IceCube

francis halzen

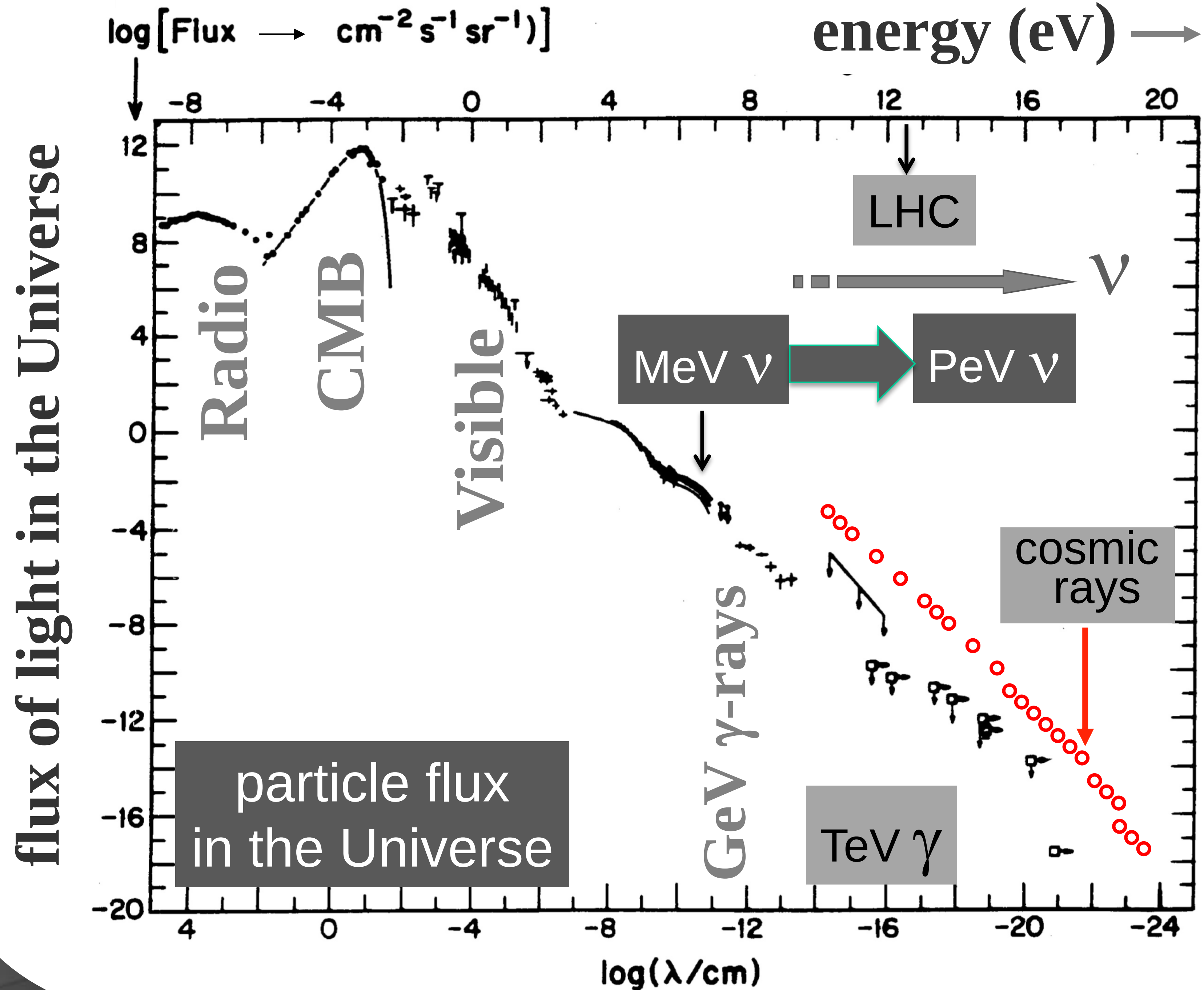
- why would you want to build a
  a kilometer scale neutrino detector?

- IceCube: a cubic kilometer detector

- the discovery (and confirmation) of cosmic neutrinos

- from discovery to astronomy

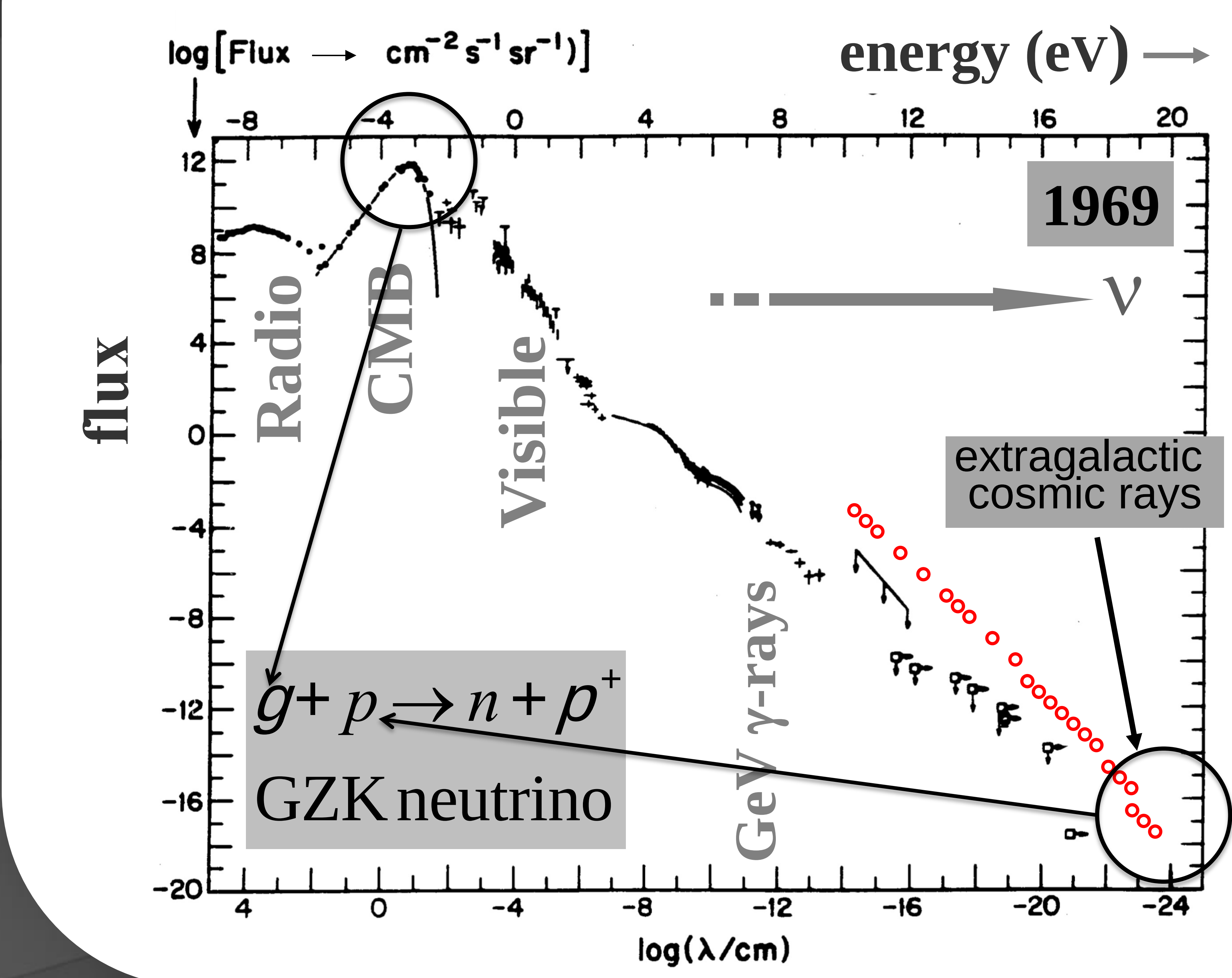
IceCube.wisc.edu



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



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

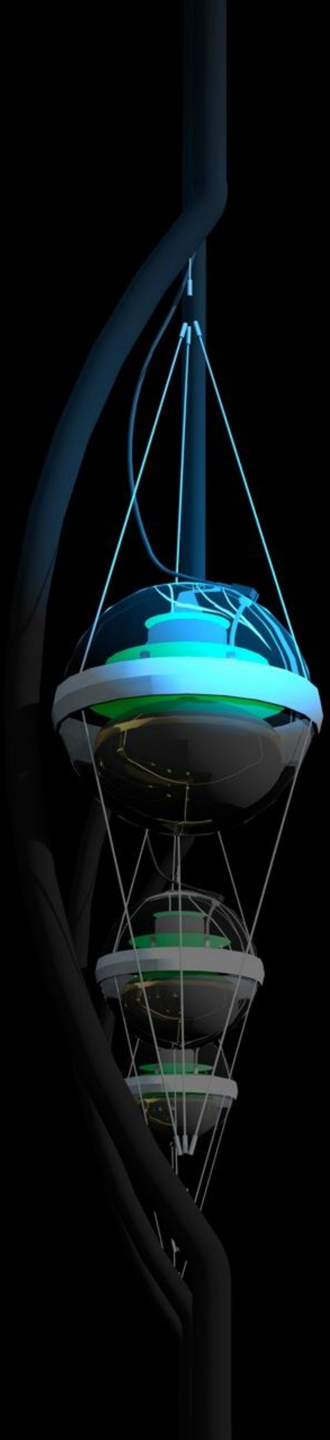
cosmic rays interact with the microwave background

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

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

$$p \rightarrow m + u_{m} \rightarrow \{e+\overline{u_{m}}+u_{e}\}+u_{m}$$

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

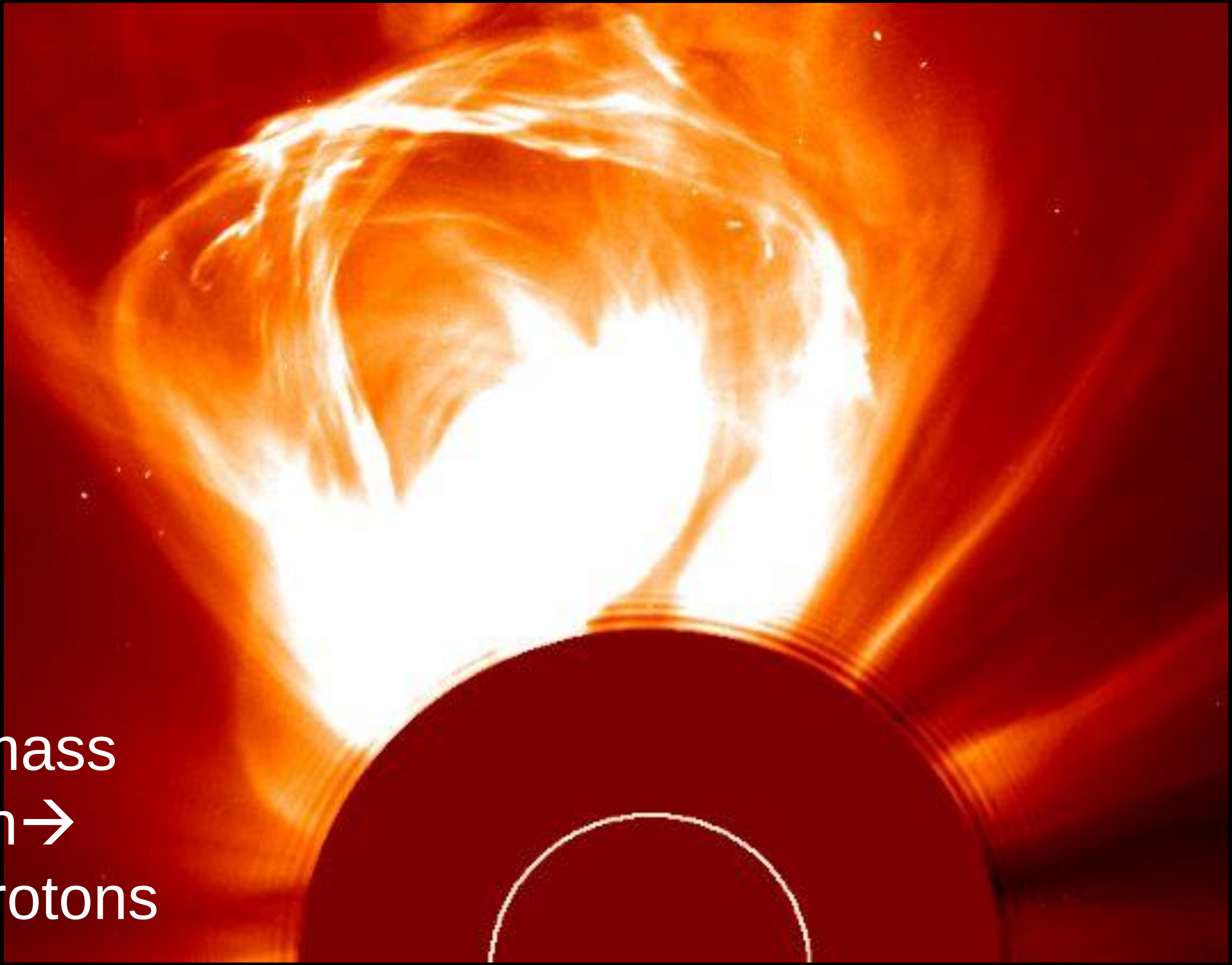
$$R_{gyro}\left(=\frac{E}{\mathrm{v}qB}\right)\leq R$$

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

challenges of cosmic ray astrophysics:

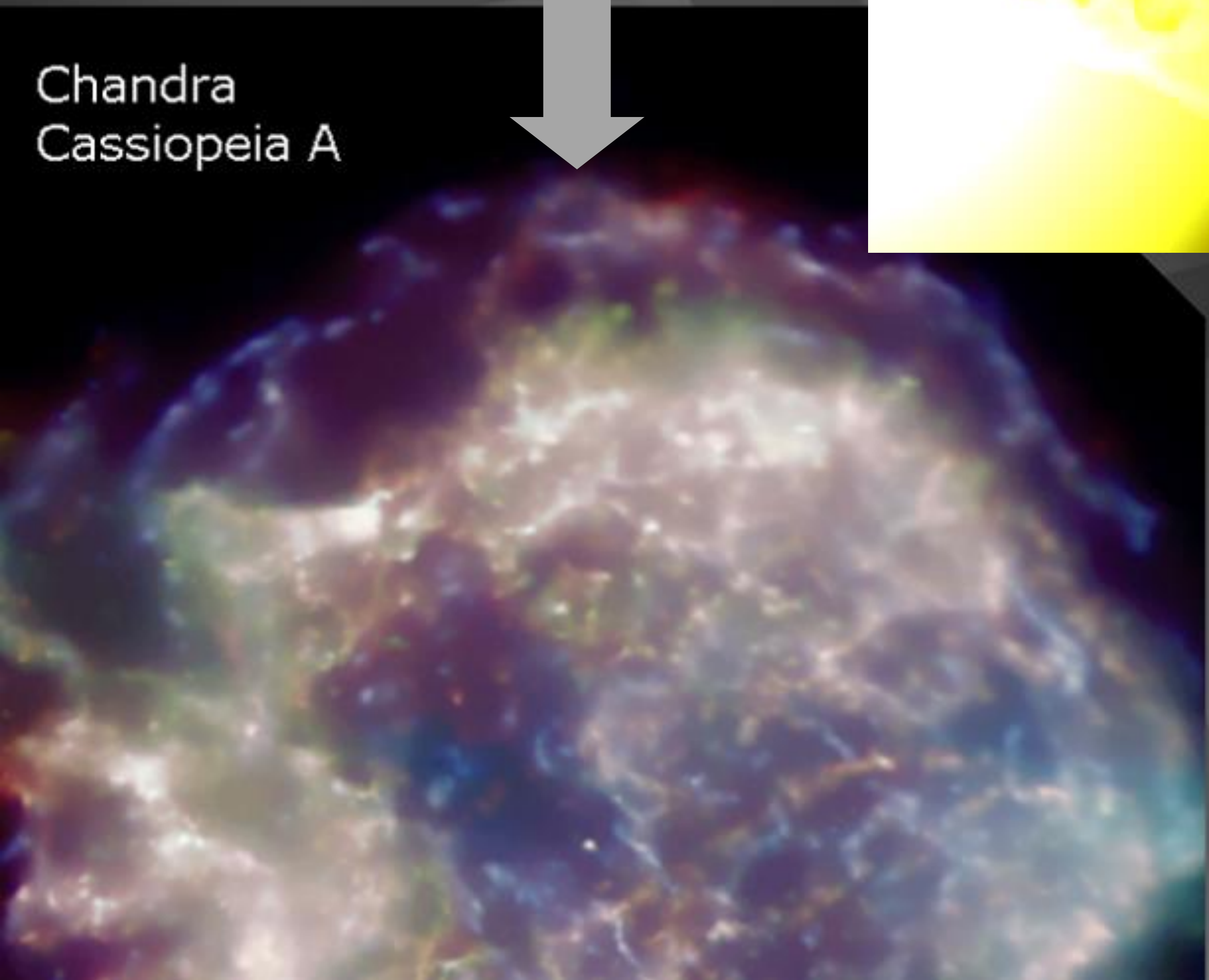
- dimensional analysis, difficult to satisfy
- accelerator luminosity is high as well

