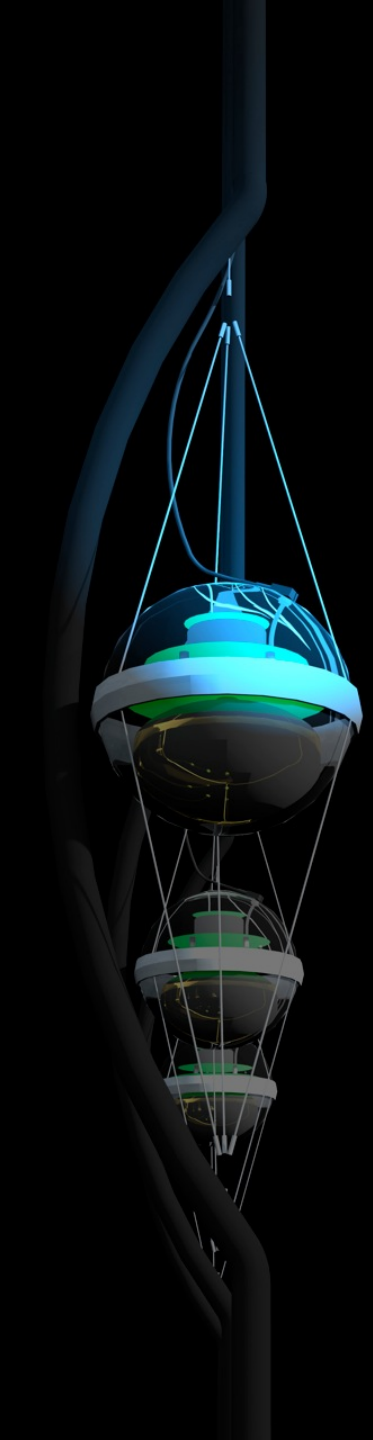
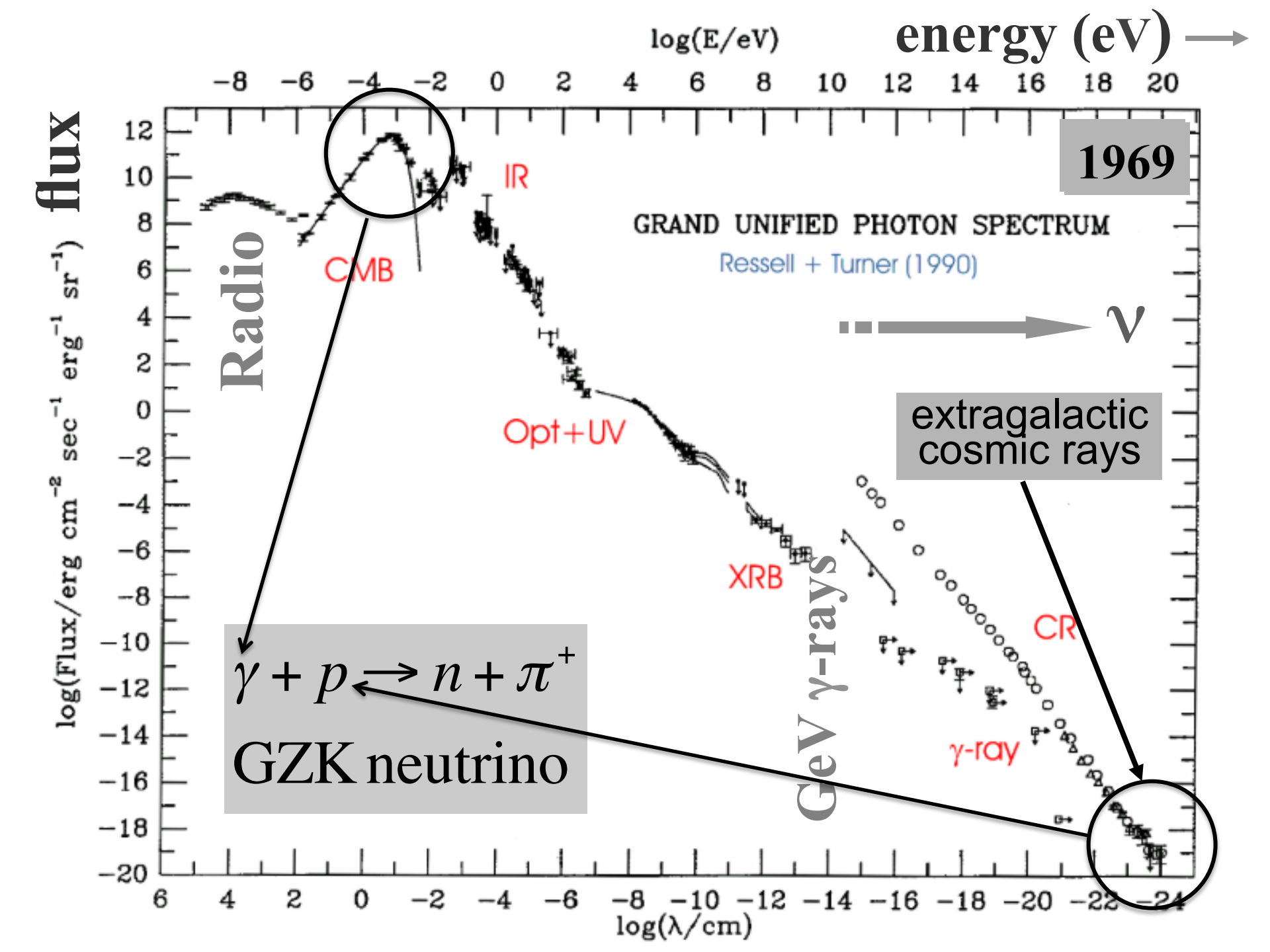


IceCube: the discovery of cosmic neutrinos

francis halzen

- cosmic ray accelerators
- IceCube
- the discovery of cosmic neutrinos ν_{μ}
- the discovery of cosmic neutrinos $\nu_{e,\tau}$
- where do they come from?
- what next

IceCube.wisc.edu


energy (eV)
log(E/eV)
flux
log(Flux/erg cm^{-2} sec^{-1} erg^{-1} sr^{-1})
log(λ/cm)
1969
GRAND UNIFIED PHOTON SPECTRUM
Ressell + Turner (1990)
Radio
CMB
IR
Opt+UV
XRB
GeV γ-rays
CR
γ-ray
ν
extragalactic cosmic rays
$\gamma + p \rightleftharpoons n + \pi^+$
GZK neutrino

cosmic rays interact with the microwave background

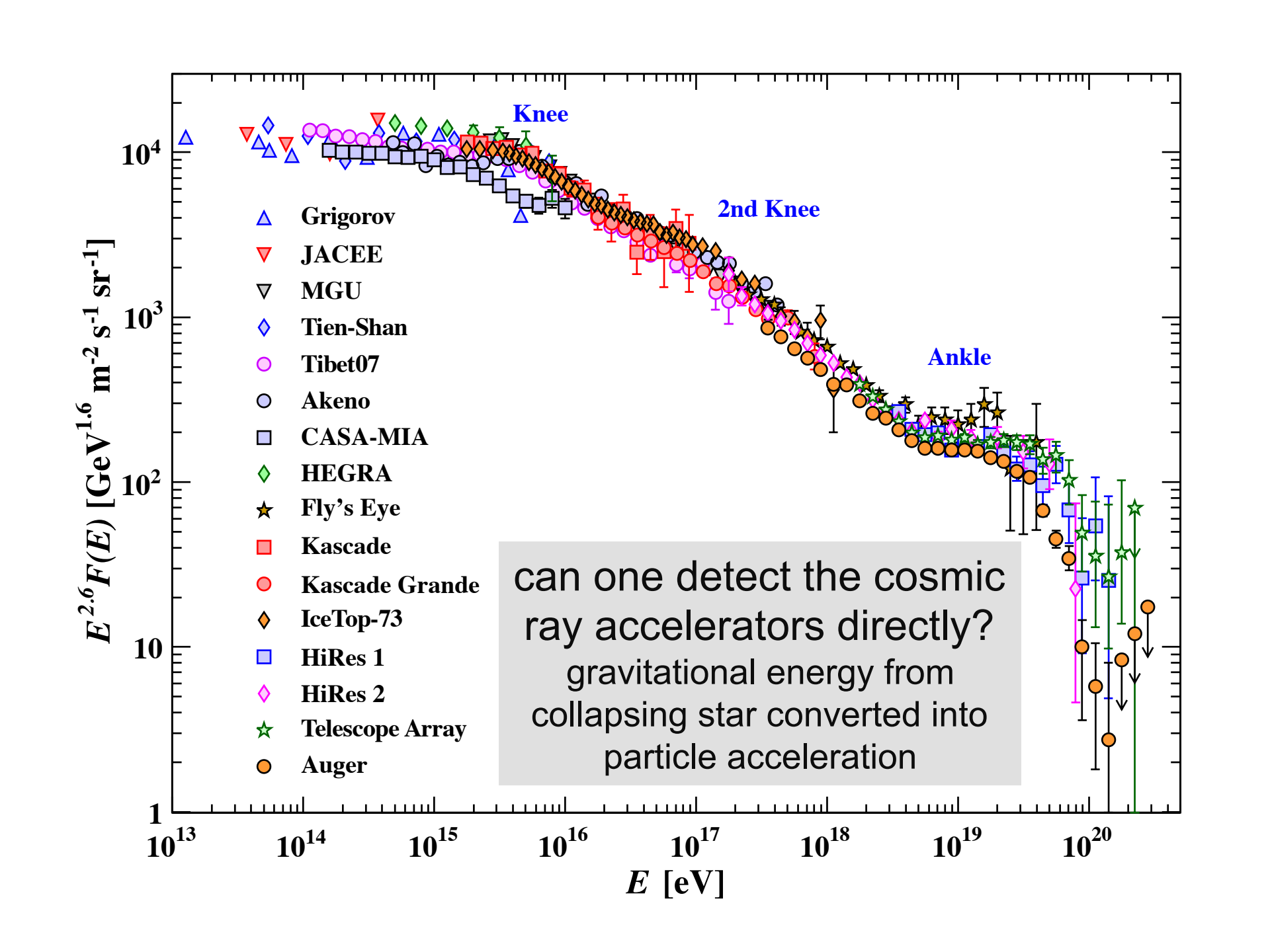
$$p + \gamma \rightarrow n + \pi^{+} \; and \; p + \pi^{0}$$

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

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

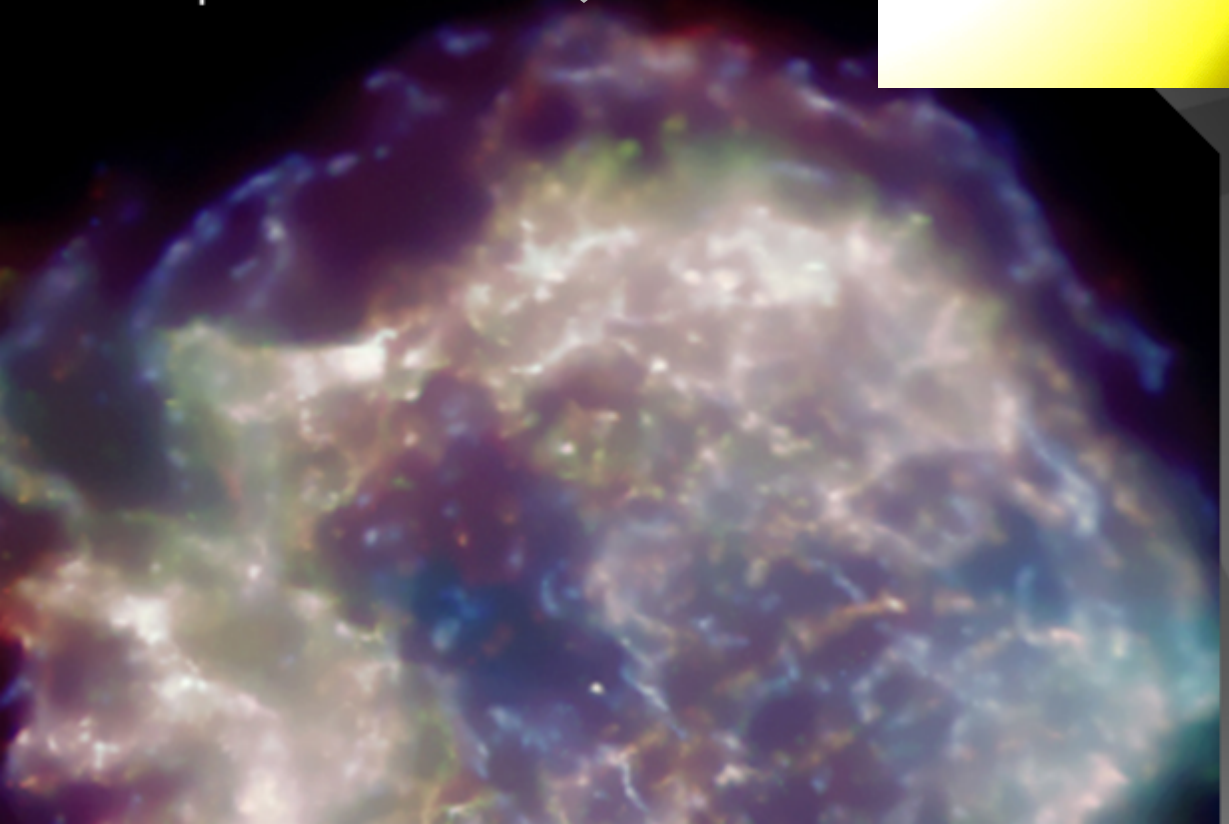
1 event per cubic kilometer per year

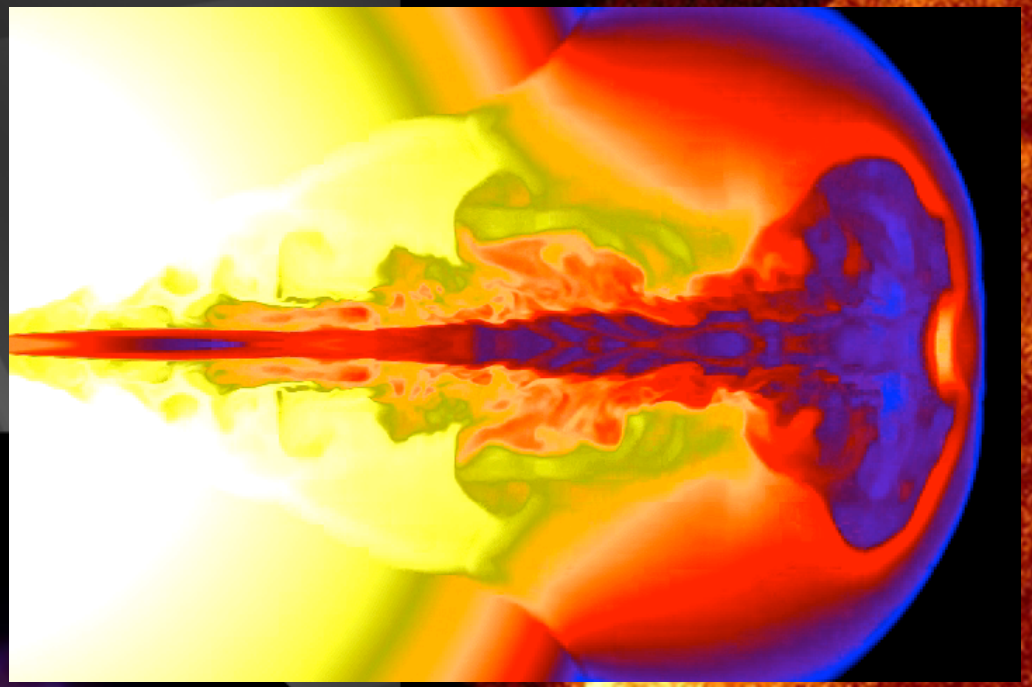
...but it points at its source!


Knee
2nd Knee
Ankle
Grigorov
JACEE
MGU
Tien-Shan
Tibet07
Akeno
CASA-MIA
HEGRA
Fly's Eye
Kascade
Kascade Grande
IceTop-73
HiRes 1
HiRes 2
Telescope Array
Auger
$E^{2.6}F(E)$ [GeV$^{1.6}$ m^{-2} s^{-1} sr^{-1}]
E [eV]
10^{4}
10^{3}
10^{2}
10
1
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
can one detect the cosmic ray accelerators directly?
gravitational energy from collapsing star converted into particle acceleration

