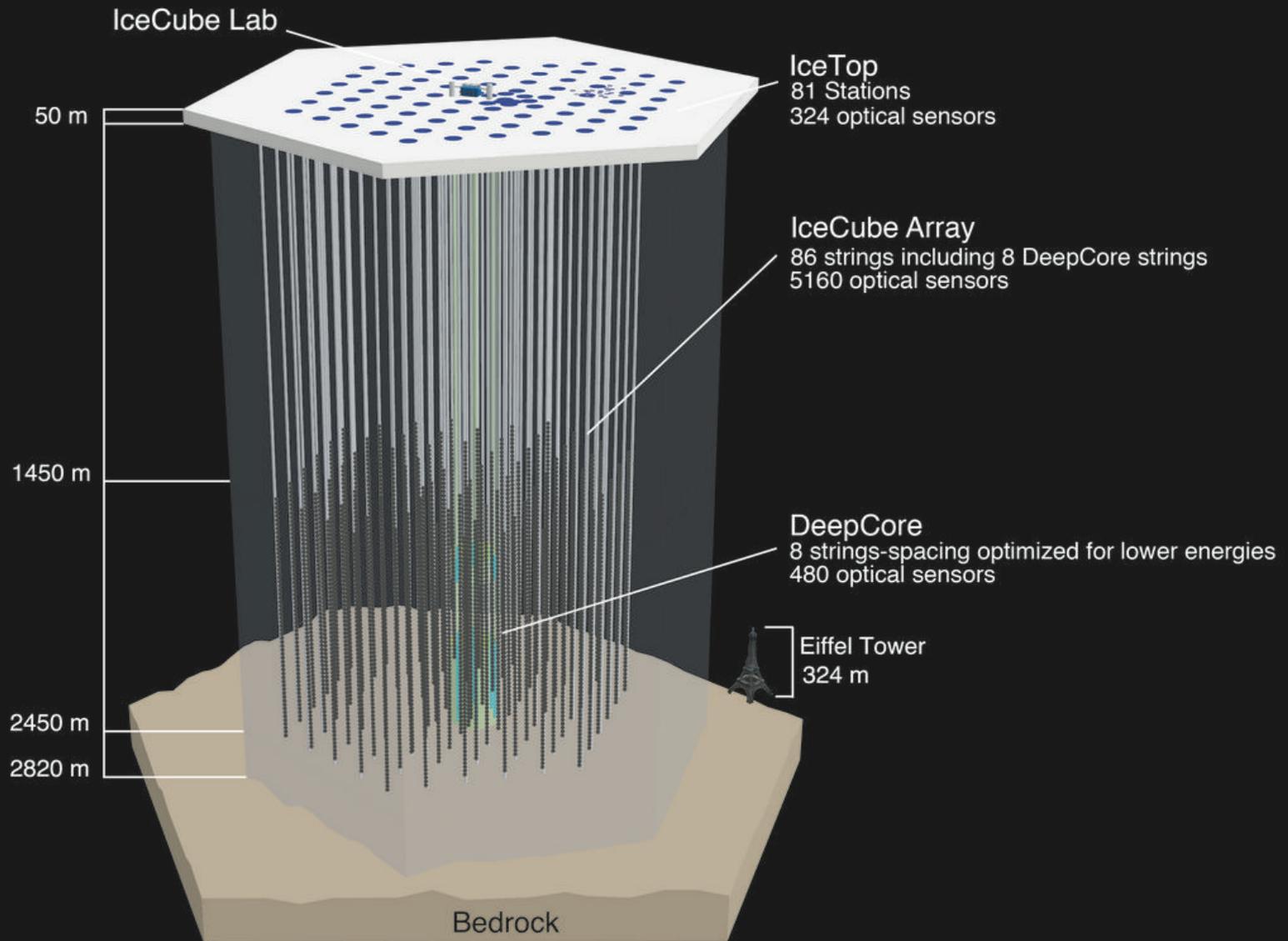


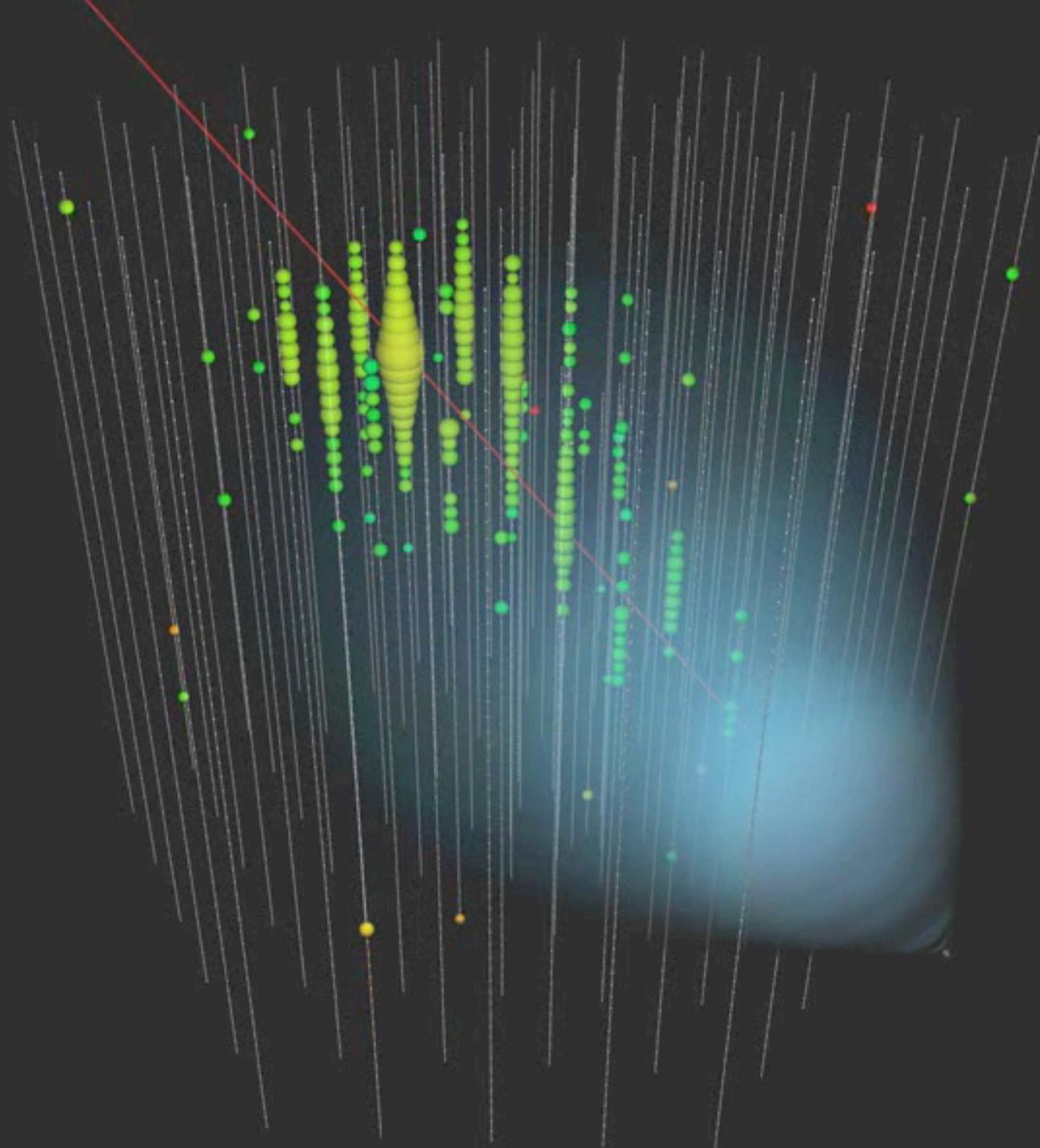
IceCube and Beyond

francis halzen

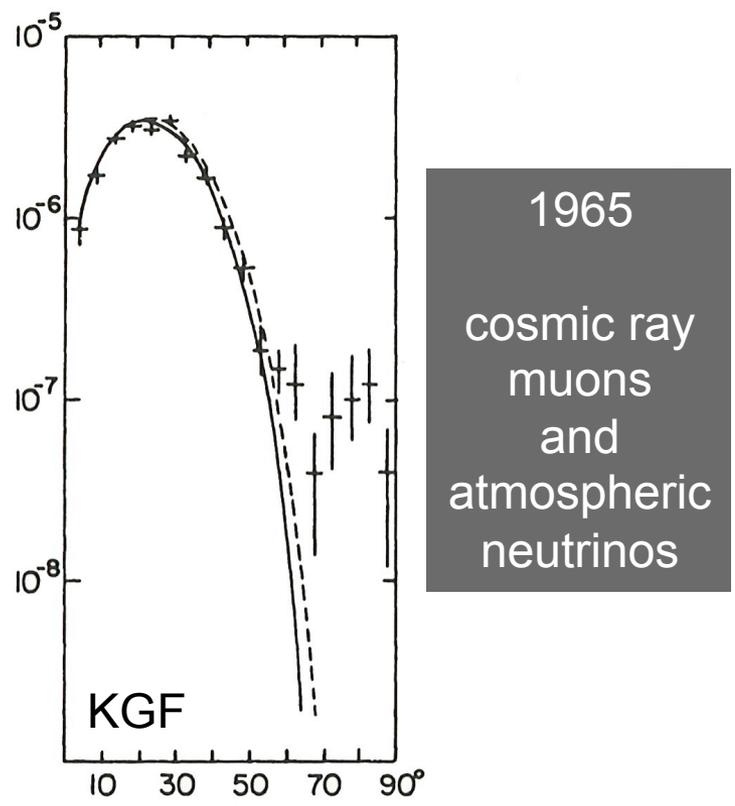
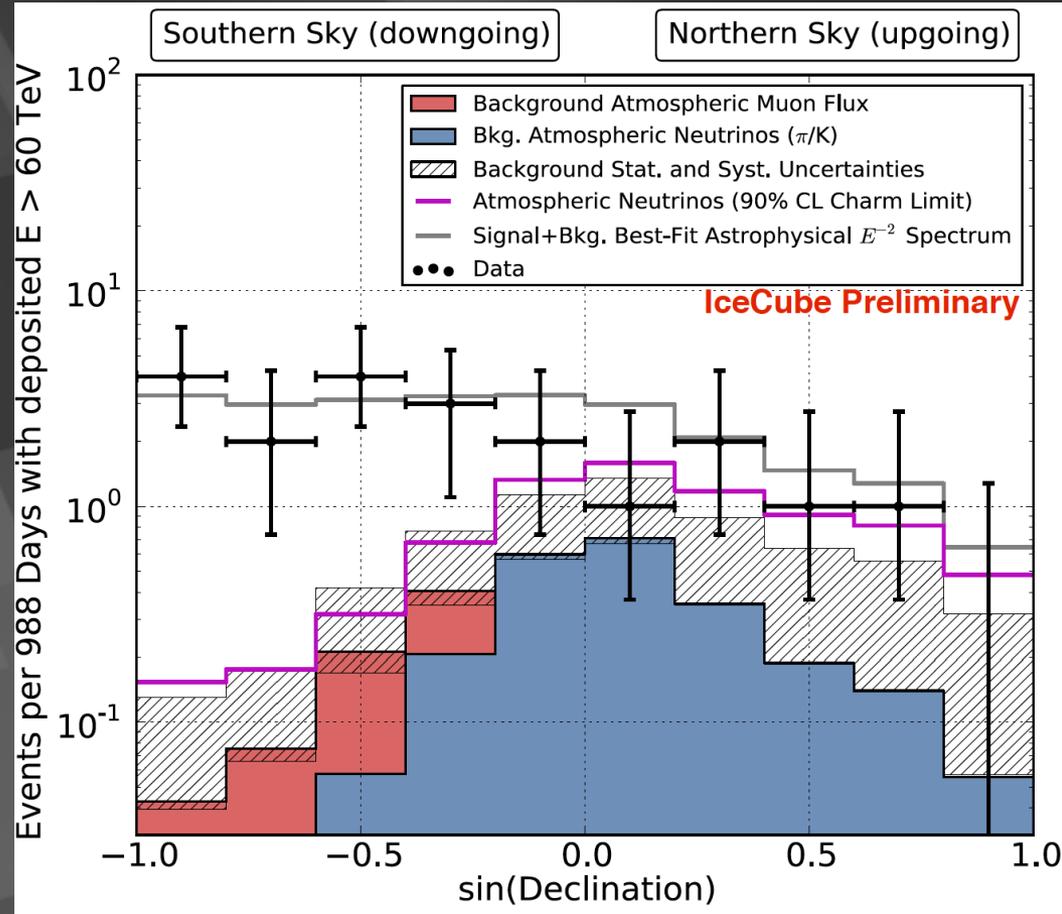
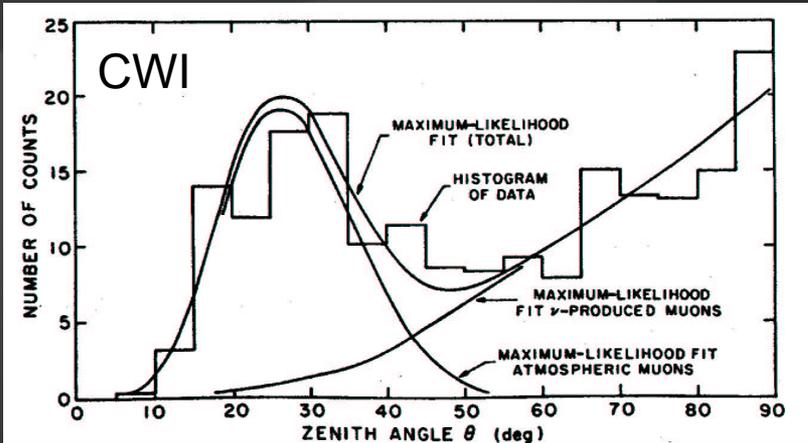
- the discovery of high-energy cosmic neutrinos
- where do they come from?
- beyond IceCube

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

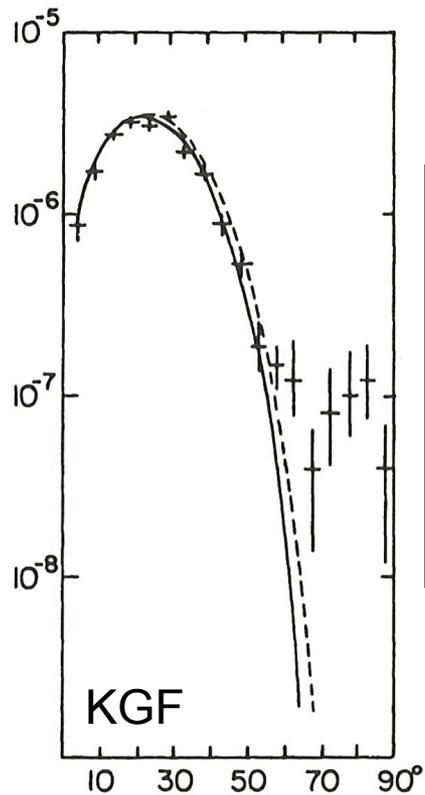
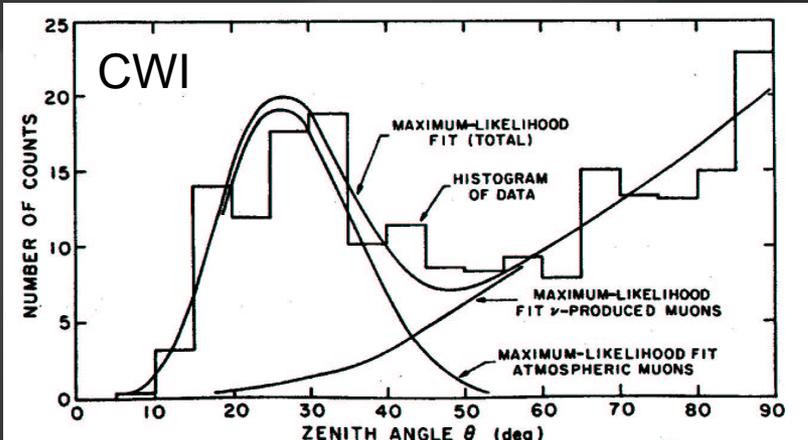




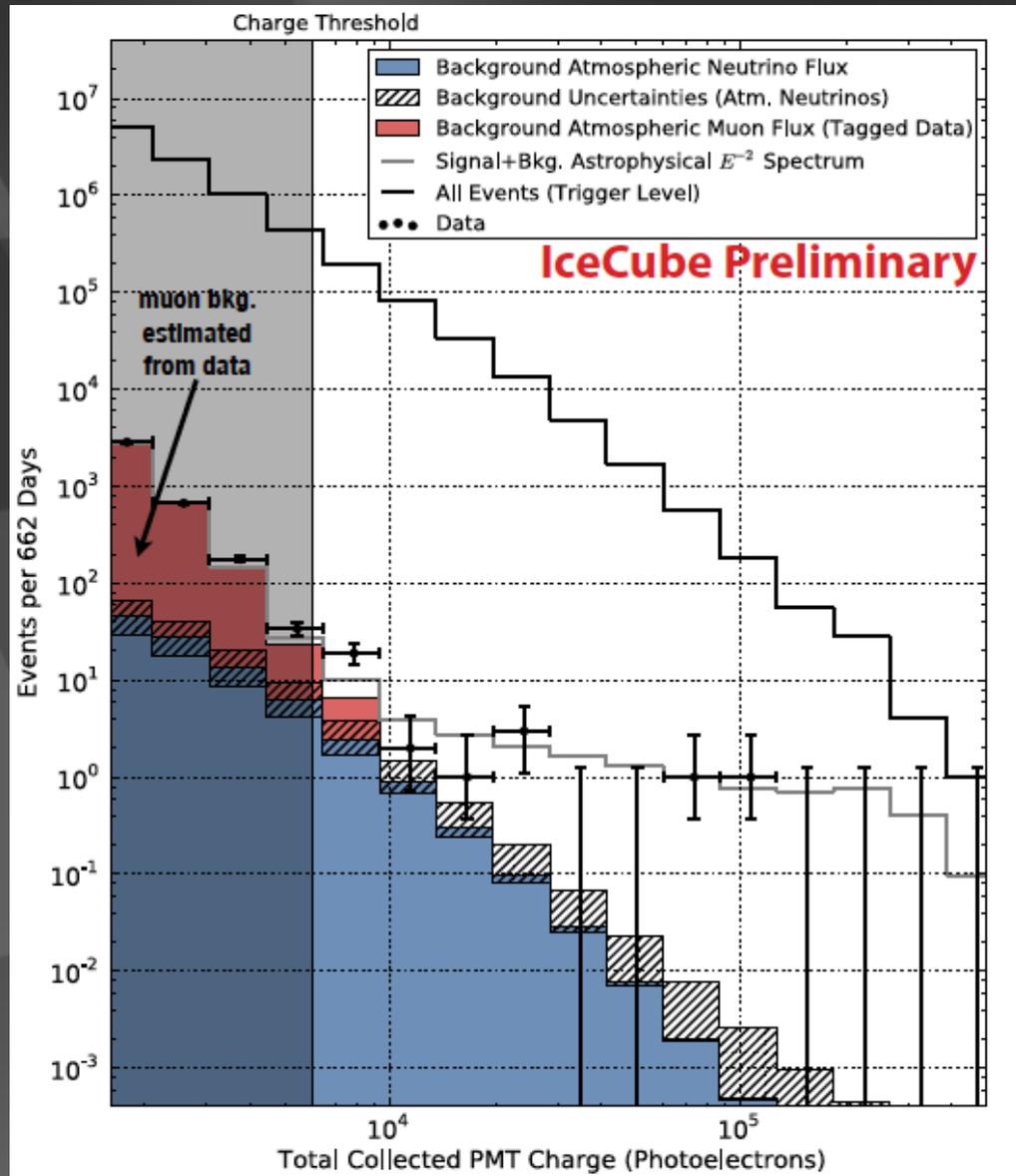
2013 atmospheric and cosmic neutrinos



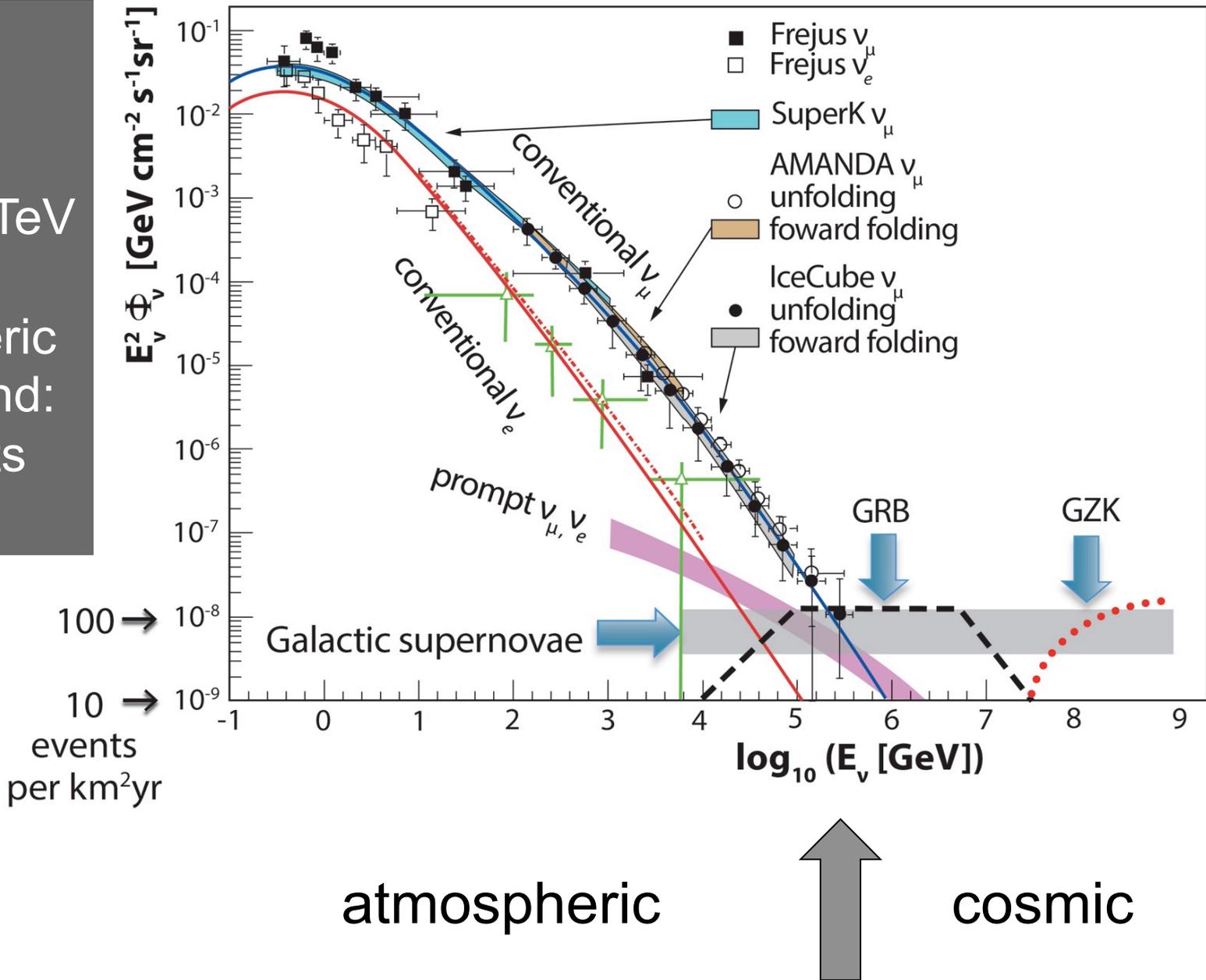
2013 atmospheric and cosmic neutrinos

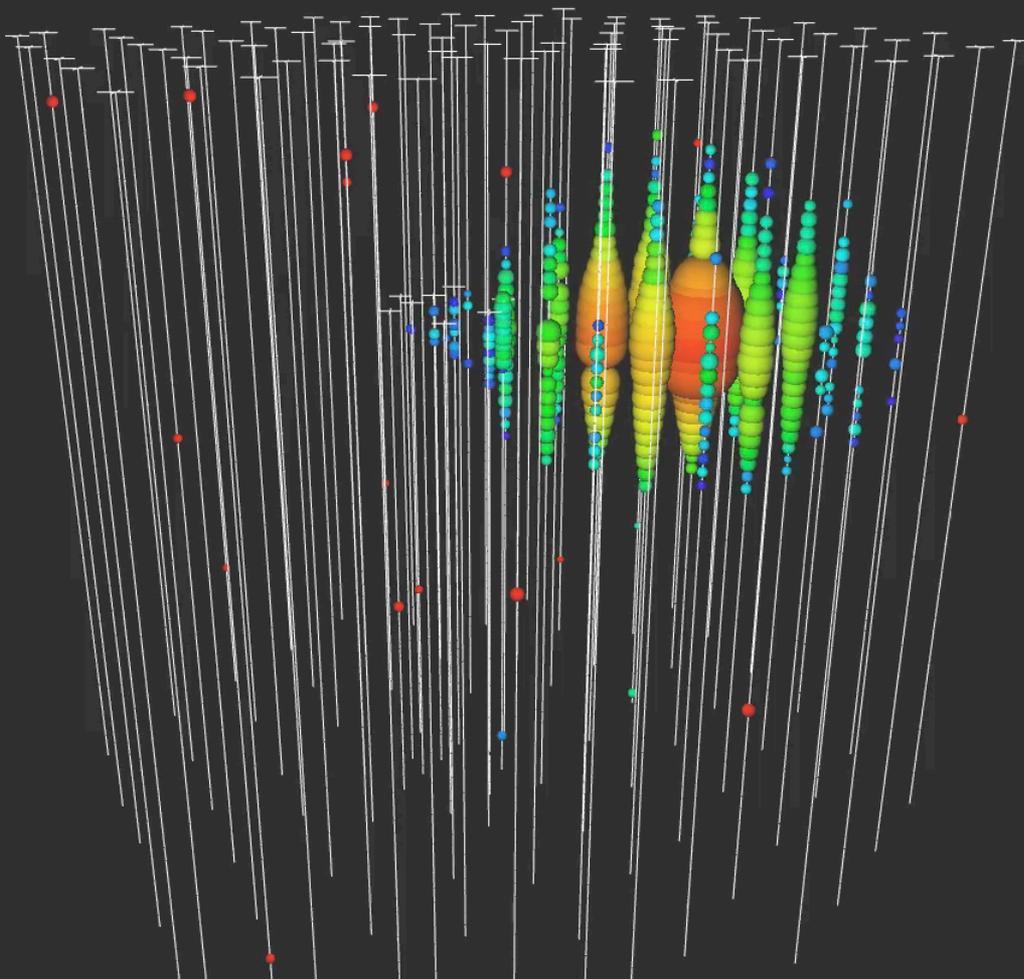
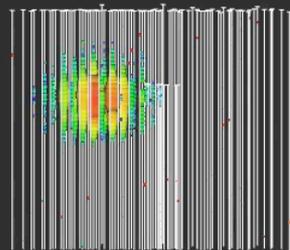
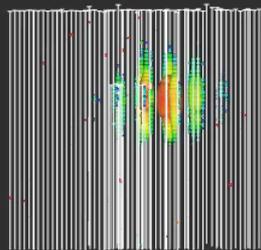
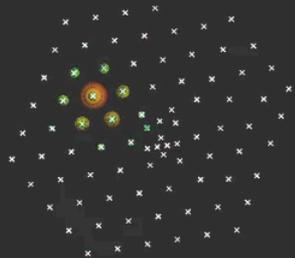