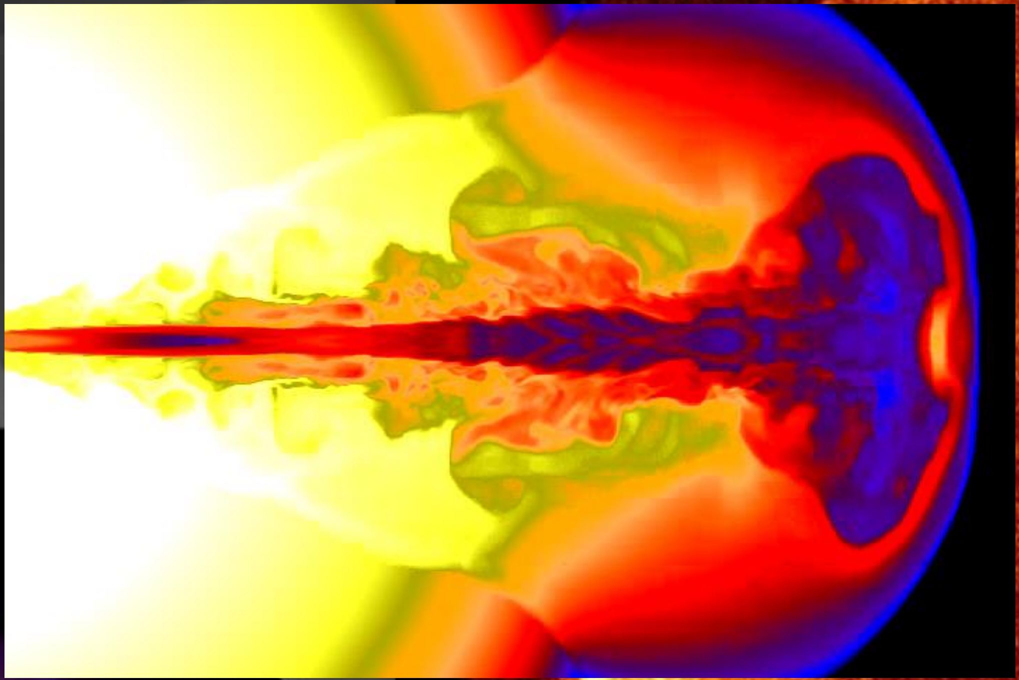
the sun constructs an accelerator



coronal mass ejection→ 10 GeV protons

supernova remnants

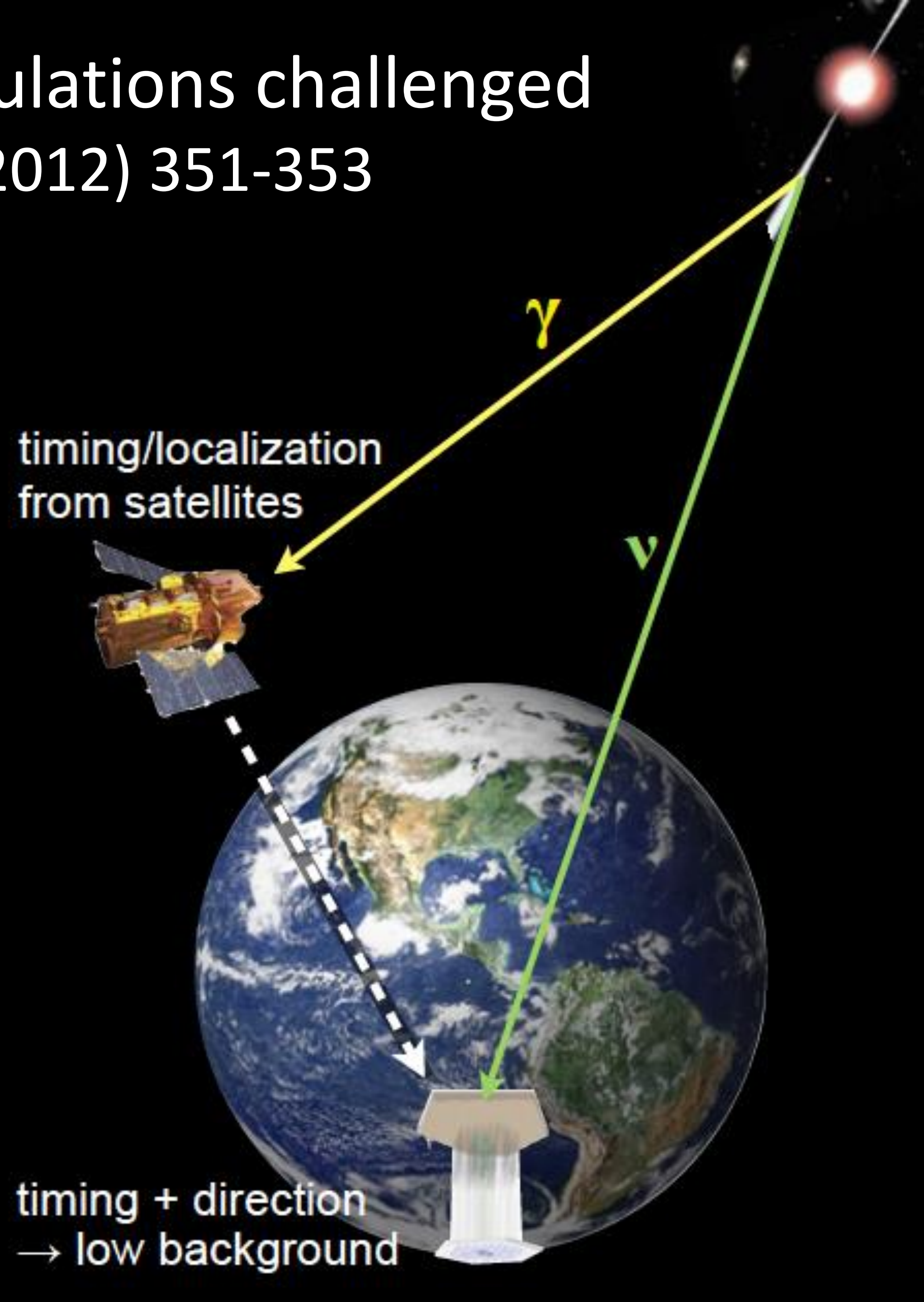


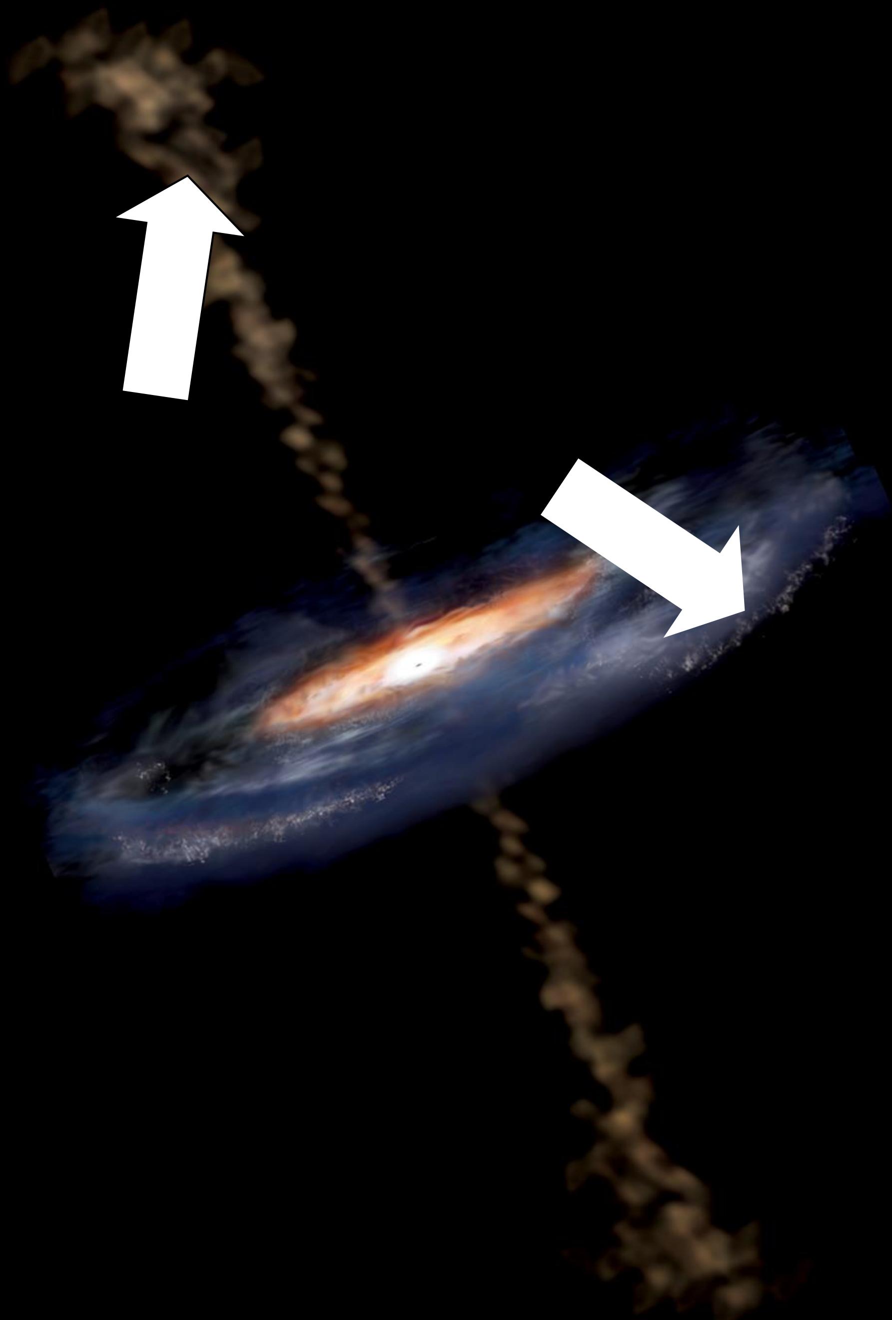


gamma ray bursts

fireball calculations challenged

Nature 484 (2012) 351-353

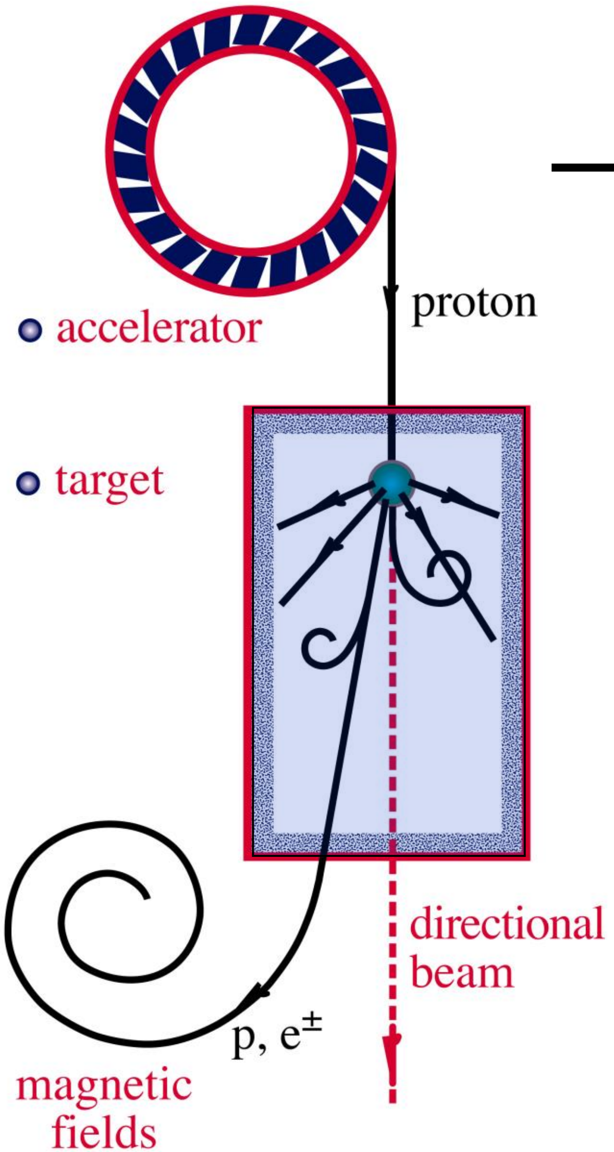




active galaxy

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

$$\rightarrow p + \pi^0$$

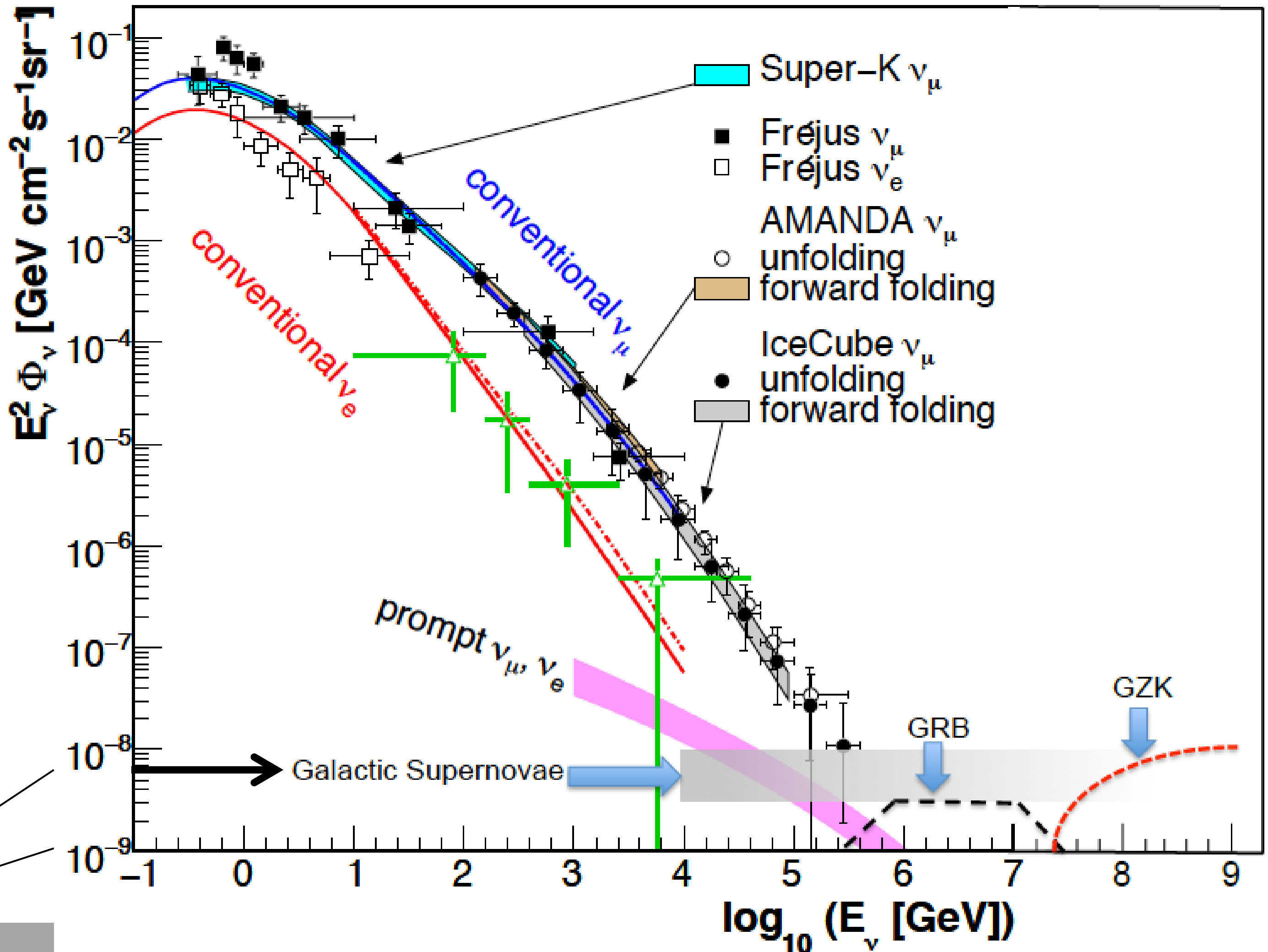
~ cosmic ray + gamma

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

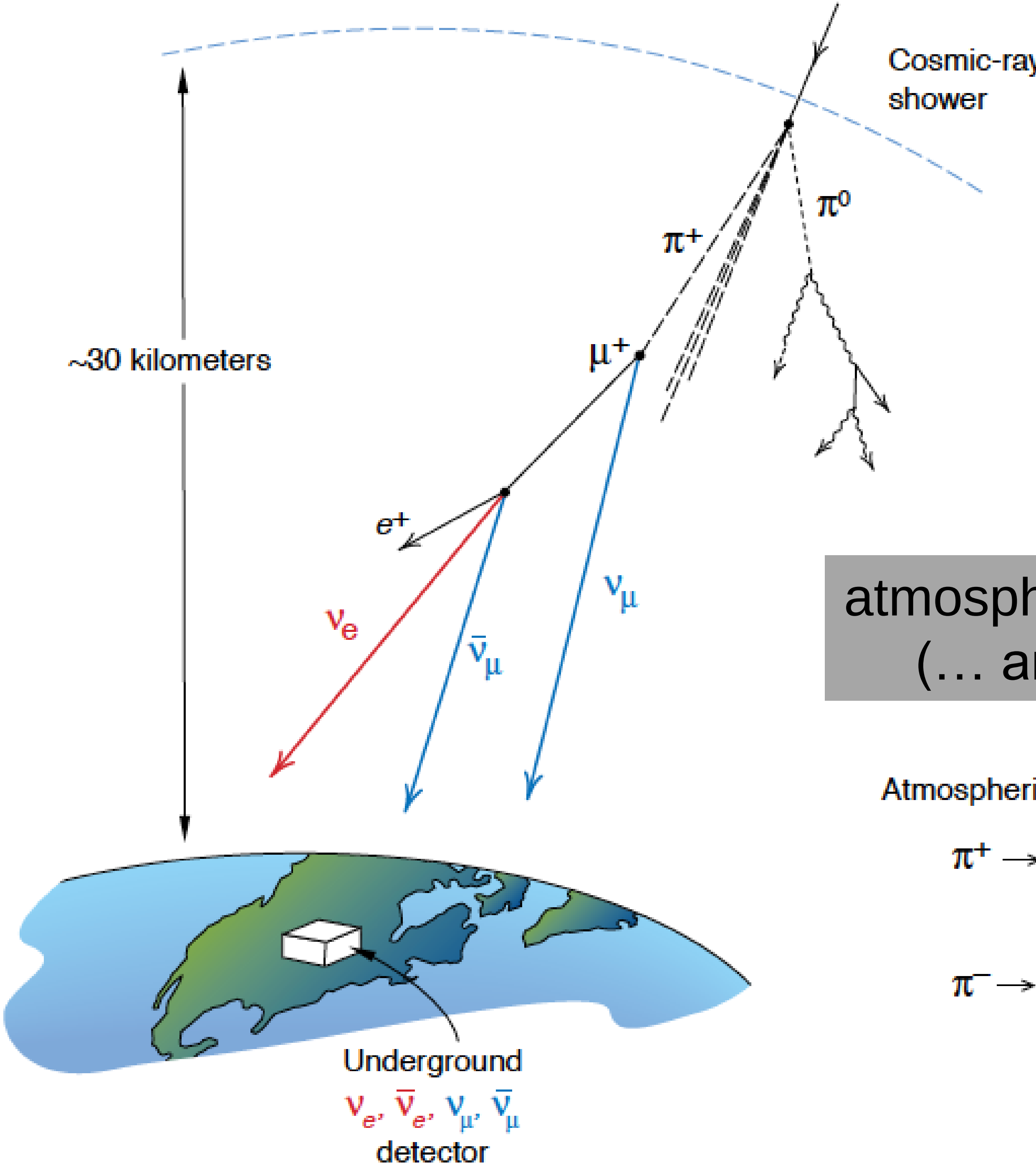


atmospheric

cosmic

100 TeV

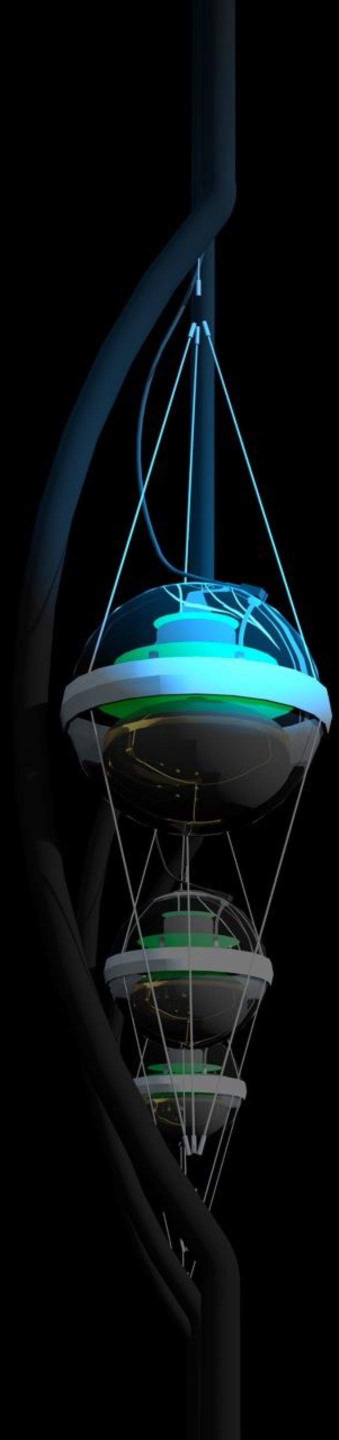
atmospheric neutrinos (… and muons!)



Atmospheric neutrino source

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

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



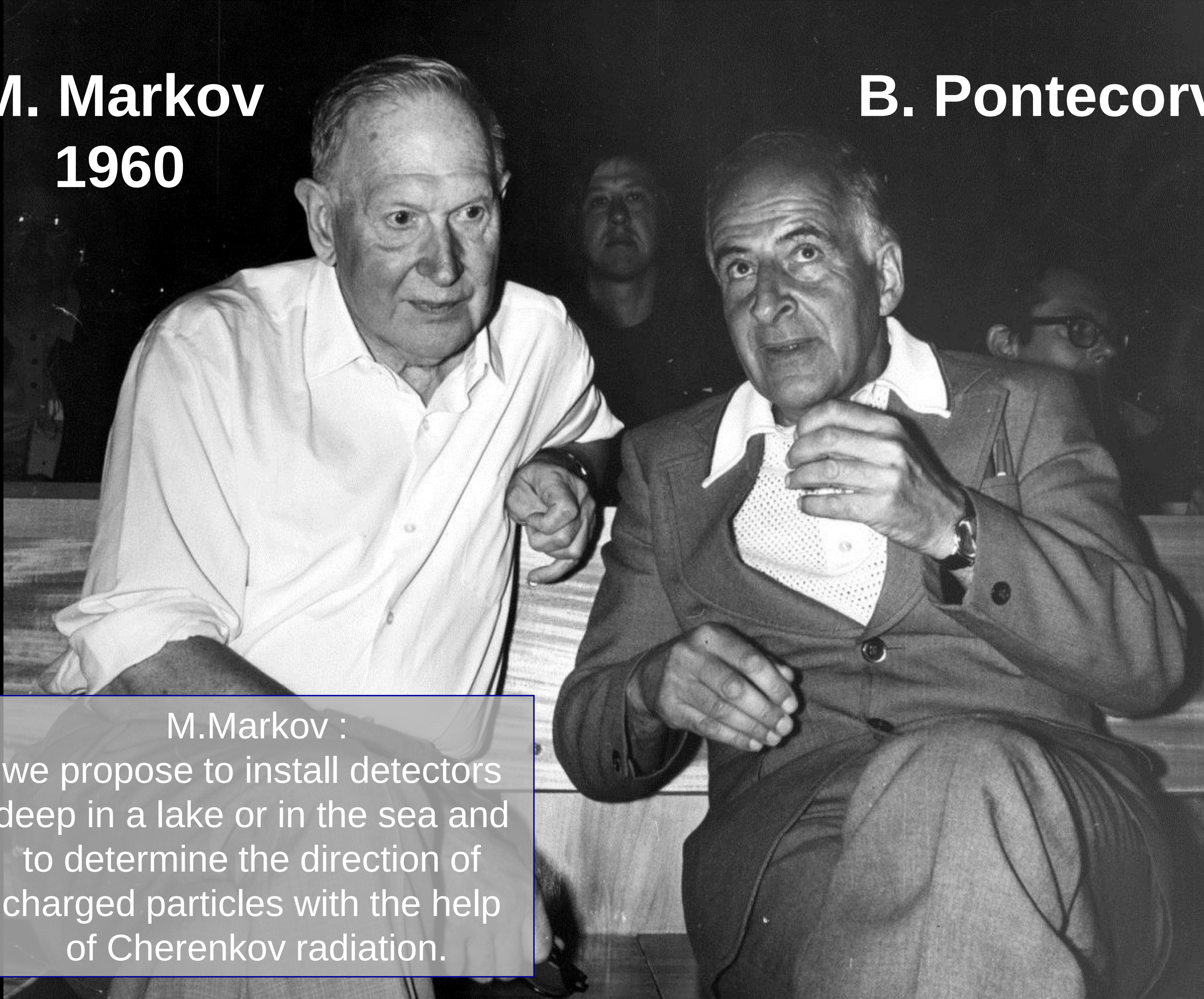
IceCube: the discovery of cosmic neutrinos
francis halzen

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

IceCube.wisc.edu

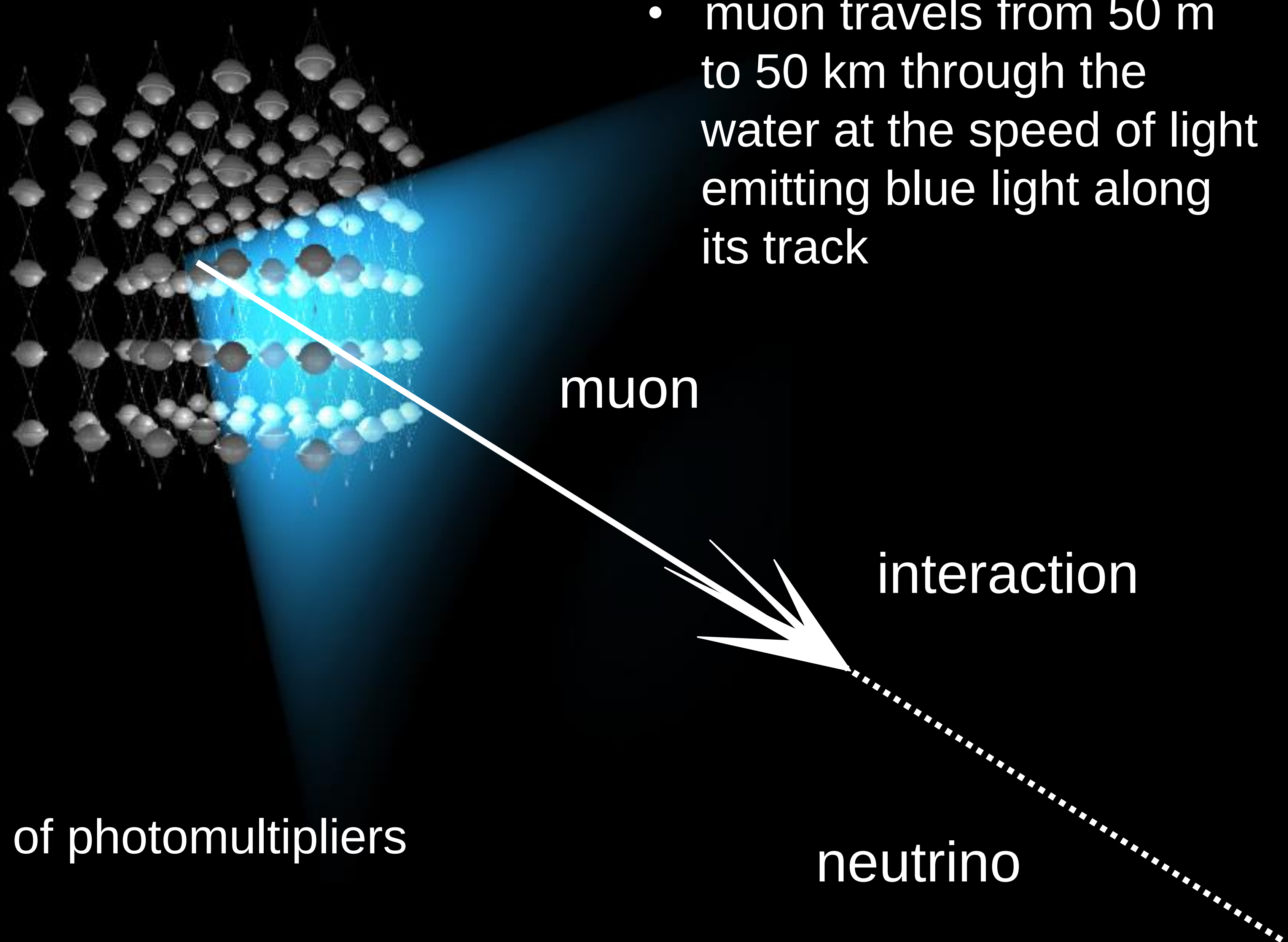
M. Markov 1960

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.

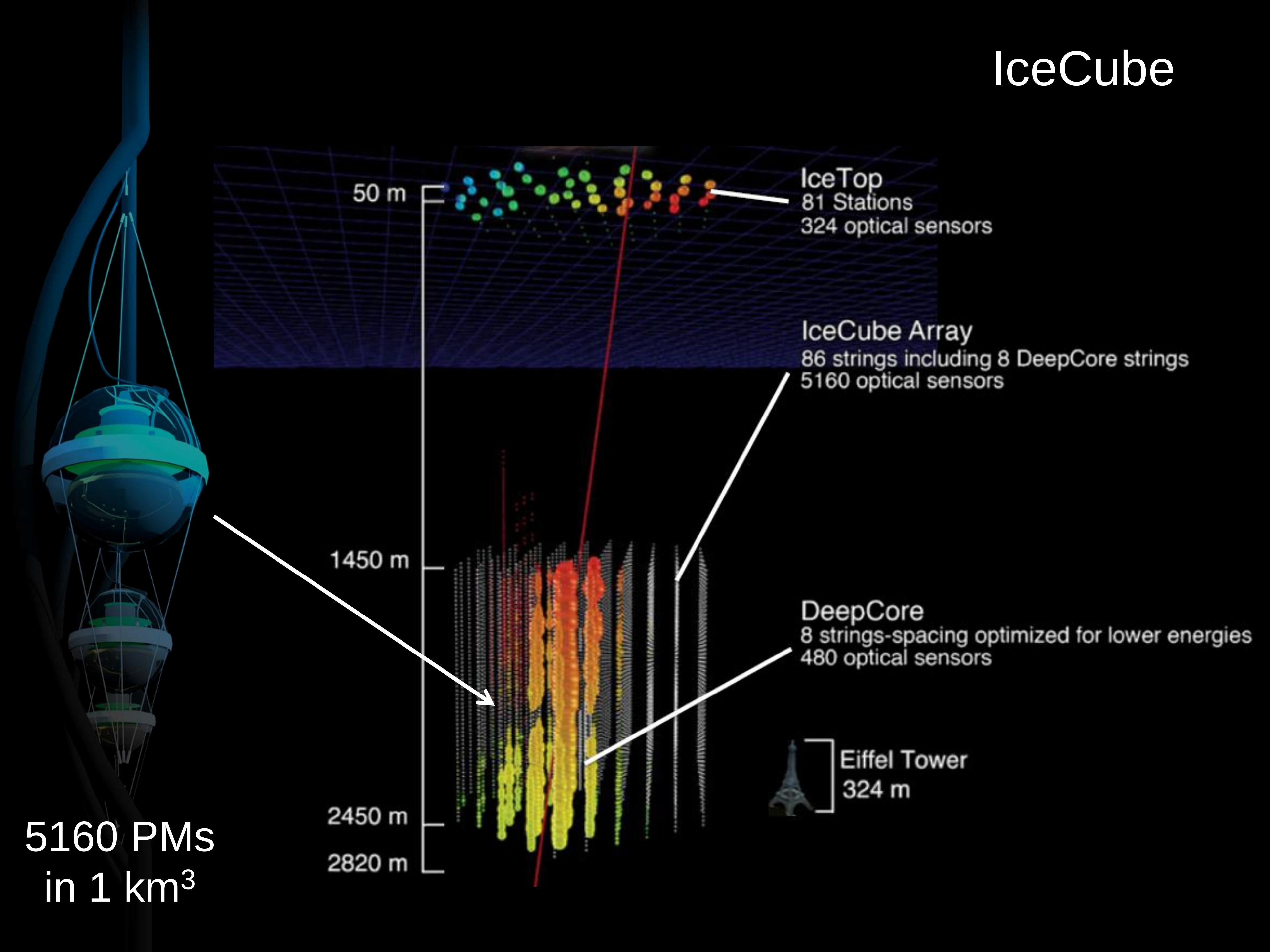
- shielded and optically transparent medium
- muon travels from 50 m to 50 km through the water at the speed of light emitting blue light along its track



- lattice of photomultipliers


ultra-transparent ice below 1.5 km

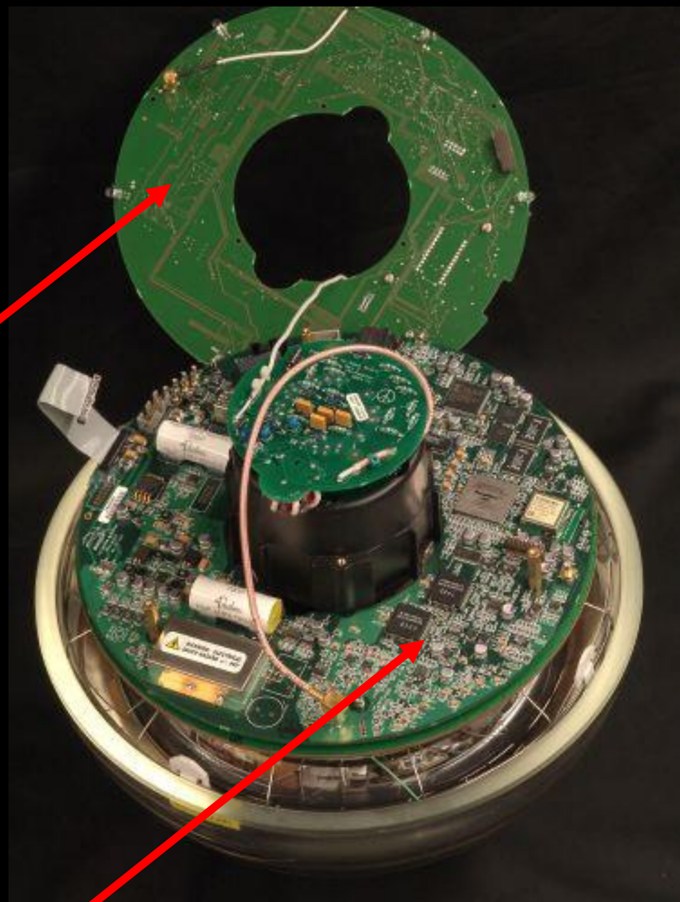
IceCube

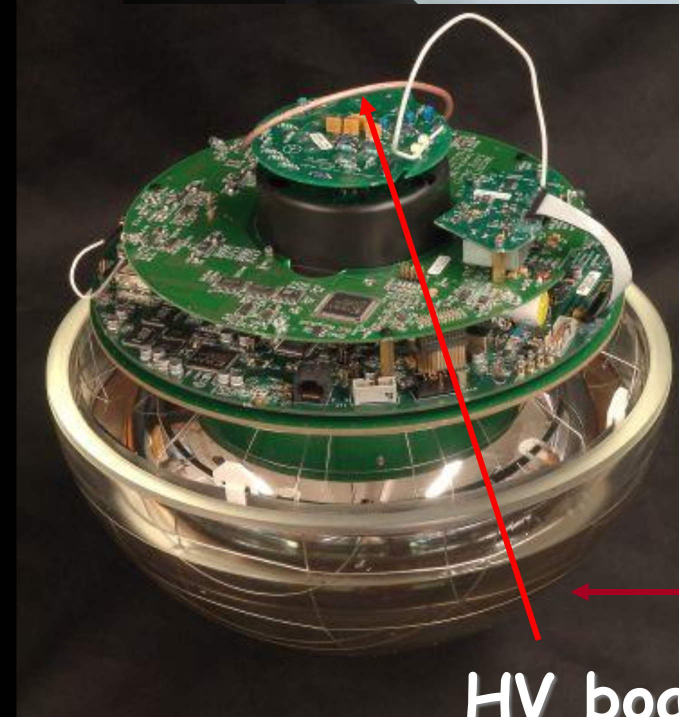


5160 PMs
in 1 km^3

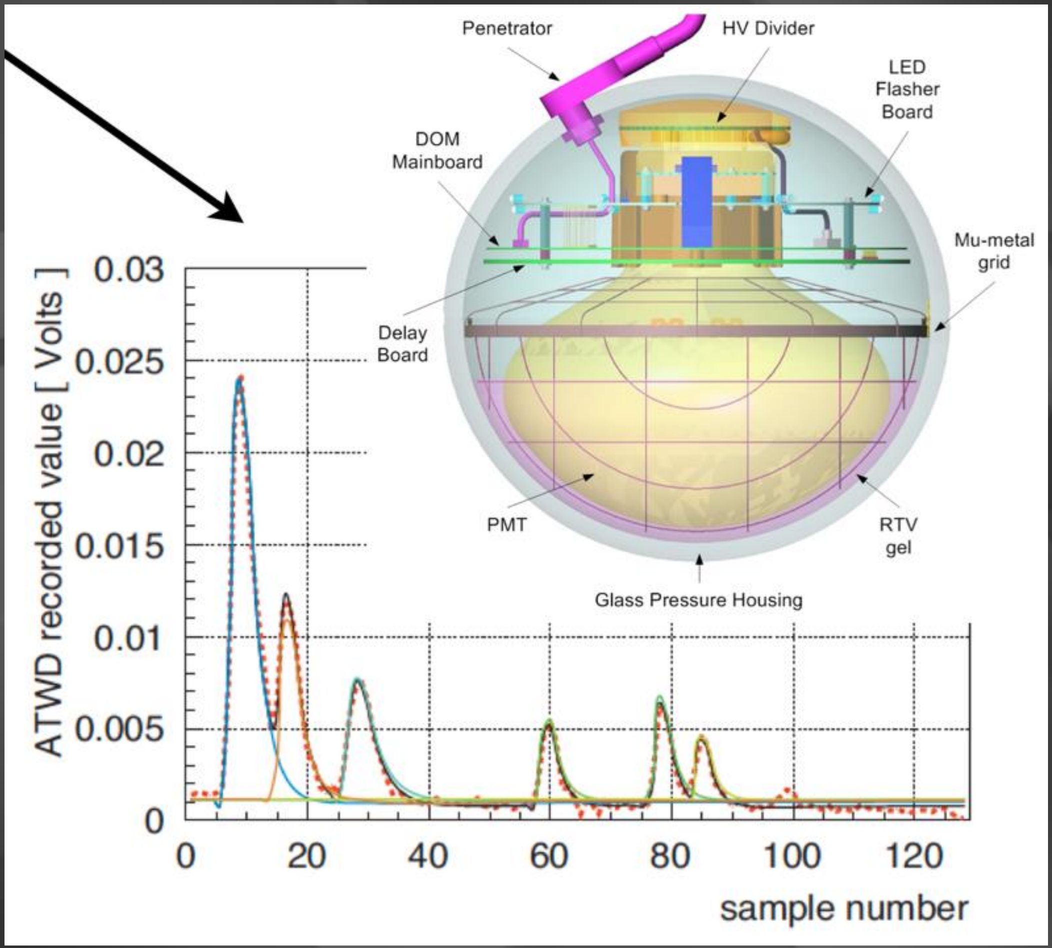
photomultiplier tube -10 inch

architecture of independent DOMs

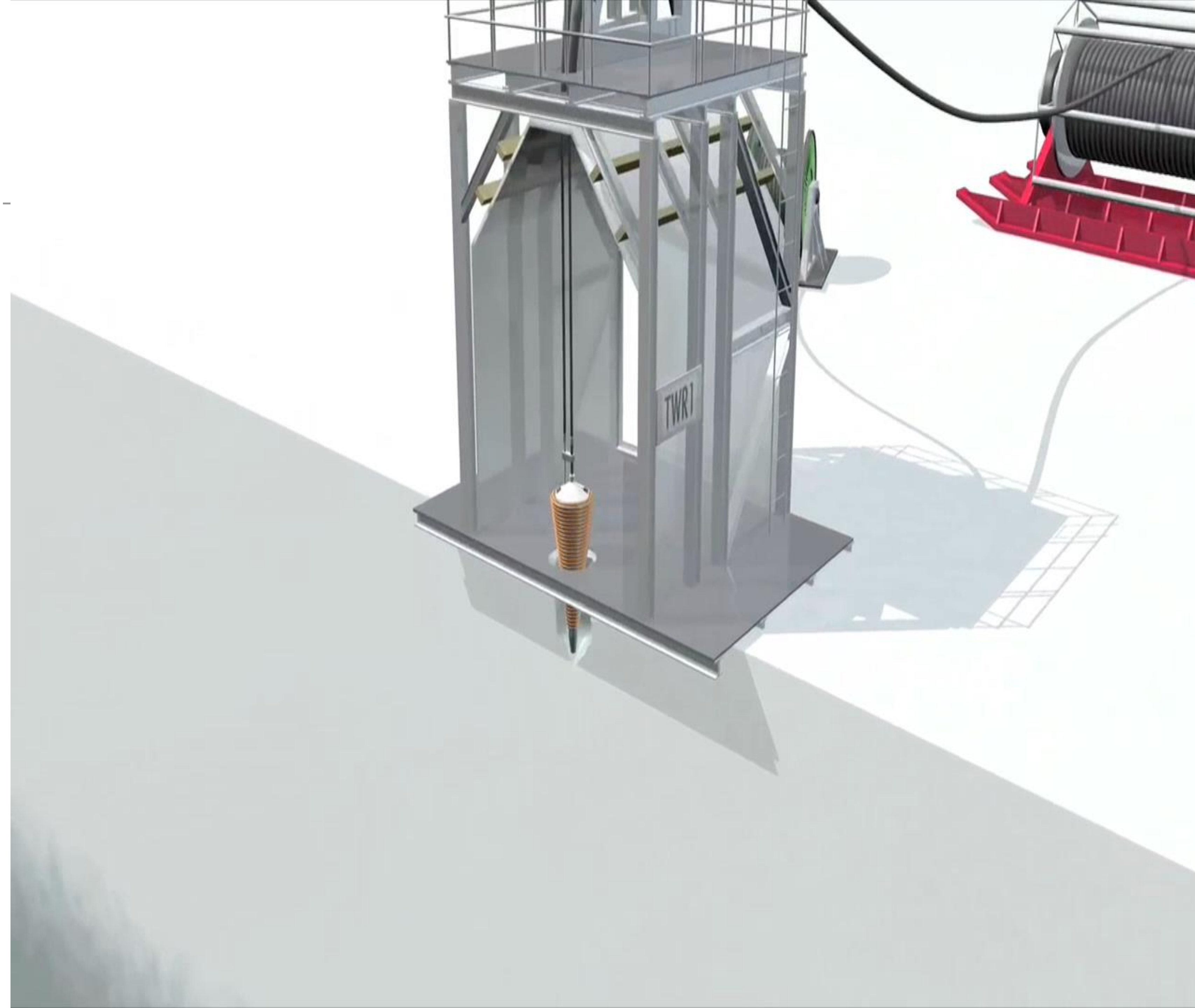


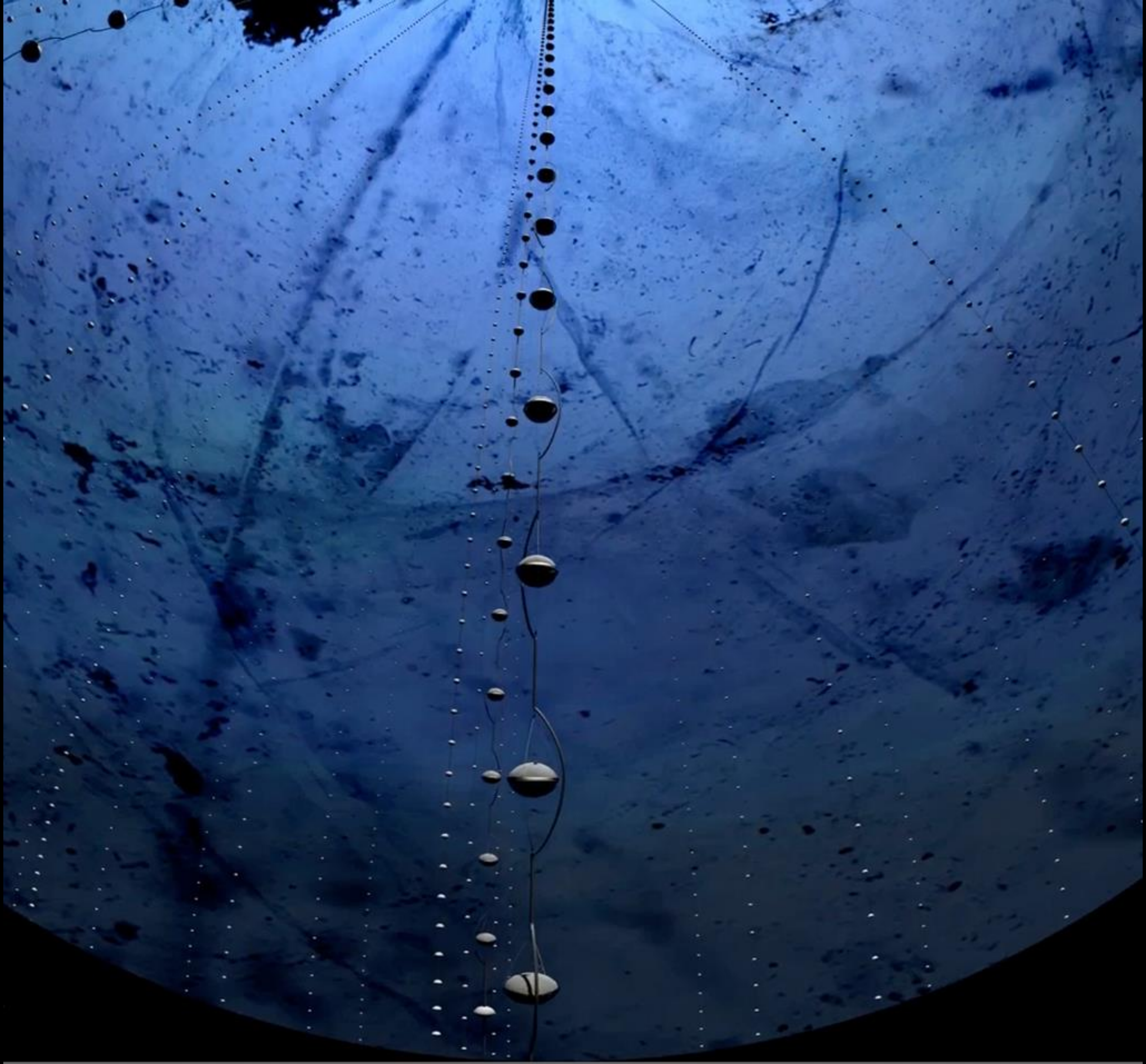


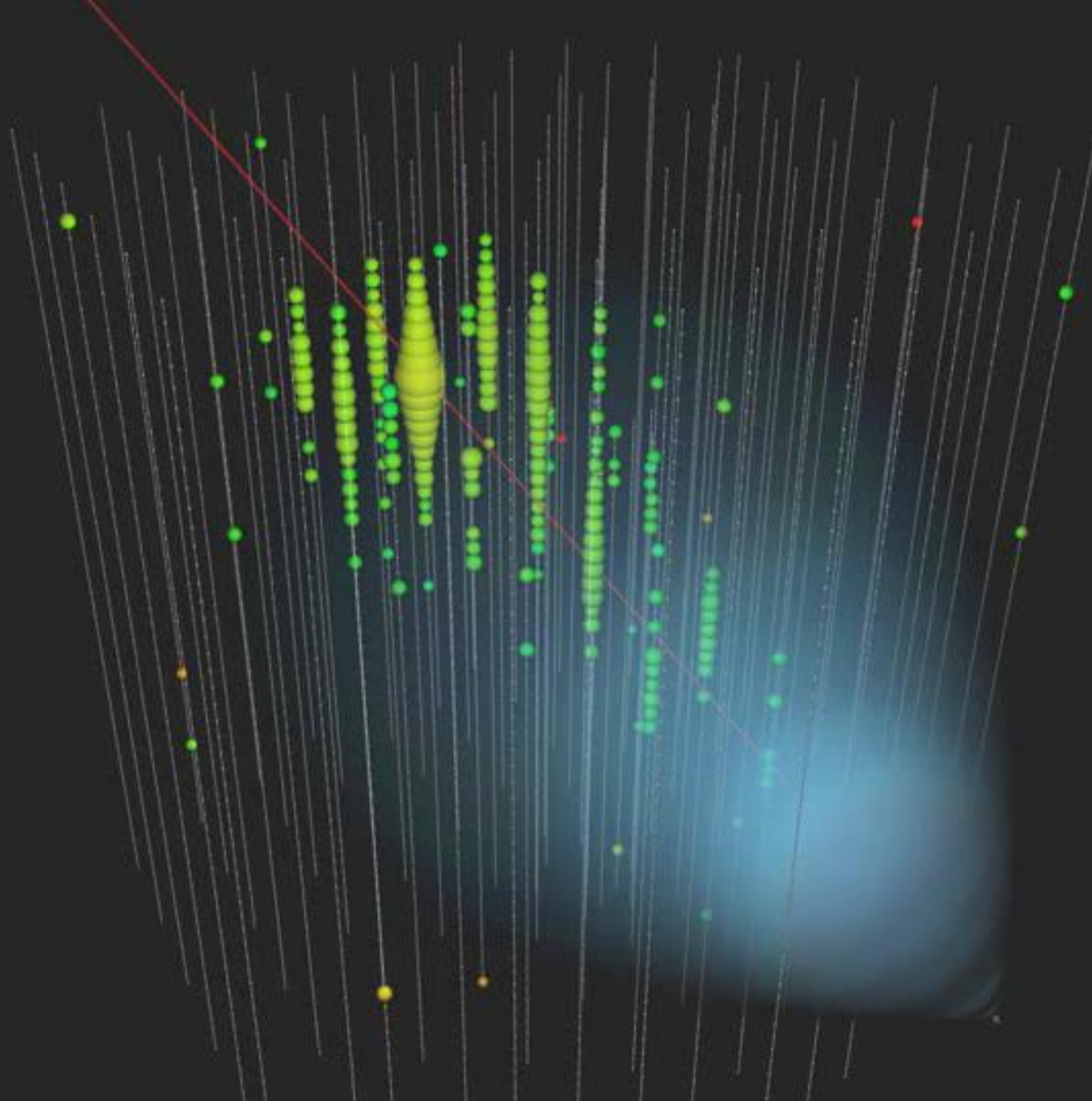
… each Digital Optical Module independently collects light signals like this, digitizes them,



