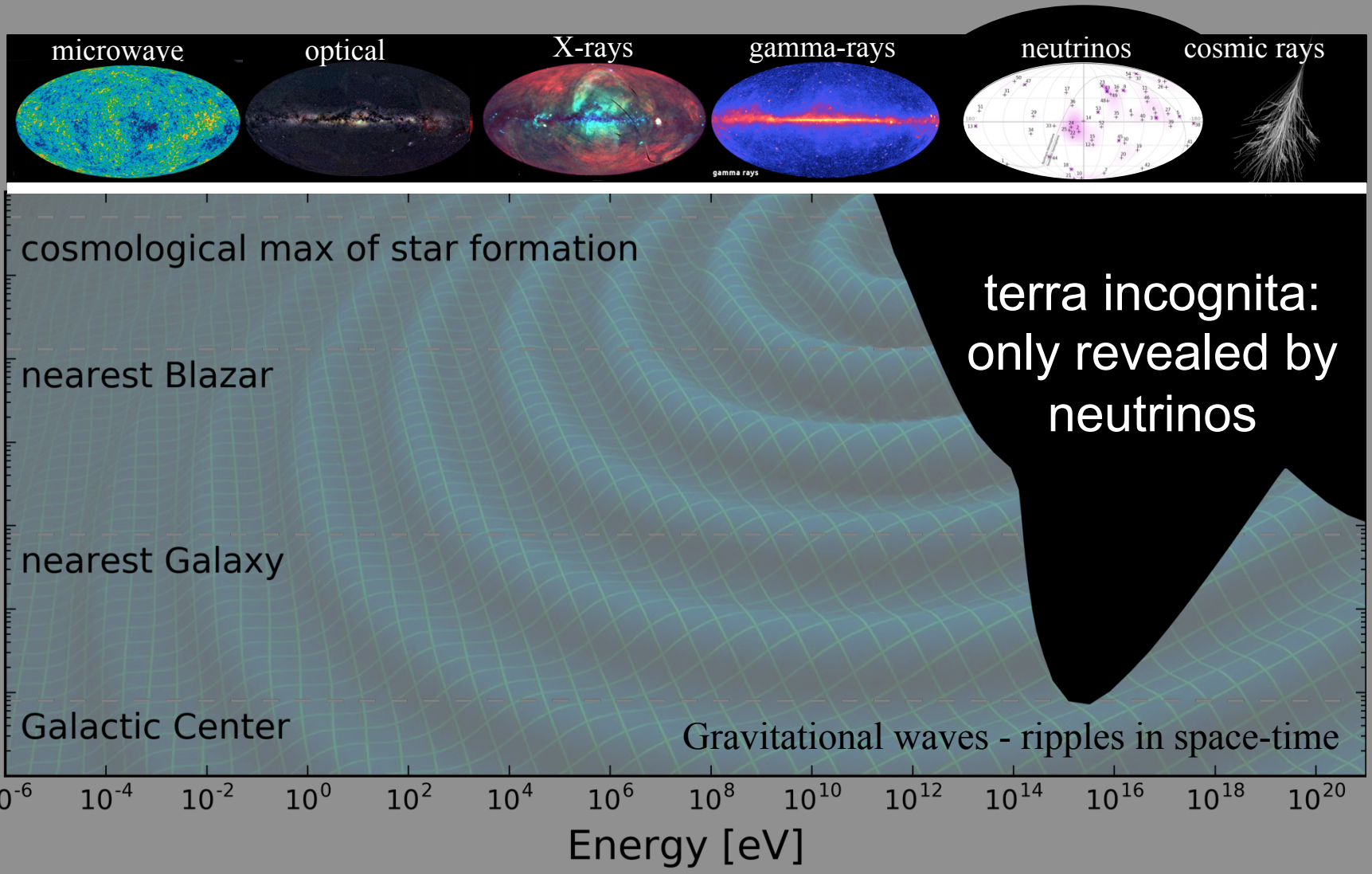
IceCube: the discovery of cosmic neutrinos

francis halzen

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

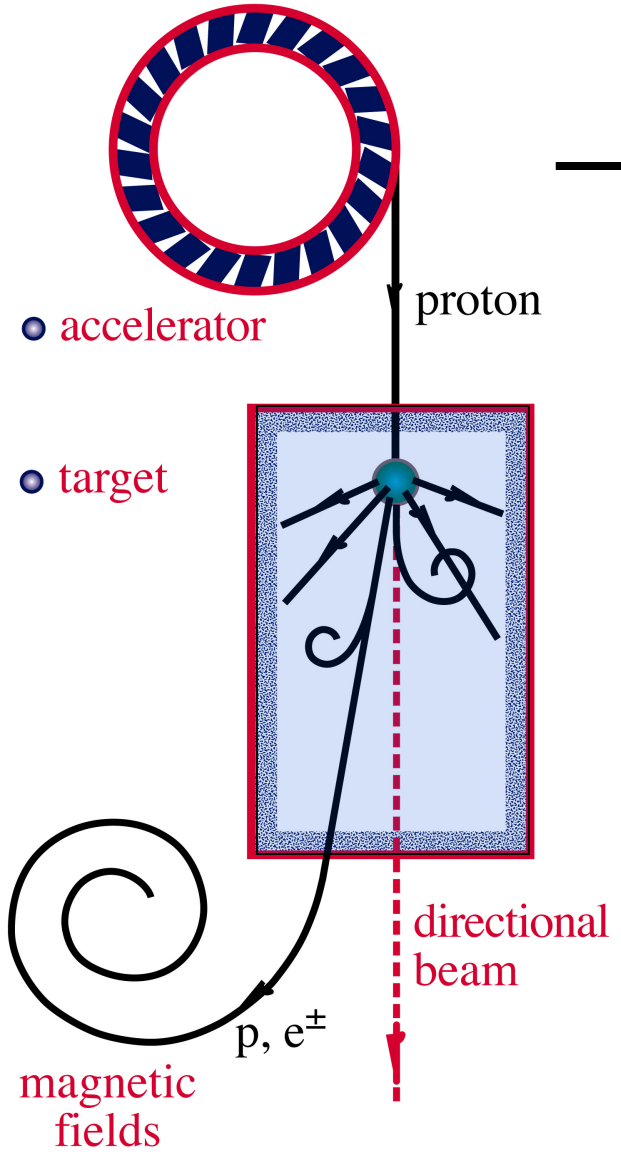
IceCube.wisc.edu

Multi-Messenger Astronomy



20% of the Universe is opaque to the EM spectrum

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

black hole
neutron star

radiation, dust, molecular clouds...

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

~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

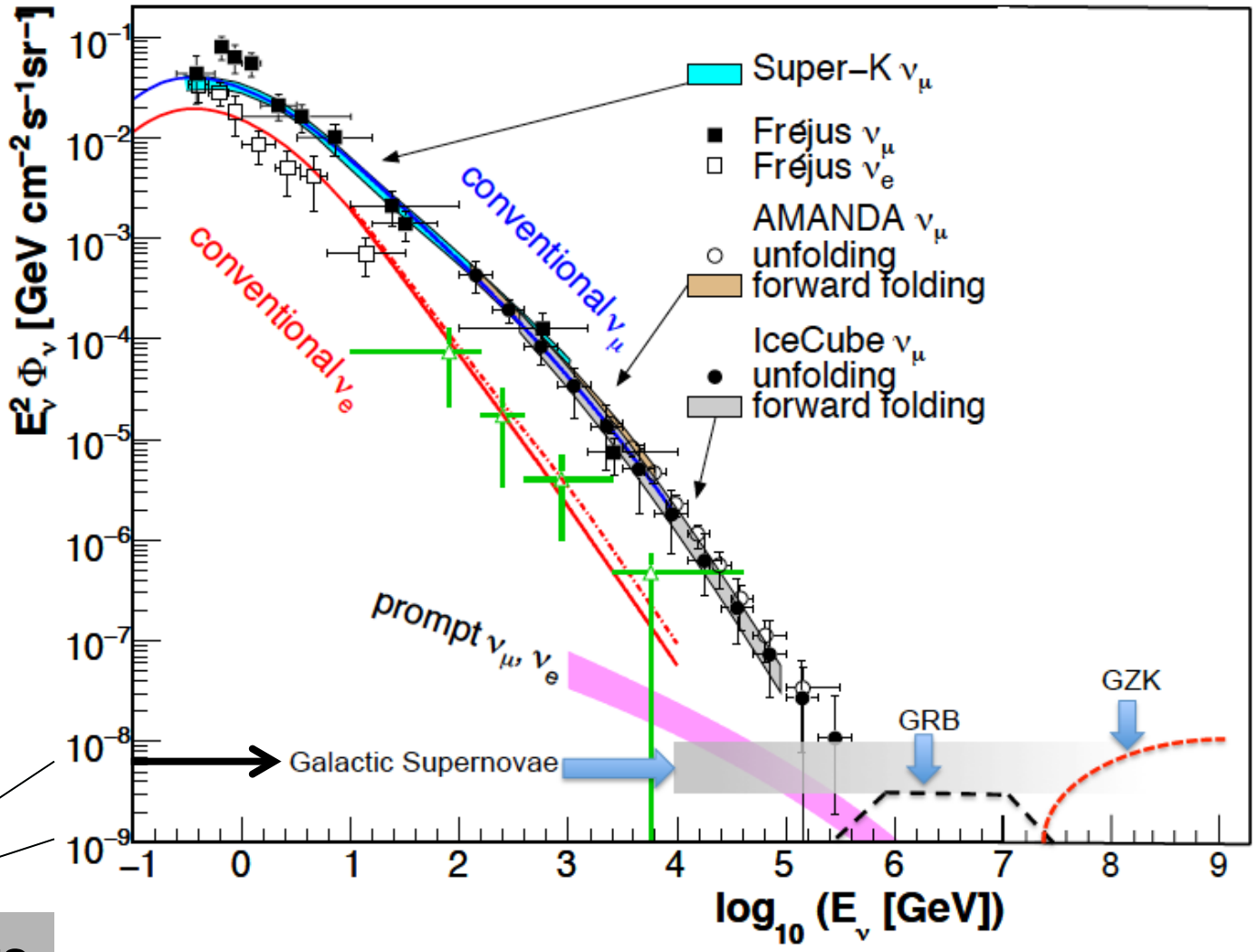
~ cosmic ray + gamma

above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

$dN/dE \sim E^{-2}$

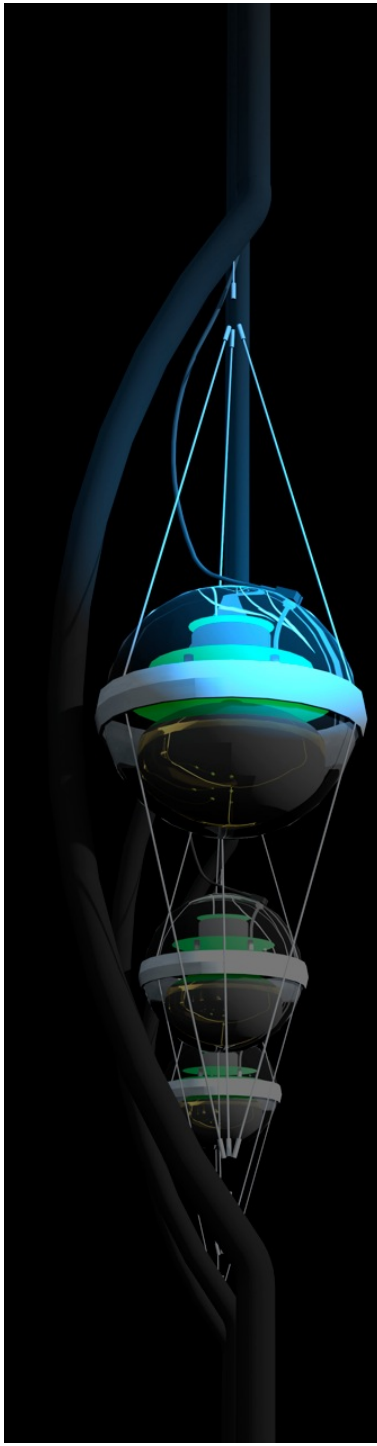
10—100 events per year for fully efficient 1 km^3 detector



atmospheric

cosmic

100 TeV



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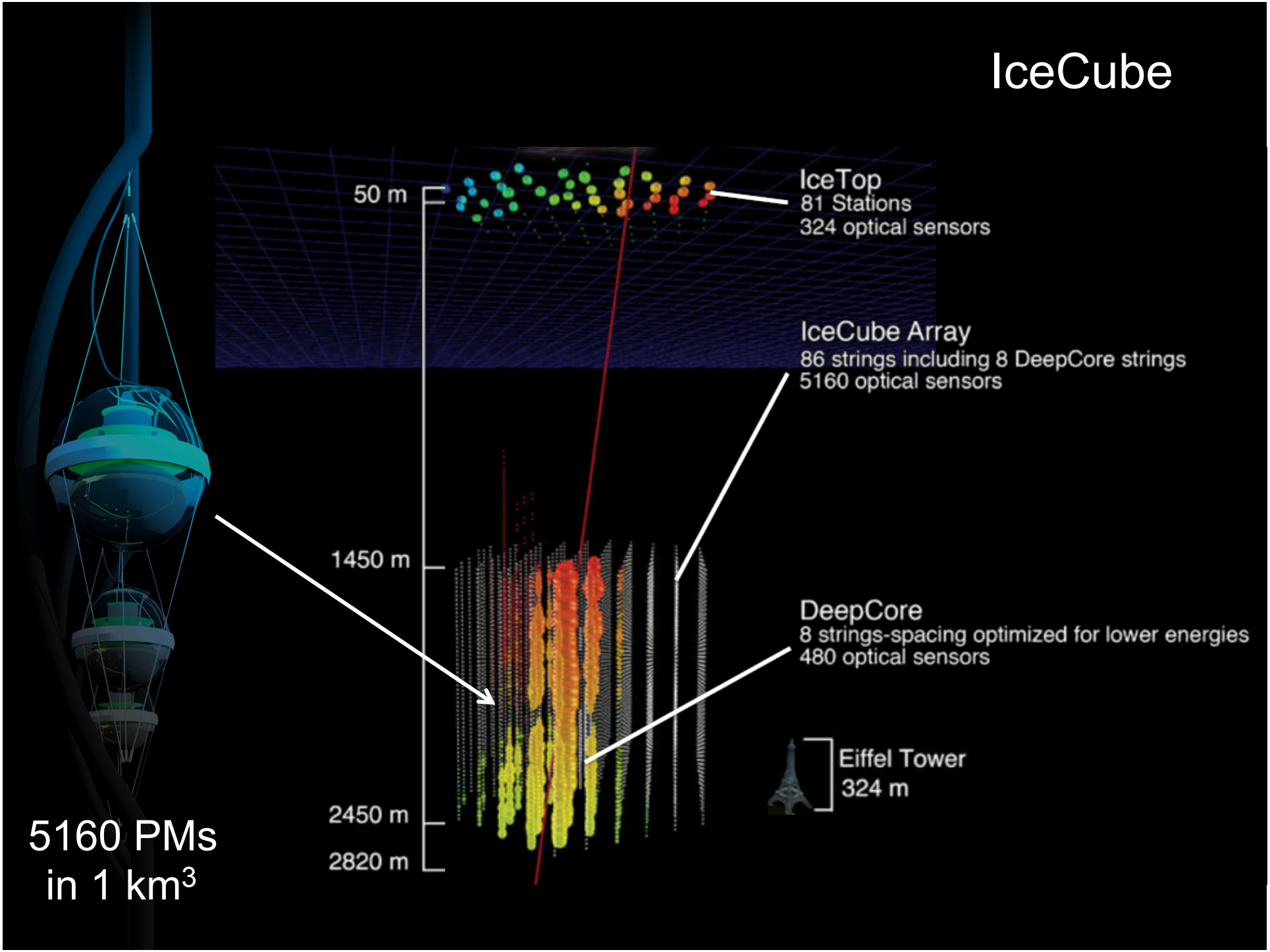
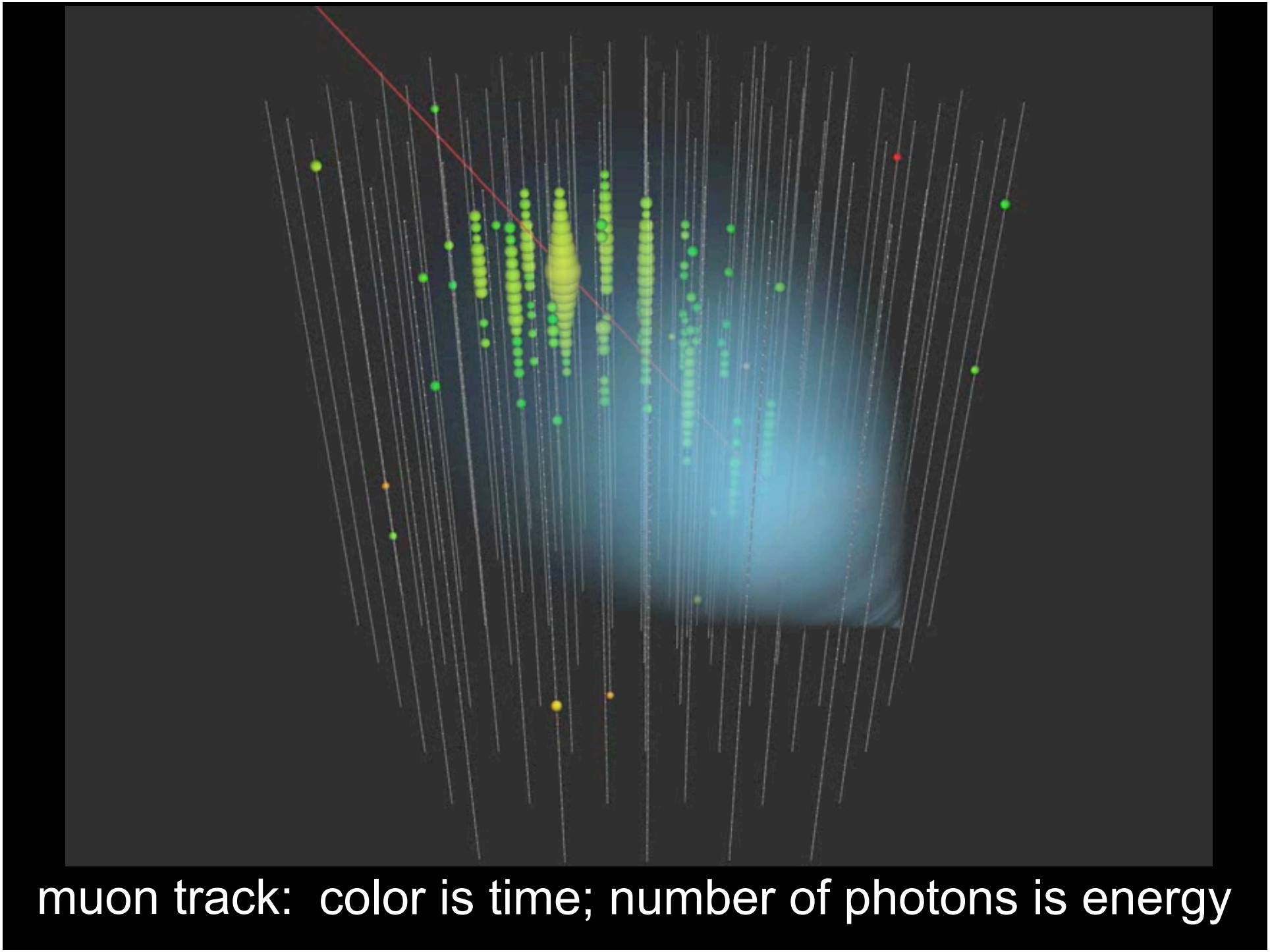

IceCube
50 m
IceTop
81 Stations
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
1450 m
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
2450 m
2820 m
5160 PMs
in 1 km3

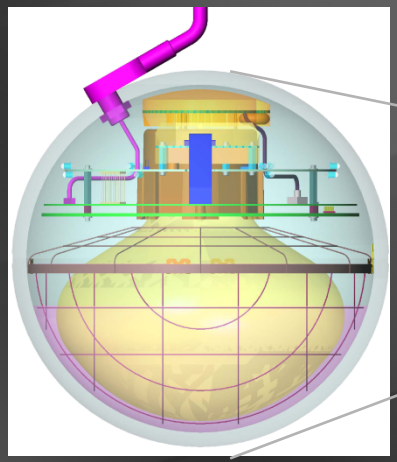
photomultiplier tube -10 inch



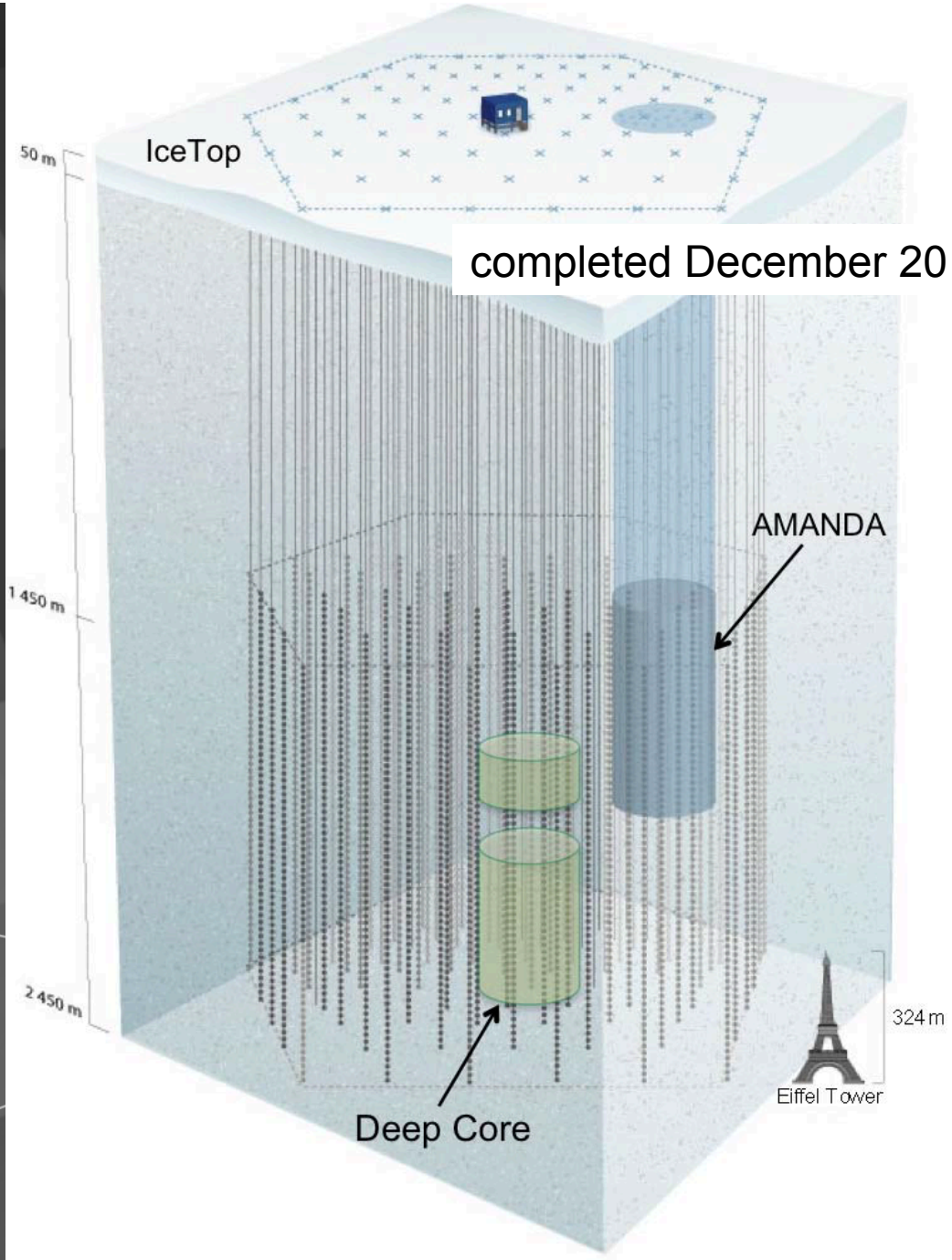
muon track: color is time; number of photons is energy