1965
cosmic ray
muons
and
atmospheric
neutrinos

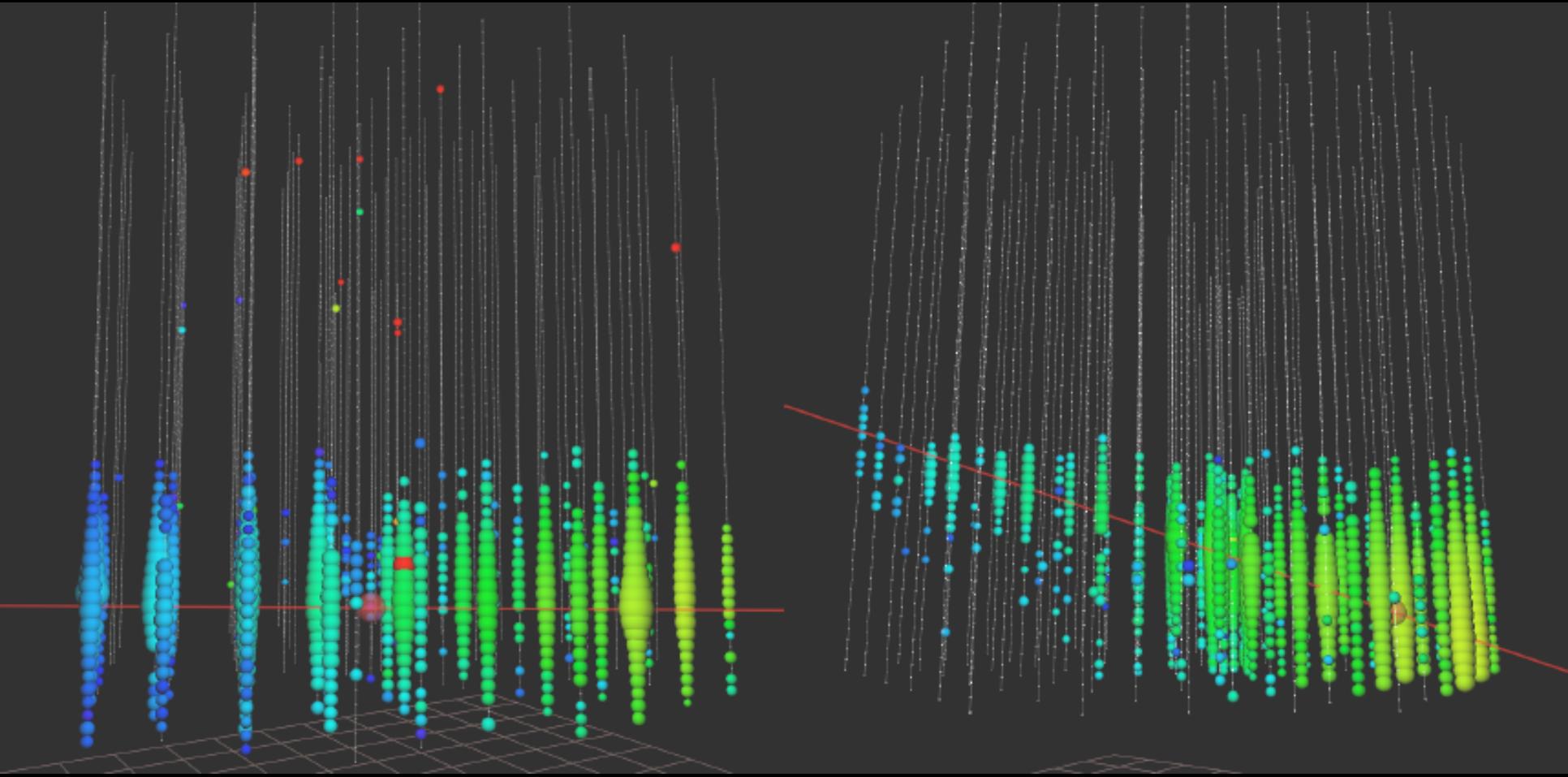


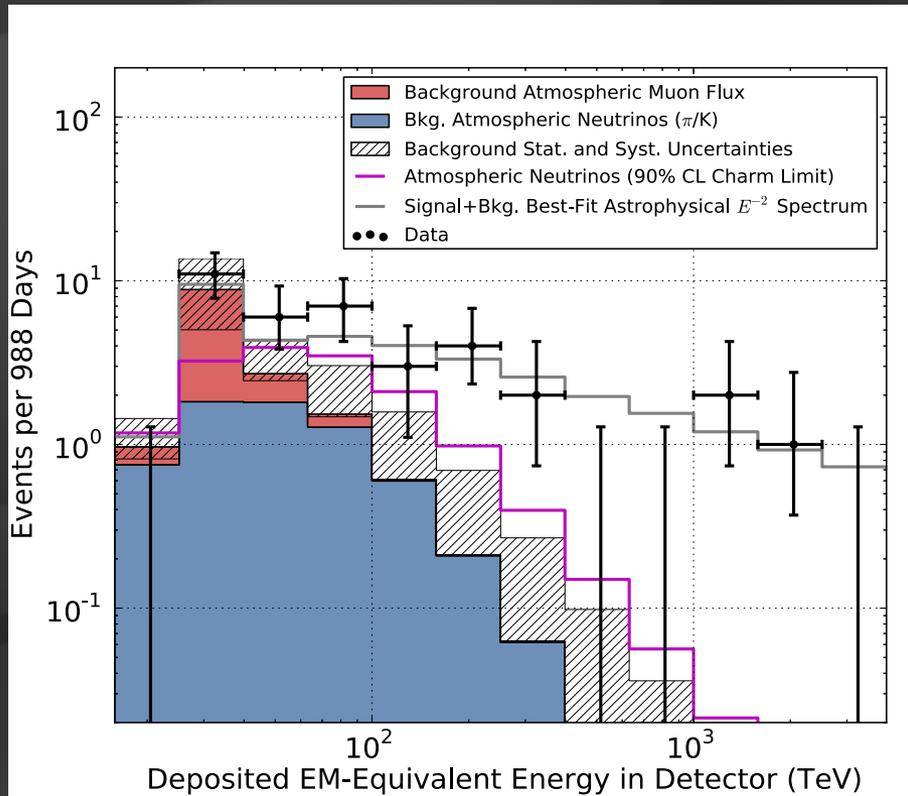
- cosmic neutrinos: energy > 100 TeV
- atmospheric background: 1~2 events per year





highest energy muon energy observed: 560 TeV

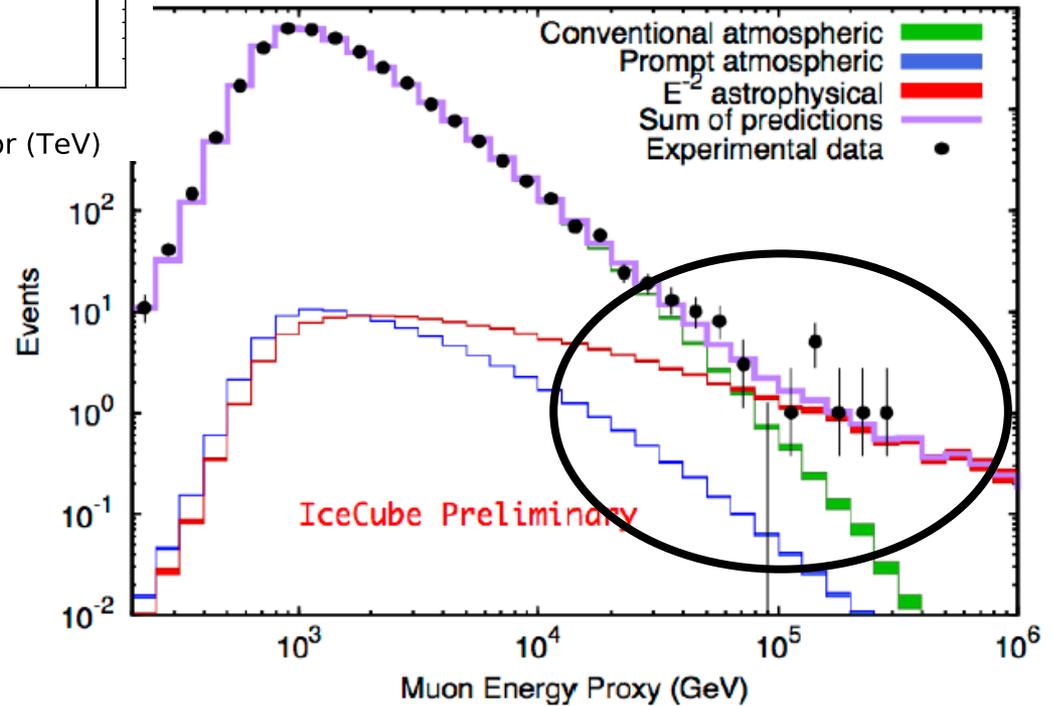




confirmation!
flux of muon neutrinos
through the Earth



neutrinos of all flavors
interacting inside
IceCube



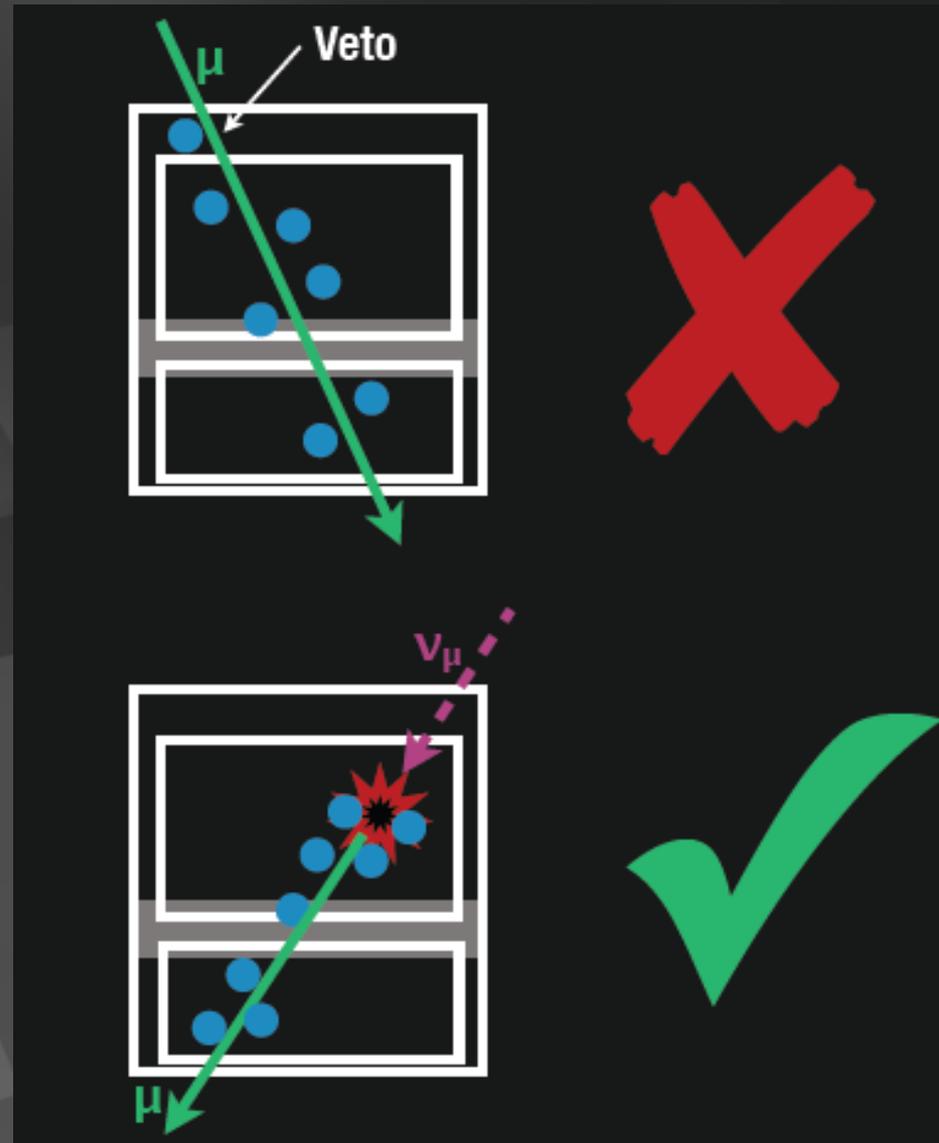
- find contained events (420 Mton)

- total calorimetry

- complete sky coverage

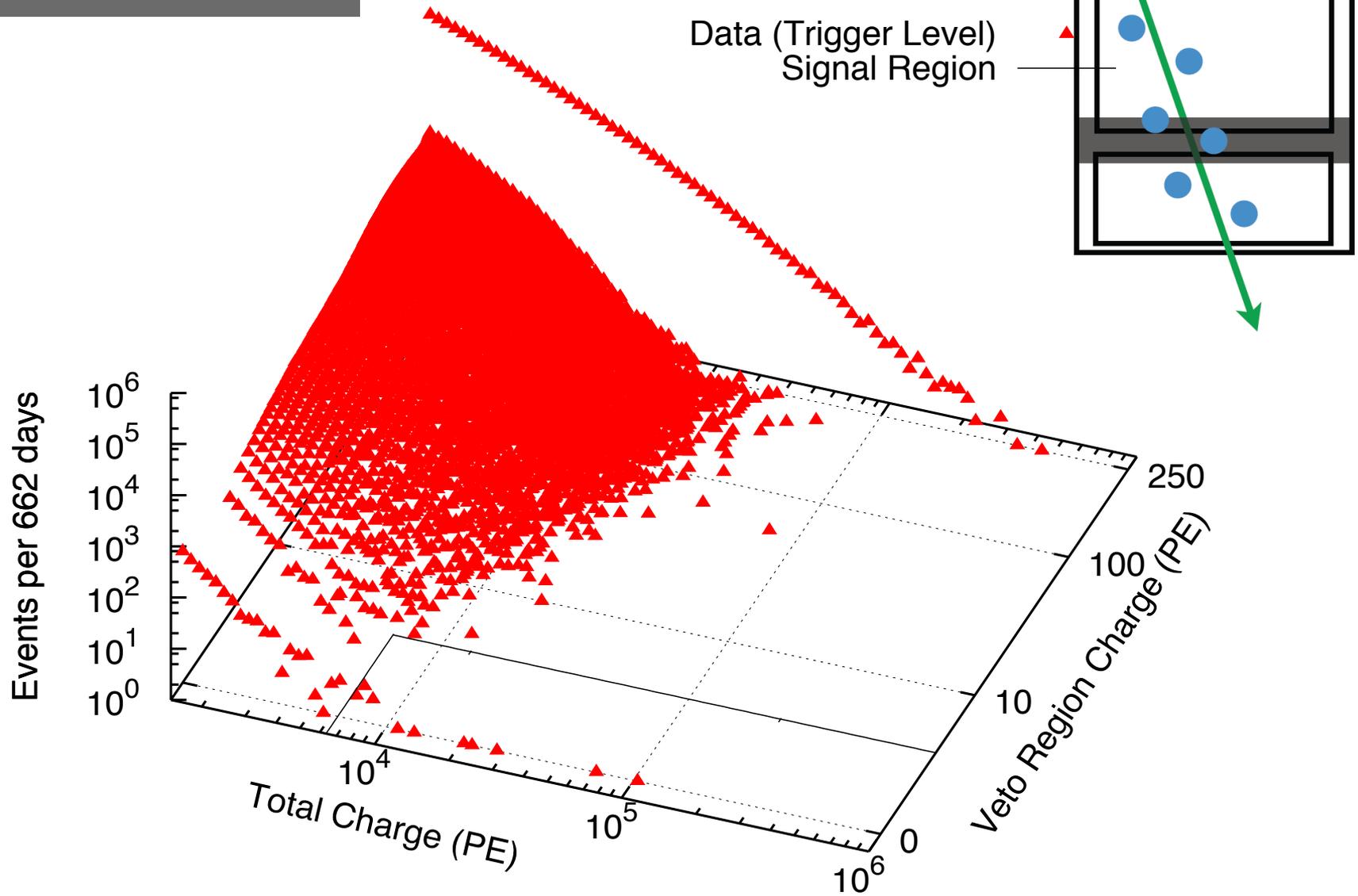
- flavor determined

- some will be muon neutrinos with good angular resolution



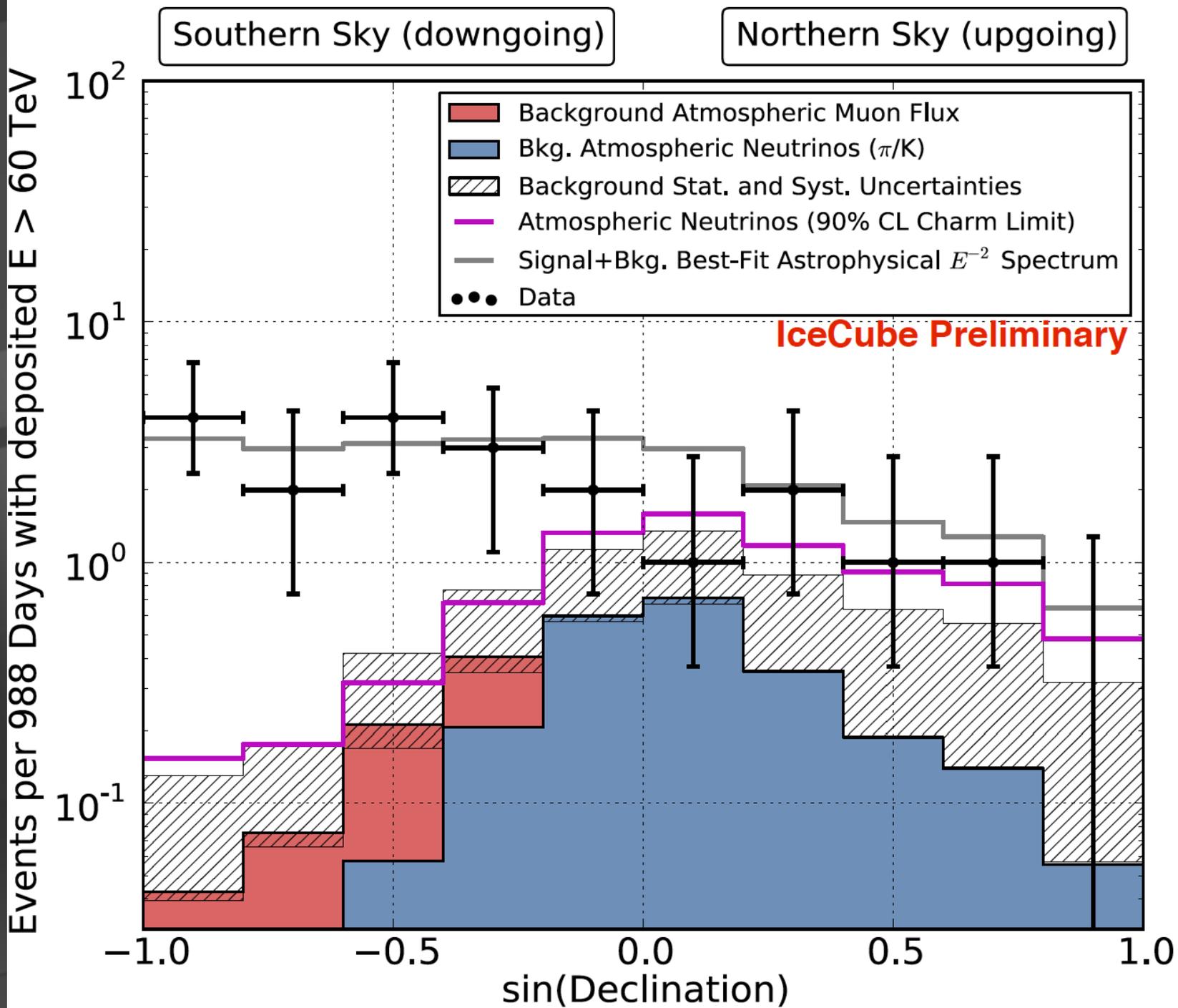
loss in statistics is compensated by event definition

...and then there were 26 more...