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

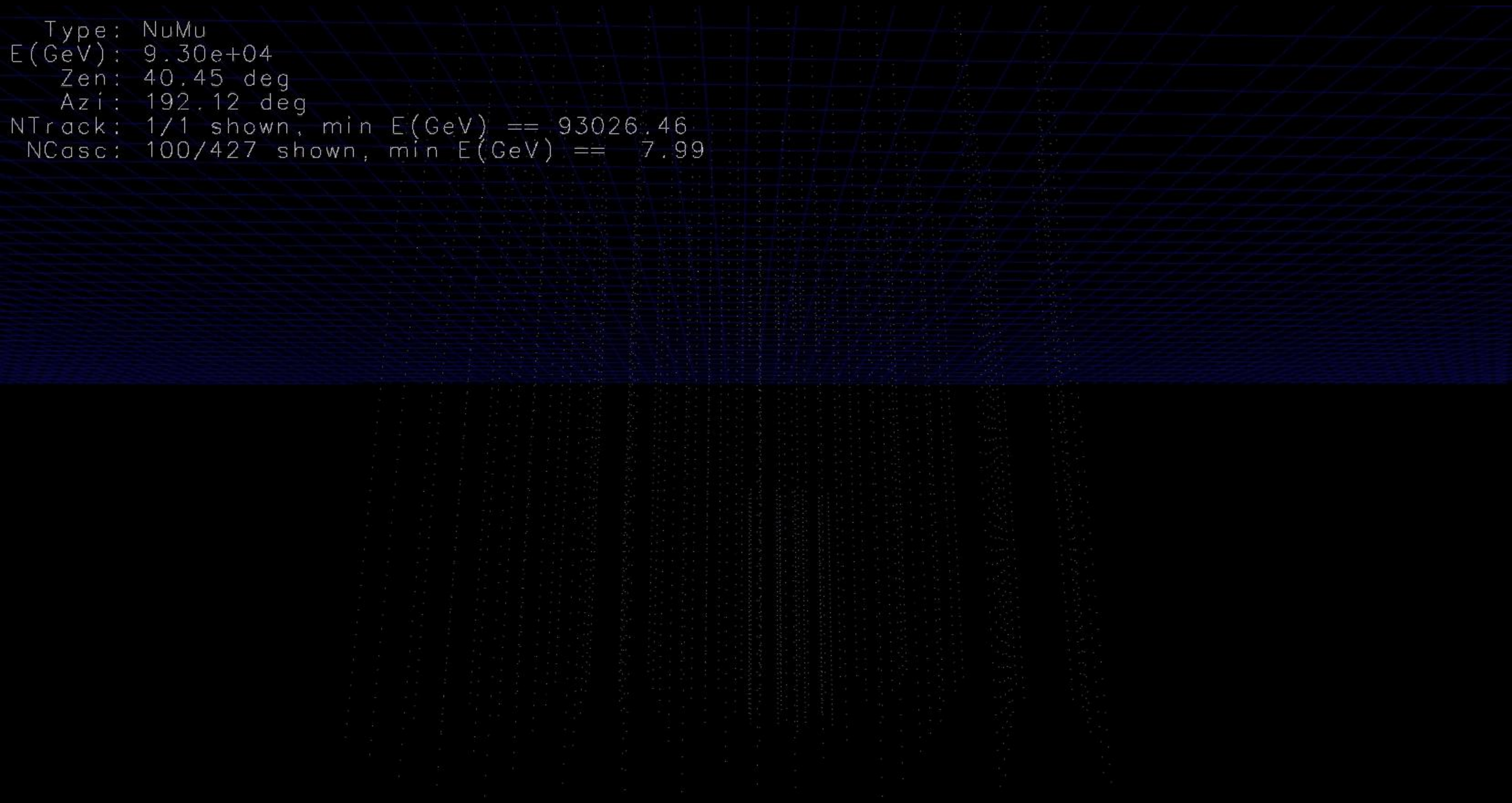

TWR1



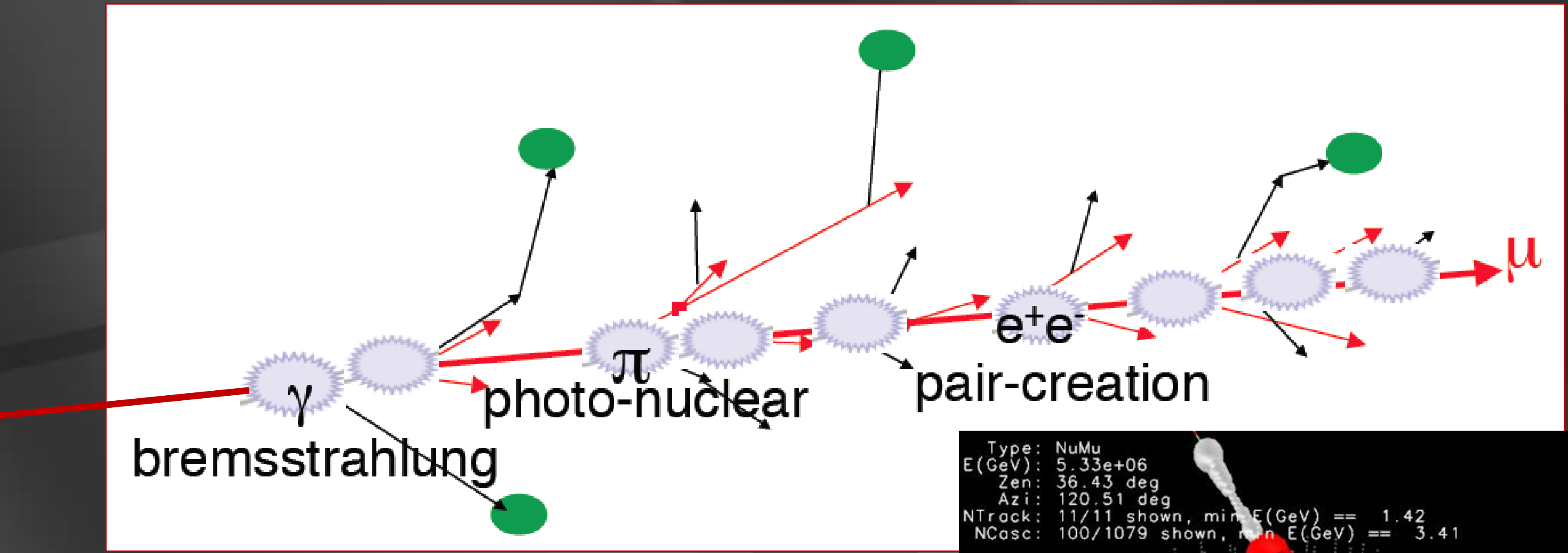


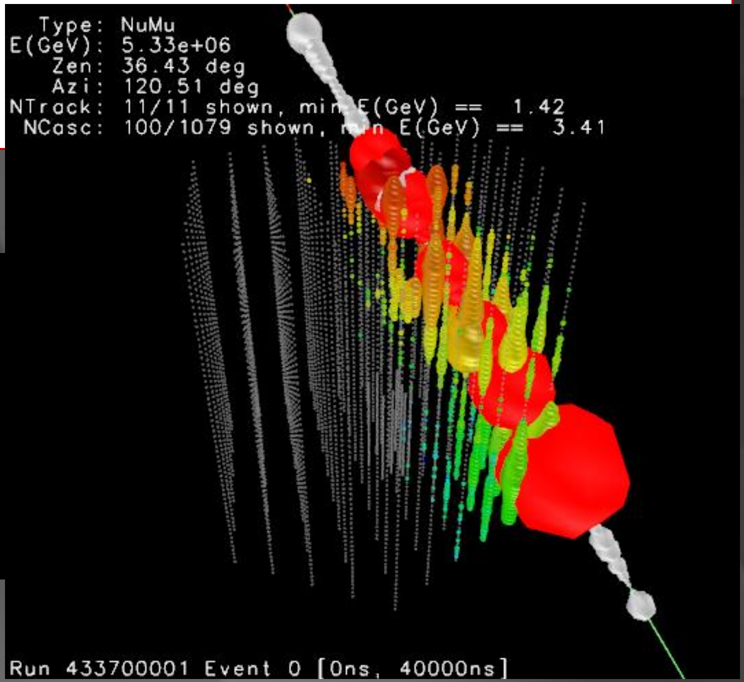
muon track: time is color; number of photons is energy

93 TeV muon

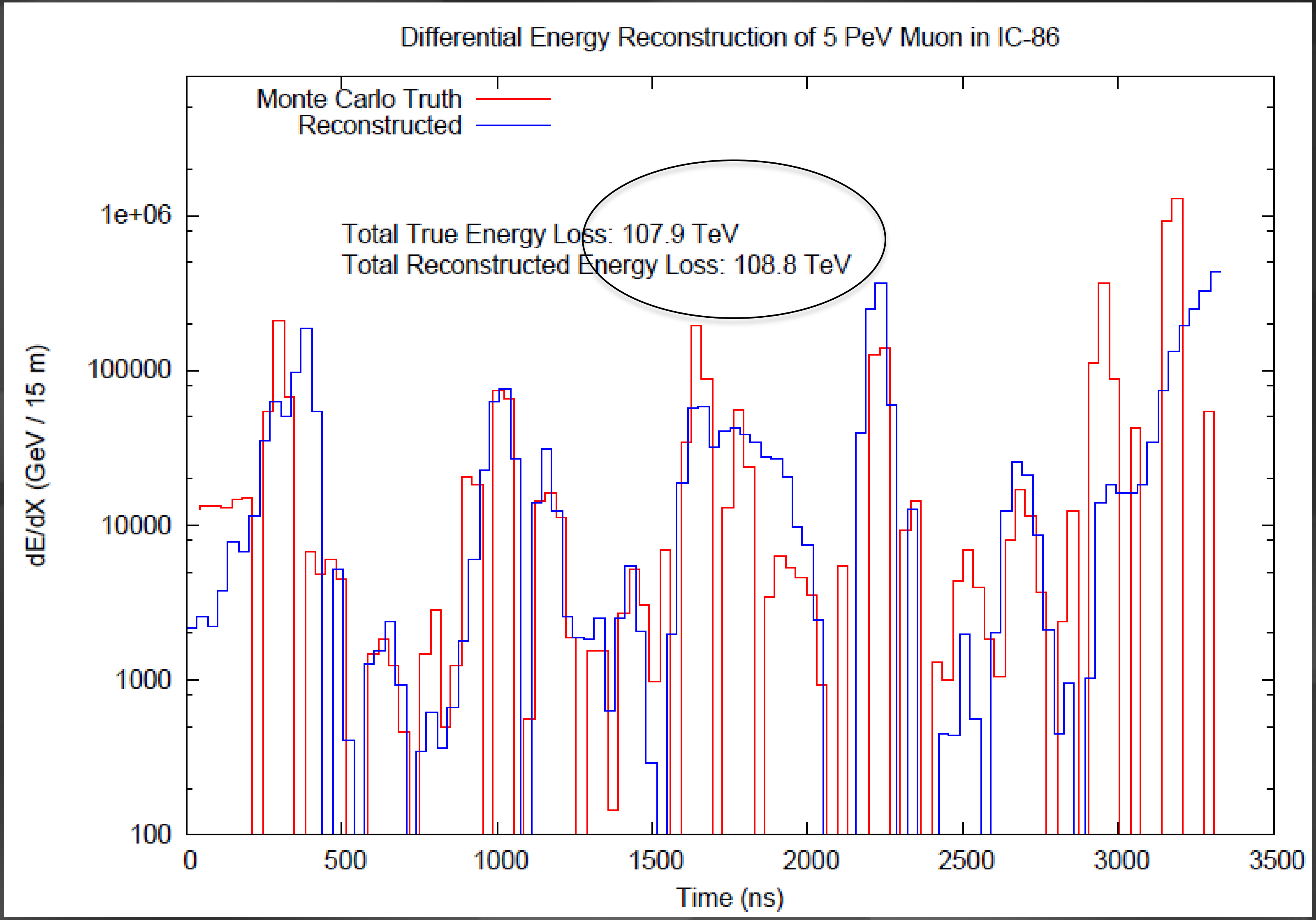

Type: NuMu
E(GeV): 9.30e+04
Zen: 40.45 deg
Azi: 192.12 deg
NTrack: 1/1 shown, min E(GeV) == 93026.46
NCasc: 100/427 shown, min E(GeV) == 7.99

energy measurement (> 1 TeV)



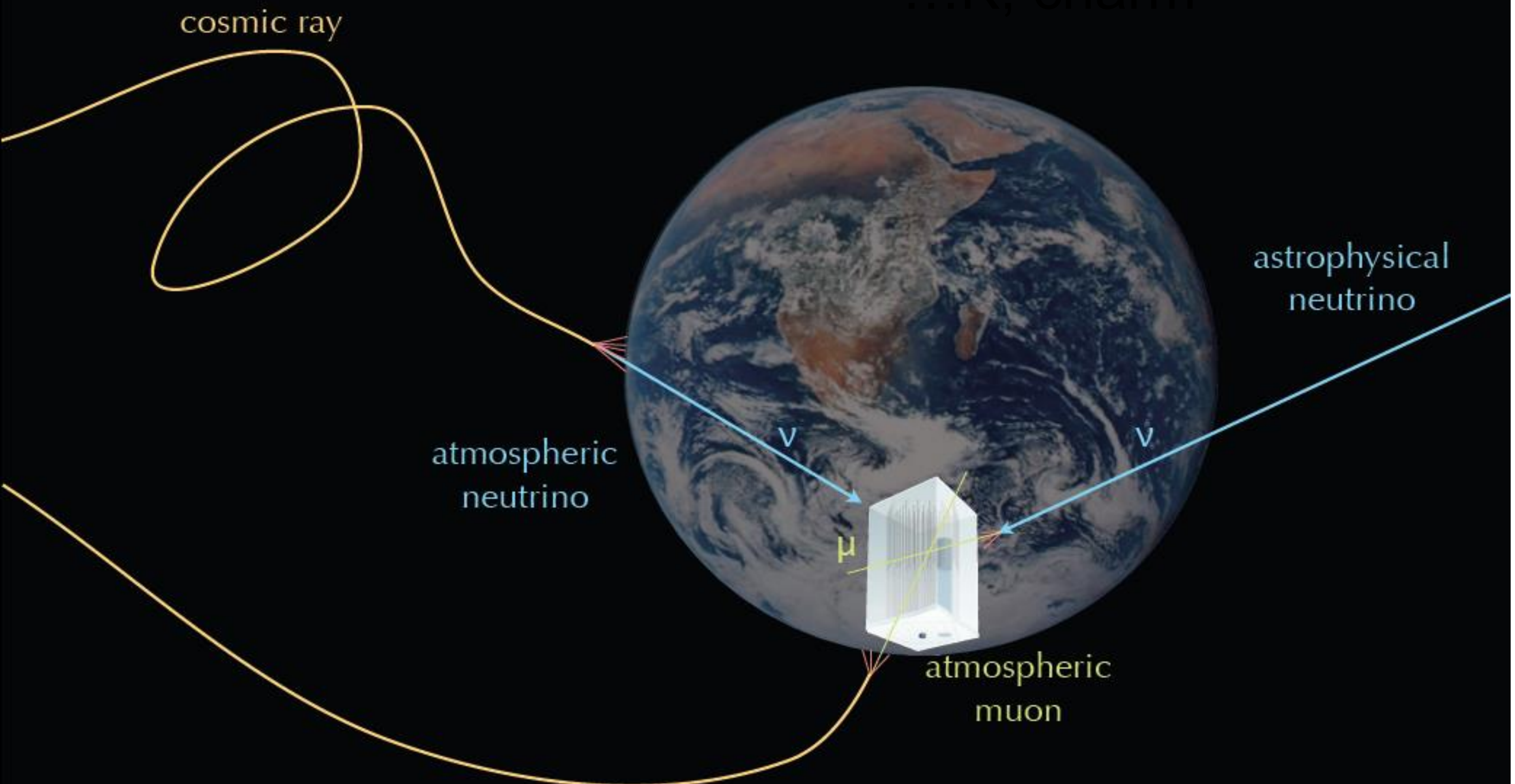


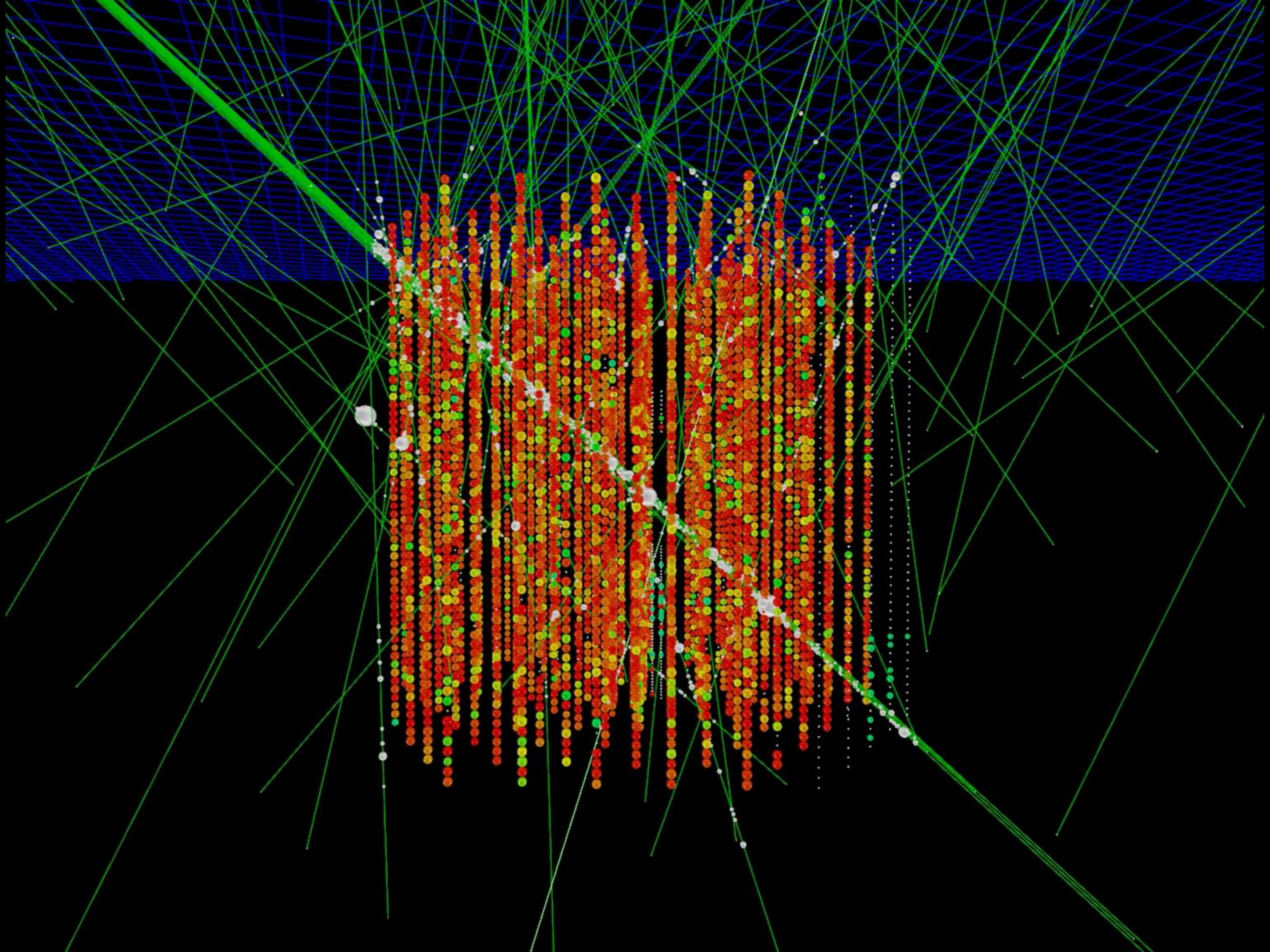
convert the amount of light emitted to measurement of the muon energy (number of optical modules, number of photons, dE/dx, …)



improving angular and energy resolution

Signals and Backgrounds





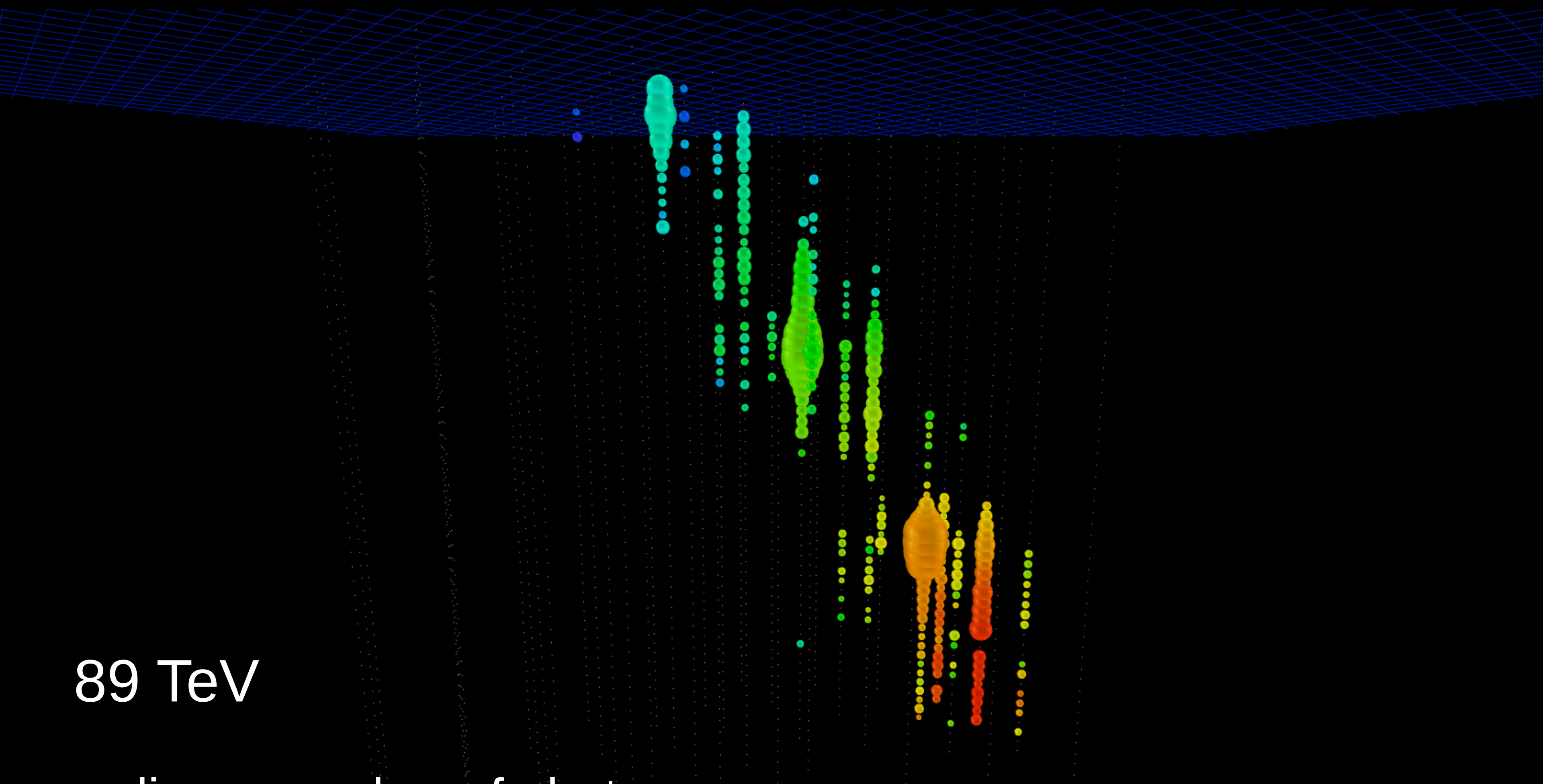
… you looked at 10msec of data !