supernova remnants

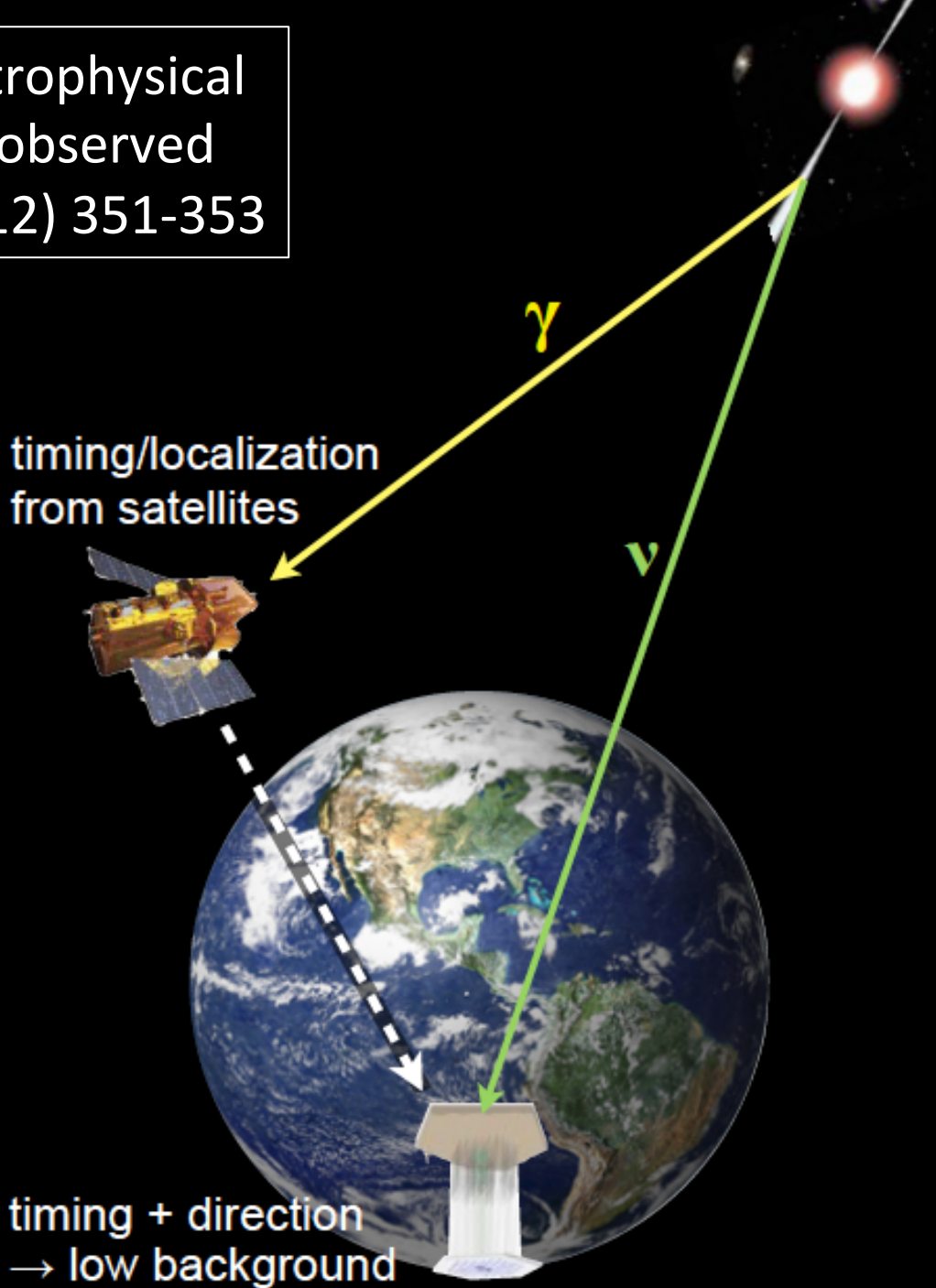
Chandra
Cassiopeia A

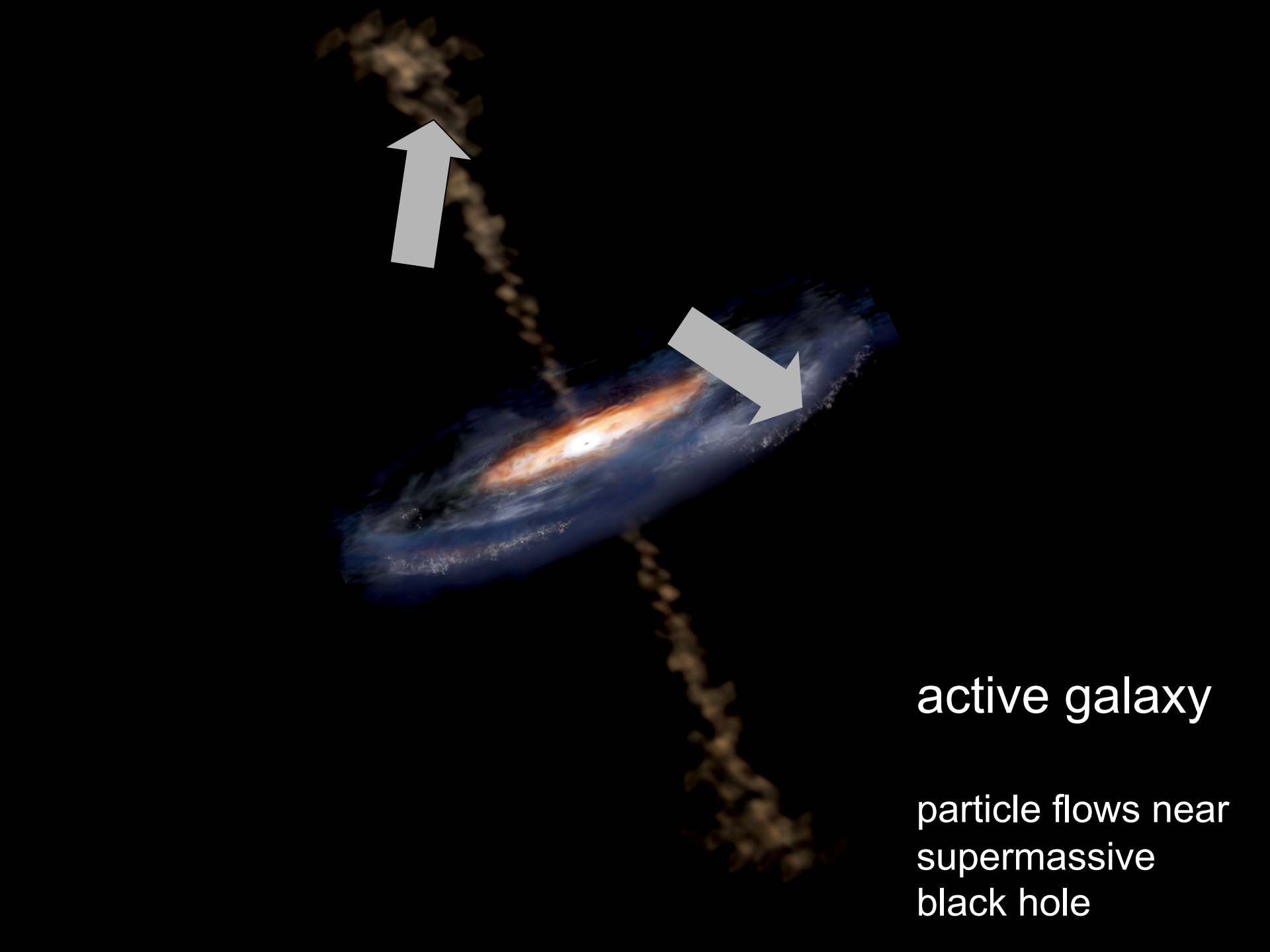




gamma ray bursts

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

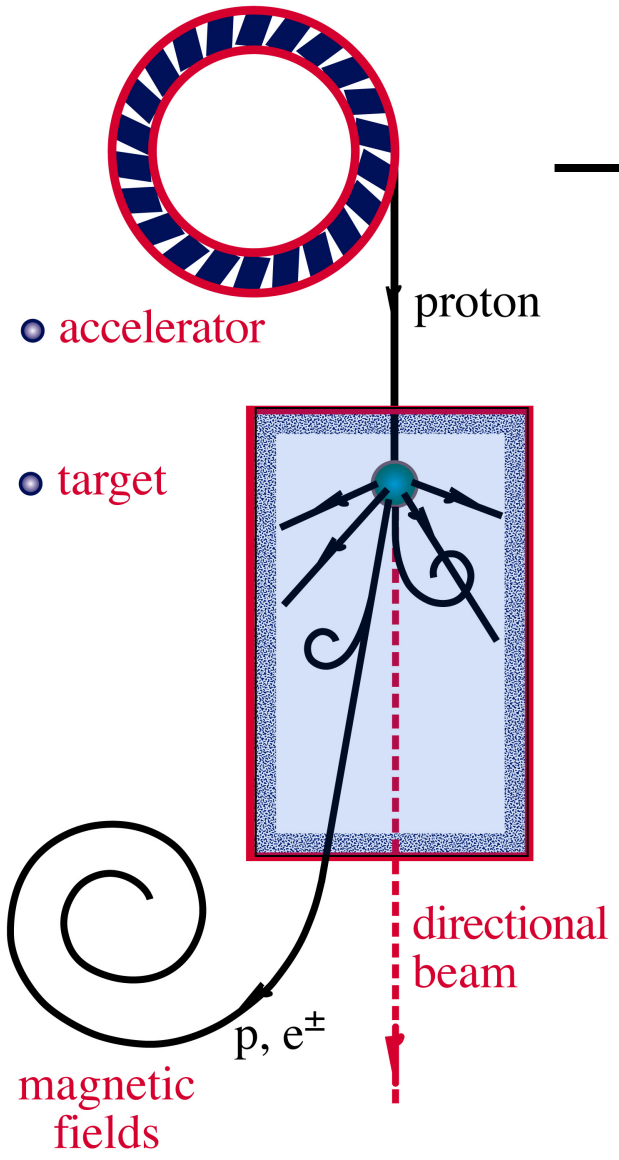




active galaxy

particle flows near supermassive black hole

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

$\rightarrow p + \pi^0$

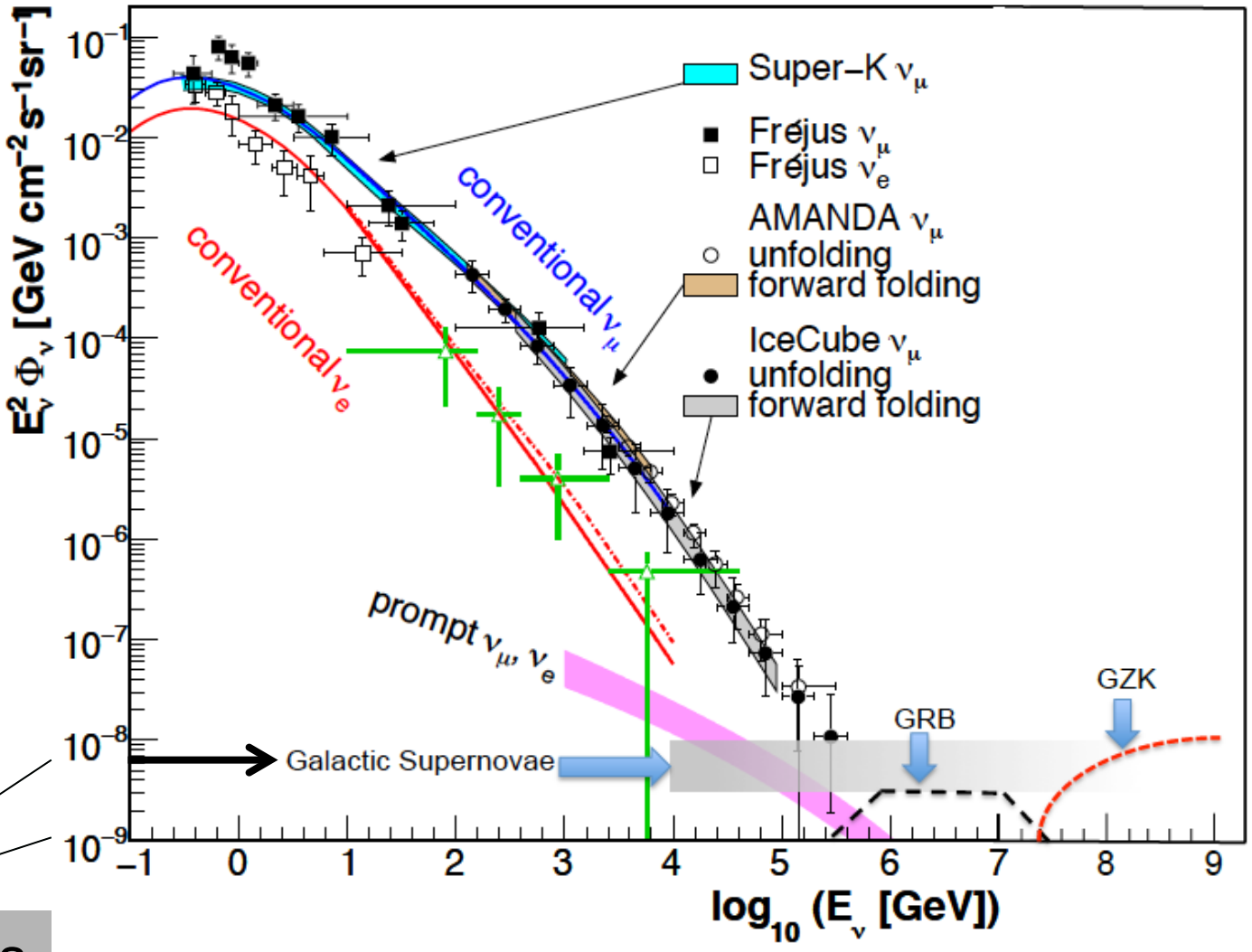
~ cosmic ray + gamma

above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

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

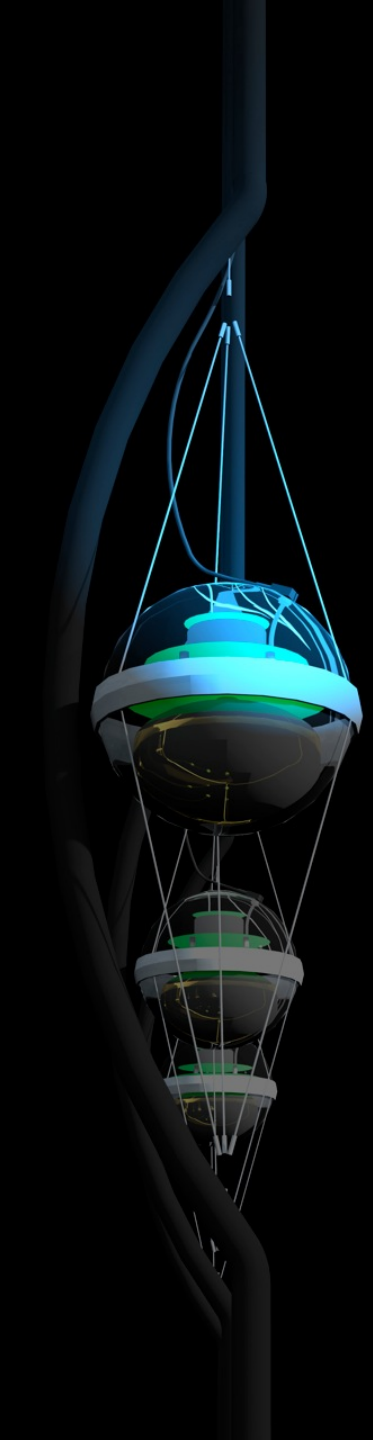
10—100 events per year for fully efficient 1 km^3 detector



atmospheric

cosmic

100 TeV



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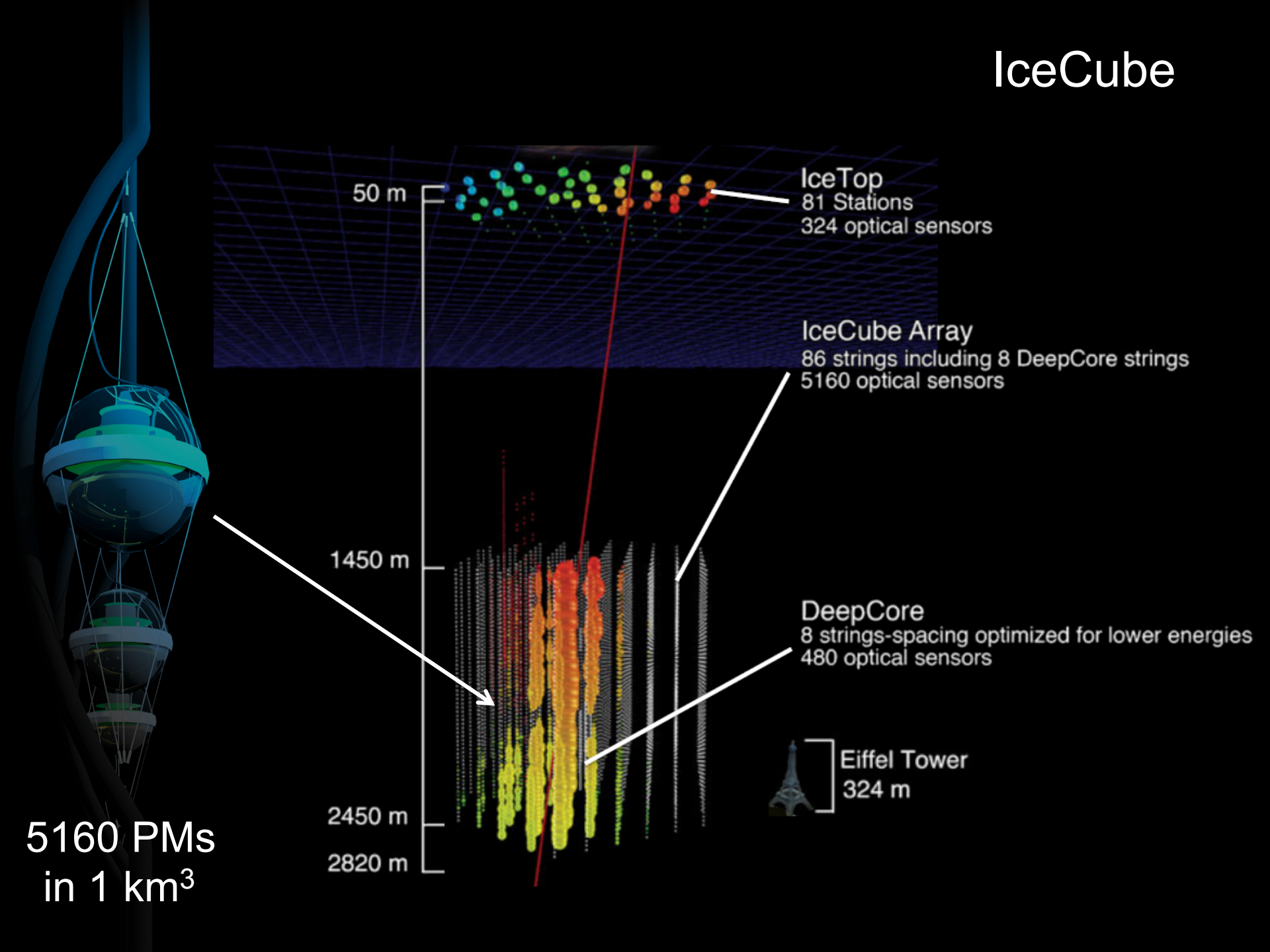
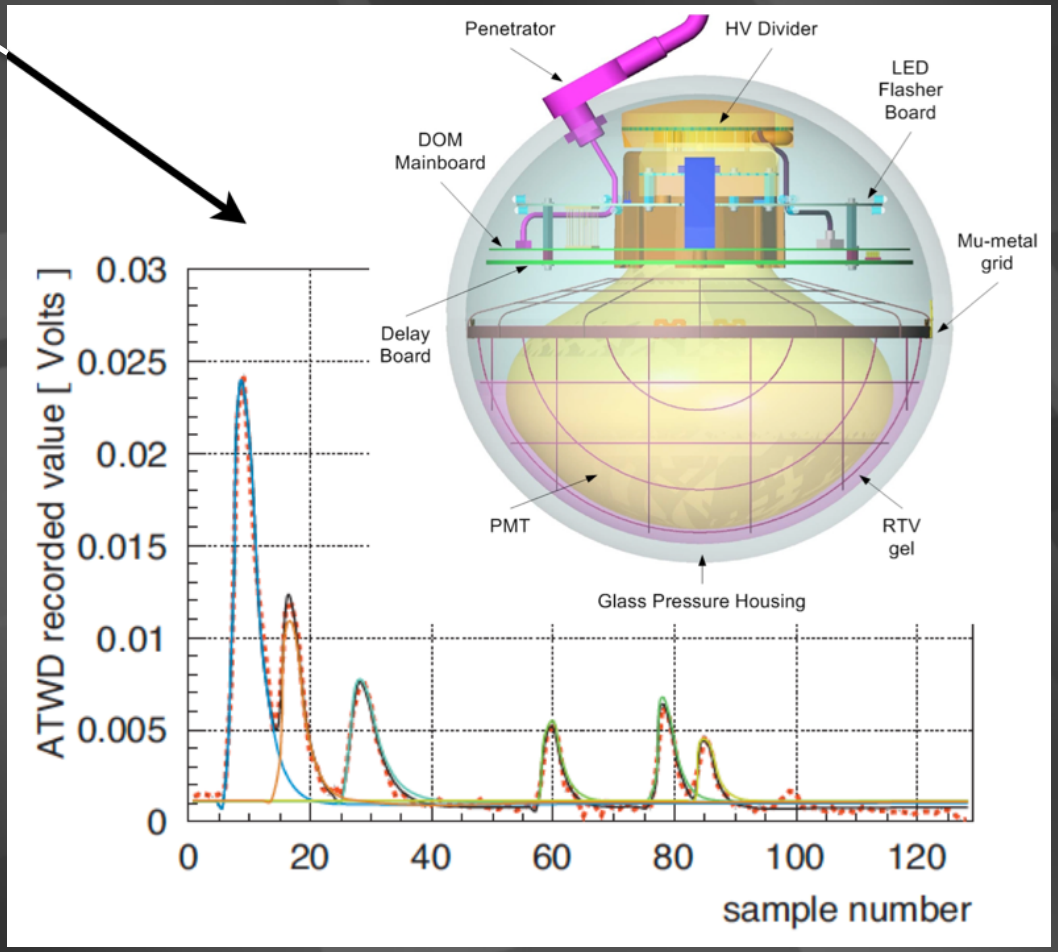
IceCube.wisc.edu


ultra-transparent ice below 1.5 km

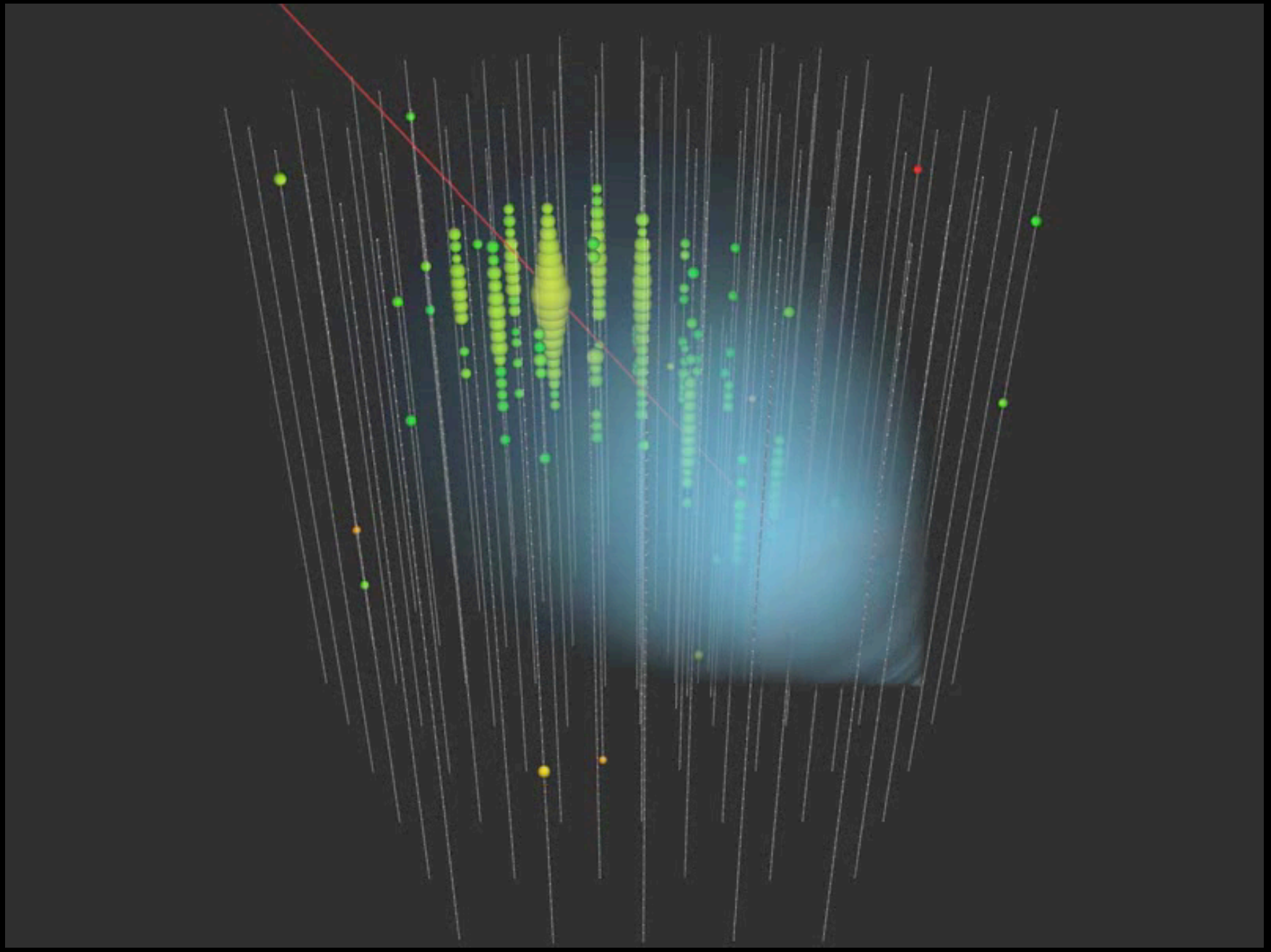
IceCube


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

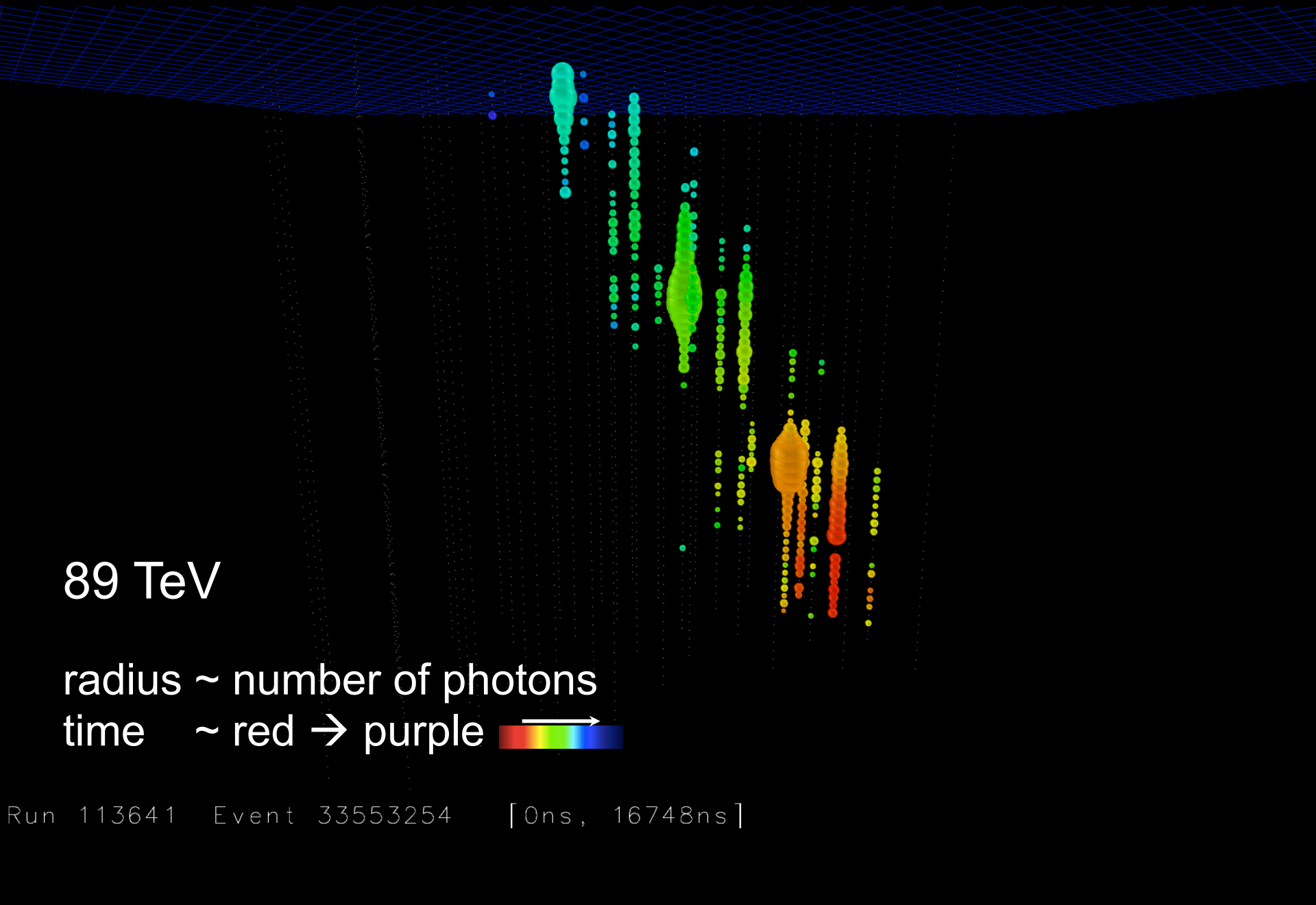
… each Digital Optical Module independently collects light signals like this, digitizes them,

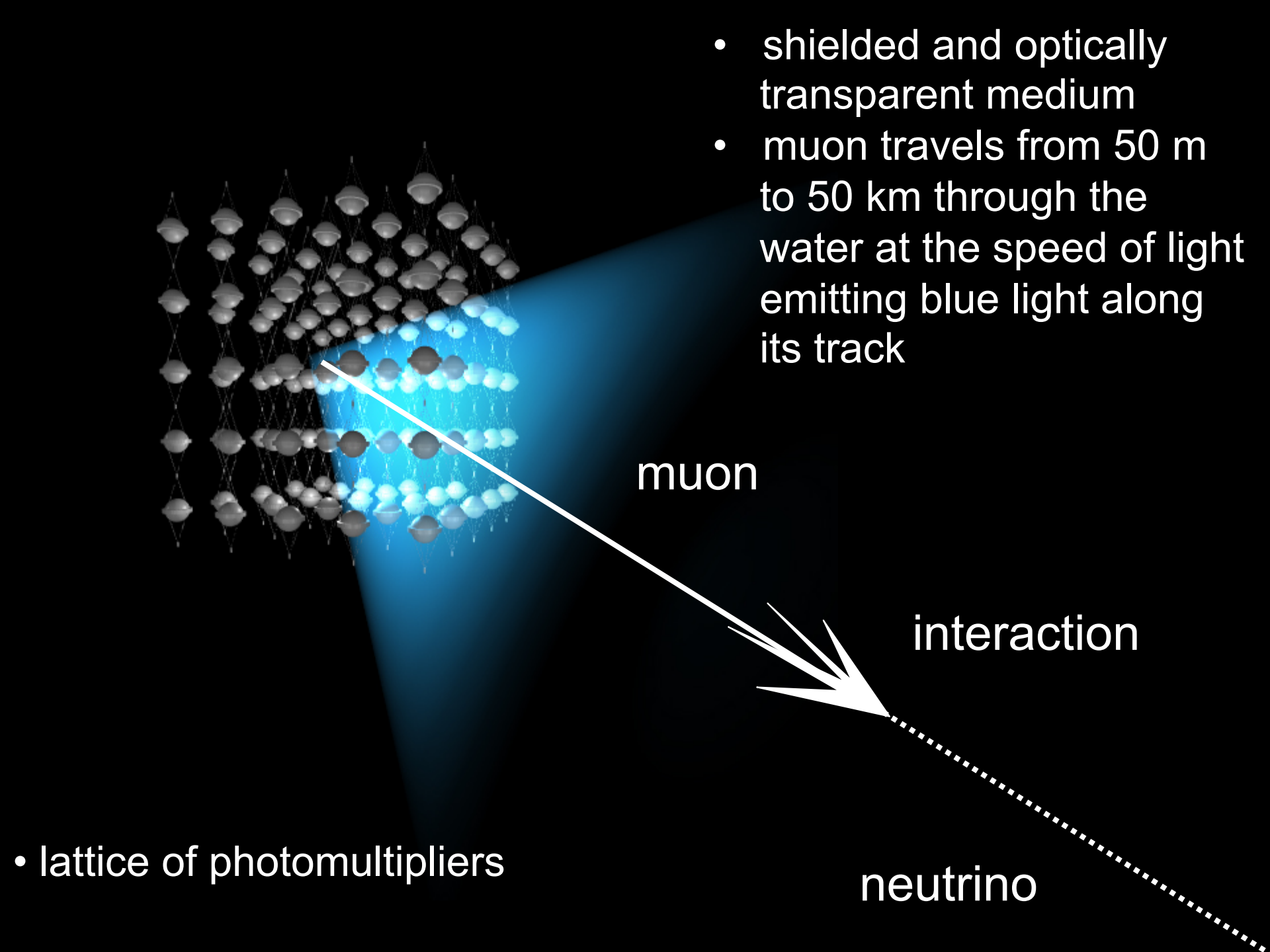


…time stamps them with 2 nanoseconds precision, and sends them to a computer that sorts them events…

