High energy astrophysical neutrinos – observations and implications

Albrecht Karle
Dept. of Physics and
Wisconsin IceCube Particle Astrophysics Center
University of Wisconsin-Madison

Kavli Institute for Astronomy and Astrophysics
Beijing 2017

IceCube

Cosmic Rays and Neutrino Sources

Can neutrinos reveal origins of cosmic rays?

$$p\gamma \rightarrow p\pi^0, n\pi^+$$

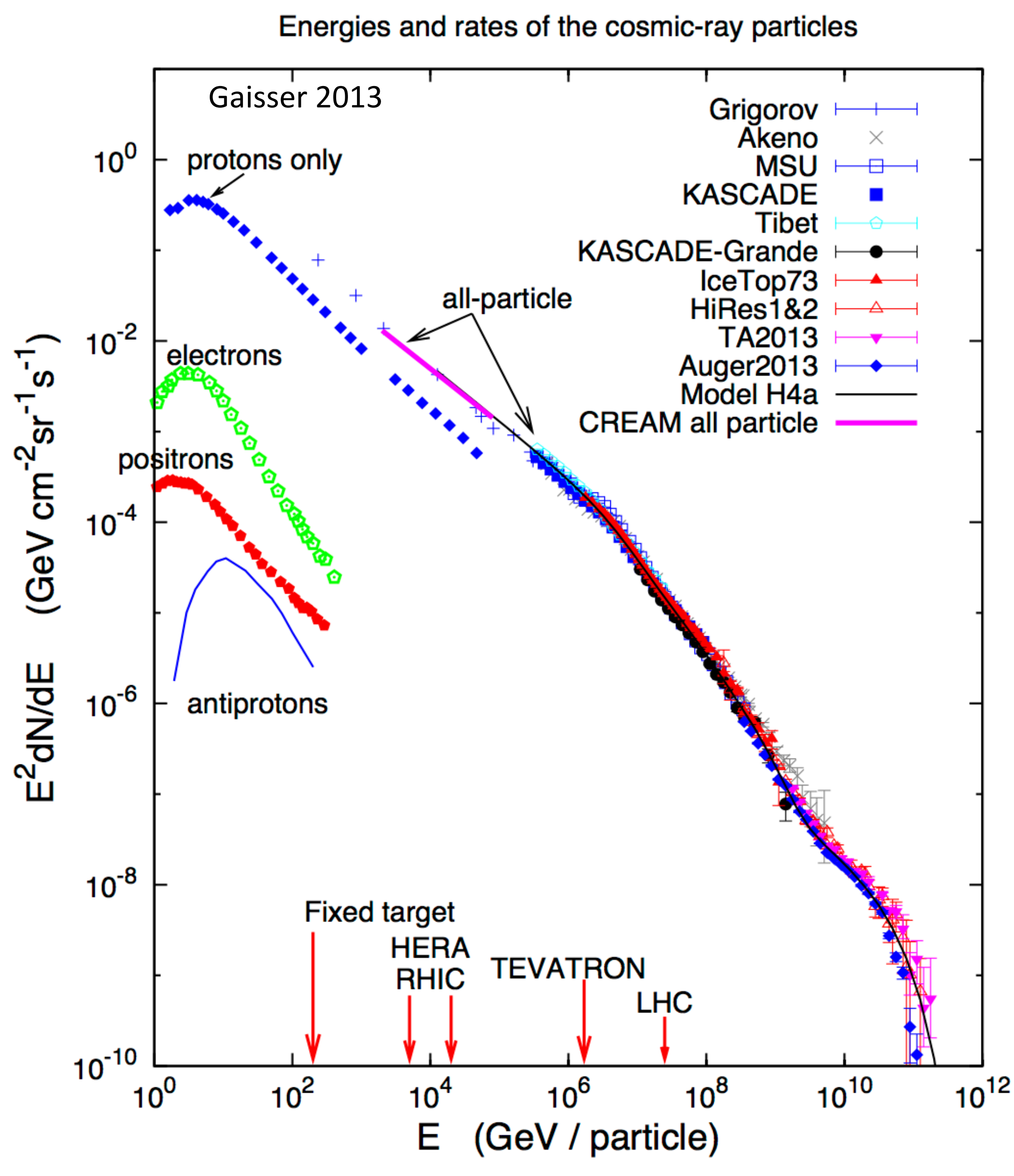
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Cosmic ray interaction in accelerator region

Prime Candidates

- SN remnants
- Active Galactic Nuclei
- Gamma Ray Bursts

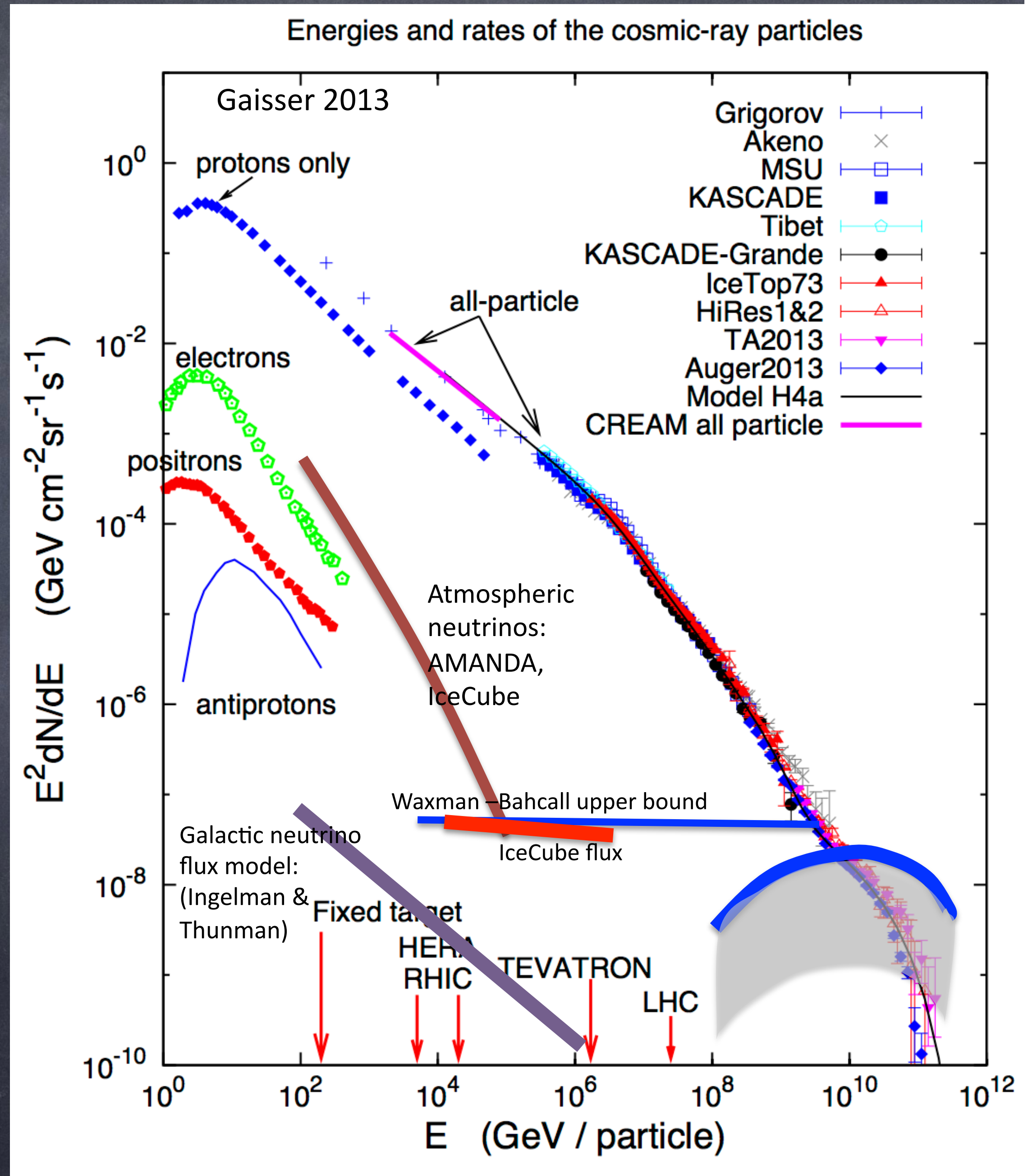


Neutrino production from cosmic rays on known targets.

$$pp \rightarrow NN + pions; \qquad p\gamma \rightarrow p\pi^0, n\pi^+$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Known targets:

- Earth's atmosphere: Atmospheric neutrinos (from π and K decay)
- Interstellar matter in Galactic plane: Cosmic rays interacting with Interstellar matter, concentrated in the disk
- Cosmic Microwave background: UHE cosmic rays interact with photons in intergalactic photon fields.



Neutrino fluxes at all energies

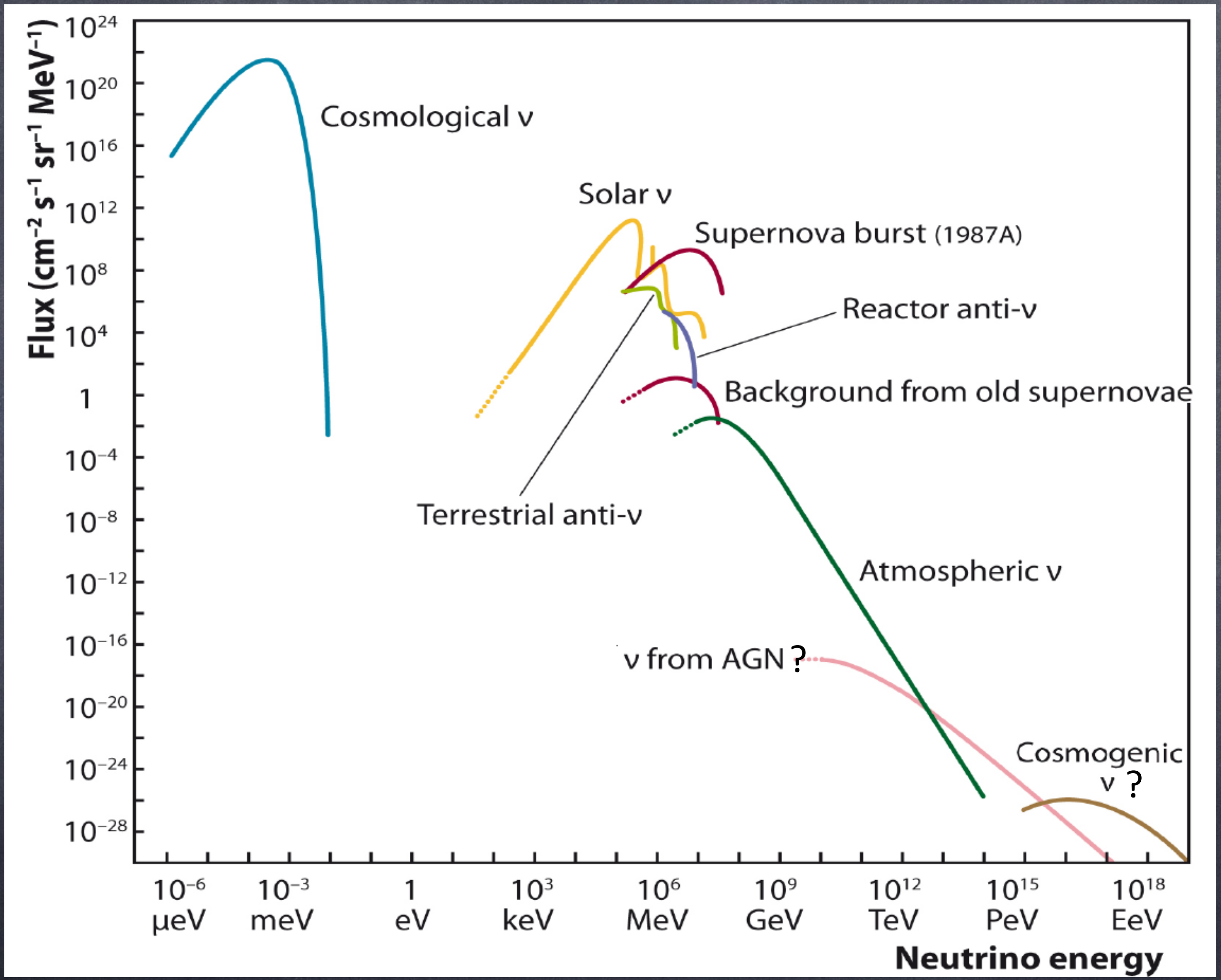
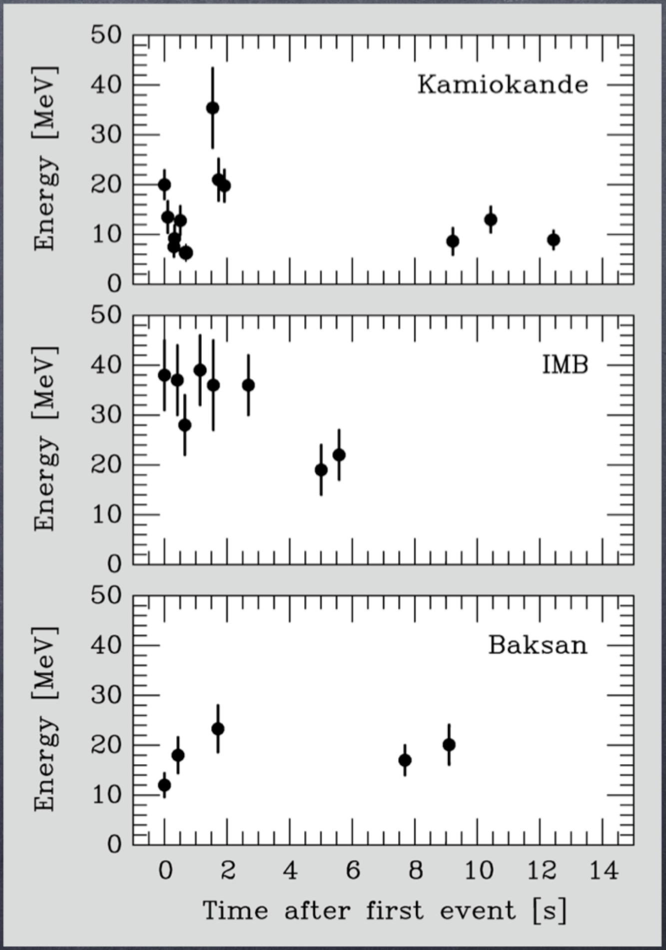


Fig.: Learned & Mannheim 2012

Astrophysical Neutrinos

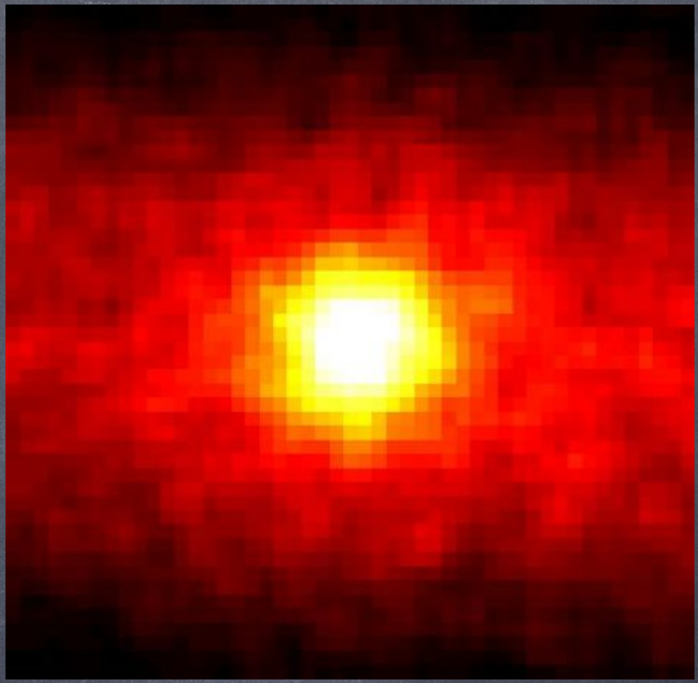
Supernova 1987a



Observation of neutrinos, MeV energy scale, confirm process of core collapse

Neutrinos from the sun

- They are around us:
  - Sun: about 1 trillion neutrinos from the sun pass your thumb every second!
  - Low energy neutrinos penetrate a million miles of lead



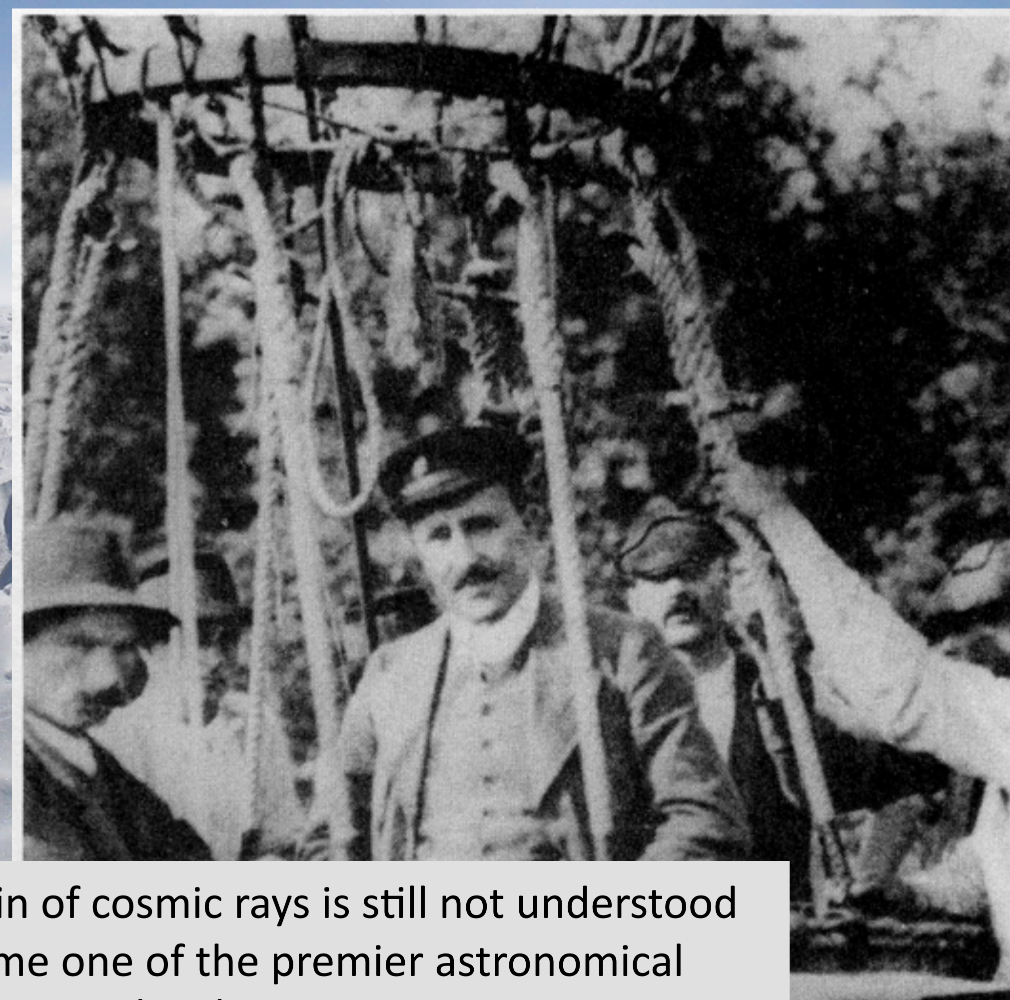
90°x90°

Neutrino image of the
(interior of the) sun.
Low energy neutrinos measured
by the SuperK underground detector.

About 100 years ago

December 14, 1911:
Rould Amundson reaches
the Geographic South Pole

1911/1912:
Victor Hess discovers
Cosmic Rays



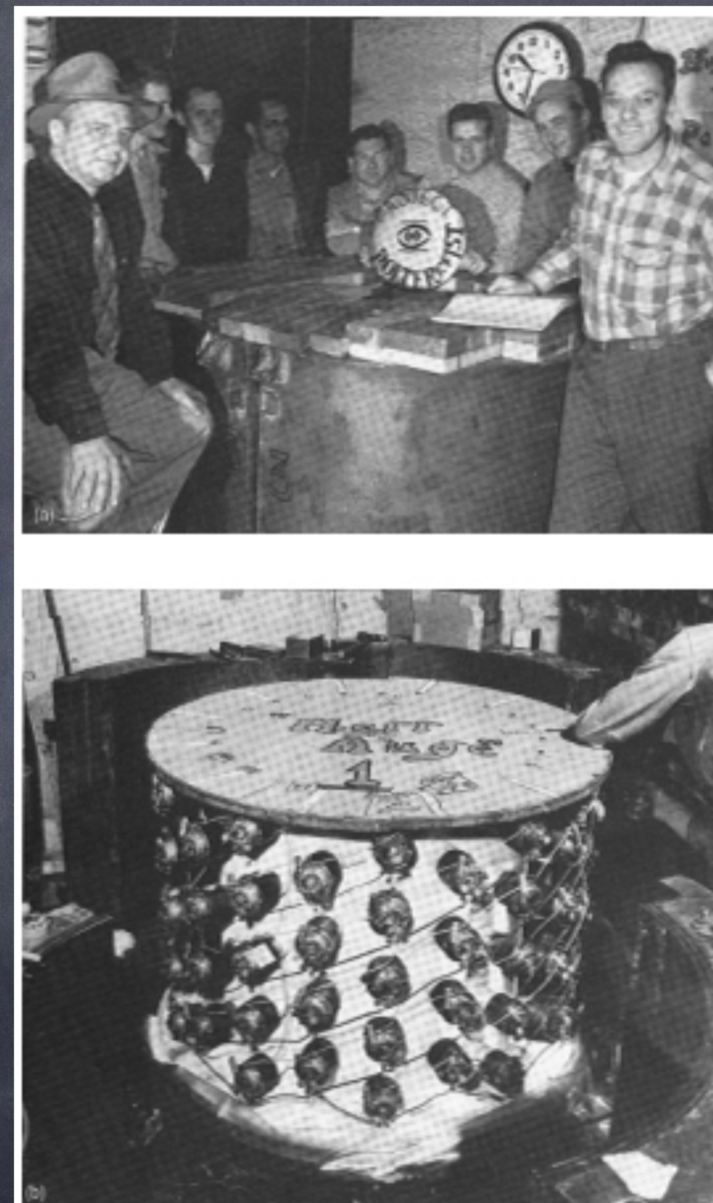
100 years later: The origin of cosmic rays is still not understood
The South Pole has become one of the premier astronomical laboratories which may give as the clues.

About 50 years later,
In 1956 the neutrino is detected.

Reines and Cowan placed a detector of 1 m diameter 10 m near the core of a nuclear reactor.

10^16 neutrinos per second would pass through this detector,
and it was very hard to see just a few.

Reines receives Nobel prize in 1995



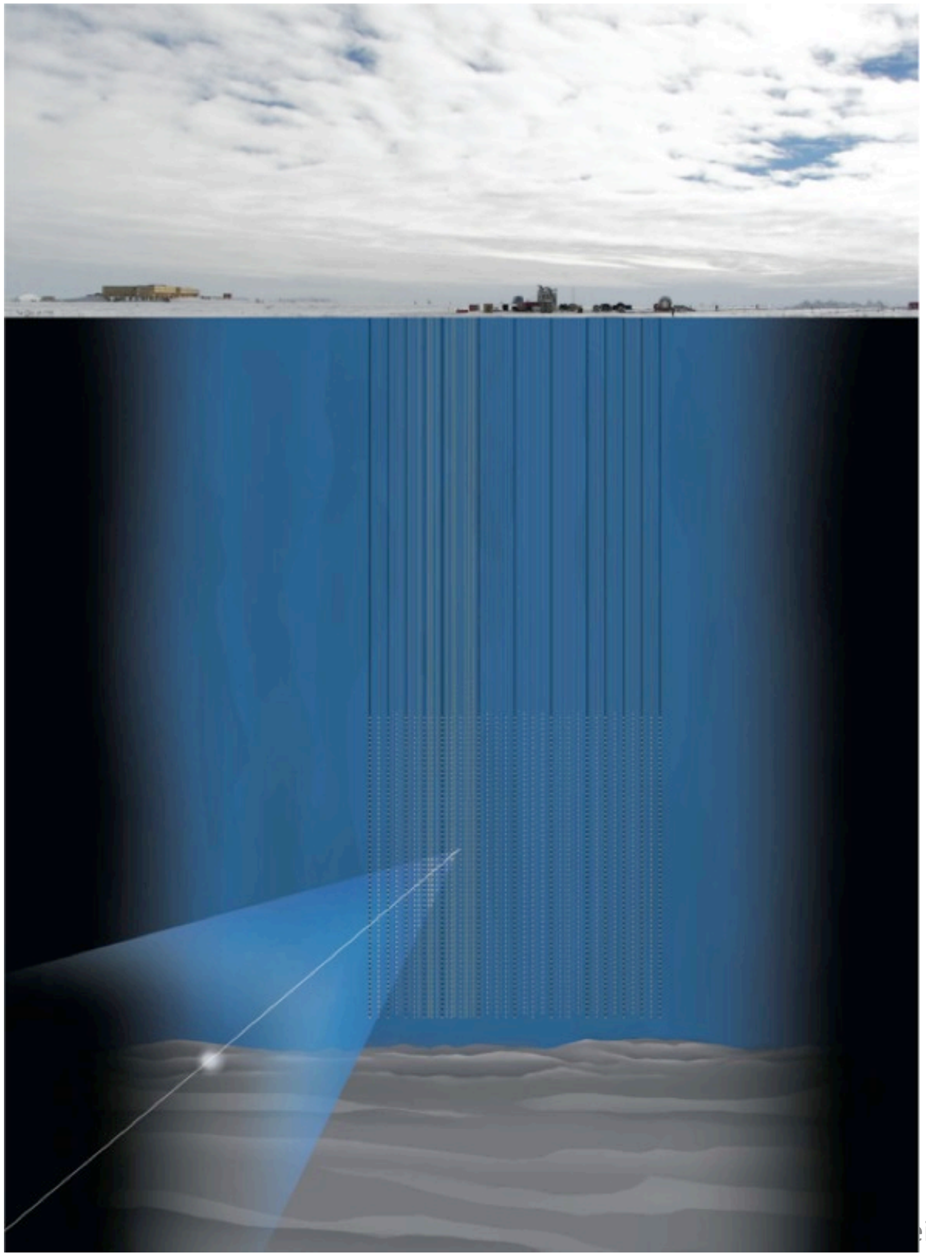
Idea for neutrino astronomy

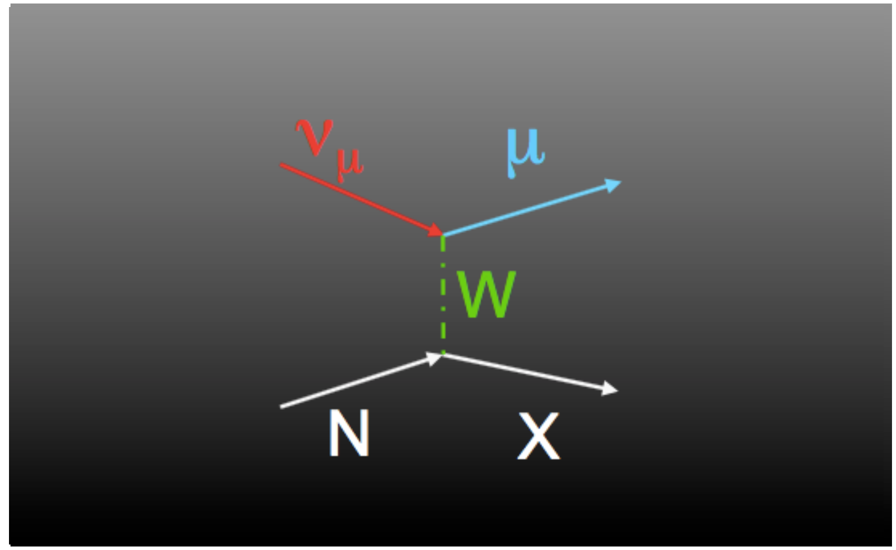
The idea for neutrino astronomy
goes back to the early 1960ies

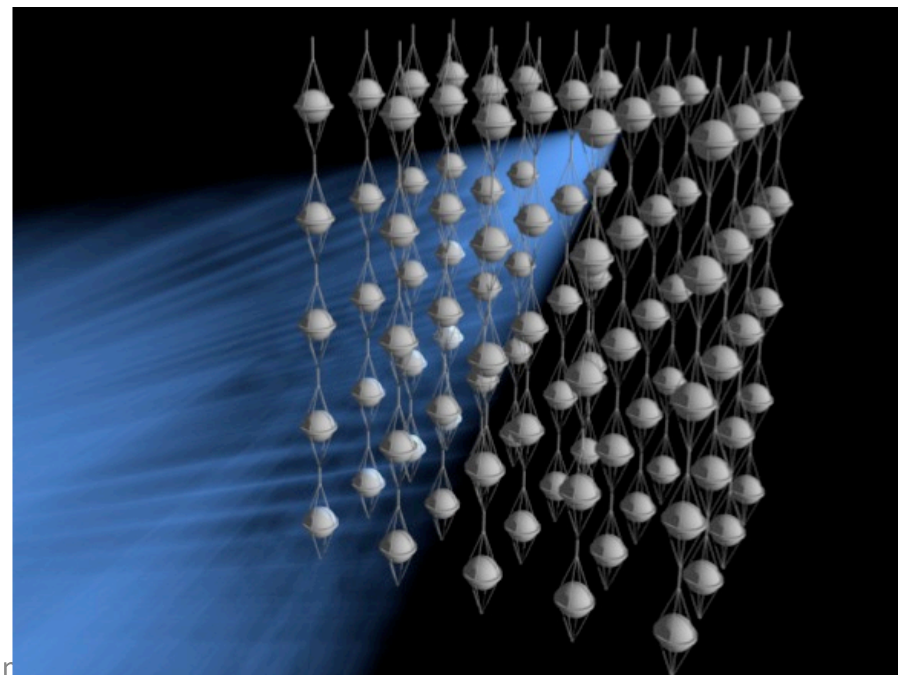
- Not long after the neutrino was detected by Reines and Cowan in 1956.

M.Markov:
„We propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation“
Proc. 1960 ICHEP, Rochester, p. 578.

High Energy Neutrino Detection Principles







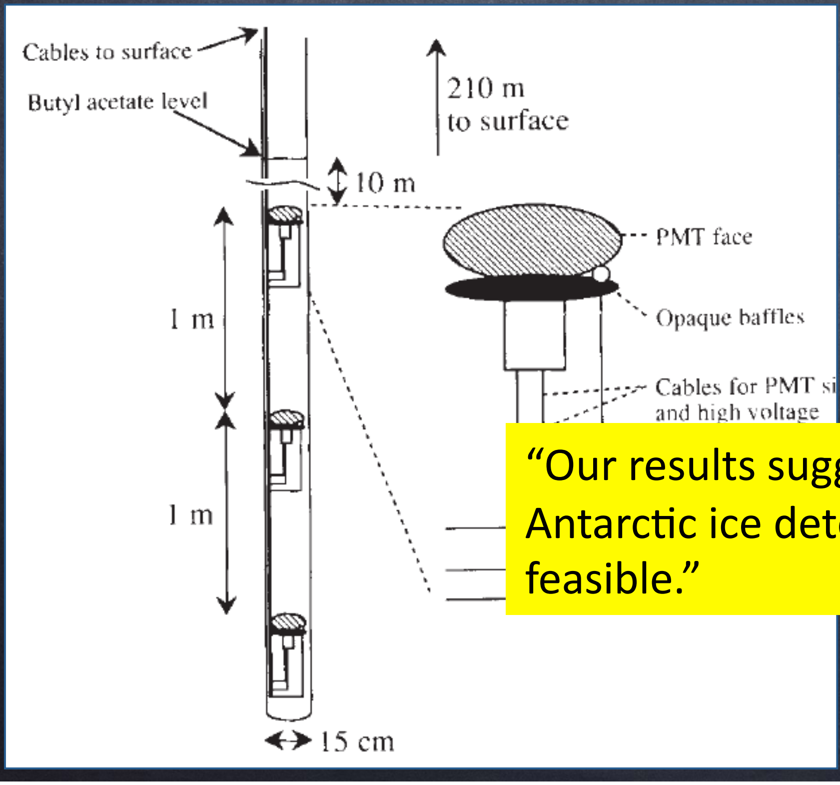
First steps
1990: Detection of cosmic ray muons using PMT in natural ice in Greenland.

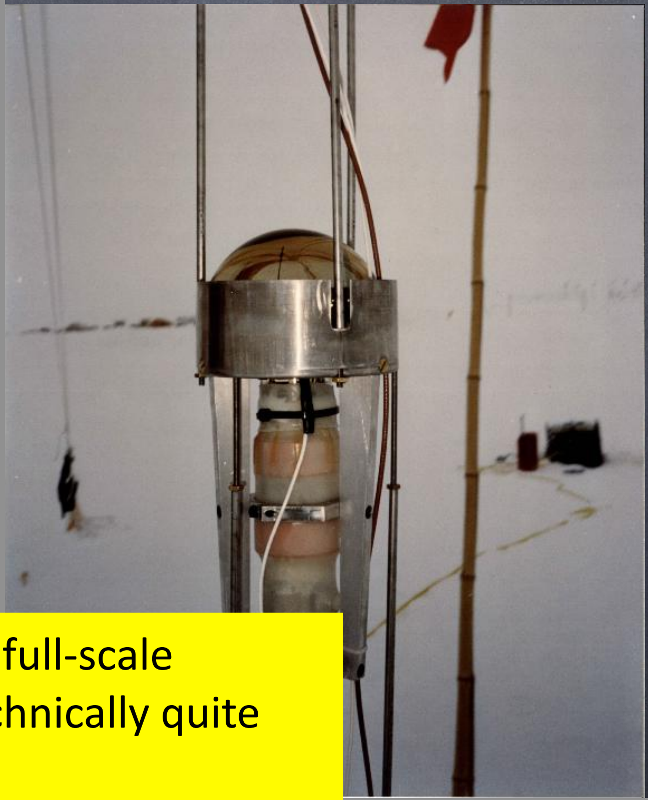
Nature 353, 331-333 (26 September 1991)

Observation of muons using the polar ice cap as a Cerenkov detector

D. M. Lowder*, T. Miller*, P. B. Price*, A. Westphal*, S. W. Barwick†, F. Halzen‡ & R. Morse‡

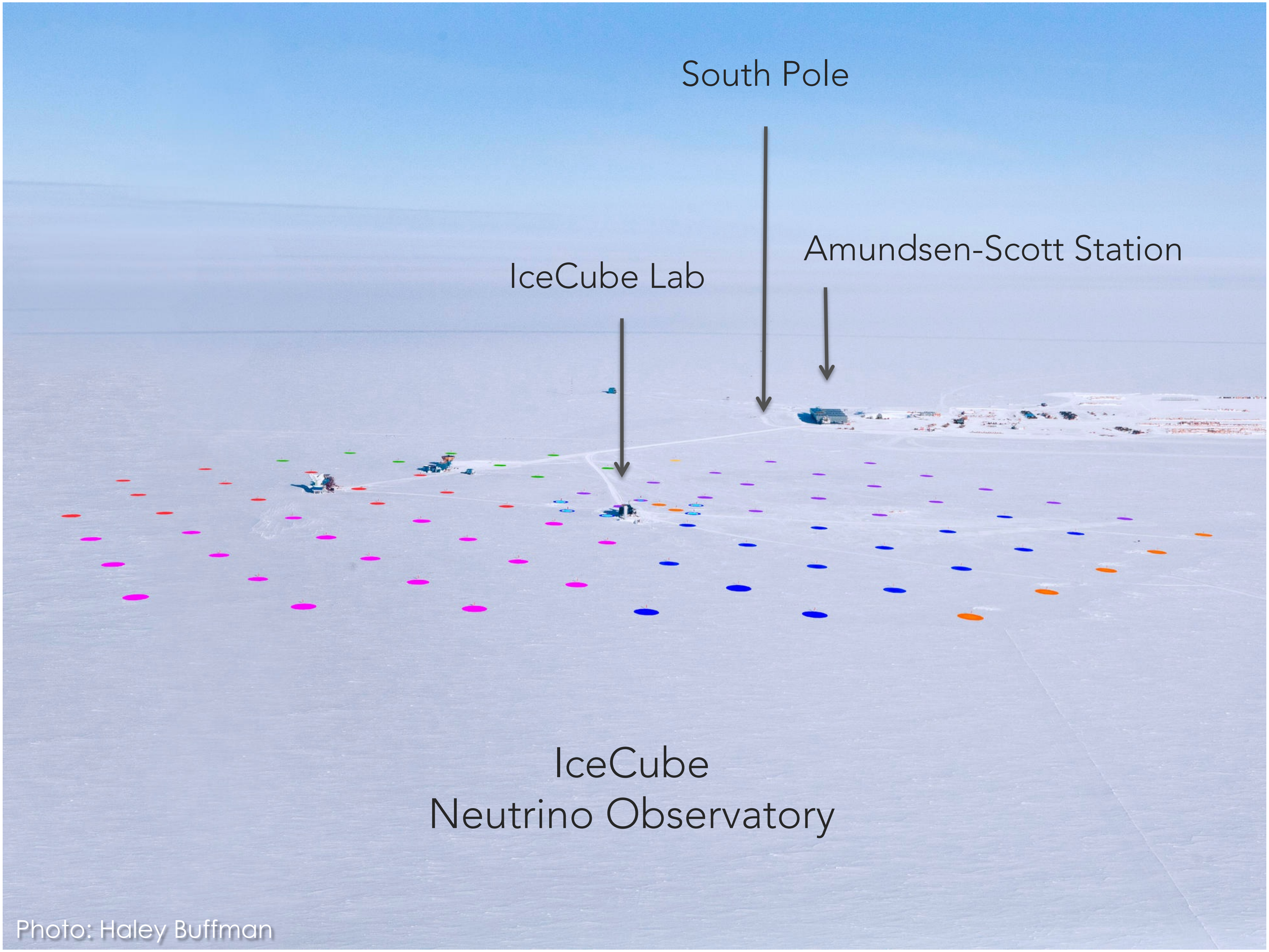
"Cerenkov radiation from muons was detected, and a comparison of count rate with the expected muon flux indicates that the ice is very transparent, with an absorption length greater than 18 m. Our results suggest that a full-scale Antarctic ice detector is technically quite feasible."





"Our results suggest that a full-scale Antarctic ice detector is technically quite feasible."

Seriously?
(And they were right!)


South Pole
Amundsen-Scott Station
IceCube Lab
IceCube
Neutrino Observatory
Photo: Haley Buffman

IceCube Neutrino Observatory

86 strings

60 Optical Modules per string

5 160 total modules in Ice

1 km^3 = Gigaton instrumented volume

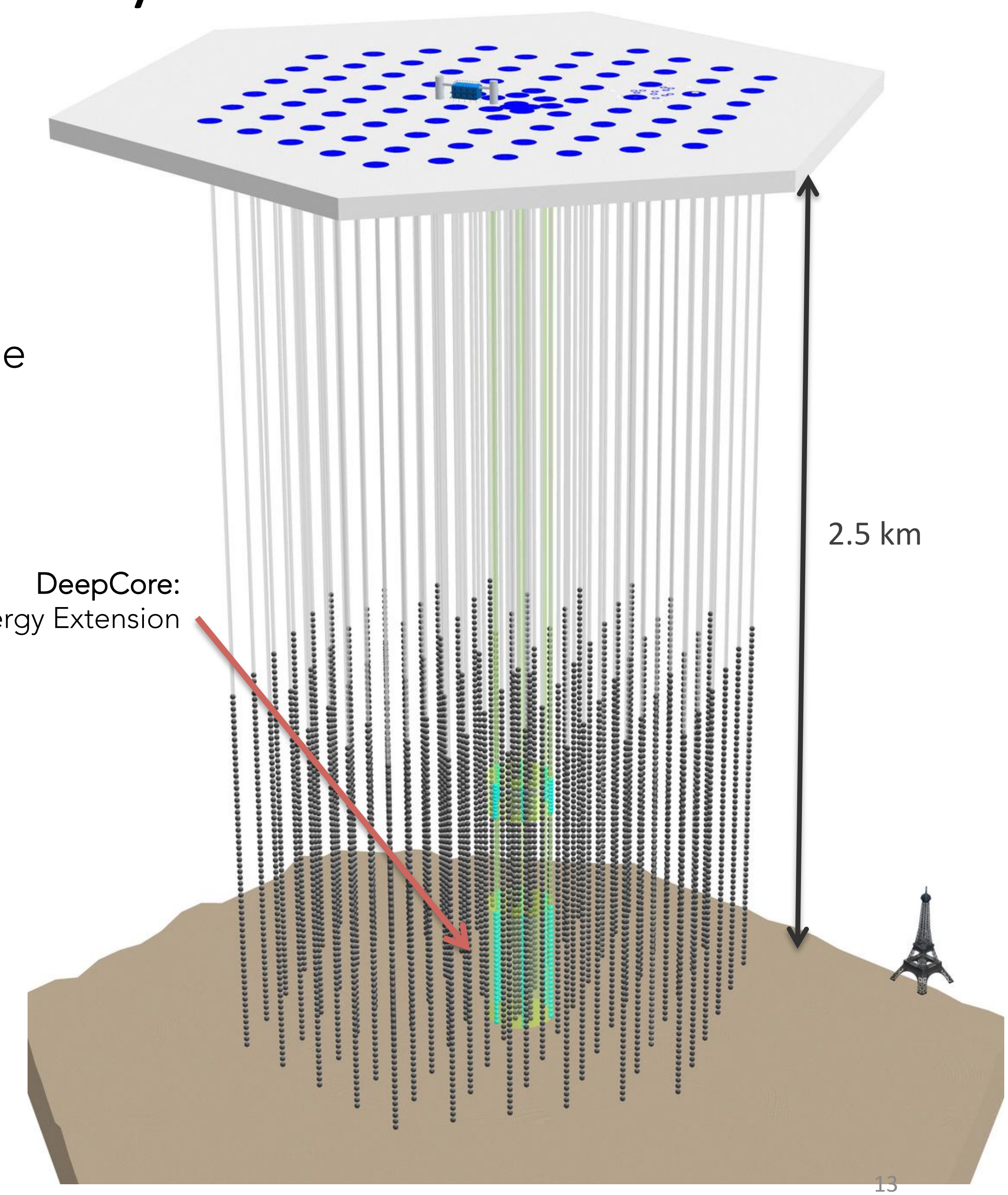
Began full operations May 2011

Highly stable operation.

Since 2014: livetime > 99%

clean-uptime 97-98%

(analysis-ready,
full-detector data)



The IceCube Collaboration

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)

Digital Optical Module (DOM)

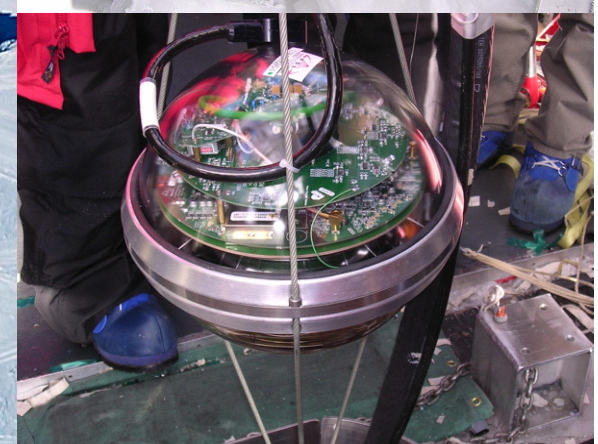
Light sensor is housed inside a pressure resistant (10000 psi) glass sphere. Each sensor is basically an independent detector with a small computer on board to digitize the recorded signals.

PMT: 10 inch Hamamatsu

Digitizing electronics records waveforms.

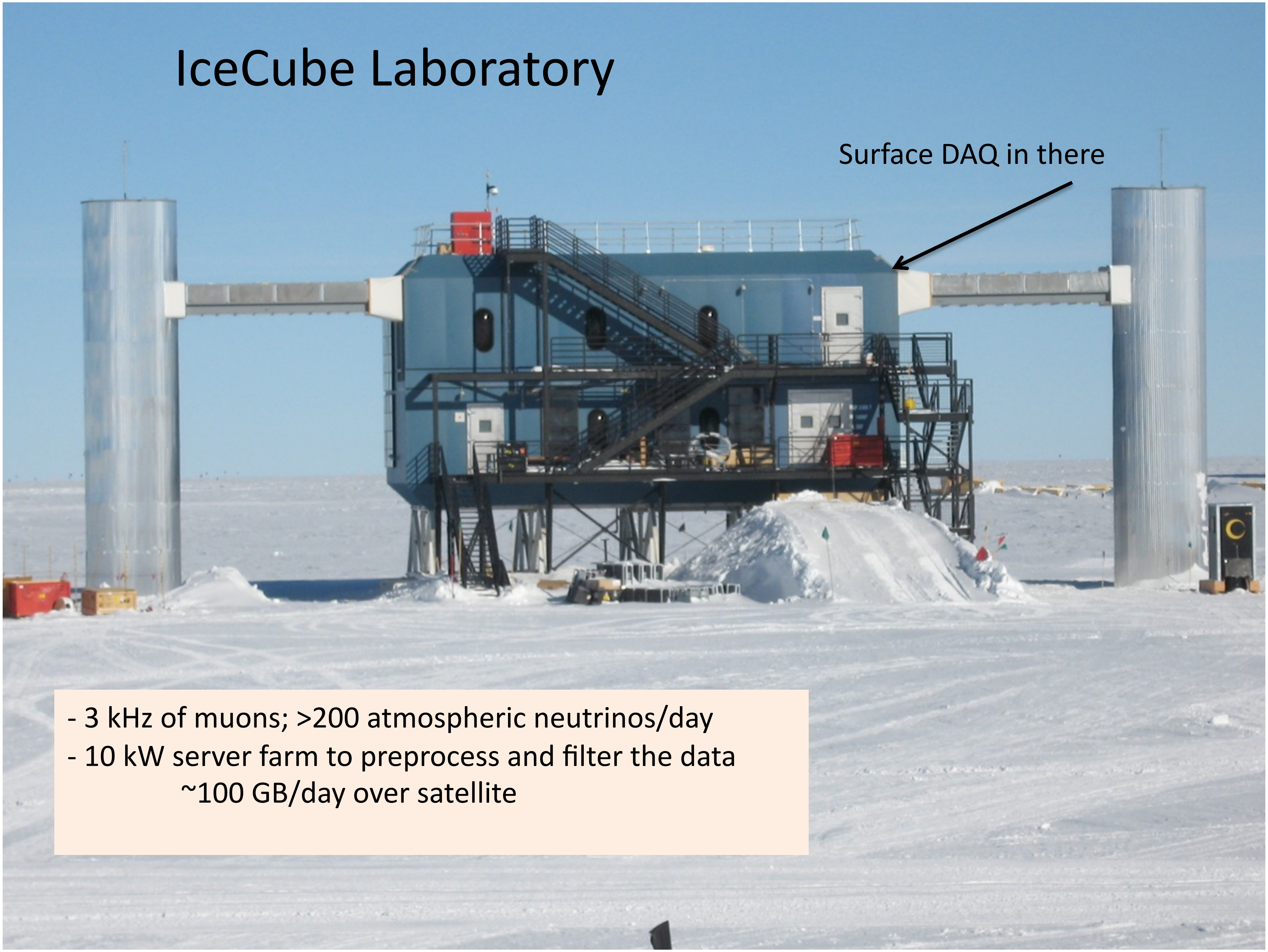
5160 DOMs
in deep ice
13 in diam.