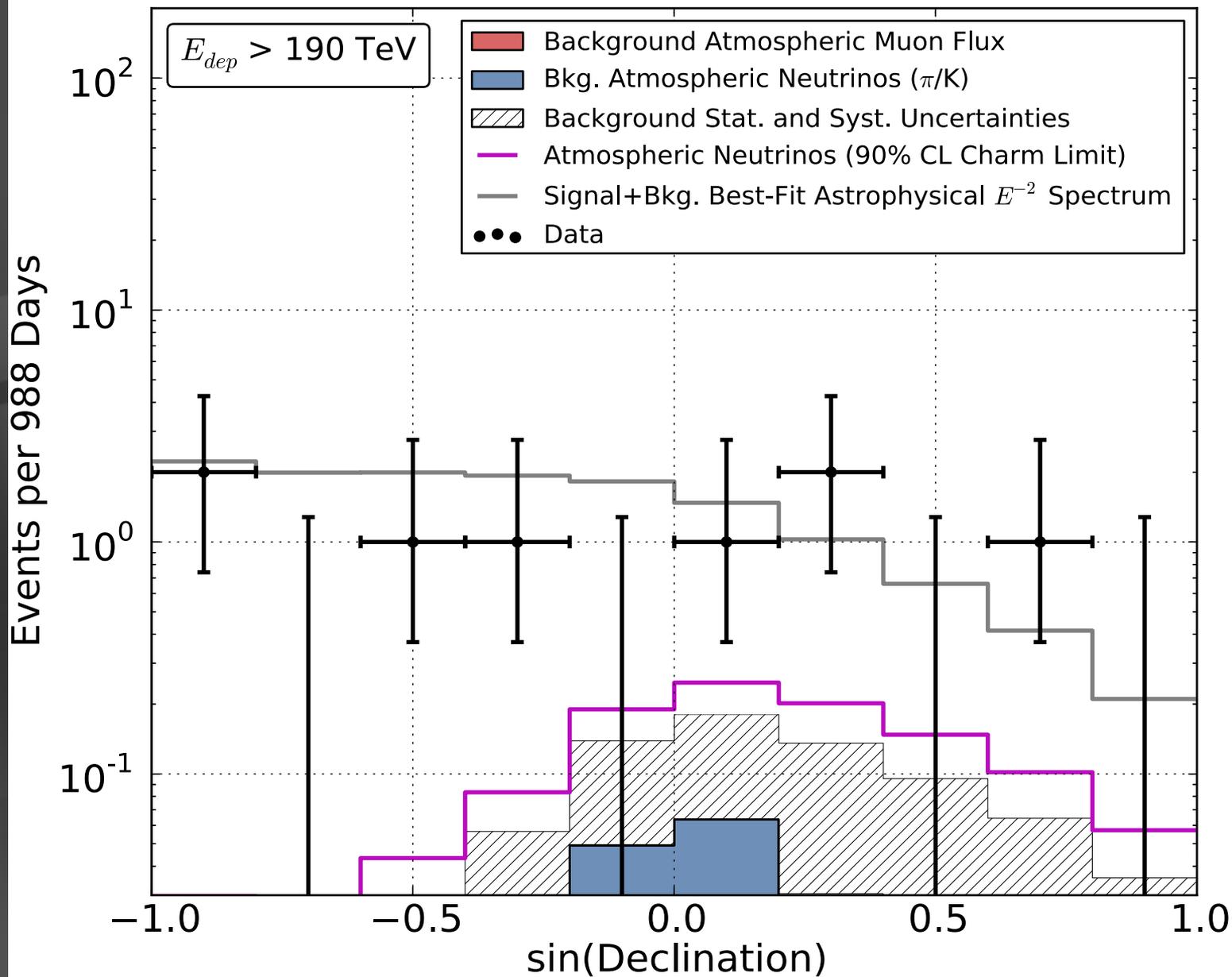
data: 86 strings one year

3 years



Southern Sky (downgoing)

Northern Sky (upgoing)



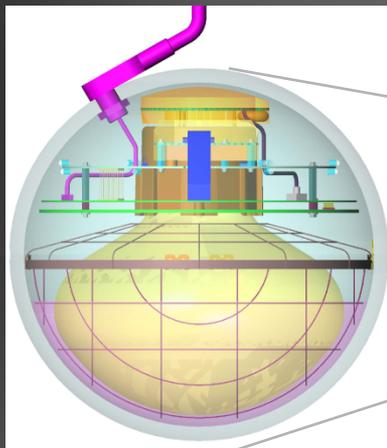
physicsworld
**BREAKTHROUGH
OF THE YEAR
2013**



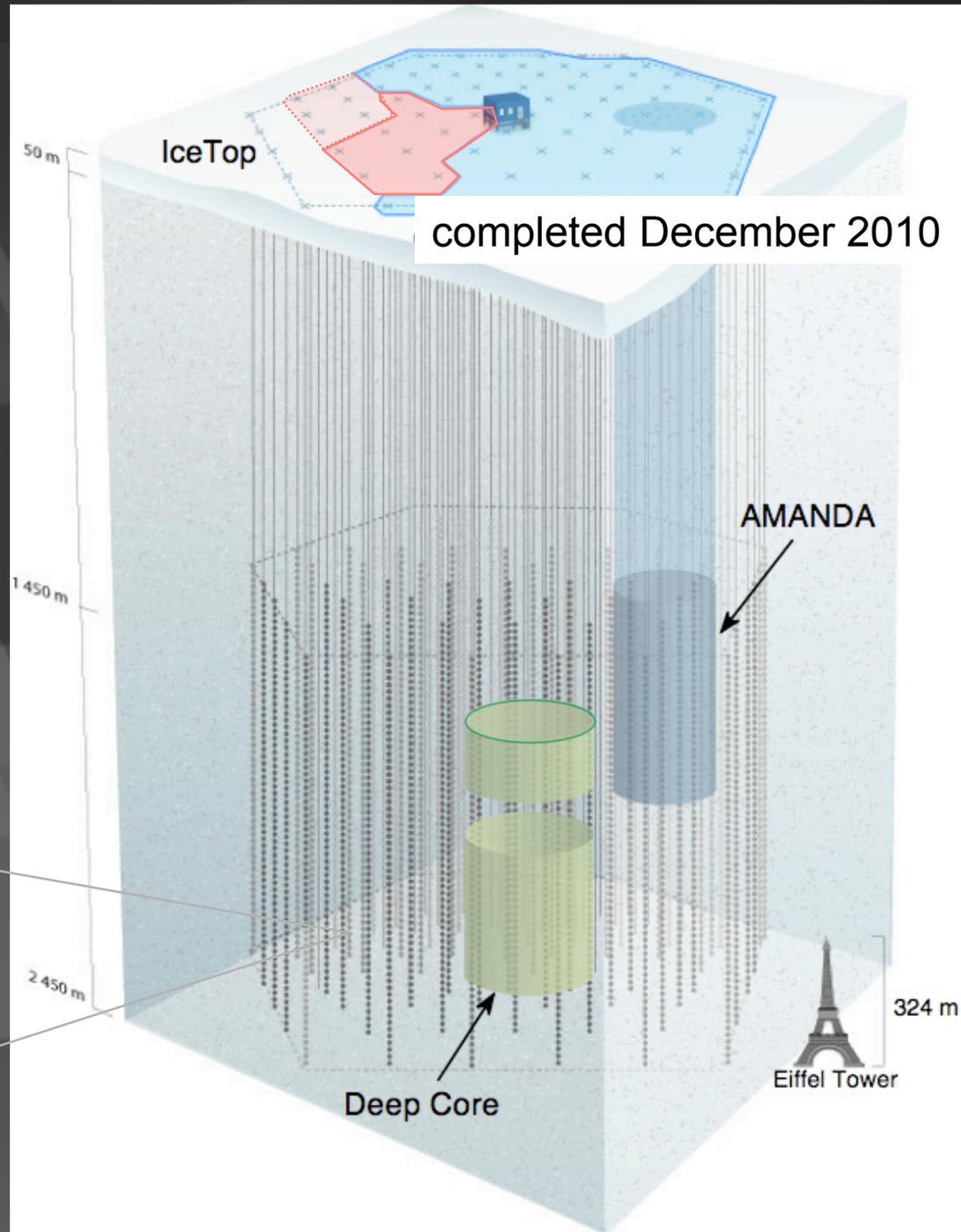
... for science and for the experimental accomplishment of building IceCube ...

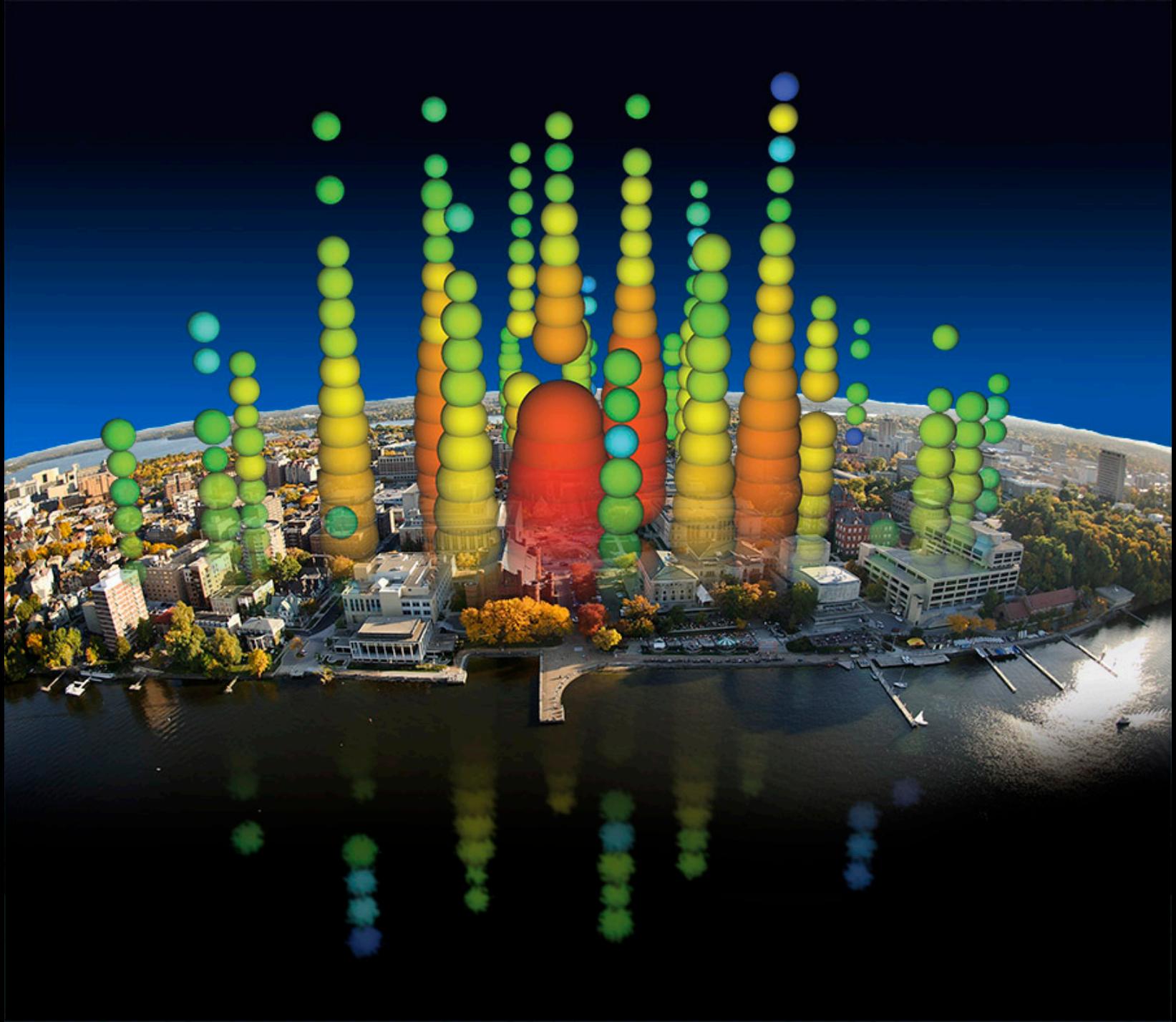
IceCube performance

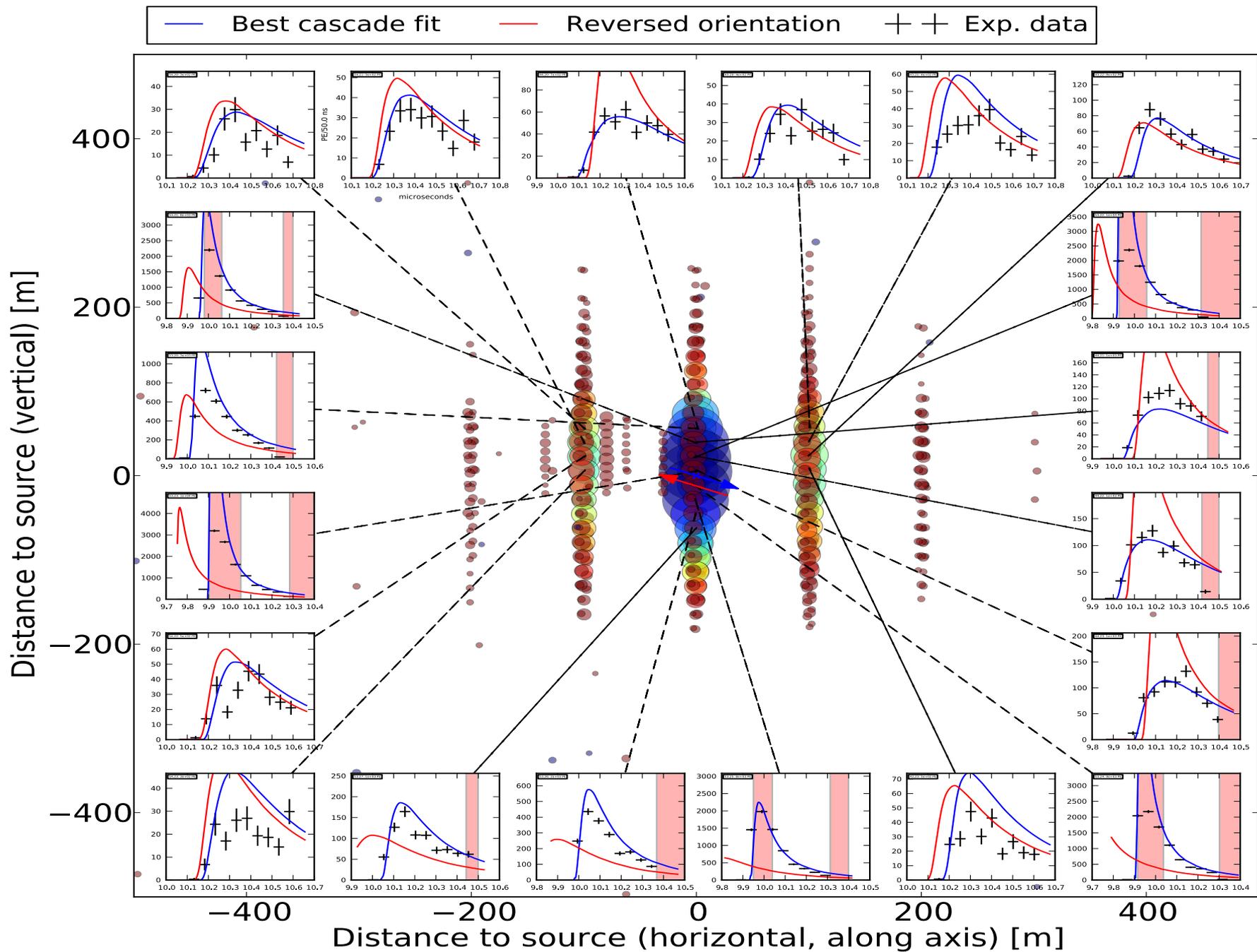
- 5160 optical sensors between 1.5 ~ 2.5 km
- 10 GeV to infinity
- < 0.5 degree on-line
 < 0.3 degree off-line for muon tracks
- 10~15 degrees for showers
- $< 15\%$ energy resolution



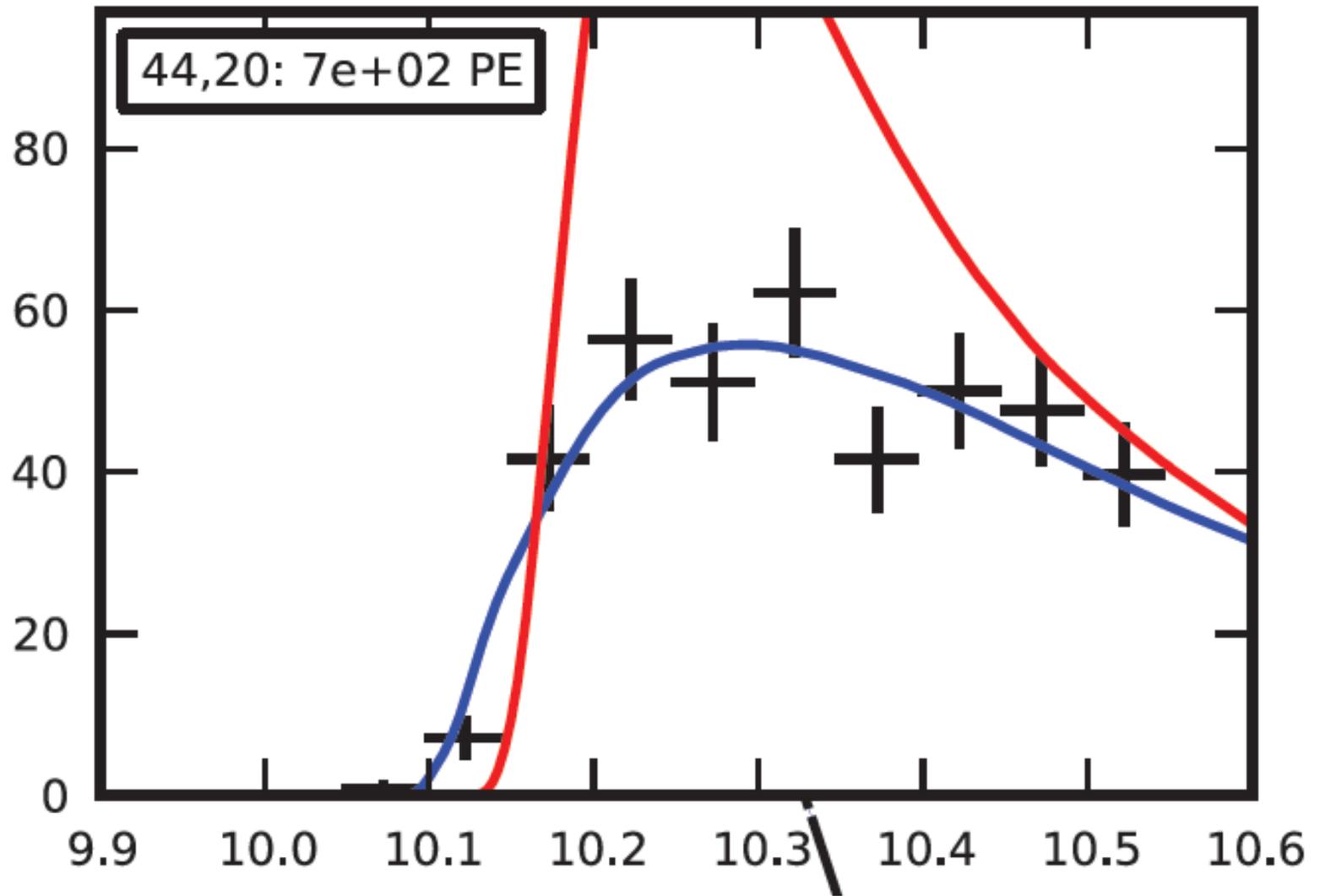
Digital Optical Module (DOM)





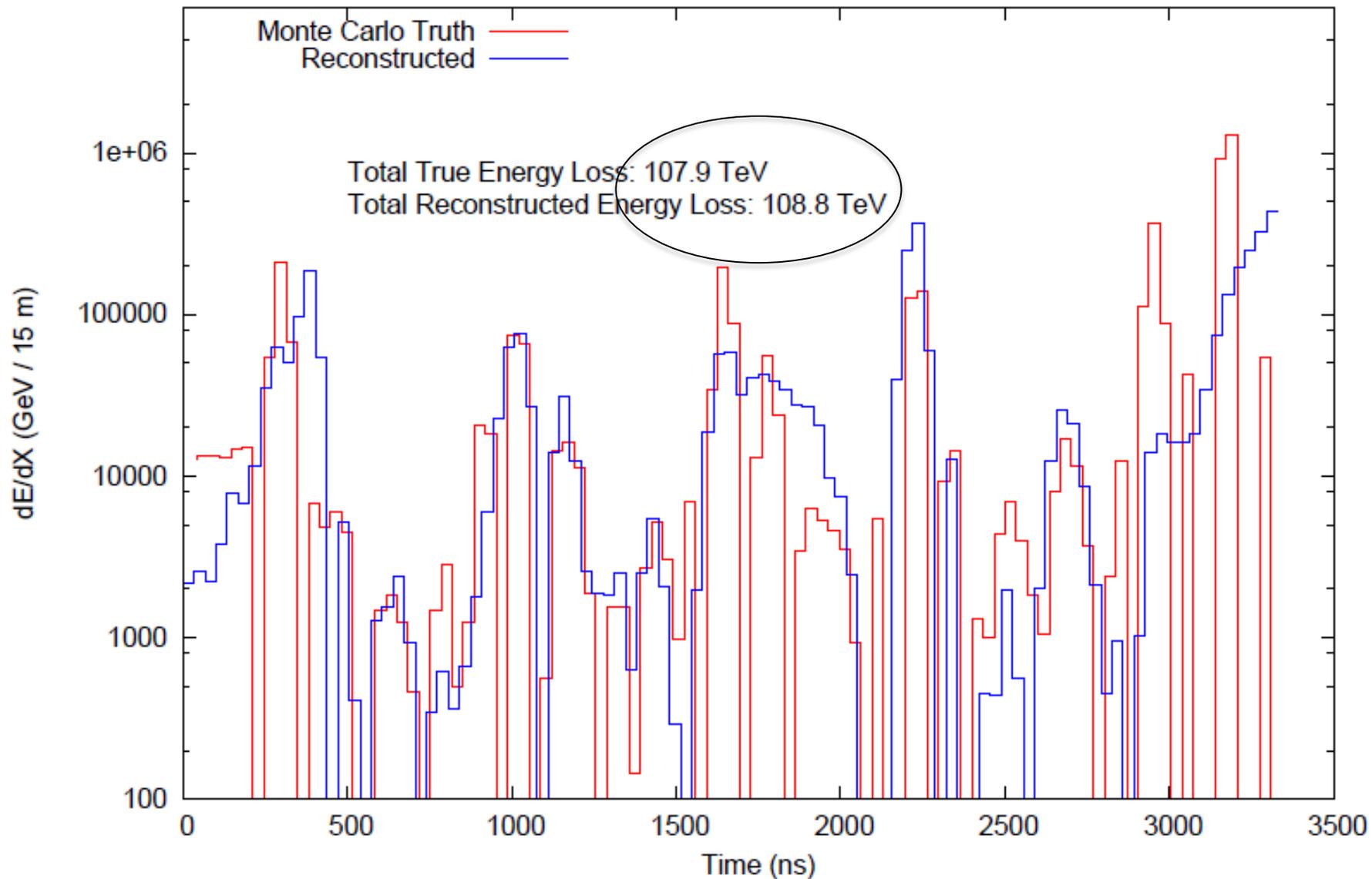


digital optical module 44 on string 20 only



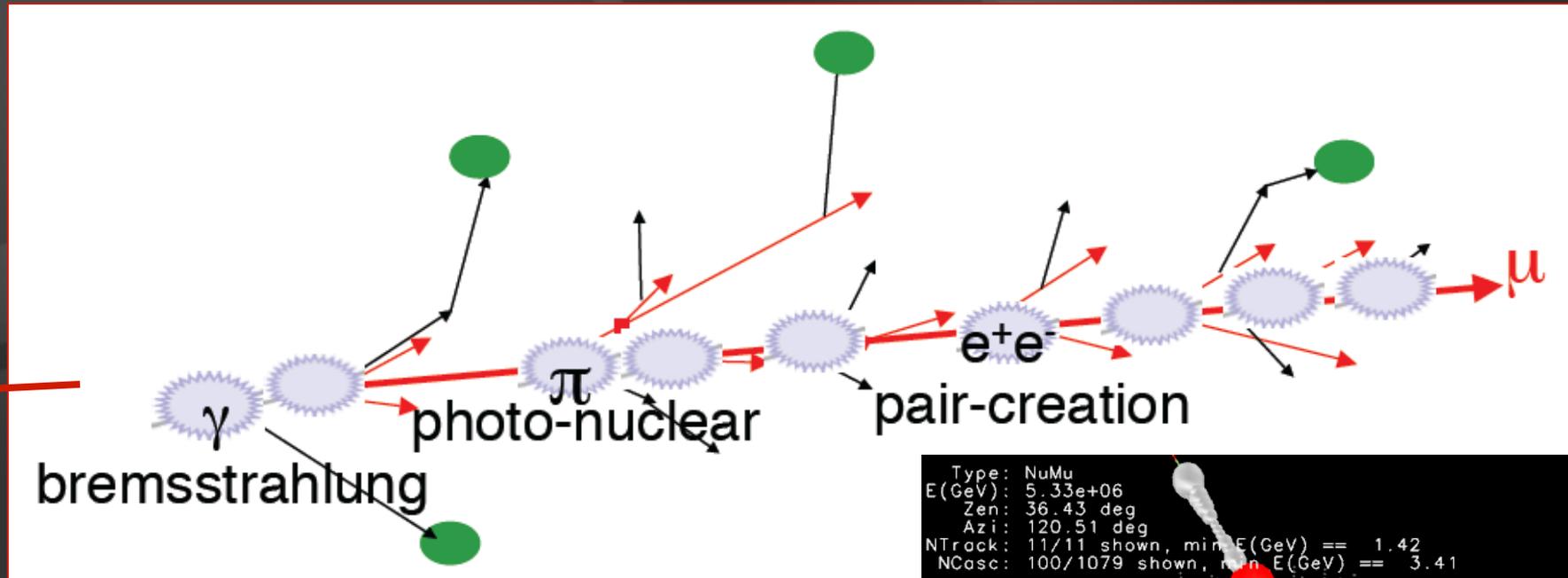
Blue: best-fit direction, red: reversed direction

