IceCube

francis halzen

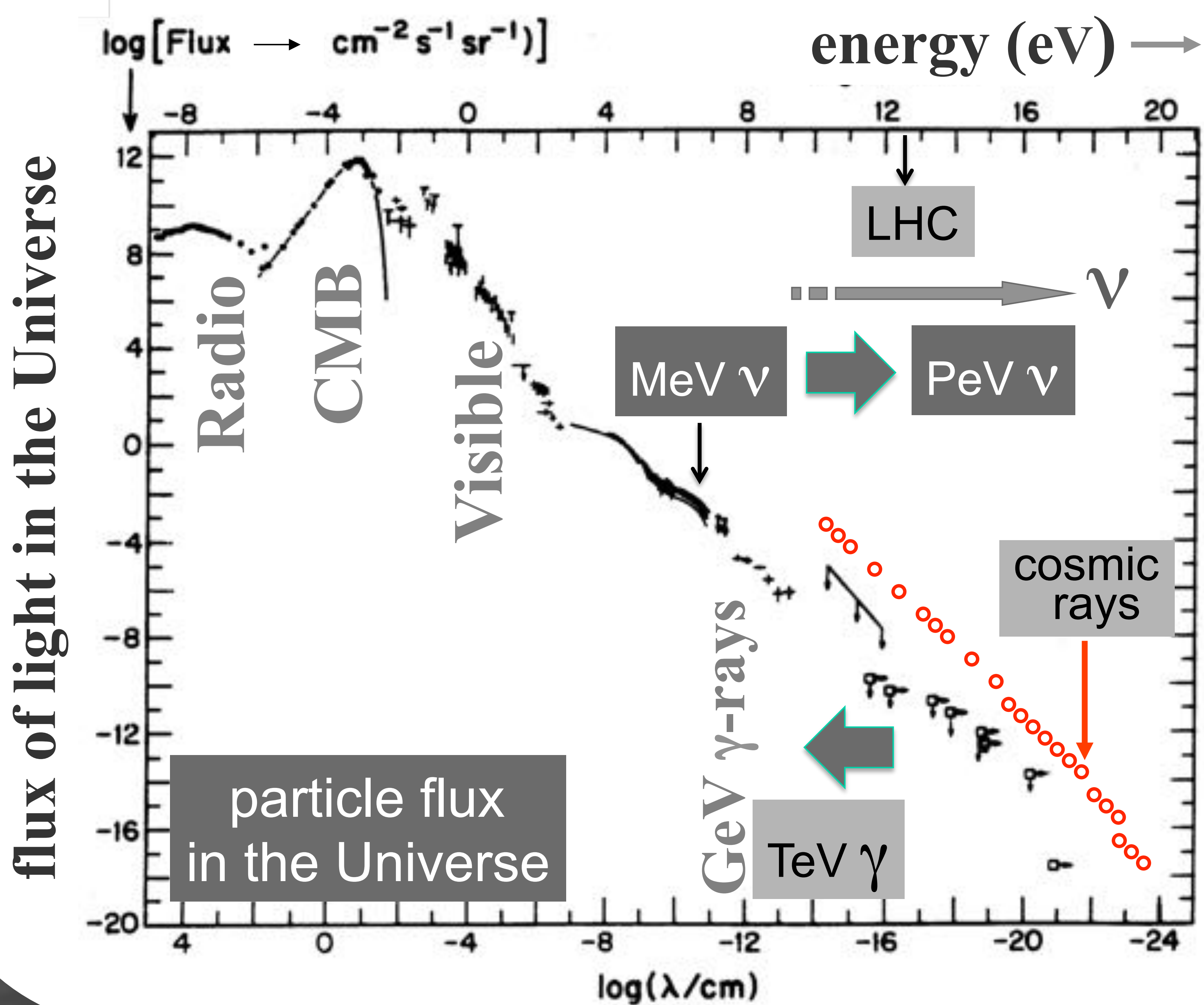
- why would you want to build a
  a kilometer scale neutrino detector?

- IceCube: a cubic kilometer detector

- the discovery (and confirmation) of cosmic neutrinos

- from discovery to astronomy

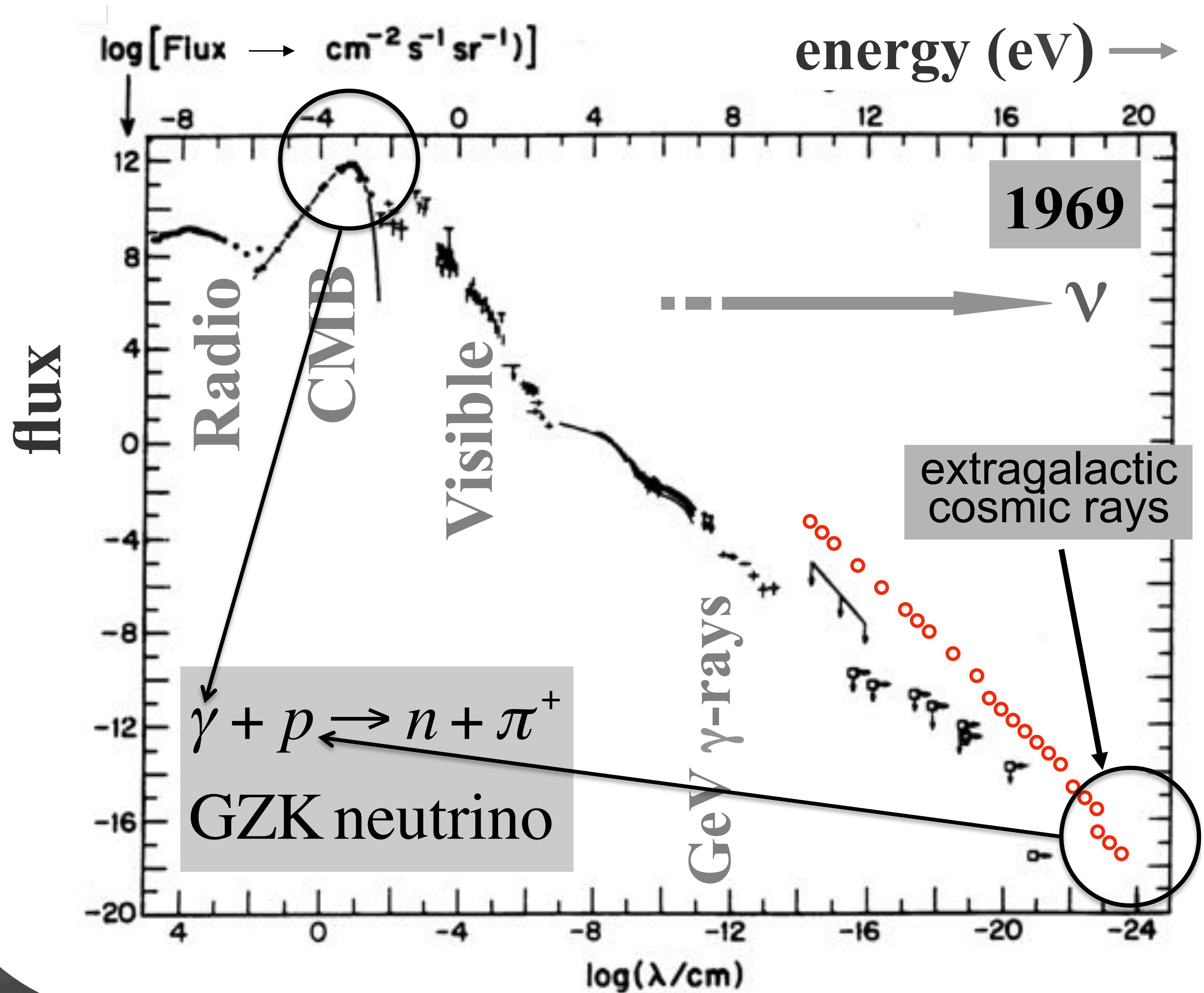
IceCube.wisc.edu



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

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) →
-8 -4 0 4 8 12 16 20
12 8 4 0 -4 -8 -12 -16 -20
1969
ν
flux
Radio
CMB
Visible
GeV γ-rays
extragalactic cosmic rays
$\gamma + p \rightarrow n + \pi^+$
GZK neutrino
4 0 -4 -8 -12 -16 -20 -24
log(λ/cm)

cosmic rays interact with the microwave background

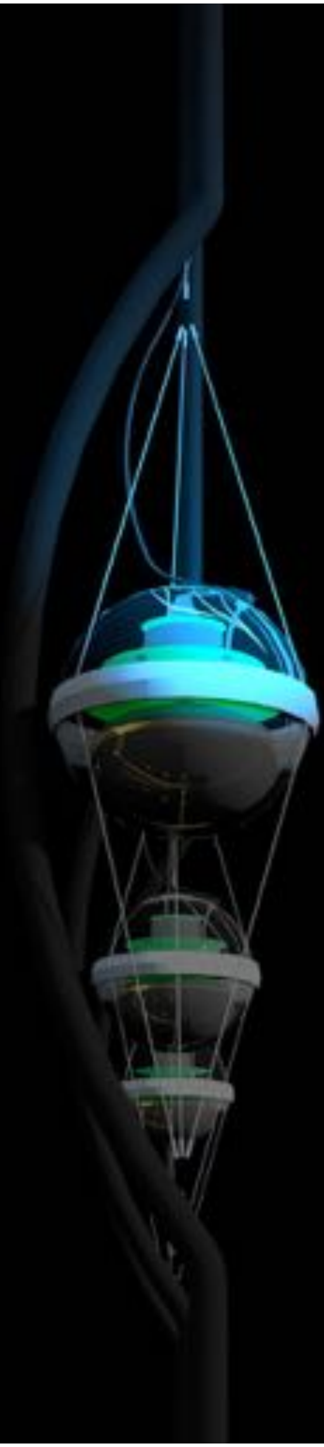
$$p + \gamma \rightarrow n + \pi^{+} \ and \ p + \pi^{0}$$

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!



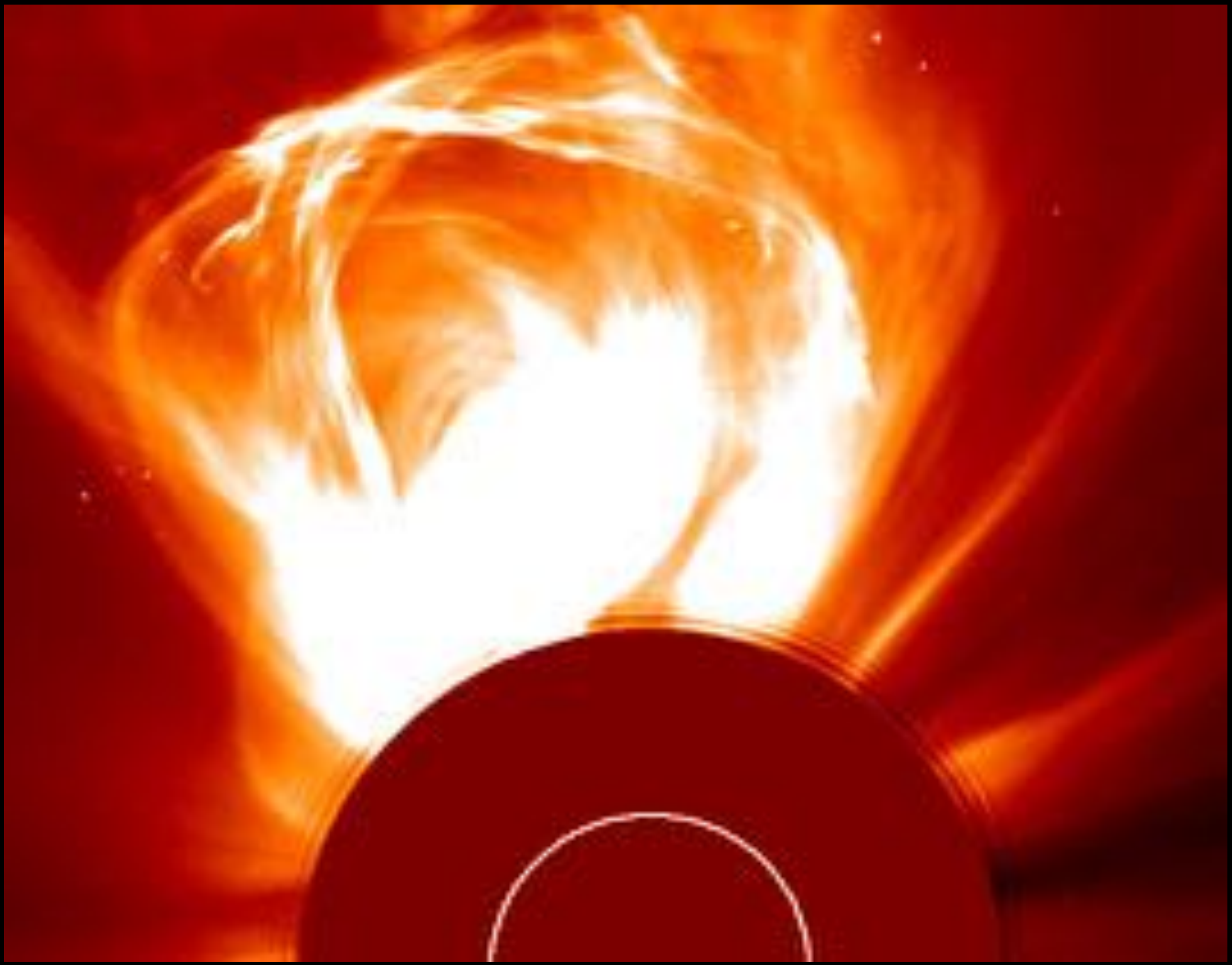
IceCube

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

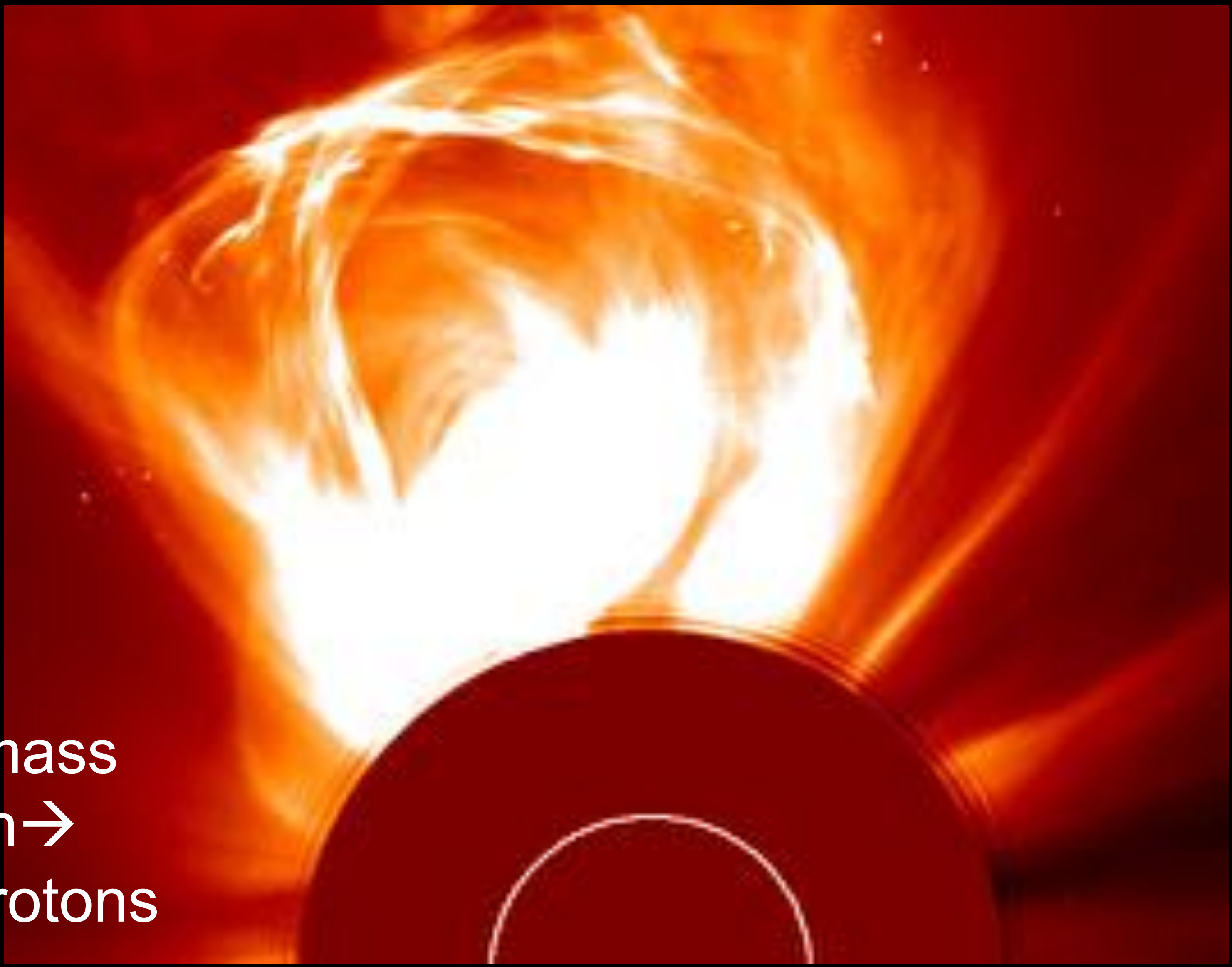
$$R_{gyro} \left(= \frac{E}{\mathrm{v} qB}\right) \leq R$$

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

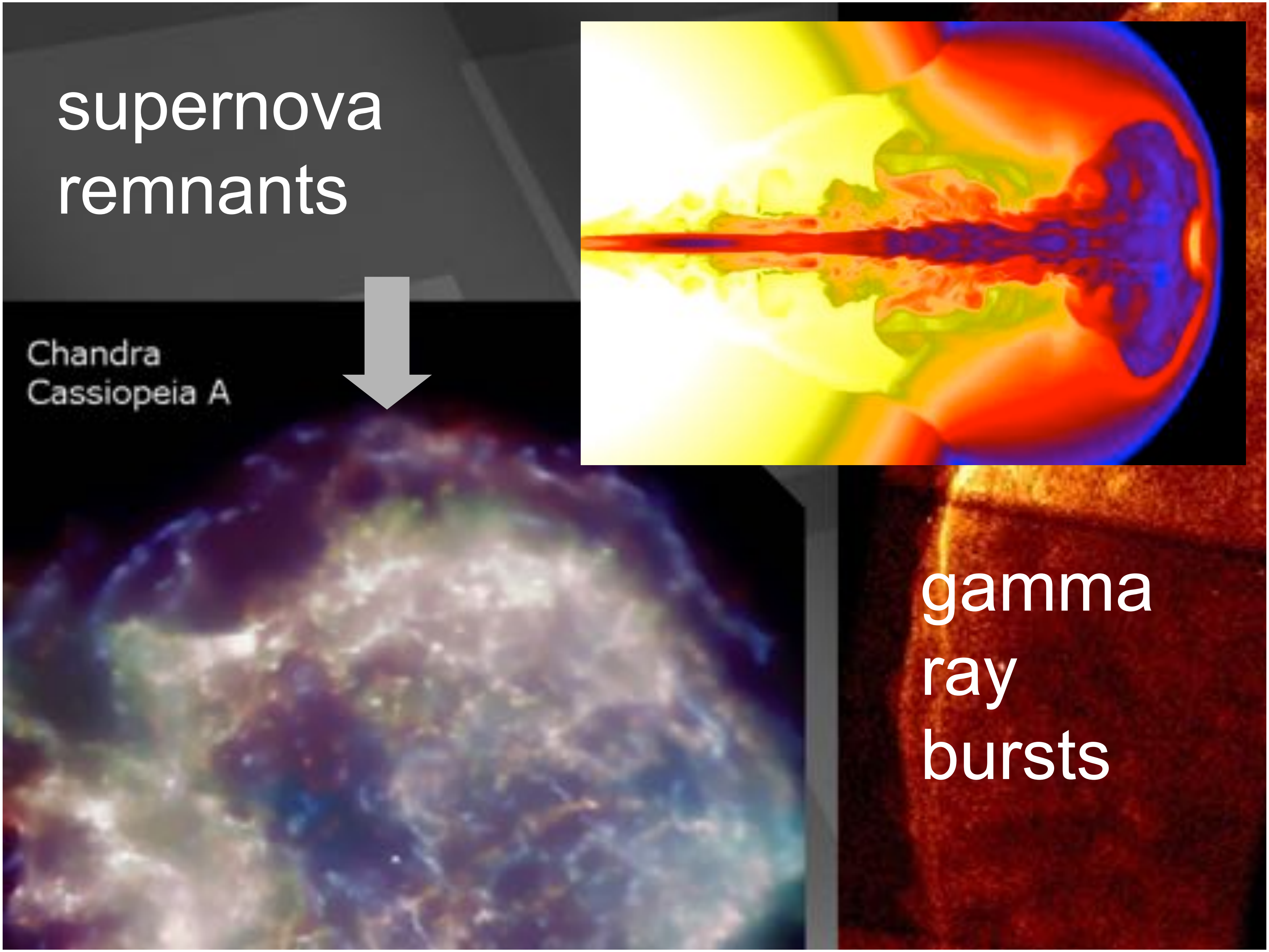
challenges of cosmic ray astrophysics:

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

the sun constructs an accelerator

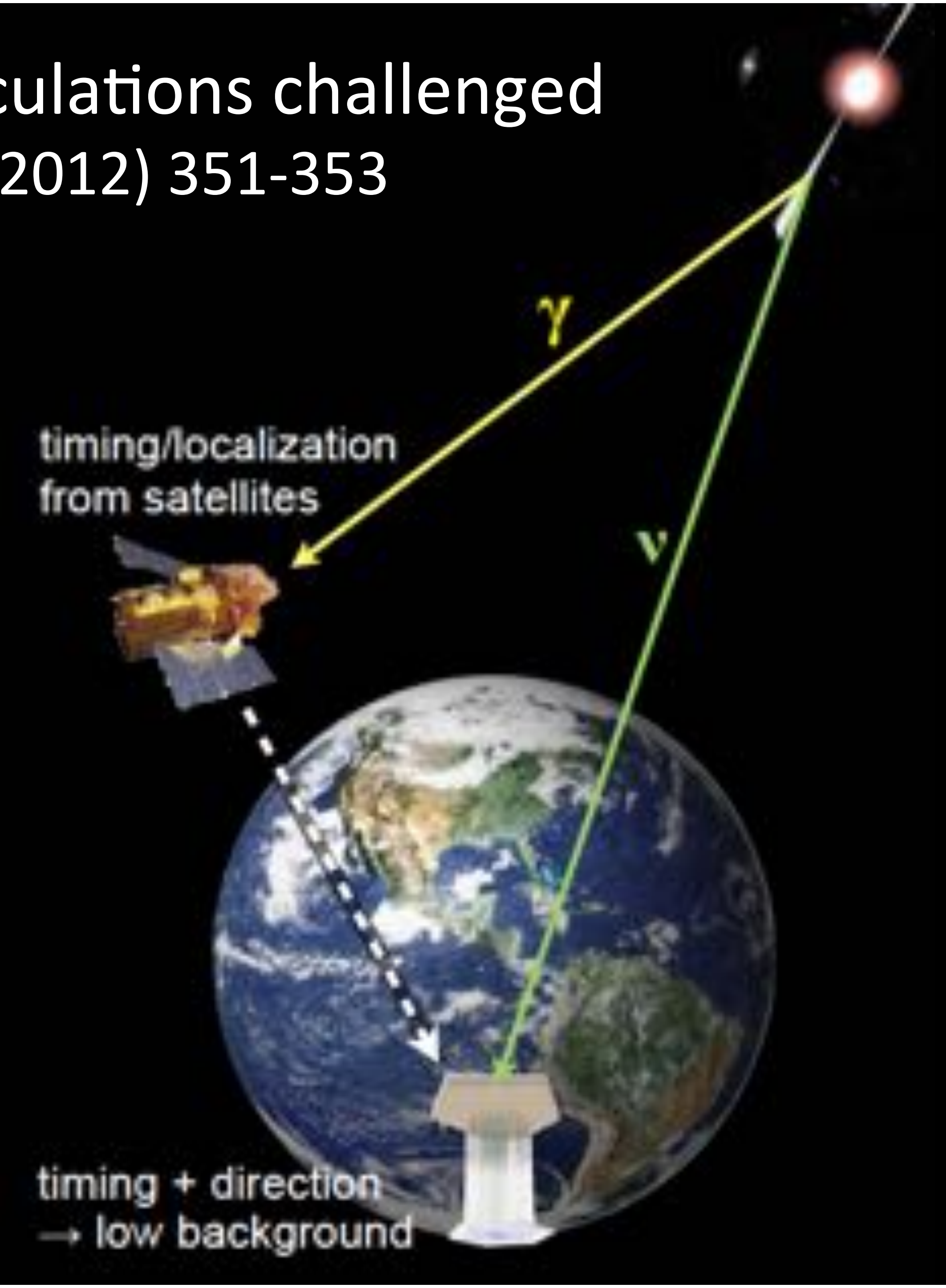


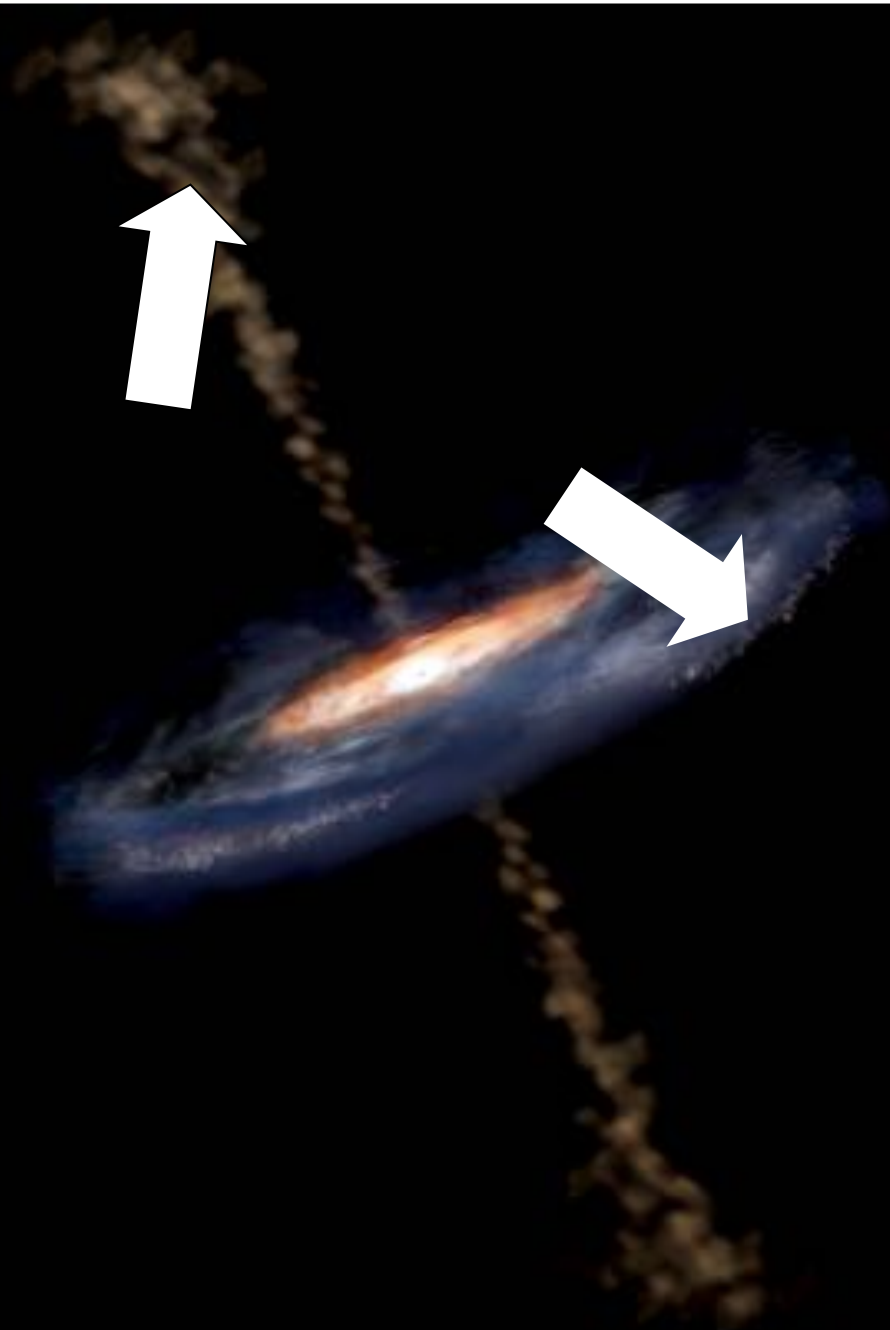
coronal mass ejection→ 10 GeV protons


supernova
remnants
Chandra
Cassiopeia A
gamma
ray
bursts

fireball calculations challenged

Nature 484 (2012) 351-353

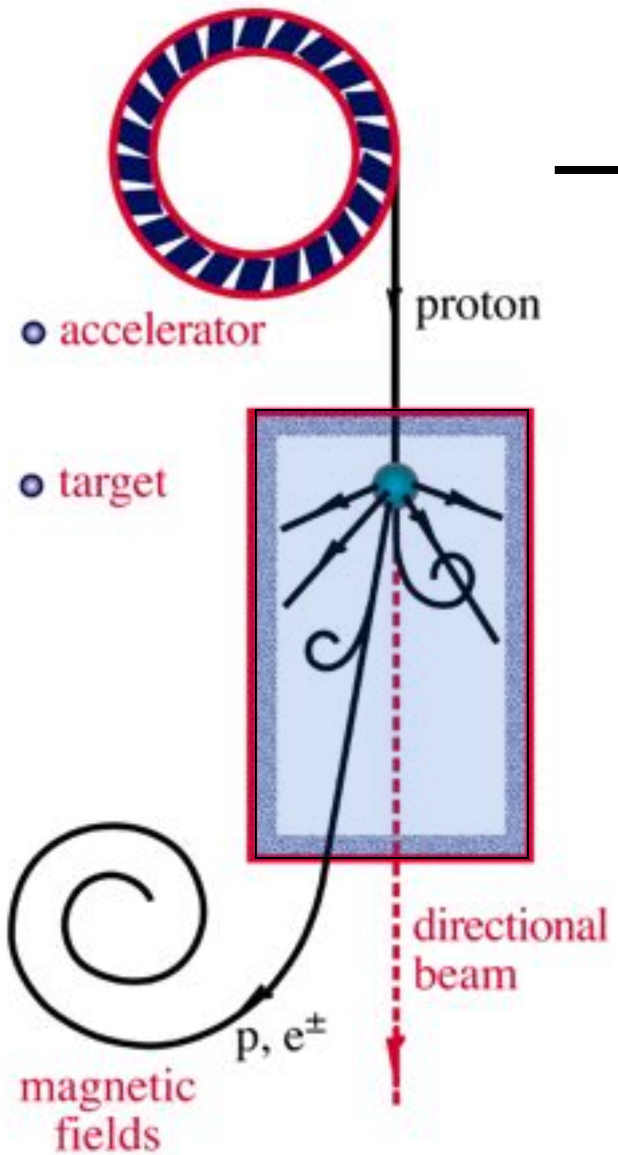




active galaxy

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

$\rightarrow p + \pi^0$

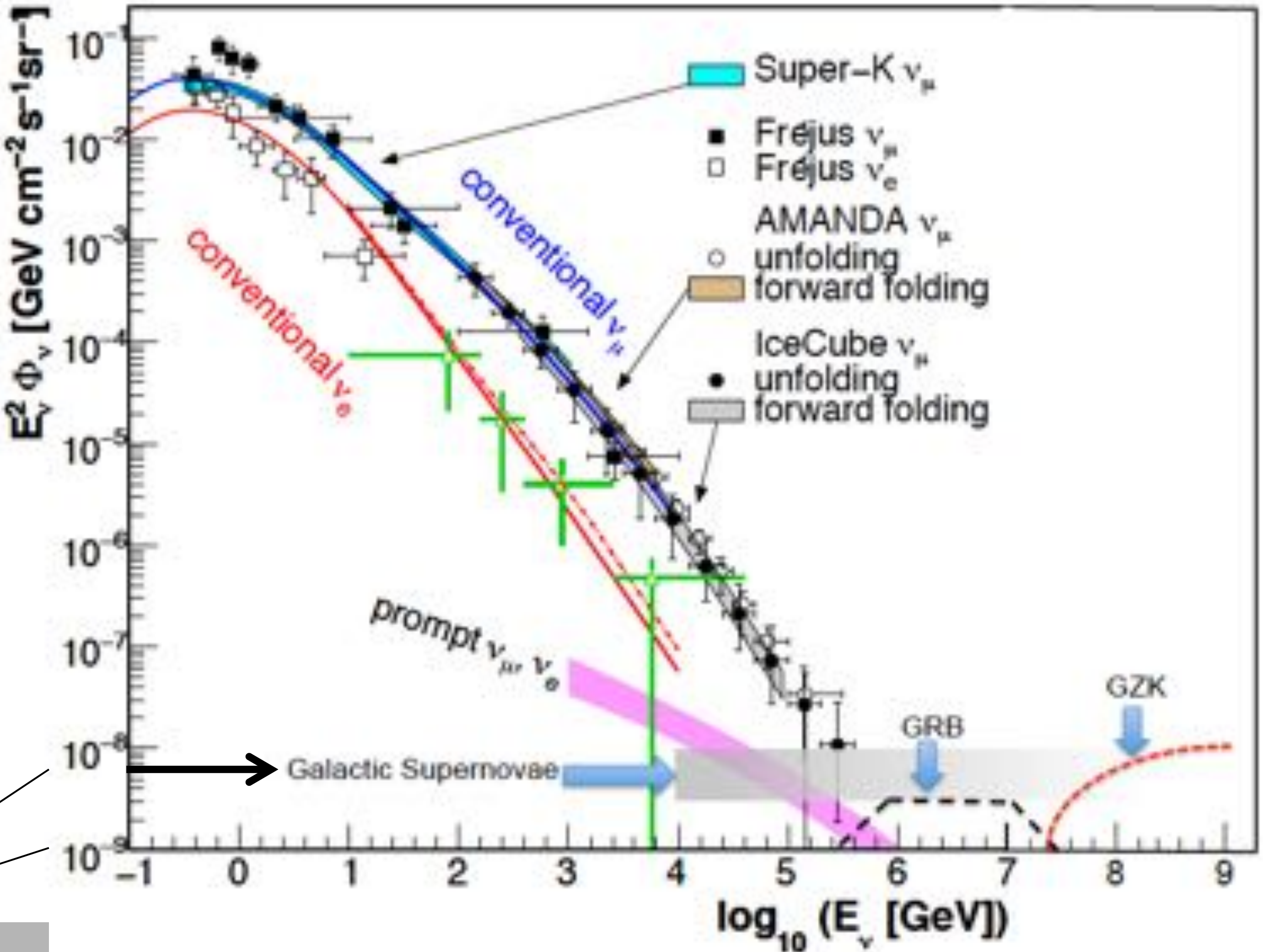
~ cosmic ray + gamma

above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

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

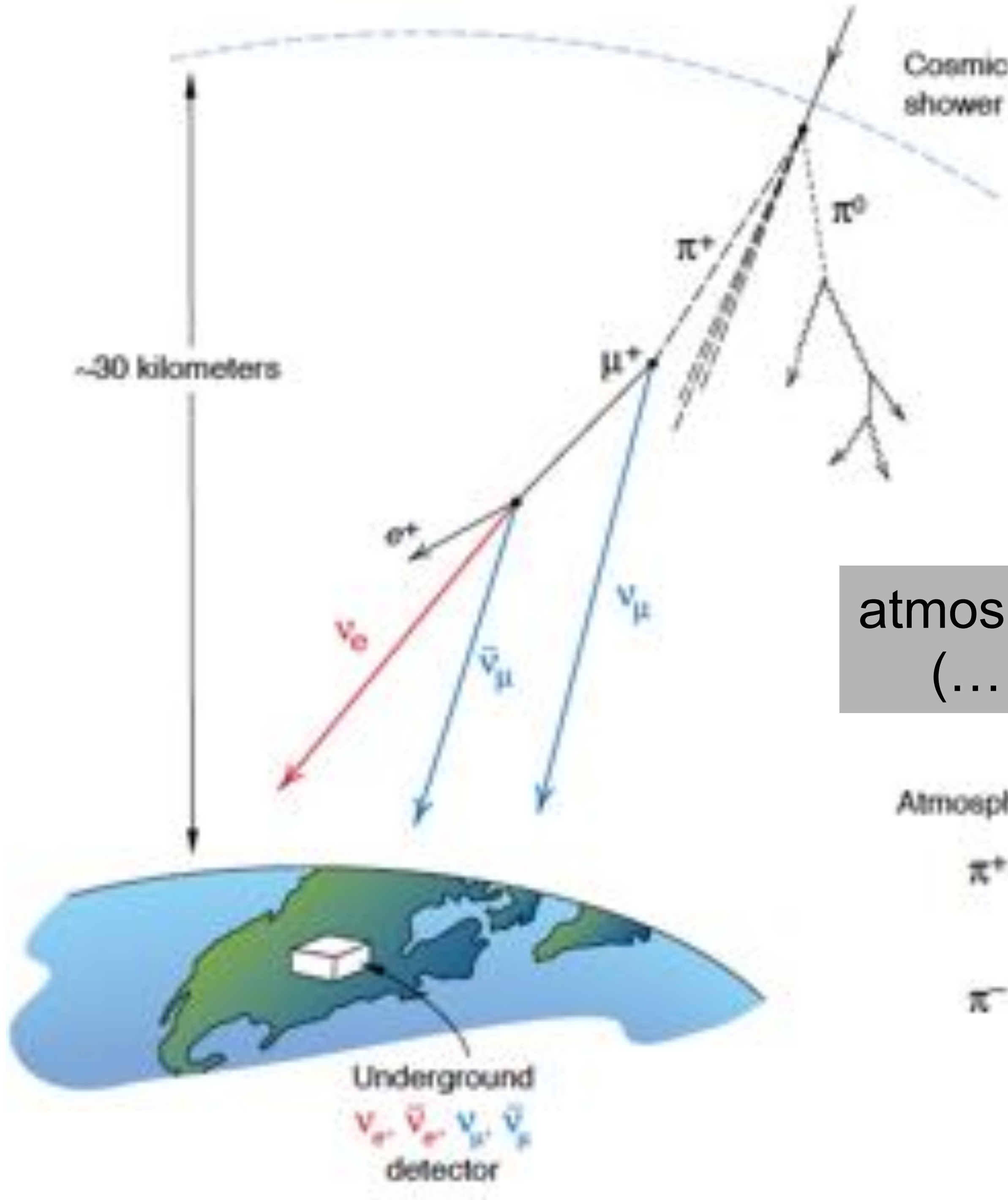
10—100 events per year for fully efficient 1 km^3 detector



atmospheric

cosmic

100 TeV



atmospheric neutrinos
(… and muons!)

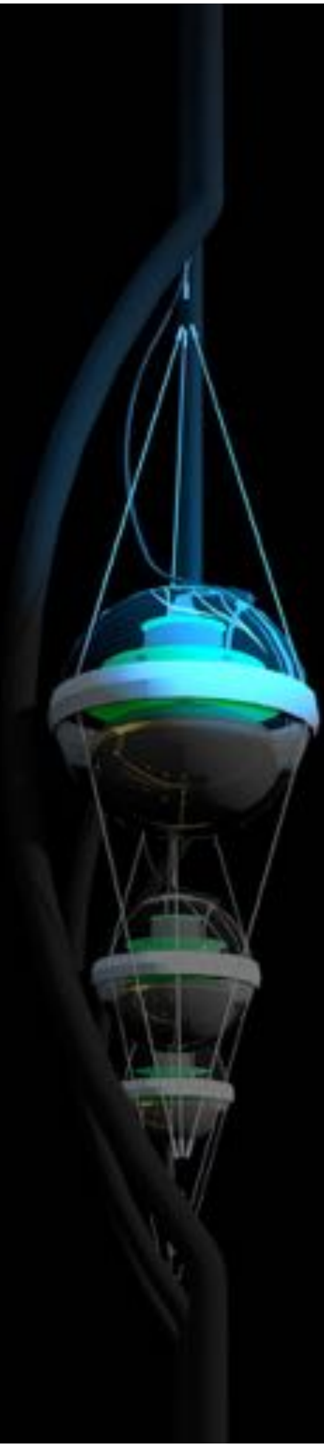
Atmospheric neutrino source

$\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\quad \hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$

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

$\quad \hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$

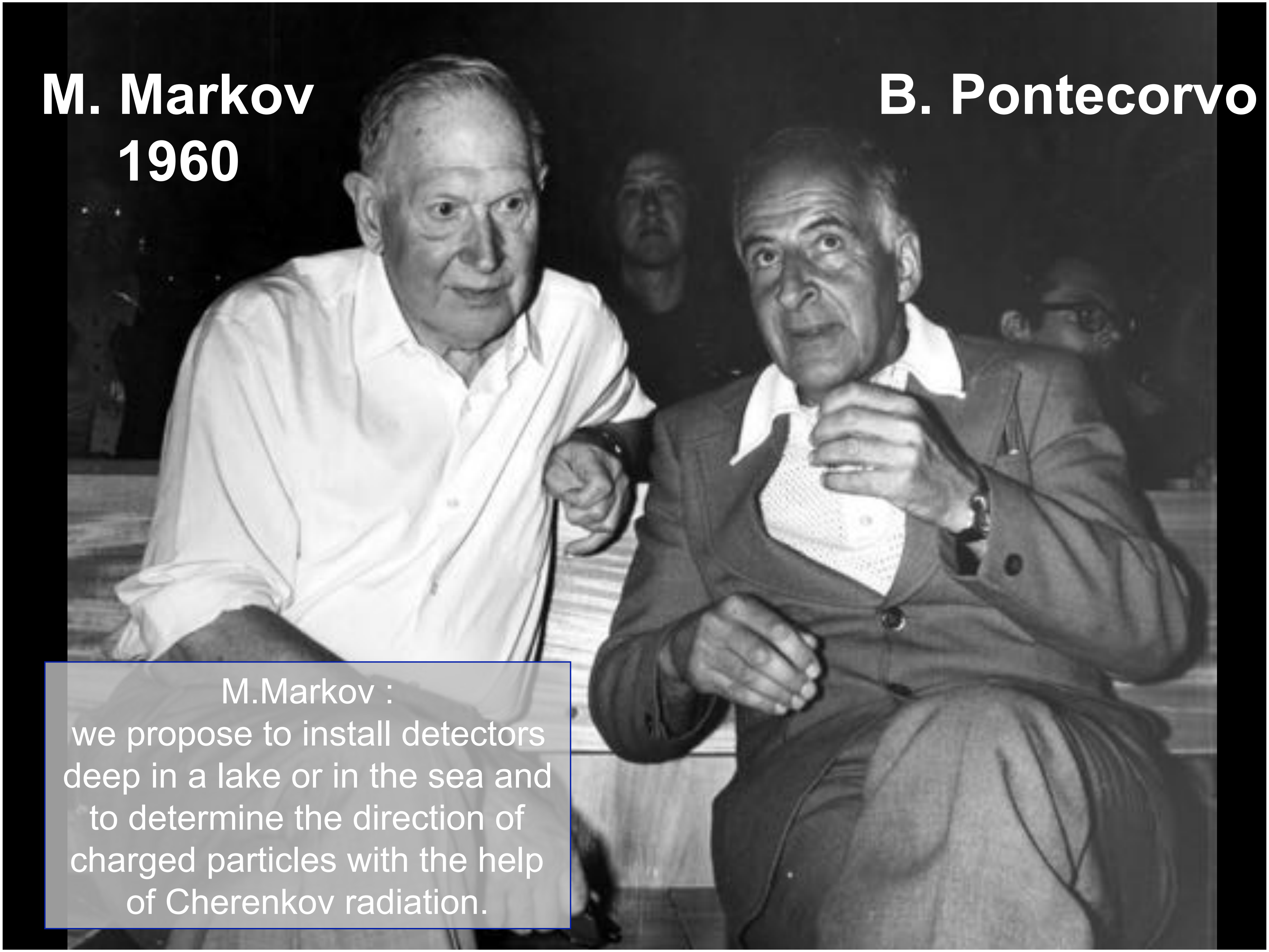


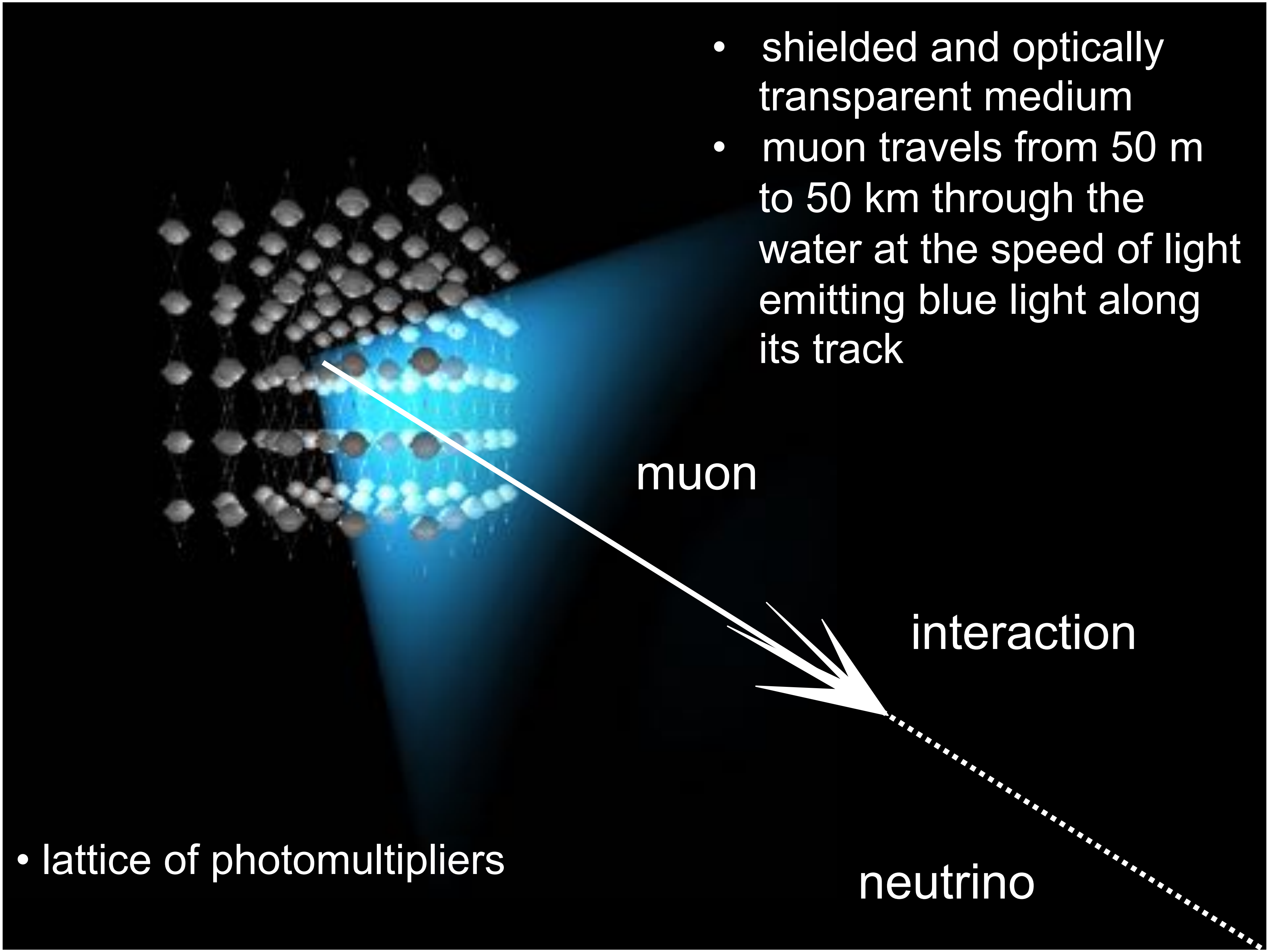
IceCube: the discovery of cosmic neutrinos

francis halzen

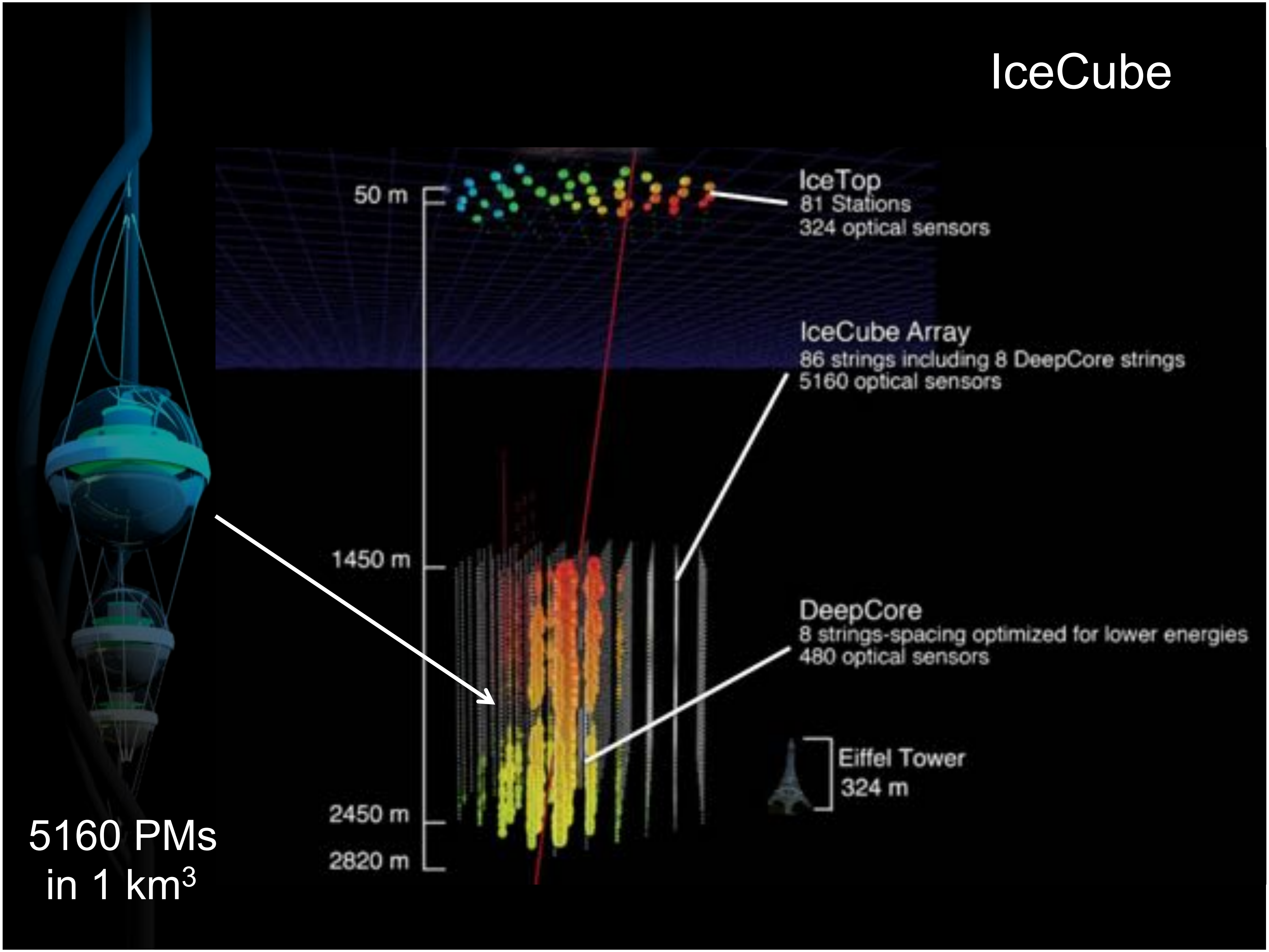
- cosmic ray accelerators
- IceCube: a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

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.

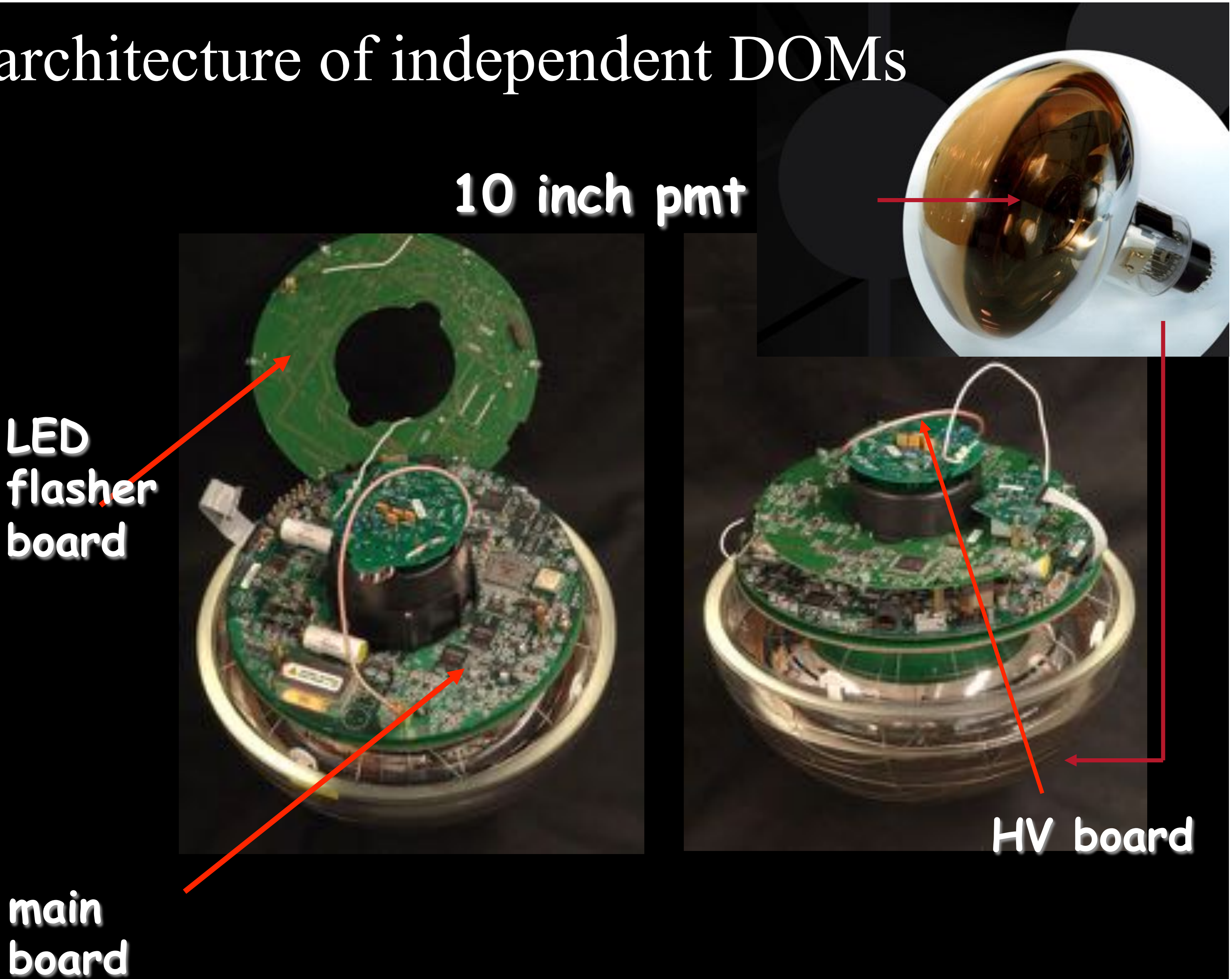

• shielded and optically transparent medium
• muon travels from 50 m to 50 km through the water at the speed of light emitting blue light along its track
muon
interaction
• lattice of photomultipliers
neutrino

ultra-transparent ice below 1.5 km

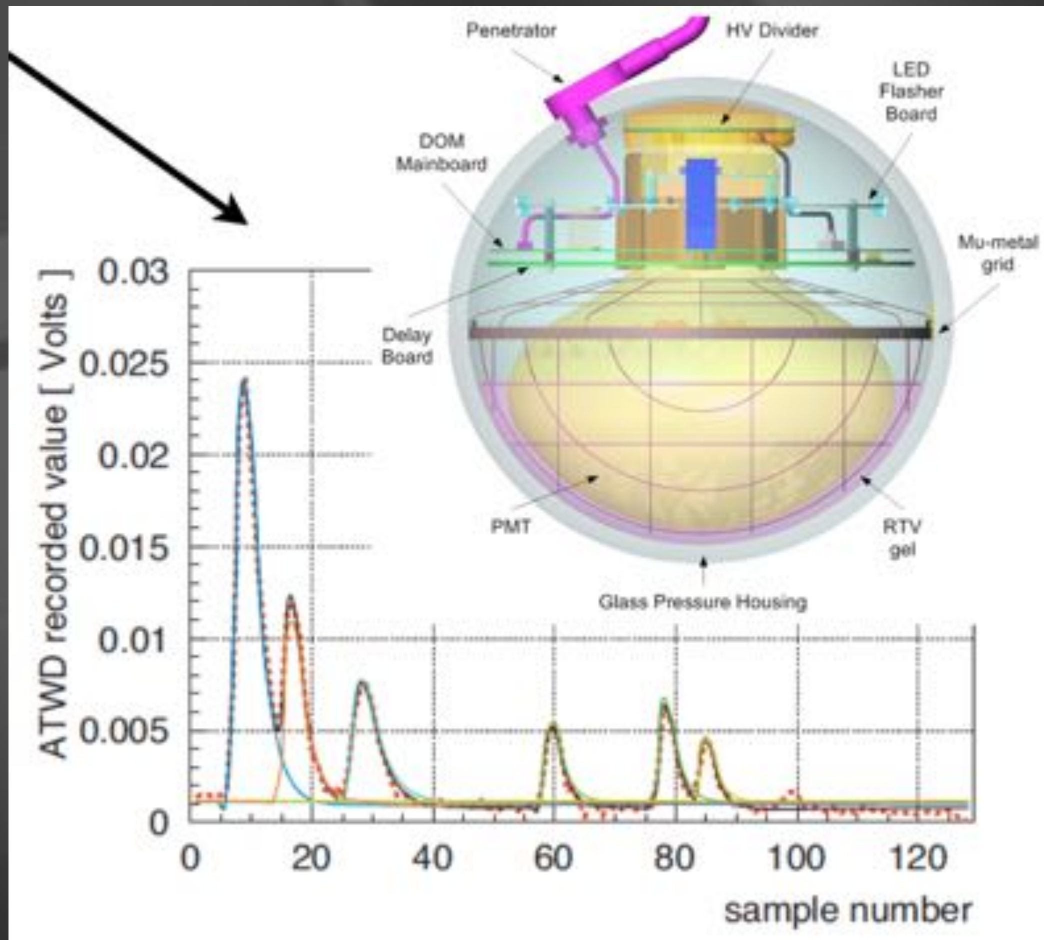

IceCube
IceTop
81 Stations
324 optical sensors
50 m
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
1450 m
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
2450 m
2820 m
5160 PMs
in 1 km3