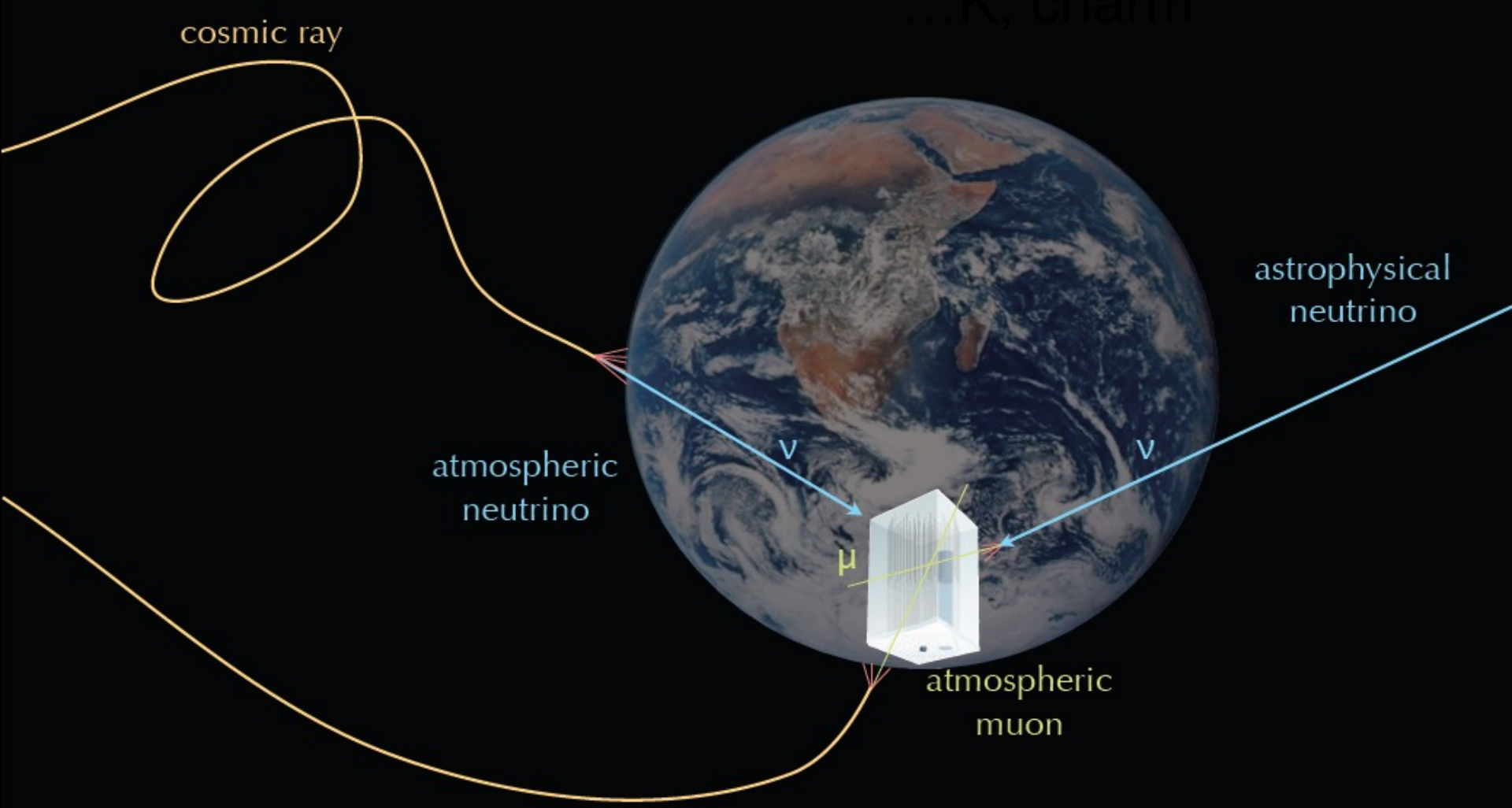


muon track: color is time; number of photons is energy


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


• 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

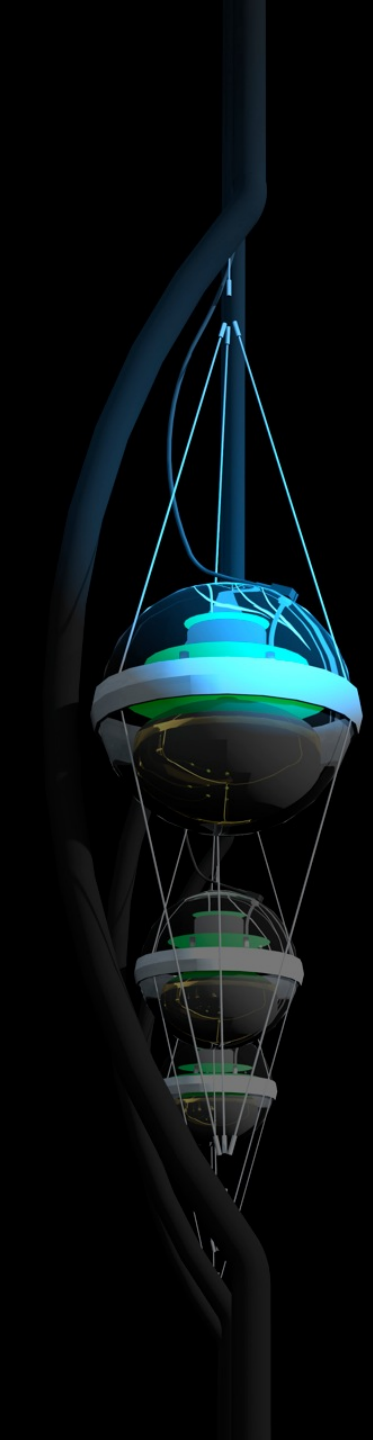
Signals and Backgrounds



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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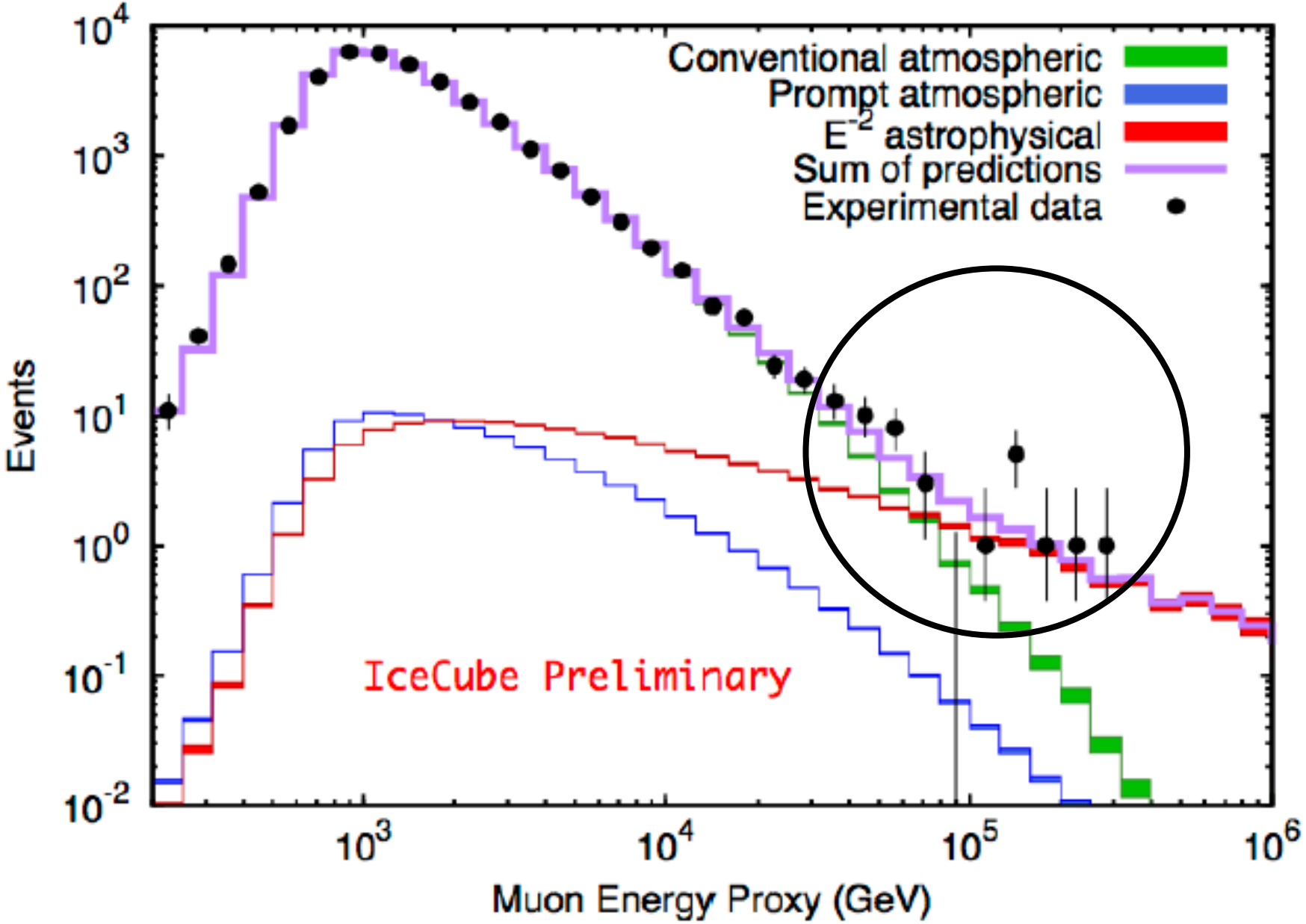
IceCube.wisc.edu

cosmic neutrinos in 2 years of data at 3.7 sigma

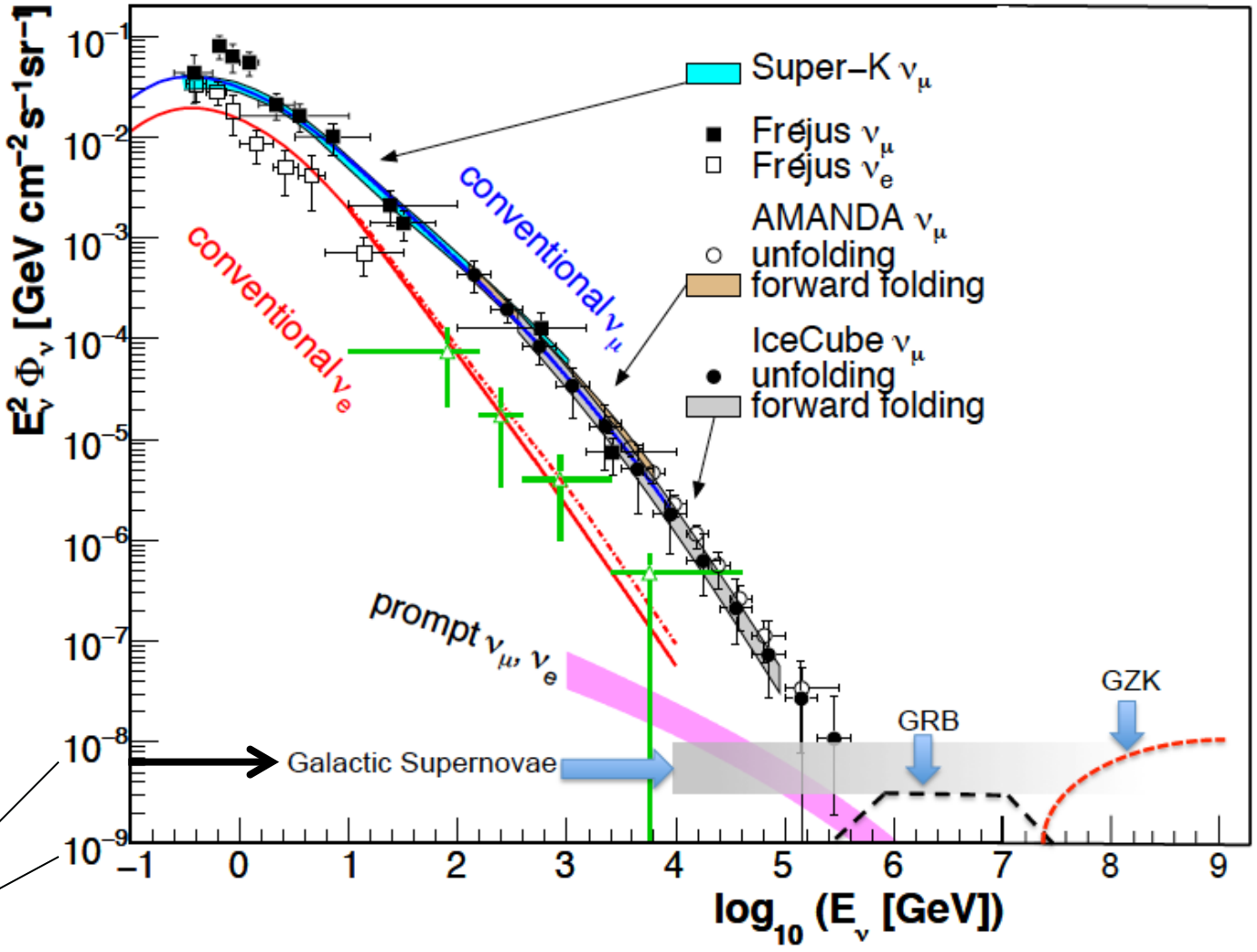


above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

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

10—100 events per year for fully efficient detector

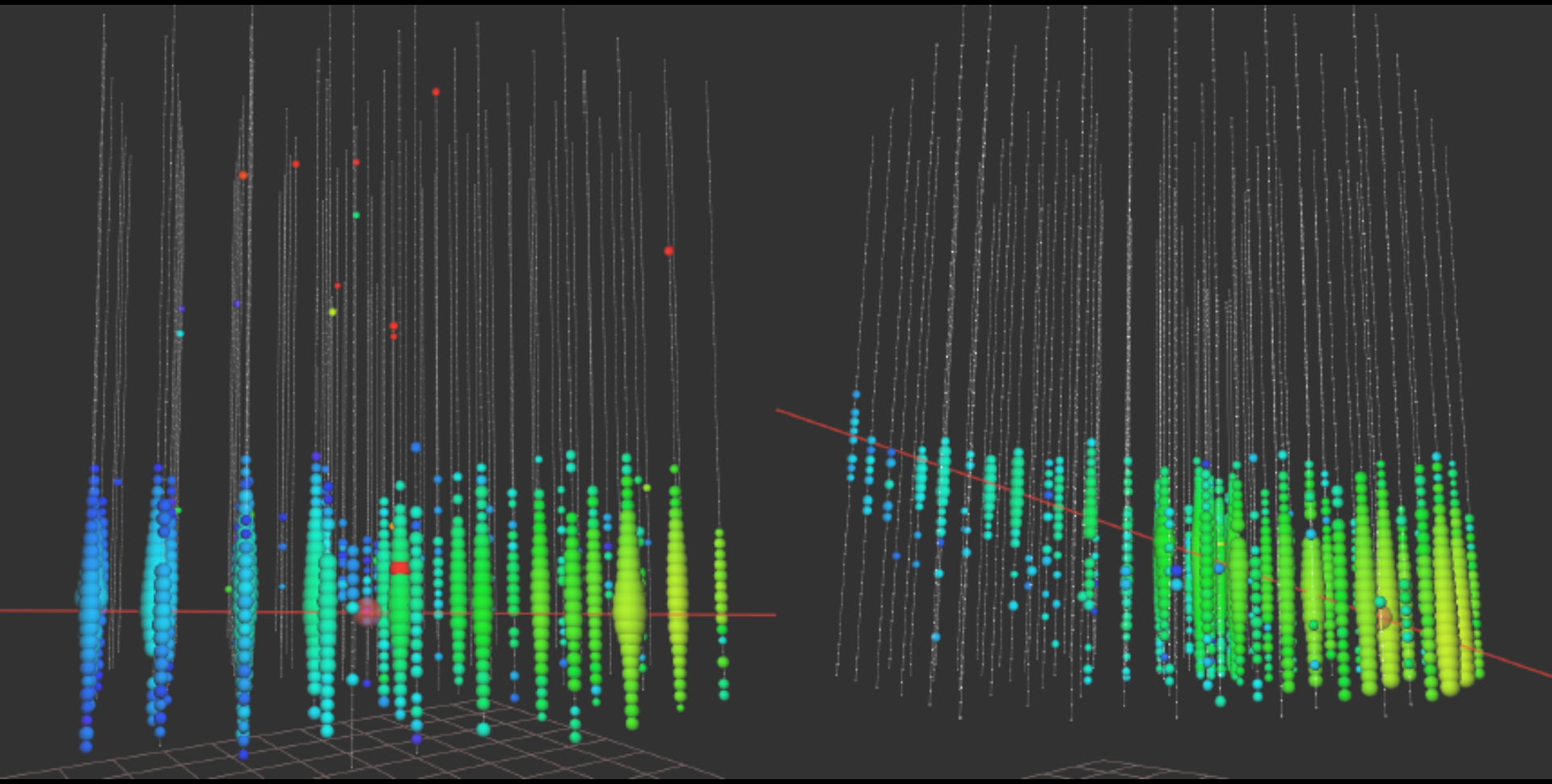


atmospheric

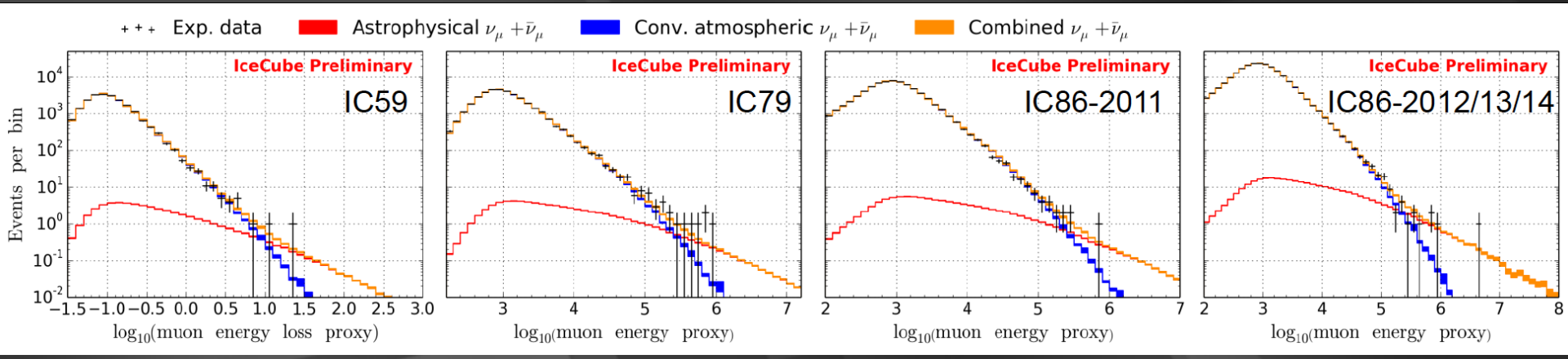
cosmic

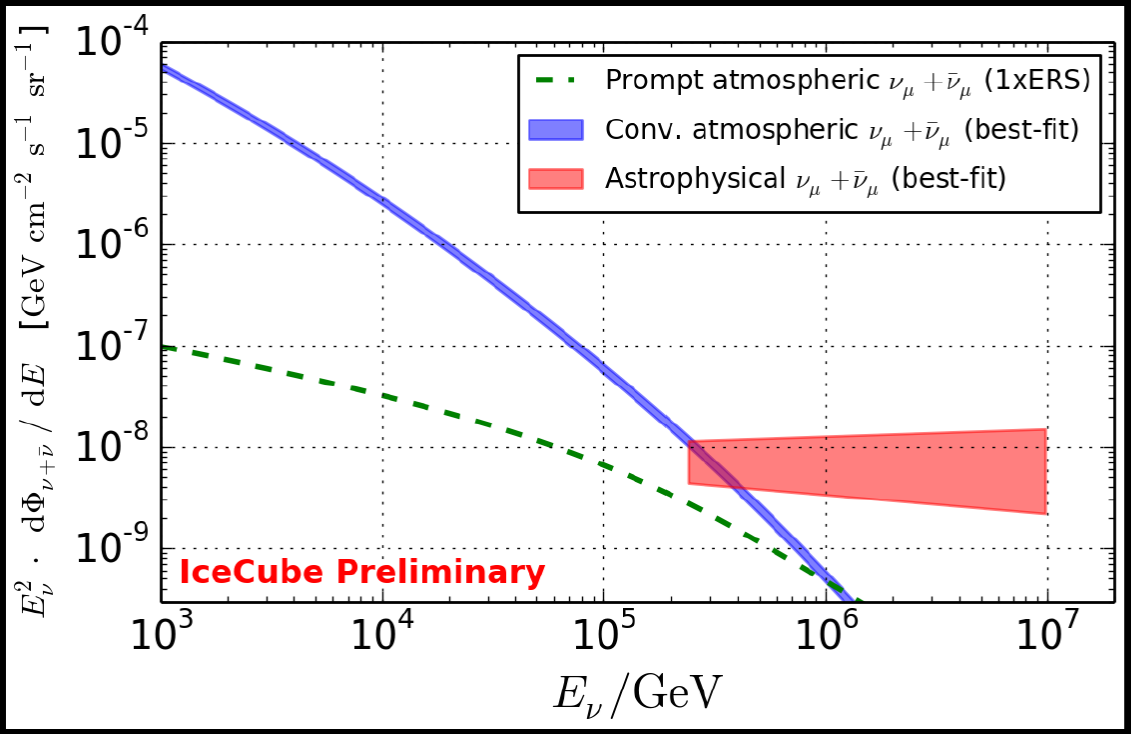
100 TeV

highest energy muon energy observed: 560 TeV
→ PeV ν_μ



after 6 years: 3.7→ 6.0 sigma





- Best-fit astrophysical normalization:

$$\left(0.78^{+0.29}_{-0.25}\right) \times 10^{-18}\ \mathrm{GeV^{-1}cm^{-2}s^{-1}sr^{-1}}$$

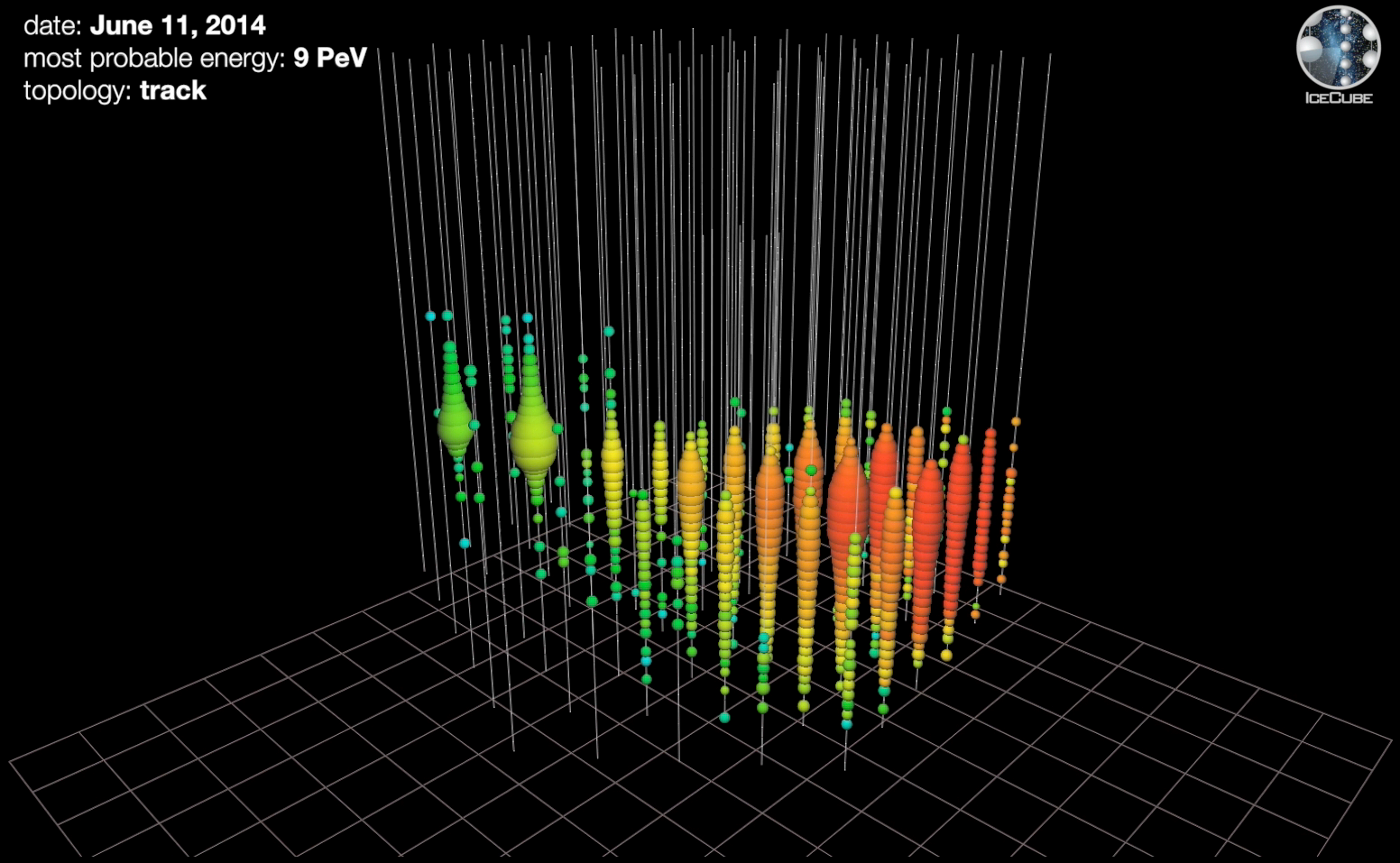
- Best-fit spectral index:

$$\gamma_{\mathrm{astro}} = 2.06 \pm 0.13$$

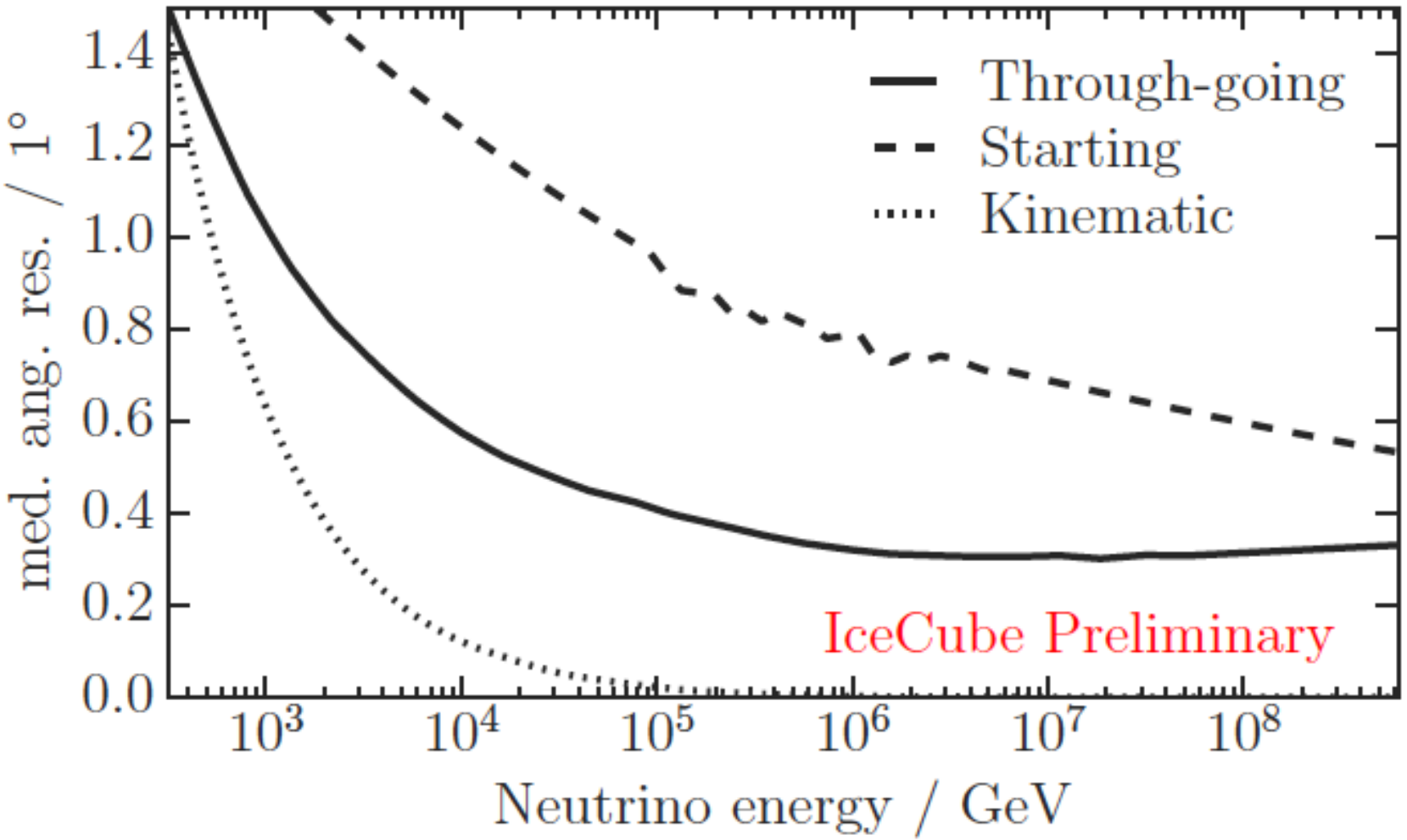
- Energy ranges:

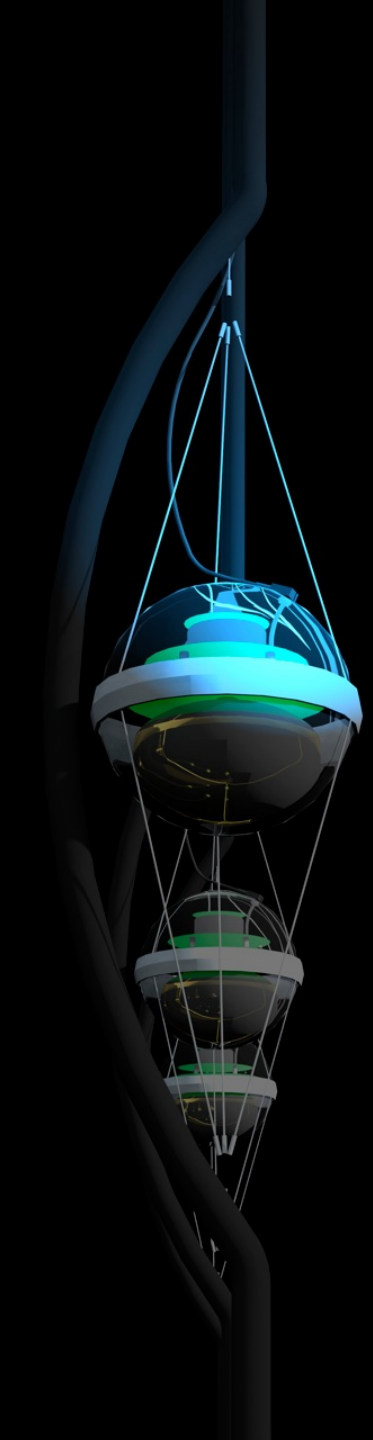
$$240\ \mathrm{TeV} - 10\ \mathrm{PeV}$$

- Atmospheric-only hypothesis excluded by 6.0σ


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

astronomy: through-going muons with resolution ~ 0.3^0





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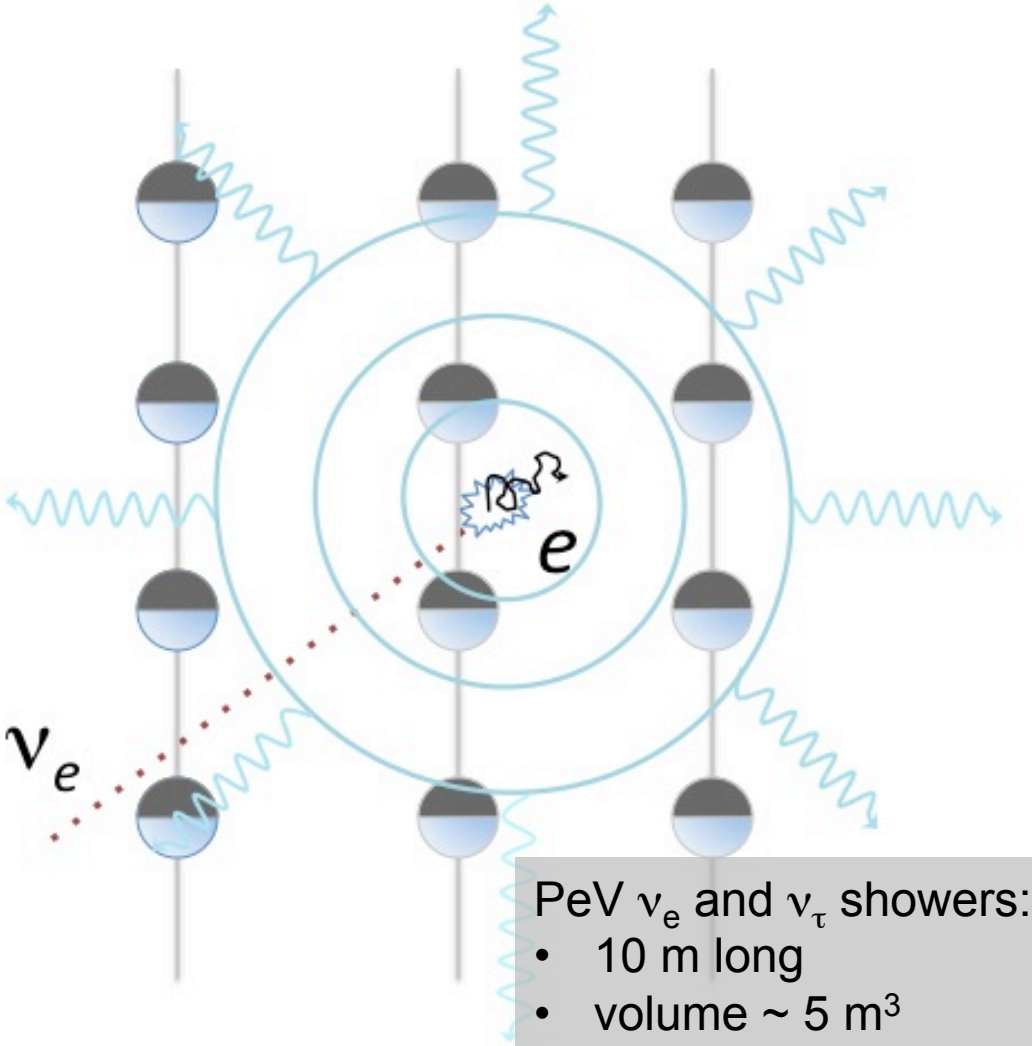
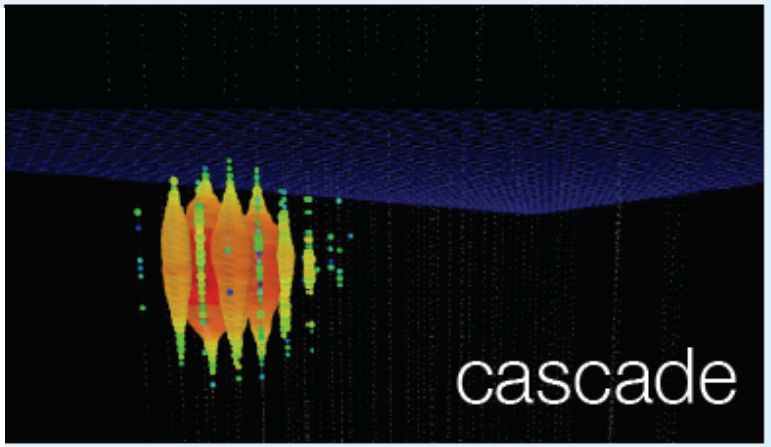
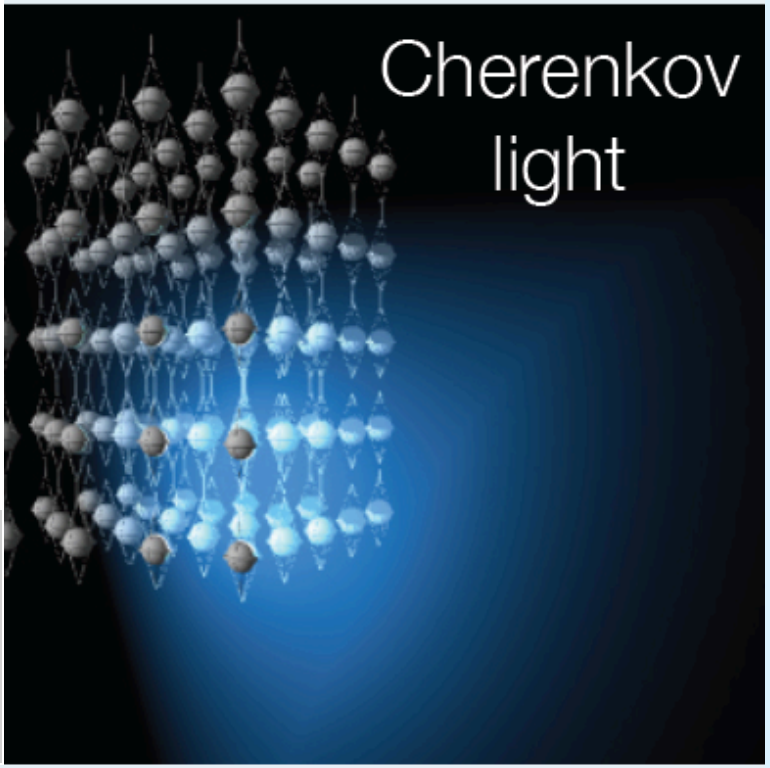
tracks and showers







PeV ν_e and ν_τ showers:

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

cosmic rays interact with the microwave background

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

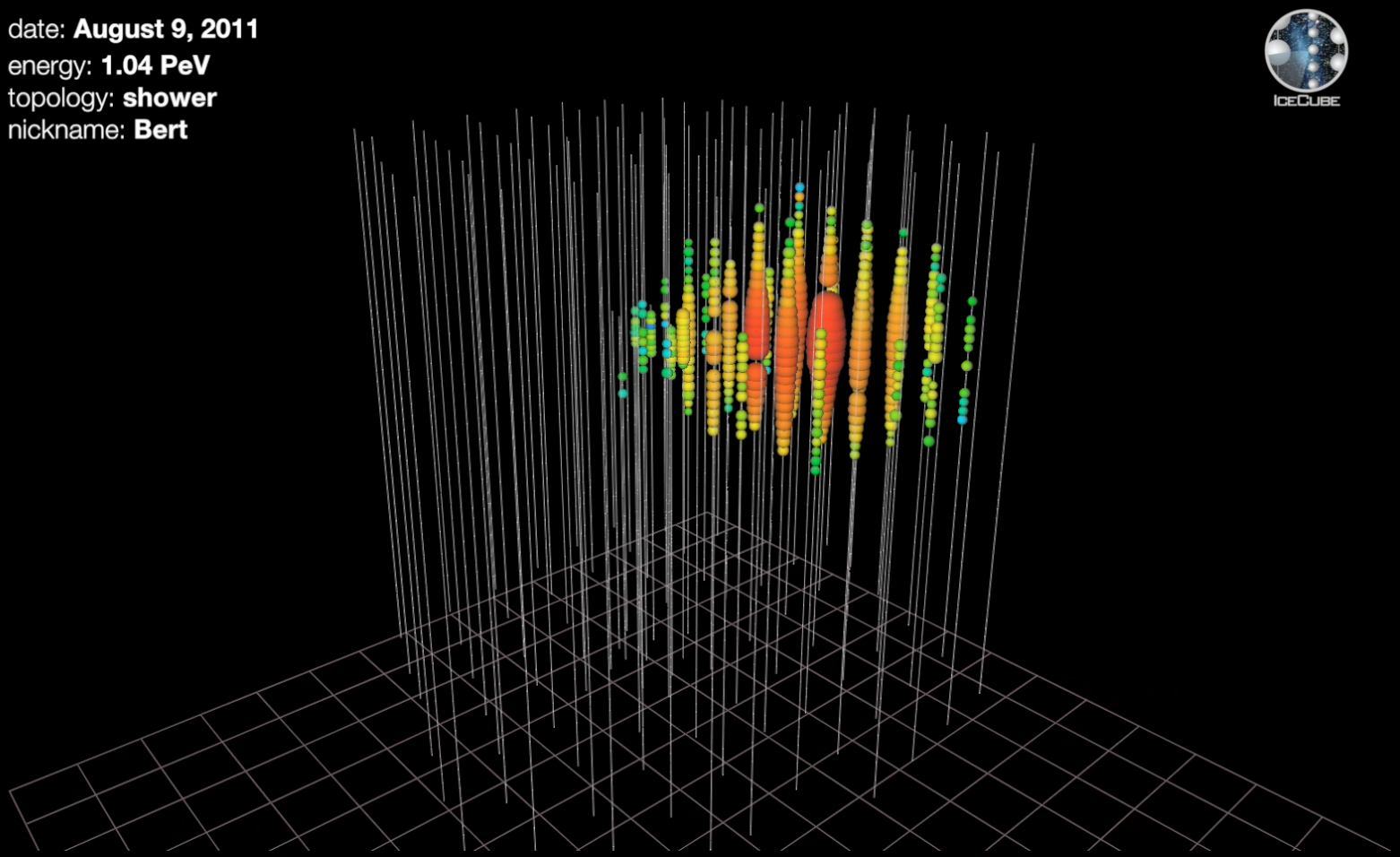
cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear

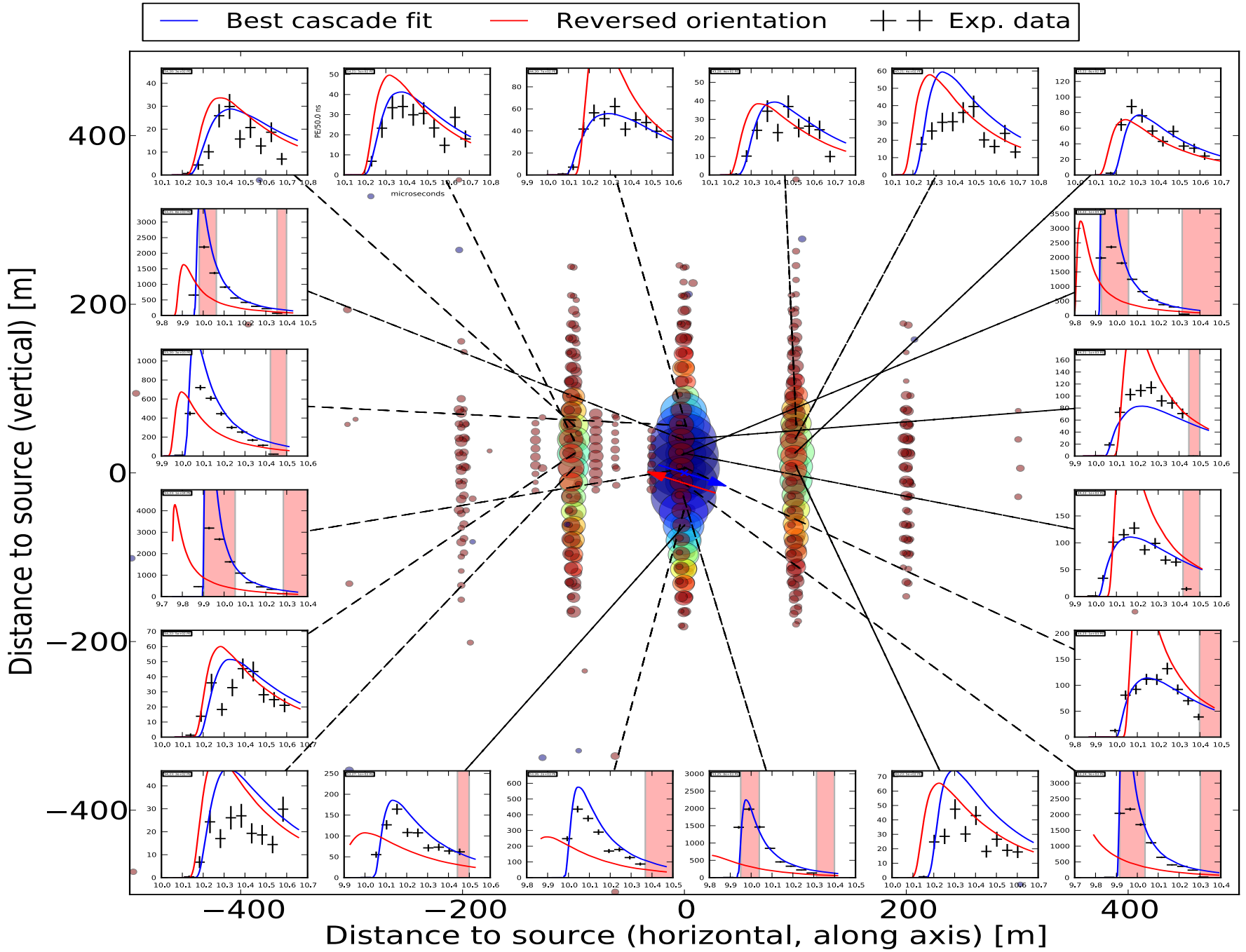
$$\pi \rightarrow \mu + \upsilon_{\mu} \rightarrow \{e + \overline{\upsilon_{\mu}} + \upsilon_{e}\} + \upsilon_{\mu}$$

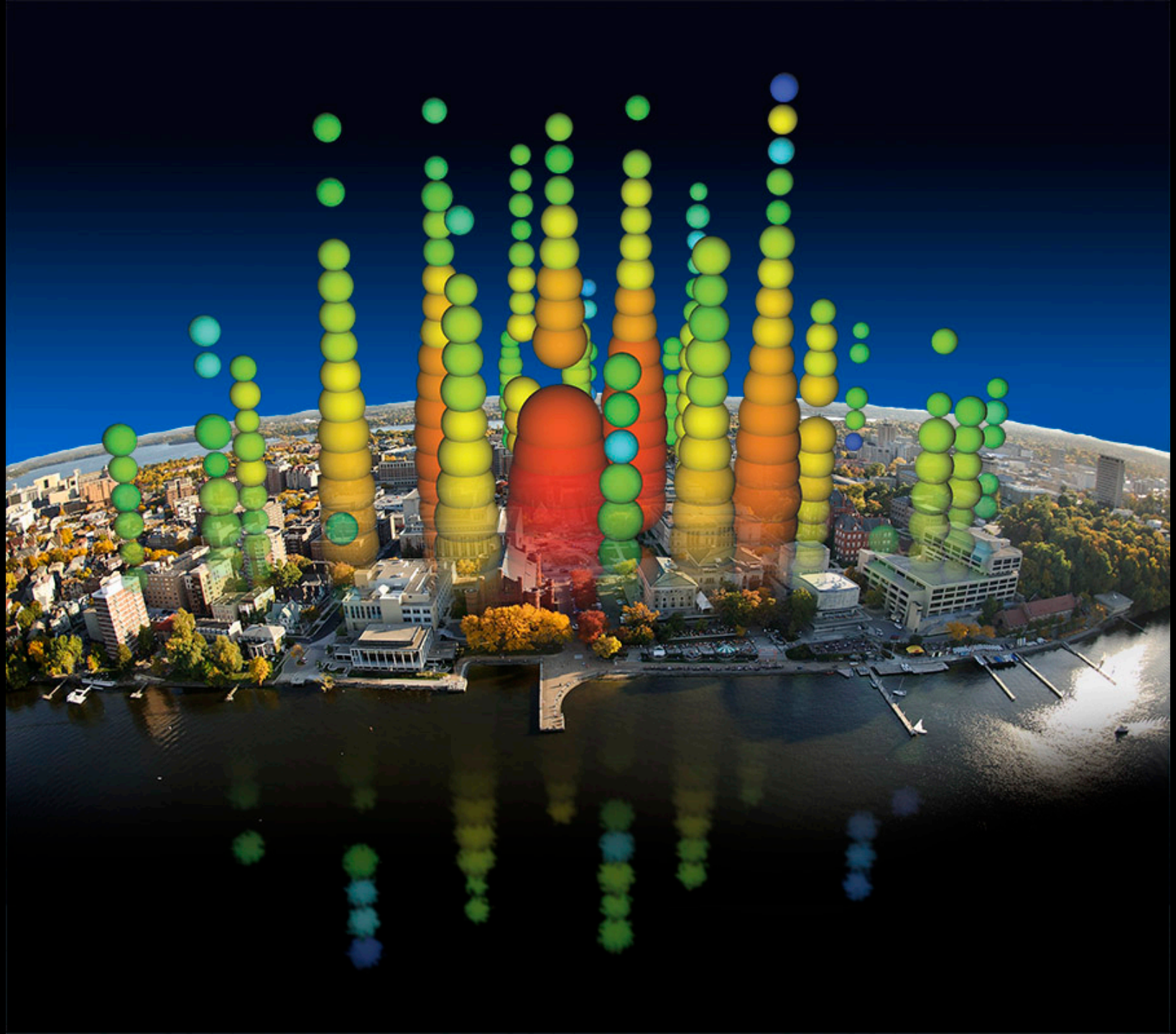
1 event per cubic kilometer per year

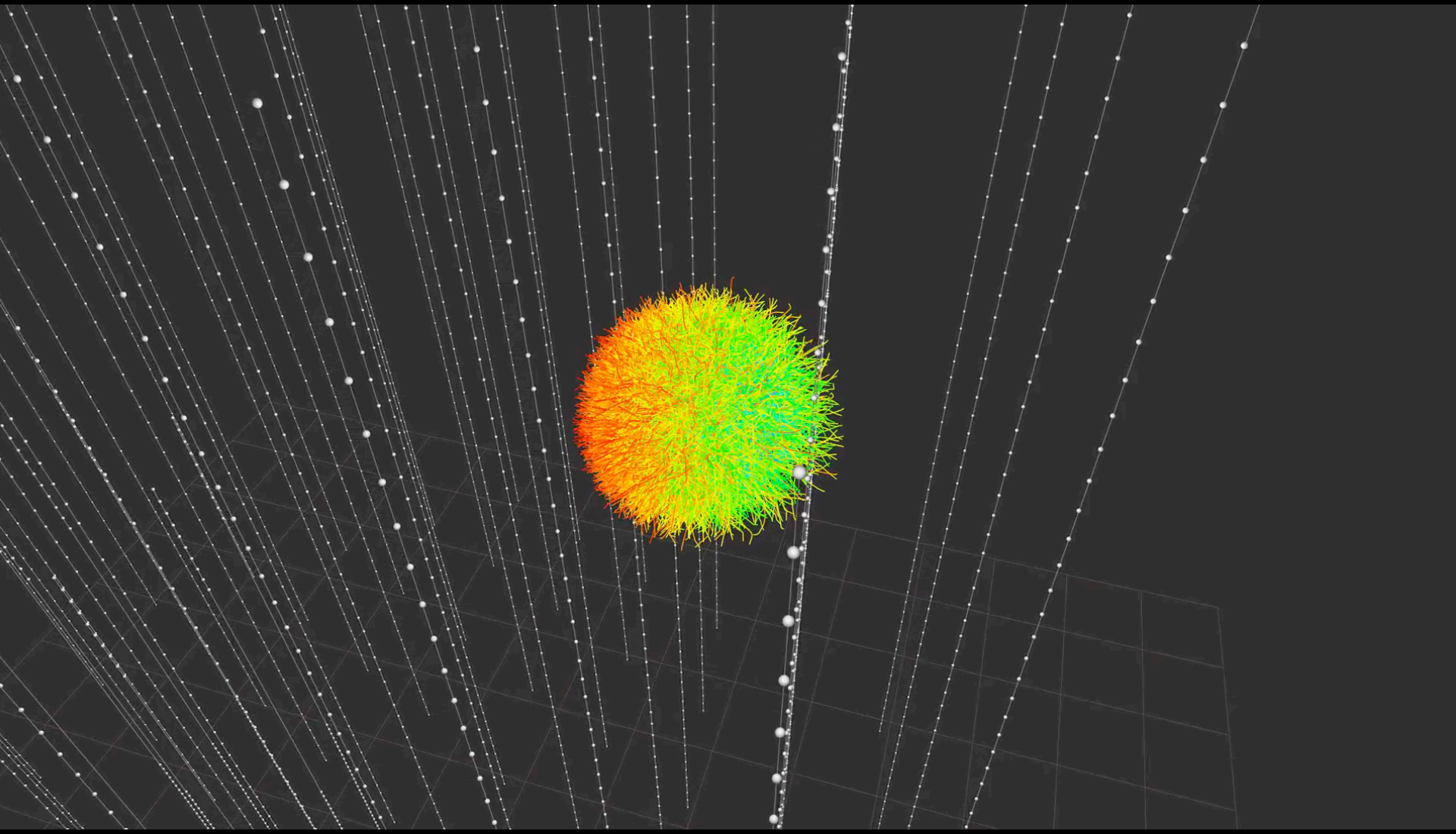
...but it points at its source!

