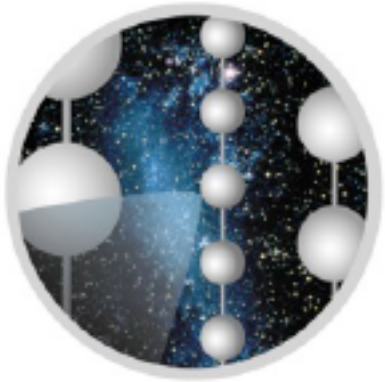


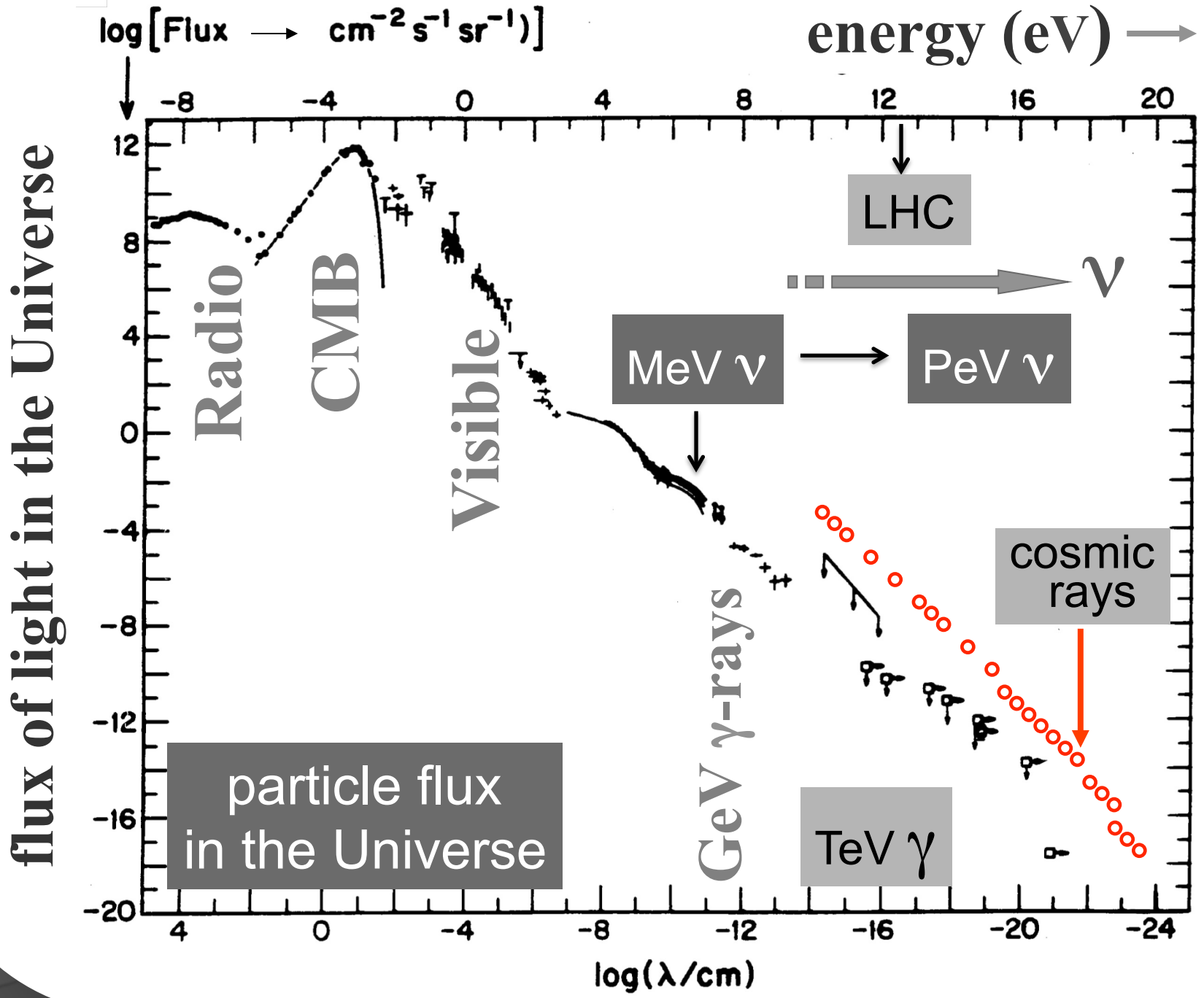
XVI international workshop on neutrino telescopes

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

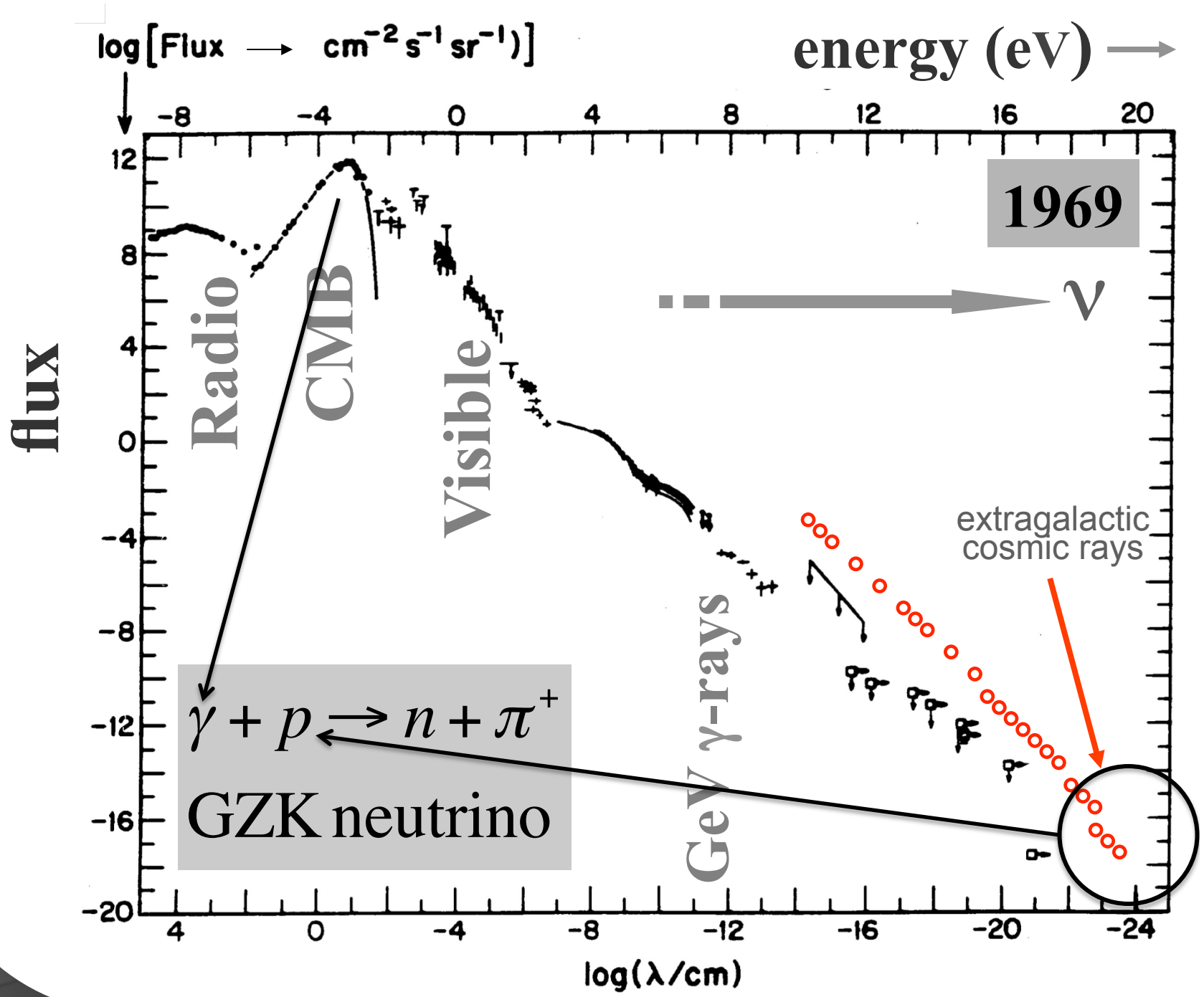
IceCube.wisc.edu

Lilla Baldo Cecchi


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


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

cosmic rays interact with the microwave background

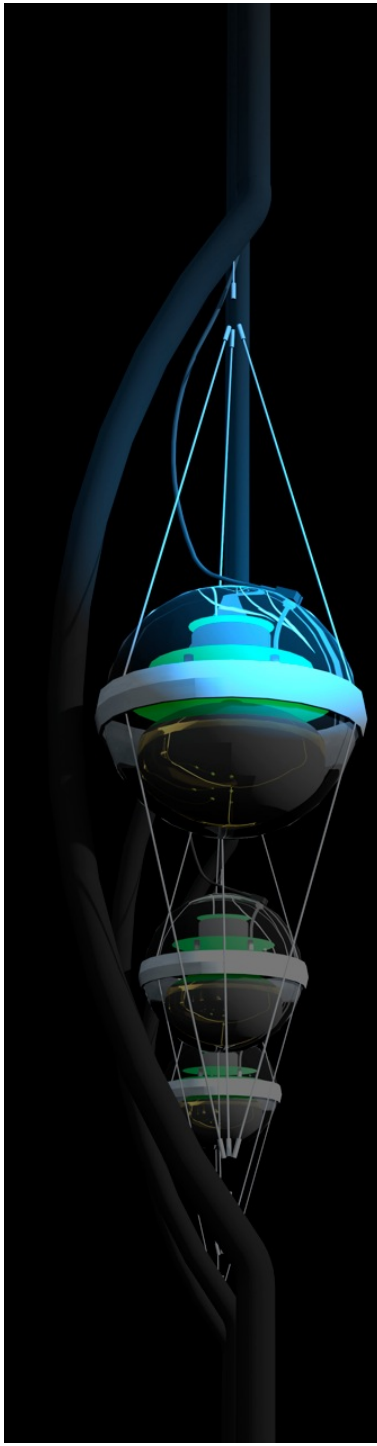
$$p + \gamma \rightarrow n + \pi^{+} \; and \; p + \pi^{0}$$

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

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

1 event per cubic kilometer per year

...but it points at its source!



IceCube

francis halzen

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

IceCube.wisc.edu

- accelerator must contain the particles

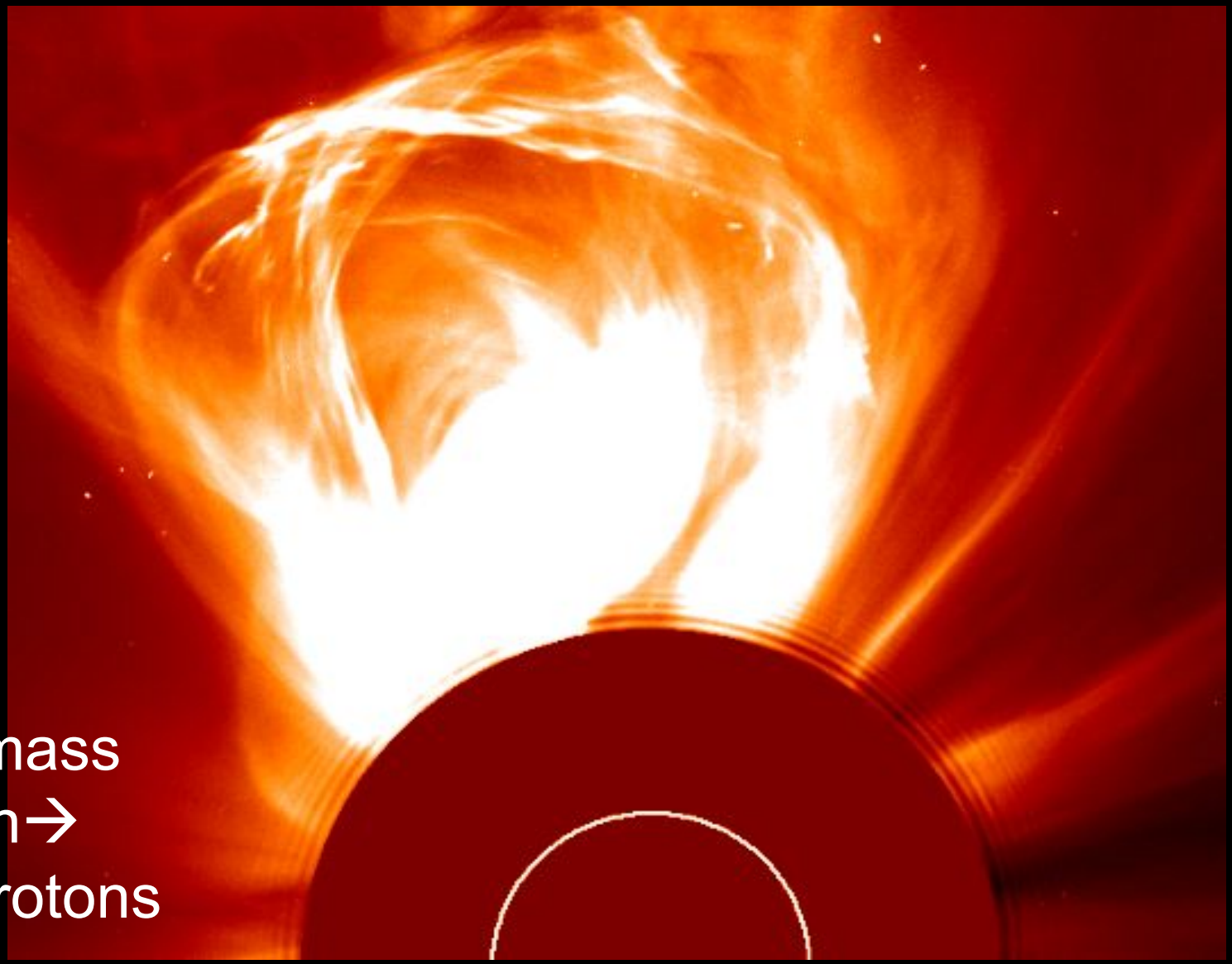
$$R_{gyro}\left(=\frac{E}{\mathrm{v}qB}\right)\leq R$$

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

challenges of cosmic ray astrophysics:

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

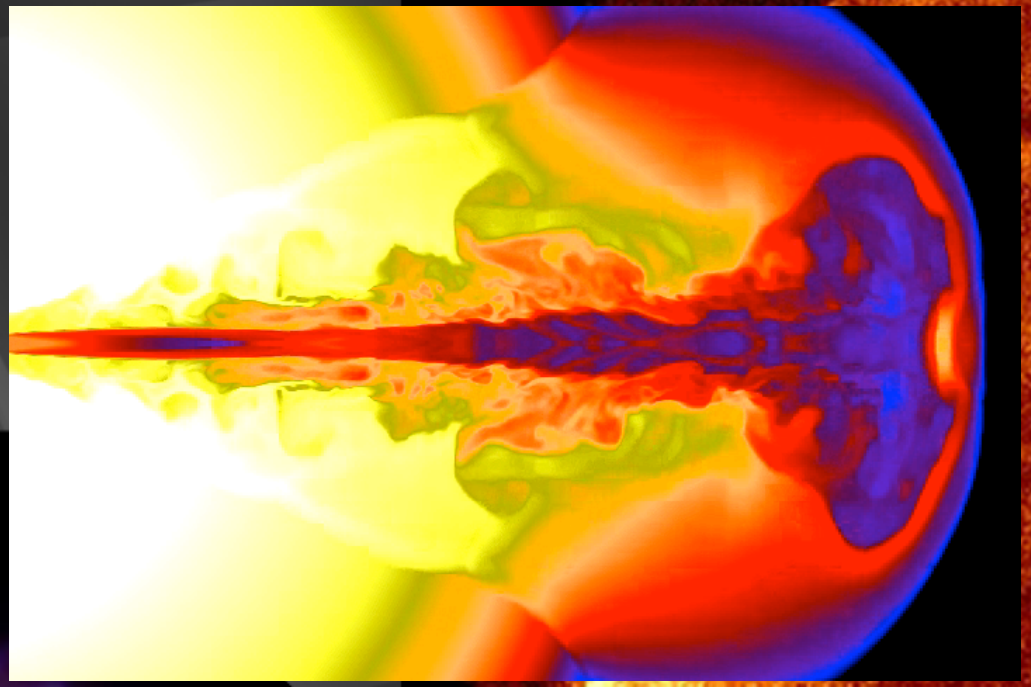
the sun constructs an accelerator



coronal mass ejection→ 10 GeV protons

supernova remnants

Chandra
Cassiopeia A

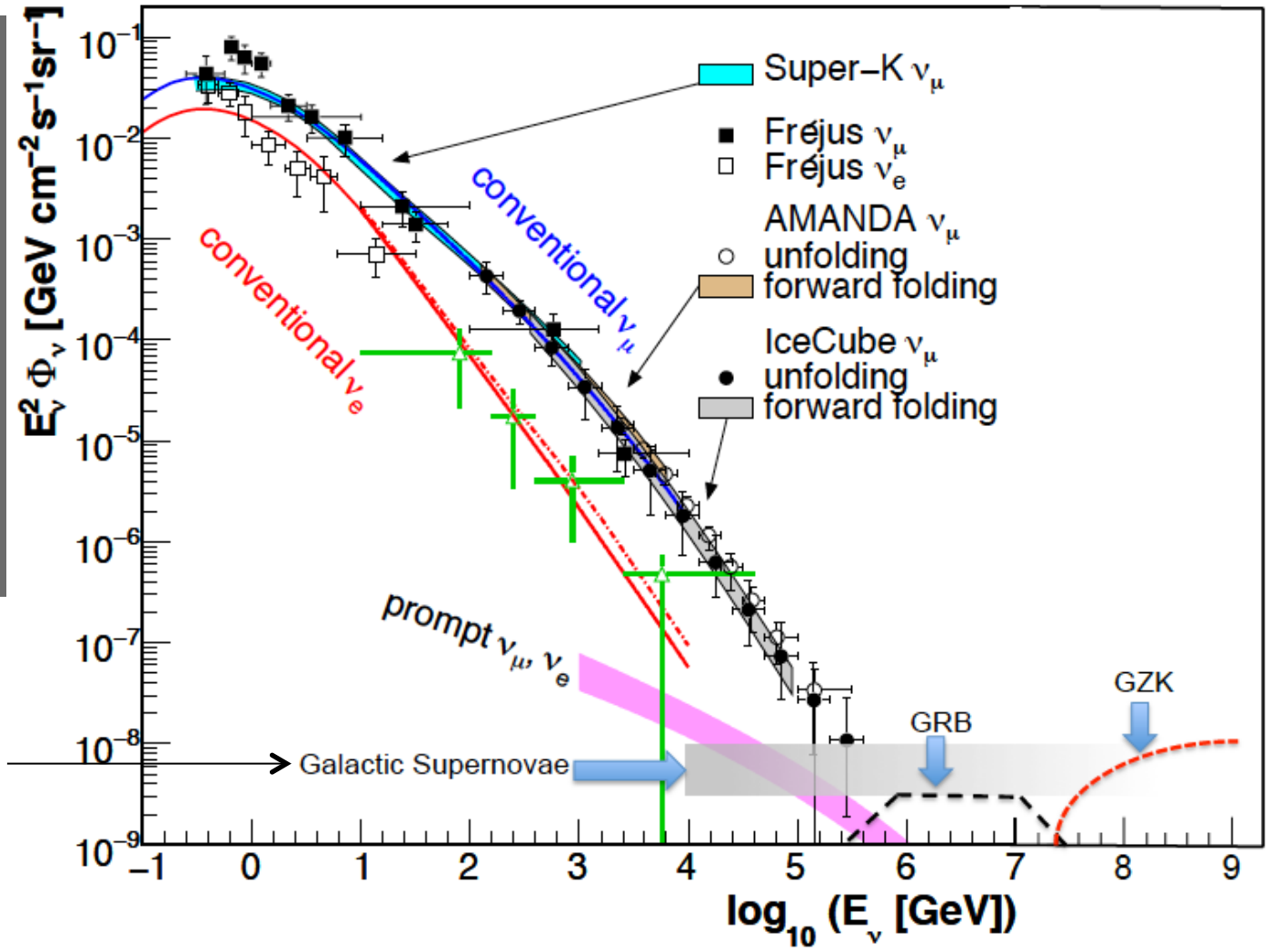


gamma ray bursts

above 100 TeV

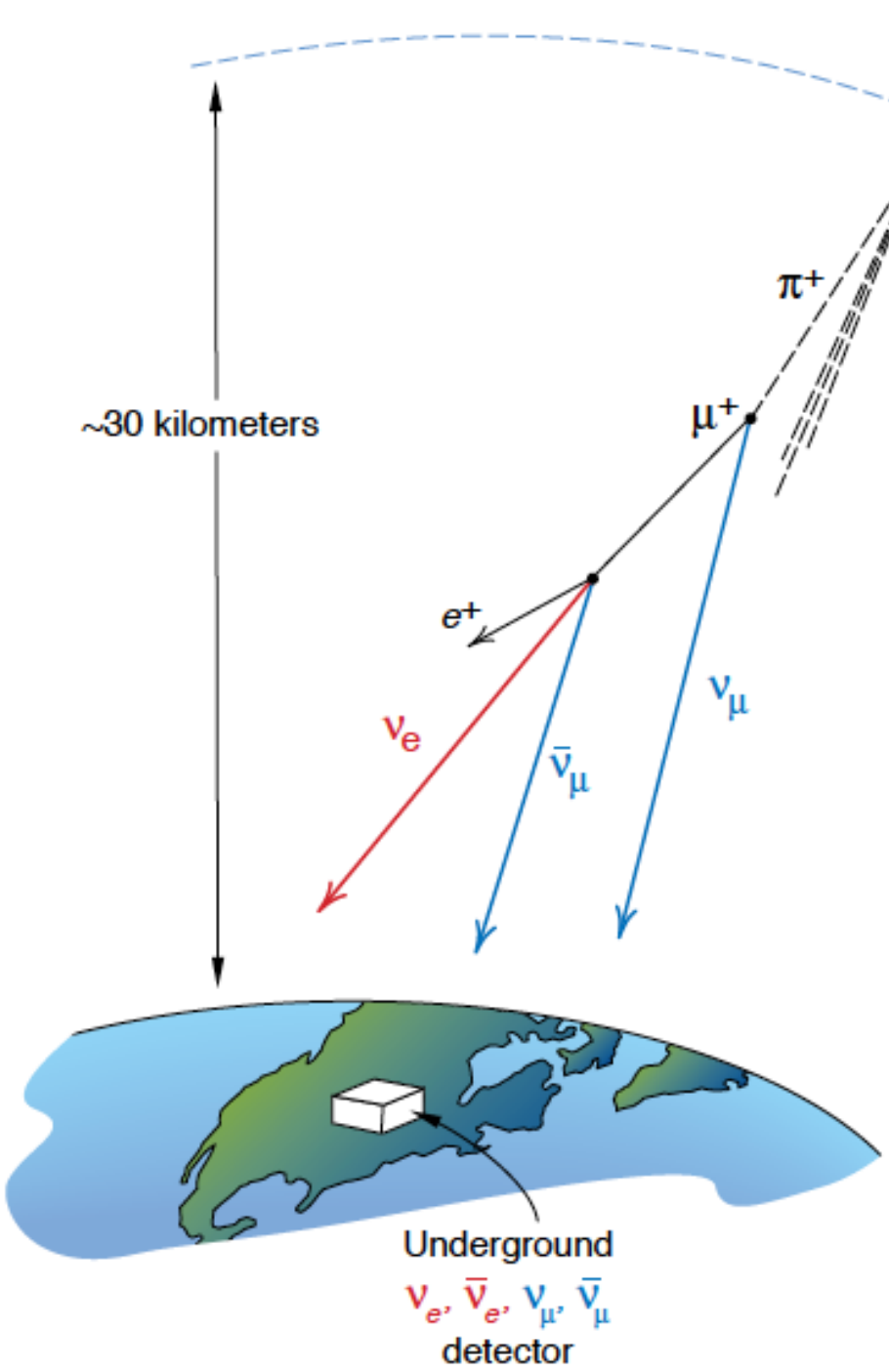
- cosmic neutrinos:
- atmospheric background disappears

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



atmospheric cosmic

100 TeV



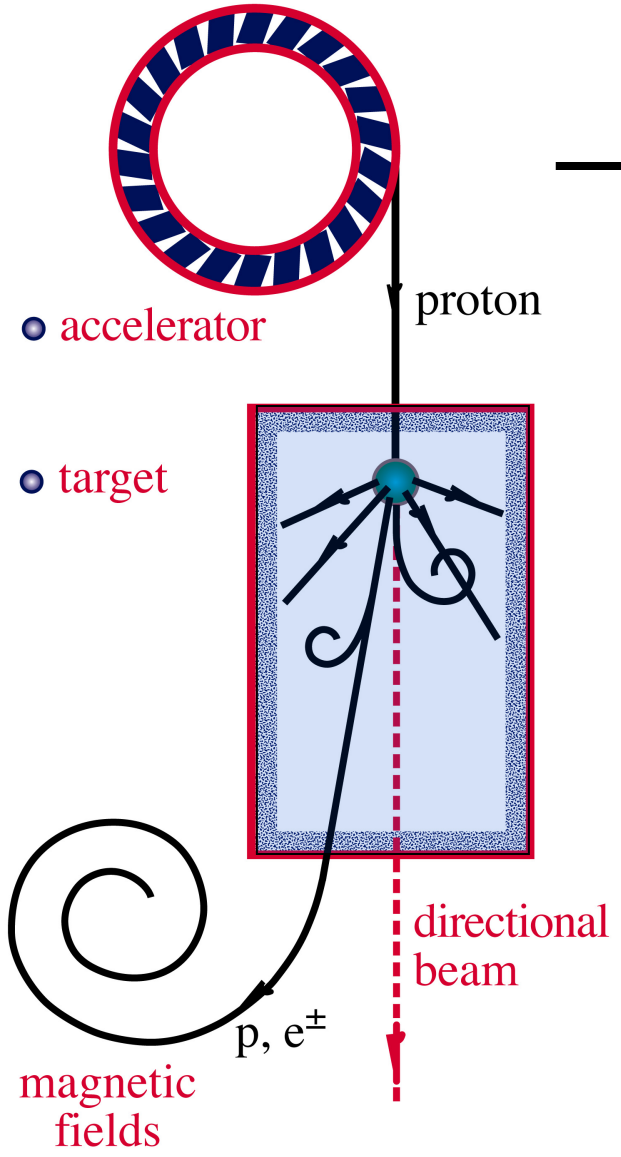
atmospheric neutrinos
(… and muons!)