IceCube / Deep Core

- 5160 optical sensors between 1.5 ~ 2.5 km
- 10 GeV to infinity
- < 0.4 degree muon track
  ~ 10 degree shower
- < 15% energy resolution



Digital Optical Module (DOM)



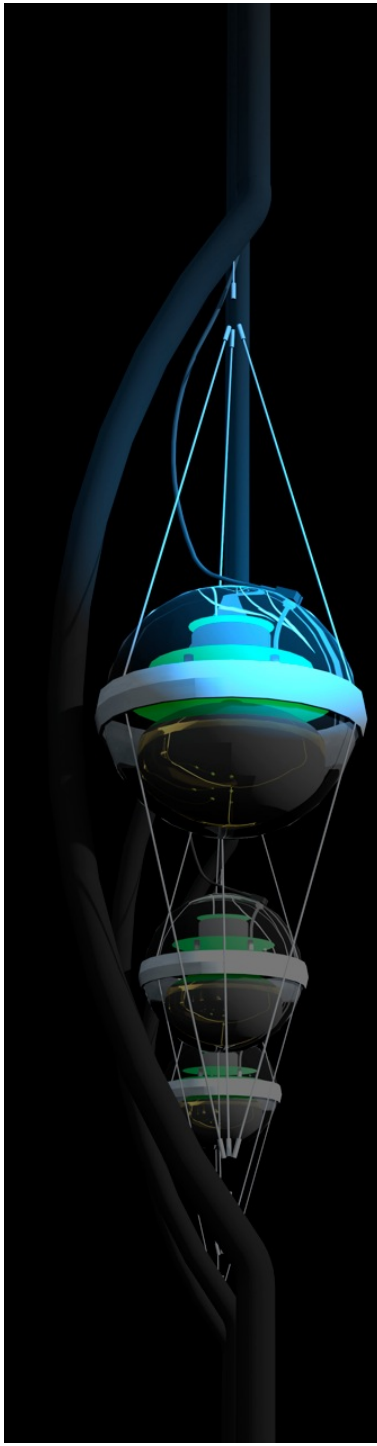
completed December 2010

… you looked at 10msec of data !

muons detected per year:

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

* 3000 per second ** 1 every 6 minutes



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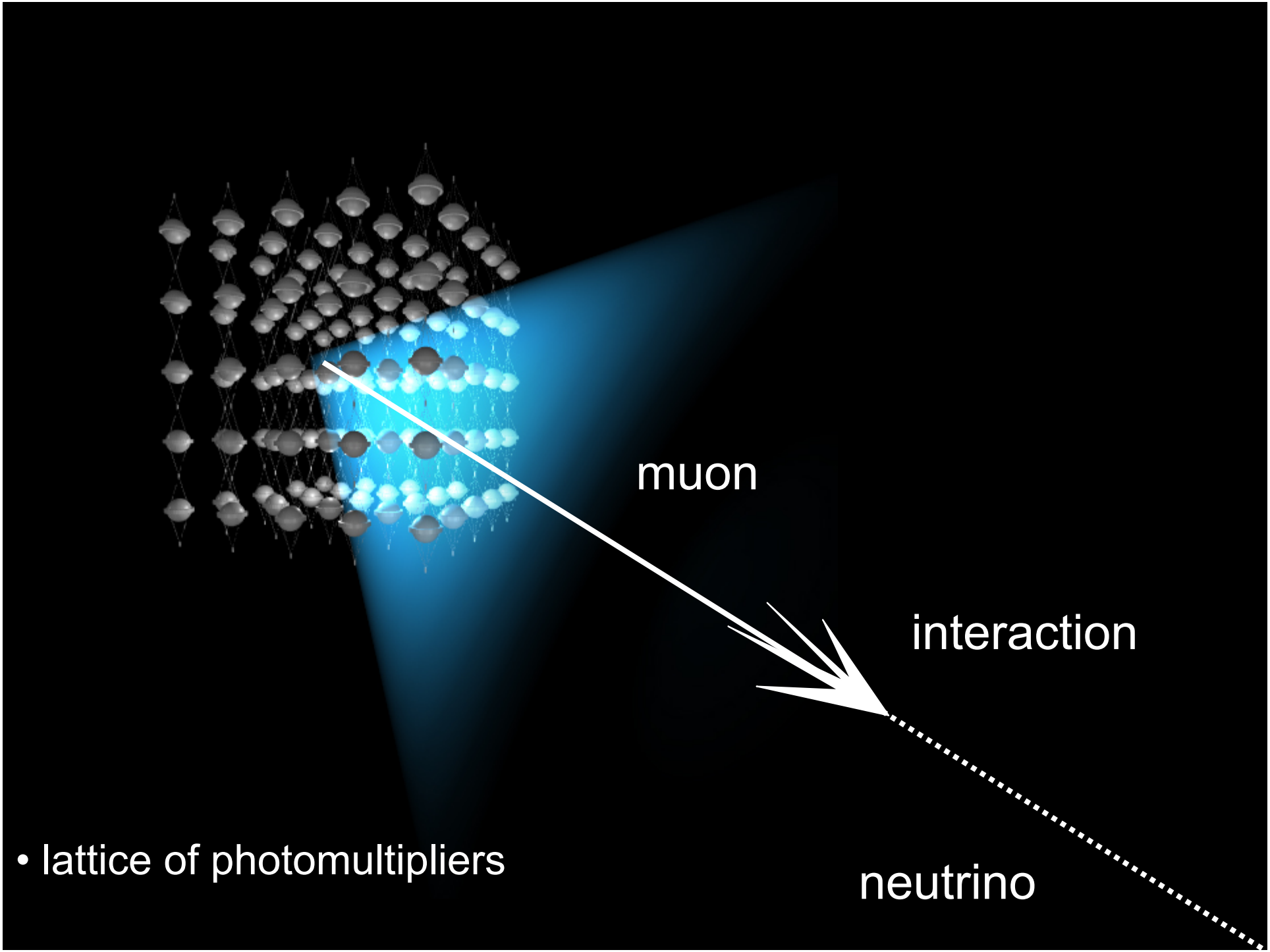
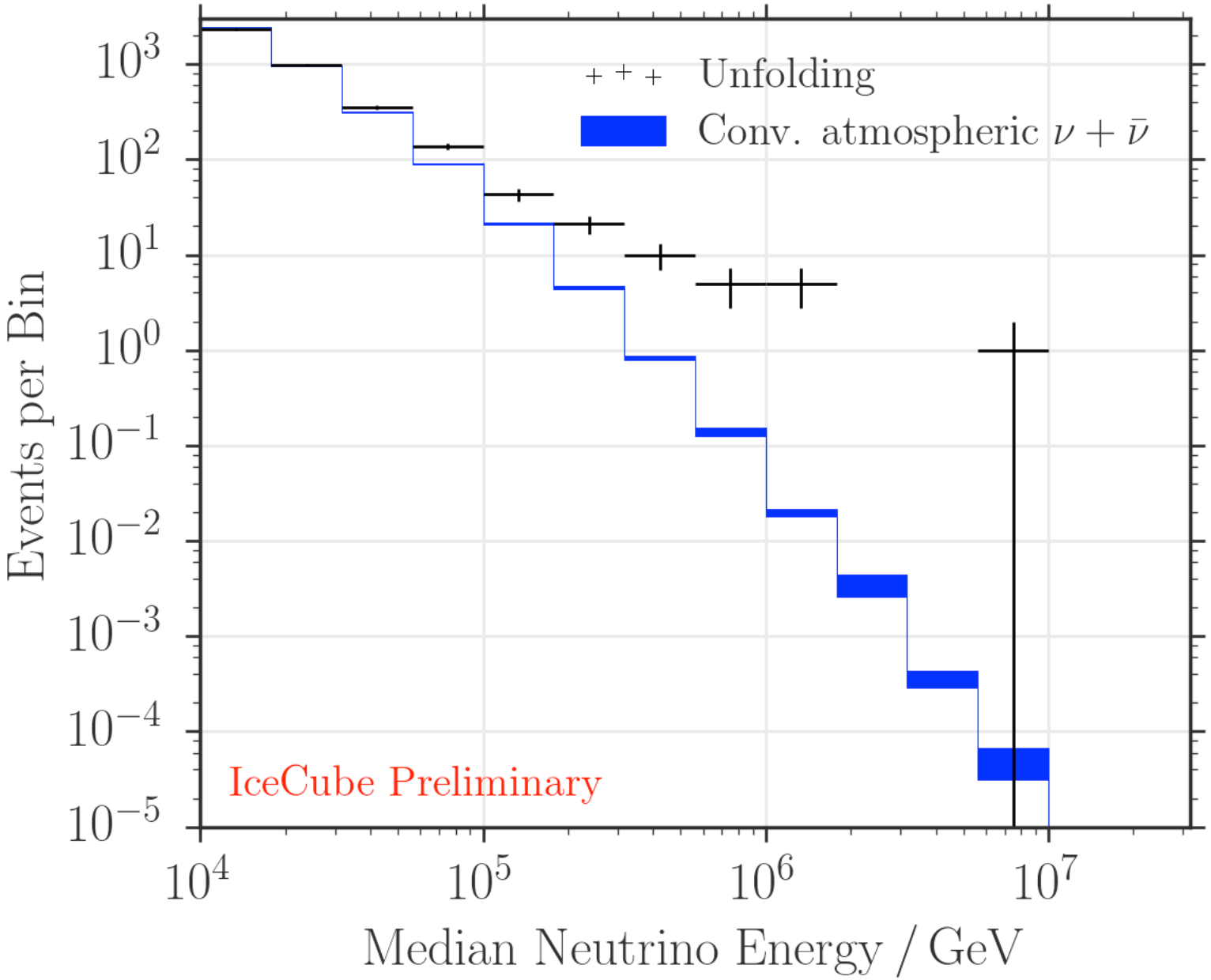
- IceCube
- the discovery of cosmic neutrinos (2)
- where do they come from?
- beyond IceCube


muon
interaction
neutrino
• lattice of photomultipliers

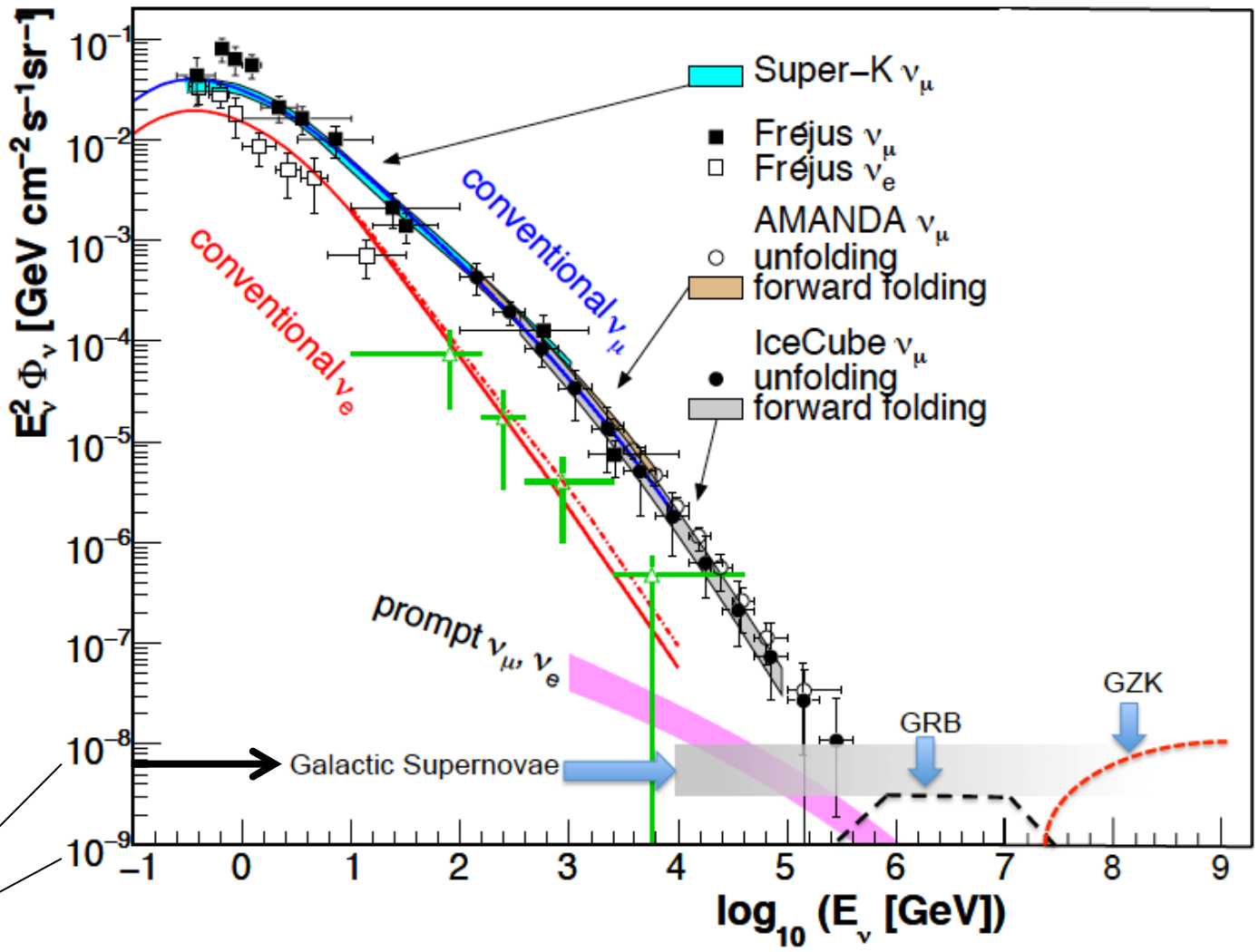
muon neutrinos through the Earth → 6 sigma



above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

$dN/dE \sim E^{-2}$

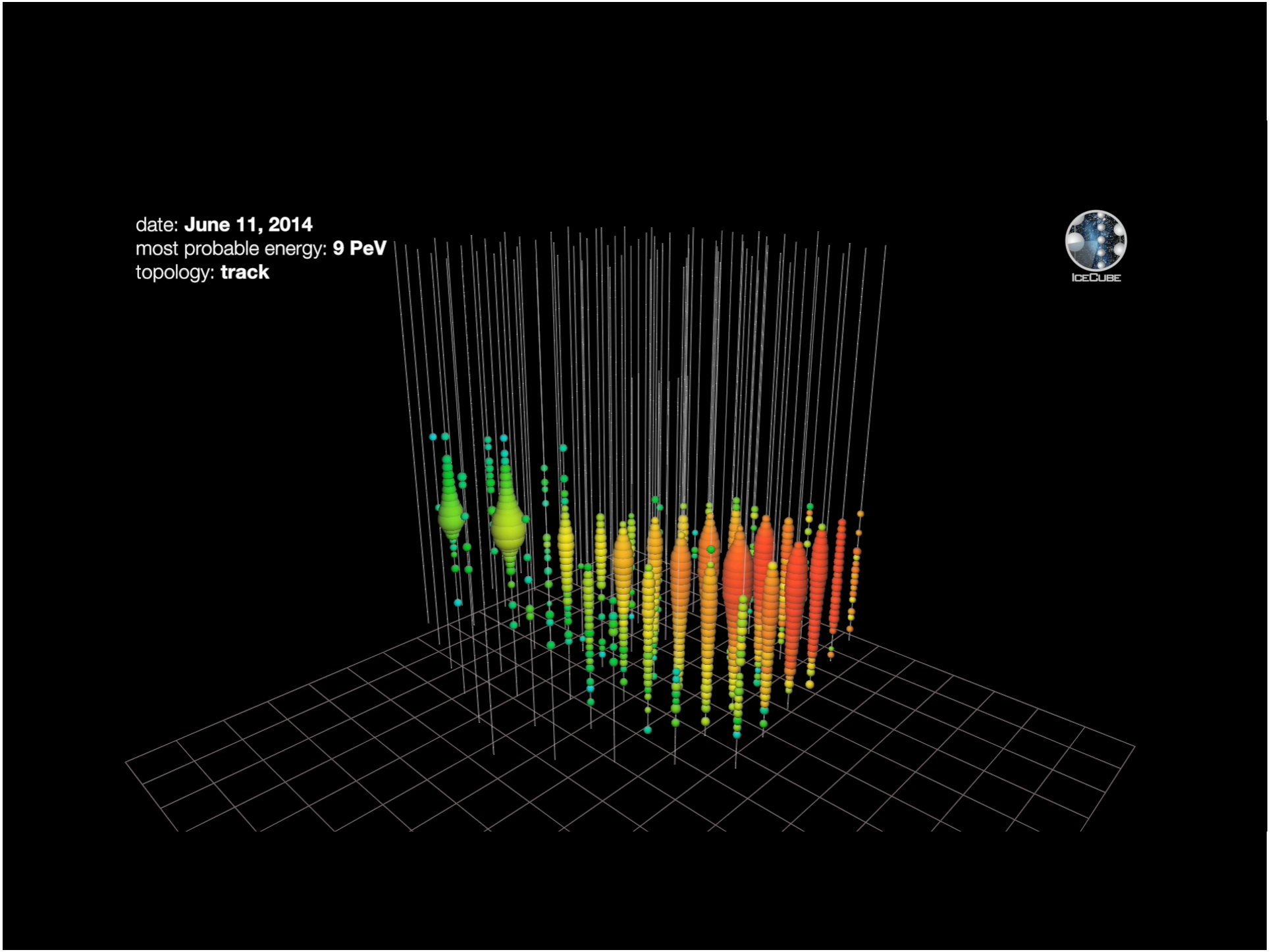


10—100 events per year for fully efficient detector

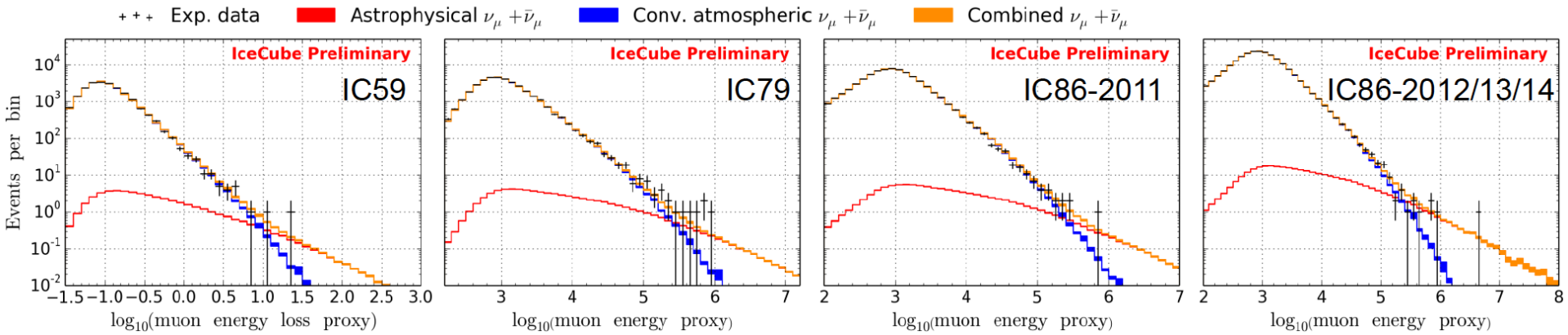
atmospheric

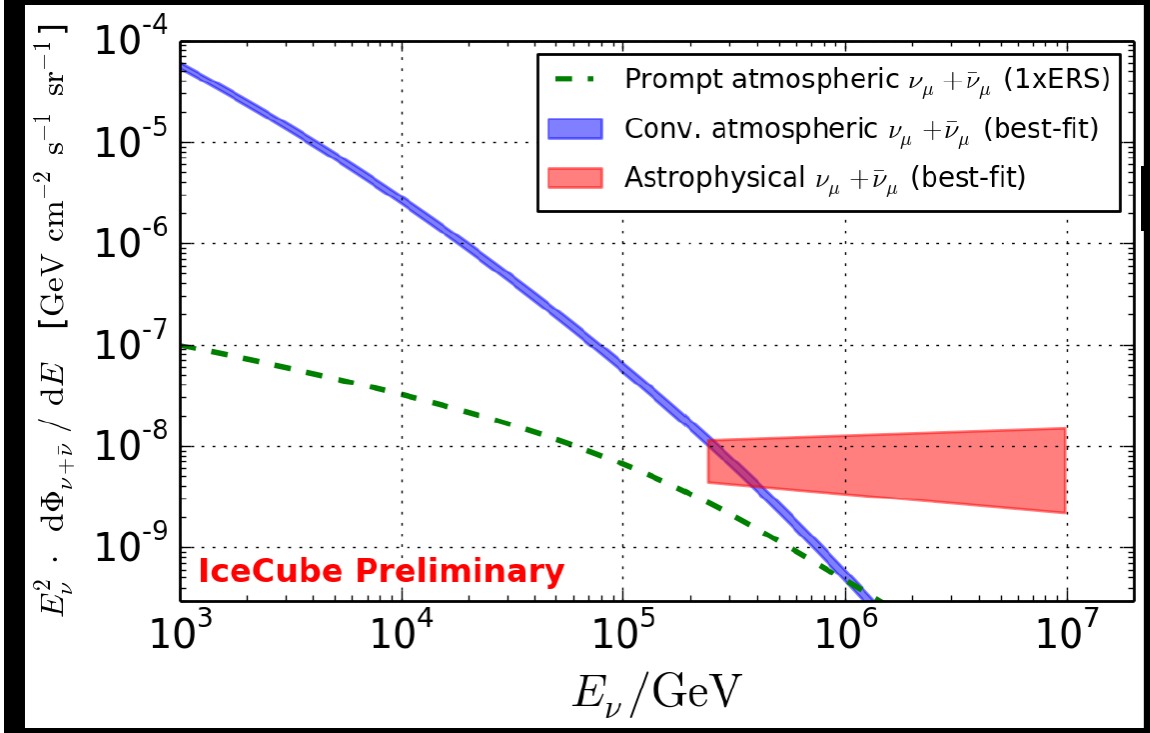
cosmic

100 TeV


date: **June 11, 2014**
most probable energy: **9 PeV**
topology: **track**
IceCube

after 7 years: 3.7 → 6 sigma





- Best-fit astrophysical normalization:

$0.97^{+0.27}_{-0.25} \times 10^{-18}\ \mathrm{GeV^{-1}cm^{-2}s^{-1}sr^{-1}}$

- Best-fit spectral index:

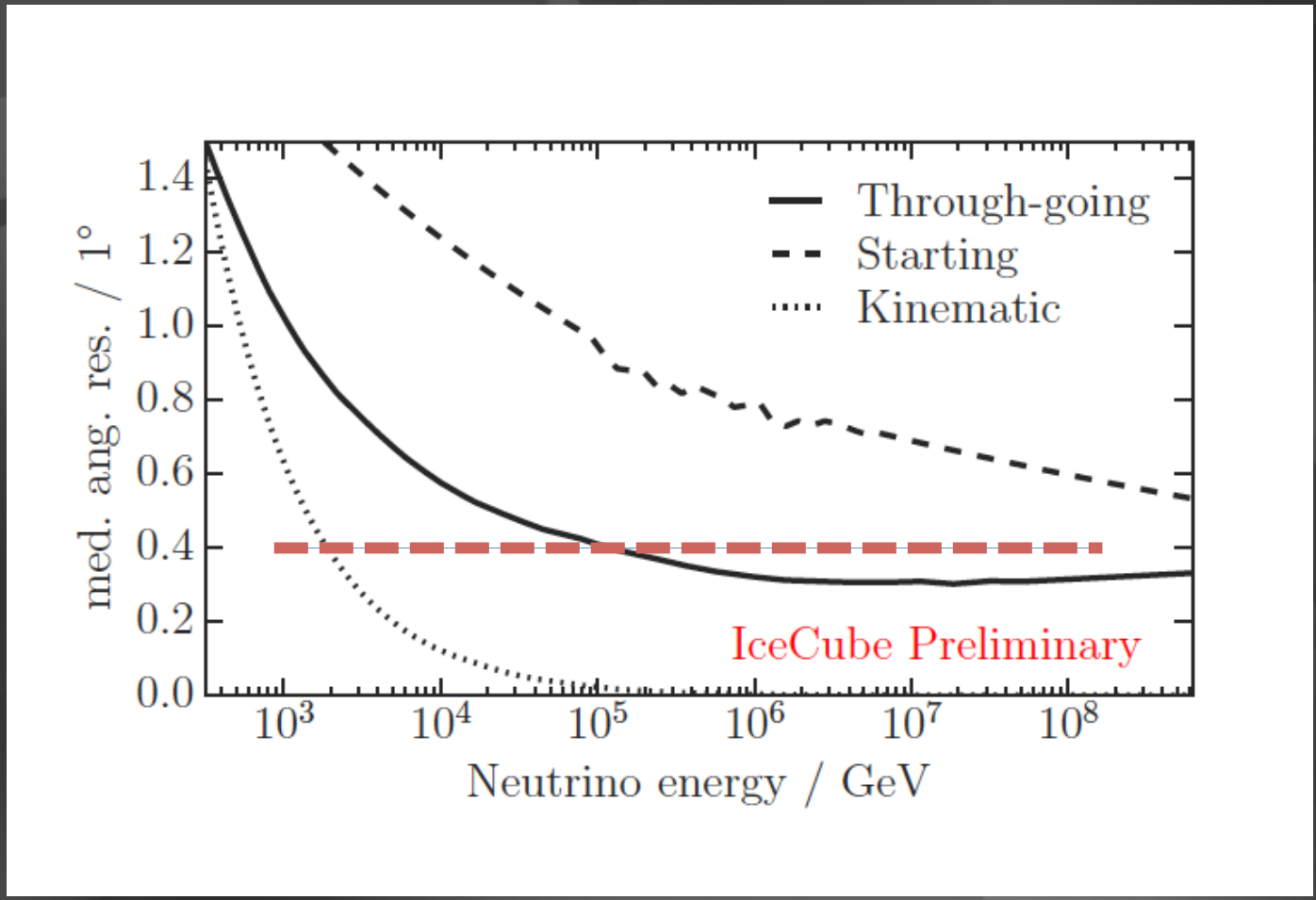
$\gamma_{\mathrm{astro}} = 2.16 \pm 0.11$

- Energy ranges:

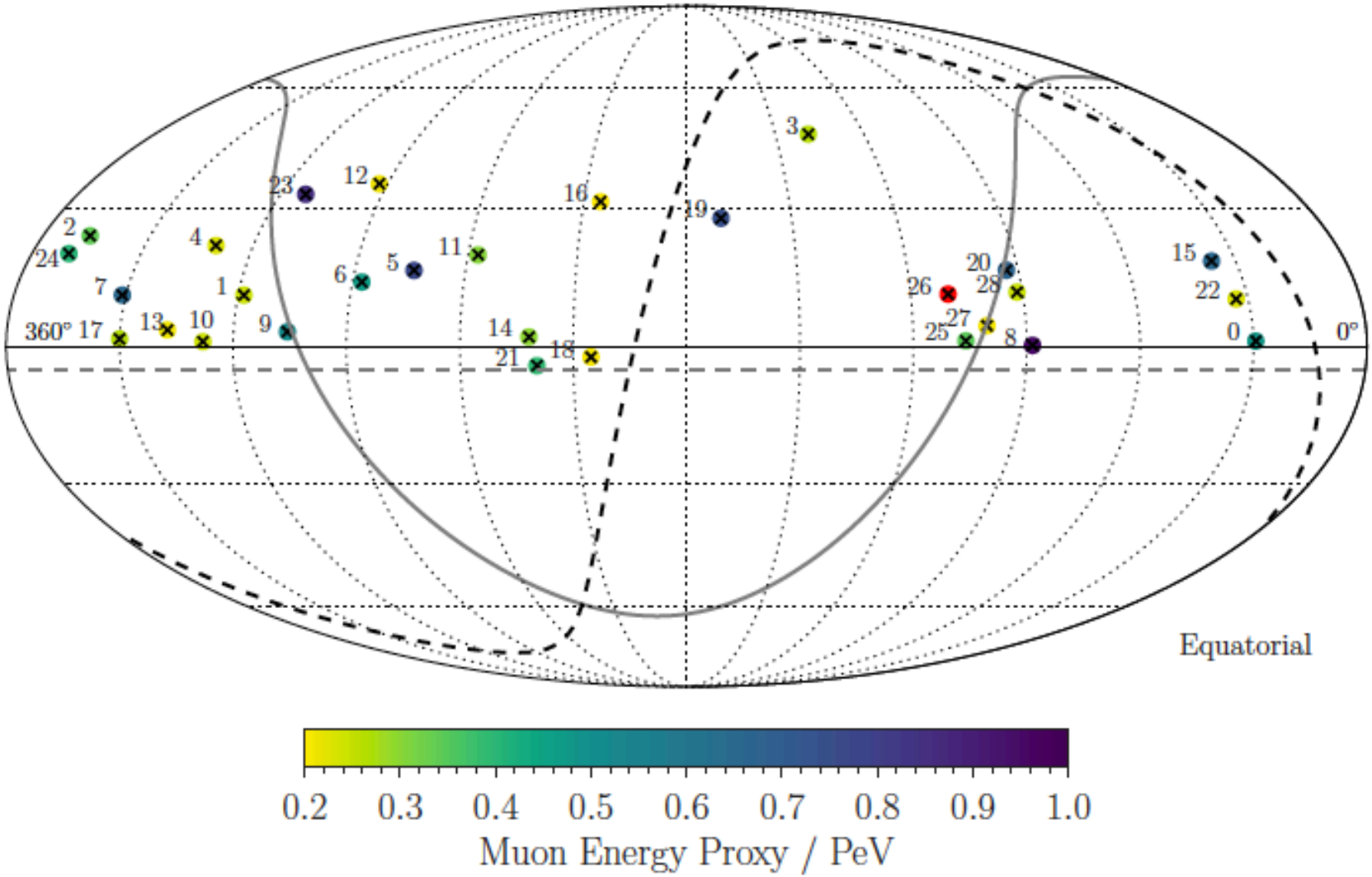
240 TeV – 10 PeV

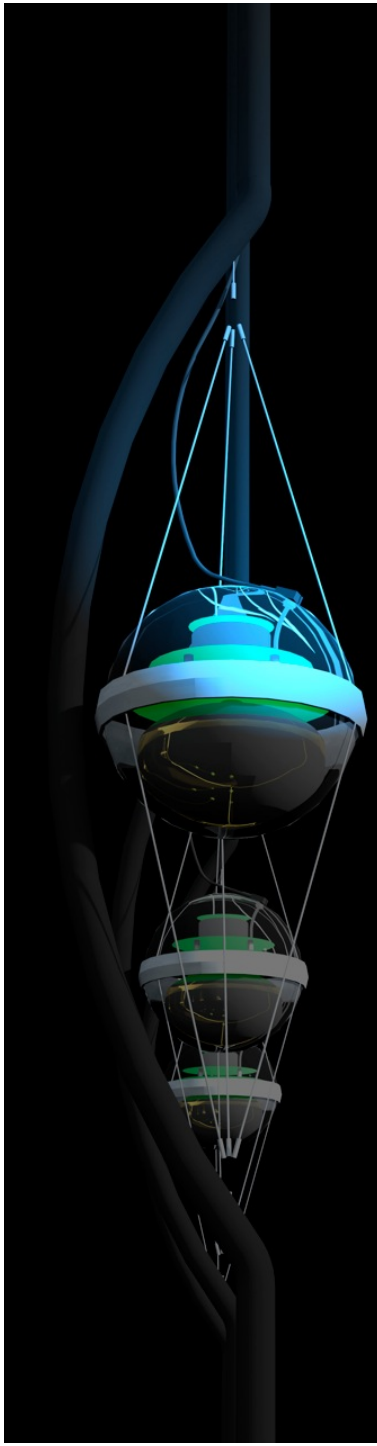
- Atmospheric-only hypothesis excluded by 6.0σ

astronomy here: through-going muons with resolution $0.2\sim0.4^0$



highest energy ν_μ: astronomy with best resolution !





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GZK neutrinos: cosmic rays interact with the microwave background

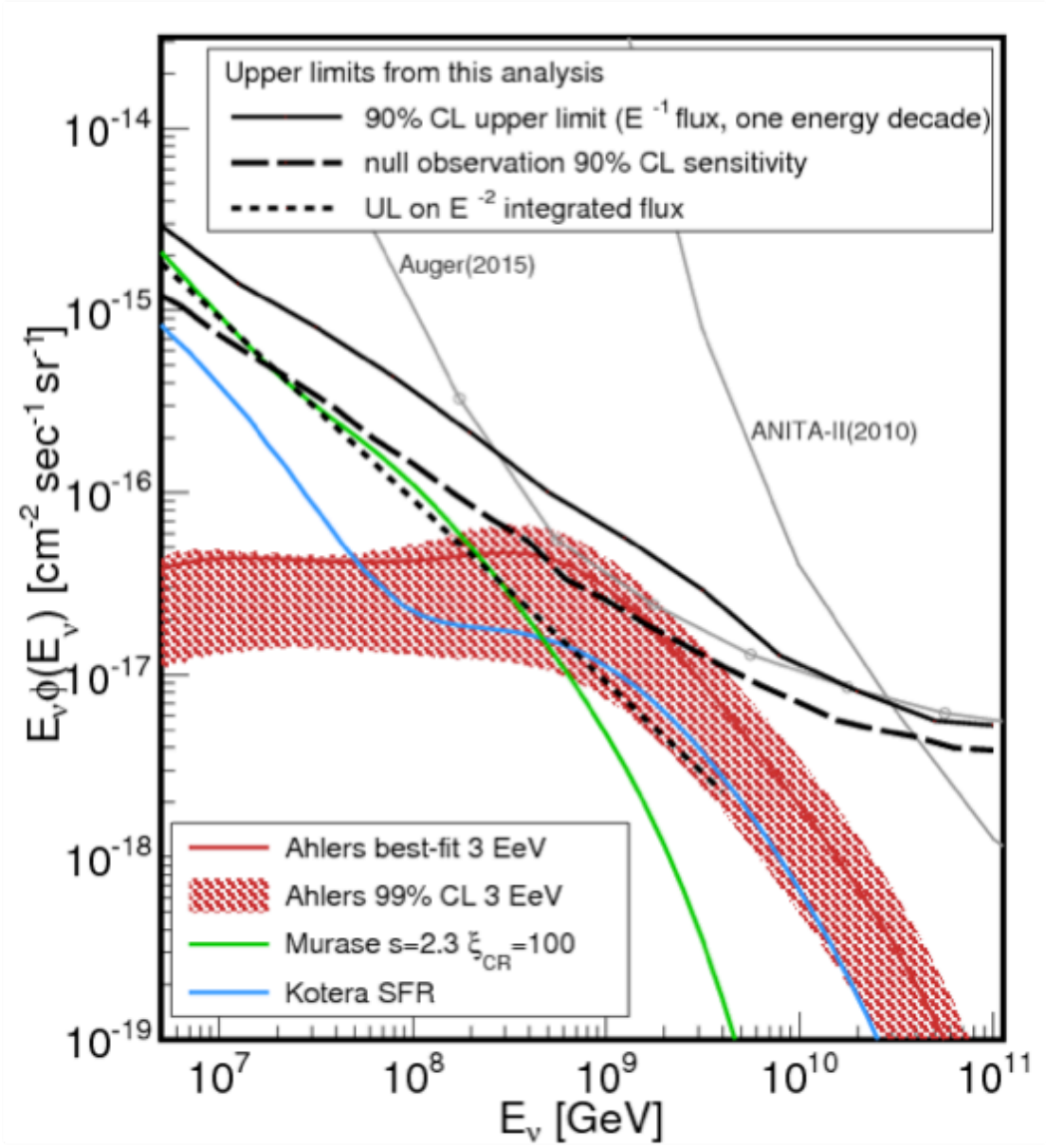
$$p + \gamma \rightarrow n + \pi^{+} \; and \; p + \pi^{0}$$

cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear

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

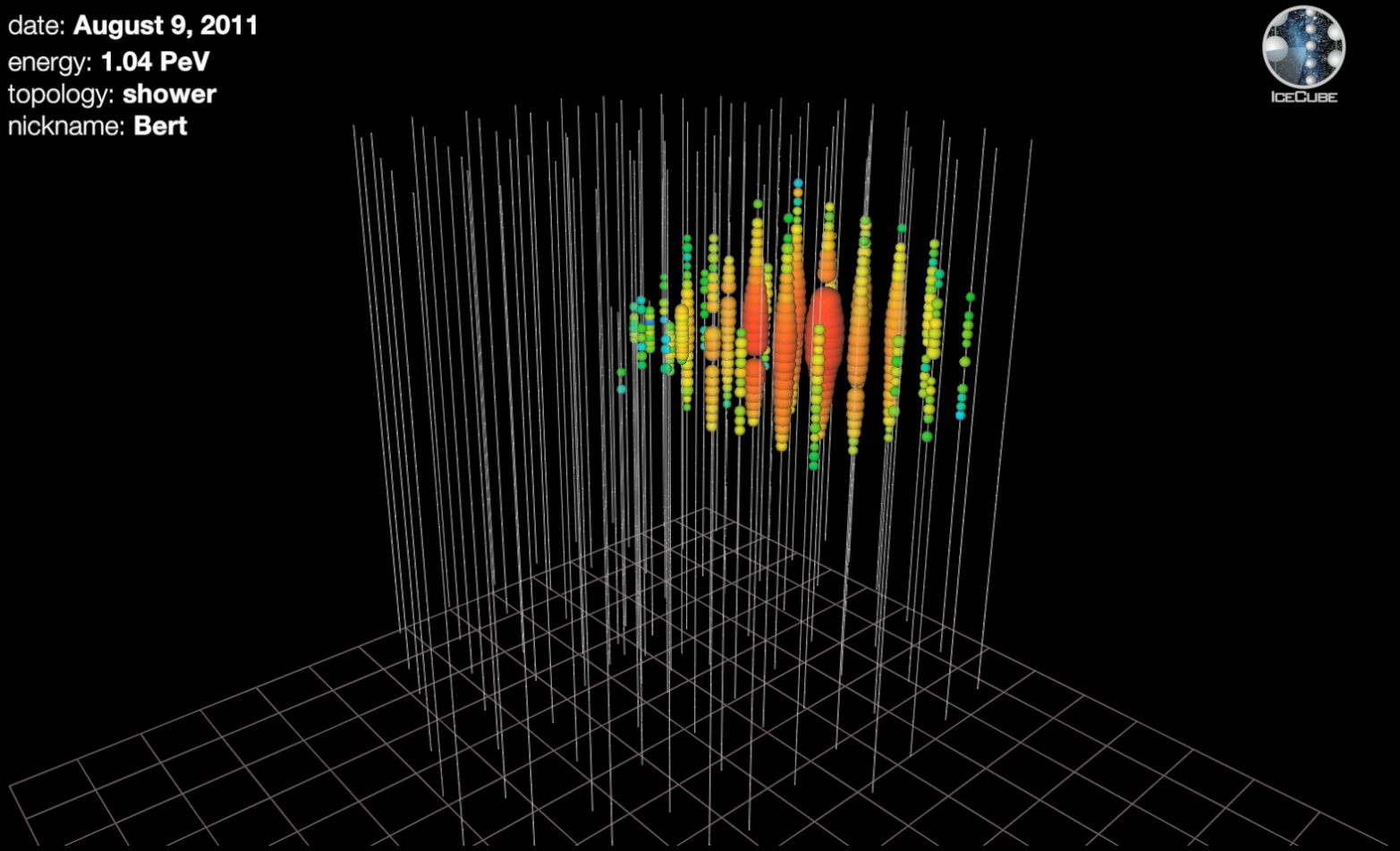
0.7 events per year in IceCube

...but it points at its source!

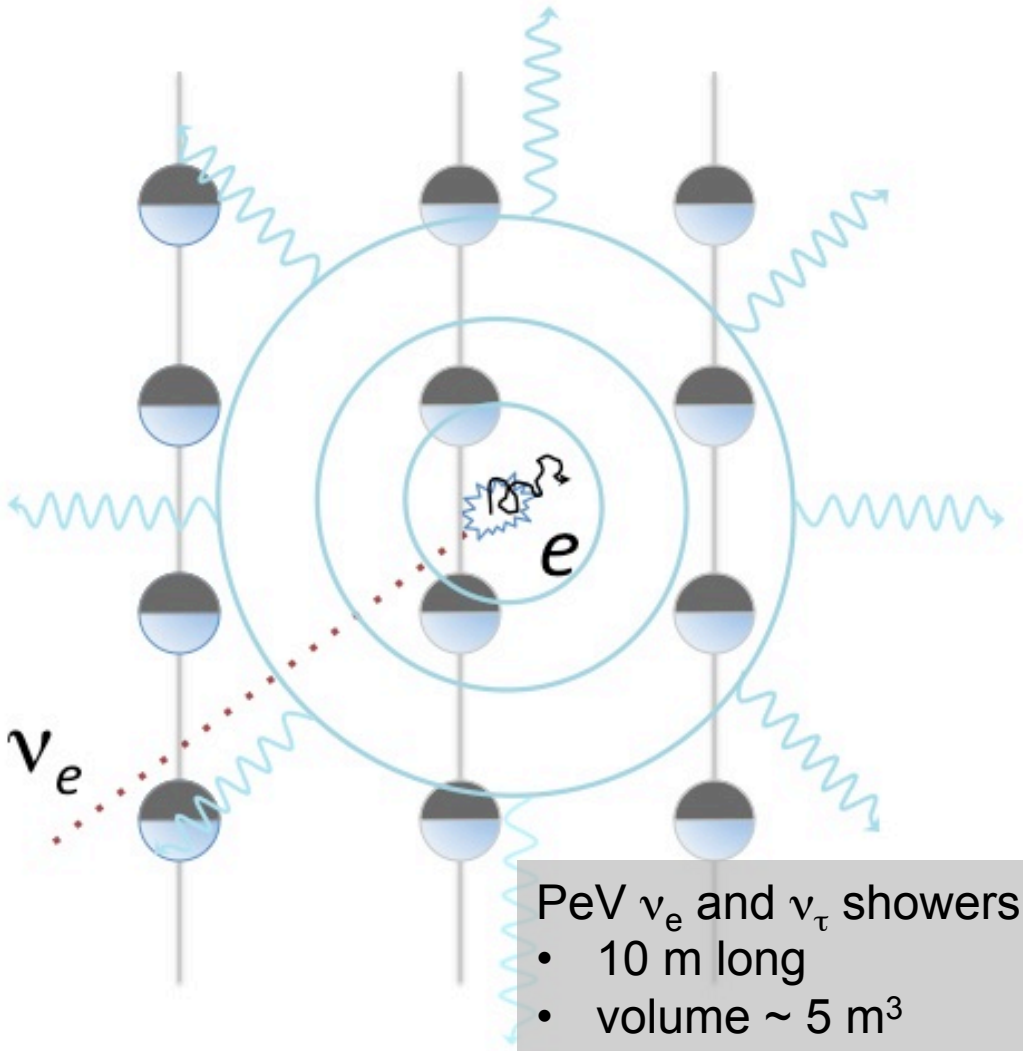

Upper limits from this analysis
90% CL upper limit (E -1 flux, one energy decade)
null observation 90% CL sensitivity
UL on E -2 integrated flux
Auger(2015)
ANITA-II(2010)
Ahlers best-fit 3 EeV
Ahlers 99% CL 3 EeV
Murase s=2.3 ξCR=100
Kotera SFR
E_ν φ(E_ν) [cm^-2 sec^-1 sr^-1]
E_ν [GeV]
10^-14
10^-15
10^-16
10^-17
10^-18
10^-19
10^7
10^8
10^9
10^10
10^11

