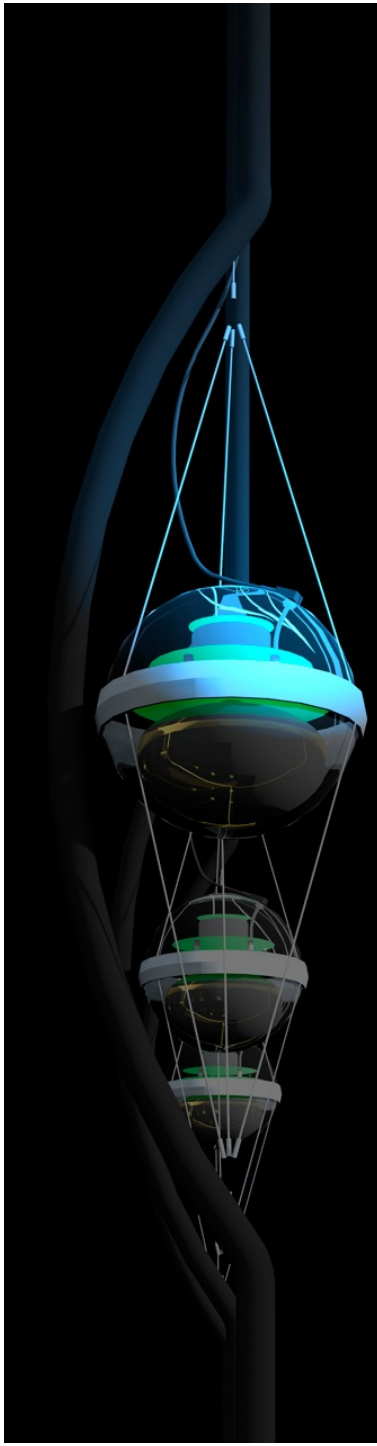


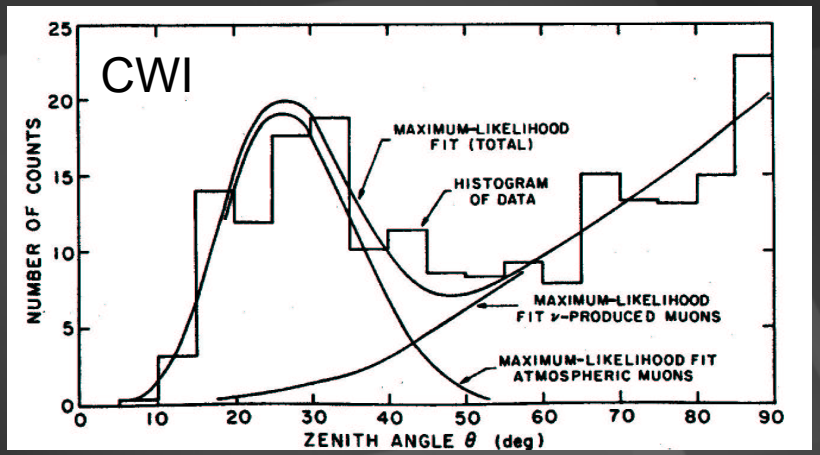
Beyond IceCube

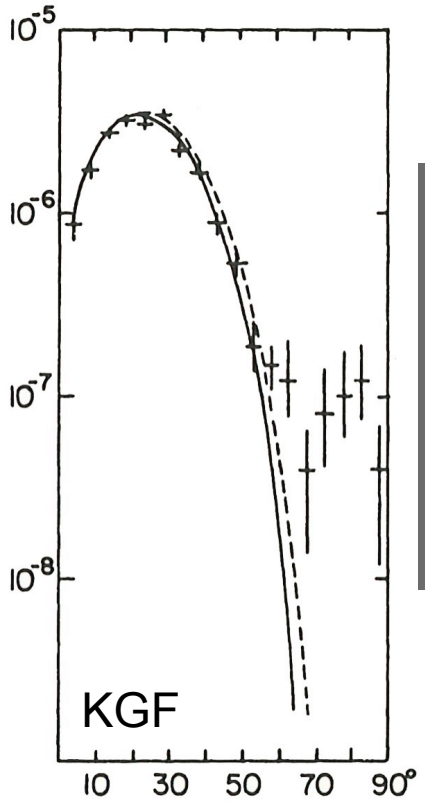
francis halzen

- the discovery of high-energy cosmic neutrinos
- where do they come from?
- neutrino stars?
- cosmogenic neutrinos
- beyond IceCube
- low threshold frontier (PINGU)

IceCube.wisc.edu

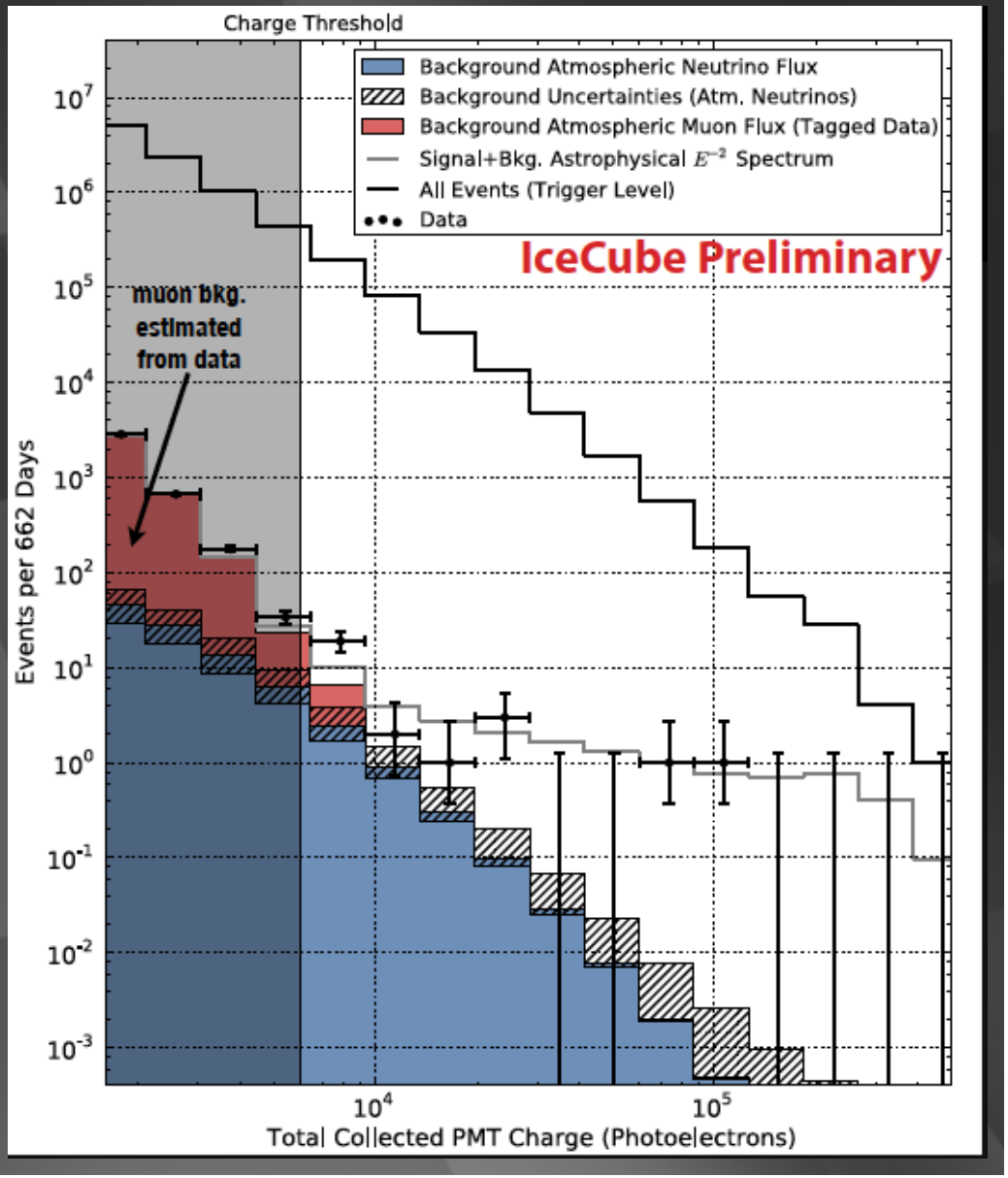
2013 atmospheric and cosmic neutrinos



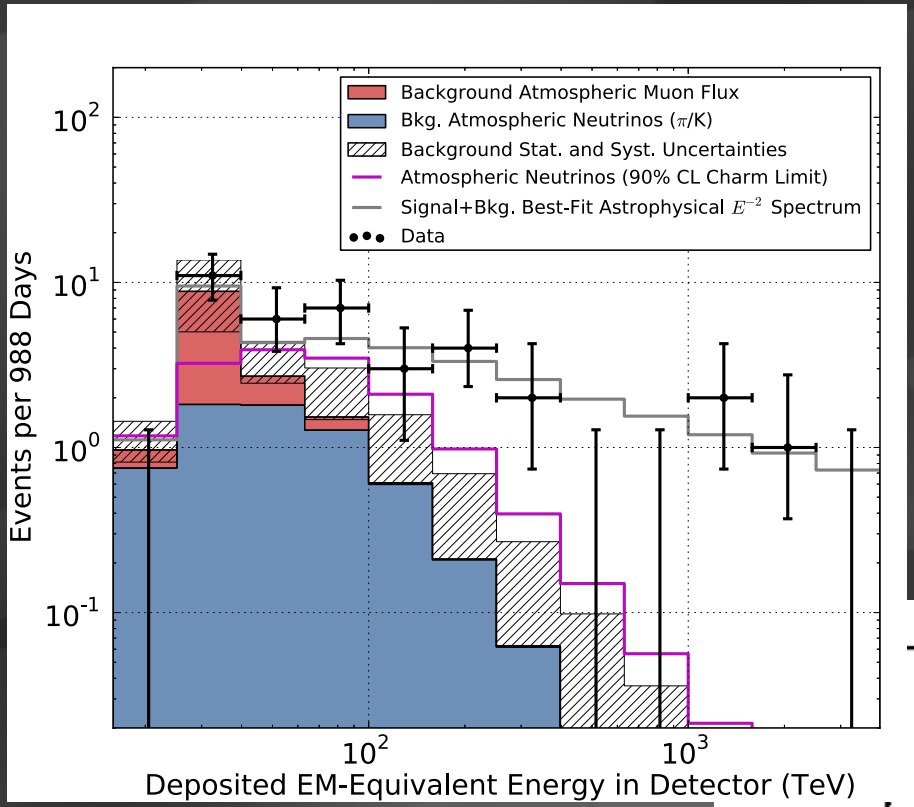


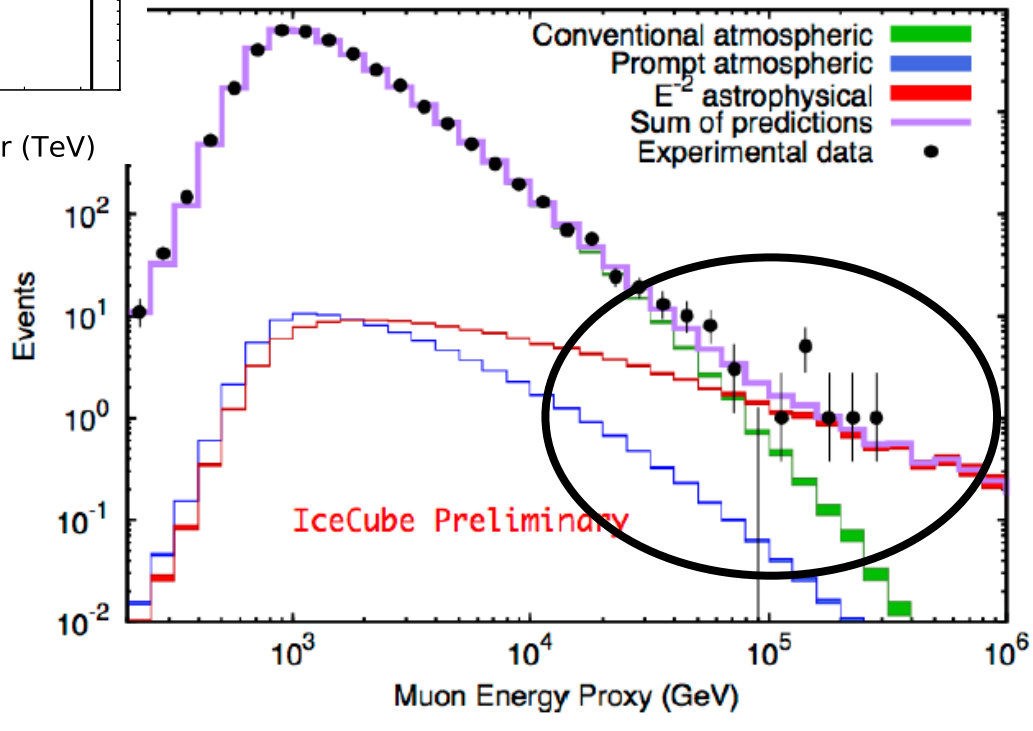
1965

cosmic ray muons and atmospheric neutrinos



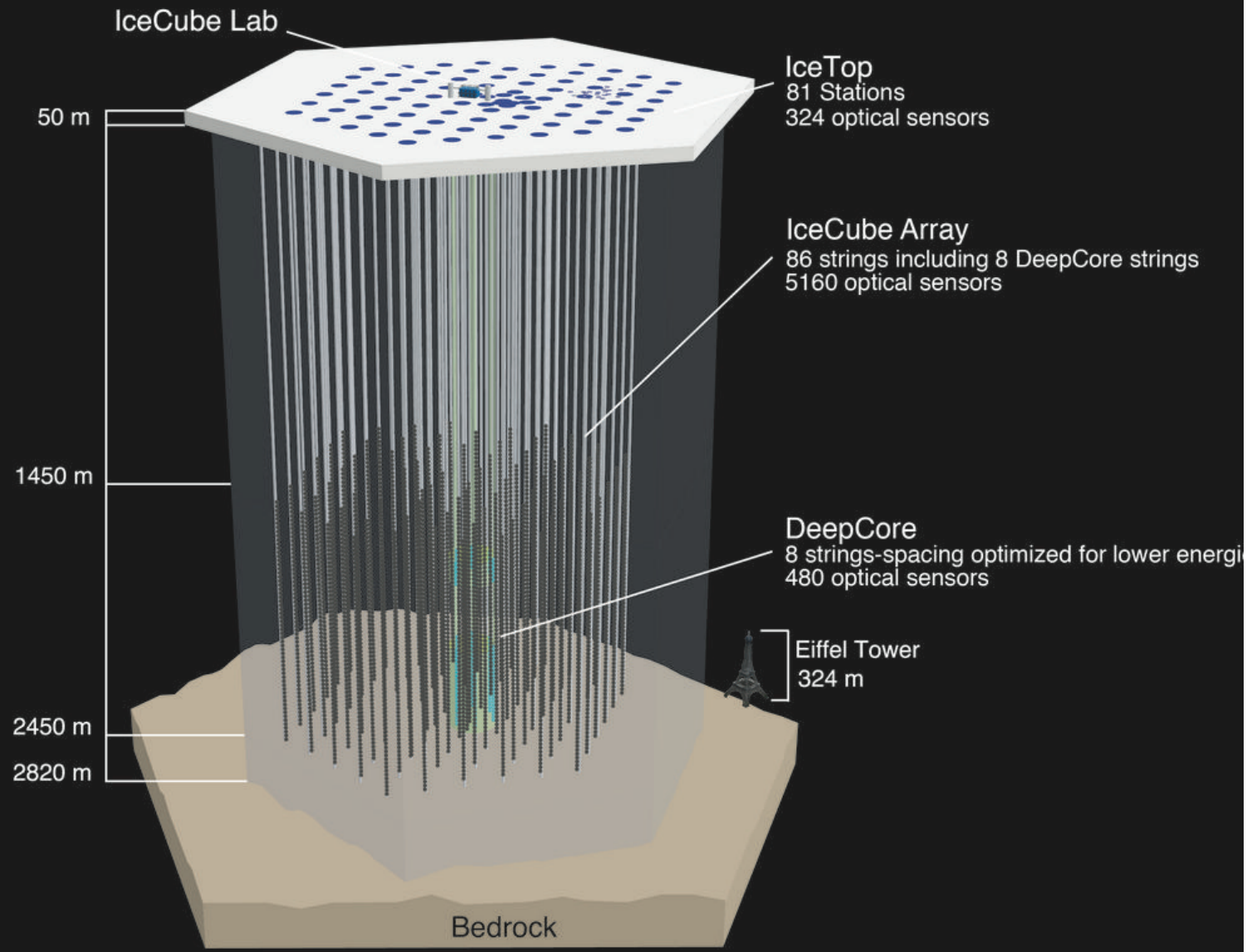
confirmation!
flux of muon neutrinos
through the Earth

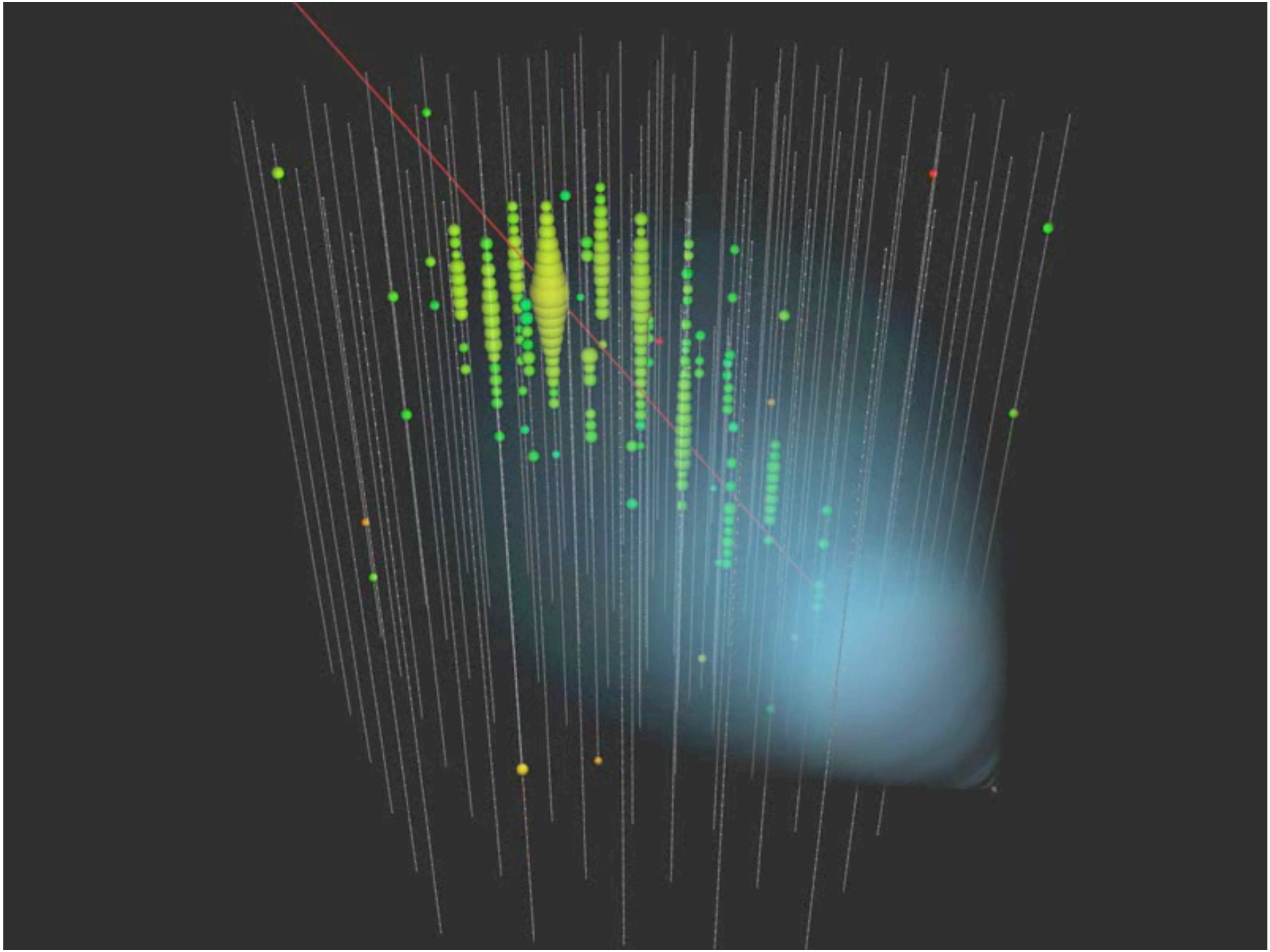


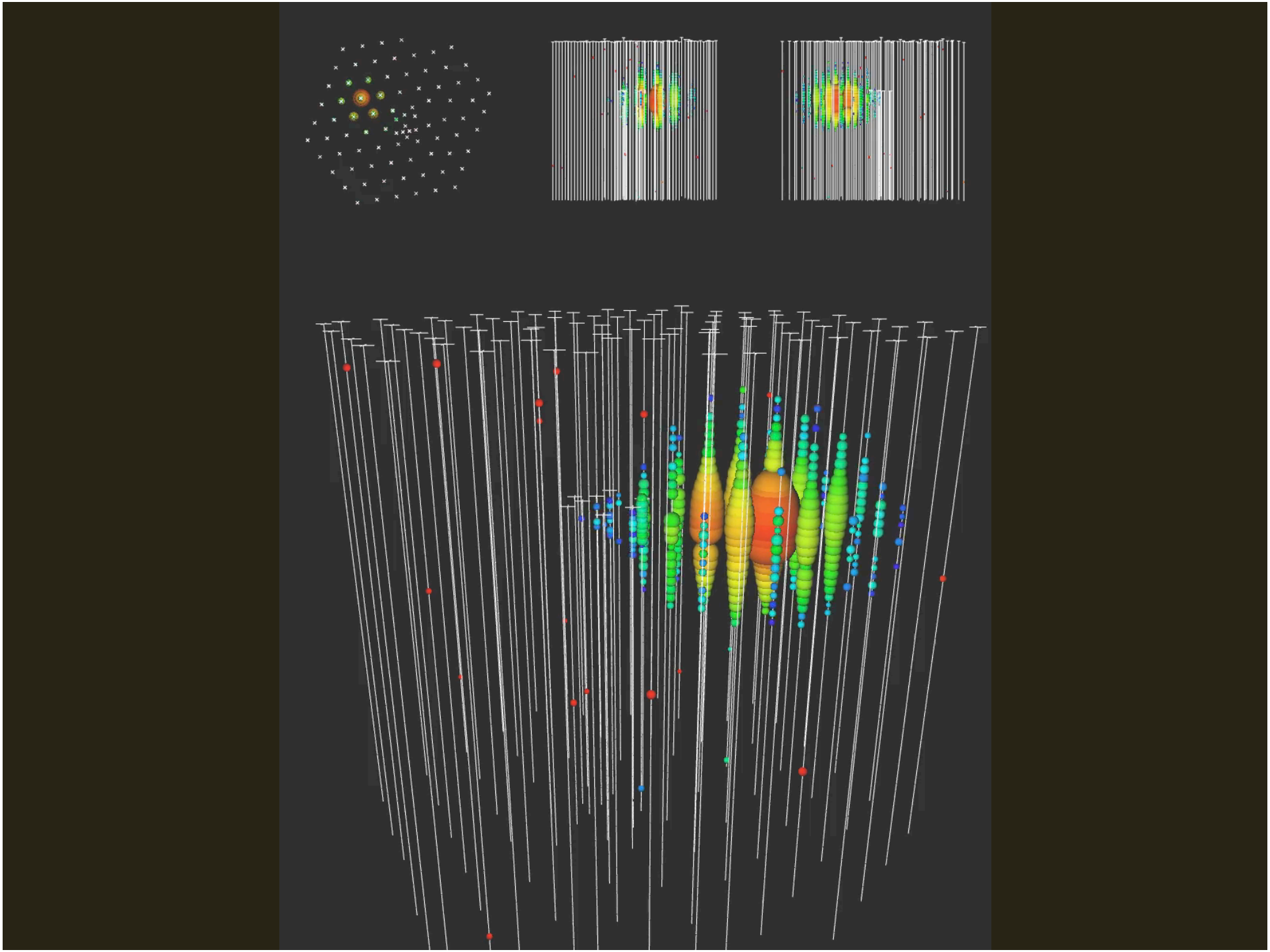


neutrinos of all flavors
interacting inside
IceCube

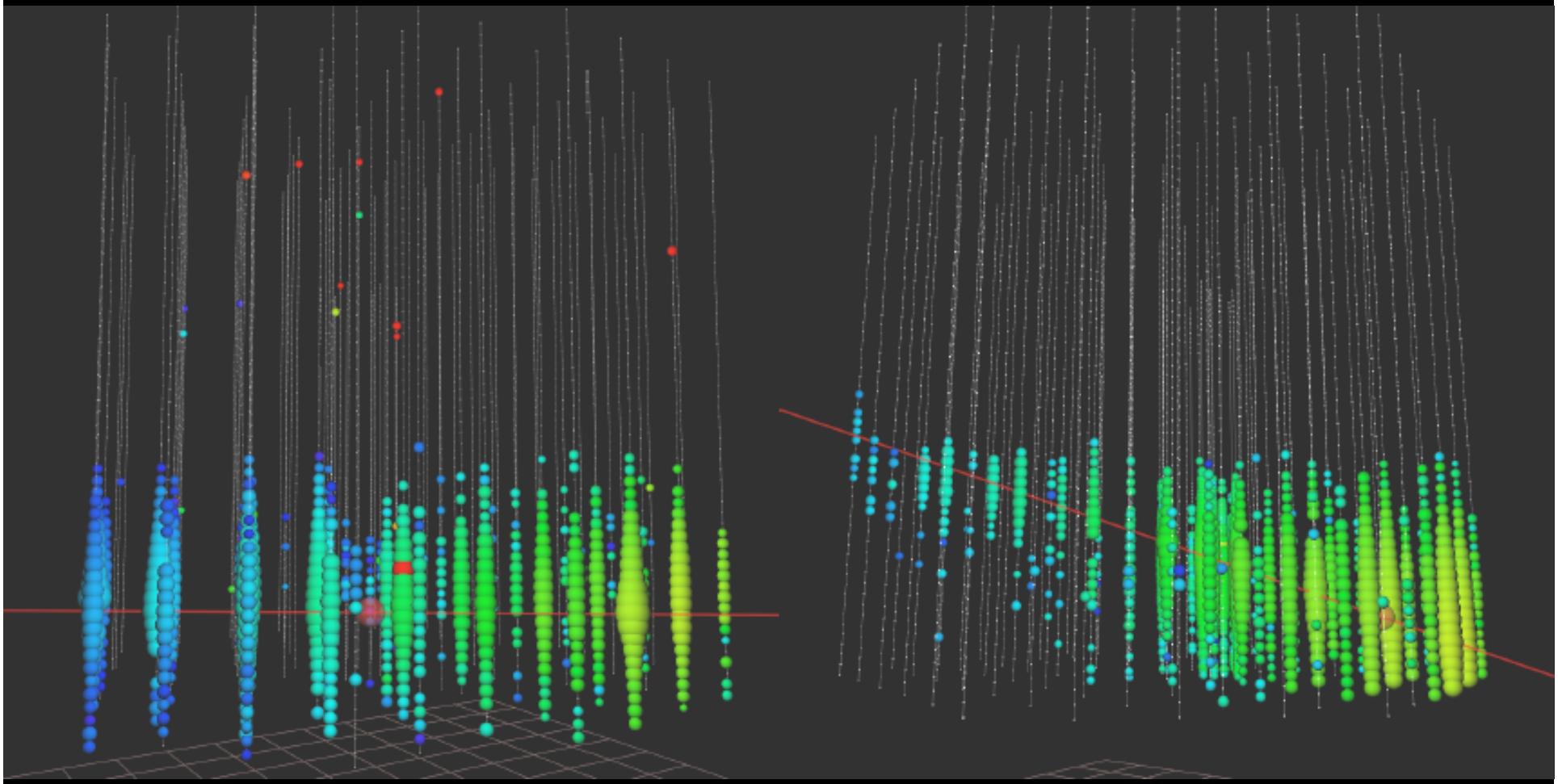
IceCube: transforms 1 km3 of natural Antarctic ice into a Cherenkov detector