Differential Energy Reconstruction of 5 PeV Muon in IC-86



improving angular and energy resolution

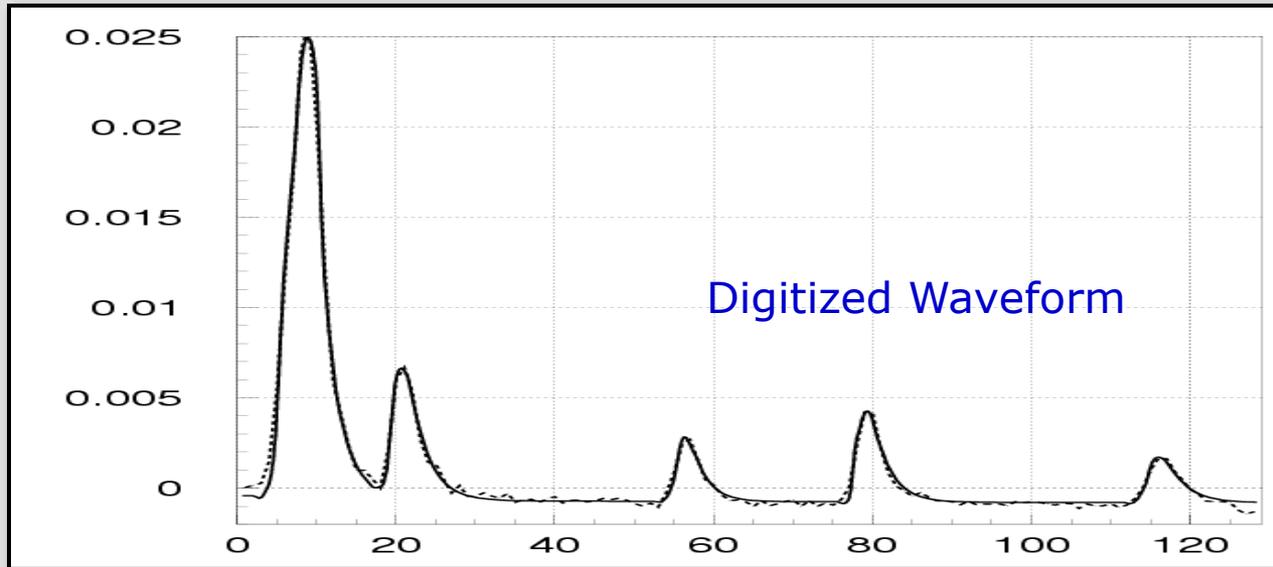
energy measurement (> 1 TeV)



convert the amount of light emitted to measurement of the muon energy (number of optical modules, number of photons, dE/dx , ...)

Digital Optical Module (DOM)

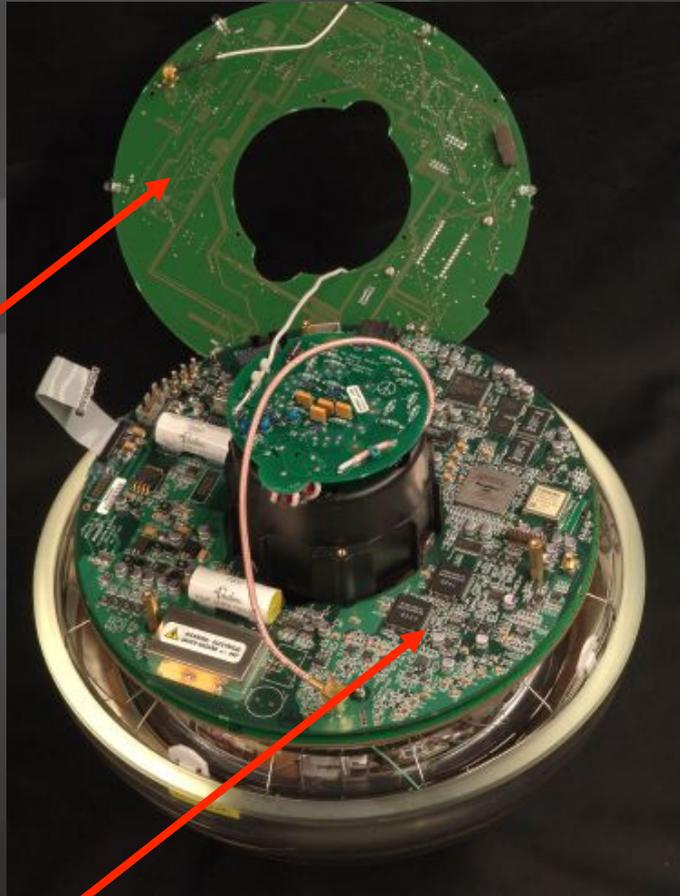
... each DOM independently collects light signals like this...



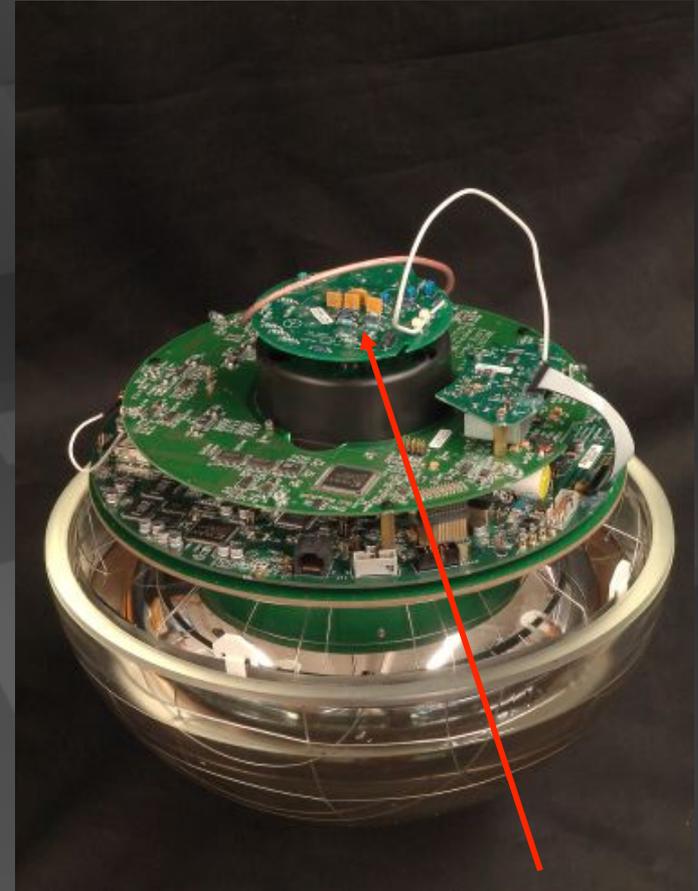
...time stamps them with 2 nanoseconds precision and sends them to a computer that sorts them into muon and neutrino events...

architecture of independent DOMs

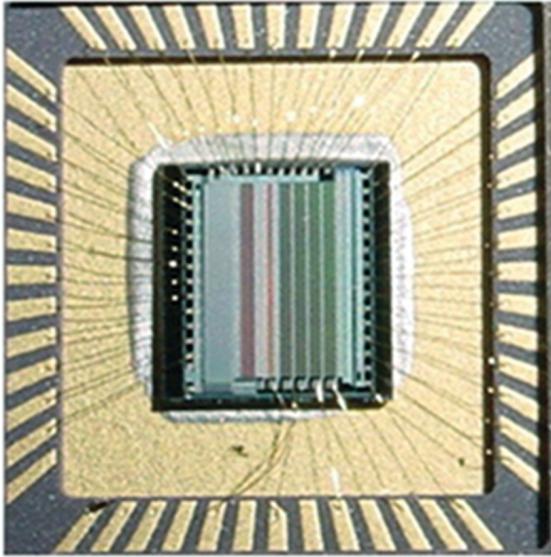
LED
flasher
board



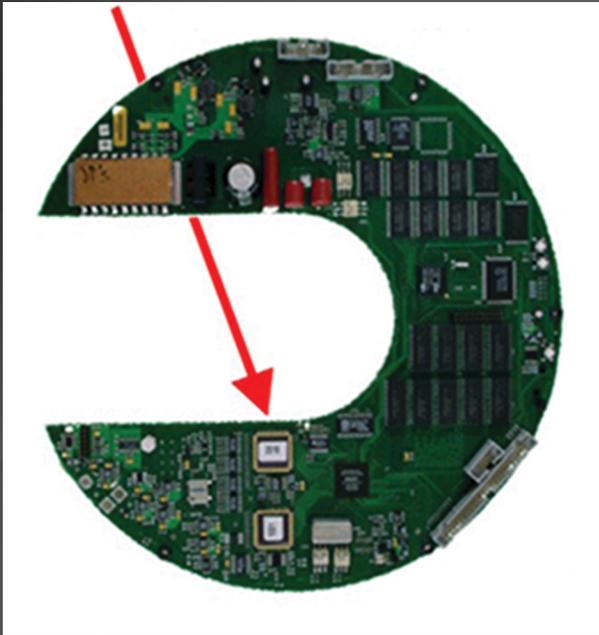
main
board

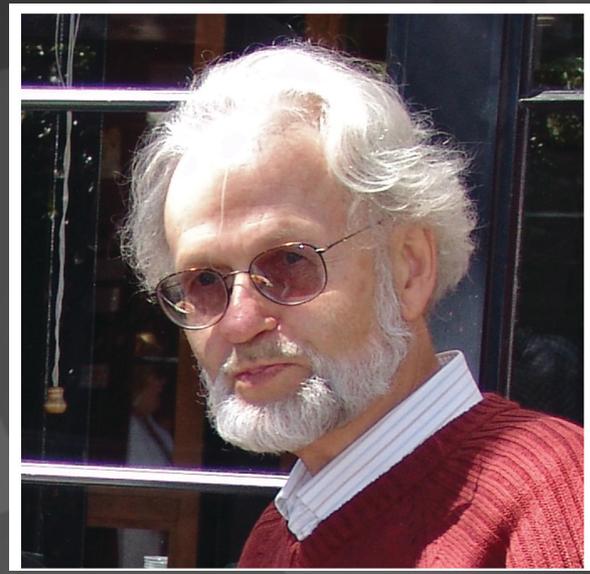


HV board

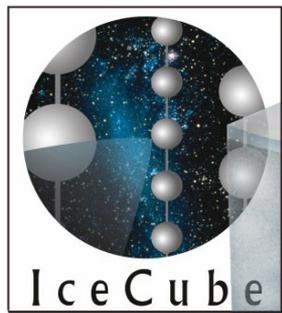


AMANDA string 18





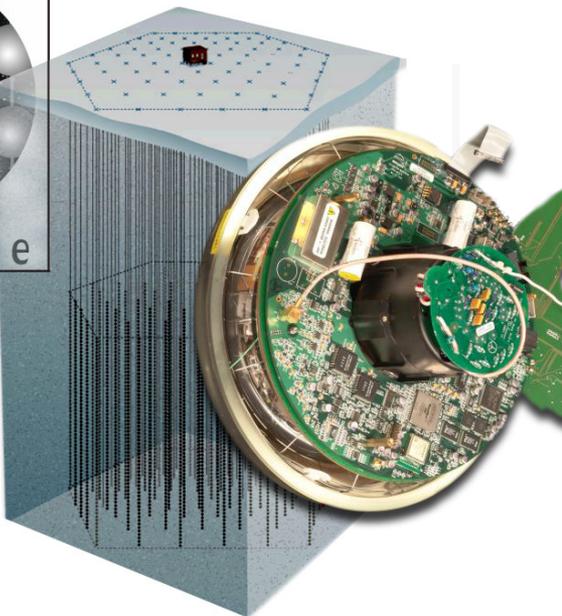
Kleinfelder Jacobsen
Sulanke Nygren



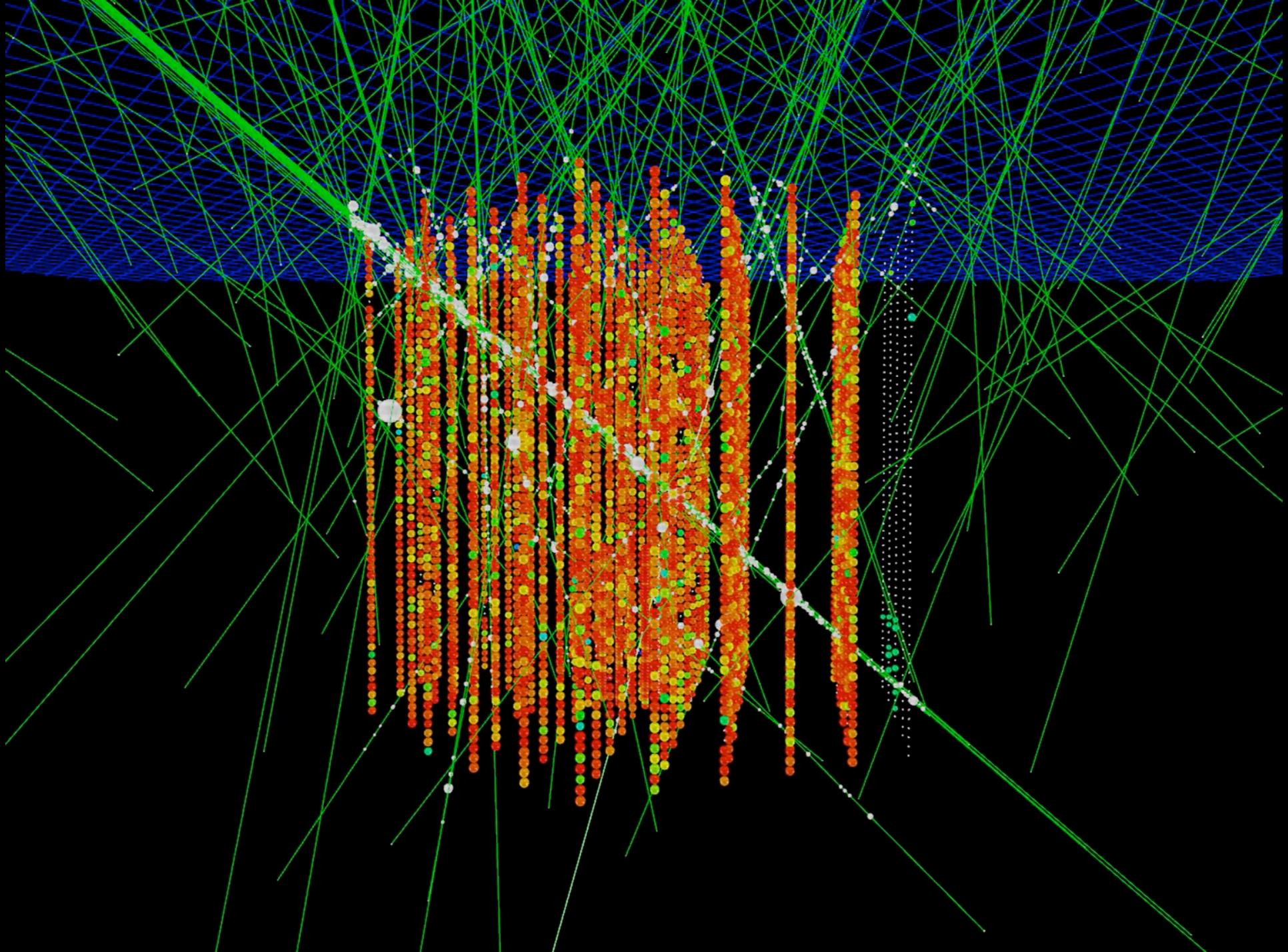
IceCube

1.5 kilometers

2.5 kilometers



5693 Main Boards Shipped
Were Done



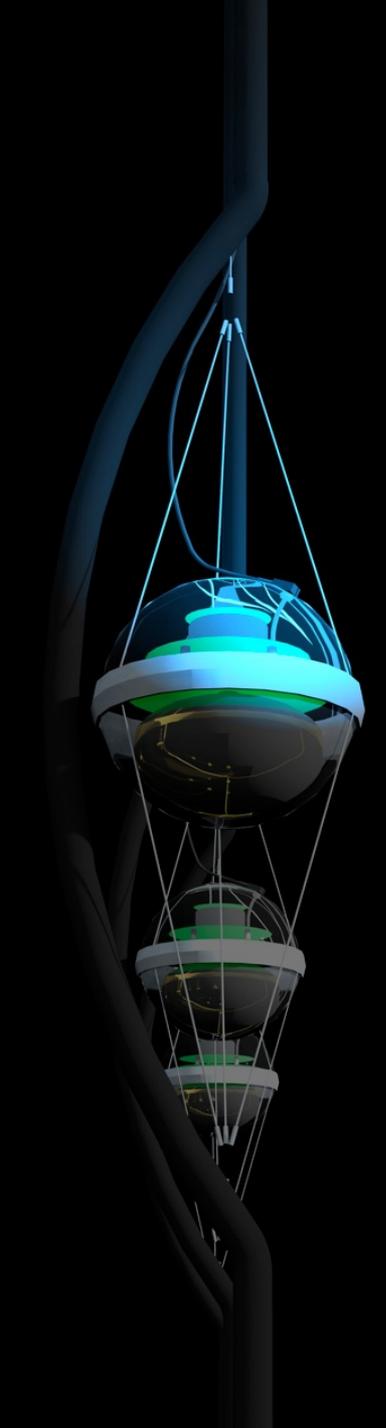
... you looked at 10msec of data !

muons detected per year:

- atmospheric* μ $\sim 10^{11}$
- atmospheric** $\nu \rightarrow \mu$ $\sim 10^5$
- cosmic $\nu \rightarrow \mu$ ~ 10

* 2700 per second

** 1 every 6 minutes

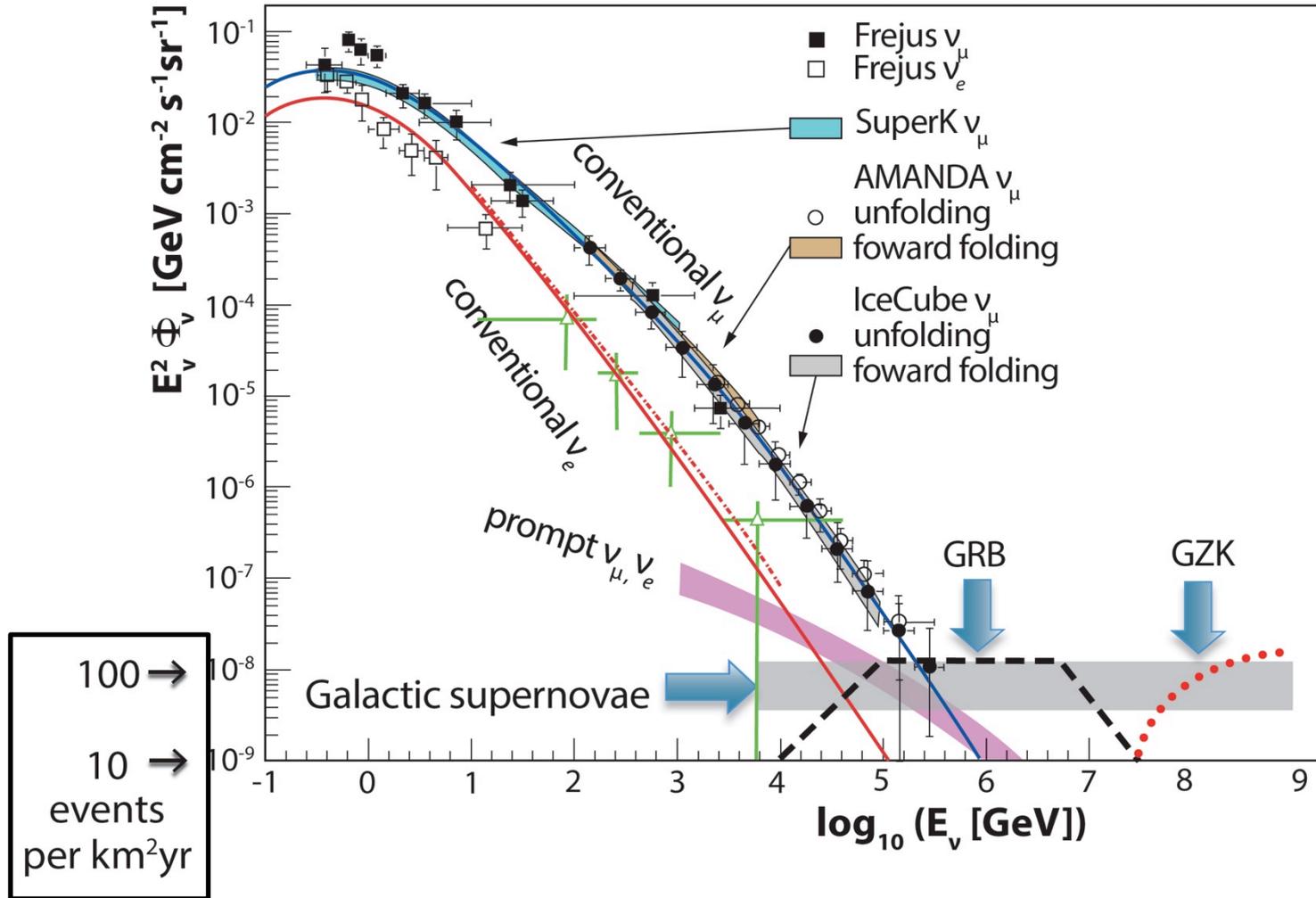


IceCube and Beyond

francis halzen

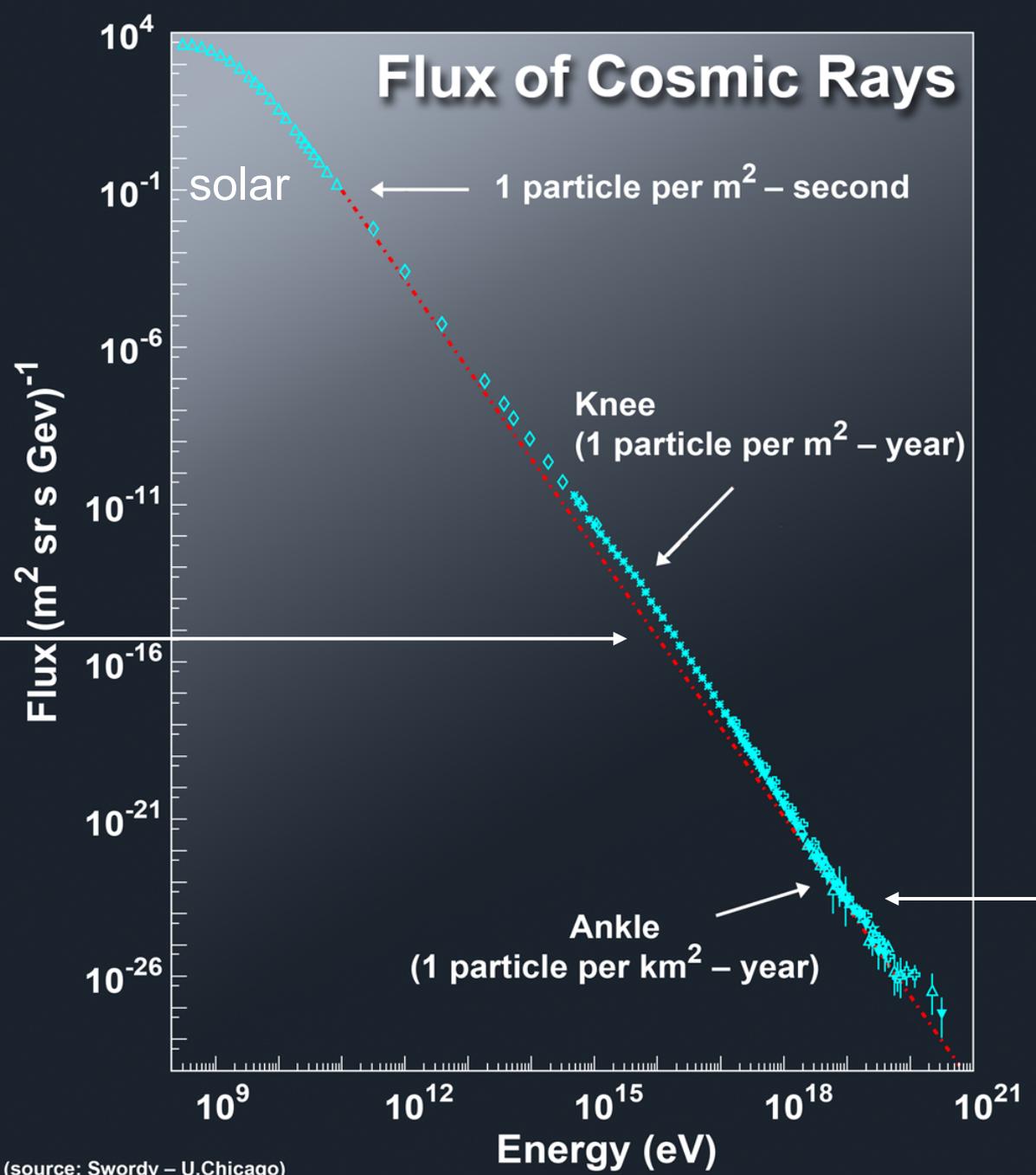
- the discovery of high-energy cosmic neutrinos
- where do they come from?
- beyond IceCube