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

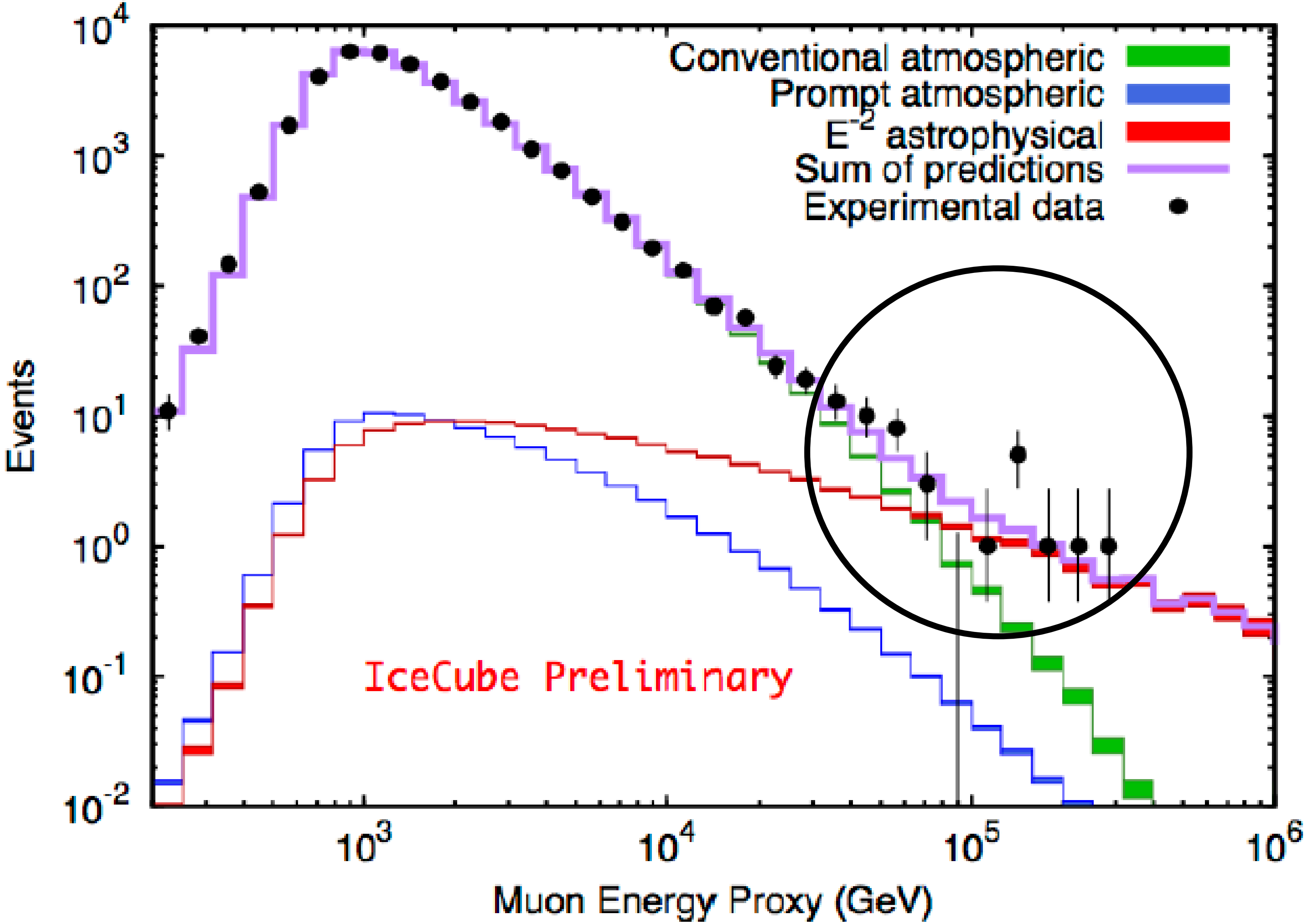


89 TeV

radius ~ number of photons
time ~ red → purple

Run 113641 Event 33553254 [0ns, 16748ns]

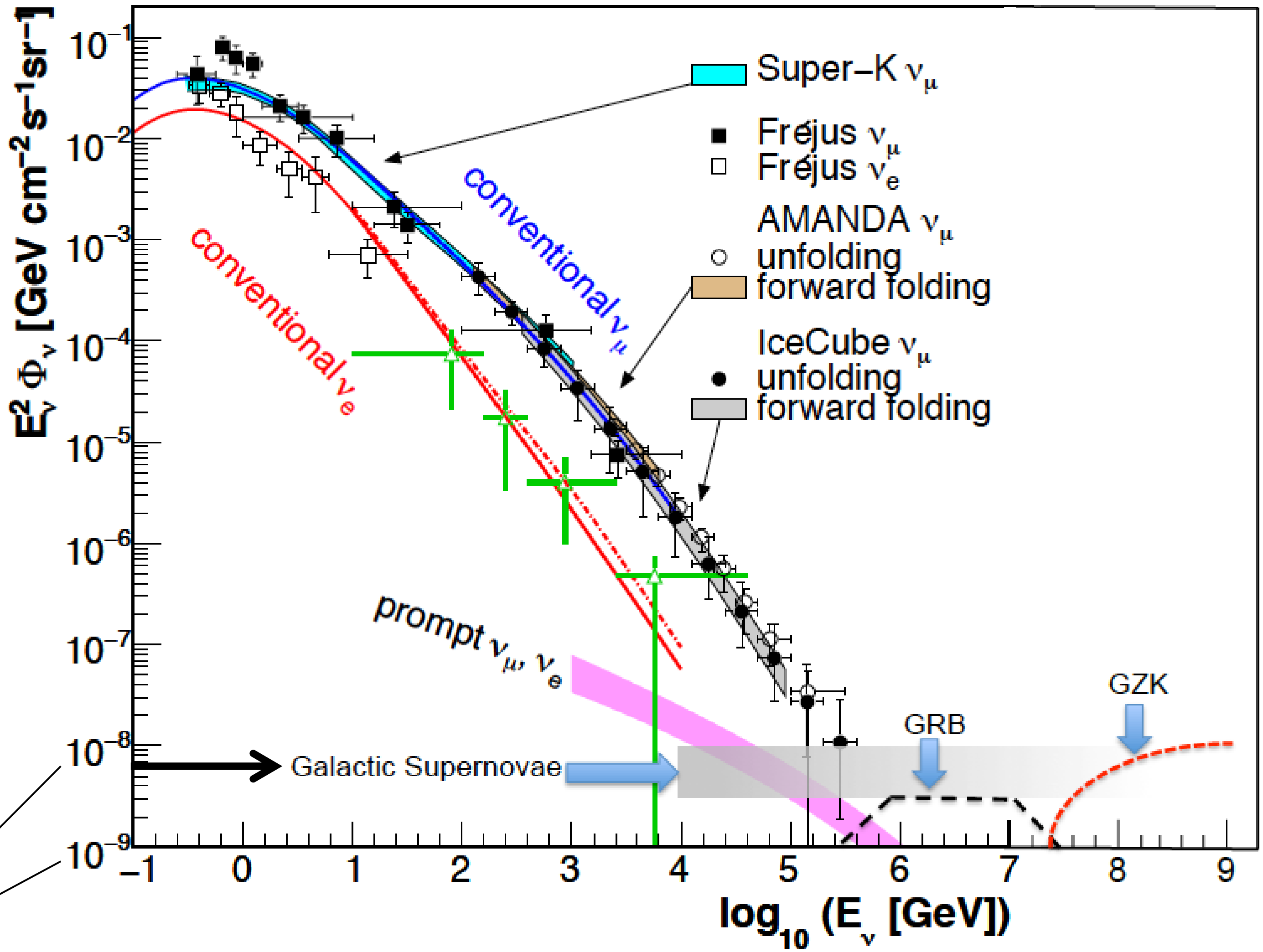
cosmic neutrinos in 2 years of data at 3.7 sigma



above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

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



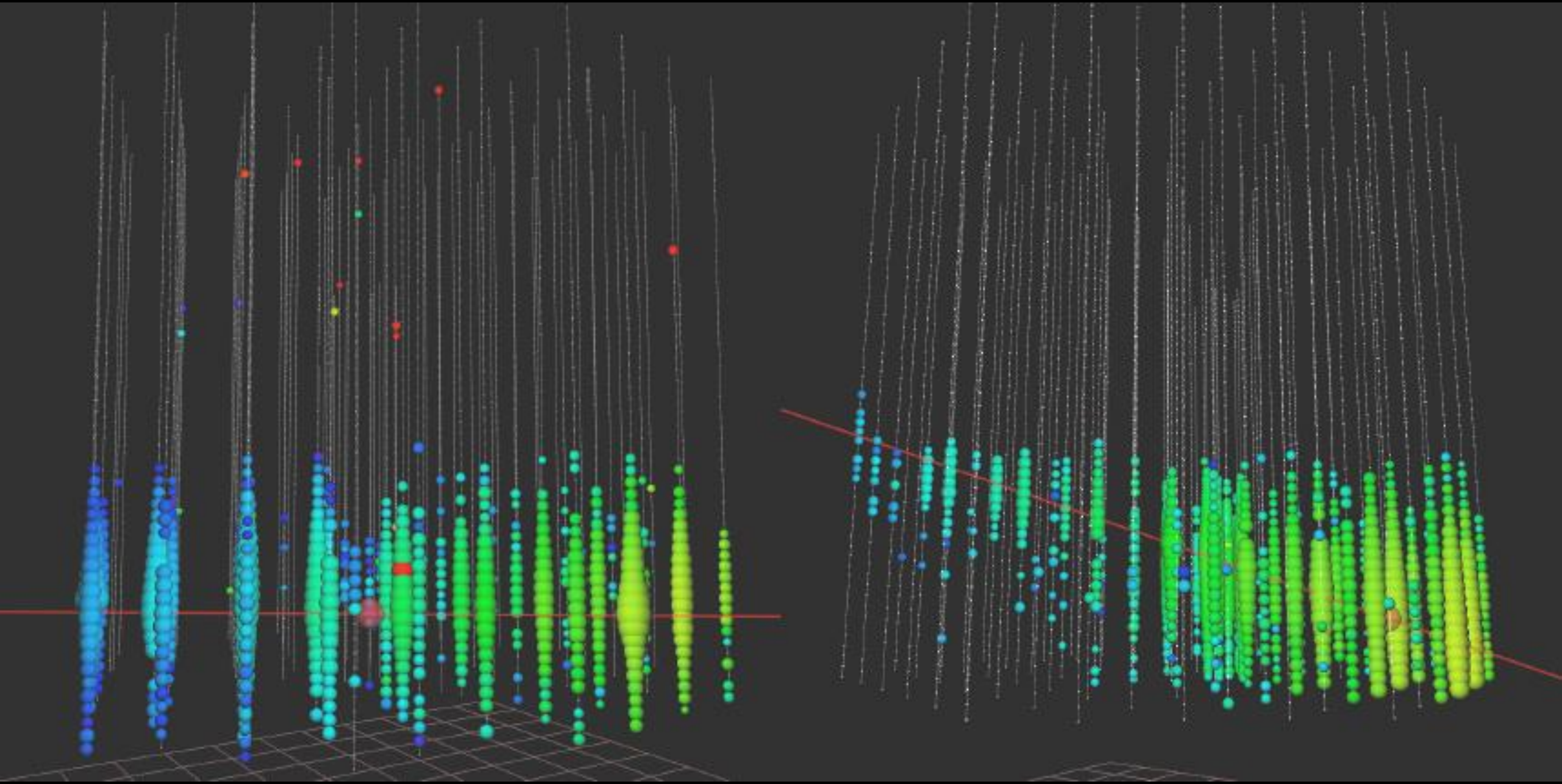
10—100 events per year for fully efficient detector

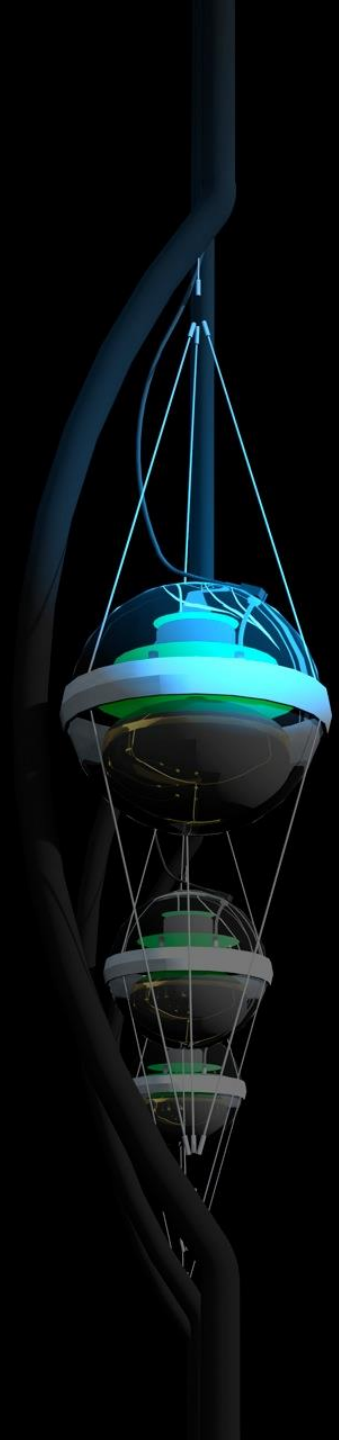
atmospheric

cosmic

100 TeV

highest energy muon energy observed: 560 TeV
→ PeV energy neutrino





IceCube: the discovery of cosmic neutrinos

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- cosmic ray accelerators
- IceCube a discovery instrument
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- where do they come from?
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cosmic rays interact with the microwave background

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

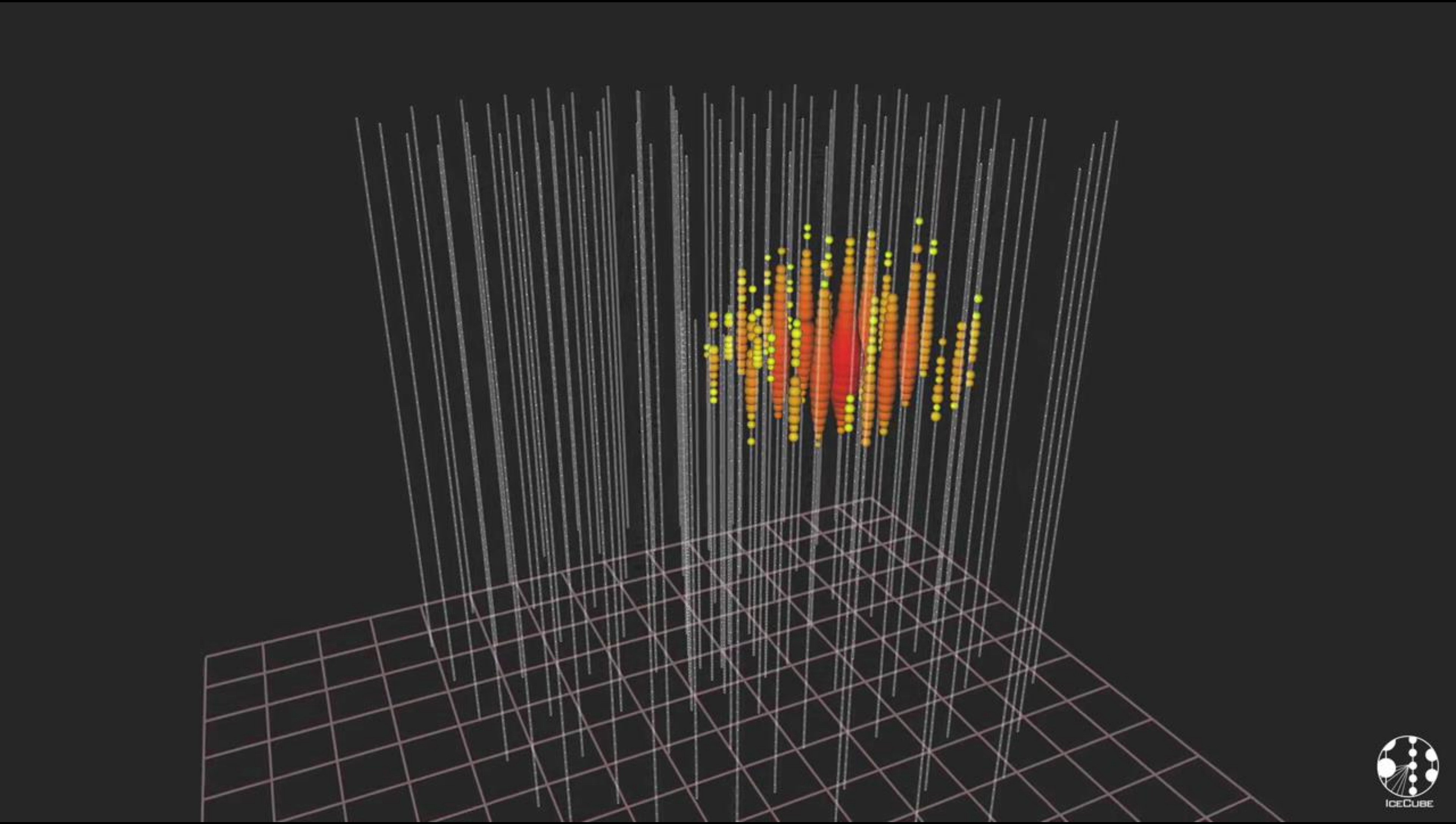
cosmic rays disappear, neutrinos with EeV (10^{6} TeV) energy appear

$$p \rightarrow m + u_{m} \rightarrow \{e + \overline{u_{m}} + u_{e}\} + u_{m}$$

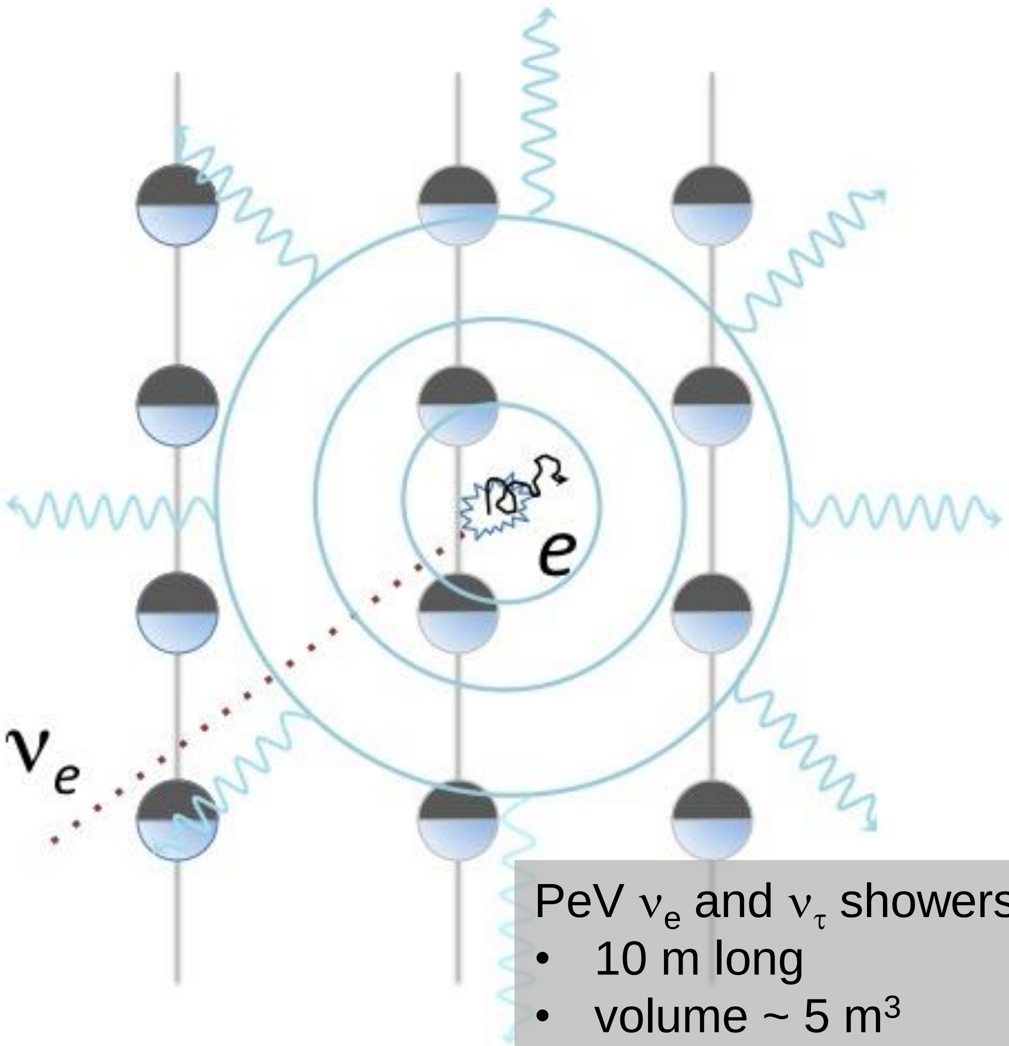
1 event per cubic kilometer per year

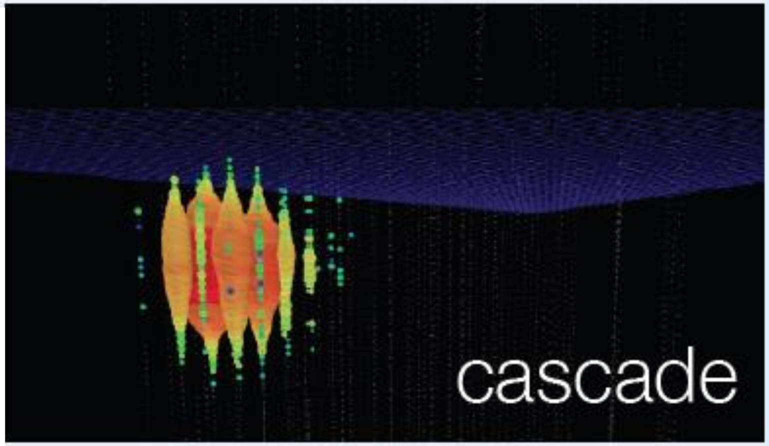
...but it points at its source!

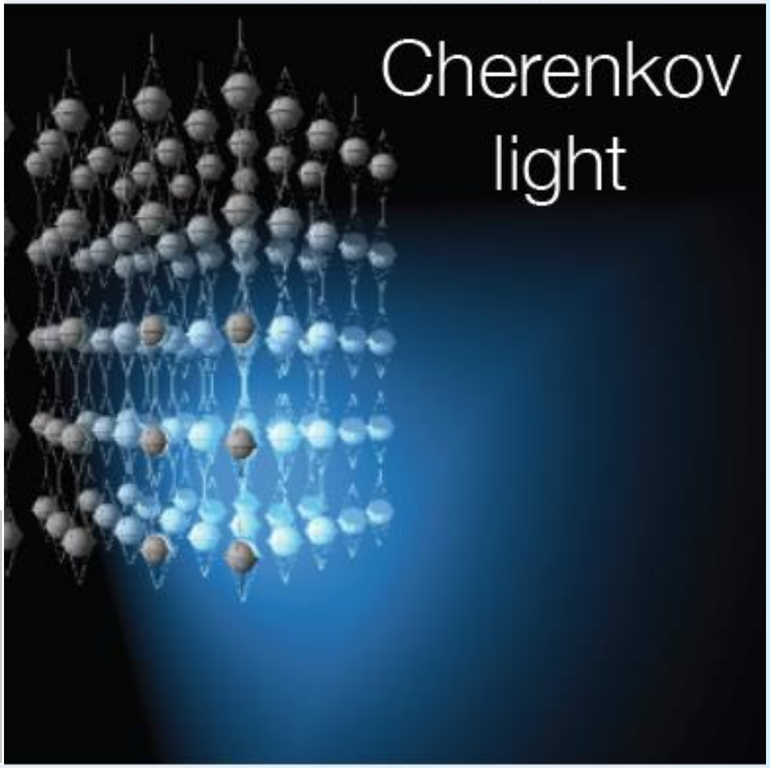
GZK neutrino search: two neutrinos with > 1,000 TeV



tracks and showers

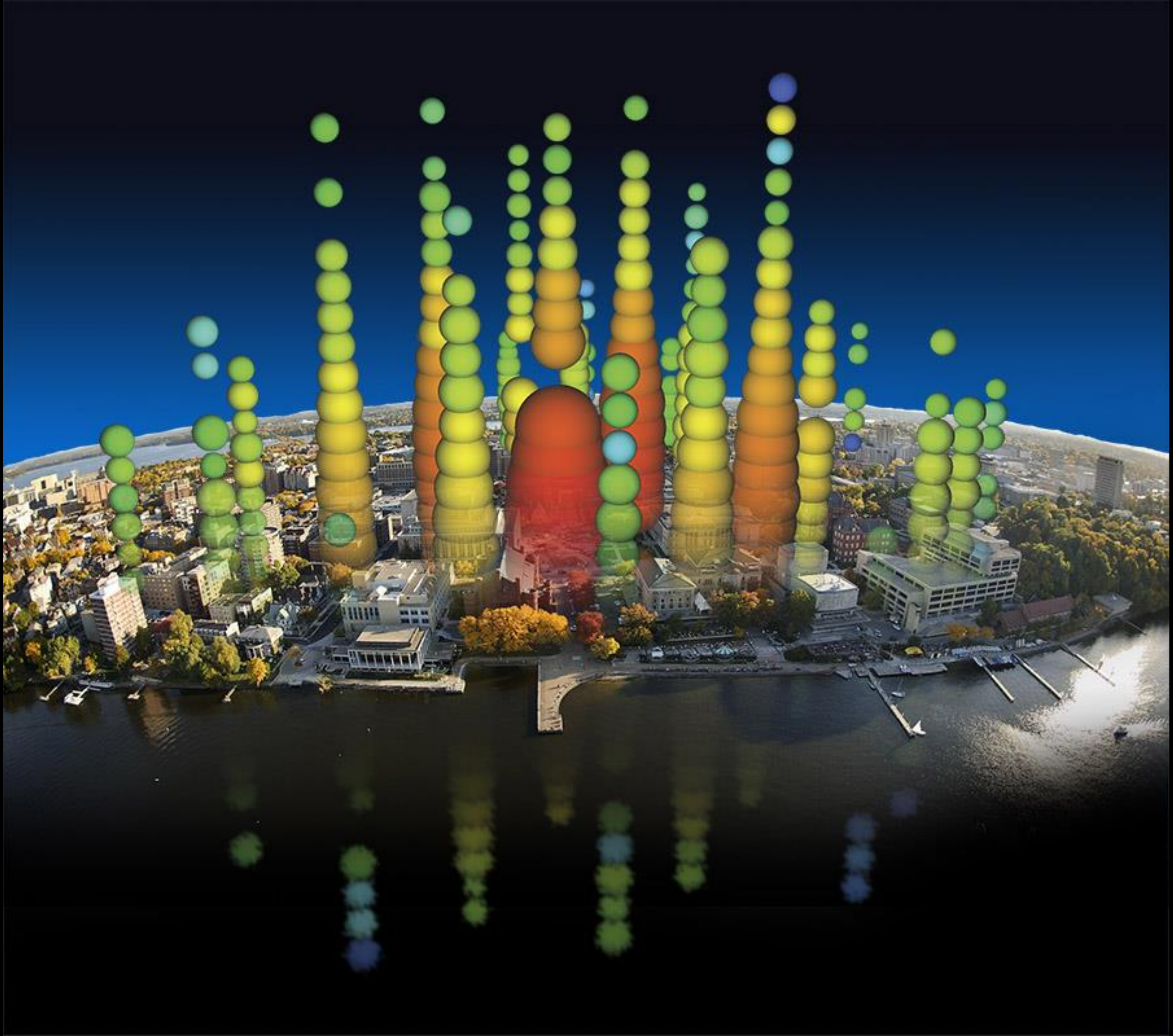


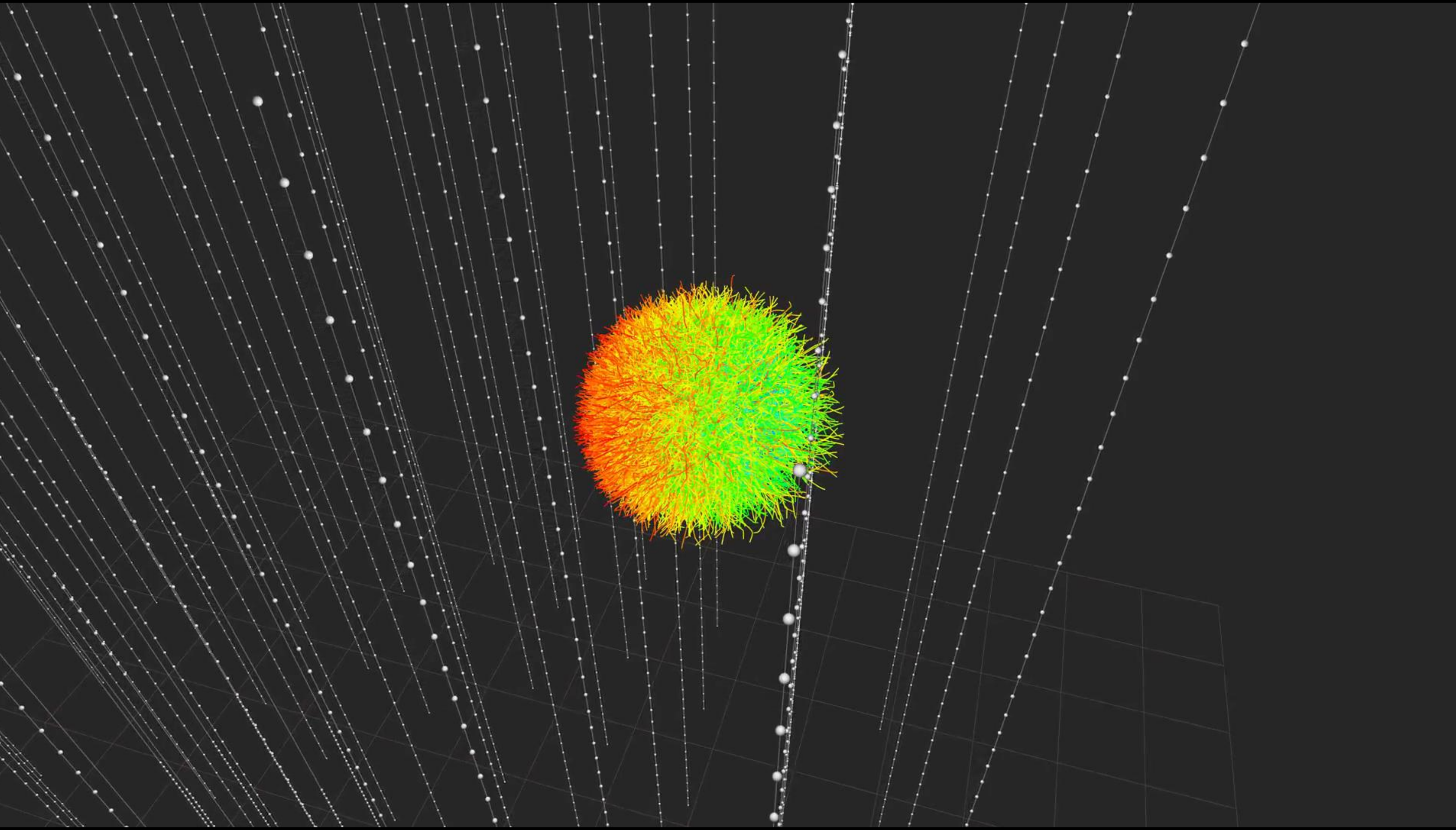




PeV ν_e and ν_τ showers:

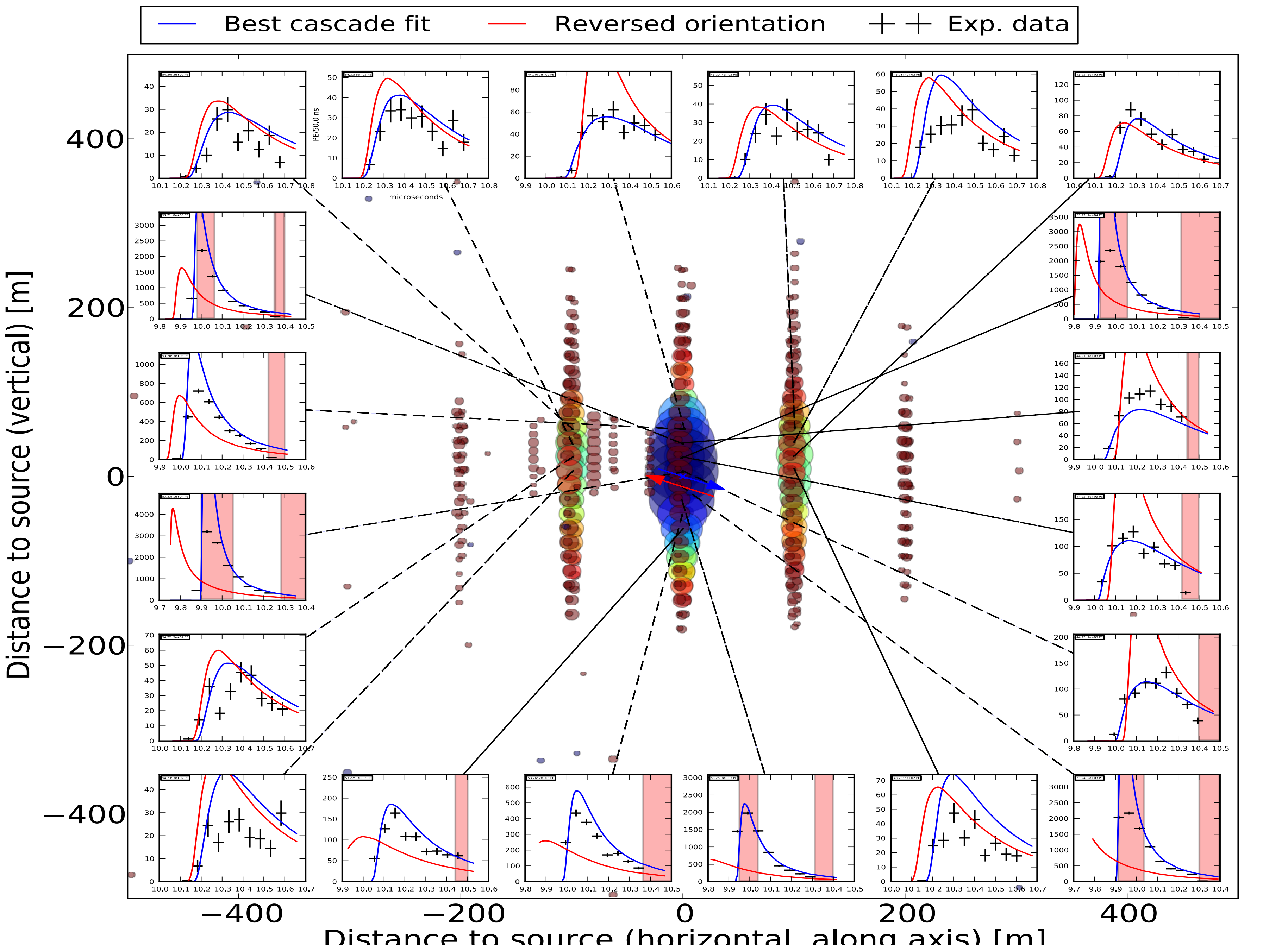
- 10 m long
- volume ~ 5 m^3
- isotropic after 25~ 50m