photomultiplier tube -10 inch

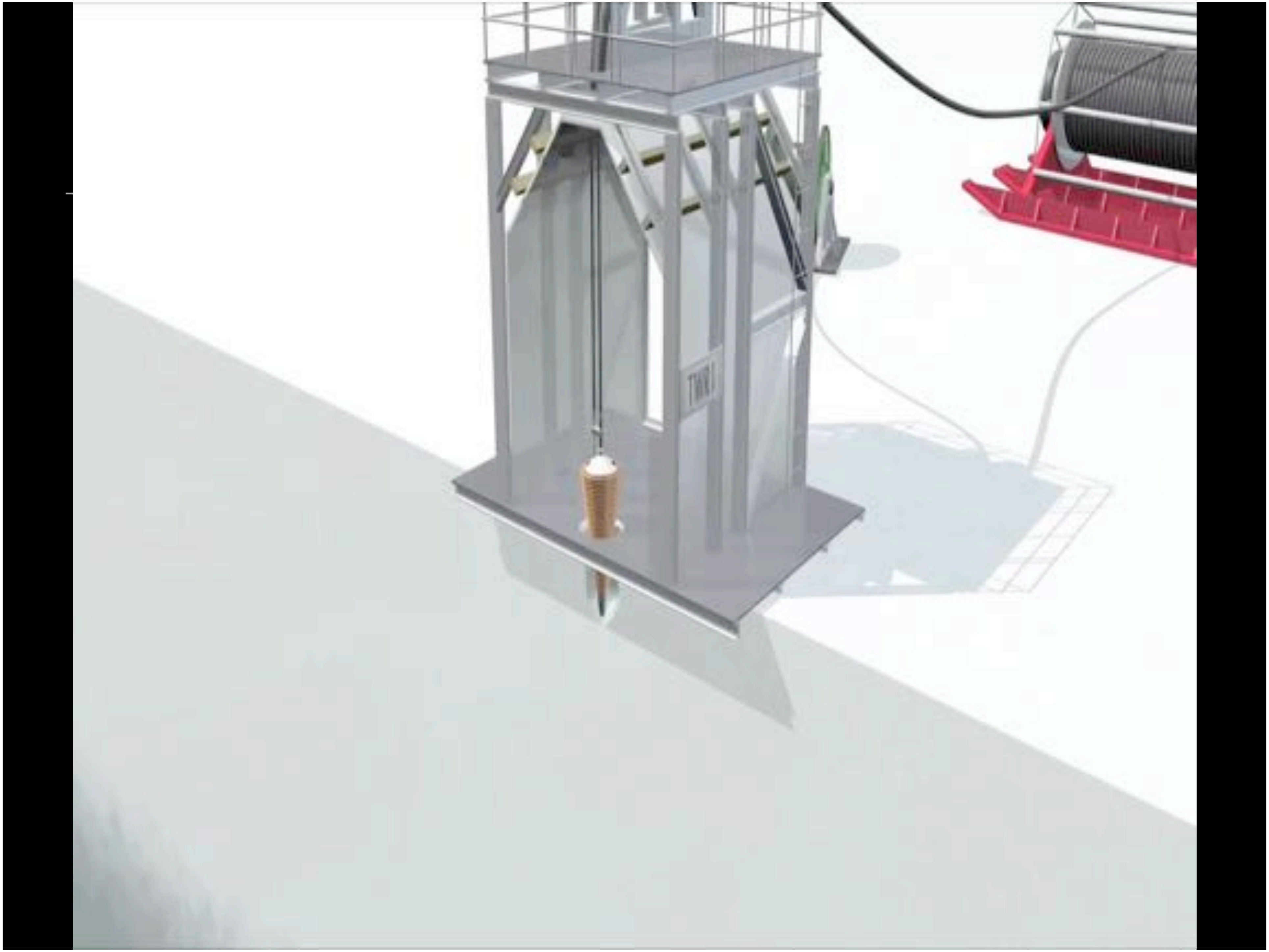
architecture of independent DOMs

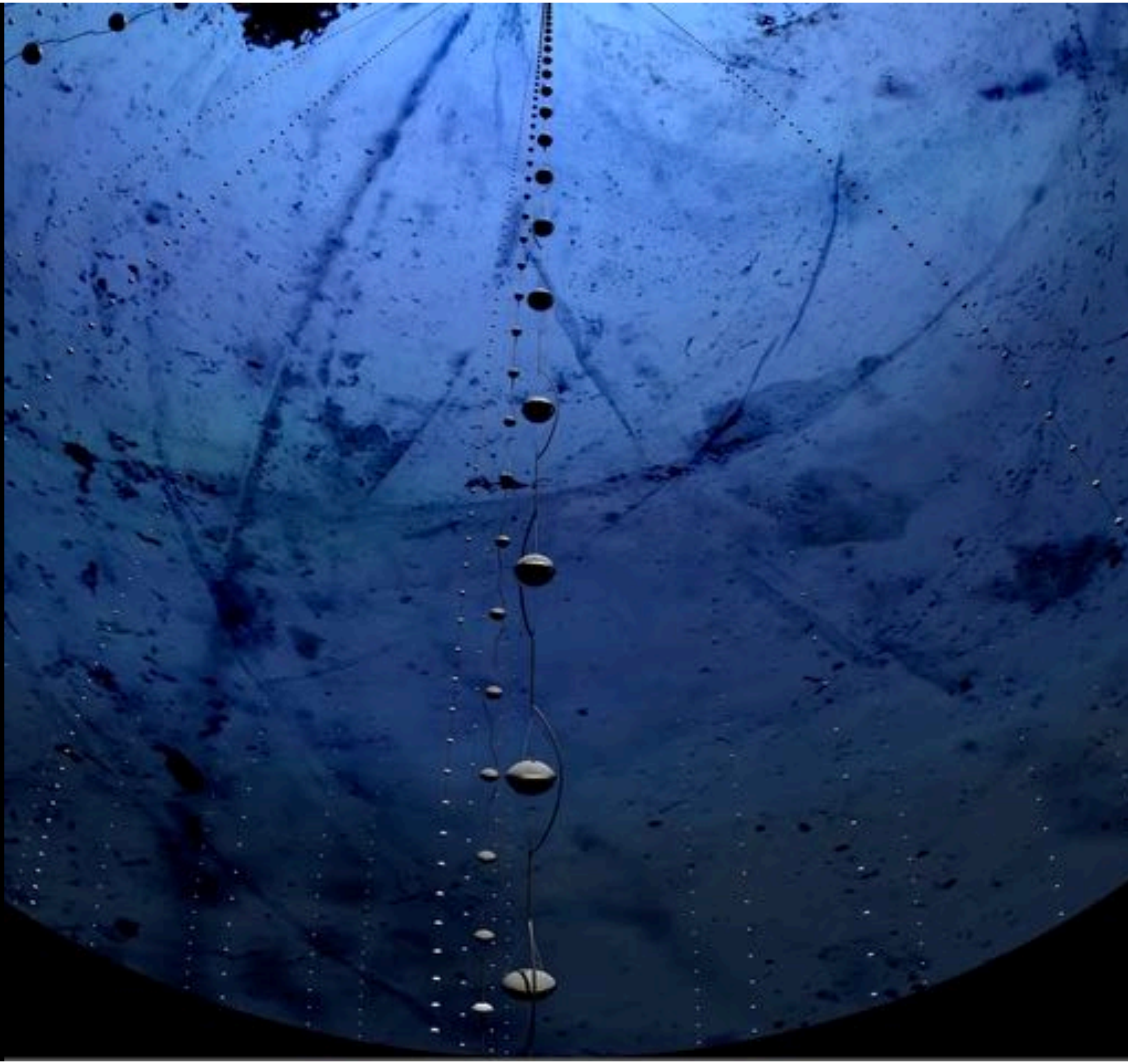


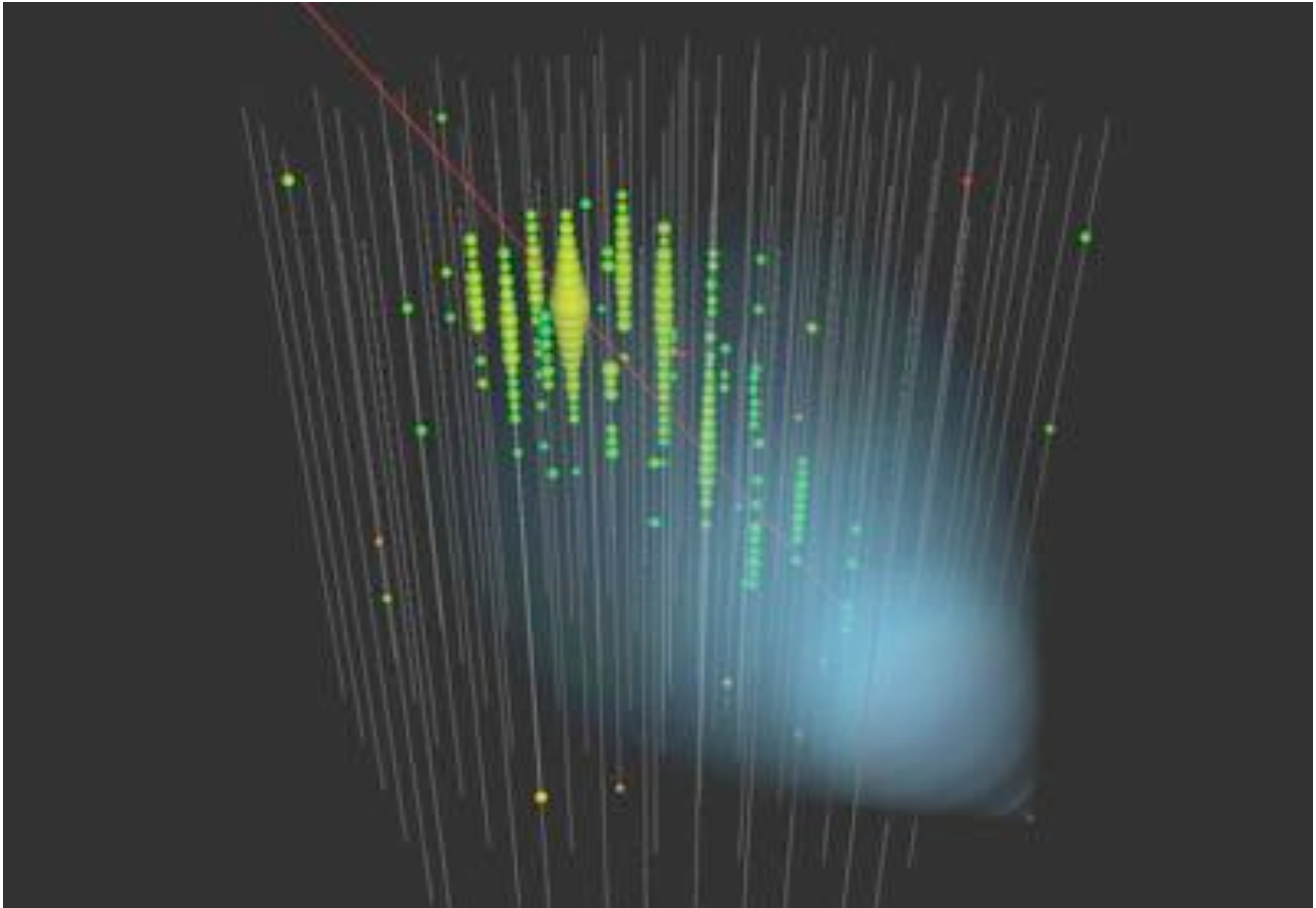
… each Digital Optical Module independently collects light signals like this, digitizes them,



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

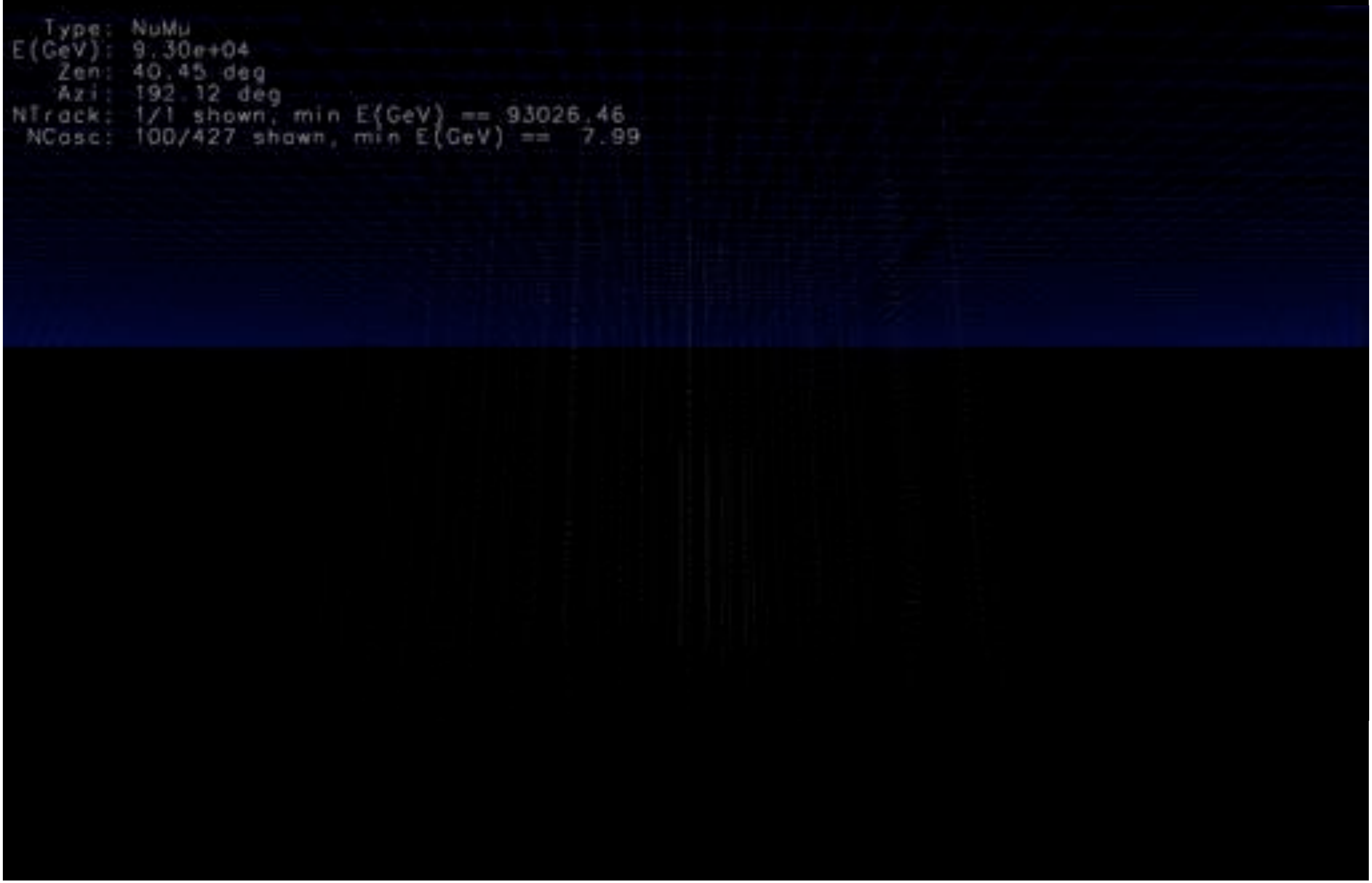






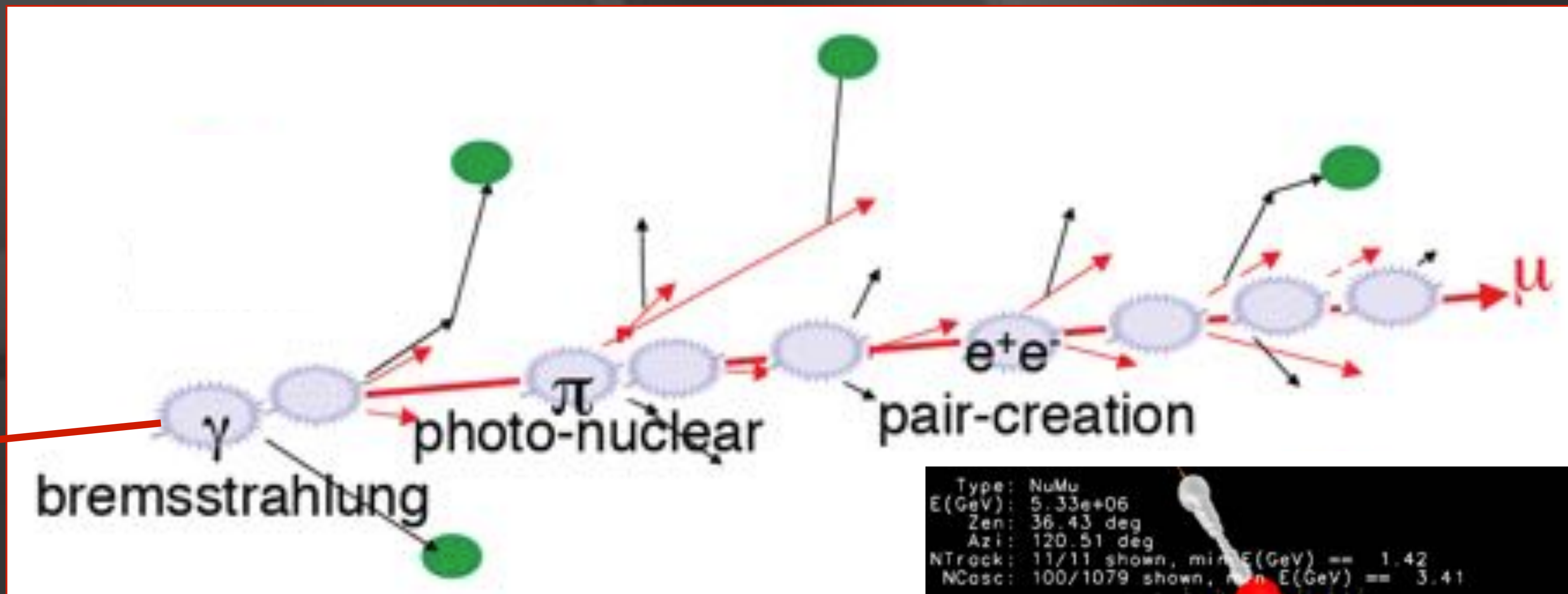
muon track: time is color; number of photons is energy

93 TeV muon

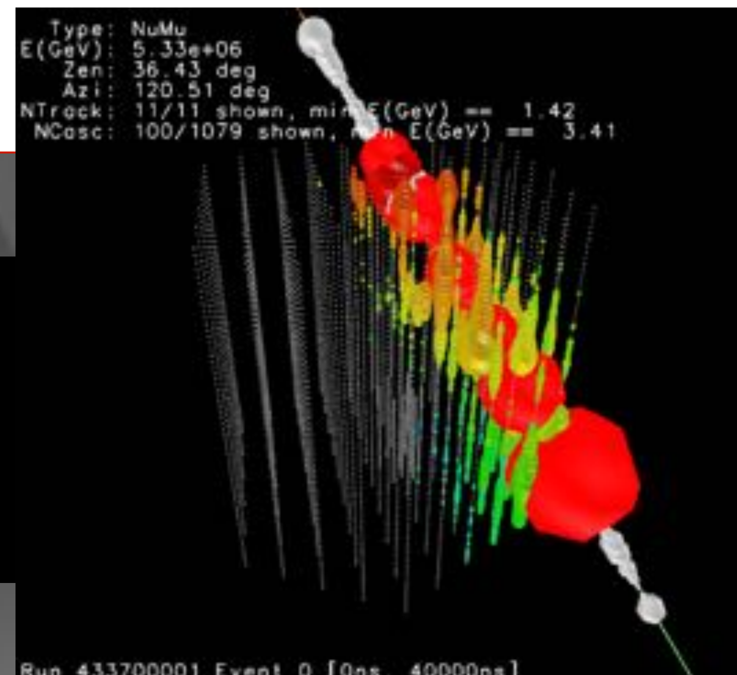


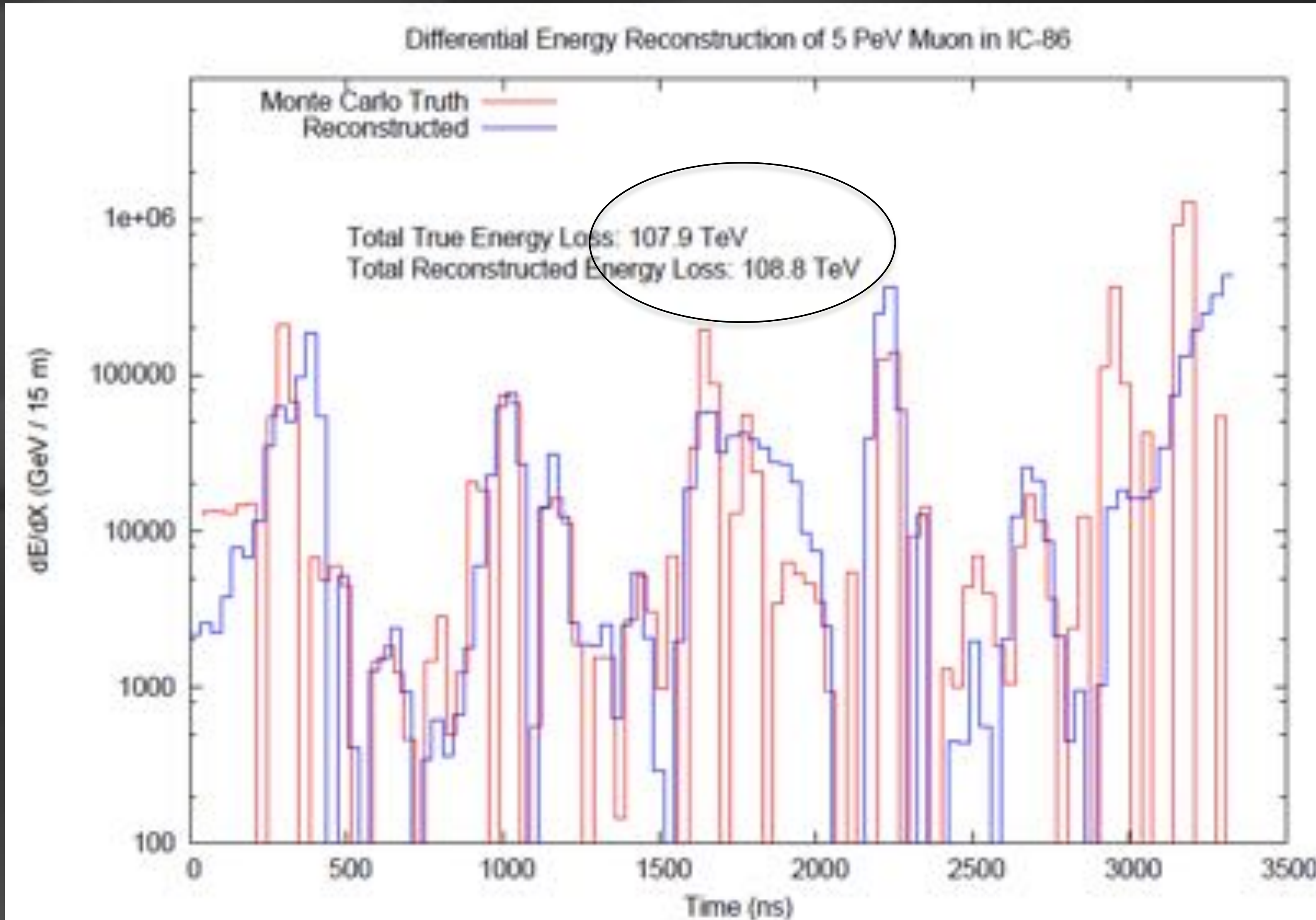
Type: NuMu
E(GeV): 9.30e+04
Zen: 40.45 deg
Azi: 192.12 deg
NTrack: 1/1 shown, min E(GeV) == 93026.46
NCosc: 100/427 shown, min E(GeV) == 7.99

energy measurement (> 1 TeV)



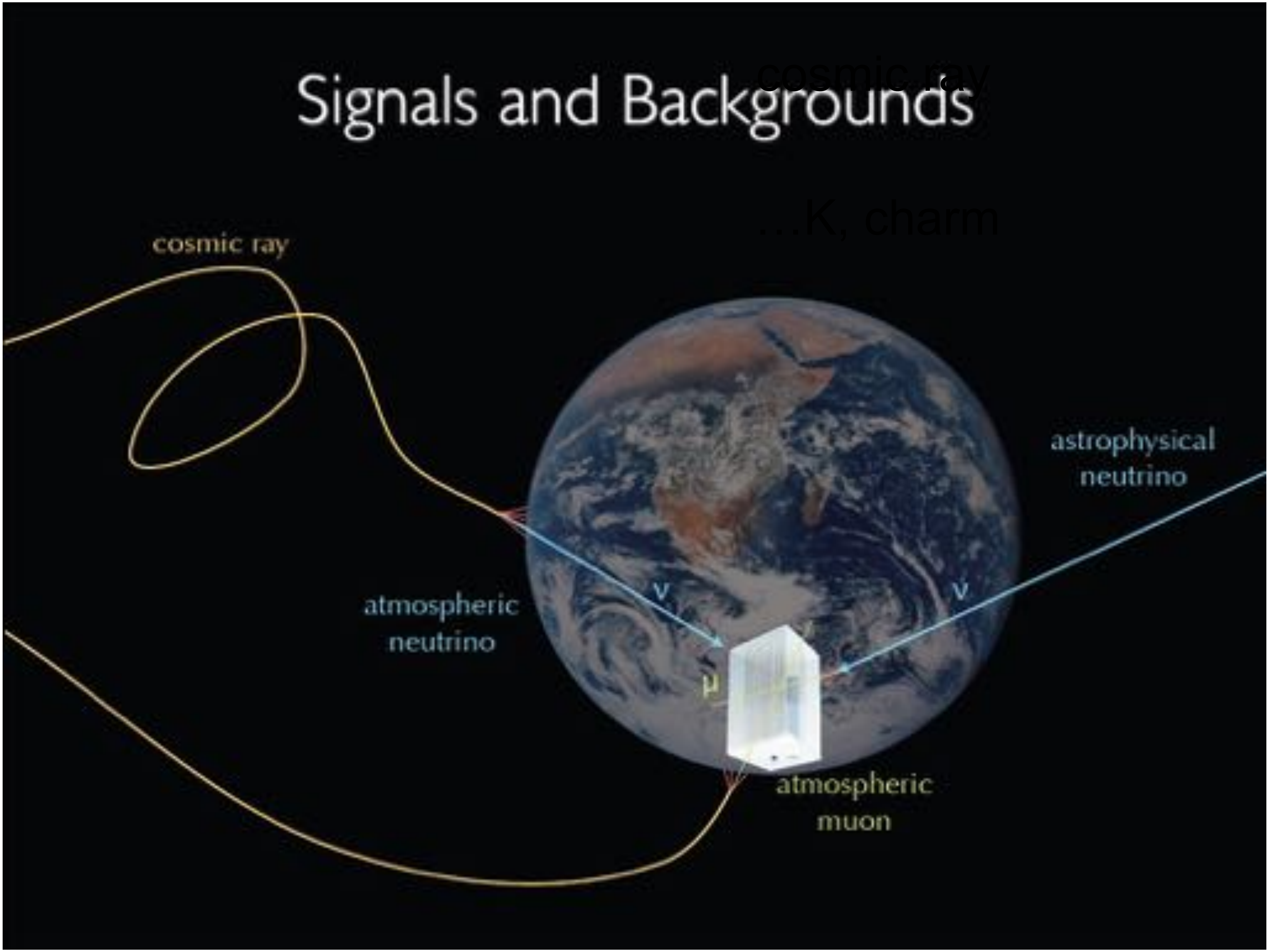
convert the amount of light emitted to measurement of the muon energy (number of optical modules, number of photons, dE/dx, …)

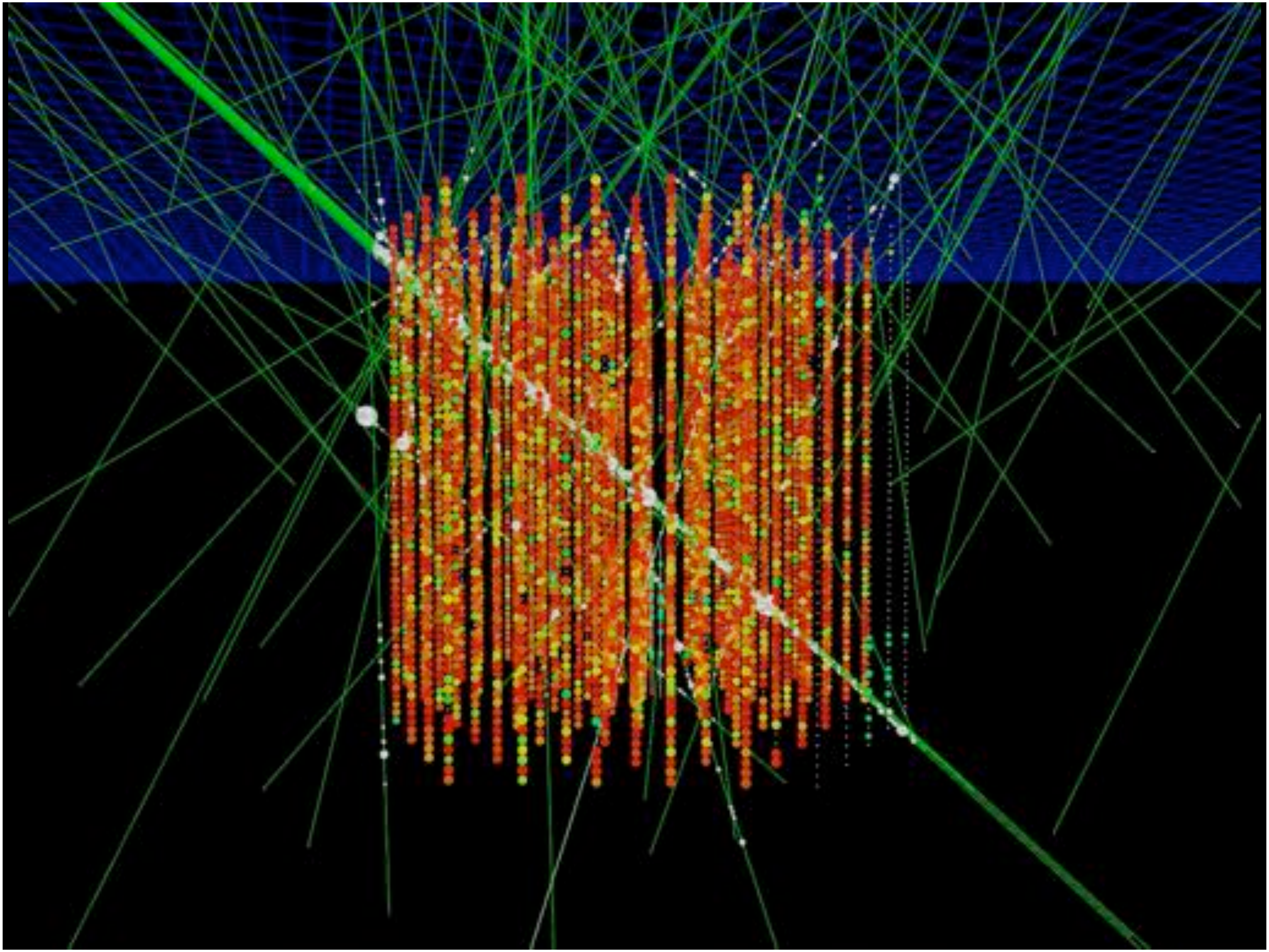




1.1 km

improving angular and energy resolution


Signals and Backgrounds
cosmic ray
…K, charm
cosmic ray
astrophysical
neutrino
atmospheric
neutrino
ν
ν
μ
atmospheric
muon



