

ICECUBE

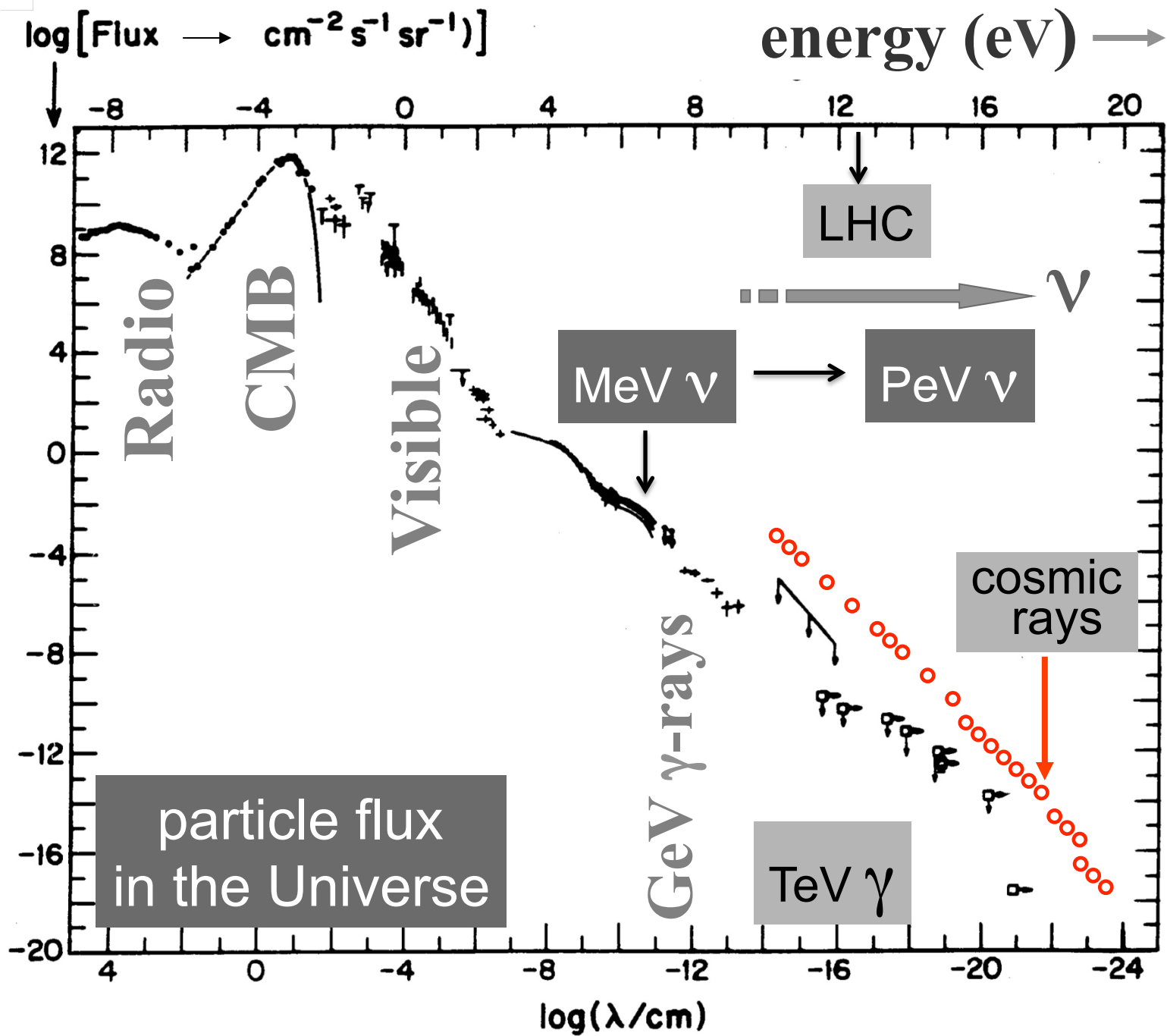


# IceCube

francis halzen

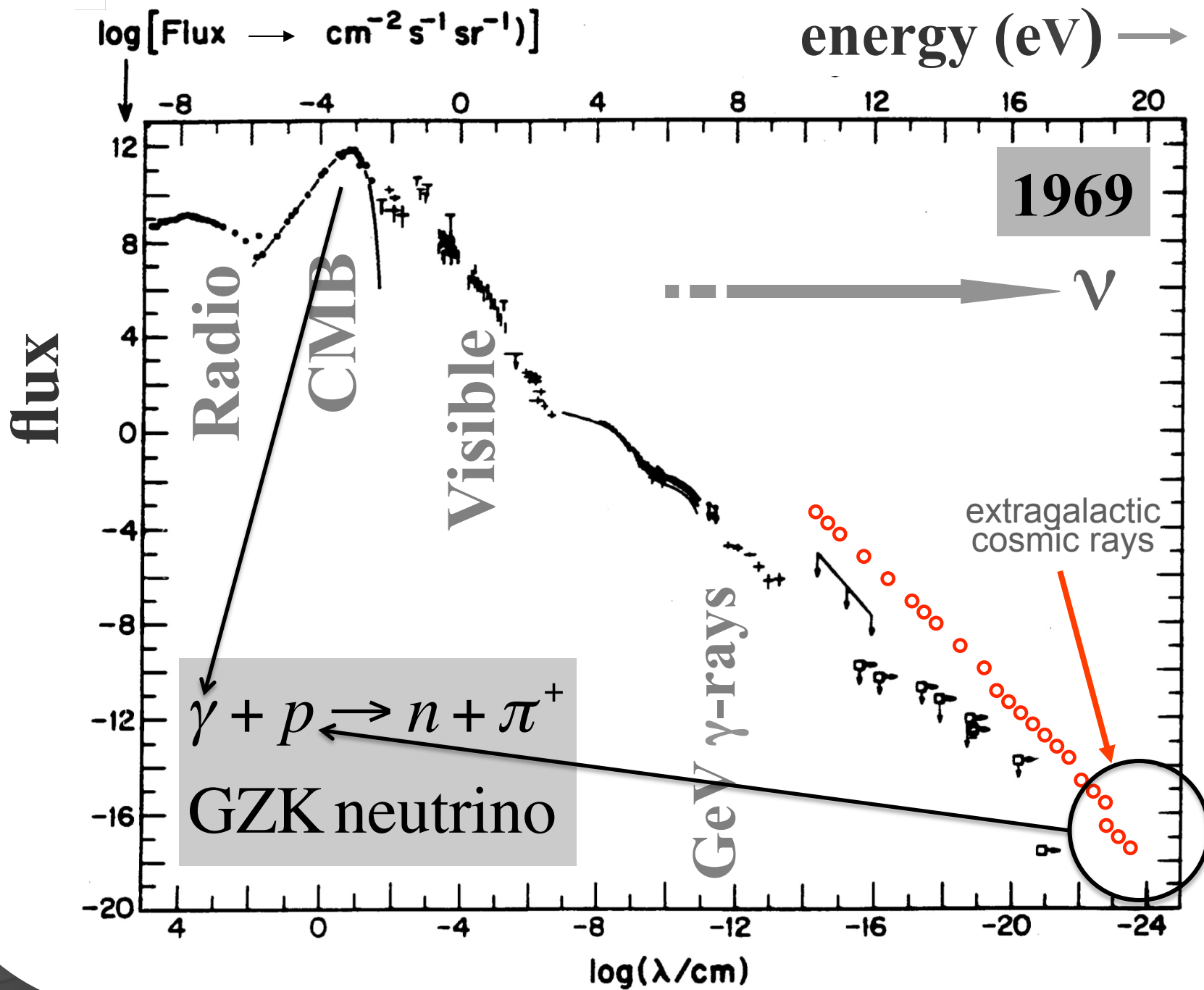
- why would you want to build a a kilometer scale neutrino detector?
- IceCube: a cubic kilometer detector
- the discovery (and confirmation) of cosmic neutrinos
- from discovery to astronomy

# flux of light in the Universe



## neutrino as a cosmic messenger:

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



cosmic rays interact with the  
microwave background

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

cosmic rays disappear, neutrinos with  
EeV (10<sup>6</sup> TeV) energy appear

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

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

- accelerator must contain the particles

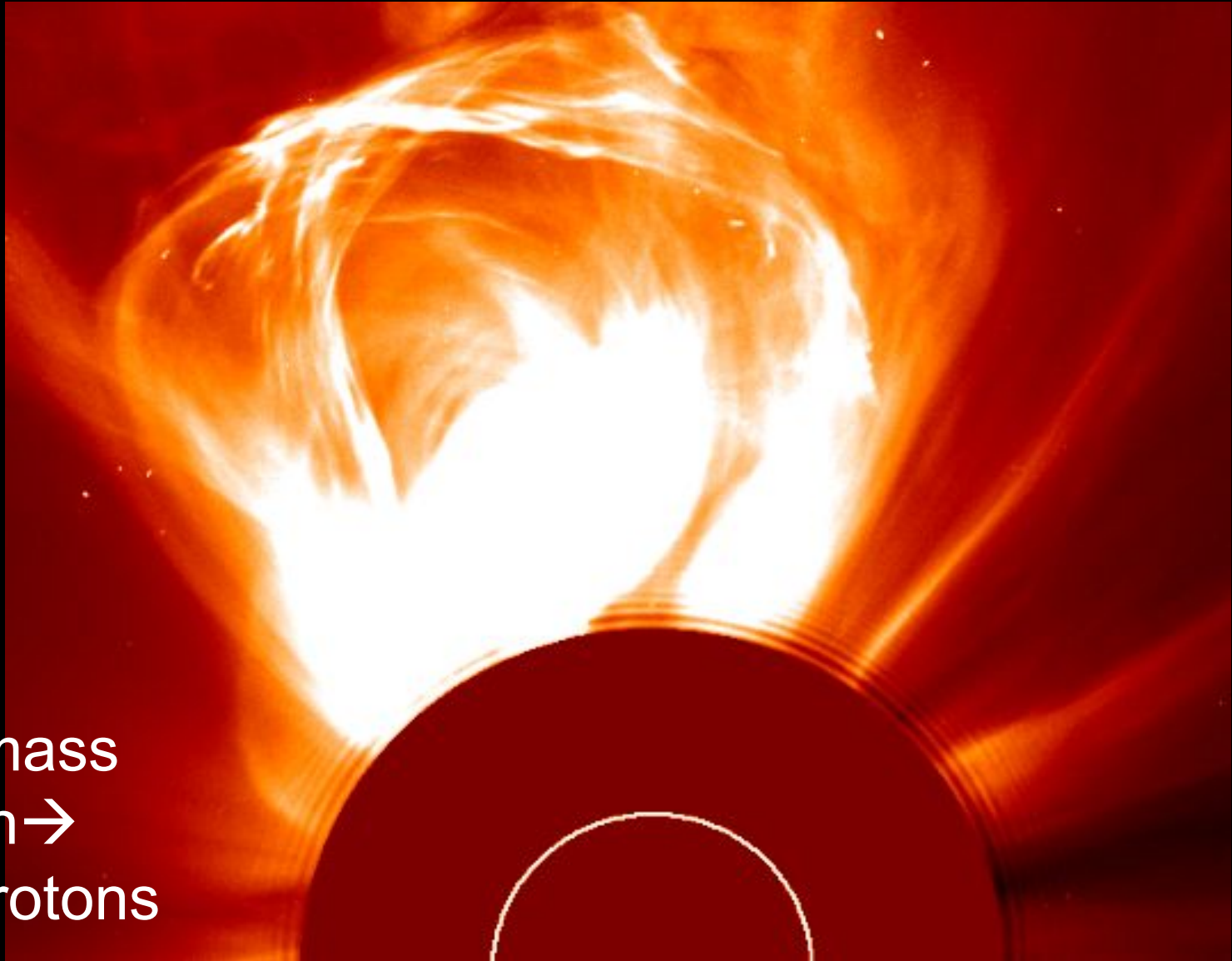
$$R_{gyro} \left( = \frac{E}{vqB} \right) \leq R$$

$$E \leq v qBR$$

challenges of cosmic ray astrophysics:

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

# the sun constructs an accelerator

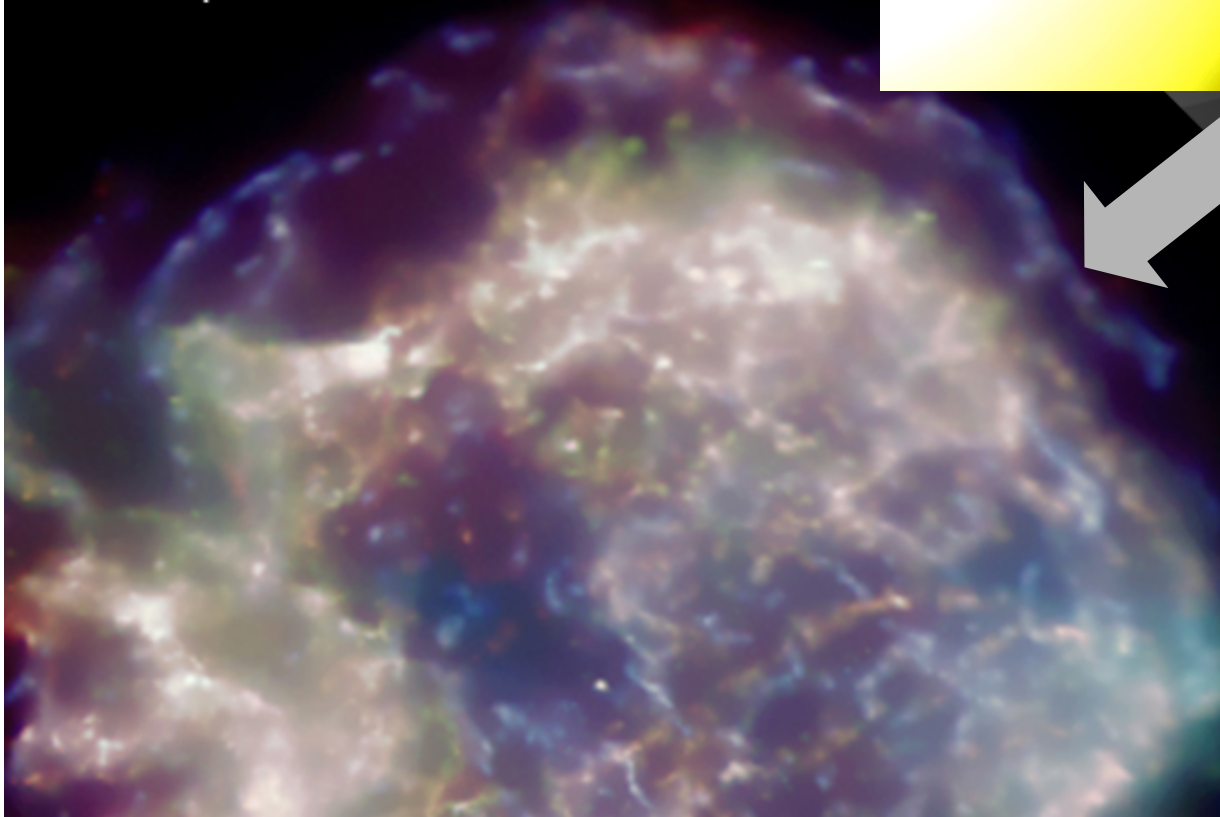
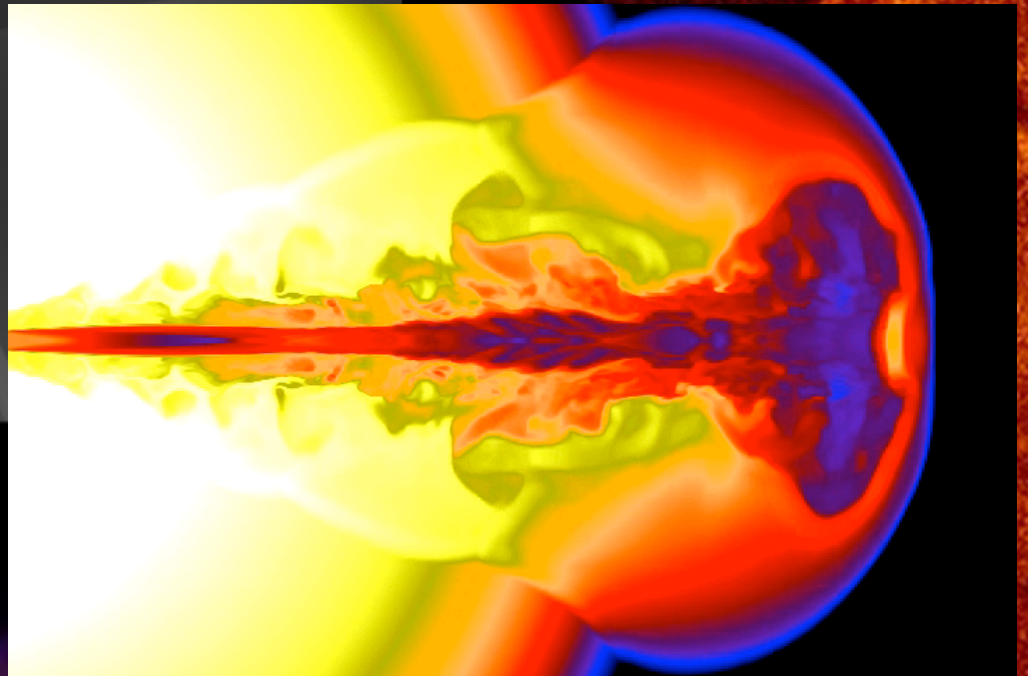


