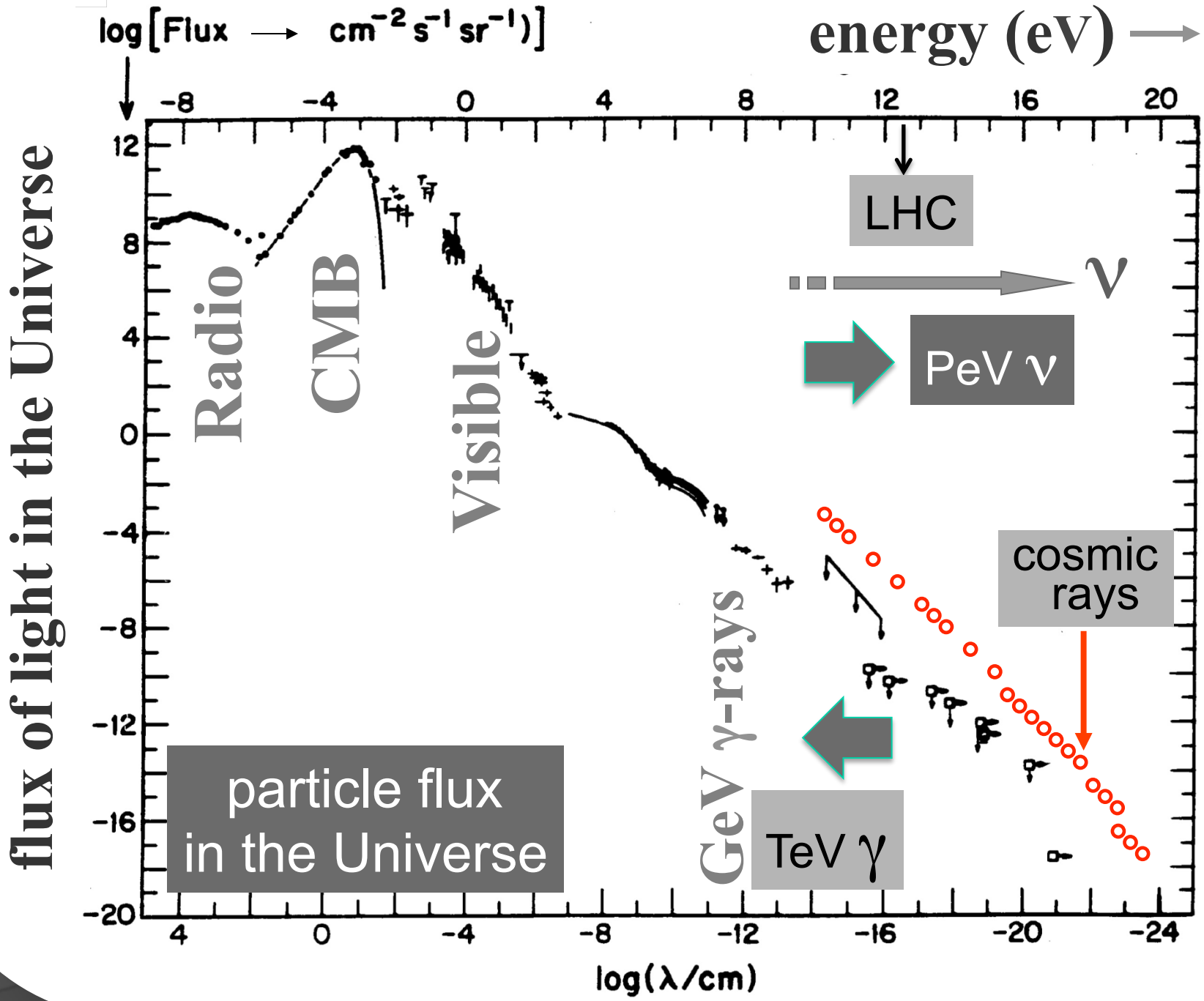
IceCube

francis halzen

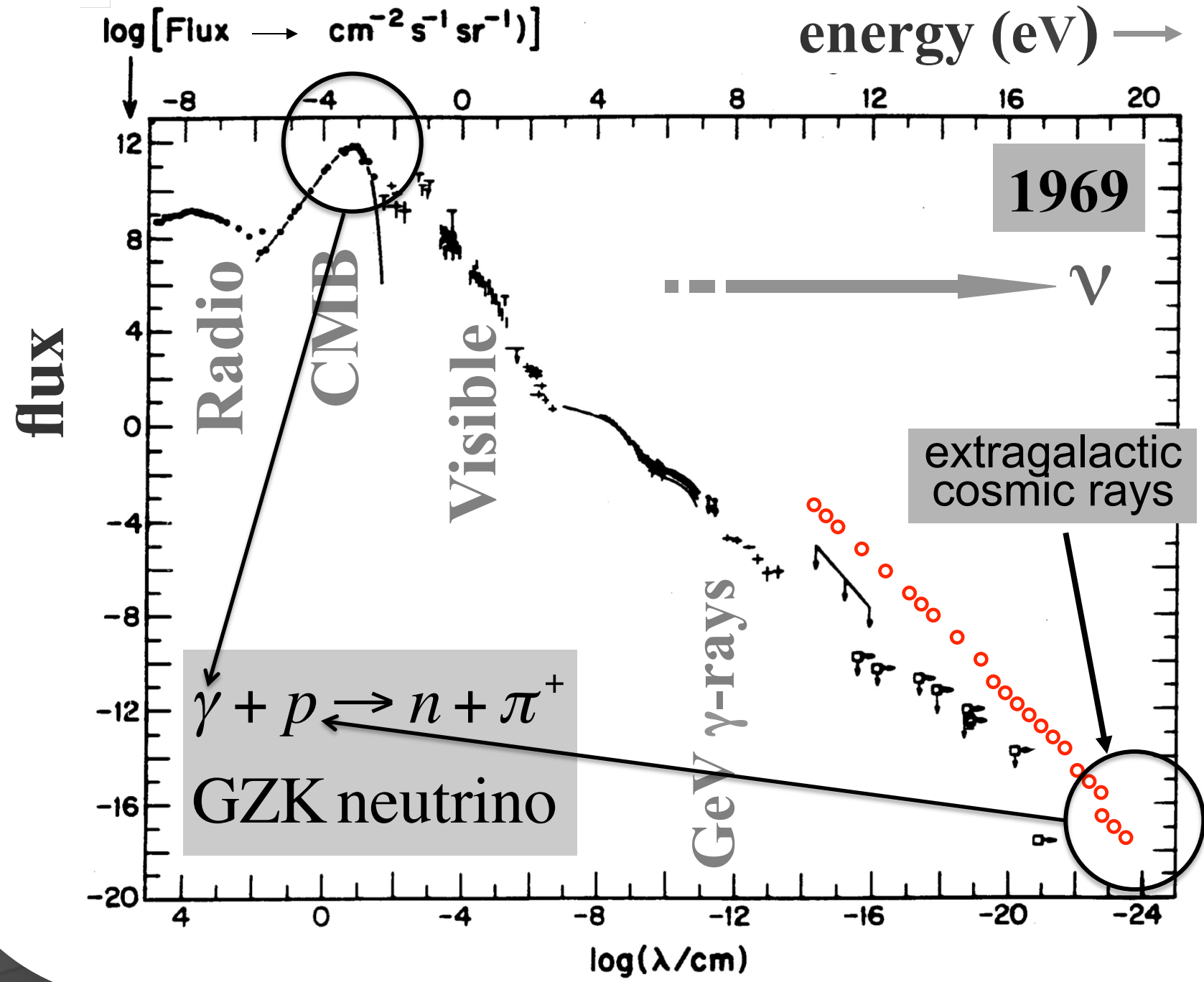
- why would you want to build a a kilometer scale neutrino detector?
- IceCube: a cubic kilometer detector
- the discovery (and confirmation) of cosmic neutrinos
- from discovery to astronomy

IceCube.wisc.edu


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
PeV ν
cosmic rays
TeV γ
particle flux in the Universe

neutrino as a cosmic messenger:

- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- … but difficult to detect


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

cosmic rays interact with the microwave background

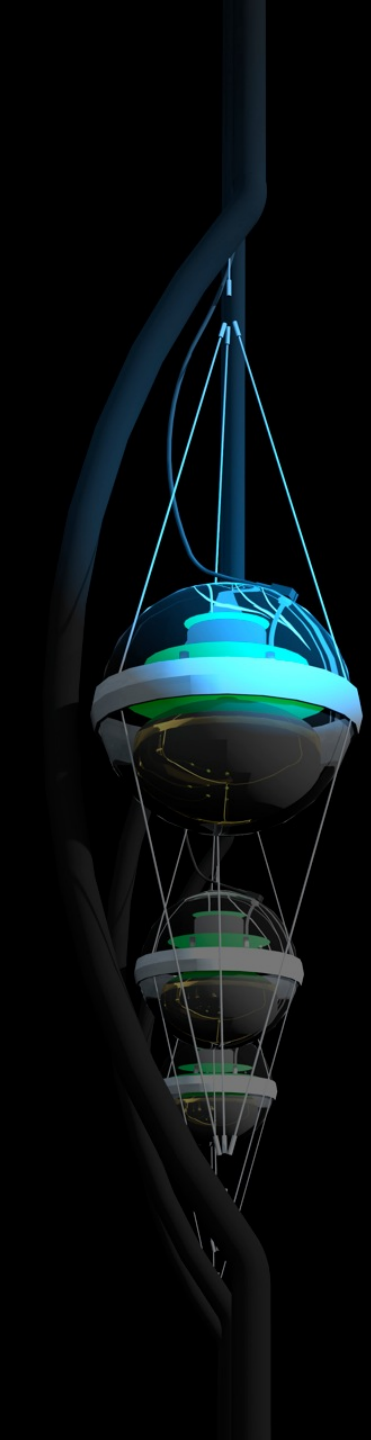
$$p + \gamma \rightarrow n + \pi^{+} \; and \; p + \pi^{0}$$

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!



IceCube

francis halzen

- cosmogenic neutrinos
- the energetics of cosmic ray sources
- neutrinos associated with cosmic rays
- a cubic kilometer detector
- evidence for extraterrestrial neutrinos
- conclusions

the sun constructs an accelerator

- accelerator must contain the particles

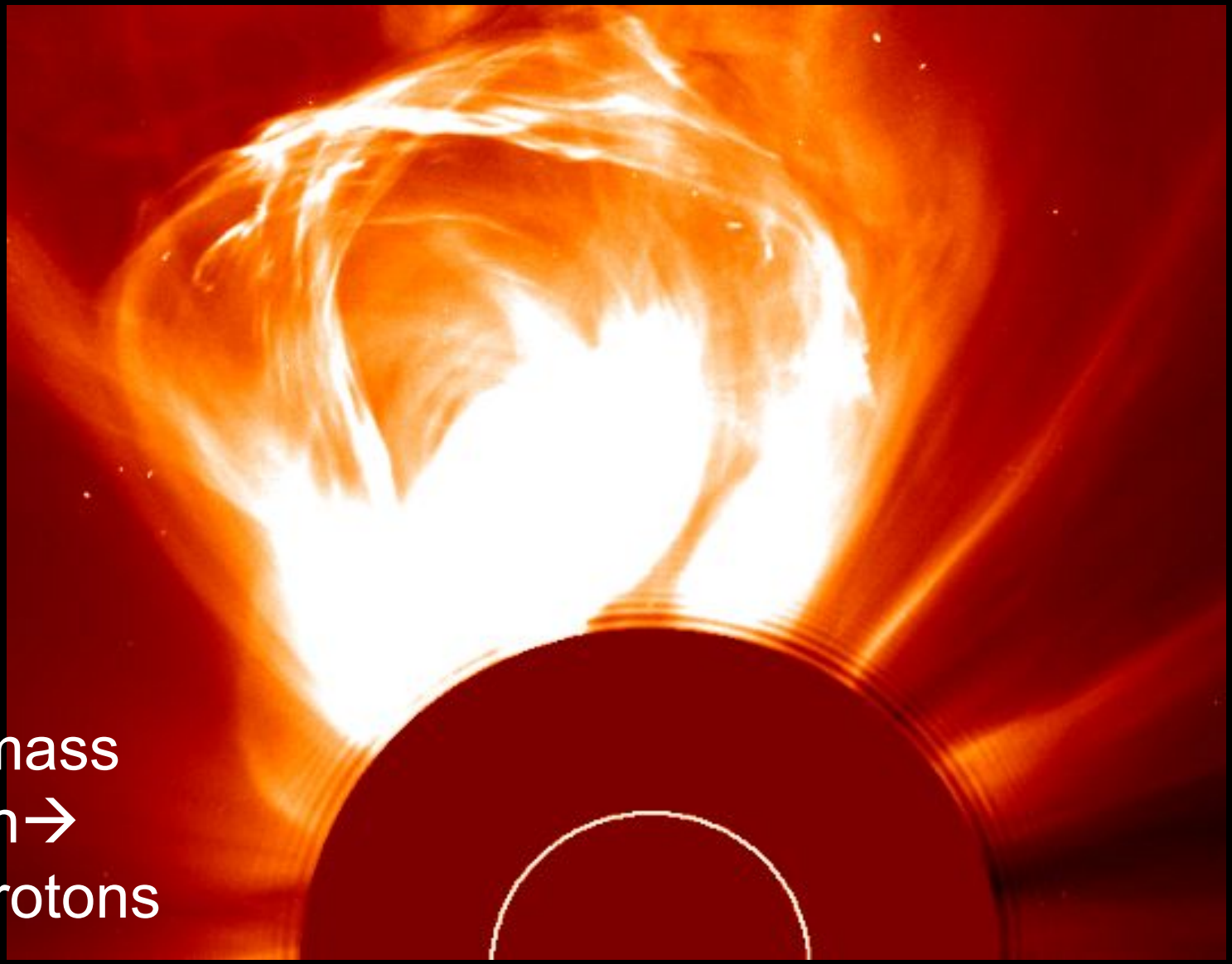
$$R_{gyro}\left(=\frac{E}{\mathrm{v}qB}\right)\leq R$$

$$E \leq \mathrm{v}\, qBR$$

challenges of cosmic ray astrophysics:

- dimensional analysis, difficult to satisfy
- accelerator luminosity is high as well

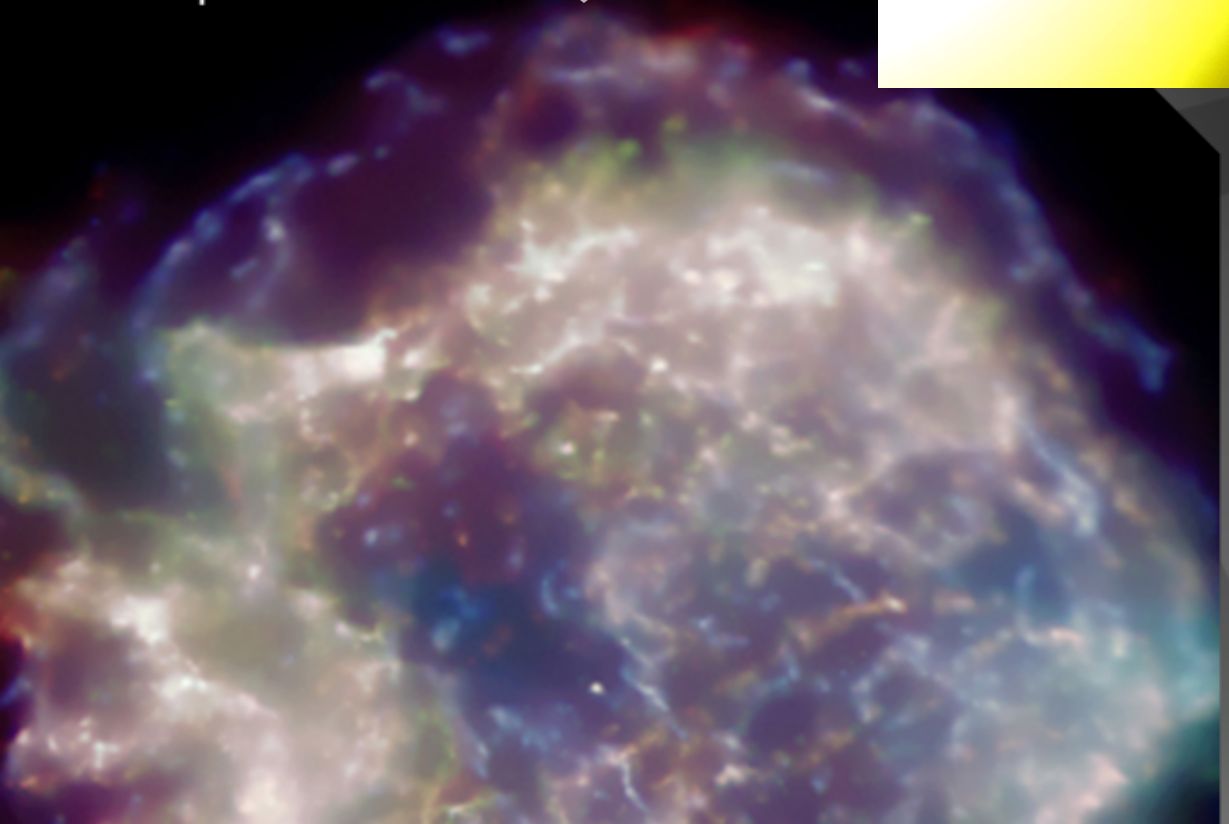
the sun constructs an accelerator

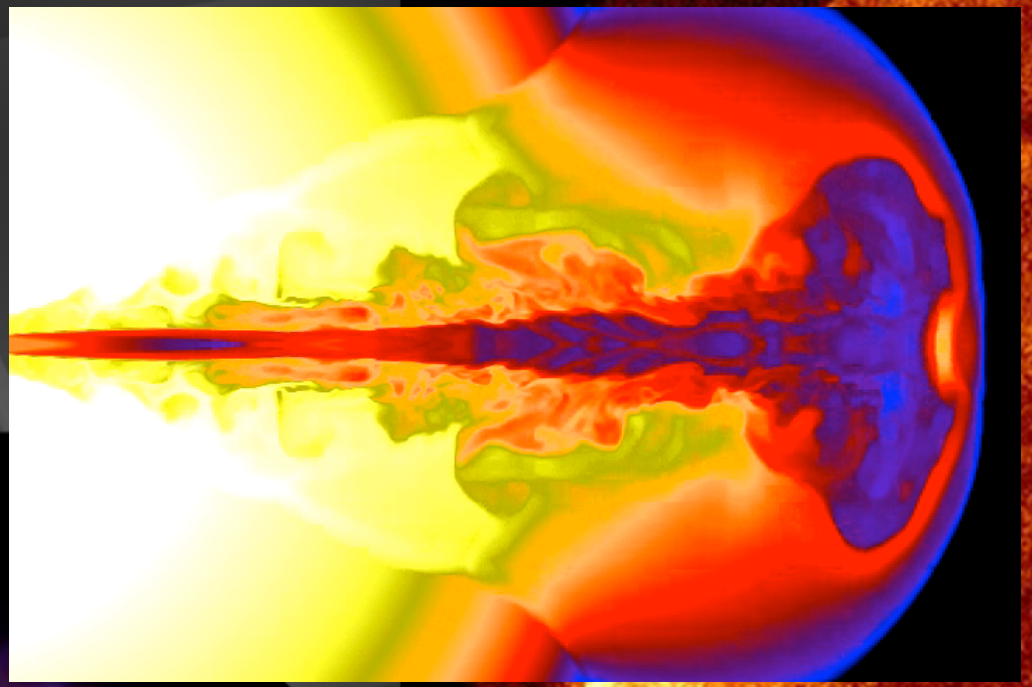


coronal mass ejection→ 10 GeV protons

supernova remnants

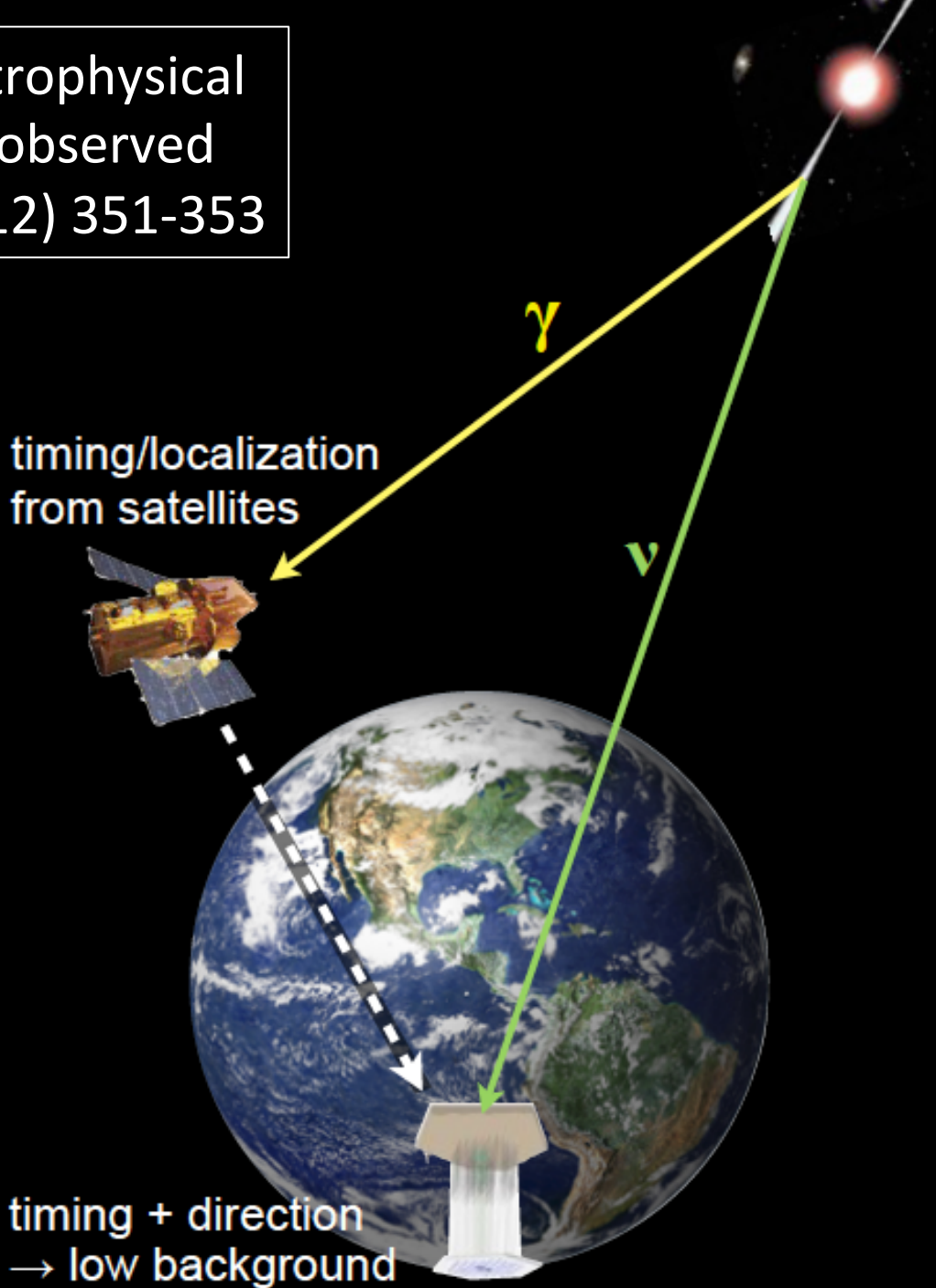
Chandra
Cassiopeia A

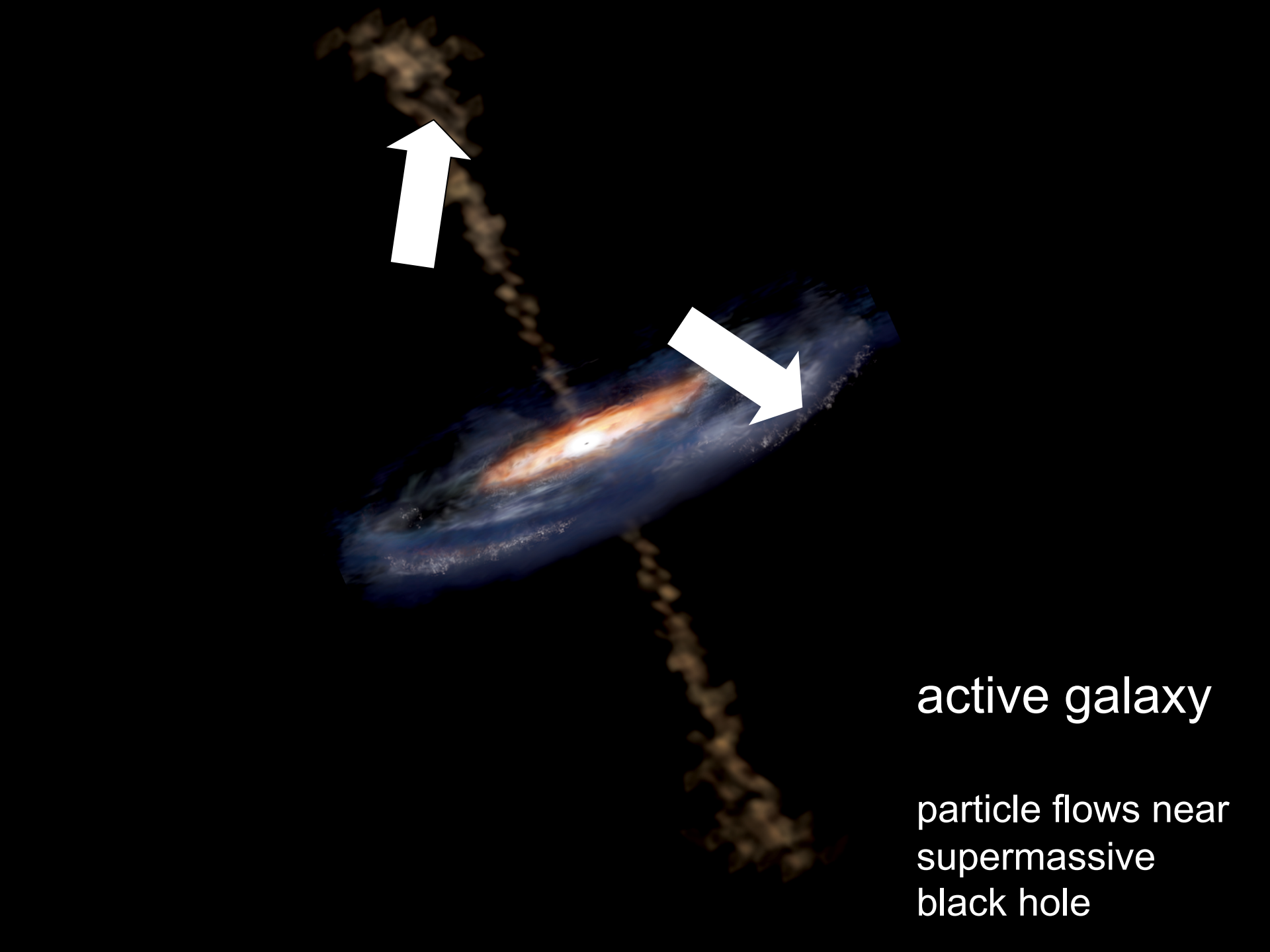




gamma ray bursts

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

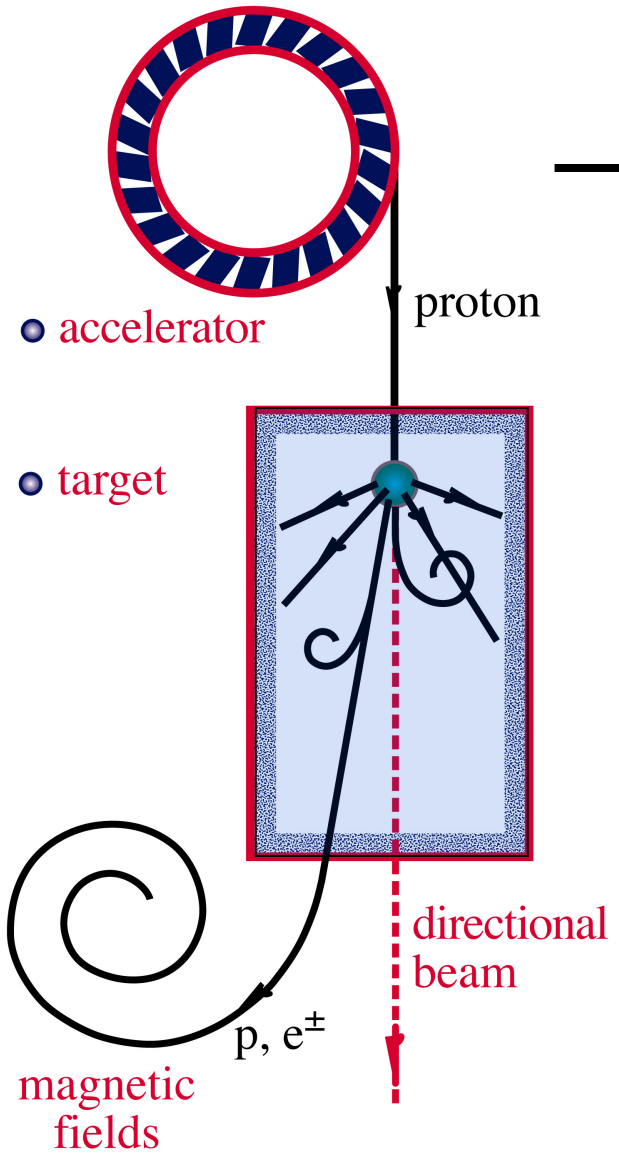




active galaxy

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

$\rightarrow p + \pi^0$

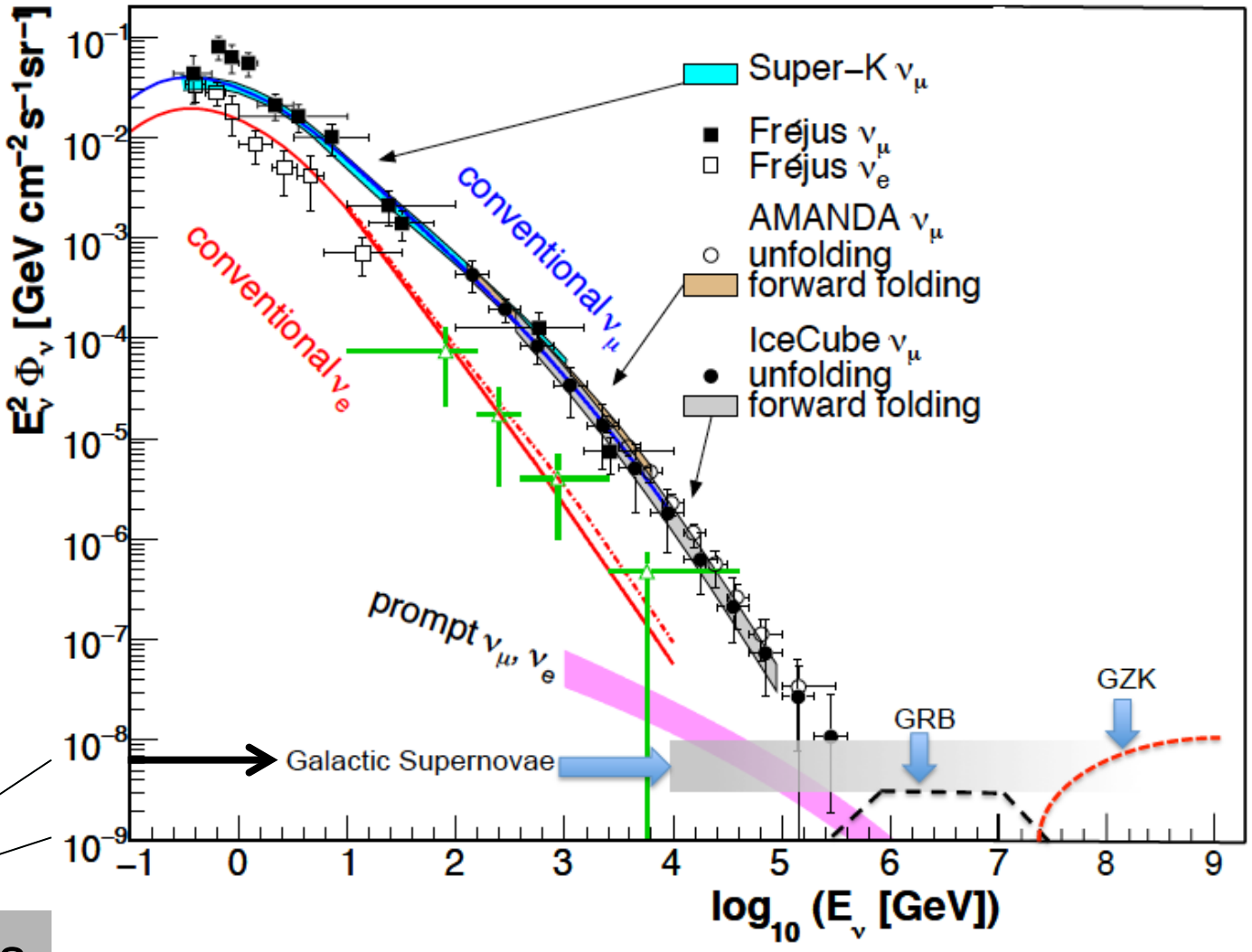
~ cosmic ray + gamma

above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

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

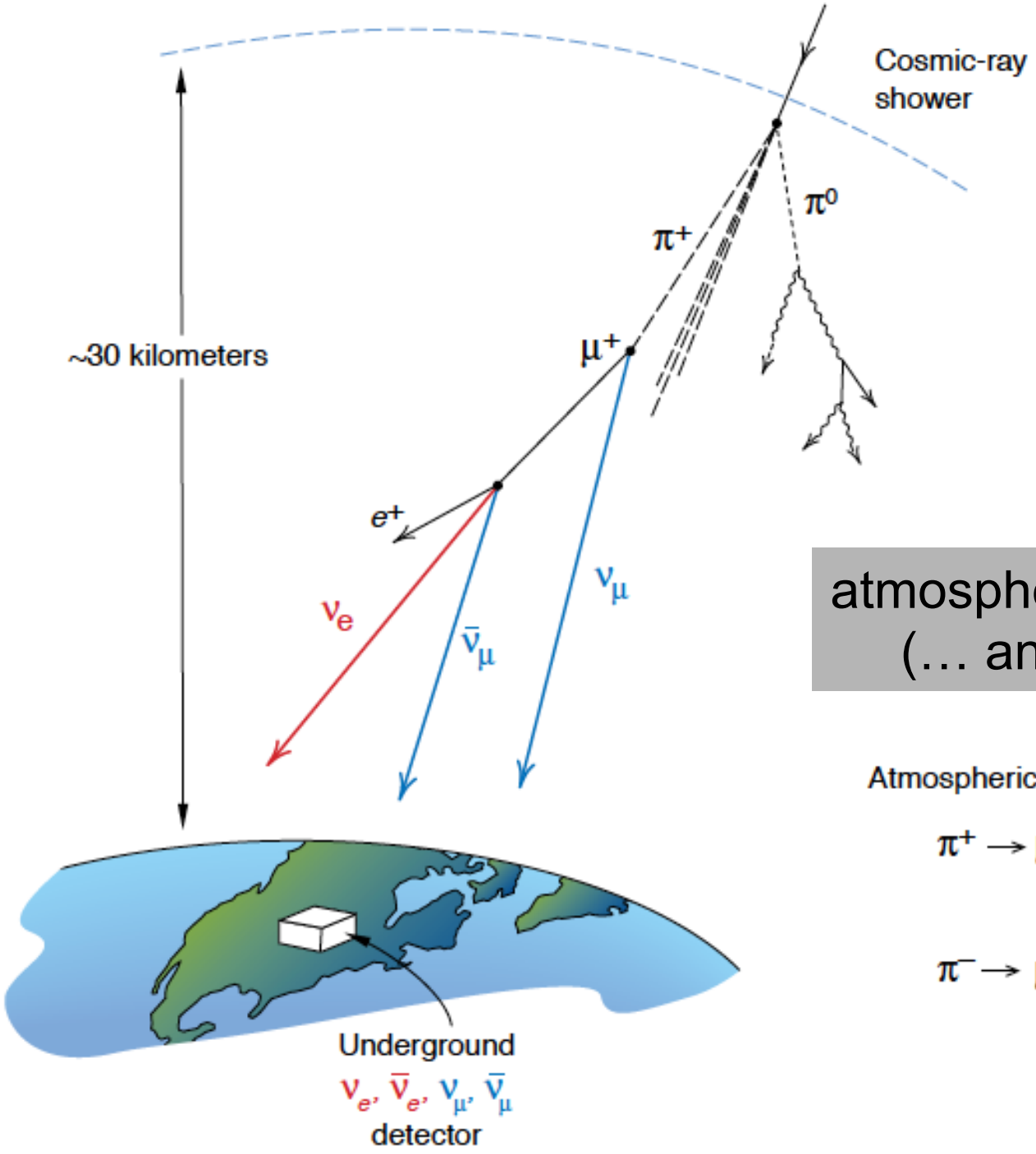
10—100 events per year for fully efficient 1 km^3 detector



atmospheric

cosmic

100 TeV

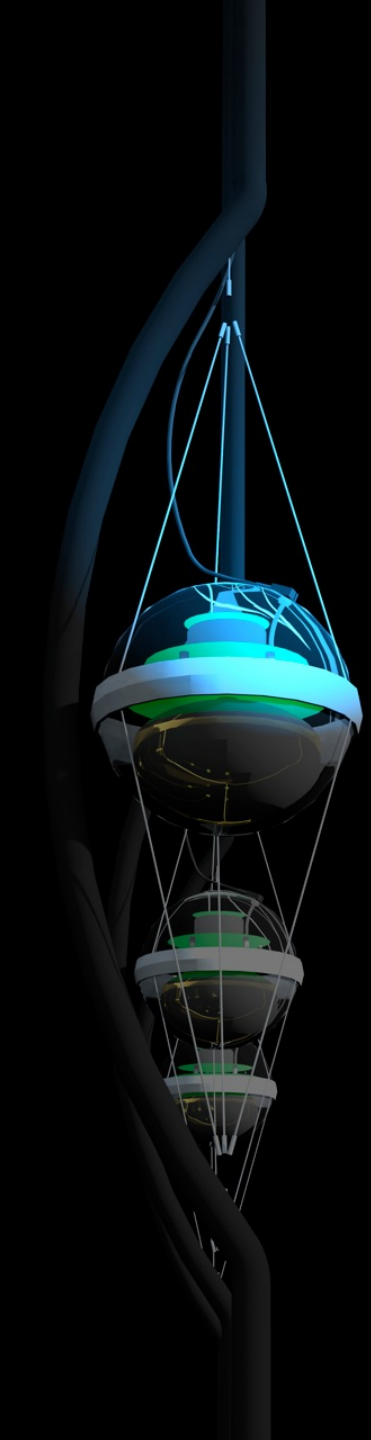


atmospheric neutrinos
(… and muons!)

