Detection of high energy neutrinos by IceCube

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for The IceCube Collaboration

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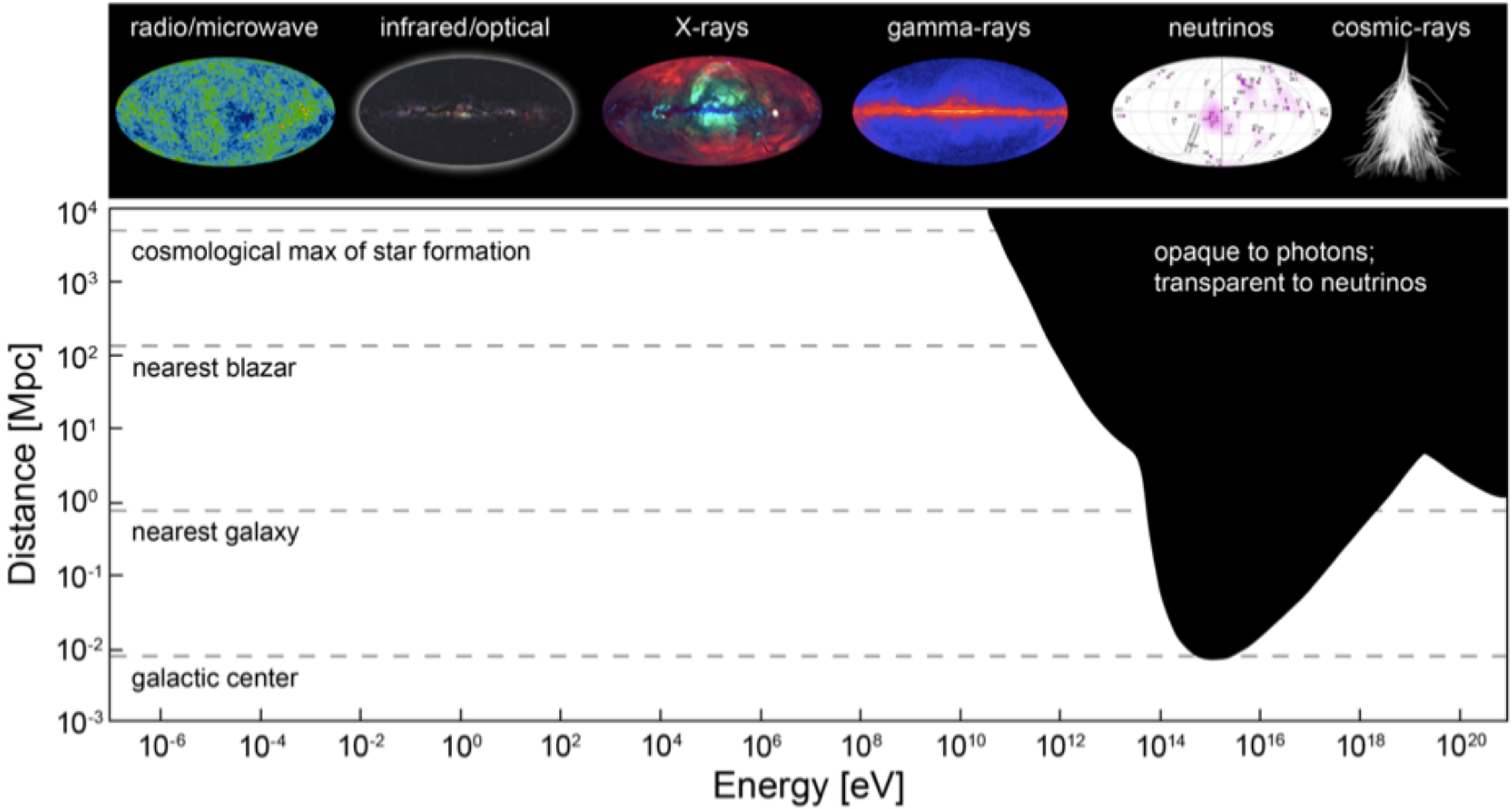
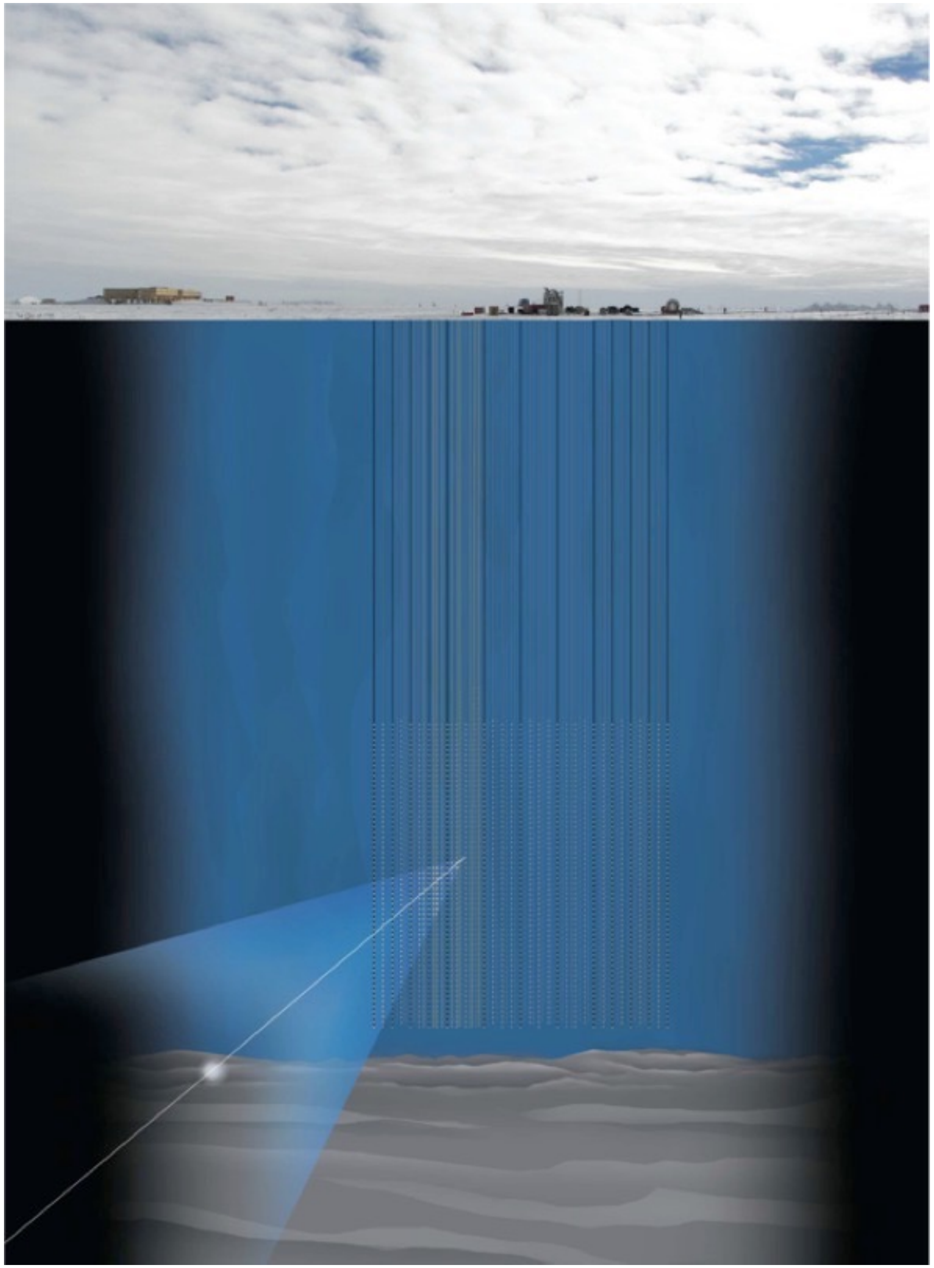
Outline:
- IceCube
- Cosmic neutrinos: evidence
- Implications
- IceCube-Gen2

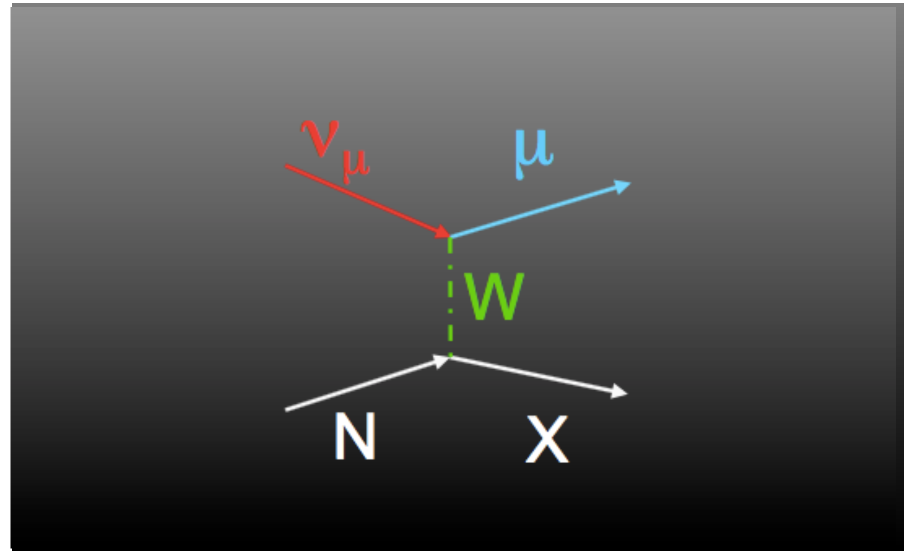
Exploring the Universe at all energies

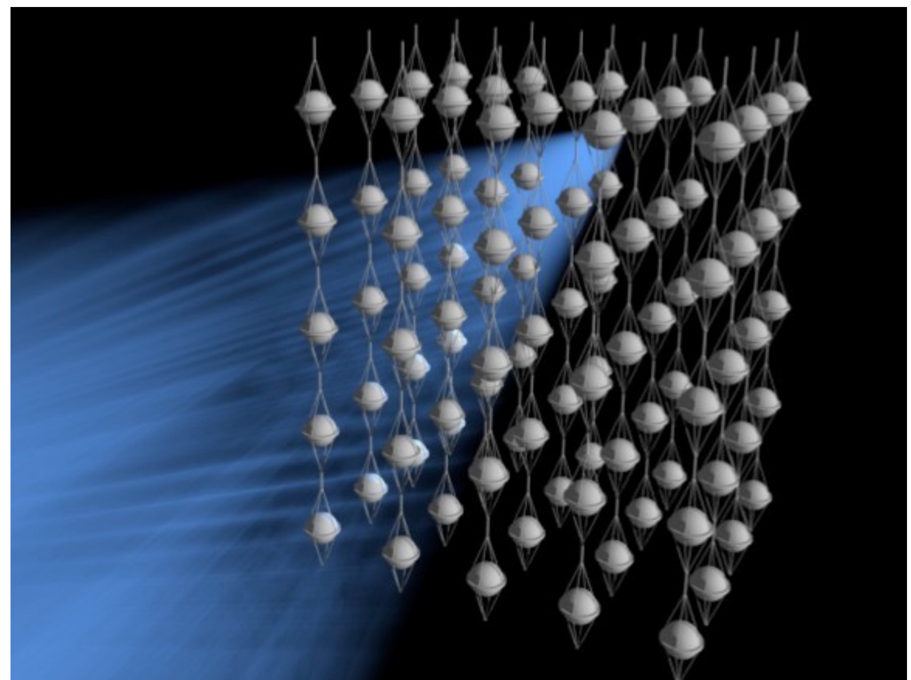


The Universe is opaque to EM radiation for 1⁄4 of the spectrum,
i.e. above 10-100 TeV where IceCube sees cosmic neutrinos.

High Energy Neutrino Detection Principle







IceCube Neutrino Observatory

86 strings

60 Optical Modules per string

5 160 total modules in Ice

1 km^3 = Gigaton instrumented volume

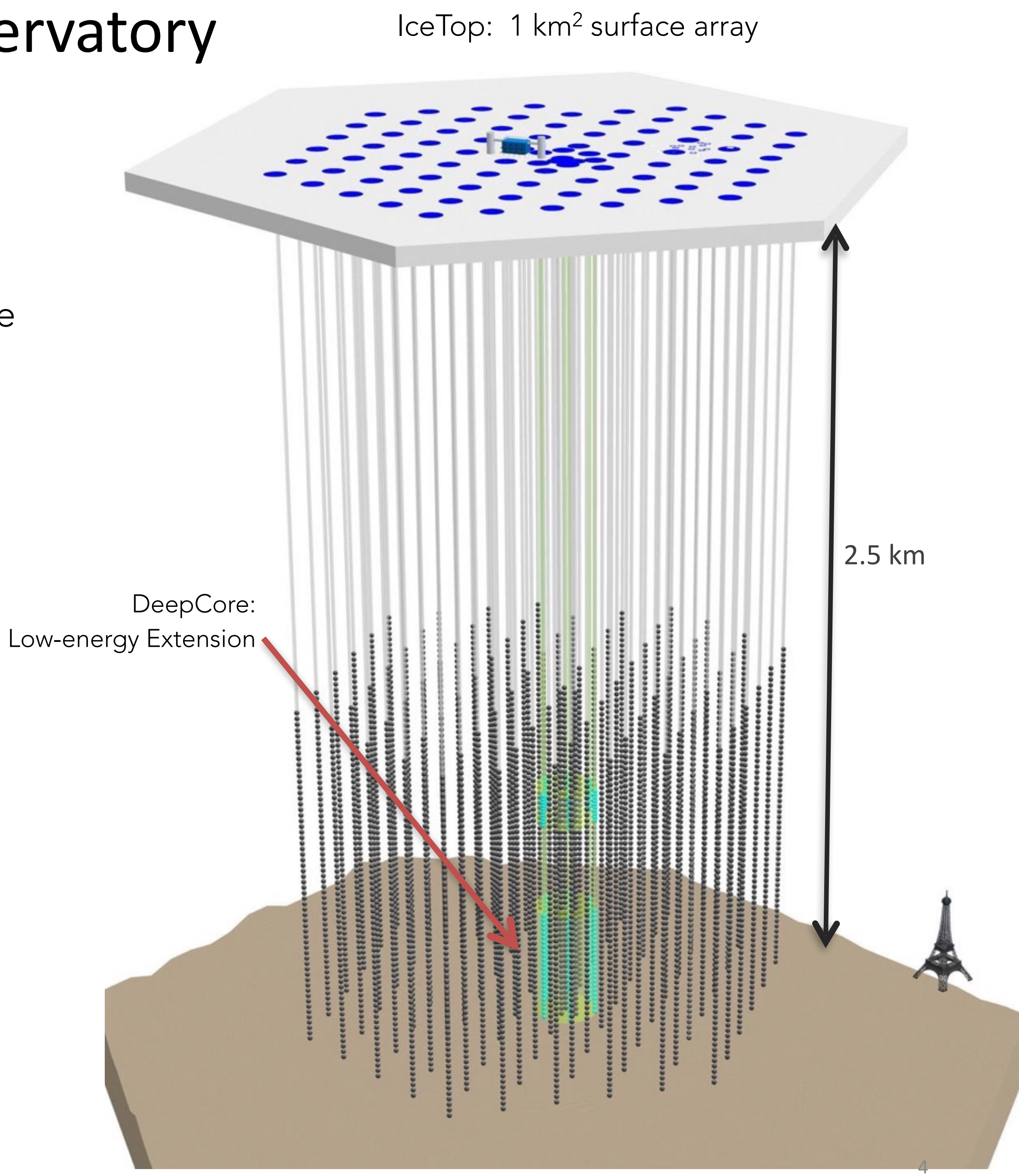
Began full operations May 2011

Highly stable operation.

Since 2014: livetime > 99%

clean-uptime 97-98%

(analysis-ready,
full-detector data)



Digital Optical Module (DOM)

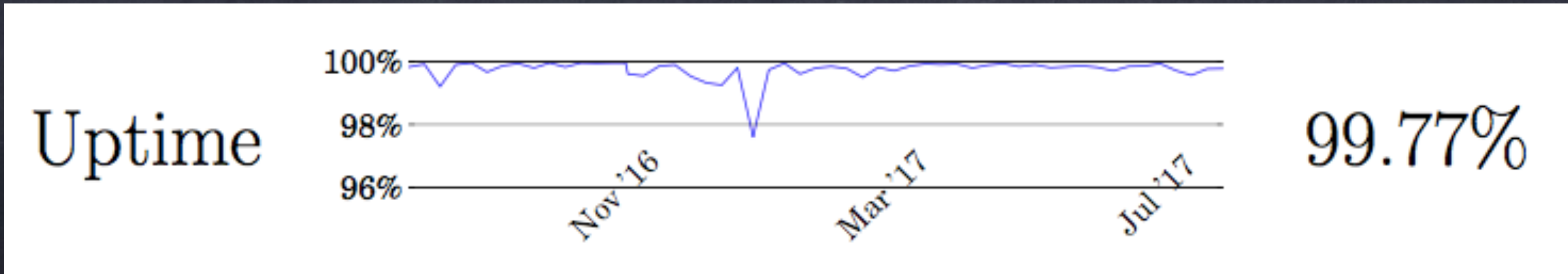
Light sensor is housed inside a pressure resistant (10000 psi) glass sphere.
Each sensor is basically an independent detector synchronized in time to all others at 2 ns precision.

PMT: 10 inch Hamamatsu

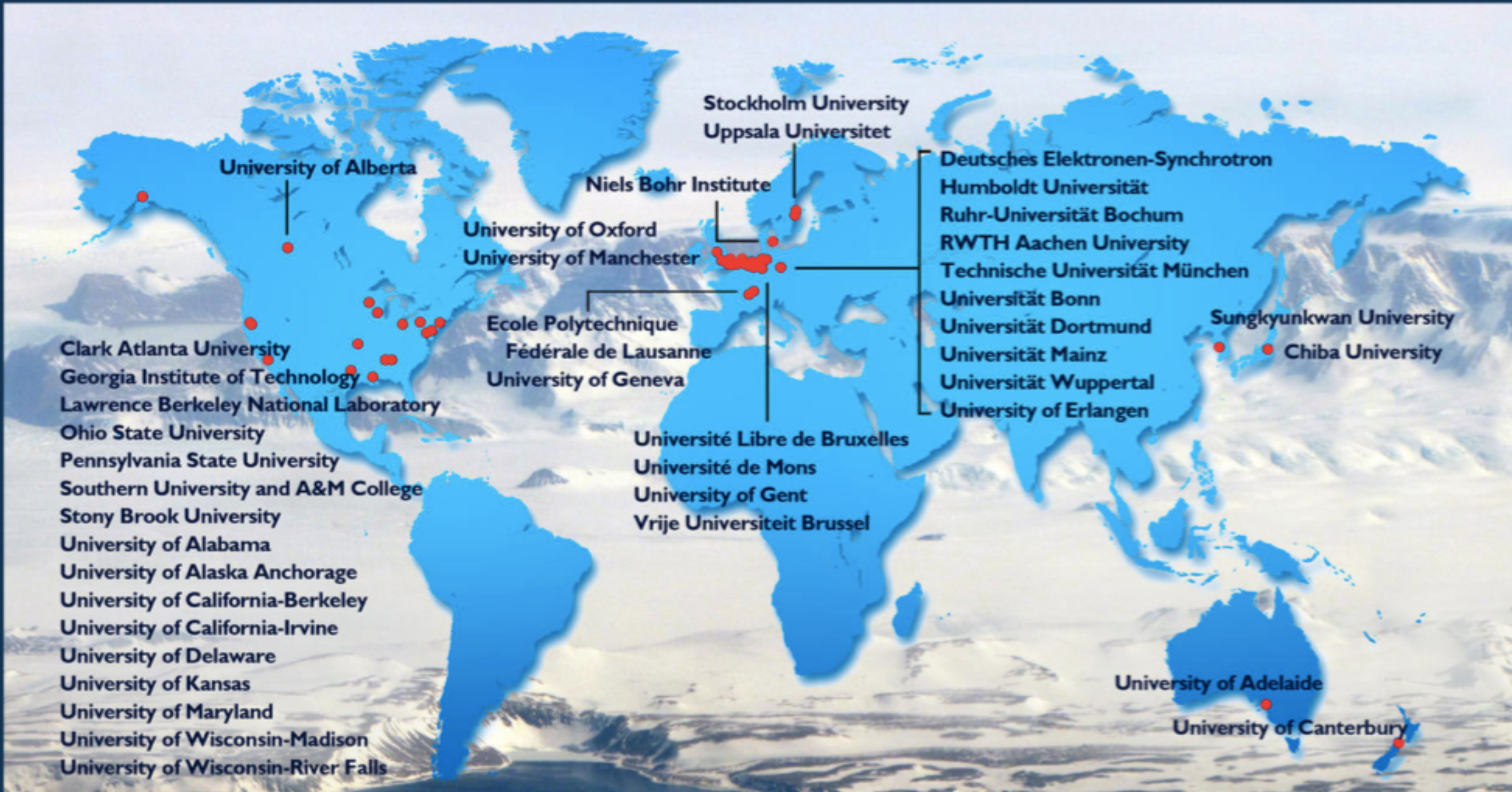
Digitizing electronics records waveforms.

