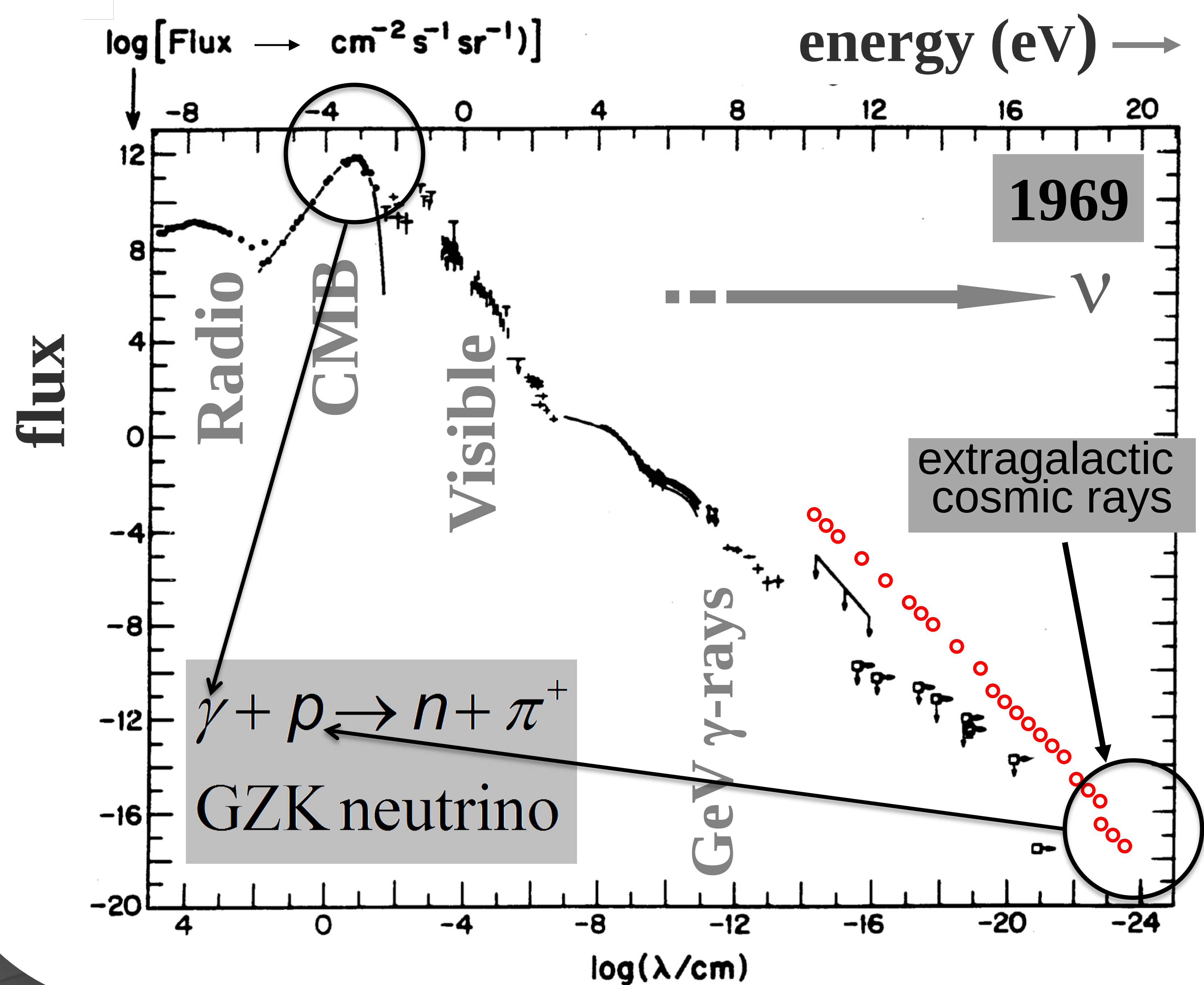
IceCube

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) →
1969
flux
Radio
CMB
Visible
GeV γ-rays
ν
extragalactic cosmic rays
$\gamma + p \rightarrow n + \pi^{+}$
GZK neutrino
log(λ/cm)

cosmic rays interact with the microwave background

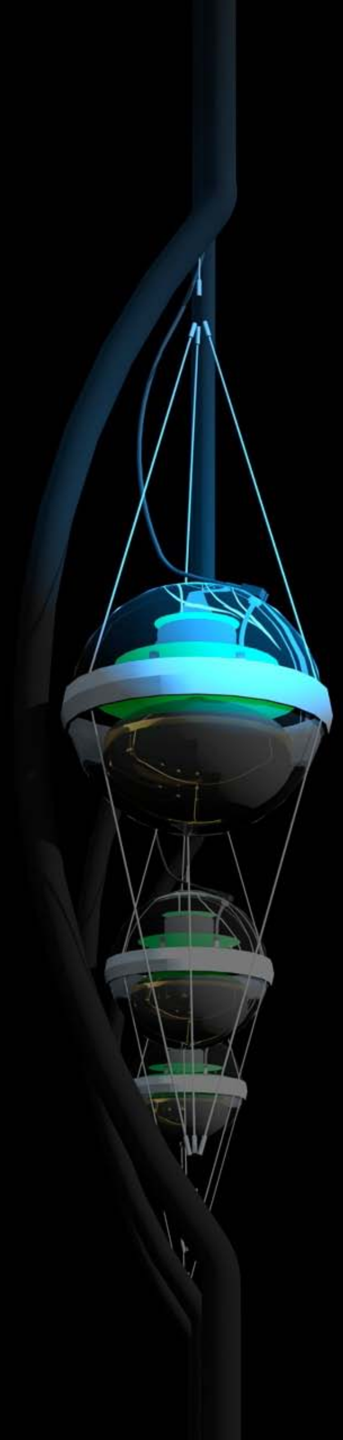
$$p+\gamma \rightarrow n+\pi^{+} \; and \; p+\pi^{0}$$

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!



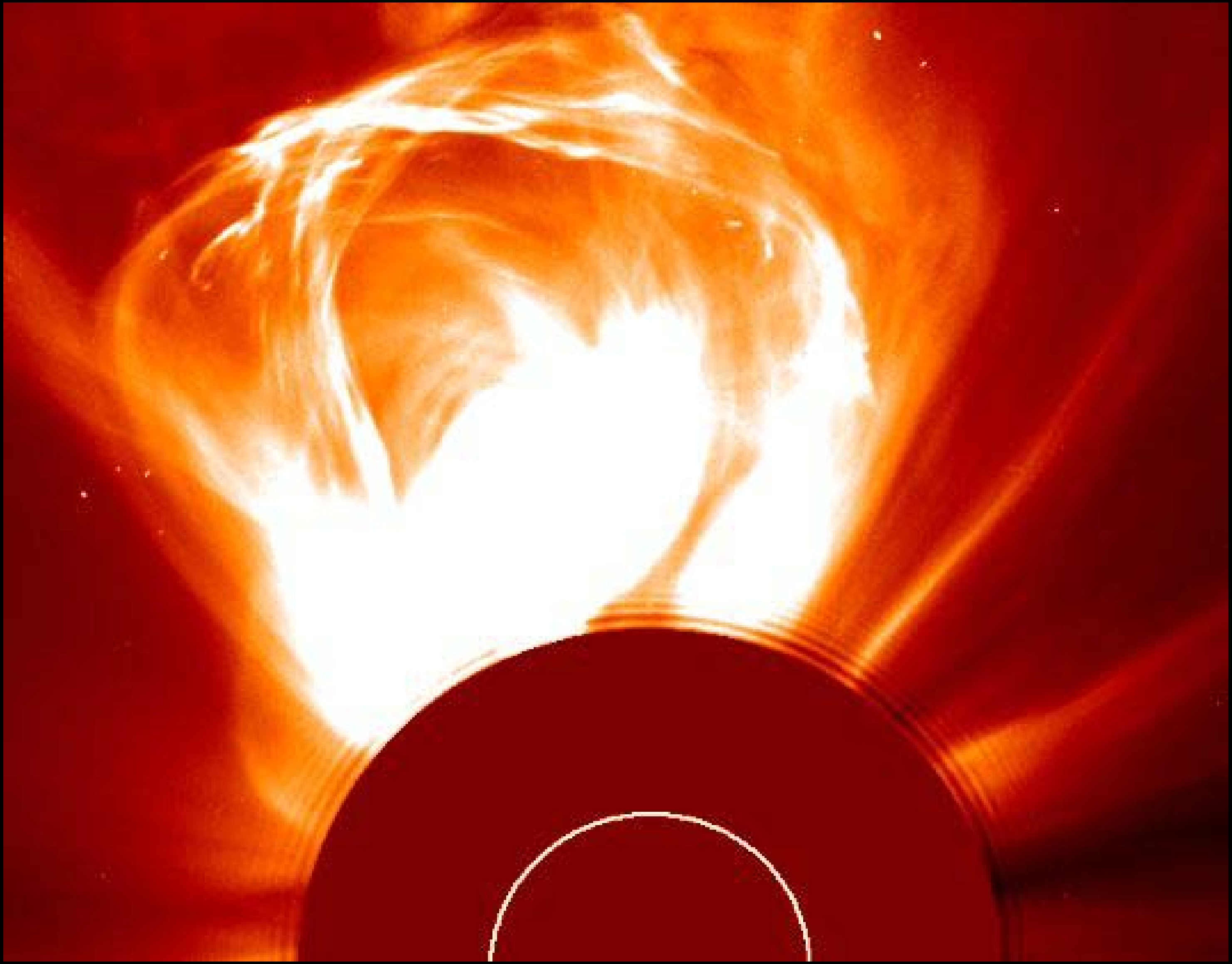
IceCube

francis halzen

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

IceCube.wisc.edu

the sun constructs an accelerator



- accelerator must contain the particles

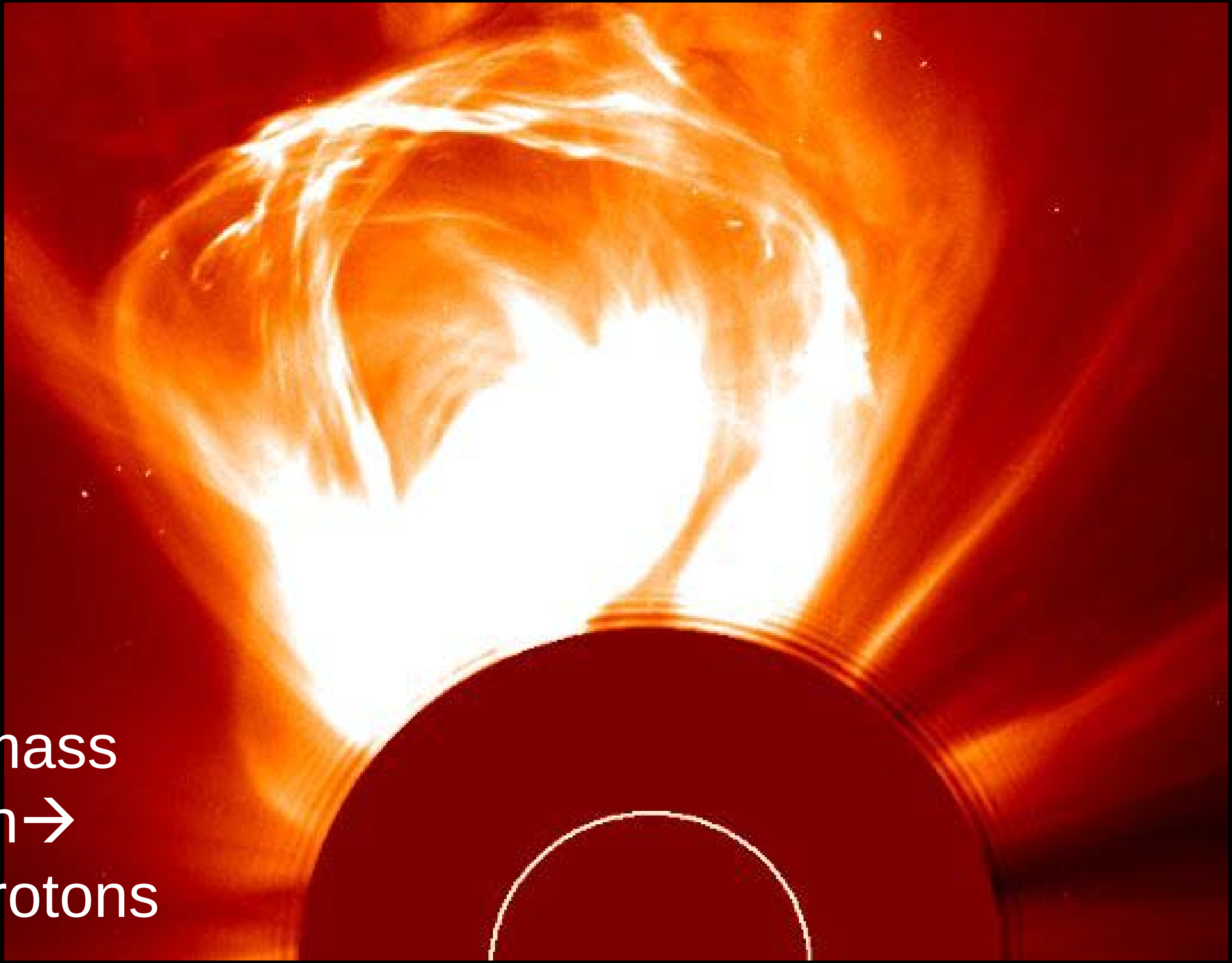
$$R_{gyro}\left(=\frac{E}{\mathrm{v}qB}\right)\leq R$$

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

challenges of cosmic ray astrophysics:

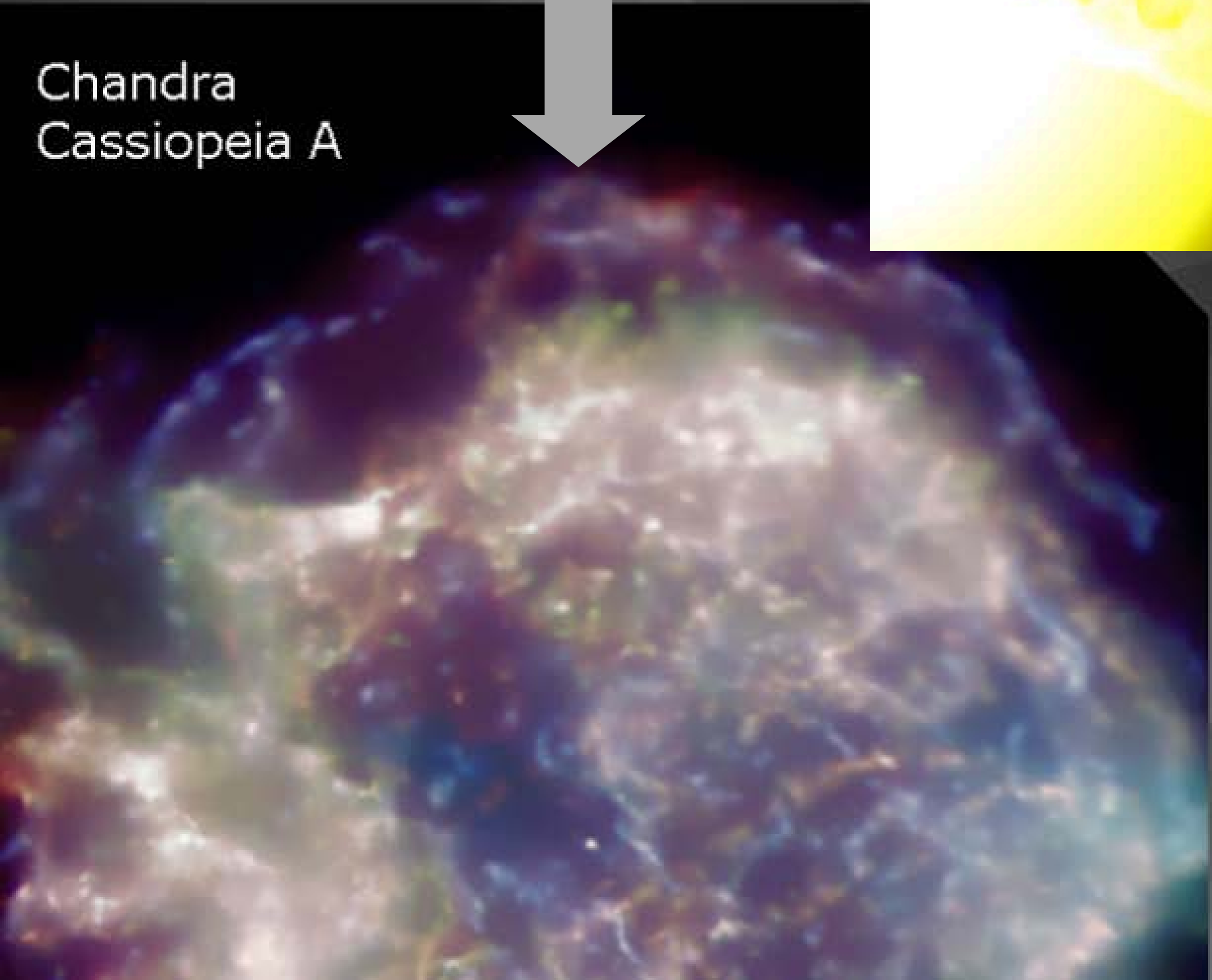
- dimensional analysis, difficult to satisfy
- accelerator luminosity is high as well