Atmospheric neutrino source

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

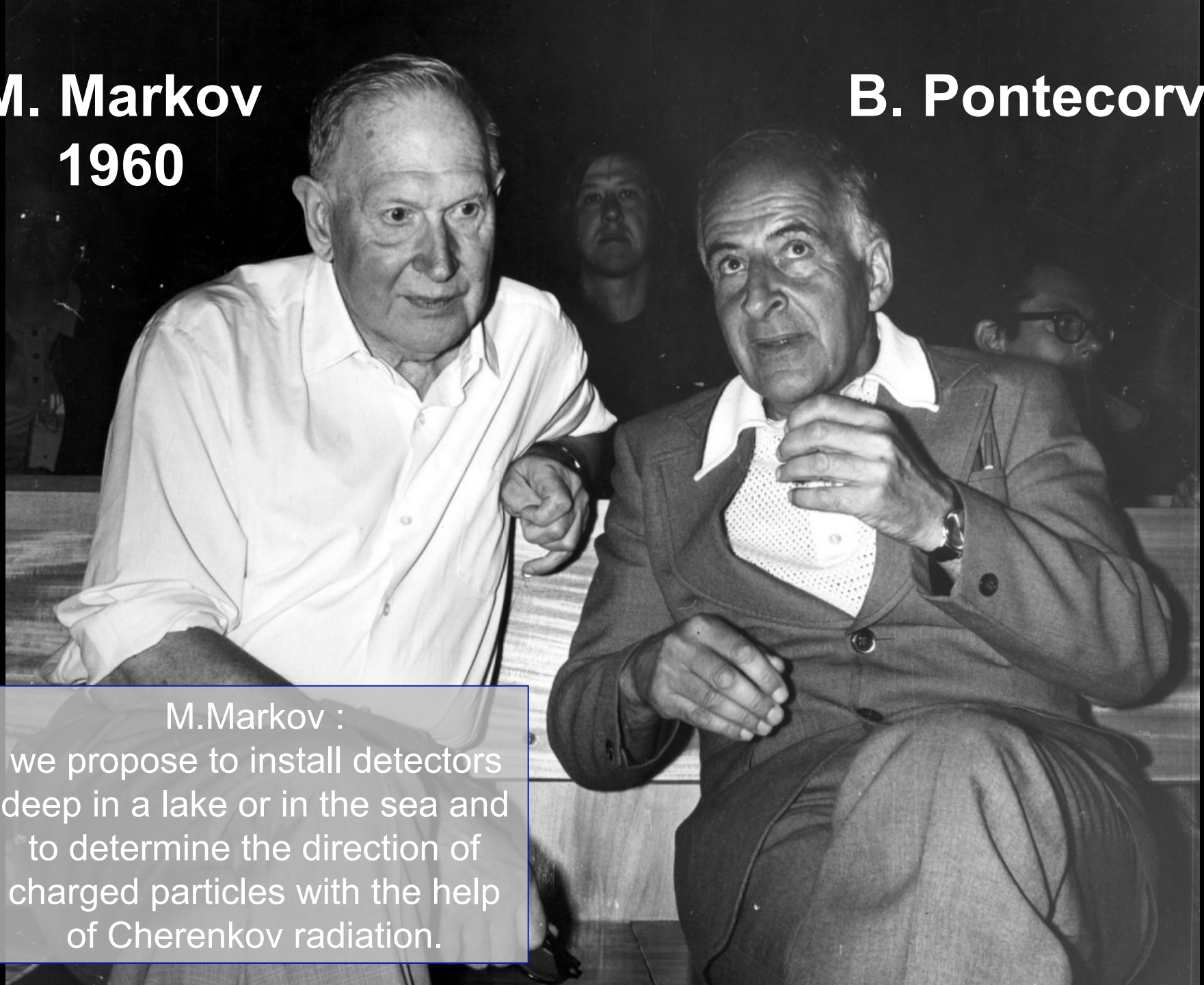
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$$



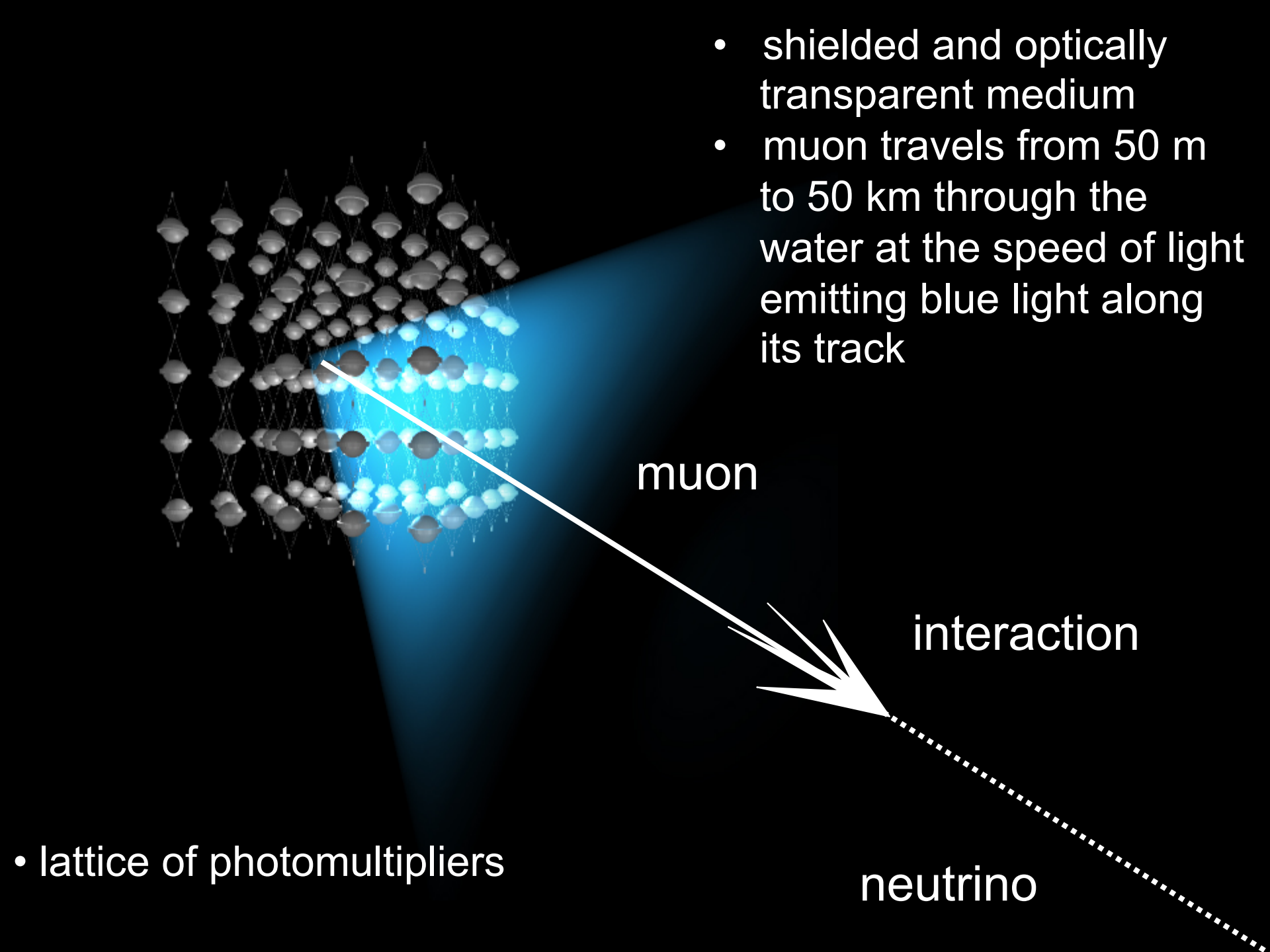
IceCube: the discovery of cosmic neutrinos

francis halzen

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

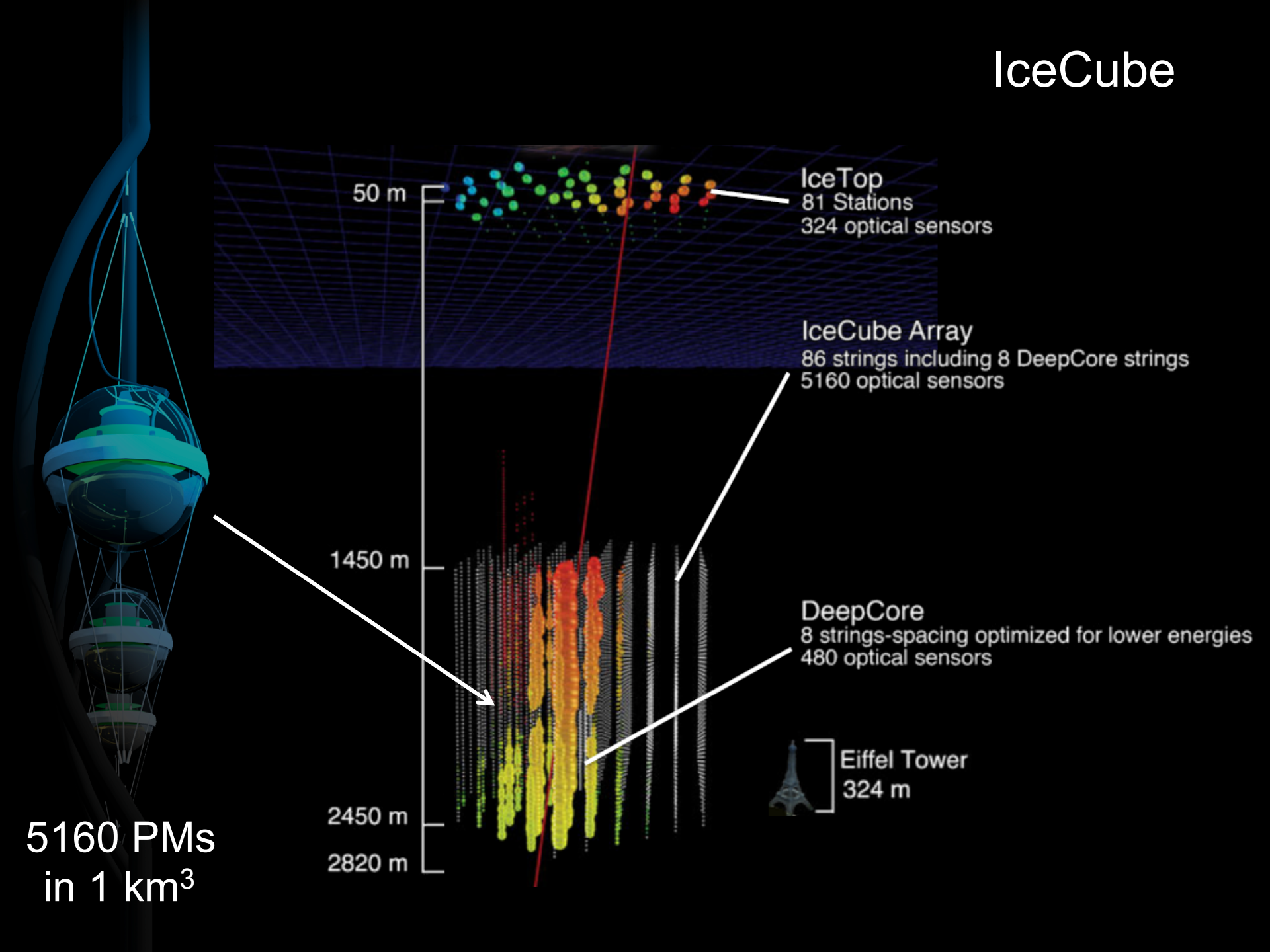


M.Markov :
we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.


• 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


ultra-transparent ice below 1.5 km

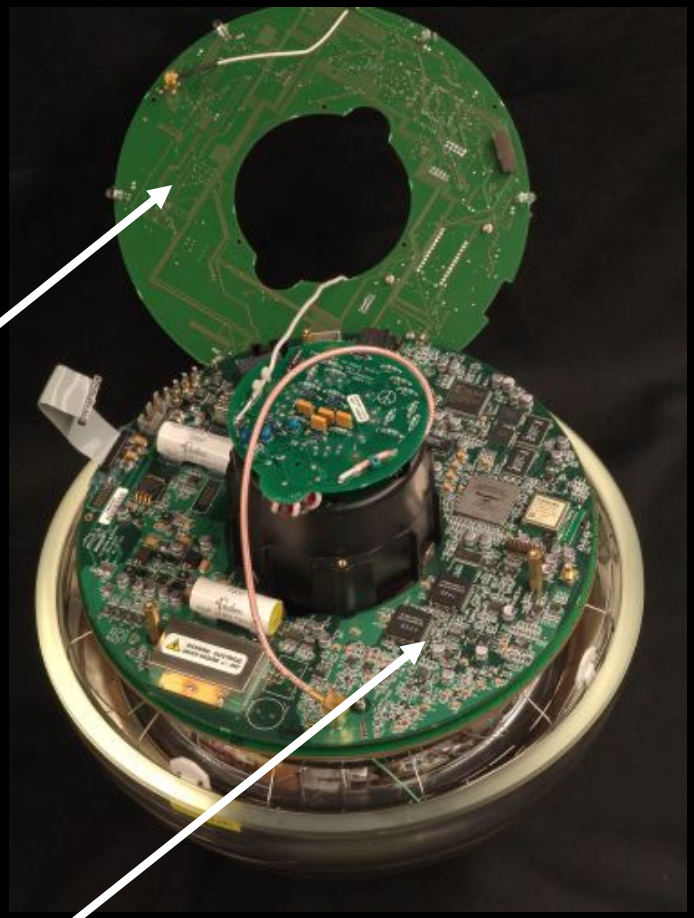
IceCube


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

photomultiplier tube -10 inch

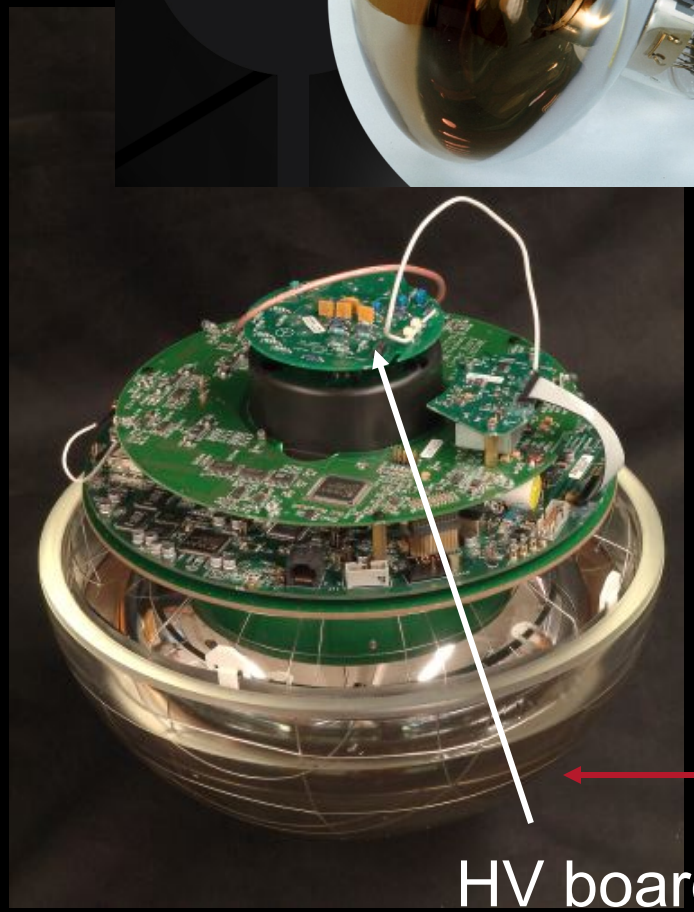
architecture of independent DOMs

10 inch pmt



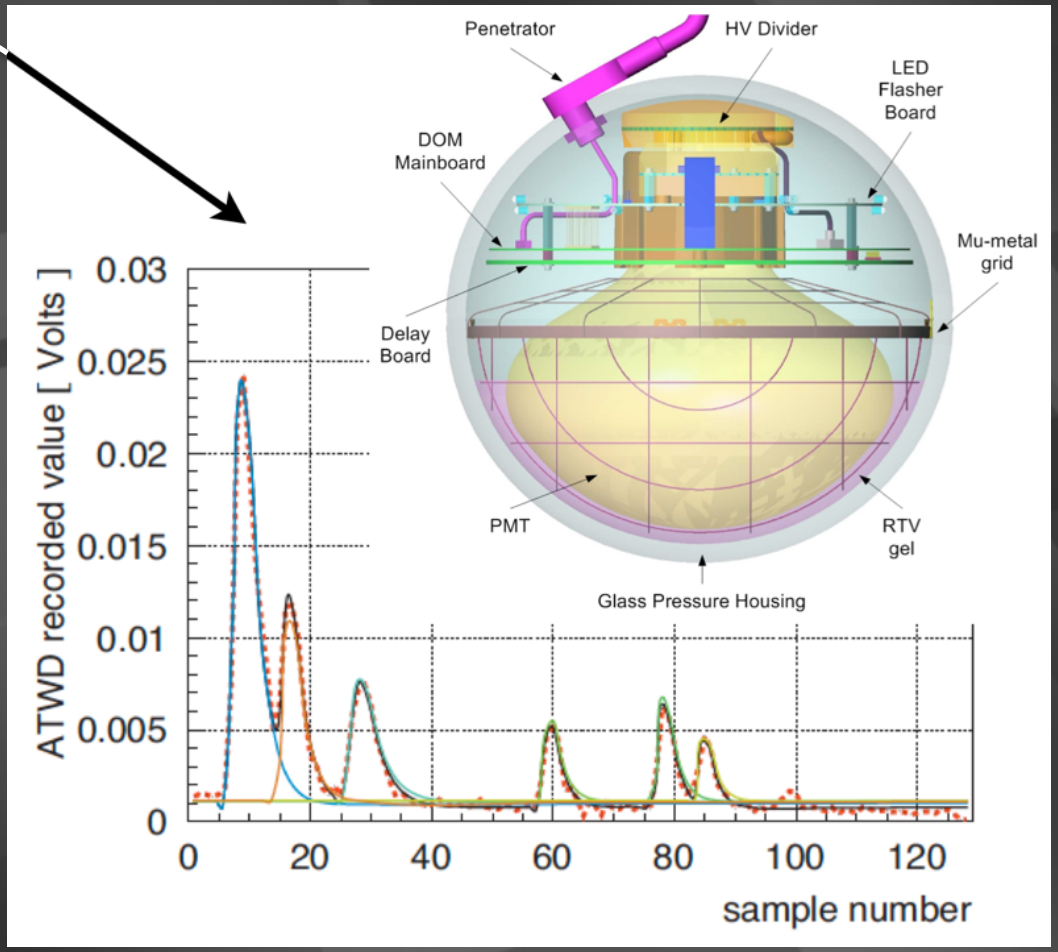
LED
flasher
board

main
board



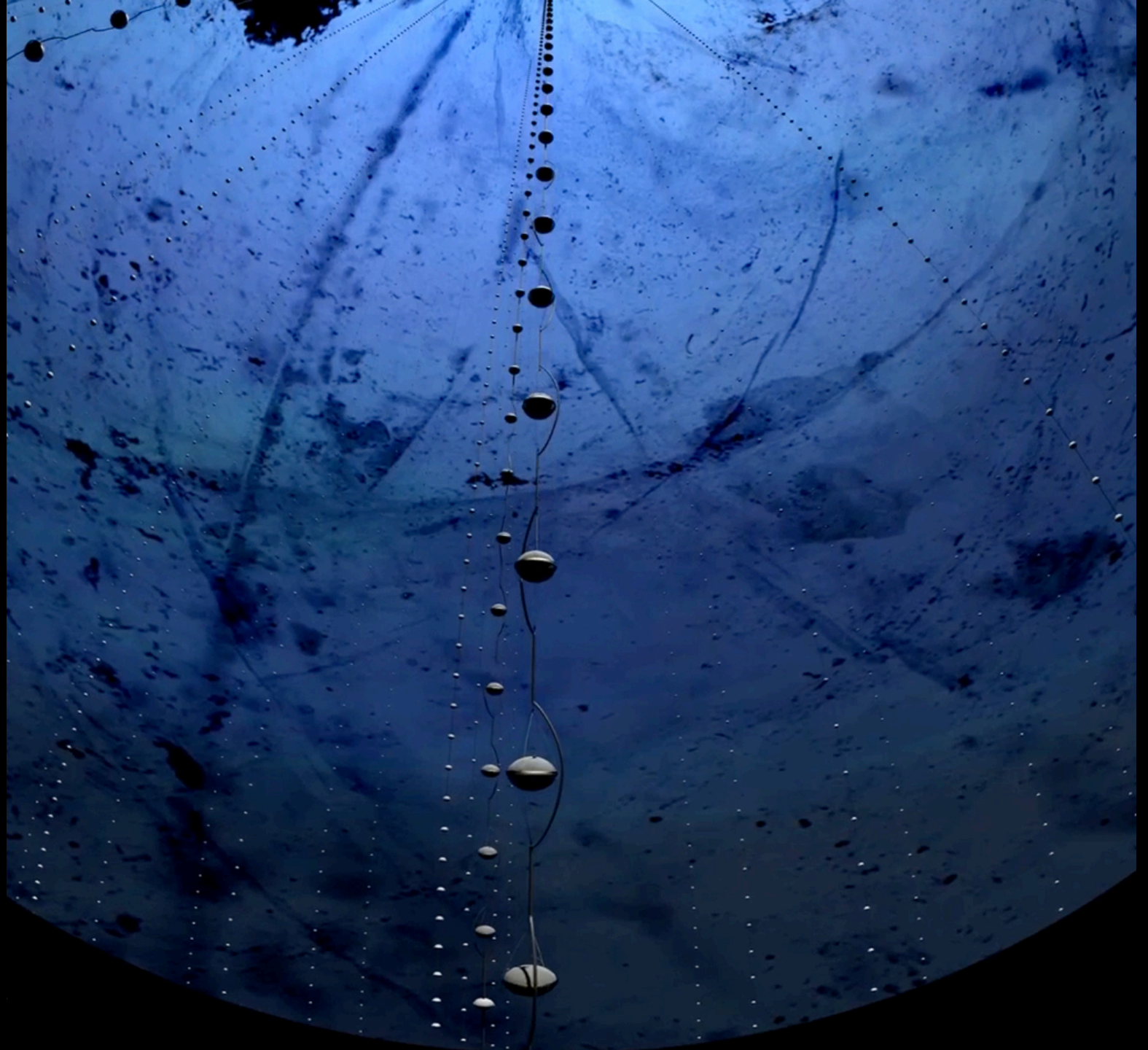
HV board

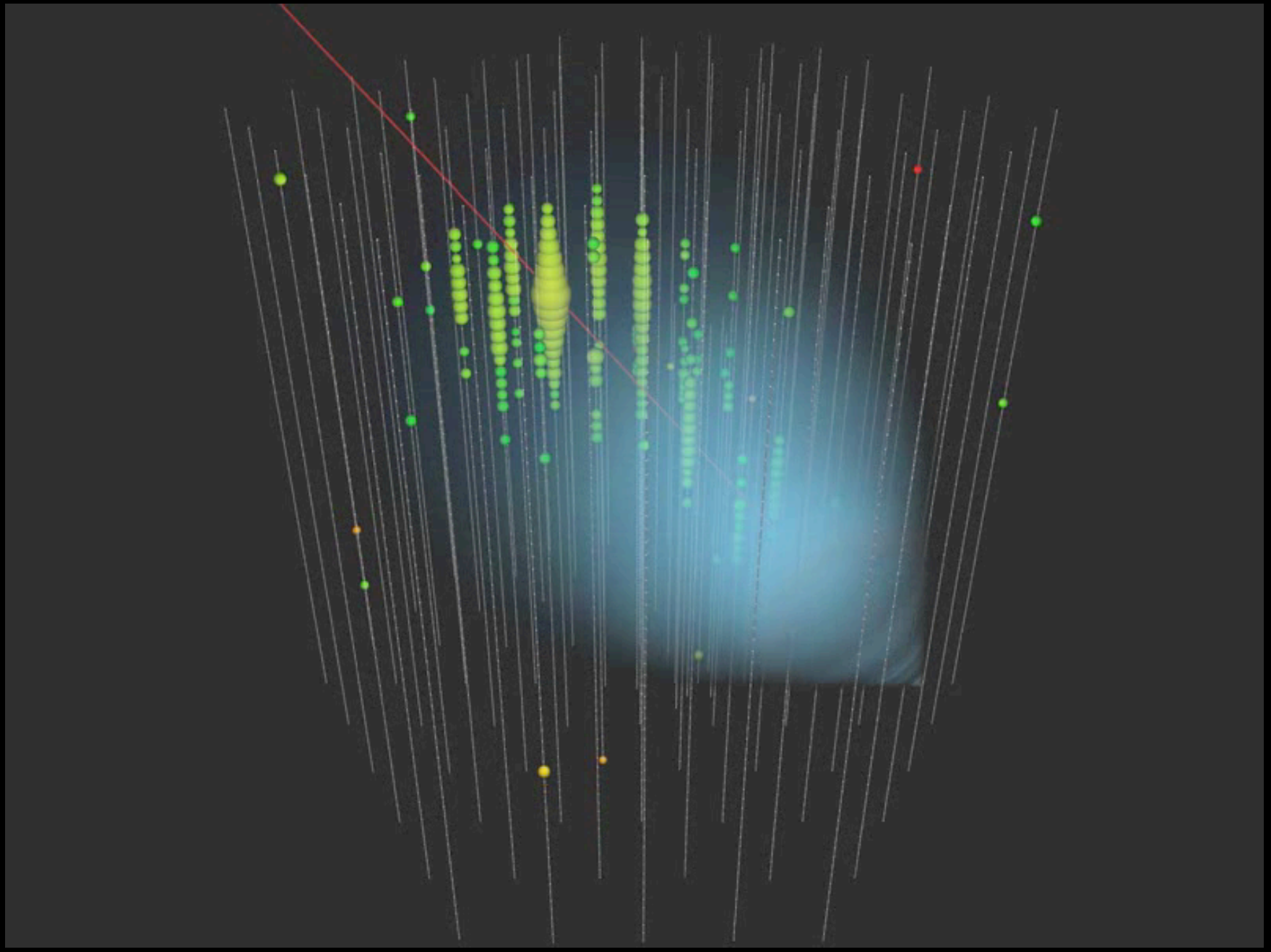
… each Digital Optical Module independently collects light signals like this, digitizes them,



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

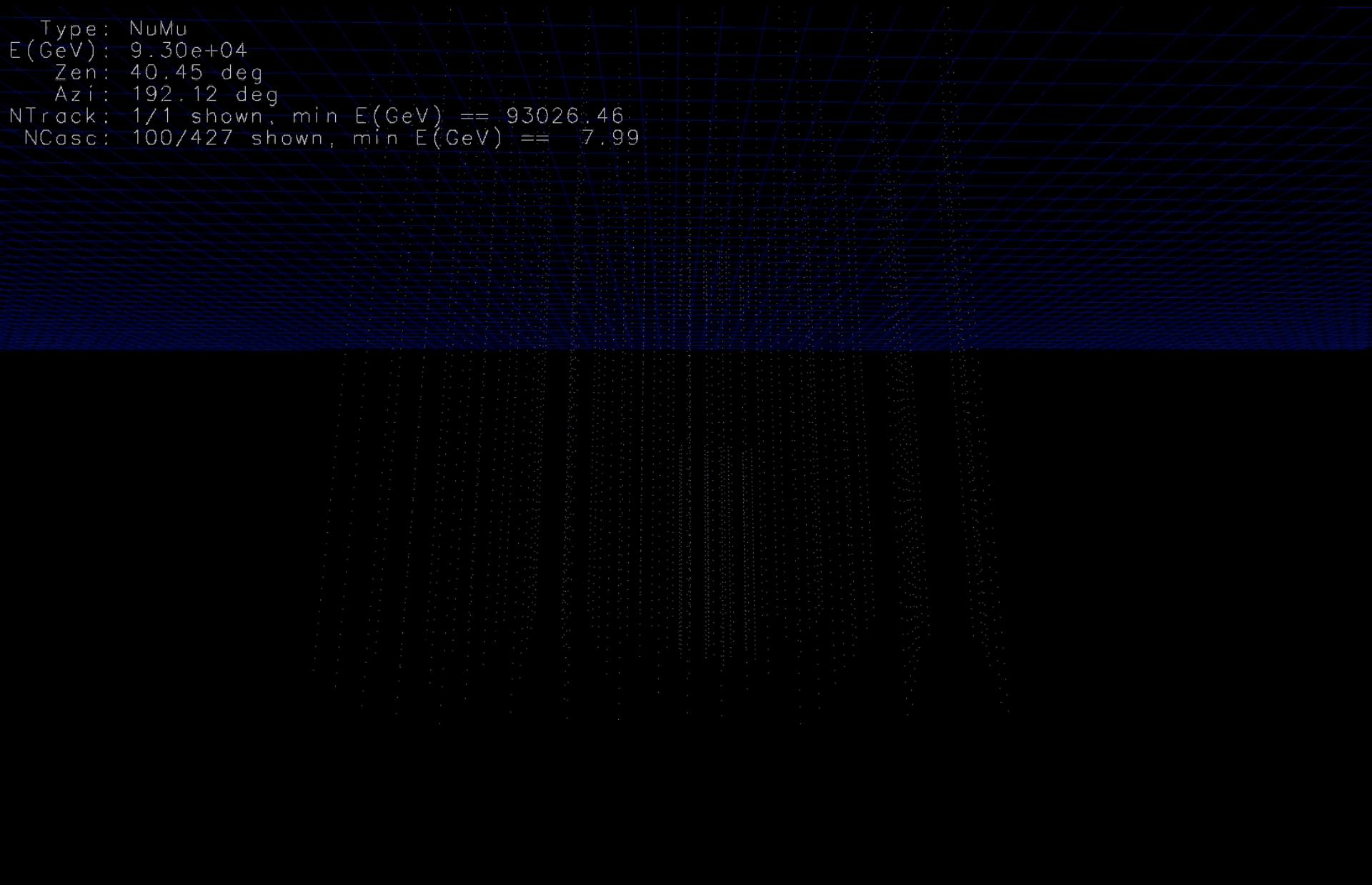

nozzle delivers:
• 200 gallons per minute
• 7 Mpa
• 90 degree C
4.8 megawatt
heating plant →



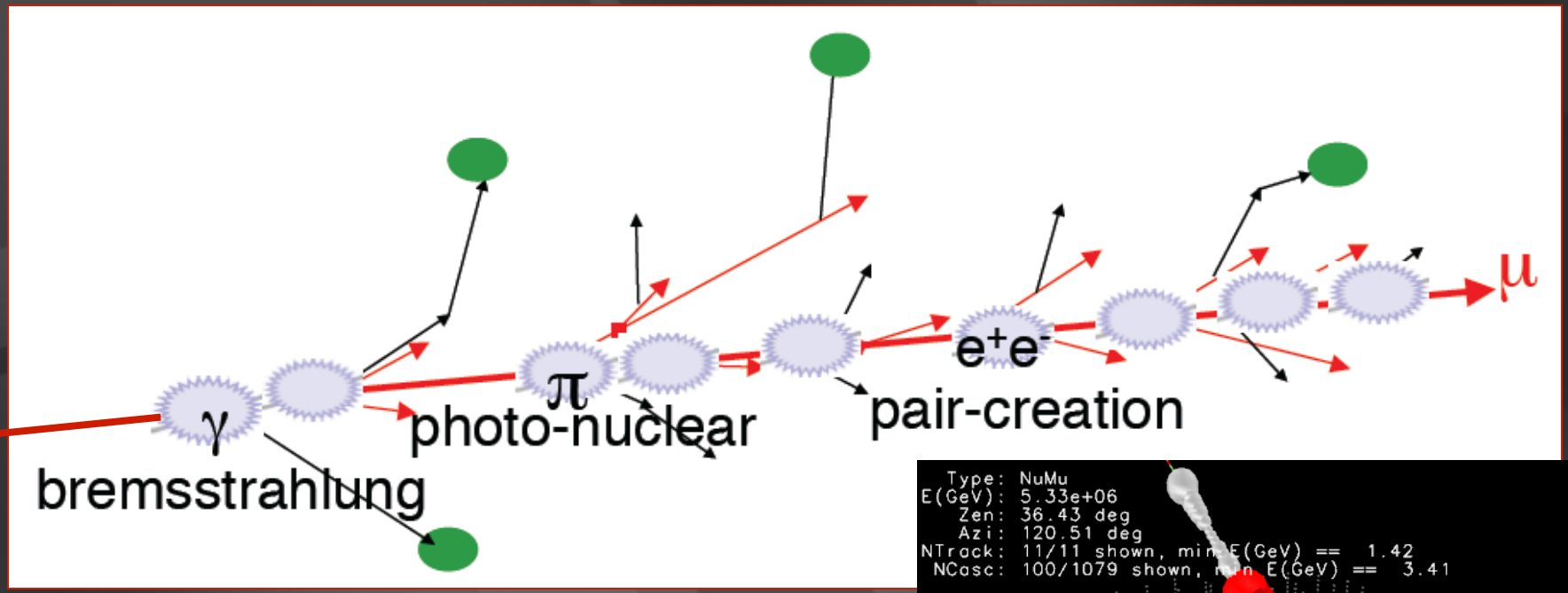


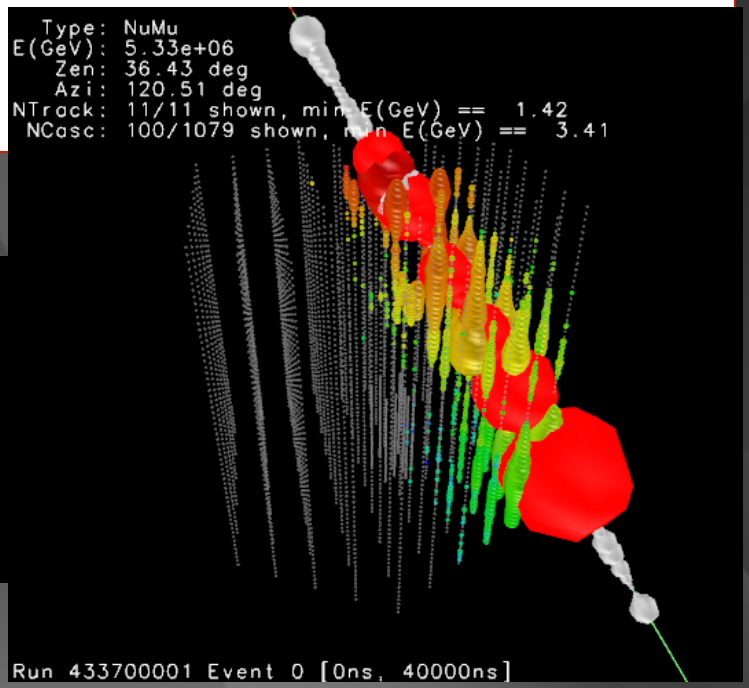
muon track: time is color; number of photons is energy