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



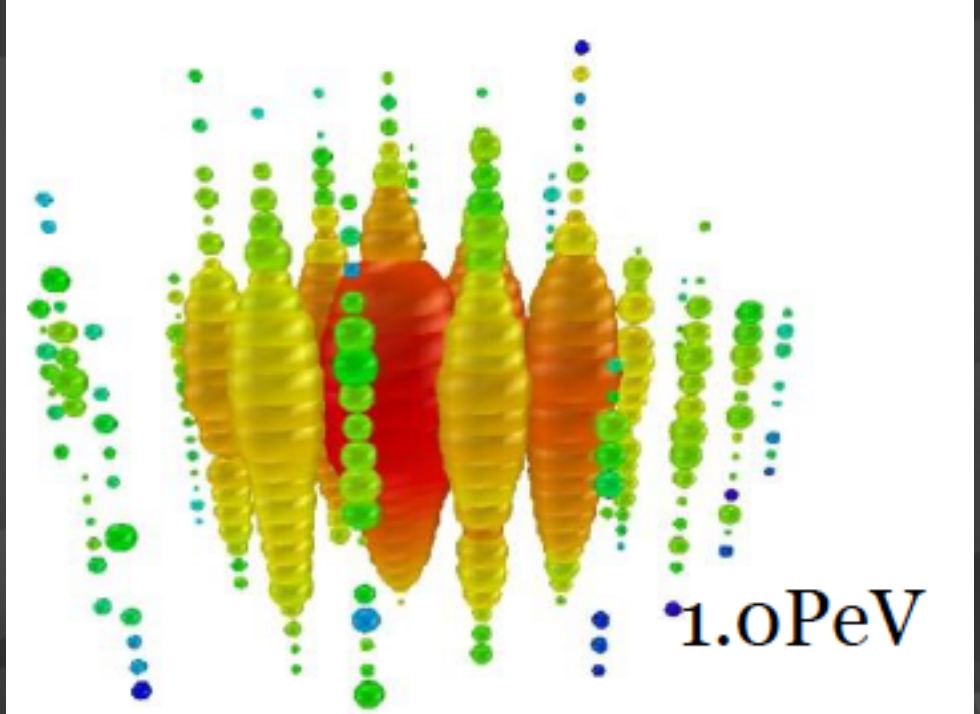

Best cascade fit
Reversed orientation
Exp. data
Distance to source (vertical) [m]
Distance to source (horizontal, along axis) [m]
400
200
0
−200
−400
−400
−200
0
200
400
PE/50.0 ns
microseconds

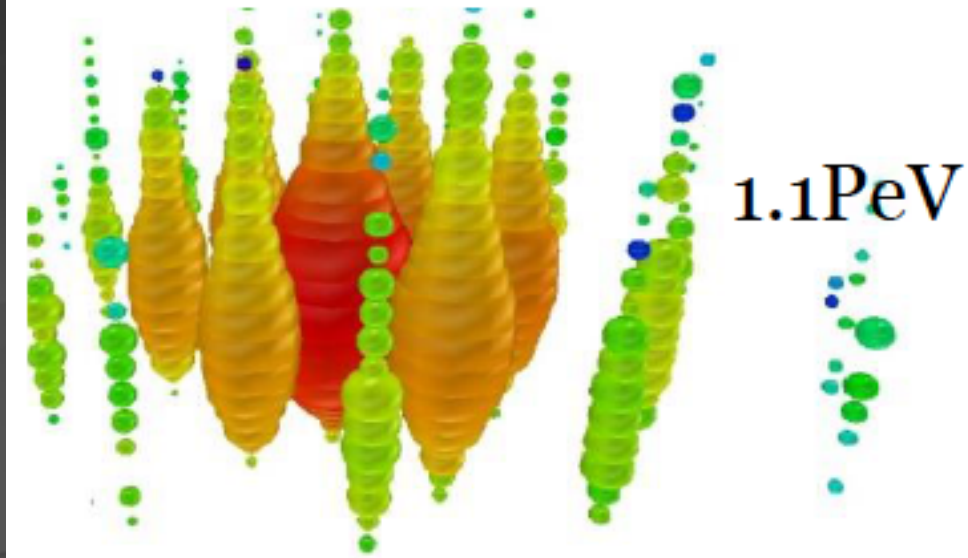




size = energy

color = time = direction





- energy:

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

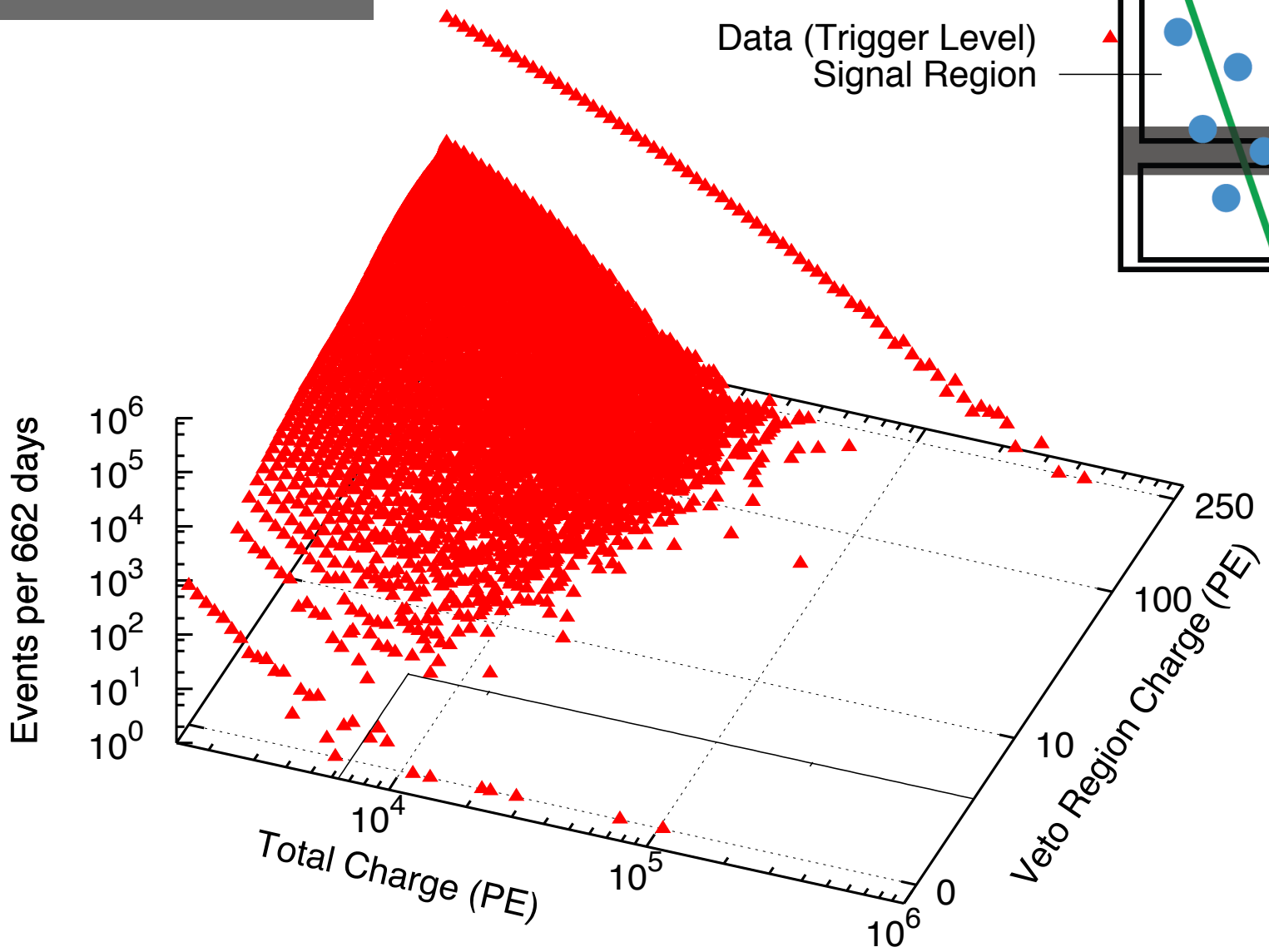
- found serendipitously in search for GZK neutrinos

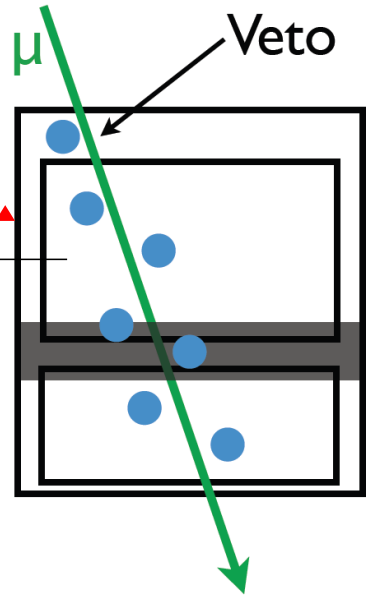
- atmospheric? too high energy and isolated

systematic analysis looking for more such events

- ✓ 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

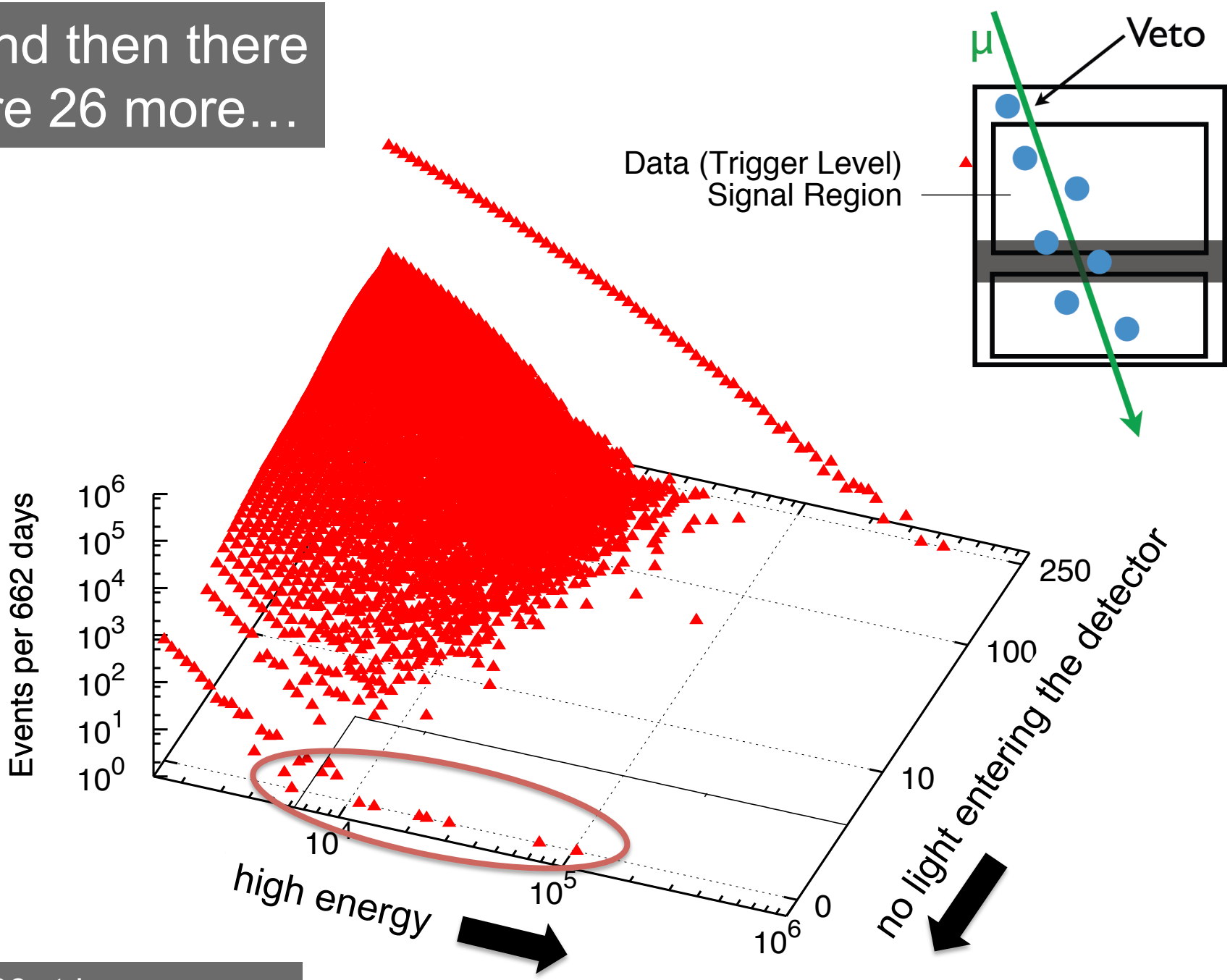
…and then there were 26 more…





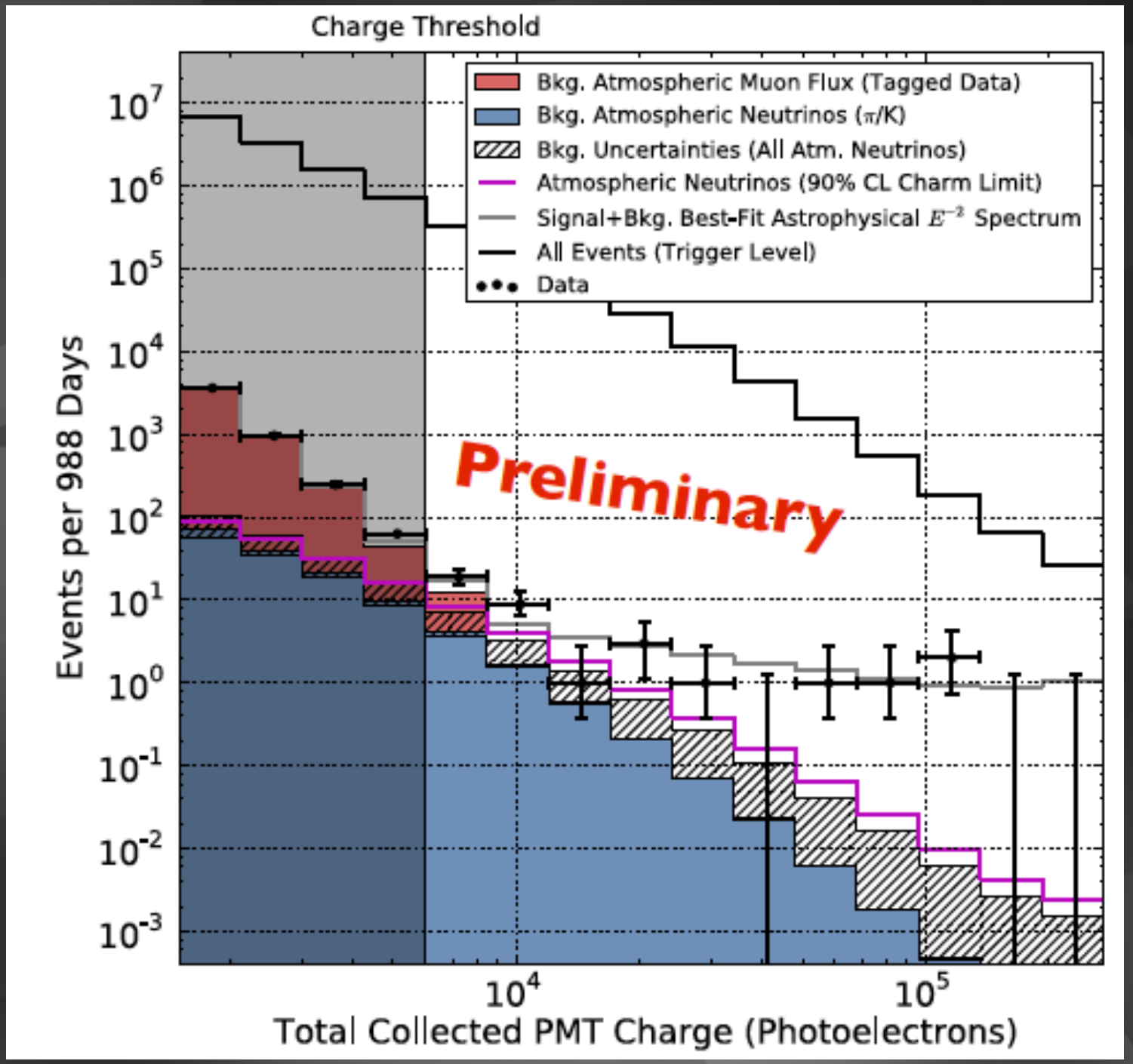
data: 86 strings one year

…and then there were 26 more…

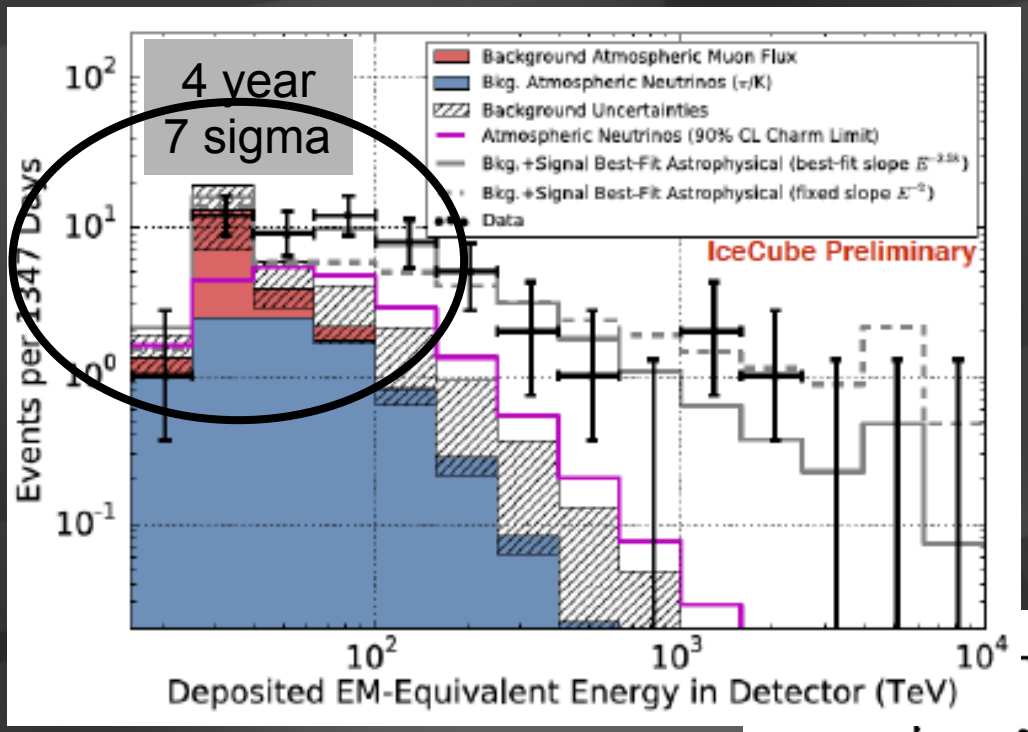


data: 86 strings one year

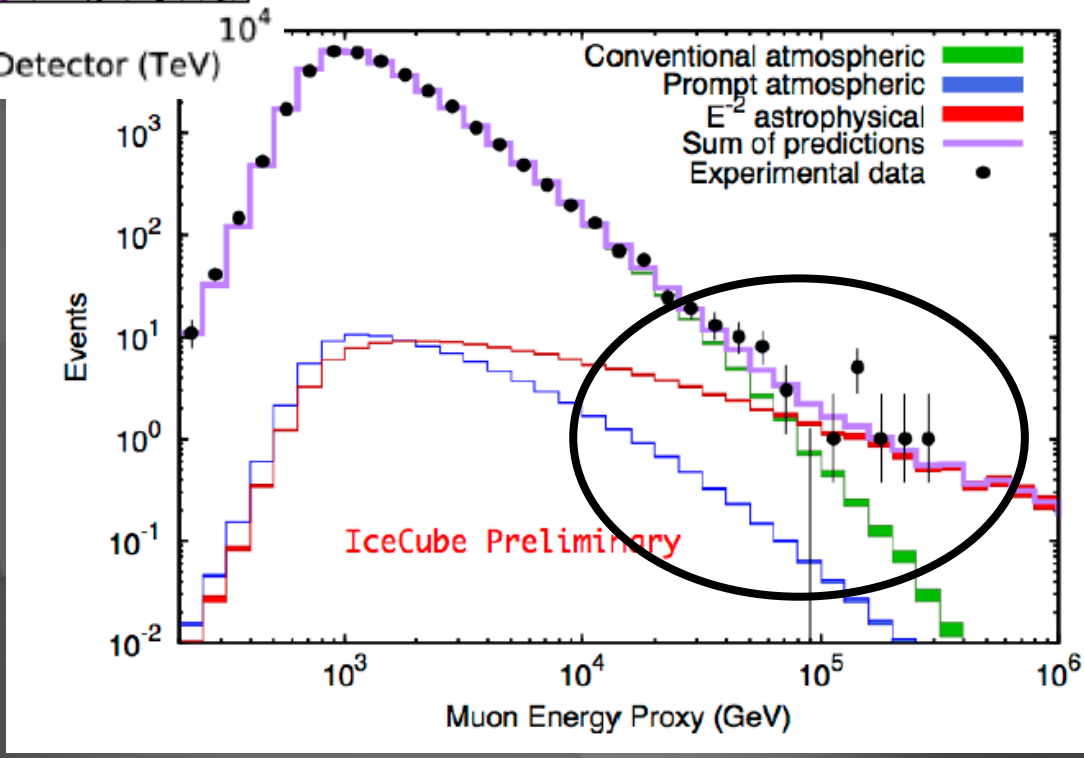
total charge collected by PMTs of events with interaction inside the detector