Atmospheric neutrino source

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

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

ν and γ beams : heaven and earth



accelerator is powered by
large gravitational energy

black hole
neutron star

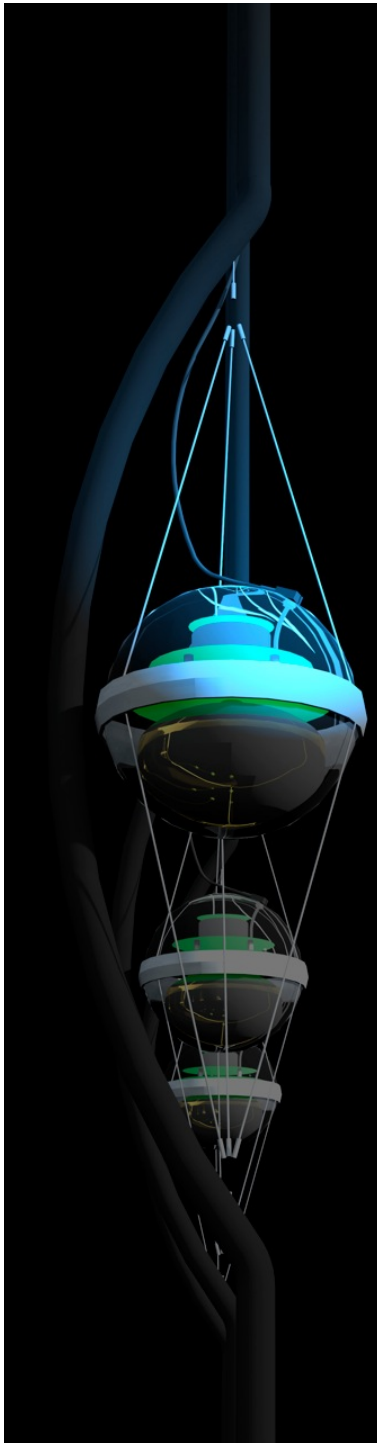
radiation
and dust

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

~ cosmic ray + neutrino

$\rightarrow p + \pi^0$

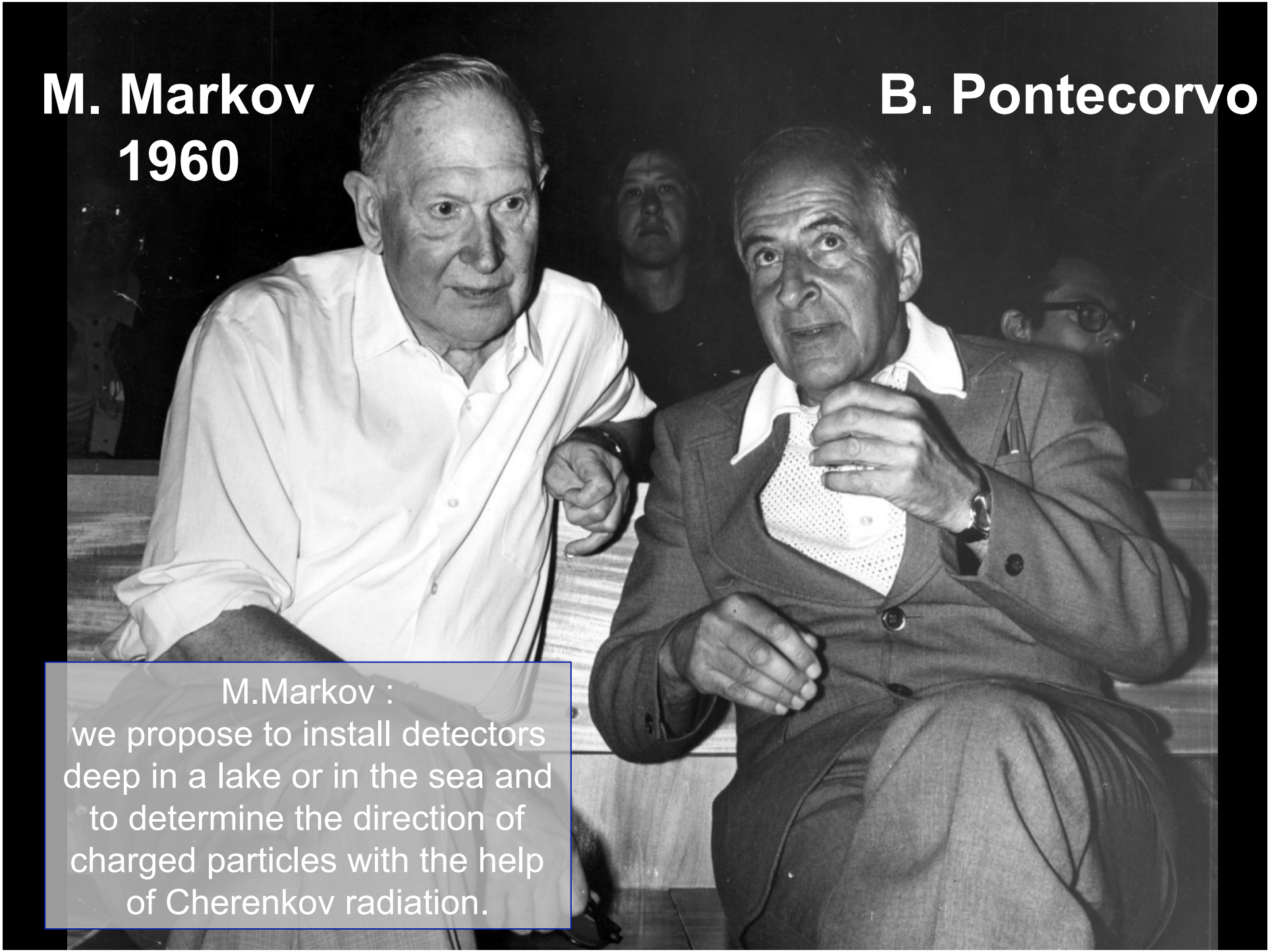
~ cosmic ray + gamma



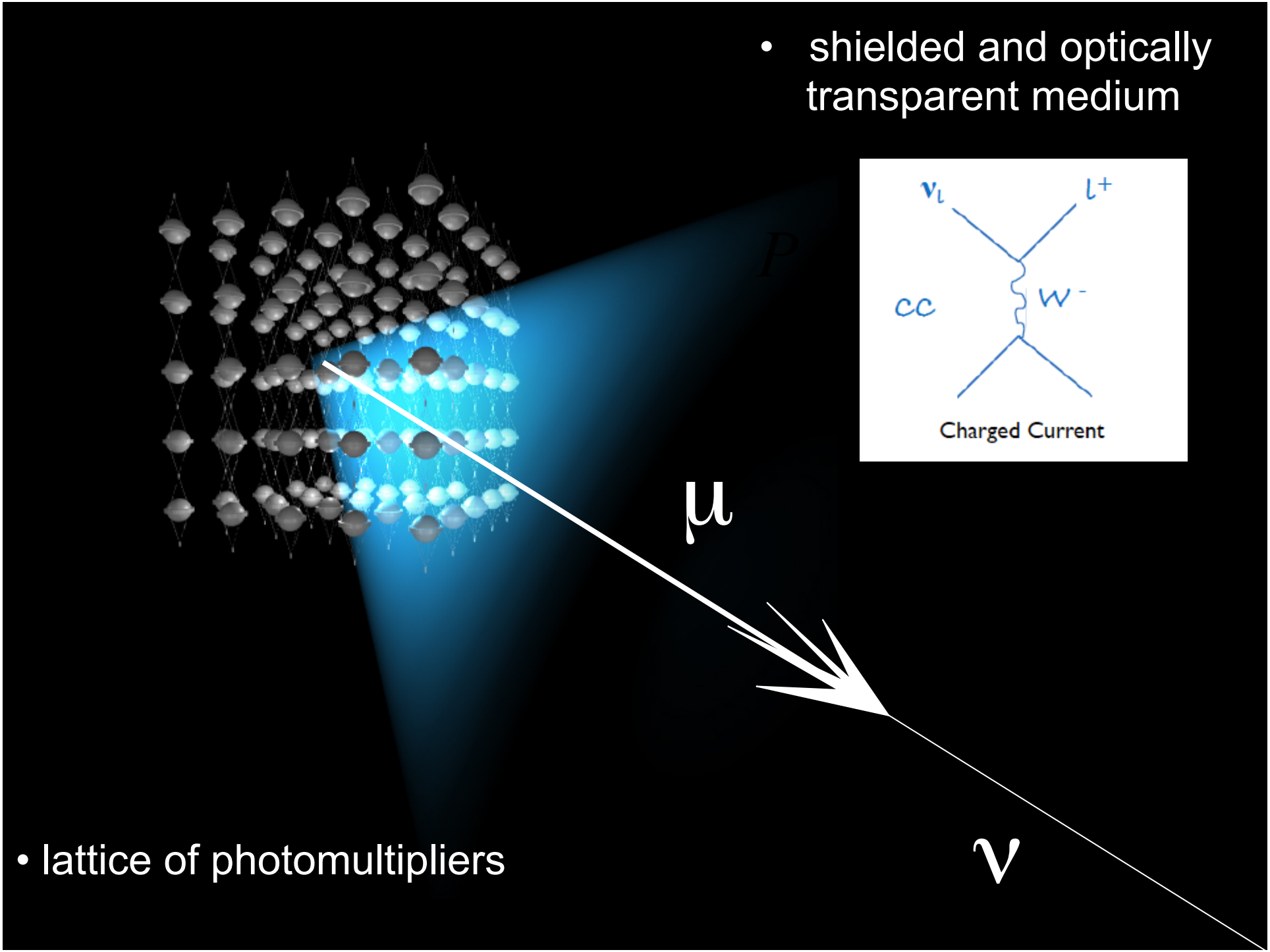
IceCube: the discovery of cosmic neutrinos

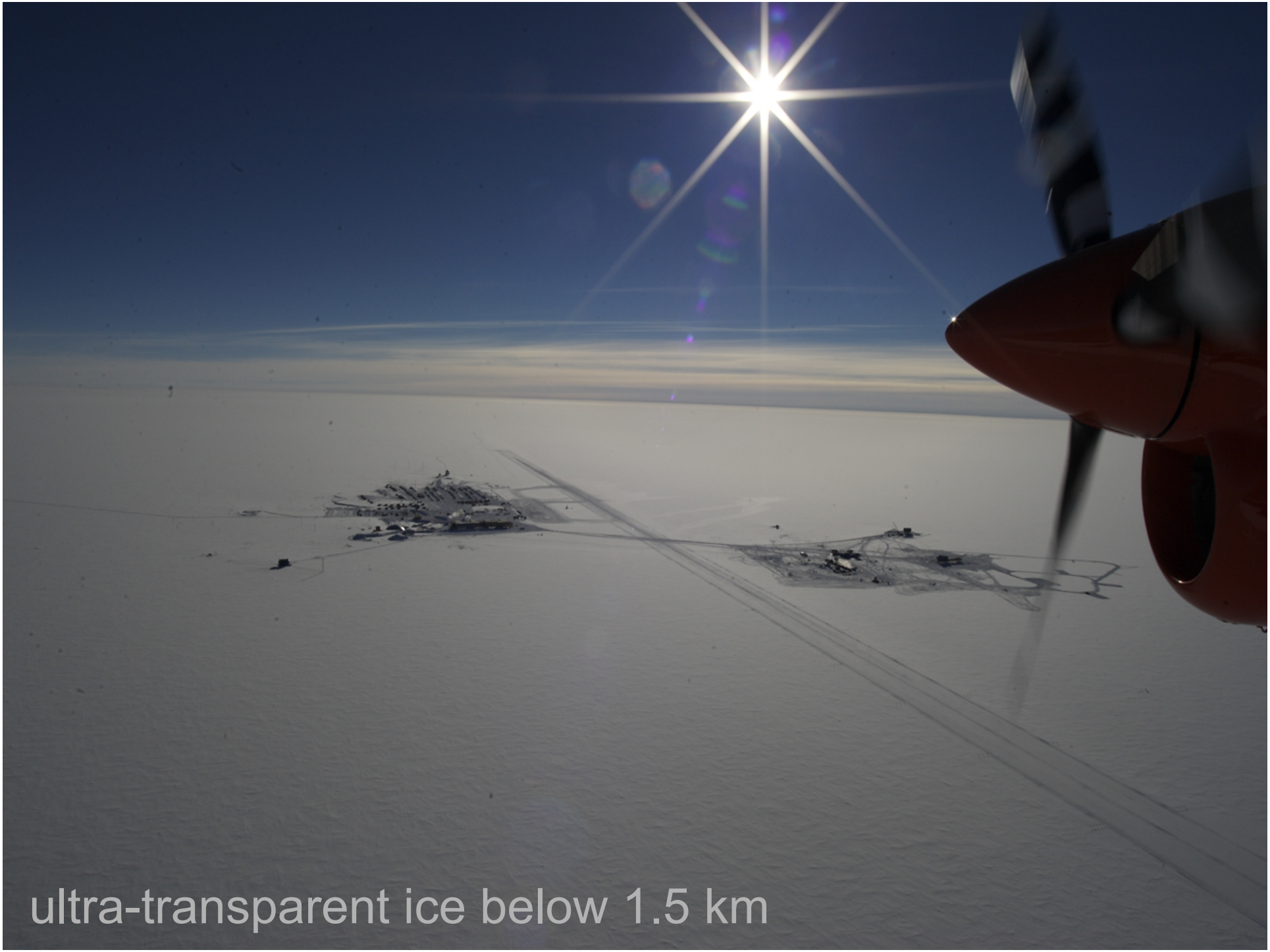
francis halzen

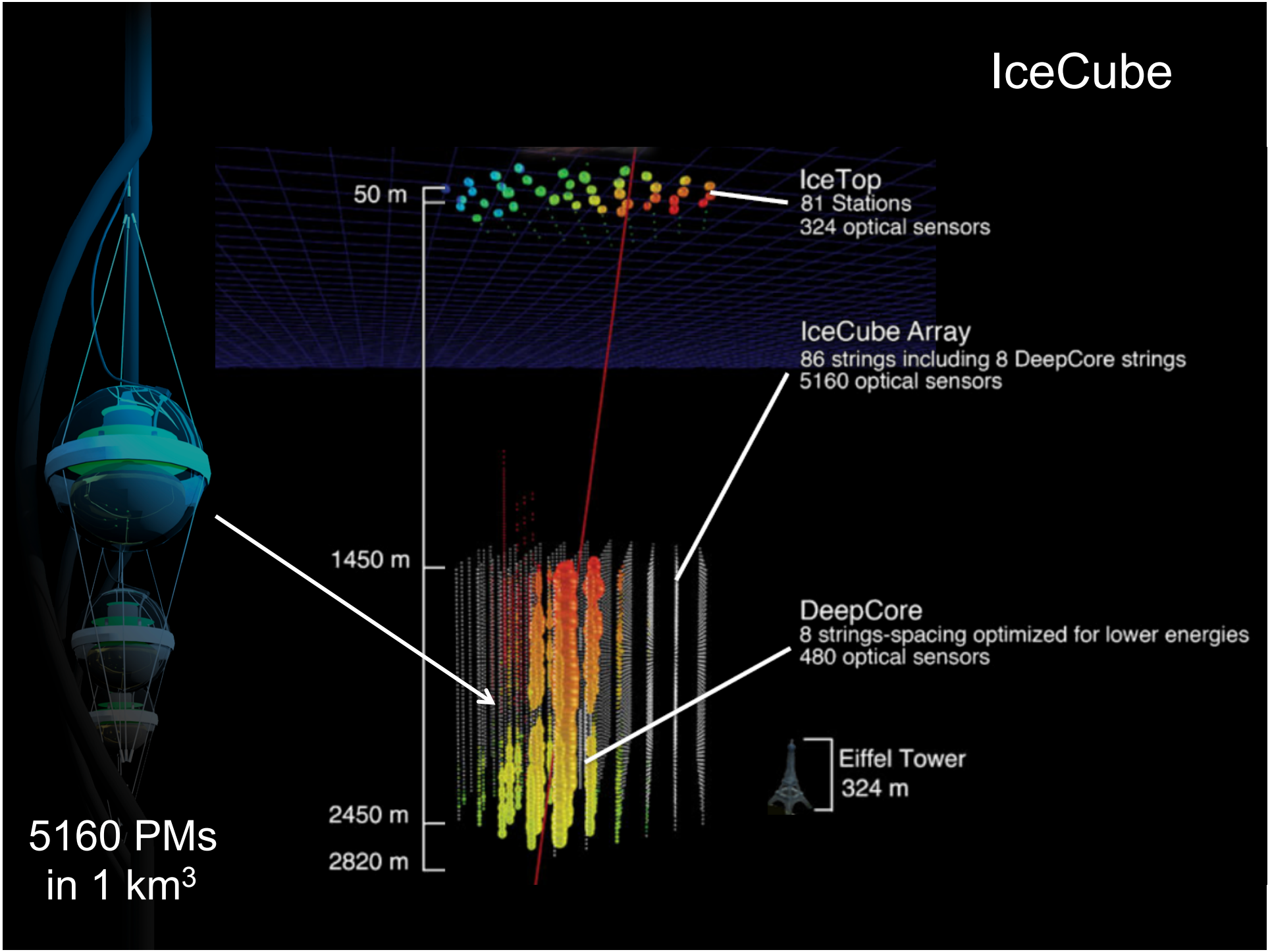
- cosmic ray accelerators
- IceCube: a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube



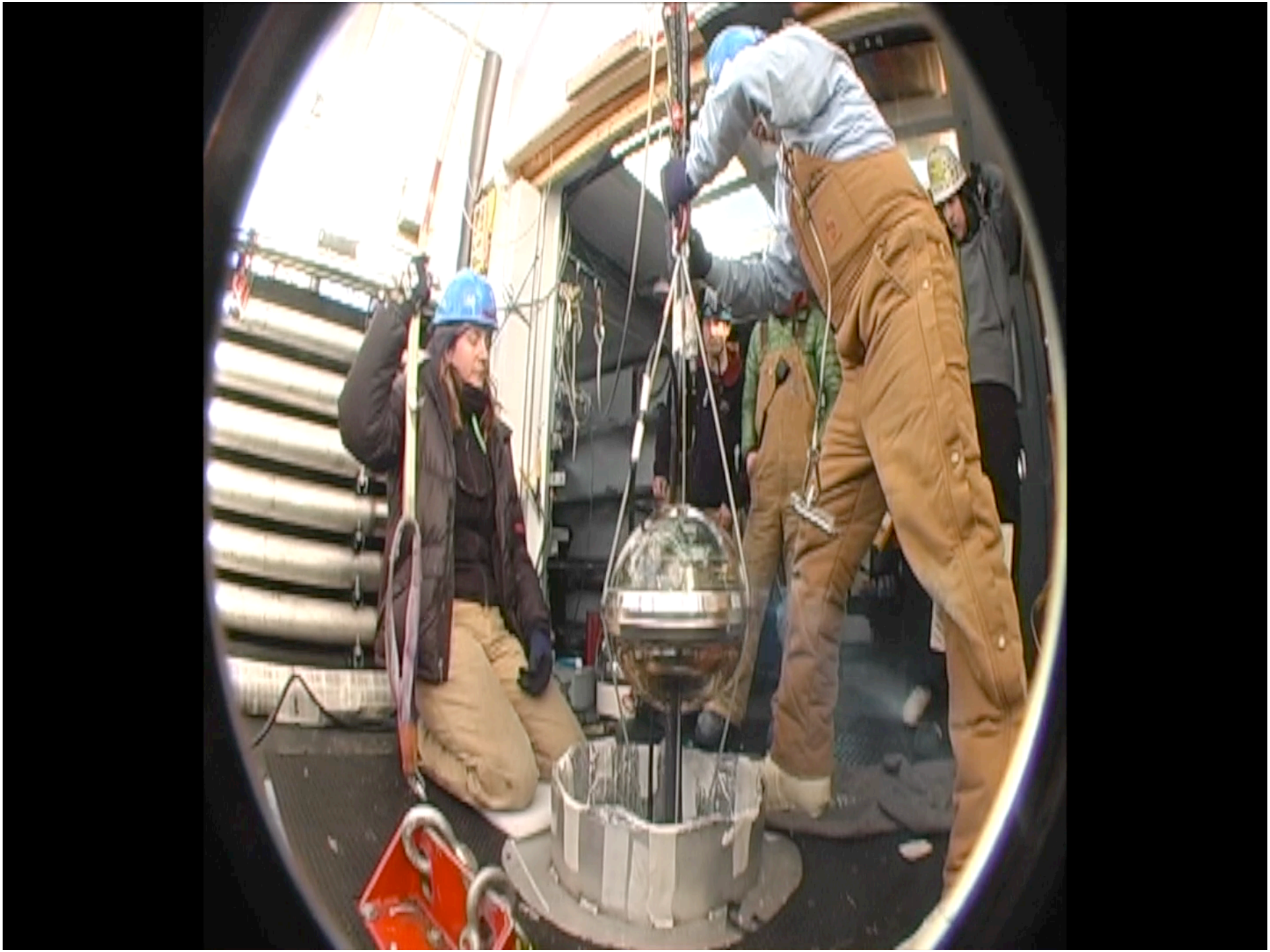
M.Markov :
we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.


