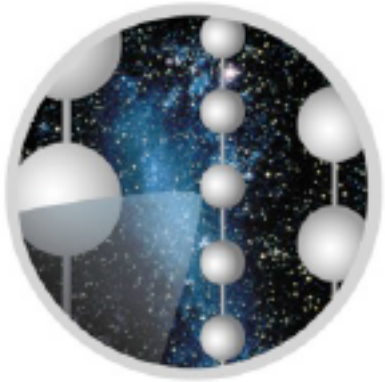
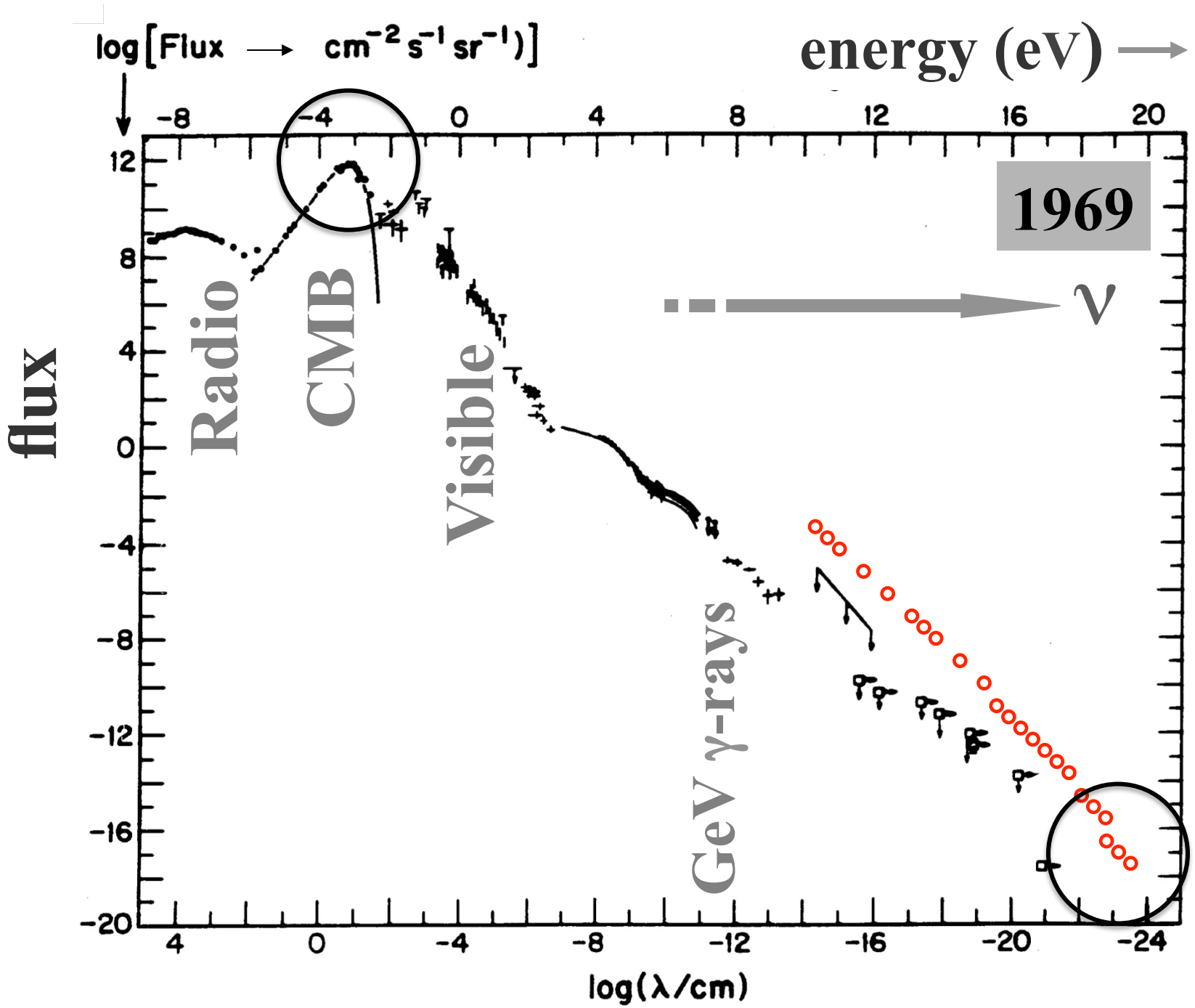


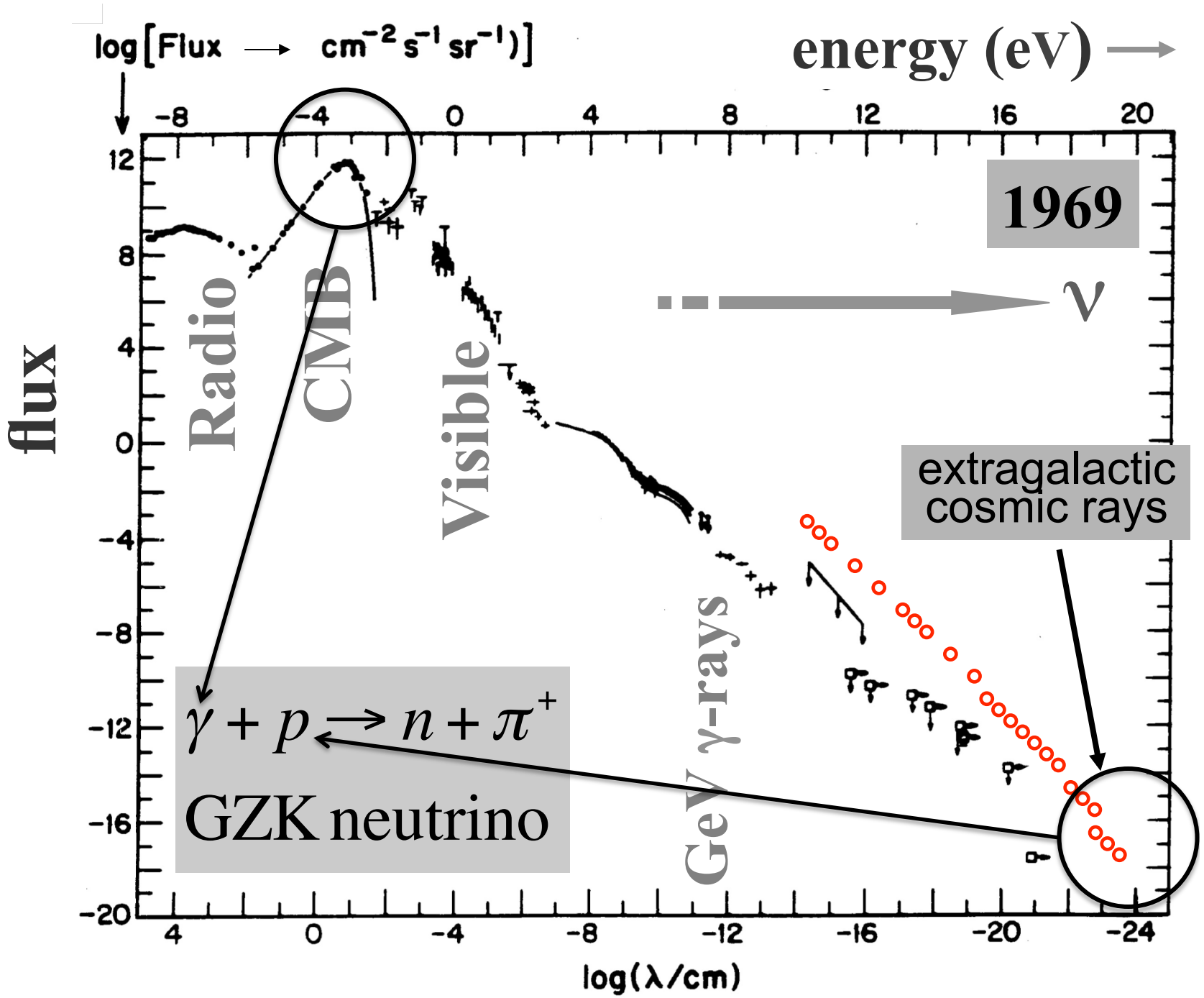
Neutrinos from Heaven and Hell

francis halzen

- why would you want to build a a kilometer scale neutrino detector?
- IceCube: a cubic kilometer detector
- the discovery (and confirmation) of cosmic neutrinos
- beyond IceCube

IceCube.wisc.edu


log [Flux → cm⁻² s⁻¹ sr⁻¹)]
energy (eV) →
flux
1969
ν
Radio
CMB
Visible
GeV γ-rays
log(λ/cm)
-8
-4
0
4
8
12
16
20
12
8
4
0
-4
-8
-12
-16
-20
4
0
-4
-8
-12
-16
-20
-24


log [Flux → cm⁻² s⁻¹ sr⁻¹)]
energy (eV) →
flux
log(λ/cm)
1969
ν
Radio
CMB
Visible
GeV γ-rays
extragalactic cosmic rays
$\gamma + p \rightleftharpoons n + \pi^+$
GZK neutrino

cosmic rays interact with the microwave background

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

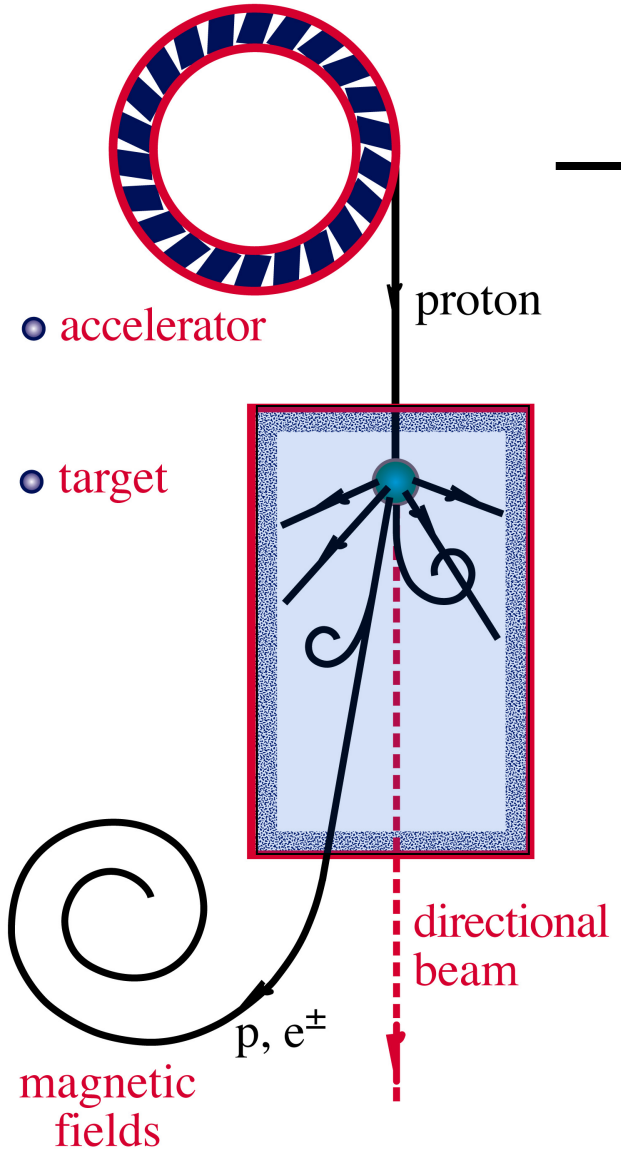
cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear

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

1 event per cubic kilometer per year

...but it points at its source!

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

$\rightarrow p + \pi^0$

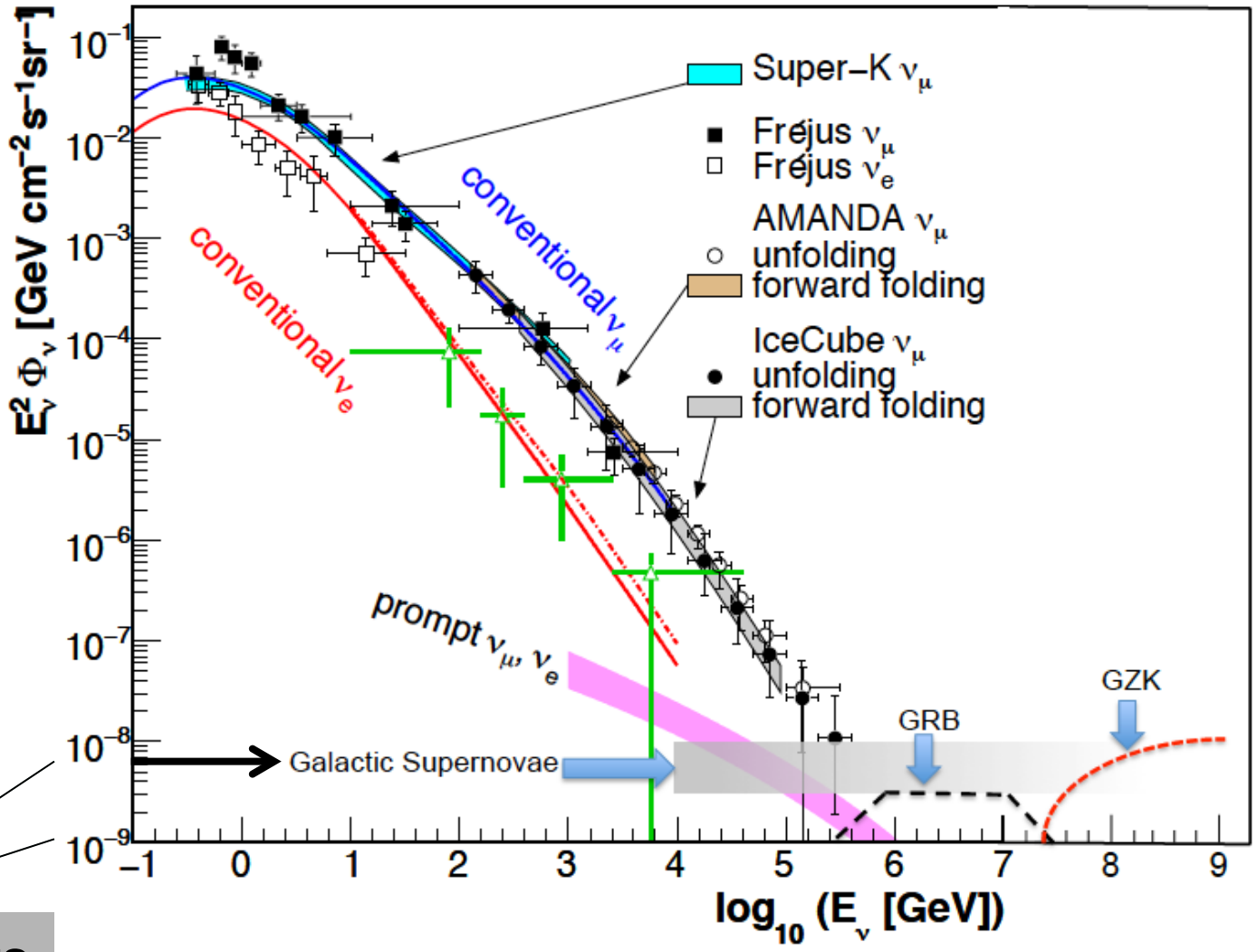
~ cosmic ray + gamma

above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

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

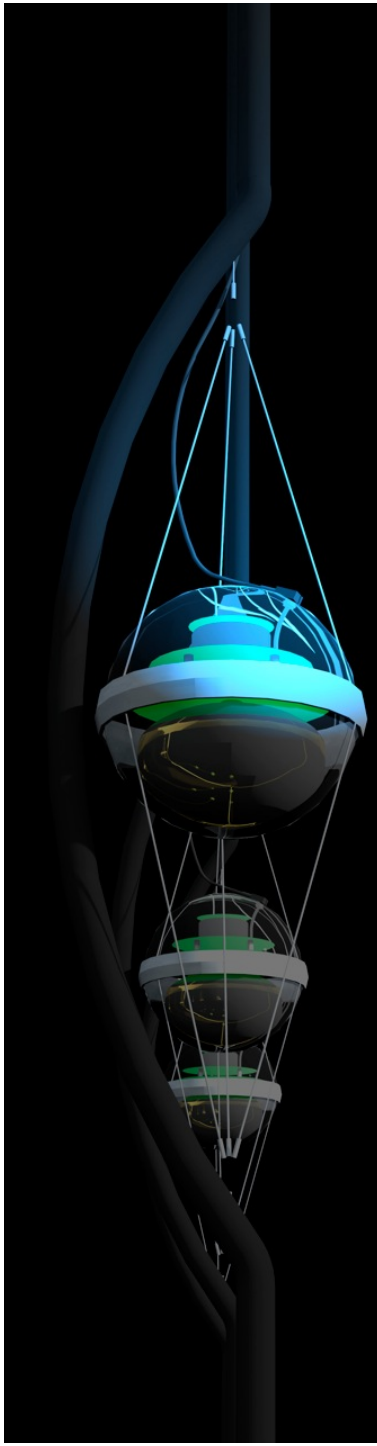
10—100 events per year for fully efficient 1 km^3 detector



atmospheric

cosmic

100 TeV

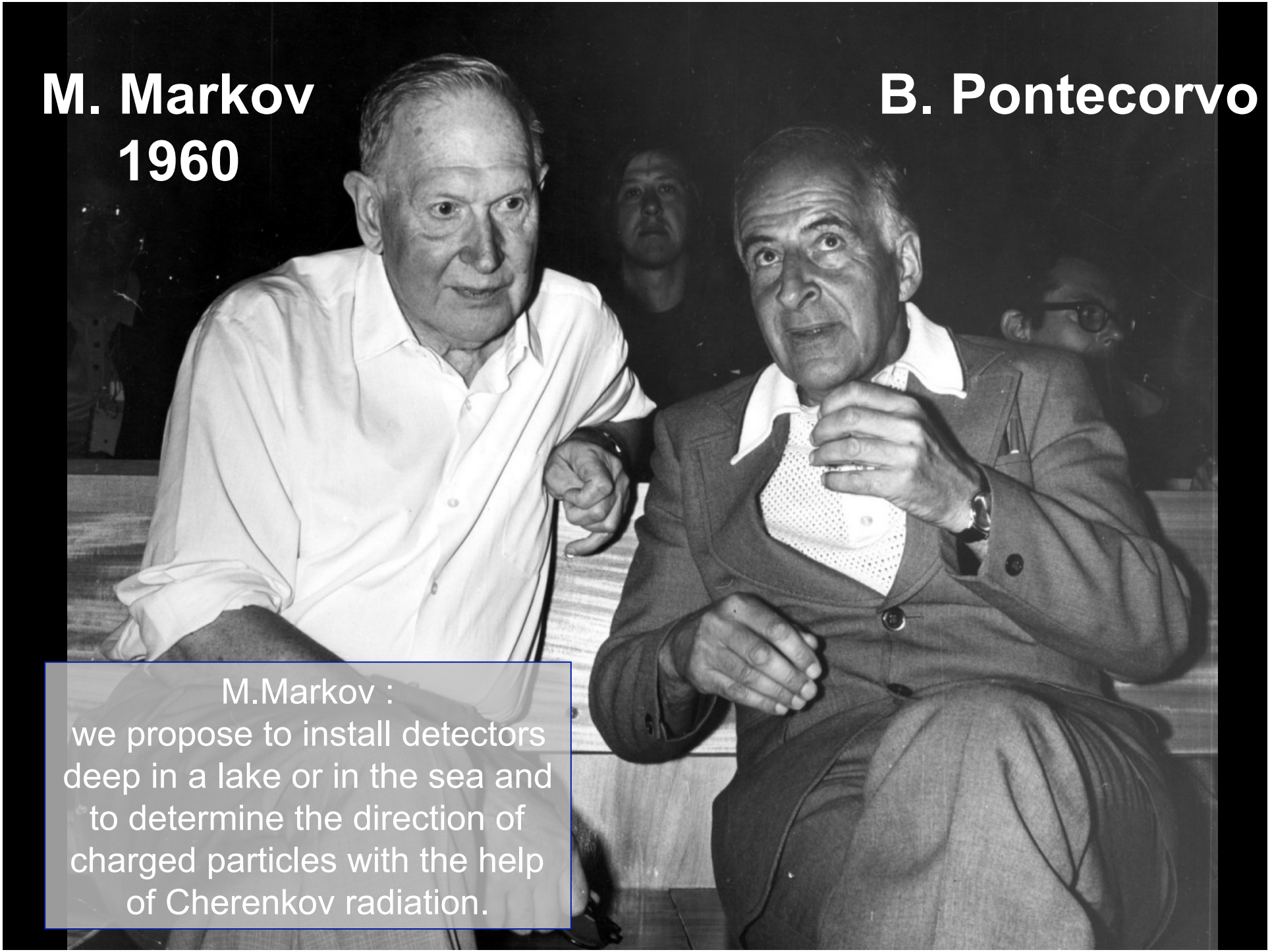


IceCube: the discovery of cosmic neutrinos

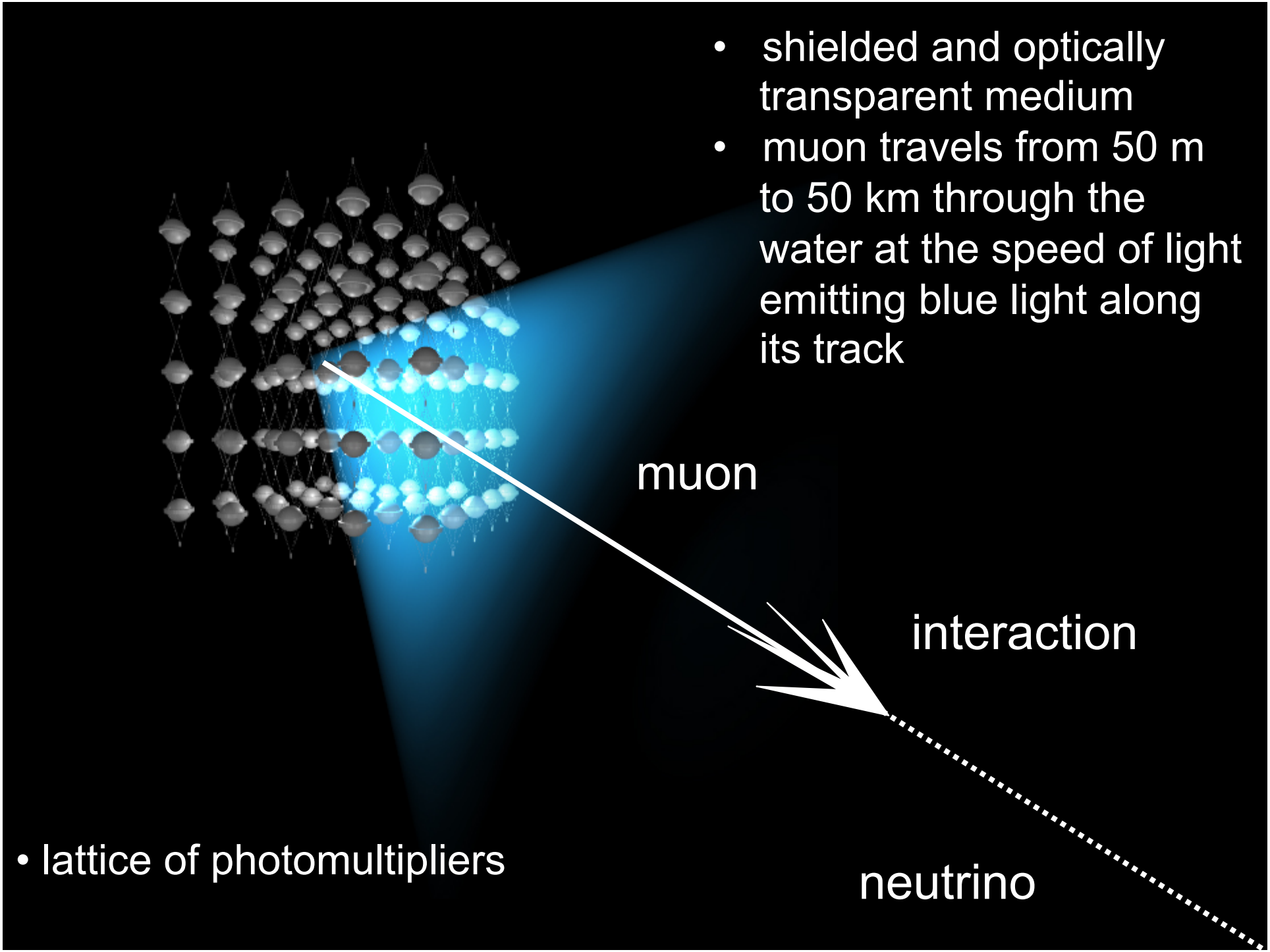
francis halzen

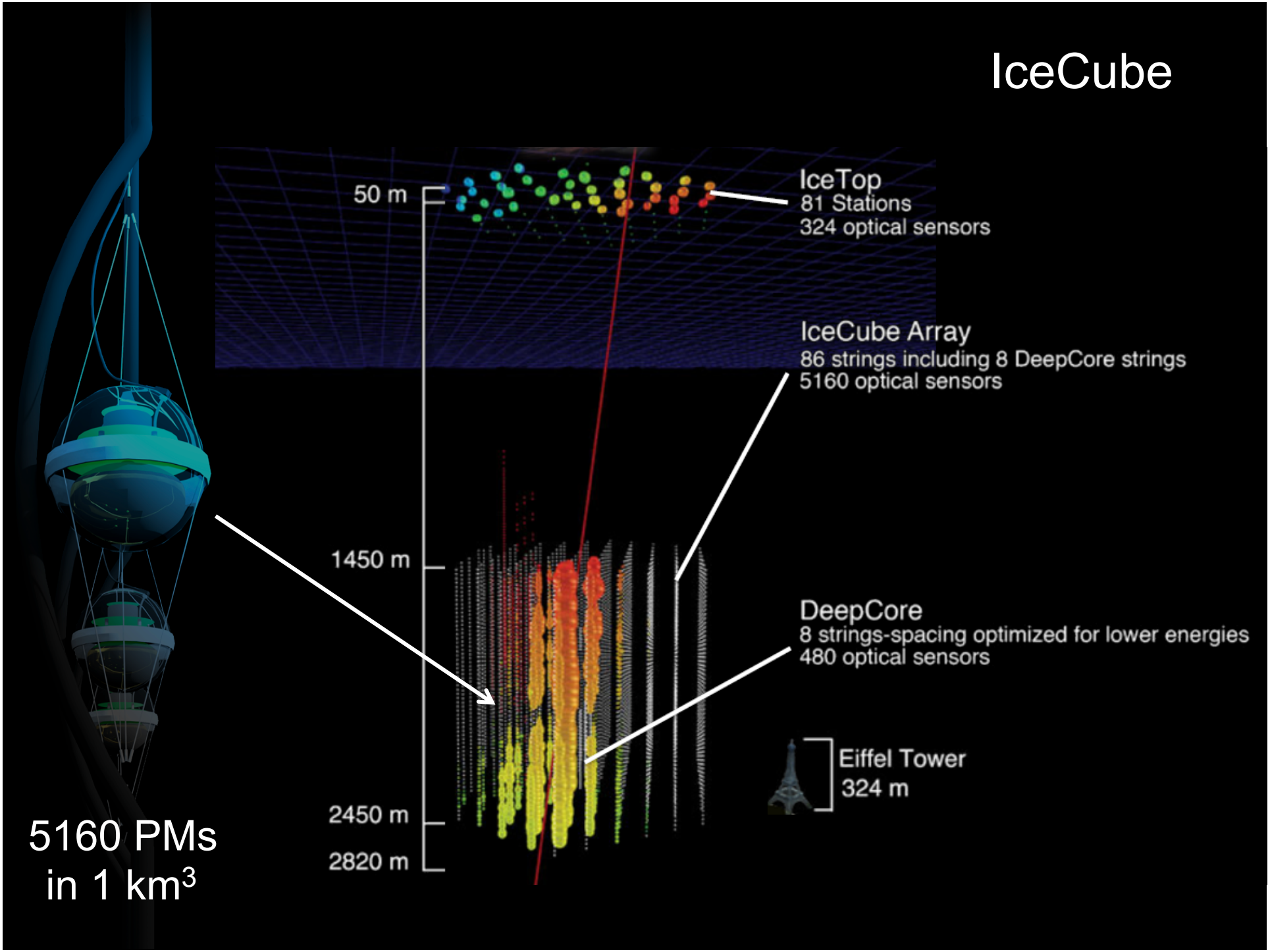
- cosmic ray accelerators
- IceCube: a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