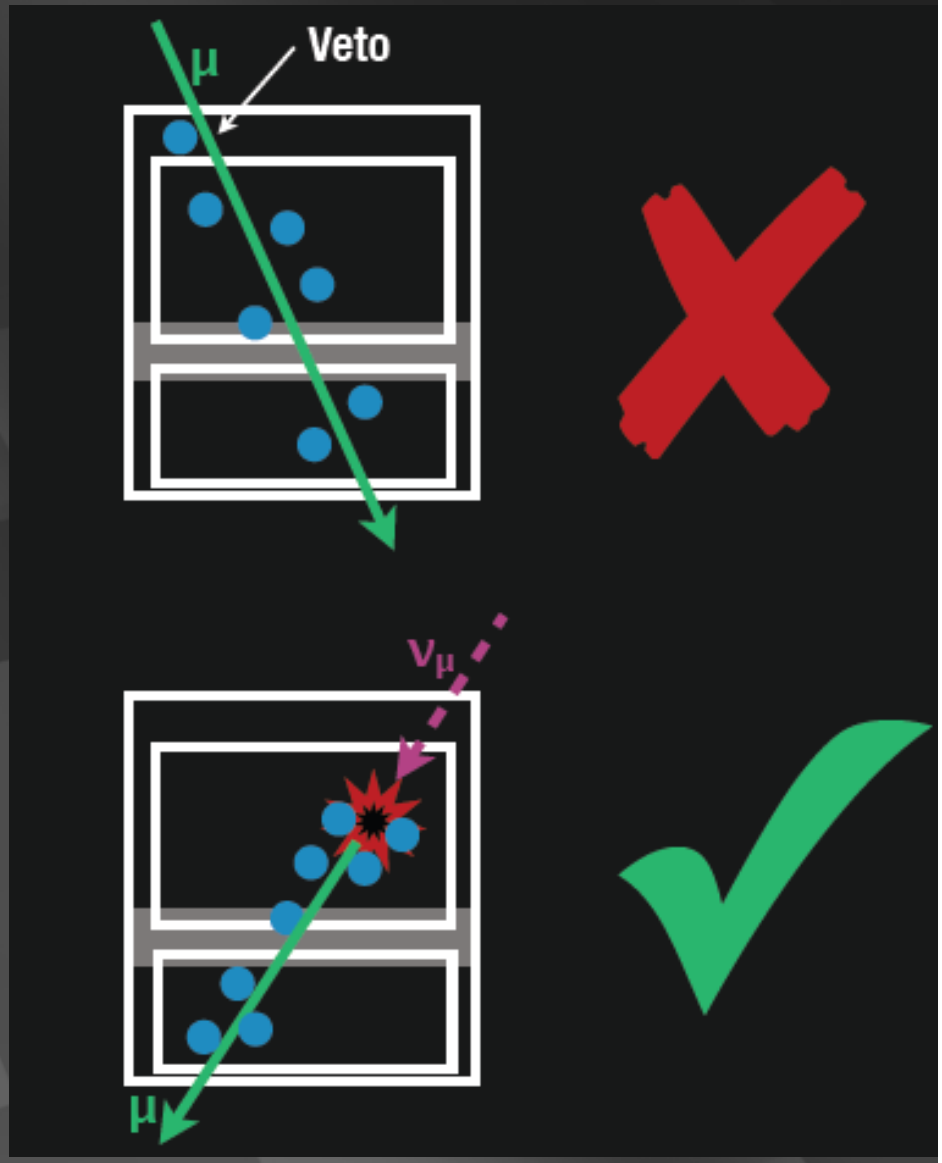




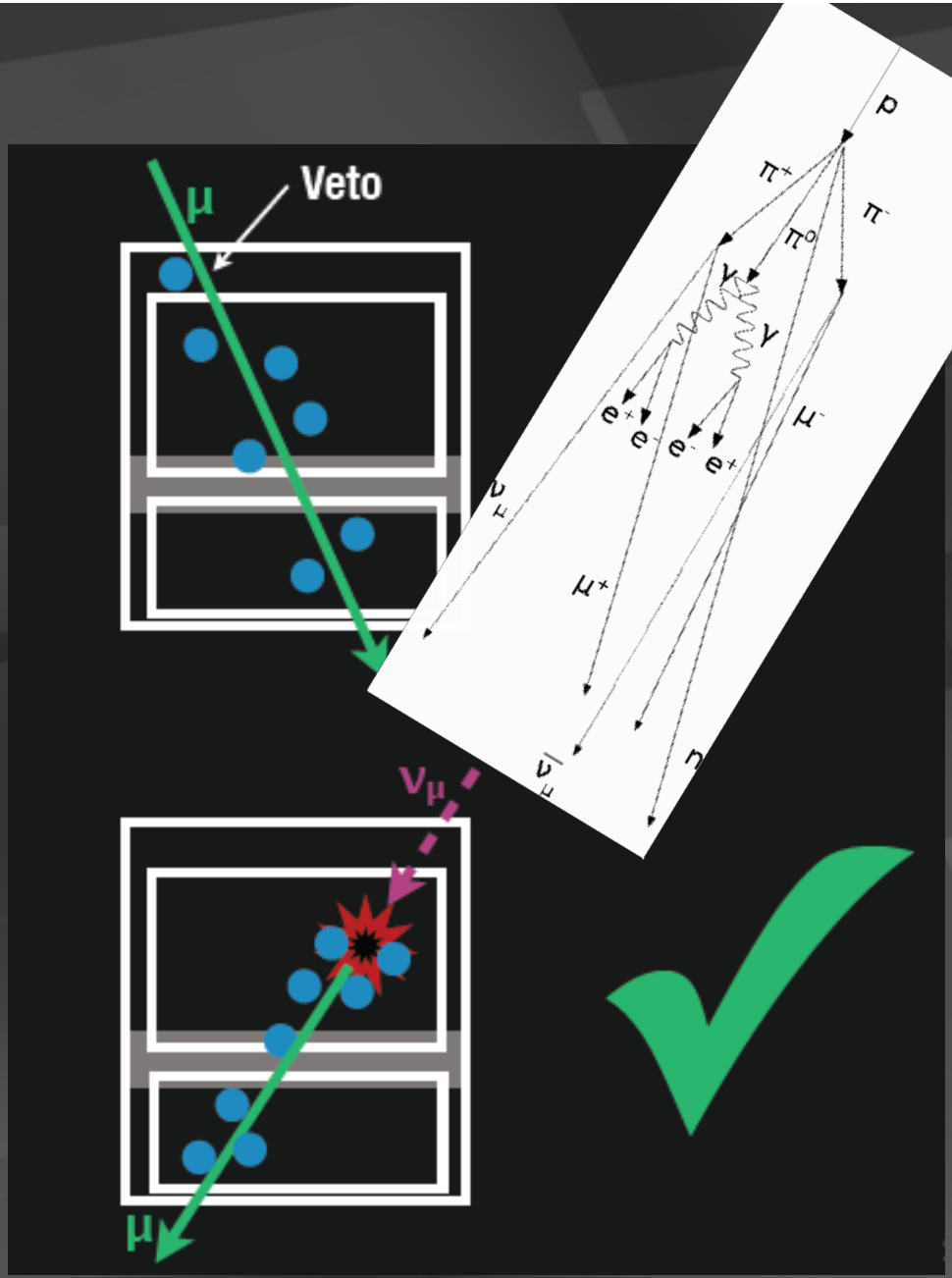
highest energy muon energy observed: 560 TeV

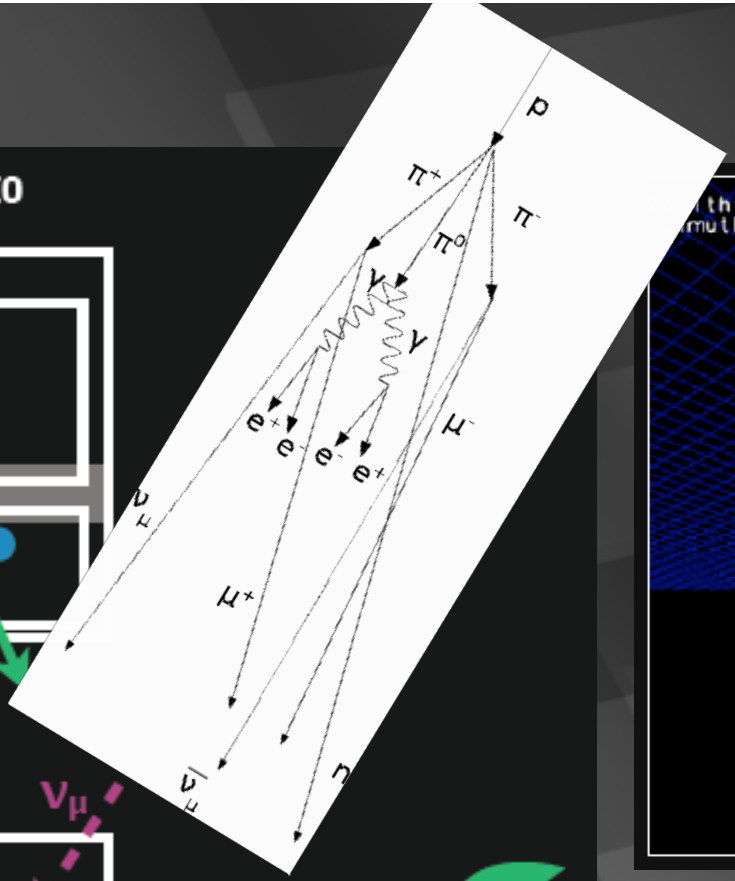


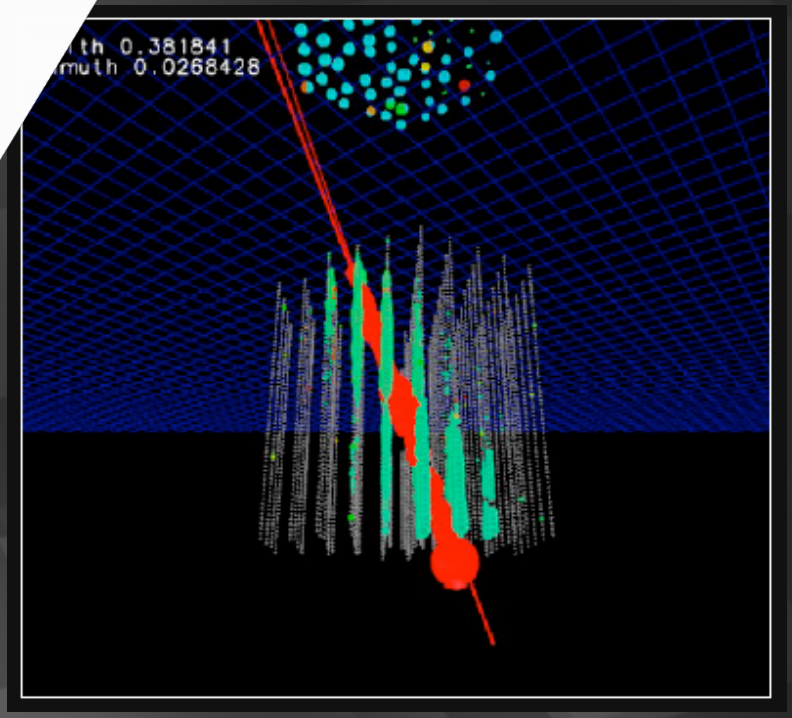
- find contained events (420 Mton)
- total calorimetry
- complete sky coverage
- flavor determined
- some will be muon neutrinos with good angular resolution



loss in statistics is compensated by event definition



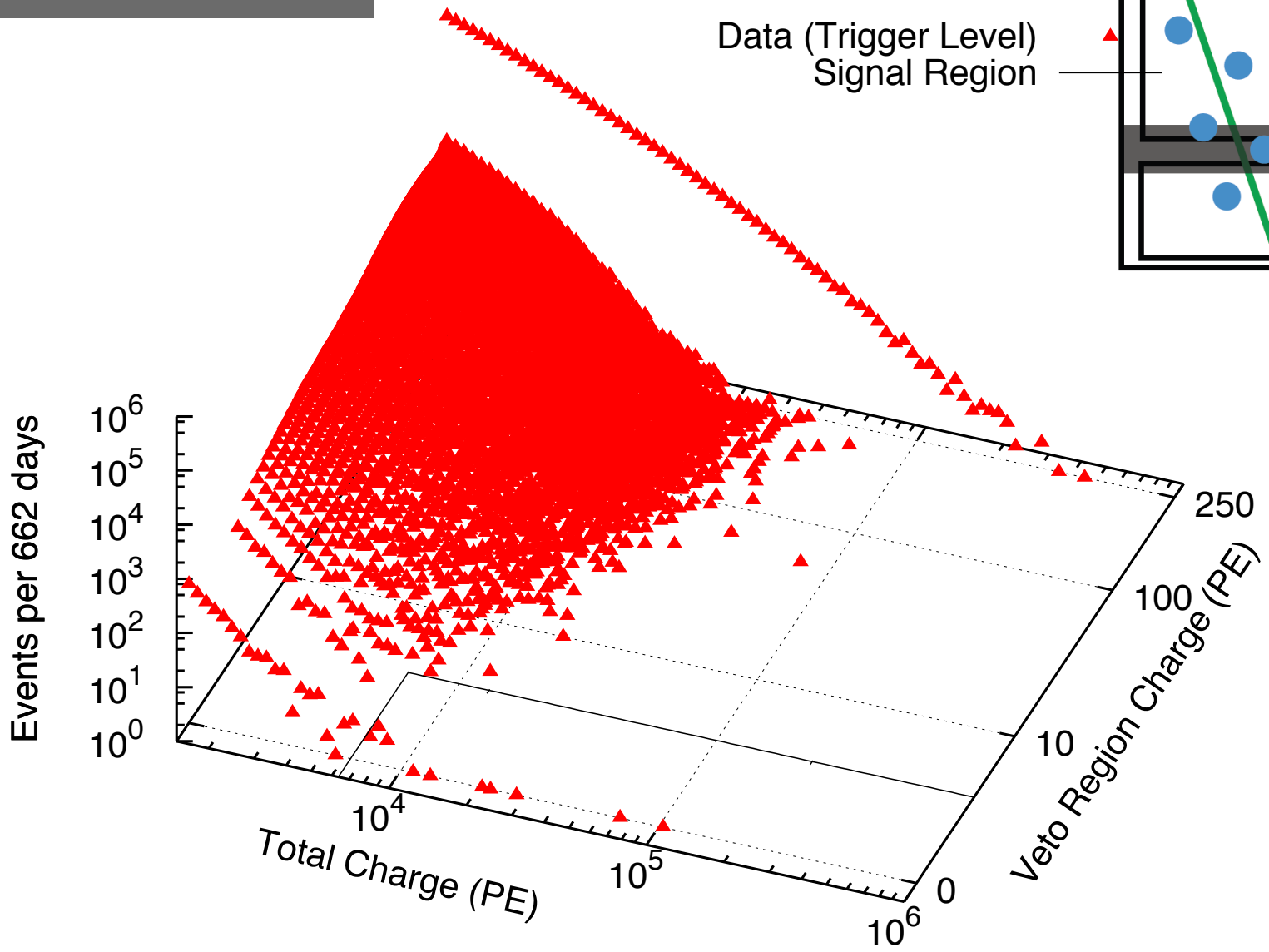


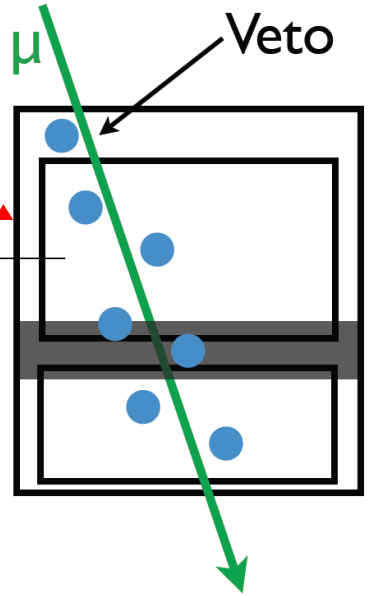


atmospheric neutrinos are accompanied by muons from the shower that produced them: none seen

(no signals in IceTop)

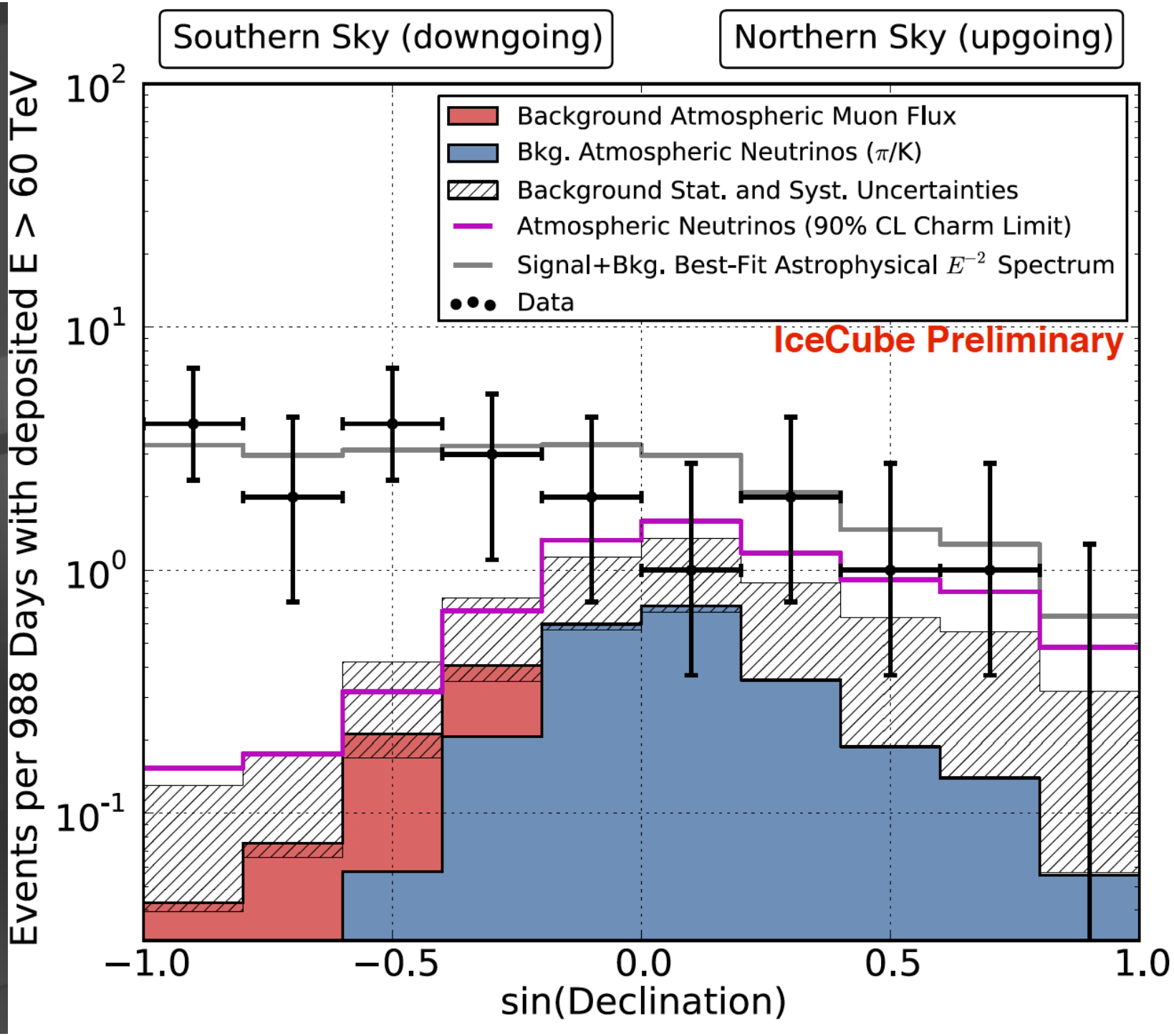
…and then there were 26 more…

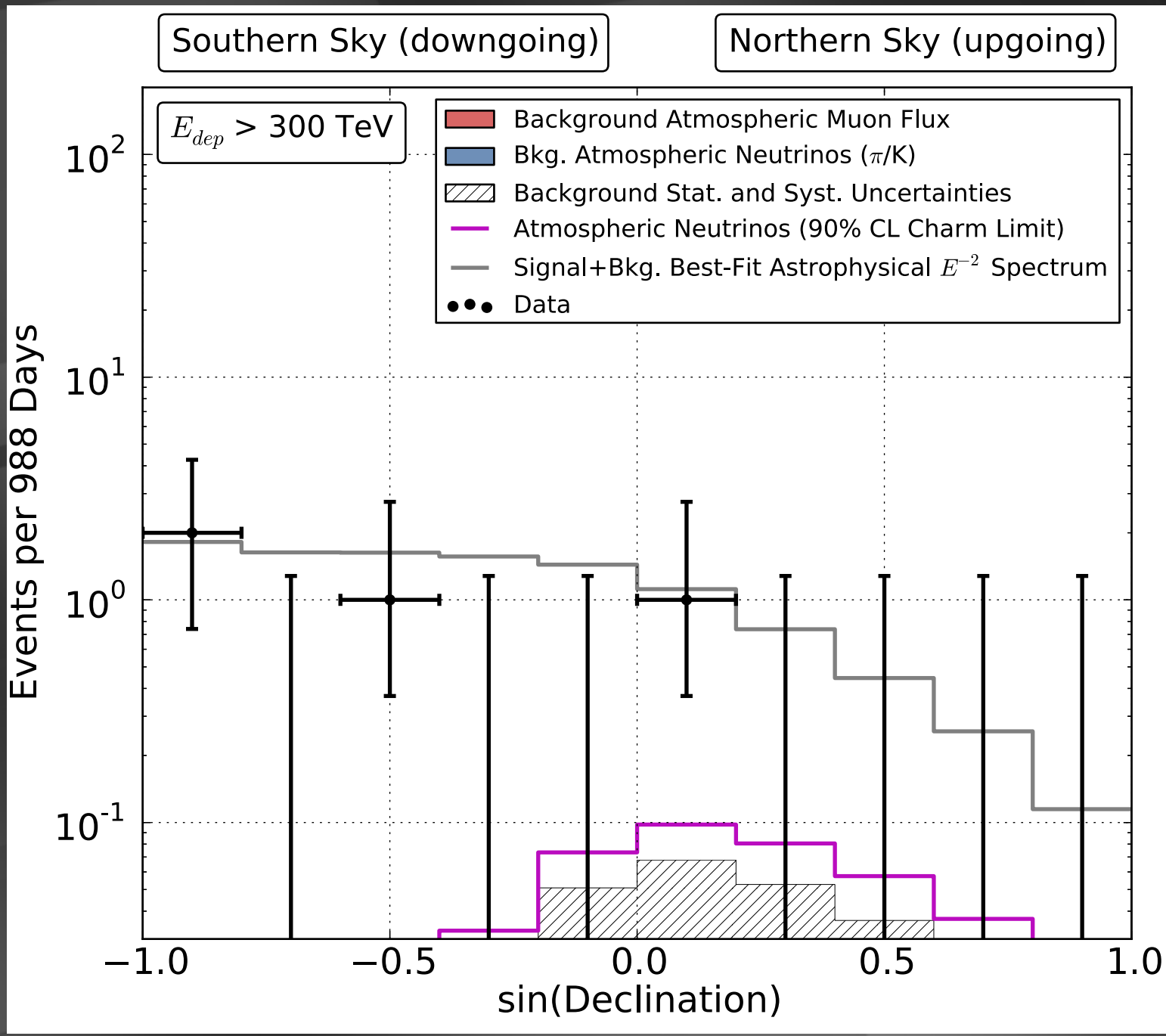




data: 86 strings one year

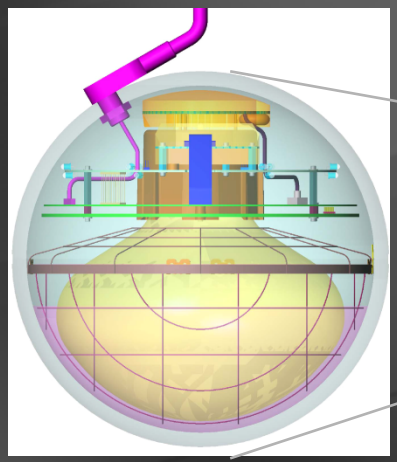
3 years


Southern Sky (downgoing)
Northern Sky (upgoing)
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
IceCube Preliminary
Events per 988 Days with deposited E > 60 TeV
10^2
10^1
10^0
10^{-1}
−1.0
−0.5
0.0
0.5
1.0
sin(Declination)