coronal mass  
ejection →  
10 GeV protons



# supernova remnants

Chandra  
Cassiopeia A



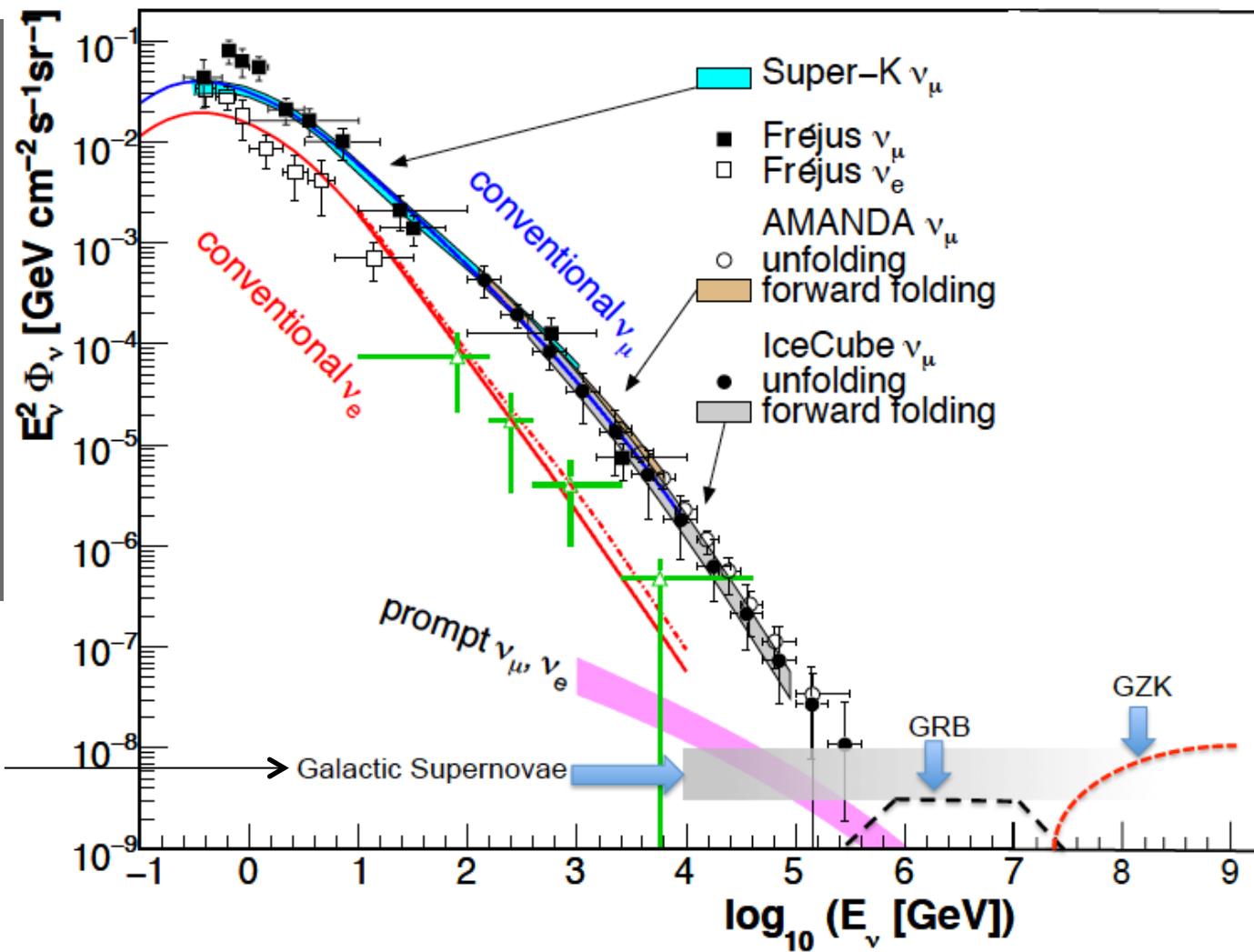
gamma  
ray  
bursts



above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

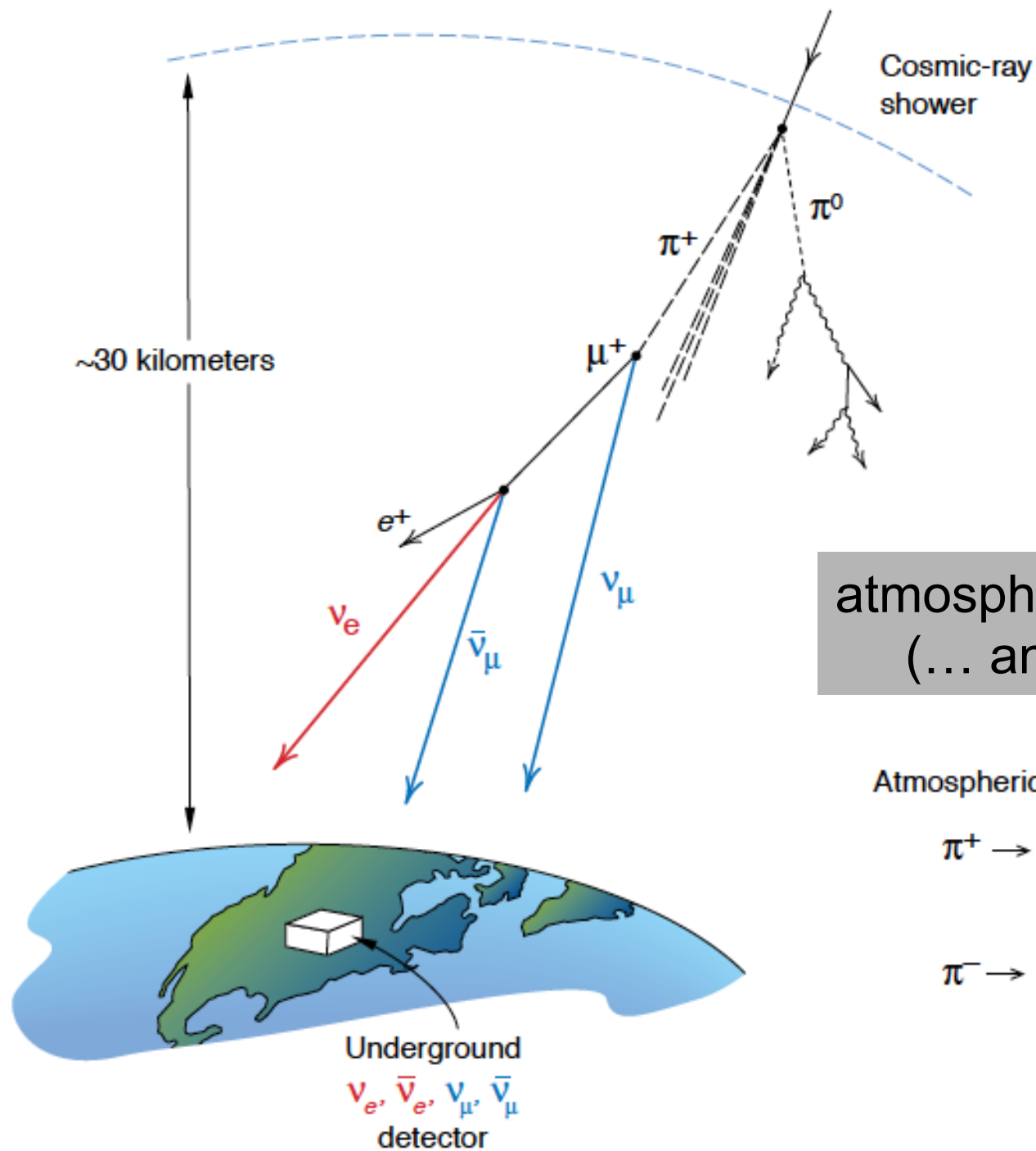
$$dN/dE \sim E^{-2}$$



atmospheric

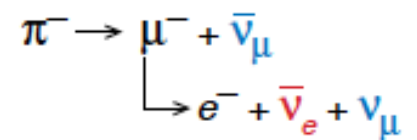
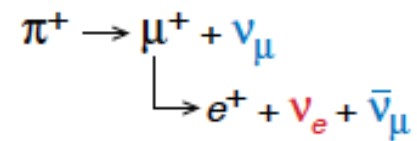
cosmic

100 TeV

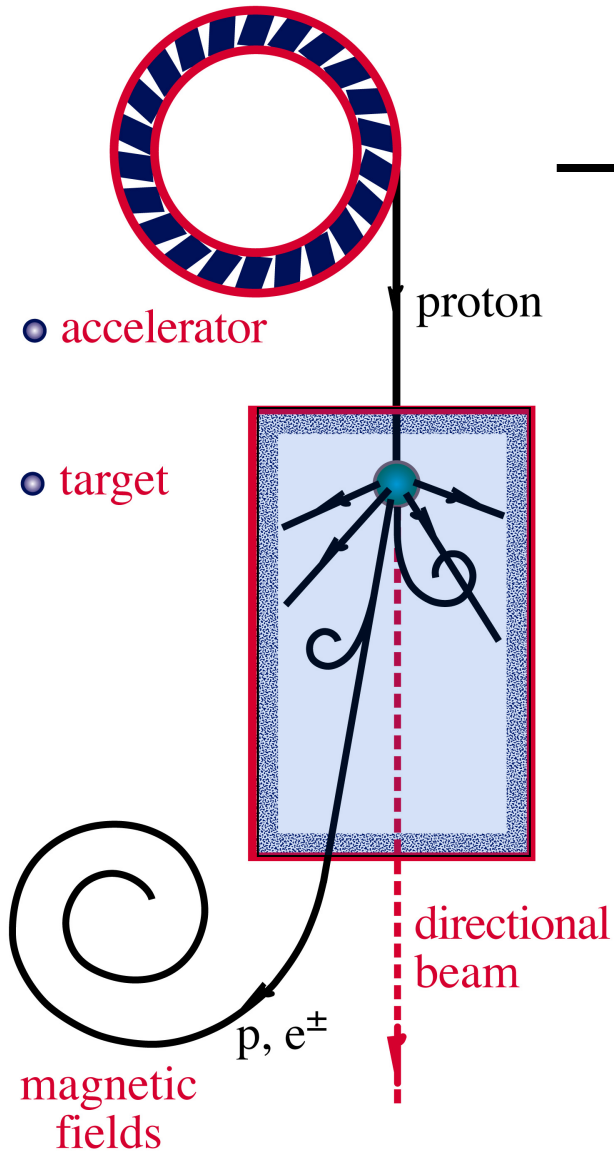


atmospheric neutrinos  
 (... and muons!)

Atmospheric neutrino source



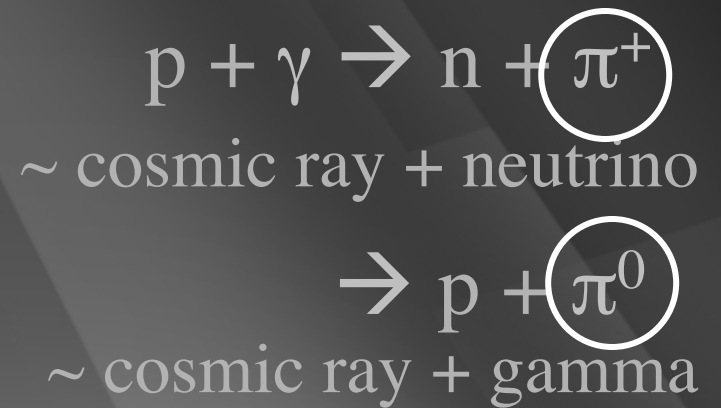
# $\nu$ and $\gamma$ beams : heaven and earth



accelerator is powered by large gravitational energy

**black hole  
neutron star**

**radiation  
and dust**





# IceCube: the discovery of cosmic neutrinos

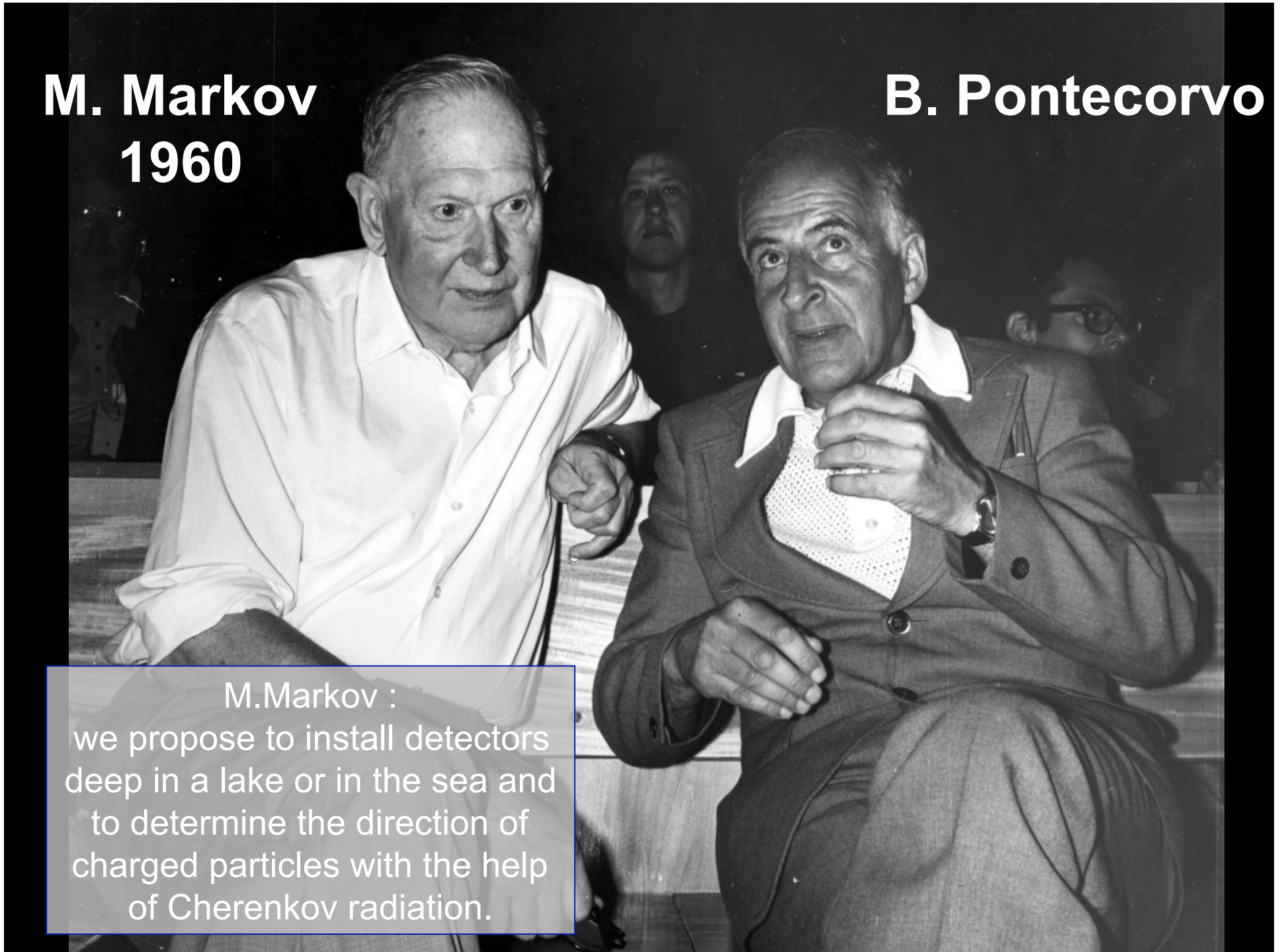
francis halzen

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

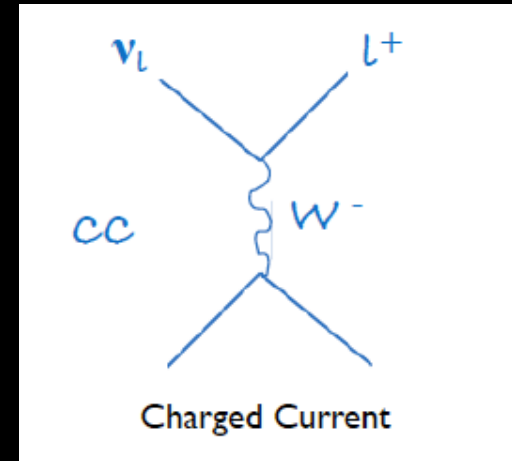
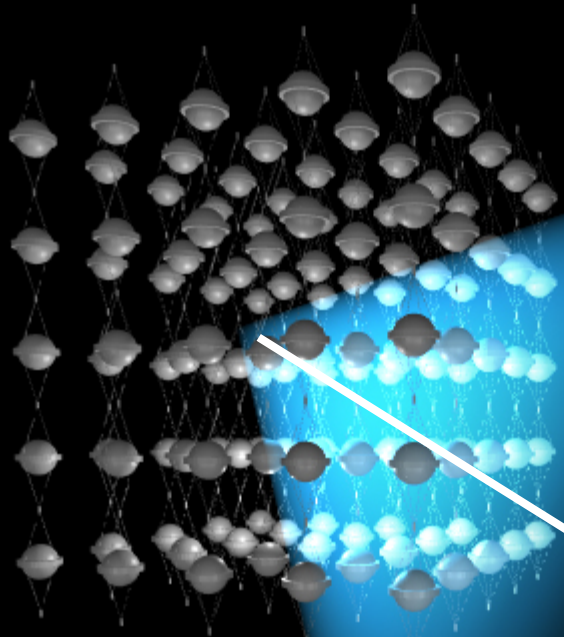
**M. Markov**  
**1960**