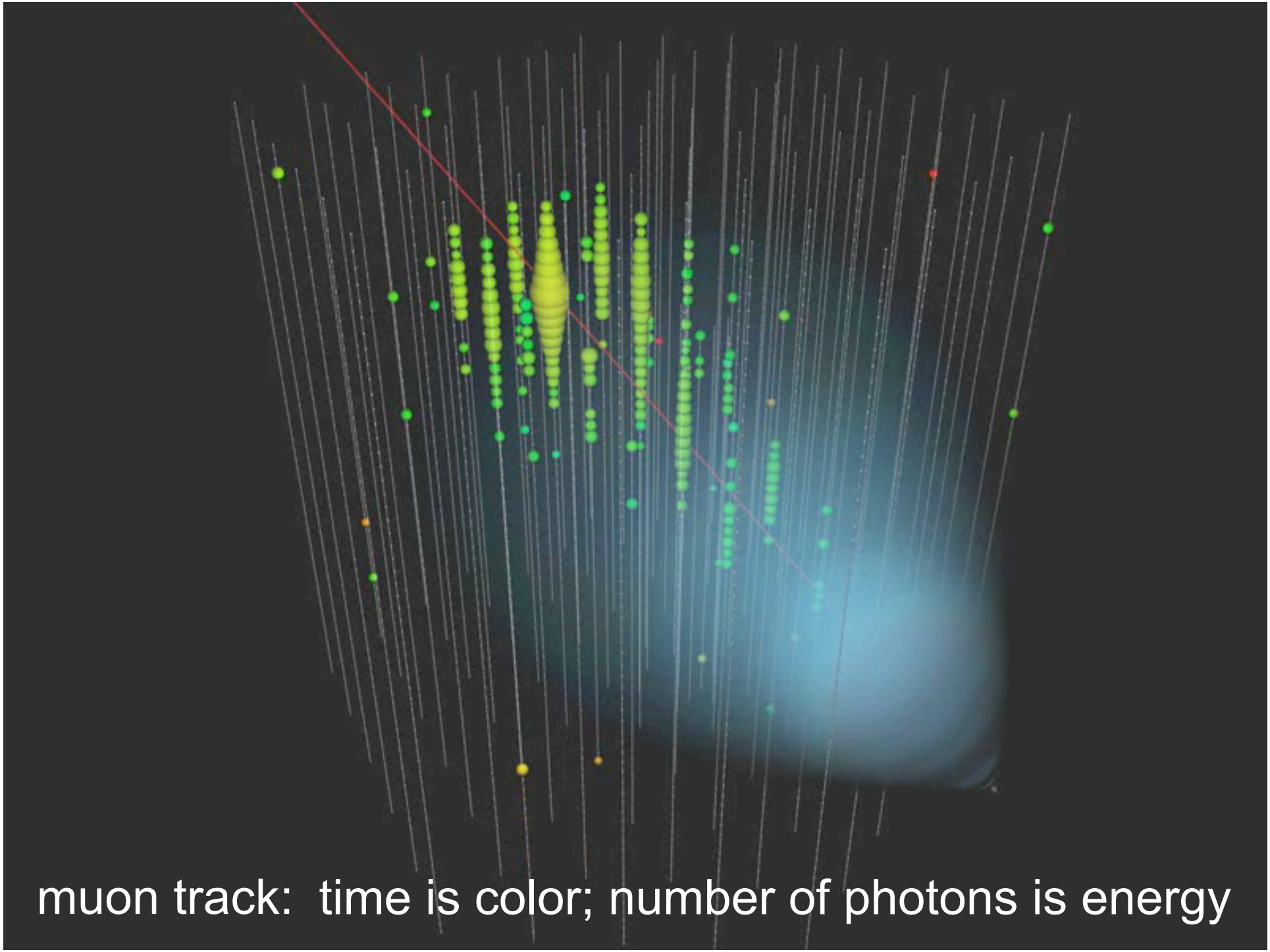
IceCube.wisc.edu



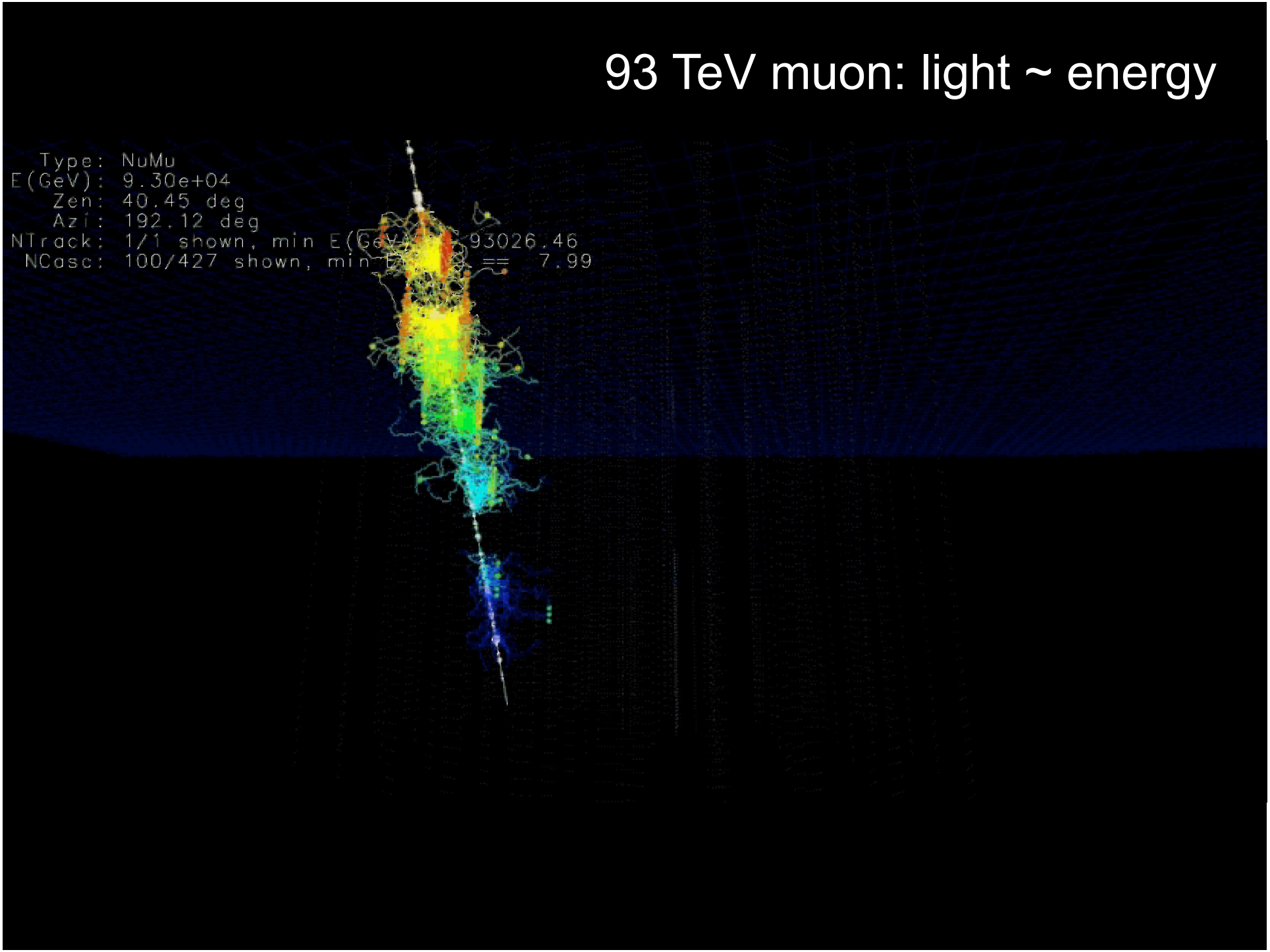
M.Markov :
we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.


• shielded and optically transparent medium
• muon travels from 50 m to 50 km through the water at the speed of light emitting blue light along its track
muon
interaction
• lattice of photomultipliers
neutrino

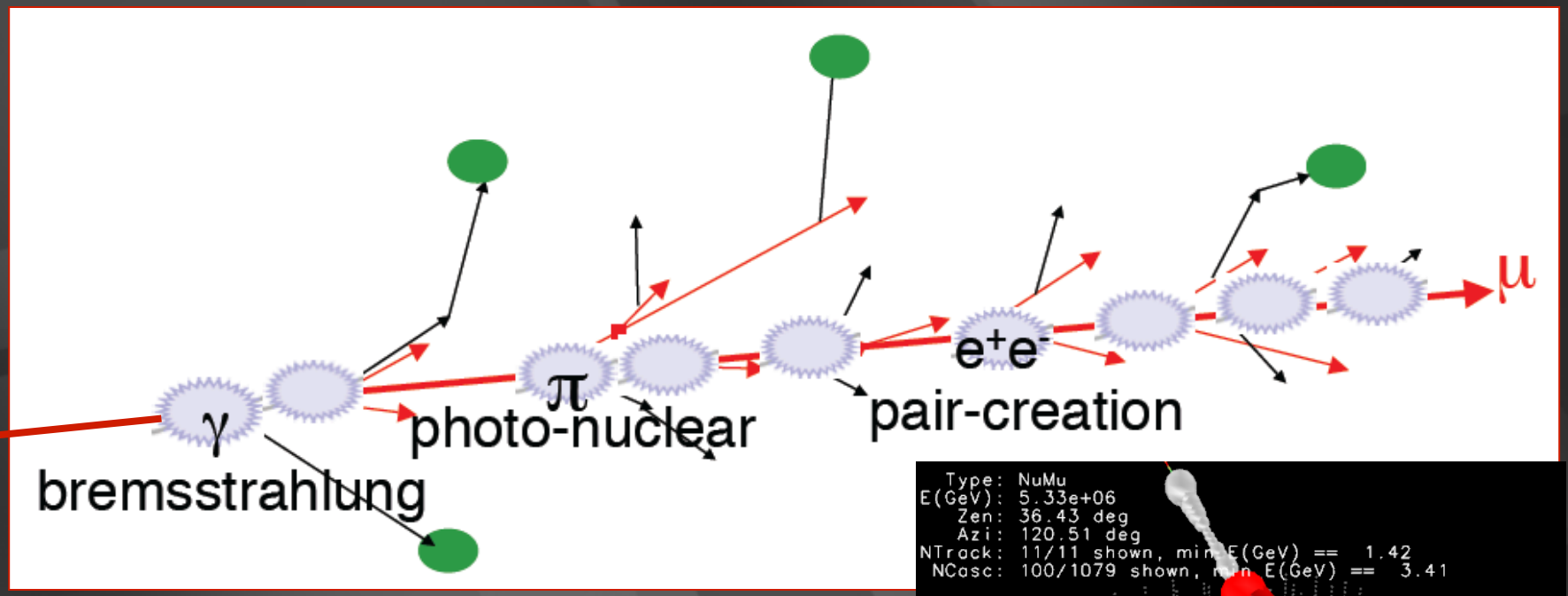

IceCube
50 m
IceTop
81 Stations
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
1450 m
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
2450 m
2820 m
5160 PMs
in 1 km3

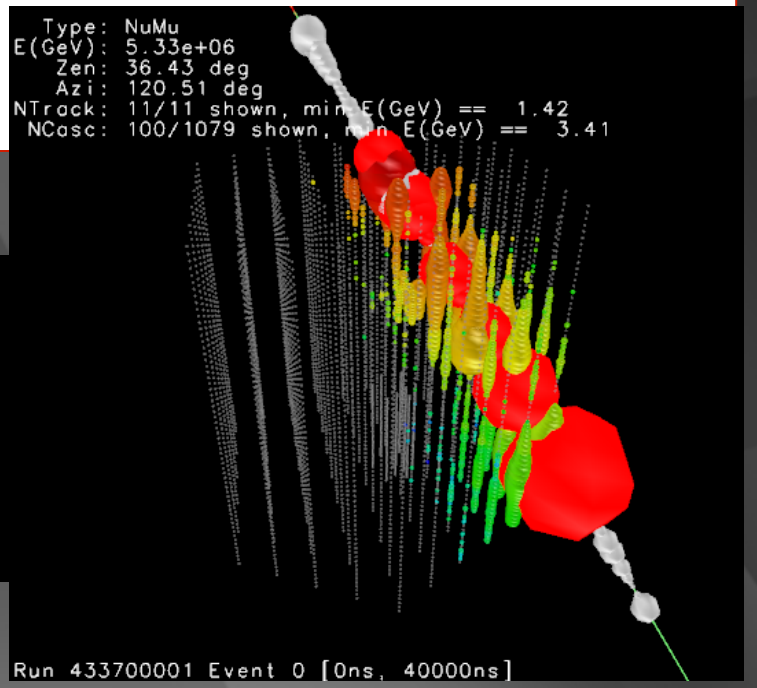

muon track: time is color; number of photons is energy

93 TeV muon: light ~ energy

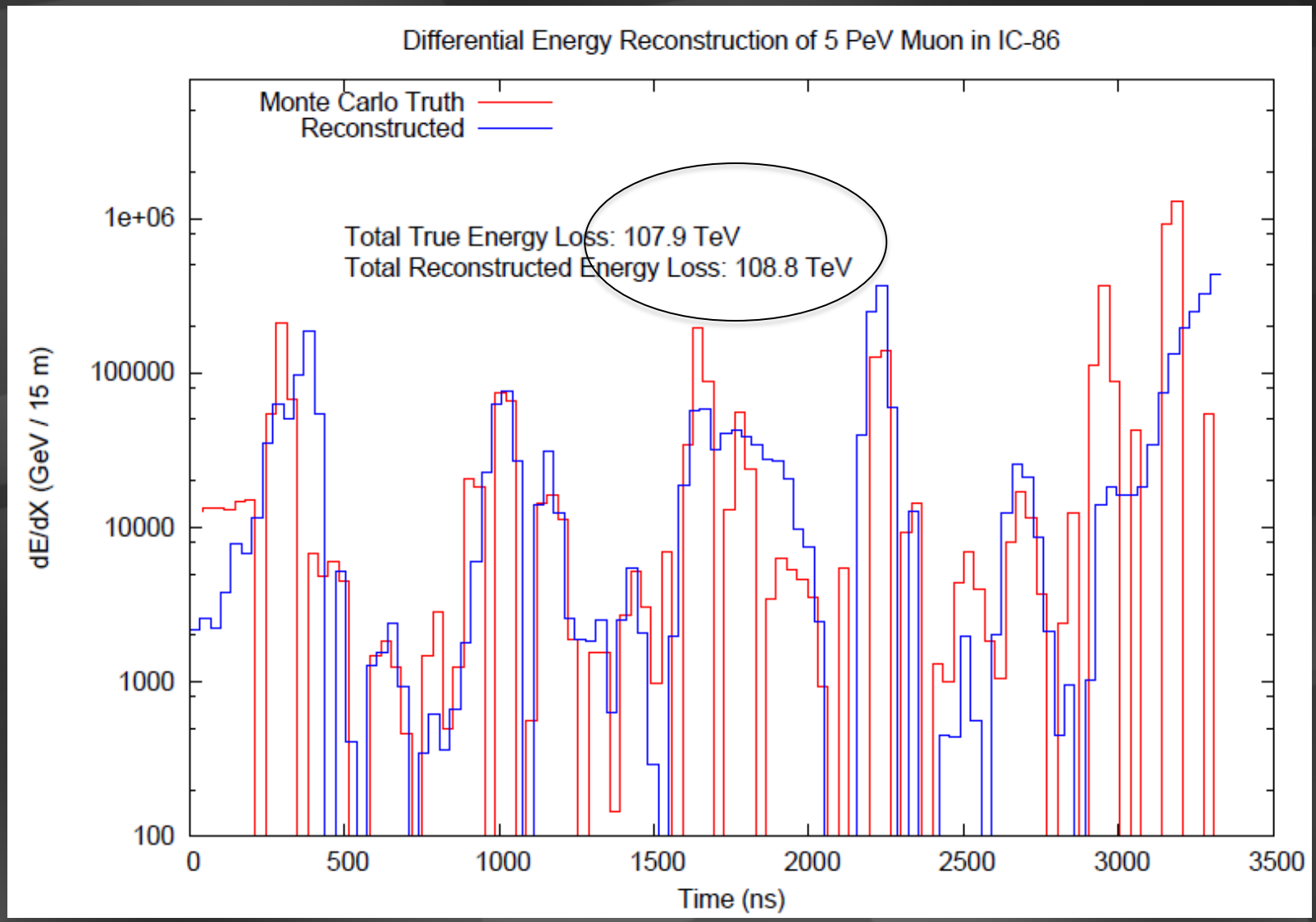


energy measurement (> 1 TeV)





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



1.1 km

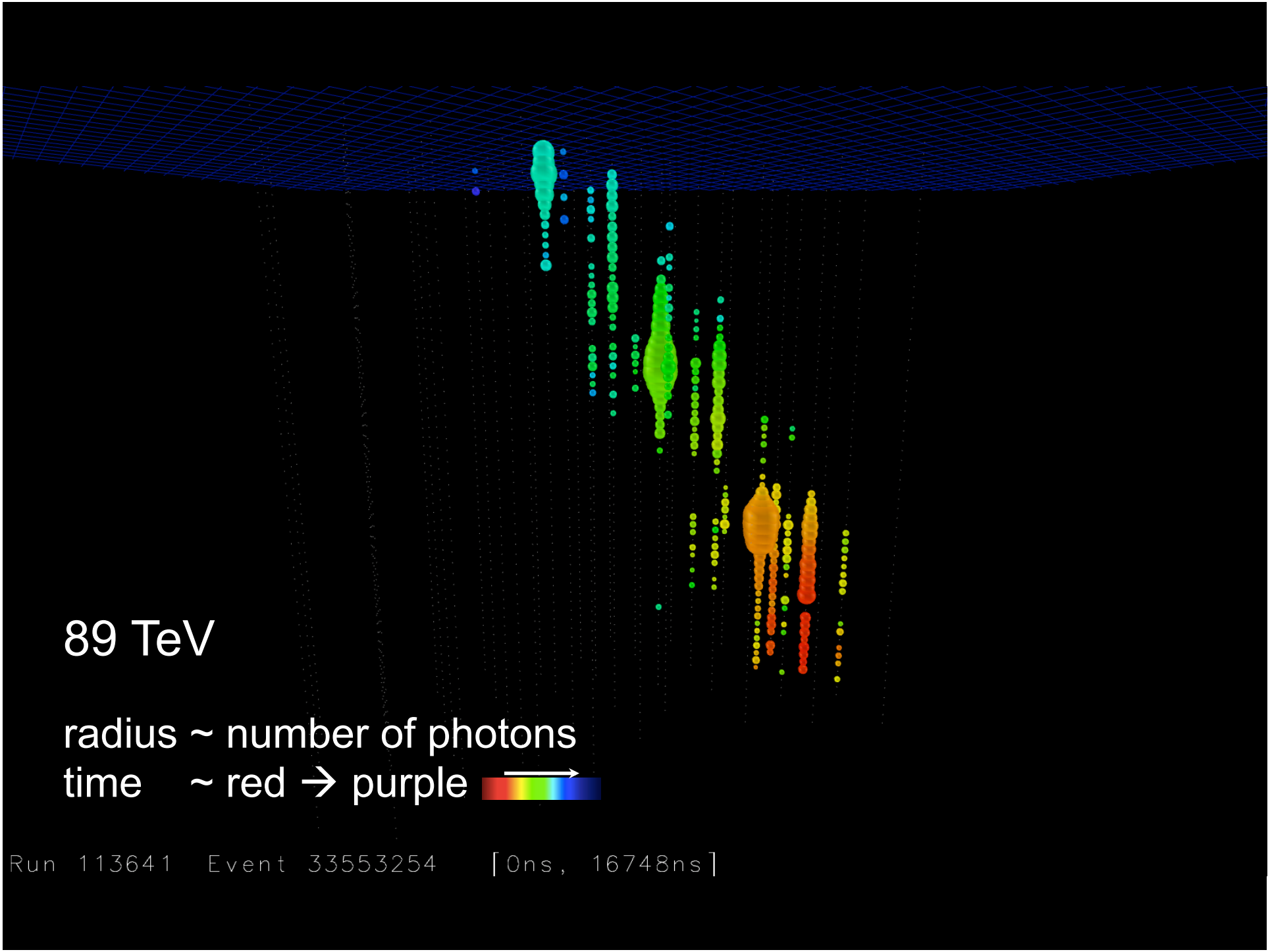
improving angular and energy resolution

… you looked at 10msec of data !

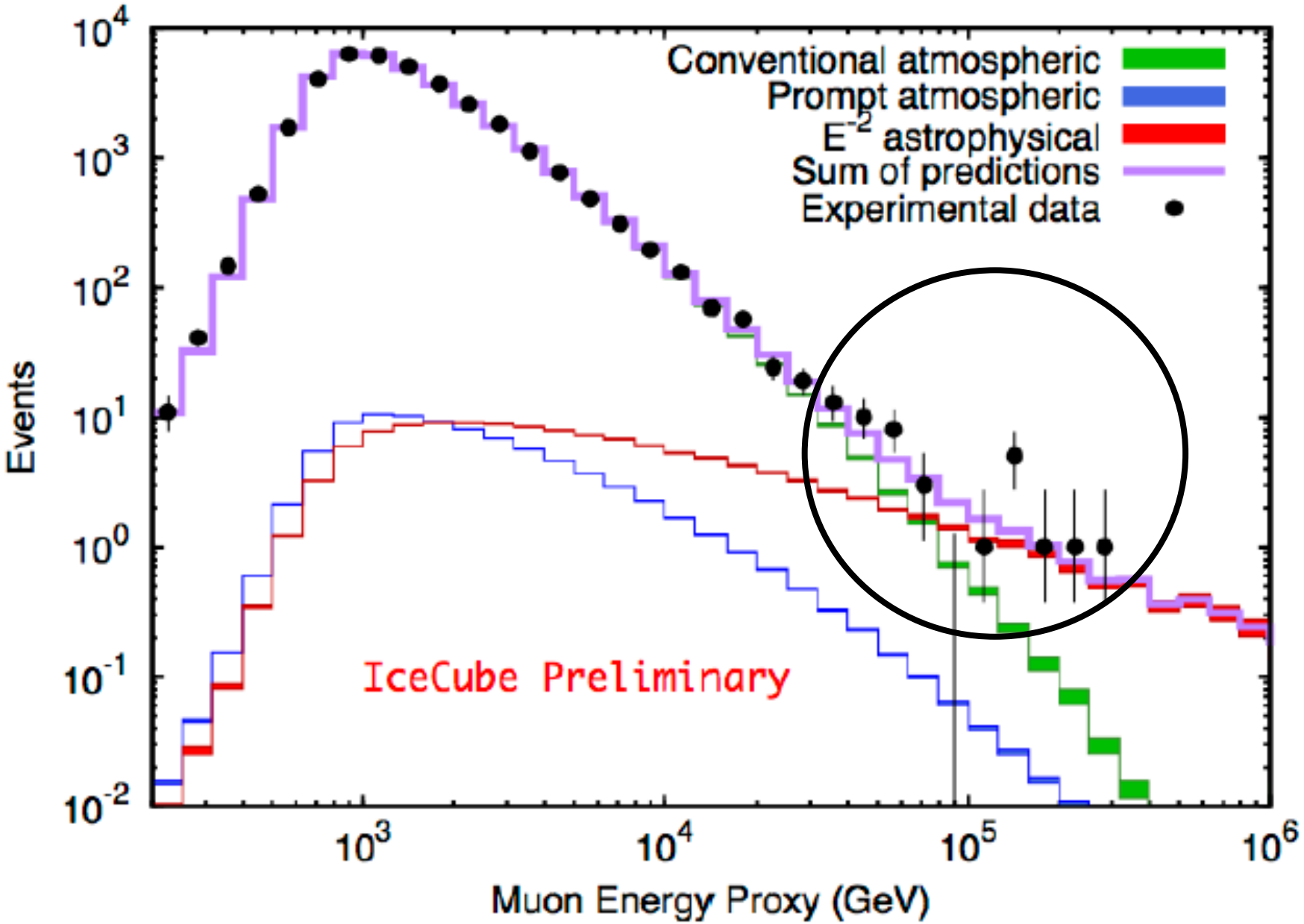
muons detected per year:

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

* 3000 per second ** 1 every 6 minutes


89 TeV
radius ~ number of photons
time ~ red → purple
Run 113641 Event 33553254 [0ns, 16748ns]

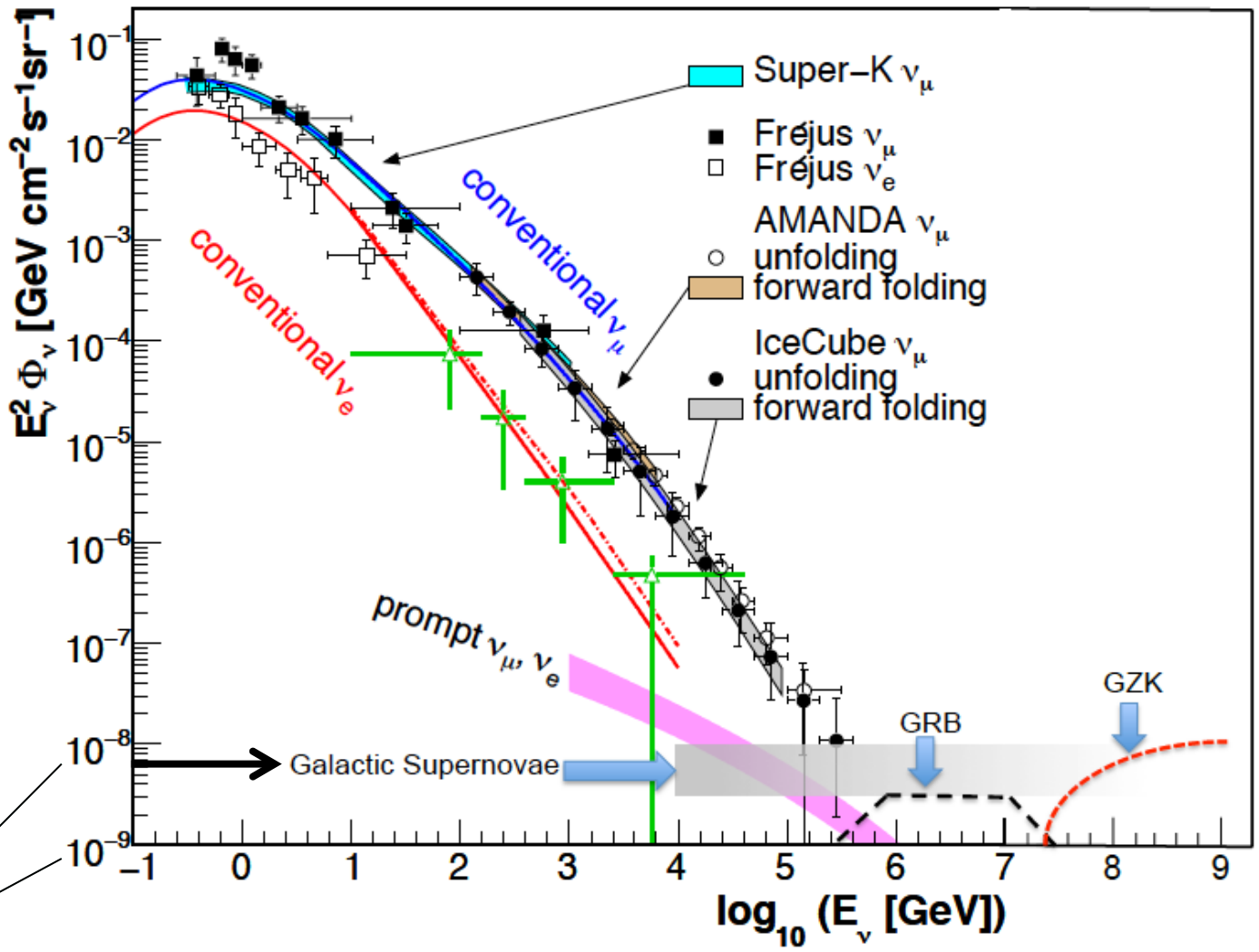
cosmic neutrinos in 2 years of data at 3.7 sigma



above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

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



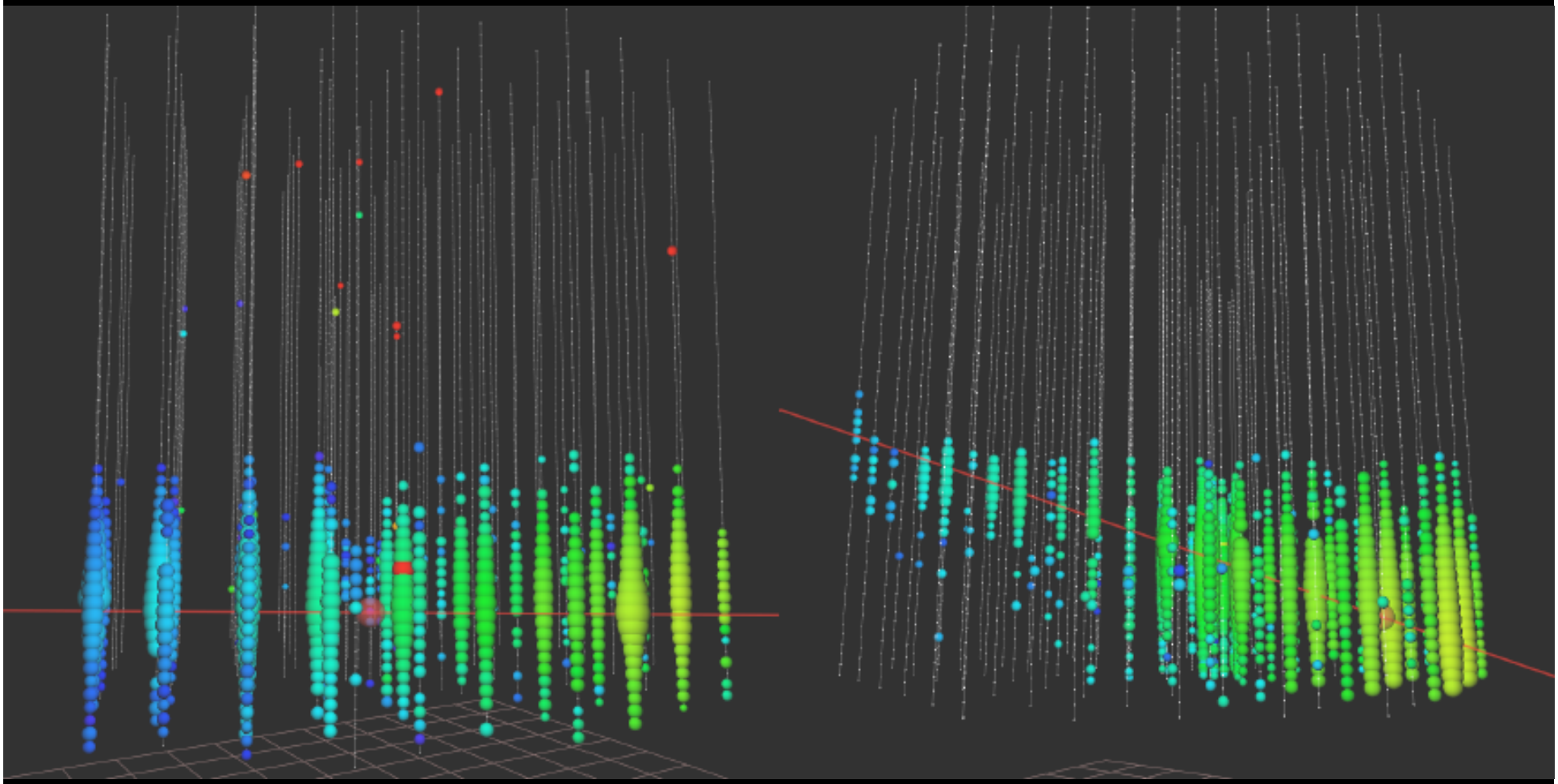
10—100 events per year for fully efficient detector

