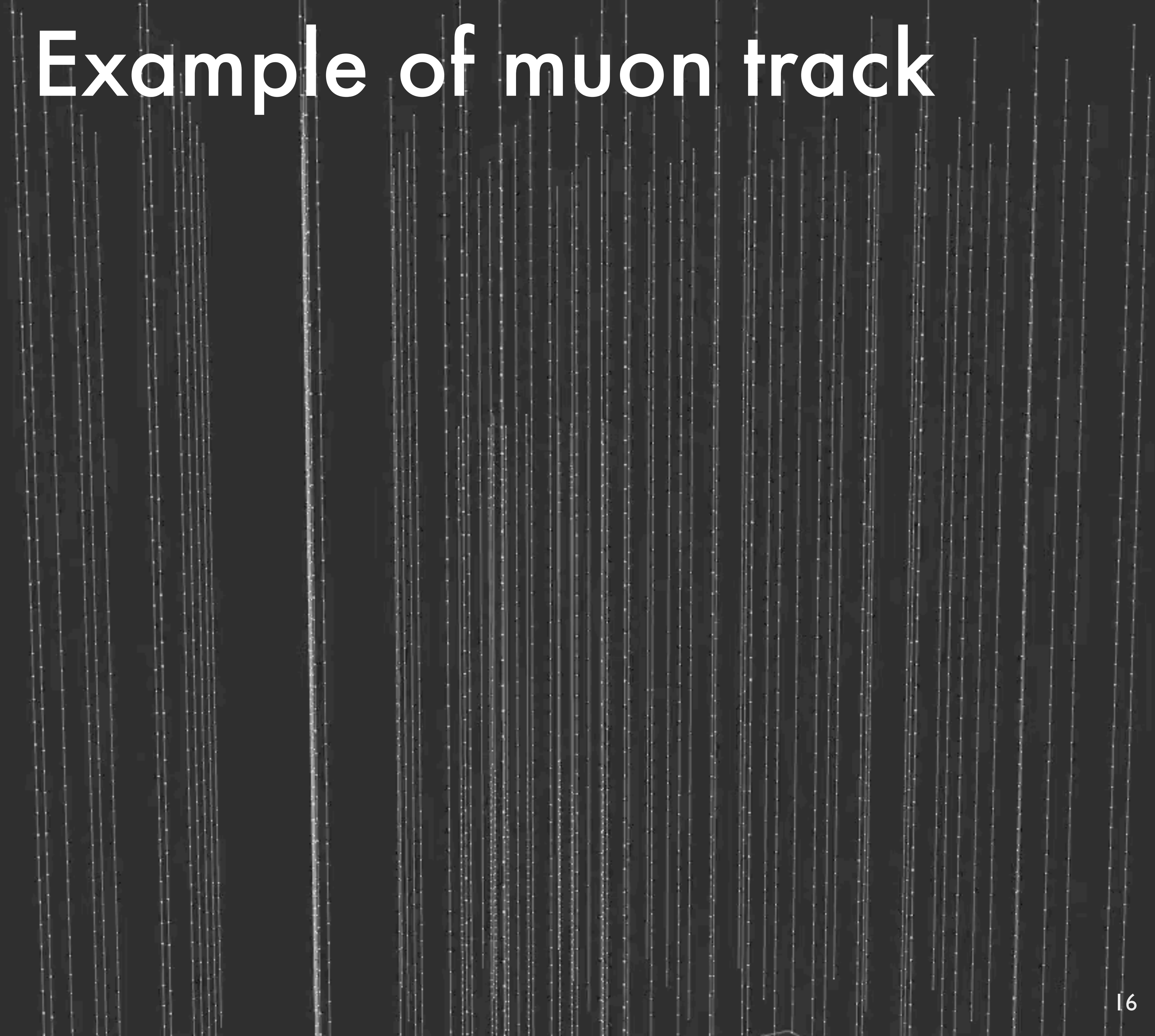
- The workhorse for neutrino astronomy, good angular resolution
- Vertex can be far outside the detector. Increased effective volume!

cascade → all flavors

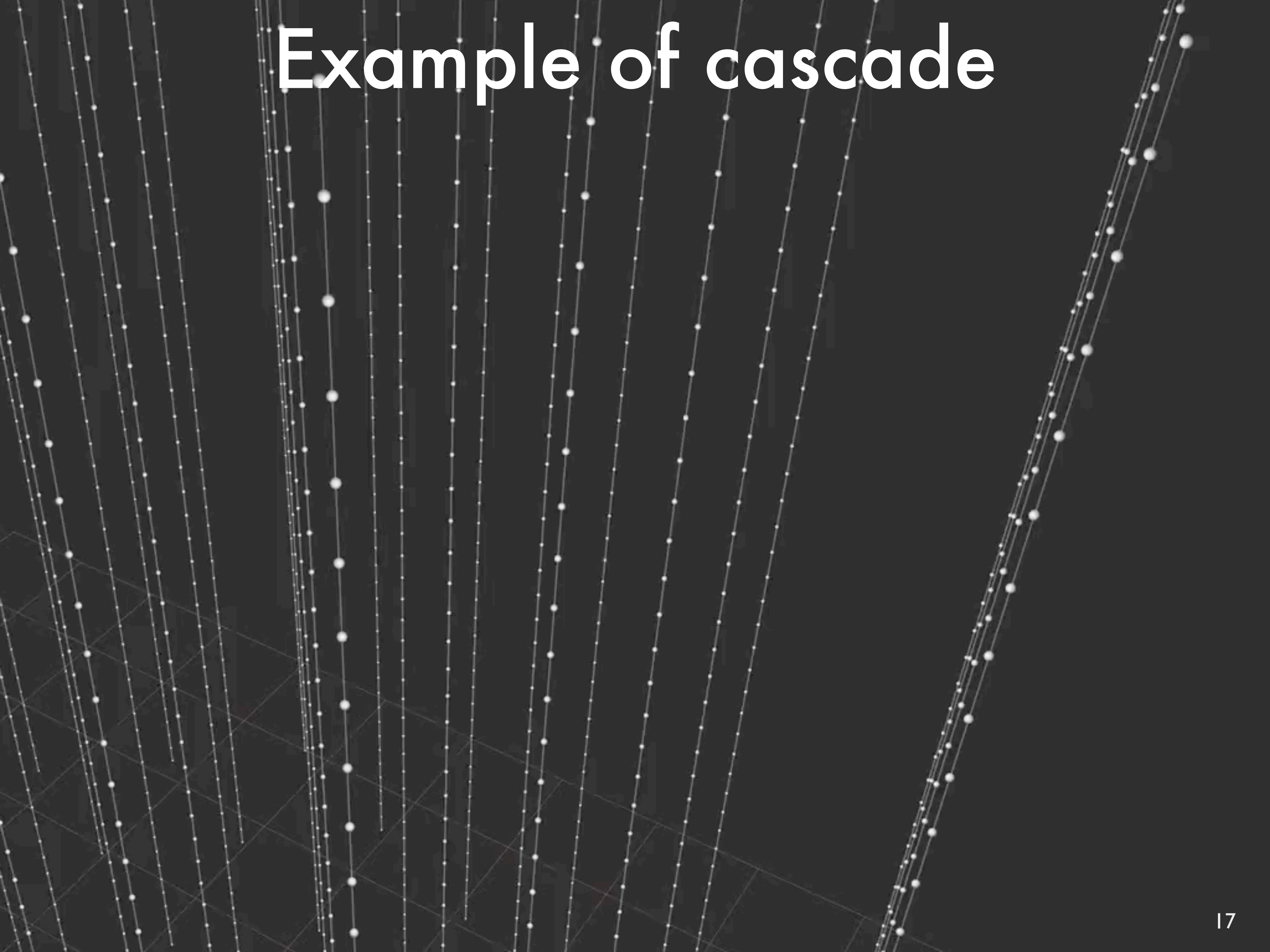


- ν_e, ν_τ and neutral current
- High energy resolution: fully active calorimeter, all energy gets deposited in the detection volume
- Angular reconstruction above ~50 TeV

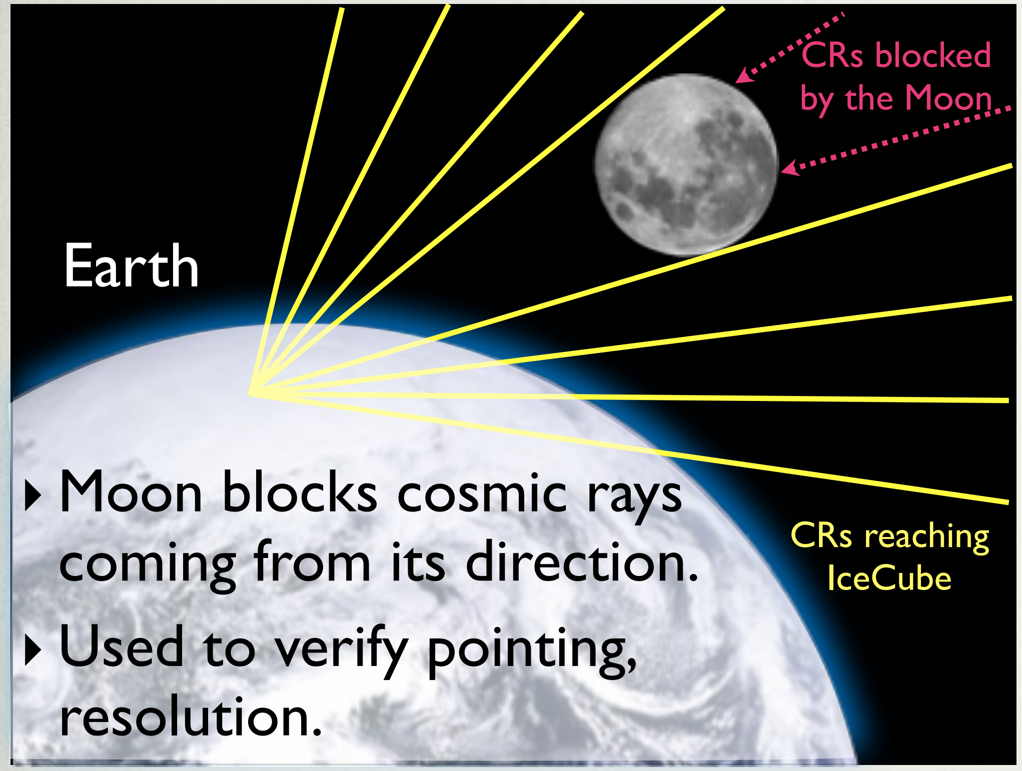
Example of muon track



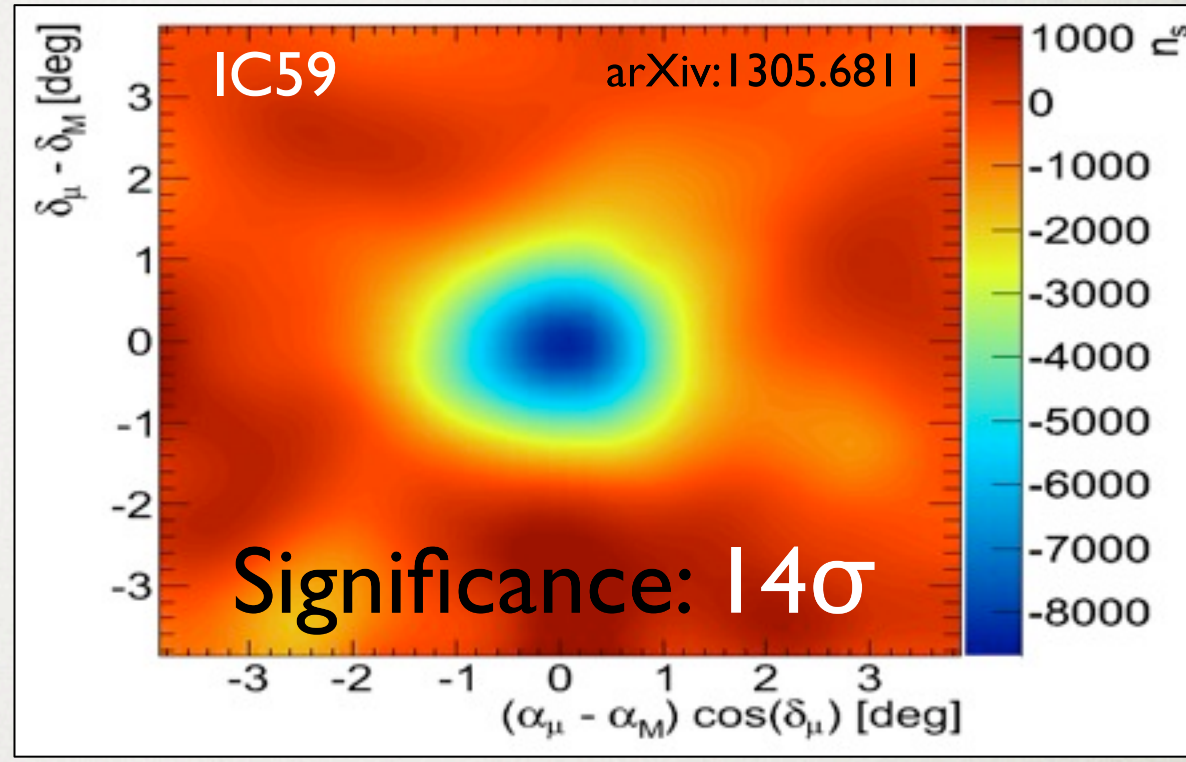
Example of cascade



Pointing: Moon shadow

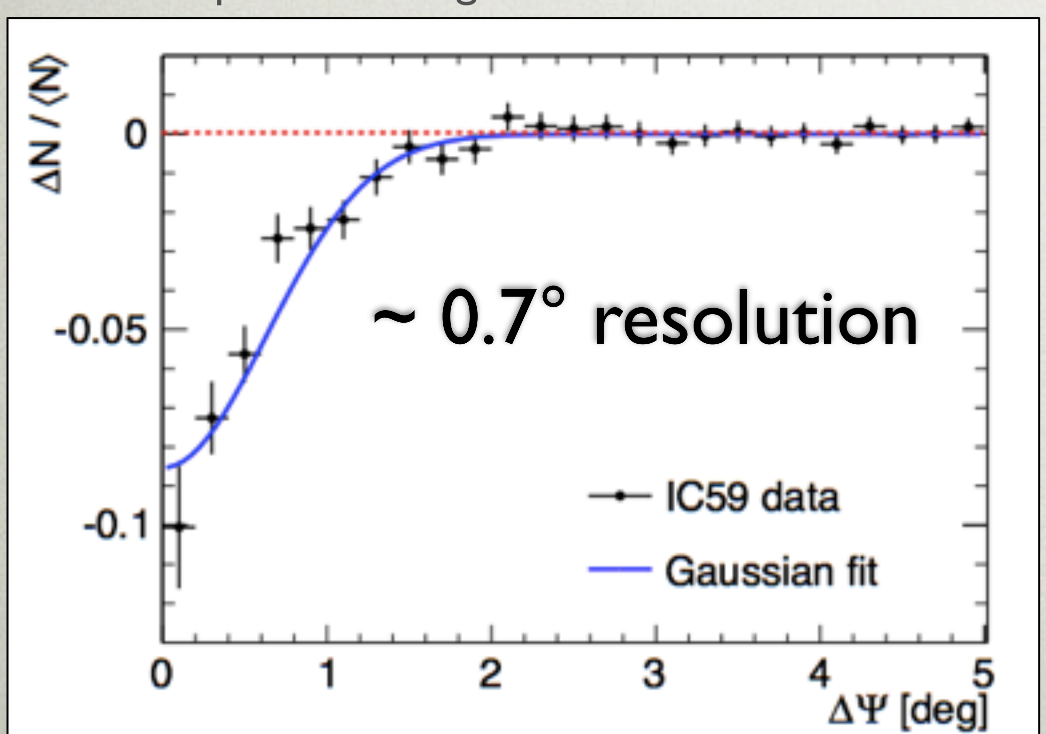


- Moon blocks cosmic rays coming from its direction.
- Used to verify pointing, resolution.



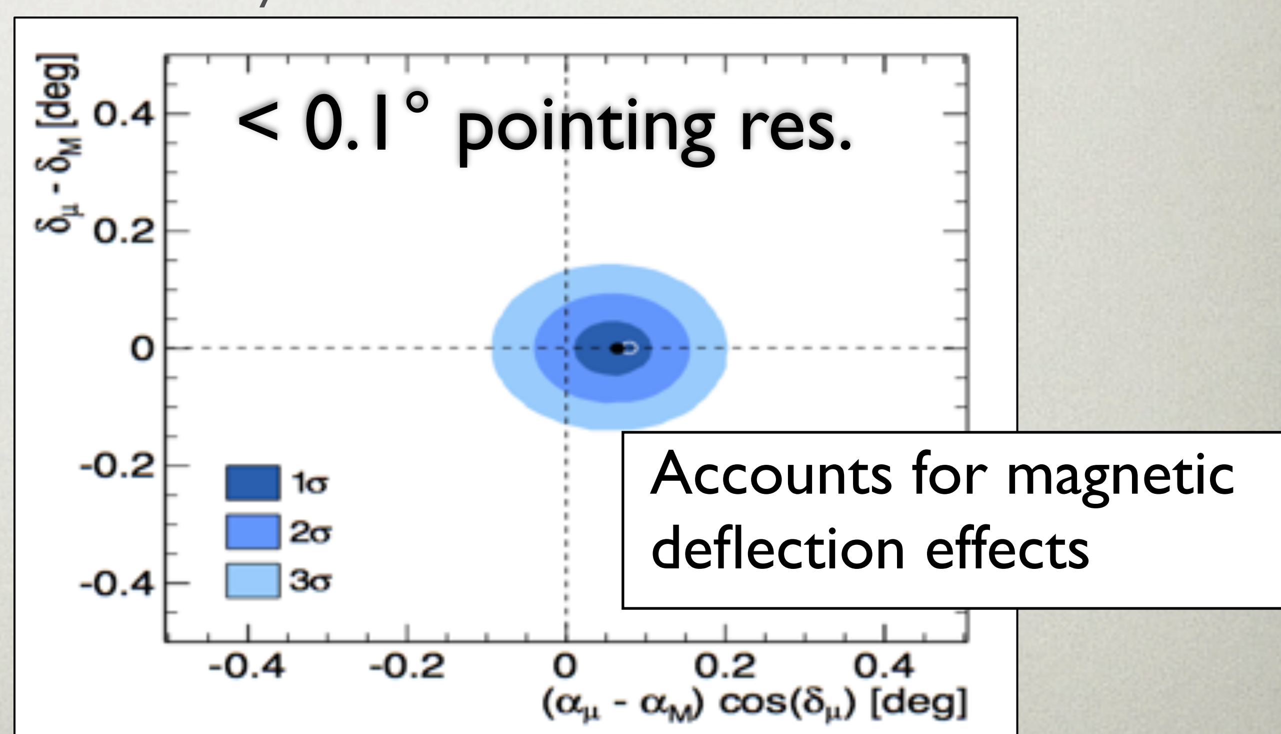
Resolution

Shadow profile vs. angular distance from the Moon

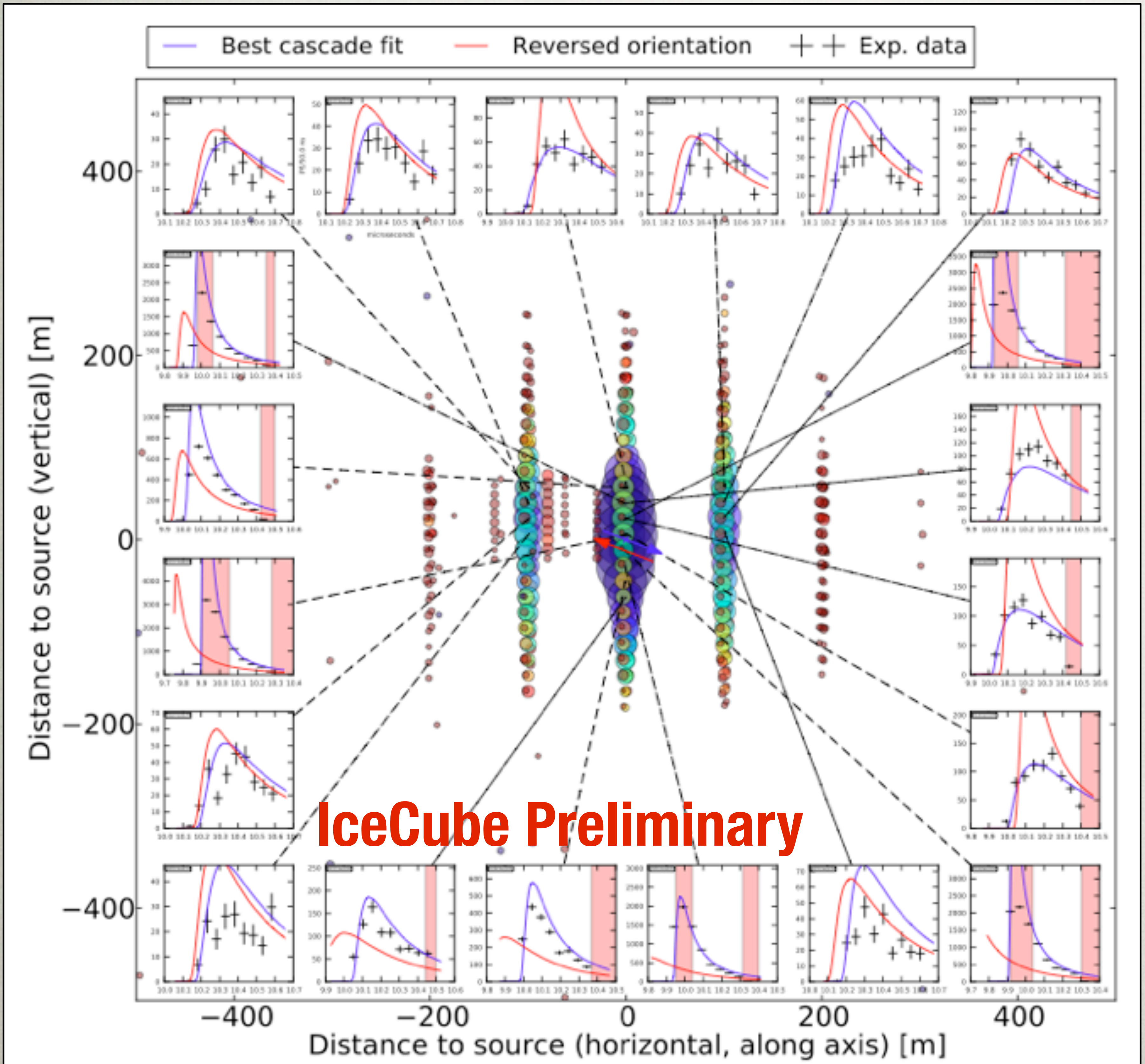


Absolute pointing

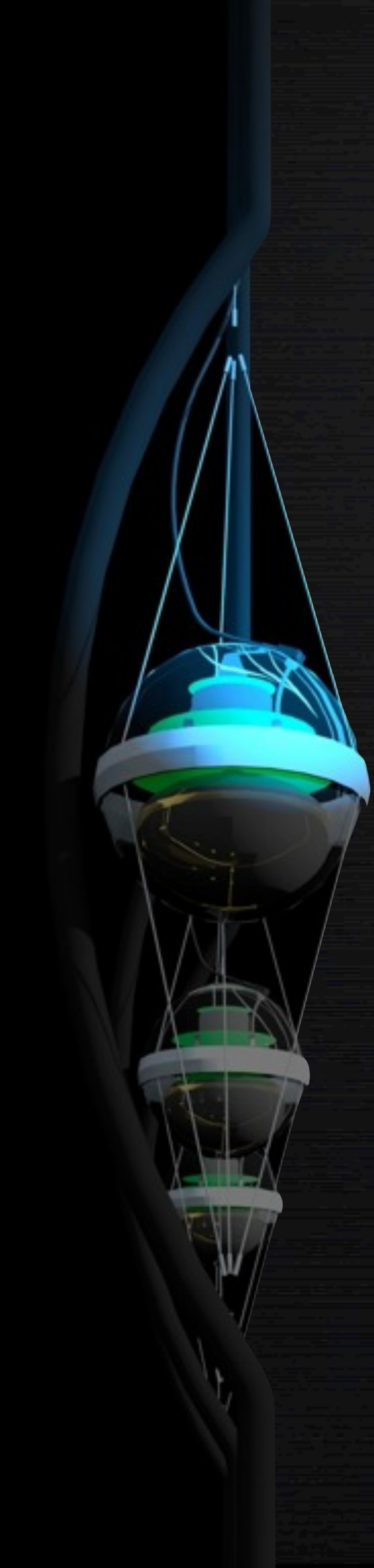
Most likely location of shadow center



Cascade reconstruction



- Shown is one event with best fit (blue) and forced reverse direction (red)
- Event contains 354 waveforms and a total of > 90,000 photoelectrons
- Achievable resolutions (Cascades):
  - **±15%** deposited energy (incl. all sys. errors)
  - **10°** angular resolution (> 100 TeV)