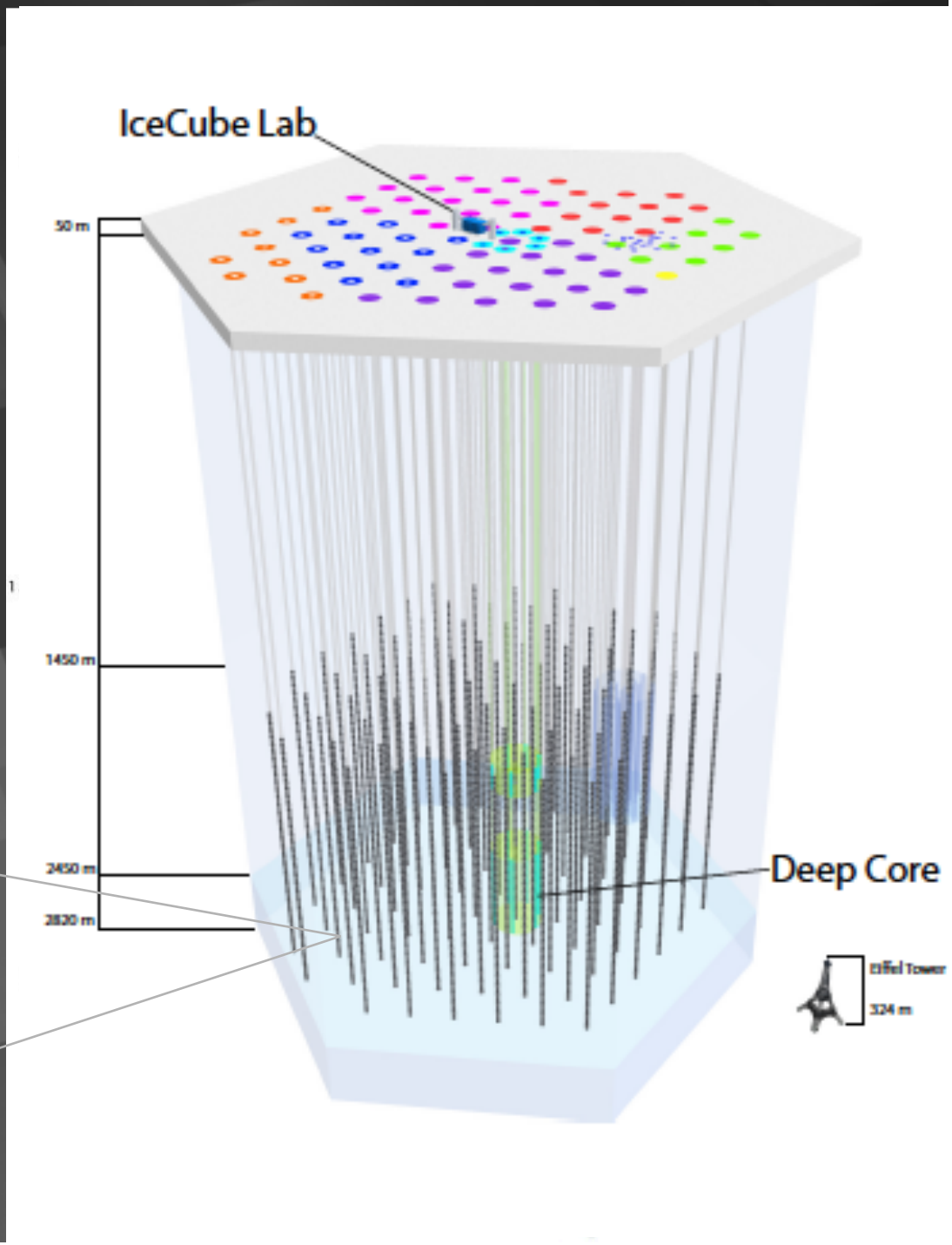

Southern Sky (downgoing)
Northern Sky (upgoing)
E_{dep} > 300 TeV
Background Atmospheric Muon Flux
Bkg. Atmospheric Neutrinos (π/K)
Background Stat. and Syst. Uncertainties
Atmospheric Neutrinos (90% CL Charm Limit)
Signal+Bkg. Best-Fit Astrophysical E^{-2} Spectrum
Data
Events per 988 Days
10^2
10^1
10^0
10^{-1}
−1.0
−0.5
0.0
0.5
1.0
sin(Declination)

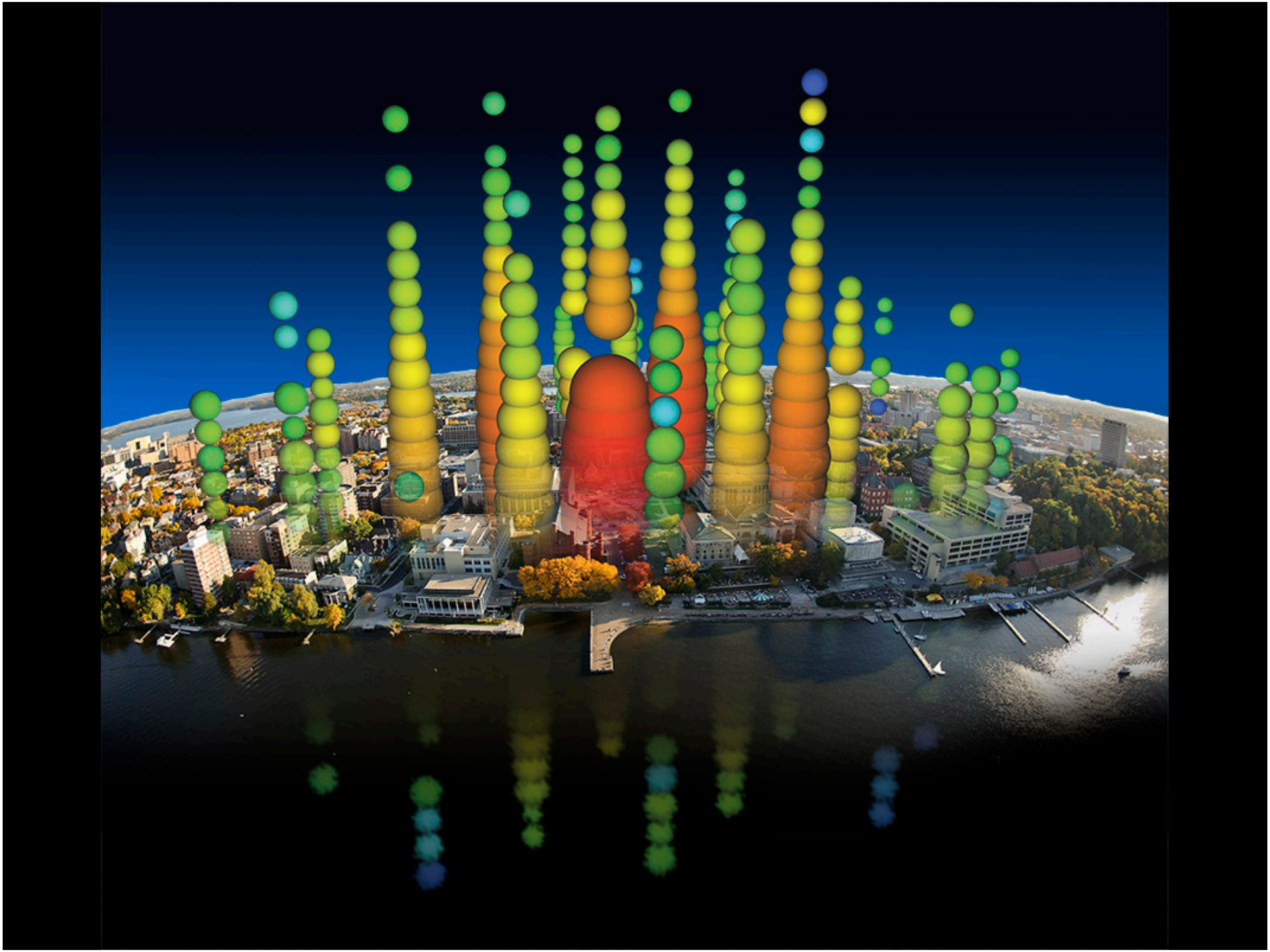
IceCube performance

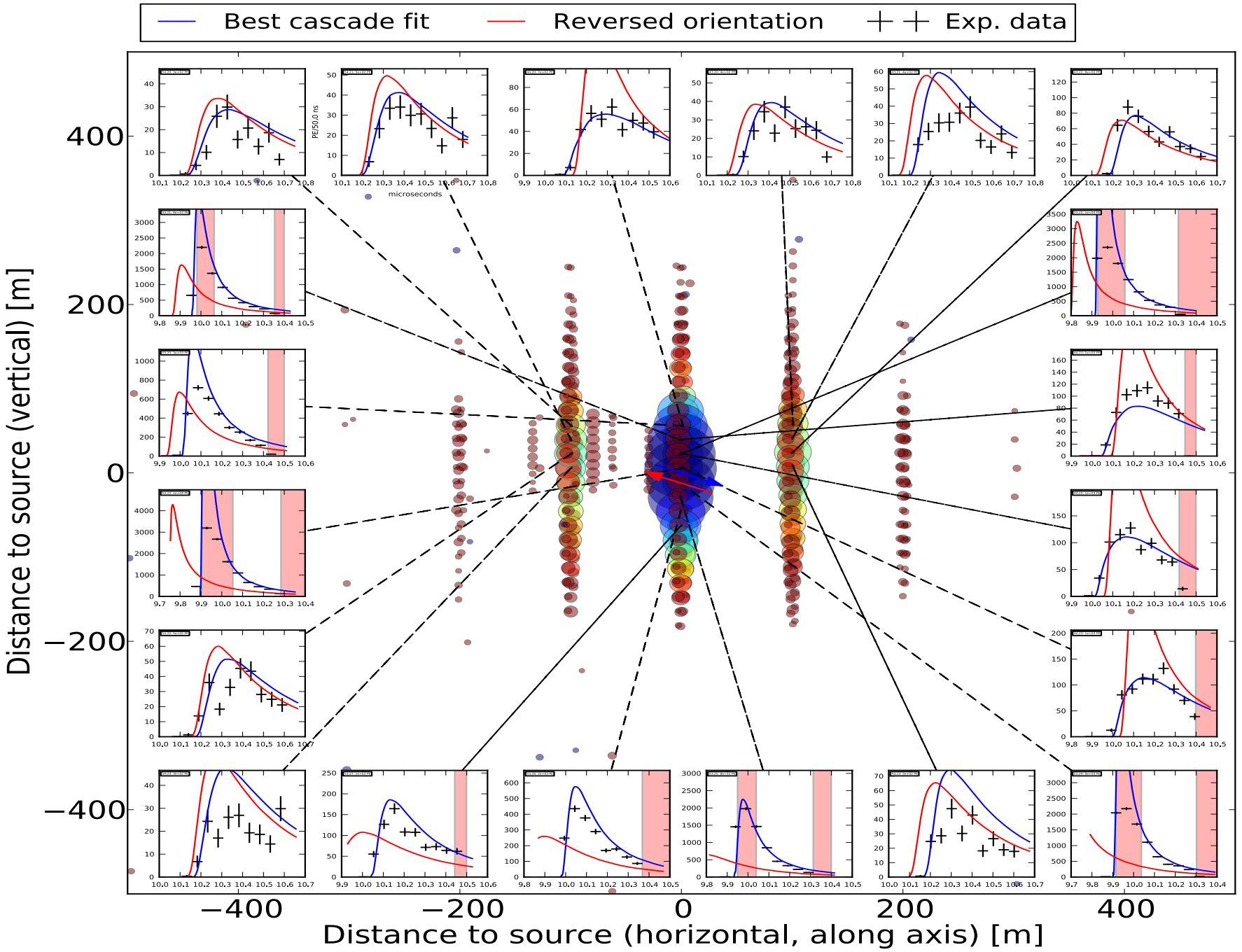
- 5160 optical sensors between 1.5 ~ 2.5 km
- 10 GeV to infinity
- < 0.5 degree on-line
  < 0.3 degree off line
  for muon tracks
  (10~15 degrees for showers)
- < 15% energy resolution

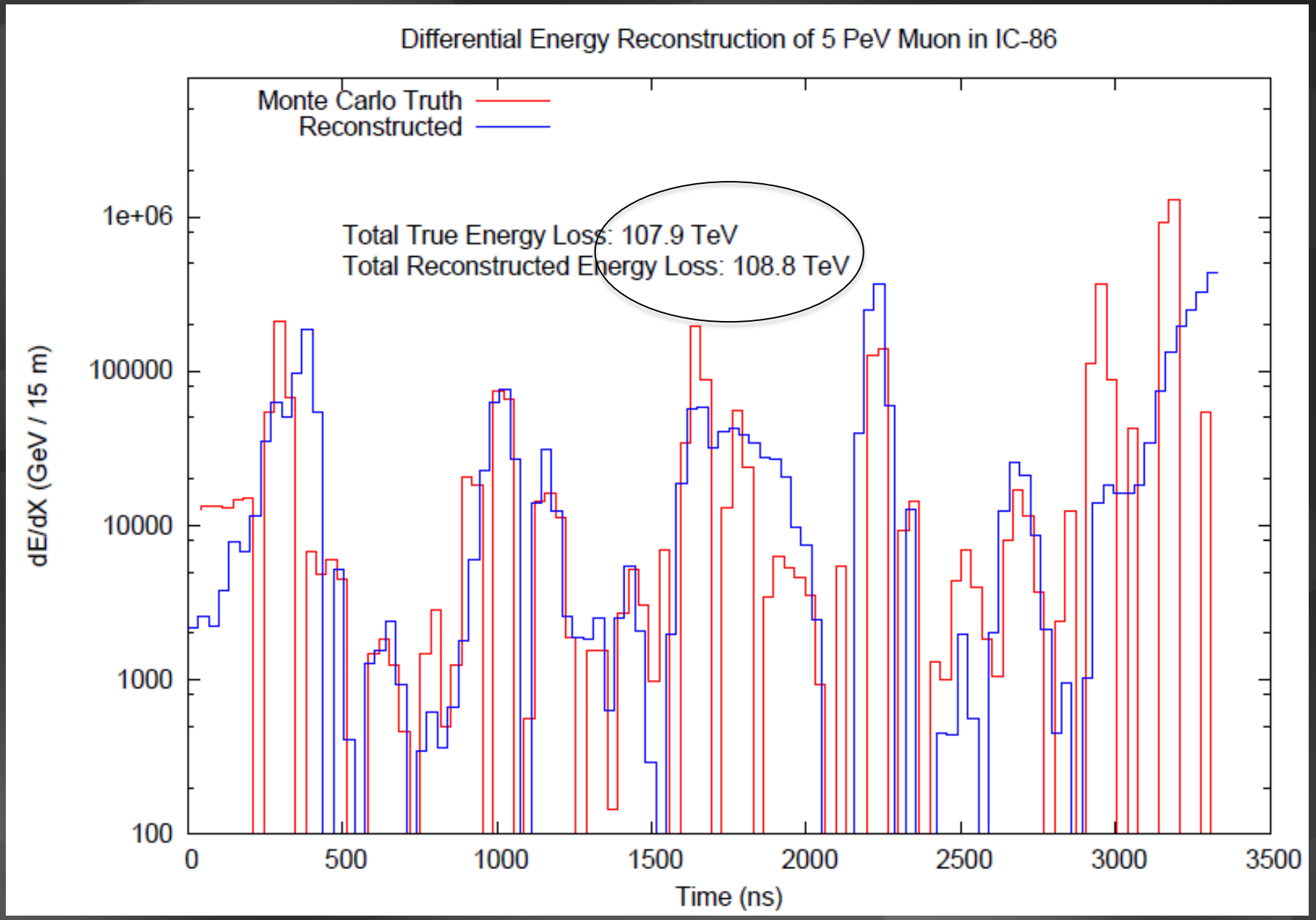


Digital Optical Module (DOM)



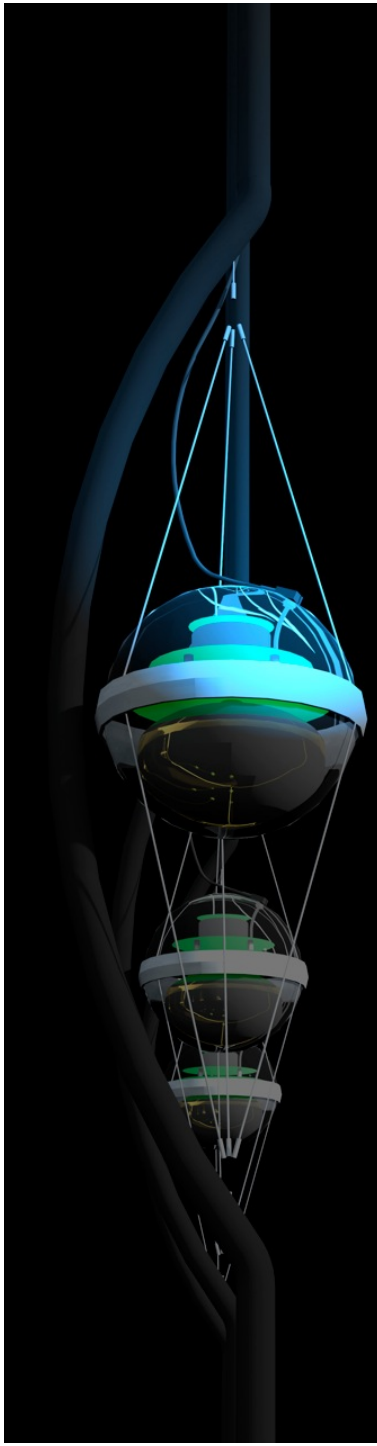



Best cascade fit
Reversed orientation
Exp. data
Distance to source (vertical) [m]
Distance to source (horizontal, along axis) [m]
400
200
0
−200
−400
PE/50.0 ns
microseconds



improving angular and energy resolution

… for science and for the experimental accomplishment of building IceCube …

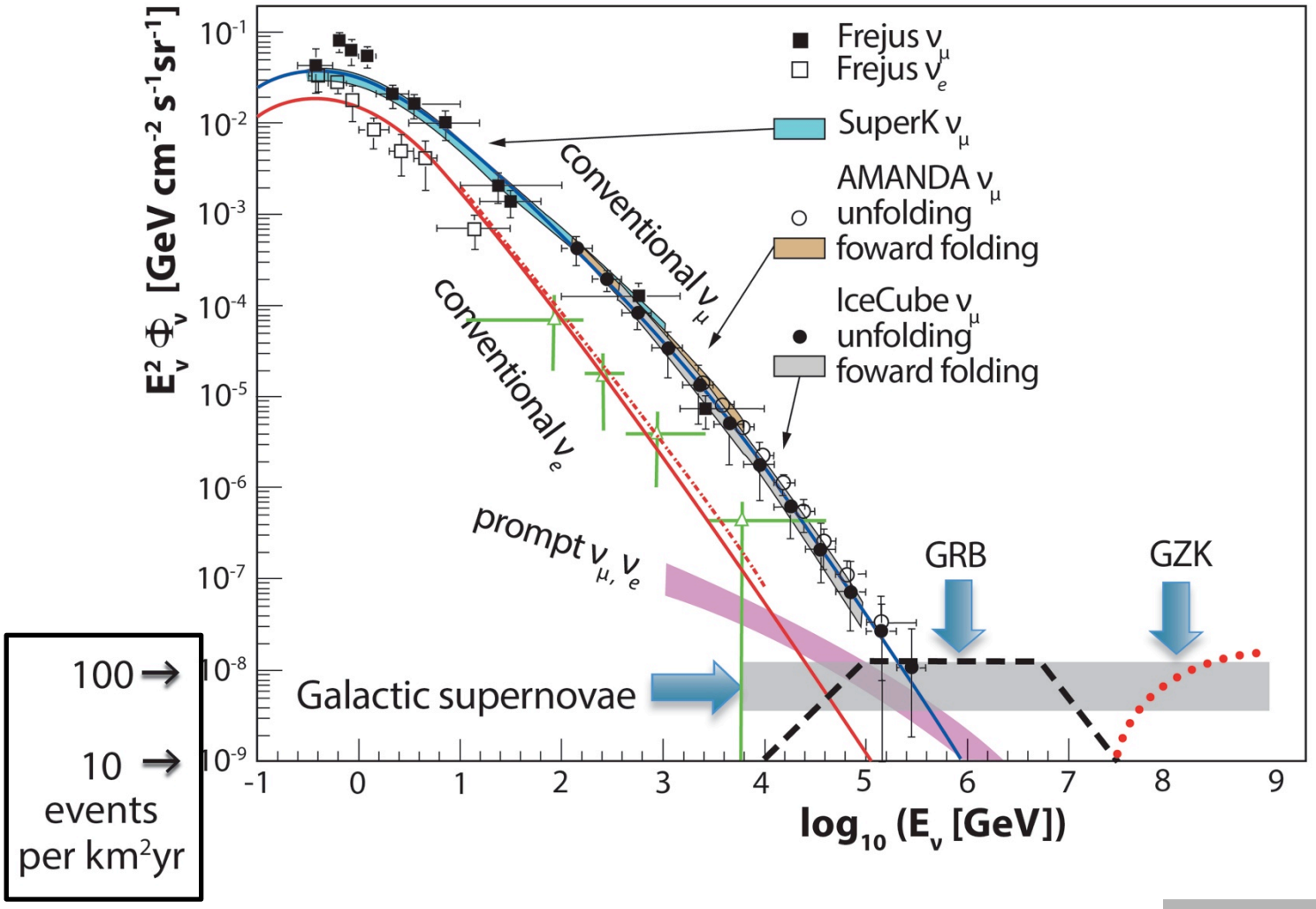


Beyond IceCube

francis halzen

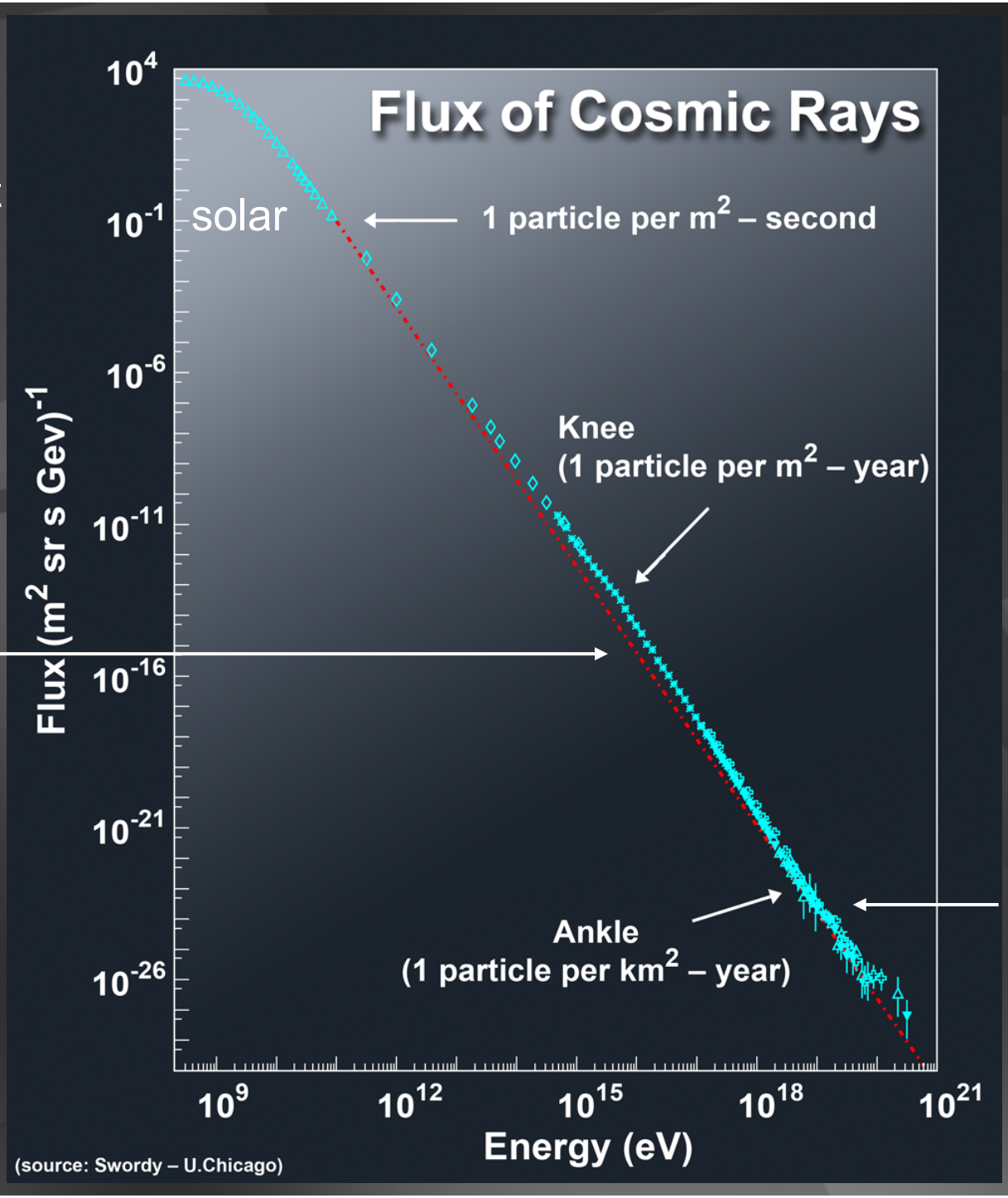
- the discovery of high-energy cosmic neutrinos
- where do they come from?
- neutrino stars?
- cosmogenic neutrinos
- beyond IceCube
- low threshold frontier (PINGU)

rationale for a kilometer-scale detector



$$\Phi_\nu \equiv \frac{dN}{dE} \approx \frac{1}{E^2}$$

sources that accommodate the observed energy budget

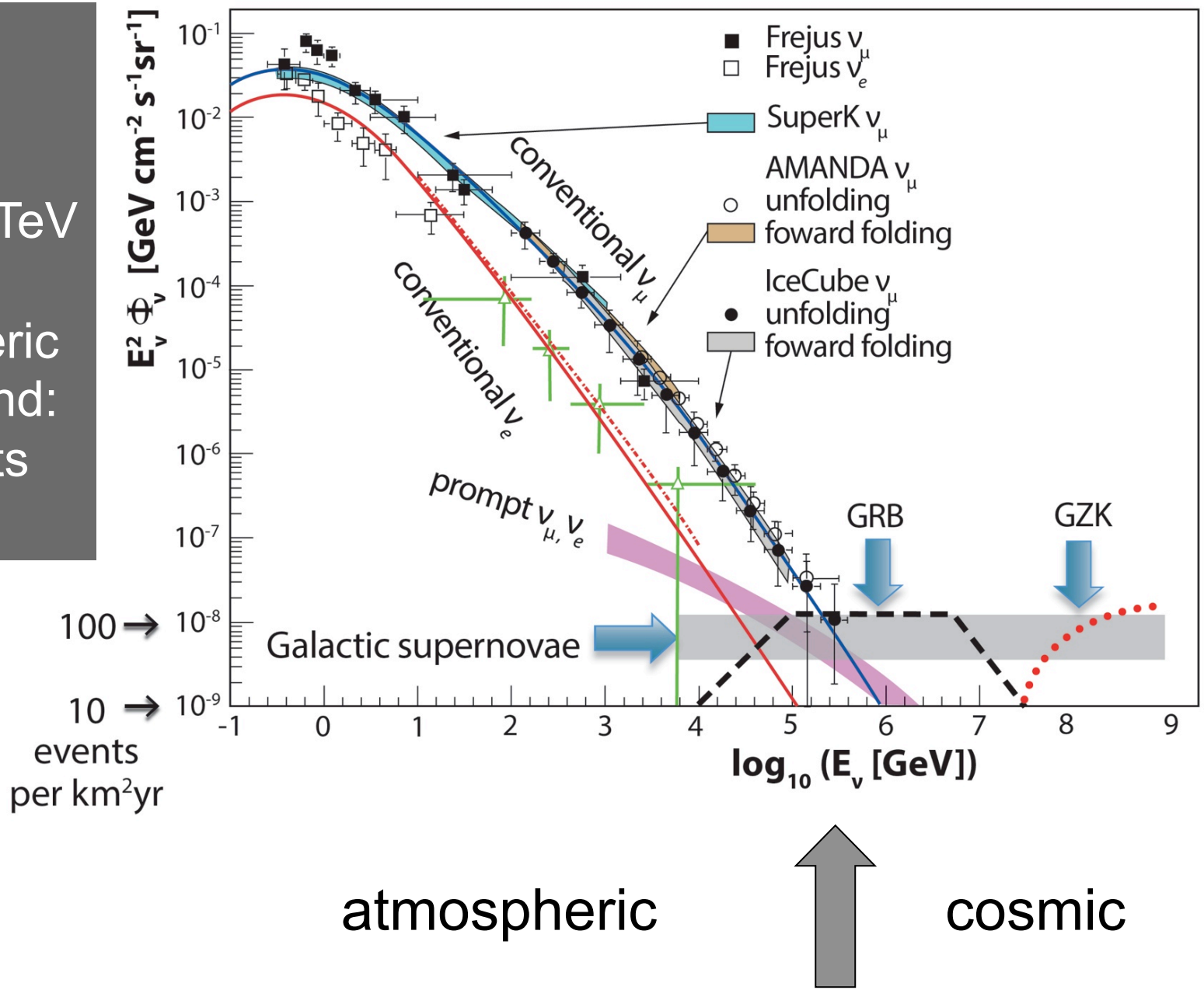


Galactic: supernova remnants?