IceCube construction

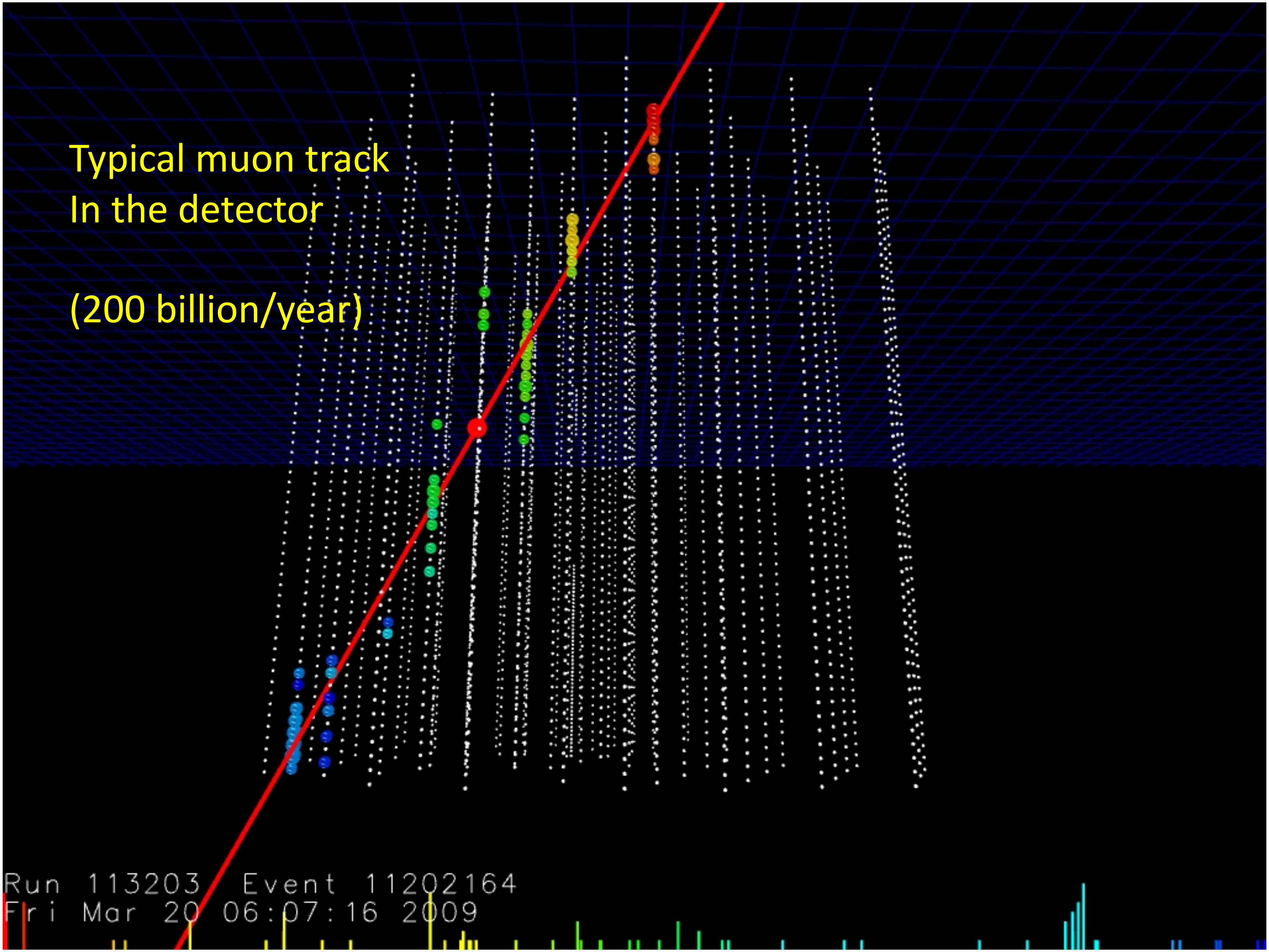


5160 sensors are deployed to a depth between 1500 and 2500m.

IceCube Laboratory

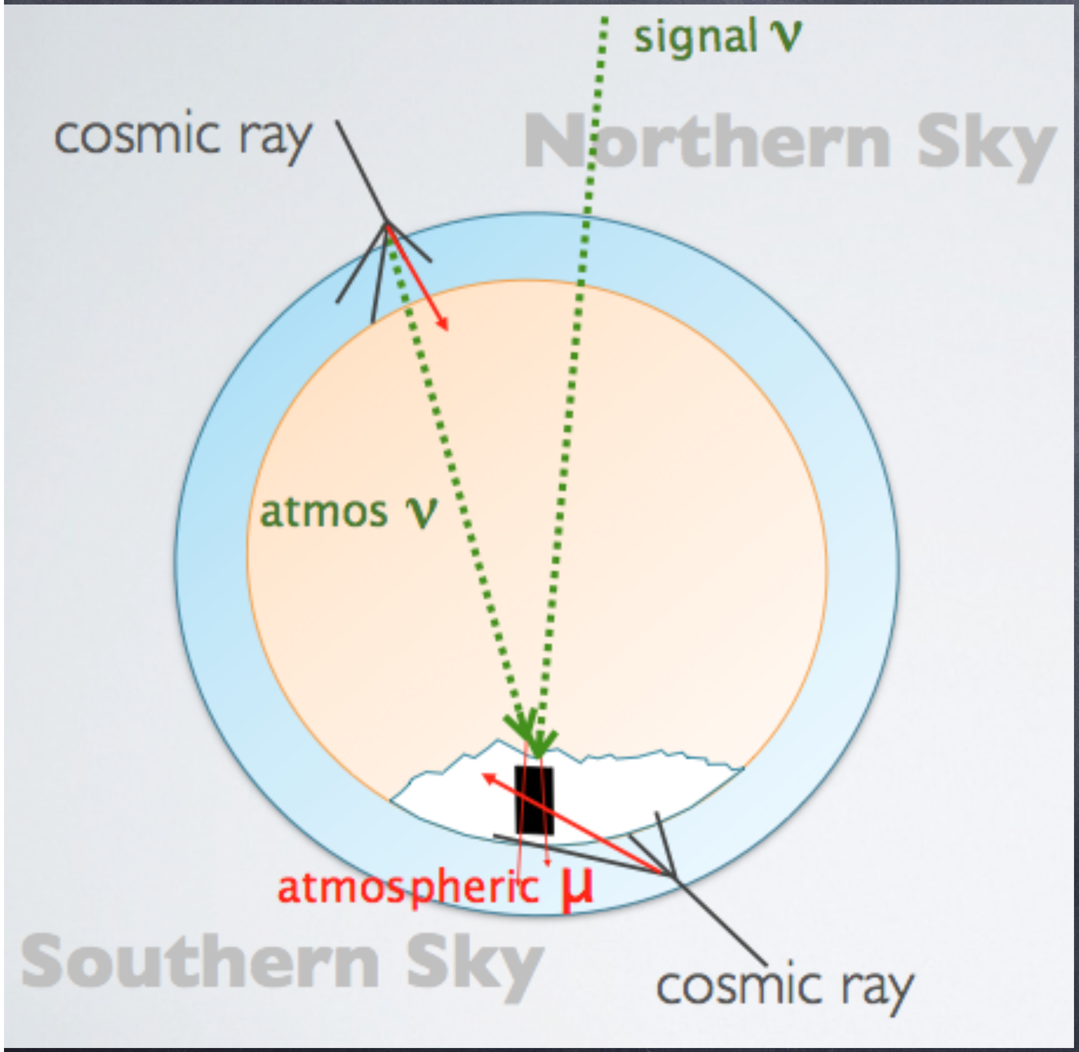


- 3 kHz of muons; >200 atmospheric neutrinos/day
- 10 kW server farm to preprocess and filter the data
  ~100 GB/day over satellite


Typical muon track
In the detector

(200 billion/year)
Run 113203 Event 11202164
Fri Mar 20 06:07:16 2009

Data



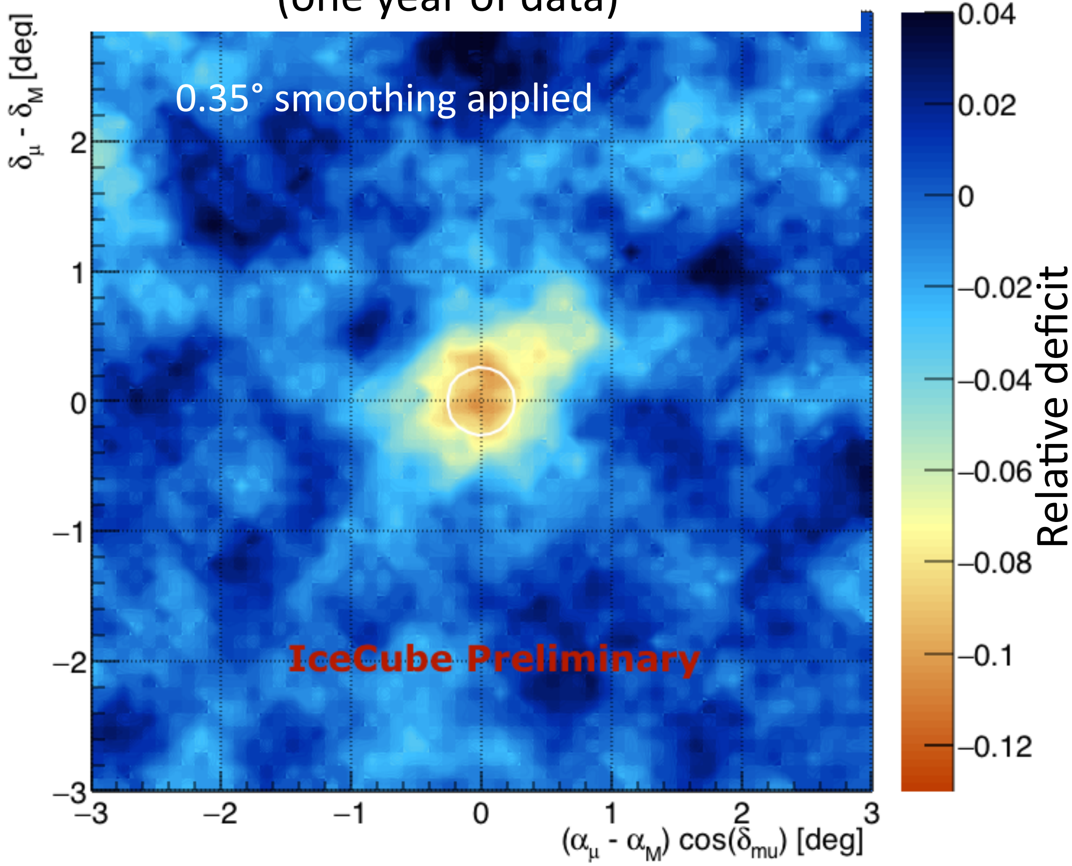
Events/year

- Cosmic Ray muons:
  2*10^11
- “Atmospheric” neutrinos:
  ~100,000
- Cosmic neutrinos:
  ~100

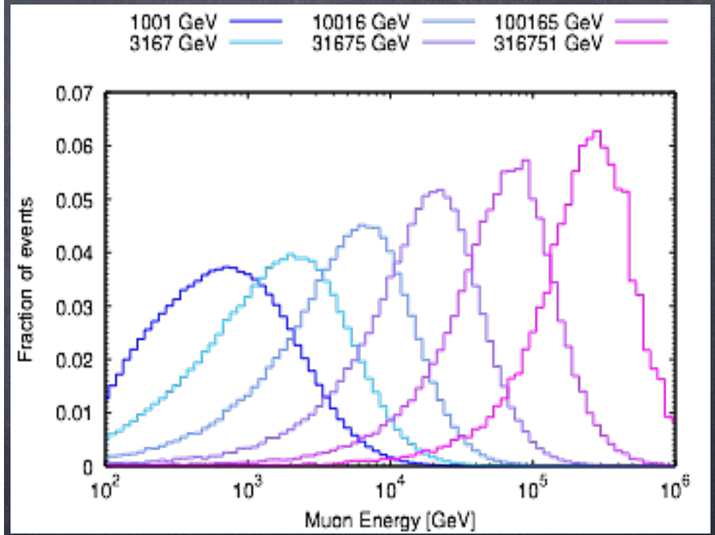
Muons

Angular resolution: 0.5° at 100 TeV

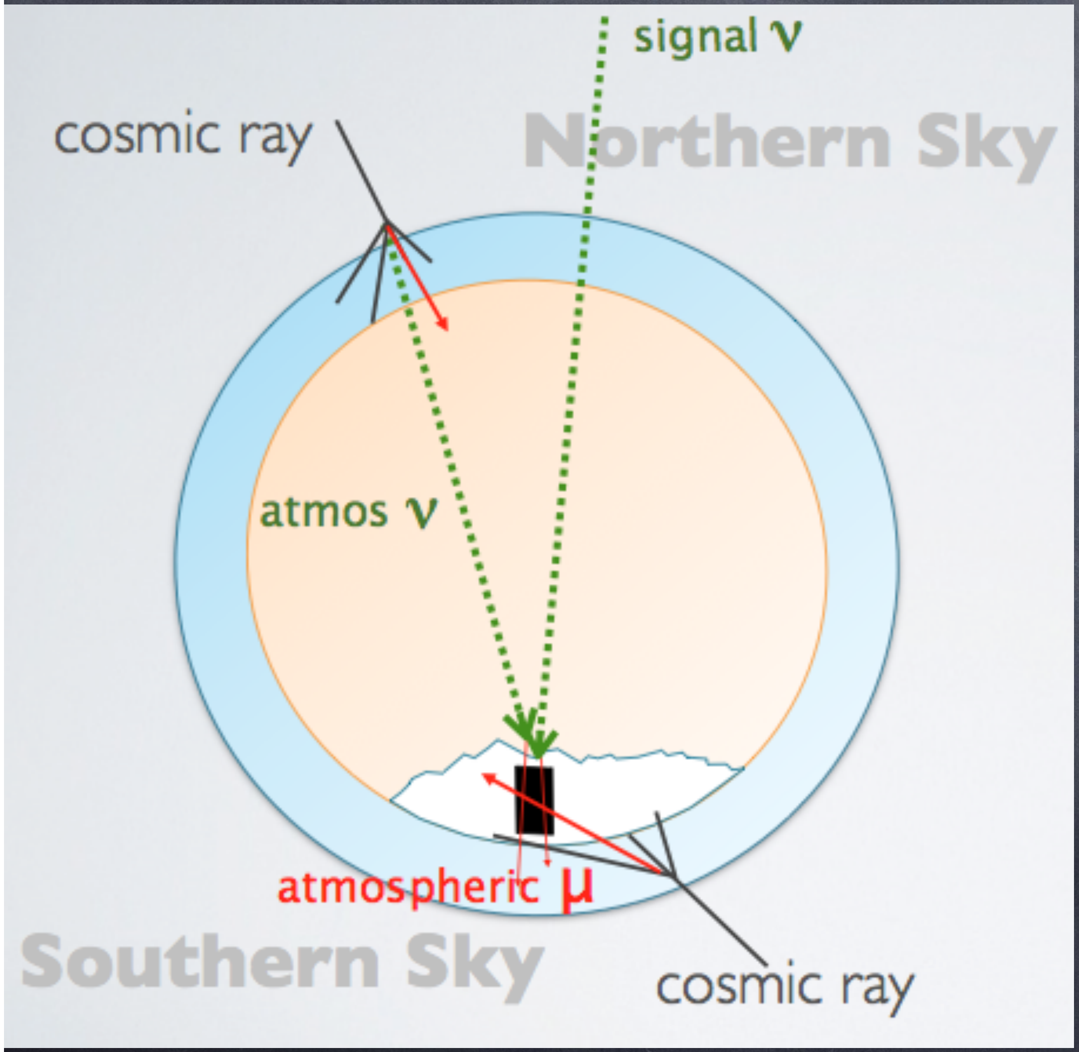
Moon shadow of cosmic ray muons
(air shower primaries get stuck in moon
→ Missing muons from moon direction)
(one year of data)



Energy resolution of muons:
~ 0.3 in log(E) at 100 TeV
(by measuring the dE/dX)



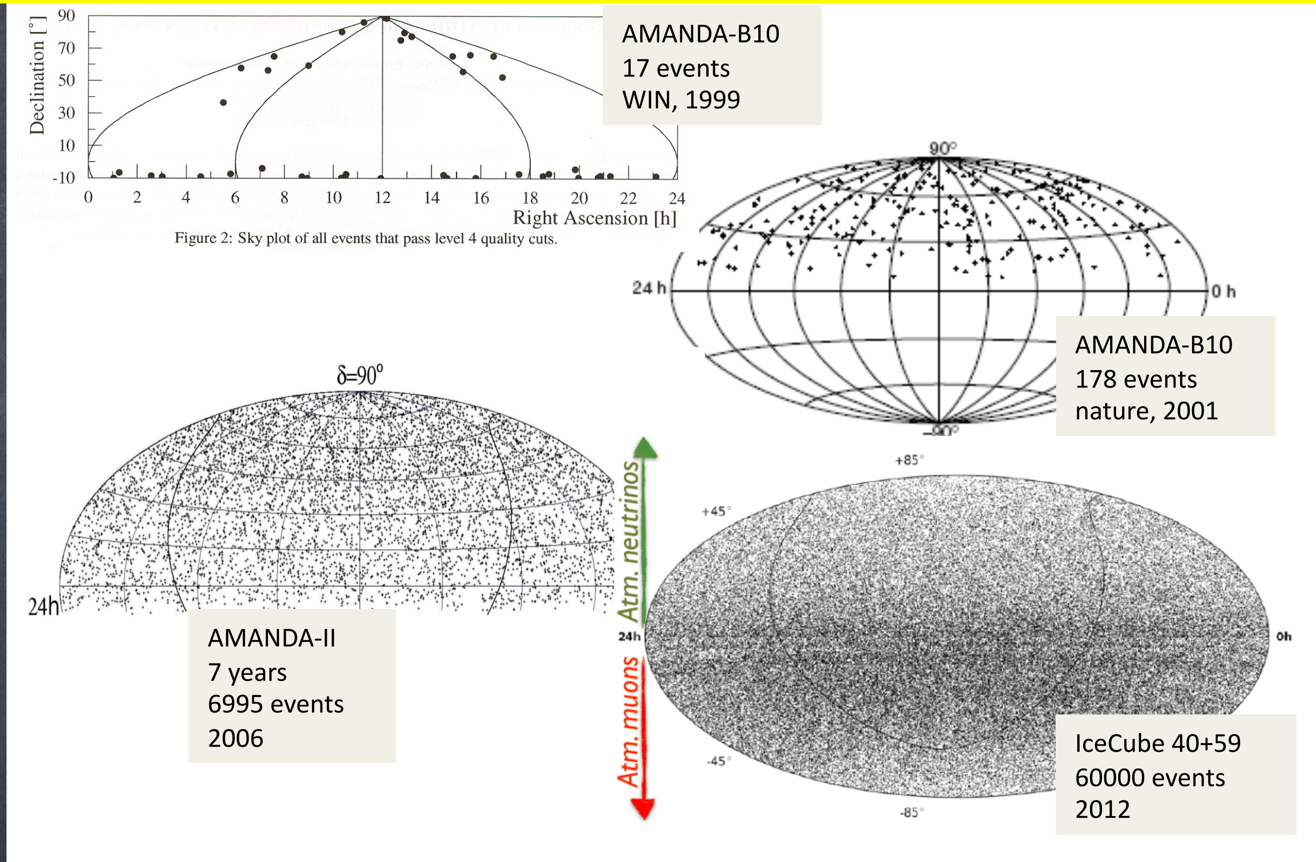
Data



Events/year

- Cosmic Ray muons: 2*10^11
- “Atmospheric” neutrinos: ~100,000
- Cosmic neutrinos: ~100

15 years of neutrino skymaps



15 years of neutrino skymaps

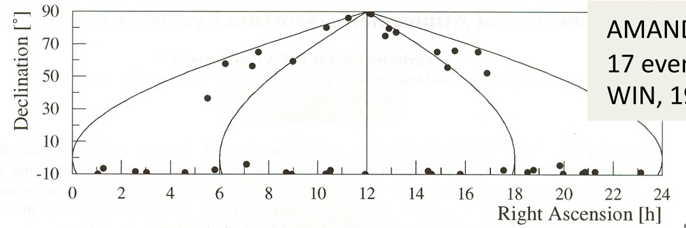
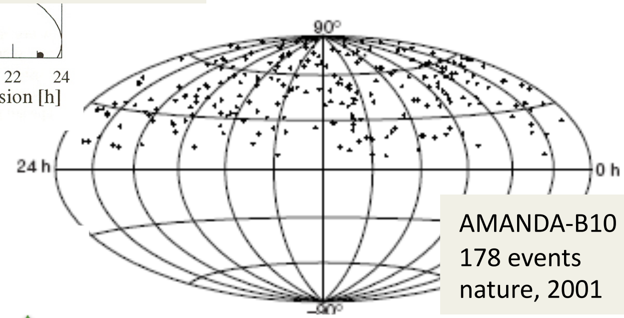
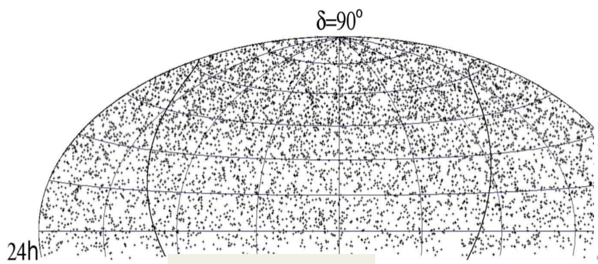


Figure 2: Sky plot of all events that pass level 4 quality cuts.

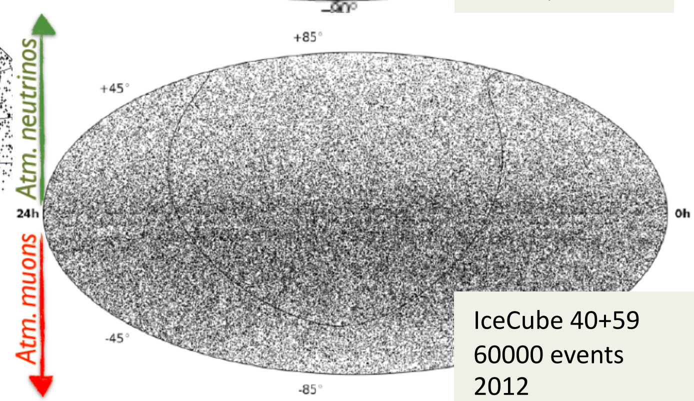
AMANDA-B10
17 events
WIN, 1999



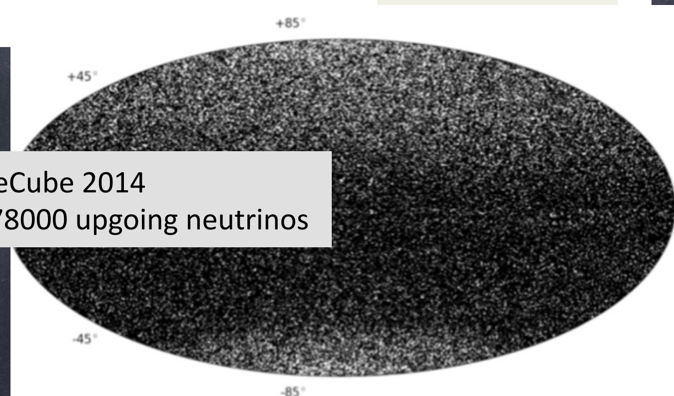
AMANDA-B10
178 events
nature, 2001



AMANDA-II
7 years
6995 events
2006



IceCube 40+59
60000 events
2012



IceCube 2014
178000 upgoing neutrinos

15 years of neutrino skymaps

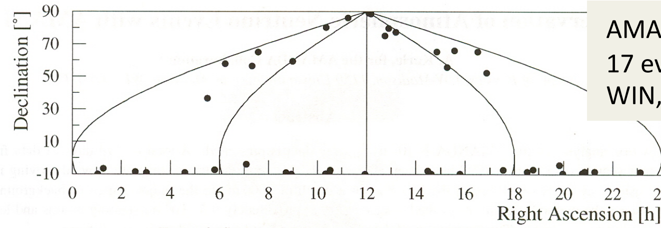
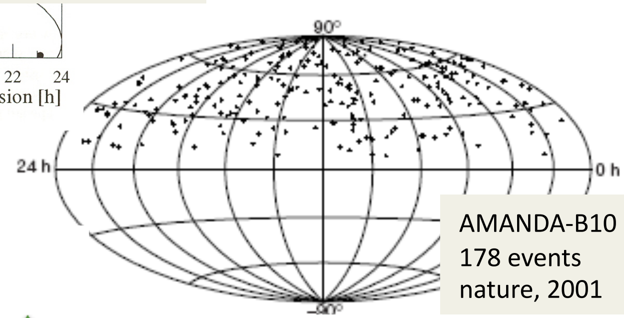
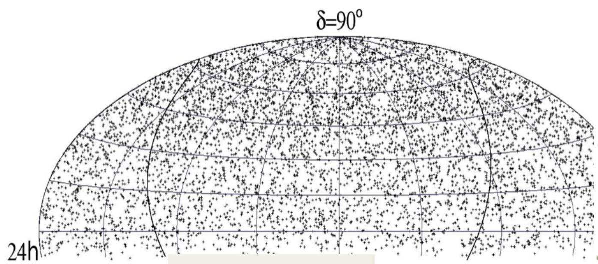


Figure 2: Sky plot of all events that pass level 4 quality cuts.

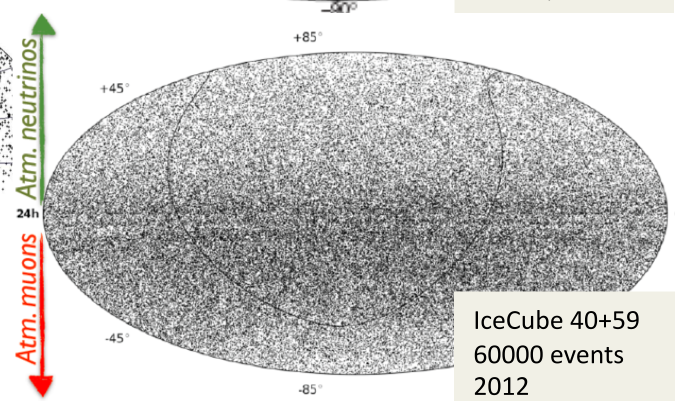
AMANDA-B10
17 events
WIN, 1999



AMANDA-B10
178 events
nature, 2001

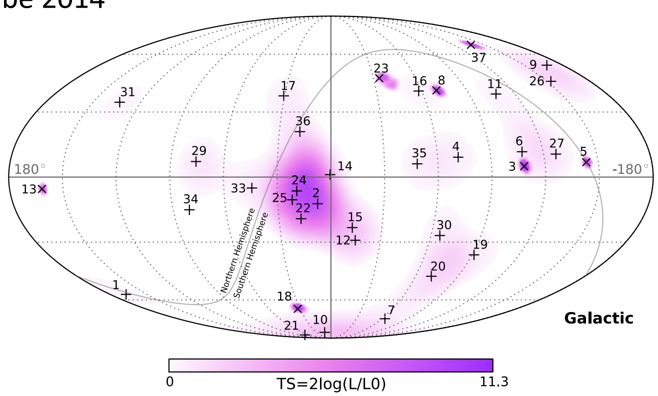


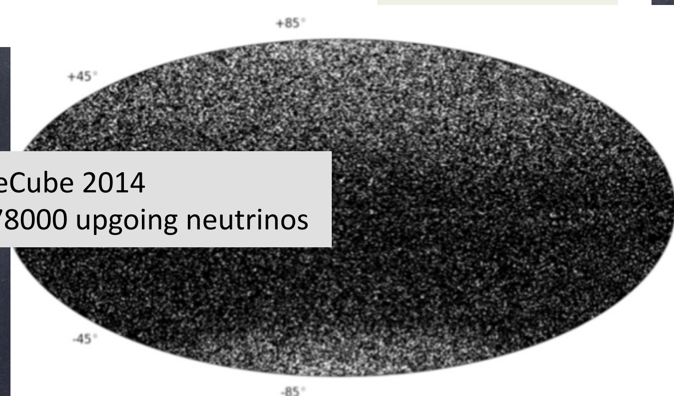
AMANDA-II
7 years
6995 events
2006



IceCube 40+59
60000 events
2012

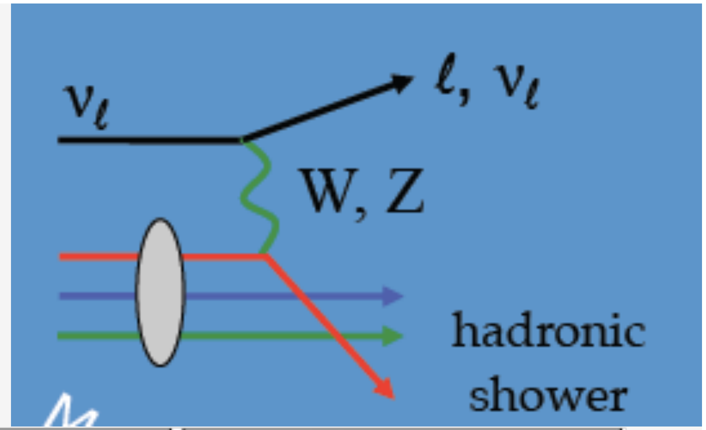
IceCube 2014

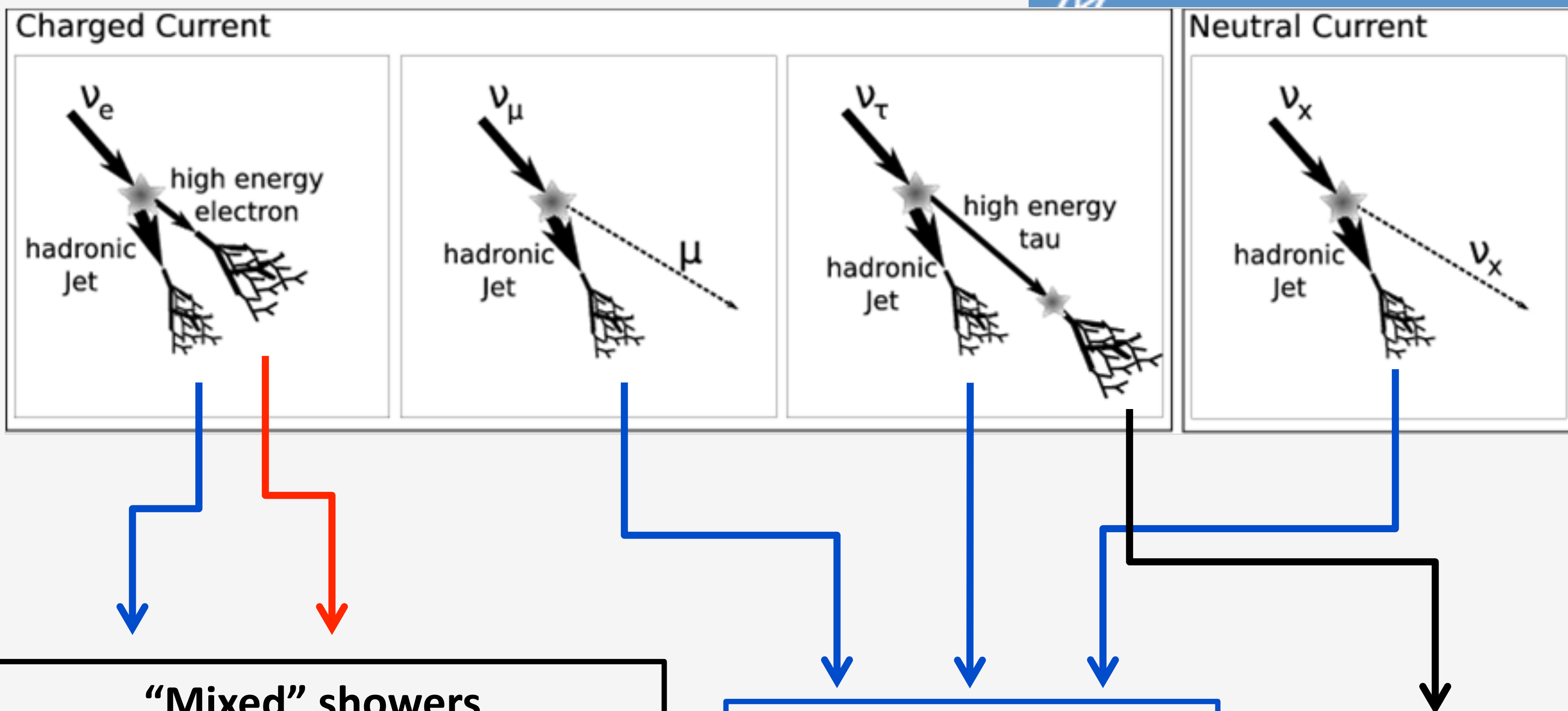




IceCube 2014
178000 upgoing neutrinos

Topology of neutrino interactions
neutrino-induced showers





"Mixed" showers

$\langle E_{electromagnetic} \rangle \approx 80\%\ E_{nu}$

$\langle E_{hadronic} \rangle \approx 20\%\ E_{nu}$

Hadronic showers

$\langle E \rangle \approx 20\%\ E_{nu}$

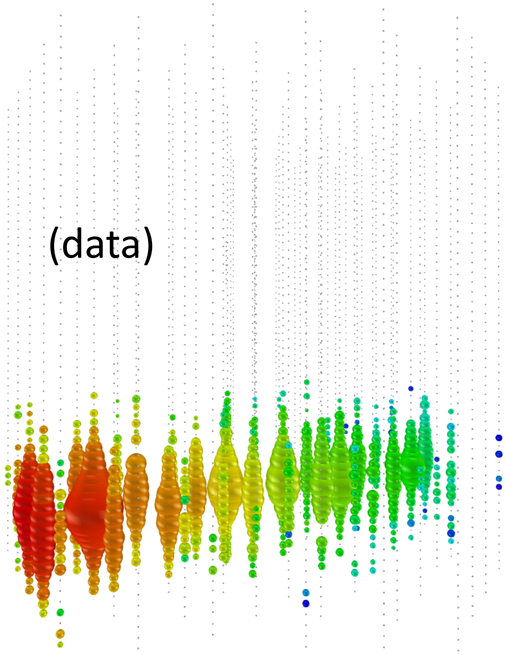
EM or Hadronic

graphics: Jaime Alvarez

Types of events and interactions

Charged-current ν_μ

(data)

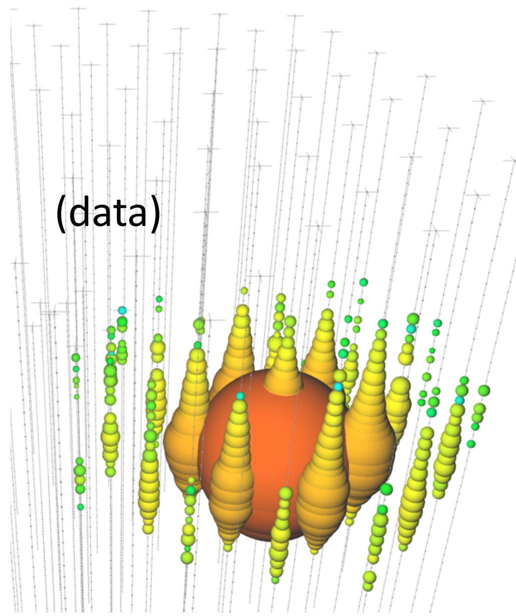


Up-going (throughgoing) track

Factor of ~2 energy resolution
< 1 degree angular resolution

Neutral-current / ν_e

(data)

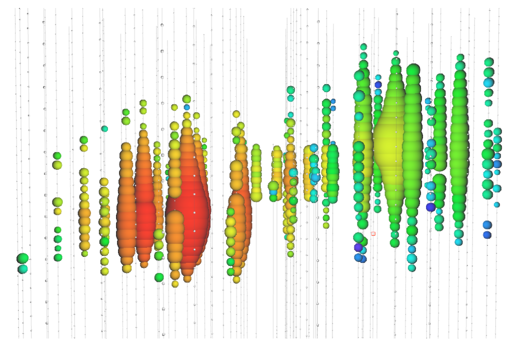


Isolated energy deposition (cascade) with no track

15% deposited energy resolution
10 degree angular resolution (above 100 TeV)

Charged-current ν_τ

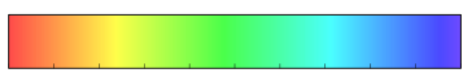
(simulation)



"Double-bang"

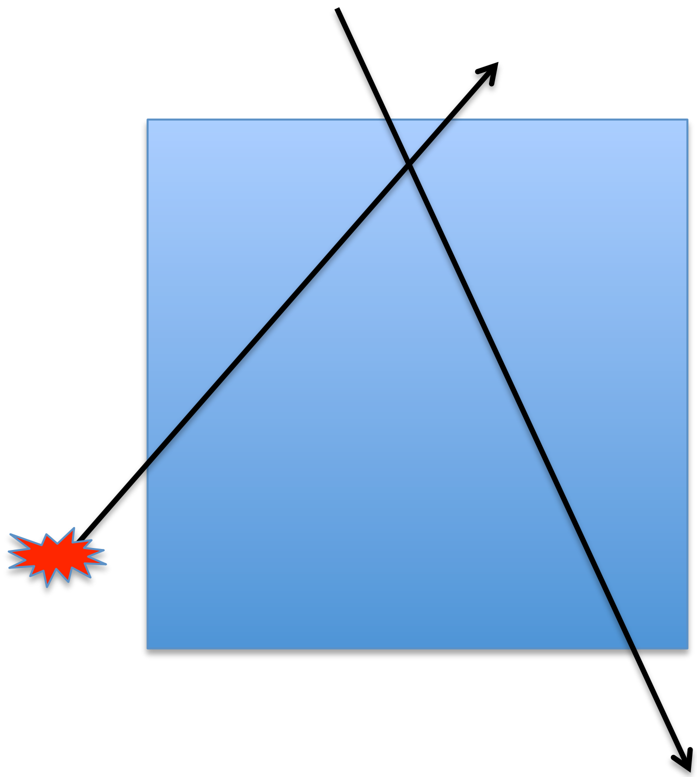
(none observed yet: τ decay length is 50 m/PeV)

ID: above 1 PeV

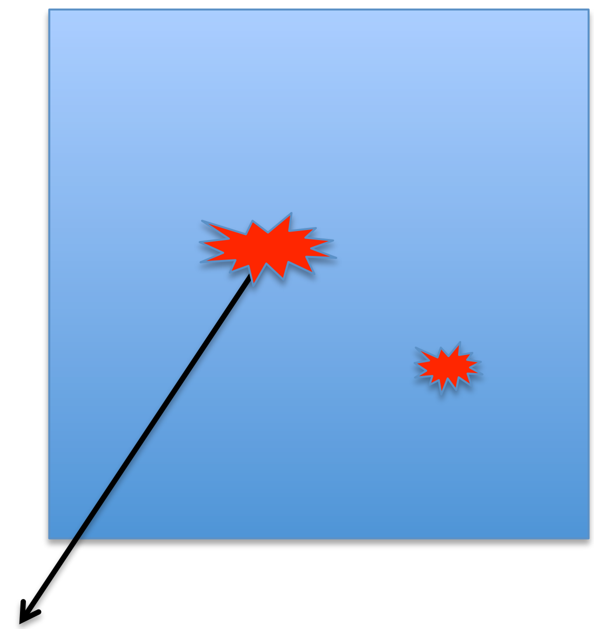
Early  Late

Event selection strategies

Throughgoing muons

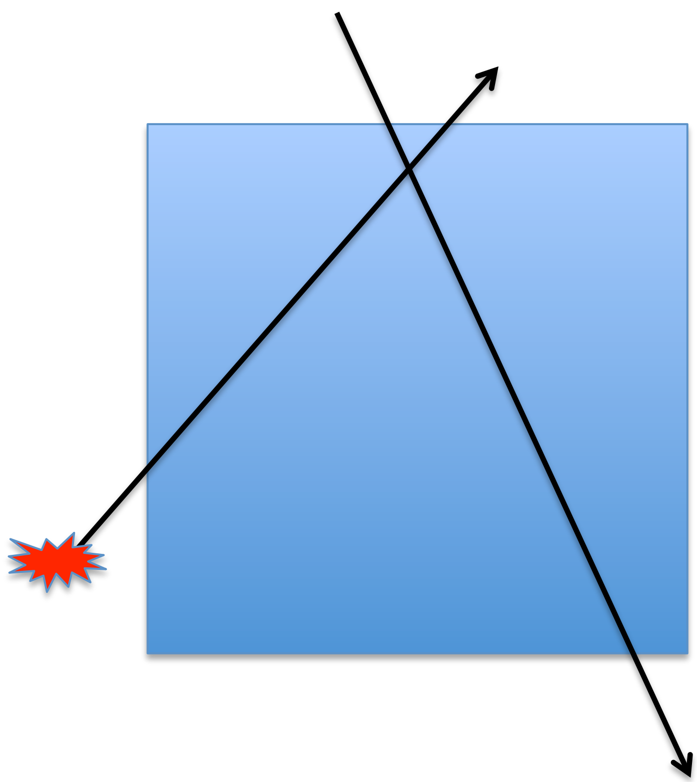


Events with contained vertex

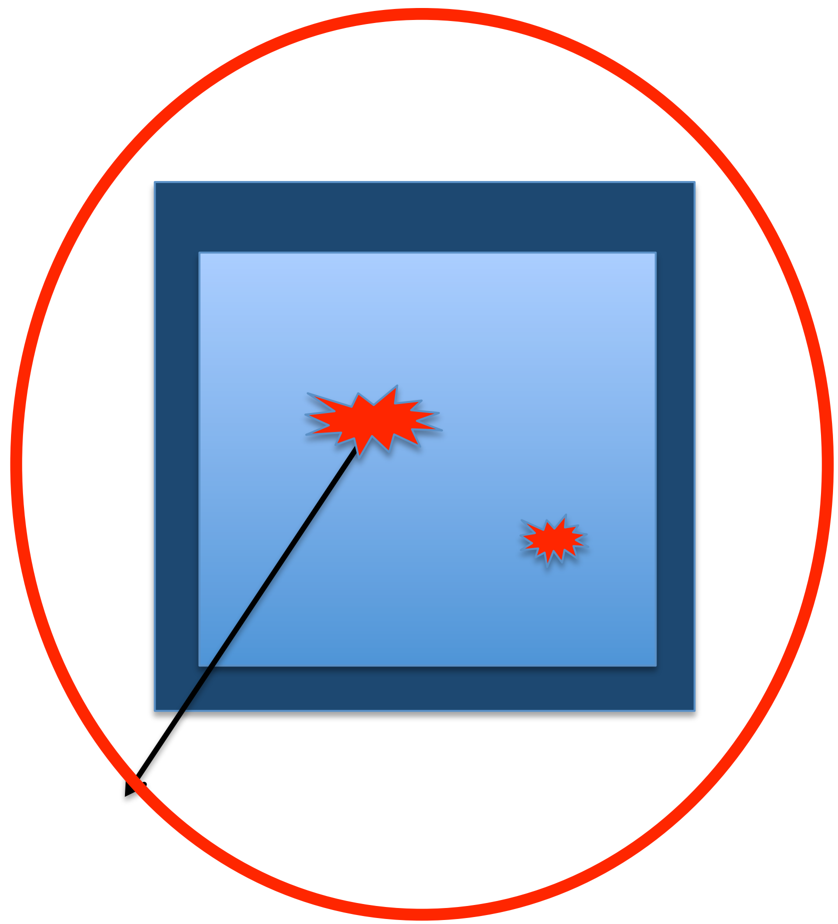


Event selection strategies

Throughgoing muons



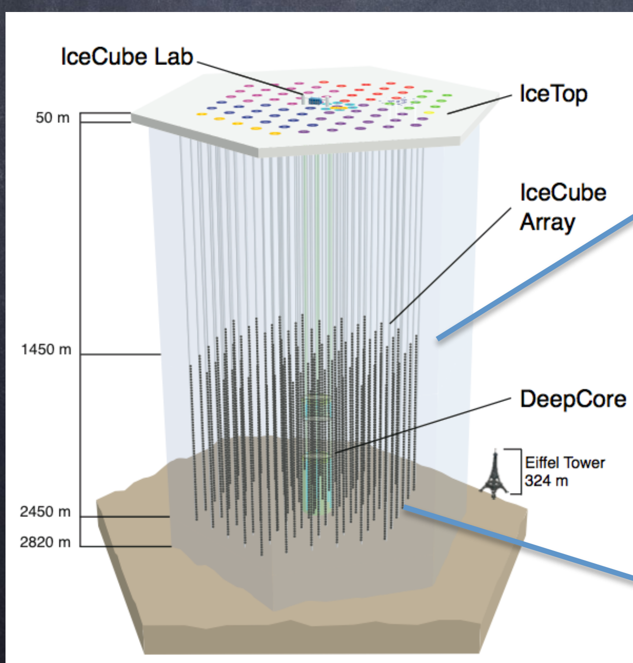
Events with contained vertex

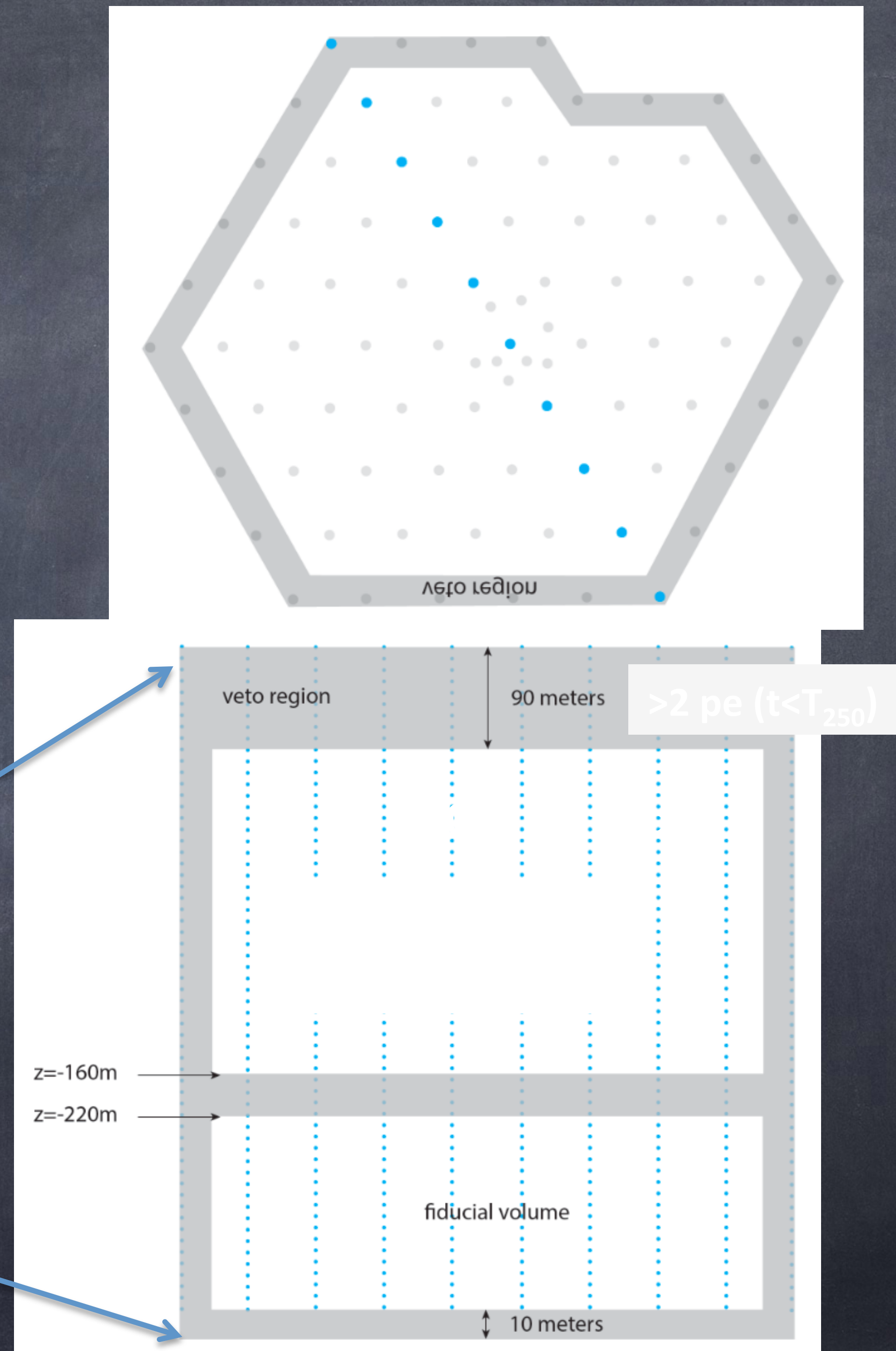


Veto region

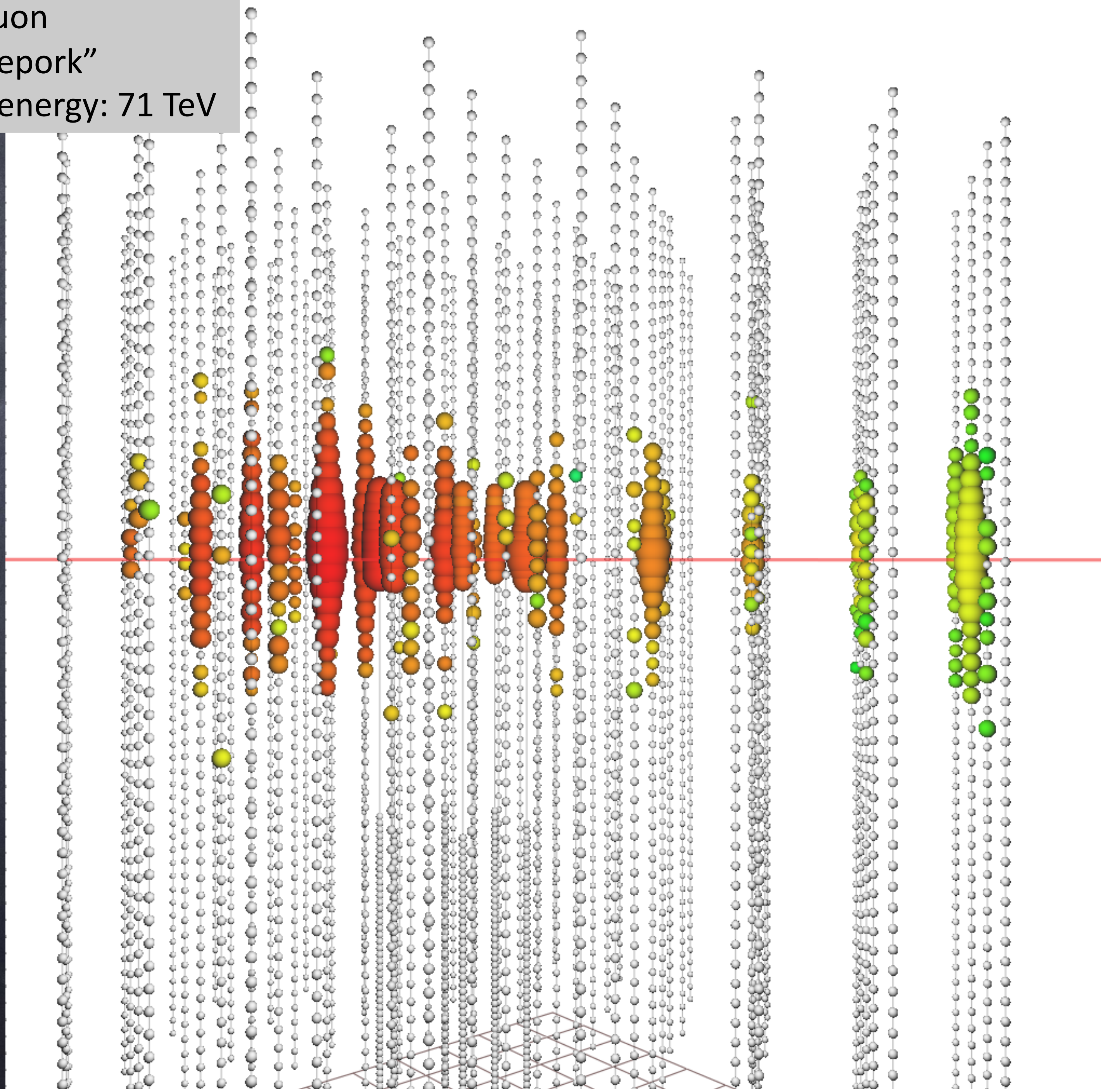
The PMT signals of all PMTs
in the veto region are treated as Veto signals:
~2400 DOMs
Contained vertex events: "First light is in fiducial region"

> Amongst the first 250 photoelectrons of an event, not more than 3.0 photoelectrons are allowed in the veto region.