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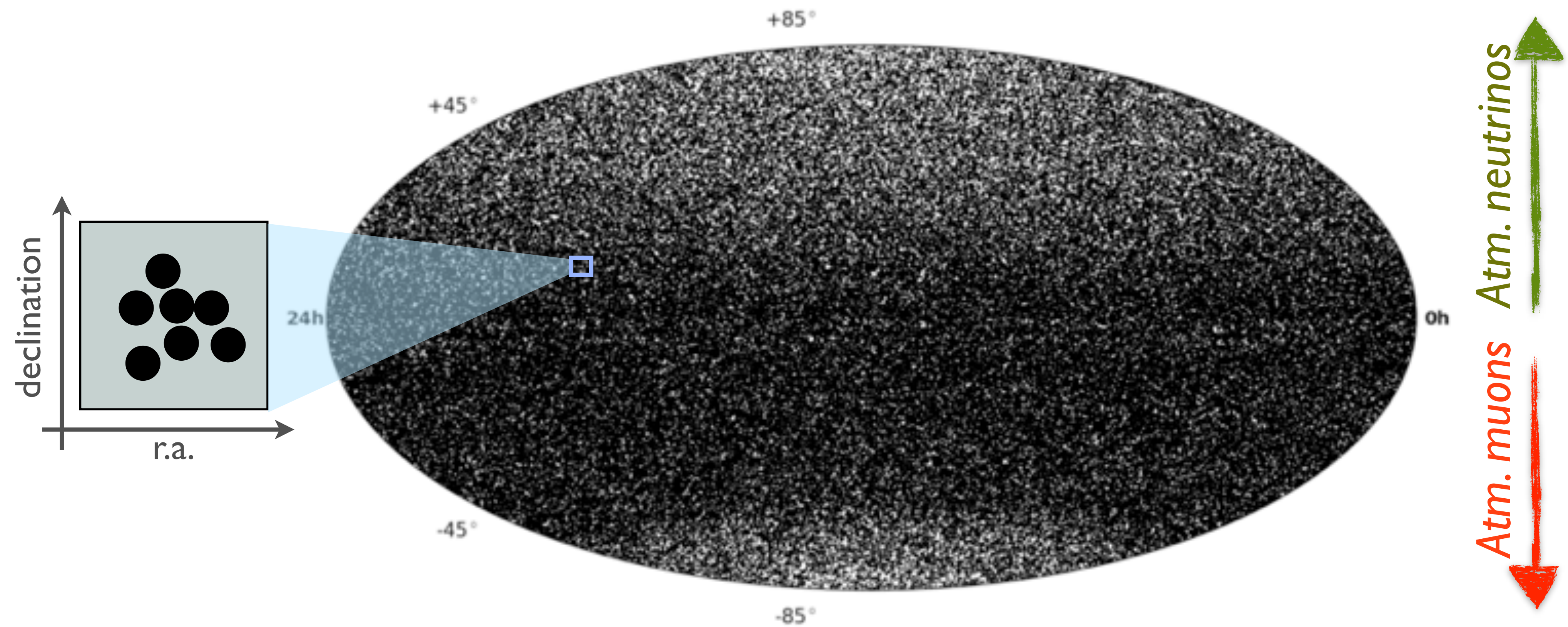
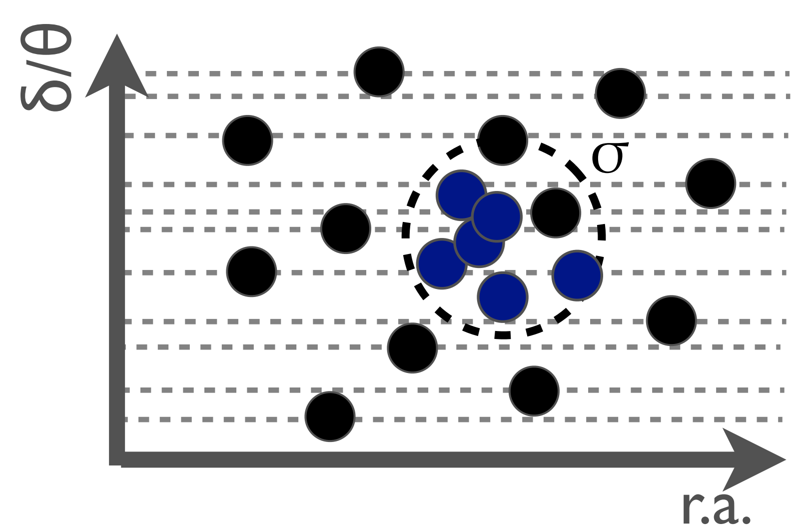
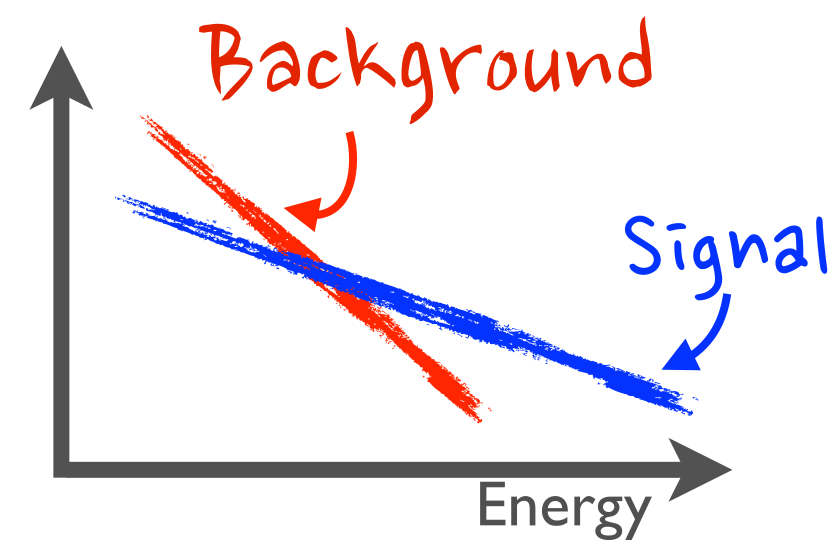
Point Source Searches

- Neutrinos are not deviated by magnetic fields.
- Scattering due to ν-μ kinematics and detector Point Spread Function.



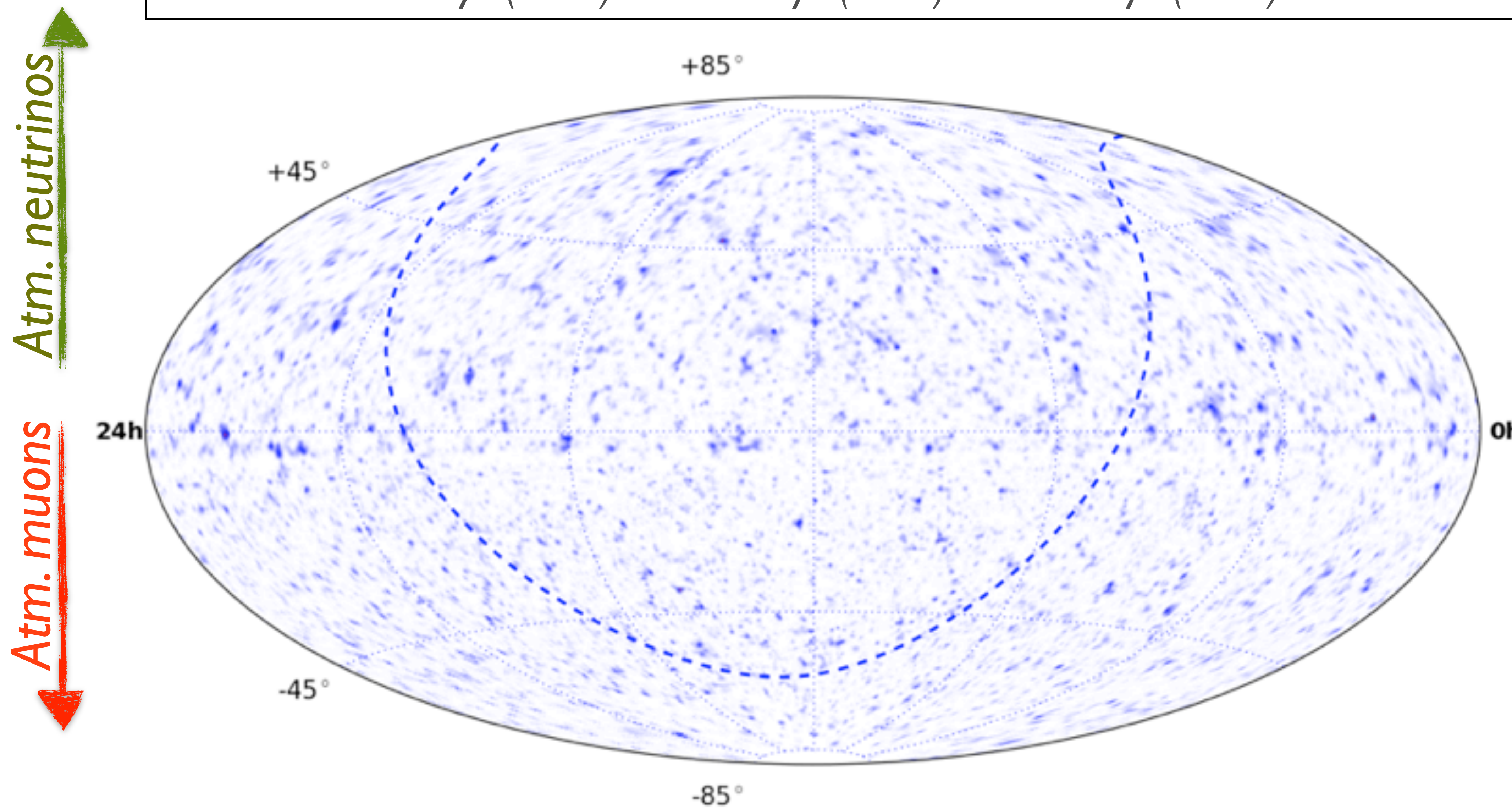
We use:



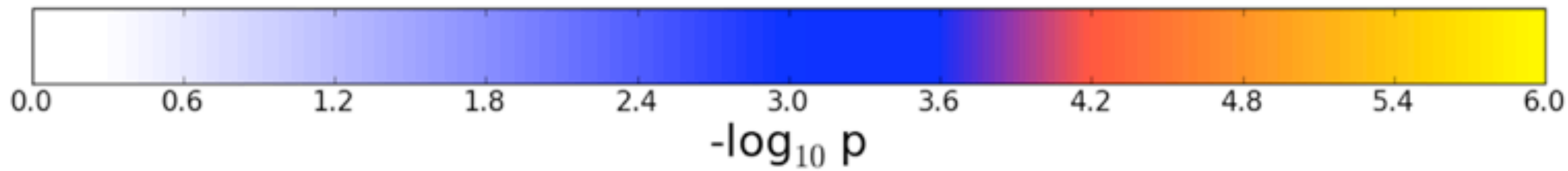


3 Years Skymap

- *Total events (IC40+IC59+IC79): 108317 (upgoing) + 146018 (downgoing)*
- *Livetime: 316 days (IC79) + 348 days (IC59) + 375 days (IC40)*



Accepted for publication in ApJ: http://arxiv.org/abs/1307.6669



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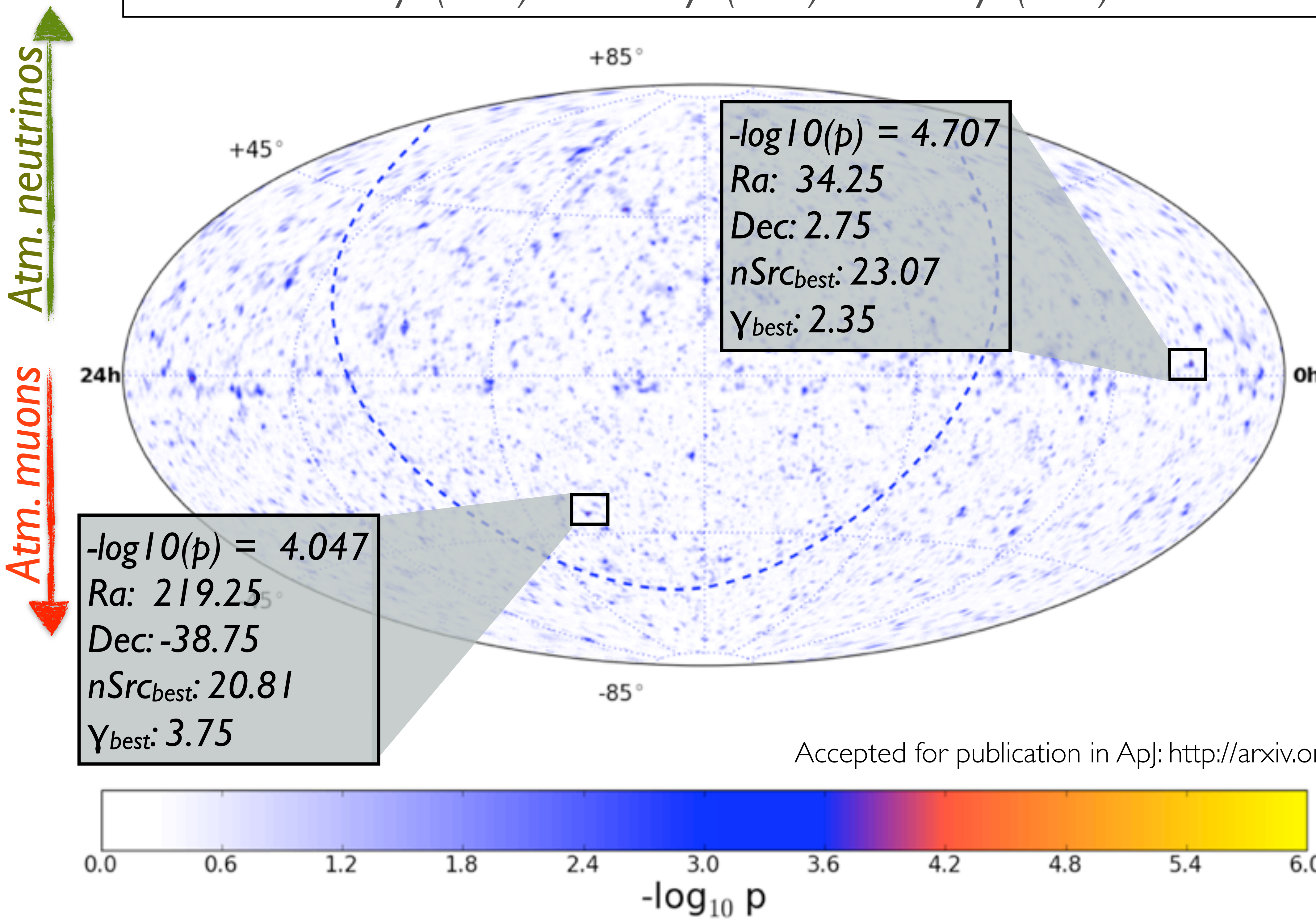

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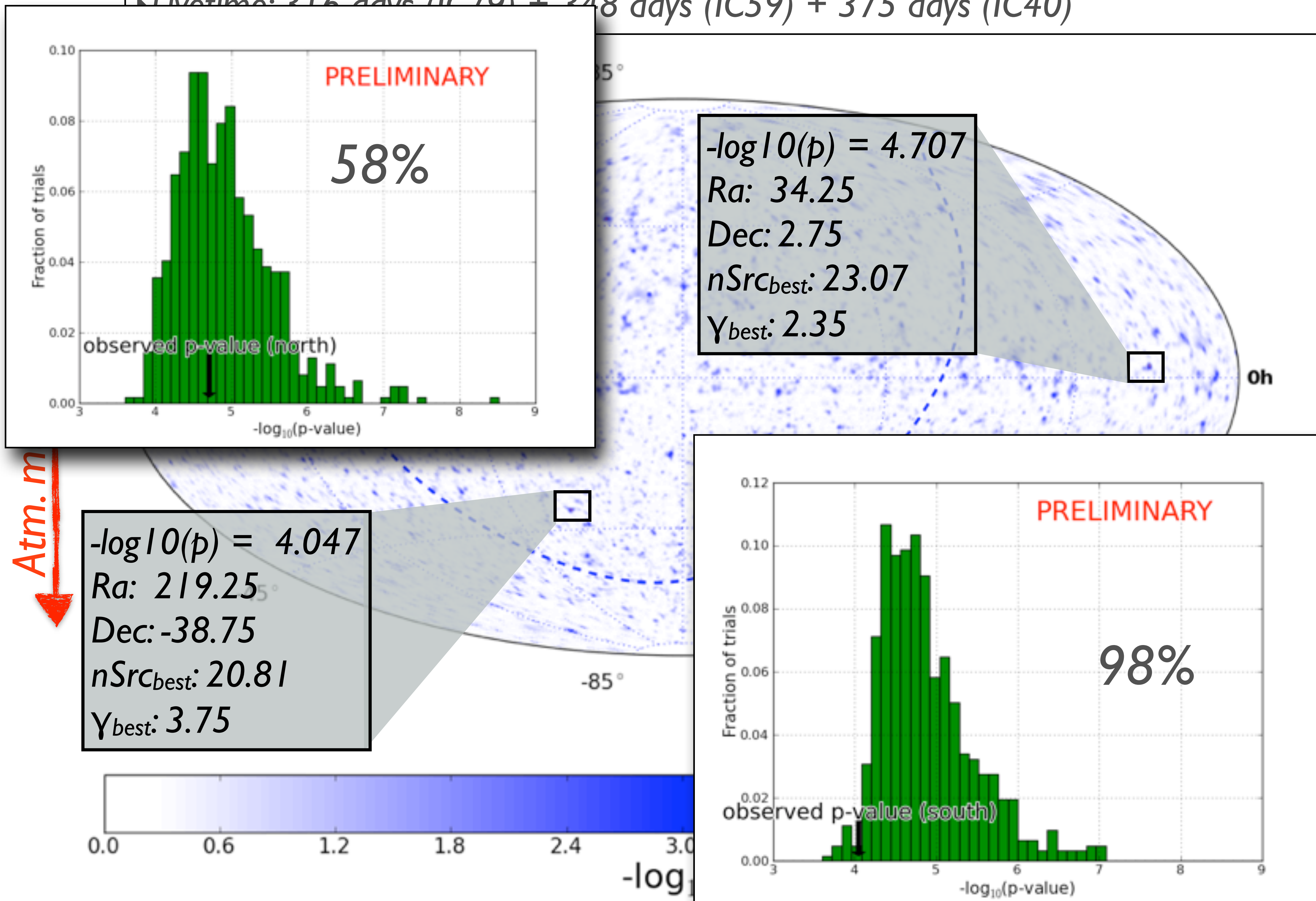
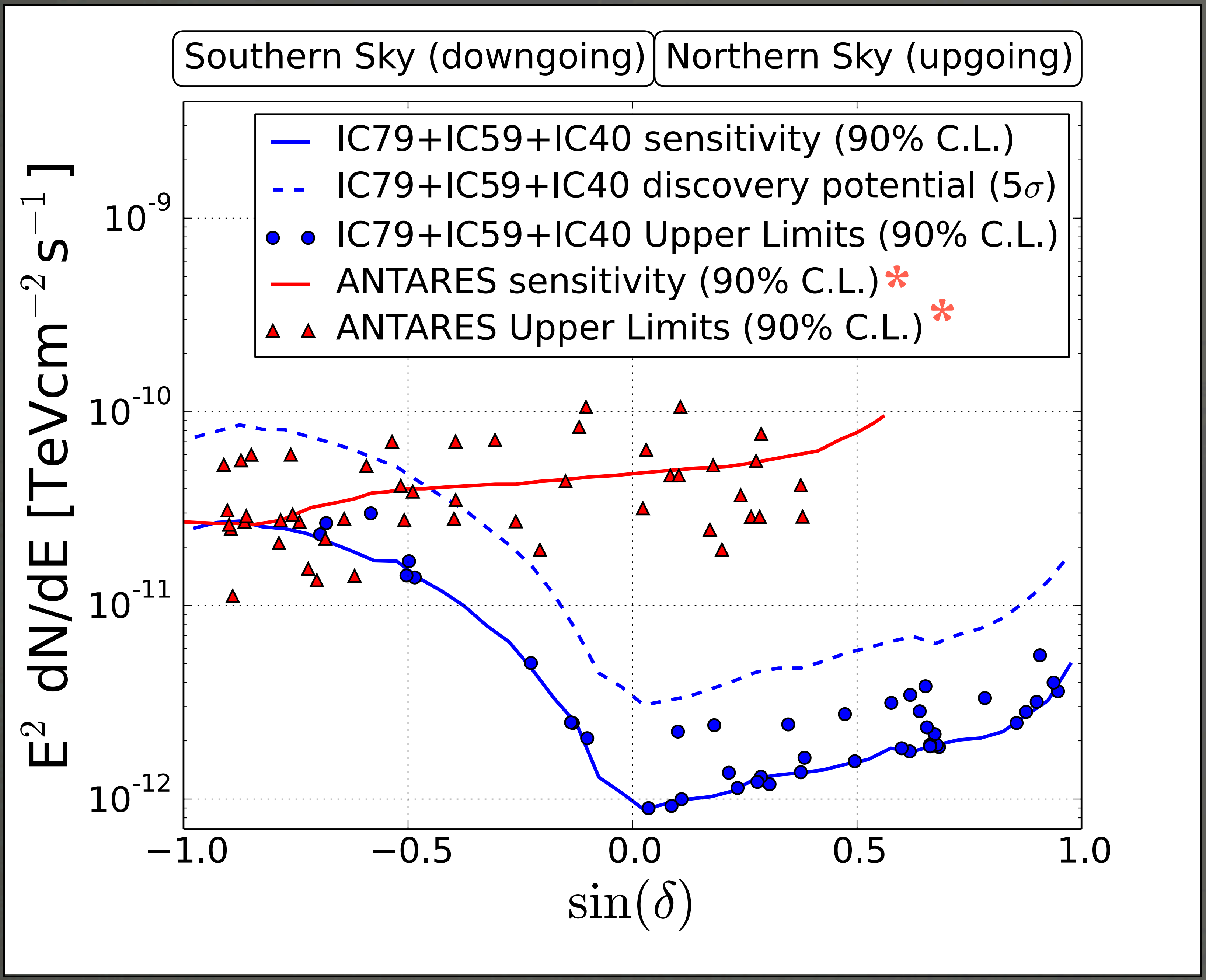
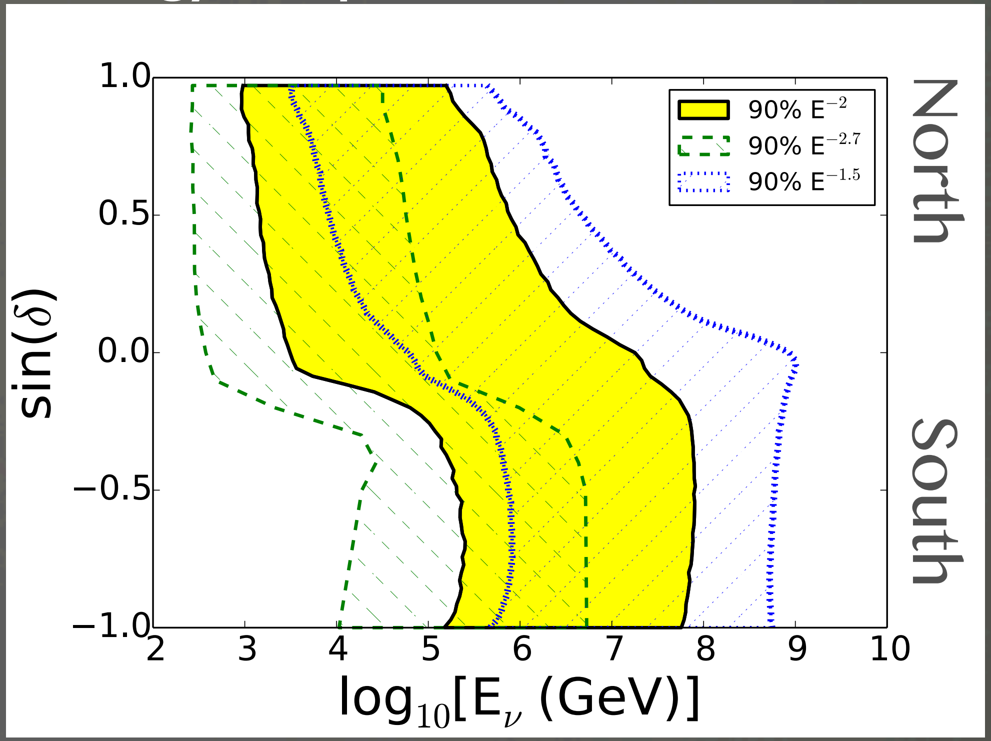