93 TeV muon: light ~ energy

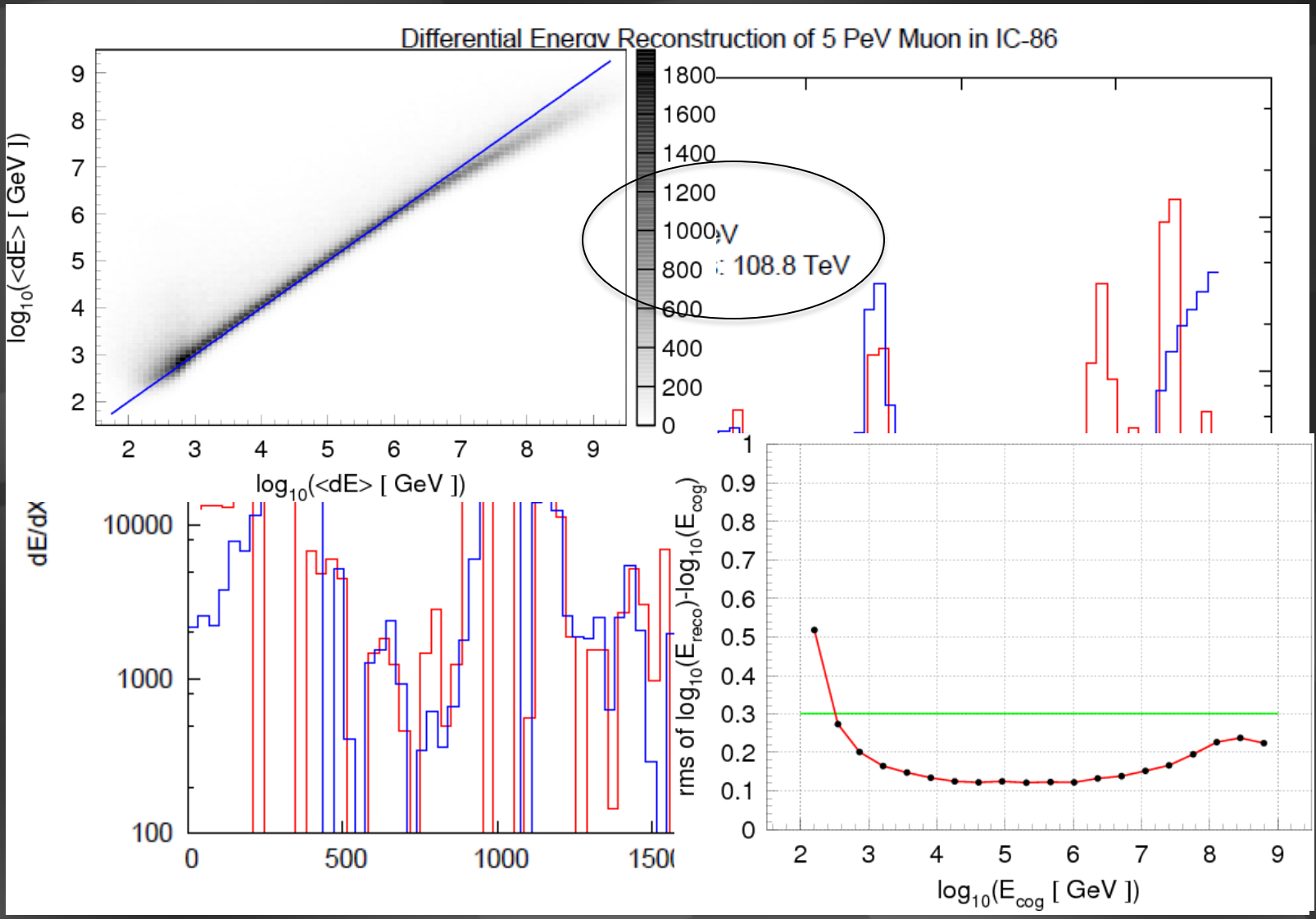


energy measurement (> 1 TeV)

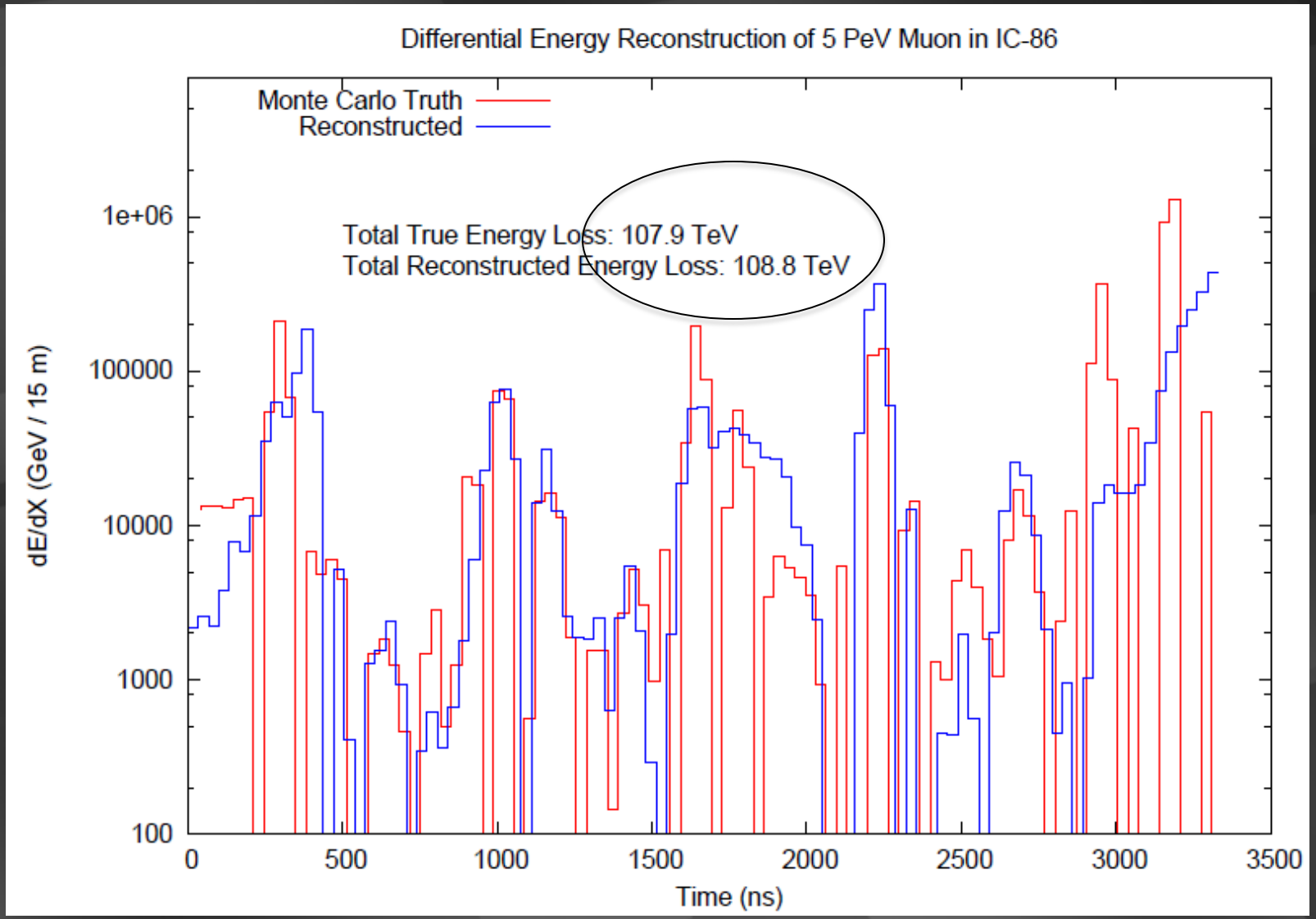




convert the amount of light emitted to measurement of the muon energy (number of optical modules, number of photons, dE/dx, …)



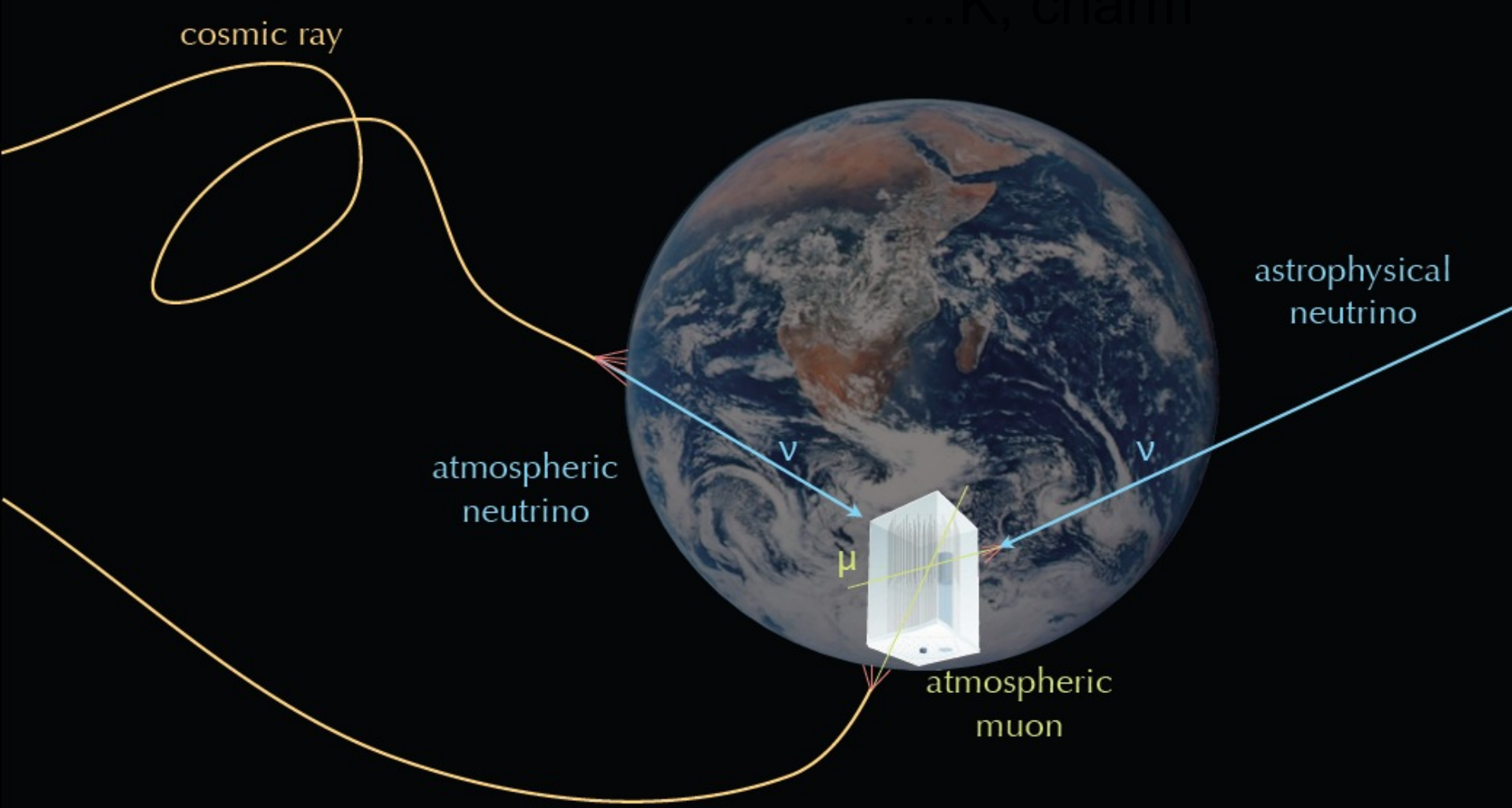
improving angular and energy resolution

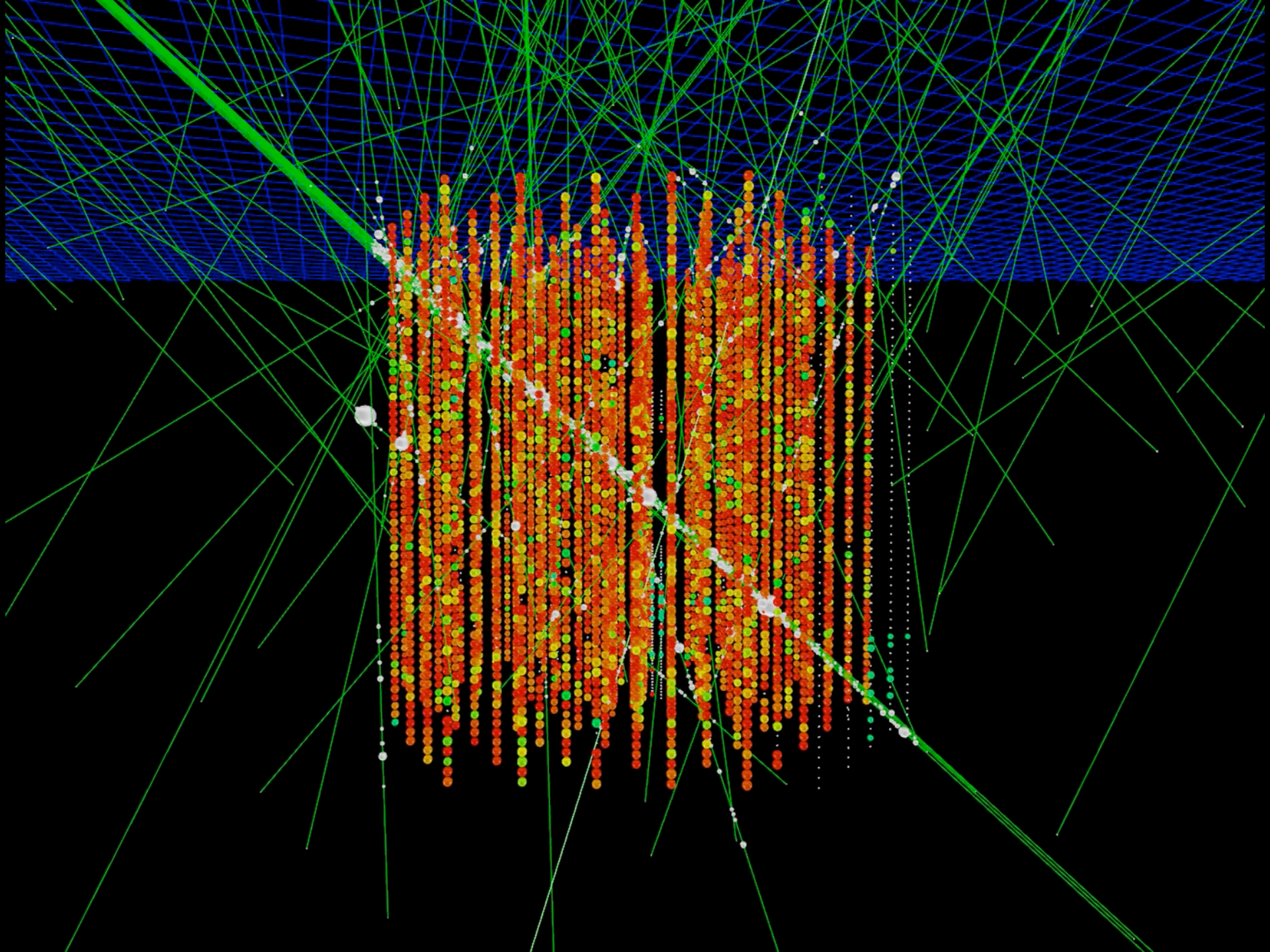


1.1 km

improving angular and energy resolution

Signals and Backgrounds





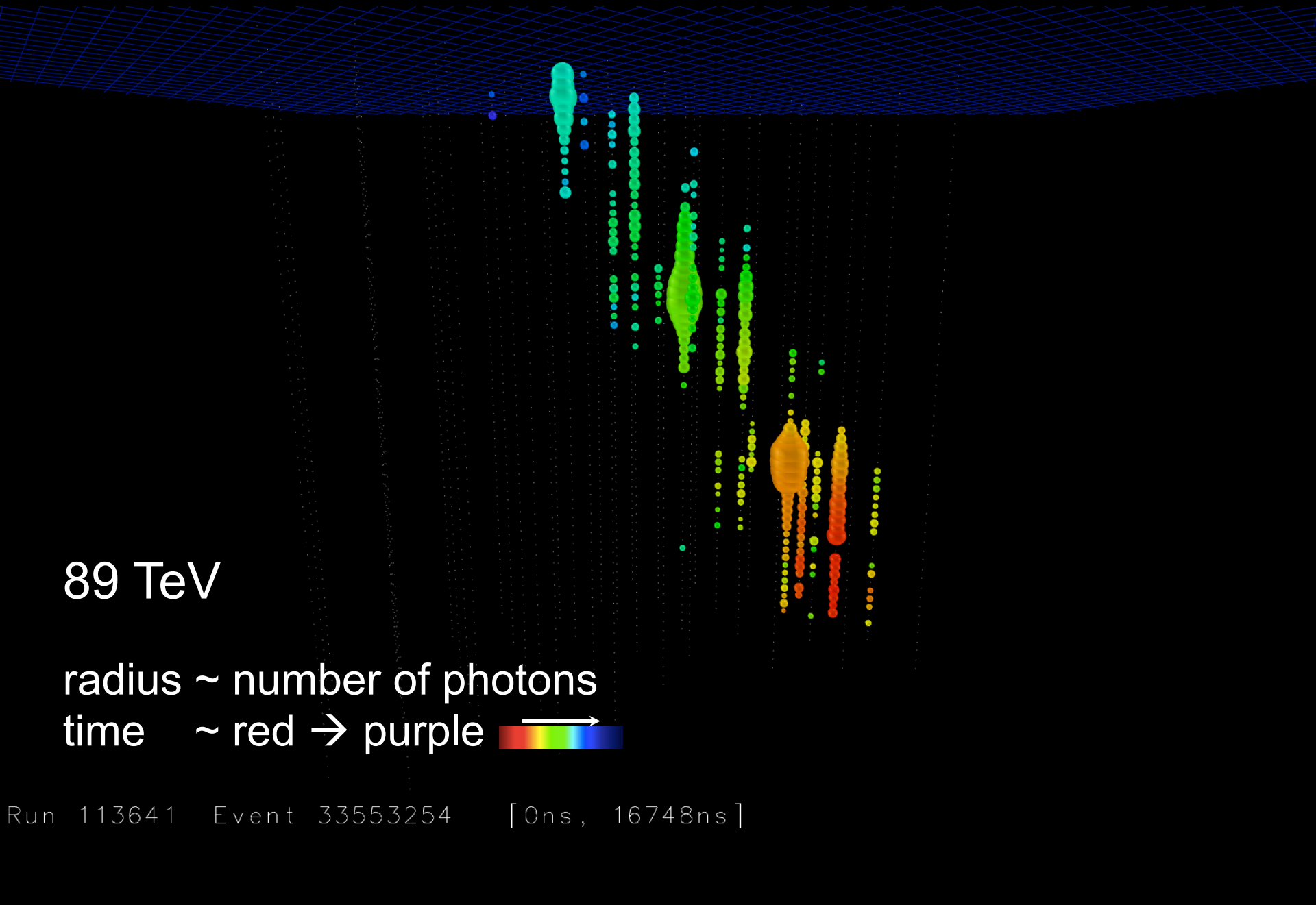
… you looked at 10msec of data !

muons detected per year:

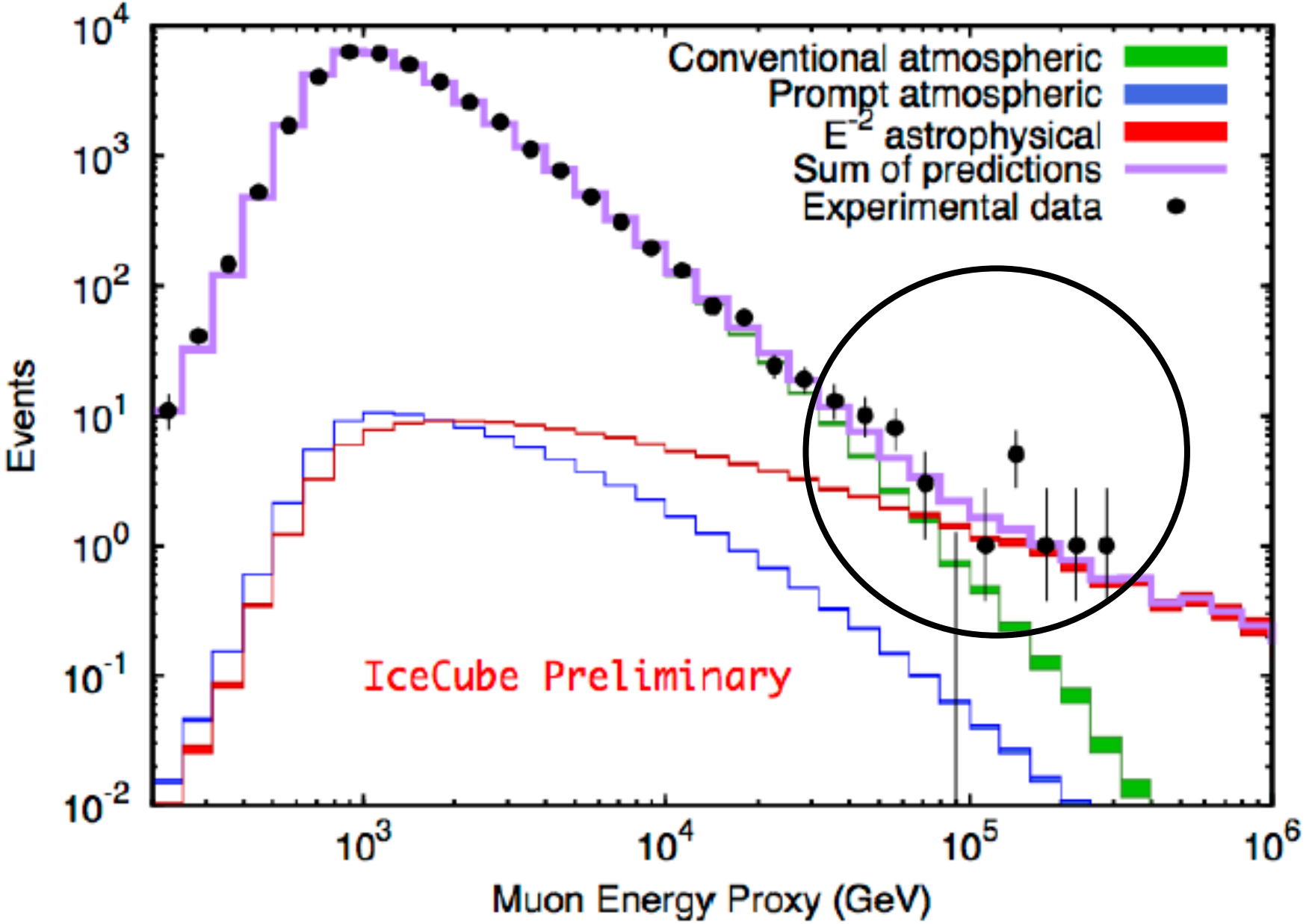
- atmospheric* μ ~ 10^{11}
- atmospheric** $\nu \rightarrow \mu$ ~ 10^{5}
- cosmic $\nu \rightarrow \mu$ ~ 10

* 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

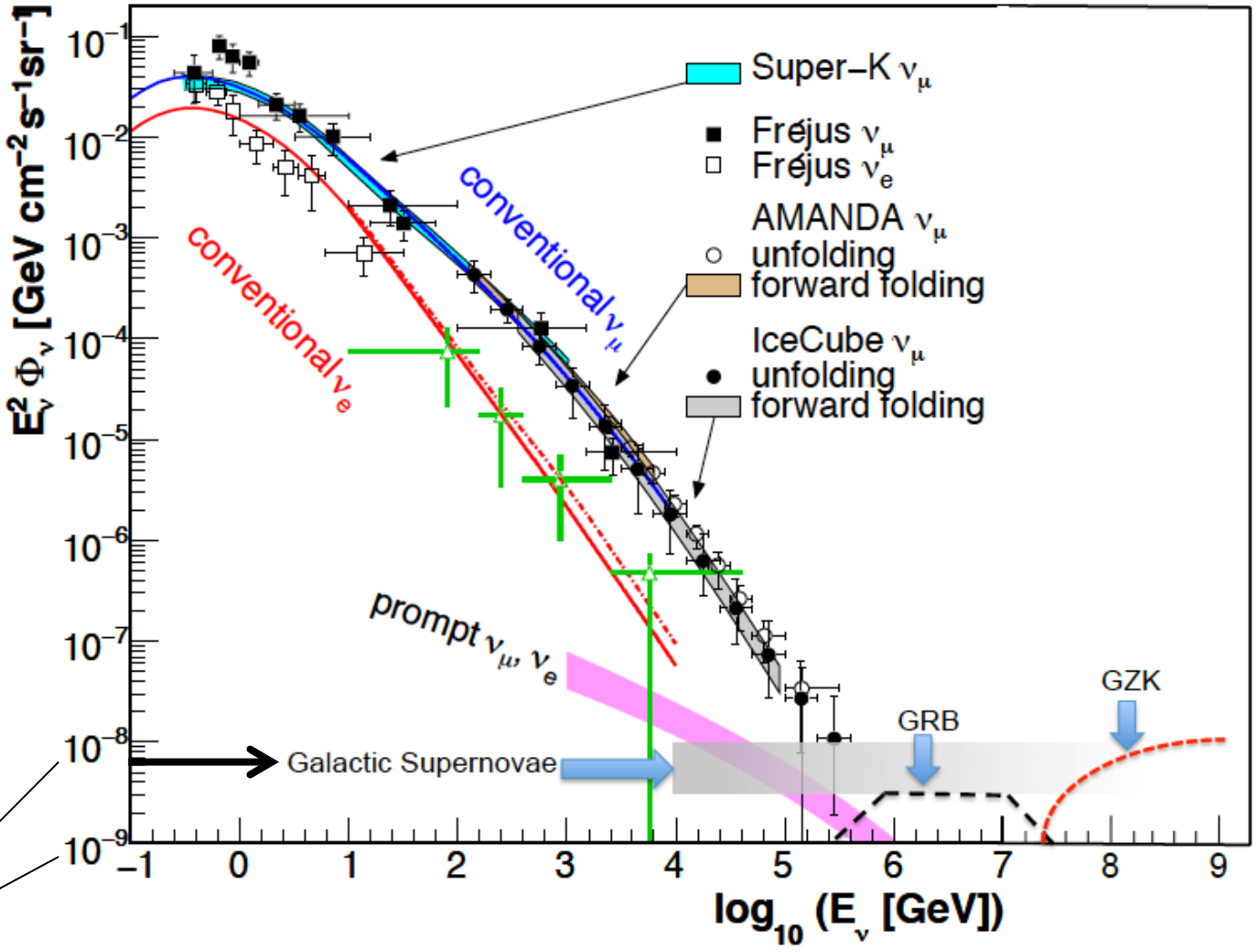


above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

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

10—100 events per year for fully efficient detector

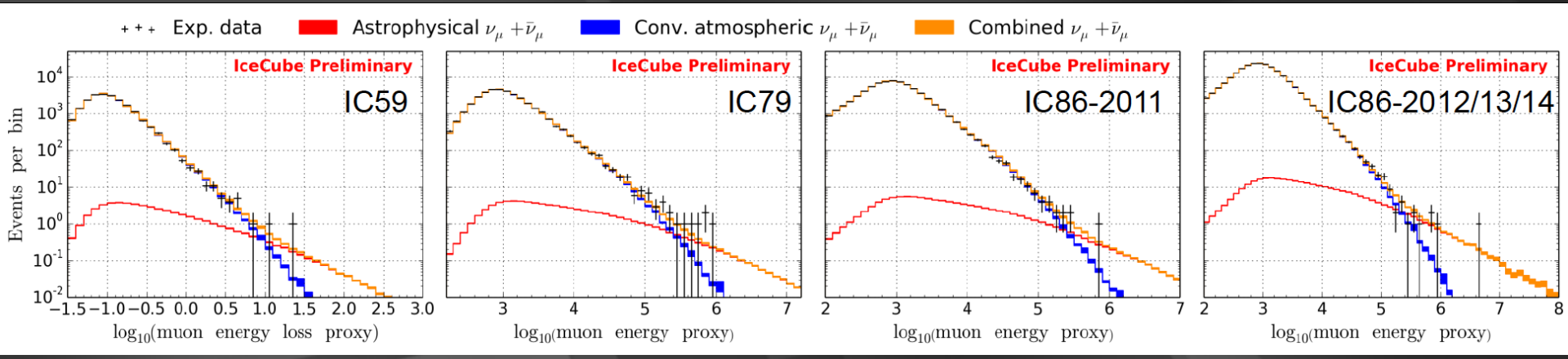


atmospheric

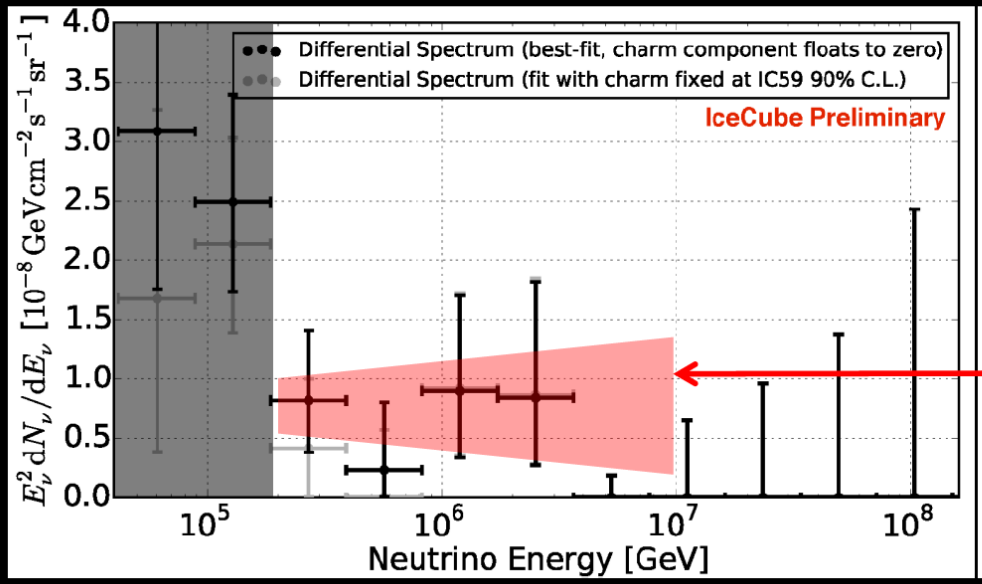
cosmic

100 TeV

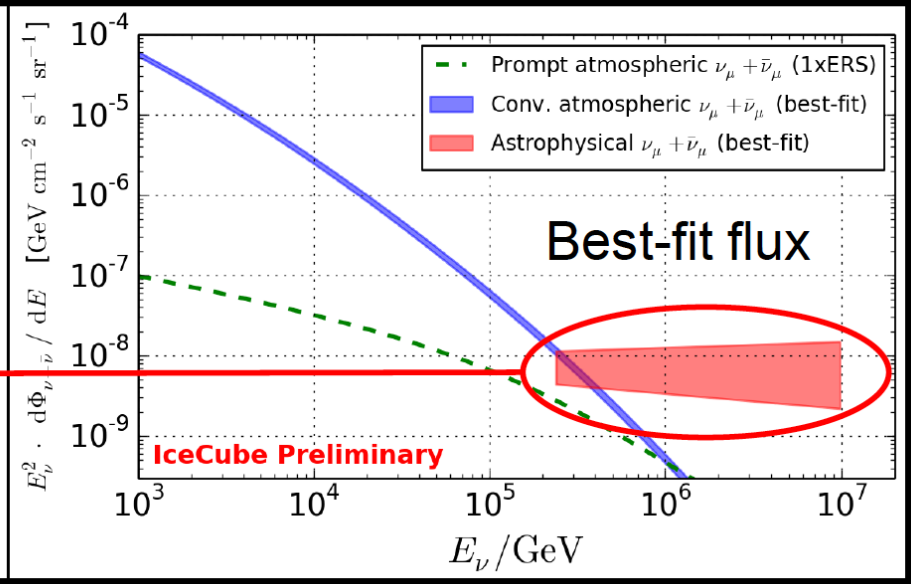
after 6 years: 3.7→ 6.0 sigma



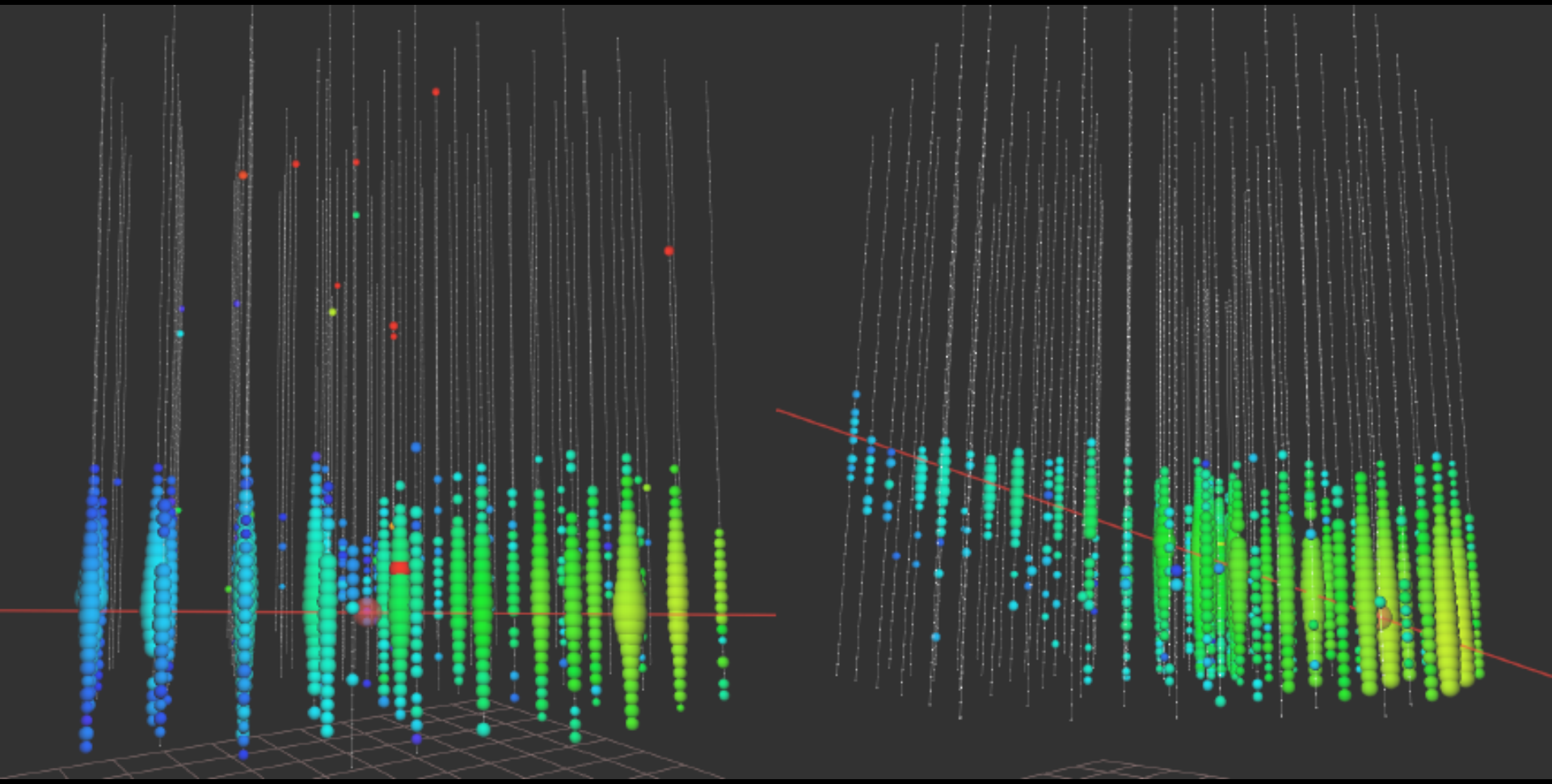
HESE 4 year unfolding
(→ dominated by shower-like events)