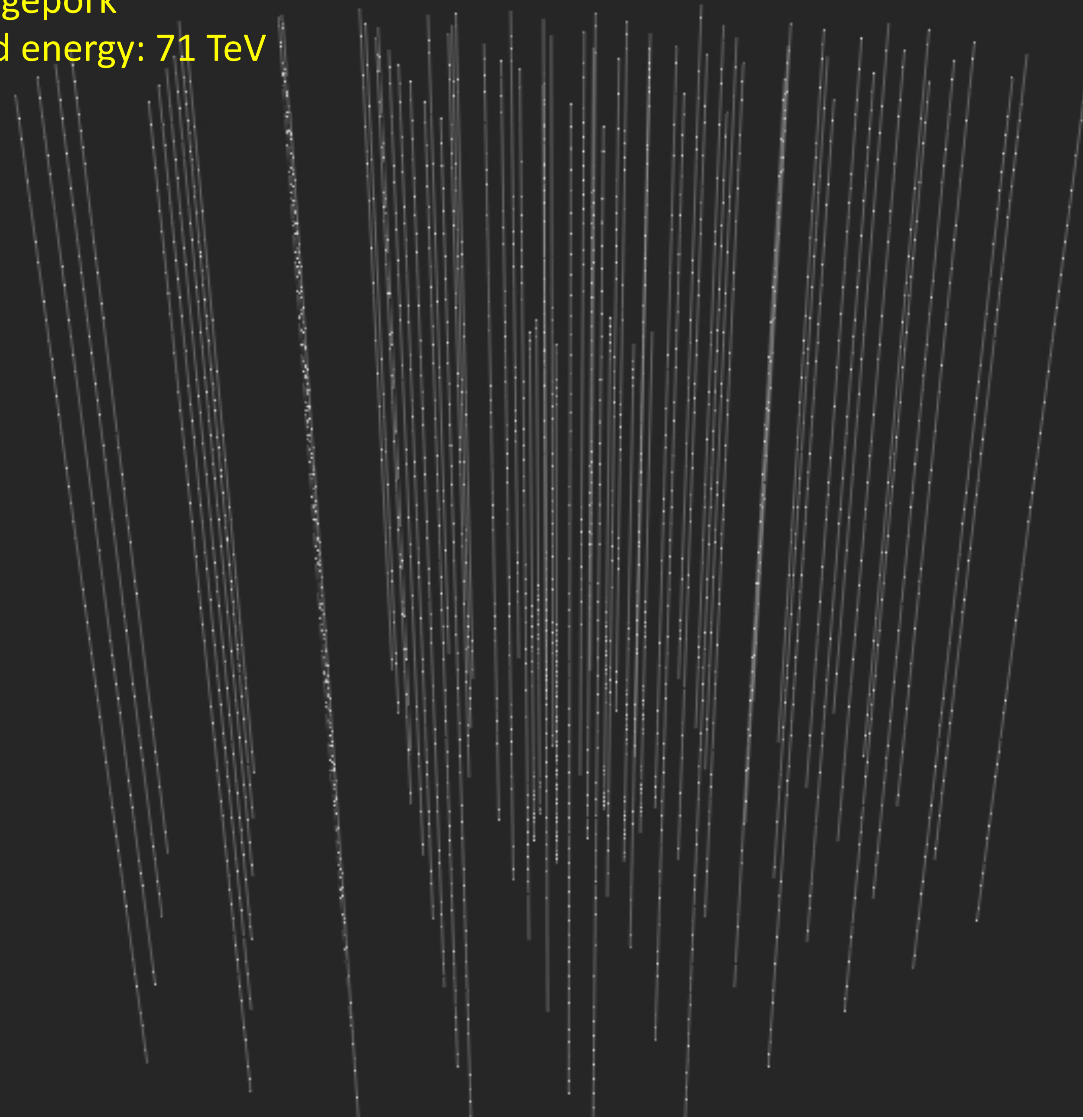




Starting muon
“Dr. Strangepork”
Deposited energy: 71 TeV

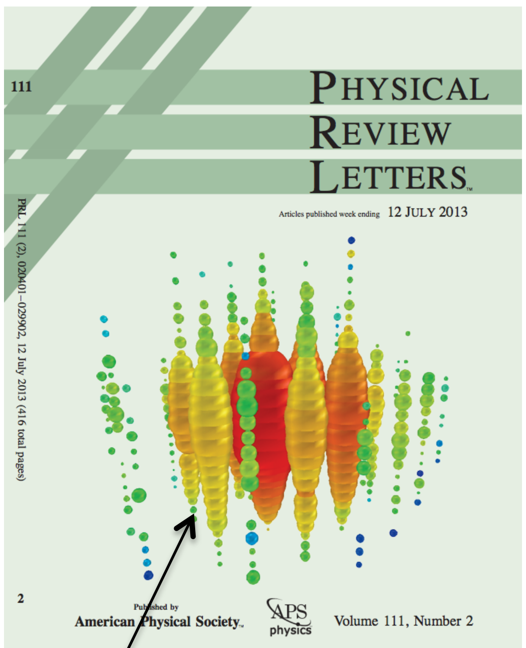


Starting muon
“Dr. Strangepork”
Deposited energy: 71 TeV



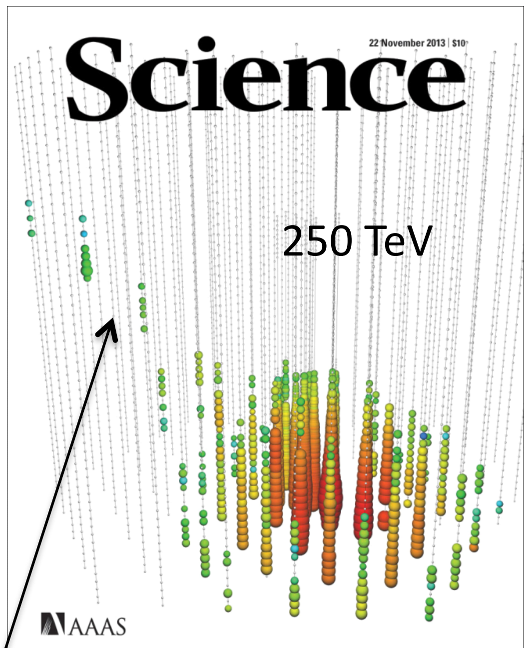
Discovery of high energy cosmic neutrinos I

July 2013:
2 events: E > 1 PeV



1.1 PeV
“Bert”

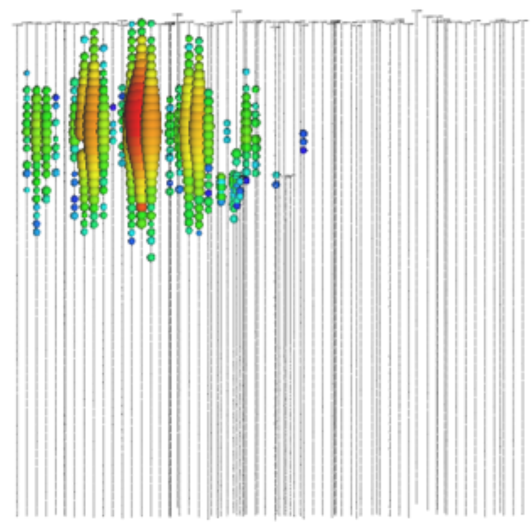
Nov 2013:
2 years of data:
28 events
~ 4 sigma above BG



Outgoing track

Phys.Rev.Lett. 113 (2014)

Excess of events compared to background at very high energies
37 events, one event at 2 PeV
5.7 sigma



2 PeV
“Big Bird”

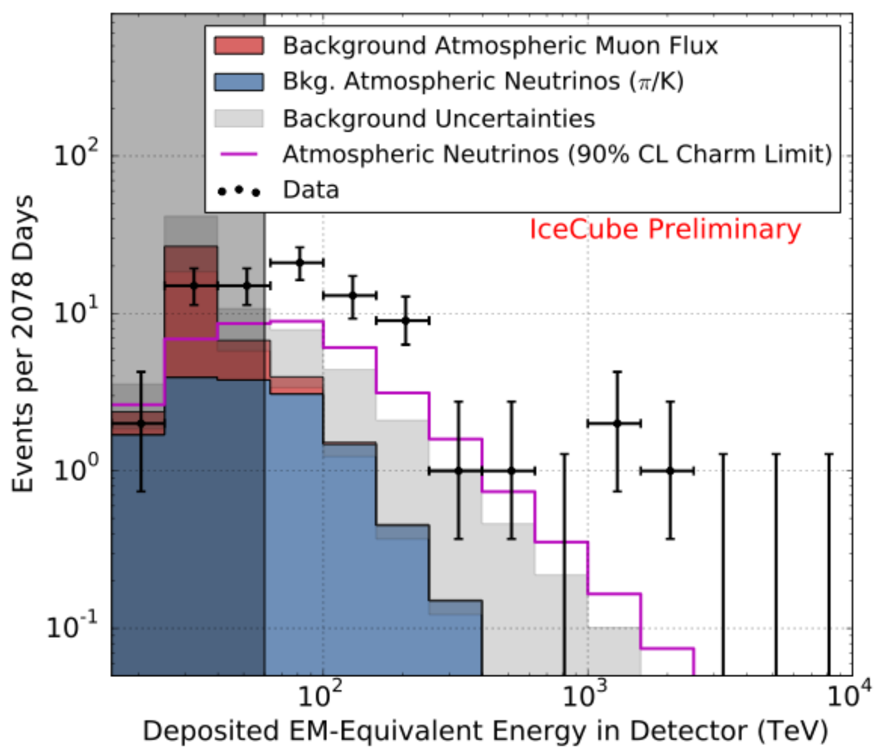
High energy events with contained vertex: 4 → 6 years

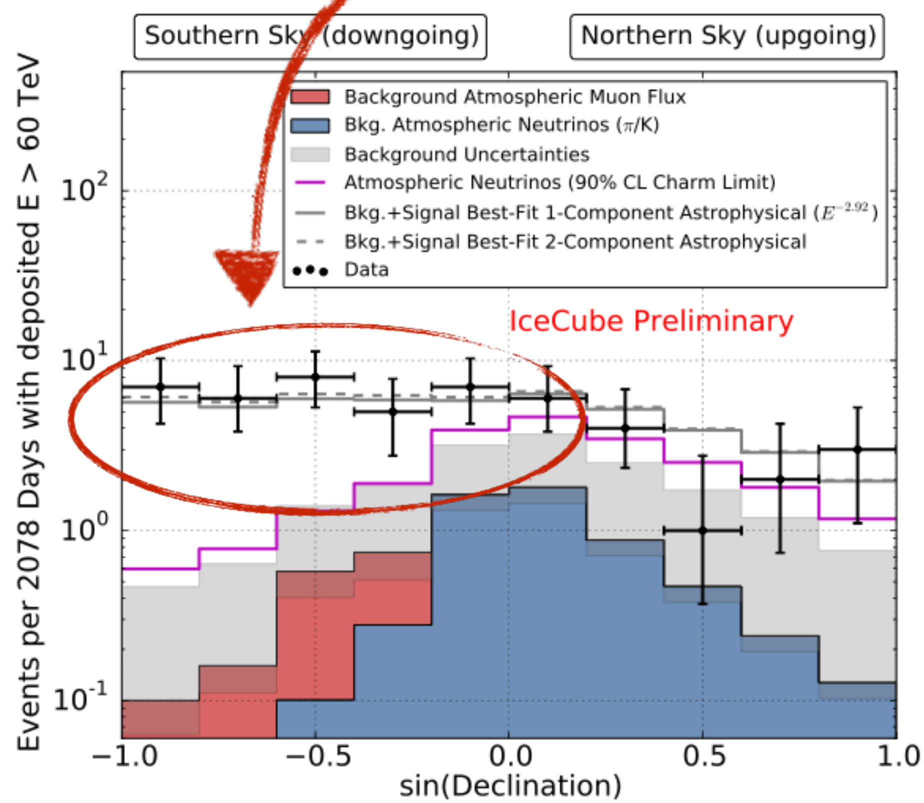
6 years (ICRC 2017)

- **82 events in 6 years** (54 in 4 years)
- ~ half (41) are expected to be bkg (atm. muons and atm. neutrinos)
- Astrophysical fit (and its significance) depends on **number, zenith angle, and energy**

Zenith distribution incompatible with atmospheric origin

Energy distribution

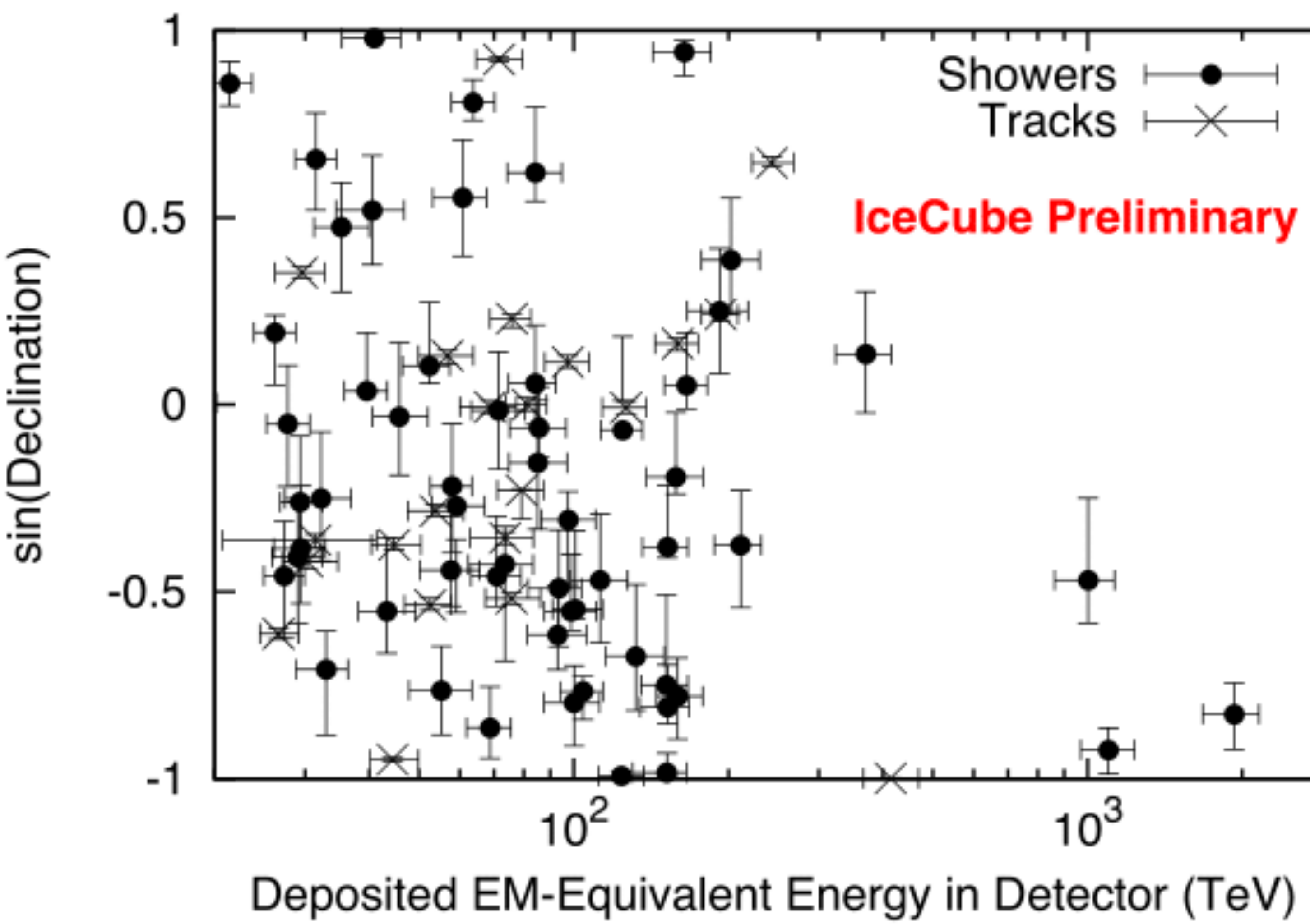




Declination vs energy

Upgoing events

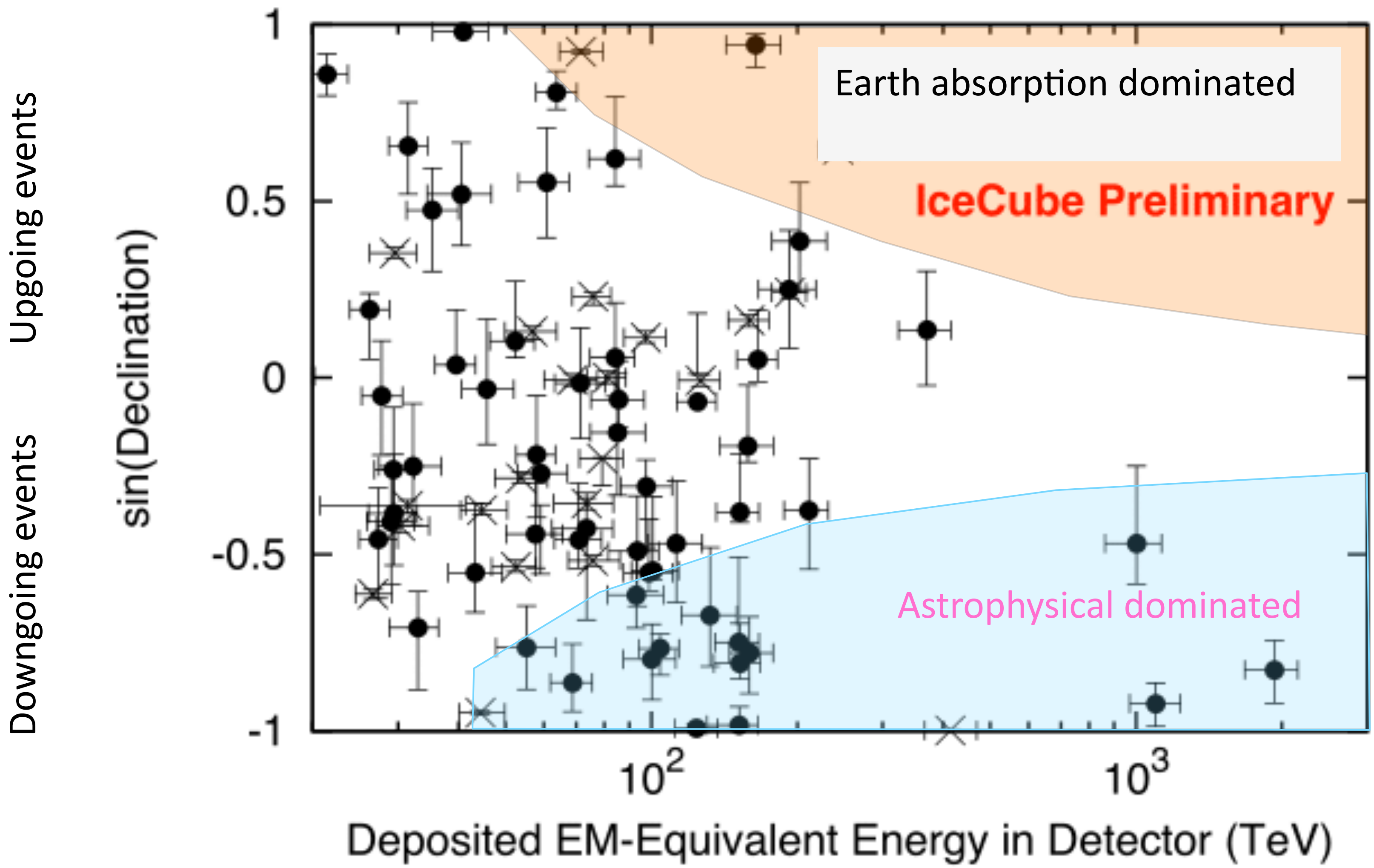
Downgoing events



Most events in Southern hemisphere (downgoing).

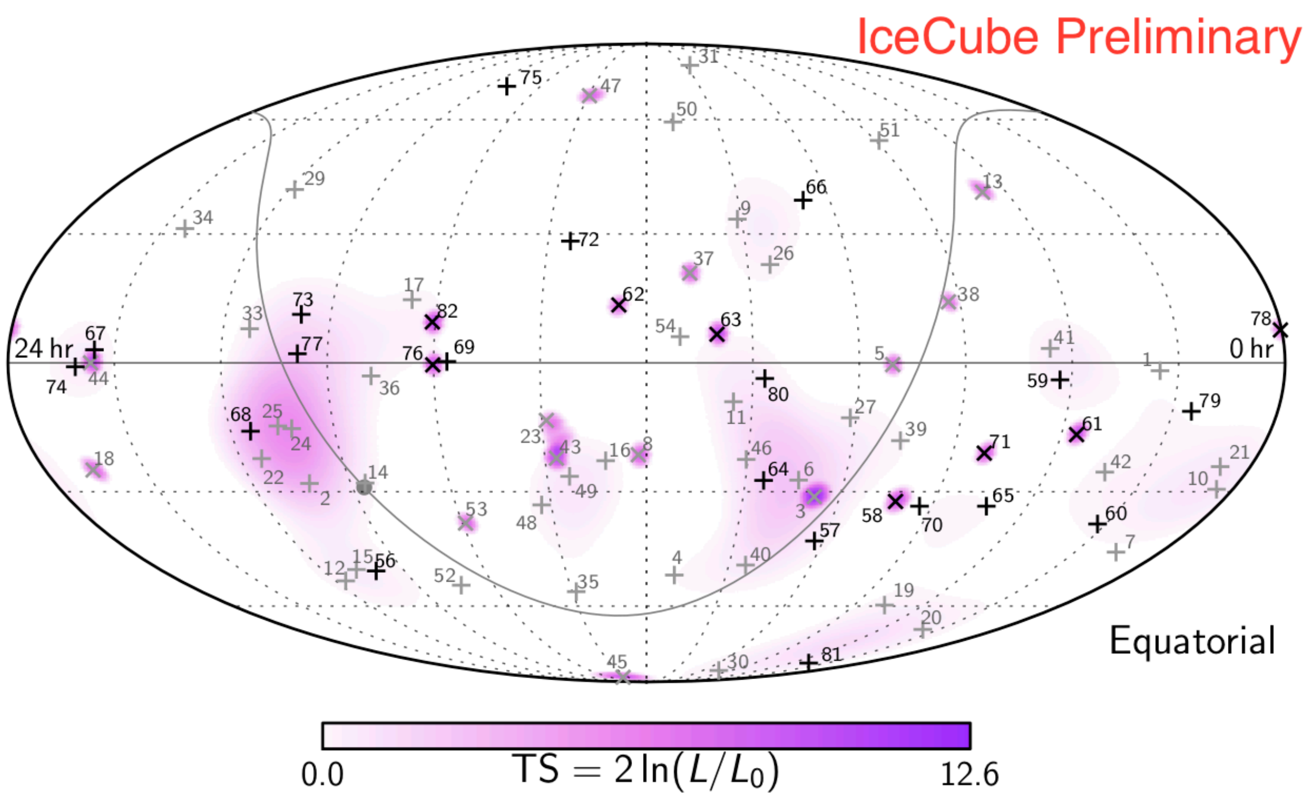
Most events in Southern hemisphere (downgoing).

Declination vs energy



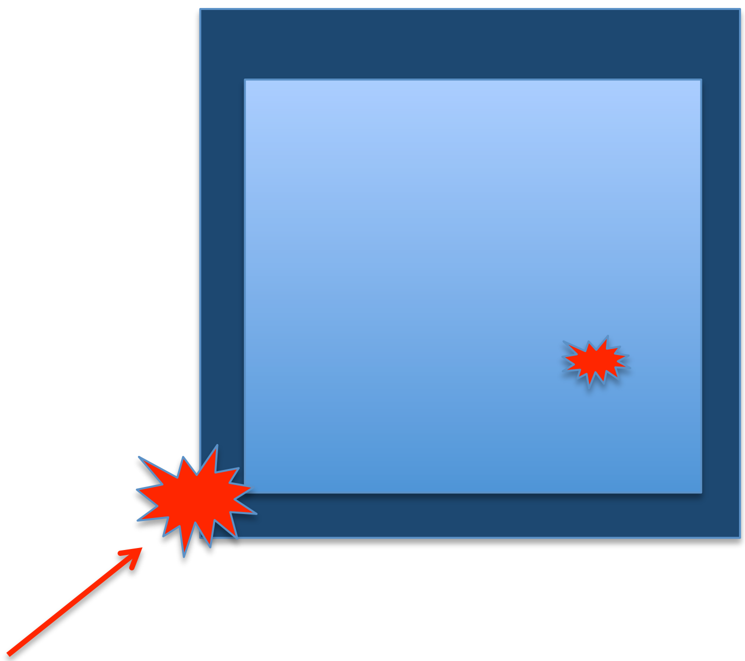
Most events in Southern hemisphere (downgoing).

Skymap in equatorial coordinates



Beyond HESE: adding partially contained events.

Events with
PARTIALLY contained vertex



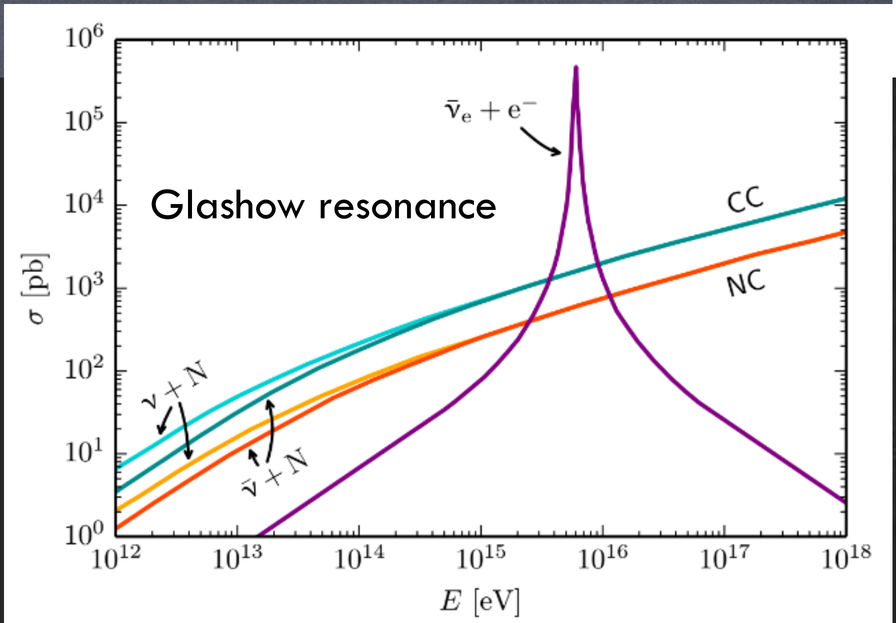
Now (as of ICRC) we have new results for such events at high energies.

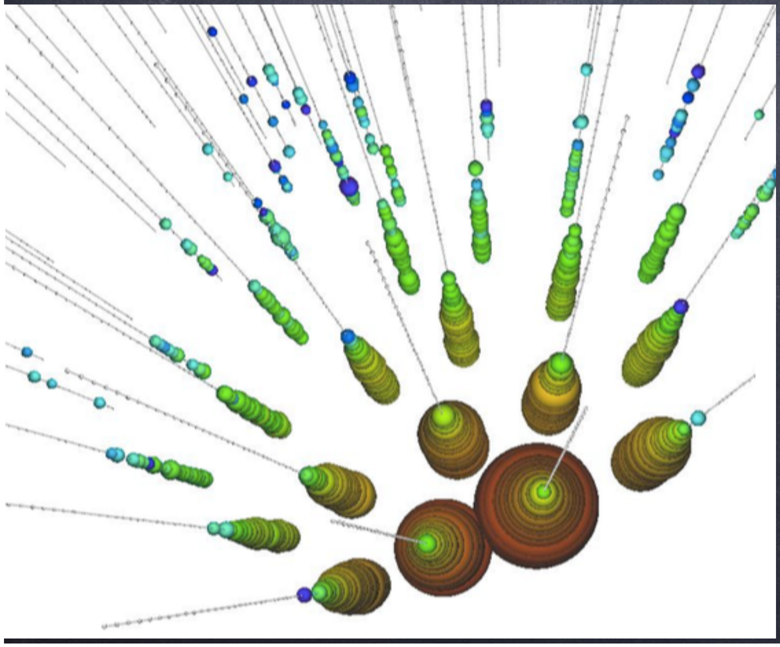
The highest energy neutrino?

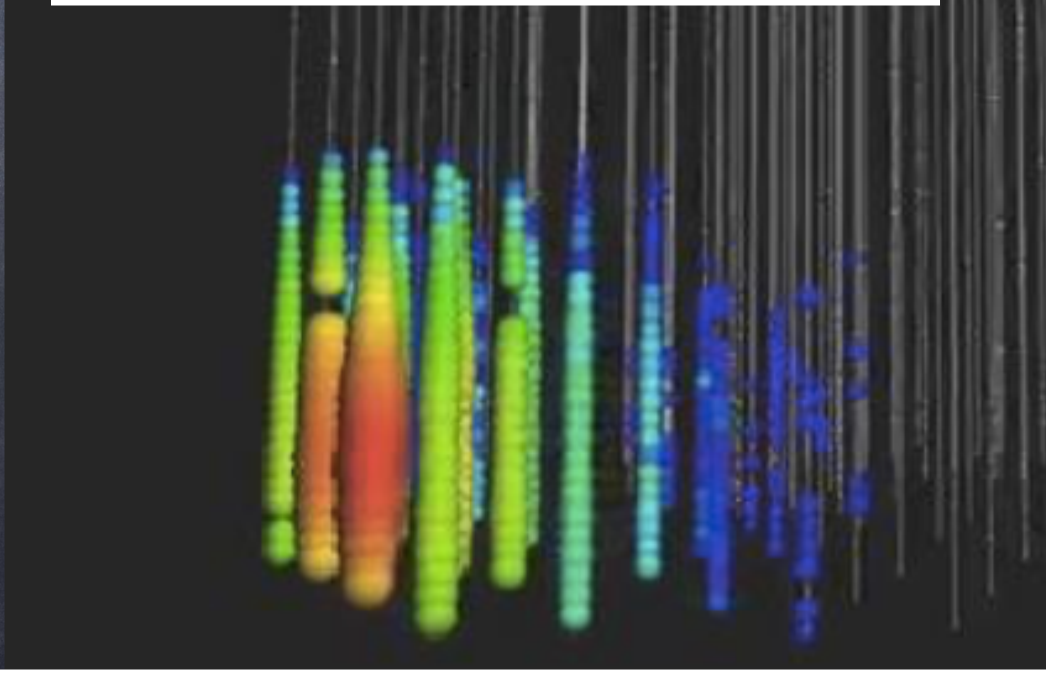
Interesting event found in expanded search

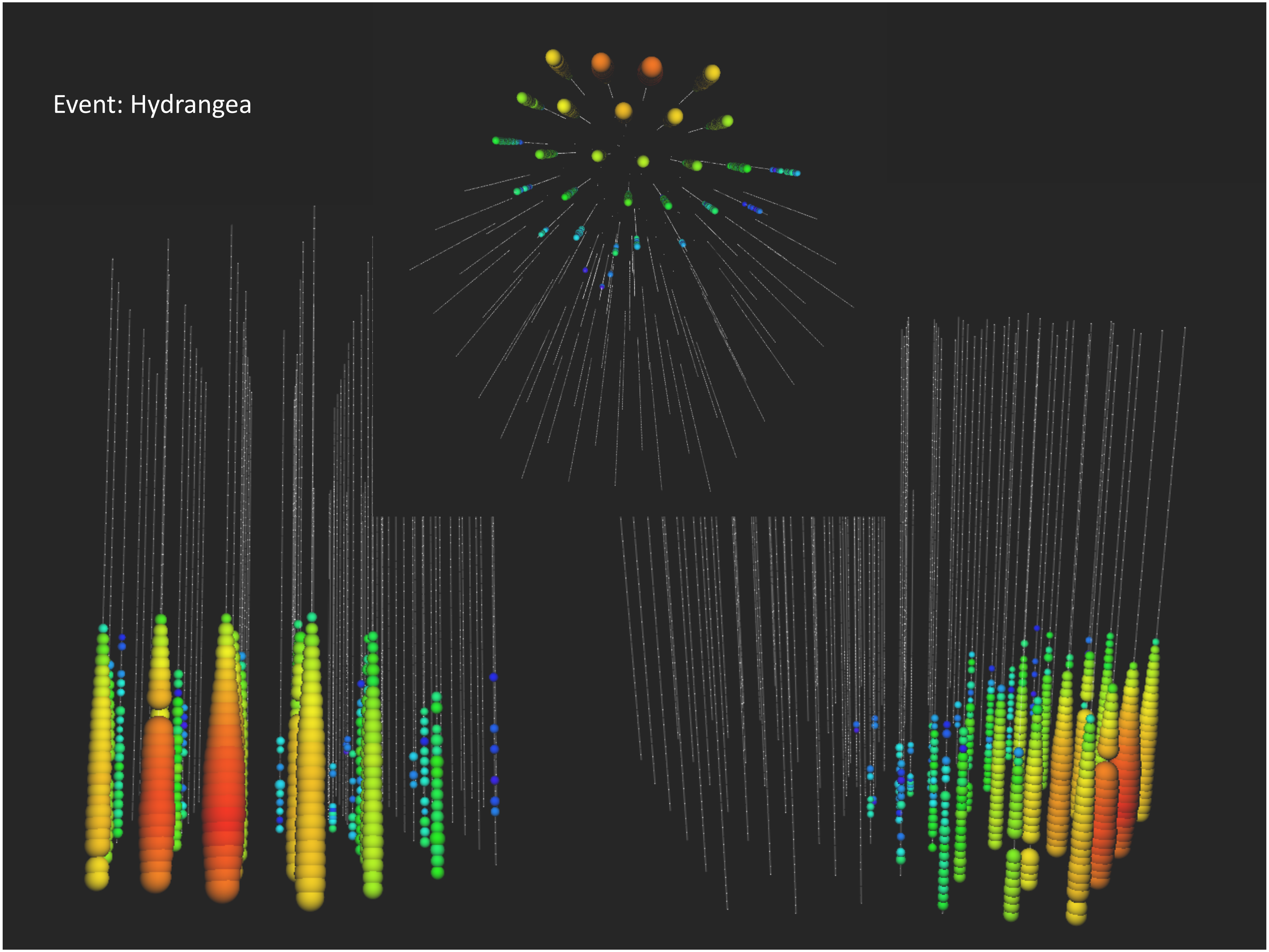
Background studies not complete yet!
If confirmed, the highest energy neutrino
Charge: 200,000 photoelectrons