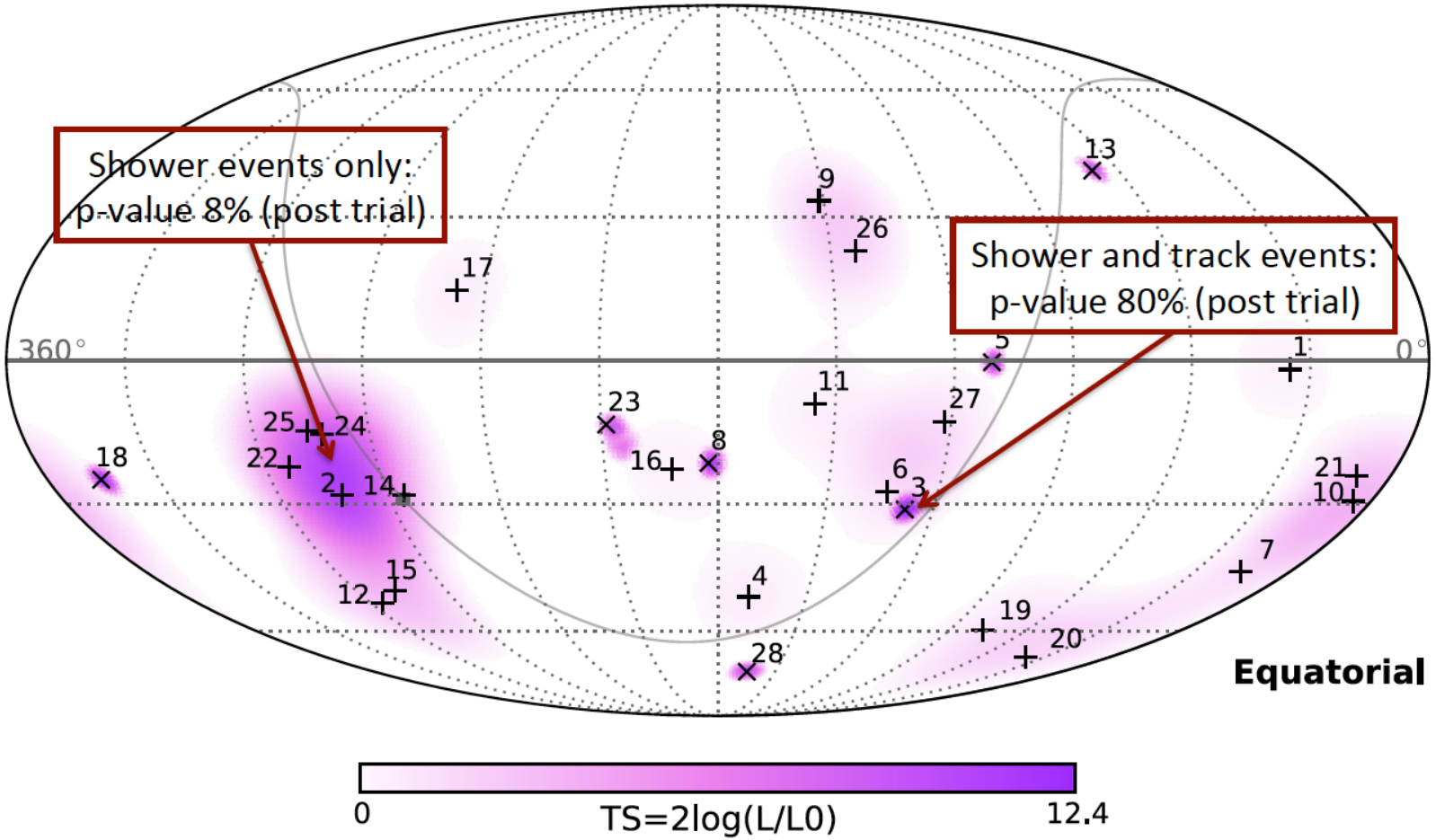
extragalactic:

- gamma ray bursts??
- active galaxies?

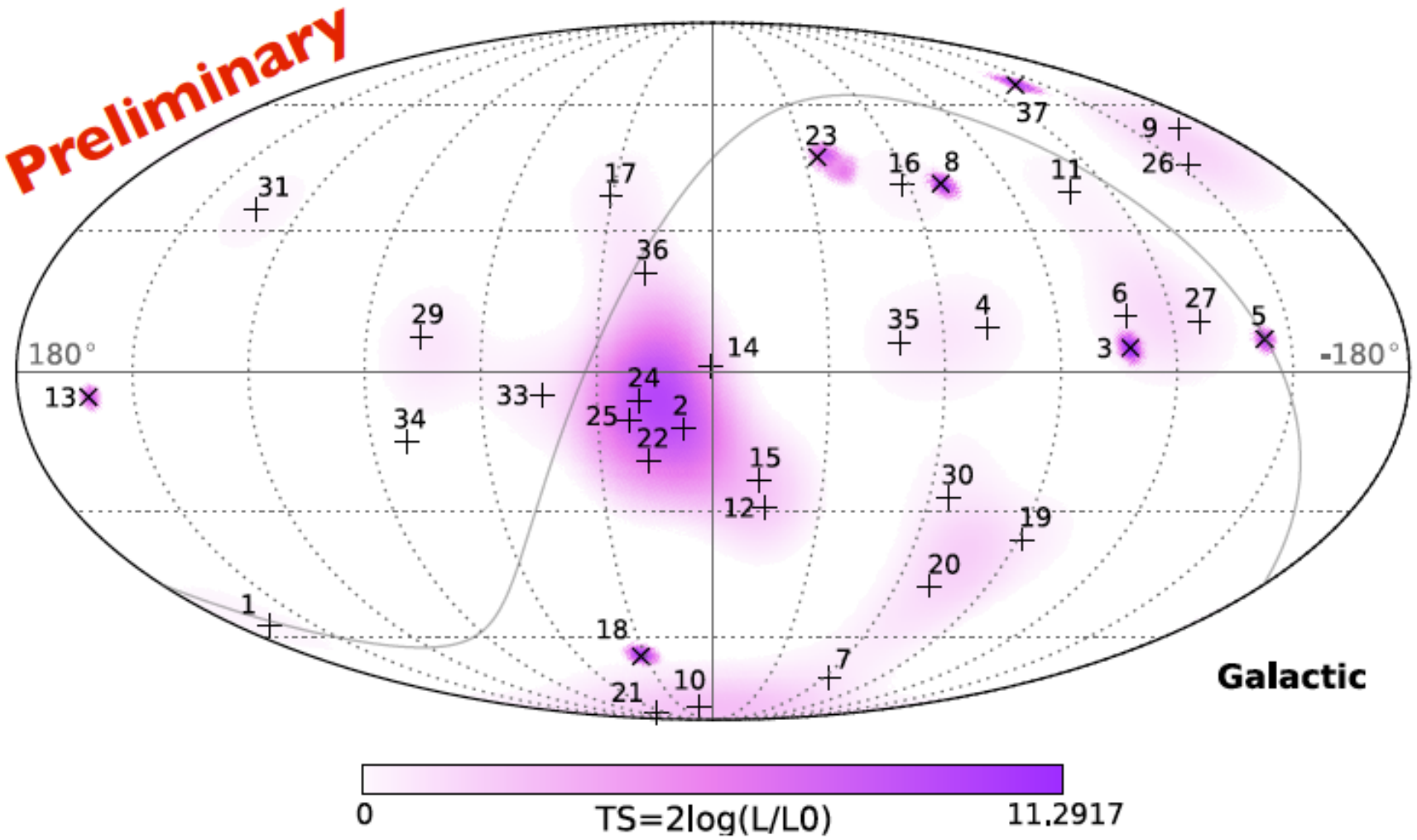
- cosmic neutrinos: energy > 100 TeV
- atmospheric background: 1~2 events per year

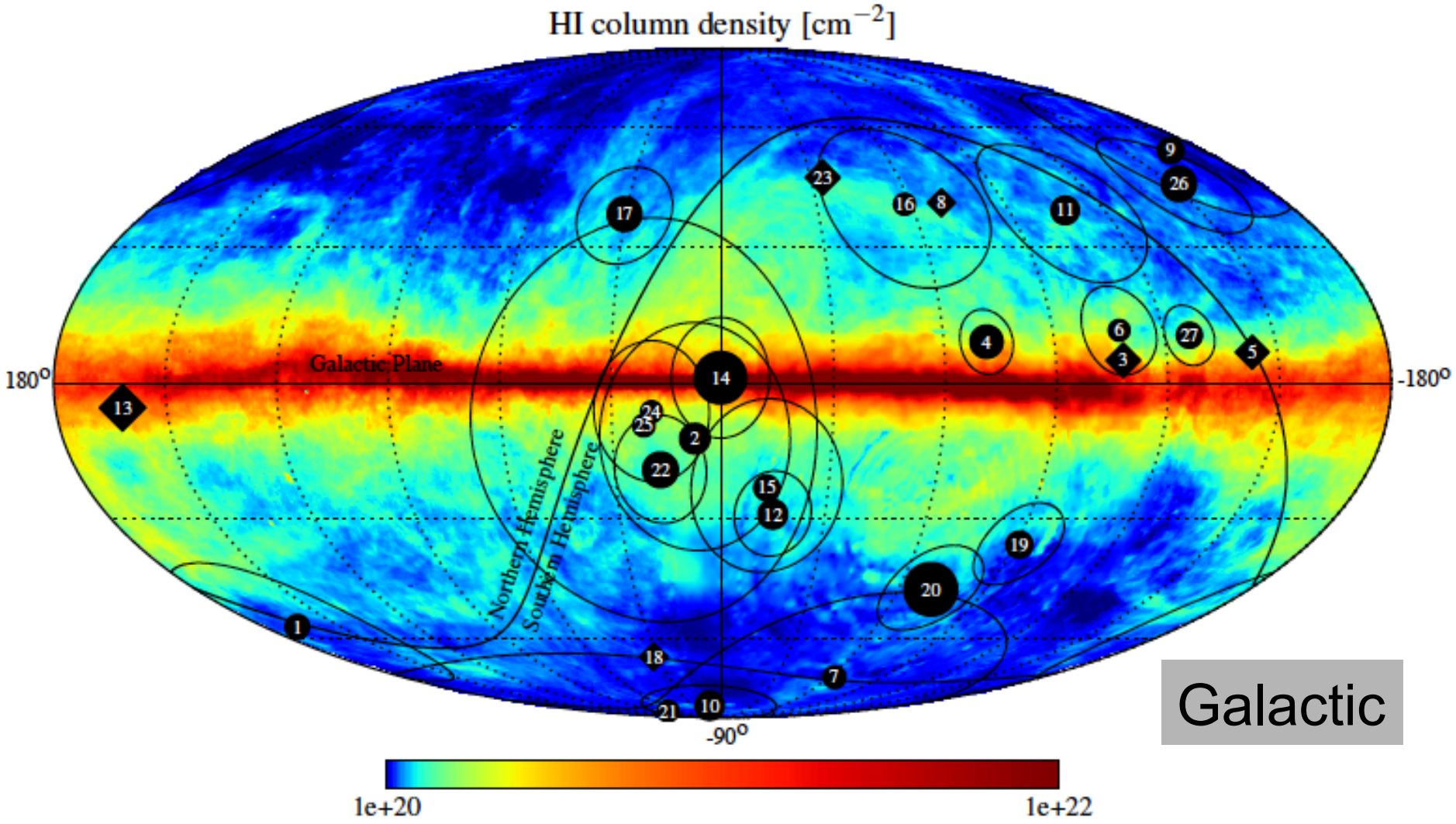


where do they come from?



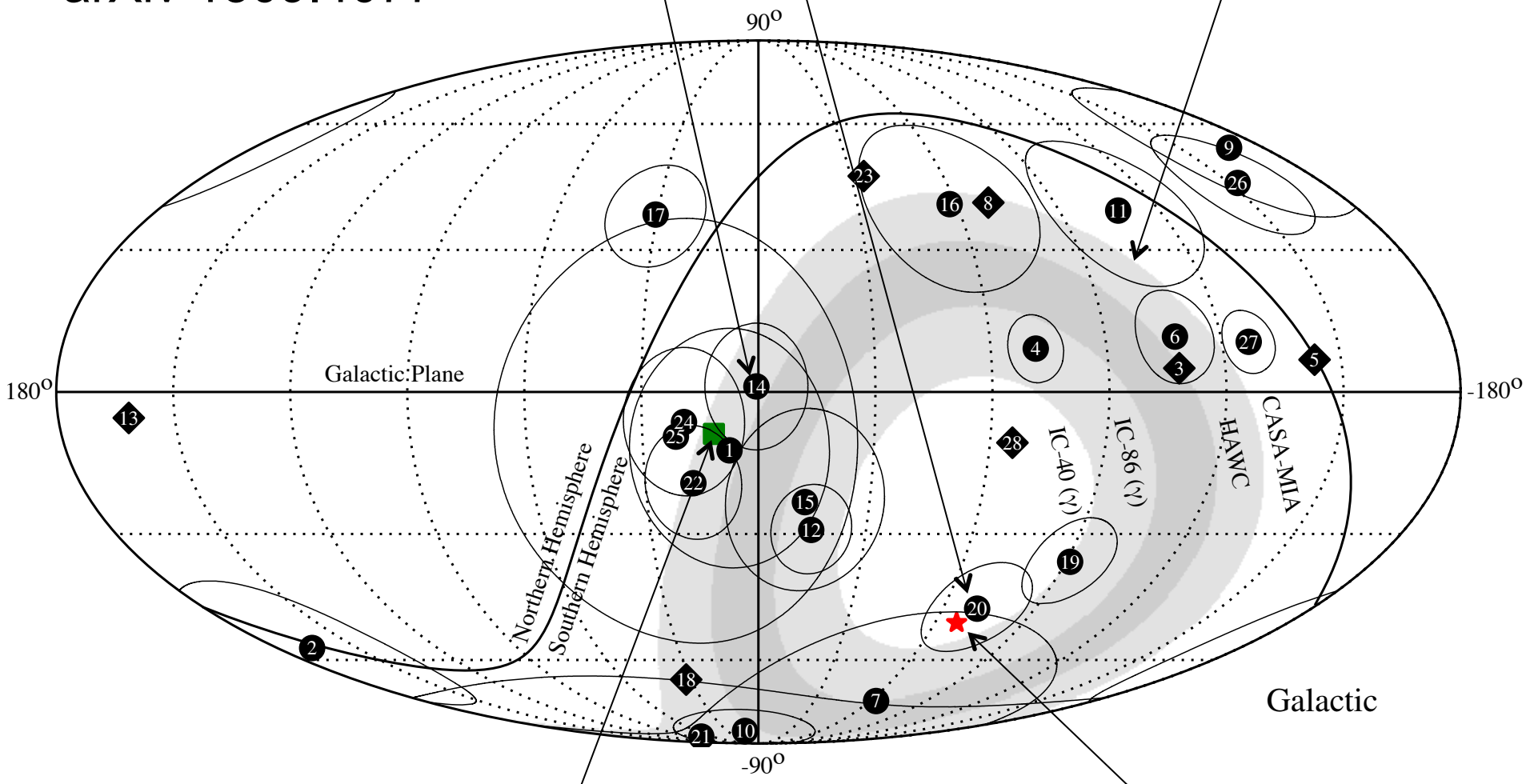
where do they come from (3 year data)?



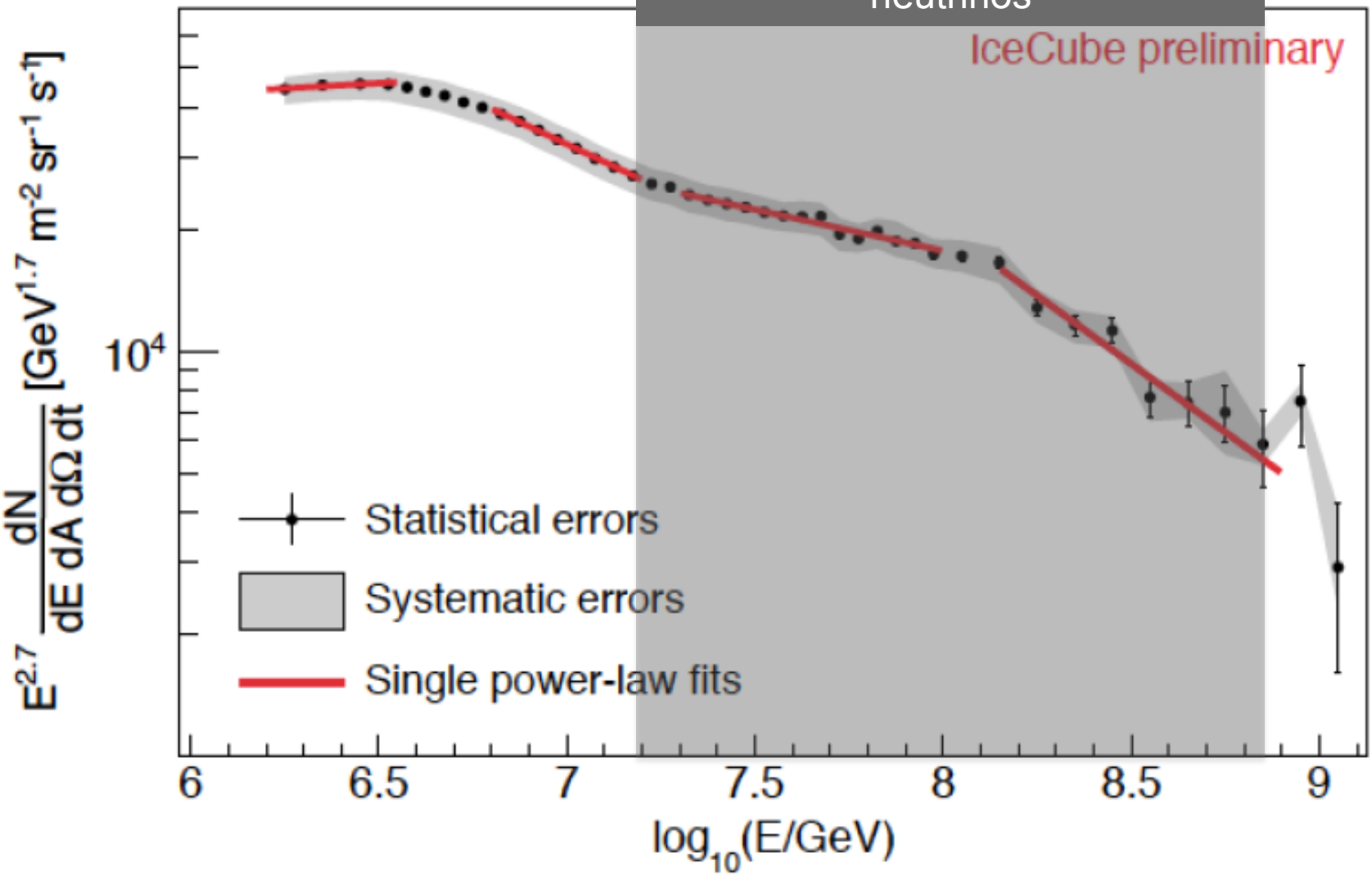

HI column density [cm^{-2}]
Galactic Plane
Northern Hemisphere
Southern Hemisphere
180°
-180°
-90°
1e+20
1e+22
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27

Galactic

Galactic coordinates
arXiv 1309.4077

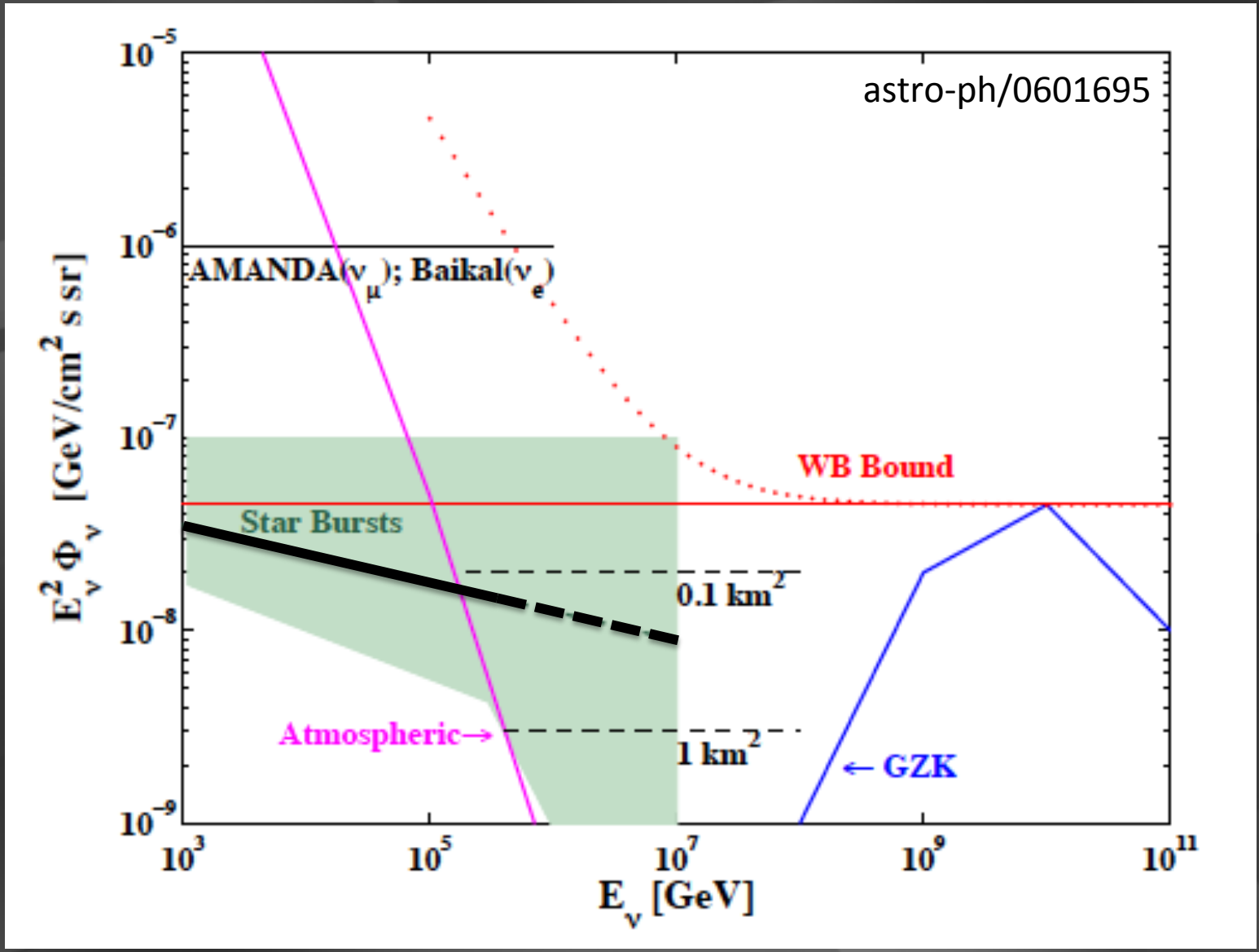


the energy range of cosmic accelerators producing PeV neutrinos

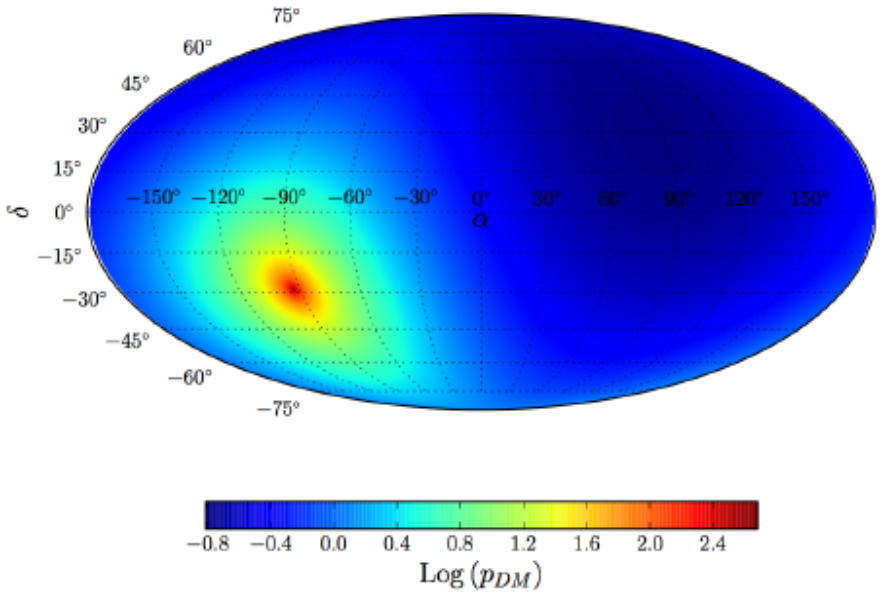


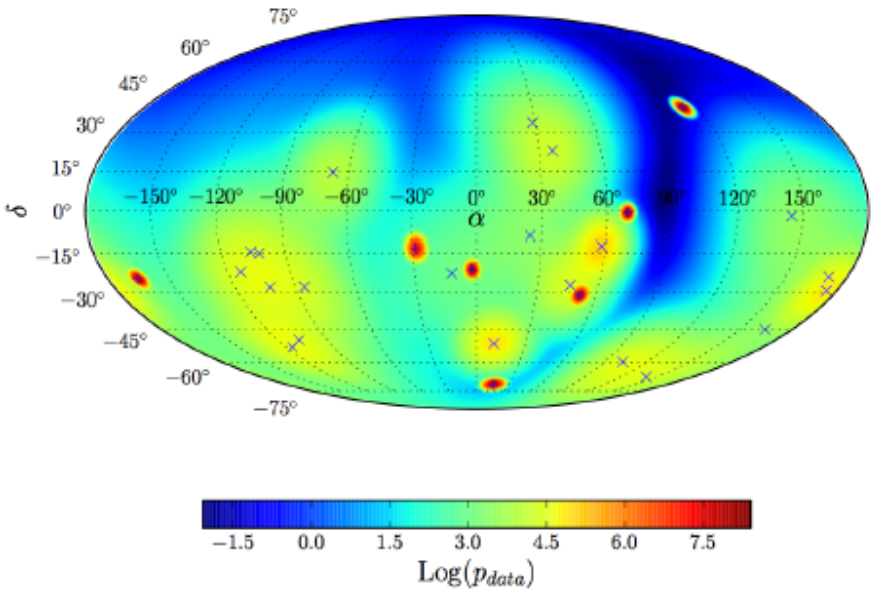
Galactic or extragalactic?

you have one guess: starburst galaxies ?