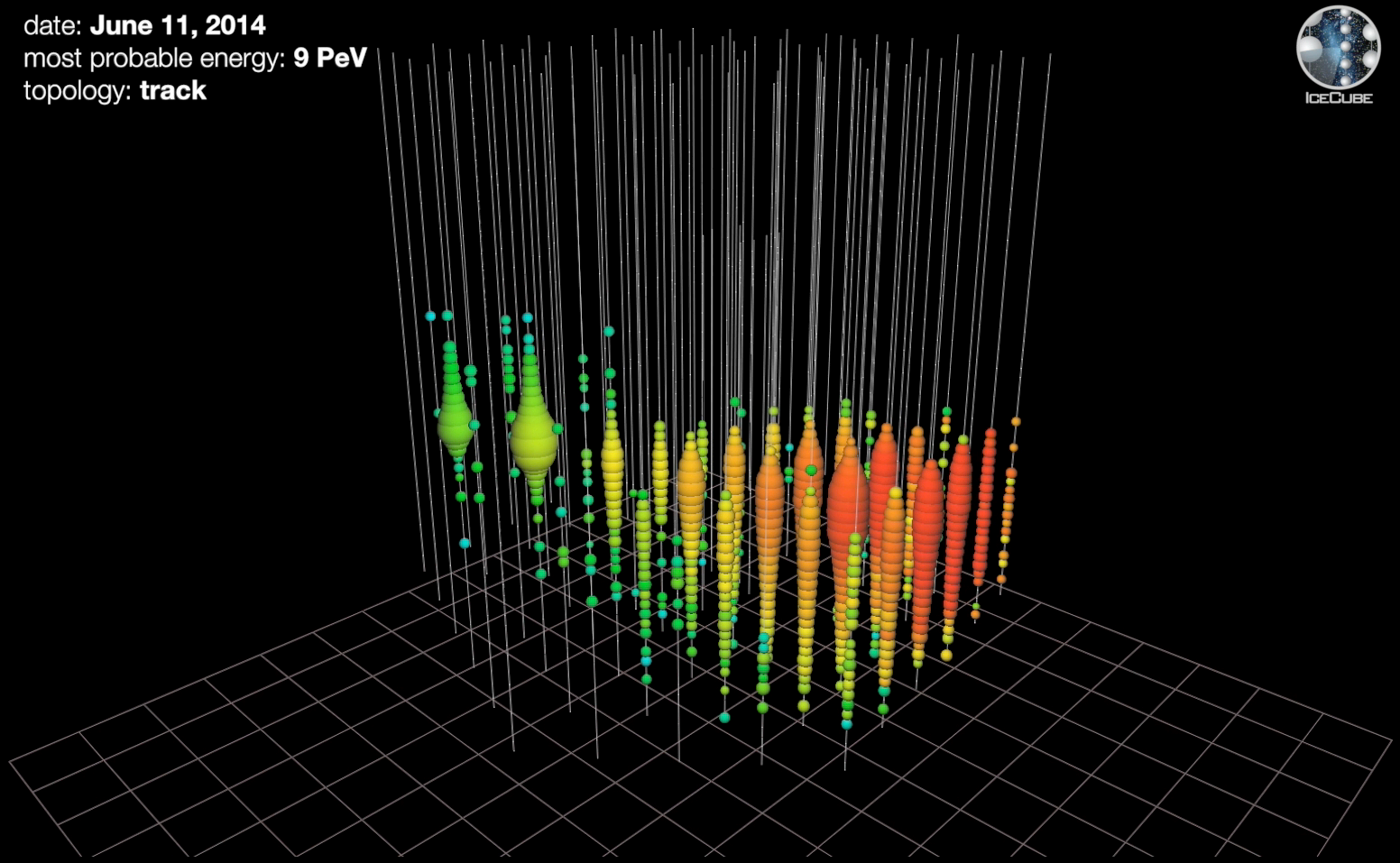


6 year up-going numu analysis

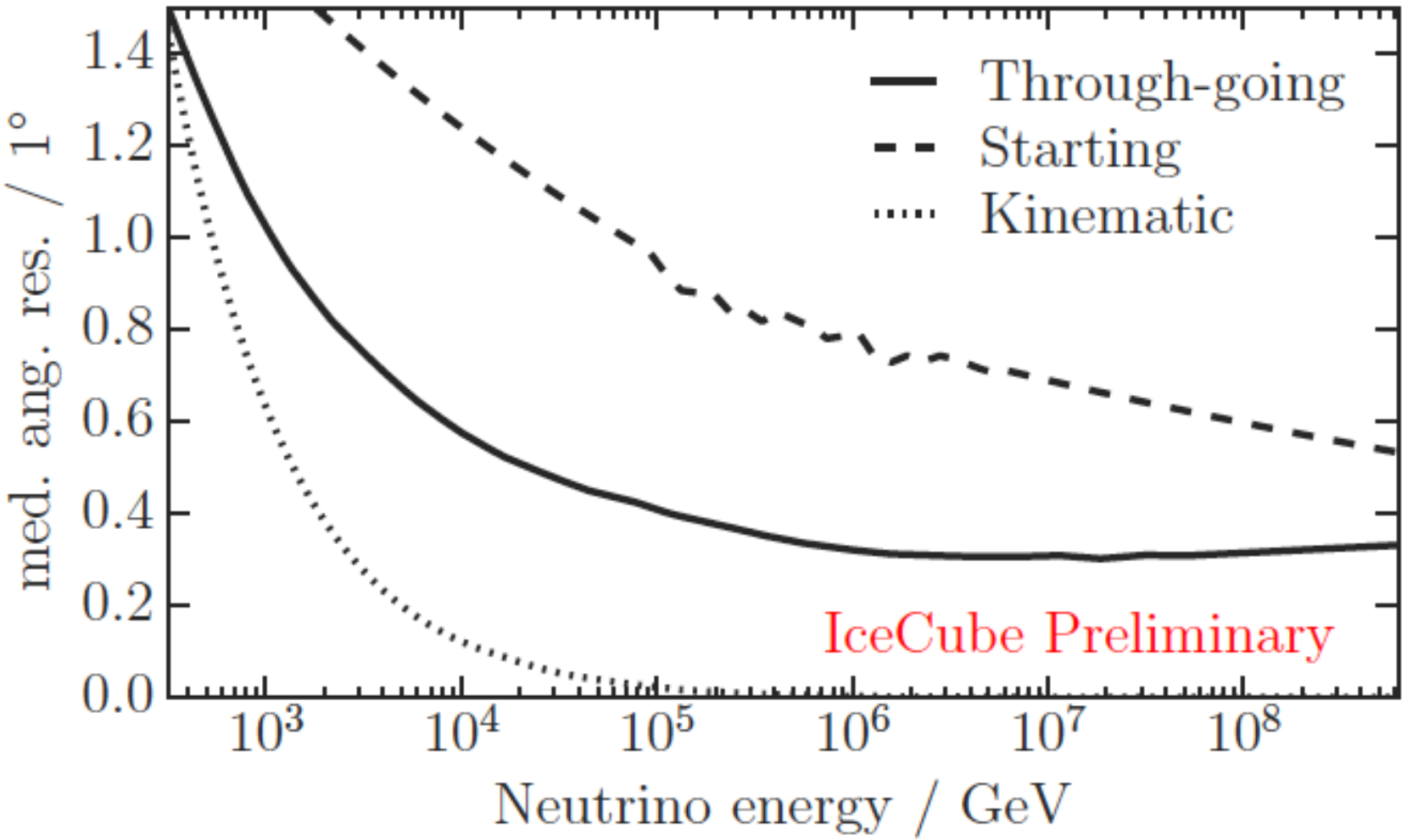


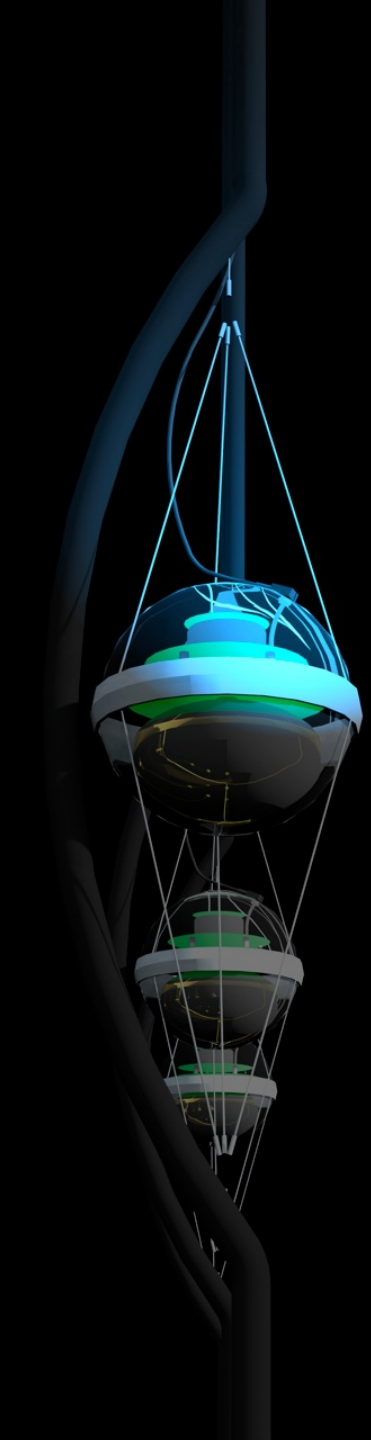
highest energy muon energy observed: 560 TeV
→ PeV ν_μ




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

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





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

cosmic rays interact with the microwave background

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

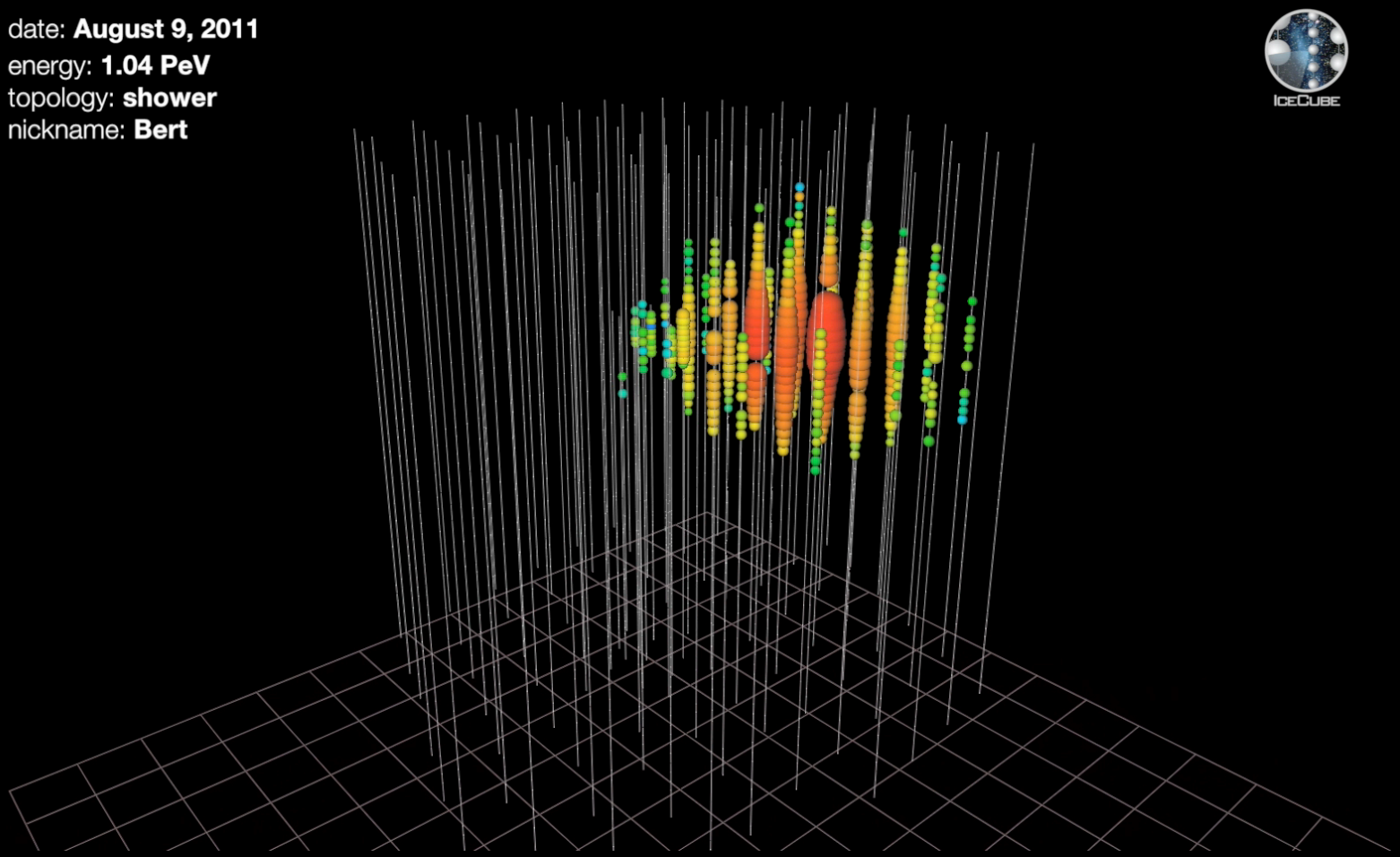
cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear

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

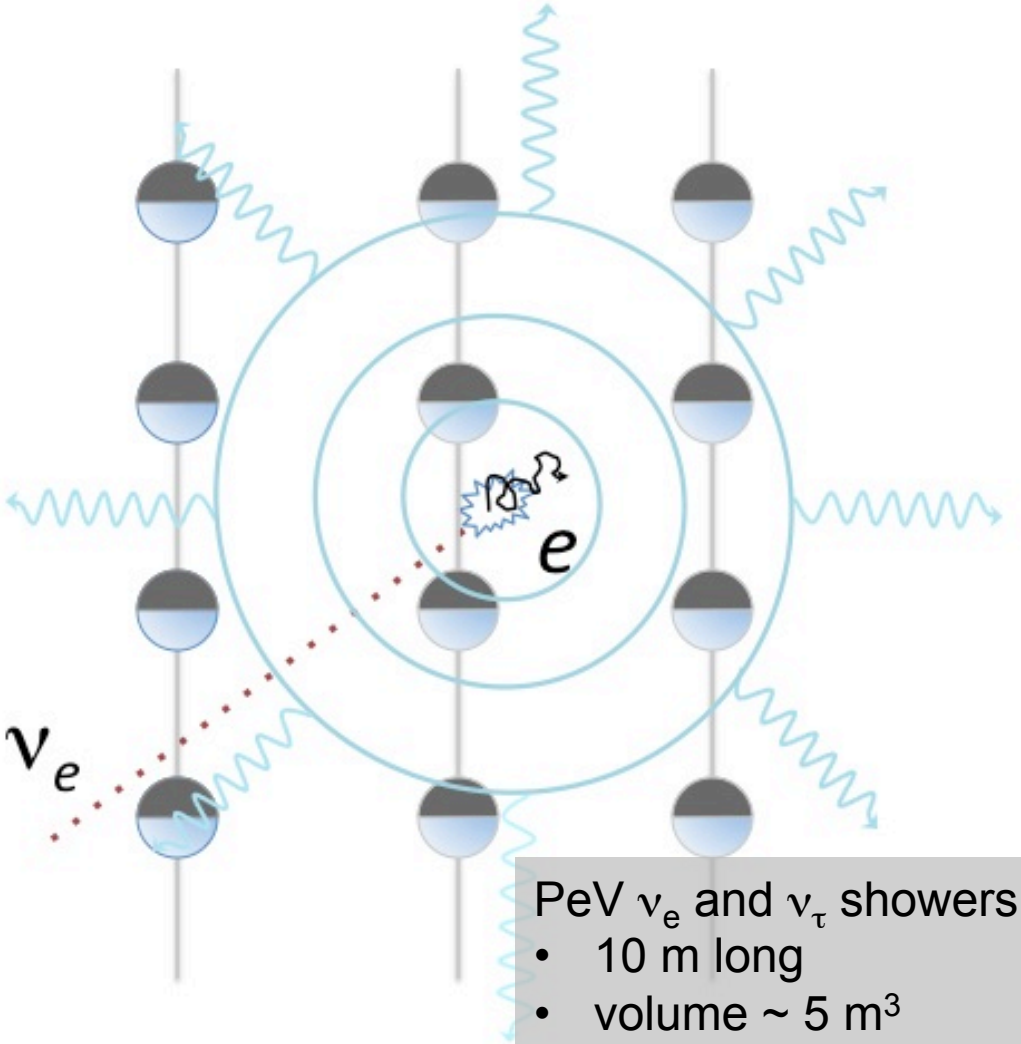
1 event per cubic kilometer per year

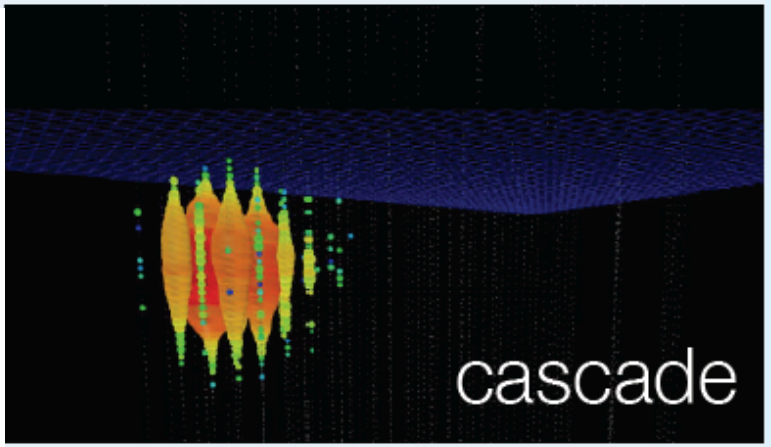
...but it points at its source!

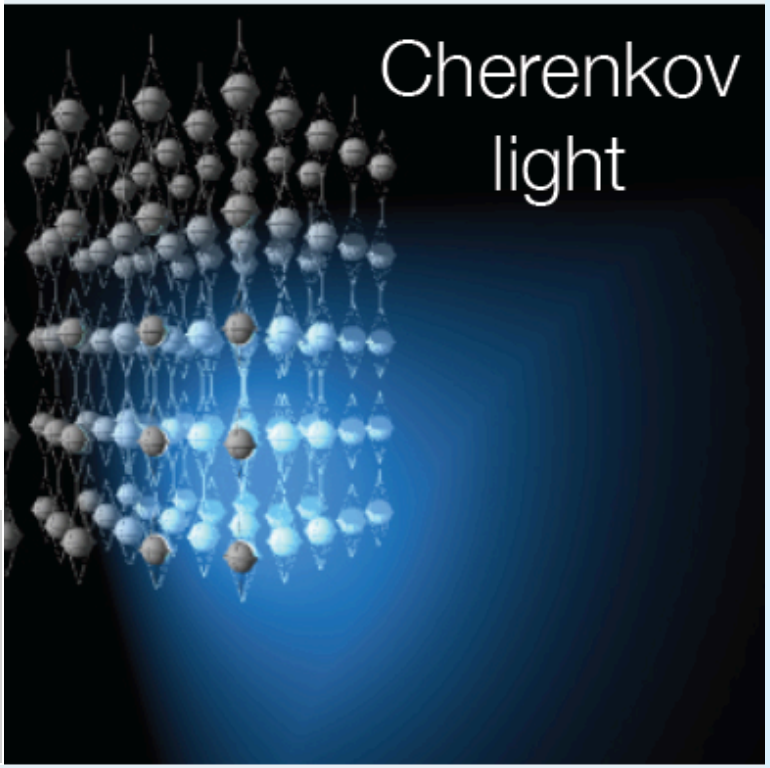
GZK neutrino search: two neutrinos with > 1,000 TeV



tracks and showers

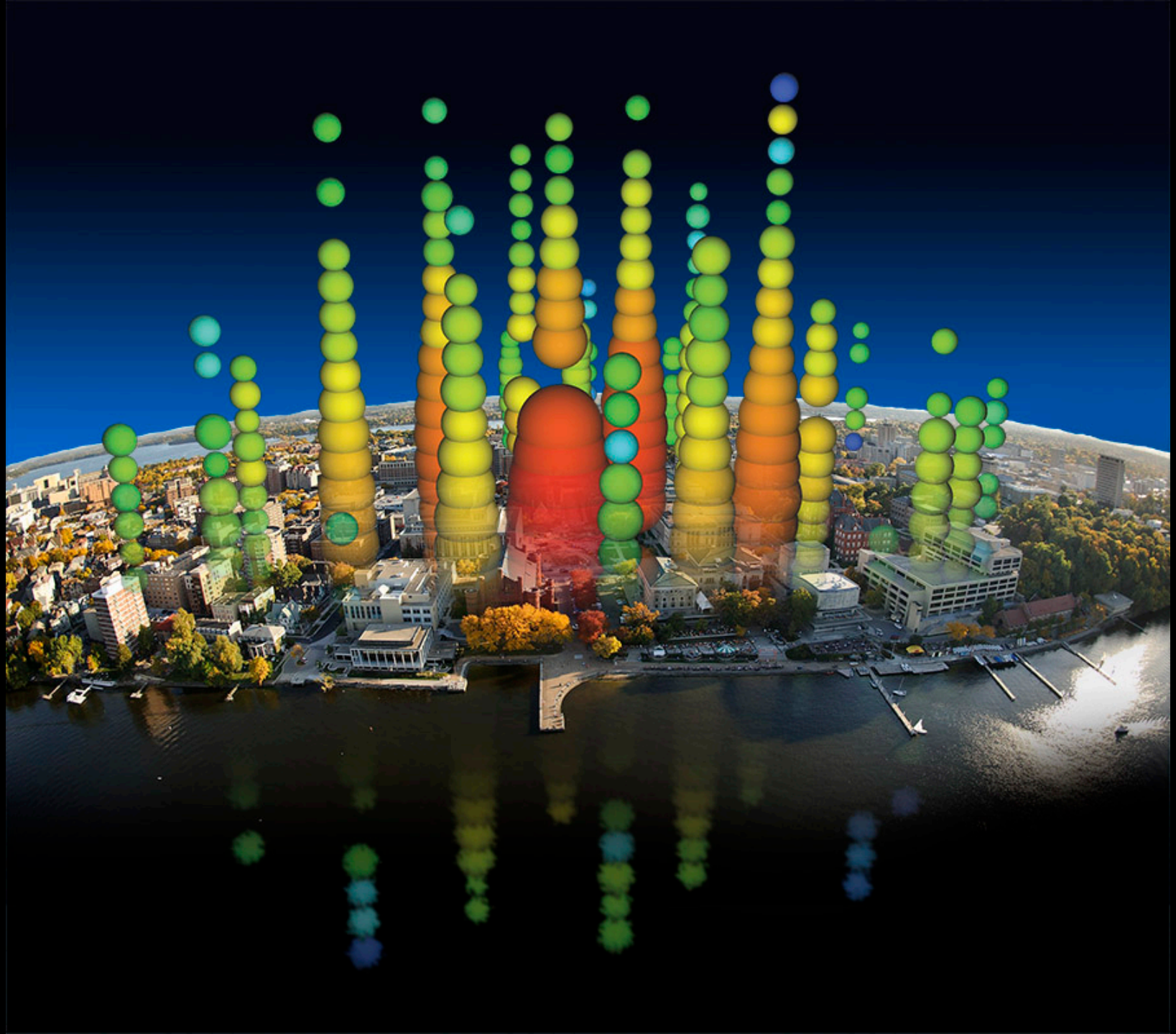


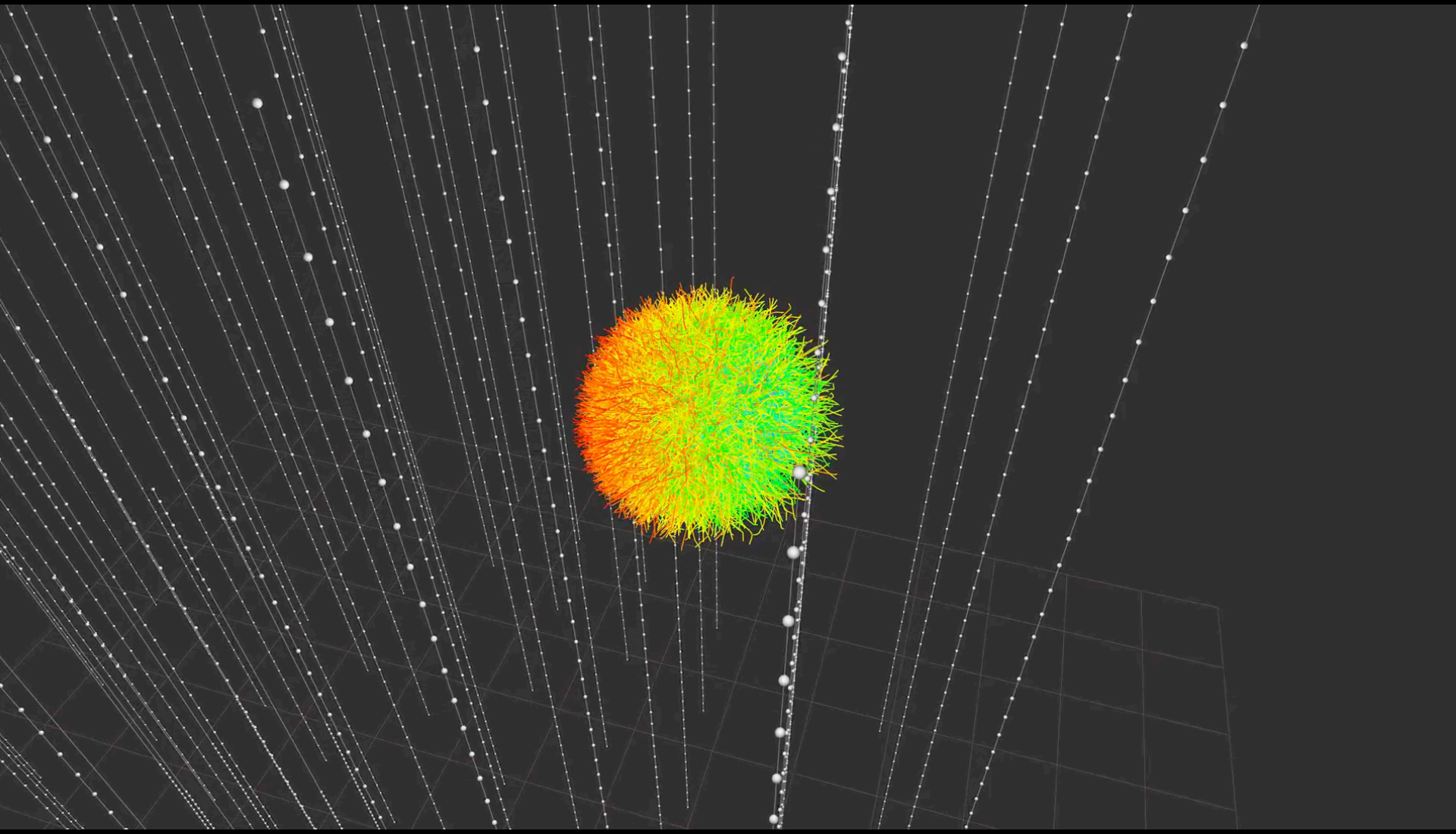




PeV ν_e and ν_τ showers:

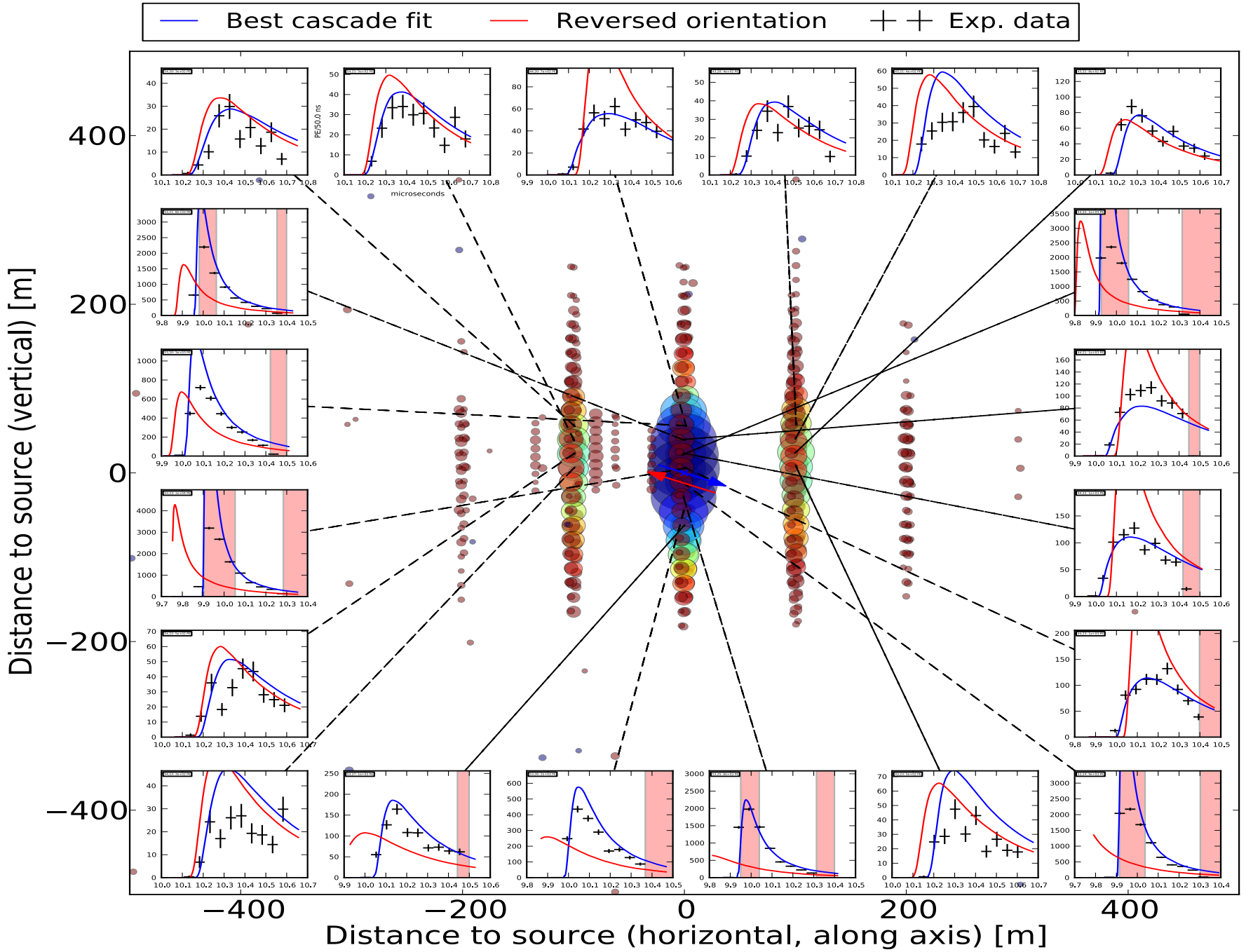
- 10 m long
- volume ~ 5 m^3
- isotropic after 25~ 50m



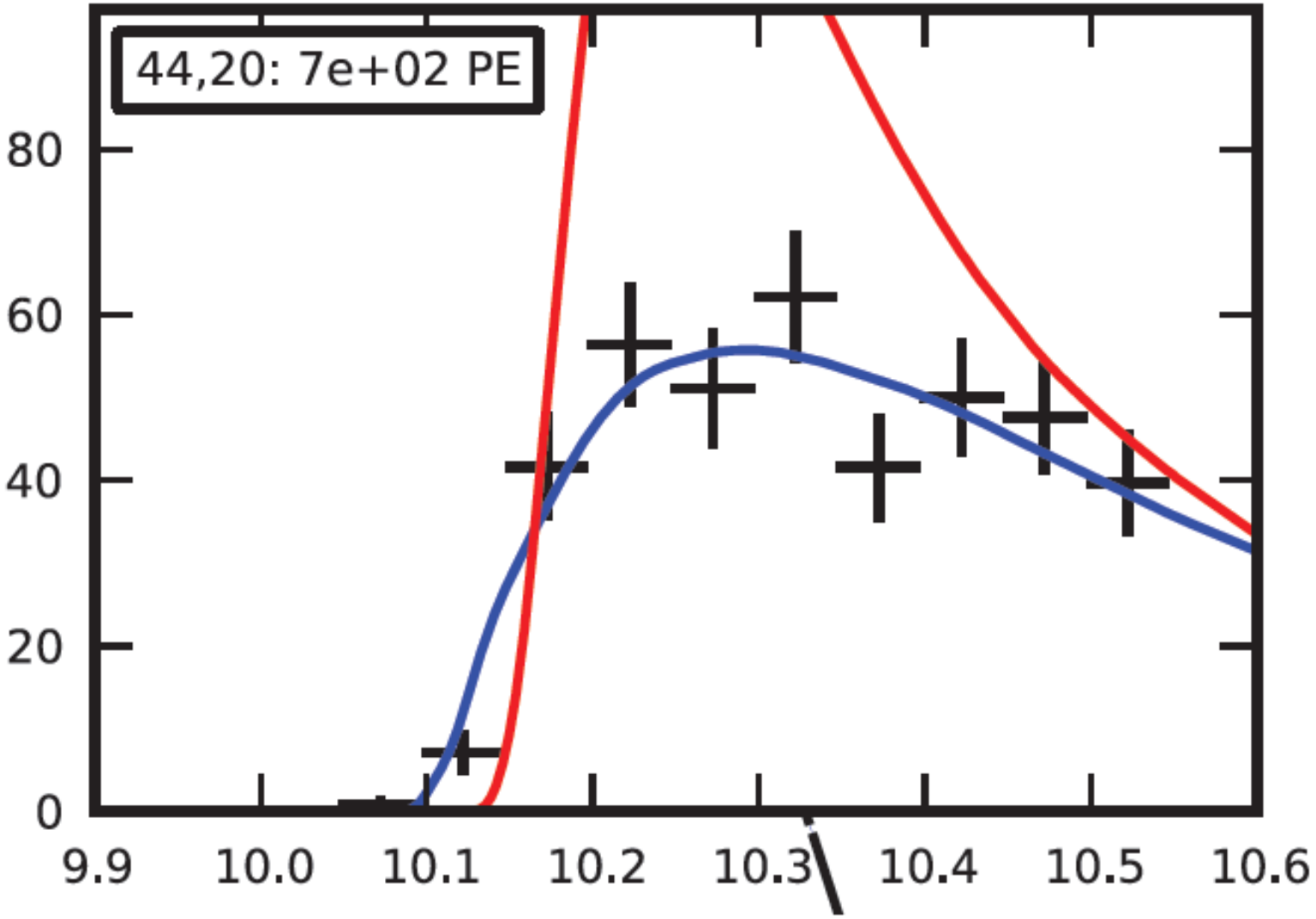


size = energy

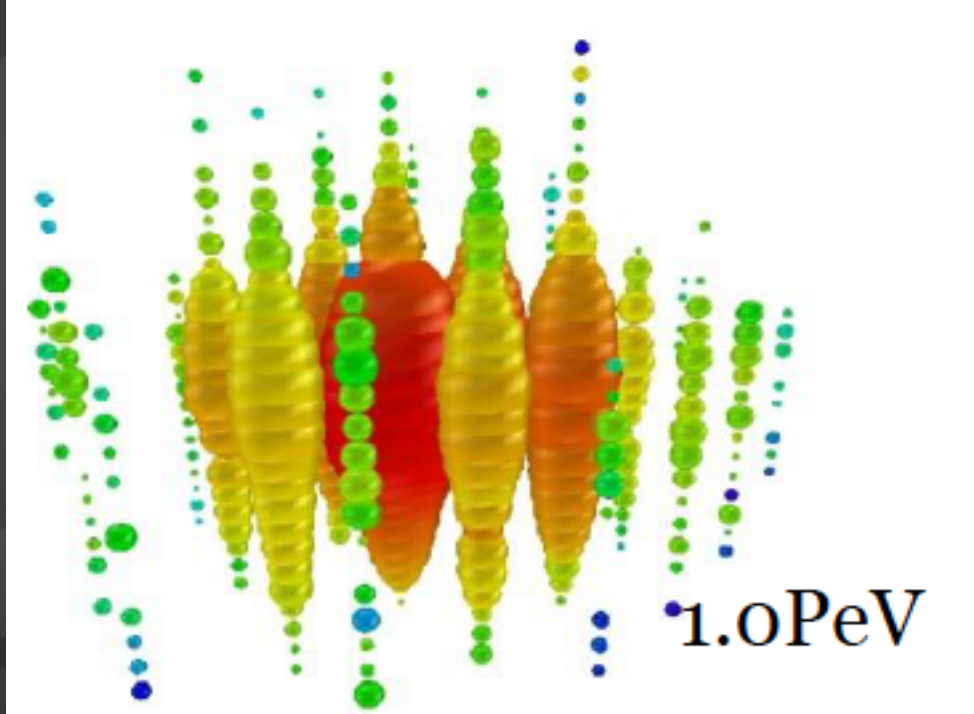
color = time = direction

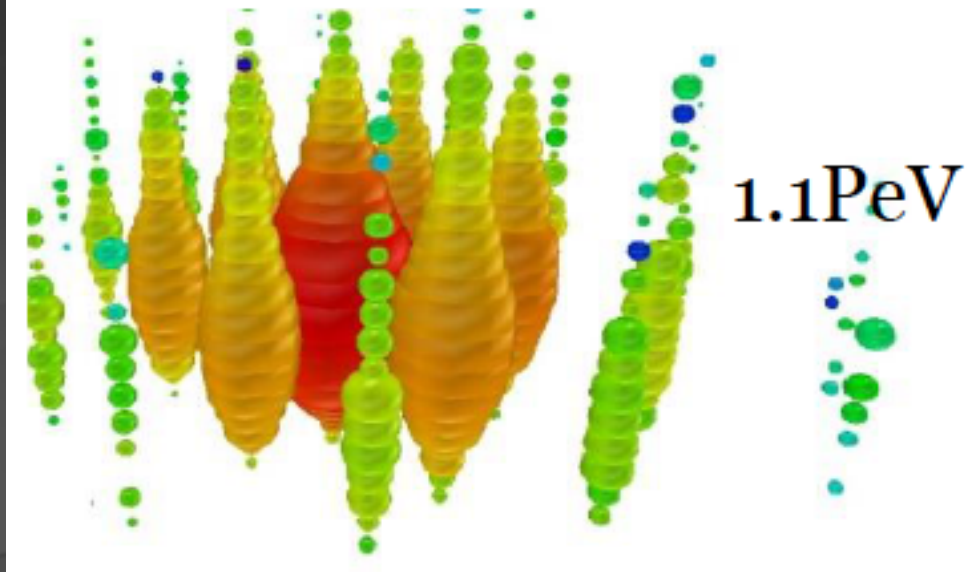

Best cascade fit
Reversed orientation
Exp. data
Distance to source (vertical) [m]
Distance to source (horizontal, along axis) [m]
400
200
0
−200
−400
−400
−200
0
200
400
PE/50.0 ns
microseconds

reconstruction limited by computing, not ice !



