



ICECUBE



## IceCube: the discovery of cosmic neutrinos

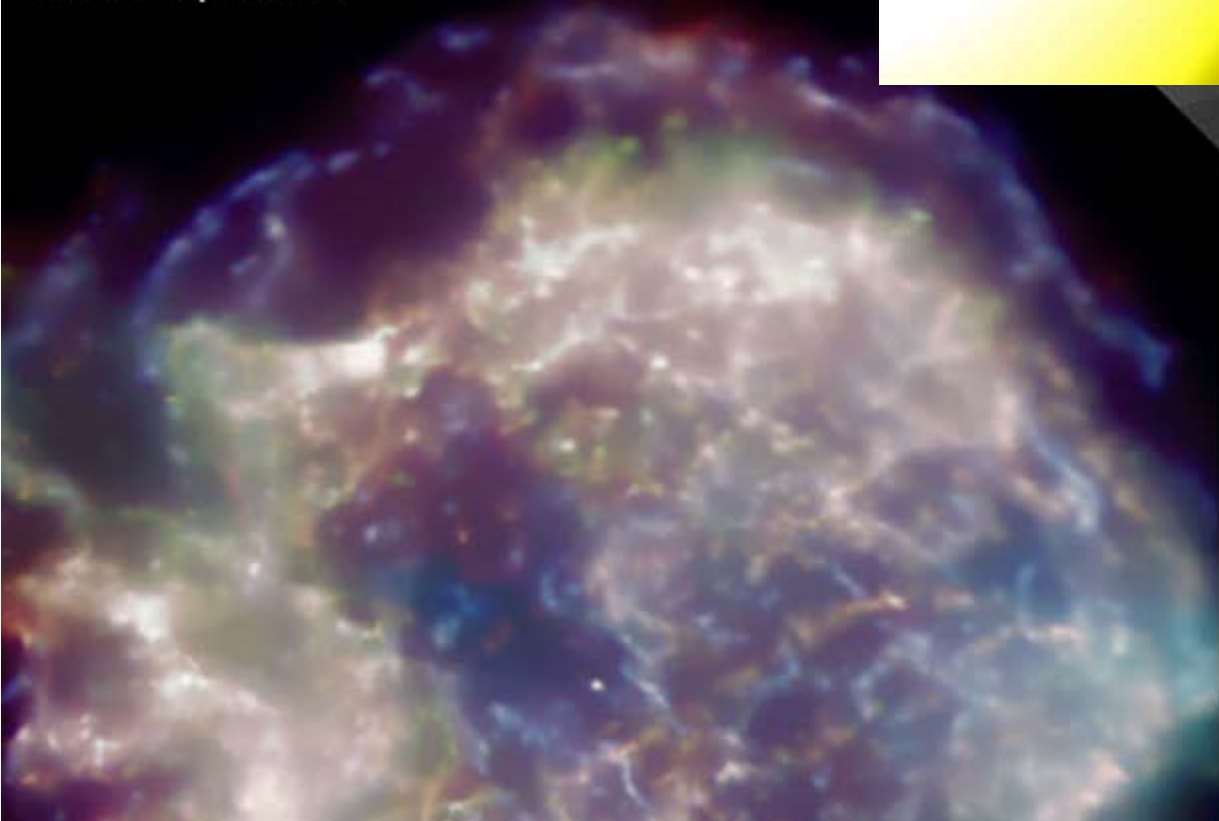
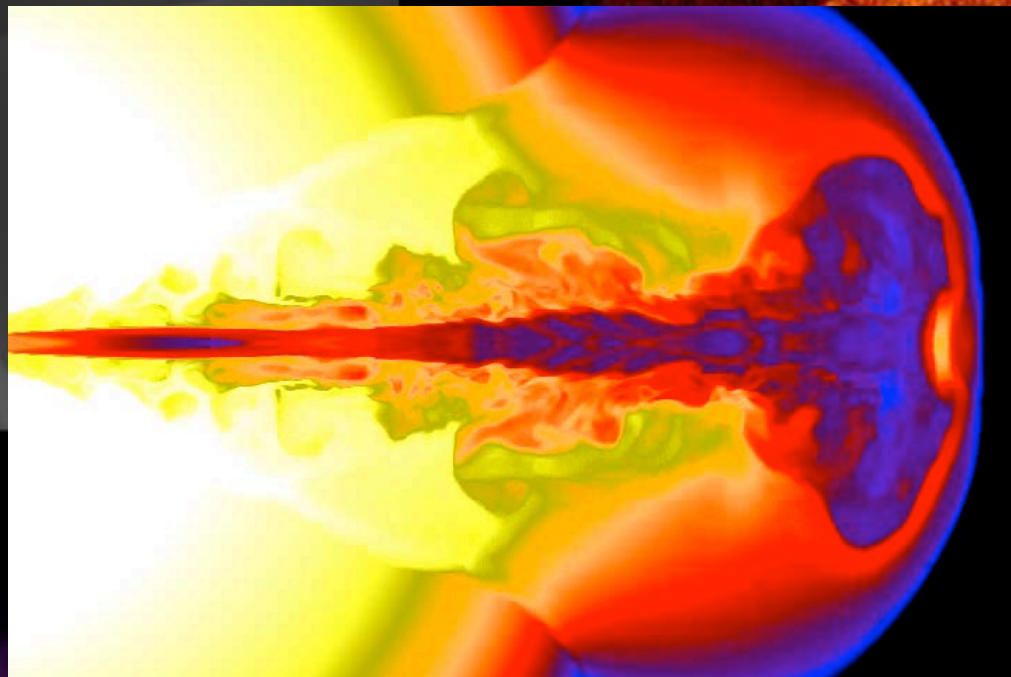
francis halzen

- IceCube
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

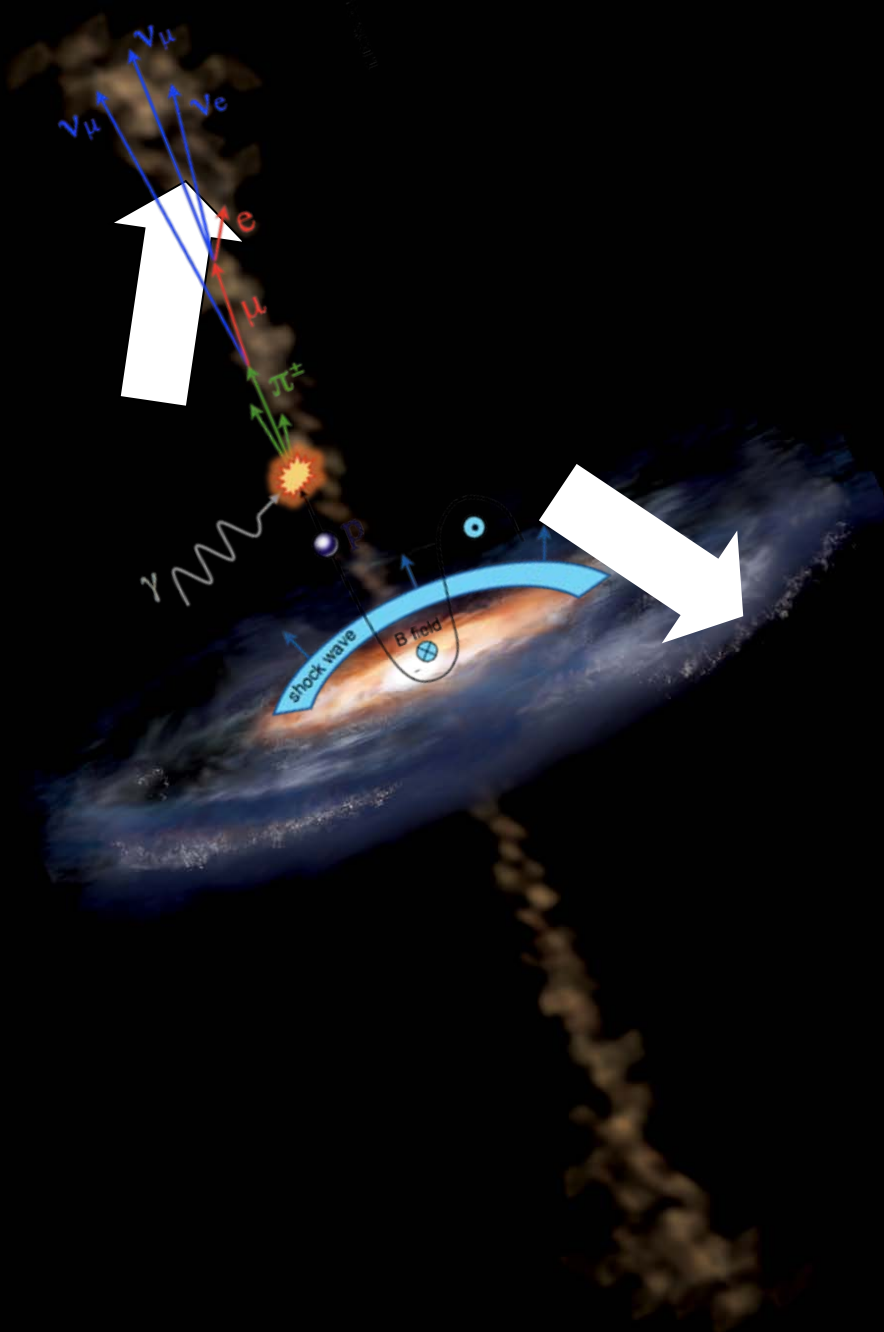


# supernova remnants

Chandra  
Cassiopeia A



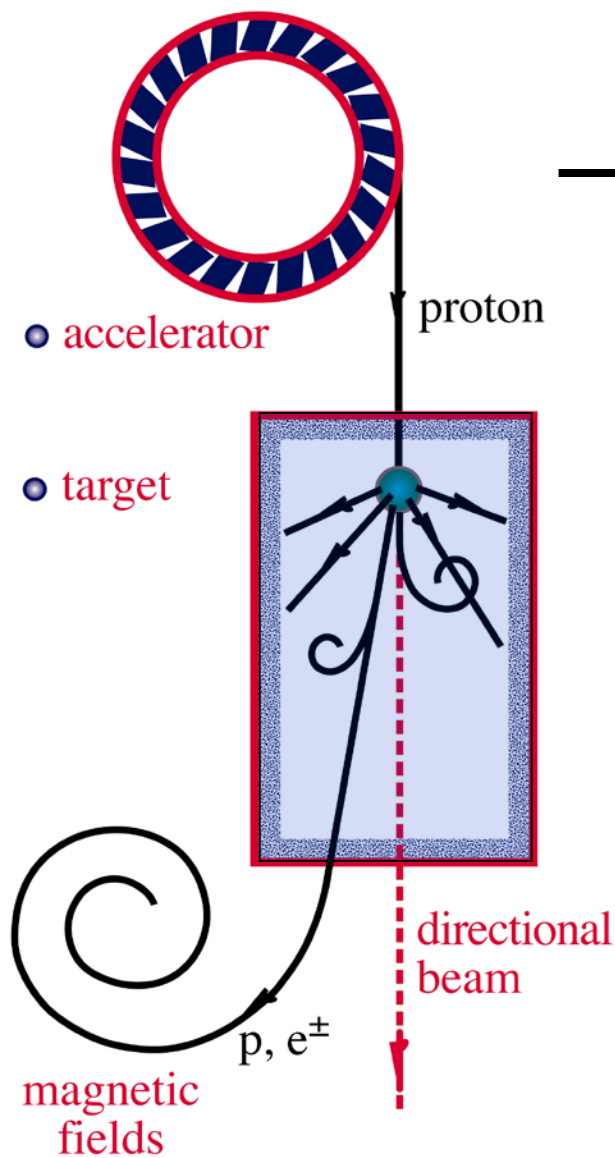
gamma  
ray  
bursts



active galaxy

particle flows near  
supermassive  
black hole

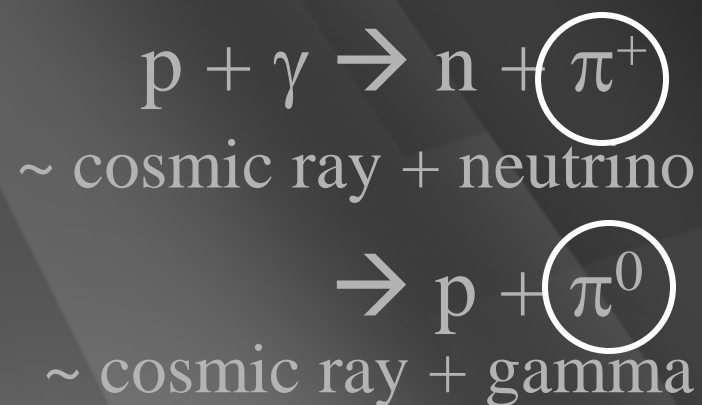
# $\nu$ and $\gamma$ beams : heaven and earth