rationale for a kilometer-scale detector



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

sources that accommodate the observed energy budget



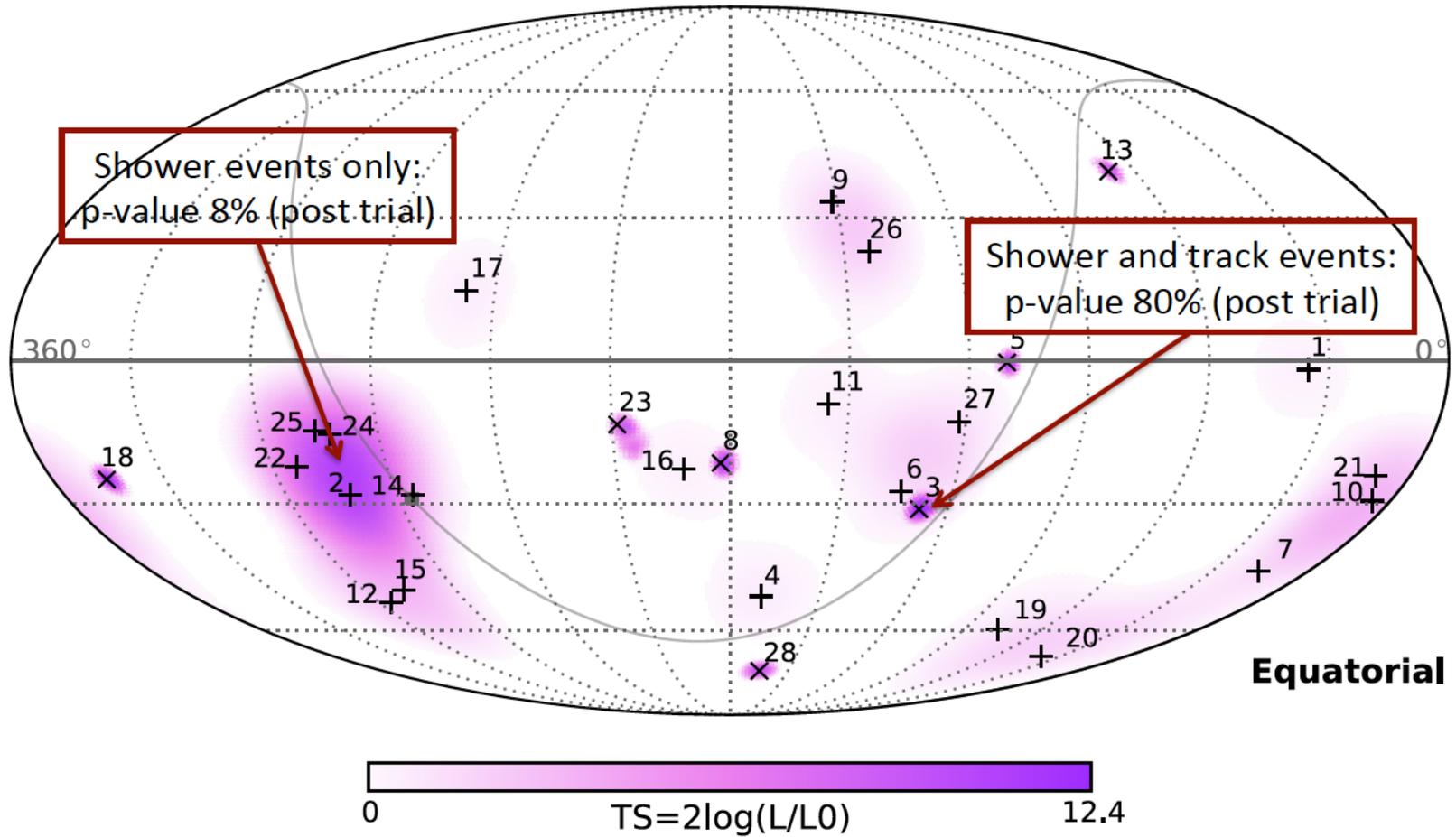
Galactic:
supernova
remnants?

extragalactic:

- gamma ray bursts??
- active galaxies?

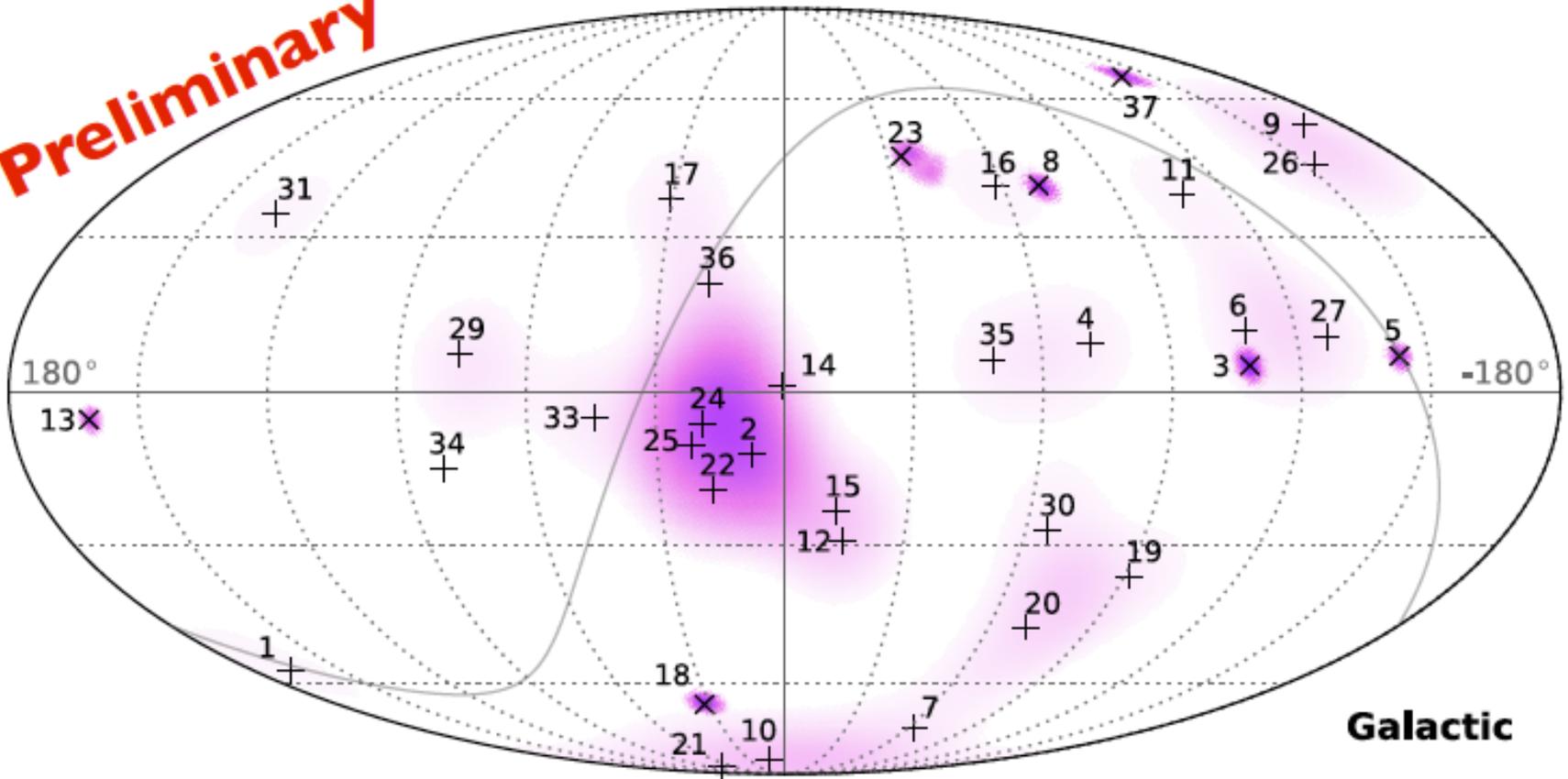
(source: Swordy – U.Chicago)

where do they come from?

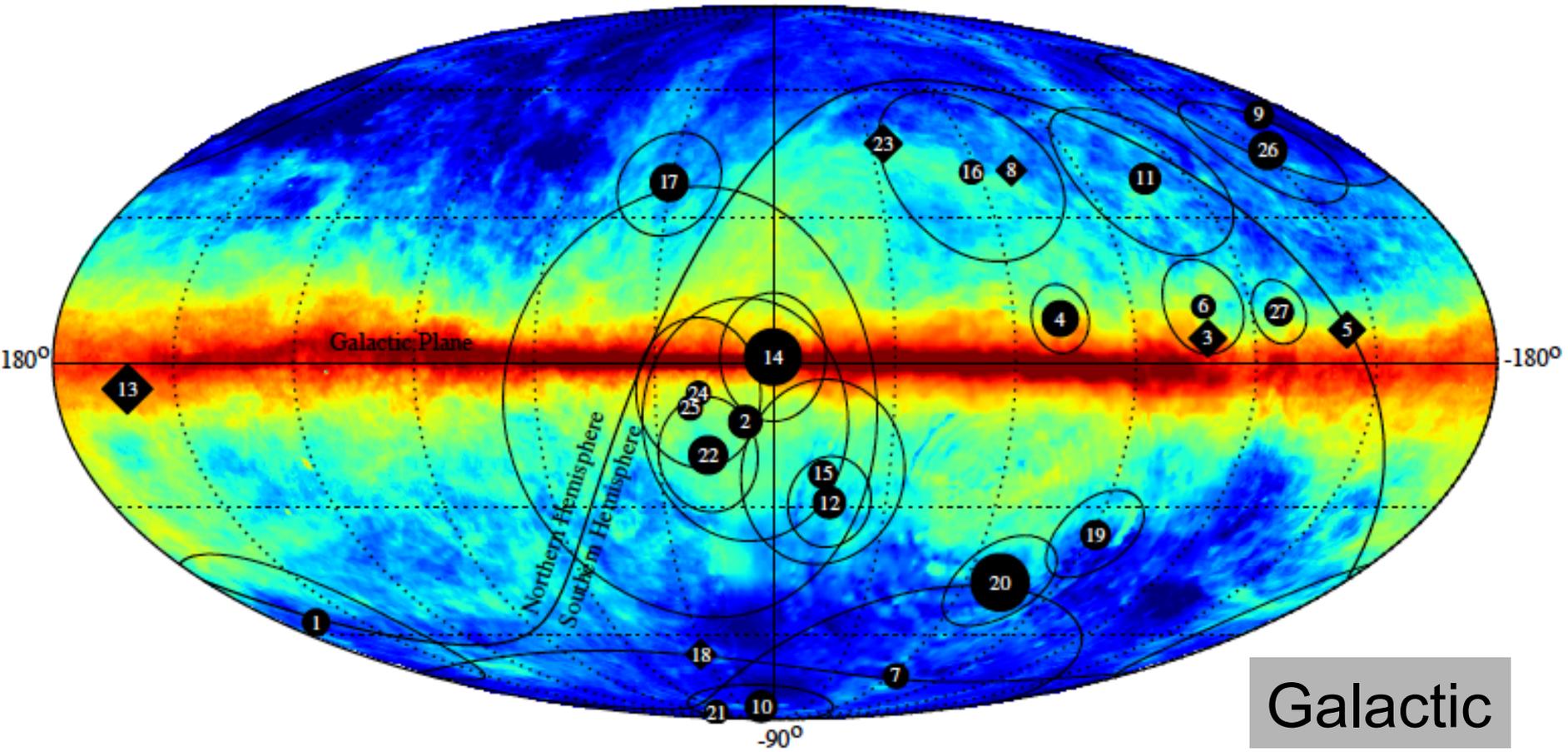


where do they come from (3 year data)?

Preliminary



HI column density [cm^{-2}]



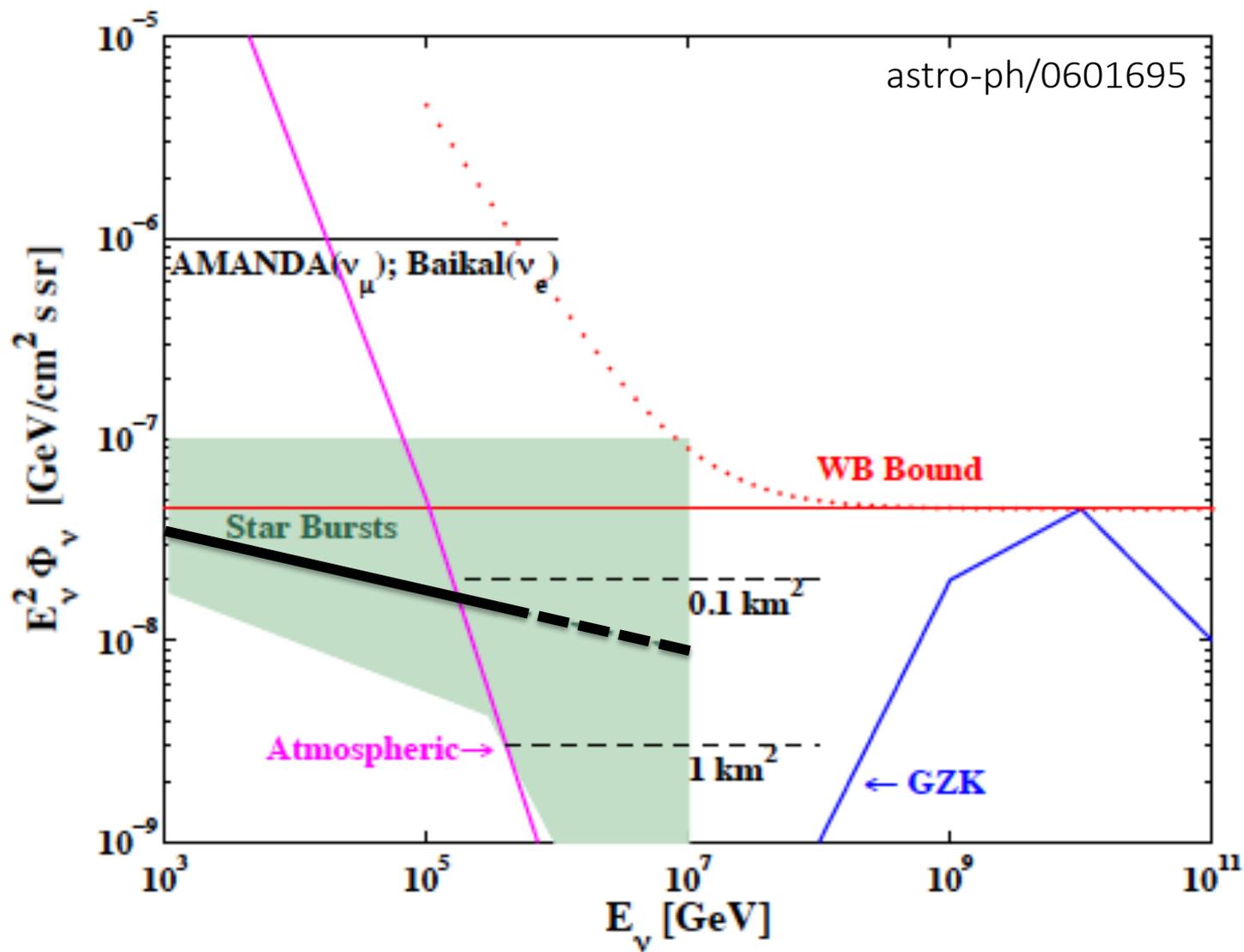
Galactic Plane

Northern Hemisphere
Southern Hemisphere

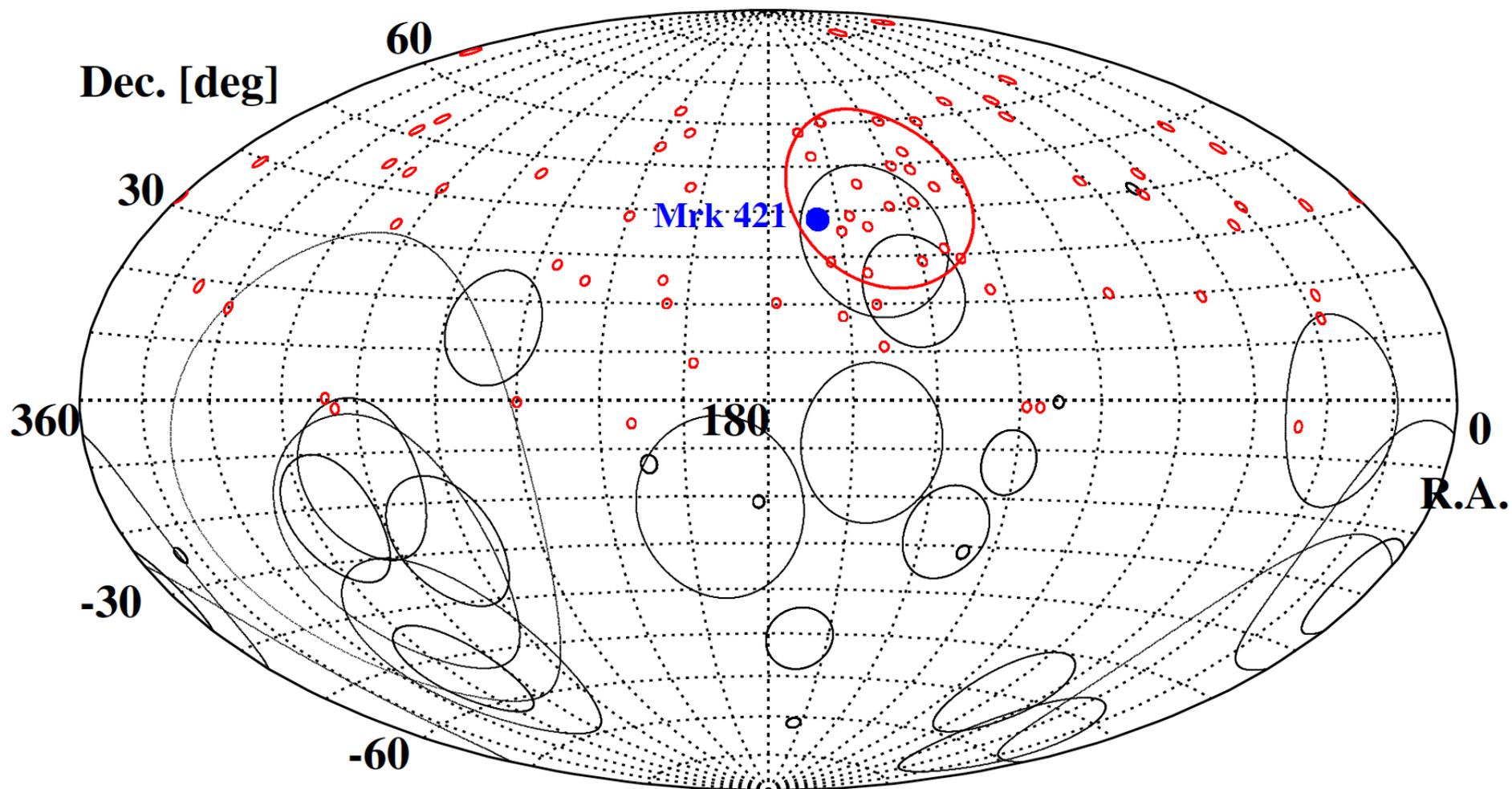
Galactic



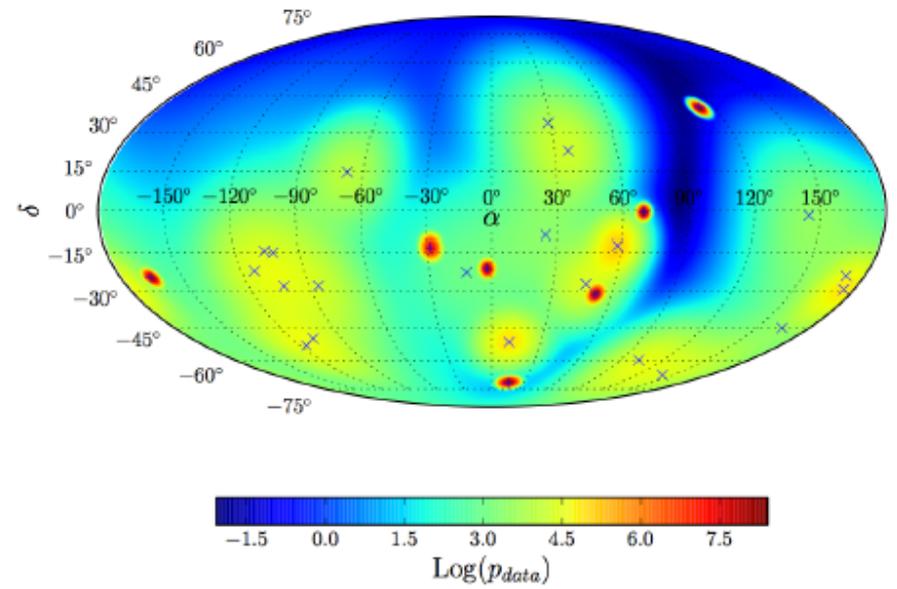
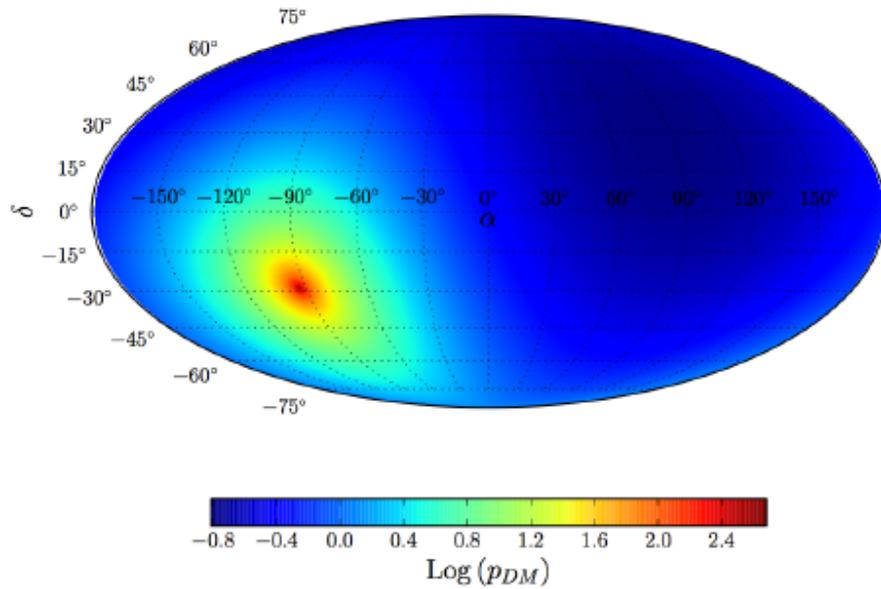
you have one guess: starburst galaxies ?