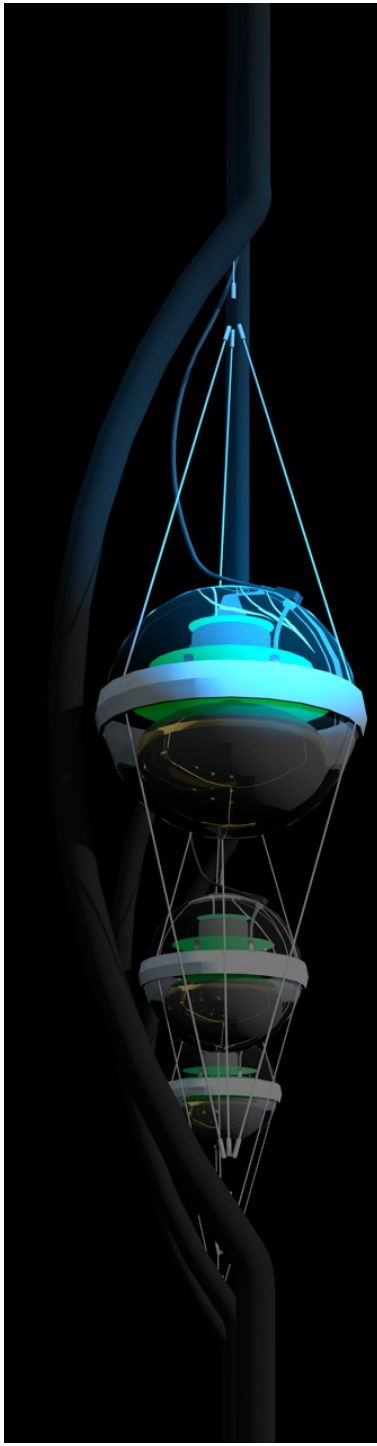
expect surprises: produced by Galactic dark matter halo?





where do they come from?

- not all Galactic
- structure of the spectrum applies directly to the accelerator, no cascading like for photons
- where are the PeV photons?
- we may be surprised, it happened before
- need more events: no SCO-X1, more like Martin Ryle's radio stars



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IceCube.wisc.edu

search for point sources of neutrinos

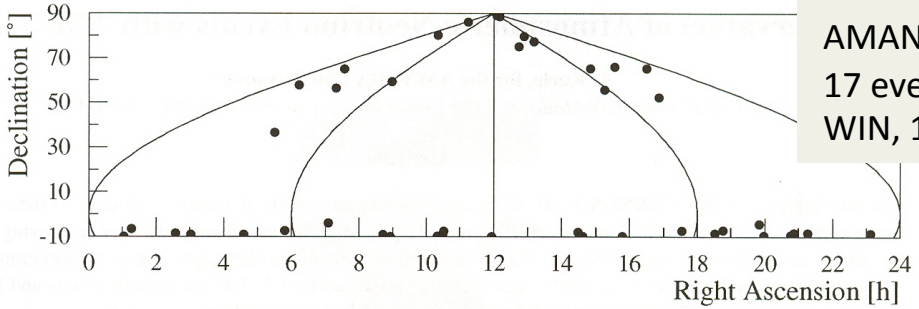
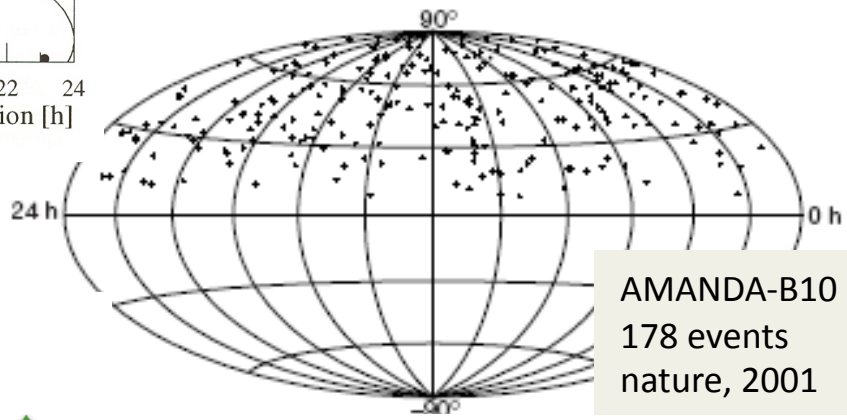
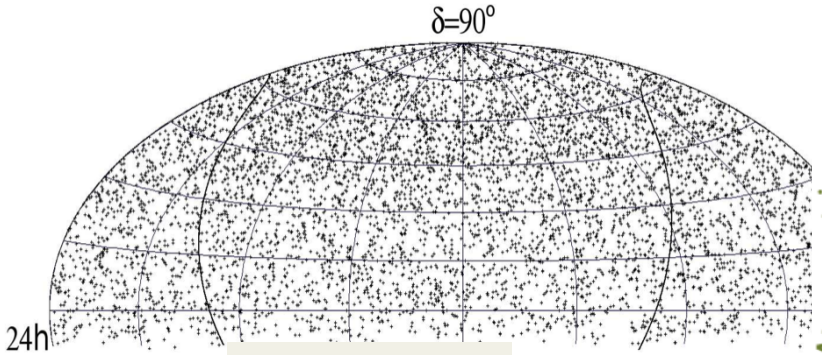


Figure 2: Sky plot of all events that pass level 4 quality cuts.

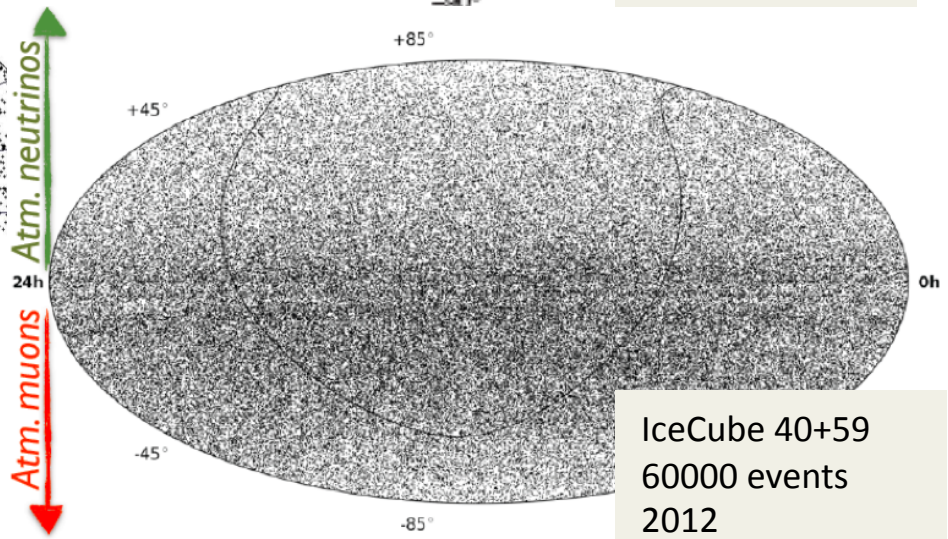
AMANDA-B10
17 events
WIN, 1999



AMANDA-B10
178 events
nature, 2001



AMANDA-II
7 years
6995 events
2006



IceCube 40+59
60000 events
2012

auto correlation: detect association with known sources

total number of events required to observe
n-events multiplets from the closest sources is

$$370 \times \mathrm{n} \times \left[\frac{\rho_0}{10^{-5}}\right]^{\frac{1}{3}} \text{ events}$$

for a observed diffuse cosmic flux and 0.4 degrees angular resolution

examples of local source densities (per Mpc^3):

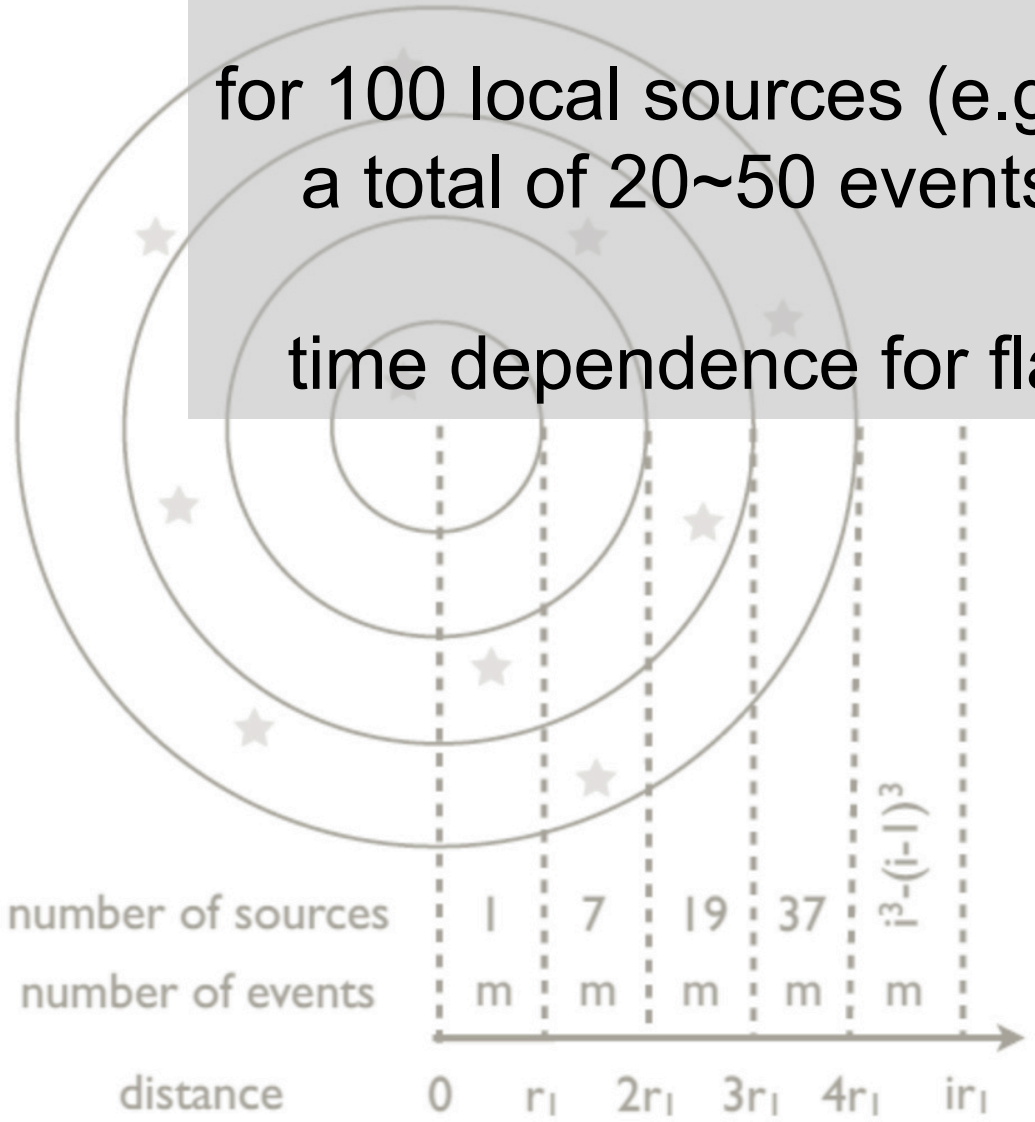
- $10^{-3} - 10^{-2}\,\mathrm{Mpc}^{-3}$ for **normal galaxies**
- $10^{-5} - 10^{-4}\,\mathrm{Mpc}^{-3}$ for **active galaxies**
- $10^{-7}\,\mathrm{Mpc}^{-3}$ for **massive galaxy clusters**
- $> 10^{-5}\,\mathrm{Mpc}^{-3}$ for **UHE CR sources**

Identification of Extra-Galactic Point Sources?

cross correlation with catalogues:

for 100 local sources (e.g. Auger and TA)
a total of 20~50 events are required

time dependence for flaring sources!



- total number of sources

$$n_s \simeq 10^6 - 10^7$$

- total number of "slices"

$$n_{\text{slice}} = (n_s)^{\frac{1}{3}}$$

- total number of events

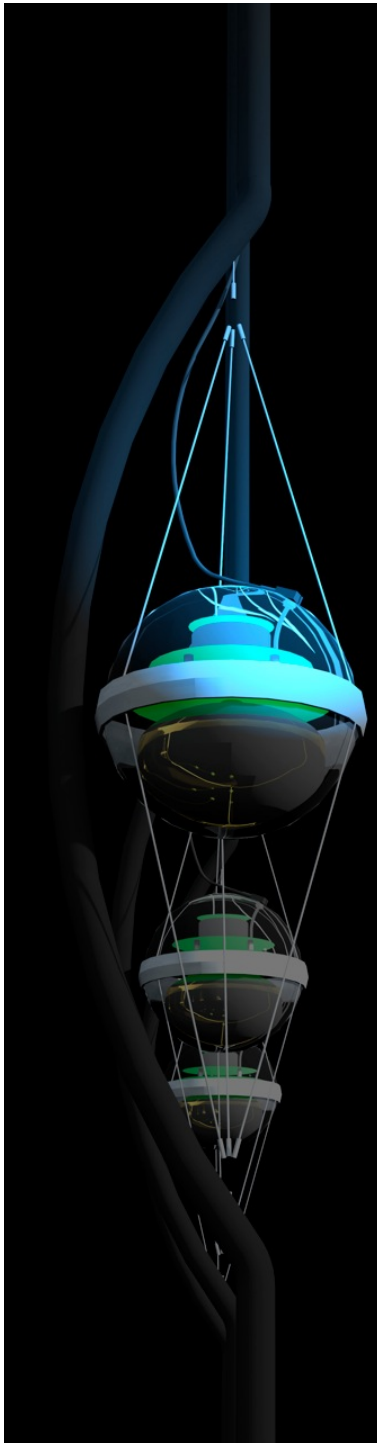
$$\bar{N} \simeq m \times n_{\text{slice}} = m \times (n_s)^{\frac{1}{3}}$$

✔ required number of events to see a doublet ($m = 2$)

$$\bar{N} \simeq 200 - 500$$

✘ random clusters are very likely with bad angular resolusion!

a next-generation IceCube with a volume of 10 km^3 and an angular resolution of < 0.5 degrees will identify the sources of a “diffuse” flux in several years and guarantee astronomy.



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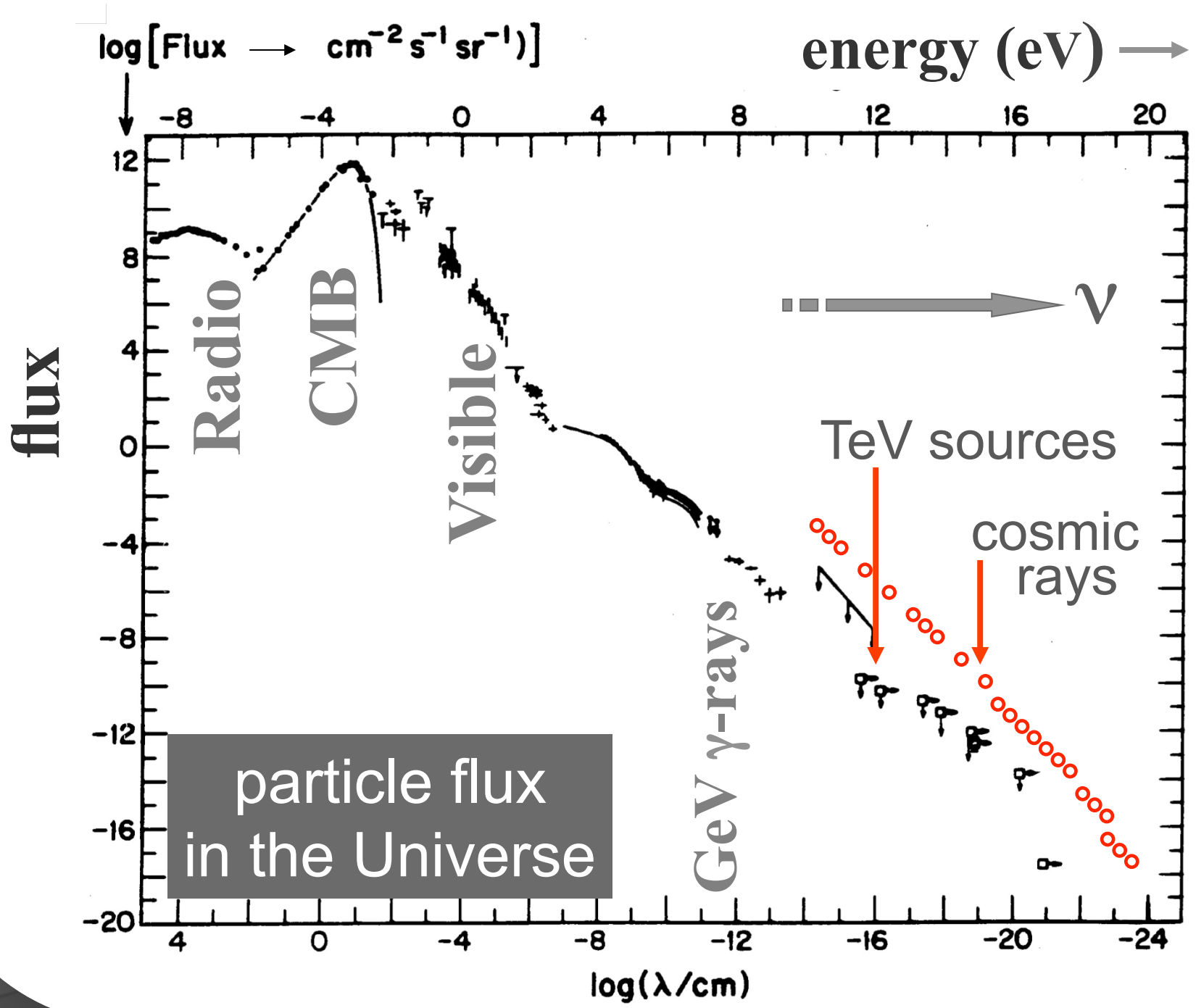
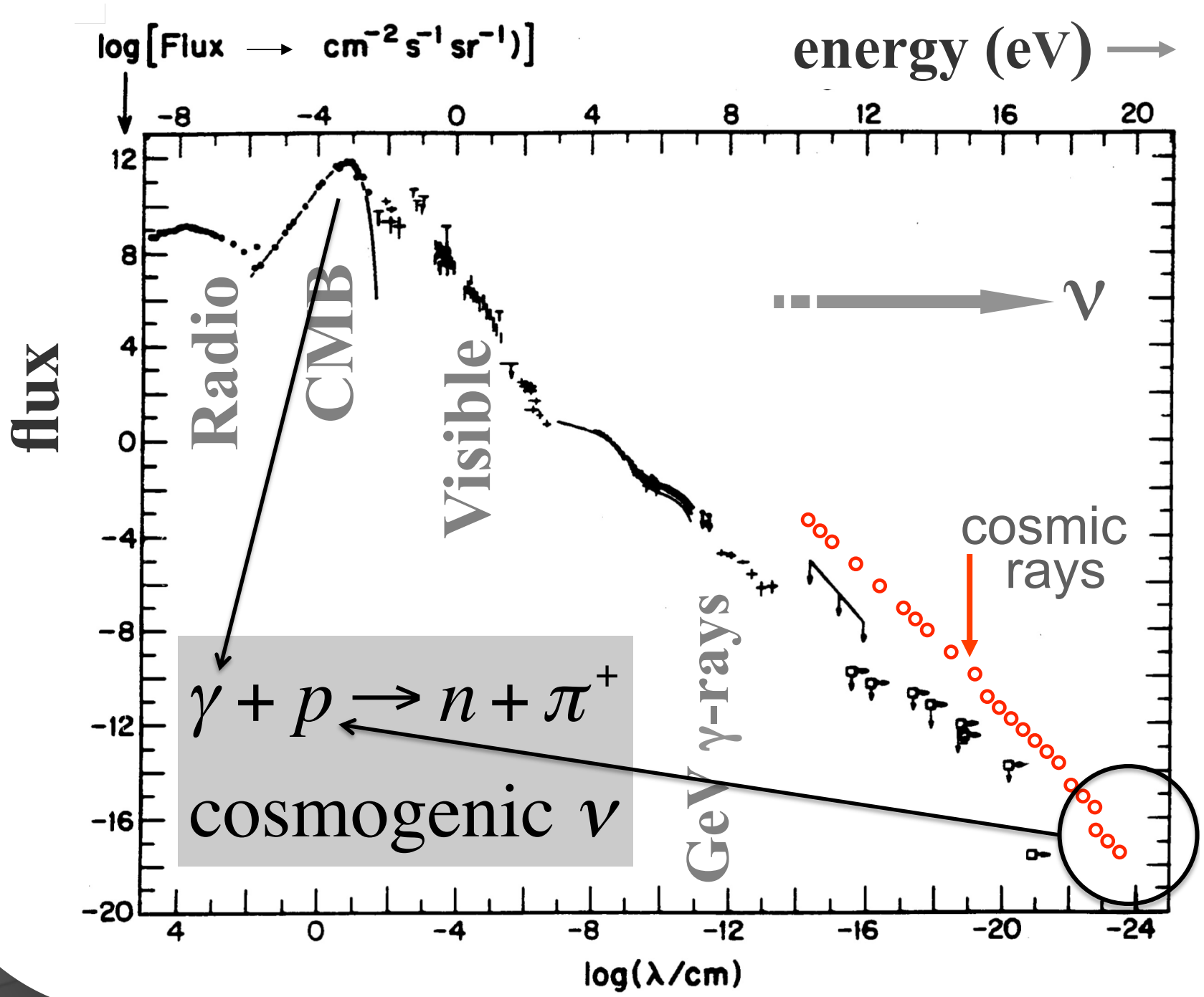
IceCube.wisc.edu


log [Flux → cm⁻² s⁻¹ sr⁻¹)]
energy (eV) →
flux
Radio
CMB
Visible
GeV γ-rays
ν
TeV sources
cosmic rays
log(λ/cm)
particle flux in the Universe


log [Flux → cm⁻² s⁻¹ sr⁻¹)]
energy (eV) →
flux
log(λ/cm)
Radio
CMB
Visible
GeV γ-rays
ν
cosmic rays
γ + p → n + π⁺
cosmogenic ν

cosmic rays interact with the microwave background

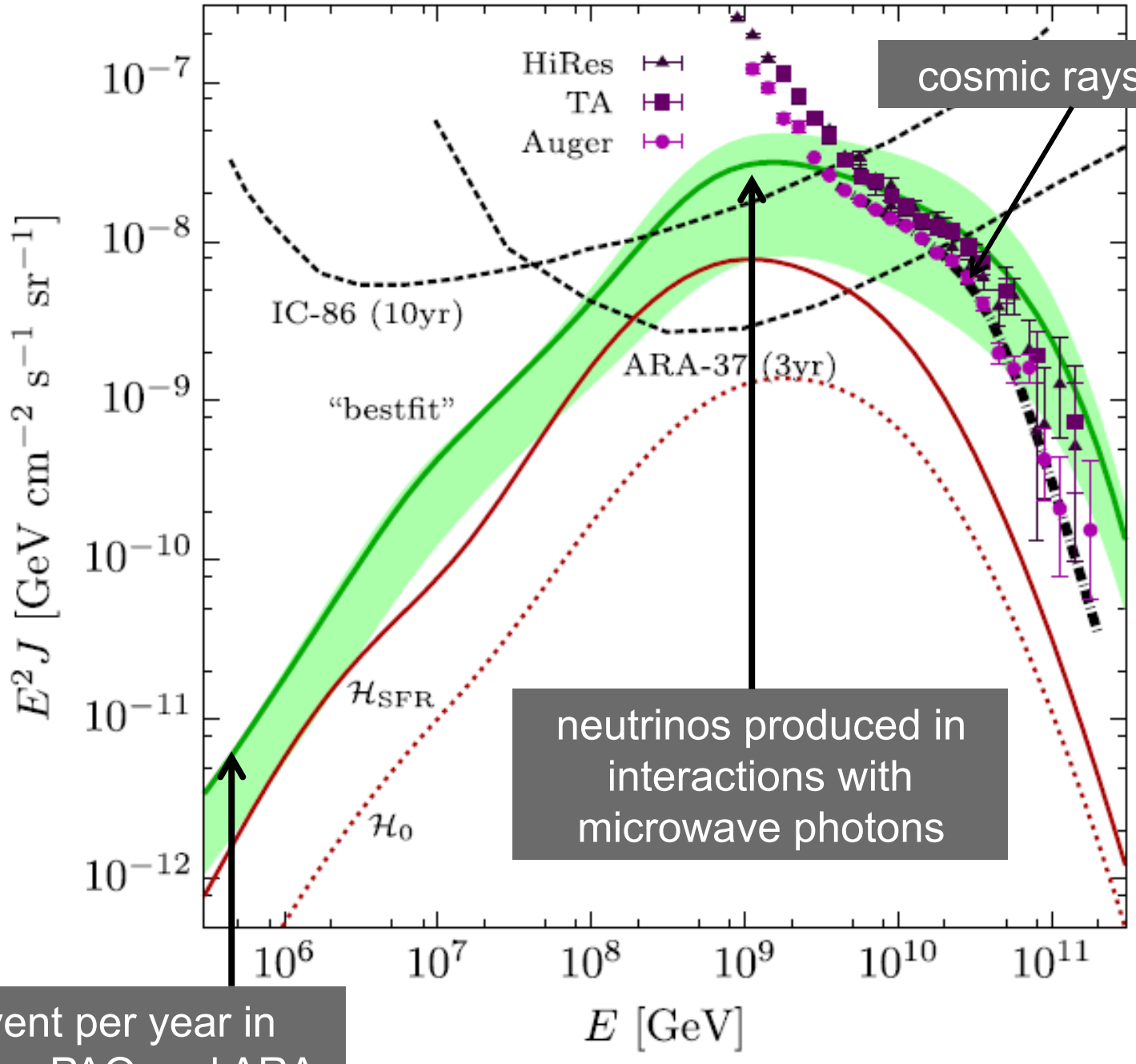
$$p + \gamma \rightarrow n + \pi^{+} \; and \; p + \pi^{0}$$

cosmic rays disappear, neutrinos with EeV (10^{18} eV) energy appear

$$\pi \rightarrow \mu + \upsilon_{\mu} \rightarrow \{e + \upsilon_{\mu} + \upsilon_{e}\} + \upsilon_{\mu}$$

1 event per cubic kilometer per year

...but it points at its source!