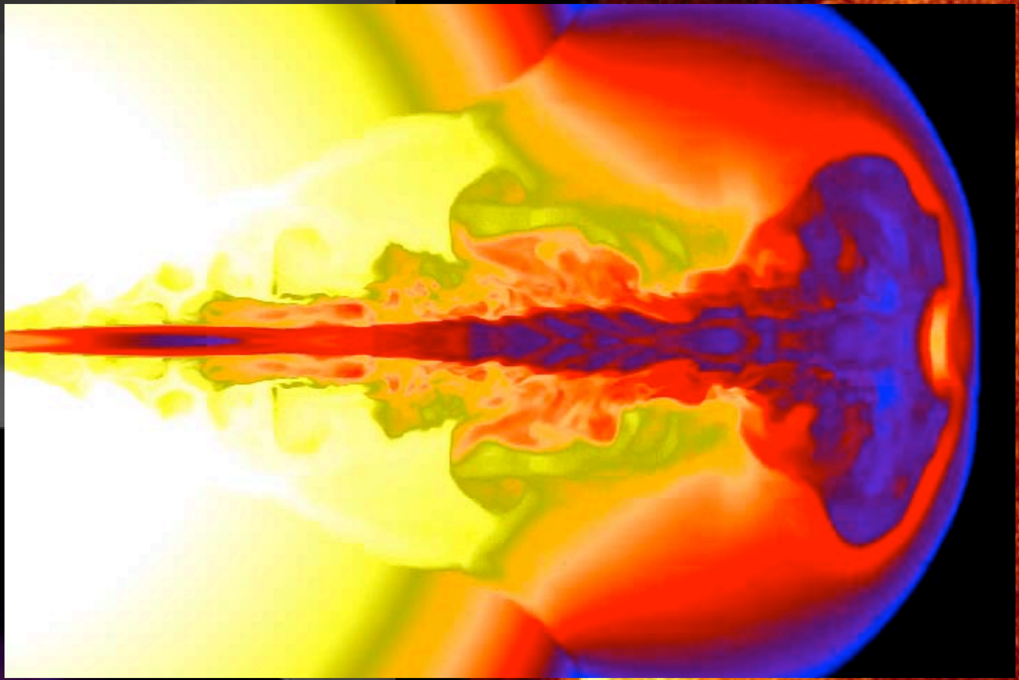
the sun constructs an accelerator



coronal mass ejection→
10 GeV protons

supernova
remnants

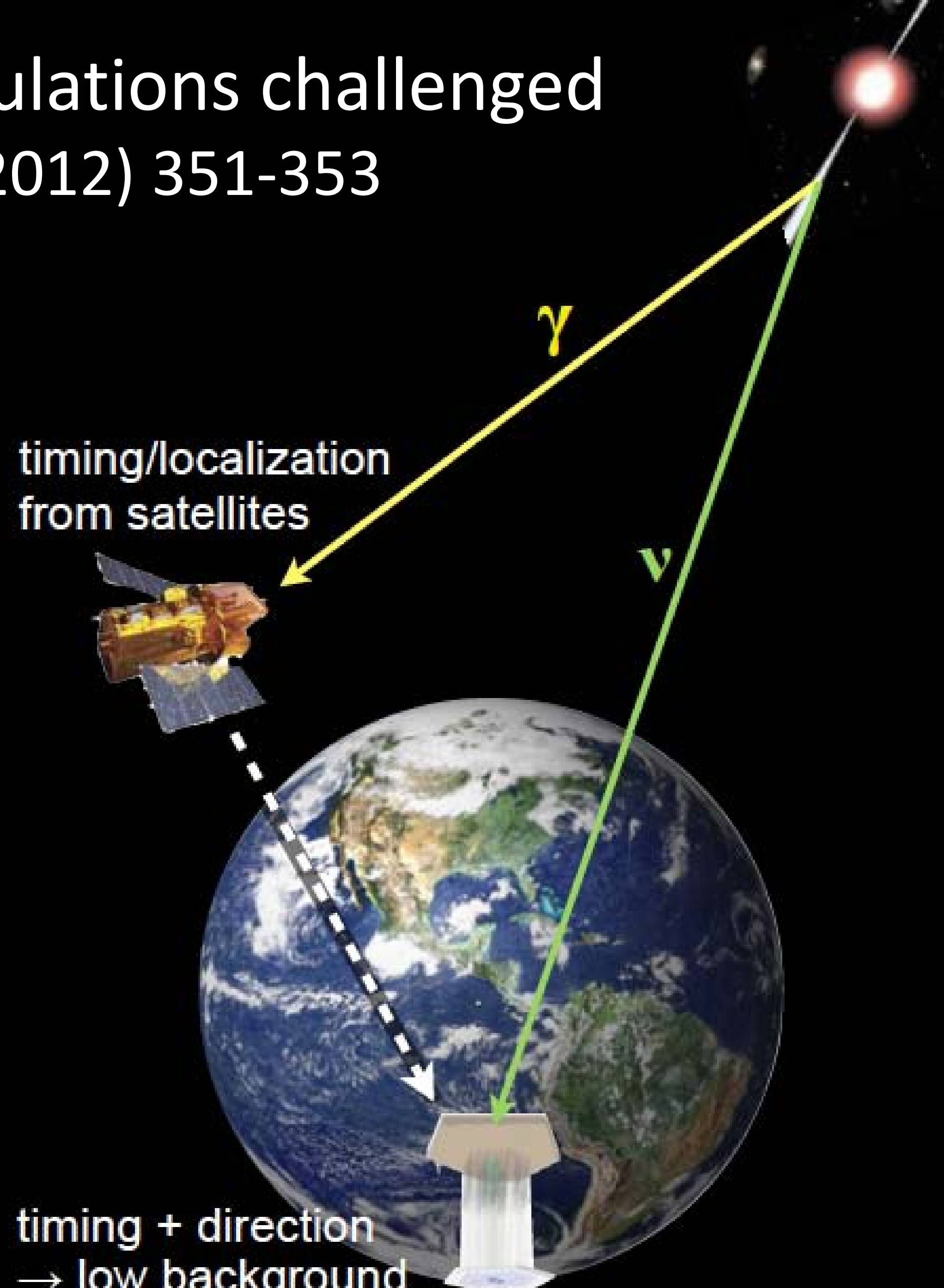


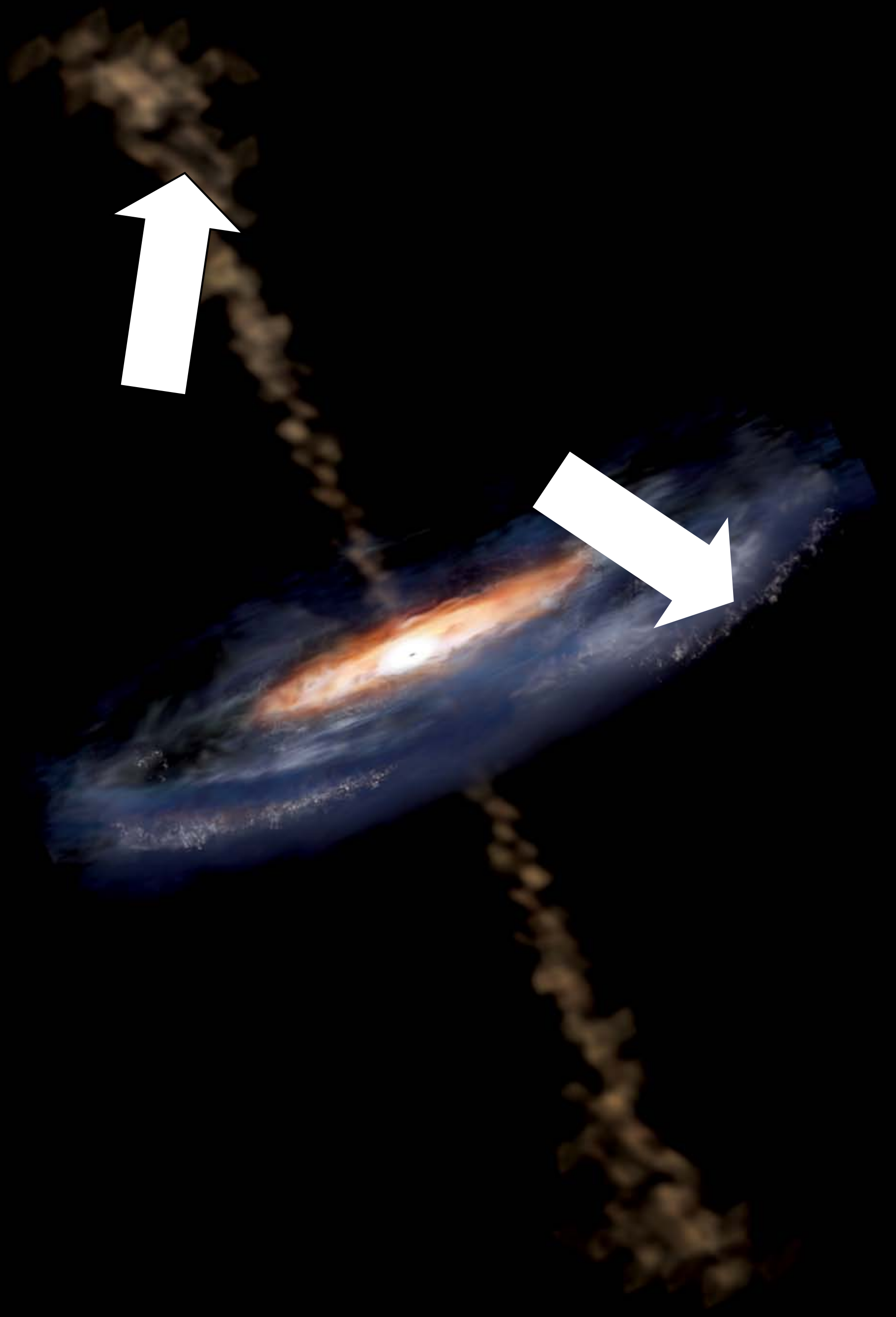


gamma
ray
bursts

fireball calculations challenged

Nature 484 (2012) 351-353

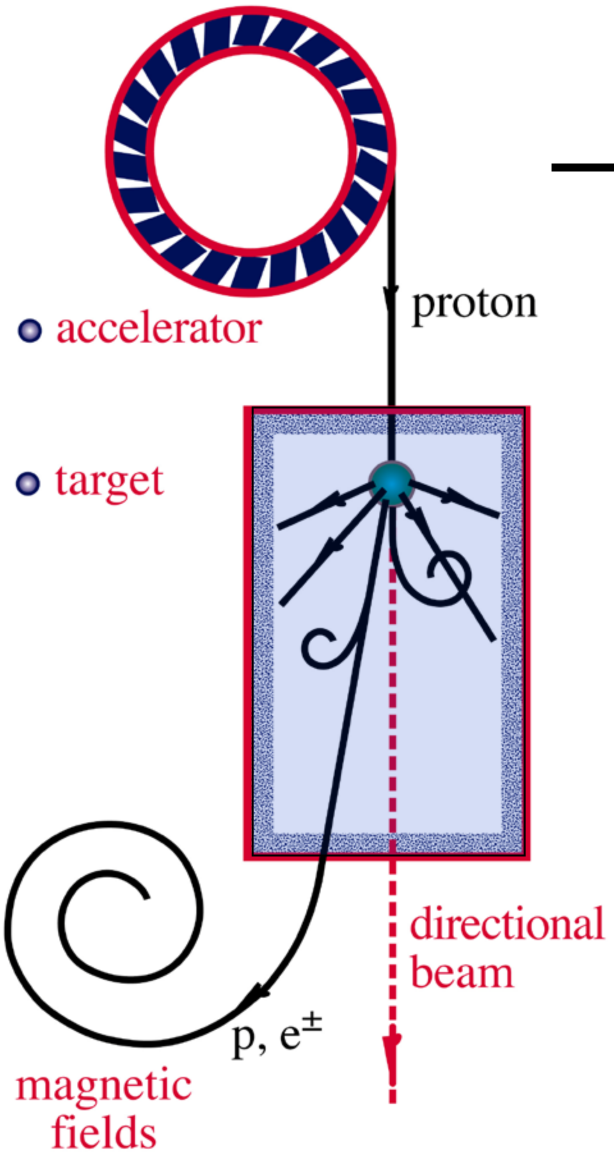




active galaxy

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

$\rightarrow p + \pi^0$

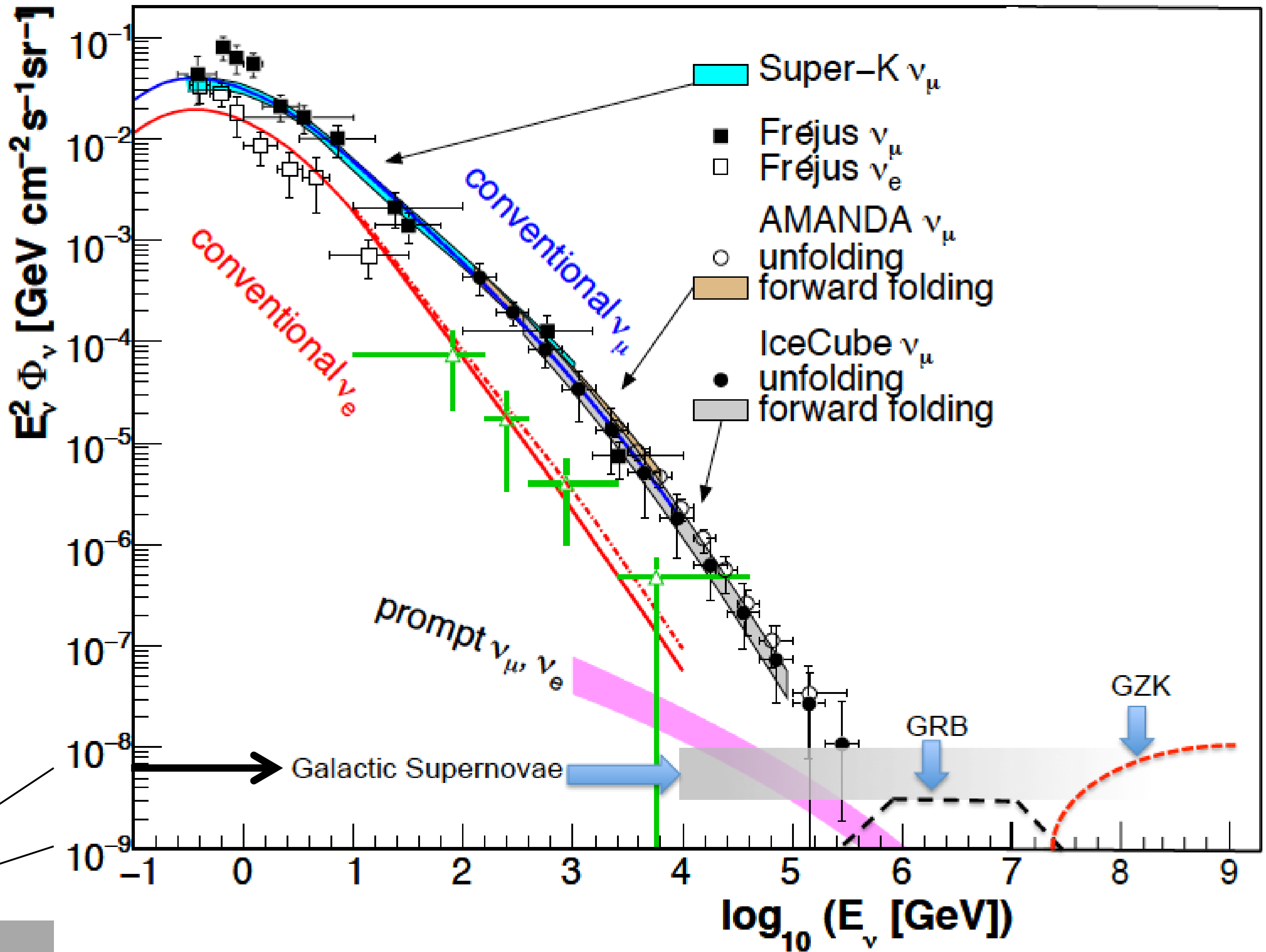
~ cosmic ray + gamma

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

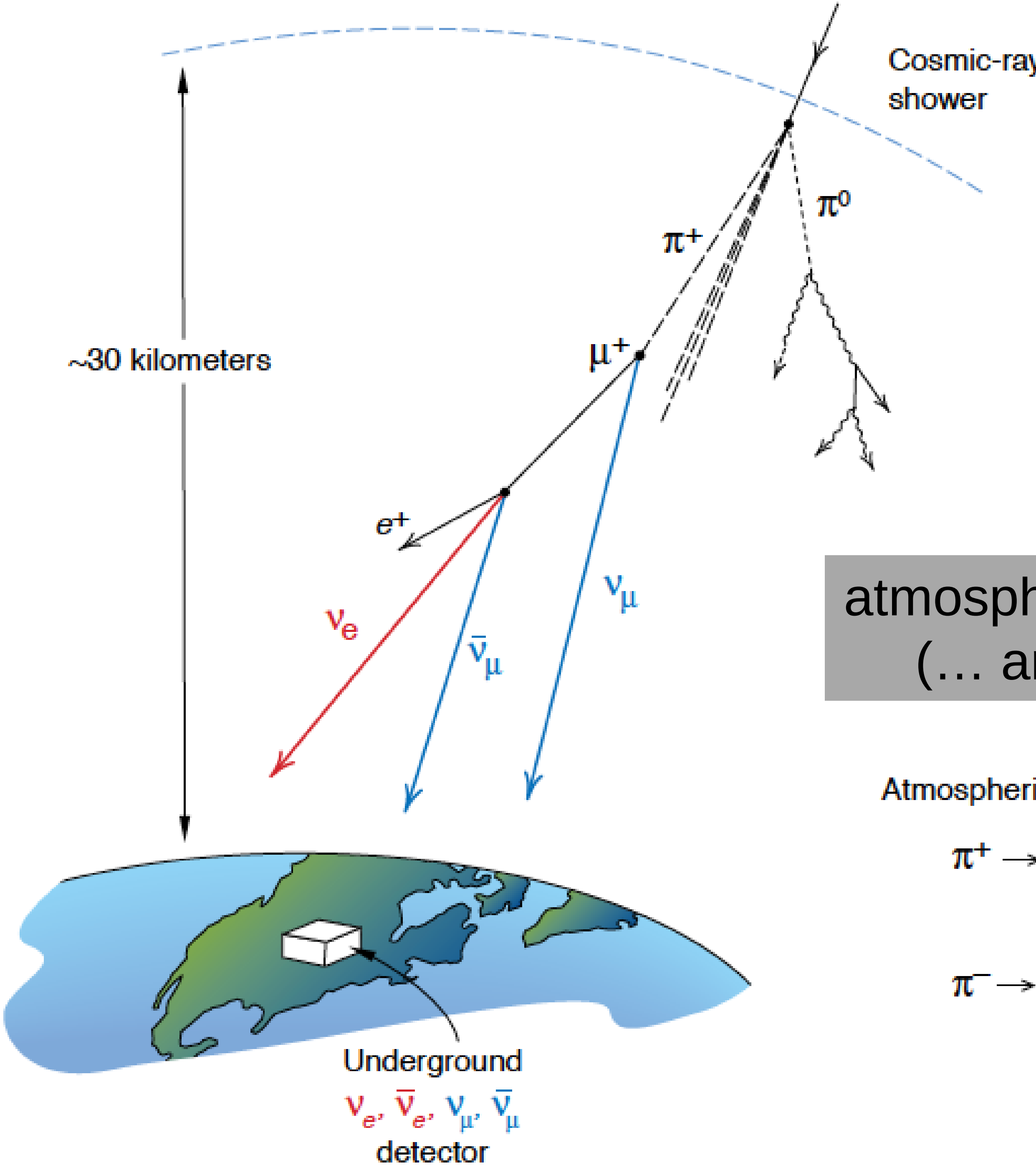


atmospheric

cosmic

100 TeV

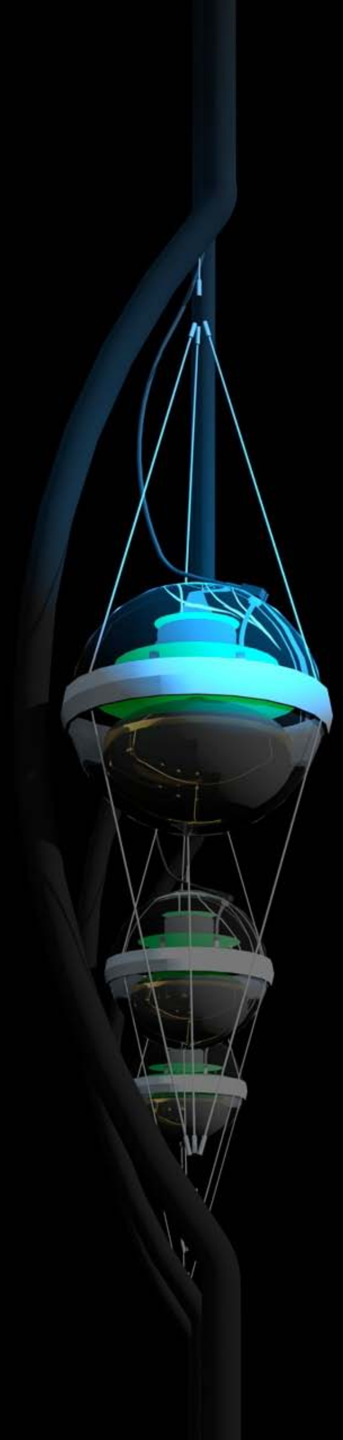
atmospheric neutrinos (… and muons!)



Atmospheric neutrino source

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

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

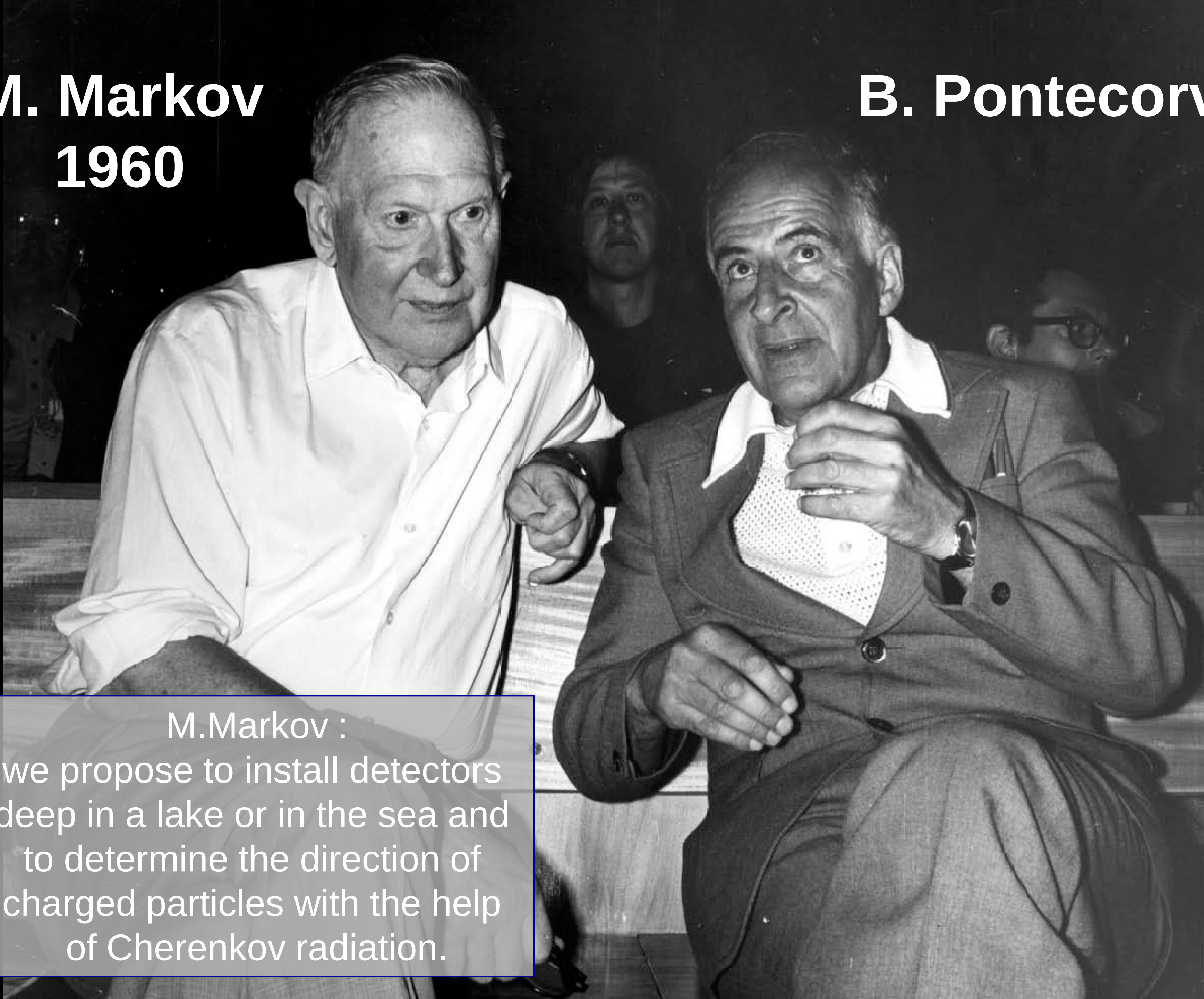


IceCube: the discovery of cosmic neutrinos

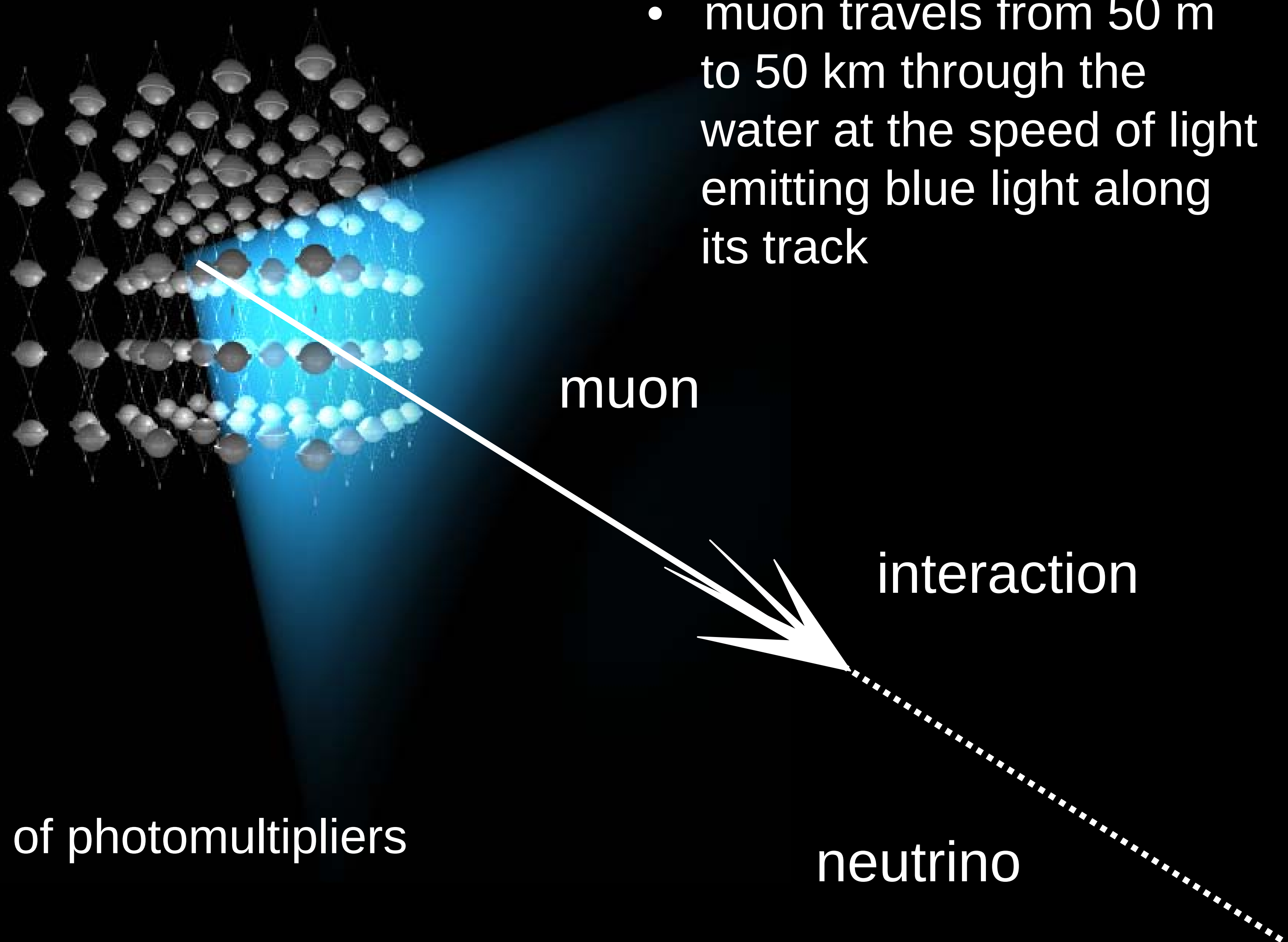
francis halzen

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

IceCube.wisc.edu


M. Markov
1960
B. Pontecorvo
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.

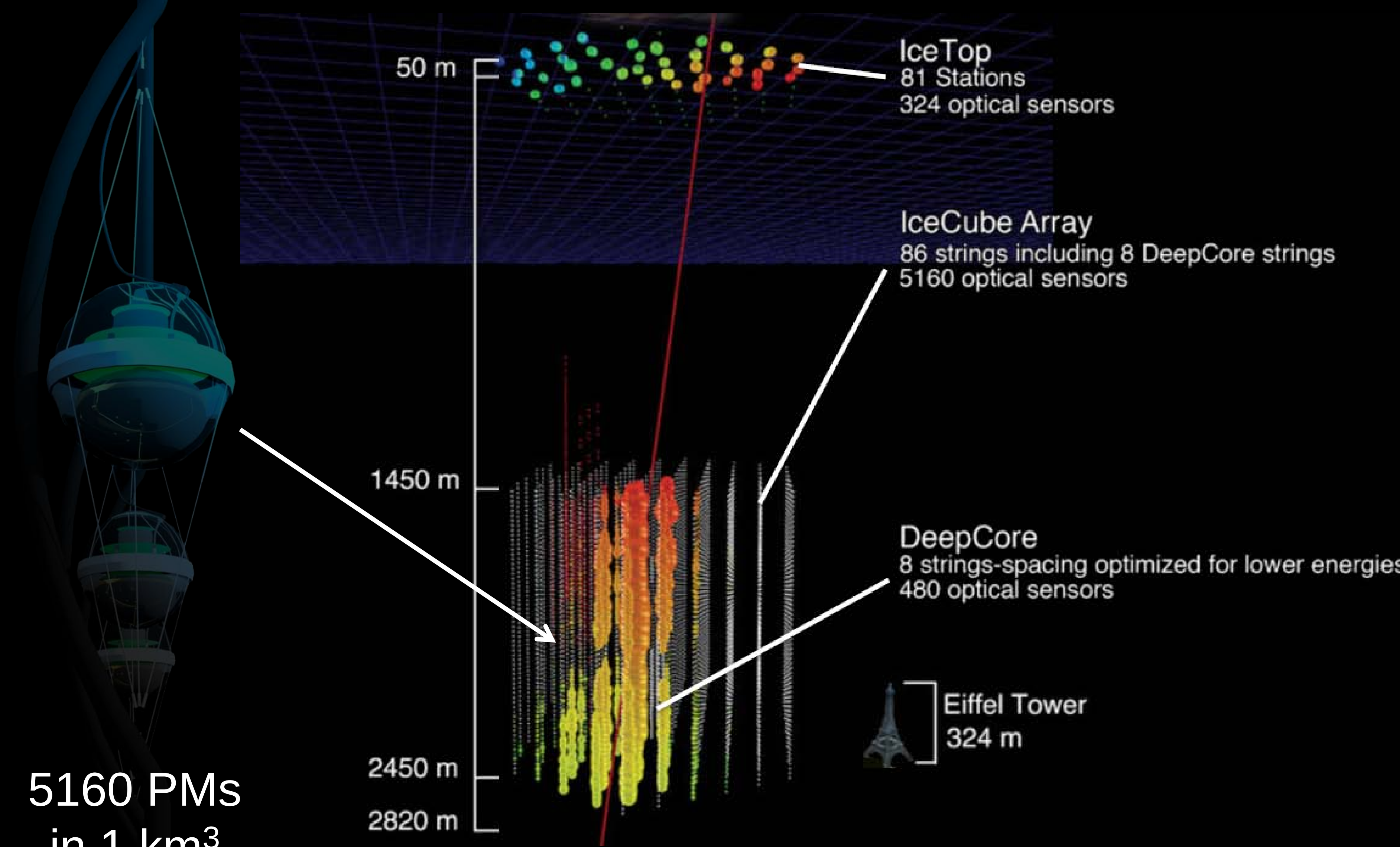
- shielded and optically transparent medium
- muon travels from 50 m to 50 km through the water at the speed of light emitting blue light along its track



- lattice of photomultipliers

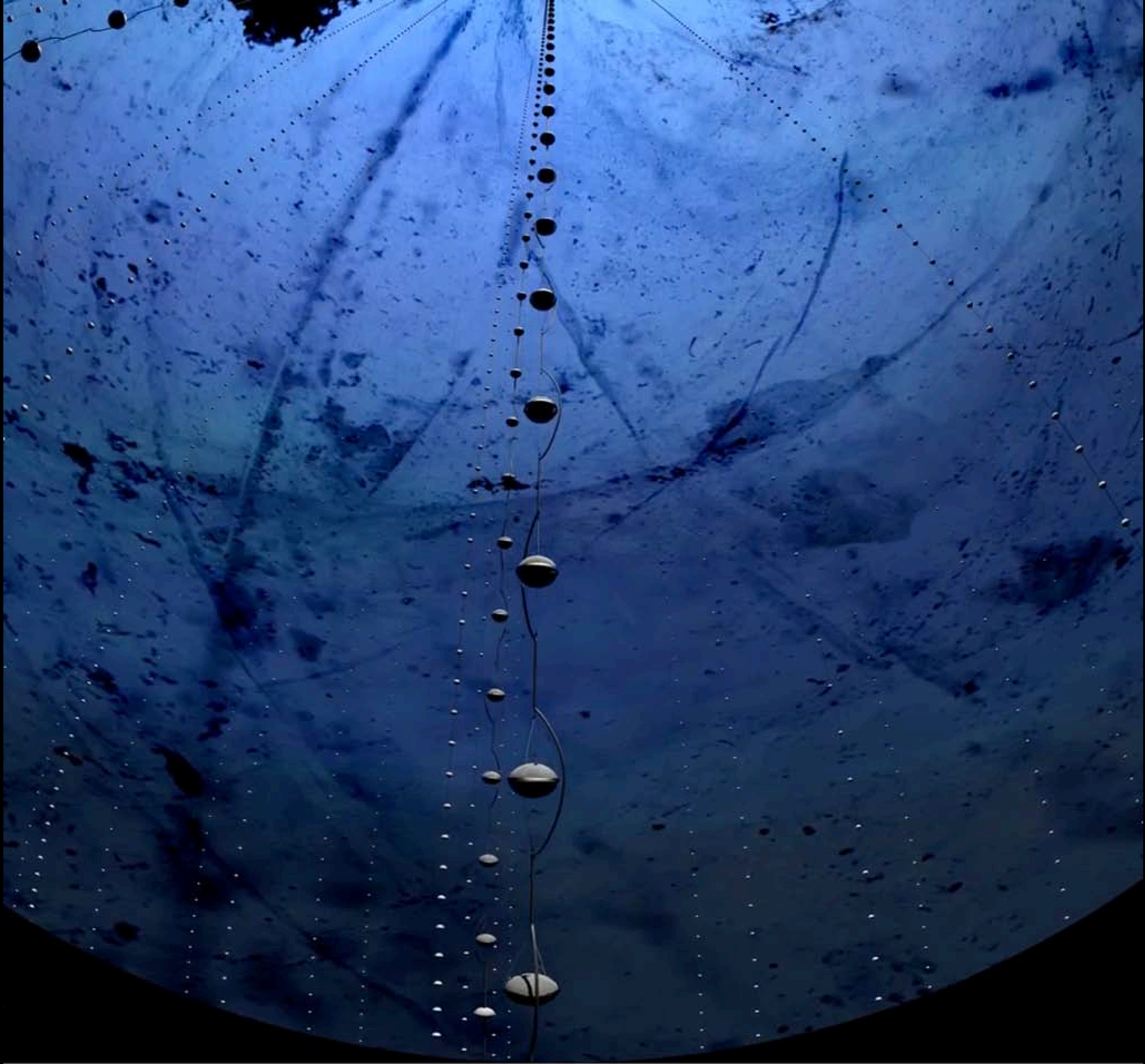

ultra-transparent ice below 1.5 km

IceCube



5160 PMs
in 1 km^3

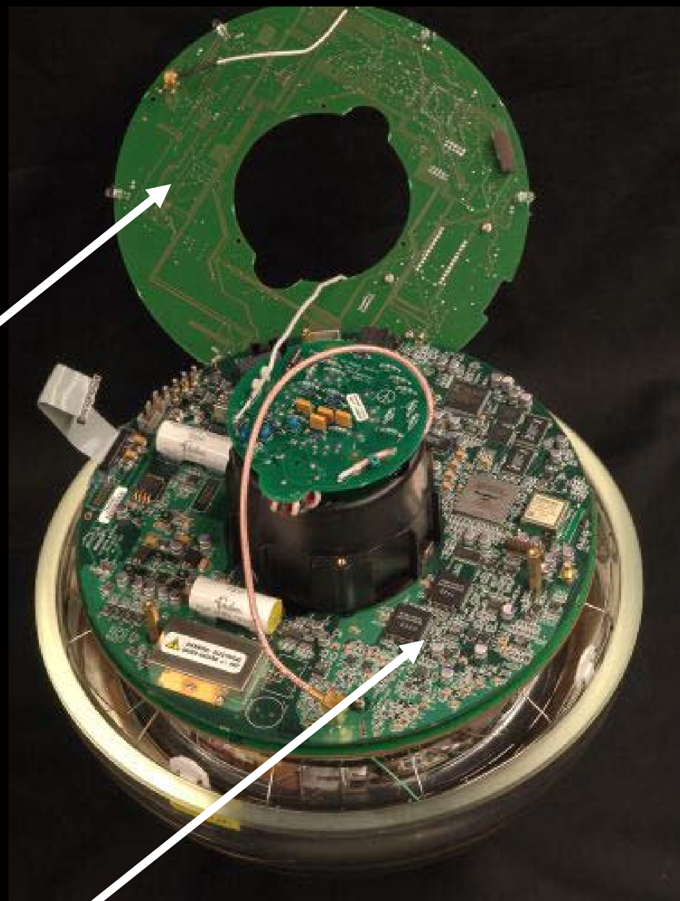
photomultiplier tube -10 inch



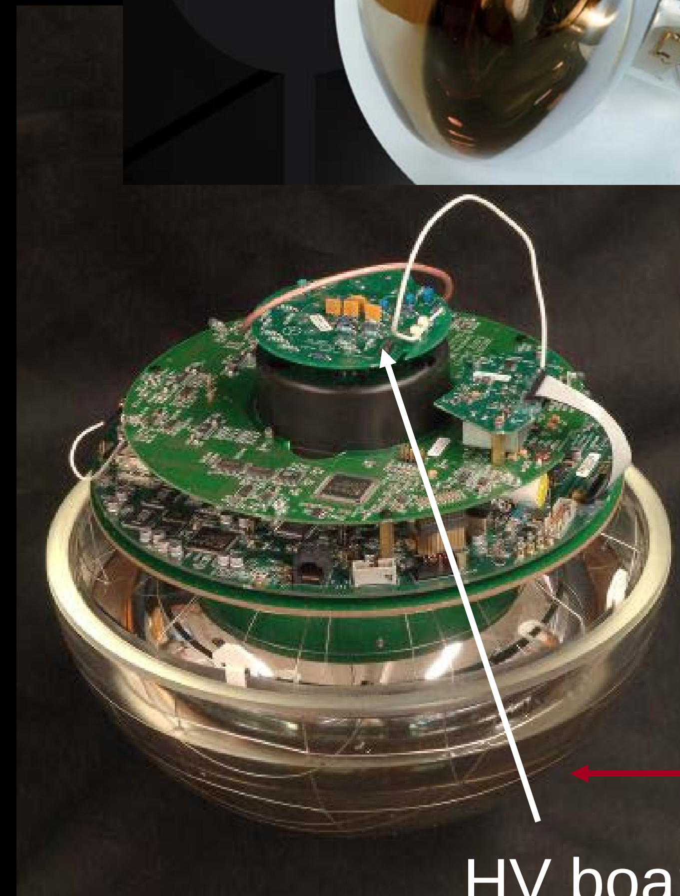
architecture of independent DOMs

10 inch pmt

LED flasher board

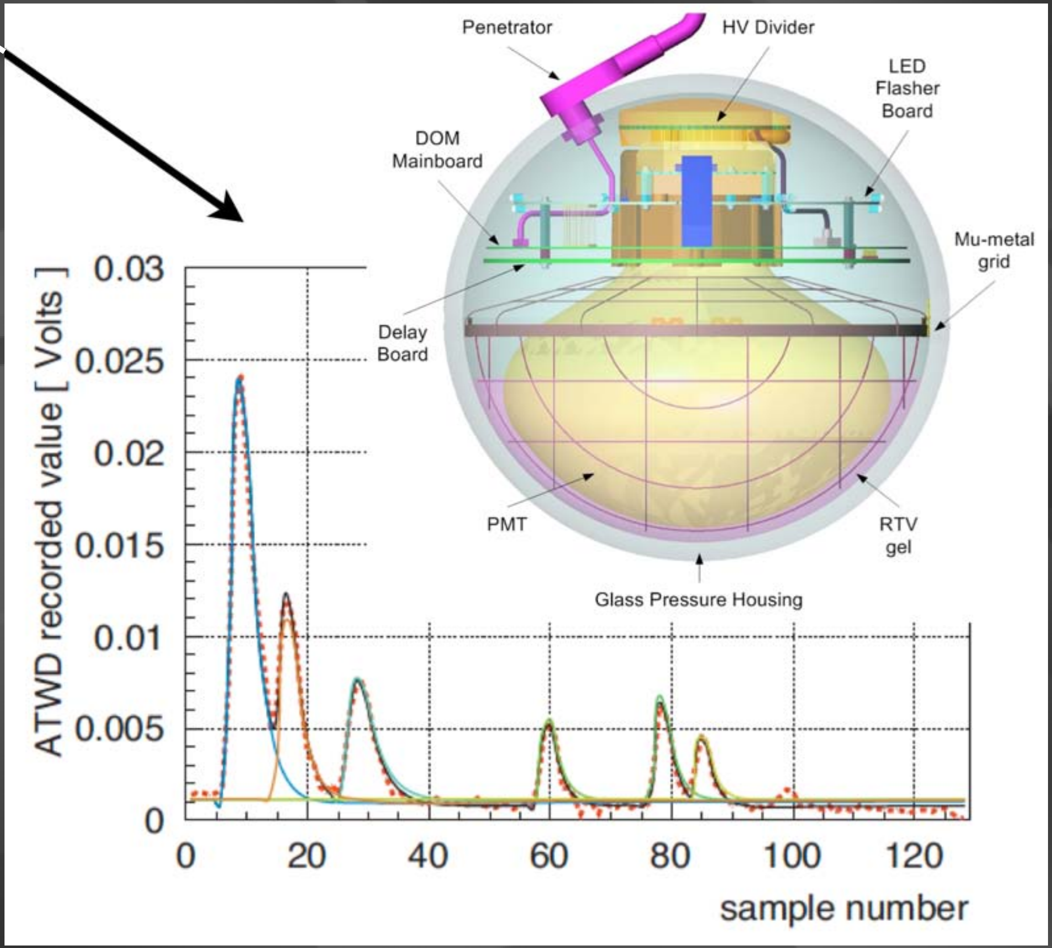


main board

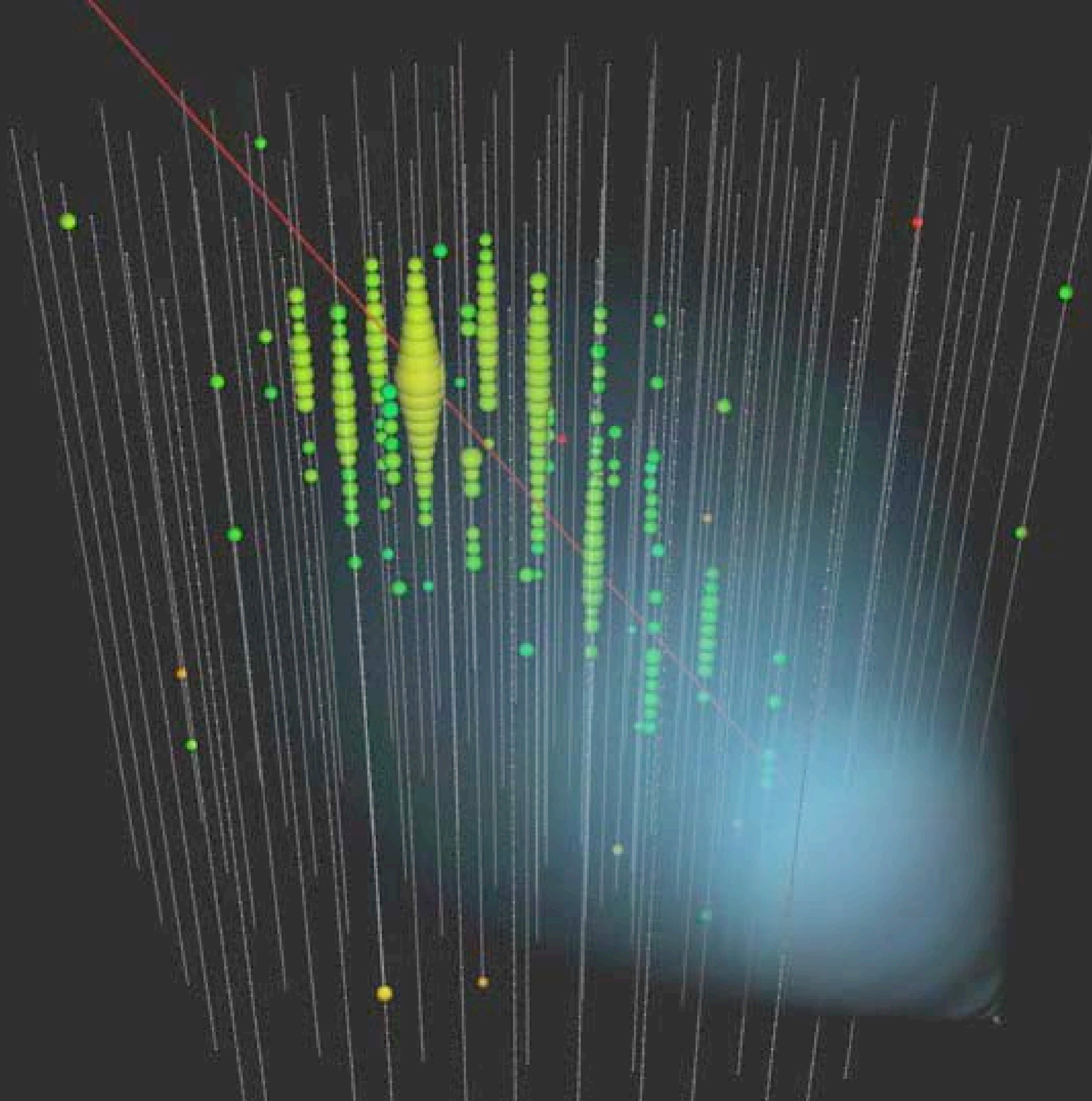


HV board

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

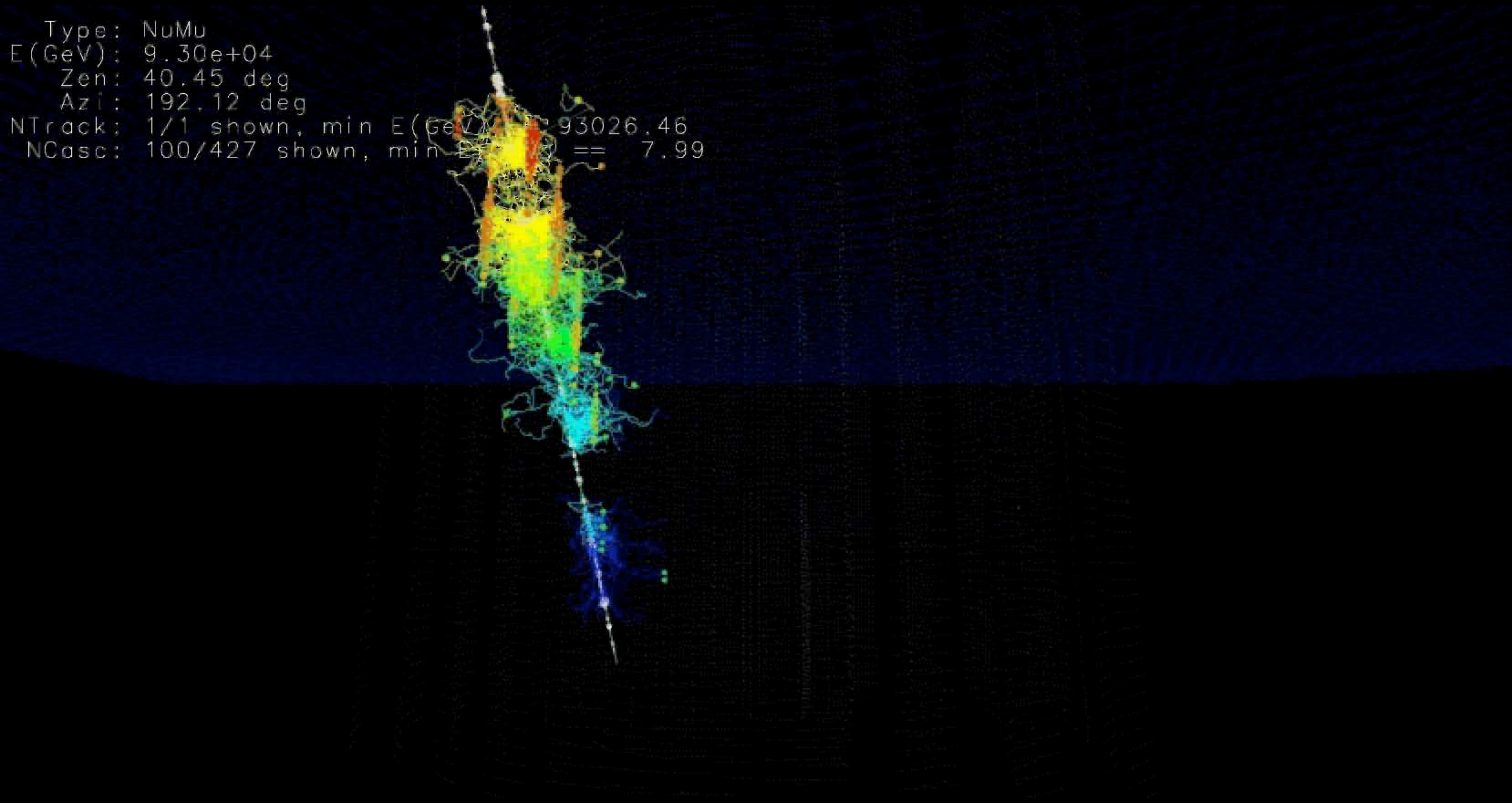


…time stamps them with 2 nanoseconds precision, and sends them to a computer that sorts them events…

