IceCube: building a new window on the Universe

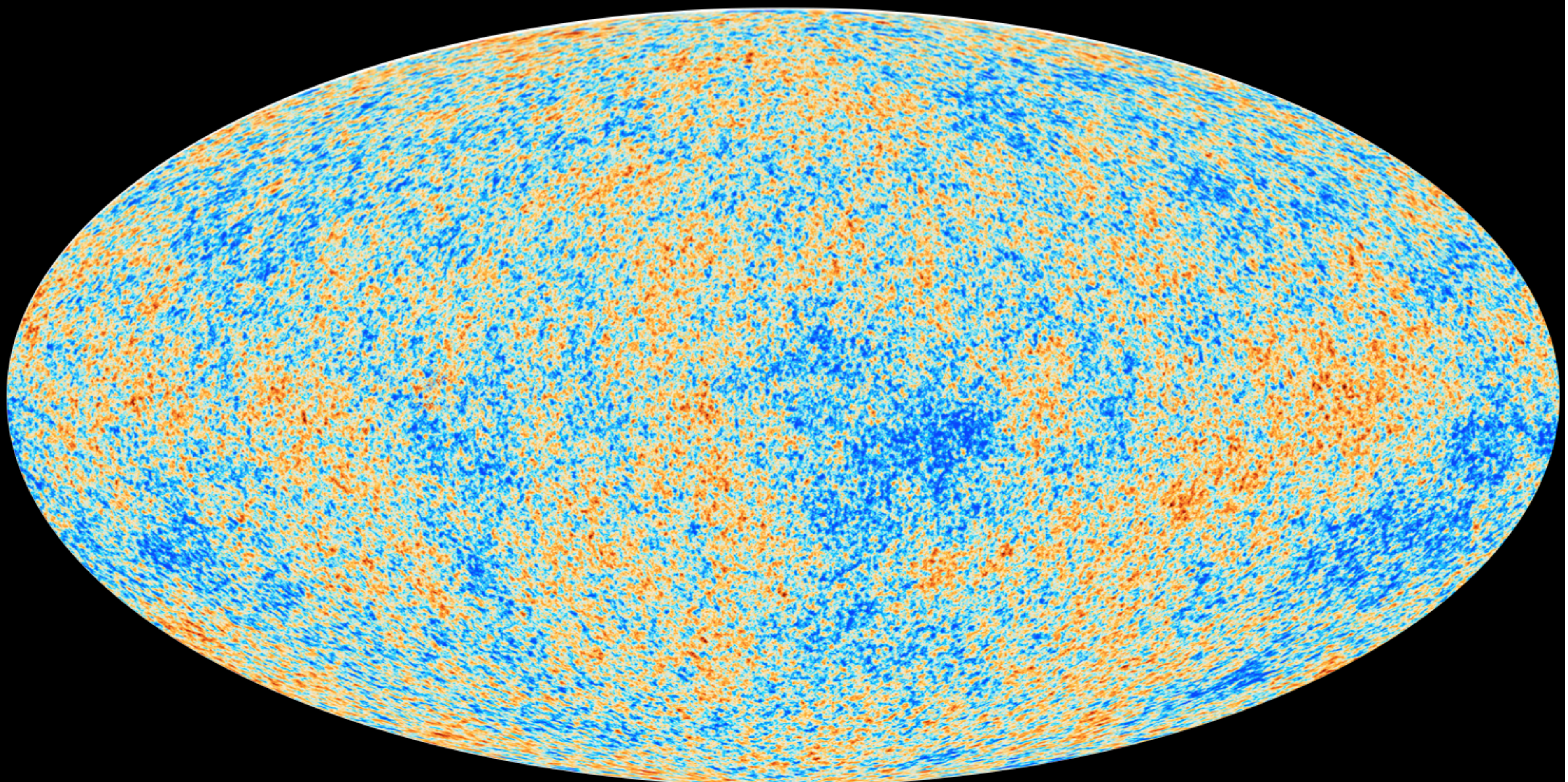
francis halzen

- 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

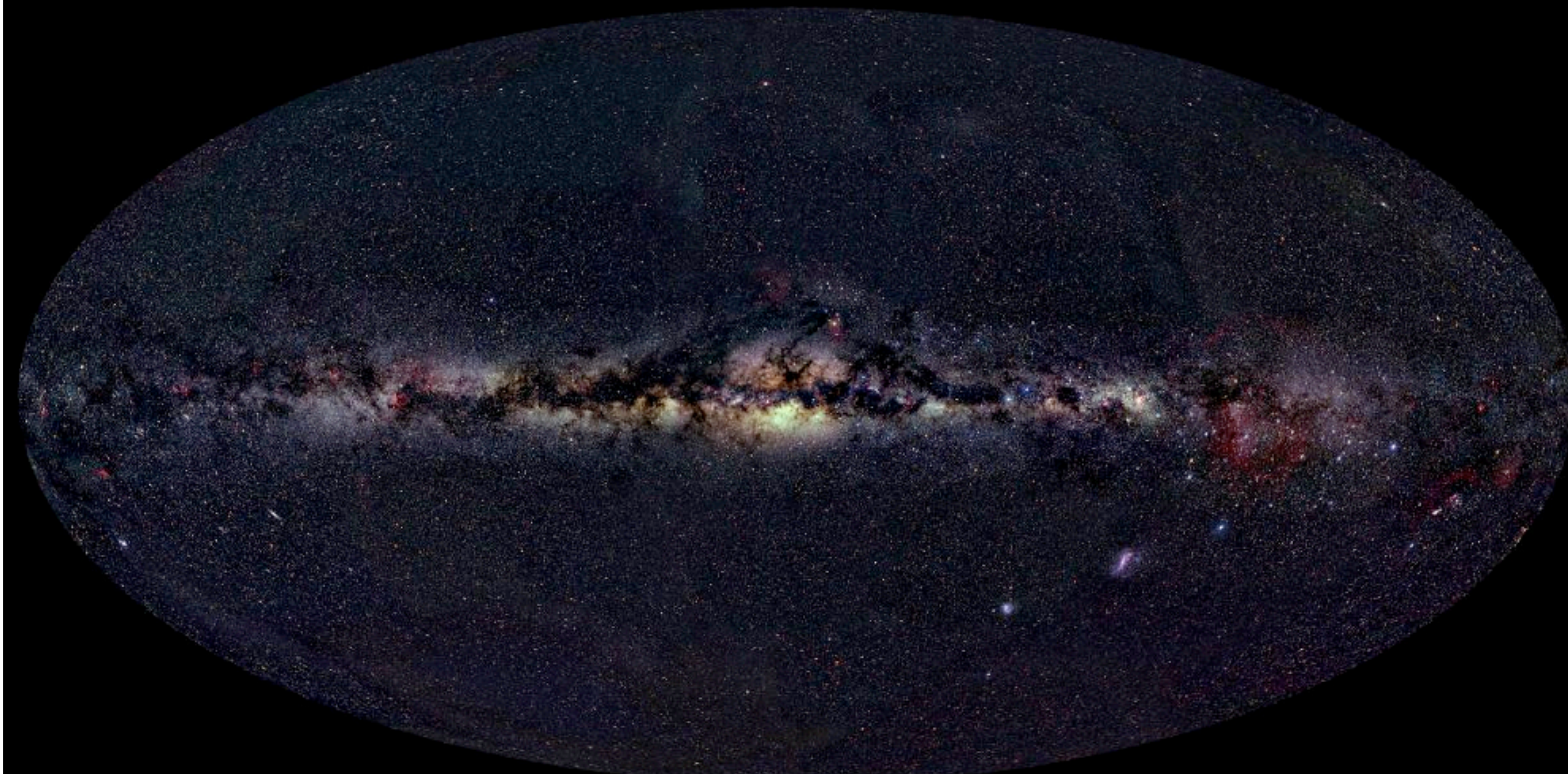
Cosmic Horizons – Microwave Radiation

380.000 years after the Big Bang



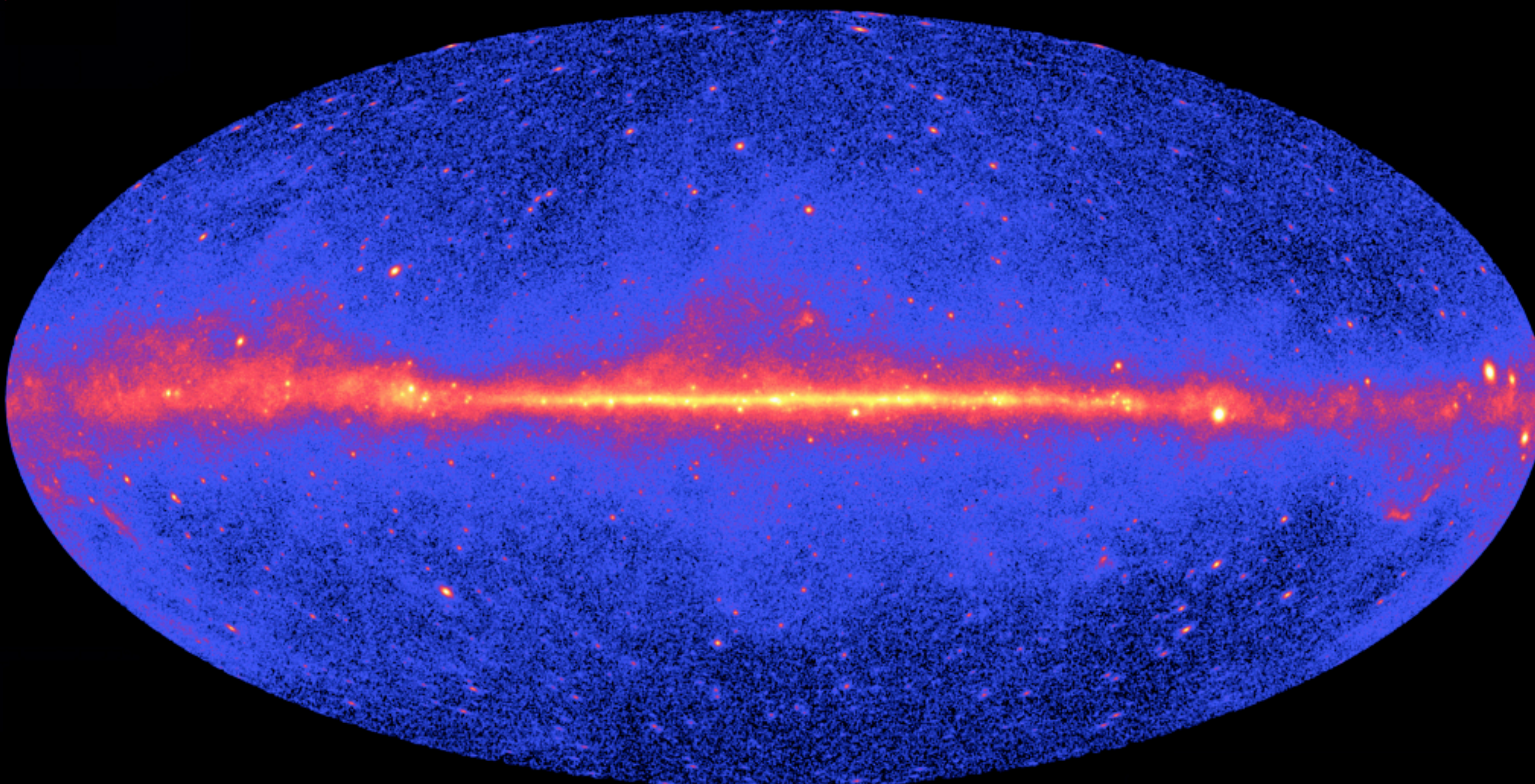
wavelength = 1 mm ⇔ energy = 10^{-4} eV

Cosmic Horizons – Optical Sky



wavelength = 10^{-6} m $\Leftrightarrow$ energy = 1 eV

Cosmic Horizons – Gamma Radiation

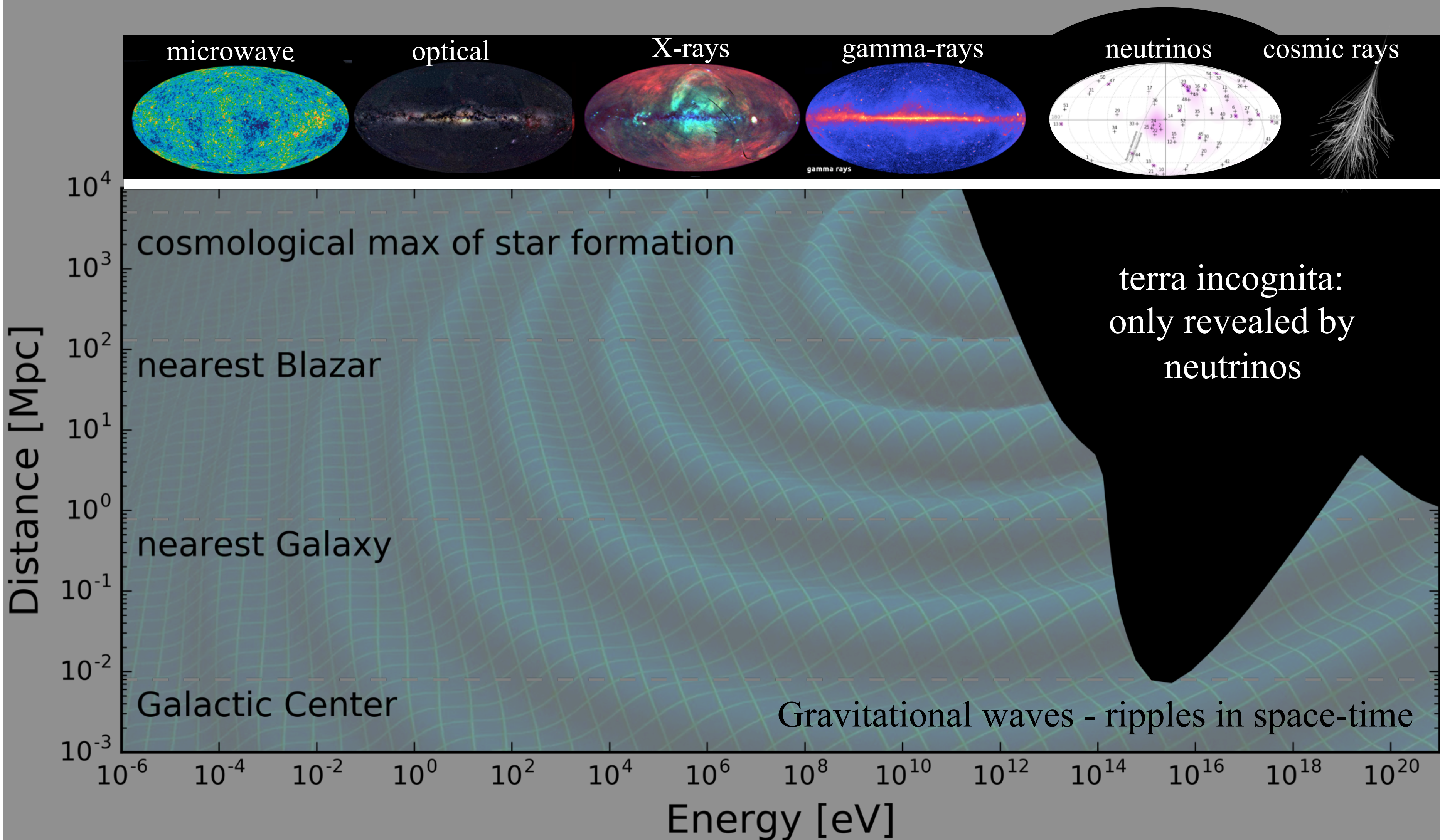


wavelength = 10^{-15} m $\Leftrightarrow$ energy = 10^{9} eV

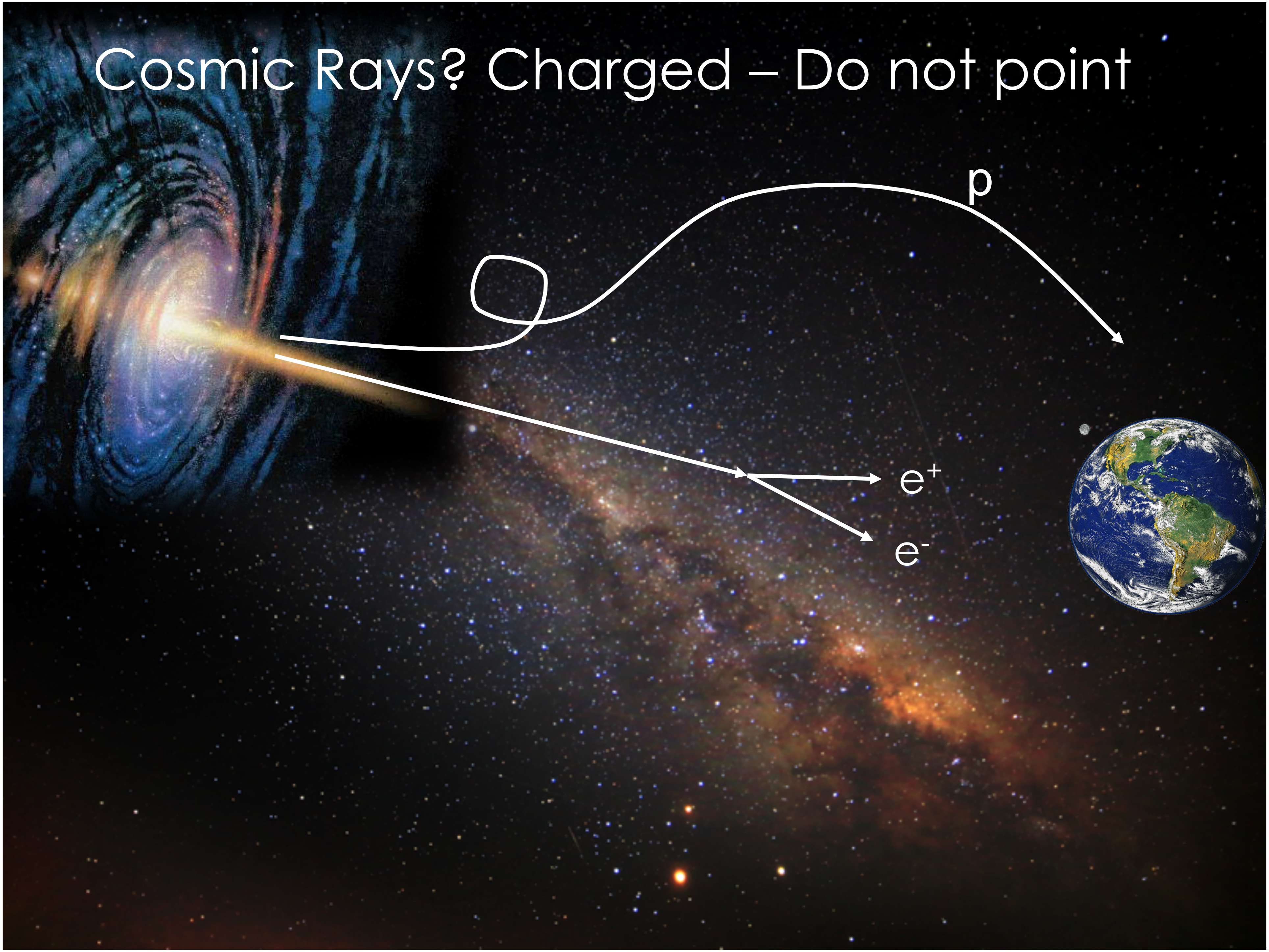
Cosmic Horizons – Gamma Radiation

energy = 10^{15} eV

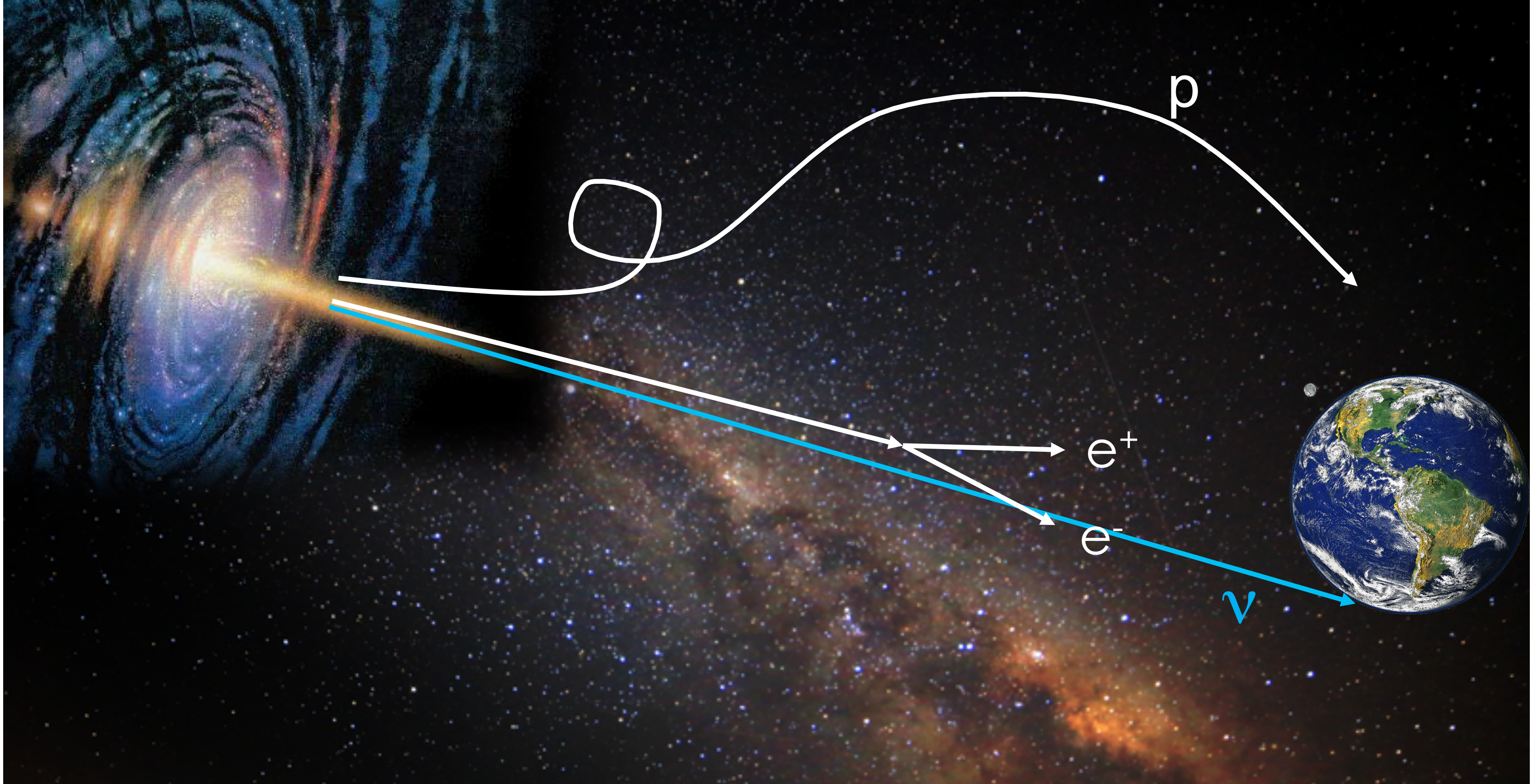
Multi-Messenger Astronomy



20% of the Universe is opaque to the EM spectrum

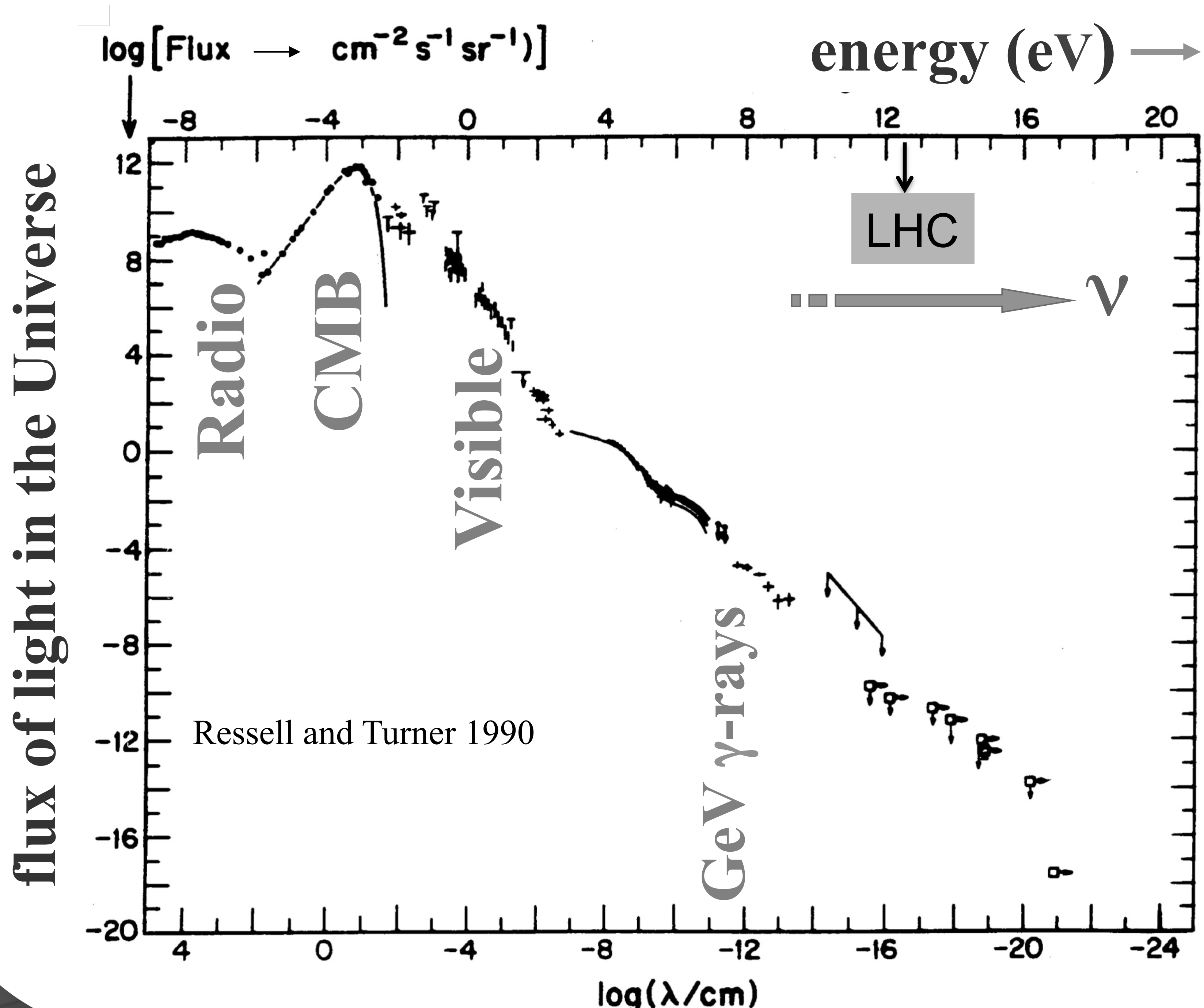

Cosmic Rays? Charged – Do not point
p
e+
e-

Neutrinos? Perfect Messenger

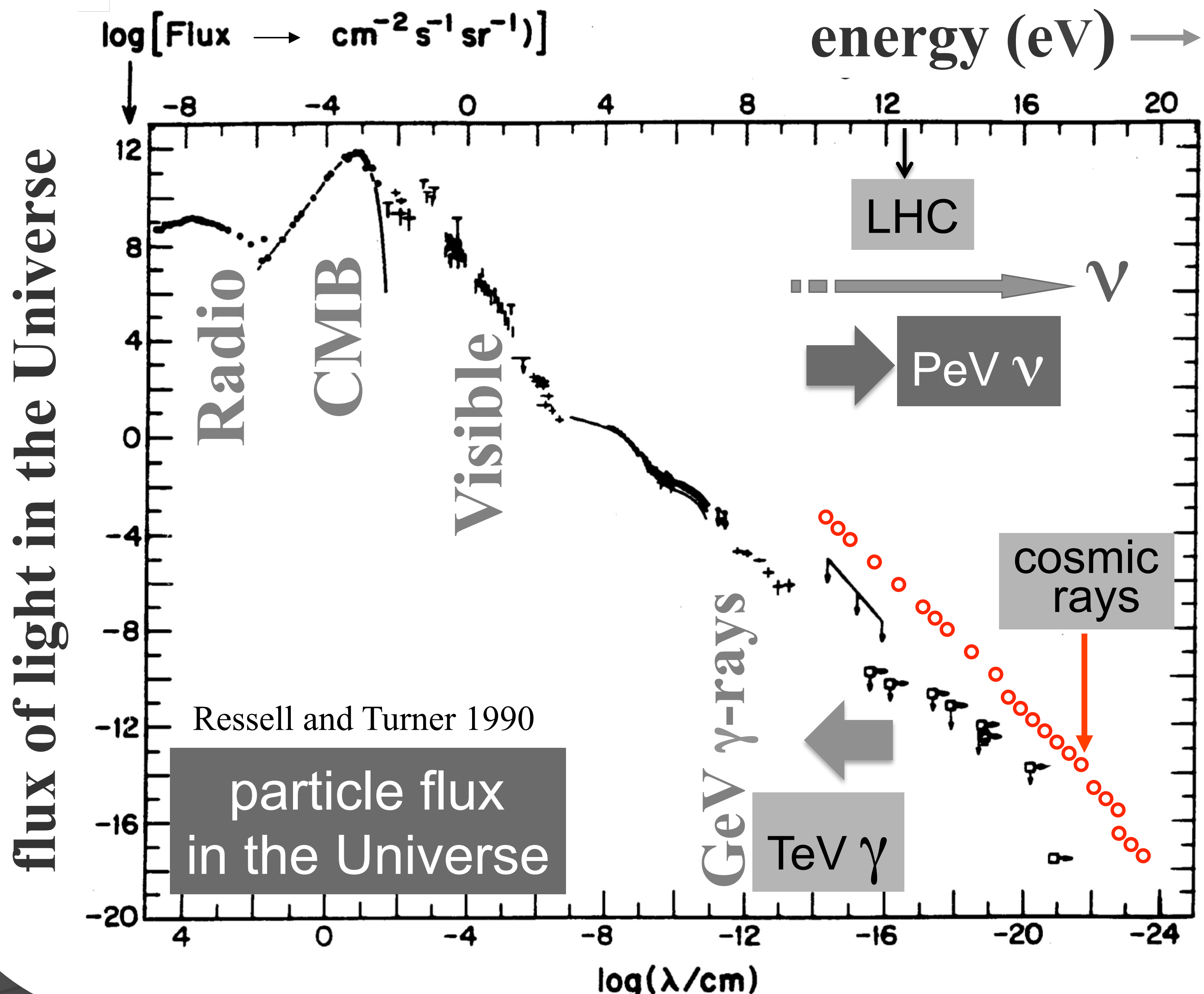


neutrinos do not interact and image the sky in regions from which even X-rays cannot escape neutrino as a cosmic messenger:

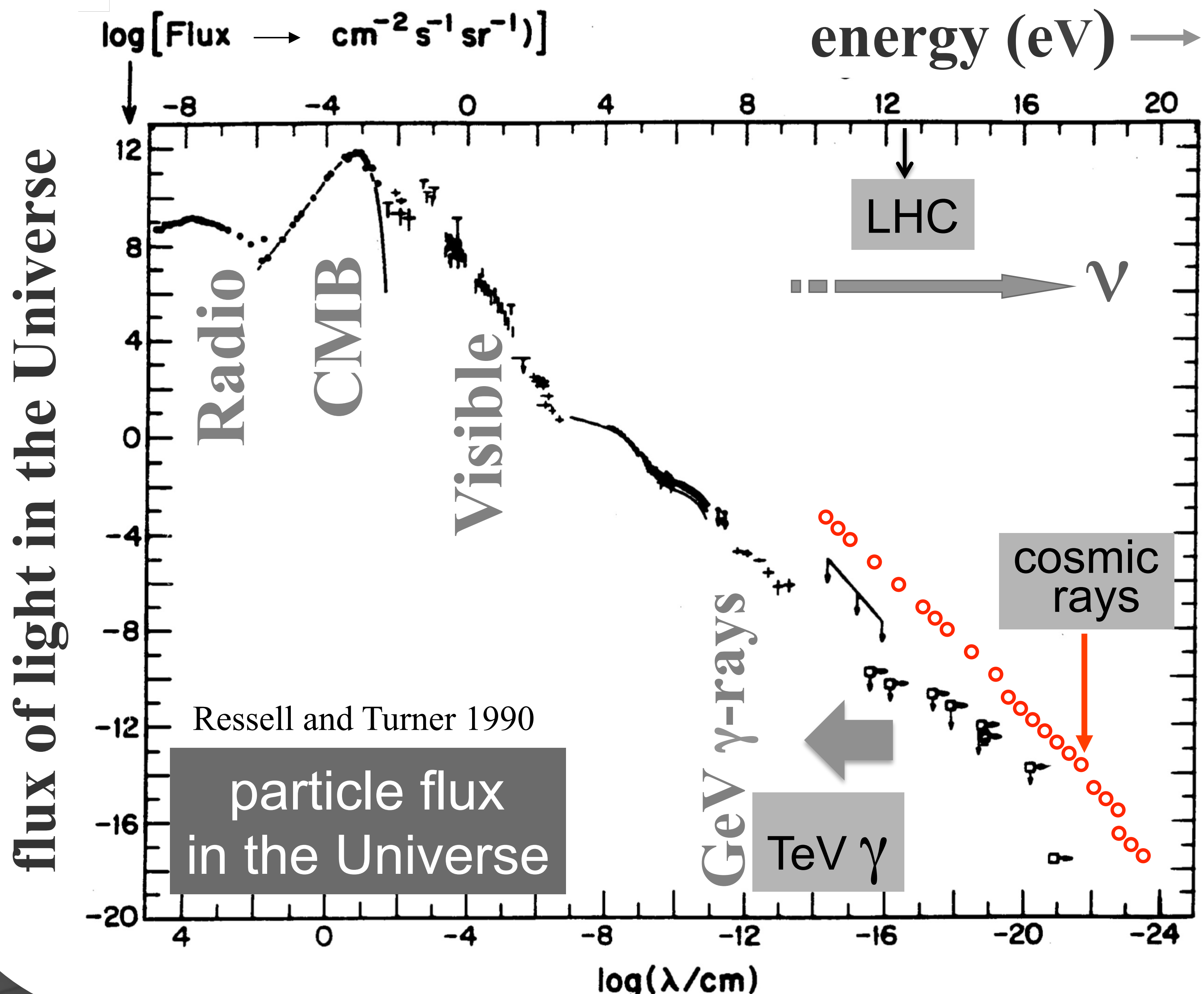
- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
  $(n \rightarrow p + e + \nu_e)$
- … but difficult to detect



log[Flux → cm^-2 s^-1 sr^-1)]
energy (eV)
LHC
ν
Radio
CMB
Visible
GeV γ-rays
flux of light in the Universe
Ressell and Turner 1990
log(λ/cm)



log[Flux → cm^-2 s^-1 sr^-1)]
energy (eV)
-8
-4
0
4
8
12
16
20
LHC
ν
PeV ν
Radio
CMB
Visible
GeV γ-rays
cosmic rays
TeV γ
flux of light in the Universe
Ressell and Turner 1990
particle flux
in the Universe
12
8
4
0
-4
-8
-12
-16
-20
4
0
-4
-8
-12
-16
-20
-24
log(λ/cm)



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
LHC
ν
Radio
CMB
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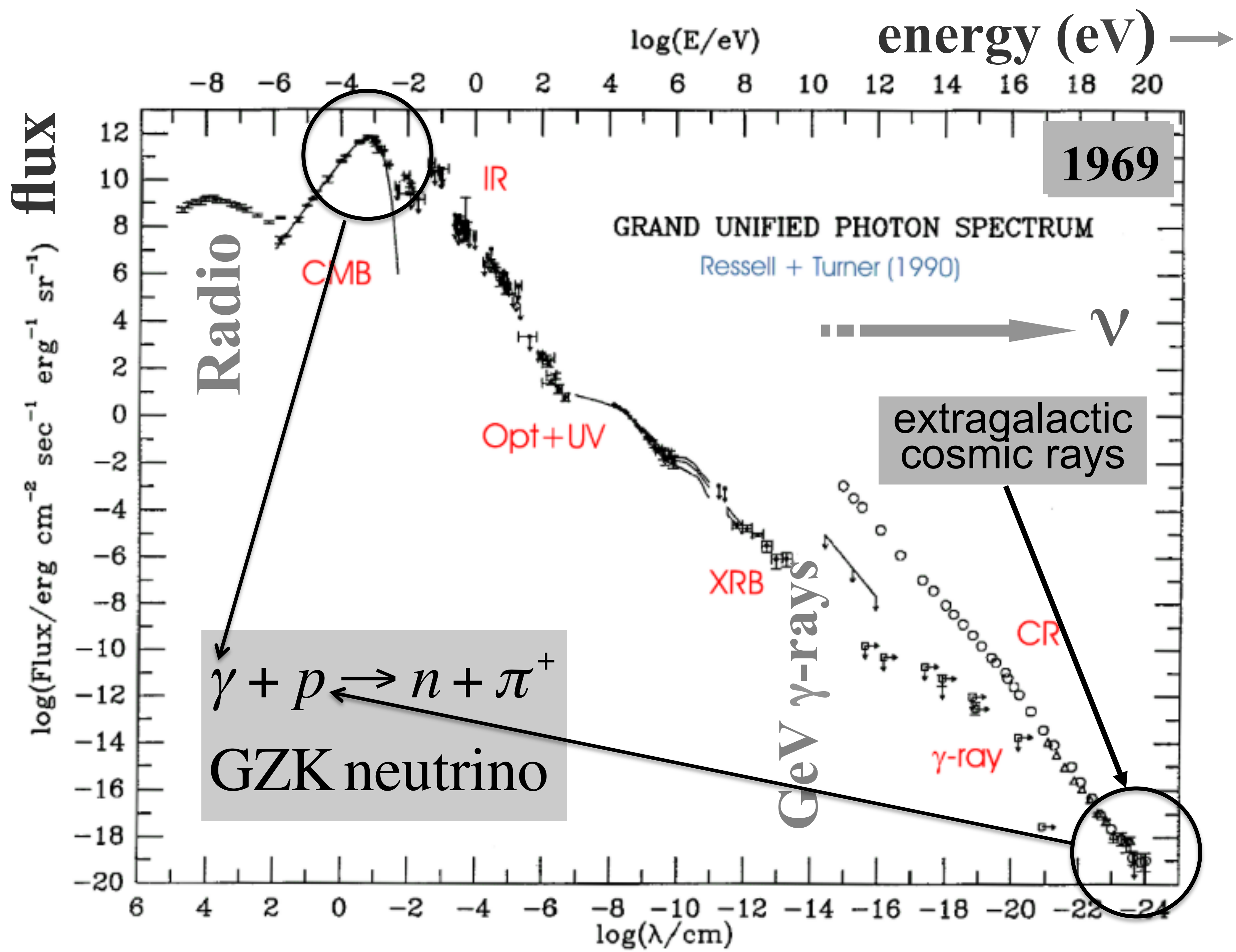
cosmic rays
TeV γ
Ressell and Turner 1990
particle flux in the Universe
flux of light in the Universe
4
0
-4
-8
-12
-16
-20
-24
log(λ/cm)


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

cosmic rays interact with the microwave background

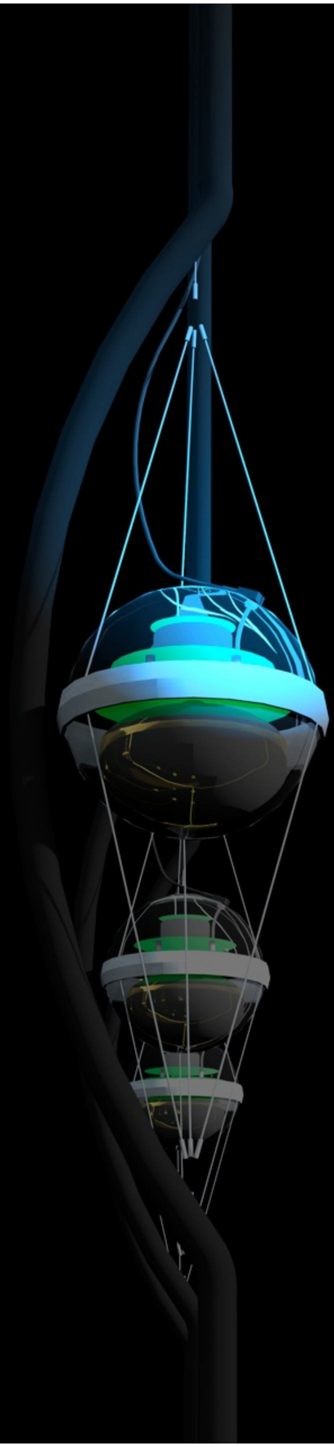
$$p+\gamma \rightarrow n+\pi^{+} \ and \ p+\pi^{0}$$

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

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

1 event per $\boxed{\text{cubic kilometer}}$ per year

...but it points at its source!



IceCube: building a new window on the Universe

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

the sun constructs an accelerator

- accelerator must contain the particles

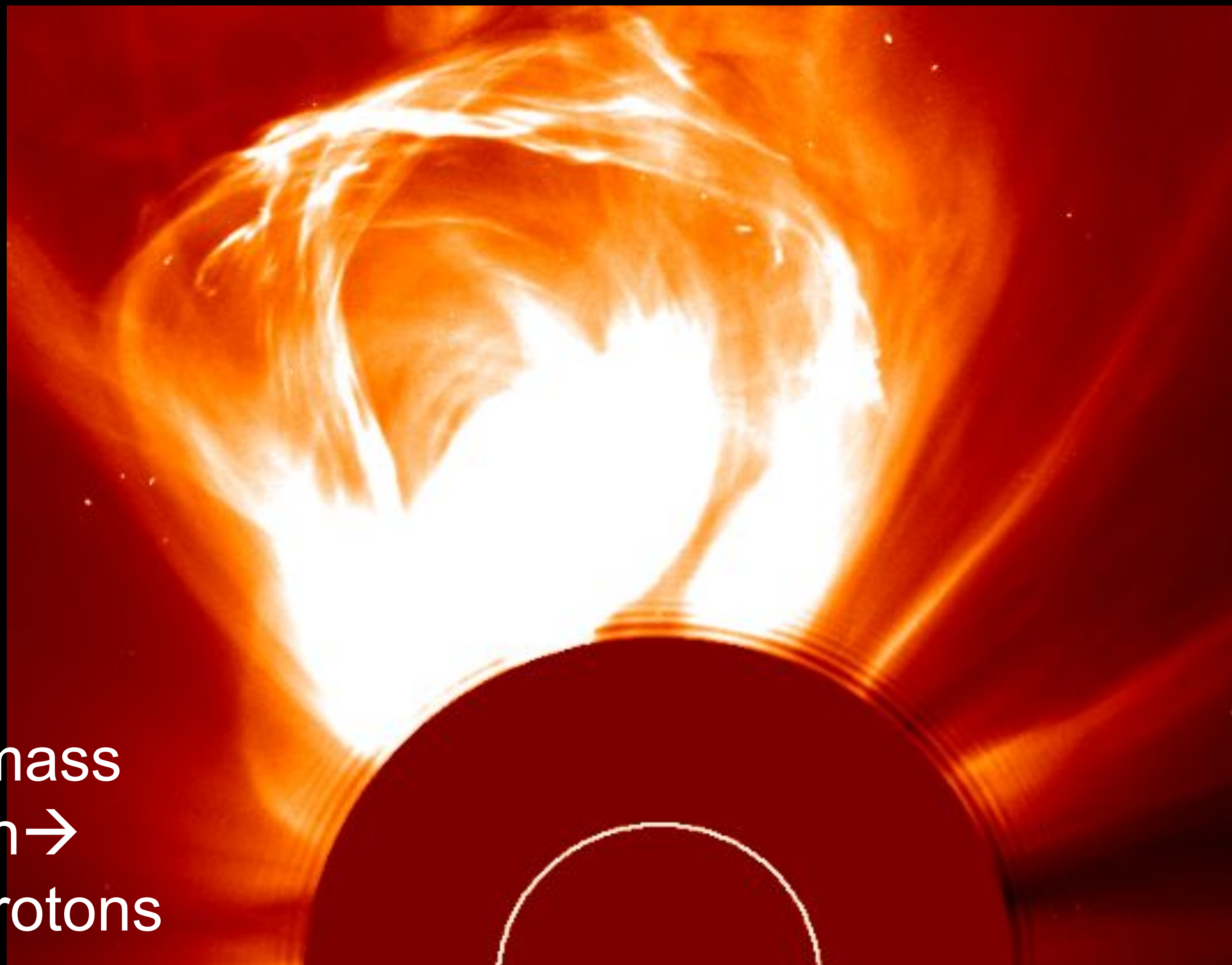
$$R_{gyro} \left(= \frac{E}{\mathrm{v}qB}\right) \leq R$$

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

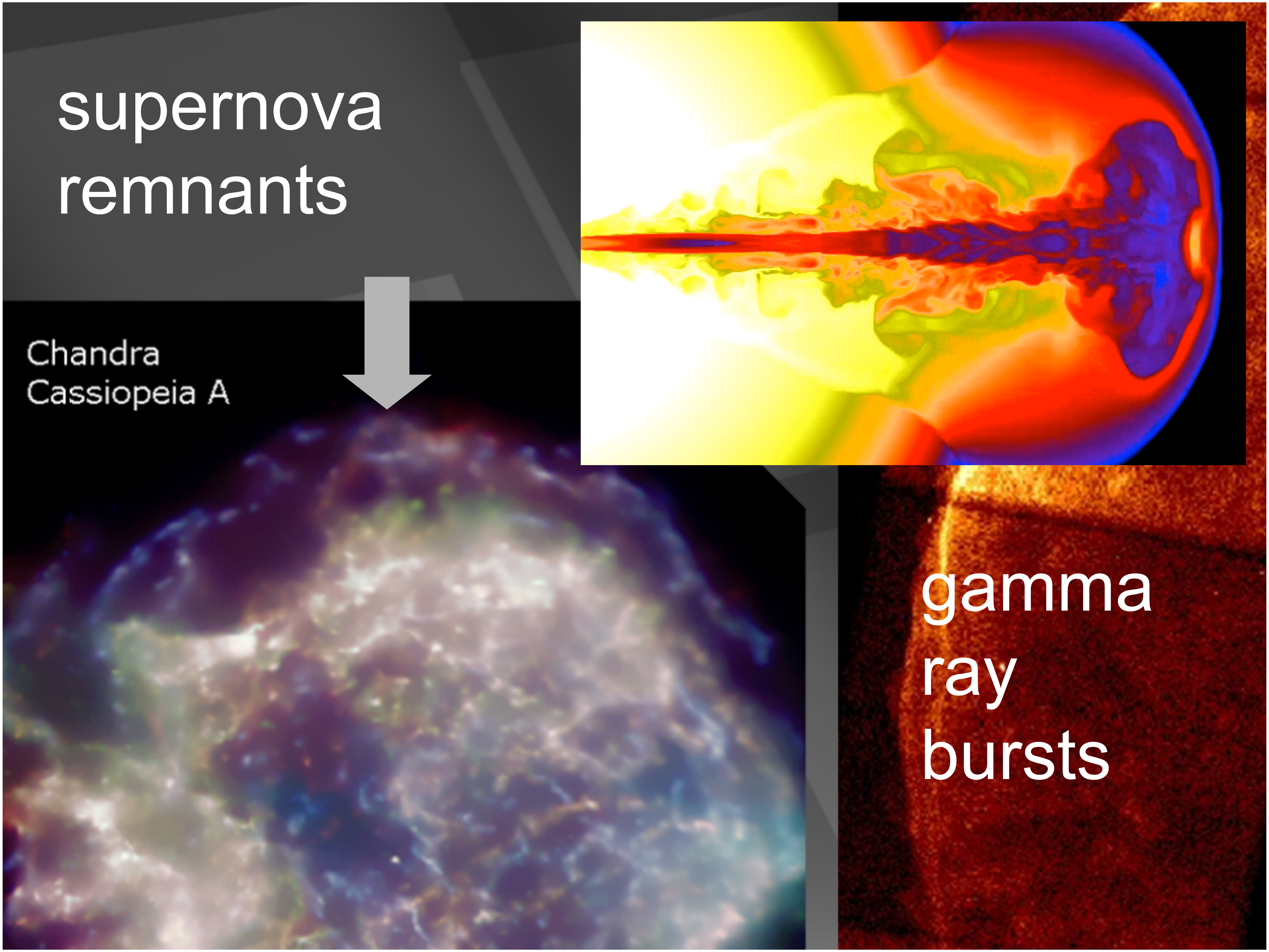
challenges of cosmic ray astrophysics:

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

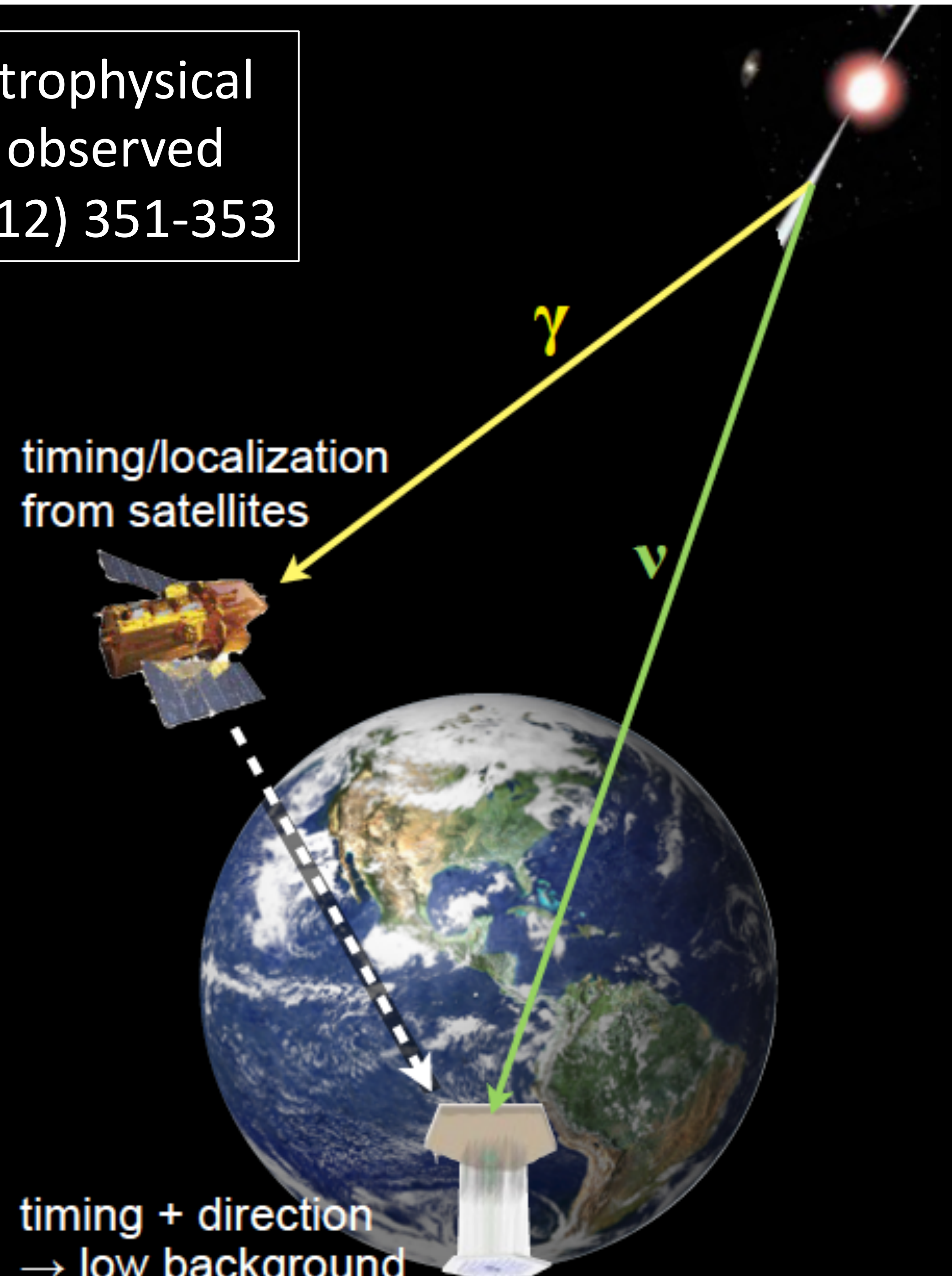
the sun constructs an accelerator

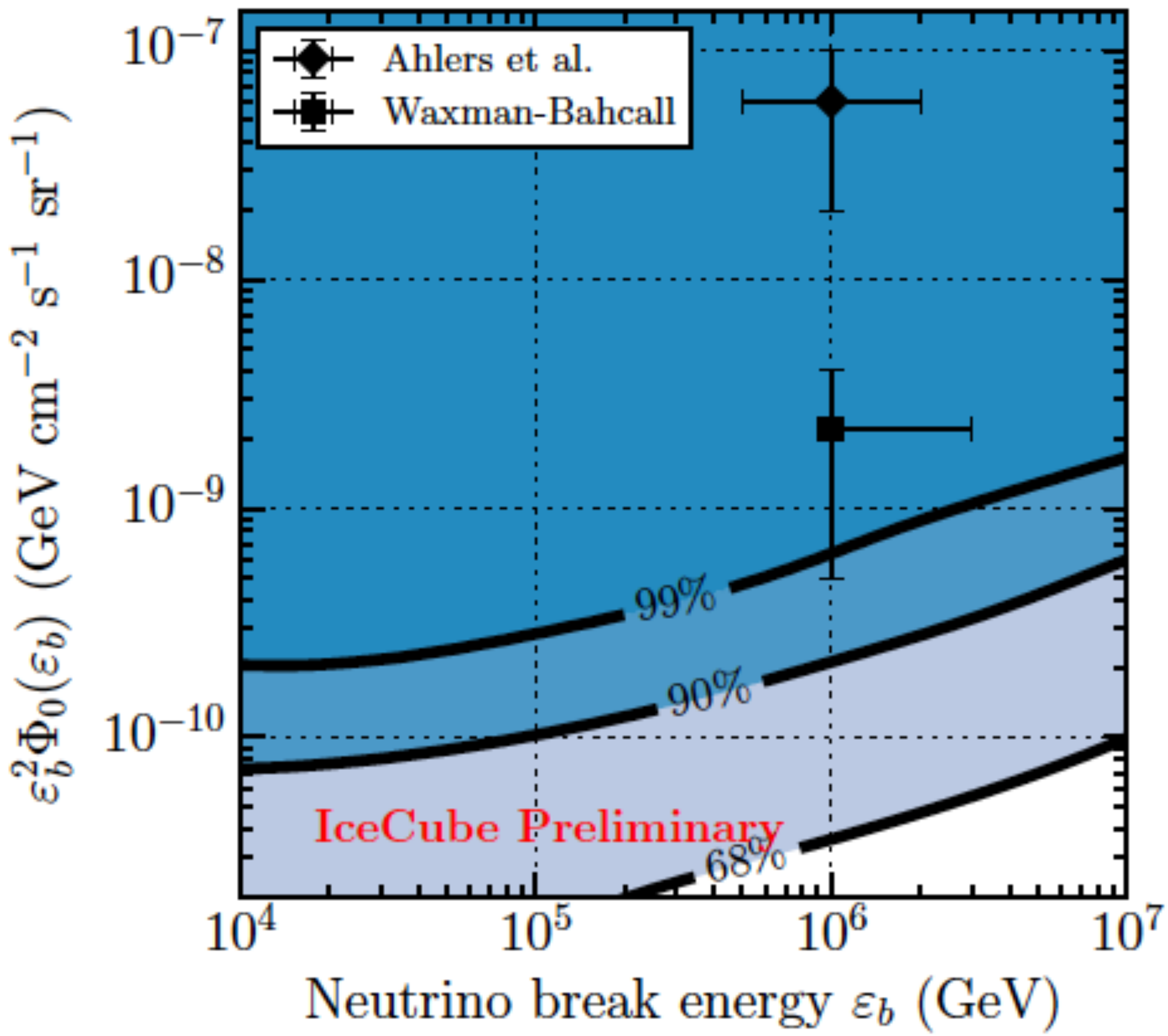


coronal mass
ejection→
10 GeV protons

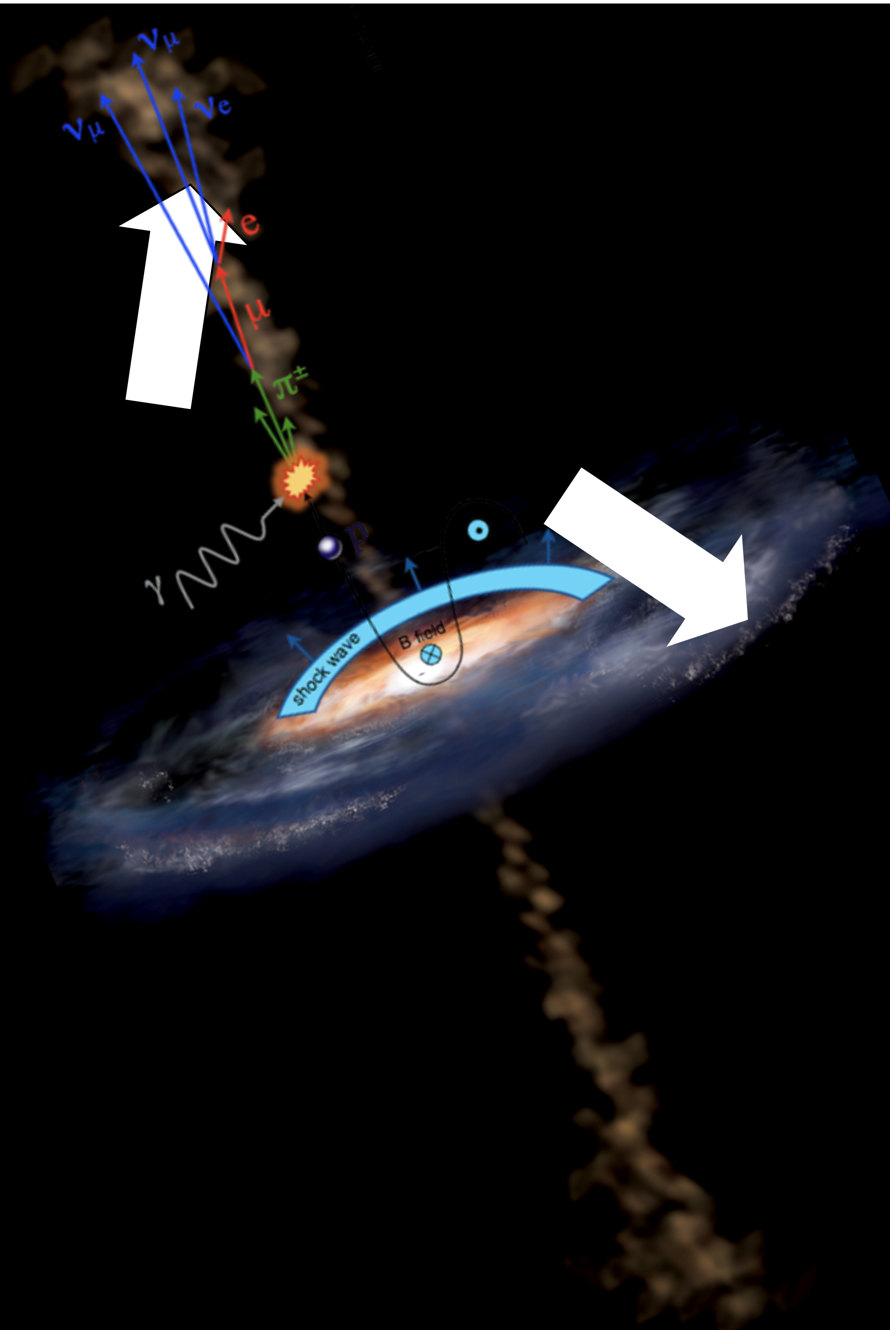

supernova
remnants
Chandra
Cassiopeia A
gamma
ray
bursts

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





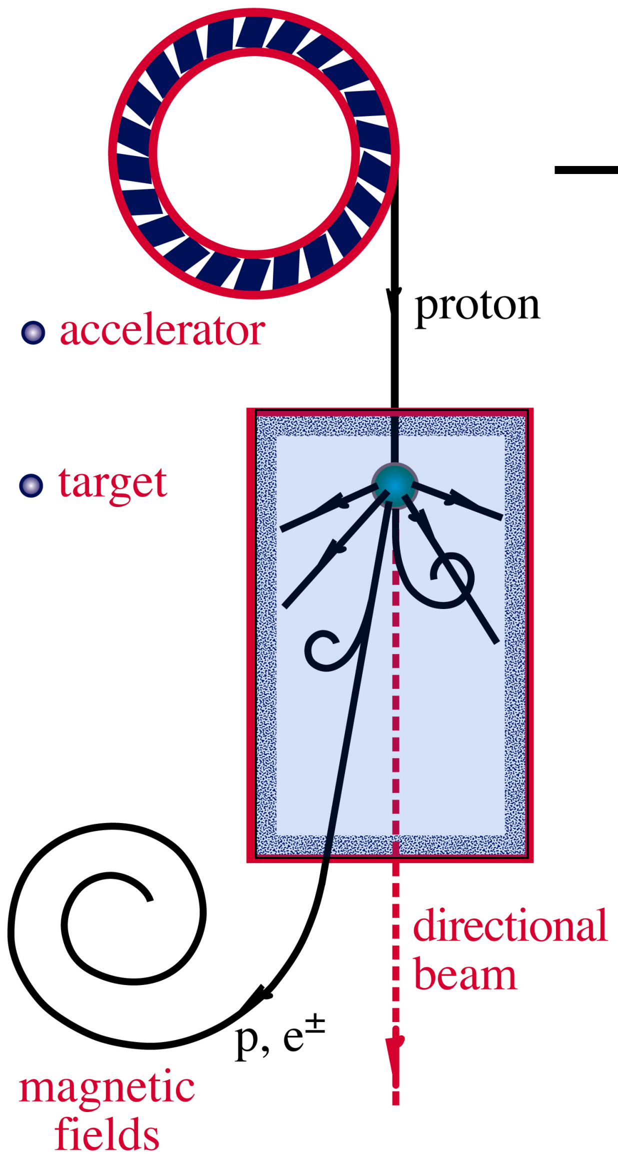
Ahlers et al.
Waxman-Bahcall
99%
90%
68%
IceCube Preliminary
10^{-7}
10^{-8}
10^{-9}
10^{-10}
$\varepsilon_b^2 \Phi_0(\varepsilon_b)$ (GeV cm^{-2} s^{-1} sr^{-1})
10^4
10^5
10^6
10^7
Neutrino break energy ε_b (GeV)



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

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

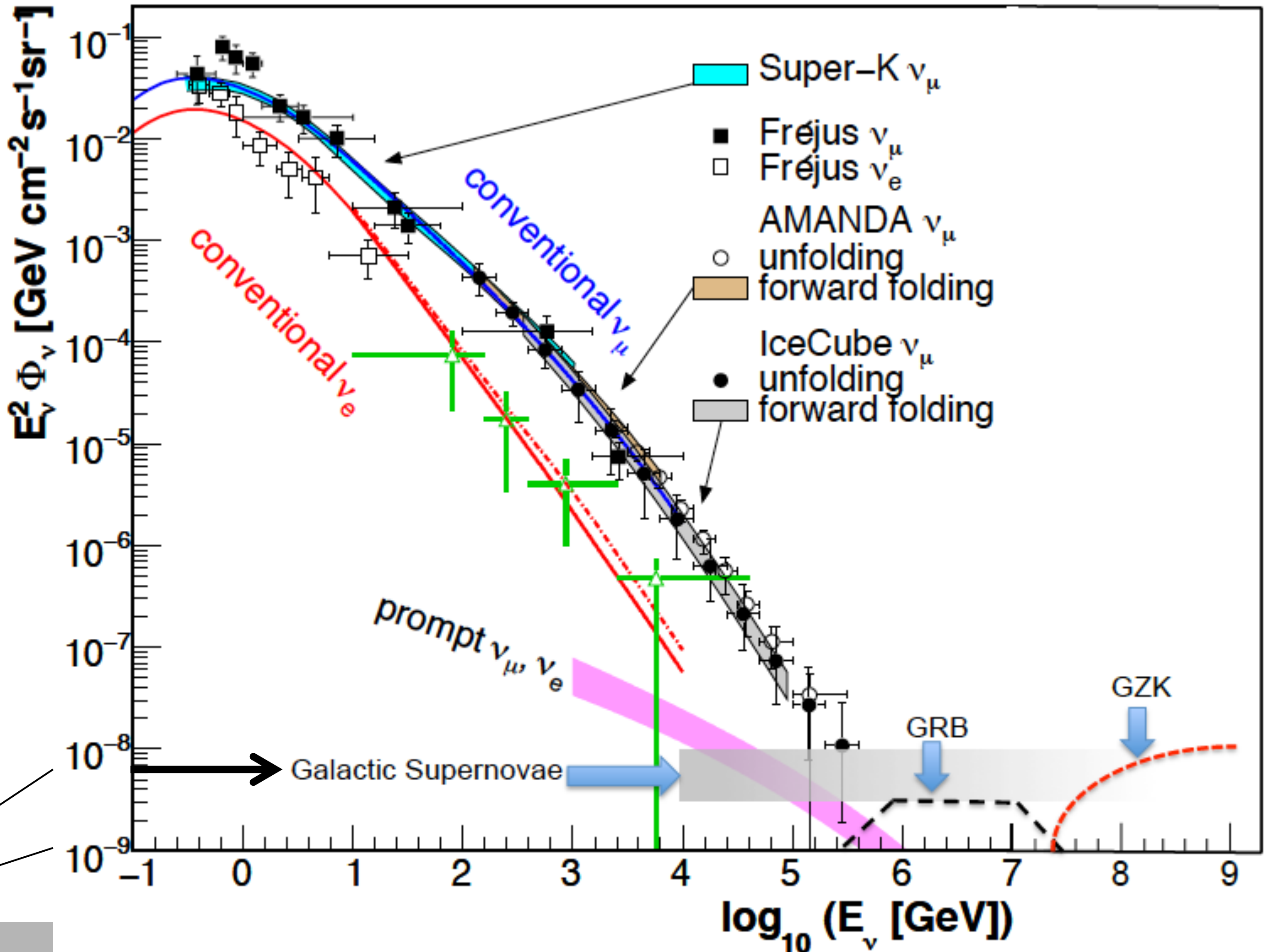
~ cosmic ray + gamma

above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

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

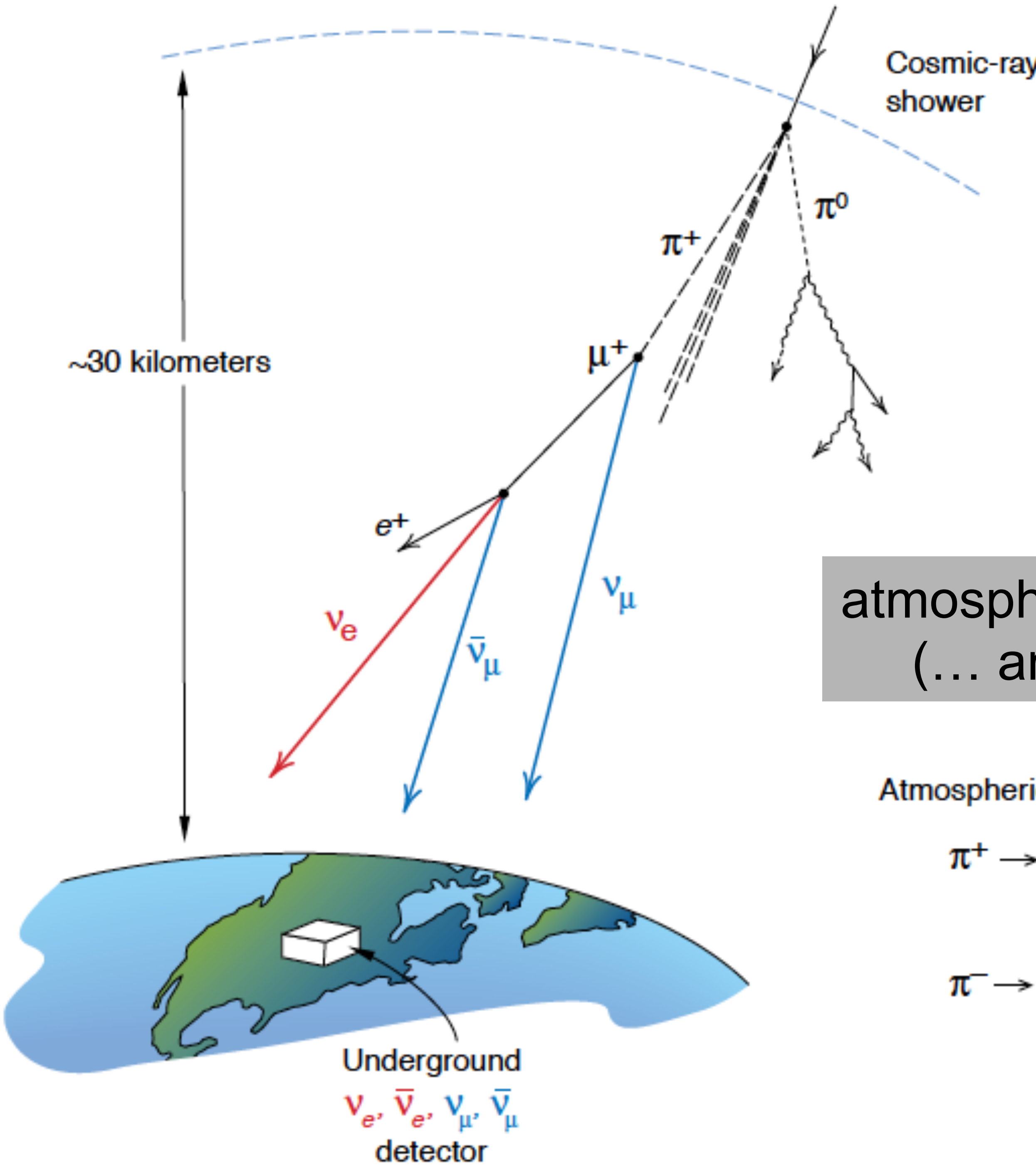
10—100 events per year for fully efficient 1 km^3 detector



atmospheric

cosmic

100 TeV

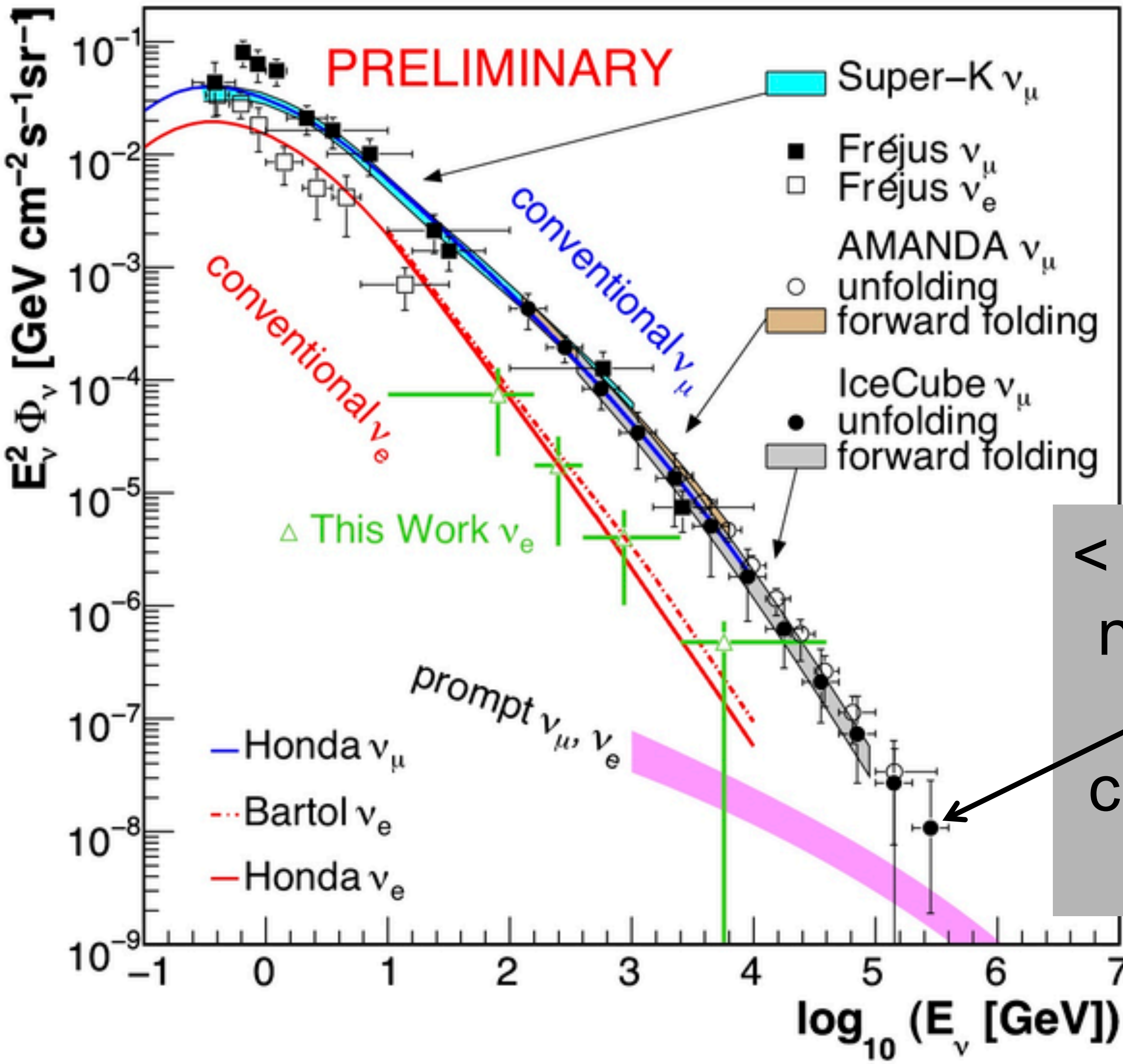


atmospheric neutrinos
(… and muons!)

Atmospheric neutrino source

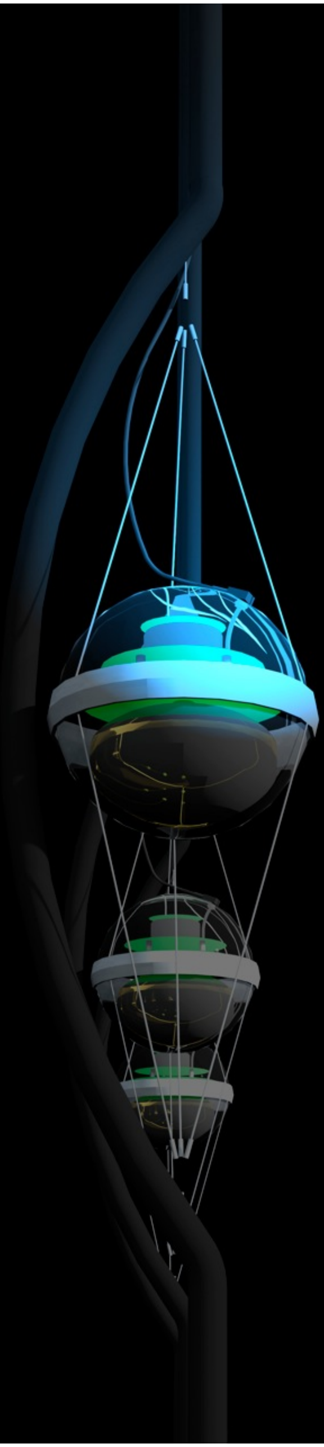
$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\quad \hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

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



< 1 atmospheric neutrino event per cubic kilometer per year

atmospheric neutrino spectrum



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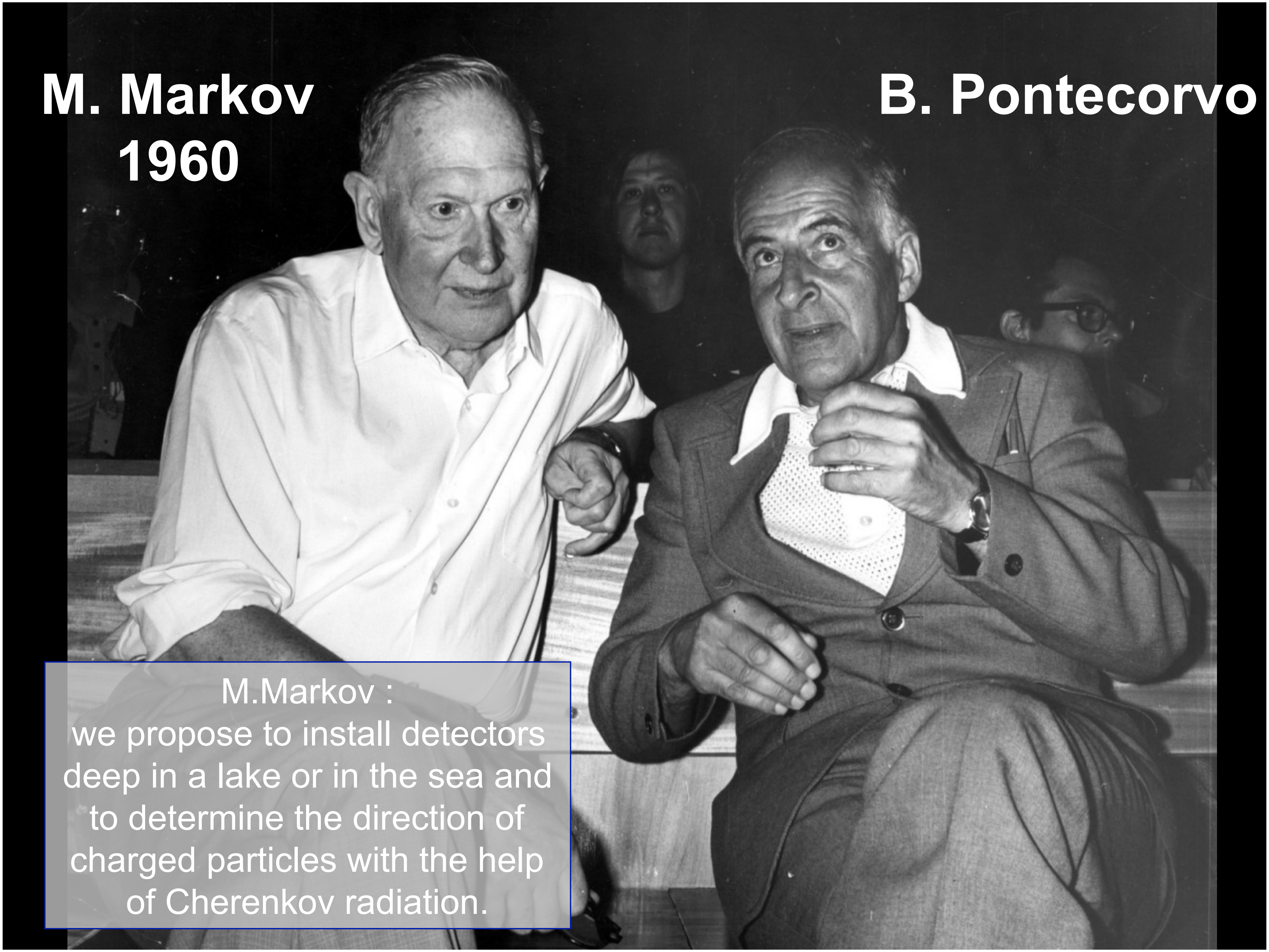
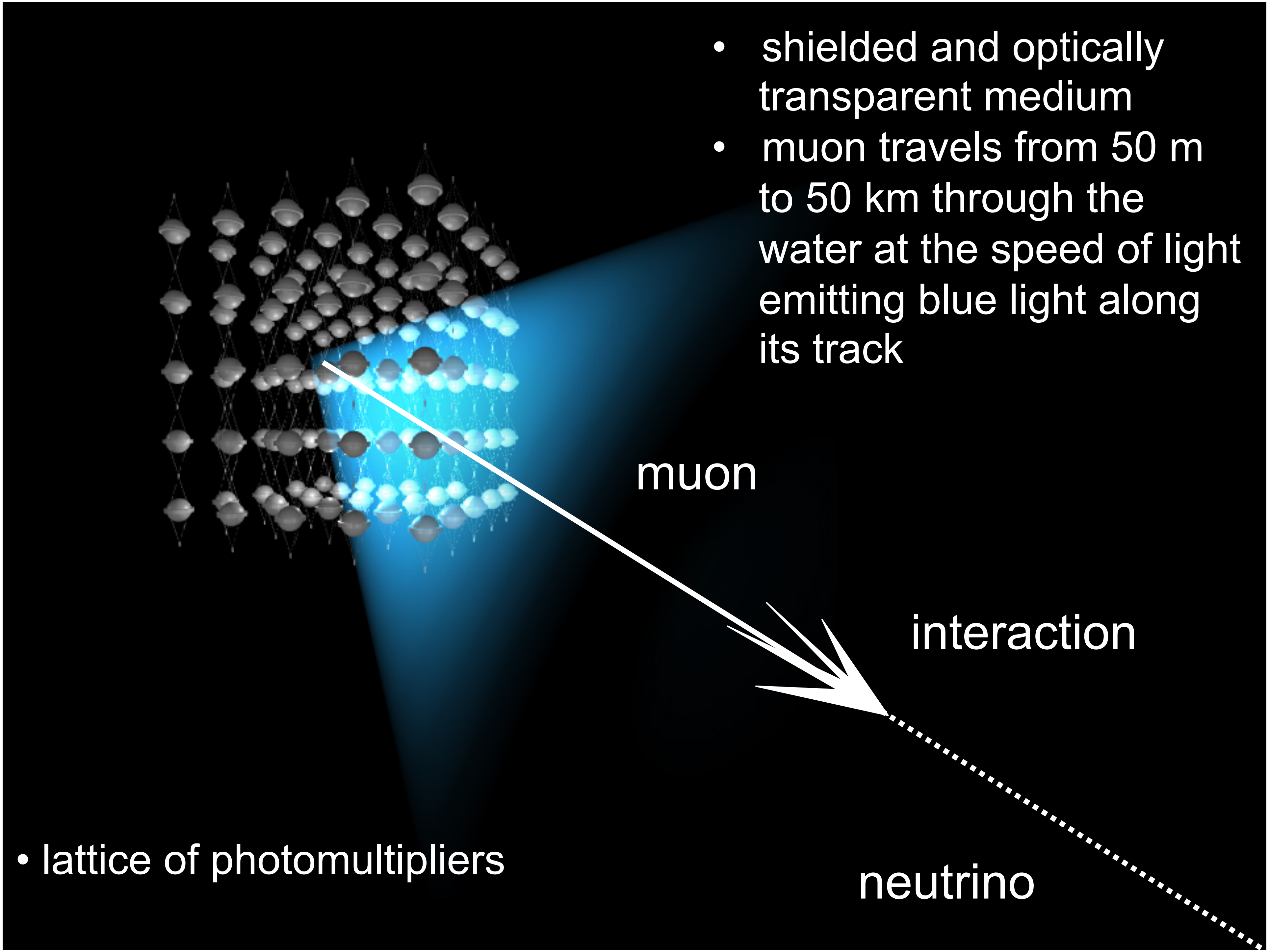
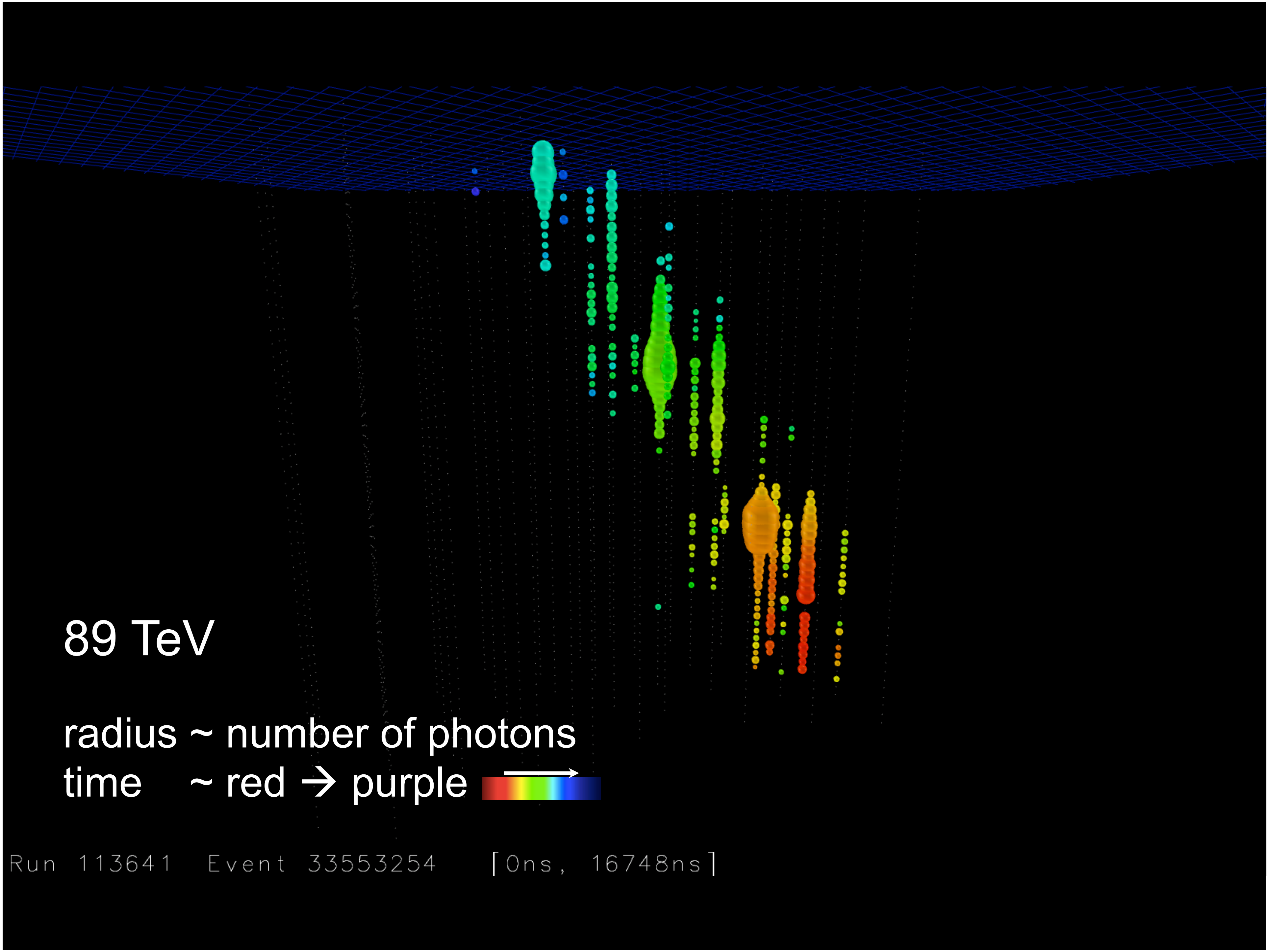
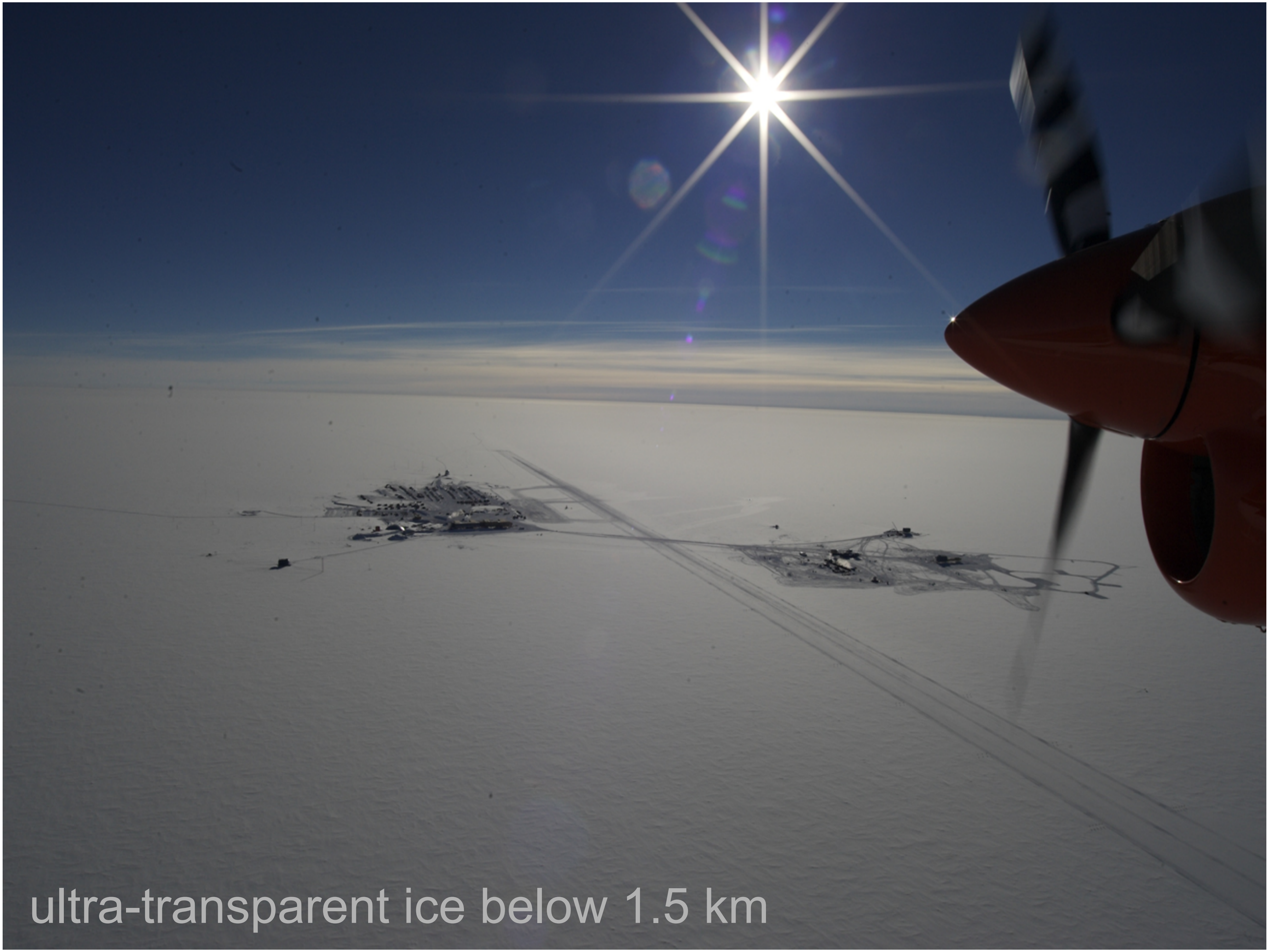
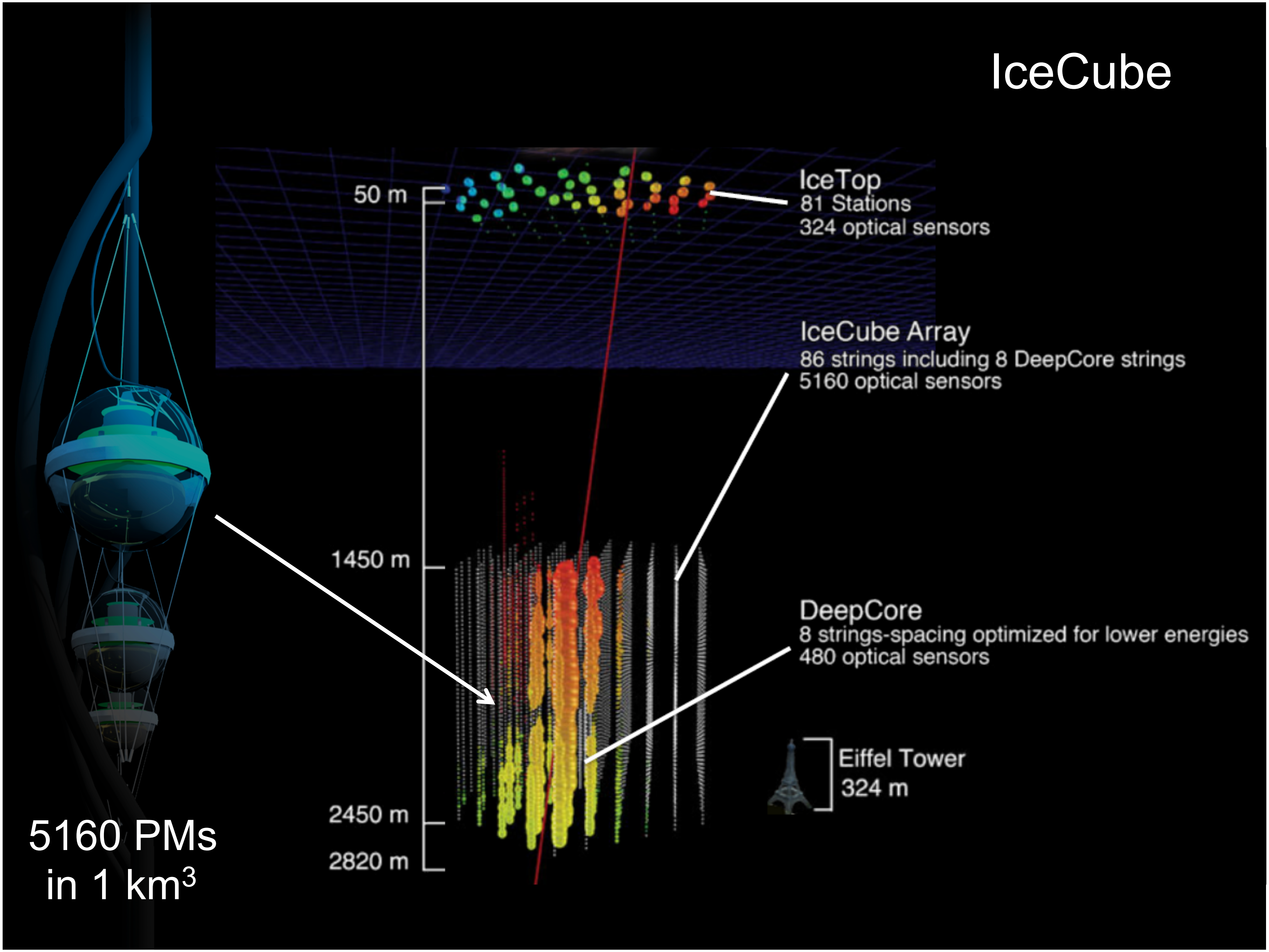
IceCube.wisc.edu


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
neutrino
• lattice of photomultipliers