... maybe one other one: blazars (TA+IceCube)

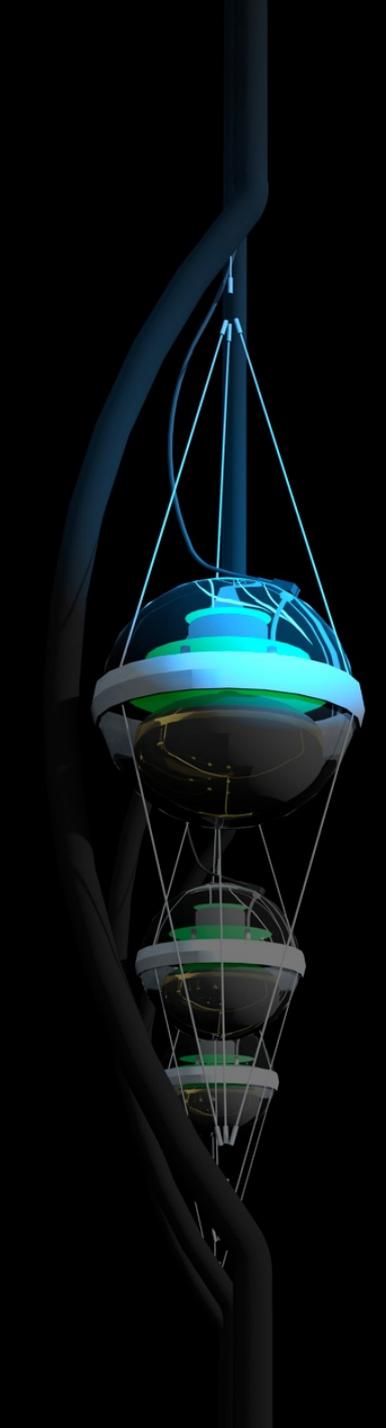


expect surprises: produced by Galactic dark matter halo?



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



IceCube and Beyond

francis halzen

- the discovery of high-energy cosmic neutrinos
- where do they come from?
- beyond IceCube

search for point sources of neutrinos

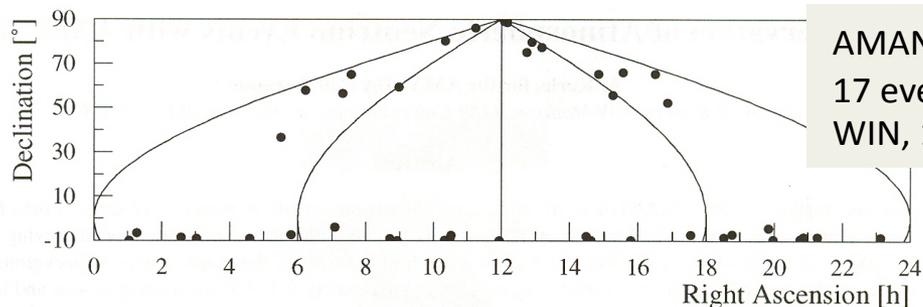
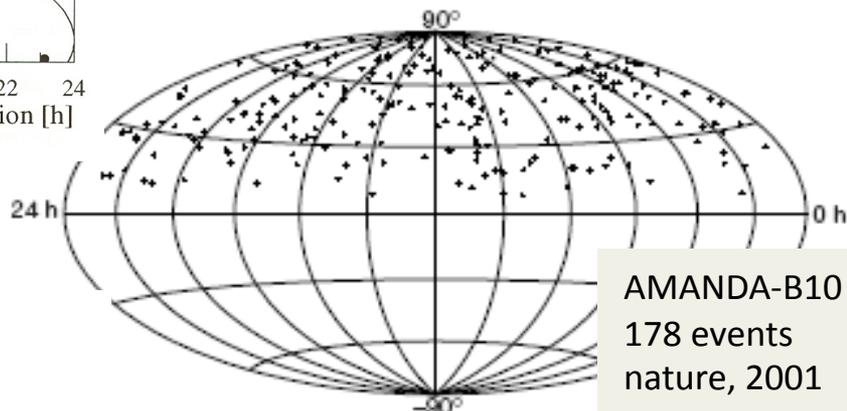
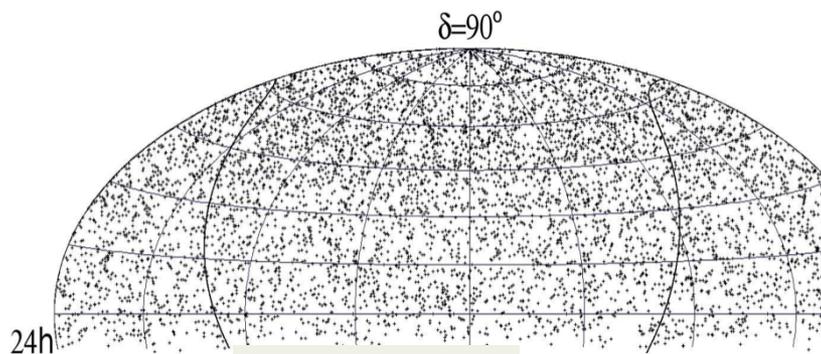


Figure 2: Sky plot of all events that pass level 4 quality cuts.

AMANDA-B10
17 events
WIN, 1999

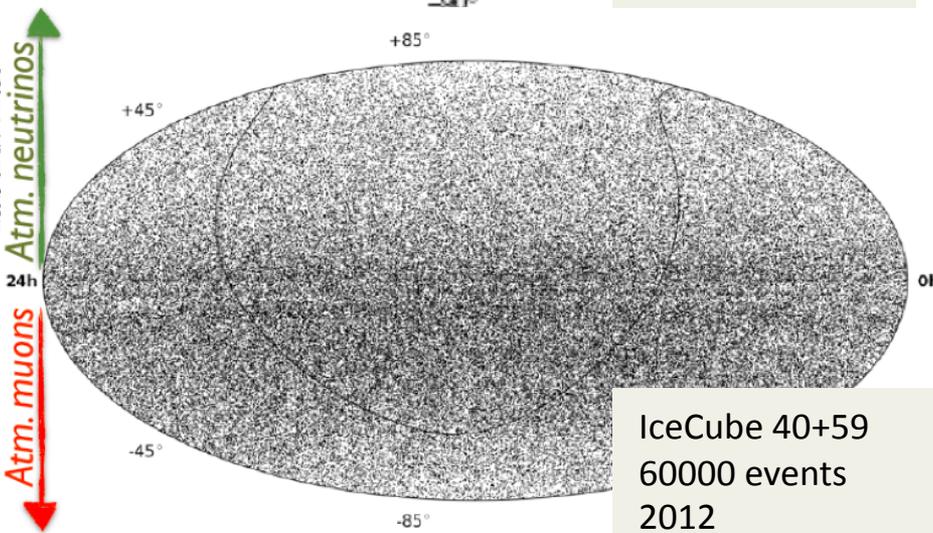


AMANDA-B10
178 events
nature, 2001



AMANDA-II
7 years
6995 events
2006

Atm. neutrinos
Atm. muons



IceCube 40+59
60000 events
2012

auto correlation: detect association with sources

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

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

for a observed diffuse cosmic flux and 0.4 degrees angular resolution

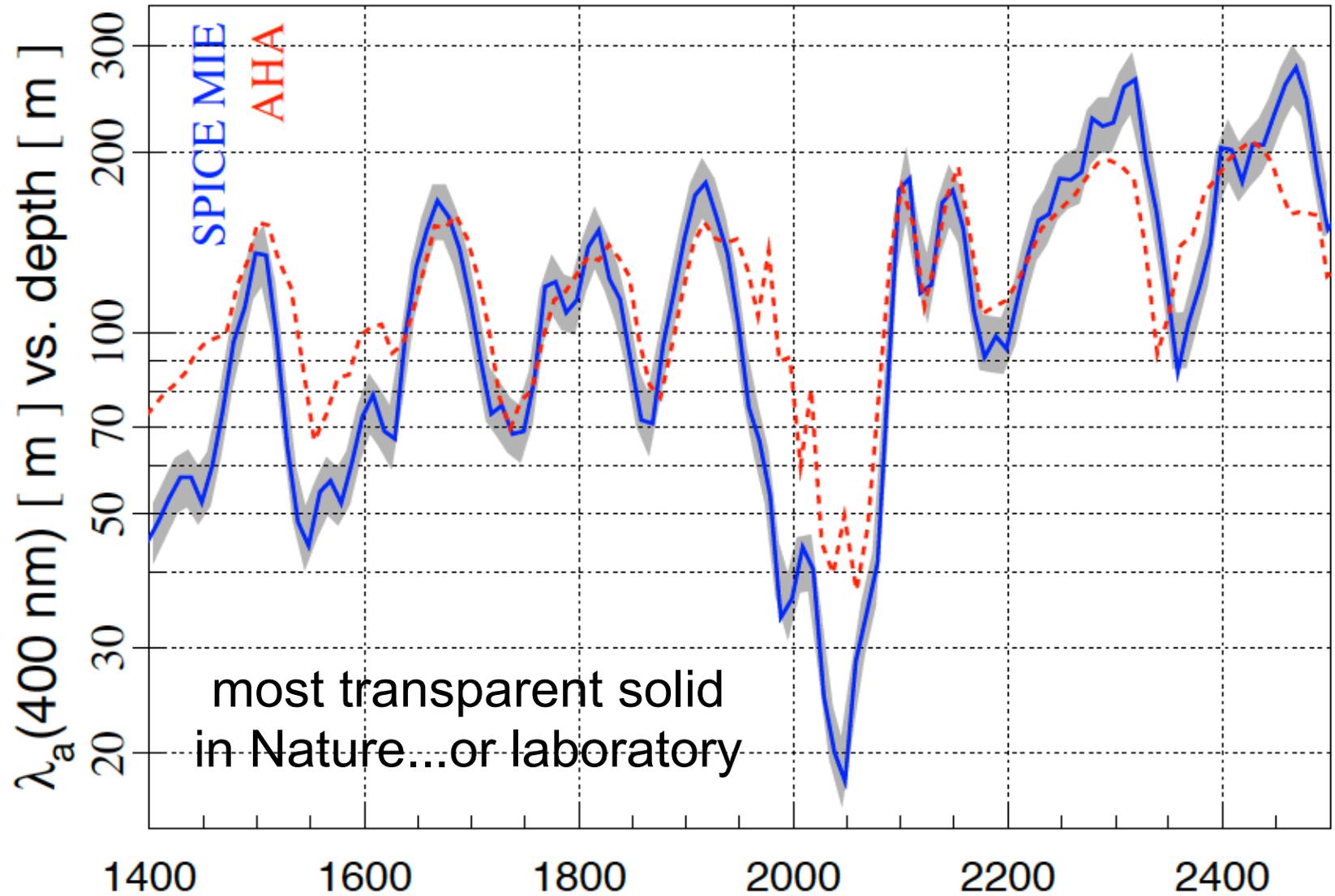
examples of local source densities (per Mpc³):

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

- 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.
- discovery instrument \rightarrow telescope

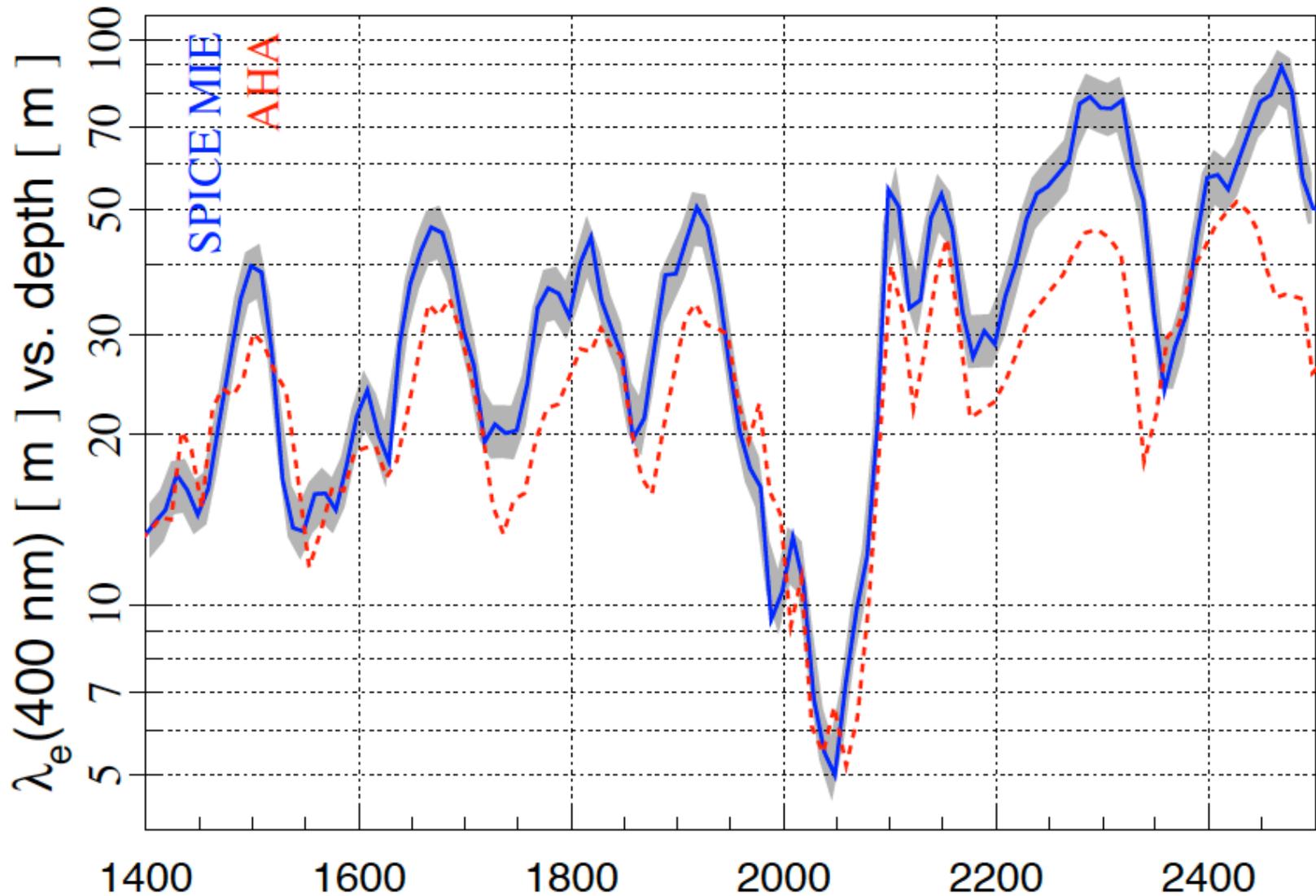
absorption length

← 220m →



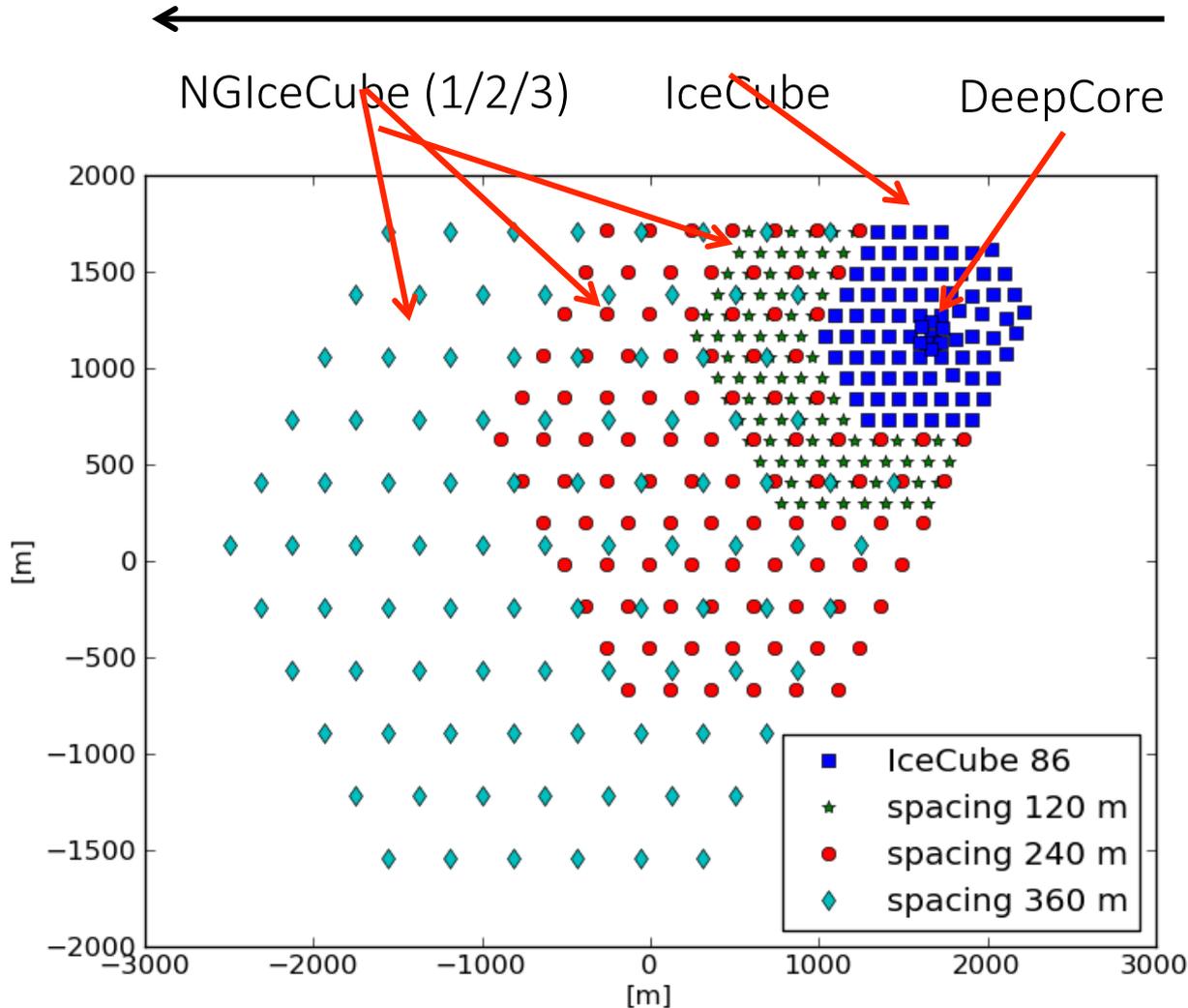
scattering length

← 47m →



measured optical properties → twice the string spacing

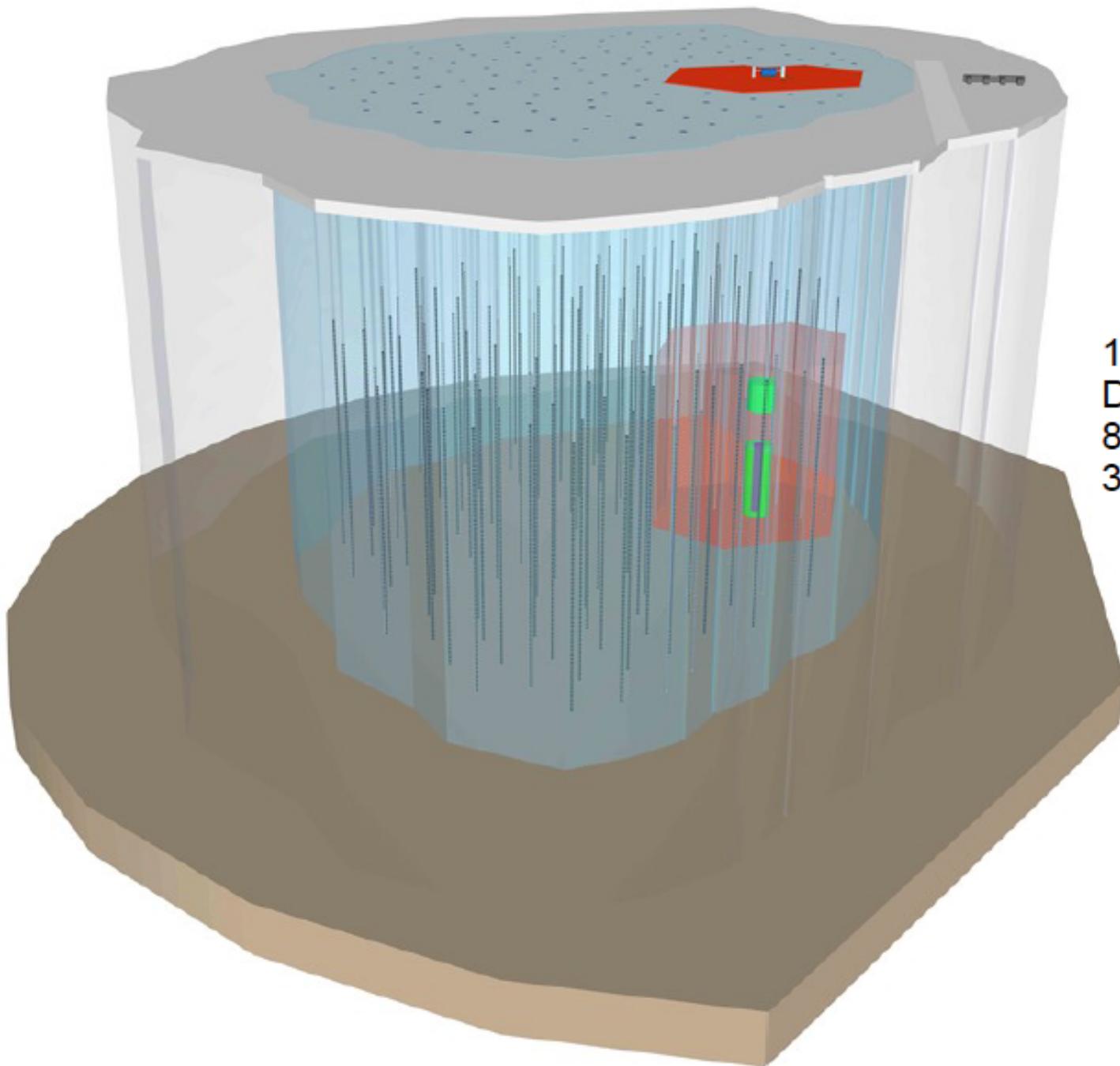
(increase in threshold not important: only eliminates energies where atmospheric background dominates)



Spacing 1 (120m):
IceCube (1 km³)
+ 98 strings (1,3 km³)
= 2,3 km³

Spacing 2 (240m):
IceCube (1 km³)
+ 99 strings (5,3 km³)
= 6,3 km³

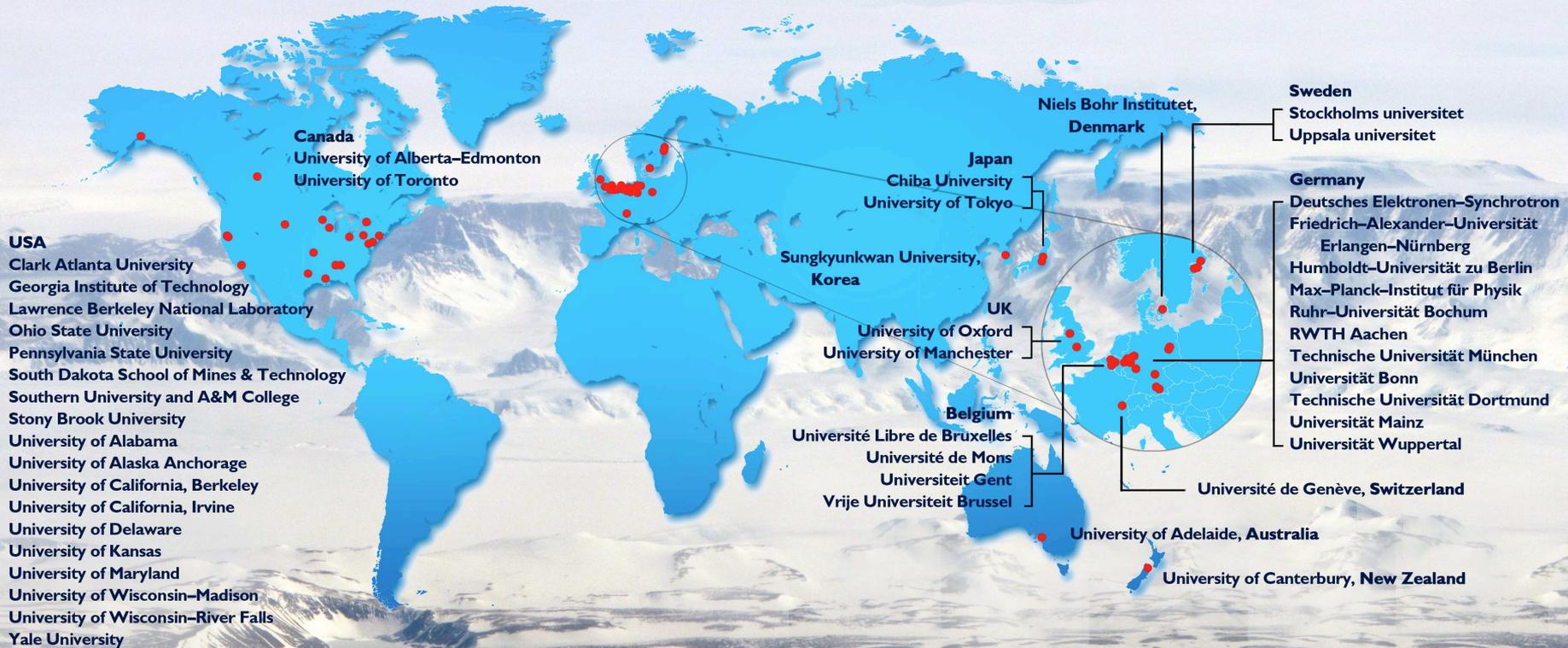
Spacing 3 (360m):
IceCube (1 km³)
+ 95 strings (11,6 km³)
= 12,6 km³



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

Dave, it could not have been done without you!