Blue: best-fit direction, red: reversed direction





• energy

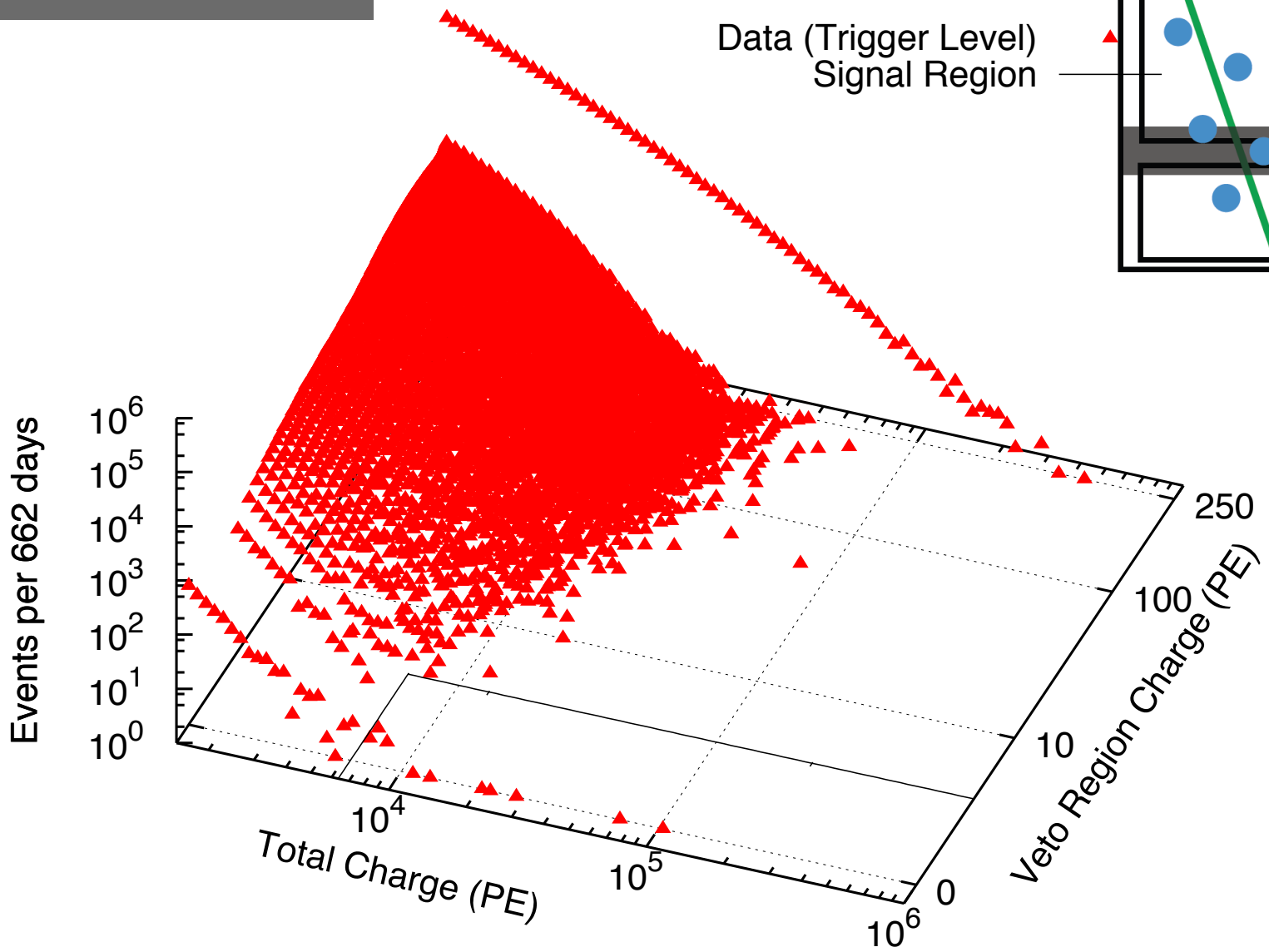
1,041 TeV
1,141 TeV
(15% resolution)

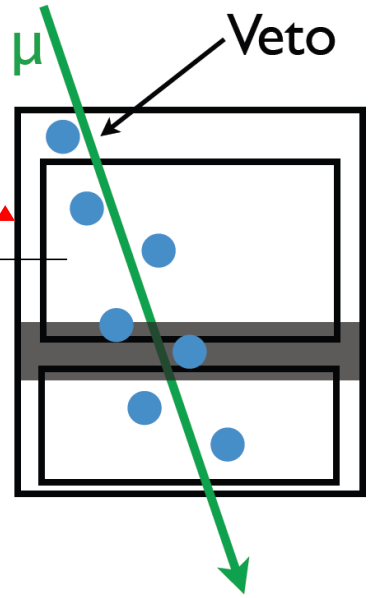
• not atmospheric: probability of no accompanying muon is 10^{-3} per event

→ 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

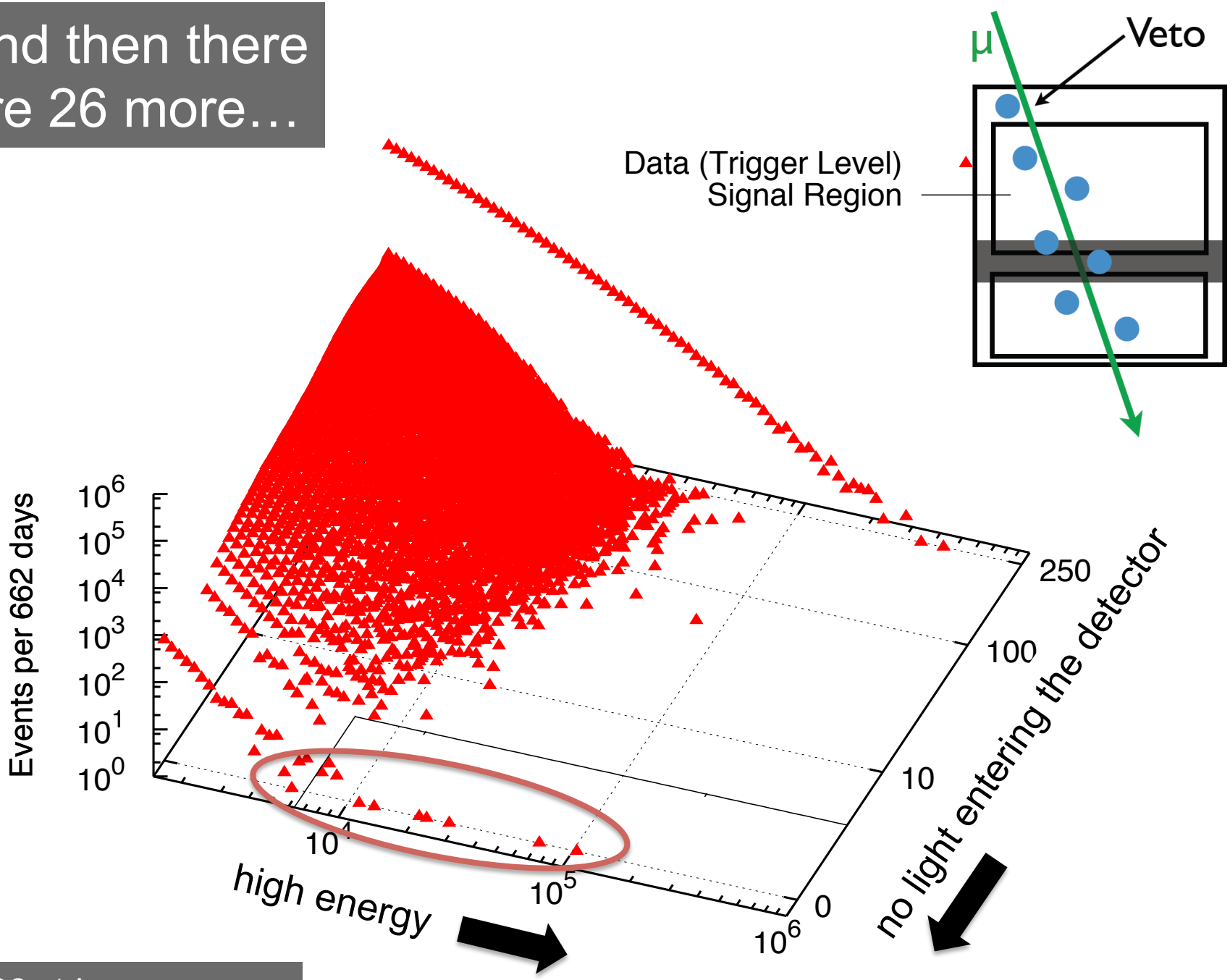
…and then there were 26 more…





data: 86 strings one year

…and then there were 26 more…



data: 86 strings one year

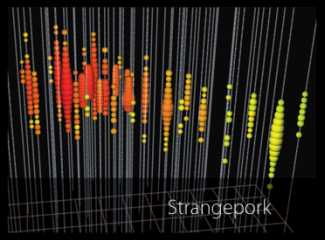
RESEARCH

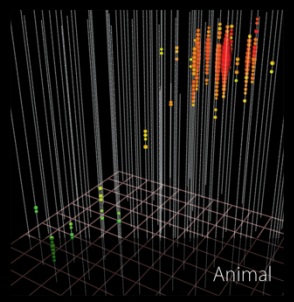
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

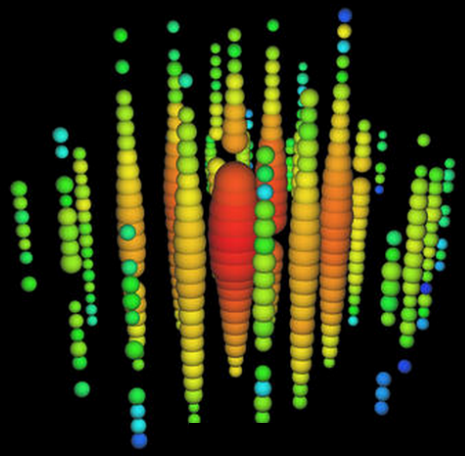
IceCube Collaboration*

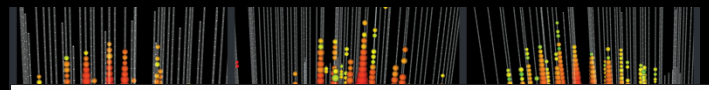
Introduction: Neutrino observations are a unique probe of the universe's highest-en

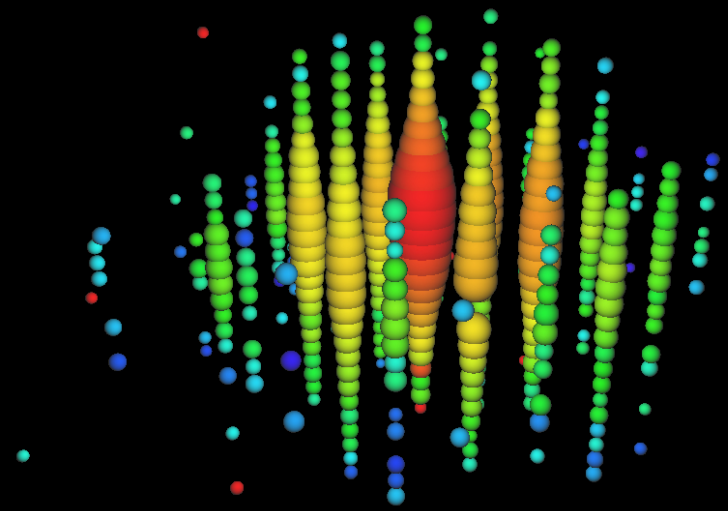
28 High Energy Events









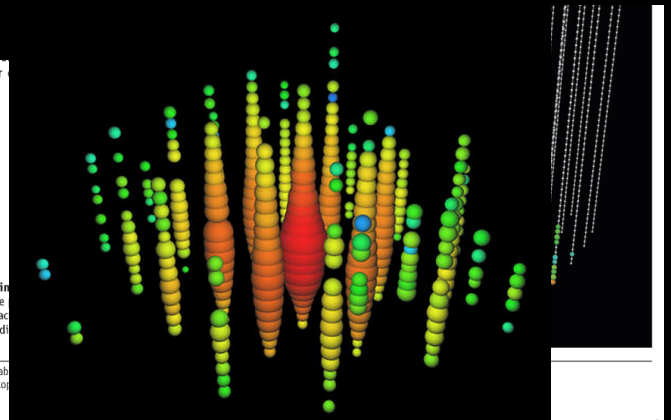


2004 TeV event in year 3

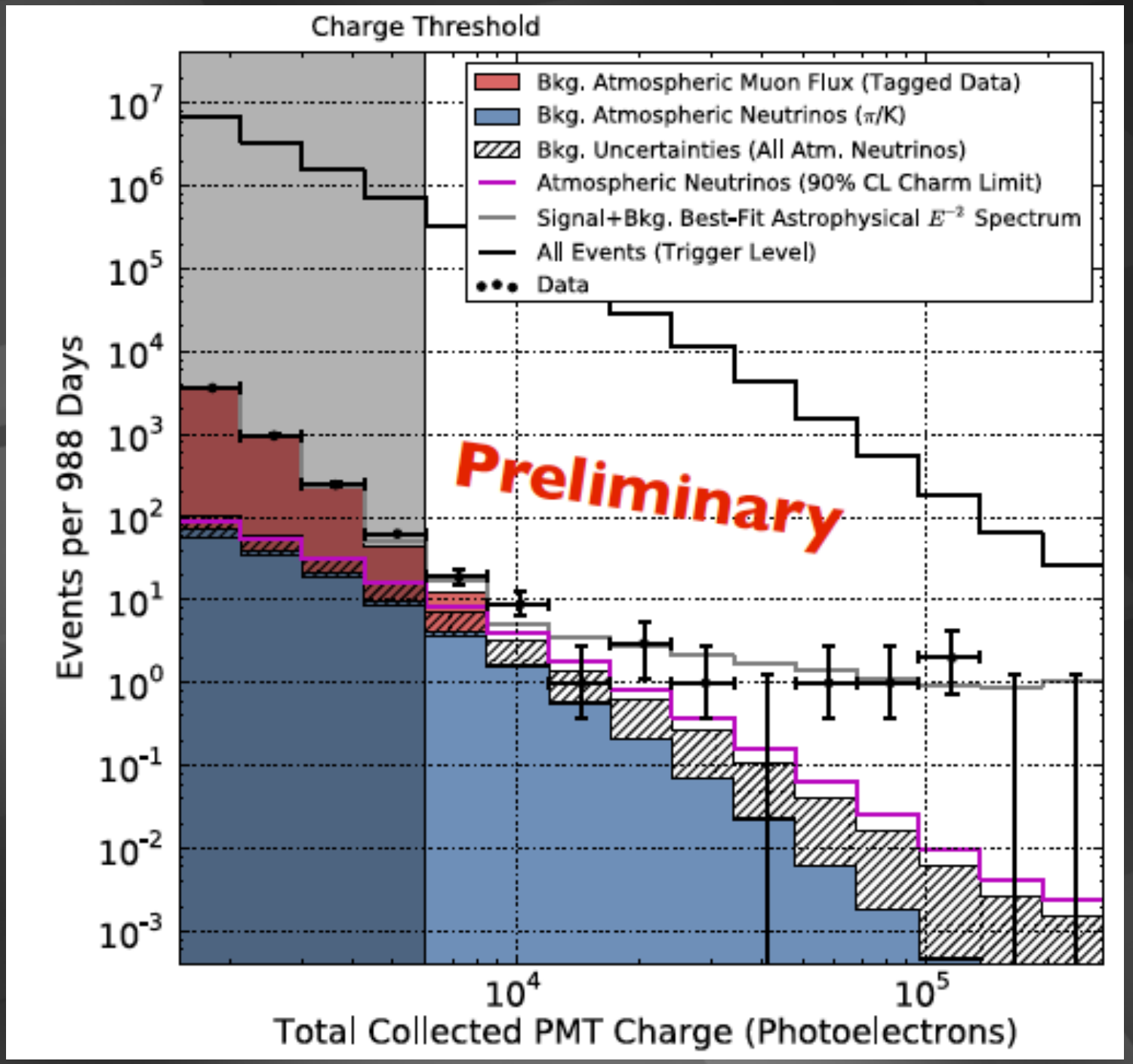
tified high-energy galactic or
accelerators.

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

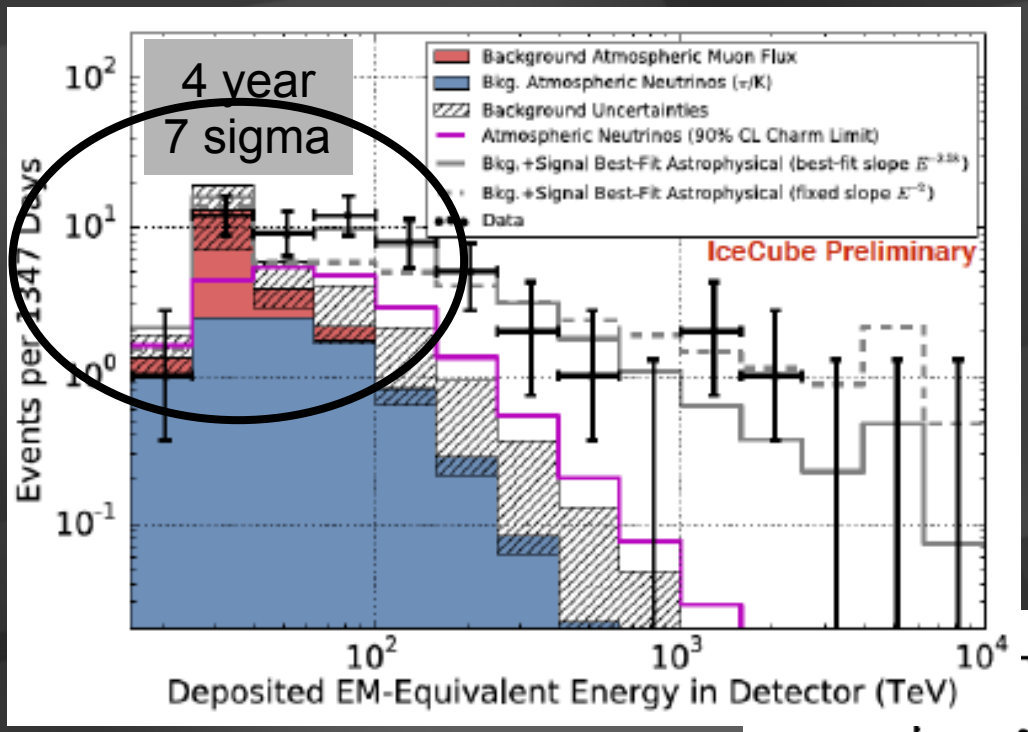
*The list of author affiliations is availab
Corresponding authors: C. Kopper (ckop



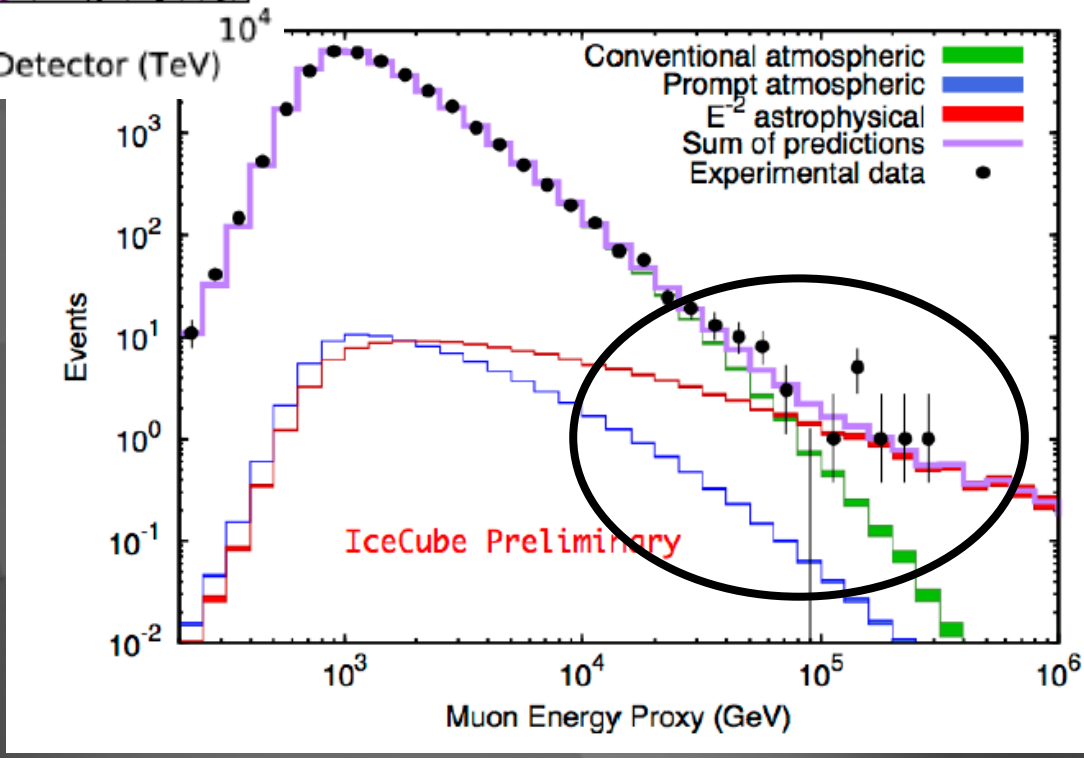
total charge collected by PMTs of events with interaction inside the detector



Science 342 (2013) 1242856



confirmation!
flux of muon neutrinos
through the Earth

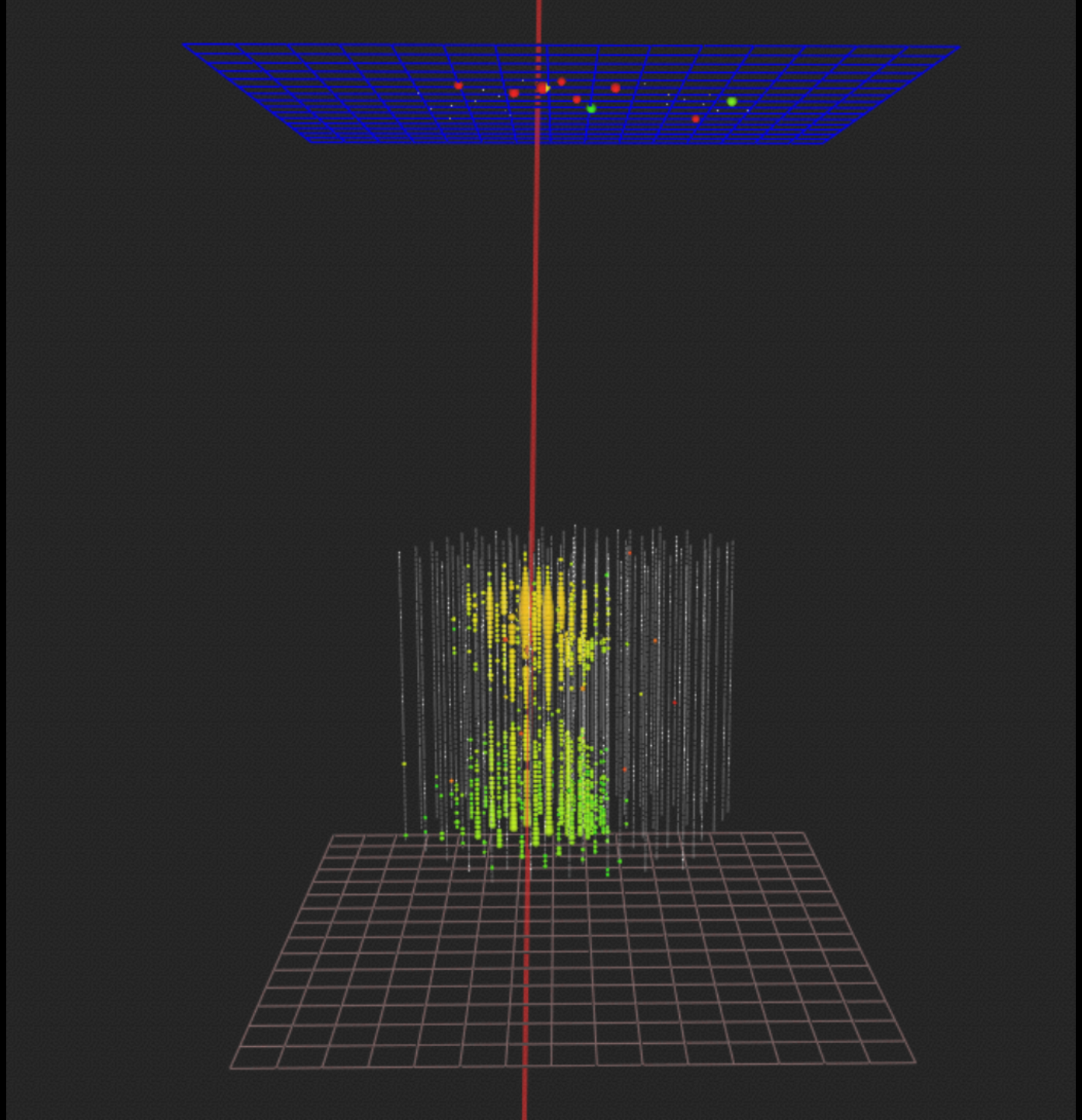


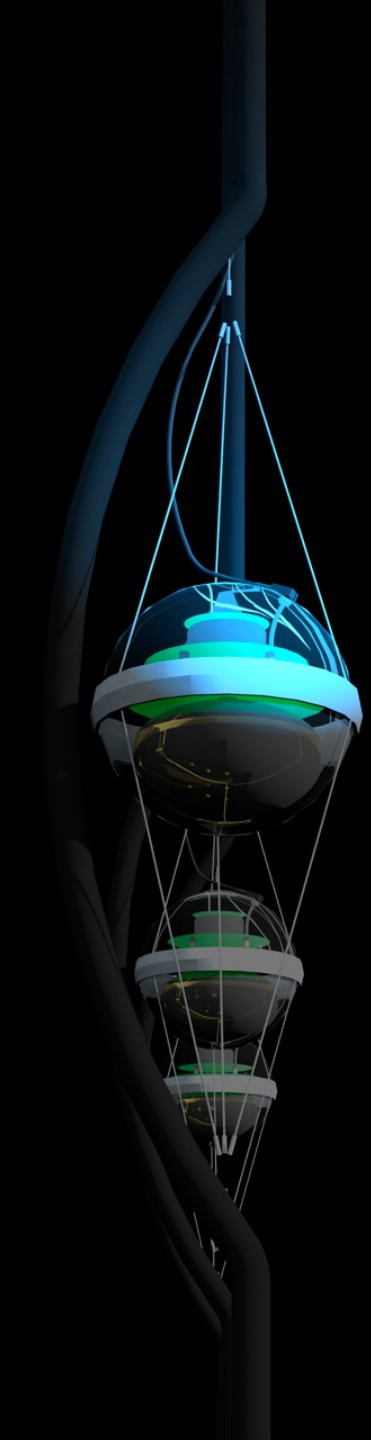
neutrinos of all flavors
interacting inside
IceCube

430 TeV

1 event:
~ 5 sigma
discovery

> PeV ν_μ



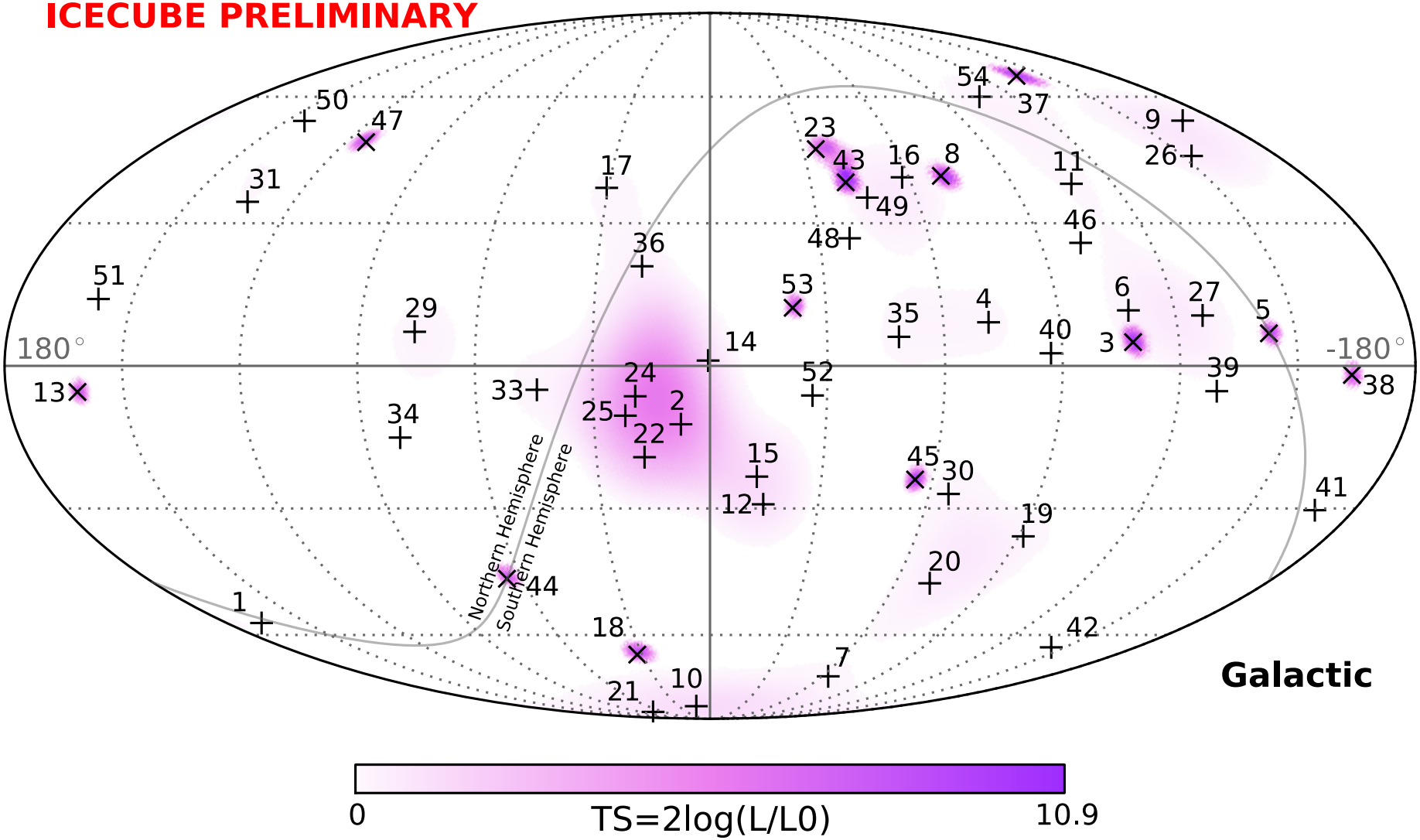


IceCube: the discovery of cosmic neutrinos

francis halzen

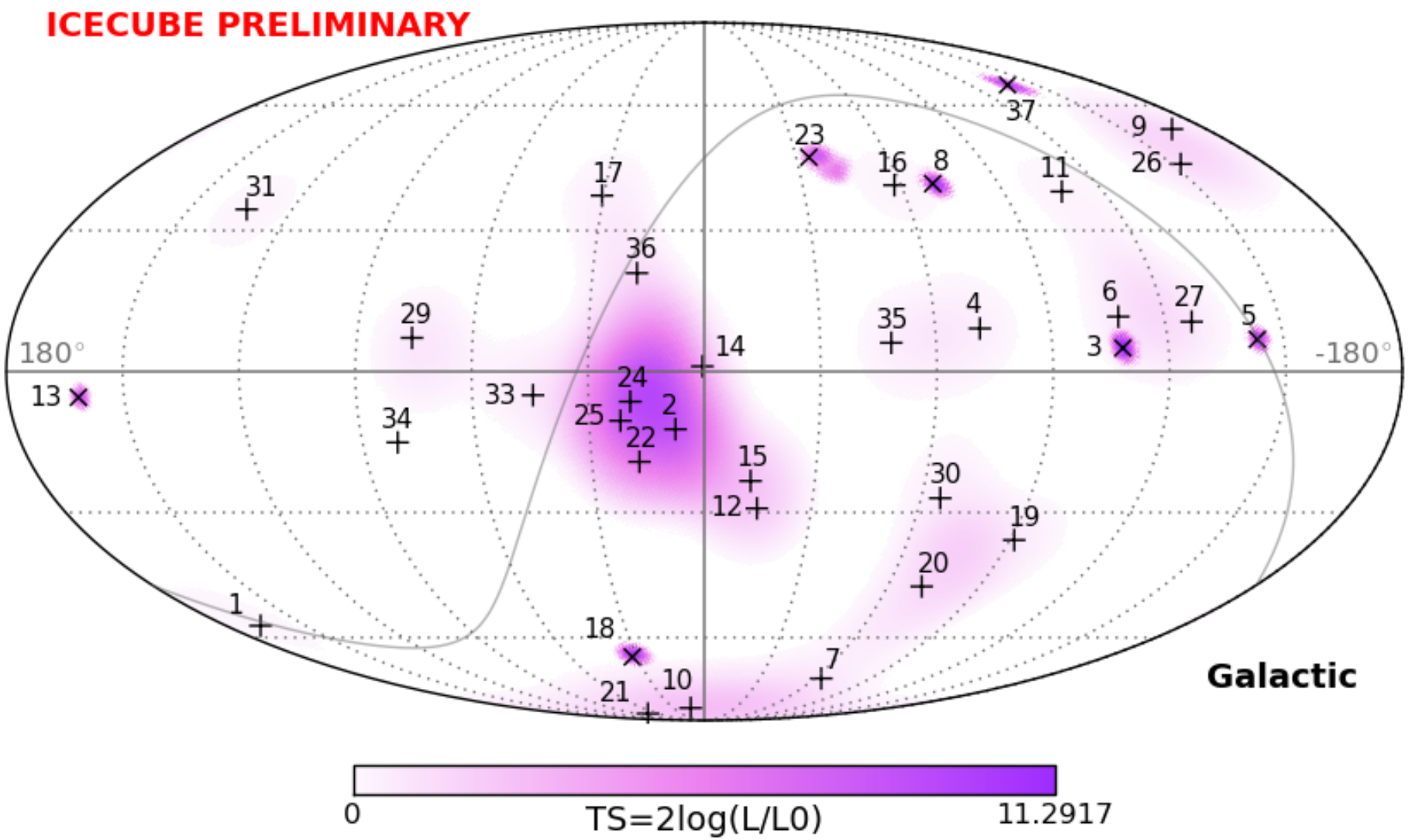
- cosmic ray accelerators
- IceCube a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

4 year HESE

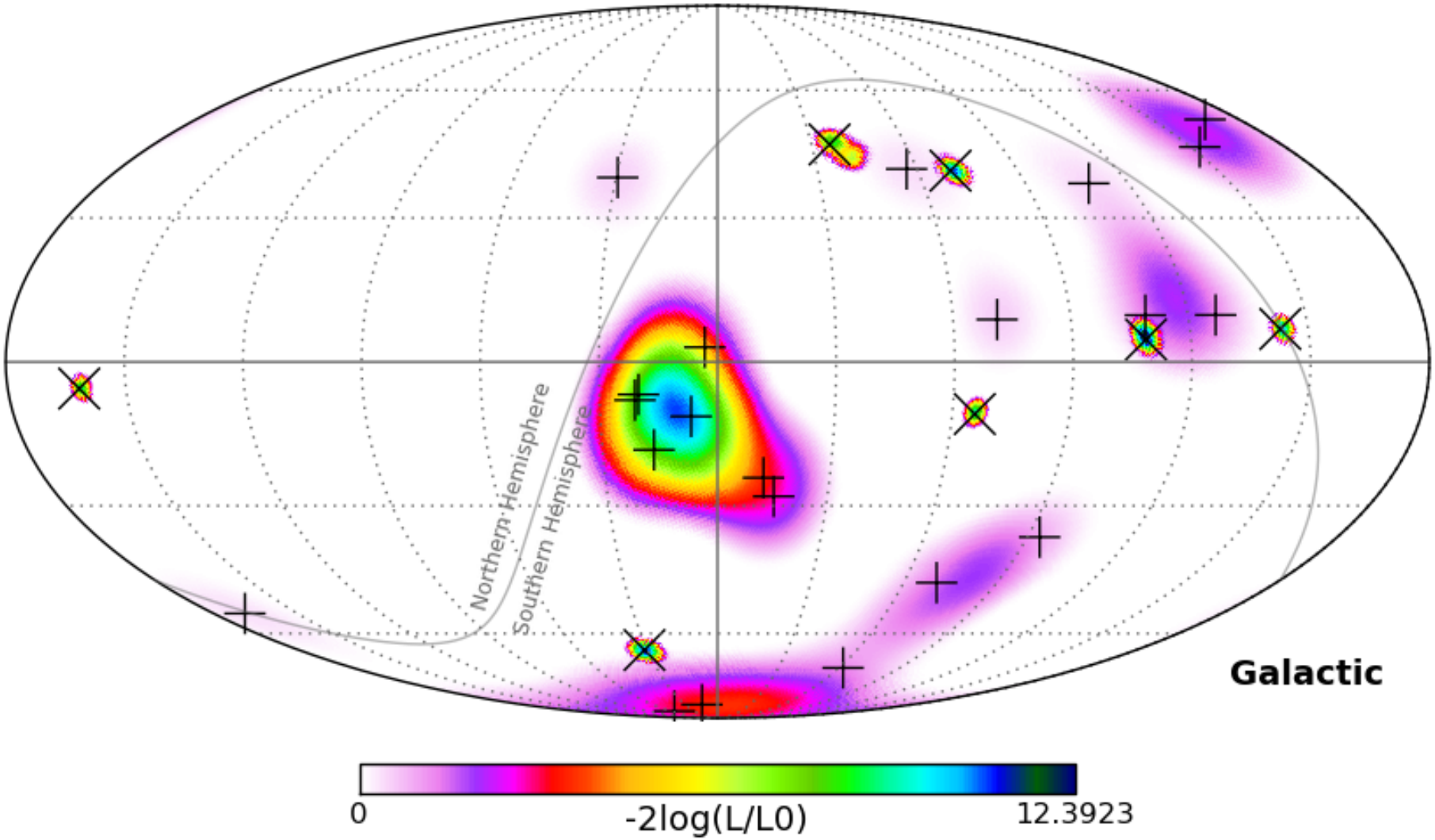


where do they come from?