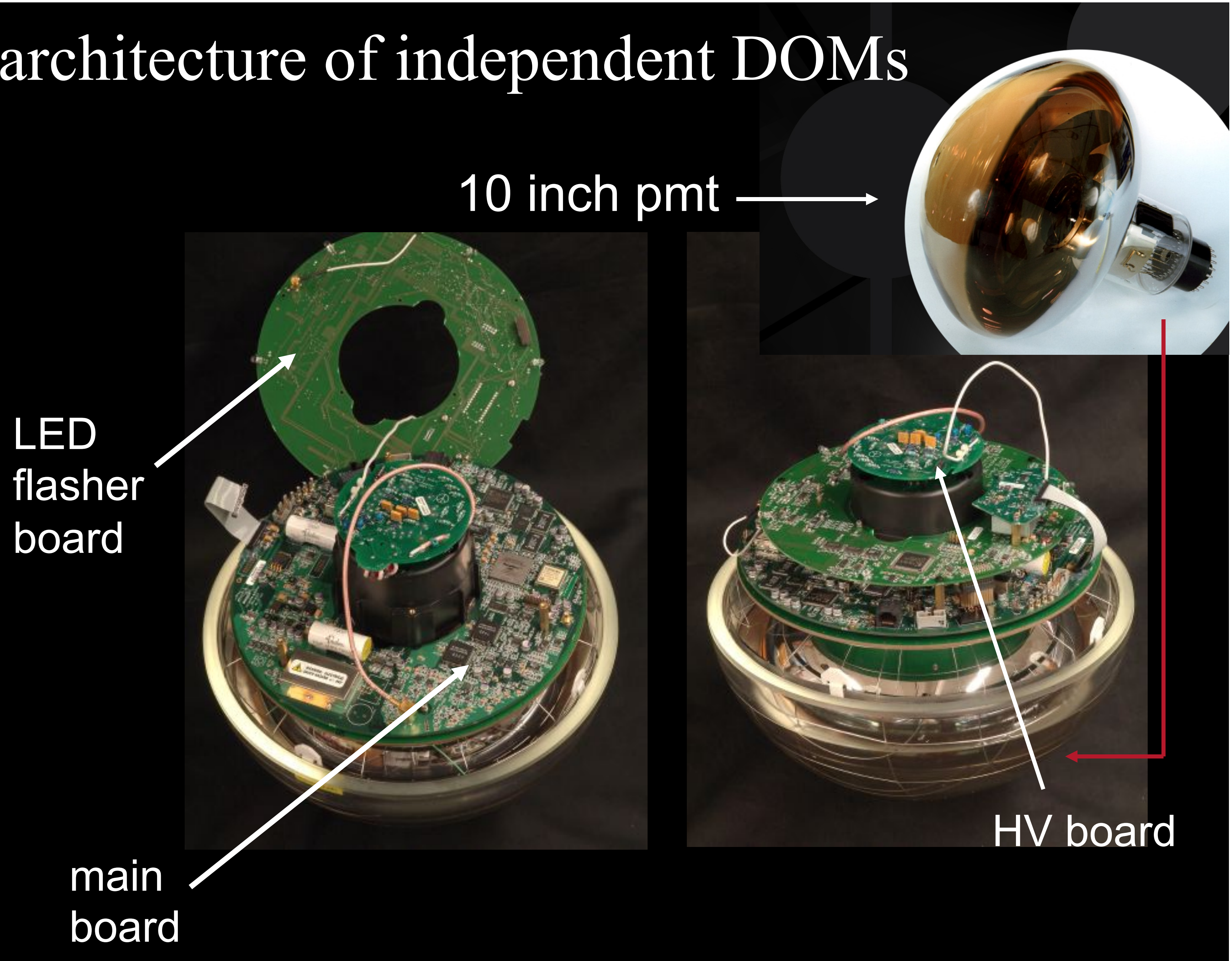

89 TeV
radius ~ number of photons
time ~ red → purple
Run 113641 Event 33553254 [0ns, 16748ns]


ultra-transparent ice below 1.5 km

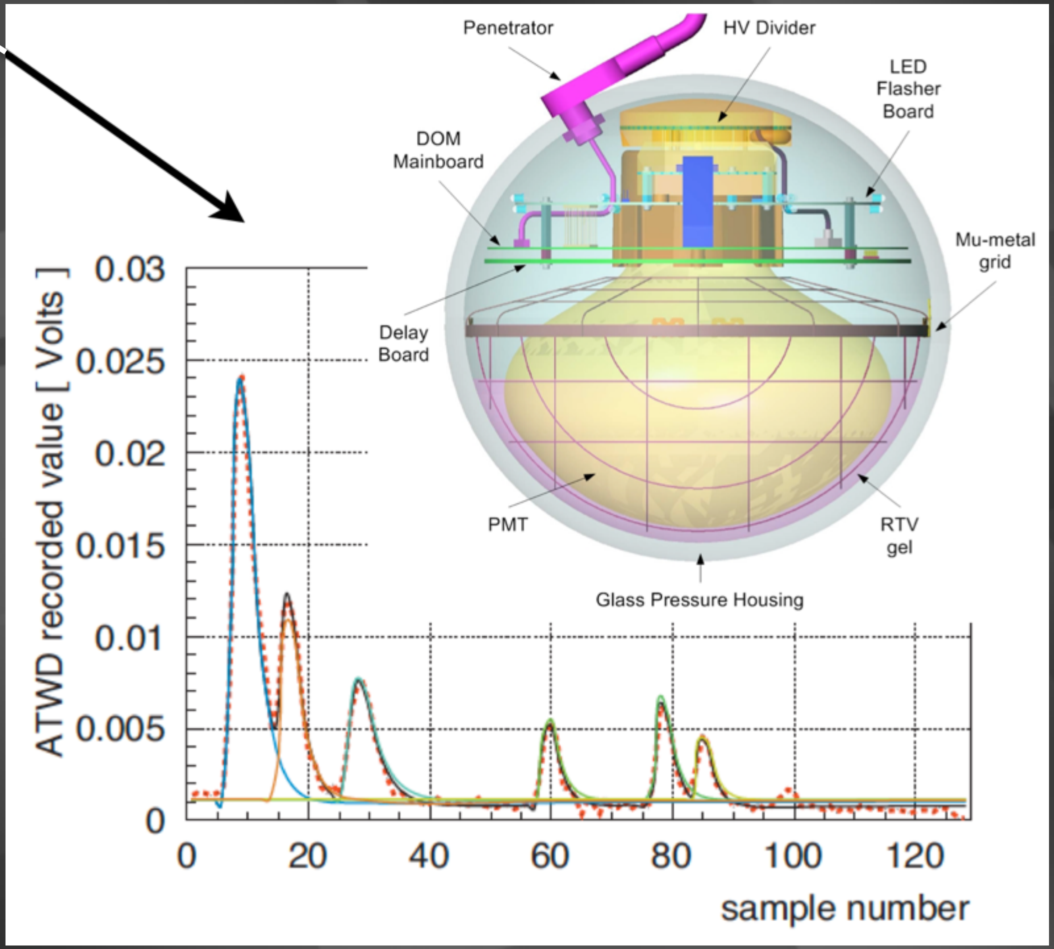

IceCube
50 m
1450 m
2450 m
2820 m
IceTop
81 Stations
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
5160 PMs
in 1 km3

photomultiplier tube -10 inch

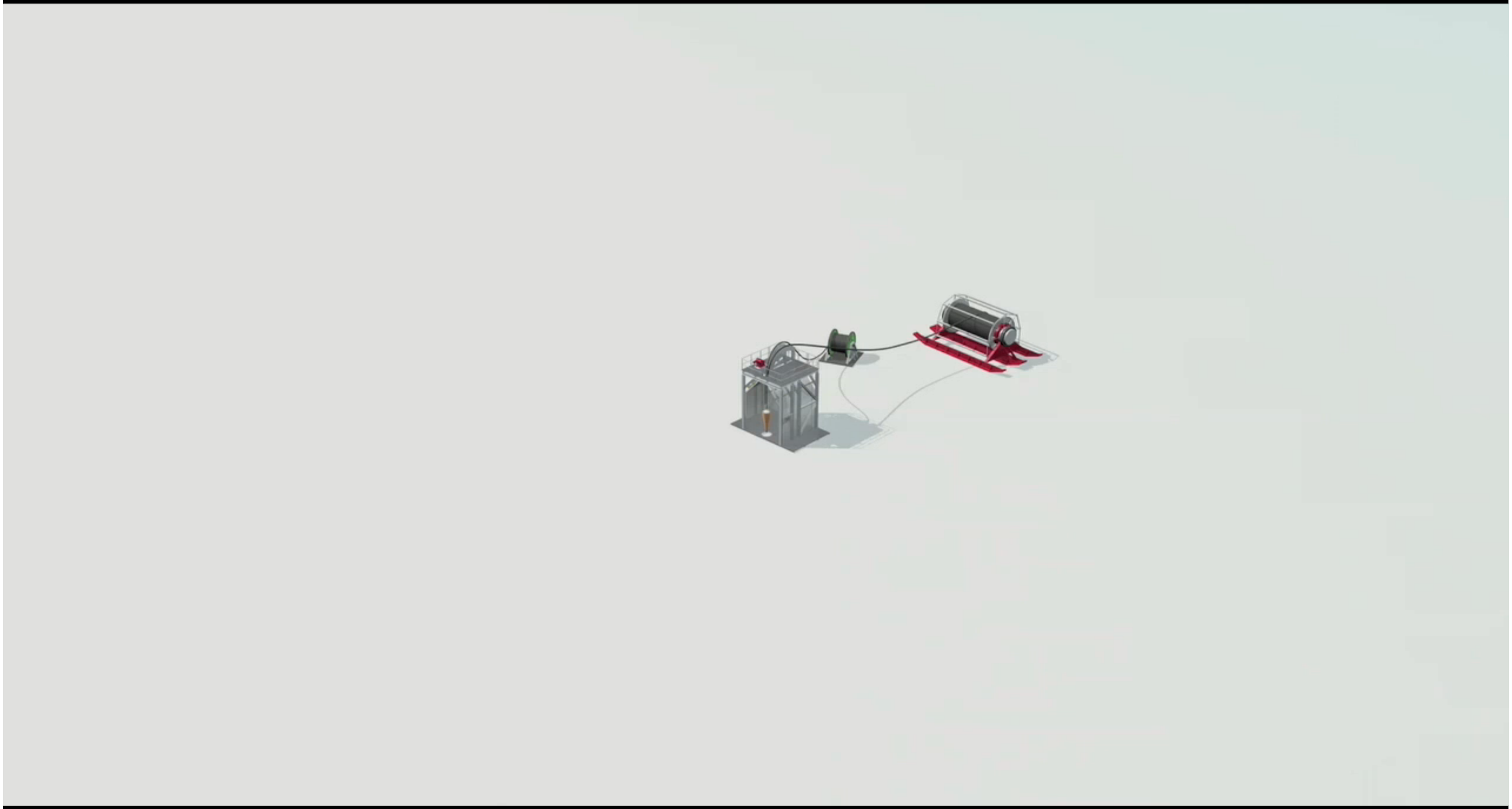
architecture of independent DOMs

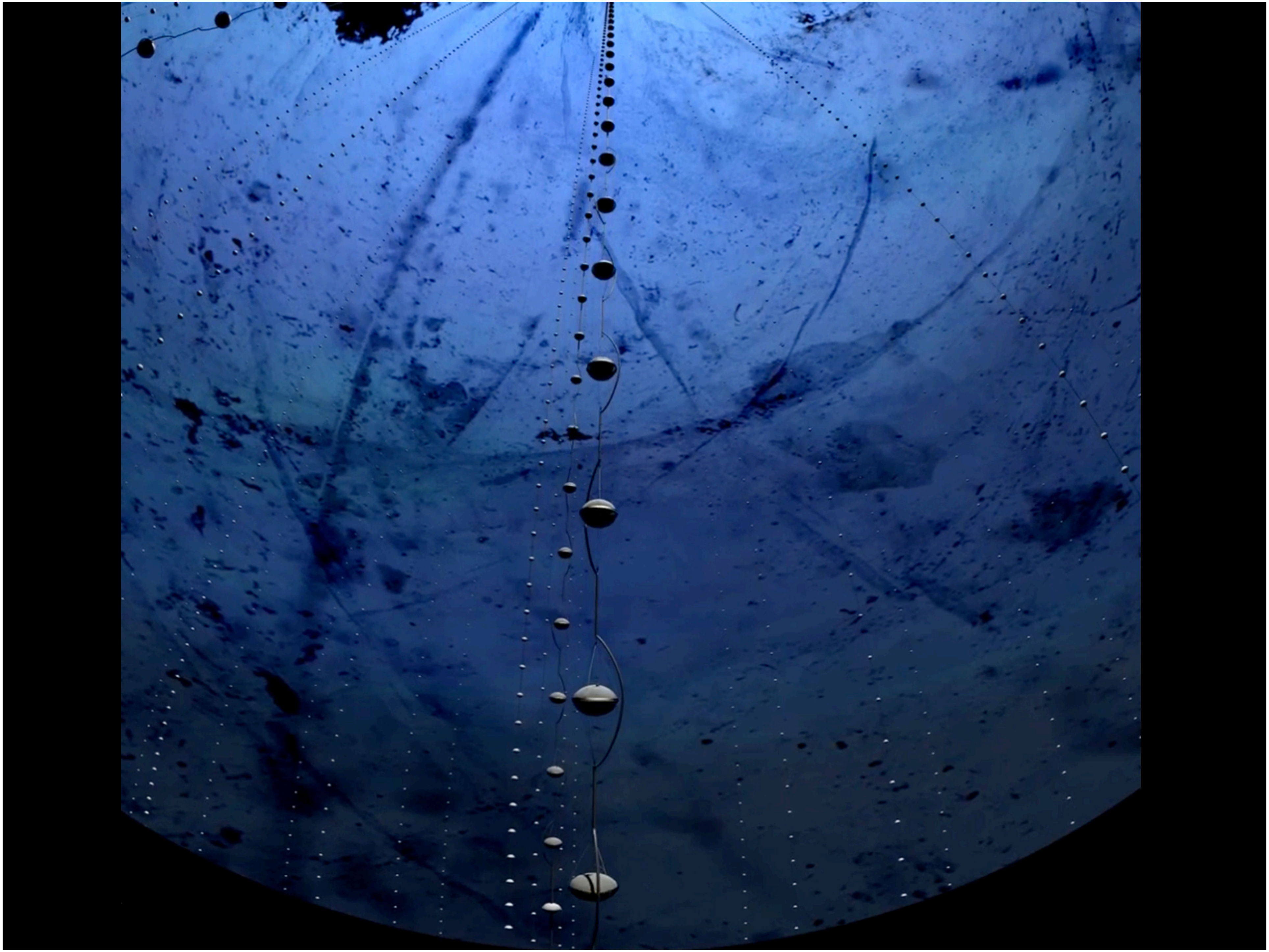


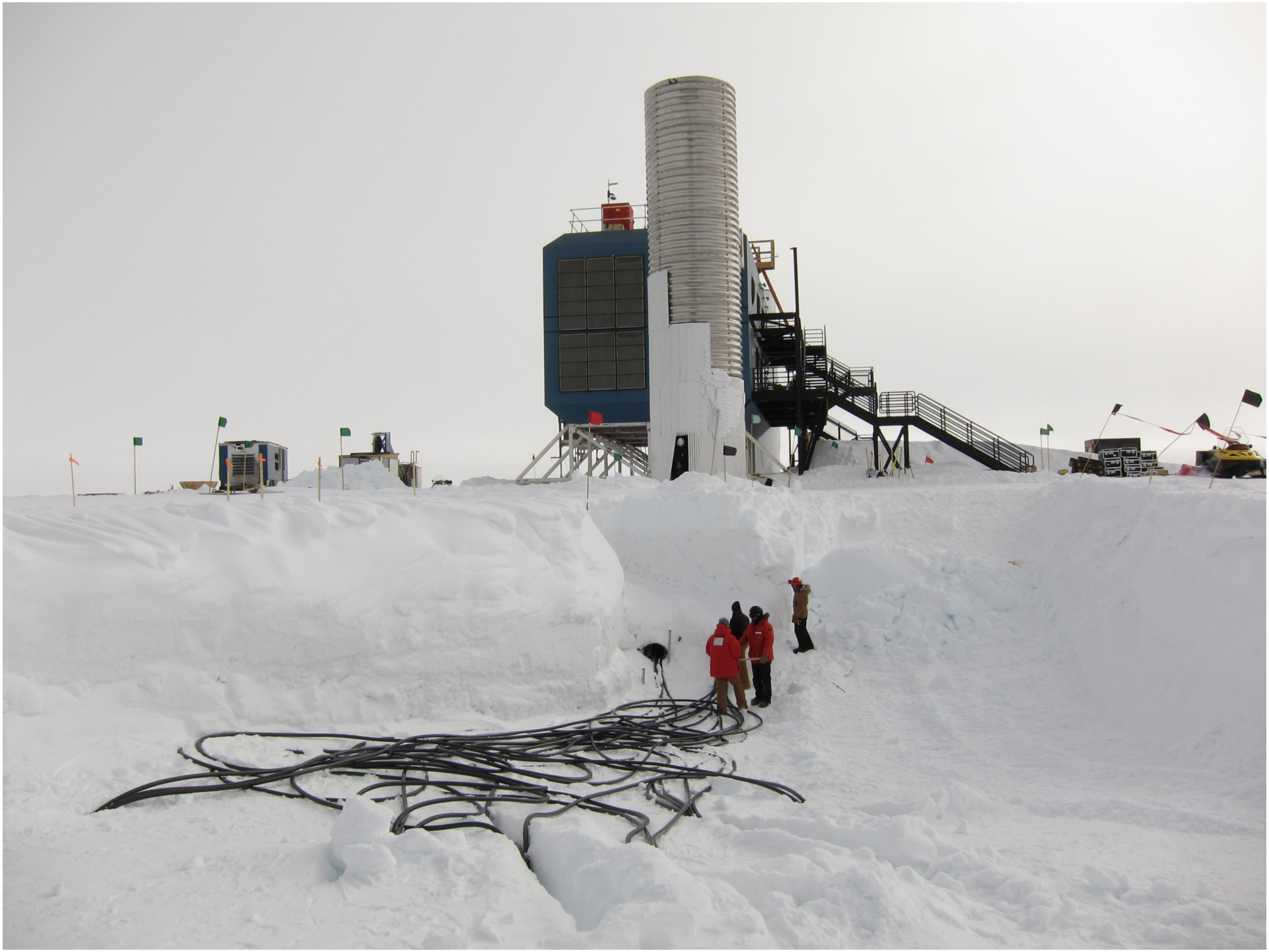
… each Digital Optical Module independently collects light signals like this, digitizes them,

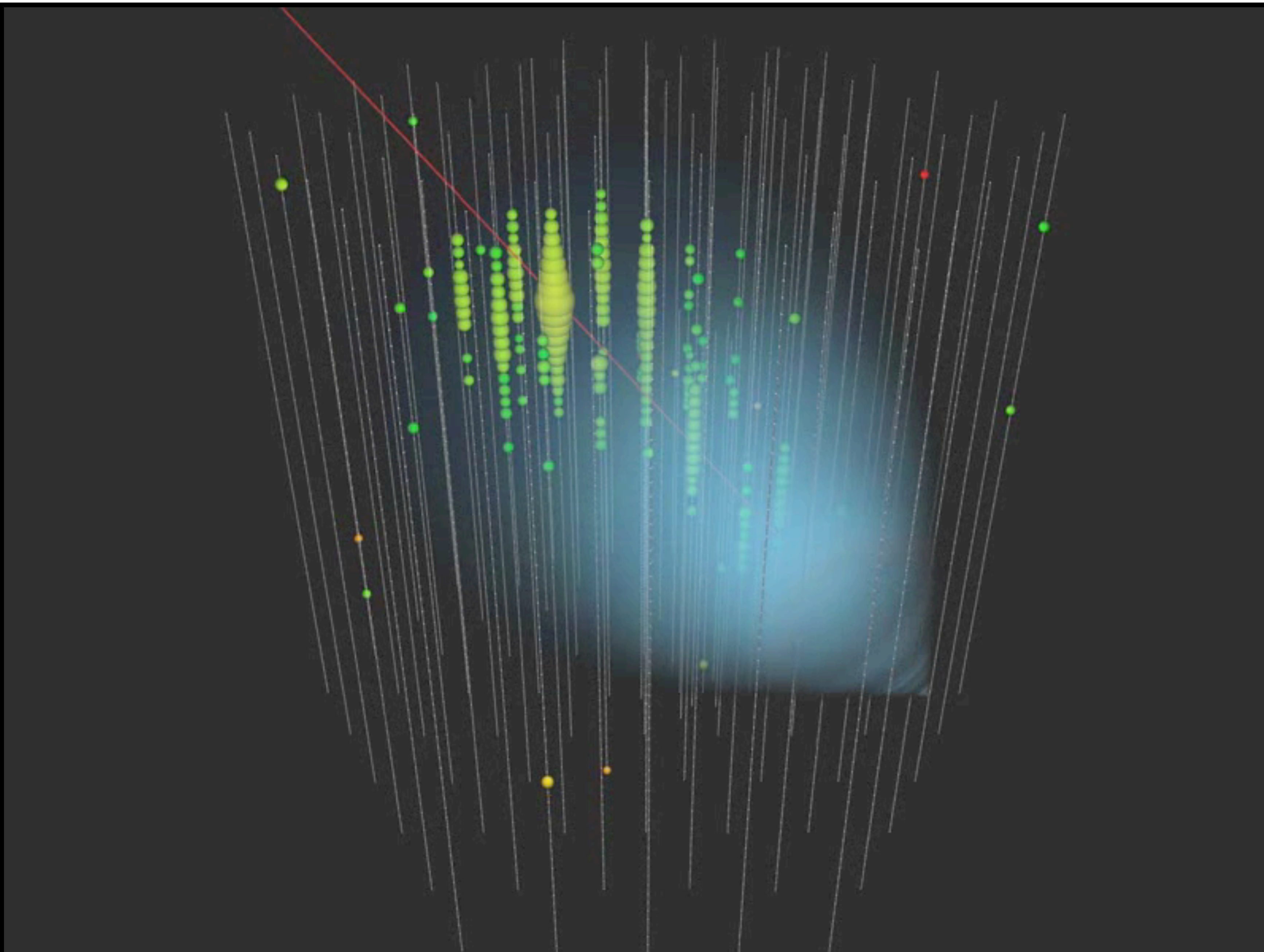


…time stamps them with 2 nanoseconds precision, and sends them to a computer that sorts them events…



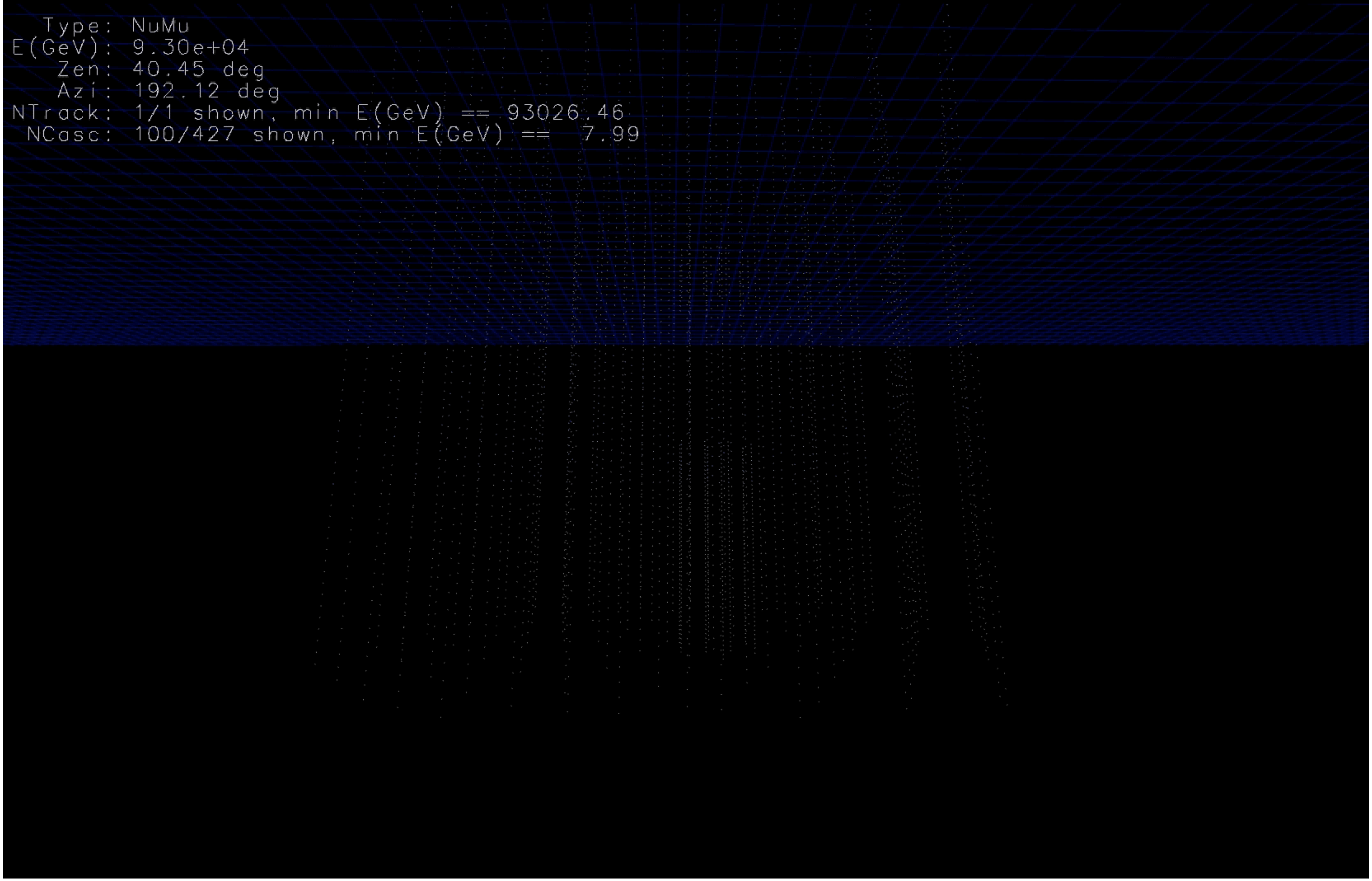




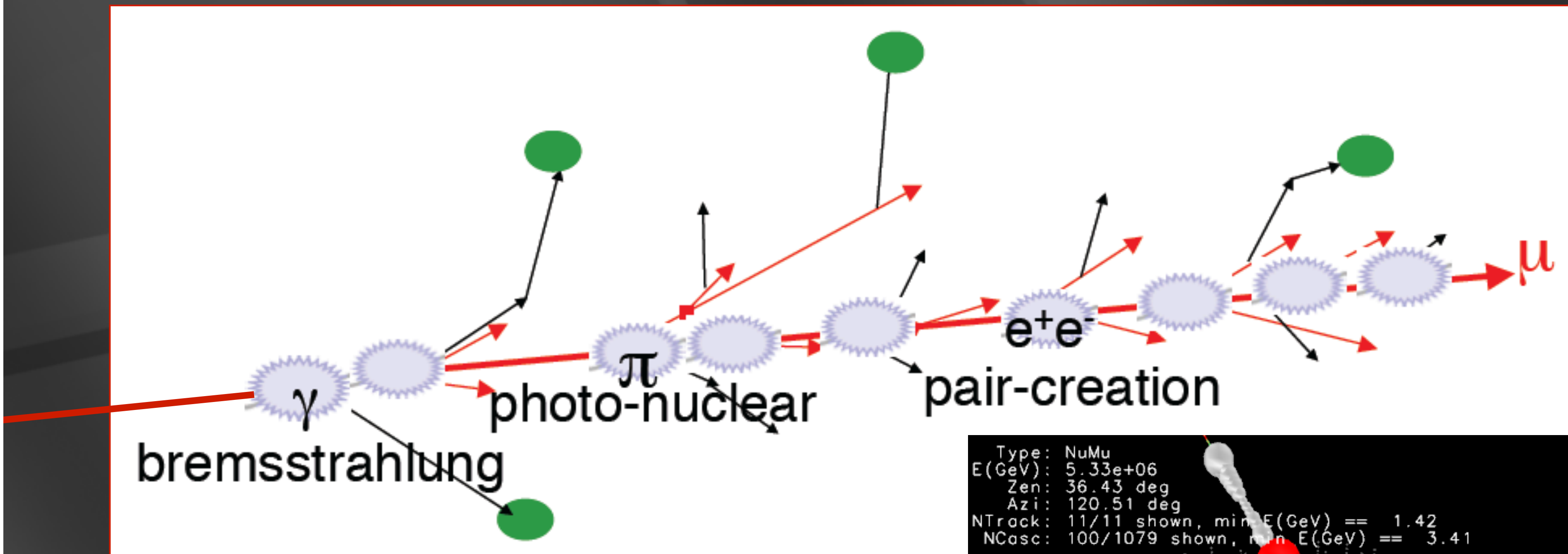


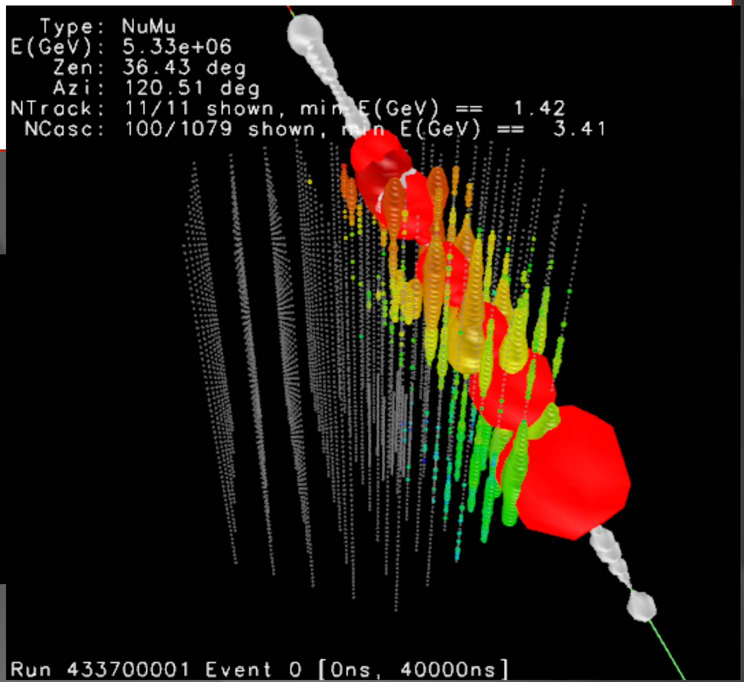
muon track: color is time; number of photons is energy

93 TeV muon: # photons ~ energy

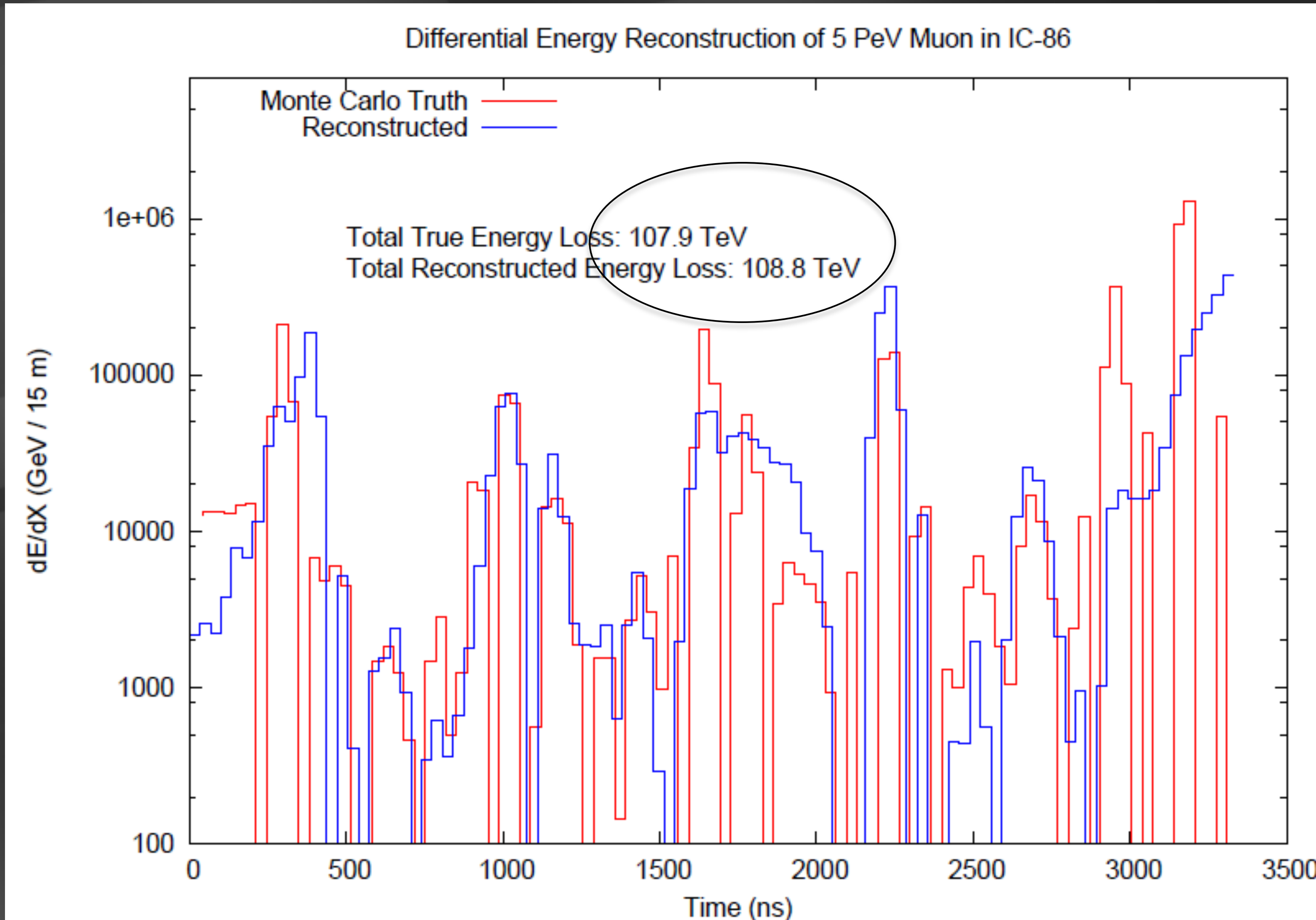


energy measurement (> 1 TeV)





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

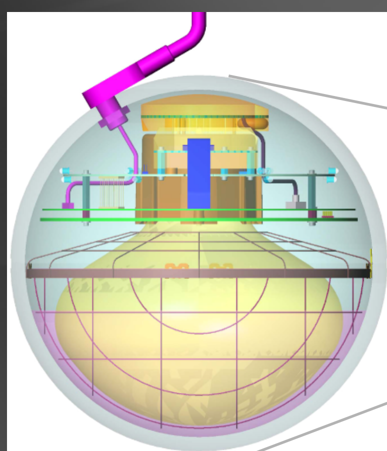


1.1 km

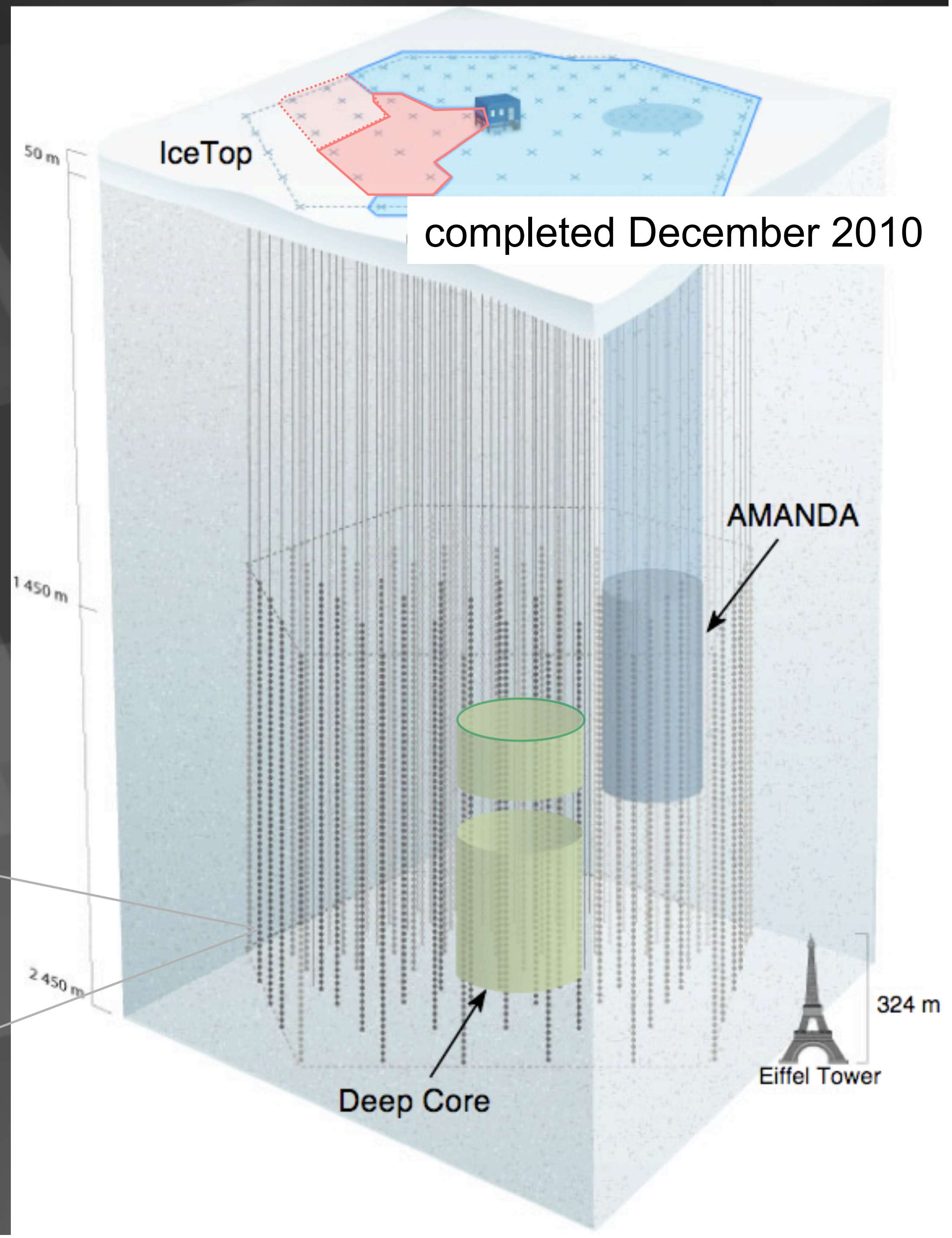
improving angular and energy resolution

IceCube / Deep Core

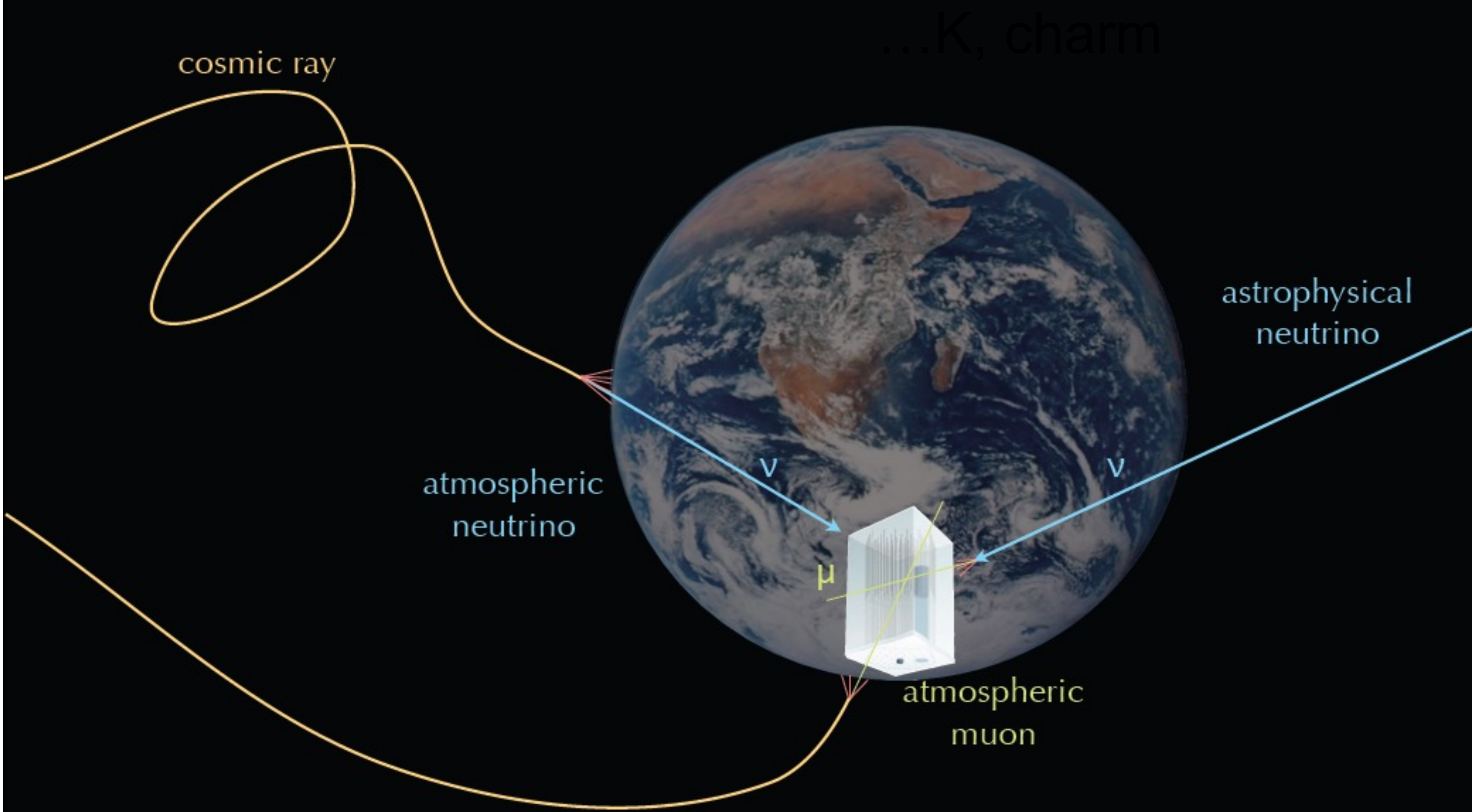
- 5160 optical sensors between 1.5 ~ 2.5 km
- 10 GeV to infinity
- 0.2-0.4 deg muon track ~ 10 degree shower
- 10% energy resolution

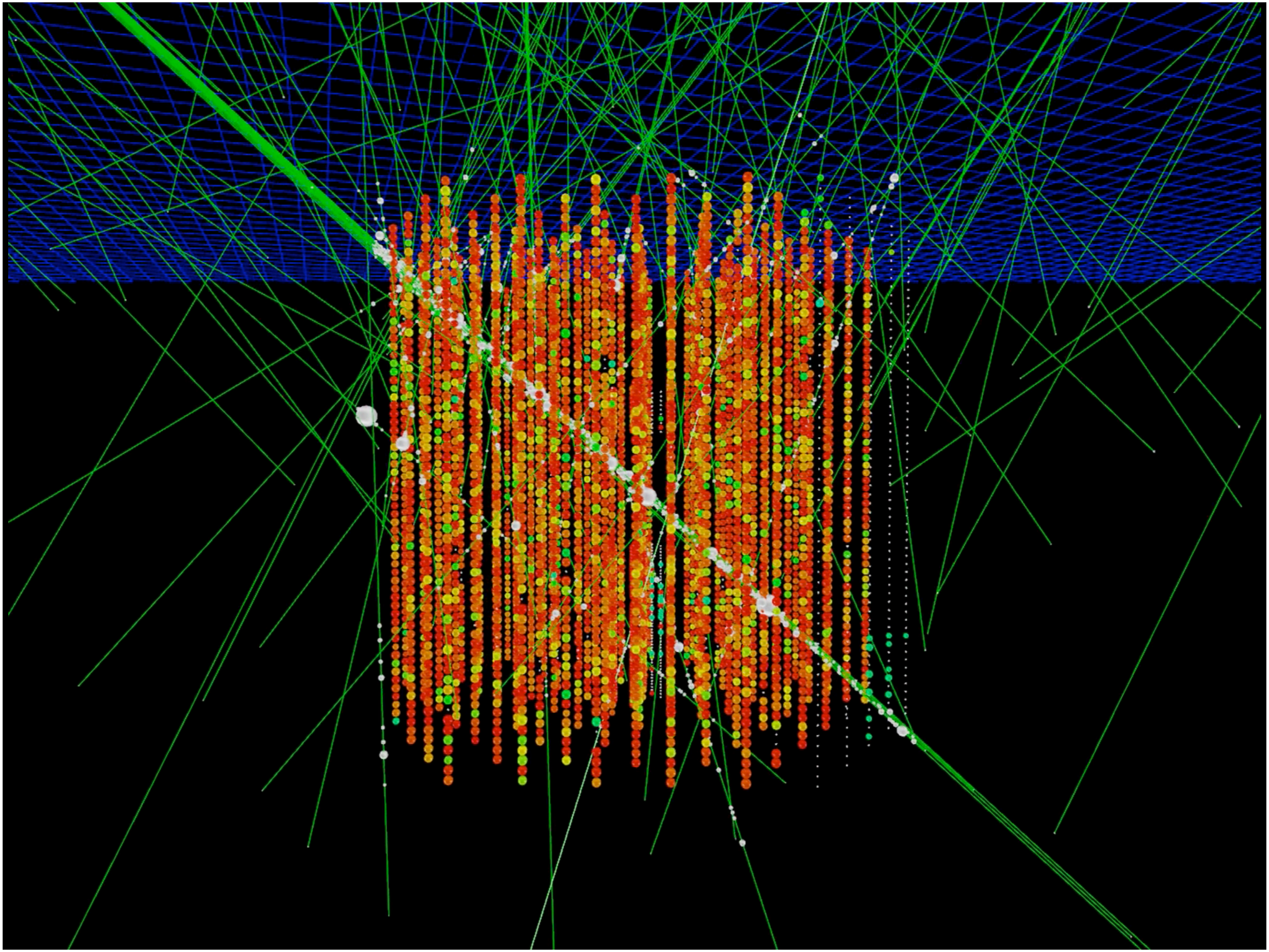


Digital Optical Module (DOM)



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

The Daily Breakdown

Monday April 18
- First magnificent Aurora display!

Tuesday April 19
- Stress test reveals that the DIMMs of *ichub75* are indeed kaputt.

Wednesday April 20
- Jim Braun successfully deployed I3MS version 1.0.13 to SPS.

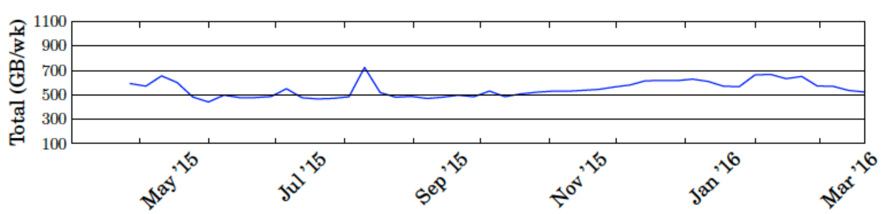
Thursday April 21
- Quiet.

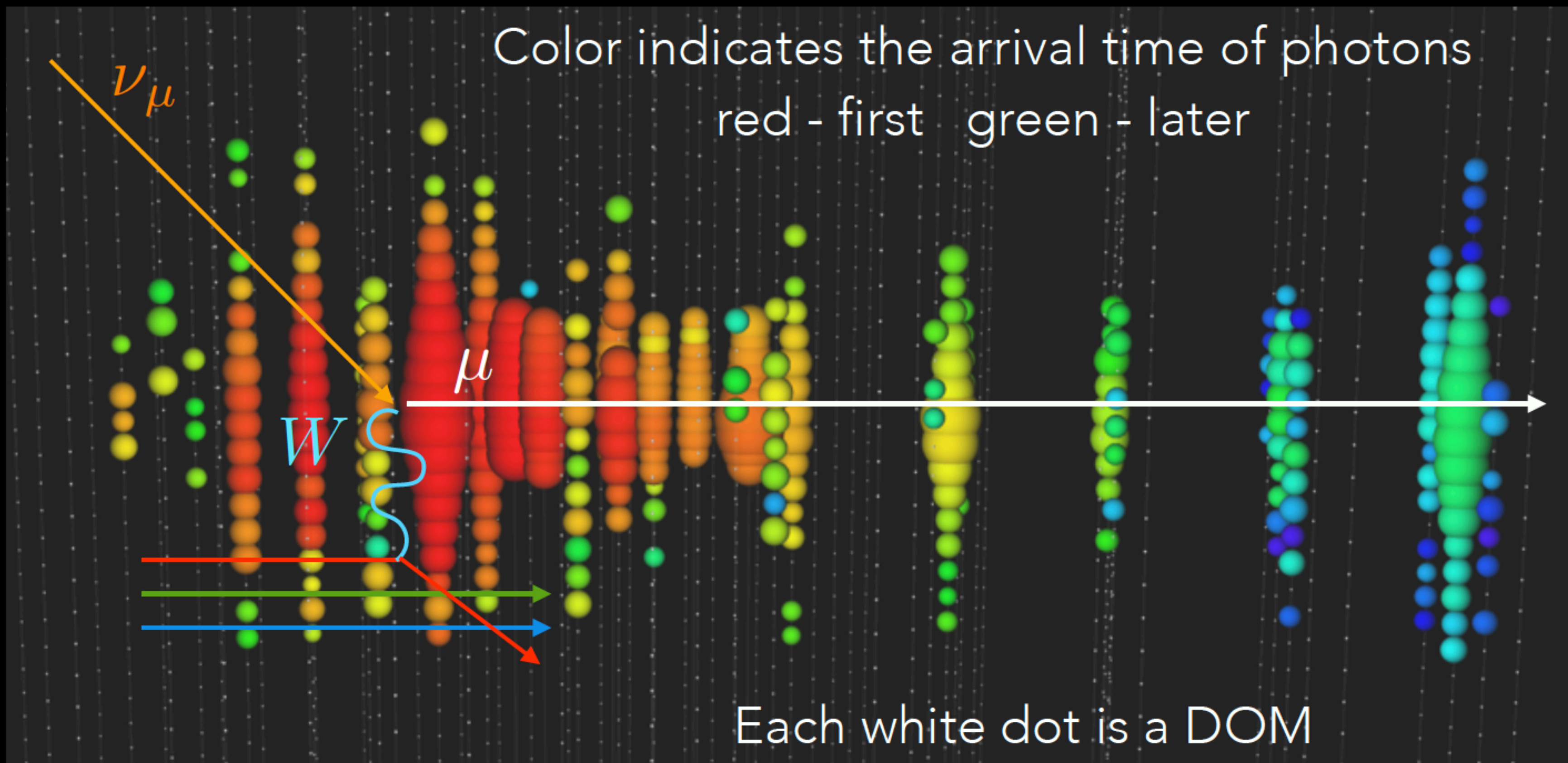
Friday April 22
- Quiet.