• shielded and optically transparent medium
ν_l
l^+
cc
W^-
Charged Current
μ
ν
• lattice of photomultipliers


ultra-transparent ice below 1.5 km

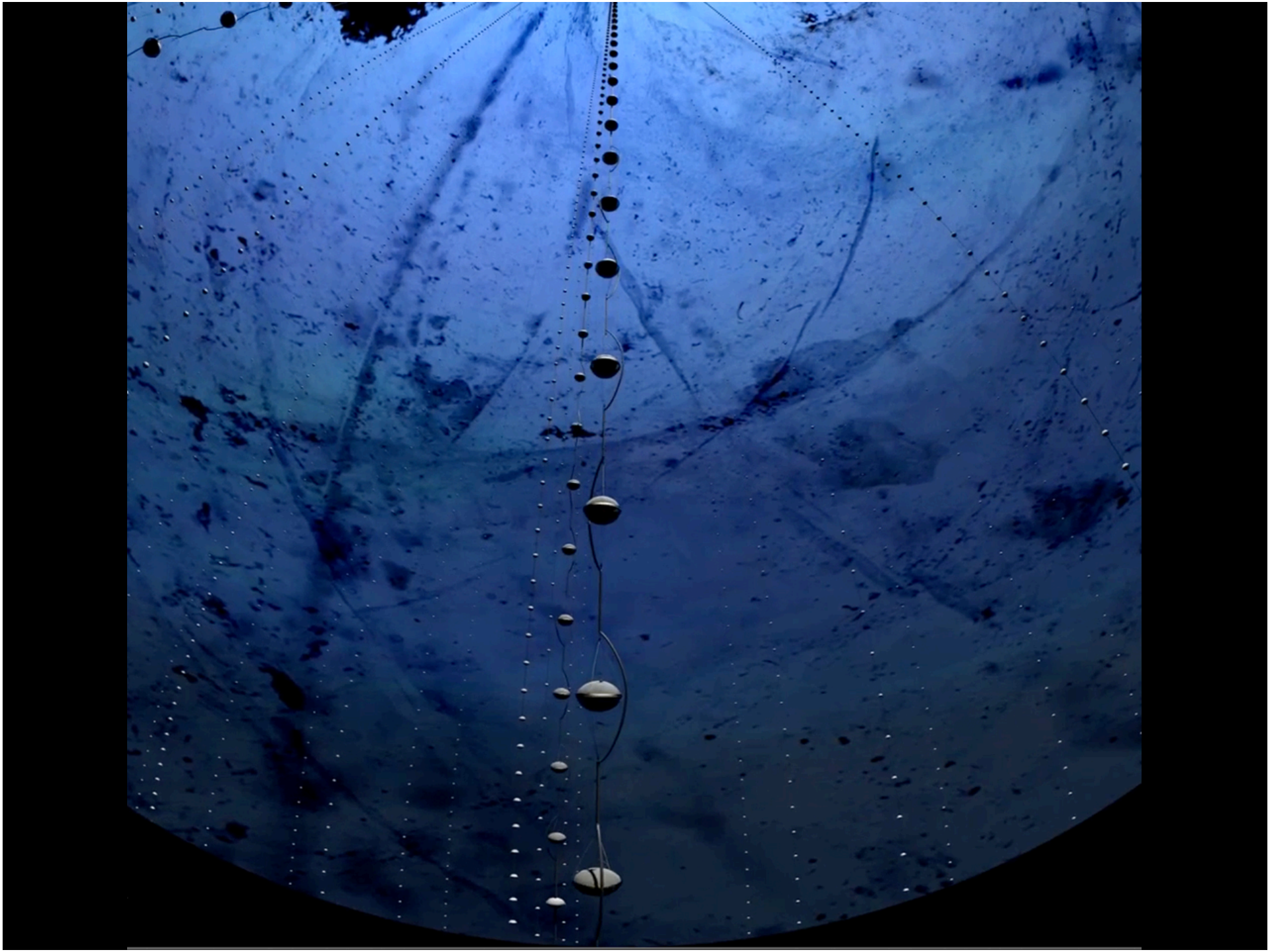

IceCube
50 m
IceTop
81 Stations
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
1450 m
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
2450 m
2820 m
5160 PMs
in 1 km3

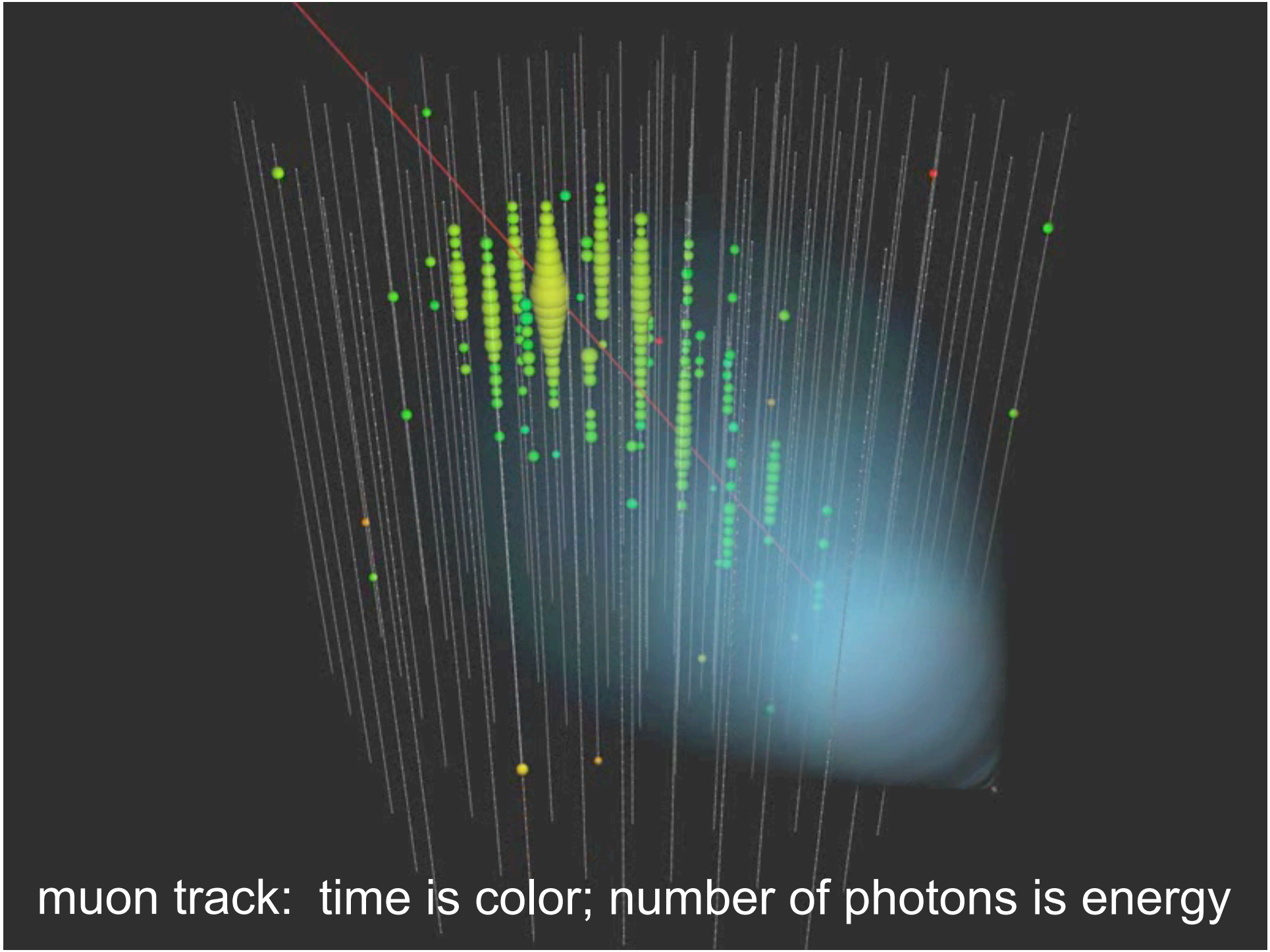
photomultiplier tube -10 inch



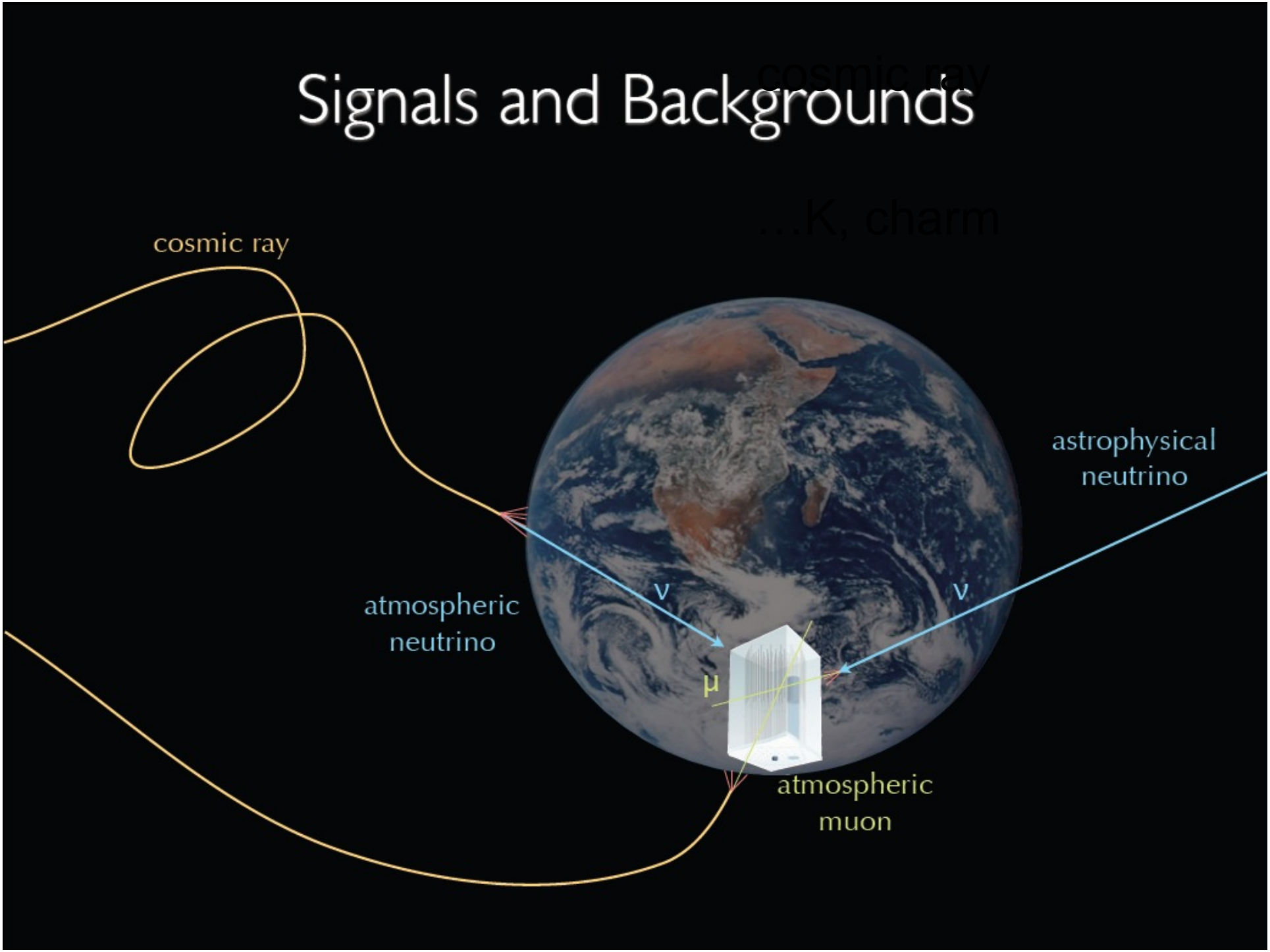
drilling and deployment

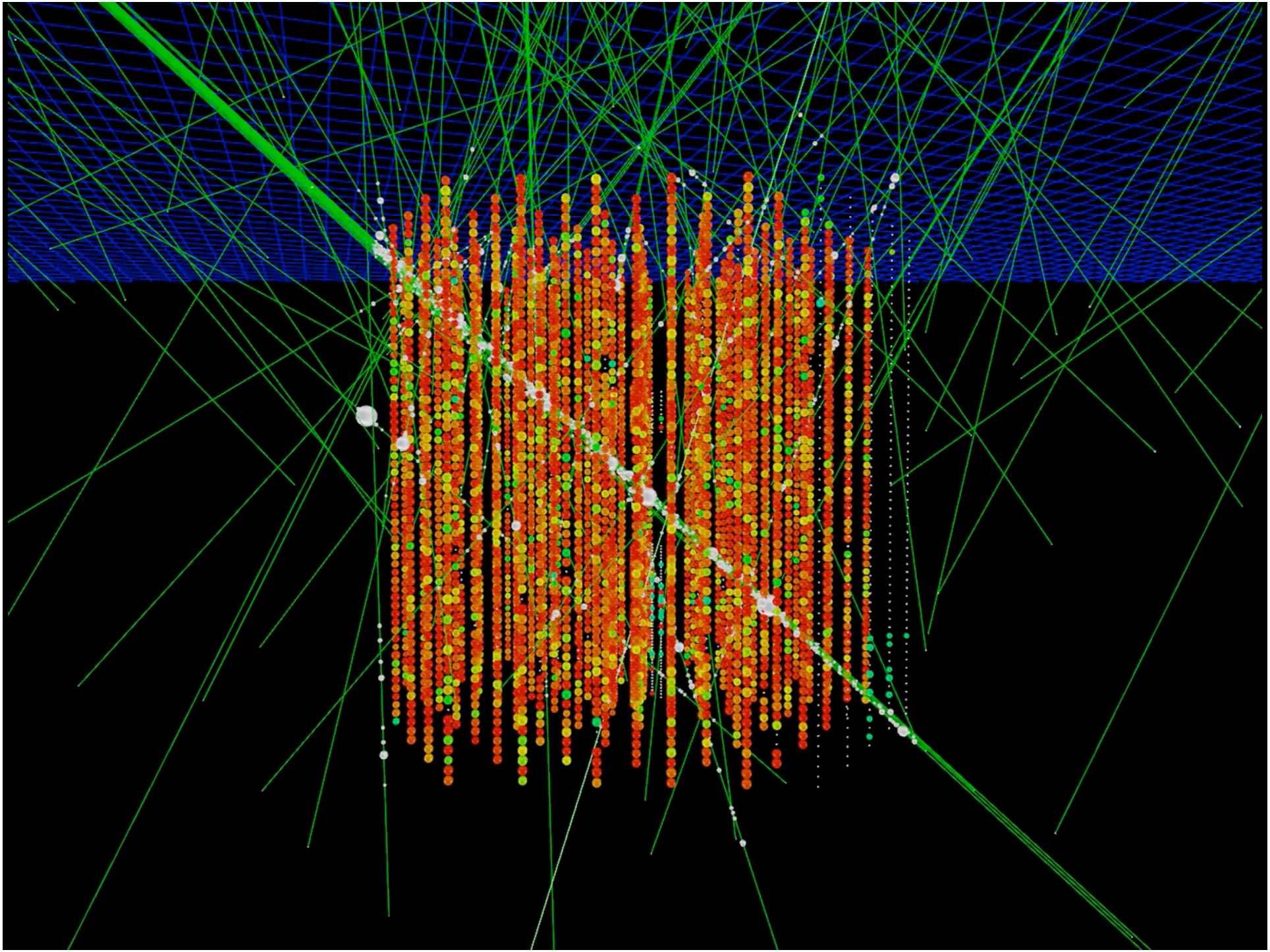
2 days per hole
3.5 cm/second




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

Signals and Backgrounds



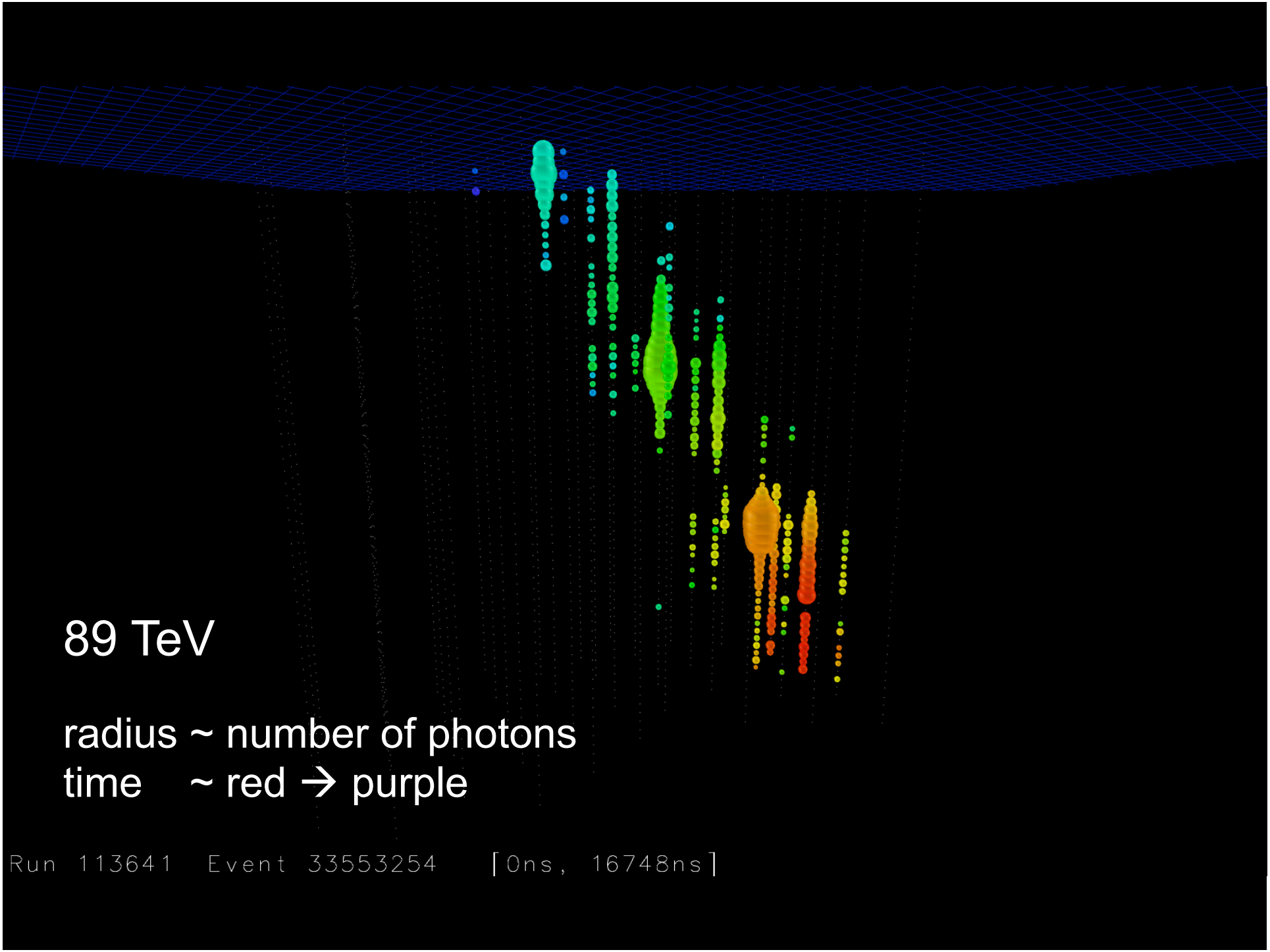


… you looked at 10msec of data !

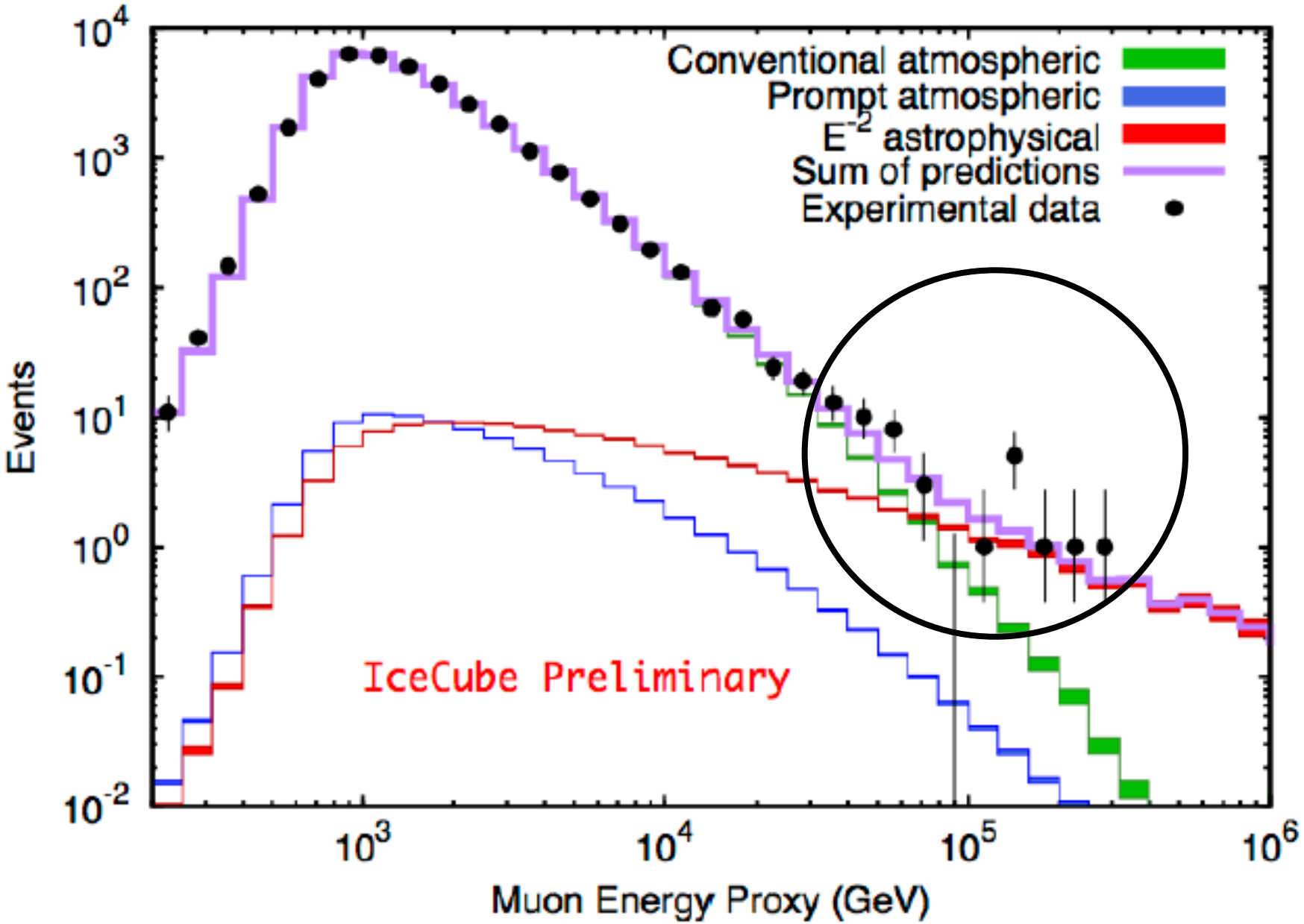
muons detected per year:

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

* 3000 per second ** 1 every 6 minutes


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

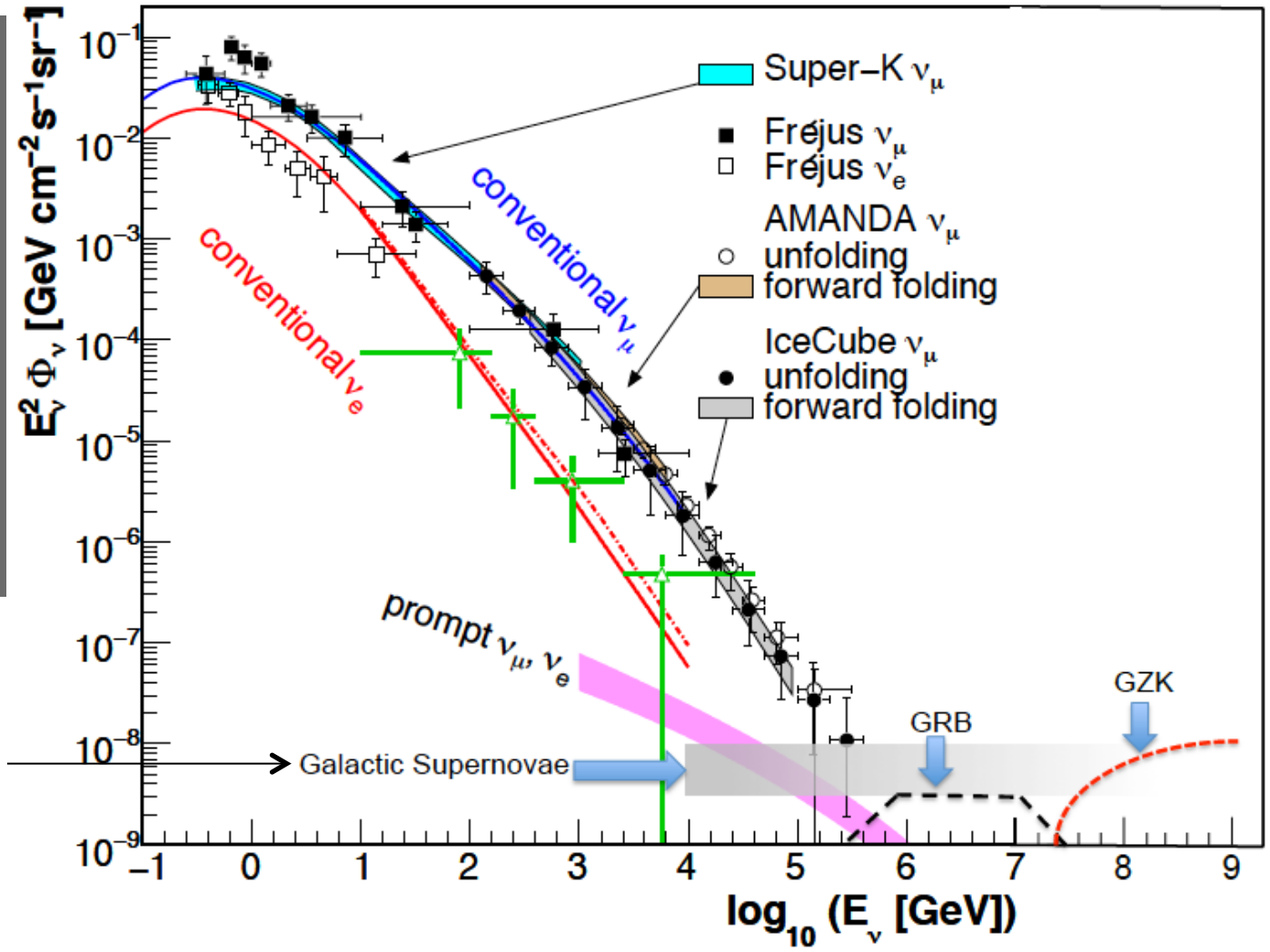
cosmic neutrinos in 2 years of data at 3.7 sigma



above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

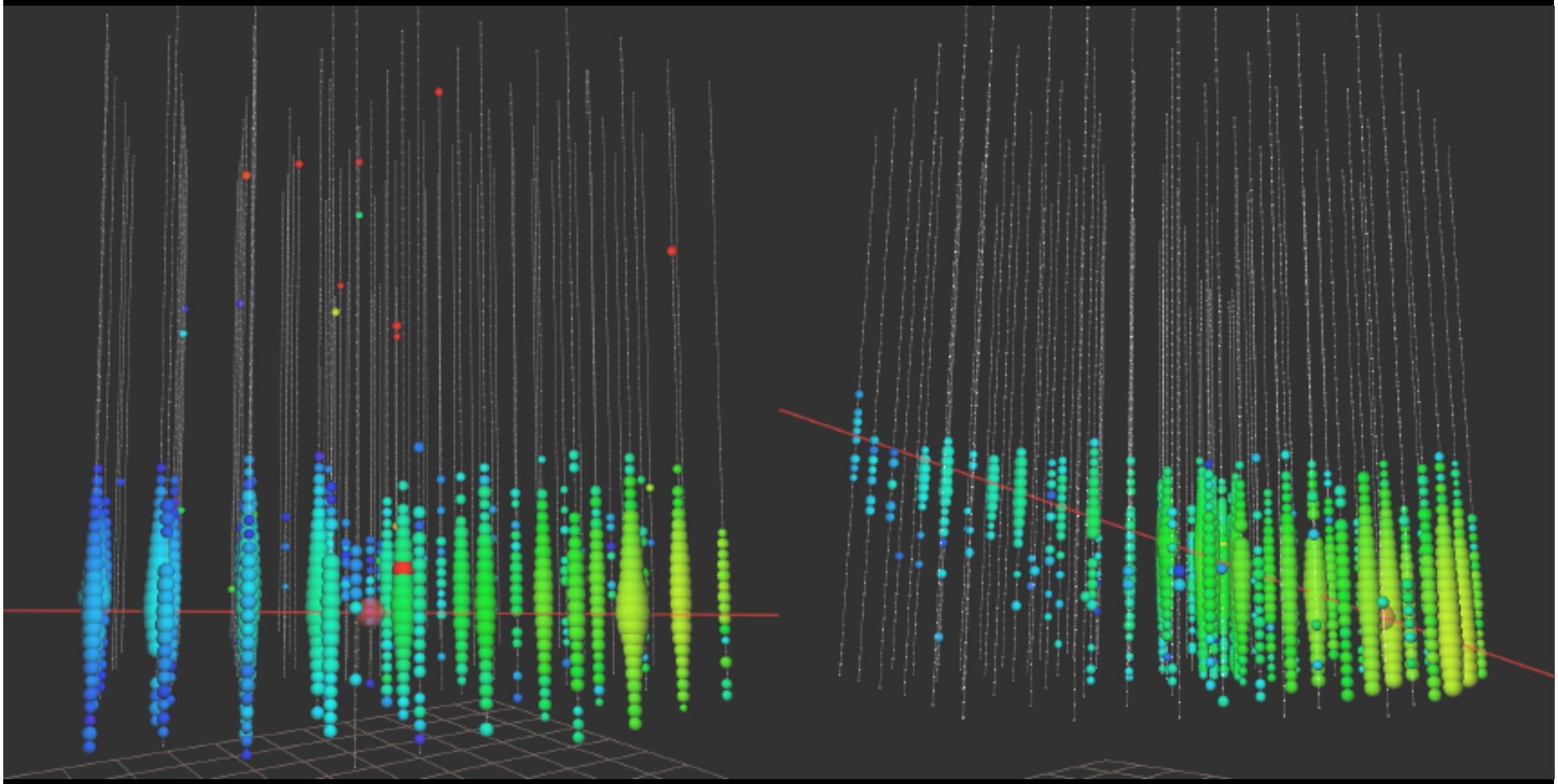
$$dN/dE \sim E^{-2}$$

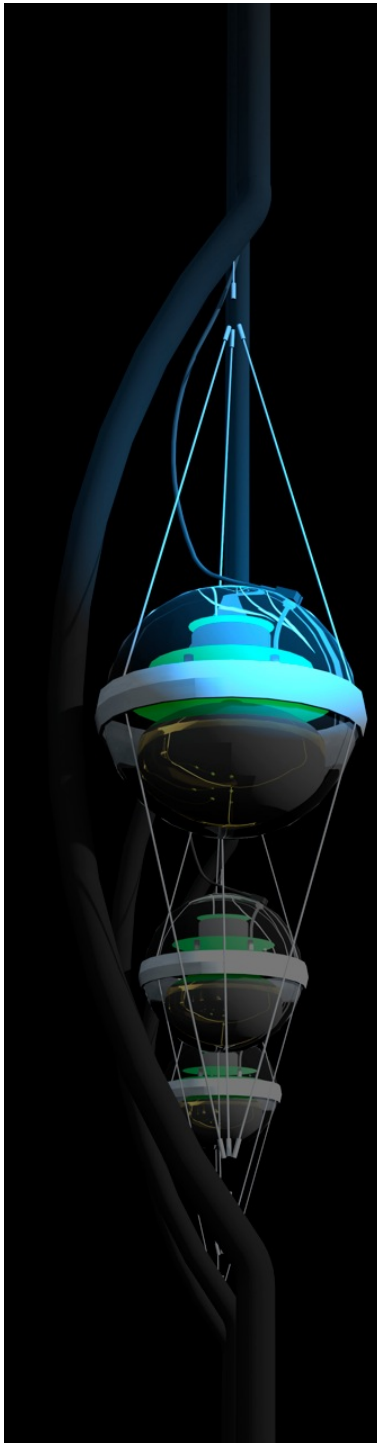


atmospheric cosmic

100 TeV

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





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

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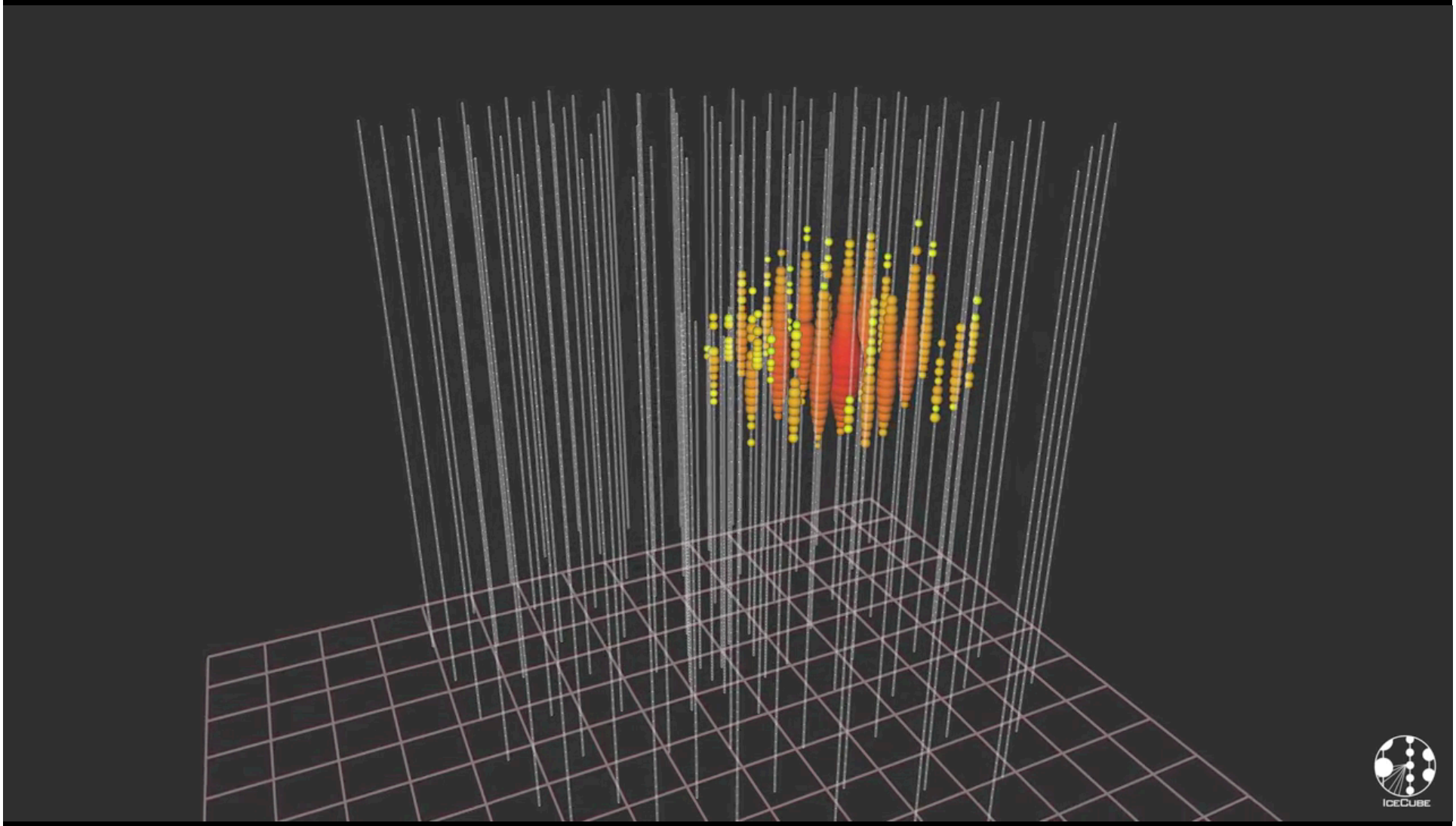
$$\pi \rightarrow \mu + \upsilon_{\mu} \rightarrow \{e + \overline{\upsilon_{\mu}} + \upsilon_{e}\} + \upsilon_{\mu}$$

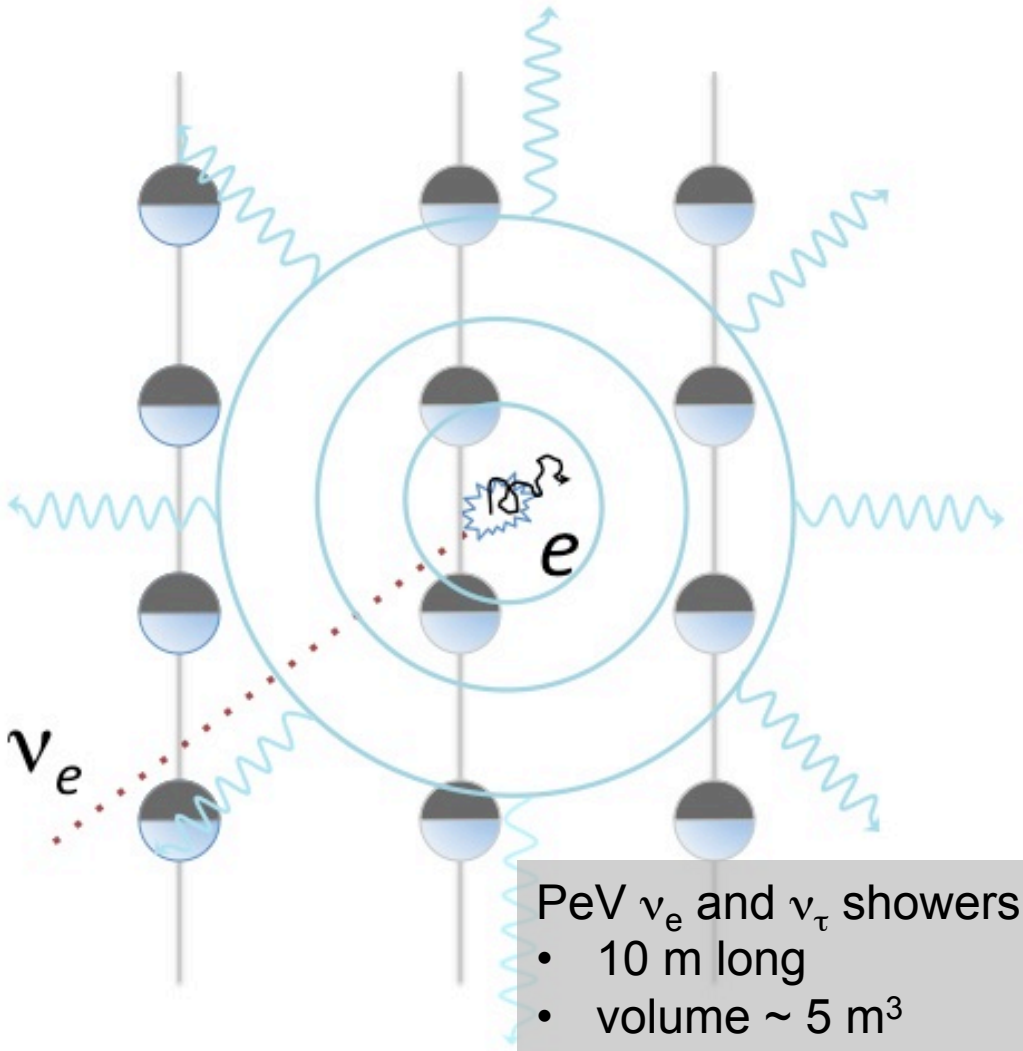
1 event per cubic kilometer per year

...but it points at its source!

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

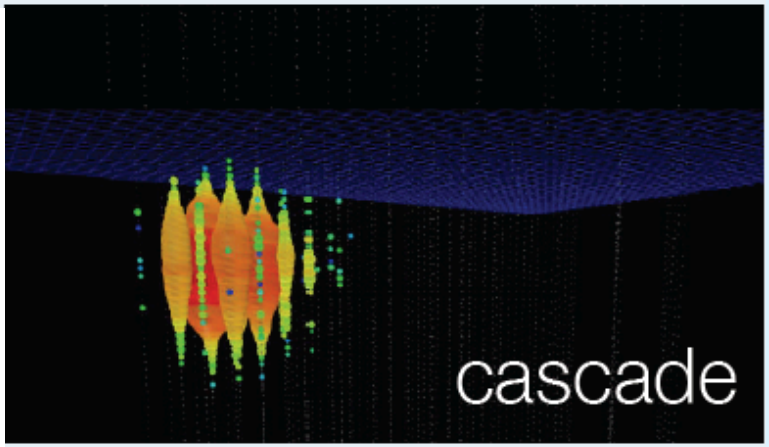


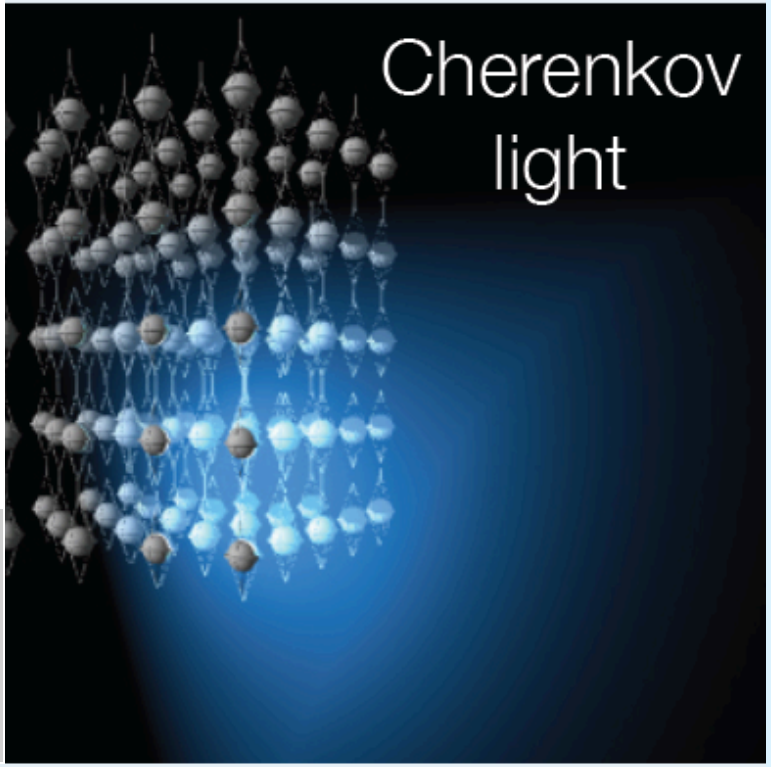
tracks and showers

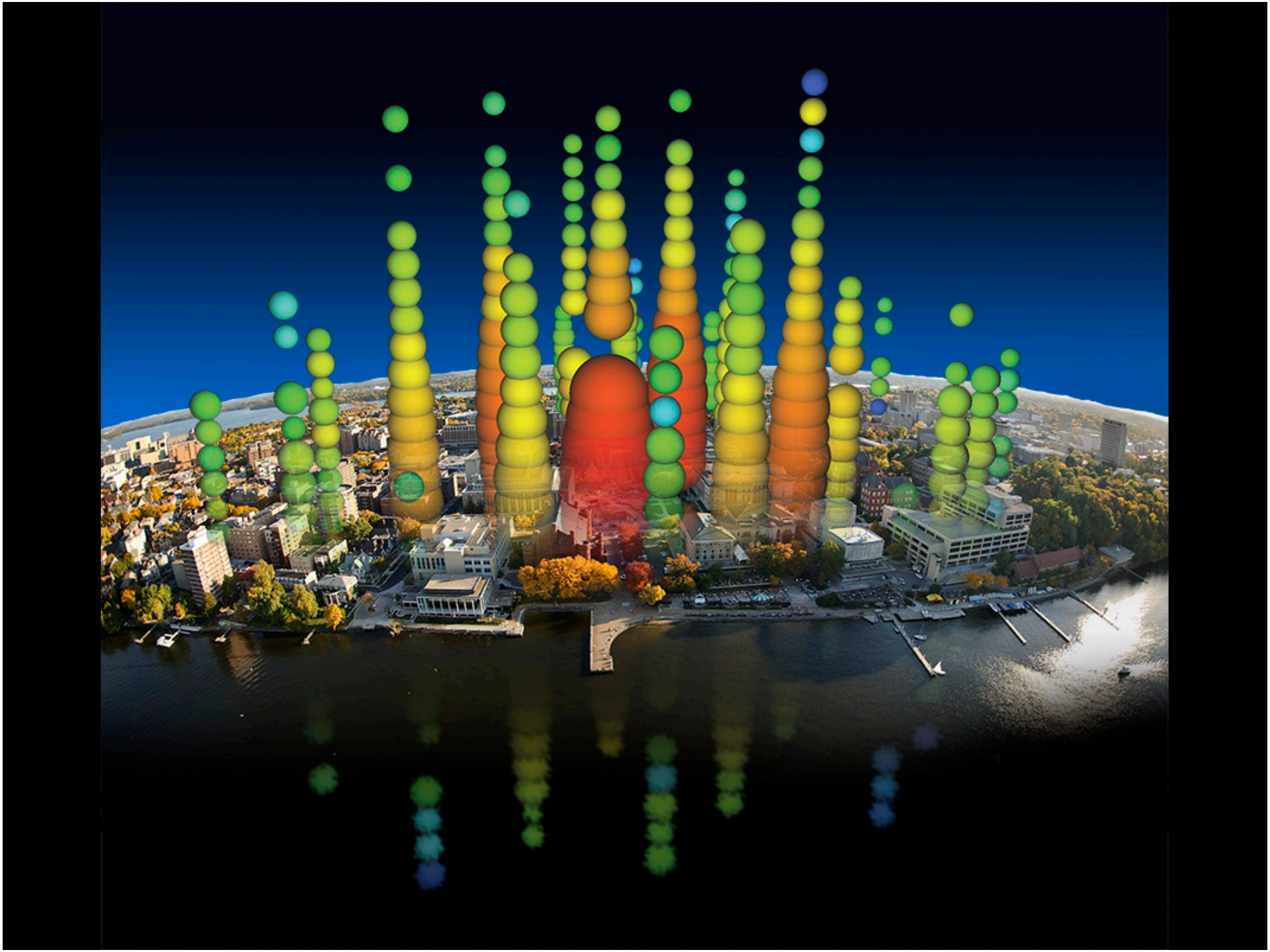


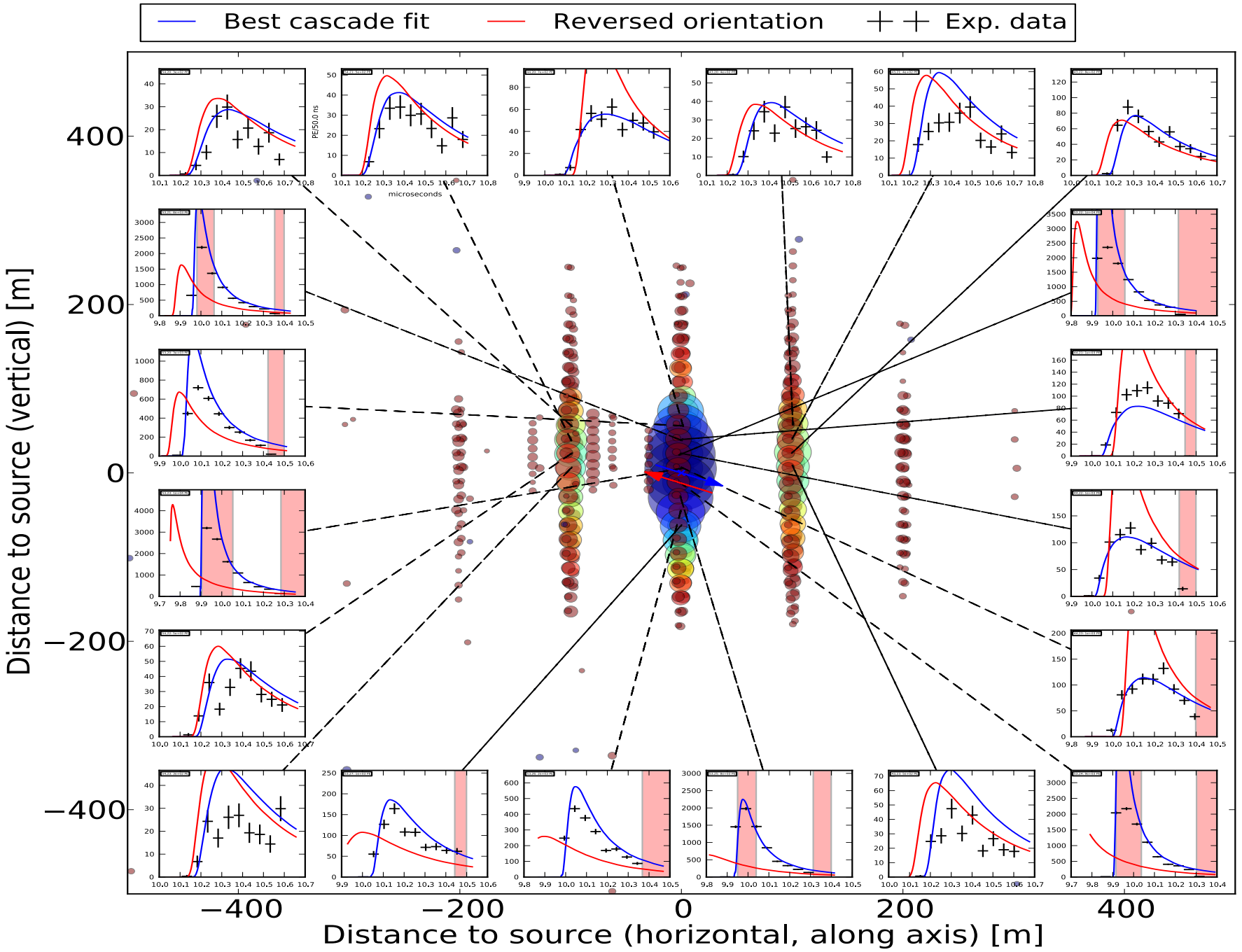
PeV ν_e and ν_τ showers:

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

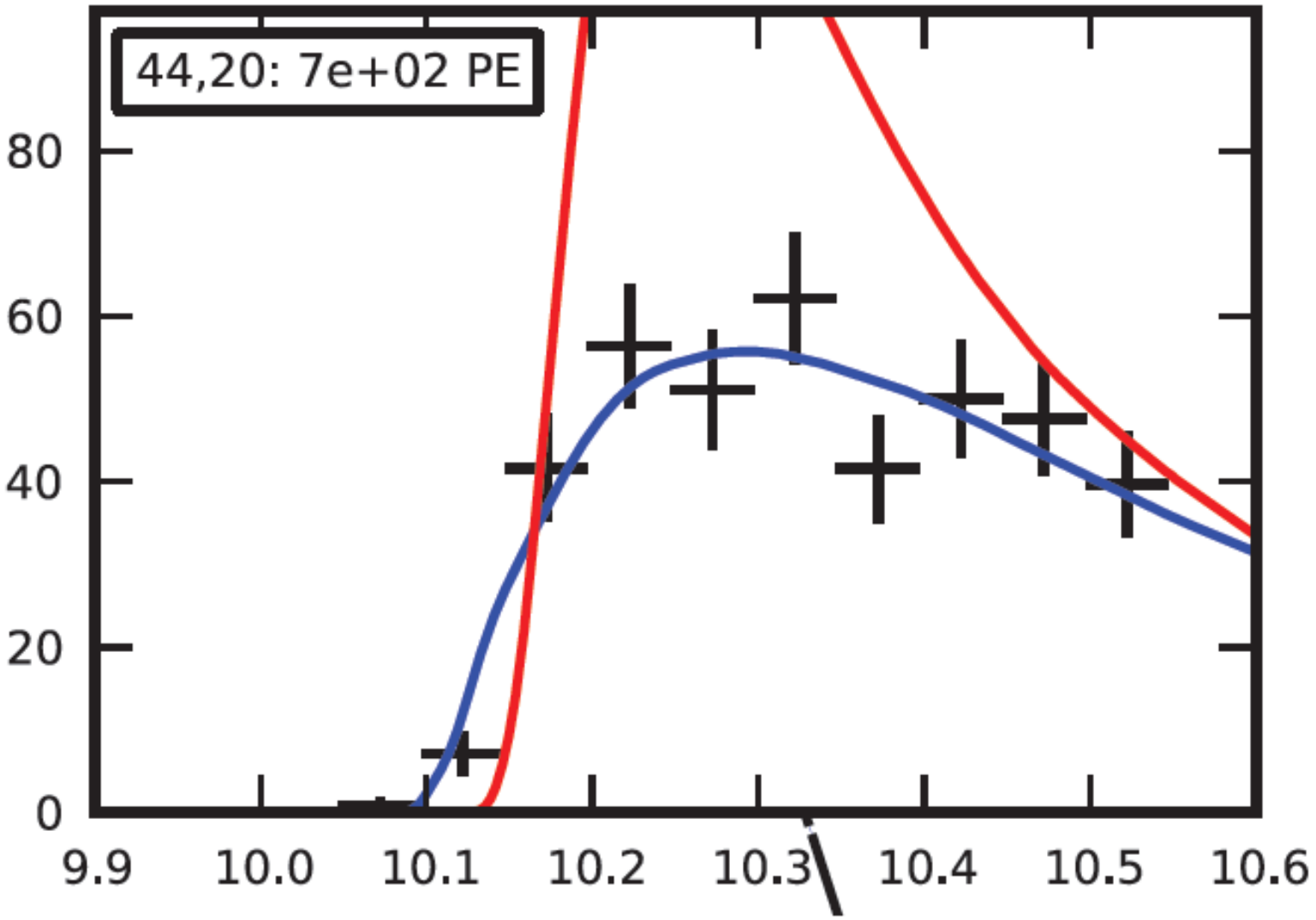






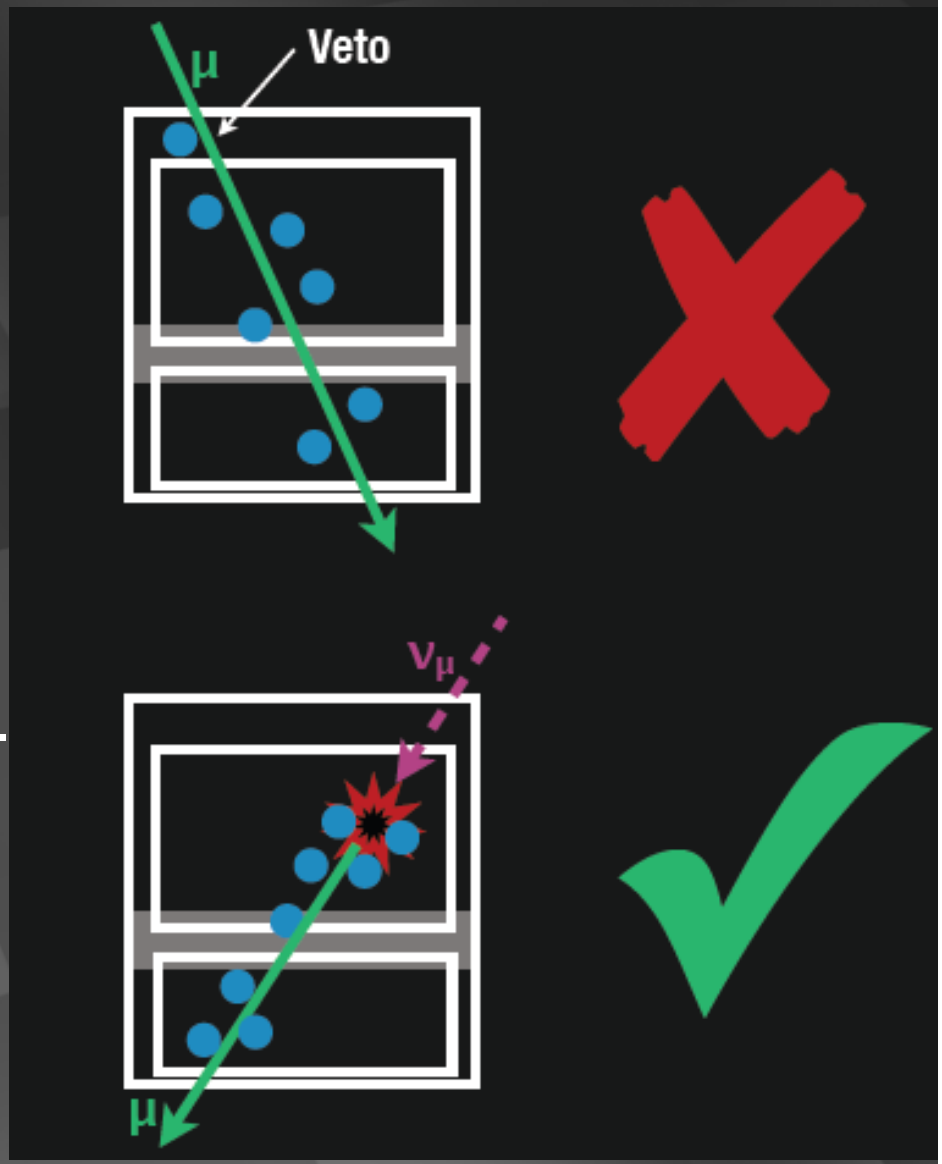

Best cascade fit
Reversed orientation
Exp. data
Distance to source (vertical) [m]
Distance to source (horizontal, along axis) [m]
400
200
0
−200
−400
PE/50.0 ns
microseconds

reconstruction limited by computing, not ice !

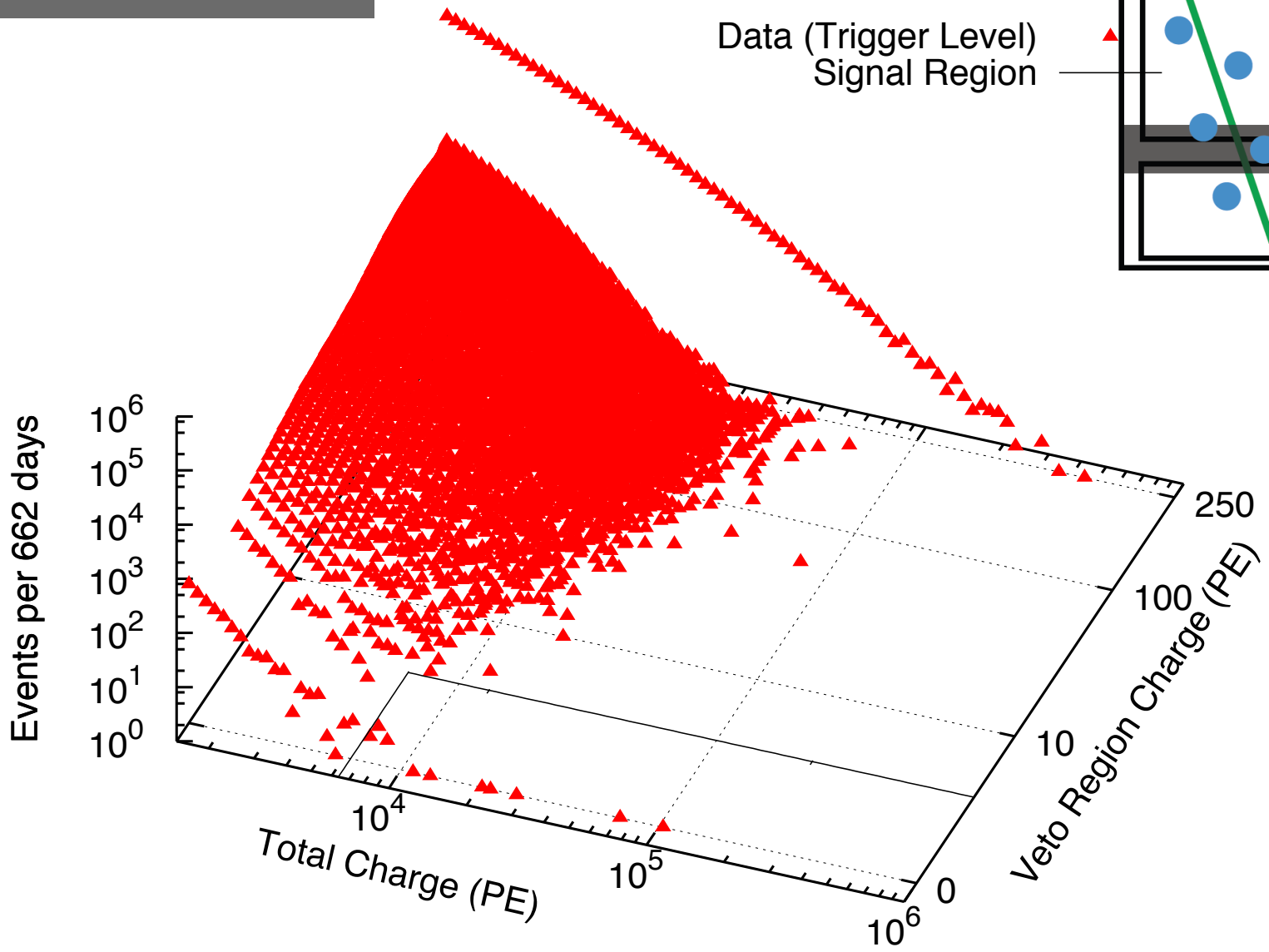


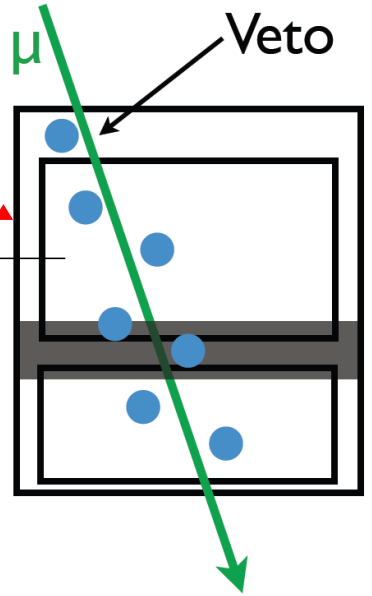
Blue: best-fit direction, red: reversed direction

- ✓ 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



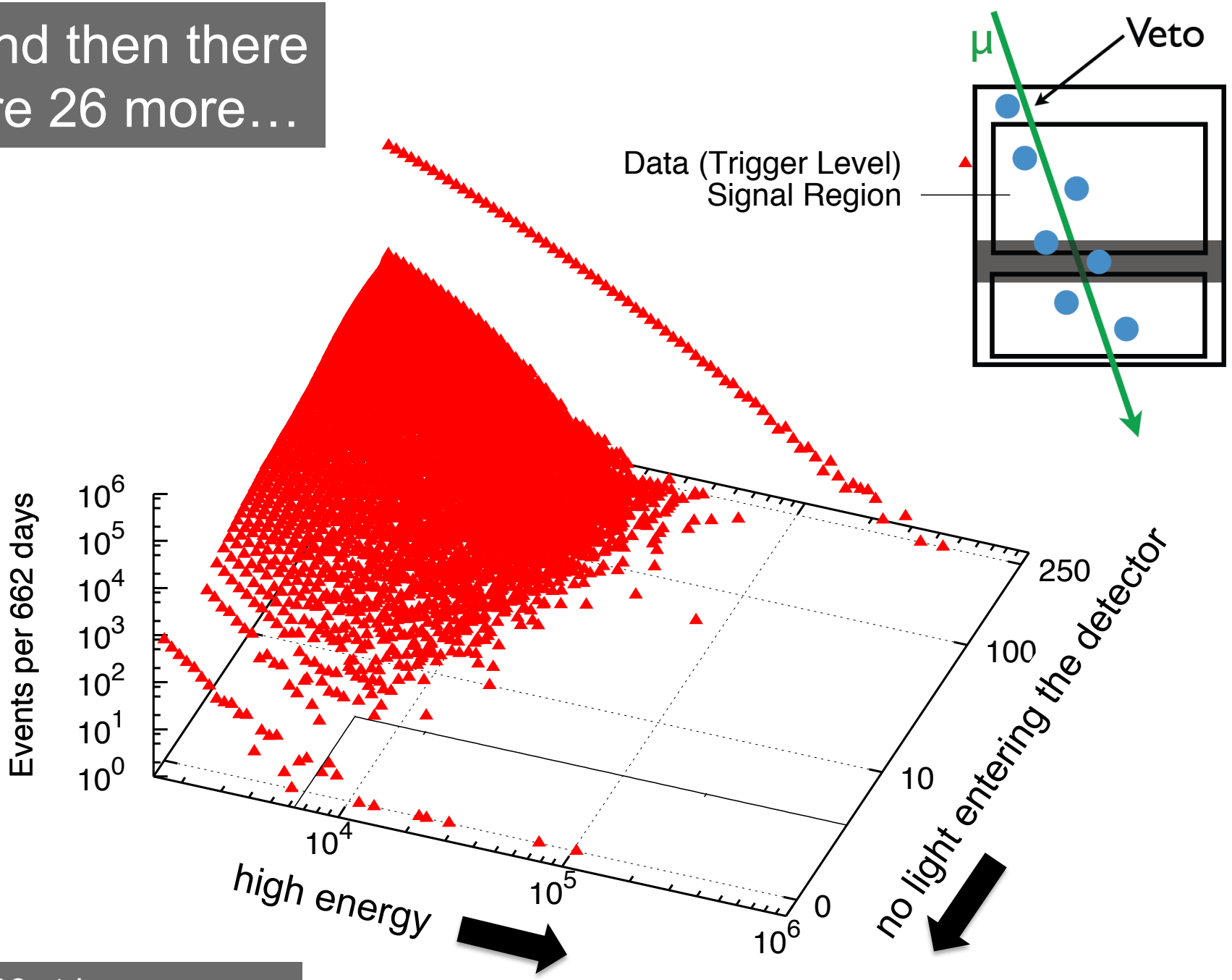
…and then there were 26 more…





data: 86 strings one year

…and then there were 26 more…



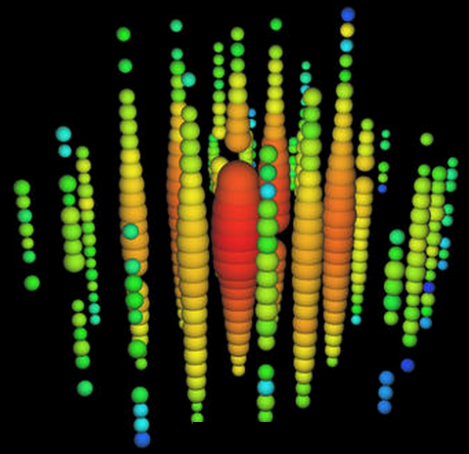
data: 86 strings one year

RESEARCH

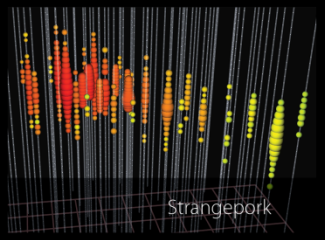
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

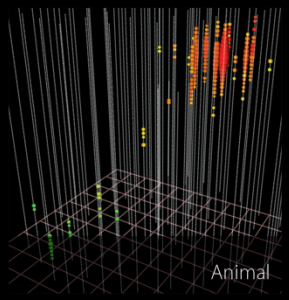
IceCube Collaboration*

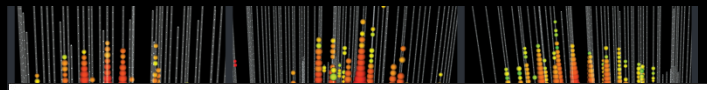
Introduction: Neutrino observations are a unique probe of the universe's highest-en



28 High Energy Events



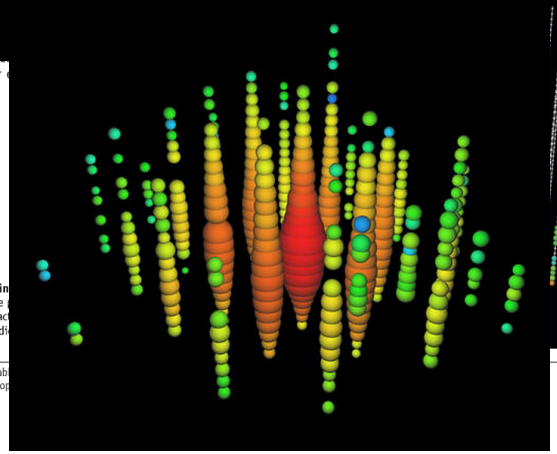


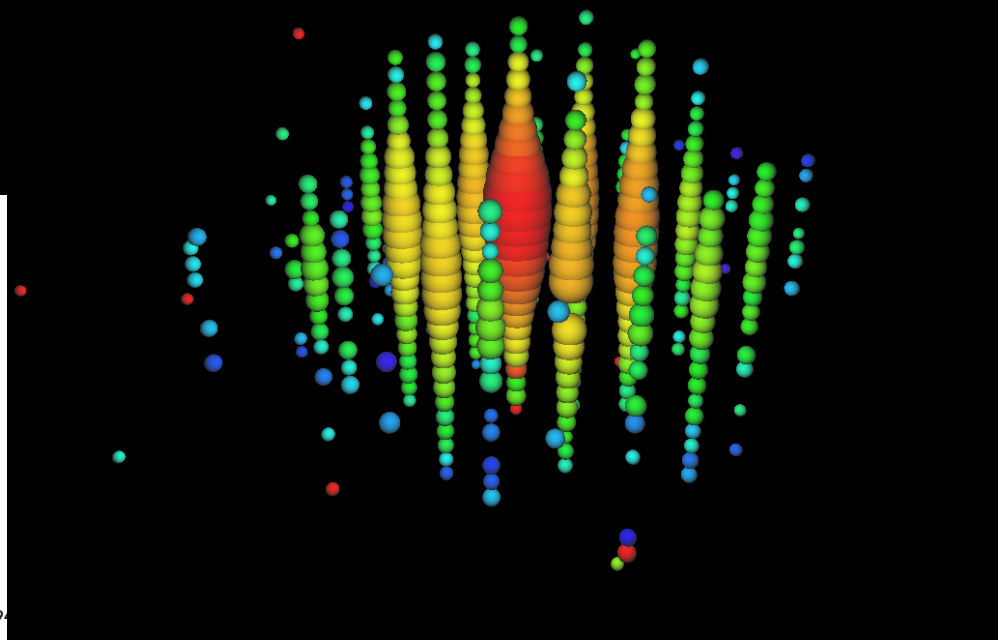


tified high-energy galactic or
accelerators.