accelerator is powered by large gravitational energy

black hole  
neutron star

radiation  
and dust

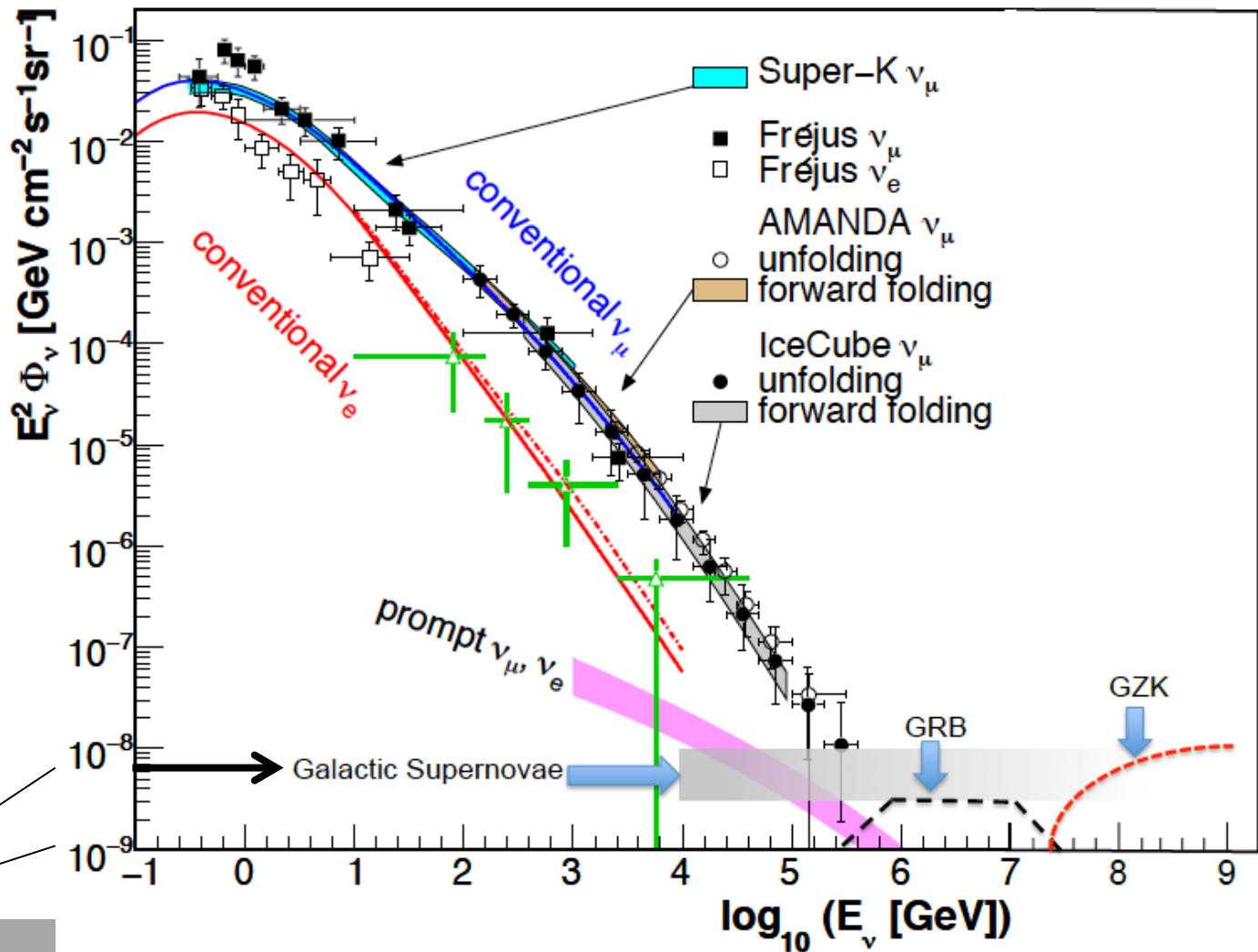


above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

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

10—100 events per year for fully efficient 1 km<sup>3</sup> detector



atmospheric

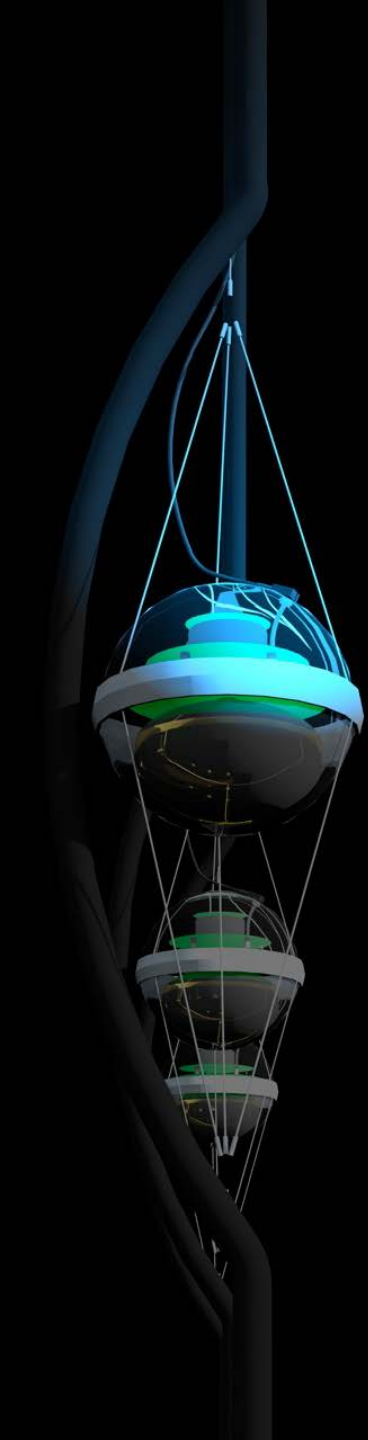
cosmic

100 TeV

# IceCube: the discovery of cosmic neutrinos

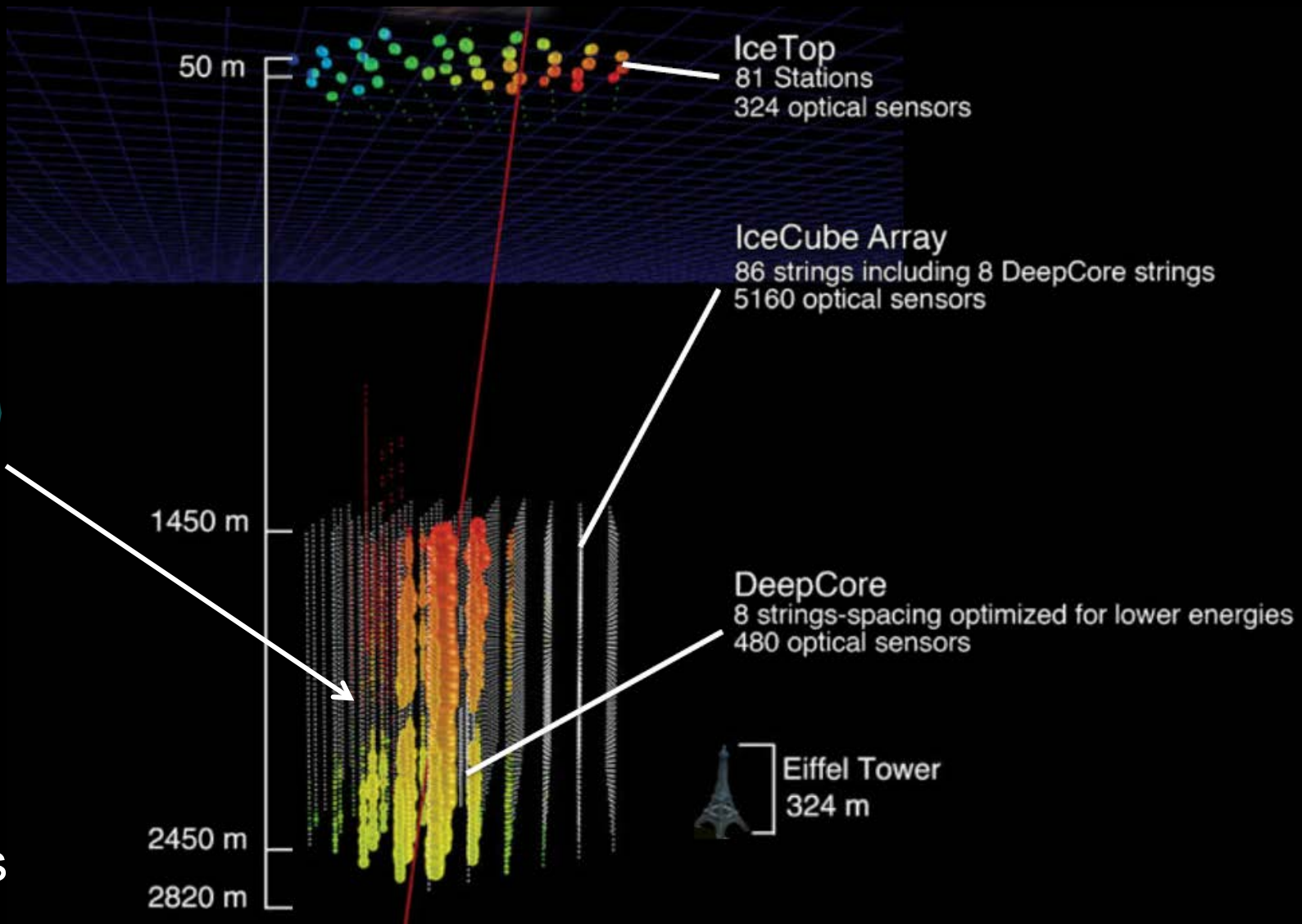
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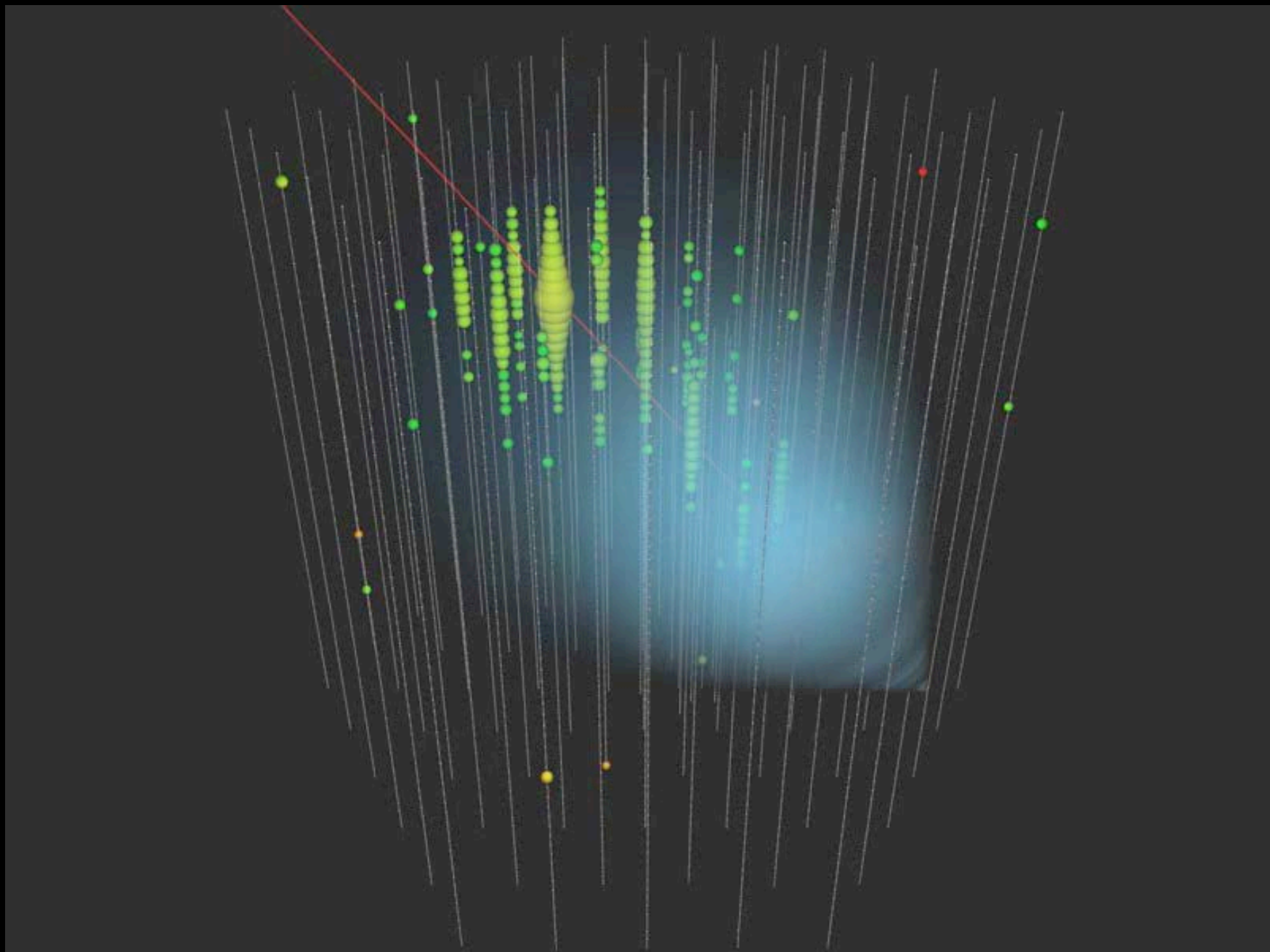




# IceCube



5160 PMs  
in 1 km<sup>3</sup>

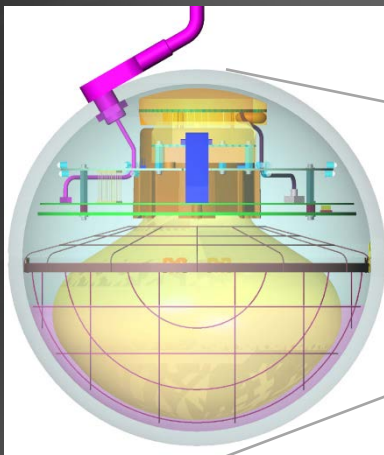


muon track: color is time; number of photons is energy

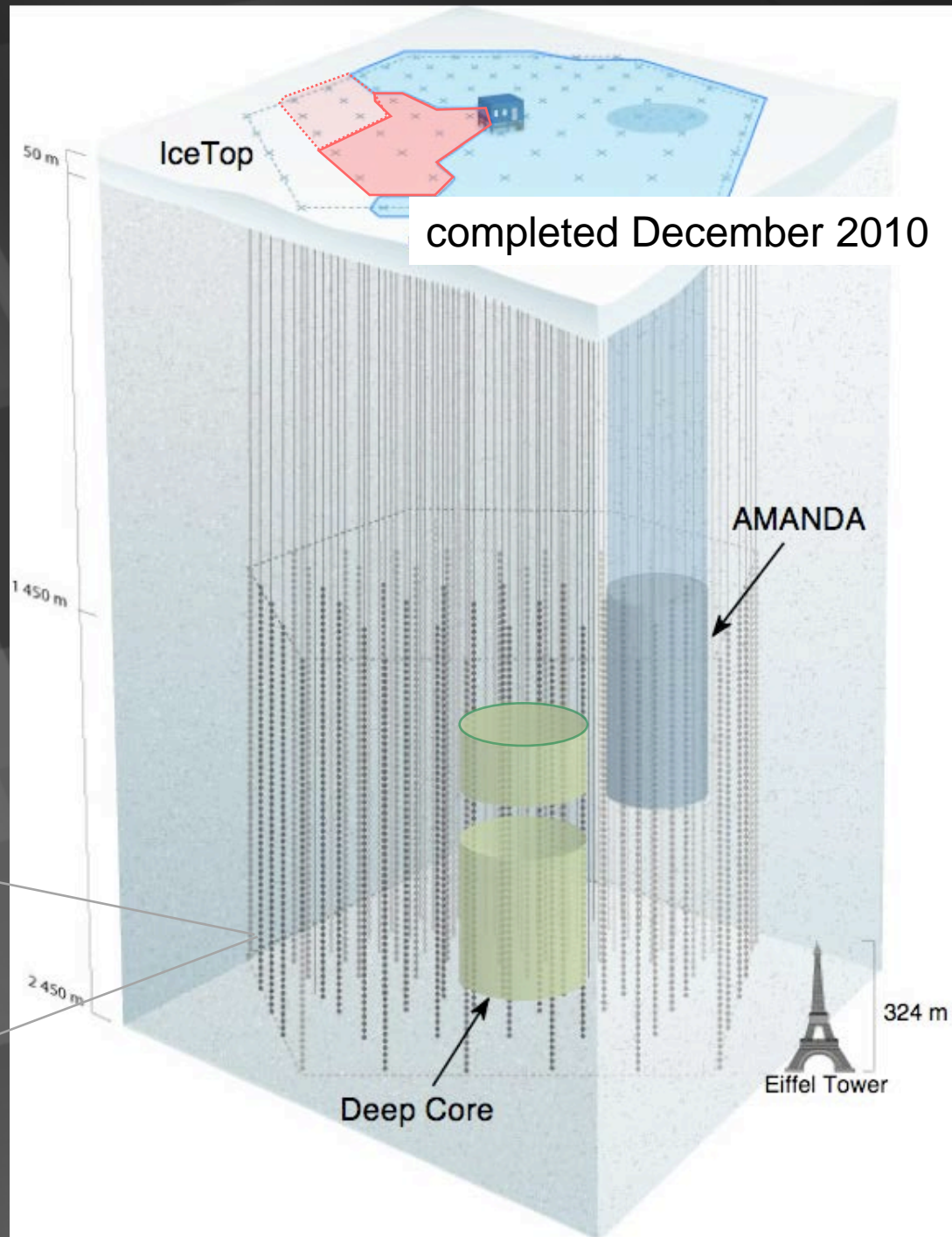


# IceCube / Deep Core

- 5160 optical sensors between 1.5 ~ 2.5 km
- 10 GeV to infinity
- $< 0.4$  degree muon track  
~ 10 degree shower
- $< 15\%$  energy resolution



Digital Optical Module (DOM)



... you looked at 10msec of data !

muons detected per year:

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

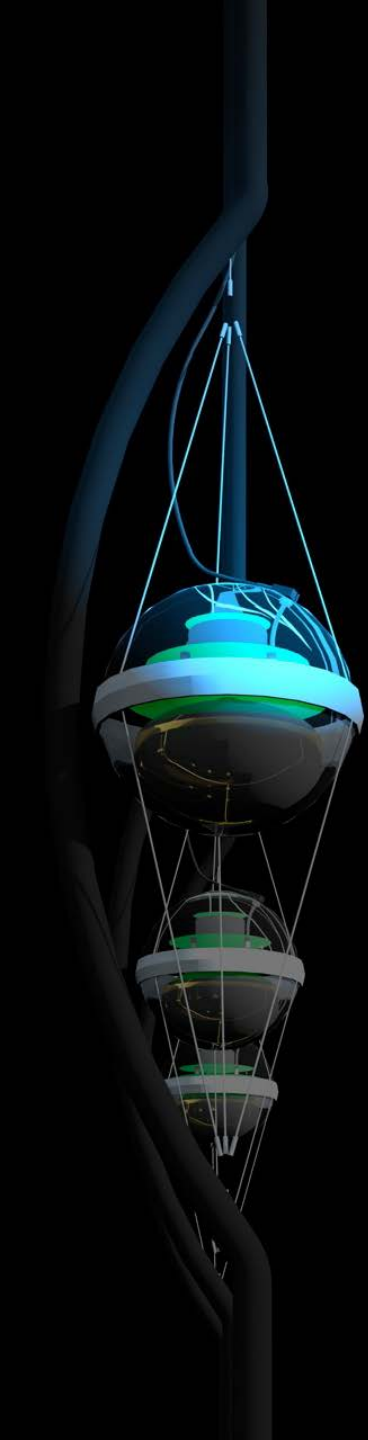
\* 3000 per second

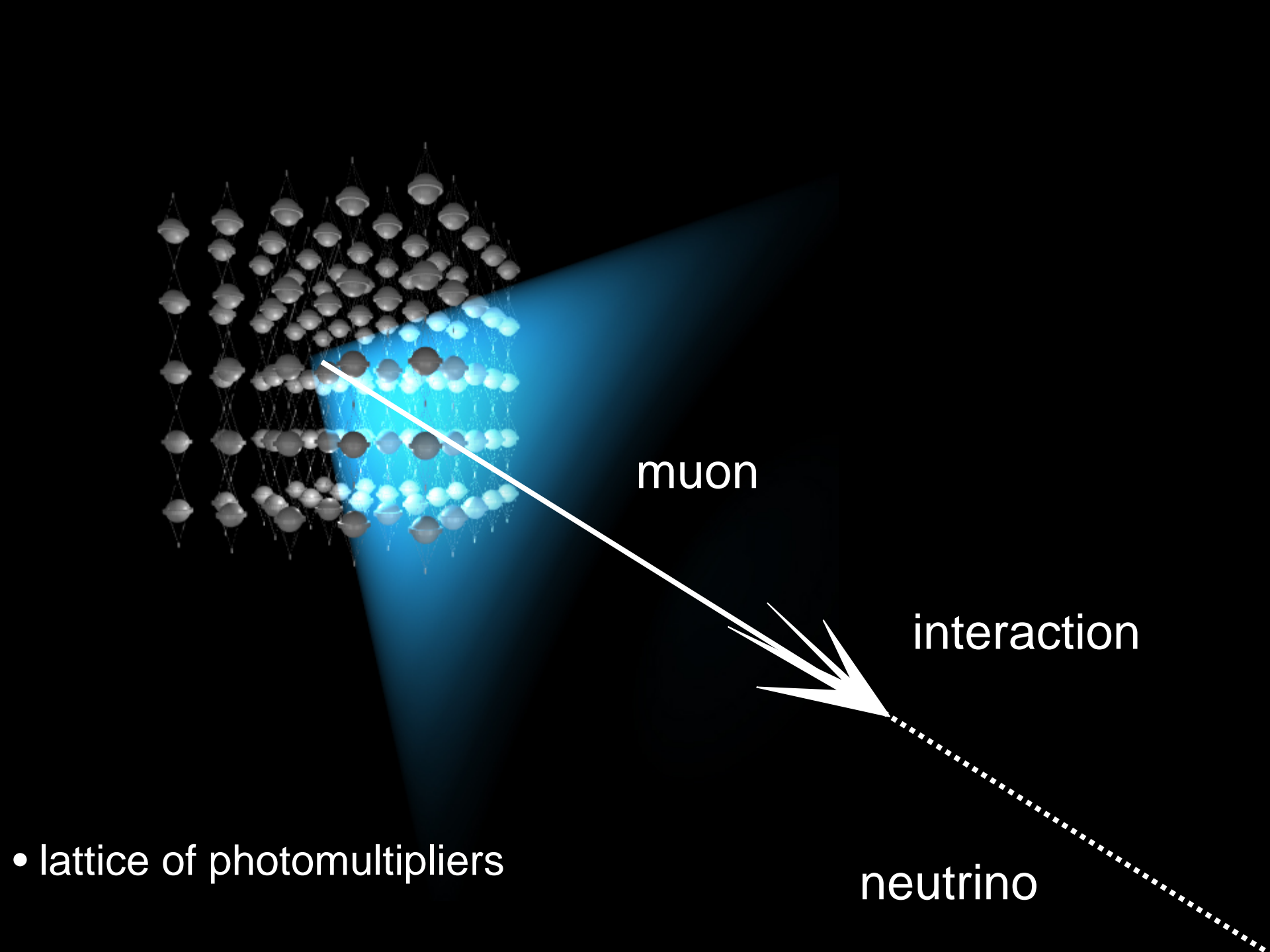
\*\* 1 every 6 minutes

# IceCube: the discovery of cosmic neutrinos

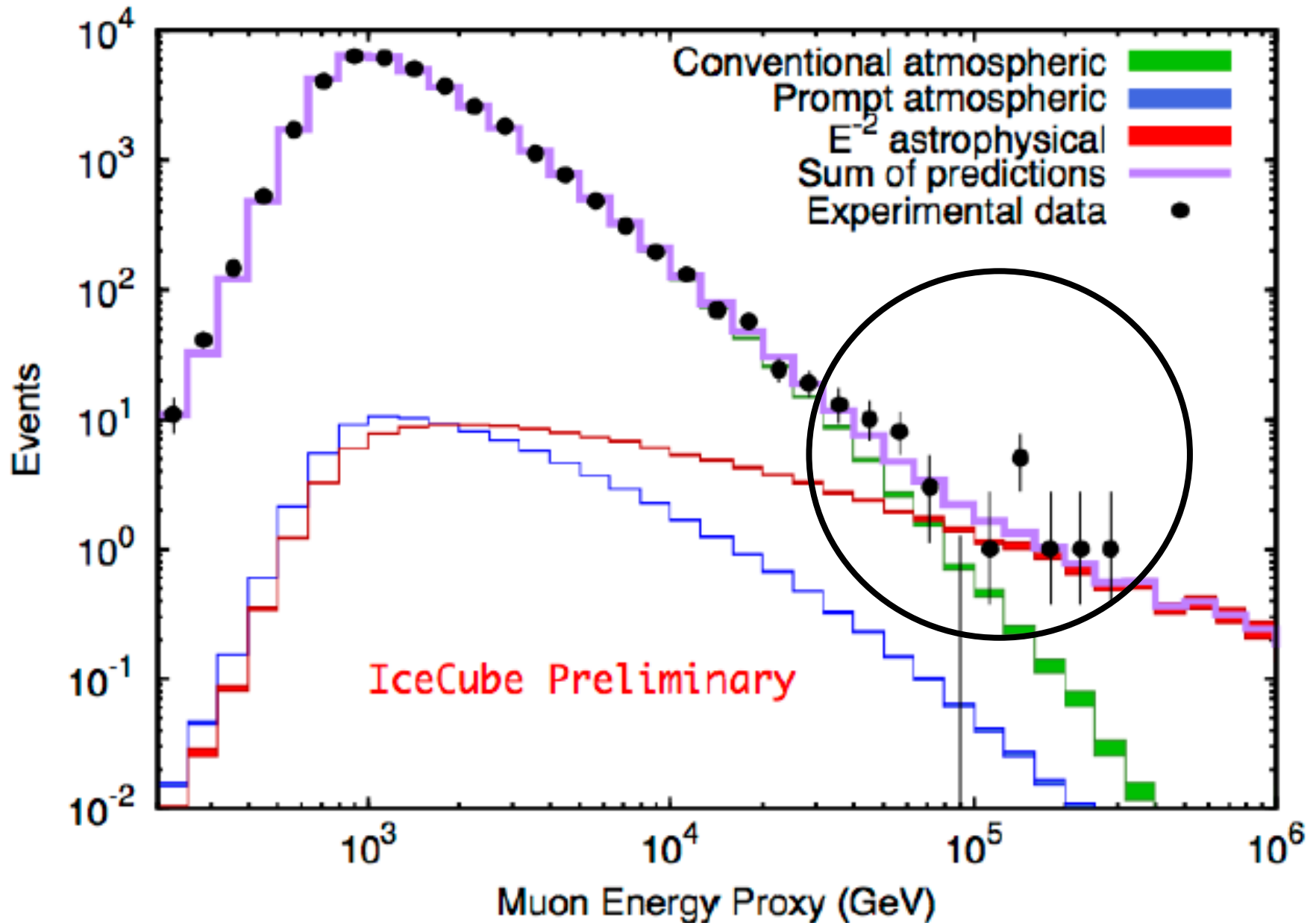
francis halzen

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# cosmic neutrinos in 2 years of data at 3.7 sigma