**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



$\mu$

- lattice of photomultipliers

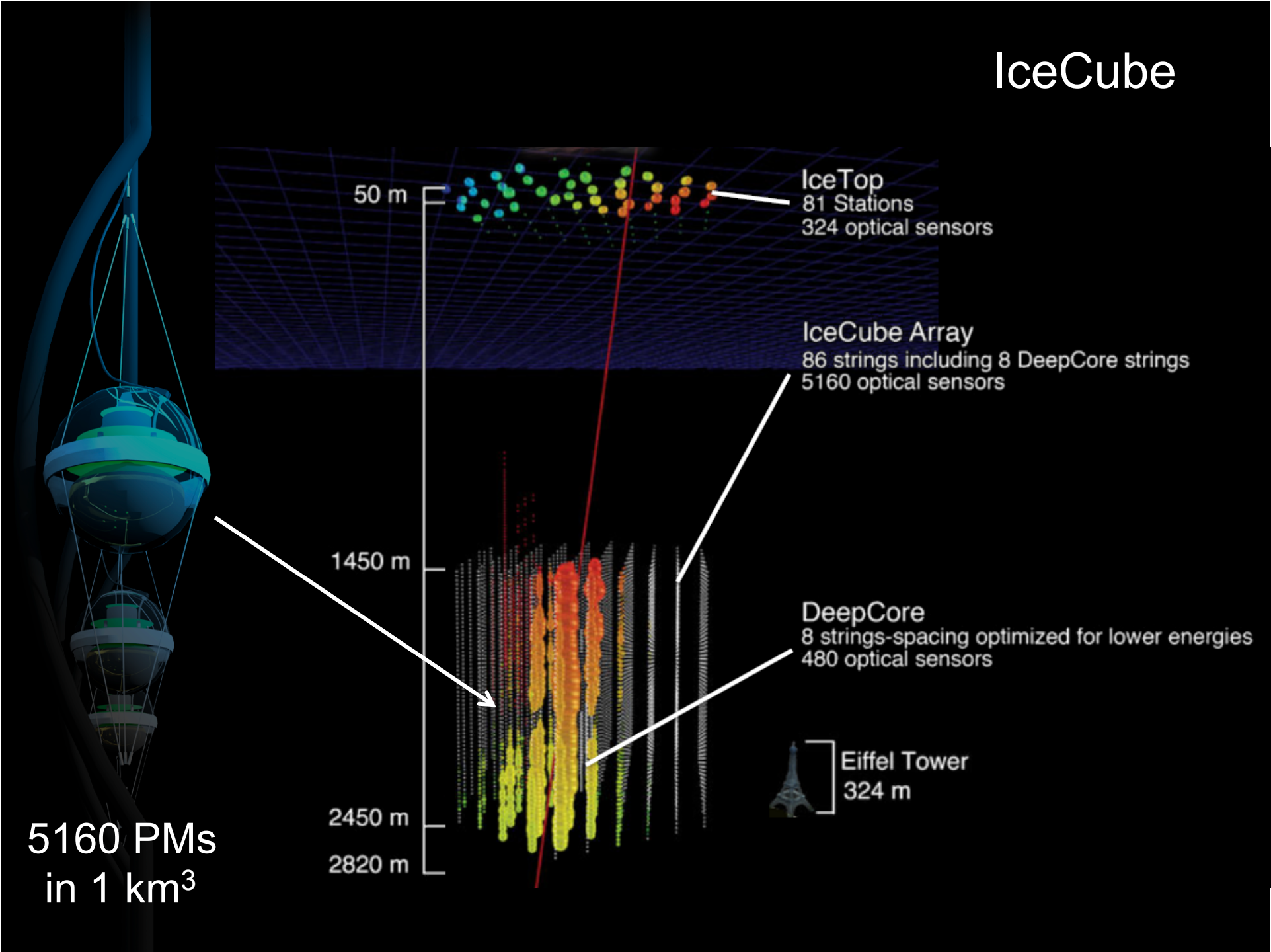
$\nu$



ultra-transparent ice below 1.5 km



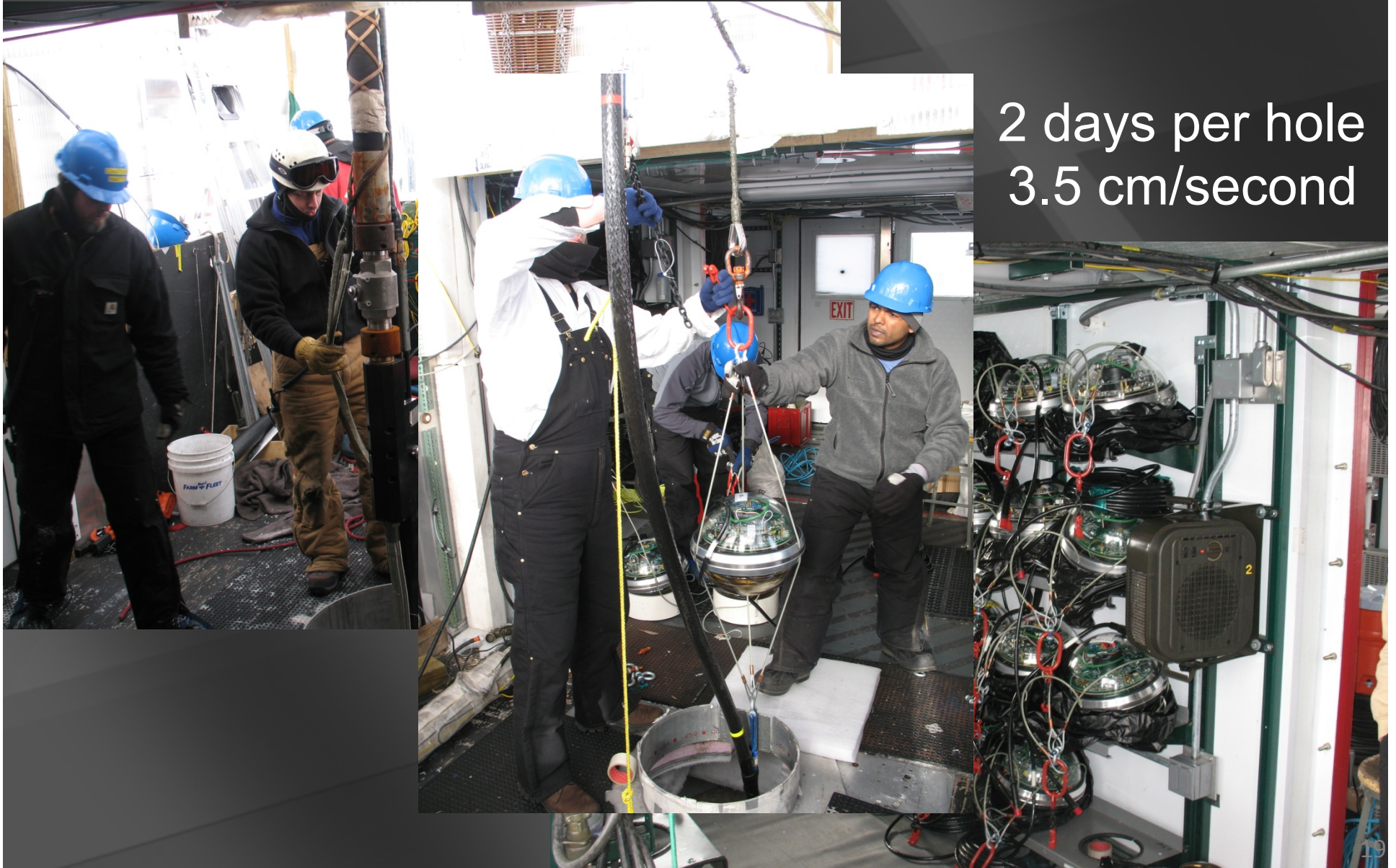
# IceCube



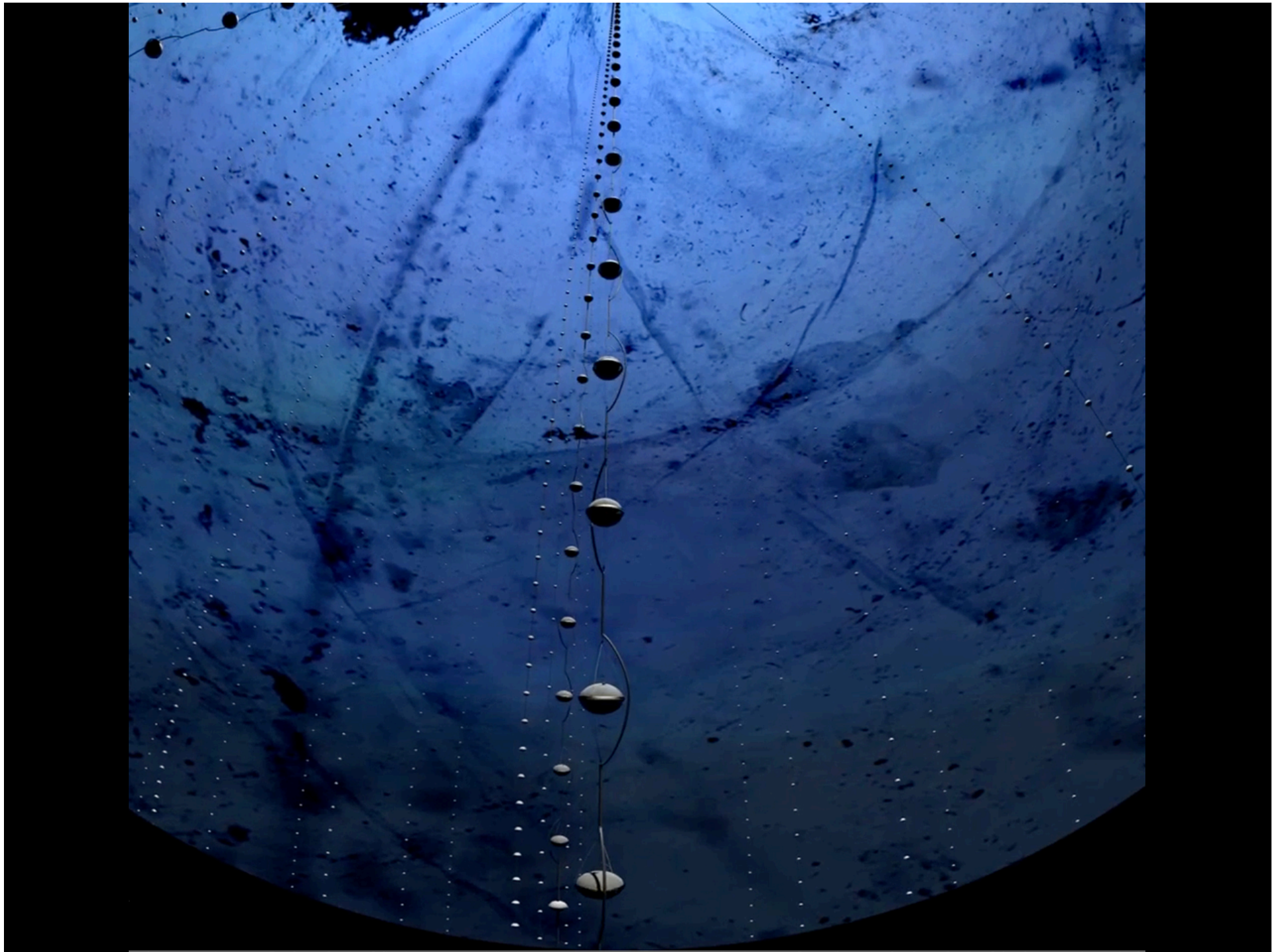
photomultiplier  
tube -10 inch

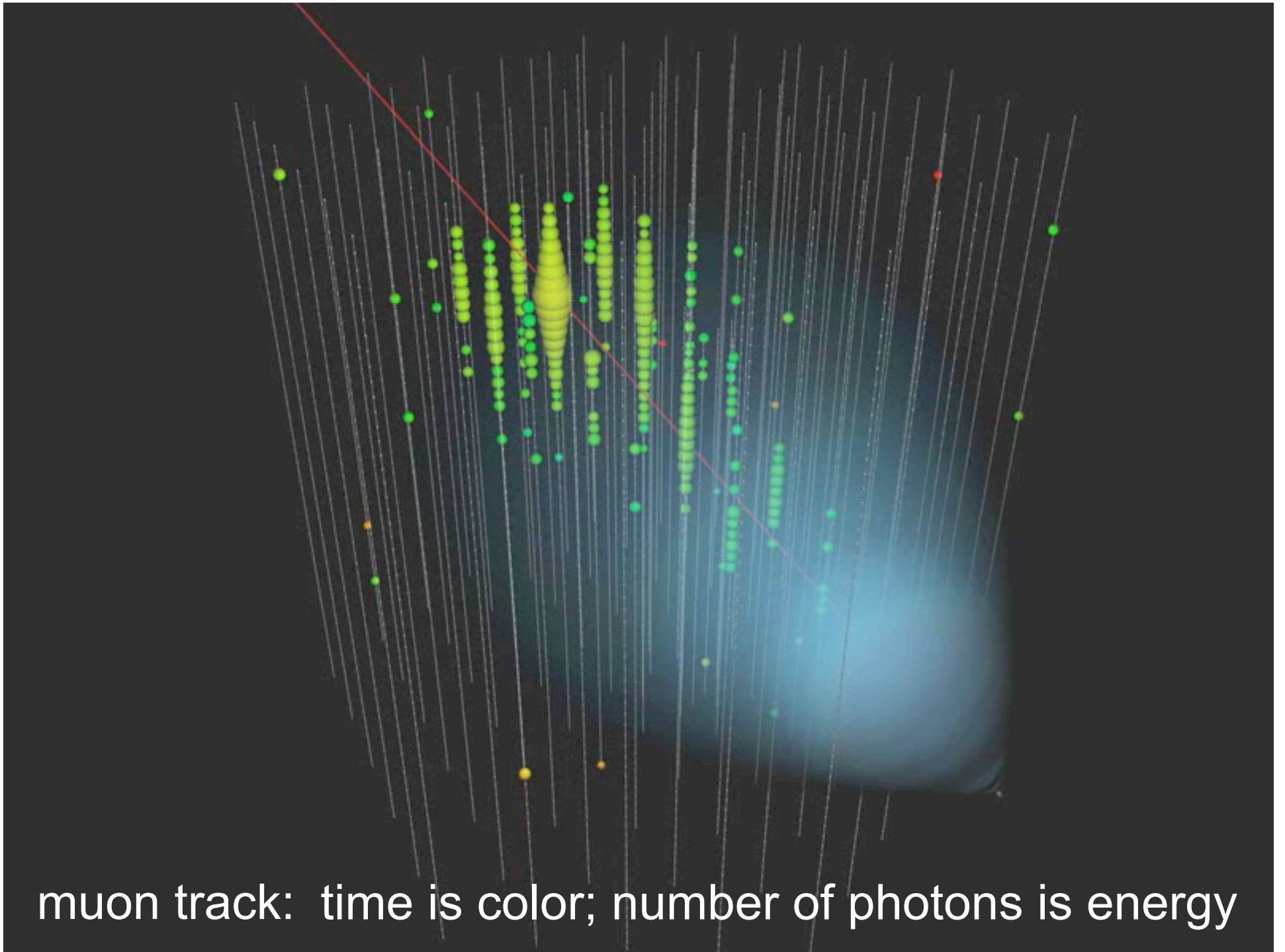


# drilling and deployment



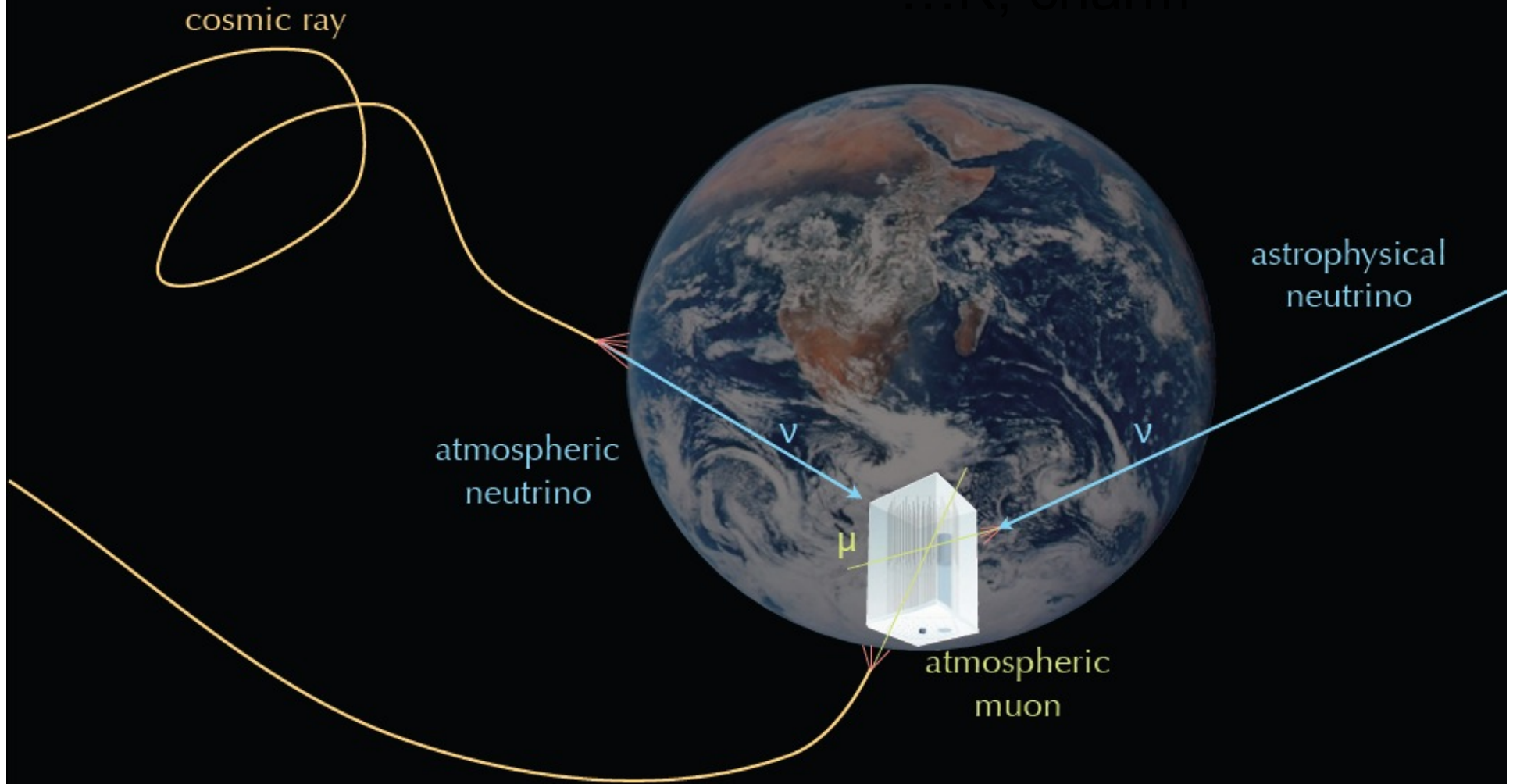
2 days per hole  
3.5 cm/second

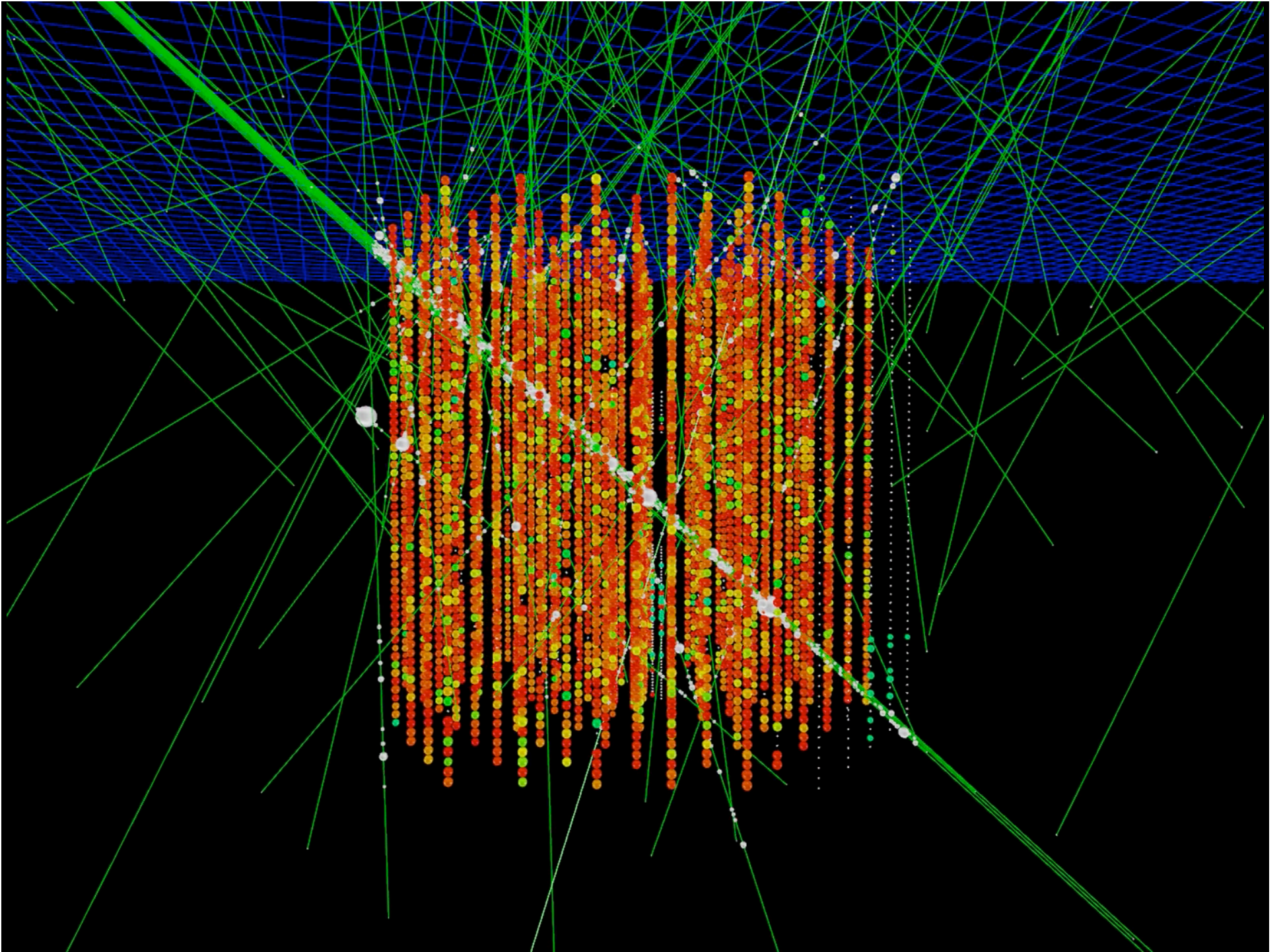




muon track: time is color; number of photons is energy

# Signals and Backgrounds





... you looked at 10msec of data !