Saturday April 23
- Quiet.

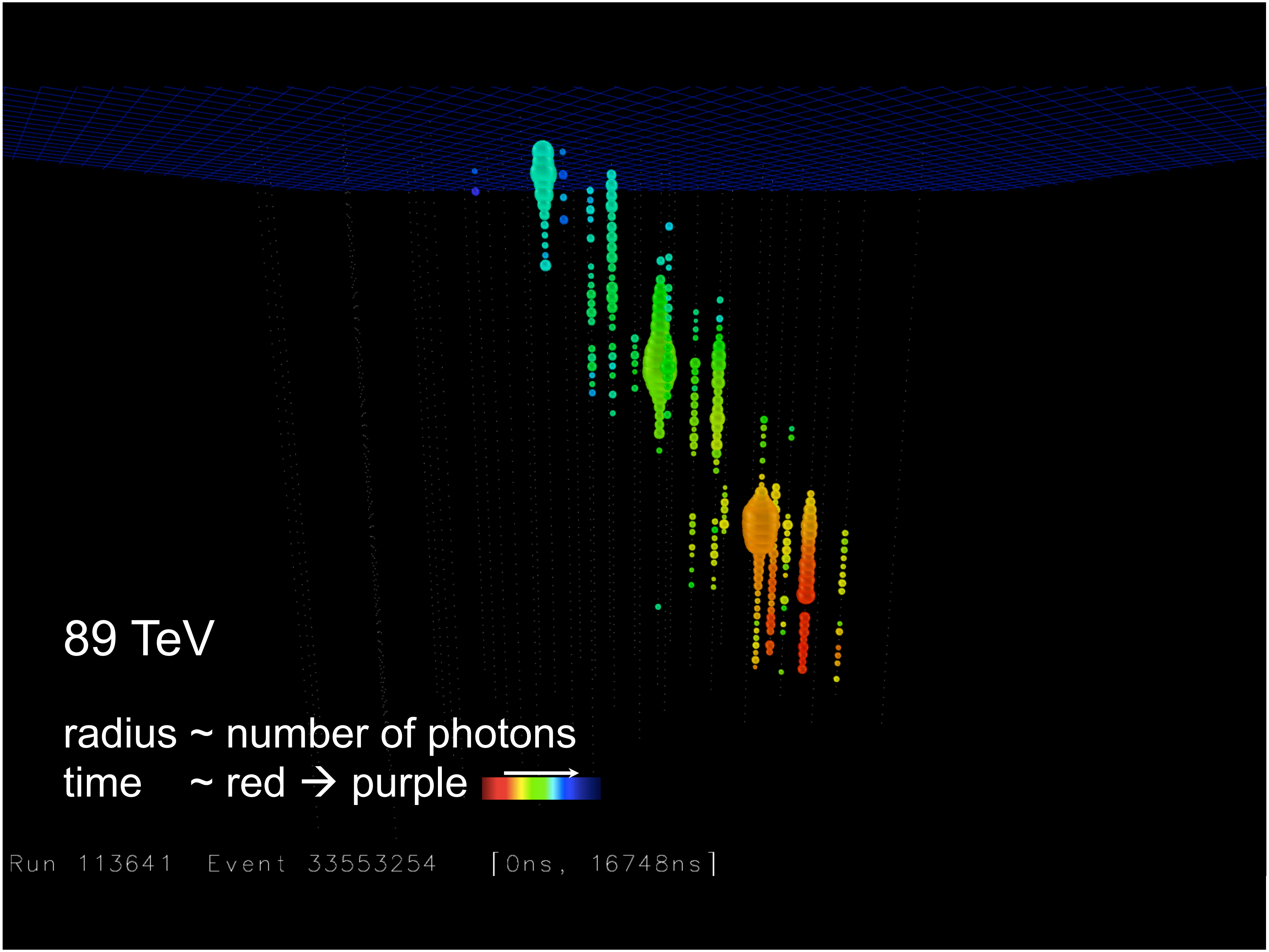
Sunday April 24
- Quiet.

TDRSS Satellite Transfer

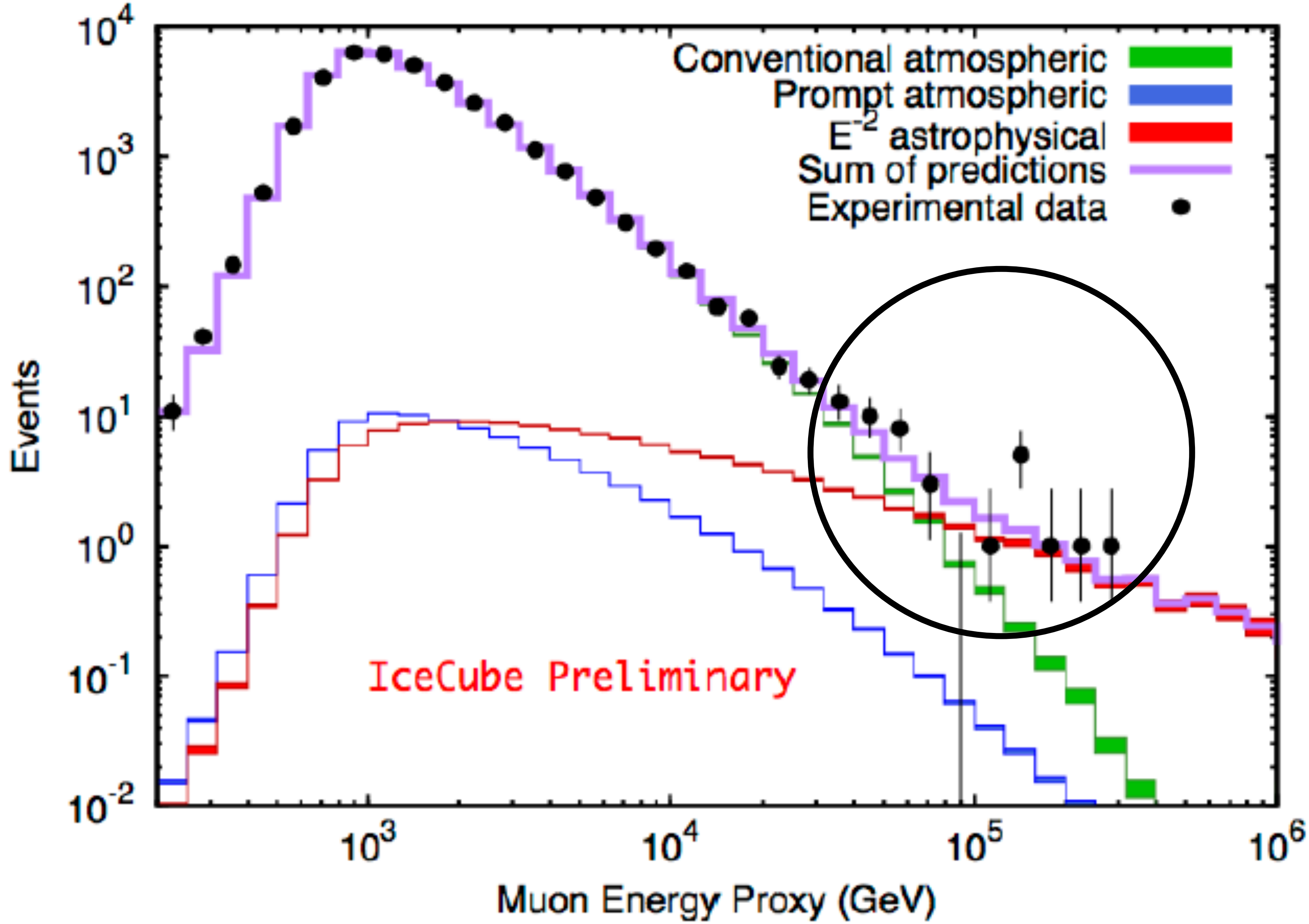




Nov.12.2010,   duration: 3,800 nanosecond,   energy: 71.4TeV


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

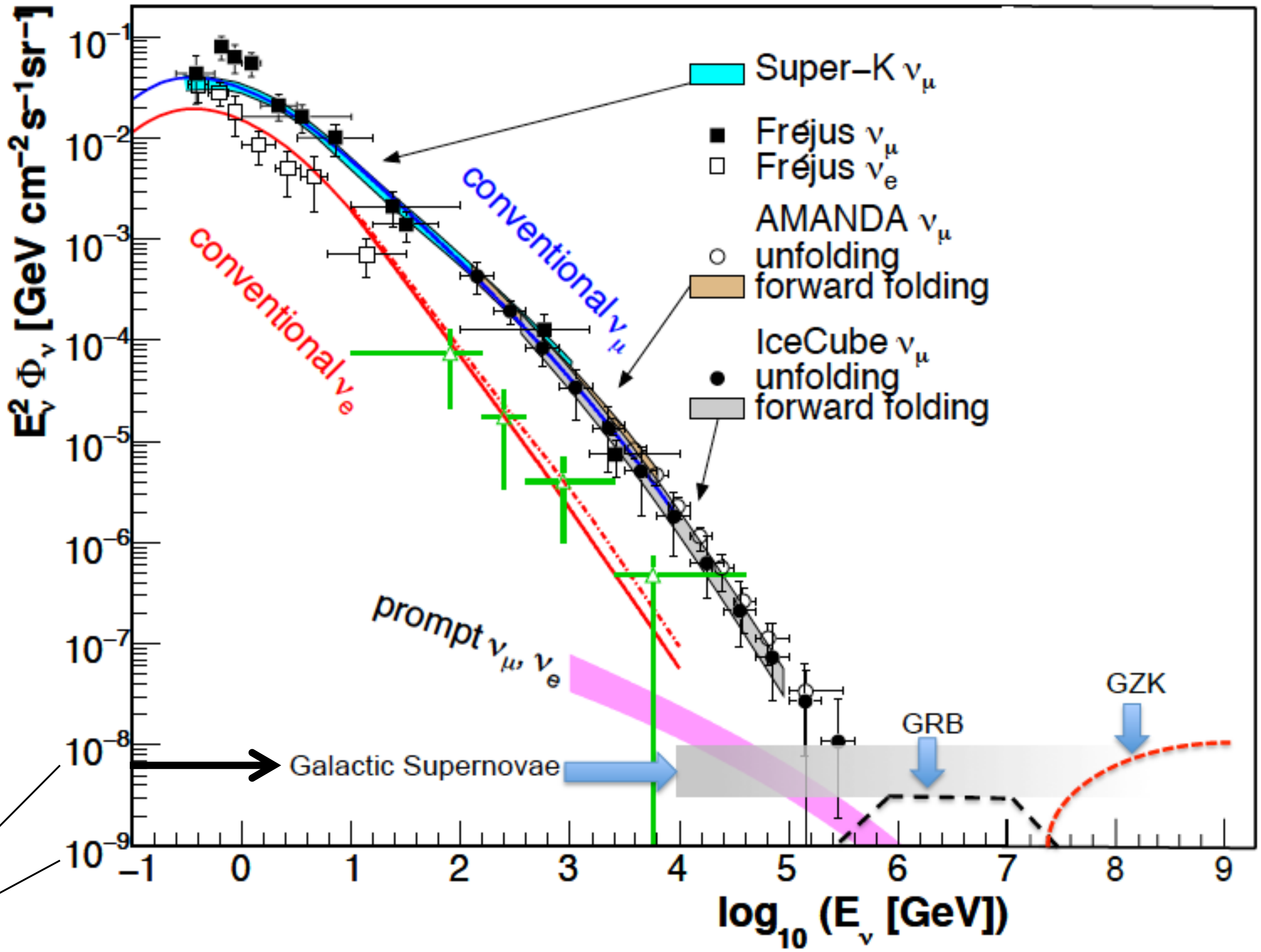


above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

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

10—100 events per year for fully efficient detector

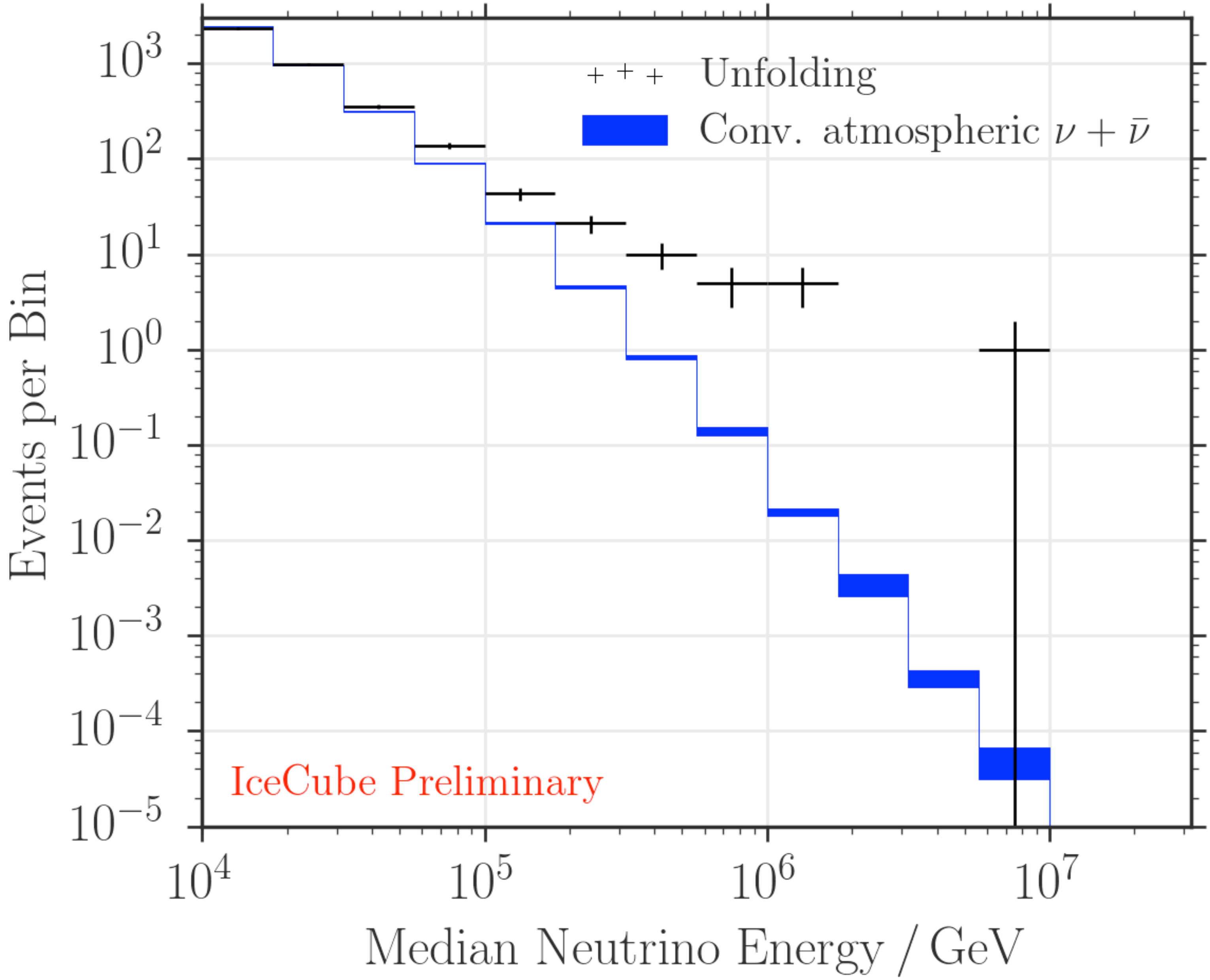


atmospheric

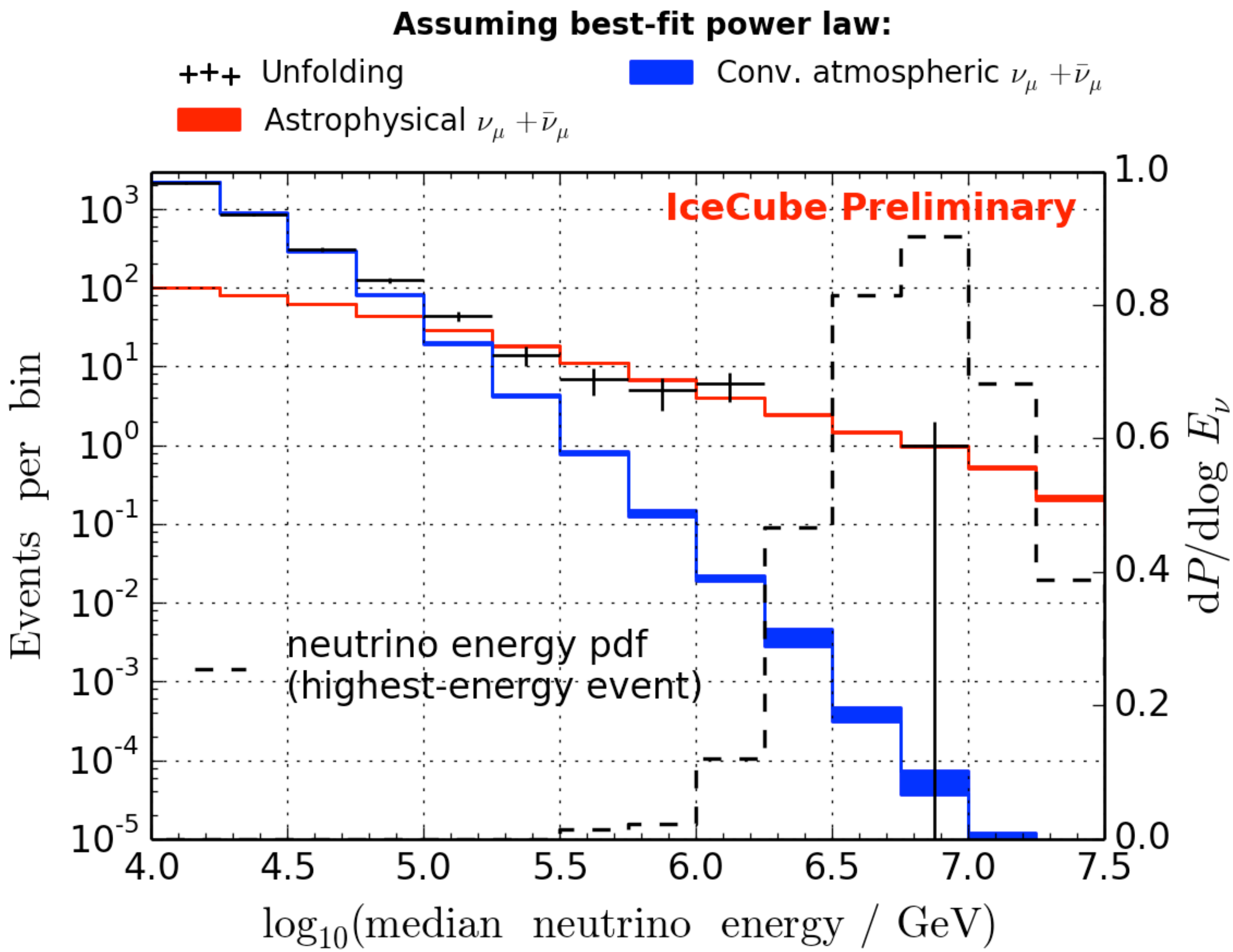
cosmic

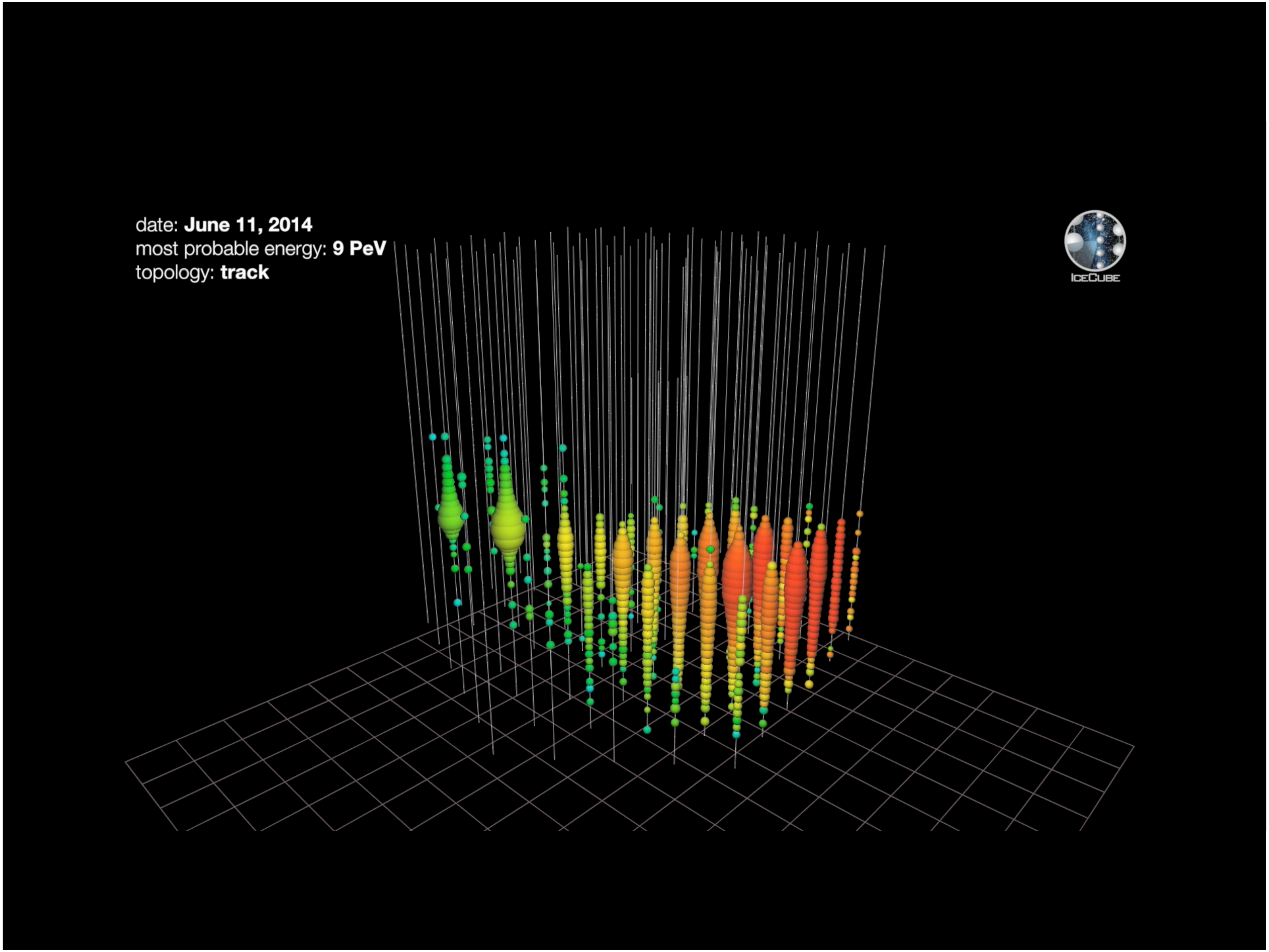
100 TeV

muon neutrinos through the Earth → 6 sigma

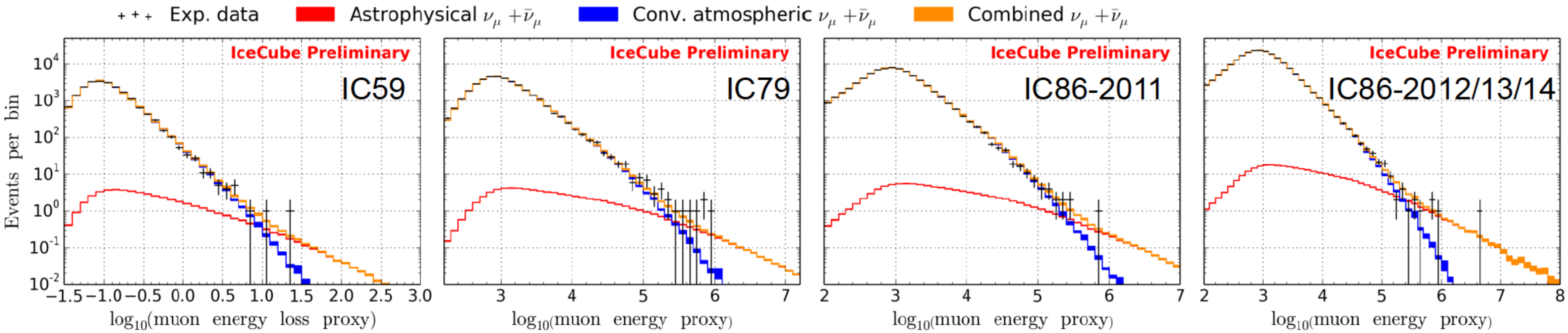


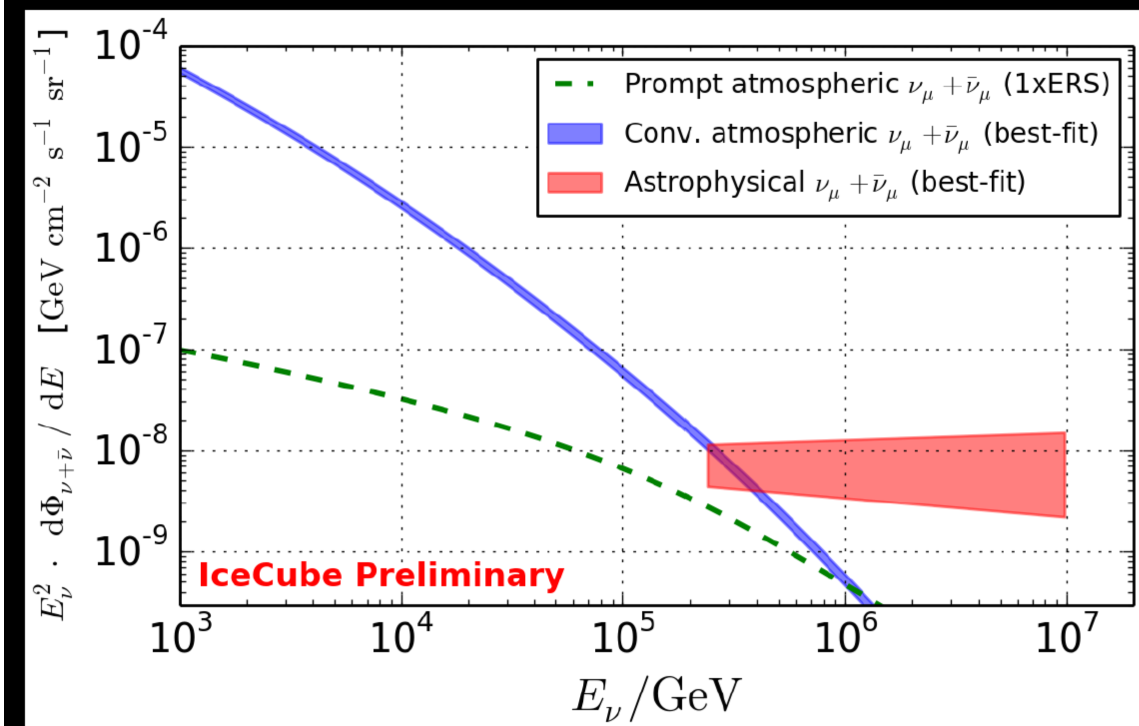
muon neutrinos through the Earth → 6 sigma




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

after 7 years: 3.7 → 6 sigma





- Best-fit astrophysical normalization:

  0.97+.27-.25 $\times 10^{-18}\ \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$

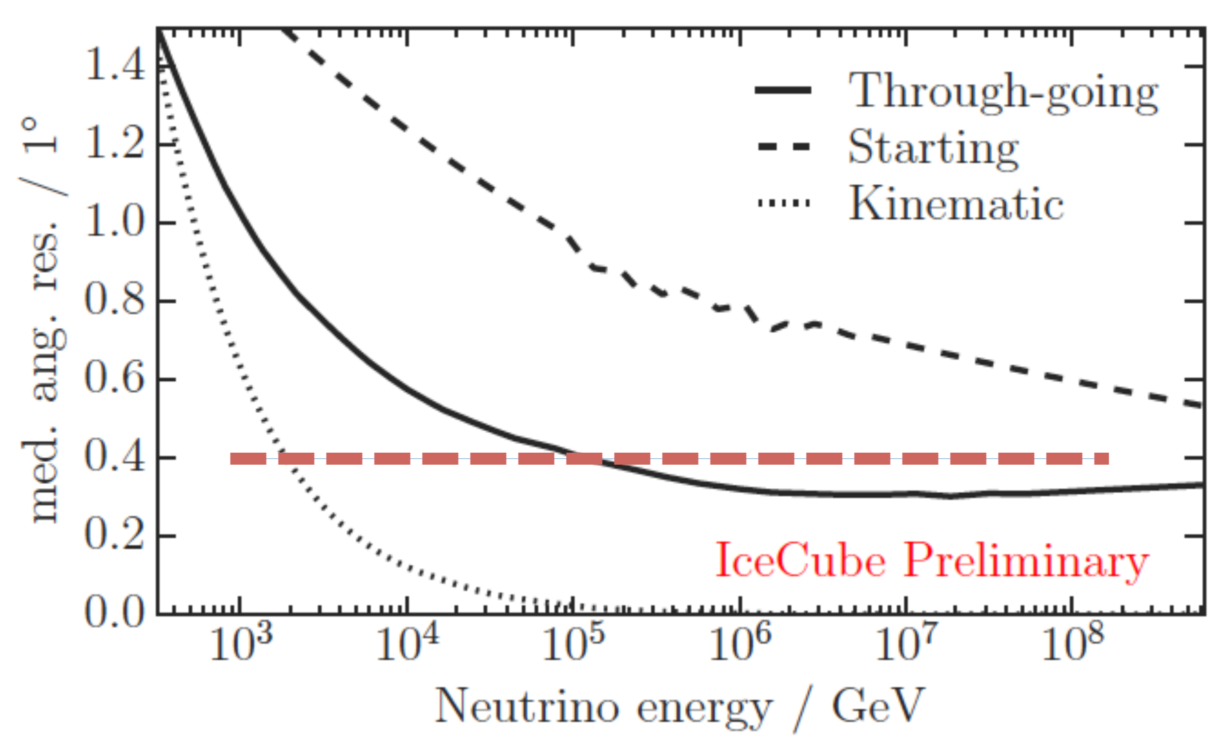
- Best-fit spectral index:

  γ_{astro} = 2.16 ± 0.11

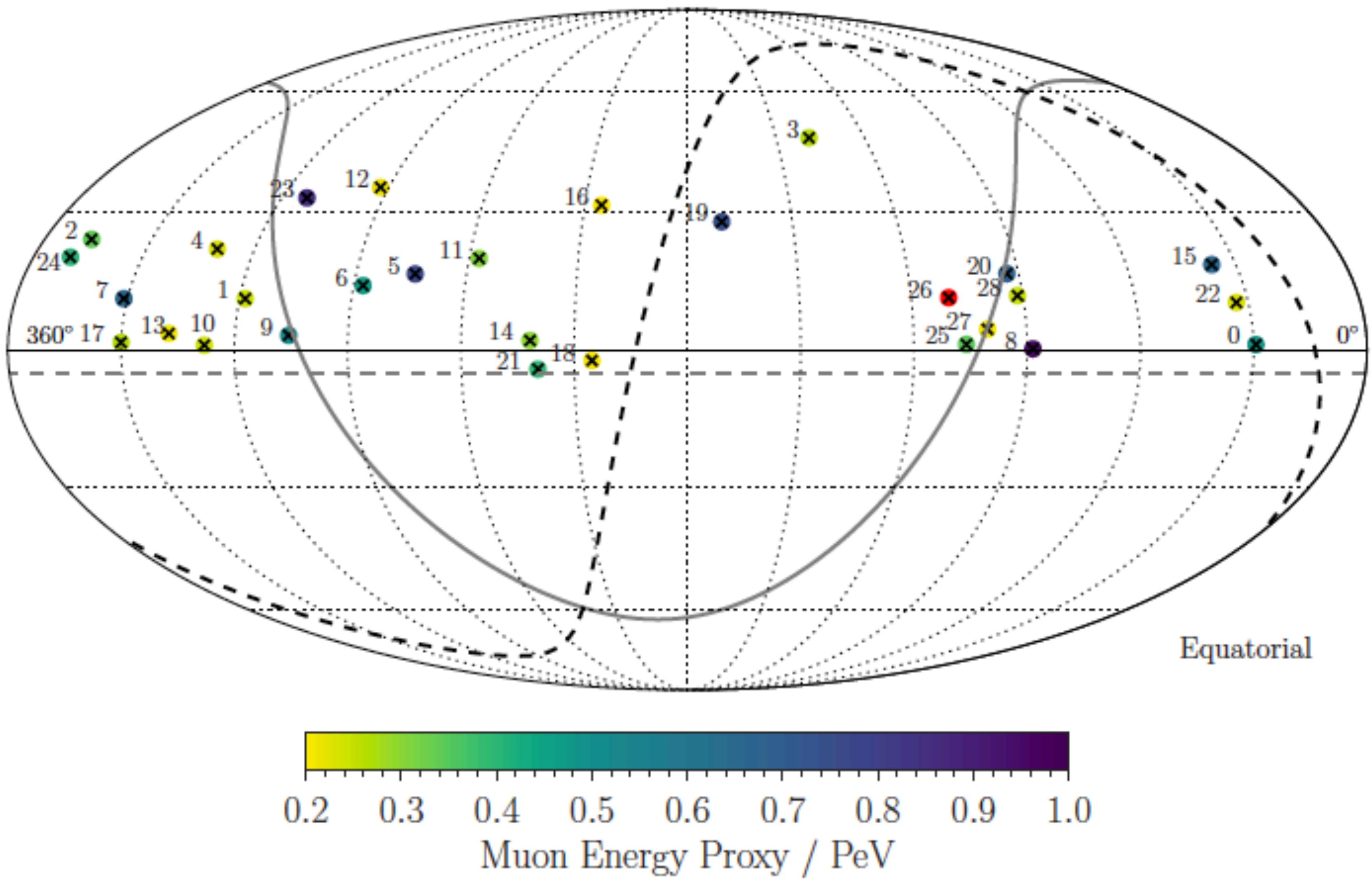
- Energy ranges:

  240 TeV – 10 PeV

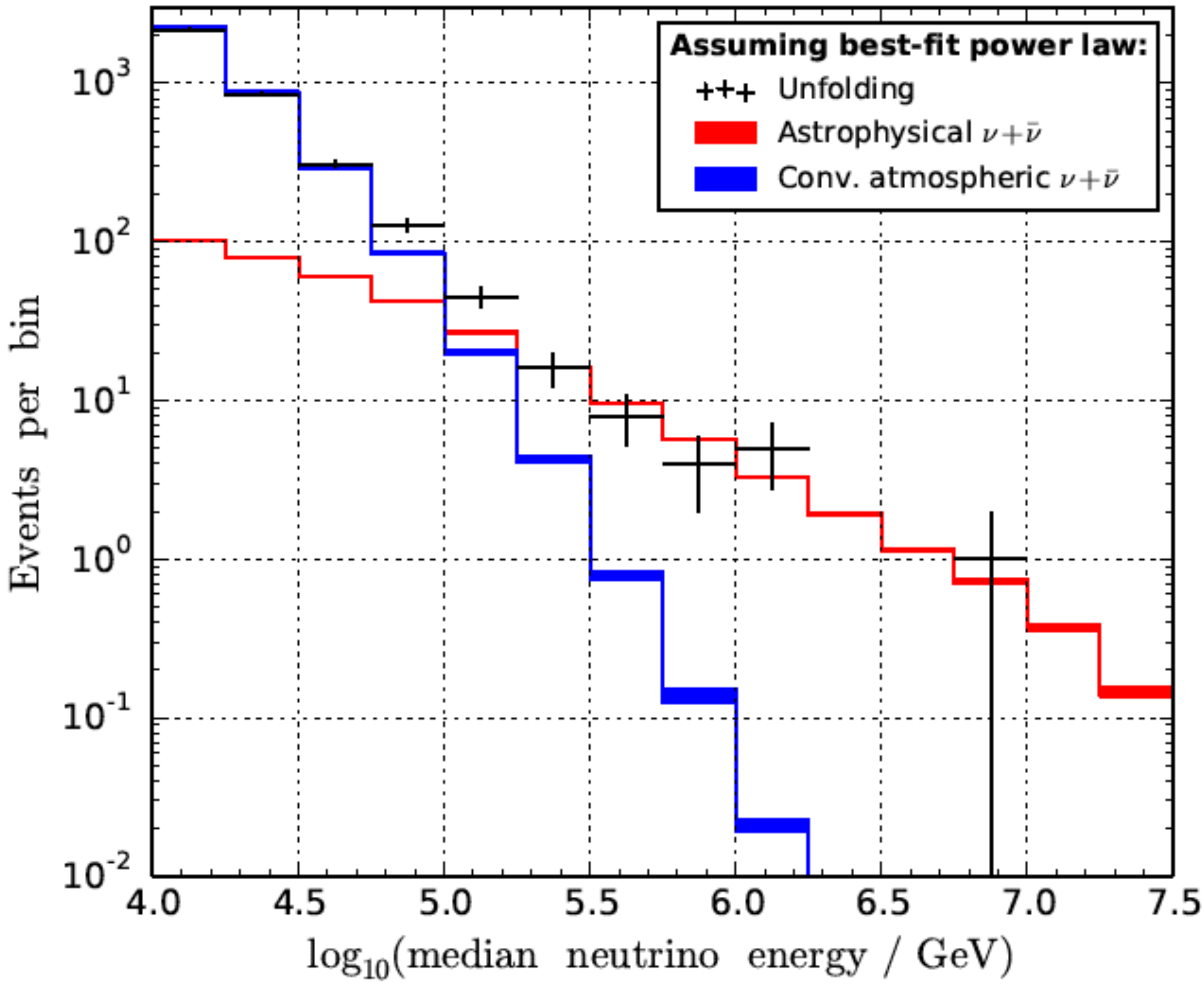
- Atmospheric-only hypothesis excluded by 6.0σ astronomy here: through-going muons with resolution $0.2{\sim}0.4^0$

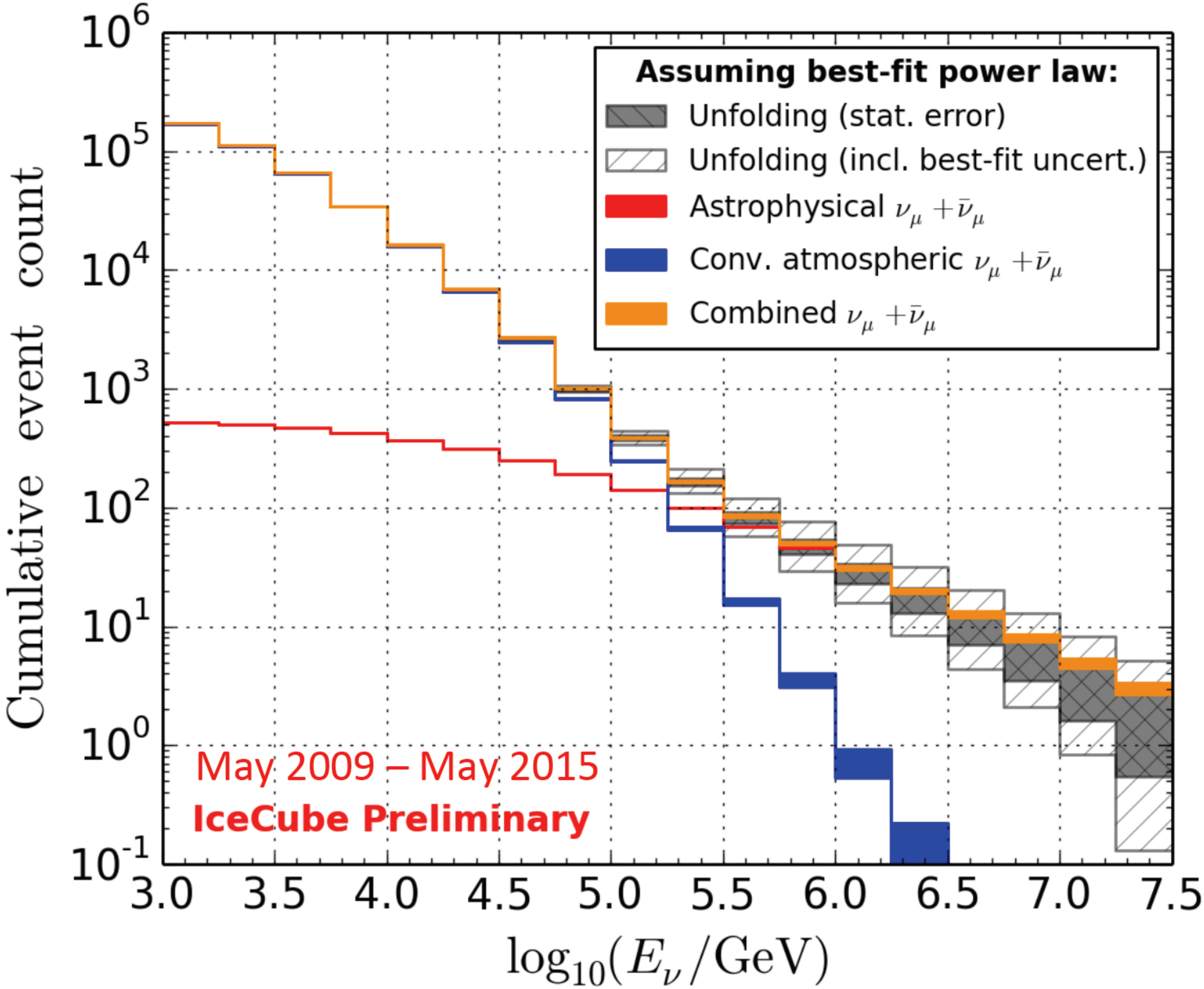


highest energy ν_μ: astronomy with best resolution !



muon neutrinos through the Earth → 5.6 sigma

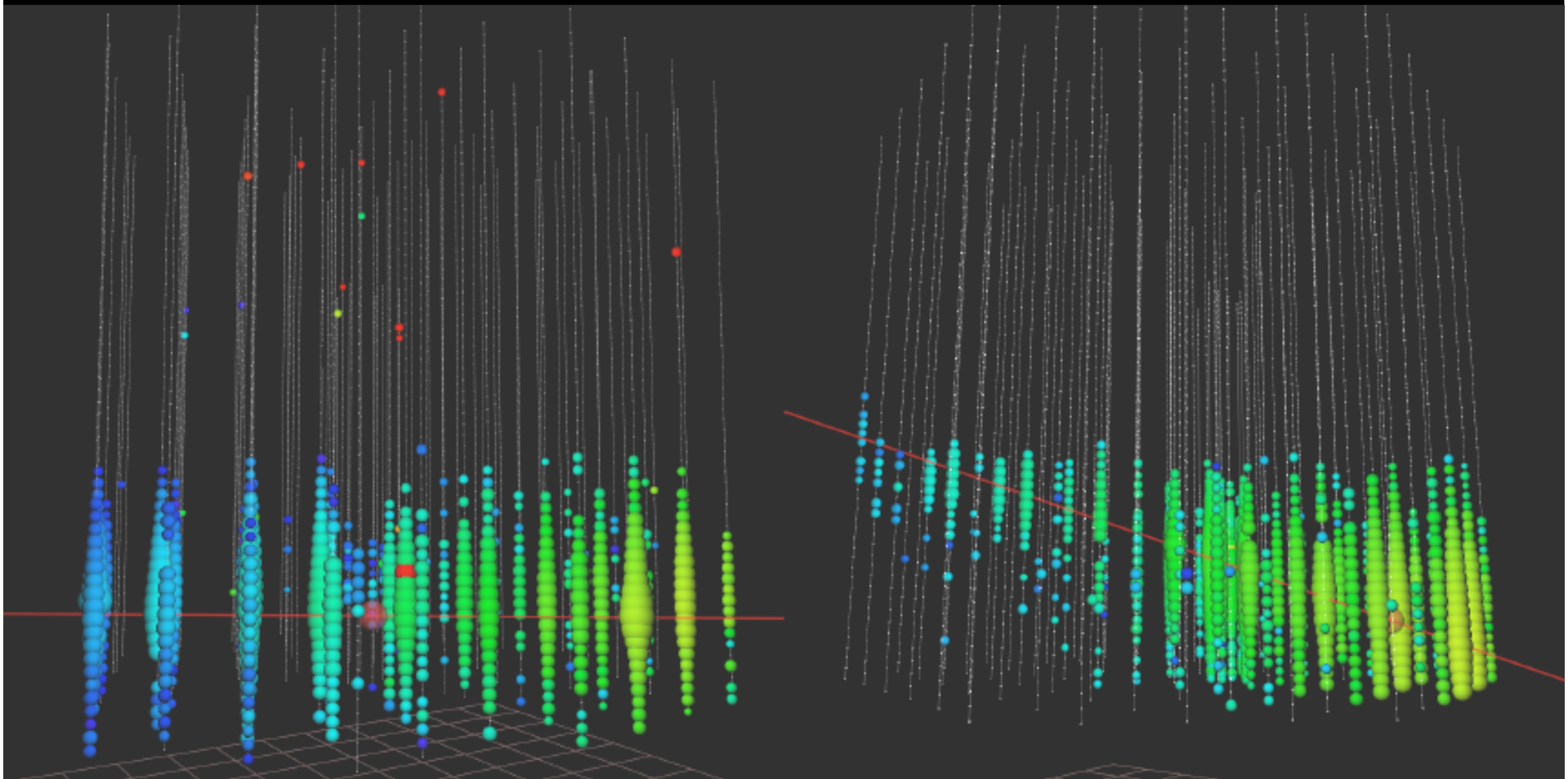


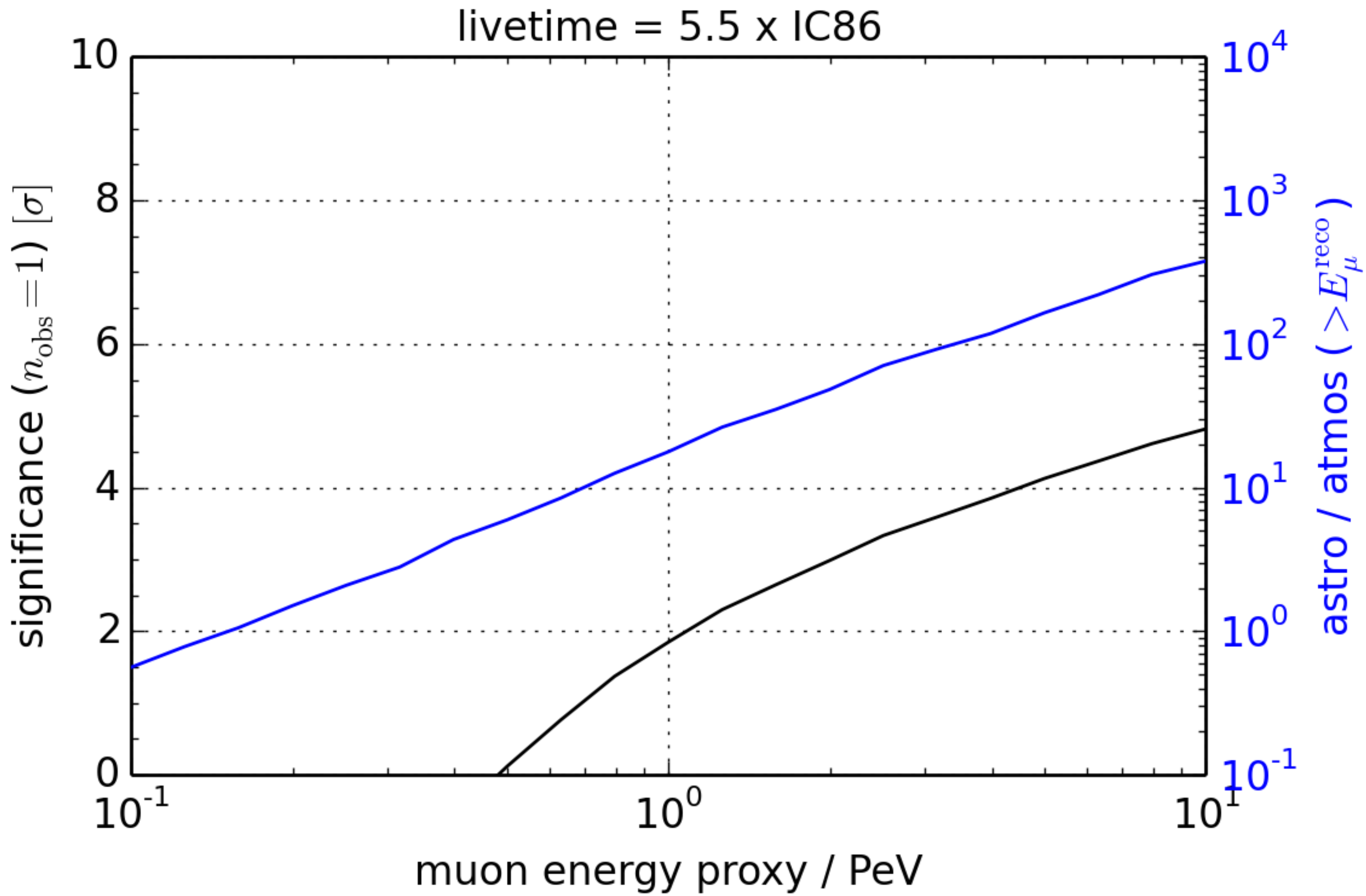


Assuming best-fit power law:
Unfolding (stat. error)
Unfolding (incl. best-fit uncert.)
Astrophysical $\nu_\mu + \bar{\nu}_\mu$
Conv. atmospheric $\nu_\mu + \bar{\nu}_\mu$
Combined $\nu_\mu + \bar{\nu}_\mu$
May 2009 – May 2015
IceCube Preliminary
Cumulative event count
$\log_{10}(E_\nu/\mathrm{GeV})$
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5

highest energy muon energy observed: 560 TeV

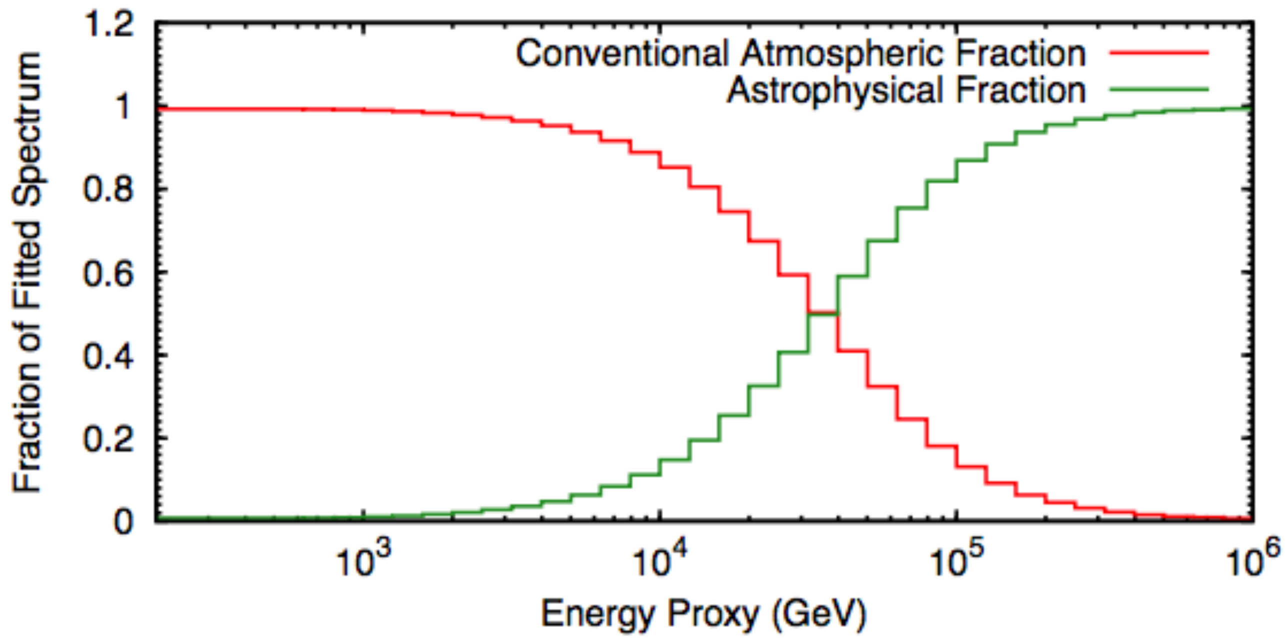
→ PeV ν_μ

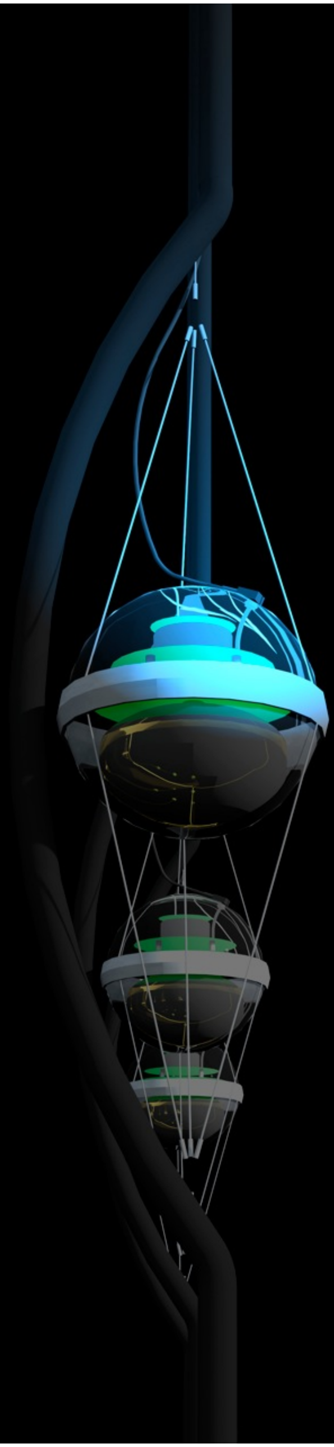




livetime = 5.5 x IC86
significance ($n_{\mathrm{obs}}=1$) [σ]
astro / atmos ($>E_\mu^{\mathrm{reco}}$)
muon energy proxy / PeV
0
2
4
6
8
10
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