1607.05886

GZK neutrino search: two neutrinos with > 1,000 TeV

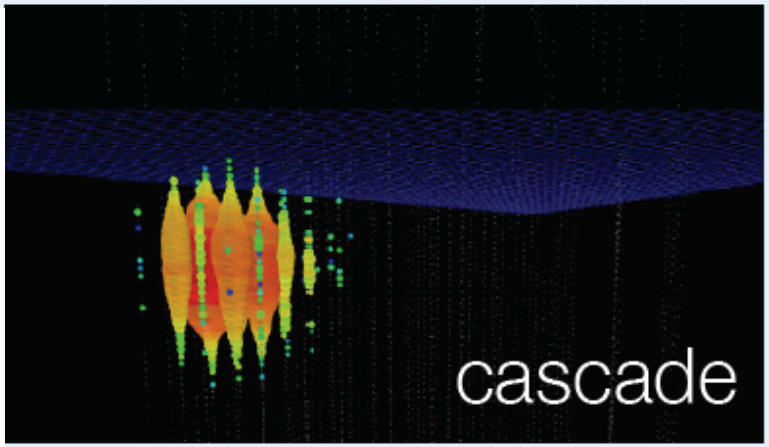


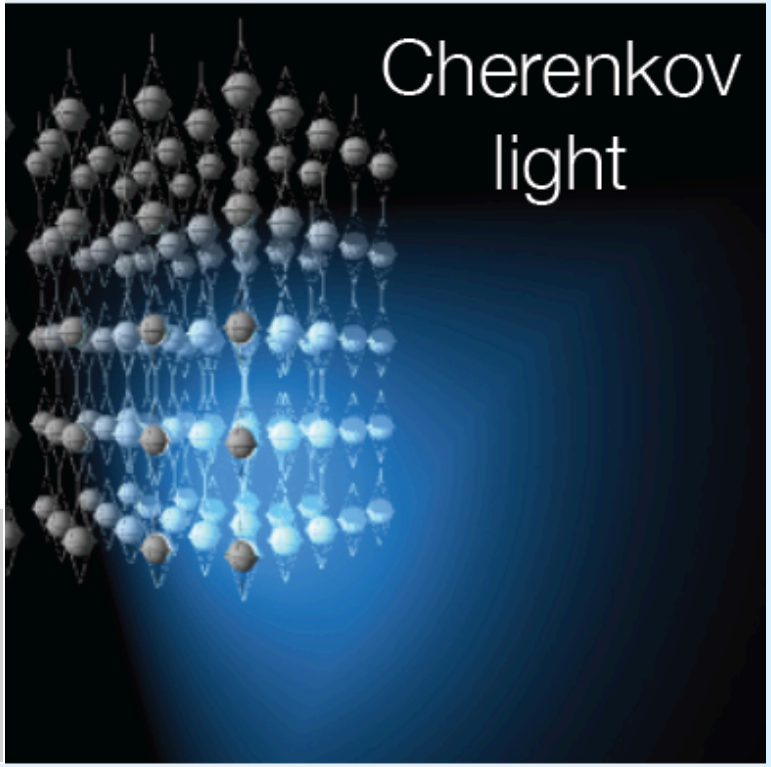
tracks and showers

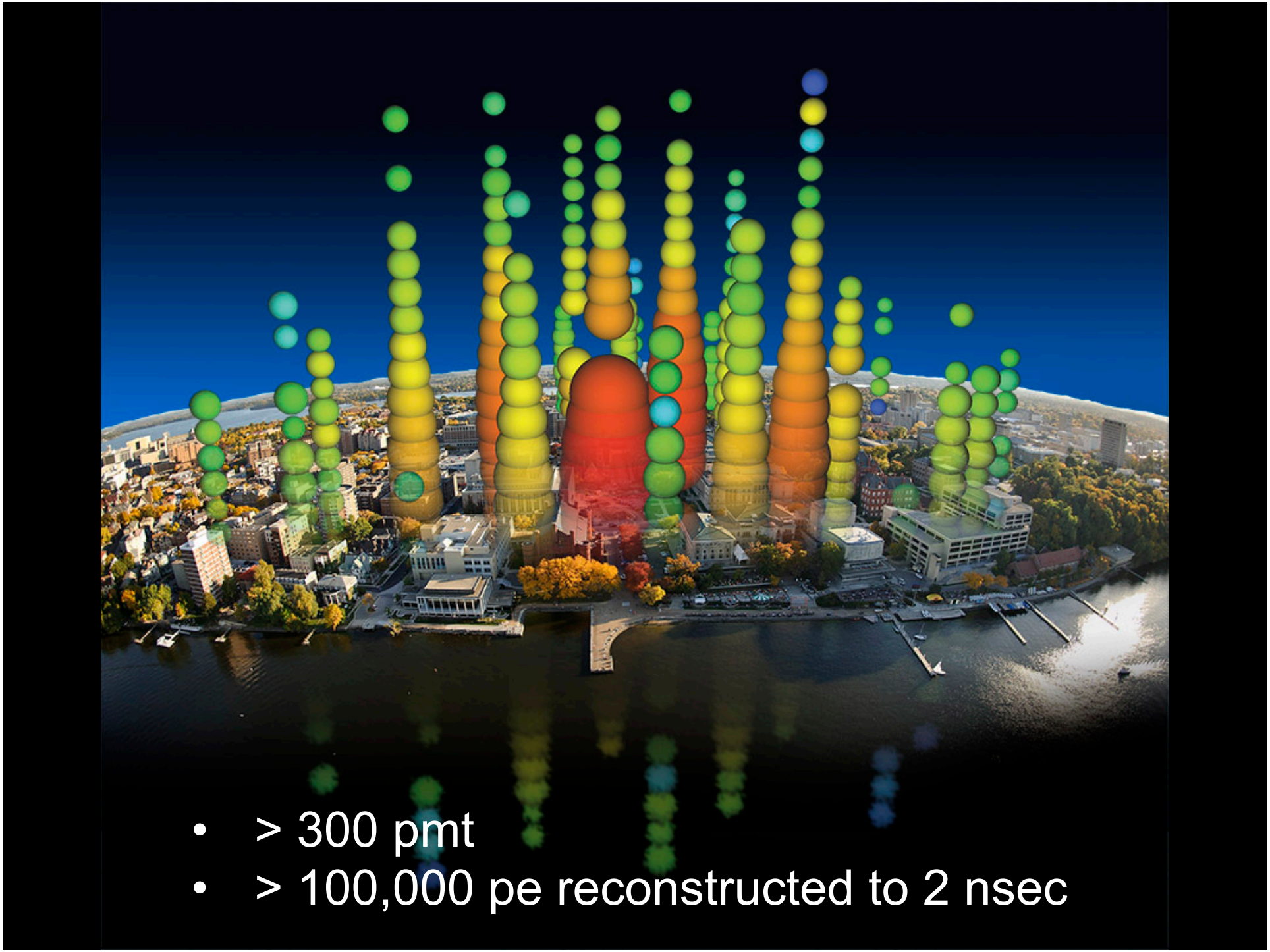


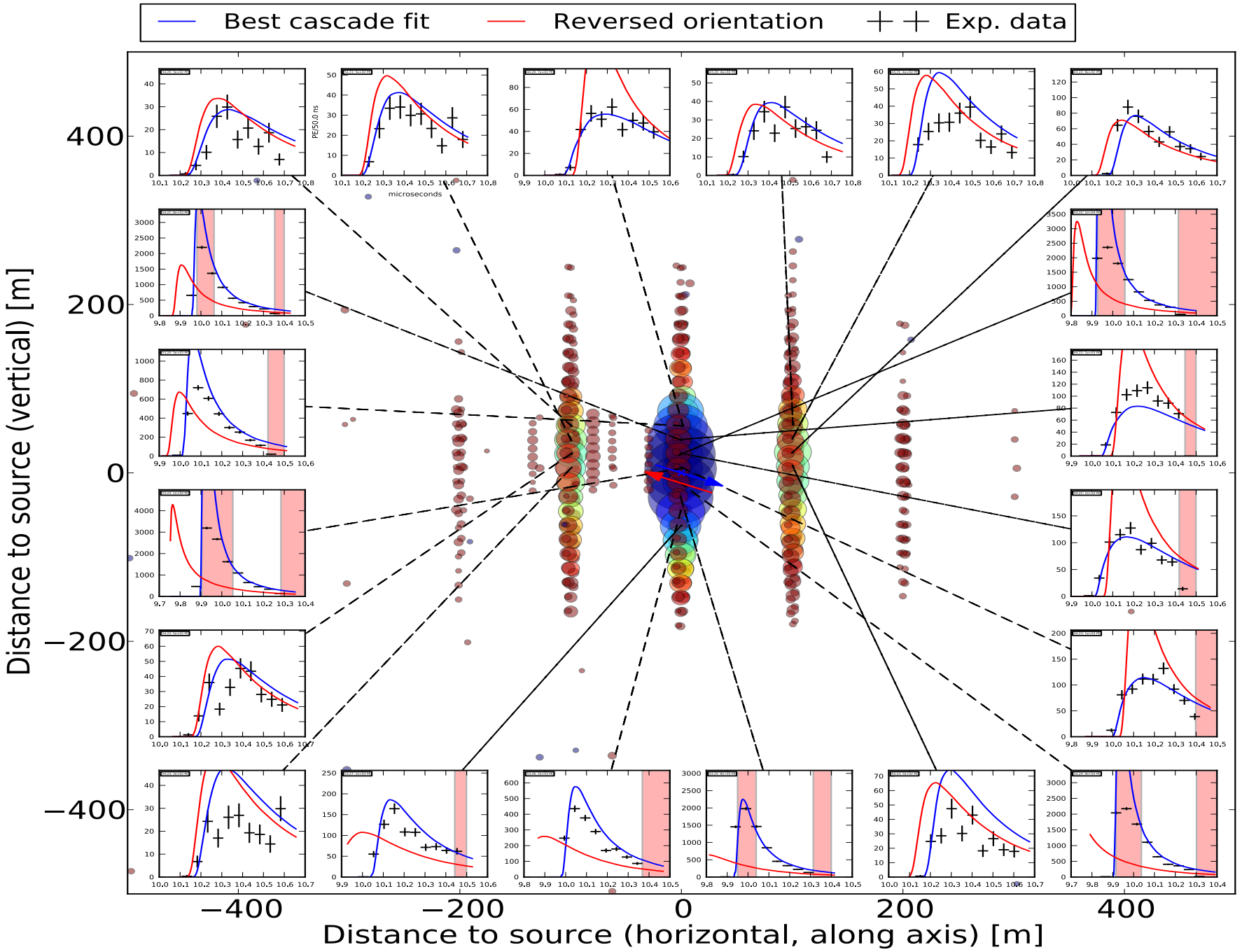
PeV ν_e and ν_τ showers:

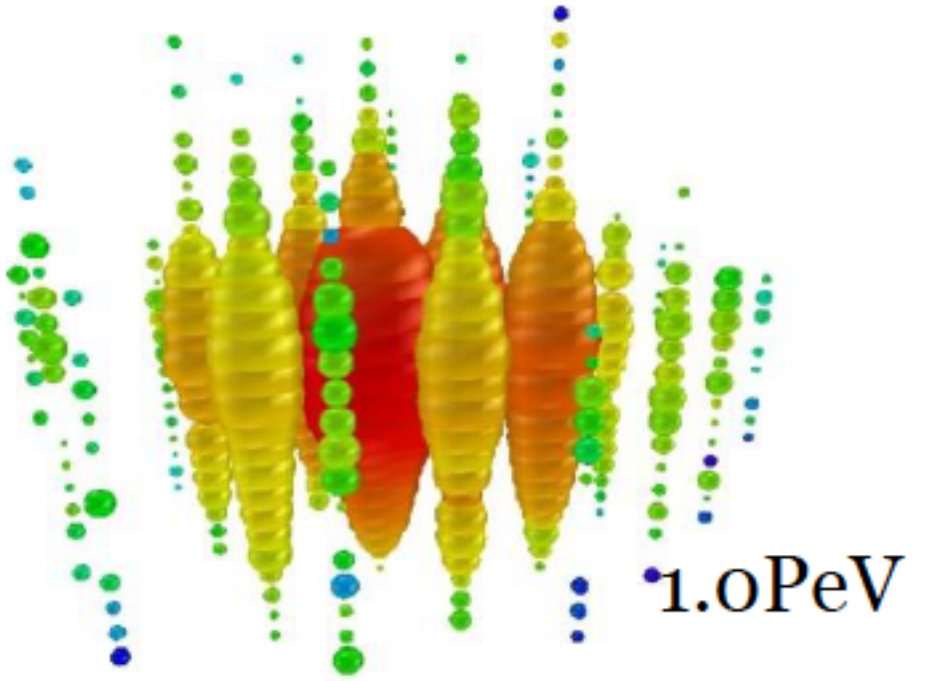
- 10 m long
- volume ~ 5 m^3
- isotropic after 25~ 50m

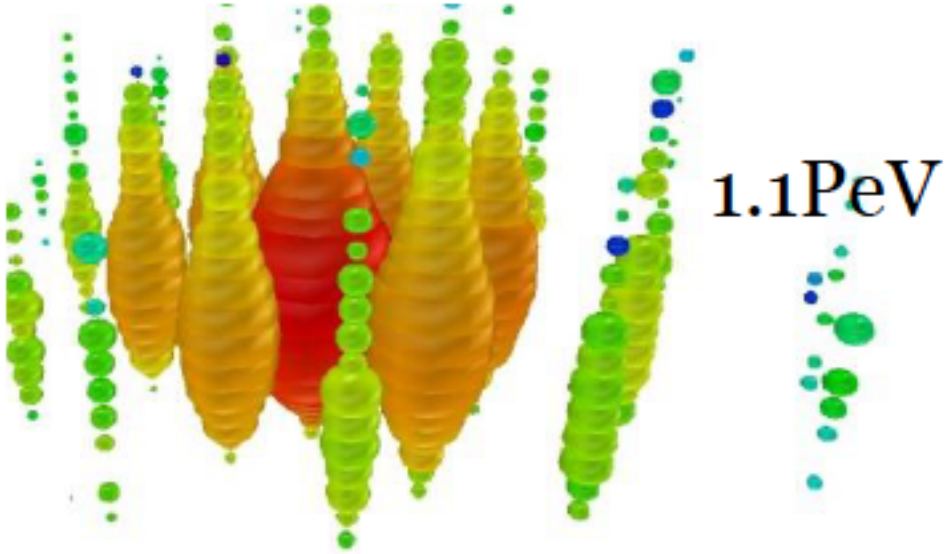





• > 300 pmt
• > 100,000 pe reconstructed to 2 nsec


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





- energy

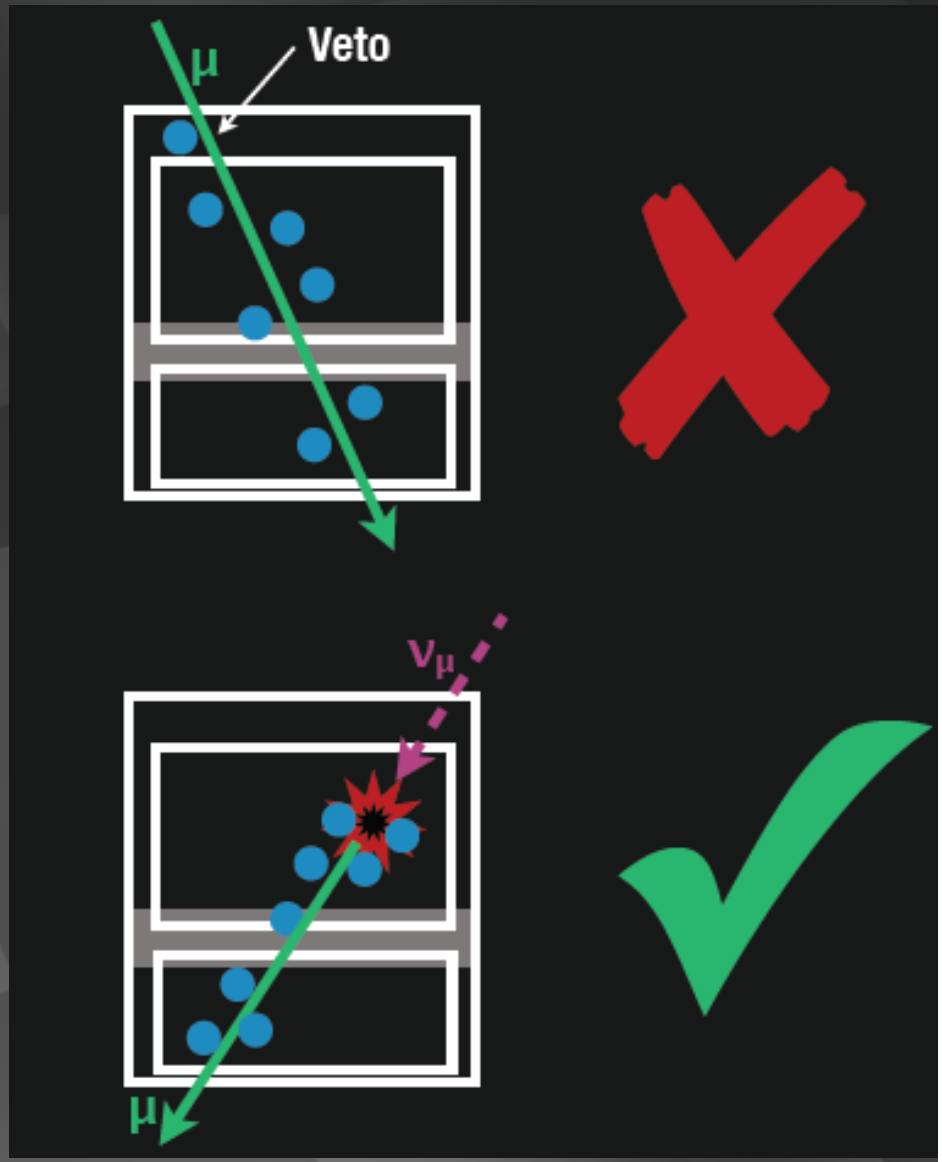
  1,041 TeV
  1,141 TeV

  (15% resolution)

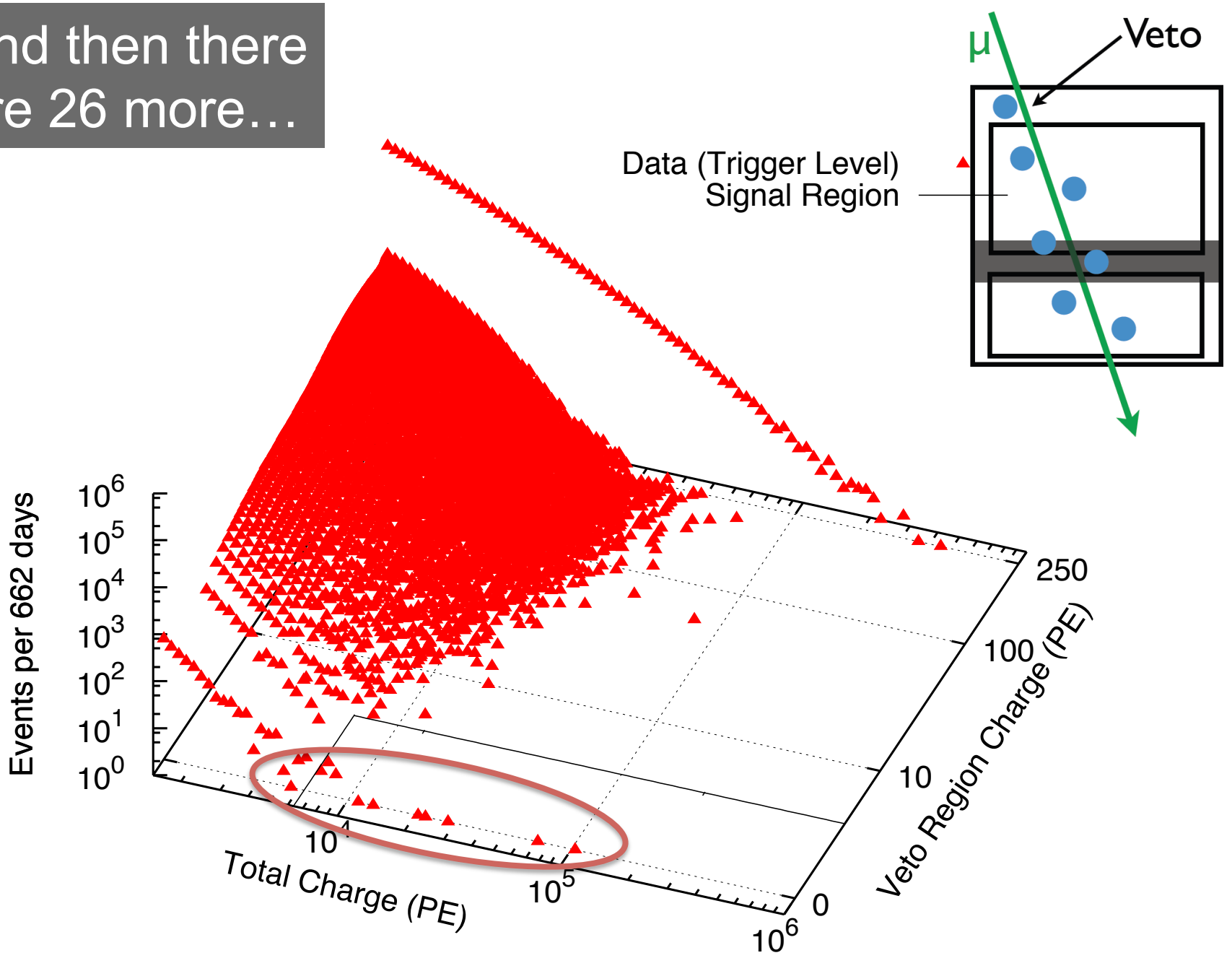
- not atmospheric at 3σ
- no muons from accompanying atmospheric shower
- look for more

neutrinos starting inside the detector

- ✓ no light in the veto region
- ✓ veto for atmospheric neutrinos that are typically accompanied by muons
- ✓ energy measurement: total absorption calorimetry
- ✓ all sky, all flavors