atmospheric

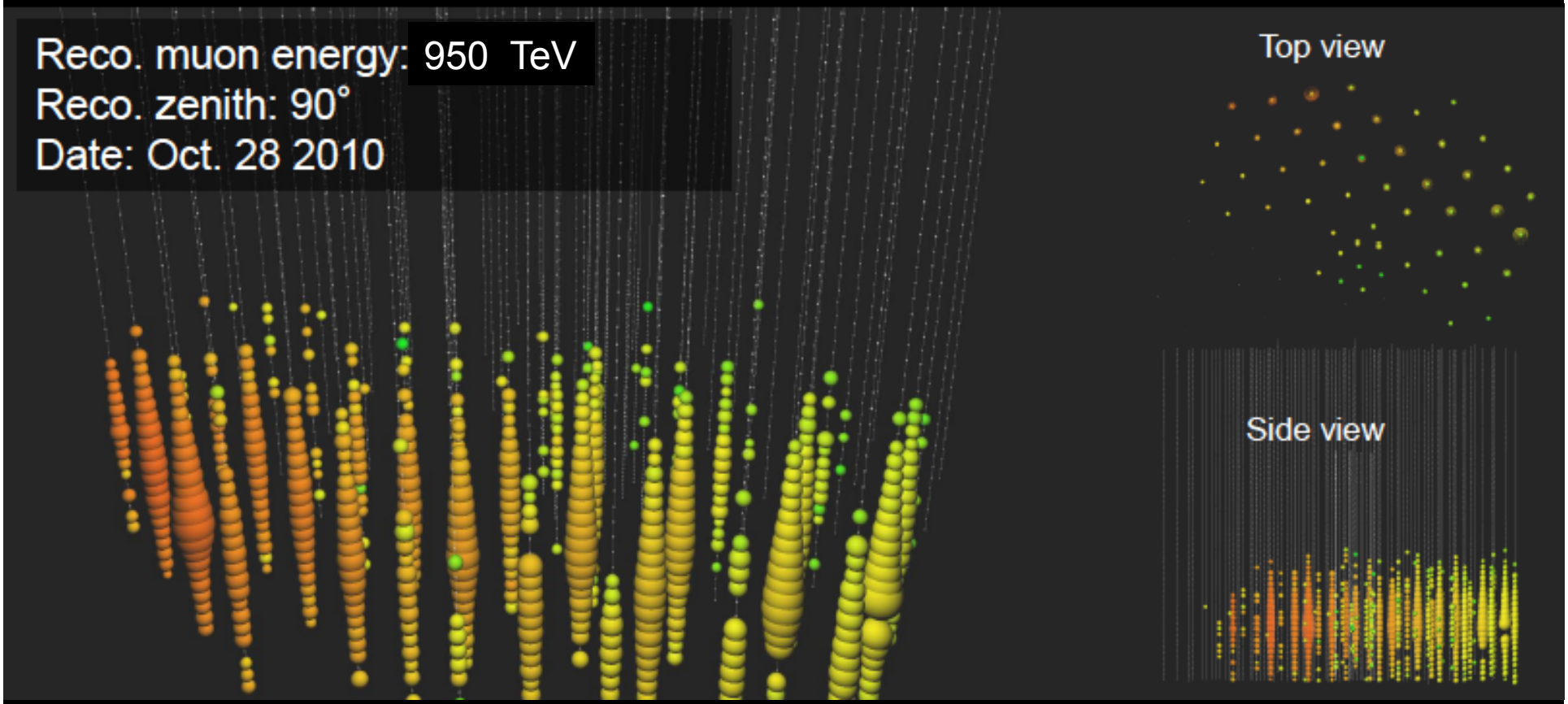
cosmic

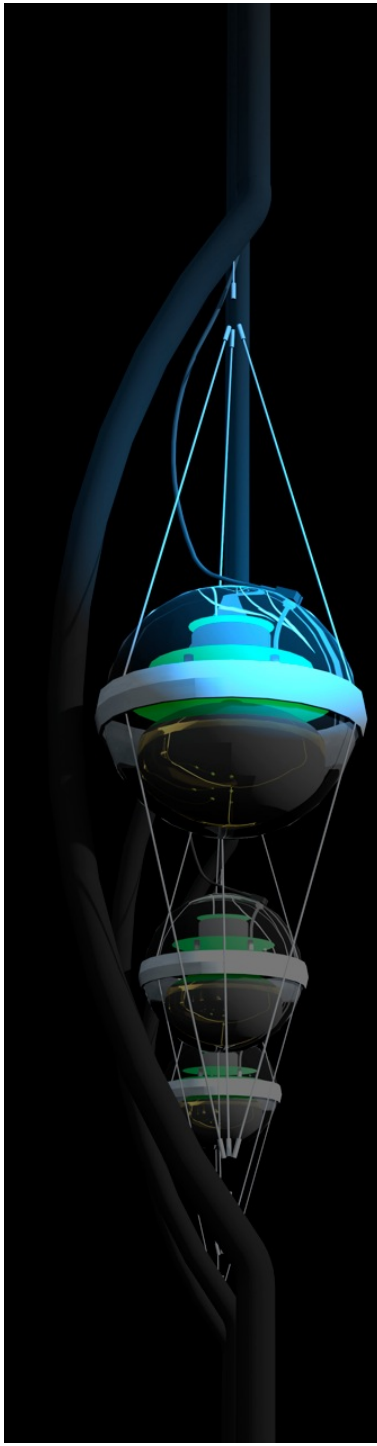
100 TeV

highest energy muon energy observed: 560 TeV
→ PeV ν_μ



3 years: 4.3 σ and more PeV ν_μ (5 years soon)





IceCube: the discovery of cosmic neutrinos

francis halzen

- cosmic ray accelerators
- IceCube a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
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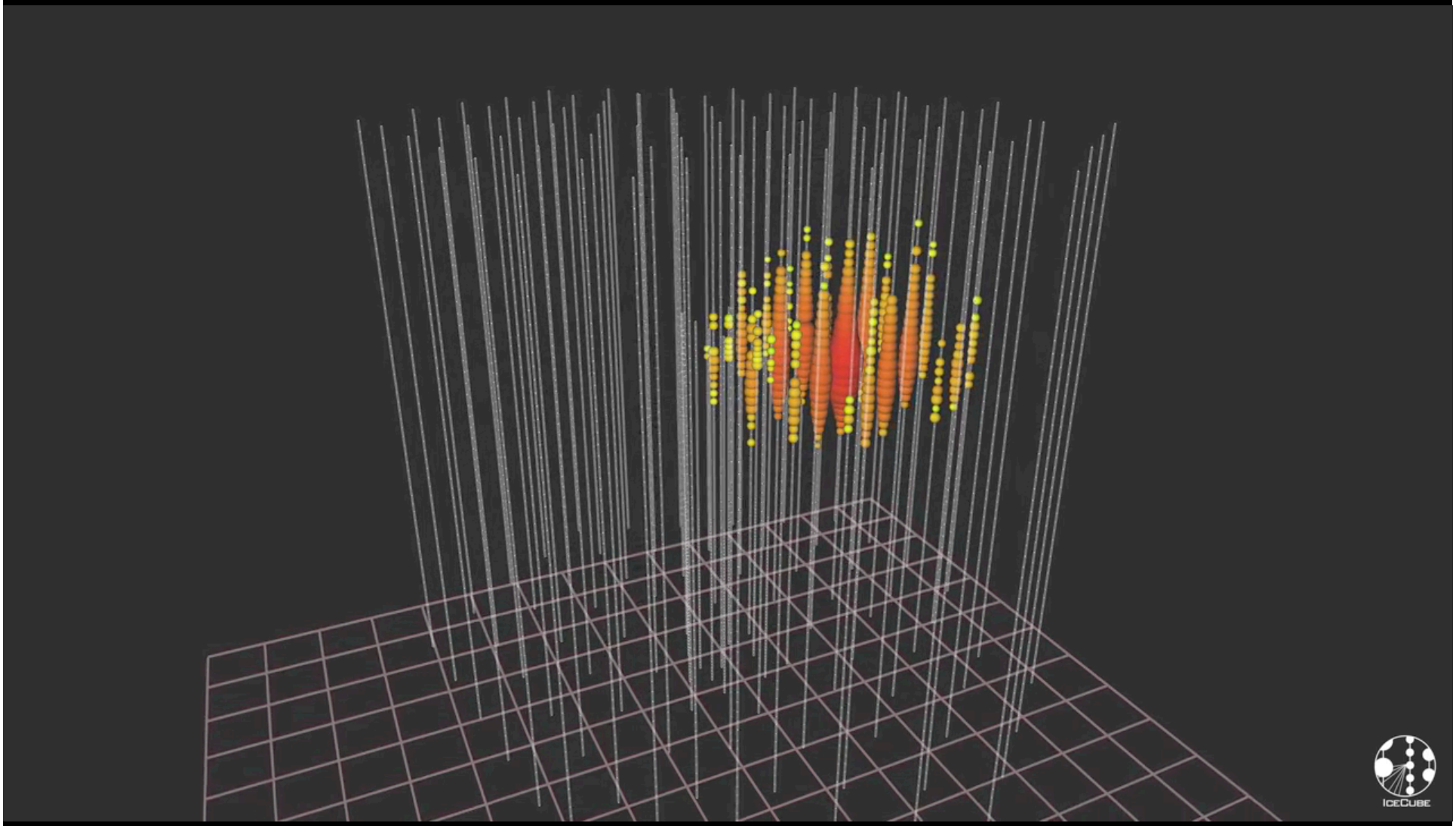
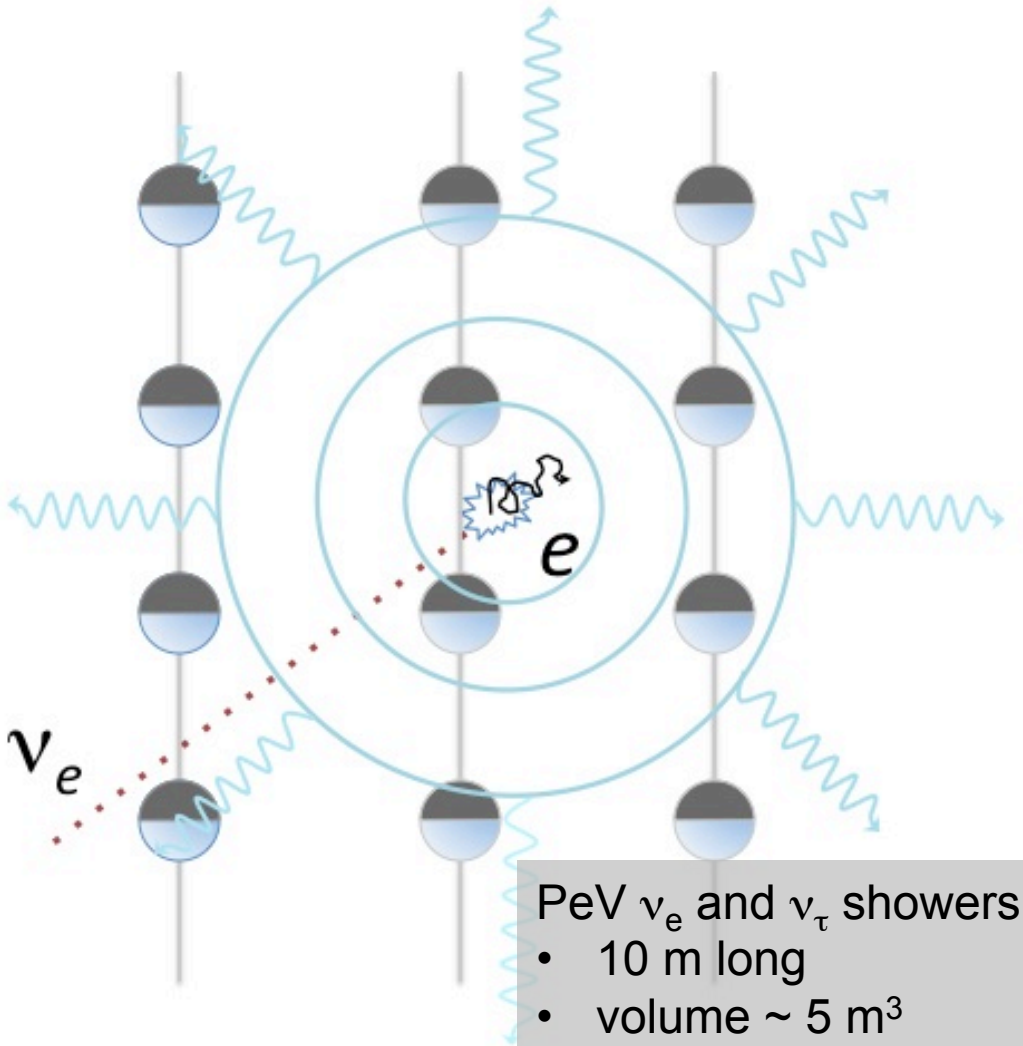
1 event per cubic kilometer per year

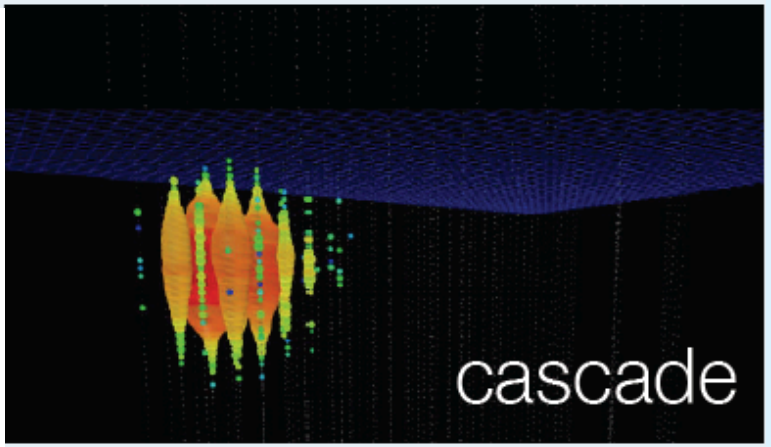
...but it points at its source!

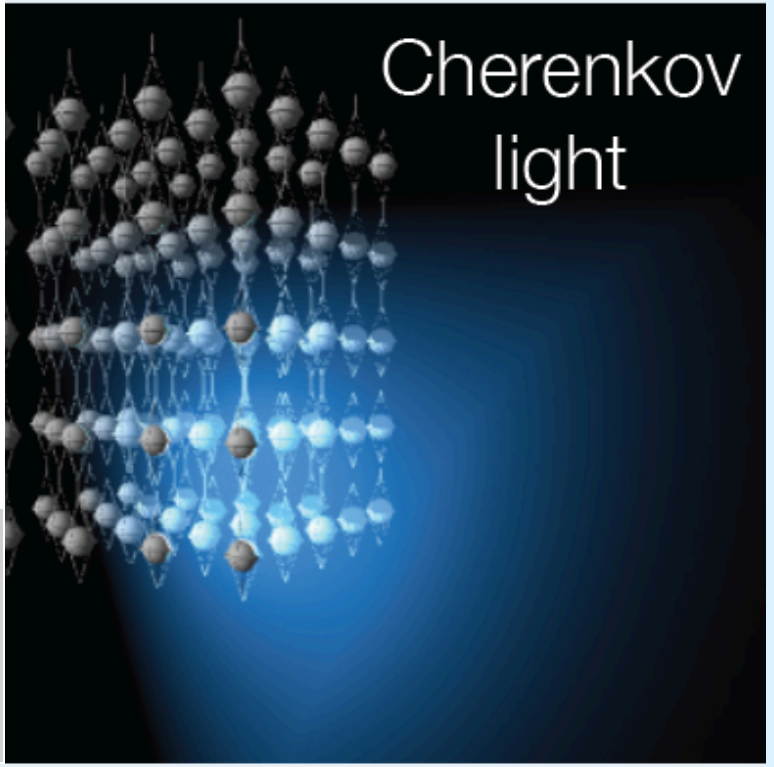
GZK neutrino search: two neutrinos with > 1,000 TeV



tracks and showers

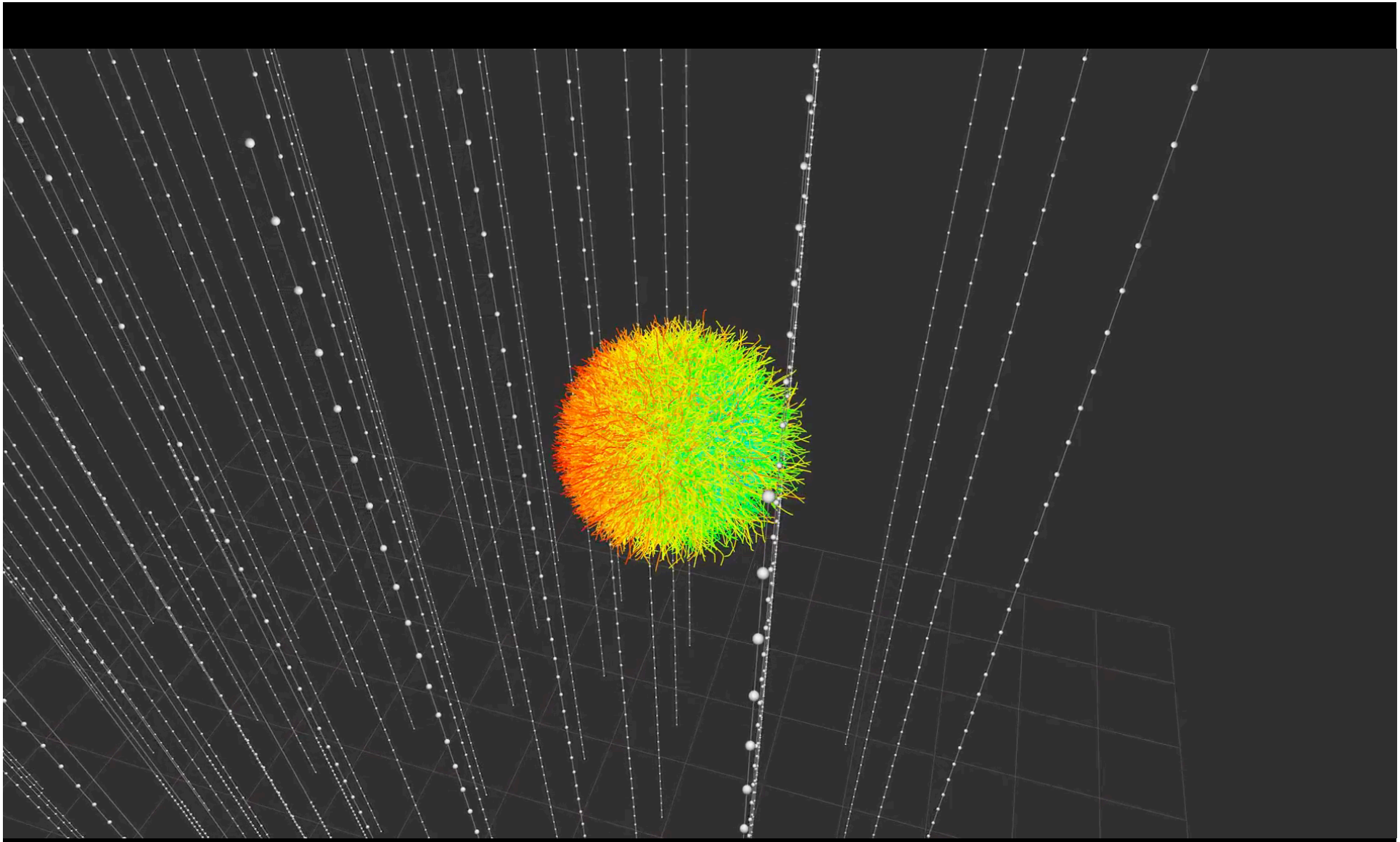






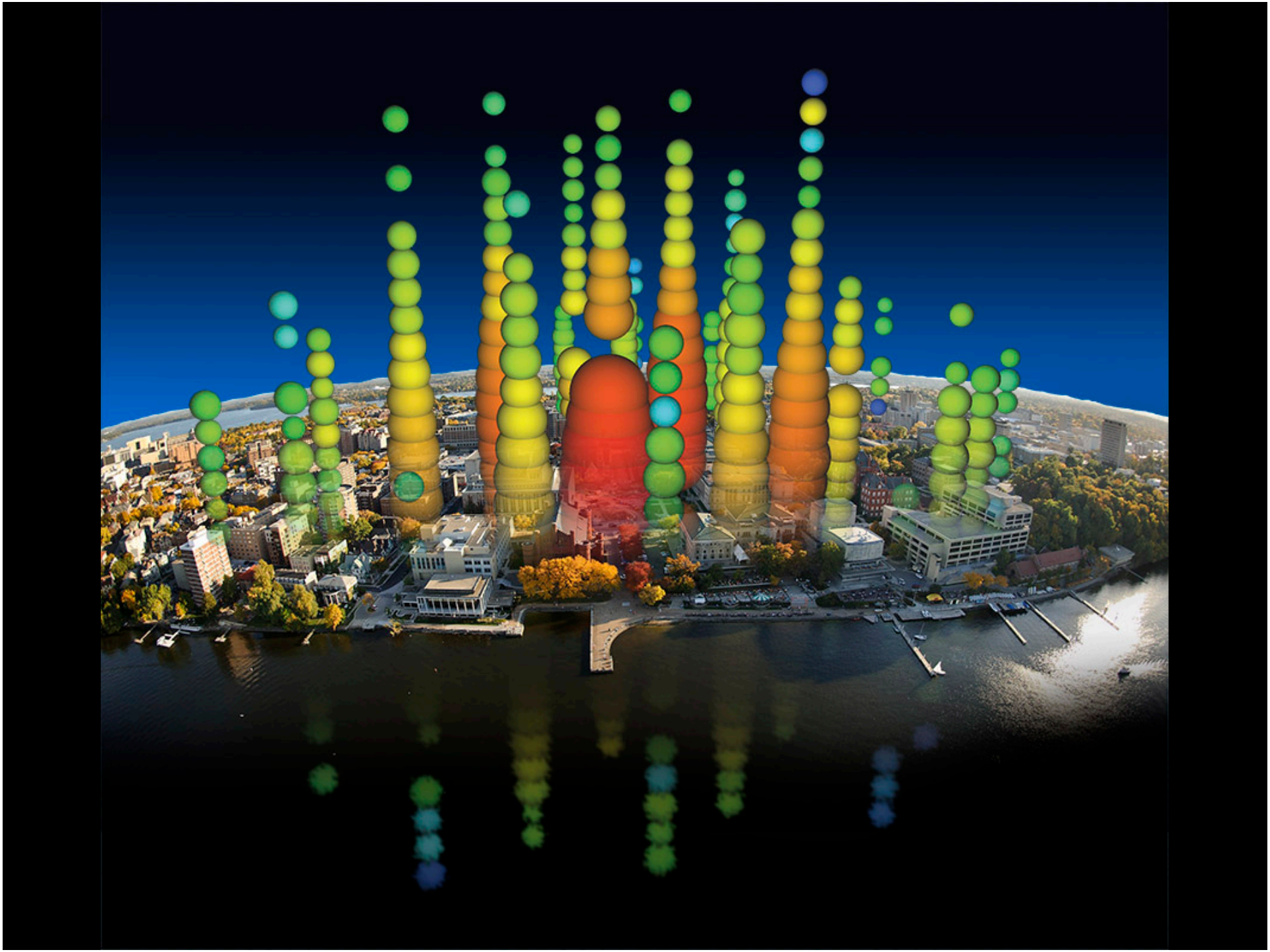
PeV ν_e and ν_τ showers:

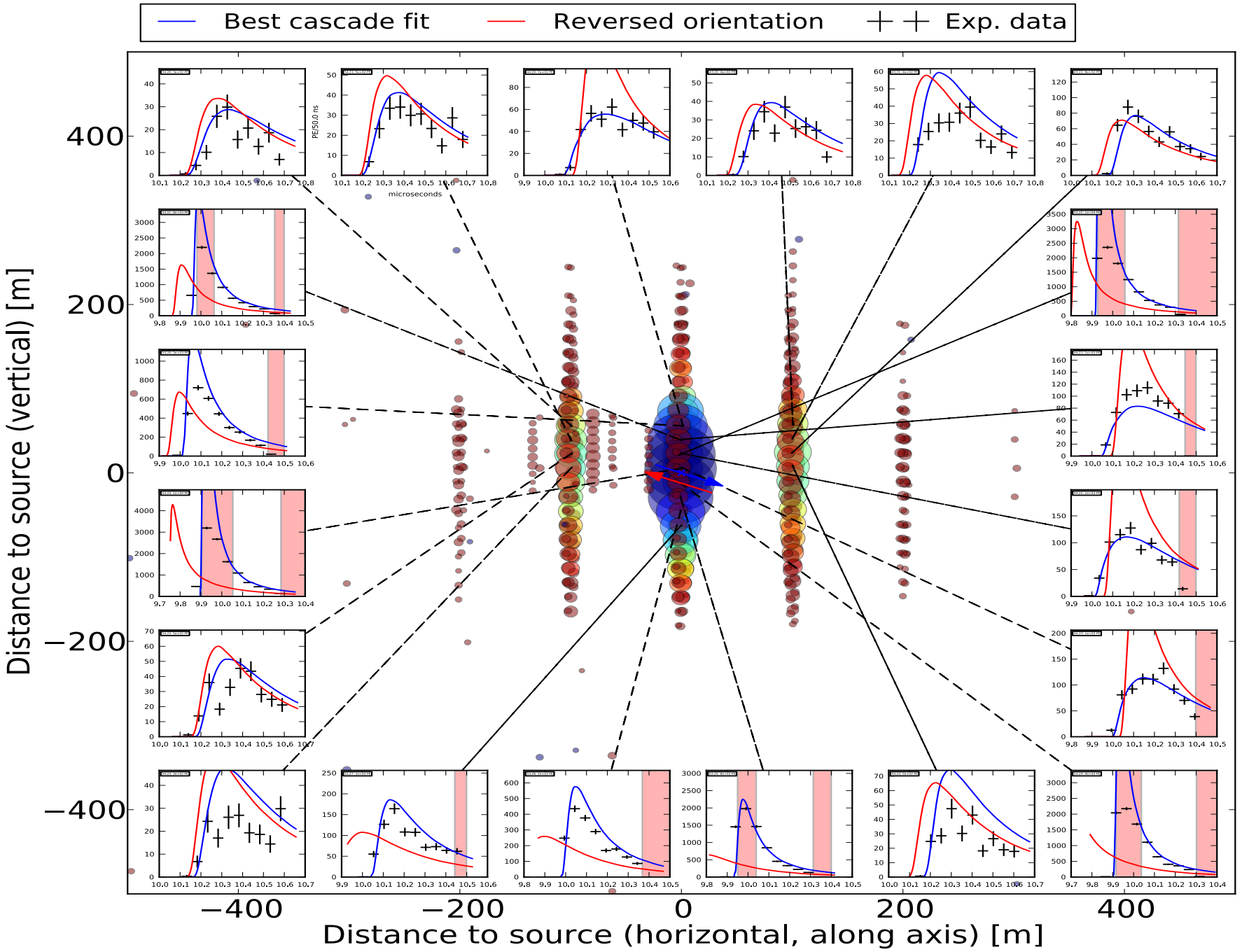
- 10 m long
- volume ~ 5 m^3
- isotropic after 25~ 50m