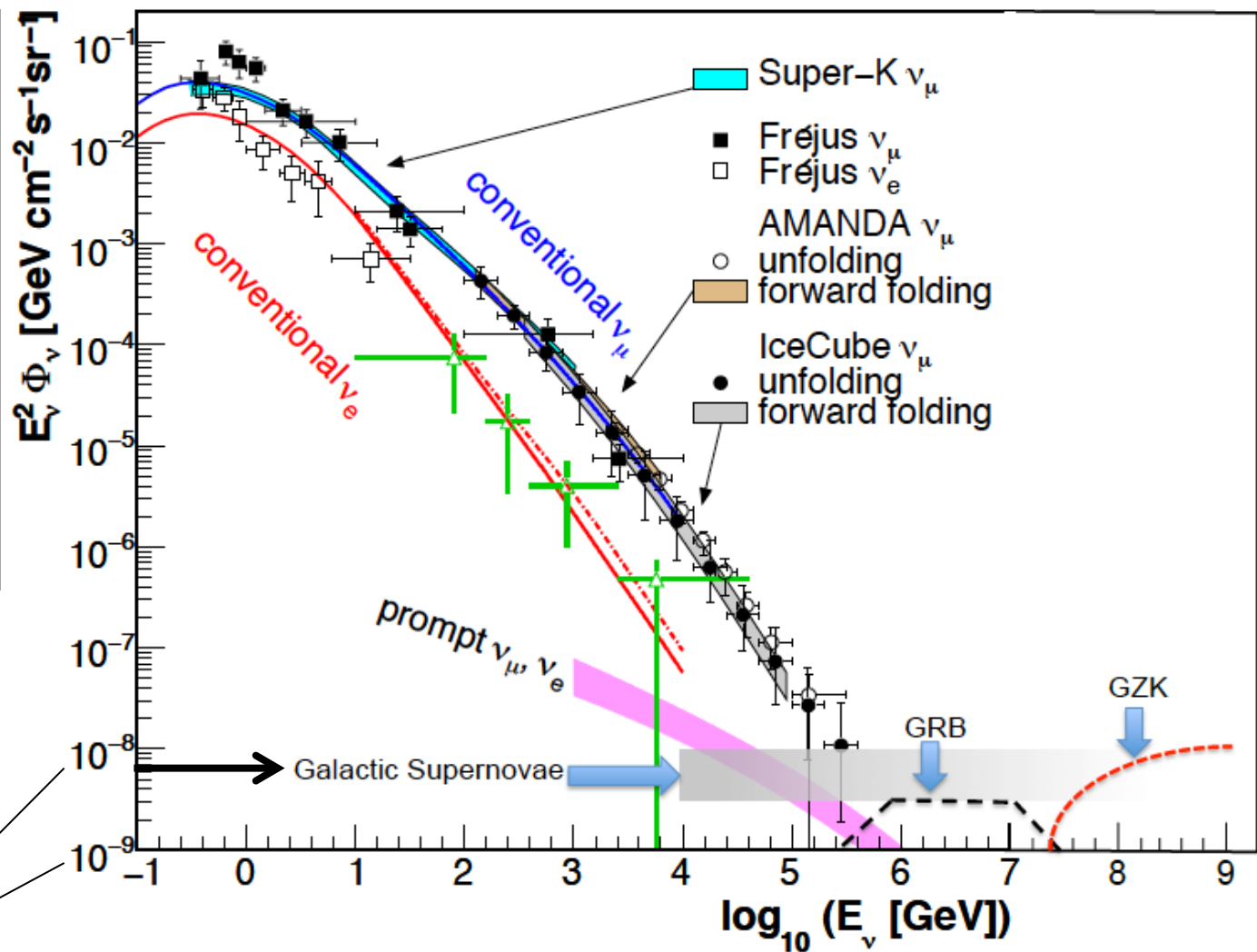


above 100 TeV

- cosmic neutrinos:
- atmospheric background disappears

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

10—100 events per year for fully efficient detector



atmospheric

cosmic

100 TeV

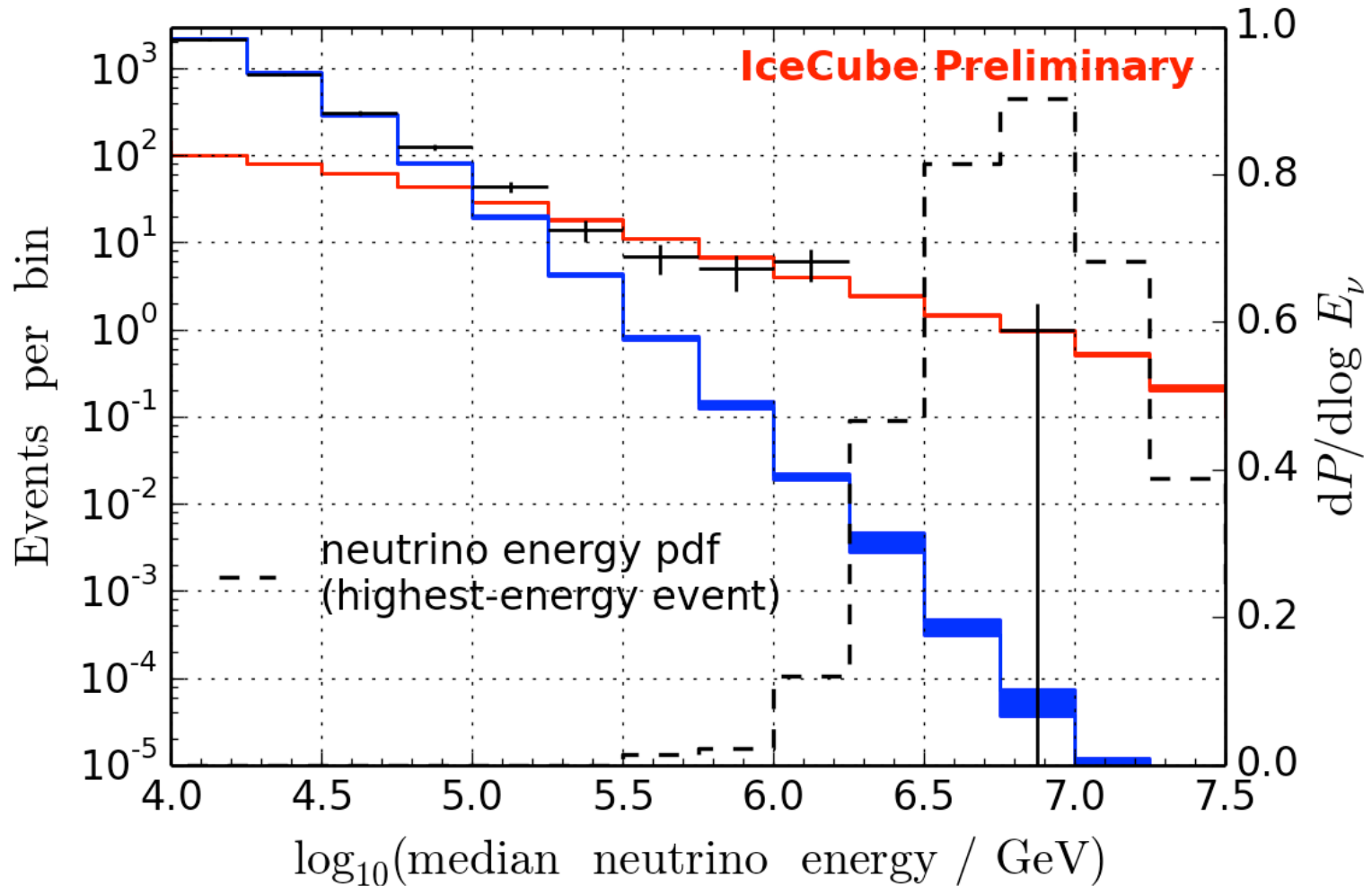
# muon neutrinos through the Earth $\rightarrow$ 5.6 sigma

Assuming best-fit power law:

+++ Unfolding

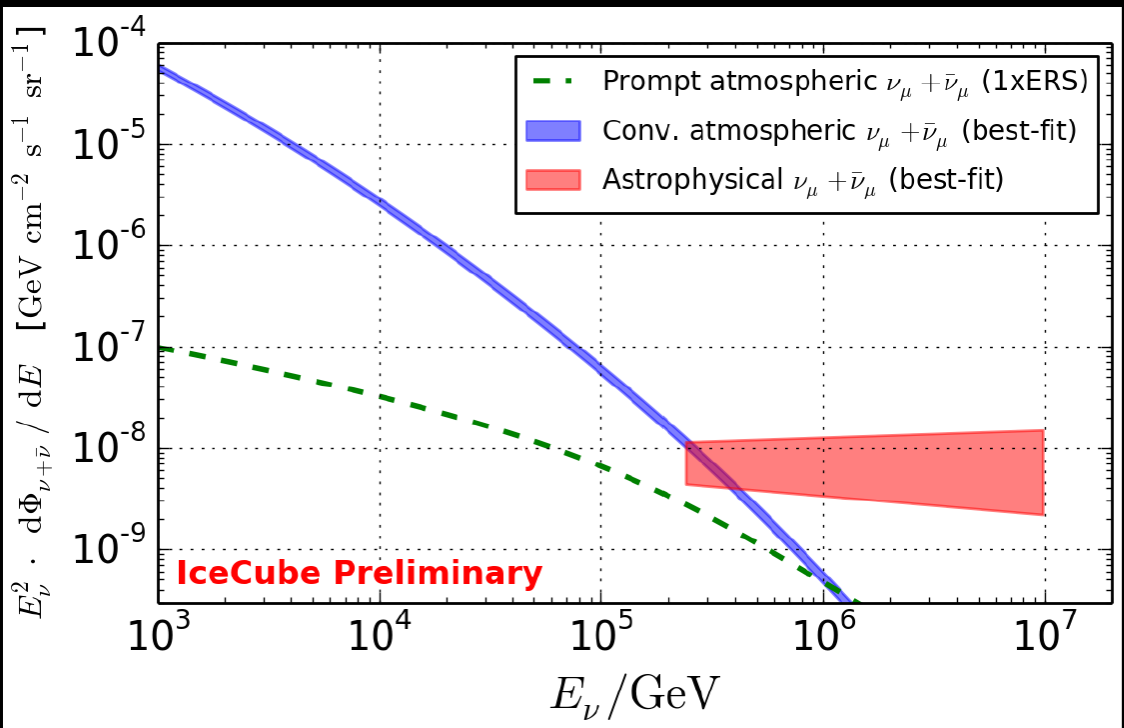
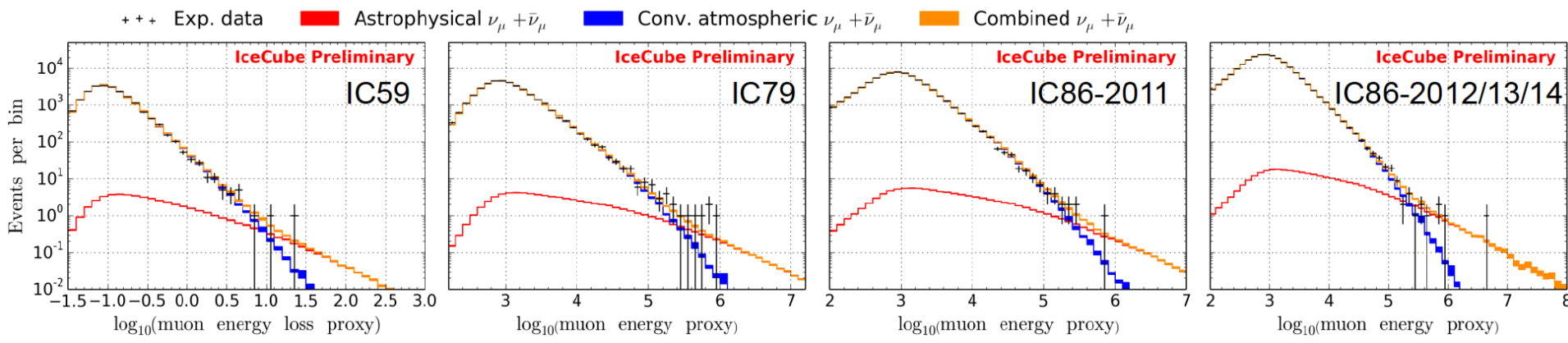
■ Conv. atmospheric  $\nu_\mu + \bar{\nu}_\mu$

■ Astrophysical  $\nu_\mu + \bar{\nu}_\mu$





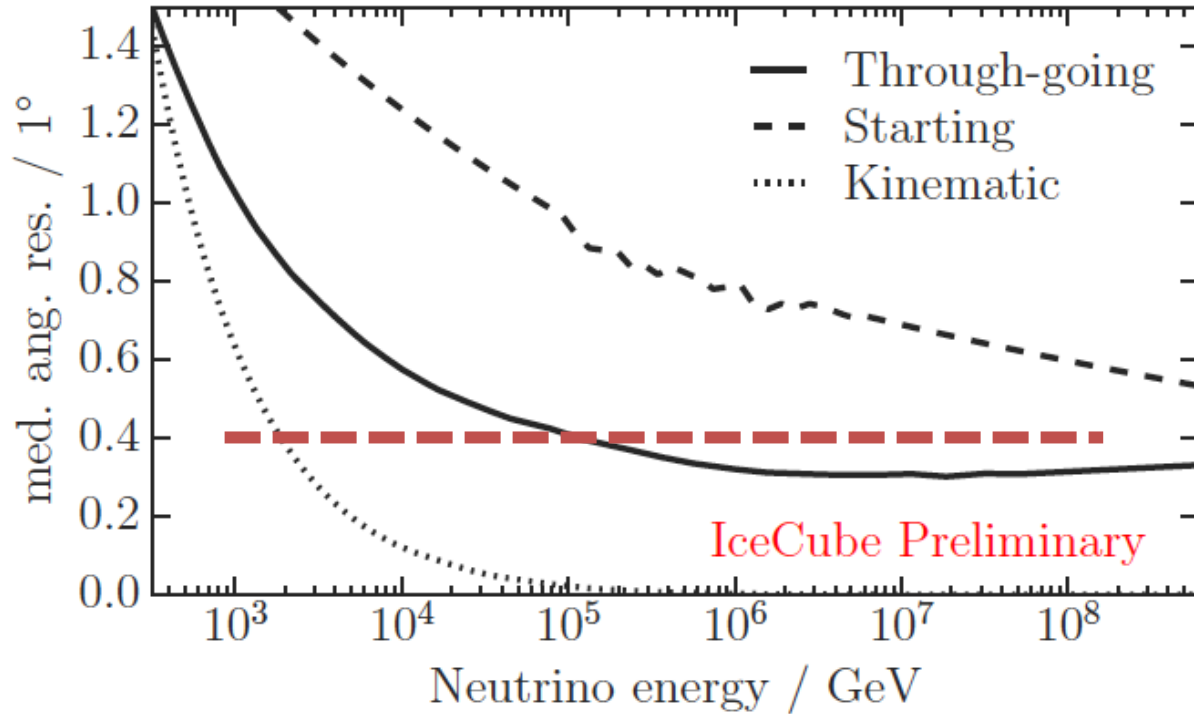
# after 7 years: 3.7 → 6 sigma



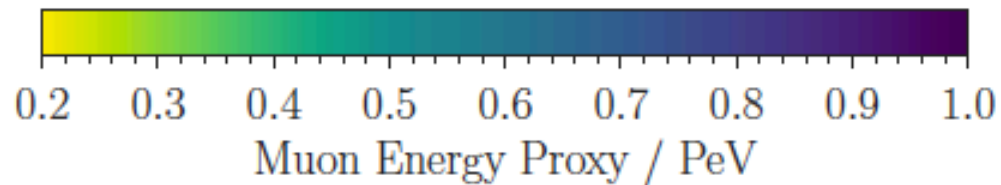
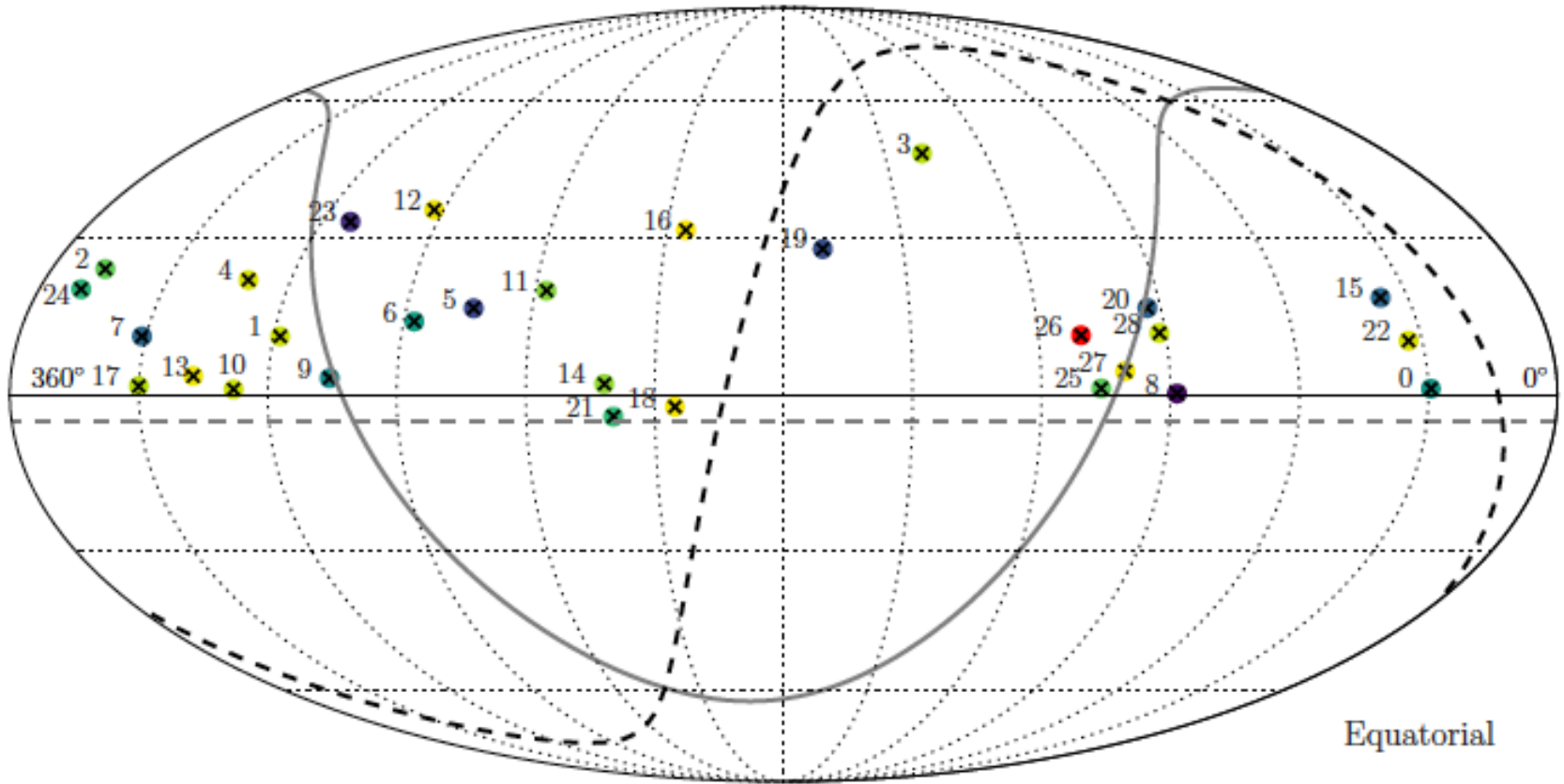
- Best-fit astrophysical normalization:  
 $(0.9^{+0.29}_{-0.25}) \times 10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$
- Best-fit spectral index:  
 $\gamma_{\text{astro}} = 2.13 \pm 0.13$
- Energy ranges:  
 240 TeV – 10 PeV
- Atmospheric-only hypothesis excluded by  $6.0\sigma$



astronomy here: through-going muons with resolution  
 $0.2 \sim 0.4^\circ$



highest energy  $\nu_\mu$ : astronomy with best resolution !