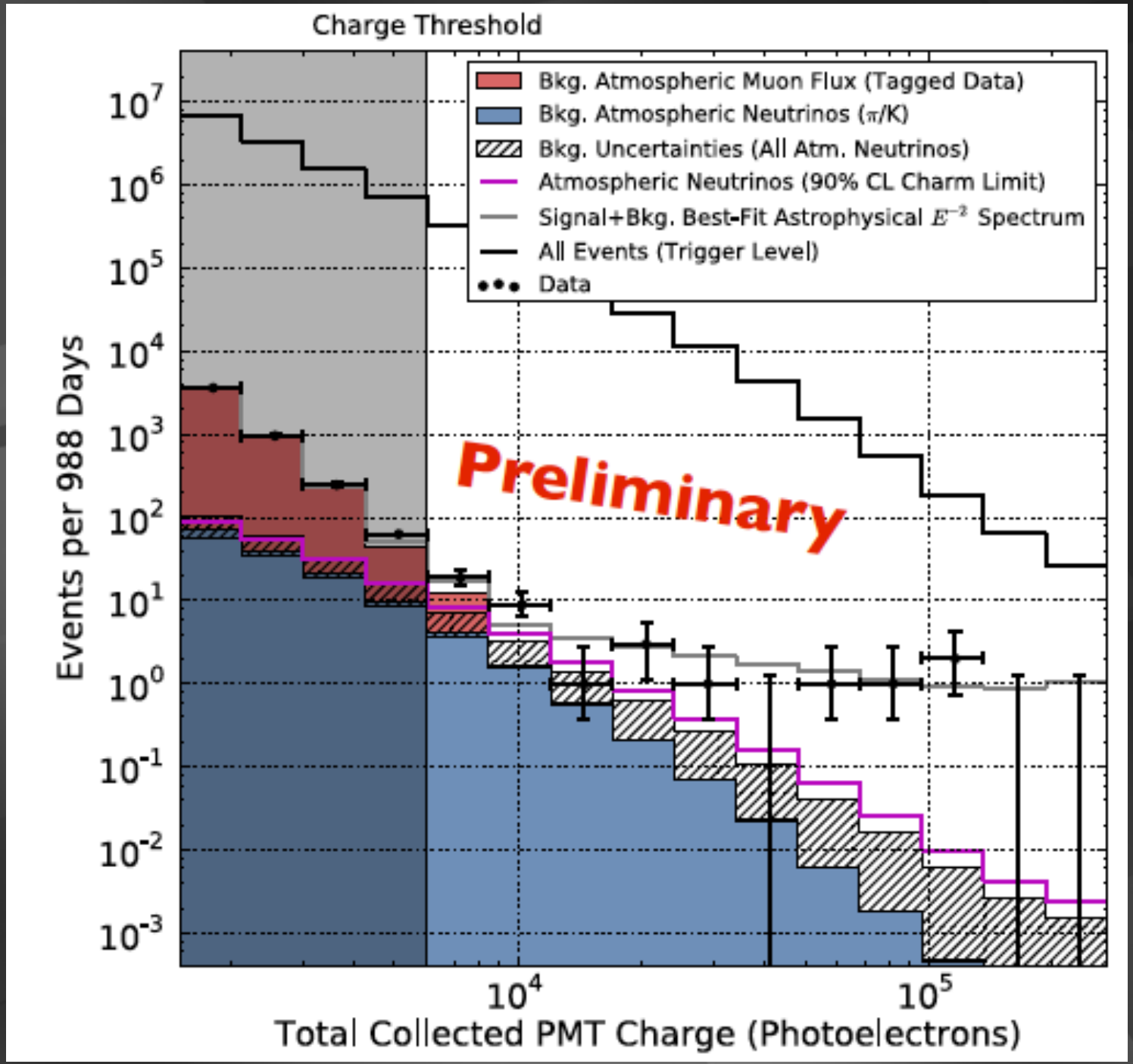


…and then there were 26 more…



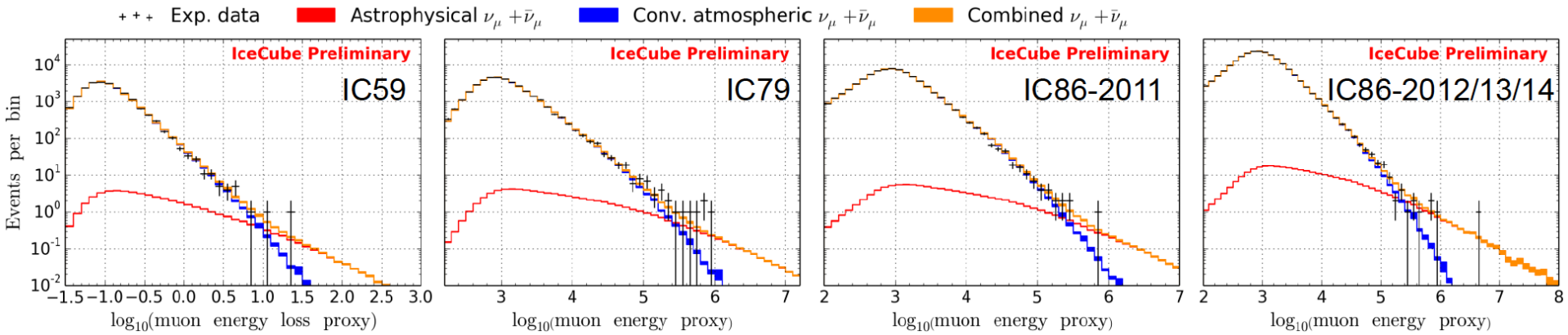
data: 86 strings one year

total charge collected by PMTs of events with interaction inside the detector

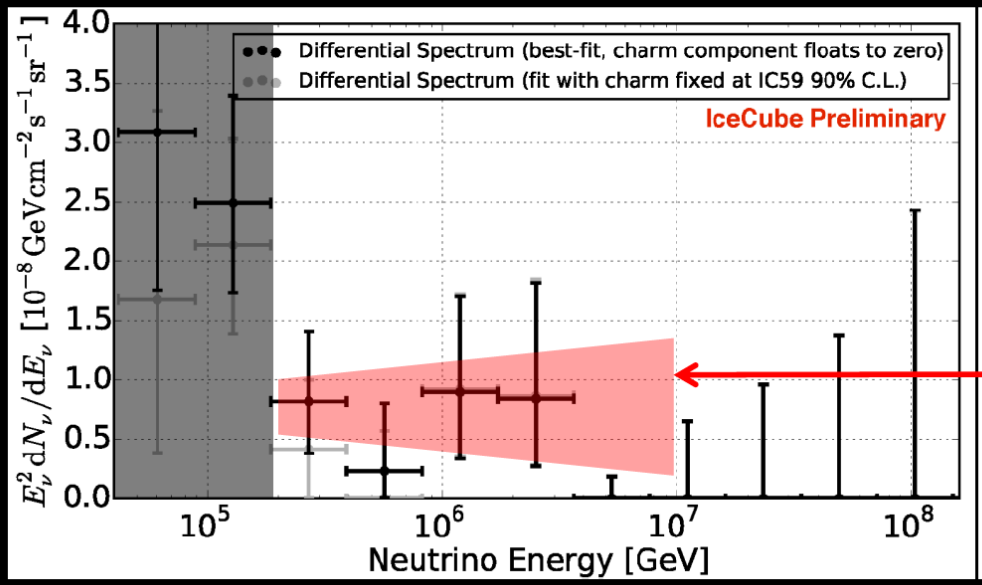


Science 342 (2013) 1242856

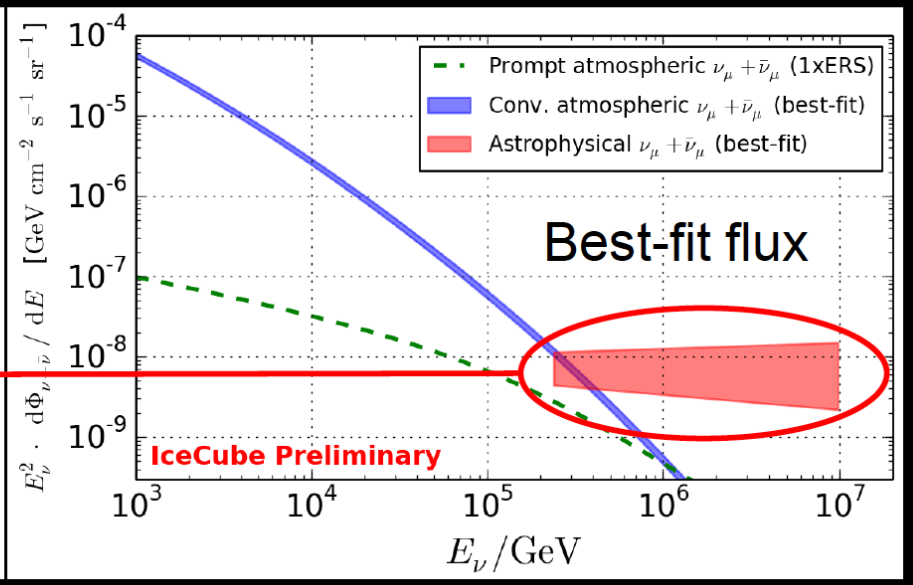
after 6 years: 3.7→ 6.0 sigma

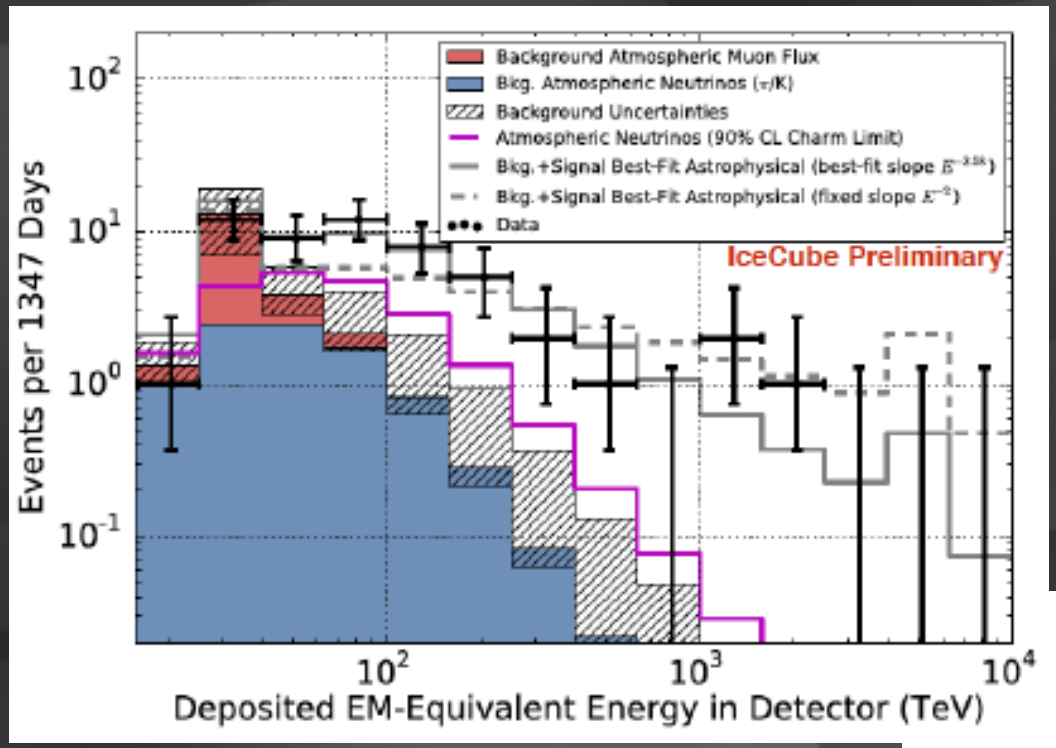


HESE 4 year unfolding
(→ dominated by shower-like events)

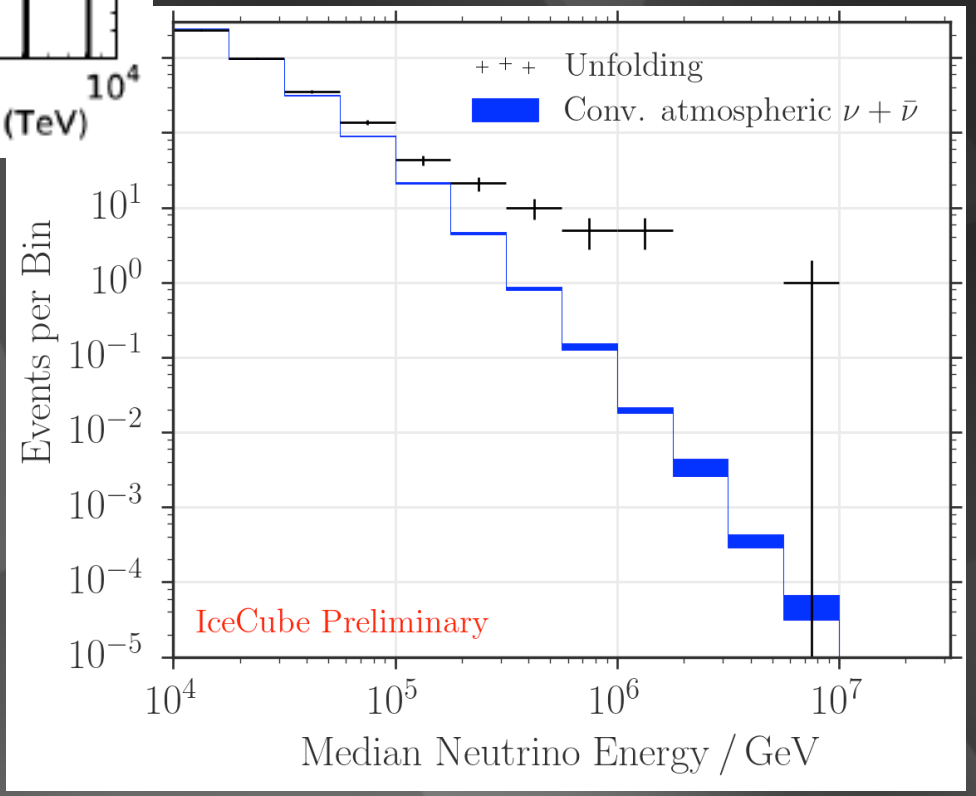


6 year up-going numu analysis





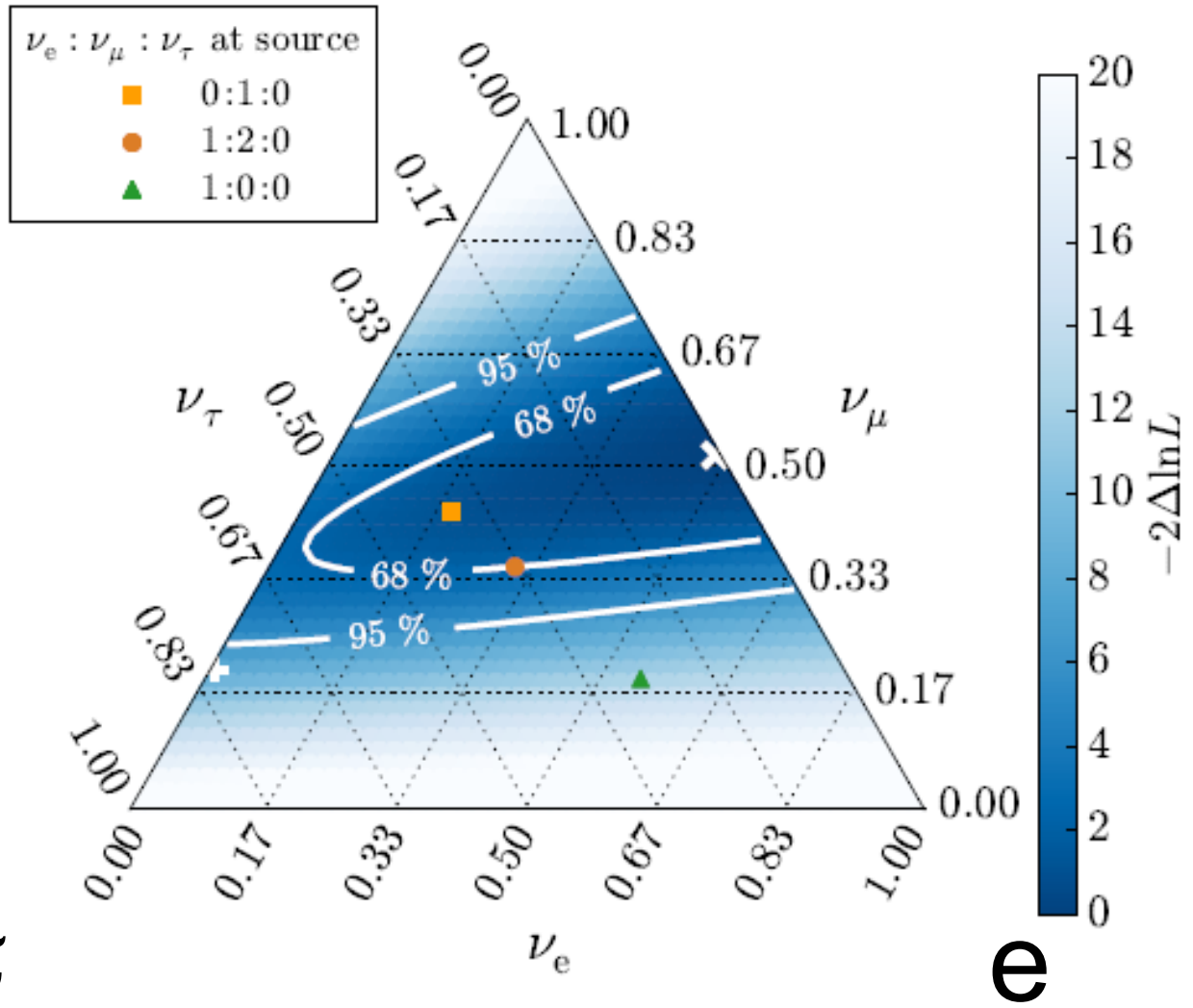
confirmation!
flux of muon neutrinos
through the Earth (6σ)



neutrinos of all flavors
interacting inside
IceCube (7σ)

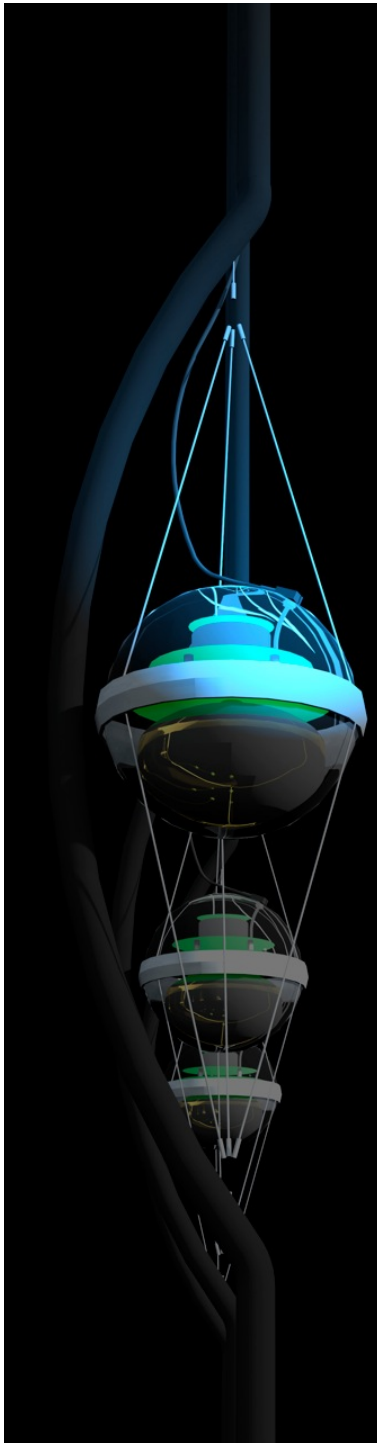
oscillate over cosmic distances to 1:1:1