Science 342 (2013) 1242856

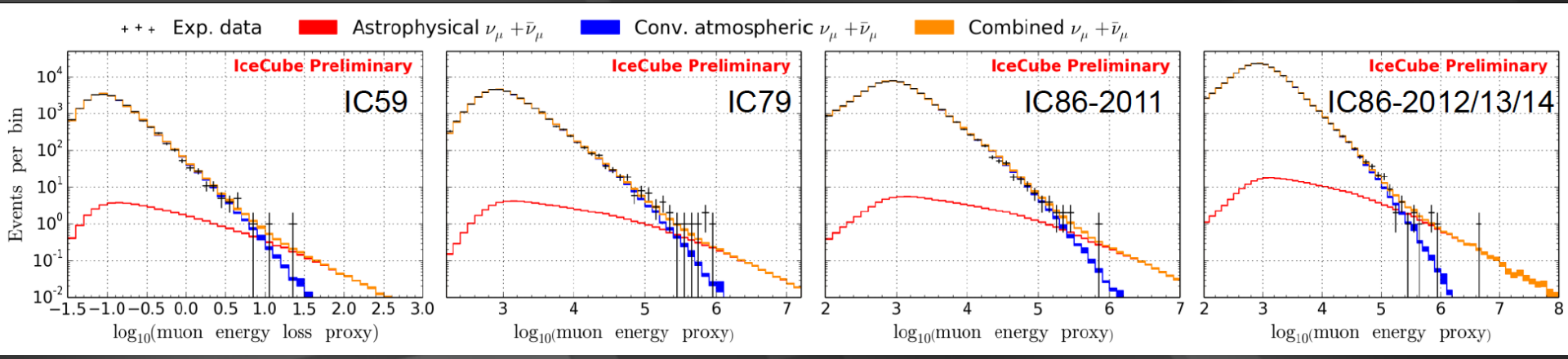


confirmation!
flux of muon neutrinos
through the Earth

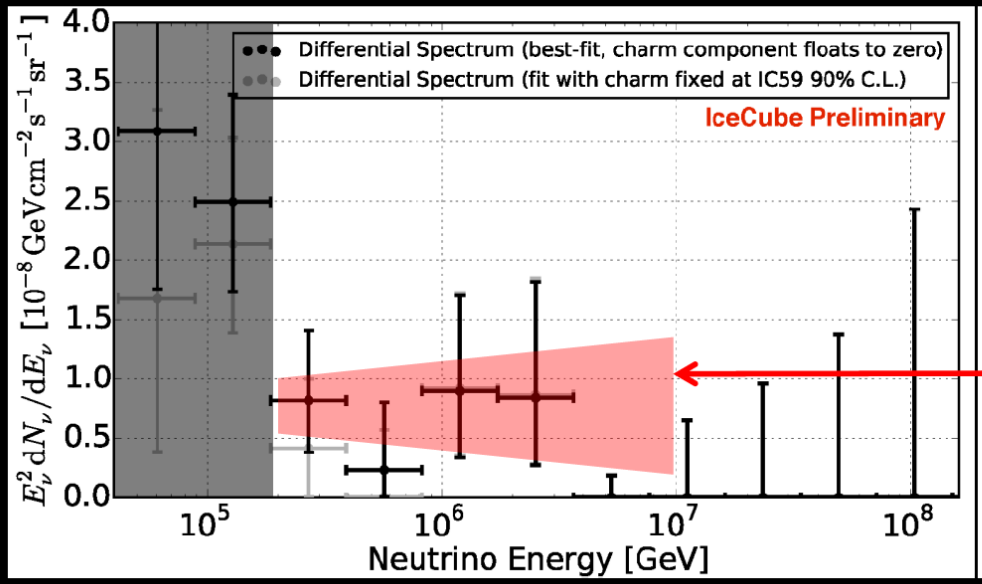


neutrinos of all flavors
interacting inside
IceCube

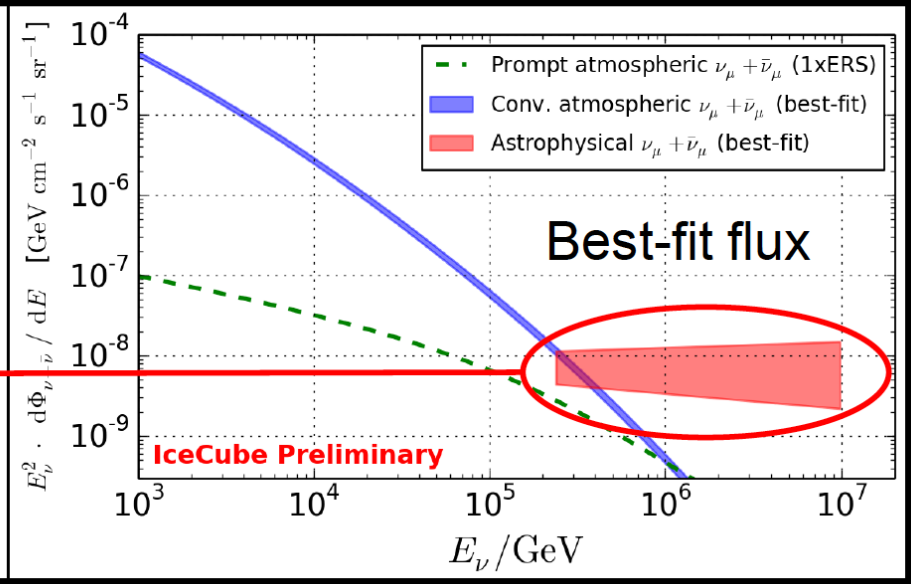
after 6 years: 3.7→ 6.0 sigma



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



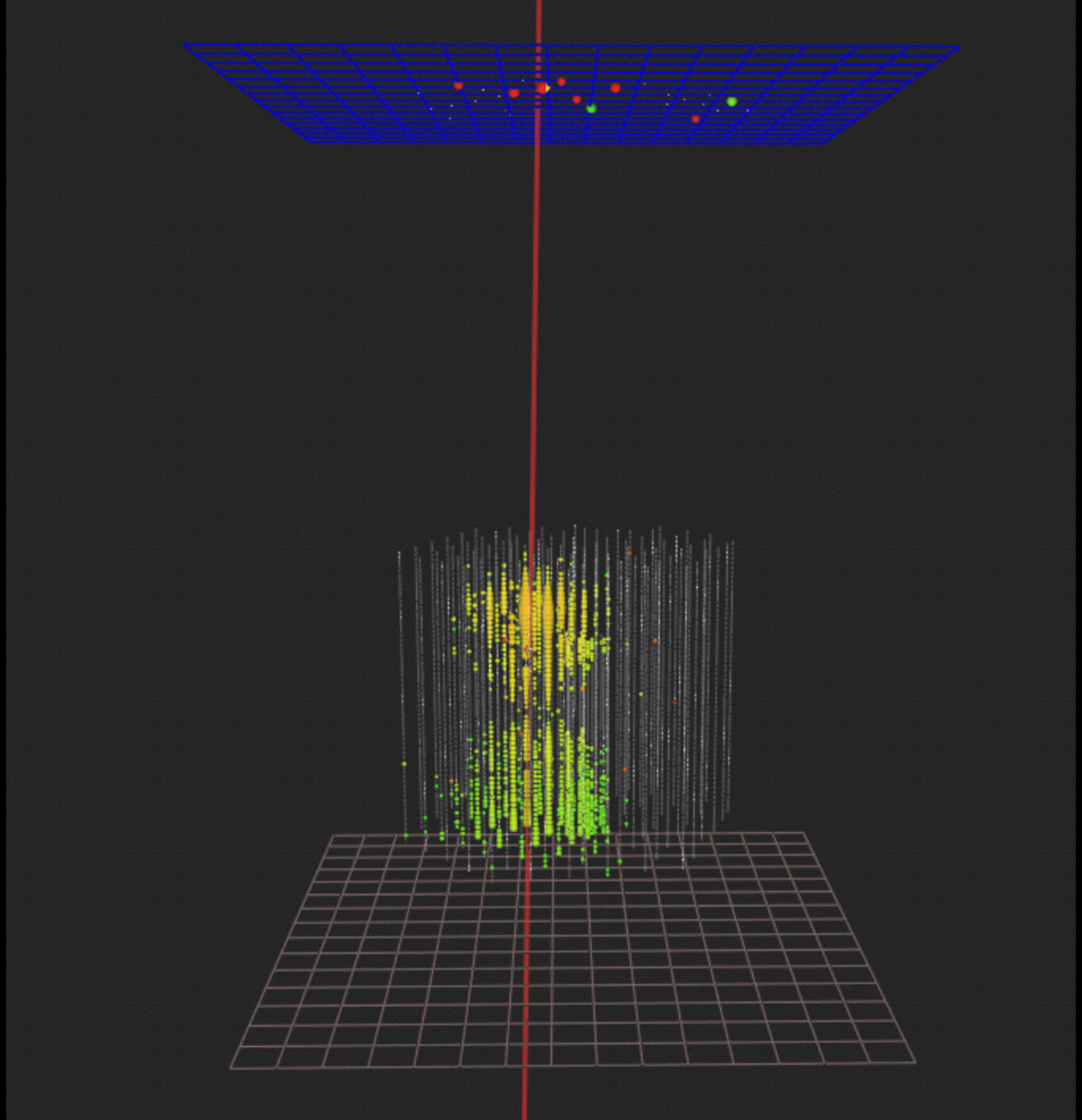
6 year up-going numu analysis

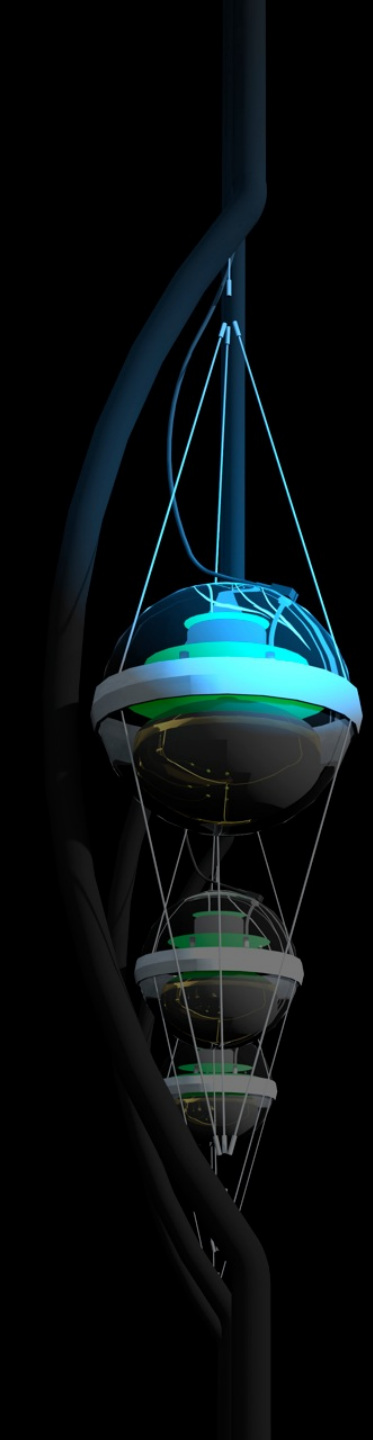


430 TeV

1 event:
~ 5 sigma
discovery

> PeV ν_μ





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- the discovery of cosmic neutrinos $\nu_{e,\tau}$
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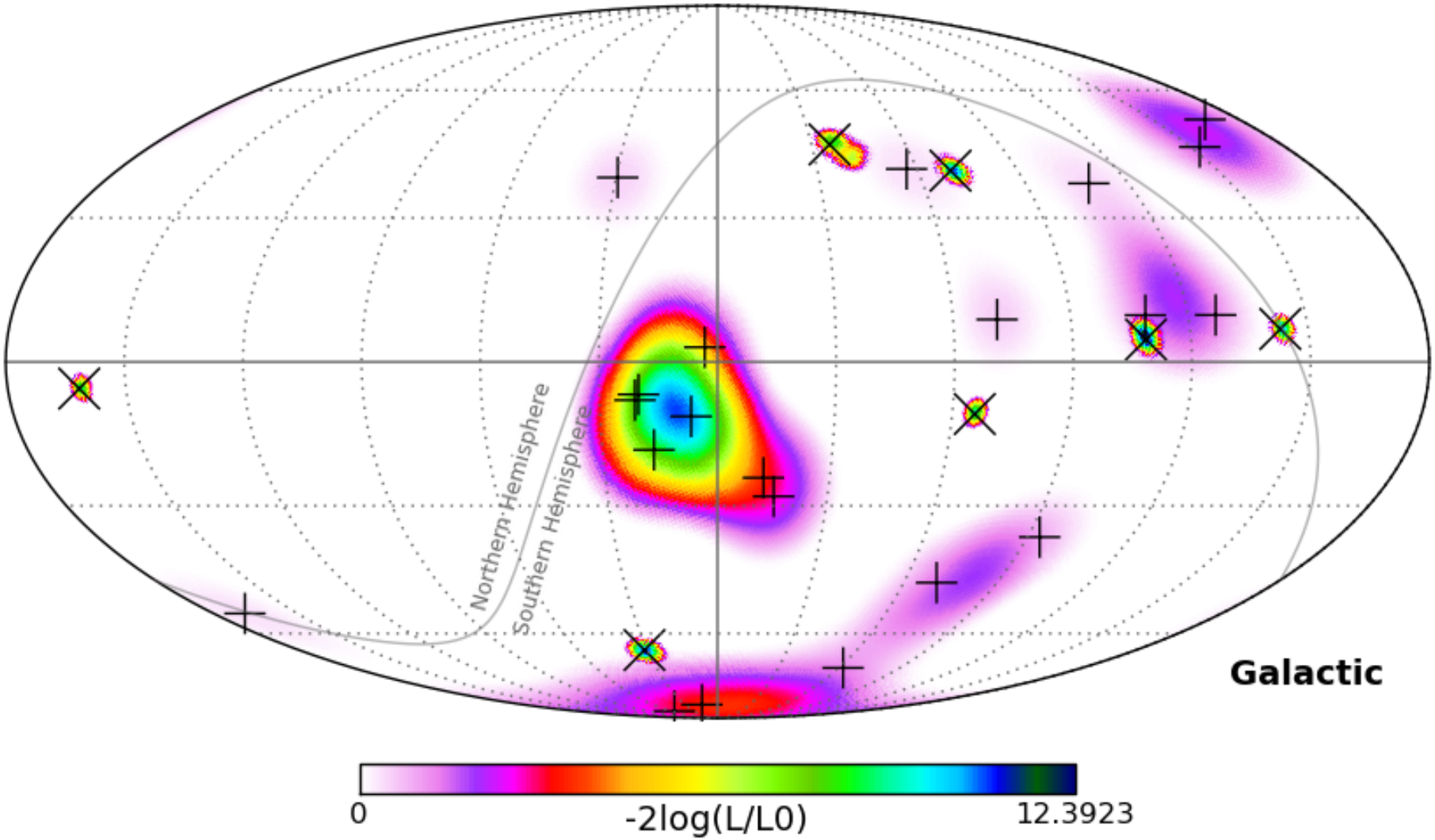
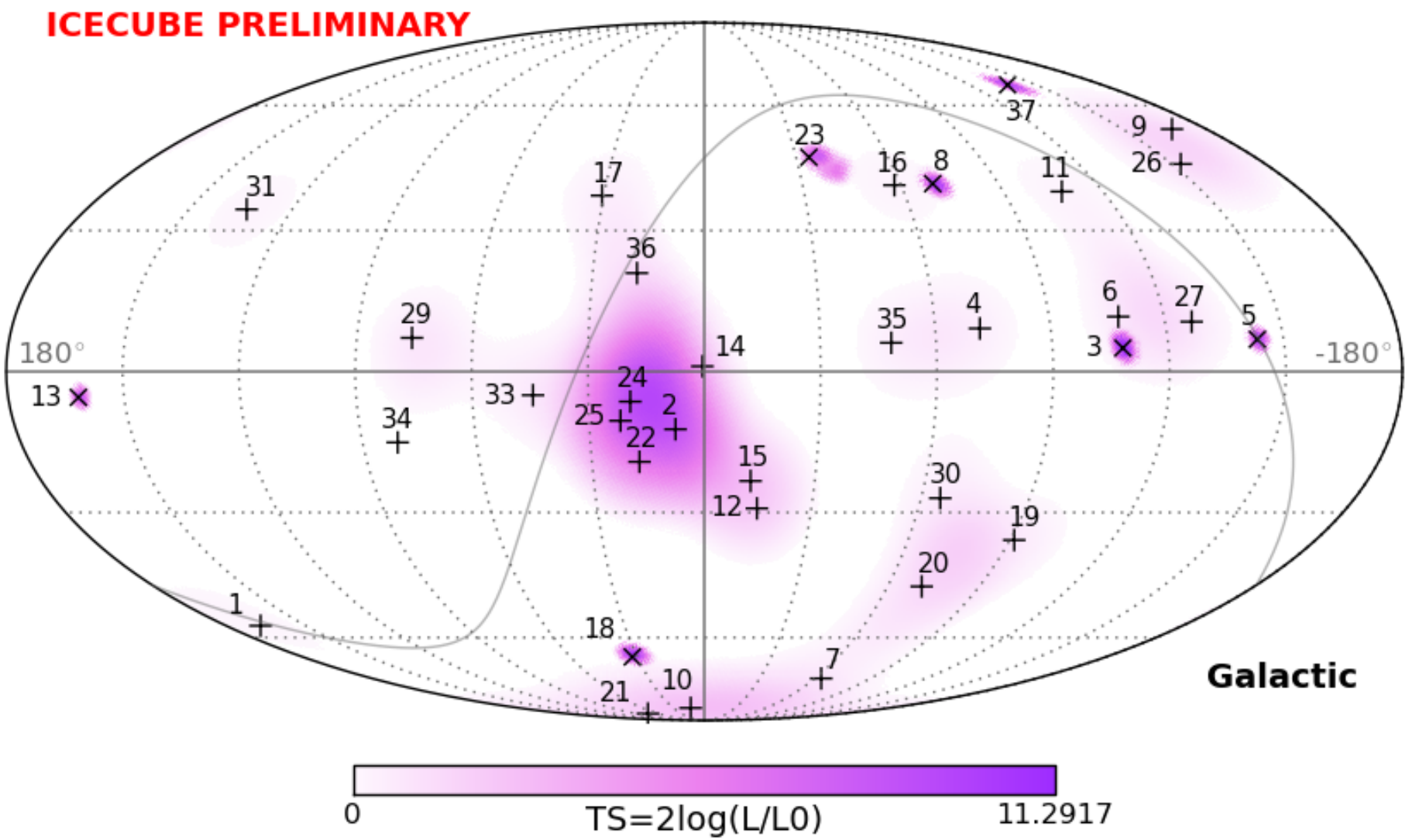
IceCube.wisc.edu

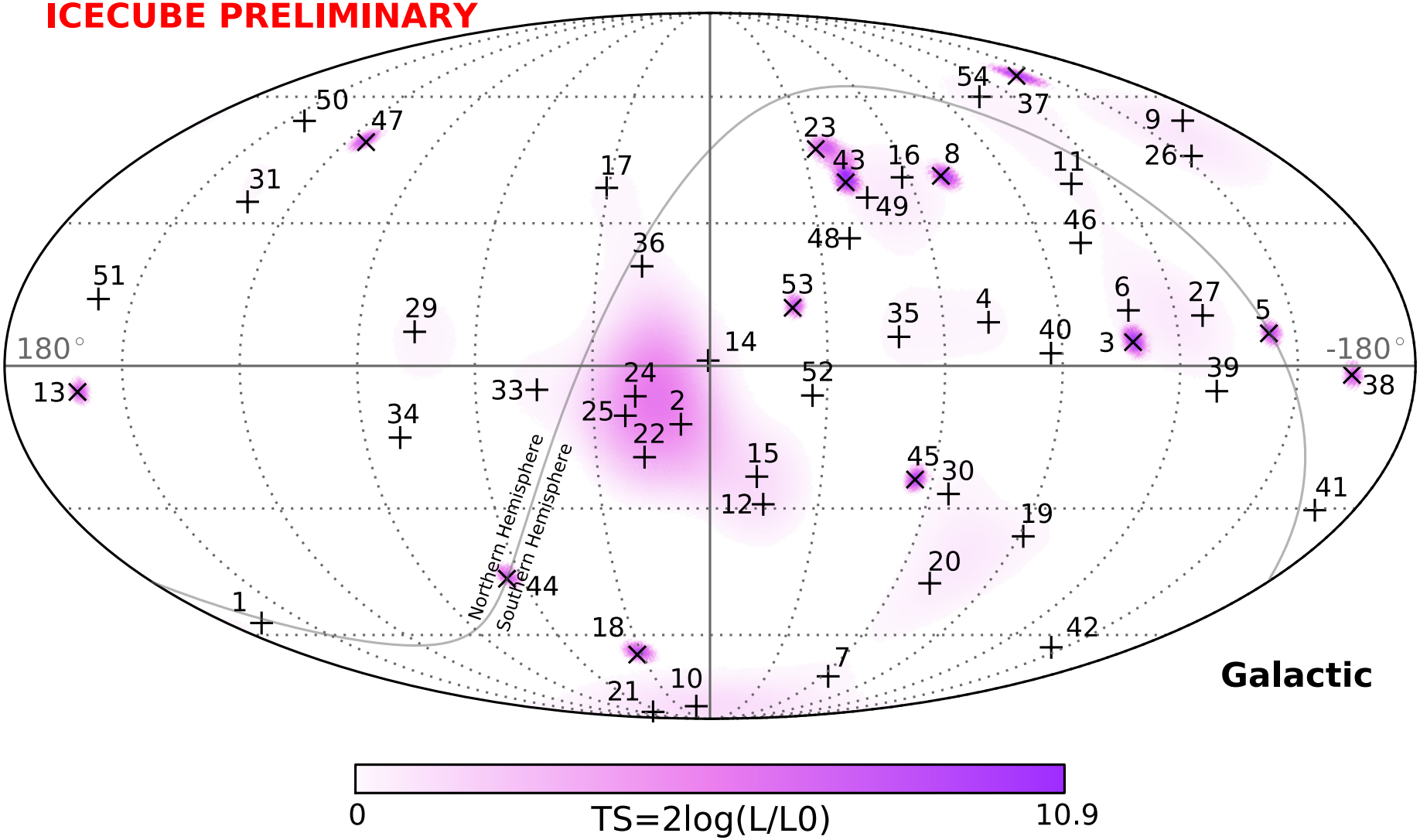
2 year HESE


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

3 year HESE



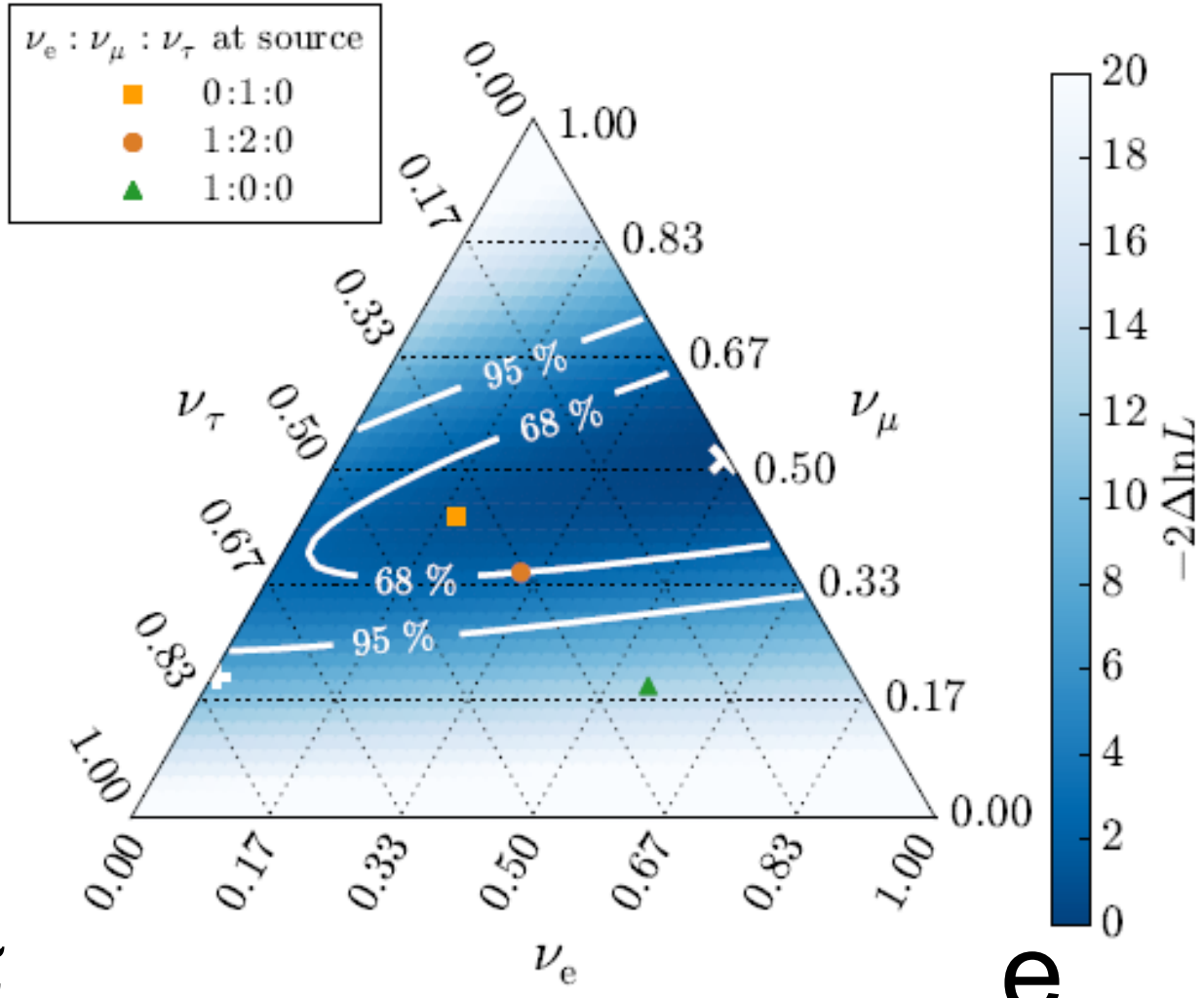
4 year HESE



where do they come from?

oscillate over cosmic distances to 1:1:1

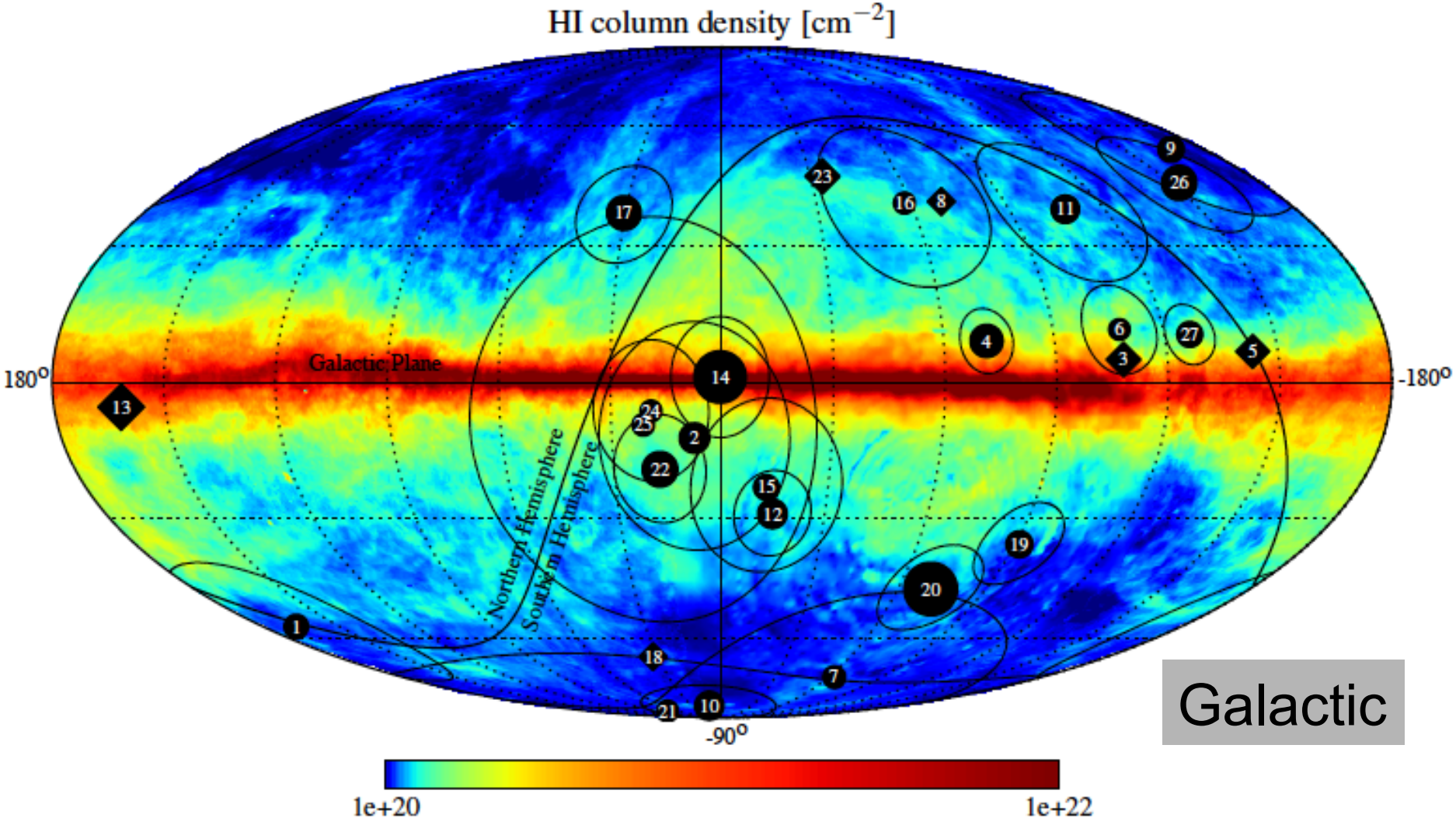
μ



τ

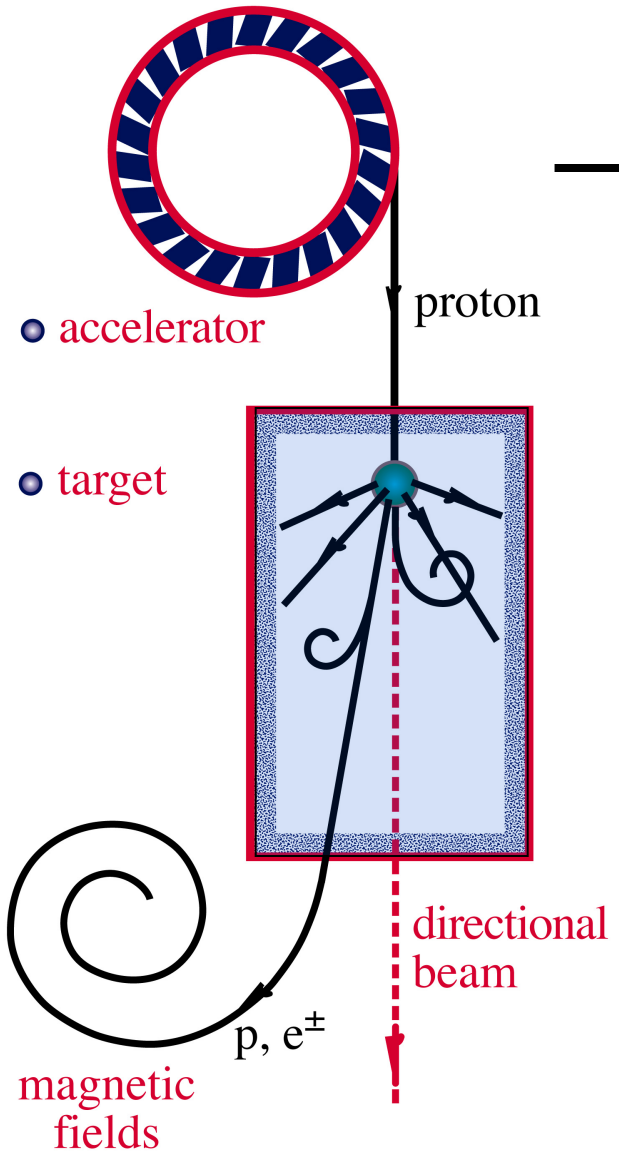
e

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



- we observe a diffuse flux of neutrinos from extragalactic sources
- a subdominant Galactic component cannot be excluded
- 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

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

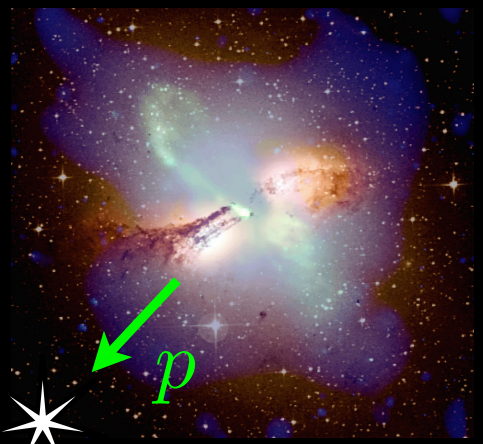
~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

~ cosmic ray + gamma

hadronic gamma rays ?