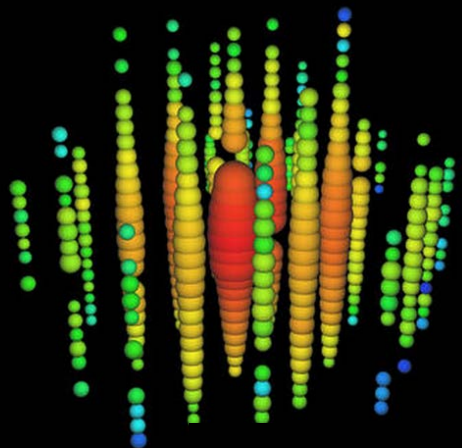


RESEARCH

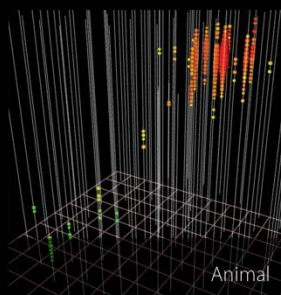
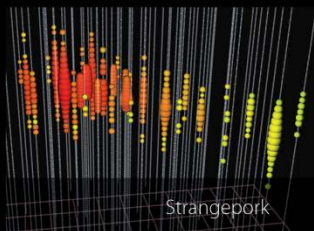
# Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

IceCube Collaboration\*

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



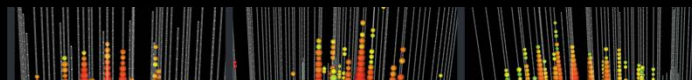
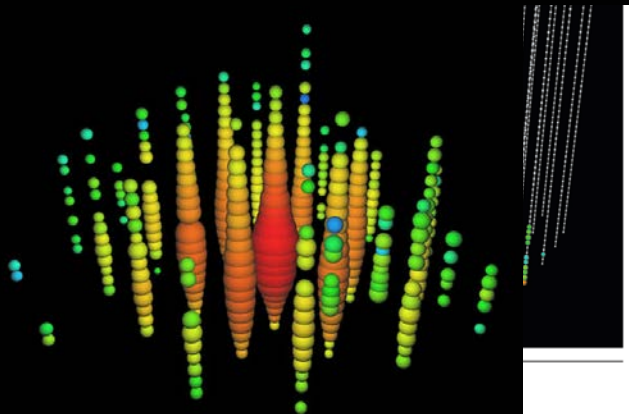
## 28 High Energy Events



tified high-energy galactic or accelerators.

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

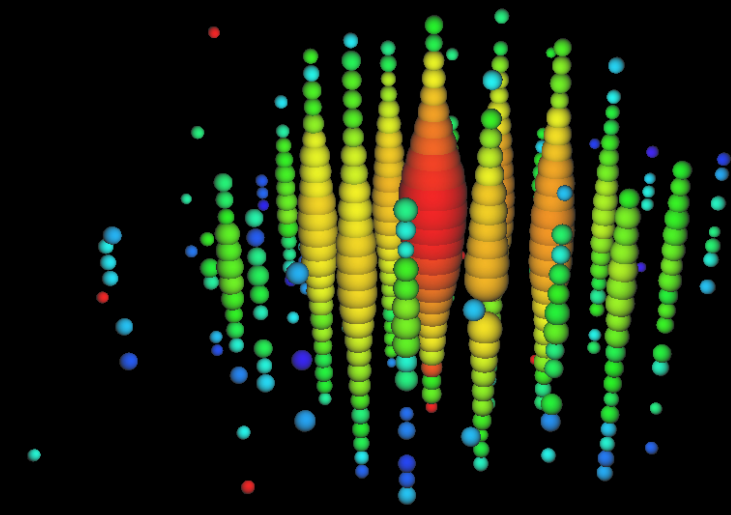
\*The list of author affiliations is availab  
Corresponding authors: C. Koppe (kopp



22 November 2013 | \$10

# Science

doubled the data since 2013



## 2004 TeV event in year 3

cosmic rays interact with the  
microwave background

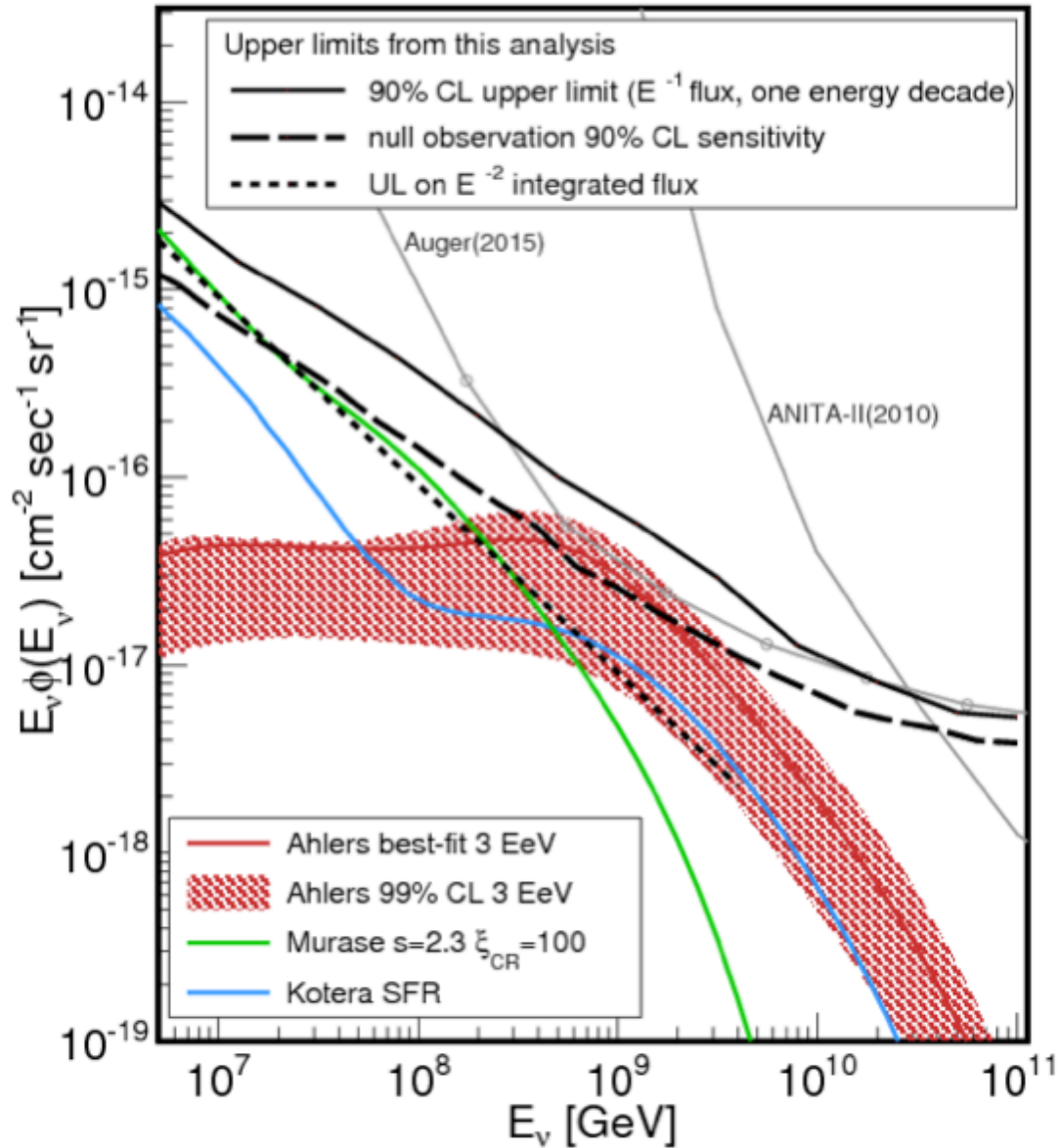
$$p + \gamma \rightarrow n + \pi^+ \text{ and } p + \pi^0$$

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

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

0.7 events per year in IceCube

...but it points at its source!

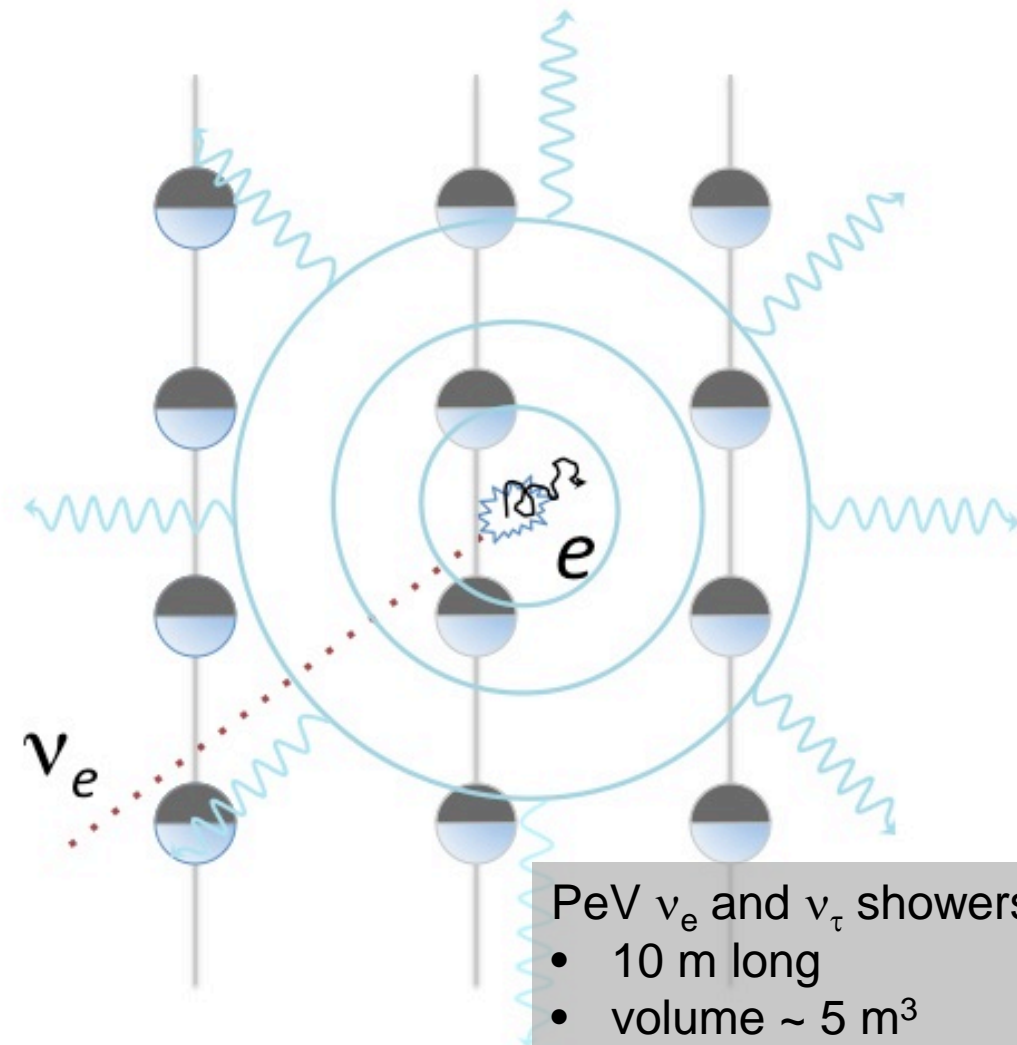




GZK neutrino search: two neutrinos with  $> 1,000$  TeV

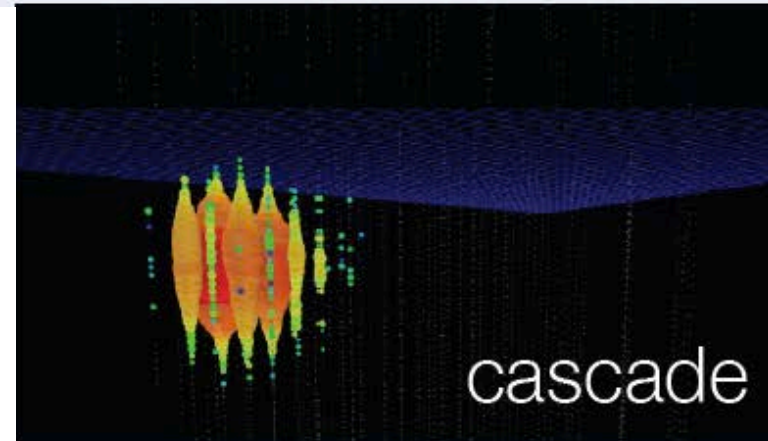


# tracks and showers

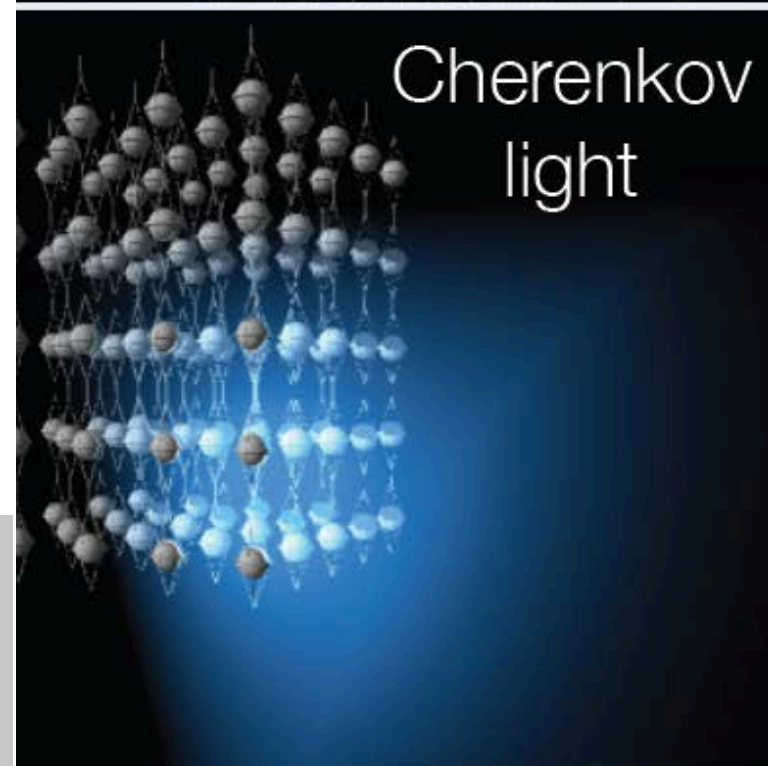


PeV  $\nu_e$  and  $\nu_\tau$  showers:

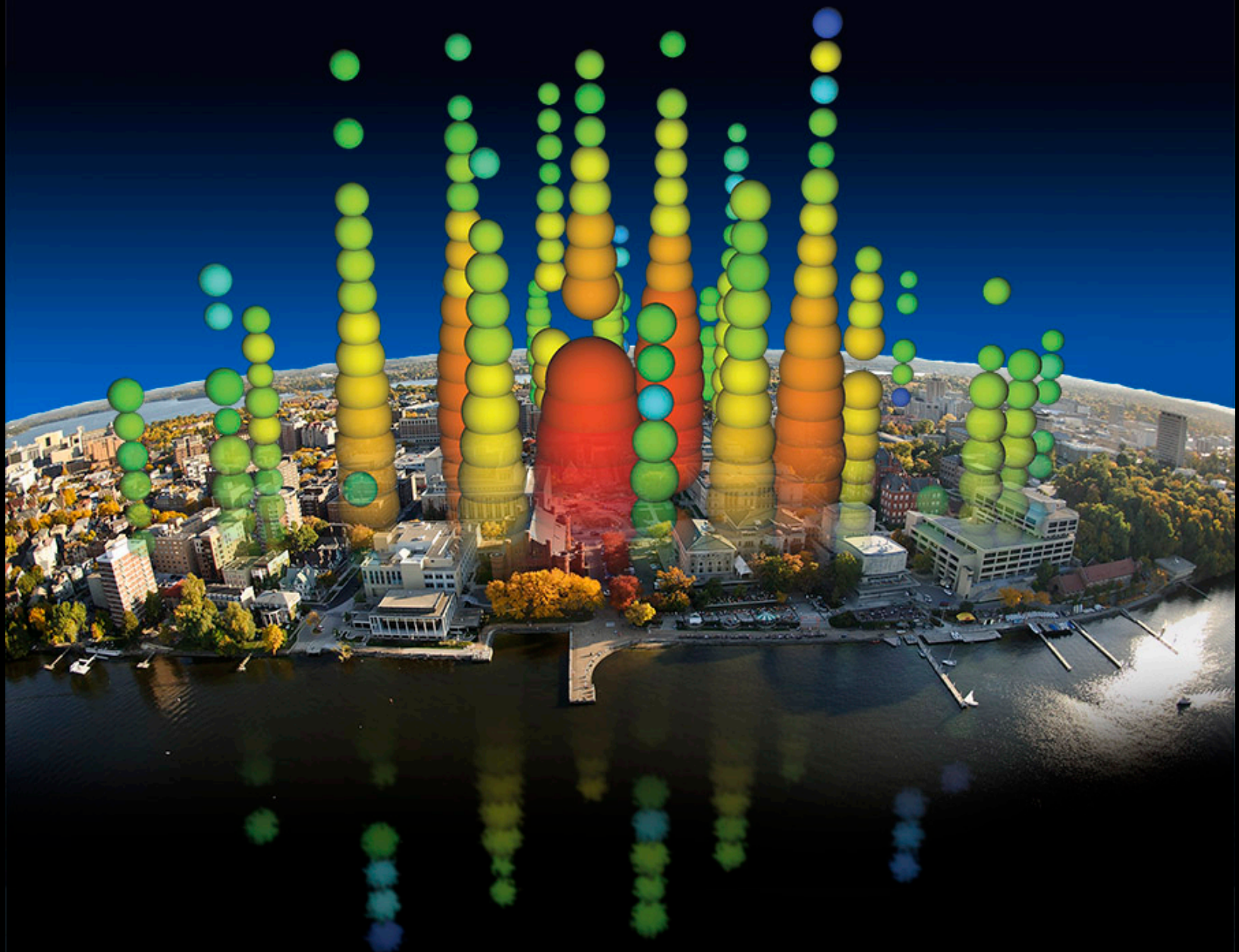
- 10 m long
- volume  $\sim 5 \text{ m}^3$
- isotropic after 25~ 50m