5160 DOMs
in deep ice
13 in diameter

High reliabillity an detector uptime:



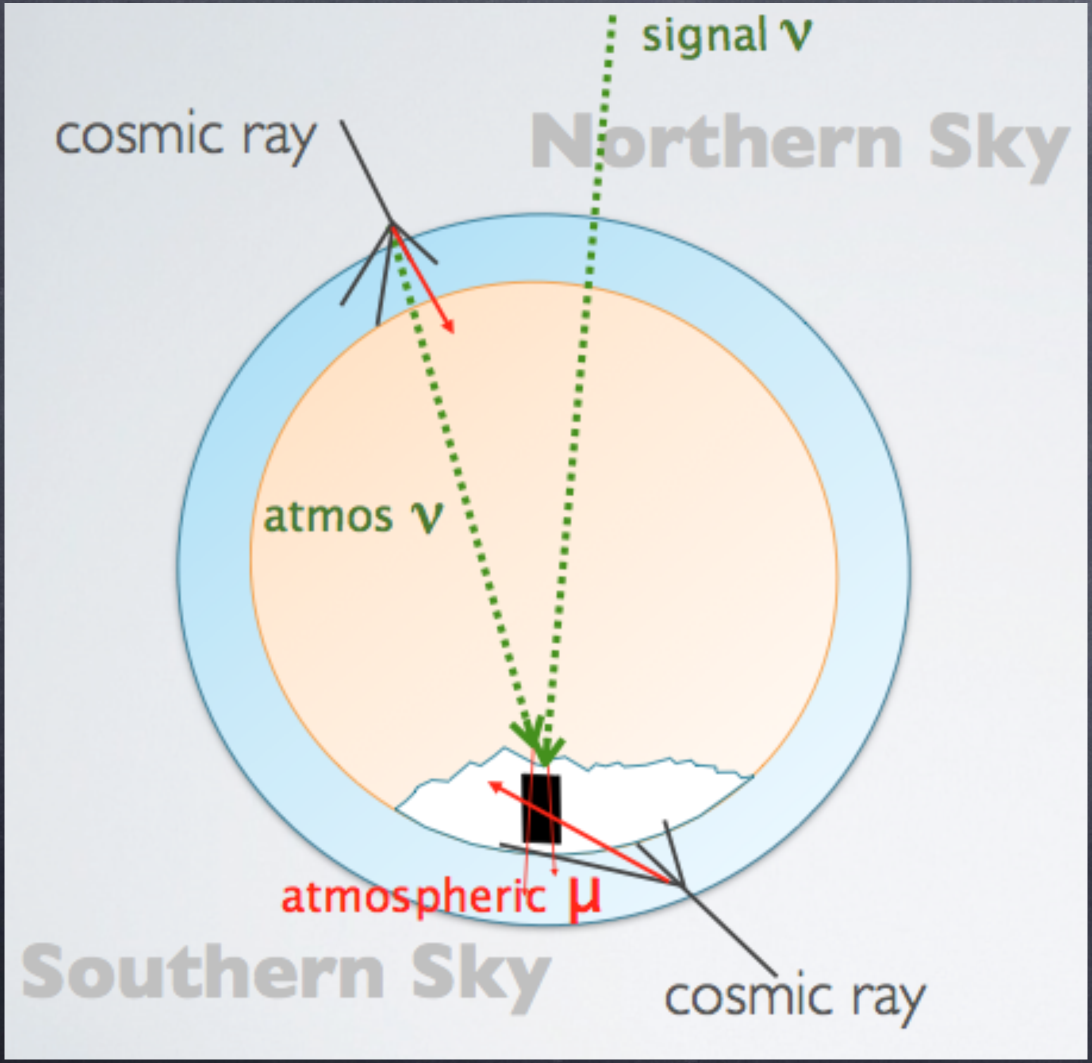
The IceCube Collaboration



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)

Data



Events/year

- Cosmic Ray muons:

  2*10^11

- "Atmospheric" neutrinos: ~100,000

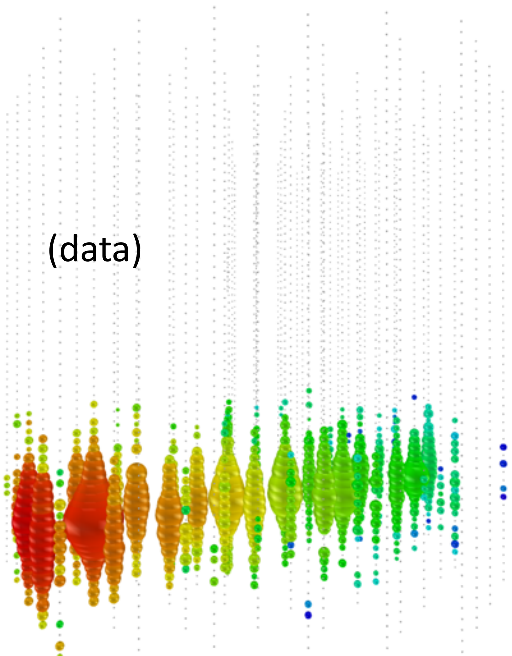
- Cosmic neutrinos:

  ~100

Types of events and interactions

Charged-current ν_μ

(data)

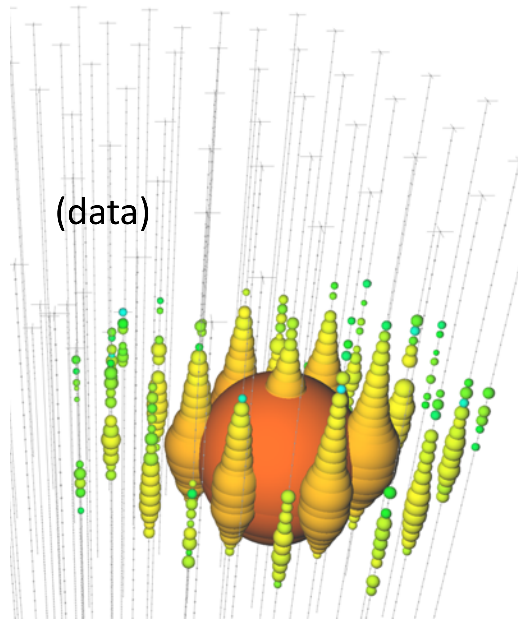


Up-going (throughgoing) track

Factor of ~2 energy resolution
~ 0.5° angular resolution

Neutral-current / ν_e

(data)

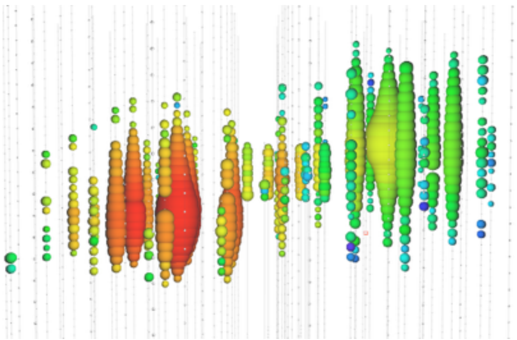


Isolated energy deposition (cascade) with no track

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

Charged-current ν_τ

(simulation)



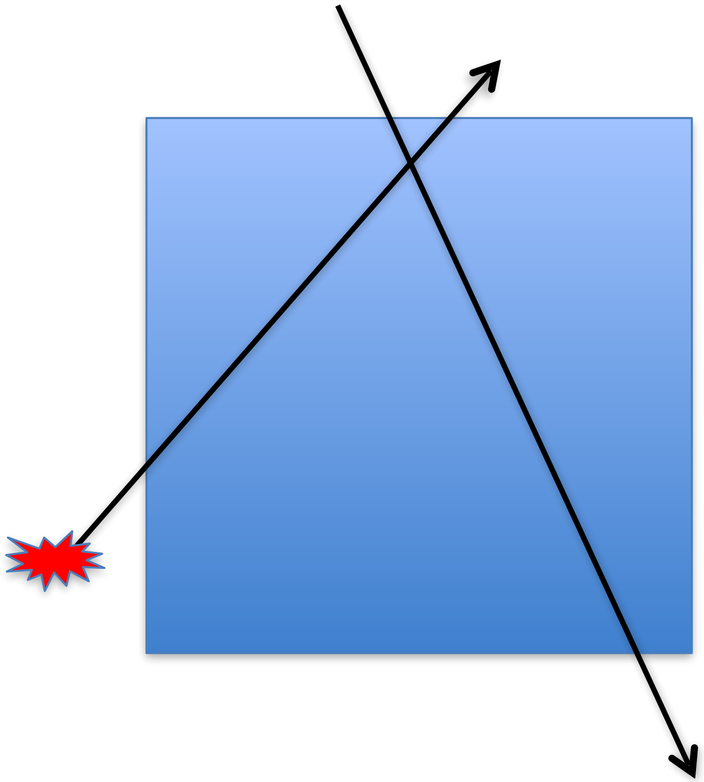
"Double-bang"

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

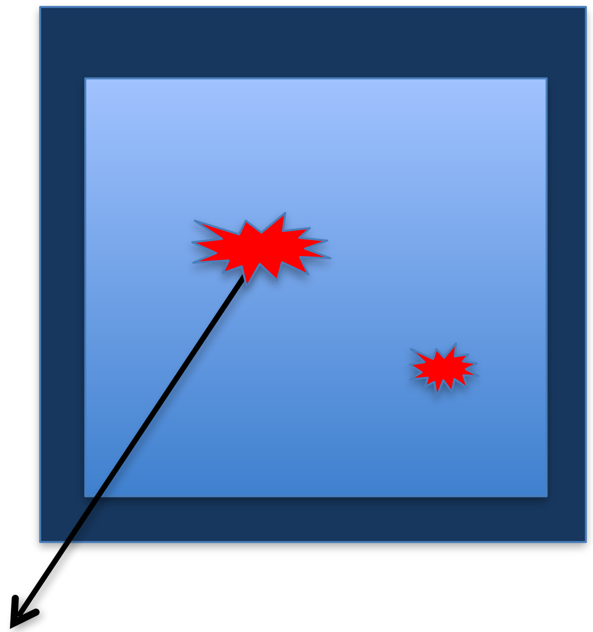
ID: above 1 PeV

Event selection strategies

Throughgoing muons

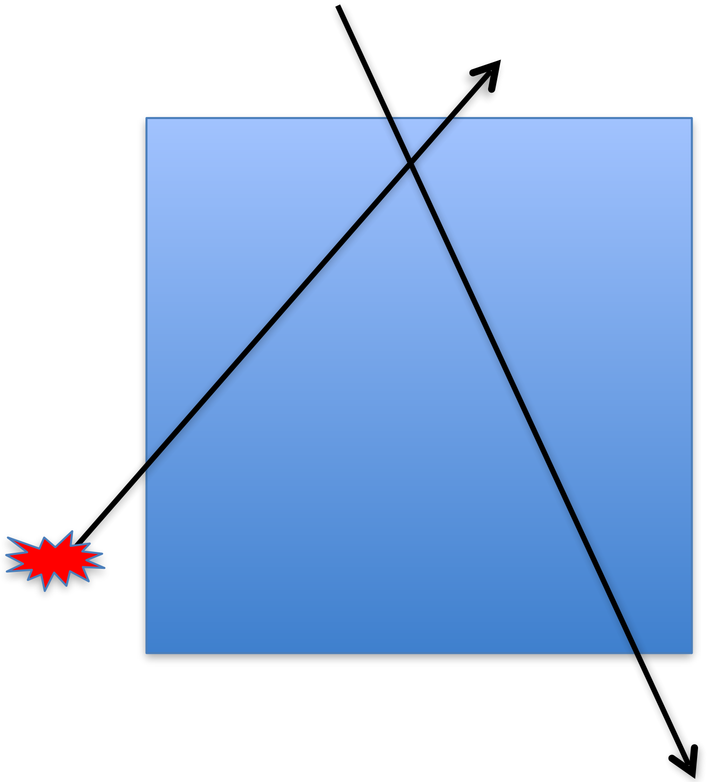


Events with contained vertex

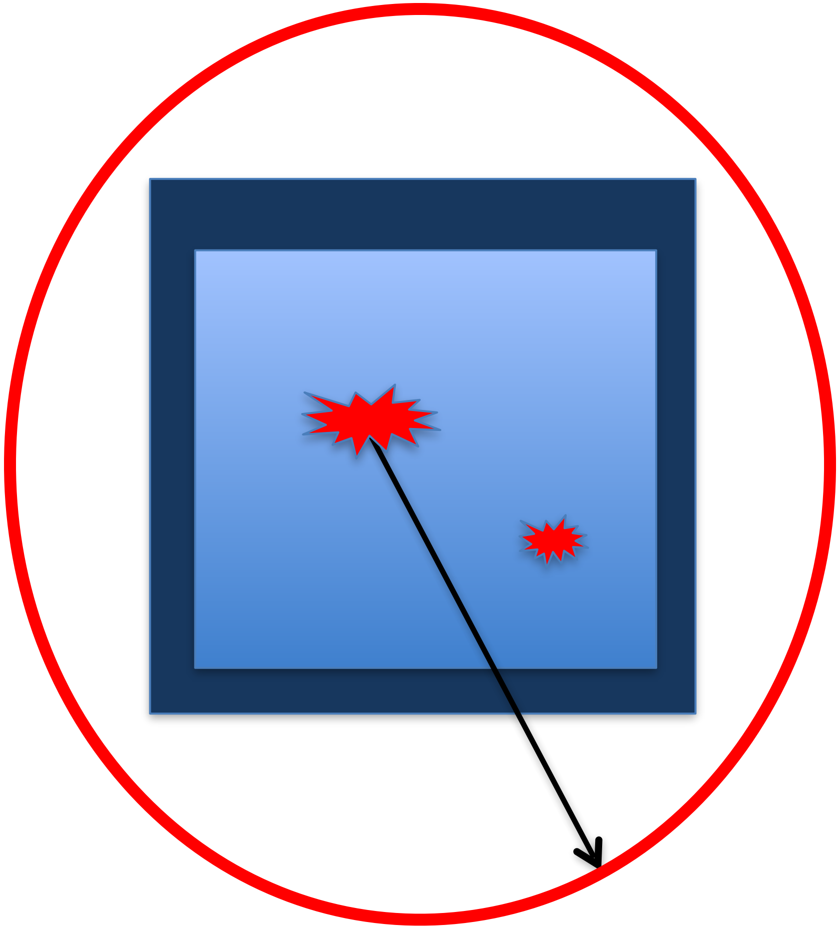


Event selection strategies

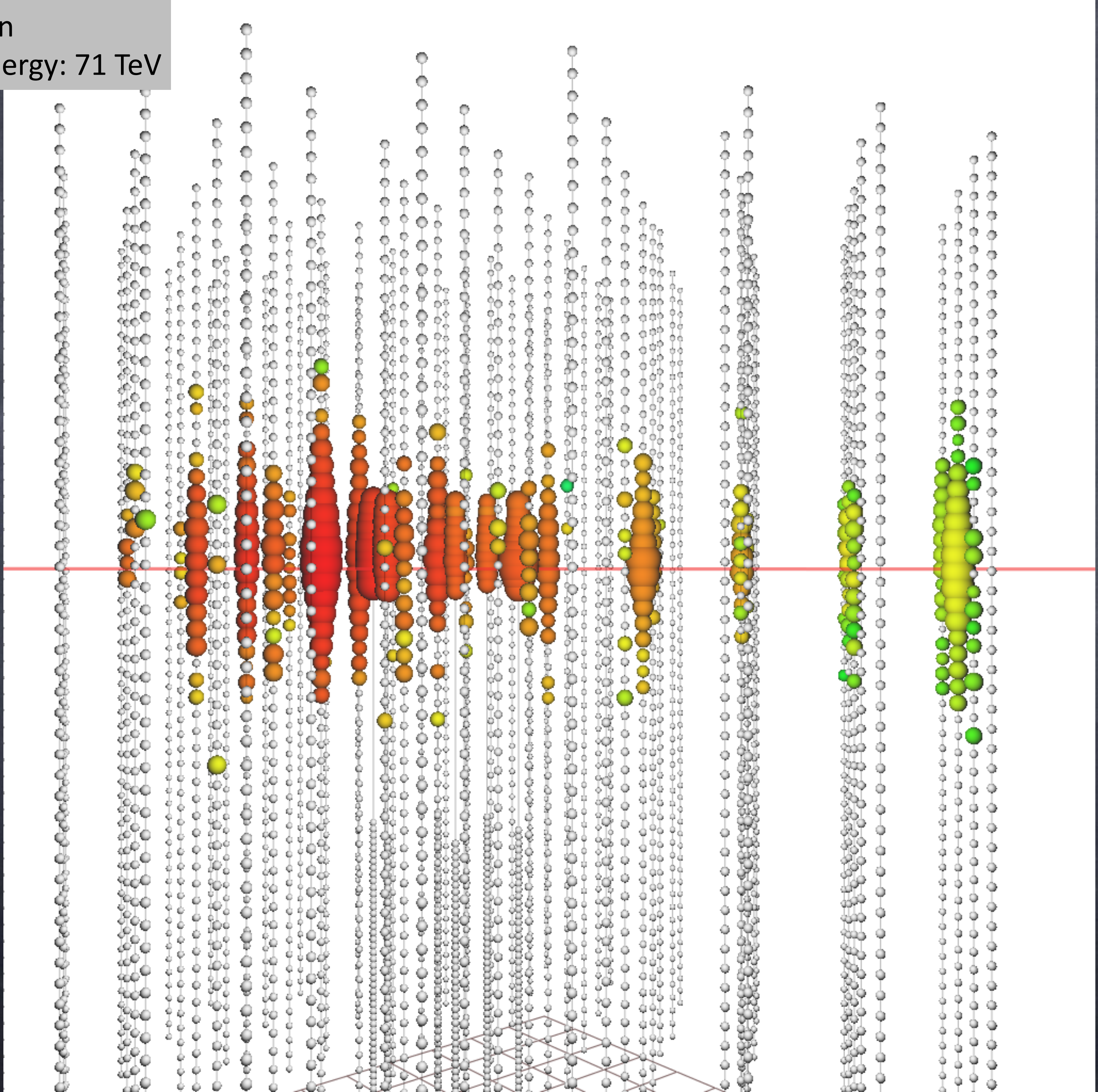
Throughgoing muons



Events with contained vertex



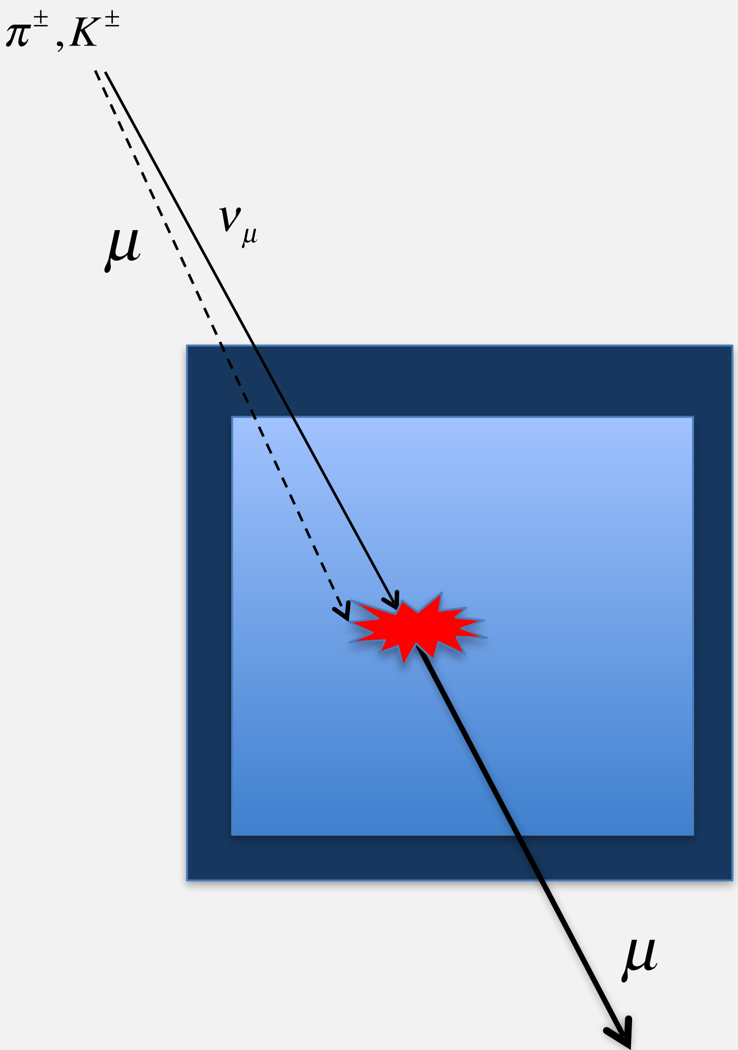
Starting muon
Deposited energy: 71 TeV



Neutrino self veto –
Rejecting cosmic ray muons AND atmospheric neutrinos

for zenith angles < 60° and above some energy (10 to 30 TeV)

- "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.



Works also for electron neutrinos.