3 Years Upper Limits

Accepted for publication in ApJ: http://arxiv.org/abs/1307.6669



Energy response North/South



Energy range for E^{-2} muon neutrino upper limits:

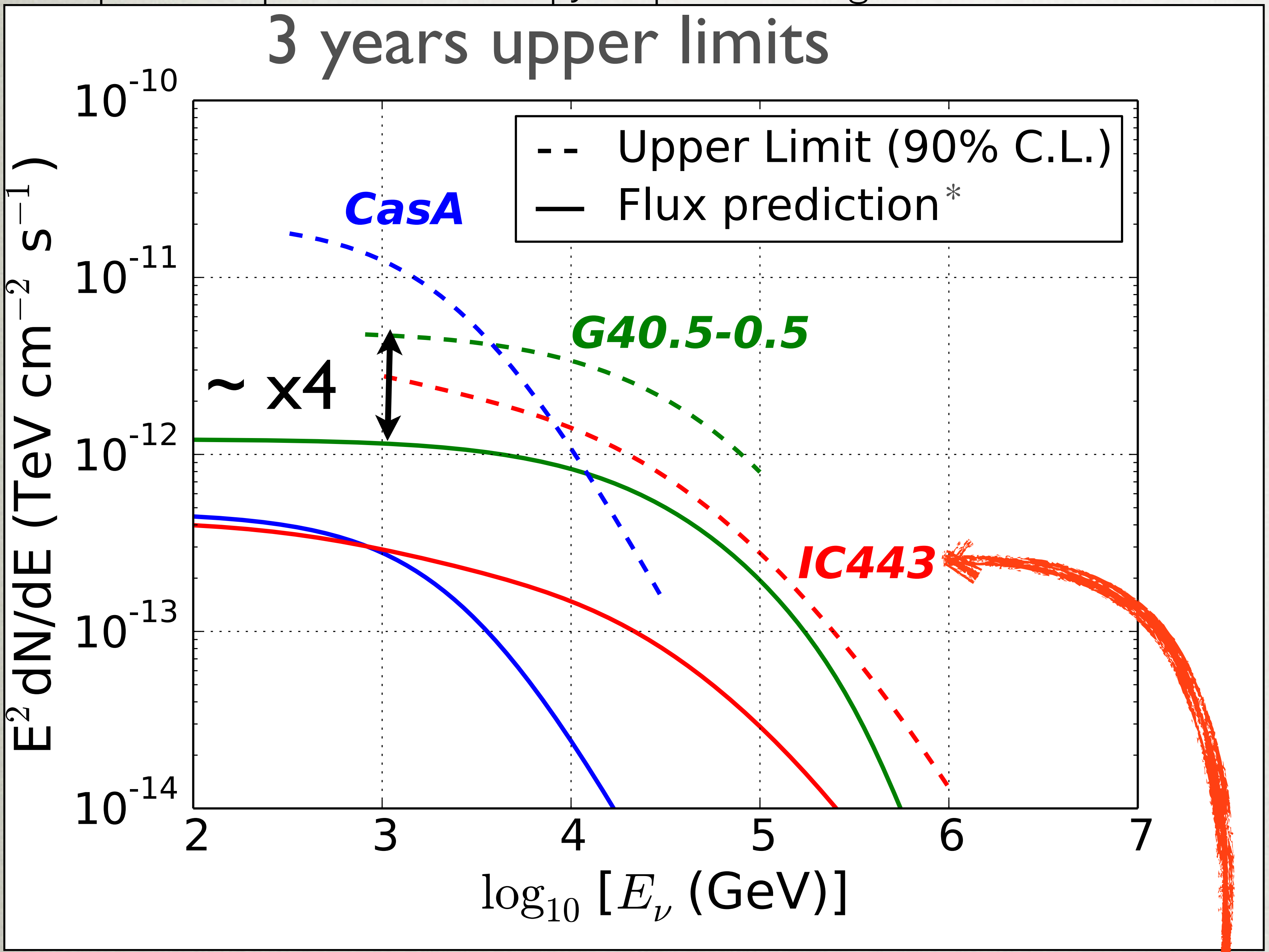
1 TeV - 1 PeV North

10^2 TeV - 10^2 PeV South

*S. Adrián-Martínez et al. Submitted to Astrop. J., arXiv:1207.3105

Limits on Supernova Remnants

Accepted for publication in ApJ: http://arxiv.org/abs/1307.6669



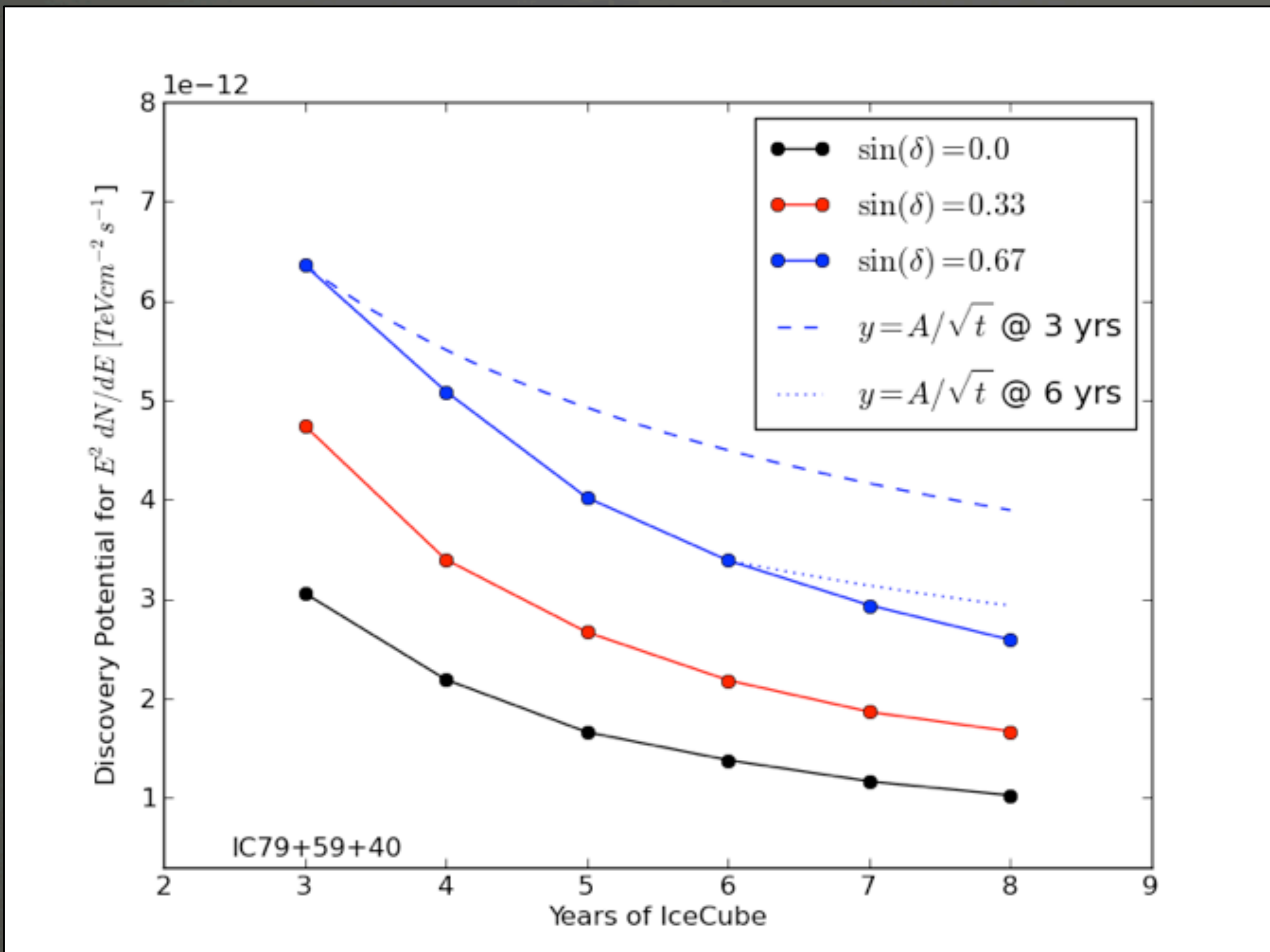
Still a bit far to exclude/detect SNRs (**factor ~ 4**).

But, cut-off energies imposed by assuming SNR as sources of CR up the *knee*. Limits without cut-off closer to models.

*M. Mandelartz, J. Becker Tjus. http://arxiv.org/abs/1301.2437

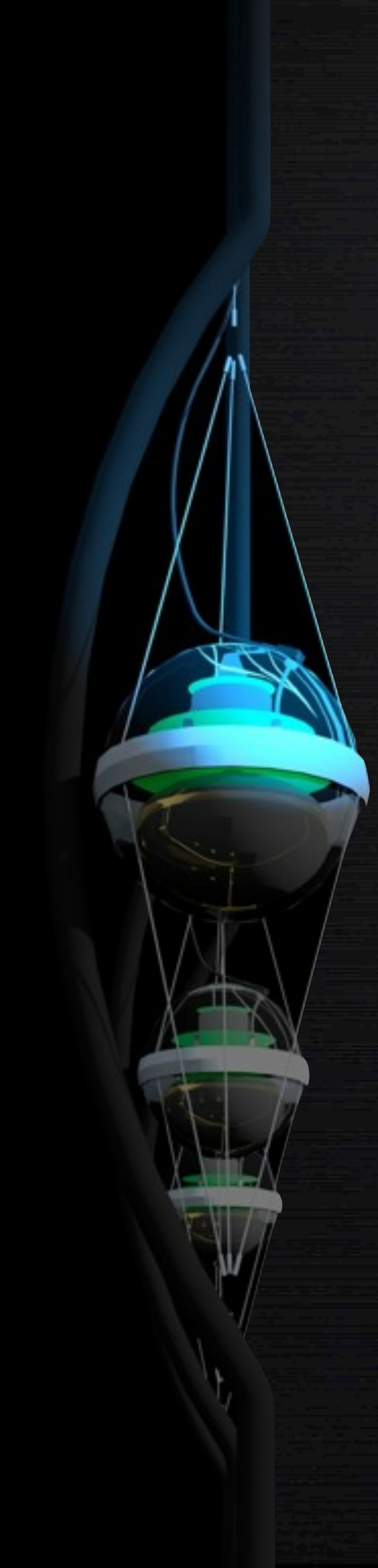
ONE OF THE FERMI CONFIRMED HADRONIC SOURCES

Future Expected Performance



Discovery potential increases more than sqrt(t) for E^{-2}.

Expect a significant additional increase by further improving angular resolution at higher energies.



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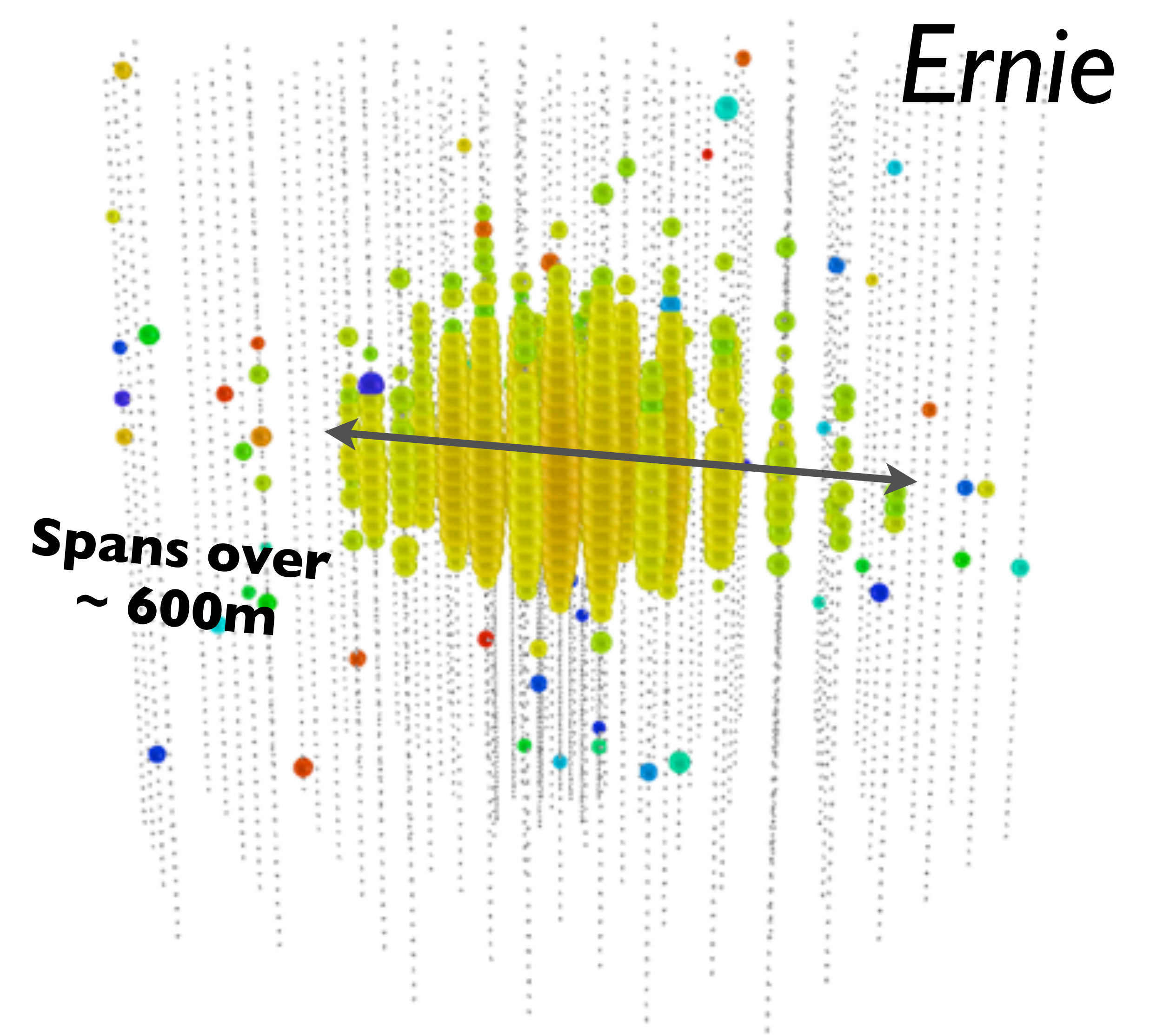
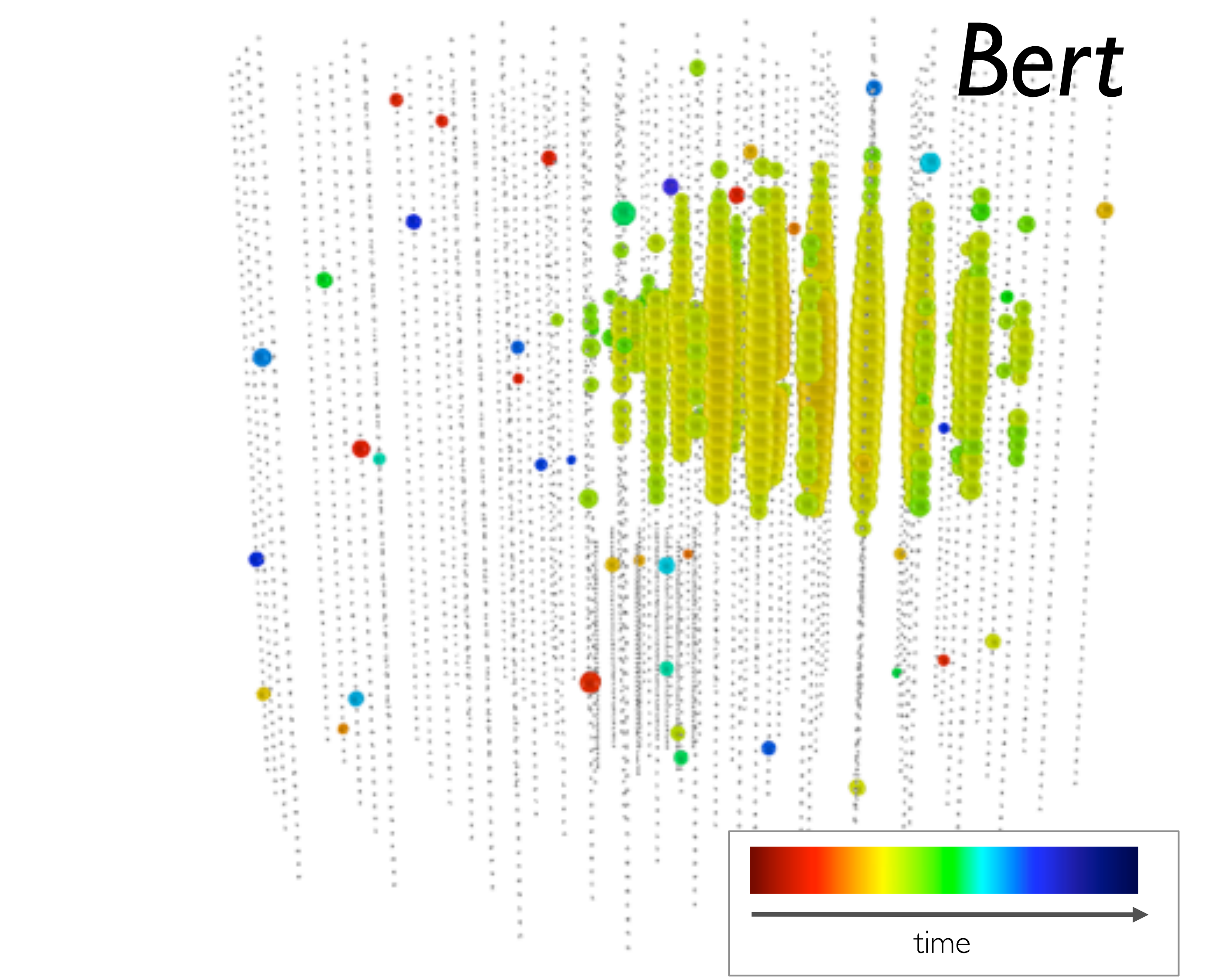
First PeV Neutrinos: 

Two very interesting events in IceCube (IC79/IC86)



1.1 +/- 0.2 PeV

http://www.youtube.com/watch?v=10Uv-glXJrc



1.0 +/- 0.2 PeV

http://www.youtube.com/watch?v=8AAEkOKLpaY

First PeV Neutrinos

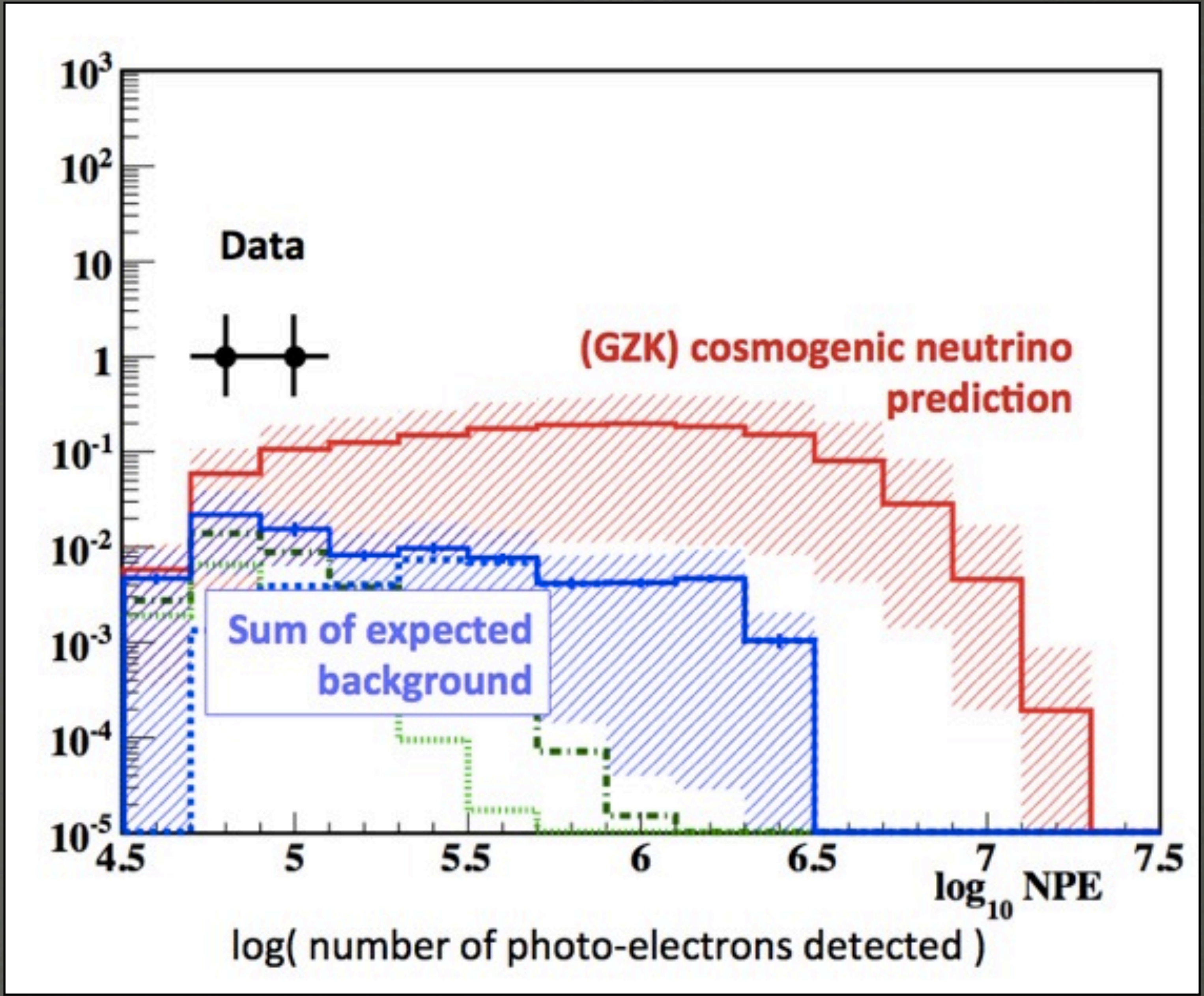
Physical Review Letters 111 (2013) 021103: arXiv:1304.5356

- Analysis targeting much higher energy neutrinos (related to GZK cutoff)
- Expected background:

  0.08 ± 0.05

- Significance:

  2.8σ

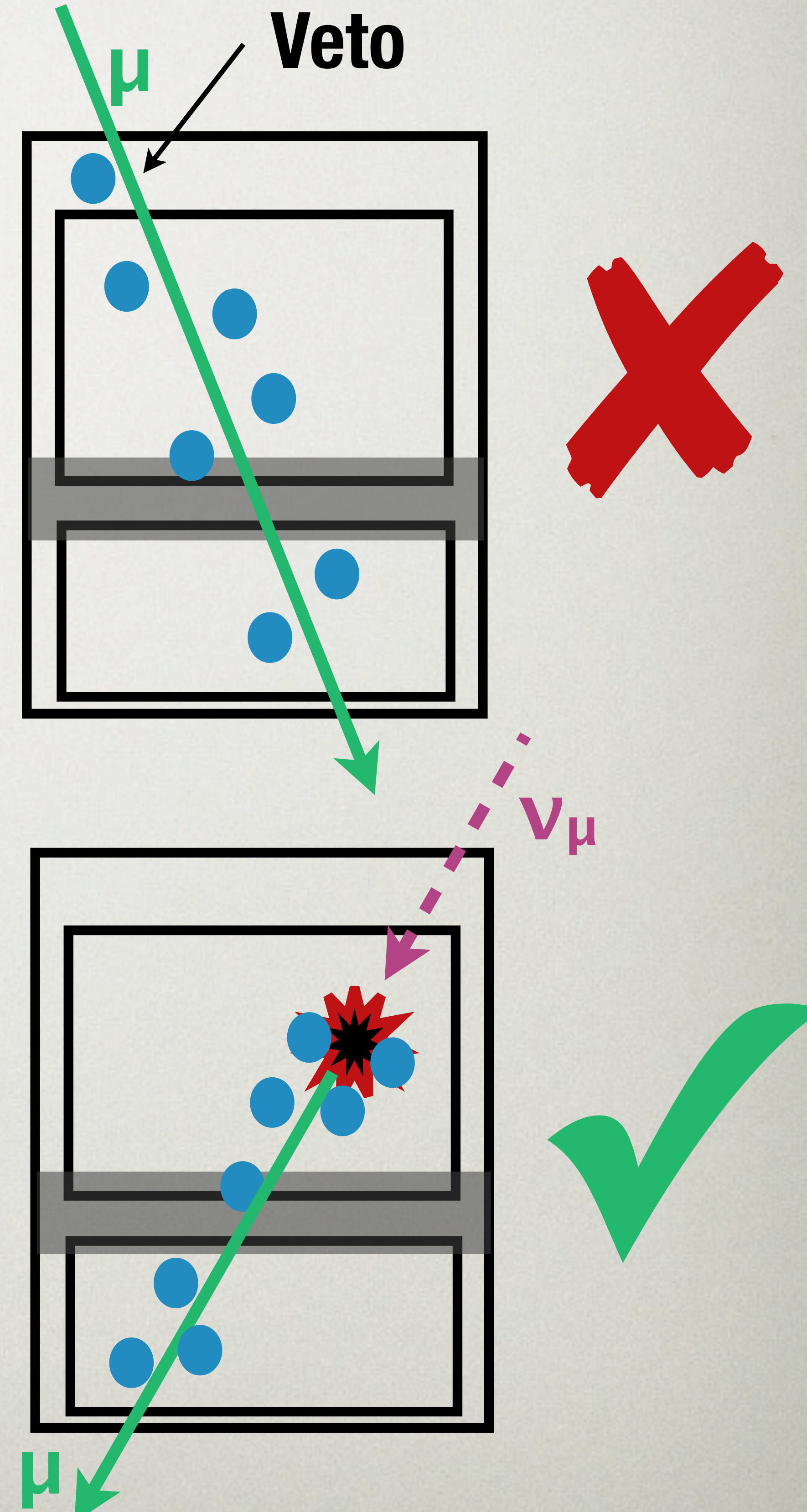


Too low in energy for GZK
Too high in energy for atmospheric

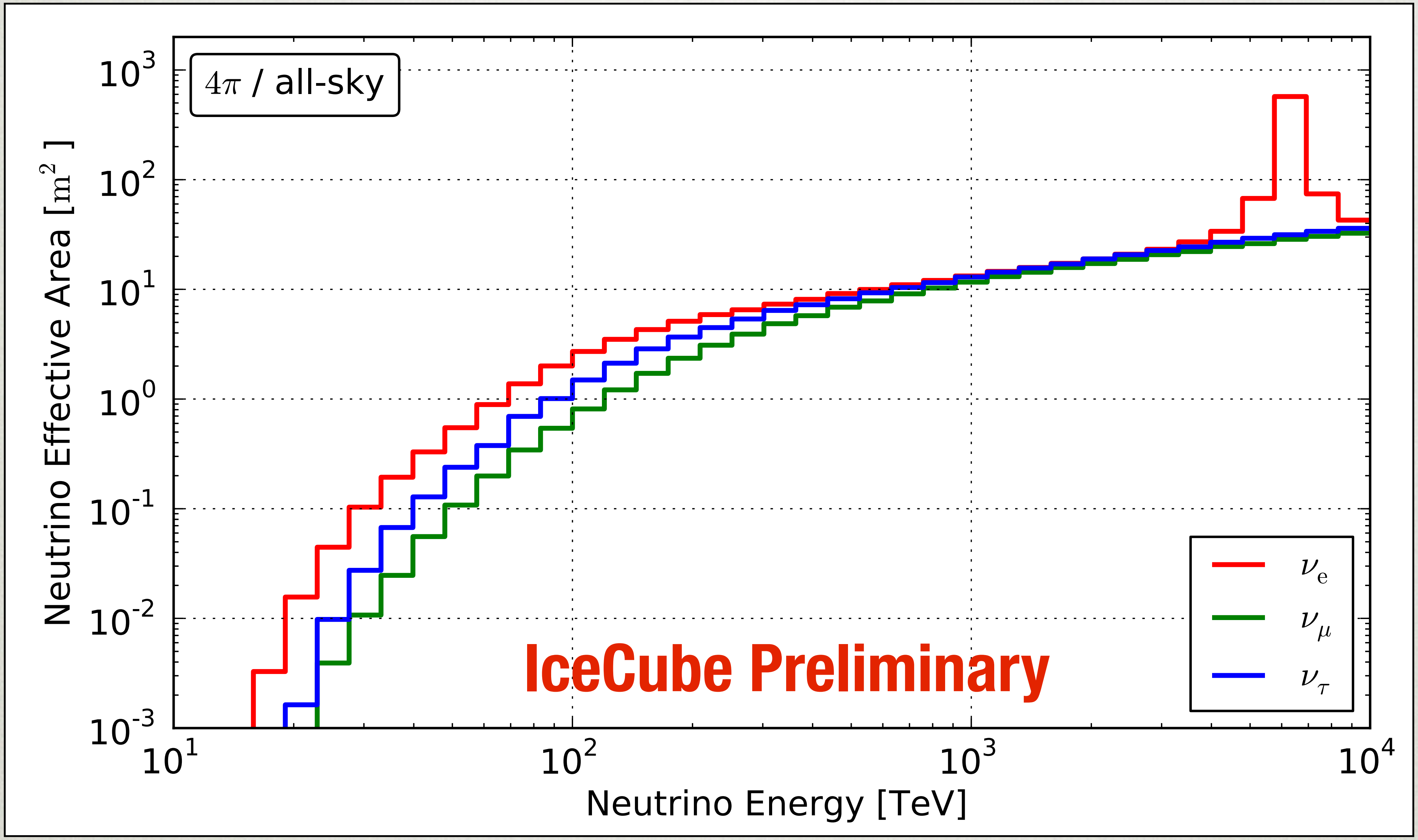
High Energy Starting Events

Analysis of dataset taken from May 2010 to May 2012 (662 days of livetime)

- Idea proposed in 2008 (arXiv:0812.4308)
- Golden channel: “down-going starting events”
  - **High energies envets: Qtot > 6000 p.e.**
  - **Use out layer of detector as veto**
- Sensitive to all flavors in region above 60 TeV.



Effective Area

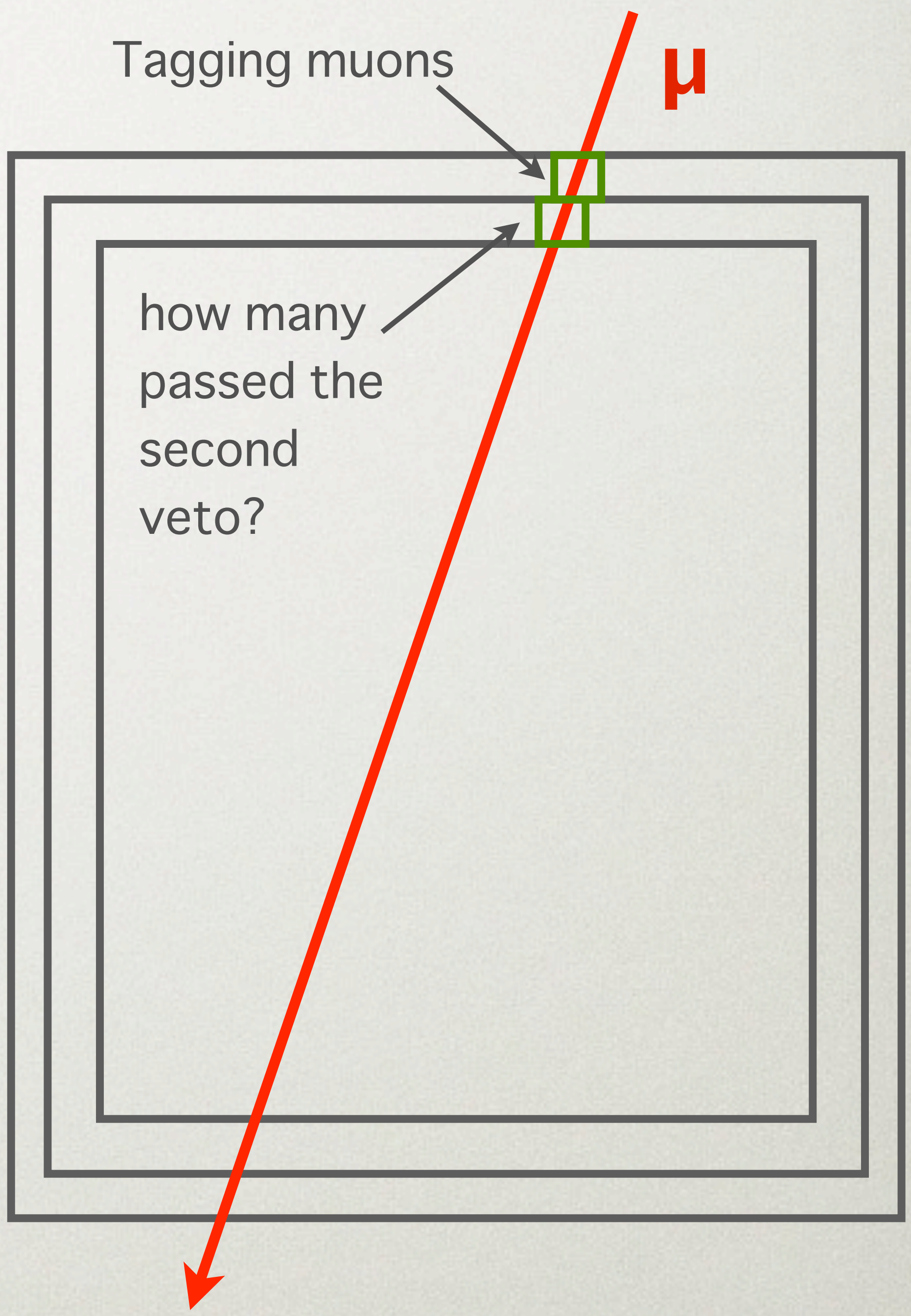


- Differences at low energies between the flavors due to leaving events at constant charge threshold

Atm. Muon Background

- Muons can (rarely) penetrate veto region
- Control sample available: tag muons with part of detector and see what fraction vetoed by another.
- Expected background (2 years):

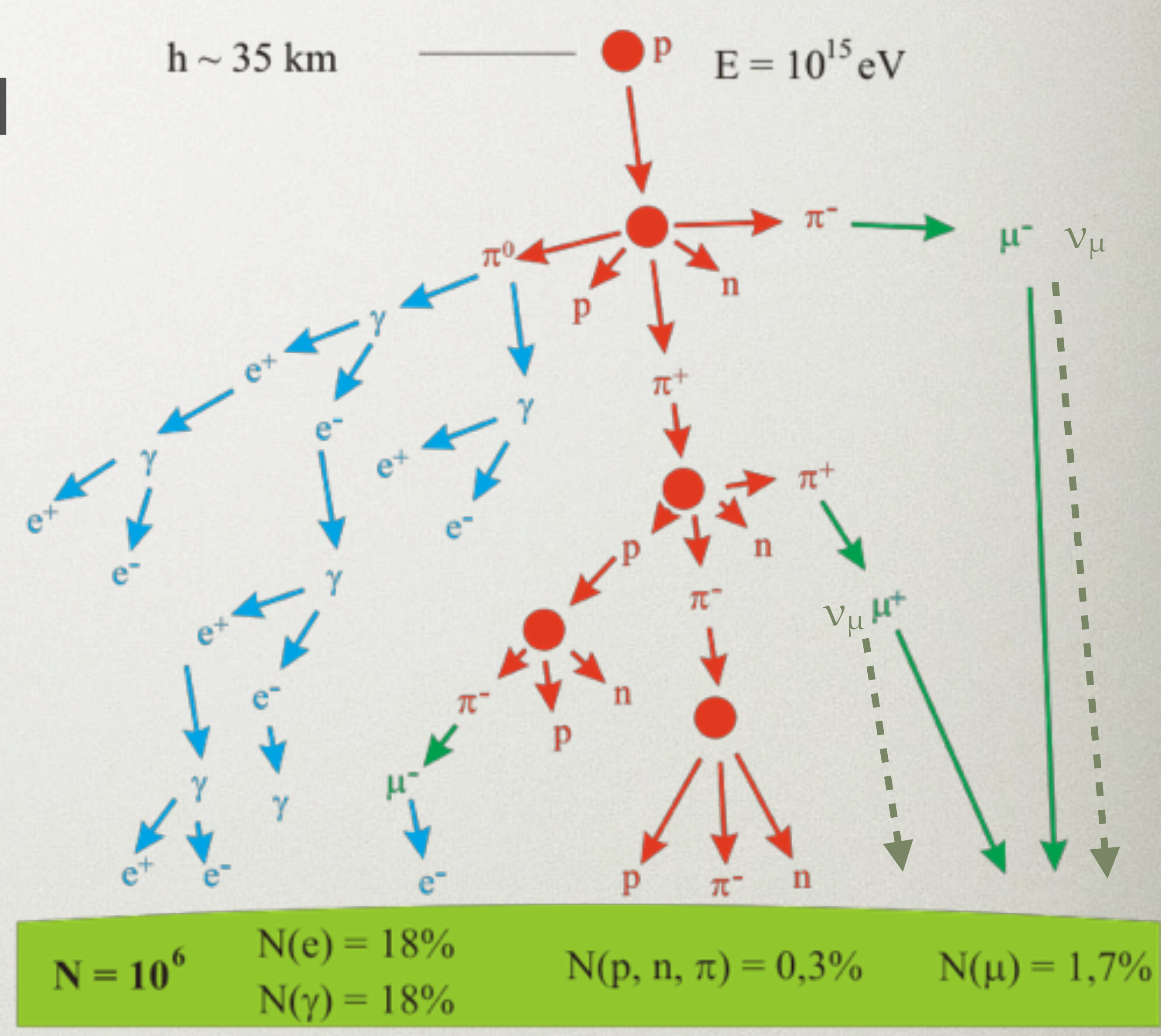
6 ± 3.4



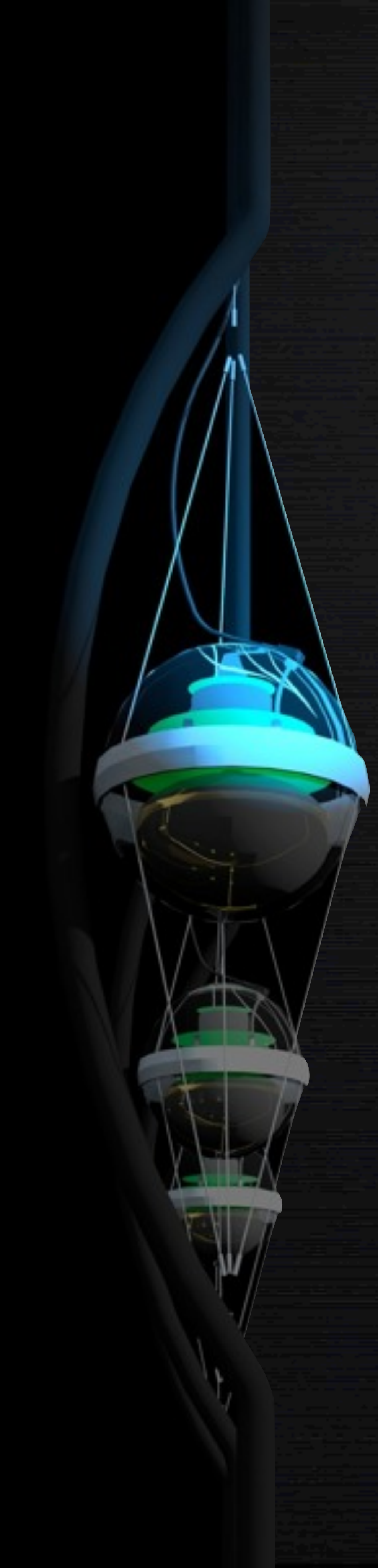
Atm. Neutrino Background

- Down-going atmospheric neutrinos will be accompanied by muons from the same shower.
- Down-going events that start in the detector are *extremely* unlikely to be atmospheric.
- Expected background (2 years):

$4.6^{+2.9}_{-1.9}$



Gaisser et al. arXiv:0812.4308



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The 28 events:

C. Kopper *et al.*, for the IceCube Coll., ICRC 2013 id 0650

7 track-like events

1° ang. resolution

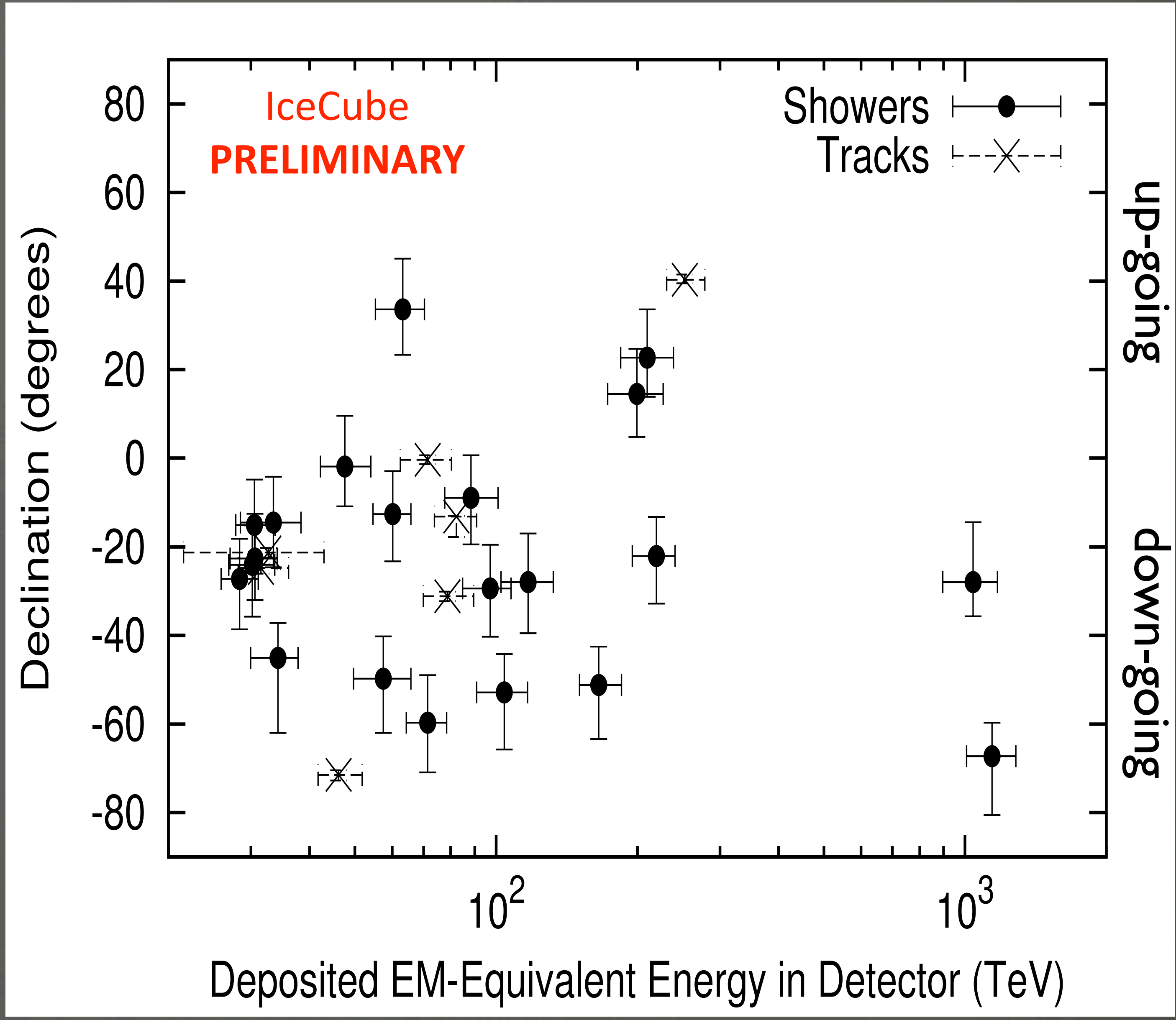
Muon takes some energy away

21 cascade-like events

10° – 45° ang. resolution

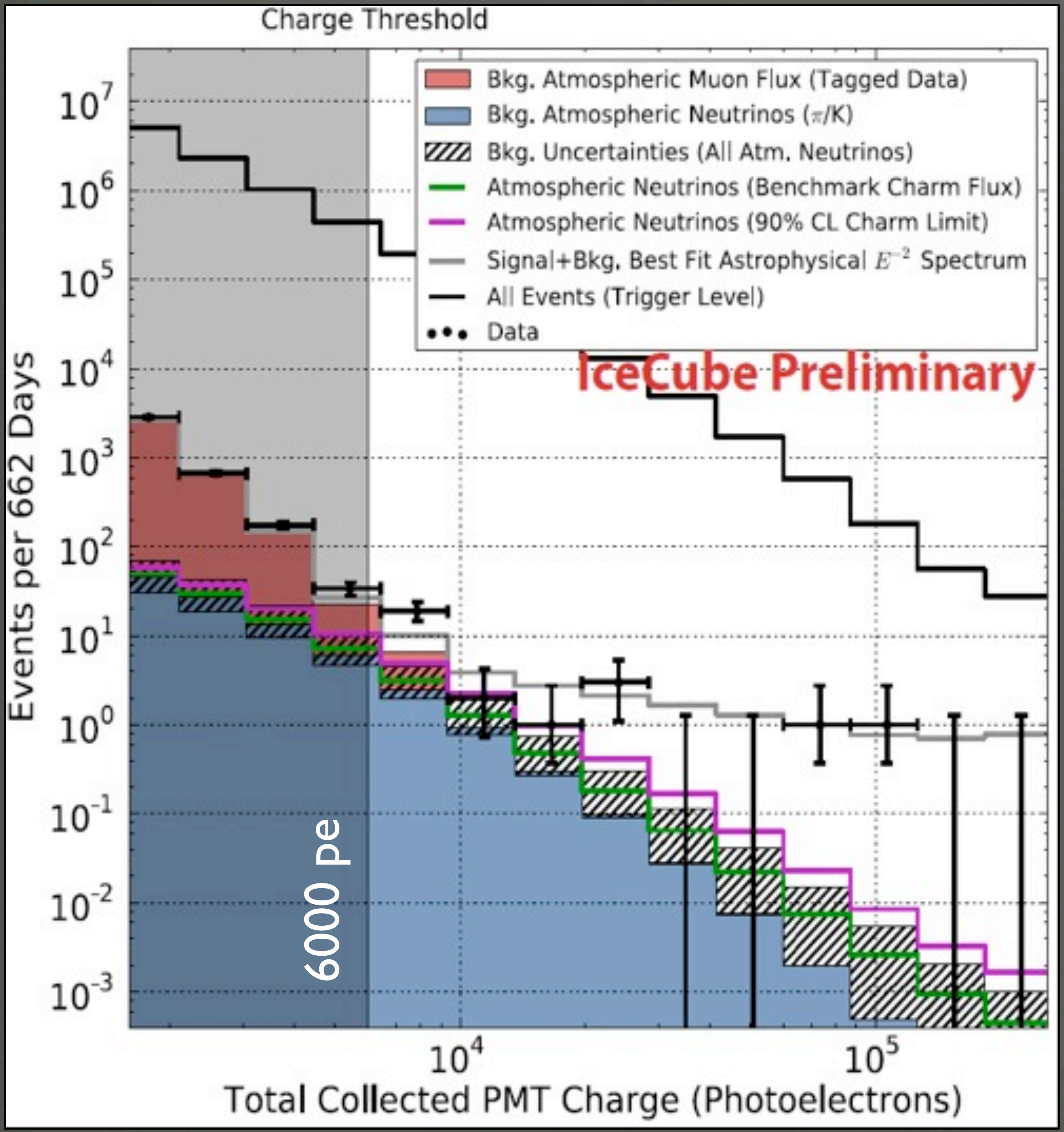
15% visible energy resolution

Track/cascade ratio consistent with neutrino oscillations & astrophysical origin.