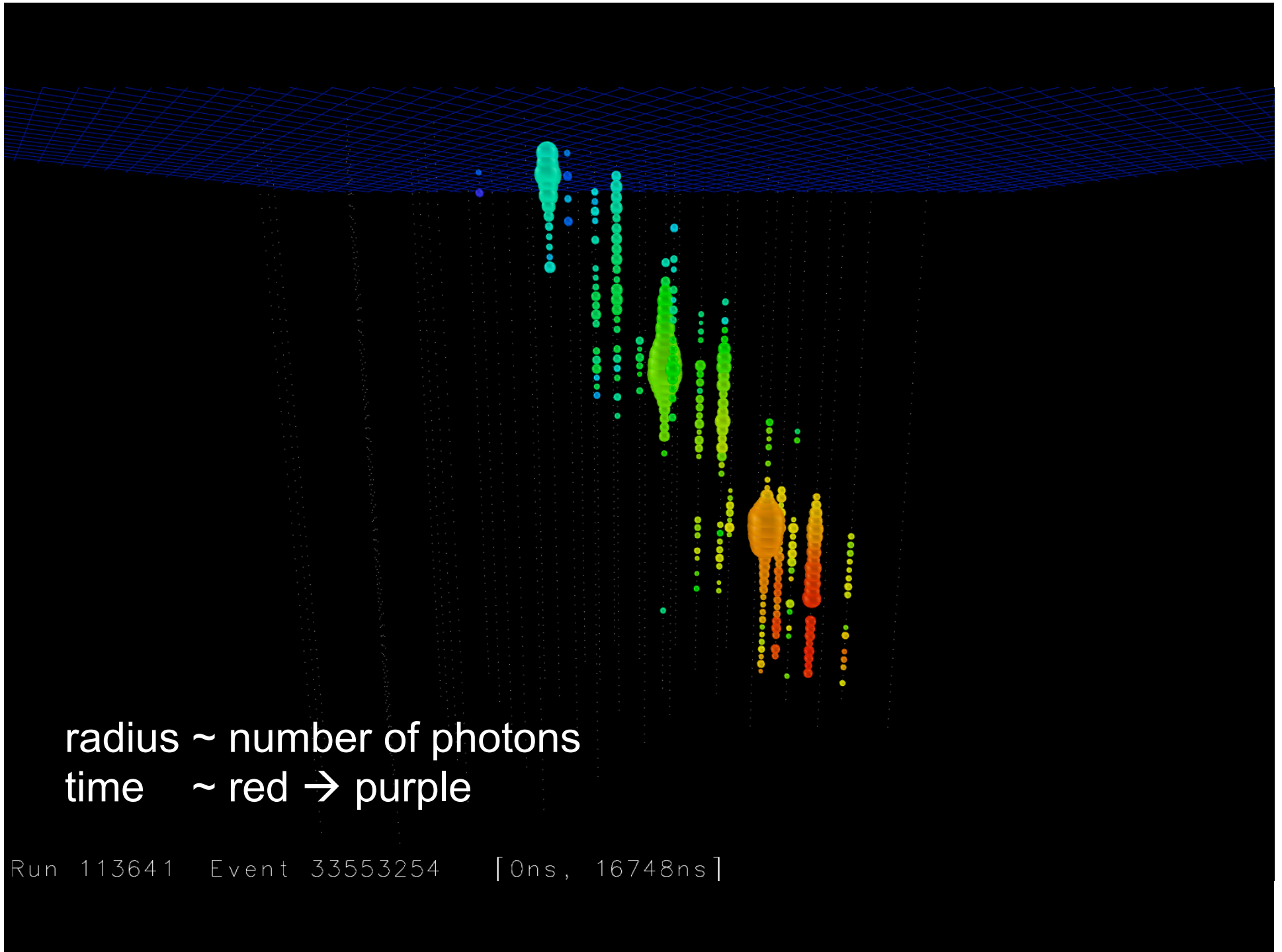
muons detected per year:

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

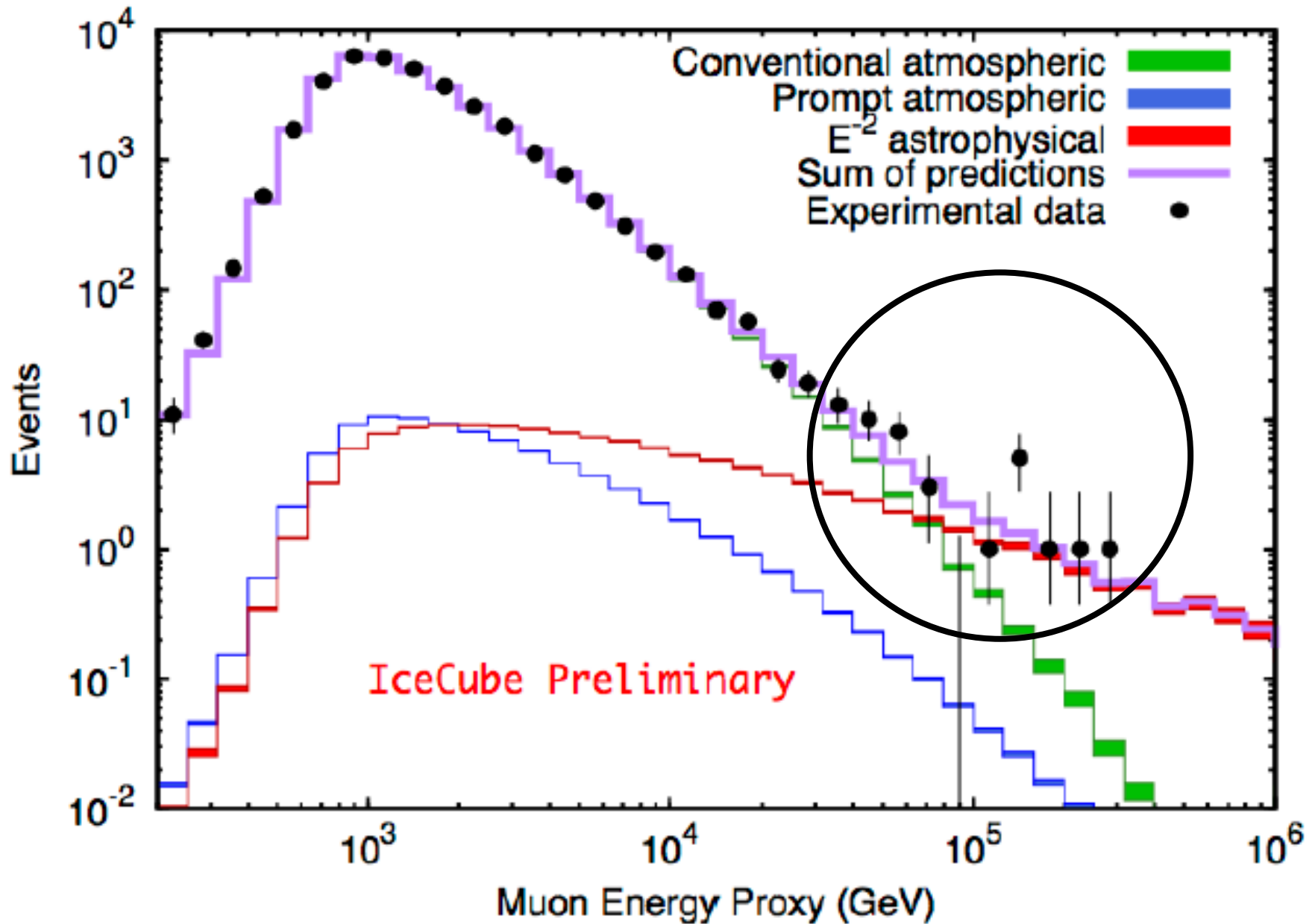
\* 3000 per second

\*\* 1 every 6 minutes





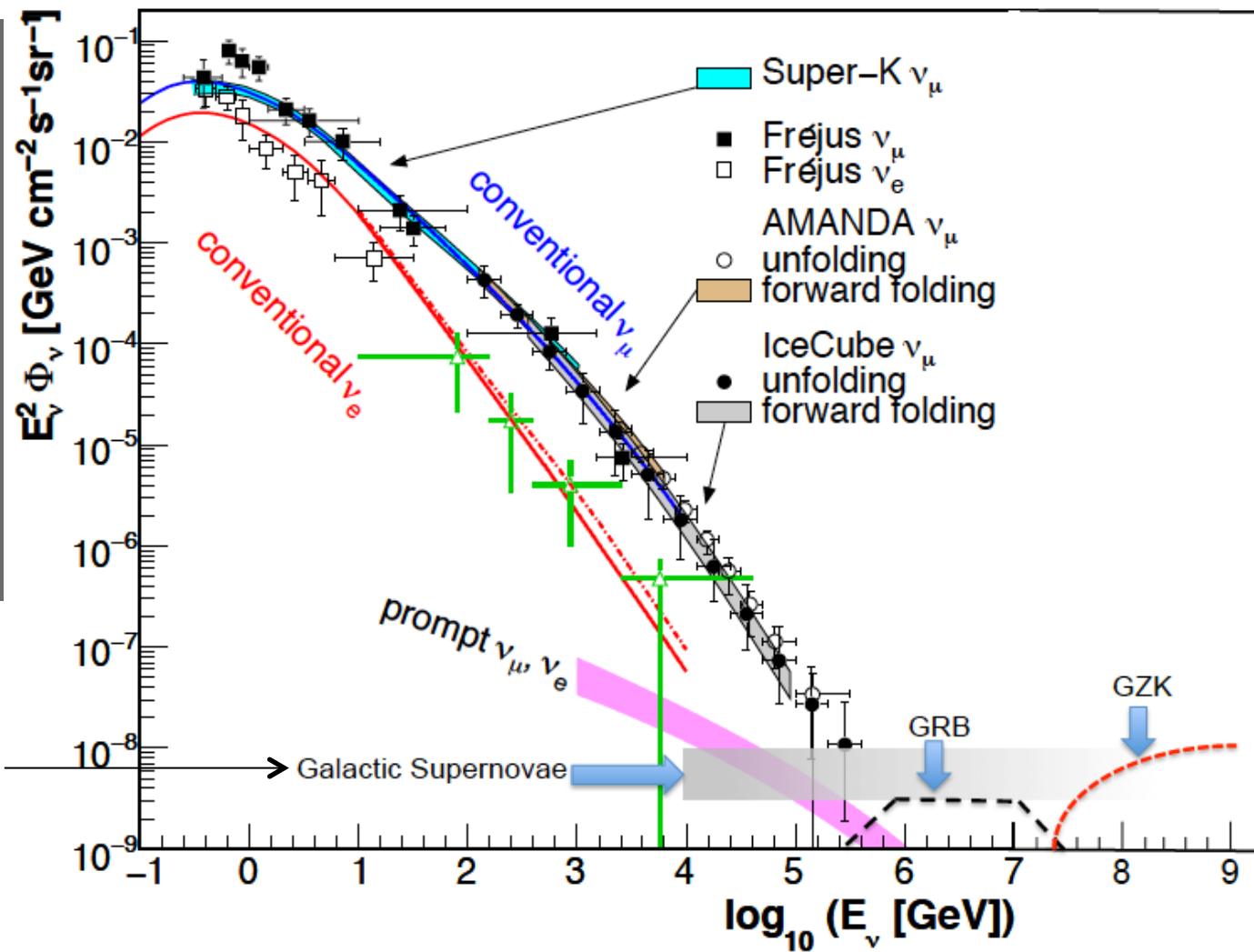
# cosmic neutrinos in 2 years of data at 3.7 sigma