The IceCube-PINGU Collaboration

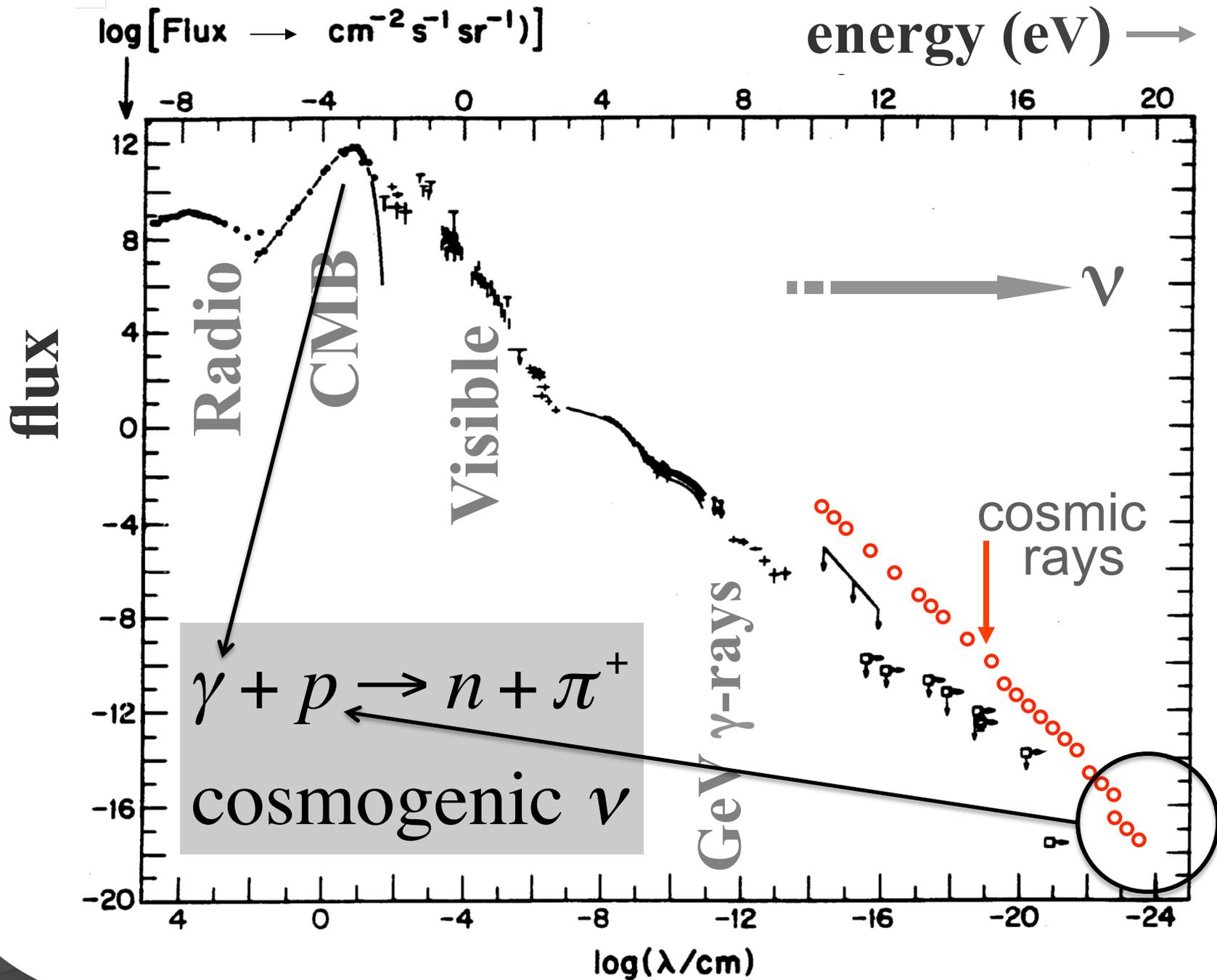


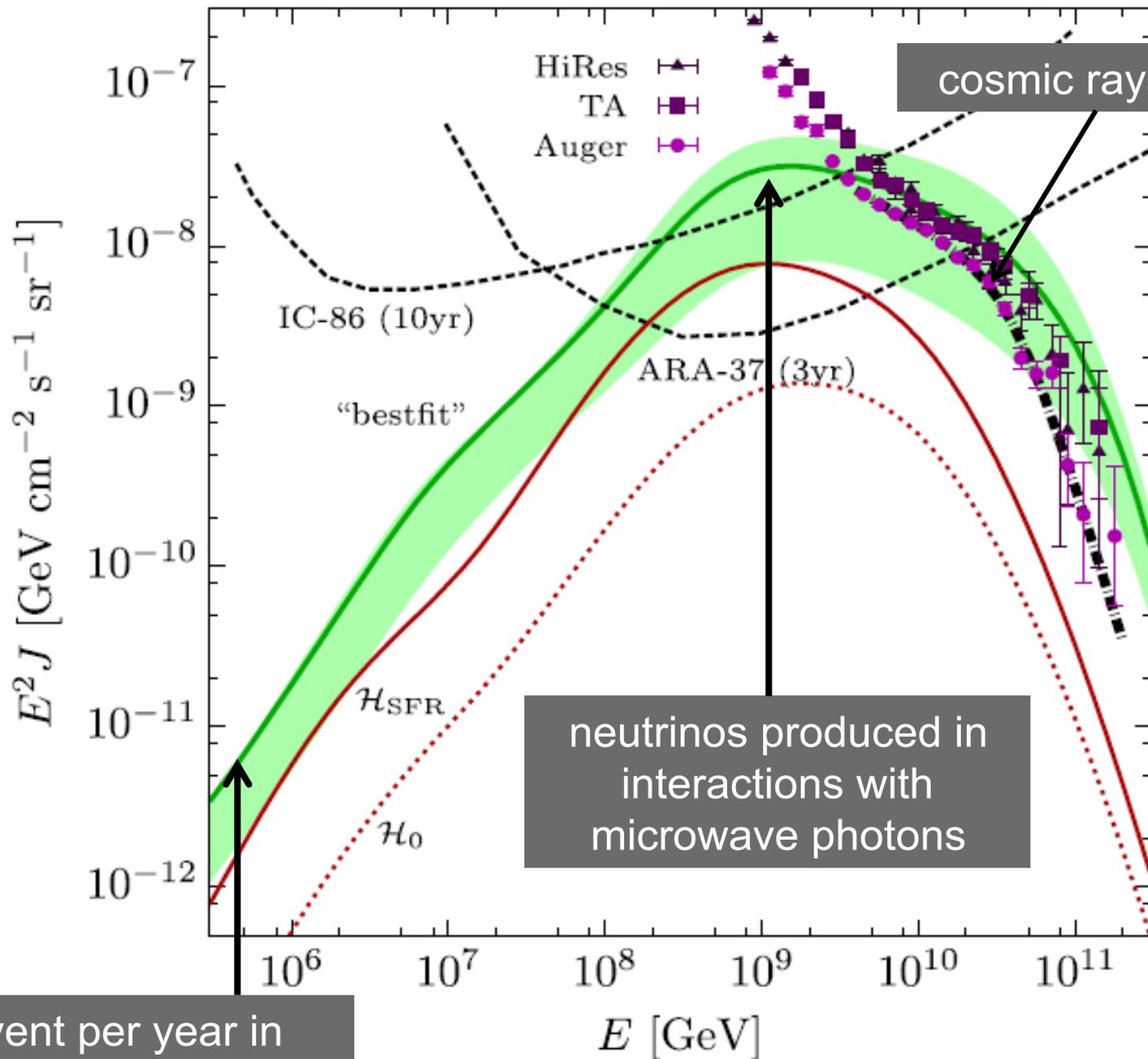
International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen
(FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)

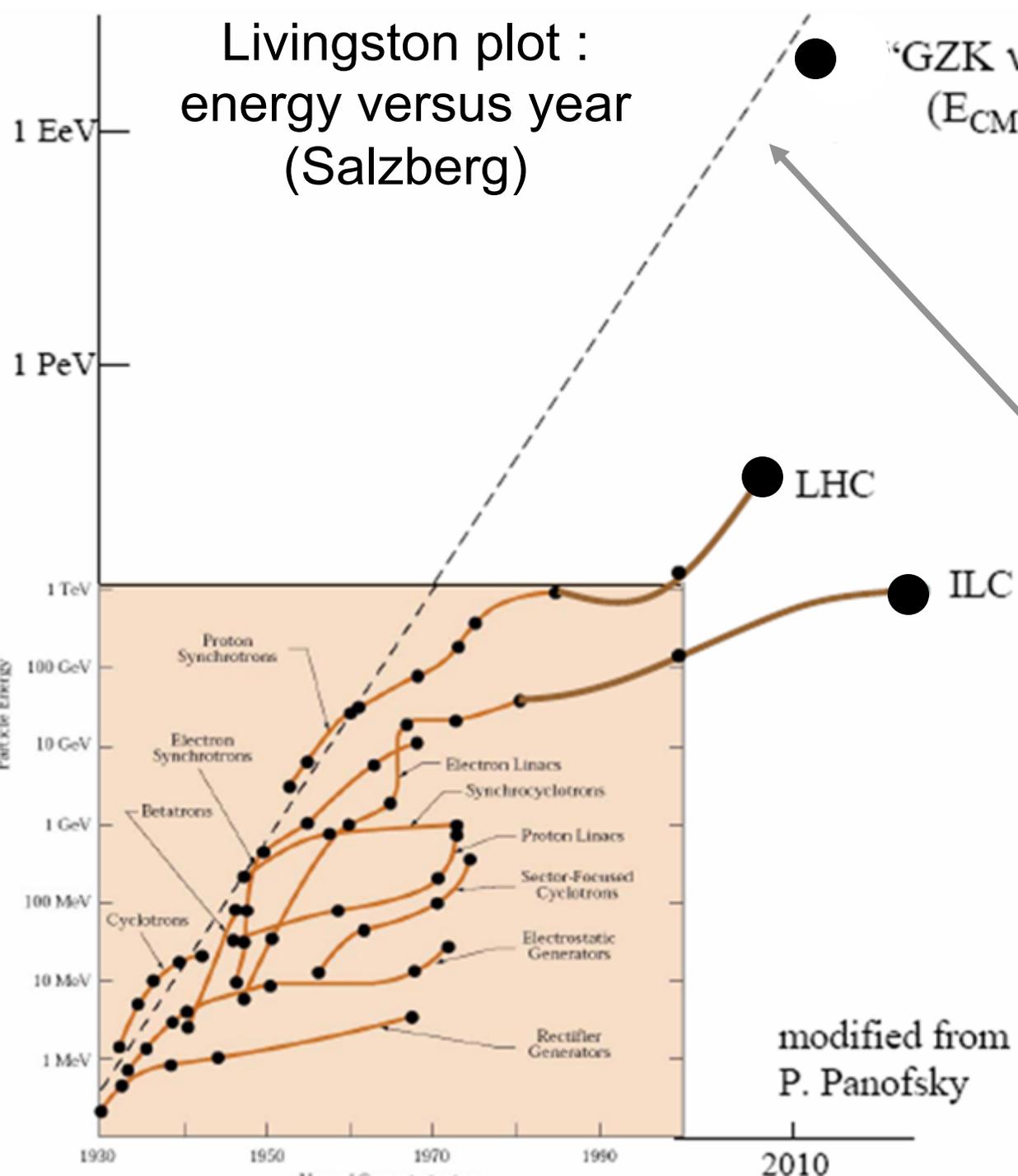
Deutsches Elektronen-Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
NSF-Office of Polar Programs
NSF-Physics Division

Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research
Foundation (WARF)
US National Science Foundation (NSF)



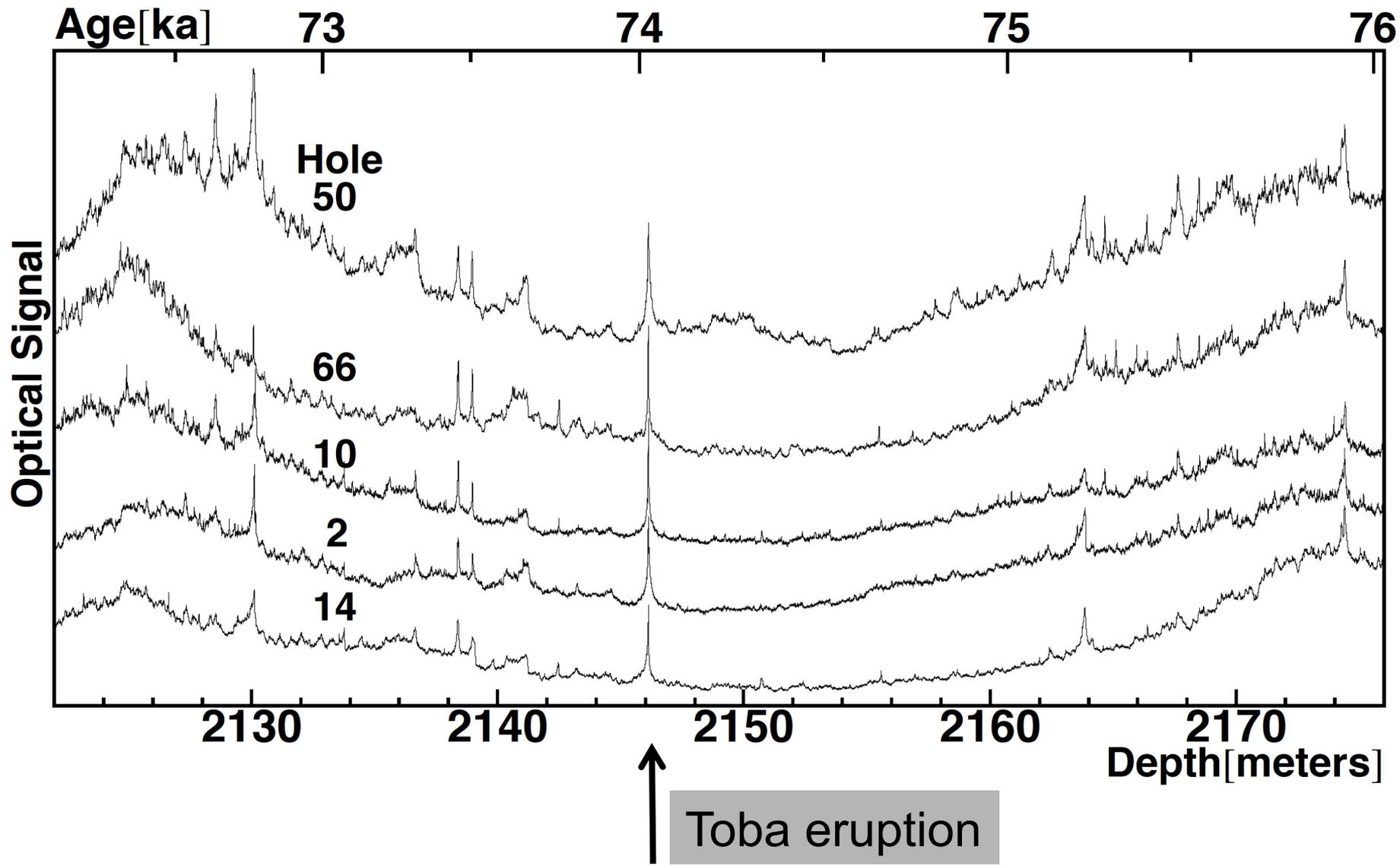


Livingston plot :
energy versus year
(Salzberg)



~ 5 events per year
in next-generation
IceCube

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



The IceCube-PINGU Collaboration



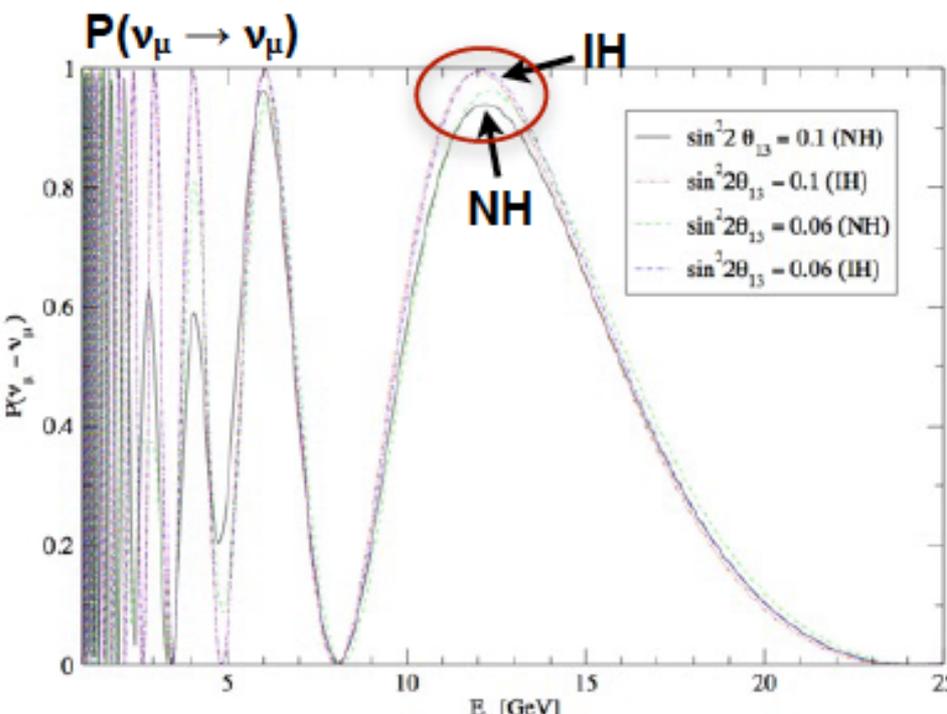
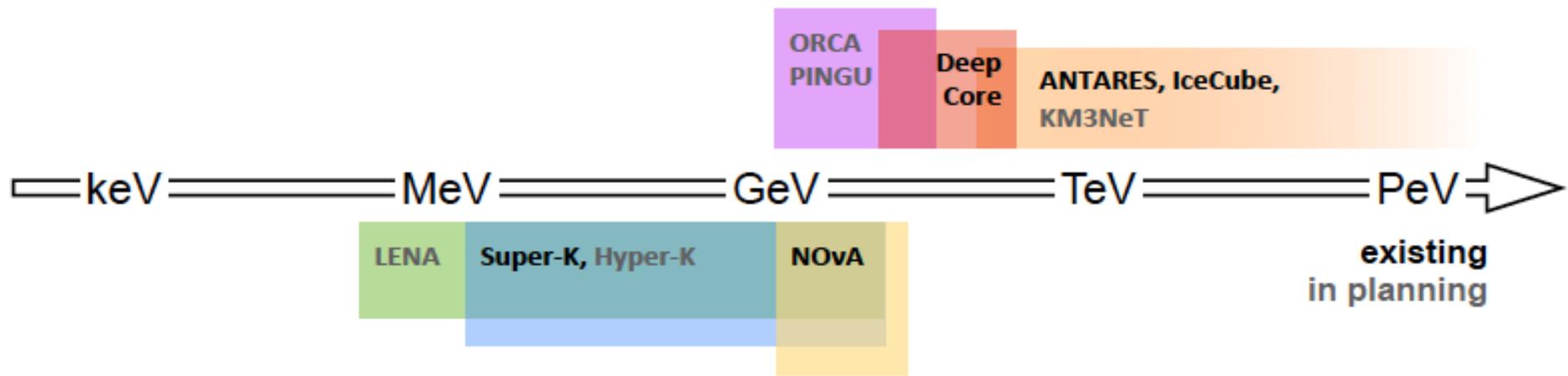
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(FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)

Deutsches Elektronen-Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
NSF-Office of Polar Programs
NSF-Physics Division