Two populations of events? Not significant at present

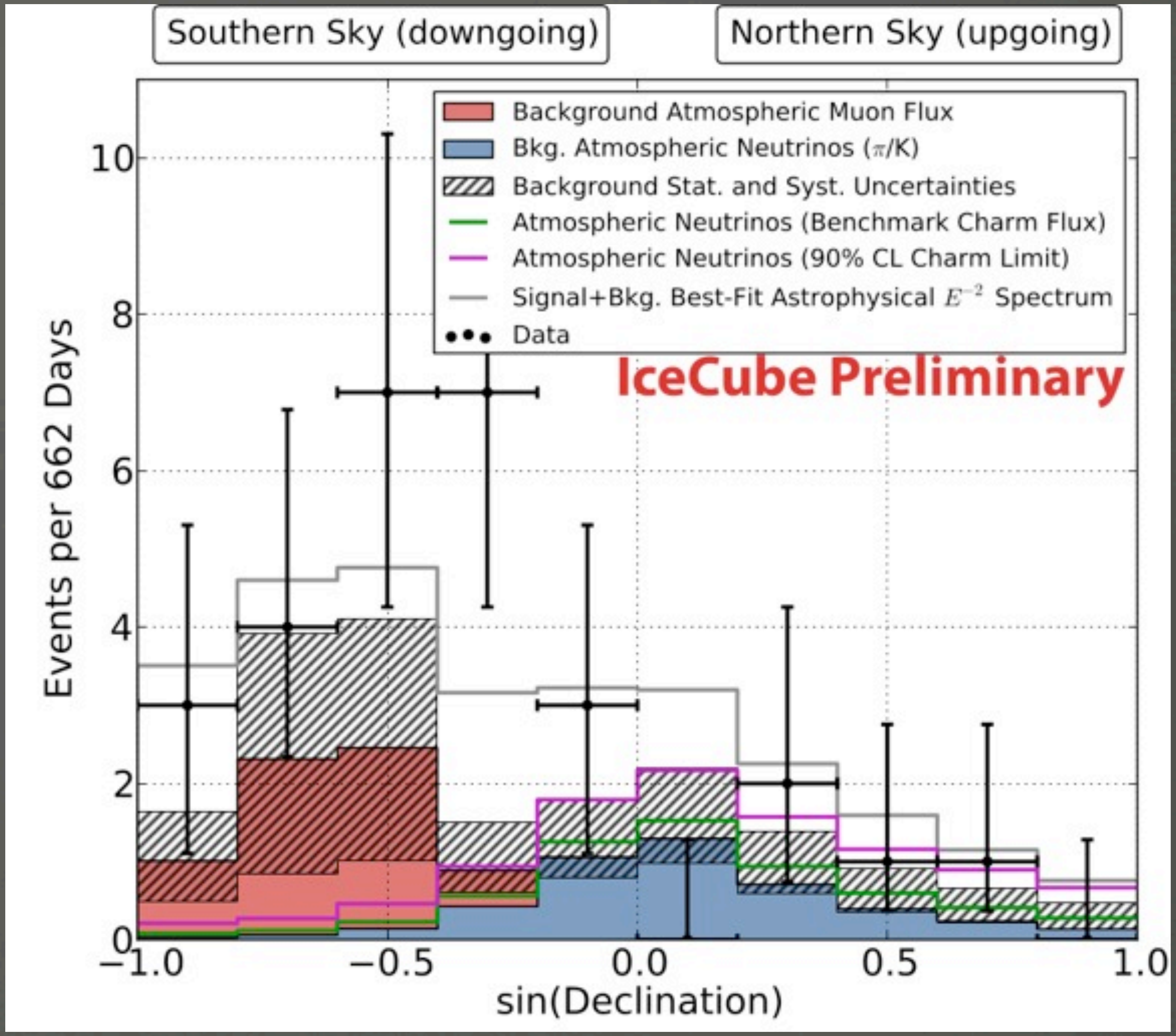
RESULTS: Meet the Muppets



- 28 events on a background of $10.6^{+4.5}_{-3.9}$
- Significance from pre-defined test (w/o Bert & Ernie): 3.6σ
- Including GZK result (2.8σ): **4.3σ**
- A posteriori including B&E: 4.9σ

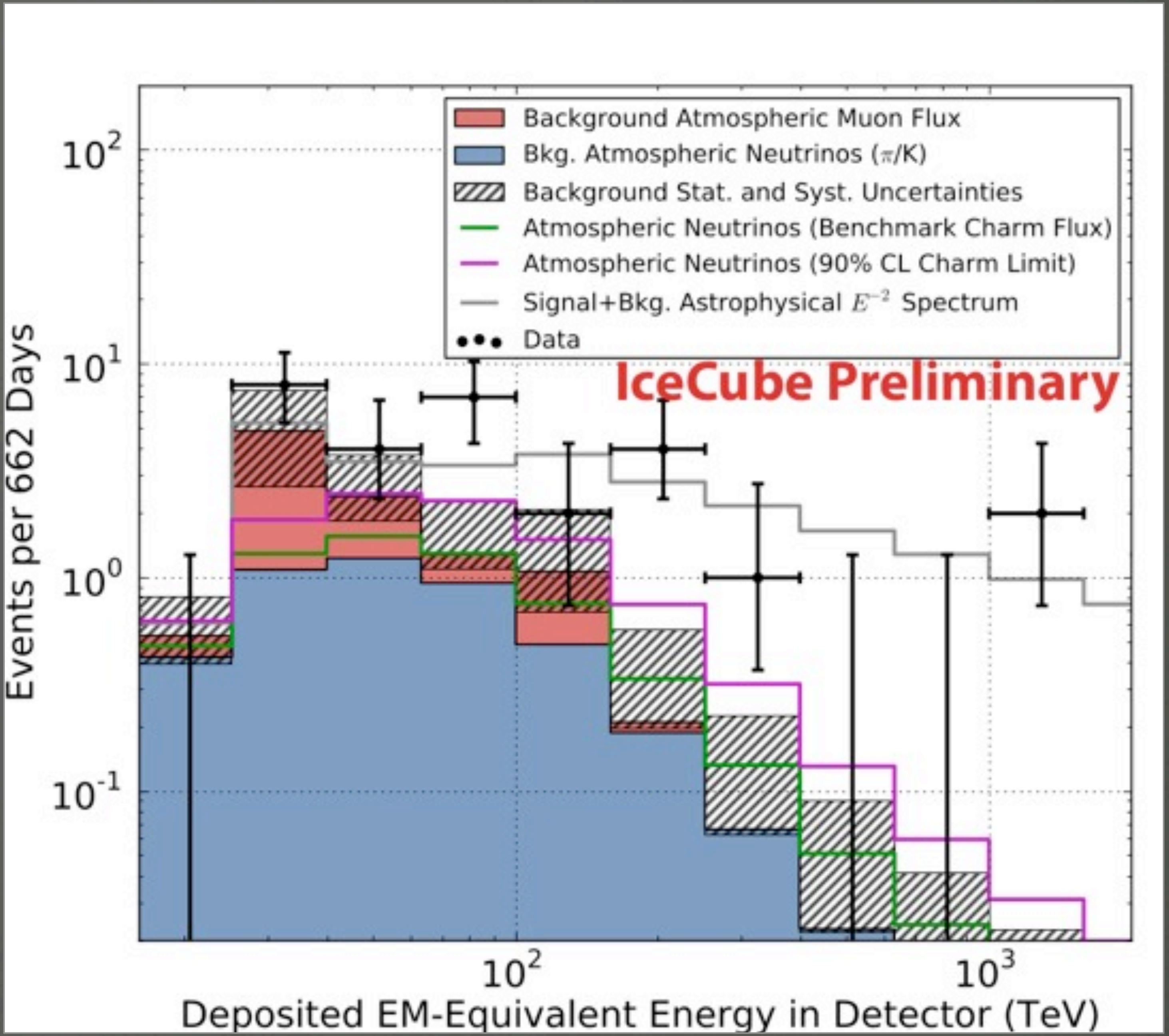
Declination Distribution

- Most astrophysical events expected from above (Southern Sky)
- Caveat: Data is reconstructed angles. Simulation is true angles.



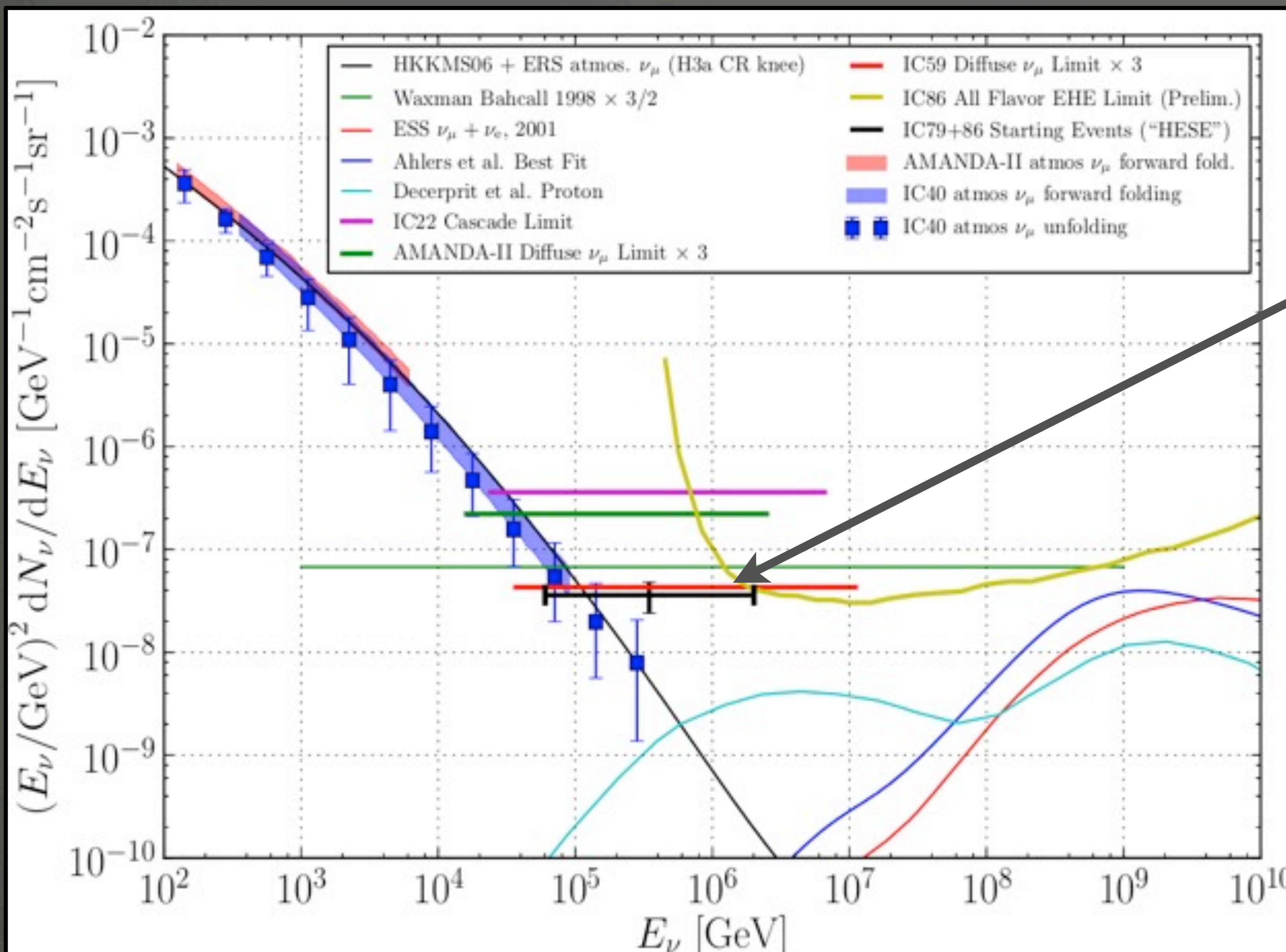
Energy Spectrum

- Harder than any expected atmospheric background.
- Hatched region includes stat.+sys. for atm. muons and neutrinos



Fit for Astronomical Component

Fit on energy range: 60 TeV < E_{dep} < 2 PeV



1) E^{-2}, no cutoff:

$E^2\Phi \sim 1.2 \pm 0.4 \times 10^{-8}$ GeV $cm^{-2}\ s^{-1}\ sr^{-1}$

2) Free spectrum

or

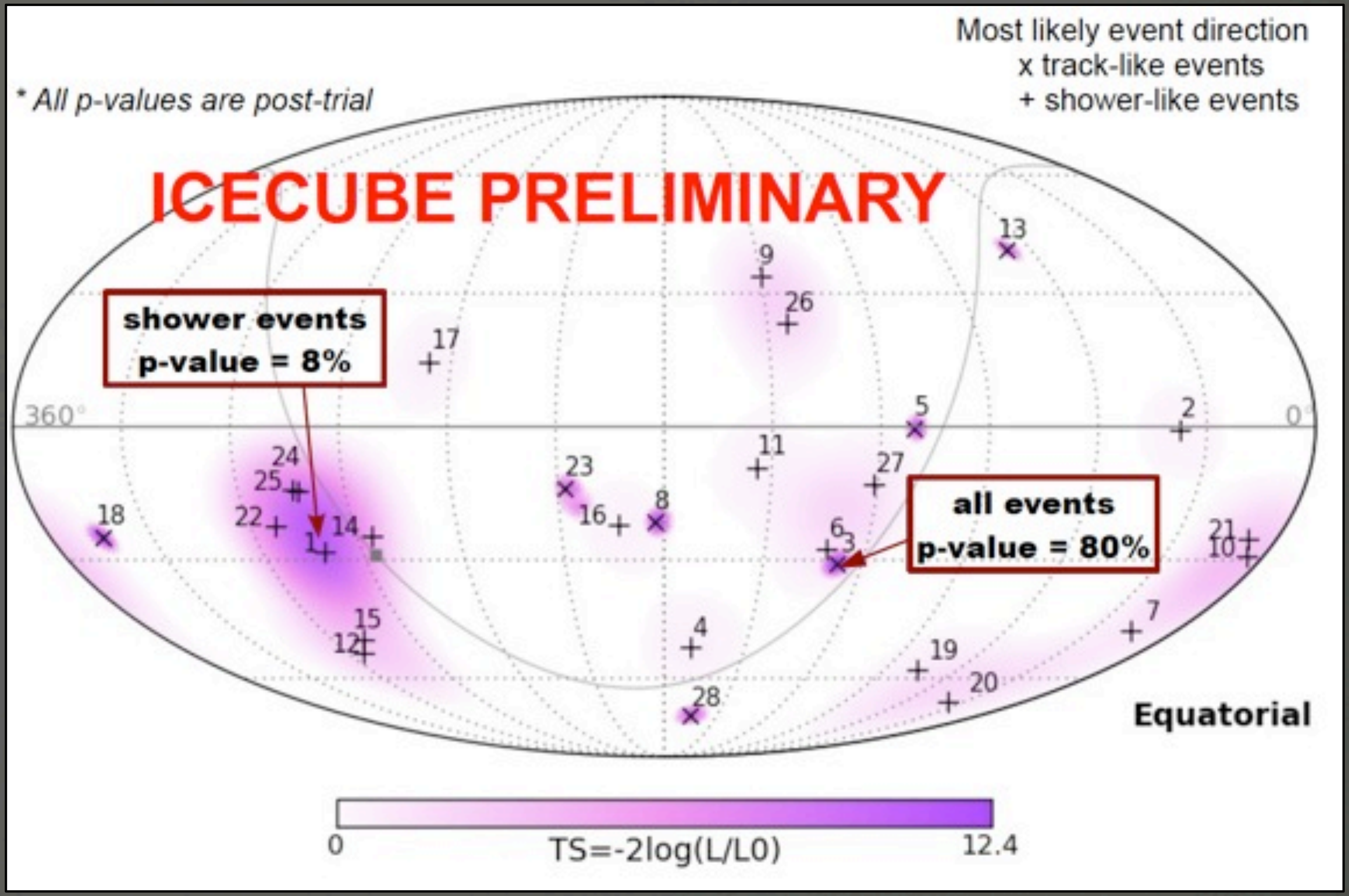
Free hard cutoff:

Spectral shape: $E^{-2.2\ +/-\ 0.4}$

Hard cutoff: $1.6\ ^{+1.5}_{-0.4}$ PeV

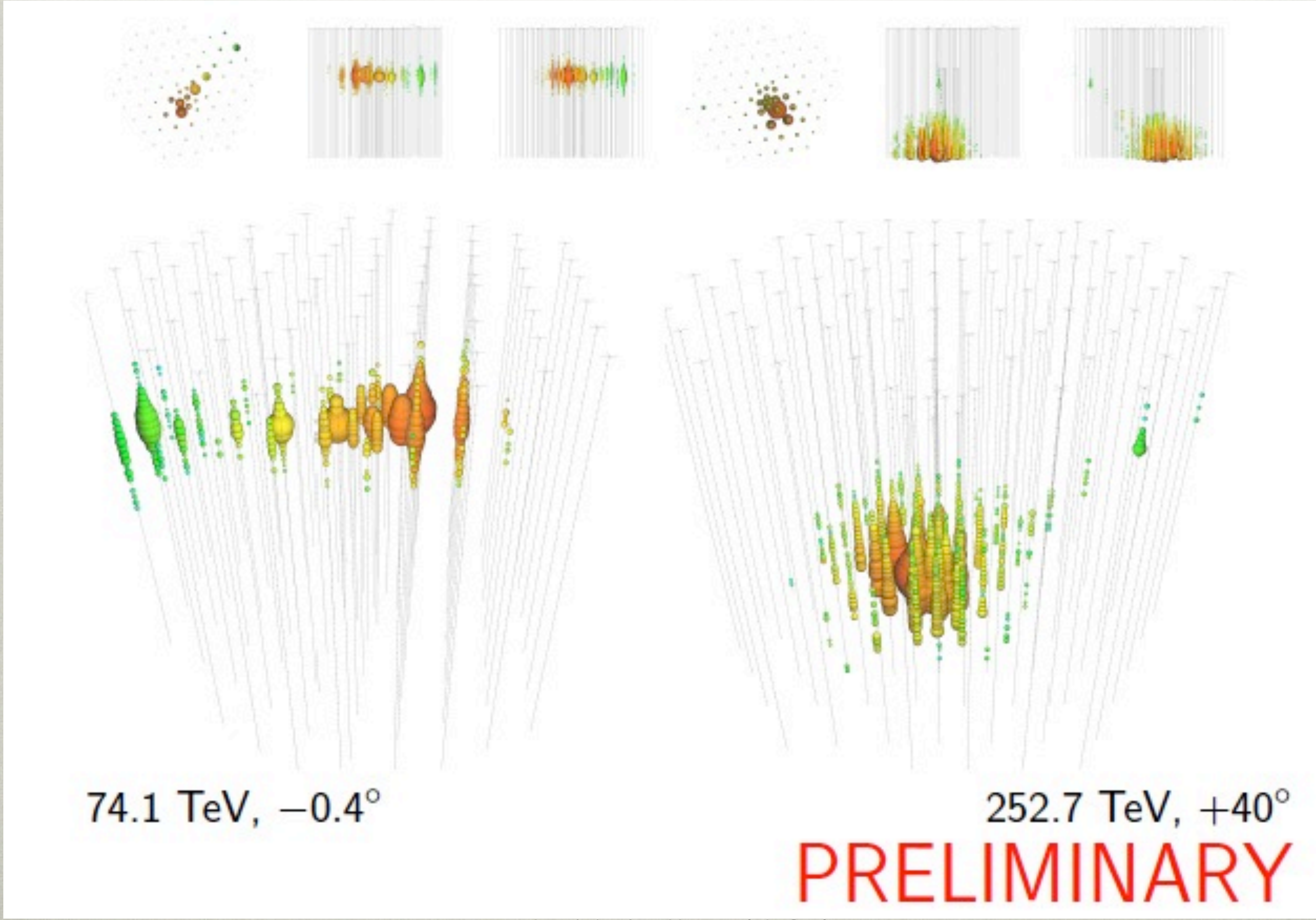
Clustering Analysis

- Analyzed with a variant of the standard PS method w/o energy (i.e. scrambling in RA → Insensitive to features in declination)
- Most significant excess only for showers: 8%
- Other searches (multi-cluster, galactic plane, time clustering) not significant either.