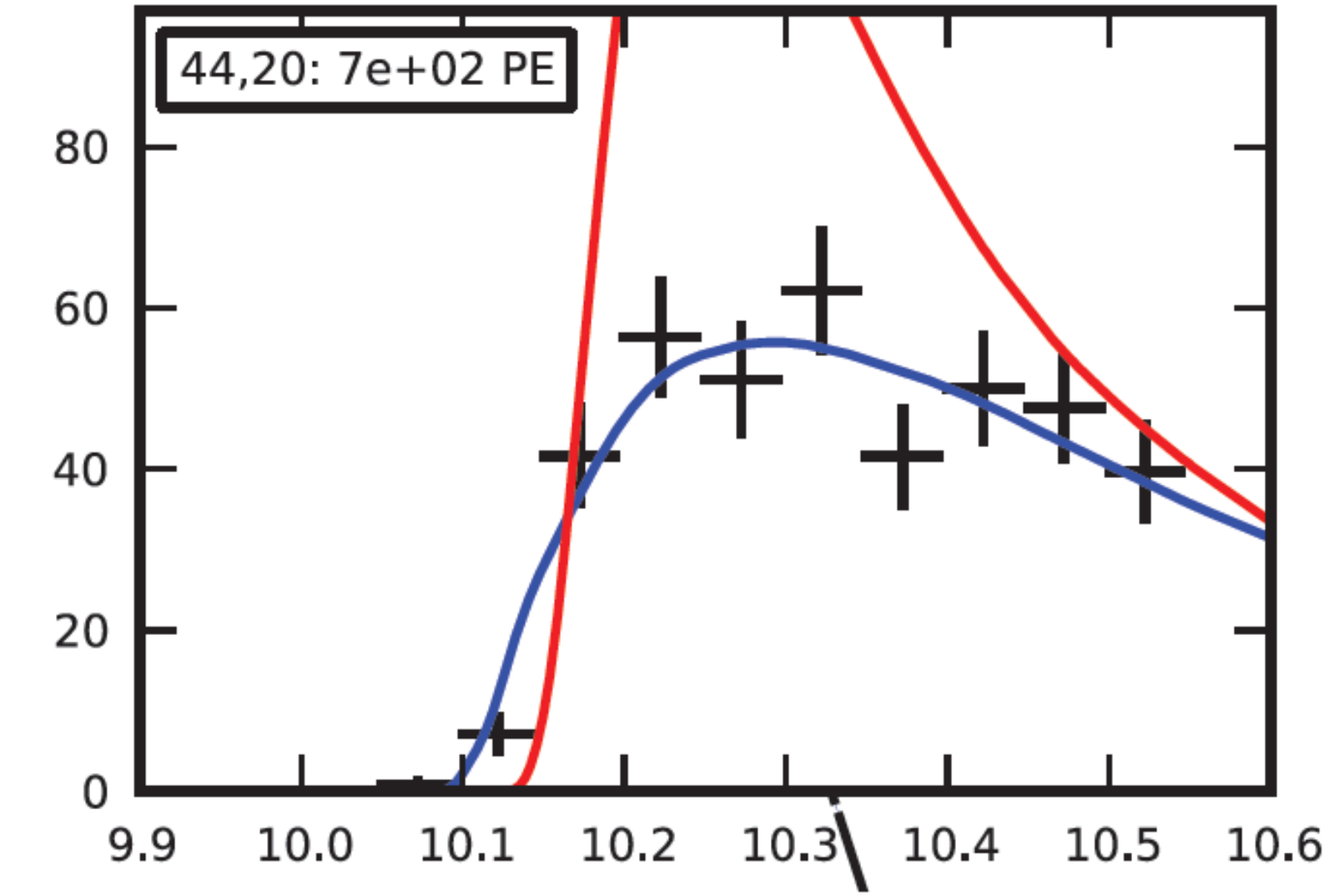
size = energy

color = time = direction

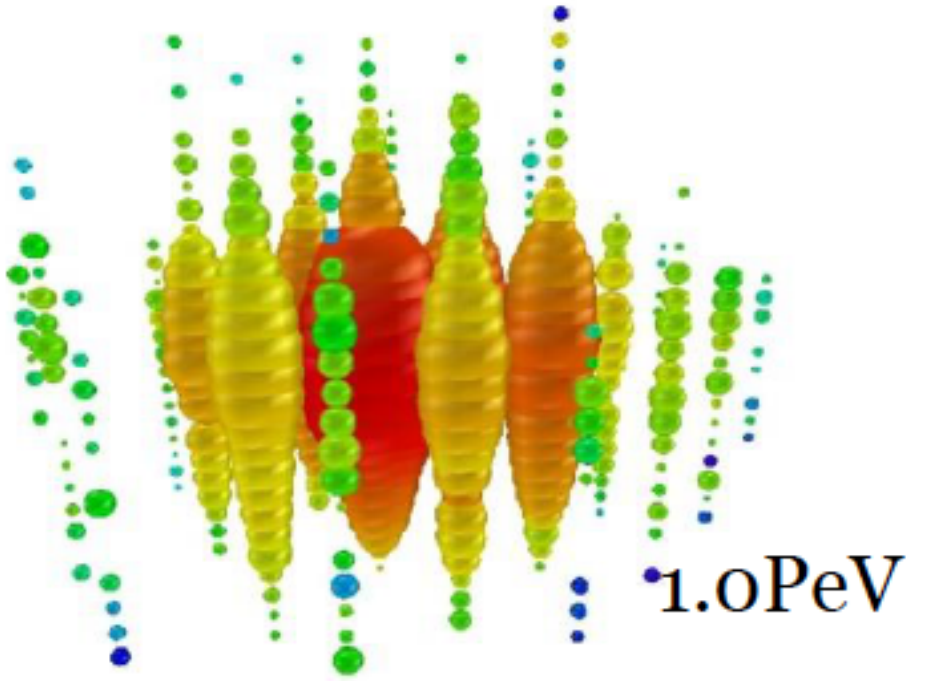


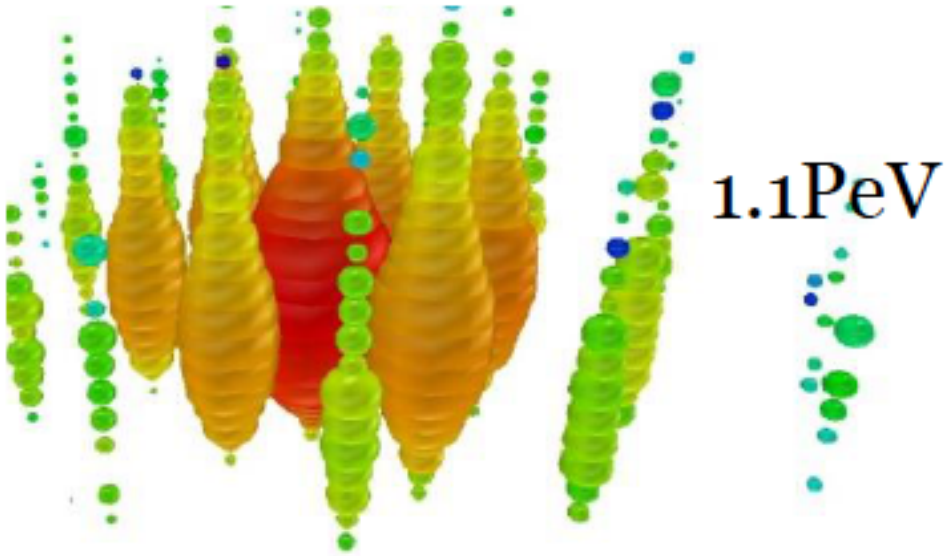

Best cascade fit
Reversed orientation
Exp. data
Distance to source (vertical) [m]
Distance to source (horizontal, along axis) [m]
400
200
0
−200
−400
−400
−200
0
200
400
PE/50.0 ns
microseconds

reconstruction limited by computing, not ice !



Blue: best-fit direction, red: reversed direction





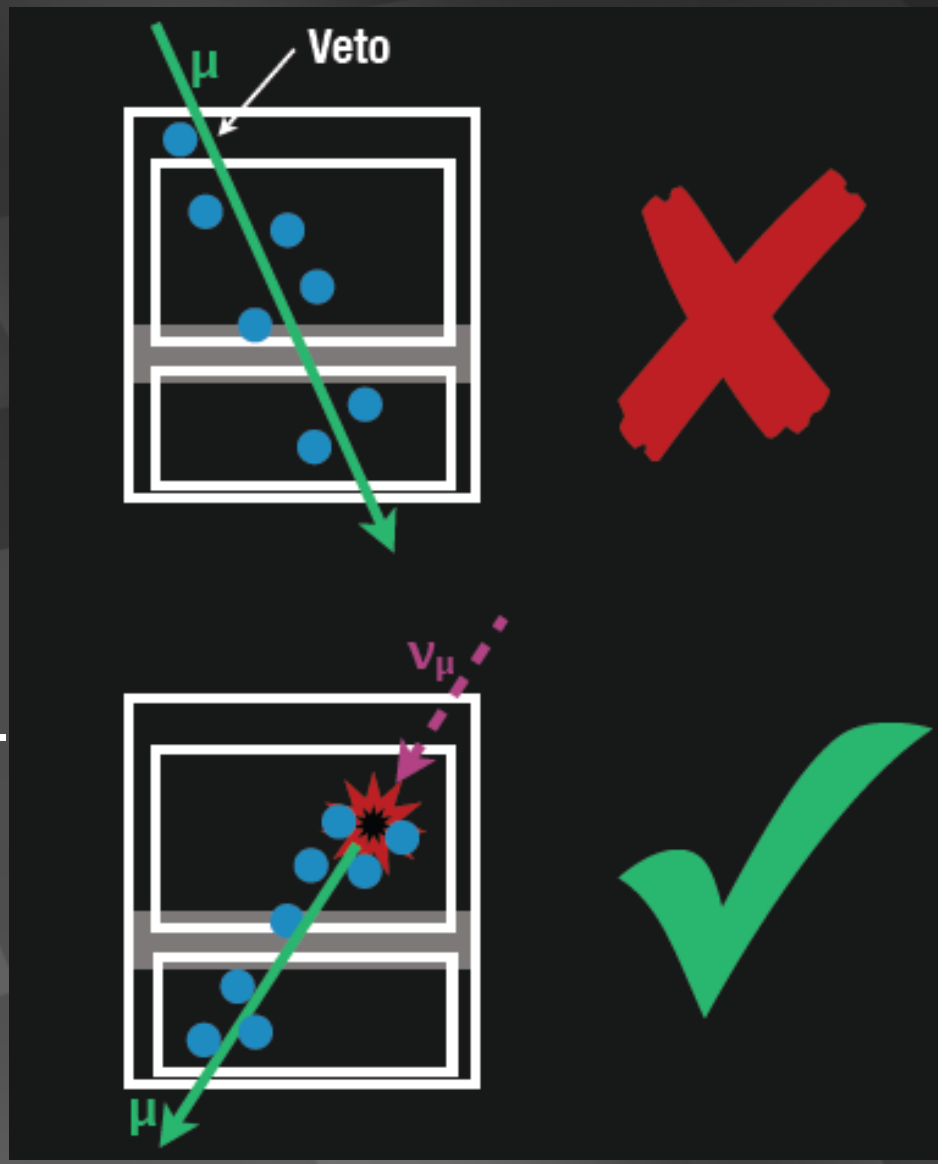
• energy

1,041 TeV
1,141 TeV
(15% resolution)

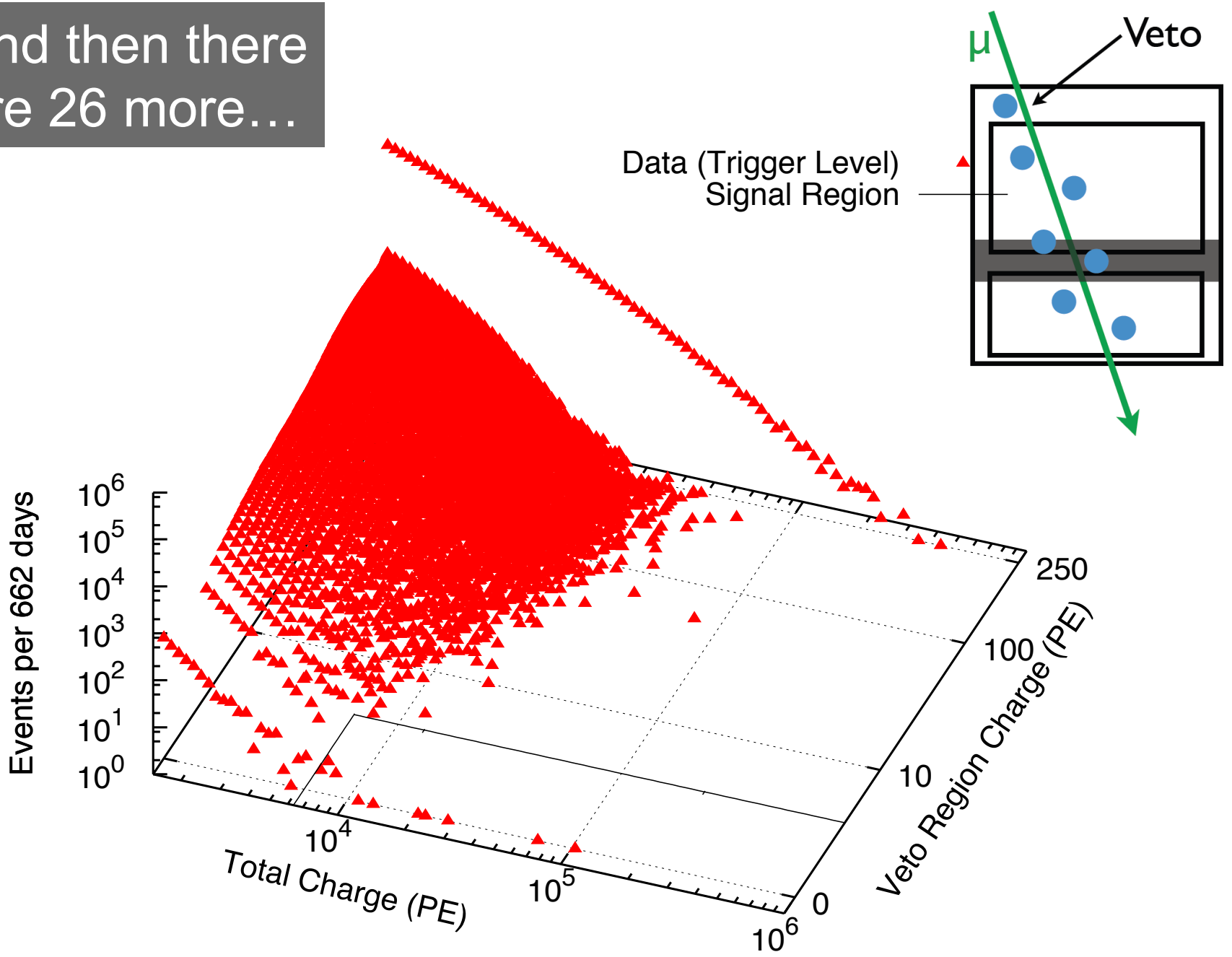
• not atmospheric: probability of no accompanying muon is 10^{-3} per event

→ flux at present level of diffuse limit

- ✓ select events interacting inside the detector only
- ✓ no light in the veto region
- ✓ veto for atmospheric muons and neutrinos (which are typically accompanied by muons)
- ✓ energy measurement: total absorption calorimetry

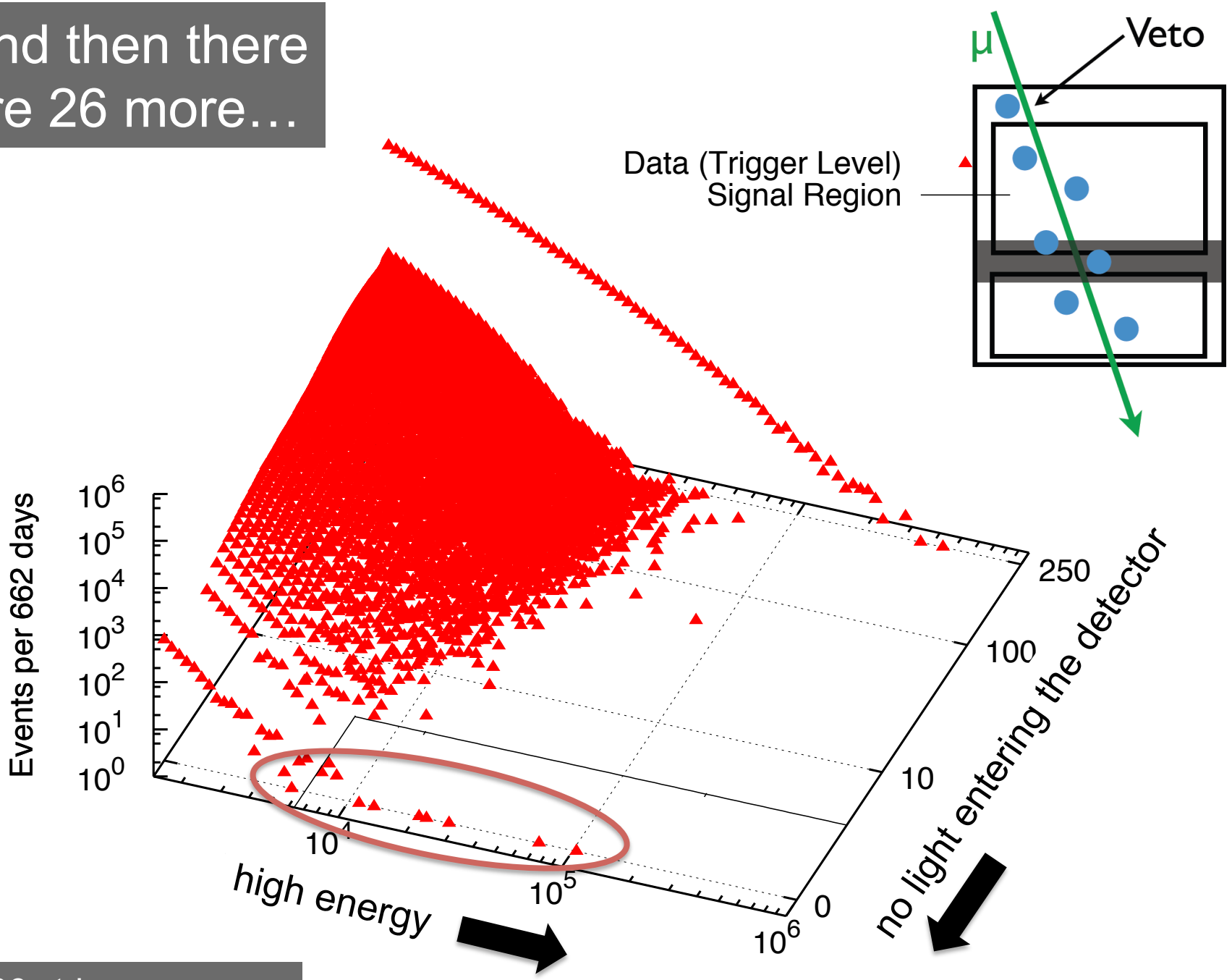


…and then there were 26 more…



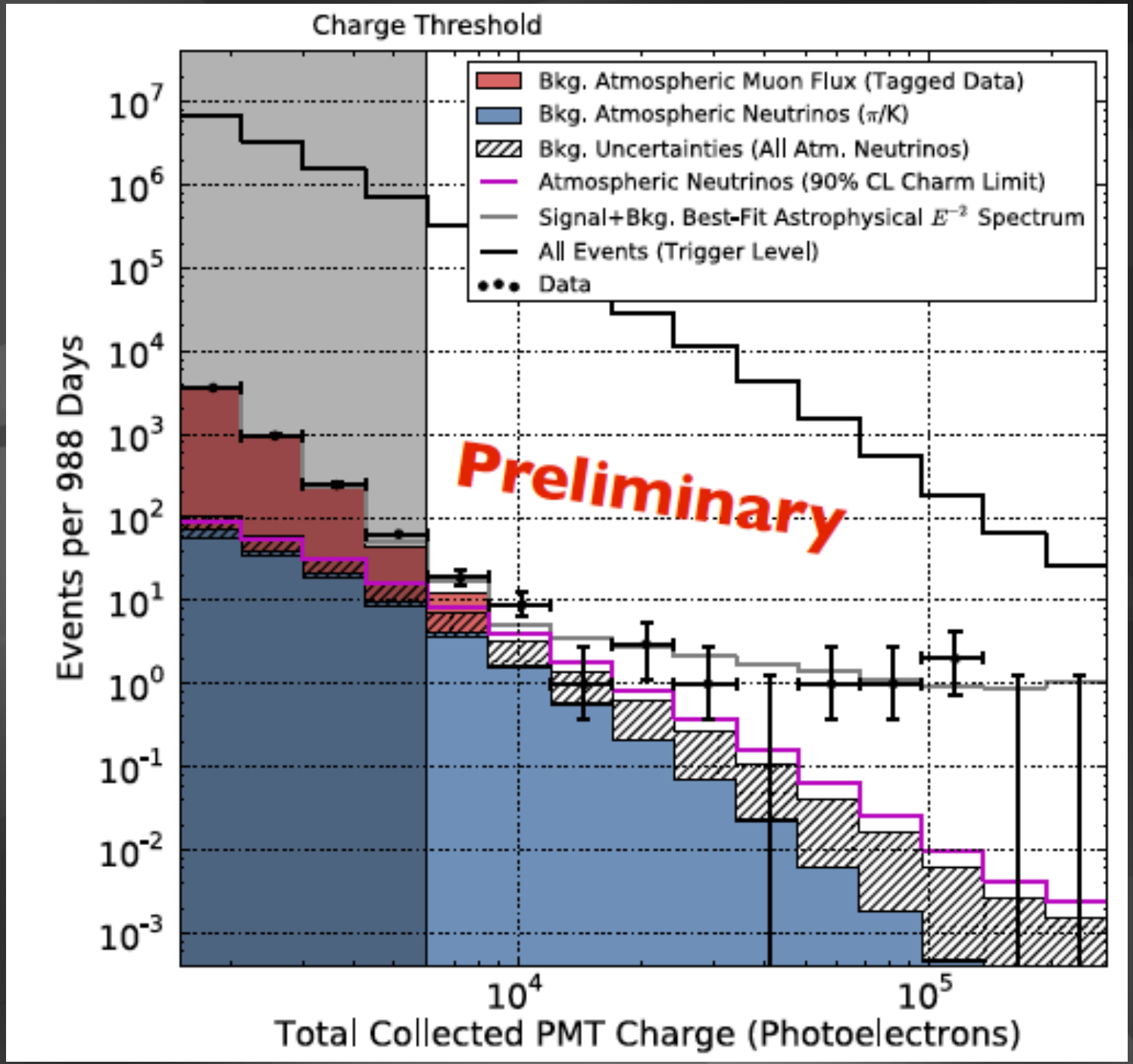
data: 86 strings one year

…and then there were 26 more…



data: 86 strings one year

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



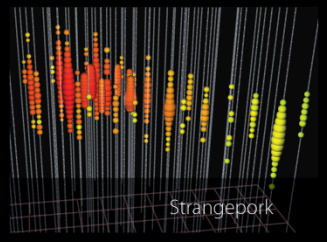
Science 342 (2013) 1242856

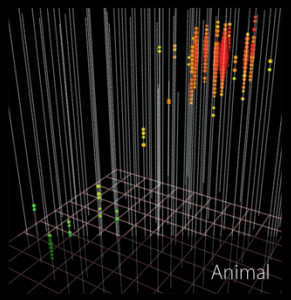
RESEARCH

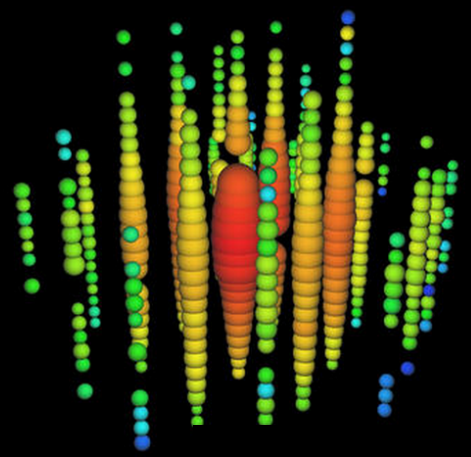
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

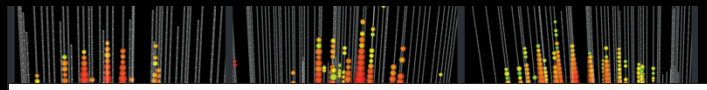
IceCube Collaboration*

28 High Energy Events

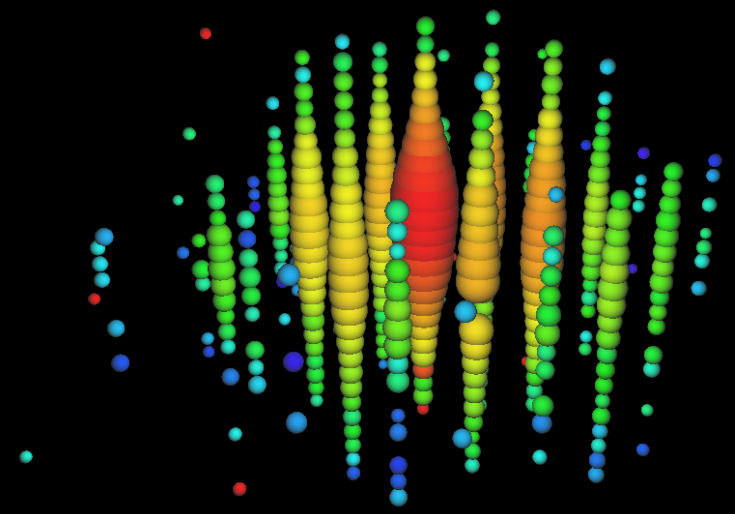








doubled the data since 2013

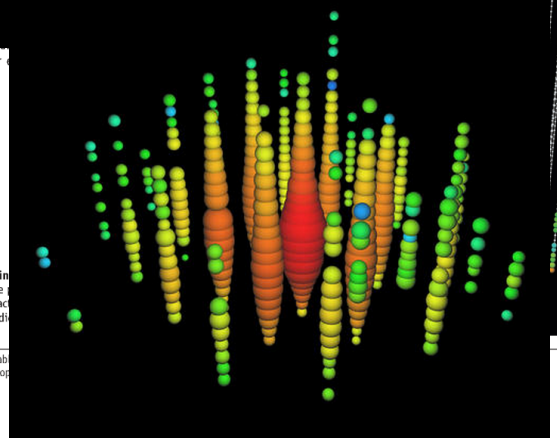


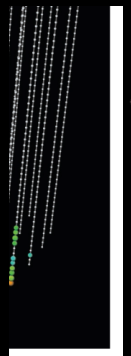
2004 TeV event in year 3

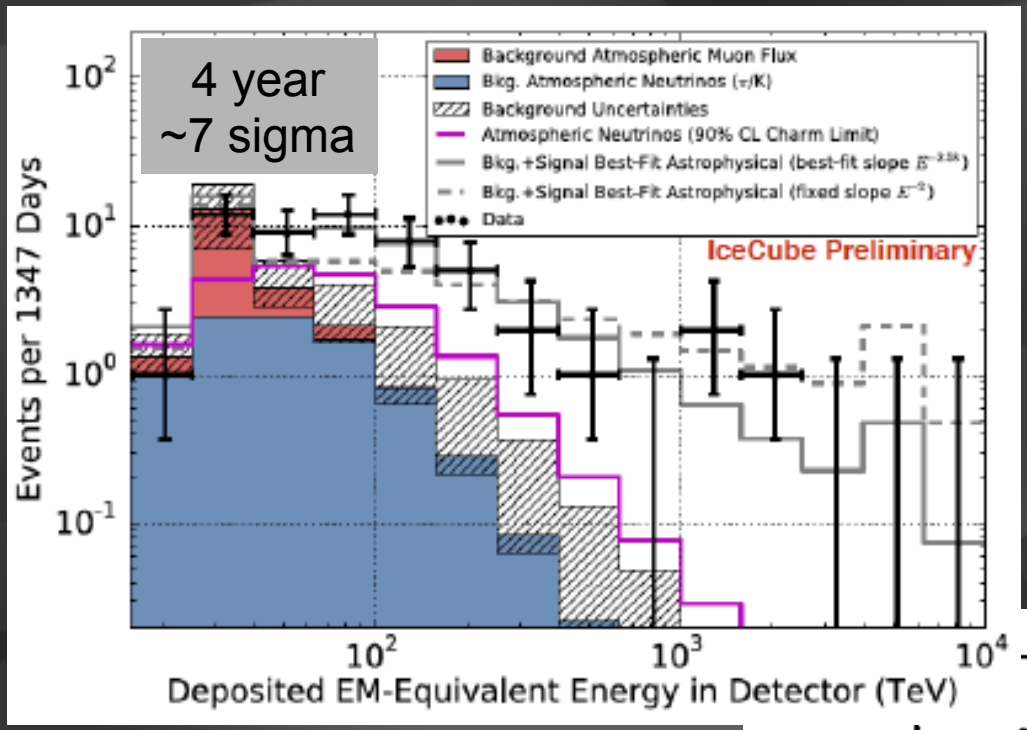
tified high-energy galactic or
accelerators.

A 250 TeV neutrino interaction in
interaction point (bottom), a large
with a muon produced in the interac
left. The direction of the muon ind
original neutrino.