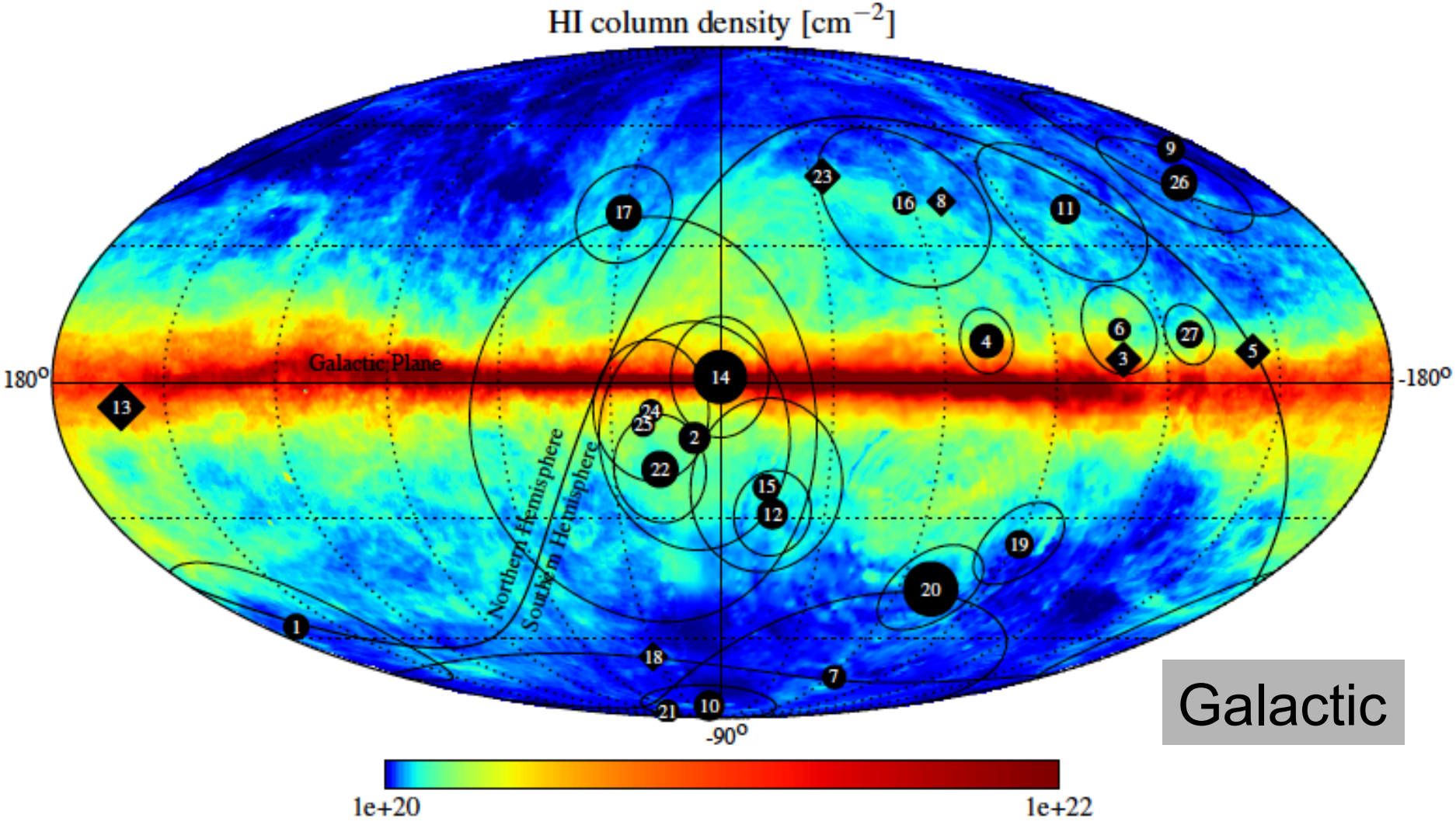
3 year HESE



2 year HESE

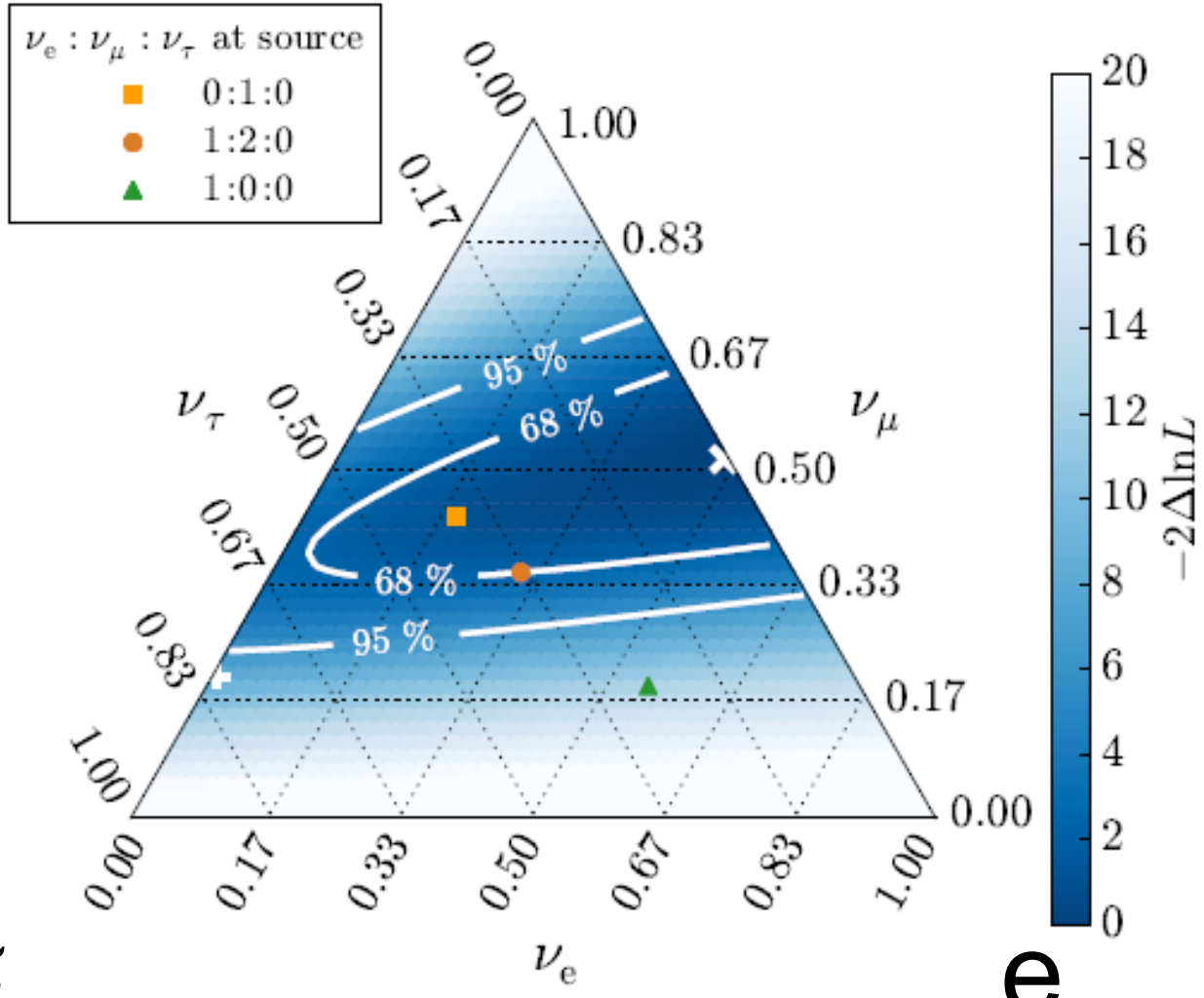

Northern Hemisphere
Southern Hemisphere
Galactic
0
-2log(L/L0)
12.3923

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



oscillate over cosmic distances to 1:1:1

μ

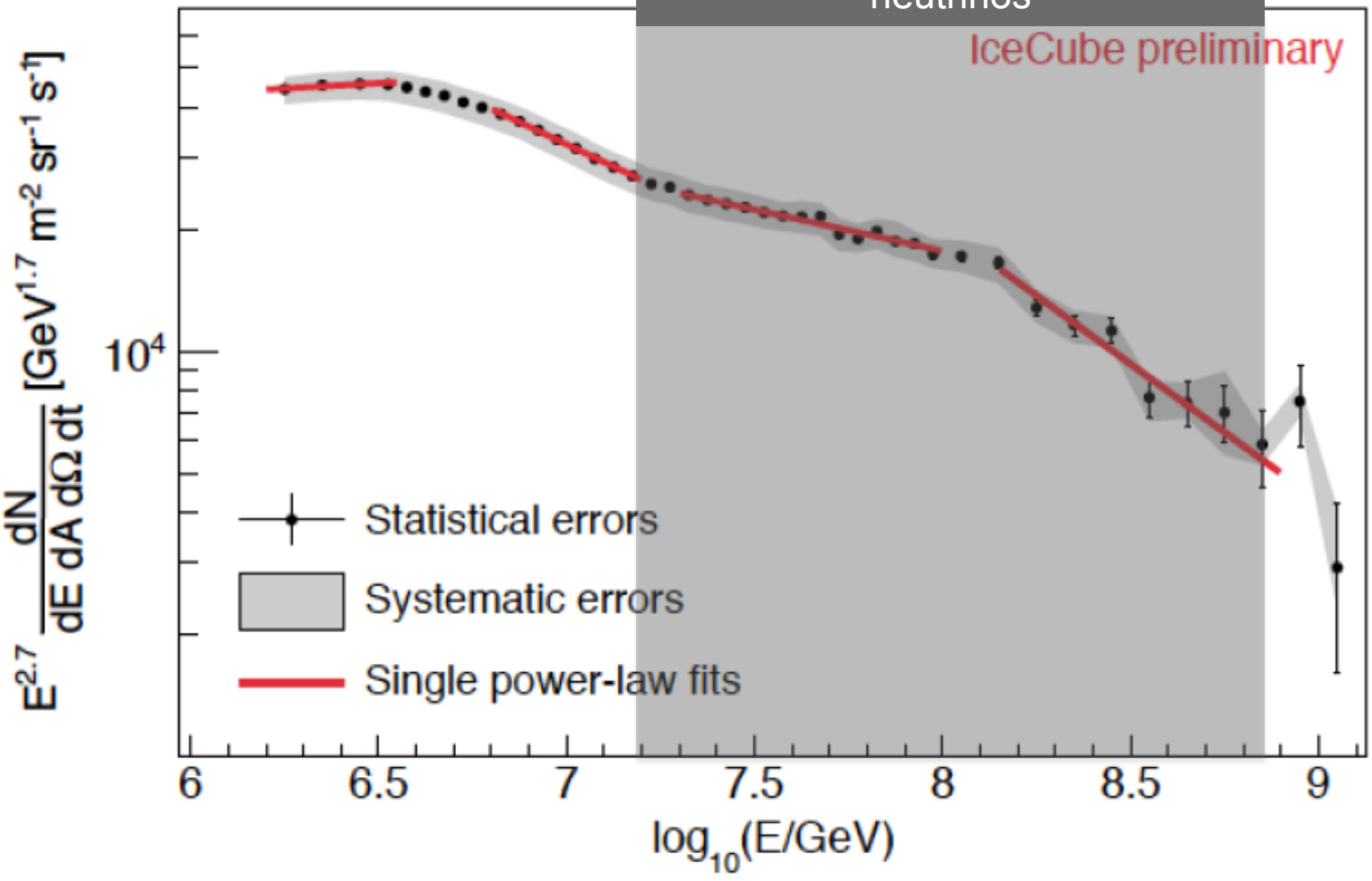


τ

e

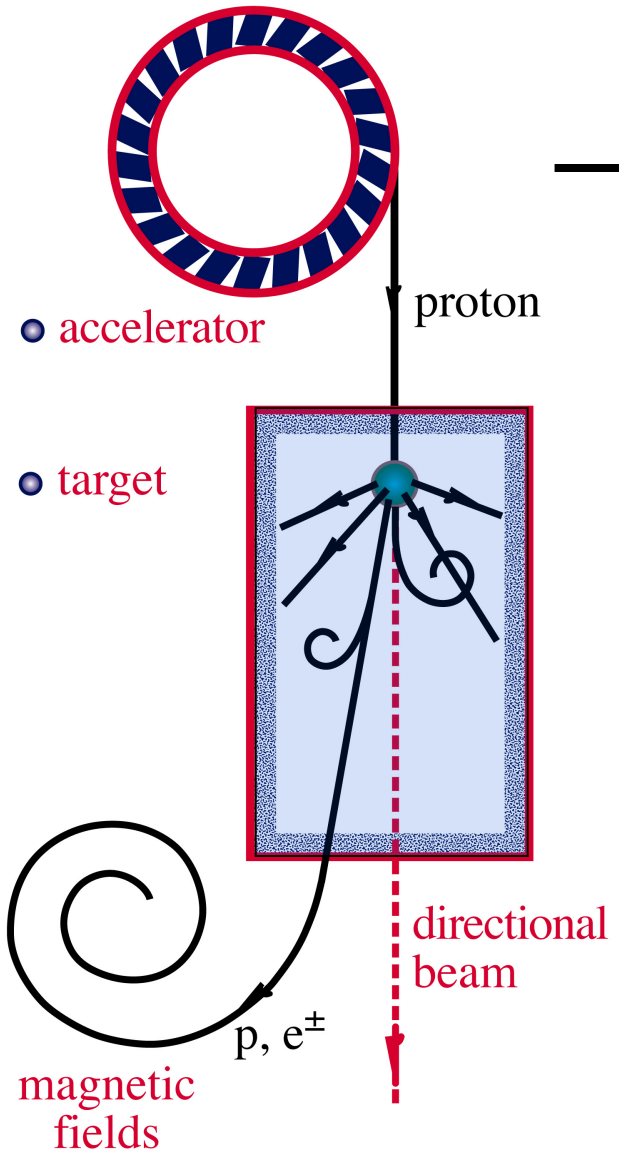
- we observe a diffuse flux of neutrinos from extragalactic sources
- a subdominant Galactic component cannot be excluded
- where are the PeV gamma rays that accompany PeV neutrinos?

the energy range of cosmic accelerators producing PeV neutrinos



Galactic or extragalactic?

ν and γ beams : heaven and earth



accelerator is powered by
large gravitational energy

black hole
neutron star

radiation
and dust

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

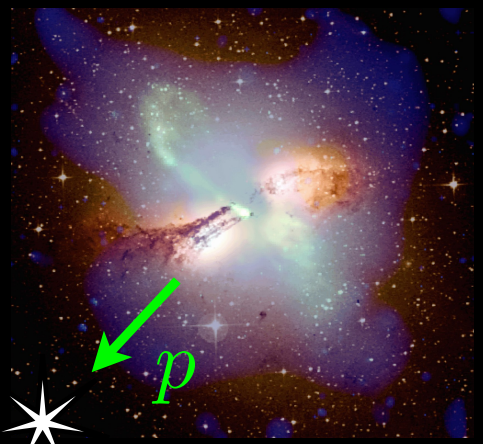
~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

~ cosmic ray + gamma

hadronic gamma rays ?

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

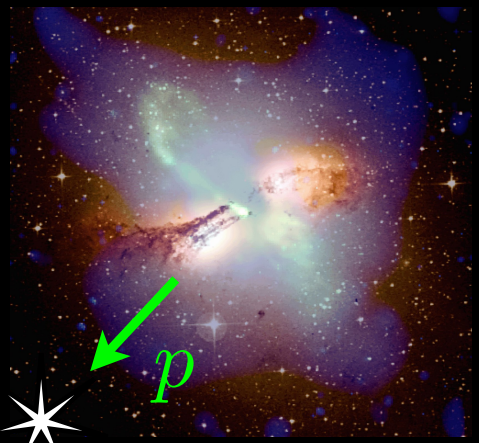


p

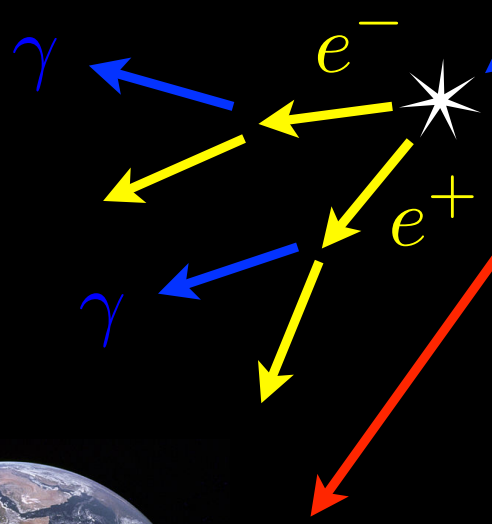
γ

ν

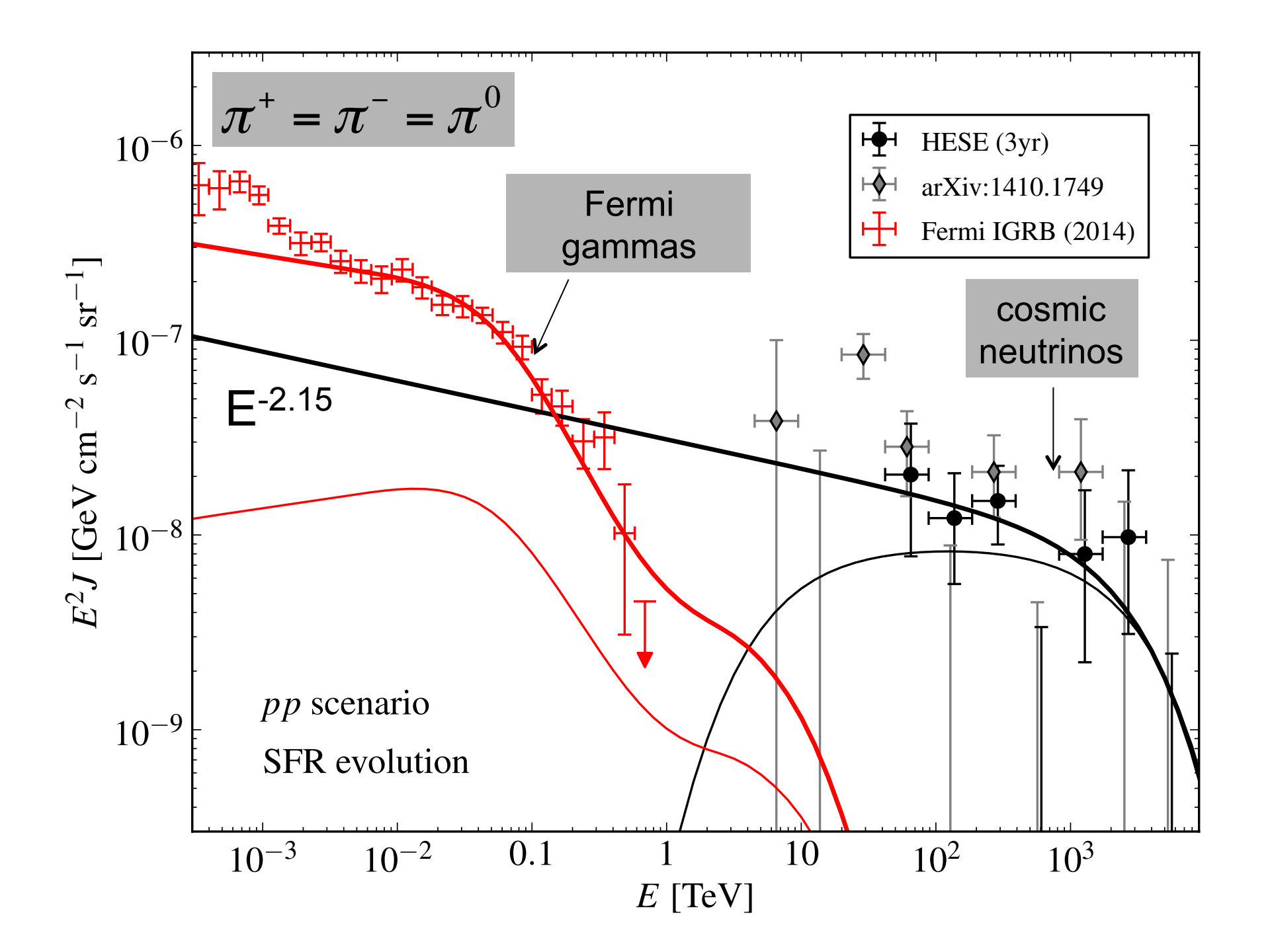
hadronic
gamma rays



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

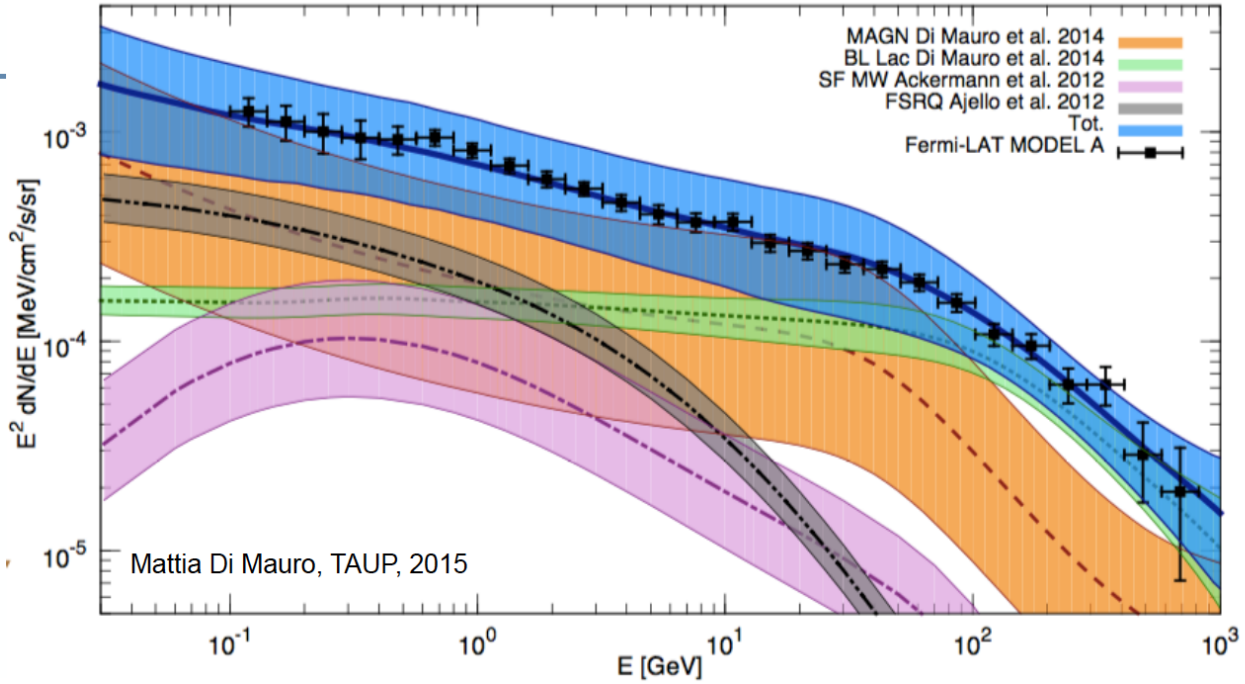
- we observe a flux of cosmic neutrinos from the cosmos whose properties correspond in all respects to the flux anticipated from PeV-energy cosmic accelerators that radiate comparable energies in light and neutrinos

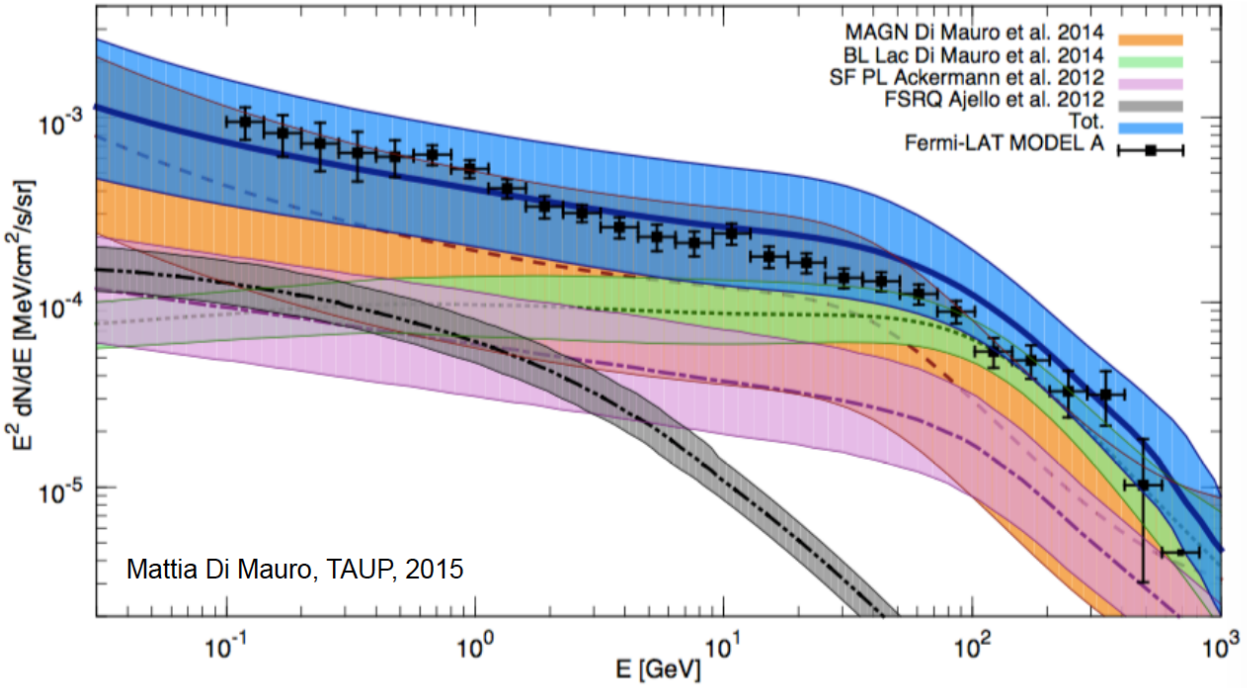
- the energy in cosmic neutrinos is also comparable to the energy observed in extragalactic cosmic rays (the Waxman-Bahcall bound)

- at some level common Fermi-IceCube sources?

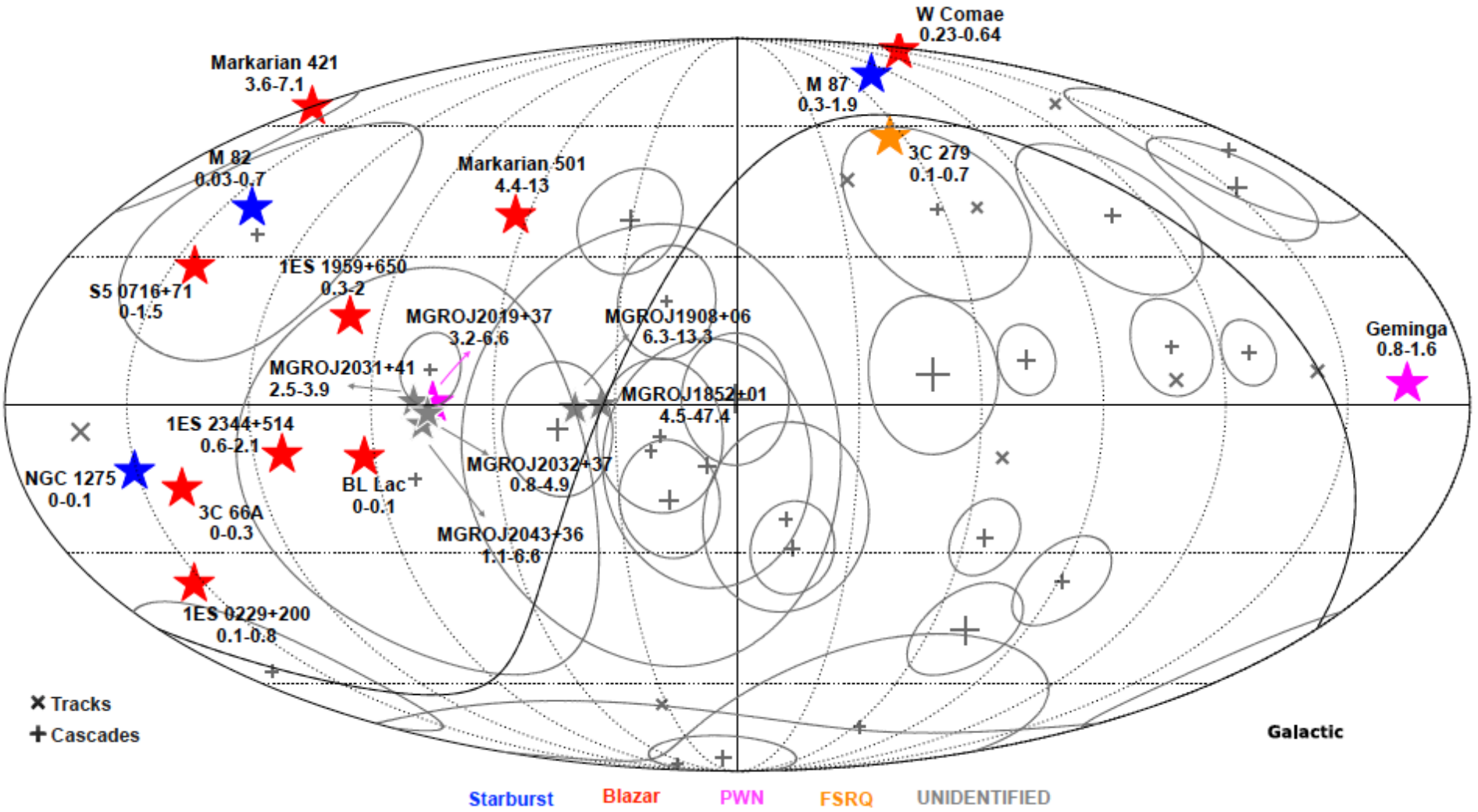
A census

- 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.