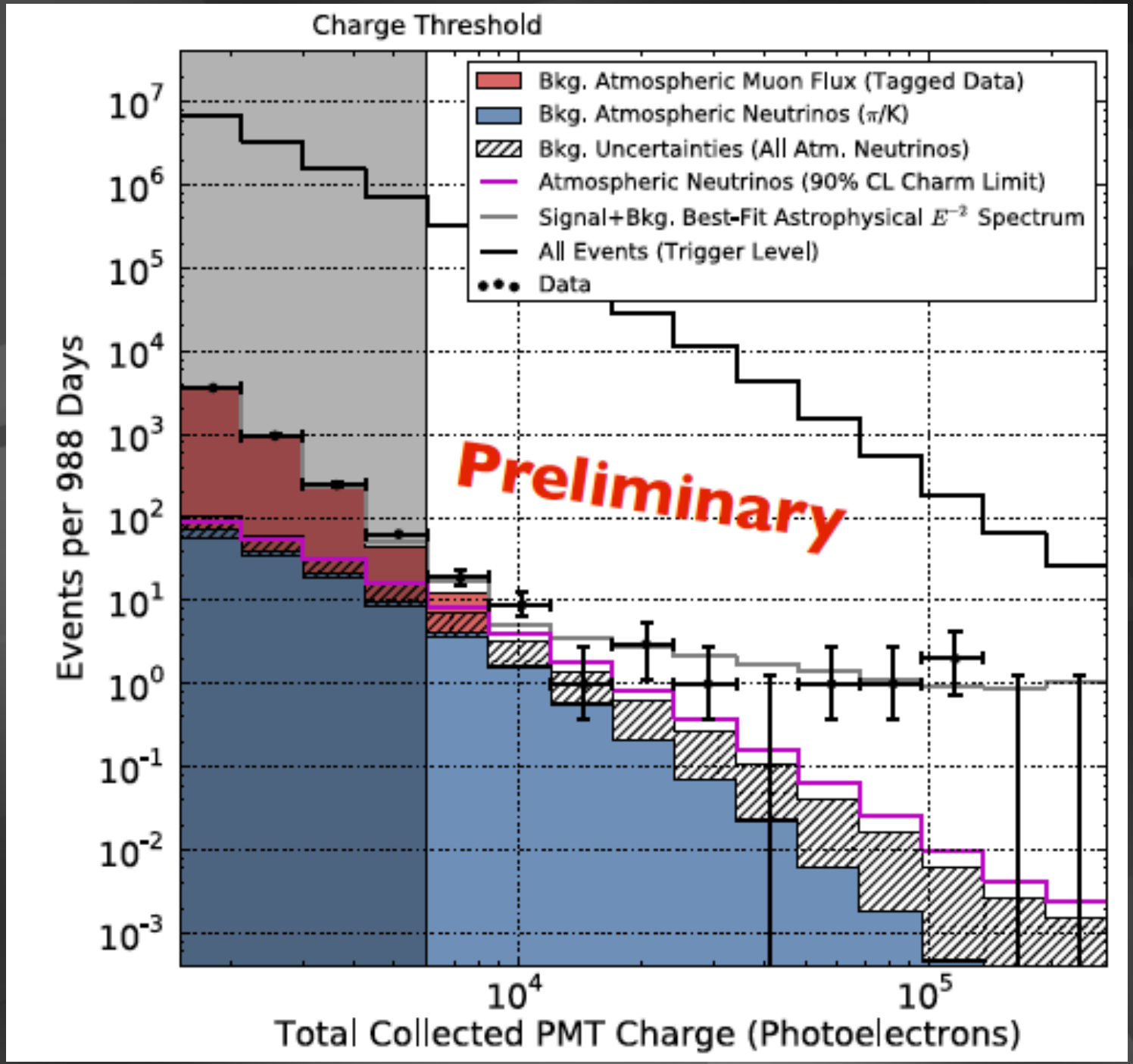
A 250 TeV neutrino interaction in
interaction point (bottom), a large
with a muon produced in the interac
left. The direction of the muon ind
original neutrino.

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



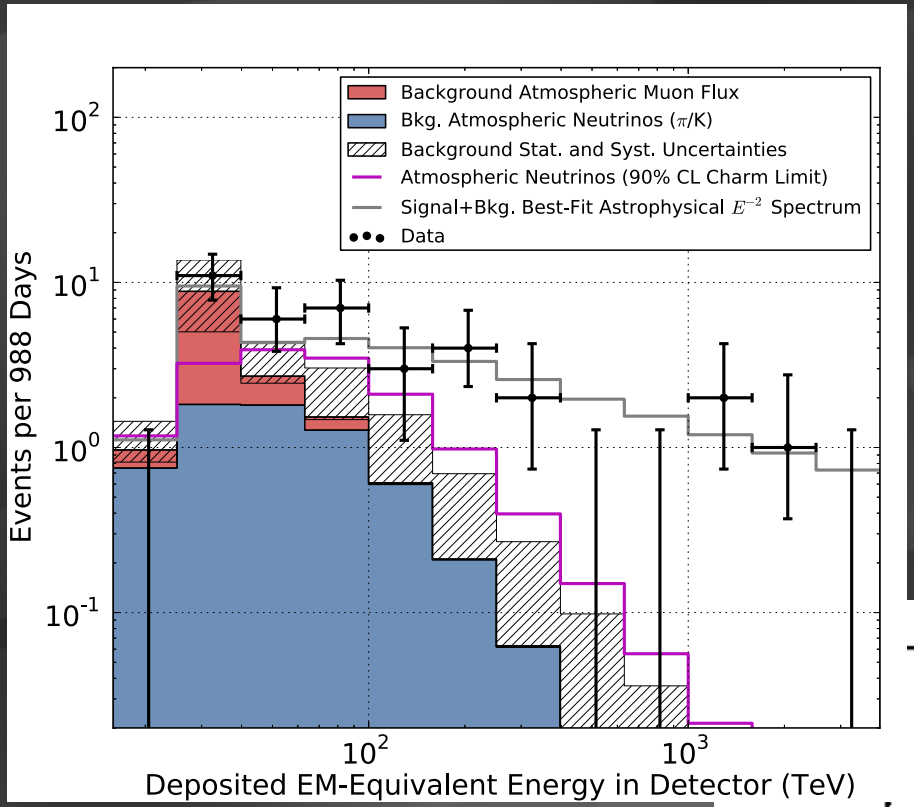


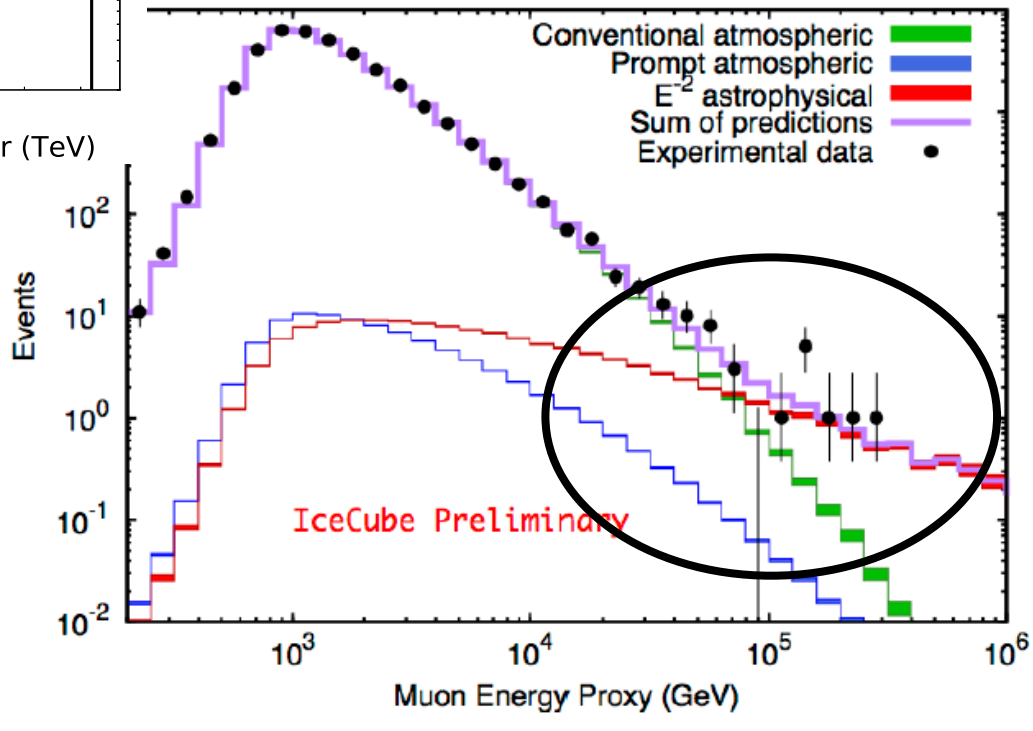
total charge collected by PMTs of events with interaction inside the detector



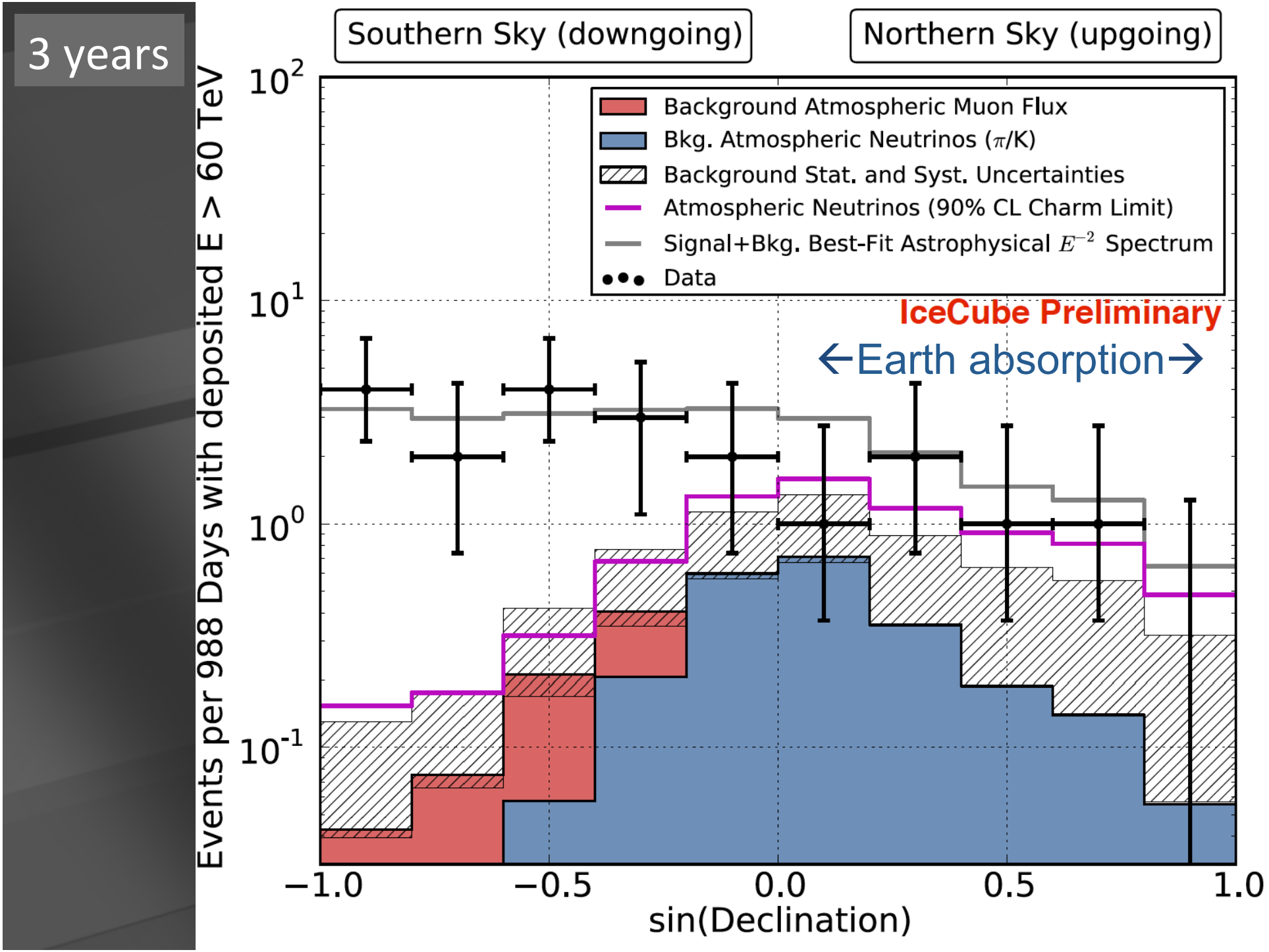
Science 342 (2013) 1242856

confirmation!
flux of muon neutrinos
through the Earth

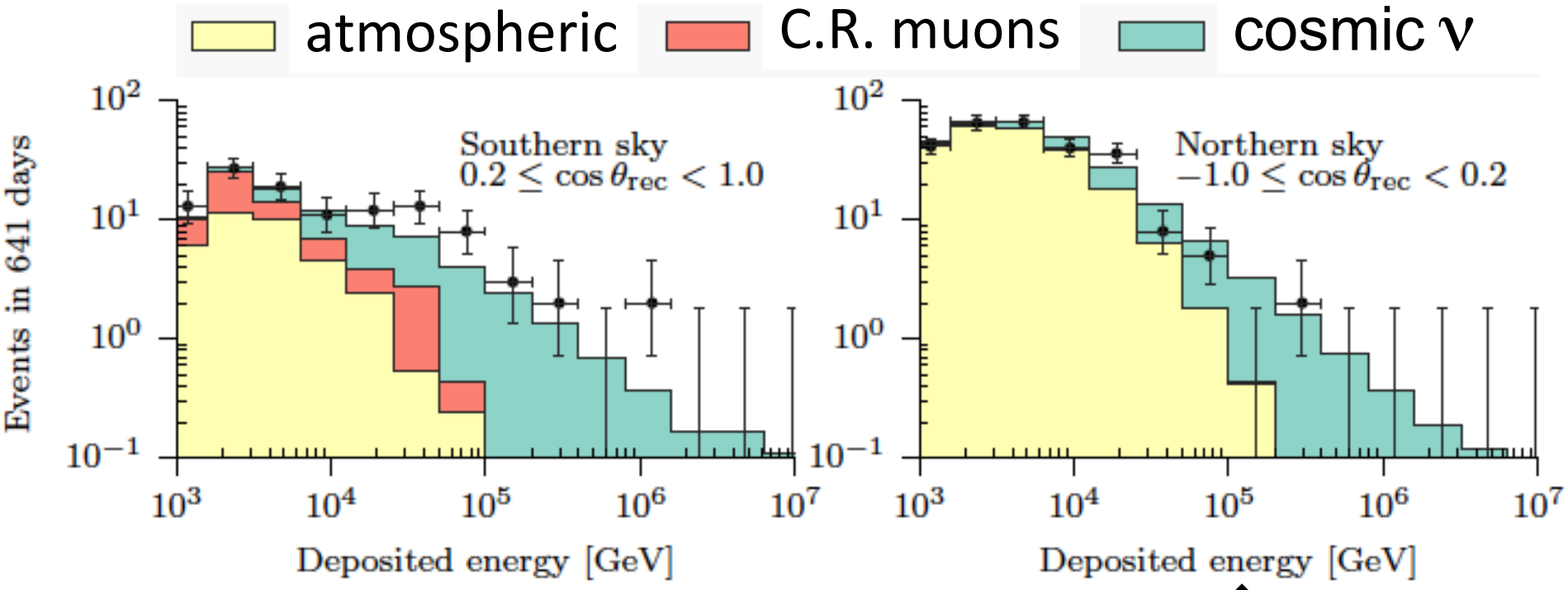




neutrinos of all flavors
interacting inside
IceCube


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
10^2
10^1
10^0
10^{-1}
−1.0
−0.5
0.0
0.5
1.0
sin(Declination)

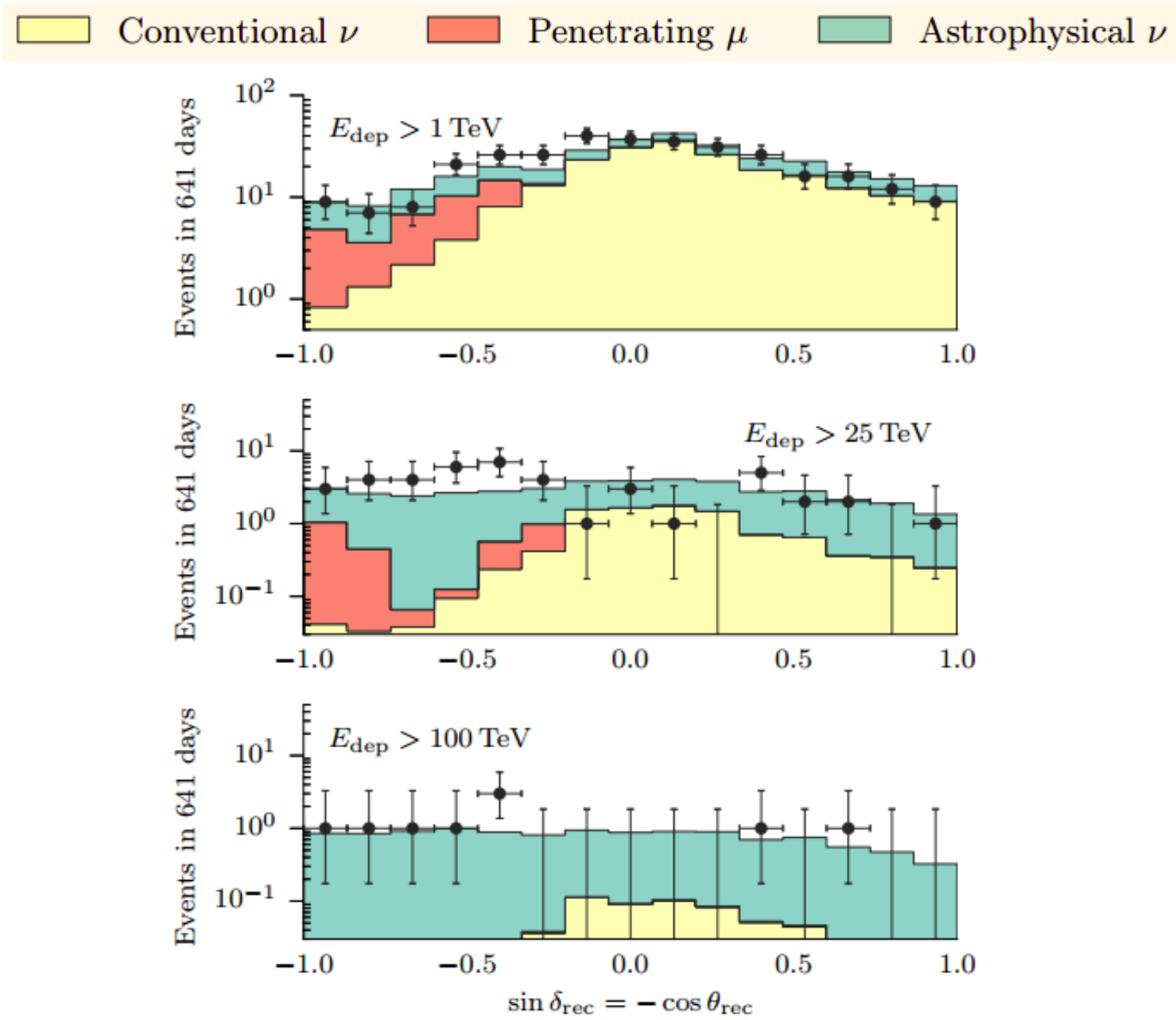
starting events; towards lower energies

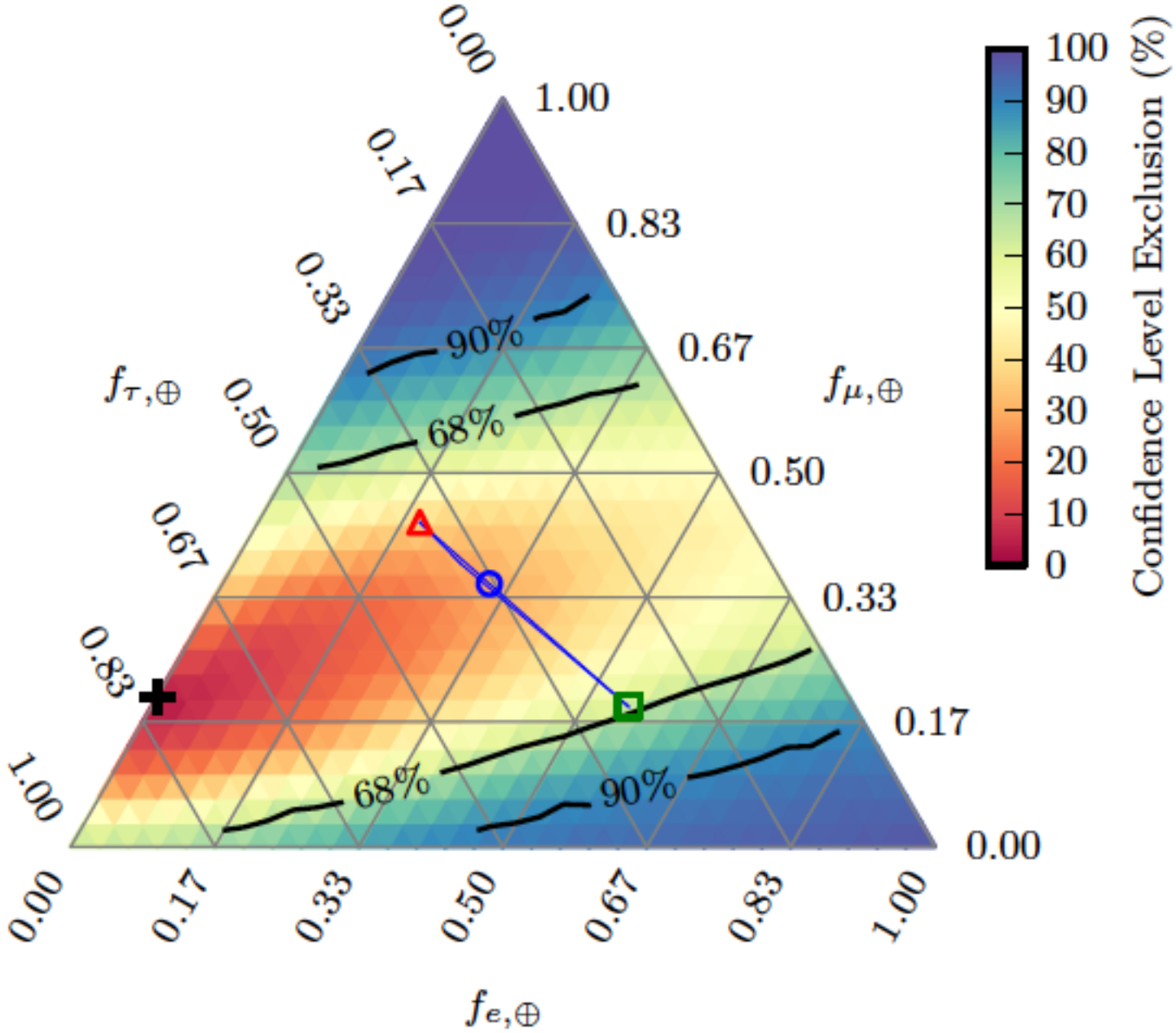


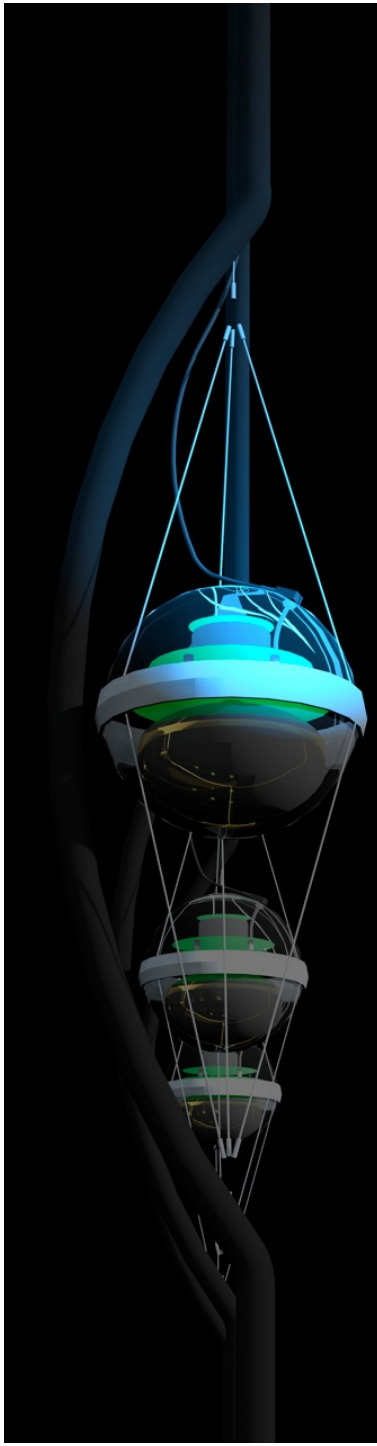
warning:
- spectrum may not be a power law
- slope depends on energy range fitted