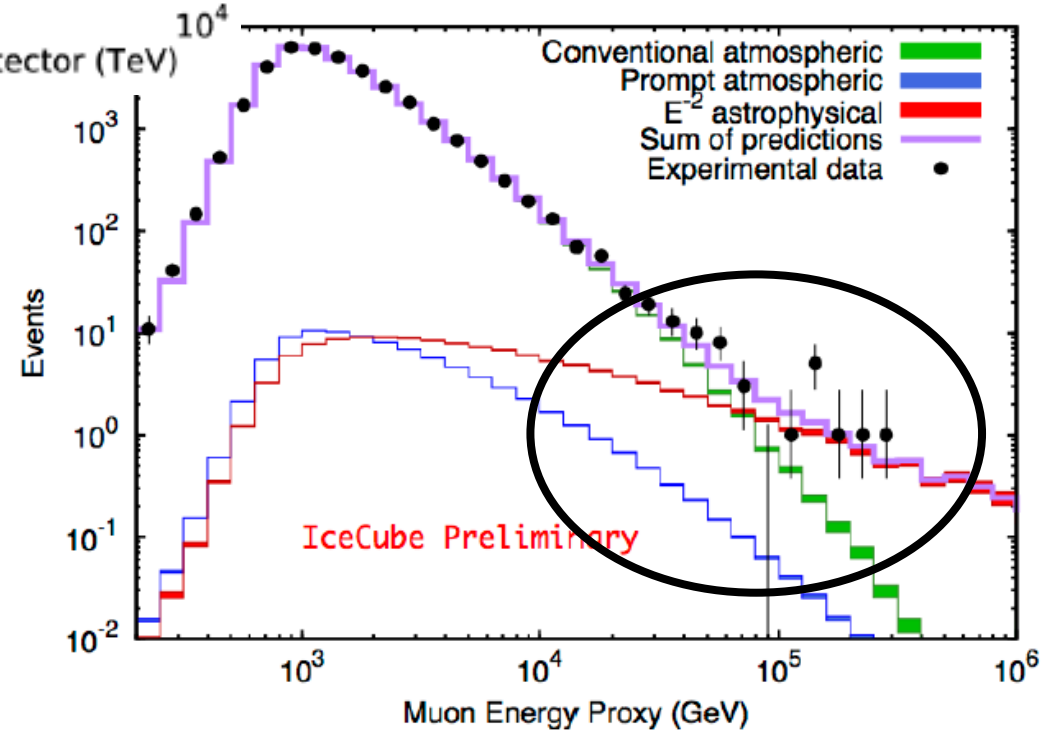
*The list of author affiliations is availab
Corresponding authors: C. Kopper (ckop







confirmation!
flux of muon neutrinos
through the Earth

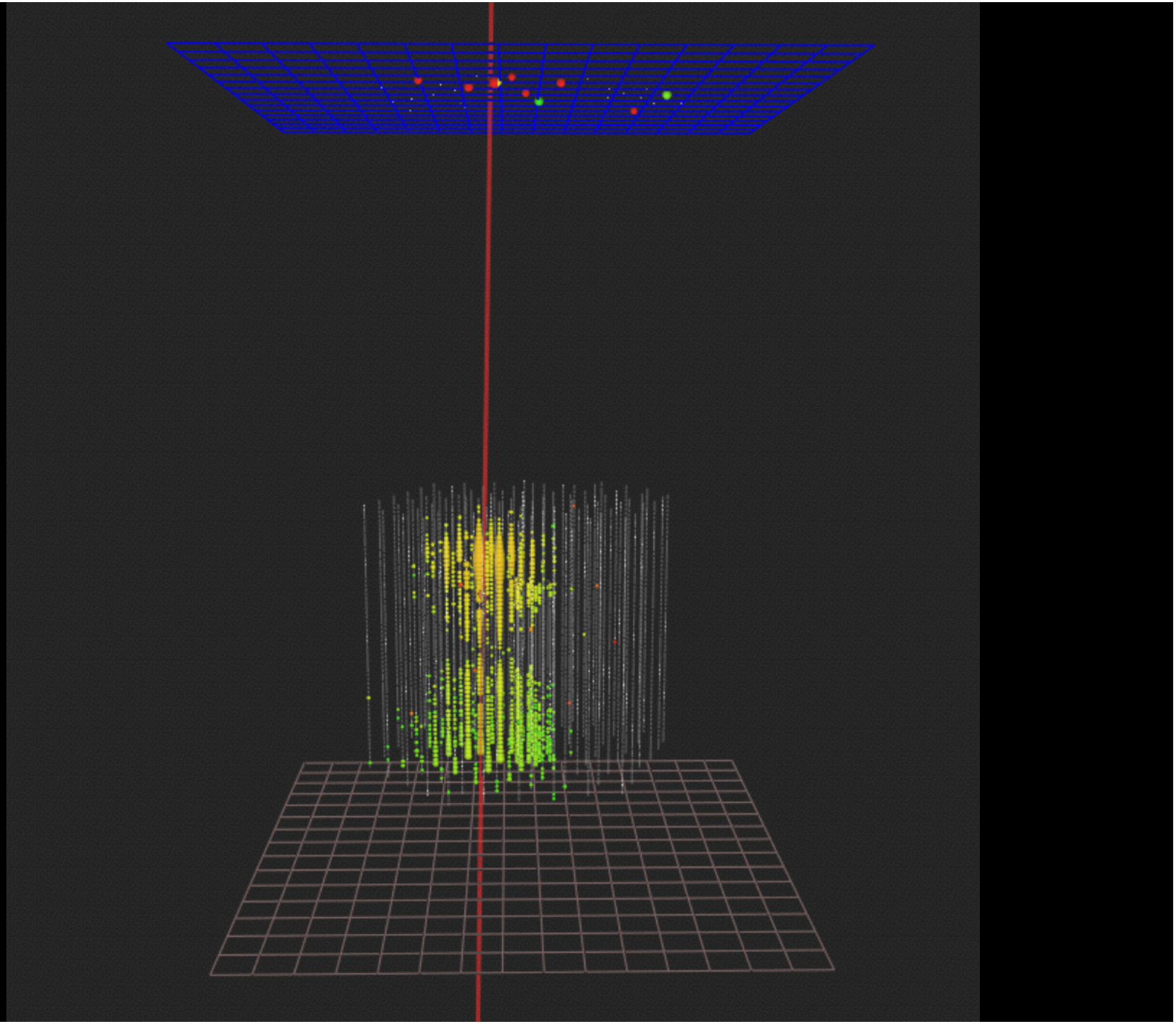


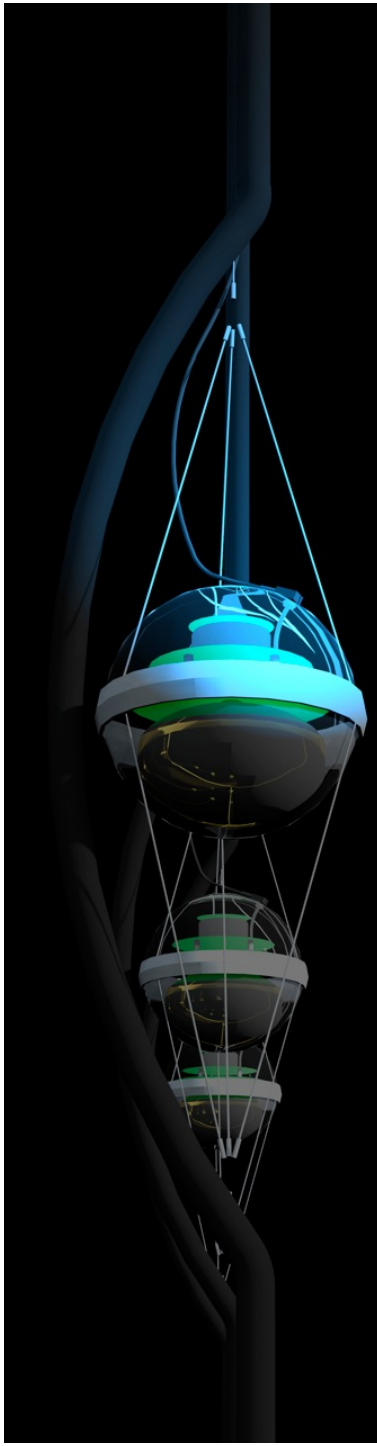
neutrinos of all flavors
interacting inside
IceCube

430 TeV

1 event:
~ 5 sigma
discovery

> PeV ν_μ





IceCube: the discovery of cosmic neutrinos

francis halzen

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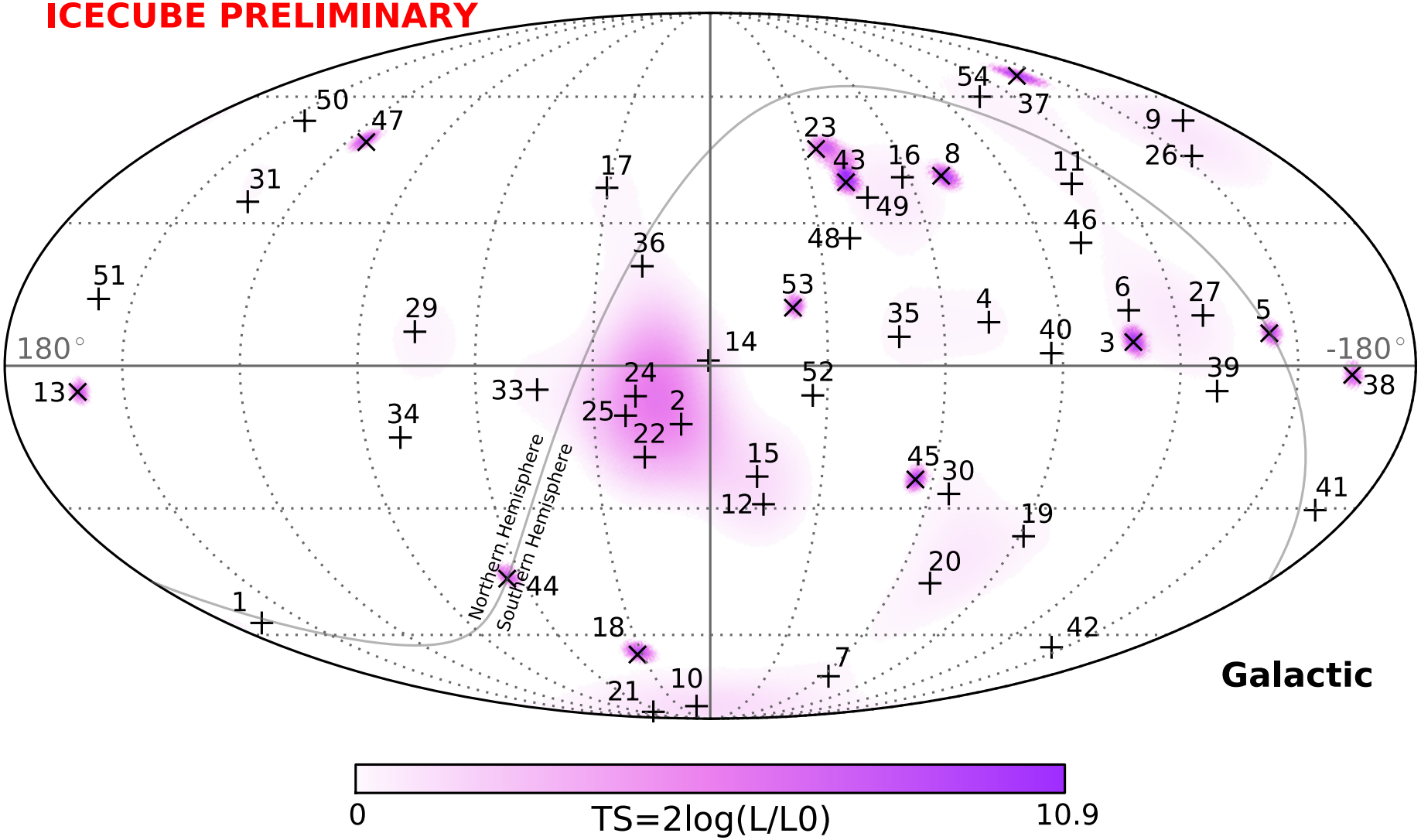
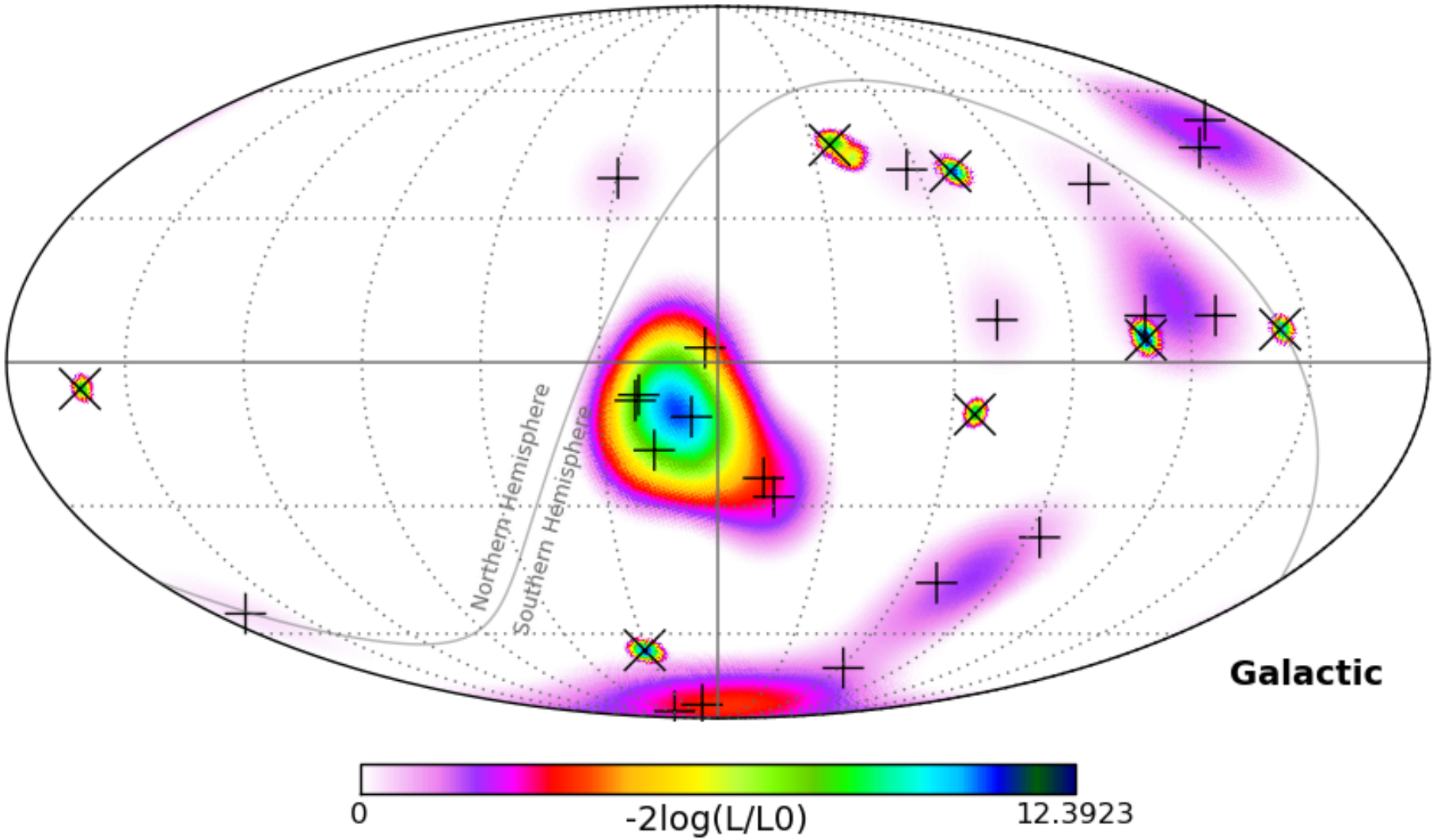
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

4 year HESE

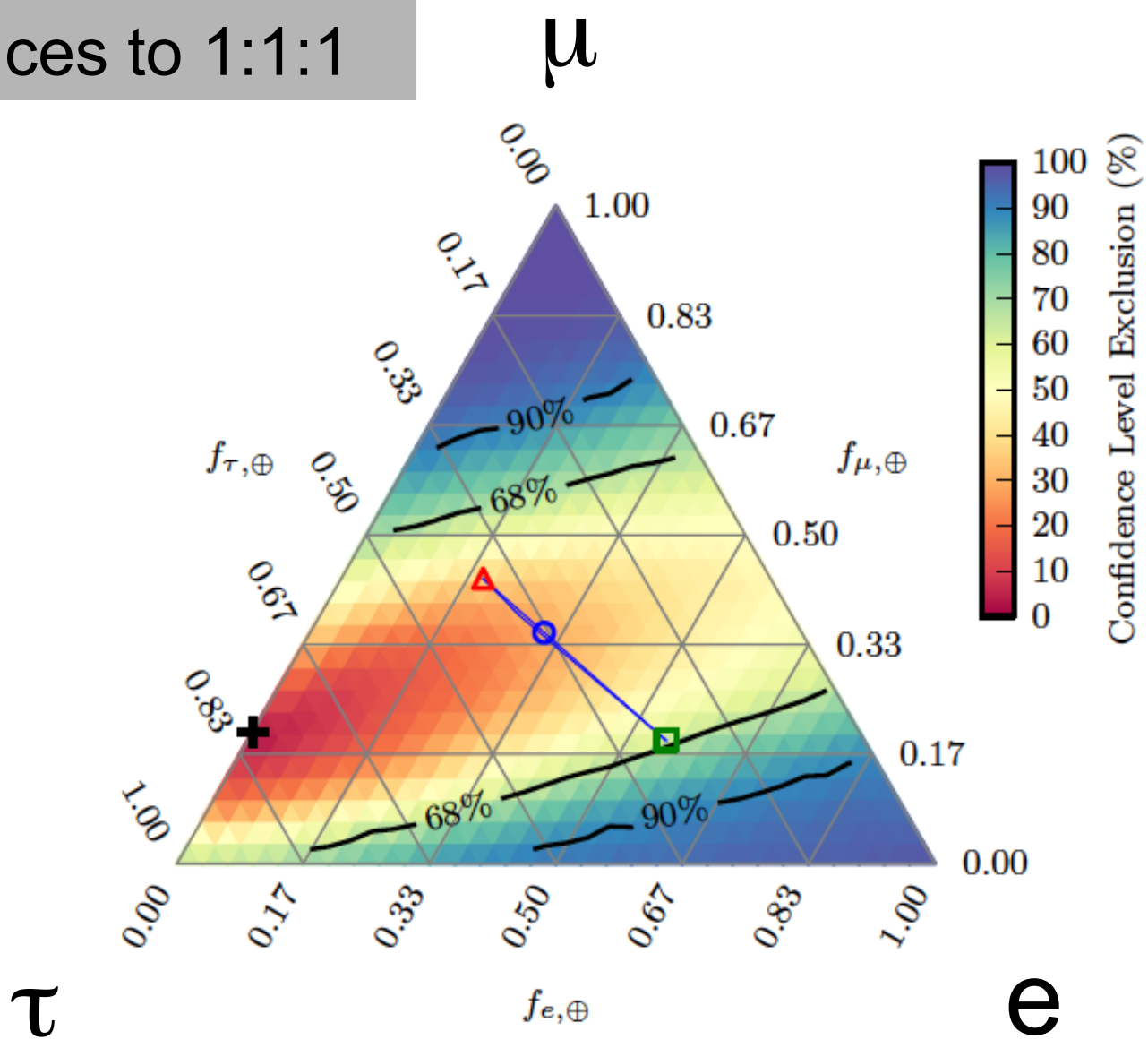


where do they come from?

2 year HESE

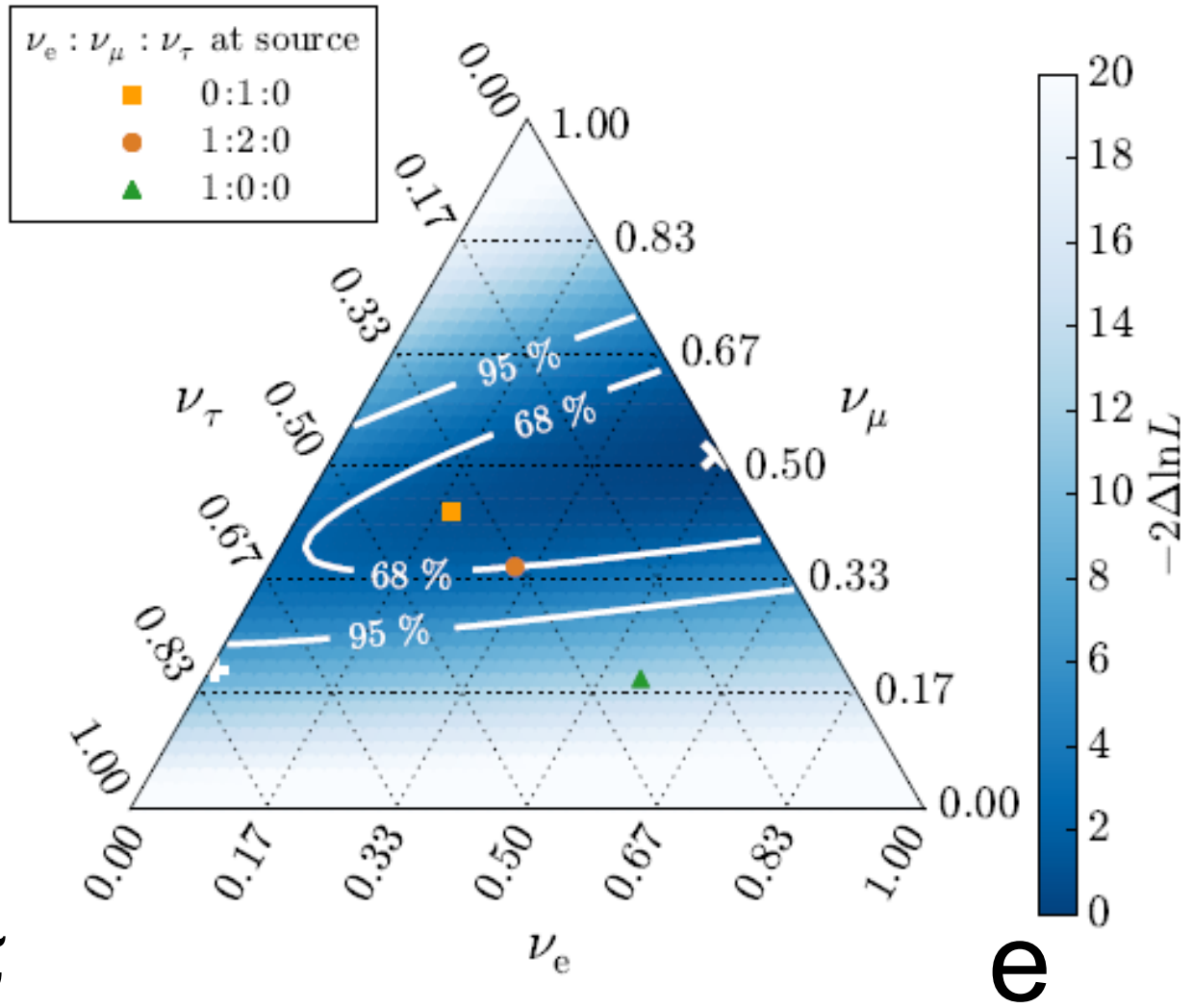

Northern Hemisphere
Southern Hemisphere
Galactic
0
-2log(L/L0)
12.3923

oscillate over cosmic distances to 1:1:1



oscillate over cosmic distances to 1:1:1

μ

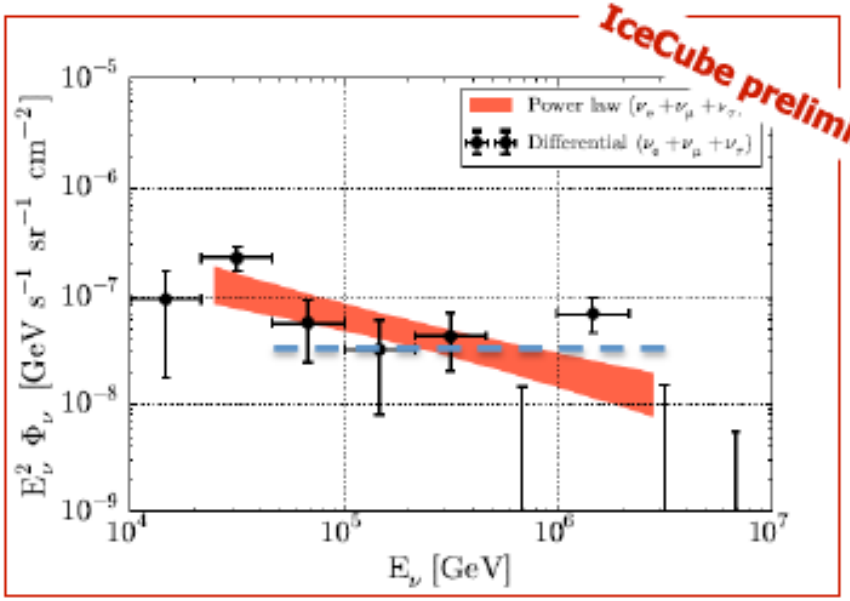


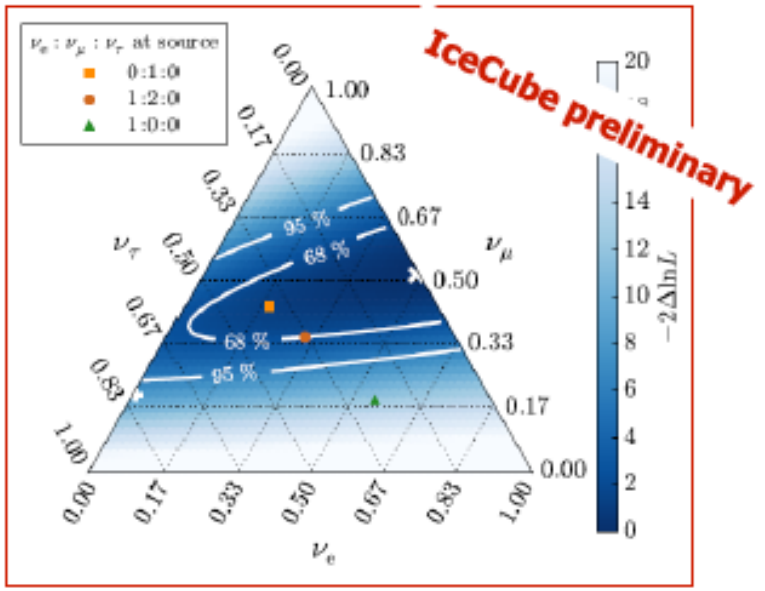
τ

e

preliminary

- 6 different data samples based on data from 2008 – 2012
- different strategies to suppress the atm. μ background
- large samples of track-like and cascade-like events





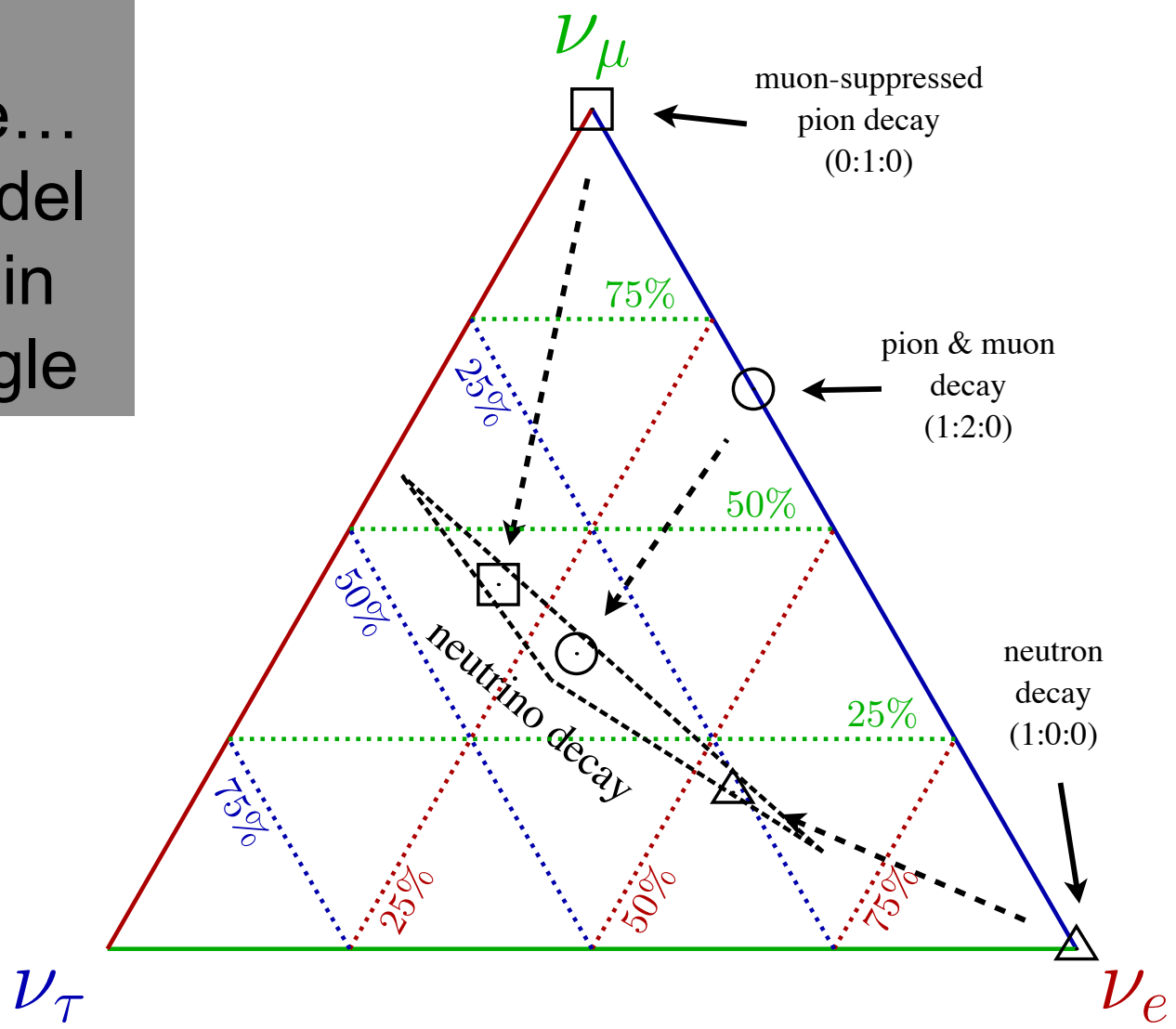
assuming isotropic astrophysical flux and ν_e:ν_μ:ν_τ = 1:1:1 at Earth →

unbroken power-law between 25 TeV and 2.8 PeV
spectral index -2.5 ± 0.09 (-2 disfavored at 3.8 σ)
flux at 100 TeV $(6.7 \pm 1.2)\times10^{-18}$ (GeV · cm^2 · s · sr)$^{-1}$

the best fit flavor composition disfavors 1:0:0 at source at 3.6 σ

new physics ?