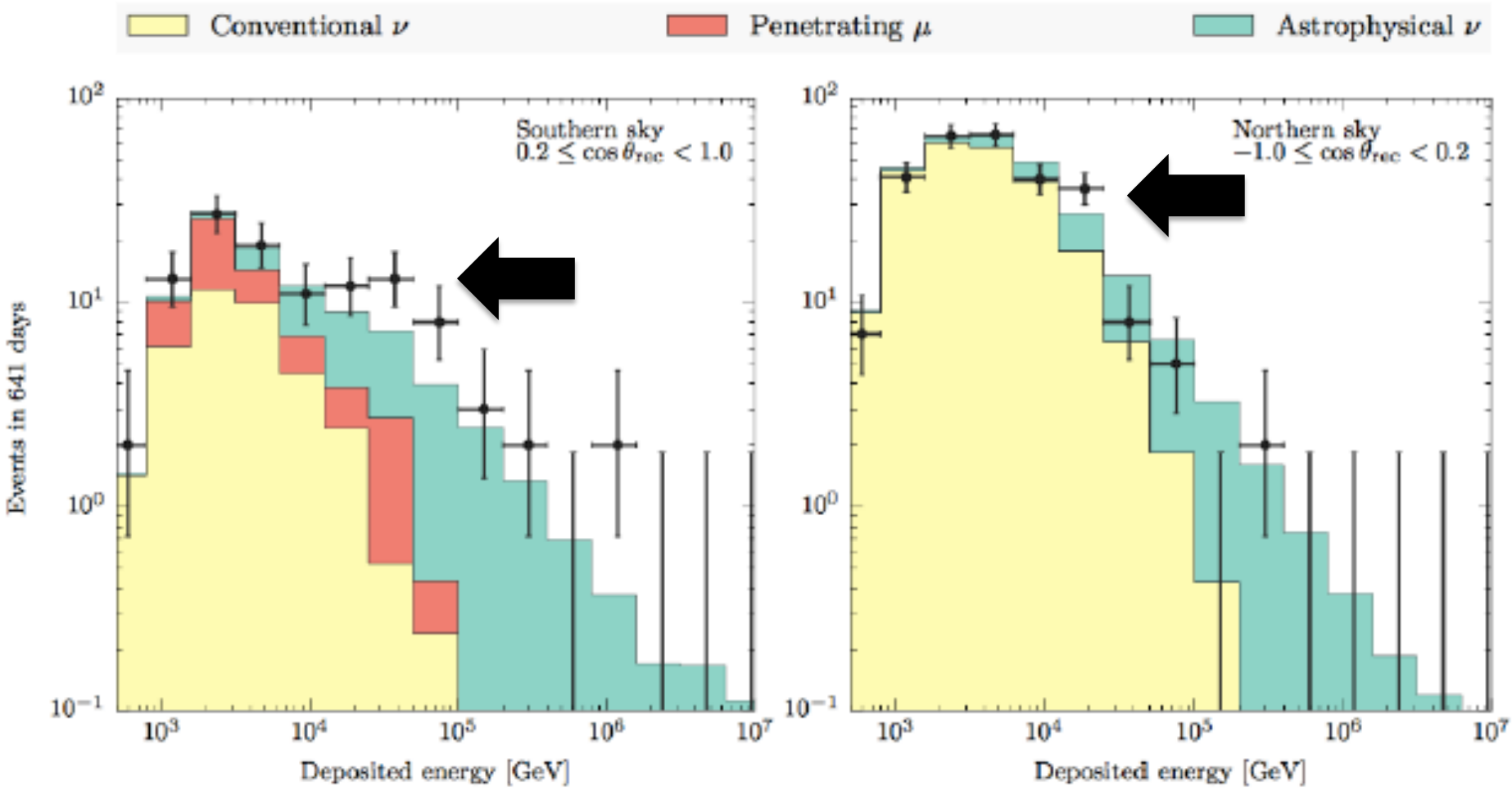


number of muon neutrino events from gamma ray sources in 5 years



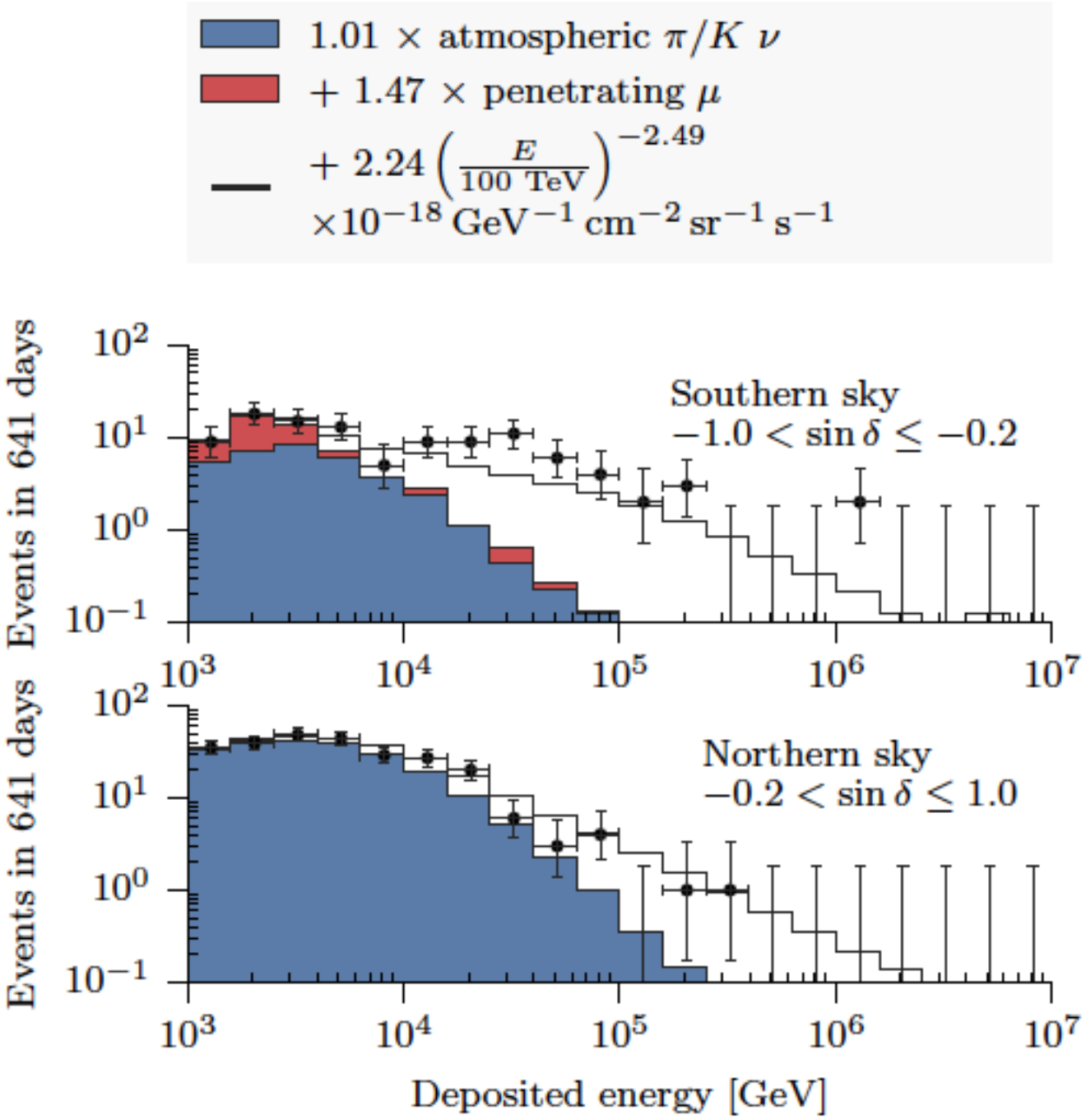
- there is more

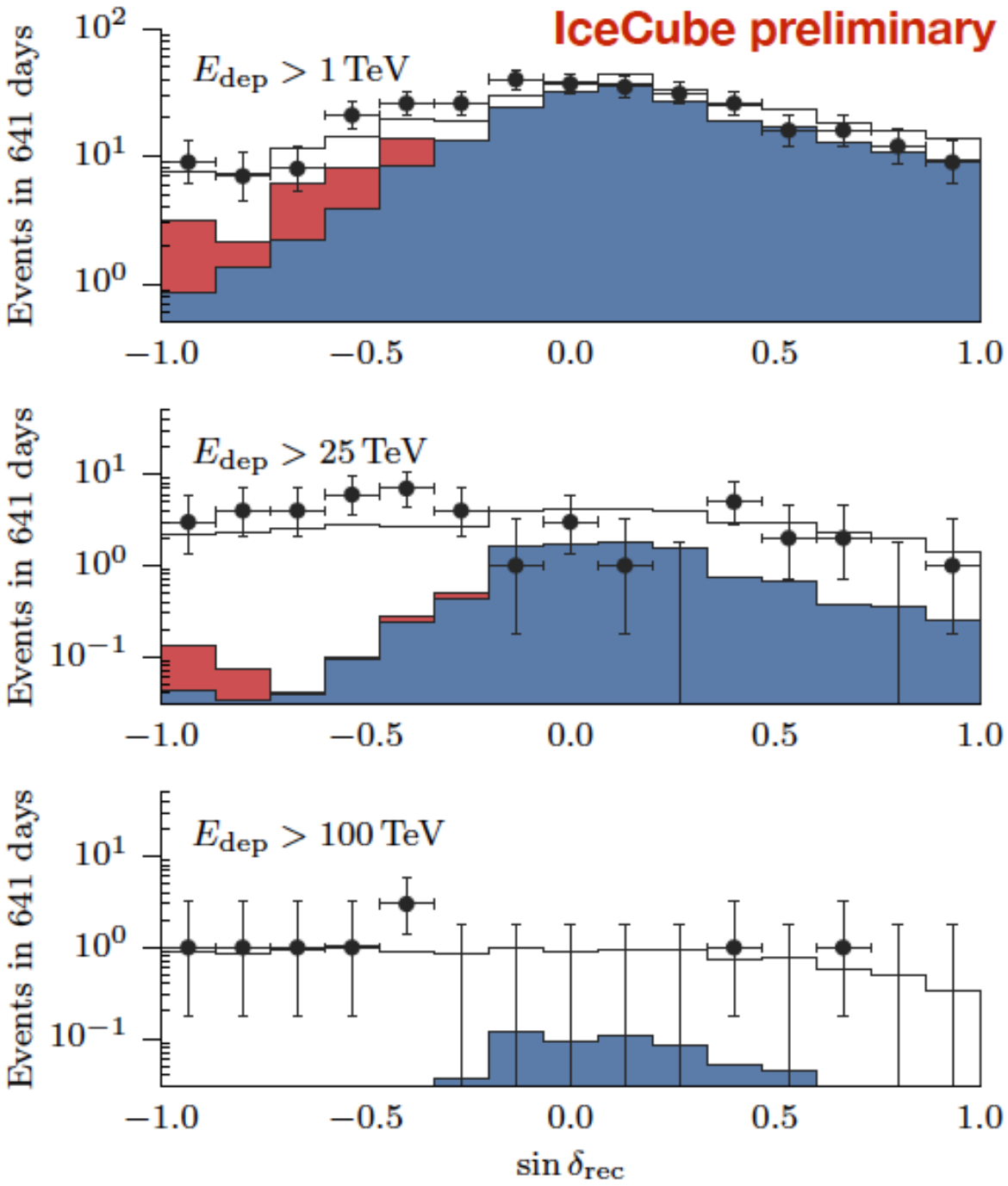
towards lower energies: a second component?

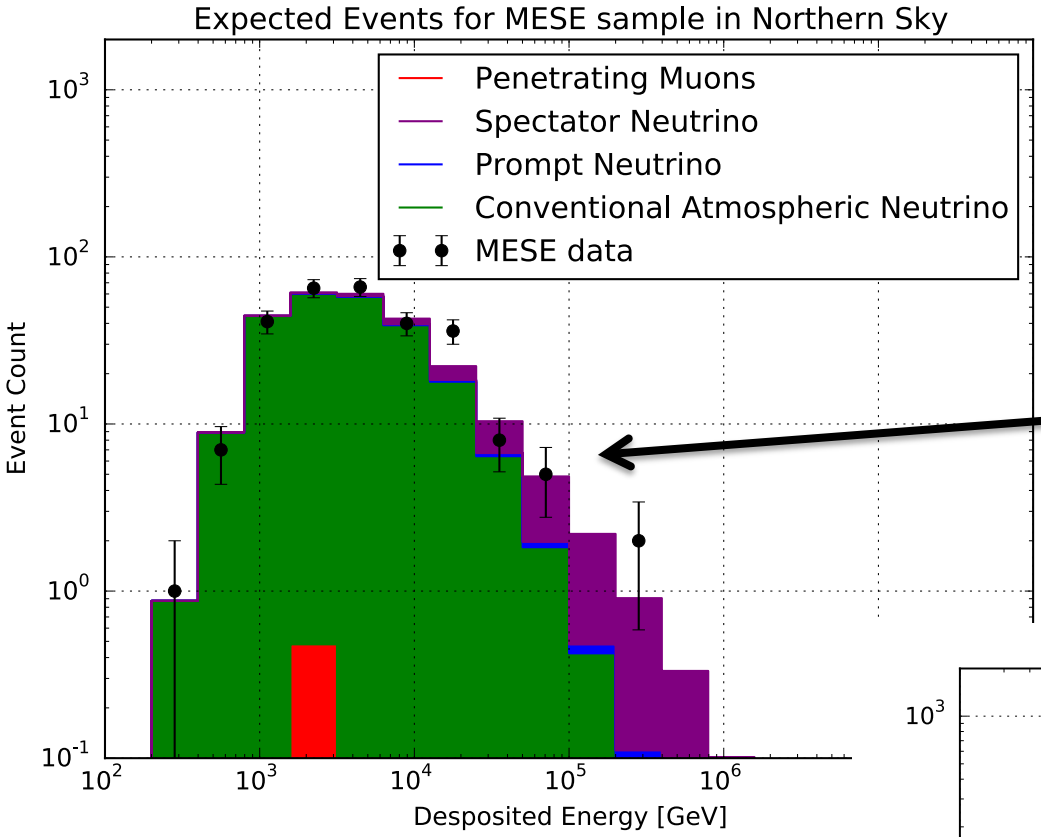


warning:
- spectrum may not be a power law
- slope depends on energy range fitted

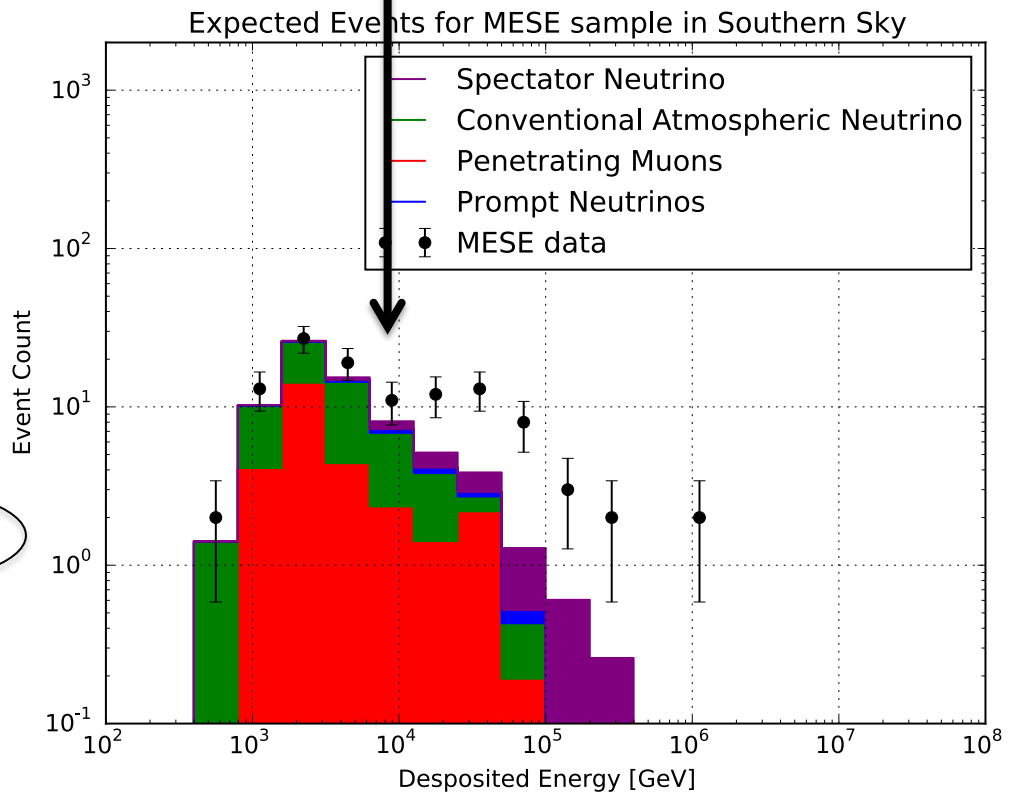
PeV neutrinos absorbed in the Earth

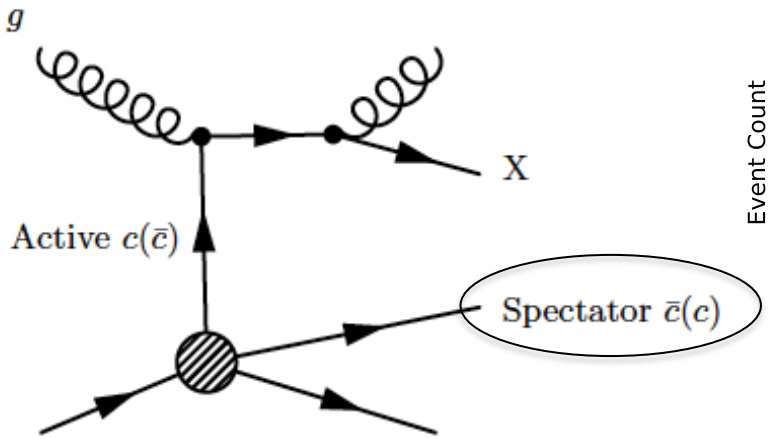

1.01 × atmospheric π/K ν
+ 1.47 × penetrating μ
+ 2.24 (E / 100 TeV)^−2.49
×10^−18 GeV^−1 cm^−2 sr^−1 s^−1
Southern sky
−1.0 < sin δ ≤ −0.2
Northern sky
−0.2 < sin δ ≤ 1.0
Events in 641 days
Events in 641 days
Deposited energy [GeV]


IceCube preliminary
$E_{\mathrm{dep}} > 1\,\mathrm{TeV}$
$E_{\mathrm{dep}} > 25\,\mathrm{TeV}$
$E_{\mathrm{dep}} > 100\,\mathrm{TeV}$
Events in 641 days
10^2
10^1
10^0
10^{-1}
−1.0
−0.5
0.0
0.5
1.0
$\sin \delta_{\mathrm{rec}}$

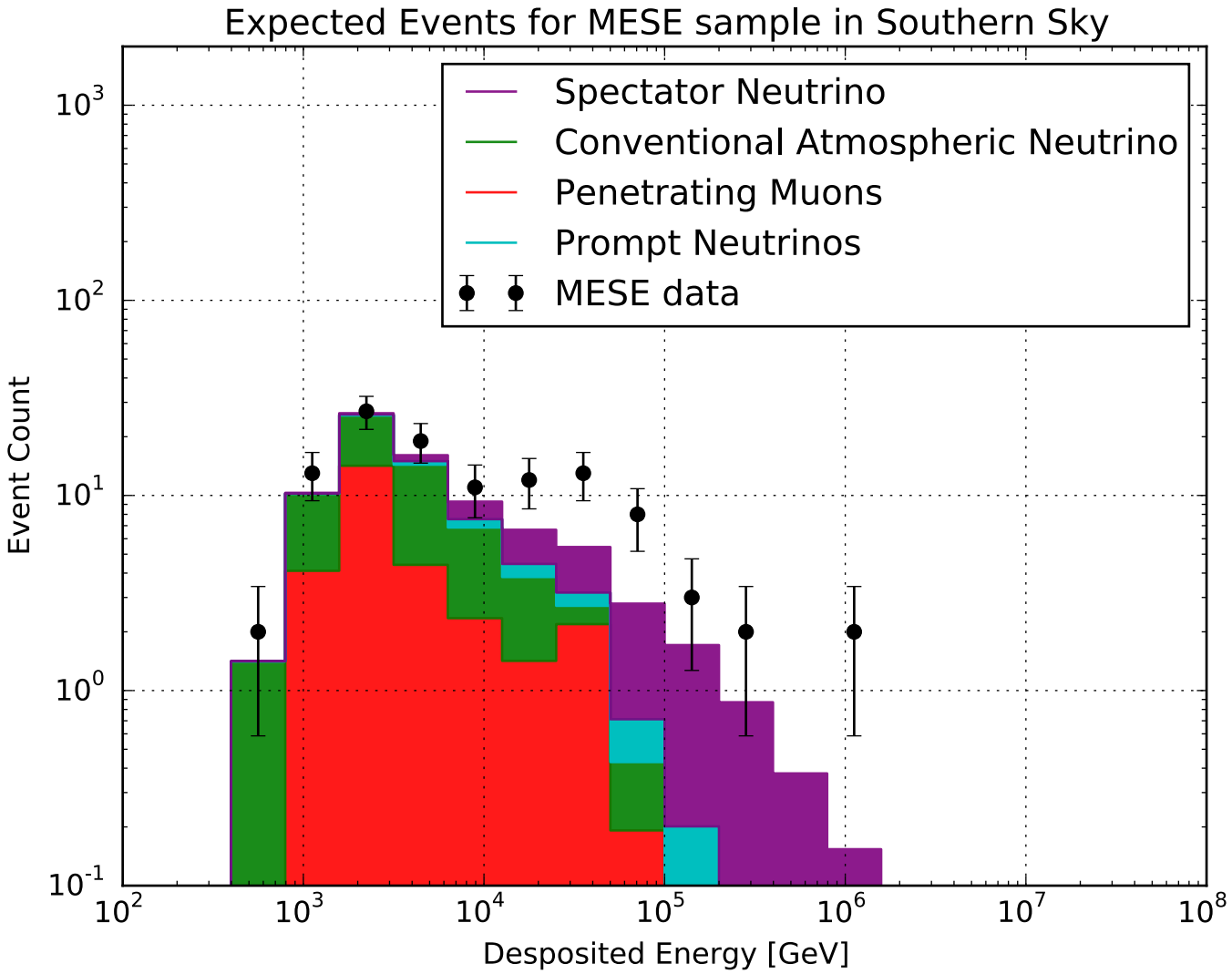


upcoming events: "extreme" charm model can fit the northern, not the southern hemisphere



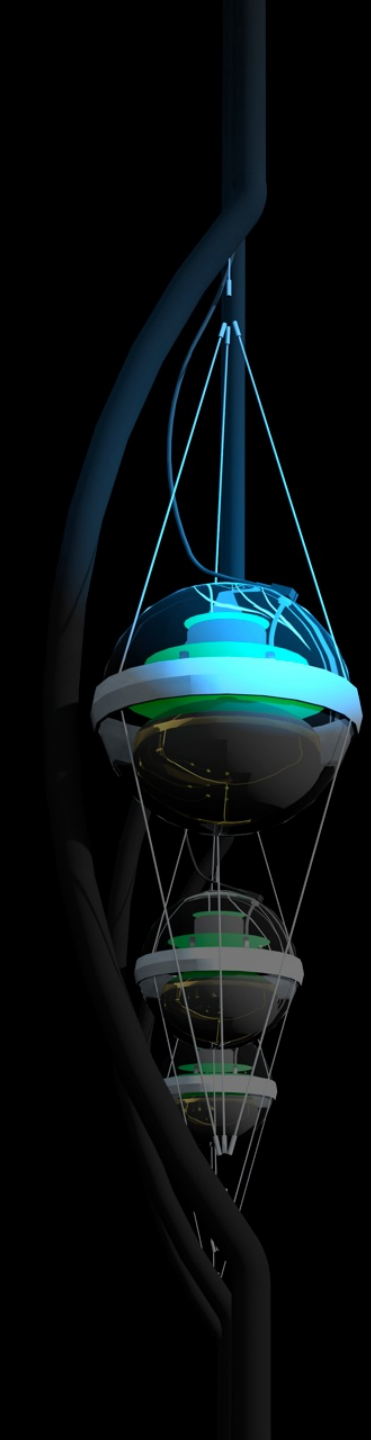


LHC: charm pairs in proton



with no isolation veto: same conclusion

- 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 with beaming angle neutrinos < light ?)



IceCube: the discovery of cosmic neutrinos

francis halzen

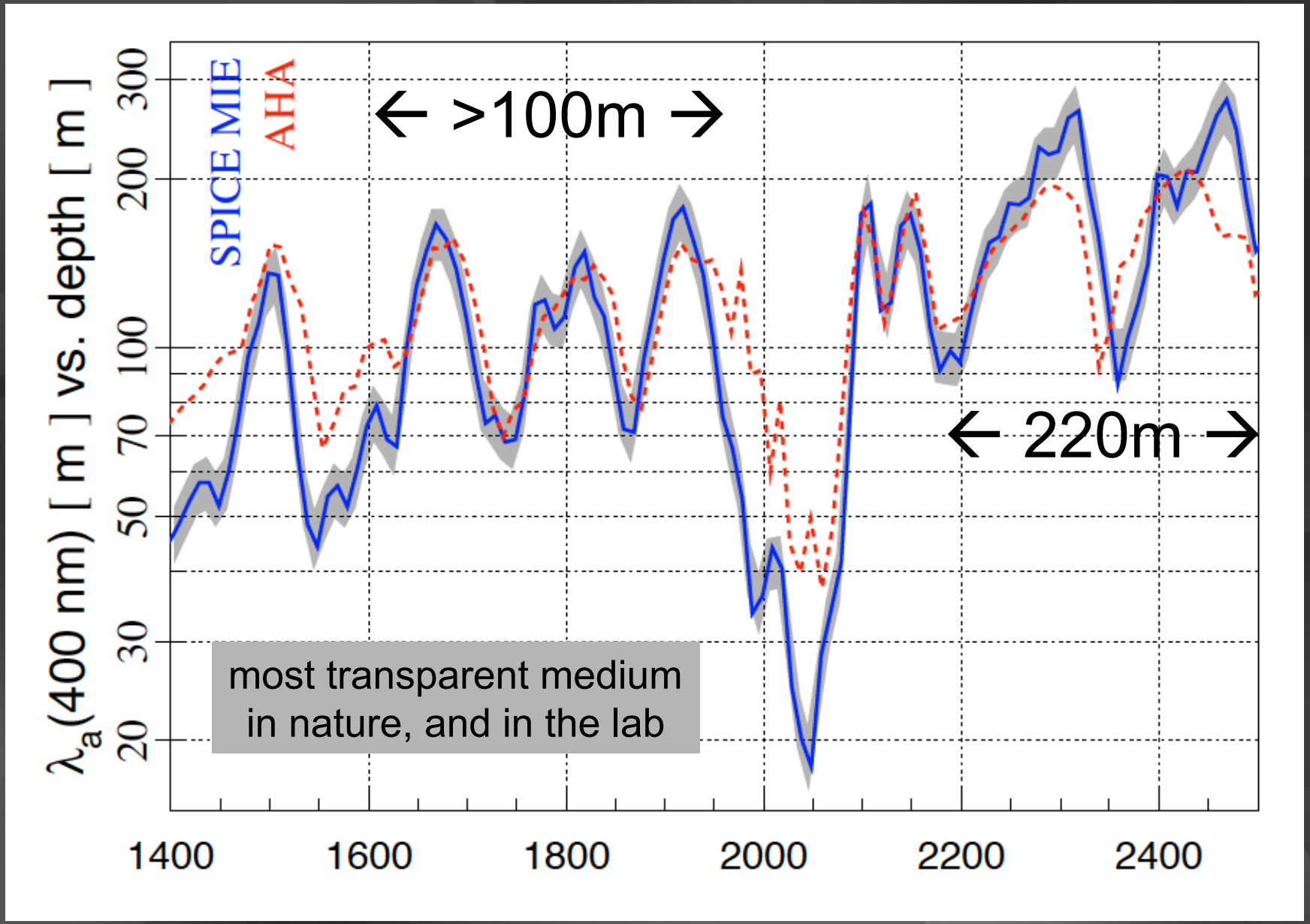
- cosmic ray accelerators
- IceCube a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

- 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

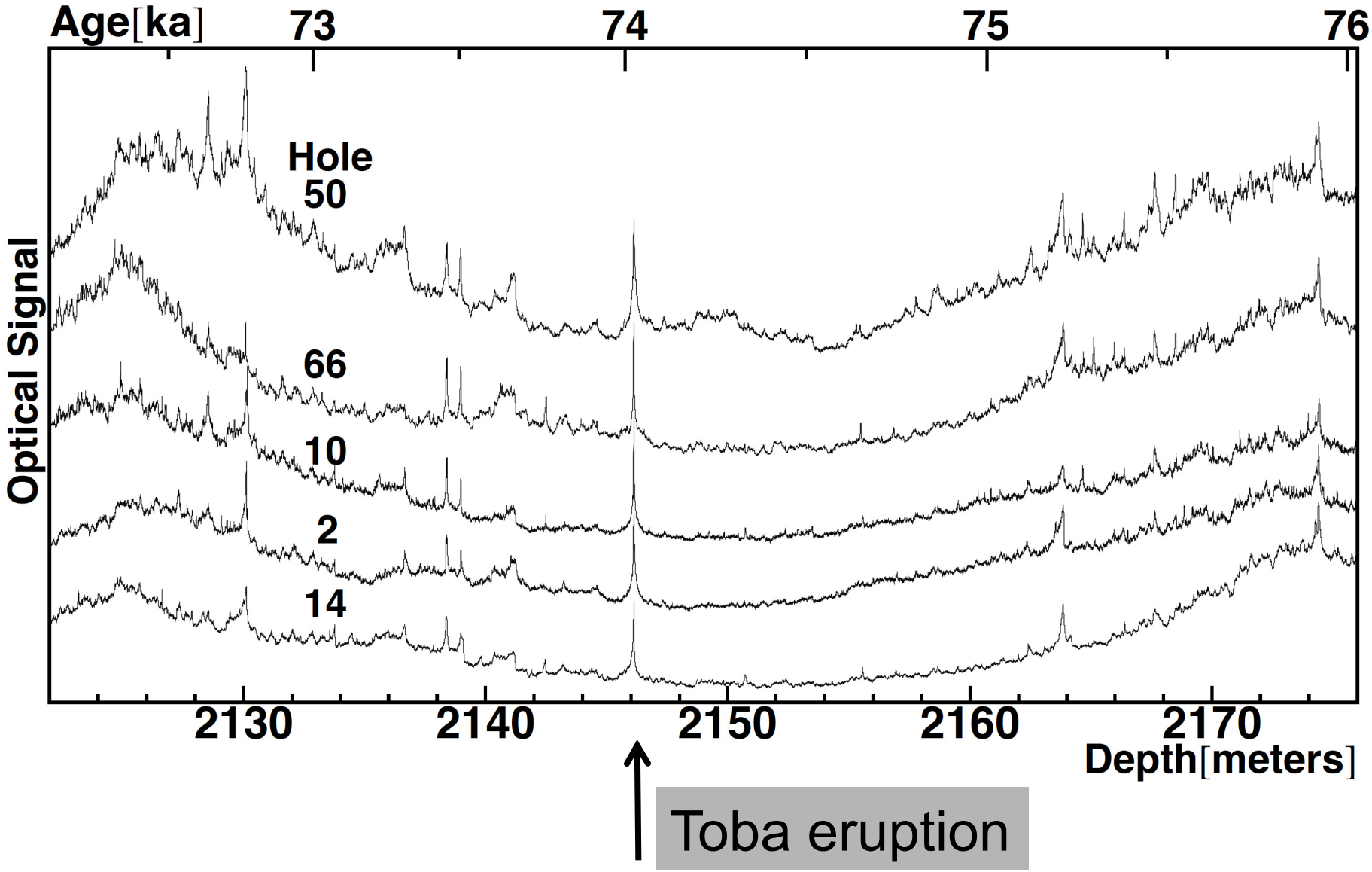
- need 1,000 events versus 100 now in a few years

- discovery instrument → astronomical telescope

absorption length of Cherenkov light

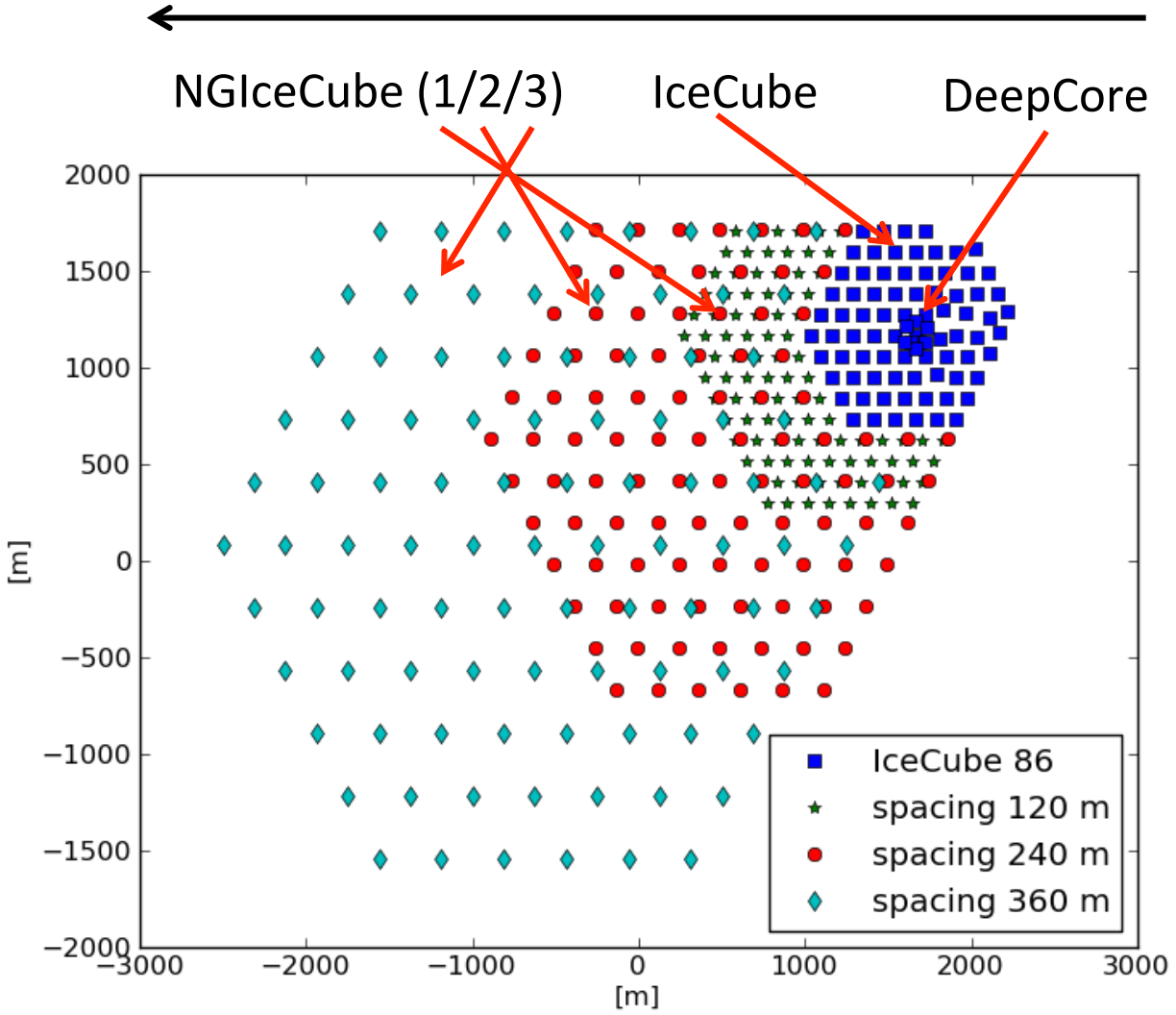


we are limited by computing, not the optics of the ice



measured optical properties → twice the string spacing

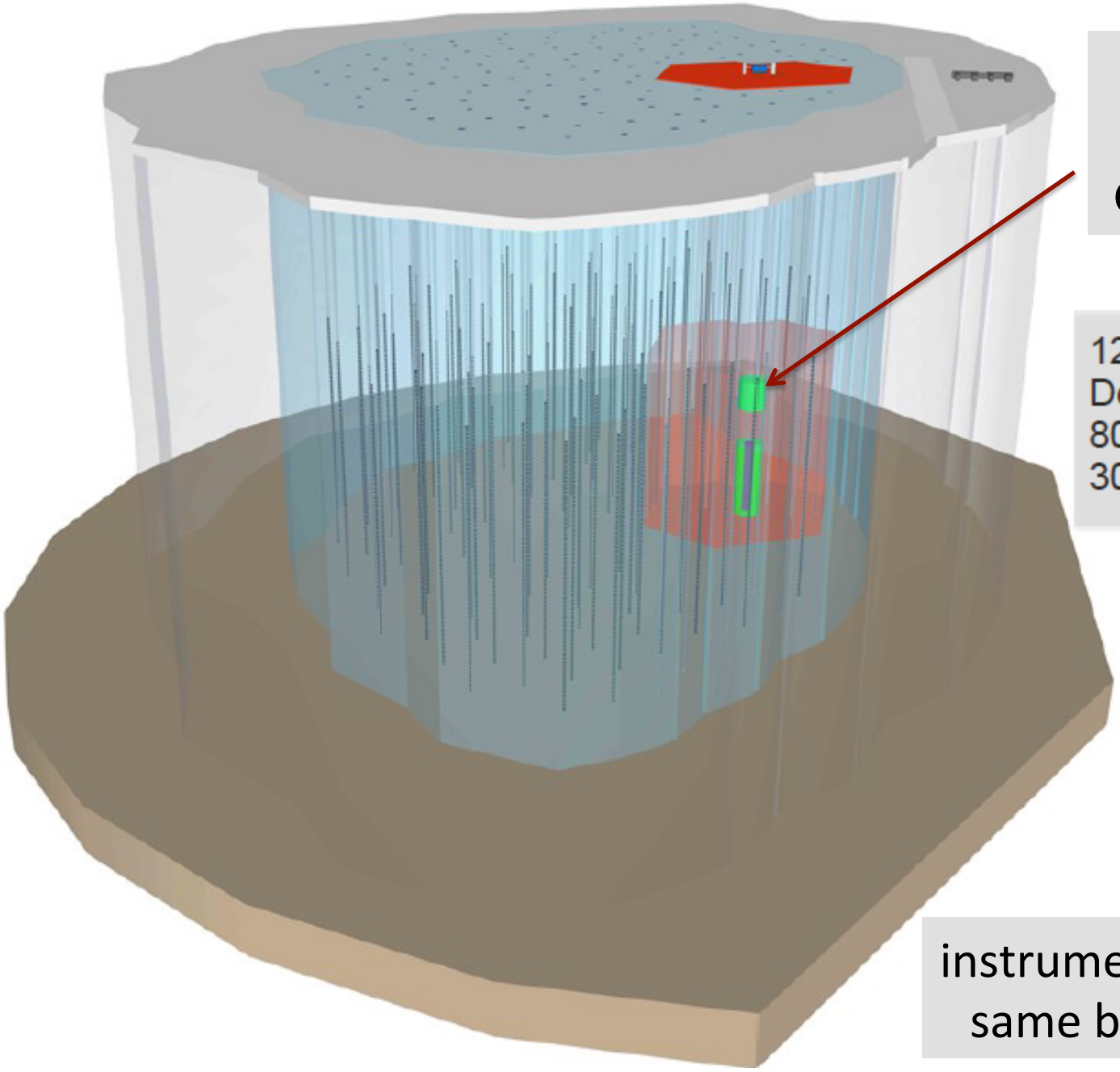
(increase in threshold not important: only eliminates energies where the atmospheric background dominates)



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



PINGU infill
40 strings
GeV threshold

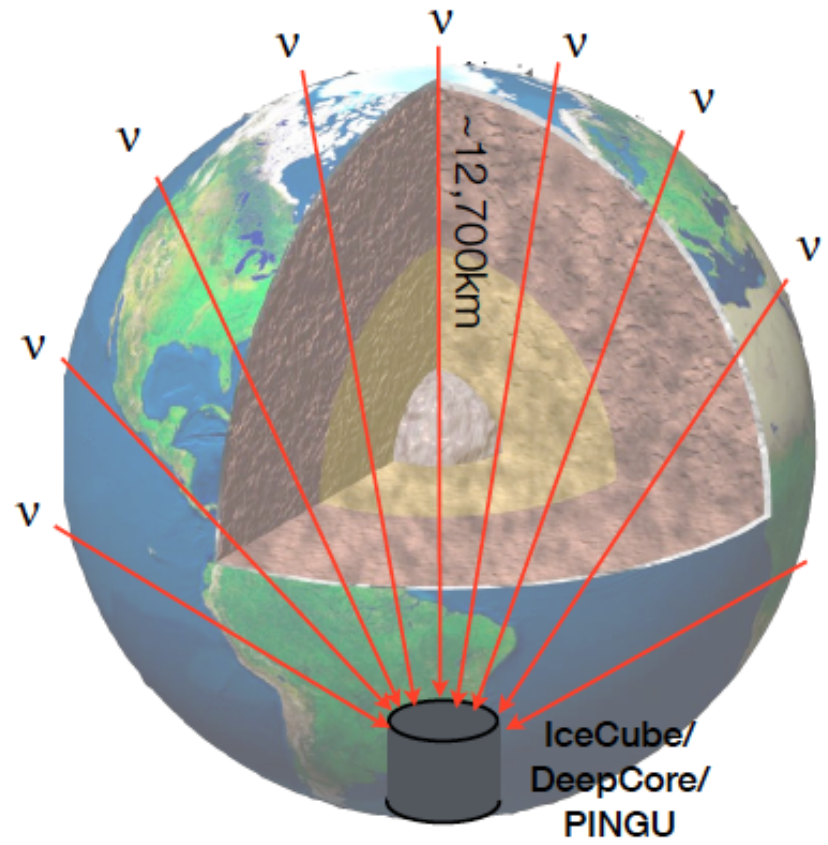
120 strings
Depth 1.35 to 2.7 km
80 DOMs/string
300 m spacing