PeV neutrinos absorbed in the Earth

arrival directions vs energy




0.00
1.00
0.17
0.83
0.33
0.67
$f_{\tau,\oplus}$
0.50
0.50
$f_{\mu,\oplus}$
0.67
0.33
0.83
0.17
1.00
0.00
90%
68%
68%
90%
0.00
0.17
0.33
0.50
0.67
0.83
1.00
$f_{e,\oplus}$
100
90
80
70
60
50
40
30
20
10
0
Confidence Level Exclusion (%)

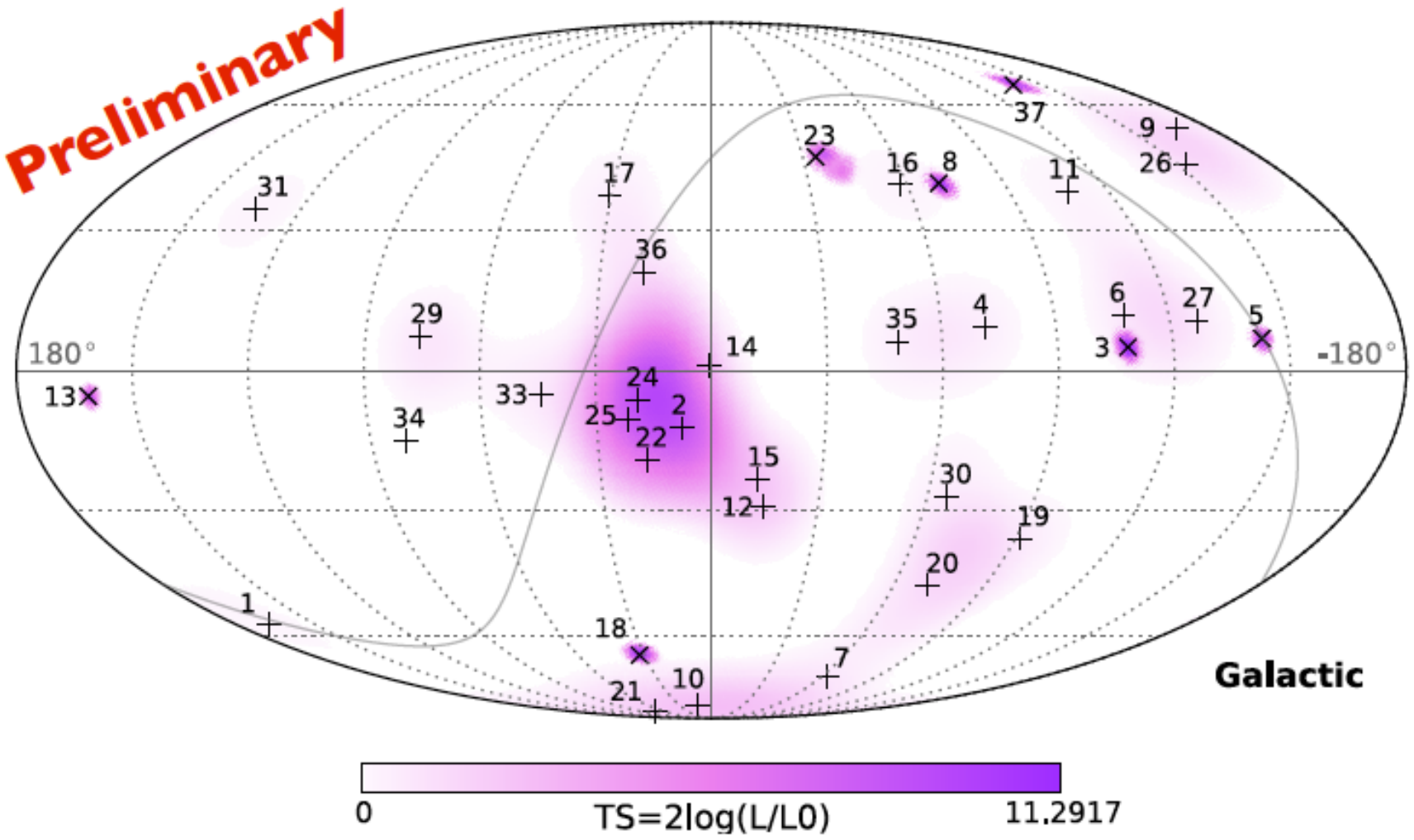


IceCube: the discovery of cosmic neutrinos

francis halzen

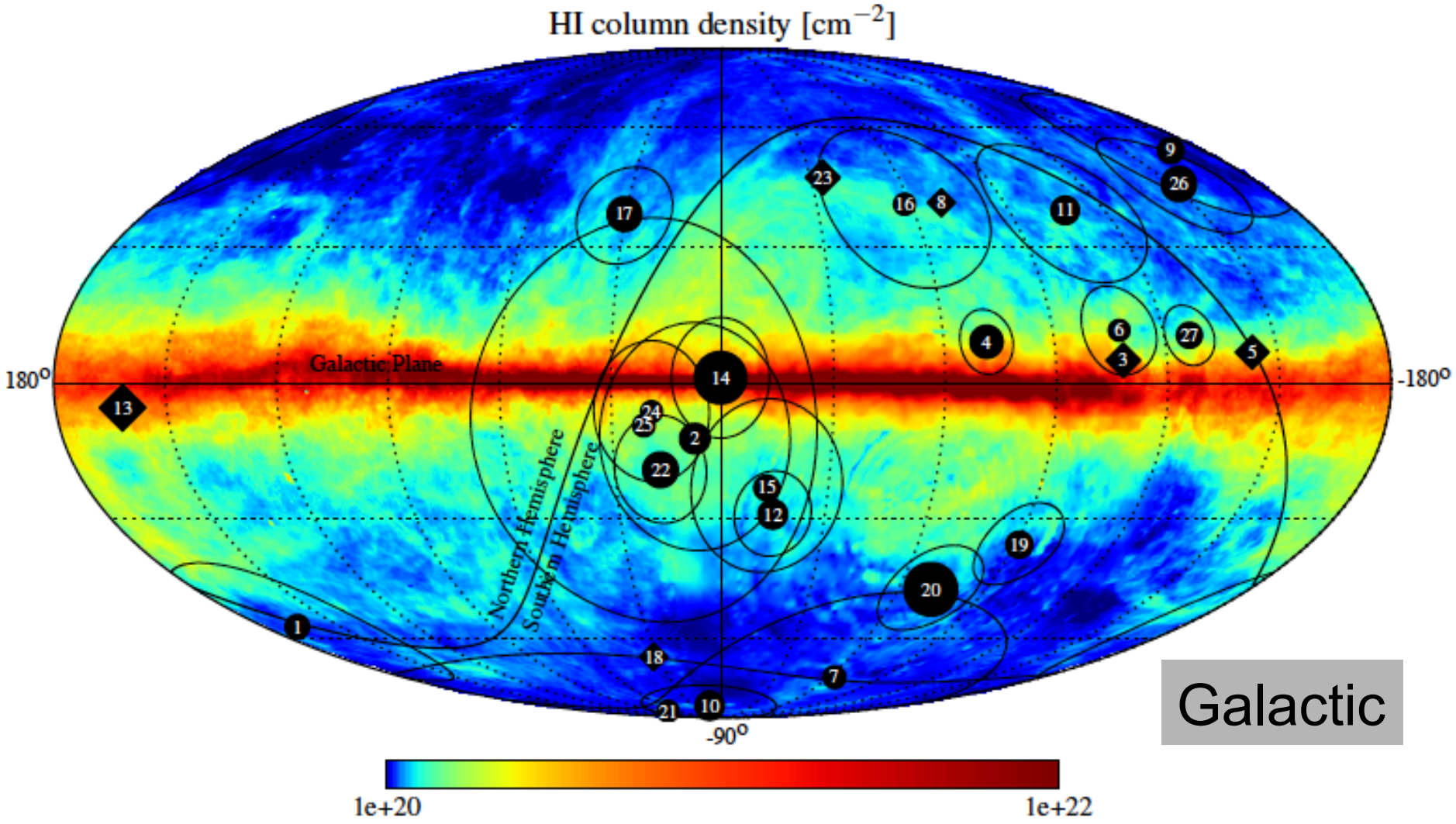
- cosmic ray accelerators
- IceCube a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

where do they come from (3 year data)?



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

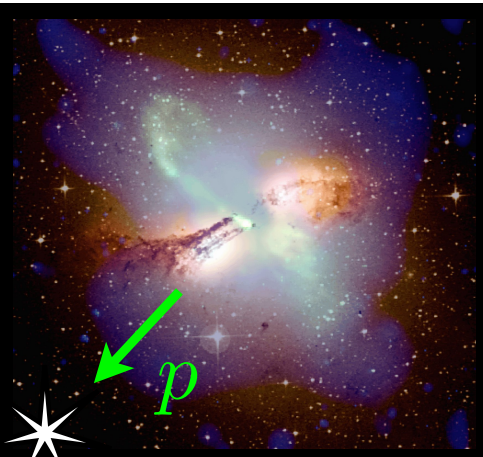
correlation with Galactic plane: TS of 2.8% for a width of 7.5



Galactic

hadronic gamma rays ?

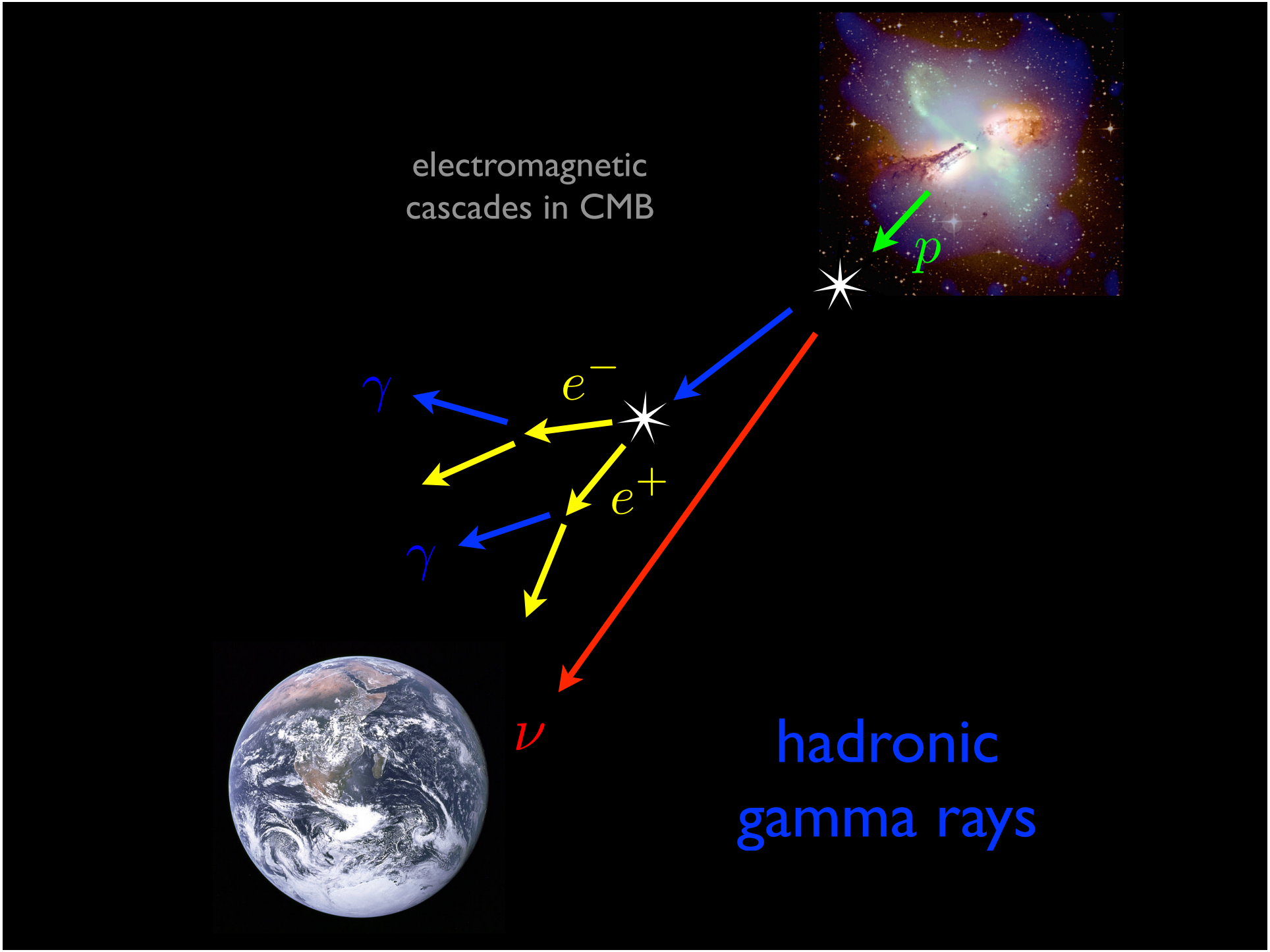
$\pi^+ = \pi^- = \pi^0$

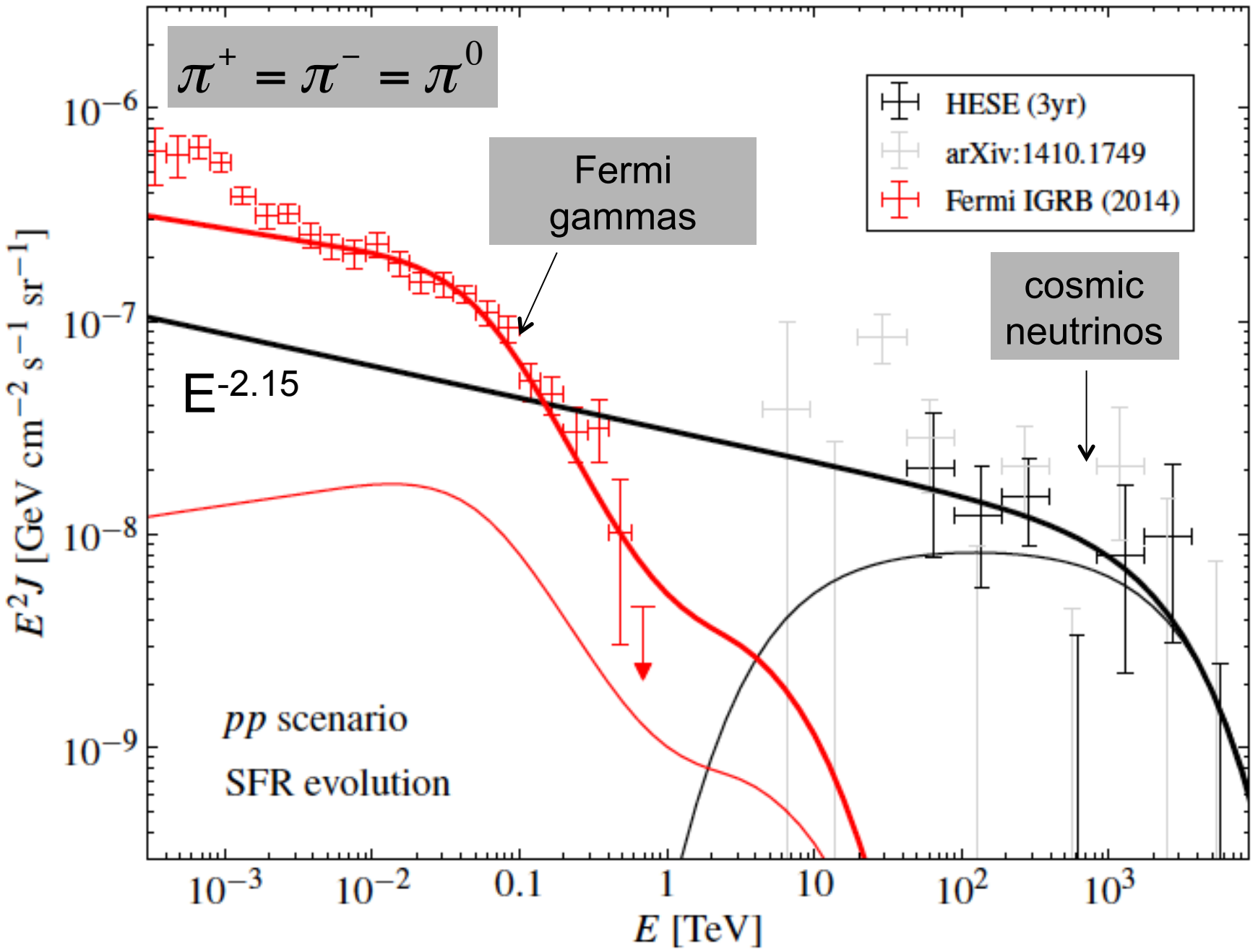


γ

ν

hadronic
gamma rays

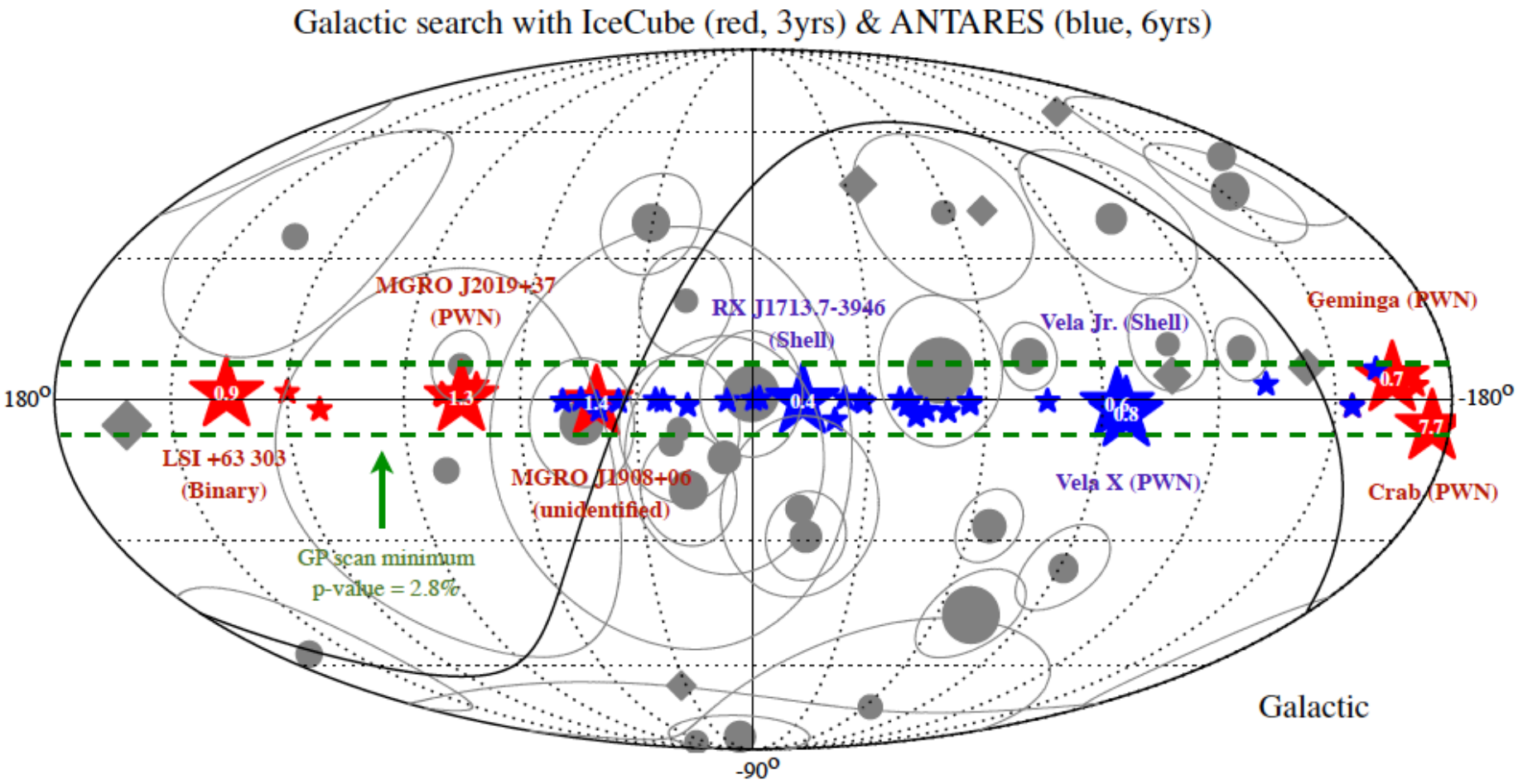

electromagnetic
cascades in CMB
p
γ
e^-
e^+
γ
ν
hadronic
gamma rays


$\pi^+ = \pi^- = \pi^0$
Fermi gammas
cosmic neutrinos
HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)
E-2.15
pp scenario
SFR evolution
E^2J [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

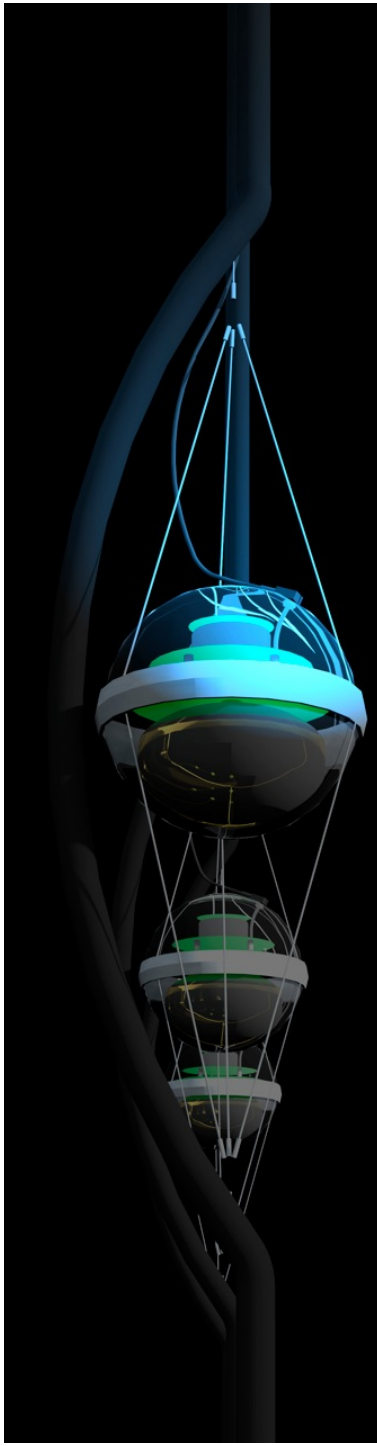
- we have observed a flux of neutrinos from the cosmos whose properties correspond in all respects to the flux anticipated from PeV-energy cosmic accelerators that radiate comparable energies in light and neutrinos