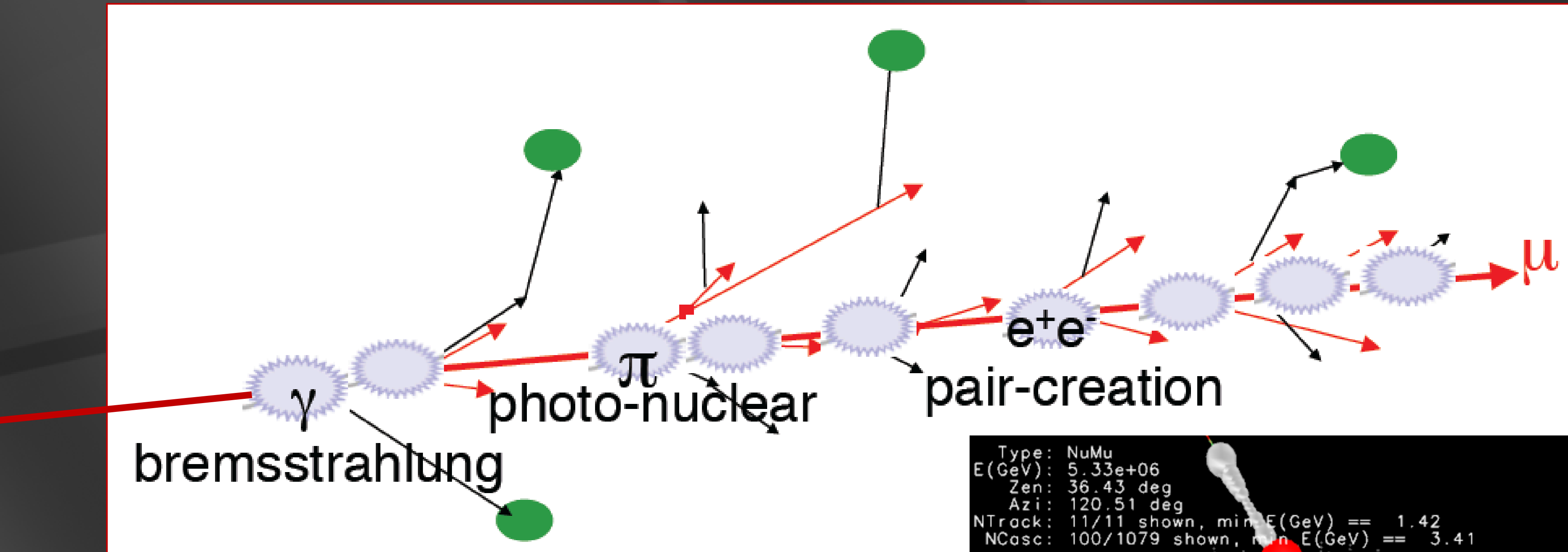


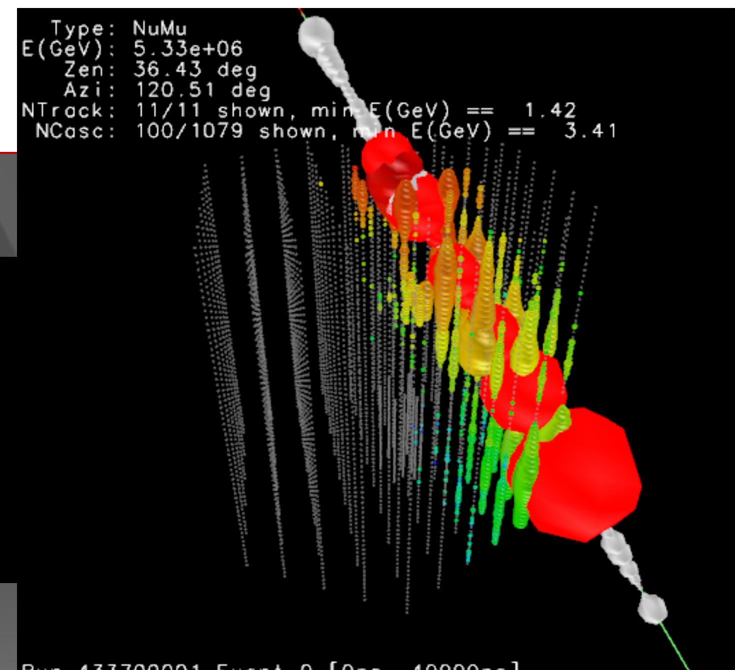
muon track: time is color; number of photons is energy

93 TeV muon: light ~ energy

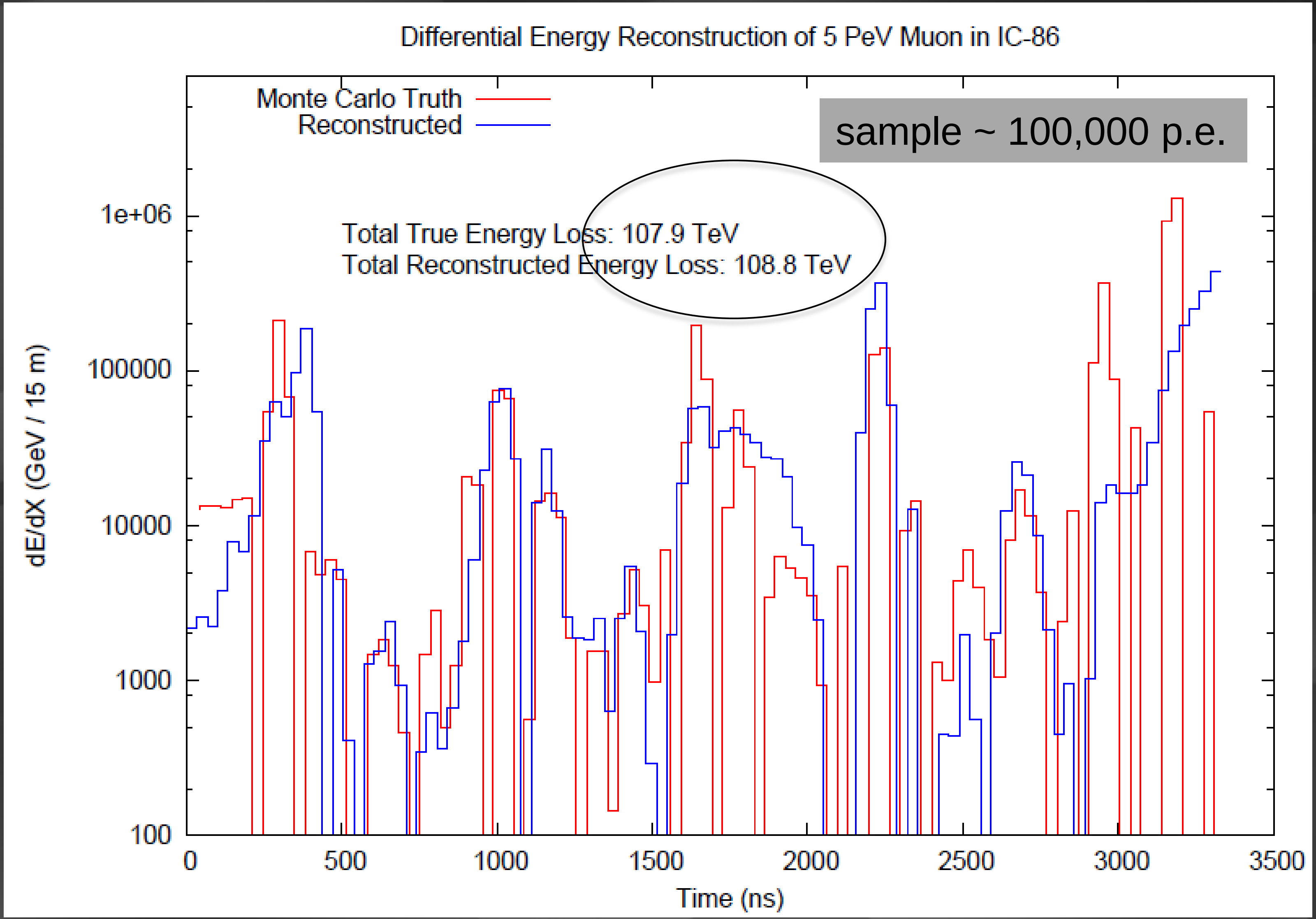


energy measurement (> 1 TeV)





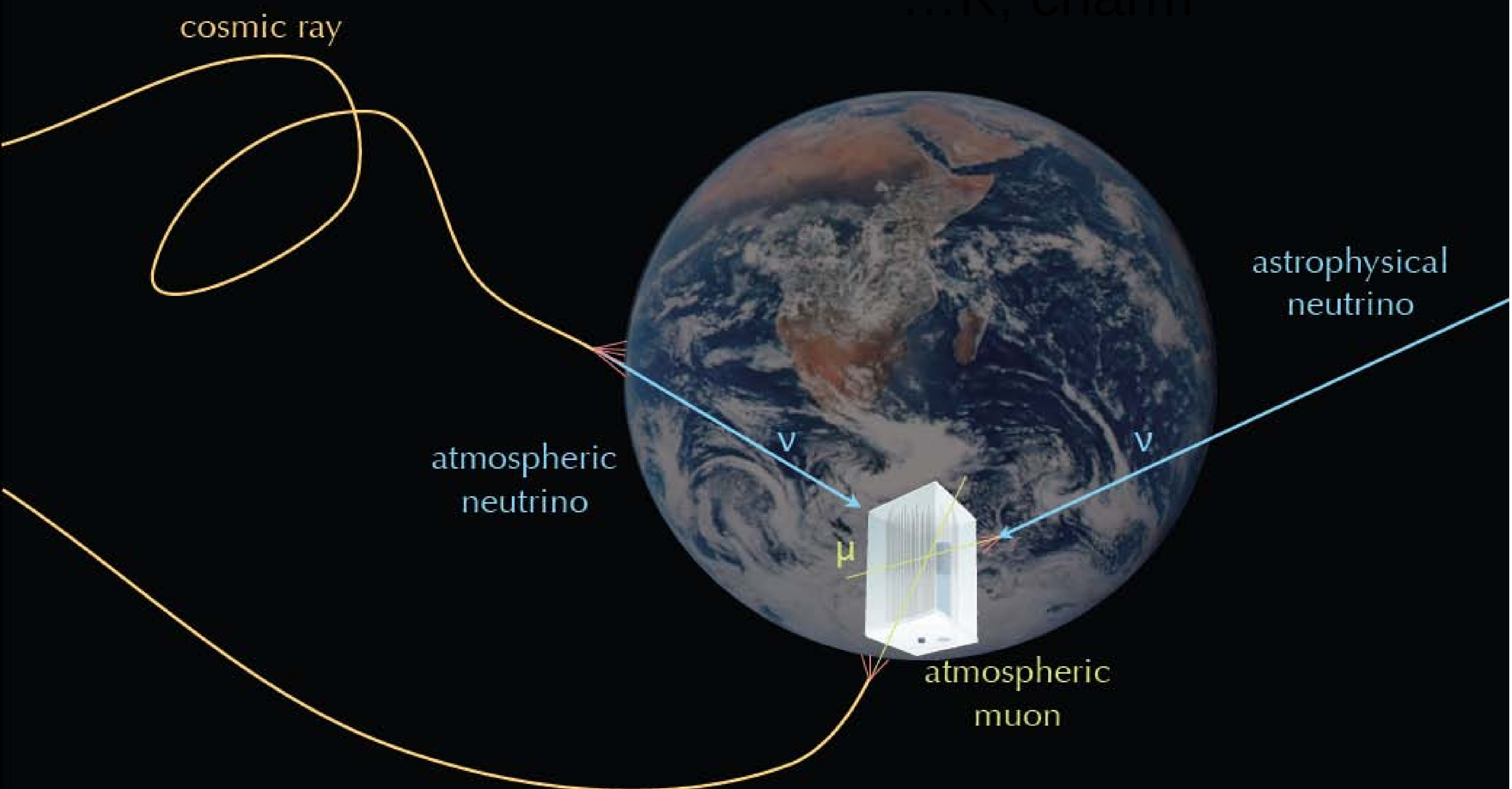
convert the amount of light emitted to measurement of the muon energy (number of optical modules, number of photons, dE/dx, …)

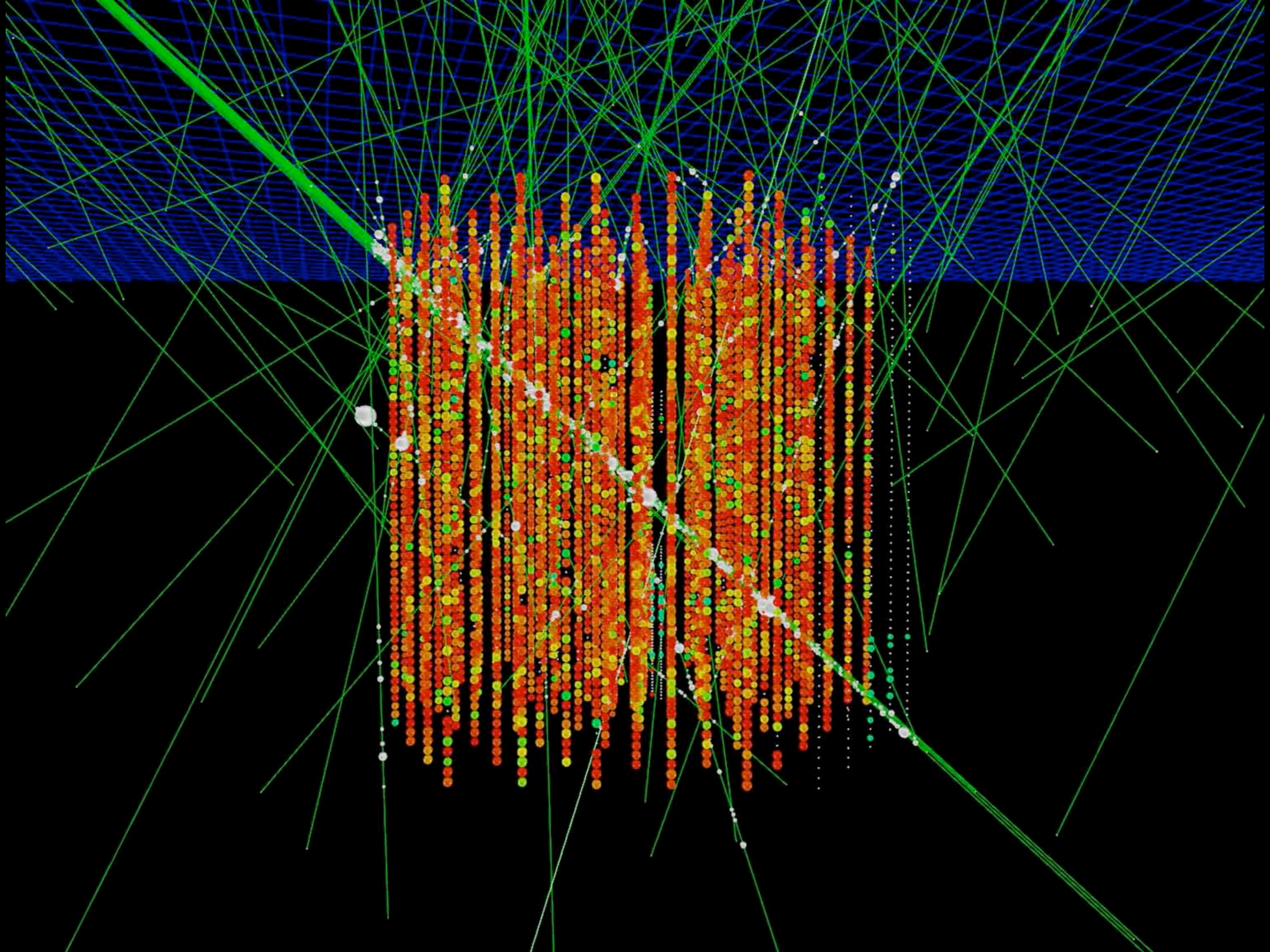


1.1 km

improved angular and energy resolution

Signals and Backgrounds





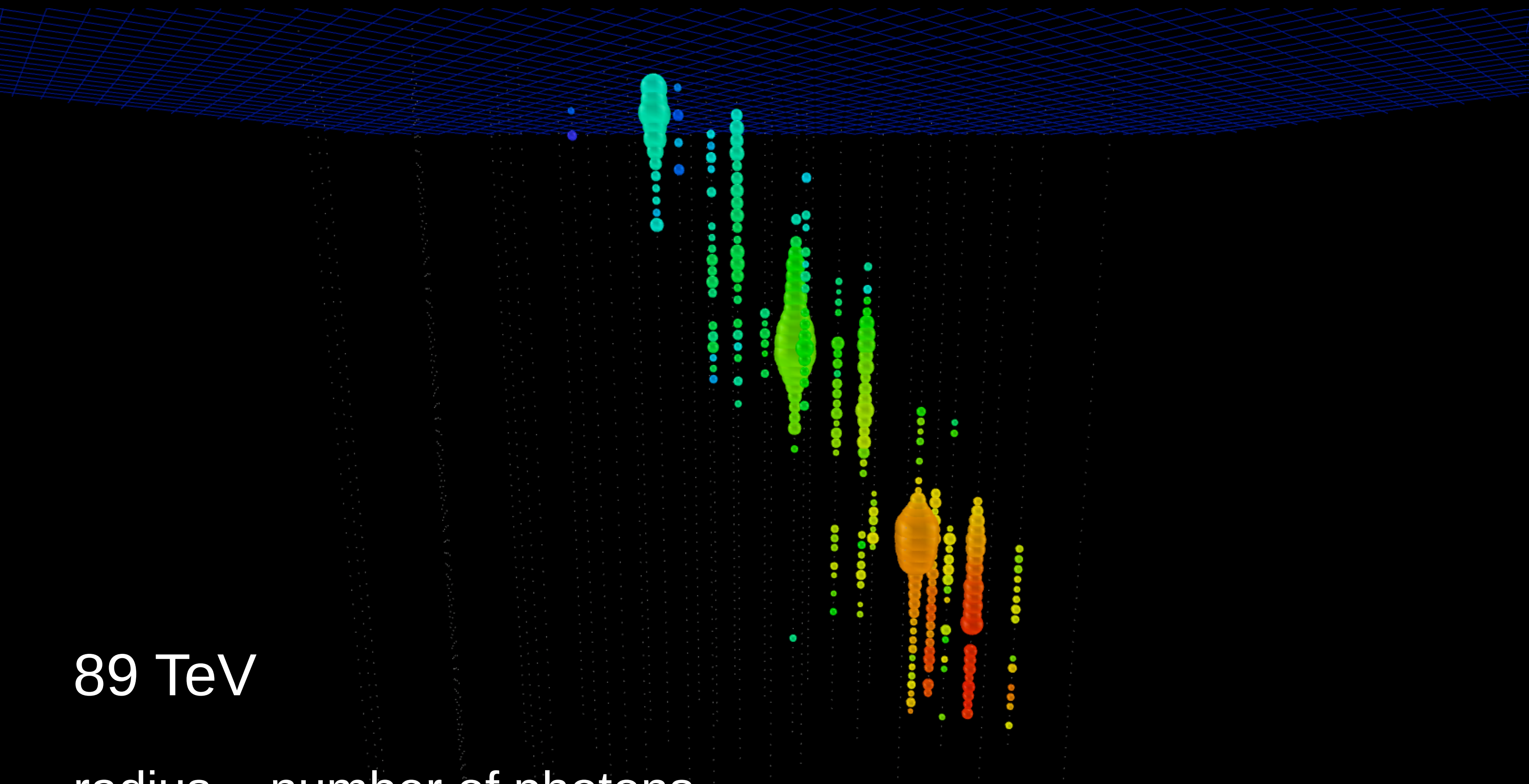
… you looked at 10msec of data !

muons detected per year:

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

* 3000 per second

** 1 every 6 minutes

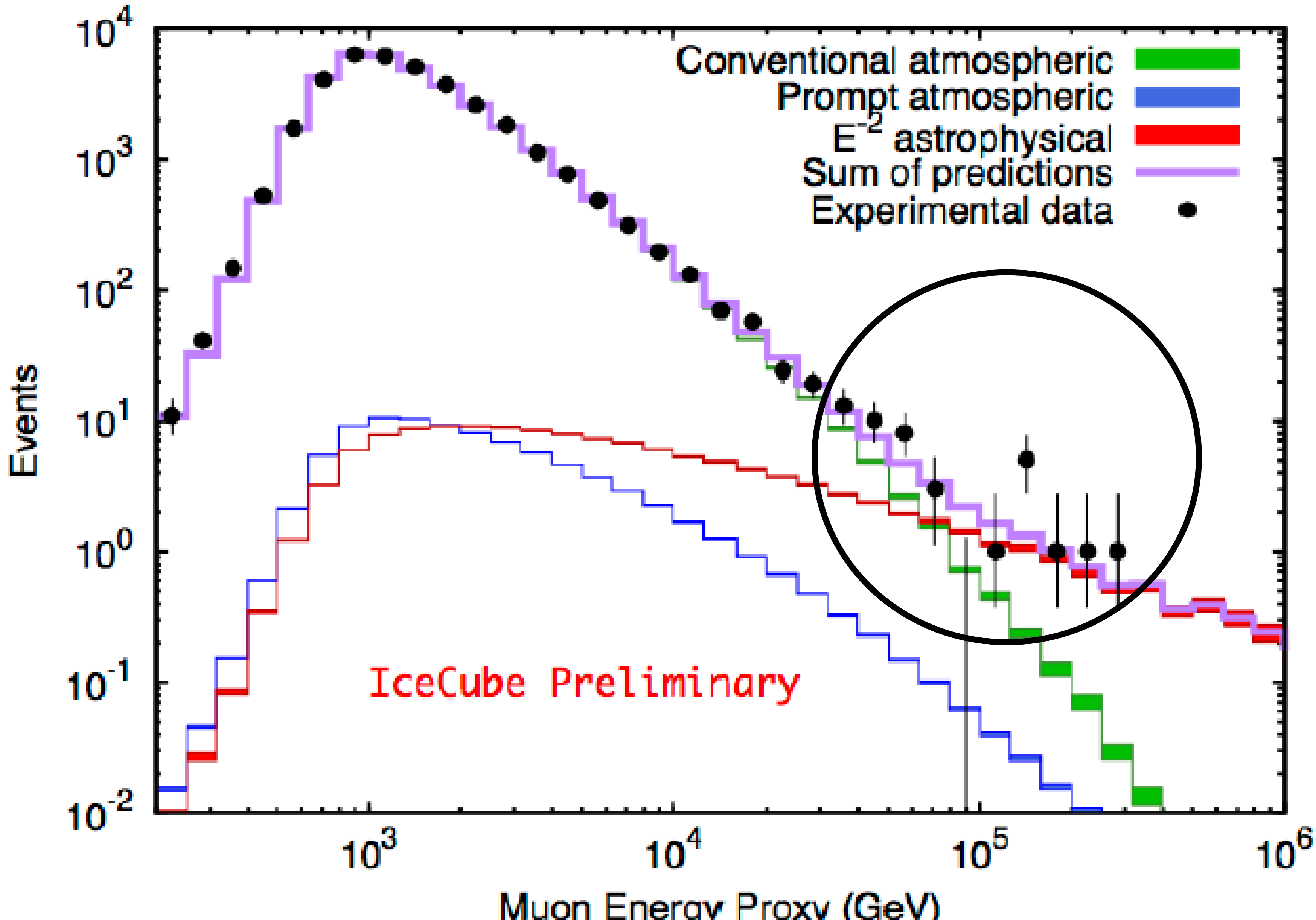


89 TeV

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

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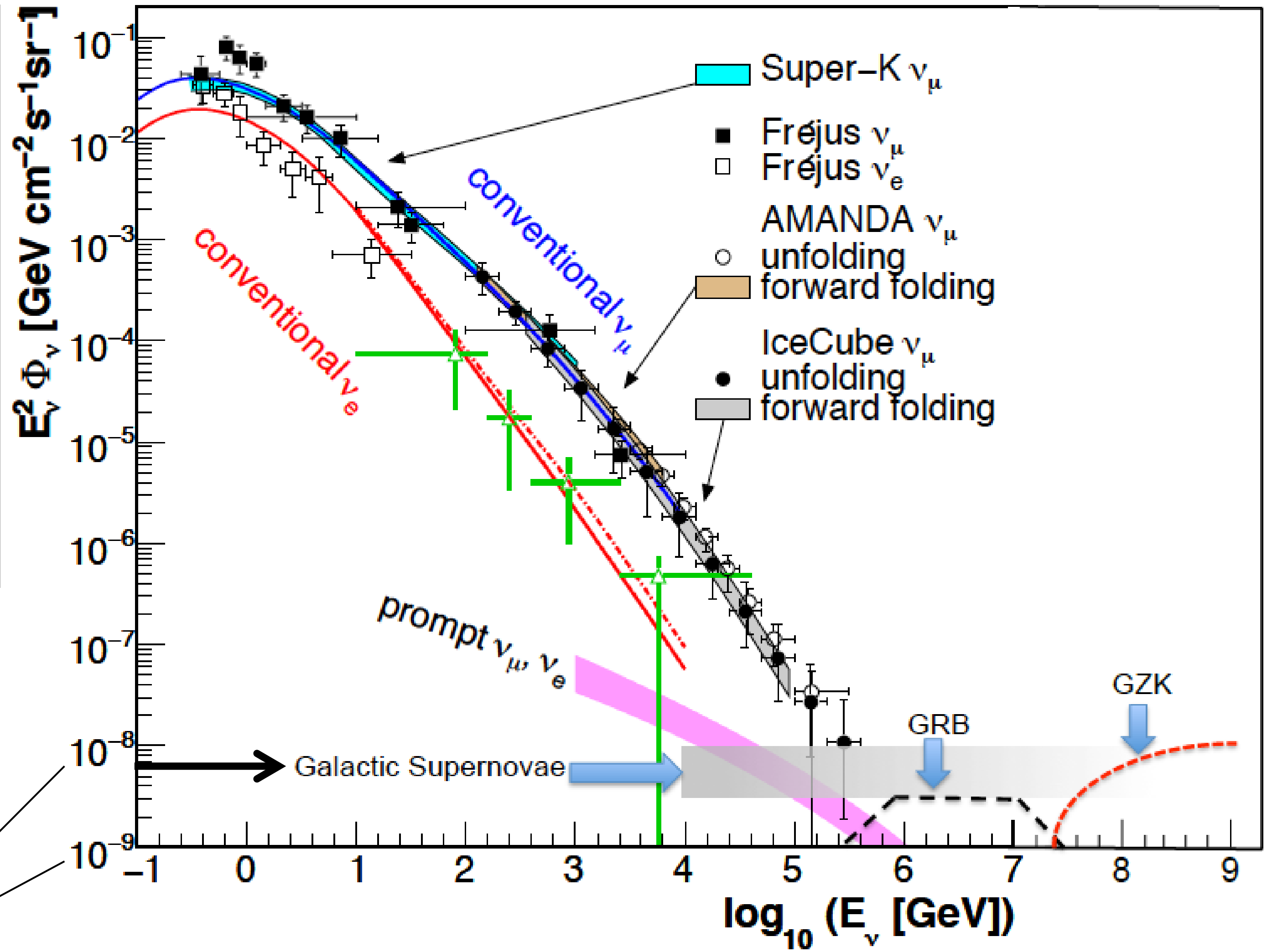


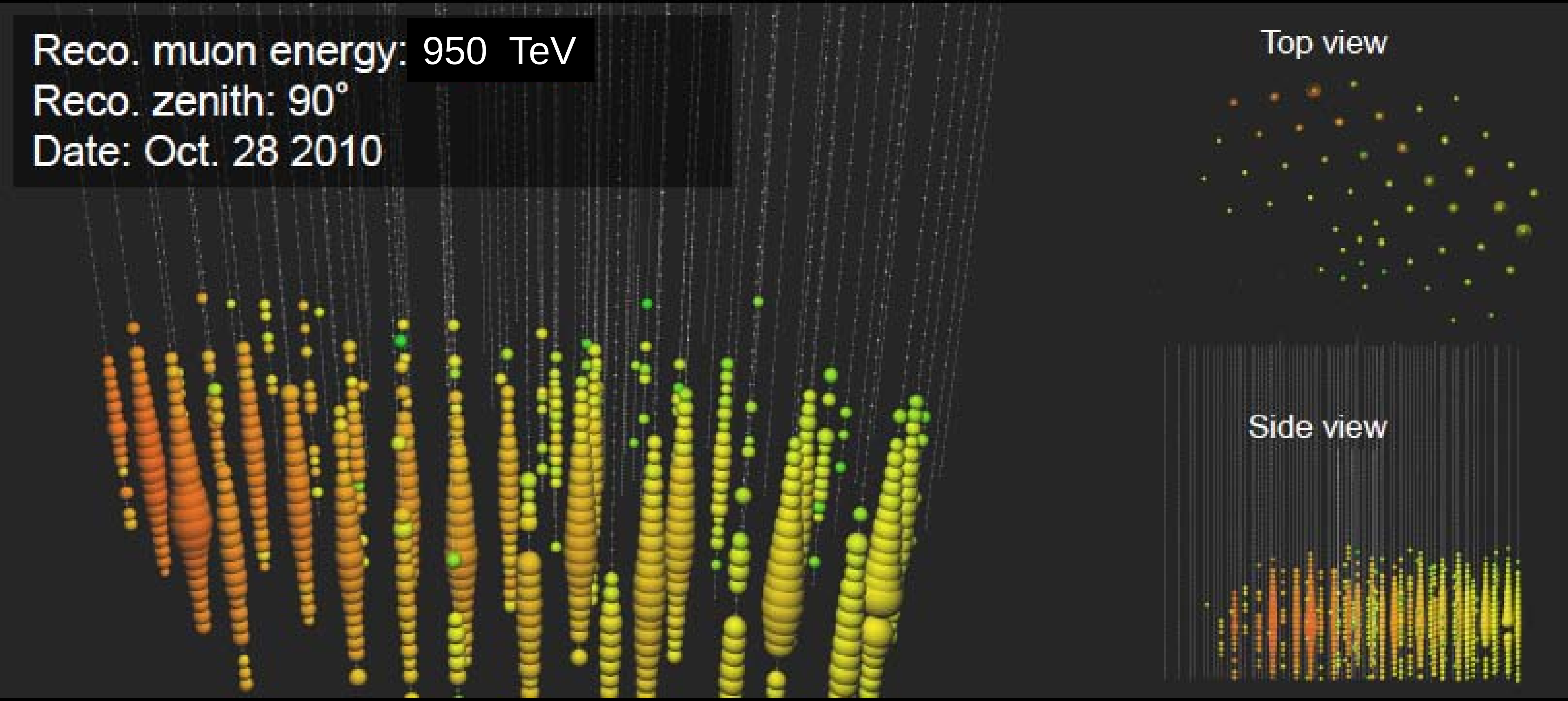
10—100 events per year for fully efficient detector

atmospheric

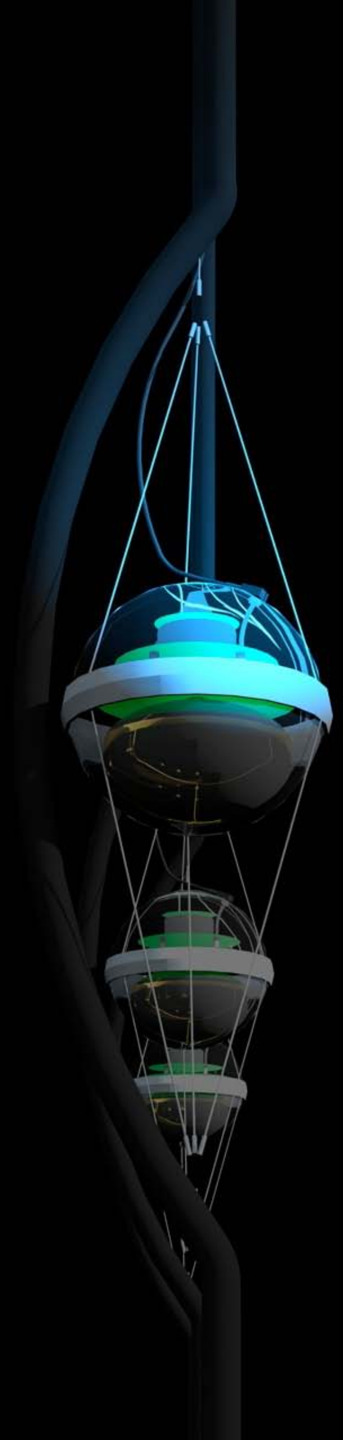
cosmic

100 TeV

3 years: 4.3 σ and more PeV ν_μ: reconstructed to 0.4 degrees!