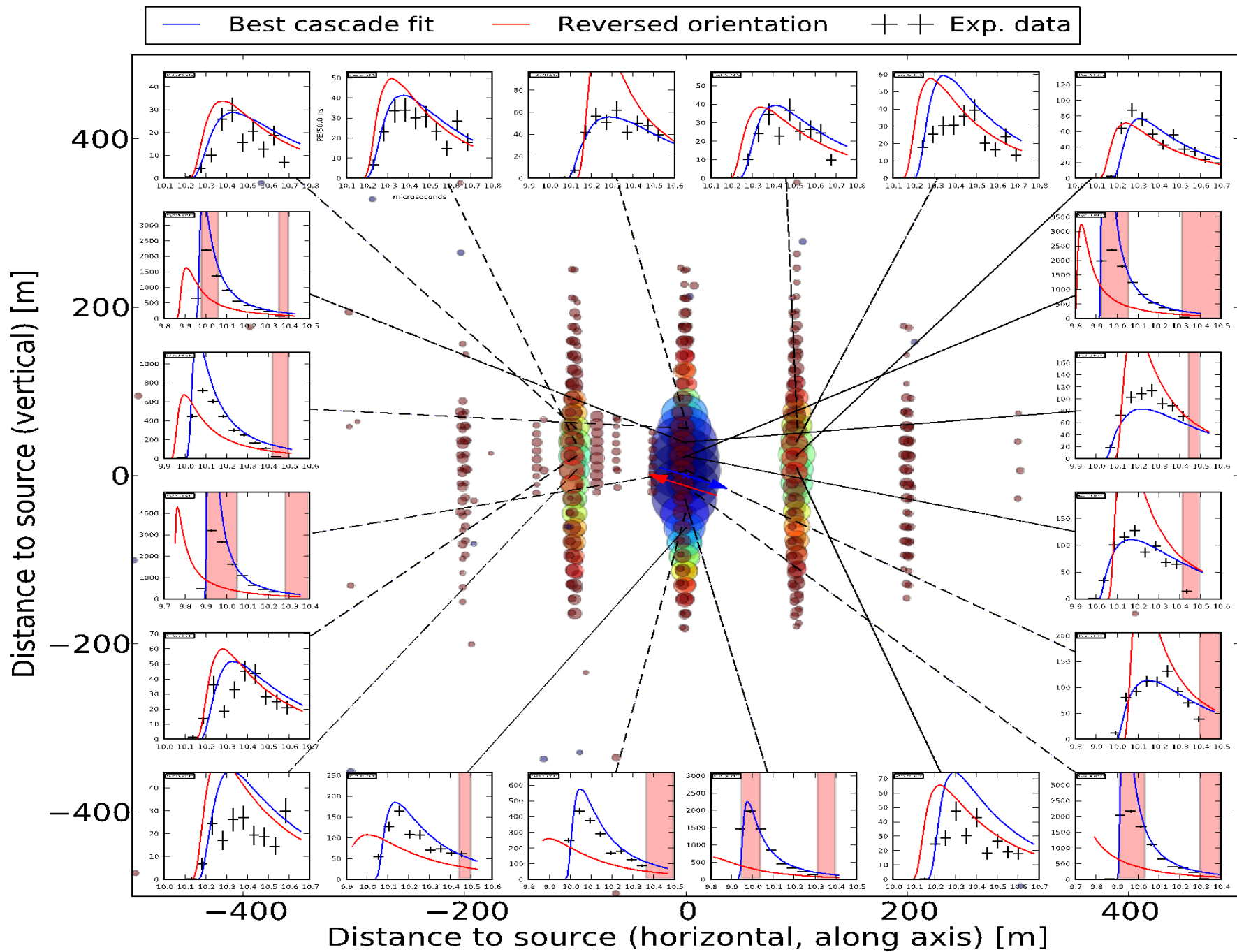


cascade

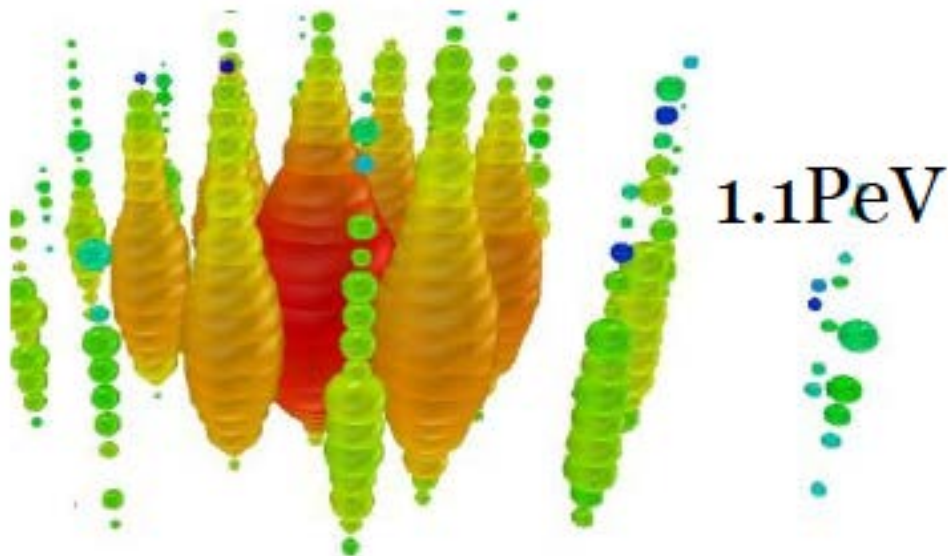
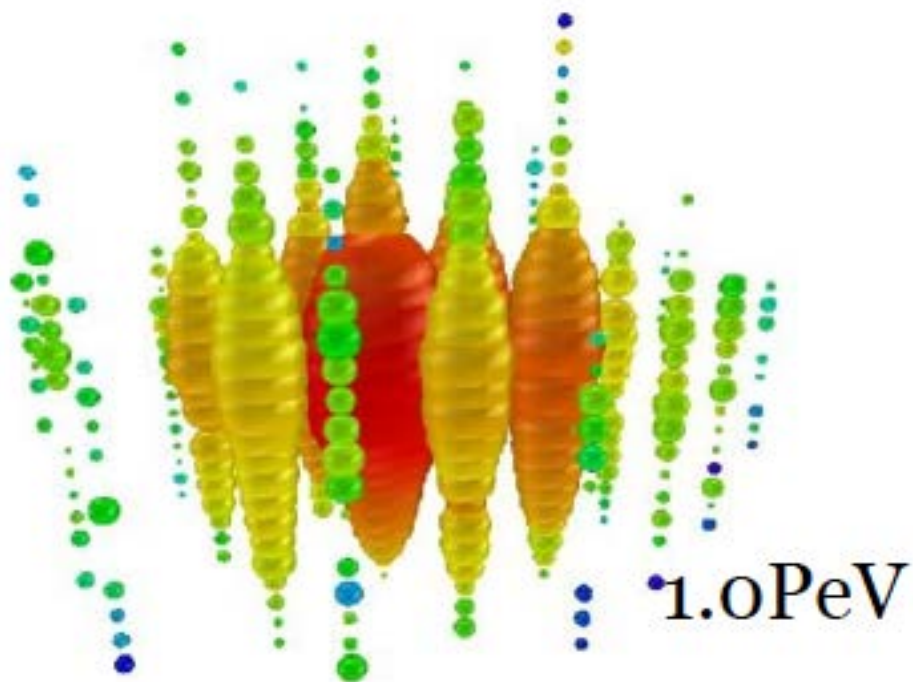


Cherenkov  
light









- energy

1,041 TeV

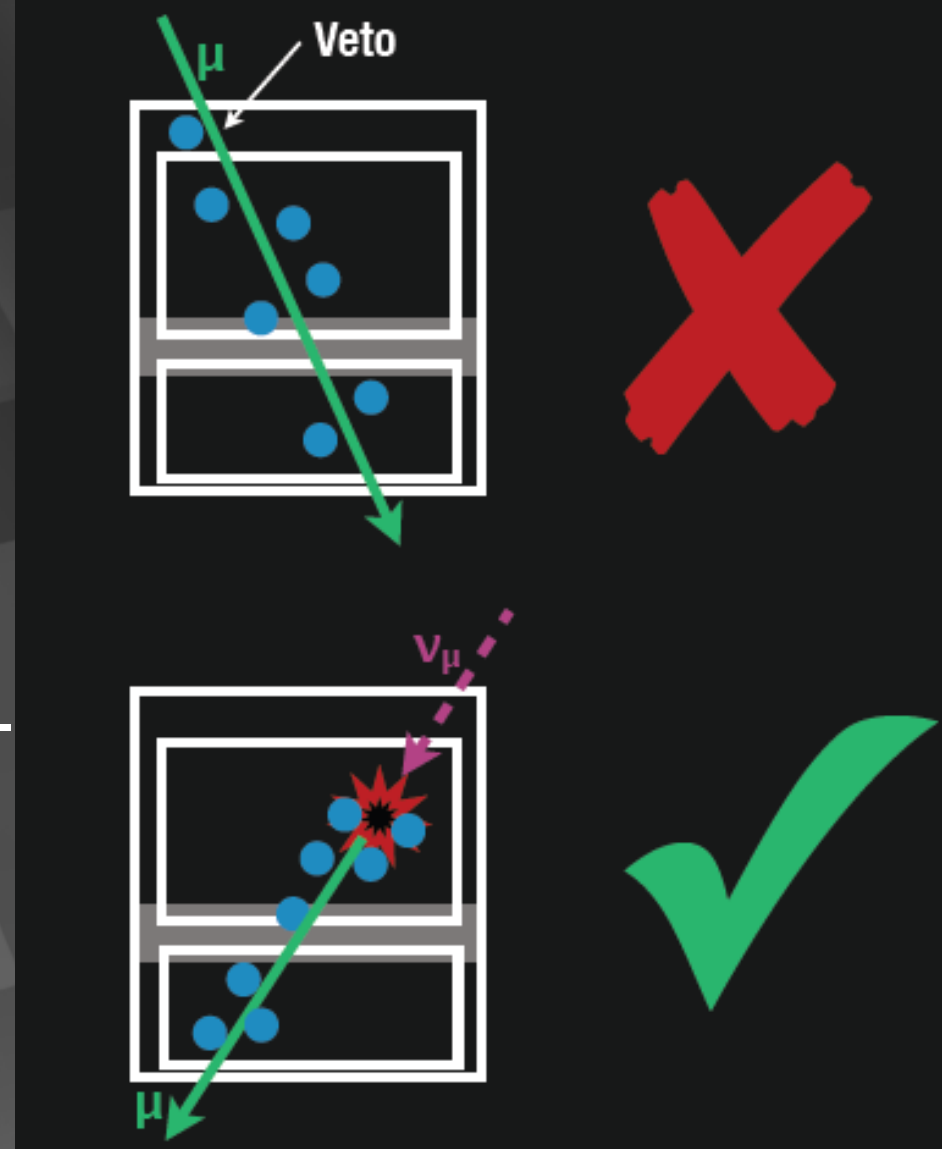
1,141 TeV

(15% resolution)

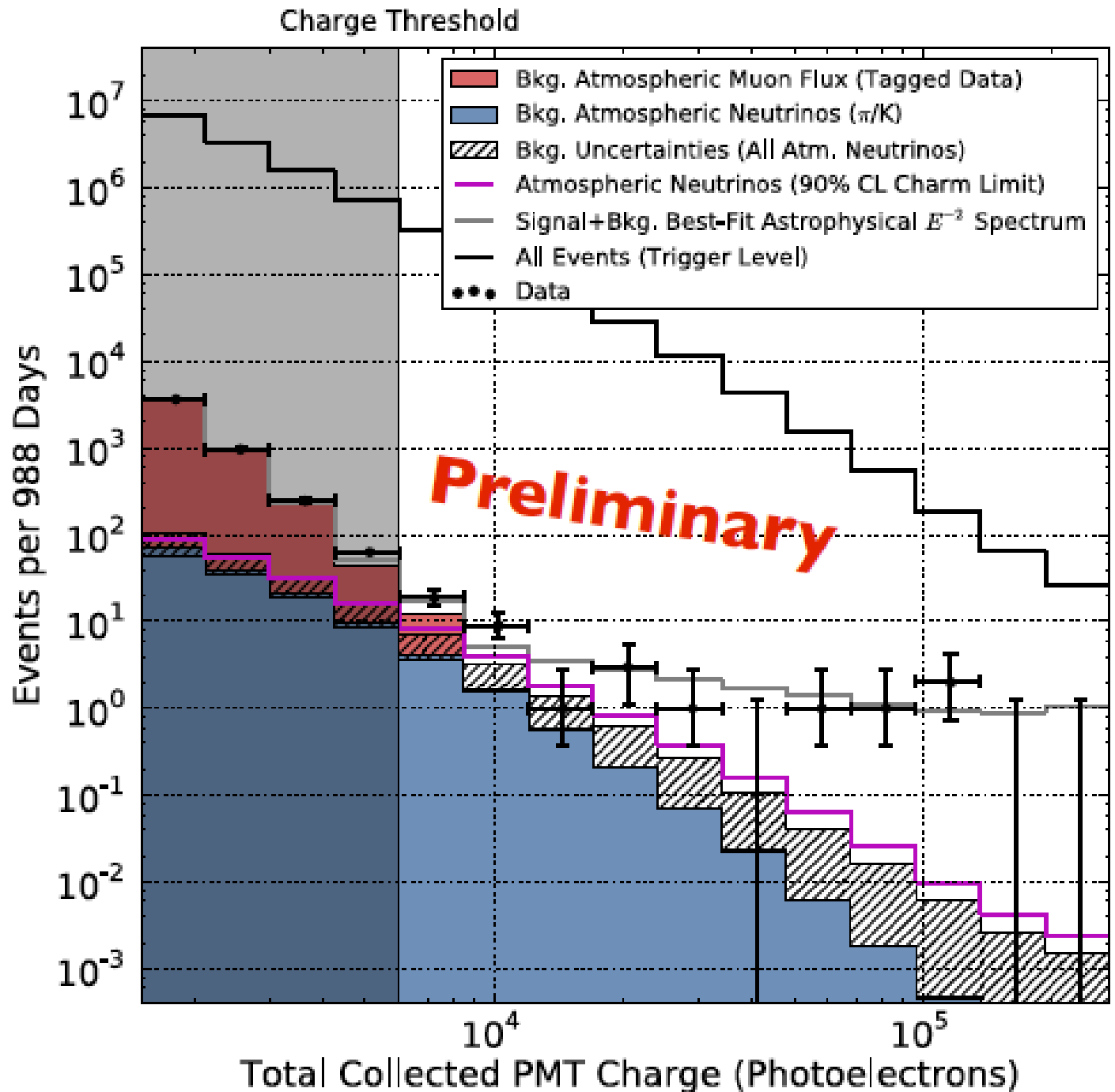
- not atmospheric:  
probability of  
no accompanying  
muon is  $10^{-3}$  per  
event