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

T. Gaisser, K. Jero, AK and J. v. Santen
arXiv:1405.0525

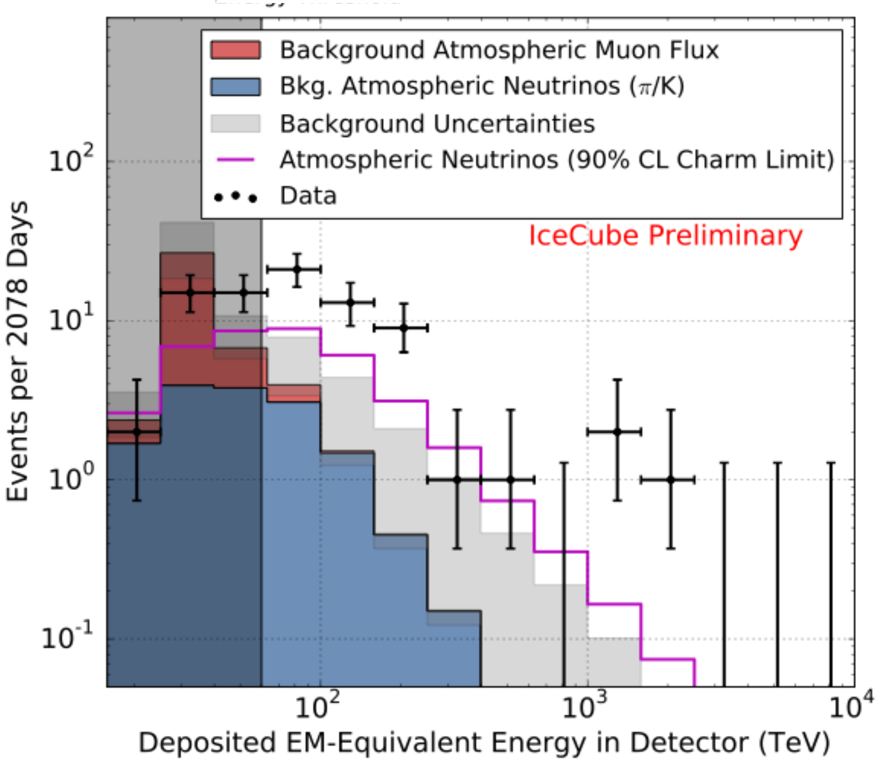
High energy events with contained vertex: 4 → 6 years

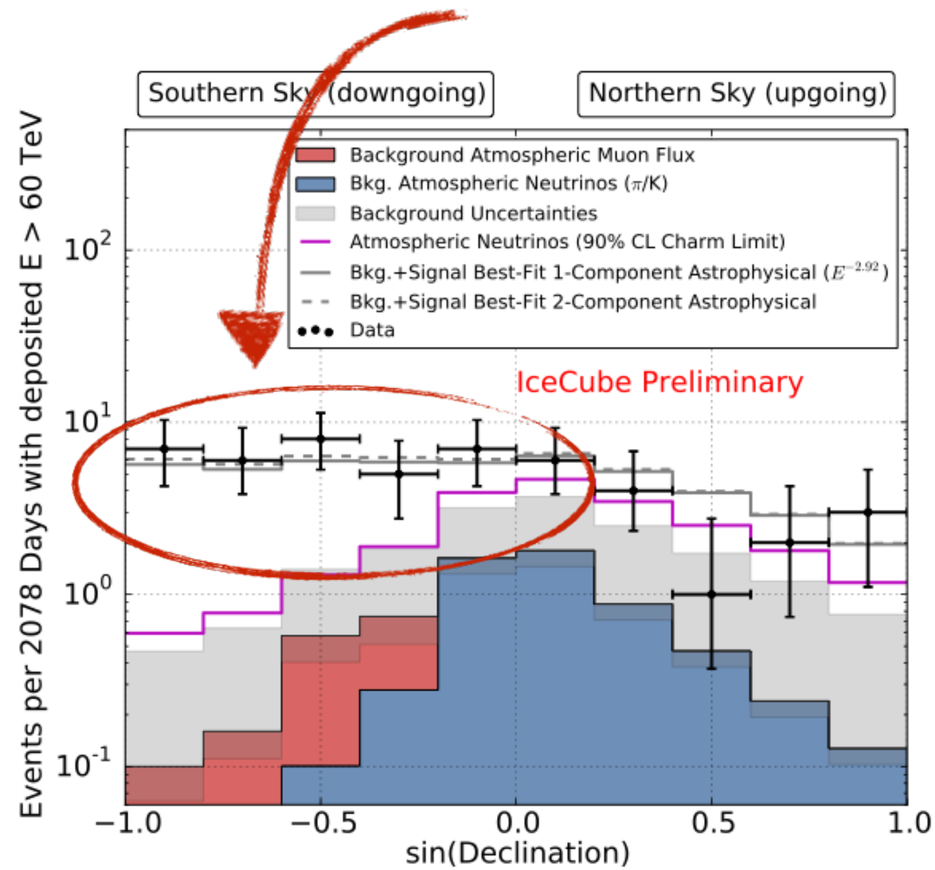
- **82 events in 6 years** (54 in 4 years)
- ~ half (41) are expected to be bkg (atm. muons and atm. neutrinos)
- Astrophysical fit (and its significance) depends on **number, zenith angle, and energy**

6 years (ICRC 2017)

Zenith distribution incompatible with atmospheric origin

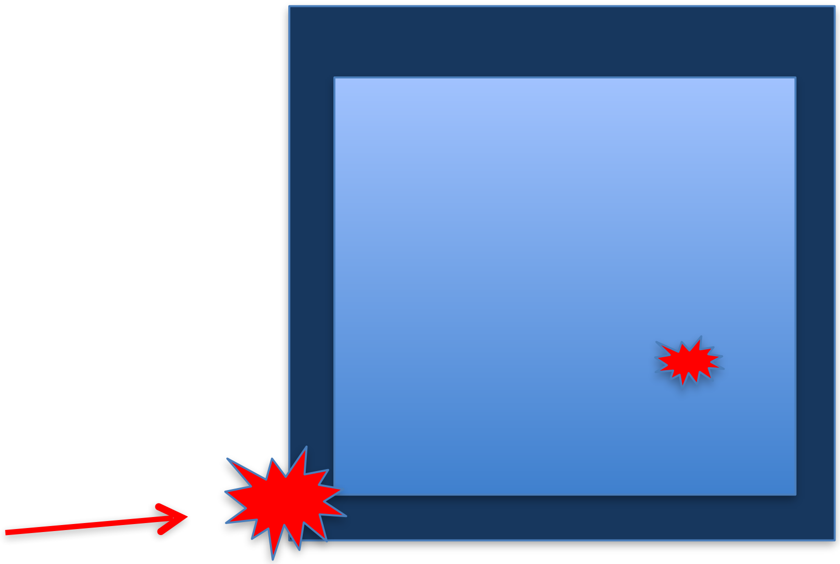
Energy distribution





Adding partially contained events at E > 1PeV

Events with
PARTIALLY contained vertex

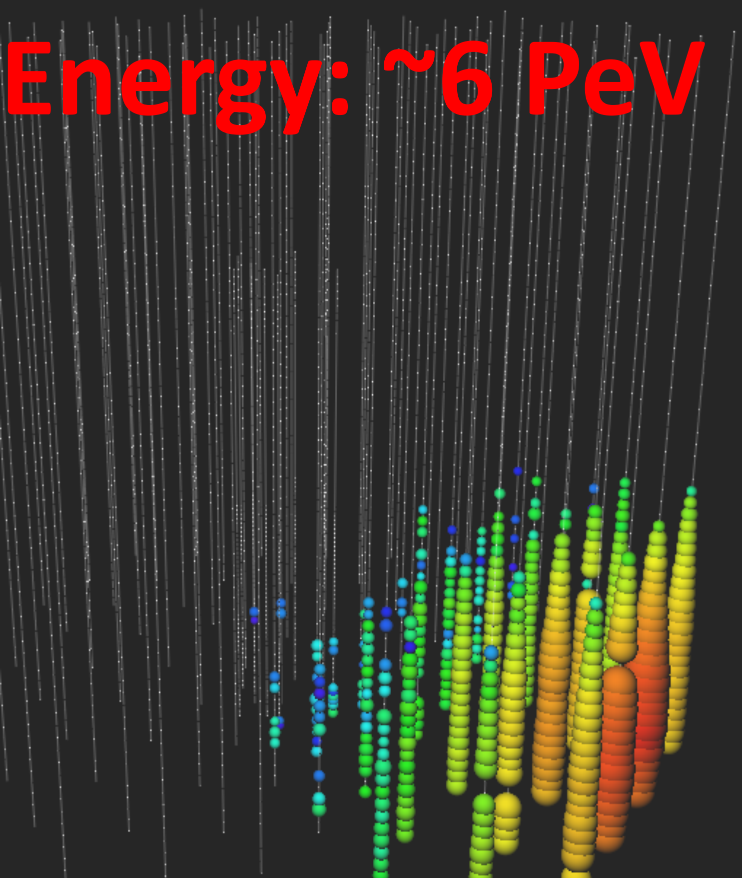


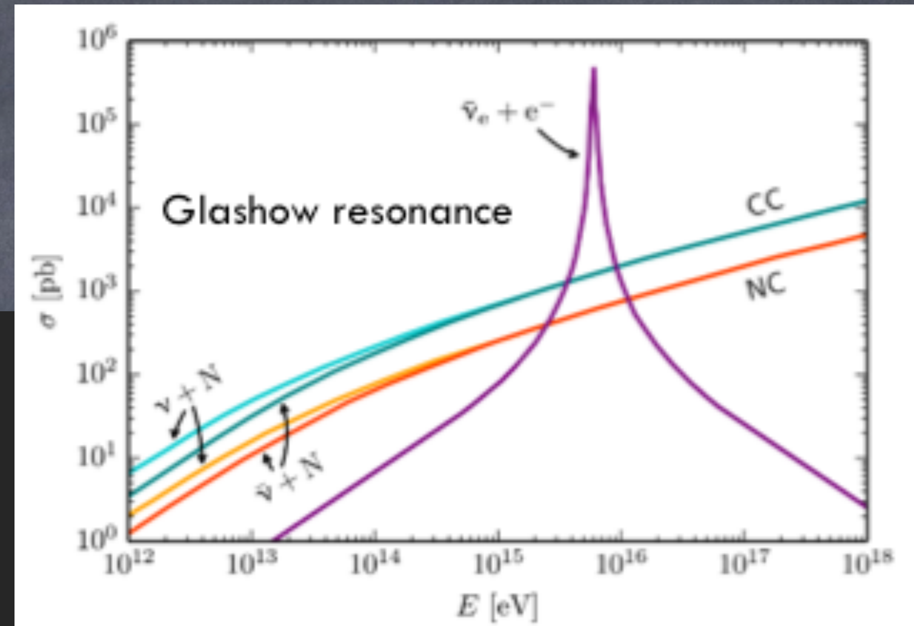
The highest energy neutrino?

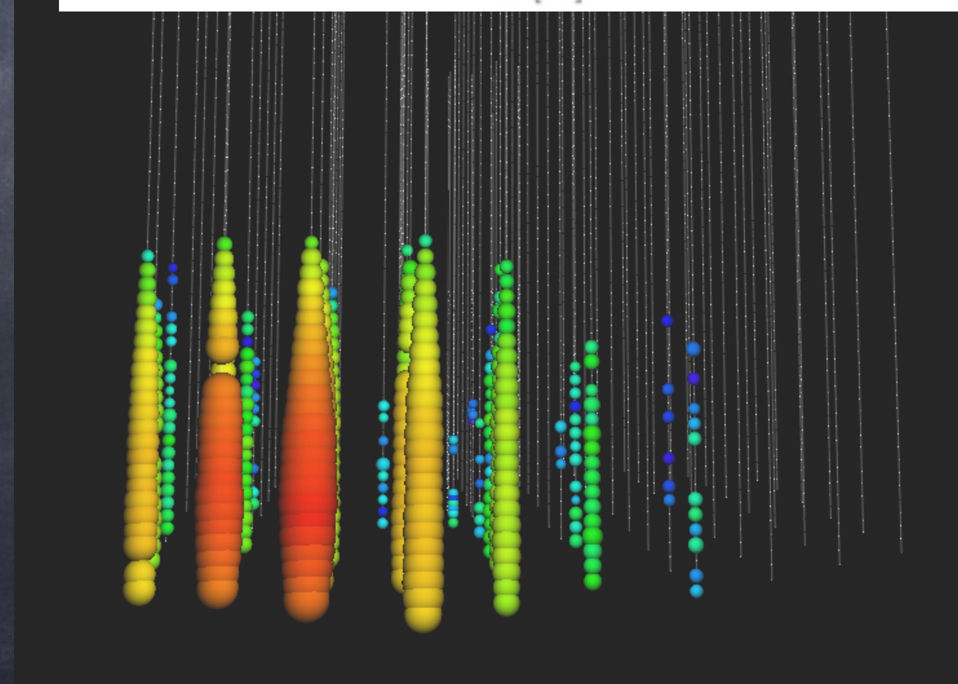
Interesting event found in expanded search

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

Energy: ~6 PeV



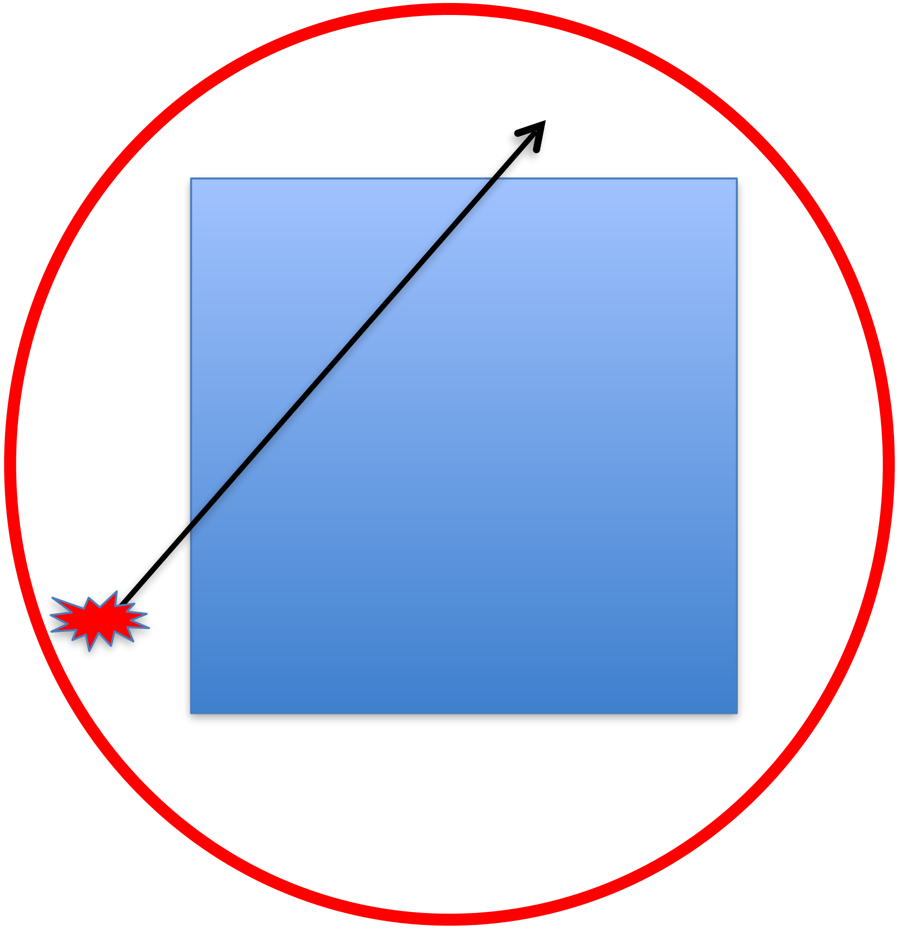




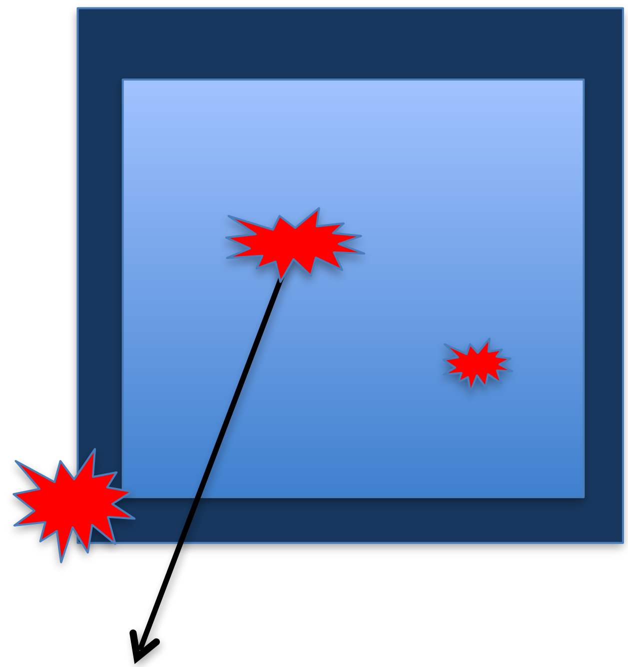
Ref: ICRC 2017, L. Lu (IceCube C.)

Event selection strategies

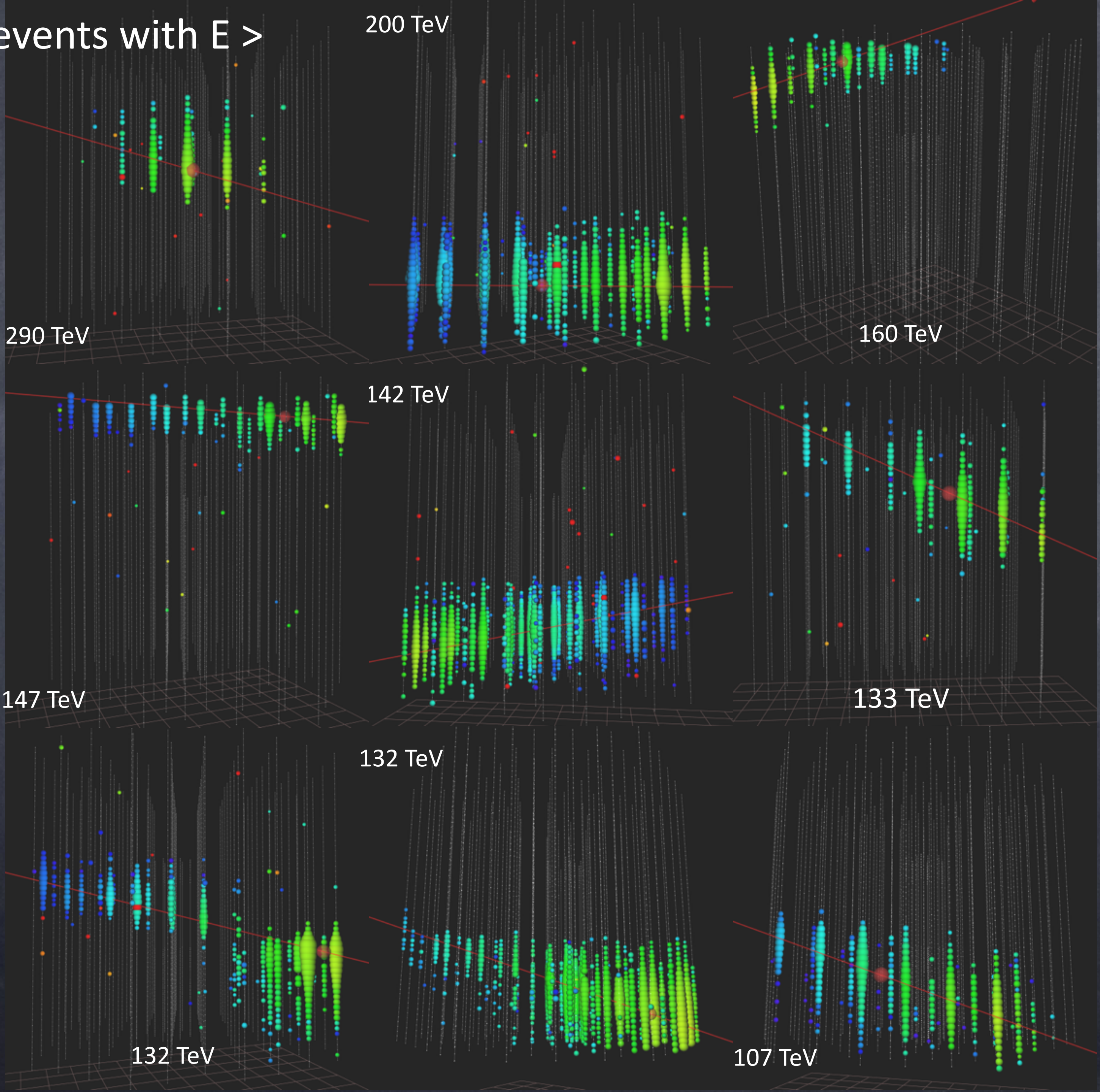
Throughgoing muons,
upgoing



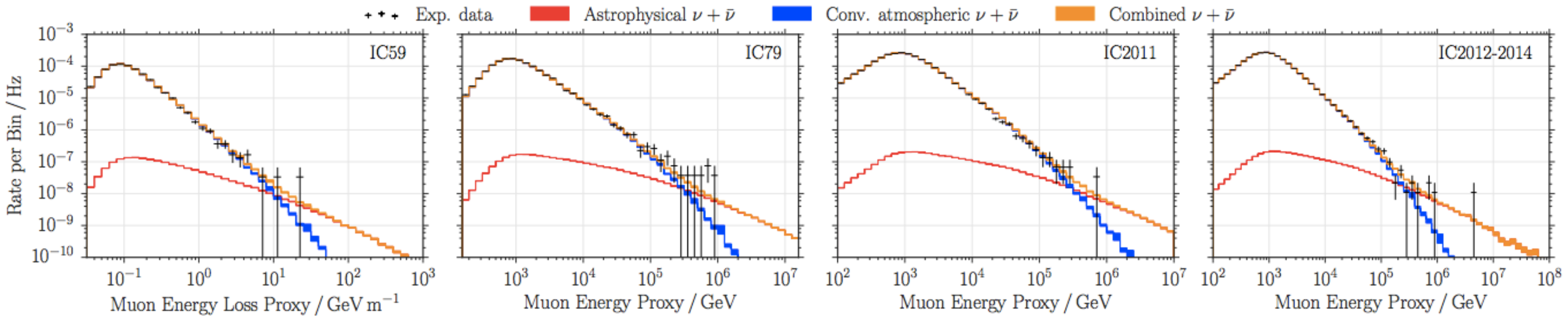
Events with contained vertex



Example events with E > 100 TeV



Diffuse Flux with upgoing muon neutrinos (6 years)