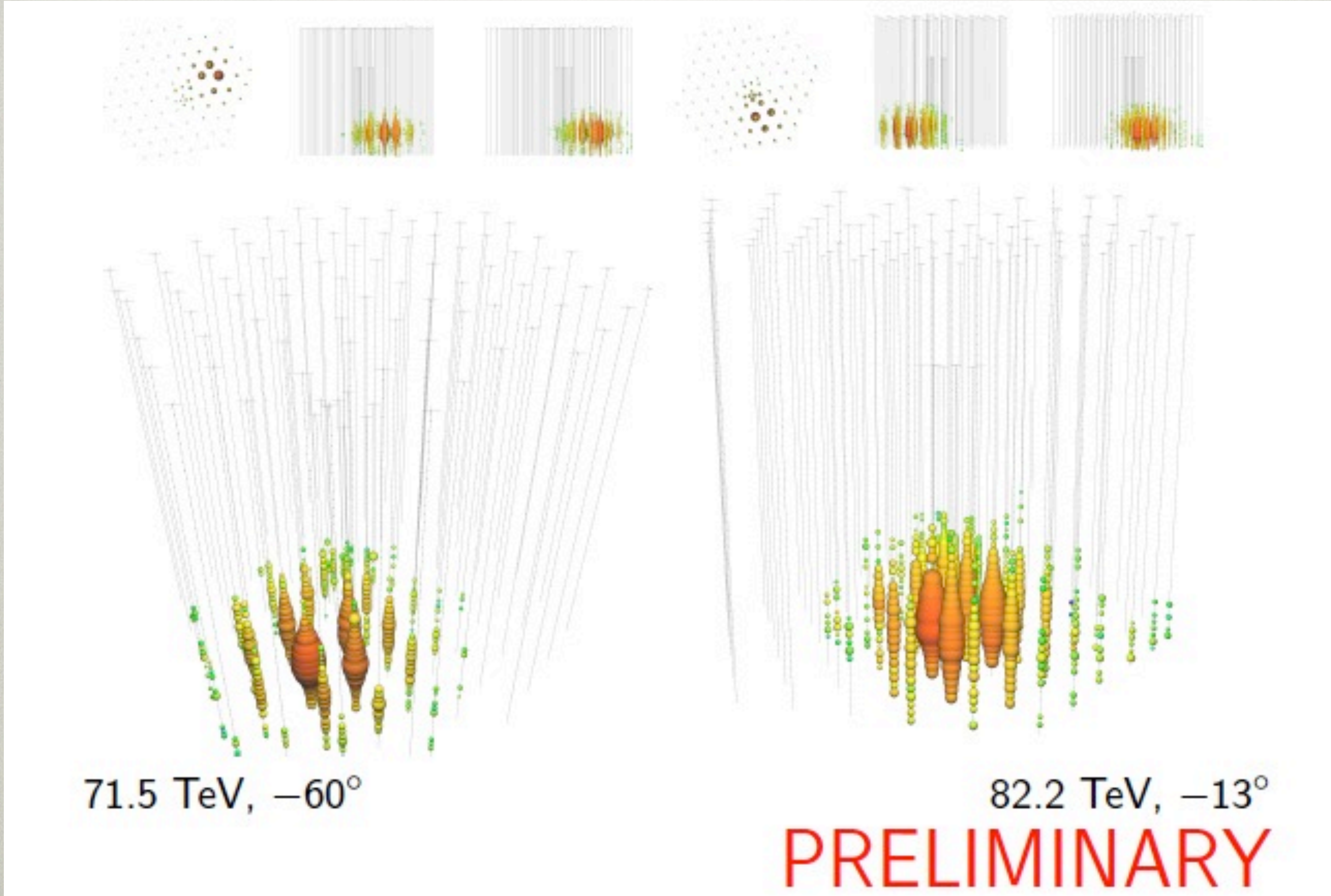


p-values are post-trial for that search
(no trial factor among searches)

Sample events: Two tracks



Sample events: Two cascades

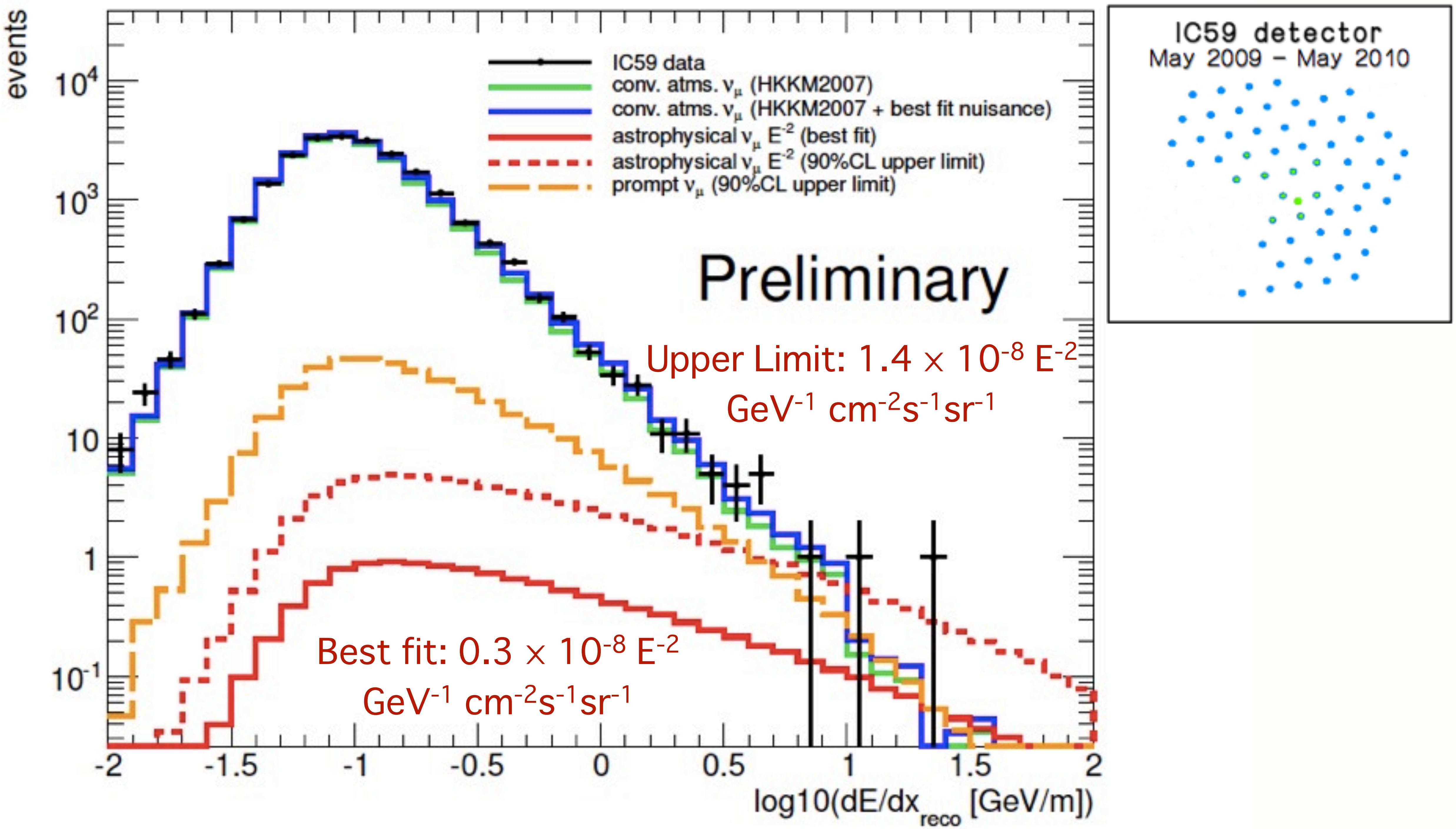


Conclusions

- ***No evidence of neutrino point sources.***
- Discovery potential for point-sources increasing at a higher rate than sqrt(t)
- ***Evidence for high energy extraterrestrial neutrinos.***
- Two events beyond 1 PeV observed (Ernie & Bert) in a cosmogenic neutrino search.
- A contained starting track analysis has uncovered an additional 26 events. Joint observations are inconsistent with atmospheric origin at the **4.3 σ** level.
- Observations compatible with an **astrophysical origin**.
- Paper accepted in Science.
- More data and analyses coming up soon!

- Back-up slides

IC59 diffuse analysis

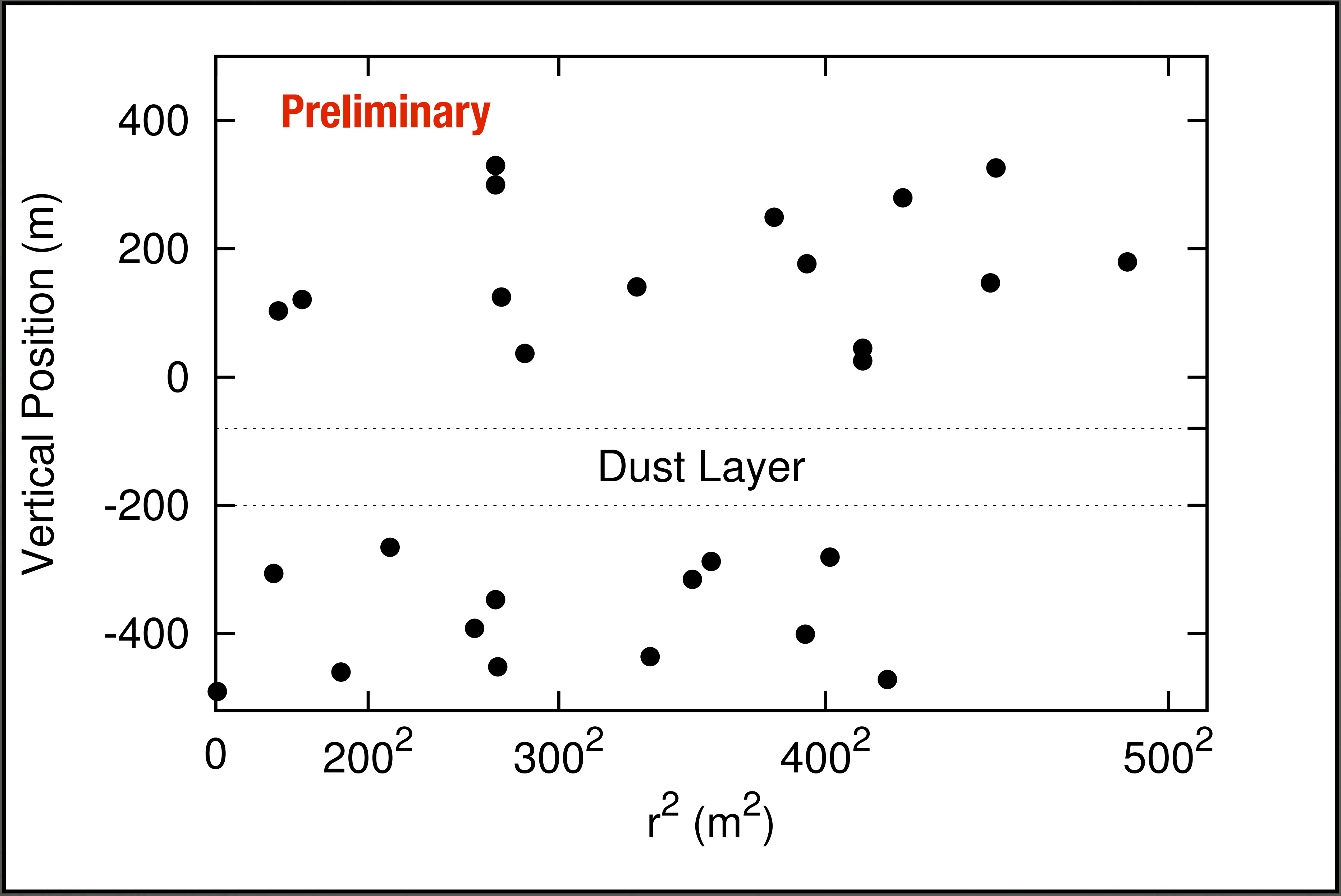


- Significance: 1.8σ

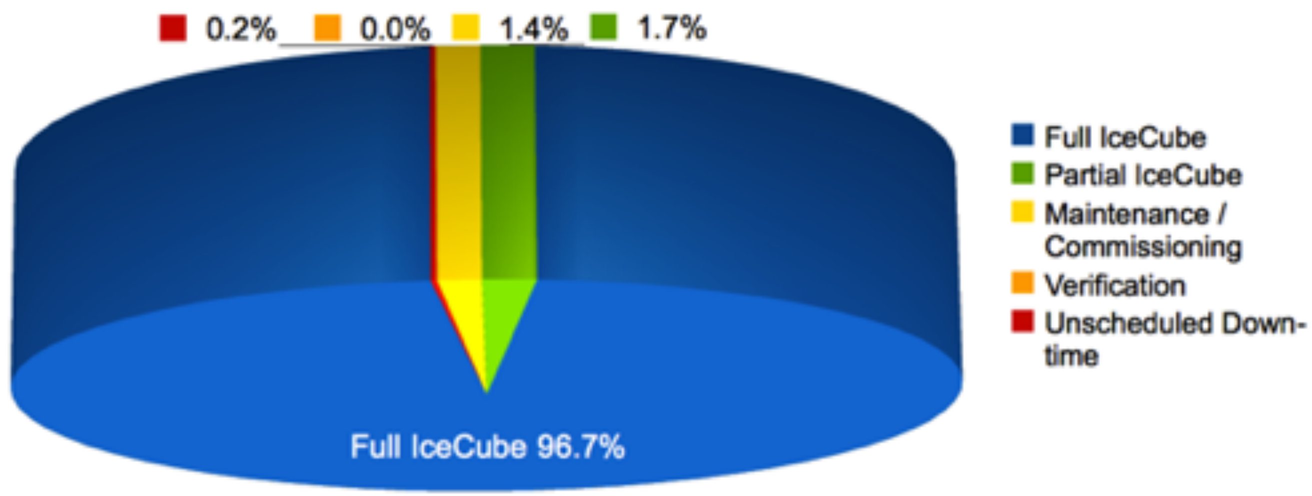
arXiv:1302.0127

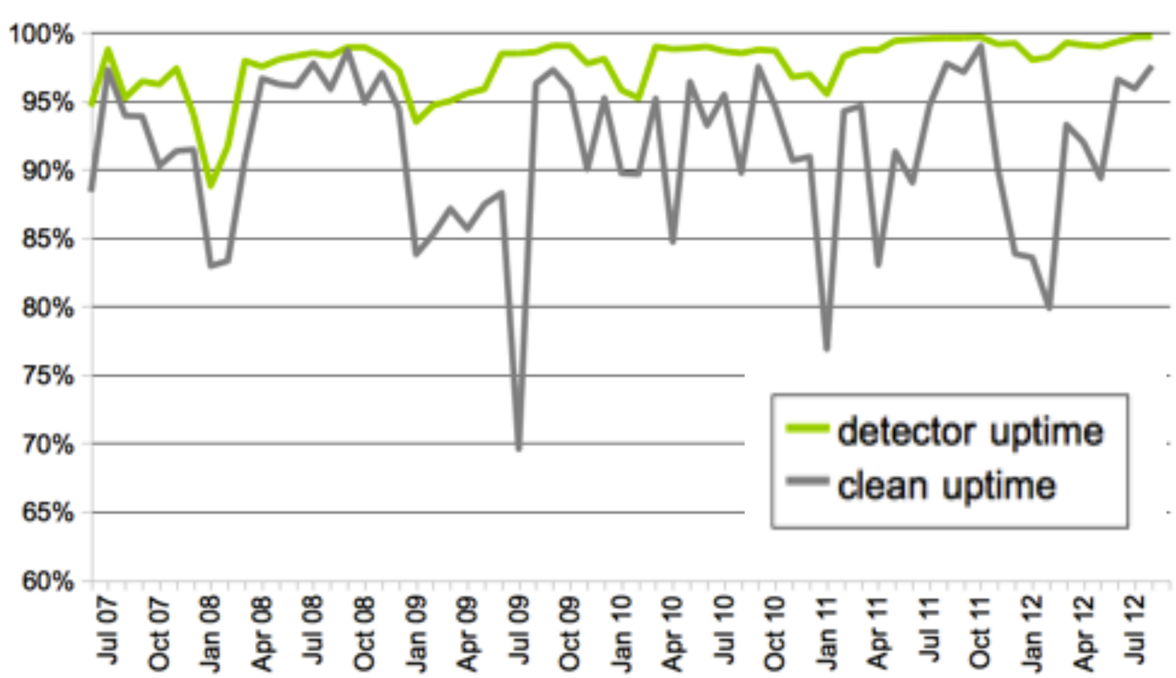
Event distribution in the detector

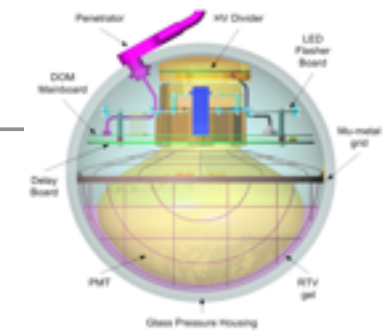
- Background events will accumulate in the edges of the veto region



Detector performance







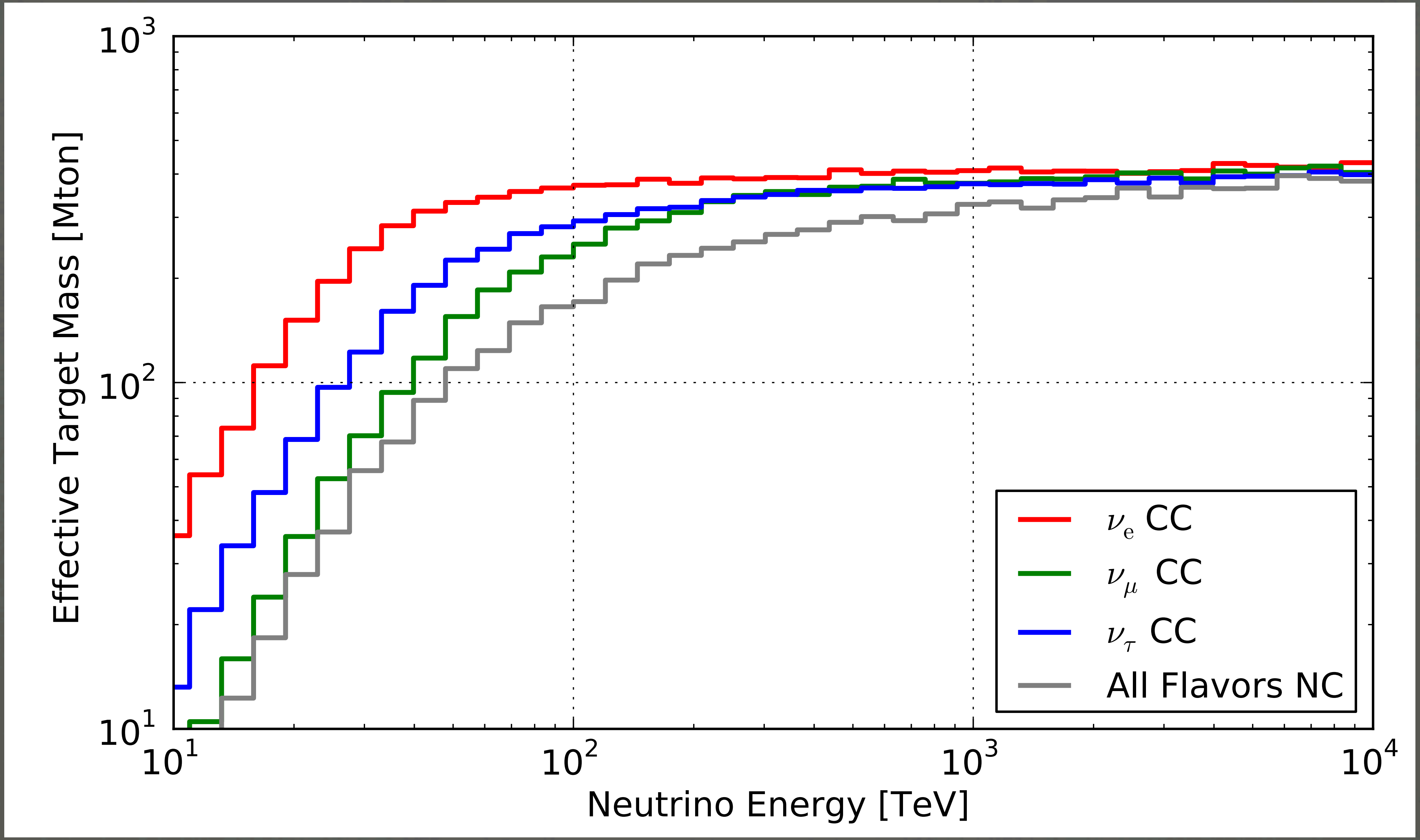
DOM performance

- 99.1% (5435) DOMs have survived installation
- Failure rate: 2/year
- After 15 years operation (2025) we expect 97.2% +/- 0.4% of the detector operational

Muon rate: ~ 3 kHz
Neutrino rate: ~ 200/day

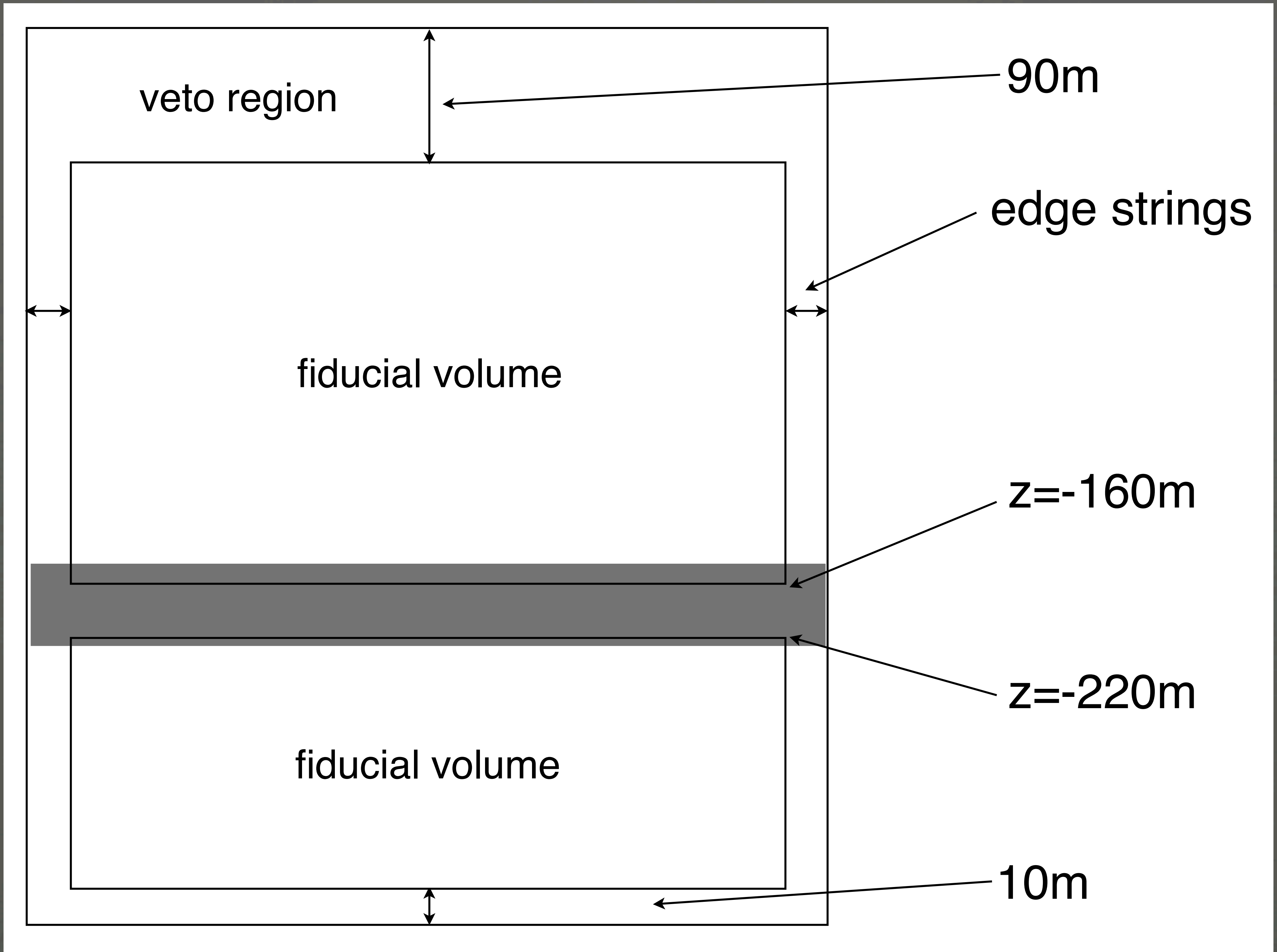
Well working detector delivering excellent data