Energy: ~7 PeV





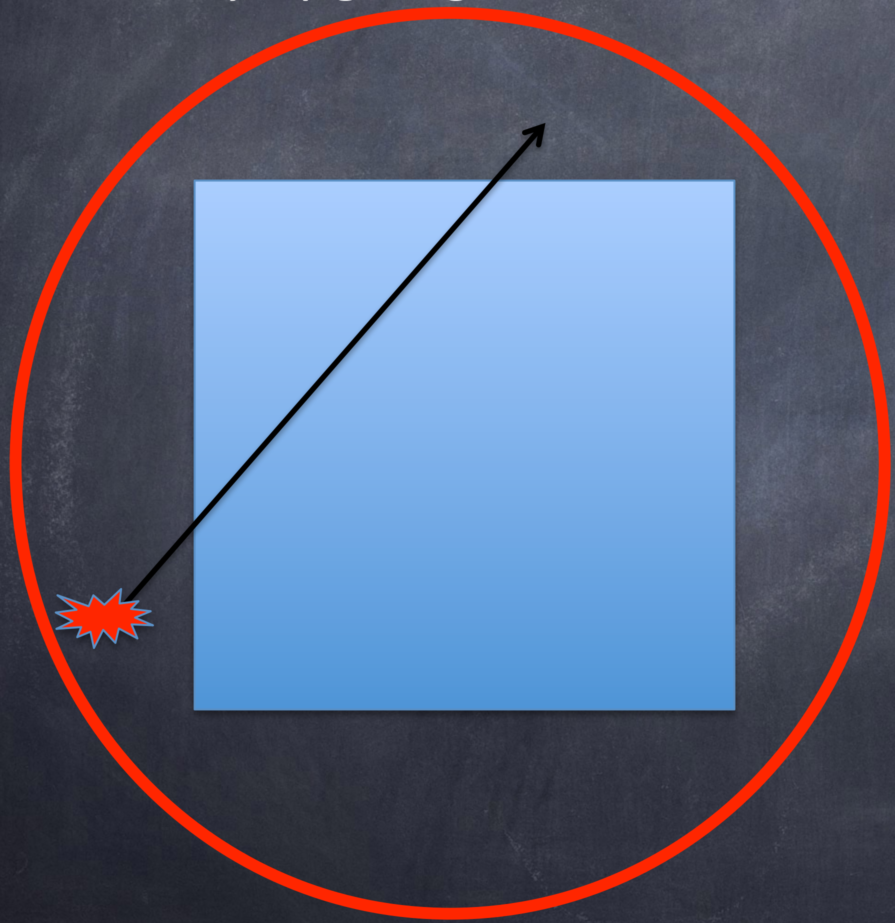


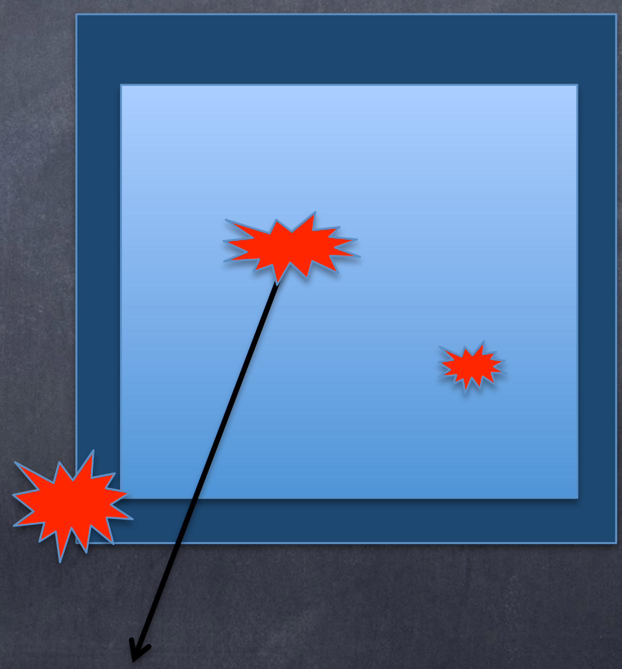

Event: Hydrangea

Event selection strategies

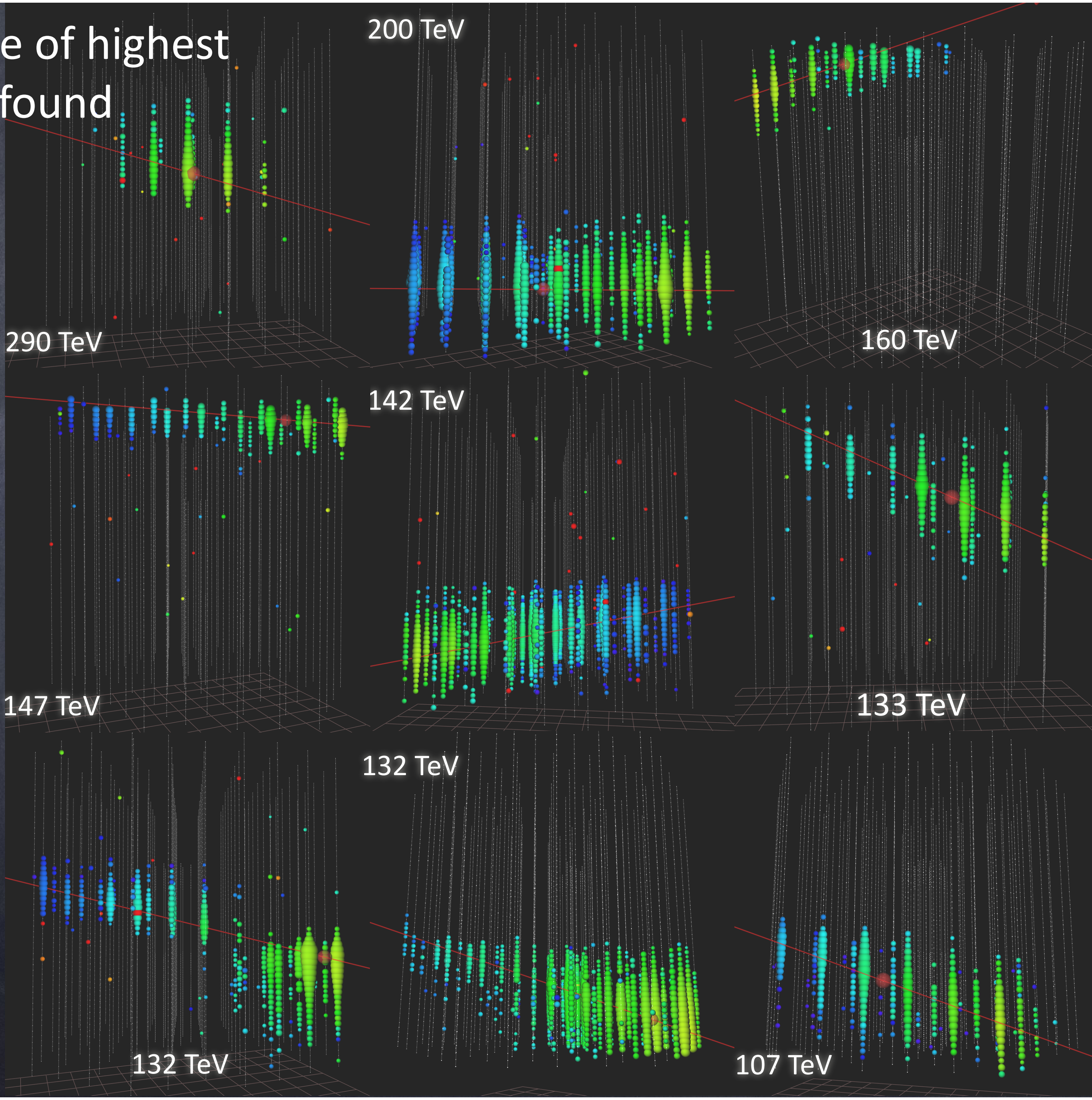
Throughgoing muons,
Mostly upgoing

Events with contained vertex

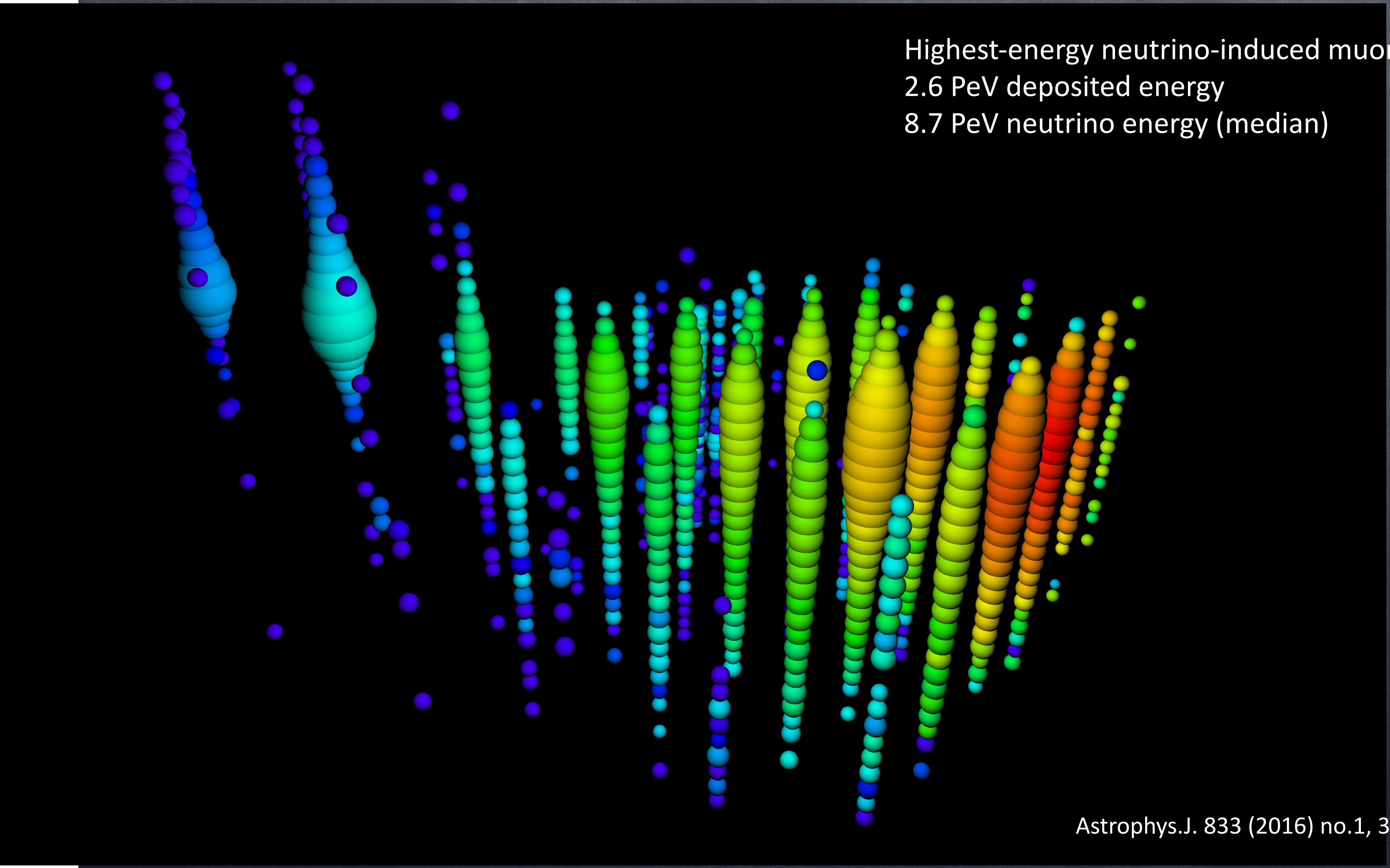




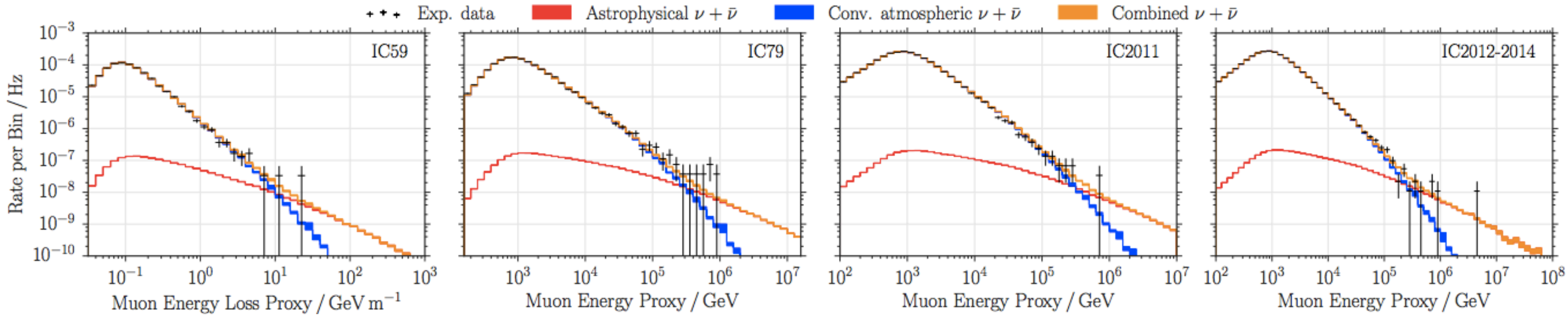
Example of highest events found



The highest energy neutrino induced muon



Diffuse Flux with Muon Neutrinos

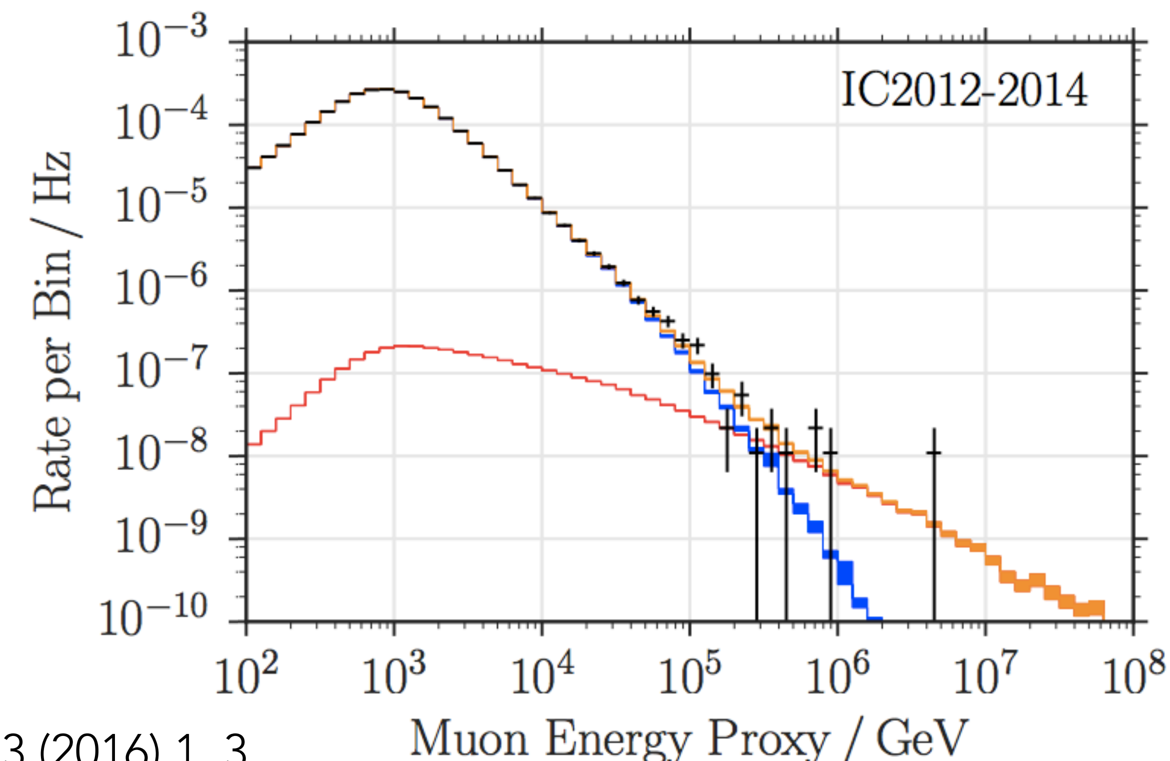


Upgoing or Horizontal track =
Earth-filtered

350 000 events in 6-year analysis

Estimated 99.7% pure muon-neutrino sample

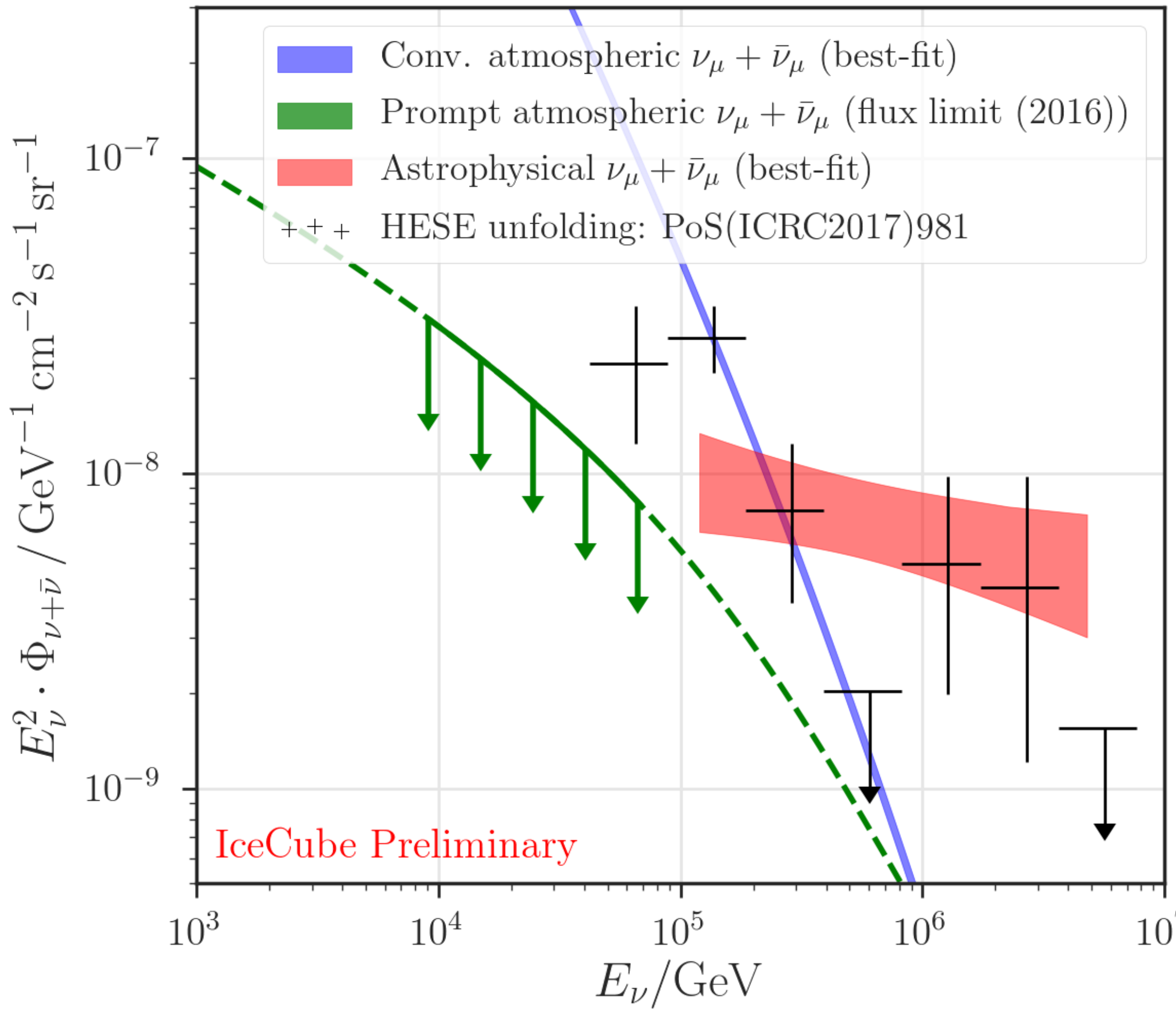
5.6σ for astrophysical flux



Astrophys.J. 833 (2016) 1, 3

Muon neutrino flux from the Northern sky

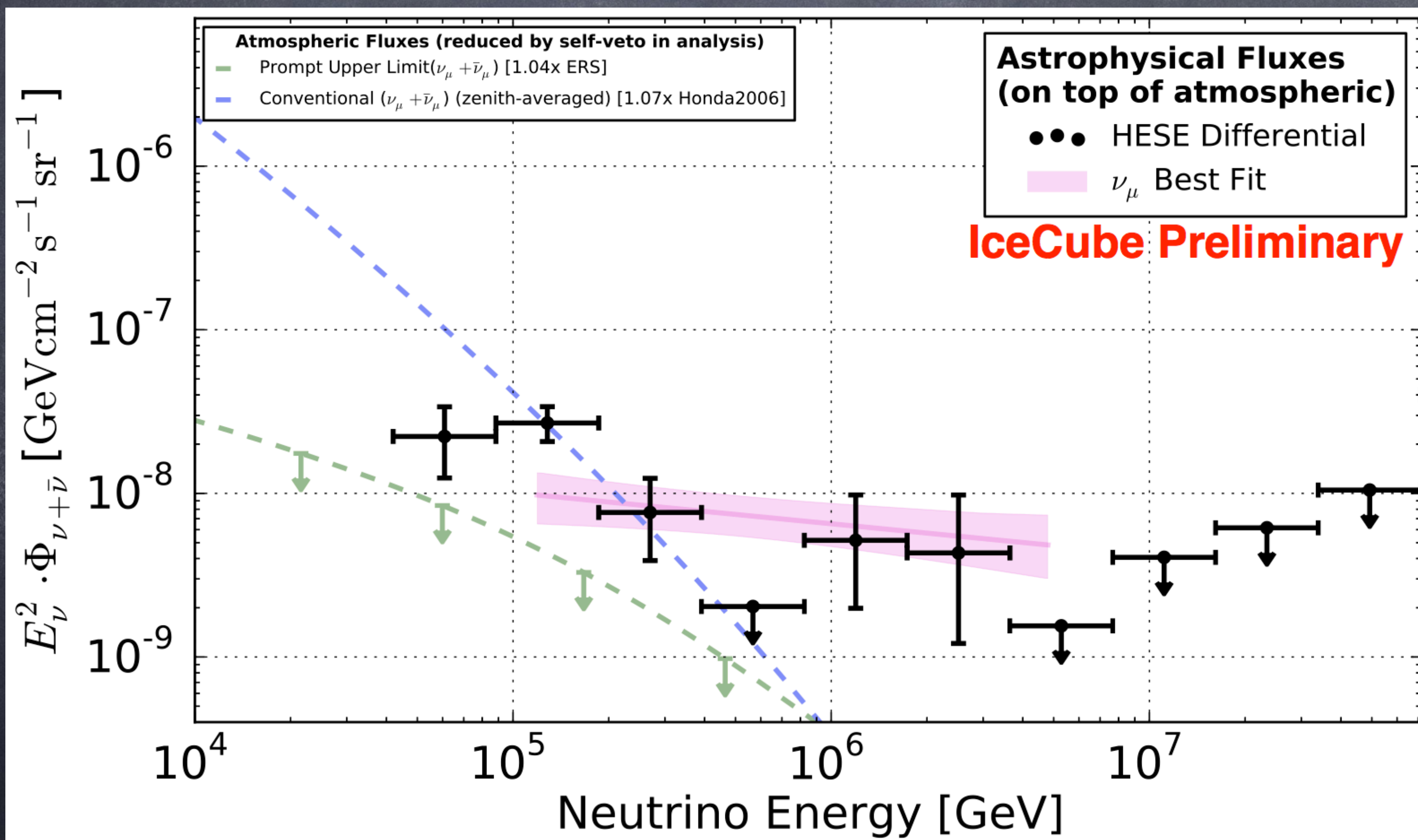
- Selected horizontal and up-going muon tracks
- Fit the astrophysical neutrino flux above ~120 TeV tp 5 PeV
- Power law index: 2.19±0.10



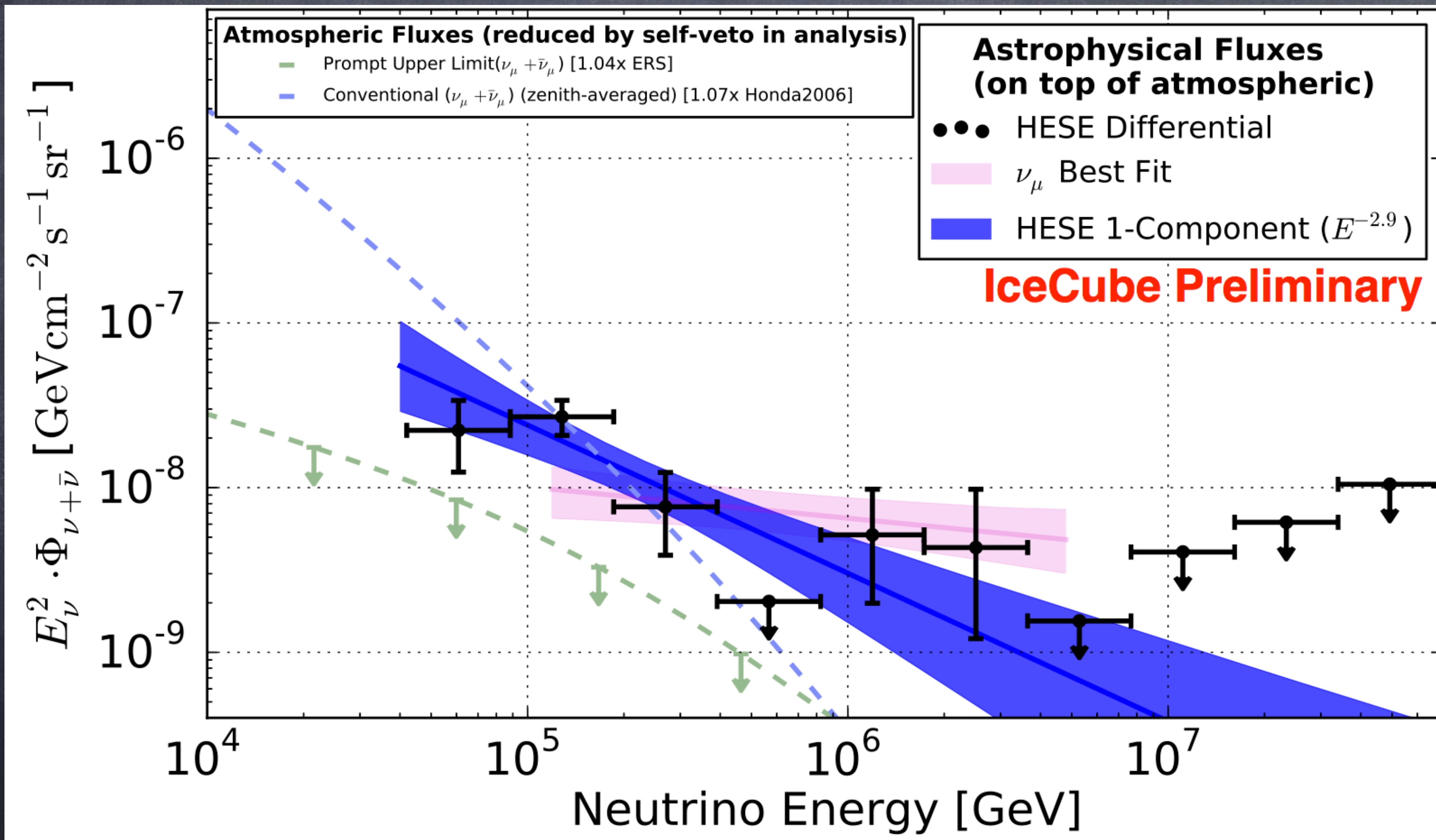
ICRC 2017, see C.Haack (IceCube C.)

See C. Haack, NU022

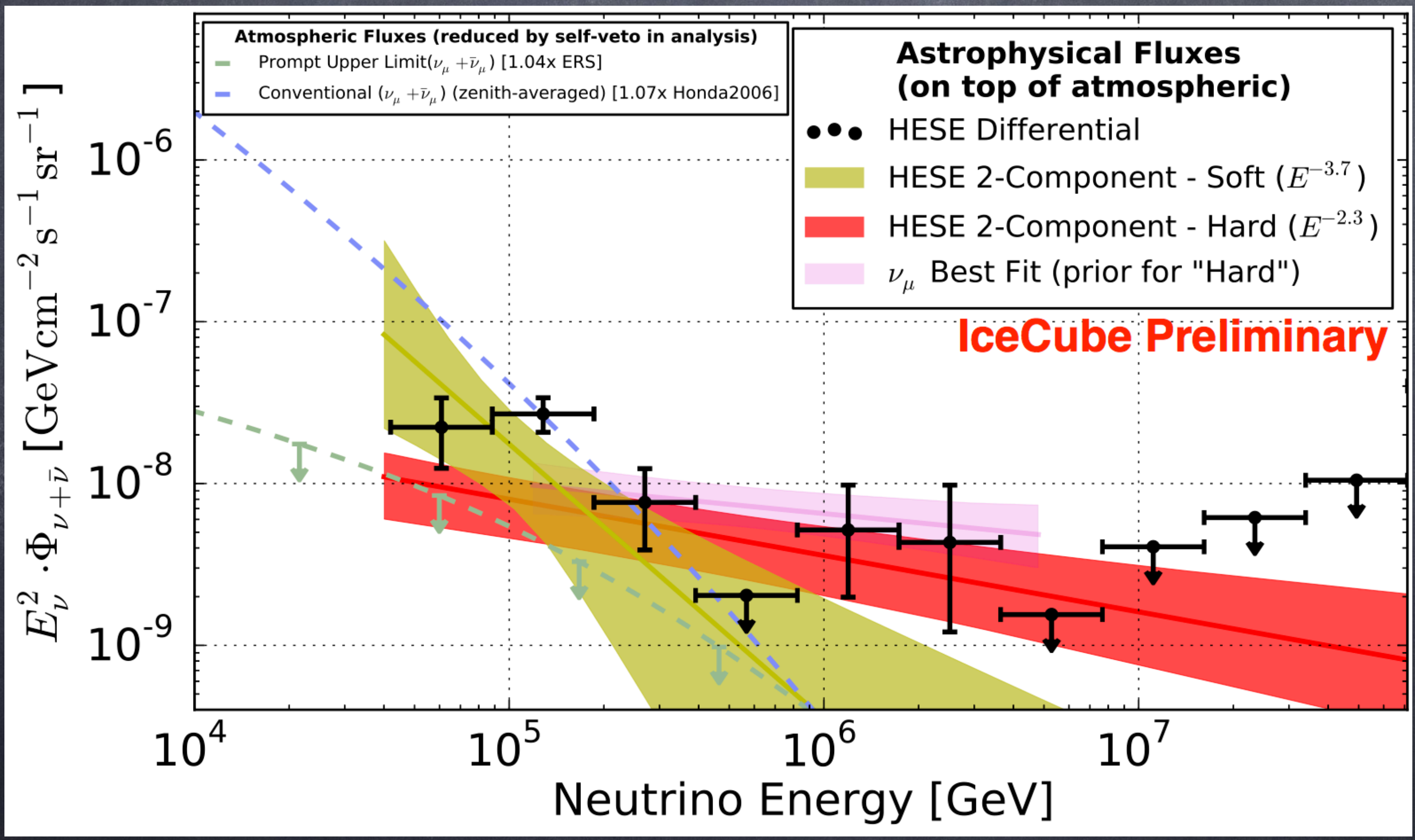
Energy spectrum combined



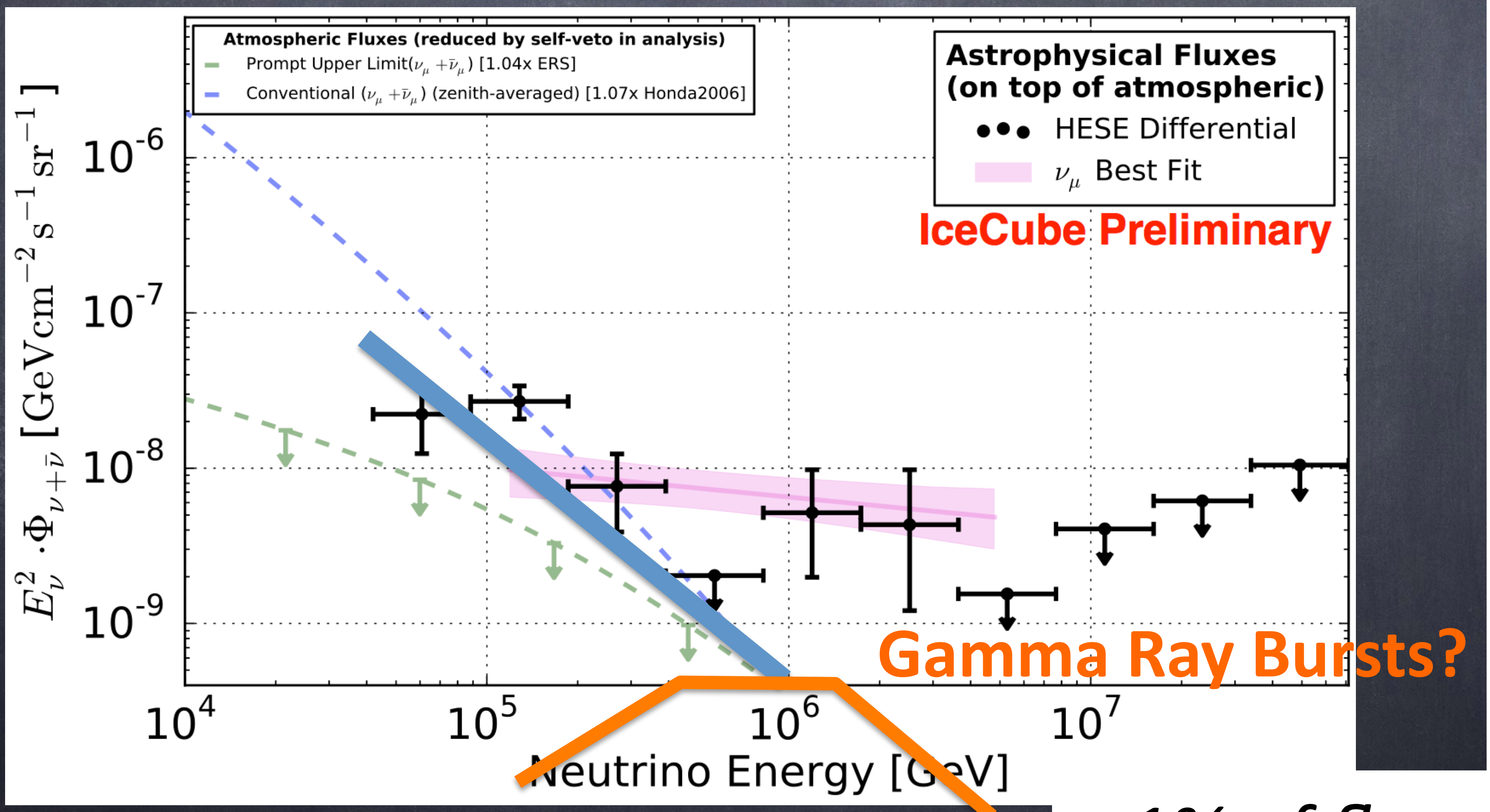
Energy spectrum (1)



Energy spectrum: 2 components?

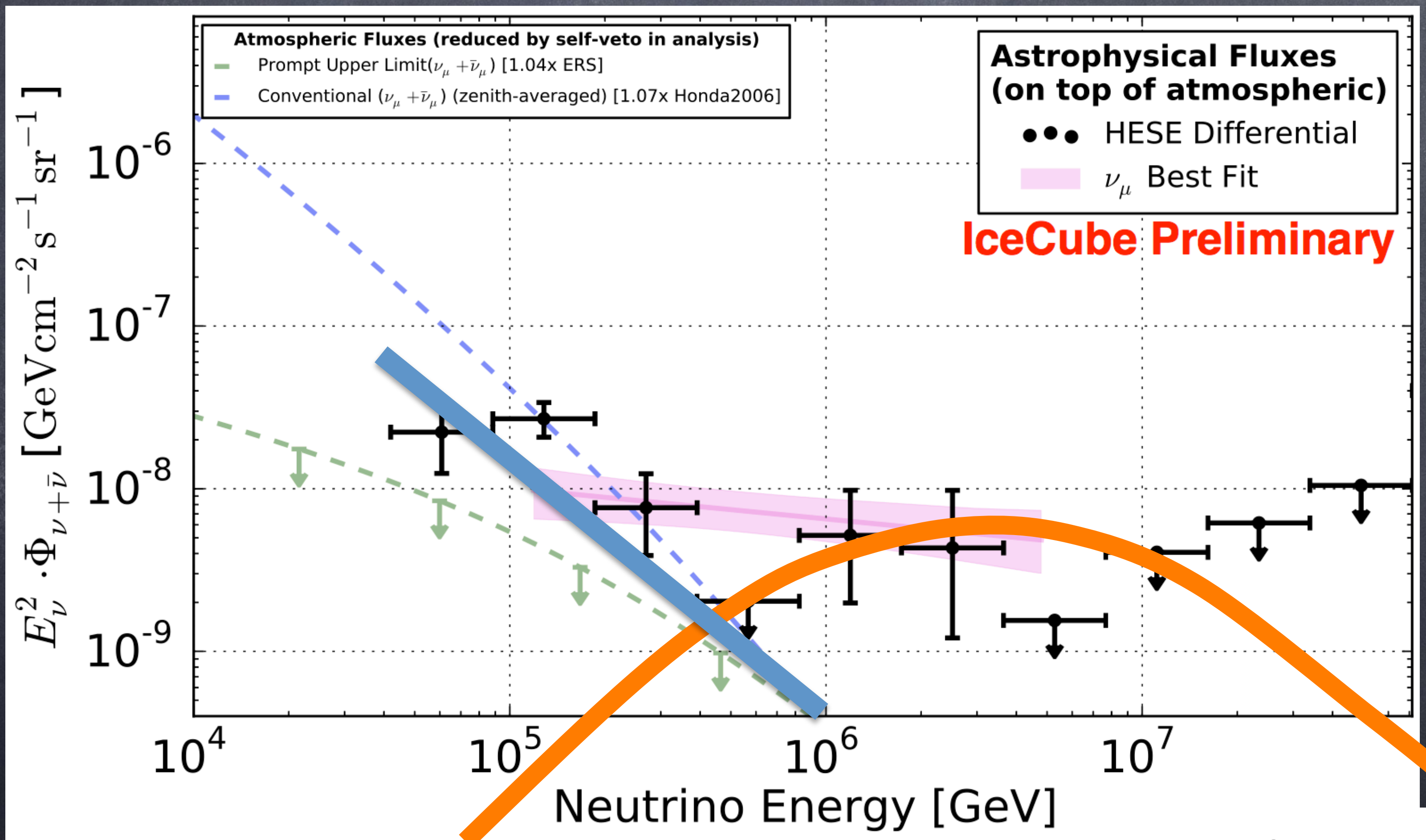


Energy spectrum combined



< 1% of flux

Energy spectrum combined

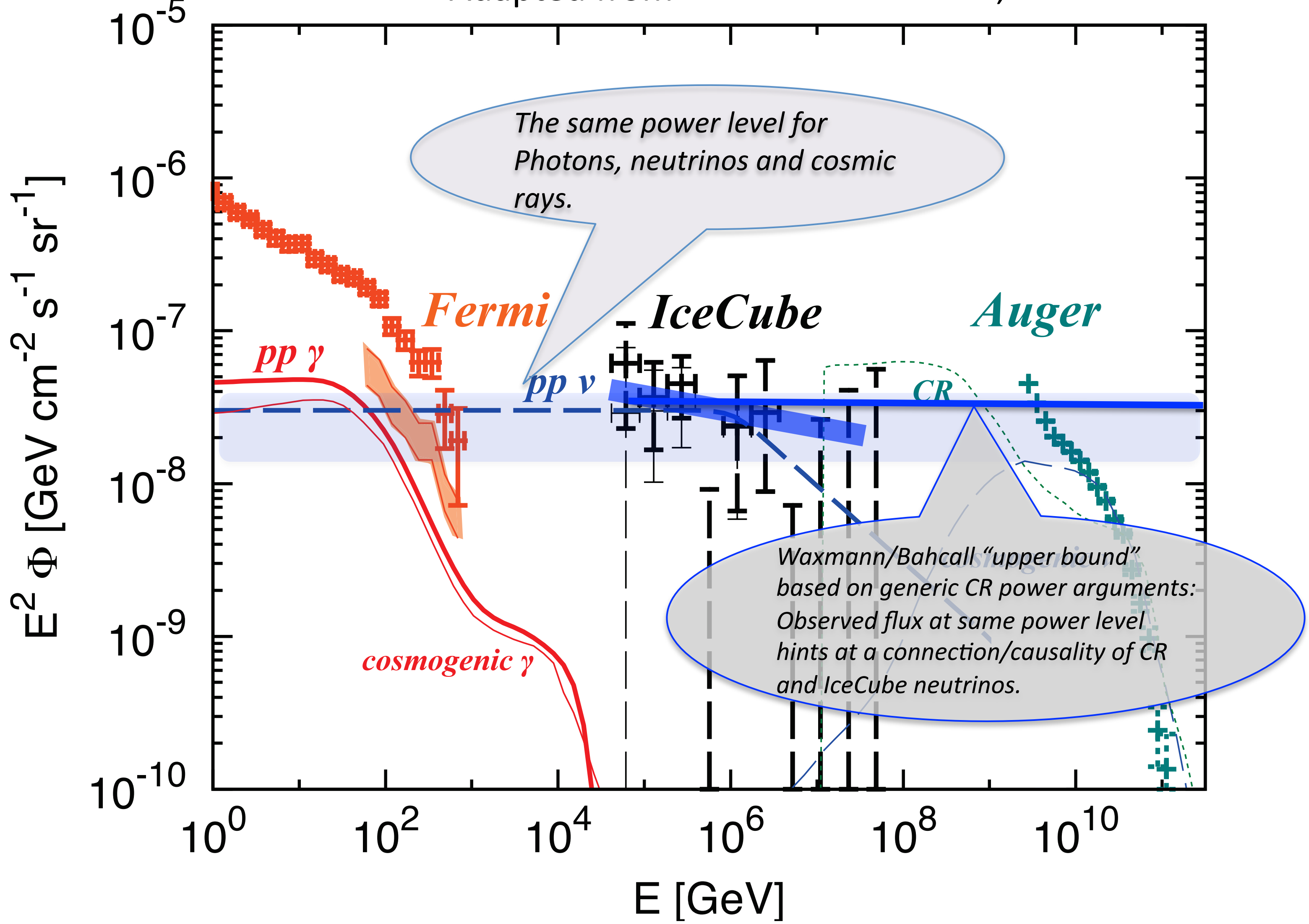


AGN? (Active Galactic Nuclei)

A better fit?

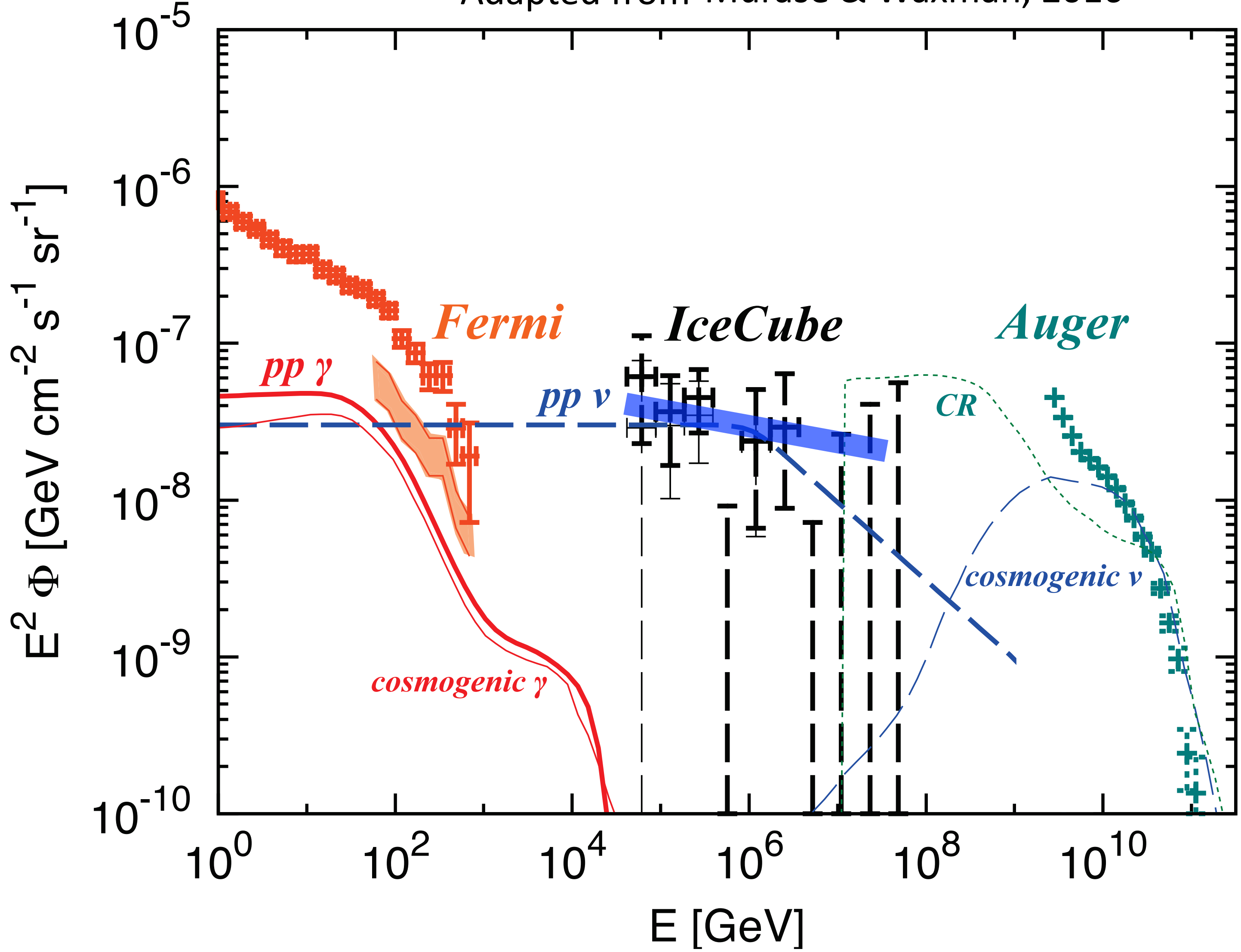
A an attempt to tie all together

Adapted from Murase & Waxman, 2016

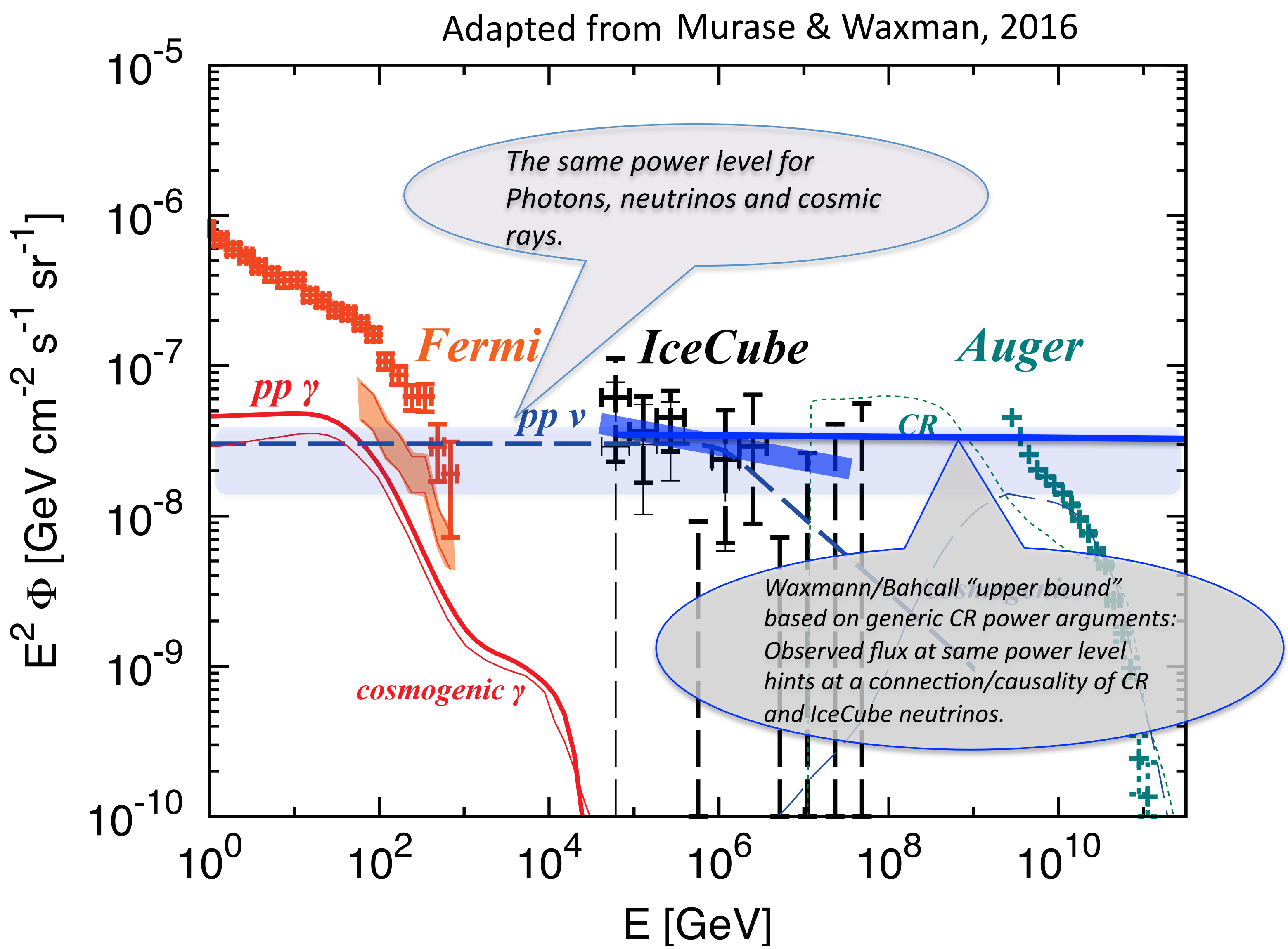


A an attempt to tie all together

Adapted from Murase & Waxman, 2016

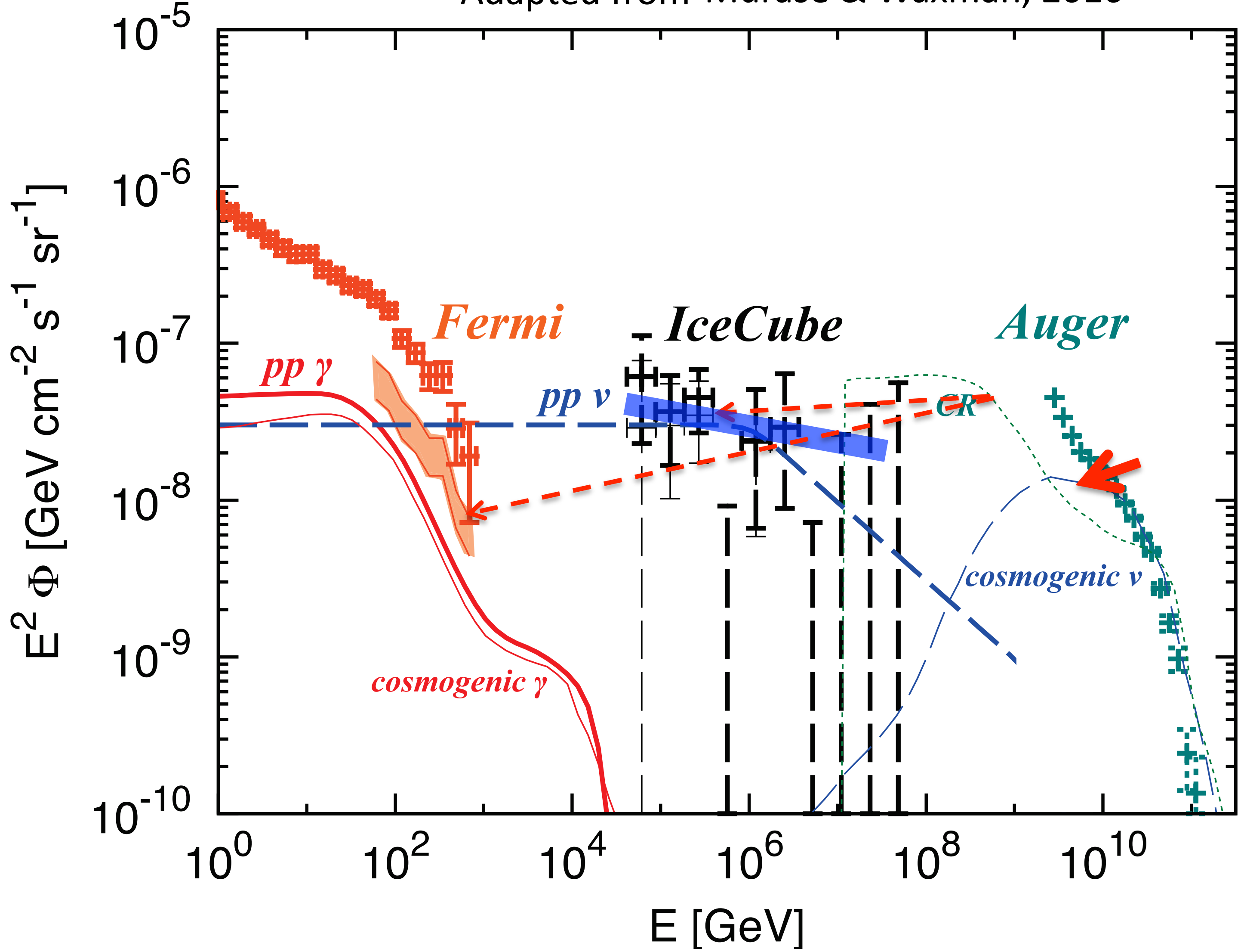


A an attempt to tie all together



A an attempt to tie all together

Adapted from Murase & Waxman, 2016



Summary on diffuse fluxes

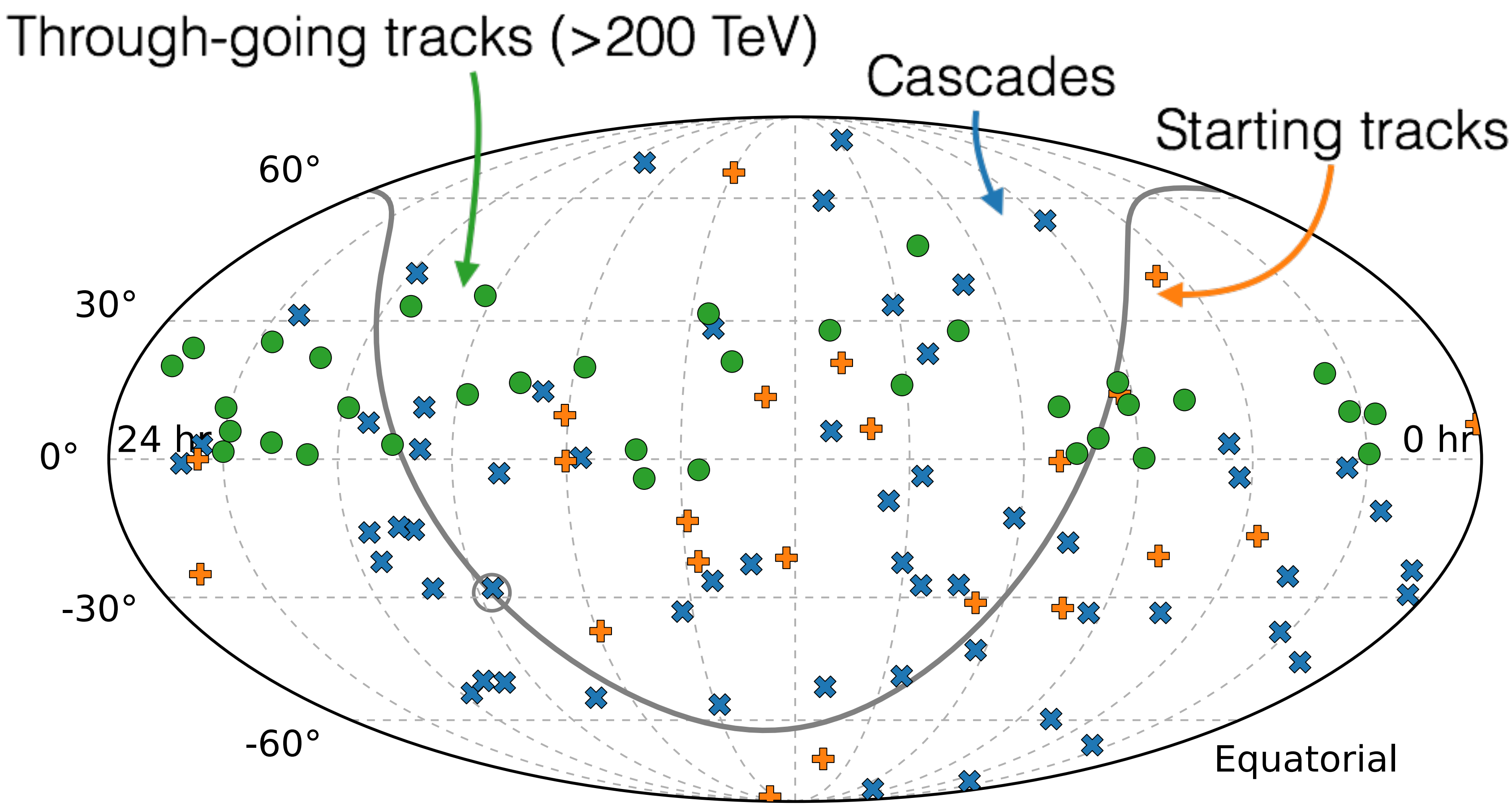
- More and very compelling evidence for an astrophysical flux,
- Consistent with all flavor
  - cascades (electron/tau, NC) and muon neutrinos observed as expected
- North and South