Flux	# of Events/year above Muon Energy		
	1 TeV	10 TeV	100 TeV
E^{-2}	110	44	11
$E^{-2.3}$	220	60	9
$E^{-2.7}$	740	110	7
Atm.	15000	500	5





IceCube: building a new window on the Universe

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

cosmic rays interact with the microwave background

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

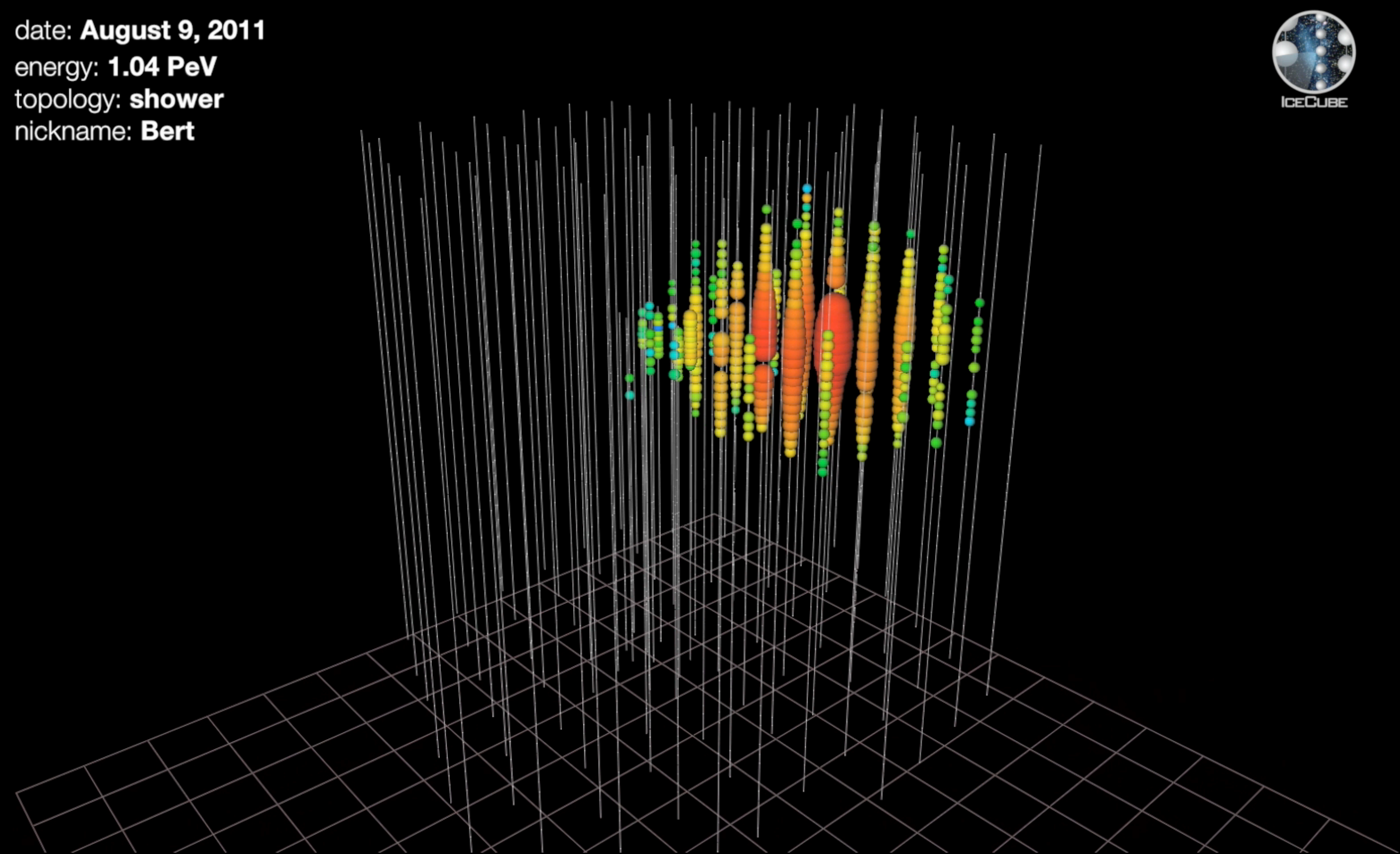
cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear

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

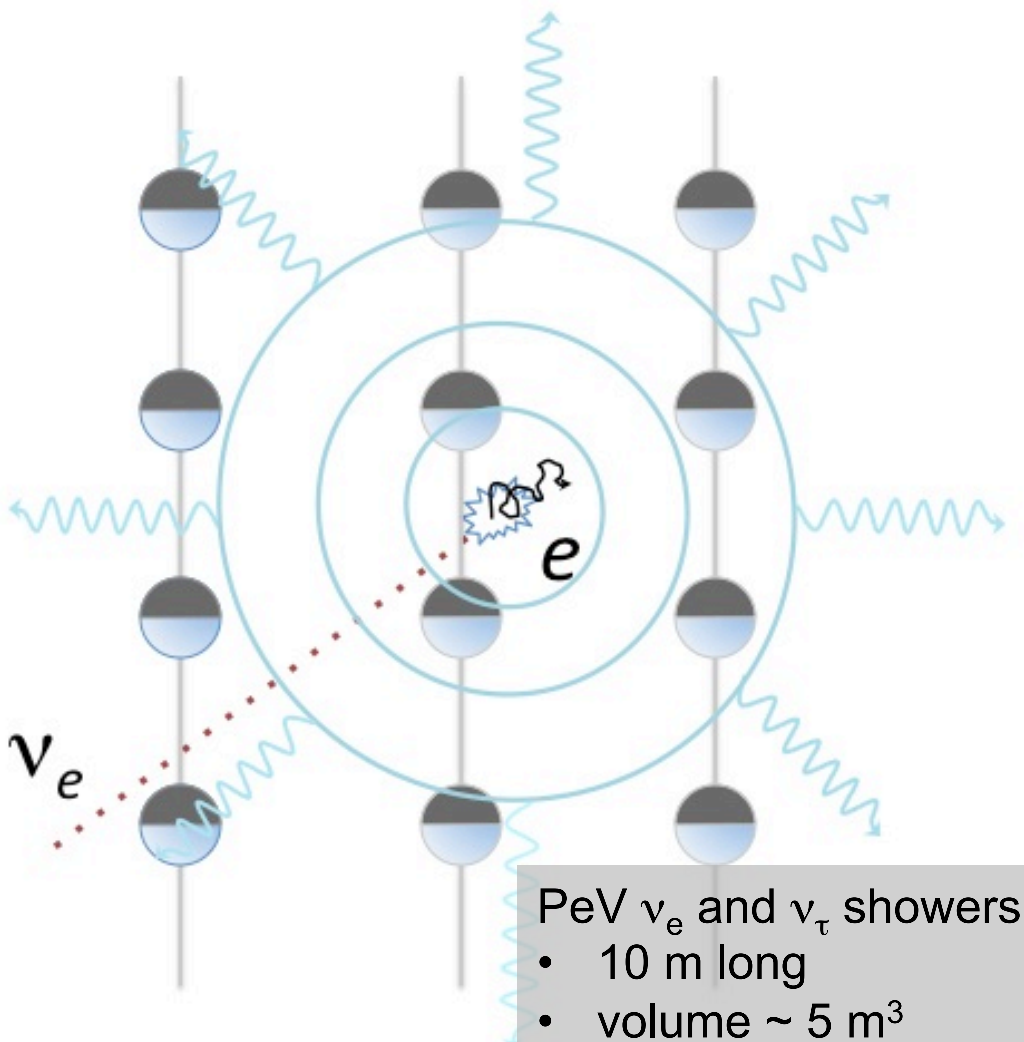
1 event per cubic kilometer per year

...but it points at its source!

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

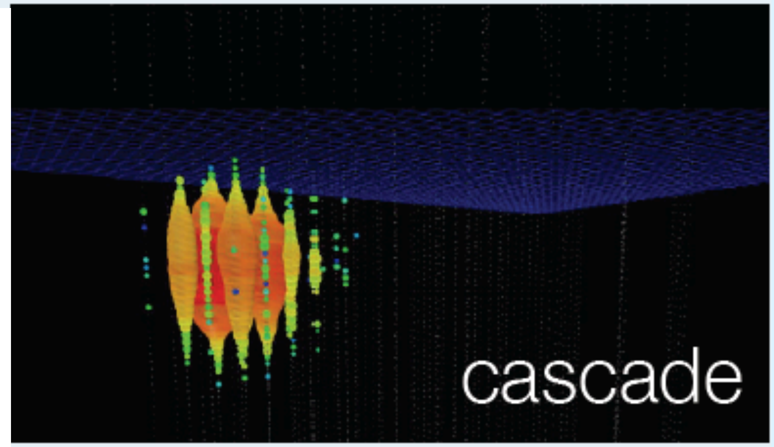


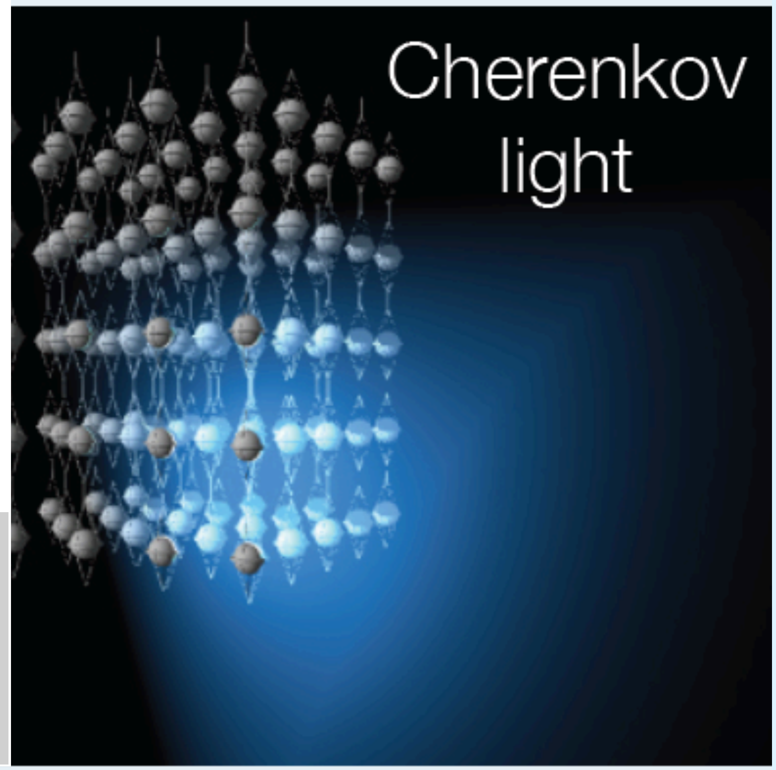
tracks and showers

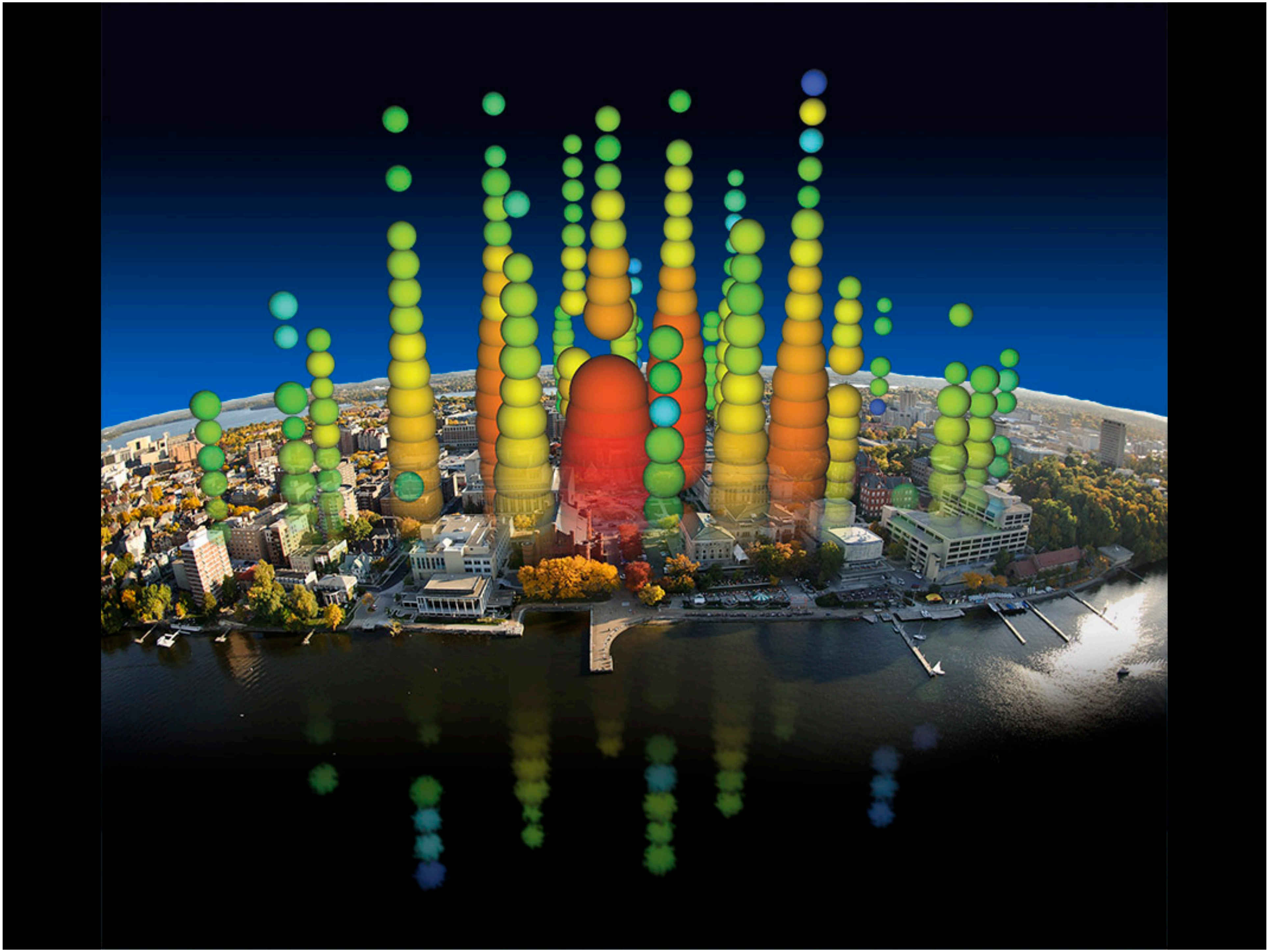


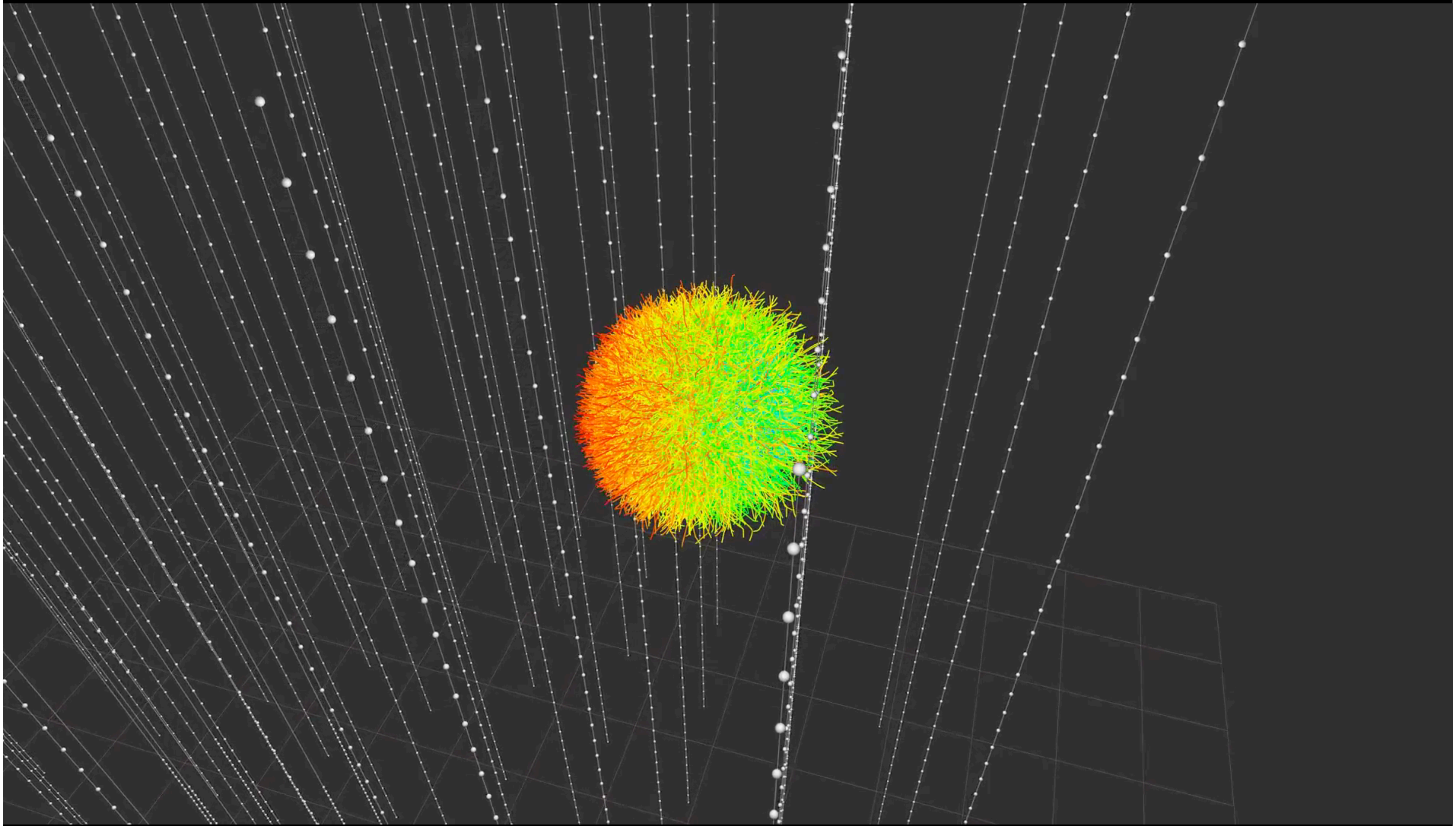
PeV ν_e and ν_τ showers:

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



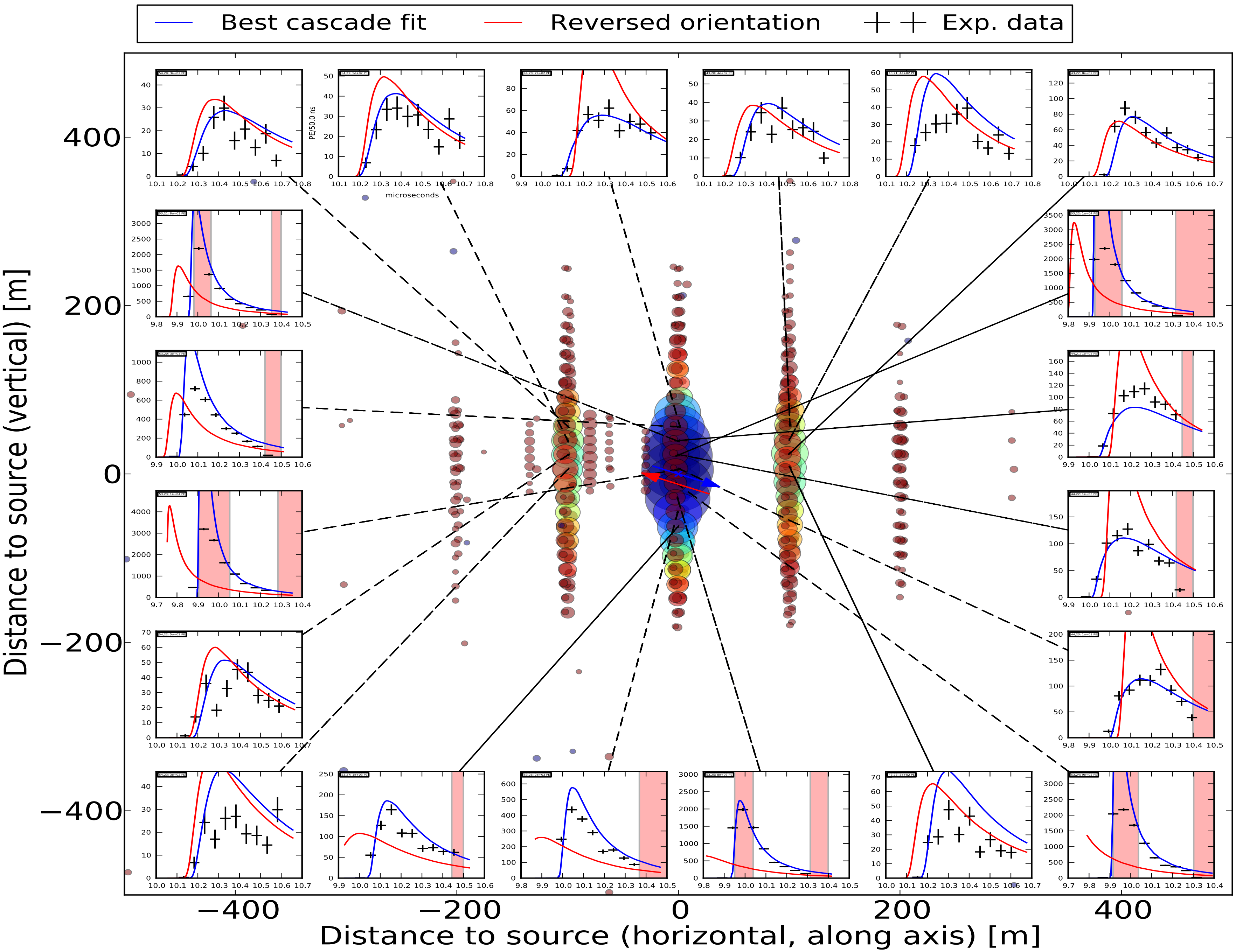






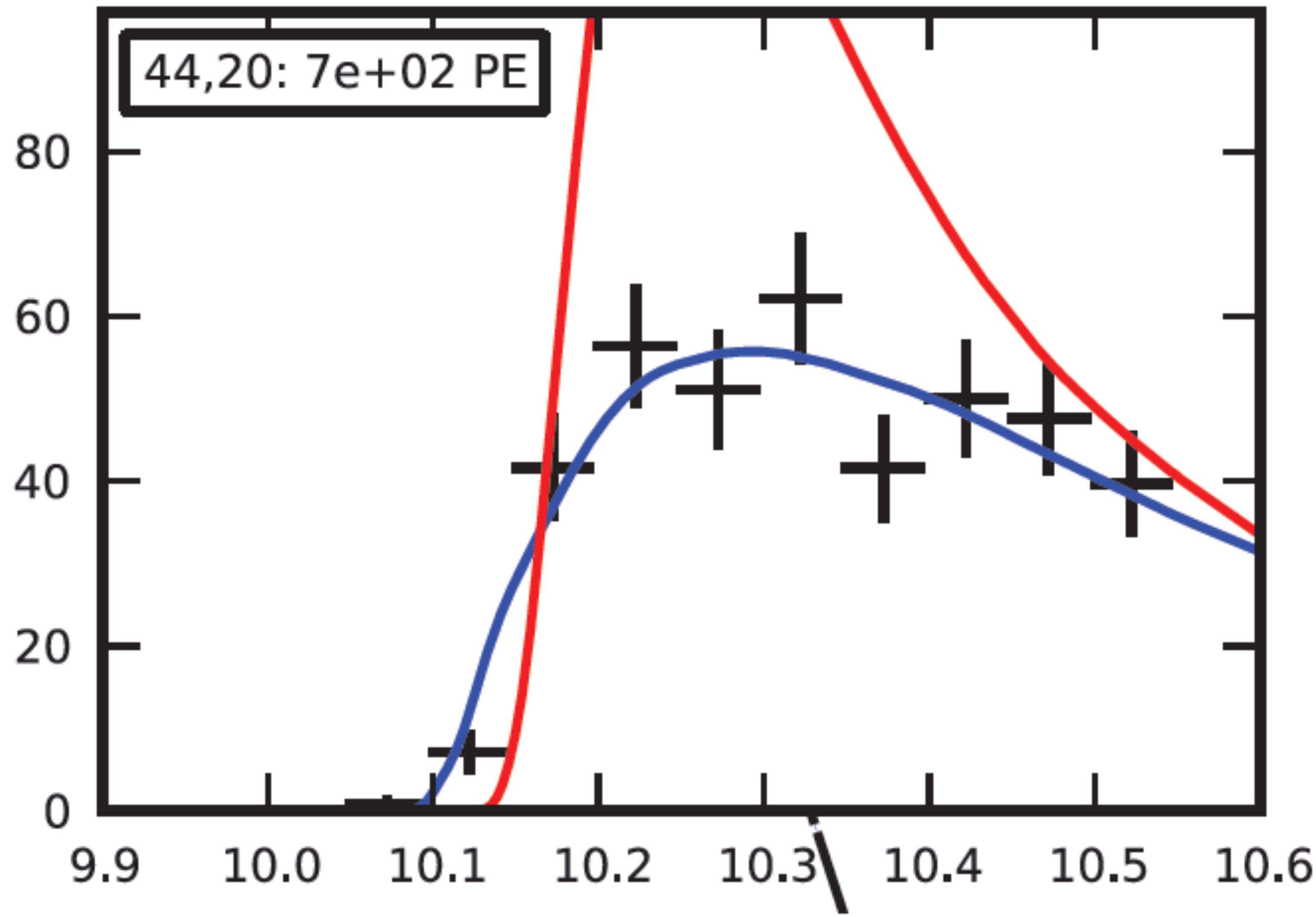
size = energy

color = time = direction

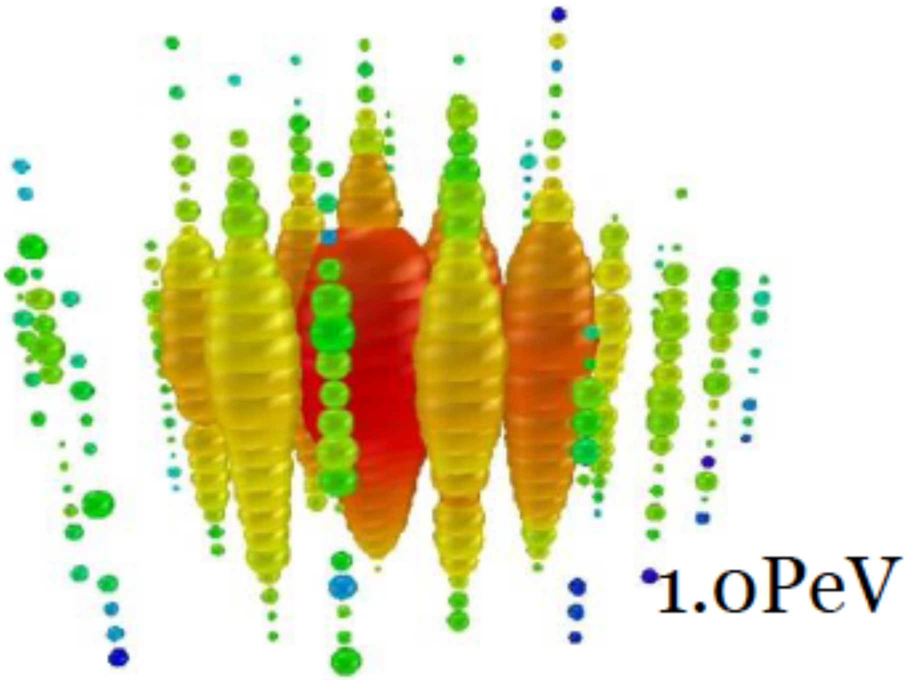


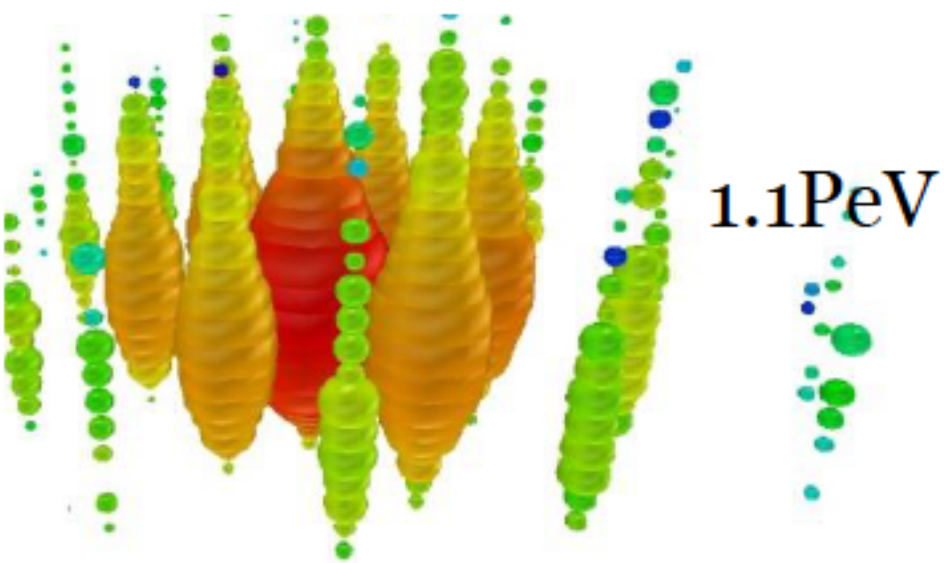
Best cascade fit
Reversed orientation
Exp. data
Distance to source (vertical) [m]
Distance to source (horizontal, along axis) [m]
PE/50.0 ns
microseconds
400
200
0
−200
−400

reconstruction limited by computing, not ice !



Blue: best-fit direction, red: reversed direction





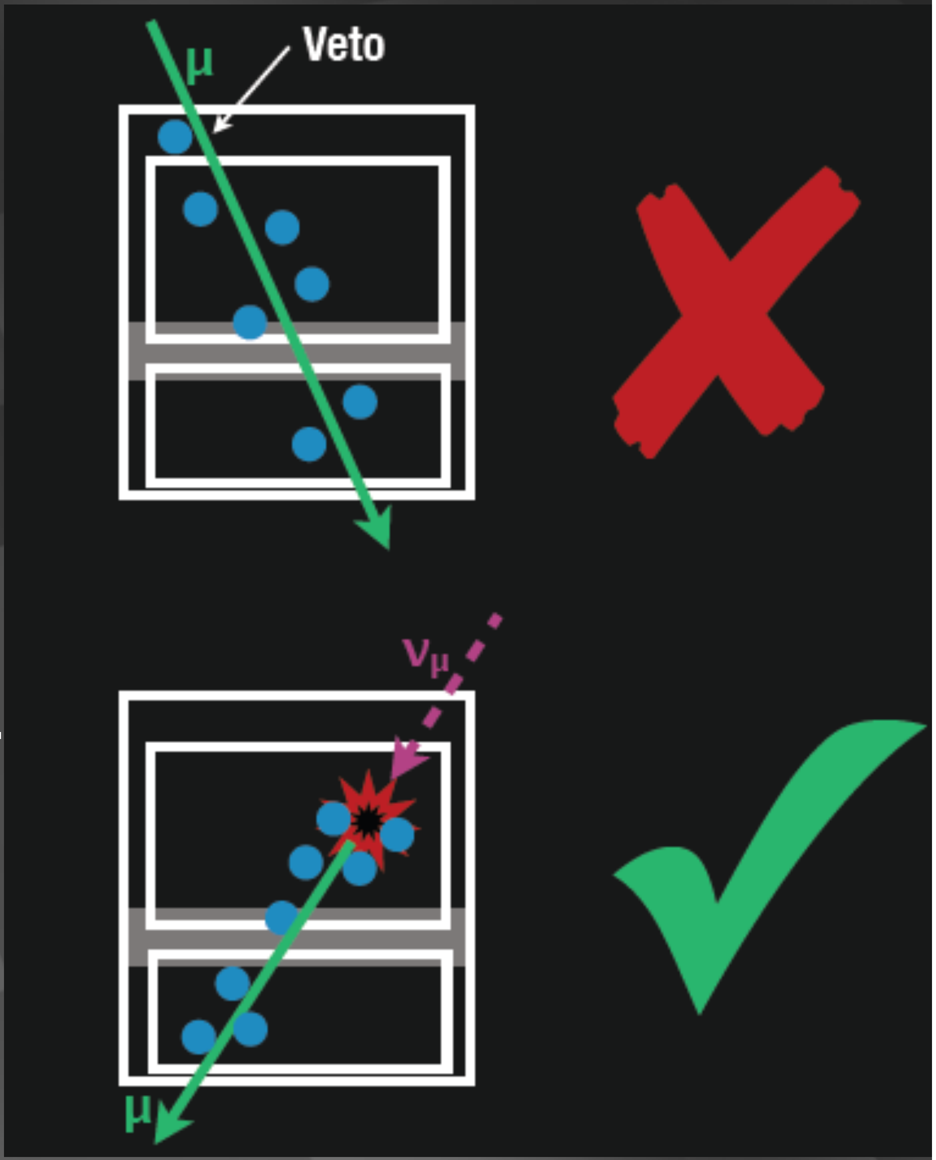
• energy

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

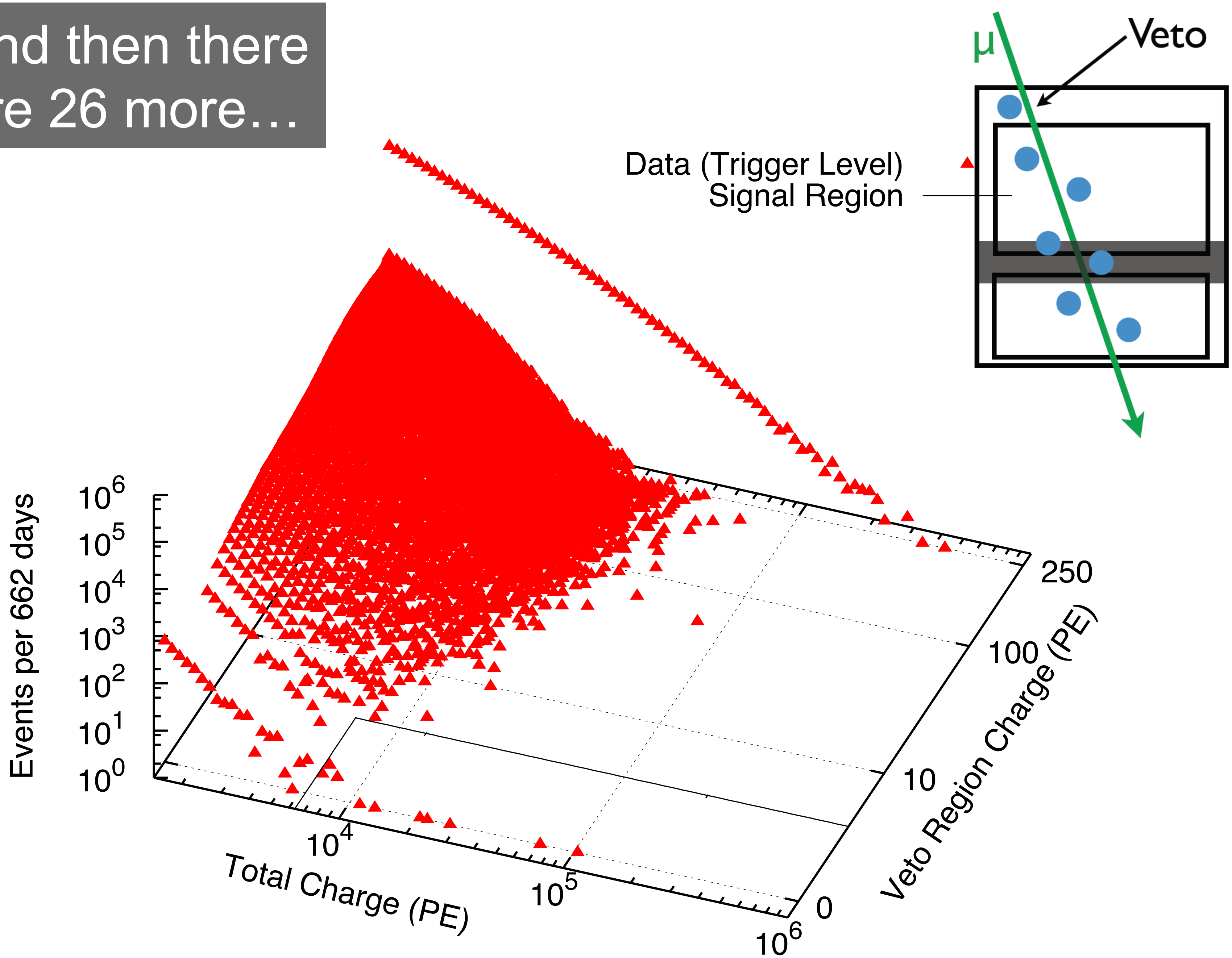
• not atmospheric: probability of no accompanying muon is 10^{-3} per event