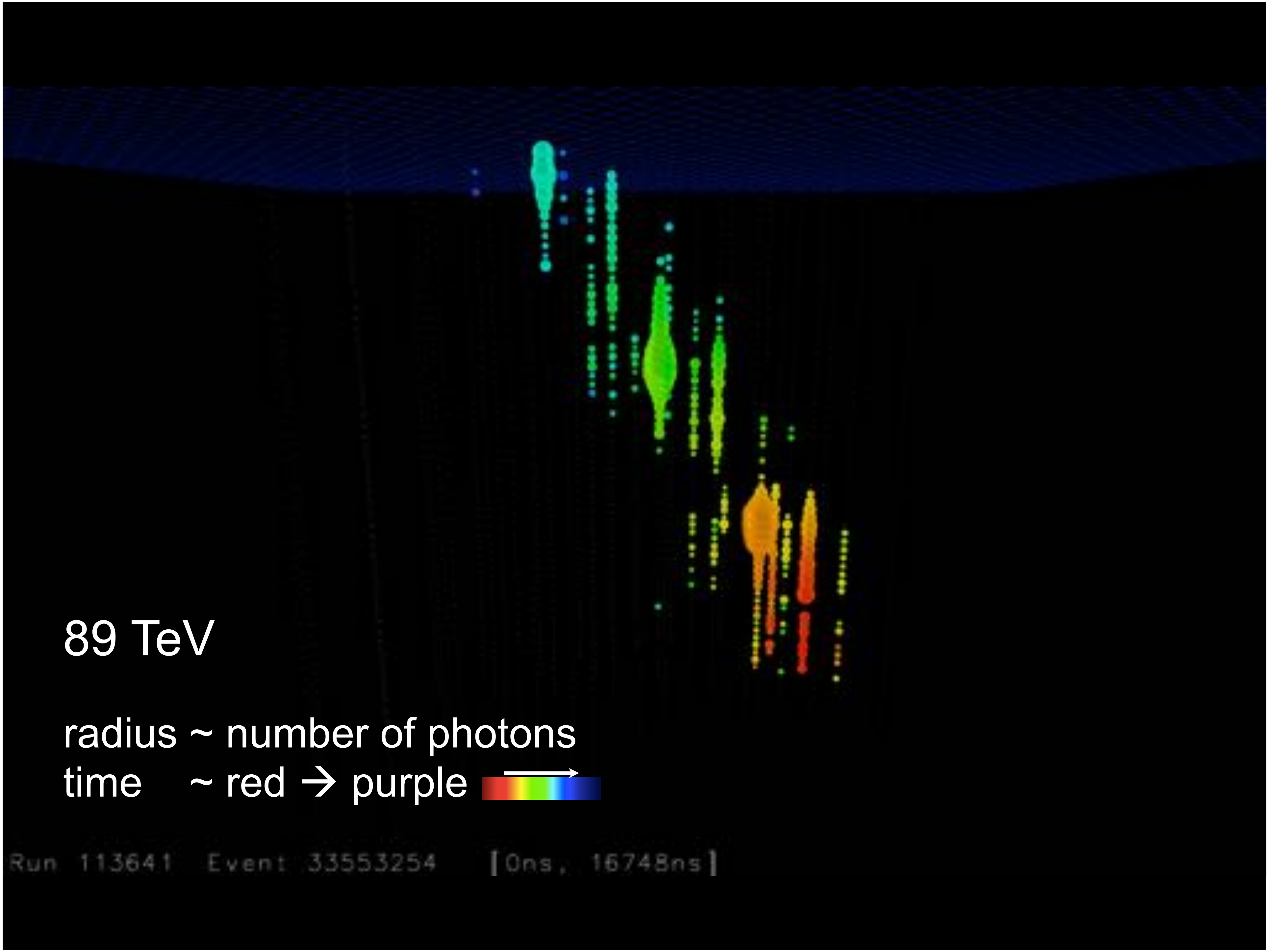
… you looked at 10msec of data !

muons detected per year:

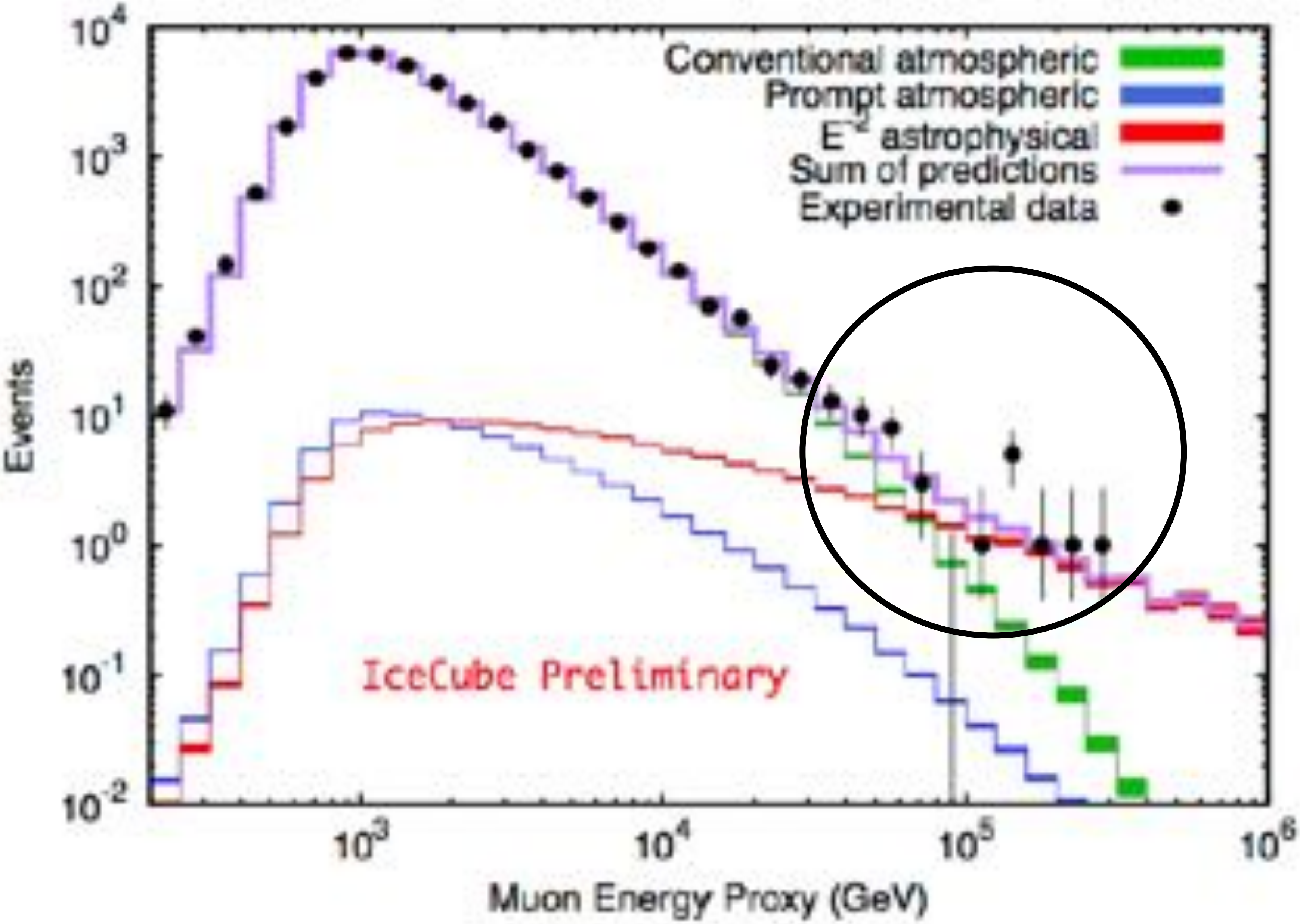
• atmospheric*	μ	~ 10^{11}
• atmospheric**	$\nu \rightarrow \mu$	~ 10^{5}
• cosmic	$\nu \rightarrow \mu$	~ 10

* 3000 per second

** 1 every 6 minutes


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

cosmic neutrinos in 2 years of data at 3.7 sigma

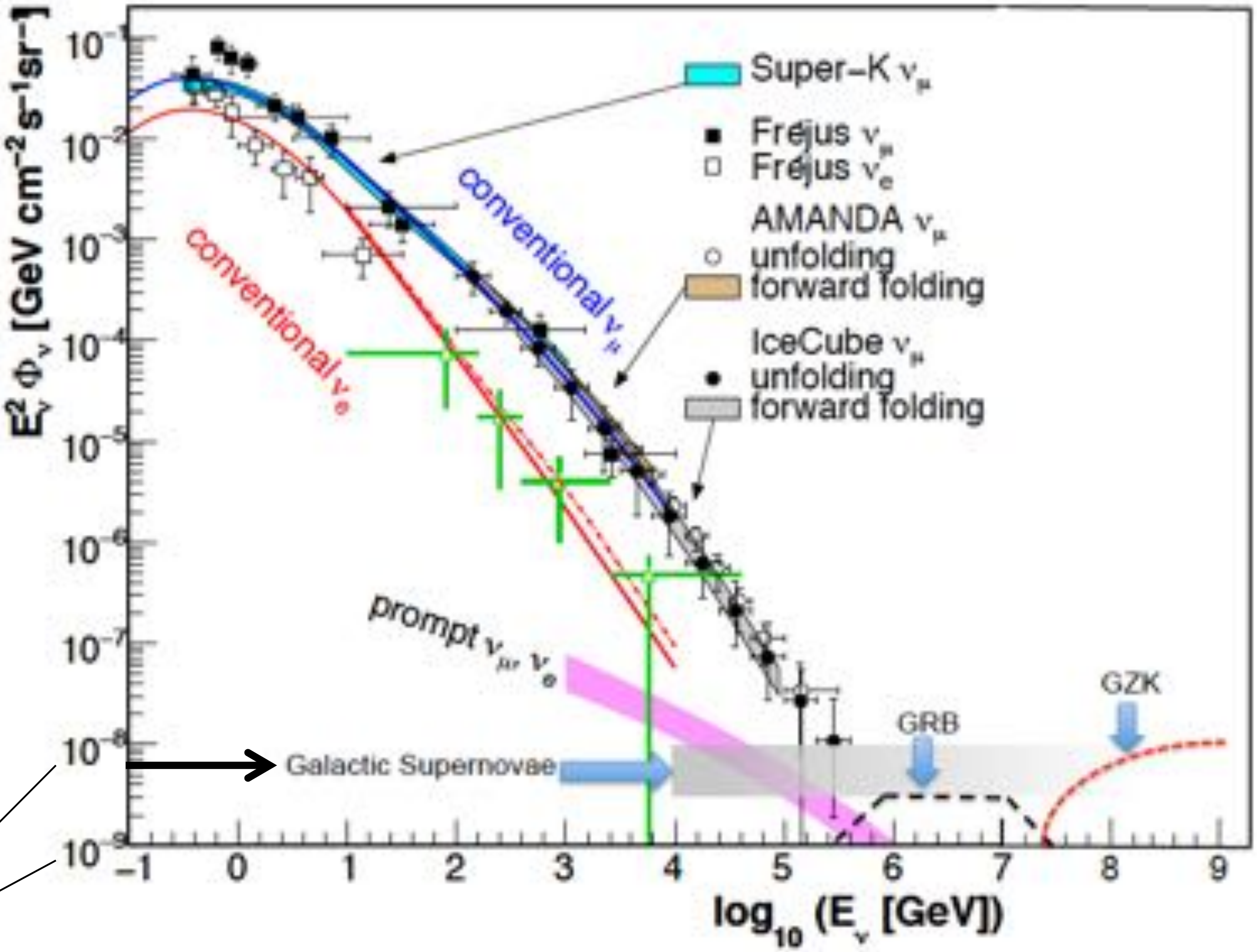


above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

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

10—100 events per year for fully efficient detector



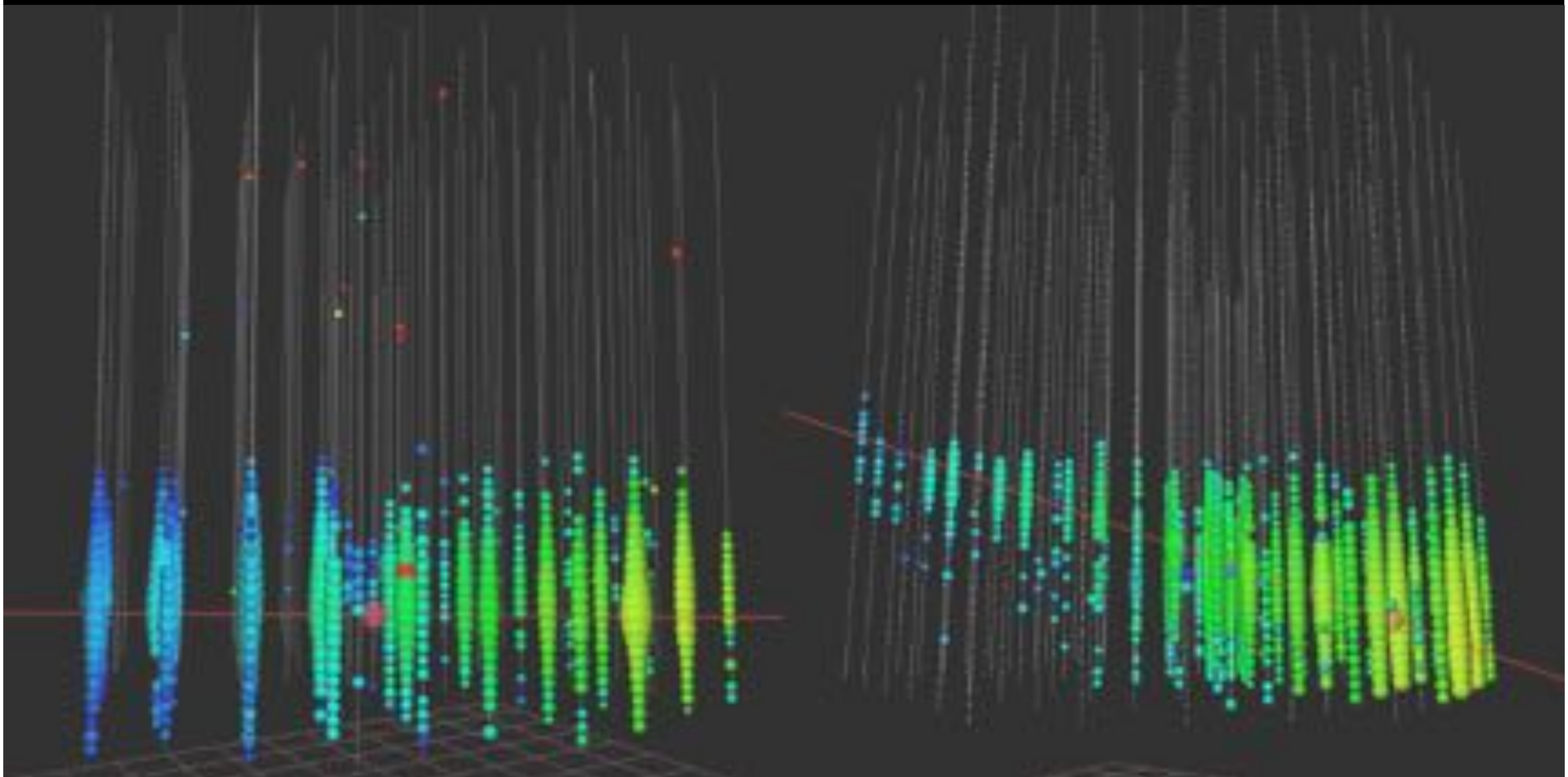
atmospheric

cosmic

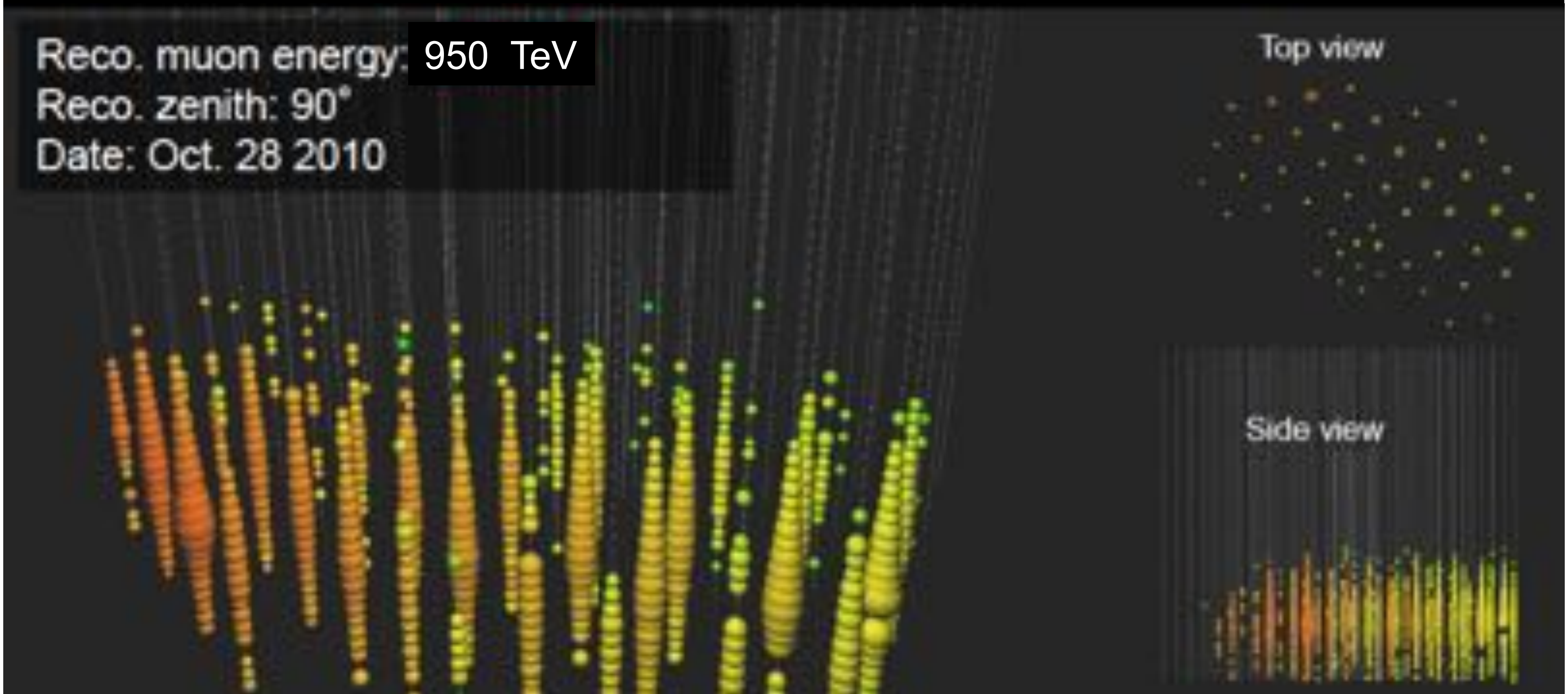
100 TeV

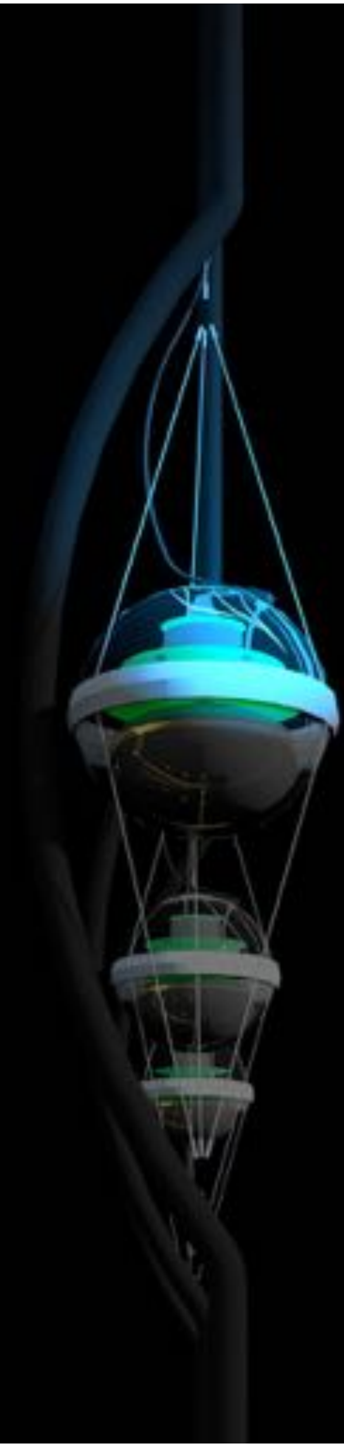
highest energy muon energy observed: 560 TeV

→ PeV ν_μ



3 years: 4.3 σ and more PeV ν_μ





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

cosmic rays interact with the microwave background

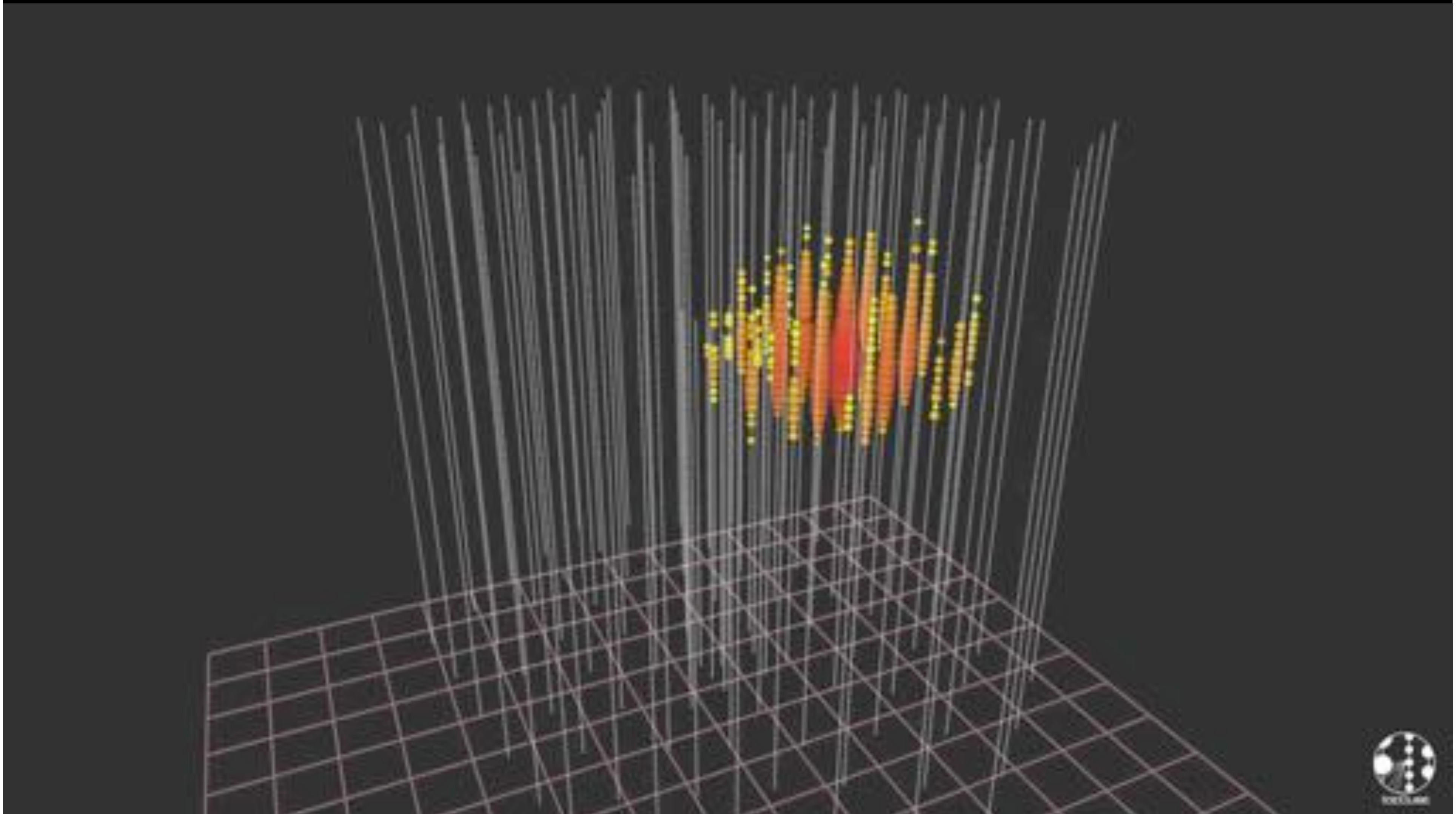
$$p + \gamma \rightarrow n + \pi^{+} \ and \ p + \pi^{0}$$

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

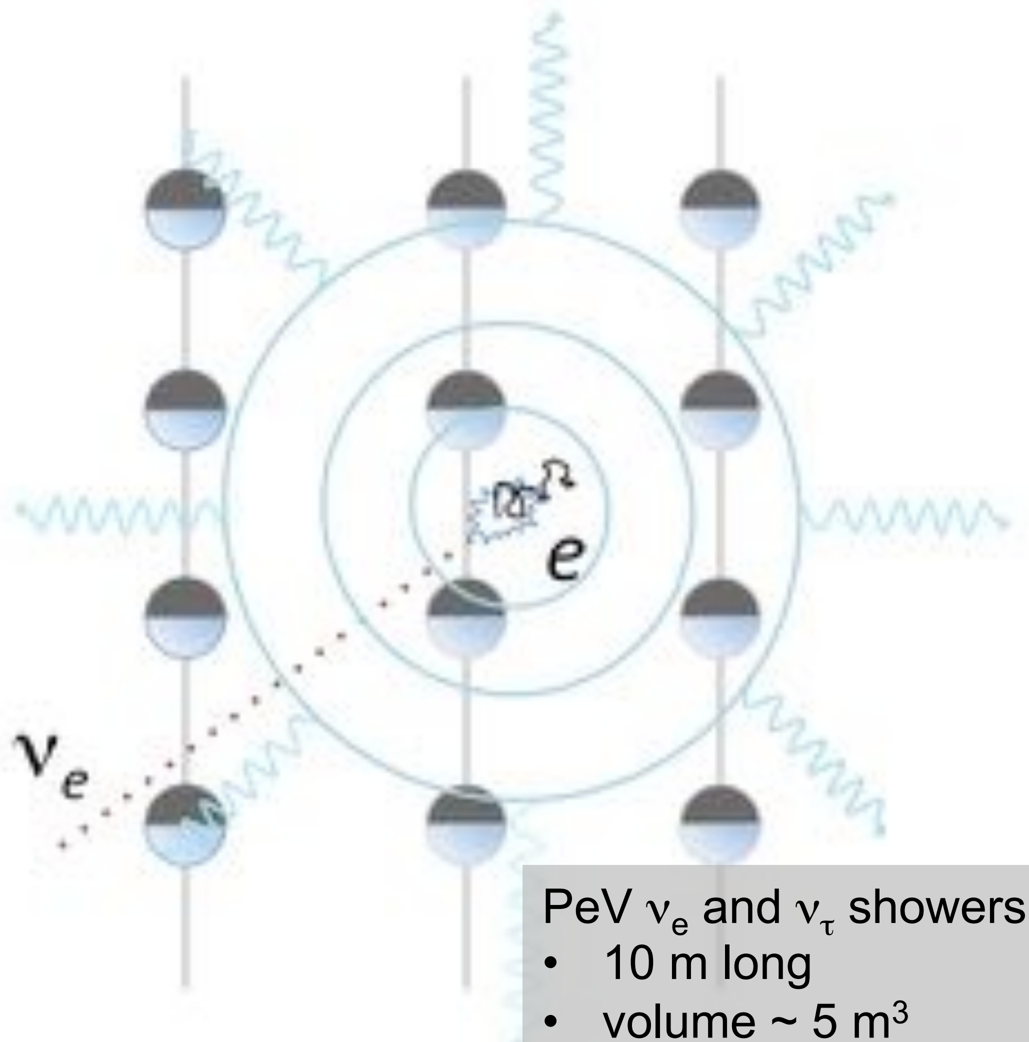
$$\pi \rightarrow \mu + \upsilon_{\mu} \rightarrow \{e + \overline{\upsilon_{\mu}} + \upsilon_{e}\} + \upsilon_{\mu}$$

1 event per cubic kilometer per year
...but it points at its source!