→

- Likely at least in part extragalactic neutrino flux

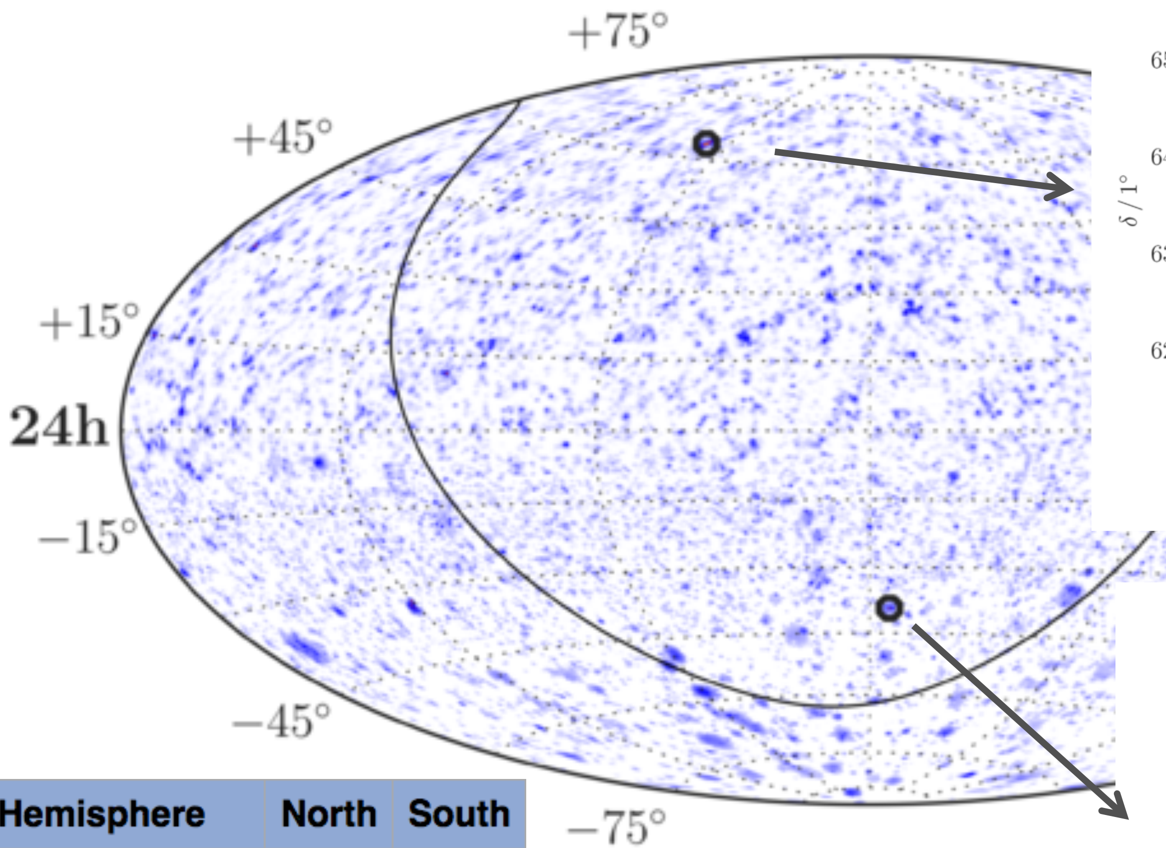
  (except for some models, eg DM scenario)

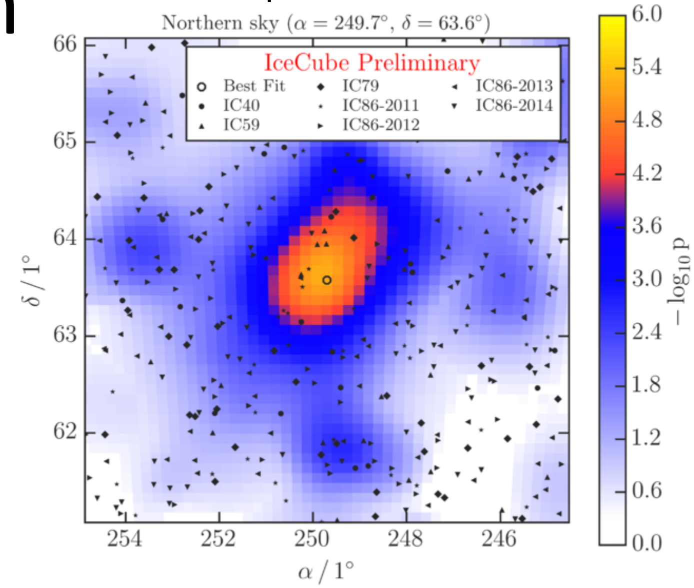
Event with energy > ~100 TeV
(more than 50% of events are astrophysical)

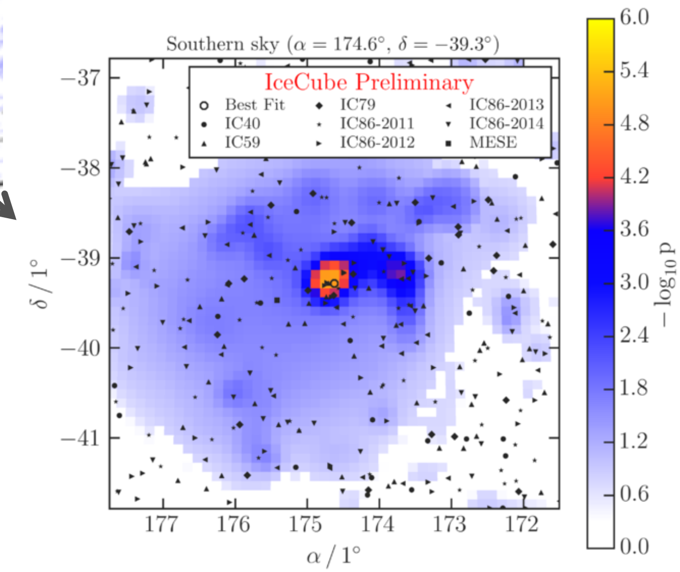


7-year Point Source Search

ApJ 835 (2017) 2, 151



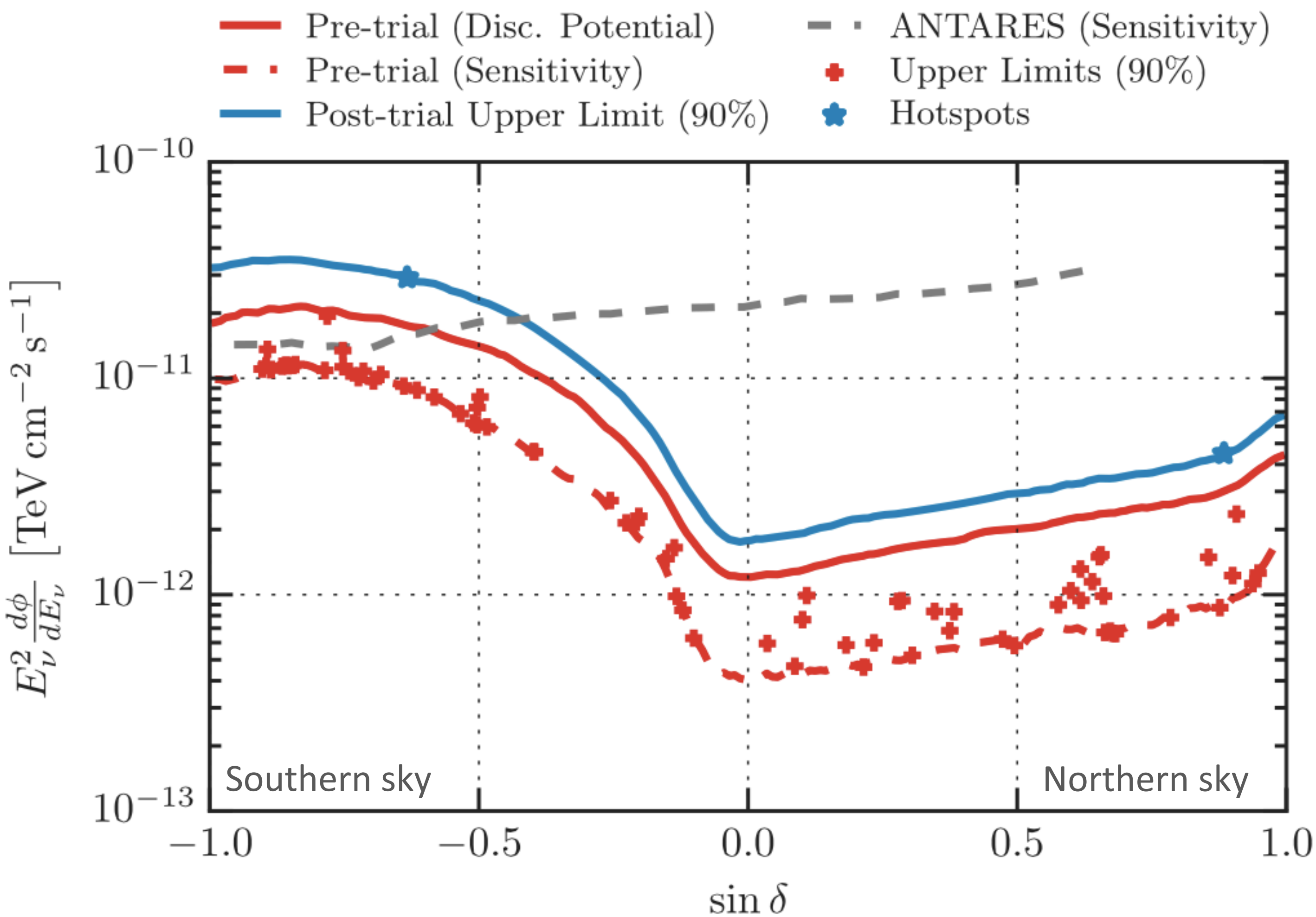




Hemisphere	North	South
N_Sources	27.22	15.54
Gamma	1.95	2.84
Test statistic	18.99	20.26
-log10(Pre-Trial P)	5.24	5.33
Post Trial P	44%	39%

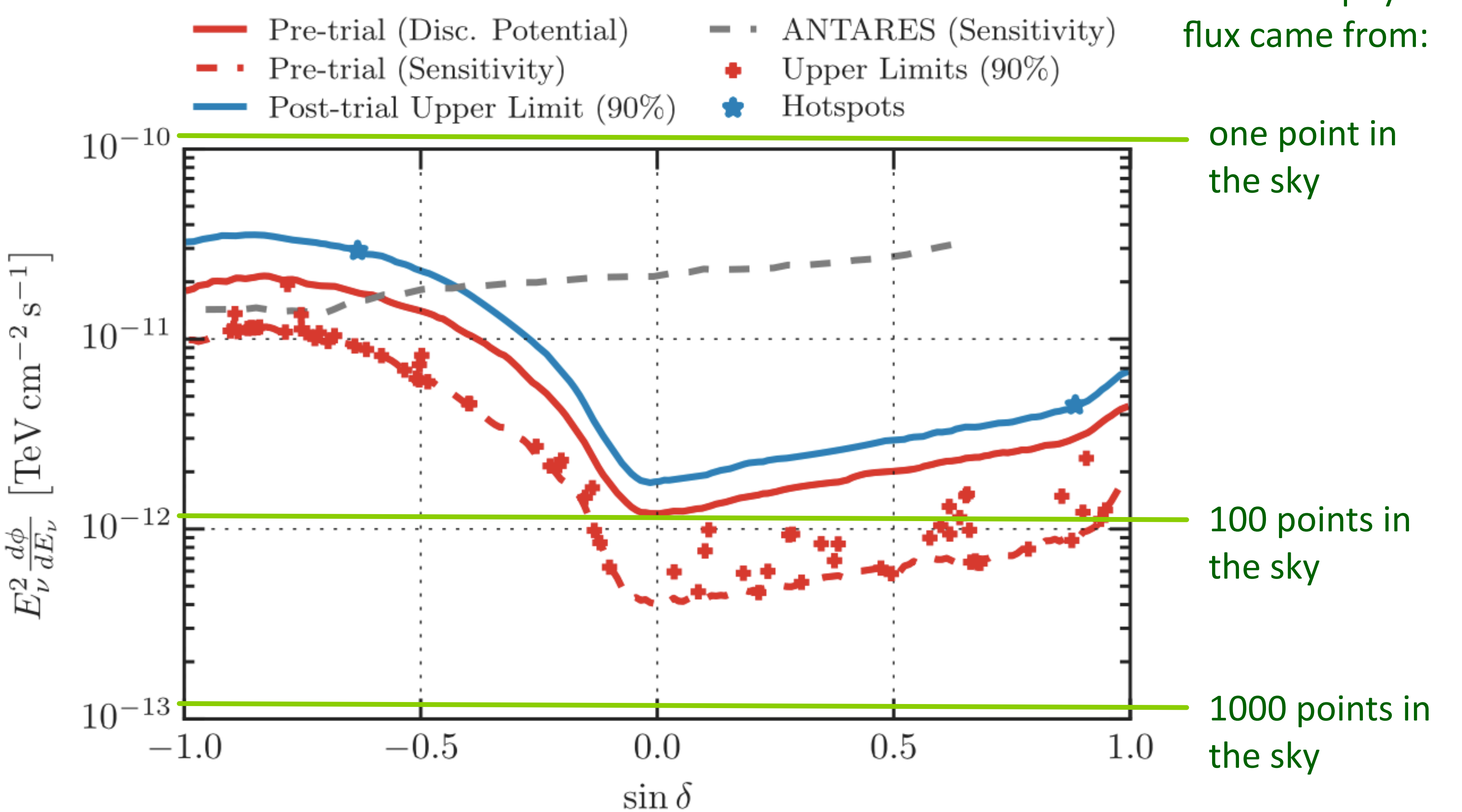
Not significant (at all)

7-year Point Source Search



ApJ 835 (2017) 2, 151

Relating Diffuse and Point Source fluxes



ApJ 835 (2017) 2, 151

Population studies with Stacking Searches

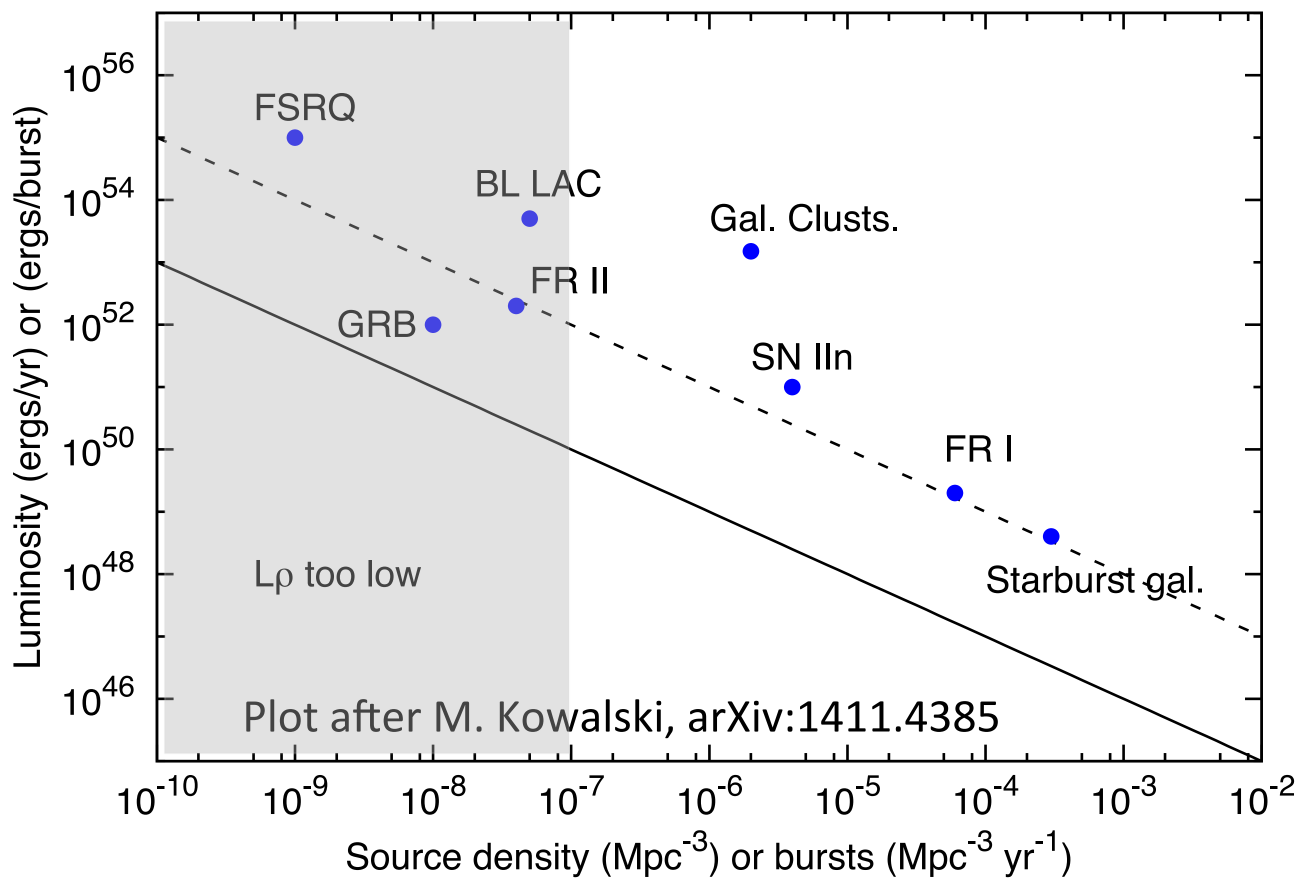
Implication from point source limits and presence of (strong) diffuse flux

Kowalski Plot

Source density and luminosity are related to produce the observed flux.

Absence of clustering sets a minimum on source density.

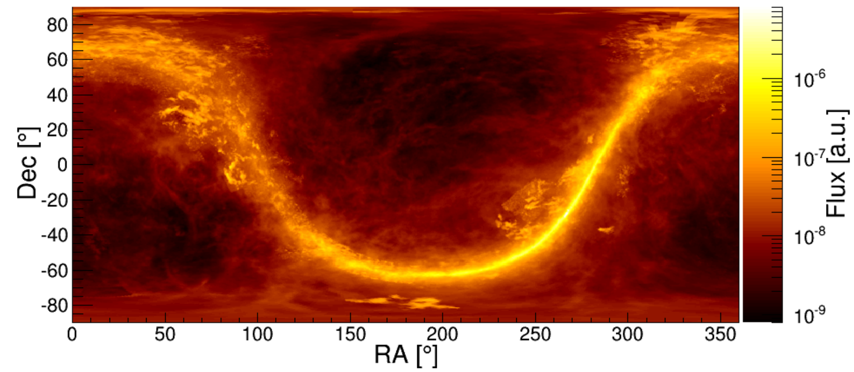
→Certain classes of sources disfavored.



Dashed line assumes 1% efficiency for production of neutrinos

Slide adapted from Gaisser

Galactic plane?



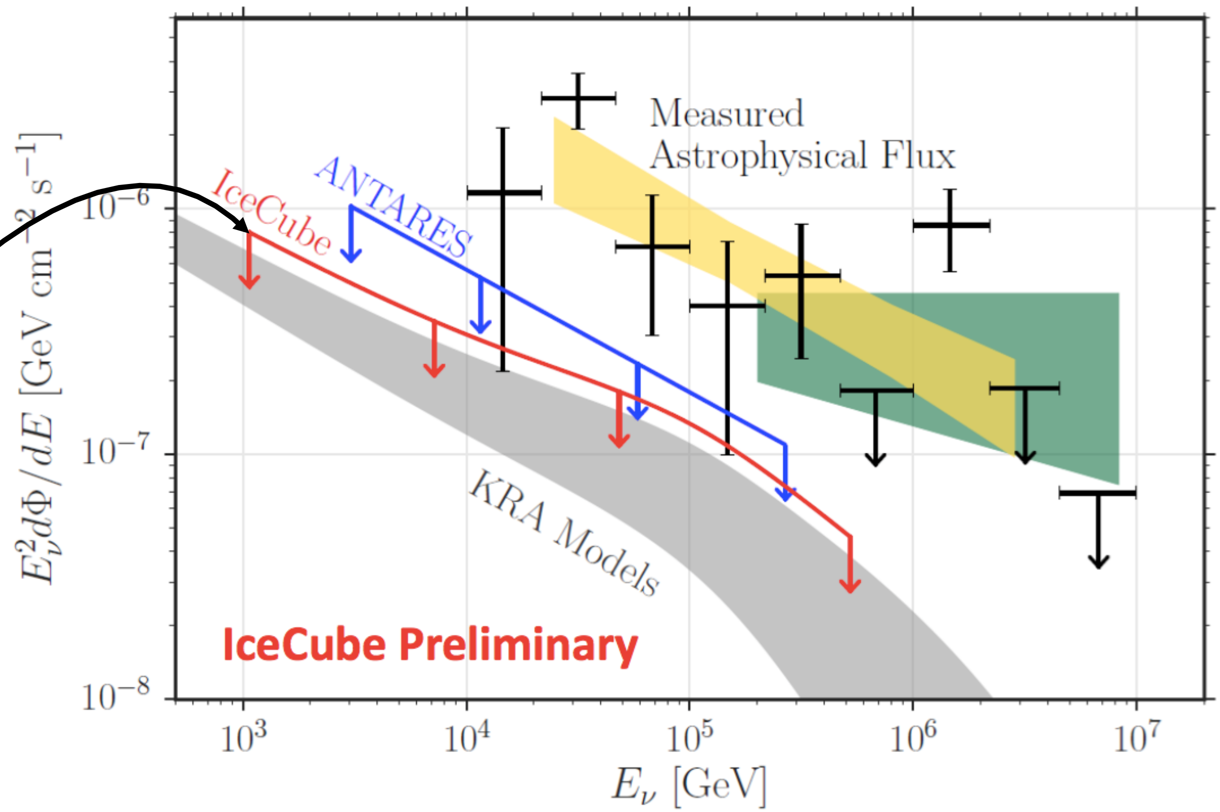
From upward muon neutrino flux.

What fraction of the diffuse flux can come from the galactic plane?

Answer: <16%

That is consistent with expectations.

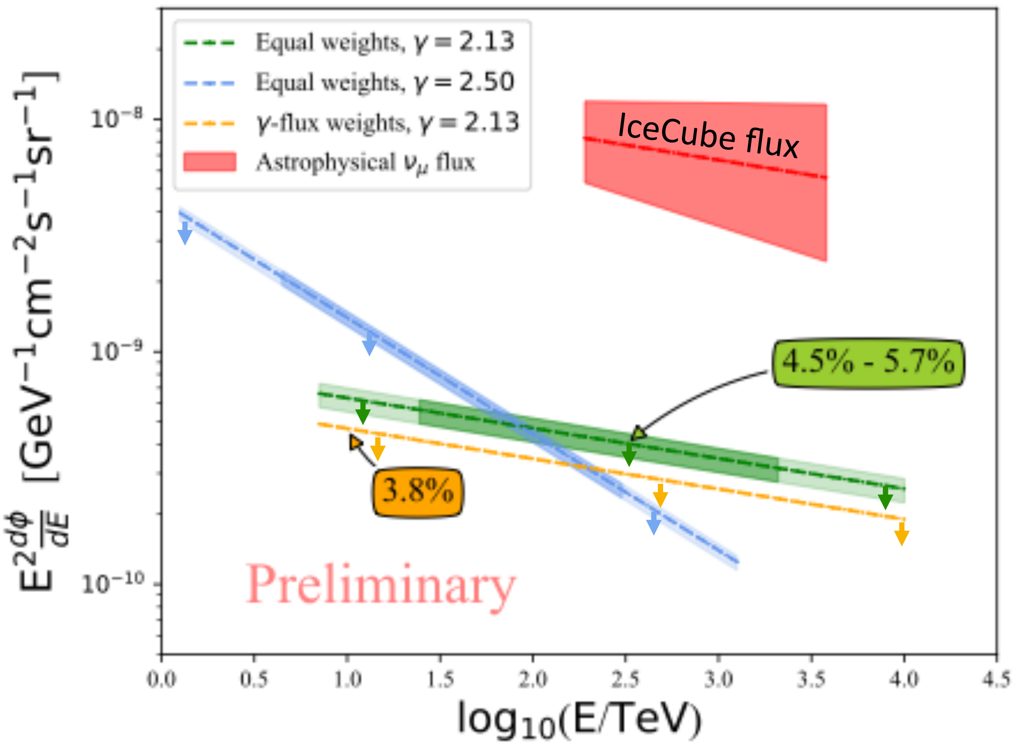
< 16% of $E^{-2.5}$ flux



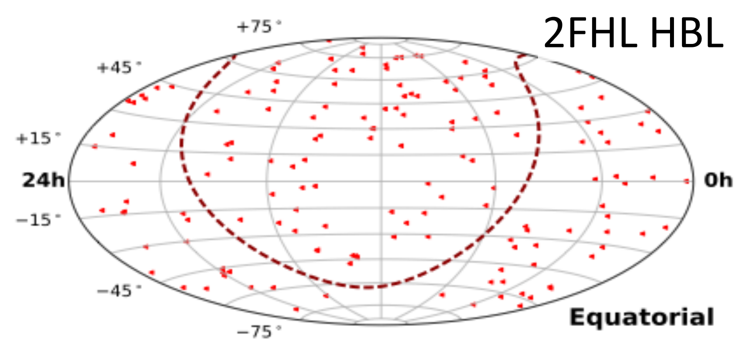
AGN Blazar catalog search

Blazars account for:

Blazar flux	FERMI gamma's	IceCube neutrinos
Fraction of diffuse flux	>85%	<6%



AGN with supermassive black hole, with Jet pointing at us.

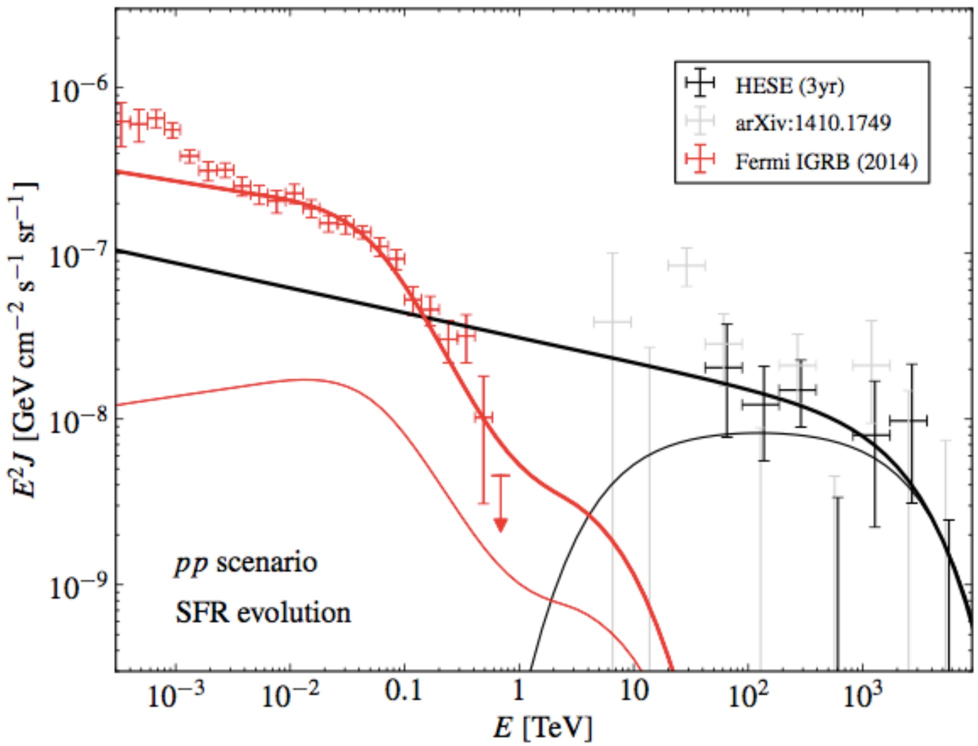


Blazar models are still not excluded. They would make the right Energy spectrum.

See: M. Huber, NU043
Fermi-LAT PRL 116(15) 151105
Astrophys.J. 835 (2017) no.1, 45

Diffuse cosmic gamma ray flux

arXiv:1412.5106,
after Murase, Ahlers, Lacki, Phys.Rev. D88, 121301 (2013)



pp interactions can produce IceCube PeV neutrino flux

corresponding PeV gamma flux cascades down, fits Fermi flux

Outlook, Future strategies

- More statistics.
- Continue searches for association with sources
- Increase multi-messenger strategies with other telescopes, including transient sources:

  → single events can serve as alerts

- Consider experimental upgrades.
  - For 0.1 PeV to 10 PeV (1000 PeV) upgrade of IceCube
  - For GZK energies, pursue other radio detection techniques (such as ARA at South Pole, ARIANNA, or elsewhere…)

Realtime Public Alerts via AMON, GCN

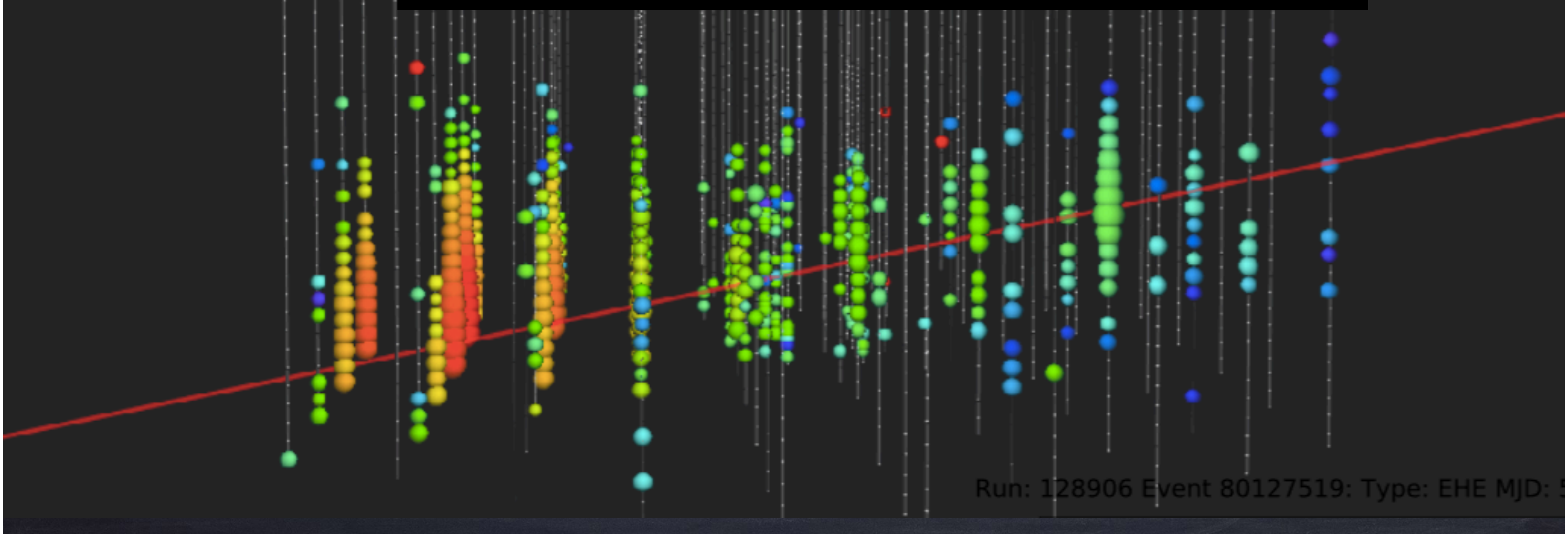
Operating since April 2016 (second filter stream added during summer)

10 alerts in first year

Example event:

```
IceCube 161210A
r.a. 46.6 ± 1.0° (90% CL)
dec  15.0 ± 0.4° (90% CL)
Energy: ~ 100 TeV
Astrophysical signal probability:  49%
```

https://gcn.gsfc.nasa.gov/other/icecube_161210.gcn3



Outlook, Future strategies

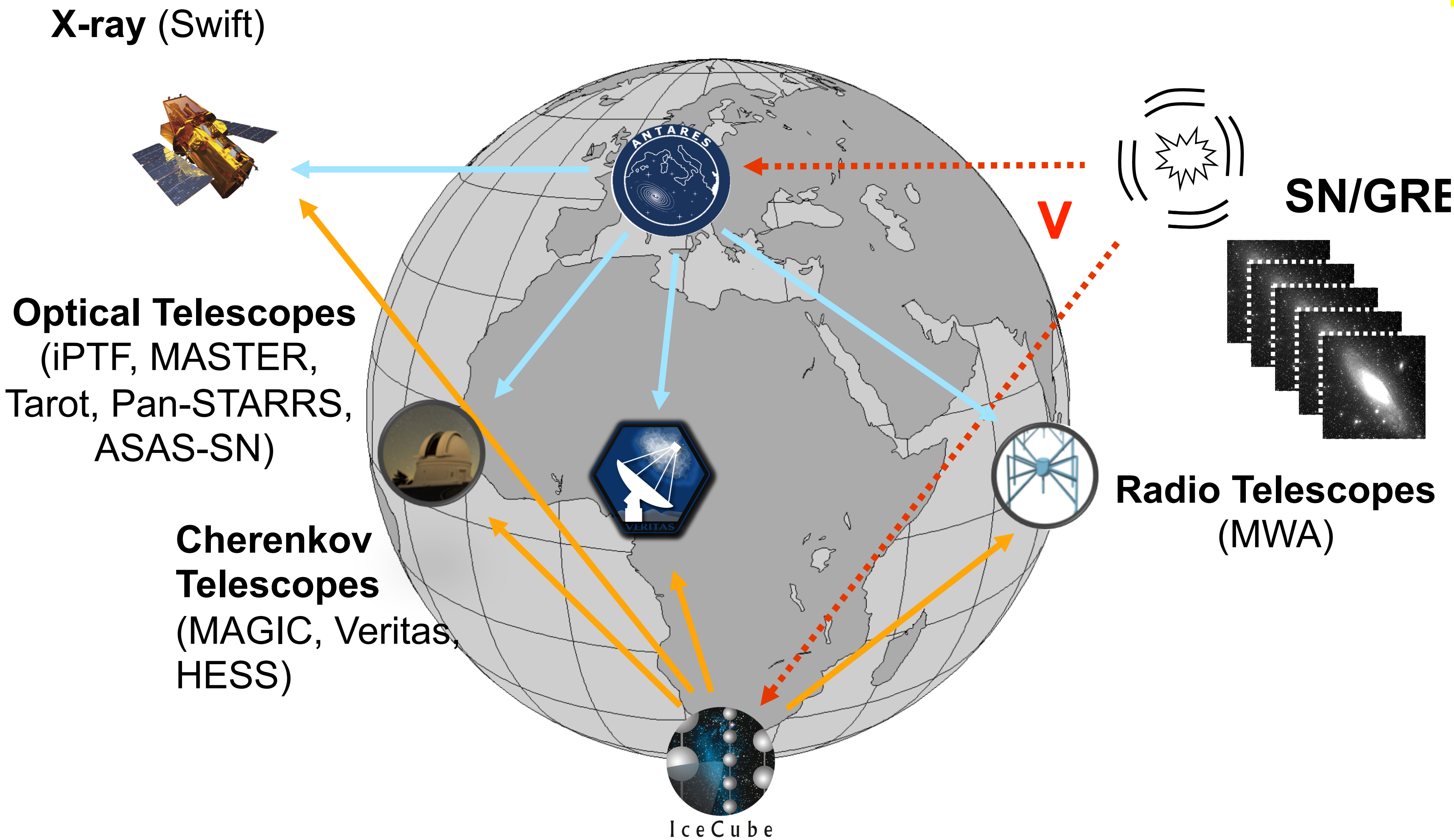
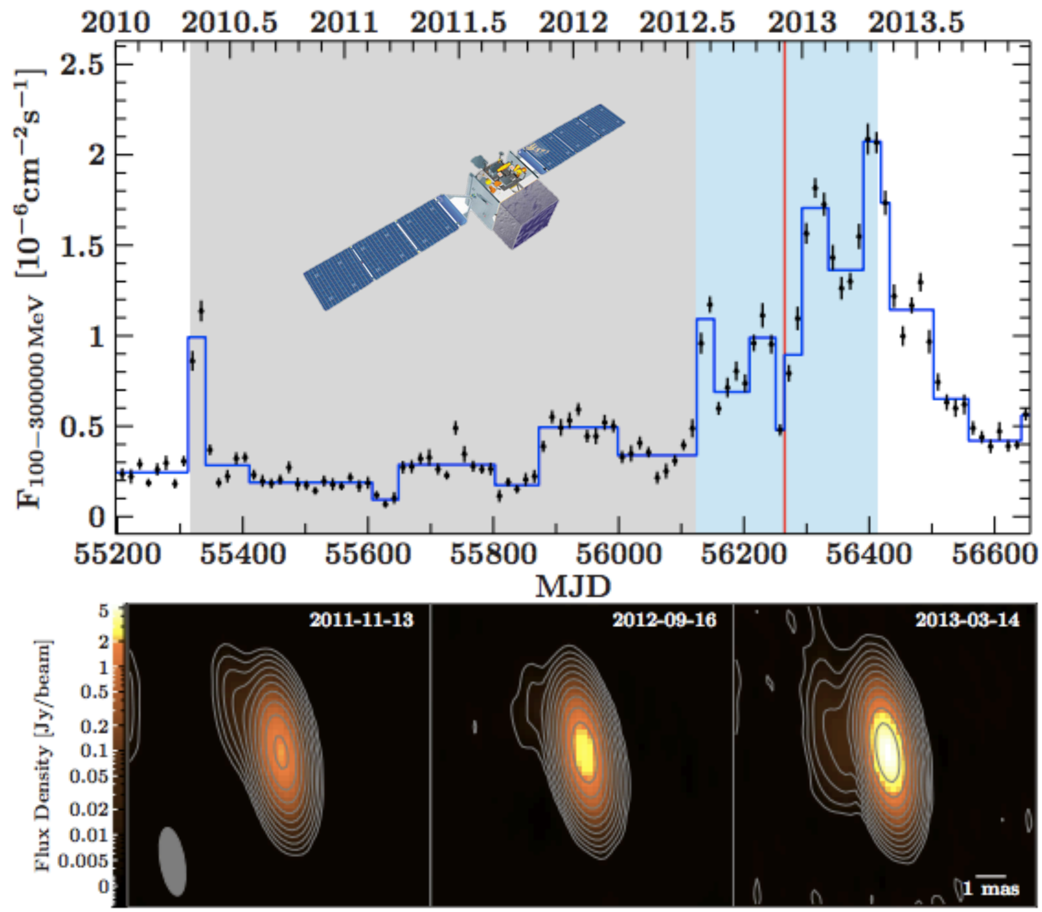


Figure credit: A. Frankoviak

Example transient: AGN flare

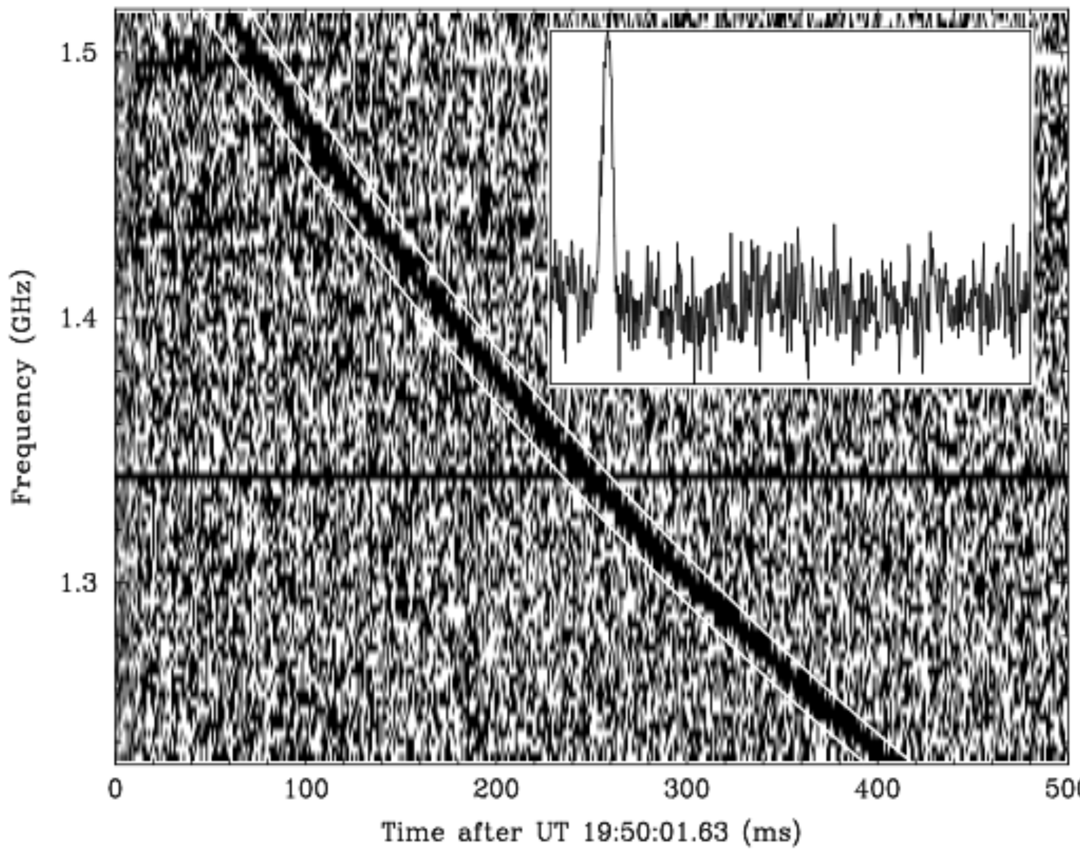
- Gamma rays tell us WHERE and WHEN
- Major outburst of blazar PKS B1424−418 occurred in temporal and positional coincidence PeV neutrino
- single source has sufficiently high fluence to explain an observed coinciding PeV neutrino event



Chance probability
For random coincidence >5%
(not significant)