no evidence for Galactic component



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cosmic rays interact with the microwave background

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

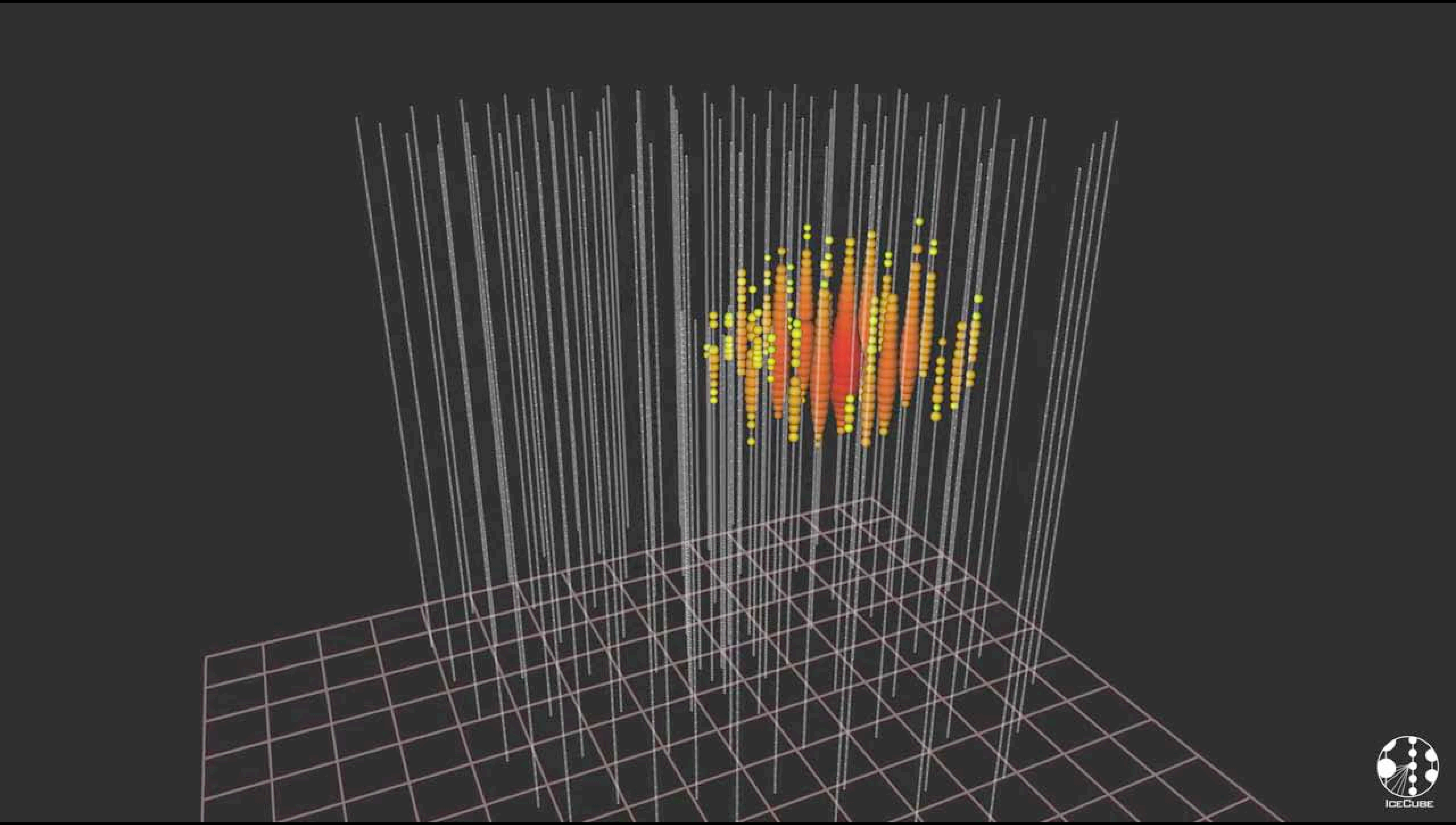
cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear

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

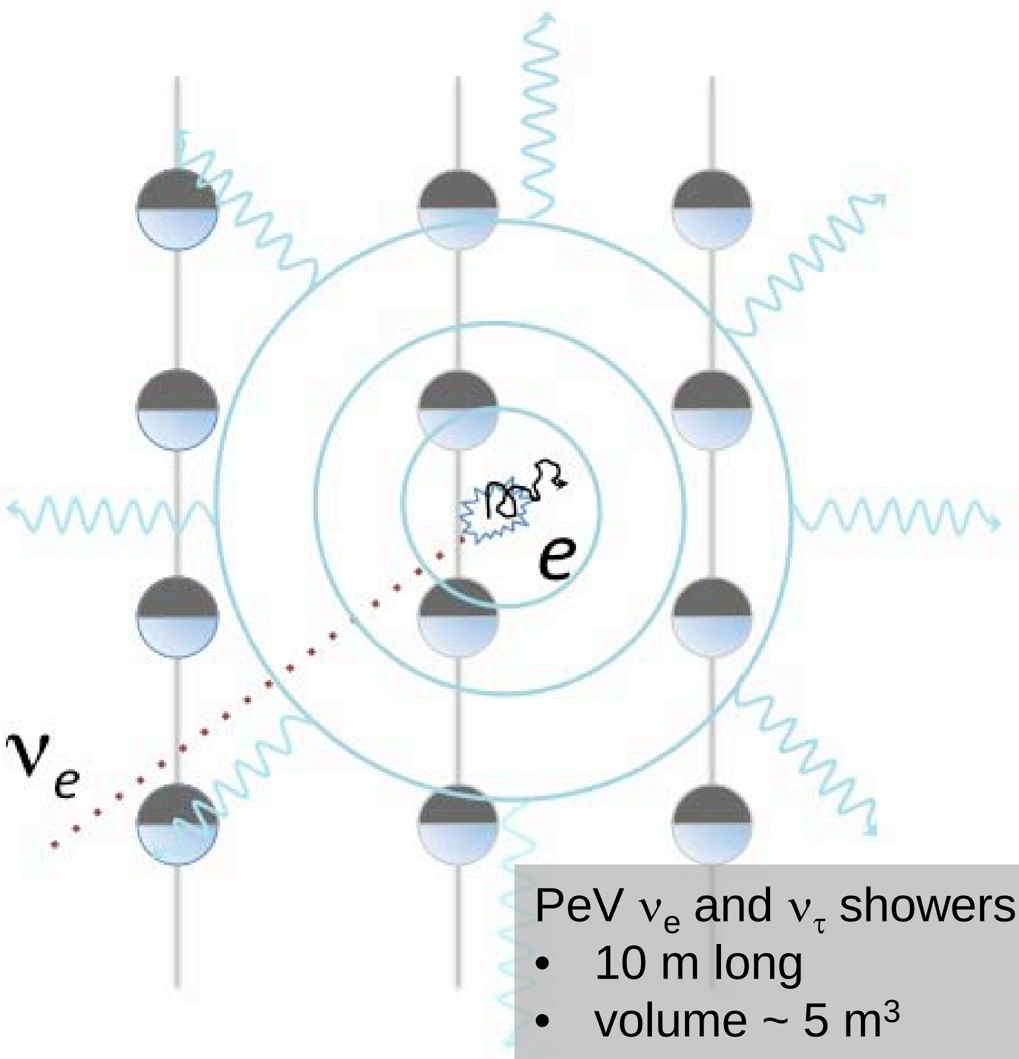
1 event per cubic kilometer per year

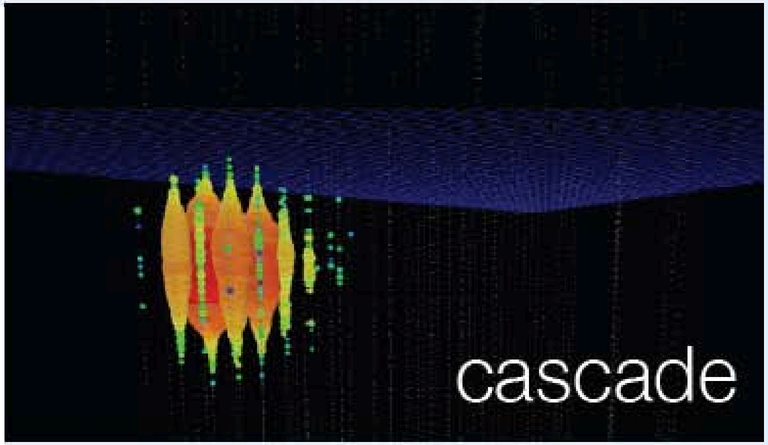
...but it points at its source!

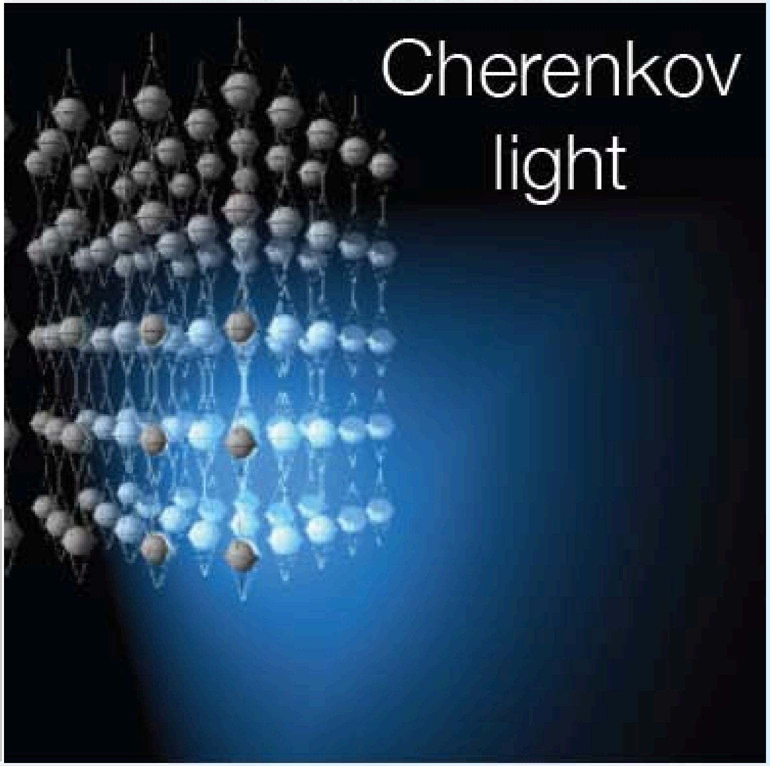
GZK neutrino search: two neutrinos with > 1,000 TeV



tracks and showers

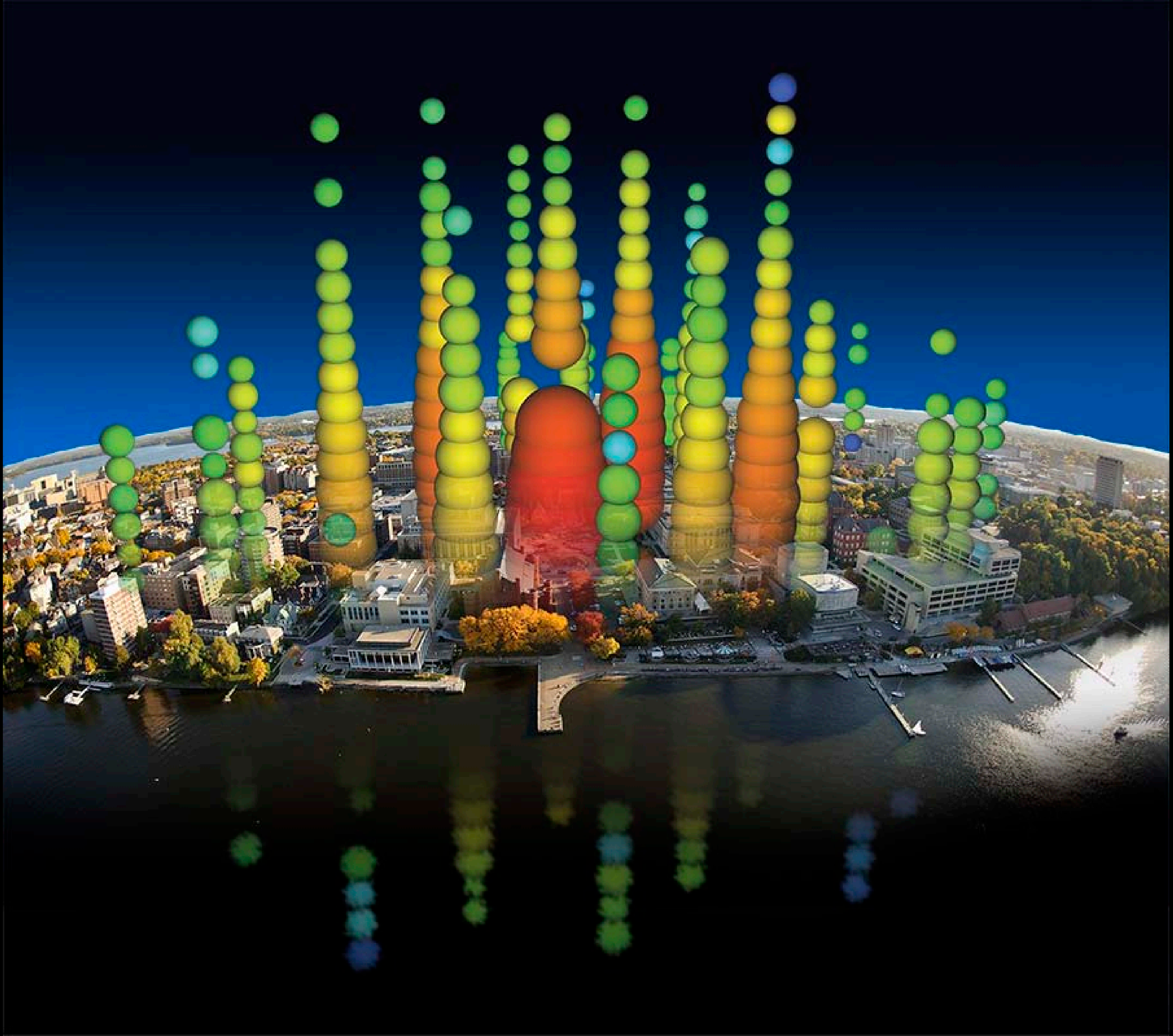


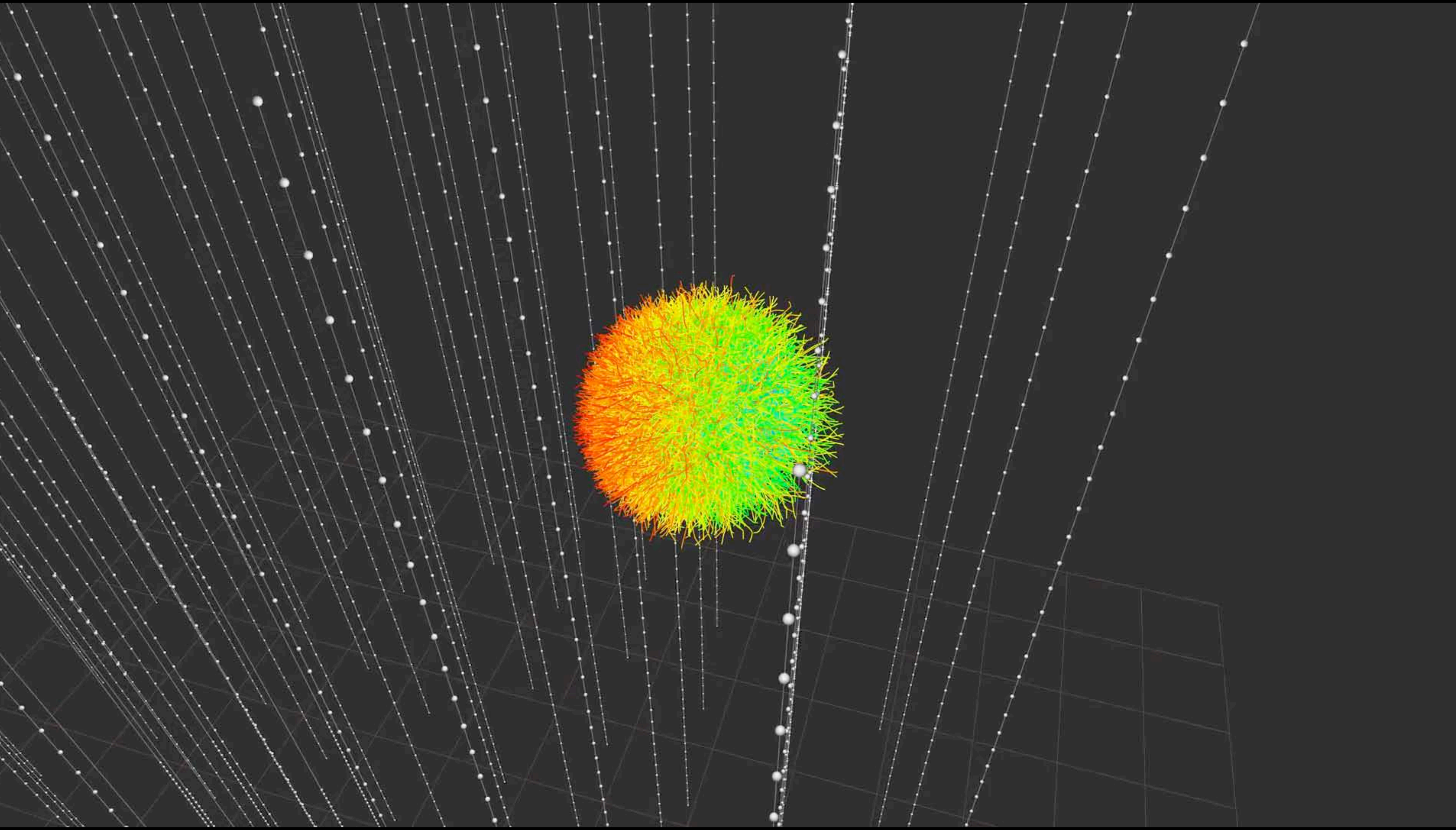




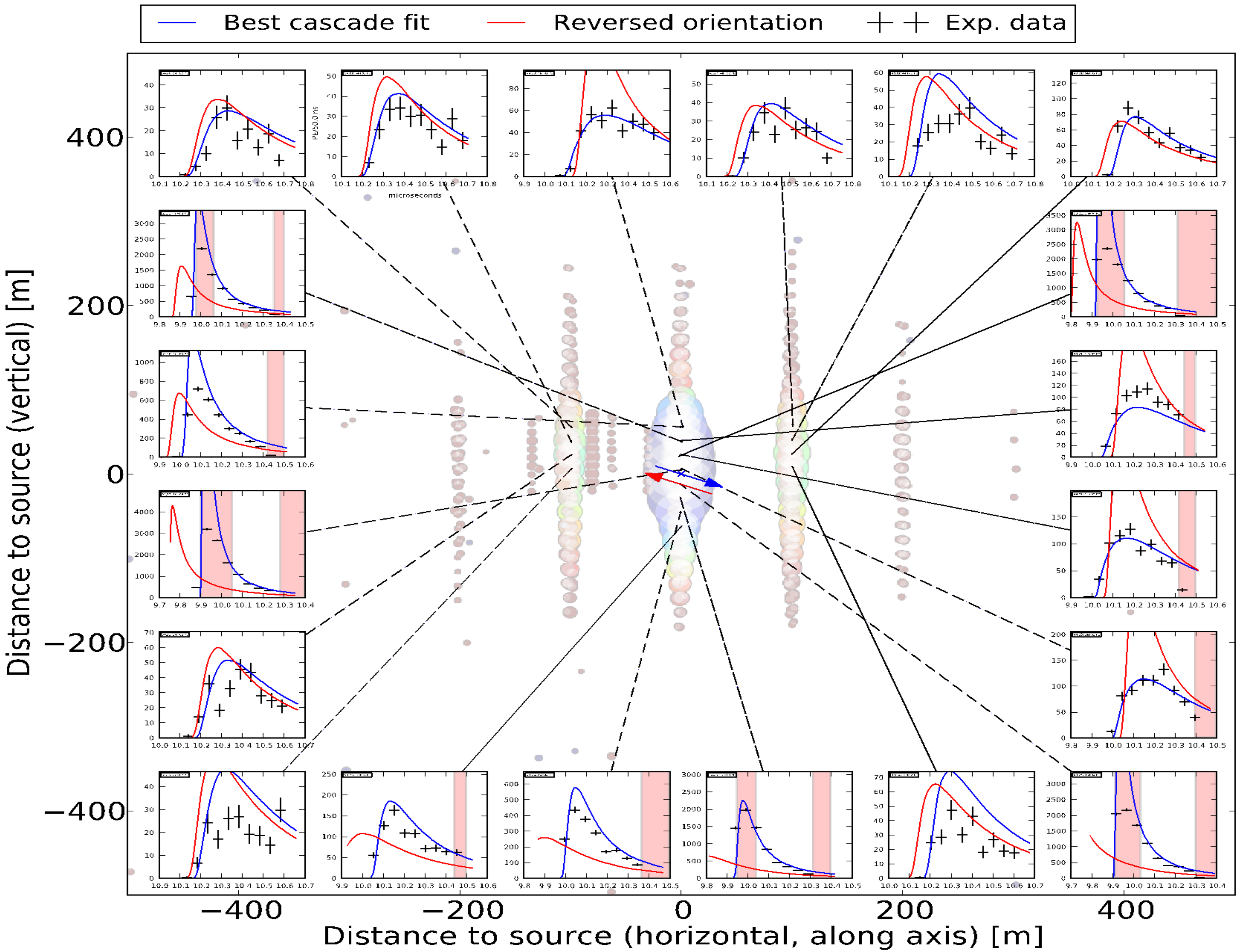
PeV ν_e and ν_τ showers:

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



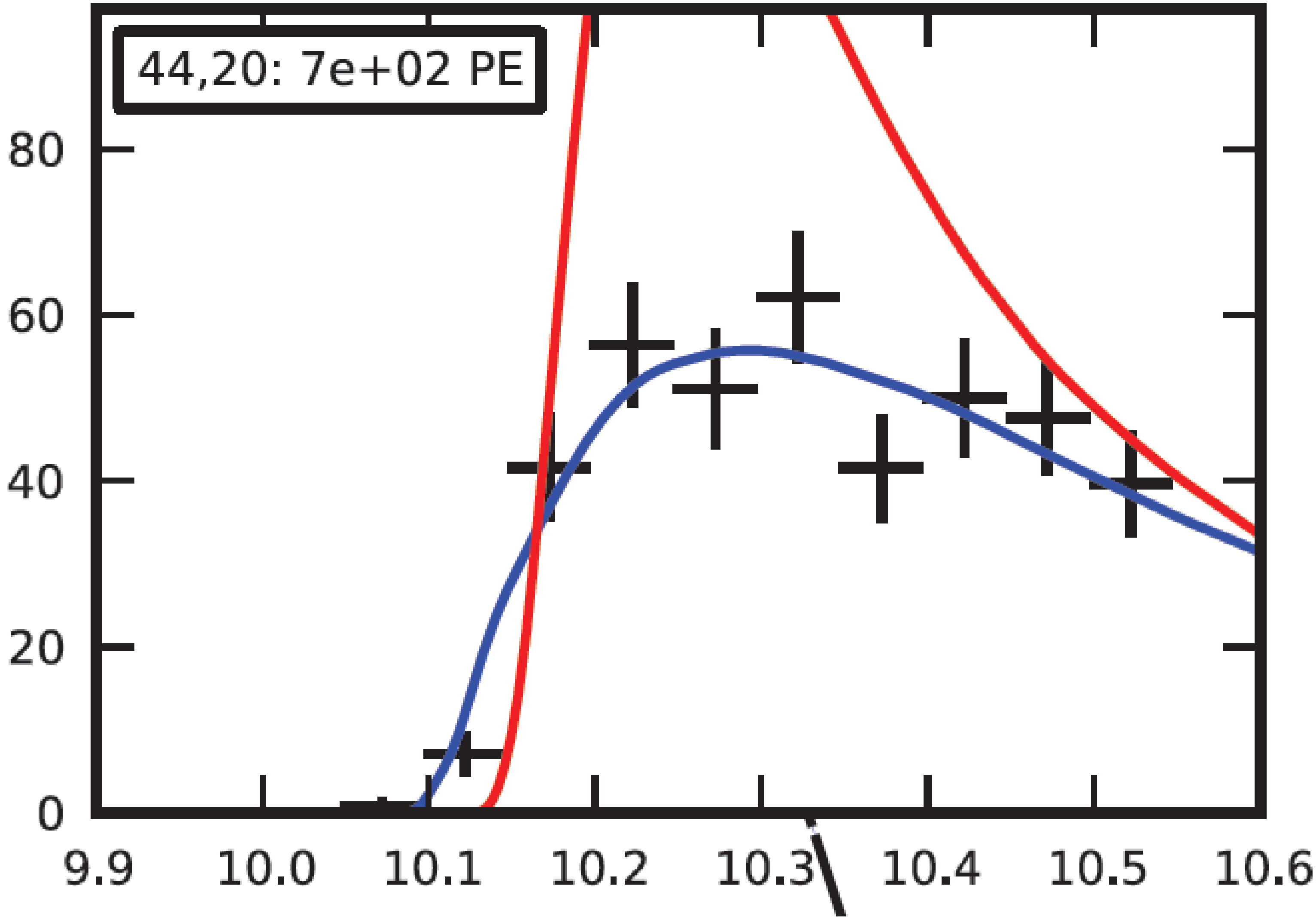


size = energy color = time = direction

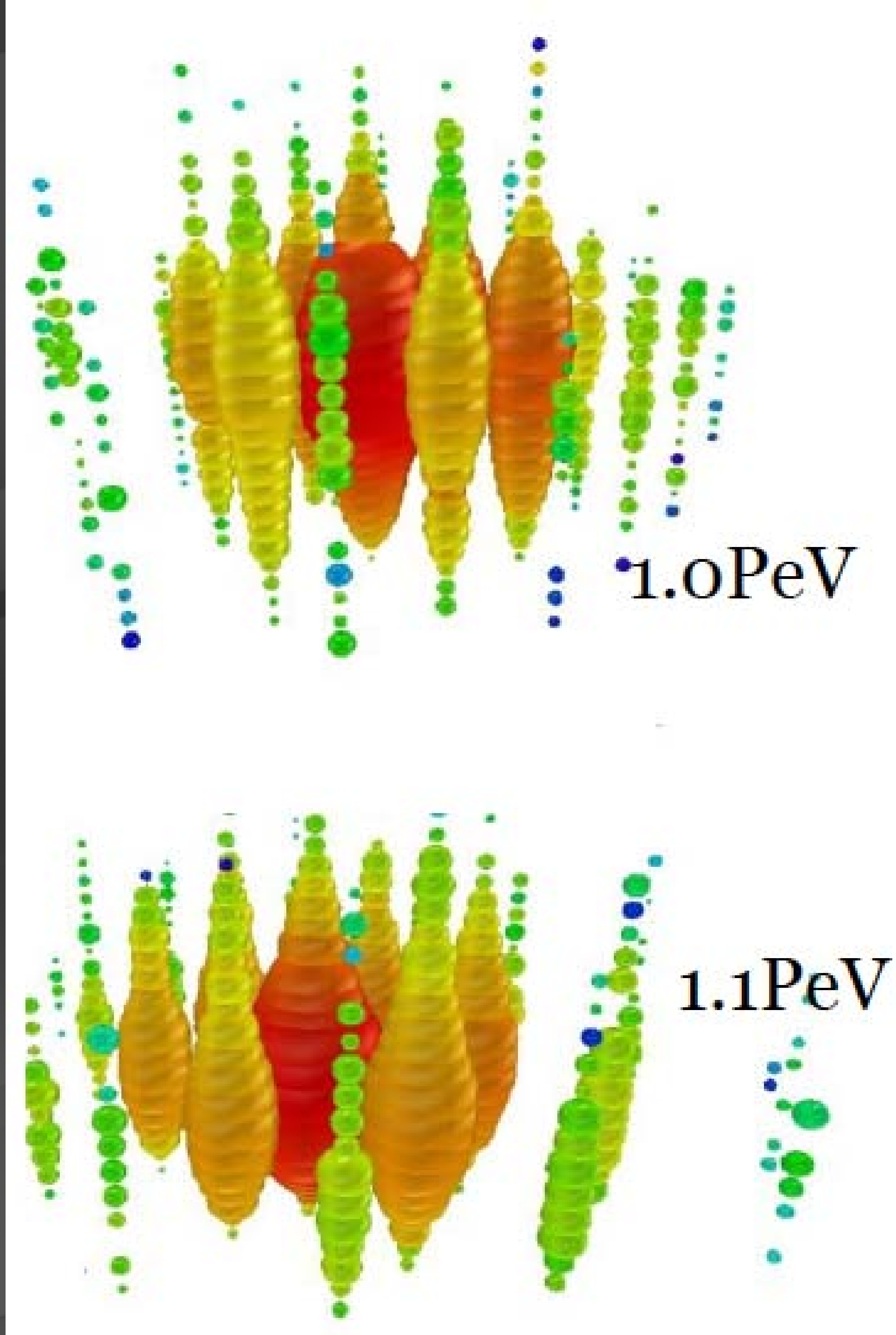


Best cascade fit
Reversed orientation
Exp. data
Distance to source (vertical) [m]
Distance to source (horizontal, along axis) [m]
microseconds

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

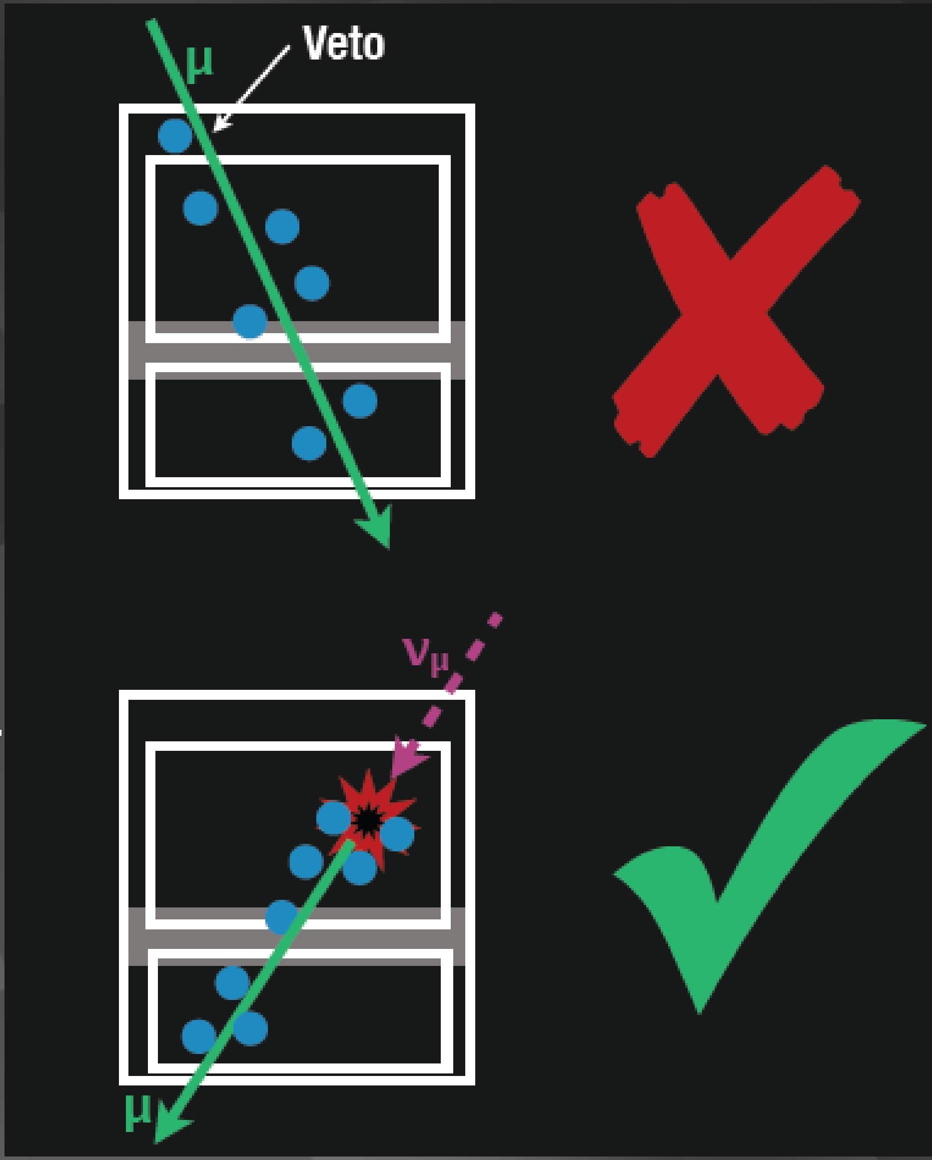
→ flux at present level of diffuse limit