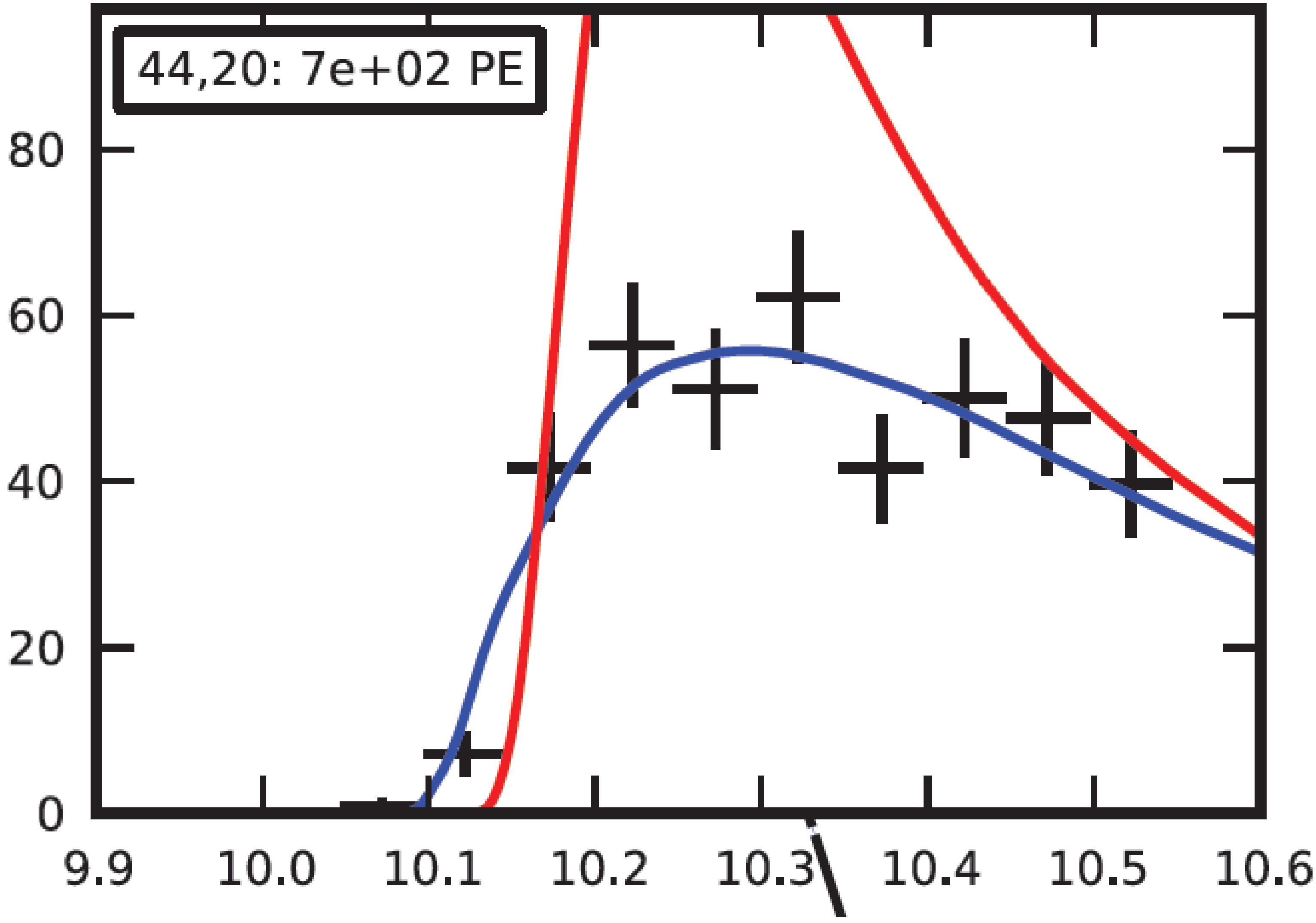
size = energy

color = time = direction

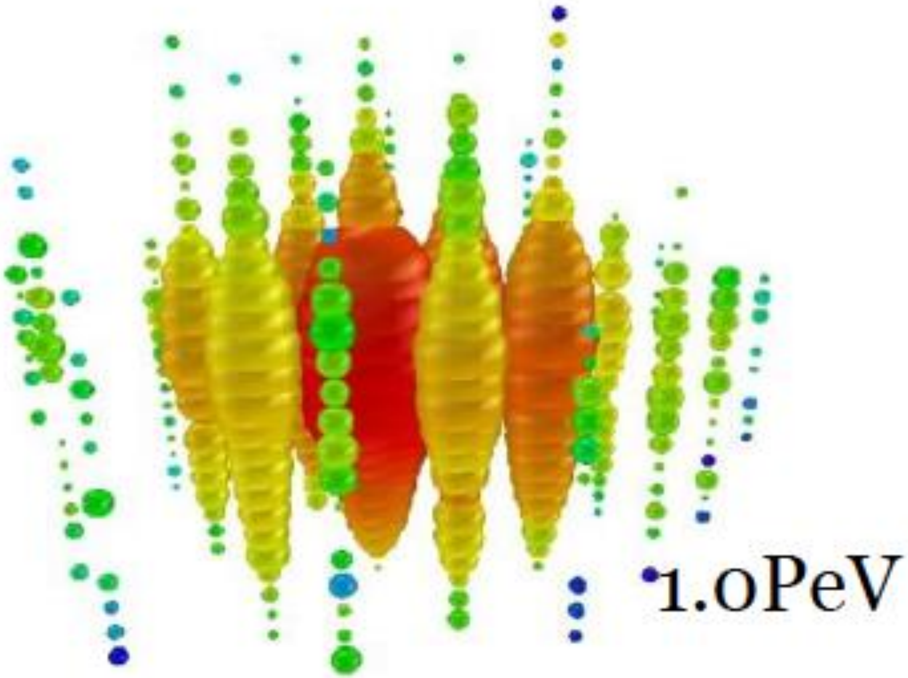


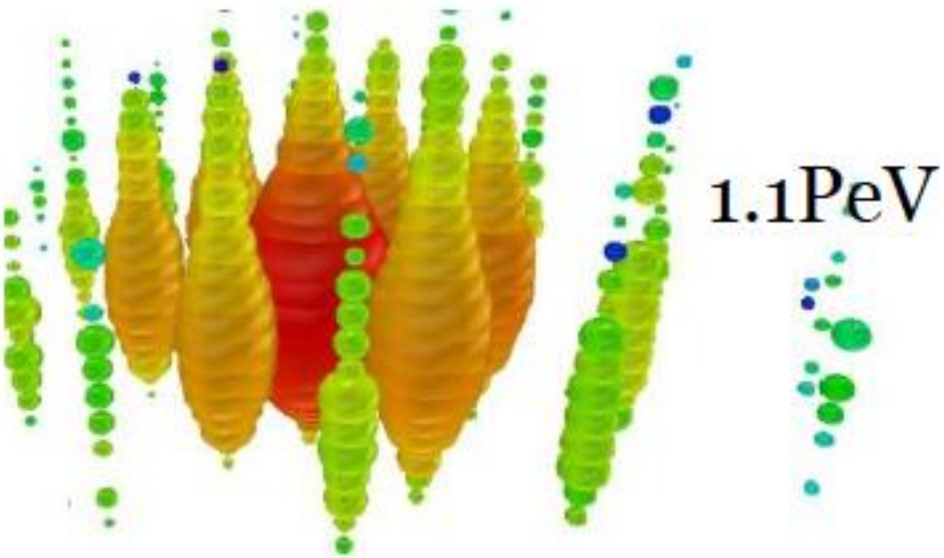
Best cascade fit
Reversed orientation
Exp. data
Distance to source (vertical) [m]
Distance to source (horizontal, along axis) [m]
PE/50.0 ns
microseconds

reconstruction limited by computing, not ice !



Blue: best-fit direction, red: reversed direction





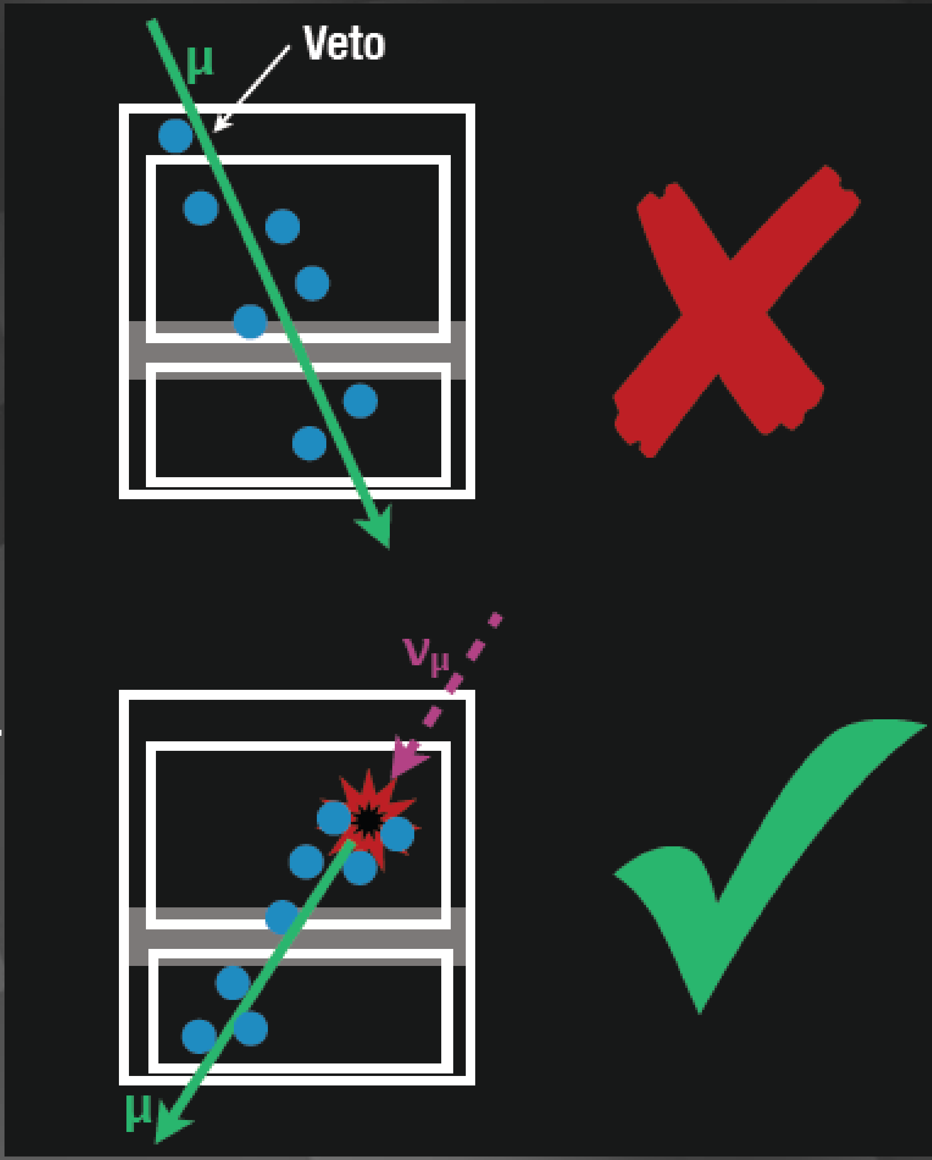
• energy

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

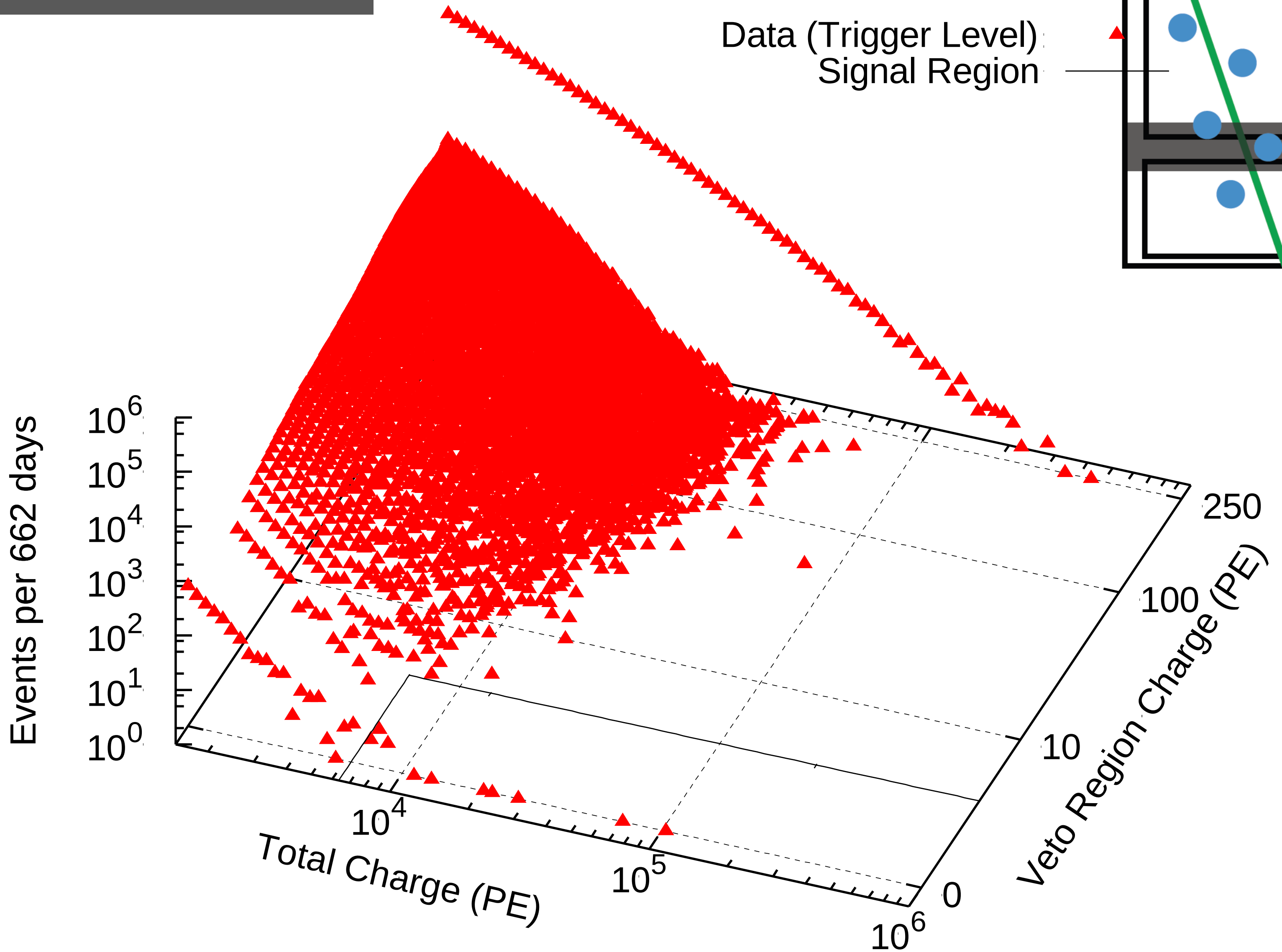
• not atmospheric: probability of no accompanying muon is 10^{-3} per event

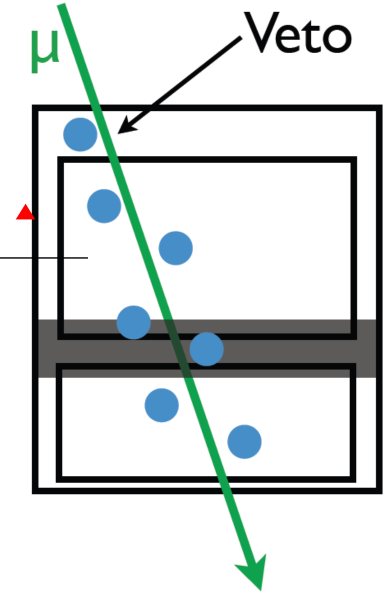
→ flux at present level of diffuse limit

- ✓ 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



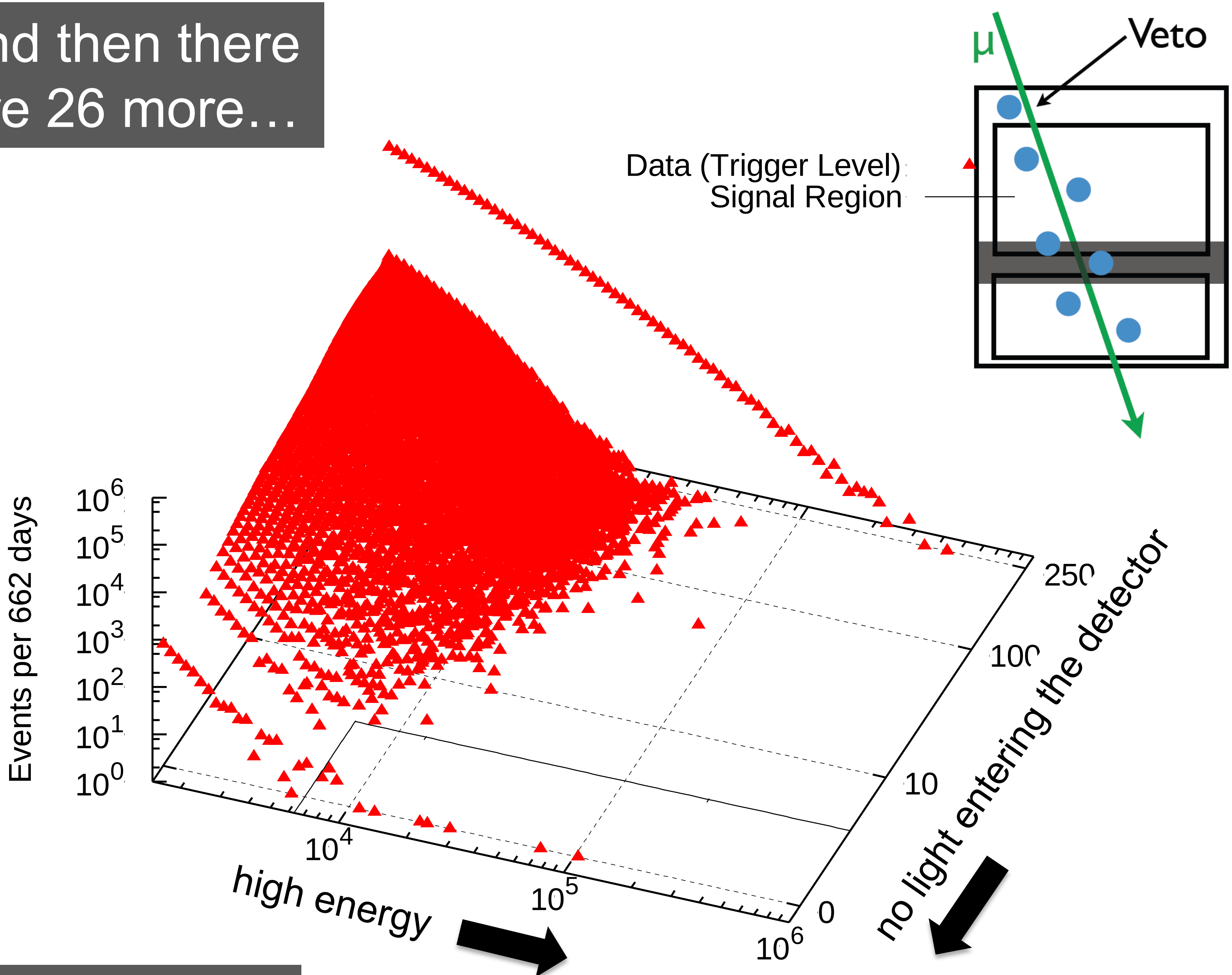
…and then there were 26 more…



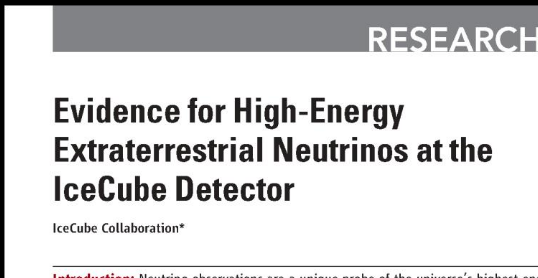


data: 86 strings one year

…and then there were 26 more…



data: 86 strings one year

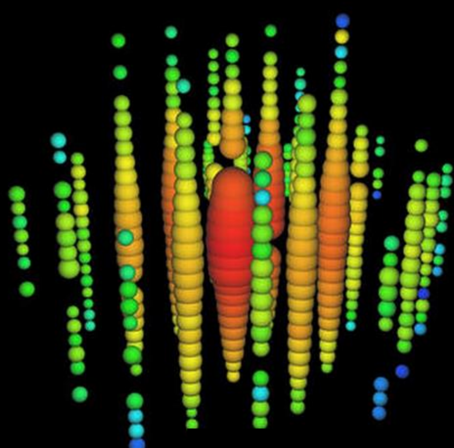


RESEARCH

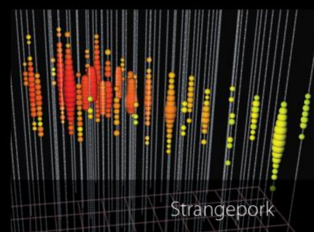
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

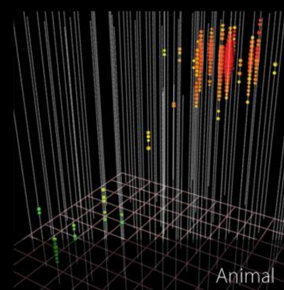
IceCube Collaboration*

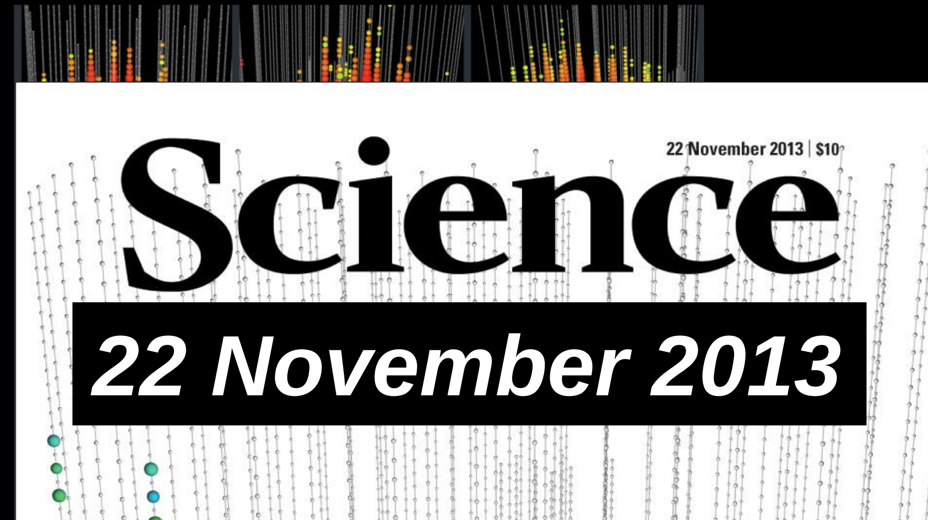
Introduction: Neutrino observations are a unique probe of the universe's highest-en



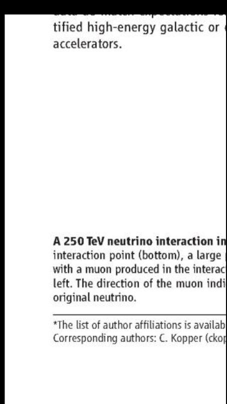
28 High Energy Events







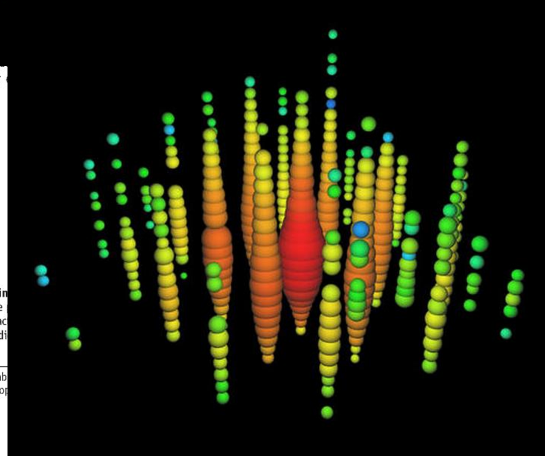
22 November 2013

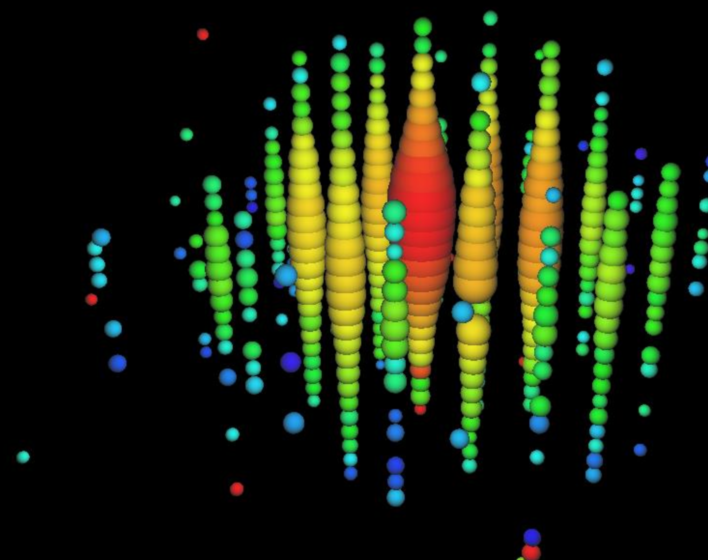


tified high-energy galactic or
accelerators.

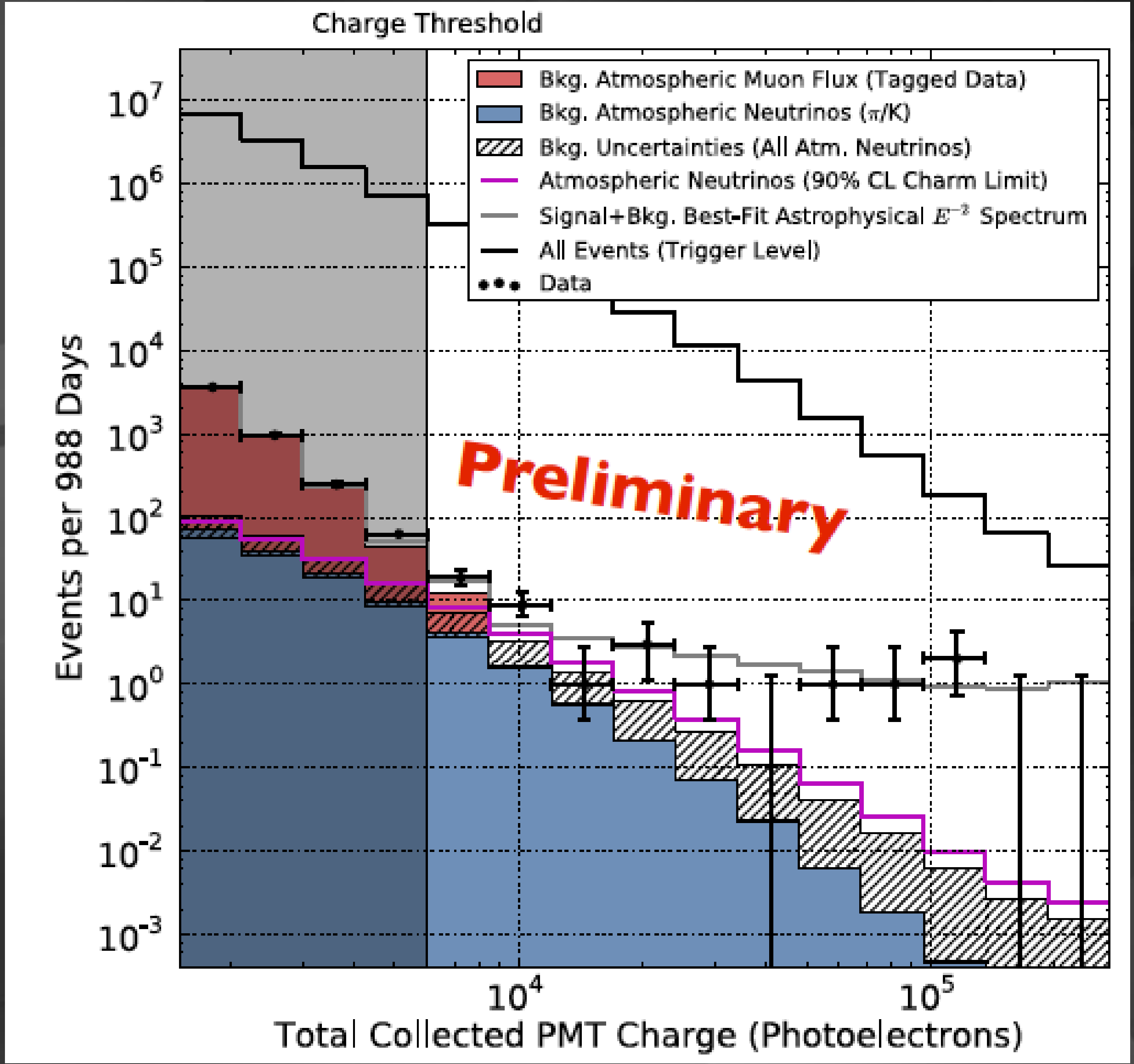
A 250 TeV neutrino interaction in interaction point (bottom), a large with a muon produced in the interac left. The direction of the muon indi original neutrino.