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

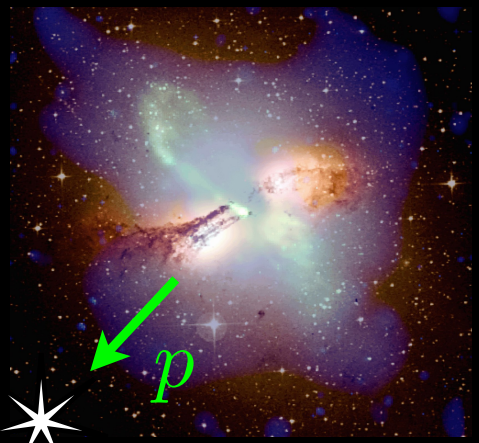


p

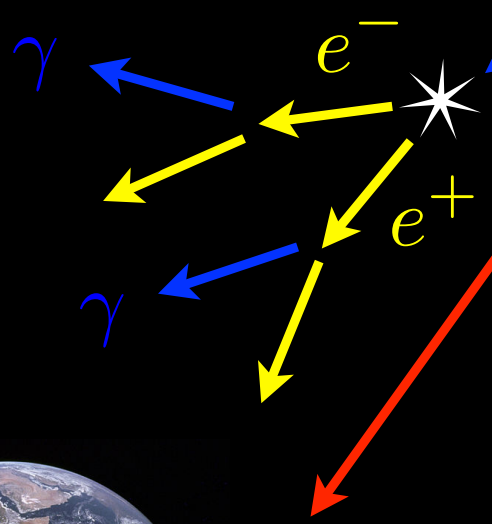
γ

ν

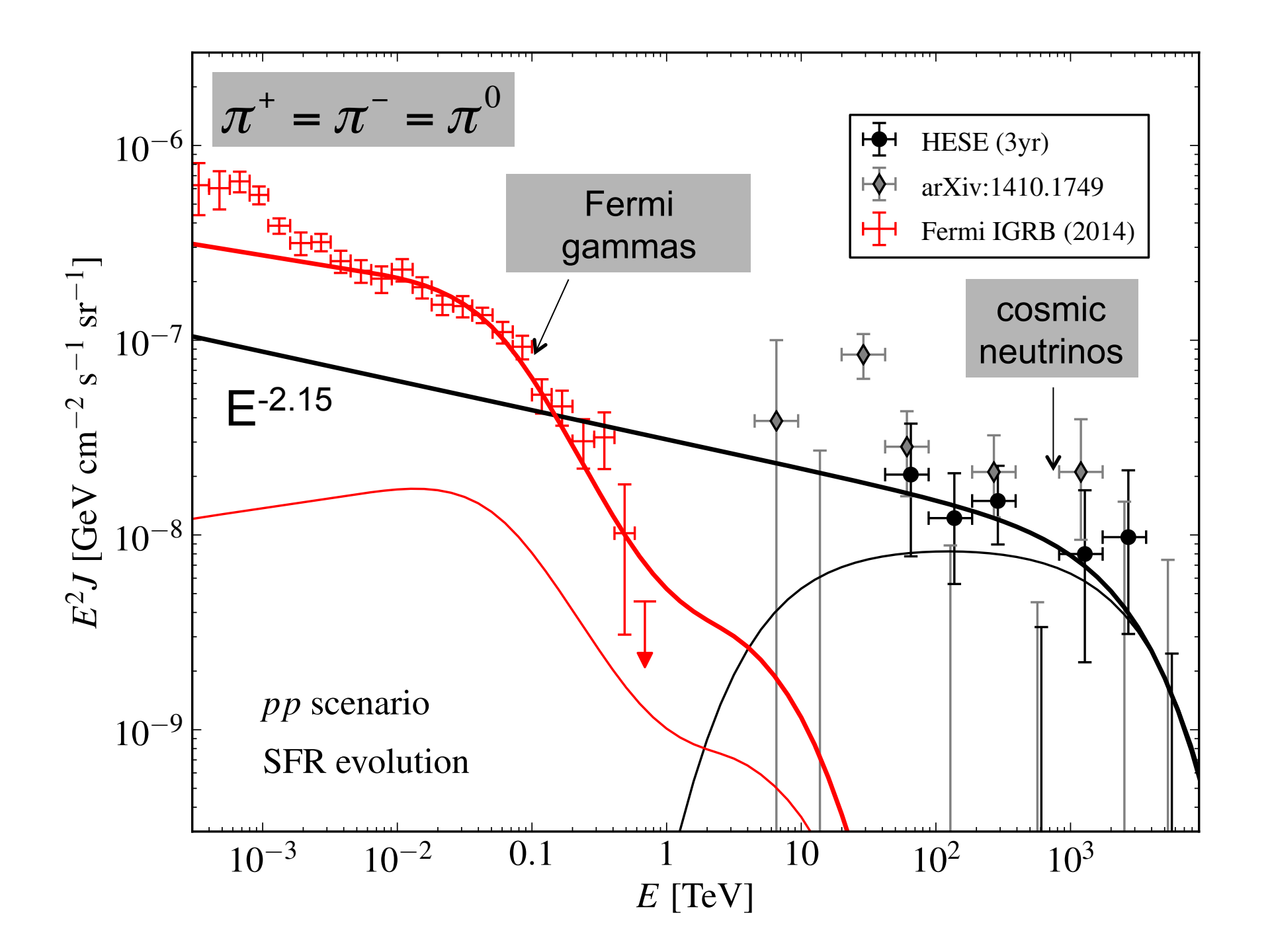
hadronic
gamma rays



electromagnetic
cascades in CMB



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
$E^2 J$ [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

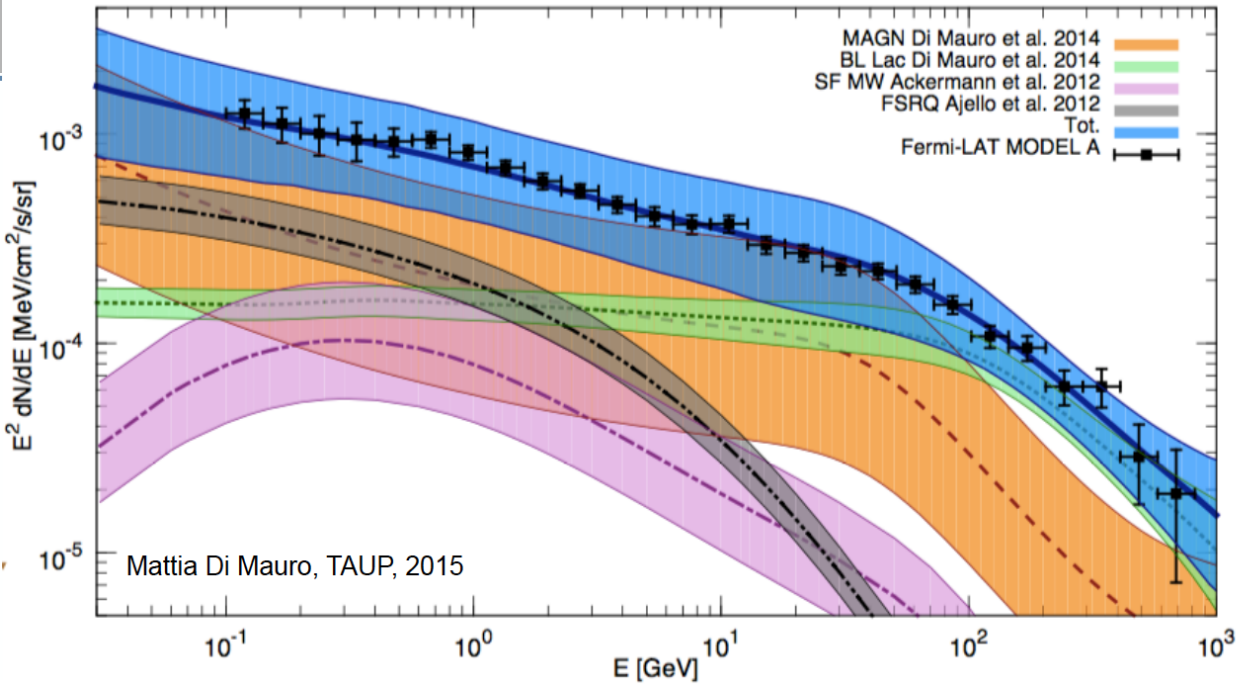
- we observe a flux of cosmic neutrinos from the cosmos whose properties correspond in all respects to the flux anticipated from PeV-energy cosmic accelerators that radiate comparable energies in light and neutrinos

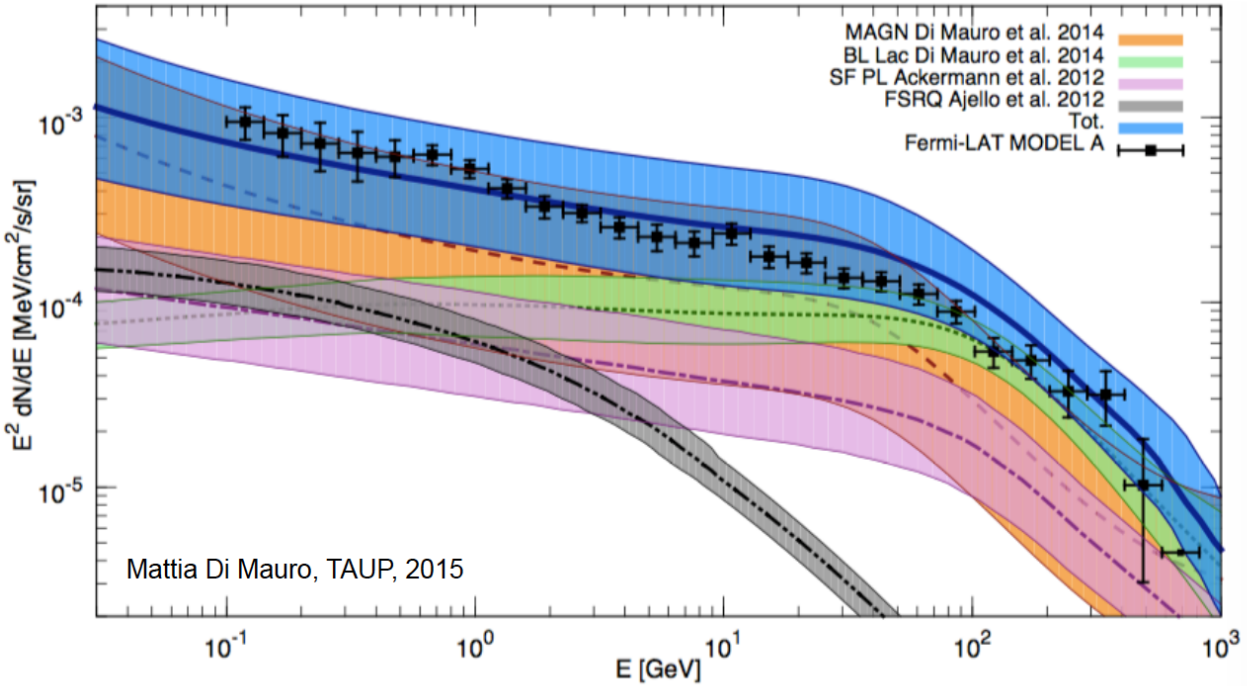
- the energy in cosmic neutrinos is also comparable to the energy observed in extragalactic cosmic rays (the Waxman-Bahcall bound)

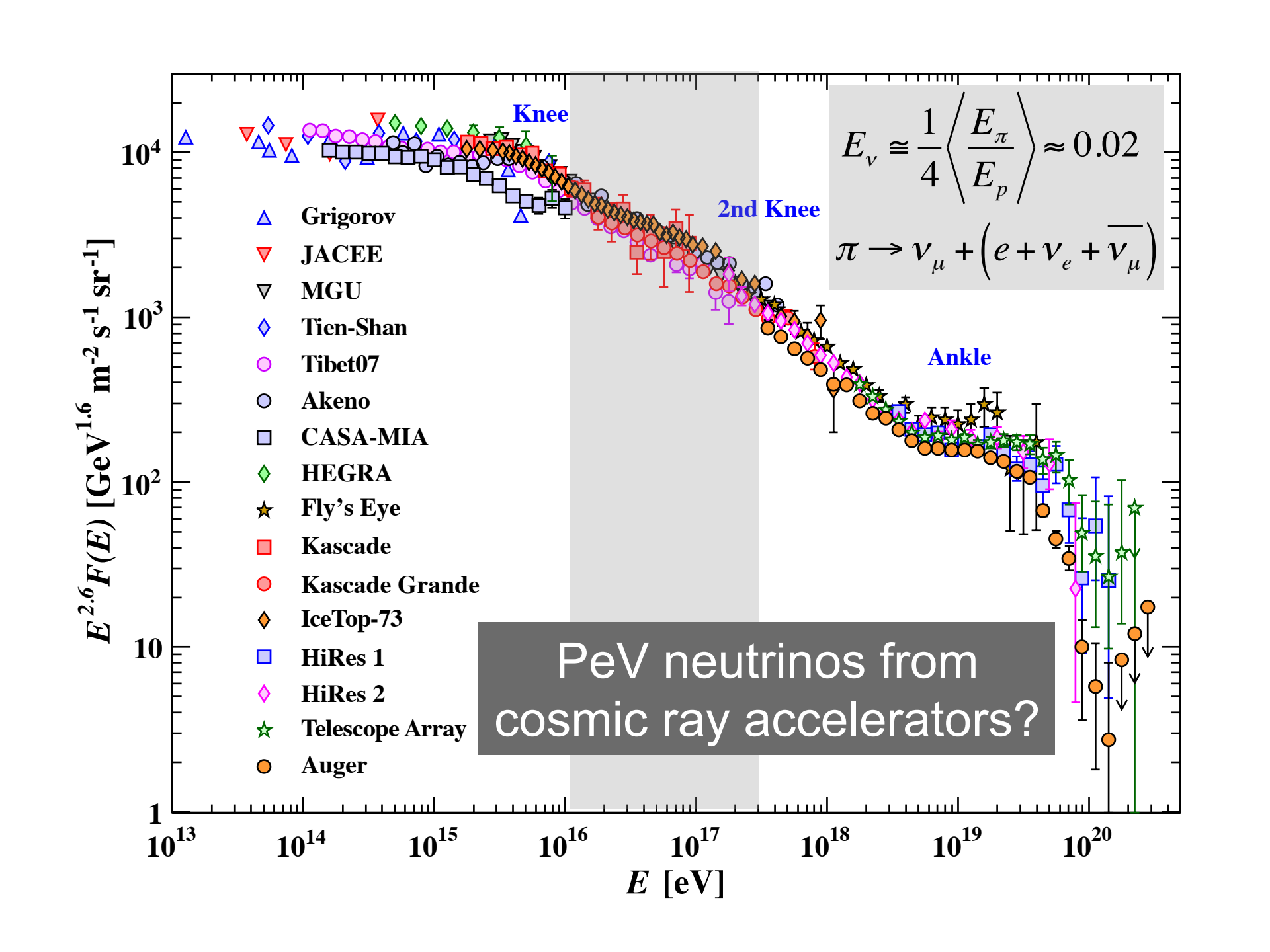
- at some level common Fermi-IceCube sources?

a Fermi census

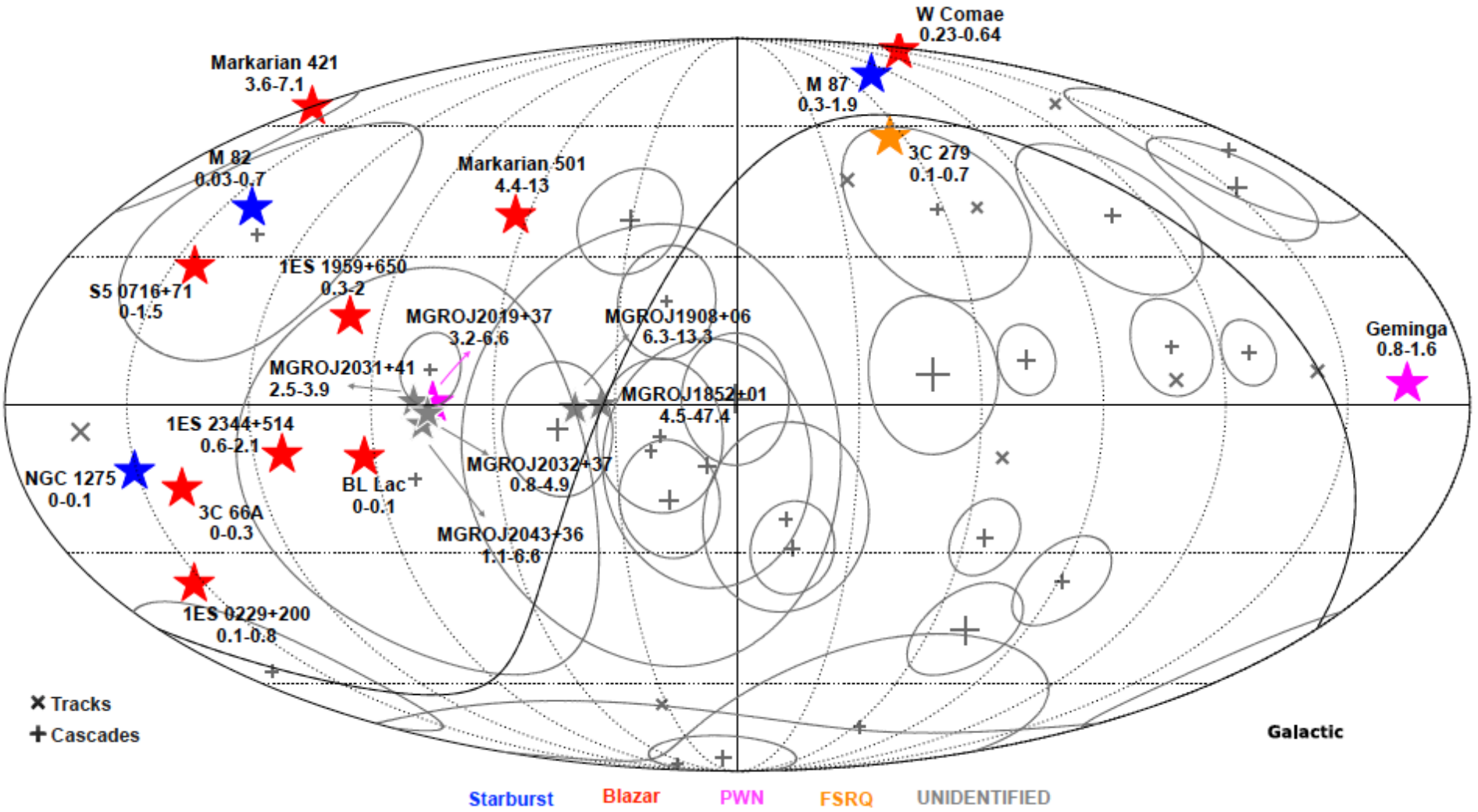
- BL Lac class of Blazars dominates the high-energy gamma-ray emission
  - 86% (+16%/-14%) above 50 GeV
- Large uncertainties in radio-galaxy and star-forming galaxy contributions
- Real diffuse contributions must be small
  - UHECR interactions
  - WIMP annihilation
  - etc.






Knee
2nd Knee
Ankle
$E_\nu \cong \frac{1}{4}\left\langle \frac{E_\pi}{E_p} \right\rangle \approx 0.02$
$\pi \rightarrow \nu_\mu + \left(e + \nu_e + \overline{\nu_\mu}\right)$
Grigorov
JACEE
MGU
Tien-Shan
Tibet07
Akeno
CASA-MIA
HEGRA
Fly's Eye
Kascade
Kascade Grande
IceTop-73
HiRes 1
HiRes 2
Telescope Array
Auger
PeV neutrinos from cosmic ray accelerators?
$E^{2.6}F(E)$ [GeV$^{1.6}$ m^{-2} s^{-1} sr^{-1}]
E [eV]
10^4
10^3
10^2
10
1
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}

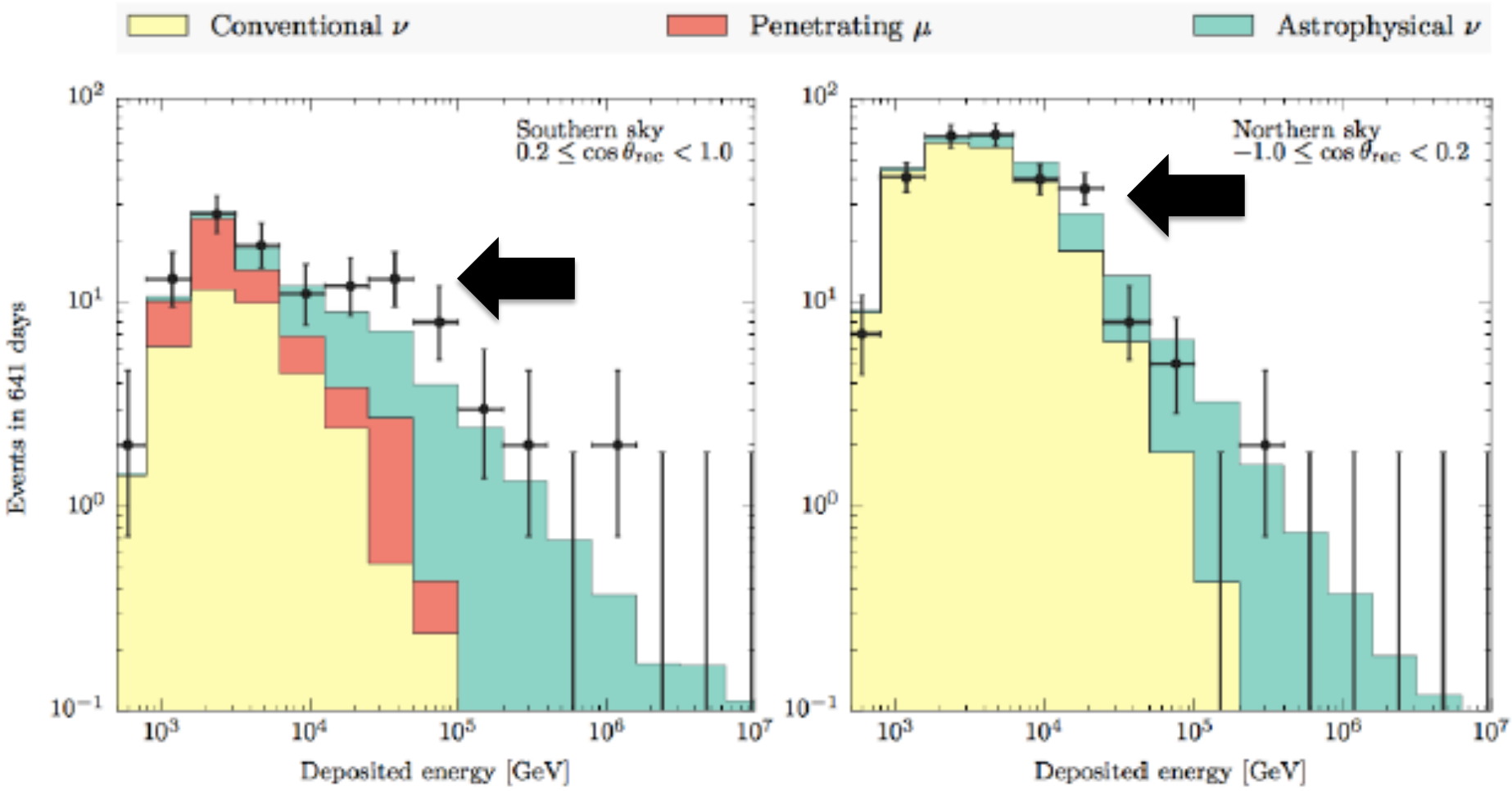
number of muon neutrino events from gamma ray sources in 5 years



- we observe a diffuse extragalactic flux
- active galaxies, most likely some form of blazars?
- correlation to catalogues should confirm this
- …. but correlation of cosmic neutrinos to < 30% of all Fermi blazars (subset if beaming angle neutrinos < light ?)

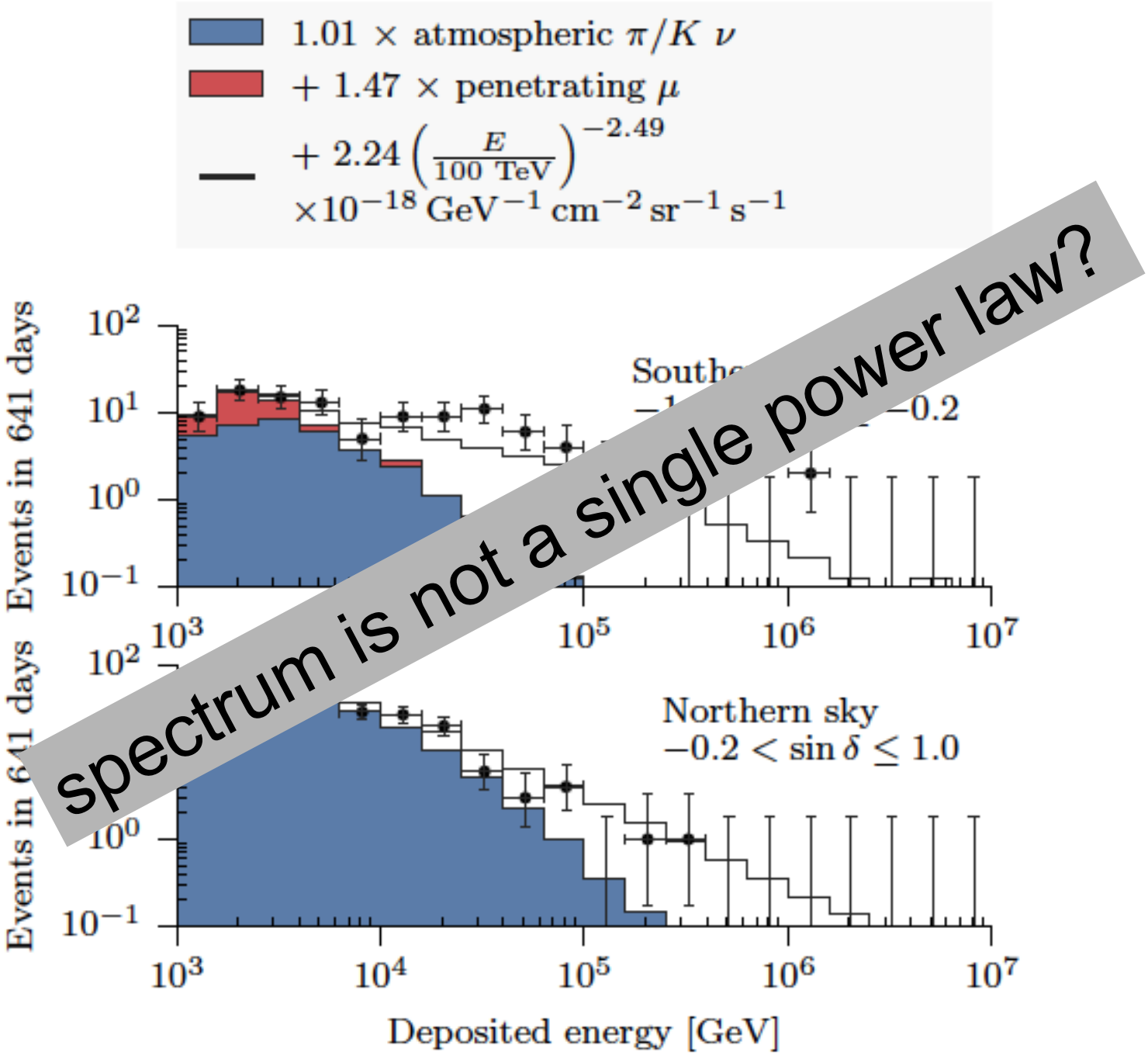
- there is more

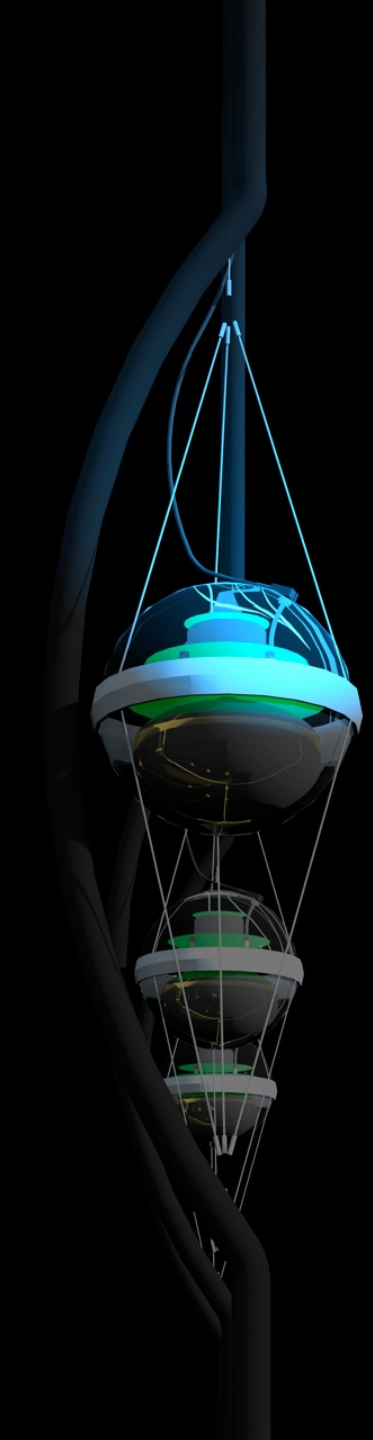
towards lower energies: a second component?



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

PeV neutrinos absorbed in the Earth


1.01 × atmospheric π/K ν
+ 1.47 × penetrating μ
$+ 2.24 \left(\frac{E}{100\ \text{TeV}}\right)^{-2.49}$
$\times 10^{-18}\,\text{GeV}^{-1}\,\text{cm}^{-2}\,\text{sr}^{-1}\,\text{s}^{-1}$
Events in 641 days
Northern sky
$-0.2 < \sin\delta \leq 1.0$
Deposited energy [GeV]
spectrum is not a single power law?