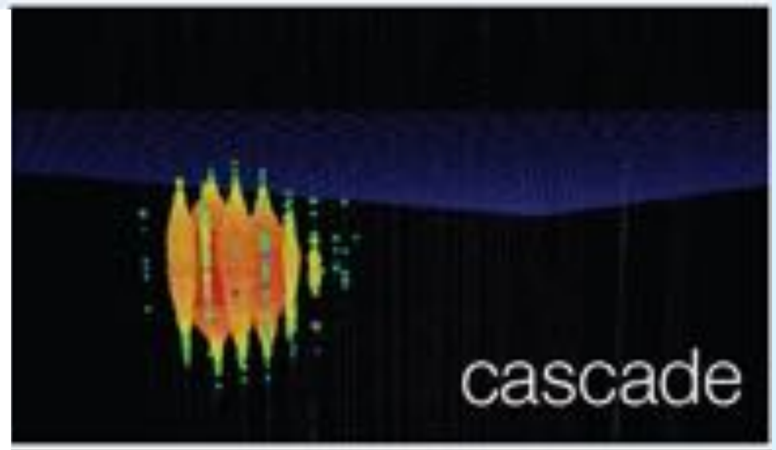
GZK neutrino search: two neutrinos with > 1,000 TeV

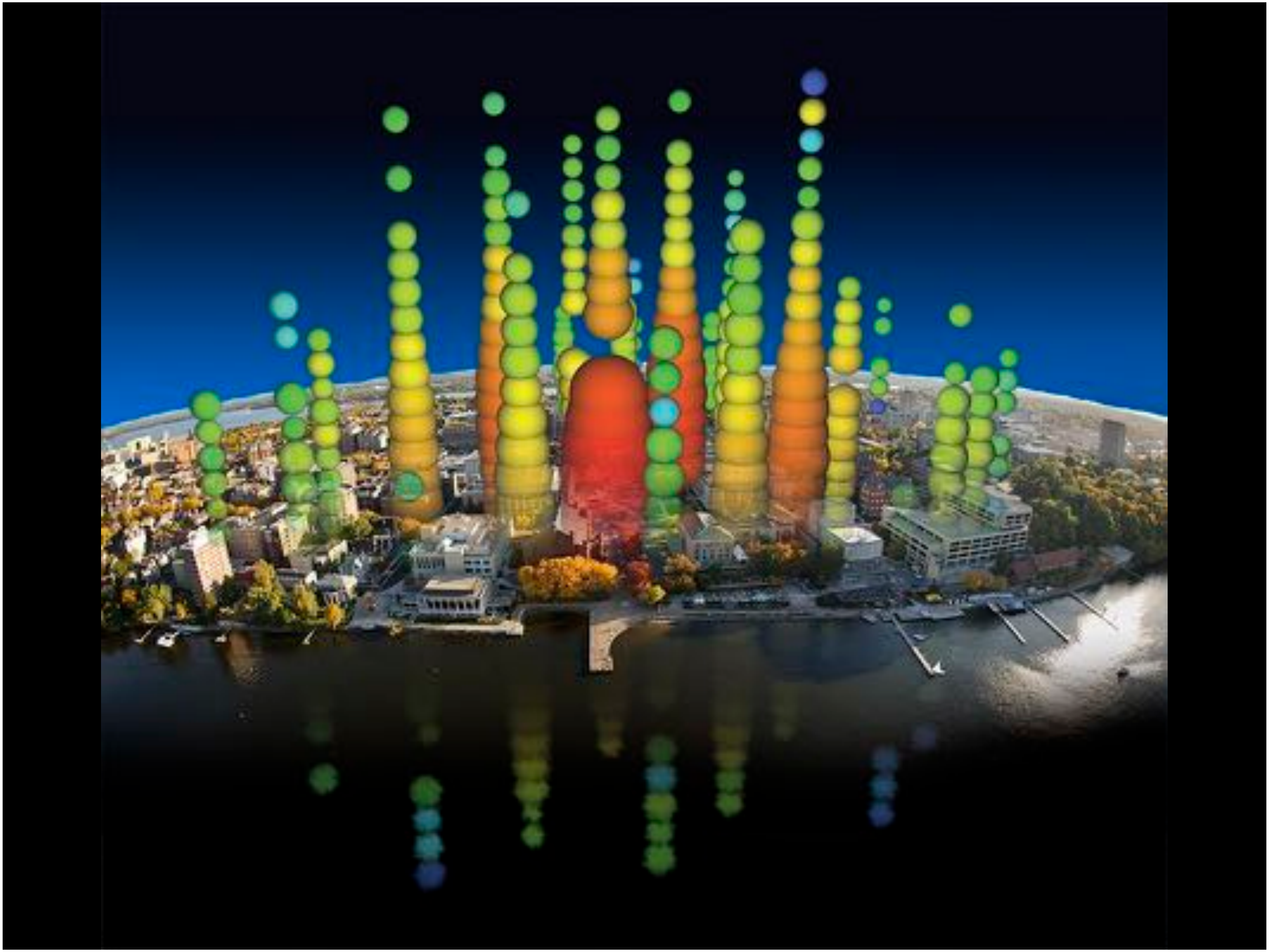


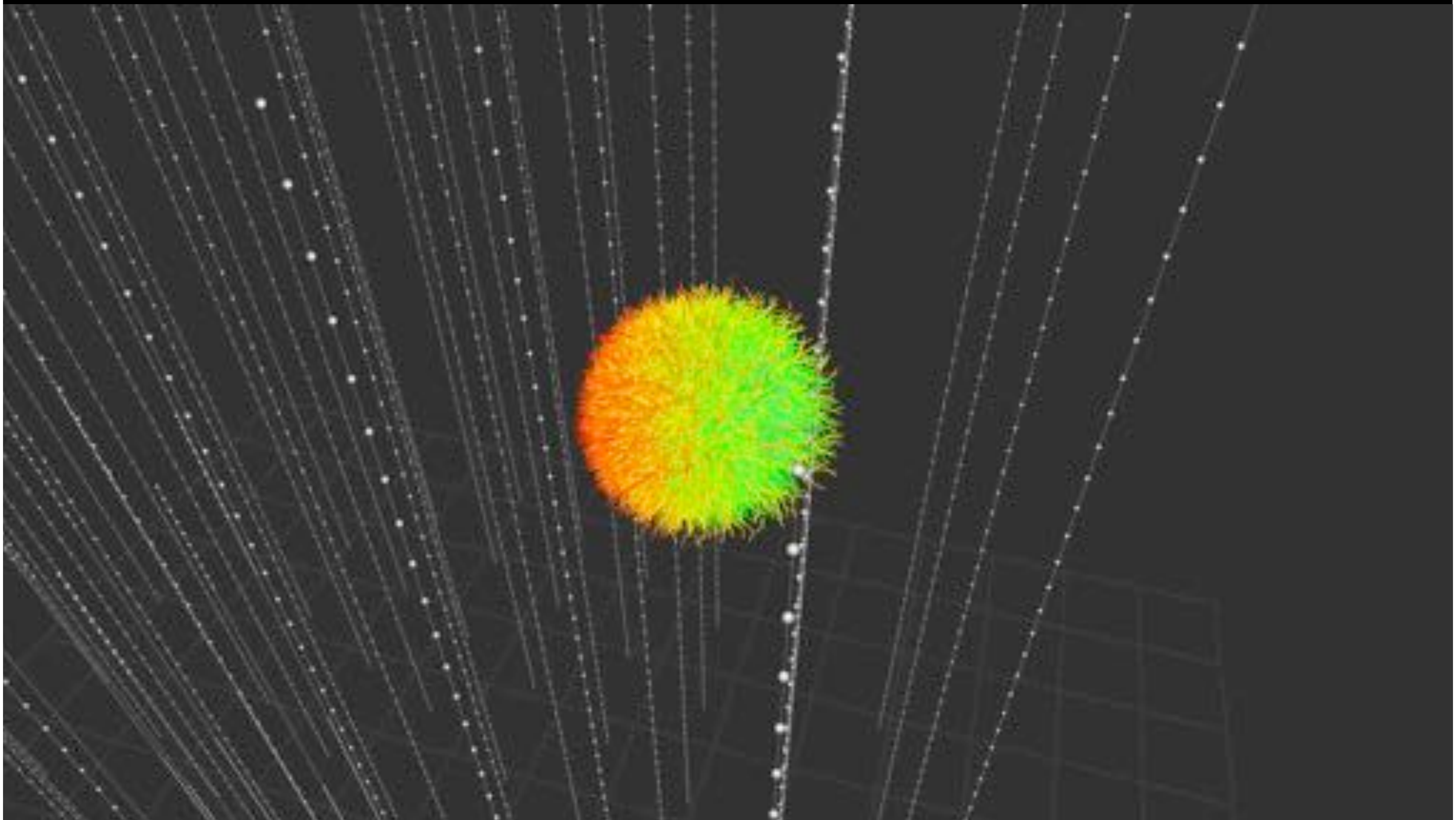
tracks and showers



PeV ν_e and ν_τ showers:
- 10 m long
- volume ~ 5 m^3
- isotropic after 25~ 50m

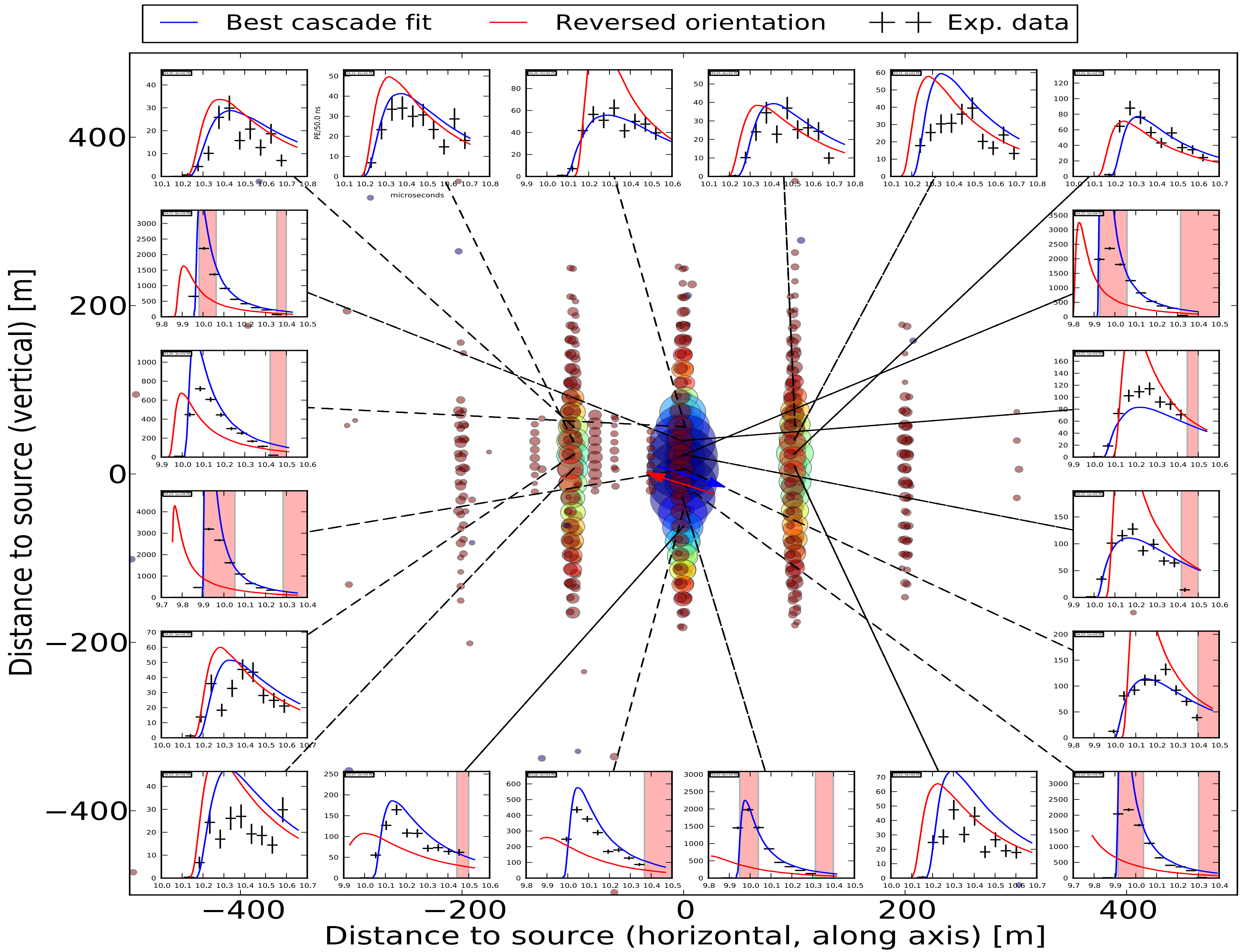






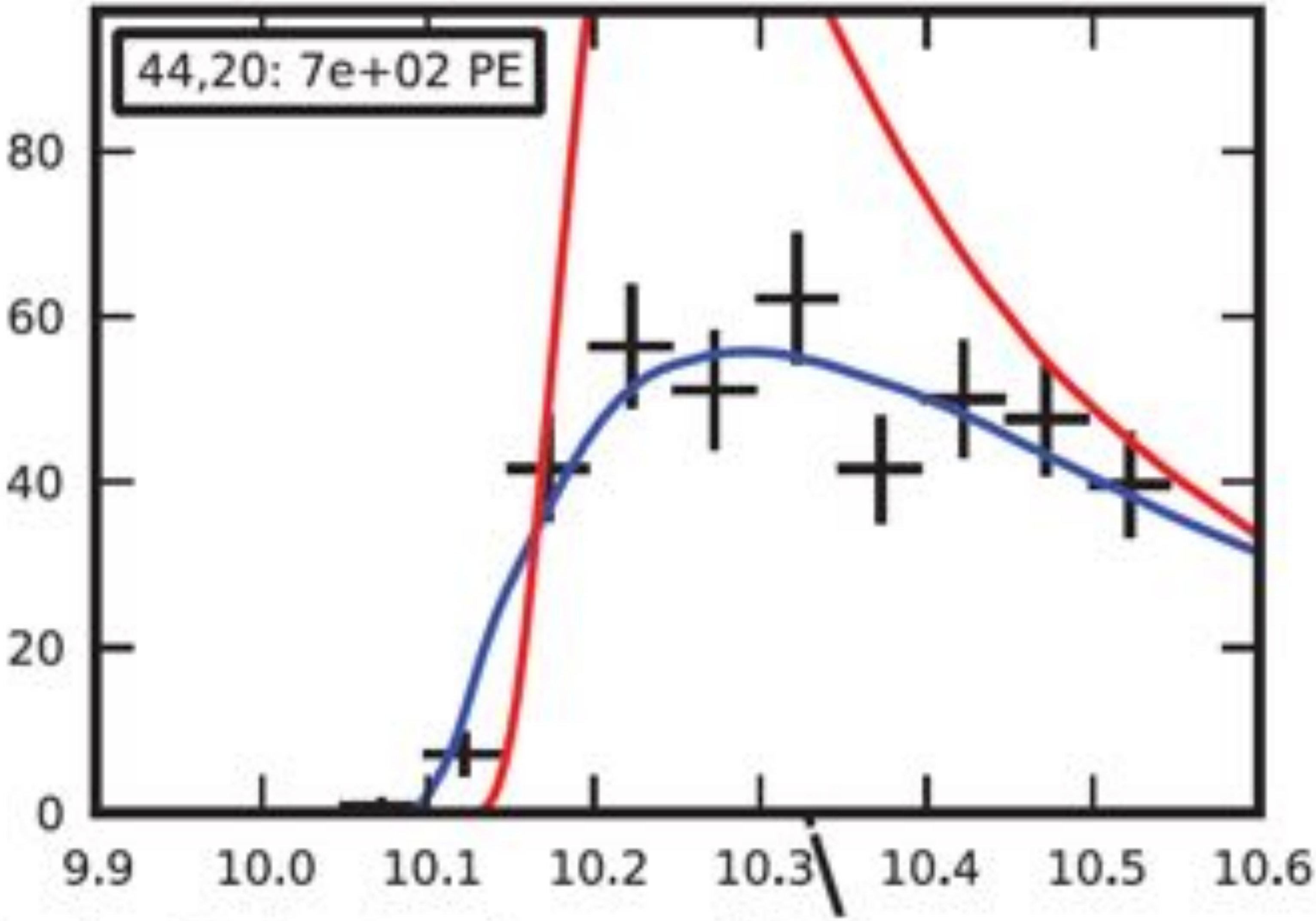
size = energy

color = time = direction

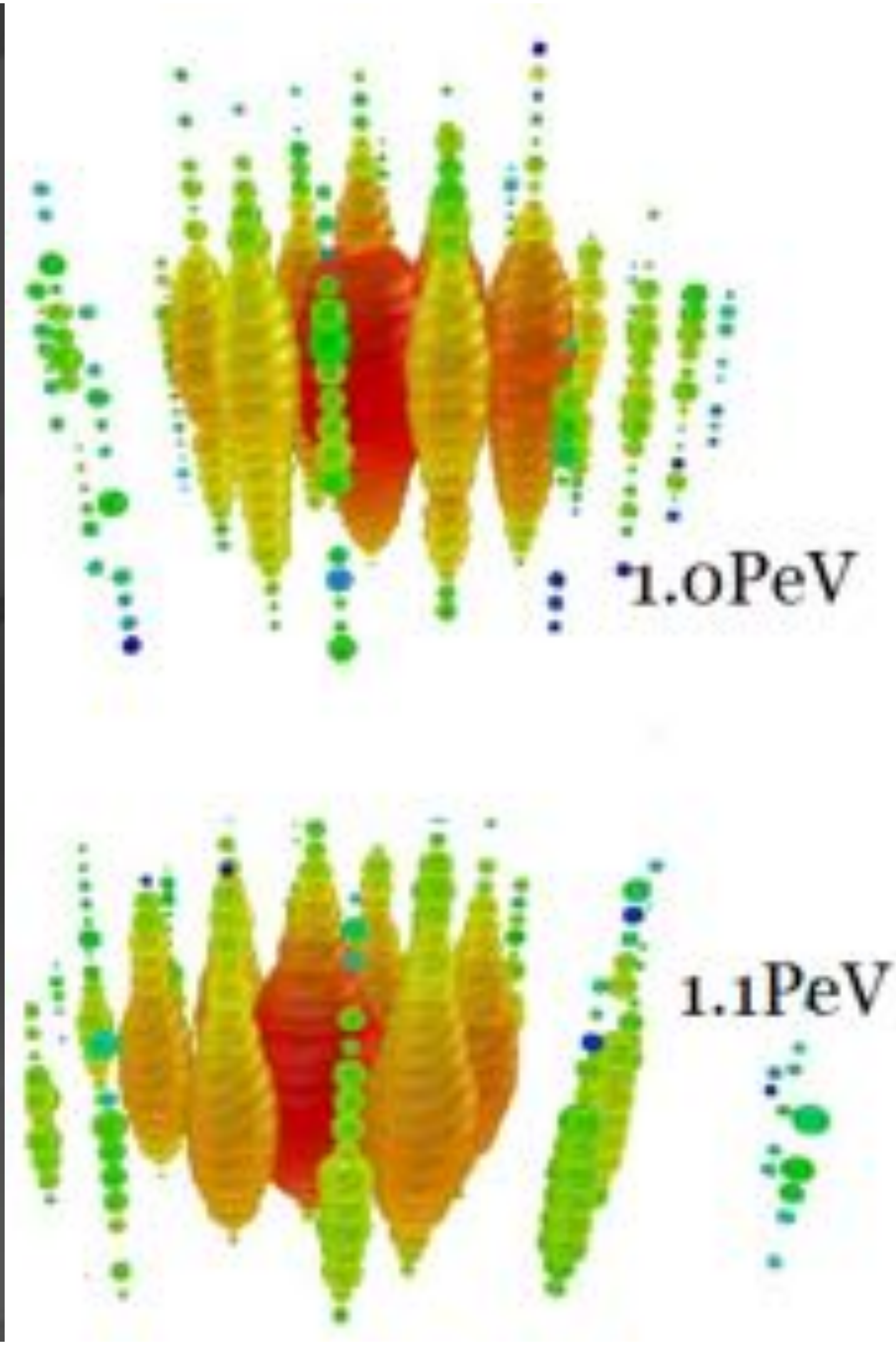


Best cascade fit
Reversed orientation
Exp. data
Distance to source (vertical) [m]
Distance to source (horizontal, along axis) [m]
PE/50.0 ns
microseconds

reconstruction limited by computing, not ice !



Blue: best-fit direction, red: reversed direction



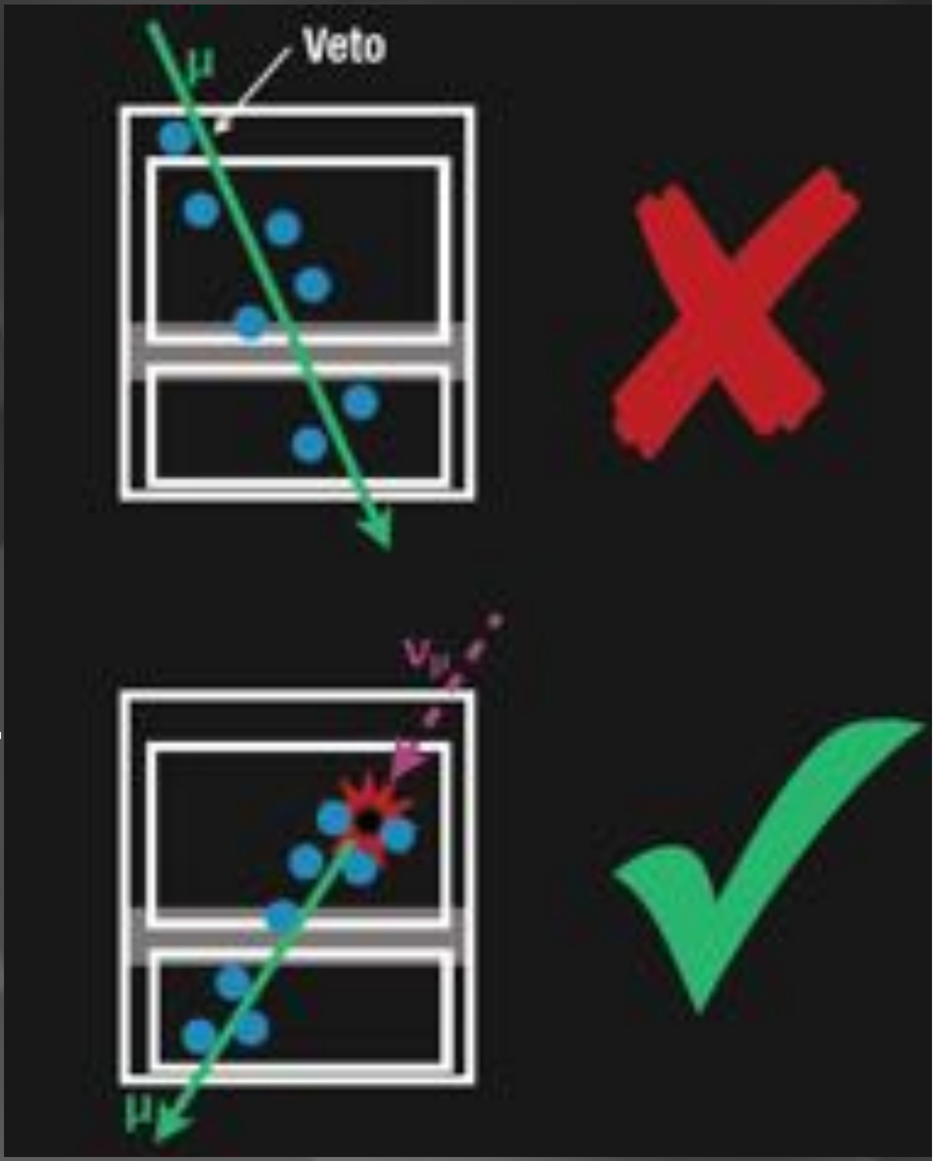
• energy

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

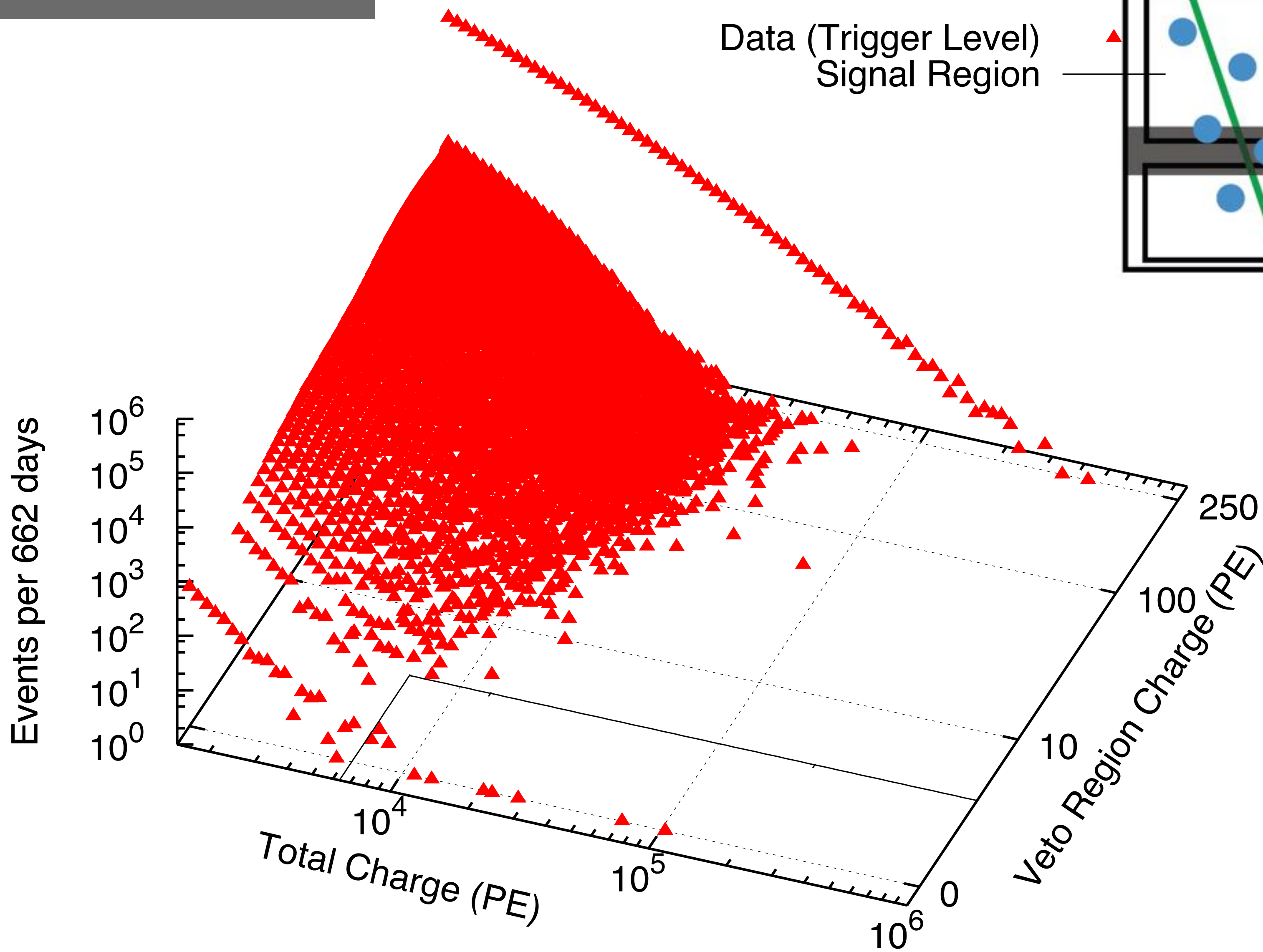
• not atmospheric: probability of no accompanying muon is 10^{-3} per event

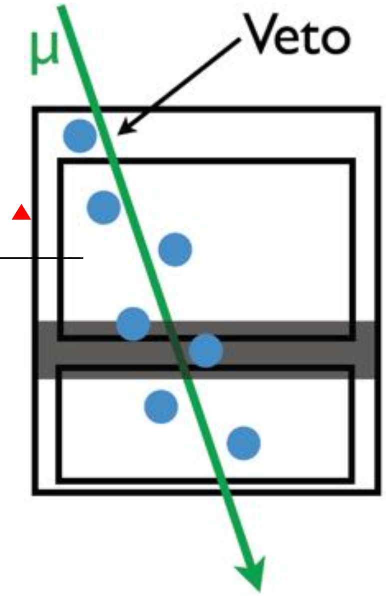
→ flux at present level of diffuse limit

- ✓ 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



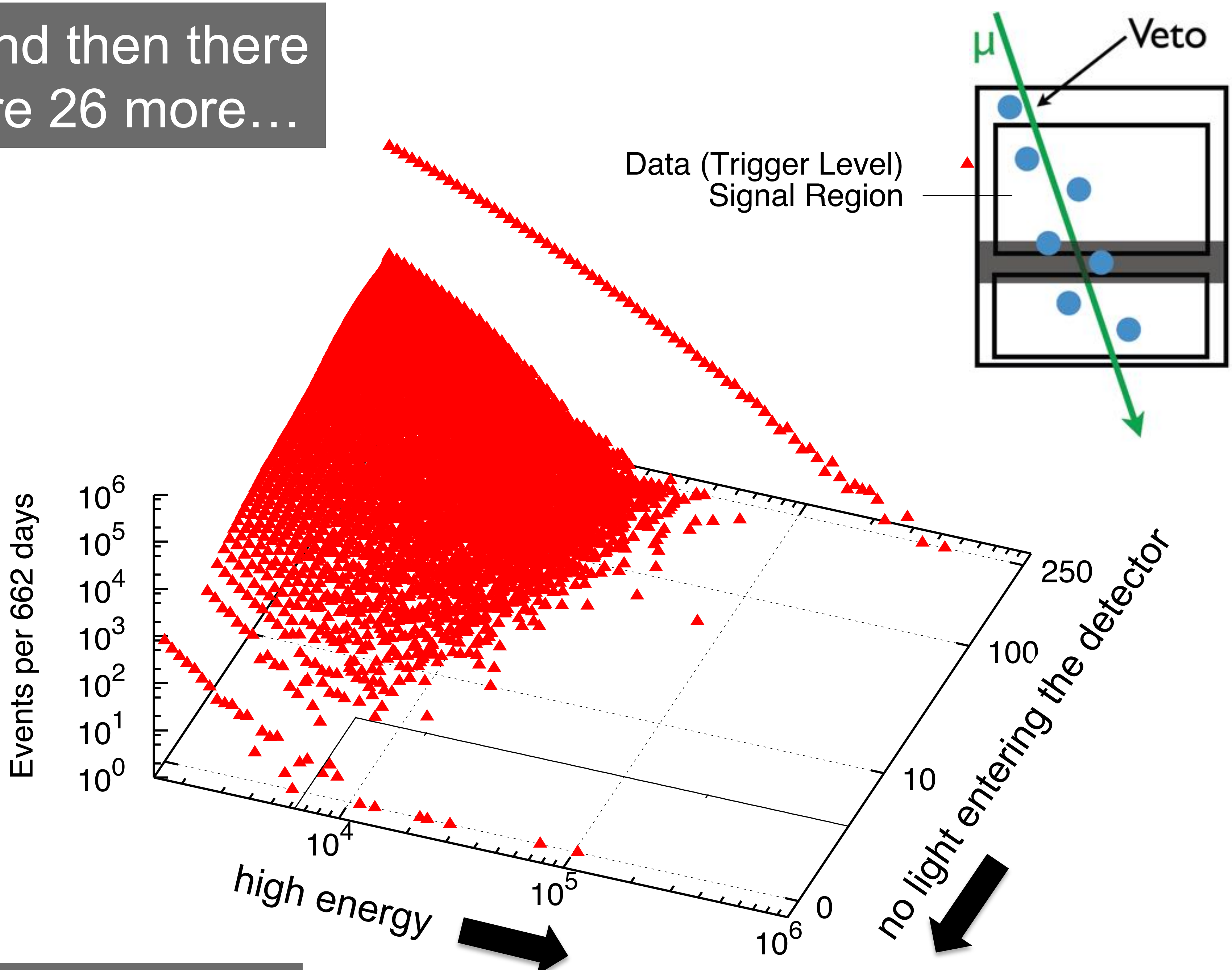
...and then there were 26 more...