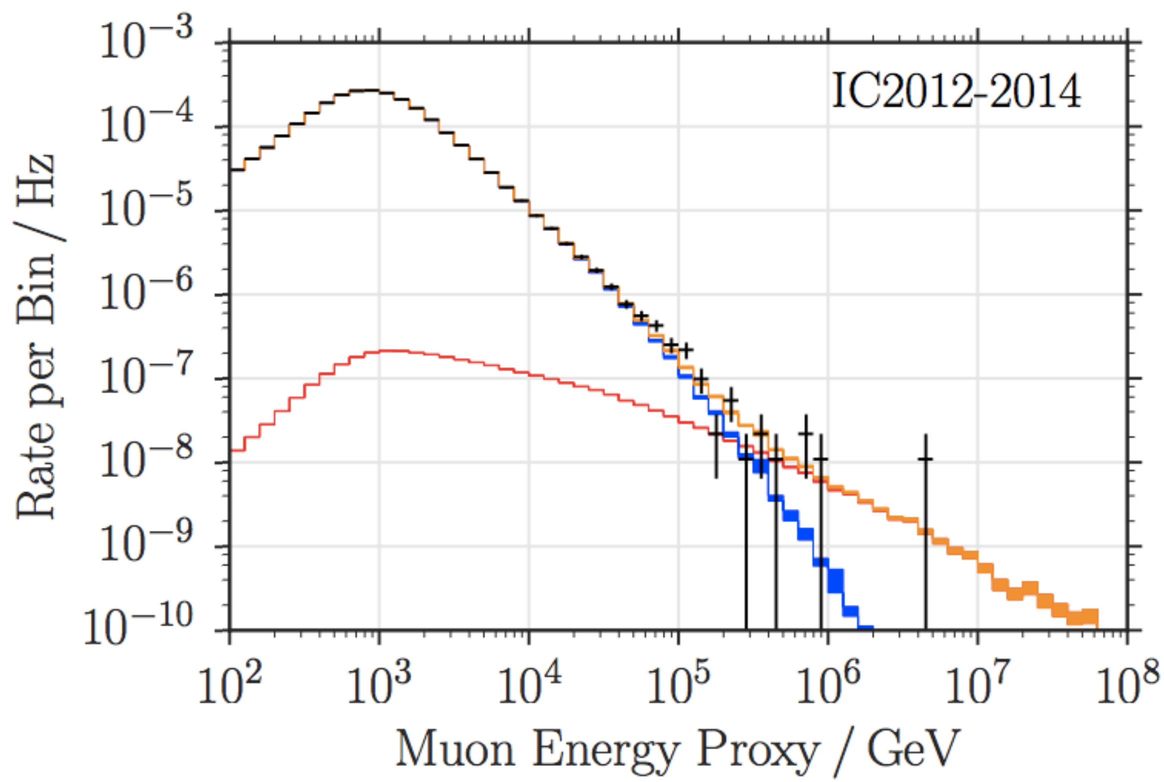


Upgoing or Horizontal track = Earth-filtered

350 000 events in 6-year analysis

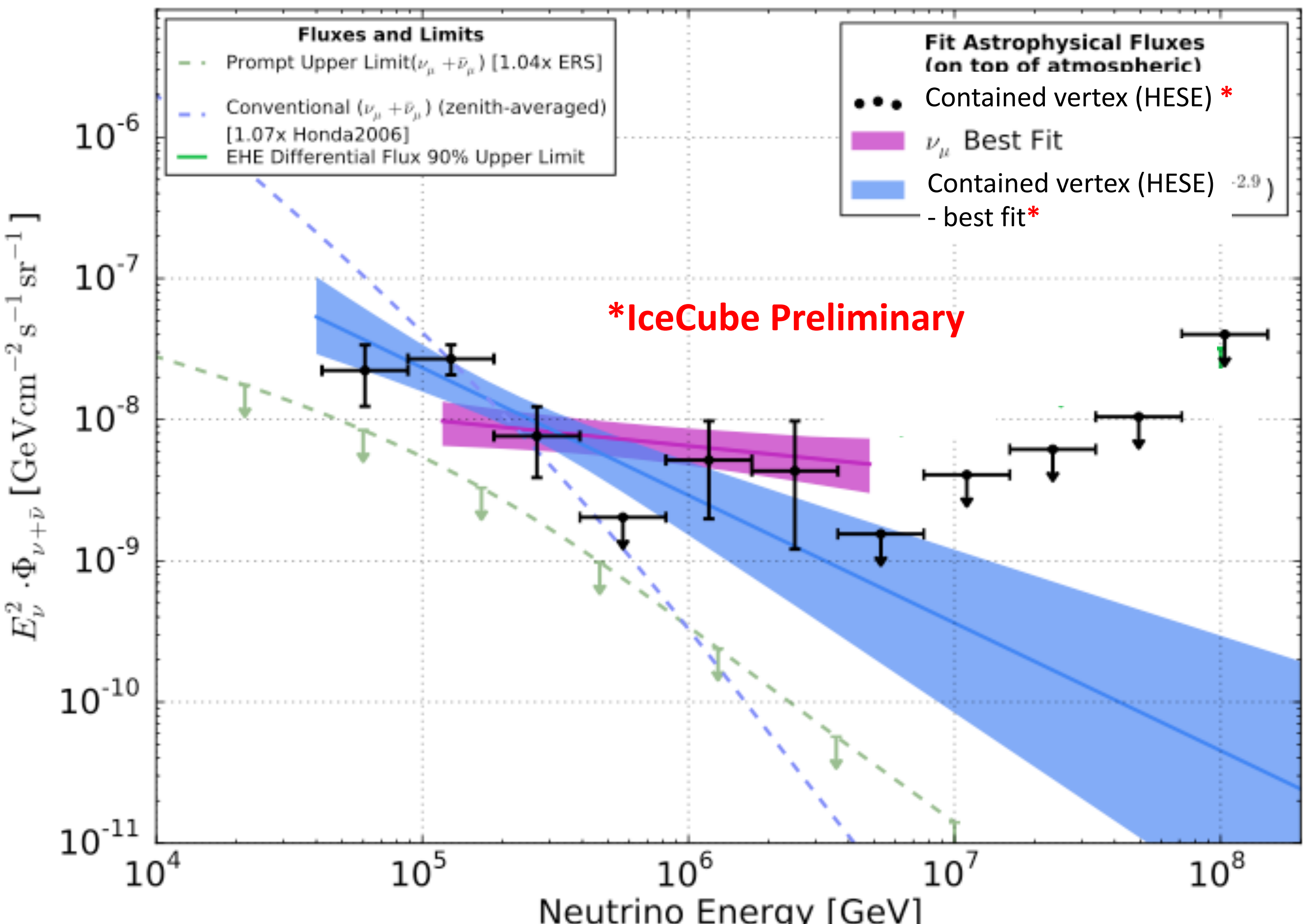
Estimated 99.7% pure muon-neutrino sample

5.6σ for astrophysical flux



- Astrophys. J. 833 (2016) 1, 3
- also Haack (IceCube C.), ICRC 2017

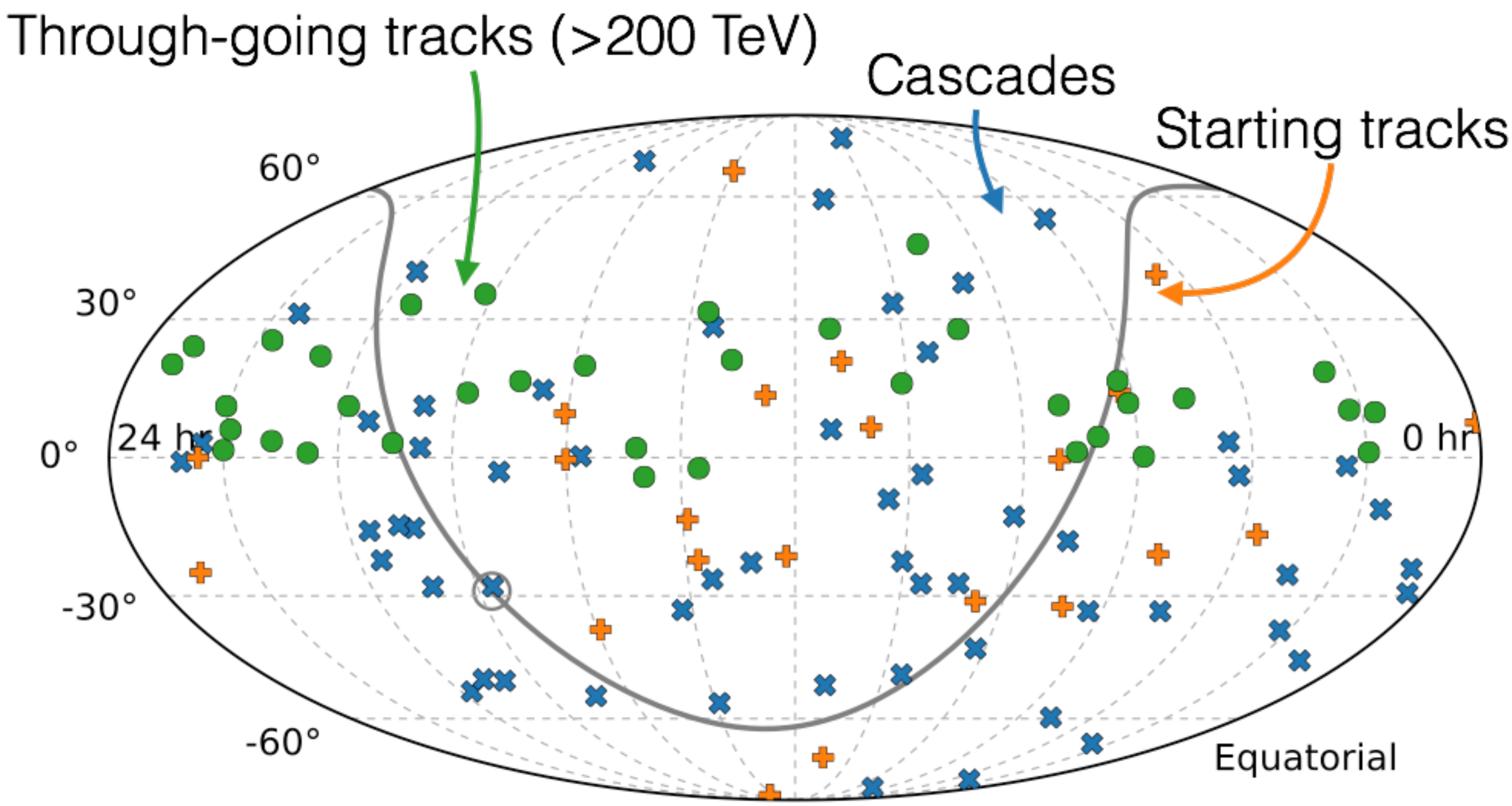
Energy spectrum with these event samples:
1.) upgoing muon neutrinos 2.) contained vertex events



ICRC 2017: Kopper, Wandkowsky for IceCube C.
ICRC 2017: Haack for IceCube C.

Events with energy > 200 TeV
(more than 50% of events are astrophysical)

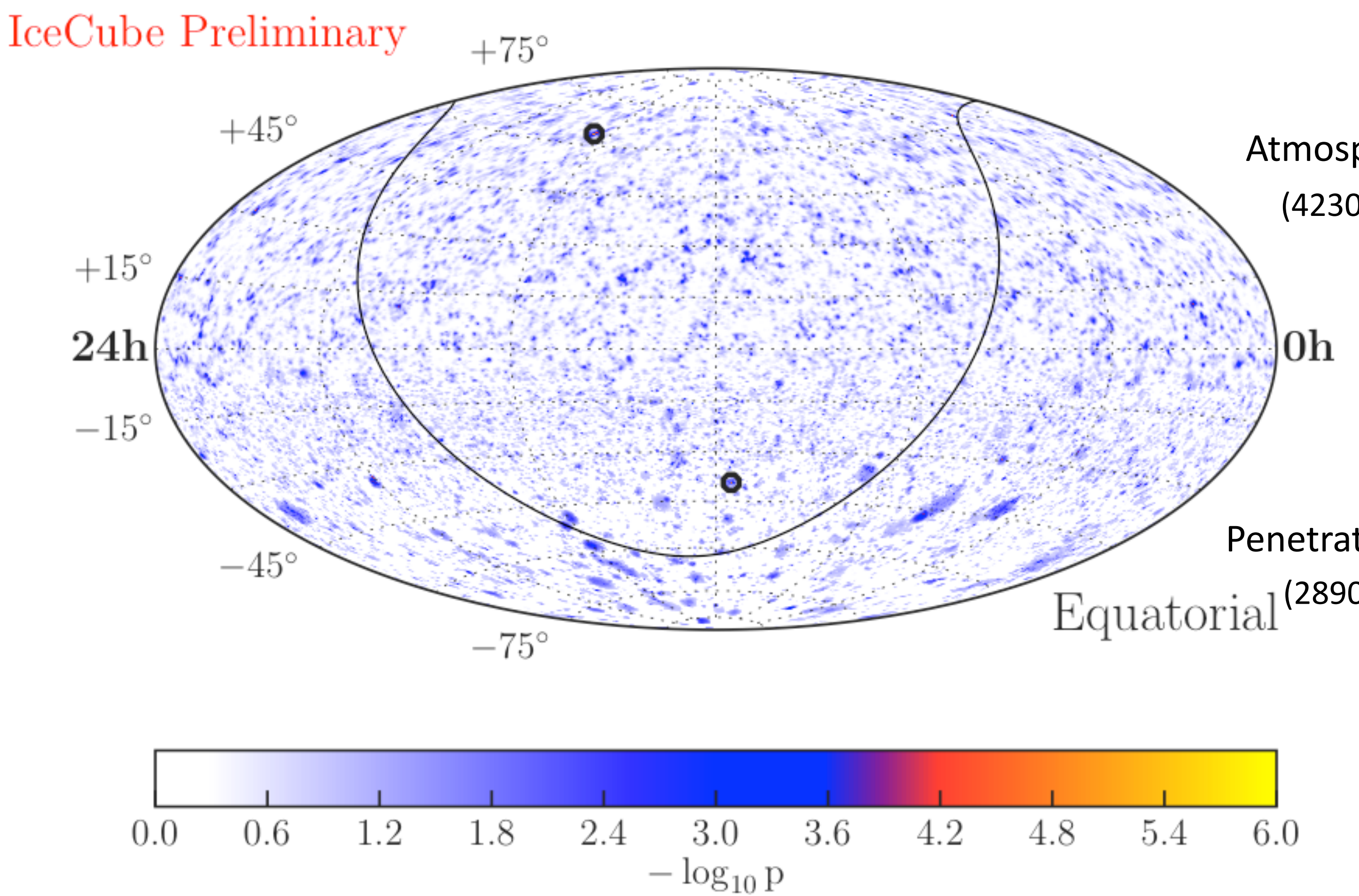
Events from above event selections with energy cut.



7-year Point Source Search

ApJ 835 (2017) 2, 151

Point source optimized muon sample.

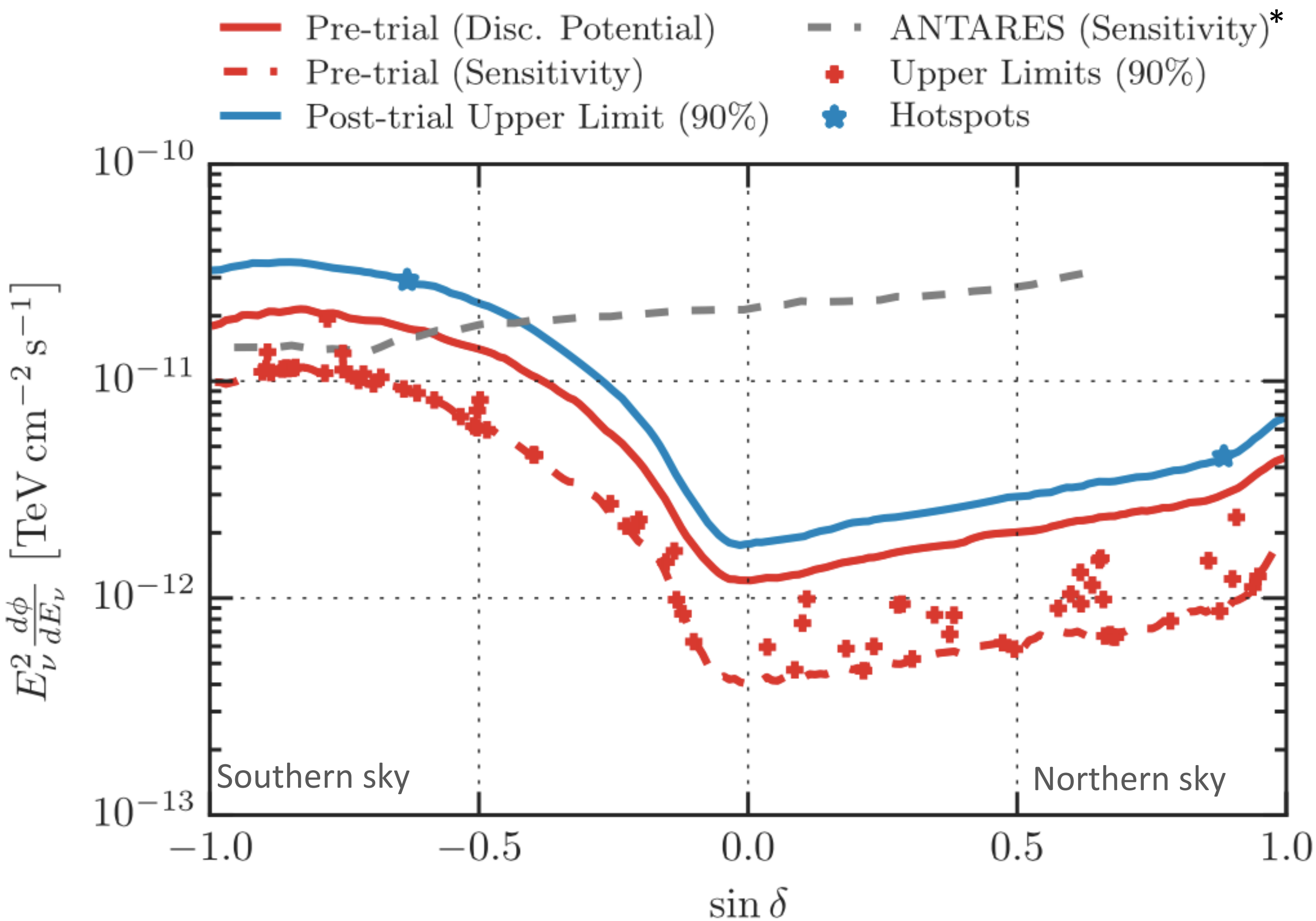


Atmospheric νμ (423000 events)

Penetrating μ (289000 events)

Not significant excess seen.