above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

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

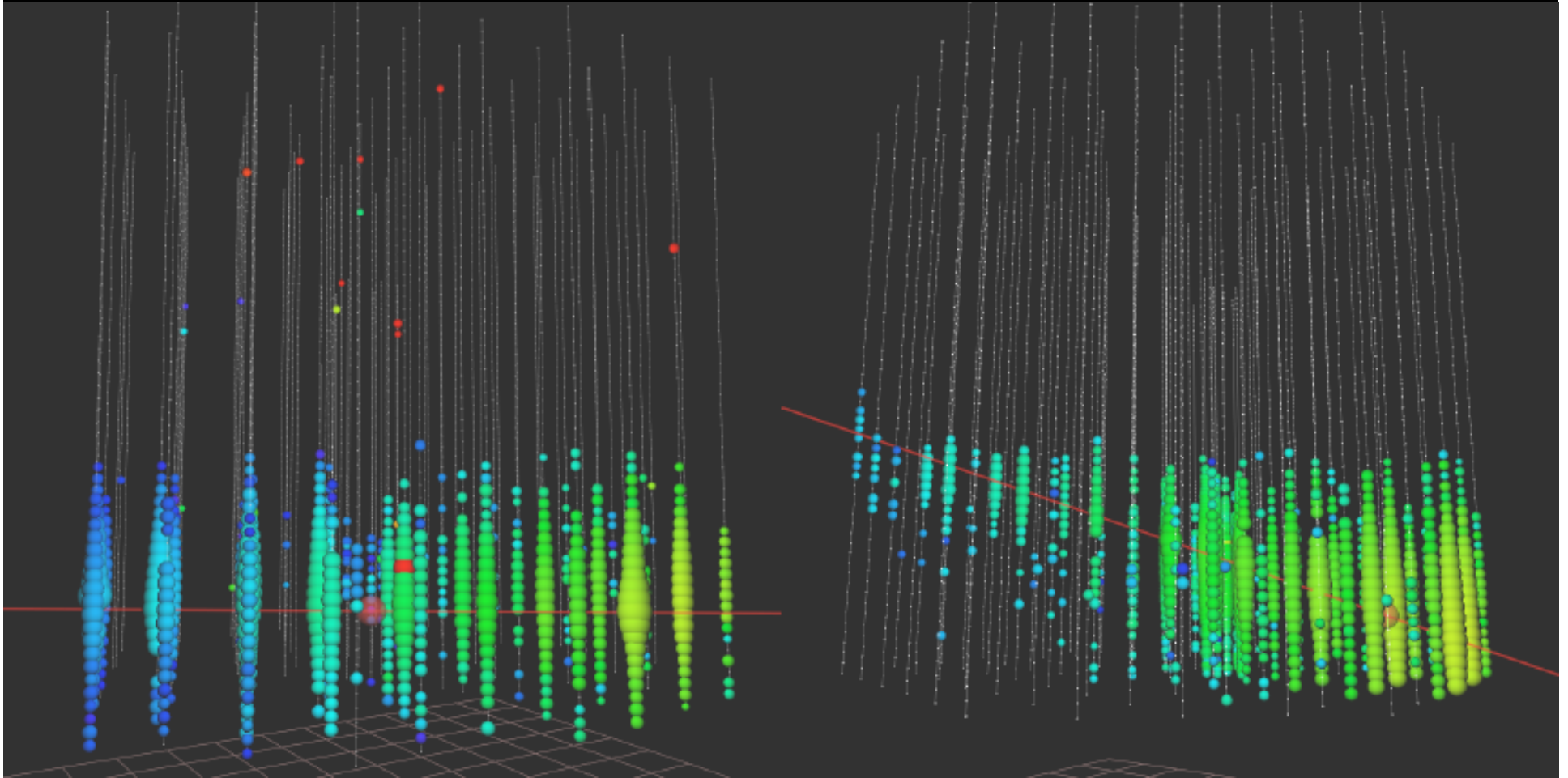


atmospheric

cosmic

100 TeV

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





# IceCube: the discovery of cosmic neutrinos

francis halzen

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- where do they come from?
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cosmic rays interact with the  
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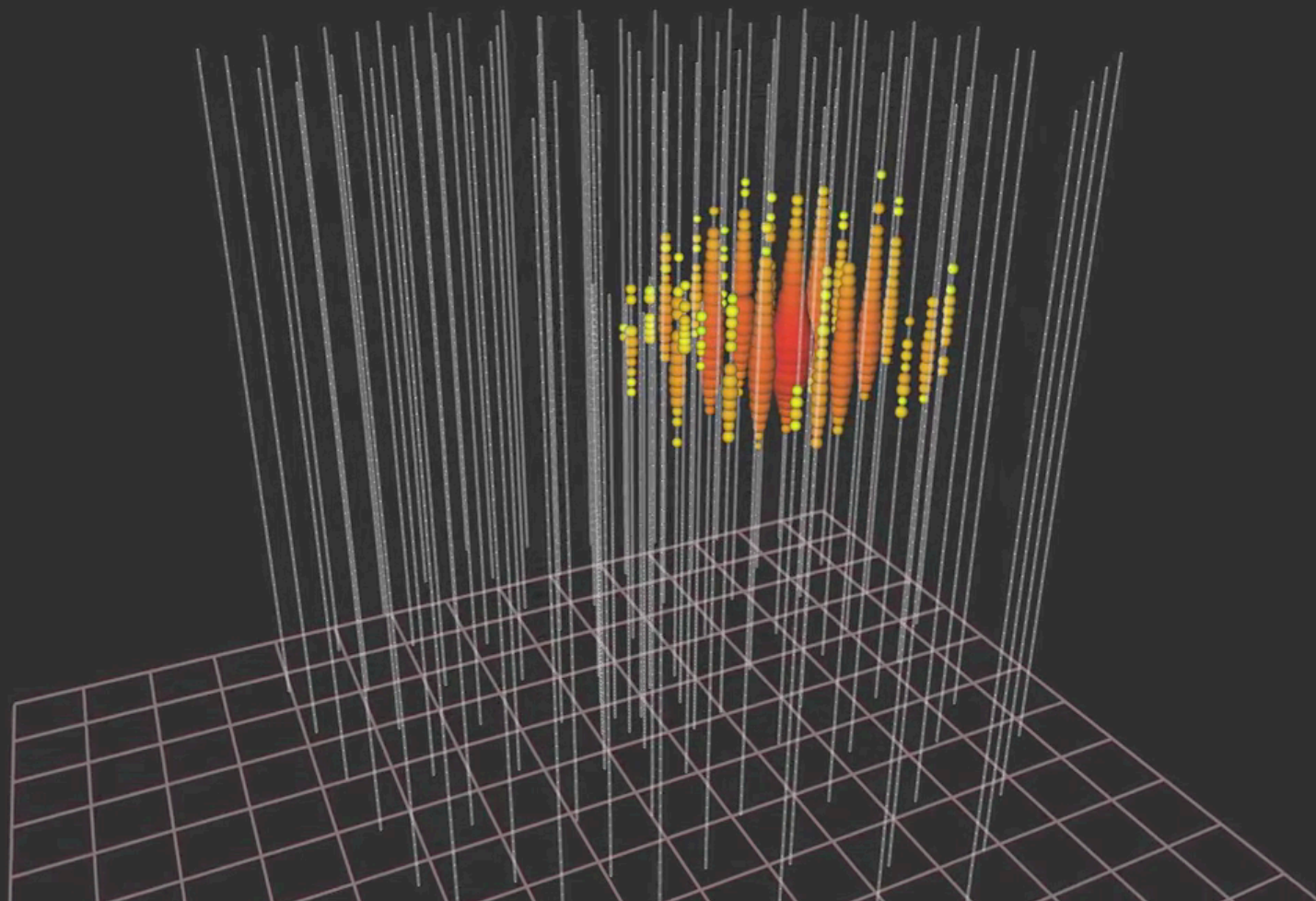
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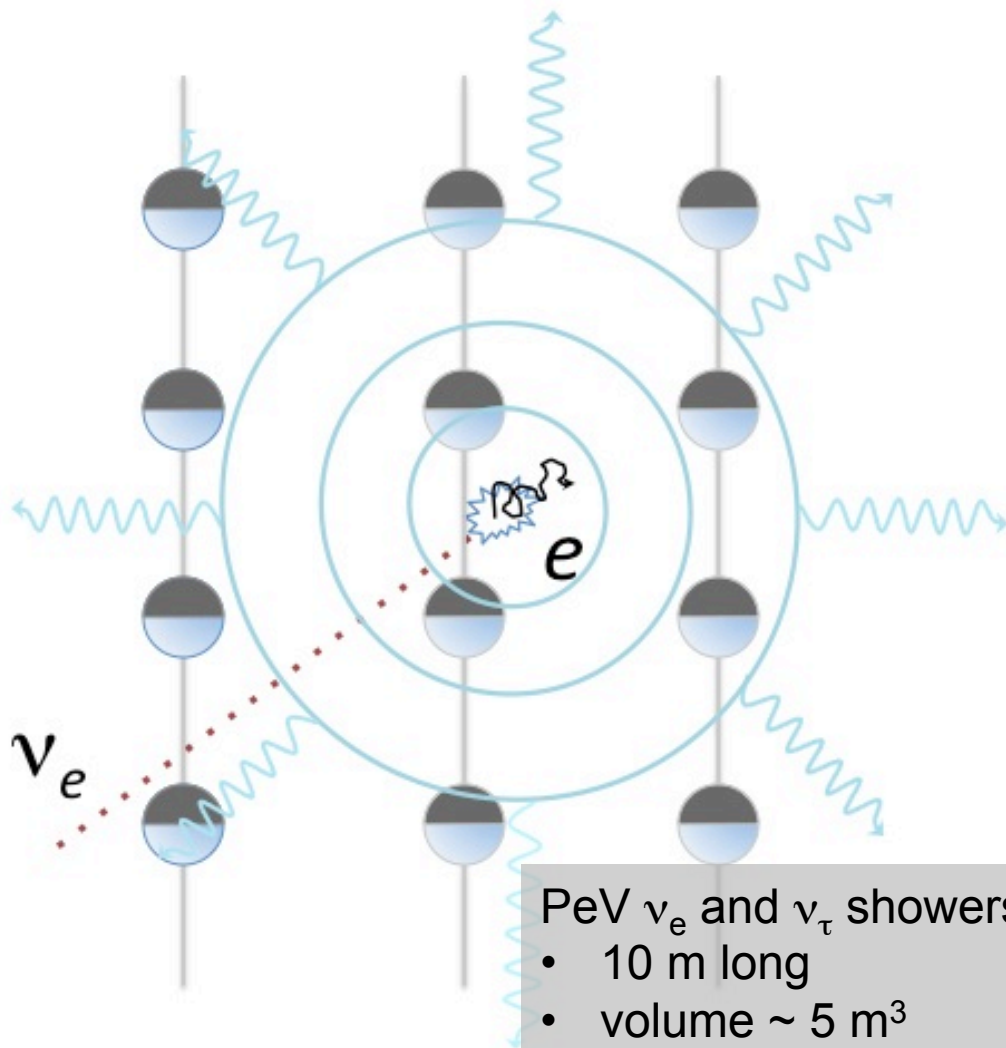
1 event per cubic kilometer per year  
...but it points at its source!

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



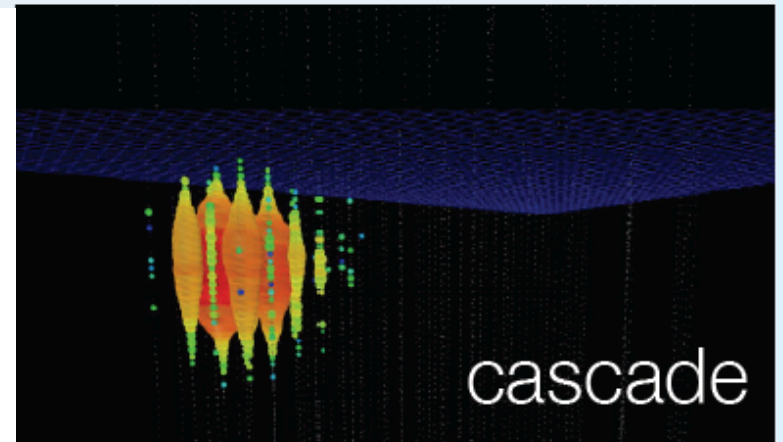
IceCube

# tracks and showers

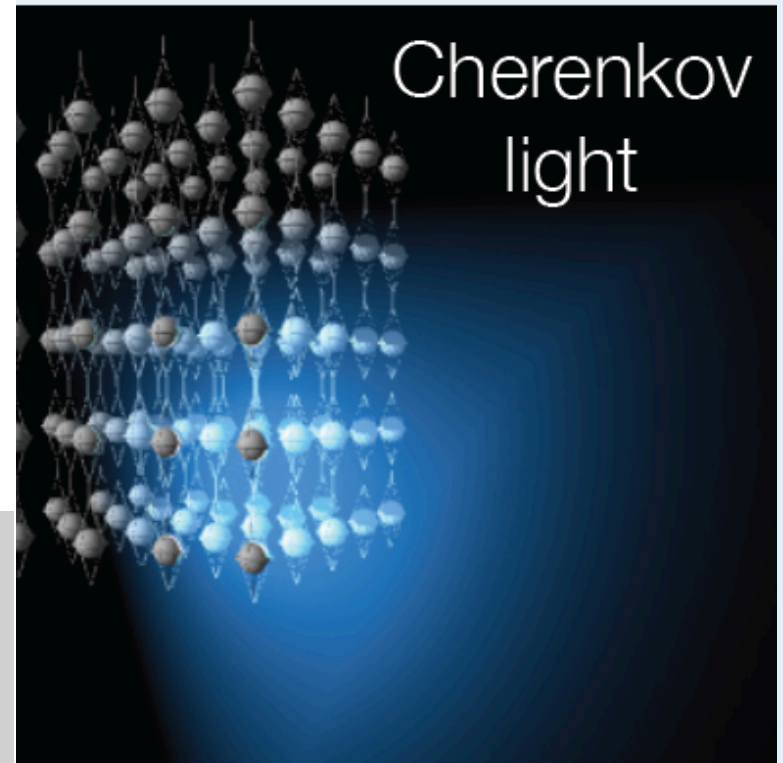


PeV  $\nu_e$  and  $\nu_\tau$  showers:

- 10 m long
- volume  $\sim 5 \text{ m}^3$
- isotropic after 25~ 50m

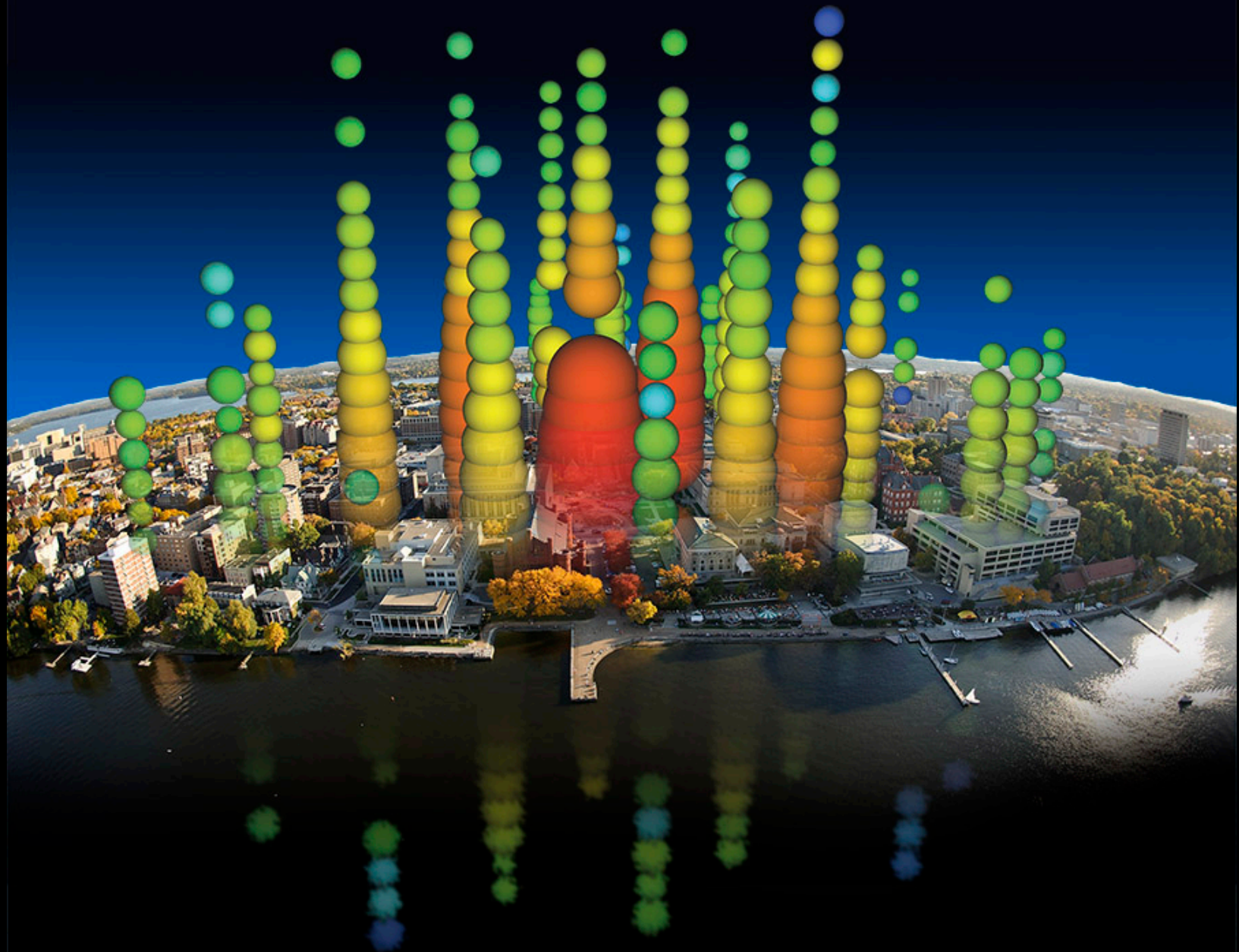


cascade

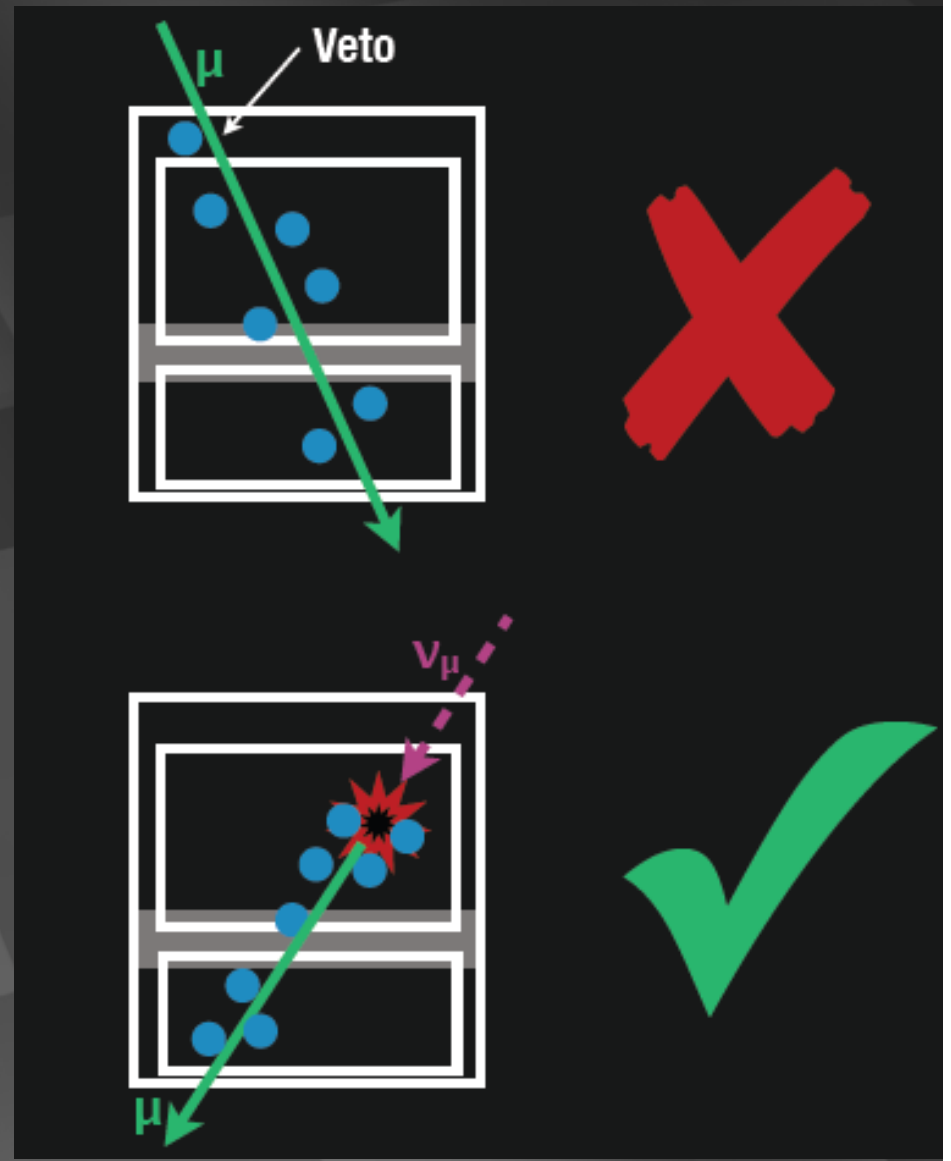


Cherenkov  
light

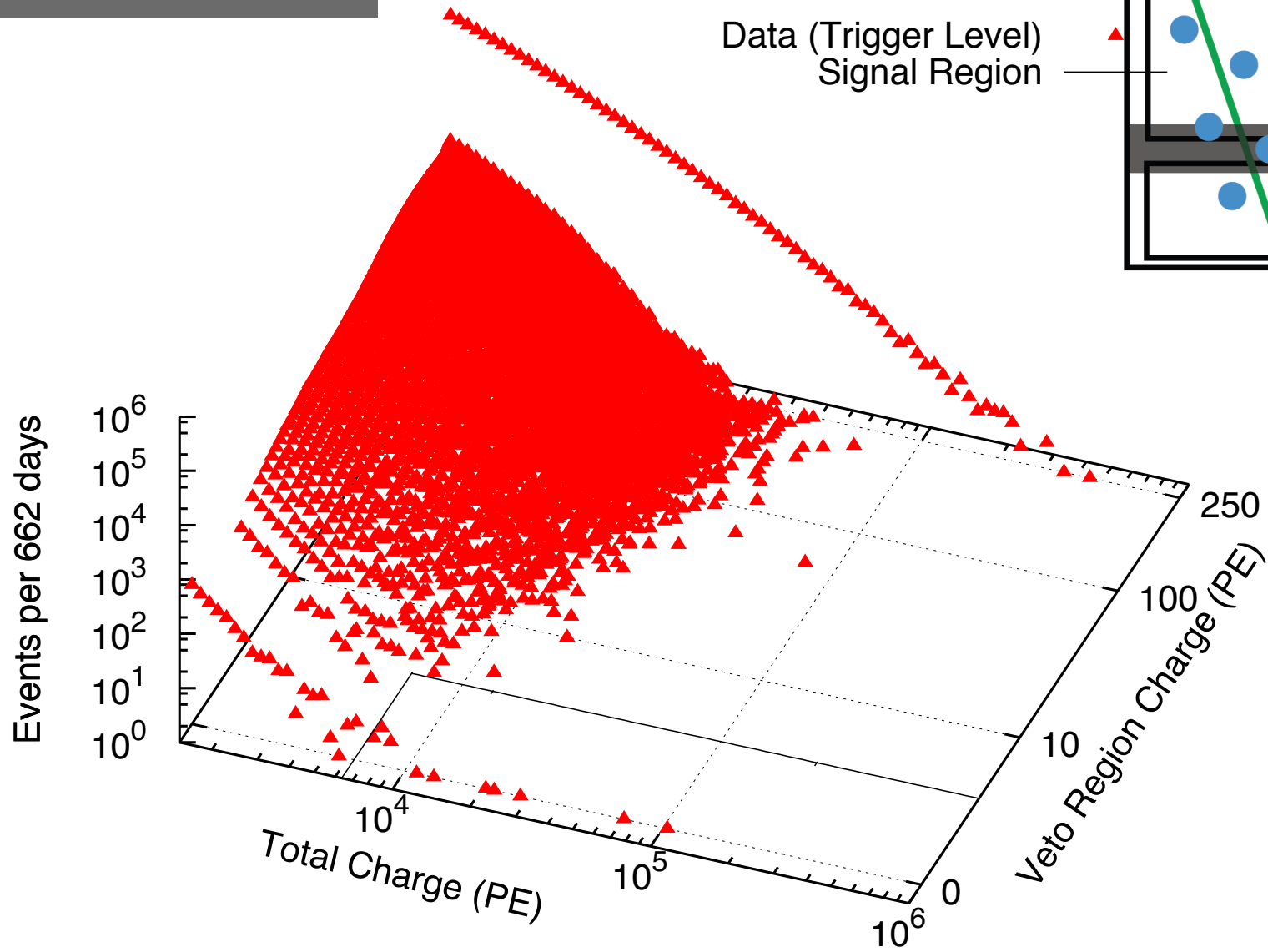




- ✓ select events interacting inside the detector only
- ✓ no light in the veto region
- ✓ energy measurement: total absorption calorimetry