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

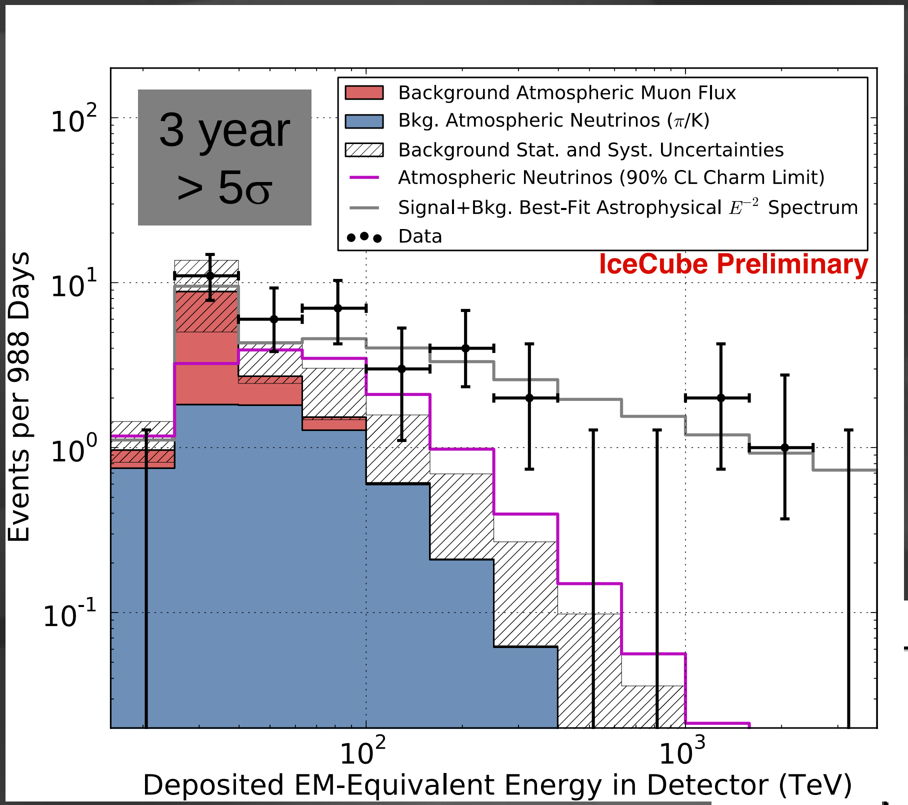




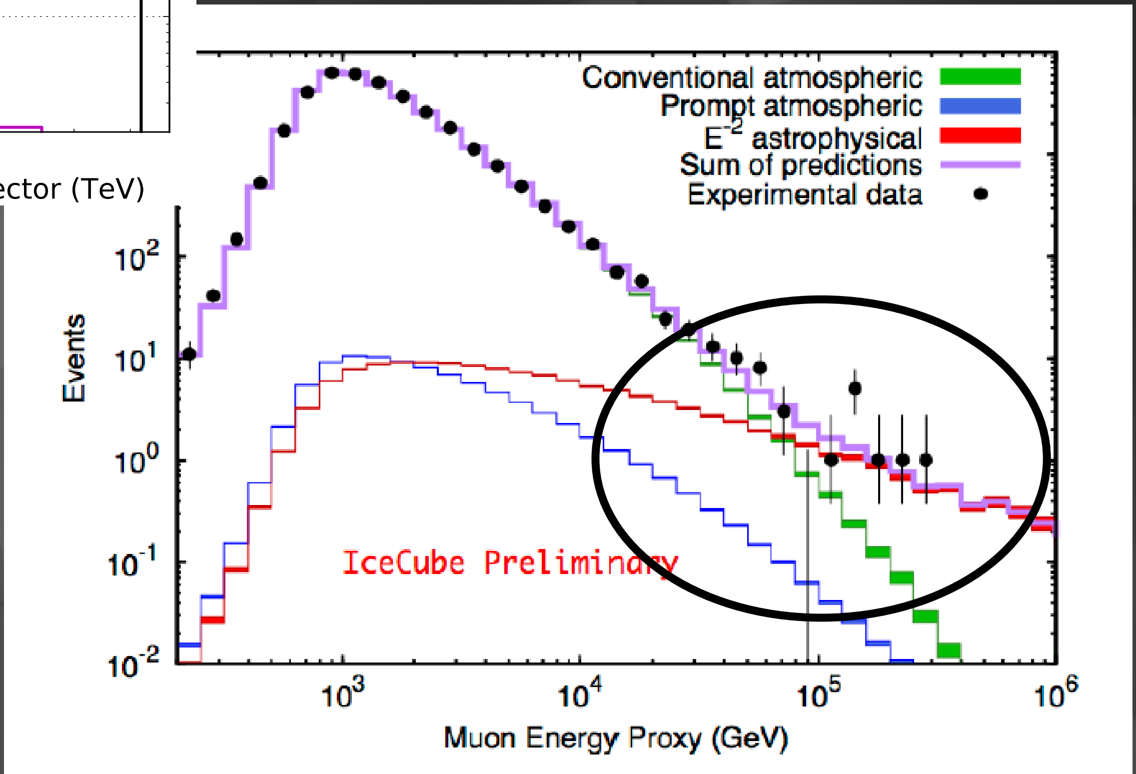
total charge collected by PMTs of events with interaction inside the detector



Science 342 (2013) 1242856

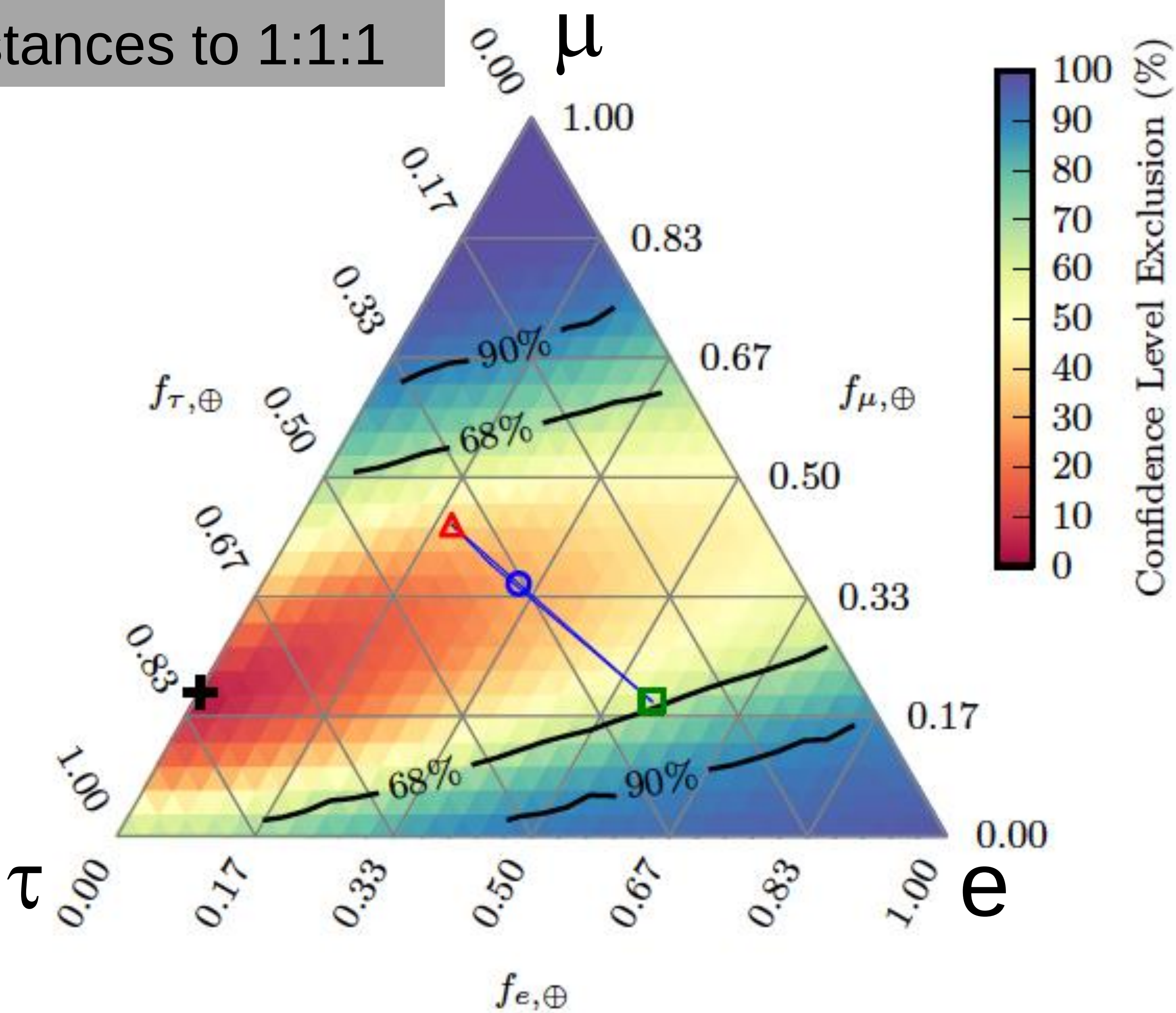


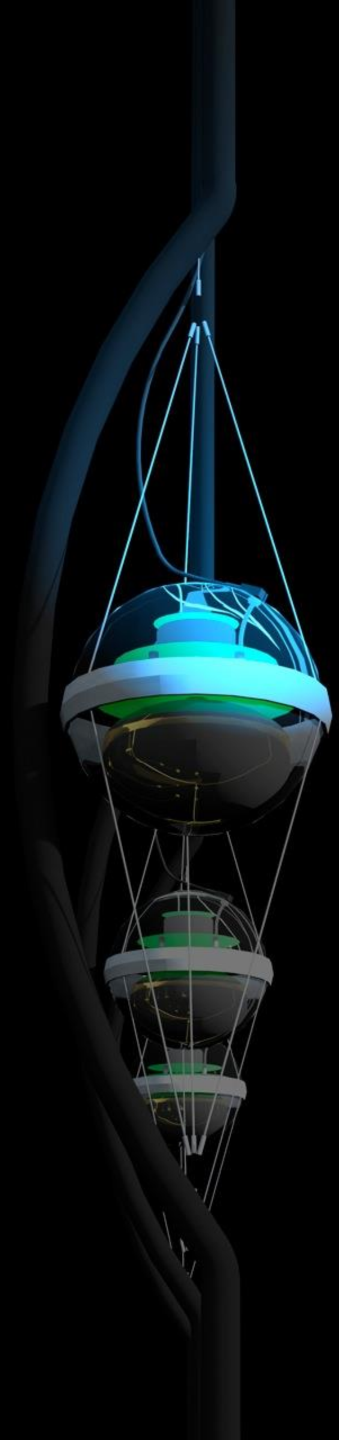
confirmation!
flux of muon neutrinos
through the Earth



neutrinos of all flavors
interacting inside
IceCube

oscillate over cosmic distances to 1:1:1



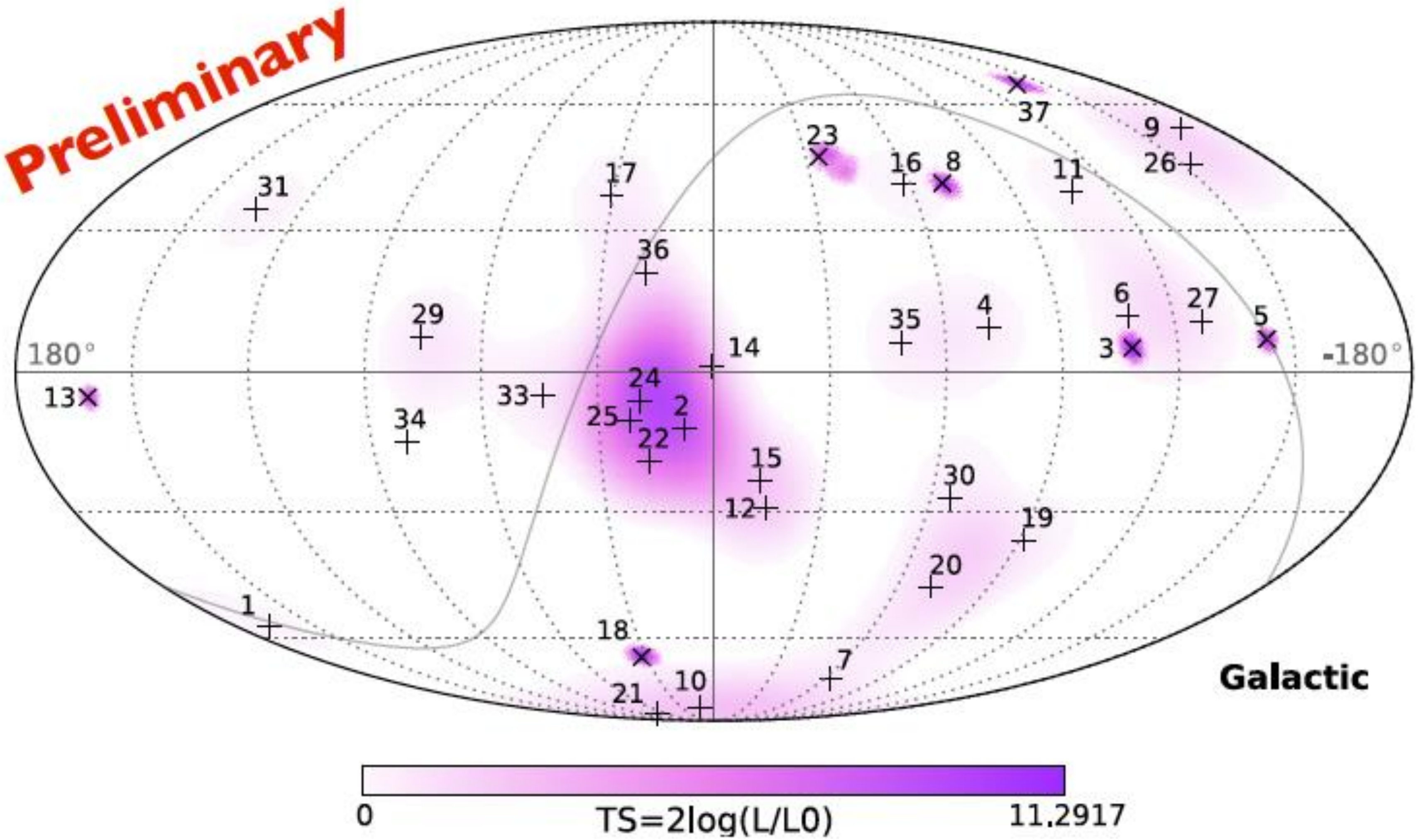


IceCube: the discovery of cosmic neutrinos
francis halzen

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

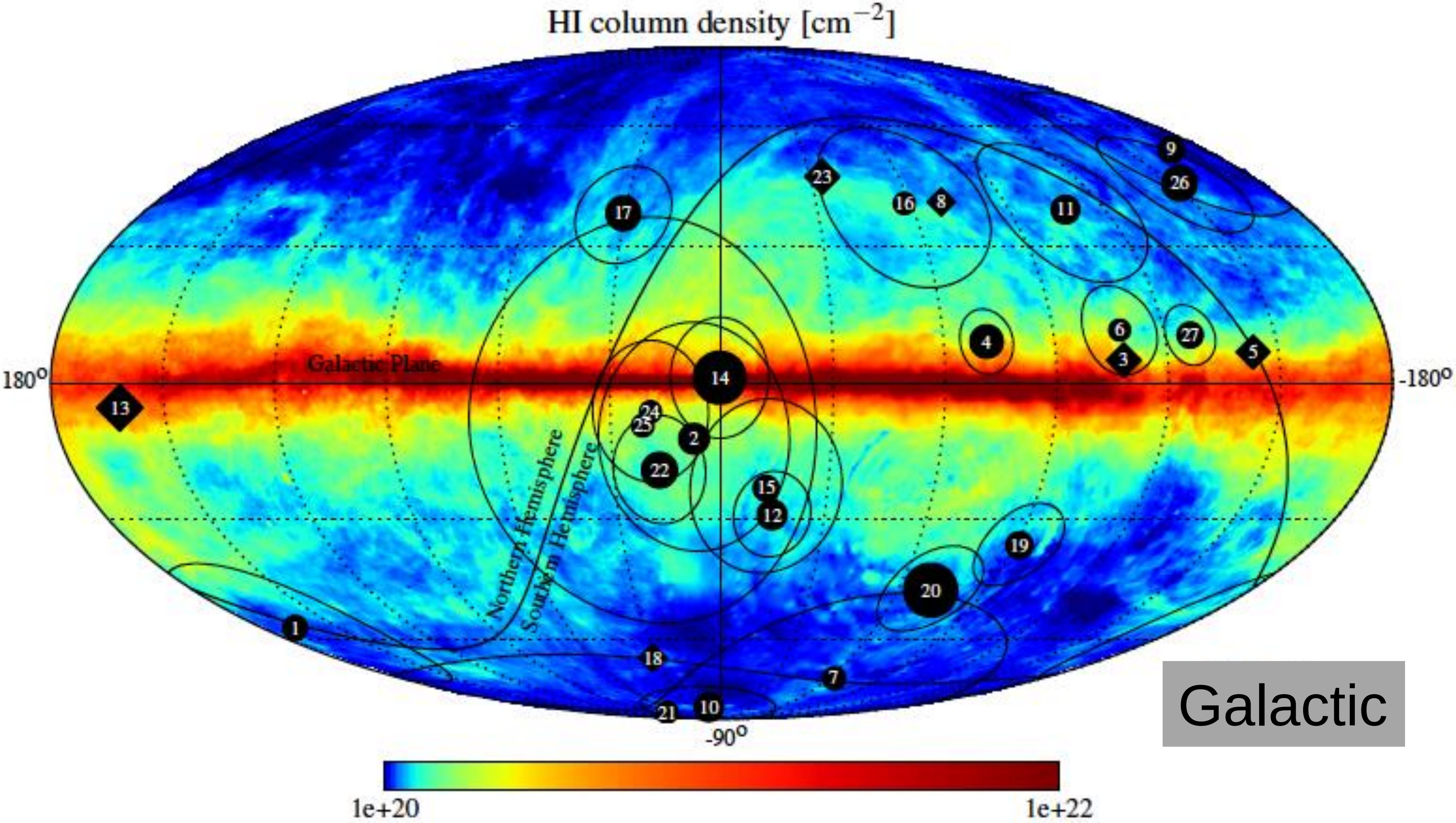
IceCube.wisc.edu

where do they come from (3 year data)?



hottest spot 7.2%: consistent with diffuse flux with fllavor 1:1:1?

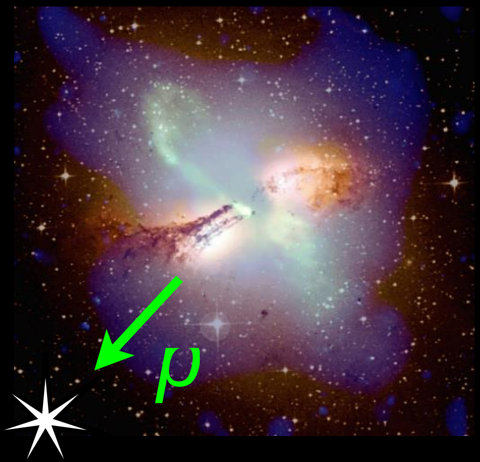
correlation with Galactic plane: TS of 2.8% for a width of 7.5 deg



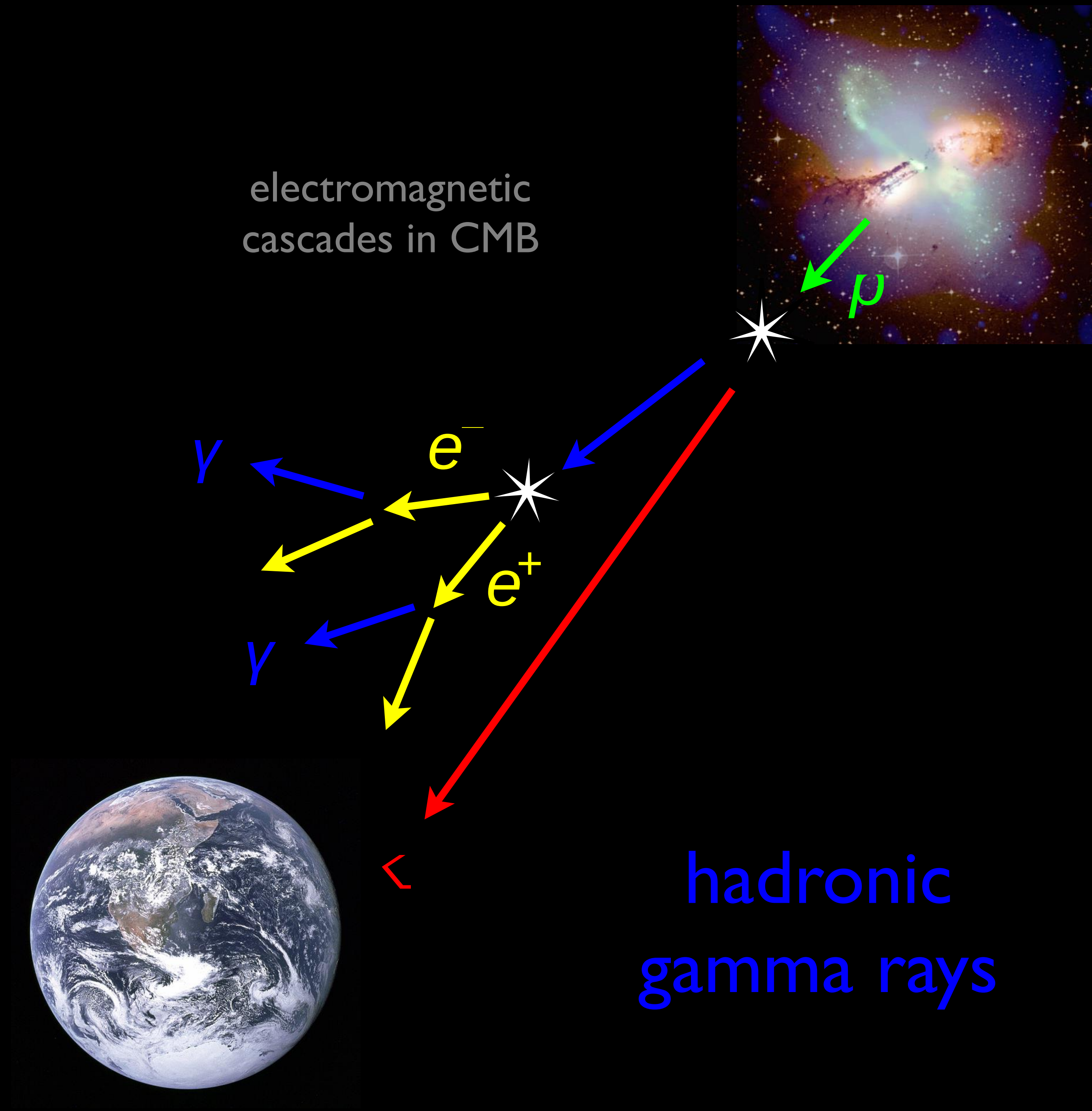
Galactic

hadronic gamma rays ?

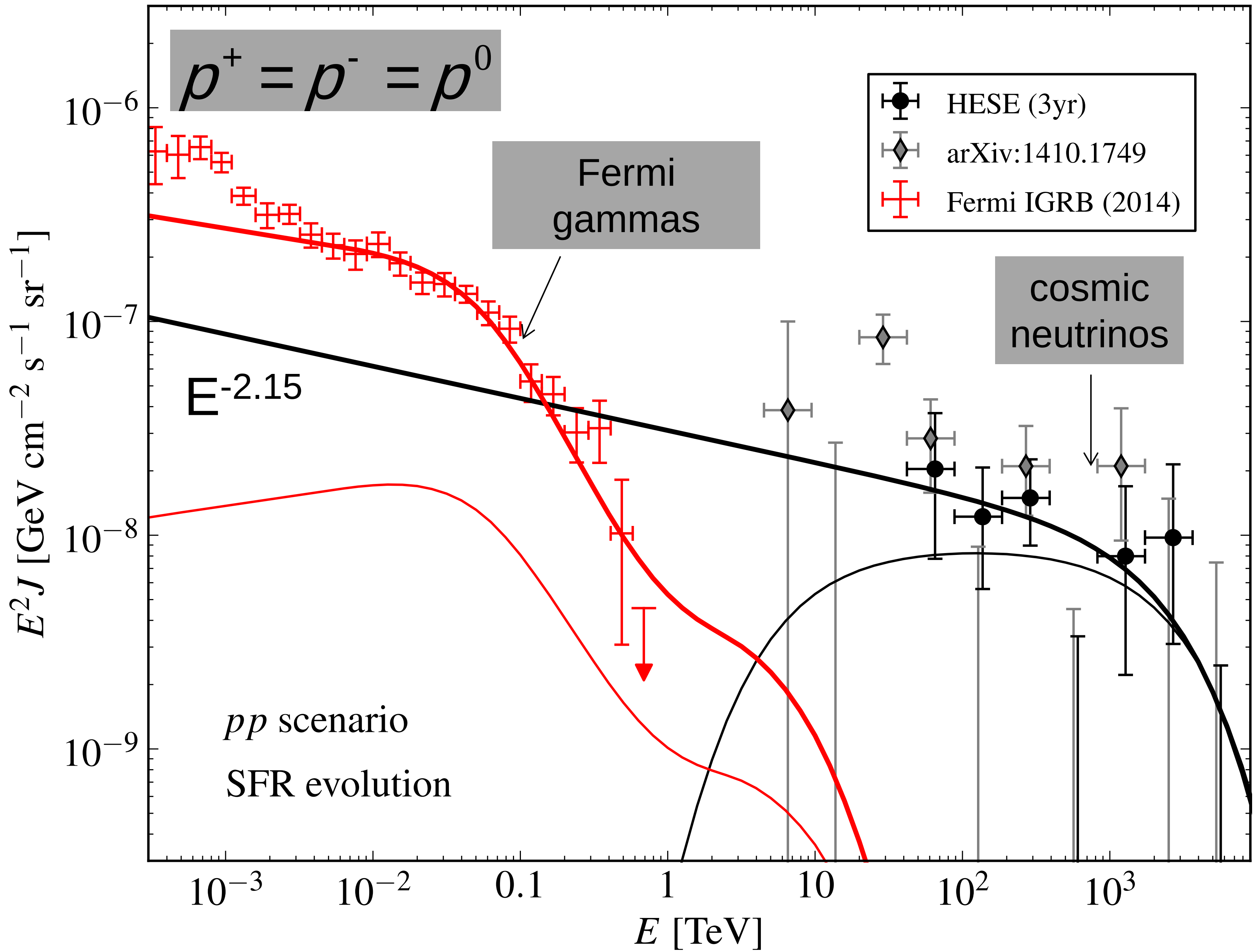
$\pi^{+} = \pi^{-} = \pi^{0}$



hadronic gamma rays



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



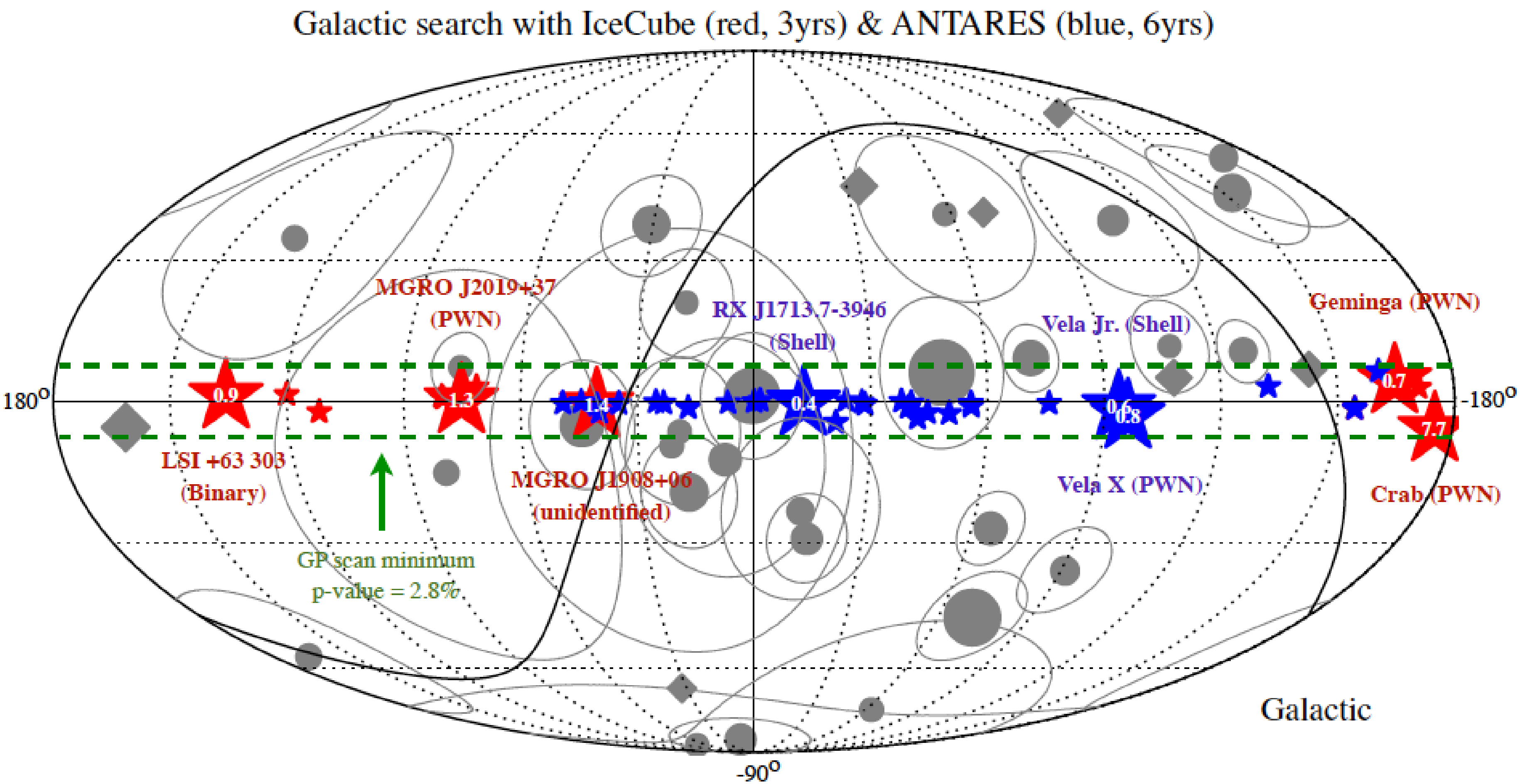
$p^+ = p^- = p^0$
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
Fermi gammas
cosmic neutrinos
$E^{-2.15}$
pp scenario
SFR evolution
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3

- we 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

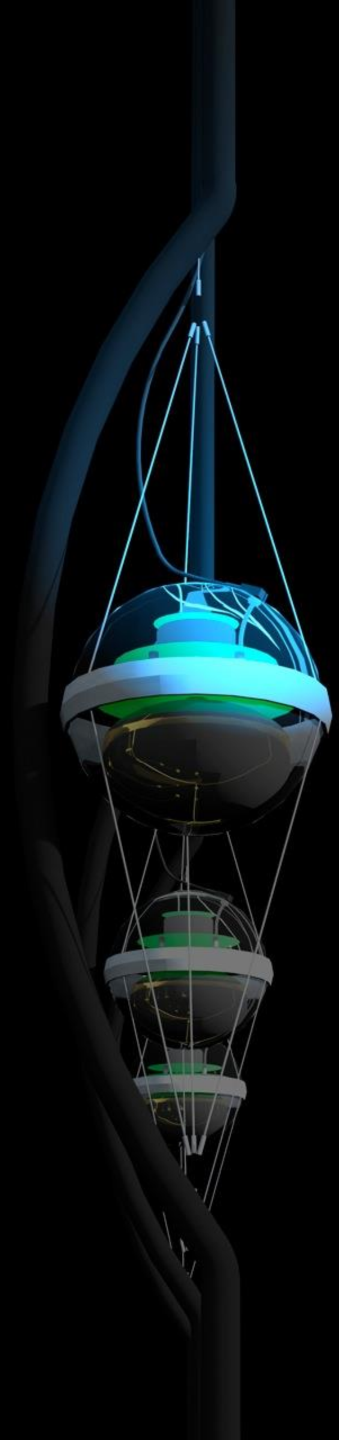
- hadronic accelerators are not a footnote to astronomy; they generate a significant fraction of the energy in the non-thermal Universe

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

neutrino event rates from gamma ray sources



as some (all?) gamma ray sources produce neutrinos, we are close to detecting neutrinos from known high energy gamma ray emitters (one neutrino per photon)