7-year Point Source Search

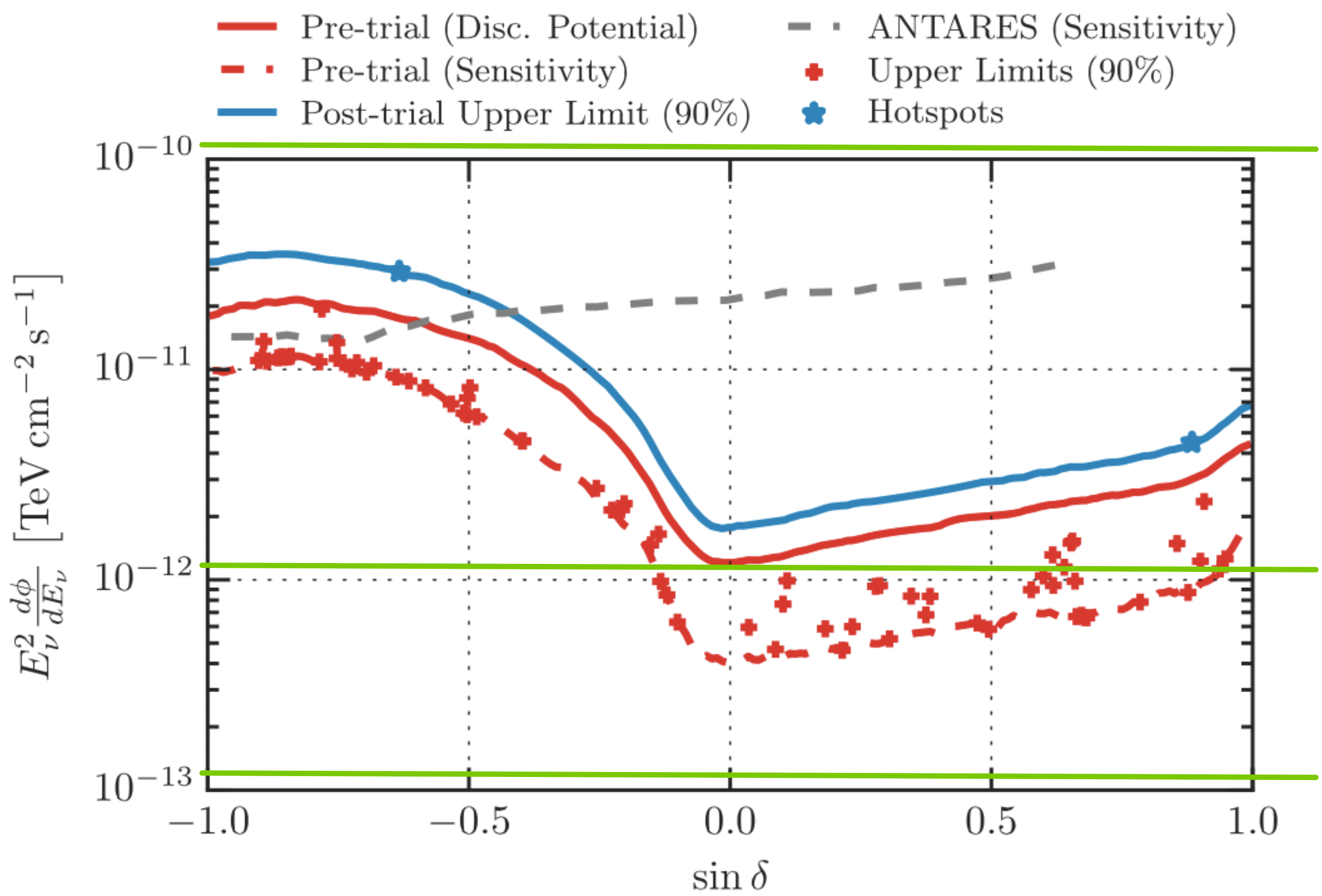


ApJ 835 (2017) 2, 151

*Updated result available for ANTARES (ICRC 2017)

Relating Diffuse and Point Source fluxes

Point-source equivalent flux if the diffuse astrophysical flux came from:



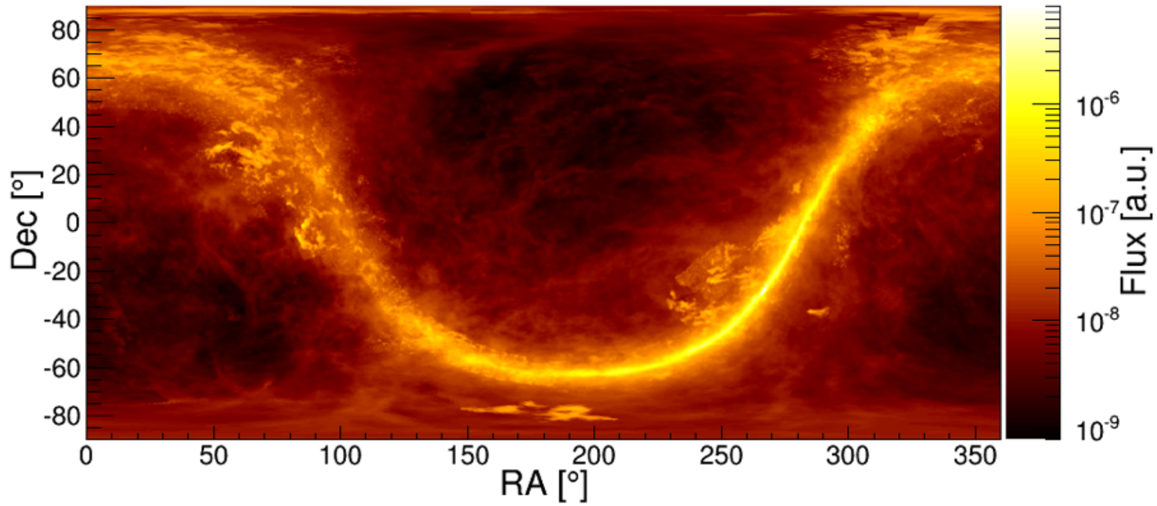
ApJ 835 (2017) 2, 151

→Can construct lower limits on source density of classes of sources. → Disfavor classes of sources.

Population studies with Stacking Searches

What fraction of the cosmic neutrino flux comes from the Milky Way?

Galactic contribution?



Gamma ray skymap of FERMI satellite data in equatorial coordinates:

Answer: < 16%

Compared to best fit spectrum in this energy range ($E^{-2.5}$ flux)

arXiv:1707.0341

What fraction of the cosmic neutrino flux comes from classes of extragalactic sources?

Gamma Ray Bursts

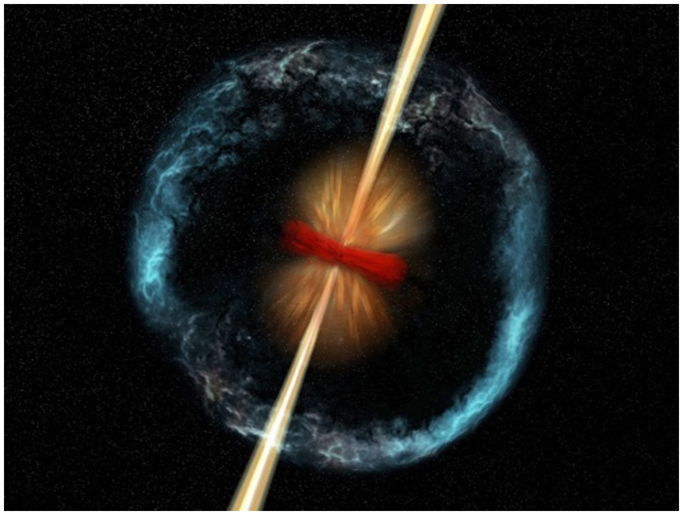


Illustration credit: NASA/CXC/M.Weiss

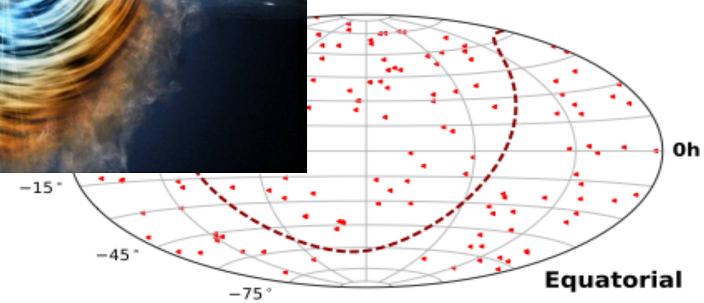
807 GRB's monitored for neutrino emission at TeV to PeV energy range

Answer: < 1%

Ref: arxiv: 1702.06868

Active Galaxies - Blazars

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



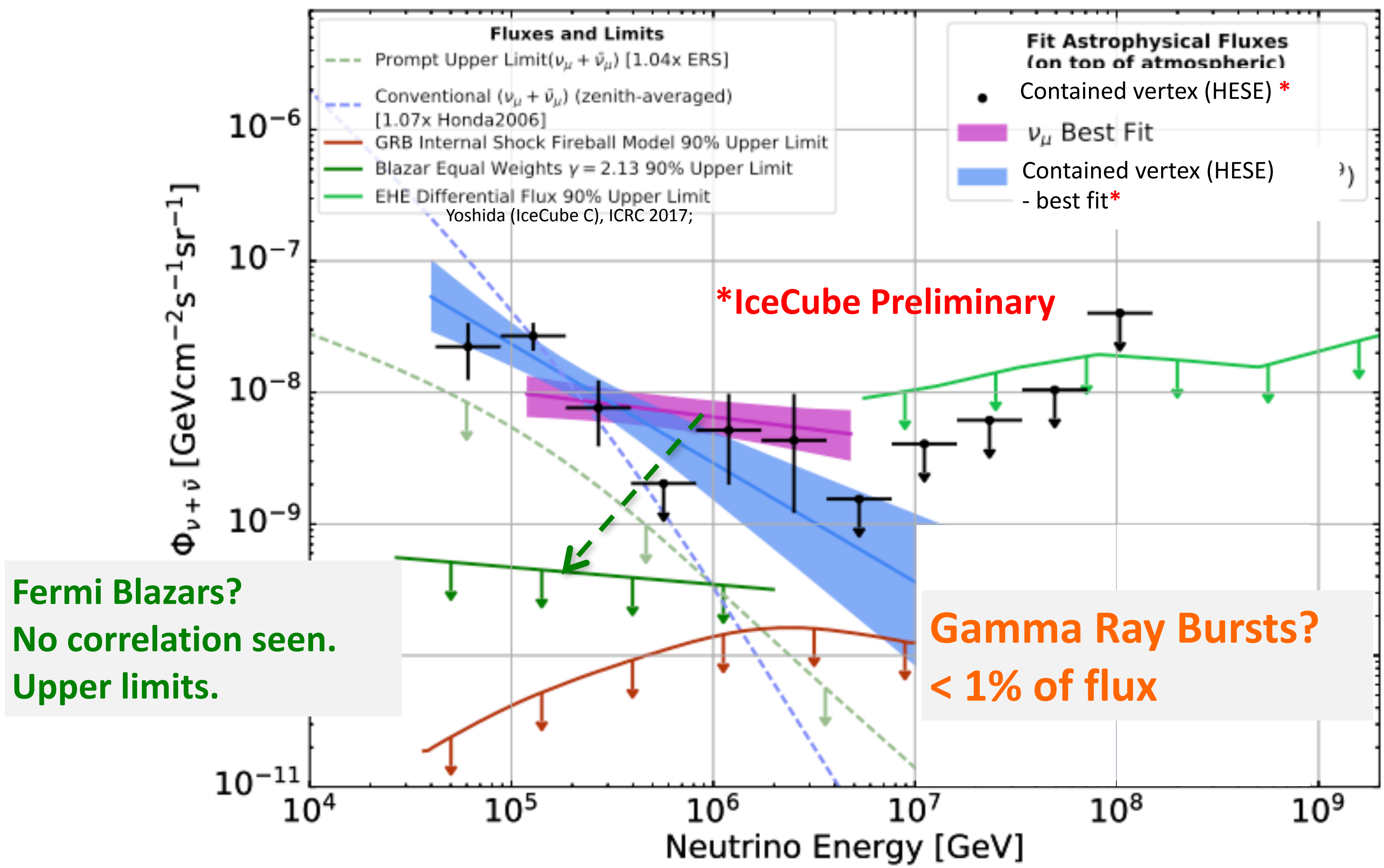
Fermi reports that ~85% of the gamma rays from the "diffuse" gamma ray flux originate from such blazars.

IceCube's

Answer: < 6% to 27%

(Some assumptions, eg assume energy spectrum, apply.
Ref: - Astrophys. J **835**, 45 (2017)
- ICRC 2017, Huber for IceCube C.

Astrophysical neutrino spectrum – with AGN Blazar and GRB limits

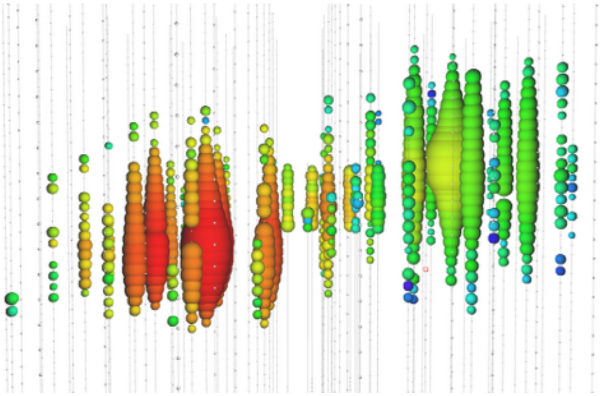


1.) GRB: arXiv:1702.06868 (IceCube C.)
2.) Blazars: See: M. Huber, IceCube C. at ICRC 2017; Astrophys.J. 835 (2017) no.1, 45

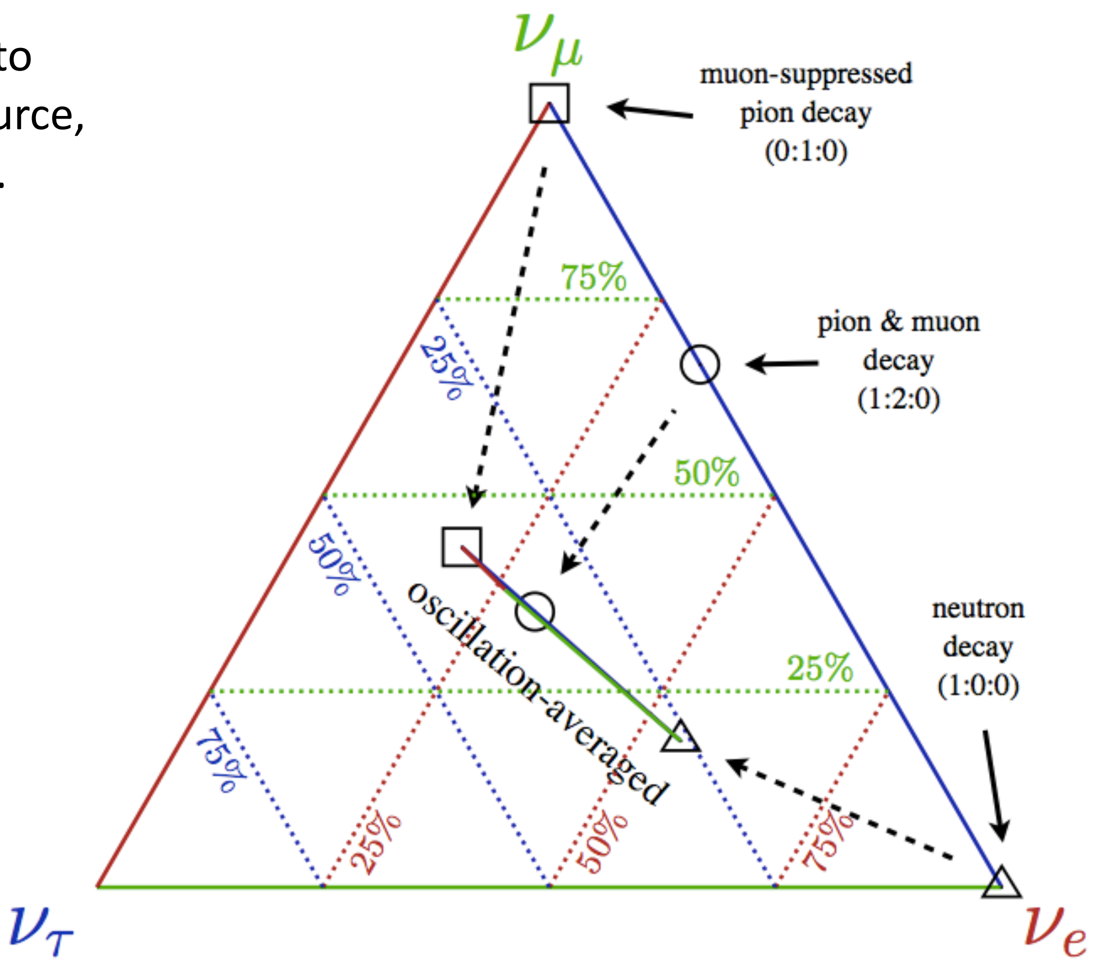
Flavor ratio

The flavor ratio at Earth is related to the flavor ratio at astrophysical source, after oscillations en route to Earth.

For a detailed flavor ratio discussion, see arXiv: 1502.03376

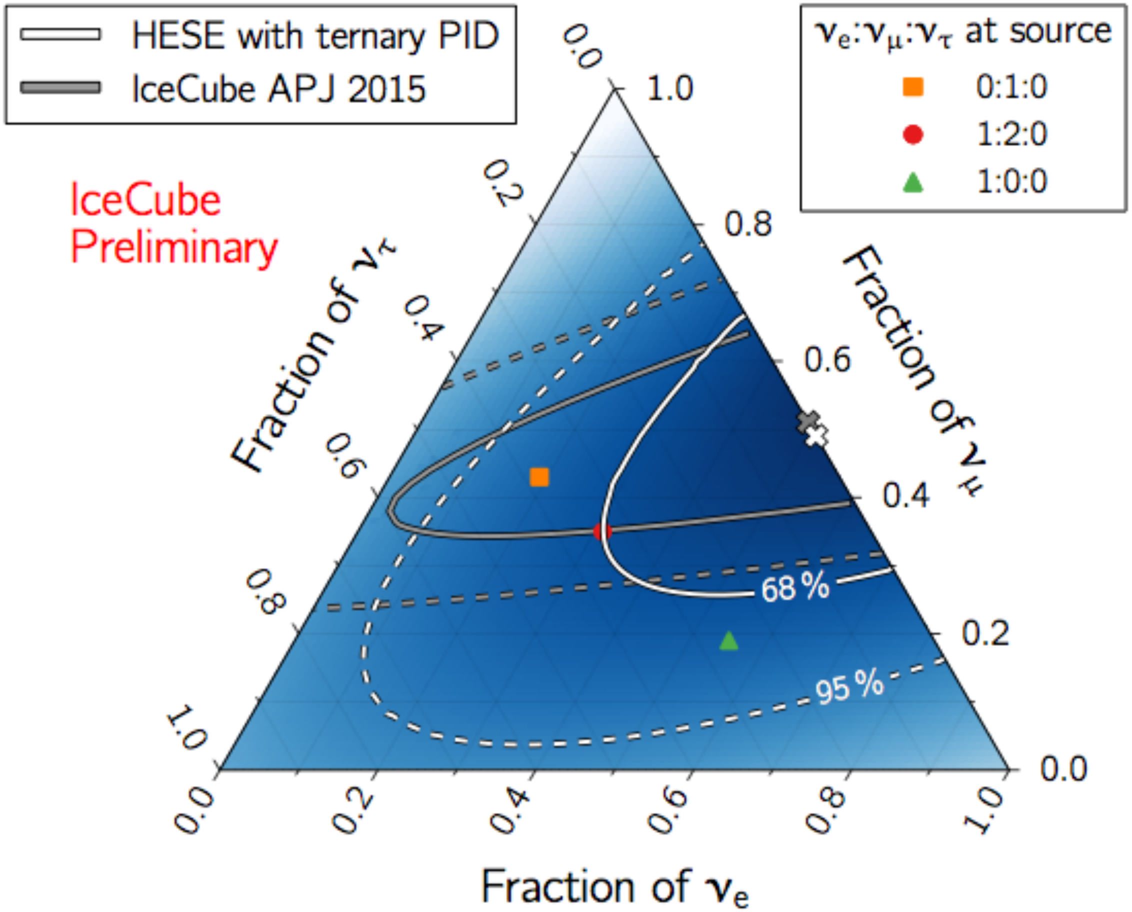


Double cascade signature:
Tau decay length: ~50m*(E/PeV)



Tau ID above ~100 TeV, better above 1 PeV

Tau neutrino search – flavor ratios



- Tau neutrinos seen: 0
- Expected: ~2.83 events
- Compatible with statistical fluctuation (9%).

$$f_{\nu_e} = 0.51^{+0.12}_{-0.13}$$

$$f_{\nu_\mu} = 0.49^{+0.12}_{-0.13}$$

$$f_{\nu_\tau} = 0.00^{+0.16}_{-0.00}$$

Usner et al. (IceCube Coll.), ICRC 2017

Realtime Public Alerts via AMON, GCN

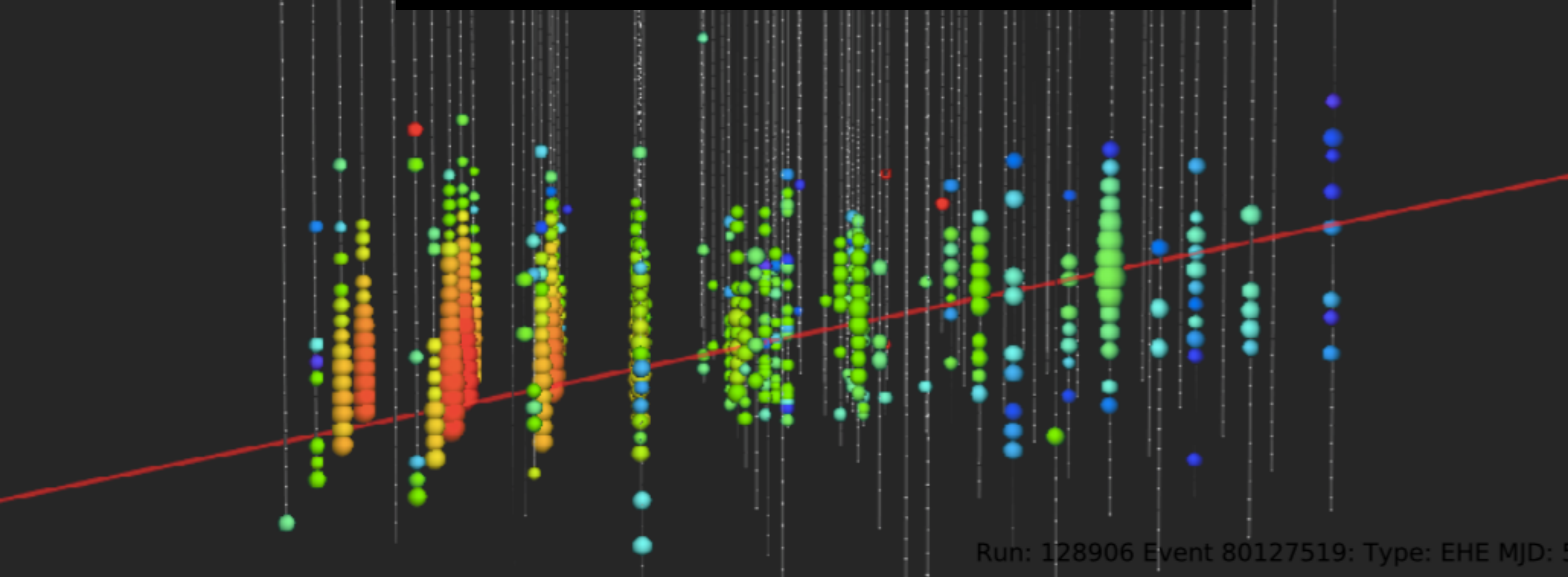
Operating since April 2016 (second filter stream added during summer)

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



Growing multimessenger program, including alerts.