data: 86 strings one year

…and then there were 26 more…



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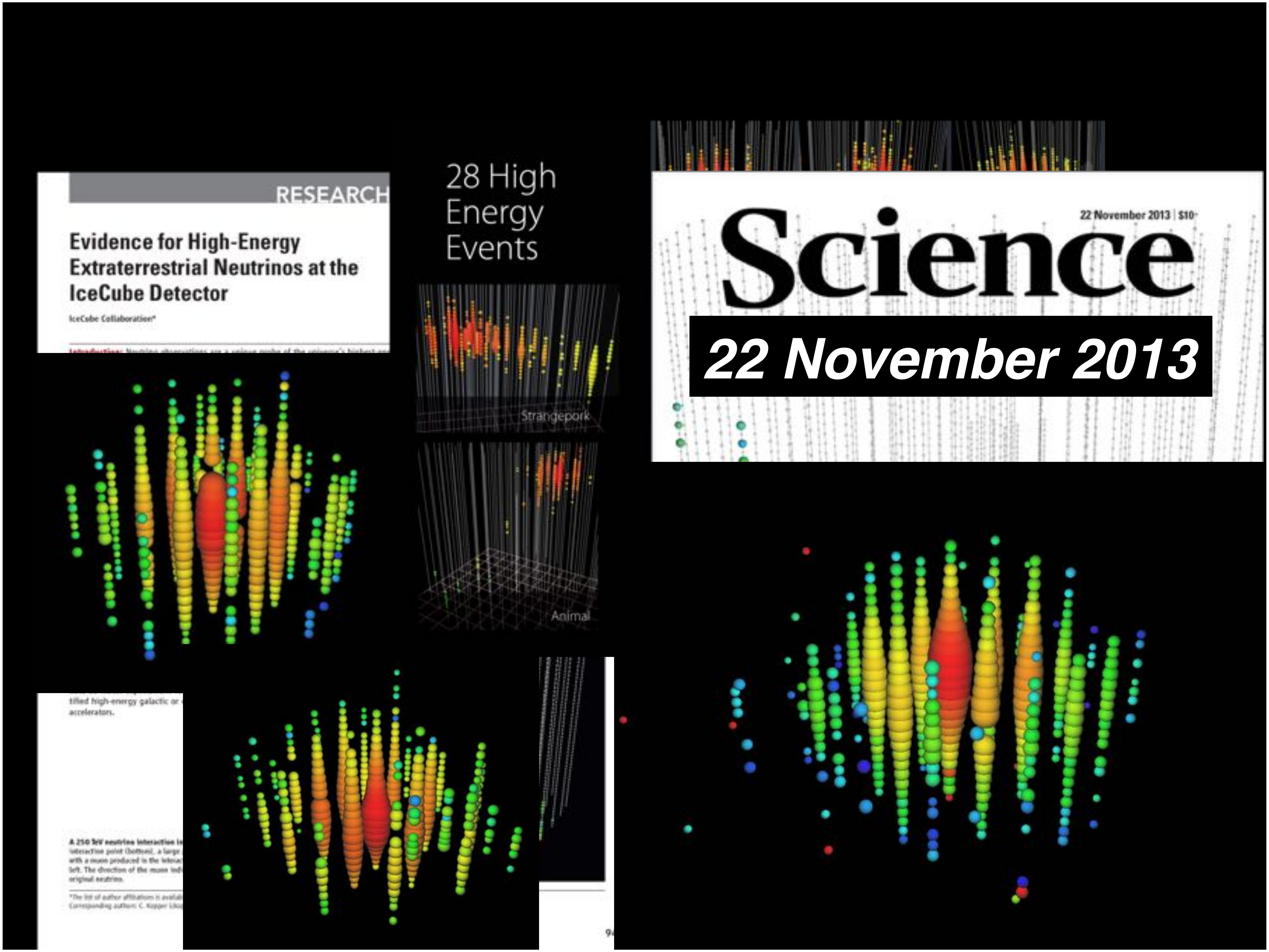
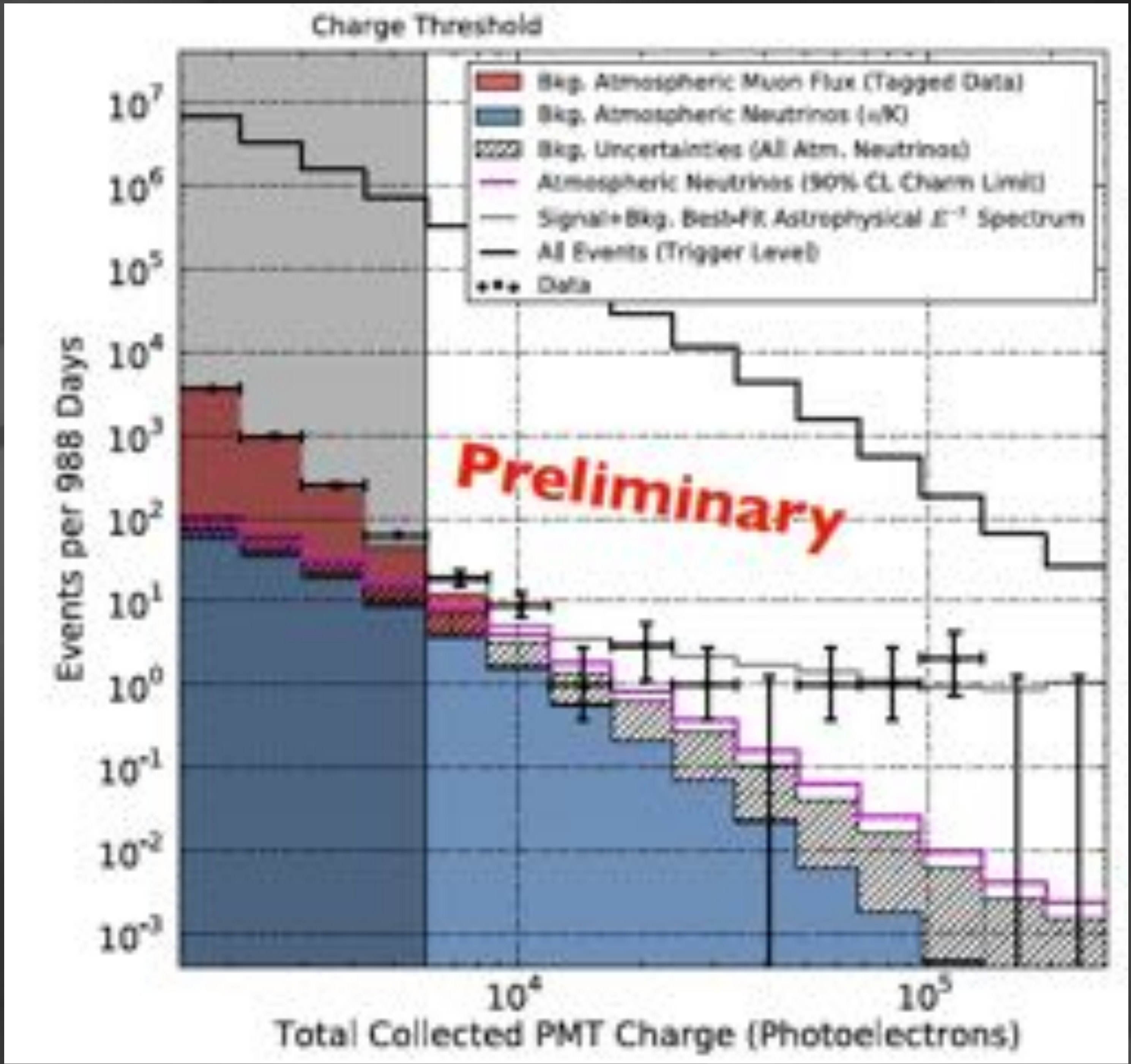
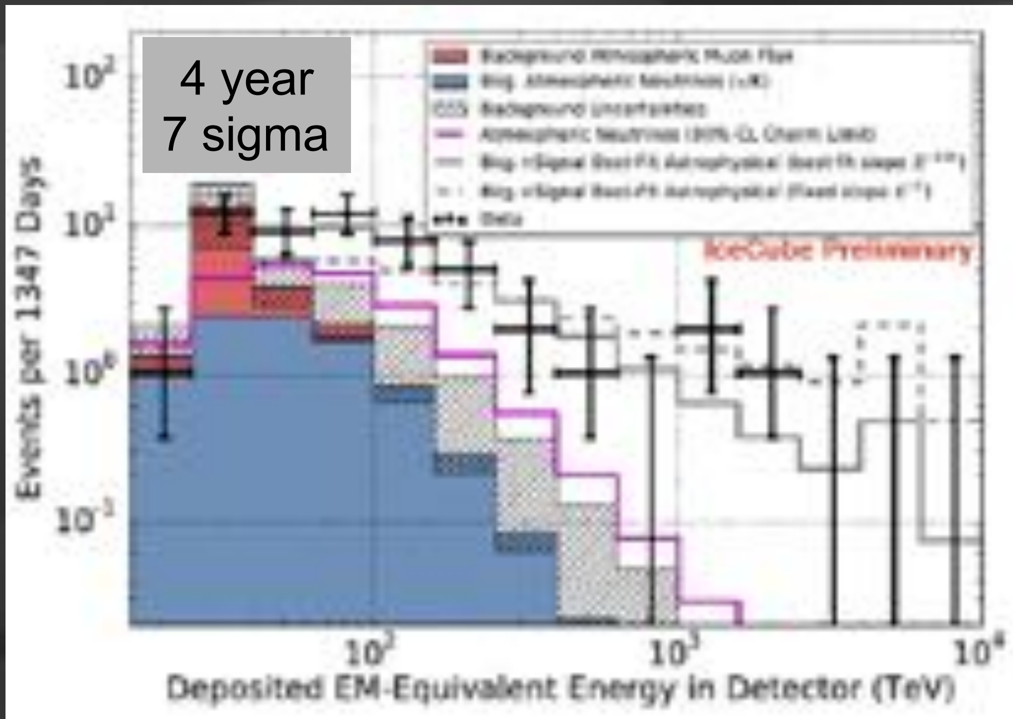


RESEARCH
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector
IceCube Collaboration*
28 High Energy Events
Strangepork
Animal
Science
22 November 2013 | $10
22 November 2013

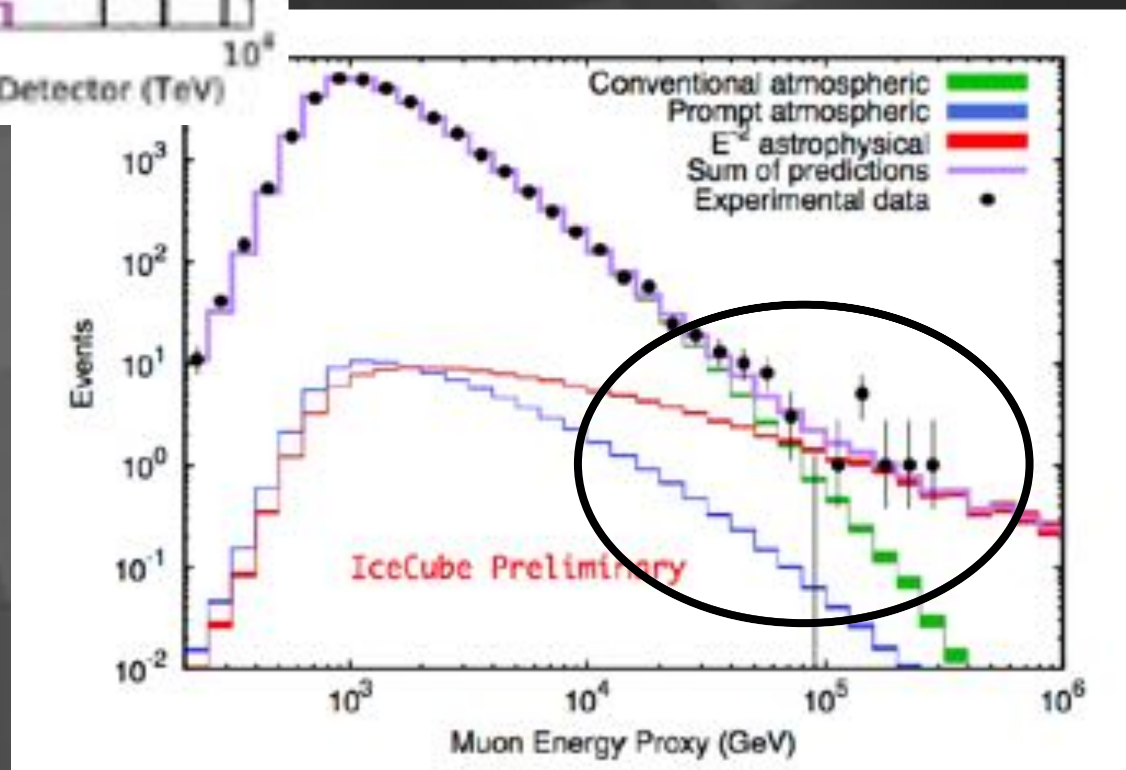
total charge collected by PMTs of events with interaction inside the detector



Science 342 (2013) 1242856



confirmation!
flux of muon neutrinos
through the Earth

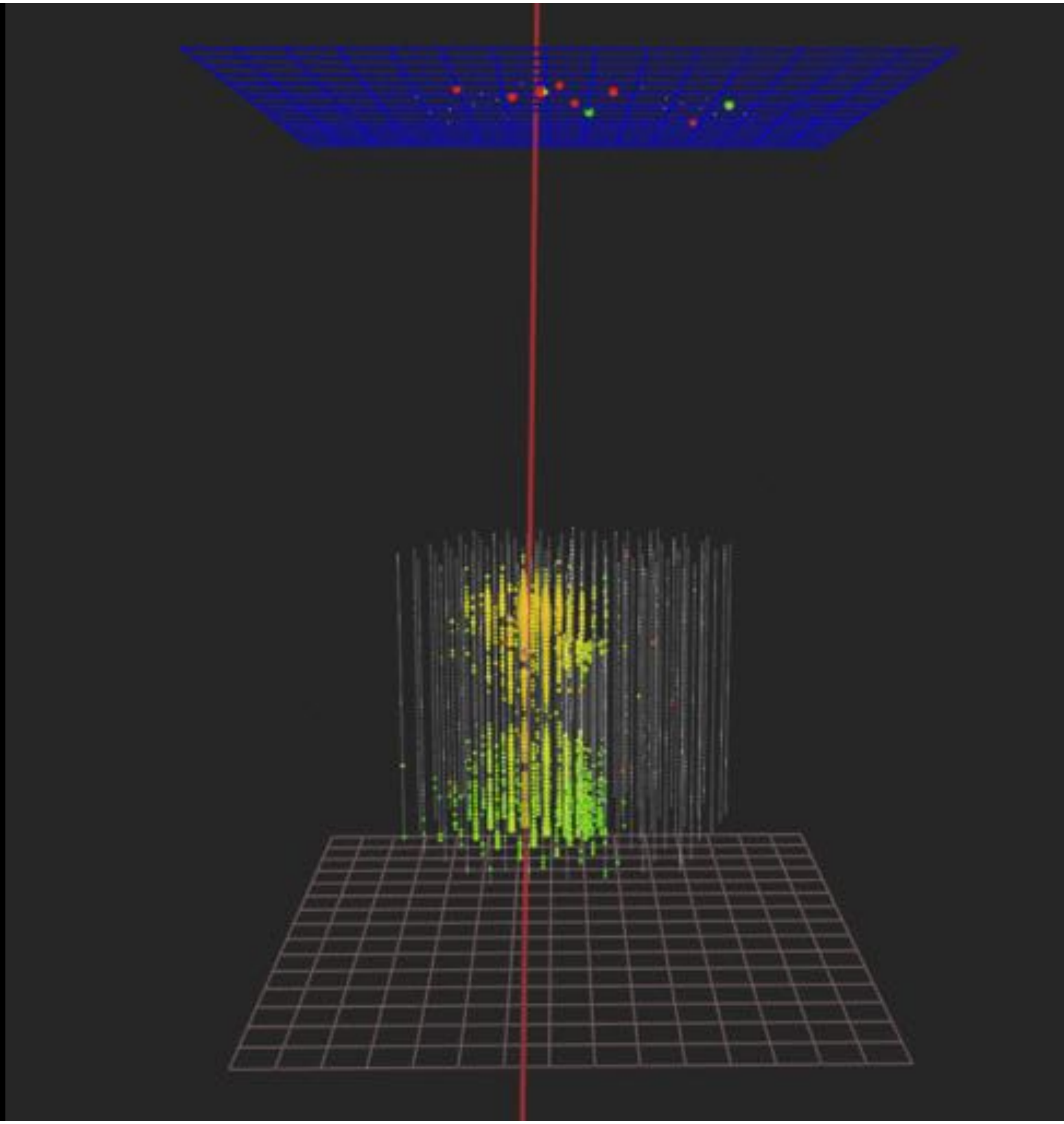


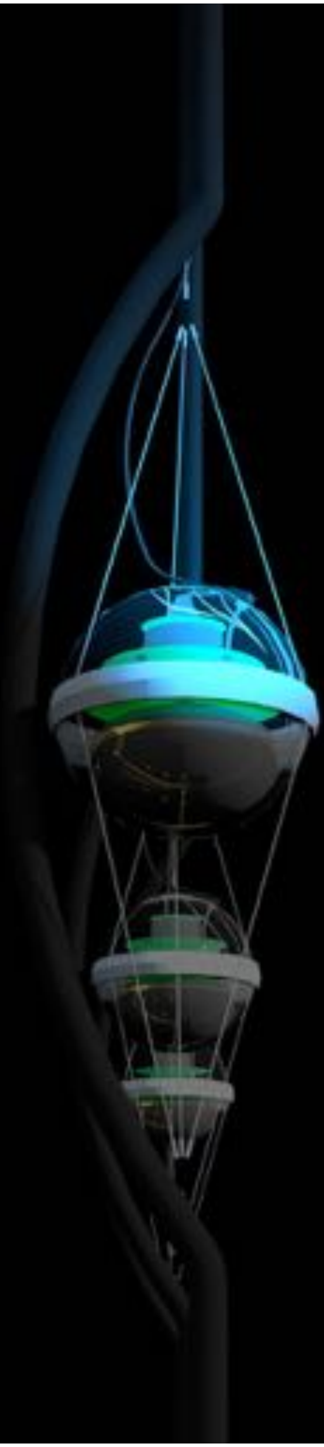
neutrinos of all flavors
interacting inside
IceCube

430 TeV

1 event:
~ 5 sigma
discovery

> PeV ν_μ





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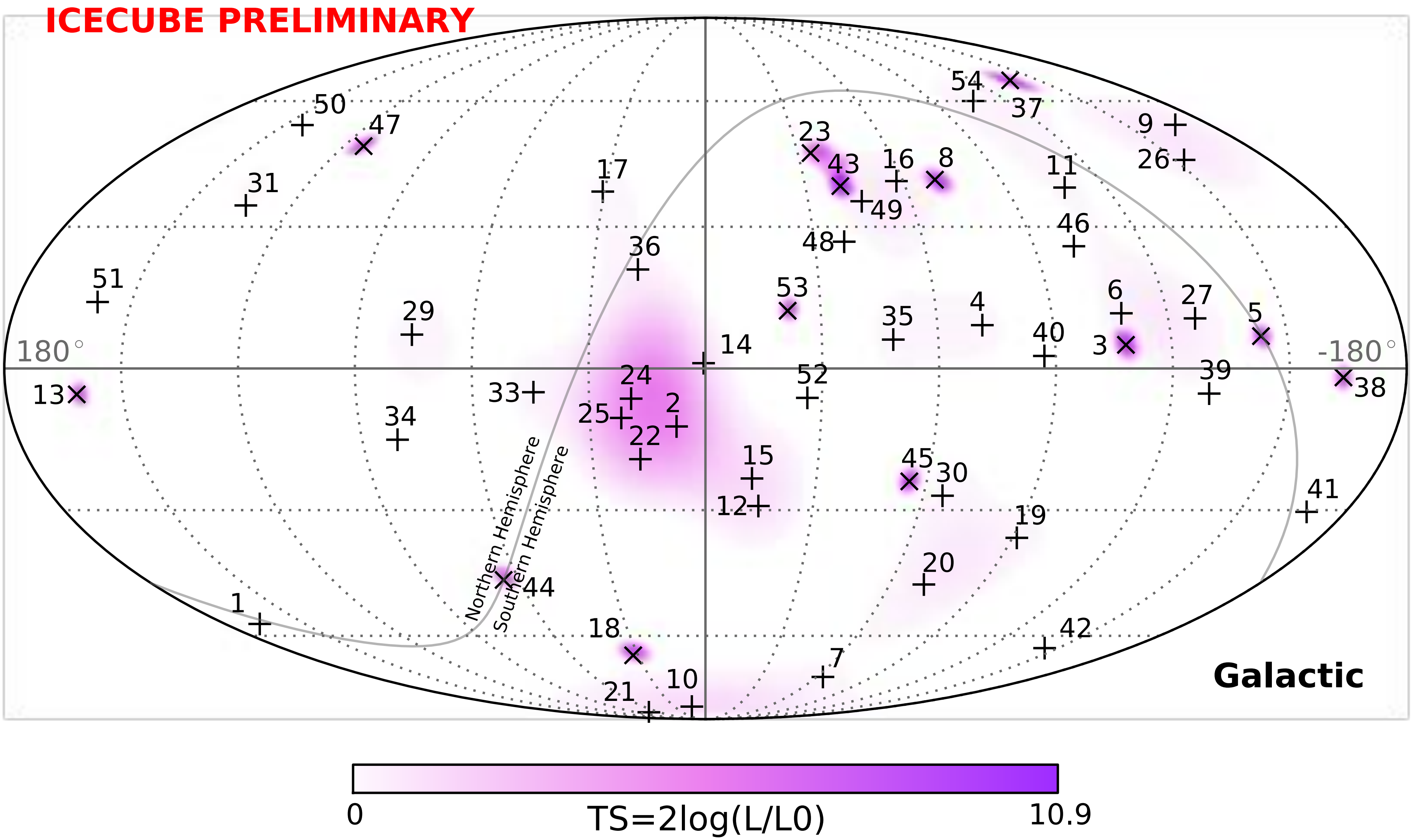
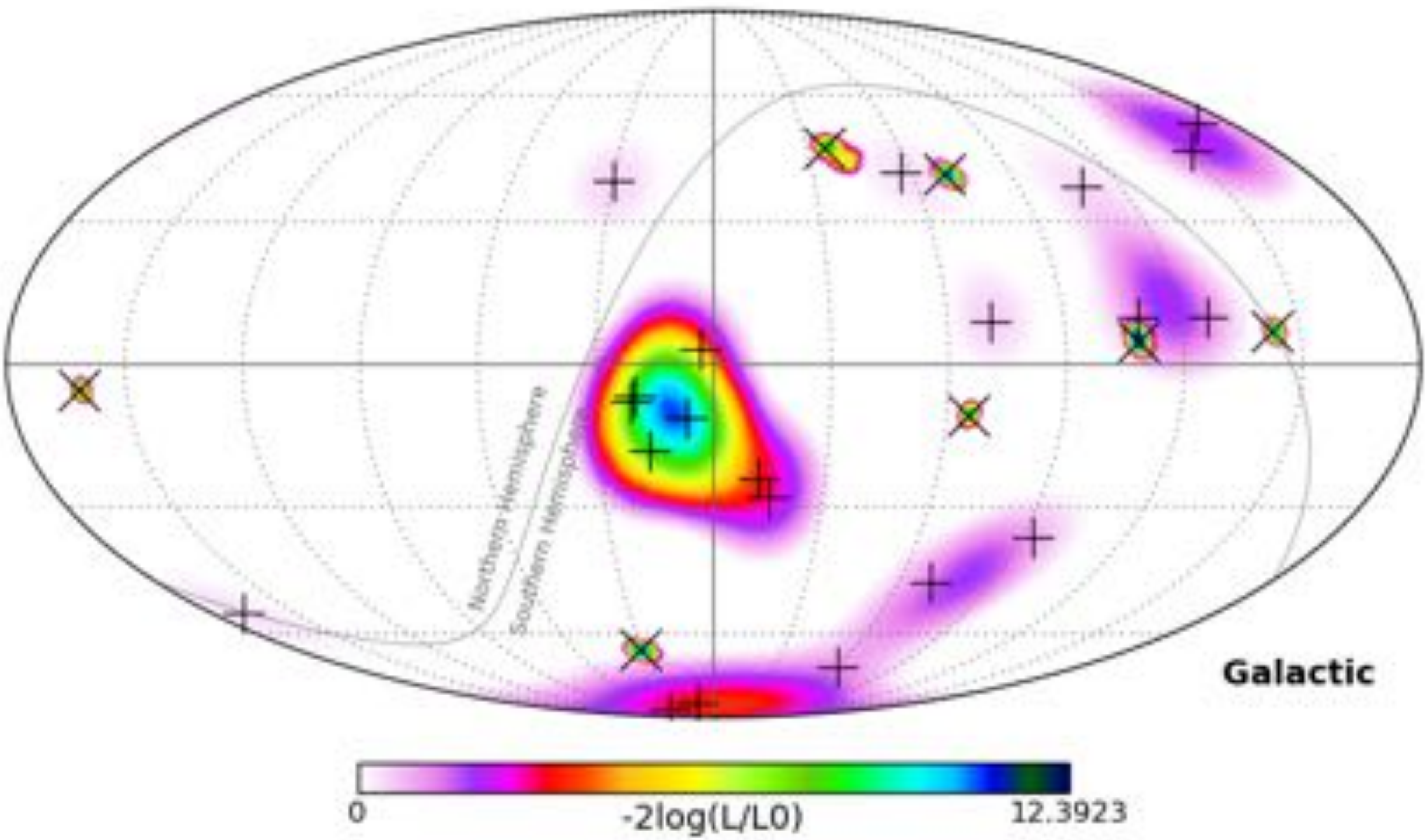
4 year HESE



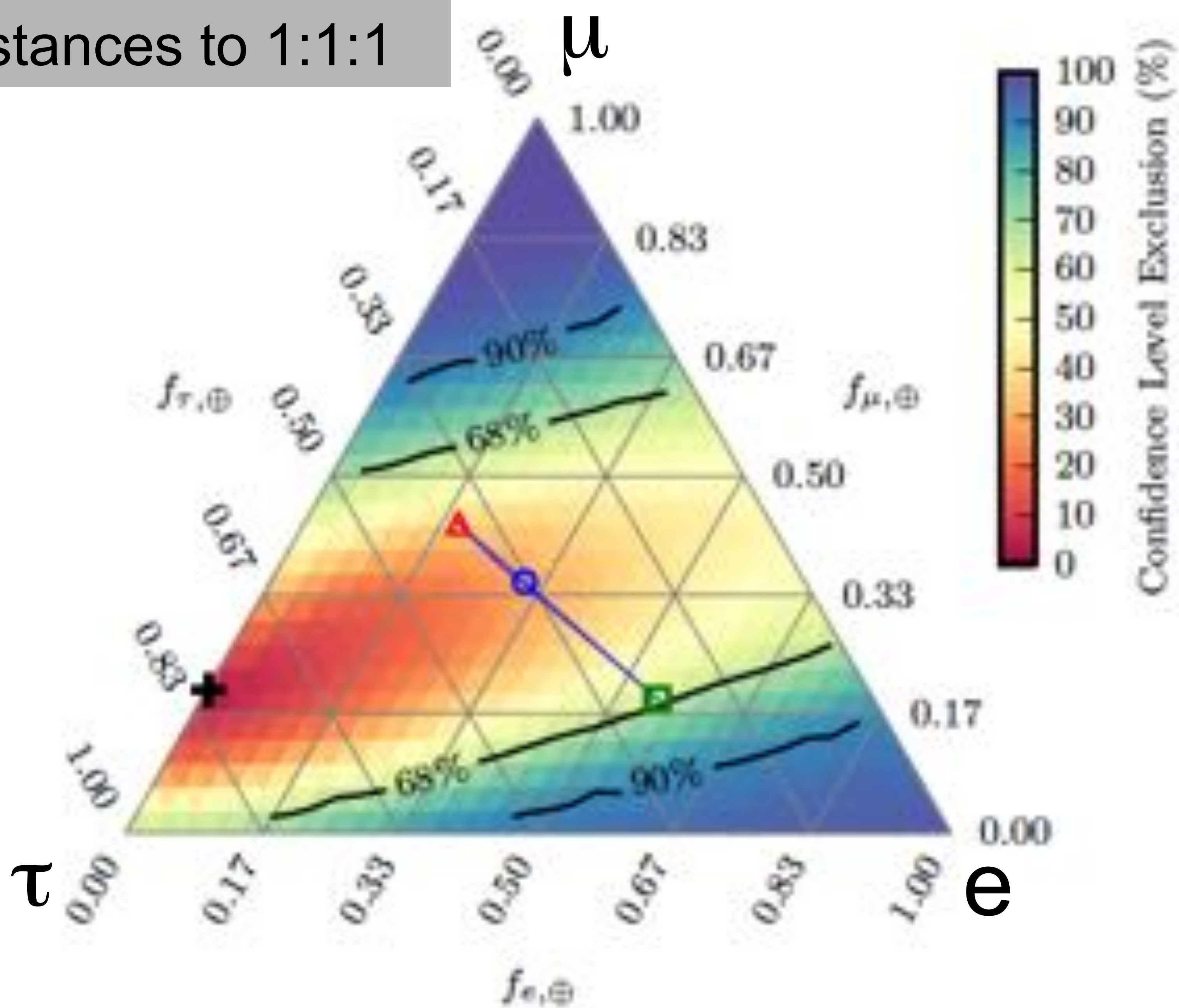
where do they come from?