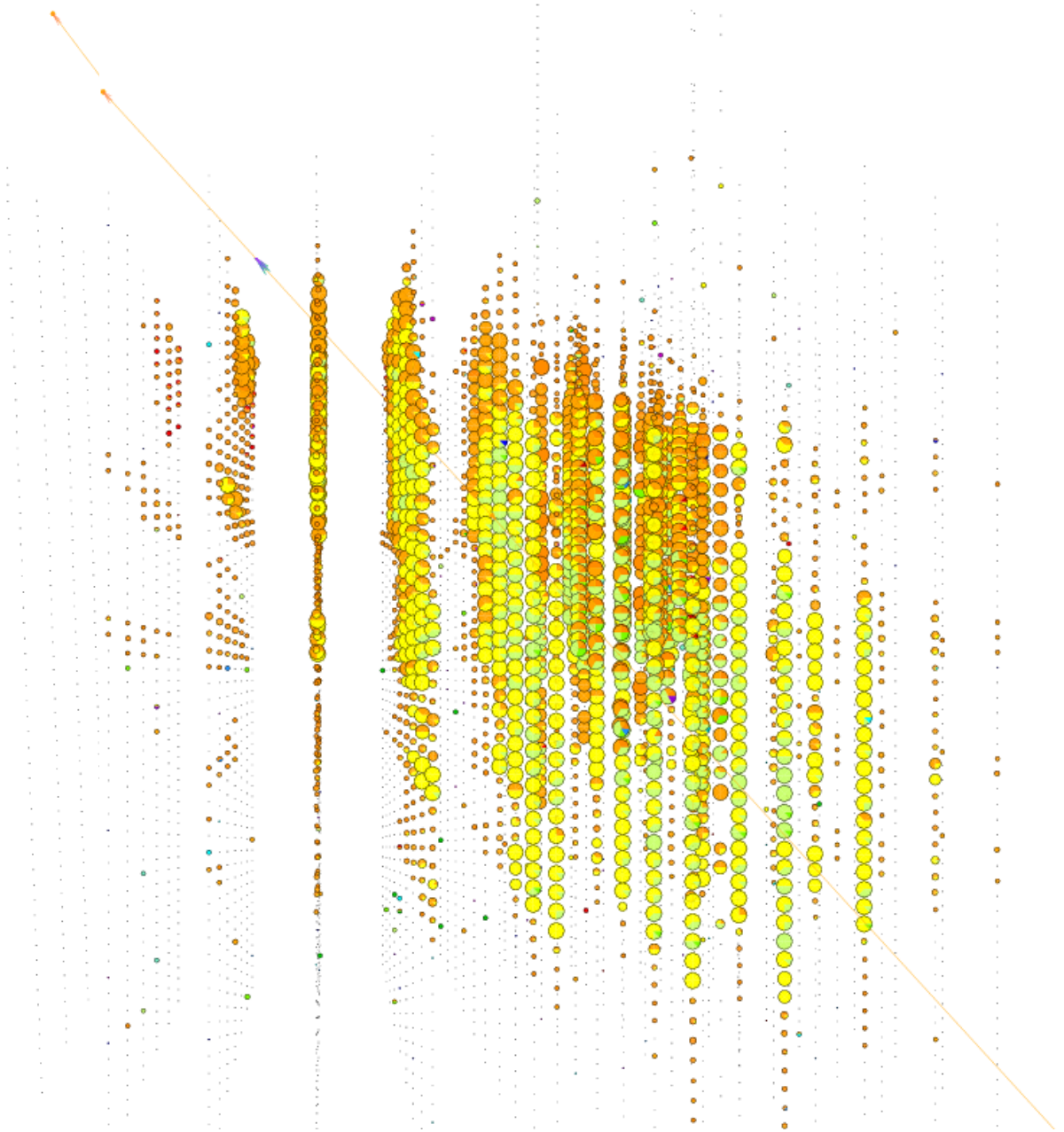


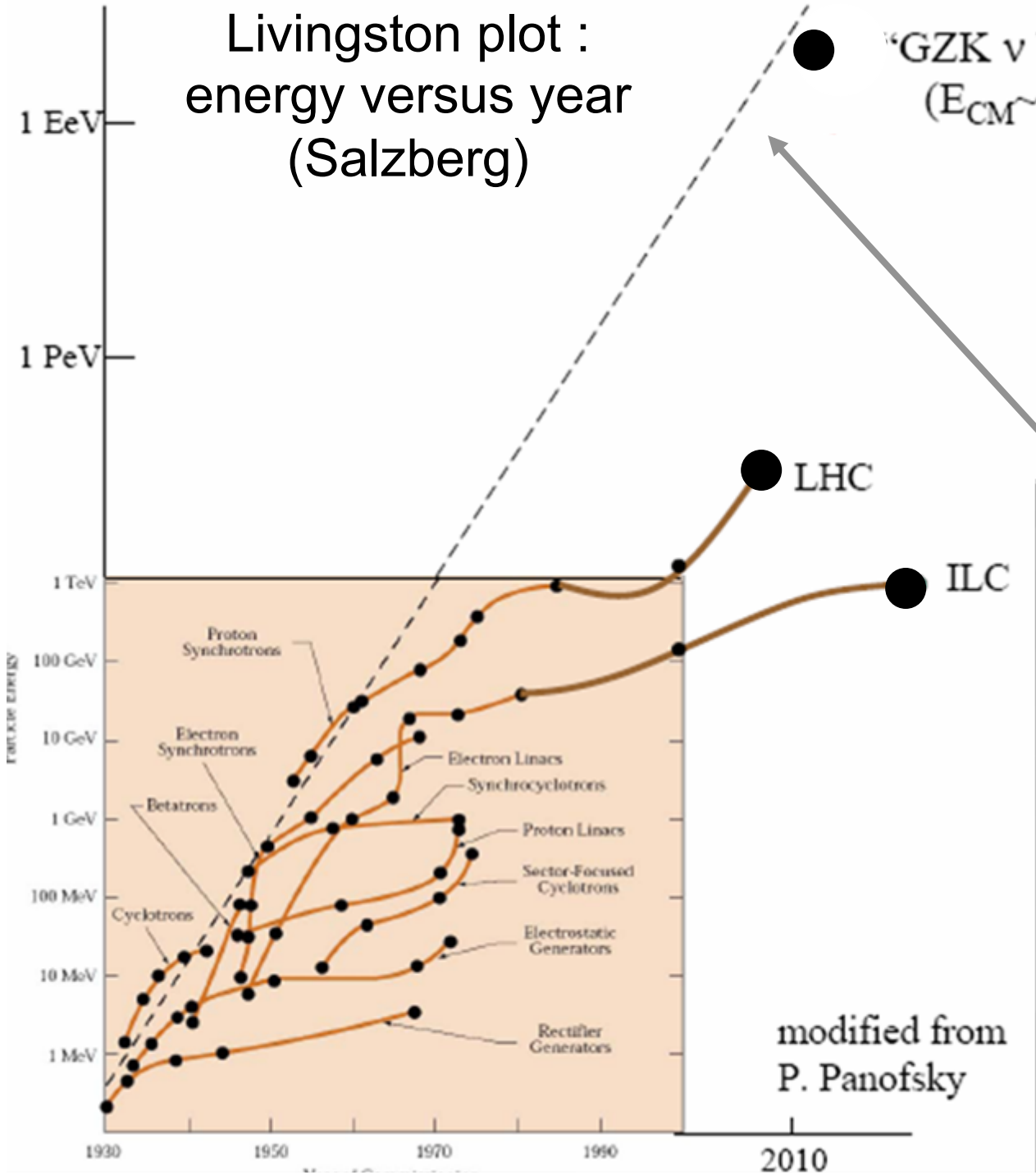
cosmic rays: protons

neutrinos produced in interactions with microwave photons

~1 event per year in IceCube, PAO and ARA

cosmogenic neutrinos: an event

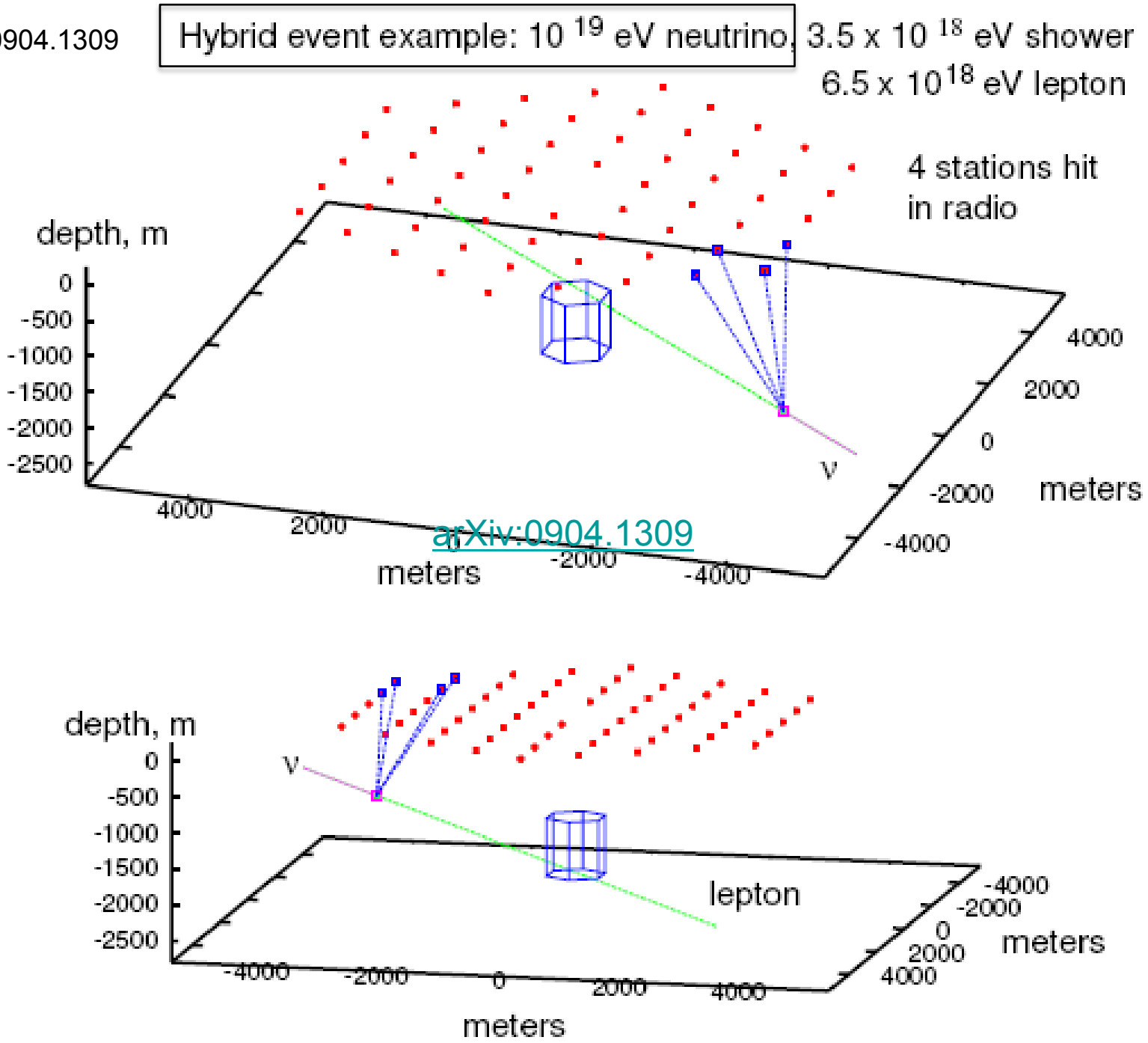


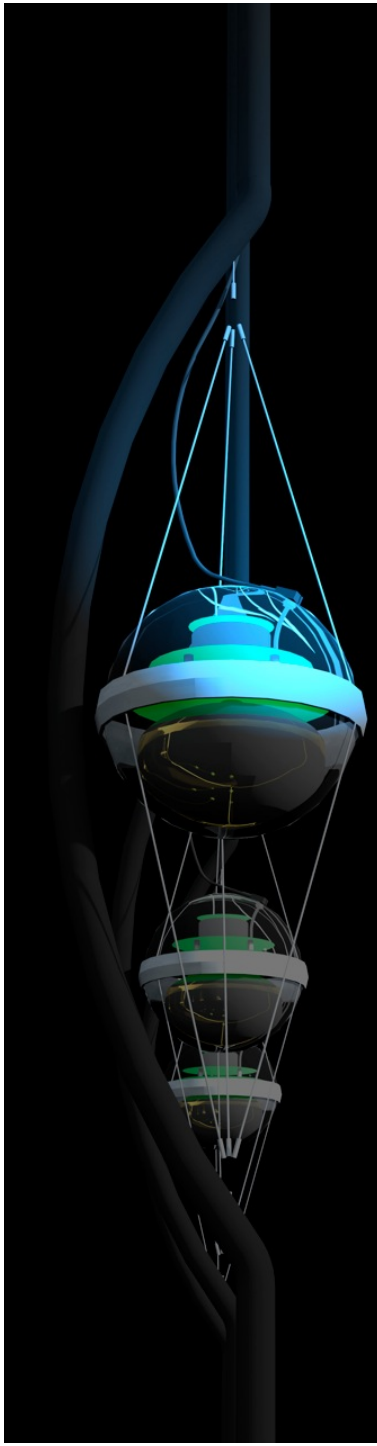


~ 5 events per year in next-generation IceCube

- ARA - IceCube coincidences
- joint PeV-EeV search
- ultimate beyond the SM measurement

arXiv:0904.1309





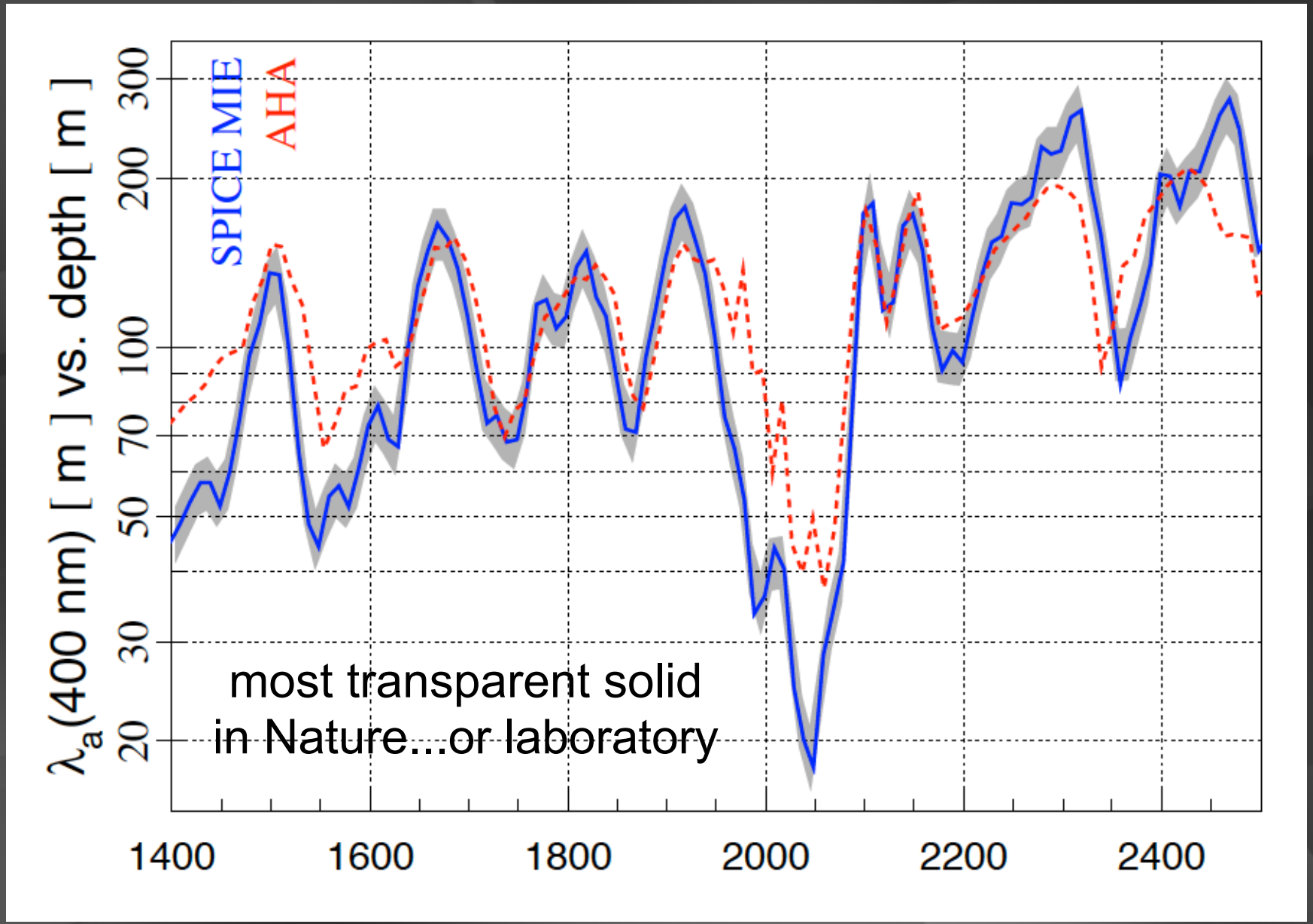
Beyond IceCube

francis halzen

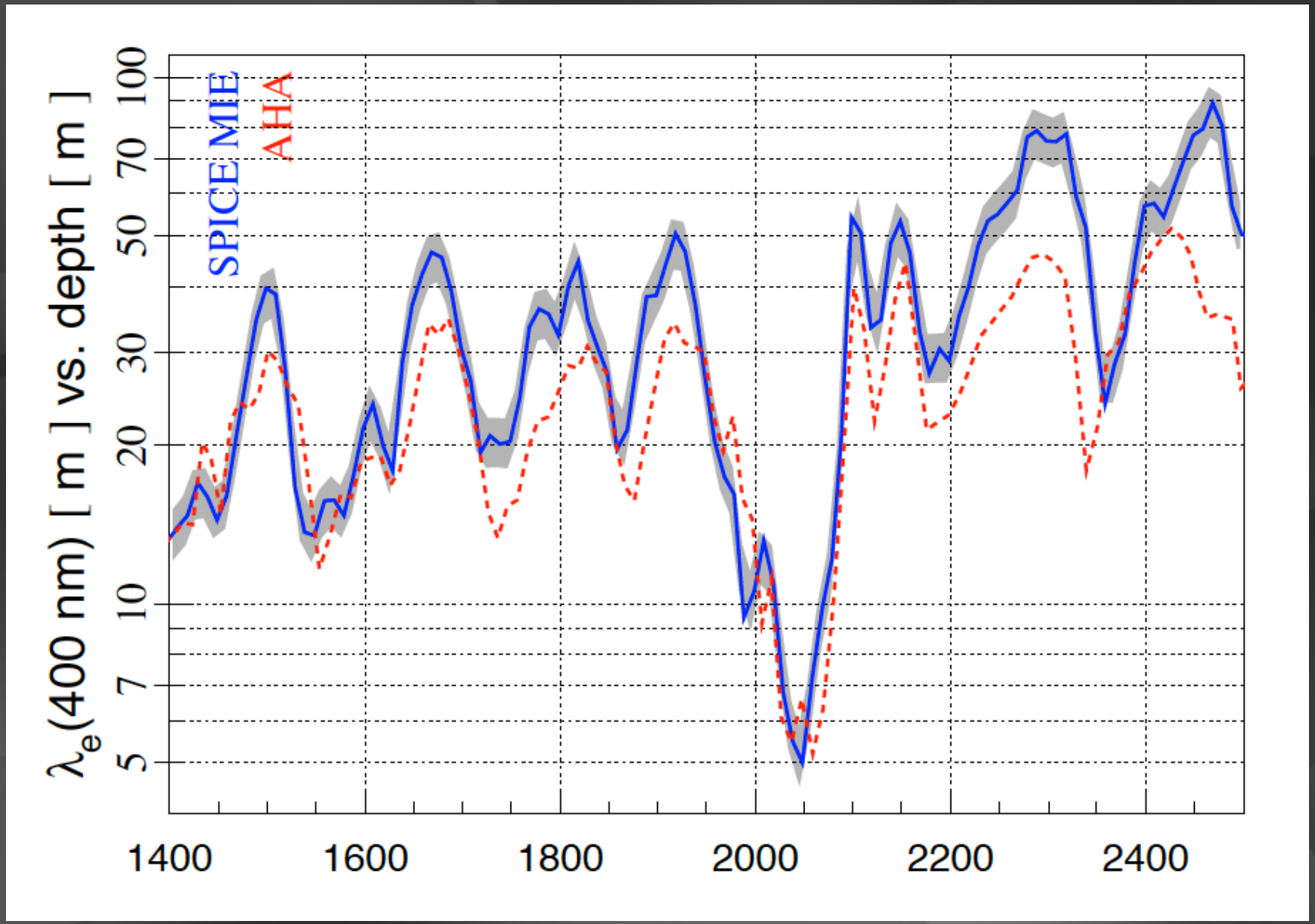
- the discovery of high-energy cosmic neutrinos
- where do they come from?
- neutrino stars?
- cosmogenic neutrinos
- beyond IceCube
- low threshold frontier (PINGU)

IceCube.wisc.edu

absorption length ← 220m →

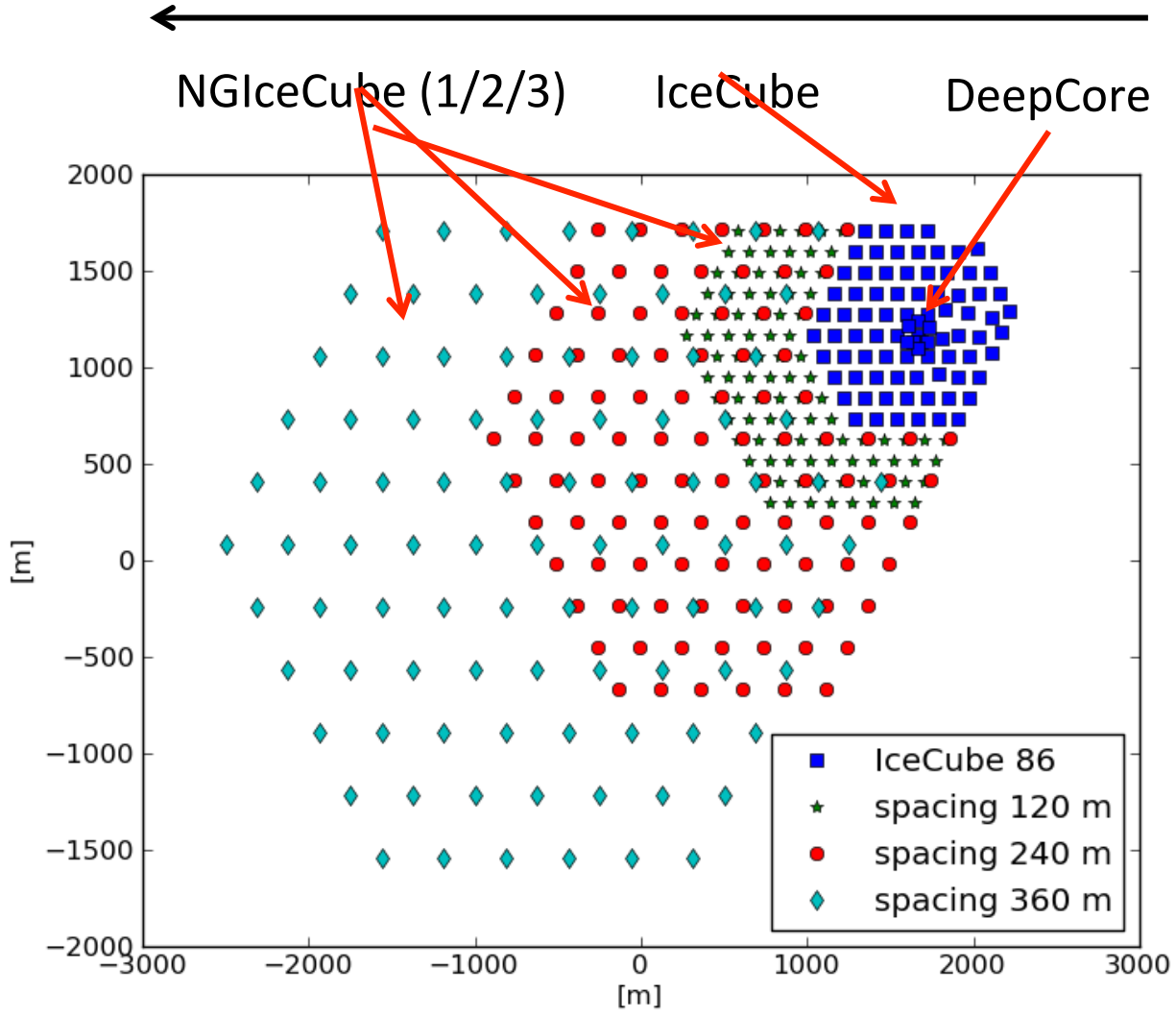


scattering length ← 47m →



measured optical properties → twice the string spacing

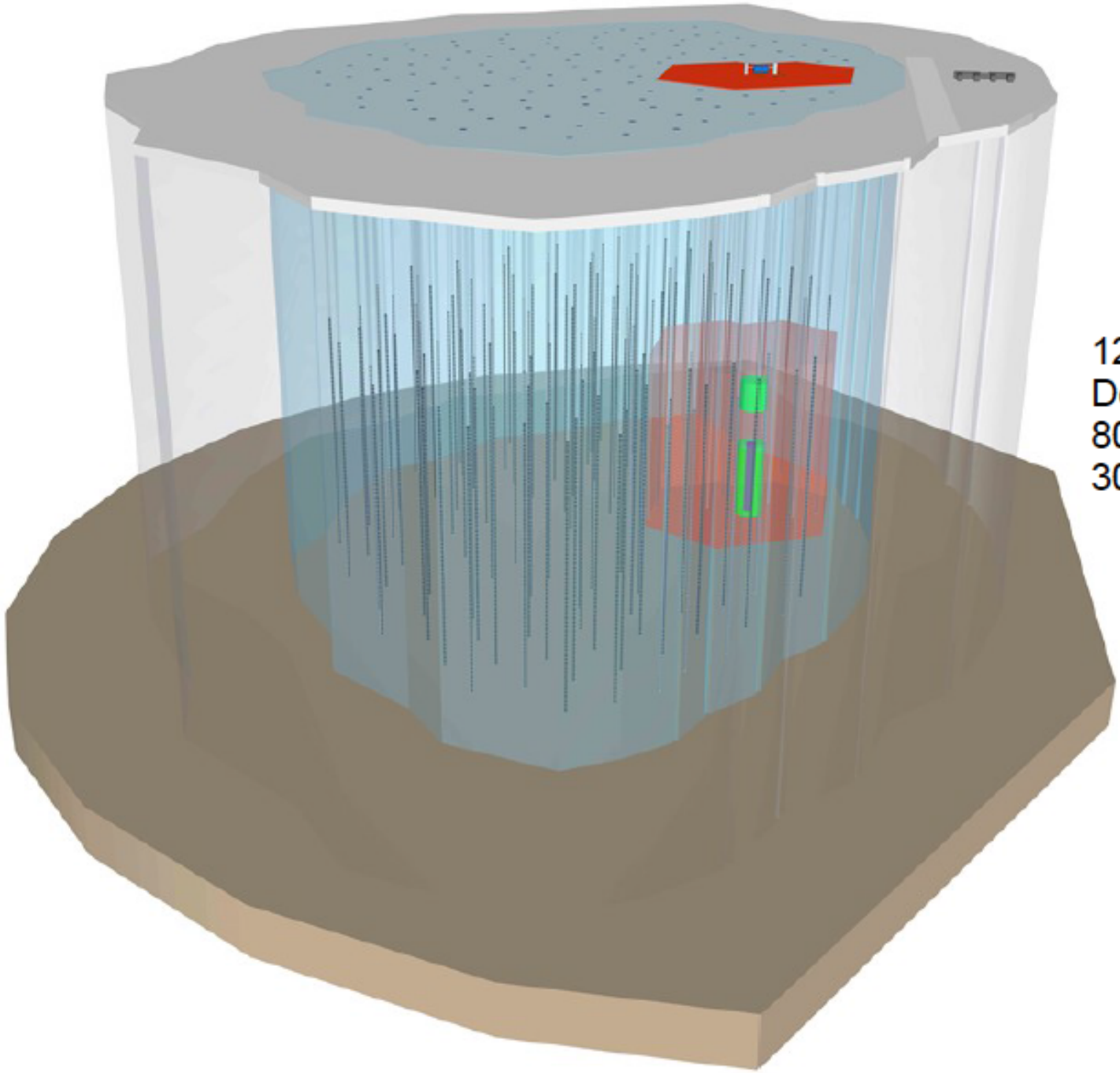
(increase in threshold not important: only eliminates energies where atmospheric background dominates)