→ 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

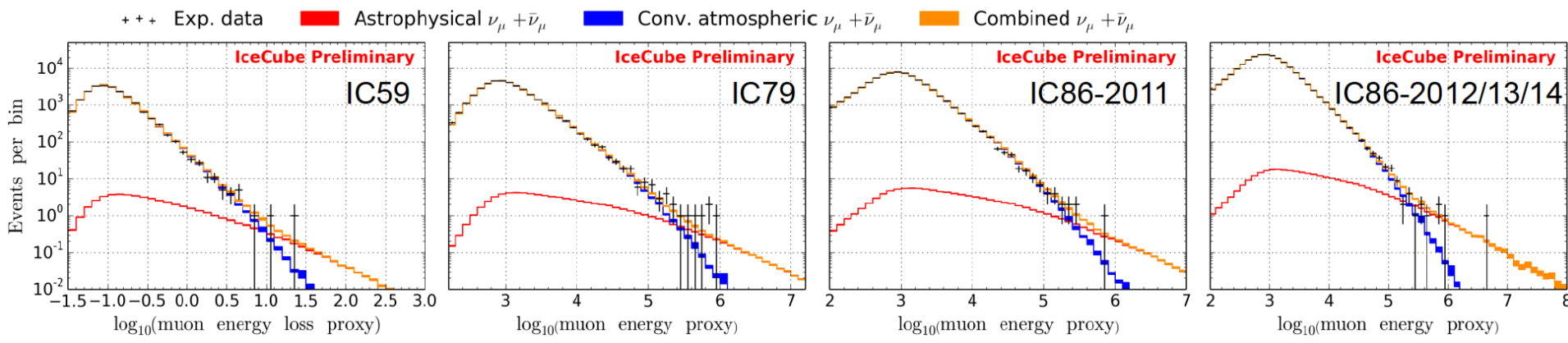


total charge collected by PMTs of events with interaction inside the detector

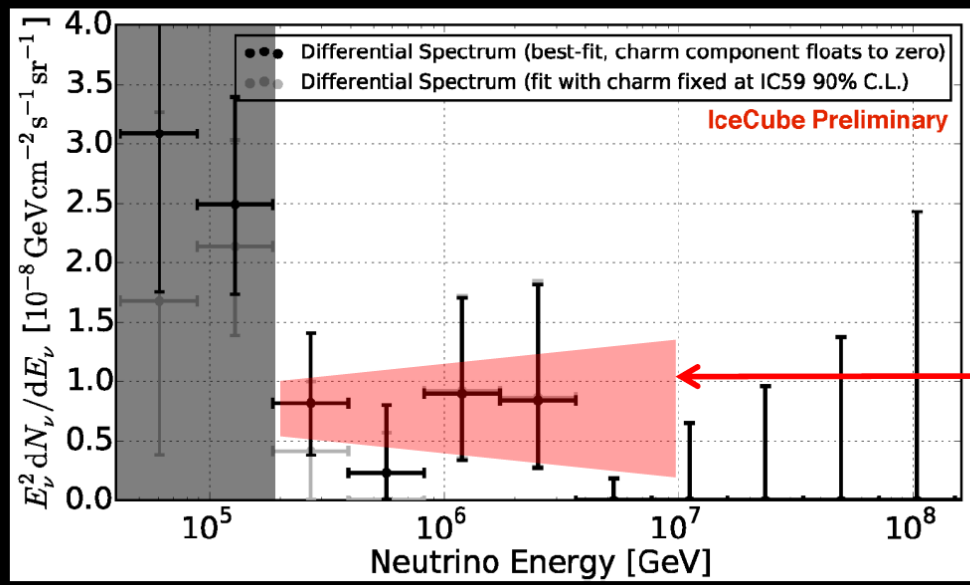




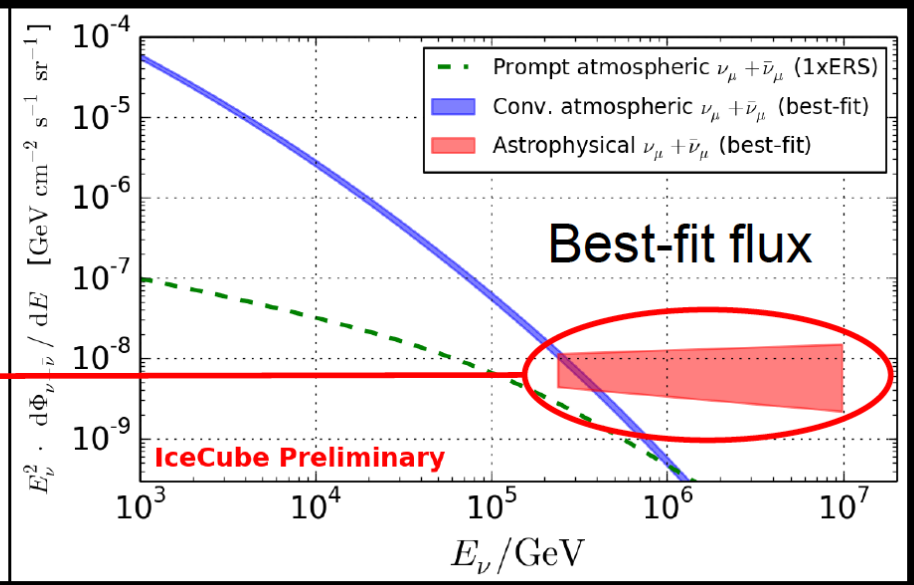
# after 6 years: 3.7 → 6.0 sigma

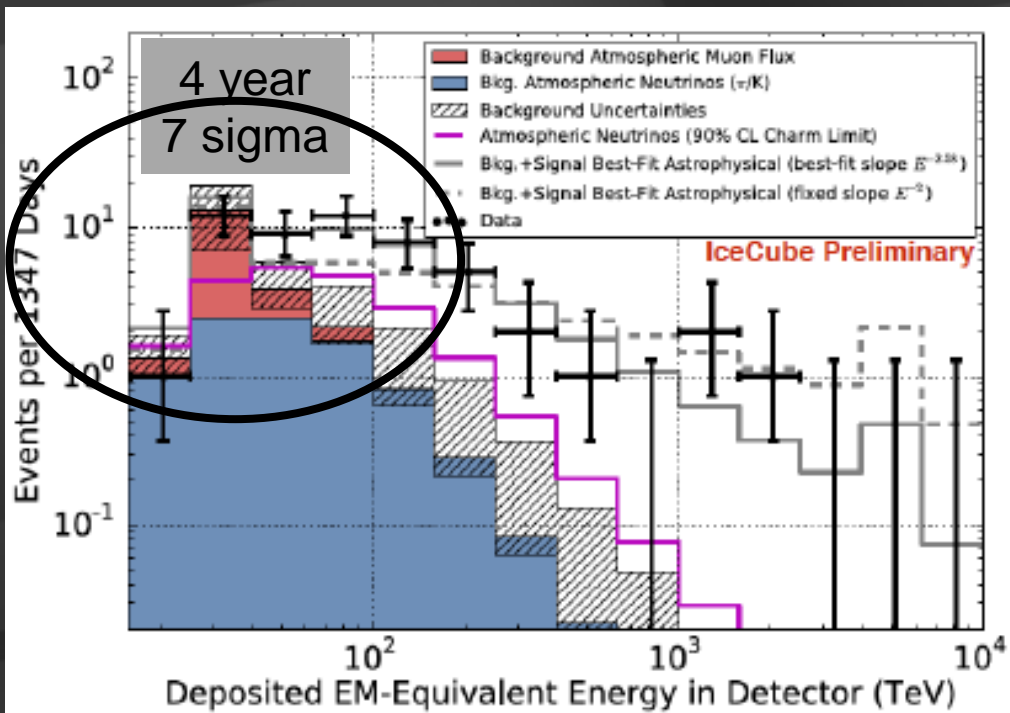


## HESE 4 year unfolding (→ dominated by shower-like events)



## 6 year up-going numu analysis

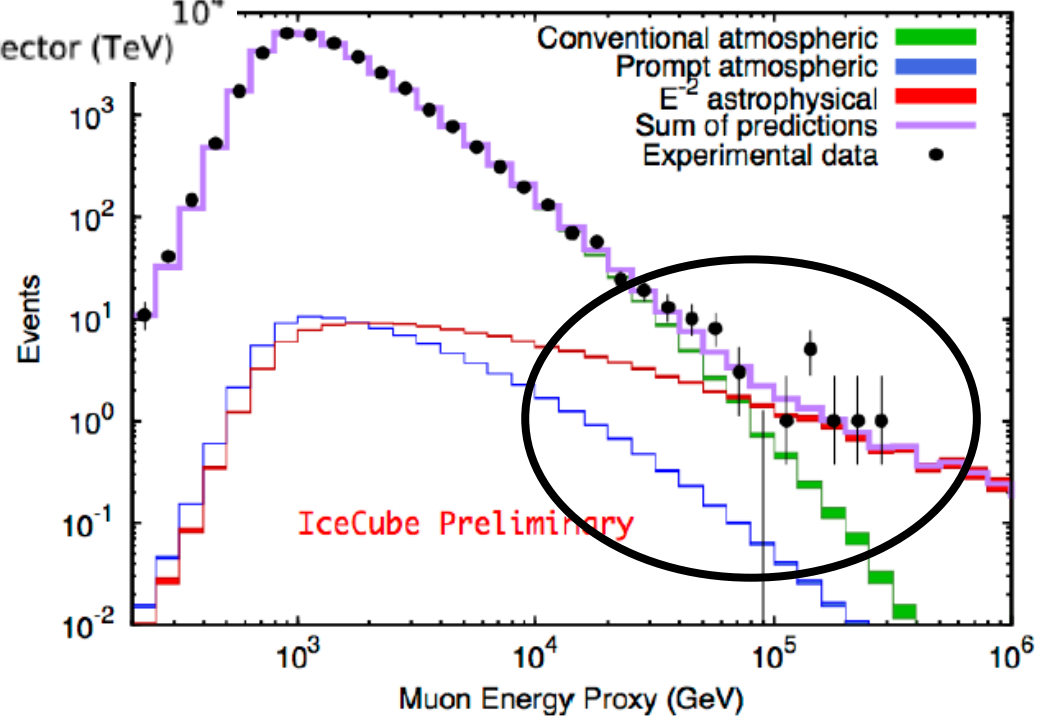




confirmation!  
flux of muon neutrinos  
through the Earth



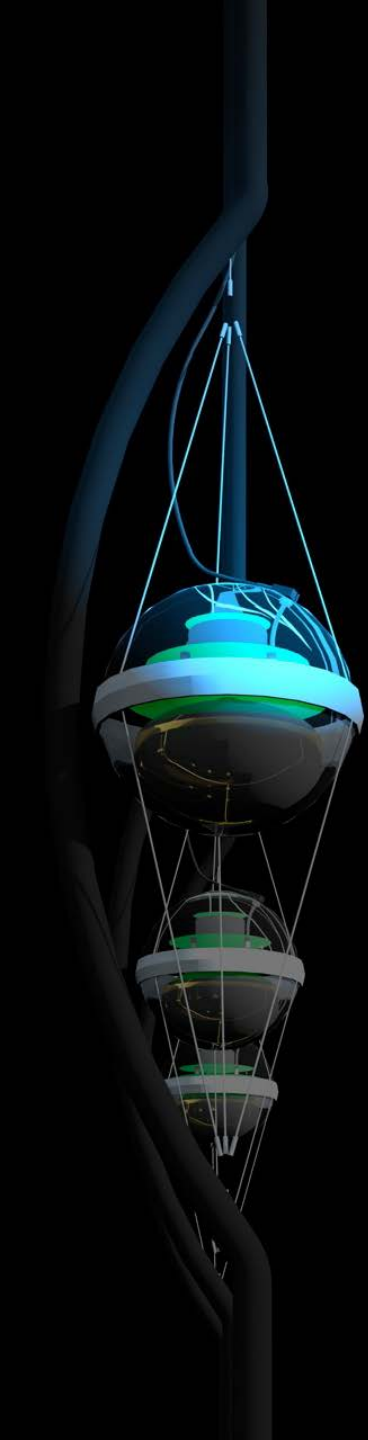
neutrinos of all flavors  
interacting inside  
IceCube



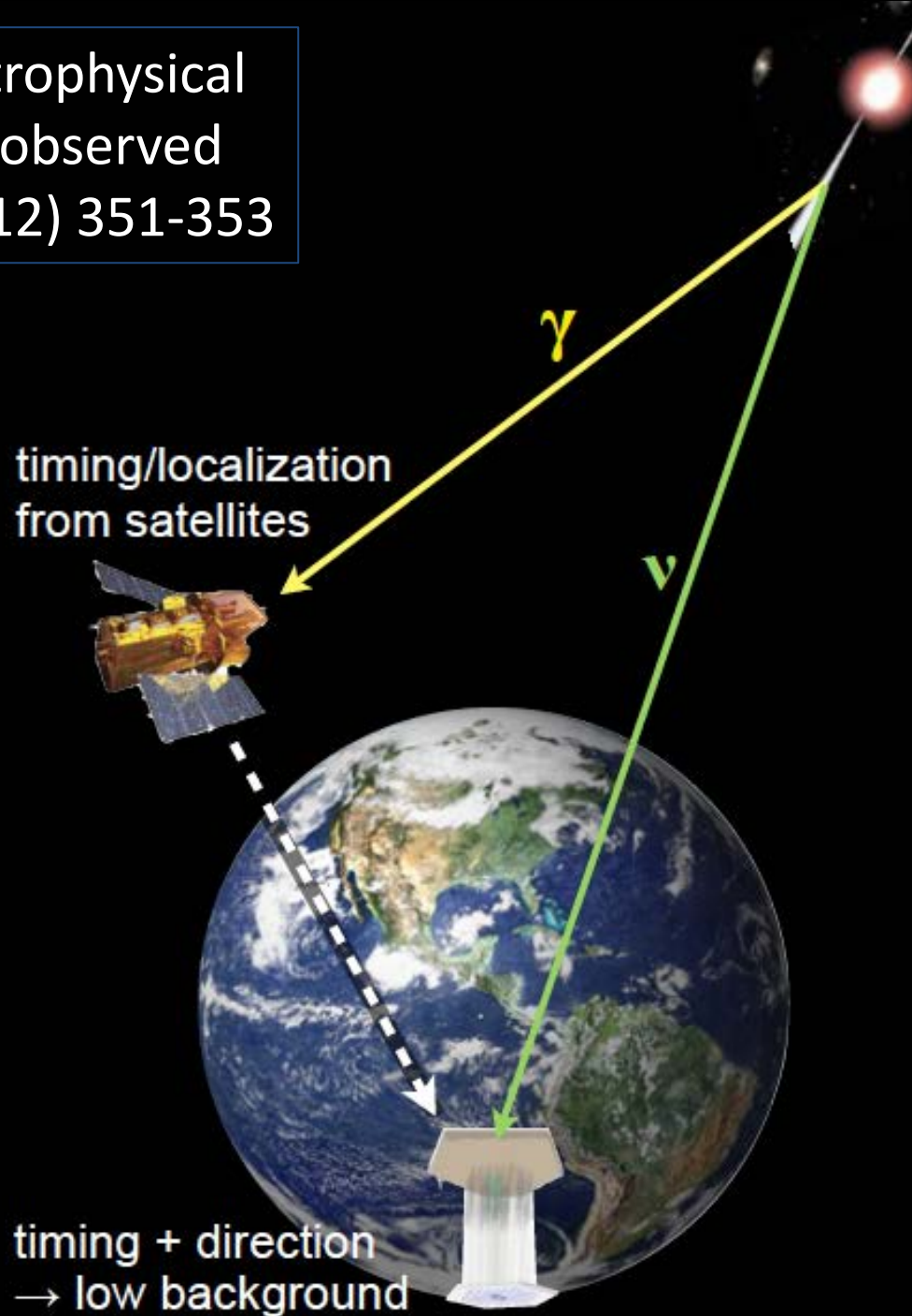
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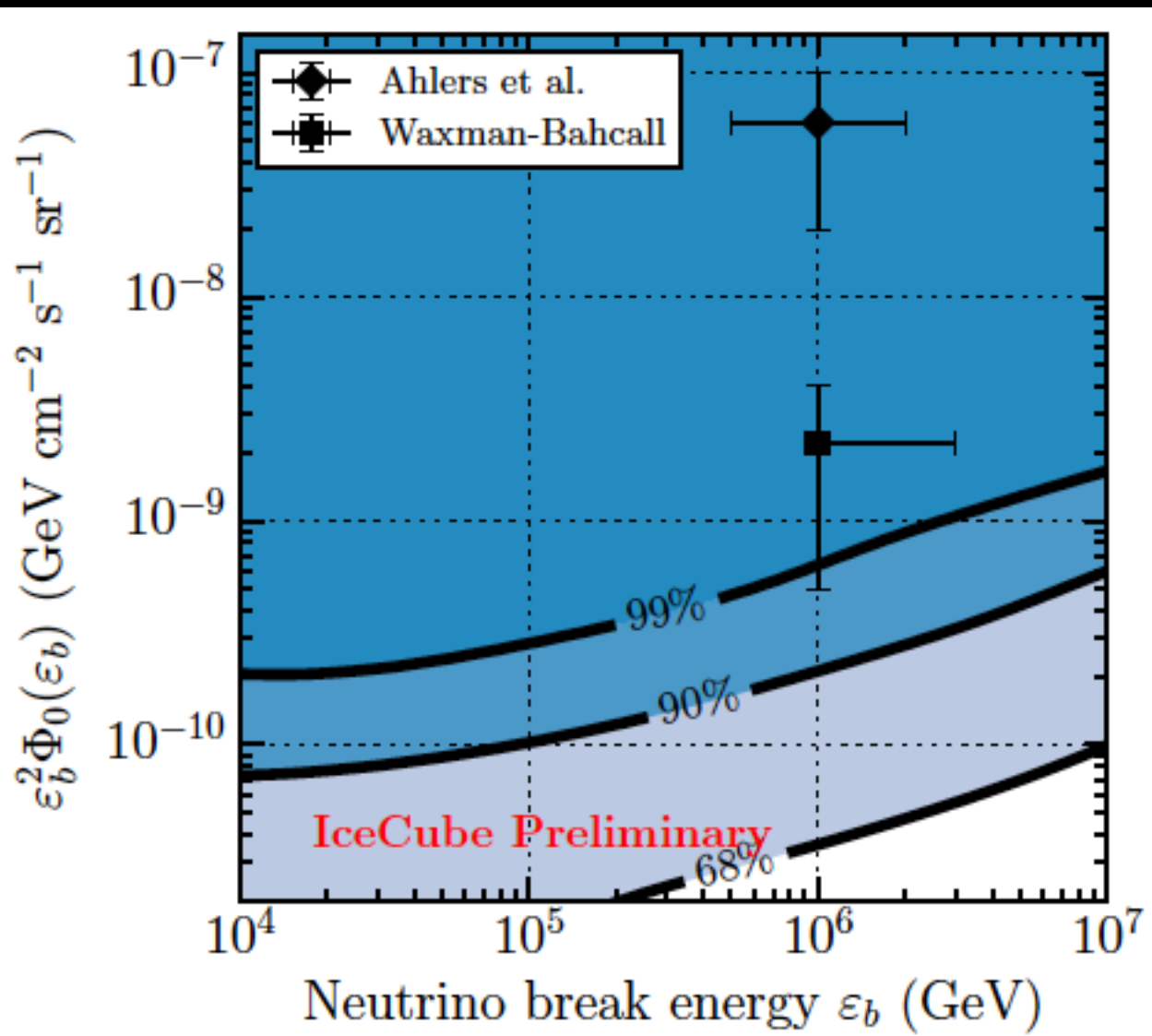
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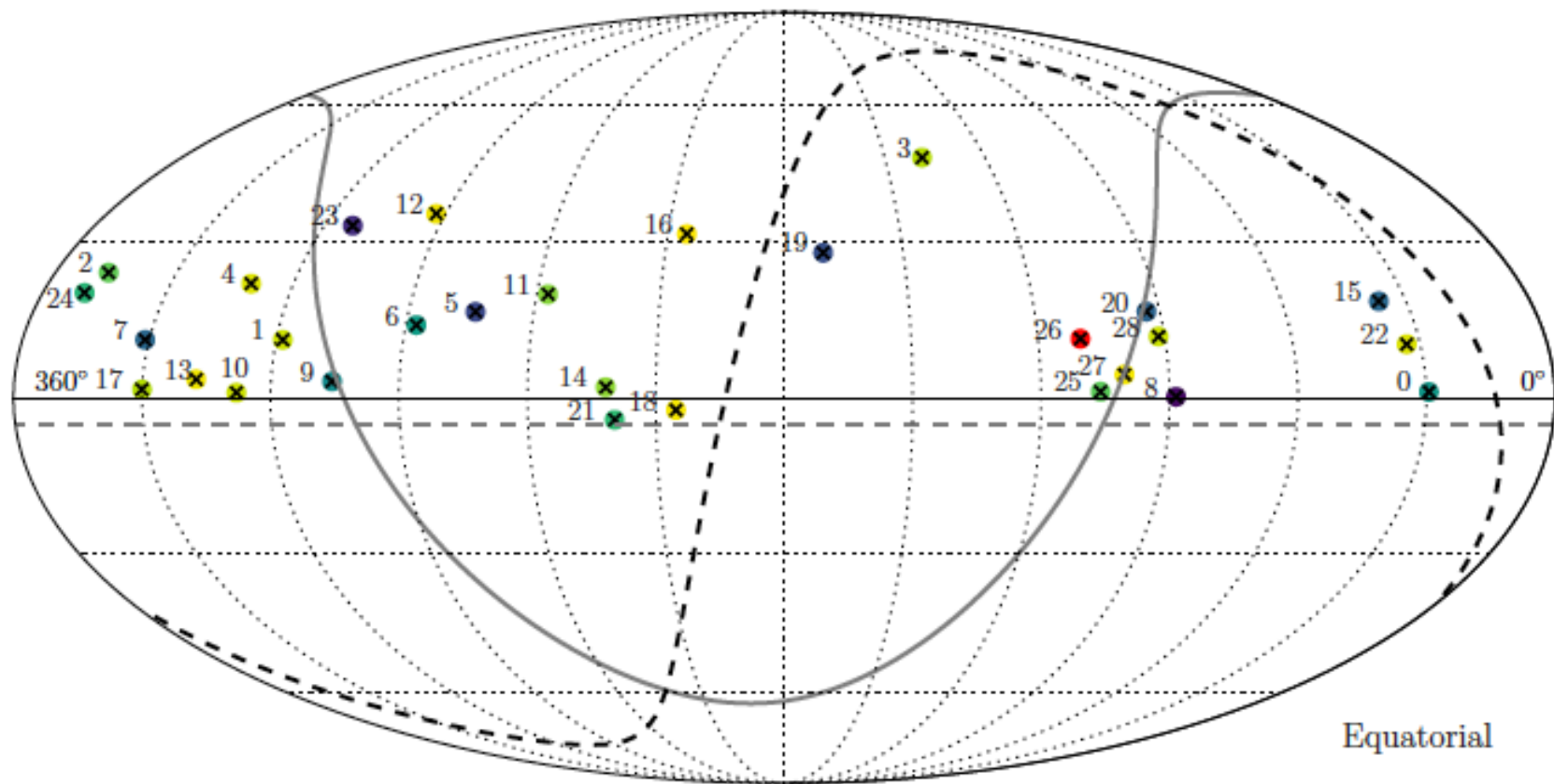
- IceCube
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- where do they come from?
- beyond IceCube



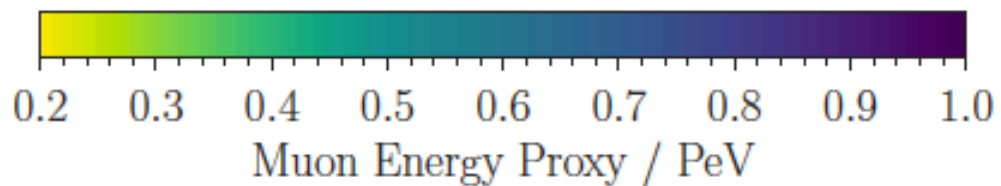
flux < 1% of astrophysical  
neutrino flux observed  
Nature 484 (2012) 351-353





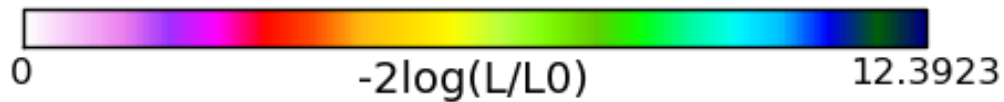
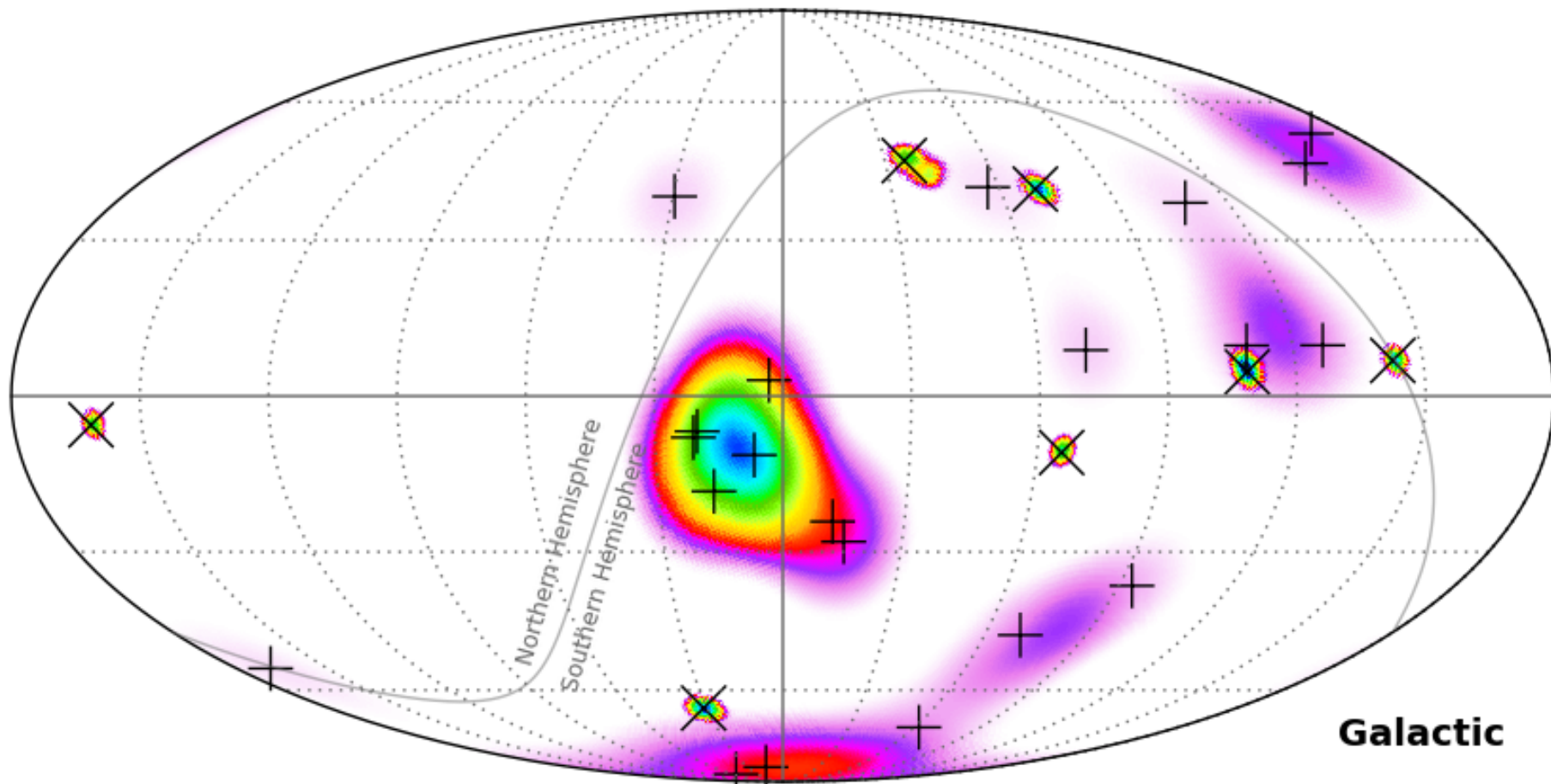