μ



τ

e



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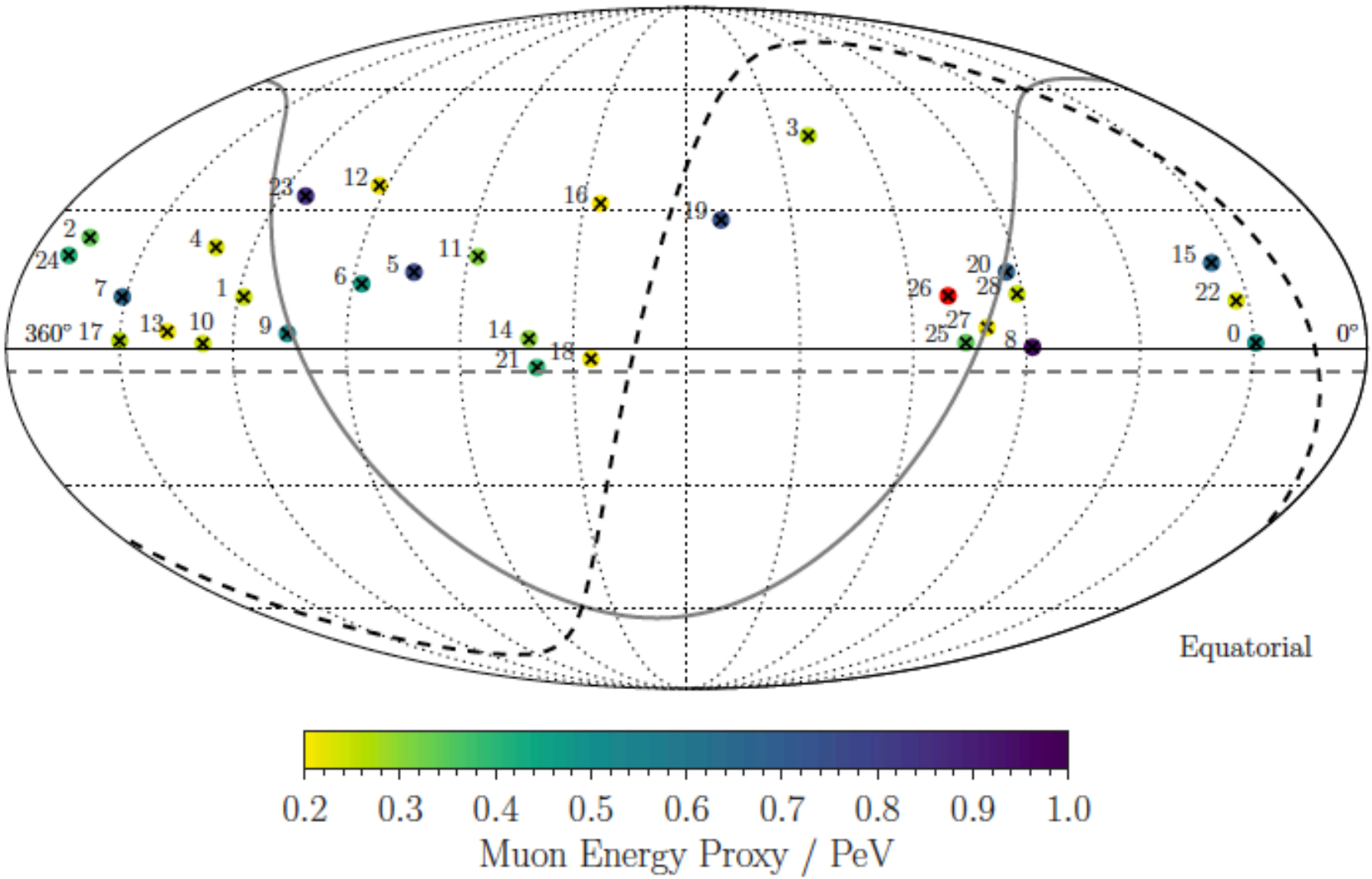
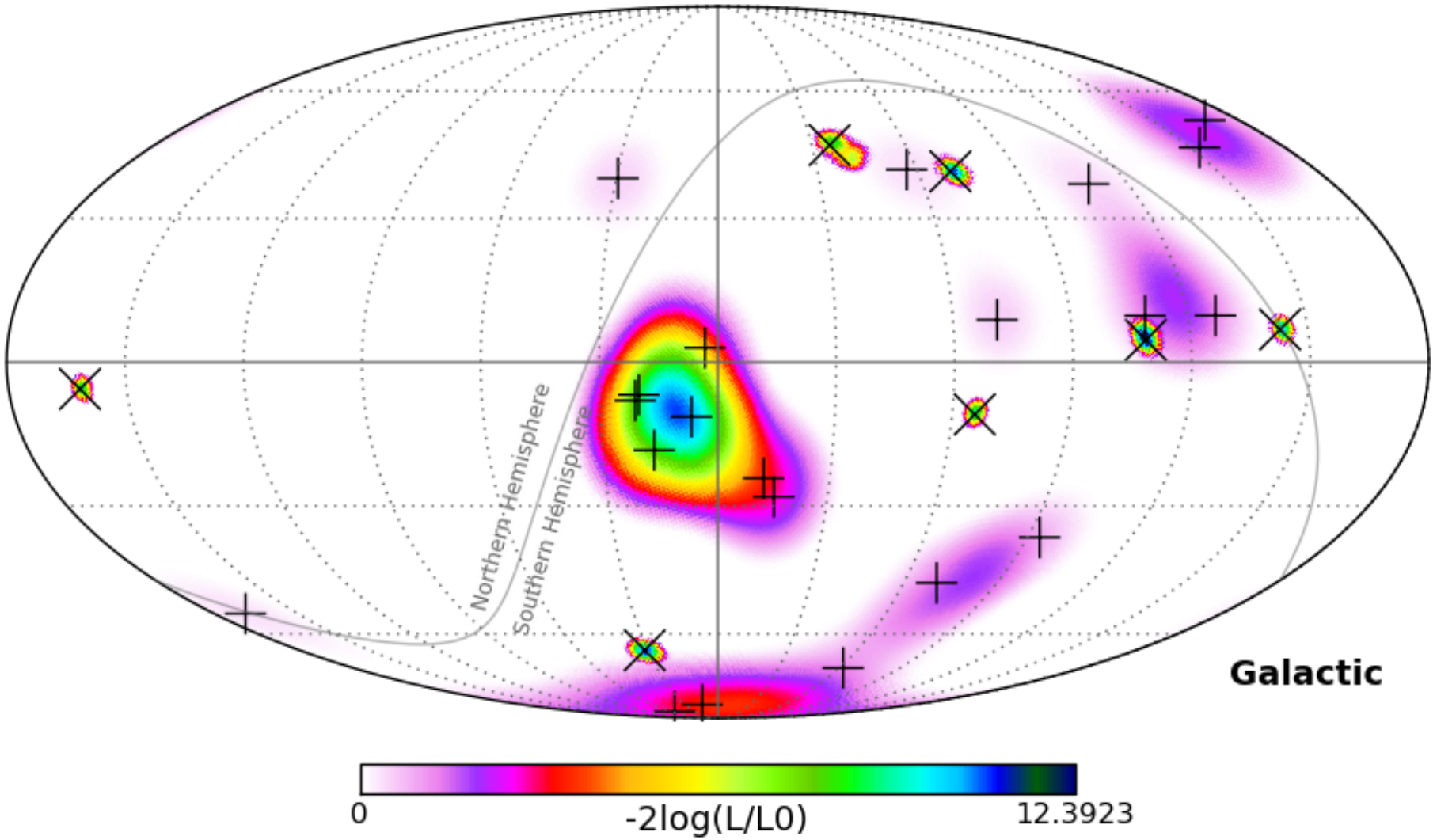
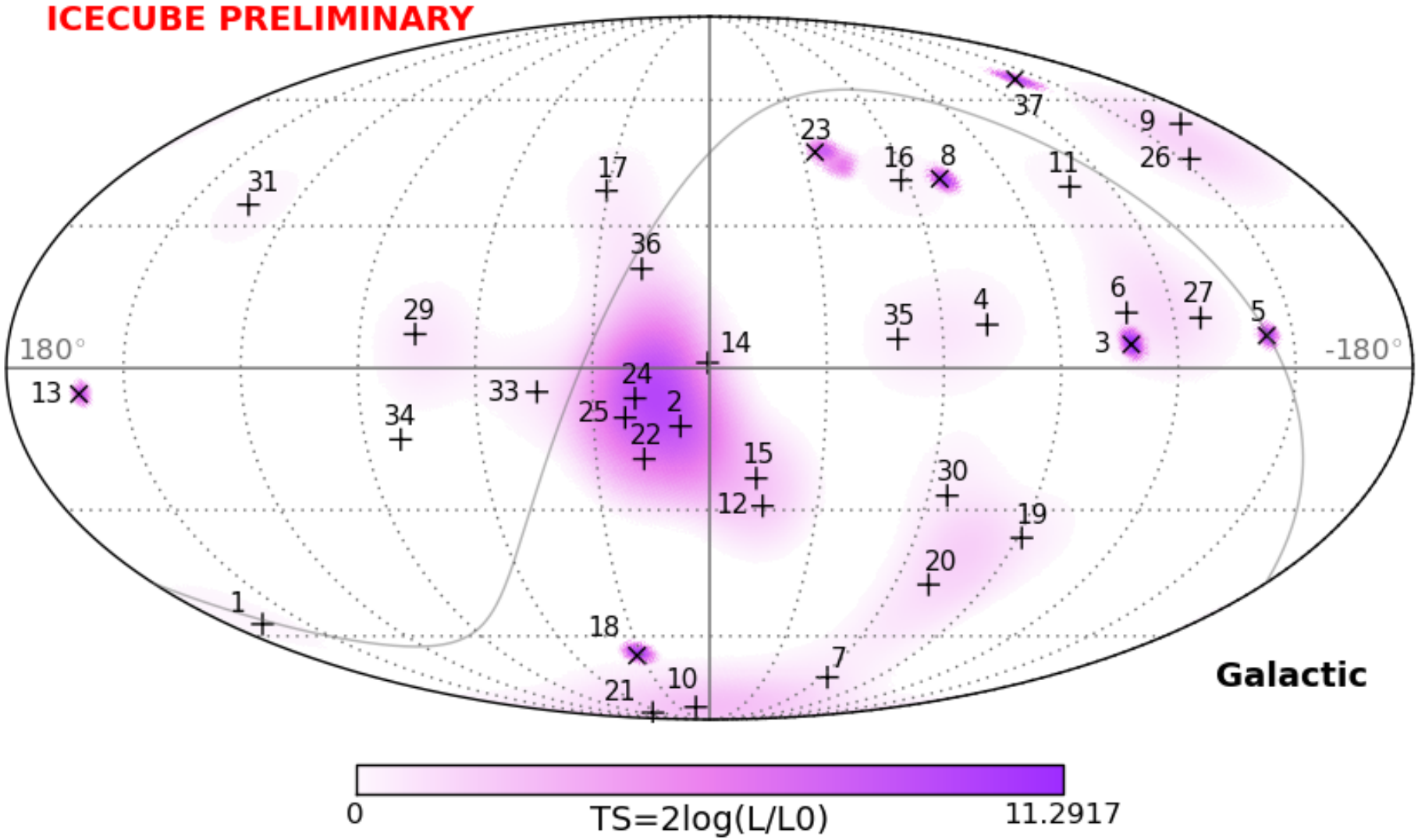

3
12
23
16
19
2
4
11
24
5
6
20
15
7
1
26
28
22
13
10
9
14
27
360°
17
25
8
0
0°
21
18
Equatorial
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Muon Energy Proxy / PeV

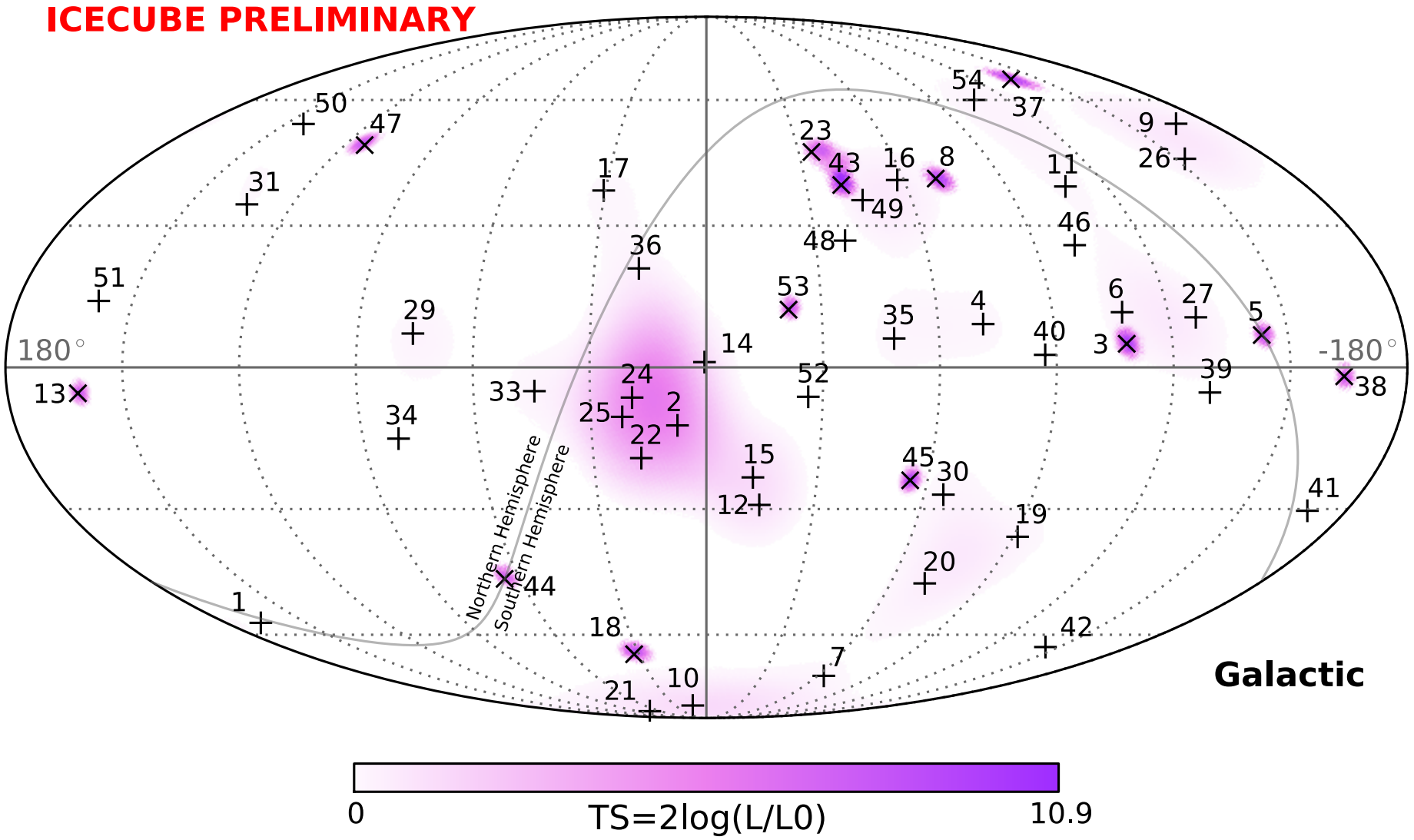
2 year HESE


Northern Hemisphere
Southern Hemisphere
Galactic
0
-2log(L/L0)
12.3923

3 year HESE

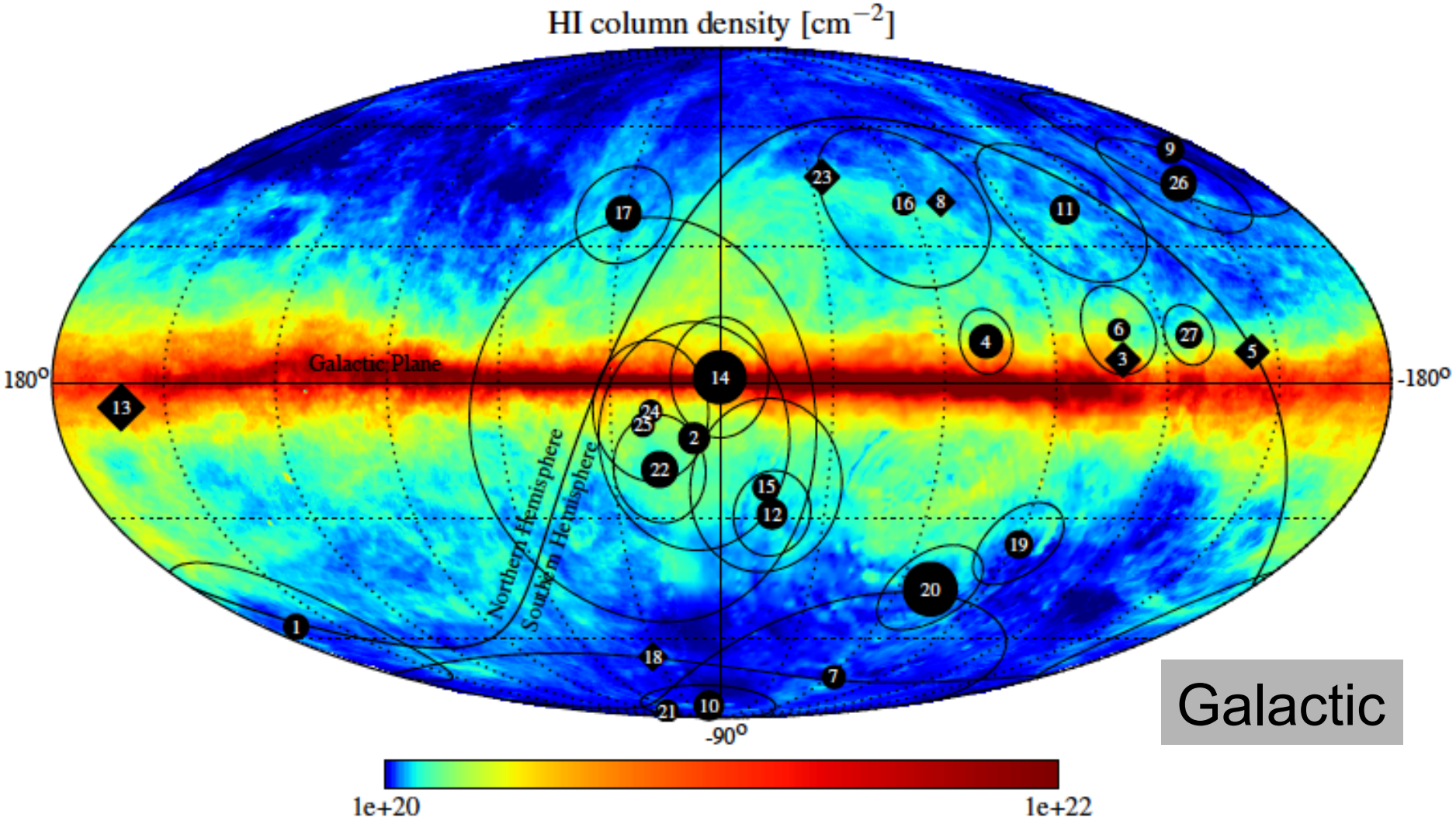


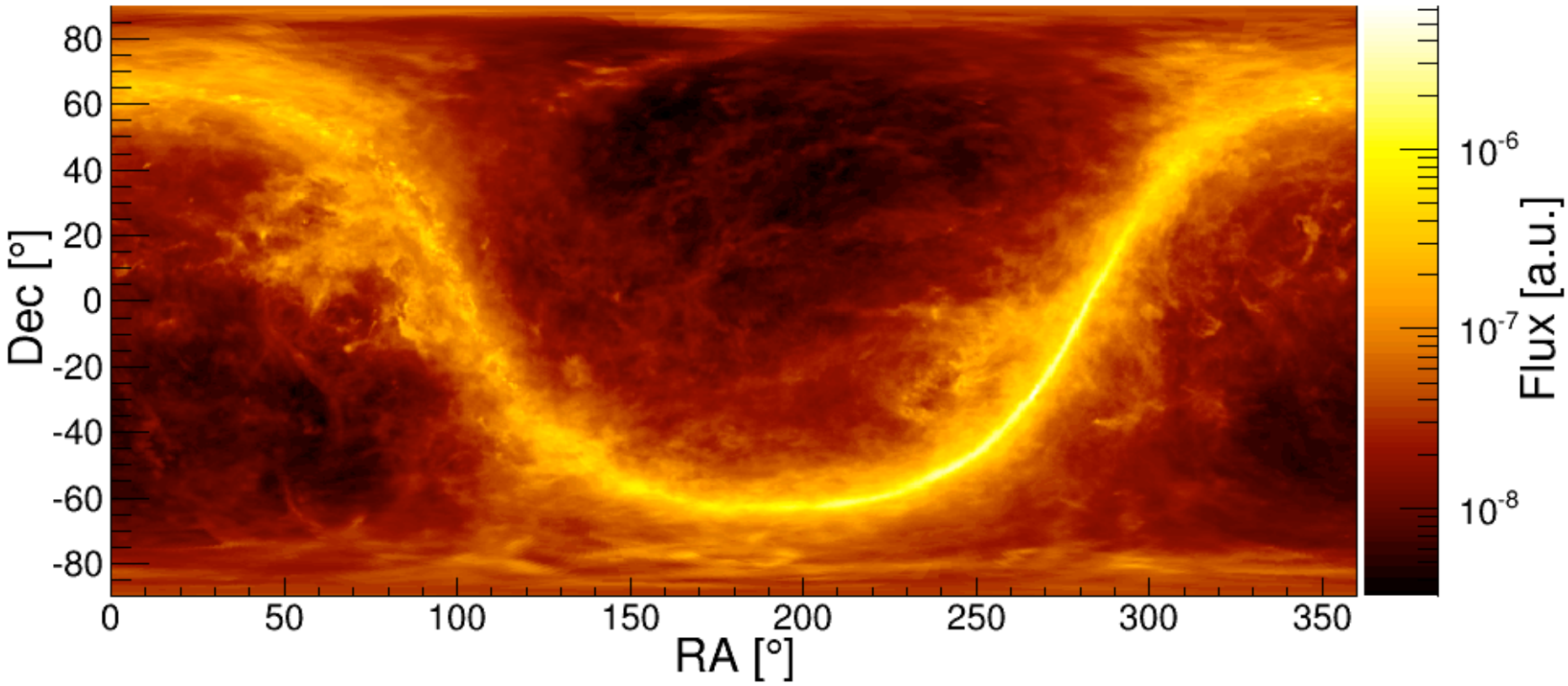
4 year HESE



where do they come from?

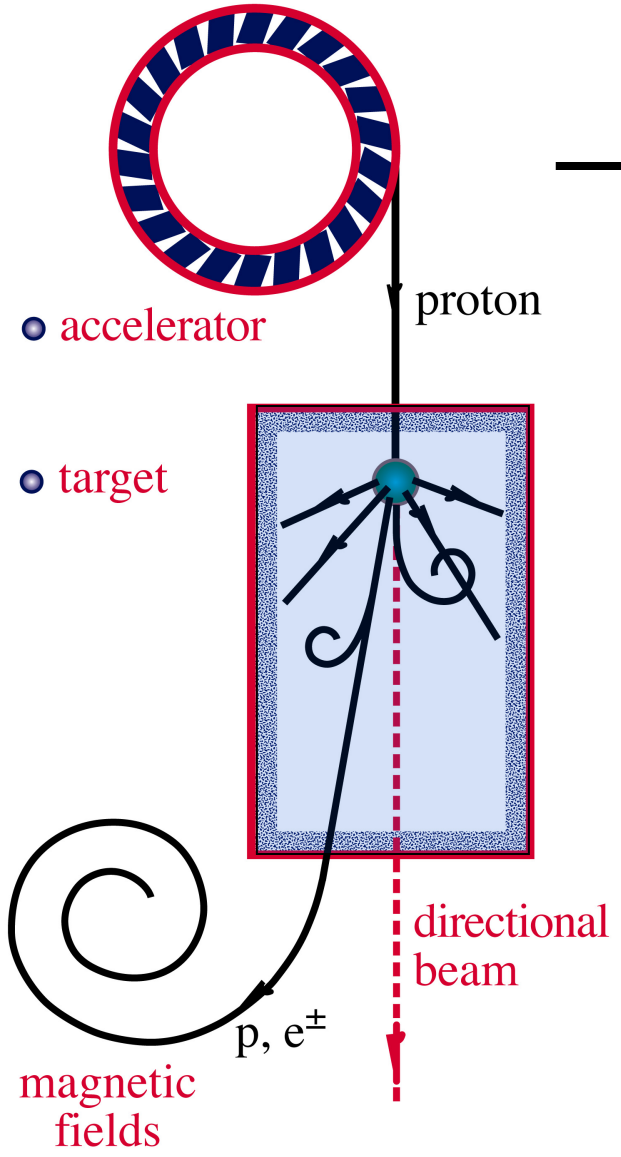
correlation with Galactic plane: TS of 2.5% for a width of 7.5 deg




Dec [°]
80
60
40
20
0
-20
-40
-60
-80
0
50
100
150
200
250
300
350
RA [°]
10^{-6}
10^{-7}
10^{-8}
Flux [a.u.]

- we observe a diffuse flux of neutrinos from extragalactic sources
- a subdominant Galactic component cannot be excluded (no evidence reaches 3σ level)
- where are the PeV gamma rays that accompany PeV neutrinos?