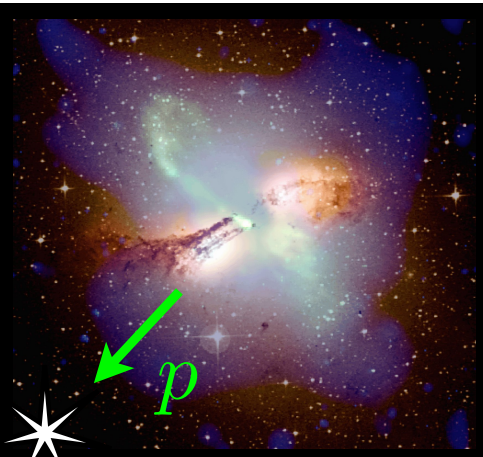
otherwise…
every model
ends up in
the triangle



- we observe a diffuse extragalactic flux
- (a subdominant Galactic component cannot be excluded)
- where are the PeV gamma rays that accompany PeV neutrinos?

hadronic gamma rays ?

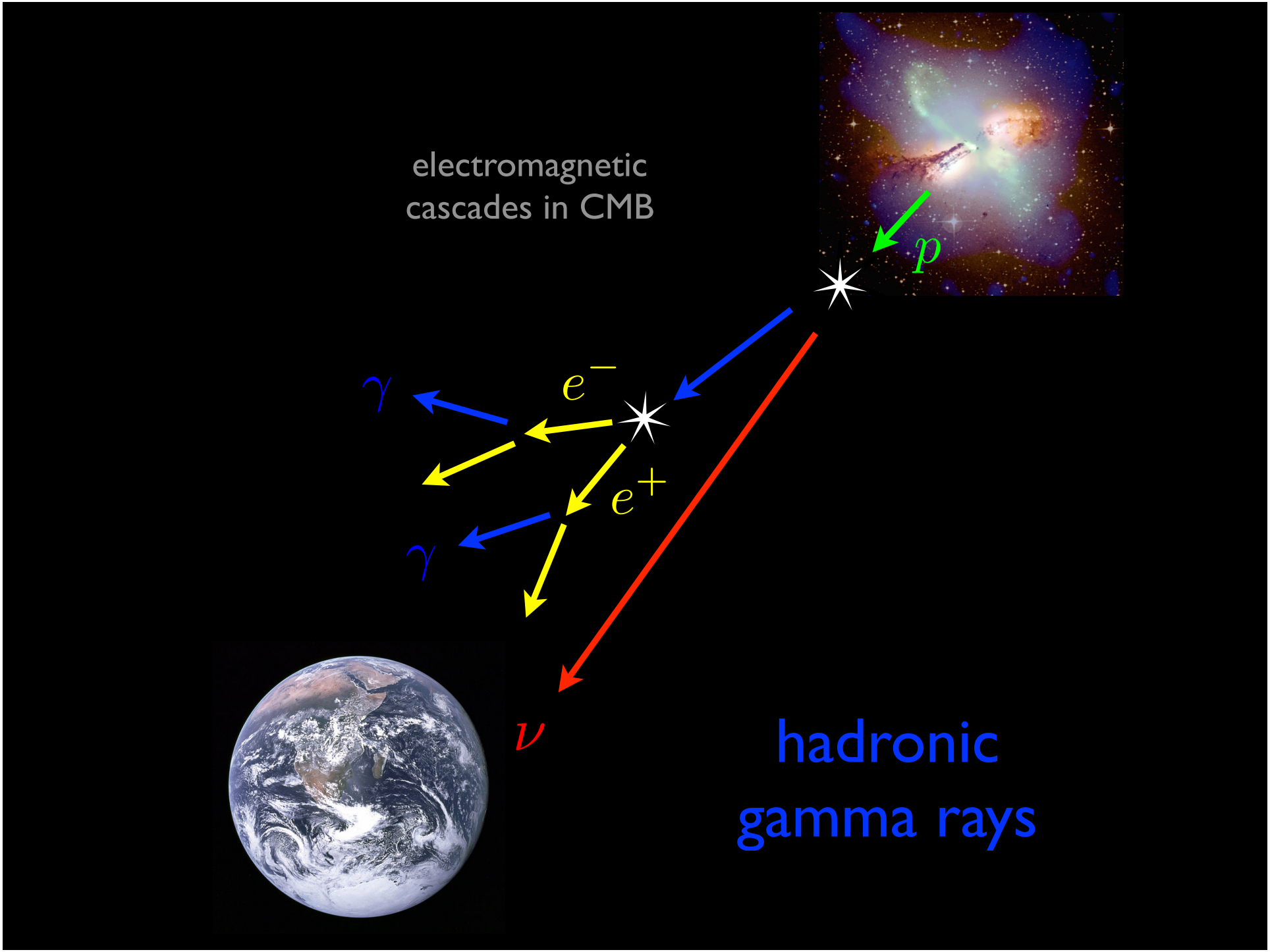
$\pi^+ = \pi^- = \pi^0$

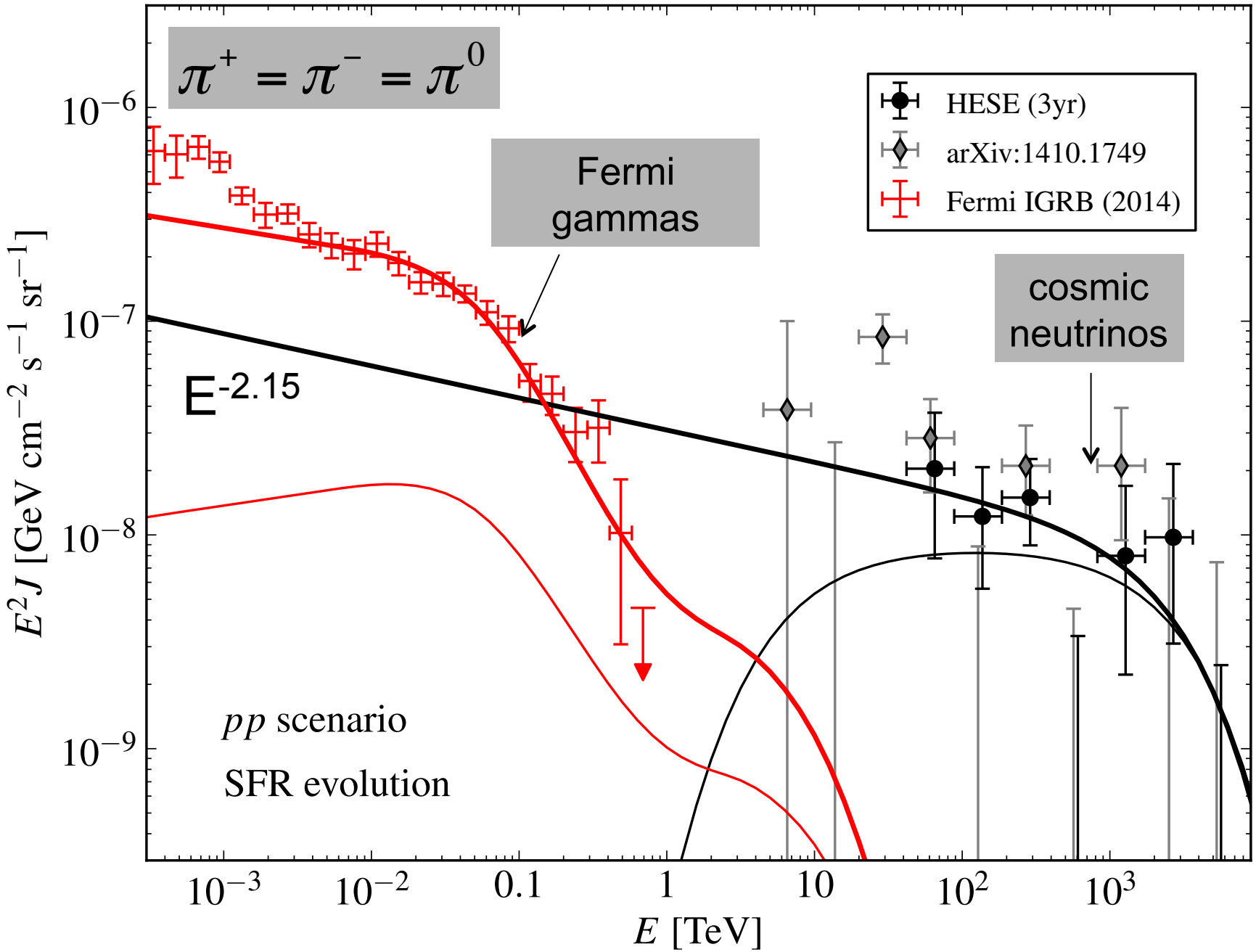


γ

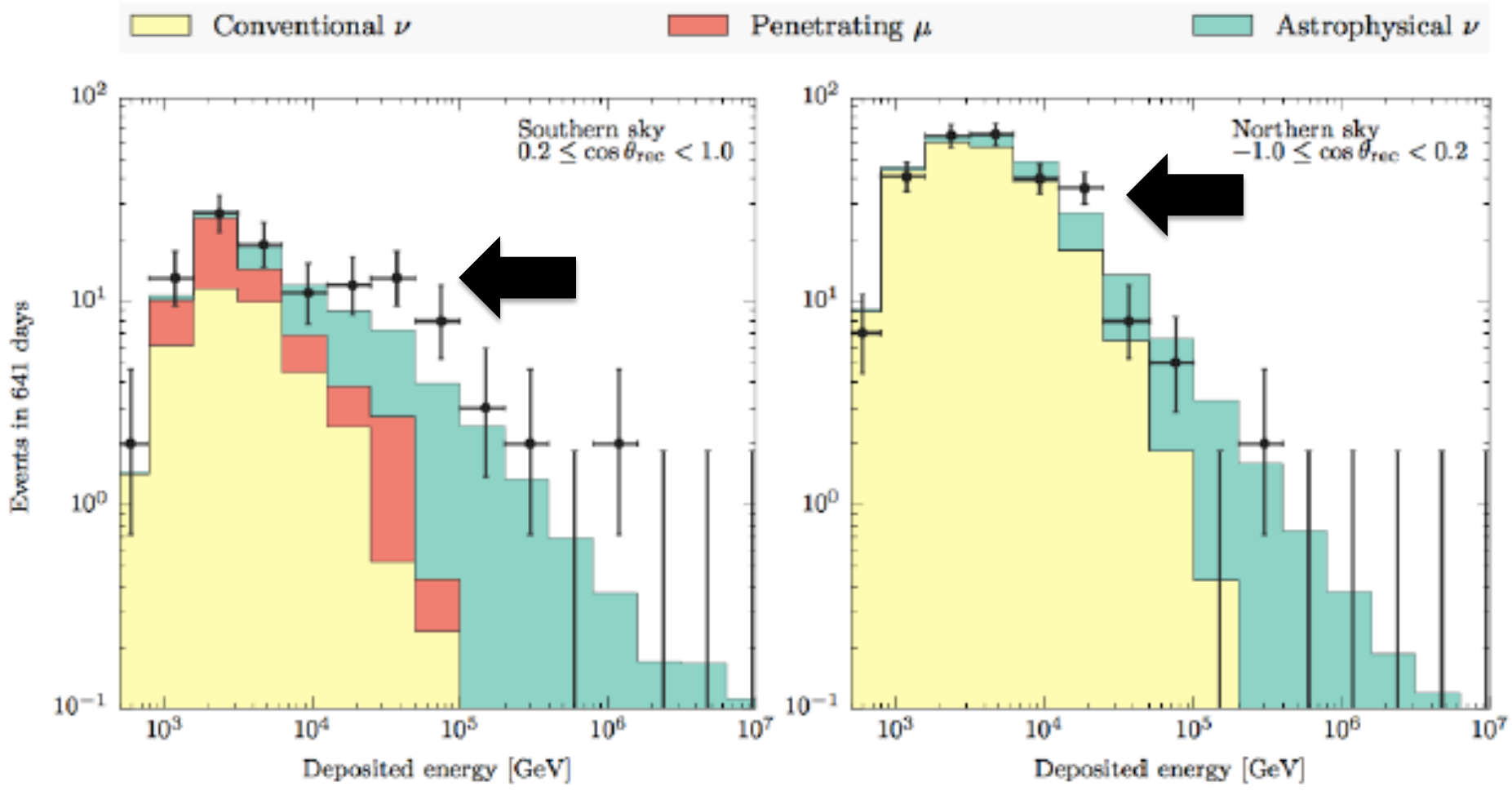
ν

hadronic
gamma rays


electromagnetic
cascades in CMB
p
γ
e^-
e^+
γ
ν
hadronic
gamma rays


$\pi^+ = \pi^- = \pi^0$
Fermi gammas
cosmic neutrinos
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
E-2.15
pp scenario
SFR evolution
E^2J [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

towards lower energies: a second component?



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

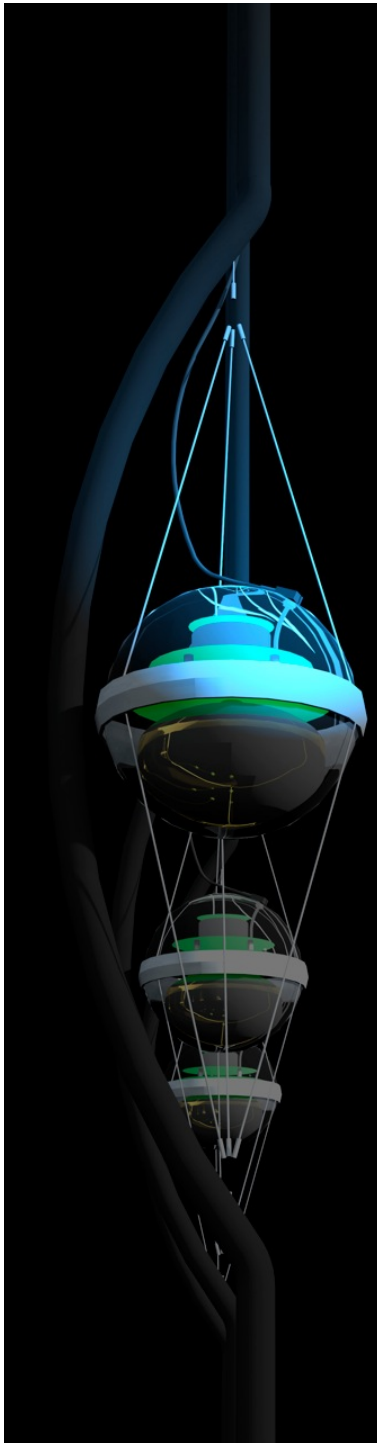
PeV neutrinos absorbed in the Earth

- we have observed a flux of neutrinos from the cosmos whose properties correspond in all respects to the flux anticipated from PeV-energy cosmic accelerators that radiate comparable energies in light and neutrinos

- hadronic accelerators are not a footnote to astronomy; they generate a significant fraction of the energy in the non-thermal Universe

- gamma ray sources predict neutrinos. We are close to identifying point sources.

- we observe a diffuse extragalactic flux
- active galaxies, most likely blazars, or starburst galaxies?
- correlation to catalogues should confirm this



IceCube: the discovery of cosmic neutrinos

francis halzen

- cosmic ray accelerators
- IceCube a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

IceCube.wisc.edu

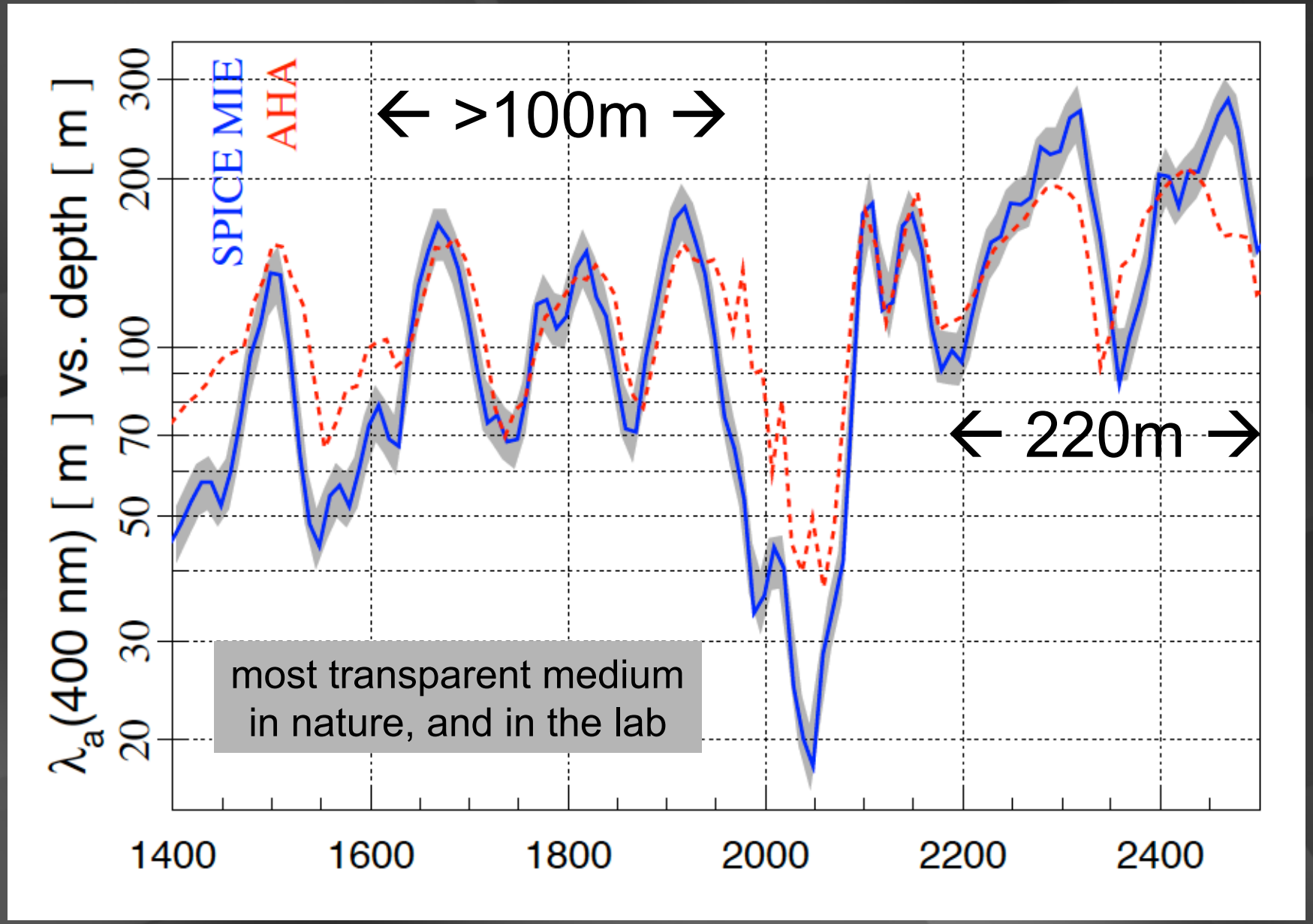
what next?

- 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

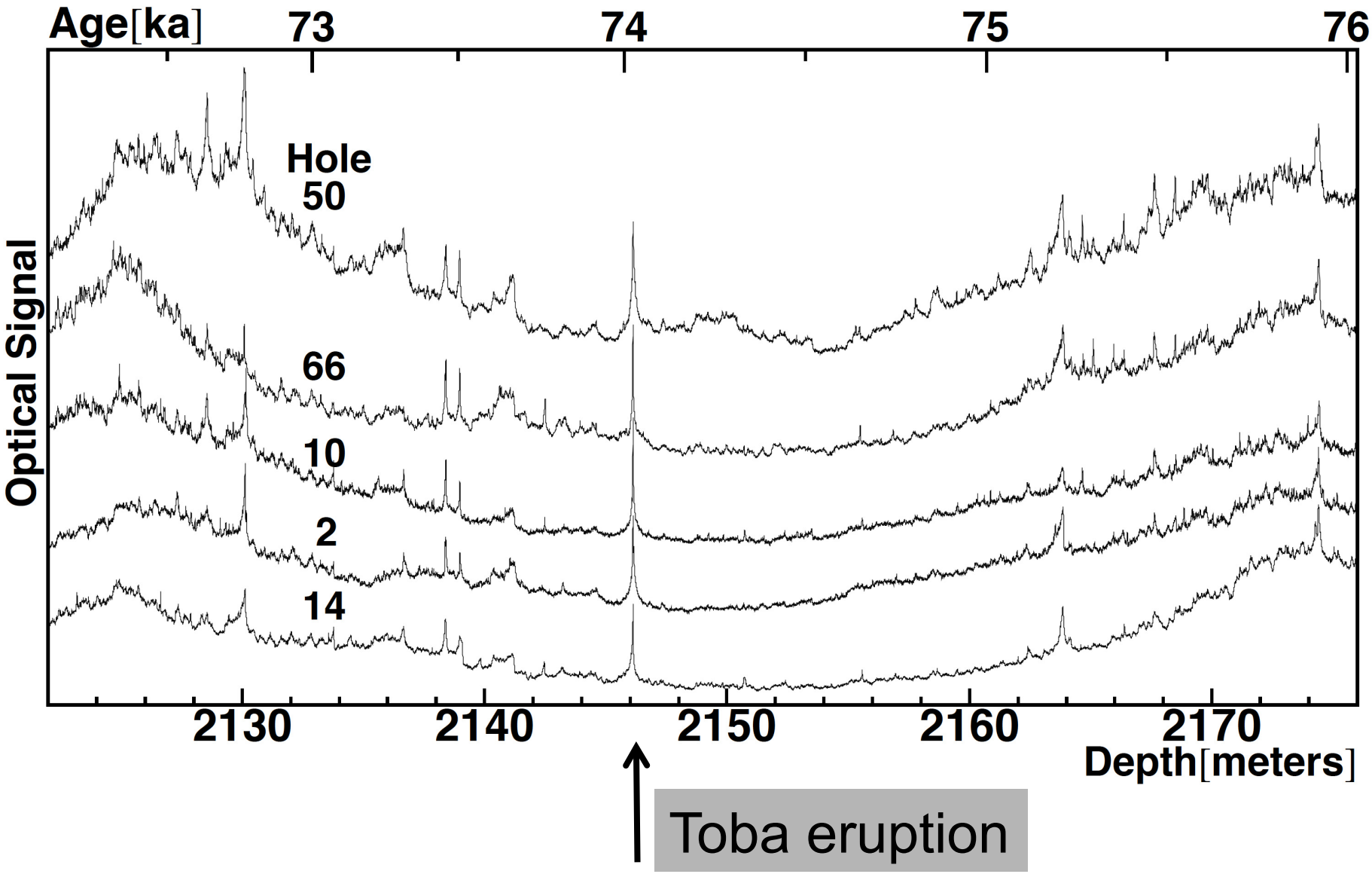
- need 1,000 events vs 100 now

- discovery instrument → astronomical telescope

absorption length of Cherenkov light

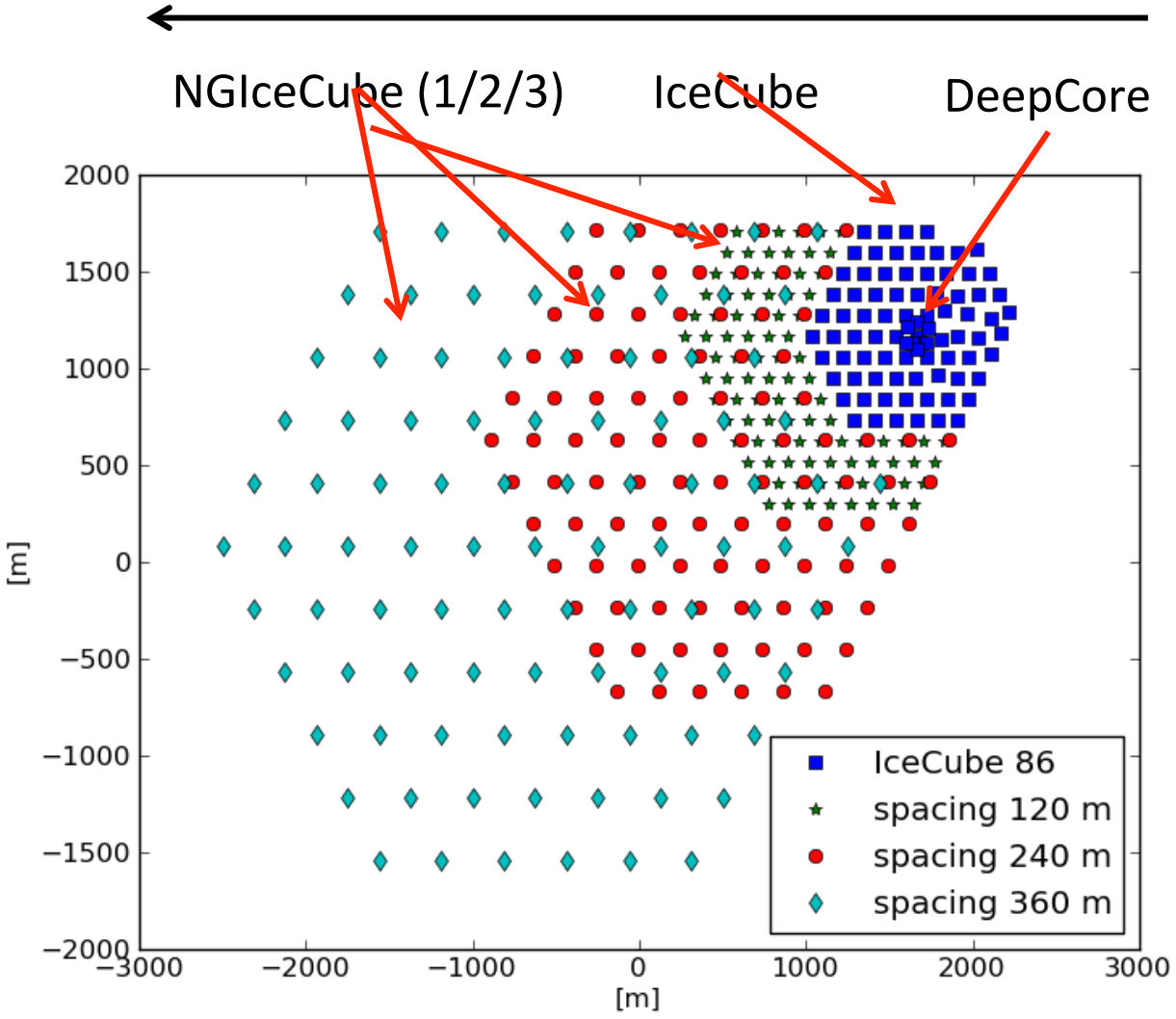


we are limited by computing, not the optics of the ice



measured optical properties → twice the string spacing

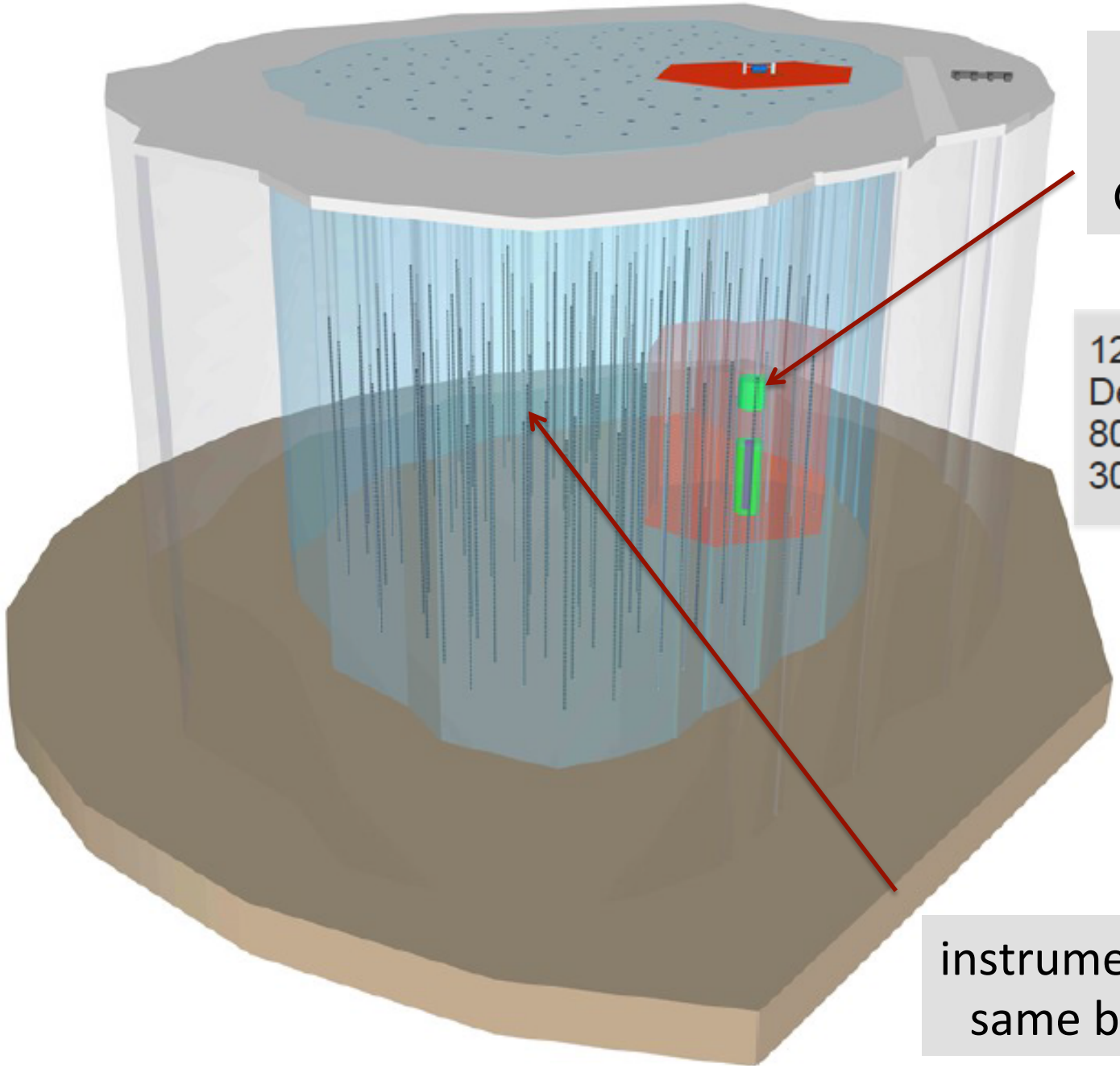
(increase in threshold not important: eliminates energies where the atmospheric background dominates)