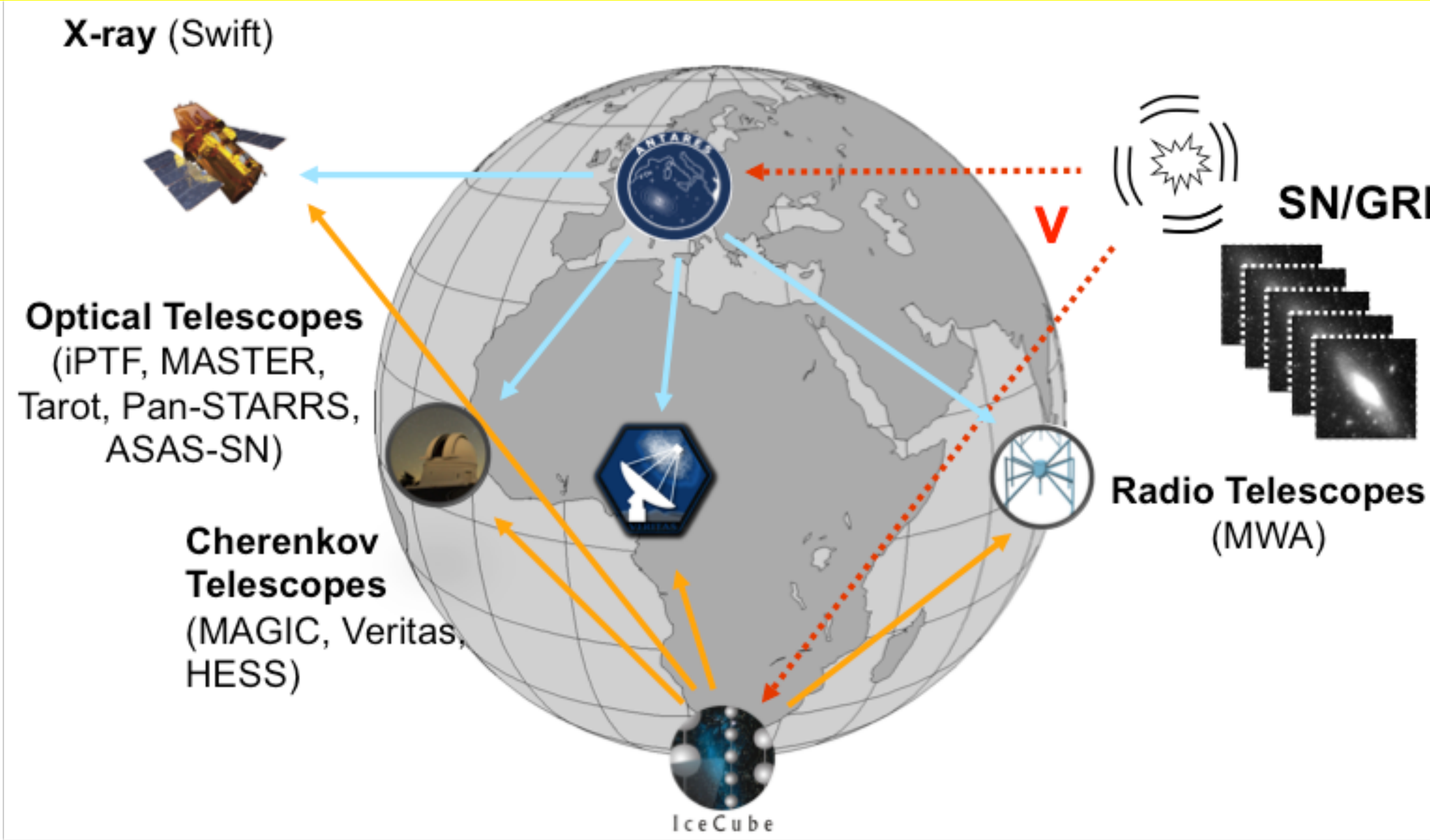
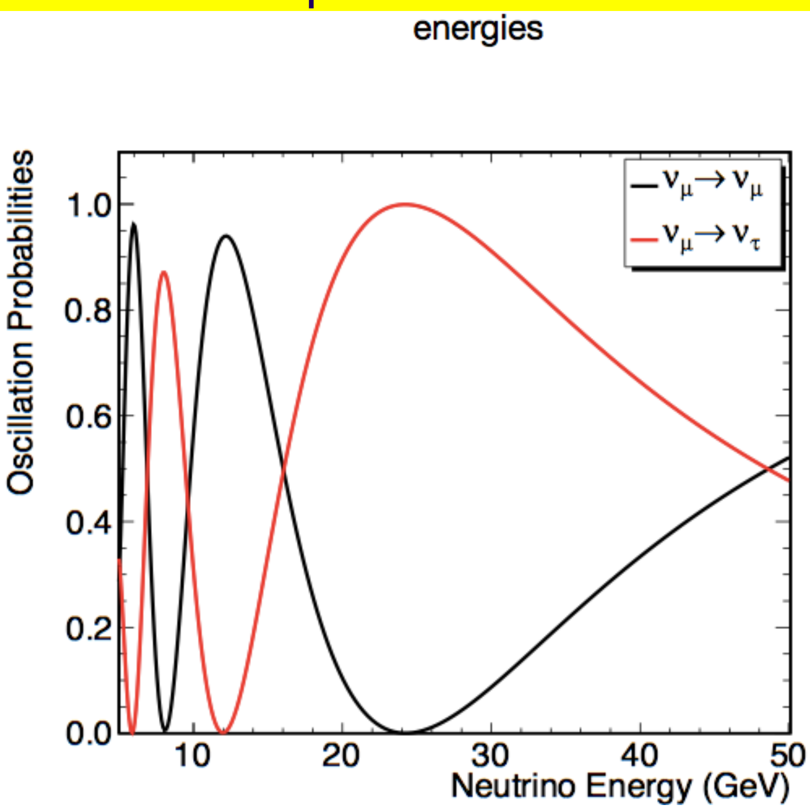
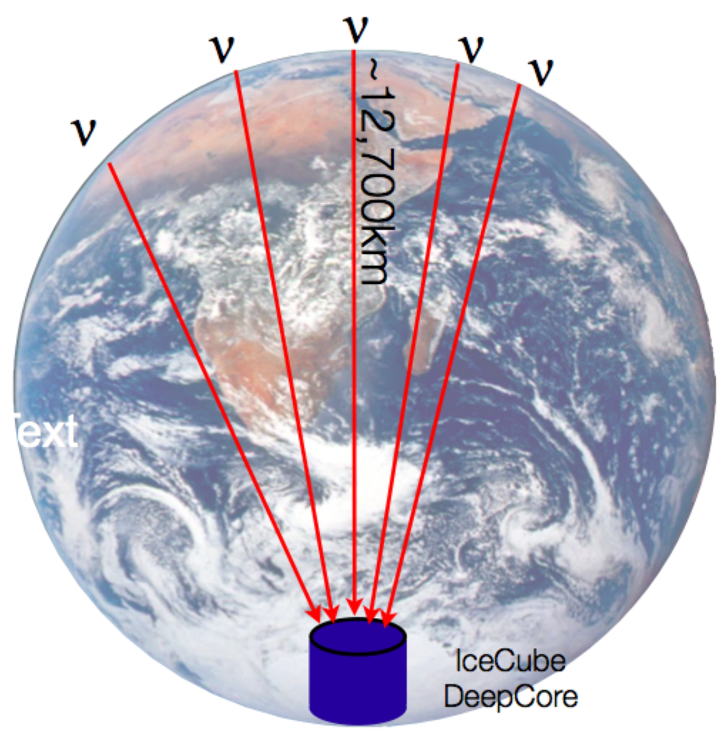
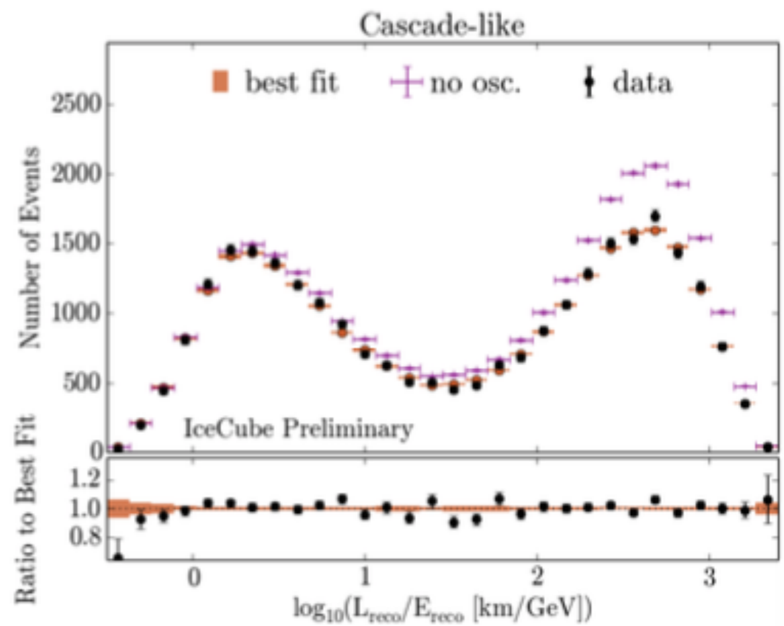


Illustration: A. Franckoviak

Neutrino oscillation analysis with IceCube-DeepCore





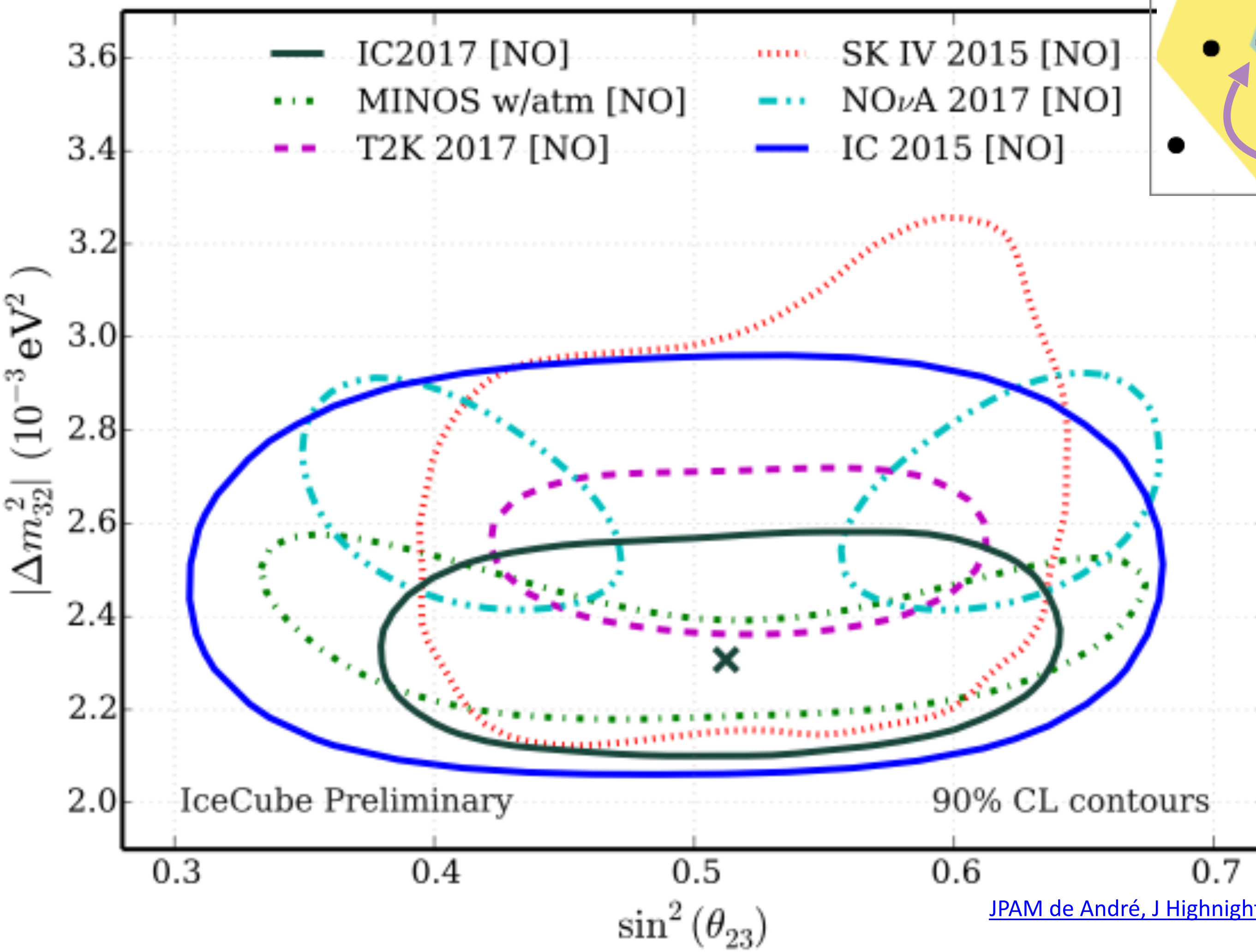


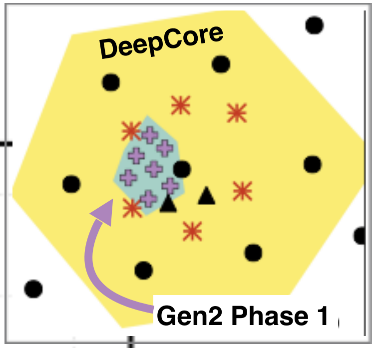
41599 events
in 3 years of data

- Range of baselines
- Effective volume: ~5 – 10 Mt
  depending on analysis

Neutrino oscillation analysis with IceCube-DeepCore

IceCube DeepCore: 3 years





JPAM de André, J Highnight, IPA 2017

Best fit: $\Delta m^2_{32} = 2.31^{+0.11}_{-0.13} \times 10^{-3}$ eV^2, $\sin^2\theta_{23} = 0.51^{+0.07}_{-0.09}$

DeYoung, Rencontre de Vietnam, 2017

Outlook, Future strategies

- The cosmic neutrino flux is real, seen in several channels, and it is large.
- Some constraints are substantial.
- Increase multi-messenger strategies with other telescopes, including transient sources:

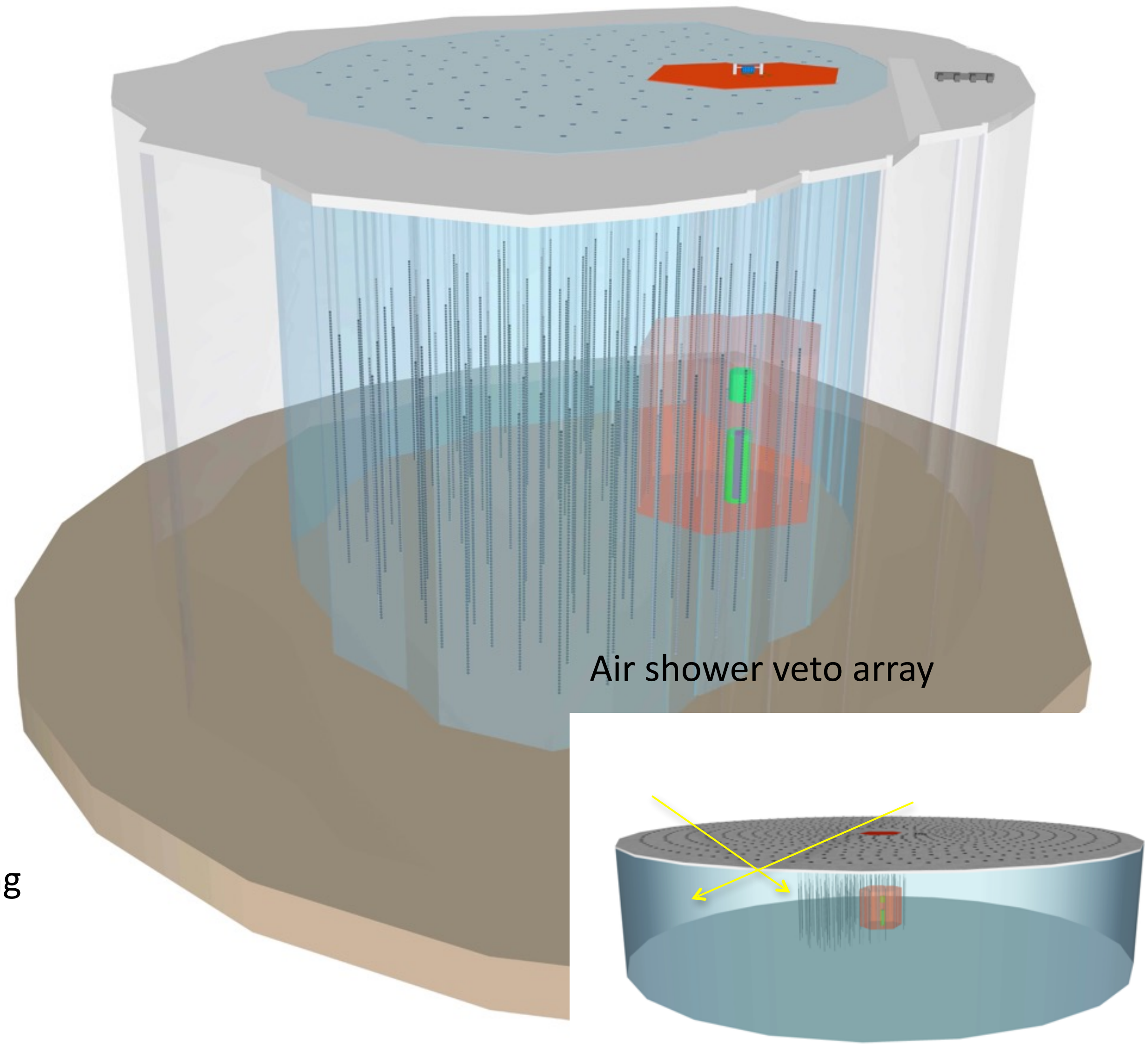
  → single events can serve as alerts

- Experimental upgrade: IceCube-Gen2

IceCube-Gen2

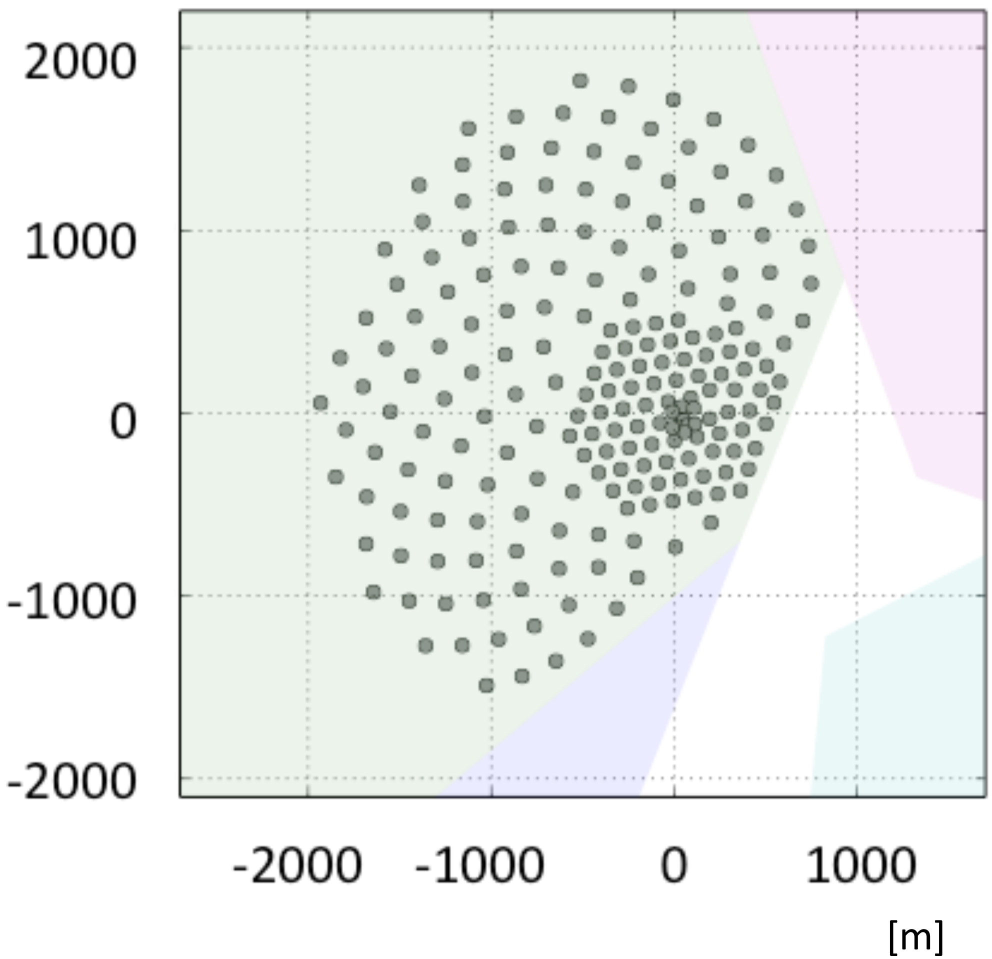
The next Generation IceCube: A wide band neutrino observatory (MeV – EeV) using several detection technologies – optical, radio, and surface veto.