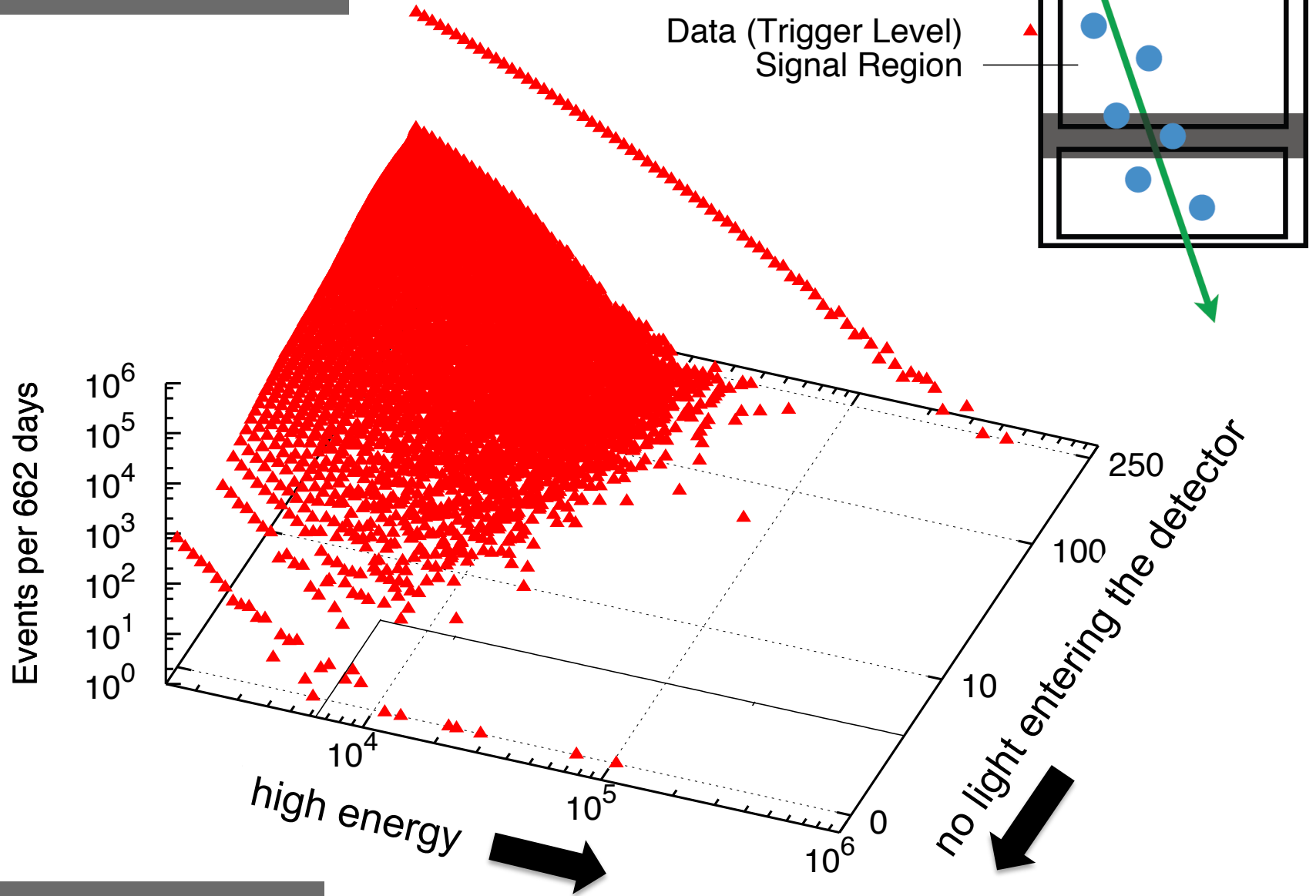


...and then there were 26 more...



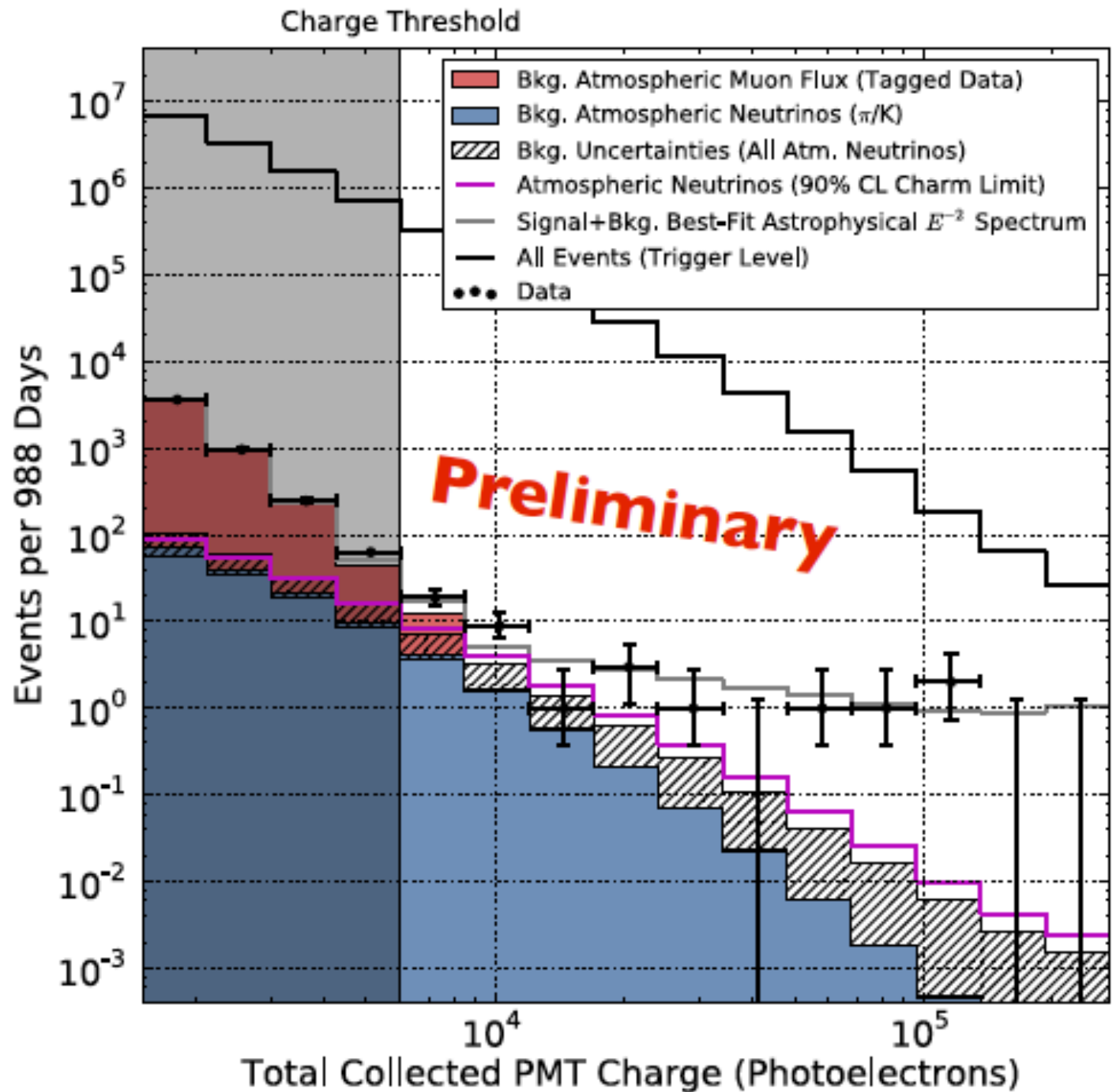
data: 86 strings one year

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



data: 86 strings one year

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

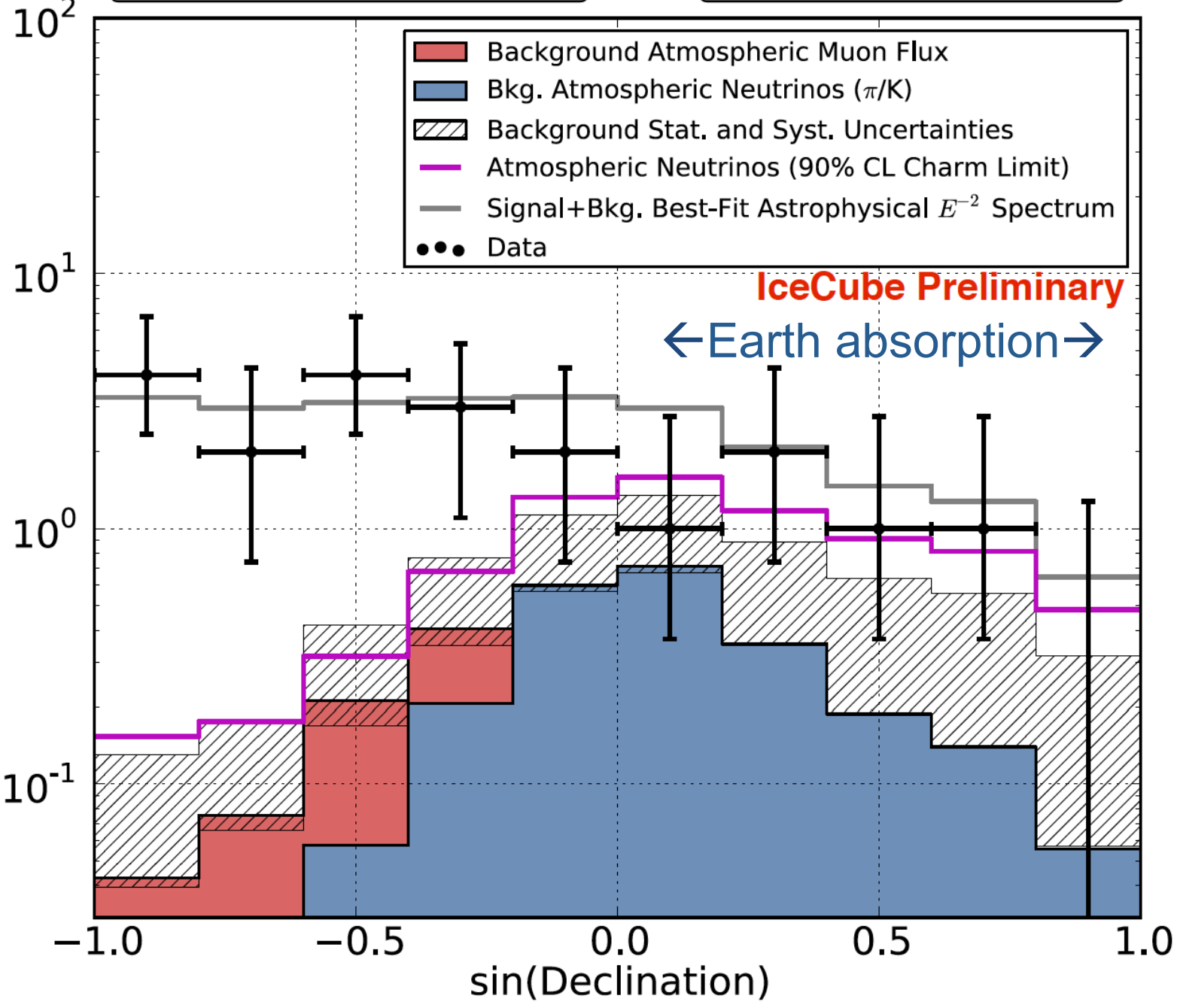


3 years

Events per 988 Days with deposited  $E > 60$  TeV

Southern Sky (downgoing)

Northern Sky (upgoing)



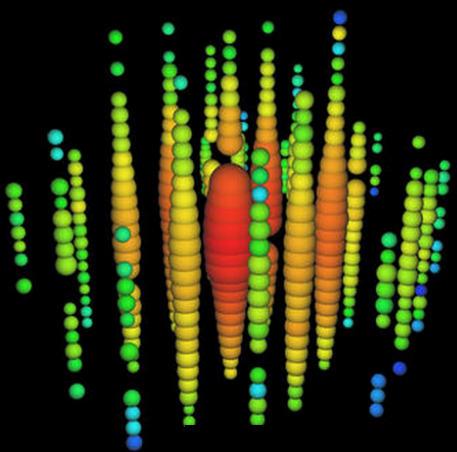
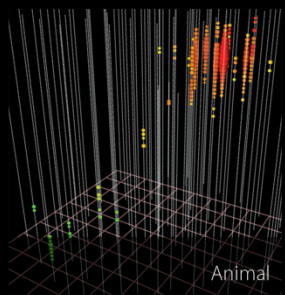
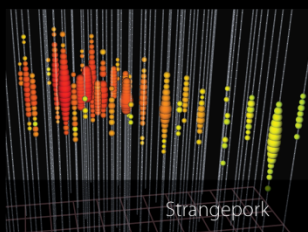
RESEARCH

# Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

IceCube Collaboration\*

**Introduction:** Neutrino observations are a unique probe of the universe's highest energy

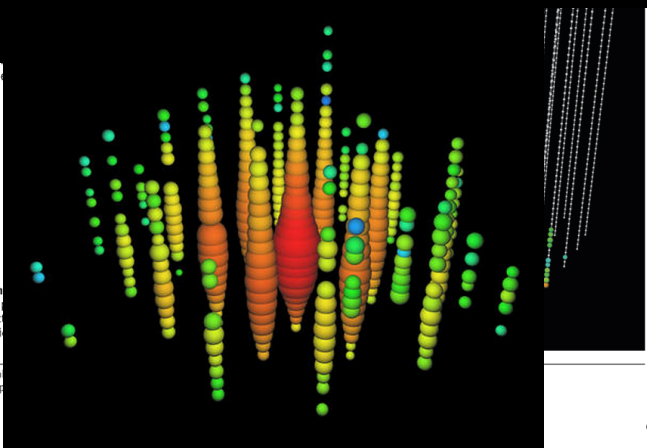
## 28 High Energy Events



identified high-energy galactic or extragalactic accelerators.

**A 250 TeV neutrino interaction in the IceCube detector.** At the interaction point (bottom), a large muon track is produced in the interaction. The direction of the muon indicates the direction of the original neutrino.