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



PINGU infill
40 strings →
GeV threshold

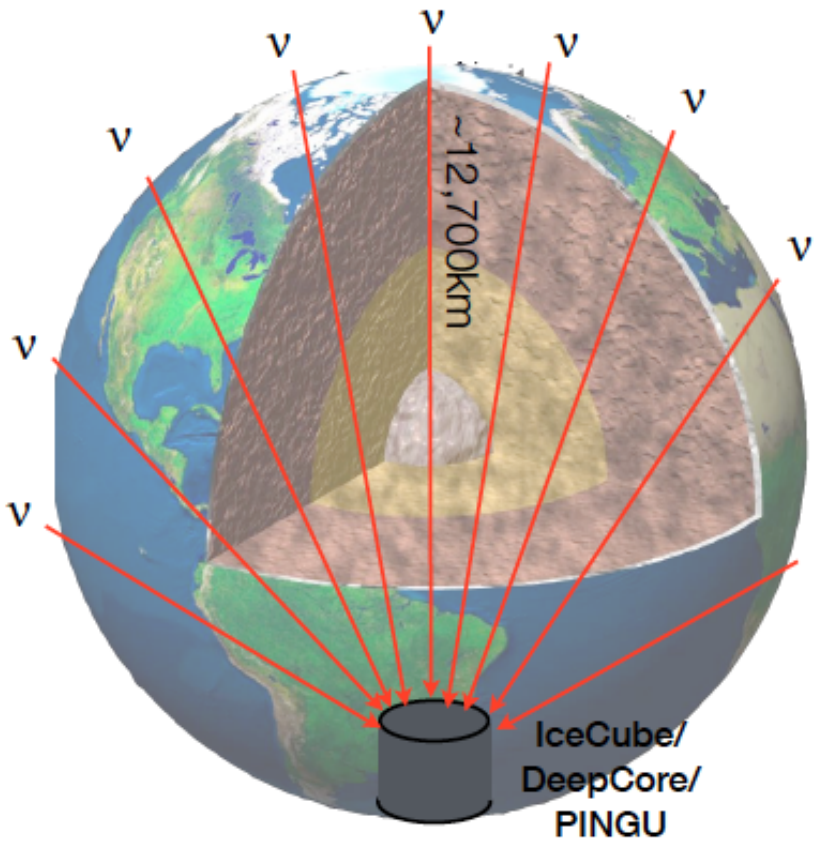
120 strings
Depth 1.35 to 2.7 km
80 DOMs/string
300 m spacing

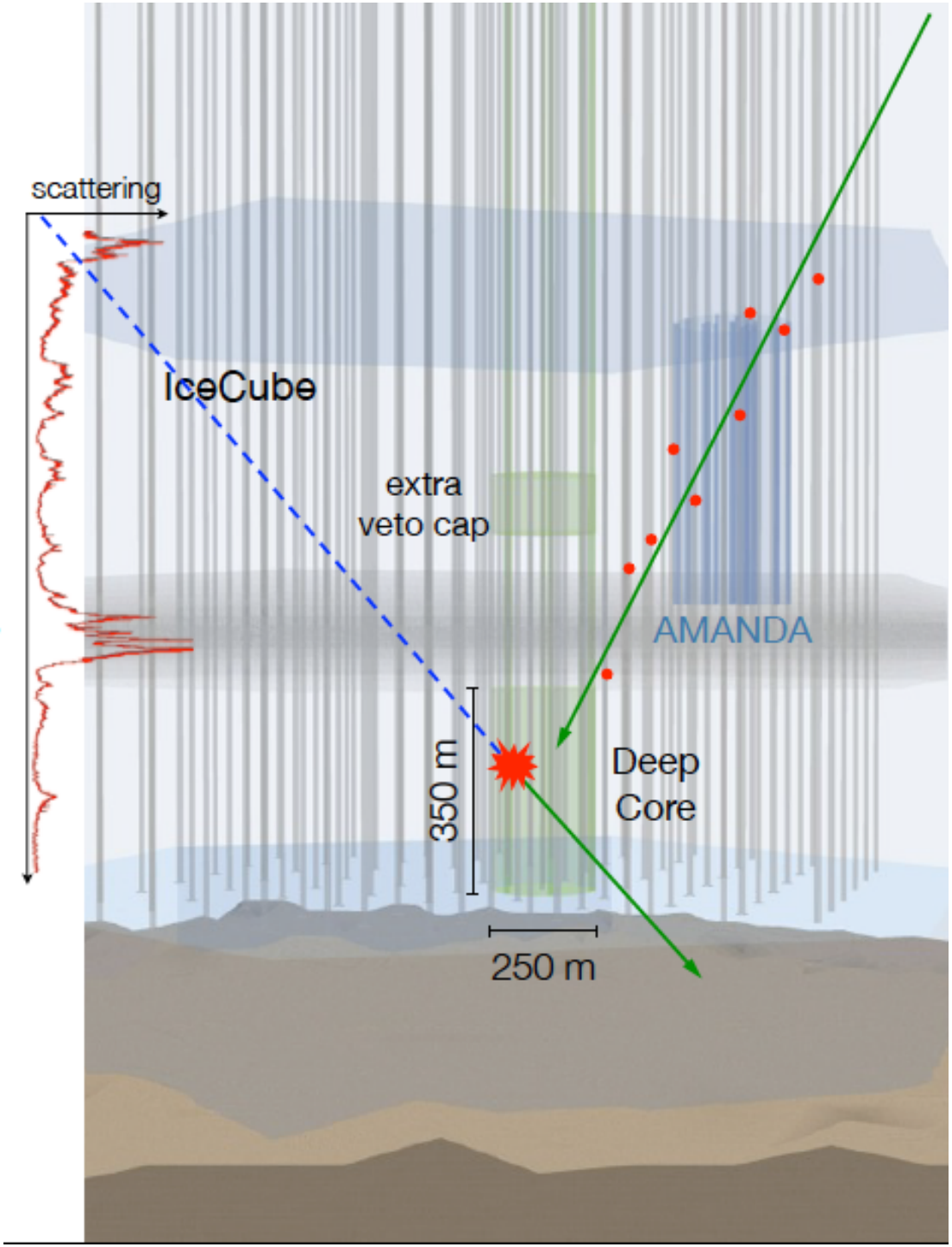
instrumented volume: x 10
same budget as IceCube

did not talk about:

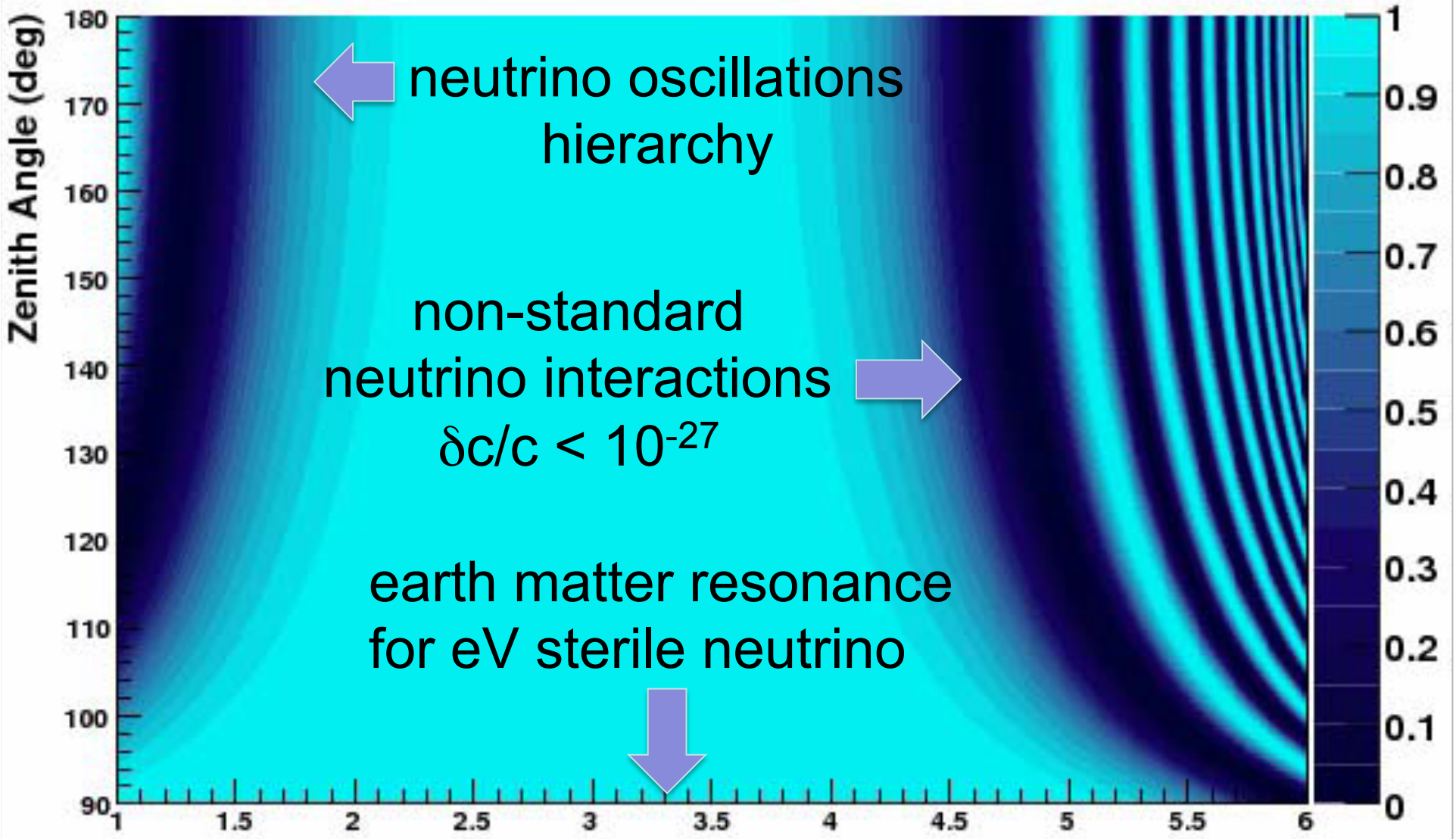
- measurement of atmospheric oscillation parameters
- supernova detection
- searches for dark matter, monopoles,…
- search for eV-mass sterile neutrinos
- PINGU/ORCA
- ….

one half million atmospheric neutrinos…





one half million atmospheric neutrinos…

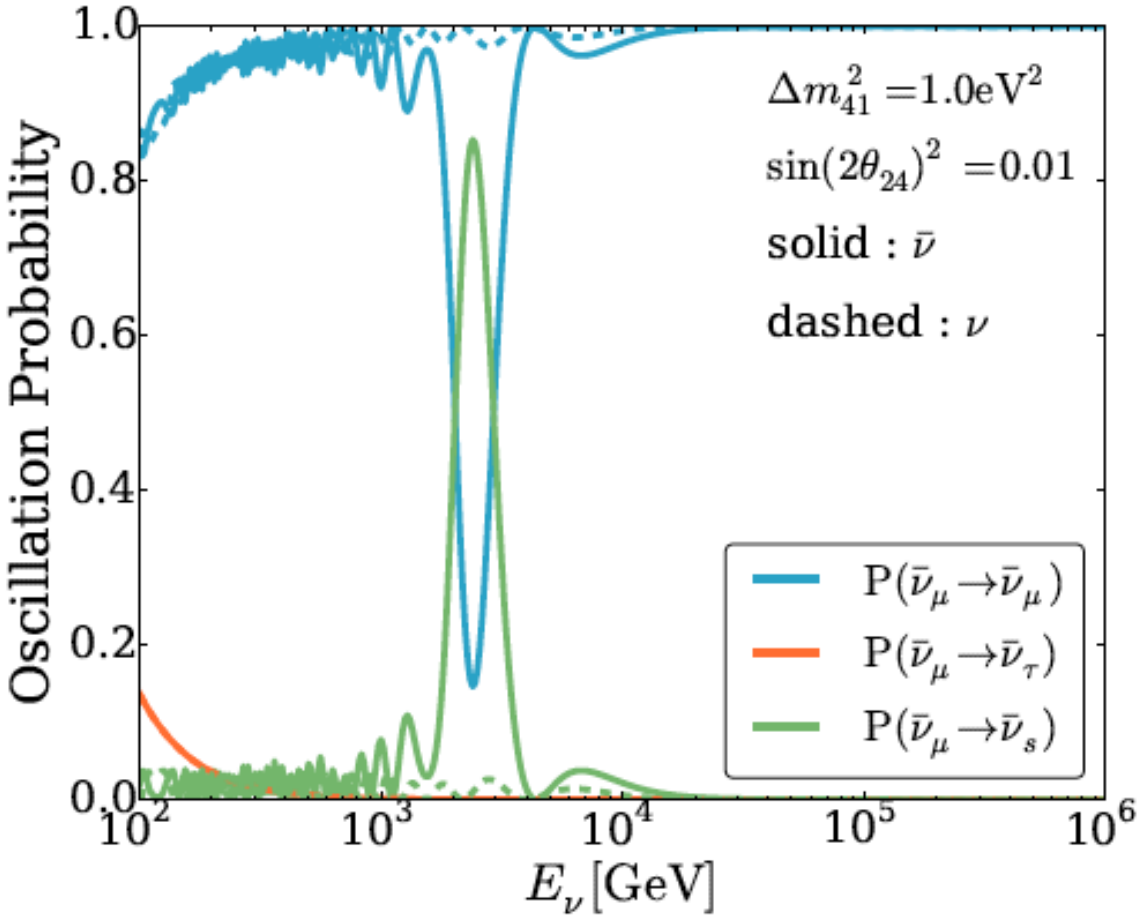


DeepCore

eV sterile neutrino → Earth MSW resonance for TeV neutrinos

In the **Earth** for sterile neutrino $\Delta m^2 = O(1eV^2)$ the MSW effect happens when

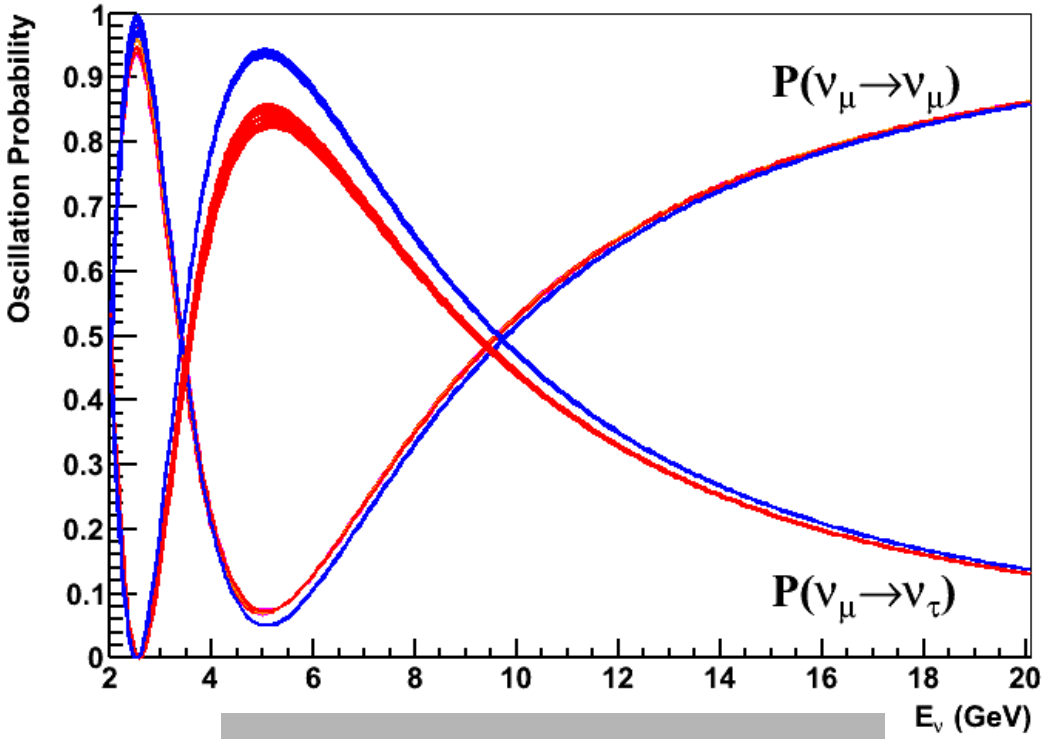
$$E_\nu = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N} \sim O(TeV)$$



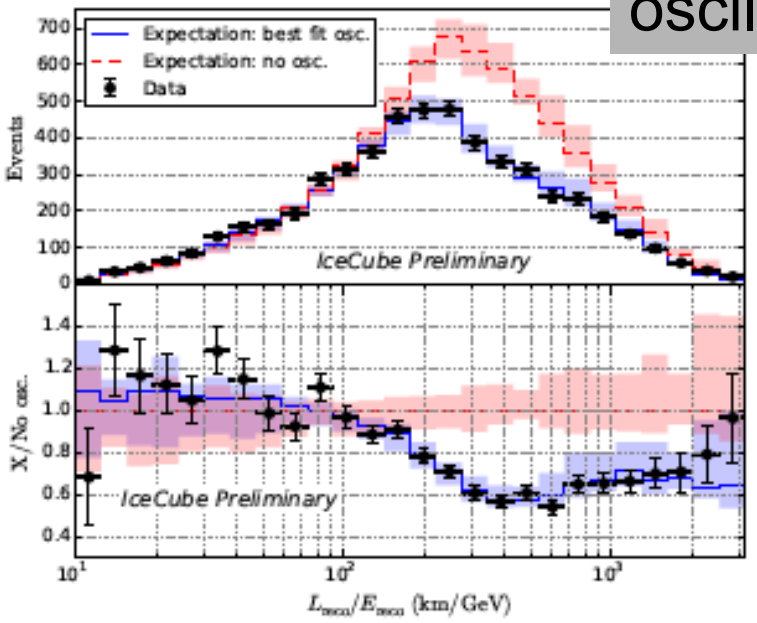
IceCube

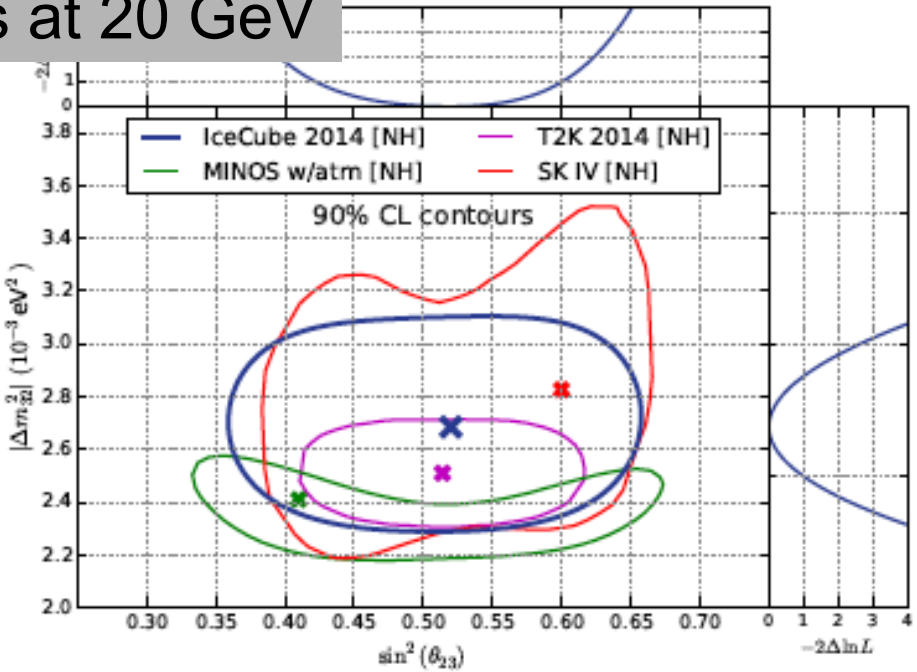
DeepCore

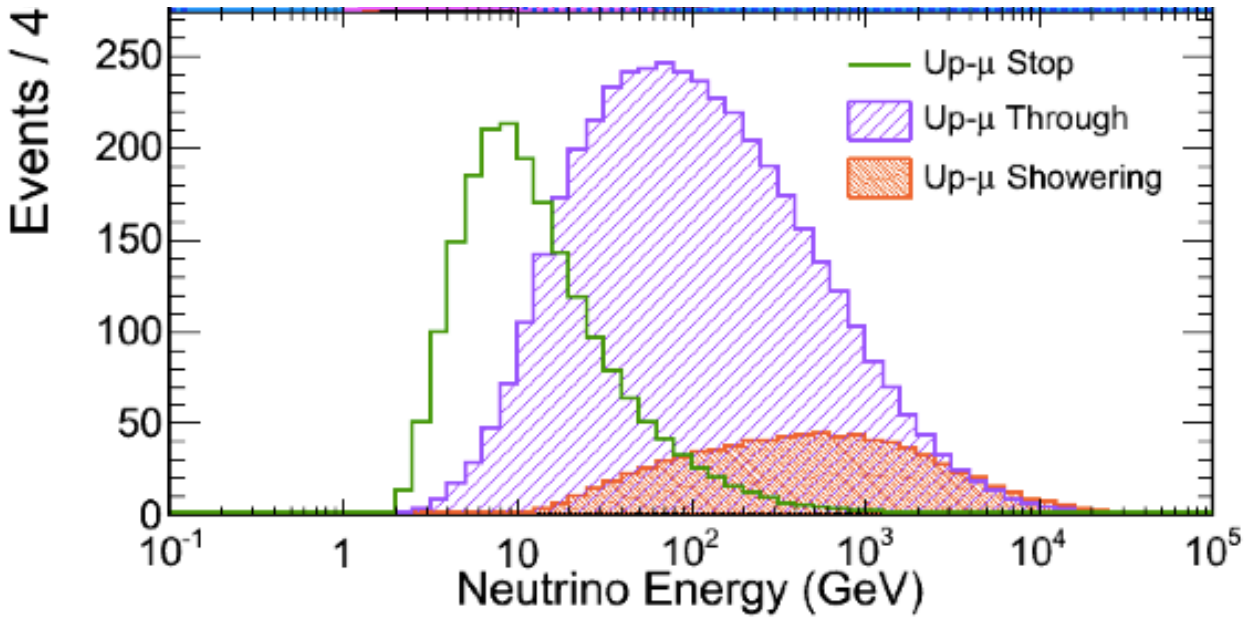
PINGU



oscillations at 20 GeV







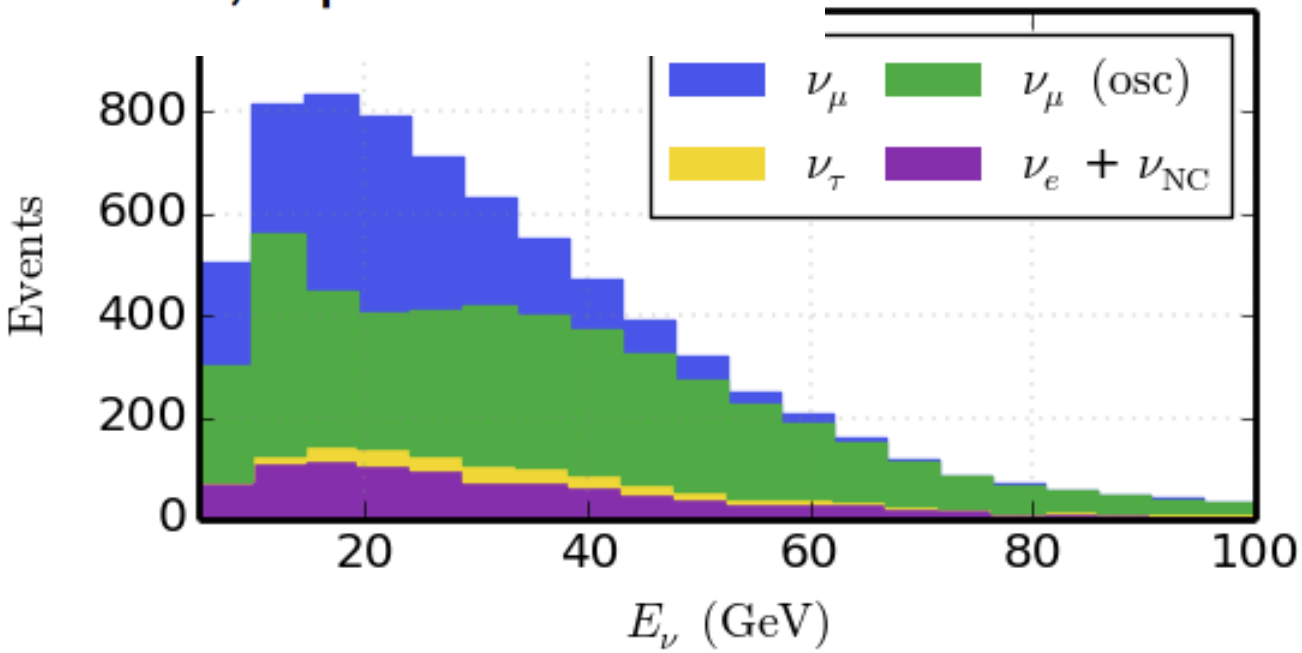
SuperK

~ 1 GeV

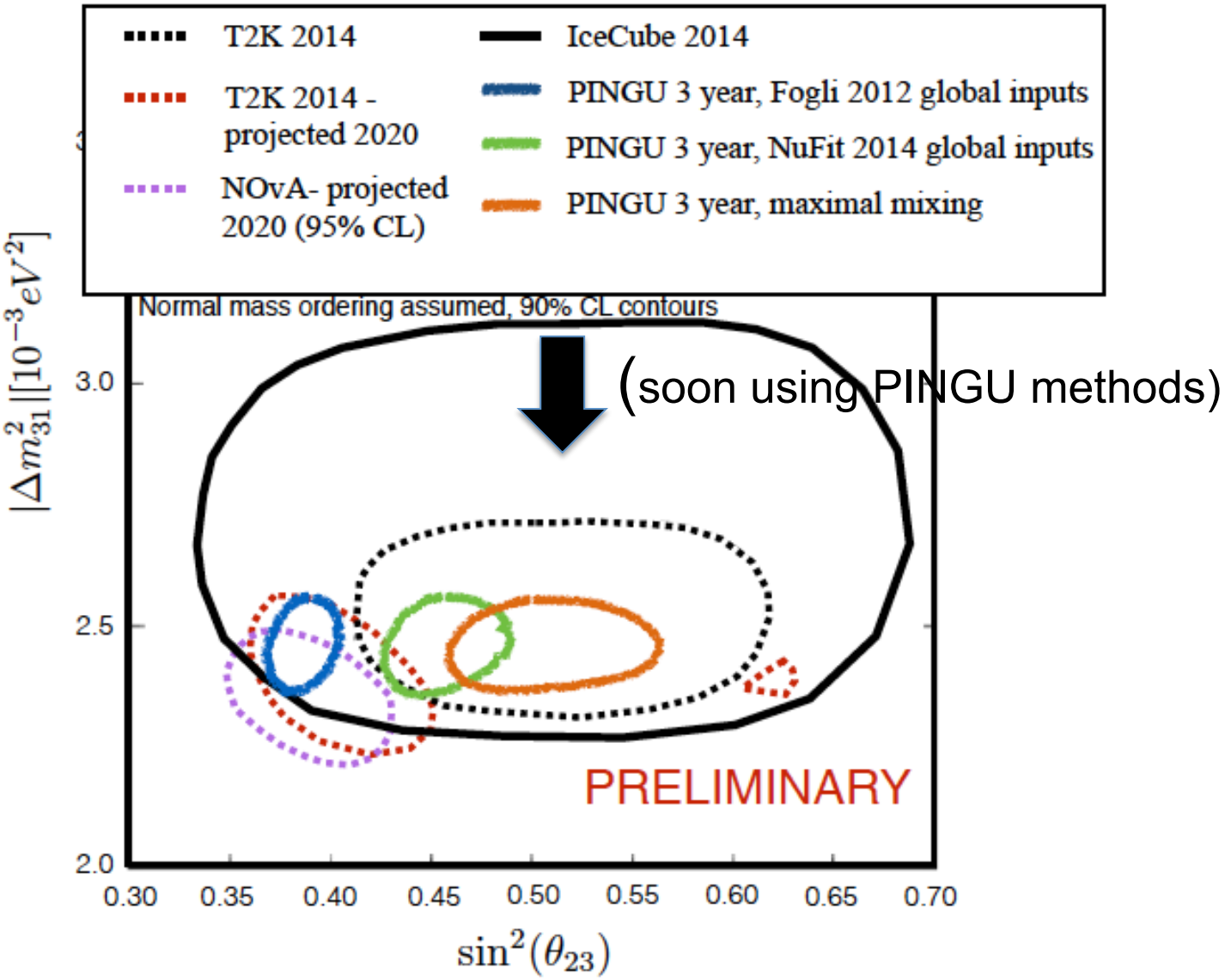
- Average energies
  - FC: ~1 GeV , PC: ~10 GeV, UpMu:~ 100 GeV