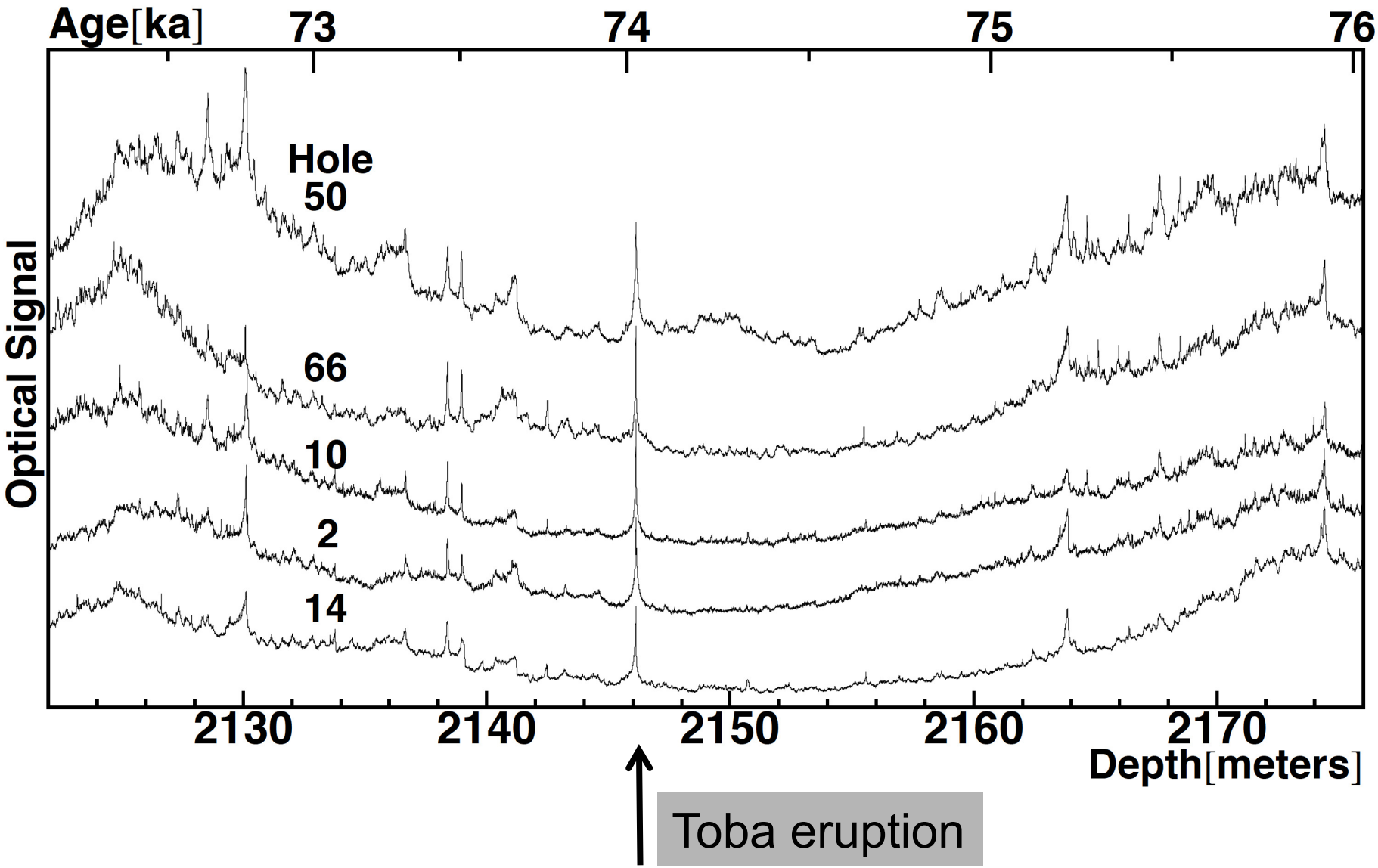
Spacing 1 (120m):
IceCube (1 km^3)
+ 98 strings (1,3 km^3)
= 2,3 km^3

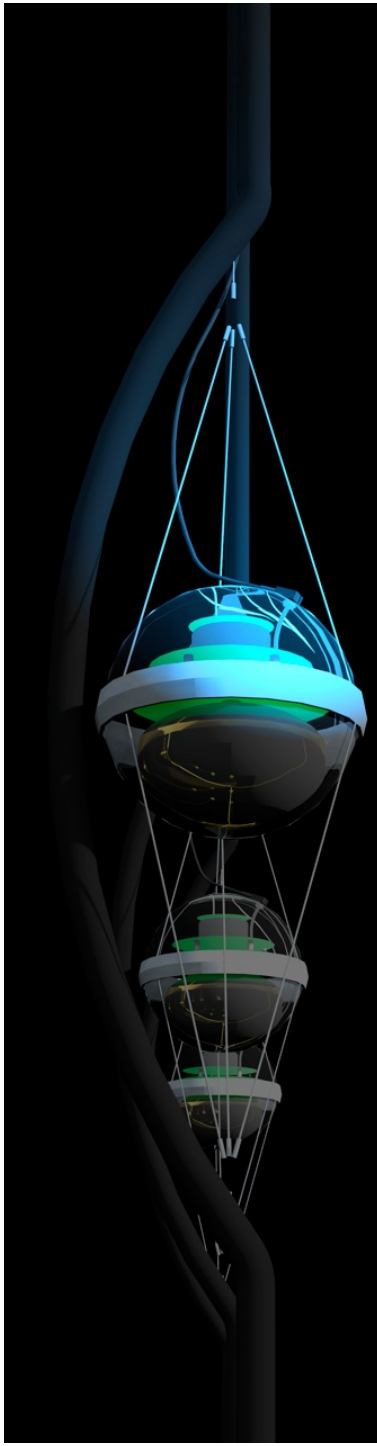
Spacing 2 (240m):
IceCube (1 km^3)
+ 99 strings (5,3 km^3)
= 6,3 km^3

Spacing 3 (360m):
IceCube (1 km^3)
+ 95 strings (11,6 km^3)
= 12,6 km^3



120 strings
Depth 1.35 to 2.7 km
80 DOMs/string
300 m spacing


Age[ka]
73
74
75
76
Hole
50
66
10
2
14
Optical Signal
2130
2140
2150
2160
2170
Depth[meters]
Toba eruption



Beyond IceCube

francis halzen

- the discovery of high-energy cosmic neutrinos
- where do they come from?
- neutrino stars?
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IceCube.wisc.edu

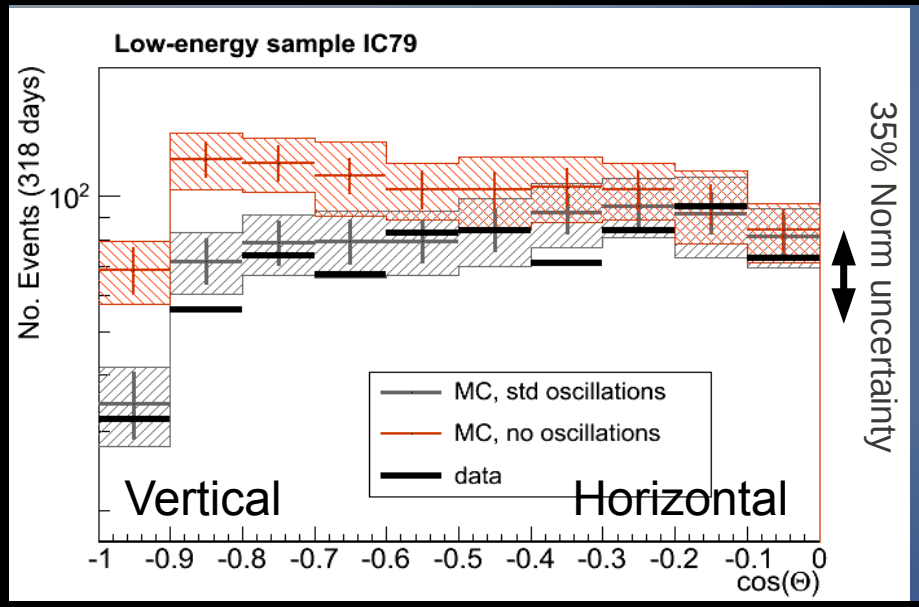
neutrinos: the sun and the Earth

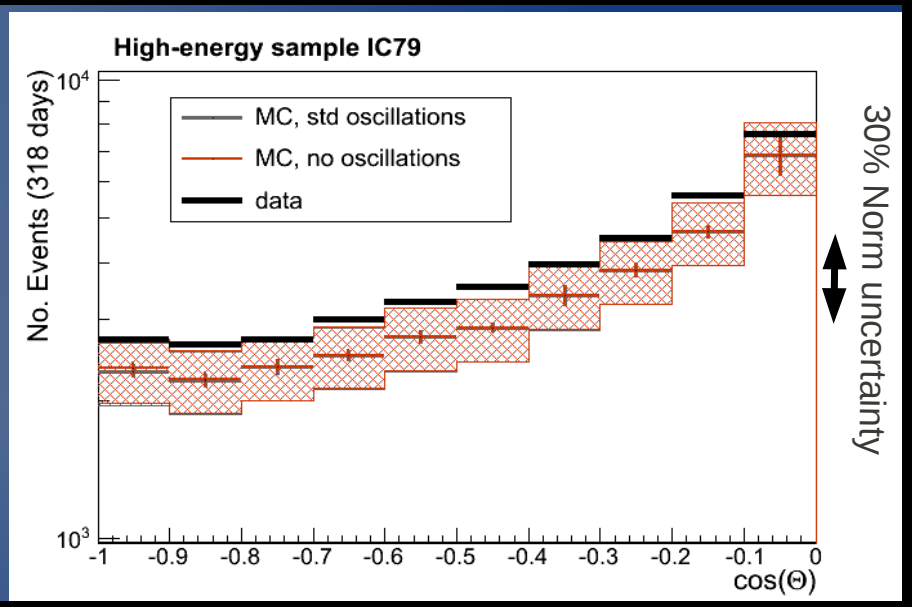
$$\nu_3 = \left(\frac{\nu_\mu + \nu_\tau}{\sqrt{2}}\right) + |s_{13}|e^{i\delta}\nu_e$$

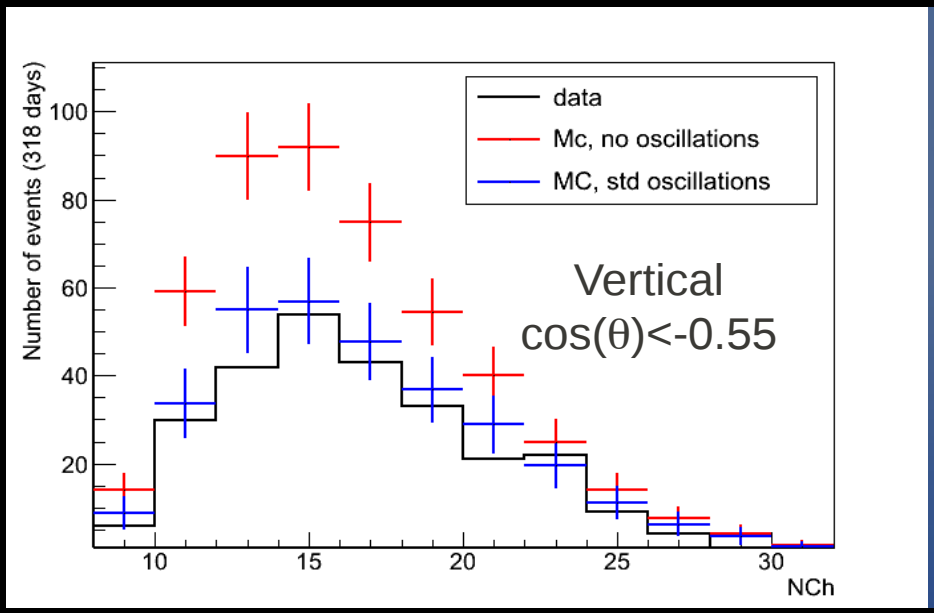
$$\nu_2 = \sin\theta_\odot \nu_e + \cos\theta_\odot \left(\frac{\nu_\mu - \nu_\tau}{\sqrt{2}}\right)$$

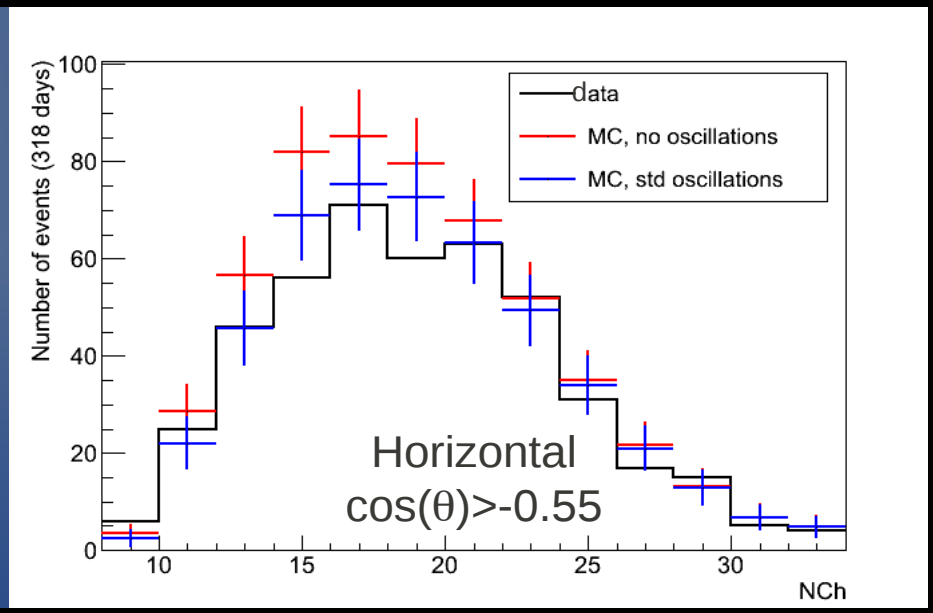
$$\nu_1 = -\cos\theta_\odot \nu_e + \sin\theta_\odot \left(\frac{\nu_\mu - \nu_\tau}{\sqrt{2}}\right)$$

oscillations in DeepCore [> 5 sigma]

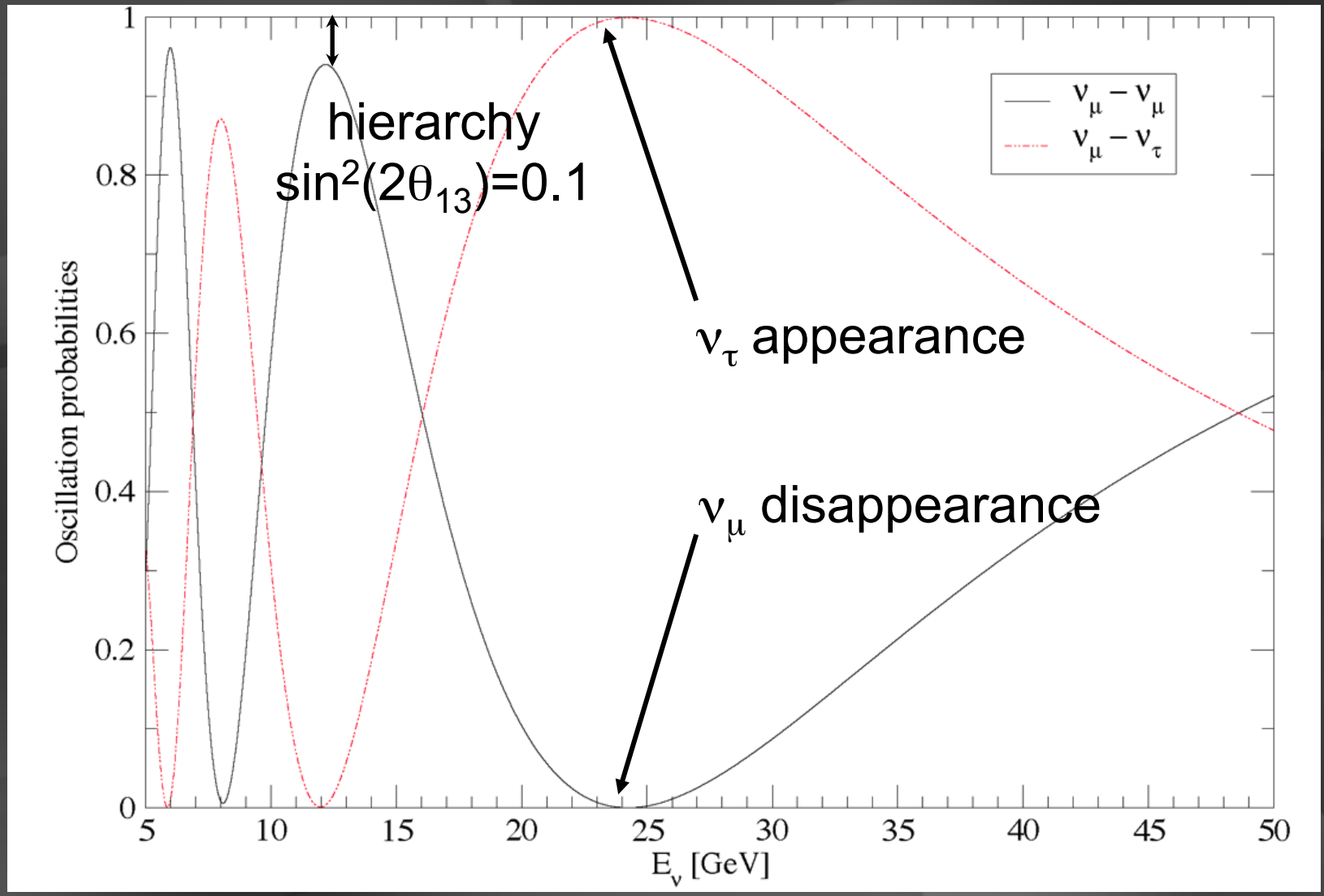






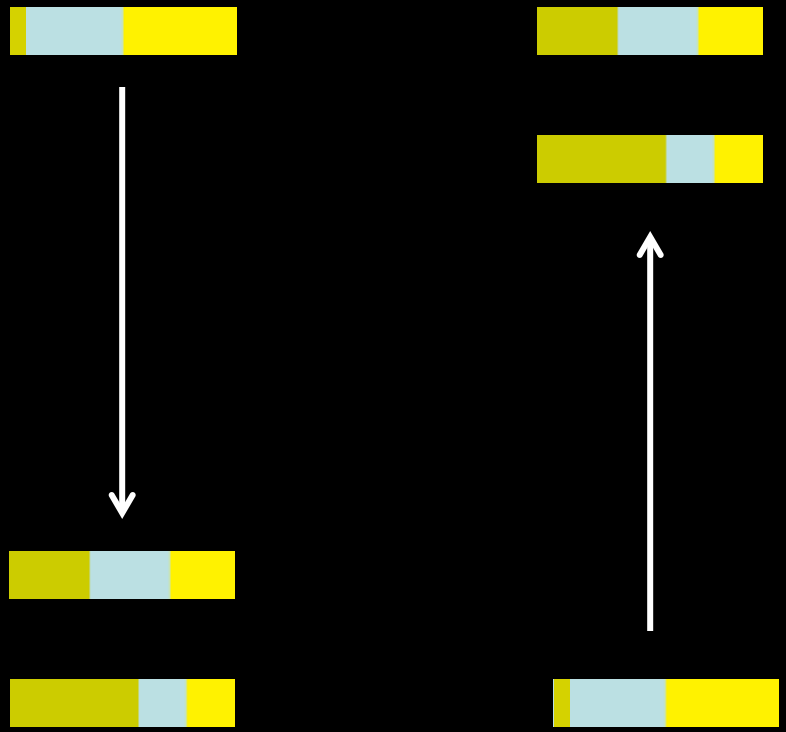


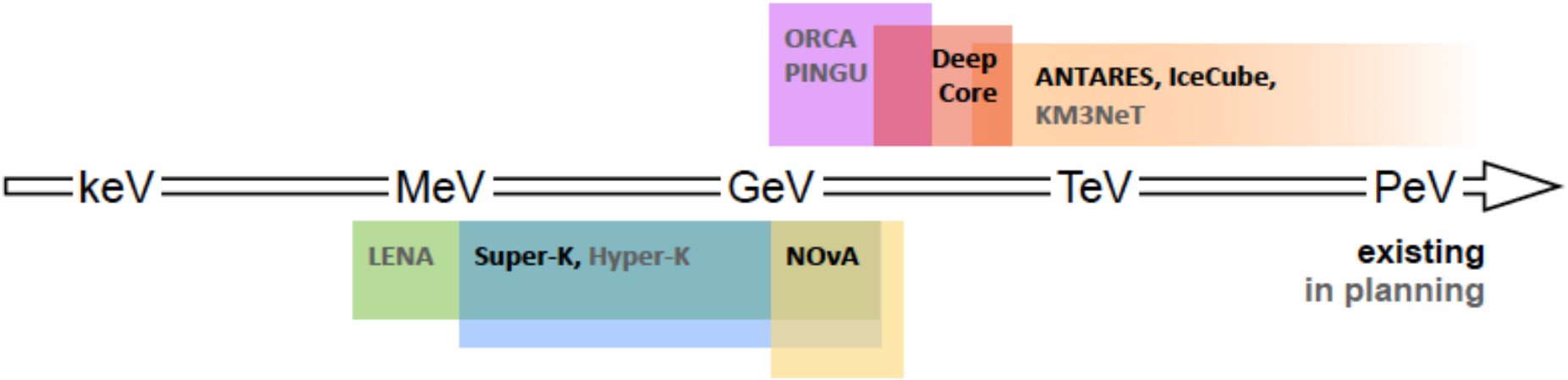
neutrino oscillations in Deep Core

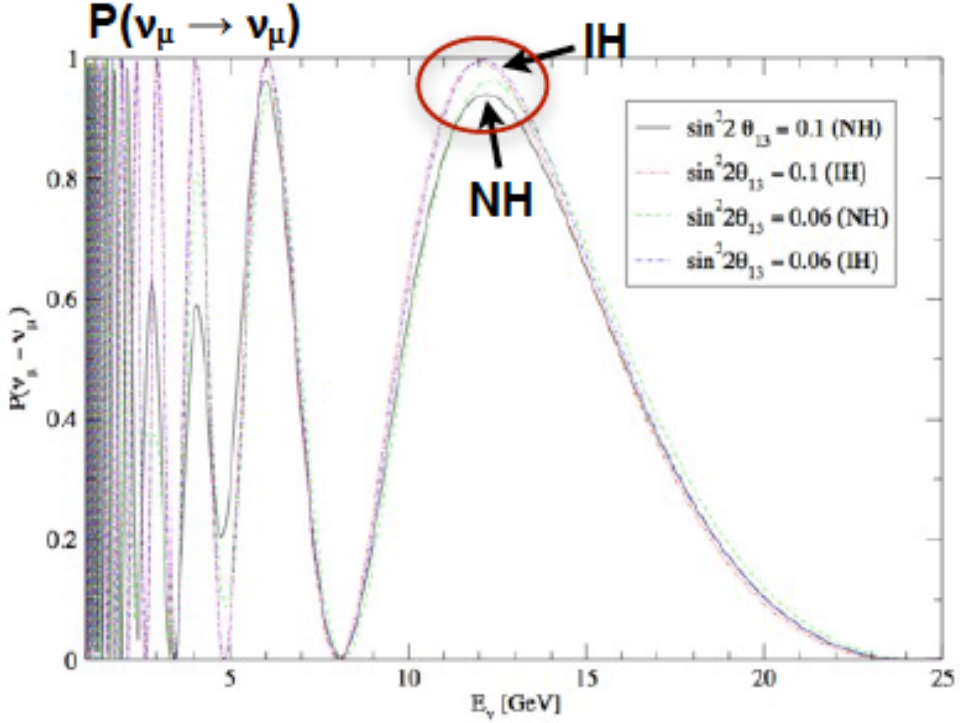


resonance in effective θ_{13} angle traversing the Earth diameter at 10 GeV

hierarchy: sign Δ_{13}?