Example transient: Fast Radio Bursts

Lorimer et al., ***Science*** *318 (5851): 777-780*



→ Donglian Xu paper at ICRC

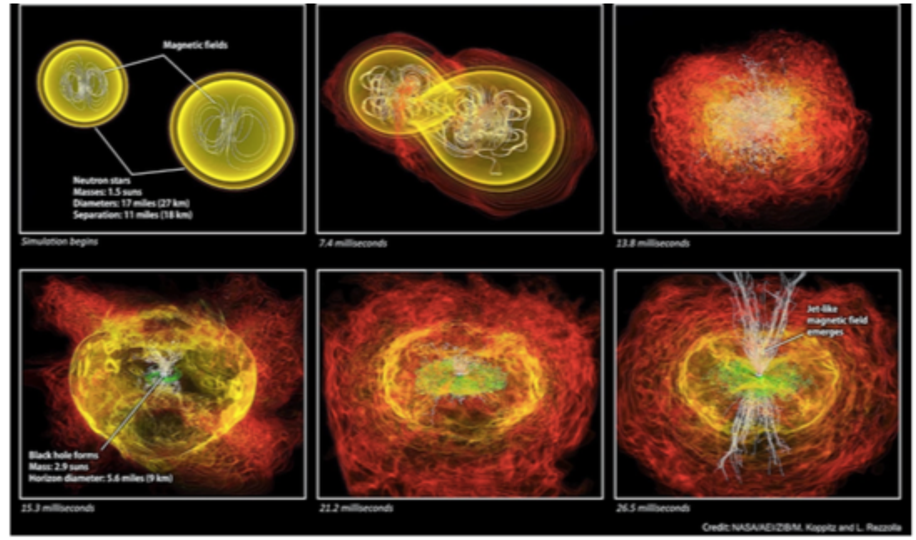
Example transient: Fast Radio Bursts

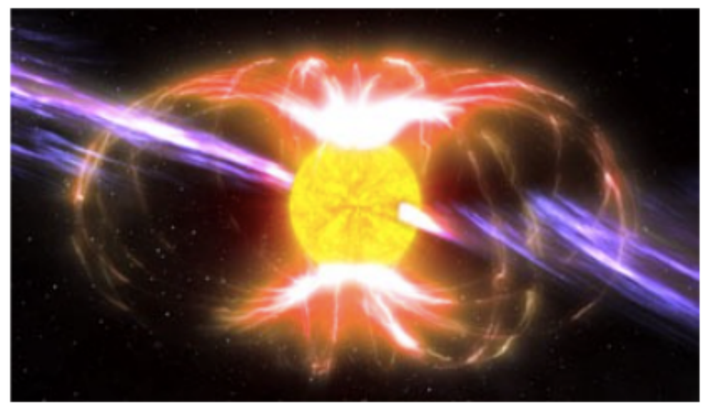
- **Blitzar** **"Cataclysmic"**
  [H. Falcke and L. Rezzolla, A&A 562, A137 (2014)]

- **Binary neutron star merger**
  [T. Totani, Pub. Astron. Soc. Jpn. 65, L12 (2013)]

- **Evaporating primordial black holes**
  [Halzen *et al.*, PRD 1995]
  "MeV neutrinos"

- **Magnetar/SGRs hyperflares**
  [S. B. Popov and K. A. Postnov, arXiv:1307.4924]
  [Halzen *et al.* (2005) astro-ph/0503348]
  "TeV neutrinos"? → this work

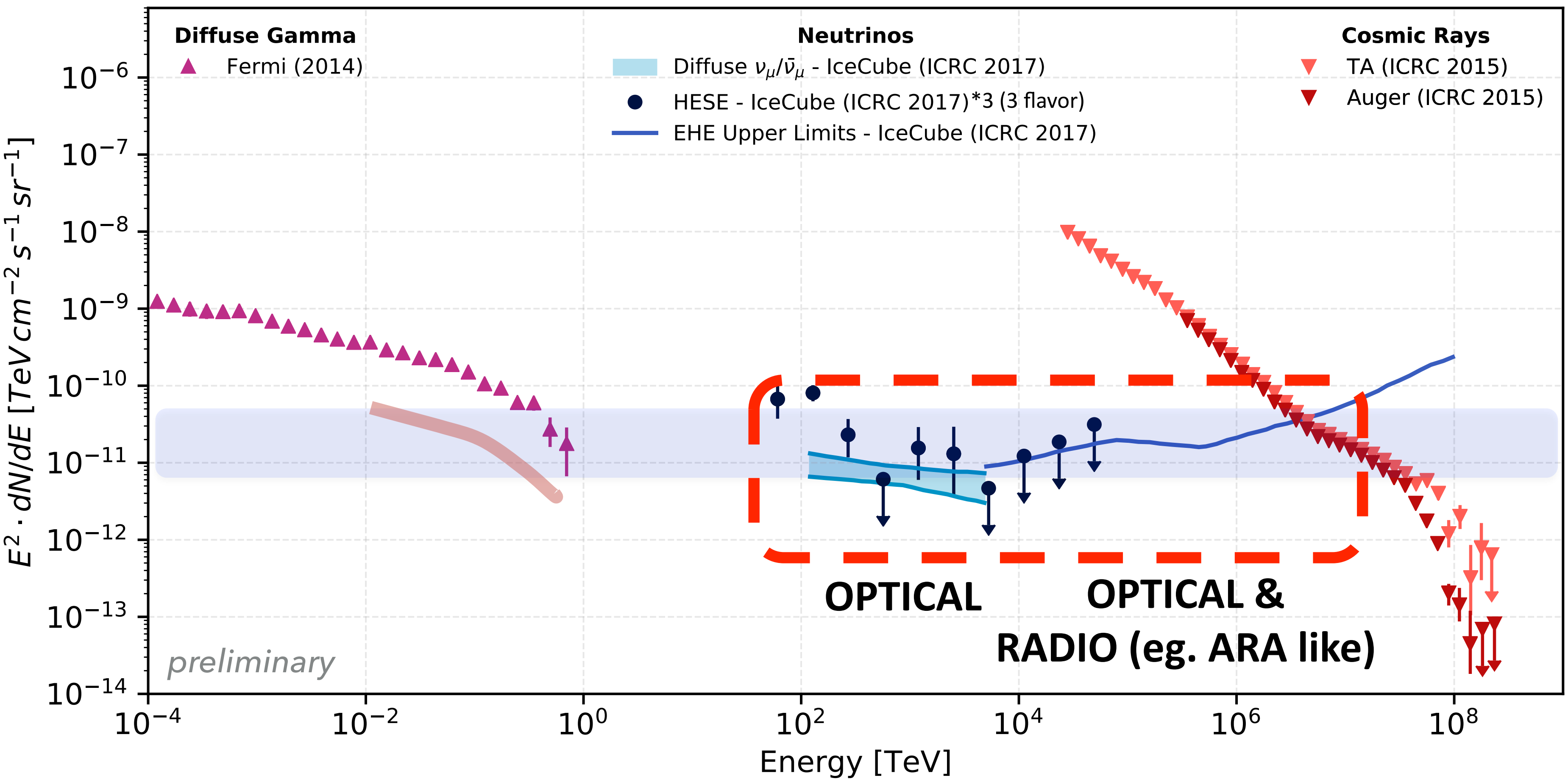




No concrete neutrino production models yet

→ Donglian Xu paper at ICRC

The big picture

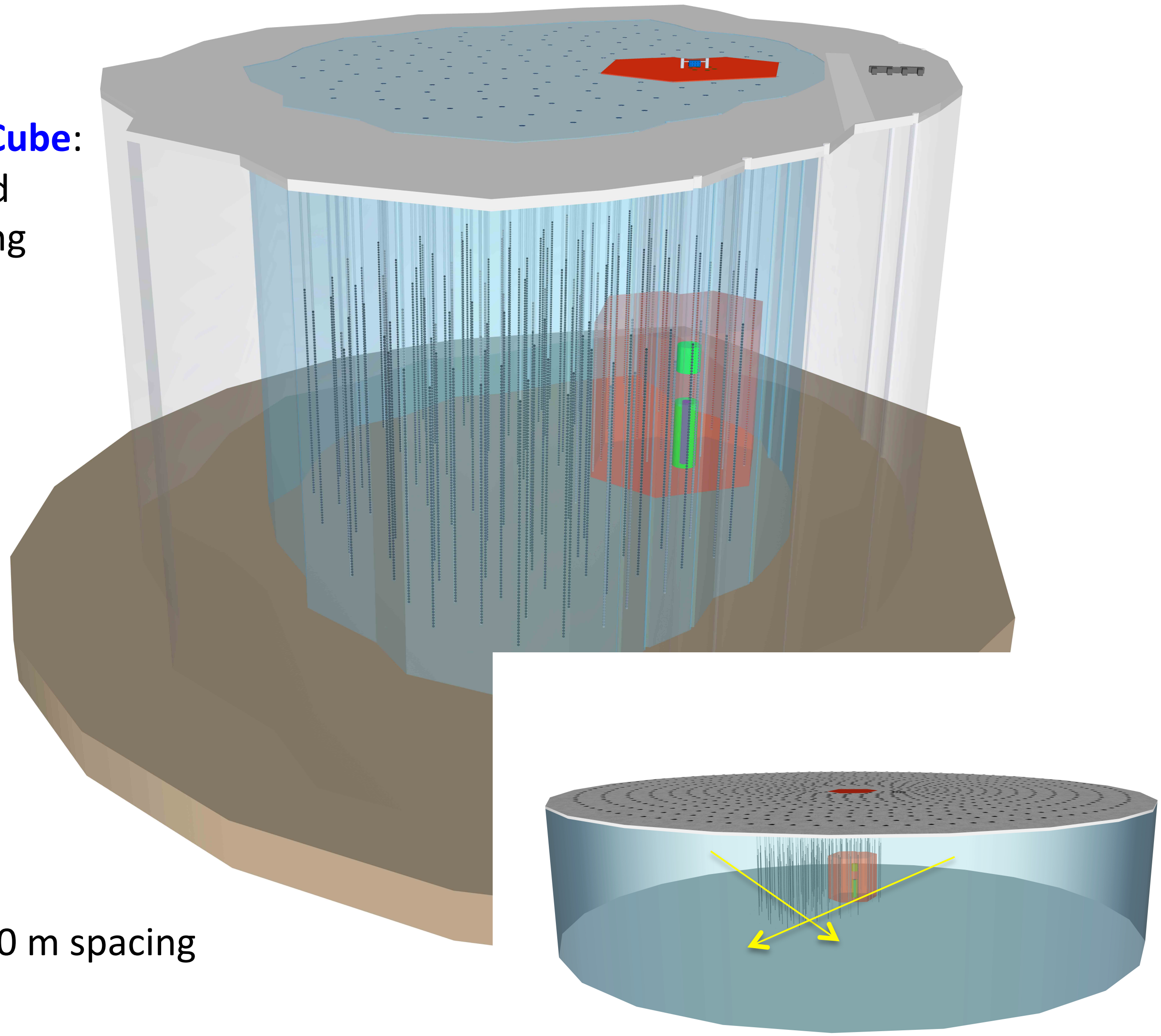


The same power level for
Photons, neutrinos and cosmic rays:

Figure: A. Turcati, after L. Mohrmann 2015

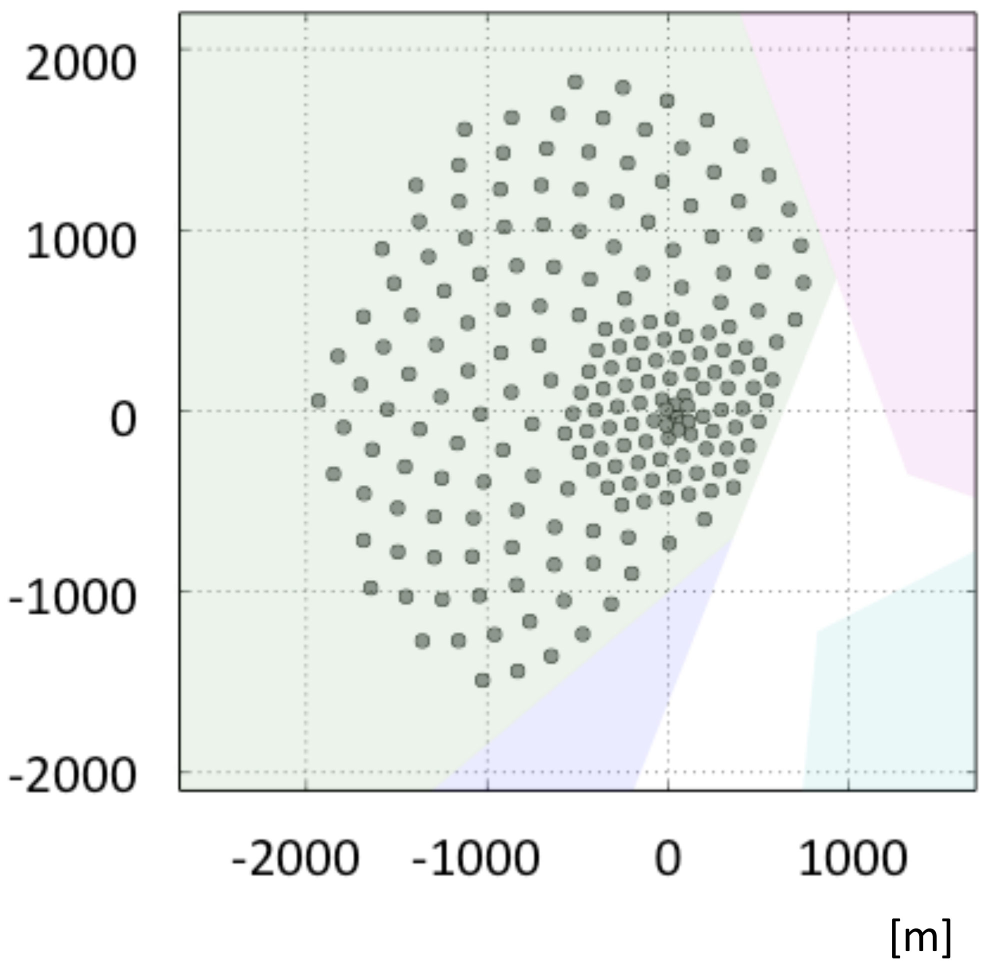
IceCube-Gen2

The next Generation IceCube:
Increase energy threshold allows larger string spacing



Artist conception
Here: 120 strings at 300 m spacing

Geometry

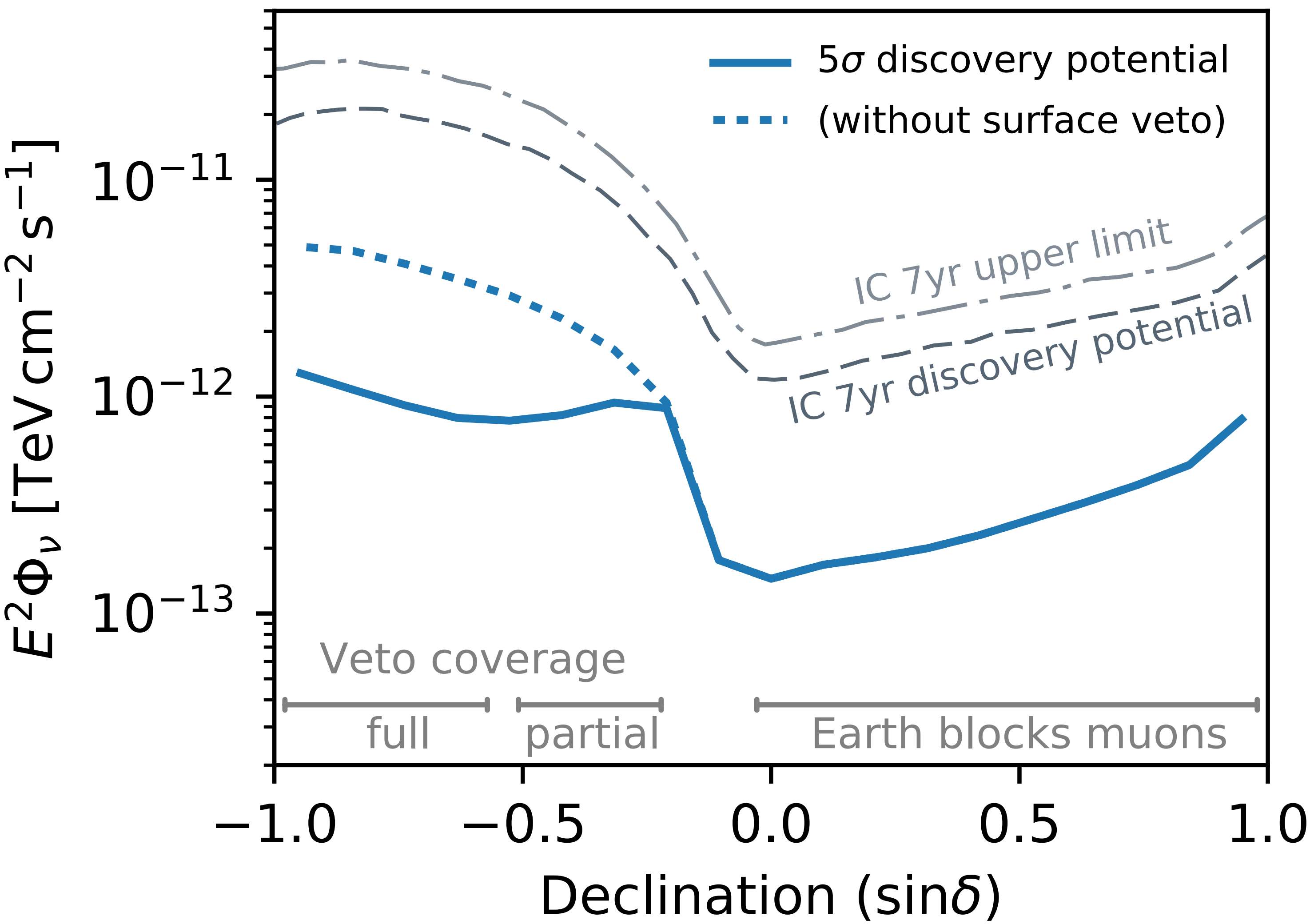


Surface Area: ~6.5km^2 (0.9)
Instrumented depth: 1.26 km (1.0)

Instrumented Volume: 8 km^3

Order of magnitude increase of contained event rate at high energies.

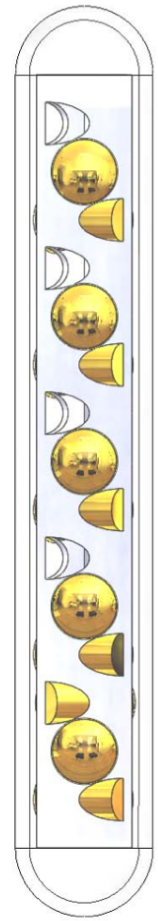
Discovery potential for point sources

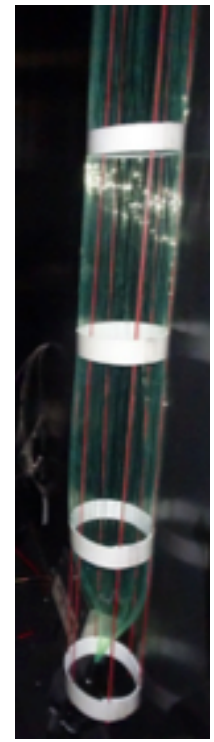


Optical sensors

Active R&D in Collaboration:

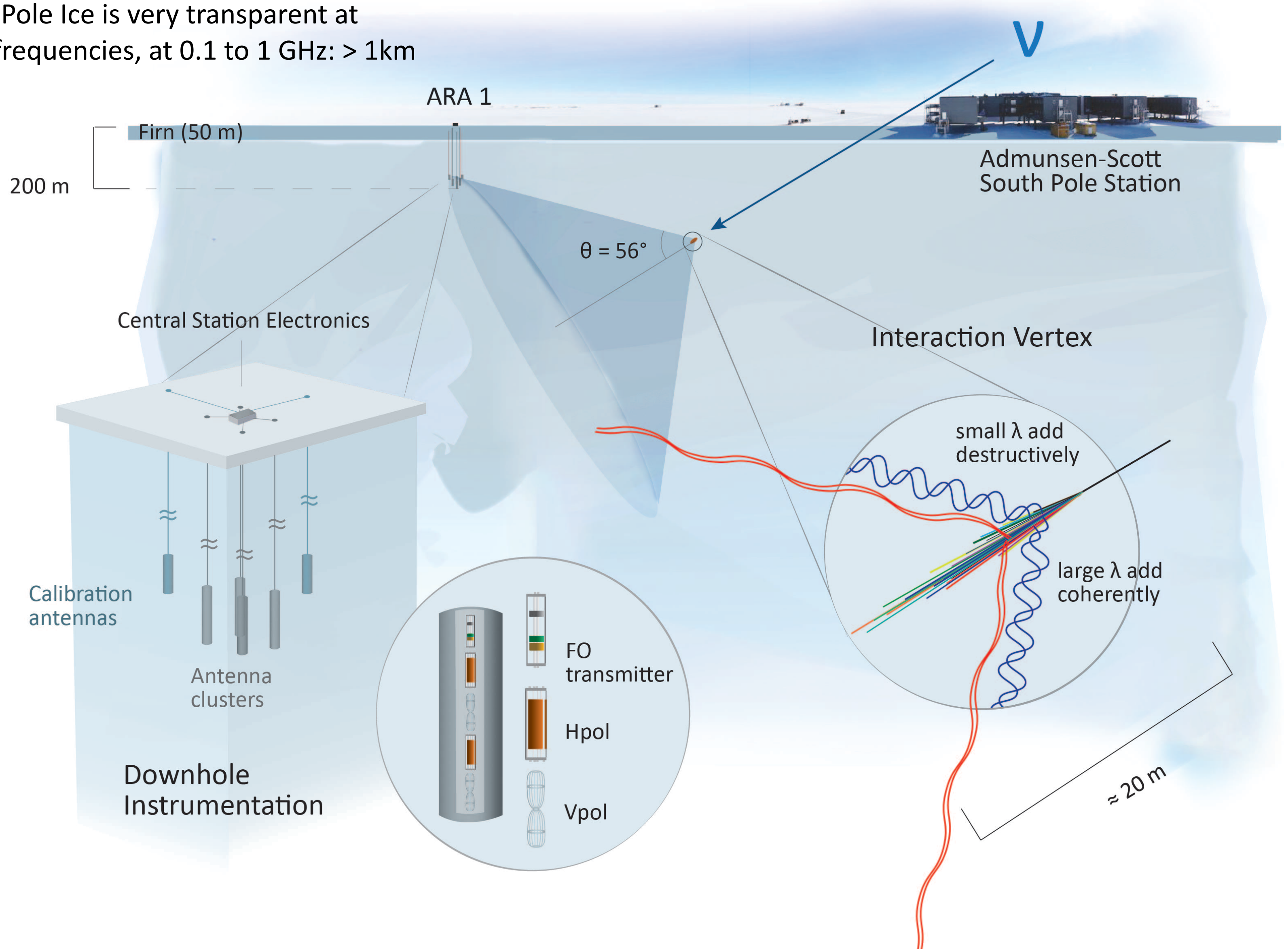
- P-DOM
- M-DOM
- D-EGG
- WOM
- Brusselsprout OM
- WLS fibers





Detection of ultrahigh-energy neutrinos in ARA

South Pole Ice is very transparent at radio frequencies, at 0.1 to 1 GHz: > 1km



Cold ice is extremely transparent to radio waves

Ground penetrating radar (350MHz) image of Antarctic ice sheet

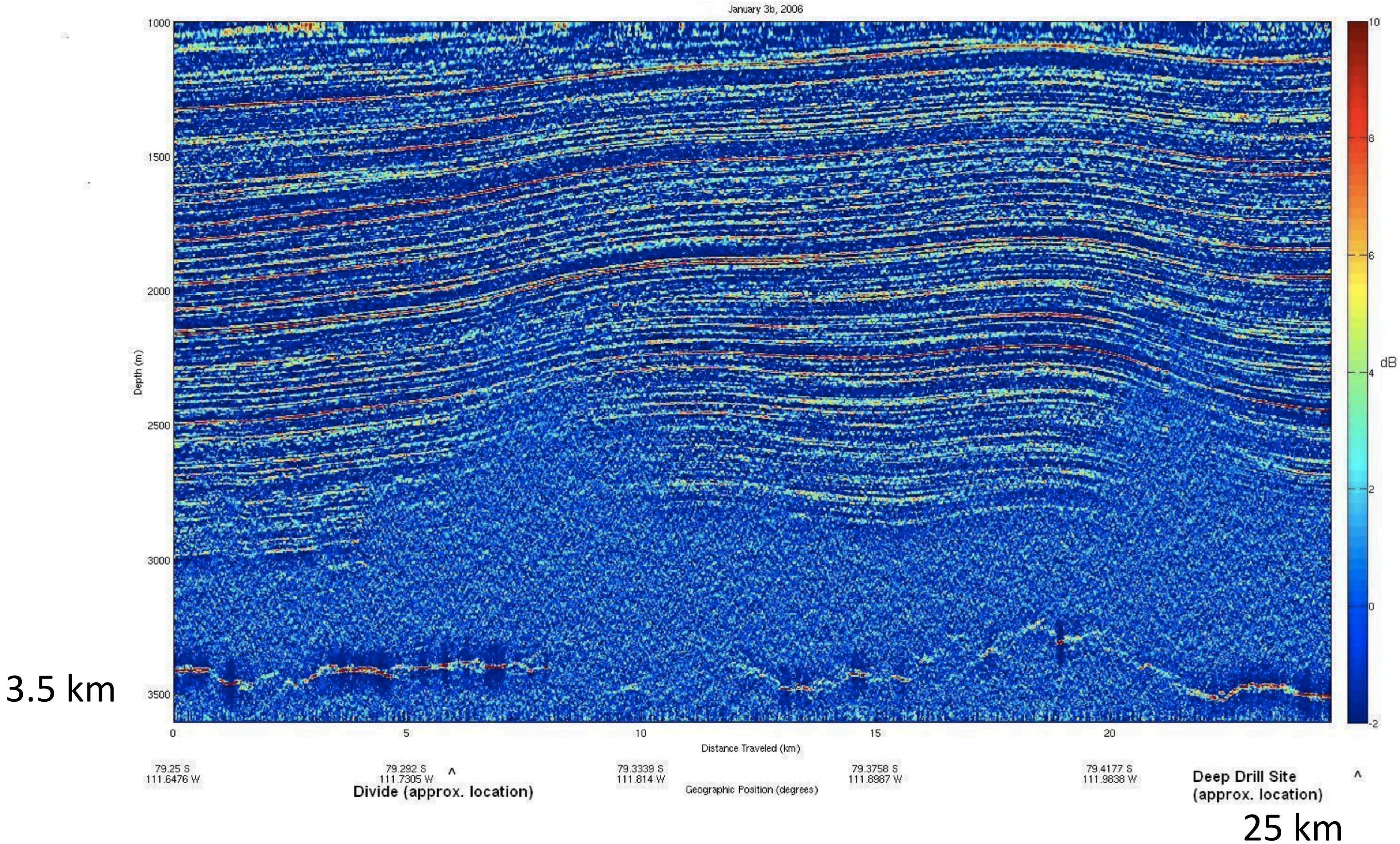


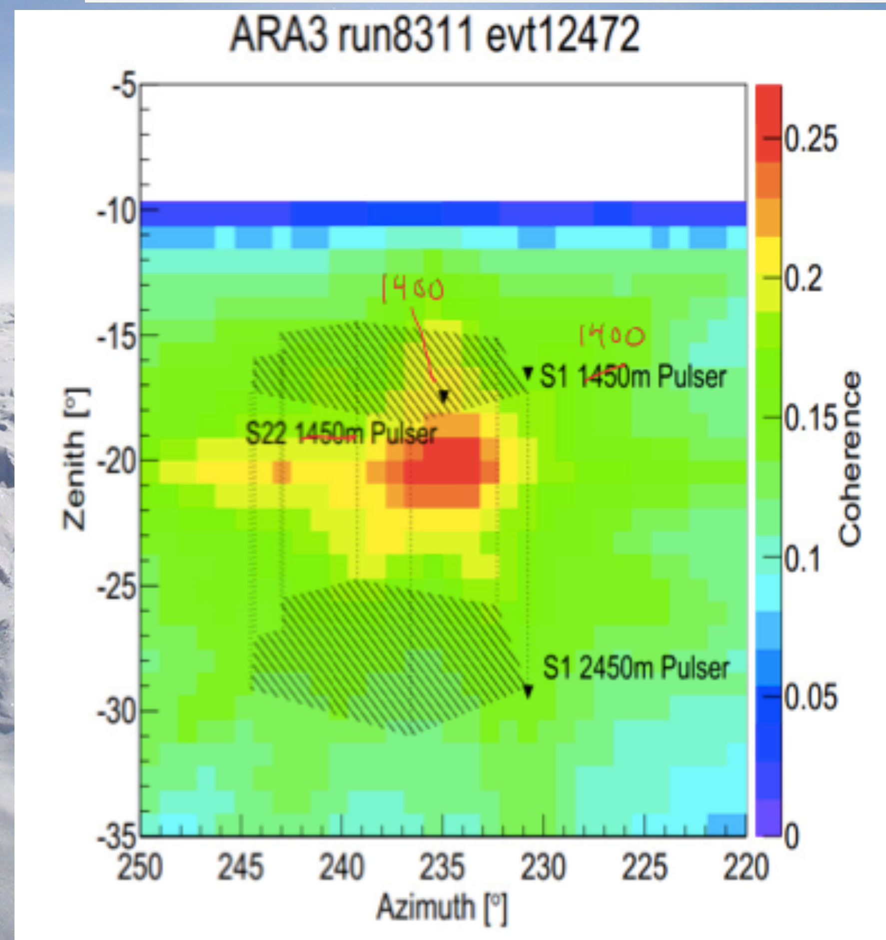
Figure:
WAIS GPR map at 350MHz

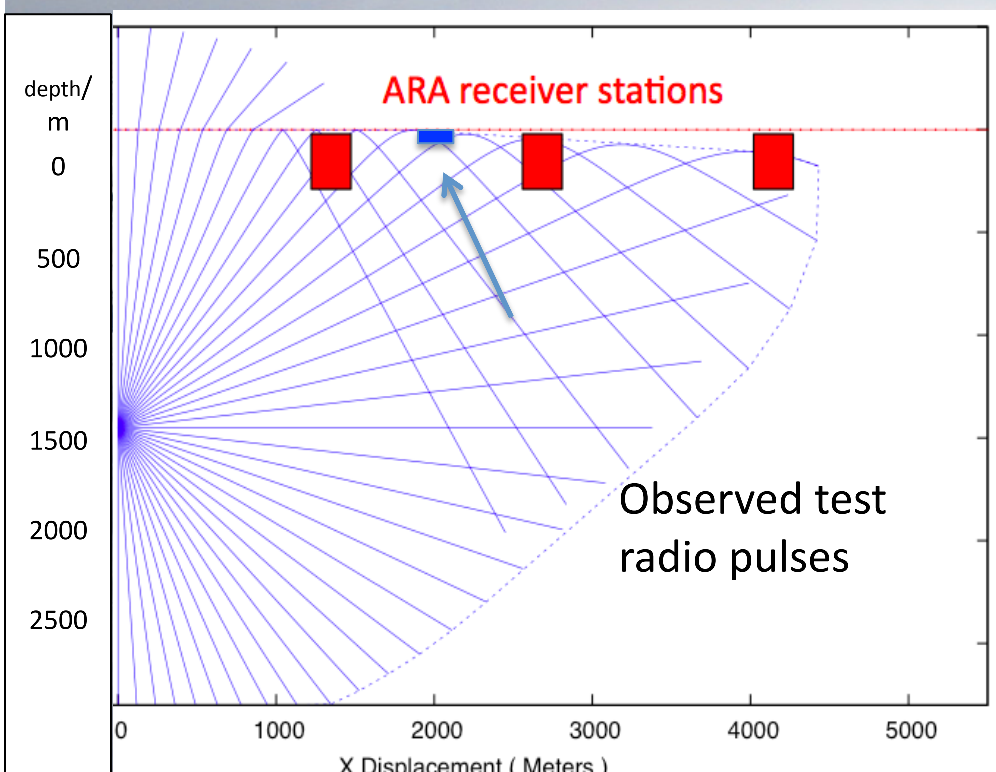
Ref: WAIS 2006 CReSIS Radar Data Summary

South Pole glacial ice – 2.8km, cold and RF transparent

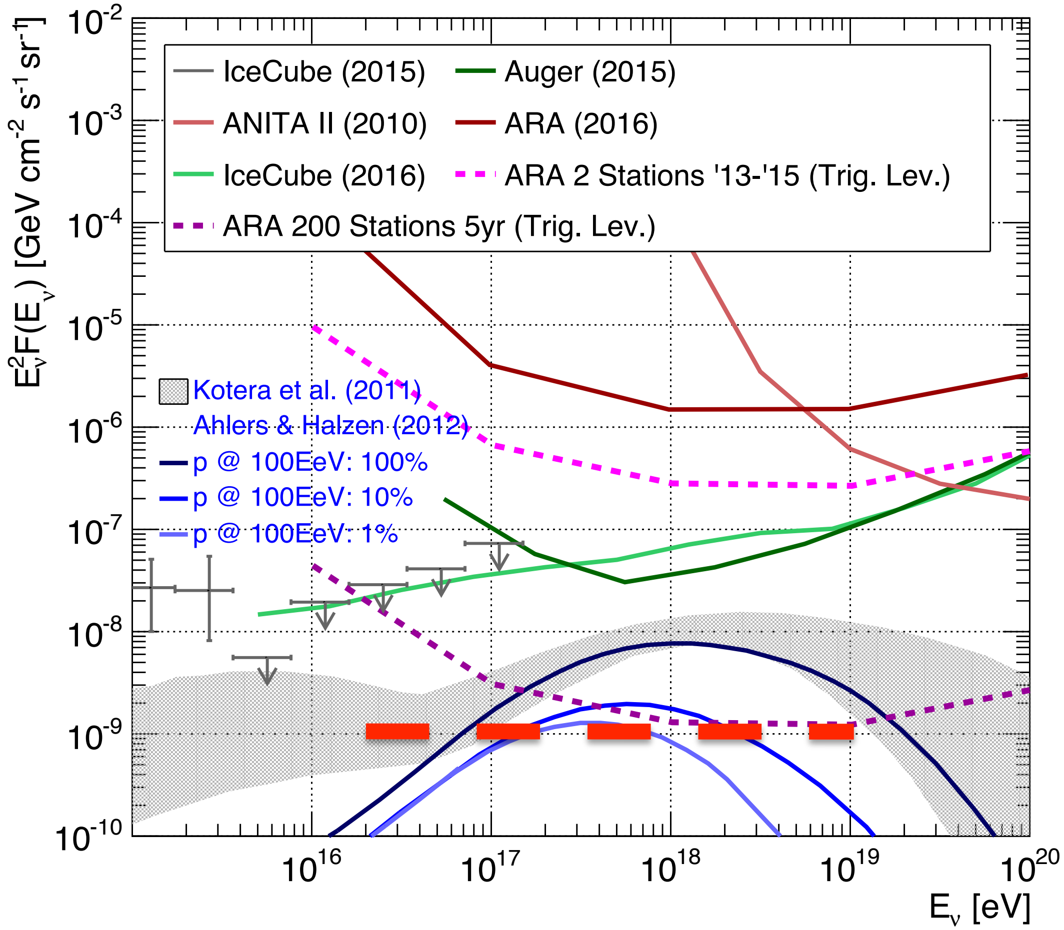
- Thickness: 2800m
- Temperature: -55°C at top, -40°C at 1500m
- Attenuation length at 300MHz: ~ 1.5km at depths < 1500m.
- Very low electromagnetic noise

Event reconstruction of test pulser using interferometric analysis





Neutrino fluxes and the potential of an ARA like detector



Lot’s of data!
Exciting times!

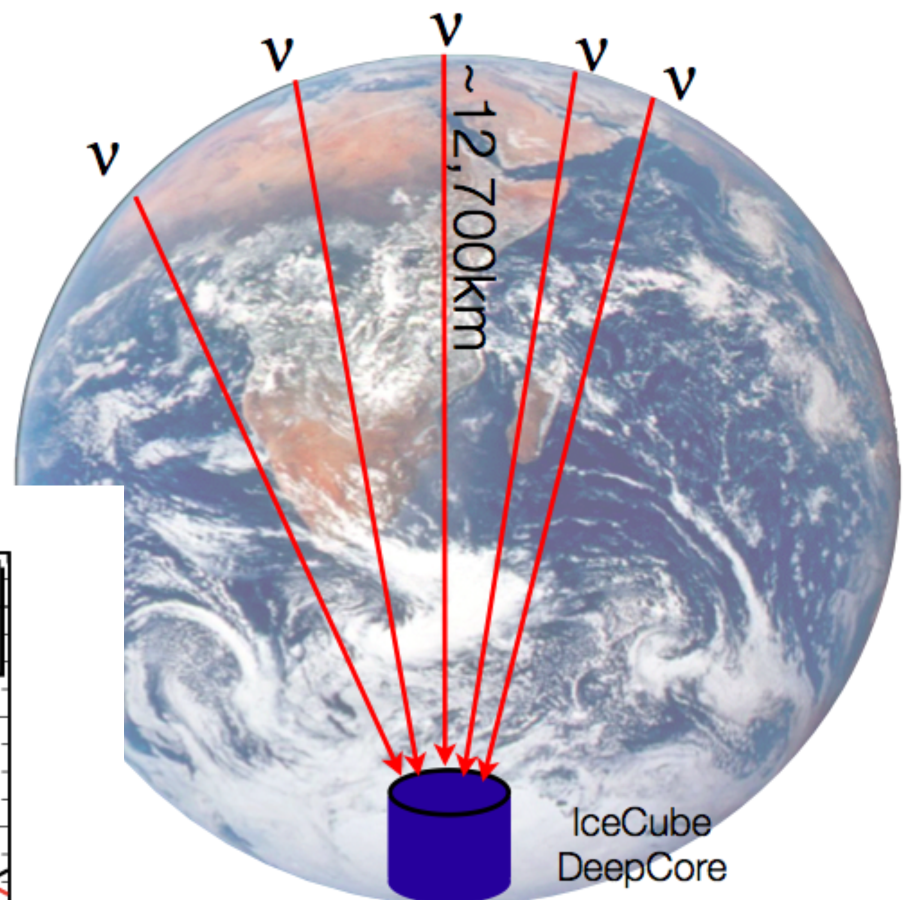
Closing in on the puzzle, but more data is needed, and more detector!

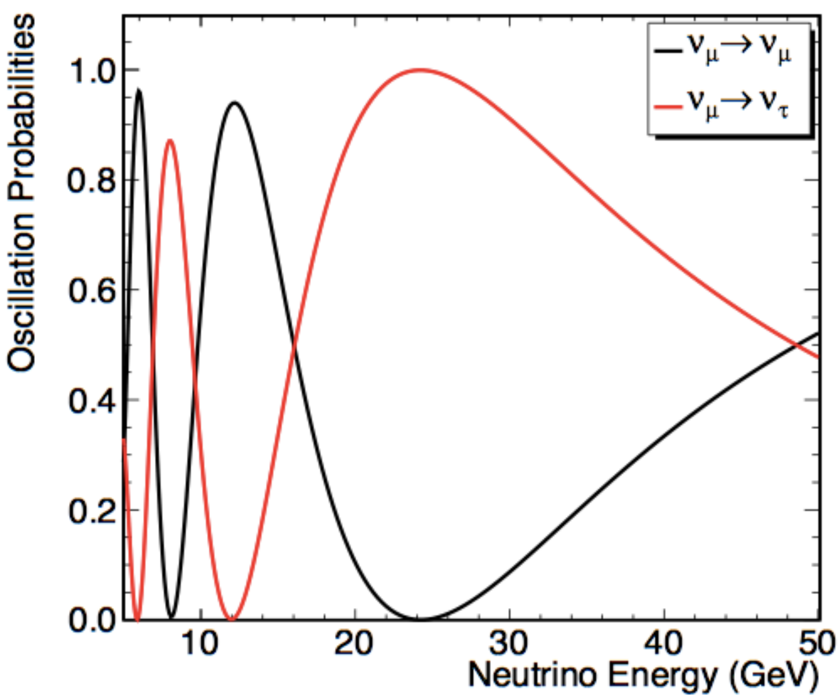
Thank you!

“Race around the World”, Dec 25, 2008

Neutrino oscillation analysis with IceCube-DeepCore

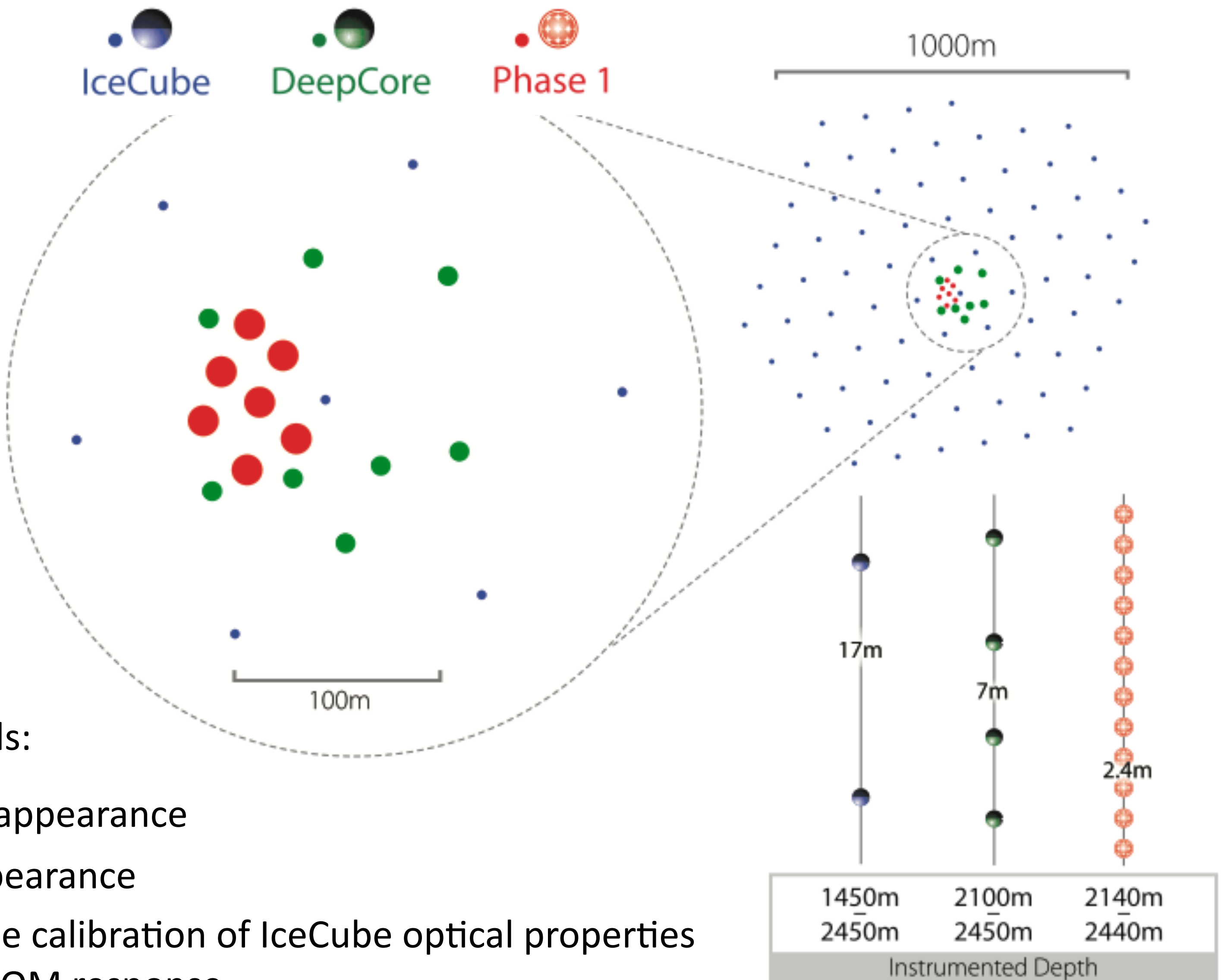
- First oscillation maximum around 24 GeV, i.e. DeepCore energies
- Hierarchy-dependent matter effects below 10 GeV – too low for DeepCore





'oster)
‹

IceCube-Gen2 Phase 1



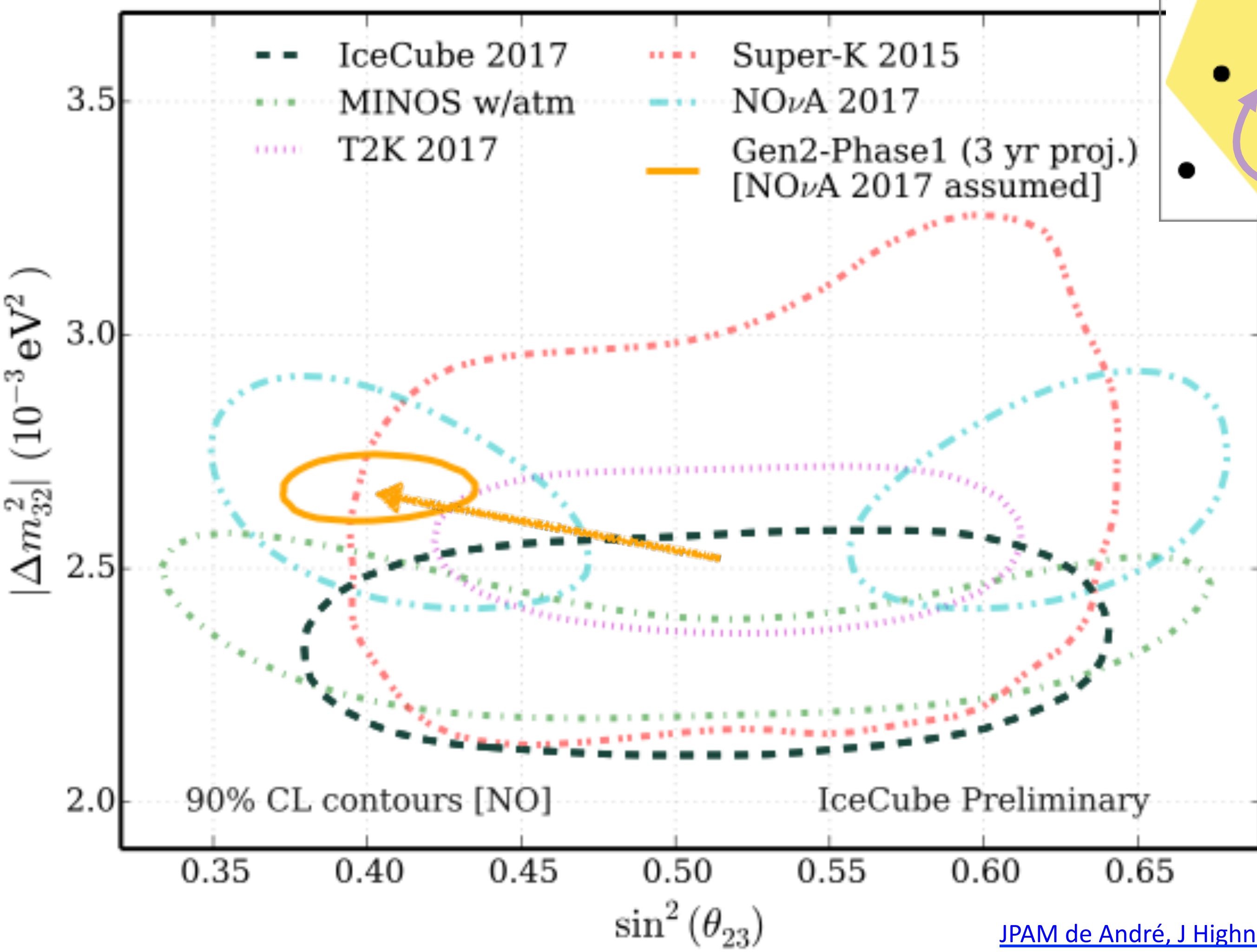
Science goals:

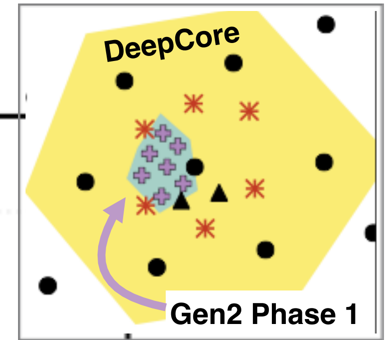
- ν_μ disappearance
- ν_τ appearance
- Precise calibration of IceCube optical properties and DOM response

Phase 1 science: precision ν_μ disappearance

IceCube DeepCore 3 years

Gen2 Phase 1 3 years



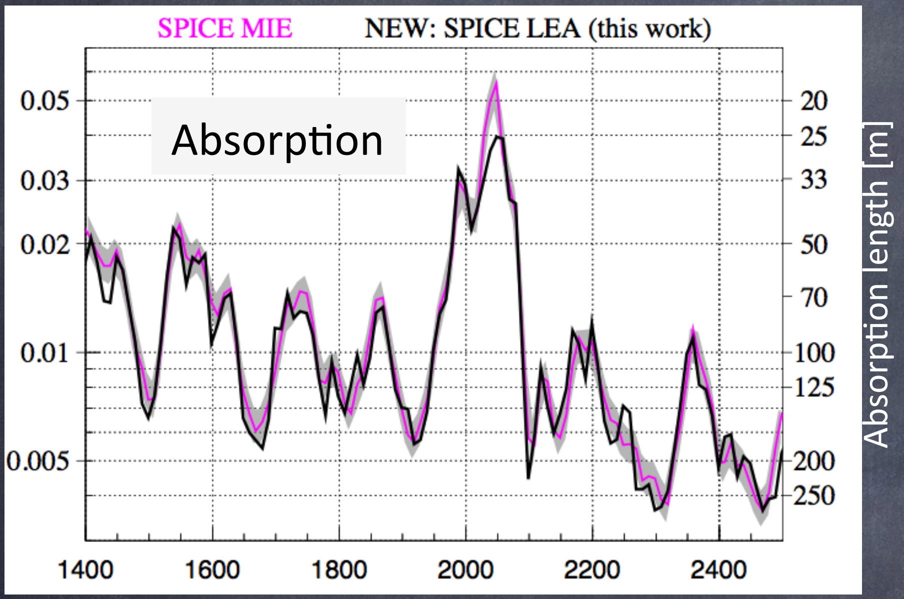


JPAM de André, J Highnight, IPA 2017

Precision significantly improved over DeepCore

Understanding the ice

1. Vertical structure of ice parameters



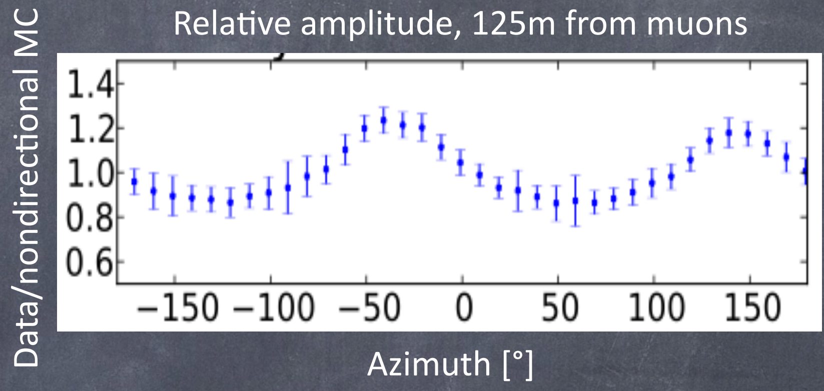
Scattering (eff.): 20 – 50 m
Absorption: 100 – 200 m

Measurement of South Pole ice transparency with the IceCube LED calibration system,

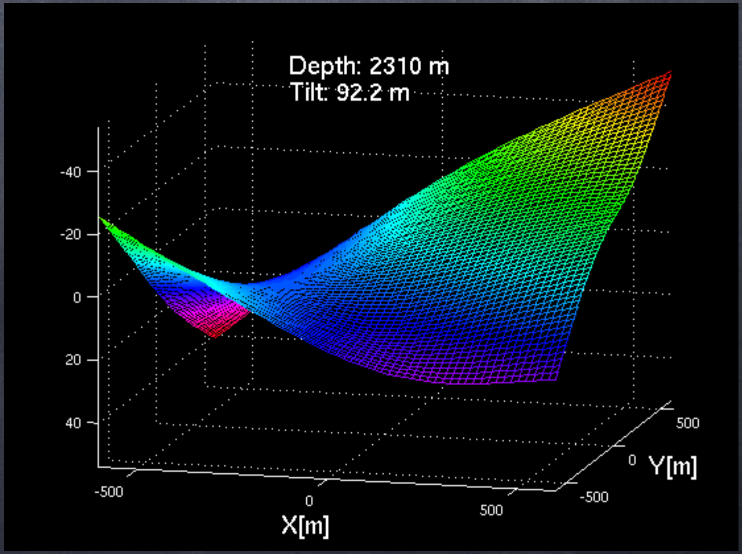
Aartsen et al., (IceCube Coll.), NIMA55353
http://arxiv.org/abs/1301.5361

2. Azimuthal variation in of scattering

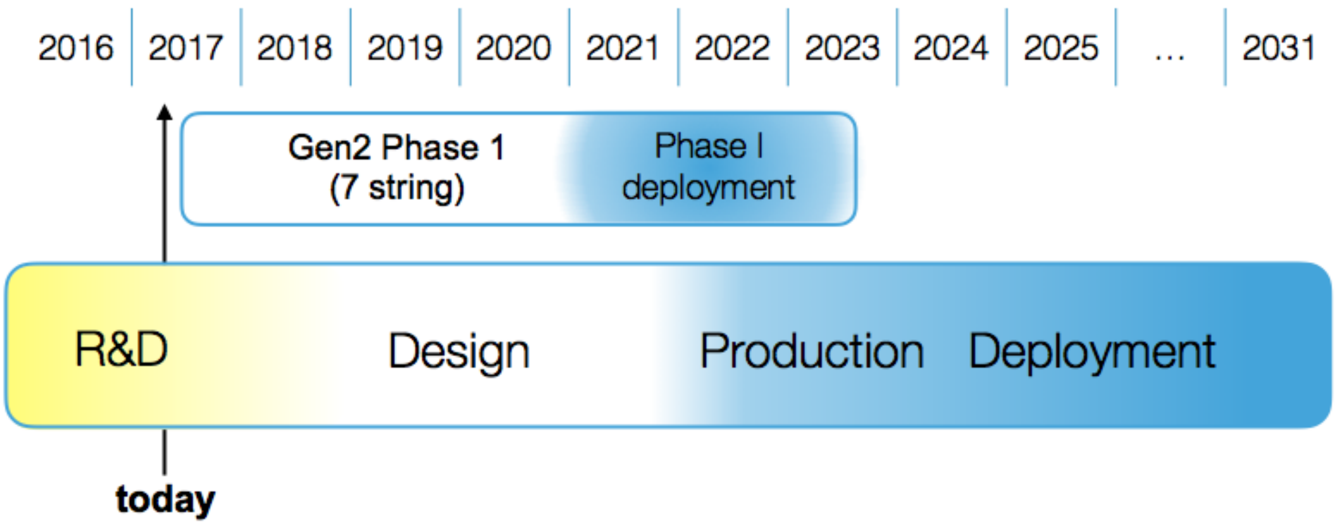
Less scattering in direction of ice flow:
→ up to ~10% /100m variation in amplitude



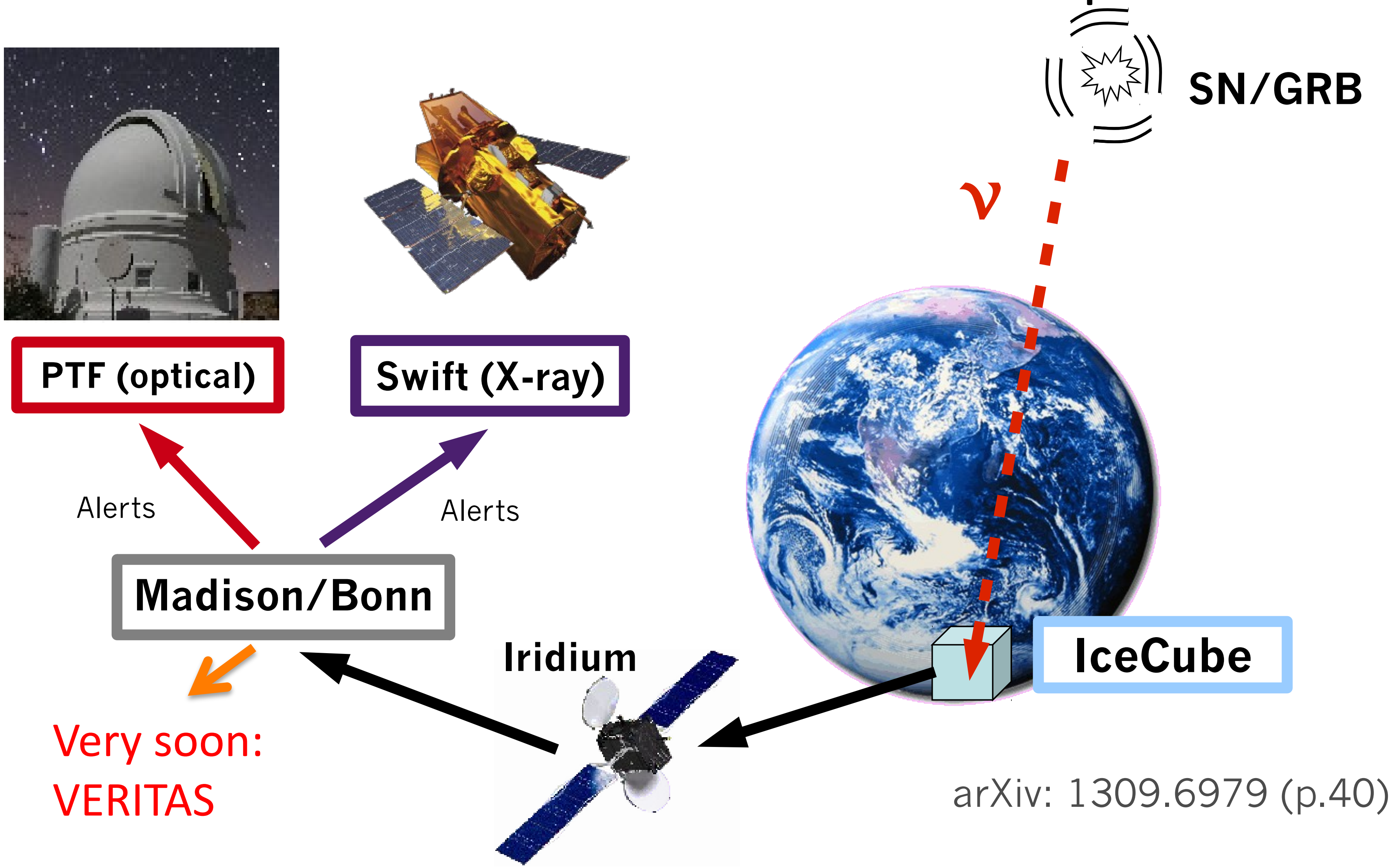
3. Ice layers are tilted – not planar



Gen2 preliminary timeline



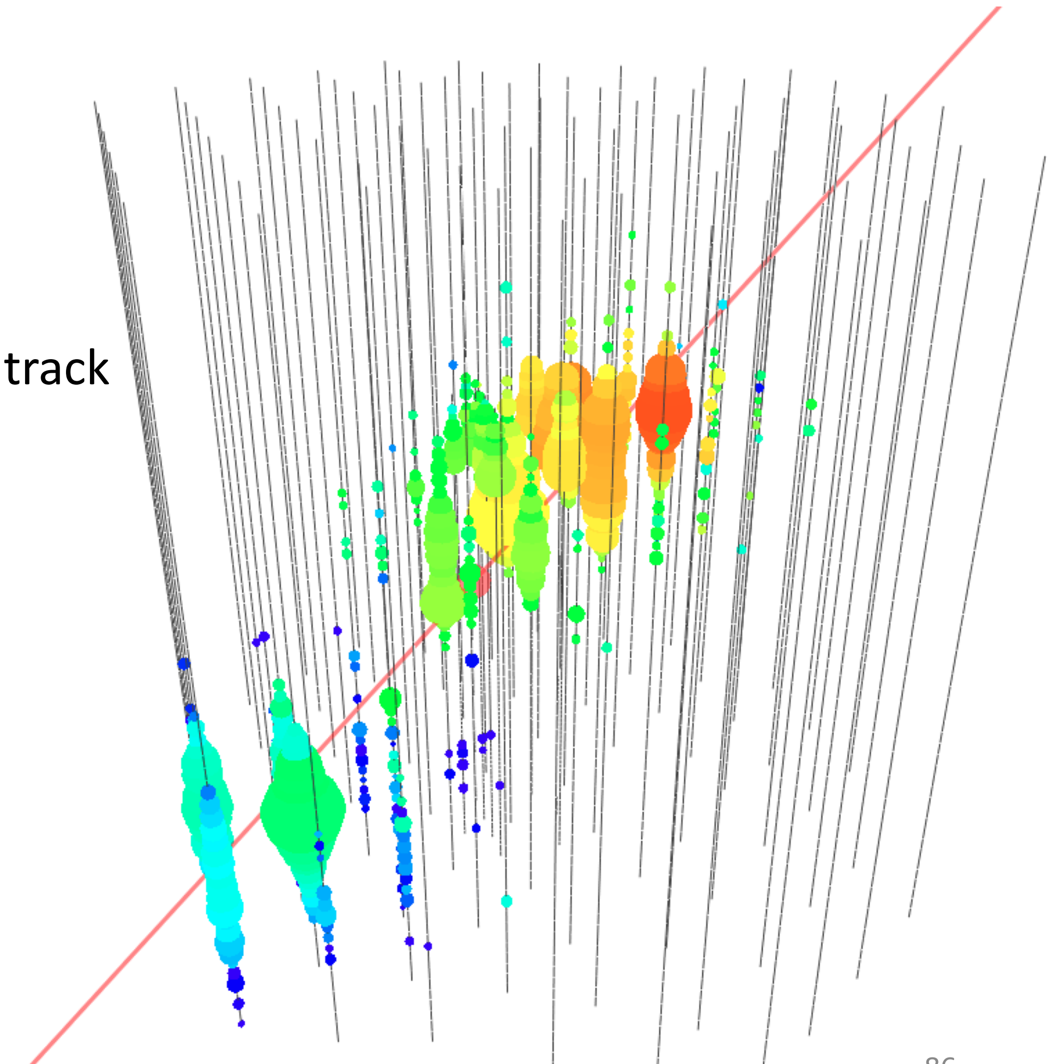
IceCube alerts optical, x-ray, and gamma-ray observatories where and when to point



Can derive on event to event basis the probability of an event being astrophysical.

- Deposited Energy: 84 TeV
- Muon energy: ~200 TeV
- Zenith angle: 55.6°
- Leaves no light along first 400m of track

This event represents a 2.8σ fluctuation of the background-only hypothesis (*a posteriori*)



Phase 1: enhancing IceCube high-energy science

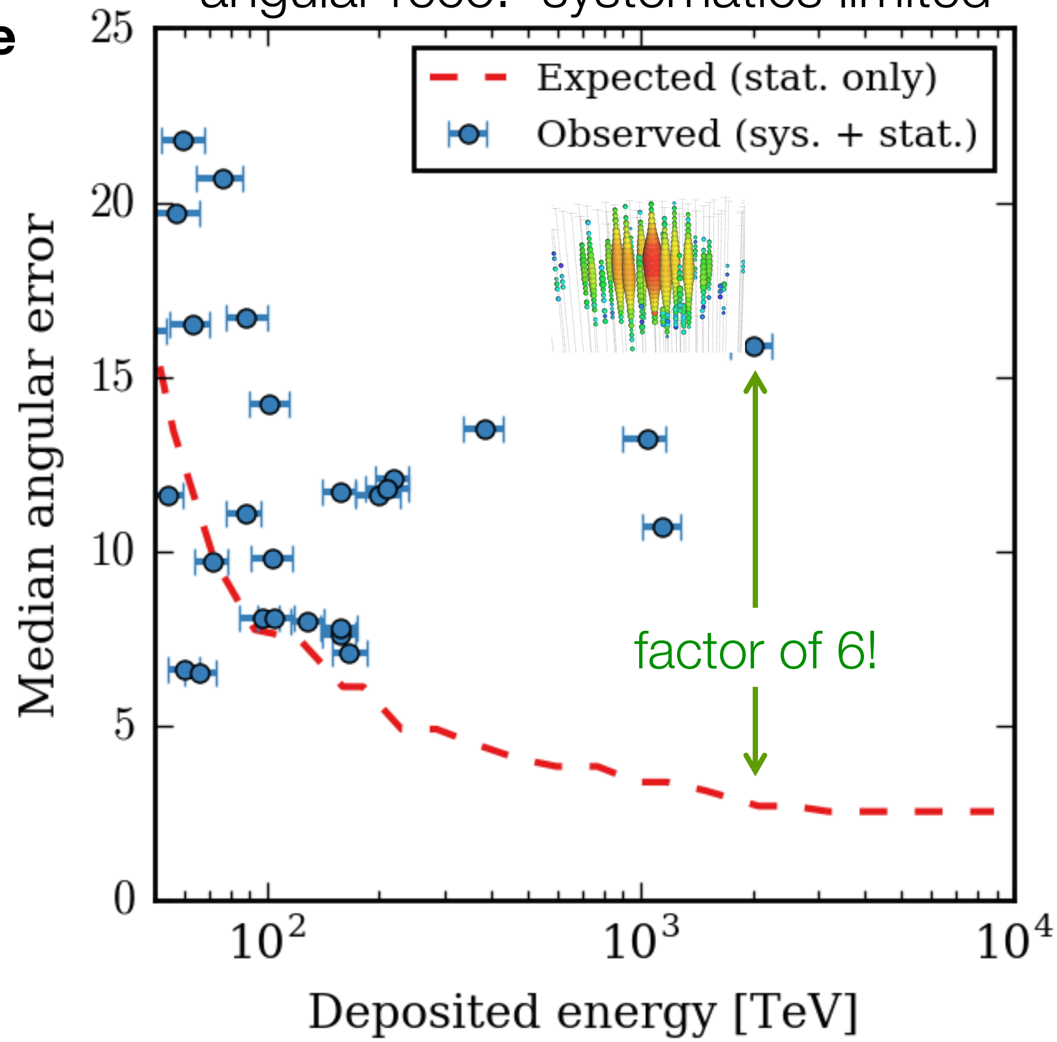
New calibration devices inside IceCube enhance HE science

- reconstructions
- tau flavor identification

POCAM being deployed at Lake Baikal

See NU143

angular reco. systematics limited



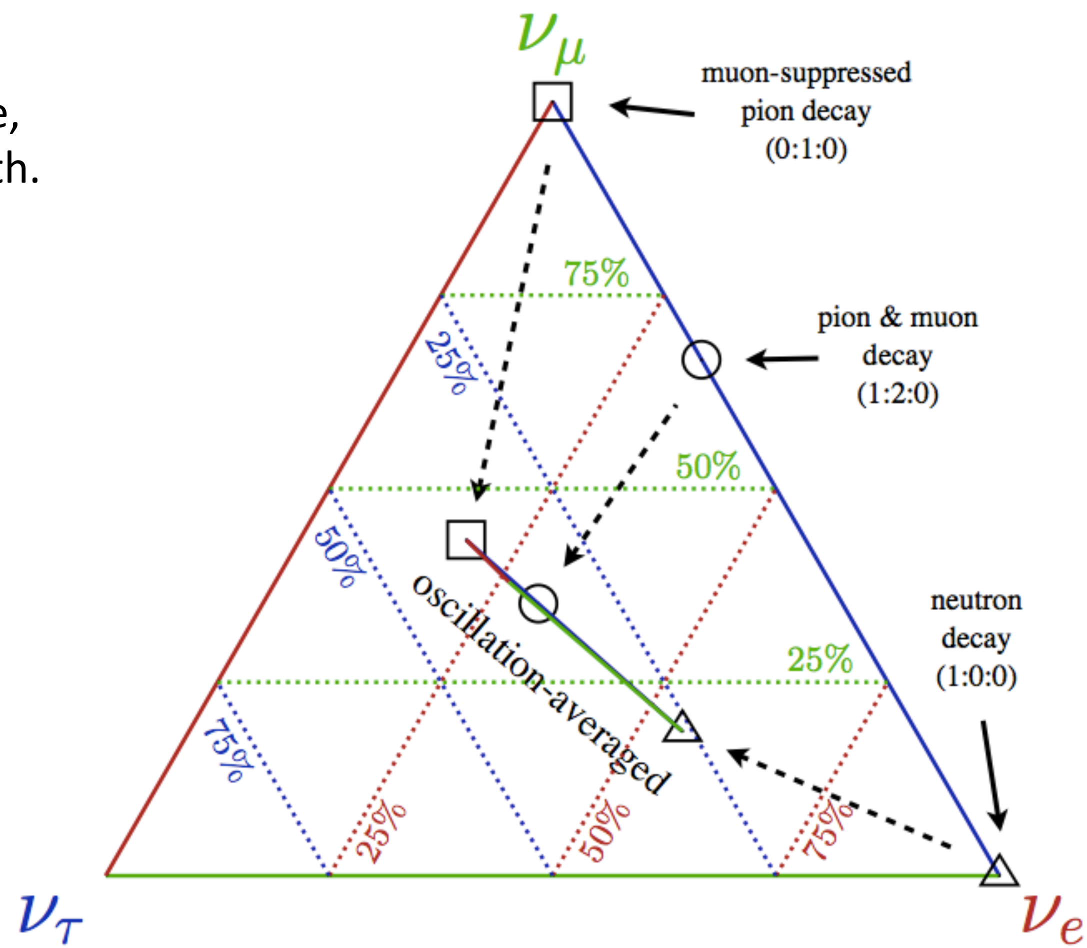
New calibration boosts the entire IceCube data set (> 10 yrs)

Flavor ratio

Flavor ratio at earth is related to flavor ratio at astrophyical source, After oscillations en route to Earth.

For a detailed flavor ratio discussion, see

arXiv: 1502.03376:



Tau neutrinos

Expected to see the first Tau already!

Charged Current tau neutrino:

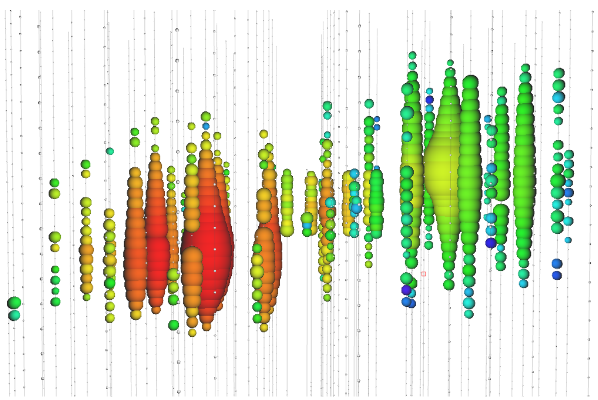
$$\nu_\tau + N \rightarrow \tau + X$$

Double-bang signature from decaying tau,

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

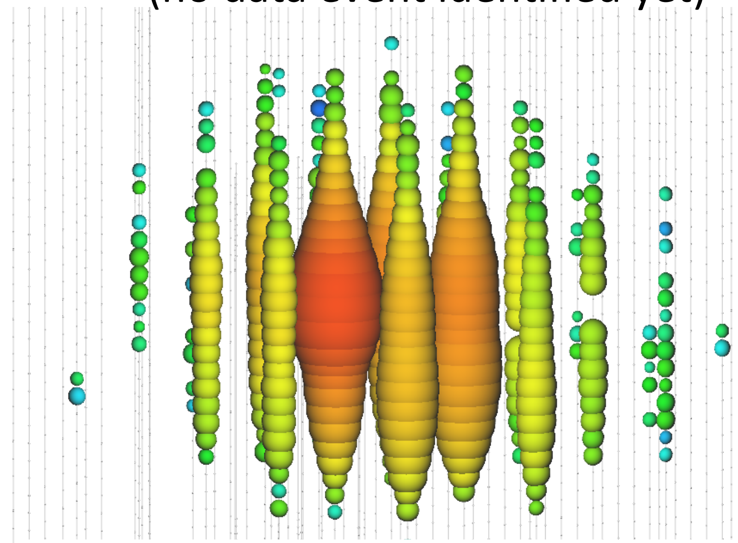
Can identify double bang above 400 TeV.

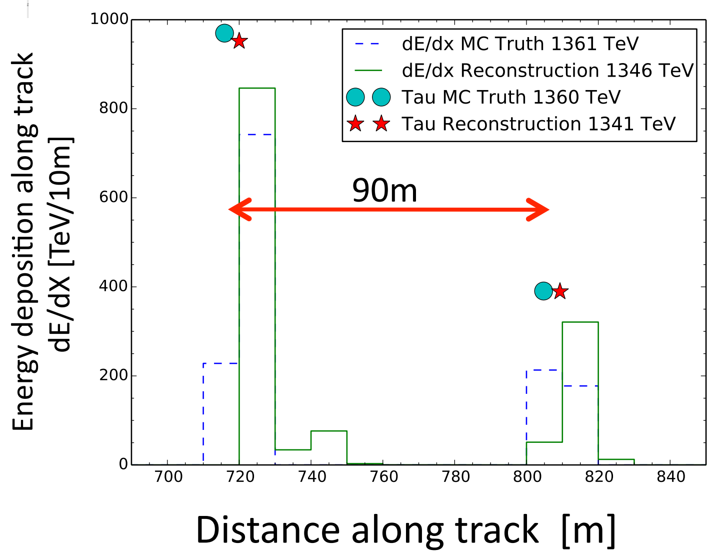
Also lower energy as developed by Donglian Xu



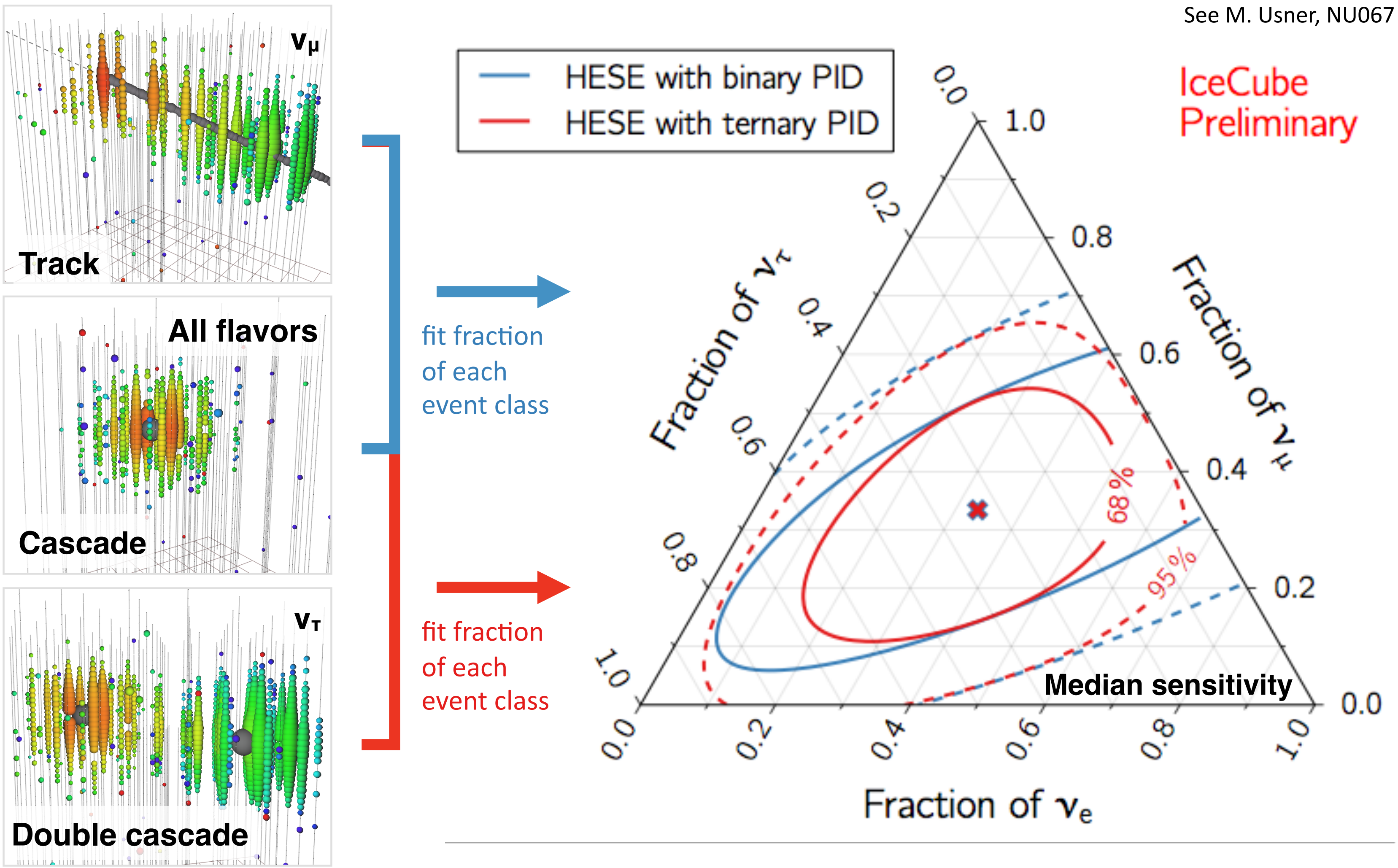
Event with longer decay length

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





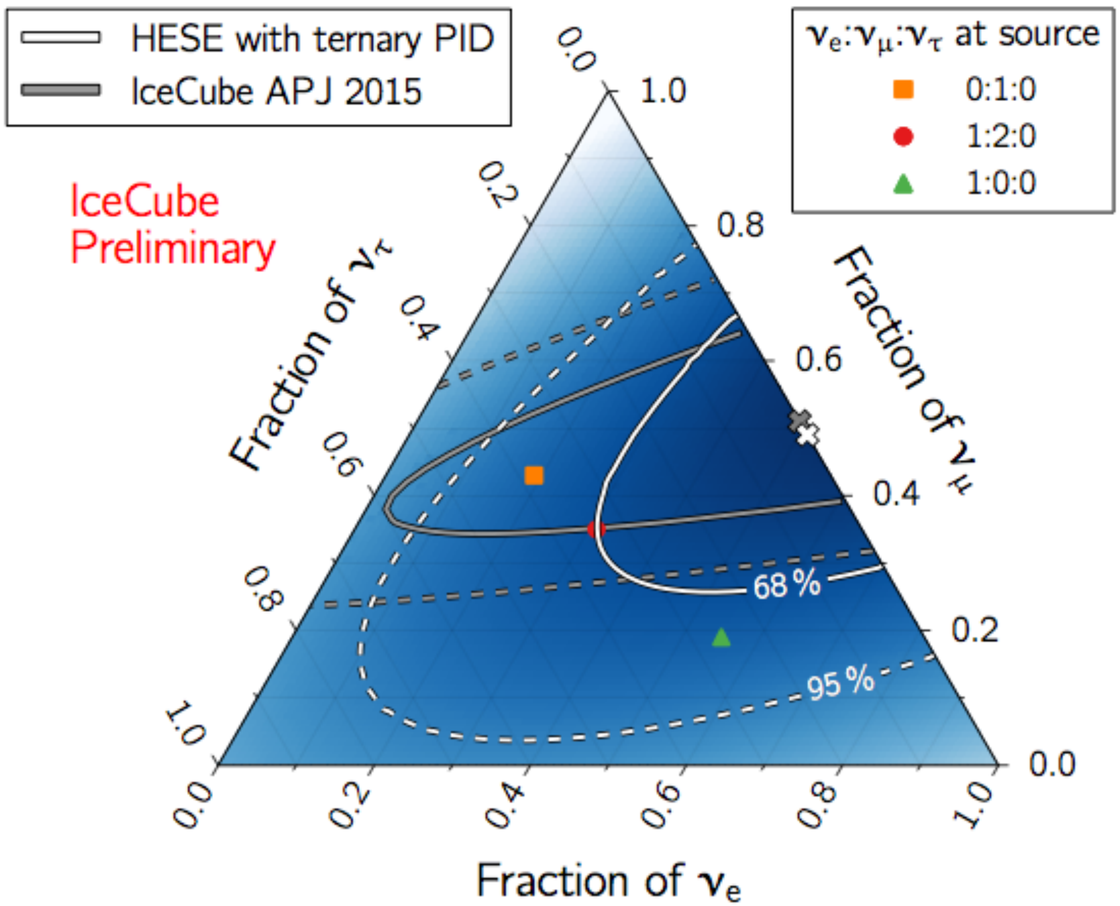
Improved ν_τ search with starting events



- Lack of ν_τ candidates compatible with statistical fluctuation

Search for tau neutrinos

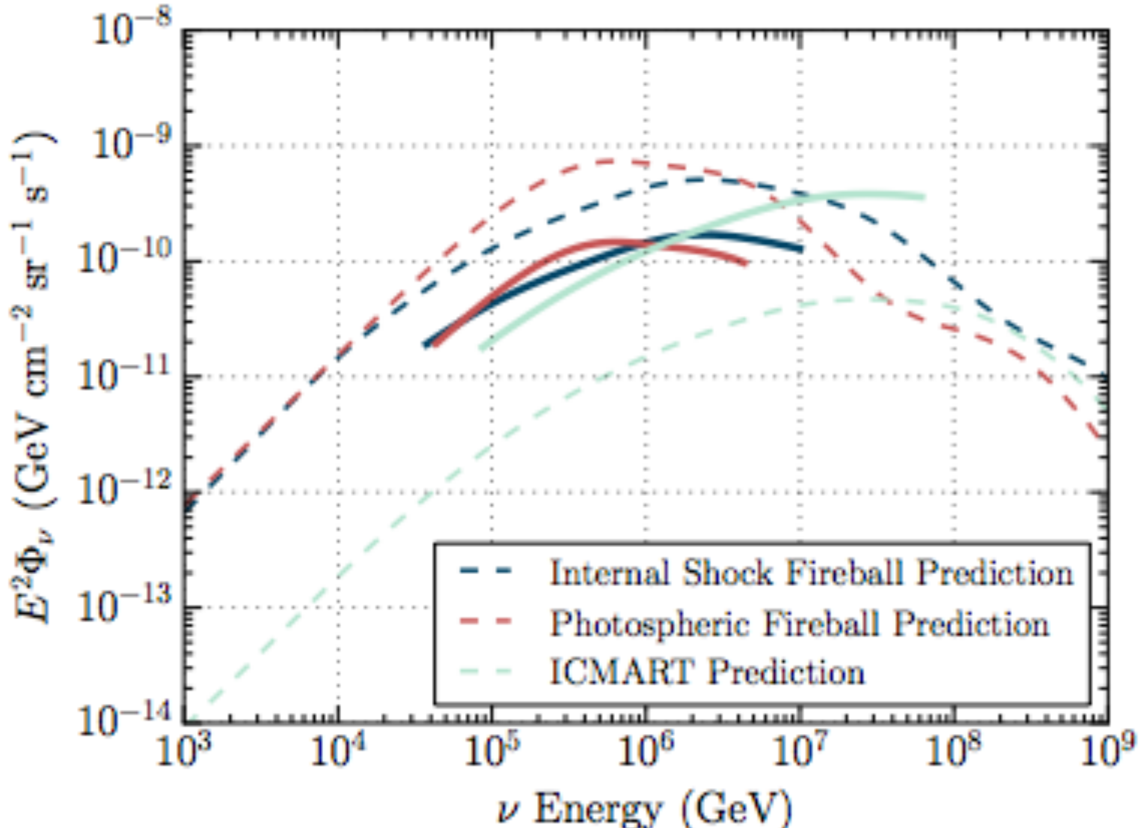
See M. Usner, NU067



- Icecube would have expected about ~2 events by now.
- Lack of ν_τ candidates compatible with statistical fluctuation

Transient population studies: gamma ray bursts

- Short duration → minimal background
- No neutrinos observed in coincidence with GRBs



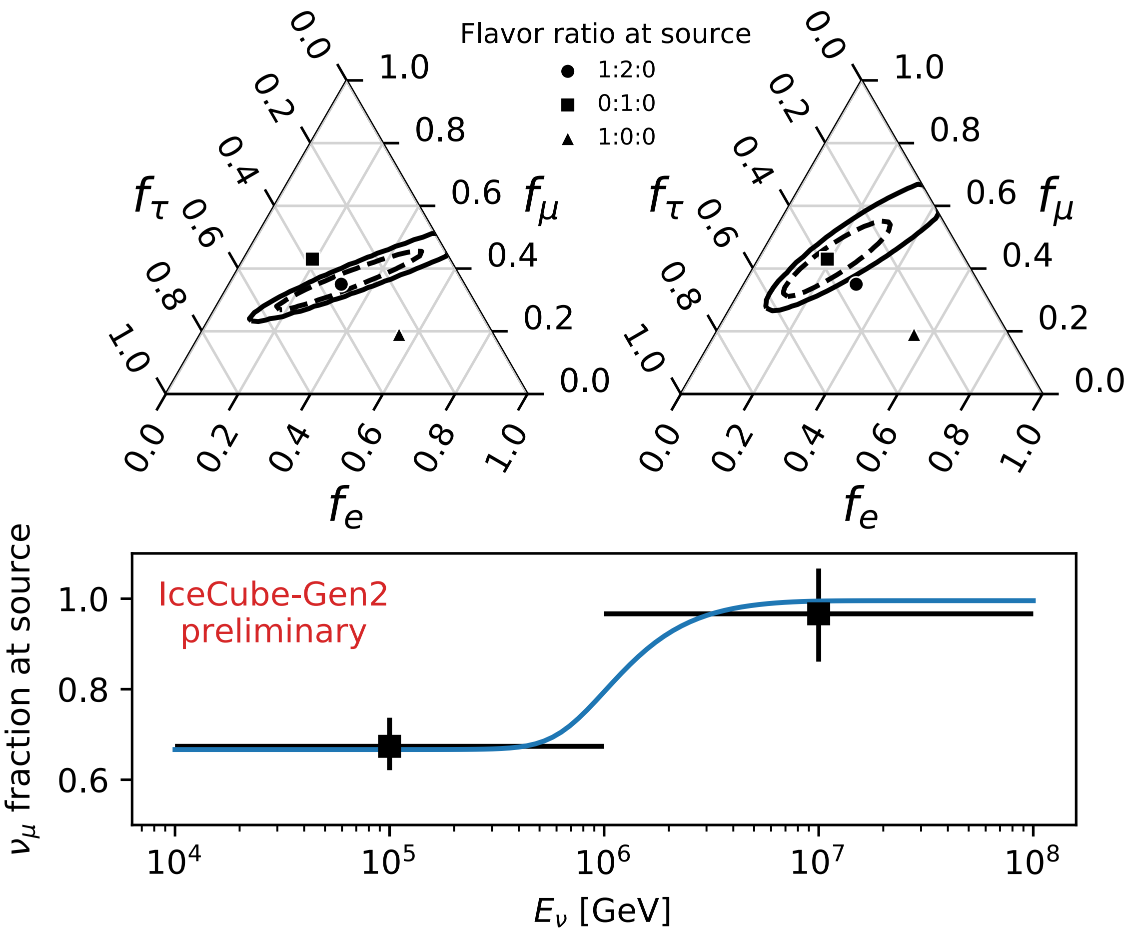
arXiv:1702.06868

Prompt emission from GRBs can produce <1% of the observed neutrino flux.

Deciphering the neutrino flavors at the astrophysical source.

Sensitivity to muon cooling in the sources with Gen2:

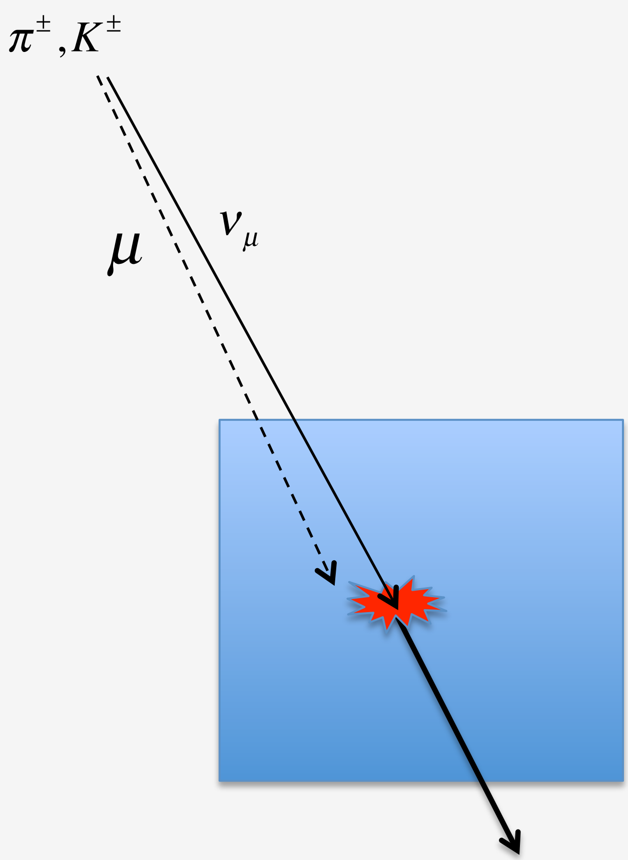
Above a critical energy, the decay time for secondary muons from pion decay exceeds the cooling time, and the flavor ratio at the source changes from 1:2:0 to 0:1:0



Gen2 sensitivity to nu_mu
Fraction at the source.

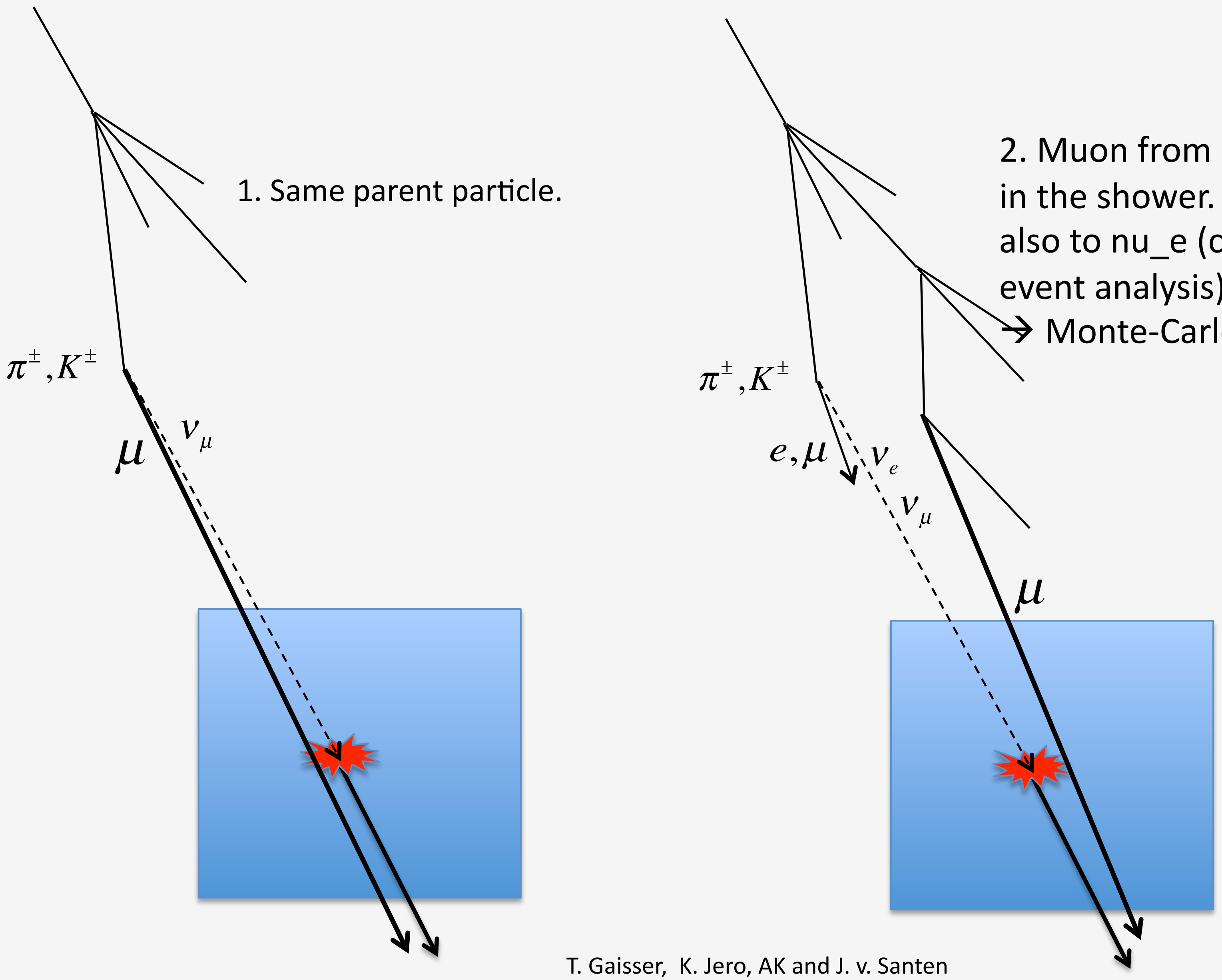
Neutrino self veto –
The neutrino telescope paradigm updside-down?

- “Atmospheric neutrinos” are generated in cosmic ray air showers.
- Above some neutrino energy, ~100 TeV, these neutrinos will likely be accompanied by one or more muons from parent air shower.
- Those muons can be used to veto atmospheric neutrino background.