\*The list of author affiliations is available in the full article. Corresponding authors: C. Kopper (ckopper@icecube.wisc.edu)

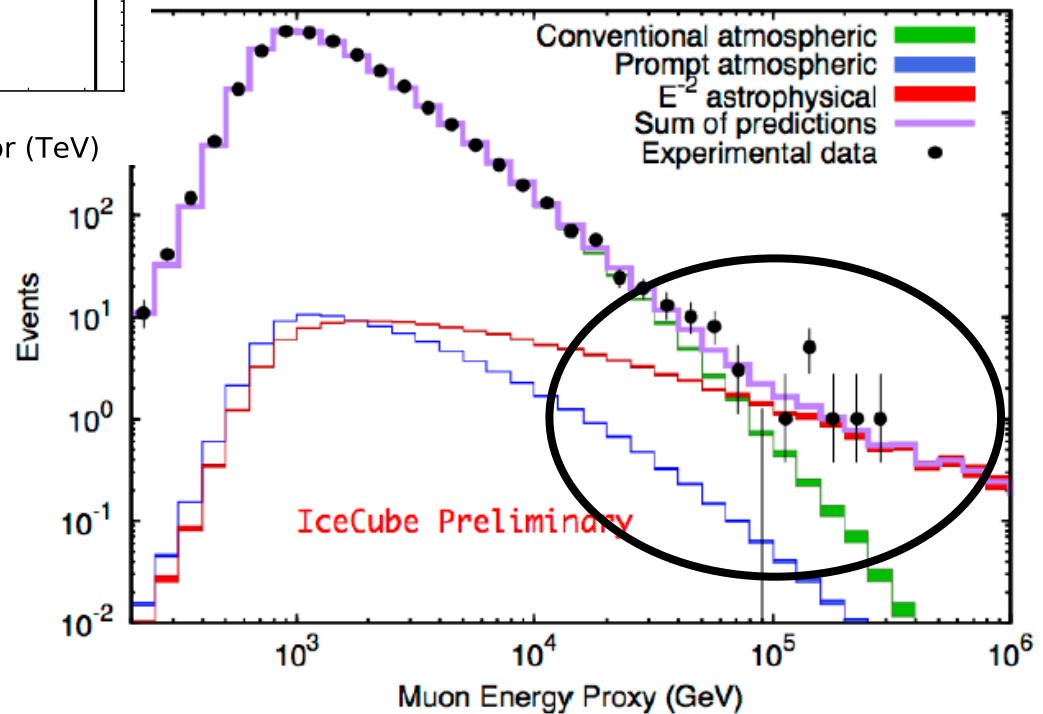
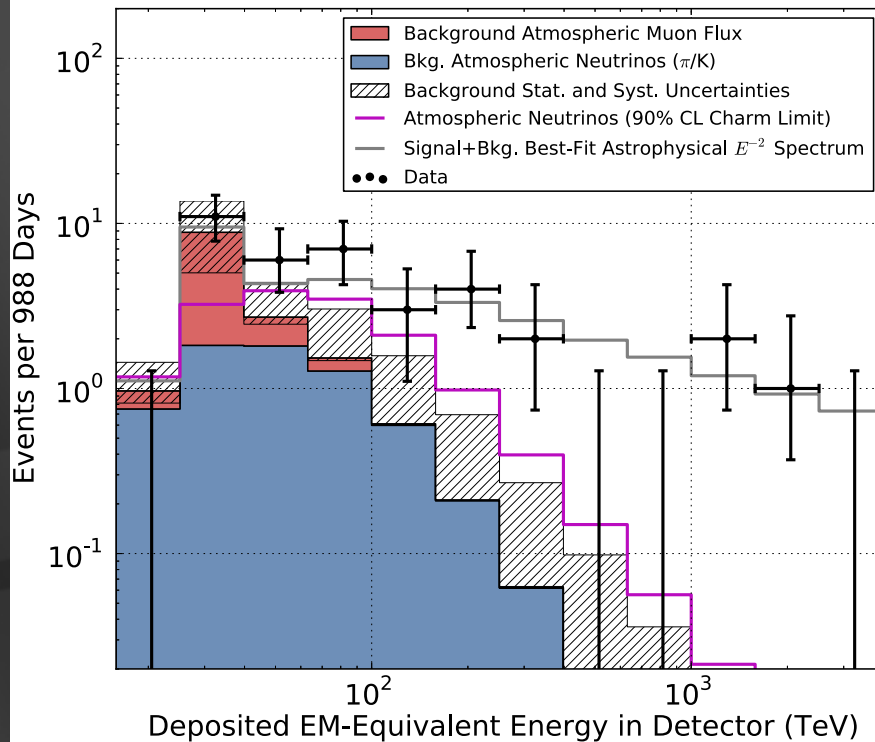


22 November 2013 | \$10

# Science

## 22 November 2013

confirmation!  
flux of muon neutrinos  
through the Earth



neutrinos of all flavors  
interacting inside  
IceCube



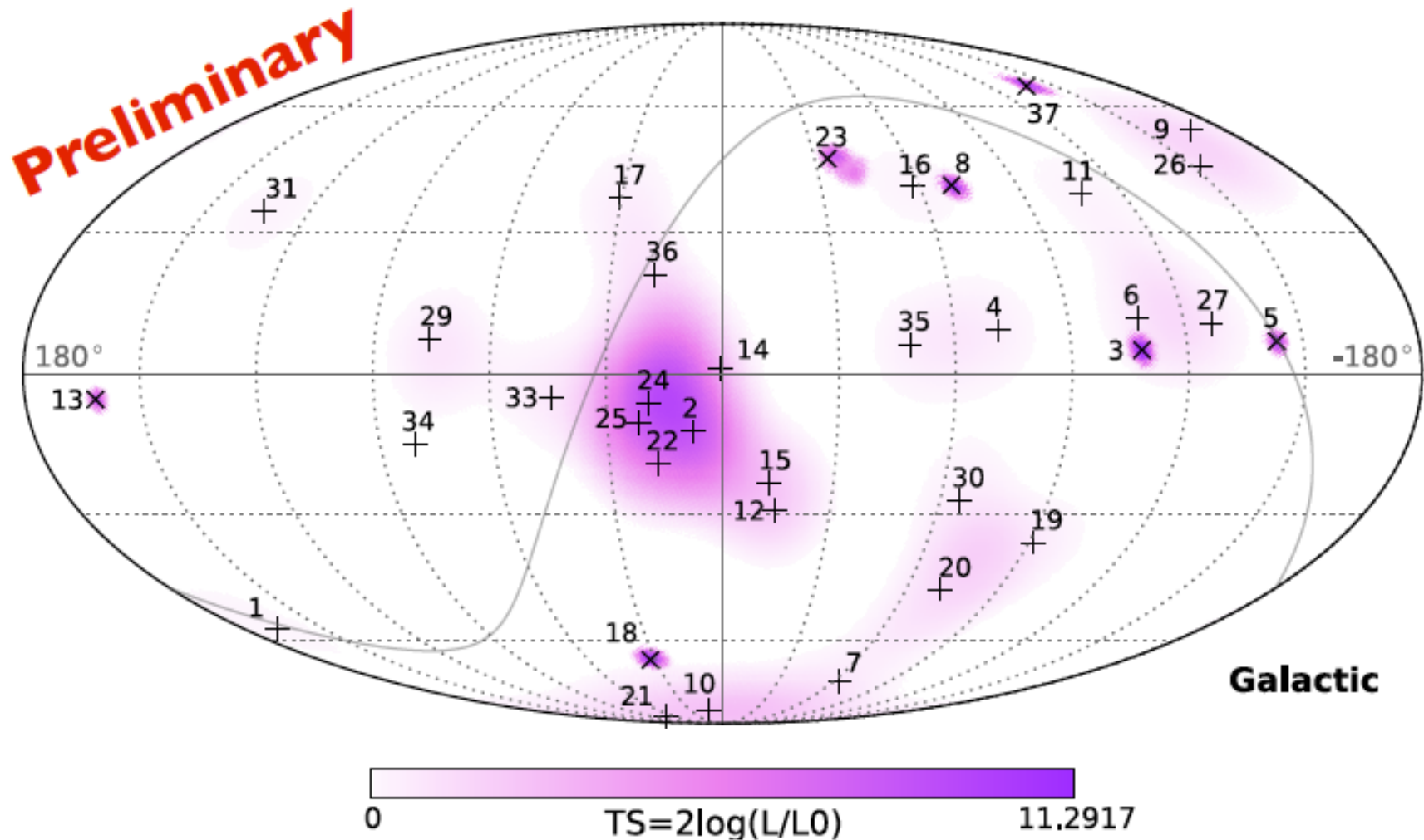


## IceCube: the discovery of cosmic neutrinos

francis halzen

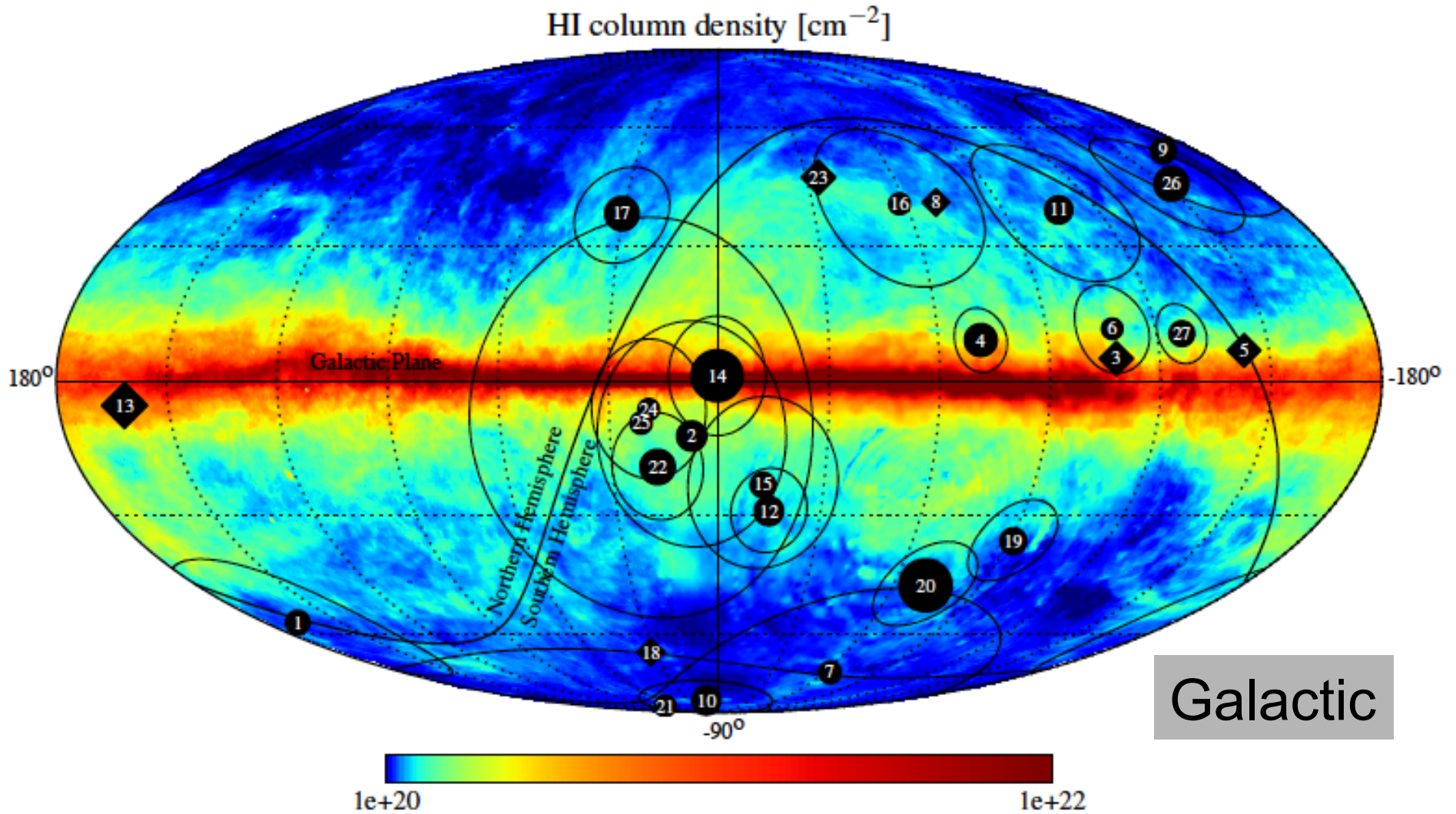
- cosmic ray accelerators
- IceCube a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

where do they come from (3 year data)?



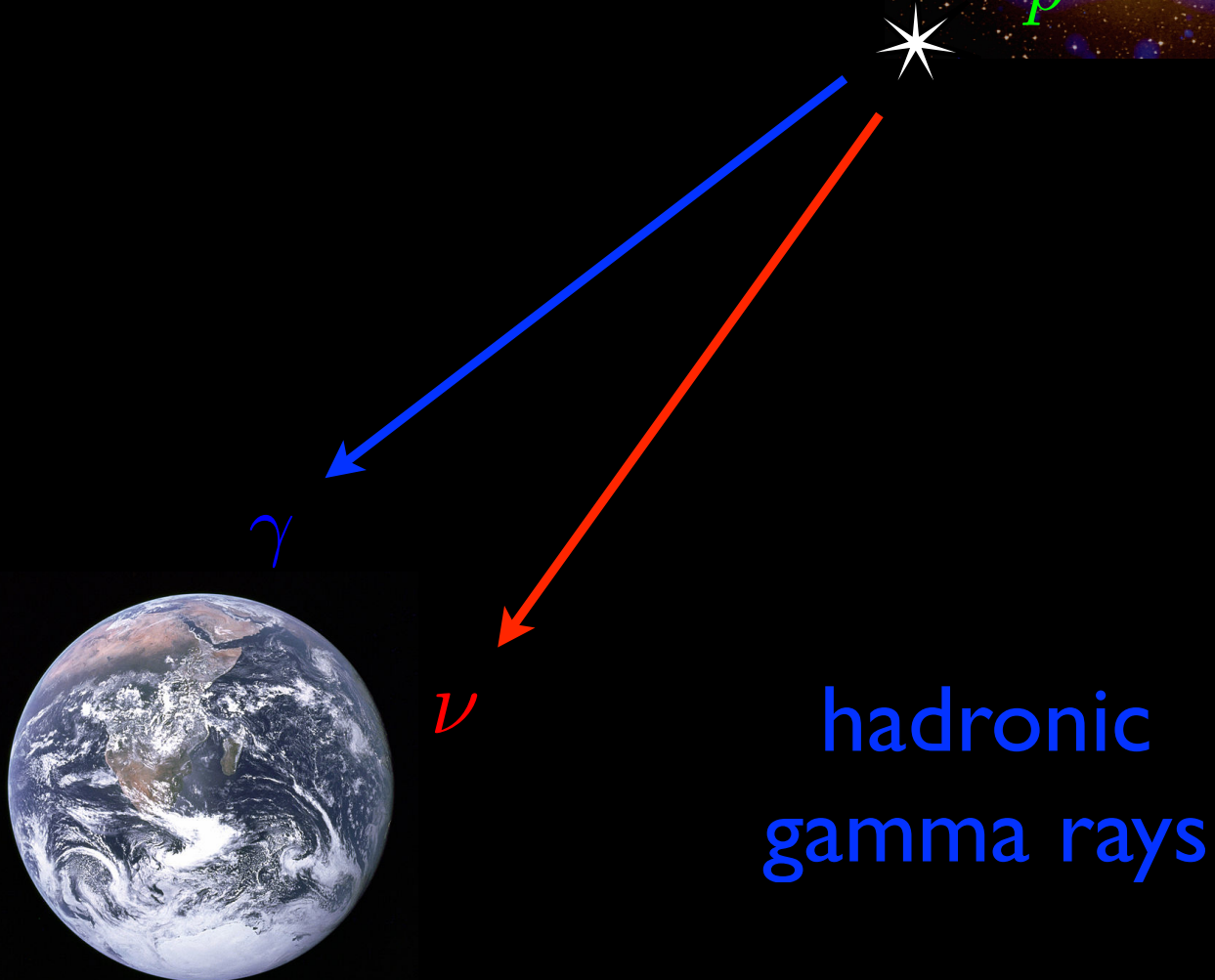
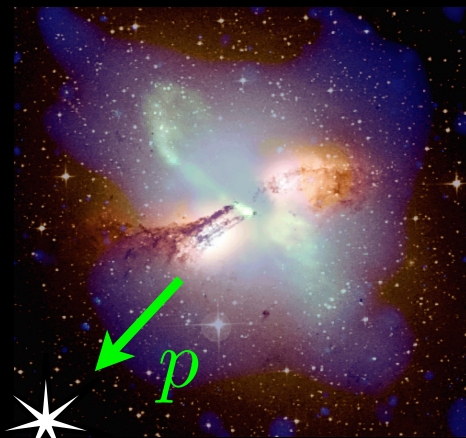
hottest spot 7.2%: consistent with diffuse flux with flavor 1:1:1?

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

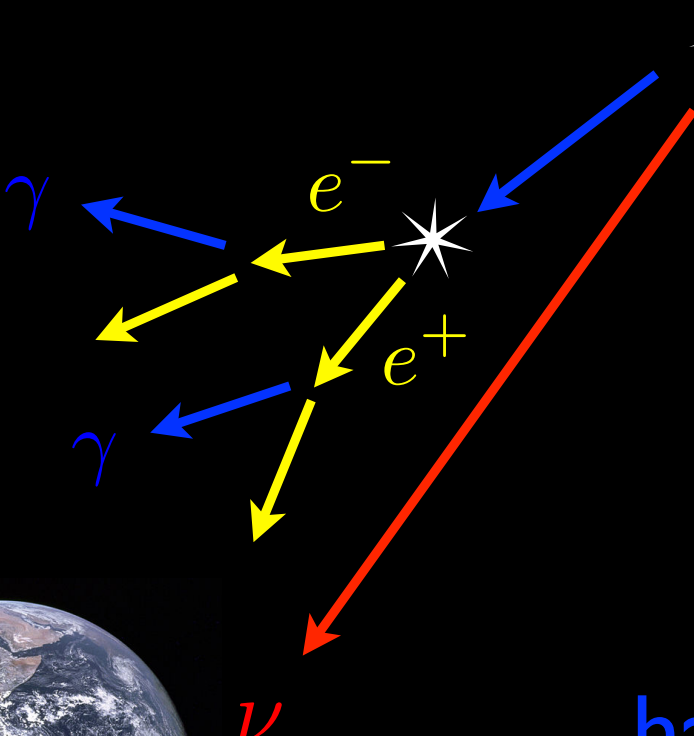
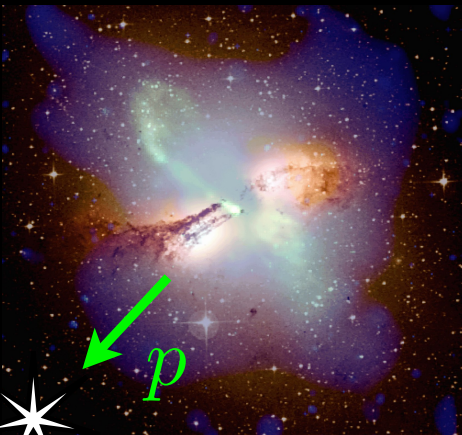


hadronic gamma rays ?