IceCube: the discovery of cosmic neutrinos

francis halzen

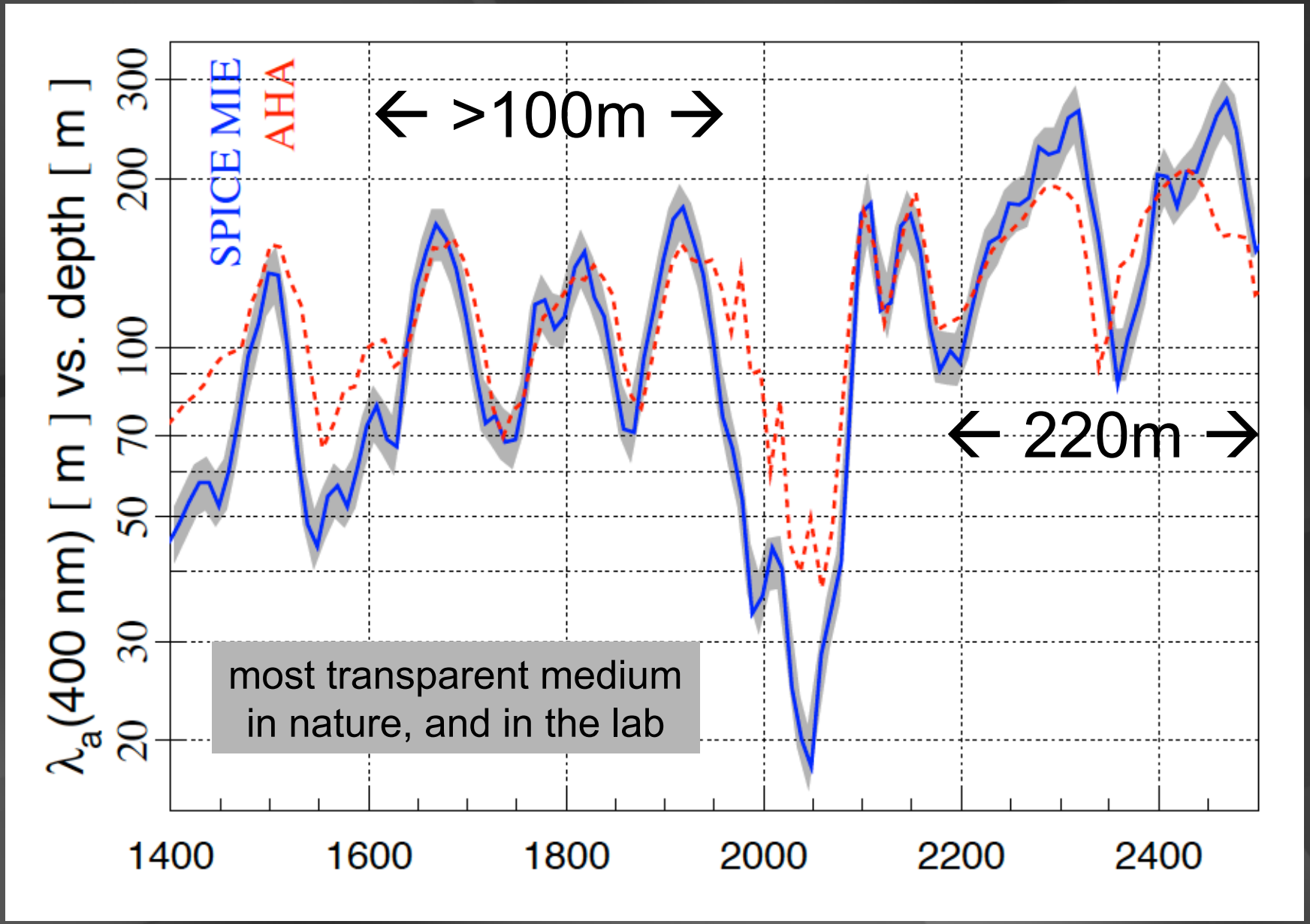
- cosmic ray accelerators
- IceCube
- the discovery of cosmic neutrinos ν_{μ}
- the discovery of cosmic neutrinos $\nu_{e,\tau}$
- where do they come from
- what next

- 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 versus 100 now in a few years

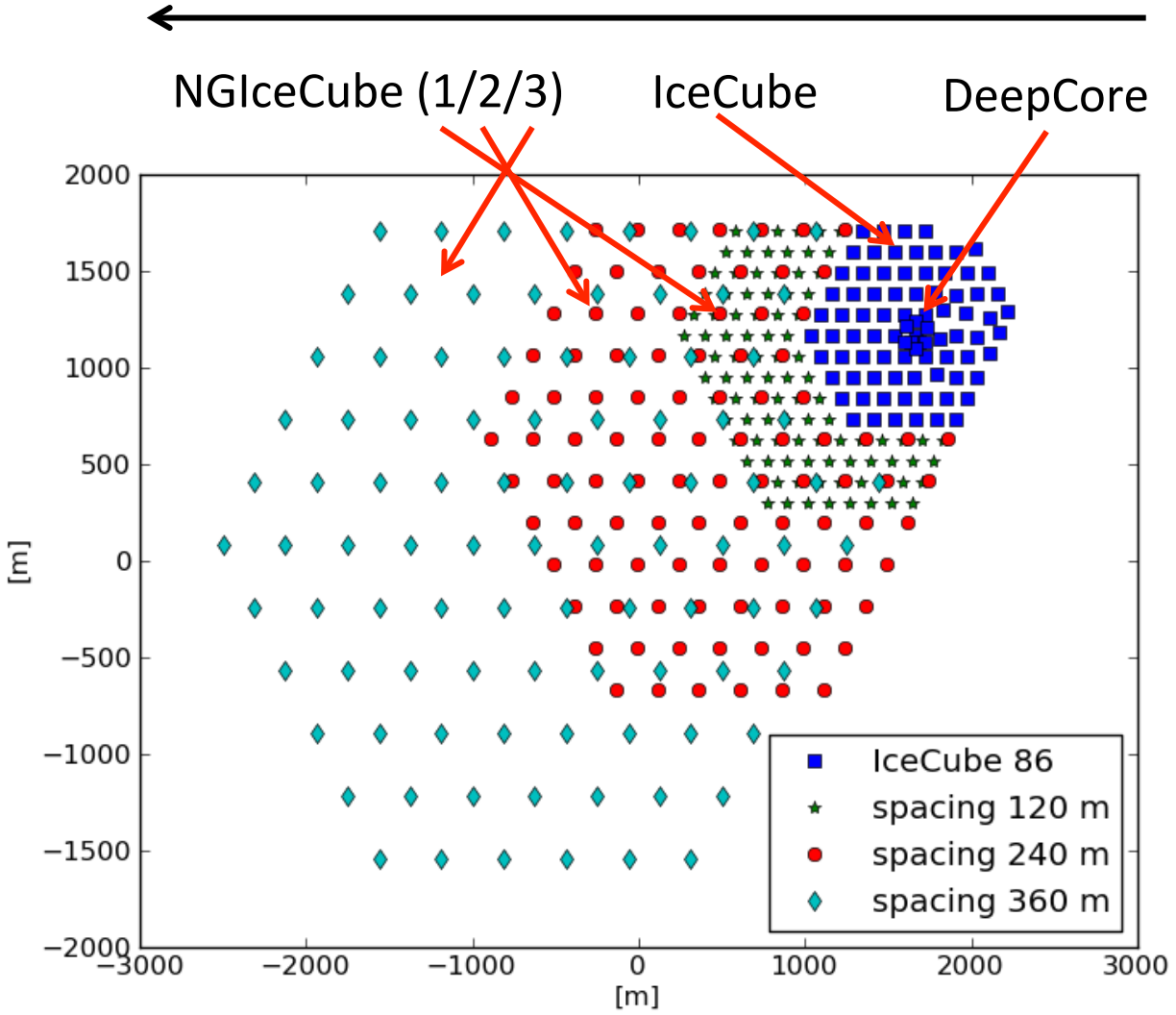
- discovery instrument → astronomical telescope

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

did not talk about:

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

Conclusions

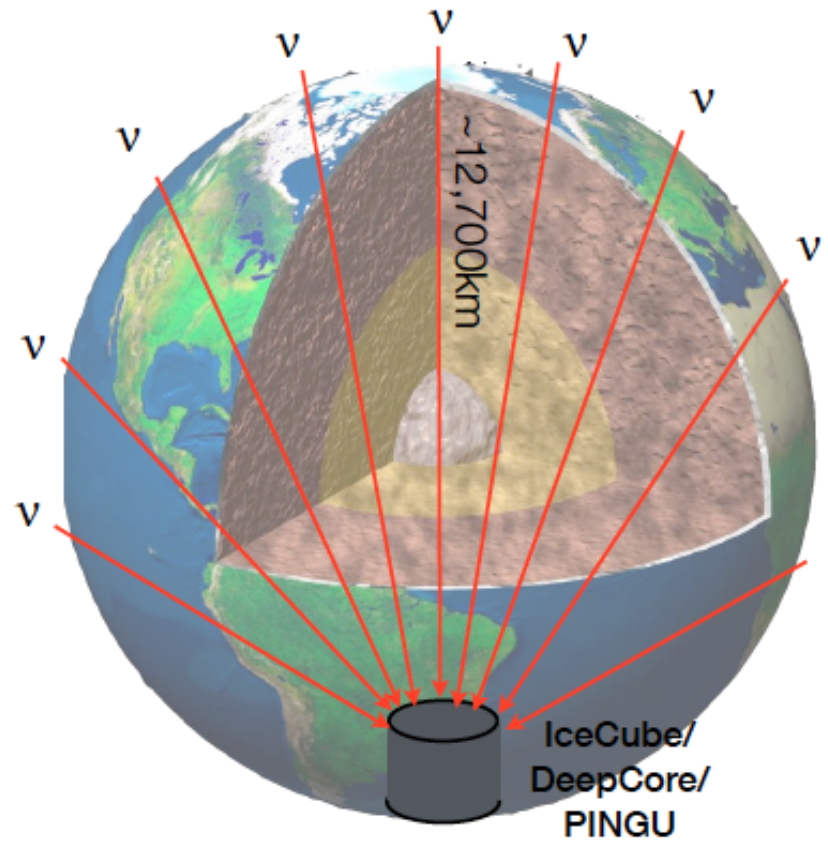
- more to come from IceCube: many analyses have not exploited more than one year of data
- analyses are not in the background-dominated regime
- next-generation detector(s):
    1. discovery → astronomy (also KM3NeT, GVD, ASHRA)
    2. neutrino physics at (relatively) low cost and on short timescales (PINGU/ORCA)
    3. potential for discovery
- neutrinos are never boring!

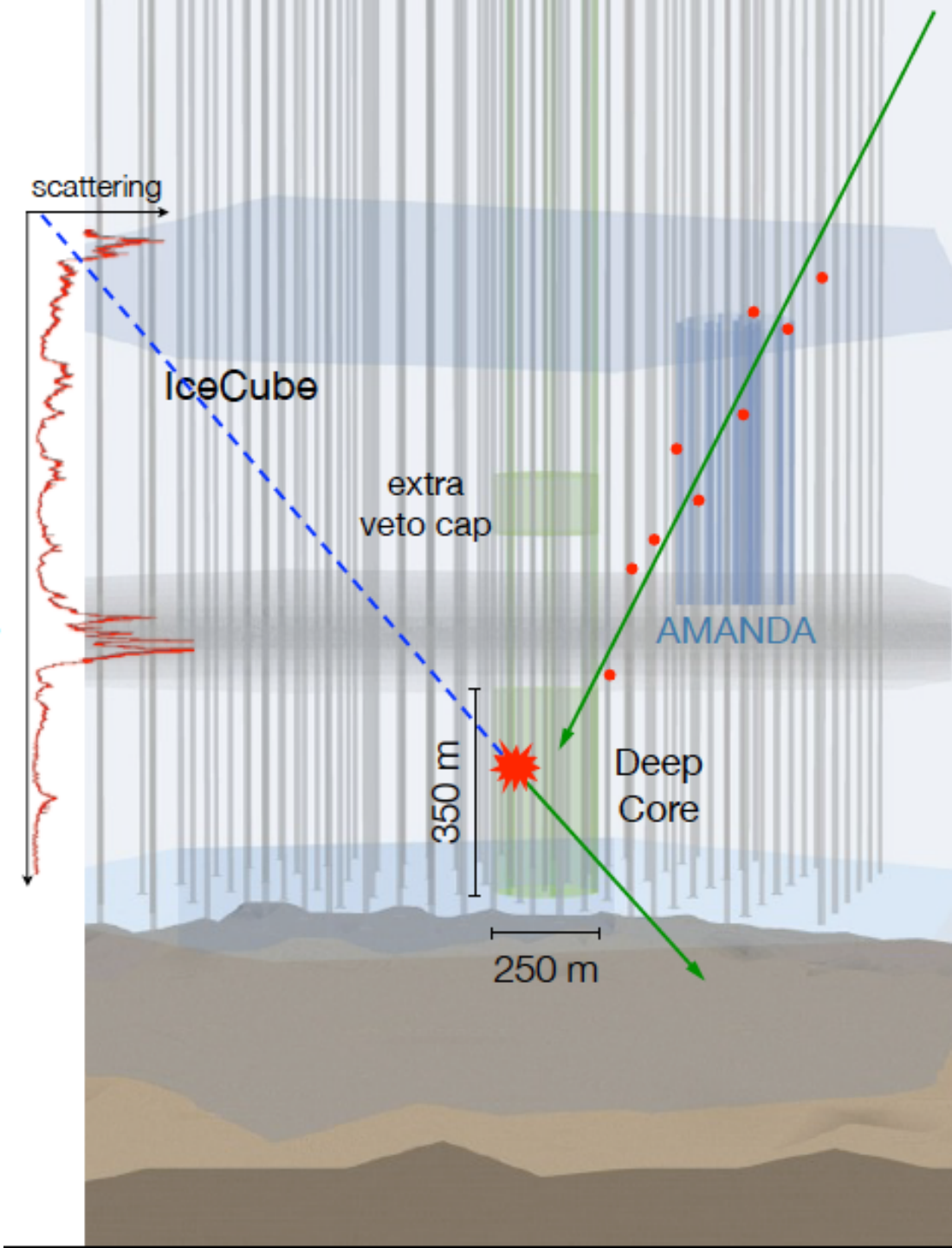
The IceCube–PINGU Collaboration

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)

one half million atmospheric neutrinos…

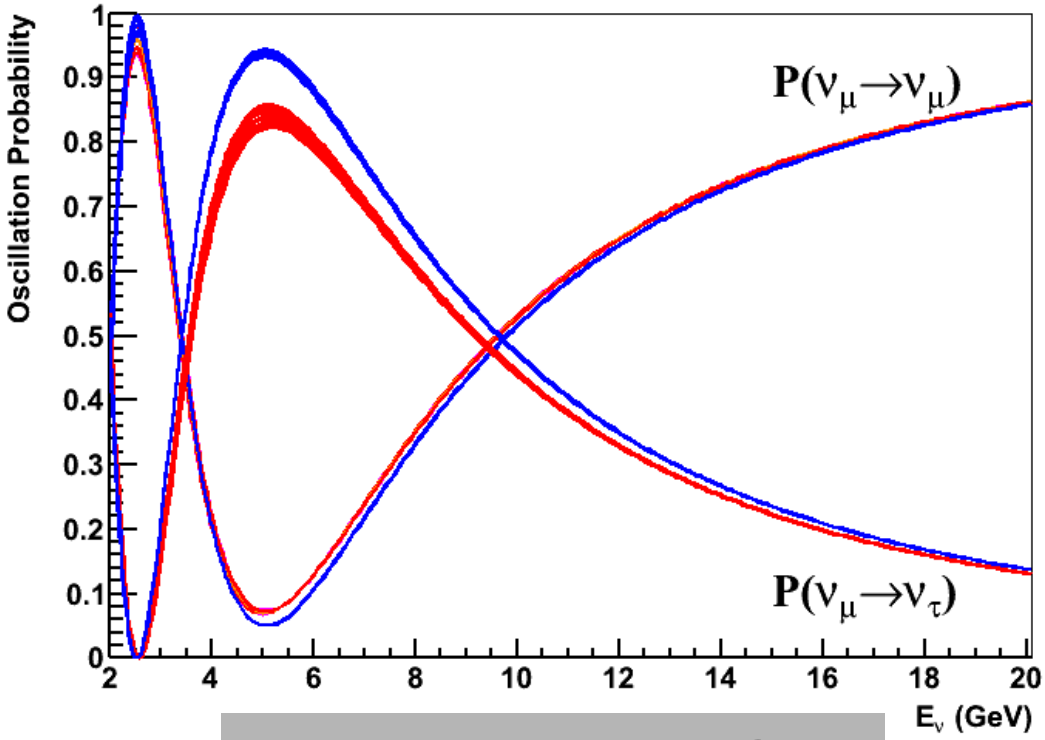




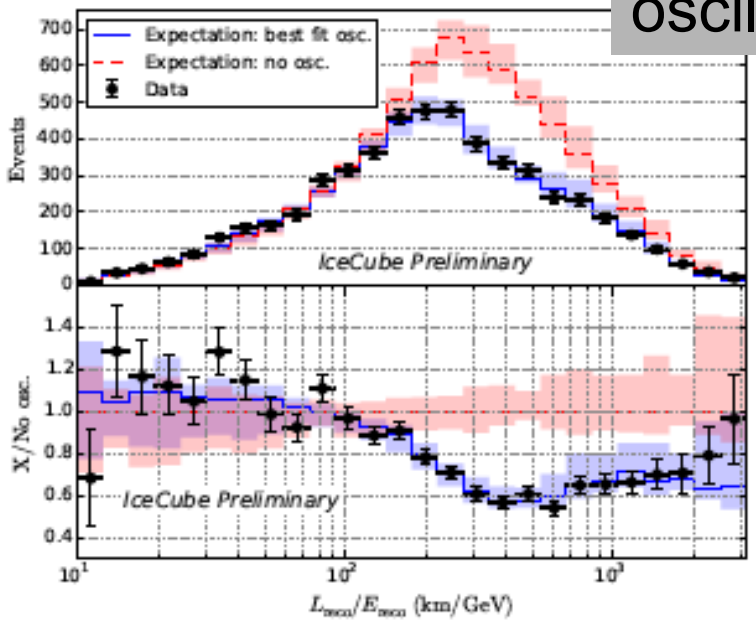
IceCube

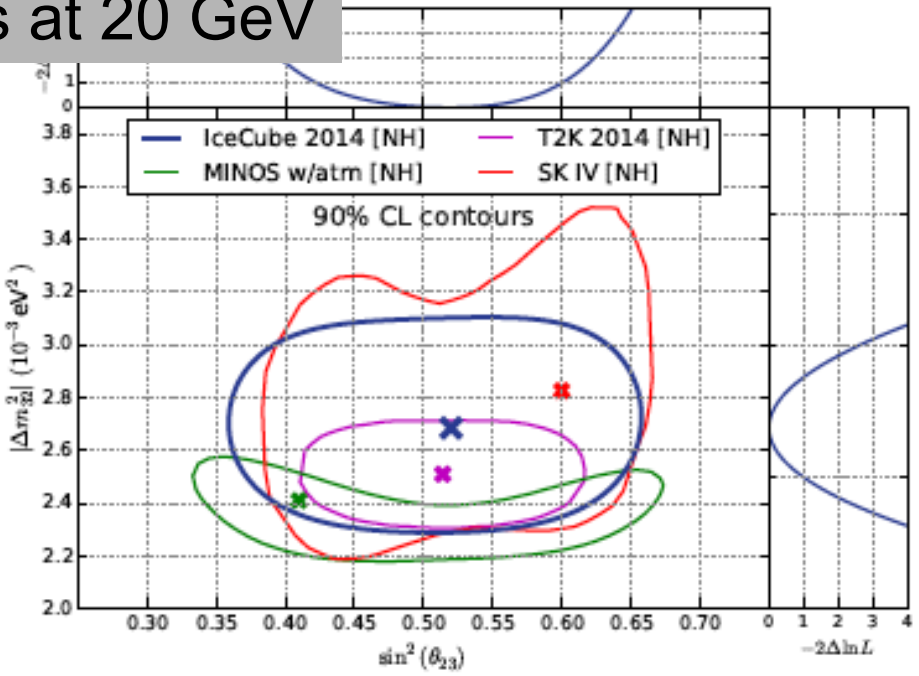
DeepCore

PINGU



oscillations at 20 GeV

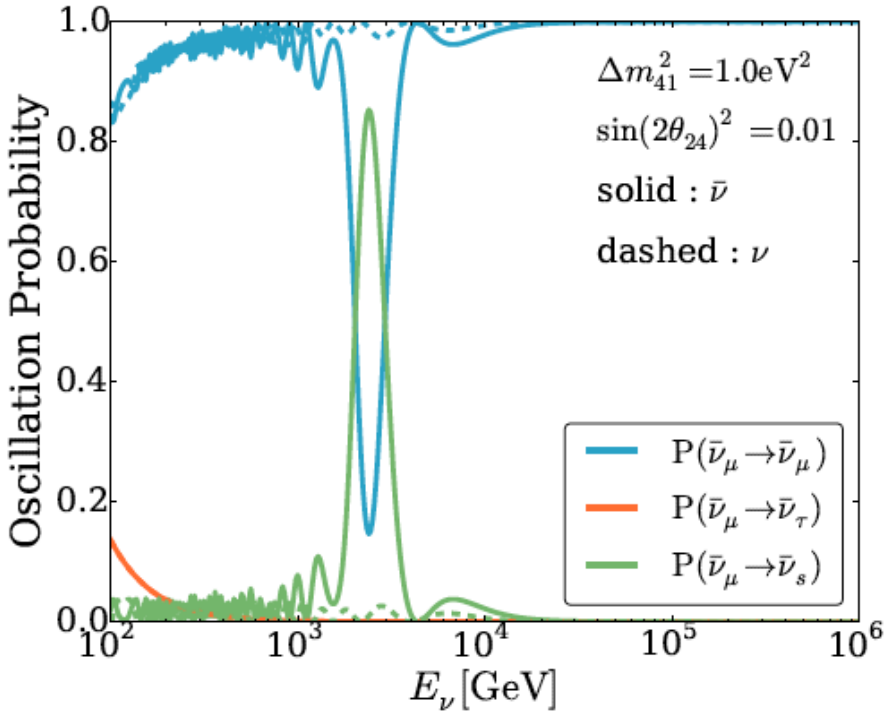




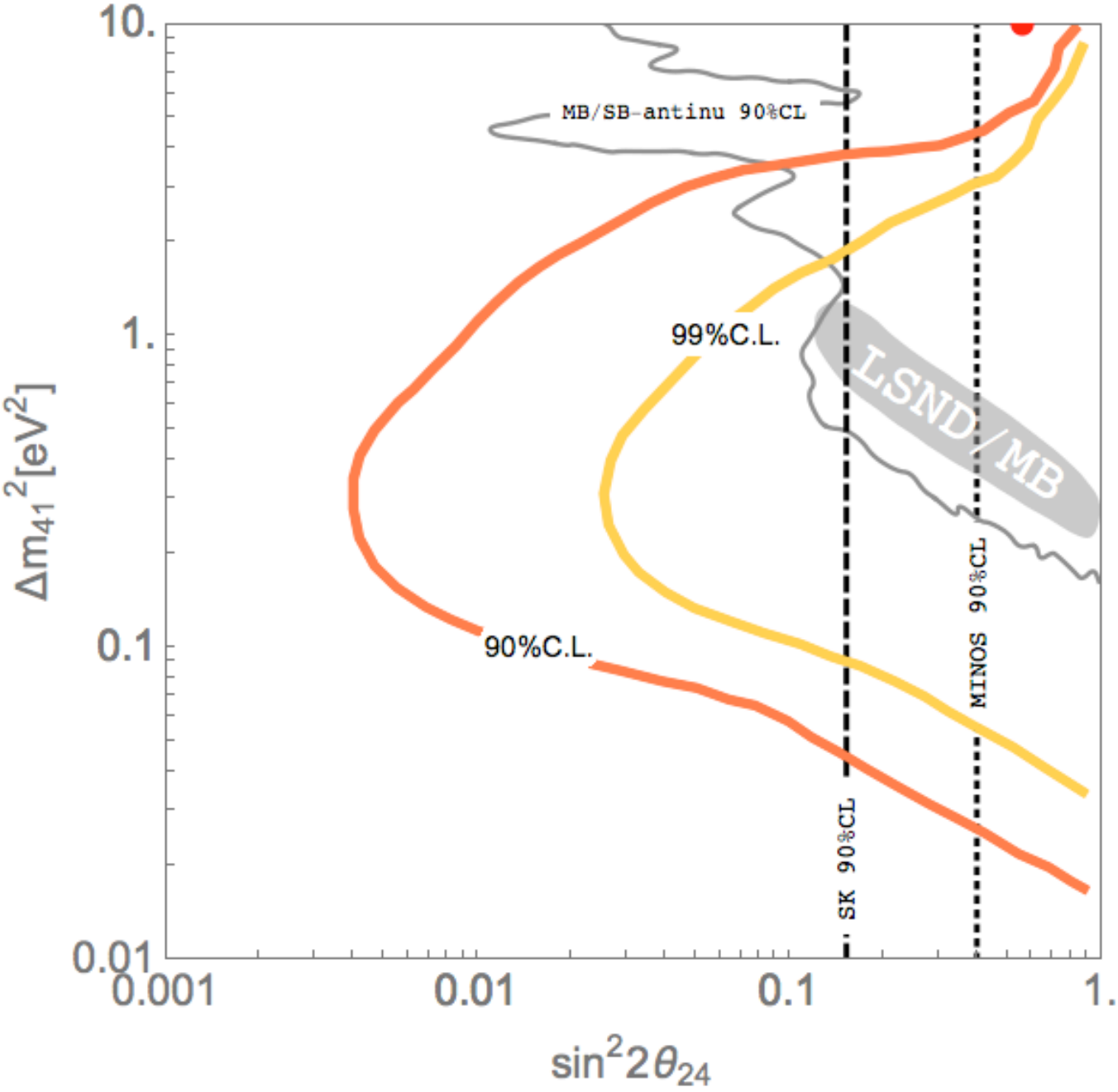
electron neutrino oscillates into sterile → modifies matter effect of the atmospheric neutrino beam observed through the Earth

happens when

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



eV sterile neutrino → Earth MSW resonance for 3 TeV neutrinos


10.
1.
0.1
0.01
0.001
0.01
0.1
1.
Δm_{41}^2[eV^2]
$\sin^2 2\theta_{24}$
MB/SB-antinu 90%CL
99%C.L.
90%C.L.
LSND/MB
SK 90%CL
MINOS 90%CL

stay tuned– rapid progress

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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)