Equatorial



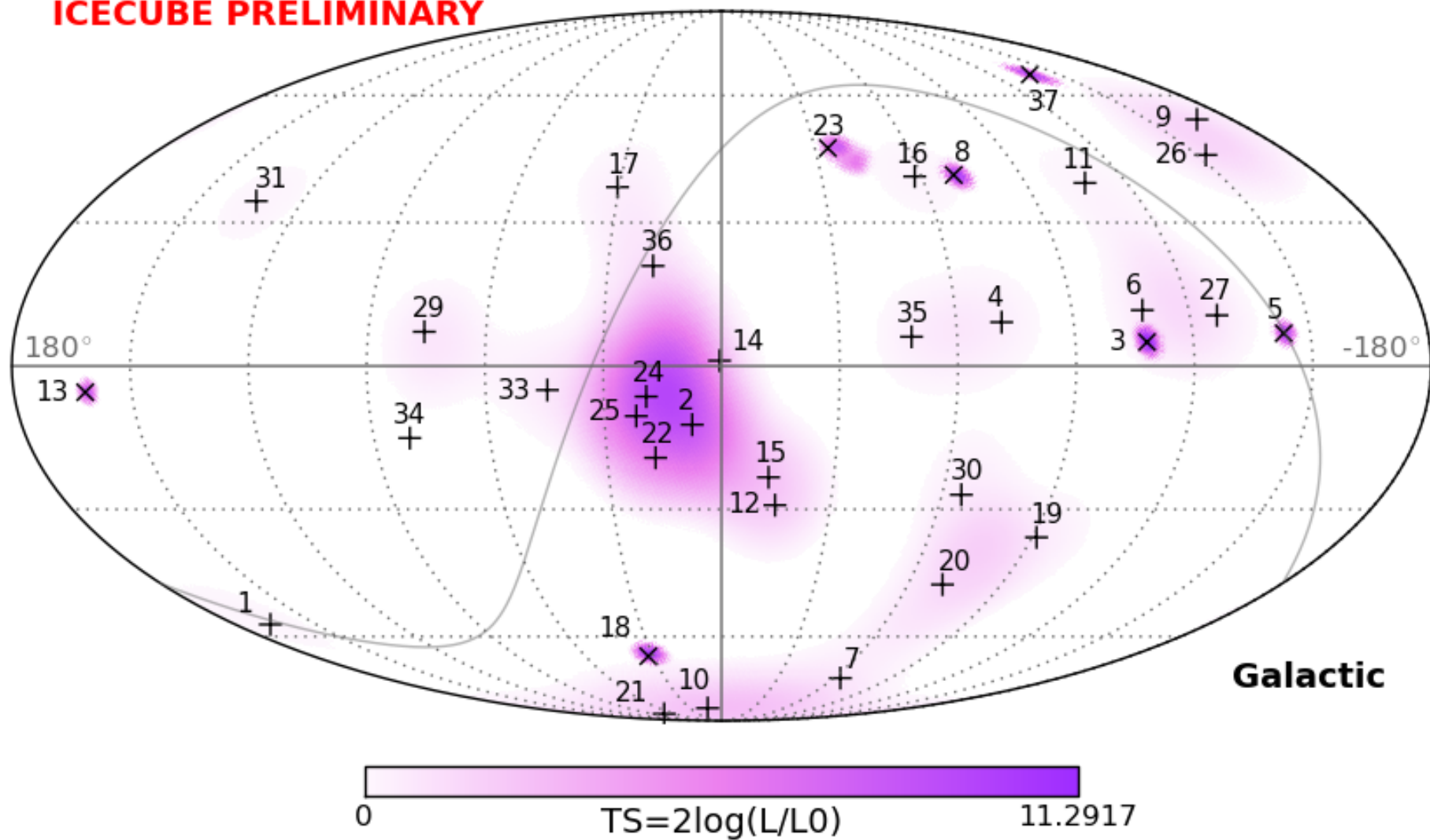


2 year HESE



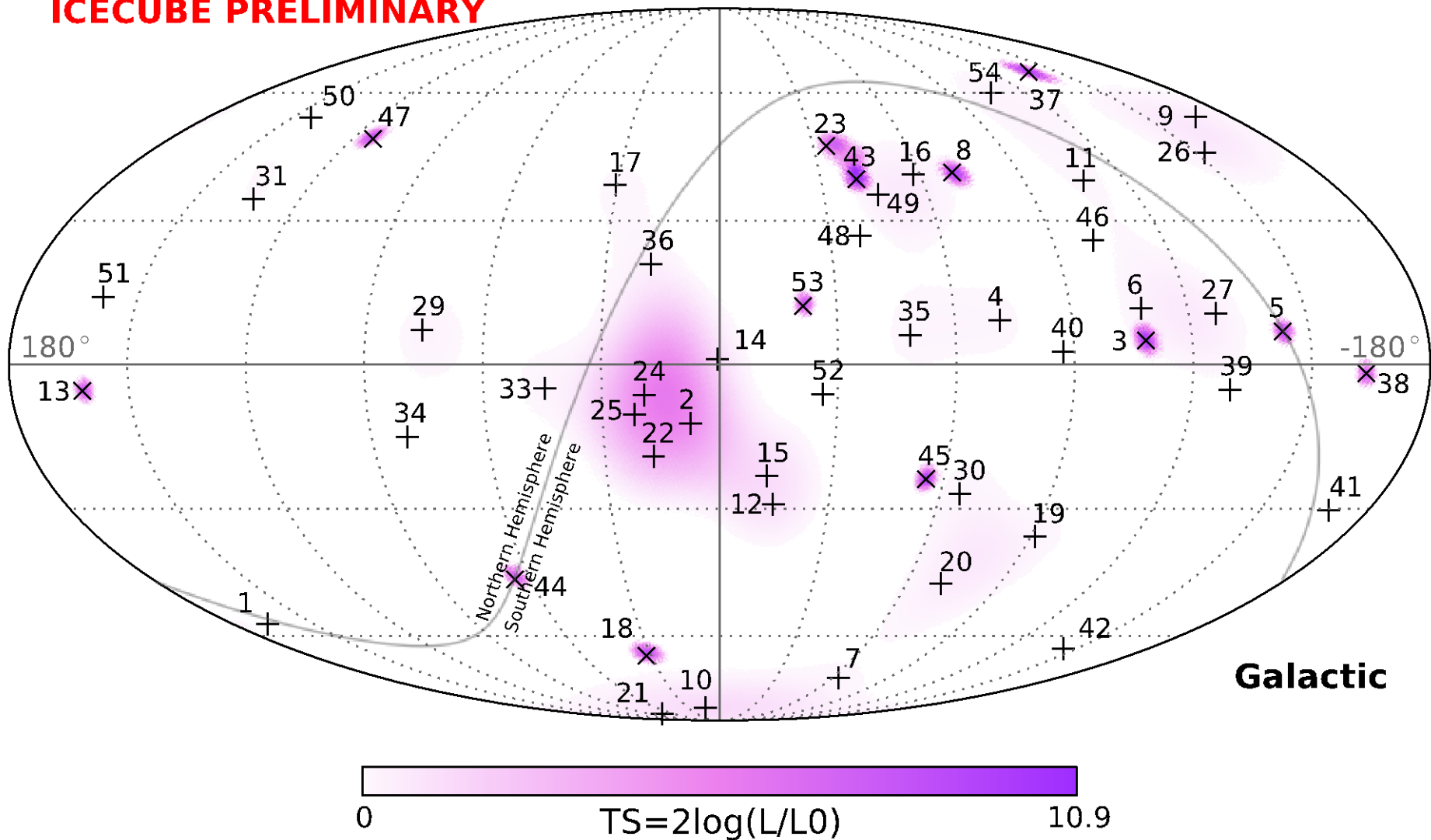
3 year HESE

**ICECUBE PRELIMINARY**



4 year HESE

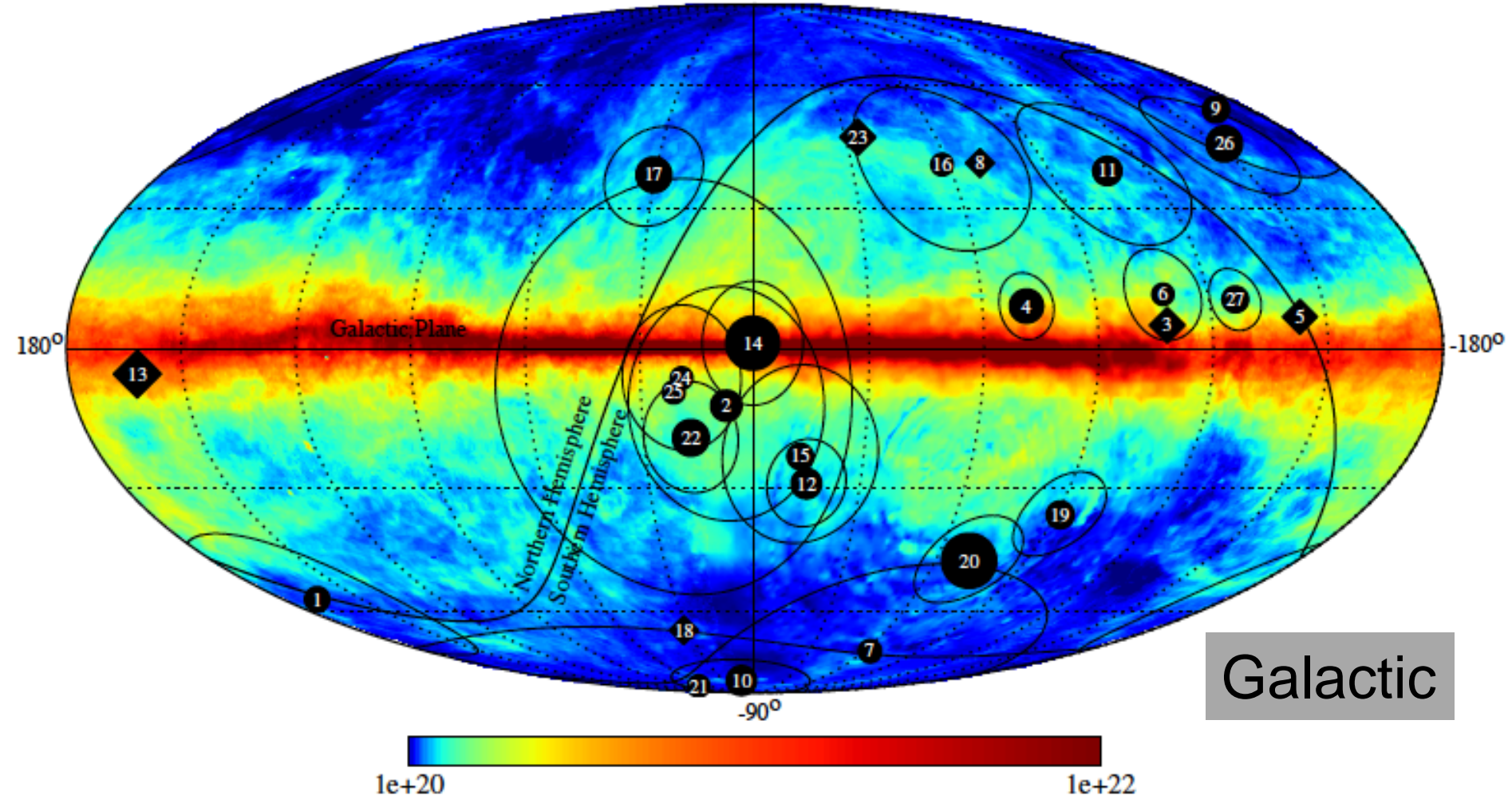
# ICECUBE PRELIMINARY



where do they come from?

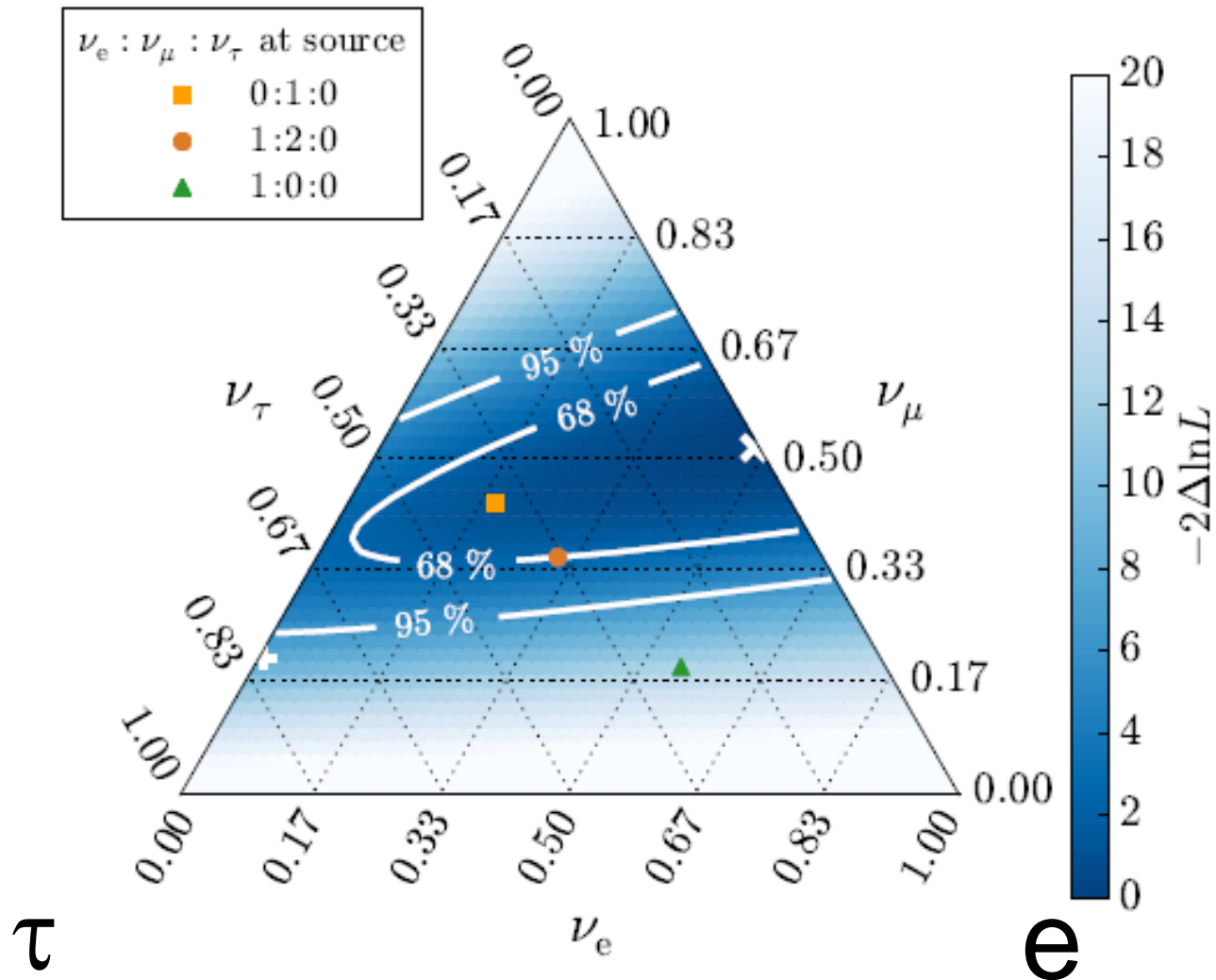
correlation with Galactic plane: TS of 2.5% for a width of 7.5 deg

HI column density [ $\text{cm}^{-2}$ ]



oscillate over cosmic distances to 1:1:1

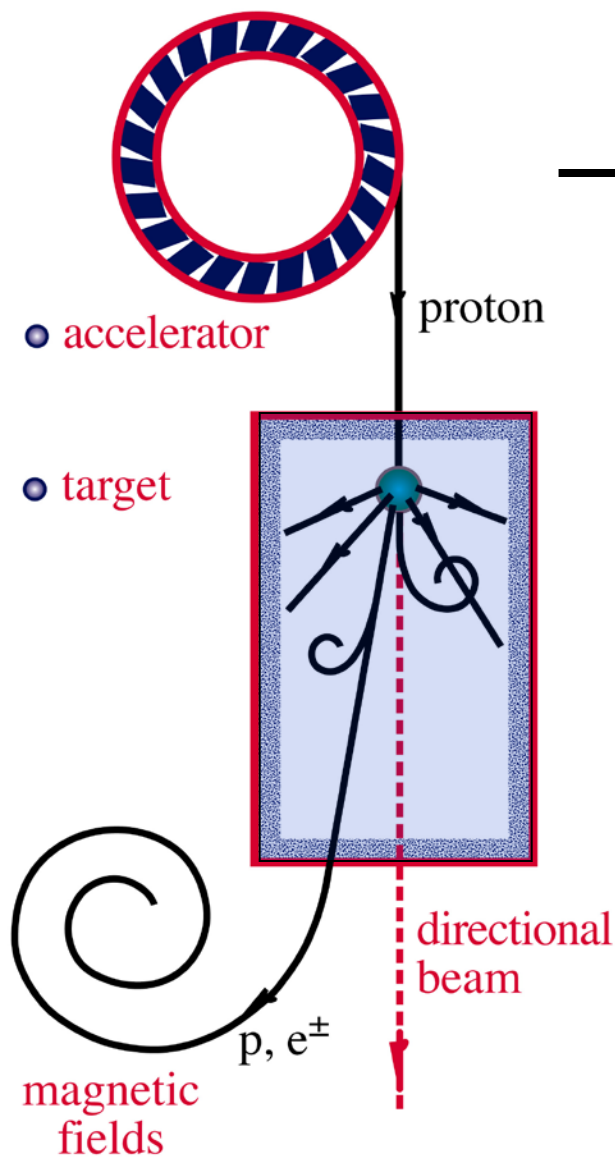
$\mu$



- 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?