2 year HESE

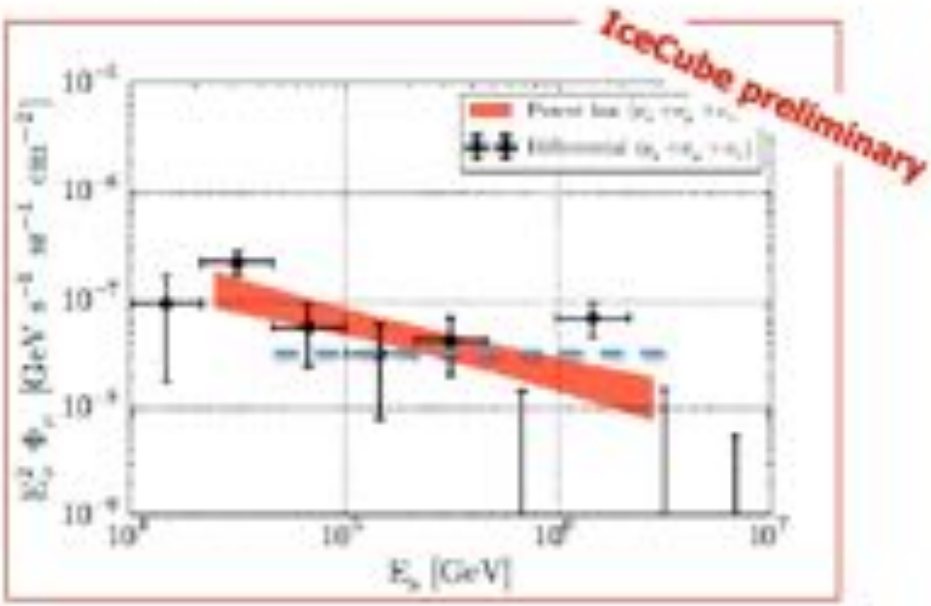


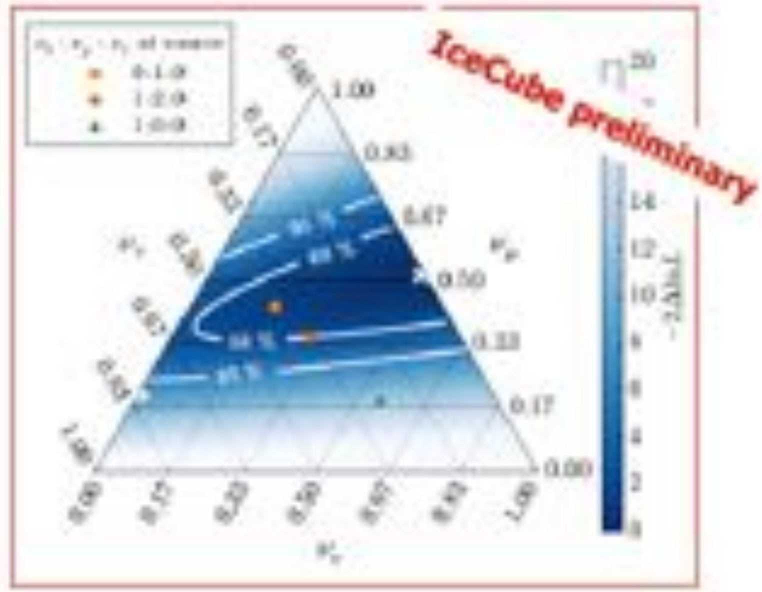
Northern Hemisphere
Southern Hemisphere
Galactic
0
-2log(L/L0)
12.3923

oscillate over cosmic distances to 1:1:1



- 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

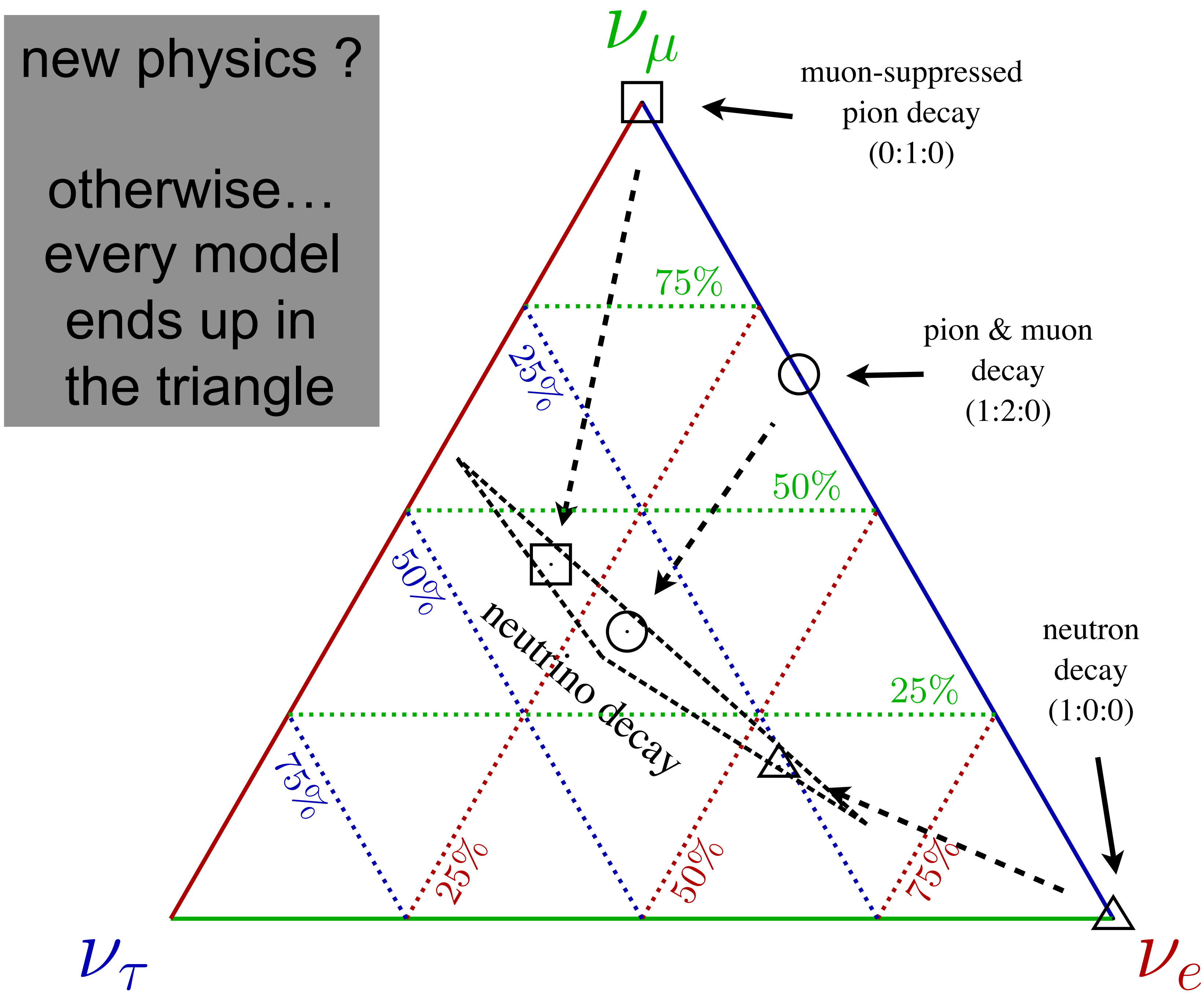




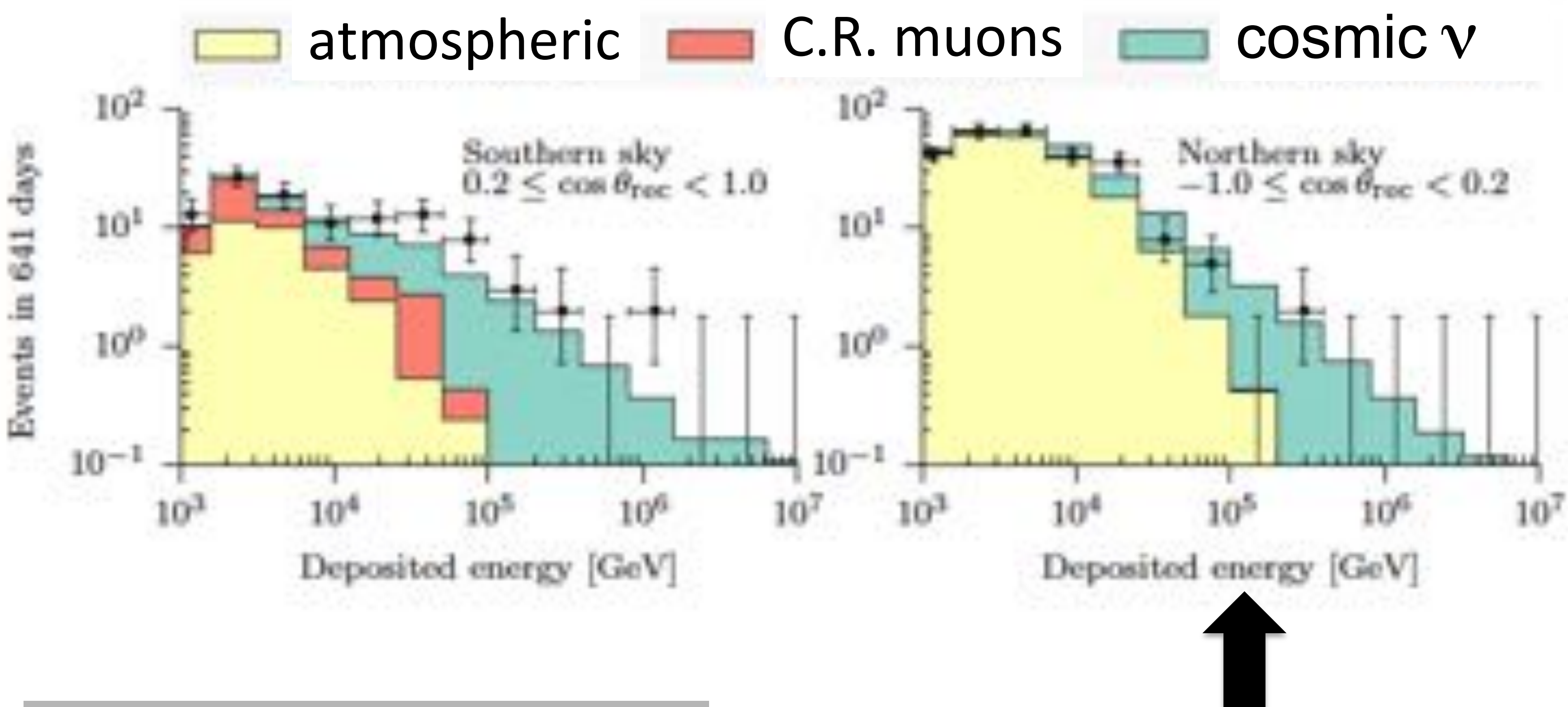
assuming isotropic astrophysical flux and $\nu_e:\nu_\mu:\nu_\tau$ = 1:1:1 at Earth →

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 $(6.7 \pm 1.2)\times10^{-18}$ $(\mathrm{GeV} \cdot \mathrm{cm}^2 \cdot \mathrm{s} \cdot \mathrm{sr})^{-1}$

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
ν_μ
ν_τ
ν_e
muon-suppressed
pion decay
(0:1:0)
pion & muon
decay
(1:2:0)
neutron
decay
(1:0:0)
neutrino decay
75%
50%
25%
25%
50%
75%
25%
50%
75%

starting events; towards lower energies: a power?

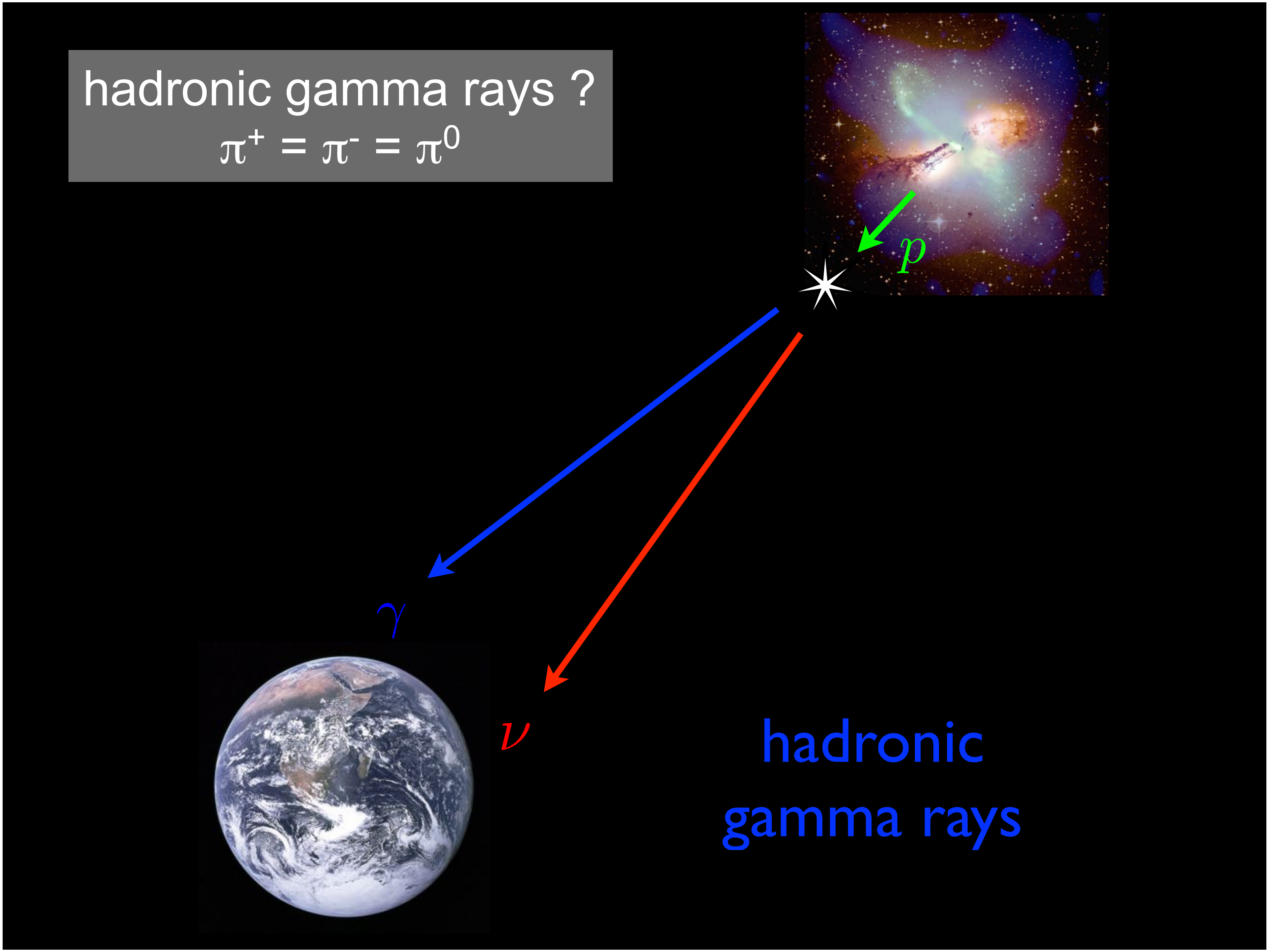


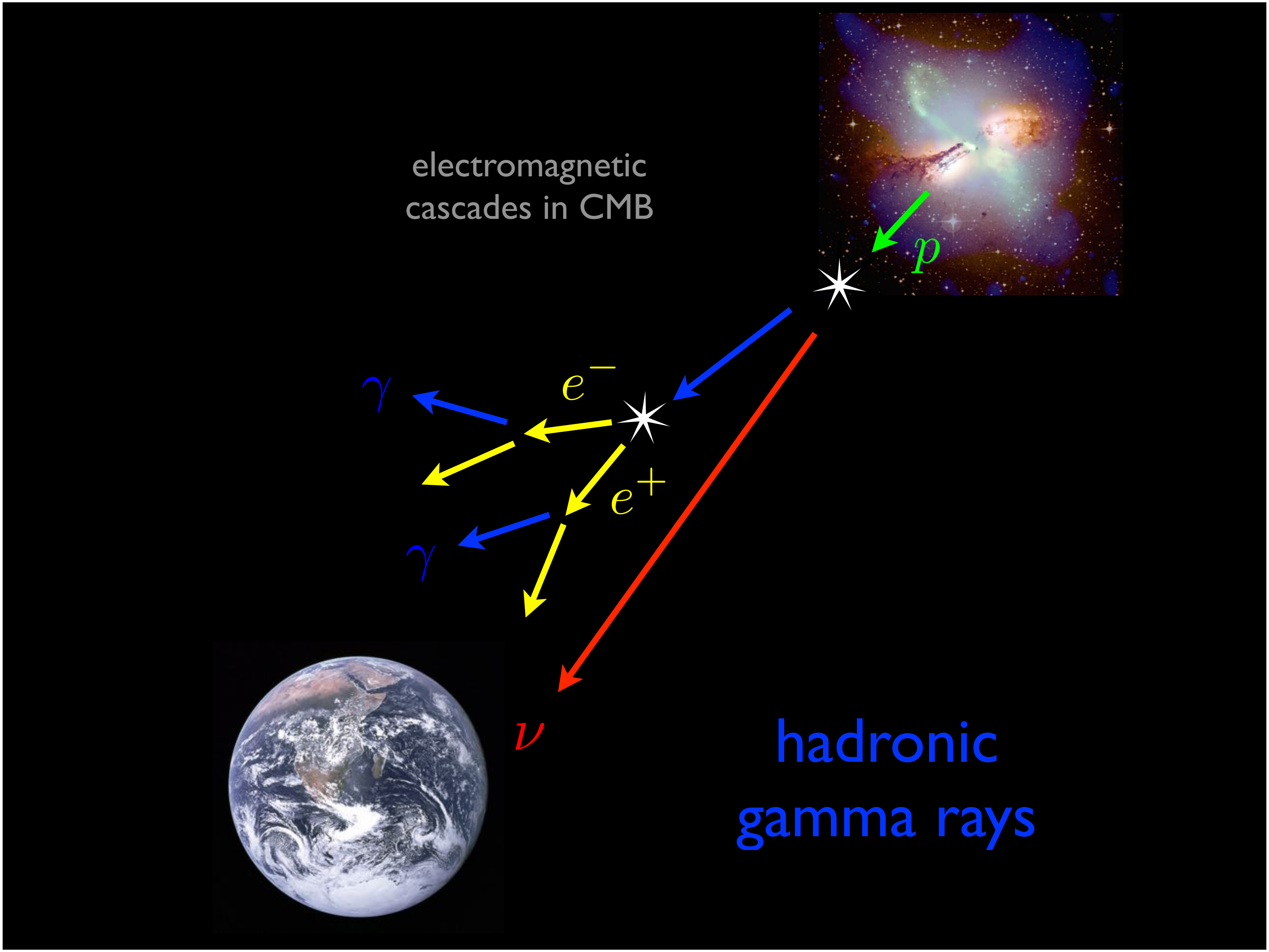
PeV neutrinos absorbed in the Earth

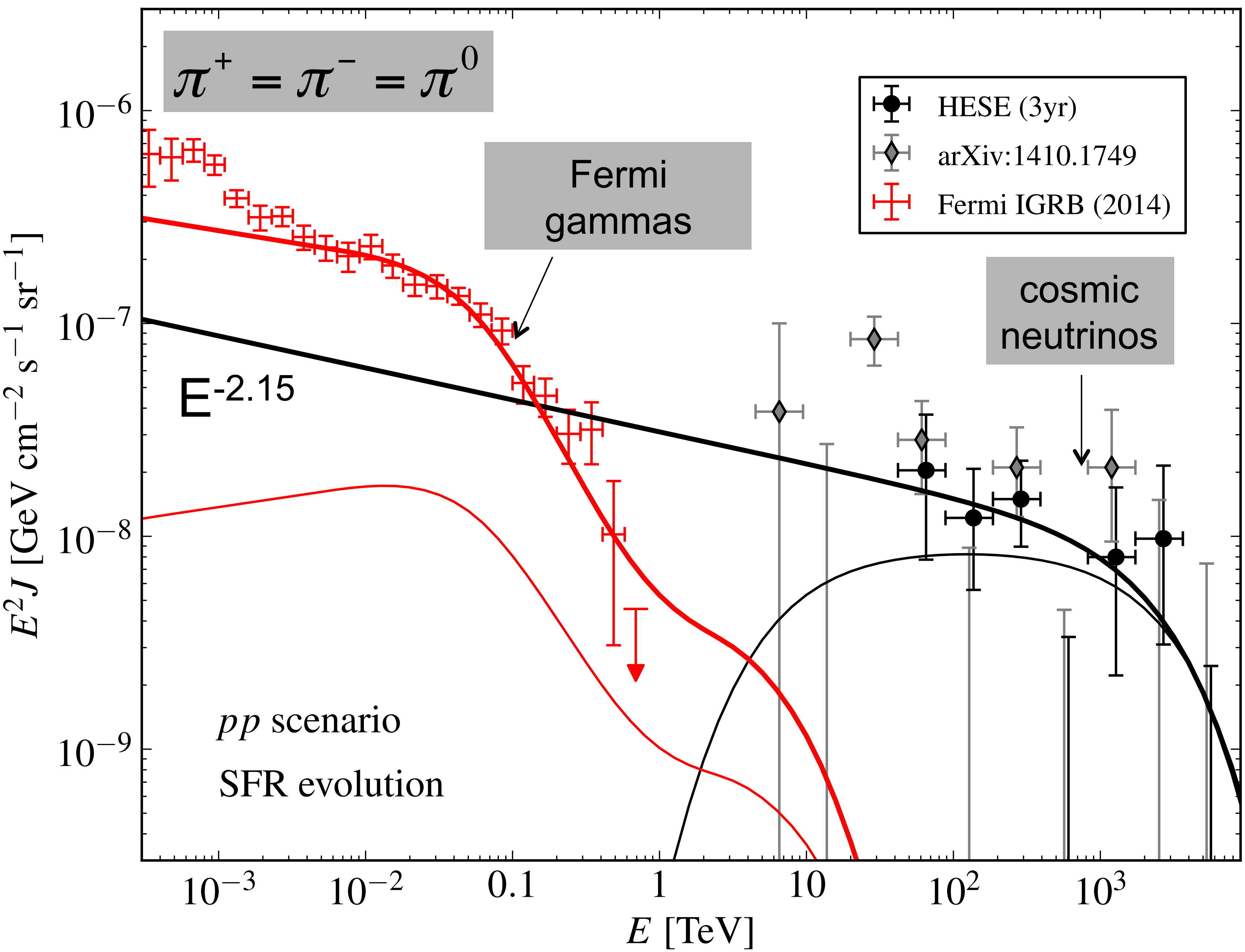
warning:

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

- 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 ?
$\pi^+ = \pi^- = \pi^0$
p
γ
ν
hadronic
gamma rays


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



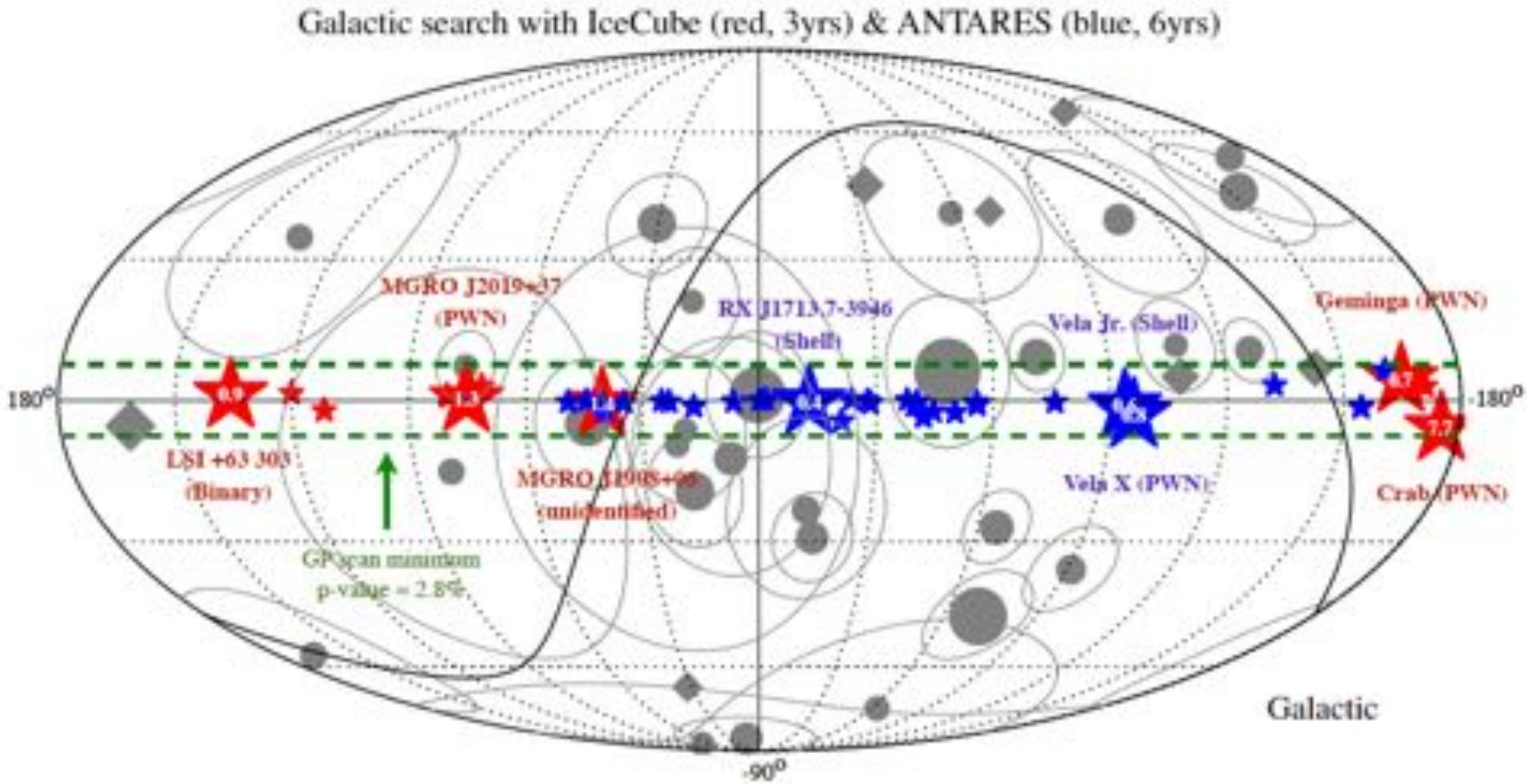
$\pi^+ = \pi^- = \pi^0$
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
Fermi gammas
cosmic neutrinos
$E^{-2.15}$
pp scenario
SFR evolution
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3

- 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

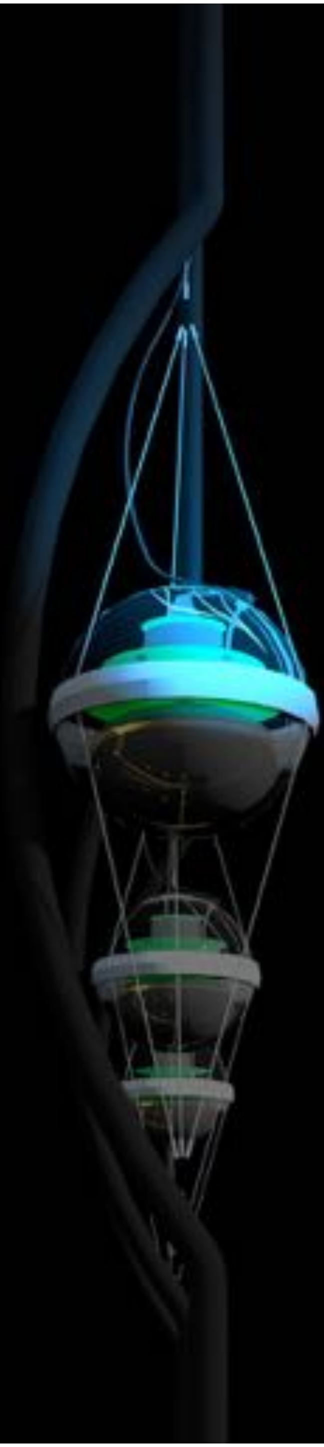
- gamma ray sources predict neutrinos. We are close to identifying point sources.