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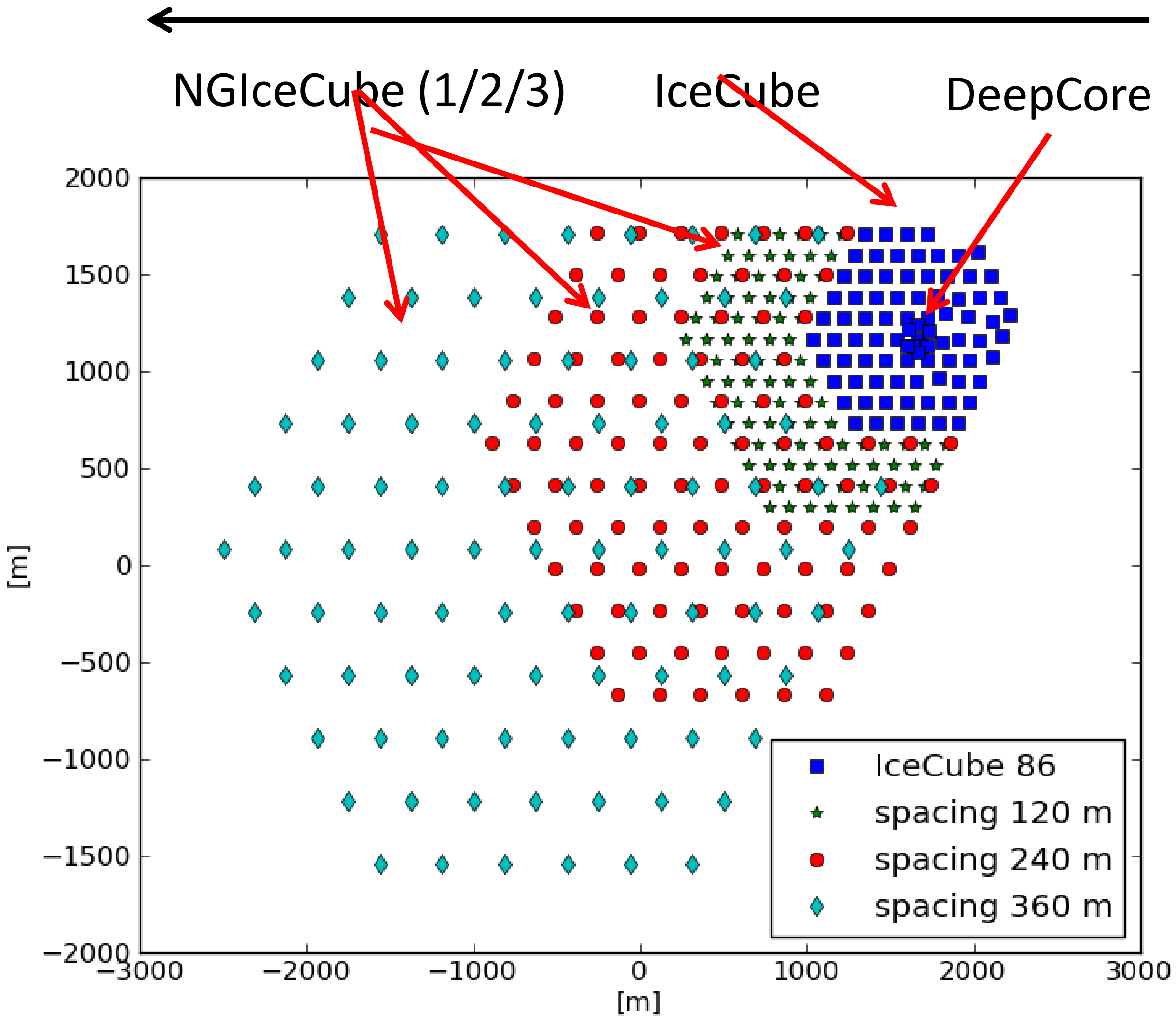
- a next-generation IceCube with a volume of 10 km^3 and an angular resolution of < 0.3 degrees will see multiple neutrinos and identify the sources, even from a “diffuse” extragalactic flux in several years
- need 1,000 events vs 100 now
- discovery instrument → astronomical telescope

measured optical properties → twice the string spacing

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

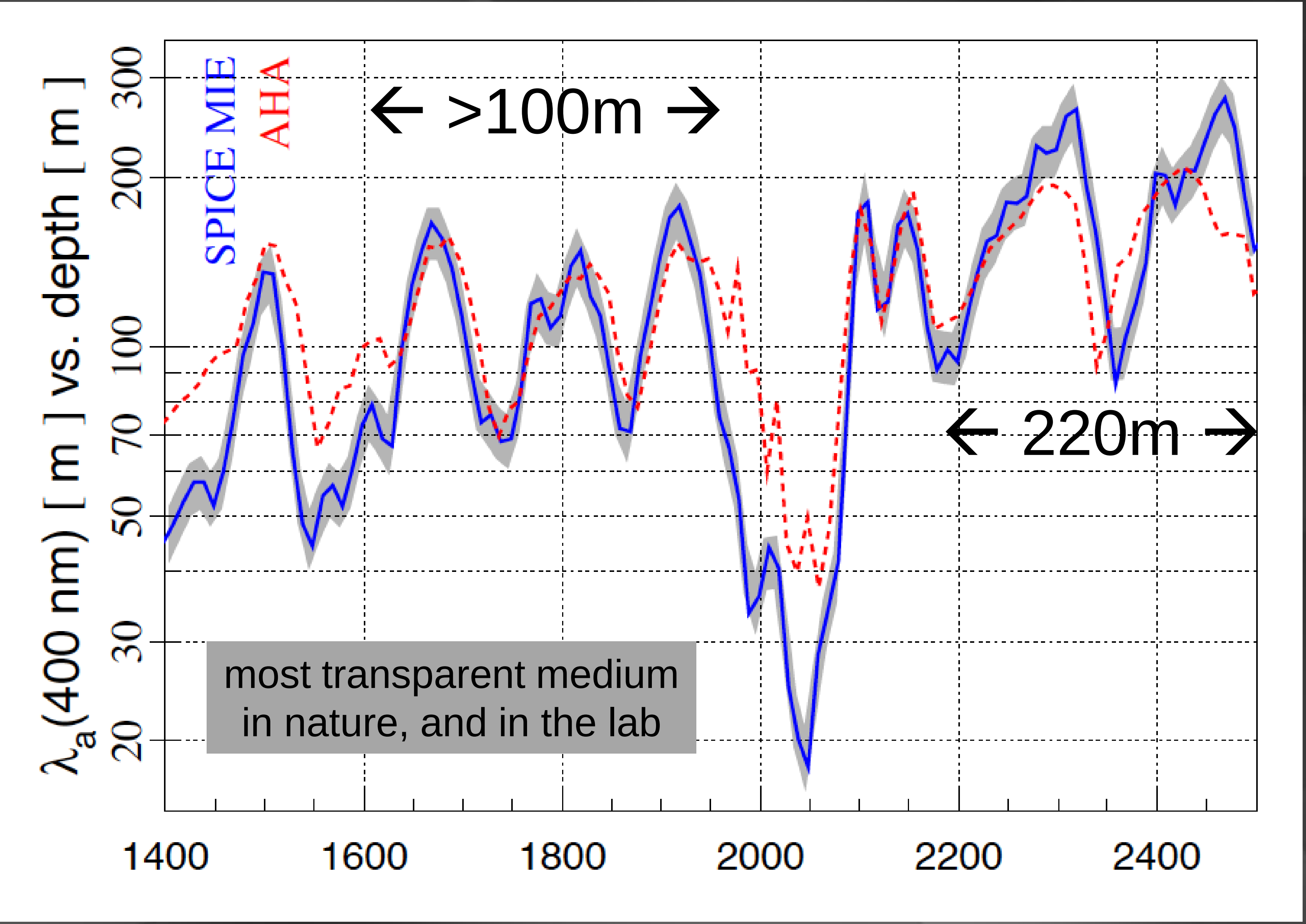


Spacing 1 (120m):
IceCube (1 km^3)
+ 98 strings (1,3 km^3)
= 2,3 km^3

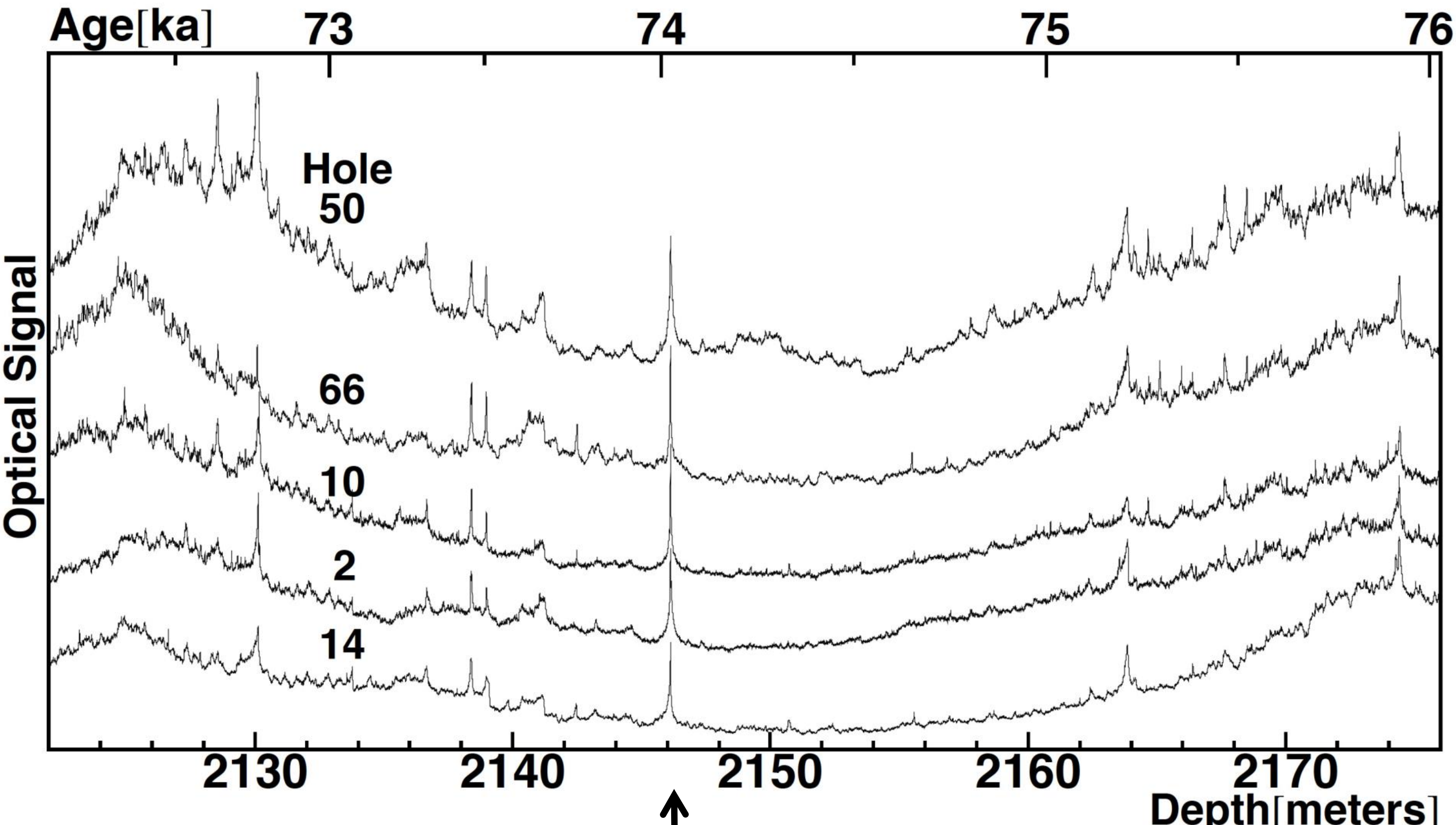
Spacing 2 (240m):
IceCube (1 km^3)
+ 99 strings (5,3 km^3)
= 6,3 km^3

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

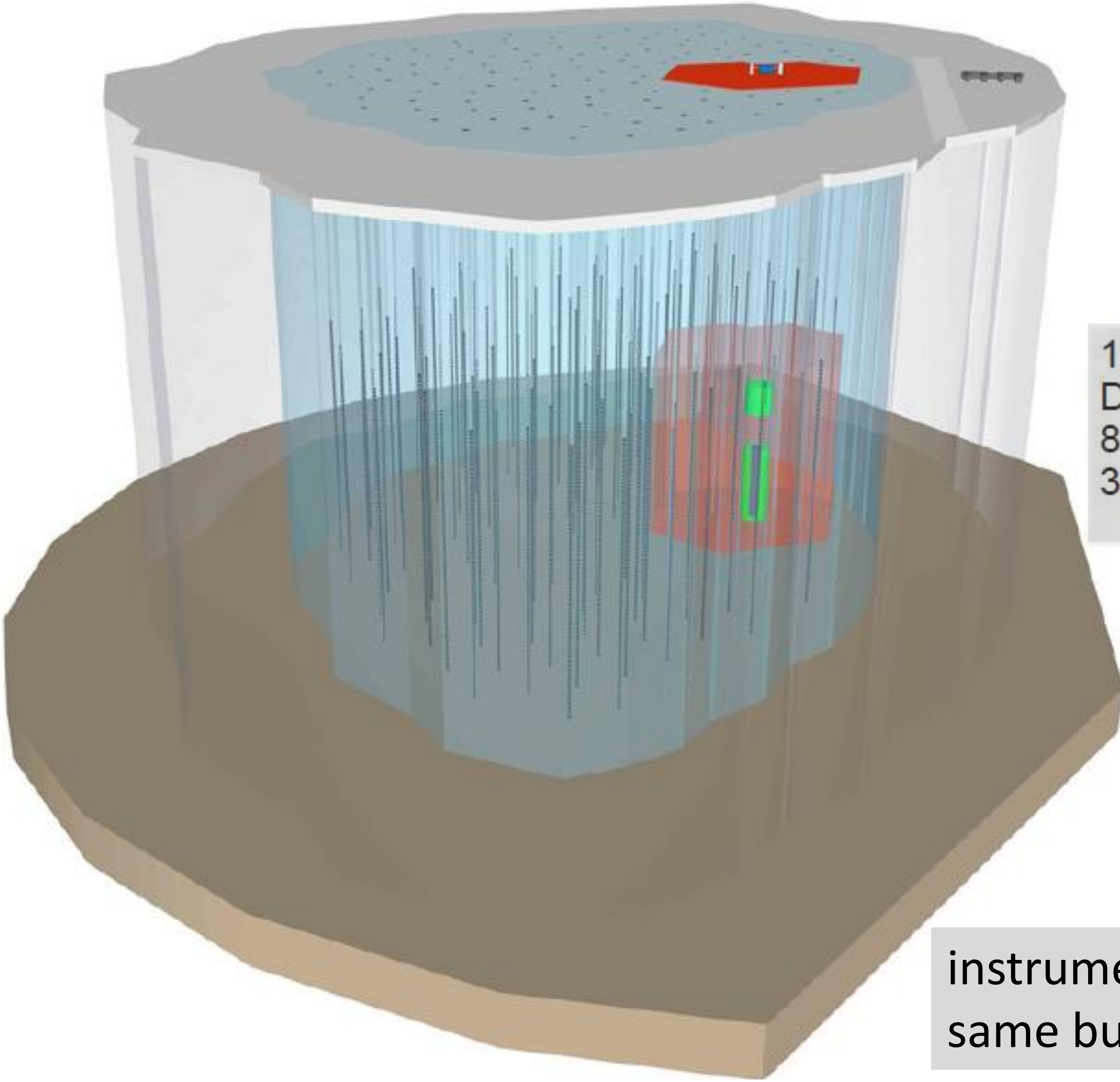
absorption length of Cherenkov light



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



Toba eruption

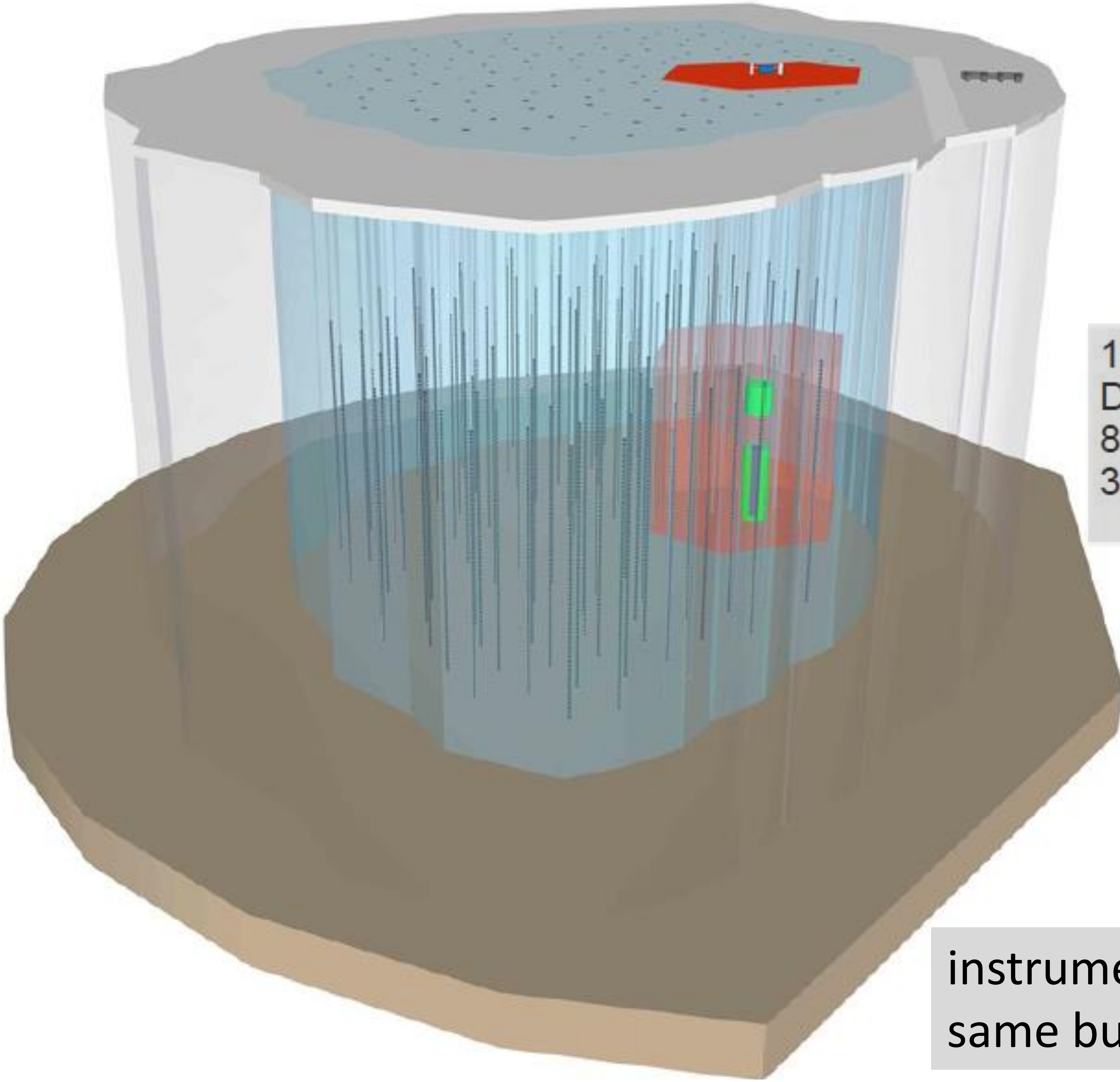


120 strings
Depth 1.35 to 2.7 km
80 DOMs/string
300 m spacing

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
- ….



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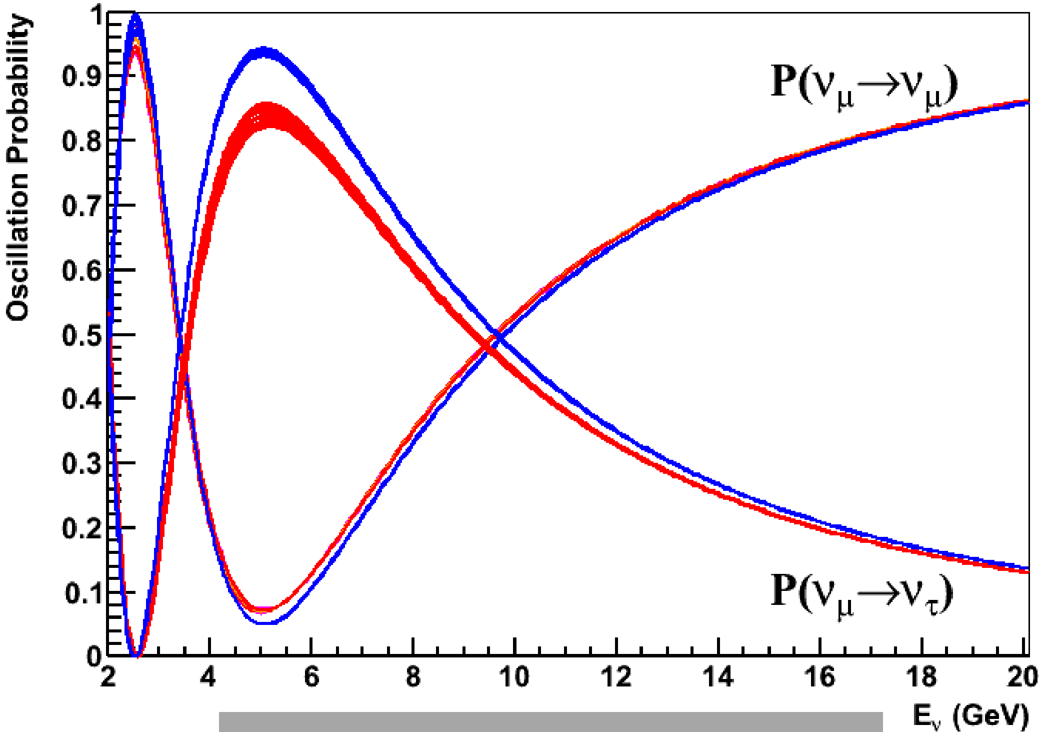
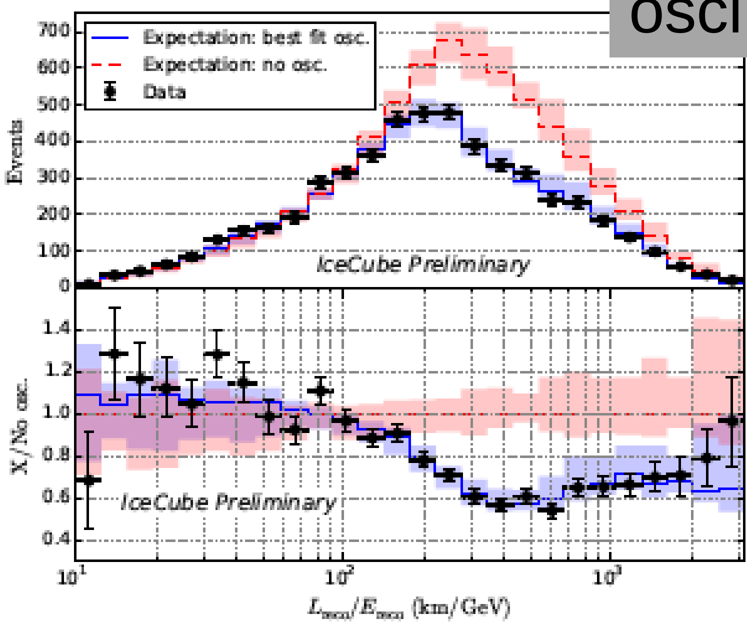
IceCube

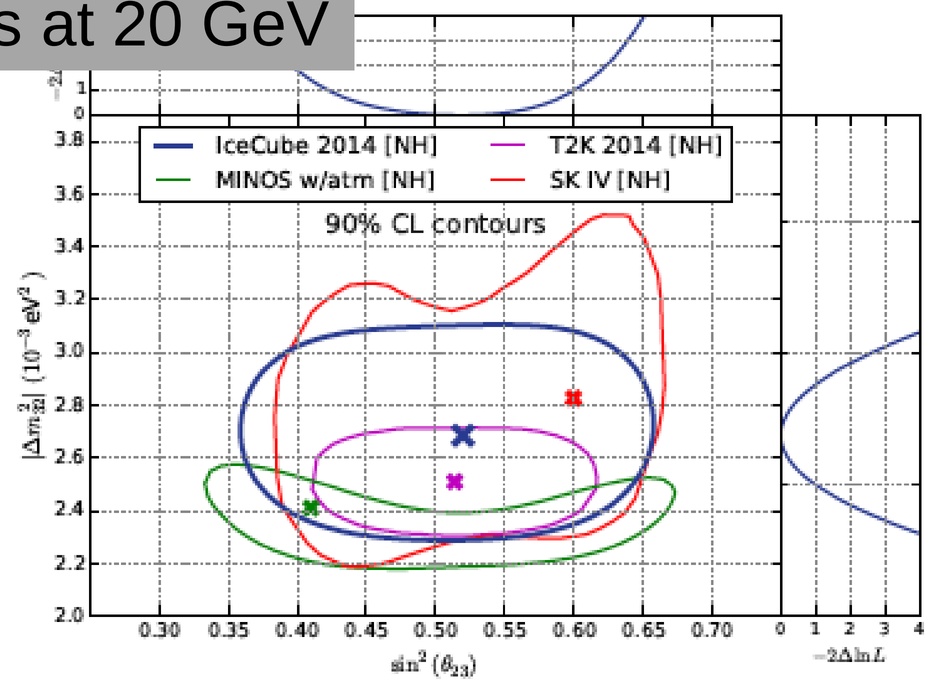
DeepCore

PINGU

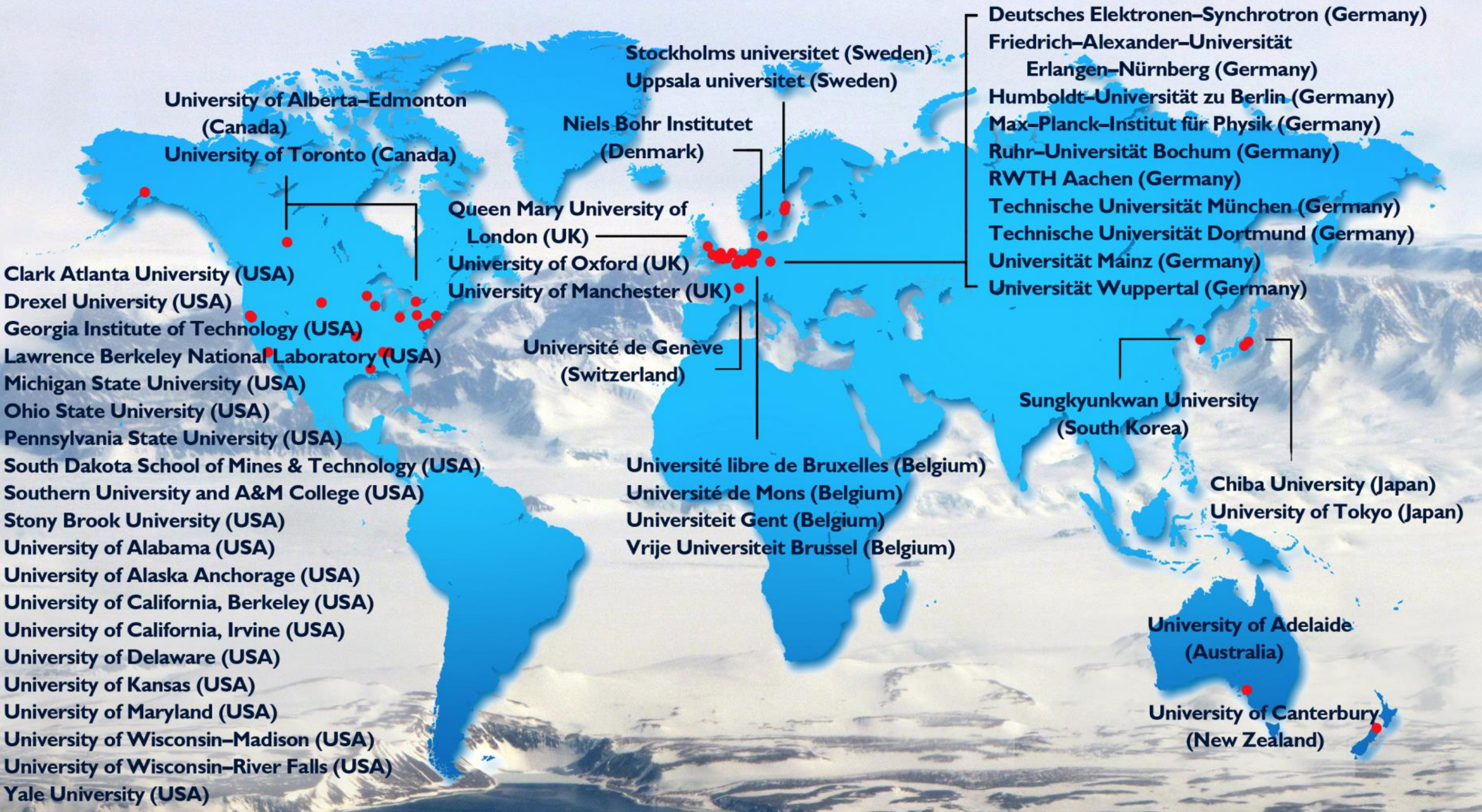


oscillations at 20 GeV



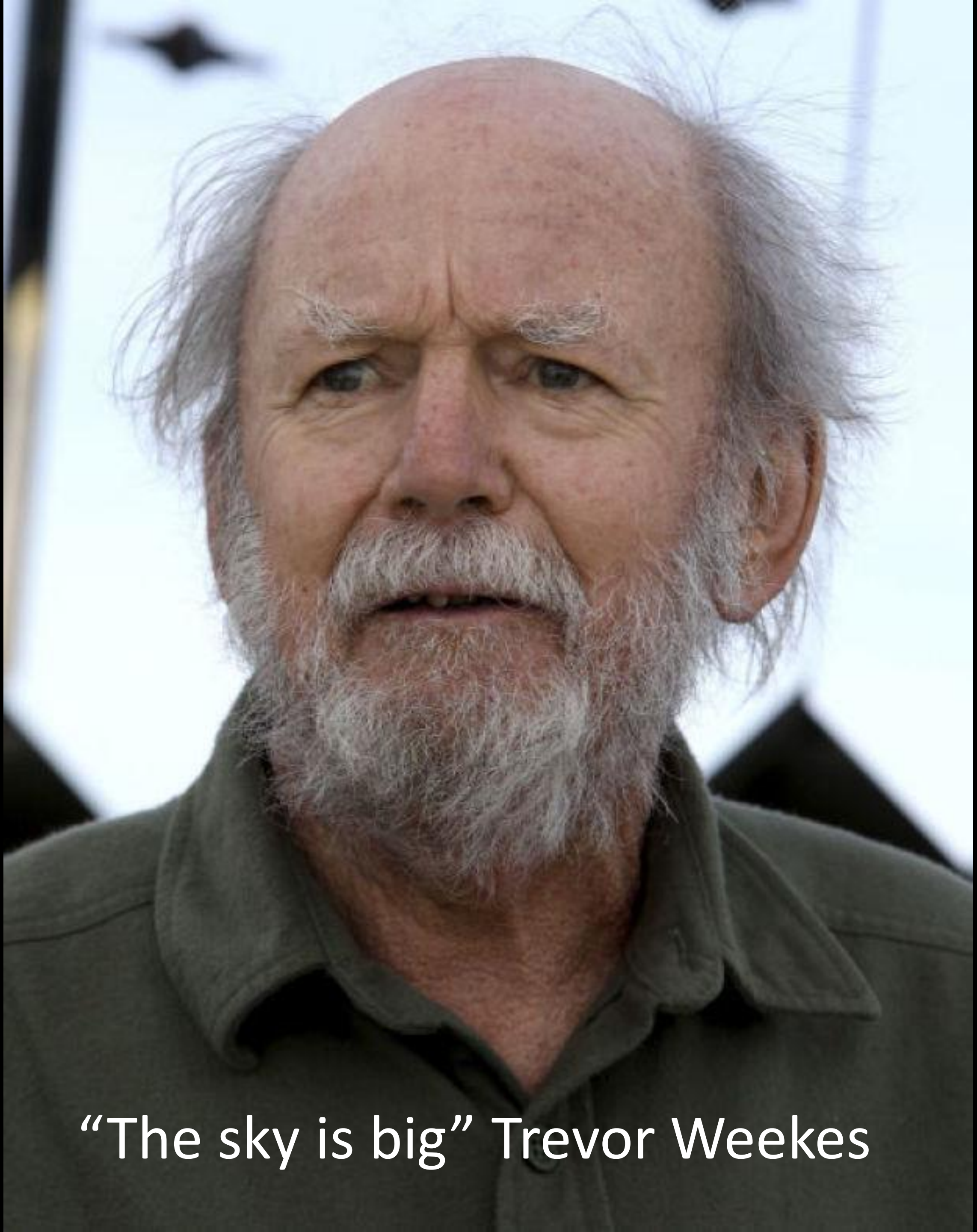


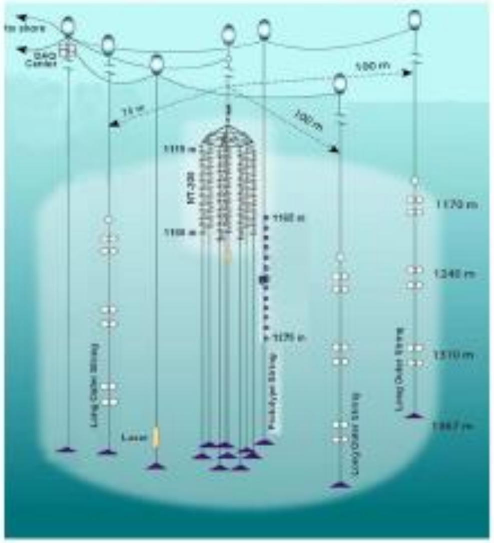
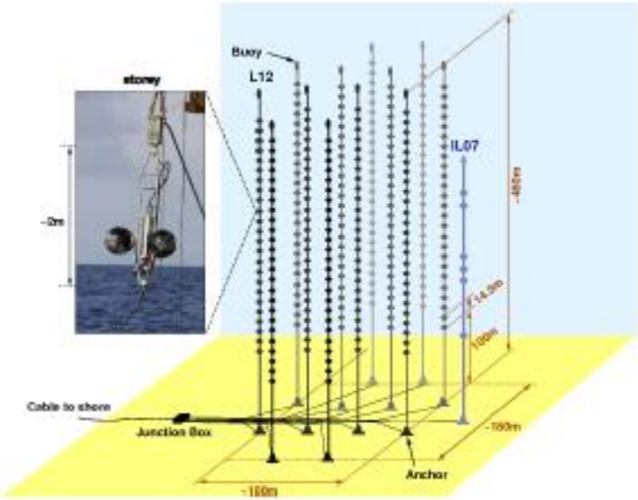
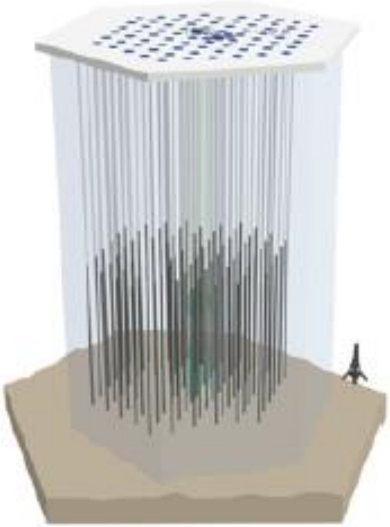
The IceCube–PINGU Collaboration