✓ select events interacting inside the detector only

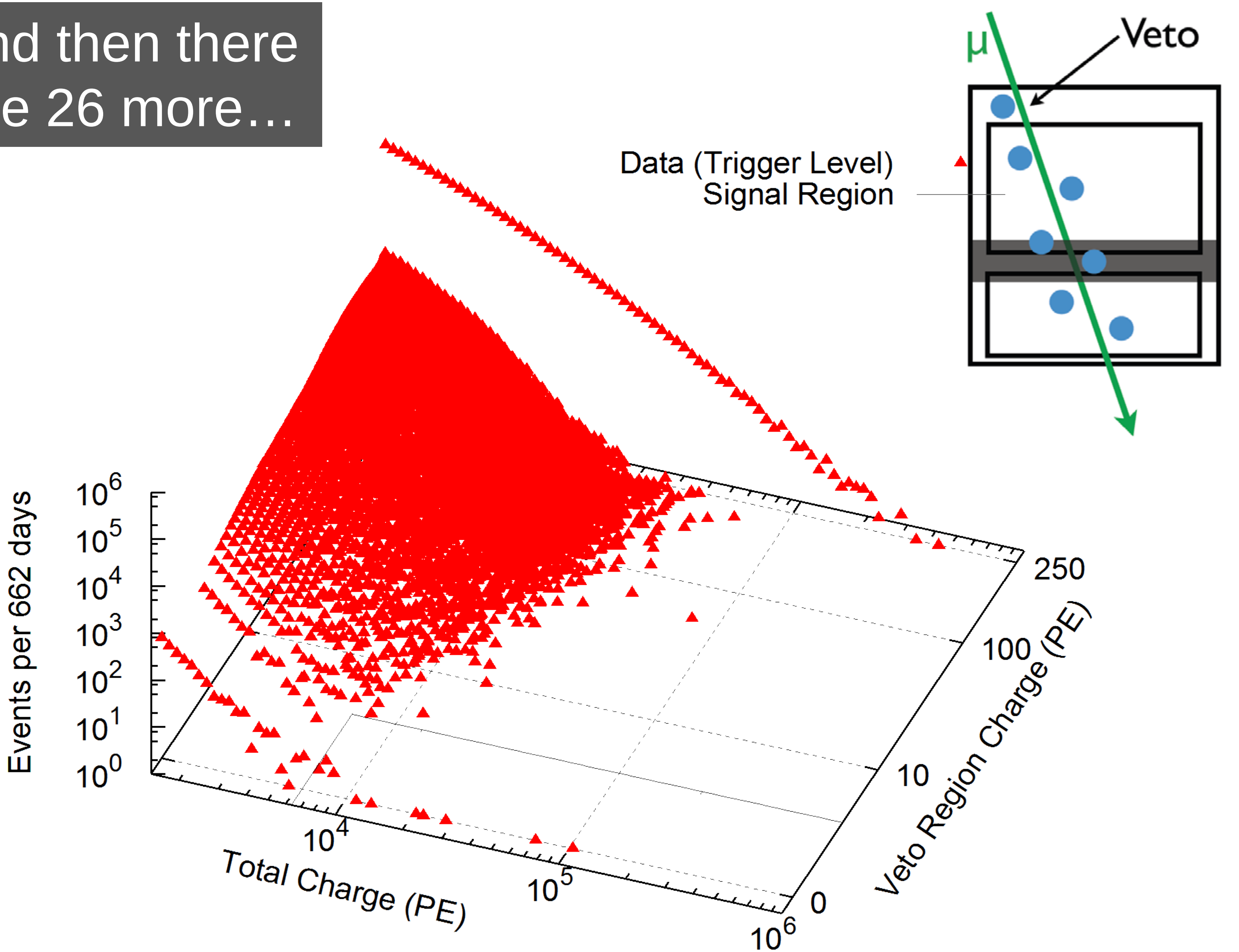
✓ no light in the veto region

✓ veto for atmospheric muons and neutrinos (which are typically accom-panied by muons)

✓ energy measurement: to-tal absorption calorimetry

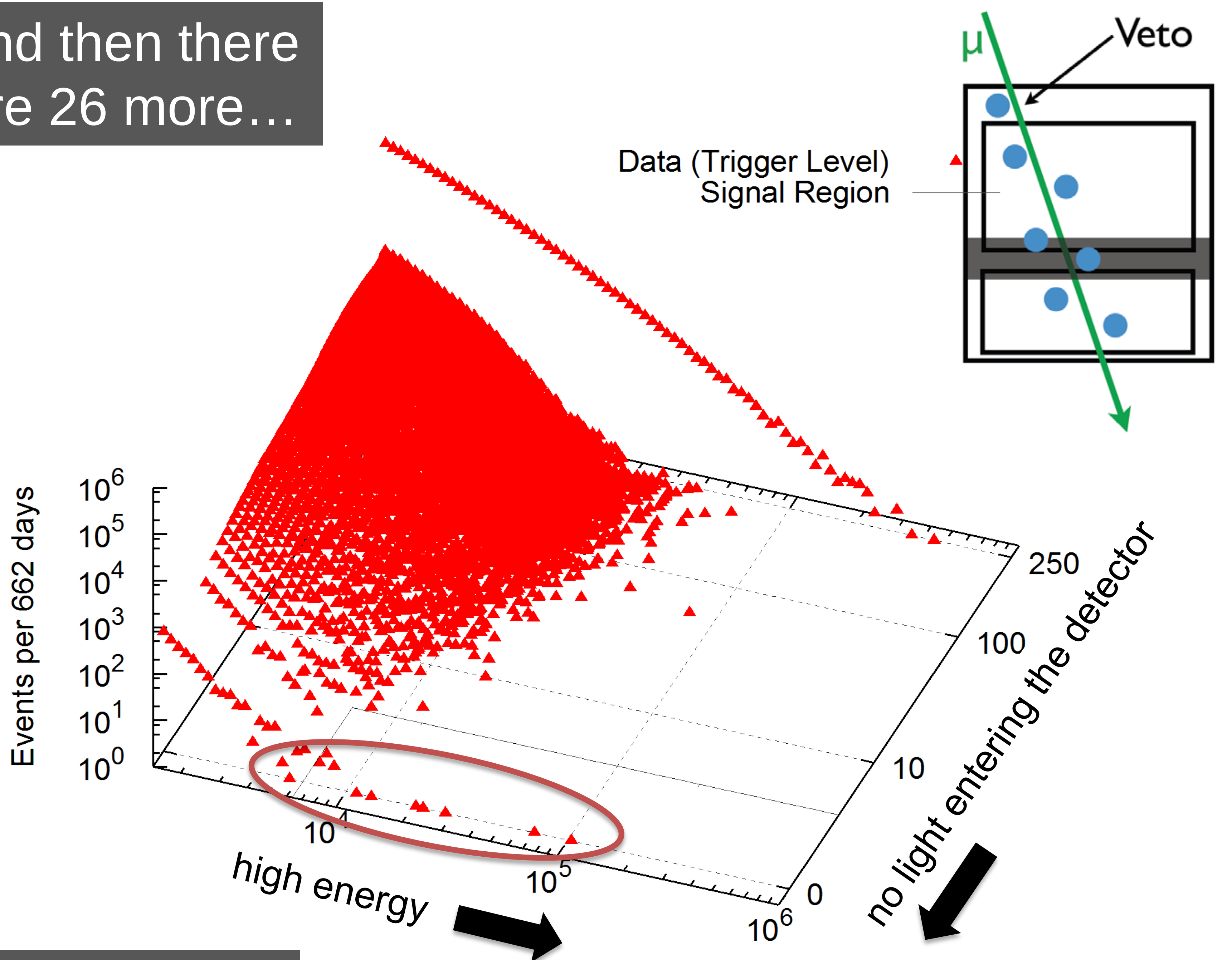


...and then there were 26 more...

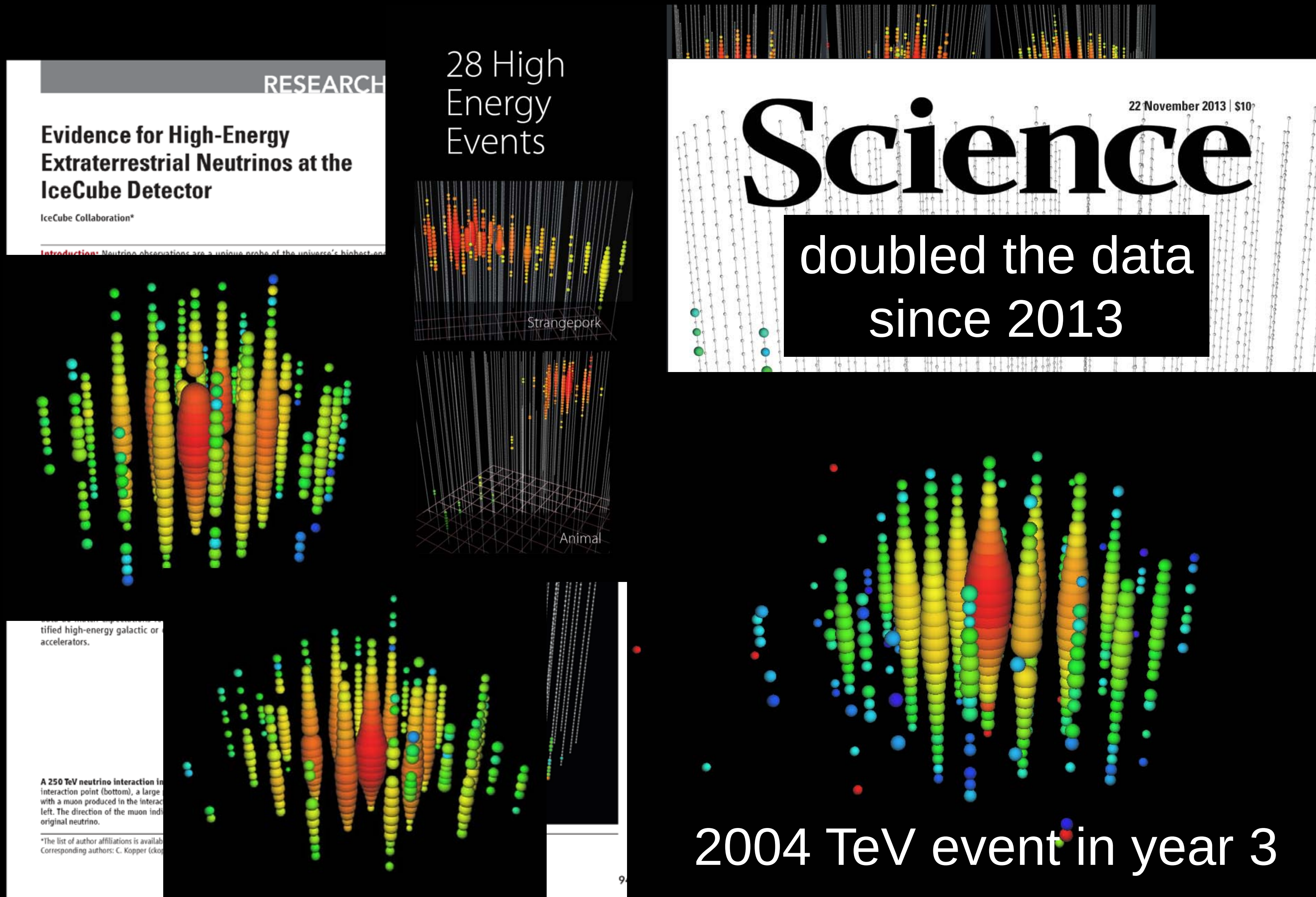


data: 86 strings one year

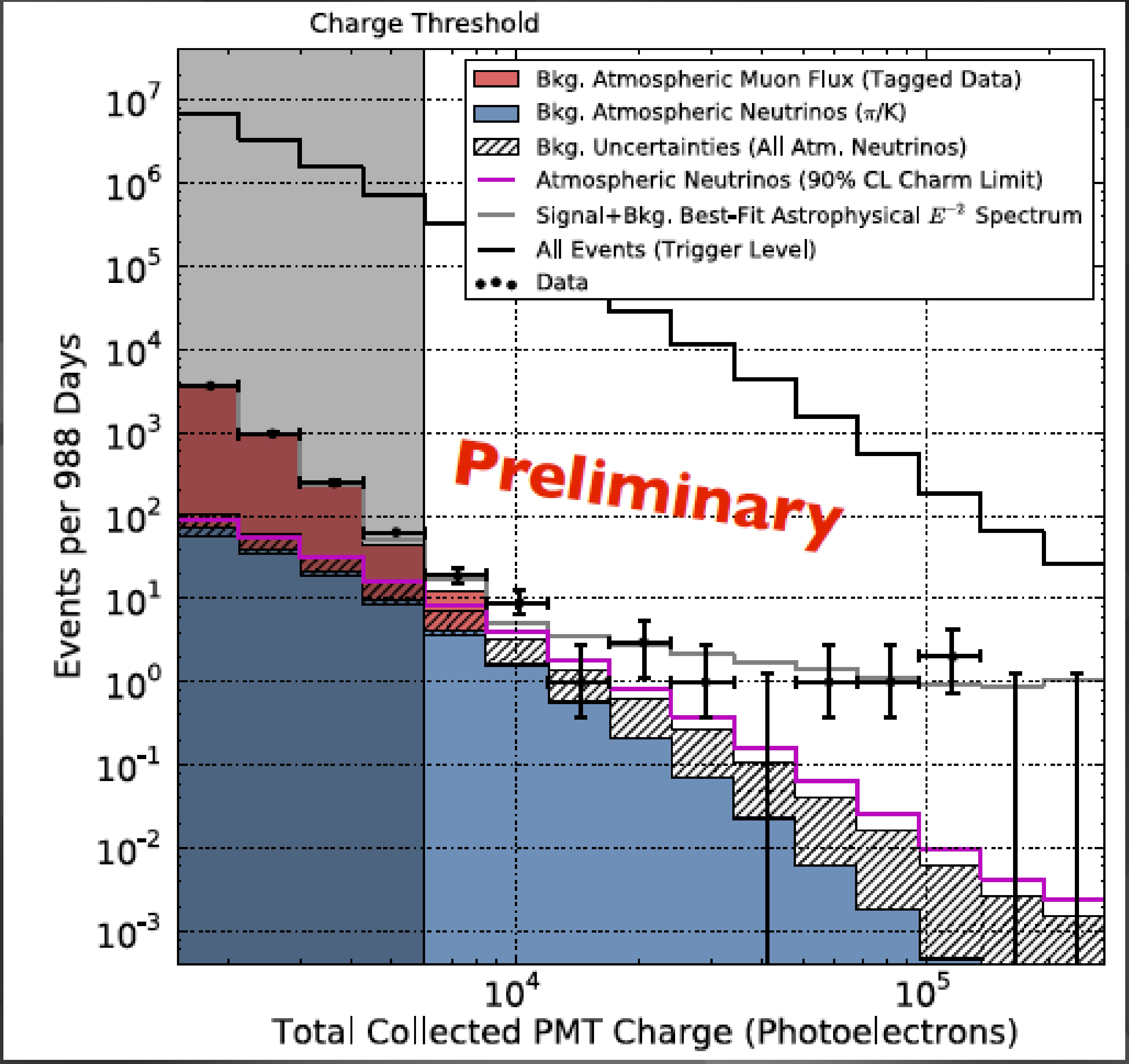
…and then there were 26 more…



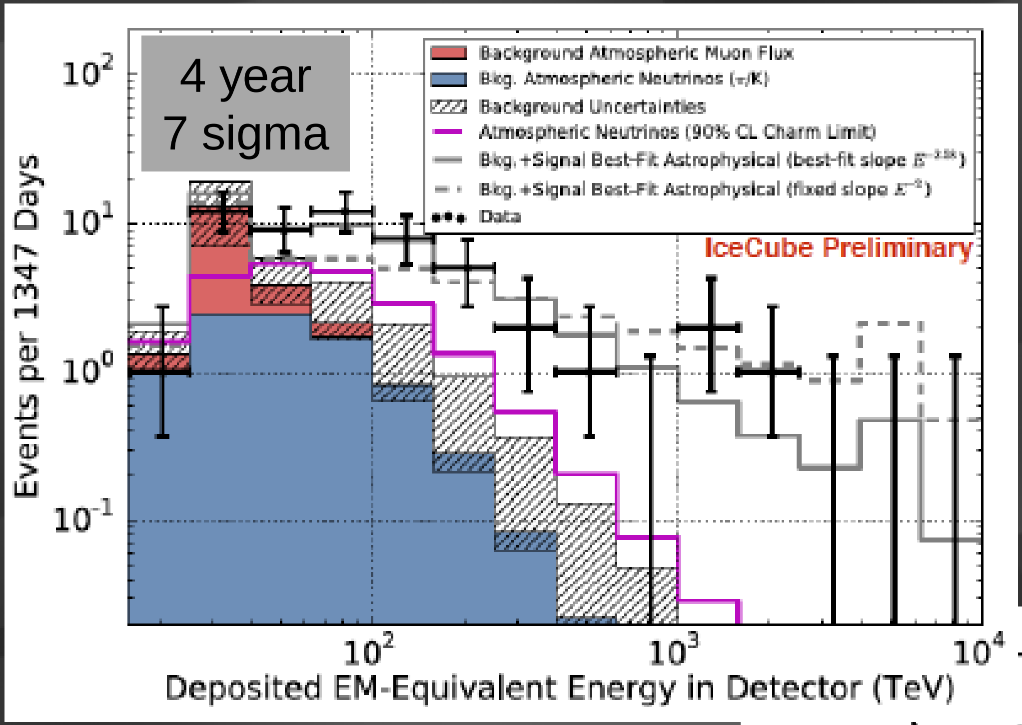
data: 86 strings one year


RESEARCH
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector
IceCube Collaboration*
28 High Energy Events
Strangepork
Animal
Science
22 November 2013 | $10
doubled the data since 2013
2004 TeV event in year 3

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

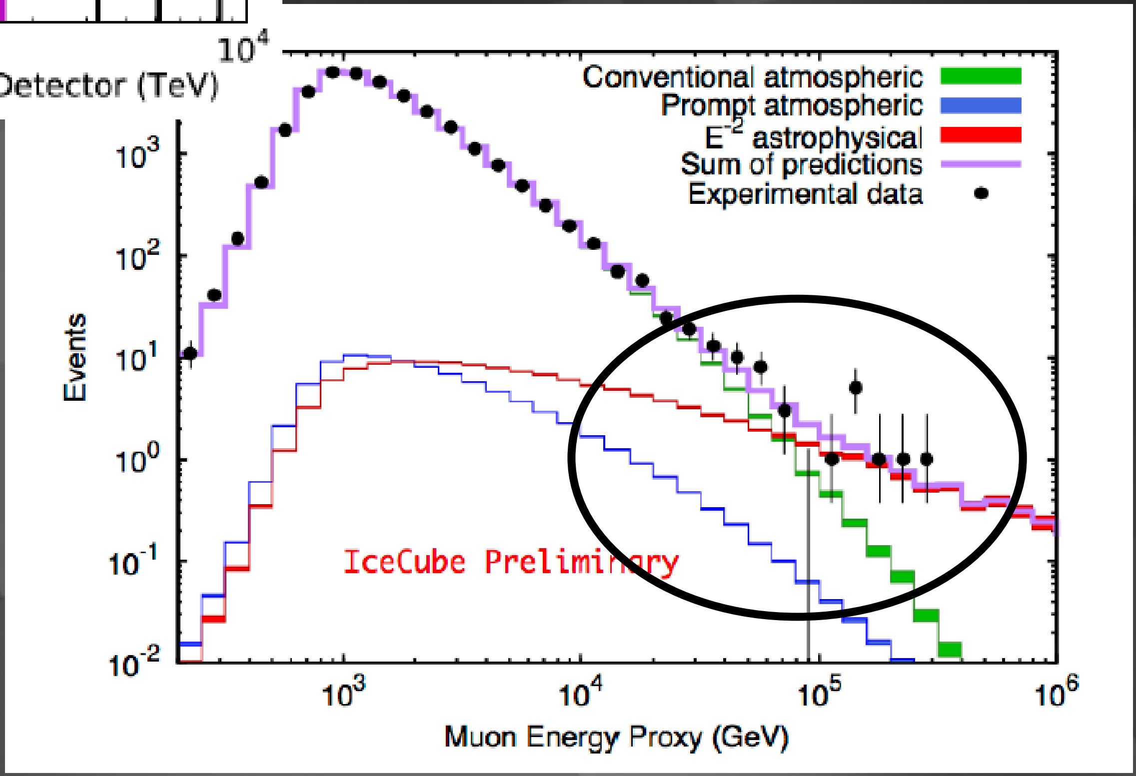


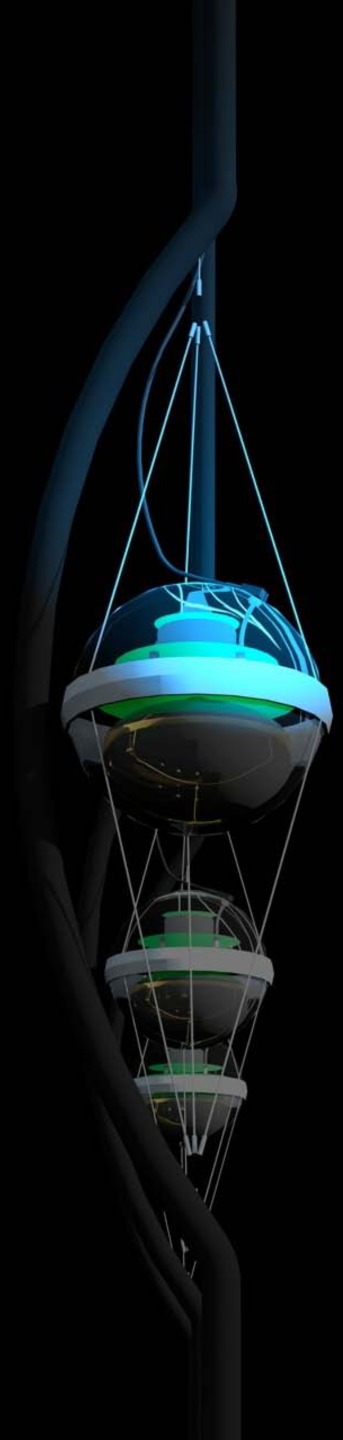
Science 342 (2013) 1242856



confirmation!
flux of muon neutrinos
through the Earth

neutrinos of all flavors
interacting inside
IceCube





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- where do they come from?
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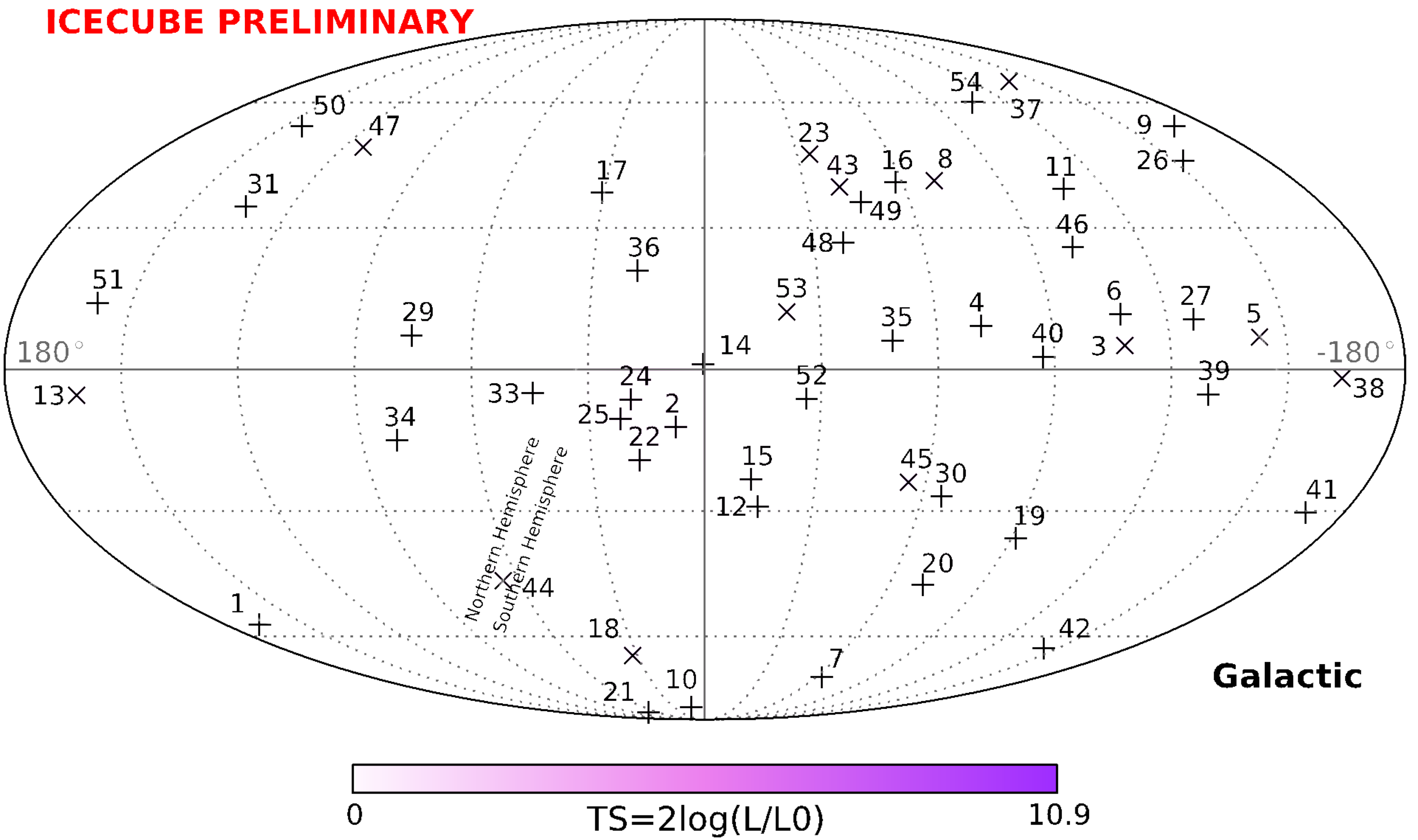
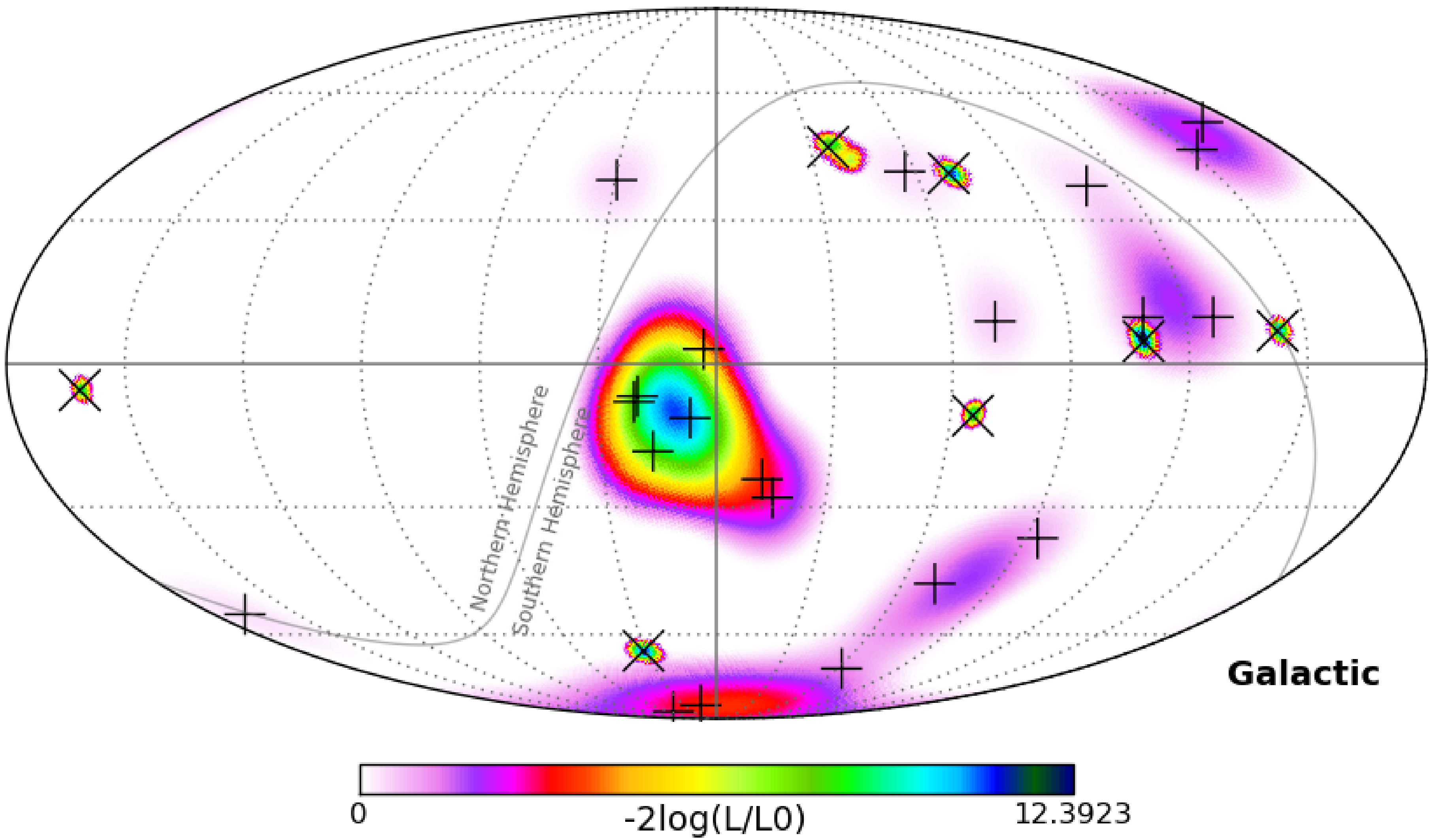
4 year HESE



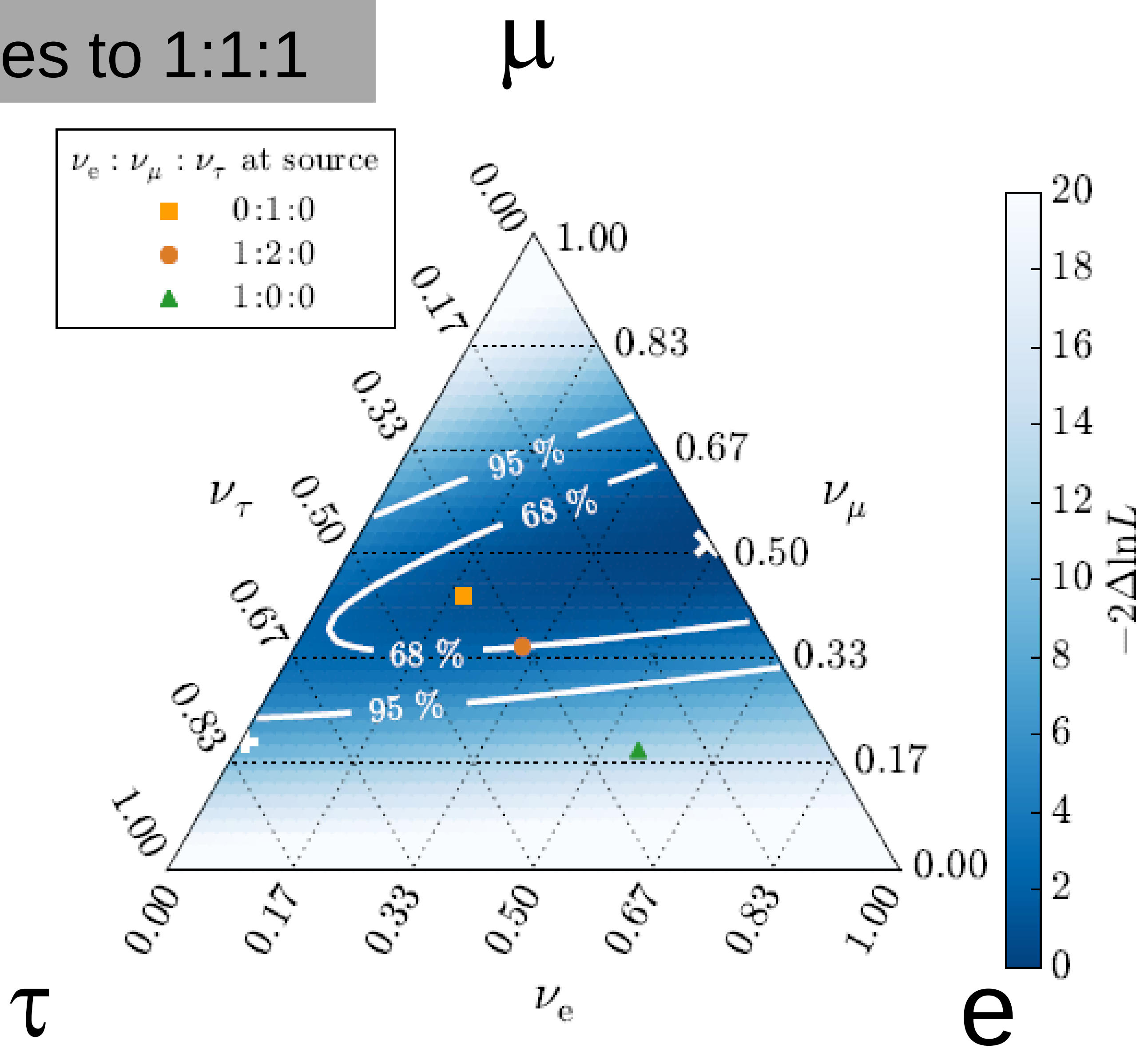
where do they come from?