→ 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

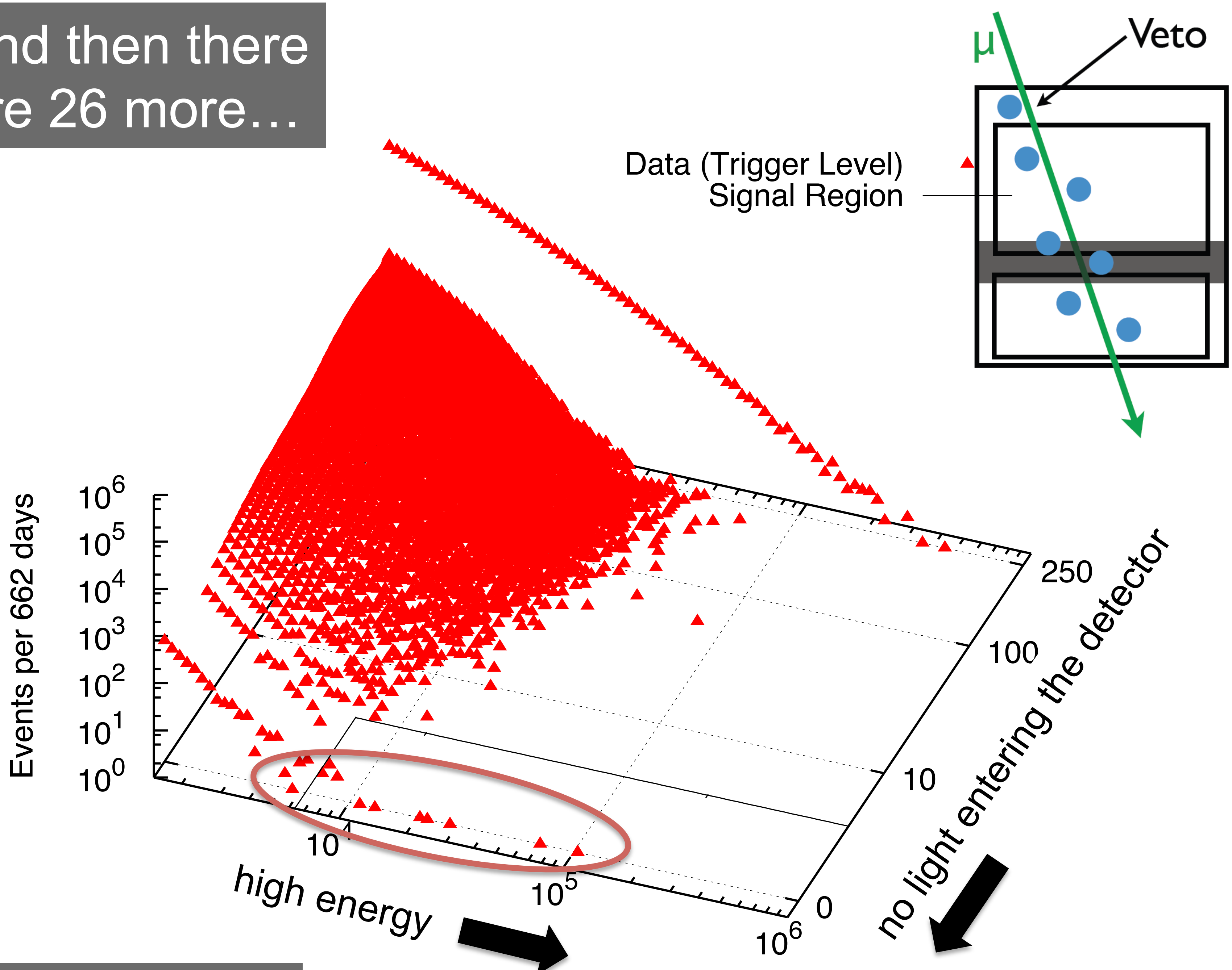


…and then there were 26 more…



data: 86 strings one year

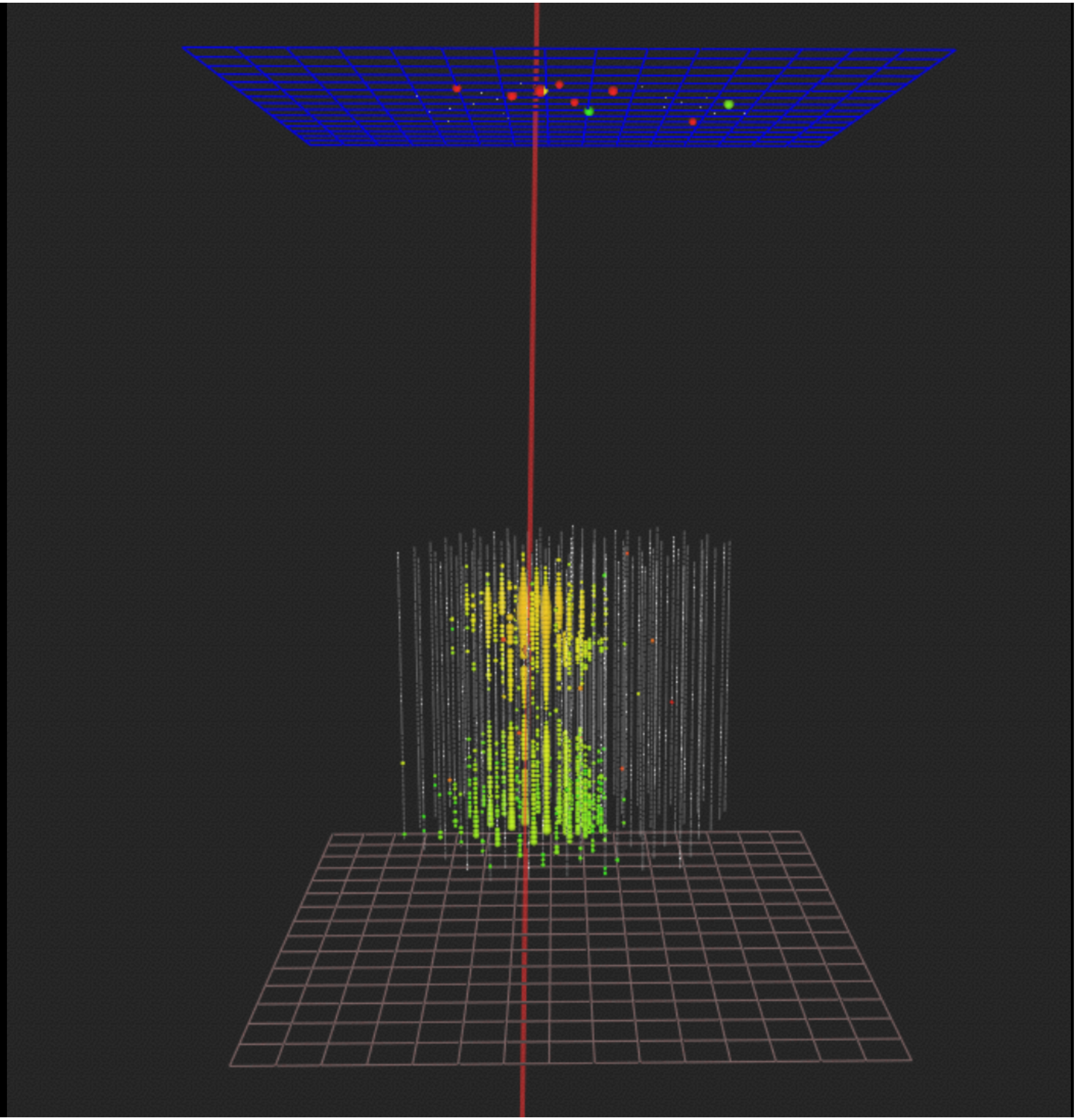
…and then there were 26 more…

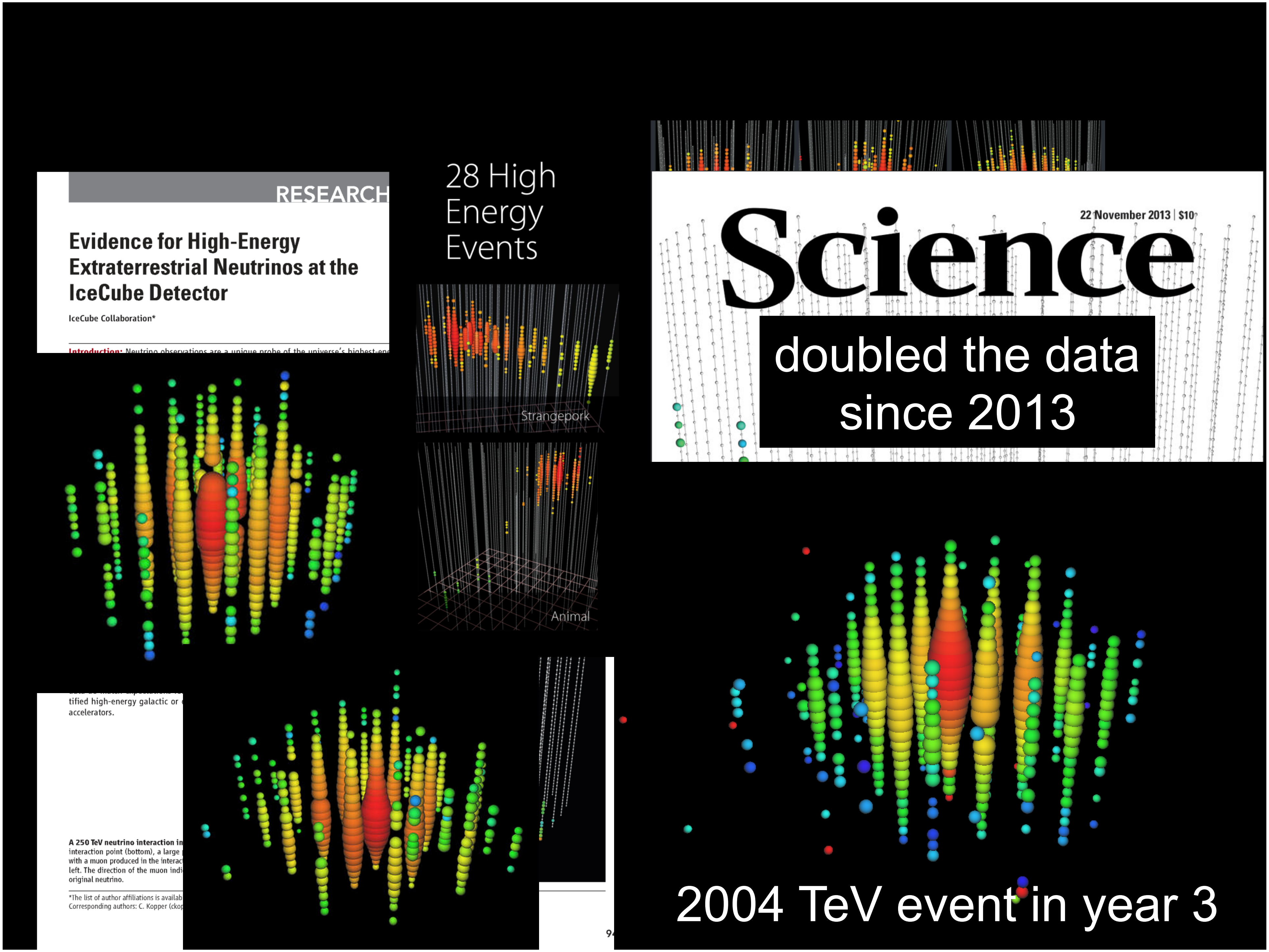


data: 86 strings one year

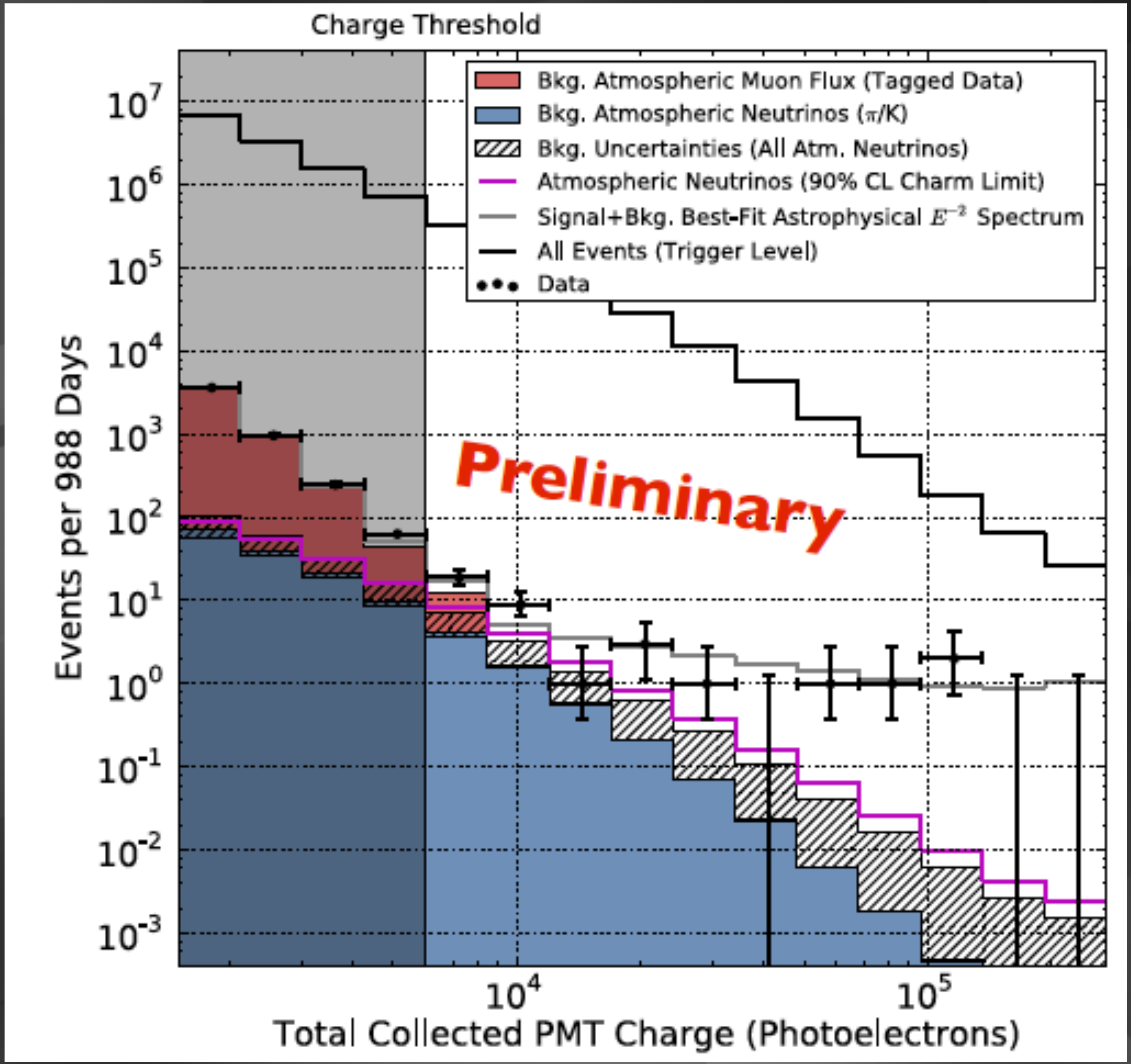
430 TeV inside detector
PeV ν_μ
no air shower

all cosmic neutrinos are isolated



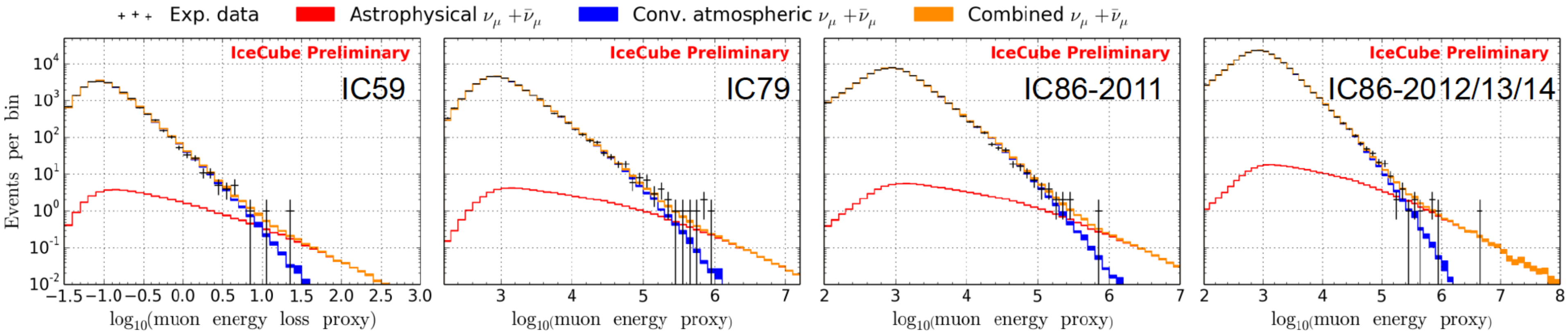

RESEARCH
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector
IceCube Collaboration*
28 High Energy Events
Strangepork
Animal
Science
22 November 2013 | $10
doubled the data since 2013
2004 TeV event in year 3

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



Science 342 (2013) 1242856

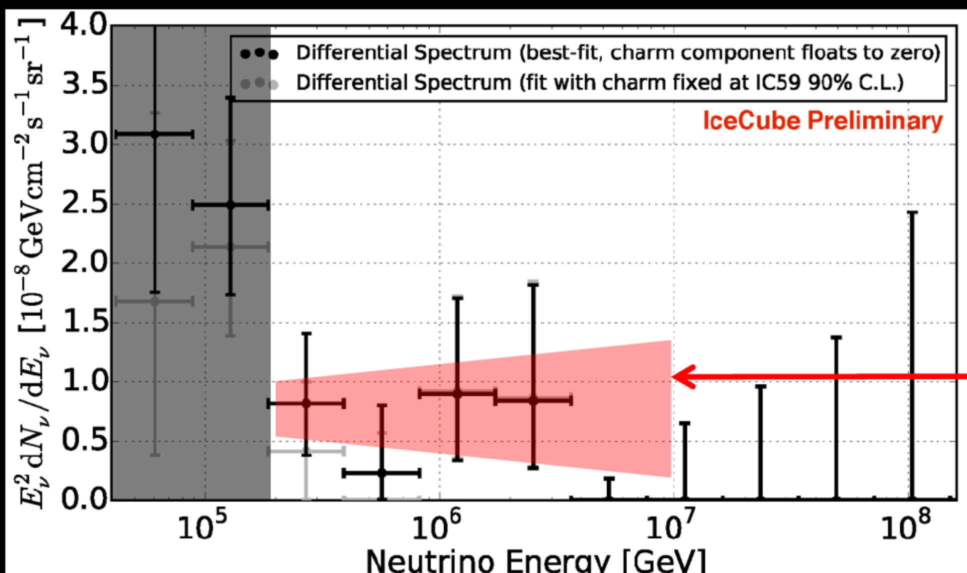
after 6 years: 3.7→ 6.0 sigma

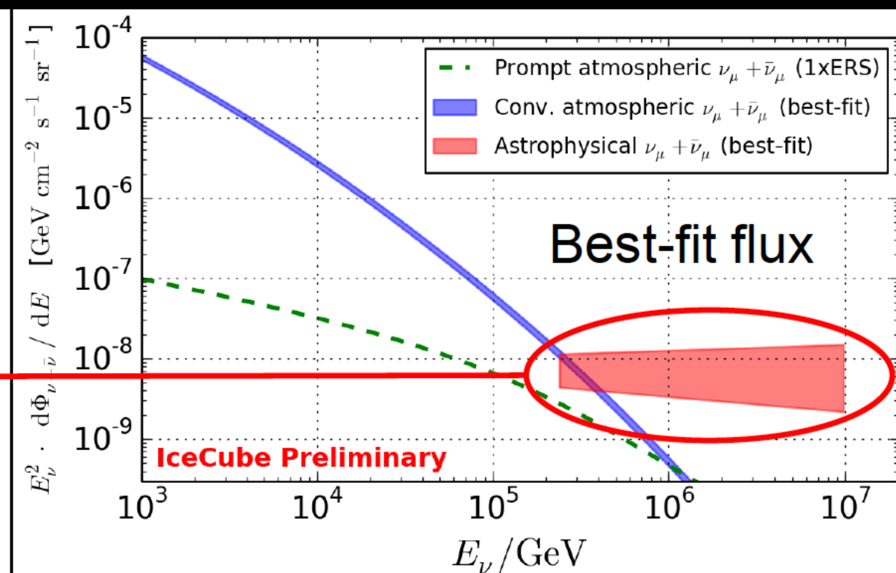


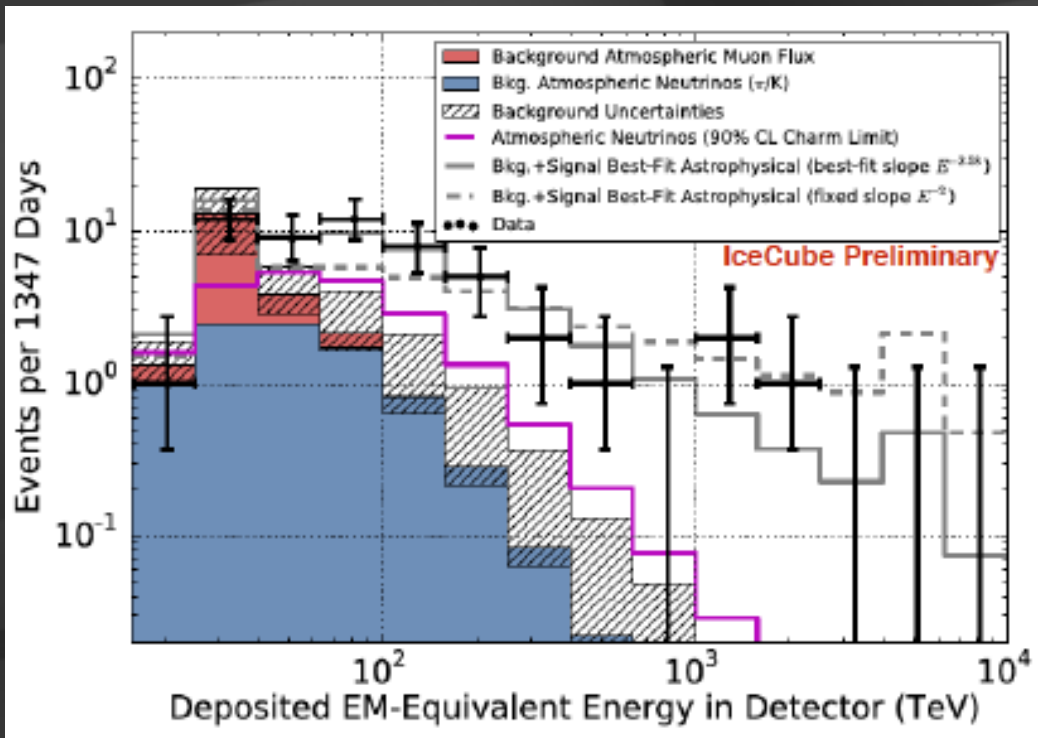
HESE 4 year unfolding

(→ dominated by shower-like events)

6 year up-going numu analysis

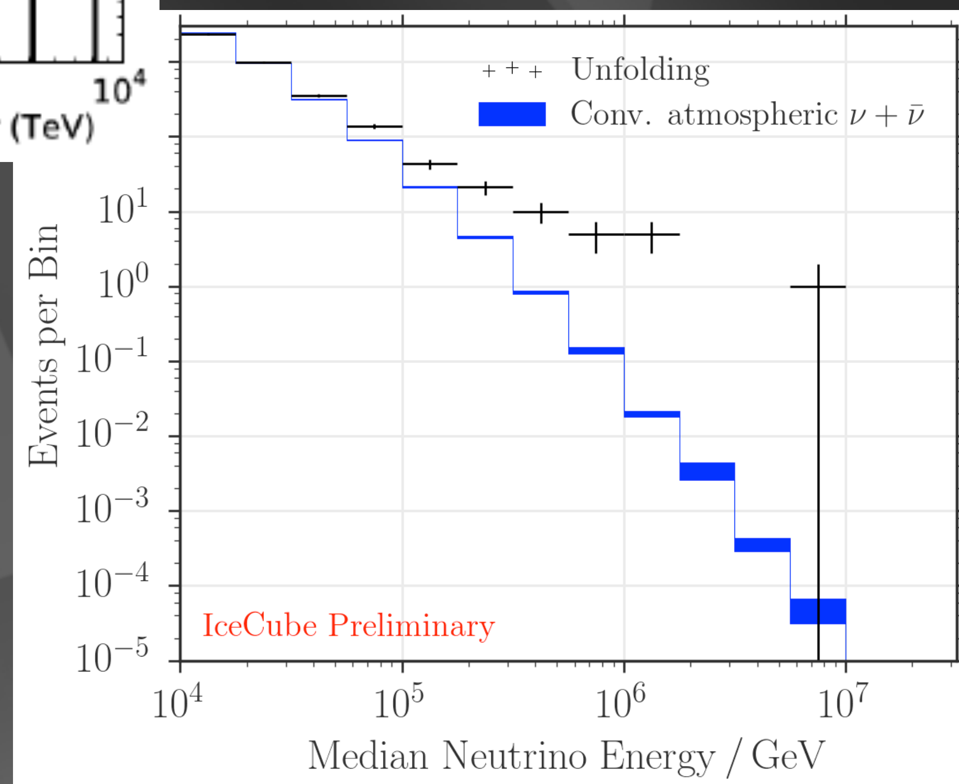


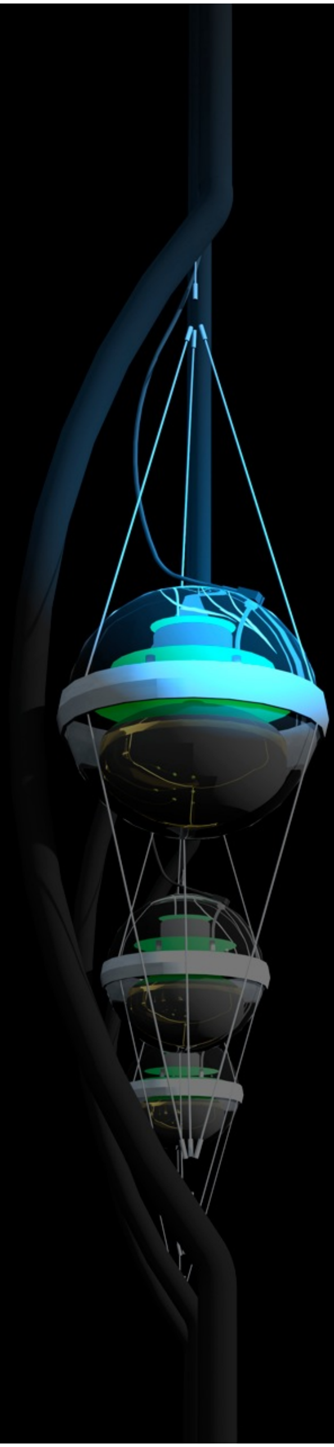




neutrinos of all flavors interacting inside IceCube

confirmation!
flux of muon neutrinos through the Earth



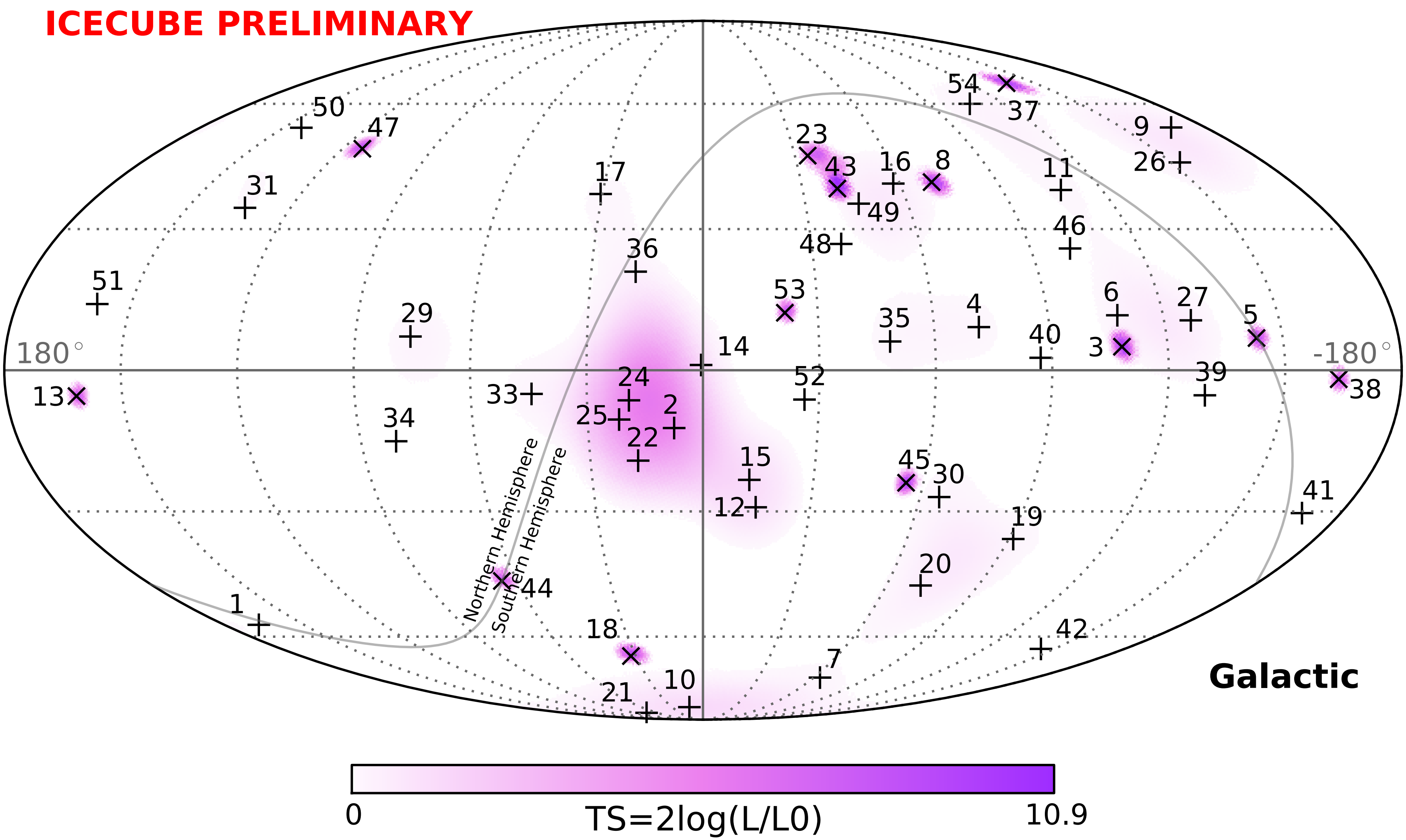


IceCube: the discovery of cosmic neutrinos
francis halzen

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

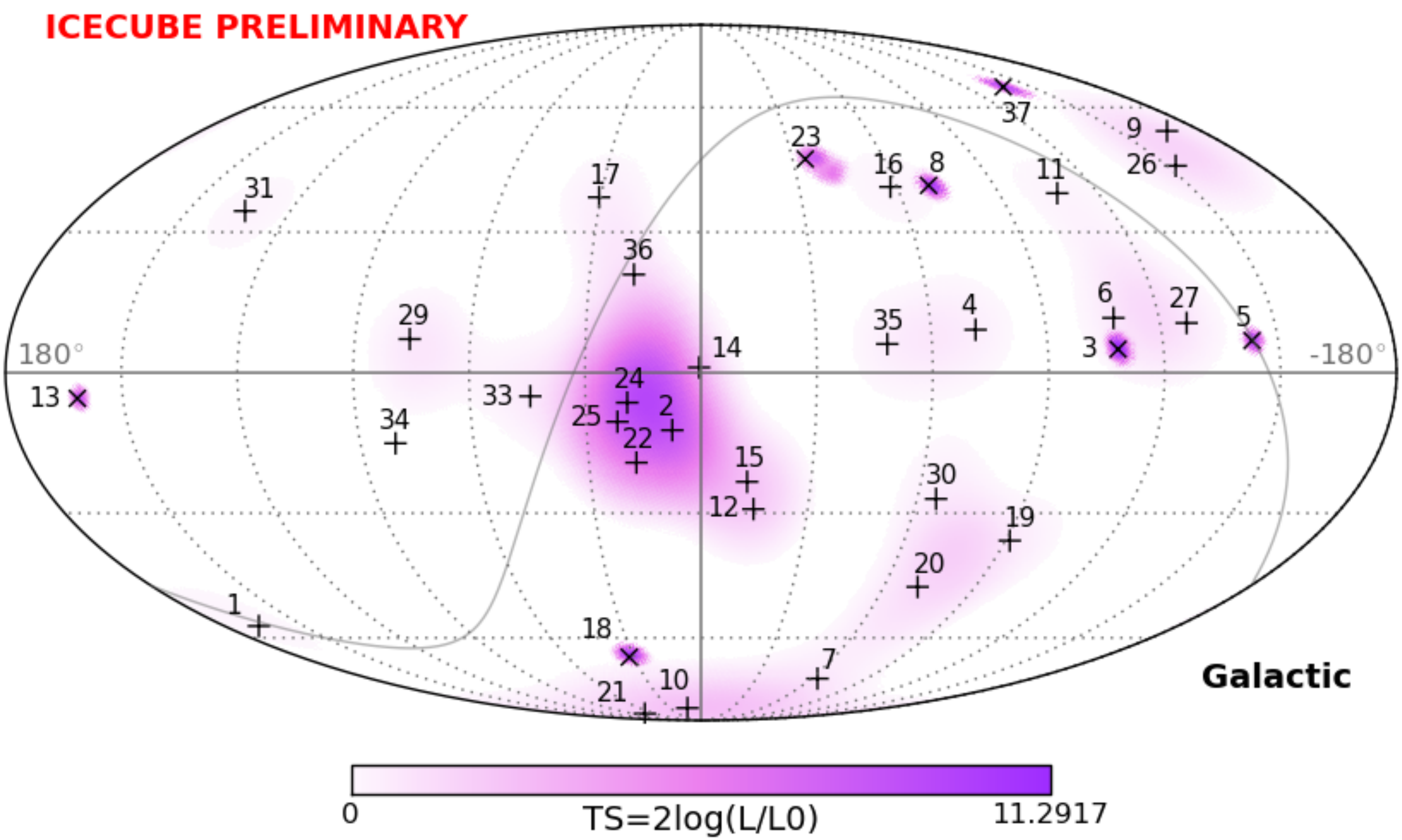
IceCube.wisc.edu

4 year HESE (6 soon)



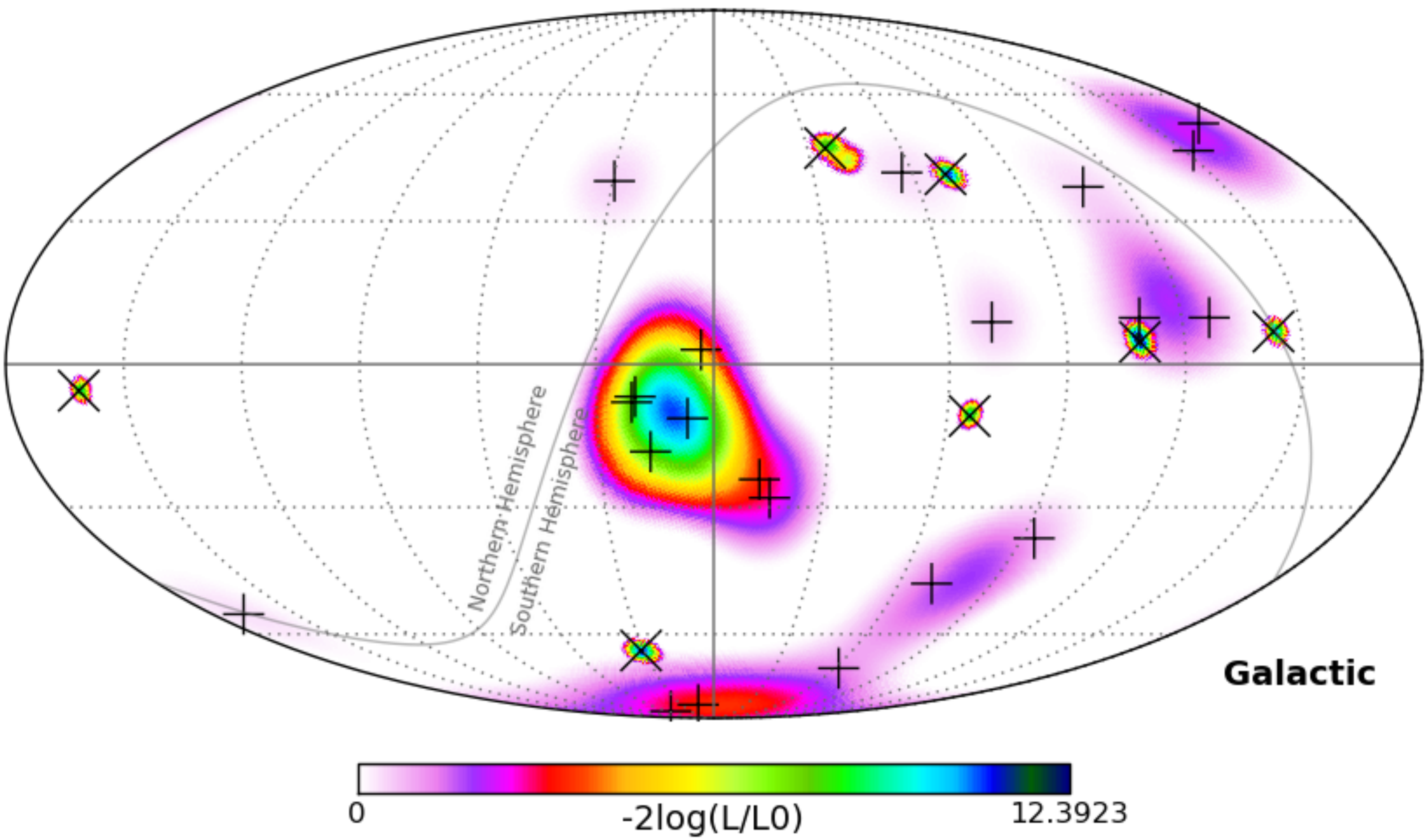
where do they come from?

3 year HESE

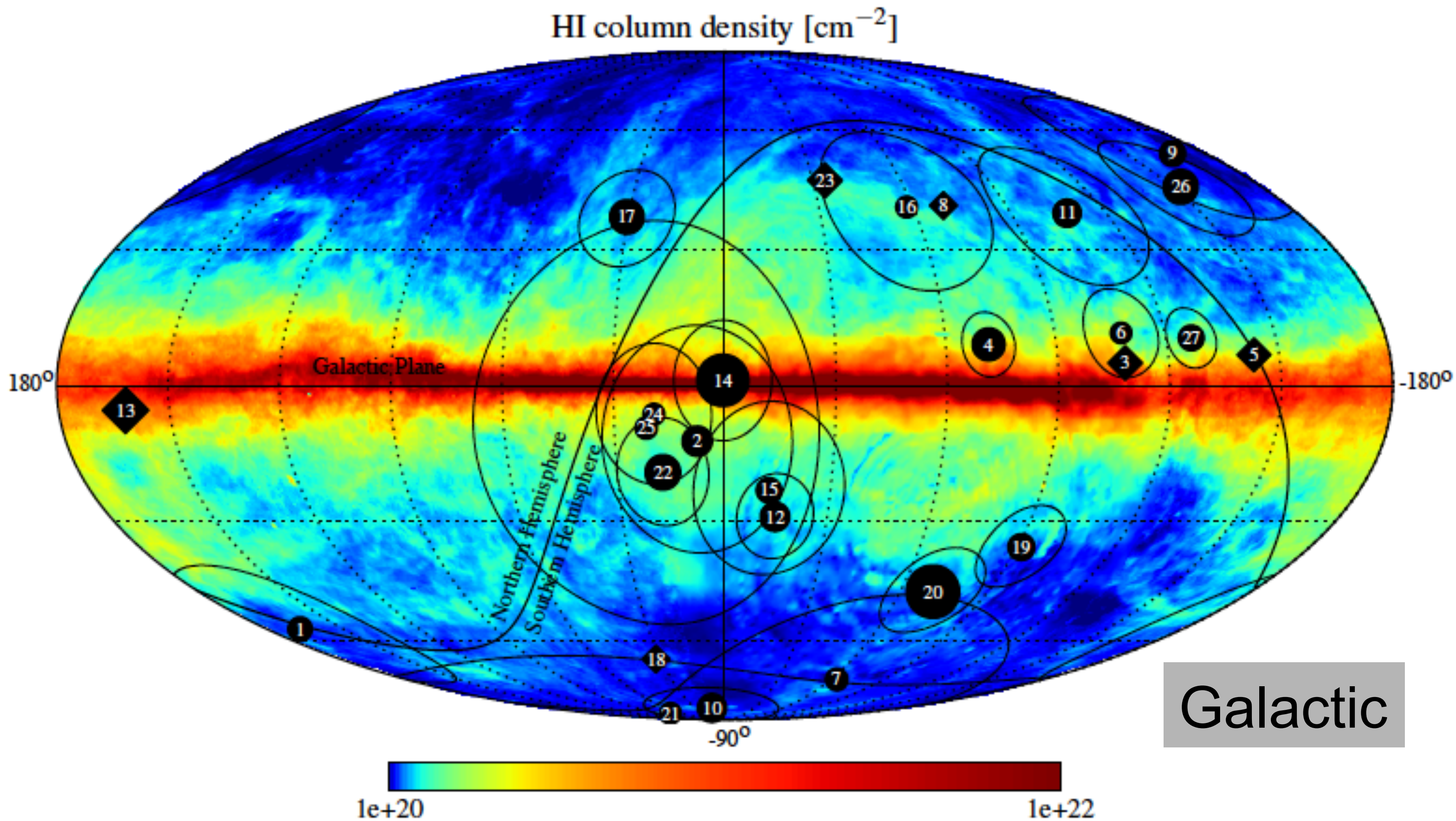


ICECUBE PRELIMINARY
180°
-180°
Galactic
0
TS=2log(L/L0)
11.2917
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
29
30
31
33
34
35
36
37

2 year HESE

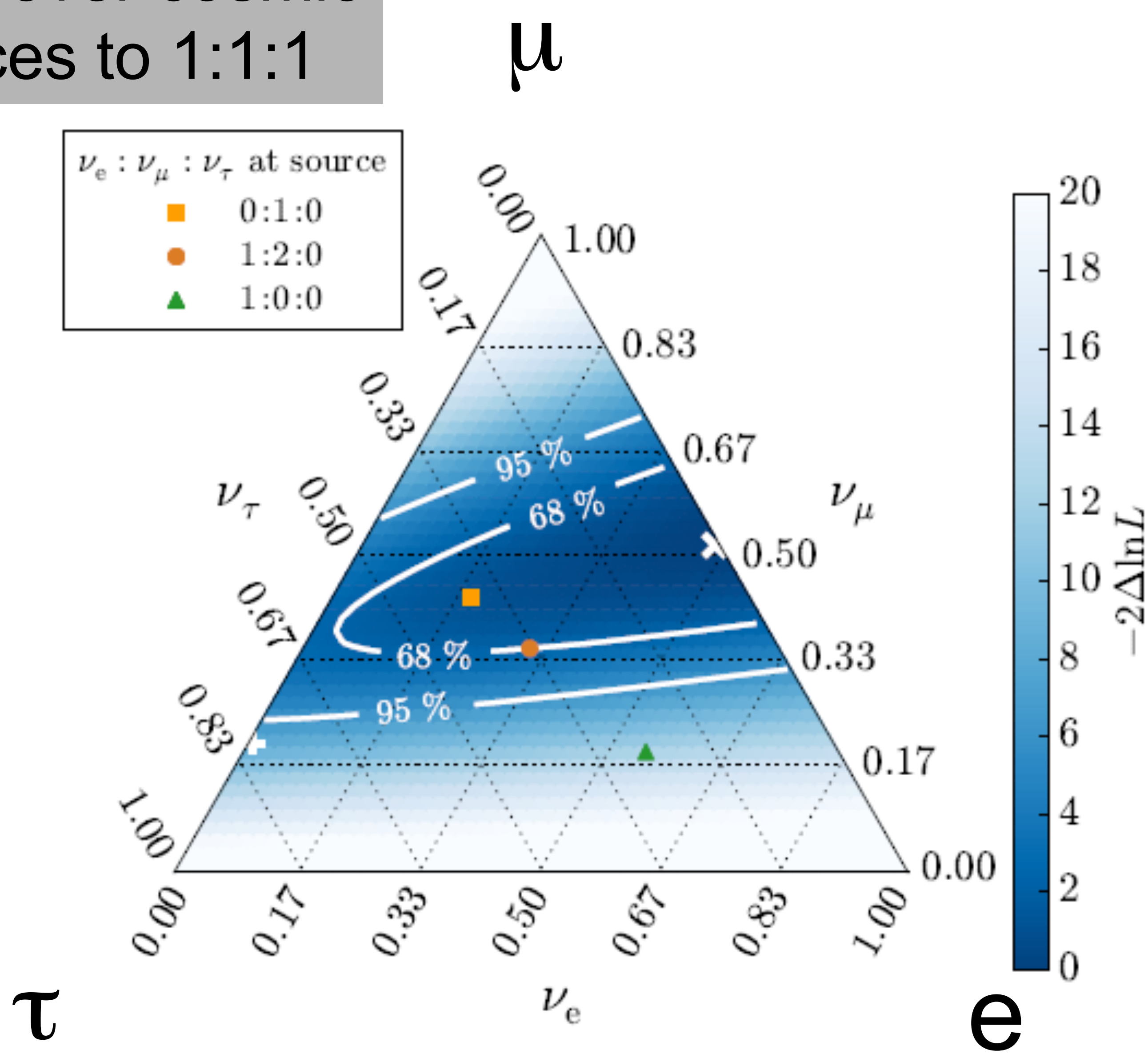

Northern Hemisphere
Southern Hemisphere
Galactic
0
-2log(L/L0)
12.3923

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



Galactic

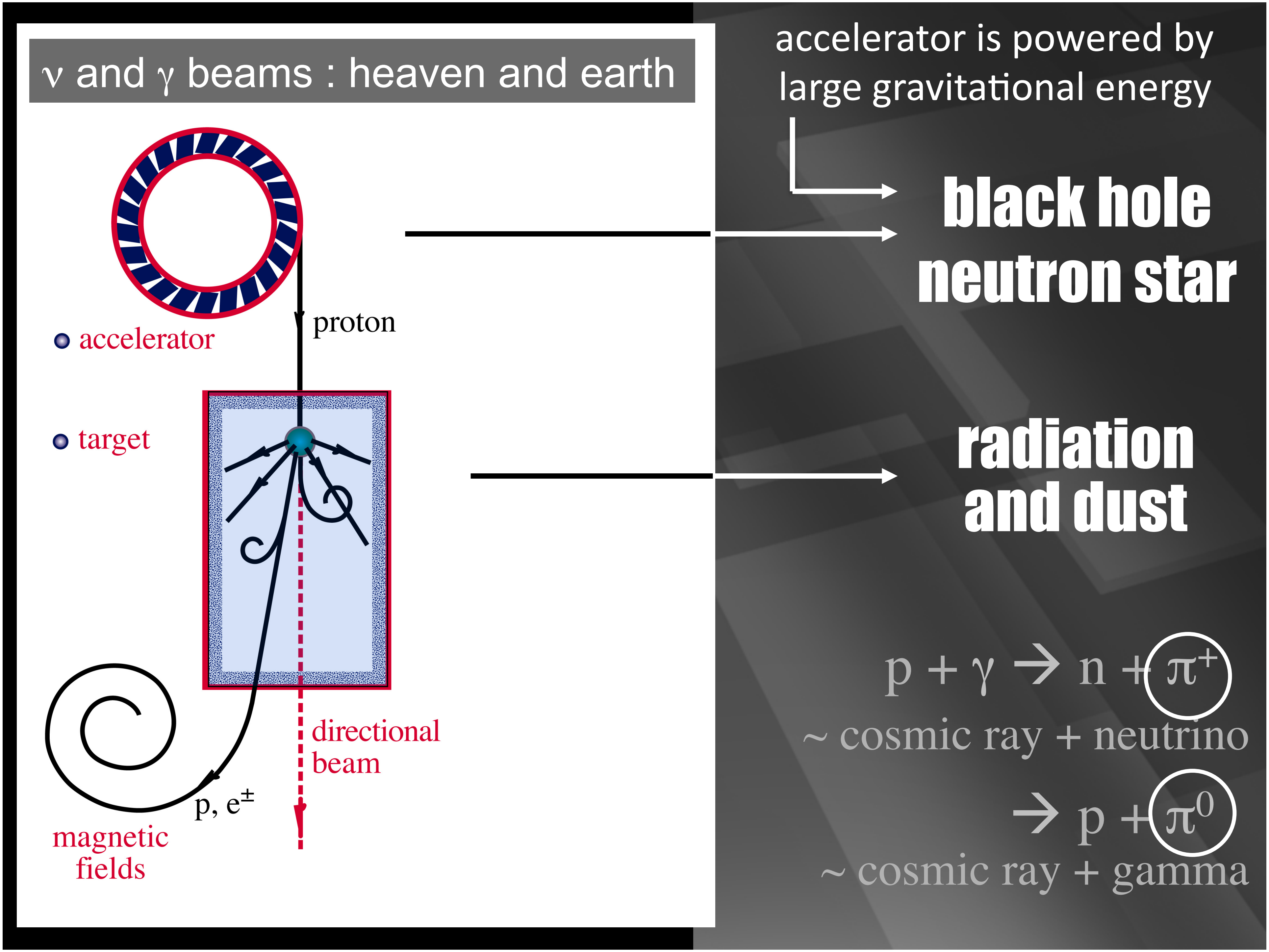
oscillate over cosmic distances to 1:1:1

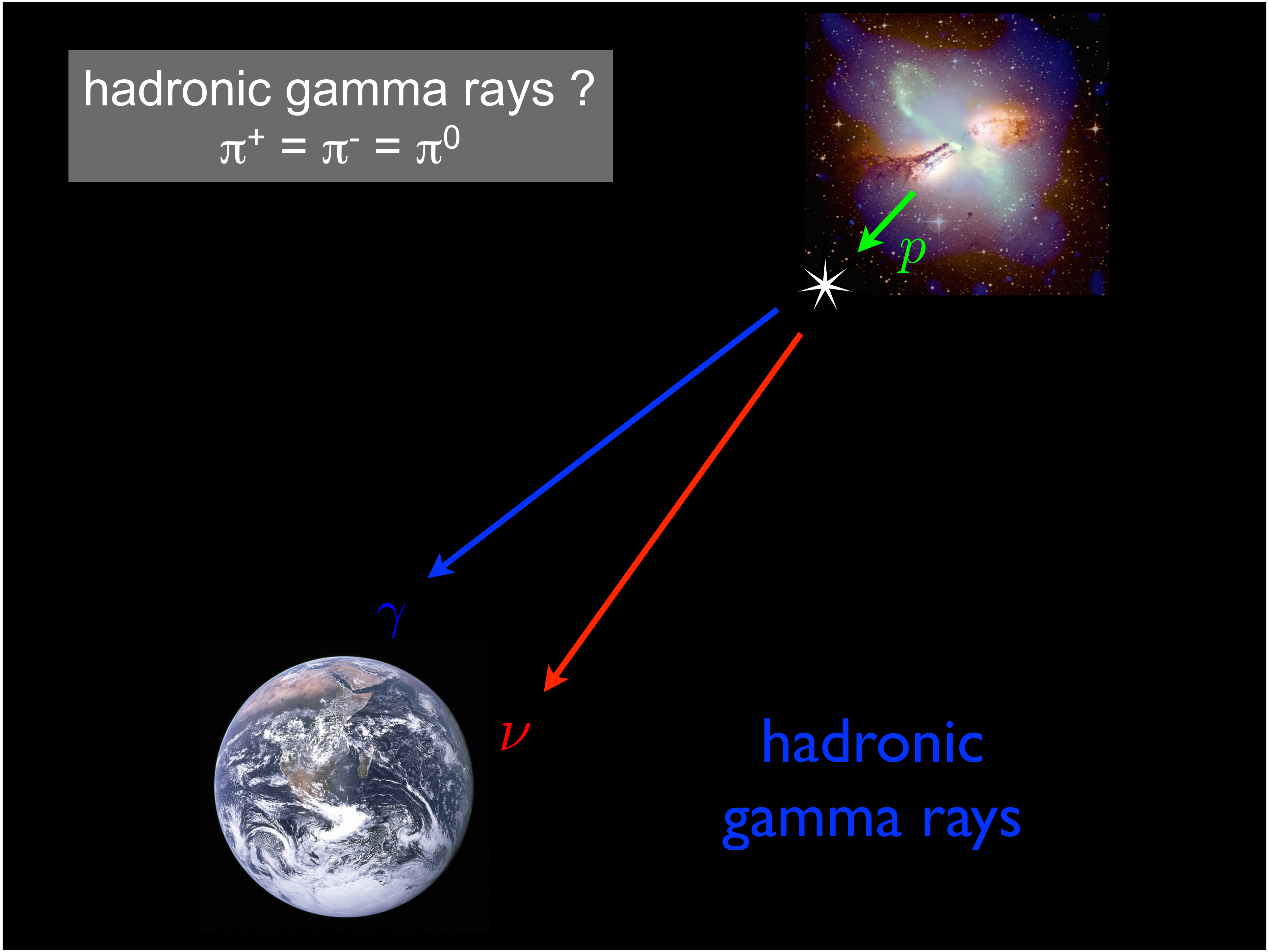


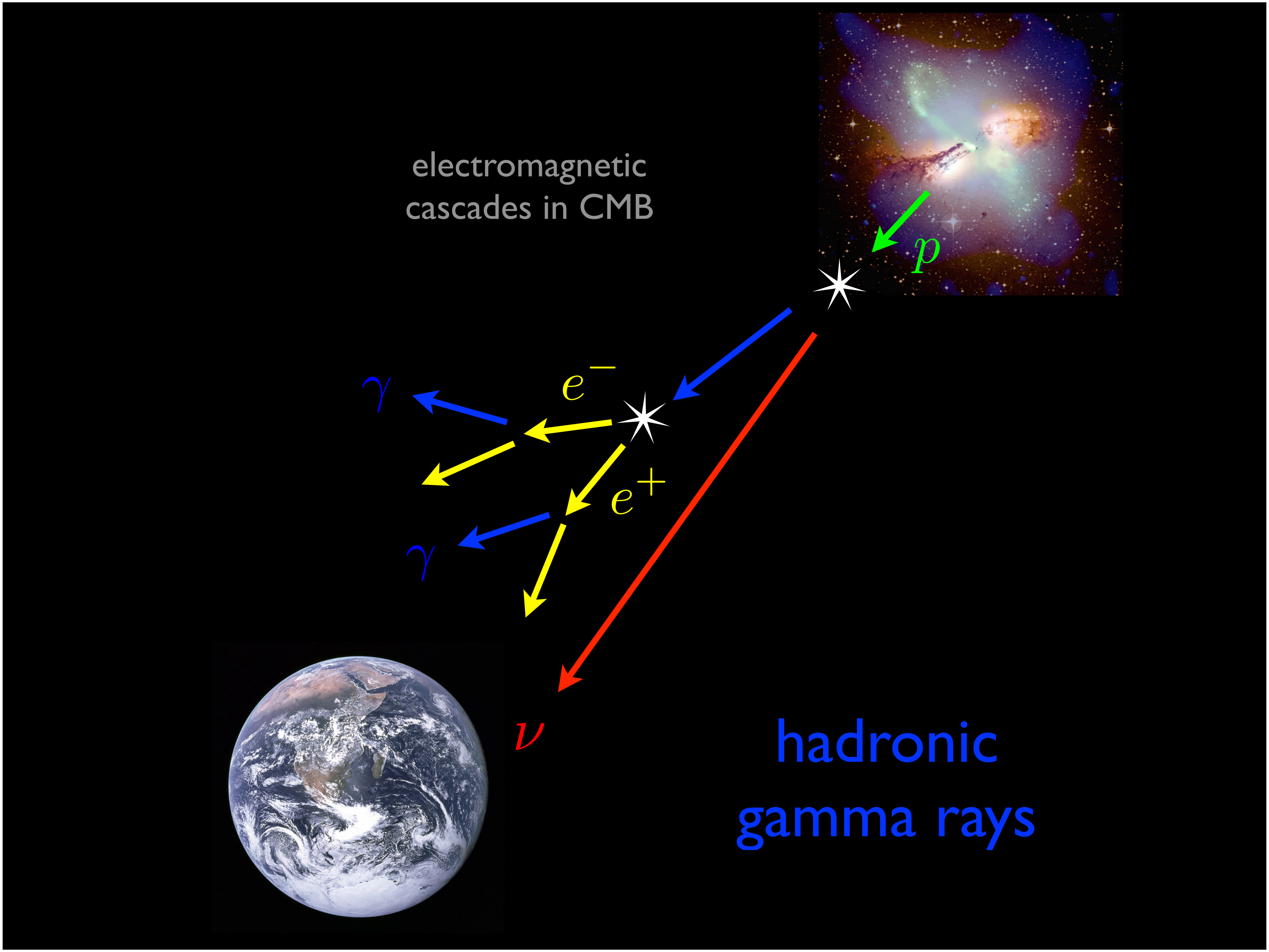
- we observe a diffuse flux of neutrinos from extragalactic sources