Effective Volume

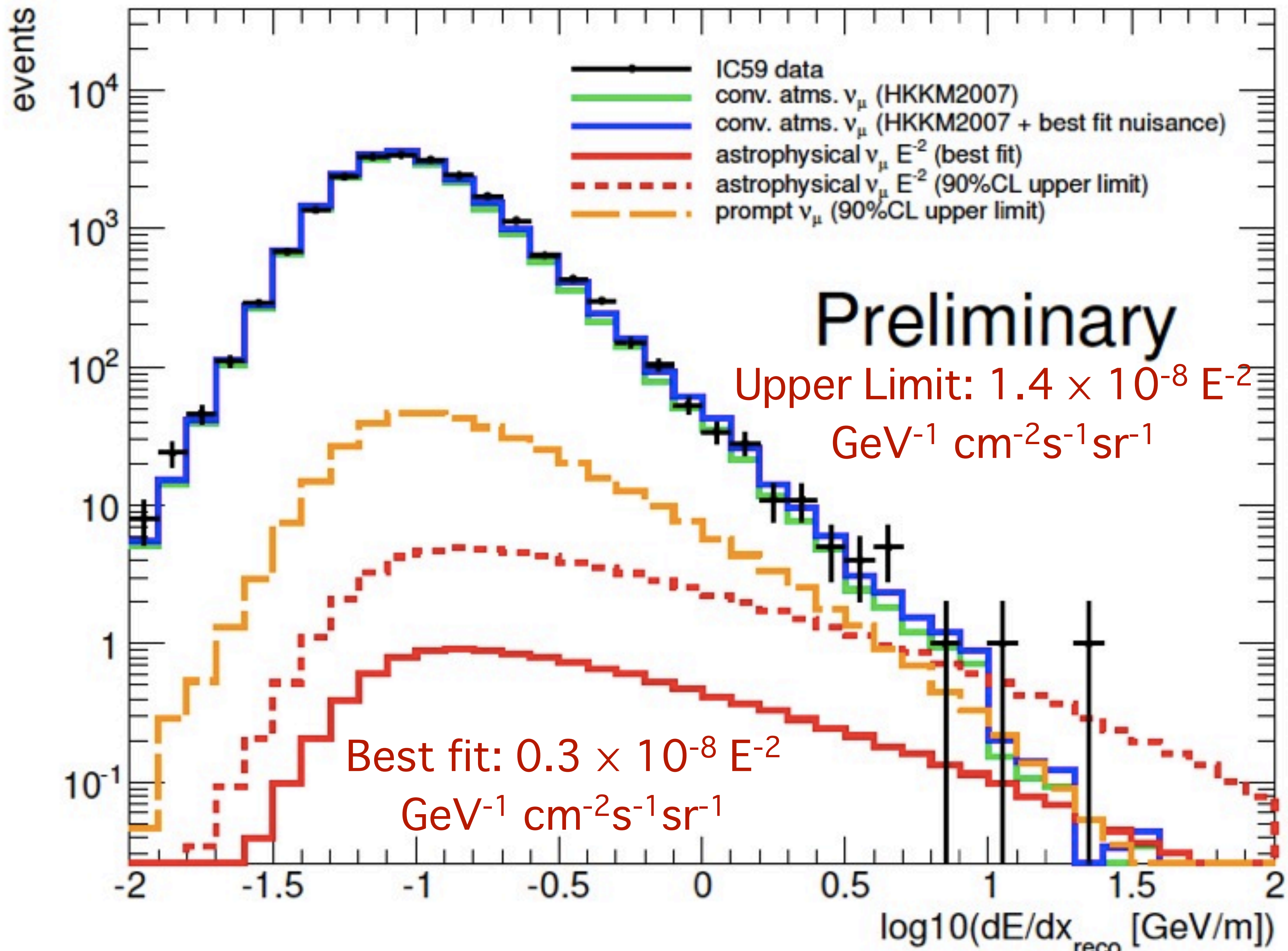


- **Fully efficient above 100 TeV for CC electron neutrinos**
- **Effective fiducial volume: 420 Mton**

Veto region


veto region
90m
edge strings
fiducial volume
z=-160m
z=-220m
fiducial volume
10m

IC59 diffuse analysis



- Significance: 1.8σ

arXiv:1302.0127

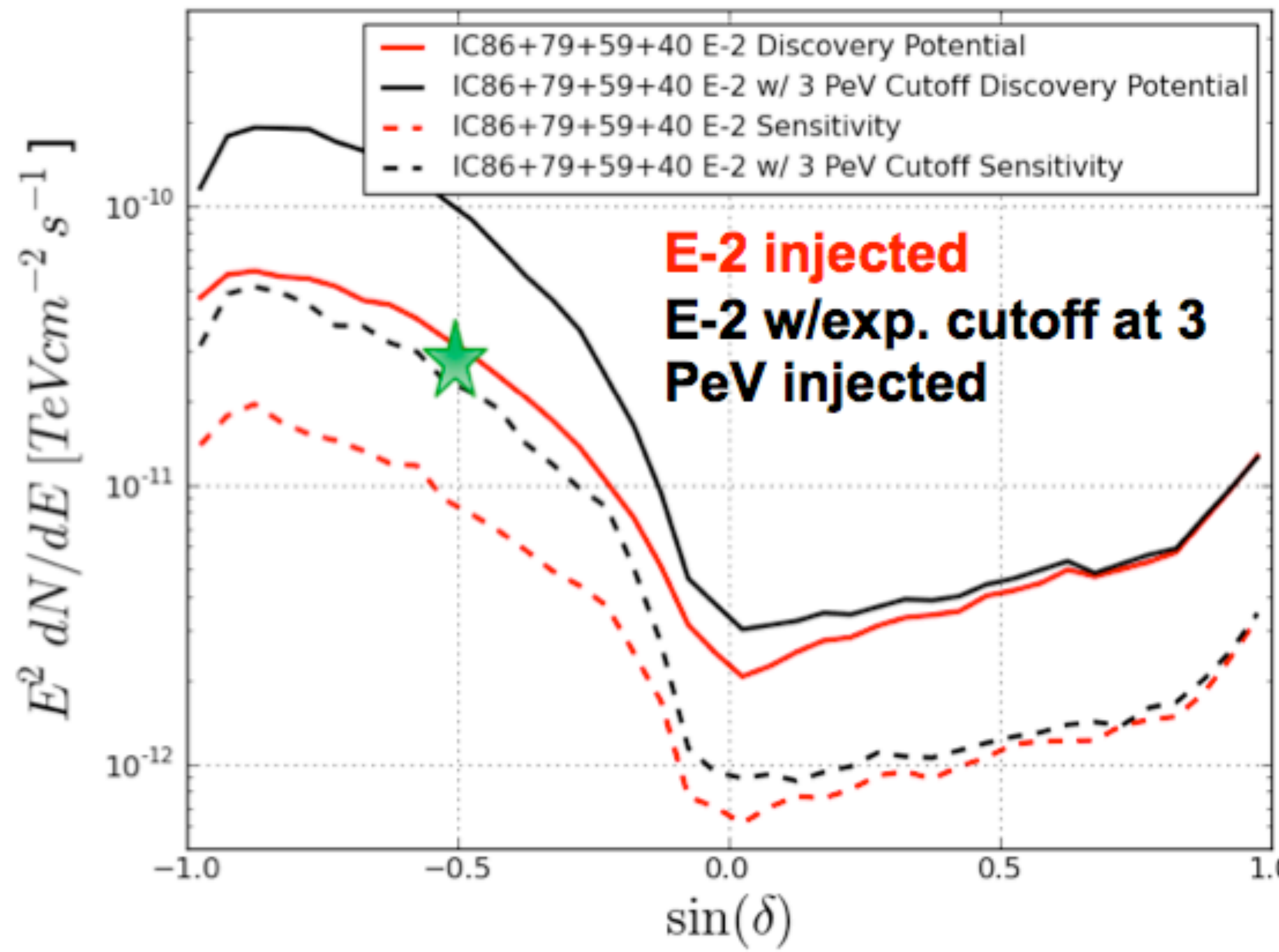
How does this result relate to high-energy starting event results?

- Back of the envelope:
  - Starting event best-fit flux is ~3 x 10^{-8} GeV/cm^2/s/sr
  - Convert to ν_μ PS flux → multiply by 4π, divide by 3 ≈ 12 x 10^{-8}
  - But only ~25% of events near hotspot: ~3 x 10^{-8} → **3 x 10^{-11} TeV/cm^{2}s**

→For optimistic scenario, the high-energy starting event "hot spot" flux is at the edge of sensitivity

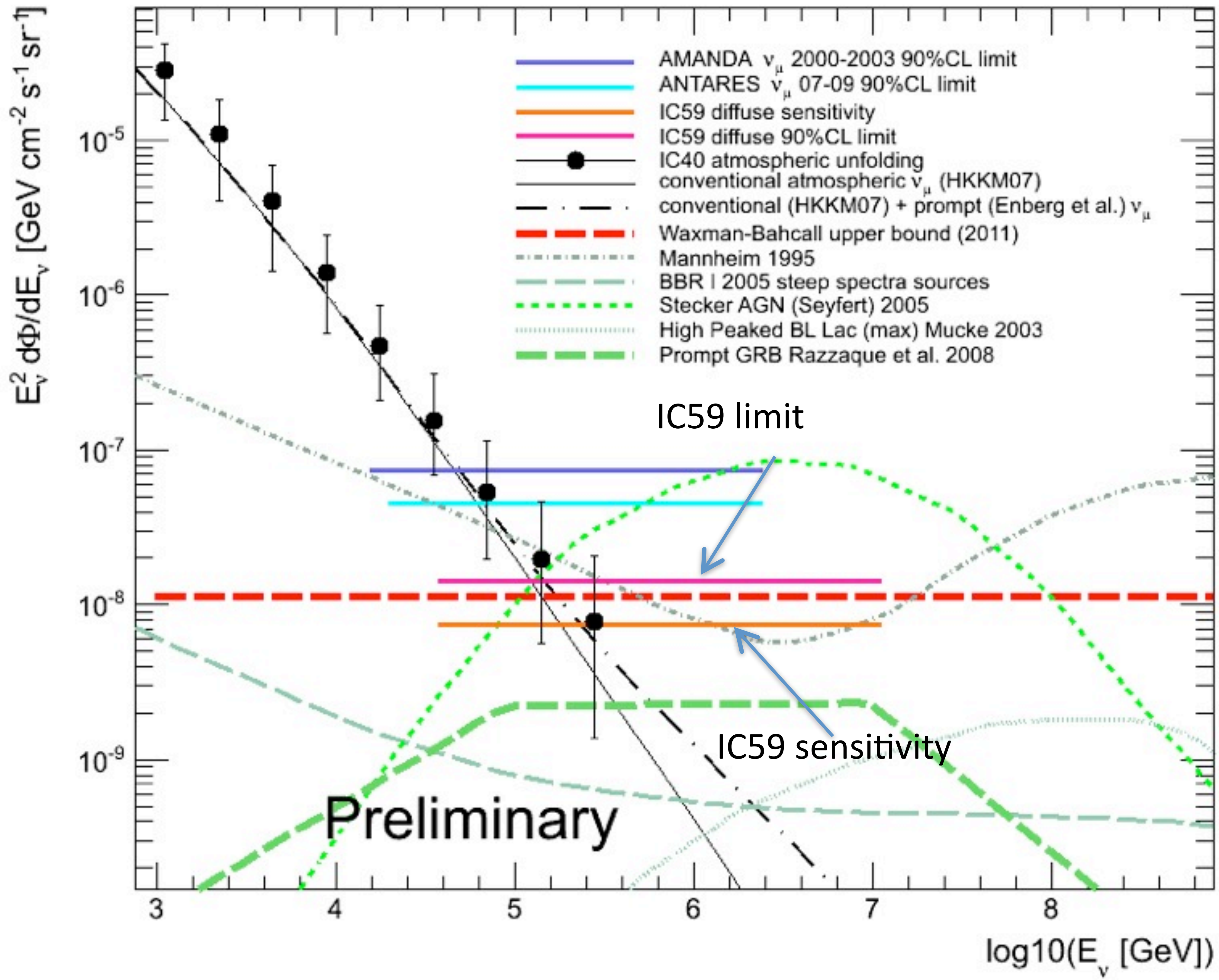
→ At 90% confidence level, there is no tension in results

→ Sensitivity to actual flux can easily be worse (cutoff position/shape, source extension, flavor ratio, etc.)



→ Feintzeig

Diffuse ν_μ -flux limits



Tau neutrinos

Charged Current tau neutrino:

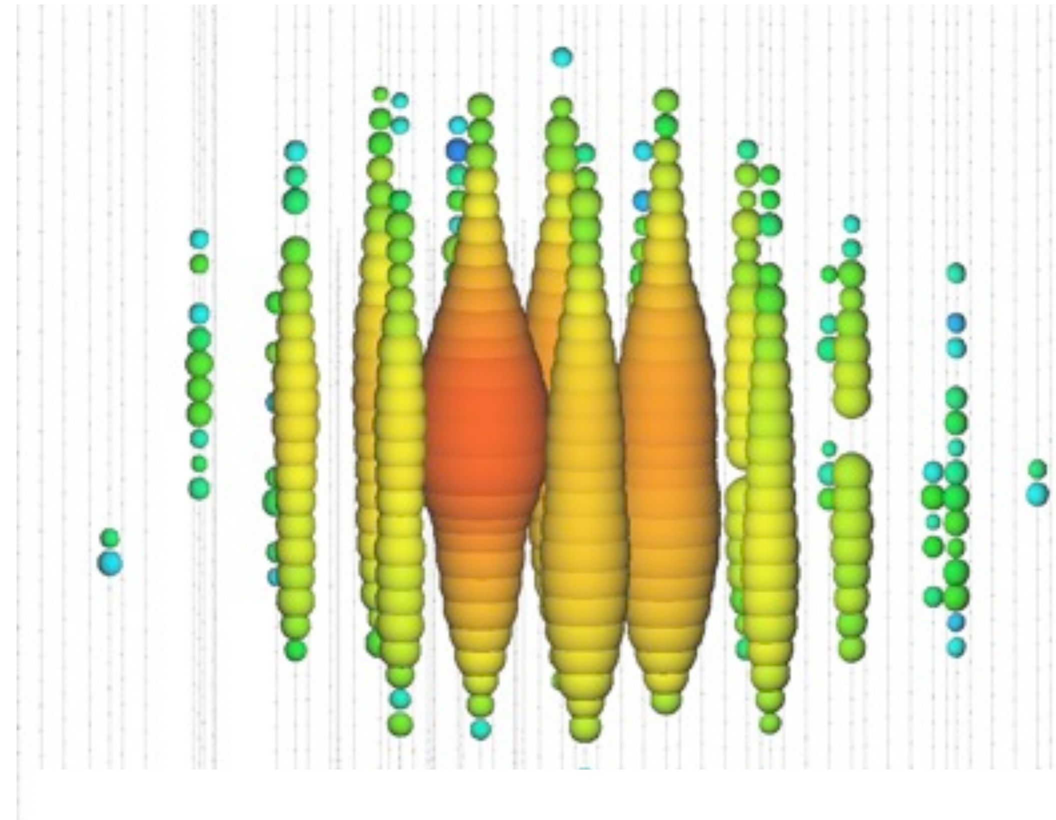
$$\nu_\tau + N \rightarrow \tau + X$$

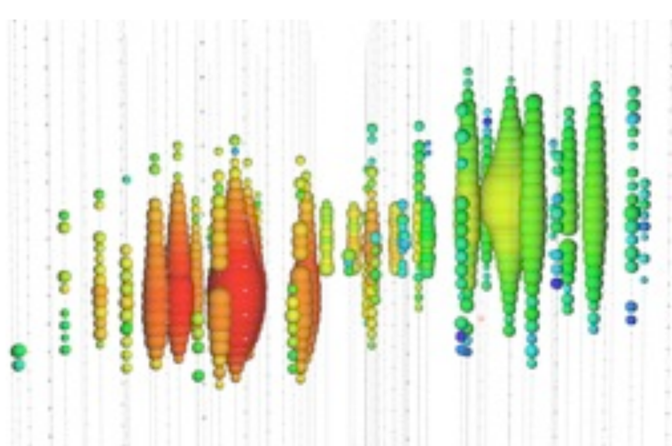
Double-bang signature from decaying tau,
Can identify double bang above ~ PeV

$$l_\tau = \gamma c t_\tau \sim 50\,(E_\tau/\mathrm{PeV})\,\mathrm{m}$$

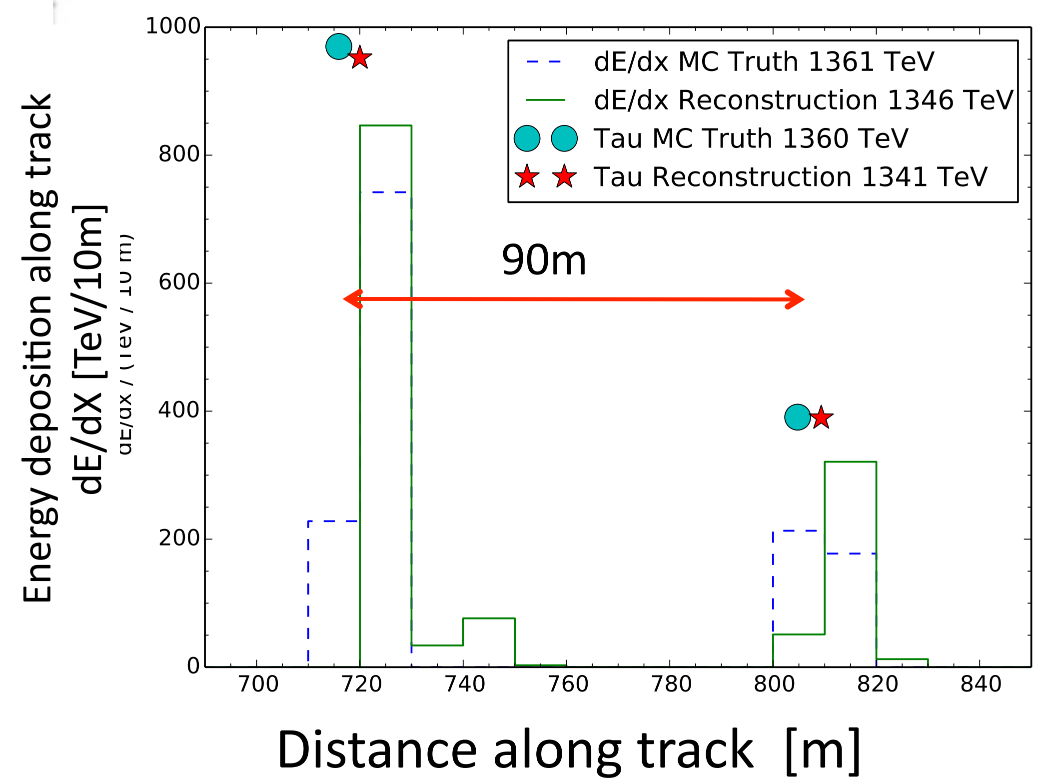
Lower energy id more limited possibilities.

Simulated event: 1.36 PeV
(no data event identified yet)