2 year HESE



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

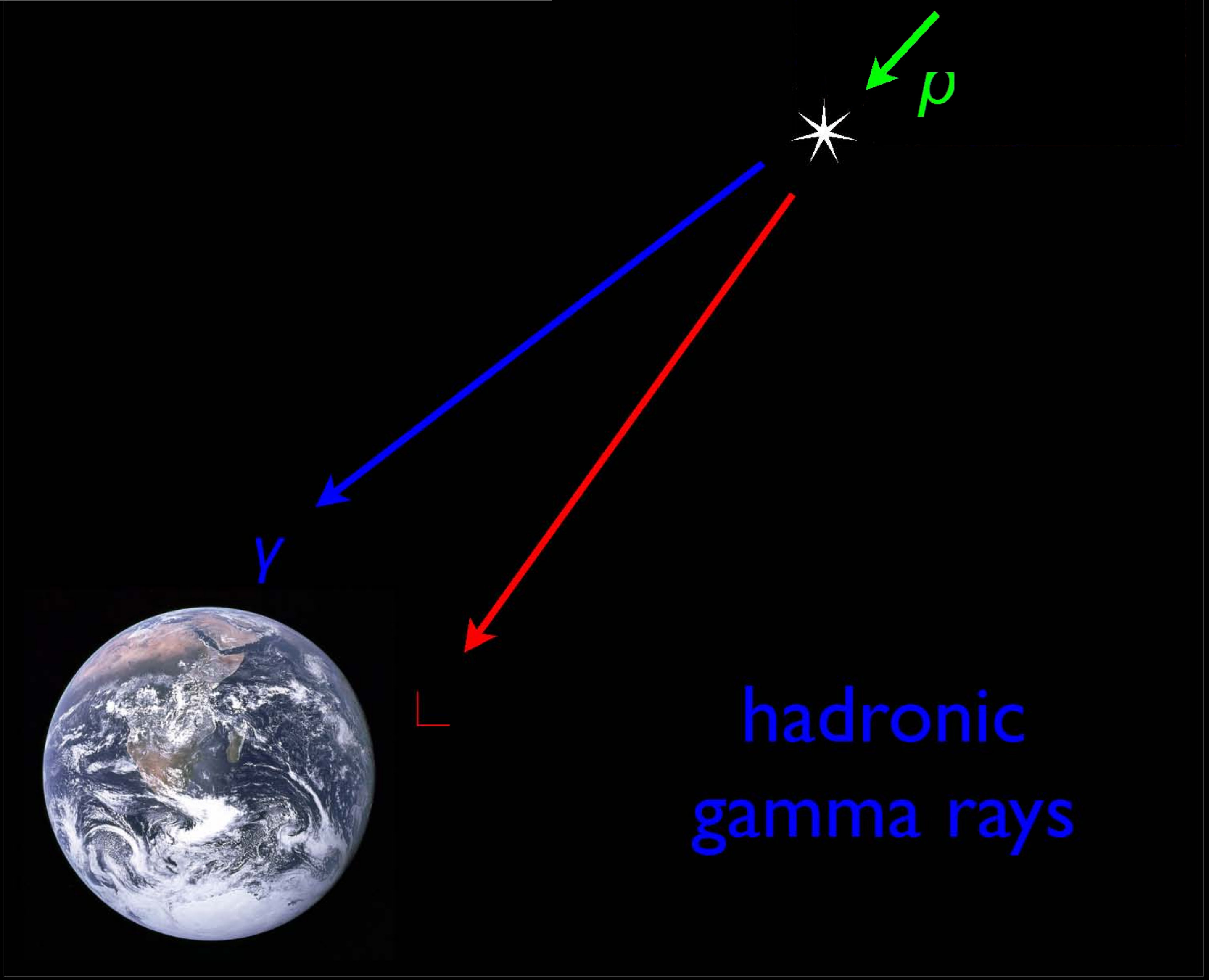
oscillate over cosmic distances to 1:1:1

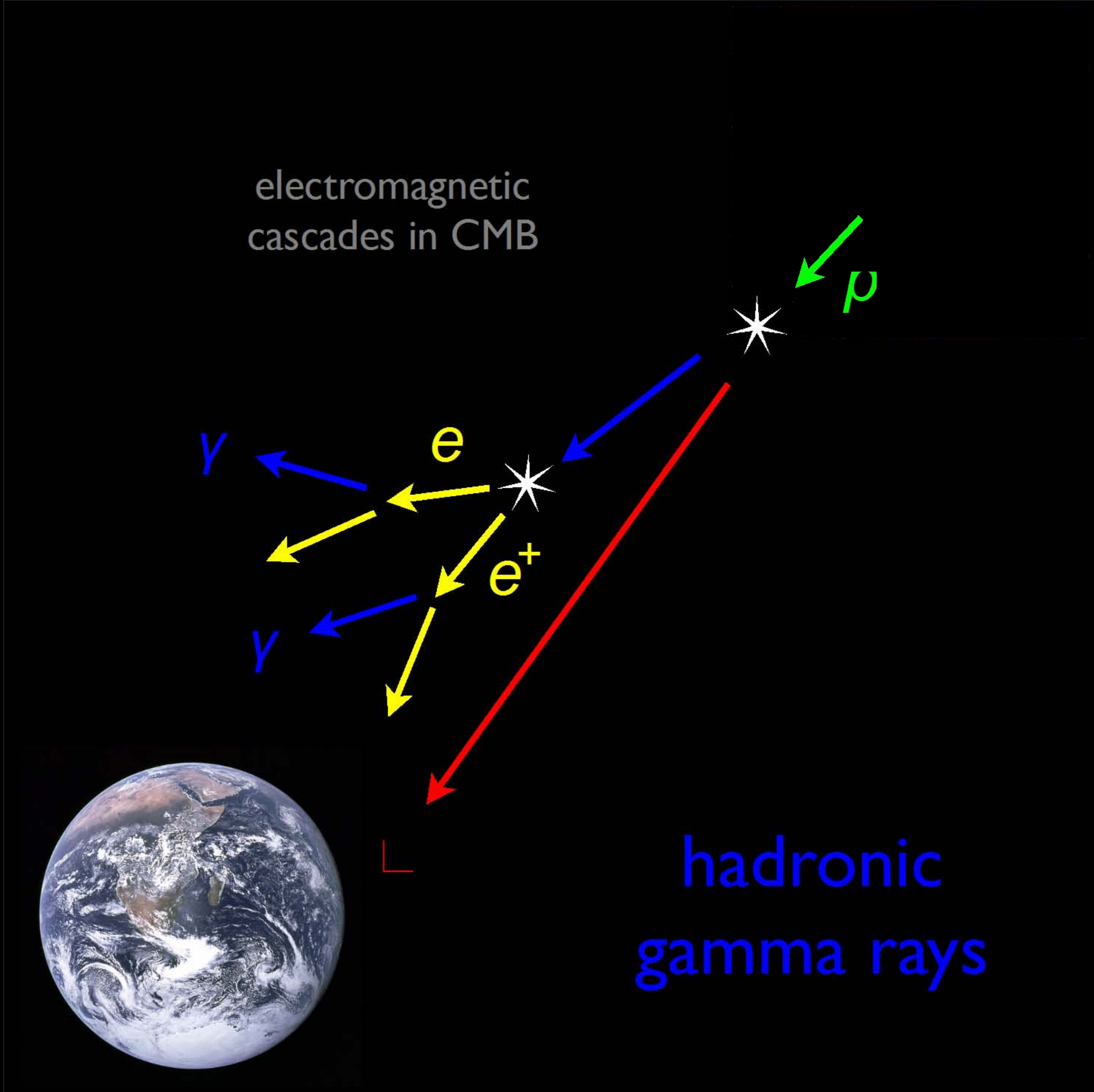


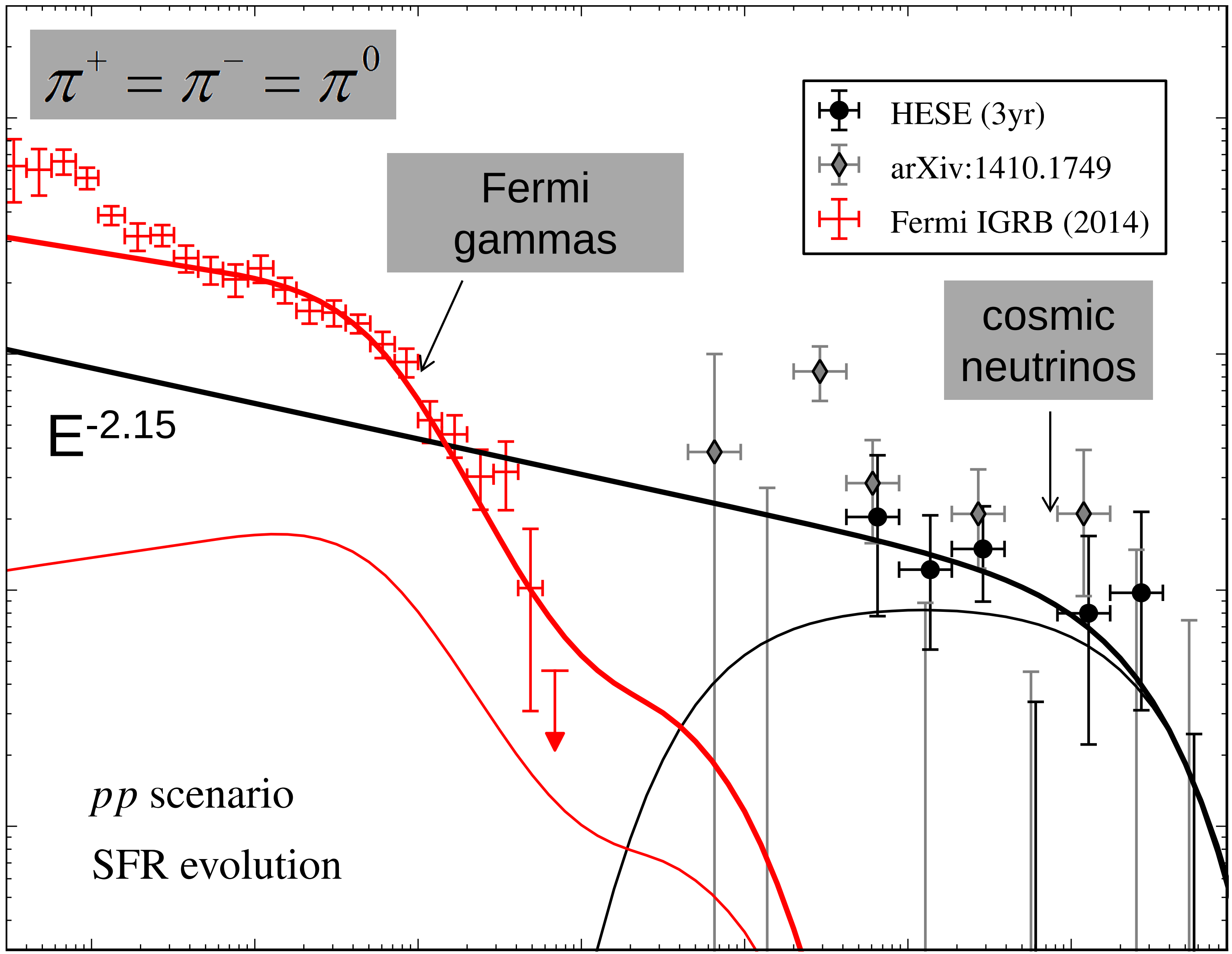
- we observe a diffuse extragalactic flux
- a subdominant Galactic component cannot be excluded
- where are the PeV gamma rays that accompany PeV neutrinos?

hadronic gamma rays ?

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

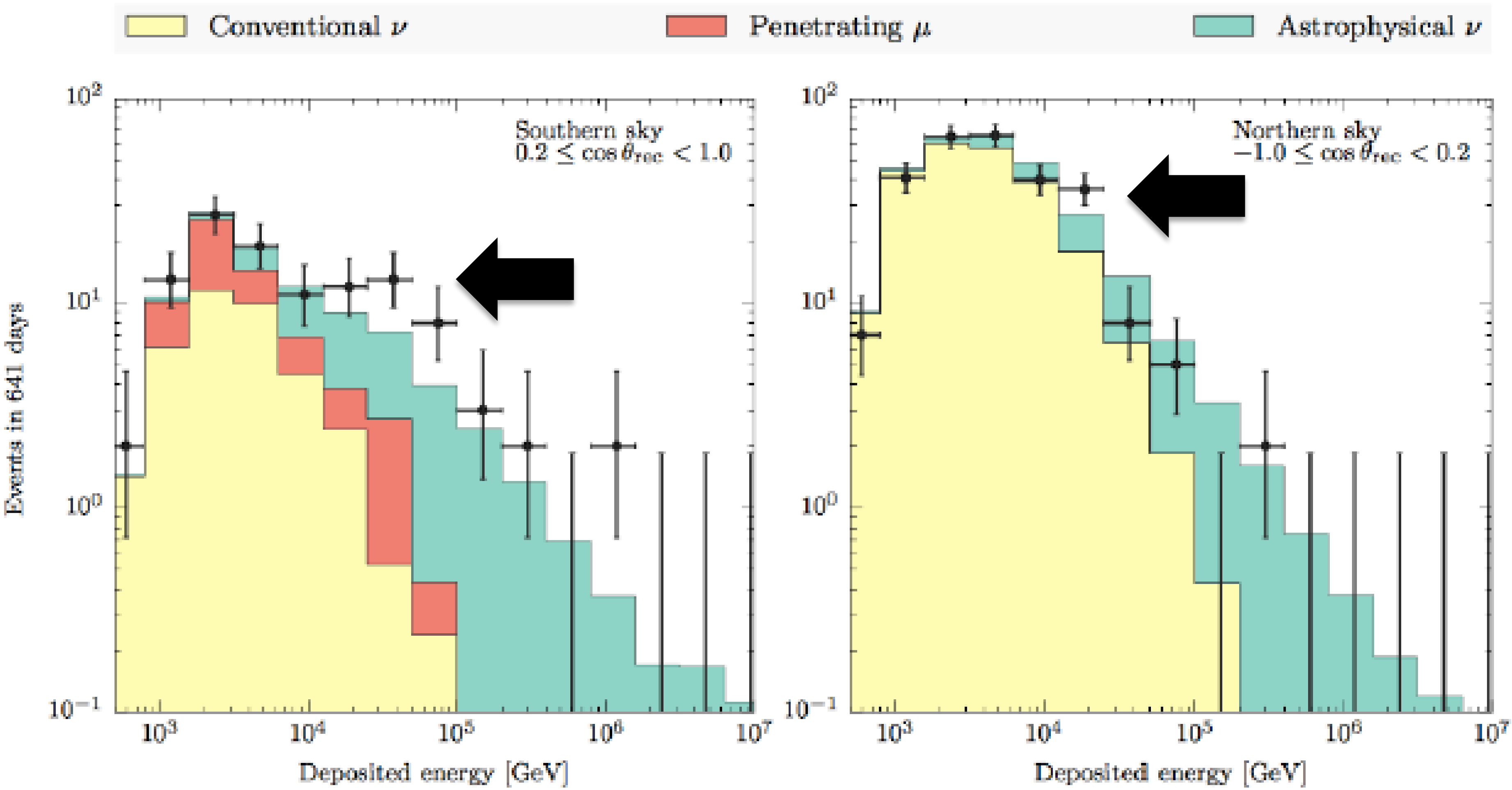



electromagnetic
cascades in CMB
p
e
e+
γ
γ
hadronic
gamma rays



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

towards lower energies: a second component?



warning:

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

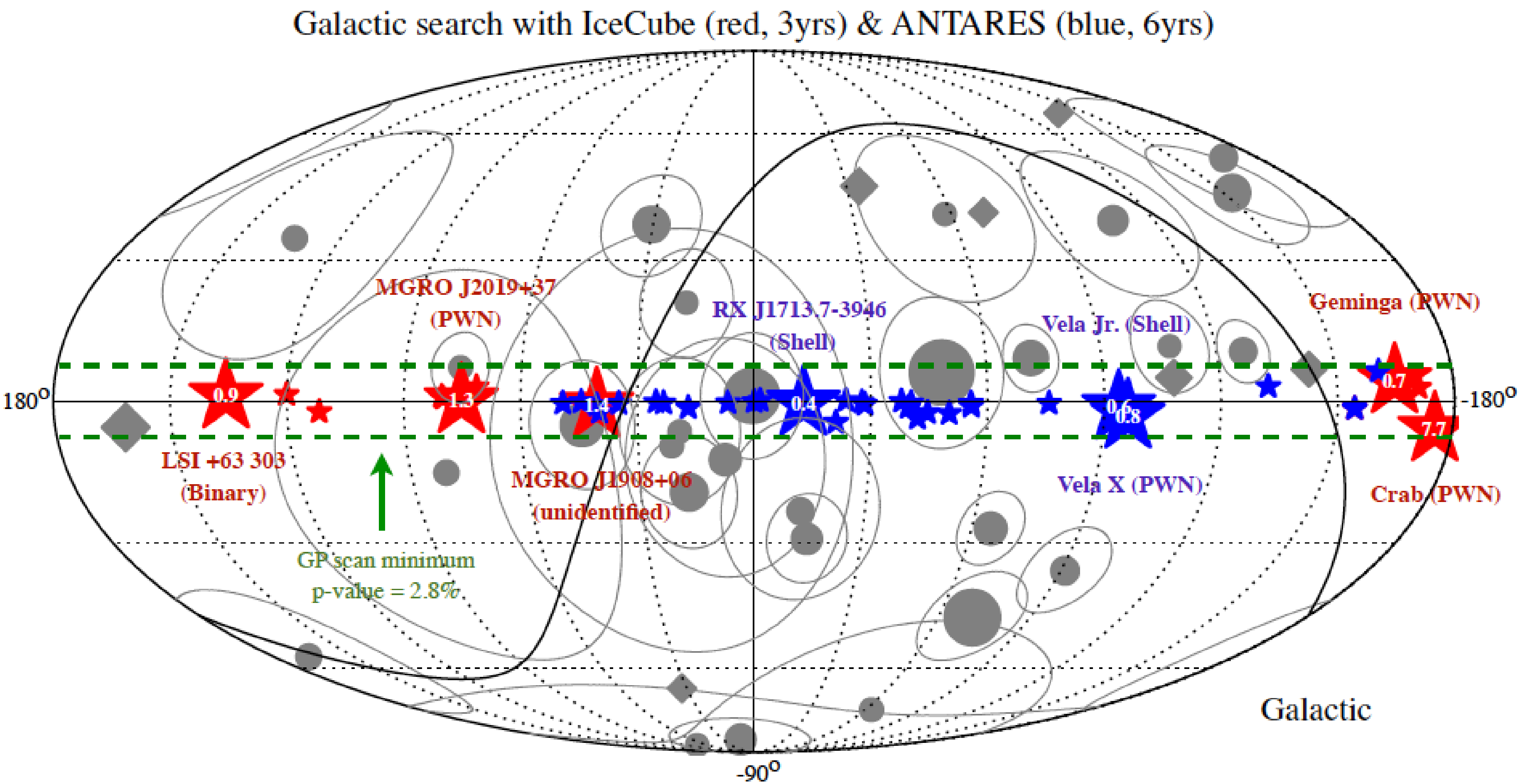
PeV neutrinos absorbed in the Earth

- 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

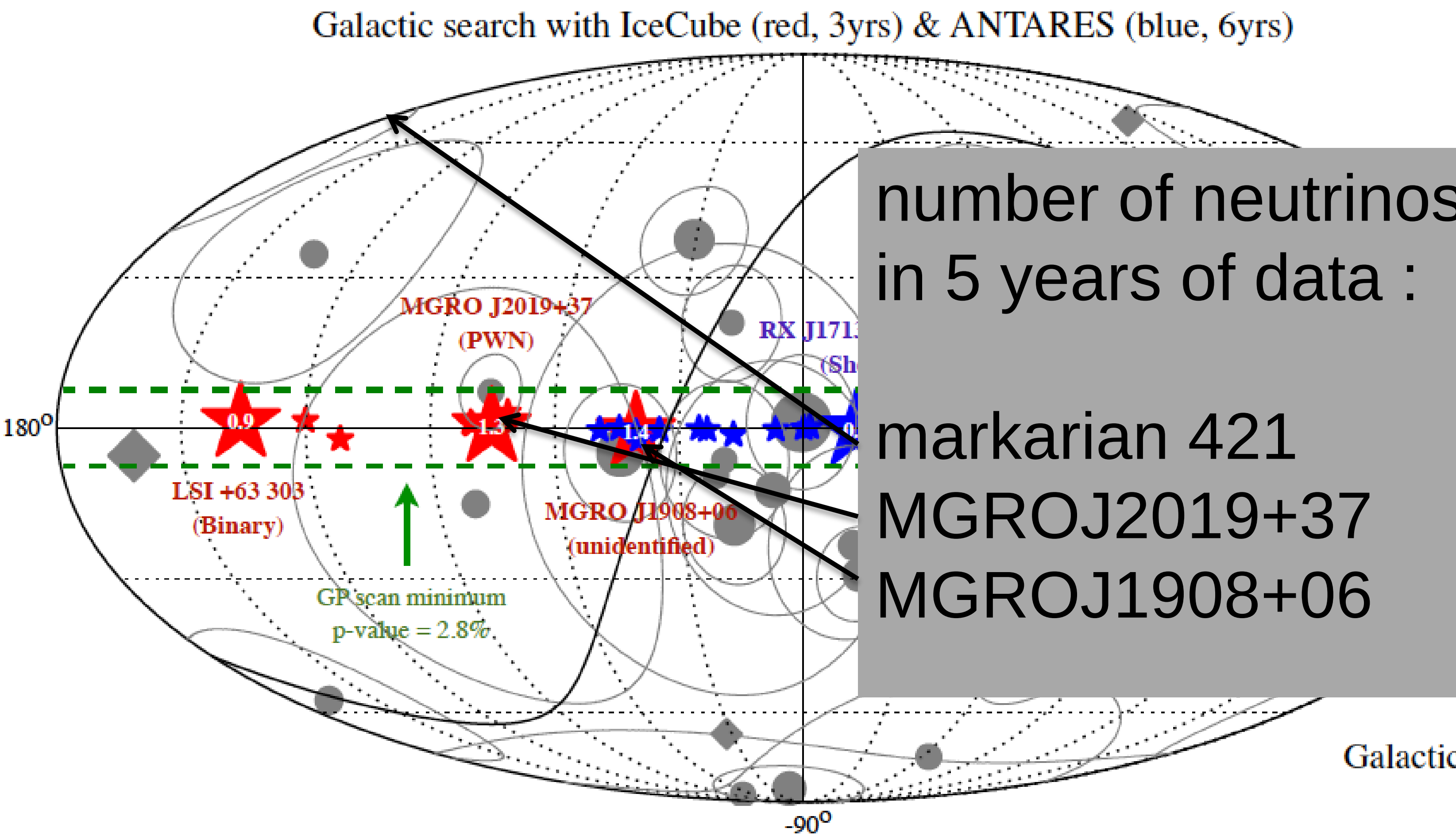
- gamma ray sources predict neutrinos. We are close to identifying point sources.

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

ratio of present limit / predicted neutrino flux

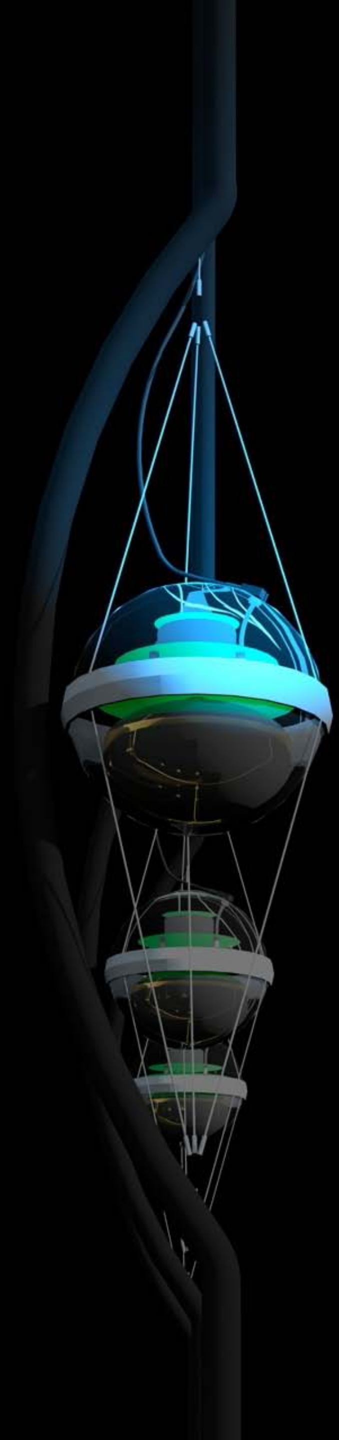


number of neutrinos
in 5 years of data :