Suggested by Schoenert et al.
Phys.Rev. D79 (2009) 043009
arXiv:0812.4308

Two cases



1. Same parent particle.

2. Muon from elsewhere in the shower. Applies also to nu_e (contained event analysis).
→ Monte-Carlo

T. Gaisser, K. Jero, AK and J. v. Santen

arXiv:1405.0525

Neutrino self-veto

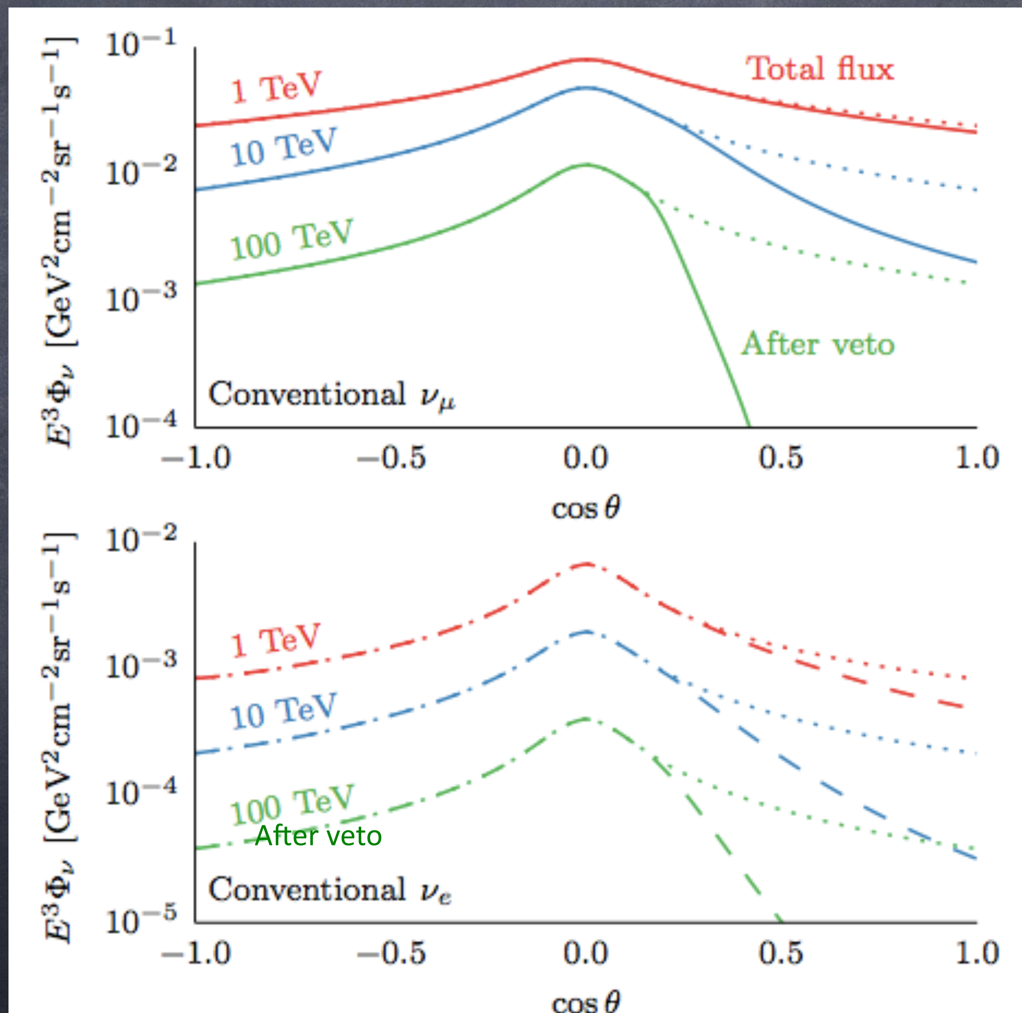
Based on full simulation

T. Gaisser, K. Jero, AK and J. v. Santen

arXiv:1405.0525

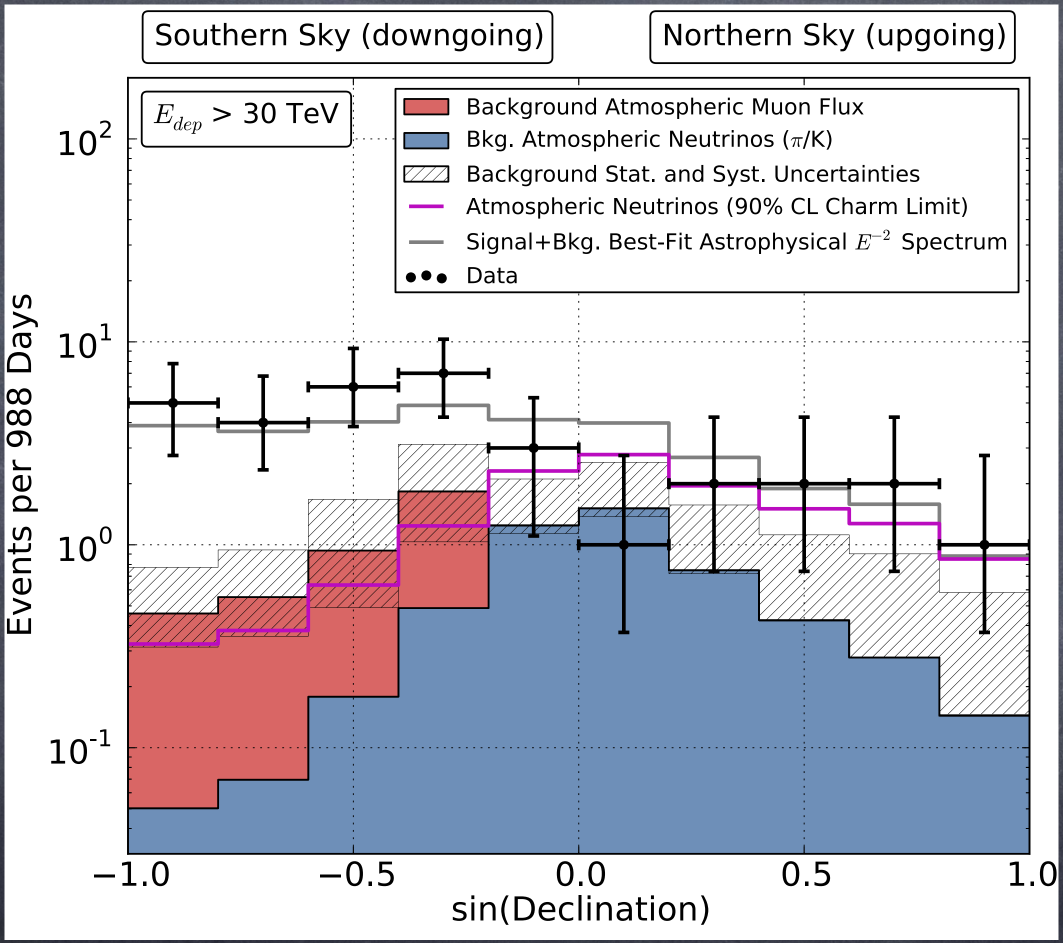
ν_μ

ν_e

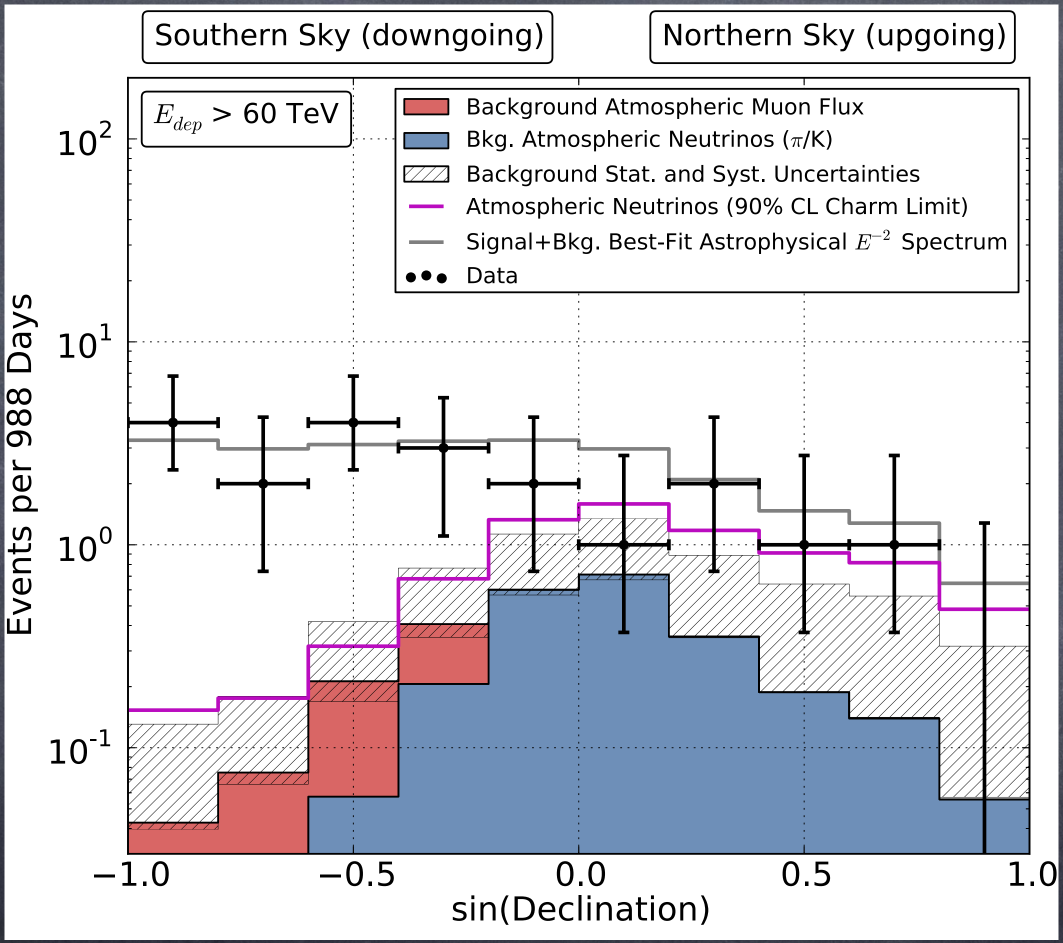


Zenith angle distribution, shows effect of built in neutrino self- veto

E_{dep} > 30 TeV

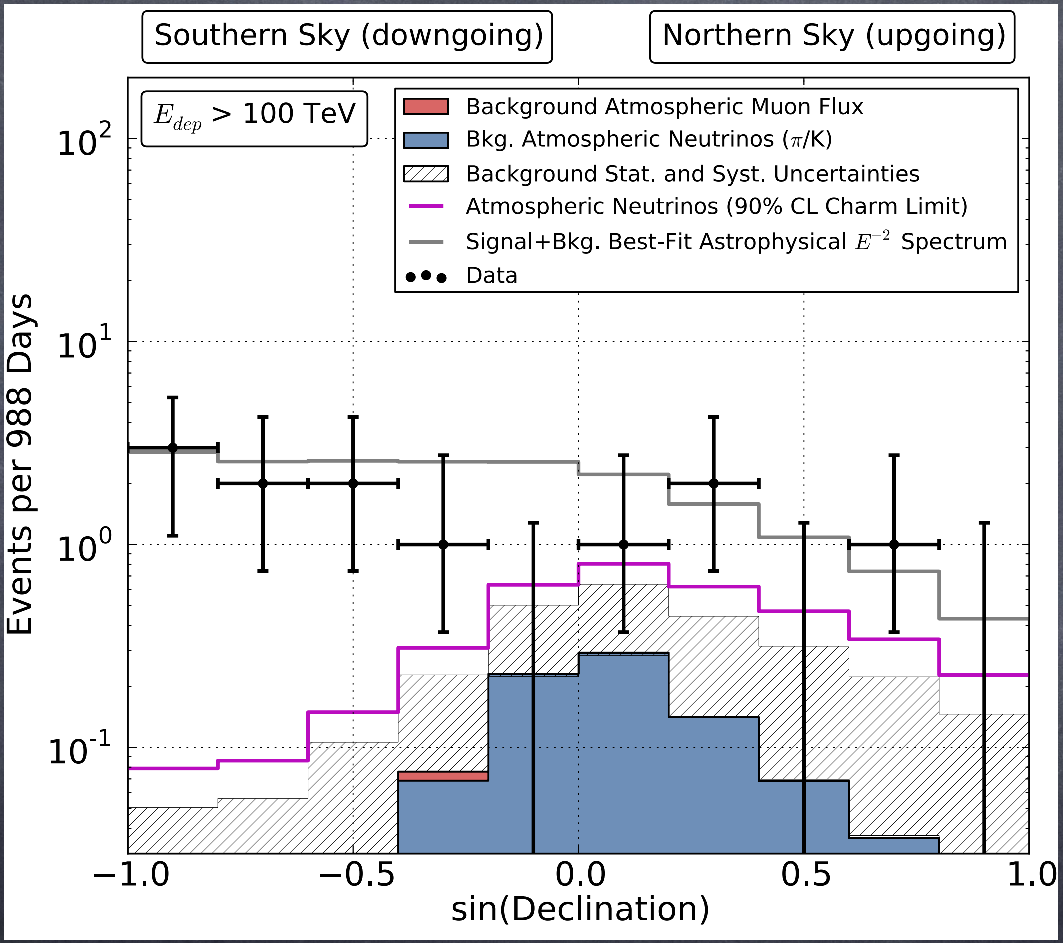


E_{dep} > 60 TeV



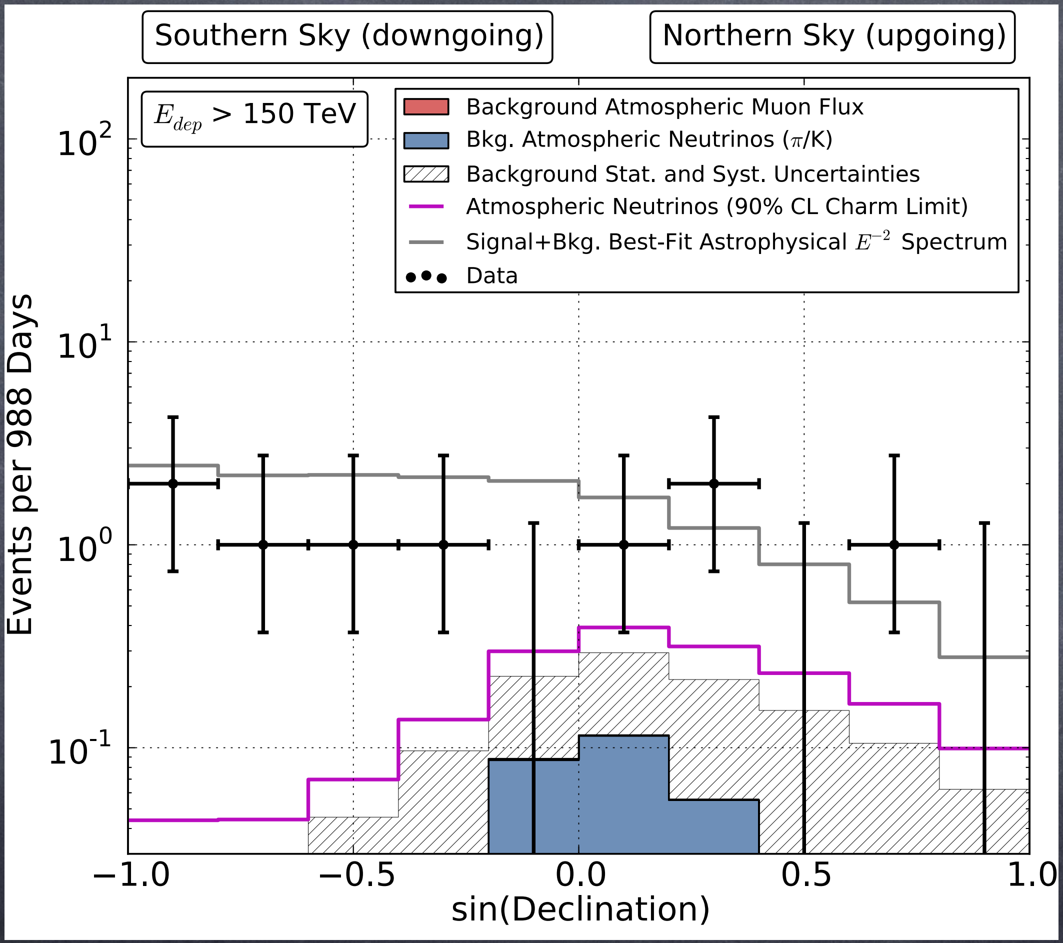
Southern Sky (downgoing)
Northern Sky (upgoing)
E_{dep} > 60 TeV
Background Atmospheric Muon Flux
Bkg. Atmospheric Neutrinos (π/K)
Background Stat. and Syst. Uncertainties
Atmospheric Neutrinos (90% CL Charm Limit)
Signal+Bkg. Best-Fit Astrophysical E^{-2} Spectrum
Data
Events per 988 Days
10^2
10^1
10^0
10^{-1}
−1.0
−0.5
0.0
0.5
1.0
sin(Declination)

E_{dep} > 100 TeV



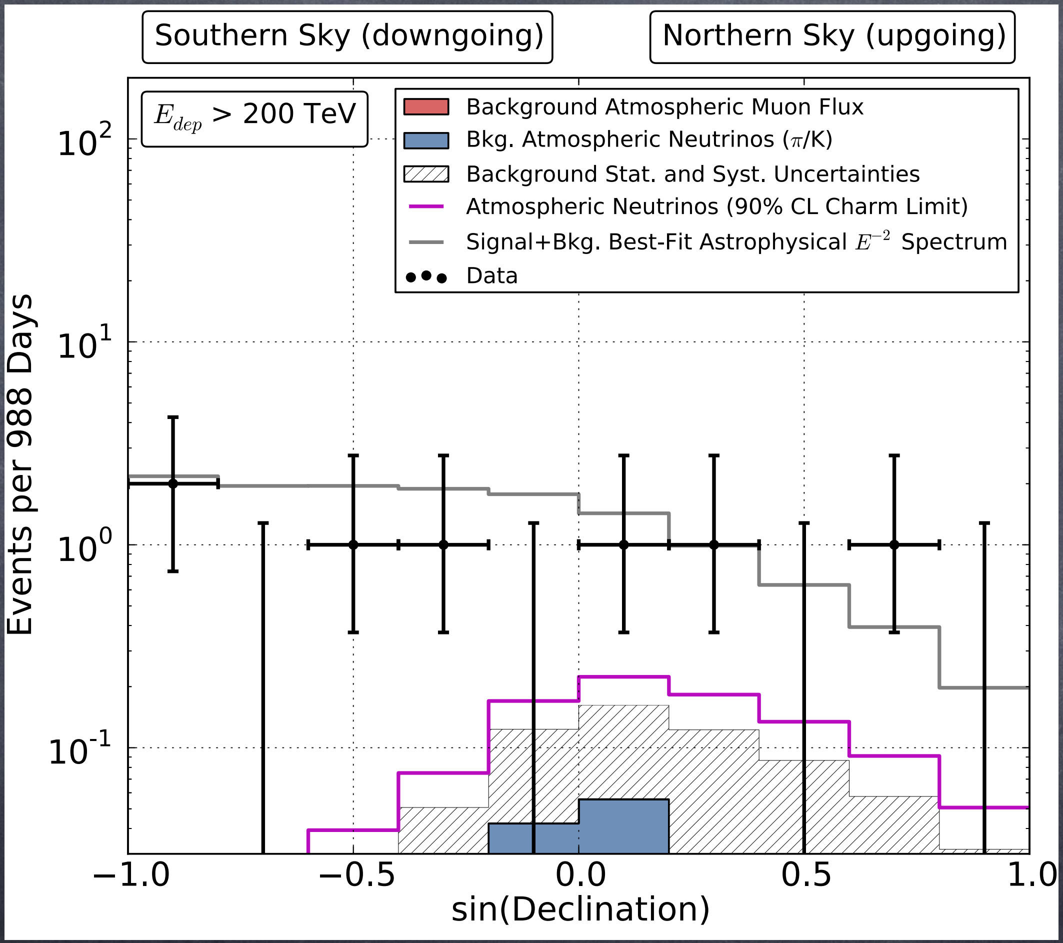
Southern Sky (downgoing)
Northern Sky (upgoing)
E_{dep} > 100 TeV
Background Atmospheric Muon Flux
Bkg. Atmospheric Neutrinos (π/K)
Background Stat. and Syst. Uncertainties
Atmospheric Neutrinos (90% CL Charm Limit)
Signal+Bkg. Best-Fit Astrophysical E^{-2} Spectrum
Data
Events per 988 Days
10^{2}
10^{1}
10^{0}
10^{-1}
−1.0
−0.5
0.0
0.5
1.0
sin(Declination)

E_{dep} > 150 TeV



Southern Sky (downgoing)
Northern Sky (upgoing)
E_{dep} > 150 TeV
Background Atmospheric Muon Flux
Bkg. Atmospheric Neutrinos (π/K)
Background Stat. and Syst. Uncertainties
Atmospheric Neutrinos (90% CL Charm Limit)
Signal+Bkg. Best-Fit Astrophysical E^{-2} Spectrum
Data
Events per 988 Days
sin(Declination)

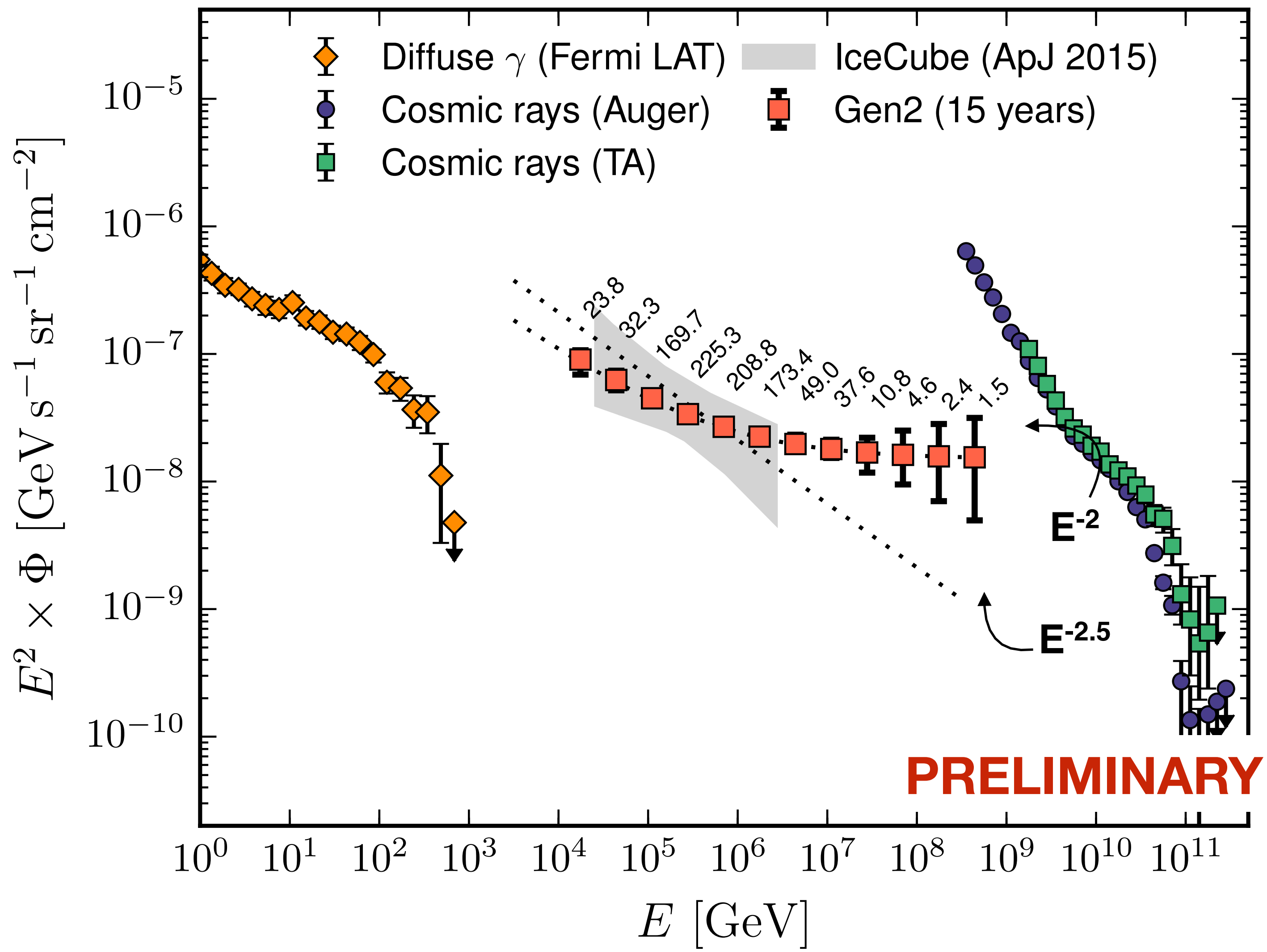
E_{dep} > 100 TeV



Southern Sky (downgoing)
Northern Sky (upgoing)
E_{dep} > 200 TeV
Background Atmospheric Muon Flux
Bkg. Atmospheric Neutrinos (π/K)
Background Stat. and Syst. Uncertainties
Atmospheric Neutrinos (90% CL Charm Limit)
Signal+Bkg. Best-Fit Astrophysical E^{-2} Spectrum
Data
Events per 988 Days
10^2
10^1
10^0
10^{-1}
−1.0
−0.5
0.0
0.5
1.0
sin(Declination)

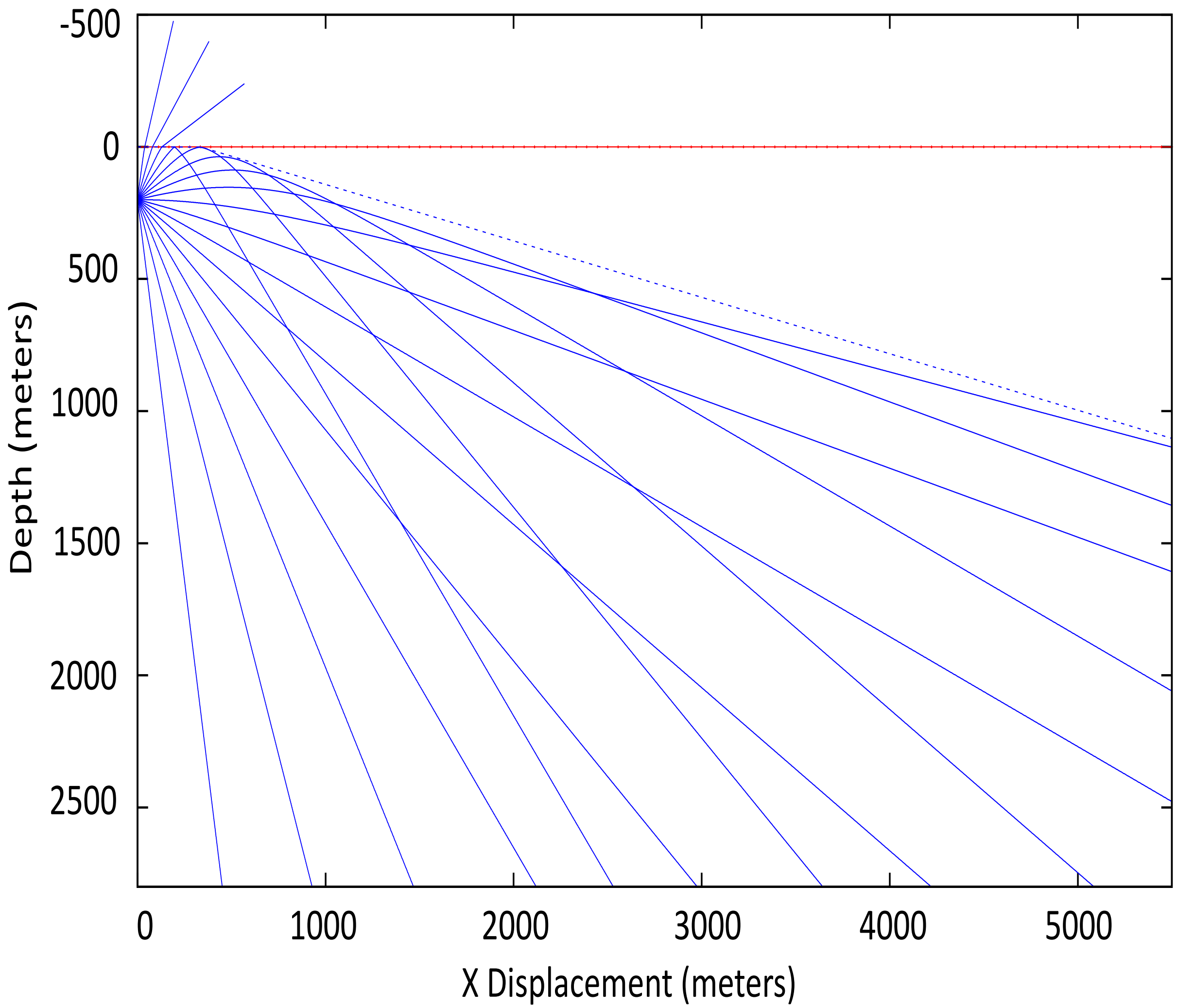
Connecting HE neutrinos to UHE cosmic rays

IceCube-Gen2 (15 year projection)



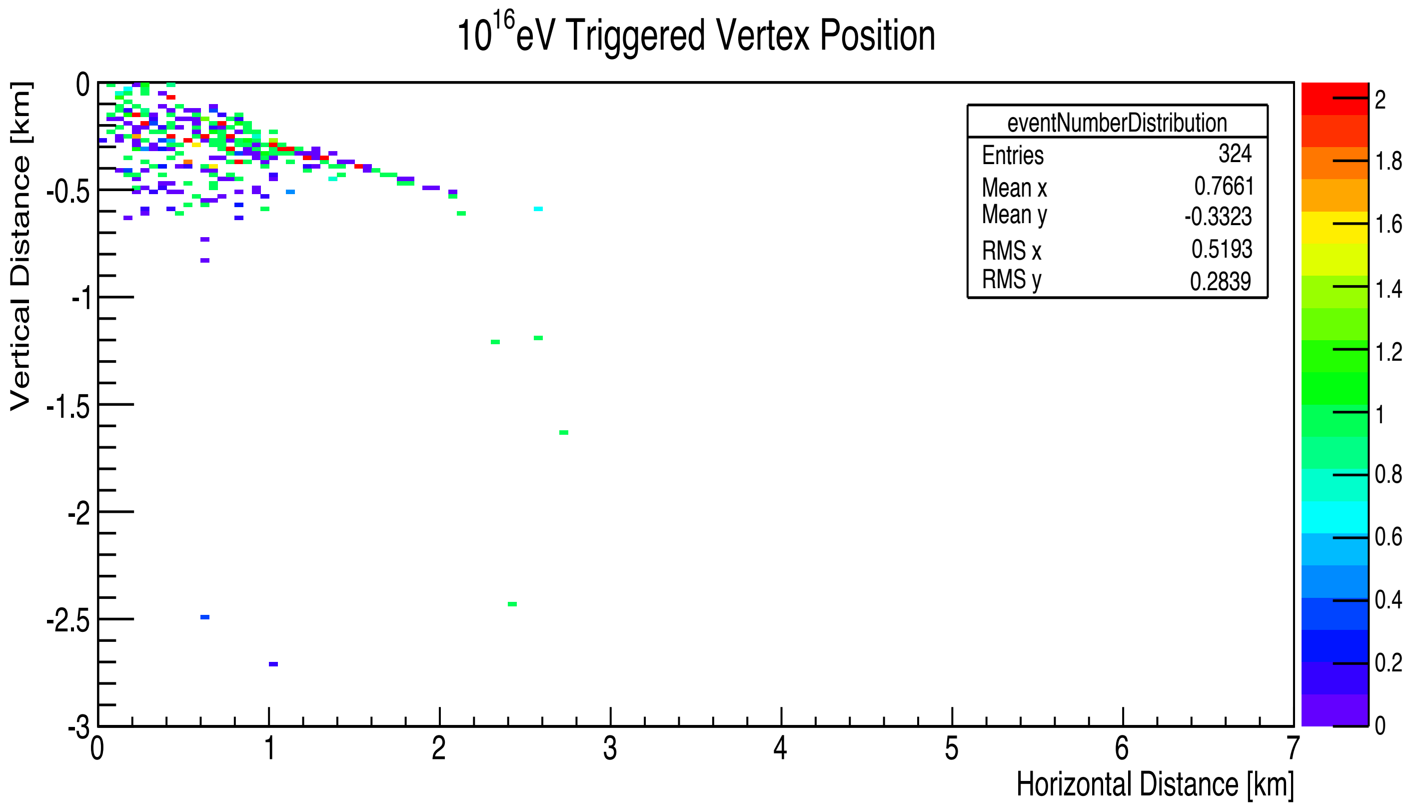
Depth and effective volume at South Pole.

Taking advantage of the deep ice.



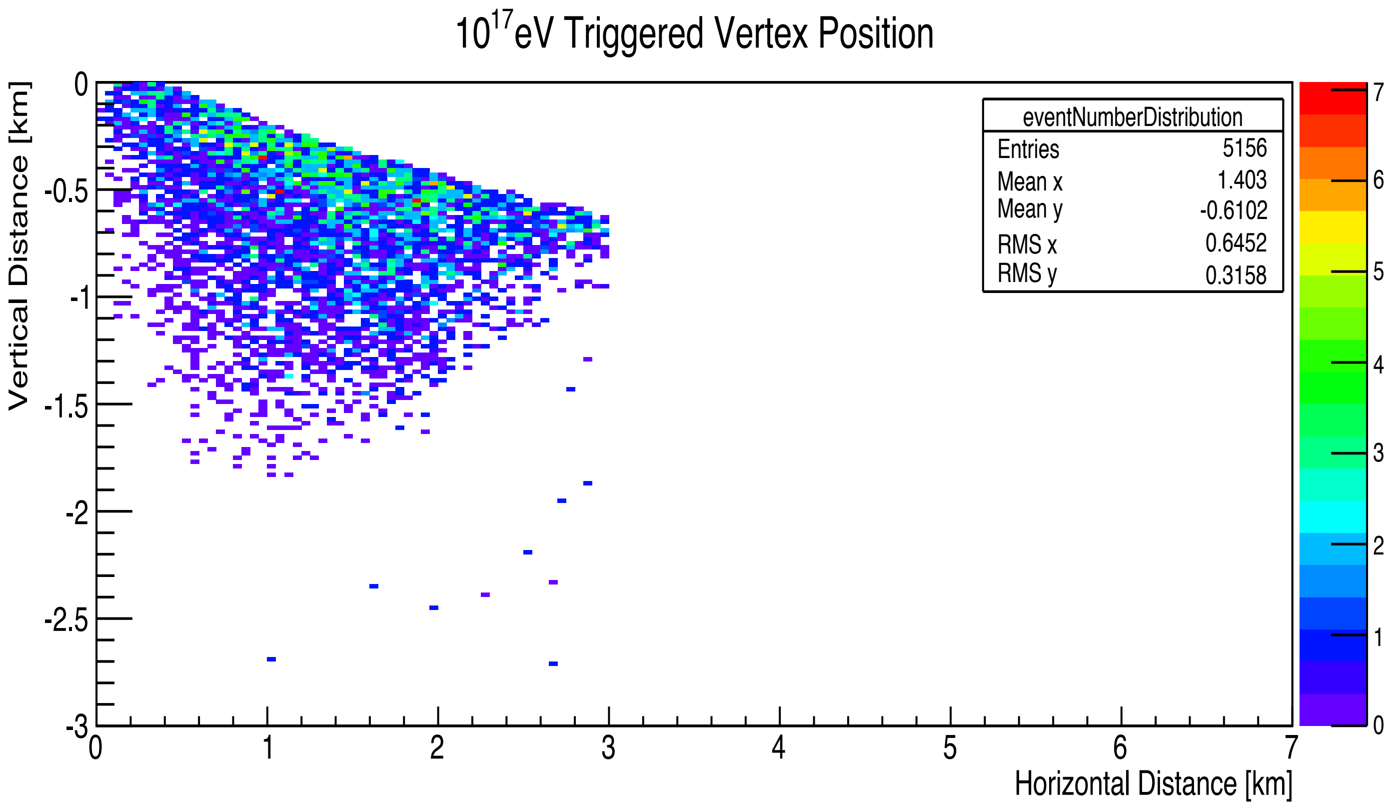
Depth and effective volume at South Pole.

Simulated events triggering
ARA station at 200m



Depth and effective volume at South Pole.

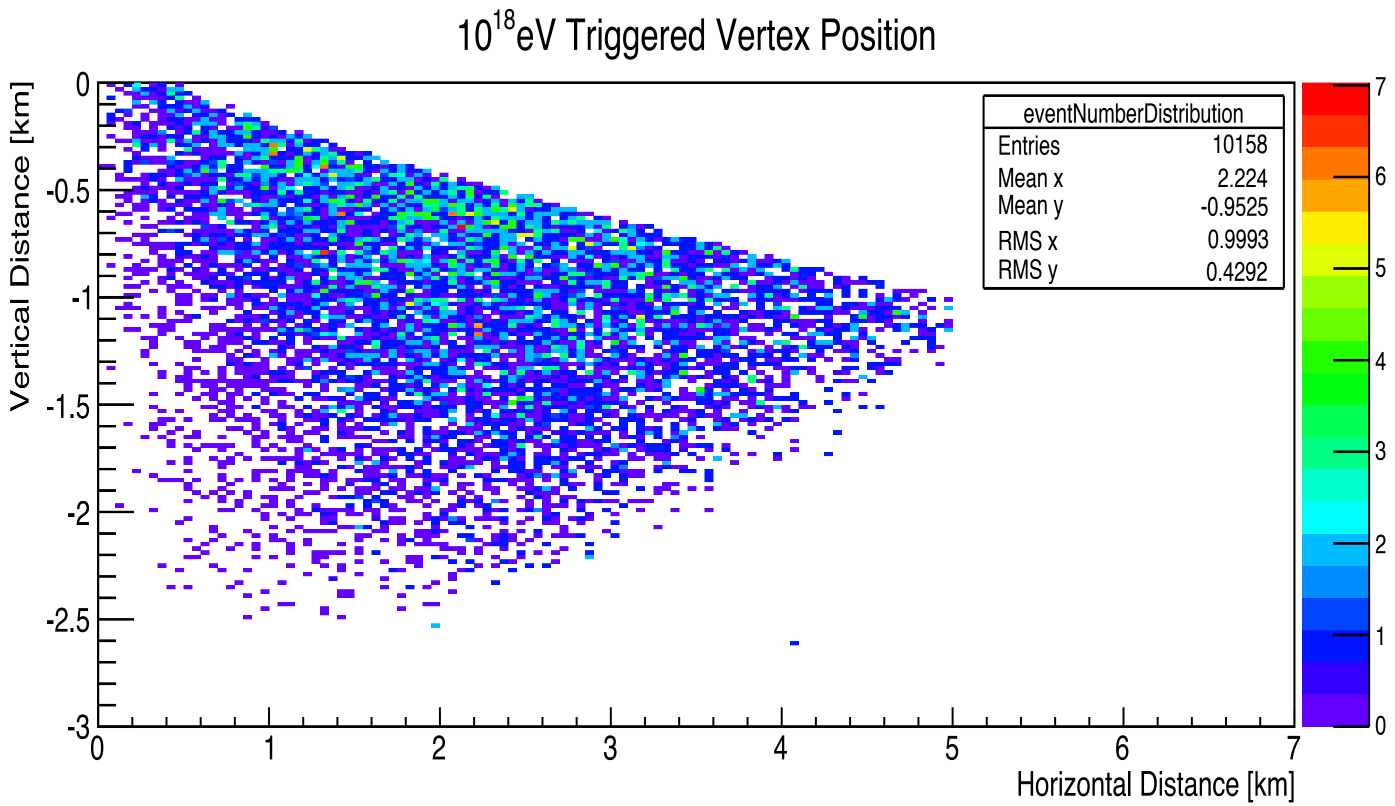
Simulated events triggering
ARA station at 200m



Plots:
ARASim,
Ming-Yuan Lu

Depth and effective volume at South Pole.

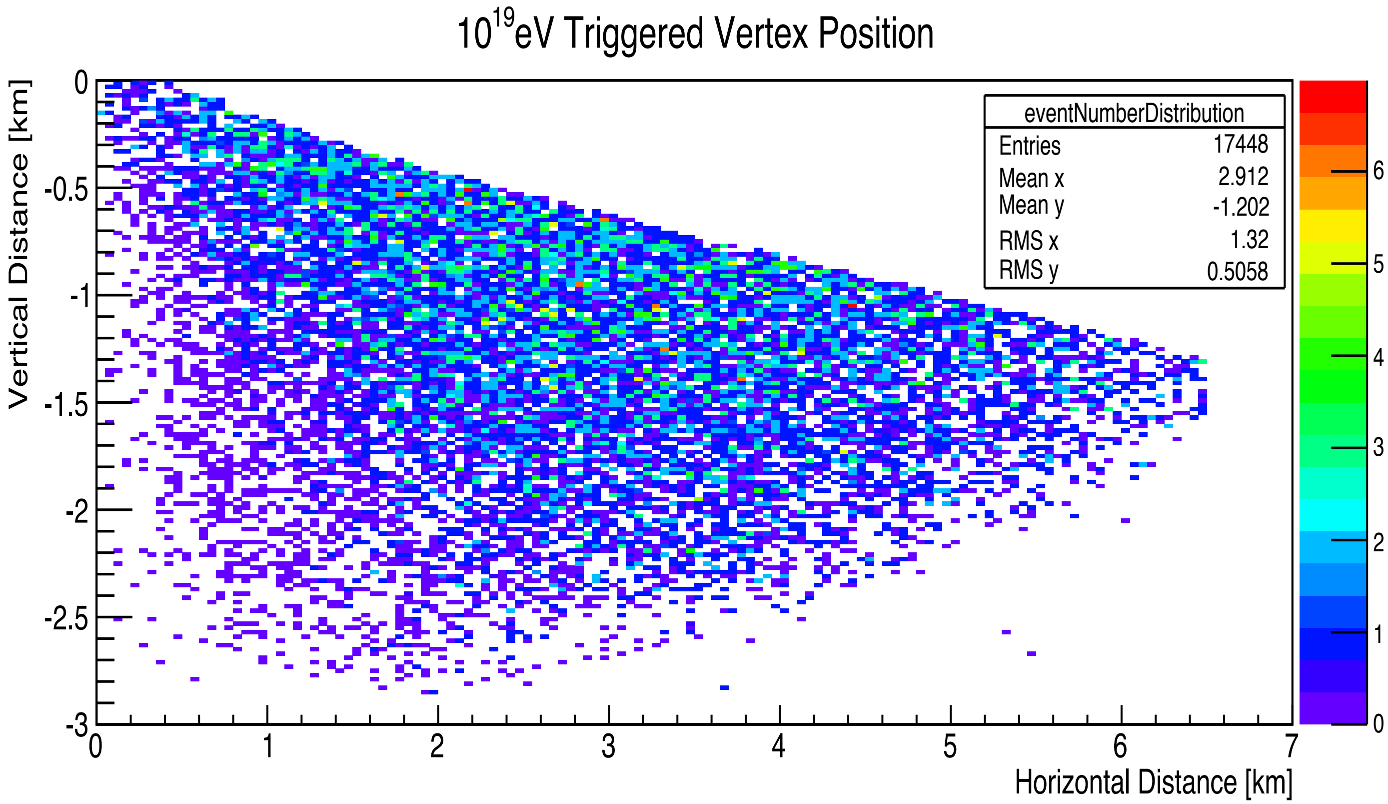
Simulated events triggering
ARA station at 200m



Plots:
ARASim,
Ming-Yuan Lu

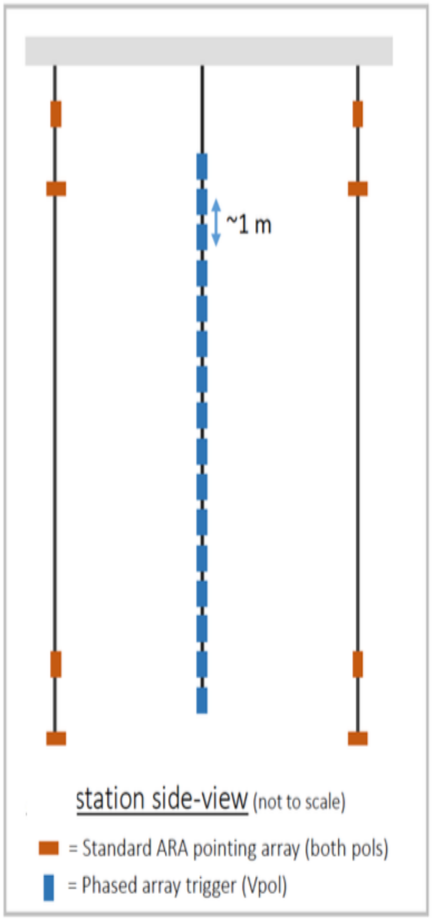
Depth and effective volume at South Pole.

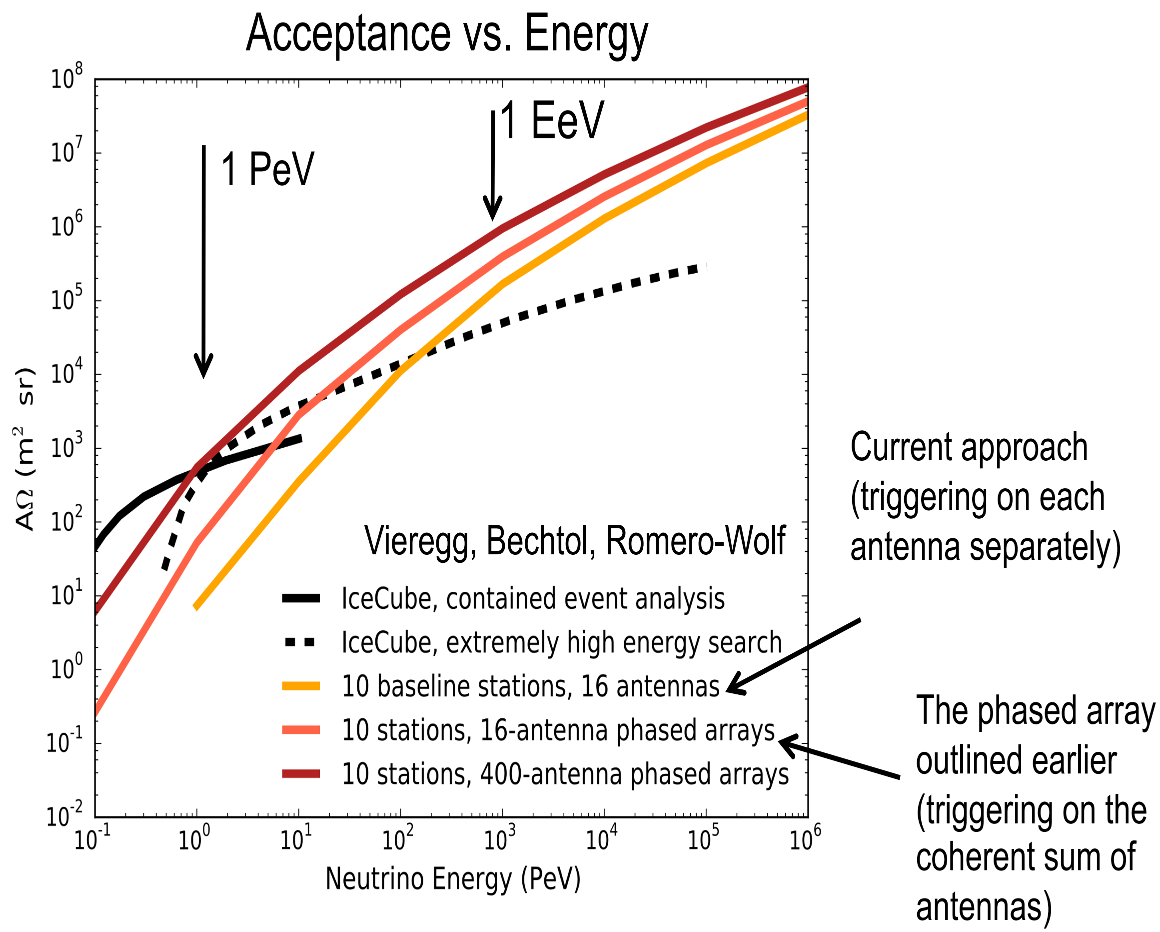
Simulated events triggering
ARA station at 200m



Plots:
ARASim,
Ming-Yuan Lu

R&D for a "phased array": Interferometric trigger
Upside potential by significant factors!





→ String of 16 antennas will be co-deployed with an ARA station next season.