IceCube

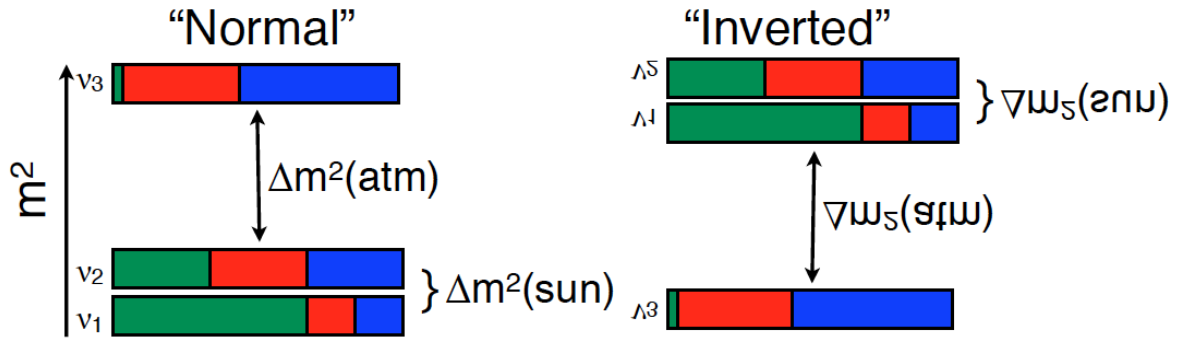
6 GeV < E_{reco} < 56 GeV

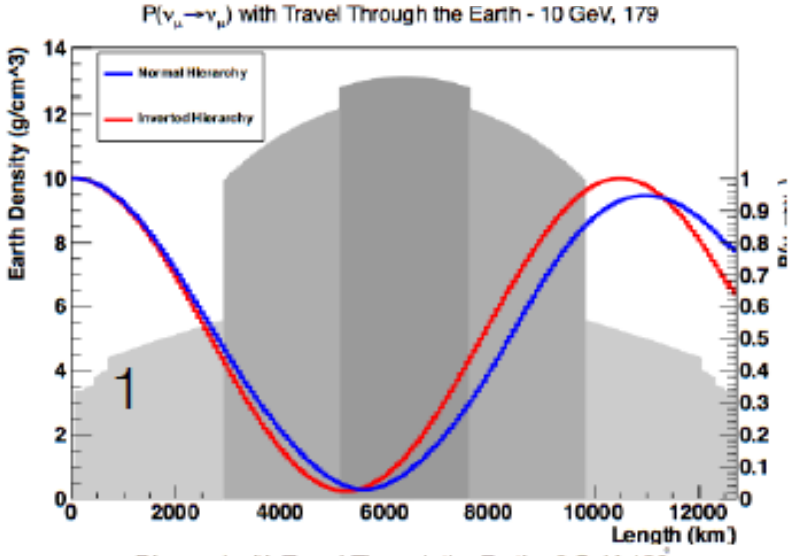


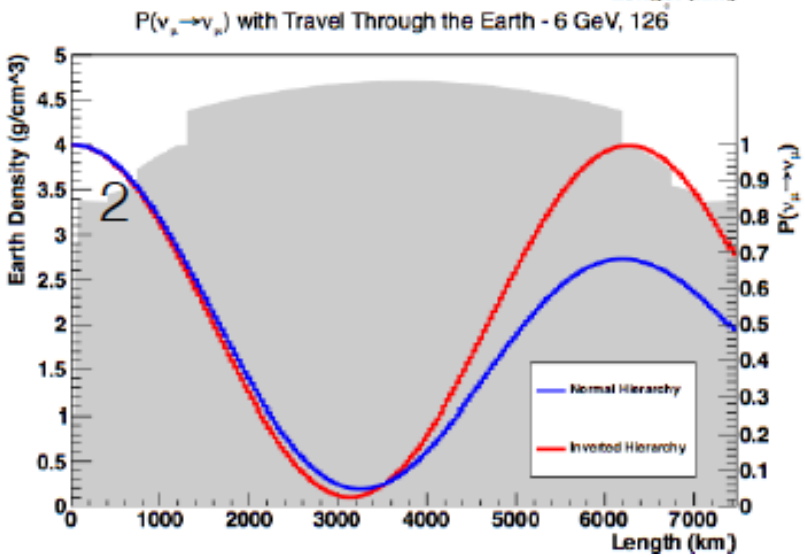
and with PINGU…

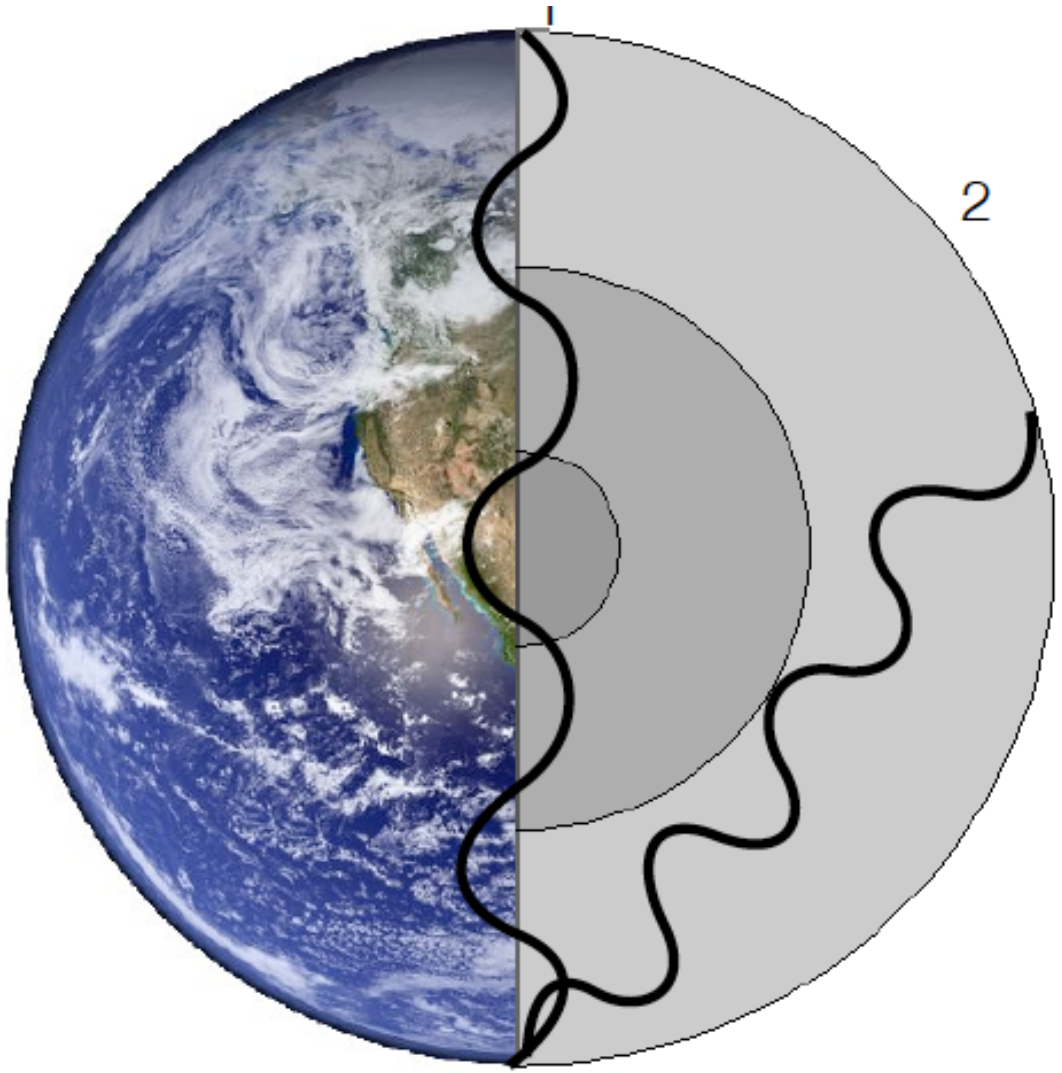


(soon using PINGU methods)


"Normal"
"Inverted"
m²
ν3
ν2
ν1
Δm²(atm)
} Δm²(sun)


P(ν_μ→ν_μ) with Travel Through the Earth - 10 GeV, 179
Normal Hierarchy
Inverted Hierarchy
Earth Density (g/cm^3)
Length (km)
1


P(ν_μ→ν_μ) with Travel Through the Earth - 6 GeV, 126
Normal Hierarchy
Inverted Hierarchy
Earth Density (g/cm^3)
Length (km)
2


2

Outlook:

- capitalize on discovery
- astronomy guaranteed
- neutrino physics at low cost and short timescale
- neutrinos are never boring!

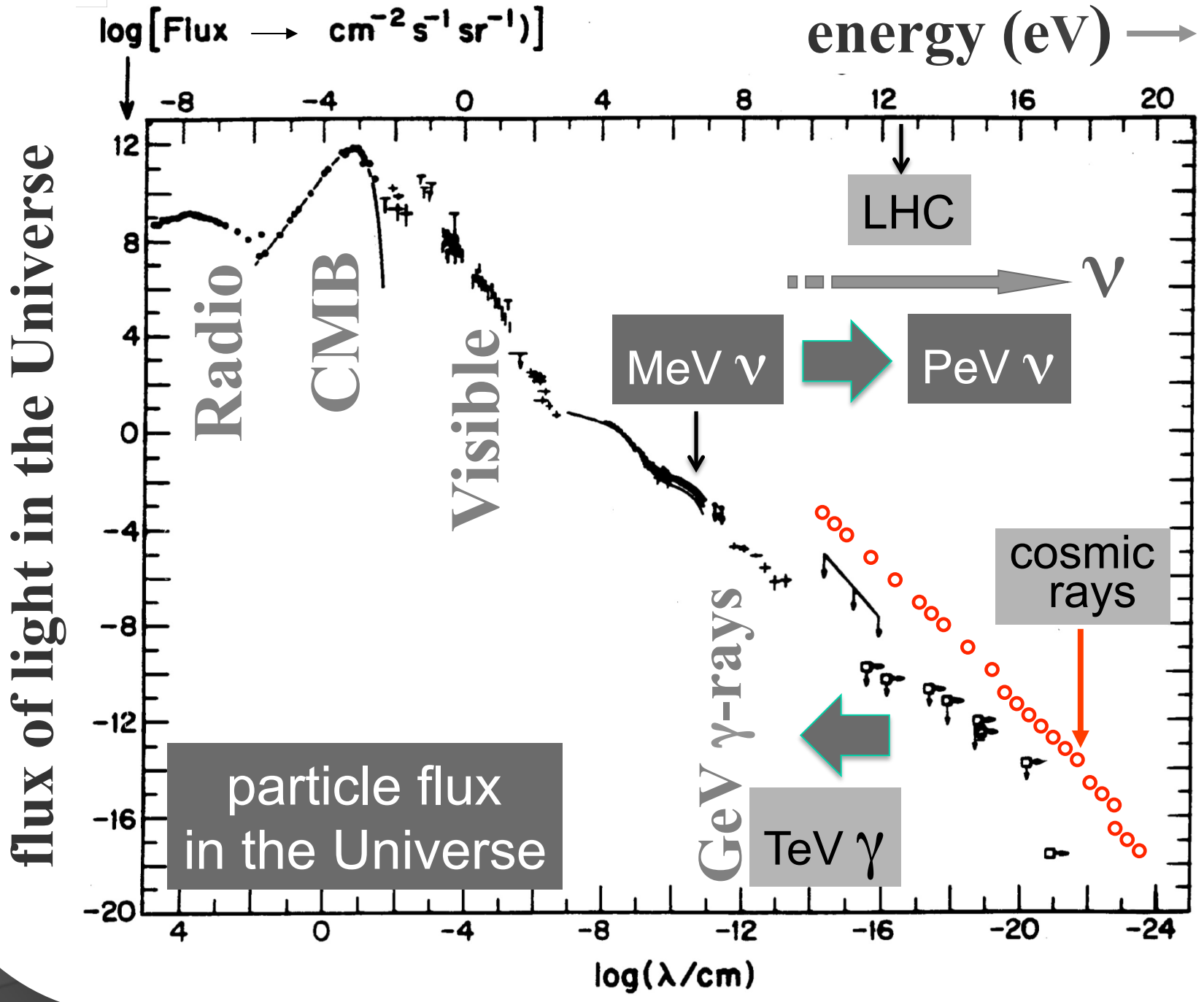
from discovery to astronomical telescopes:
parallel development in the Mediterranean
ANTARES → KM3NeT
Baikal → GVD

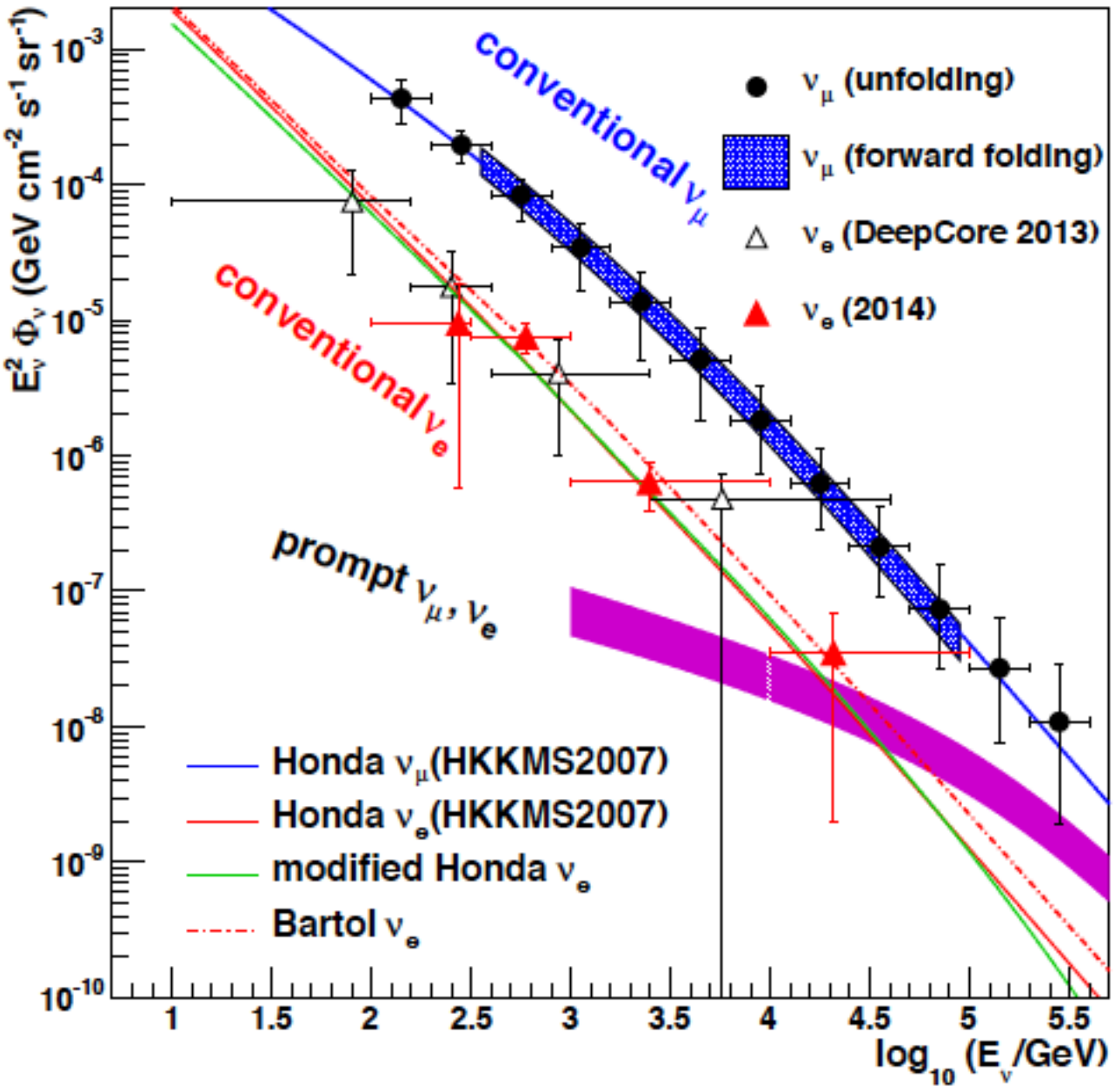

ANTARES → KM3NeT

The IceCube–PINGU Collaboration

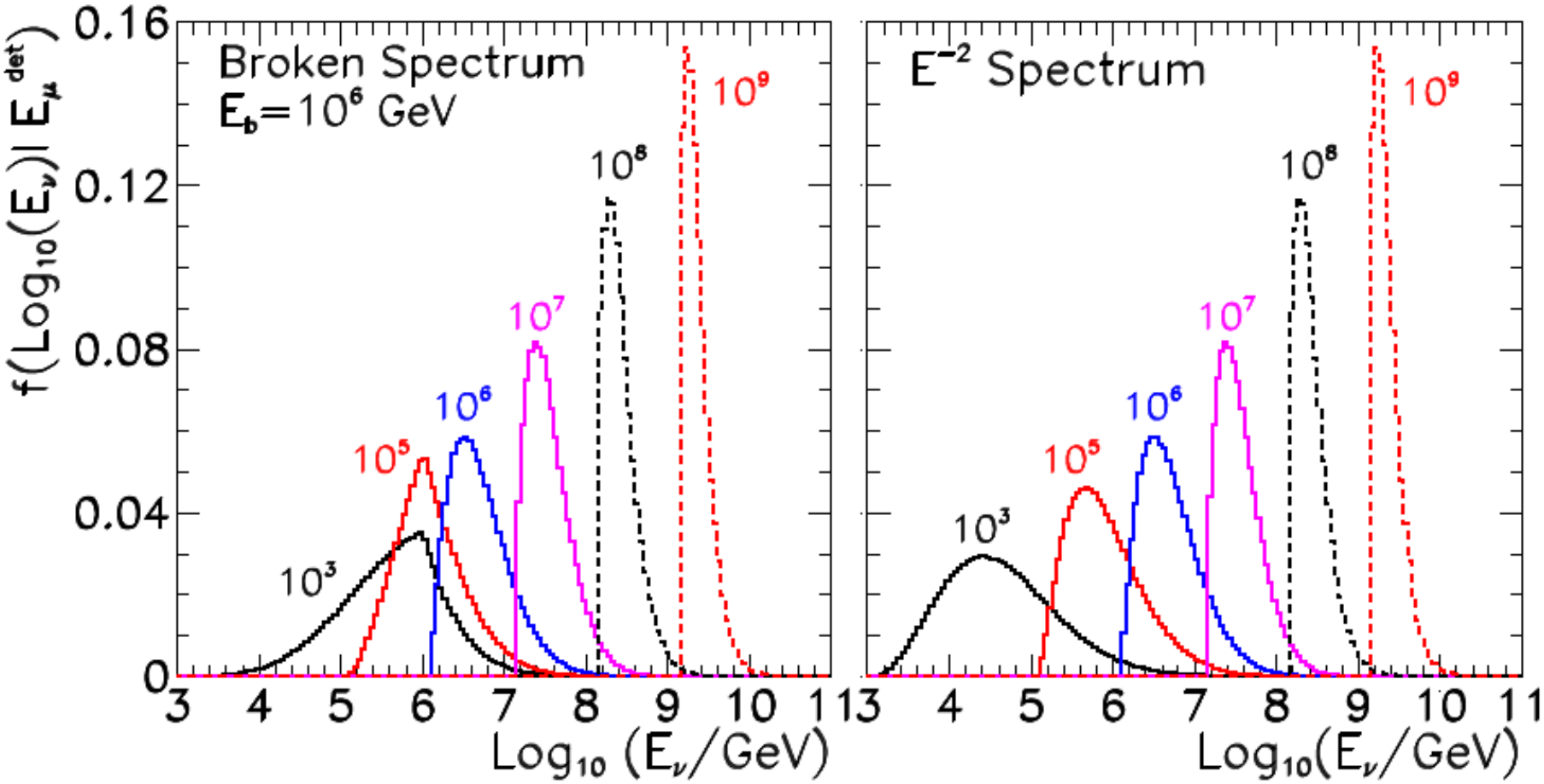
International Funding Agencies

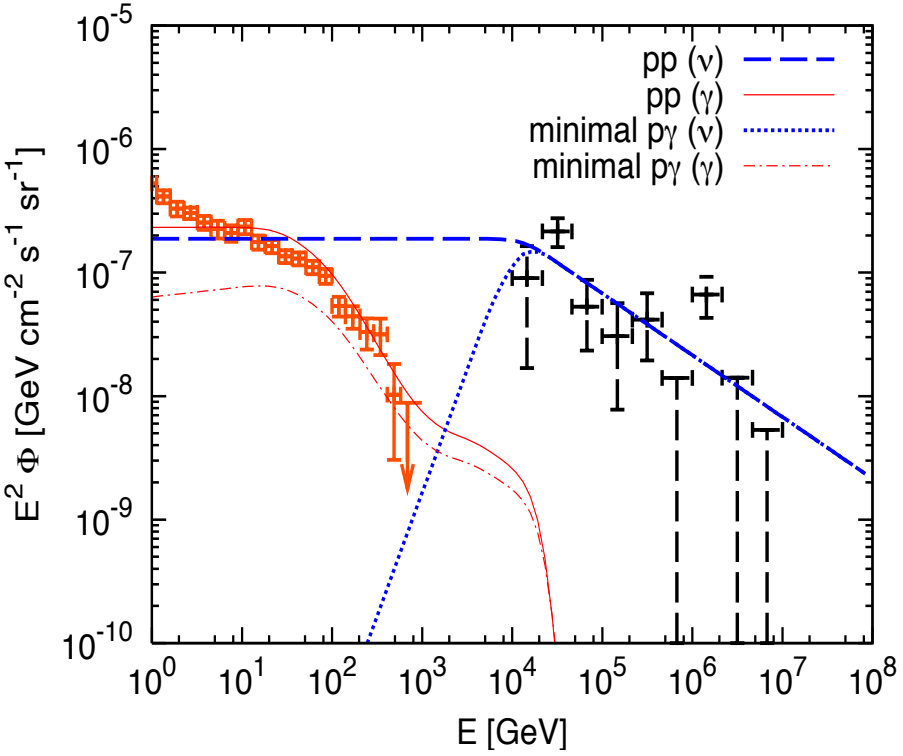
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek–Vlaanderen (FWO–Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen–Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
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)

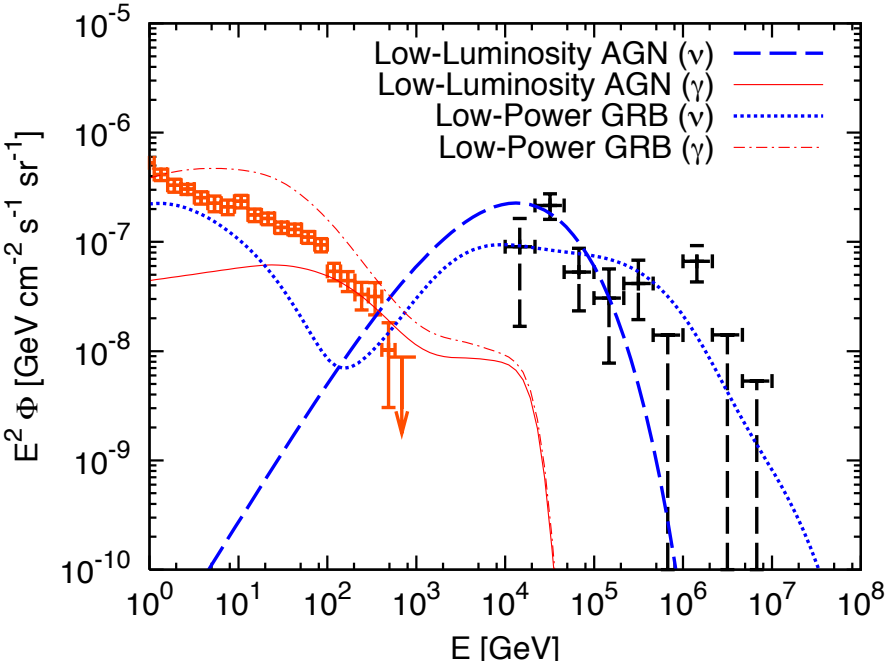

log [Flux → cm⁻² s⁻¹ sr⁻¹)]
energy (eV) →
flux of light in the Universe
log(λ/cm)
Radio
CMB
Visible
GeV γ-rays
LHC
ν
MeV ν
PeV ν
cosmic rays
TeV γ
particle flux in the Universe


$E_\nu^2 \Phi_\nu$ (GeV cm^{-2} s^{-1} sr^{-1})
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
$\log_{10}(E_\nu/\mathrm{GeV})$
conventional ν_μ
conventional ν_e
prompt ν_μ, ν_e
ν_μ (unfolding)
ν_μ (forward folding)
ν_e (DeepCore 2013)
ν_e (2014)
Honda ν_μ(HKKMS2007)
Honda ν_e(HKKMS2007)
modified Honda ν_e
Bartol ν_e

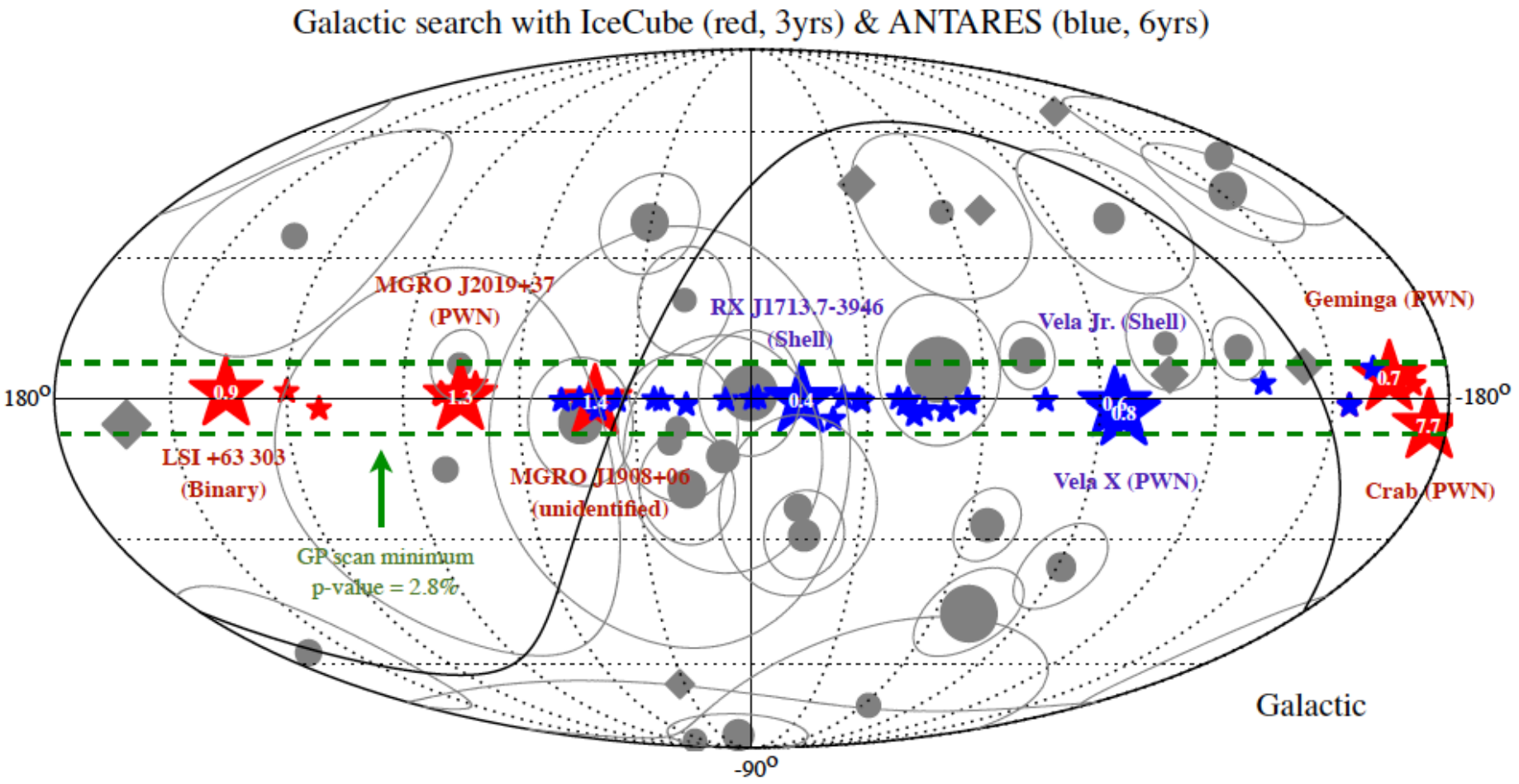
distribution of the parent neutrino energy corresponding to the energy deposited by the secondary muon inside IceCube




pp (ν)
pp (γ)
minimal pγ (ν)
minimal pγ (γ)
E² Φ [GeV cm⁻² s⁻¹ sr⁻¹]
E [GeV]


Low-Luminosity AGN (ν)
Low-Luminosity AGN (γ)
Low-Power GRB (ν)
Low-Power GRB (γ)
E² Φ [GeV cm⁻² s⁻¹ sr⁻¹]
E [GeV]

ratio of present limit / predicted neutrino flux



even for Galactic sources the photon to neutrino conversation implies that we are close to detecting neutrinos from known high energy gamma ray emitters