markarian 421	8—14
MGROJ2019+37	3—7
MGROJ1908+06	6—13

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

- 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

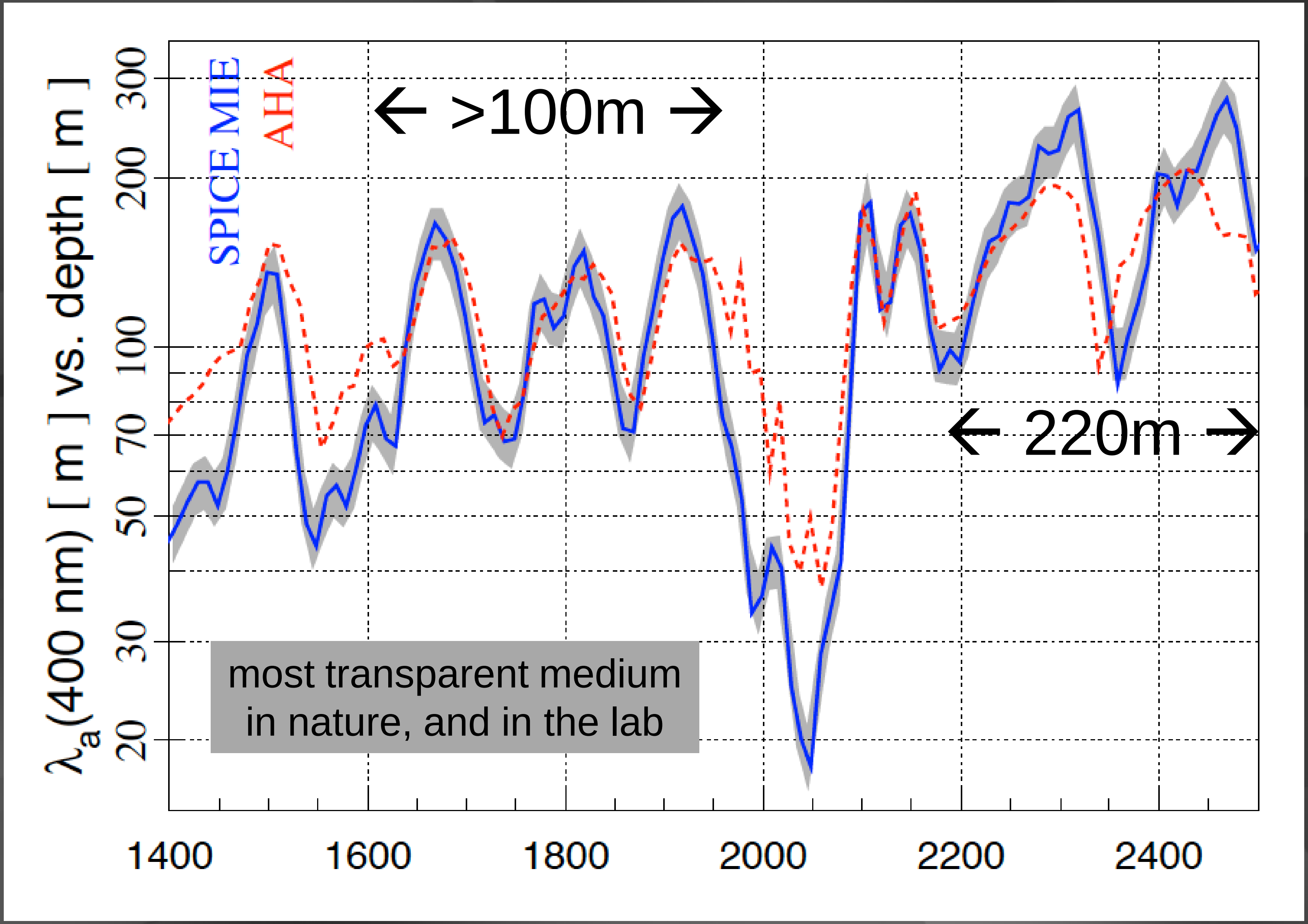
francis halzen

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

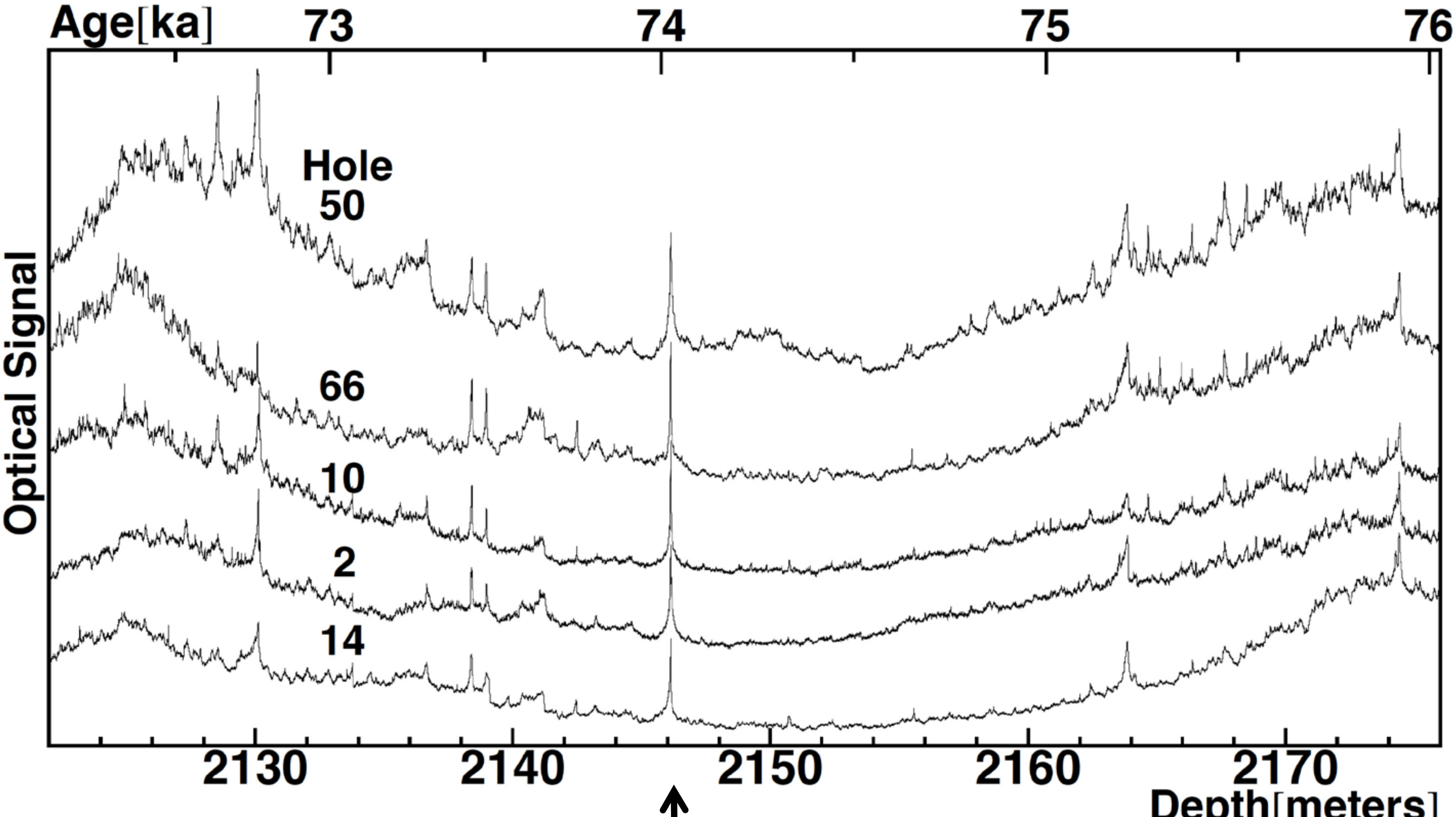
IceCube.wisc.edu

- 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



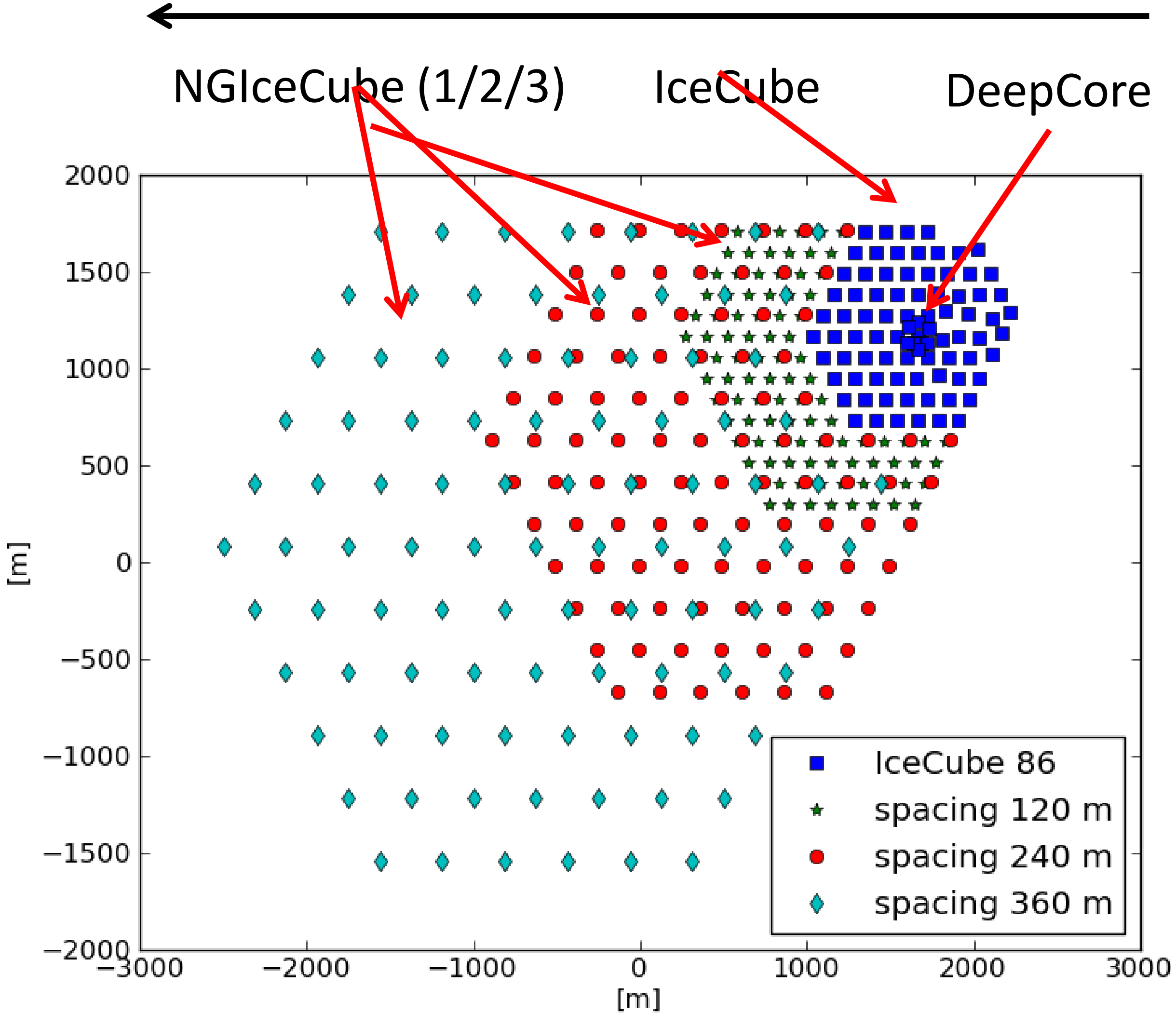
we are limited by computing, not the optics of the ice



Toba eruption

measured optical properties → twice the string spacing

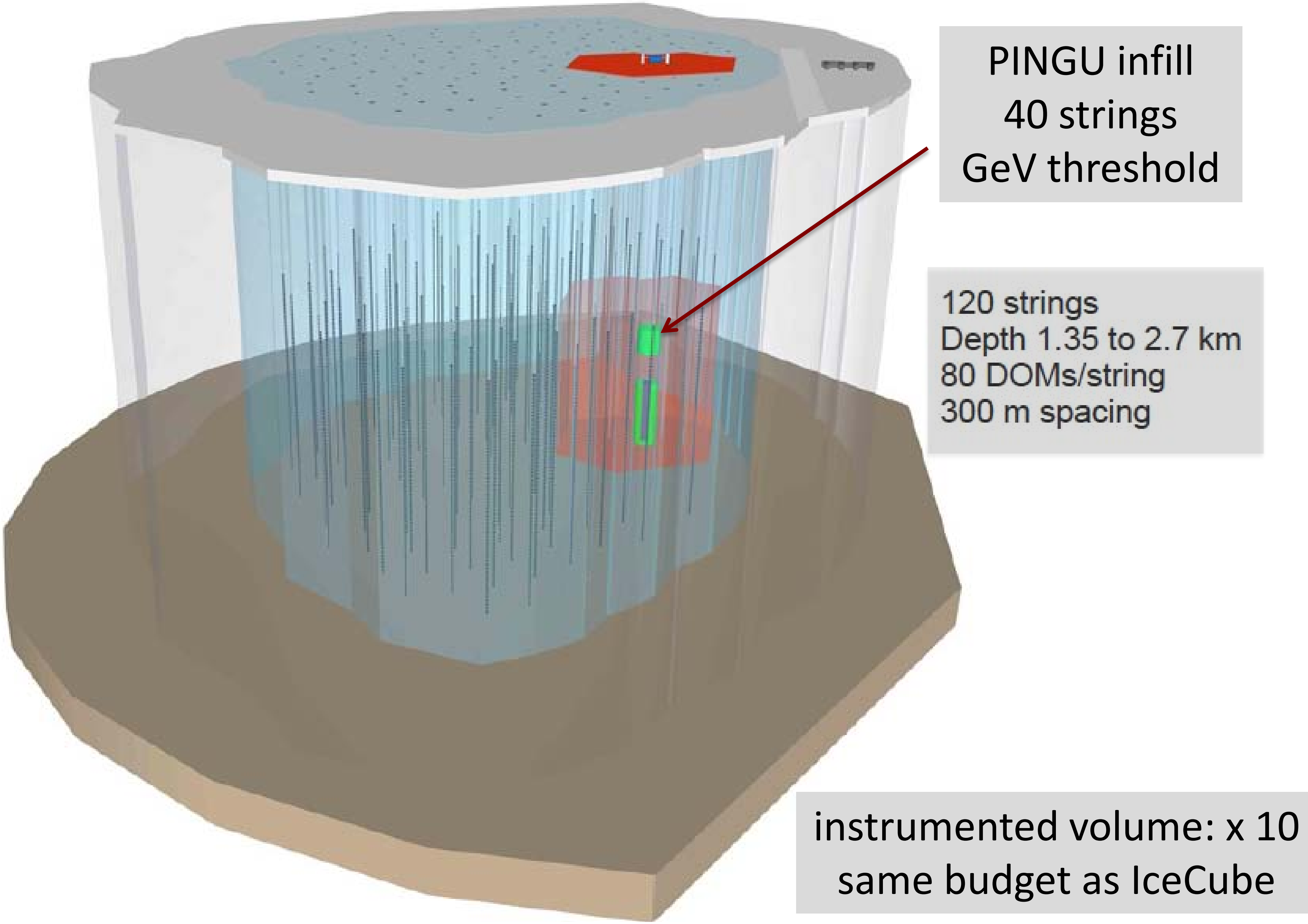
(increase in threshold not important: only eliminates energies where the atmospheric background dominates)



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

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

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


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 (world-best spin-dependent limits), monopoles,…
- search for eV-mass sterile neutrinos
- PINGU/ORCA
- ….

ANTARES → KM3NeT

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

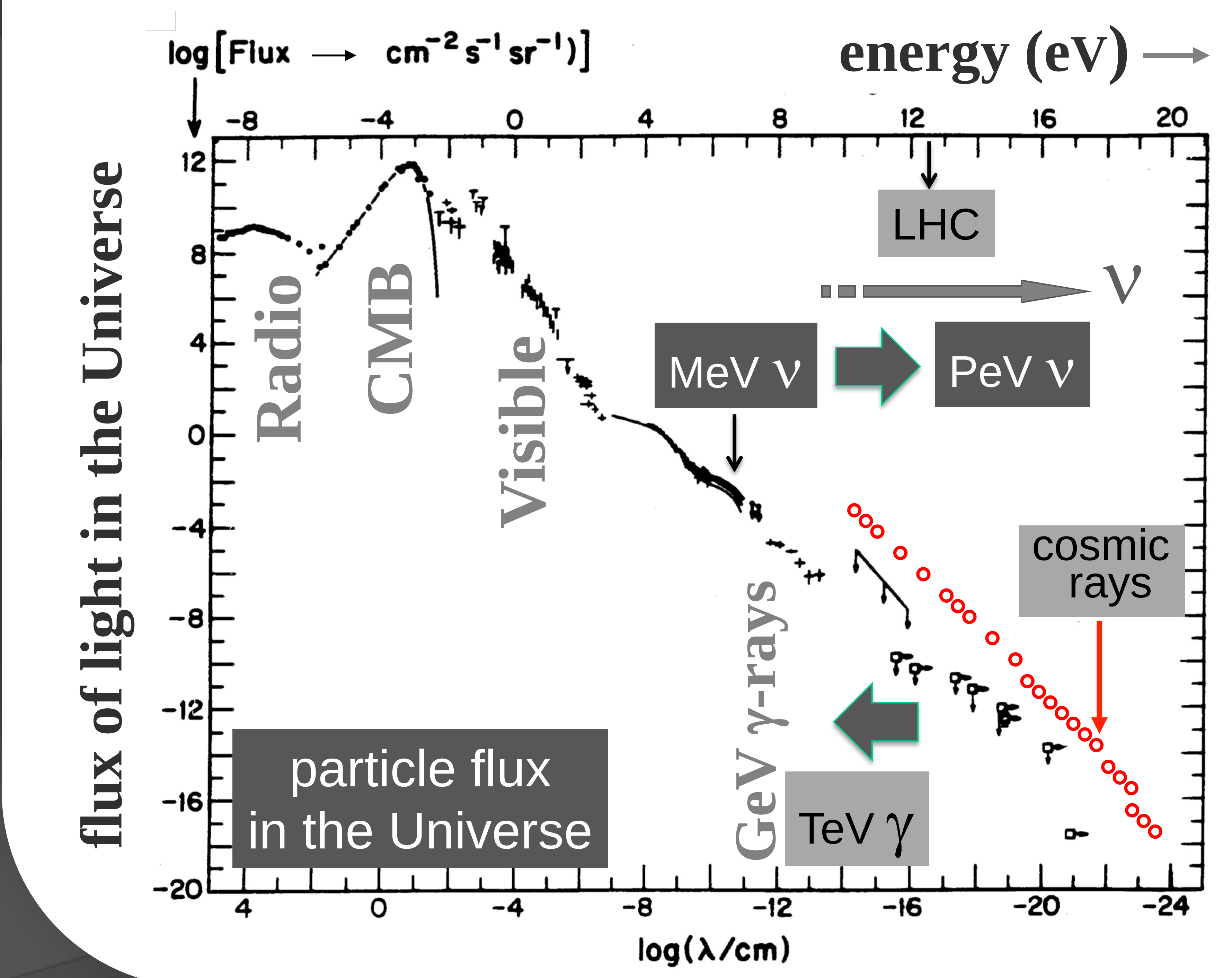
ANTARES → KM3NeT

Baikal → GVD

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)

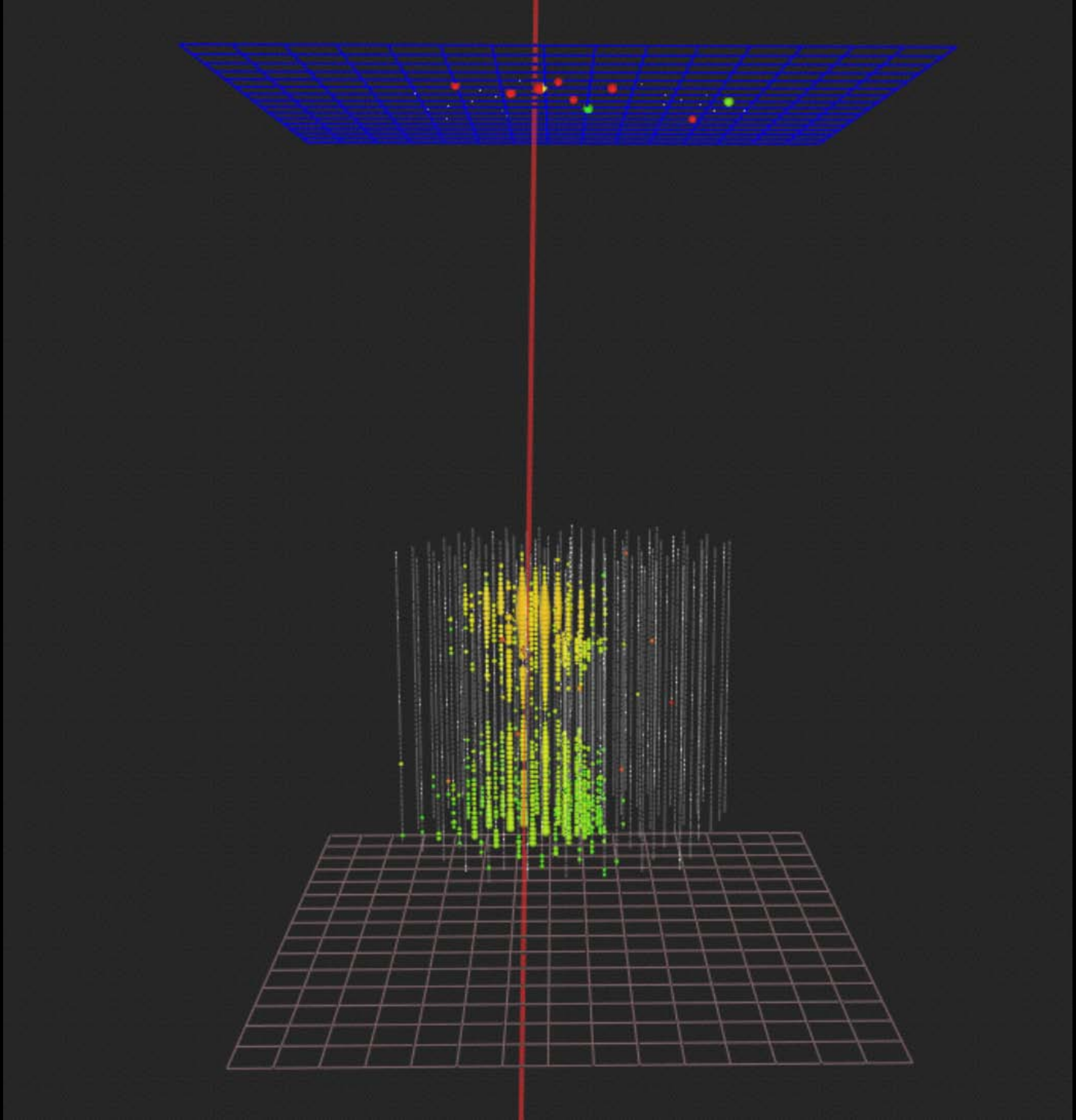

log[Flux → cm^-2 s^-1 sr^-1)]
energy (eV)
flux of light in the Universe
Radio
CMB
Visible
GeV γ-rays
LHC
ν
MeV ν
PeV ν
cosmic rays
particle flux in the Universe
TeV γ
log(λ/cm)


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

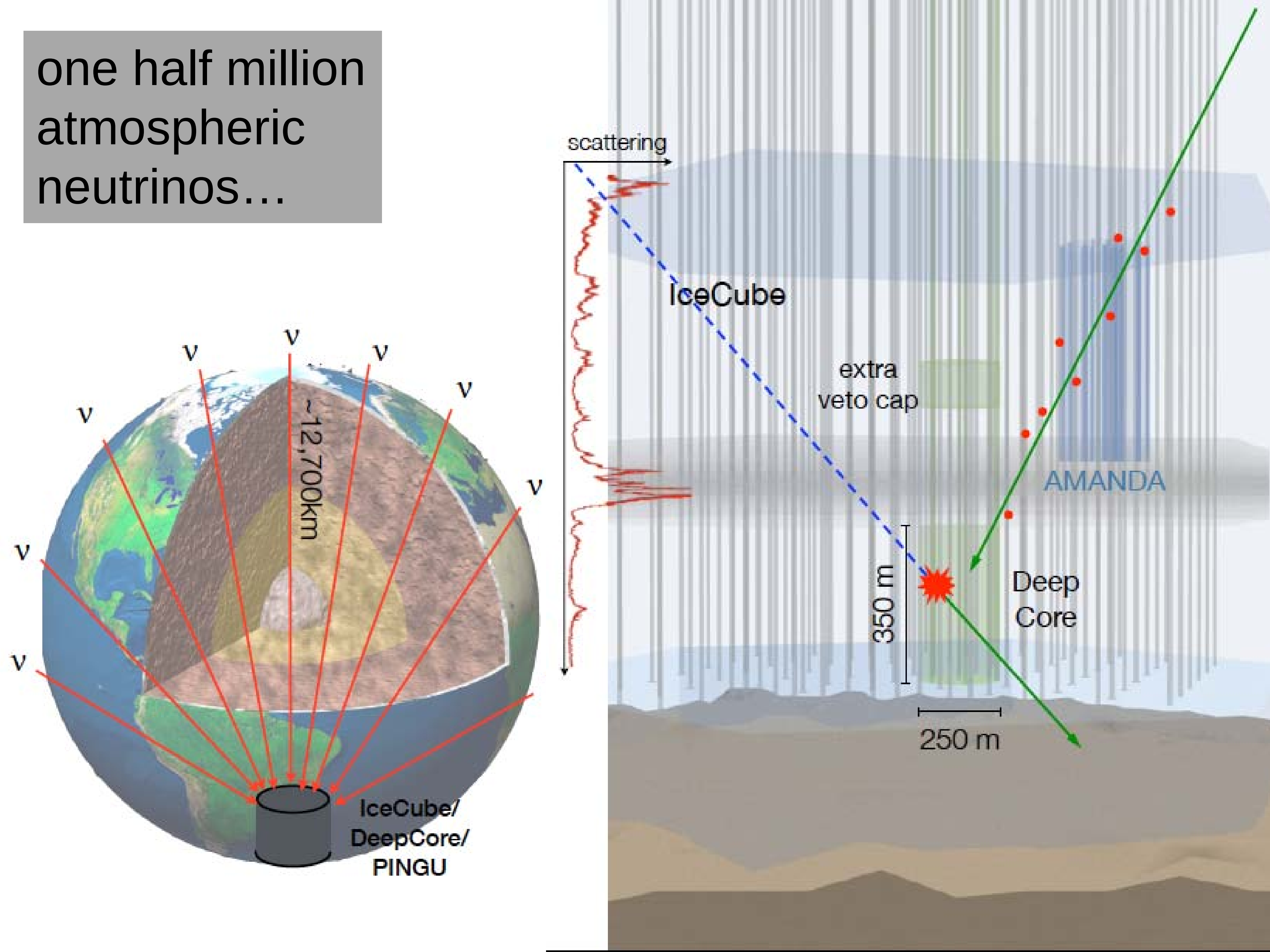
430 TeV

1 event:
~ 5 sigma
discovery

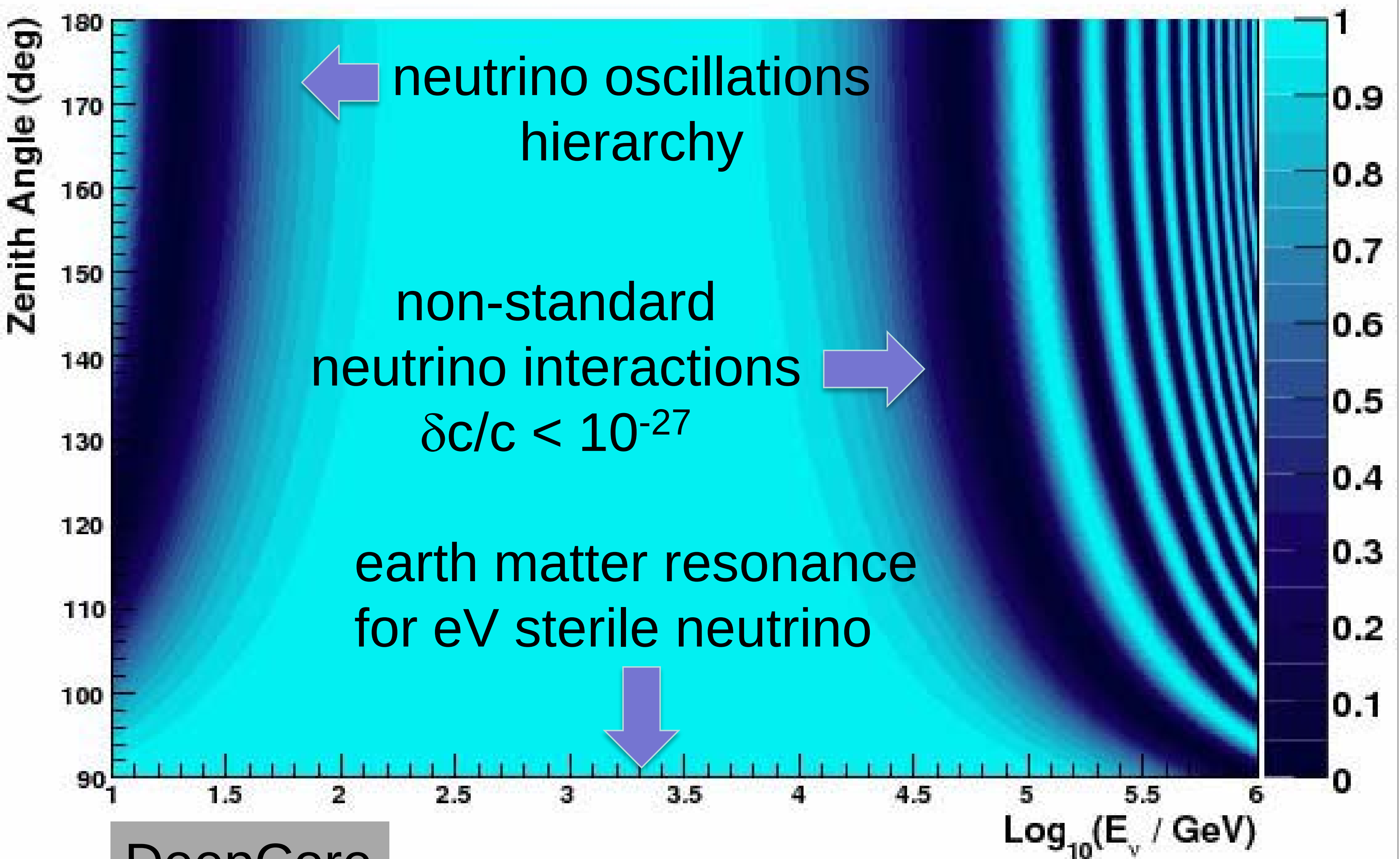
> PeV ν_μ



one half million atmospheric neutrinos…



one half million atmospheric neutrinos…

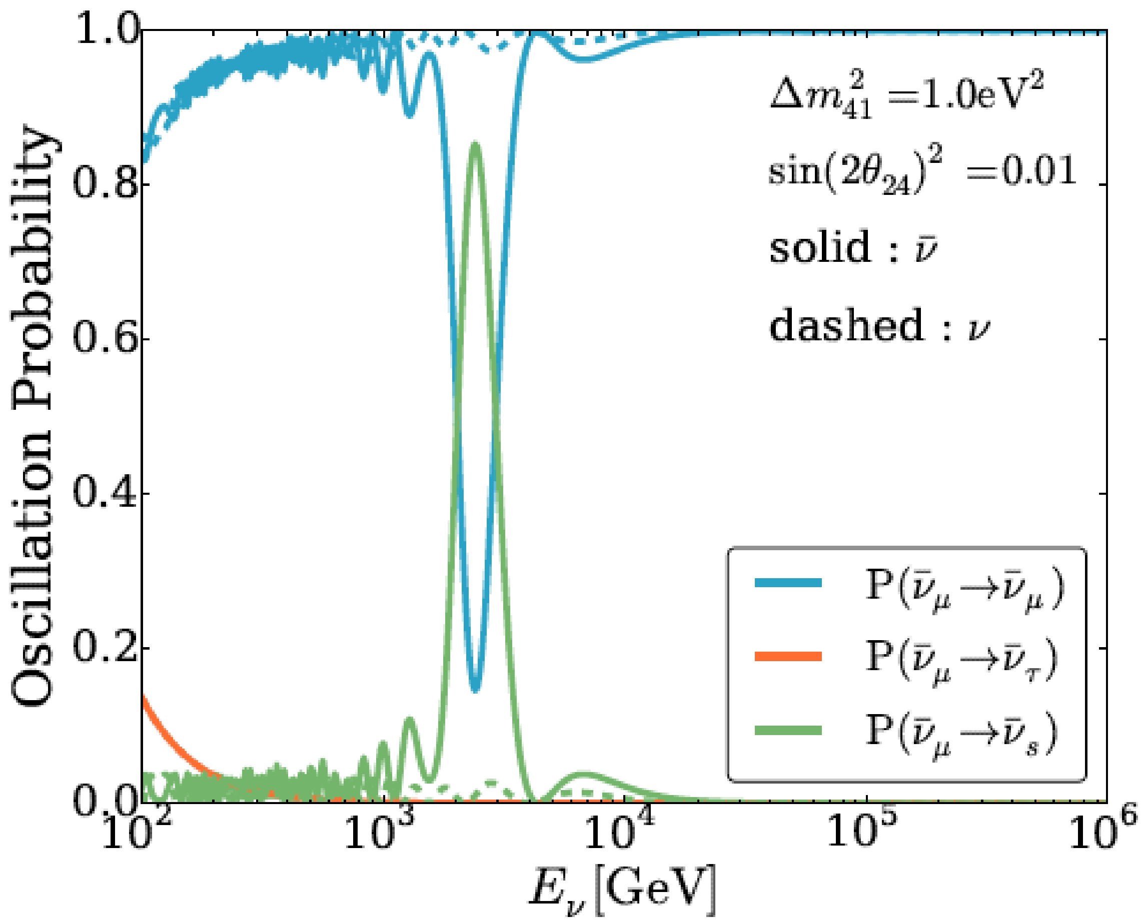


DeepCore

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

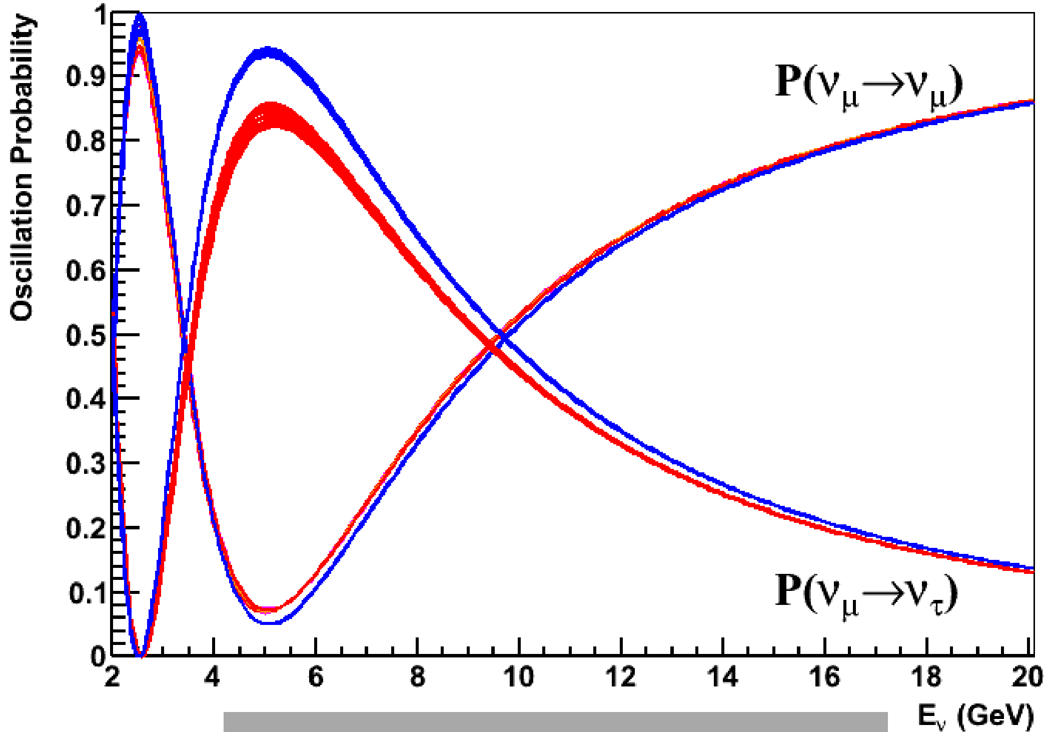
$$E_\nu = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N} \sim O(TeV)$$