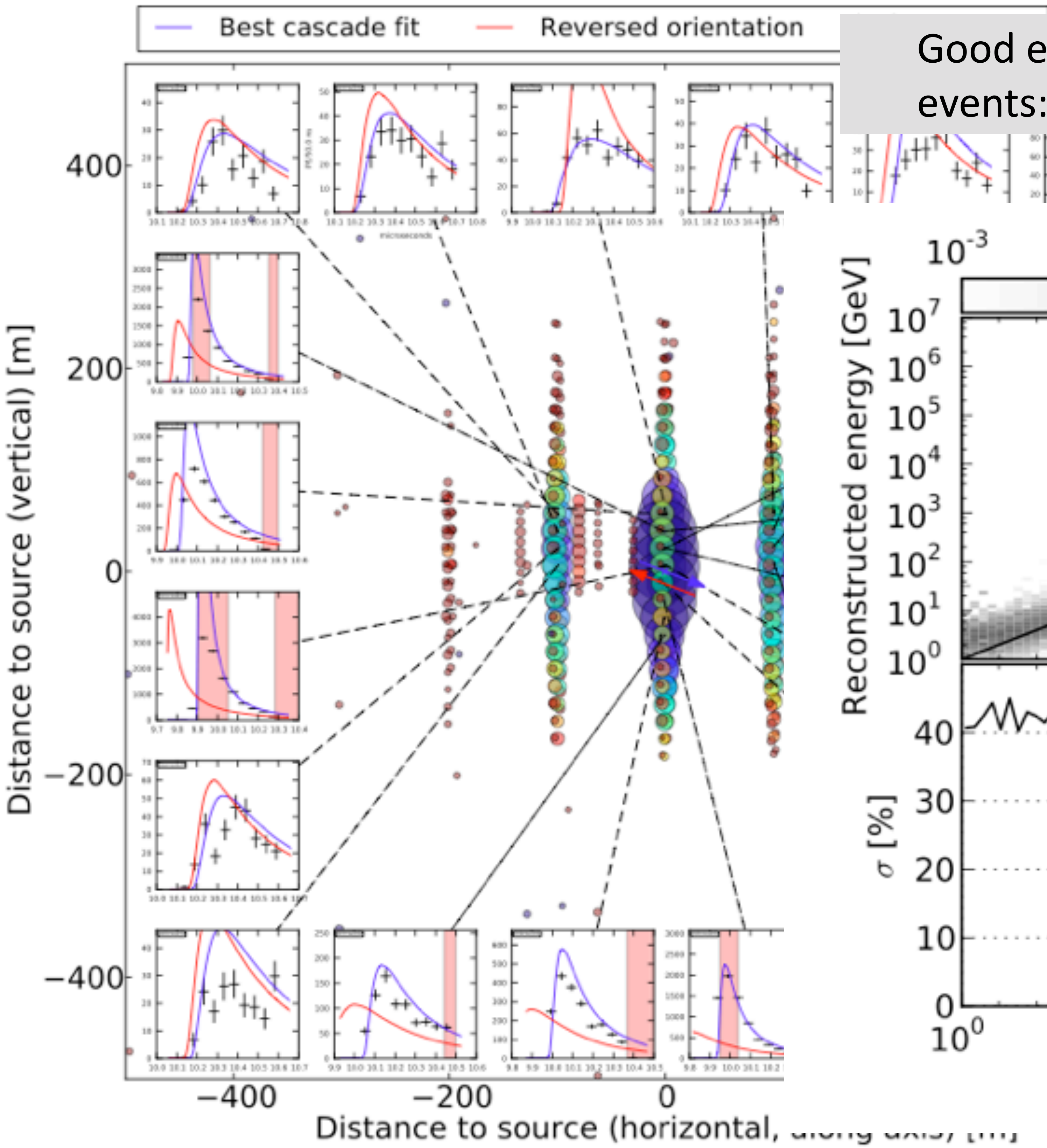


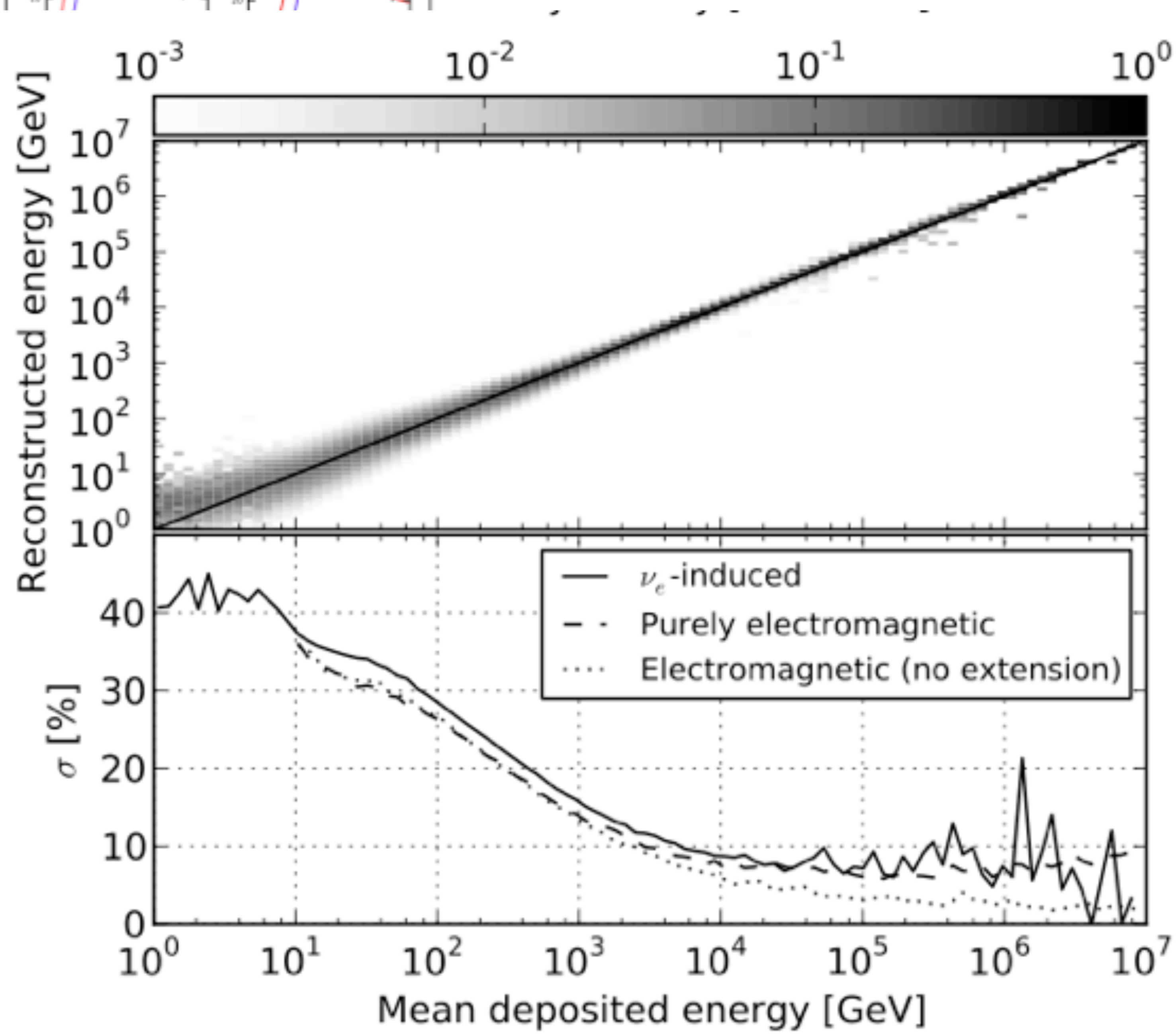
Event with longer decay length



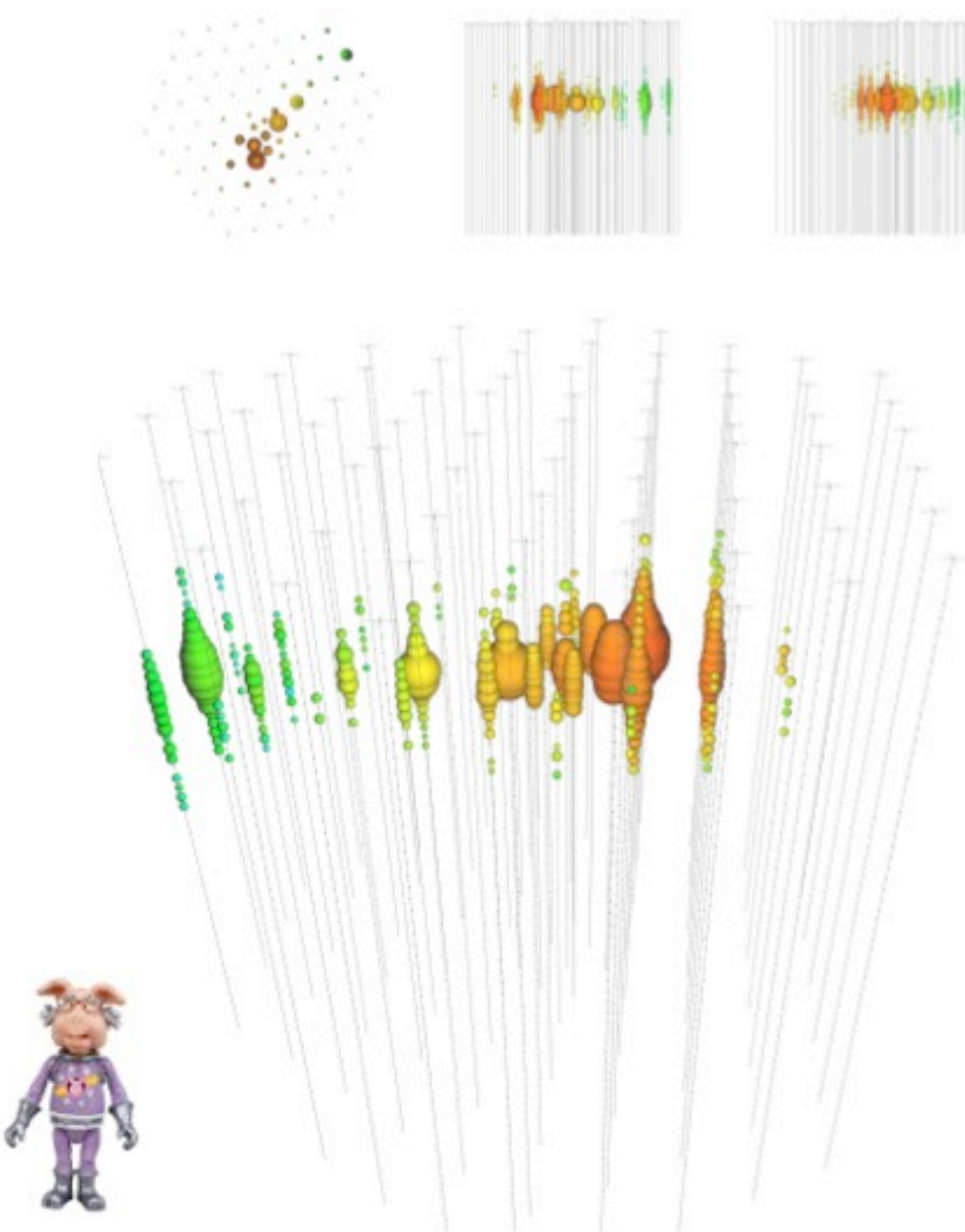
Observed neutrino event at E=1.1x10^6 GeV

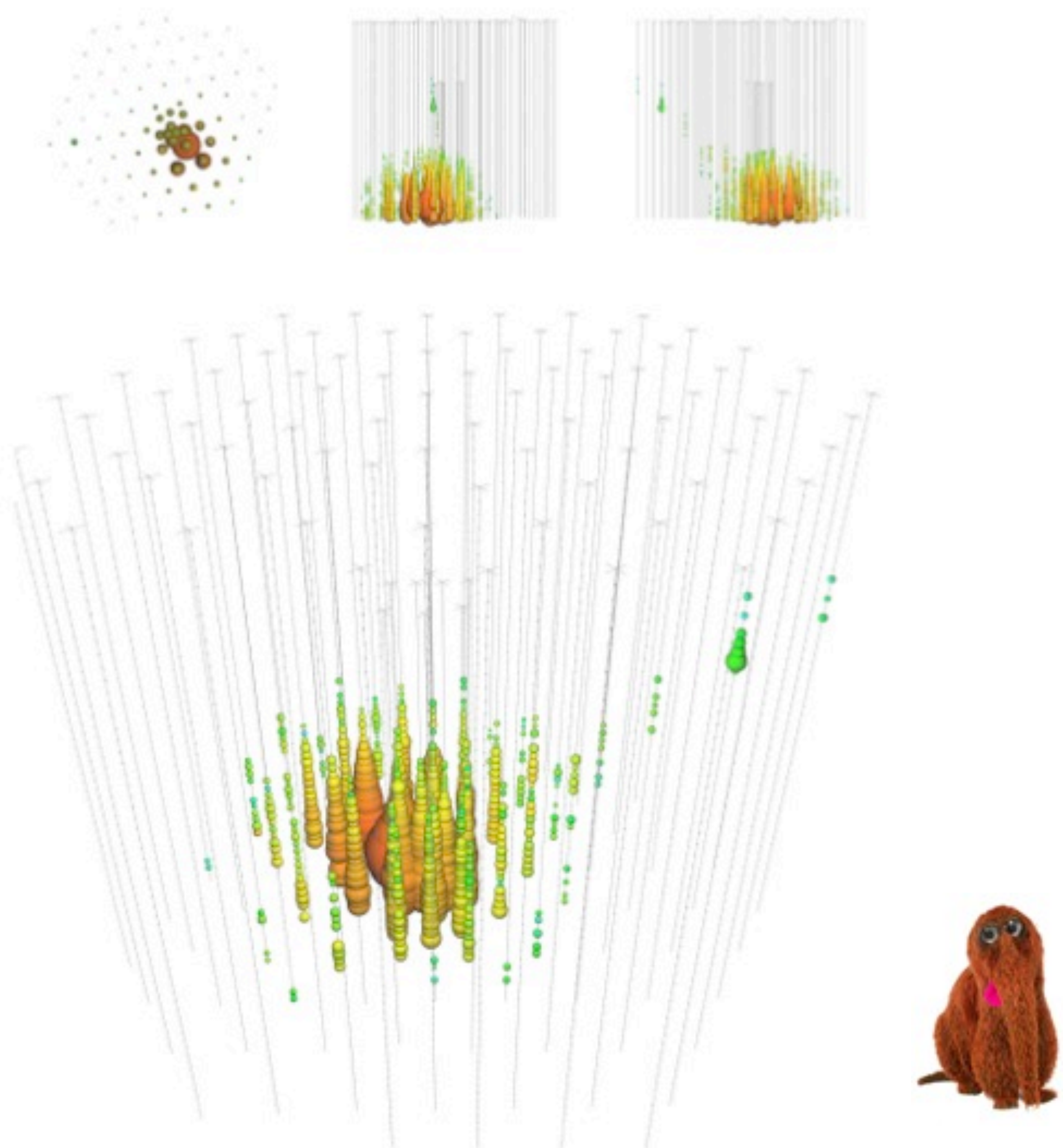
Good energy energy resolution for cascade like events: ~ 10 % at high energies





Two track examples



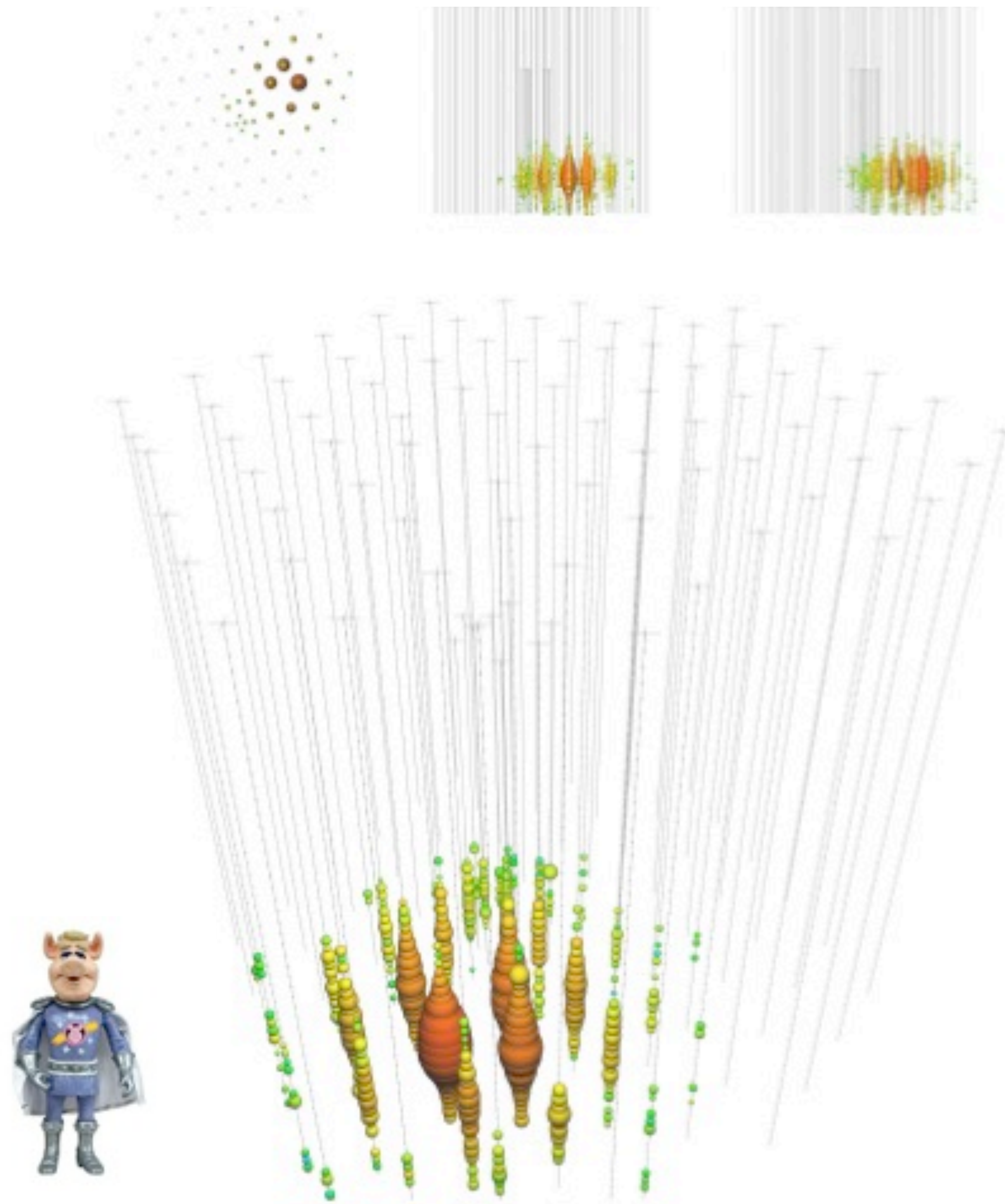


74.1 TeV, $-0.4°$

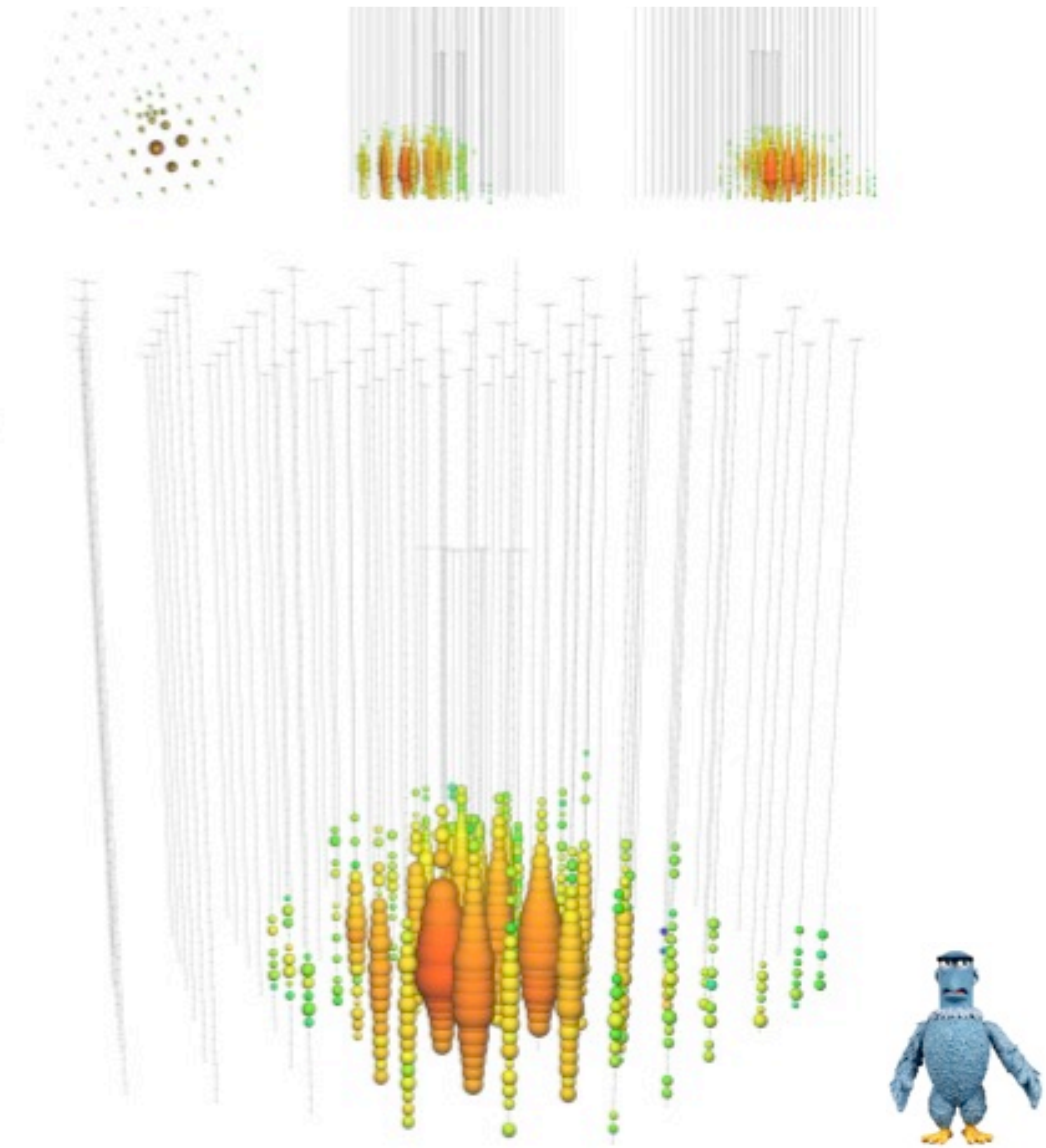
252.7 TeV, $+40°$

PRELIMINARY

Two shower examples



71.5 TeV, -60°



82.2 TeV, -13°

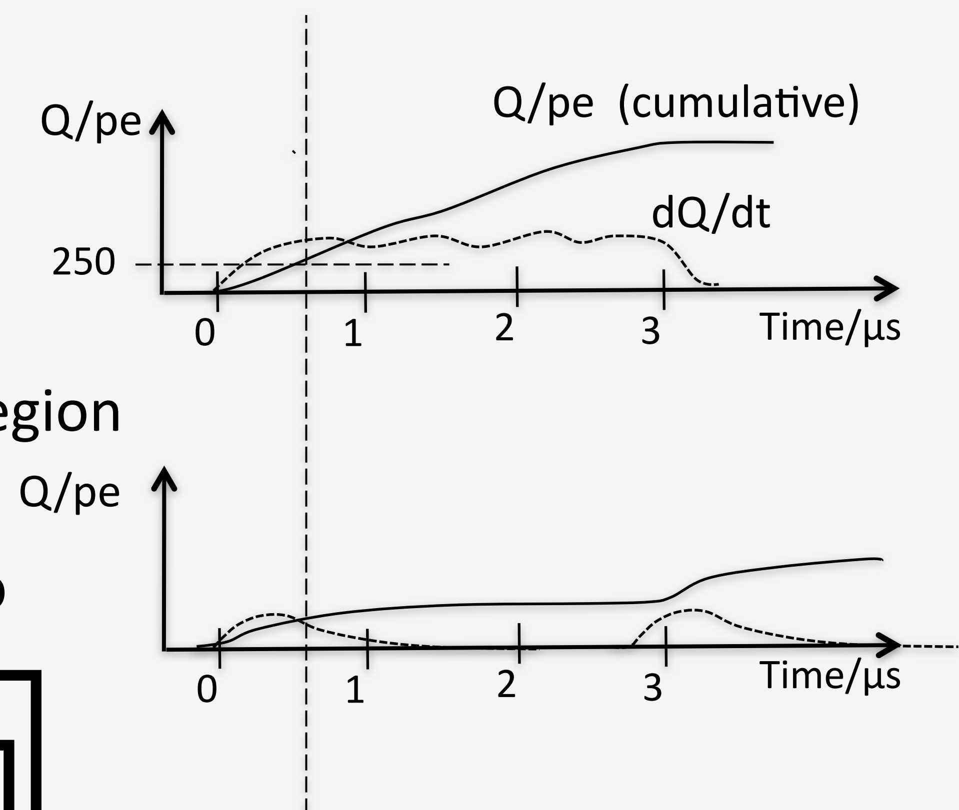
PRELIMINARY

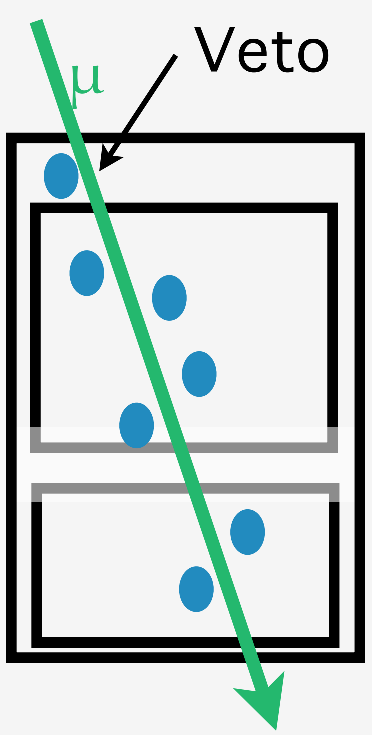
Atmospheric Muons

What's "early charge"?

Through-going muon

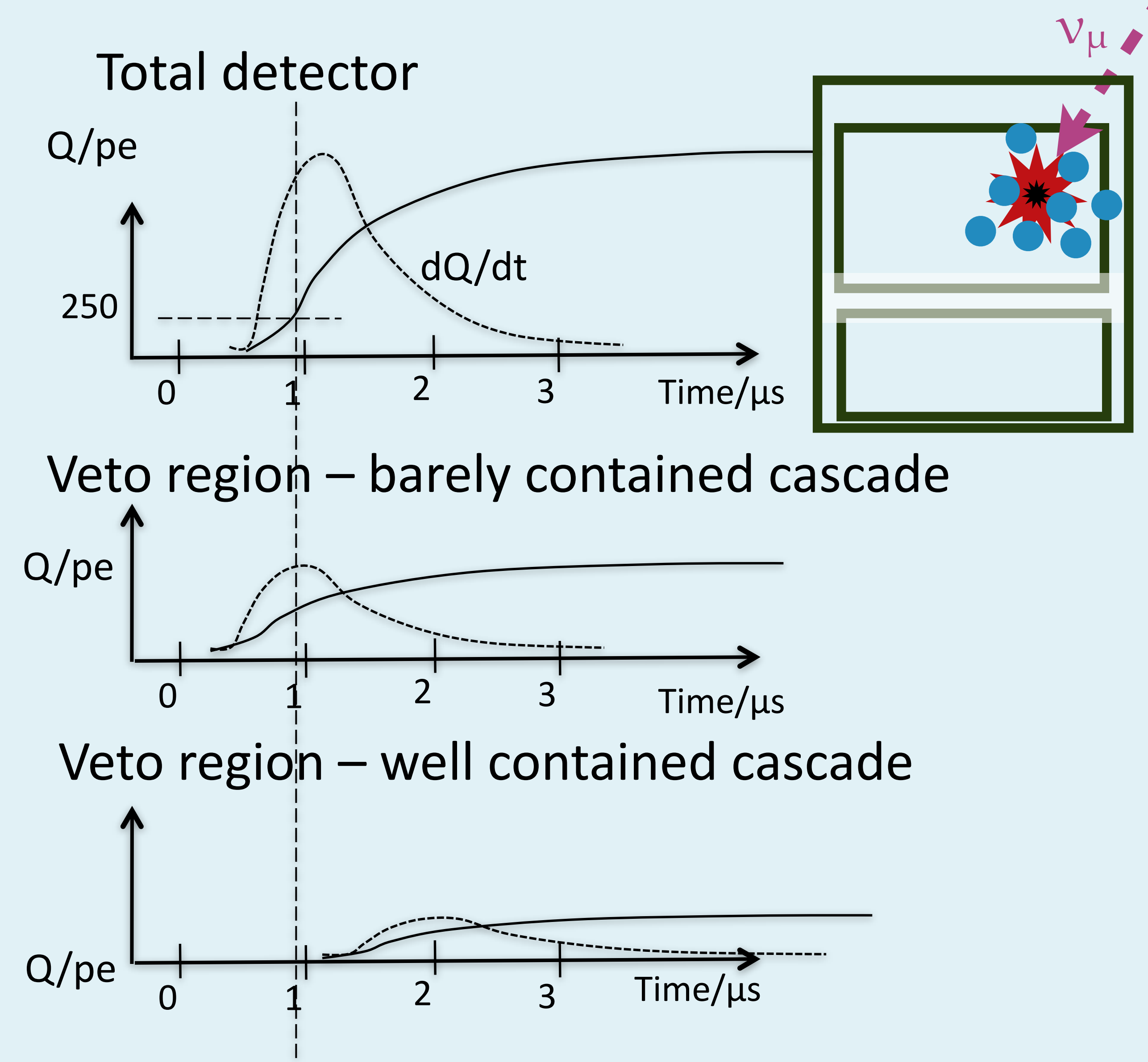
Total detector





T_{250}= time at which Q= 250 pe

Contained cascade



T_{250}= time at which Q= 250 pe