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

- 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

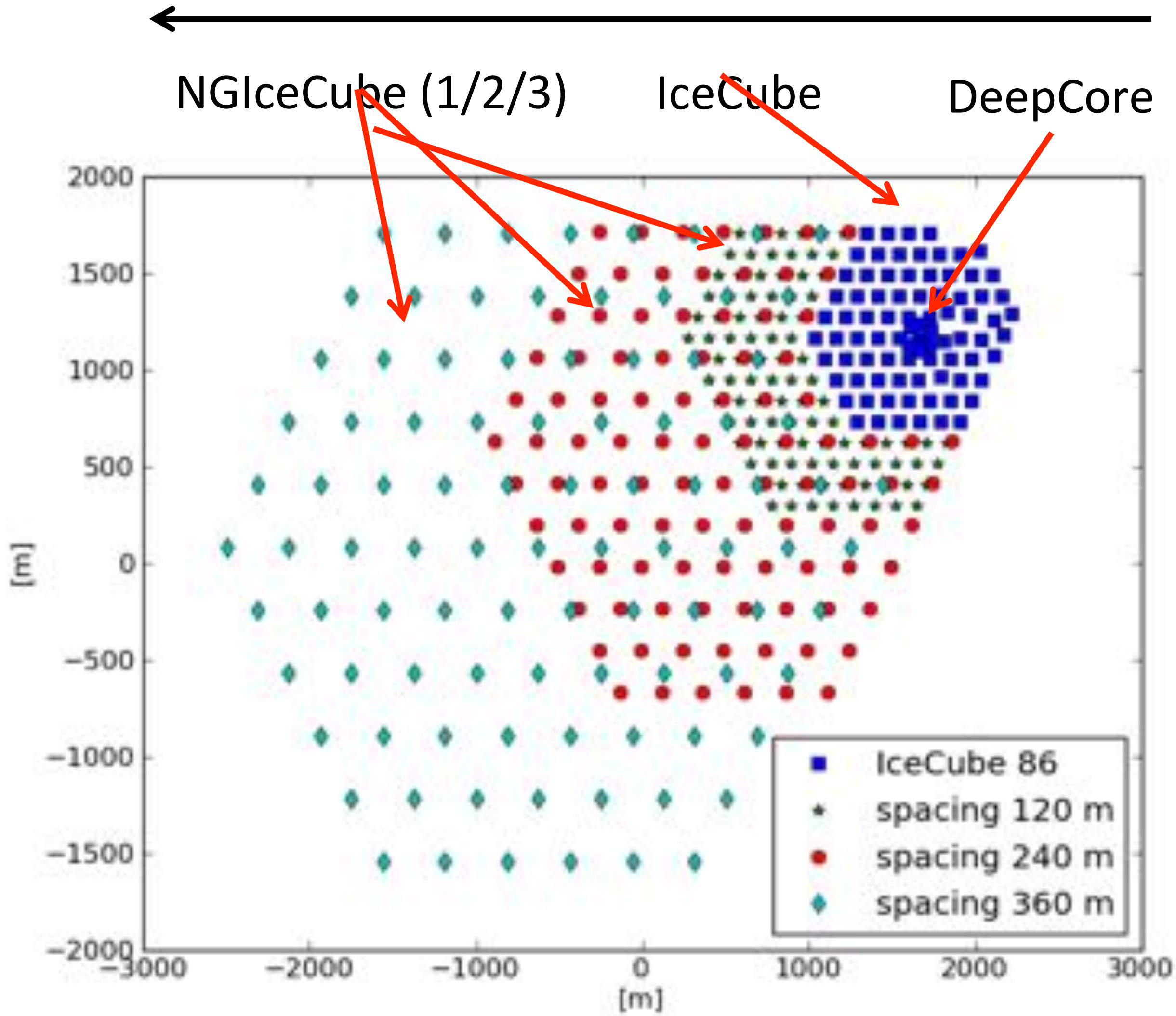
- a next-generation IceCube with a volume of 10 km^3 and an angular resolution of < 0.3 degrees will see multiple neutrinos and identify the sources, even from a “diffuse” extragalactic flux in several years

- need 1,000 events vs 100 now

- discovery instrument → astronomical telescope

measured optical properties → twice the string spacing

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

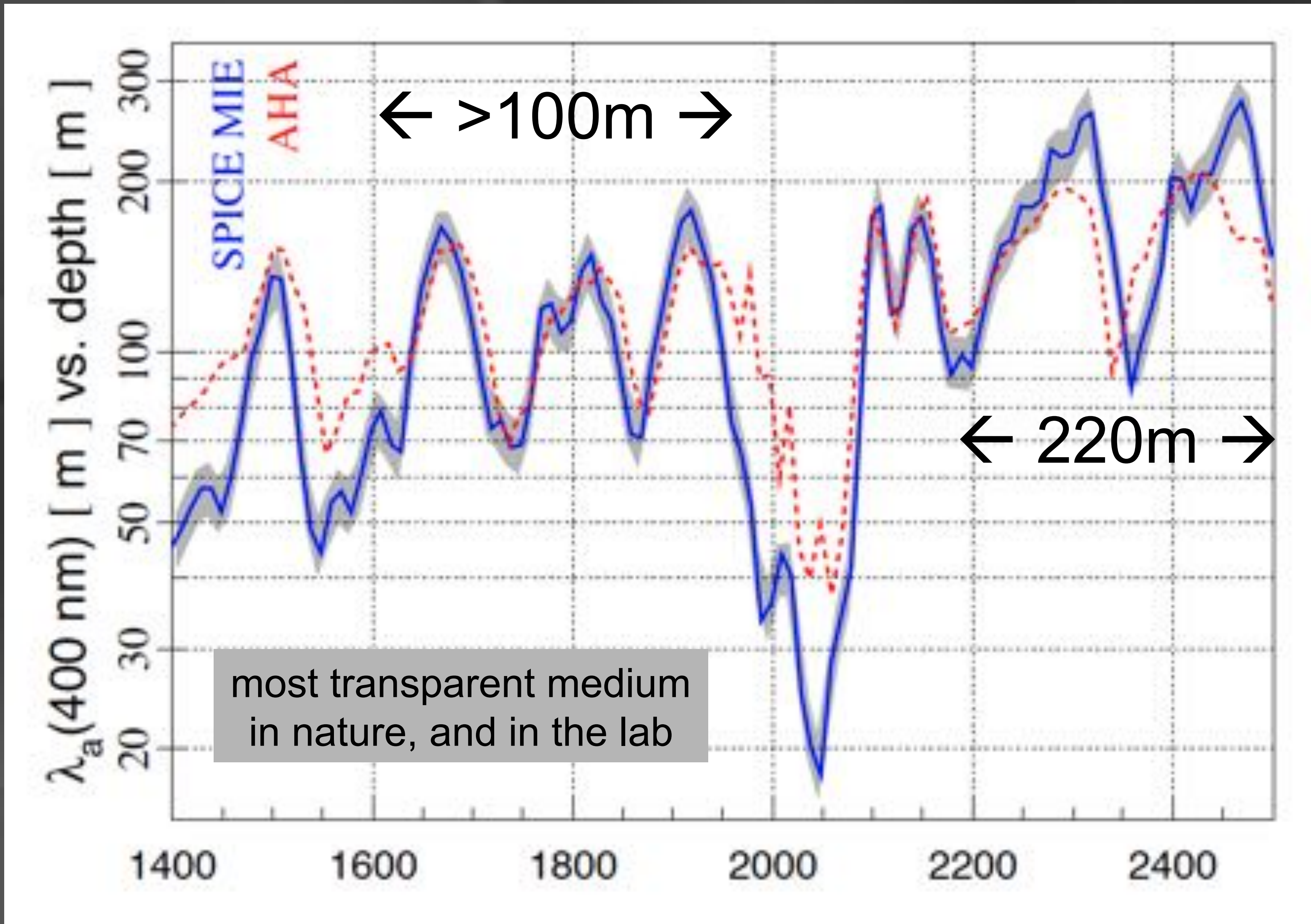


Spacing 1 (120m):
IceCube (1 km^3)
+ 98 strings (1,3 km^3)
= 2,3 km^3

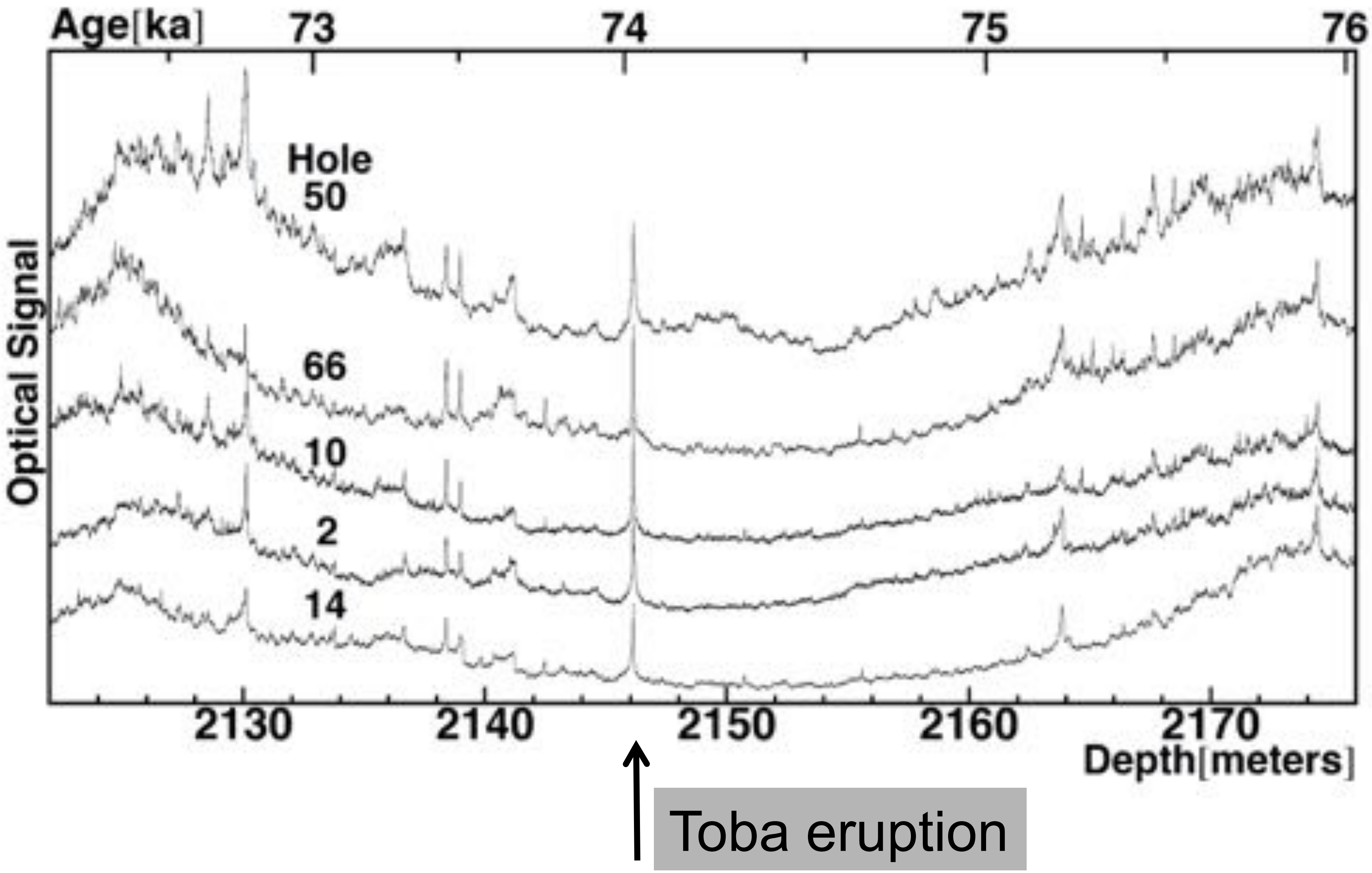
Spacing 2 (240m):
IceCube (1 km^3)
+ 99 strings (5,3 km^3)
= 6,3 km^3

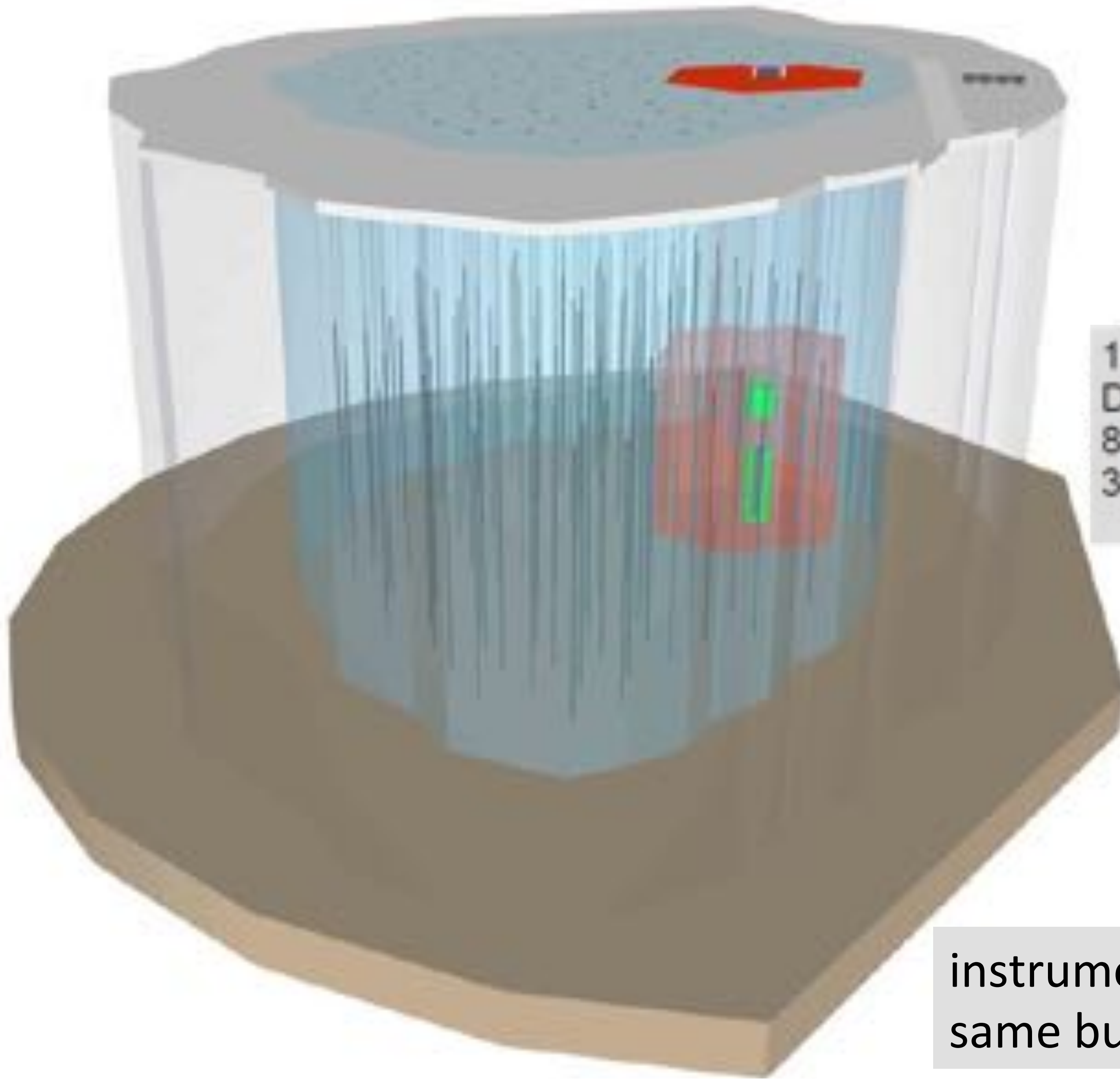
Spacing 3 (360m):
IceCube (1 km^3)
+ 95 strings (11,6 km^3)
= 12,6 km^3

absorption length of Cherenkov light



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





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

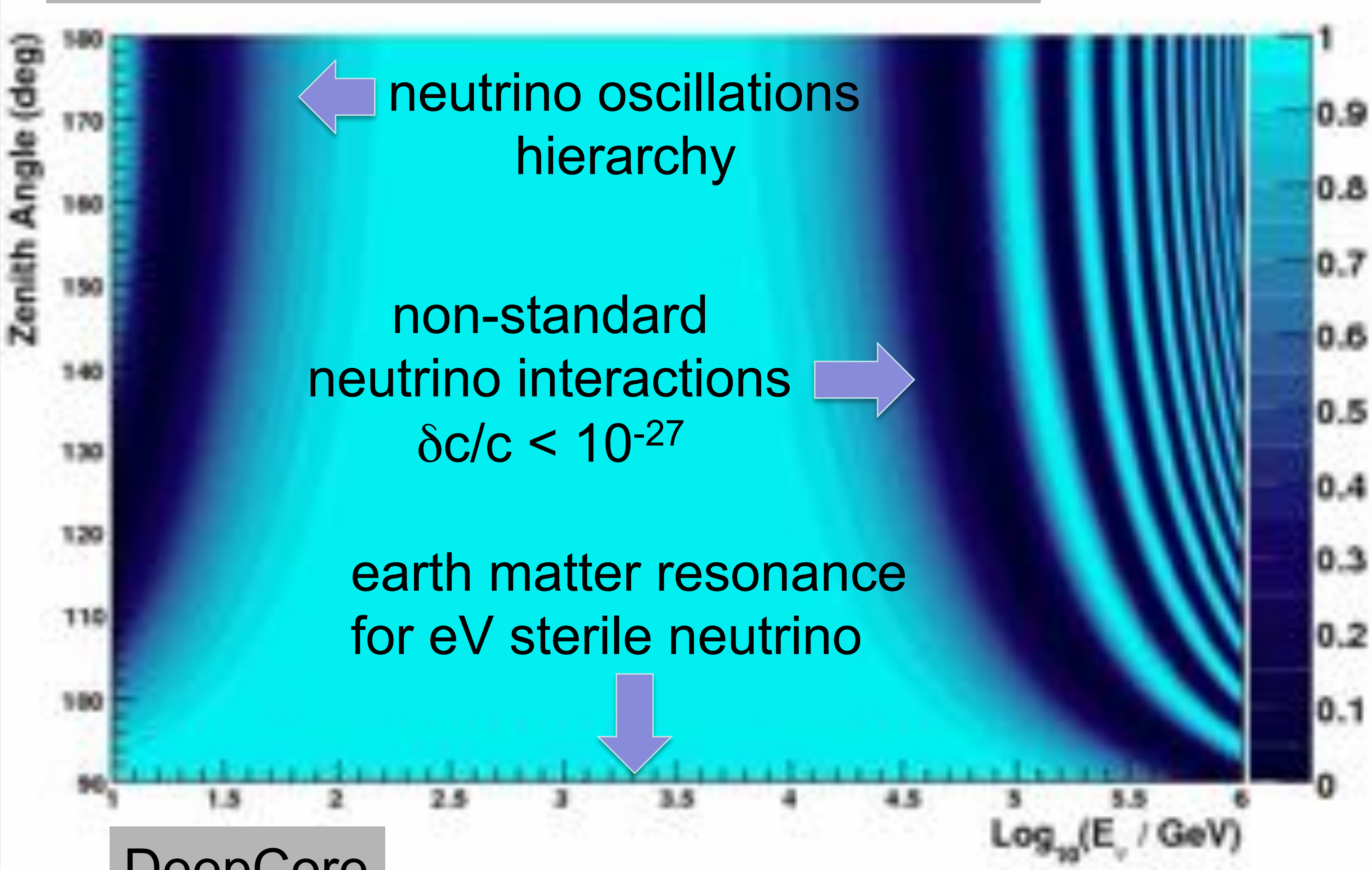
instrumented volume: x 10
same budget as IceCube

ANTARES → KM3NeT

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…

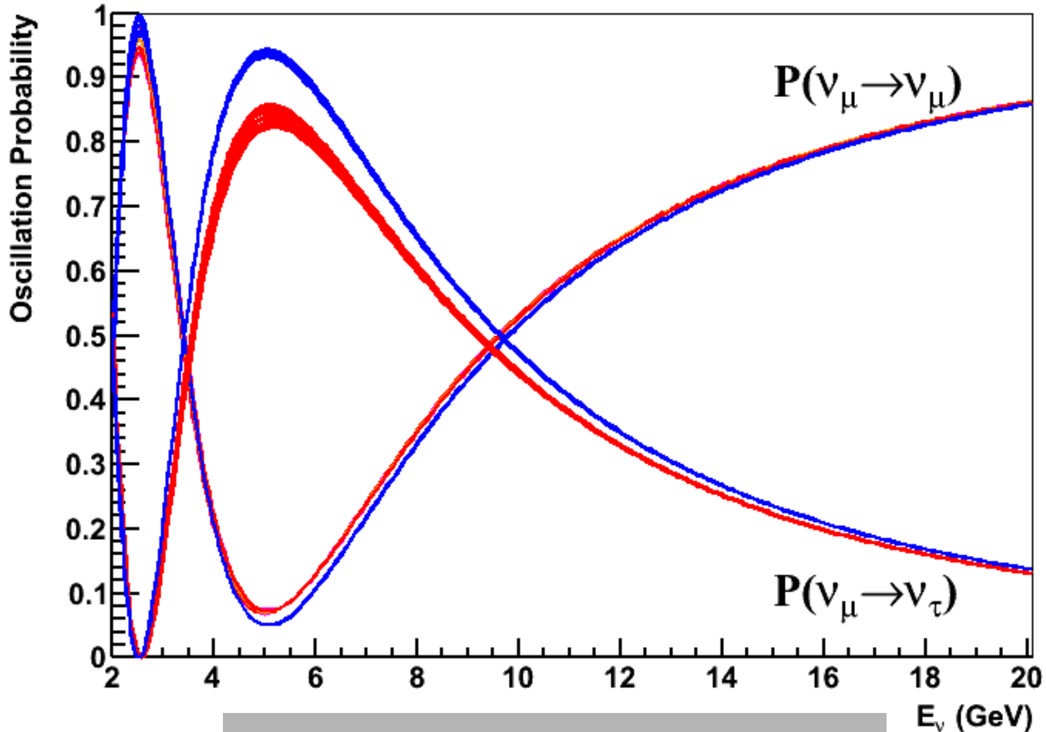


DeepCore

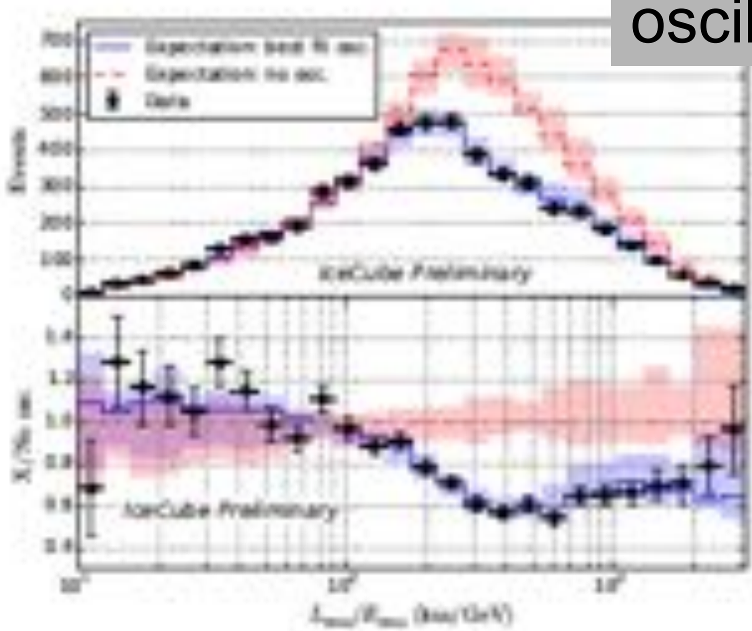
IceCube

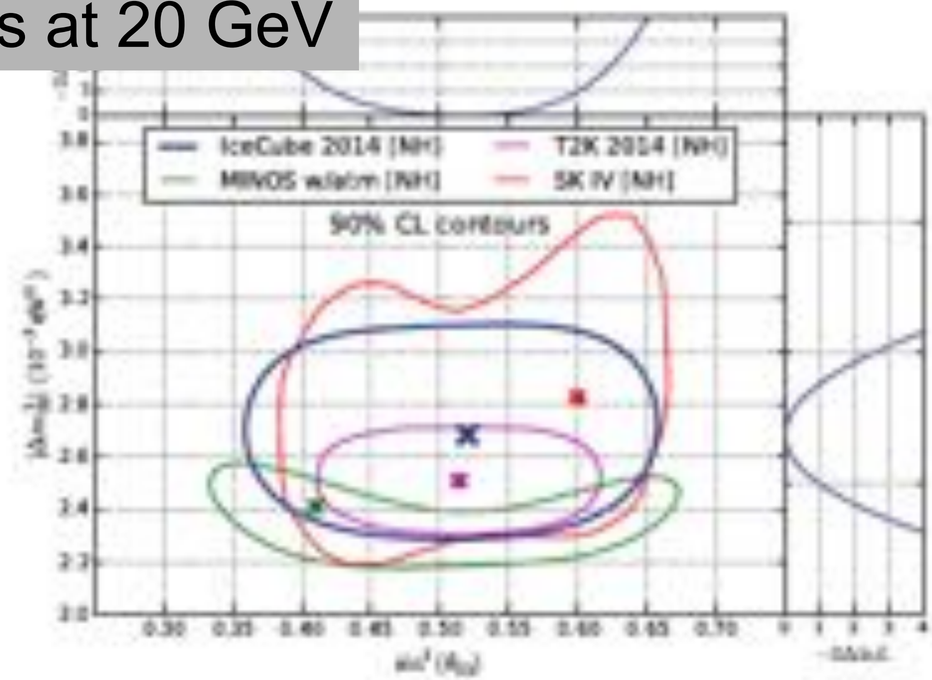
DeepCore

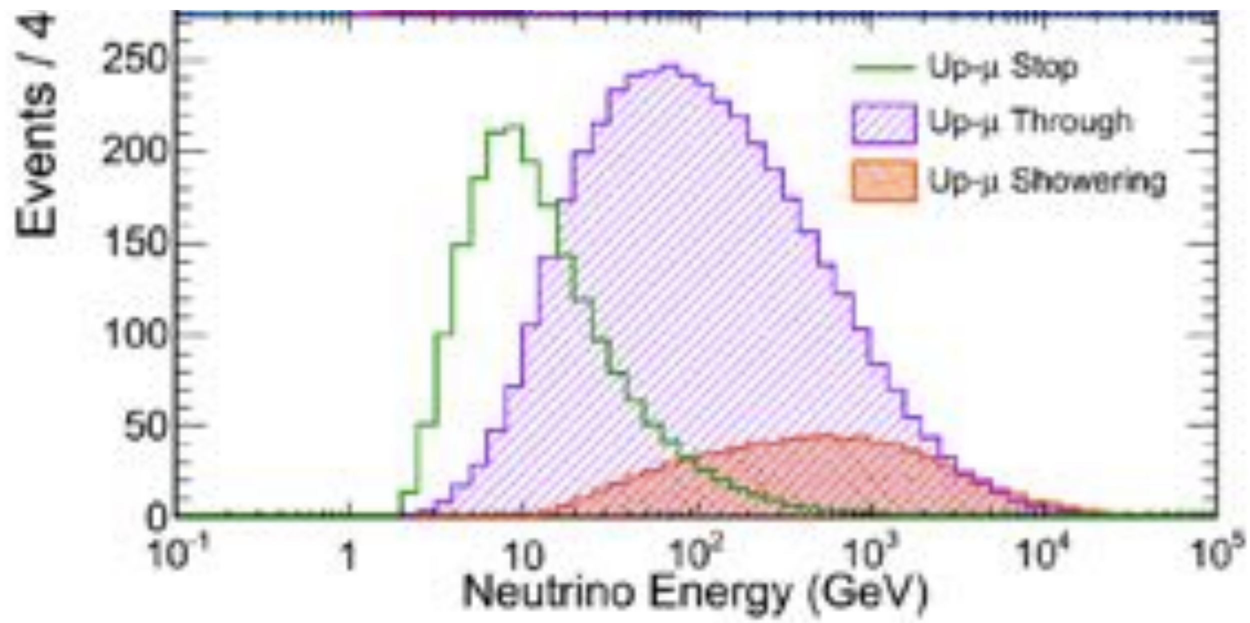
PINGU



oscillations at 20 GeV



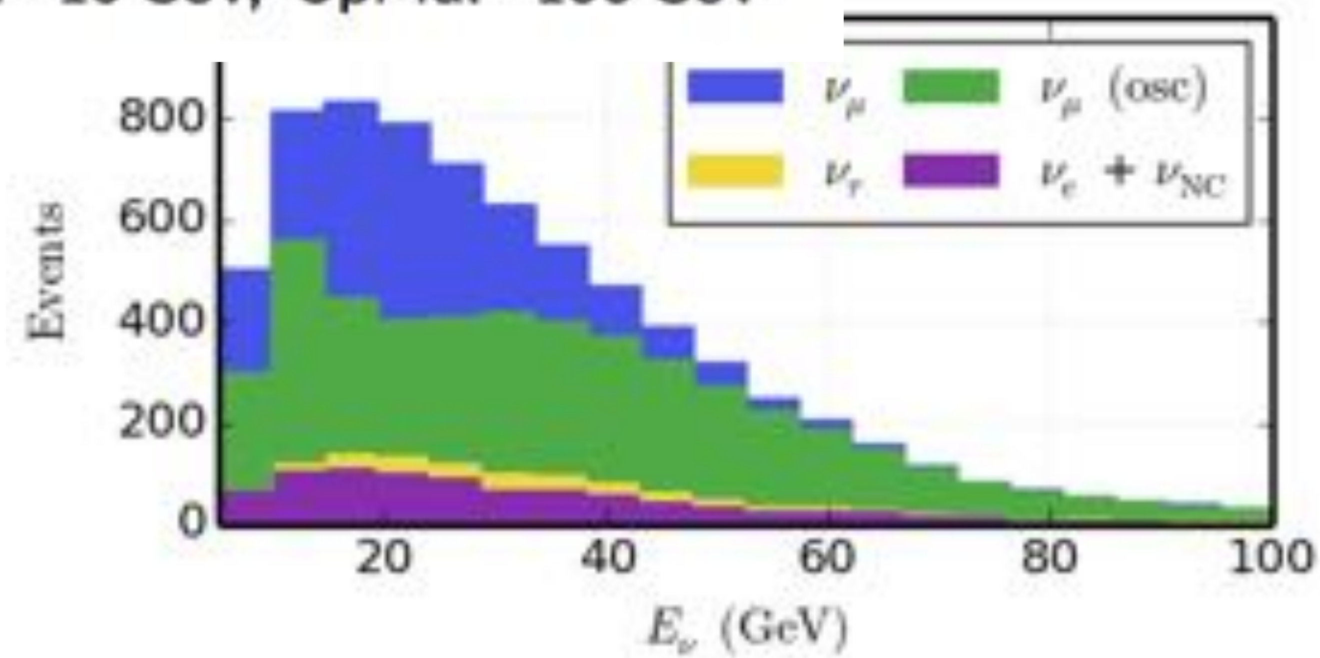




SuperK

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

IceCube



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
University of Alberta–Edmonton (Canada)
University of Toronto (Canada)
Clark Atlanta University (USA)
Drexel University (USA)
Georgia Institute of Technology (USA)
Lawrence Berkeley National Laboratory (USA)
Michigan State University (USA)
Ohio State University (USA)
Pennsylvania State University (USA)
South Dakota School of Mines & Technology (USA)
Southern University and A&M College (USA)
Stony Brook University (USA)
University of Alabama (USA)
University of Alaska Anchorage (USA)
University of California, Berkeley (USA)
University of California, Irvine (USA)
University of Delaware (USA)
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