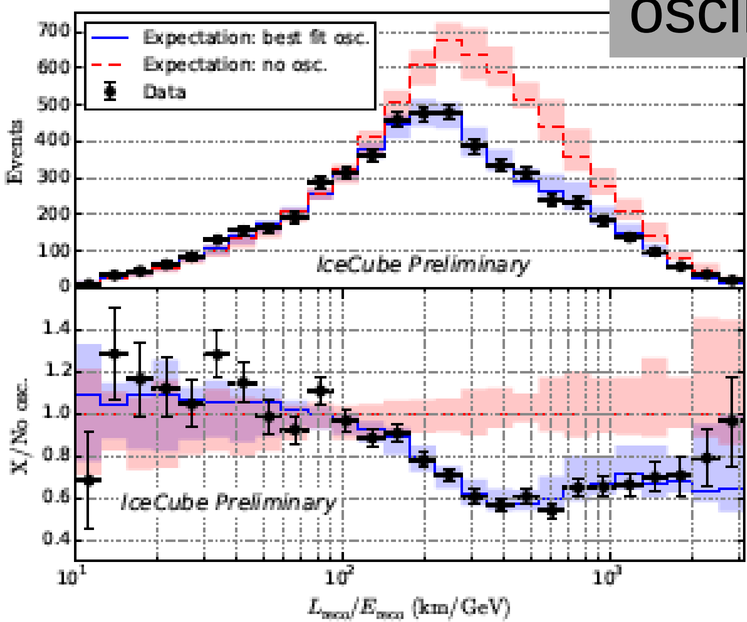
IceCube

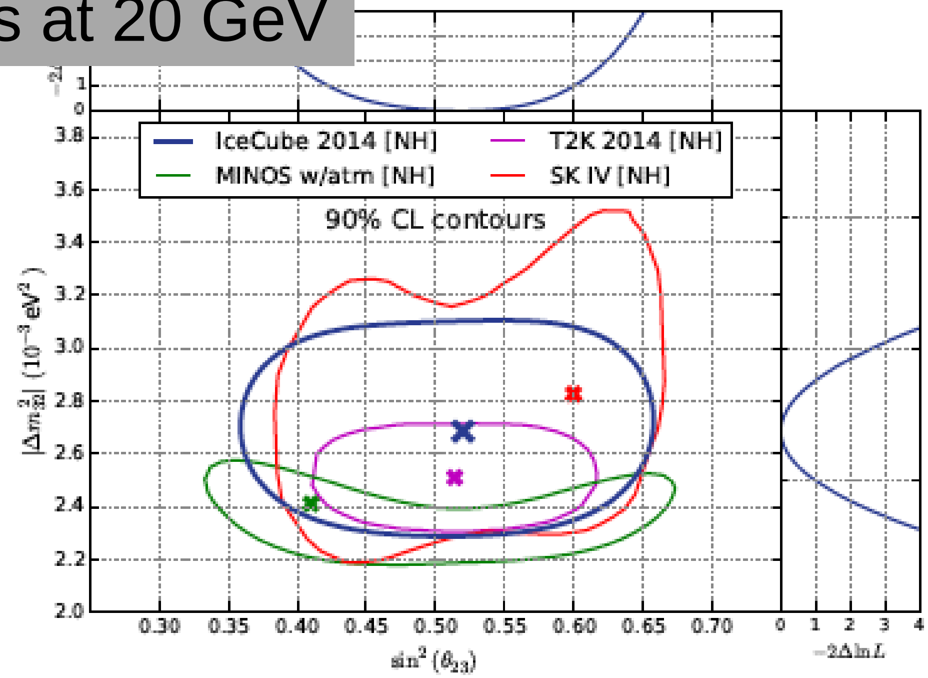
DeepCore

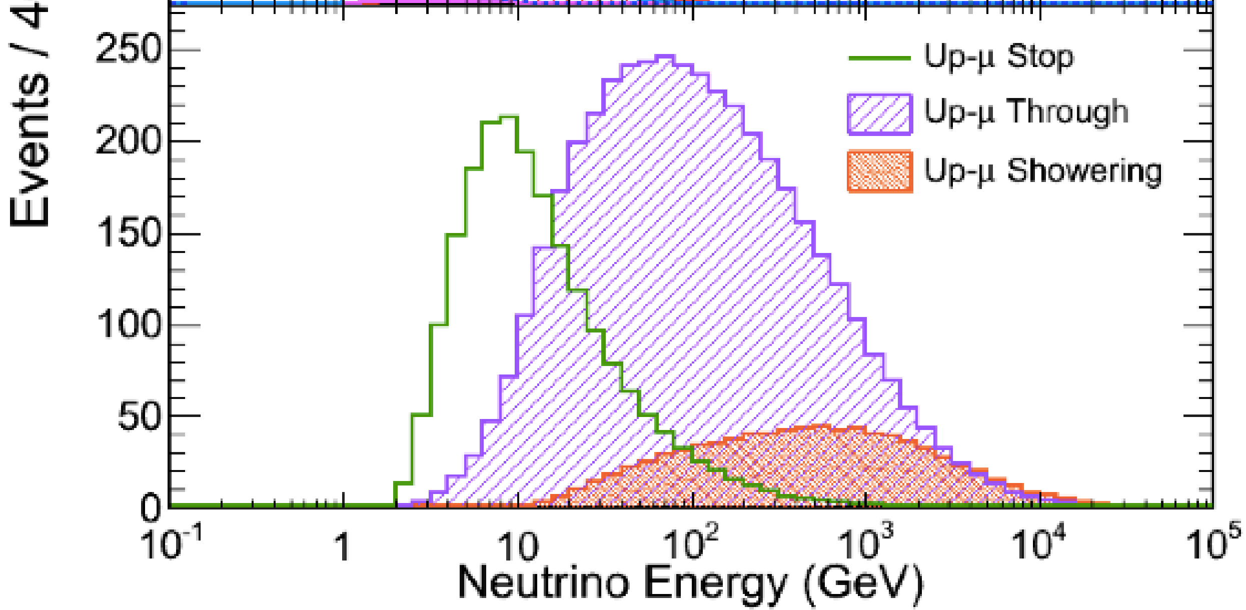
PINGU



oscillations at 20 GeV







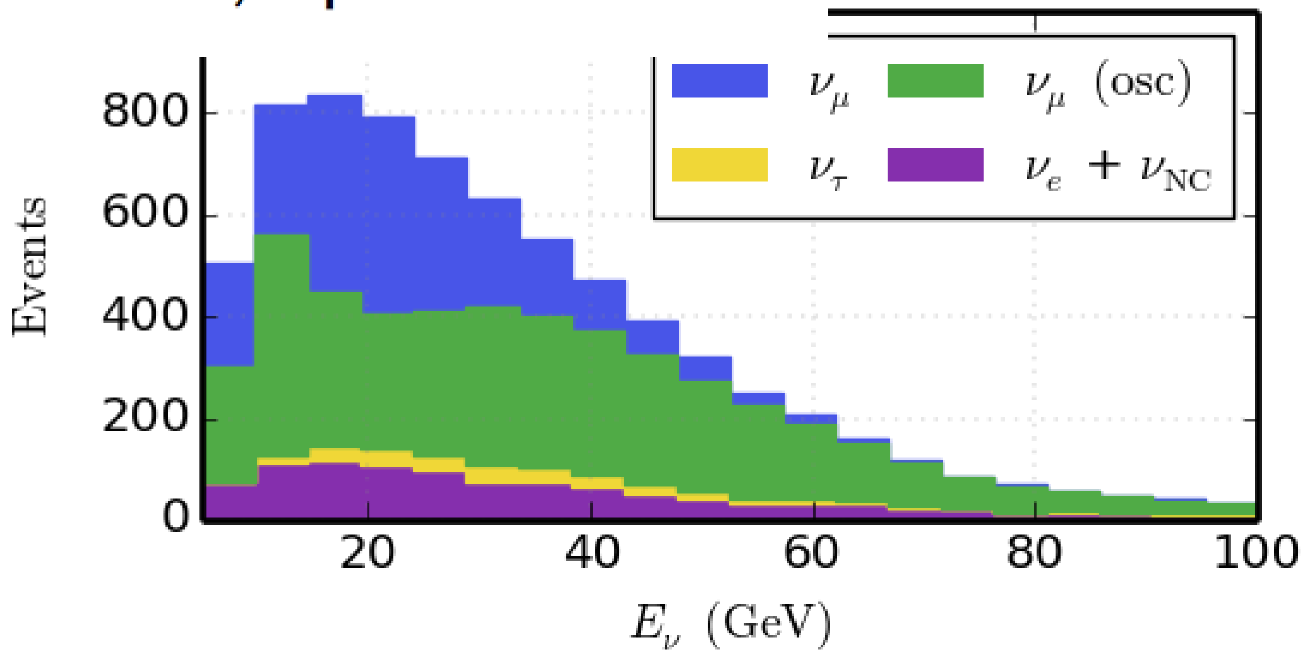
SuperK

~ 1 GeV

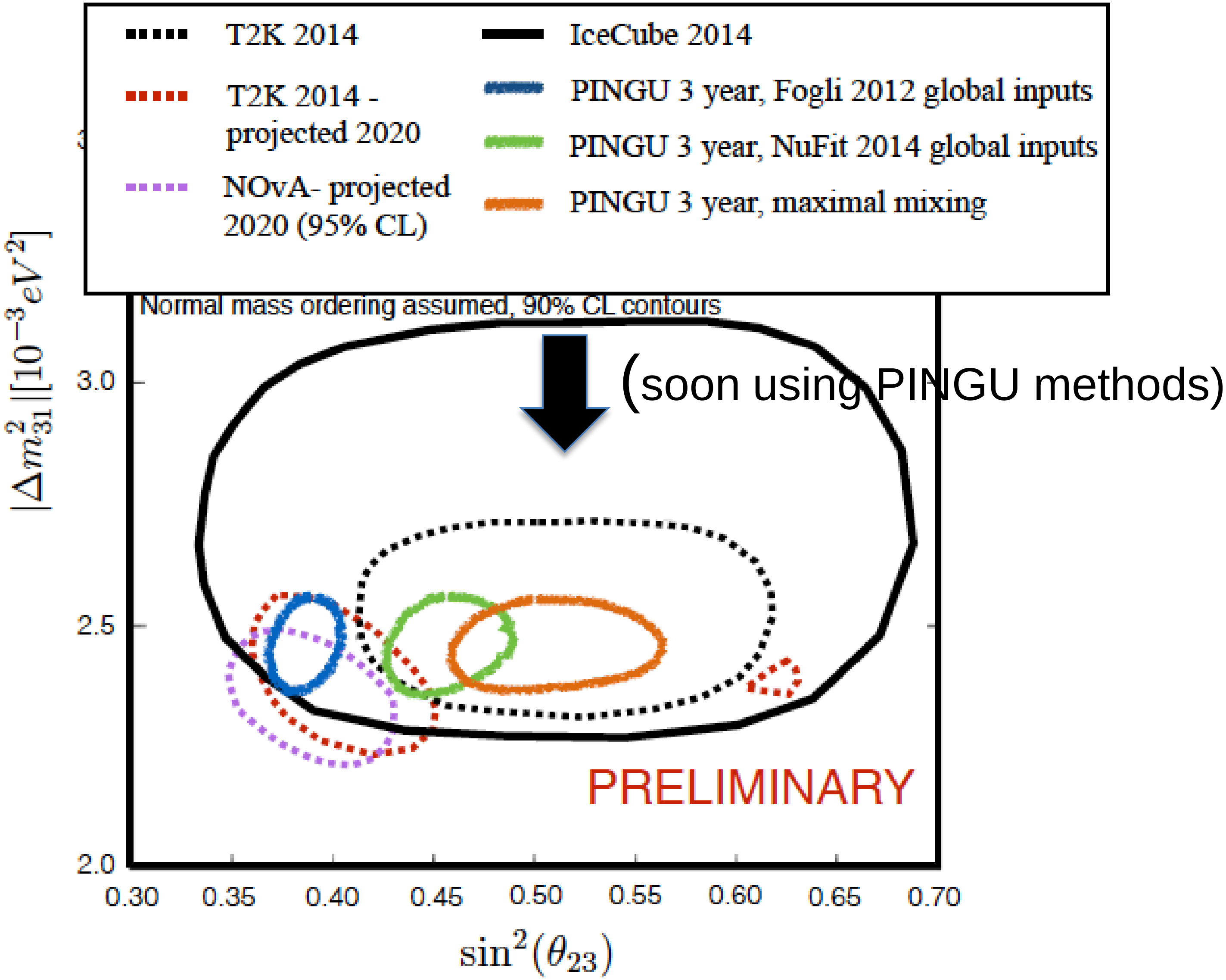
- Average energies
  - FC: ~1 GeV , PC: ~10 GeV, UpMu:~ 100 GeV

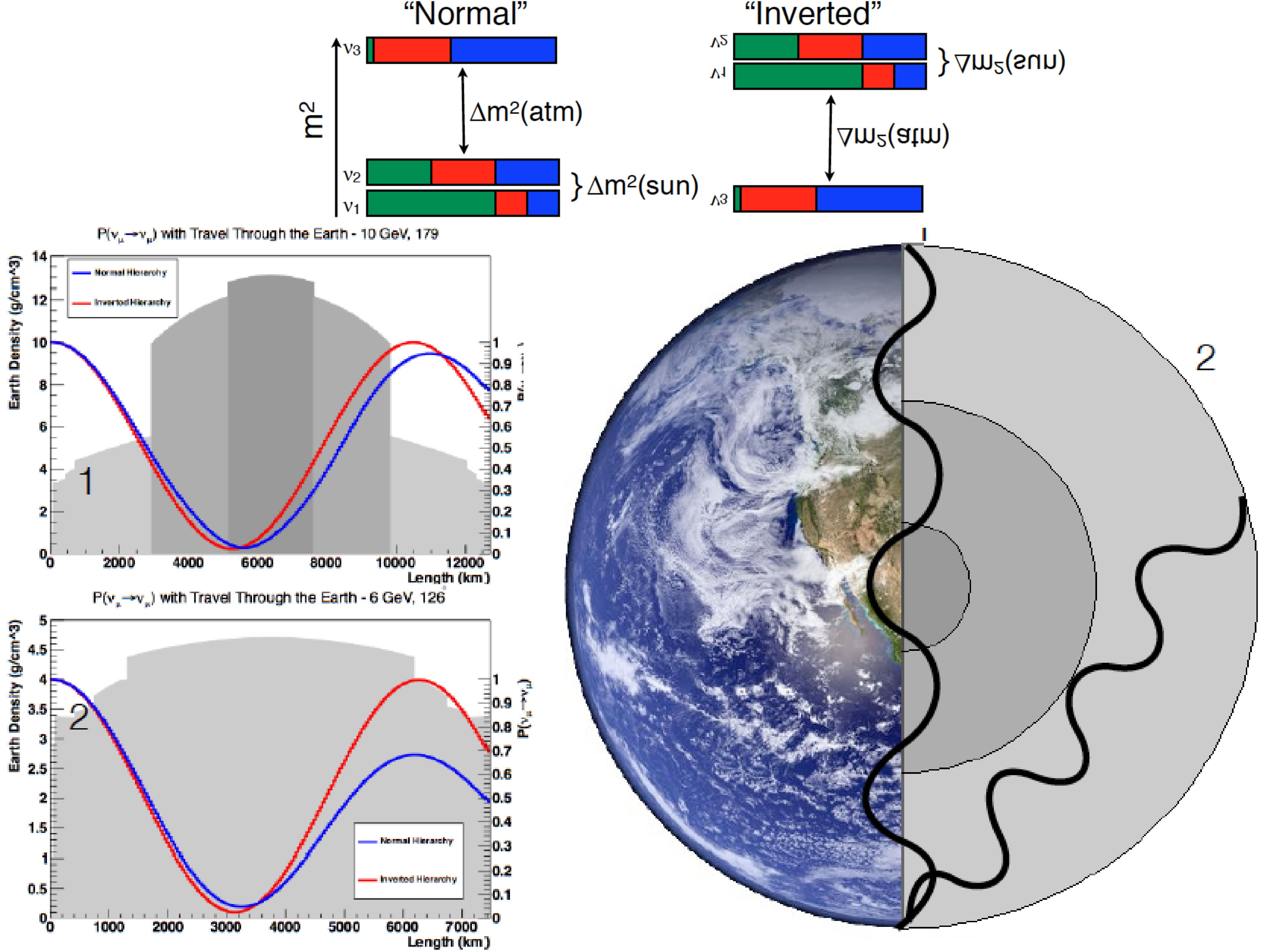
IceCube

6 GeV < E_{reco} < 56 GeV



and with PINGU…



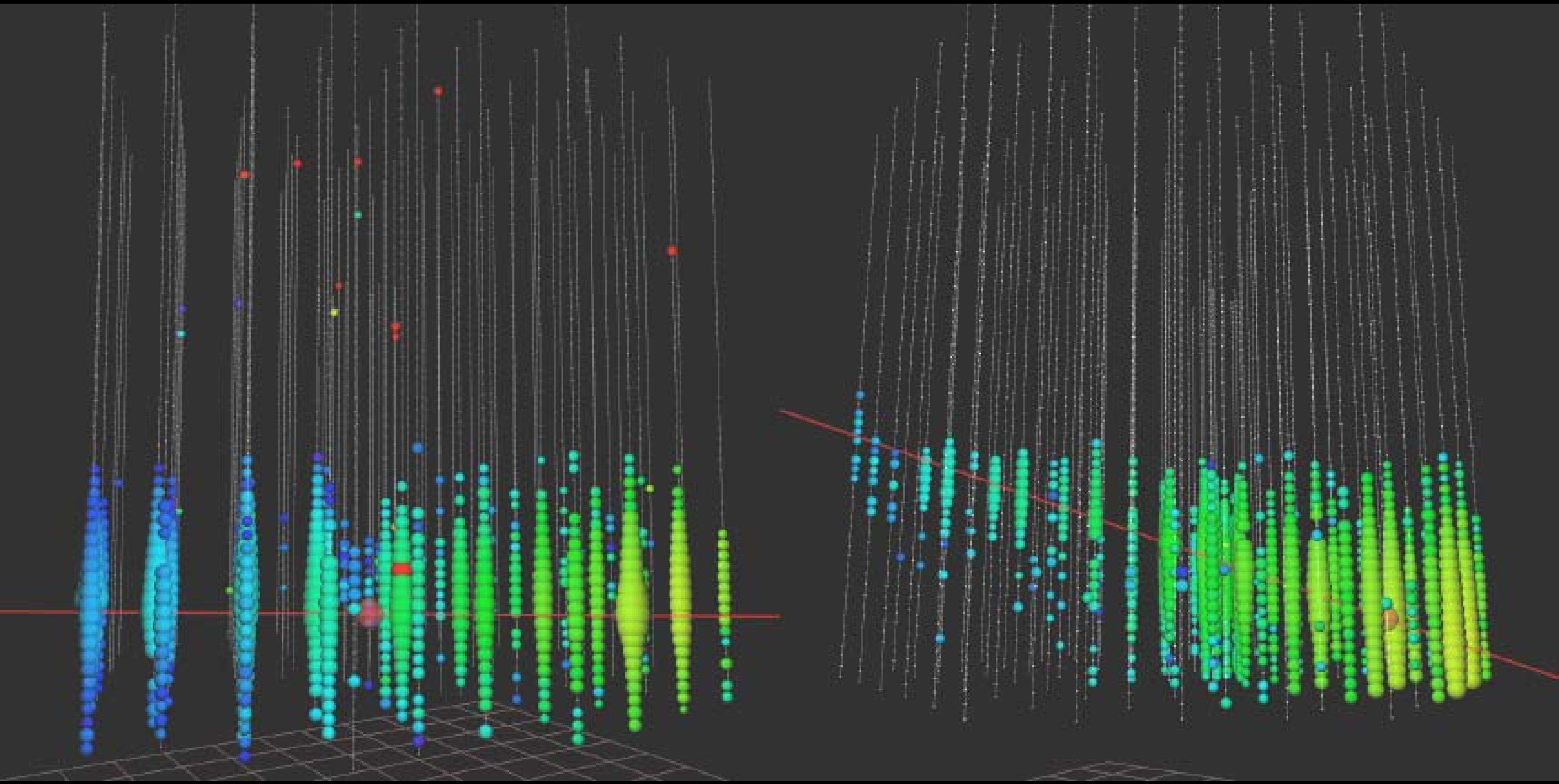


"Normal"
"Inverted"
m²
ν3
ν2
ν1
Δm²(atm)
Δm²(sun)
P(νμ→νμ) with Travel Through the Earth - 10 GeV, 179
Earth Density (g/cm^3)
Normal Hierarchy
Inverted Hierarchy
1
Length (km)
P(νμ→νμ) with Travel Through the Earth - 6 GeV, 126
Earth Density (g/cm^3)
P(νμ→νμ)
2
Normal Hierarchy
Inverted Hierarchy
Length (km)
2

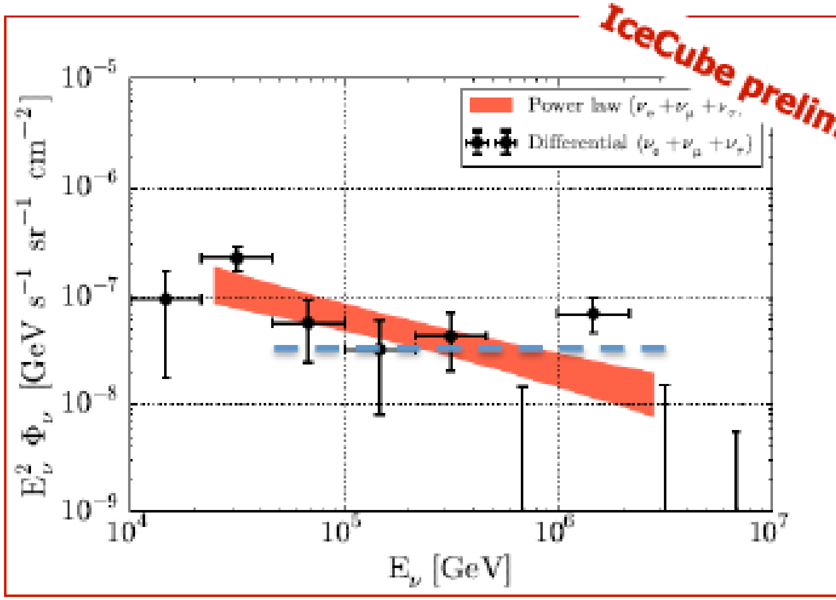
neutrino as a cosmic messenger:

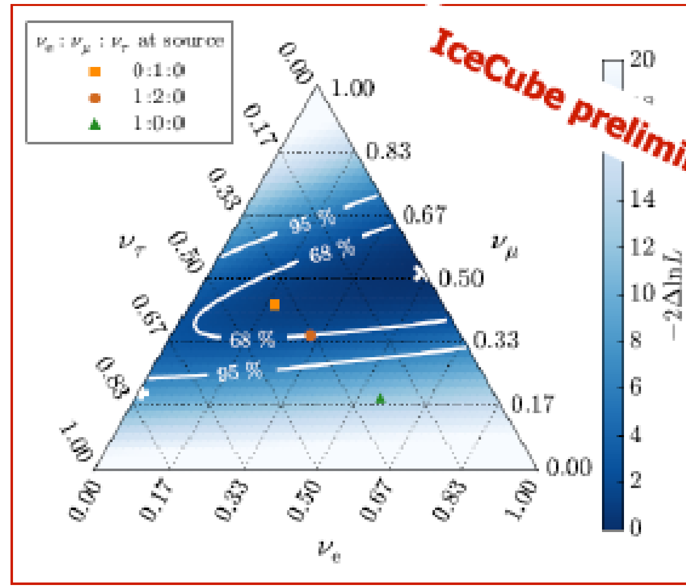
- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- … but difficult to detect

highest energy muon energy observed: 560 TeV
→ PeV ν_μ



- 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 $\nu_e:\nu_\mu:\nu_\tau$ = 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)

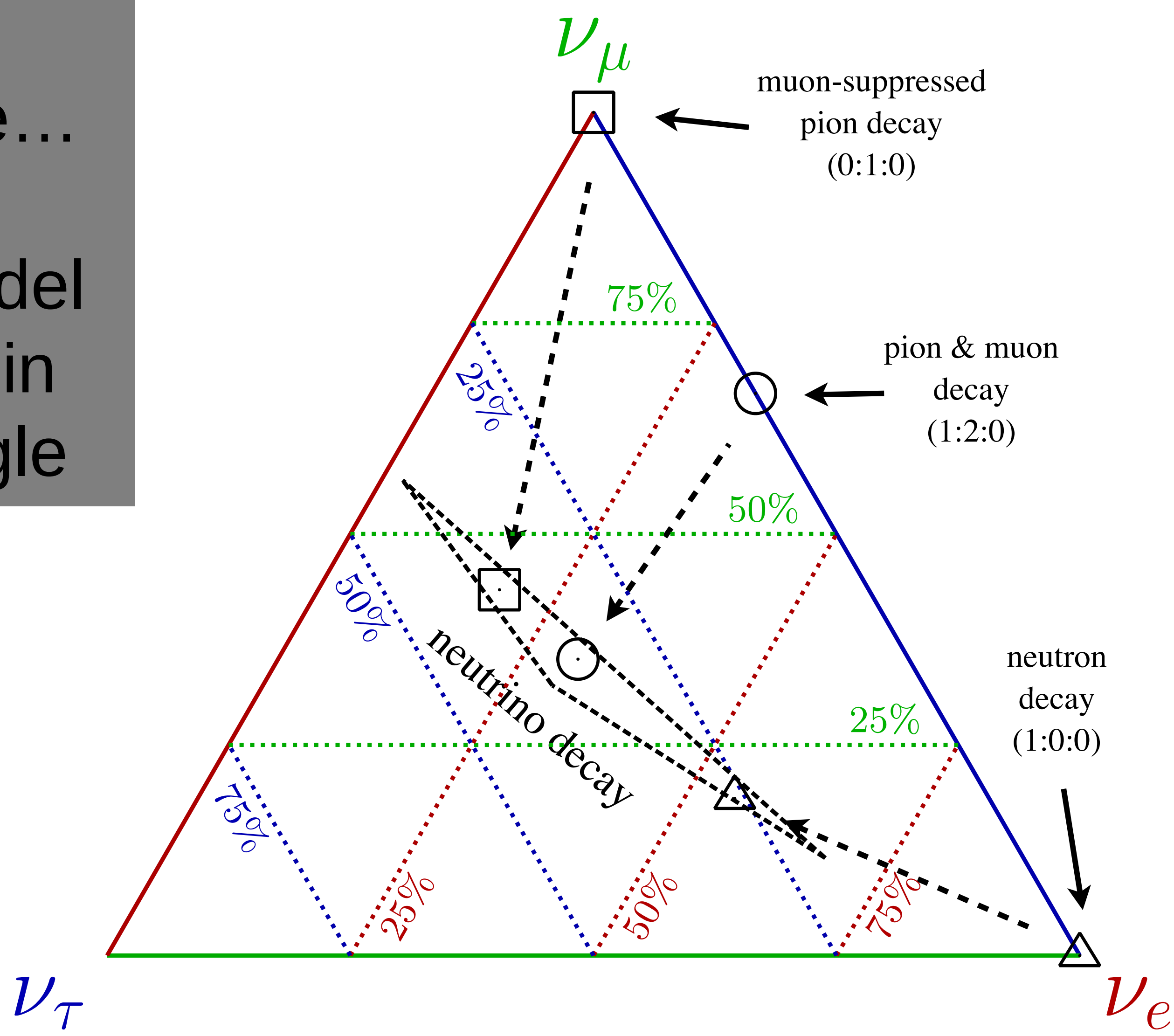
flux at 100 TeV $(6.7 \pm 1.2)\times10^{-18}$ (GeV · cm^2 · s · sr)$^{-1}$

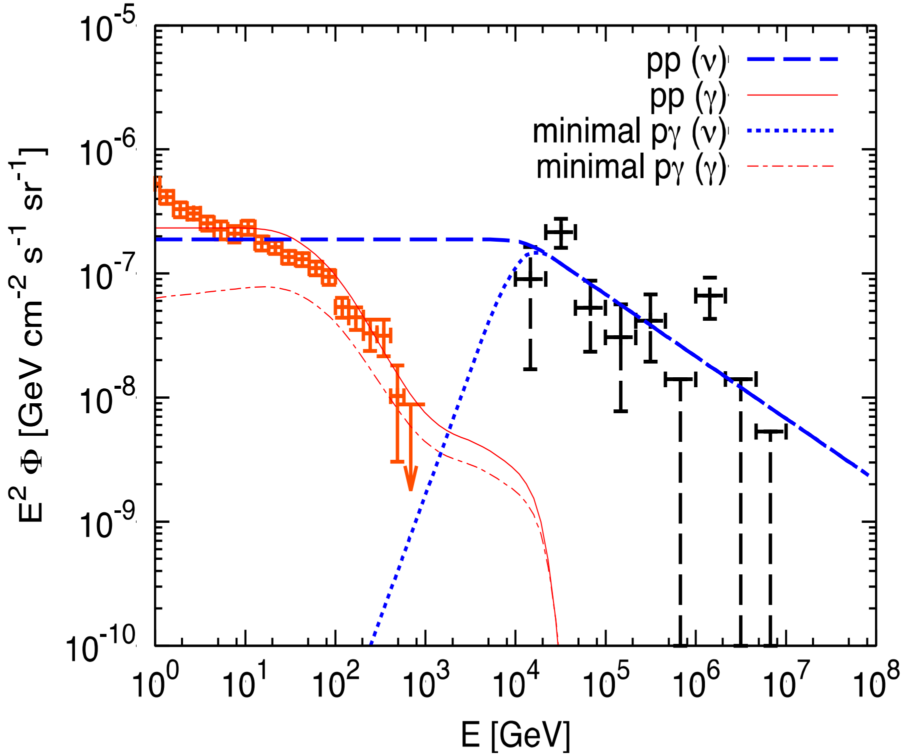
the best fit flavor composition disfavors 1:0:0 at source at 3.6 σ

new physics ?

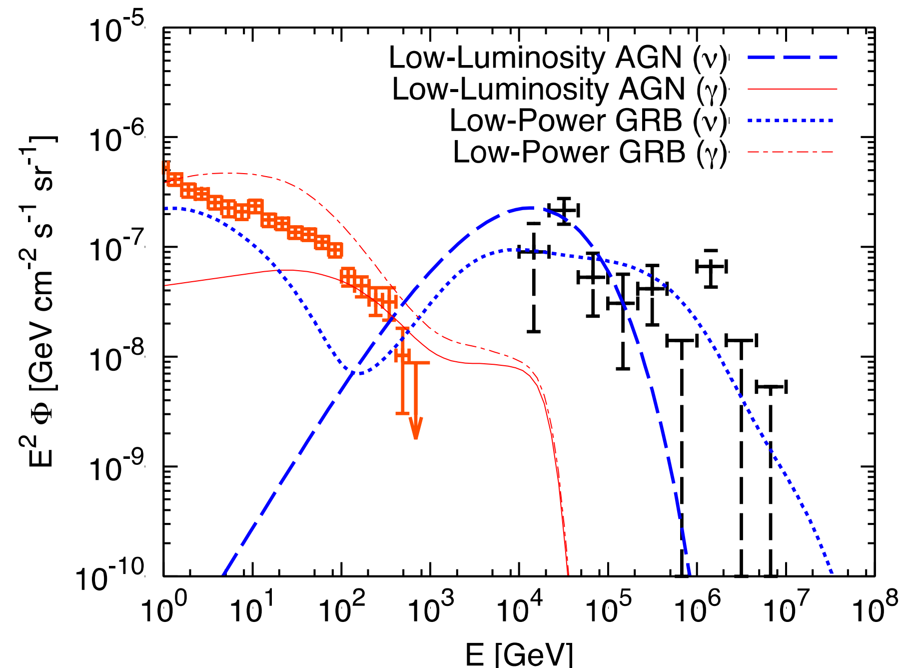
otherwise...

every model ends up in the triangle

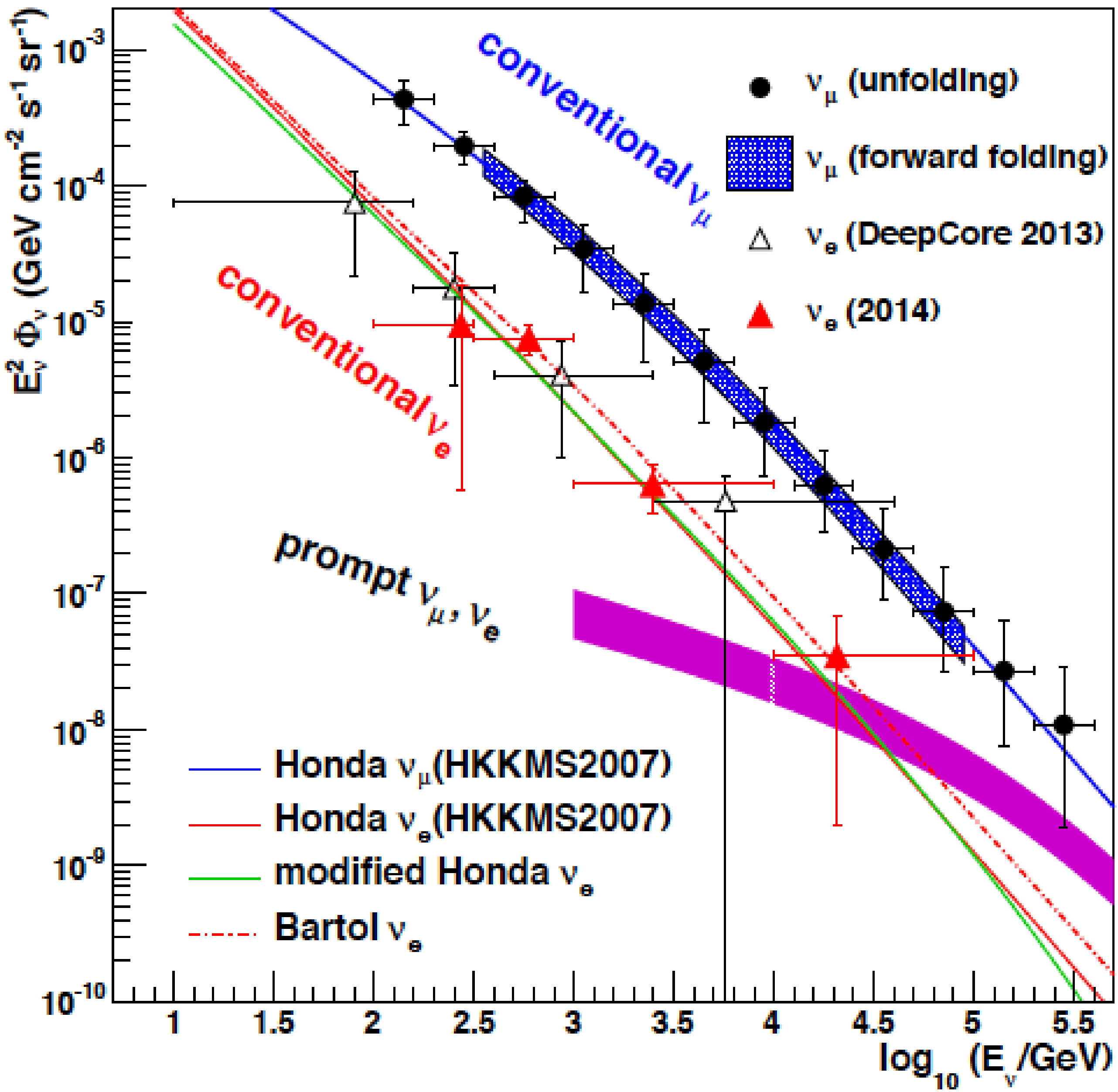




pp (ν)
pp (γ)
minimal pγ (ν)
minimal pγ (γ)
E² Φ [GeV cm⁻² s⁻¹ sr⁻¹]
E [GeV]



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]



$E_\nu^2 \Phi_\nu$ (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_ν/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