ν and γ beams : heaven and earth



accelerator is powered by
large gravitational energy

black hole
neutron star

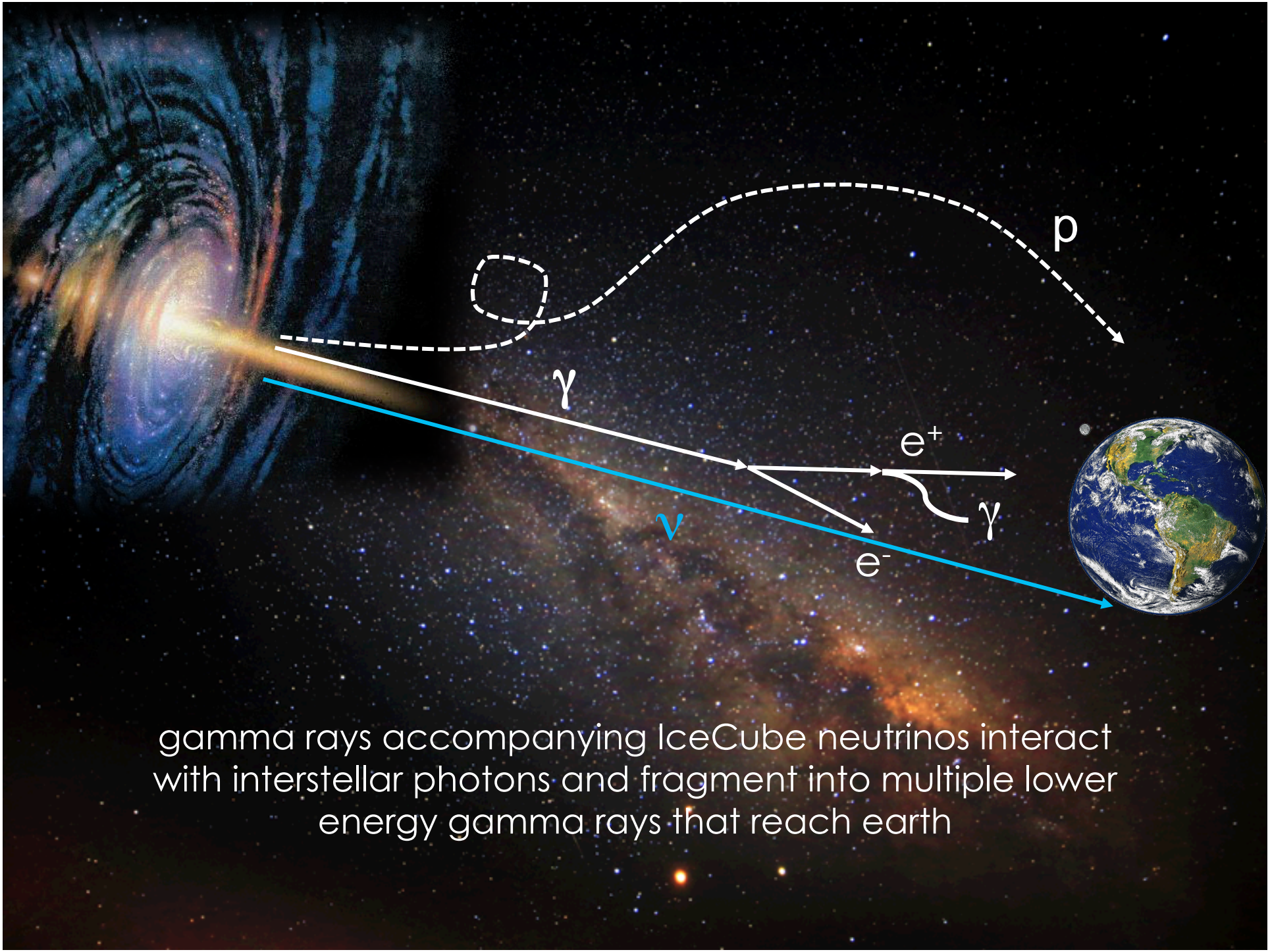
radiation
and dust

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

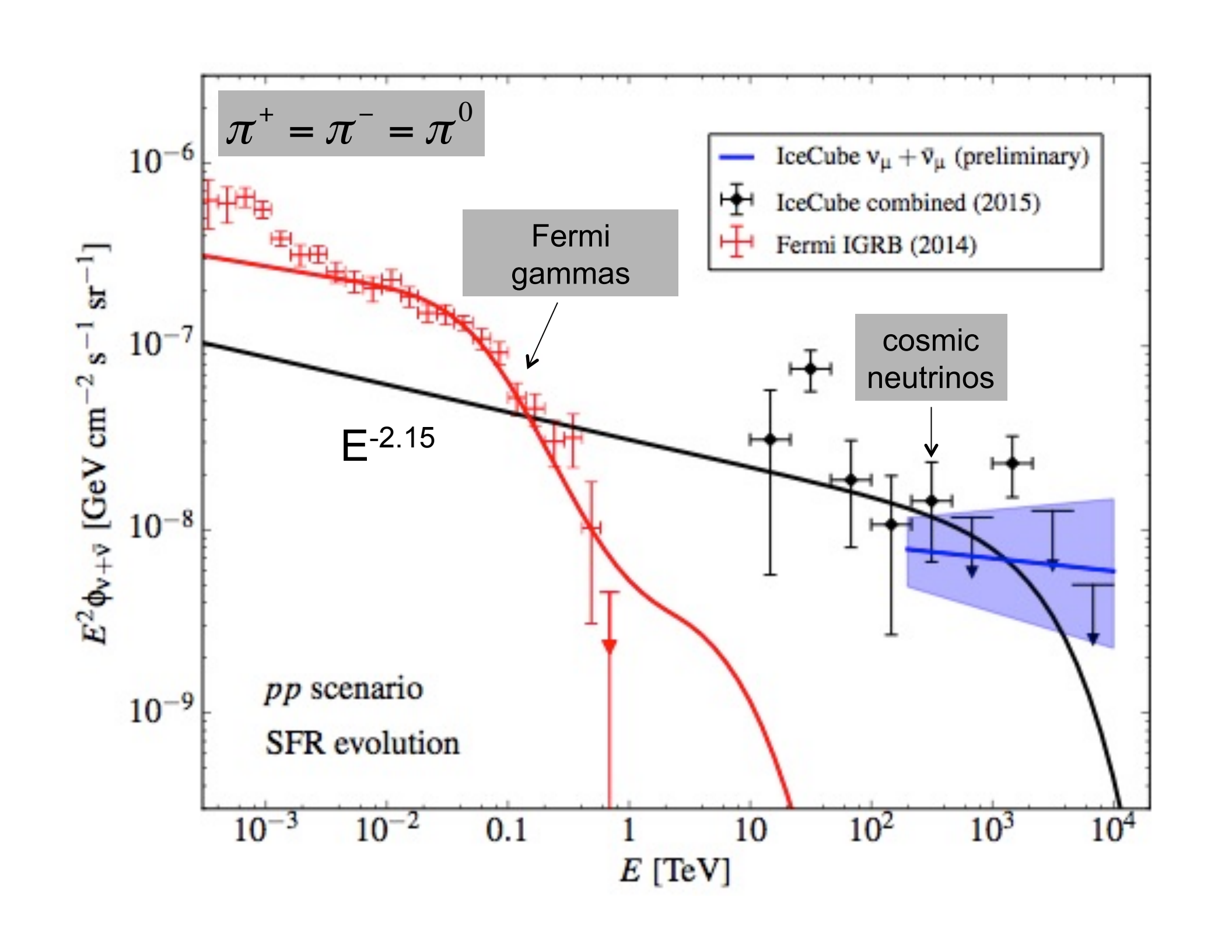
~ cosmic ray + neutrino

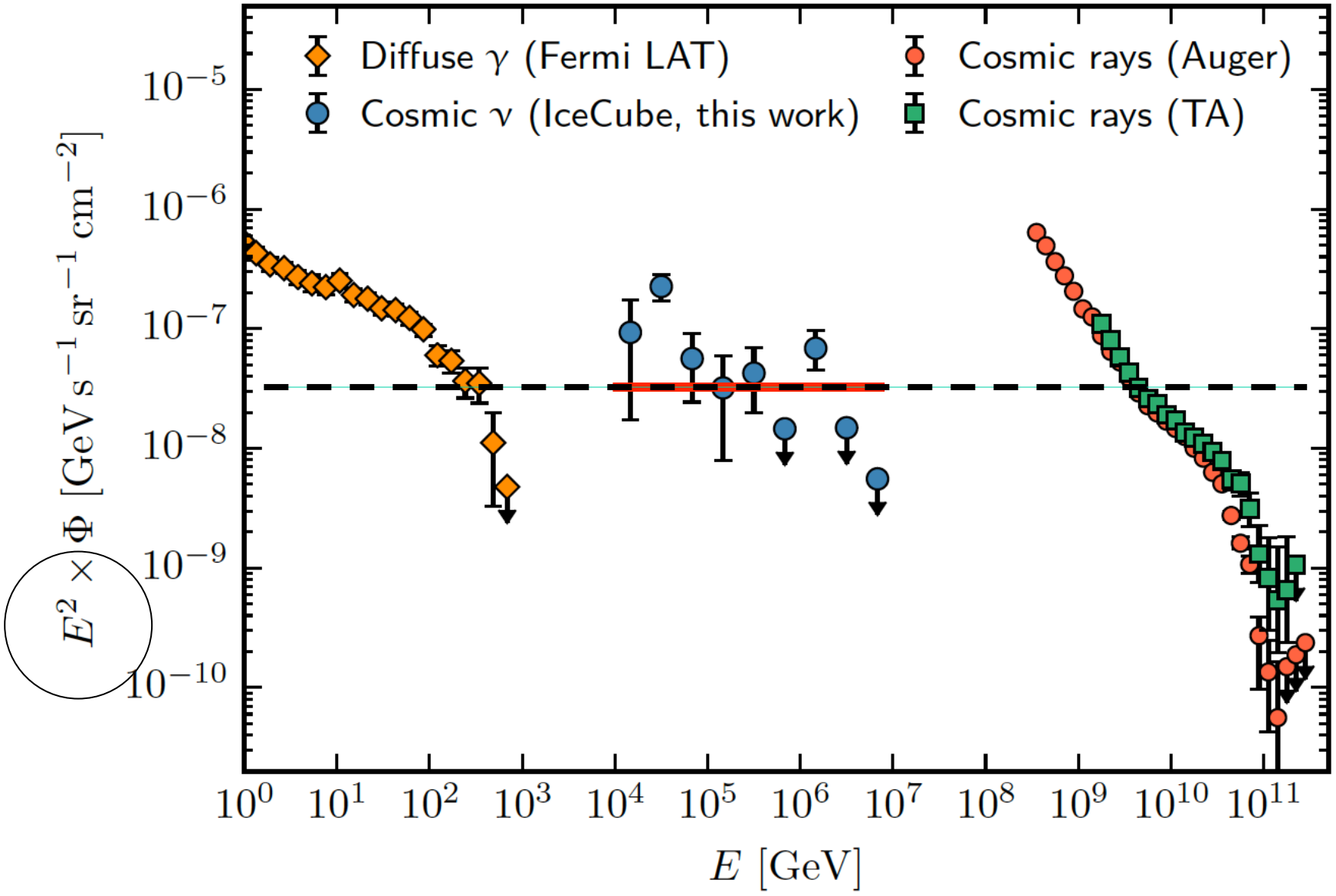
$\rightarrow p + \pi^0$

~ cosmic ray + gamma



gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth


$\pi^+ = \pi^- = \pi^0$
IceCube $\nu_\mu + \bar{\nu}_\mu$ (preliminary)
IceCube combined (2015)
Fermi IGRB (2014)
Fermi gammas
cosmic neutrinos
$E^{-2.15}$
pp scenario
SFR evolution
$E^2\phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3
10^4

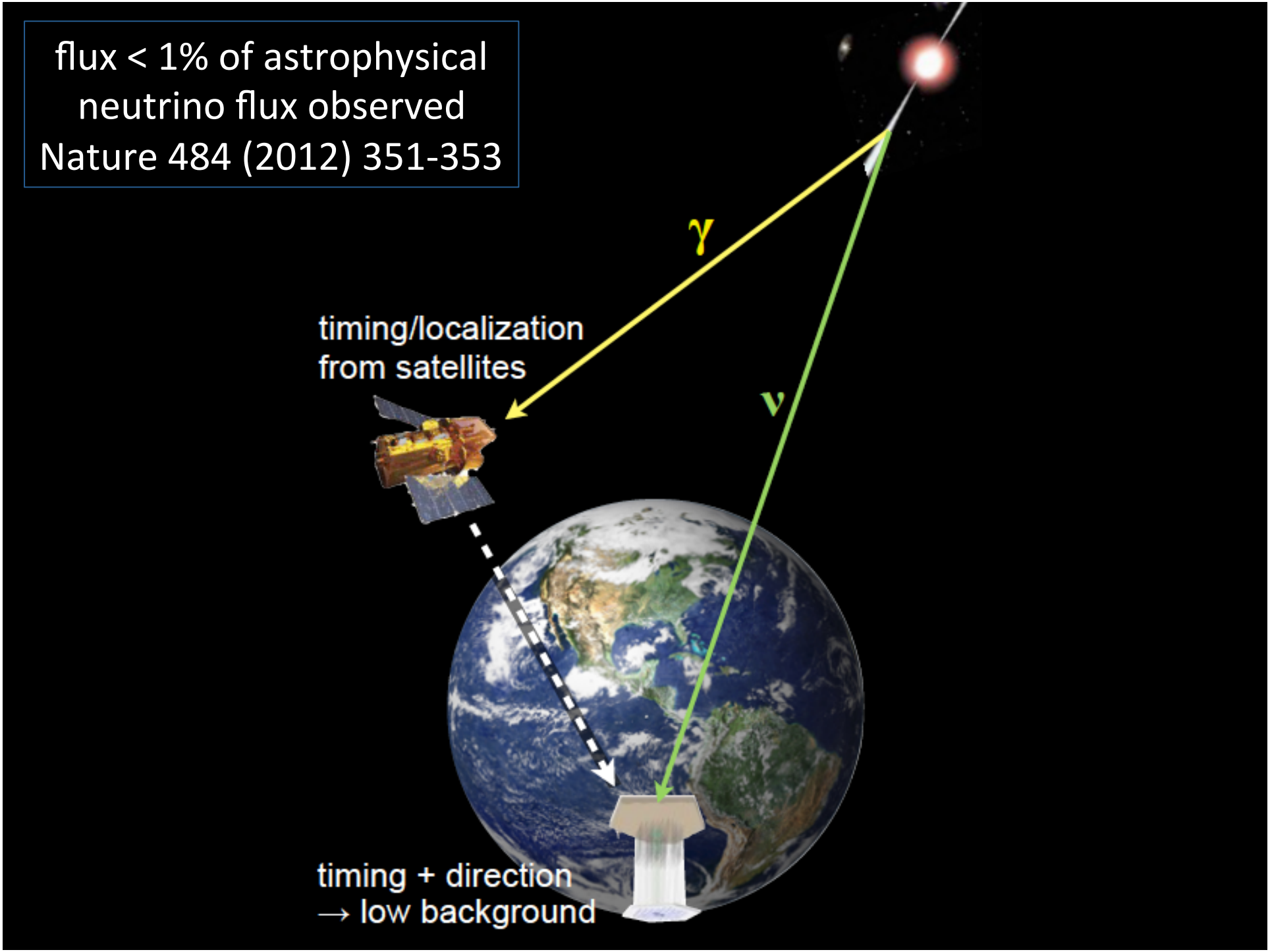


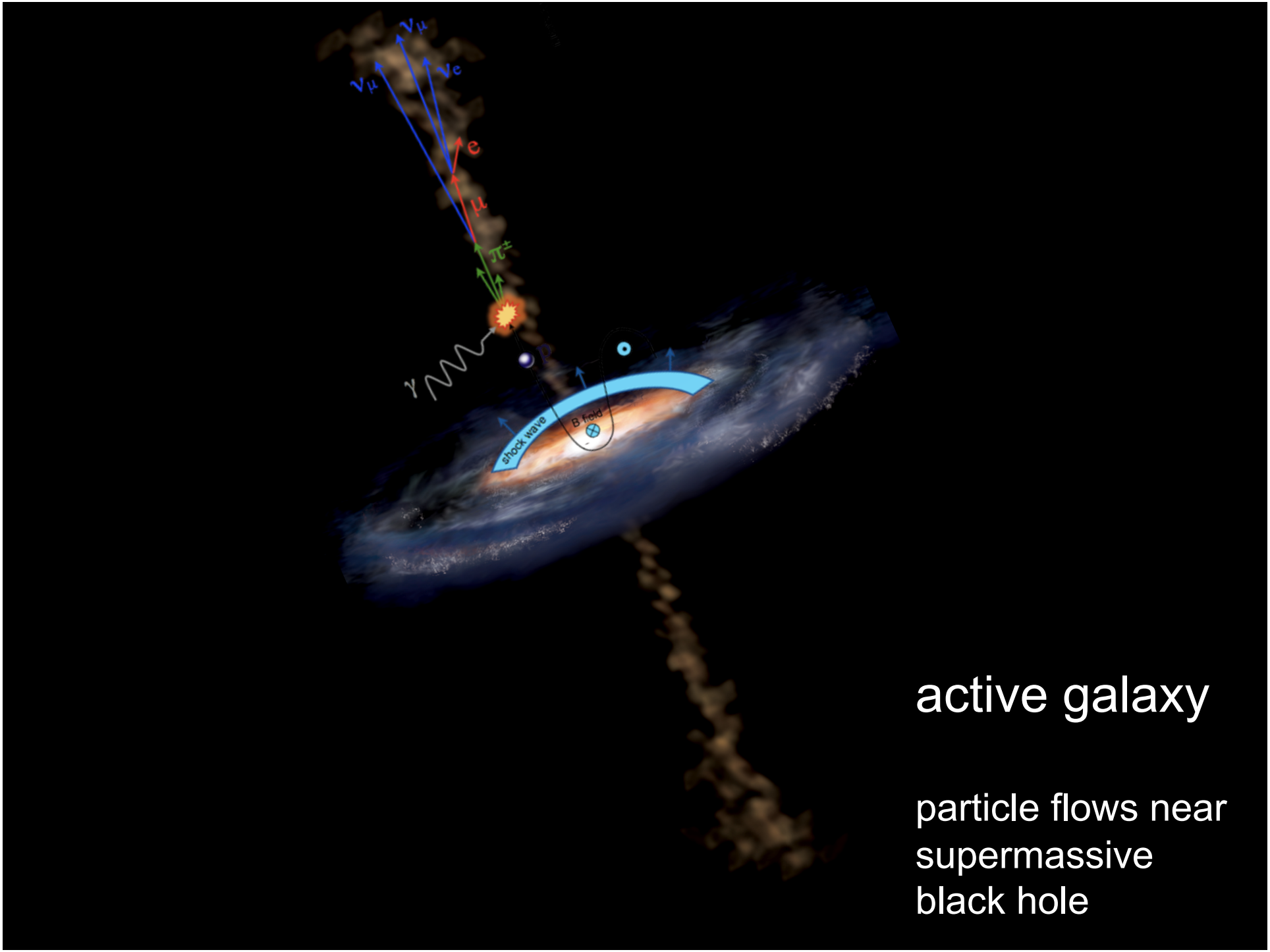
energy in the Universe in gamma rays, neutrinos and cosmic rays

- energy density of neutrinos in the non-thermal Universe is the same as that in gamma-rays

- at some level common Fermi-IceCube sources?
  → multimessenger campaign of telescope follow-up of IceCube real-time neutrino alerts

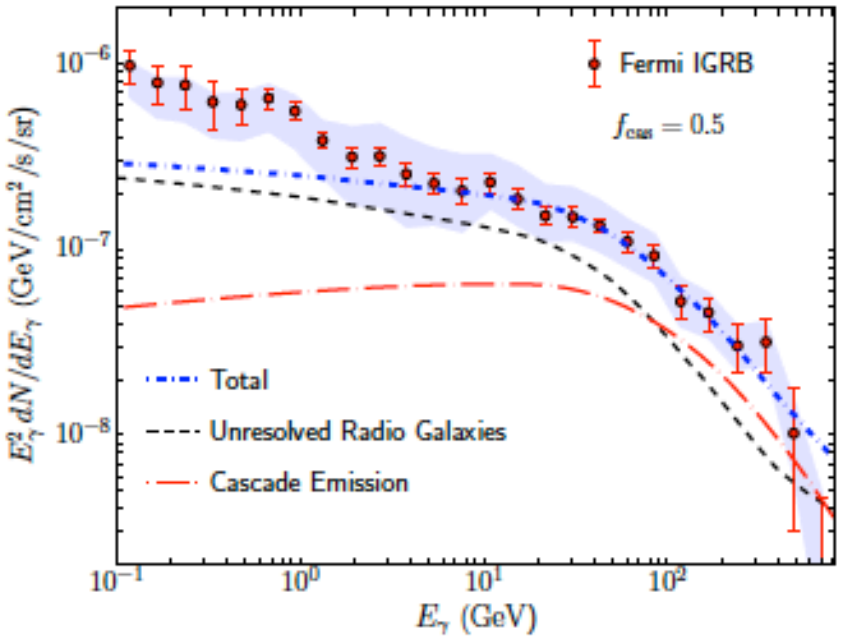
flux < 1% of astrophysical neutrino flux observed
Nature 484 (2012) 351-353