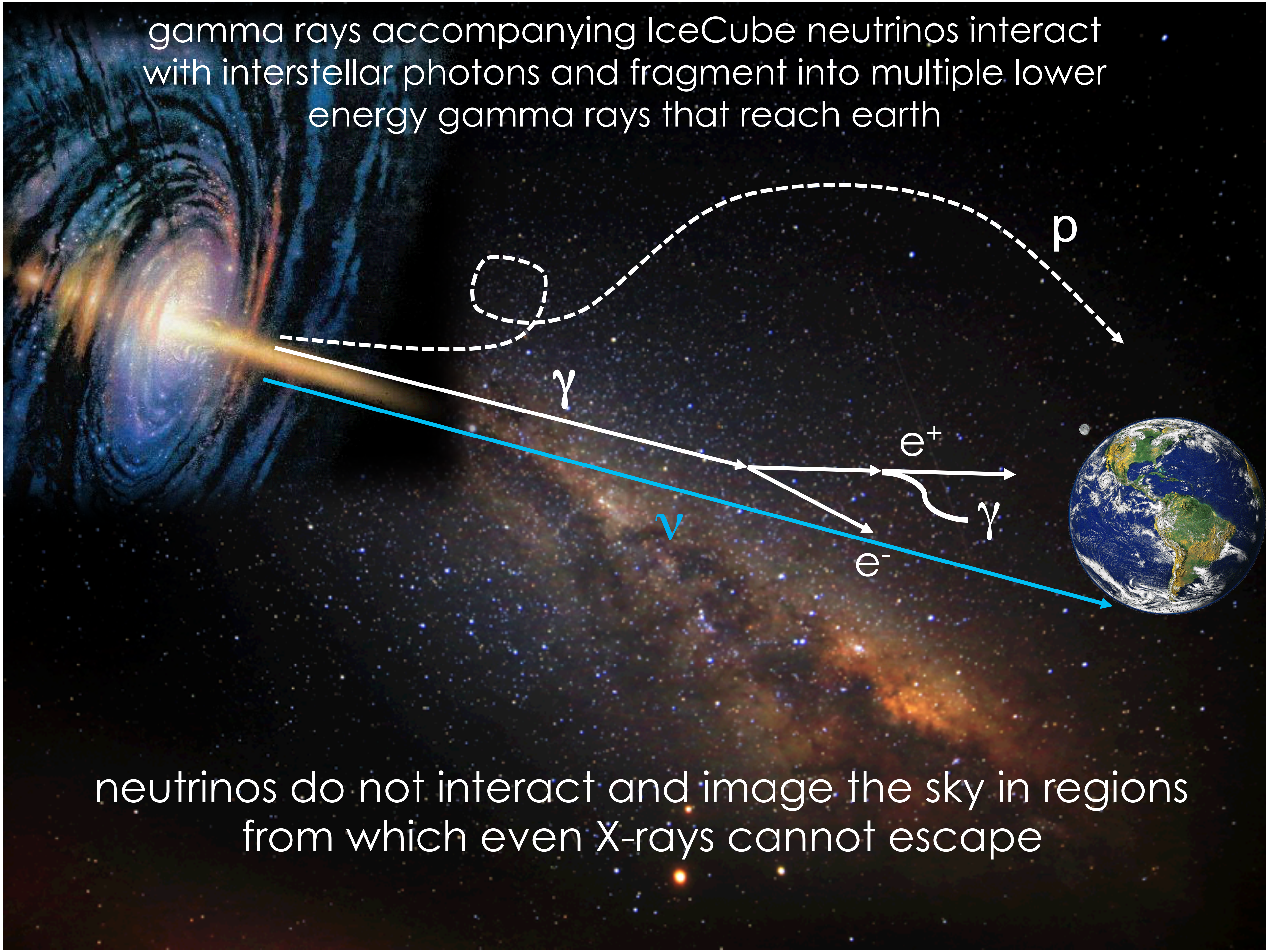
- a subdominant Galactic component cannot be excluded

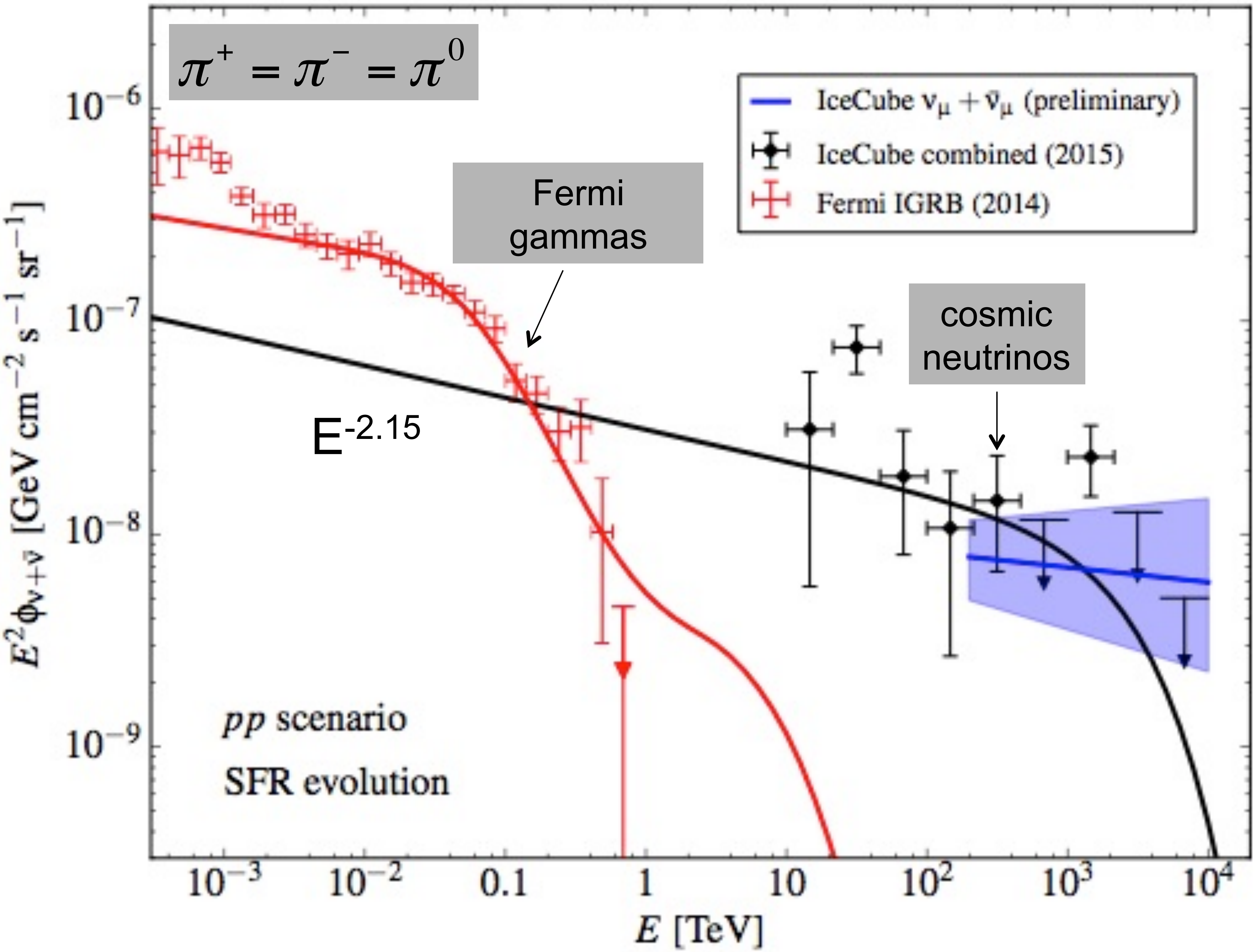
- where are the PeV gamma rays that accompany PeV neutrinos?


ν and γ beams : heaven and earth
accelerator
proton
target
directional
beam
p, e±
magnetic
fields
accelerator is powered by
large gravitational energy
black hole
neutron star
radiation
and dust
p + γ → n + π+
~ cosmic ray + neutrino
→ p + π0
~ cosmic ray + gamma


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


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


gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth
p
γ
e^+
γ
ν
e^-
neutrinos do not interact and image the sky in regions from which even X-rays cannot escape

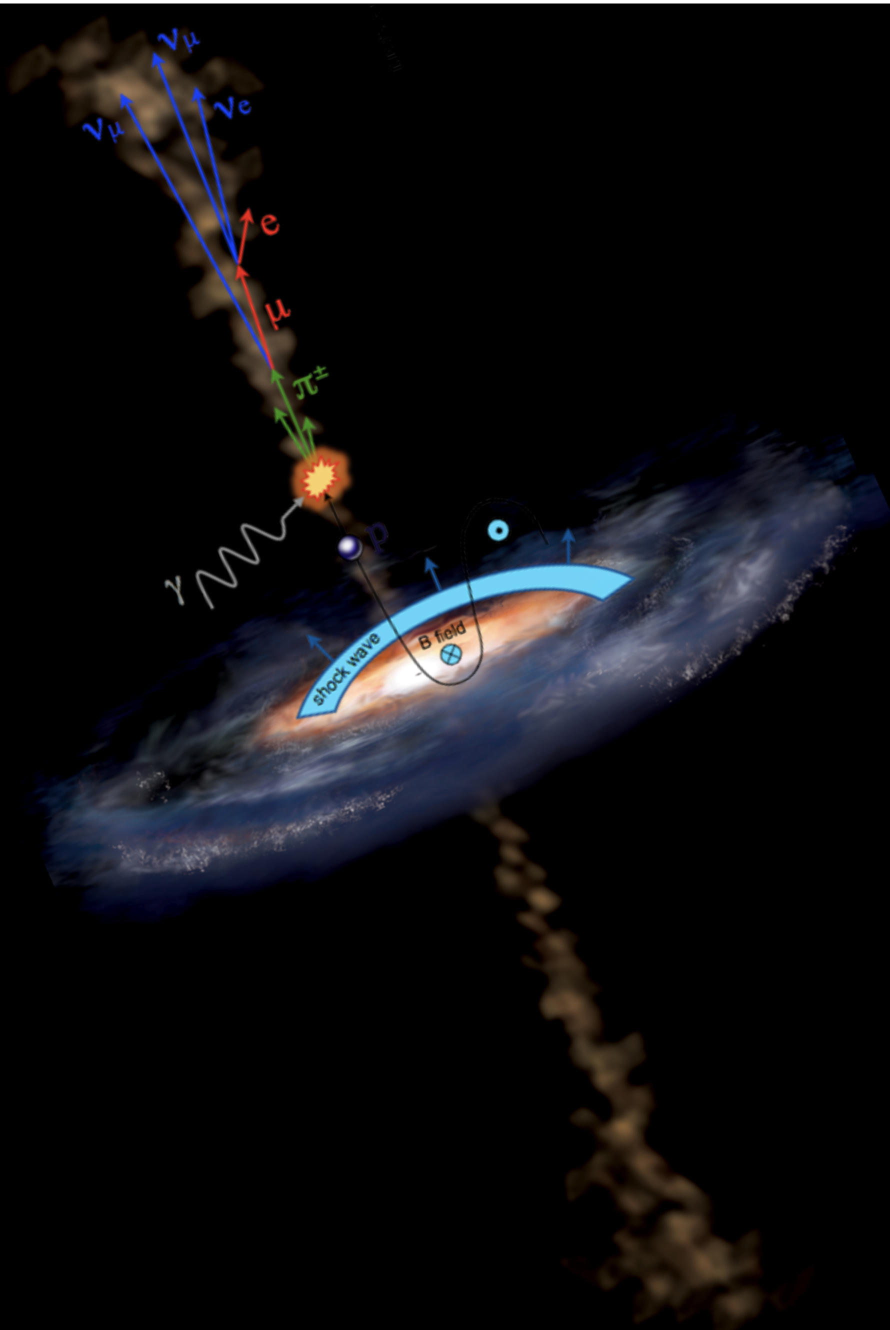


$\pi^+ = \pi^- = \pi^0$
IceCube $\nu_\mu + \bar{\nu}_\mu$ (preliminary)
IceCube combined (2015)
Fermi IGRB (2014)
Fermi gammas
cosmic neutrinos
$E^{-2.15}$
pp scenario
SFR evolution
$E^2\Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [TeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3
10^4

- 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 photons (and cosmic rays}

- at some level common Fermi-IceCube sources? look for spatial and especially temporal coincidences

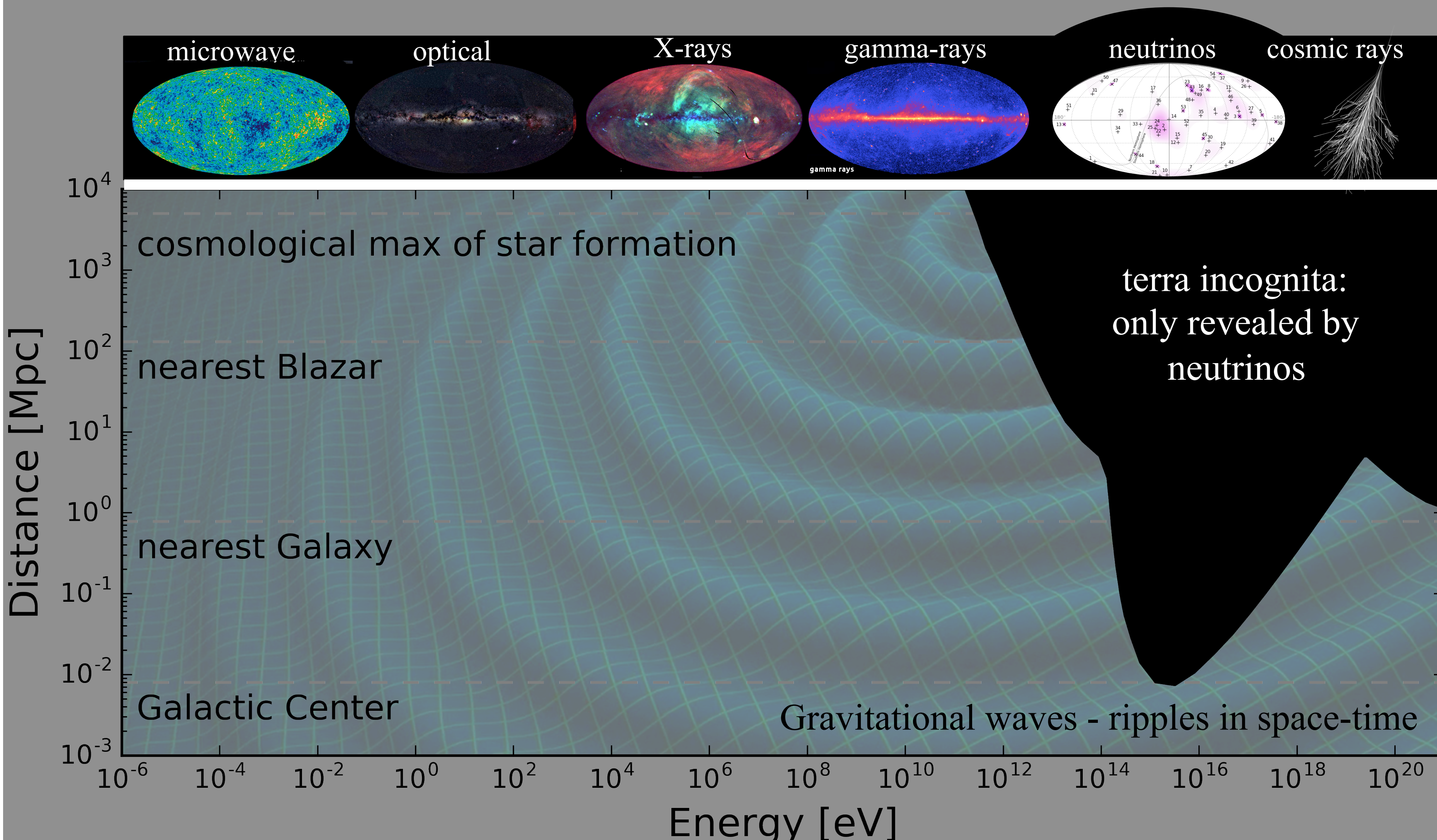


high energy photons
escape from regions
with low density where
neutrino production is
suppressed
not identical sources

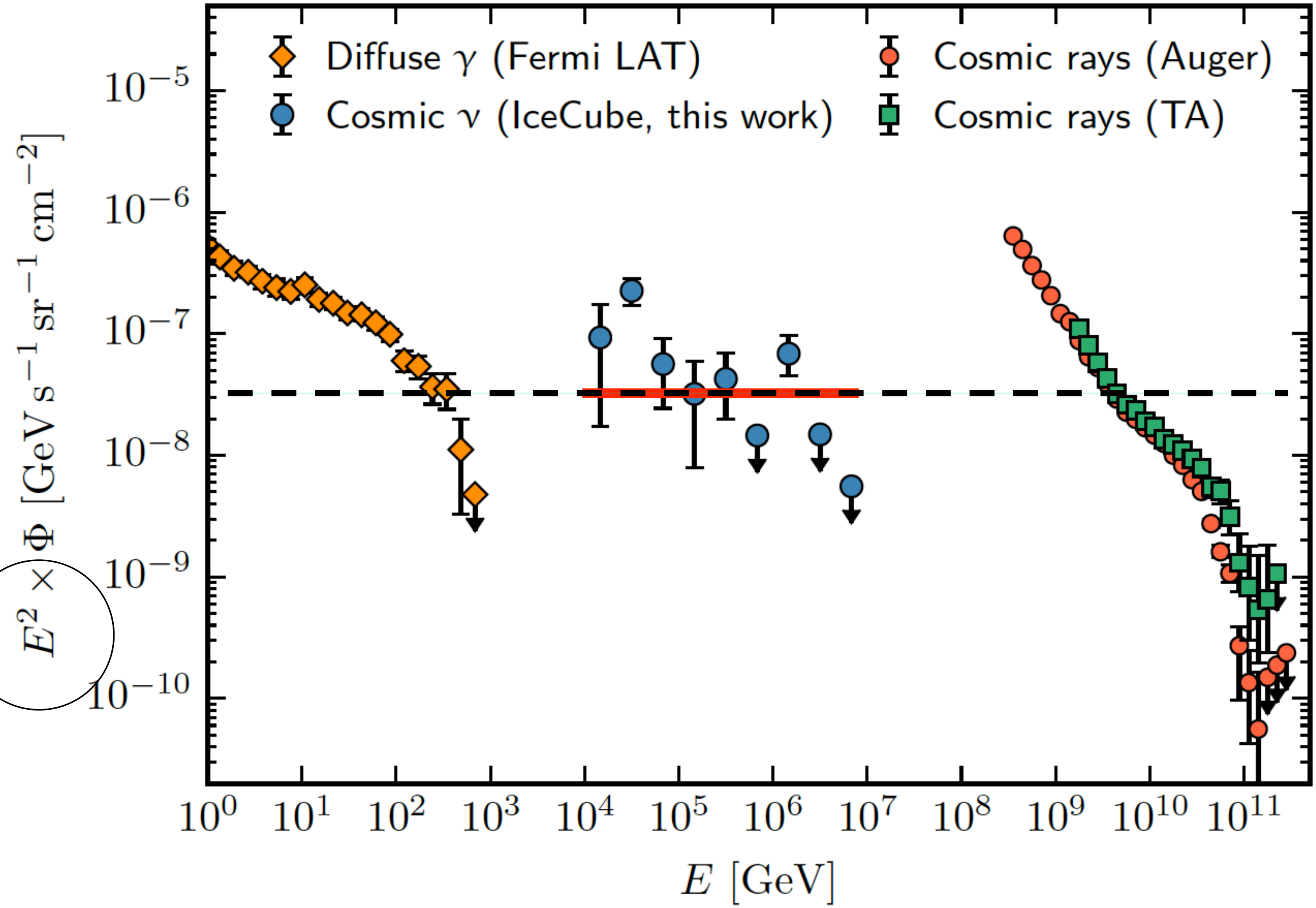
active galaxy

particle flows near
supermassive
black hole

Multi-Messenger Astronomy



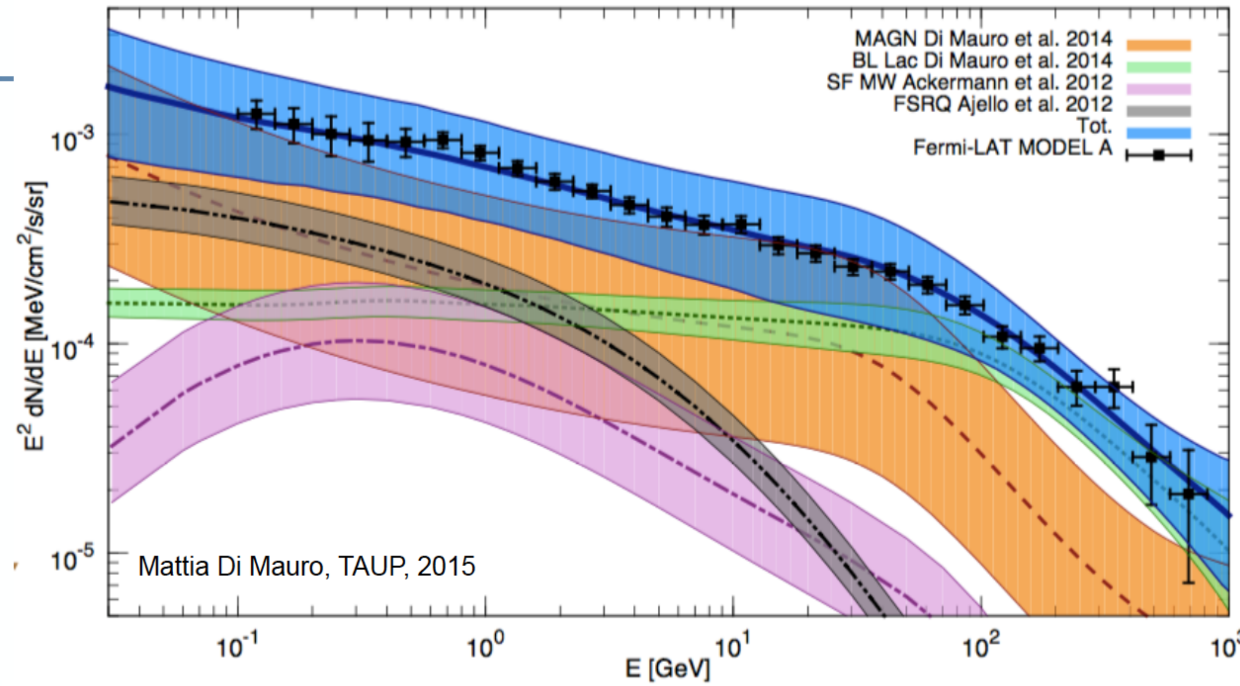
20% of the Universe is opaque to the EM spectrum

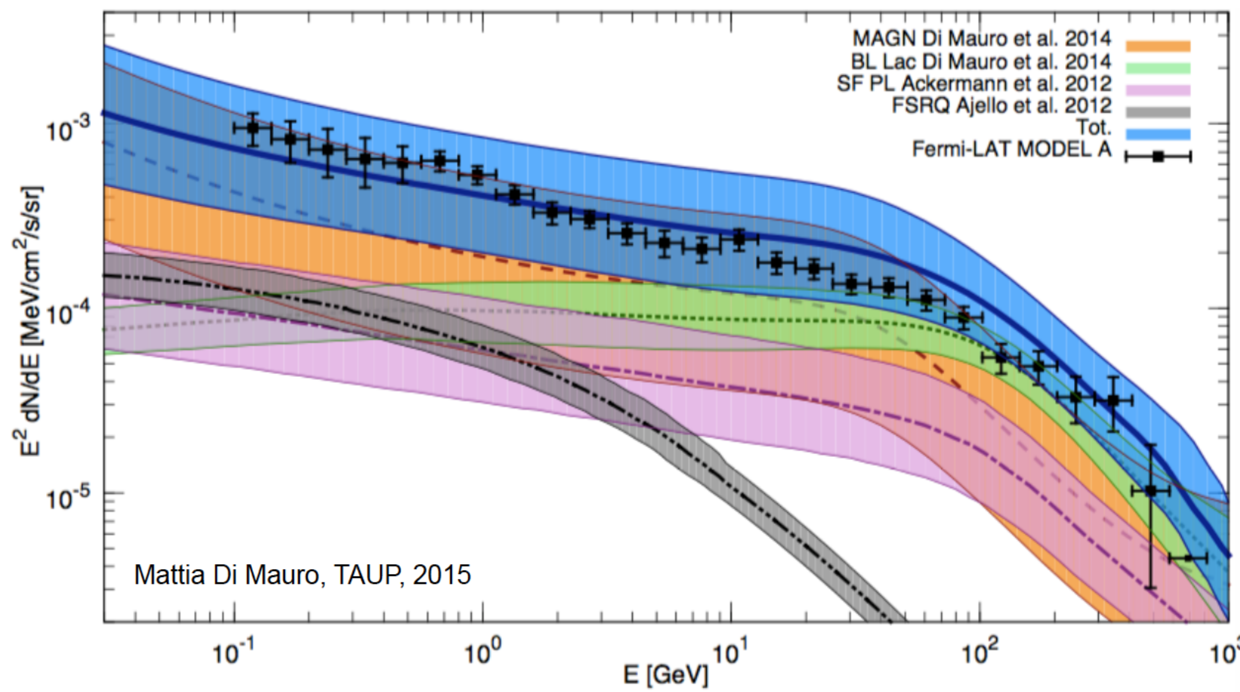


energy in the Universe in gamma rays, neutrinos and cosmic rays

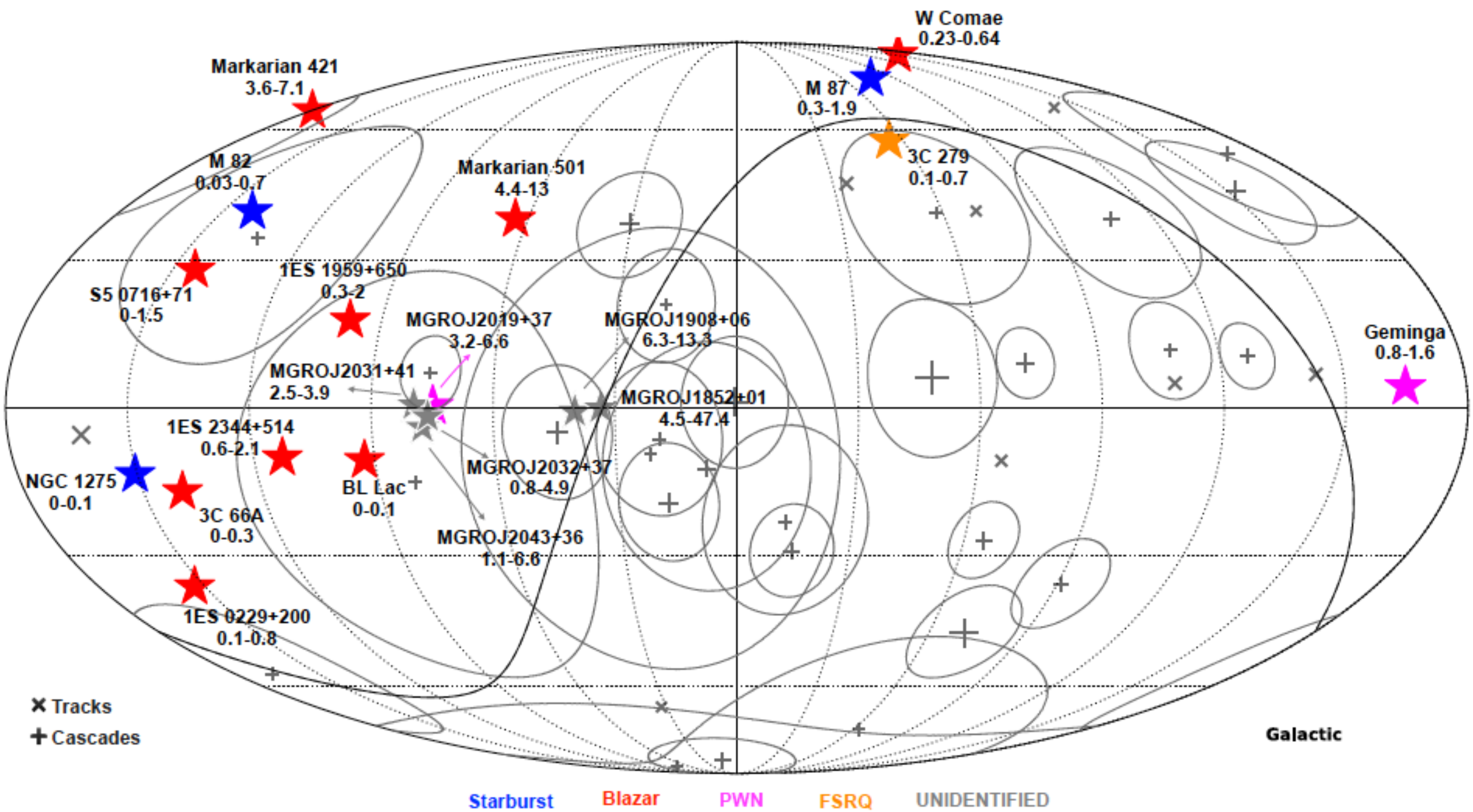
A census

- **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.



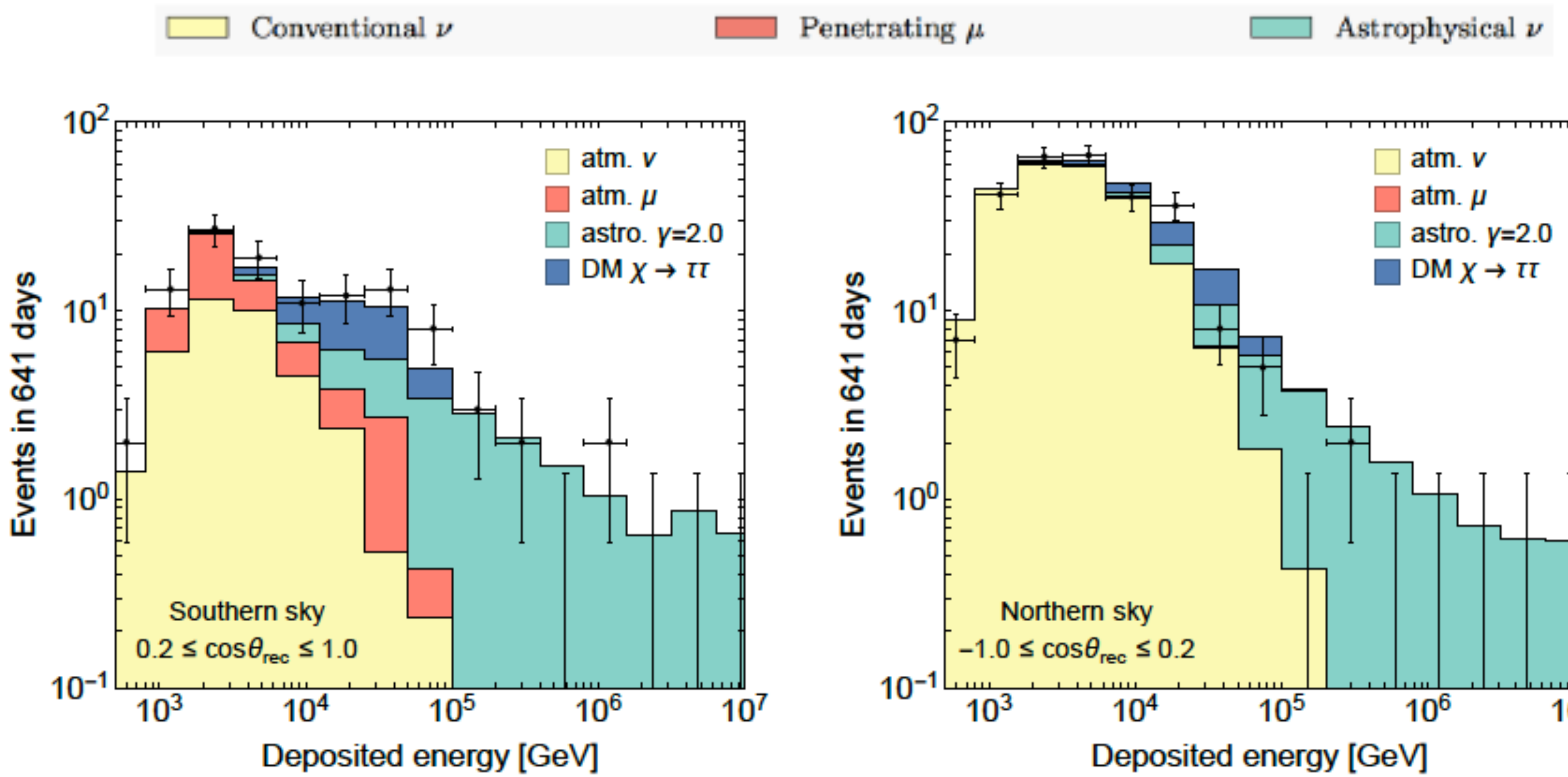


number of muon neutrino events from gamma ray sources in 5 years



- there is more

towards lower energies: a second component?

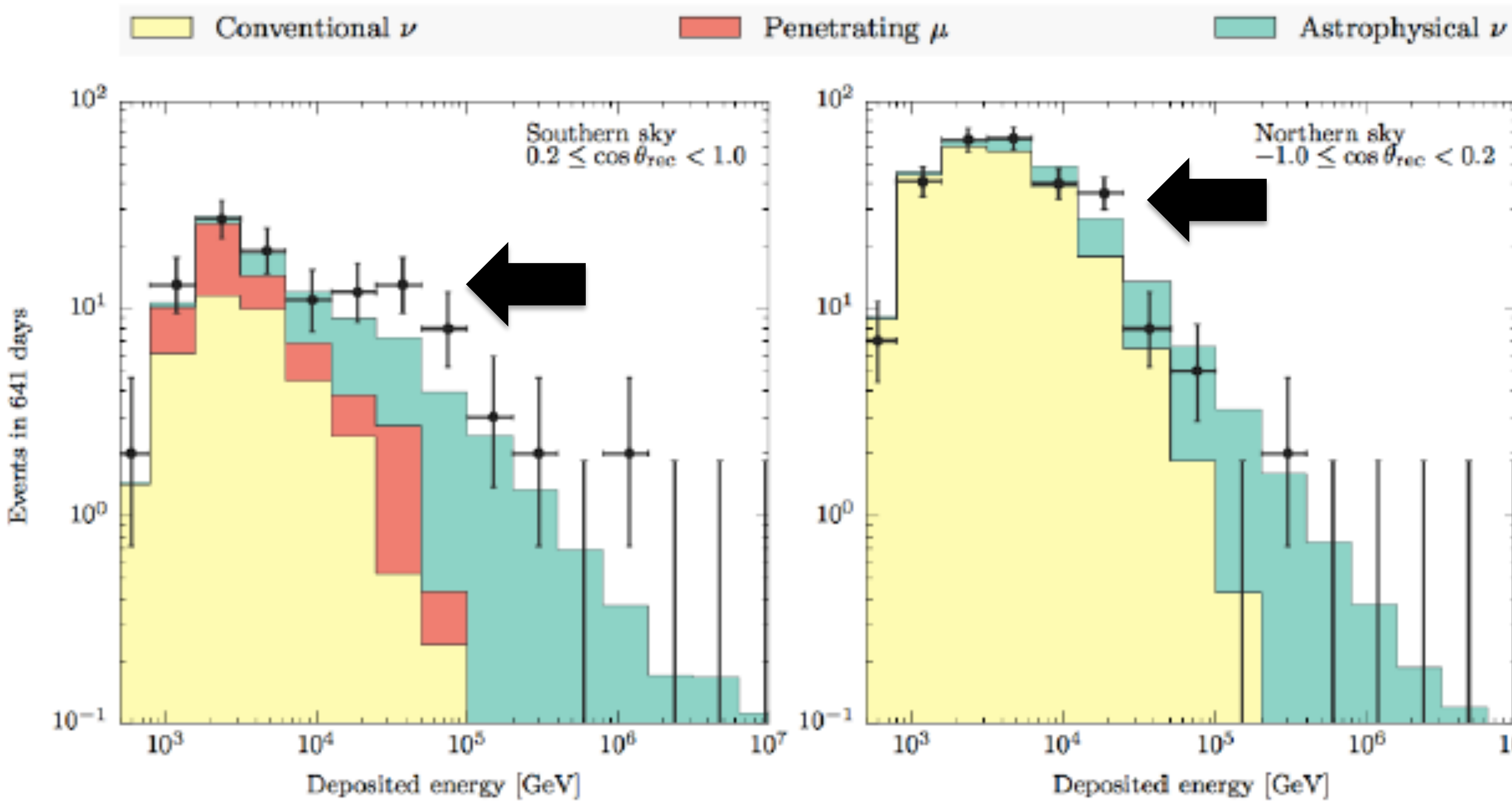


warning:

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

PeV neutrinos absorbed in the Earth

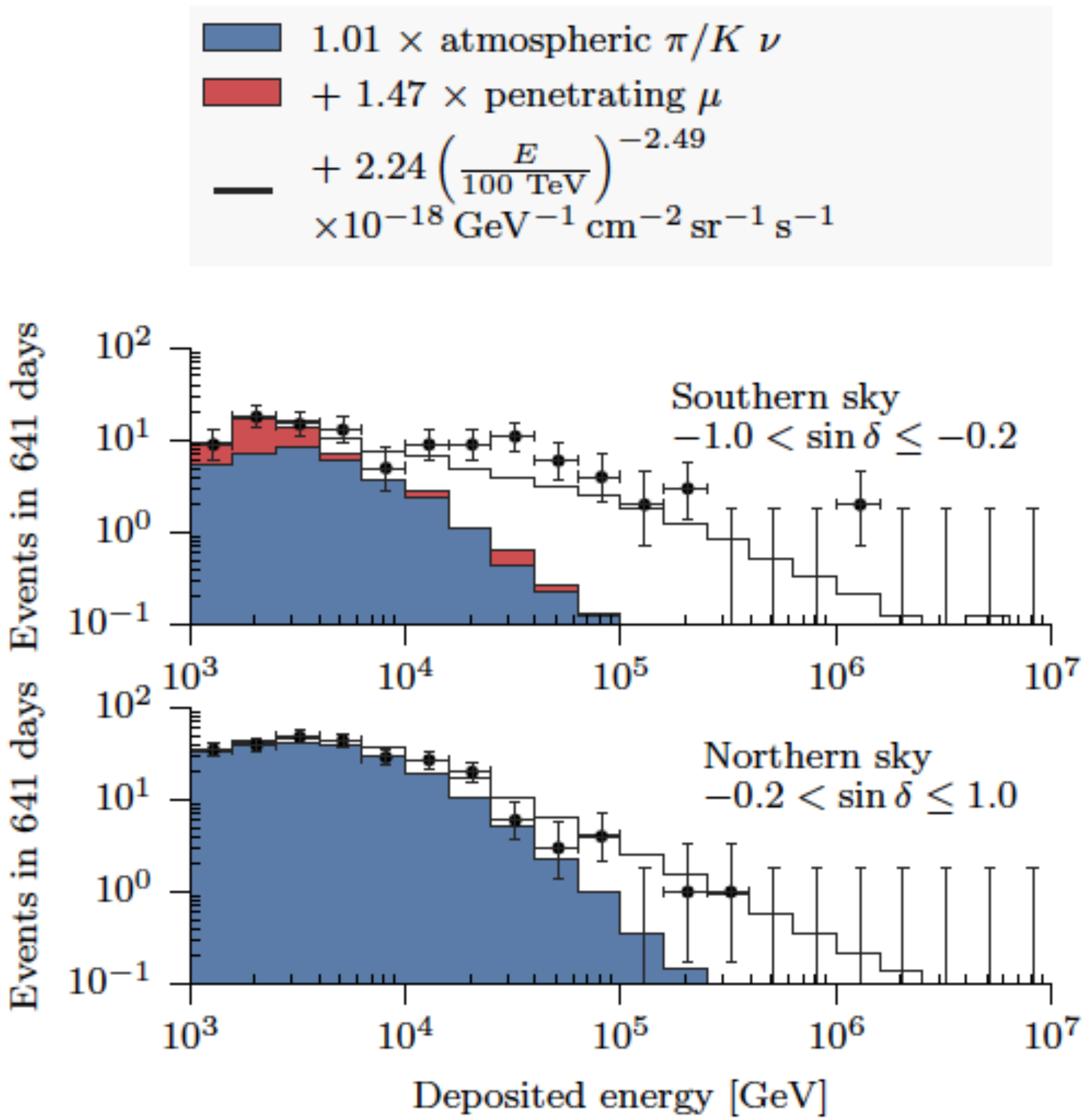
towards lower energies: a second component?



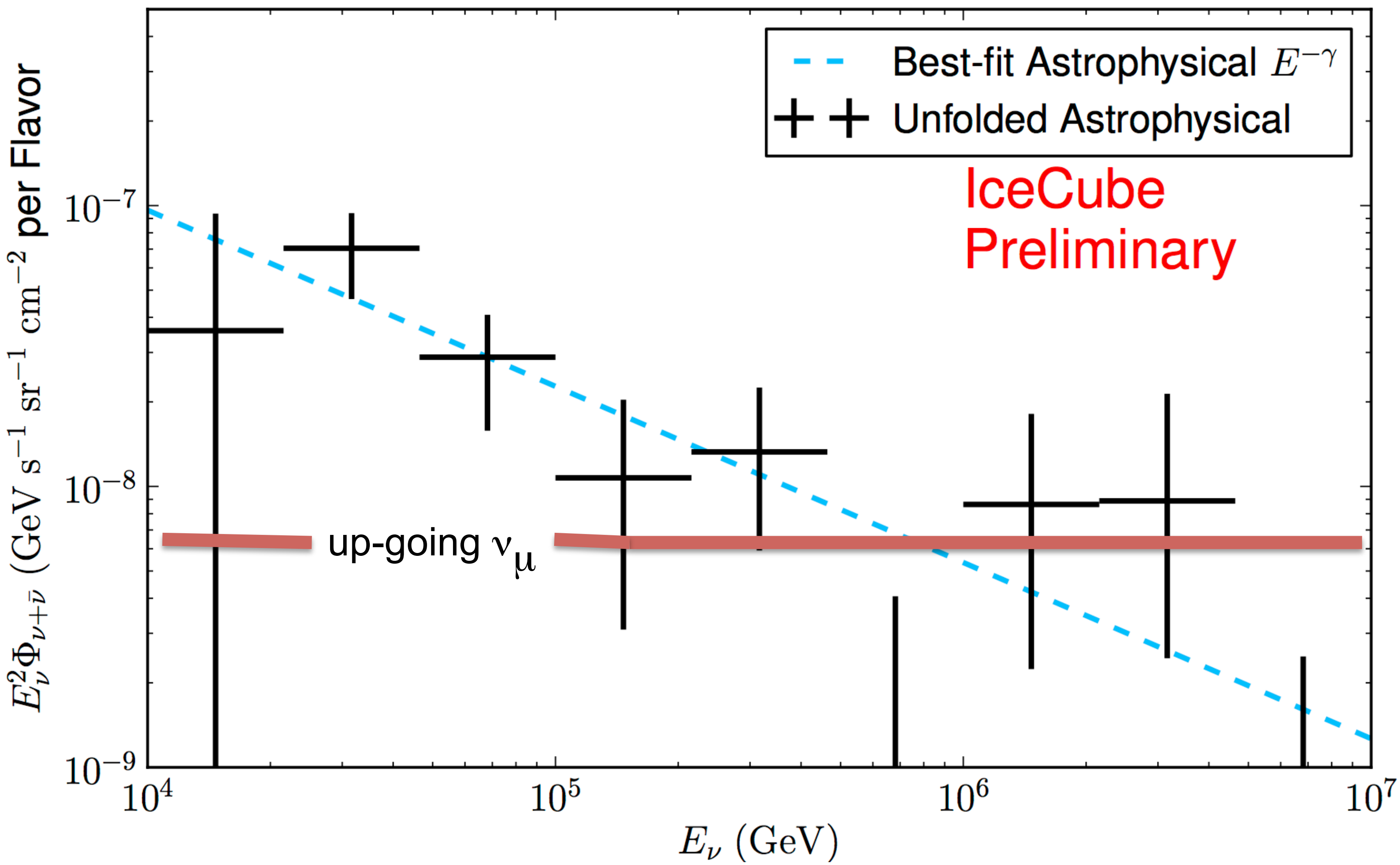
warning:

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

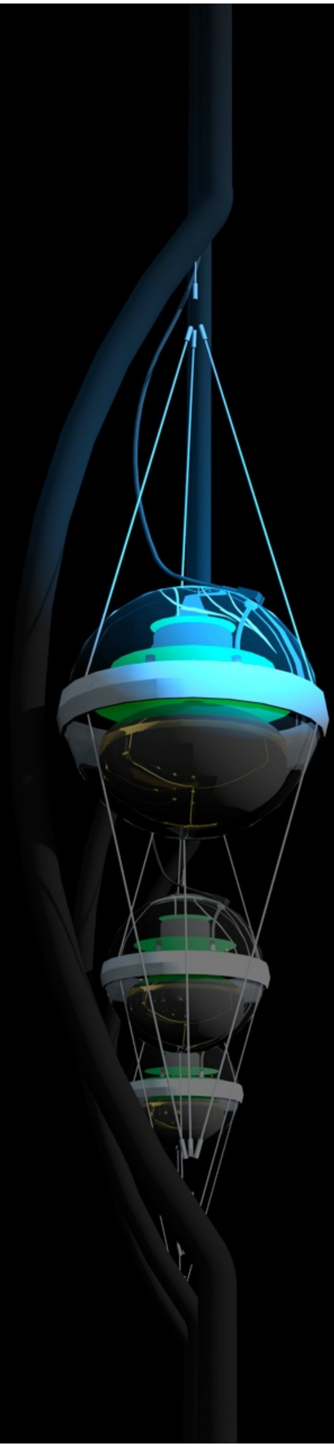
PeV neutrinos absorbed in the Earth


1.01 × atmospheric π/K ν
+ 1.47 × penetrating μ
$+ 2.24 \left(\frac{E}{100\ \mathrm{TeV}}\right)^{-2.49}$
$\times 10^{-18}\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1}$
Southern sky
$-1.0 < \sin\delta \leq -0.2$
Northern sky
$-0.2 < \sin\delta \leq 1.0$
Events in 641 days
Deposited energy [GeV]

yet lower energies….