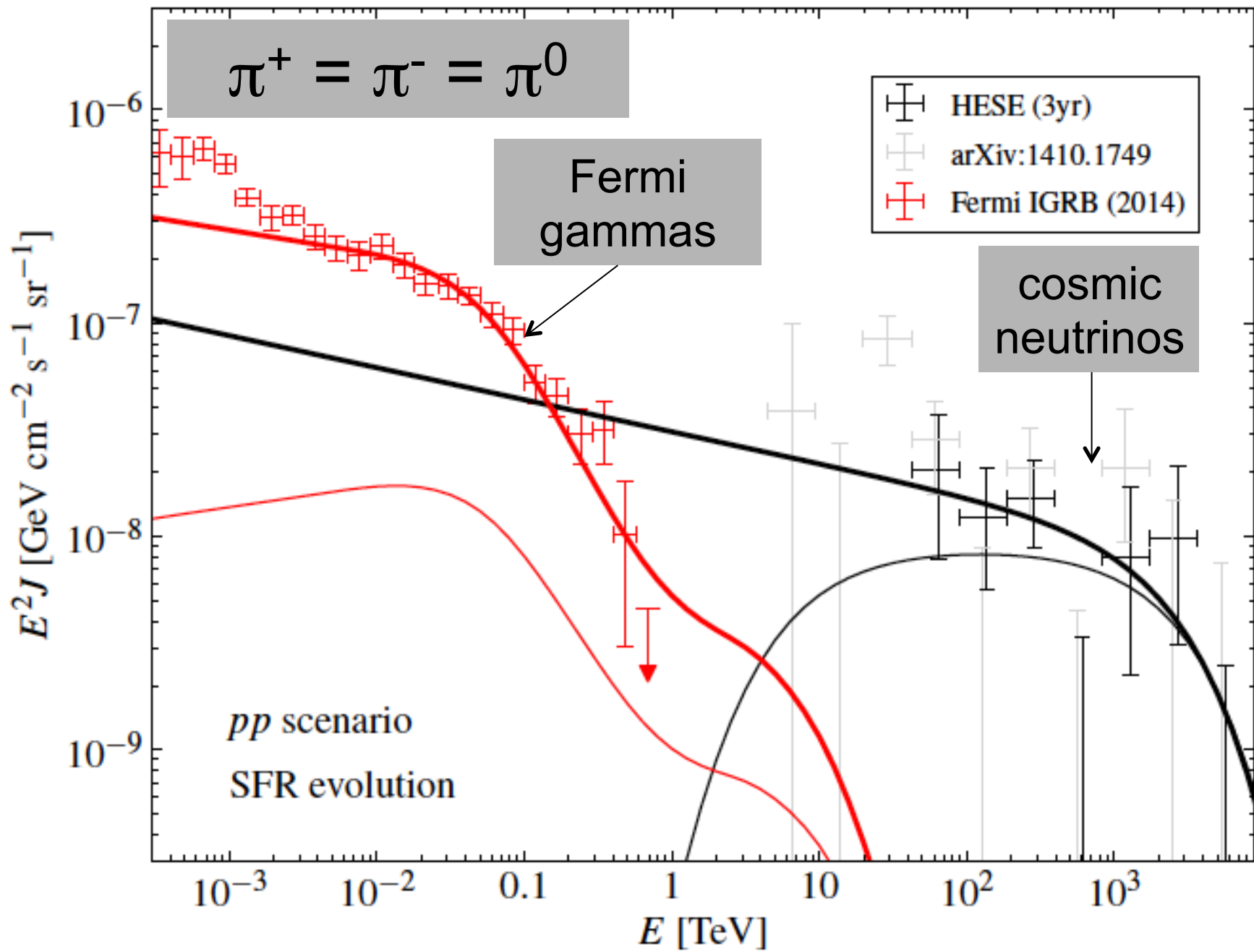
$$\pi^+ = \pi^- = \pi^0$$



electromagnetic  
cascades in CMB



hadronic  
gamma rays

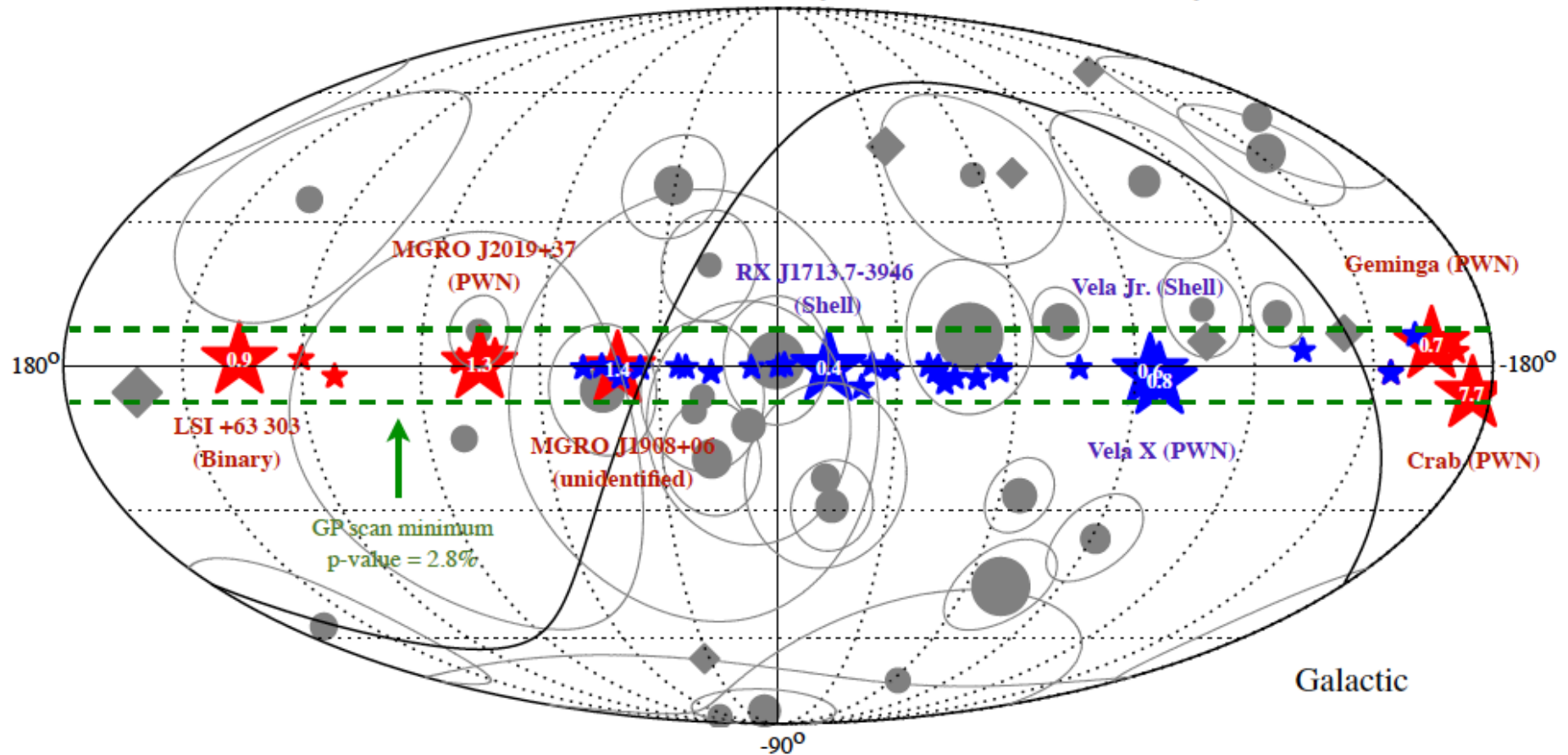


## Conclusion:

- 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

# event rates from point sources

Galactic search with IceCube (red, 3yrs) & ANTARES (blue, 6yrs)



we are close to detecting neutrinos from known high energy gamma ray emitters





# IceCube: the discovery of cosmic neutrinos

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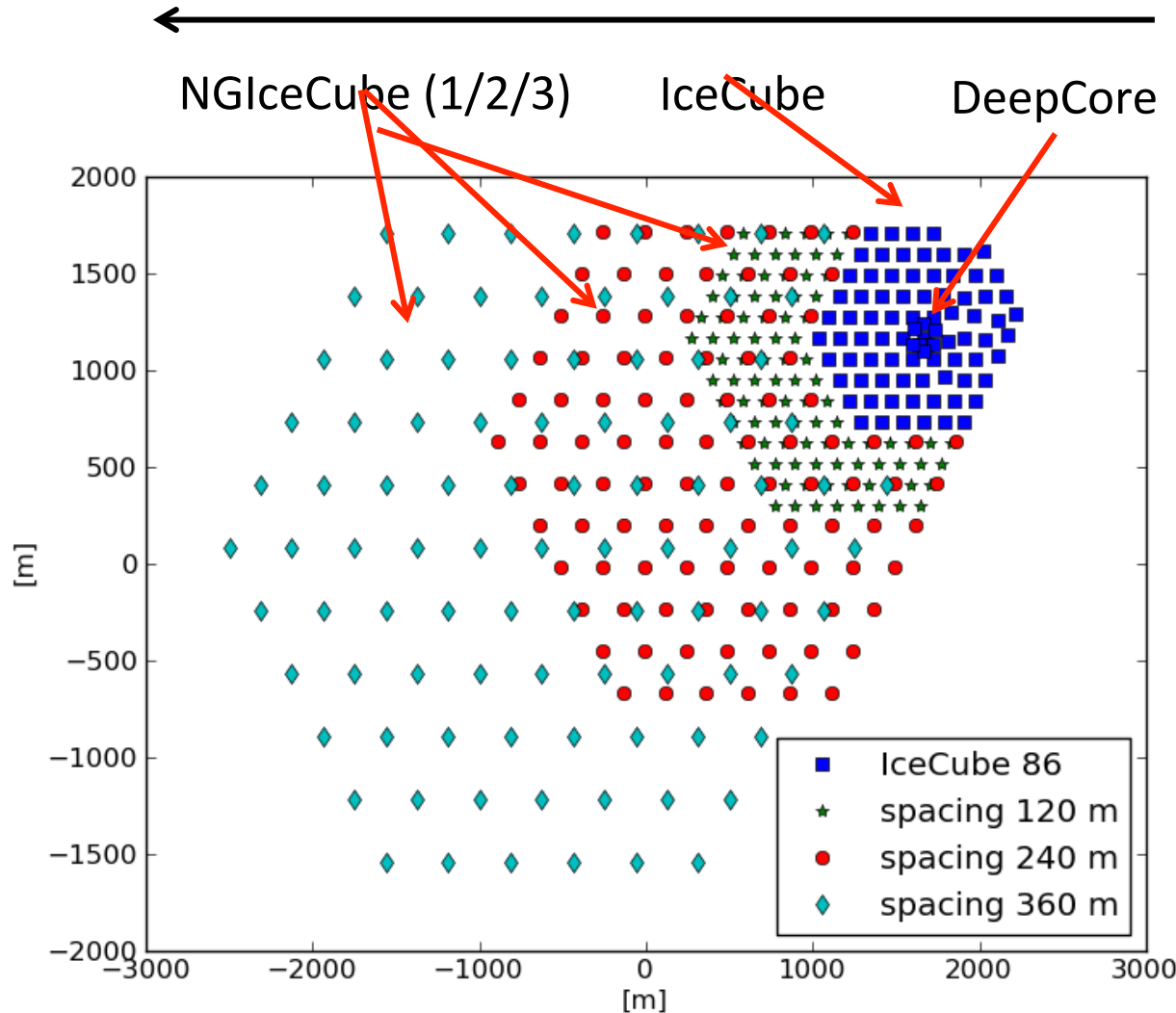
- cosmic ray accelerators
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- where do they come from?
- beyond IceCube

a next-generation IceCube with a volume of  $10 \text{ km}^3$   
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  
and guarantee astronomy

discovery instrument  $\rightarrow$  astronomical telescope

measured optical properties → twice the string spacing

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

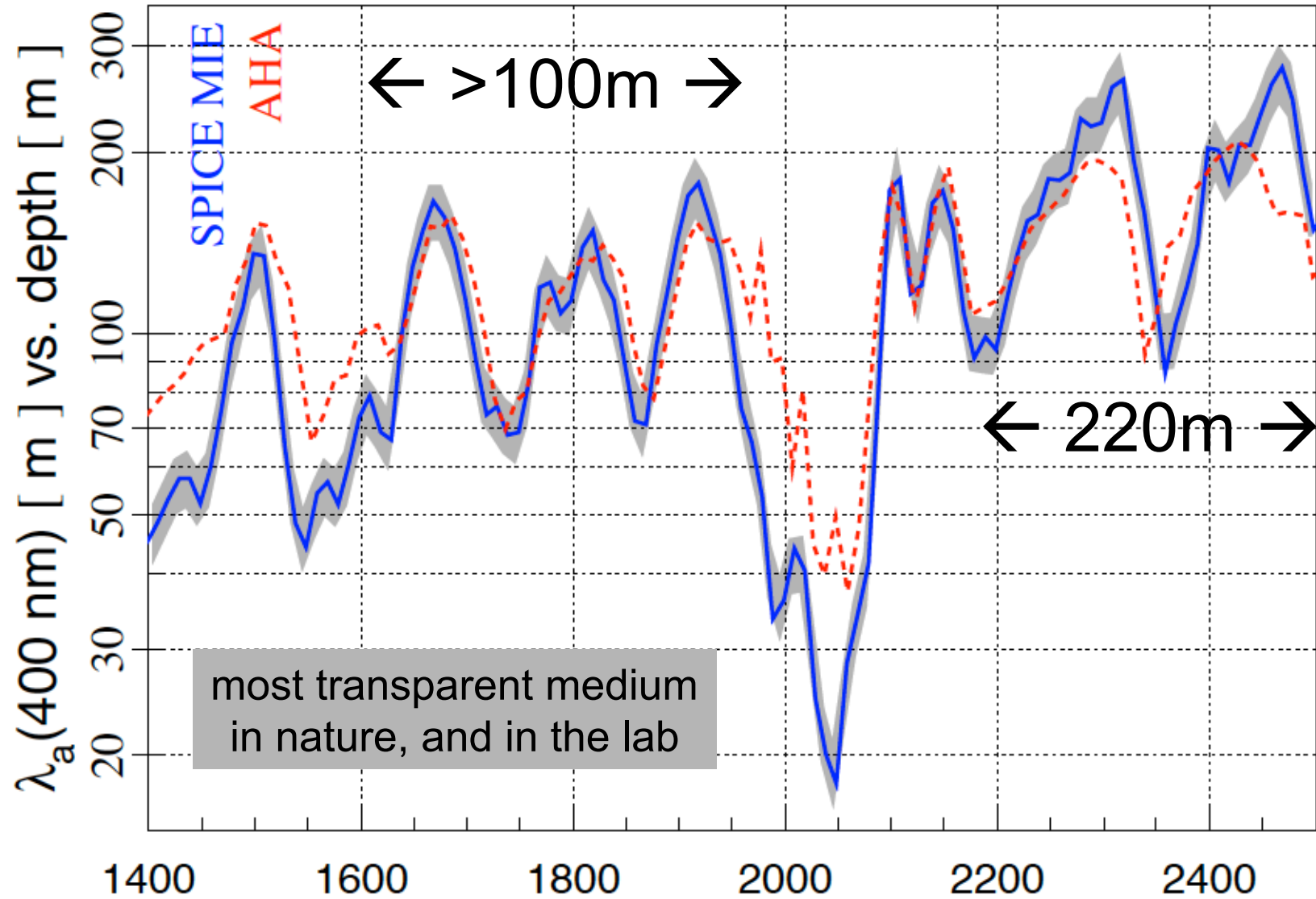


**Spacing 1 (120m):**  
IceCube (1 km<sup>3</sup>)  
+ 98 strings (1,3 km<sup>3</sup>)  
**= 2,3 km<sup>3</sup>**

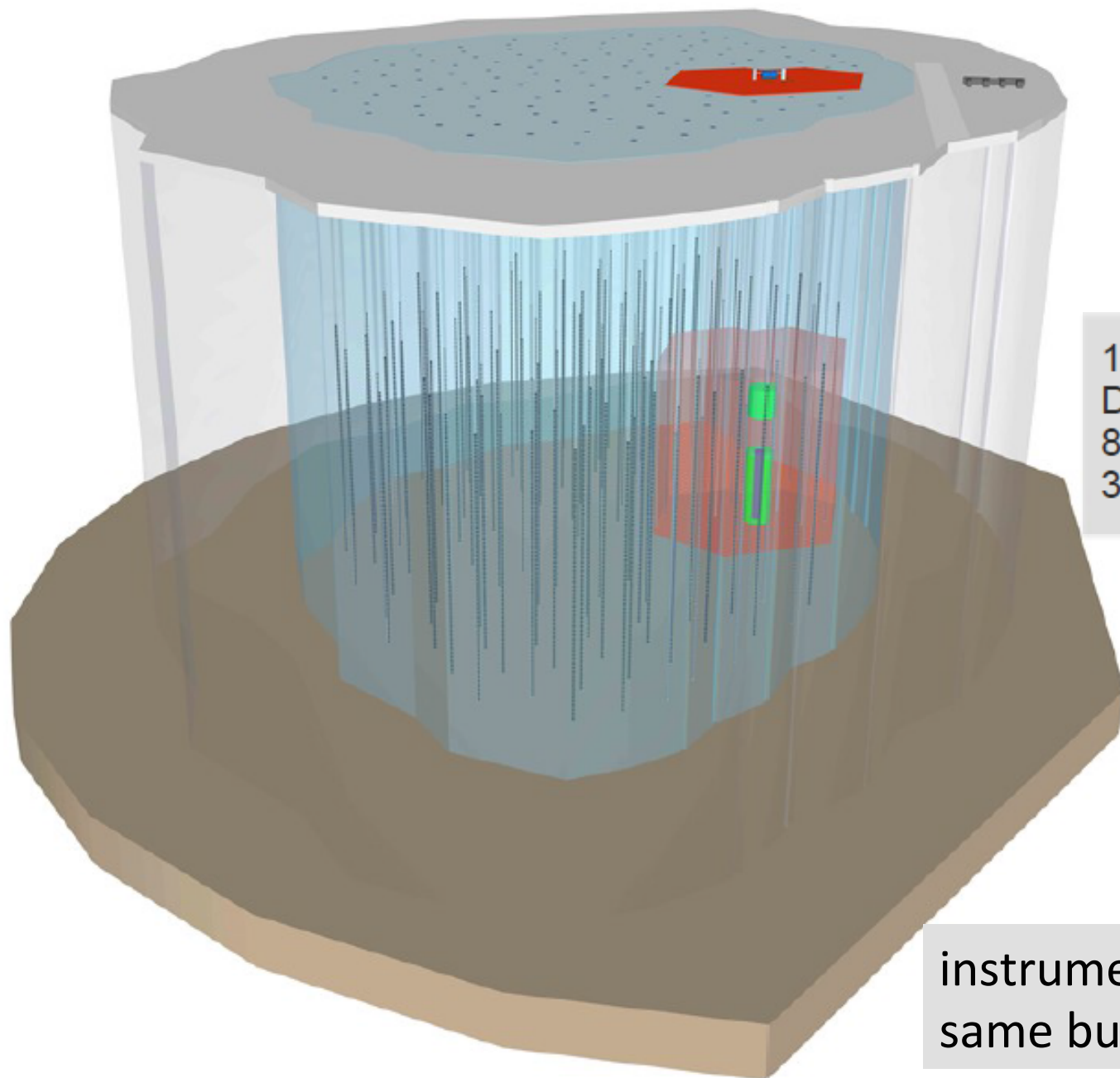
**Spacing 2 (240m):**  
IceCube (1 km<sup>3</sup>)  
+ 99 strings (5,3 km<sup>3</sup>)  
**= 6,3 km<sup>3</sup>**

**Spacing 3 (360m):**  
IceCube (1 km<sup>3</sup>)  
+ 95 strings (11,6 km<sup>3</sup>)  
**= 12,6 km<sup>3</sup>**

# absorption length of Cherenkov light



most transparent medium  
in nature, and in the lab



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

instrumented volume: x 10  
same budget as IceCube

## 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

## 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

# 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)