$m(\nu_e)$ $m(\nu_\mu)$ $m(\nu_\tau)$

- First maximum for $P(\nu_\mu \rightarrow \nu_\mu)$ @ 12 GeV (L = Earth diameter)
- For $\bar{\nu}$ NH and IH approximately swapped → effect cancels if $N(\nu) = N(\bar{\nu})$
- Fortunately, $\Phi(\nu_{atm}) > \Phi(\bar{\nu}_{atm})$ and $\sigma(\nu) > \sigma(\bar{\nu})$

Mena et al., arXiv:0803.3044

~ 8 GeV : hierarchy revealed by
“large” matter effects in the Earth

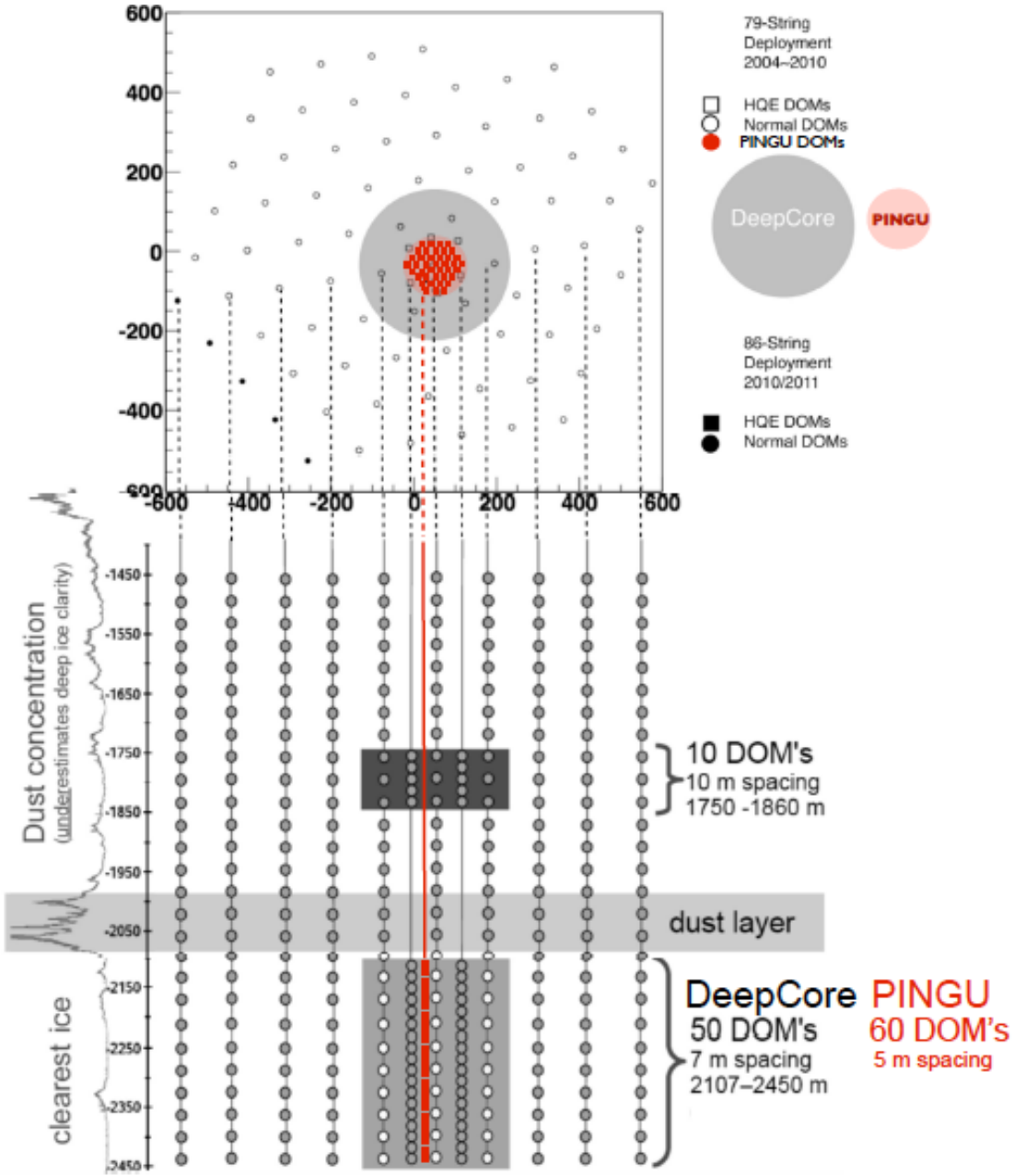
$$\sin^2 2\theta_{13}^m = \frac{\sin^2 2\theta_{13}}{\sin^2 2\theta_{13} + \left[\cos 2\theta_{13} \pm \frac{\sqrt{2G_F}\, n_e}{\Delta_{13}}\right]}$$

(mostly) neutrino + antineutrino -

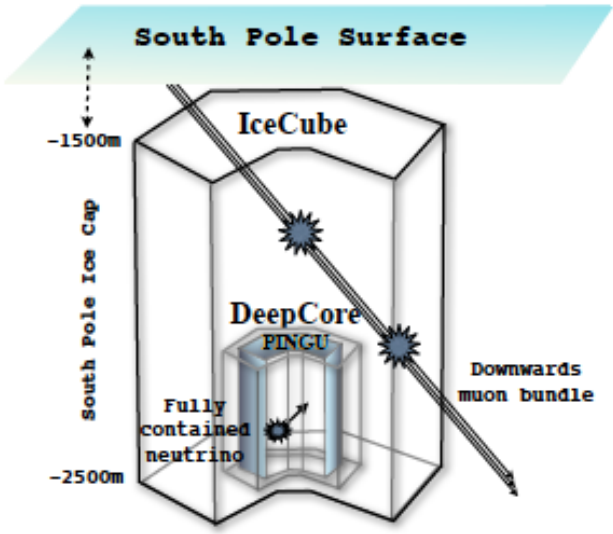
sign Δ_{13} : hierarchy !

low energy infill:

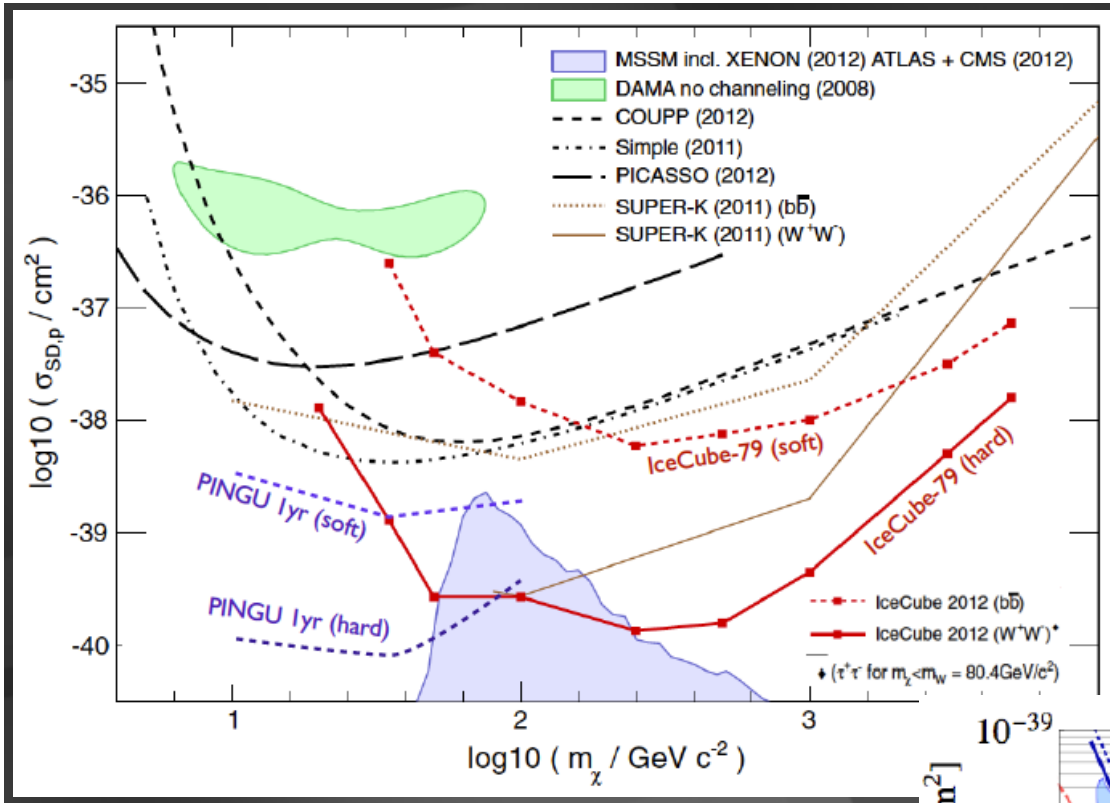
PINGU



(a) Baseline PINGU geometry.

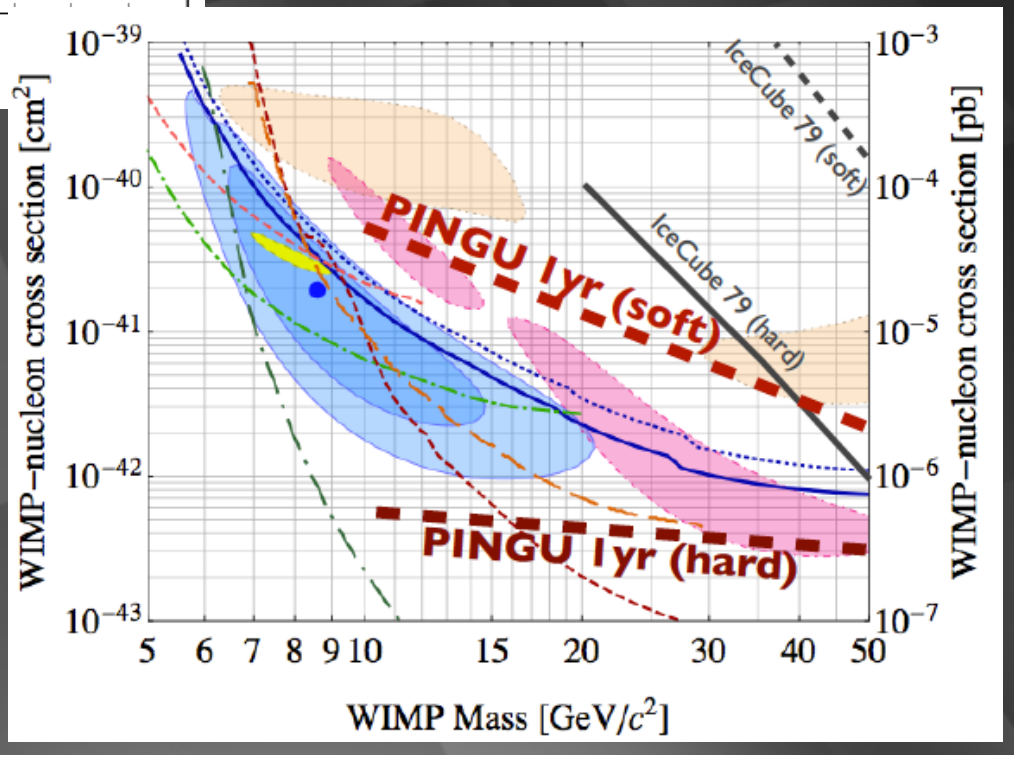


(b) Signal and background.



PINGU:

low-mass dark matter



Next-Generation IceCube

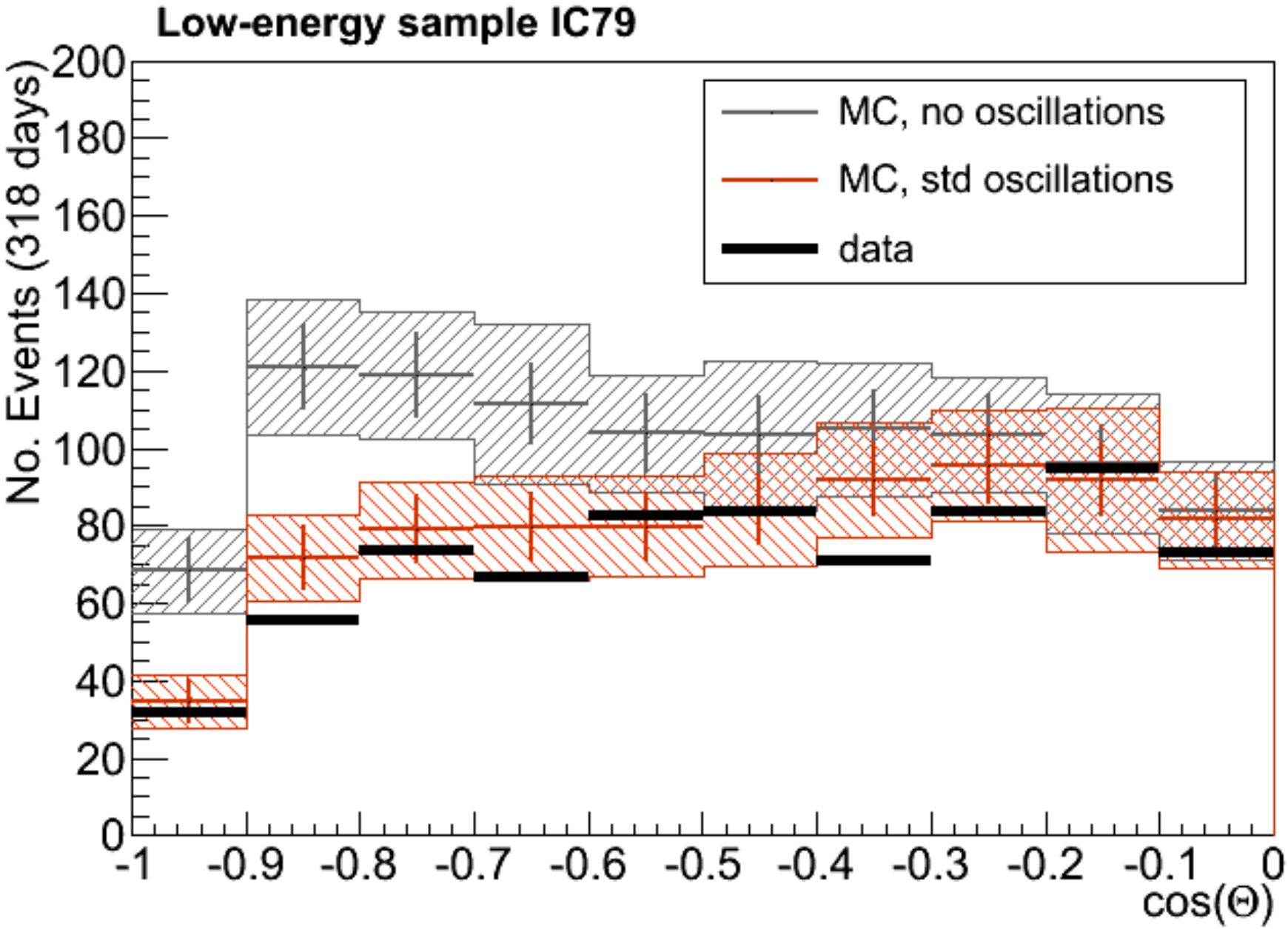
- capitalize on discovery
- astronomy guaranteed
- ~ 120 strings: more sensors per string with higher quantum efficiency
- proven techniques, low risk
- flexibility of deployment per seasons: optimization
- cost similar to original detector

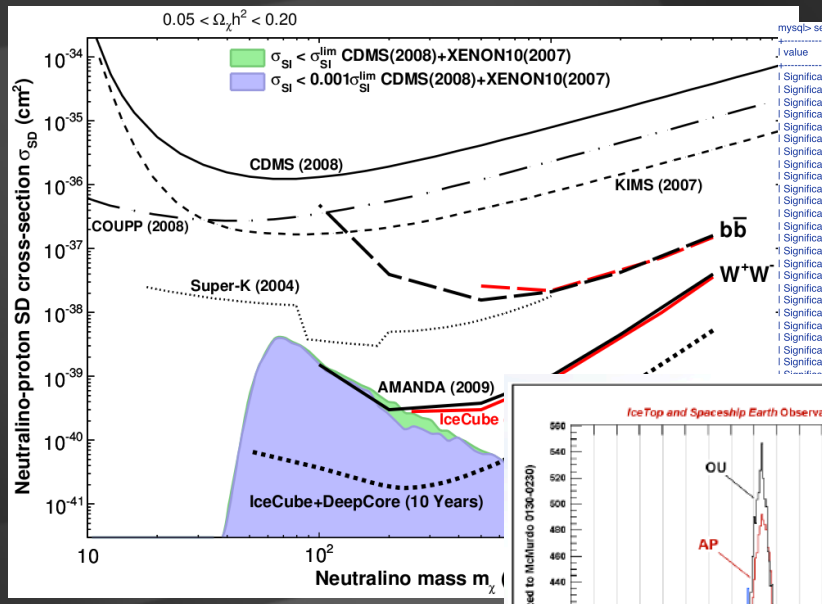
The IceCube–PINGU Collaboration

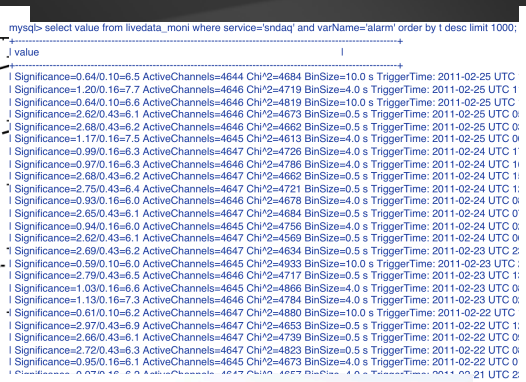
International Funding Agencies

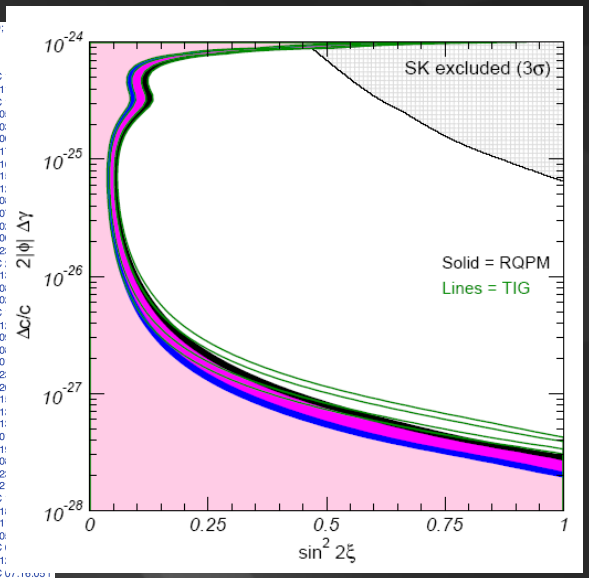
Fonds de la Recherche Scientifique (FRS–FNRS)
Fonds Wetenschappelijk Onderzoek–Vlaanderen (FWO–Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation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

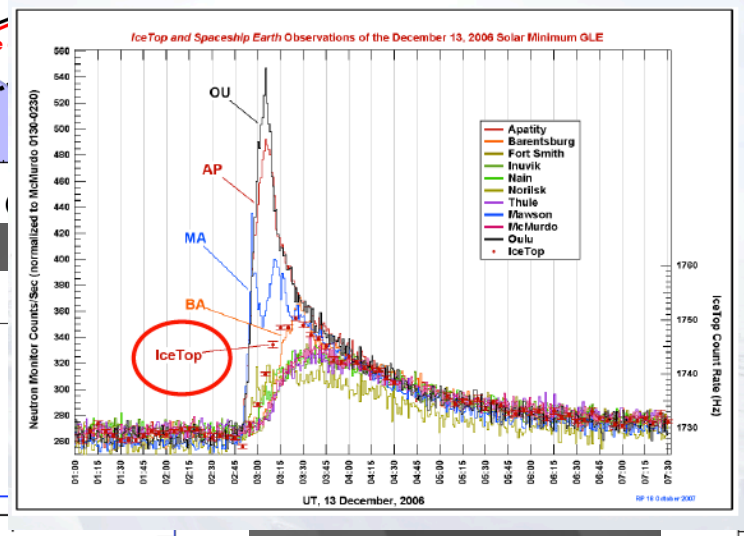
Overflow slides

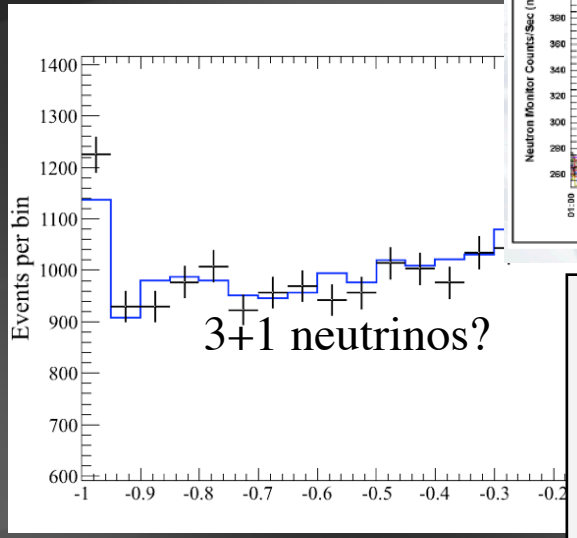

Low-energy sample IC79
No. Events (318 days)
200
180
160
140
120
100
80
60
40
20
0
-1
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
cos(Θ)
MC, no oscillations
MC, std oscillations
data

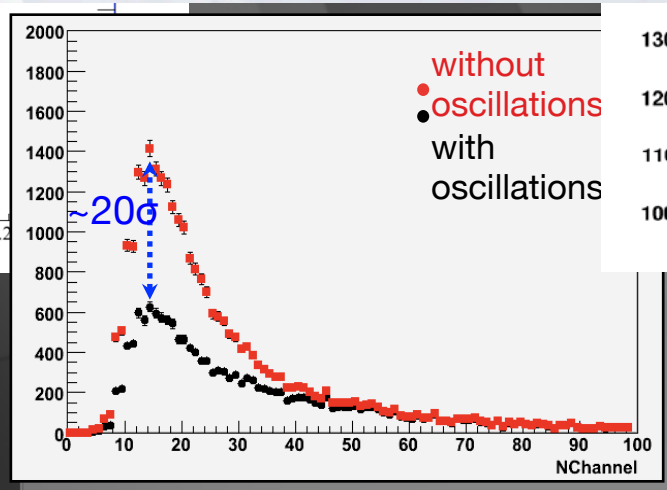


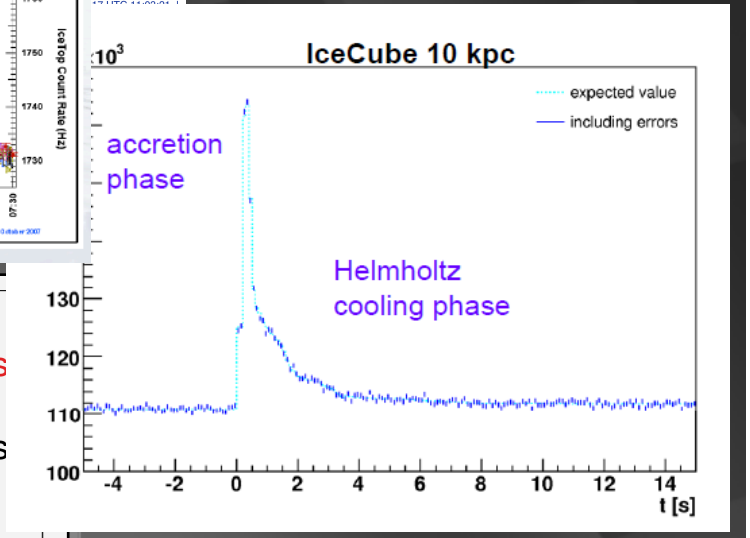




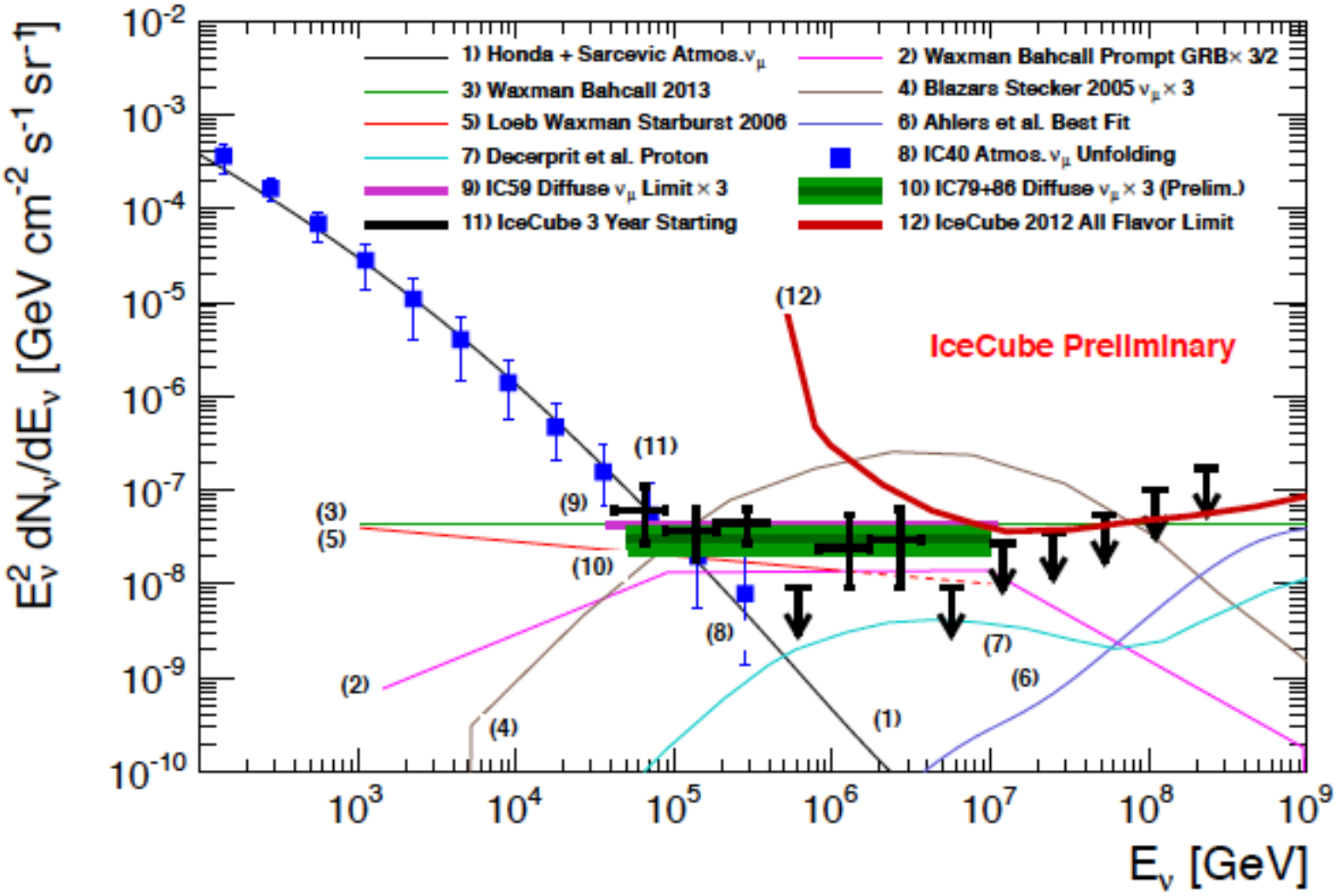






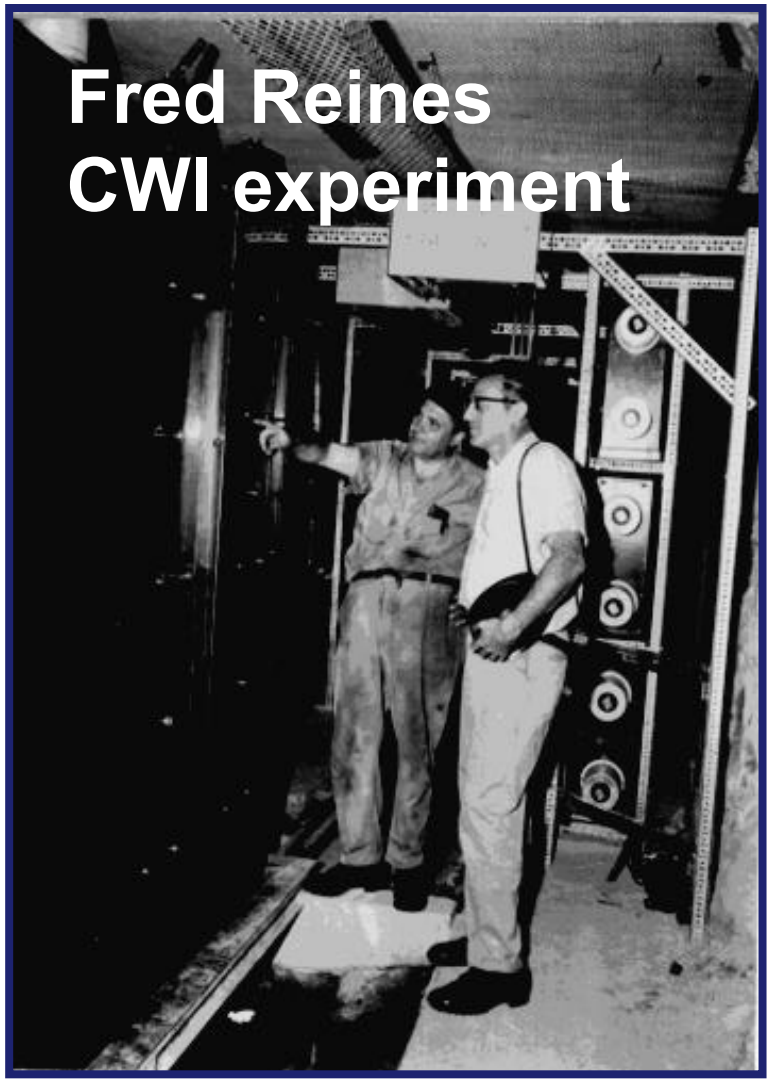


IceCube science


1) Honda + Sarcevic Atmos. ν_μ
2) Waxman Bahcall Prompt GRB× 3/2
3) Waxman Bahcall 2013
4) Blazars Stecker 2005 ν_μ× 3
5) Loeb Waxman Starburst 2006
6) Ahlers et al. Best Fit
7) Decerprit et al. Proton
8) IC40 Atmos. ν_μ Unfolding
9) IC59 Diffuse ν_μ Limit × 3
10) IC79+86 Diffuse ν_μ × 3 (Prelim.)
11) IceCube 3 Year Starting
12) IceCube 2012 All Flavor Limit
IceCube Preliminary
$E_\nu^2\, dN_\nu/dE_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
E_ν [GeV]

Discovery of atmospheric neutrinos

February 23, 1965

East Rand Proprietary Mine, South Africa, Depth = 3200 meters

Case-Witwatersrand Collaboration (later Case-Wits-Irvine)