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



IceCube: building a new window on the Universe

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

- 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

auto correlation: multiple neutrinos from the same source

total number of events required to observe
n-events multiplets from the closest sources is

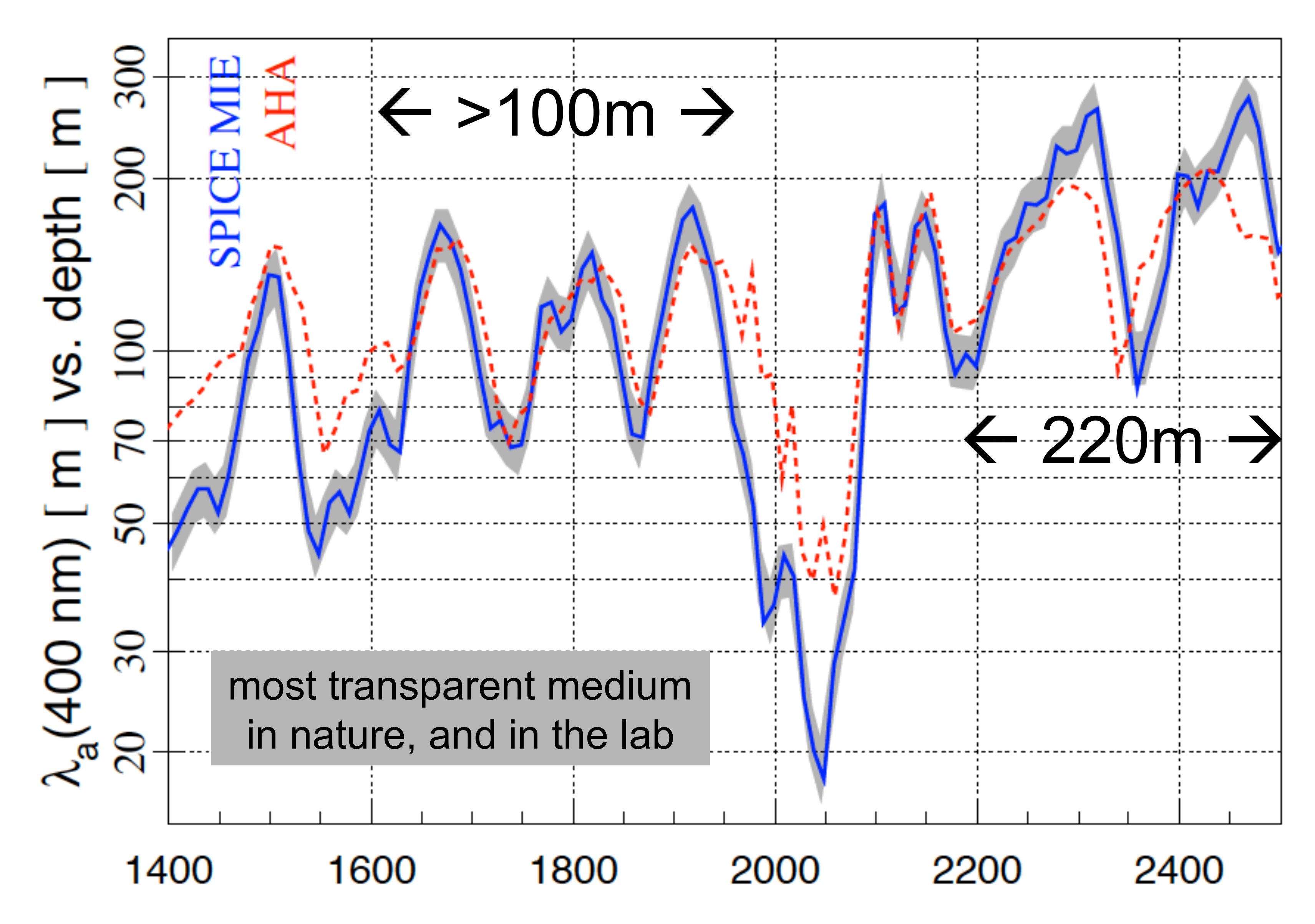
$$\boxed{740 \times \left[\frac{n}{2}\right] \times \left[\frac{\rho_0}{10^{-5}}\right]^{\frac{1}{3}} \text{ events}}$$

for a observed diffuse cosmic flux and 0.4 degrees
angular resolution

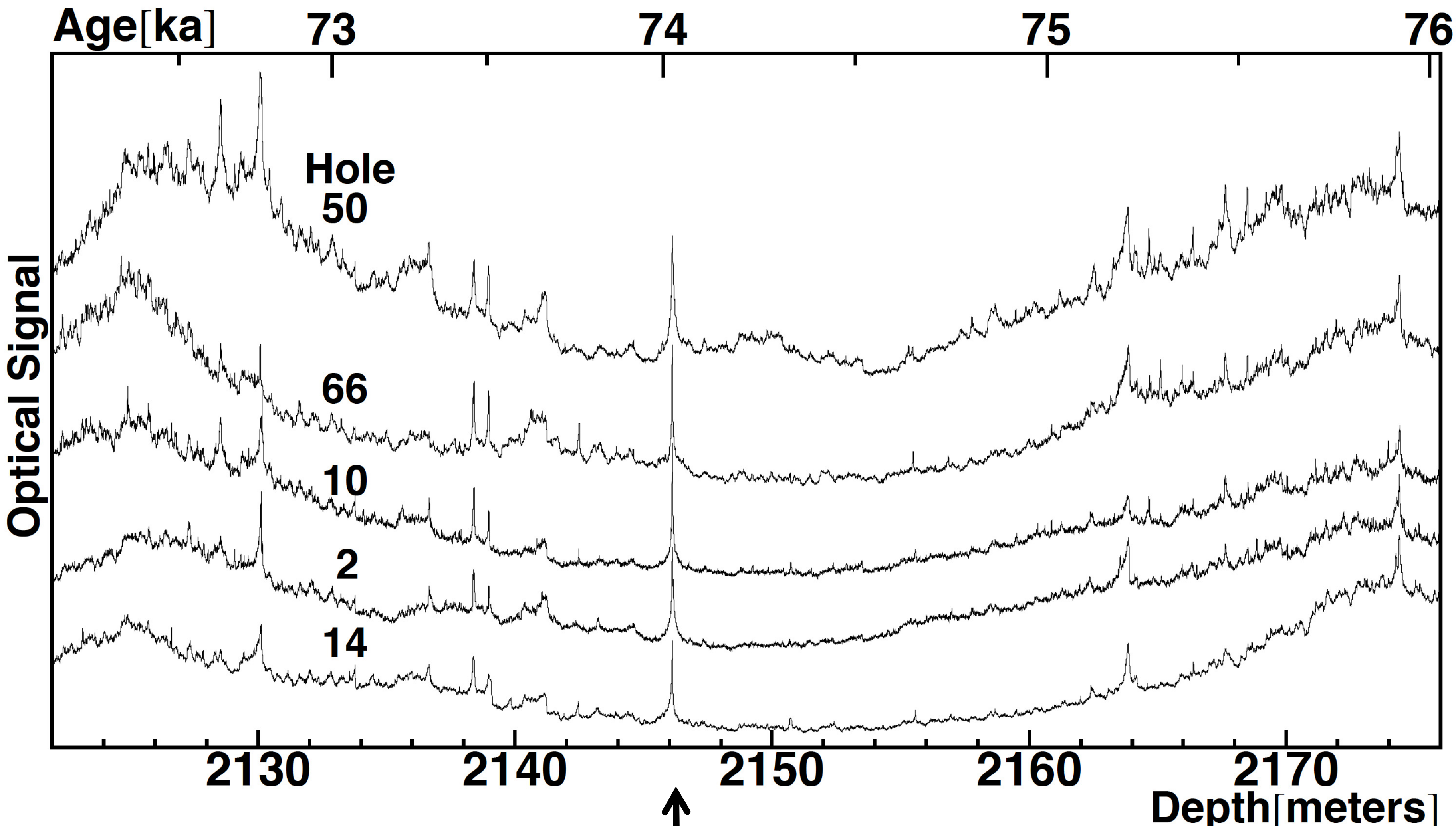
examples of local source densities (per Mpc^3):

- $10^{-3} - 10^{-2}\,\mathrm{Mpc}^{-3}$ for **normal galaxies**
- $10^{-5} - 10^{-4}\,\mathrm{Mpc}^{-3}$ for **active galaxies**
- $10^{-7}\,\mathrm{Mpc}^{-3}$ for **massive galaxy clusters**
- $> 10^{-5}\,\mathrm{Mpc}^{-3}$ for **UHE CR sources**

absorption length of Cherenkov light



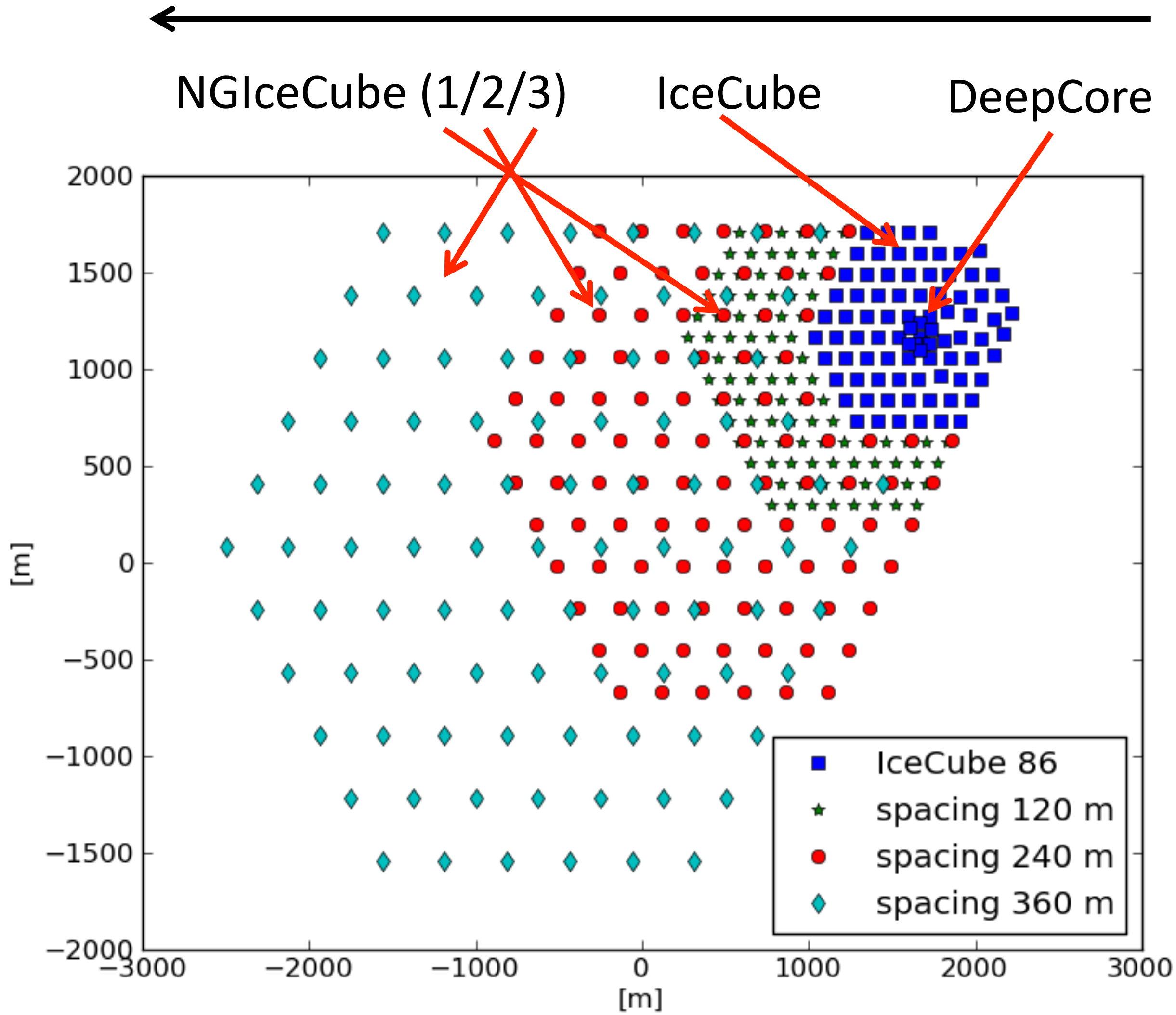
we are limited by computing, not the optics of the ice



Toba eruption

measured optical properties → twice the string spacing

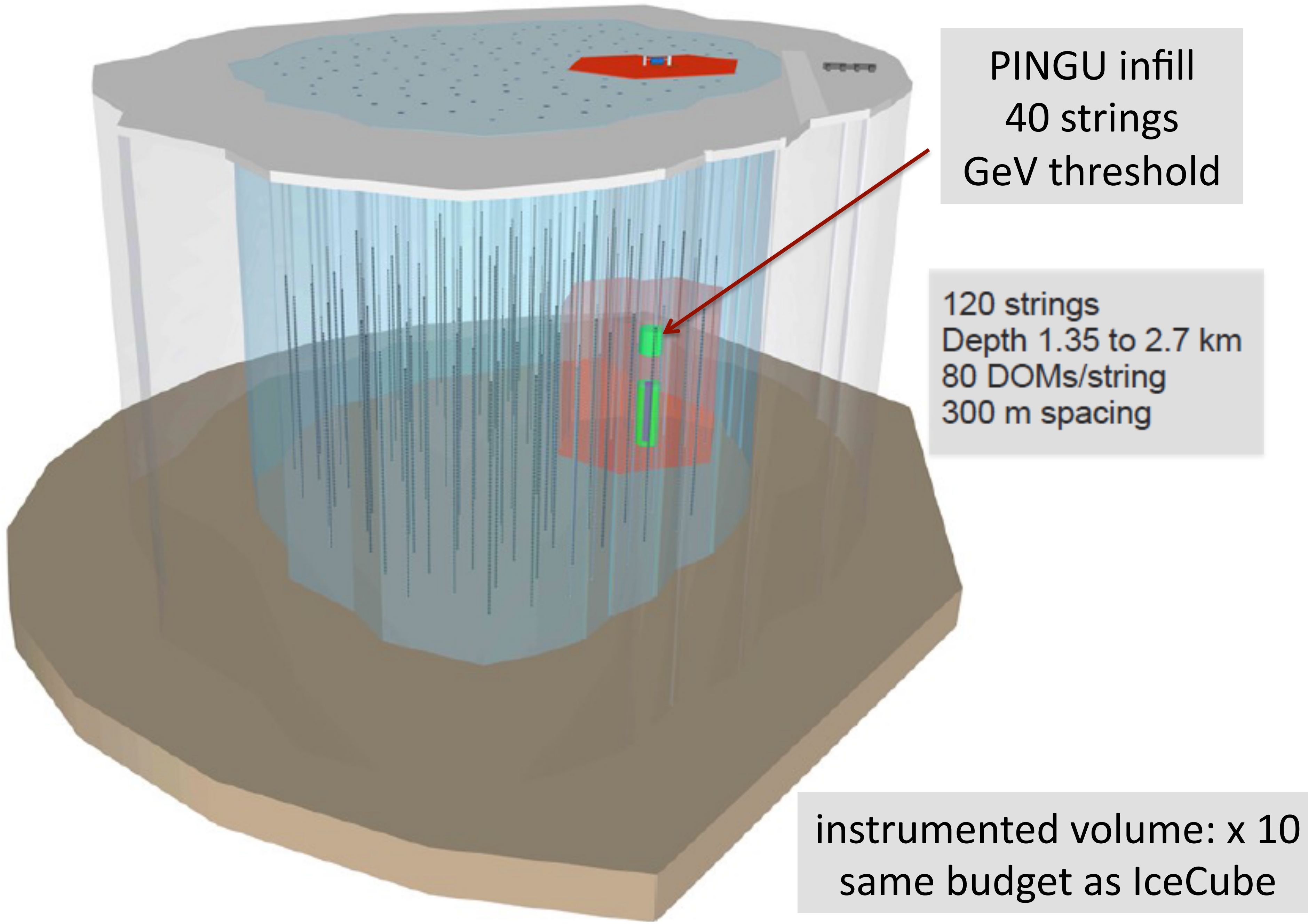
(increase in threshold not important: only eliminates energies where the atmospheric background dominates)

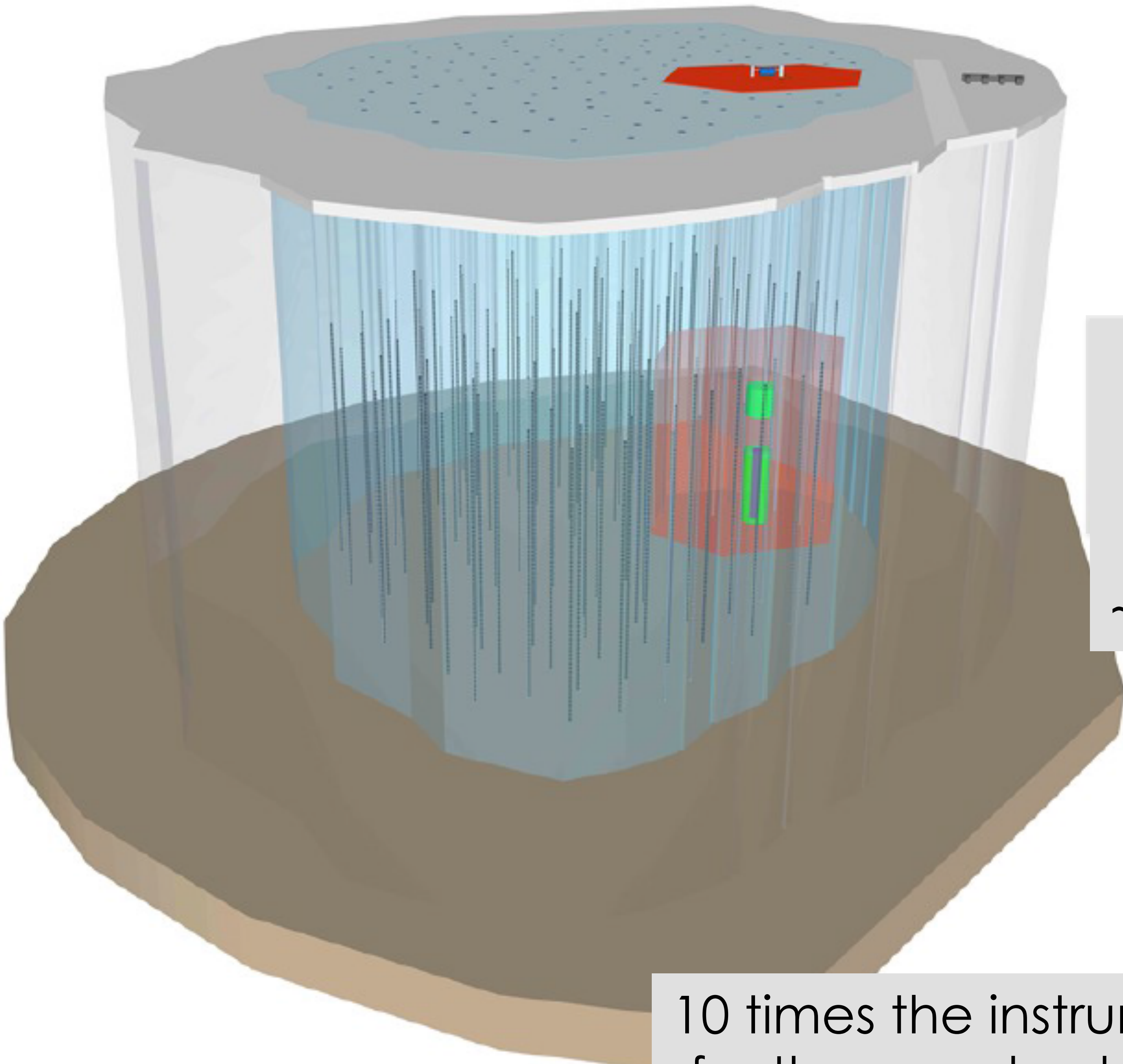


Spacing 1 (120m):
IceCube (1 km^3)
+ 98 strings (1,3 km^3)
= 2,3 km^3

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

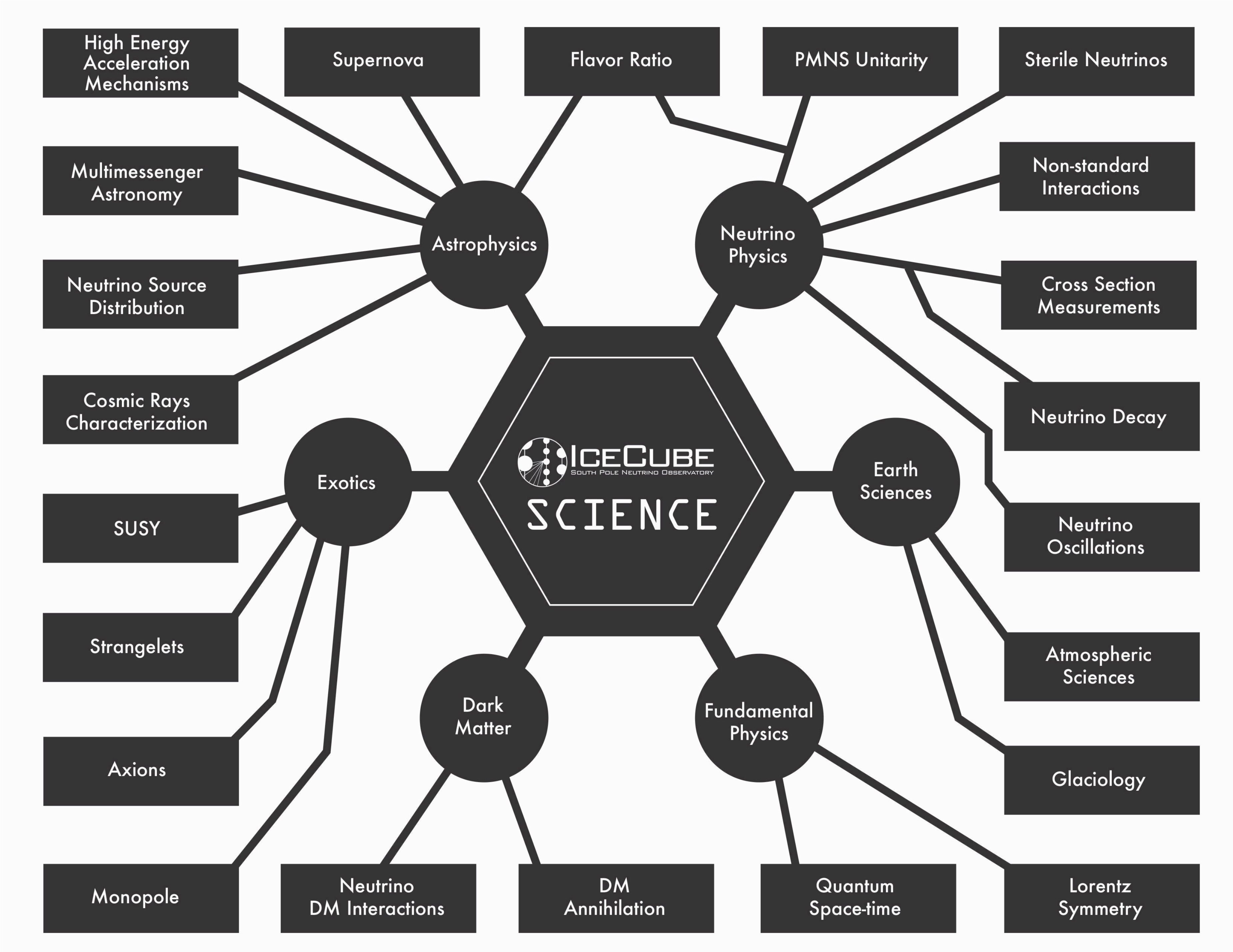


120 strings
depth 1.35 to
2.7 km
80 DOM/string
~250 m spacing

10 times the instrumented volume
for thesame 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
- ….



High Energy Acceleration Mechanisms
Supernova
Flavor Ratio
PMNS Unitarity
Sterile Neutrinos
Multimessenger Astronomy
Non-standard Interactions
Astrophysics
Neutrino Physics
Neutrino Source Distribution
Cross Section Measurements
Cosmic Rays Characterization
Neutrino Decay
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
SCIENCE
Exotics
Earth Sciences
SUSY
Neutrino Oscillations
Strangelets
Atmospheric Sciences
Dark Matter
Fundamental Physics
Axions
Glaciology
Monopole
Neutrino DM Interactions
DM Annihilation
Quantum Space-time
Lorentz Symmetry

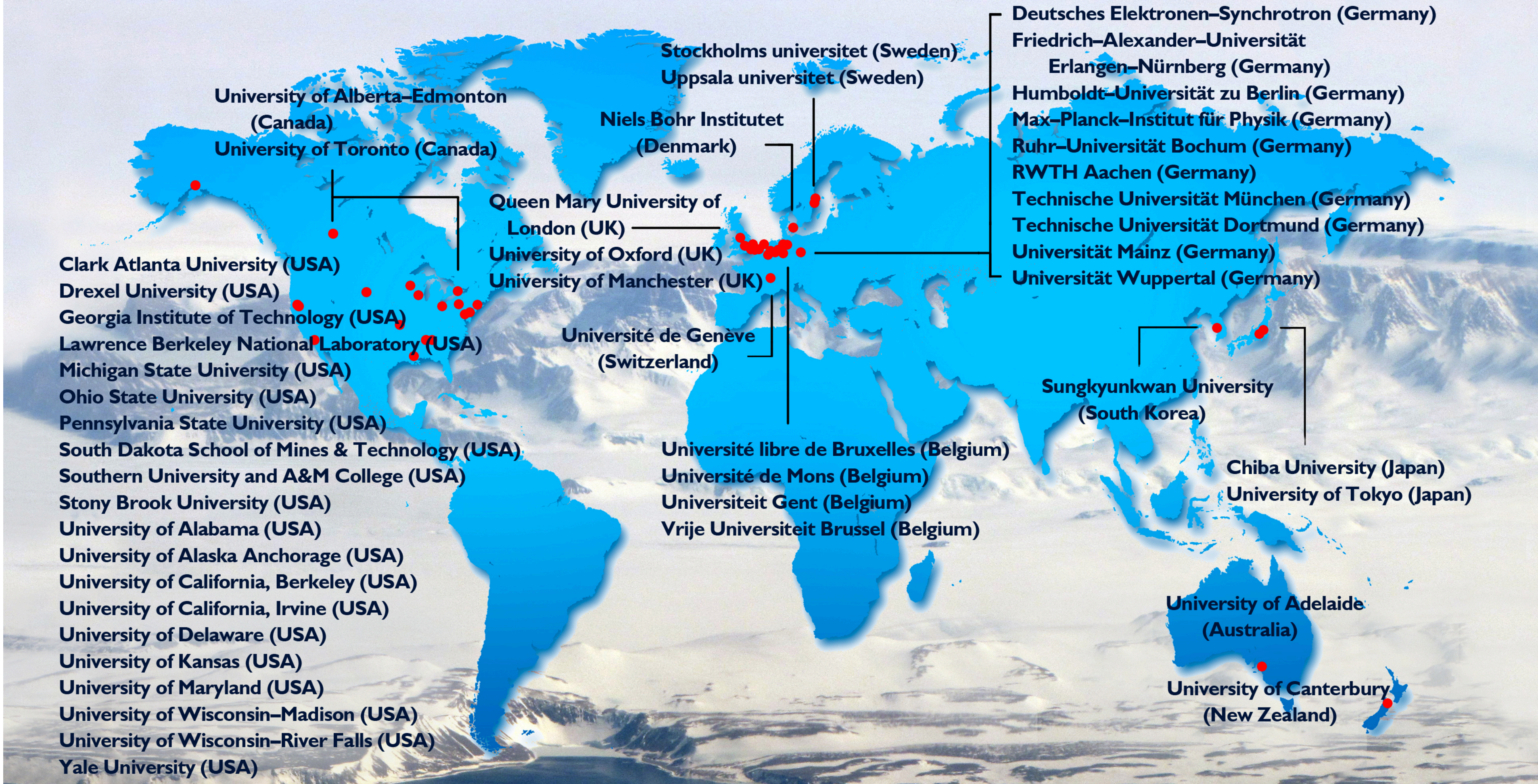
Conclusions

- 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)
  2. neutrino physics at (relatively) low cost and on short timescales (PINGU/ORCA)
  3. potential for discovery

- neutrinos are never boring!

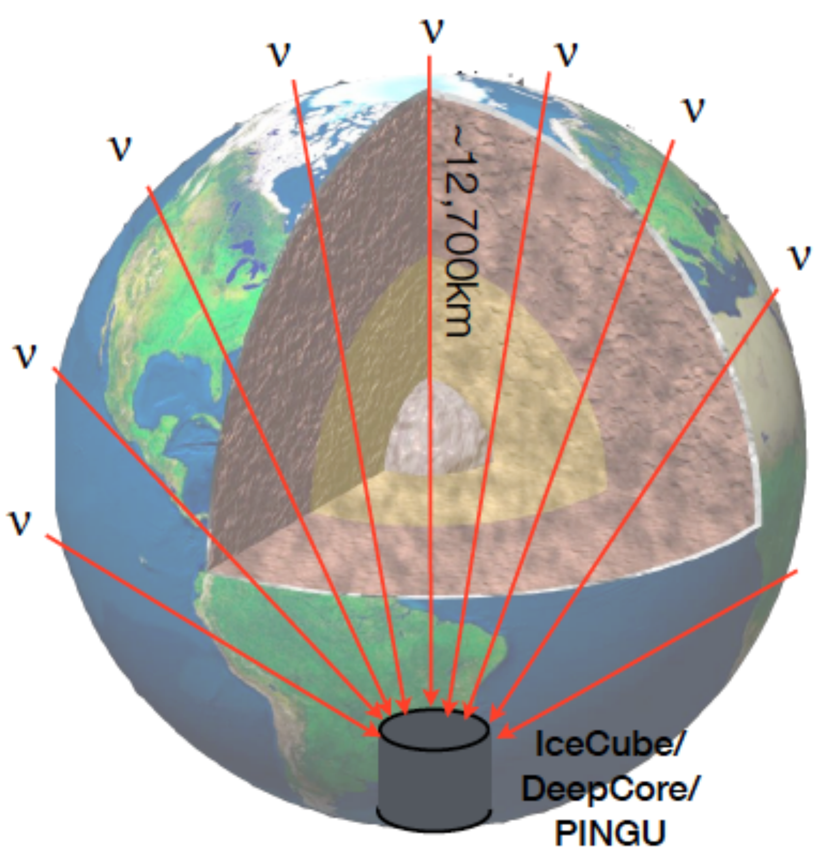
The IceCube–PINGU Collaboration

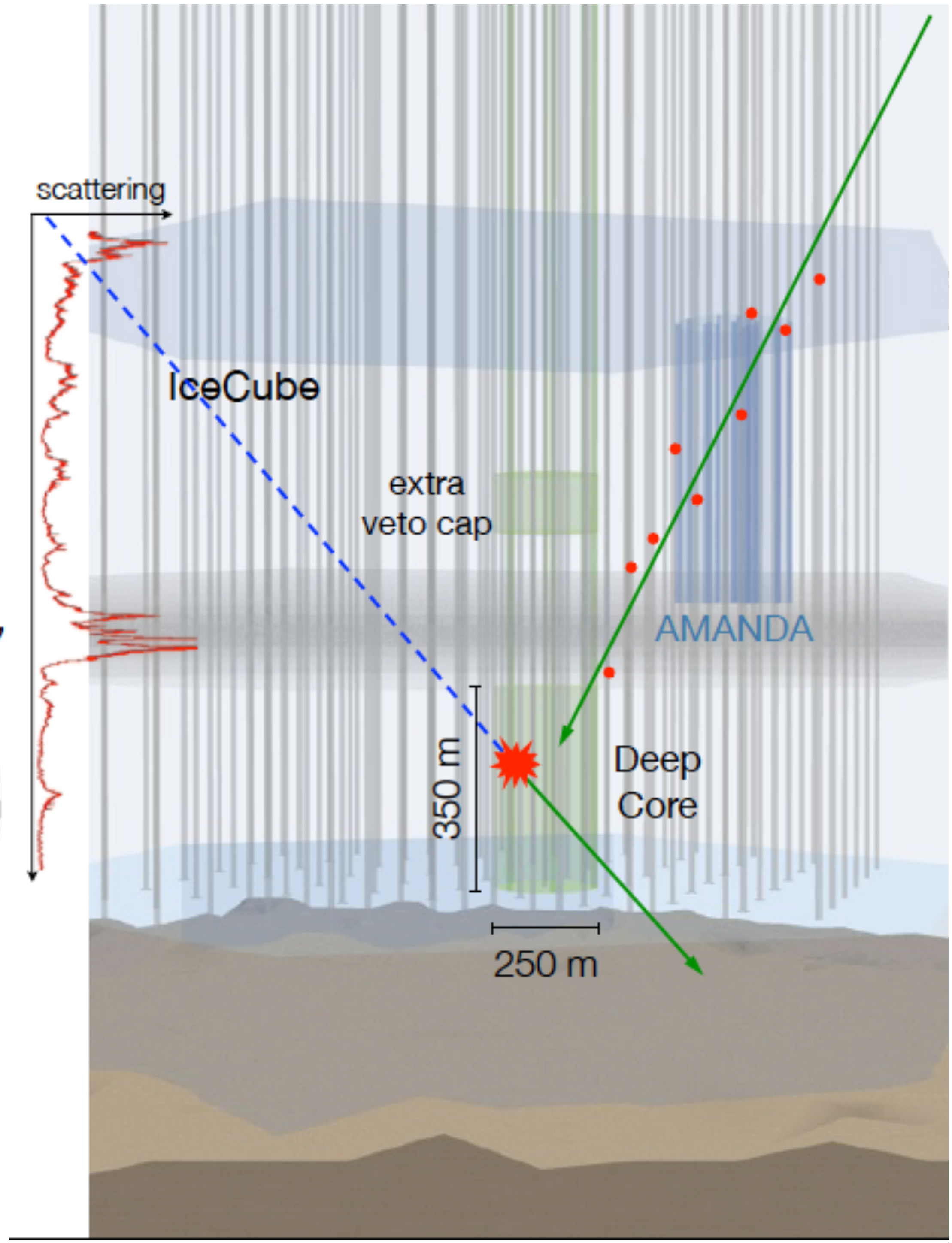


International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek–Vlaanderen (FWO–Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen–Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
NSF–Office of Polar Programs
NSF–Physics Division
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

one half million atmospheric neutrinos…



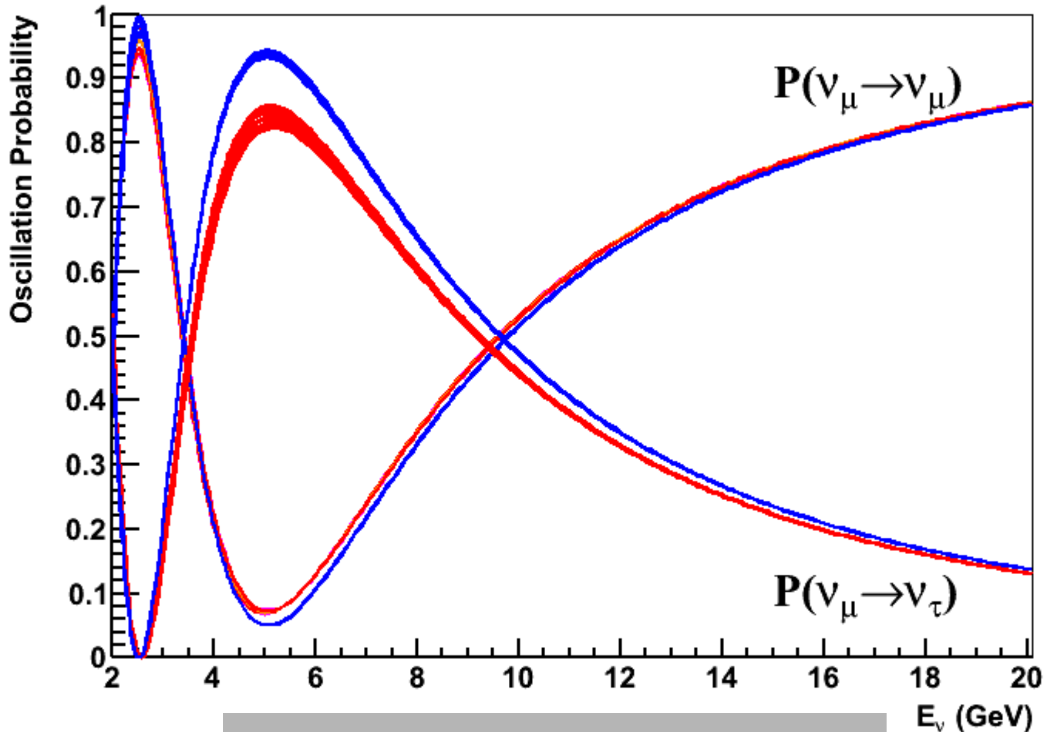


IceCube

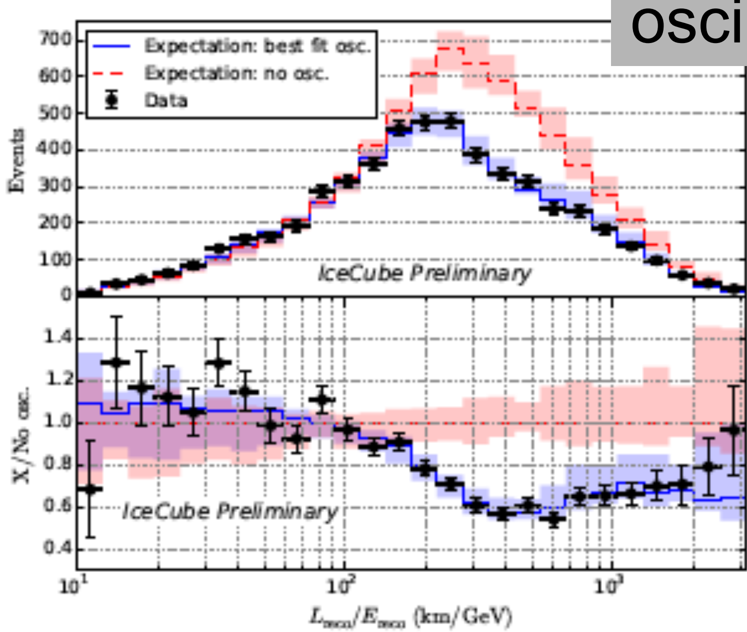
DeepCore

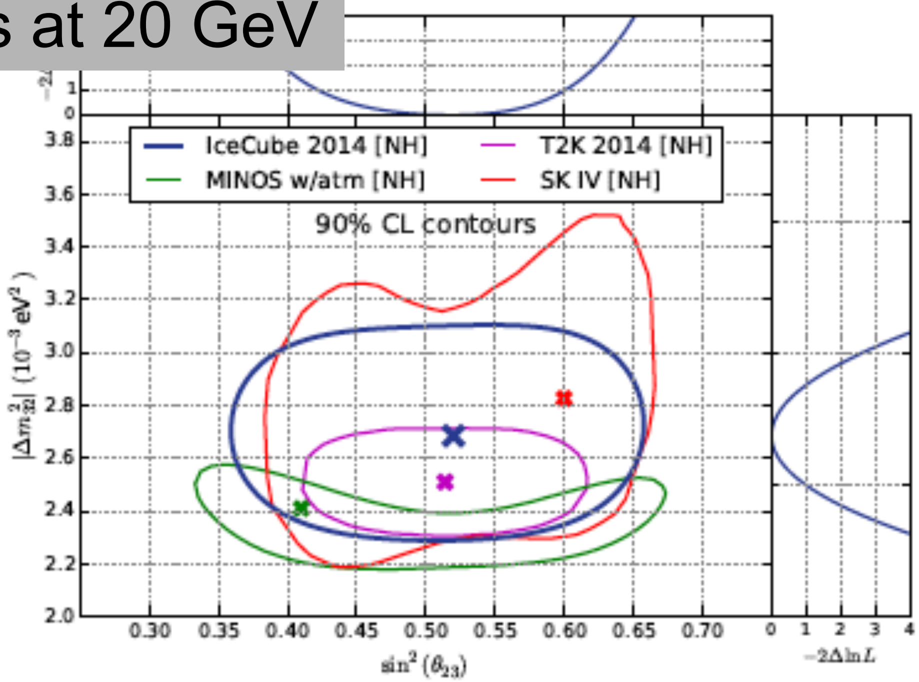
Phase 1

one year only!



oscillations at 20 GeV

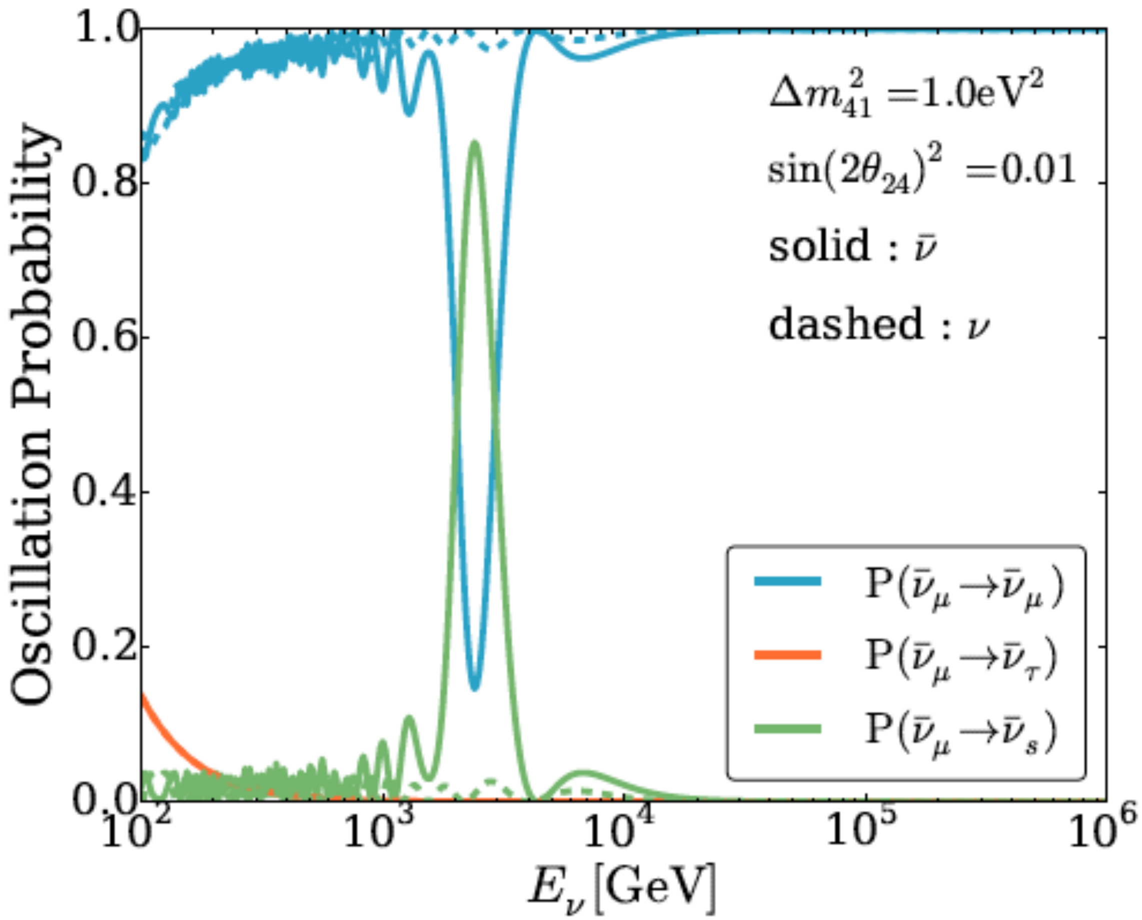


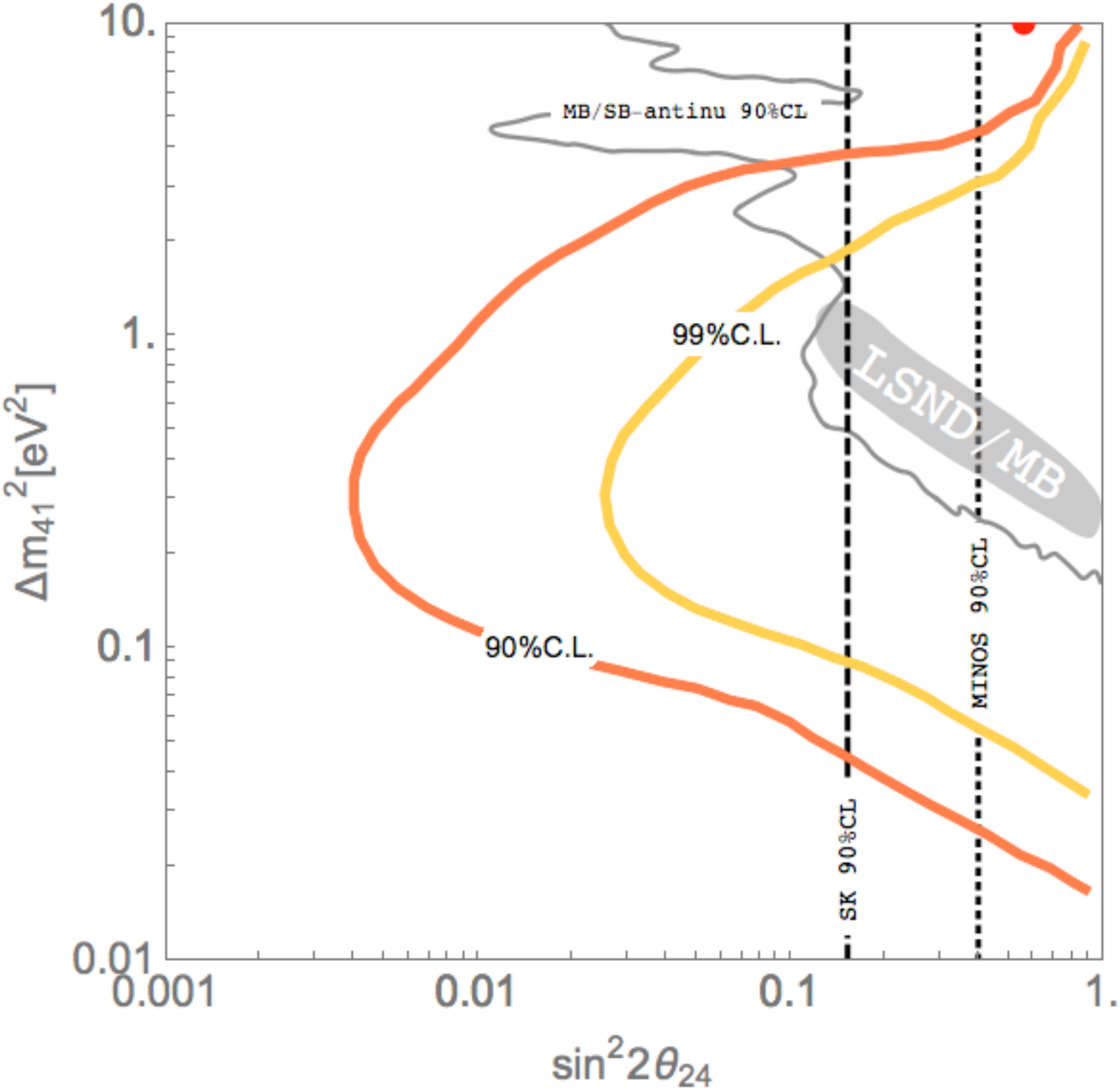


eV sterile neutrino → Earth MSW resonance for TeV neutrinos

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

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





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

Conclusions

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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)