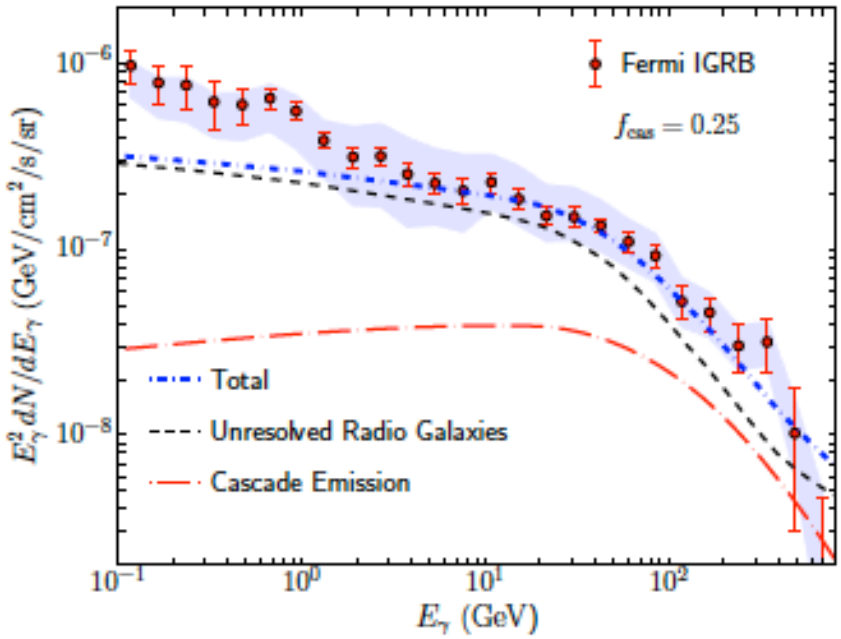


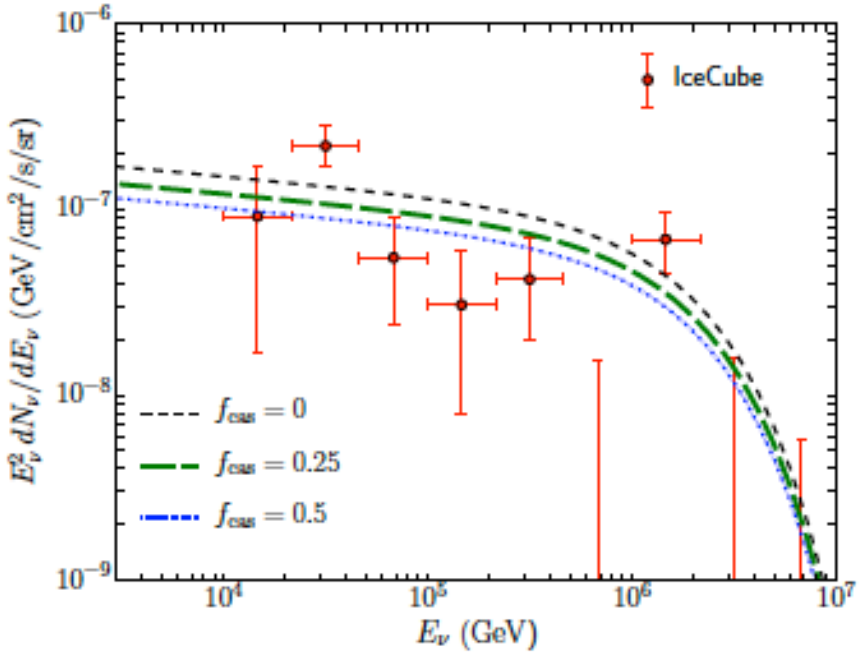


active galaxy

particle flows near supermassive black hole



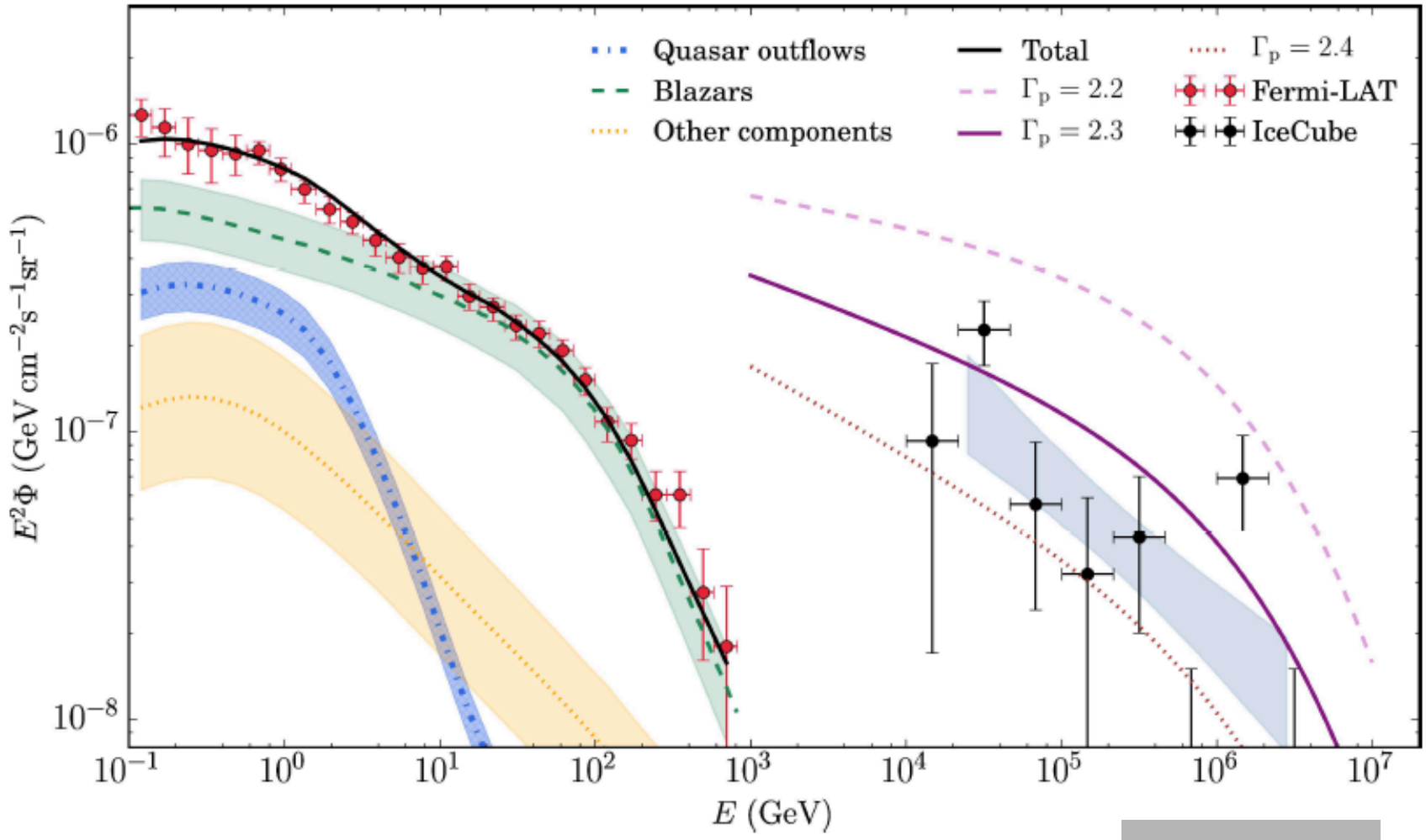




radiogalaxies

Tjus et al.

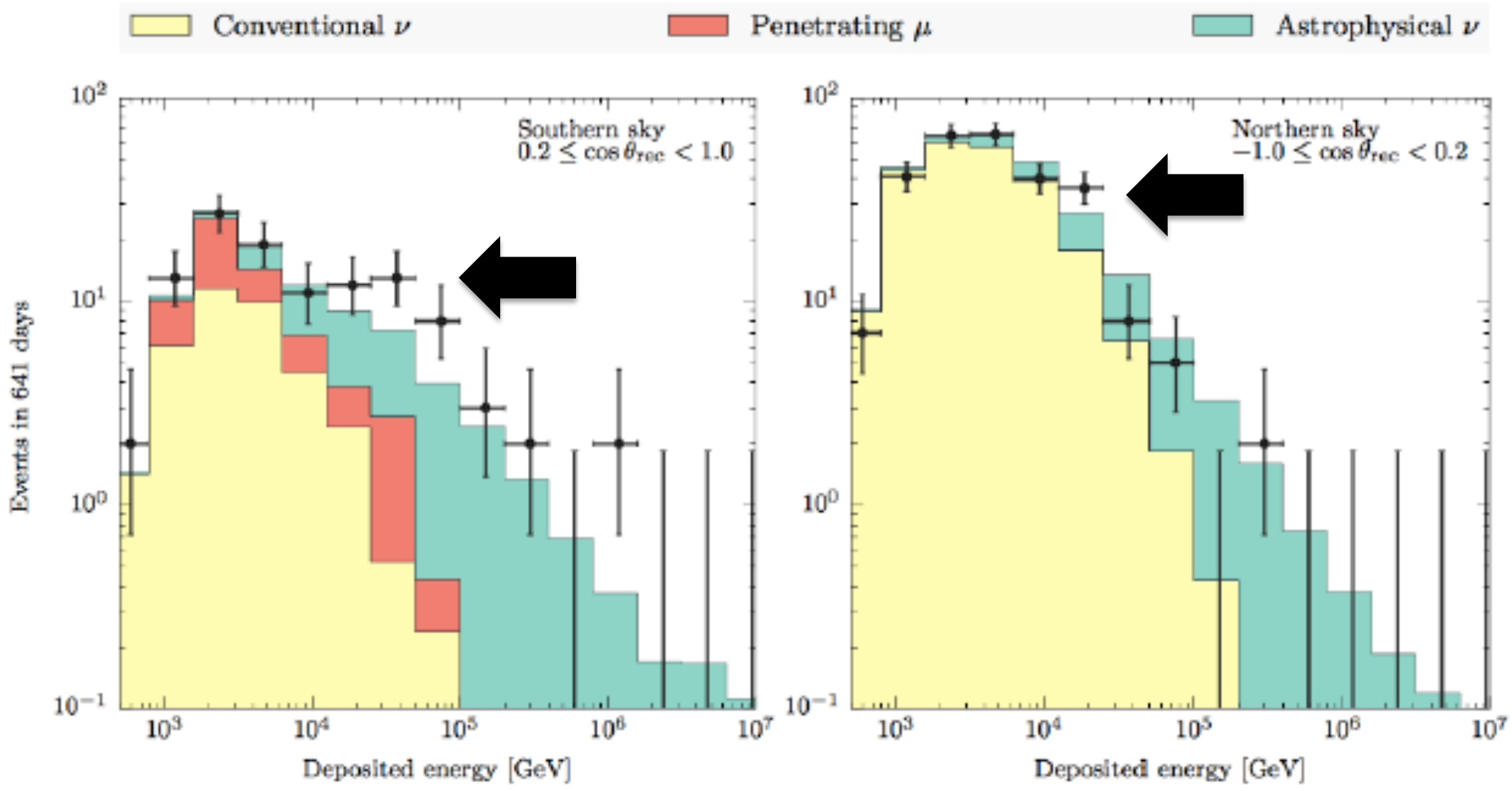
Hooper



quasars
Loeb

- there is more

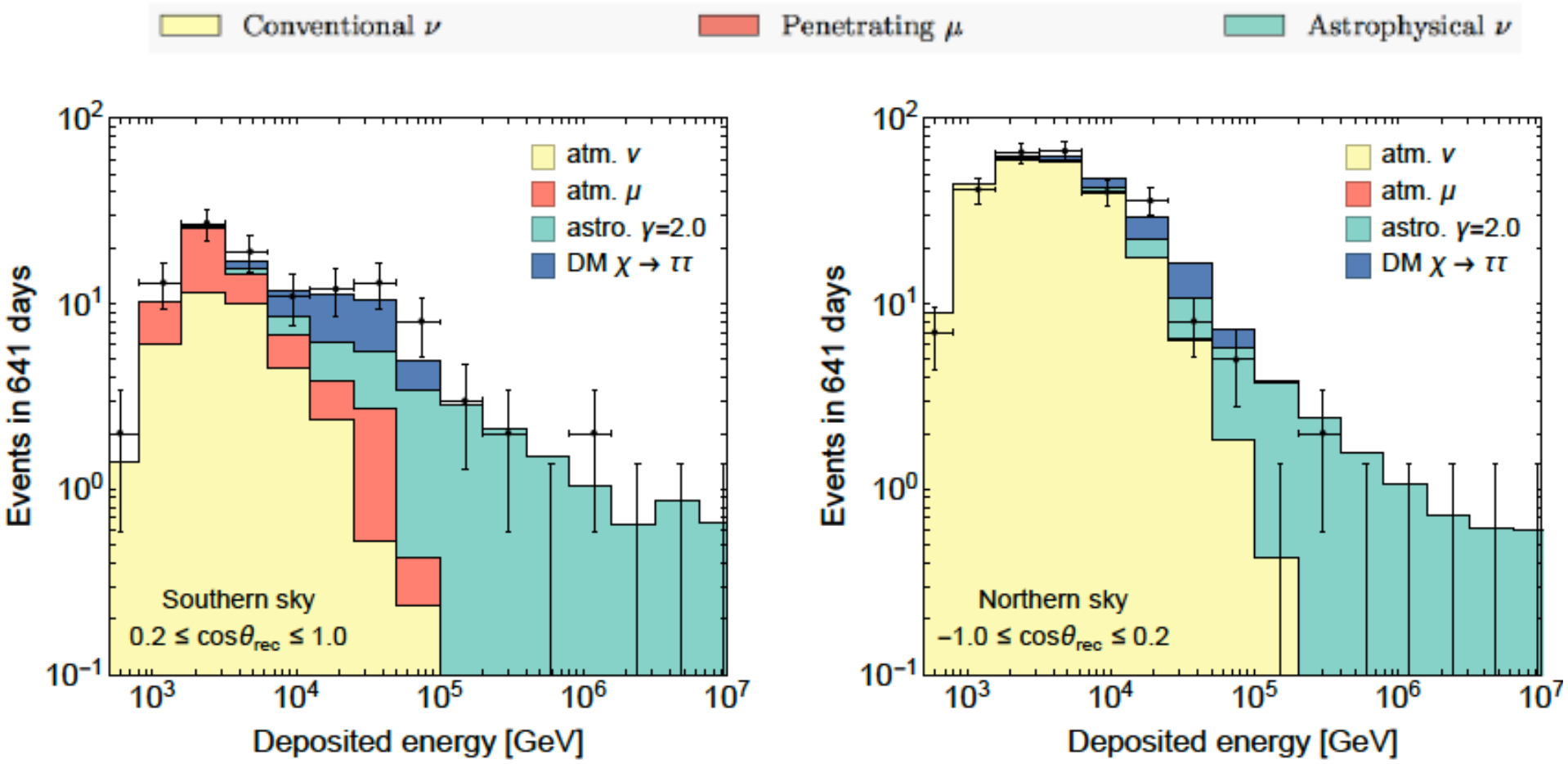
towards lower energies: a second component?



warning:
- spectrum may not be a power law
- slope depends on energy range fitted

PeV neutrinos absorbed in the Earth

towards lower energies: a second component?



warning:
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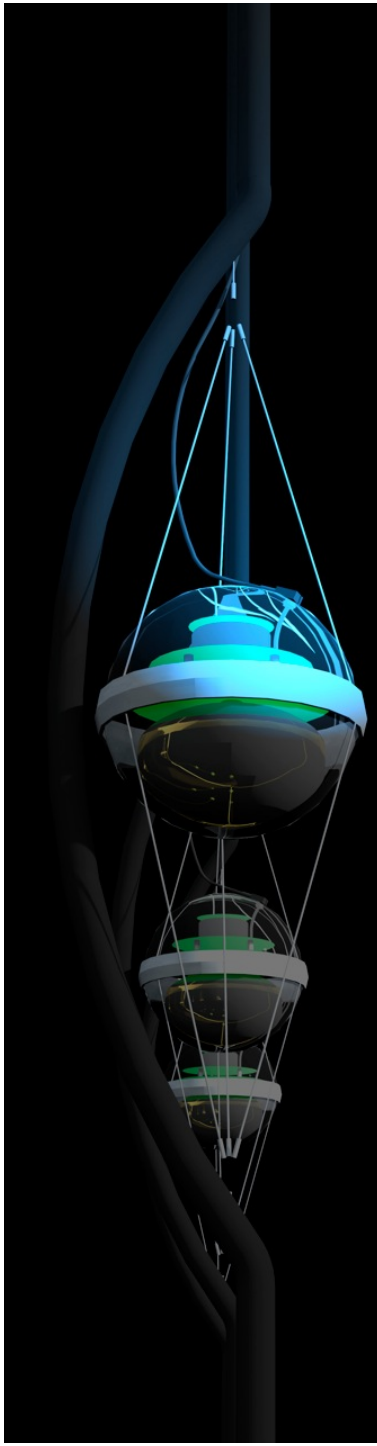
PeV neutrinos absorbed in the Earth



IceCube: the discovery of cosmic neutrinos

francis halzen

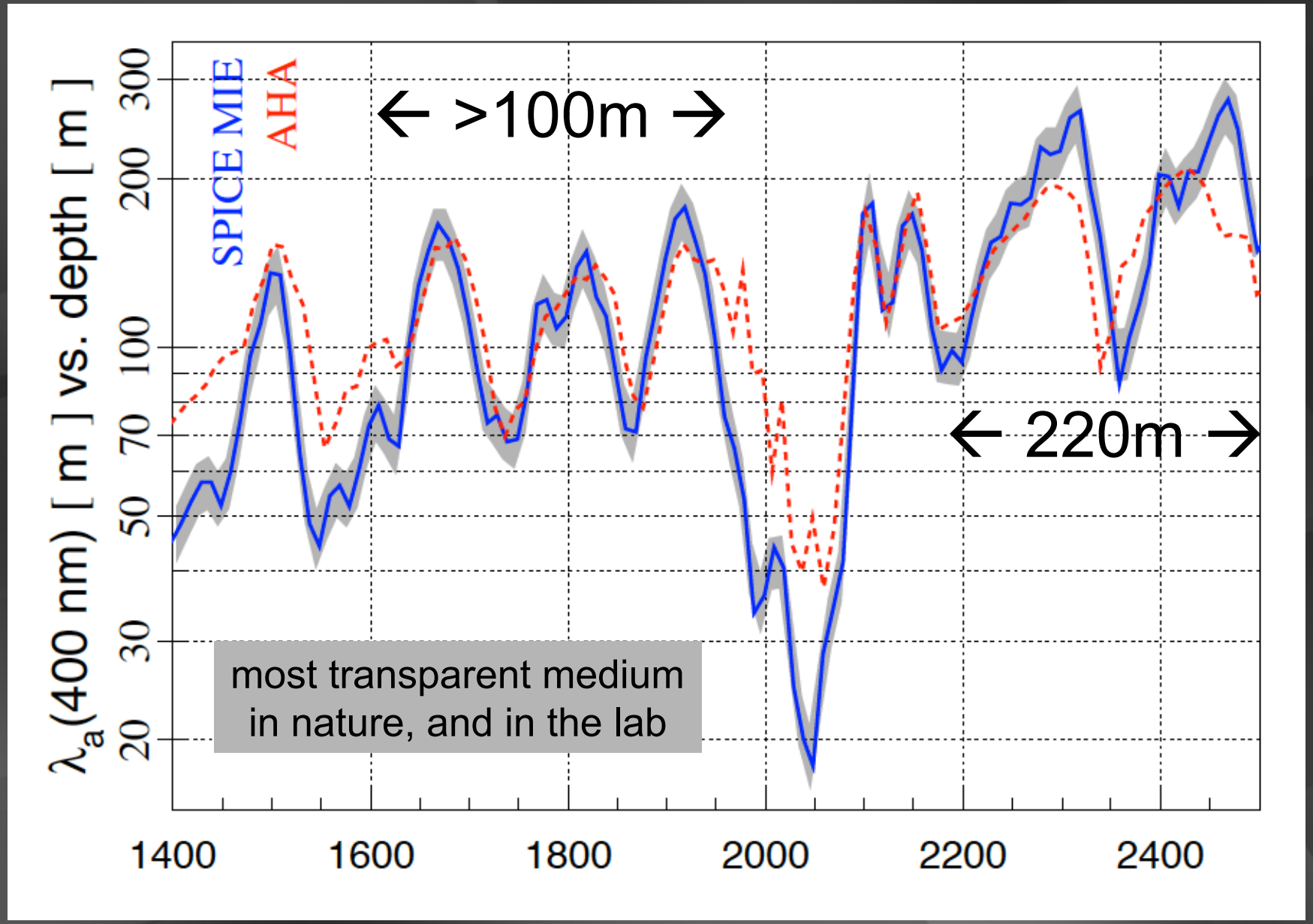
- IceCube
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

- a next-generation IceCube with a volume of 10 km^3 and an angular resolution of < 0.3 degrees will see multiple neutrinos and identify the sources, even from a “diffuse” extragalactic flux in several years

- need 1,000 events versus 100 now in a few years

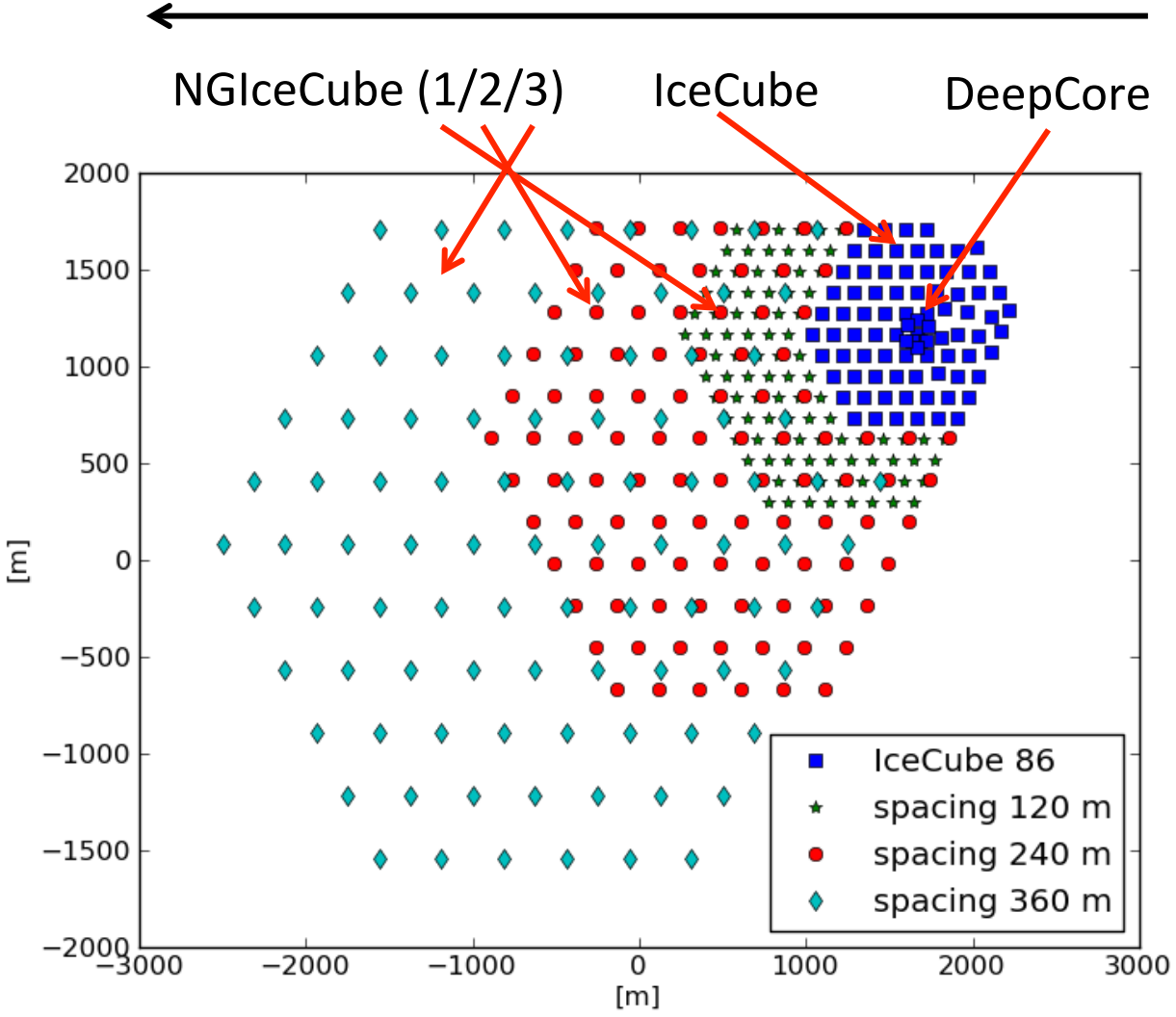
- discovery instrument → astronomical telescope

absorption length of Cherenkov light



measured optical properties → twice the string spacing

(increase in threshold not important: only eliminates energies where the 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

Conclusions

- discovered cosmic neutrinos with an energy density similar to the one of gamma rays.
- neutrinos (cosmic rays) are essential in understanding the non-thermal universe.
- from discovery to astronomy: more events, more telescopes
- neutrinos are never boring!

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)