International Funding Agencies

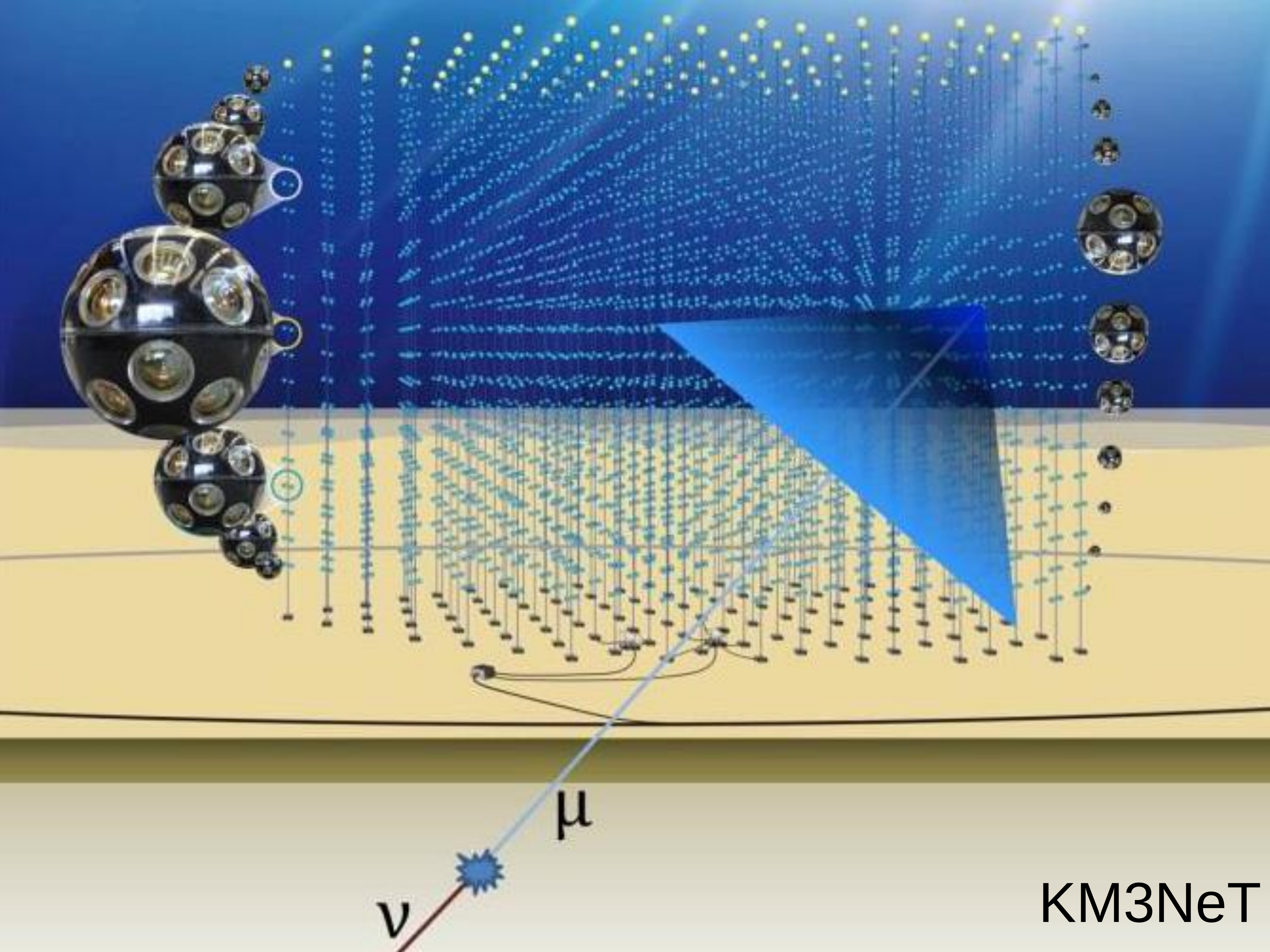
- Fonds de la Recherche Scientifique (FRS-FNRS)
- Fonds Wetenschappelijk Onderzoek–Vlaanderen (FWO–Vlaanderen)
- Federal Ministry of Education & Research (BMBF)
- German Research Foundation (DFG)
- Deutsches Elektronen–Synchrotron (DESY)
- Inoue Foundation for Science, Japan
- Knut and Alice Wallenberg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


“The sky is big” Trevor Weekes

NT-200+	ANTARES	IceCube
		
•Lake Baikal	•Mediterranean Sea	•South Pole glacier
•1/2000 km^3	•1/100 km^3	•1 km^3
•228 PMTs	•885 PMTs	•5160 PMTs

Larger, sparser → higher energies

future: < 100 m (lower threshold) 250m (high energy)


μ
ν
KM3NeT

Outlook:

- capitalize on discovery
- astronomy guaranteed
- neutrinos are never boring!

from discovery to astronomical telescopes:

parallel development in the Mediterranean

ANTARES → KM3NeT

Baikal → GVD

The IceCube–PINGU Collaboration

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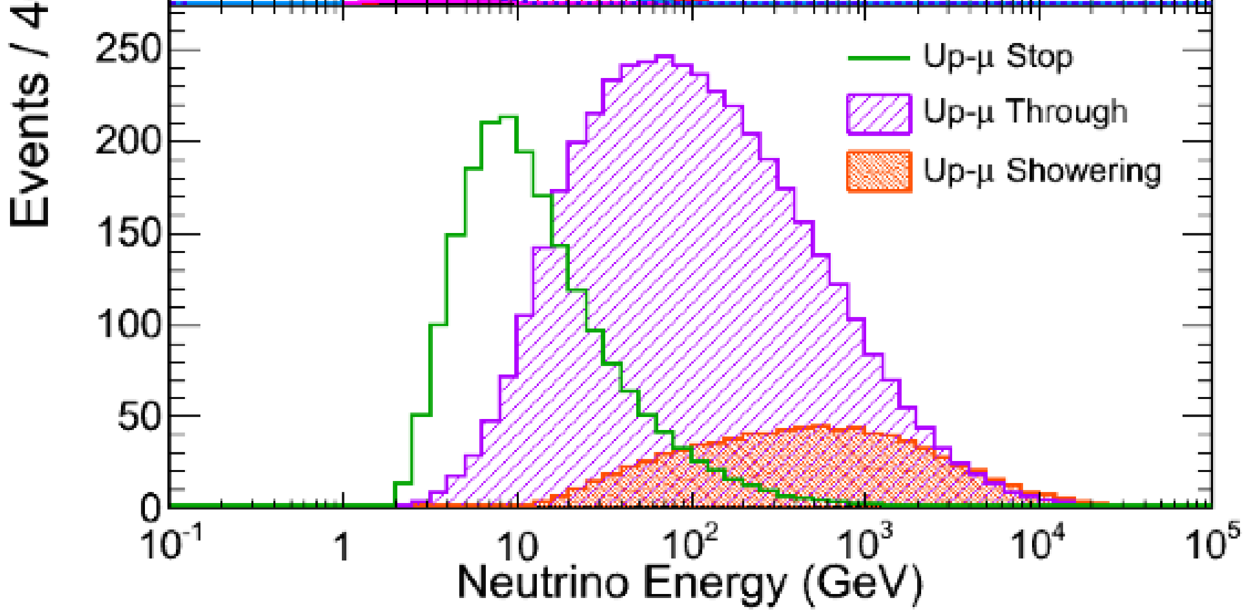
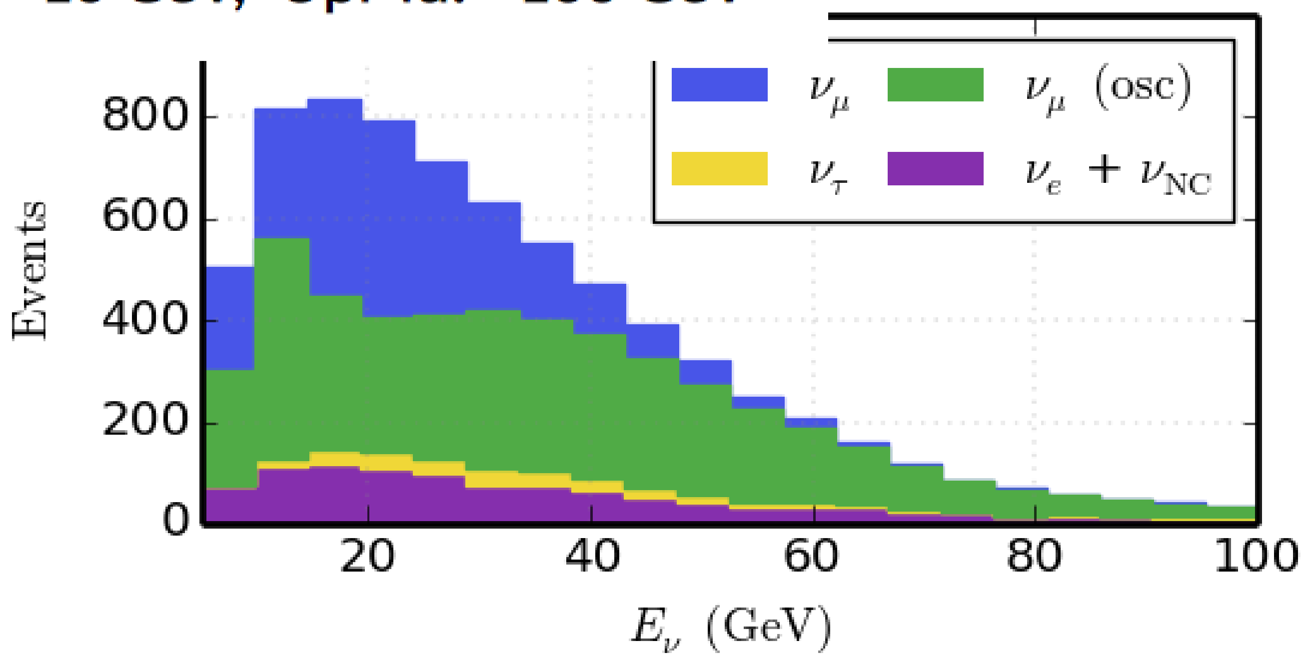
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
NSF–Office of Polar Programs
NSF–Physics Division
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)



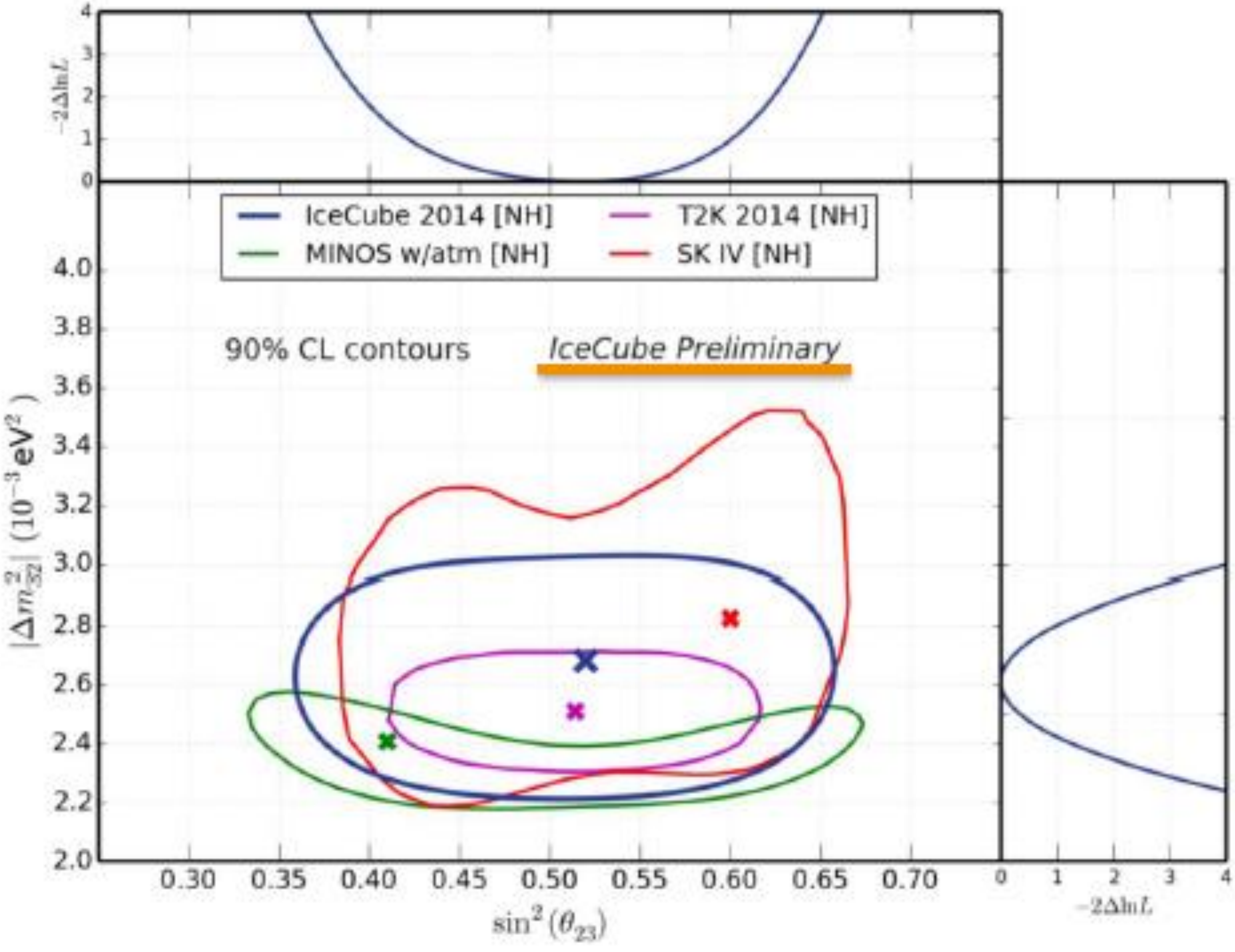
SuperK

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

IceCube

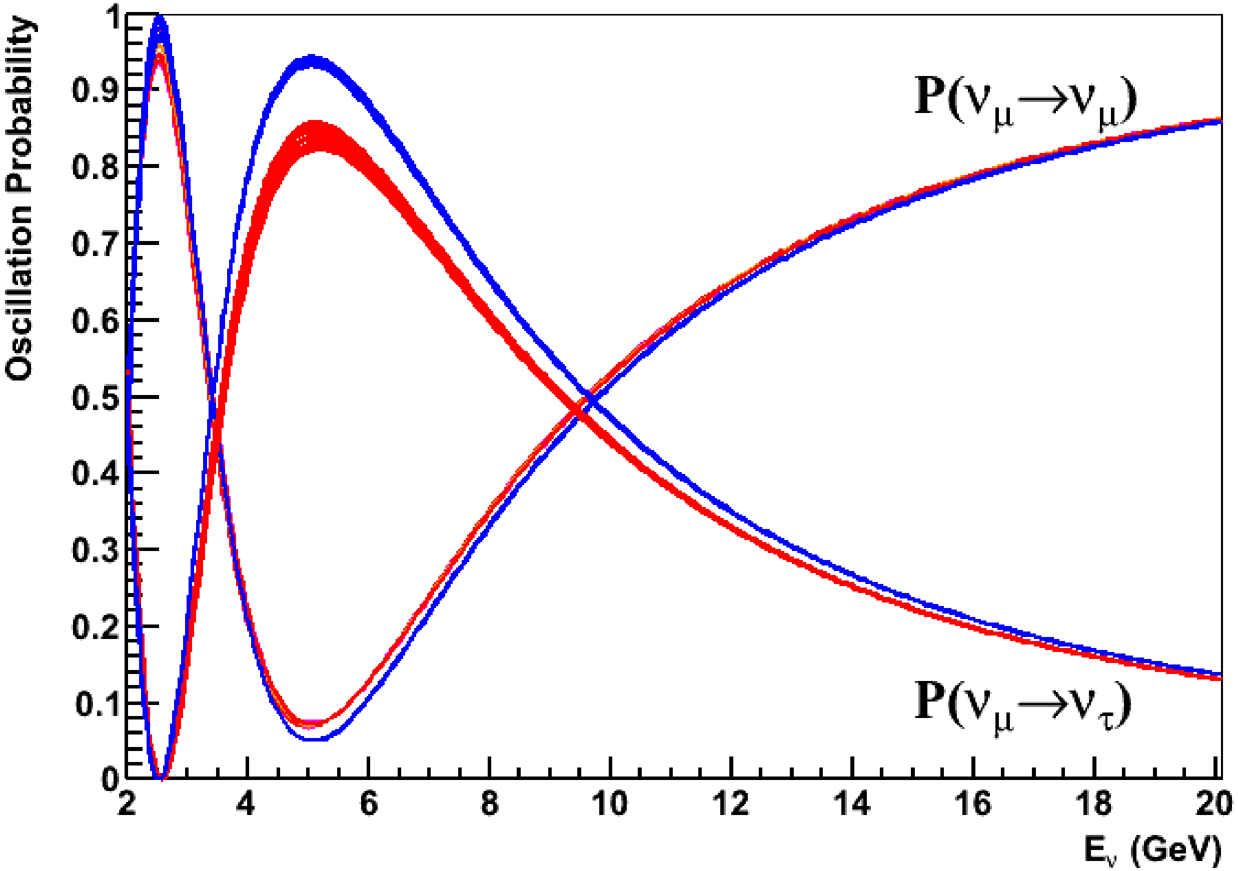


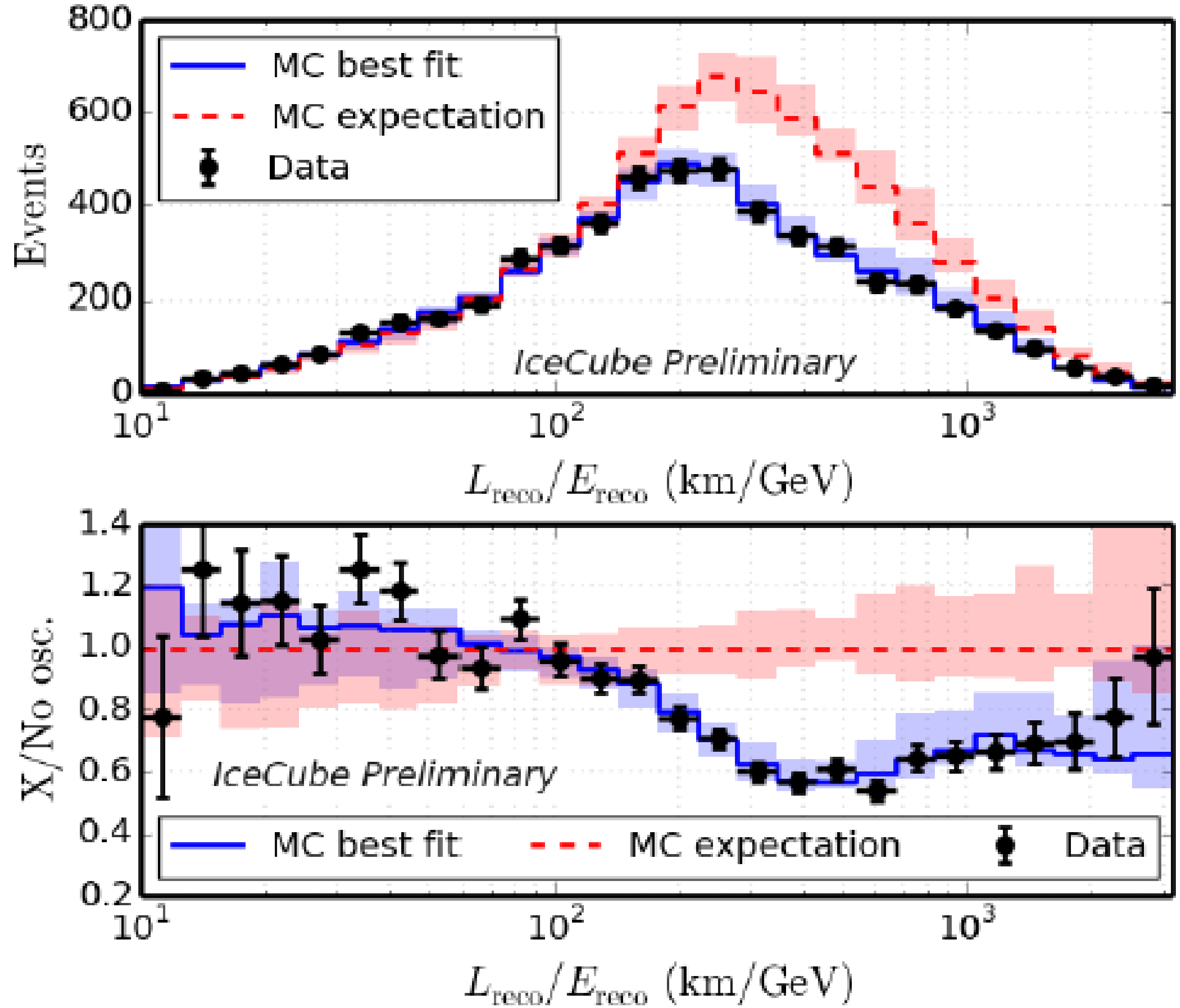
DeepCore



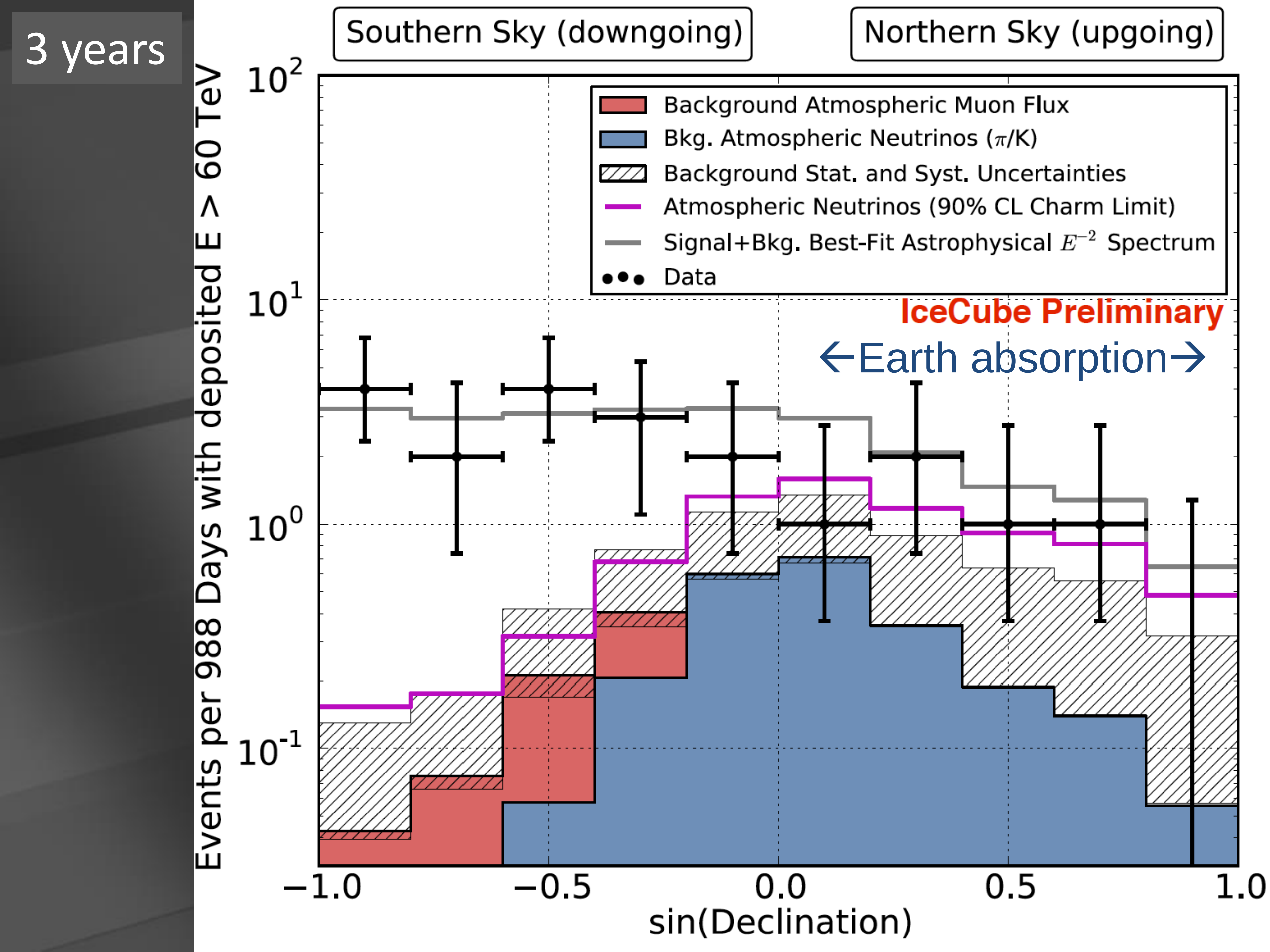
IceCube 2014 [NH]
T2K 2014 [NH]
MINOS w/atm [NH]
SK IV [NH]
90% CL contours
IceCube Preliminary
$|\Delta m^2_{32}|$ (10^{-3} eV^2)
$\sin^2(\theta_{23})$
$-2\Delta\ln L$

- oscillations at 10 GeV energy and above
- same oscillation parameters measured in a new energy range.



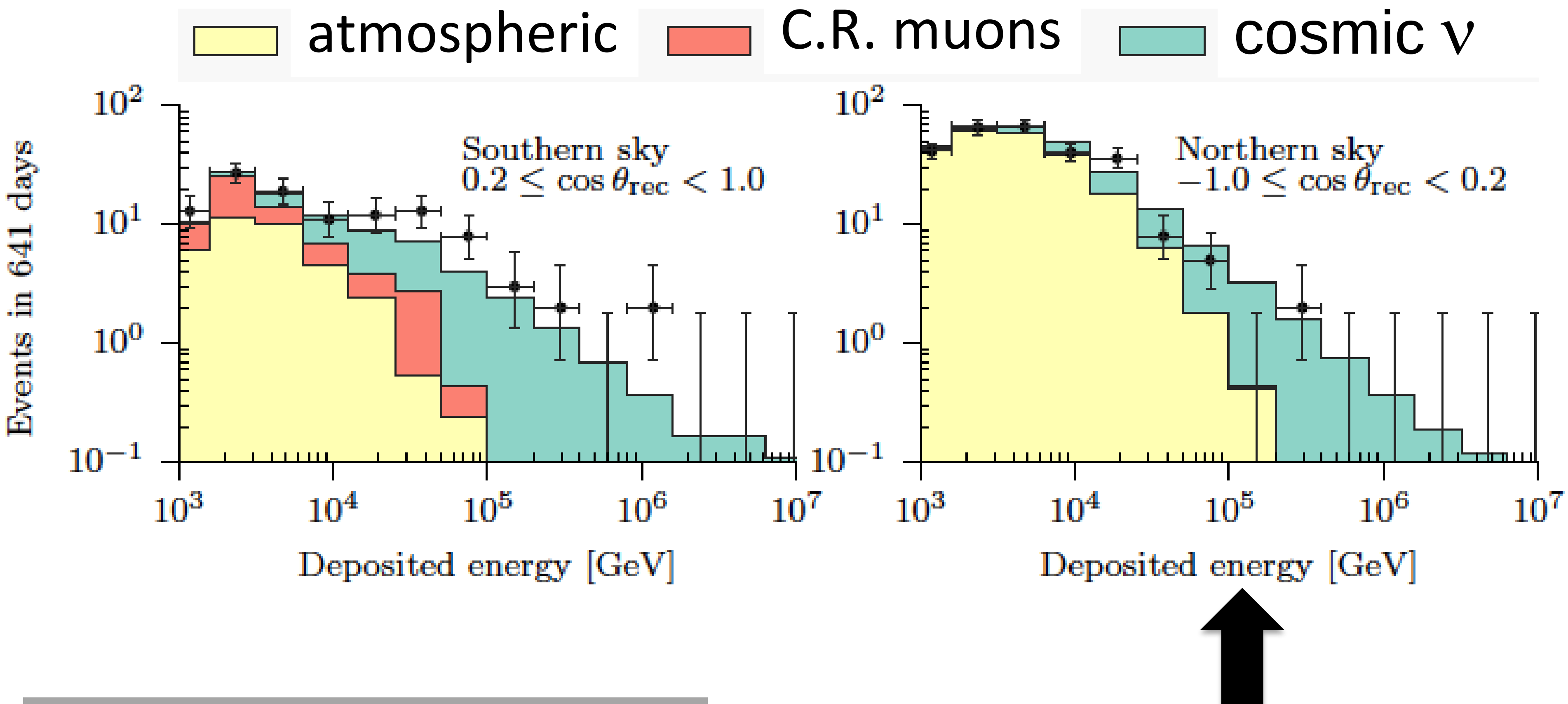


800
600
400
200
0
Events
MC best fit
MC expectation
Data
IceCube Preliminary
10^1
10^2
10^3
$L_{\rm reco}/E_{\rm reco}$ (km/GeV)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
X/No osc.
IceCube Preliminary
MC best fit
MC expectation
Data
10^1
10^2
10^3
$L_{\rm reco}/E_{\rm reco}$ (km/GeV)



3 years
Southern Sky (downgoing)
Northern Sky (upgoing)
Background Atmospheric Muon Flux
Bkg. Atmospheric Neutrinos (π/K)
Background Stat. and Syst. Uncertainties
Atmospheric Neutrinos (90% CL Charm Limit)
Signal+Bkg. Best-Fit Astrophysical E^{-2} Spectrum
Data
IceCube Preliminary
←Earth absorption→
Events per 988 Days with deposited E > 60 TeV
sin(Declination)

starting events; towards lower energies



warning:

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

PeV neutrinos absorbed in the Earth