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

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)



IceCube: the discovery of cosmic neutrinos

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IceCube.wisc.edu

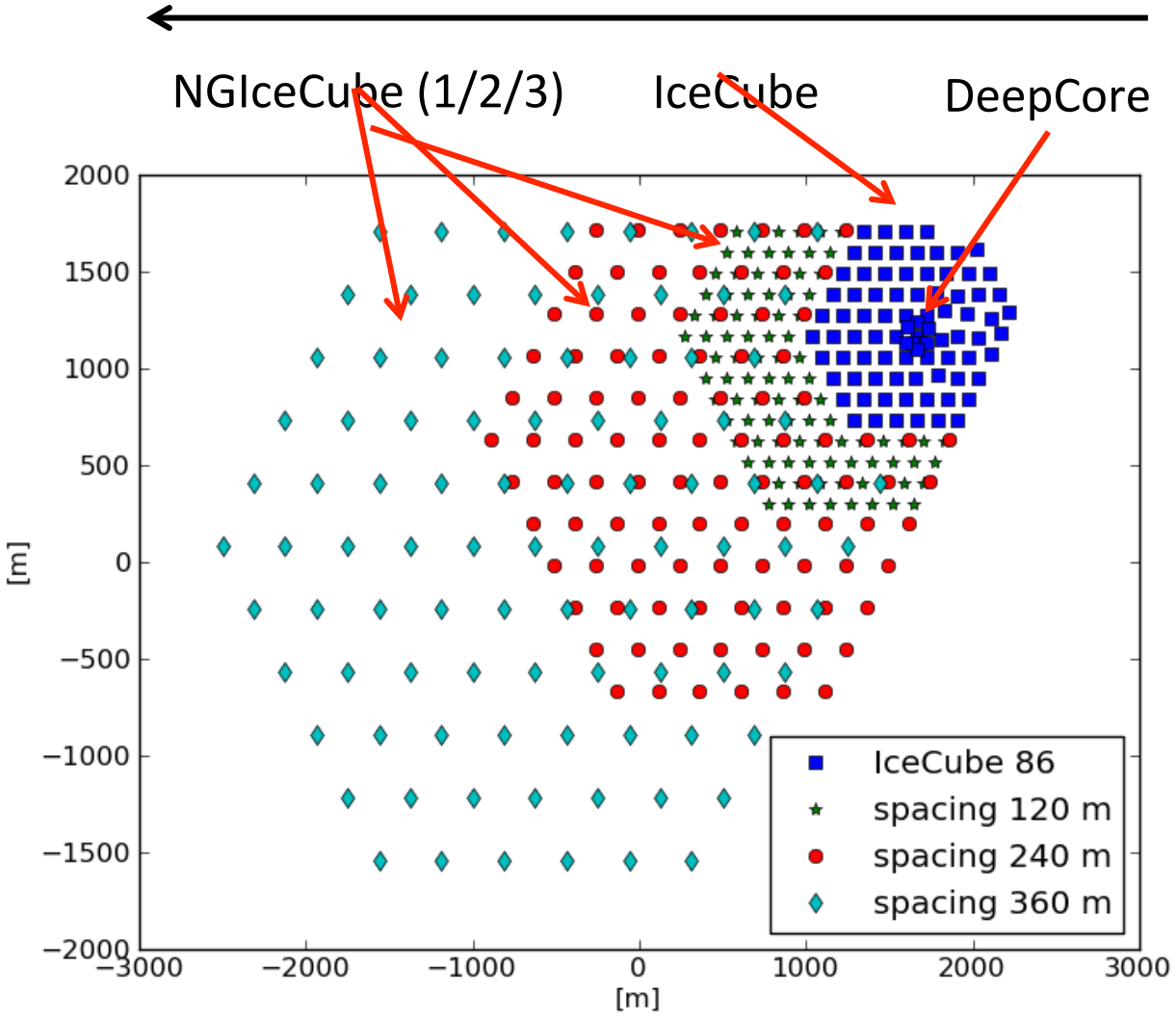
- a next-generation IceCube with a volume of 10 km^3 and an angular resolution of < 0.3 degrees will see multiple neutrinos and identify the sources, even from a “diffuse” extragalactic flux in several years (see also M. Ahlers’s talk)

- 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)

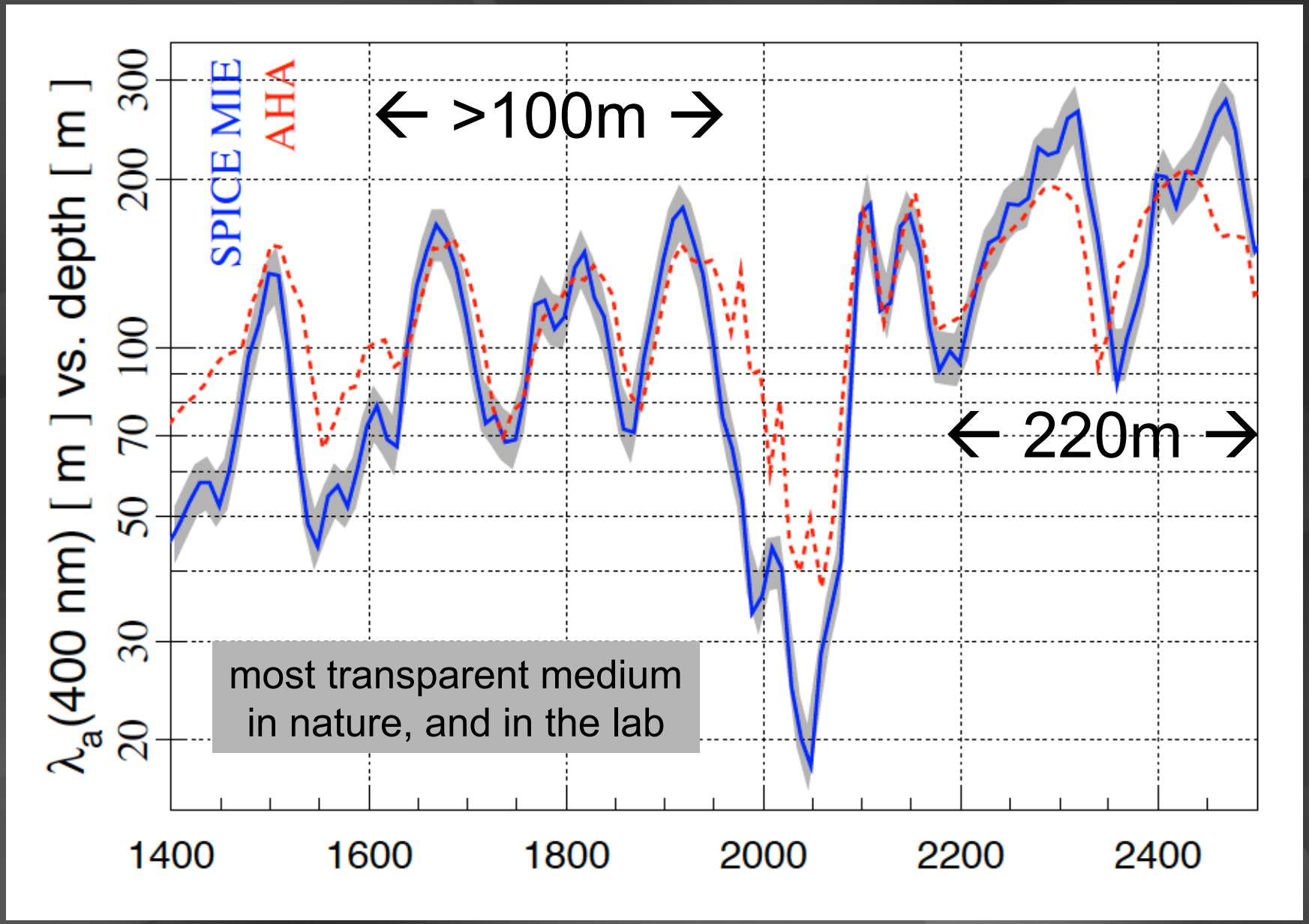


Spacing 1 (120m):
IceCube (1 km^3)
+ 98 strings (1,3 km^3)
= 2,3 km^3

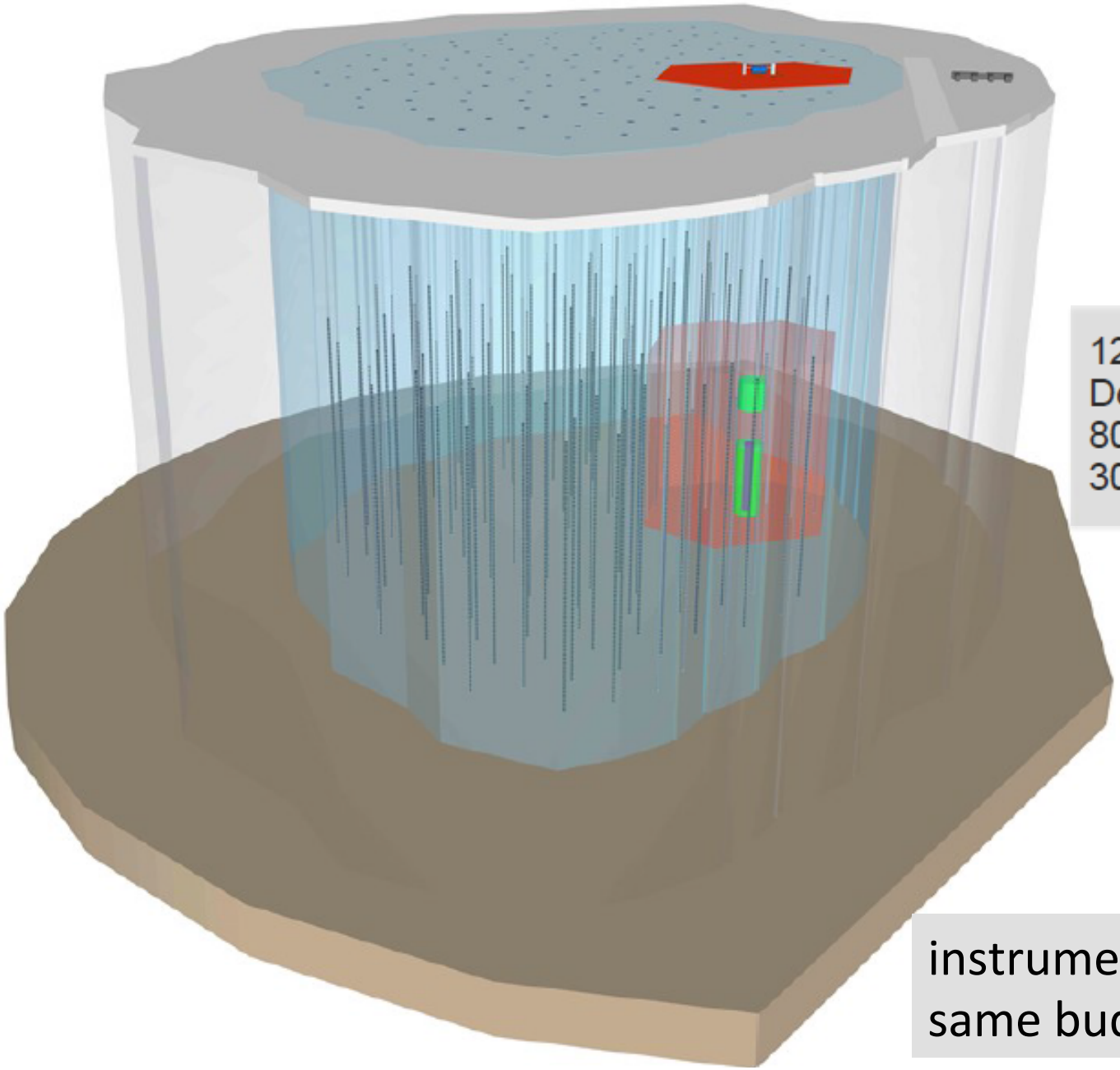
Spacing 2 (240m):
IceCube (1 km^3)
+ 99 strings (5,3 km^3)
= 6,3 km^3

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

absorption length of Cherenkov light

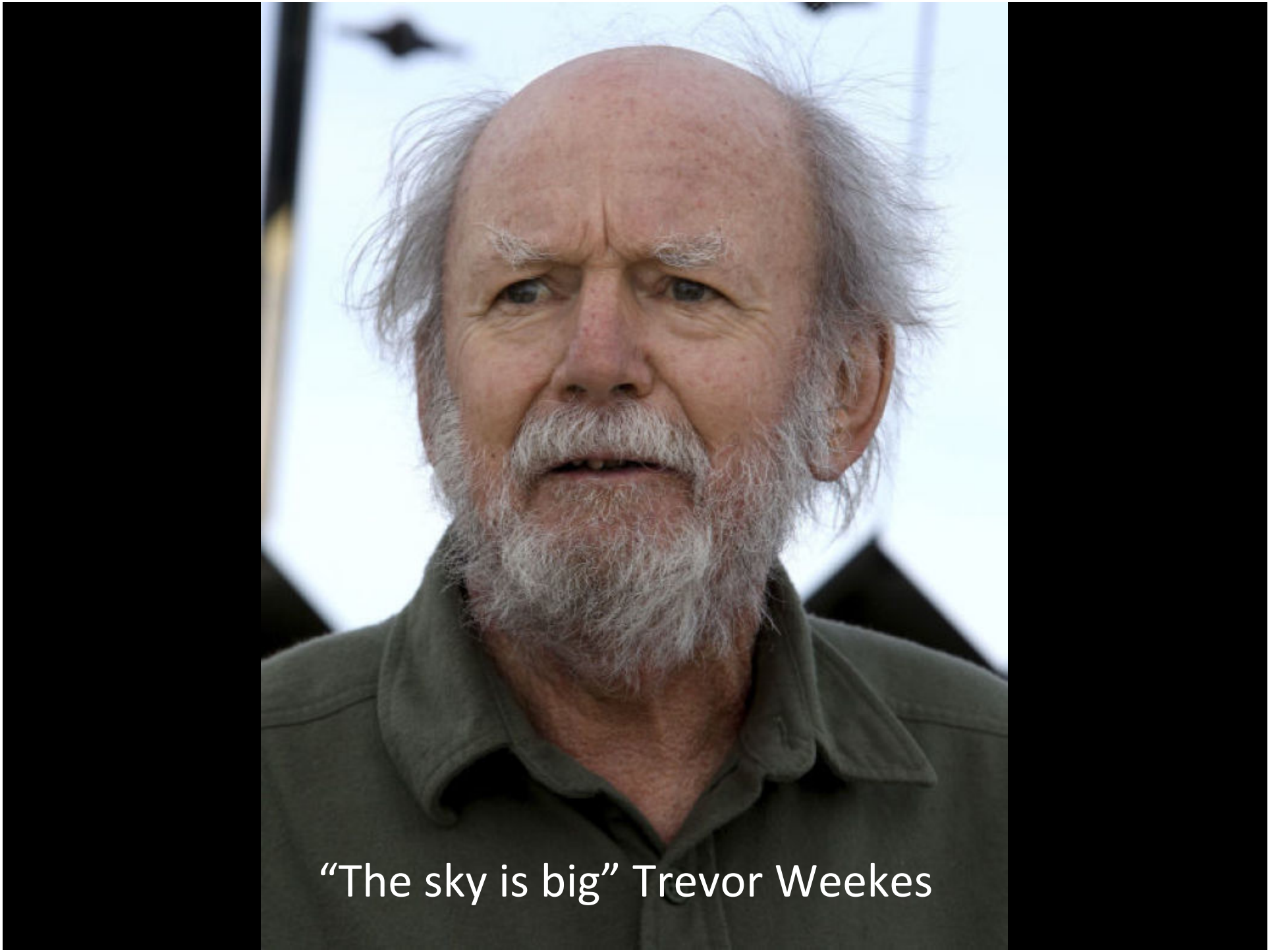



Per Olof Hulth (1943-2015)

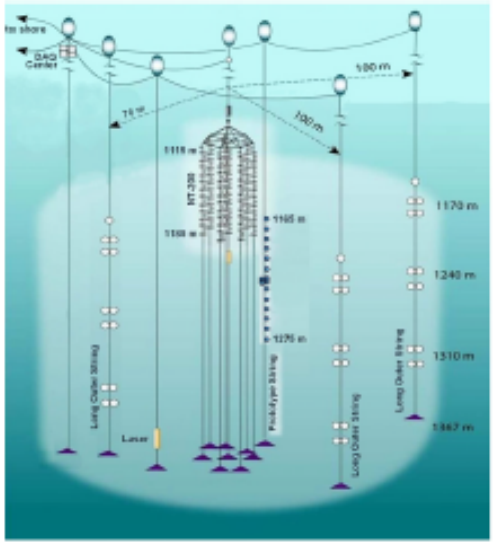


120 strings
Depth 1.35 to 2.7 km
80 DOMs/string
300 m spacing

instrumented volume: x 10
same budget as IceCube

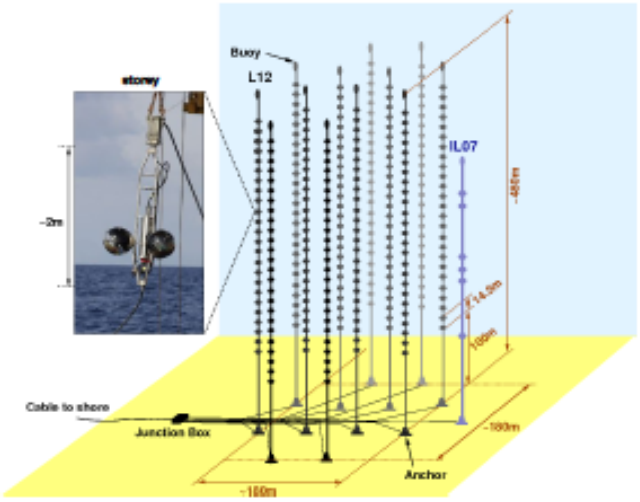

“The sky is big” Trevor Weekes

NT-200+



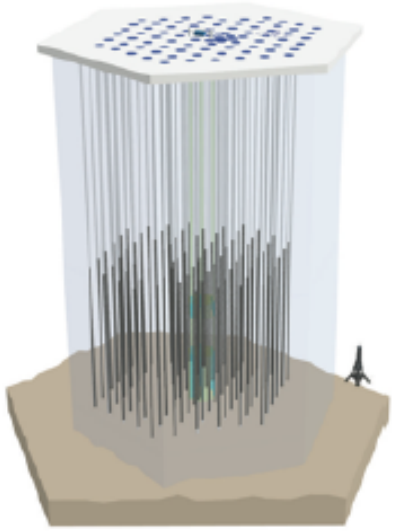
- Lake Baikal
- 1/2000 km^3
- 228 PMTs

ANTARES



- Mediterranean Sea
- 1/100 km^3
- 885 PMTs

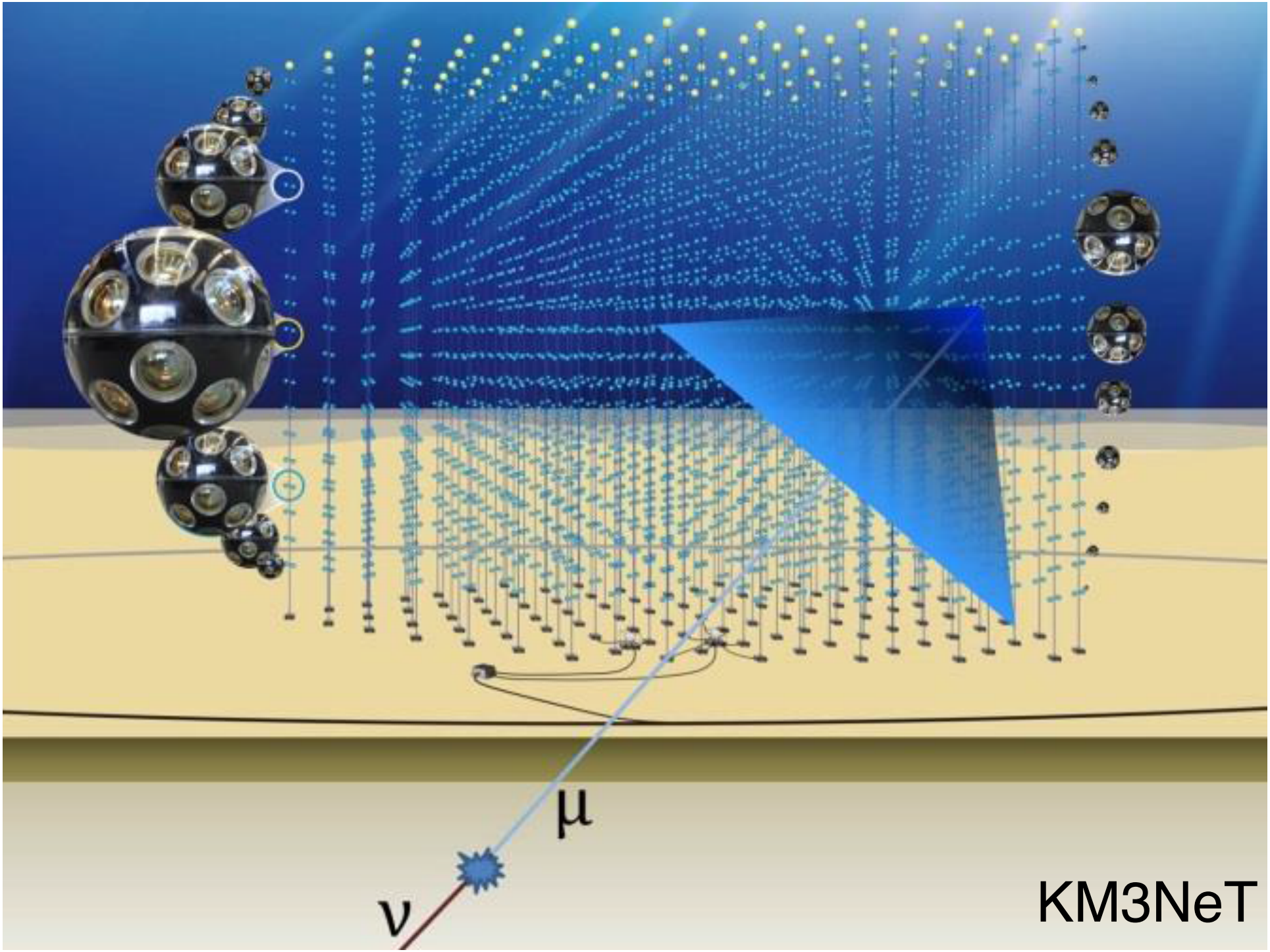
IceCube



- South Pole glacier
- 1 km^3
- 5160 PMTs

Larger, sparser → higher energies

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


μ
ν
KM3NeT

Next-Generation IceCube

- capitalize on discovery
- astronomy guaranteed
- ~ 120 strings: more sensors per string with higher quantum efficiency
- proven techniques, low risk
- flexibility of deployment per seasons: optimization
- cost similar to original detector

from discovery to astronomical telescopes:

parallel development in the Mediterranean

ANTARES → KM3NeT

Baikal → GVA

Outlook:

- capitalize on discovery
- astronomy guaranteed

from discovery to astronomical telescopes:
parallel development in the Mediterranean
ANTARES → KM3NeT
Baikal → GVA

Conclusions

- 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
- we are close to identifying point sources

did not talk about:

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

The IceCube–PINGU Collaboration

International Funding Agencies

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Swedish Polar Research Secretariat
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