Multi-component observatory:
- IceCube-Gen2 High-Energy Array
- Surface air shower detector
- Sub-surface radio detector
- Low energy core (~PINGU like)



Artist conception
Here: 120 strings at 300 m spacing

Geometry



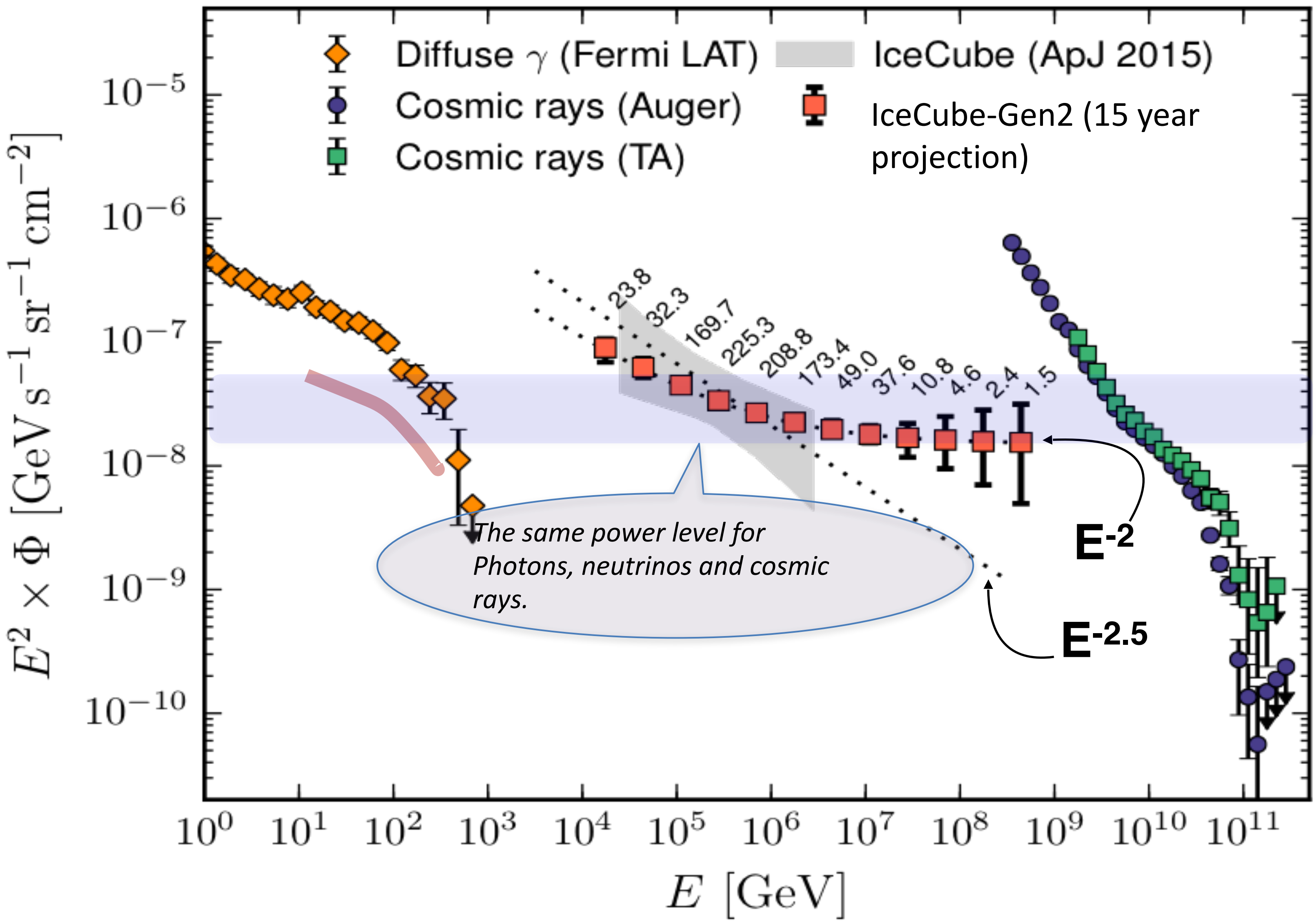
Increase energy threshold allows larger string spacing

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

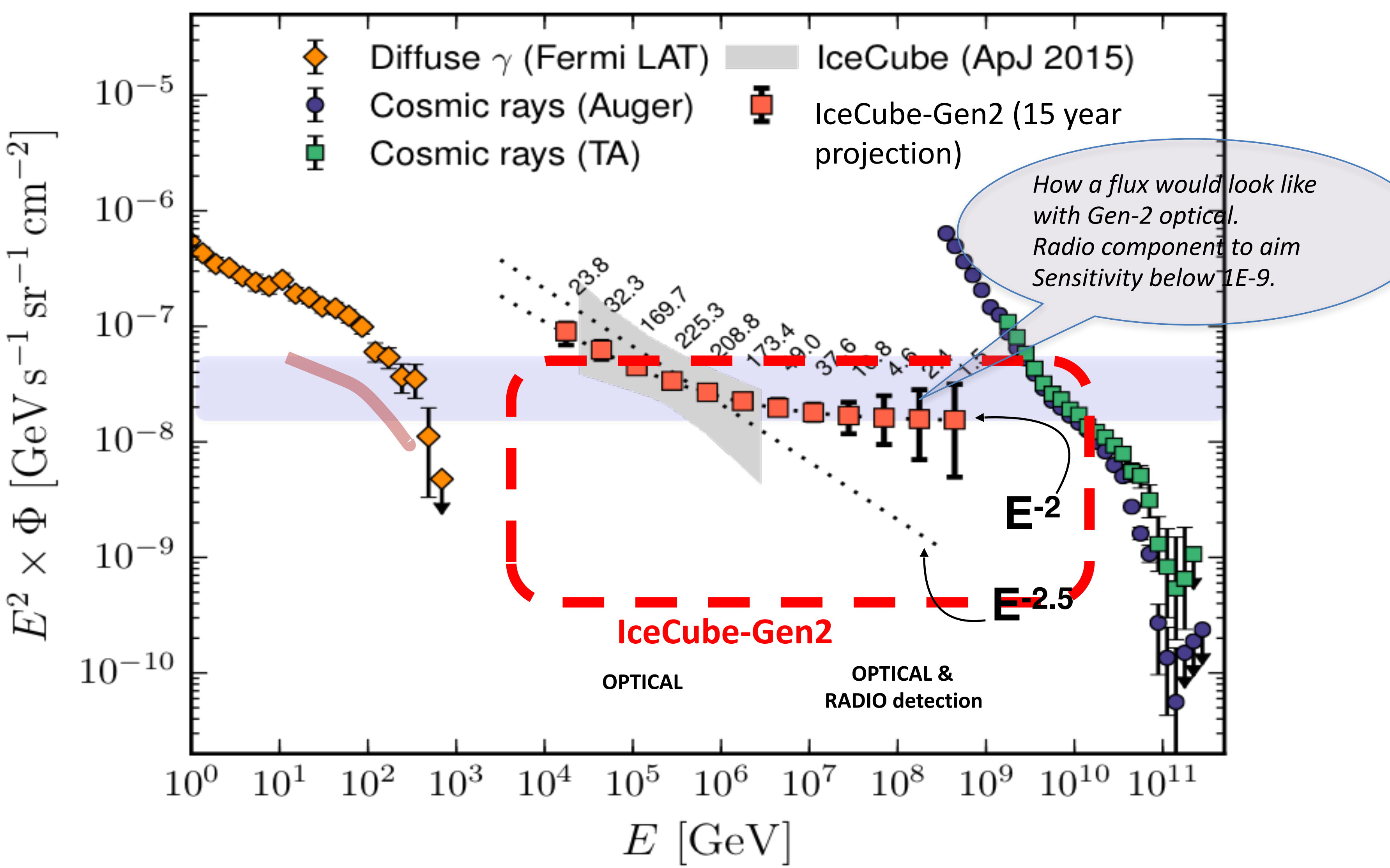
Instrumented Volume: 8 km^3

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

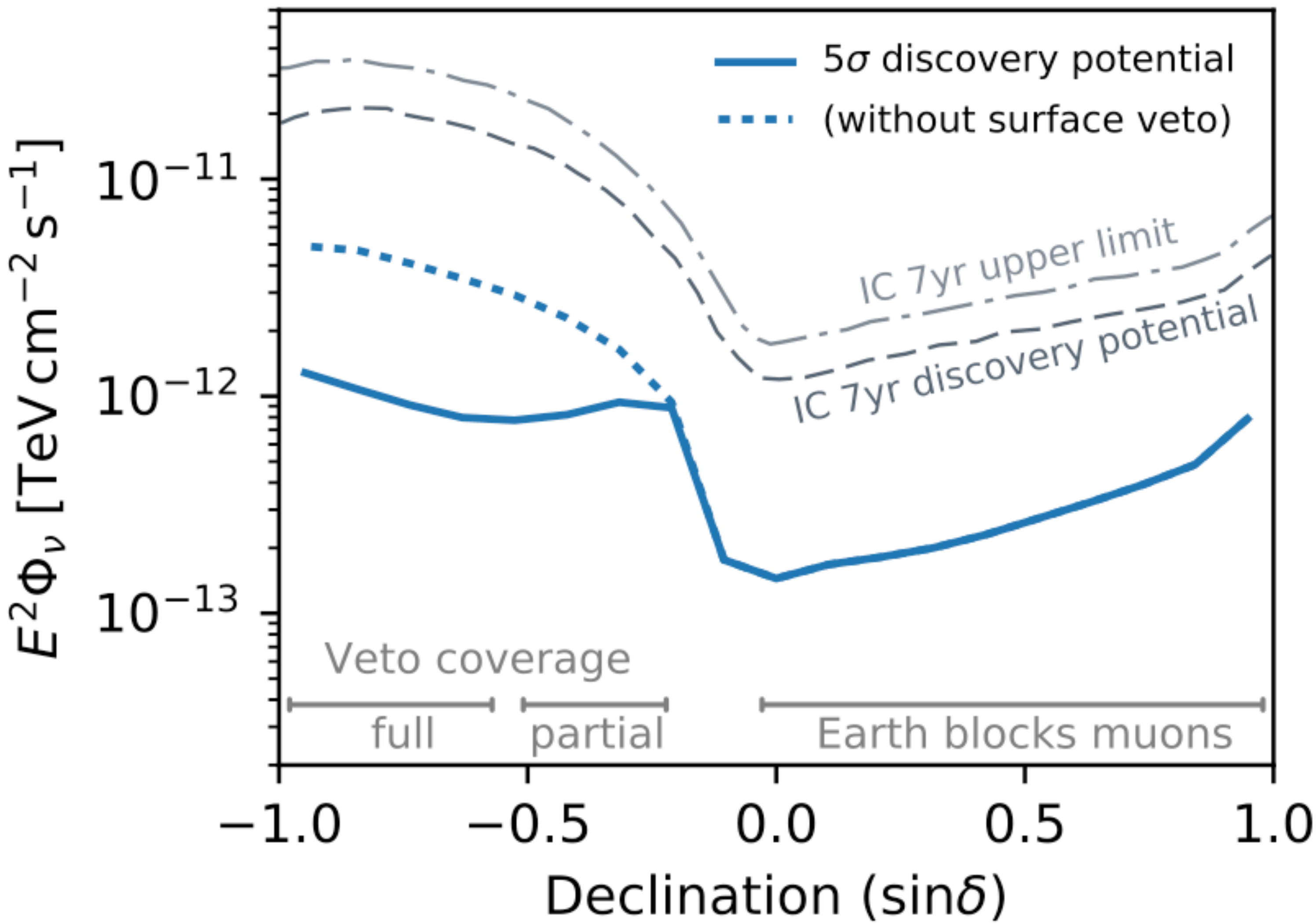
Connecting HE neutrinos to UHE cosmic rays



Connecting HE neutrinos to UHE cosmic rays

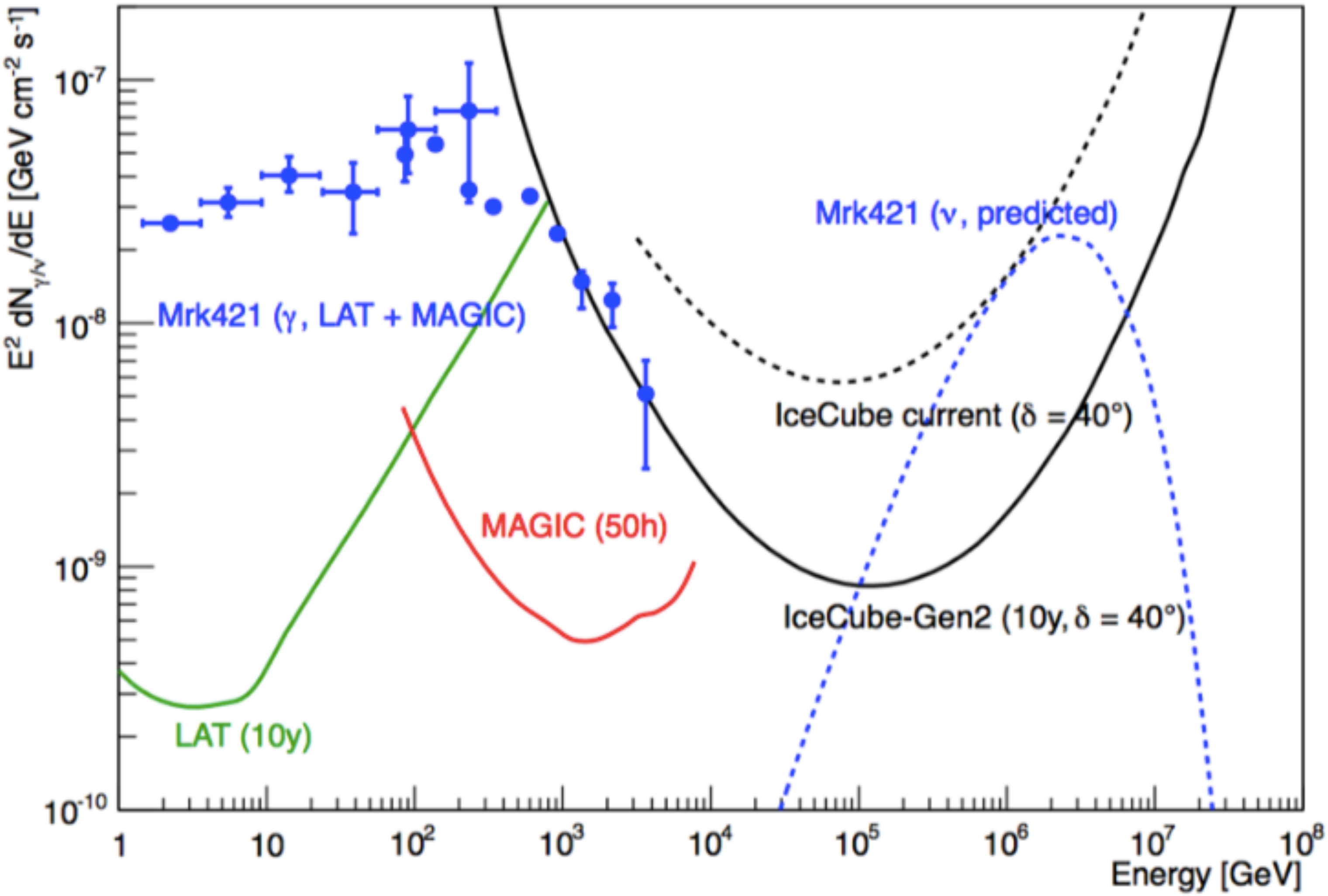


Discovery potential for point sources



Point source sensitivity example: Mrk421

Mrk 421 is an active galaxy,
Known gamma ray emitter
Distance: 122 Mpc



Sensor design R&D for improved performance

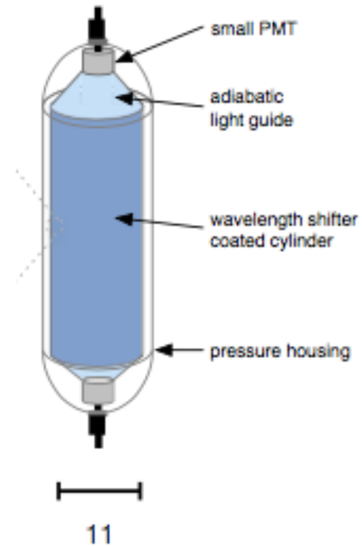
mDOM

- Directional information
- More sensitive area per module

D-Egg

- Directional information
- More sensitive area per module
- Smaller geometry

WOM

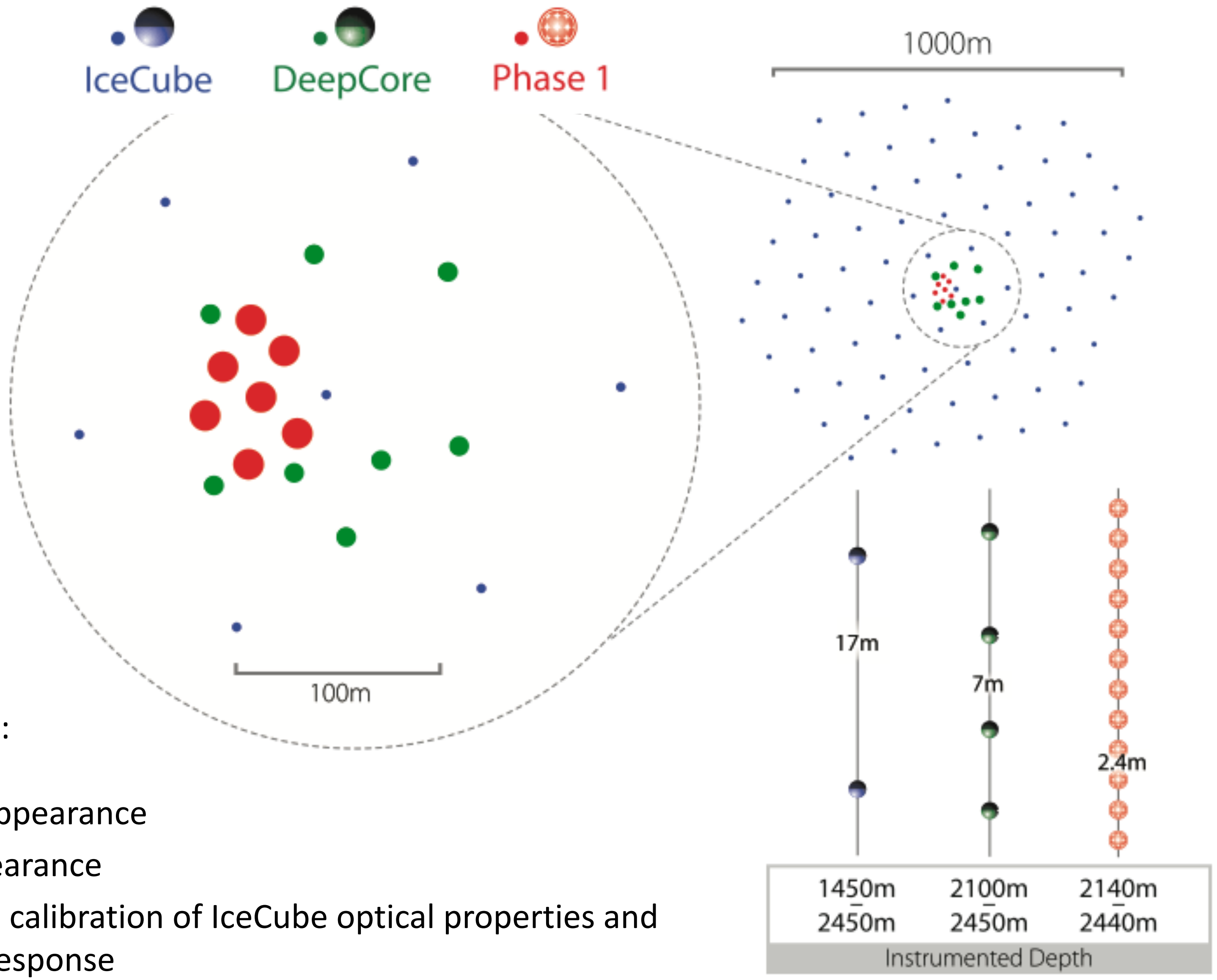


- more sensitive area per $
- Small diameter
- Lower noise rate

LOM

- Small diameter
- Directional info.
- More area per module

IceCube-Gen2 Phase 1

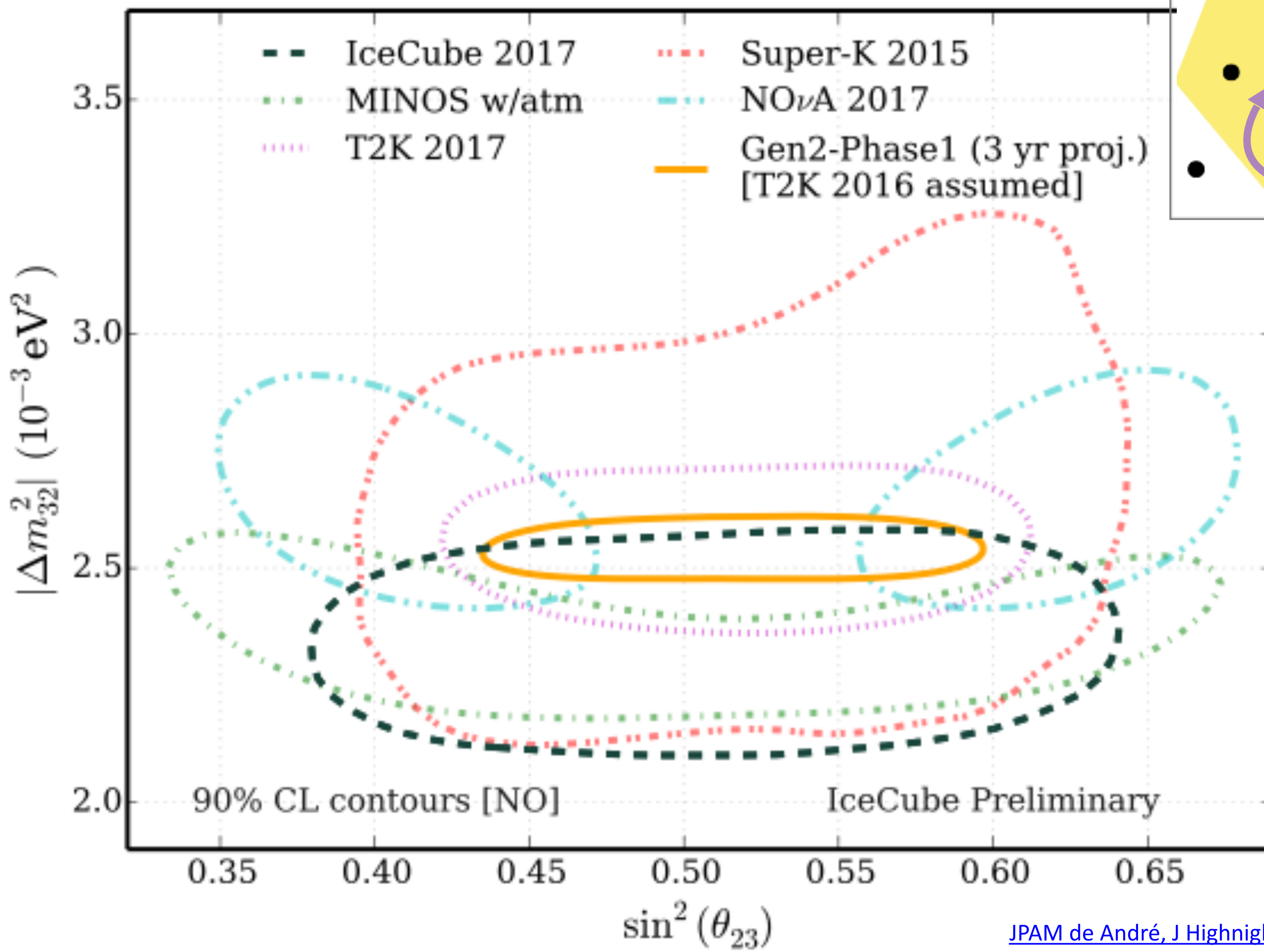


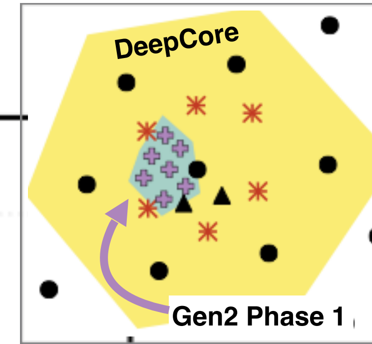
Science goals:

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

Phase 1 science: precision ν_μ disappearance

IceCube DGen2 Phase1 3 years

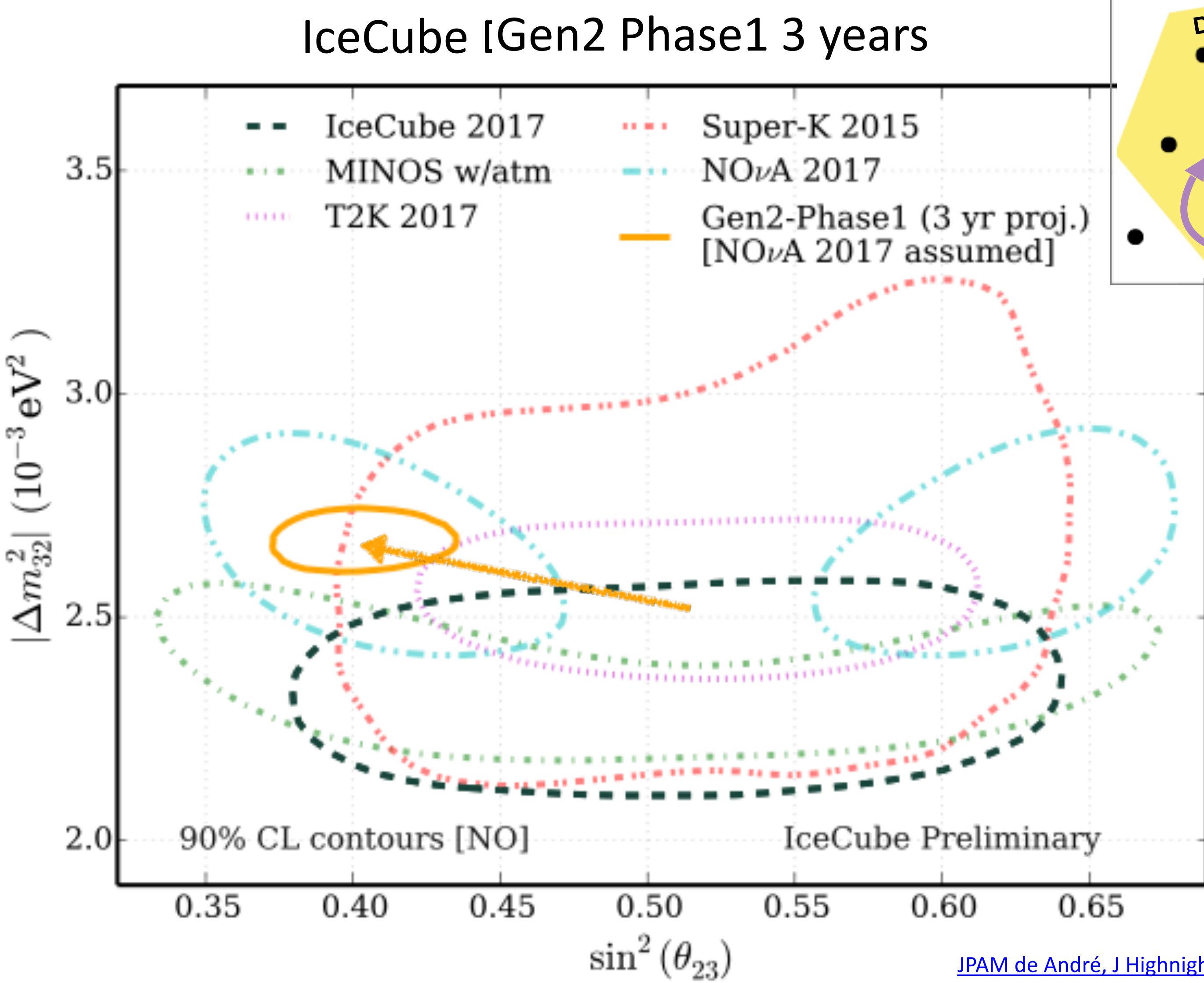


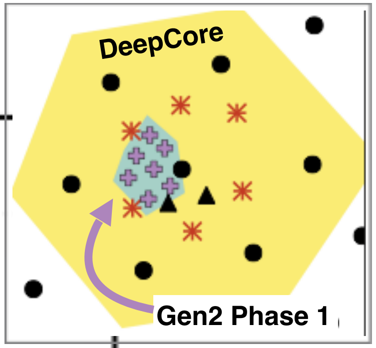


JPAM de André, J Highnight, IPA 2017

Precision significantly improved over DeepCore

Phase 1 science: precision ν_μ disappearance





JPAM de André, J Highnight, IPA 2017

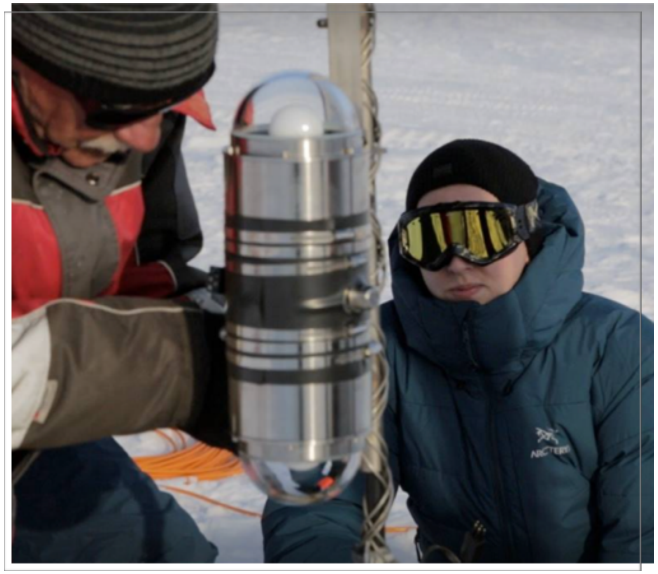
Precision significantly improved over DeepCore

Phase 1: enhancing IceCube high-energy science

New calibration devices inside IceCube enhance HE science

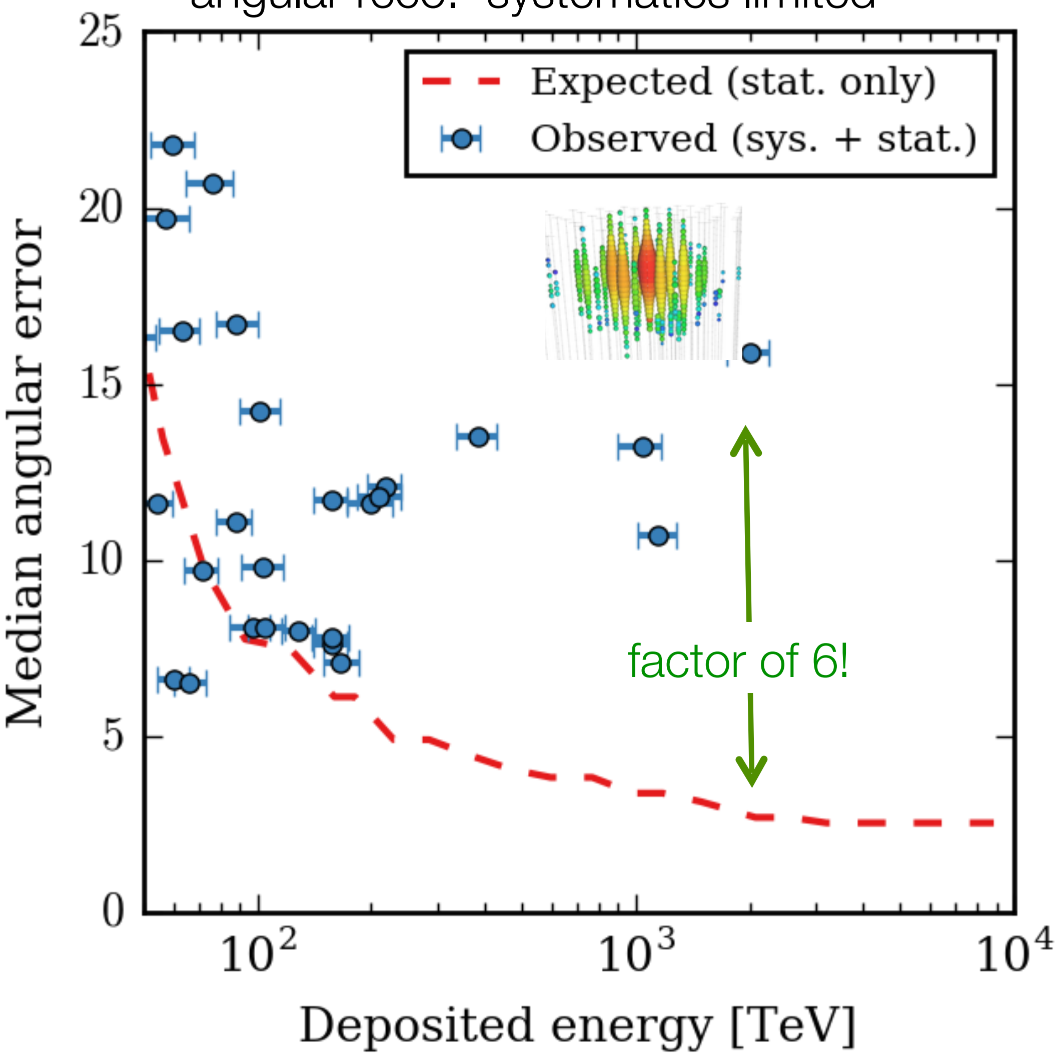
- reconstructions
- tau flavor identification

Prototype calibration device being deployed at Lake Baikal



See ICRC NU143

angular reco. systematics limited



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

- **IceCube has discovered astrophysical neutrinos**
- Starting to quantify their properties
  - Spectral indices, Flavor composition
  - Constraints on possible source classes (Galactic plane, GRB, AGN blazars).
- Physics with atmospheric neutrinos
- Continue to reduce systematic errors, increase efficiencies and reconstruction.
- IceCube-Gen2 will take us from discovery to precision science.
  - Phase1 as first step towards that

"Race around the World", Dec 25, 2008

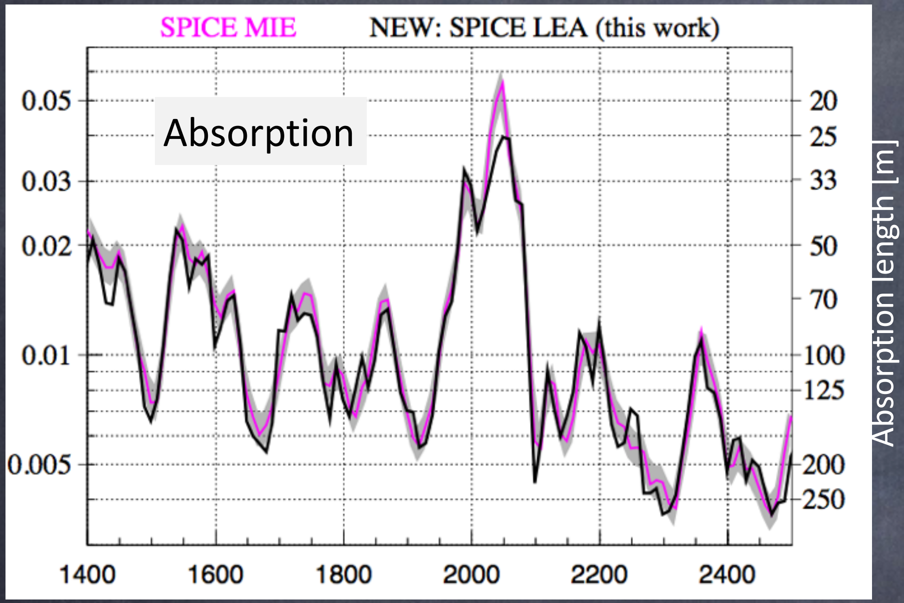
Right now: T(South Pole) ≈ T(Guangzhou) - 100°C

Thank you!

IceCube

Understanding the ice

1. Vertical structure of ice parameters



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

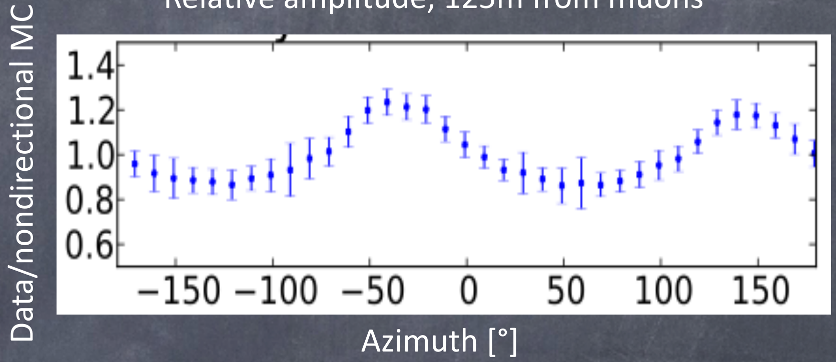
Measurement of South Pole ice transparency with the IceCube LED calibration system,

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

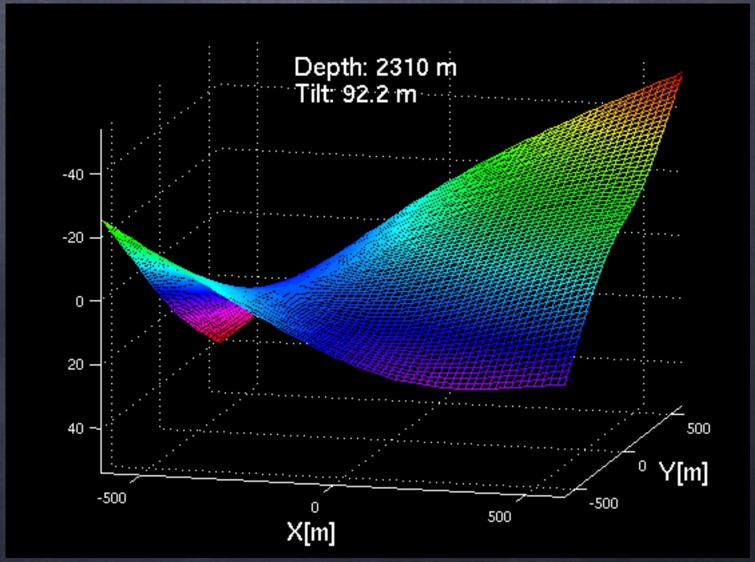
2. Azimuthal variation in of scattering

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

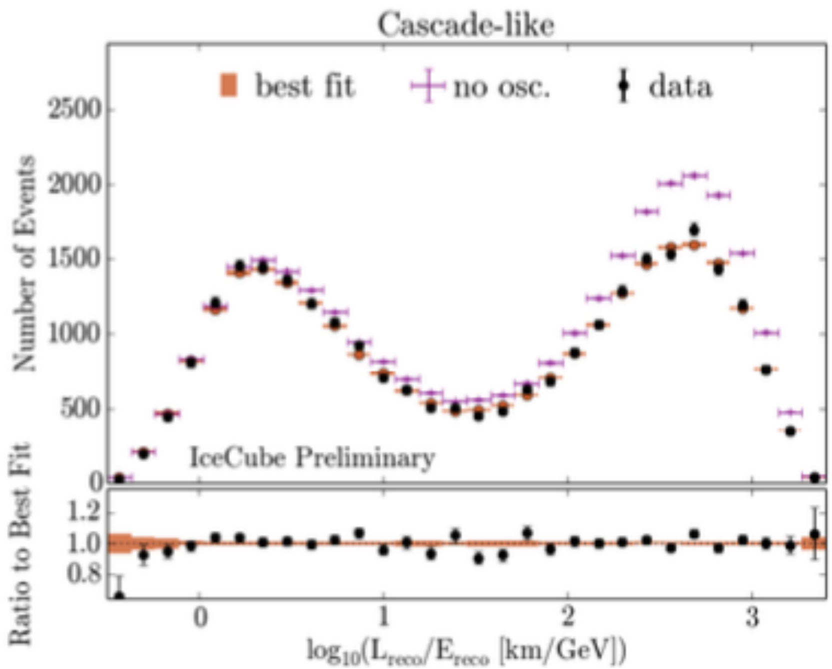
Relative amplitude, 125m from muons

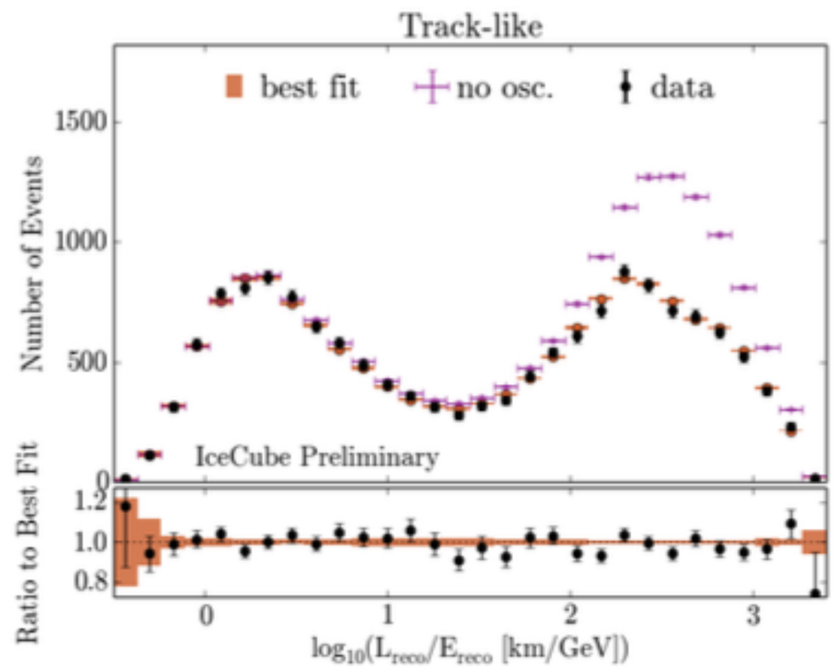


3. Ice layers are tilted – not planar



Atmospheric Oscillations with DeepCore





- 41,599 events from 2012-14 data sets, χ^2/n.d.f. = 117 / 119
  - Full analysis is $L \times E_\nu \times$ particle type, projected onto (L/E_ν) for illustration
  - Shaded range shows uncertainty in prediction at best fit (mostly atm. μ)

The highest energy neutrino induced muon