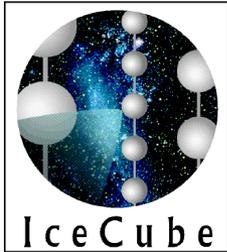
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research
Foundation (WARF)
US National Science Foundation (NSF)

overflow slides

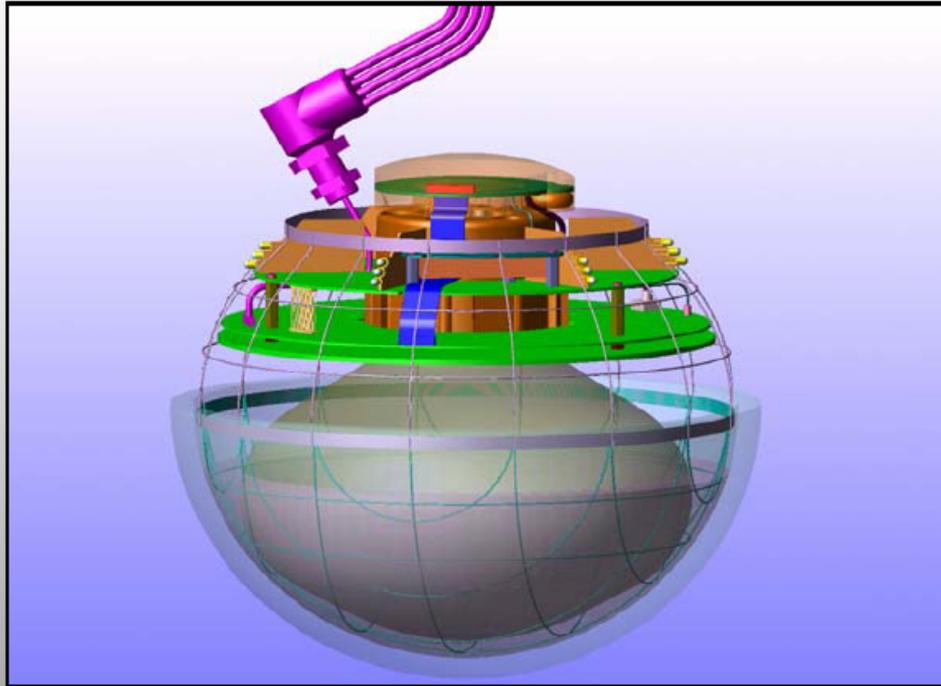


- ▶ First maximum for $P(\nu_\mu \rightarrow \nu_\mu)$ @ 12 GeV ($L = \text{Earth diameter}$)
- ▶ For $\bar{\nu}$ NH and IH approximately swapped \rightarrow effect cancels if $N(\nu) = N(\bar{\nu})$
- ▶ Fortunately, $\Phi(\nu_{\text{atm}}) > \Phi(\bar{\nu}_{\text{atm}})$ and $\sigma(\nu) > \sigma(\bar{\nu})$

Mena et al., arXiv:0803.3044

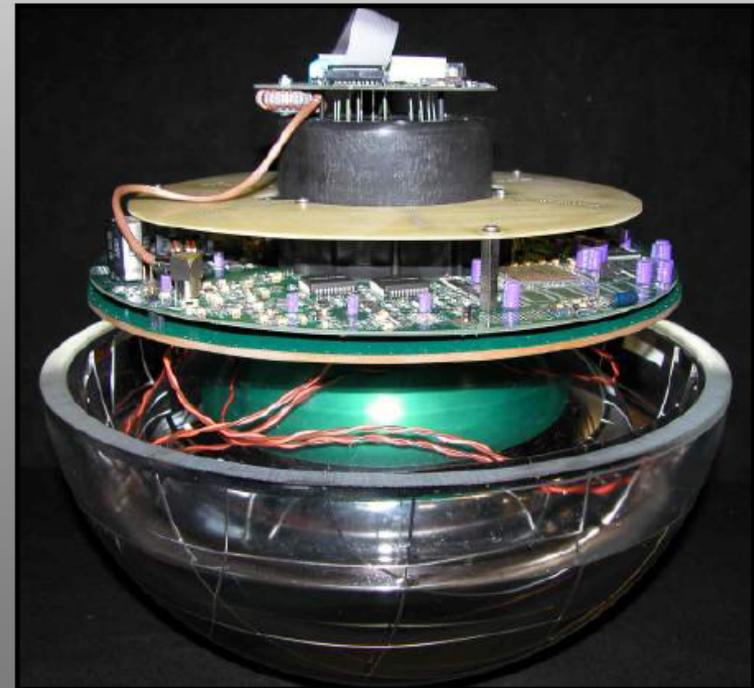


The Digital Optical Module (DOM)

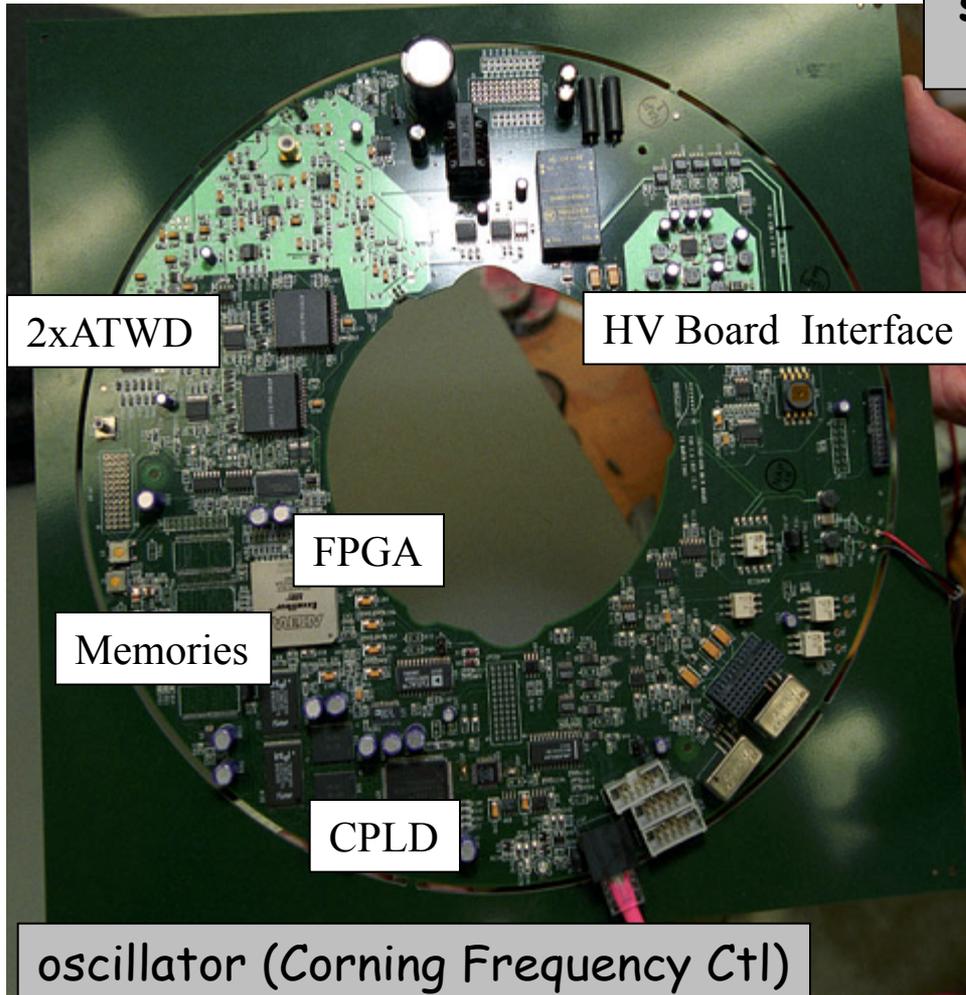


- DOM asynchronously records hits – buffers until surface readout requests data (8 MB acquisition memory)
- Hits time stamped with local oscillator. This must be transformed at surface to UT /w/ overall time res. of < 5 ns!
- DOM-to-surface communication bandwidth approximately 50 kbaud per DOM.

- IceCube detector contains 4800 InIce and 360 IceTop modules.
- Each DOM is autonomous DAQ platform
- *In situ* digitization of PMT pulses for increased S/N and better dynamic range: 200 pe instantaneous, 10^4 pe integrated



DOM Mainboard



- 2 four-channel ATWDs
Analog Transient Waveform Digitizers
low-power ASICs
recording at 300 MHz over first $0.5\mu\text{s}$
signal complexity at the start of event

- fast ADC
recording at 40 MHz over $5\mu\text{s}$
event duration in ice

- Dead time < 1%

Dynamic range

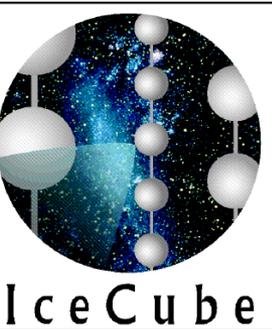
- 200 p.e./15 ns

- 2000 p.e./ $5\mu\text{s}$

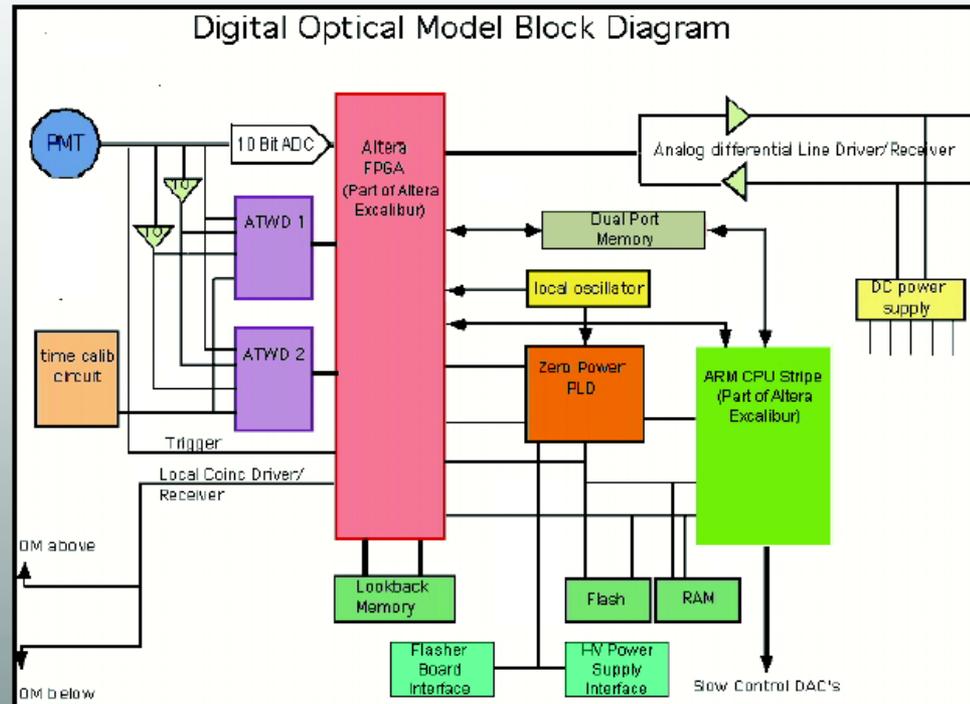
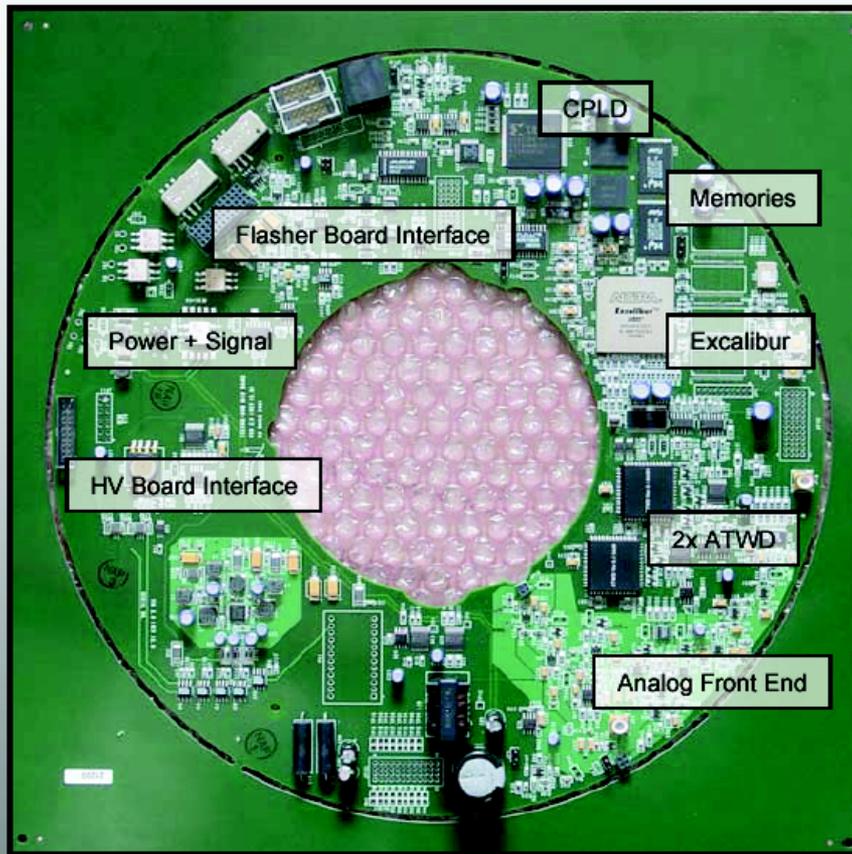
energy measurement (TeV - PeV)

- FPGA (Excalibur/Altera)
reads out the ATWD
handles communications
time stamps events
system time stamp resolution
 7 ns wrt master clock

oscillator (Corning Frequency Ctl)
running at 20 MHz
maintains $\delta f/f < 2 \times 10^{-10}$



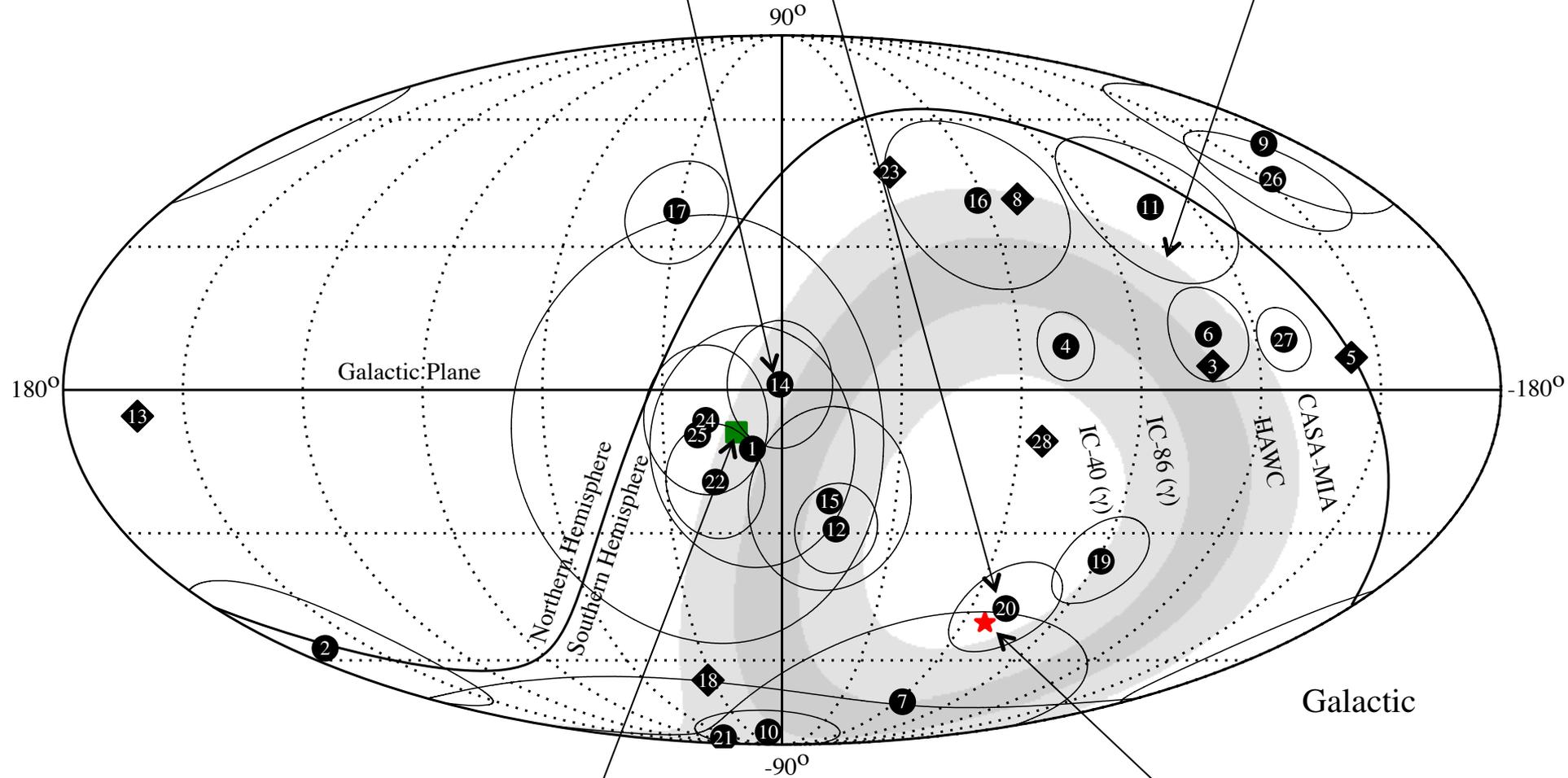
DOM Mainboard



Galactic coordinates arXiv 1309.4077

PeV events

boundary with no gamma ray observations in Southern sky

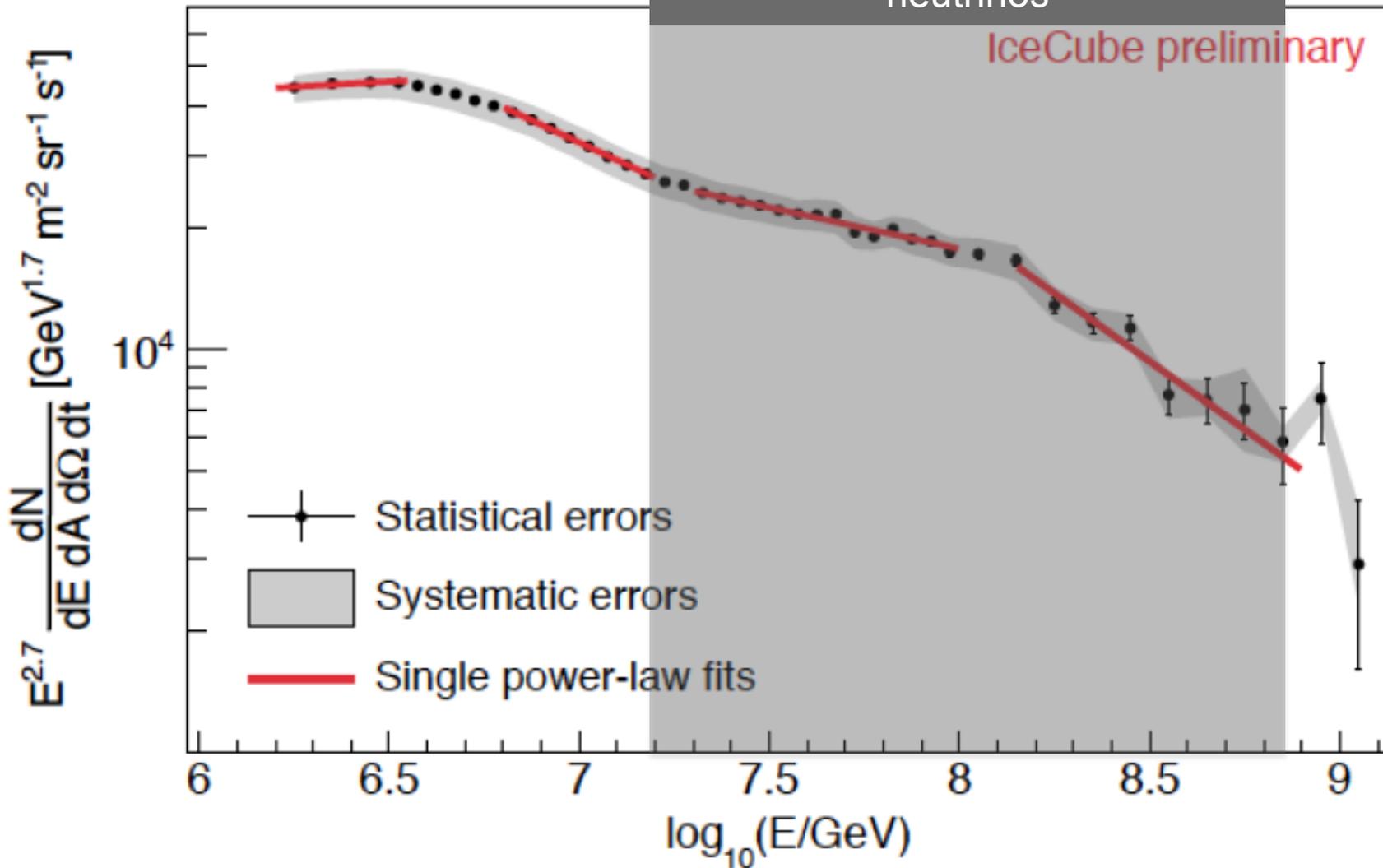


c.o.g of 5-event cluster

hottest spot in IceCube
PeV gamma ray map

the energy range of cosmic accelerators producing PeV neutrinos

IceCube preliminary



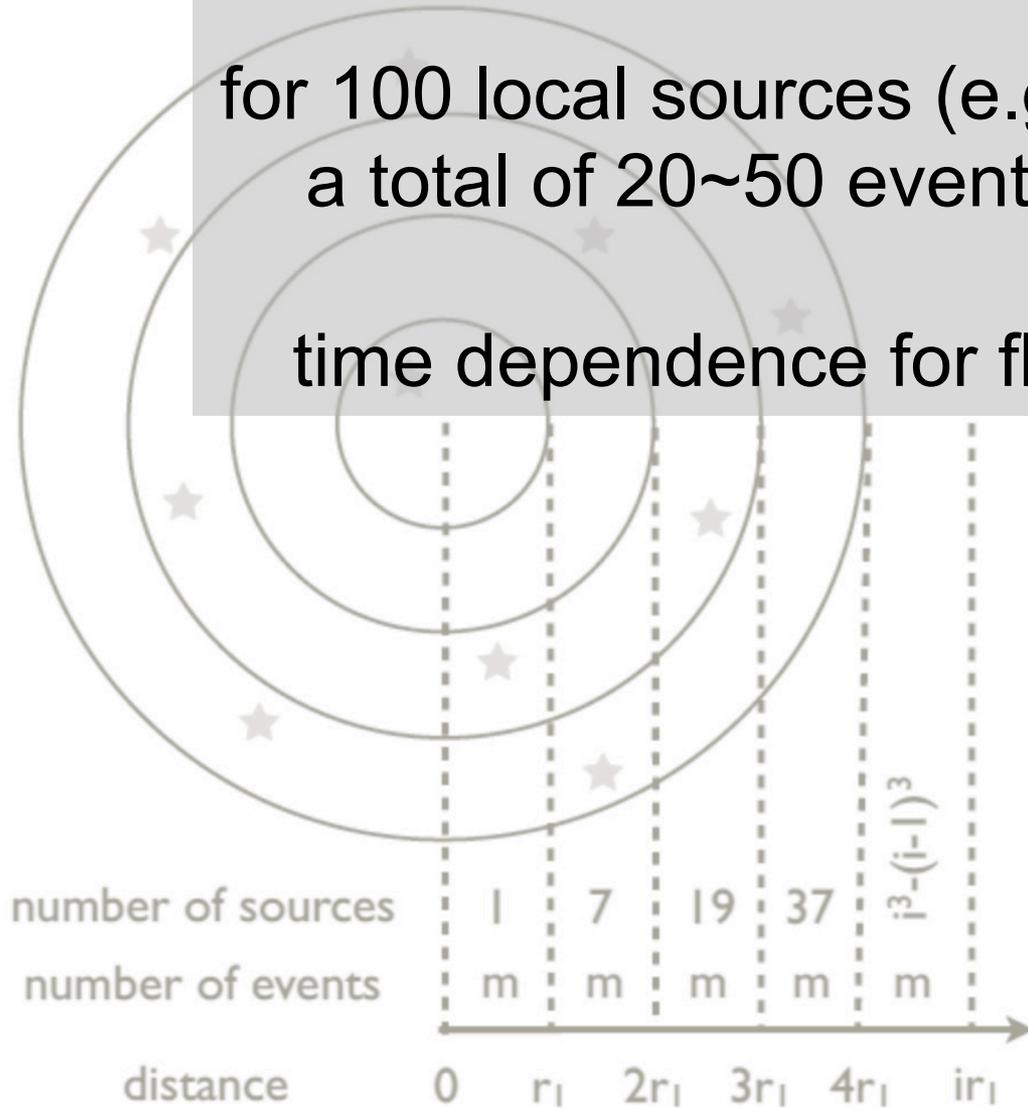
Galactic or extragalactic?

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

$$m \approx 10^6 - 10^7$$

- total number of "slices"

$$(n_s)^{\frac{1}{3}}$$

- 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 resolution!