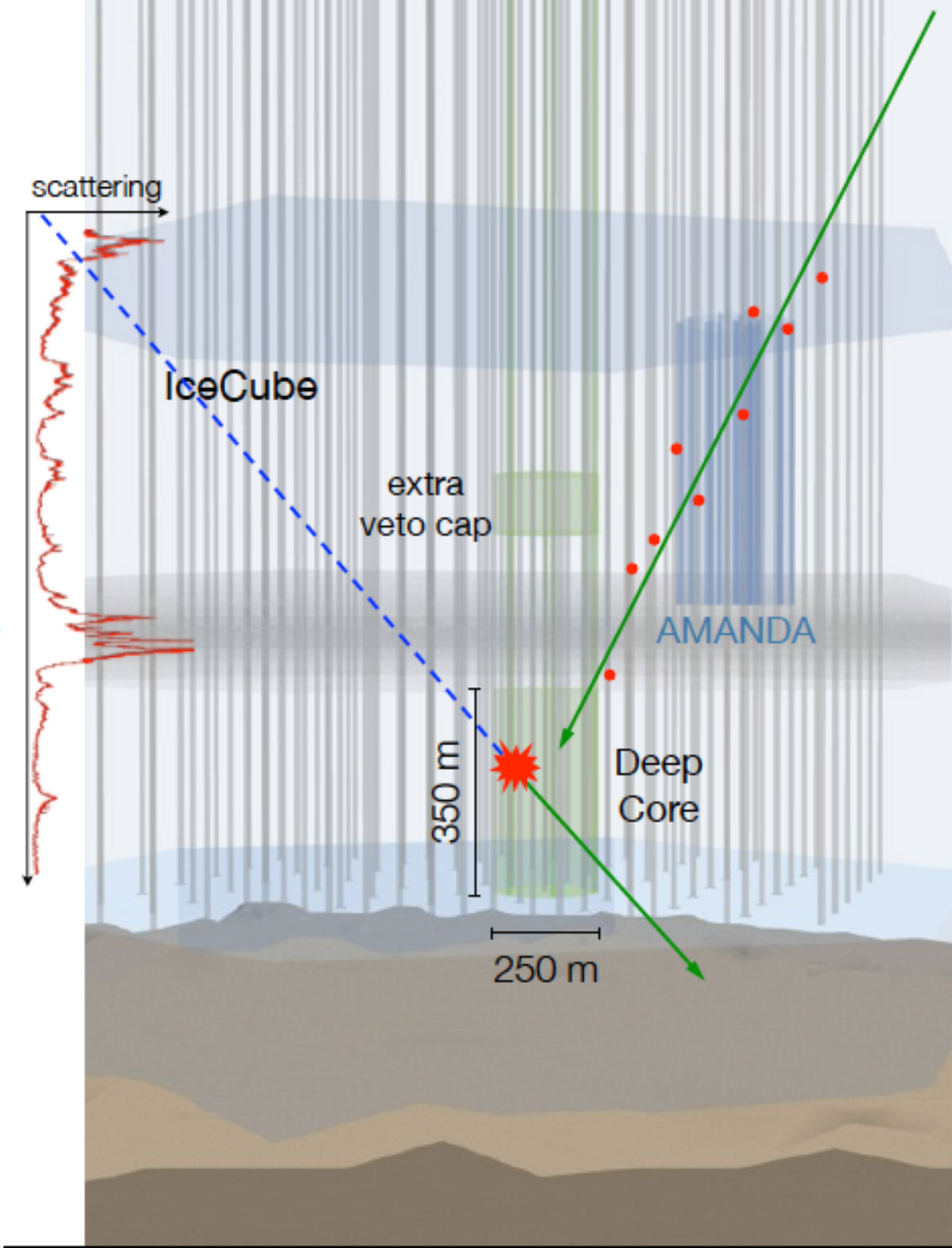
instrumented volume: x 10
same budget as IceCube

did not talk about:

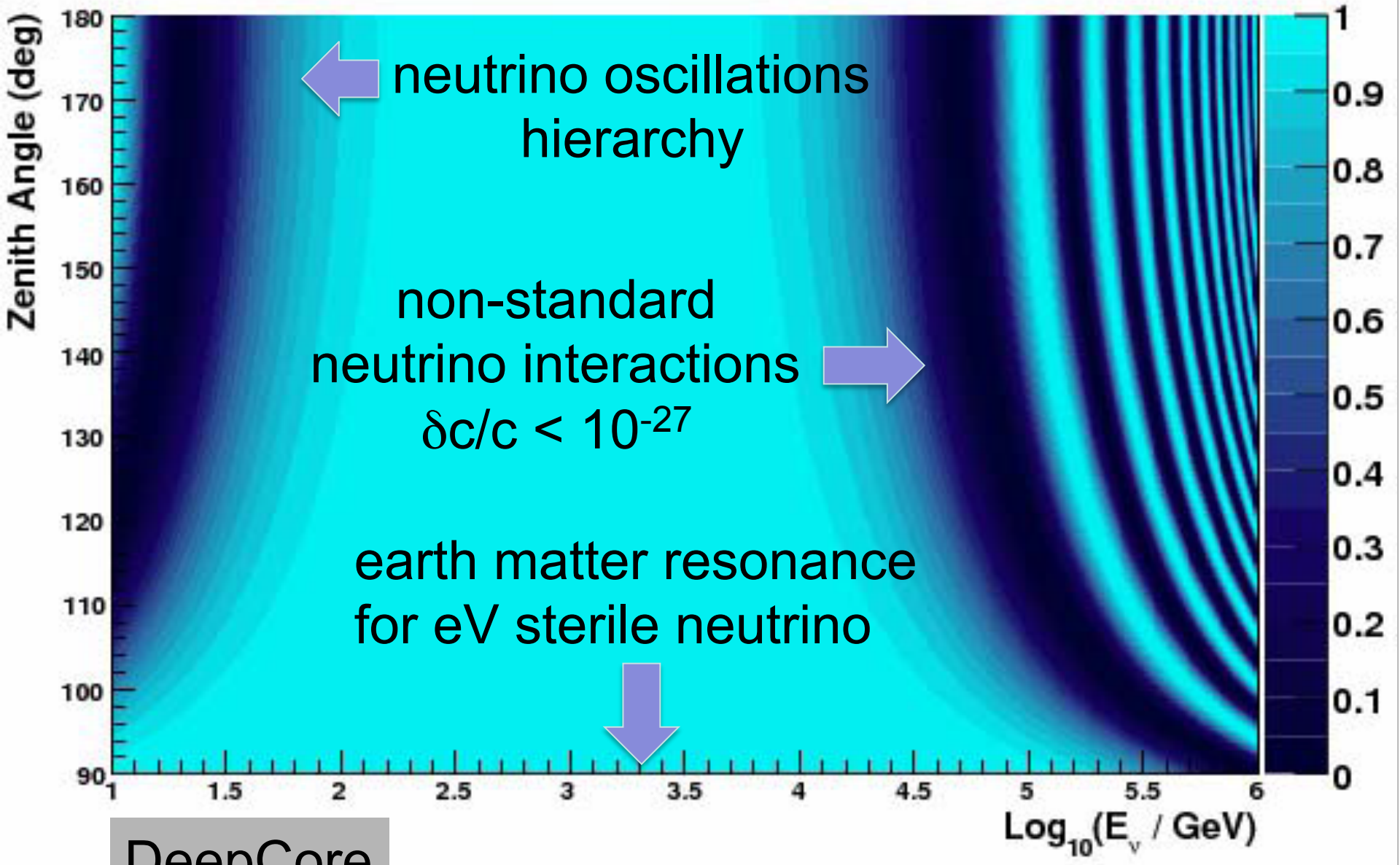
- measurement of atmospheric oscillation parameters
- supernova detection
- searches for dark matter, monopoles,…
- search for eV-mass sterile neutrinos
- PINGU/ORCA
- ….

one half million atmospheric neutrinos…





one half million atmospheric neutrinos…

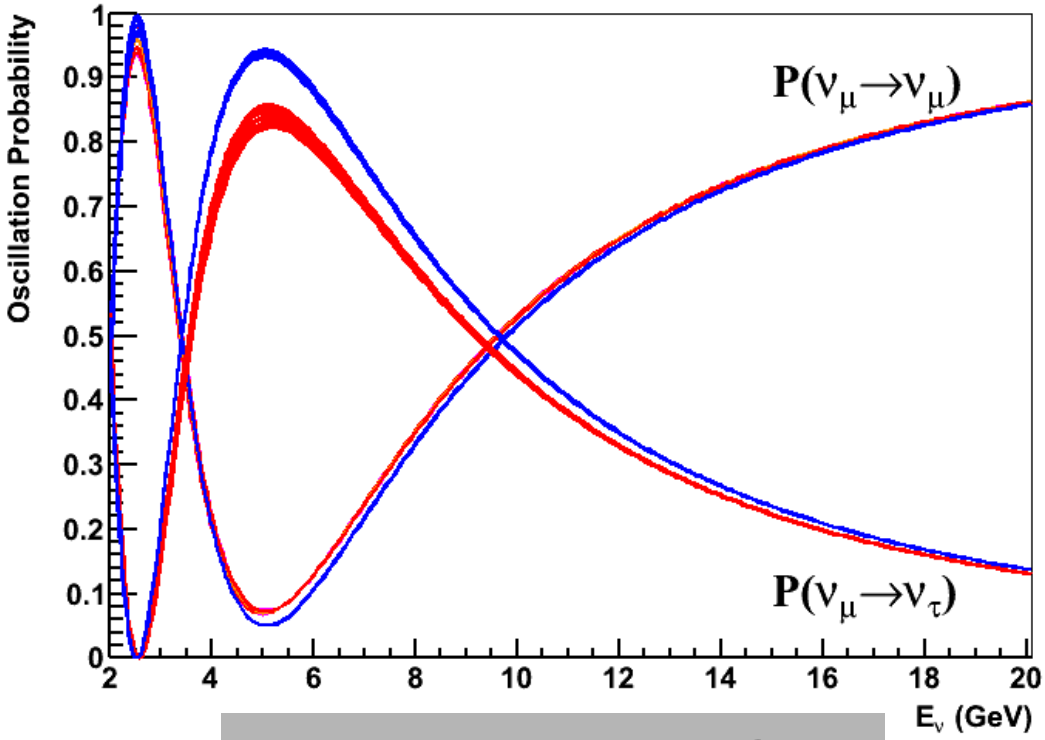


DeepCore

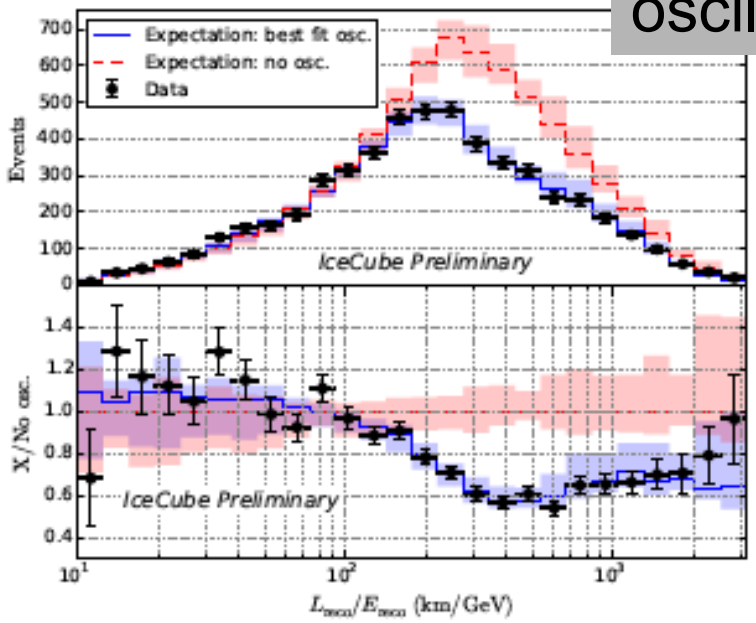
IceCube

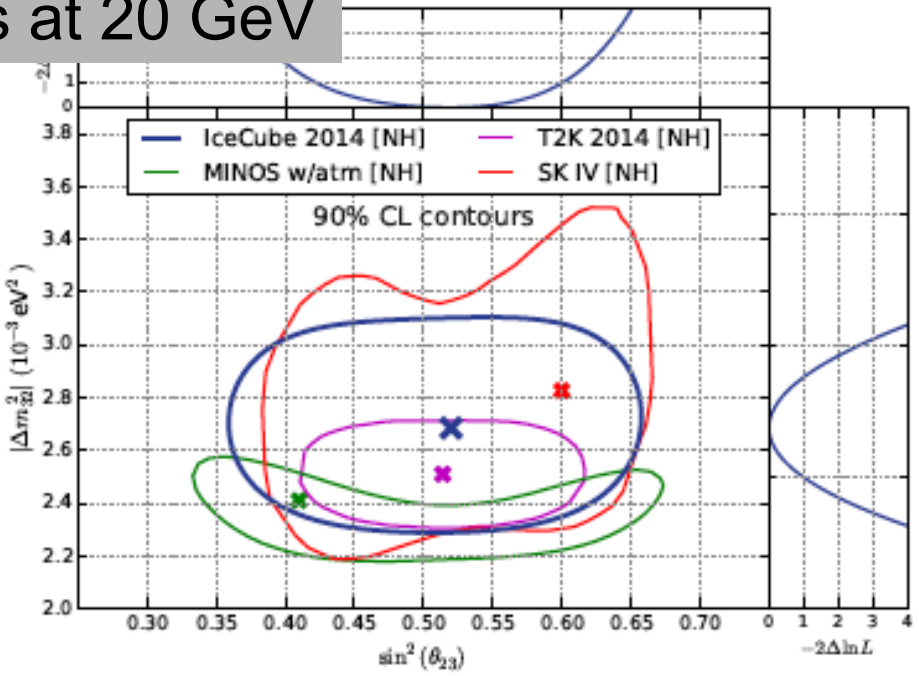
DeepCore

PINGU



oscillations at 20 GeV

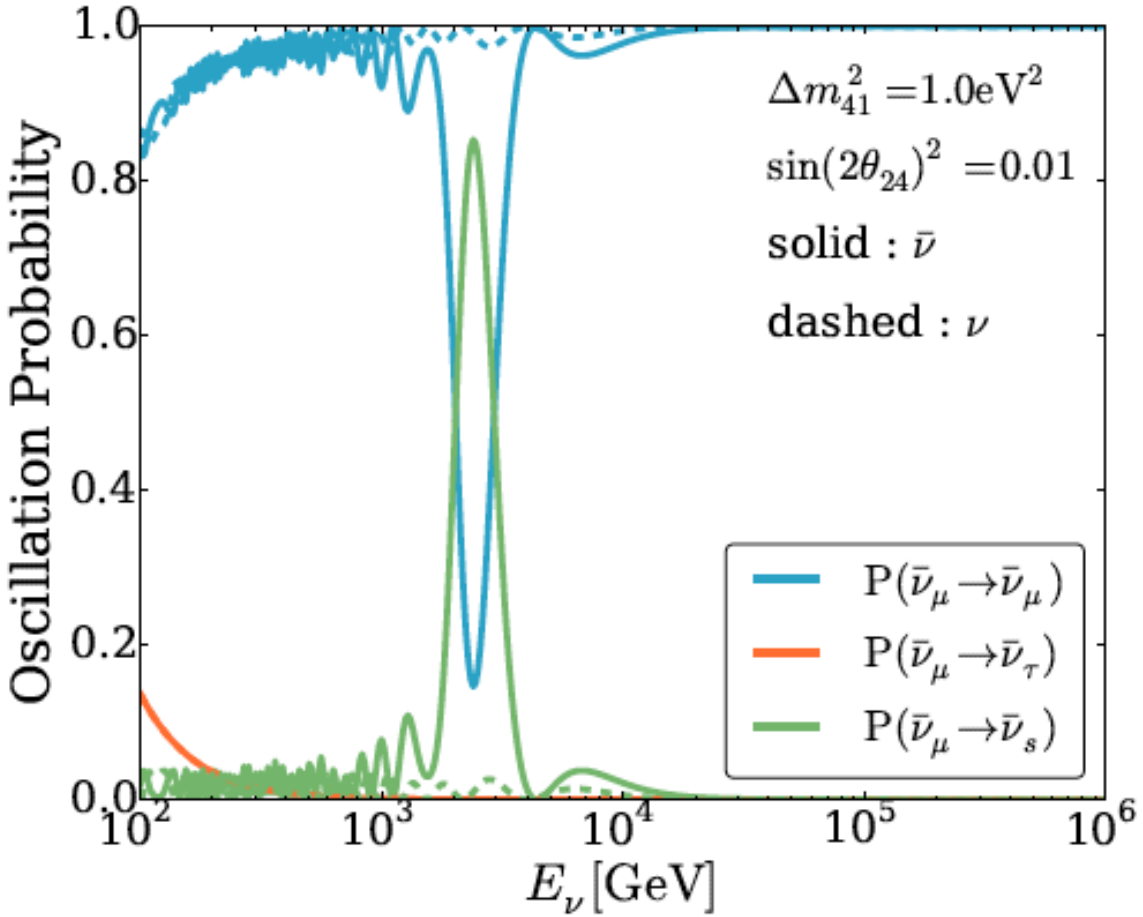


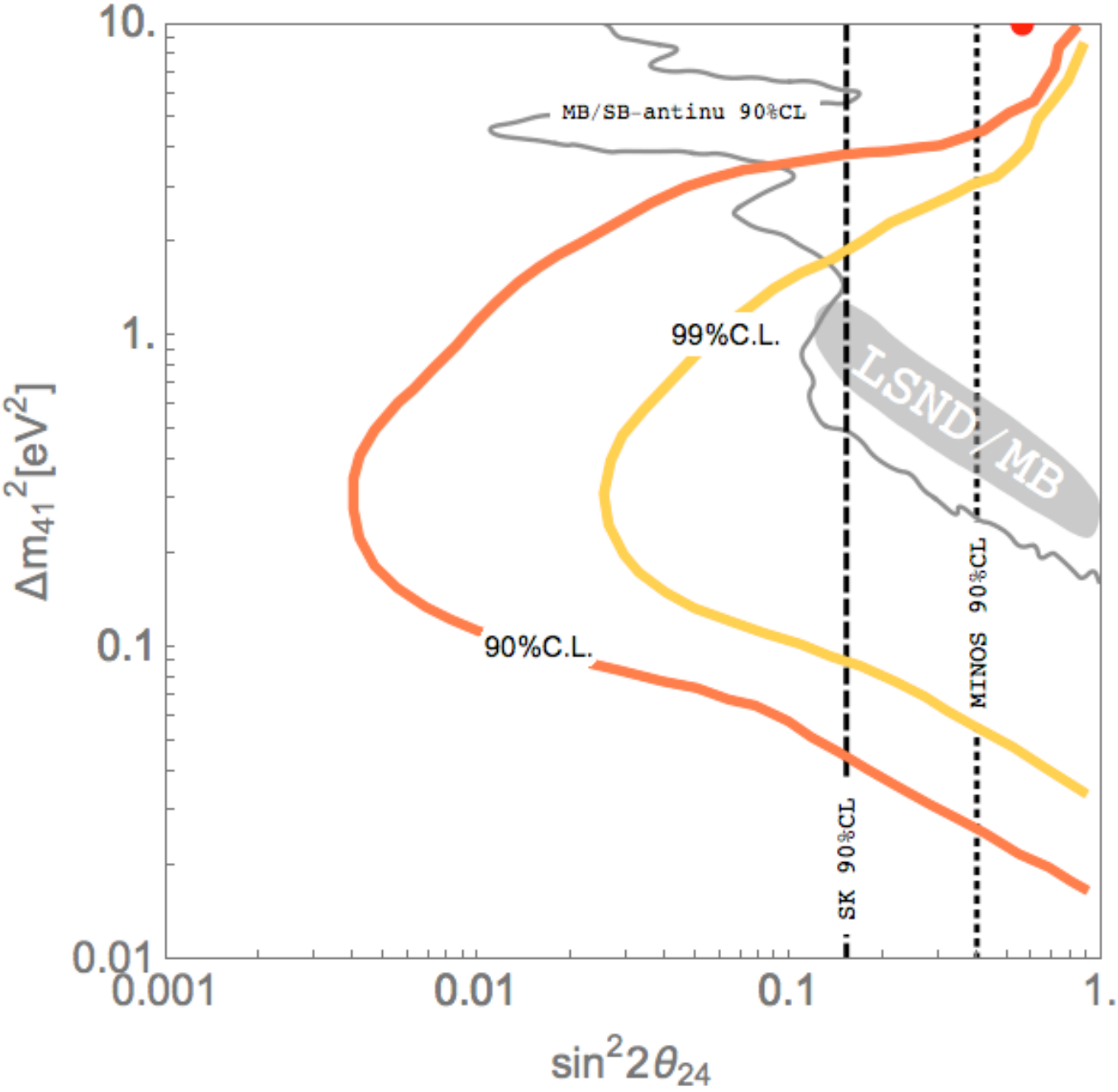


eV sterile neutrino → Earth MSW resonance for TeV neutrinos

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

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




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

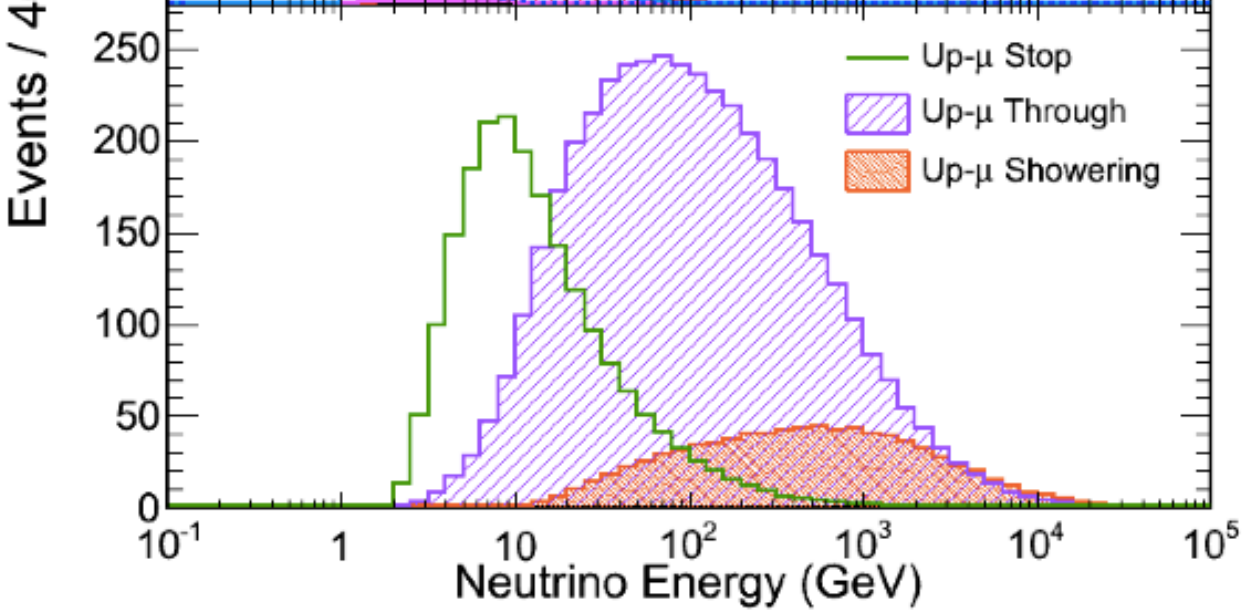
Conclusions

- 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)



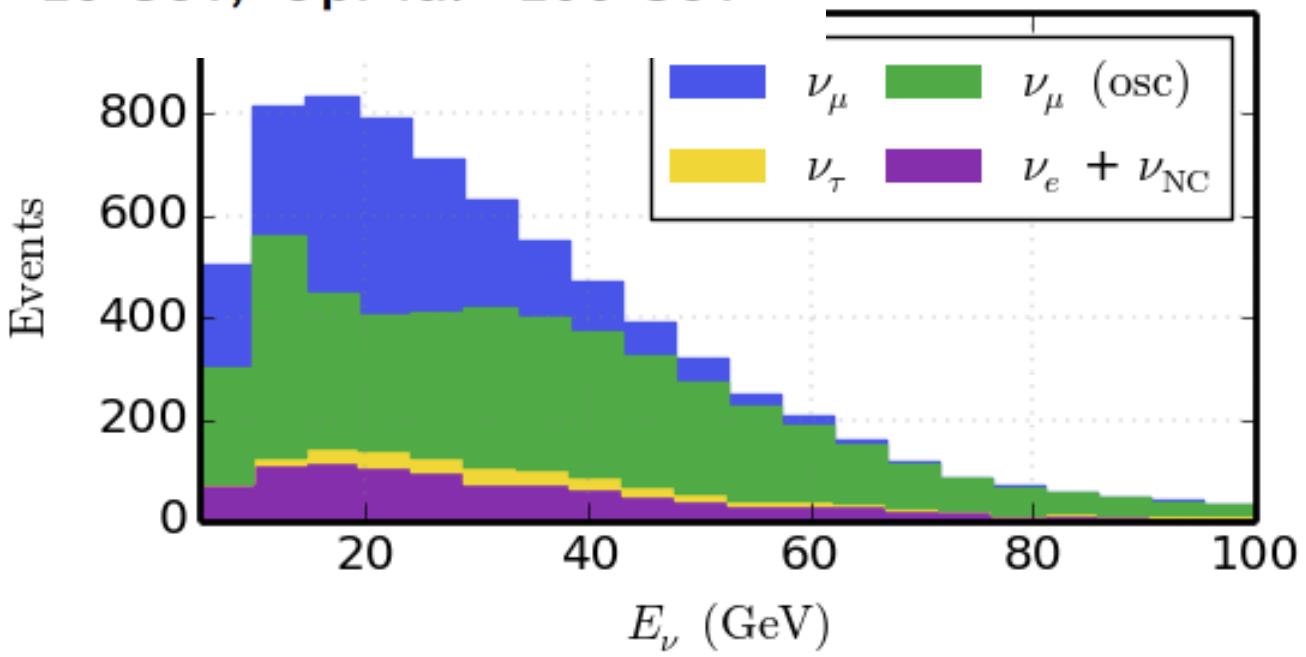
SuperK

~ 1 GeV

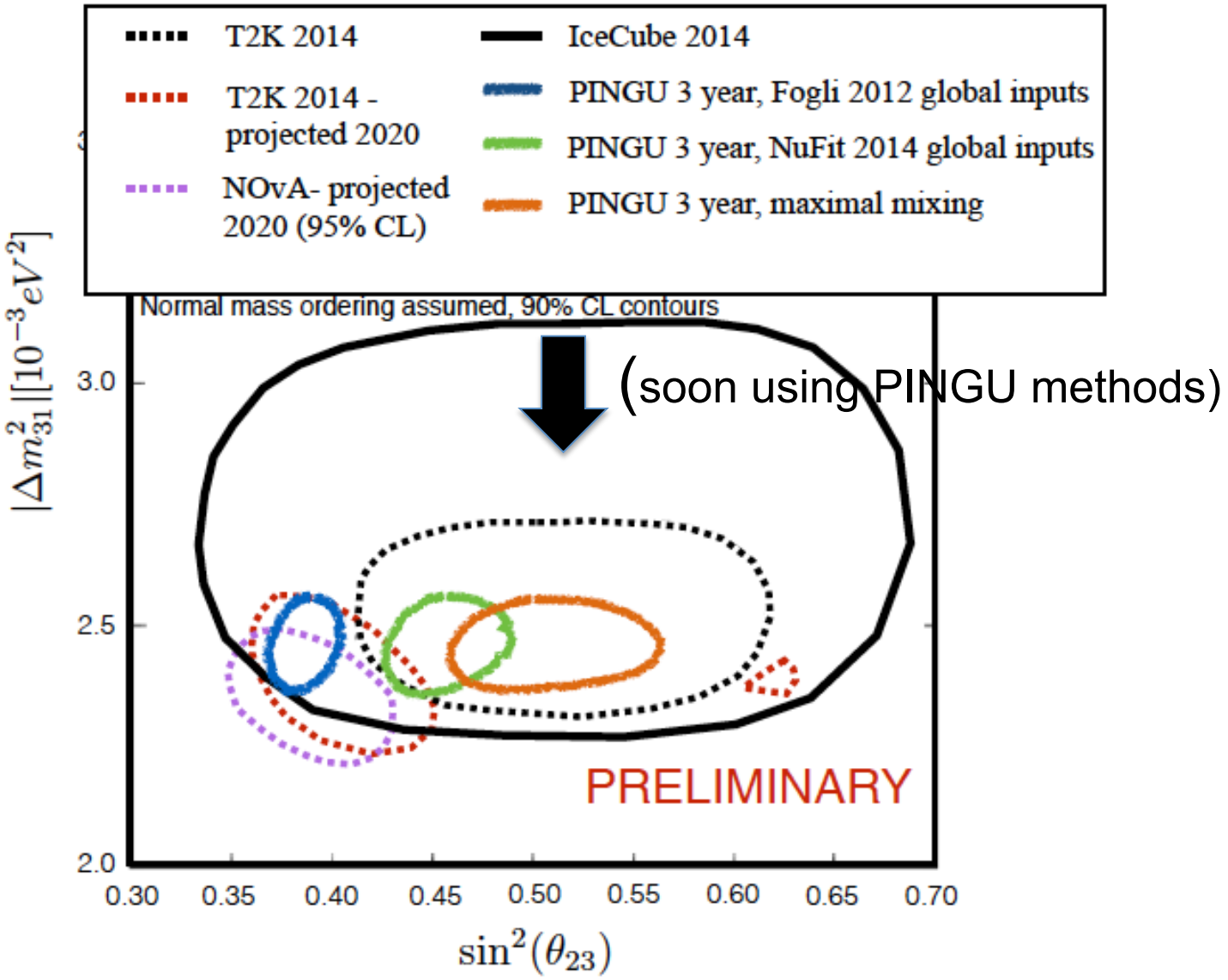
- Average energies
  - FC: ~1 GeV , PC: ~10 GeV, UpMu:~ 100 GeV

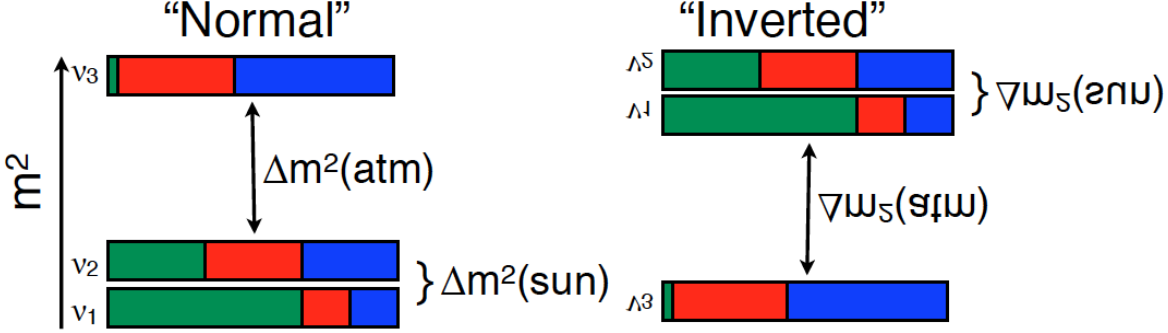
IceCube

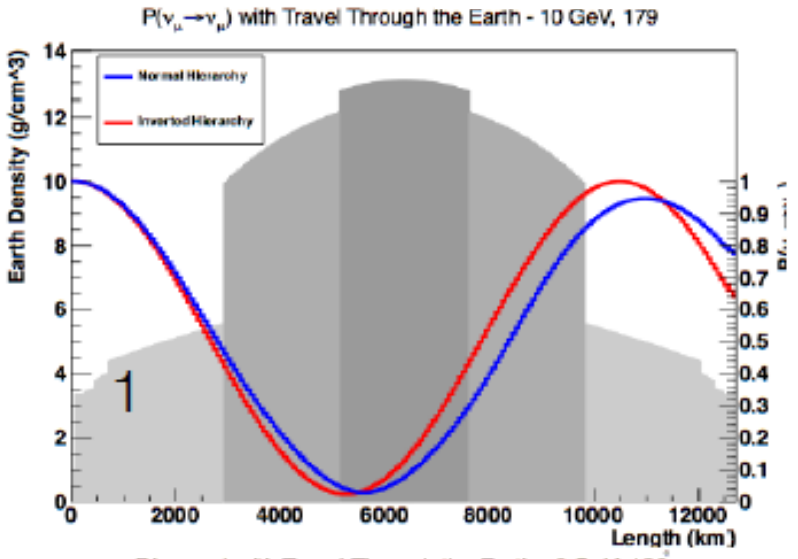
6 GeV < E_{reco} < 56 GeV

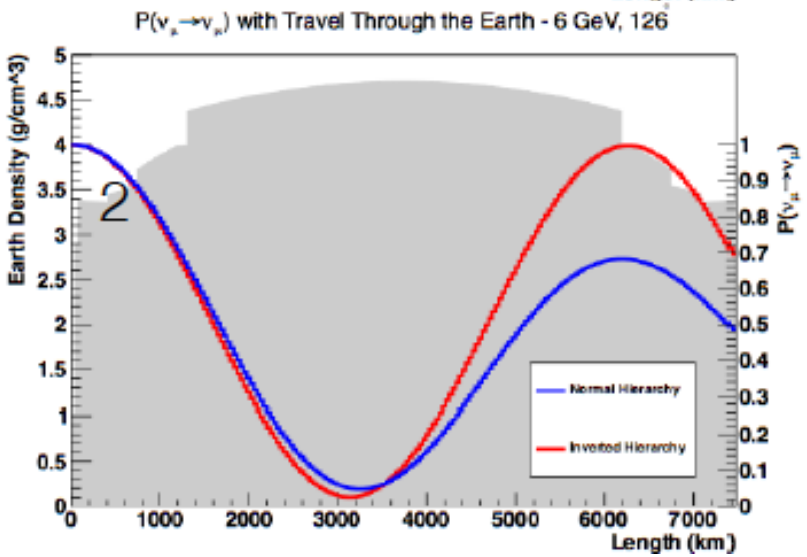


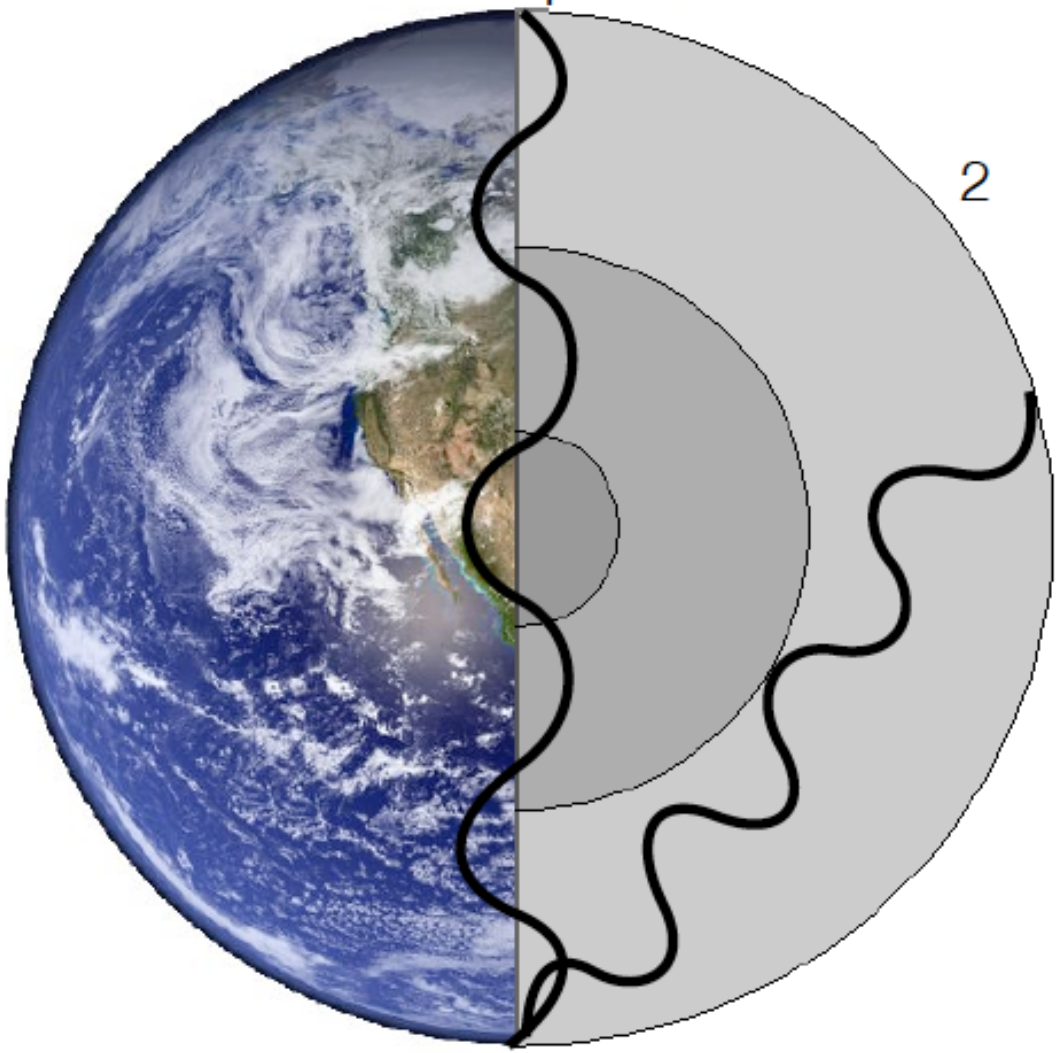
and with PINGU…




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


1
2

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