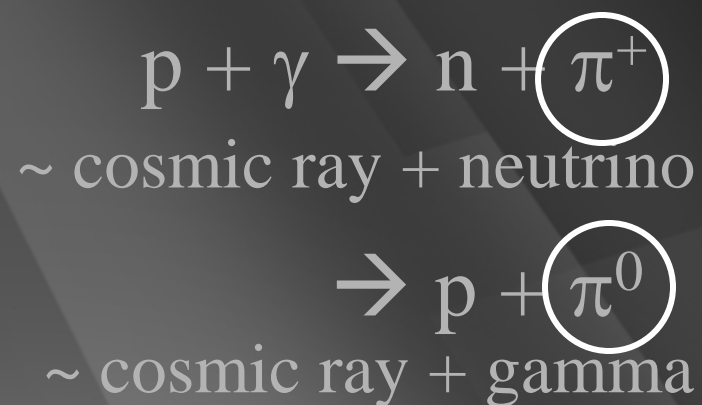
# $\nu$ and $\gamma$ beams : heaven and earth



accelerator is powered by large gravitational energy

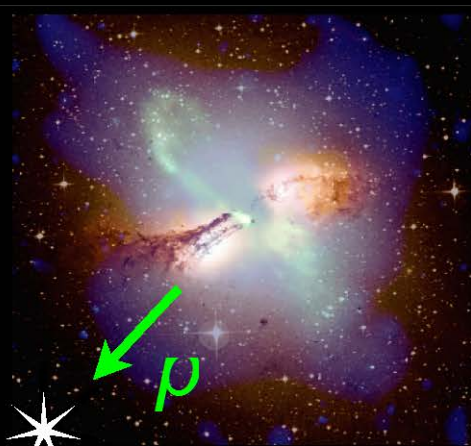
black hole  
neutron star

radiation  
and dust



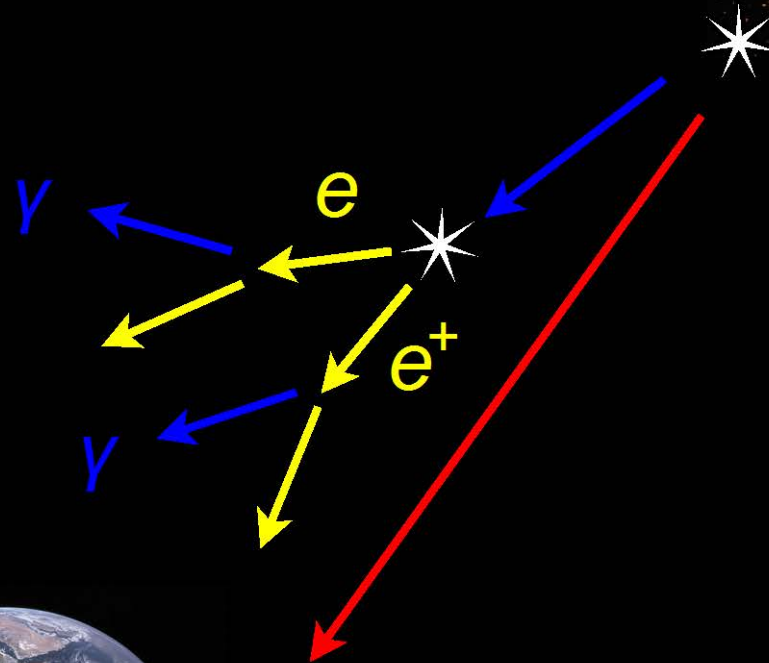
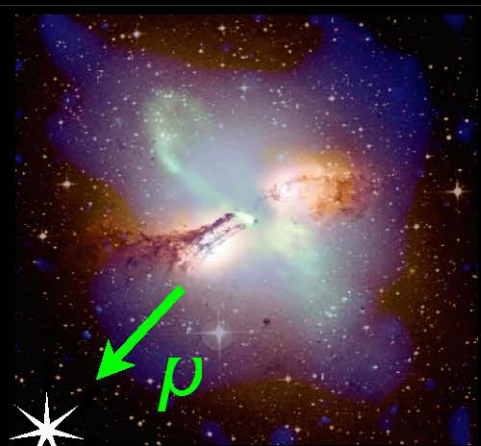
# hadronic gamma rays ?

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

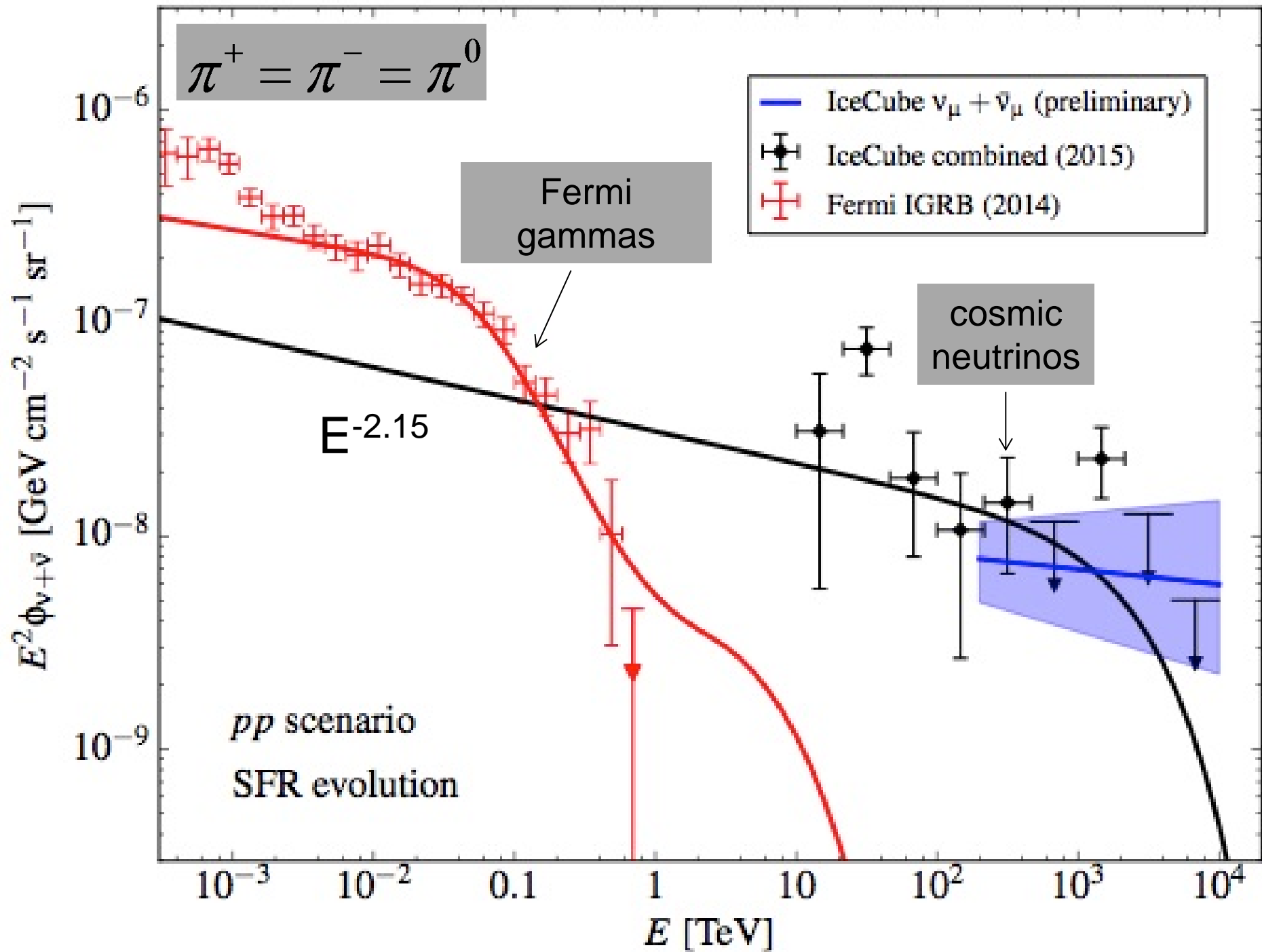


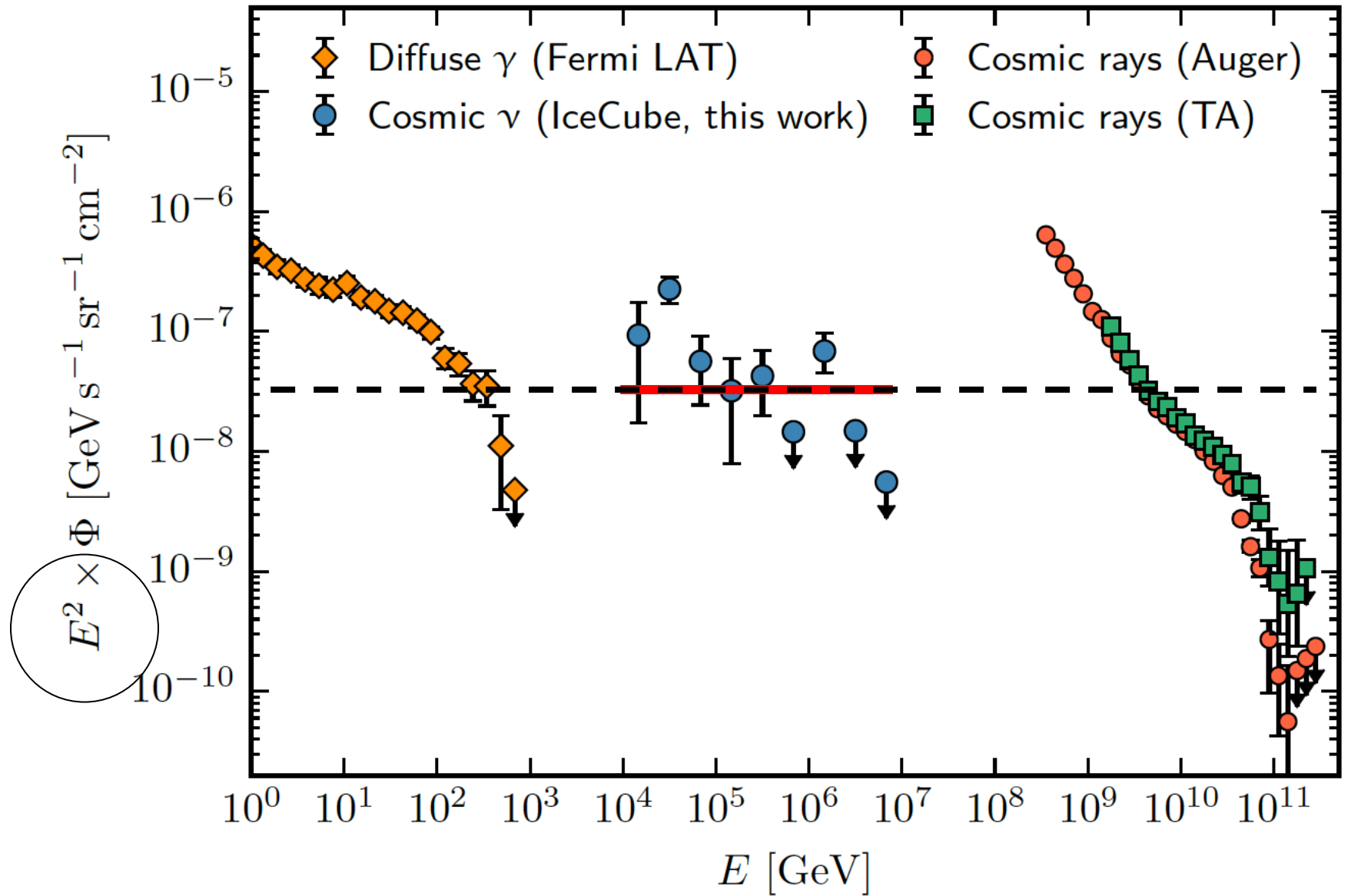
hadronic  
gamma rays

electromagnetic  
cascades in CMB



hadronic  
gamma rays

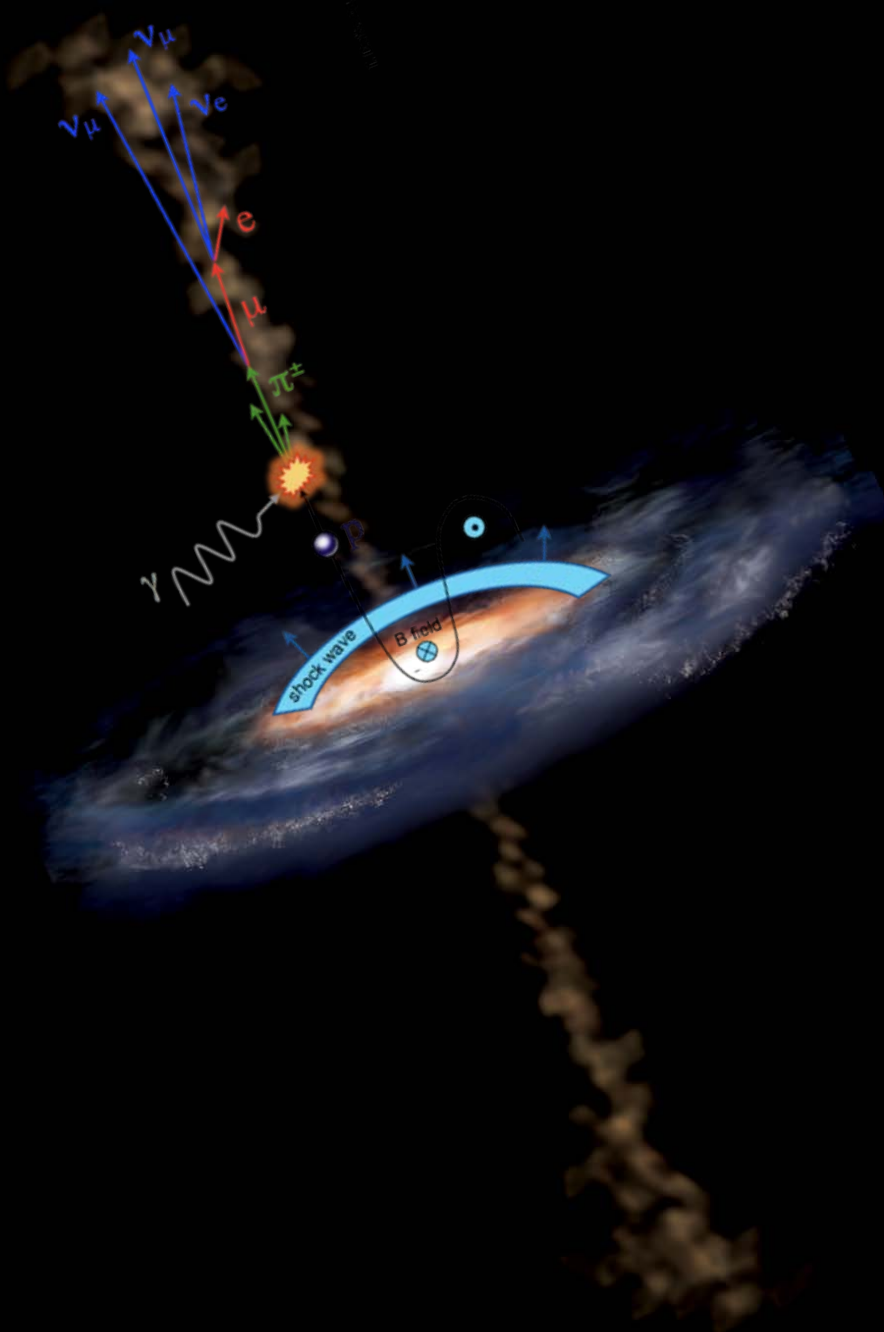




energy in the Universe in gamma rays, neutrinos and cosmic rays

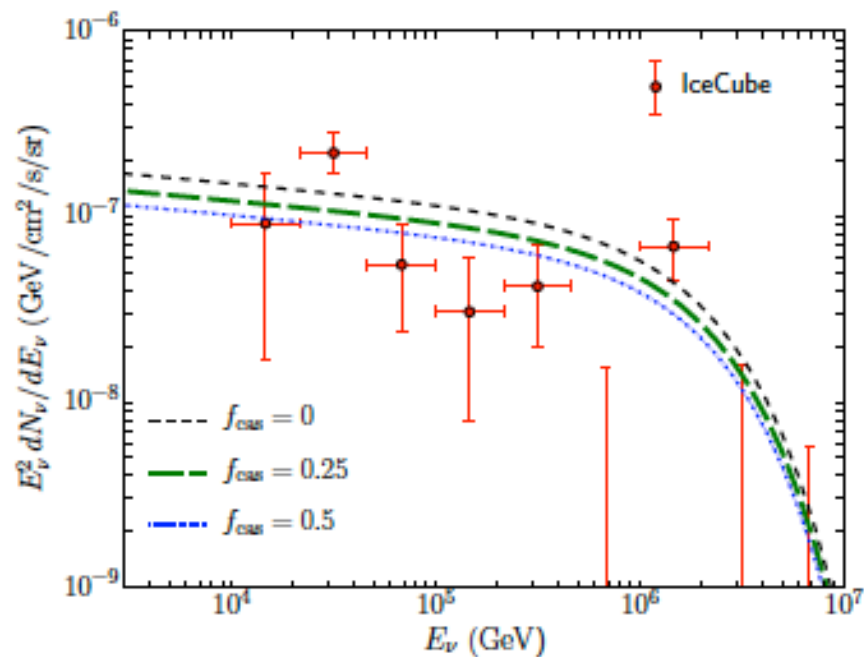
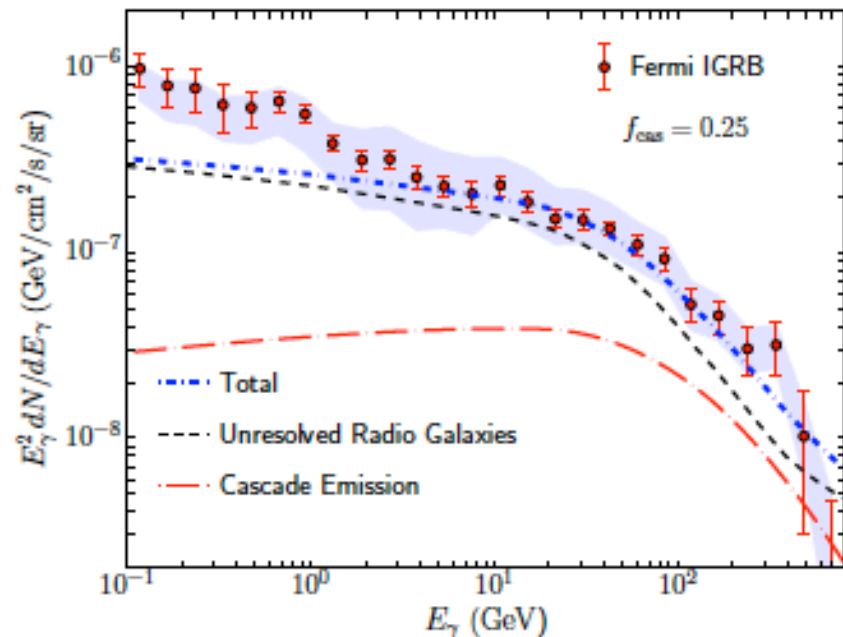
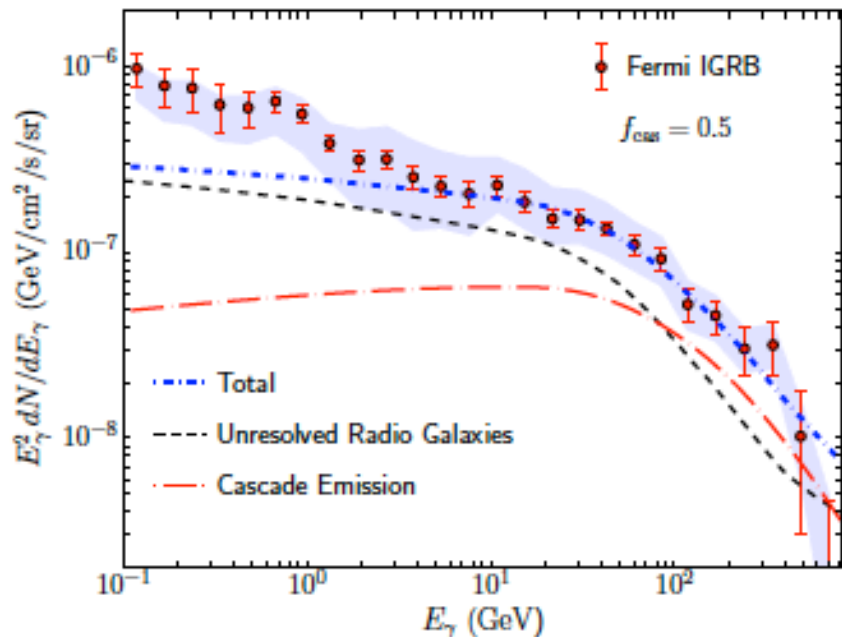
- we observe a flux of cosmic neutrinos from the cosmos whose properties correspond in all respects to the flux anticipated from PeV-energy cosmic accelerators that radiate comparable energies in light and neutrinos
- the energy in cosmic neutrinos is also comparable to the energy observed in extragalactic cosmic rays (the Waxman-Bahcall bound)
- at some level common Fermi-IceCube sources?





active galaxy

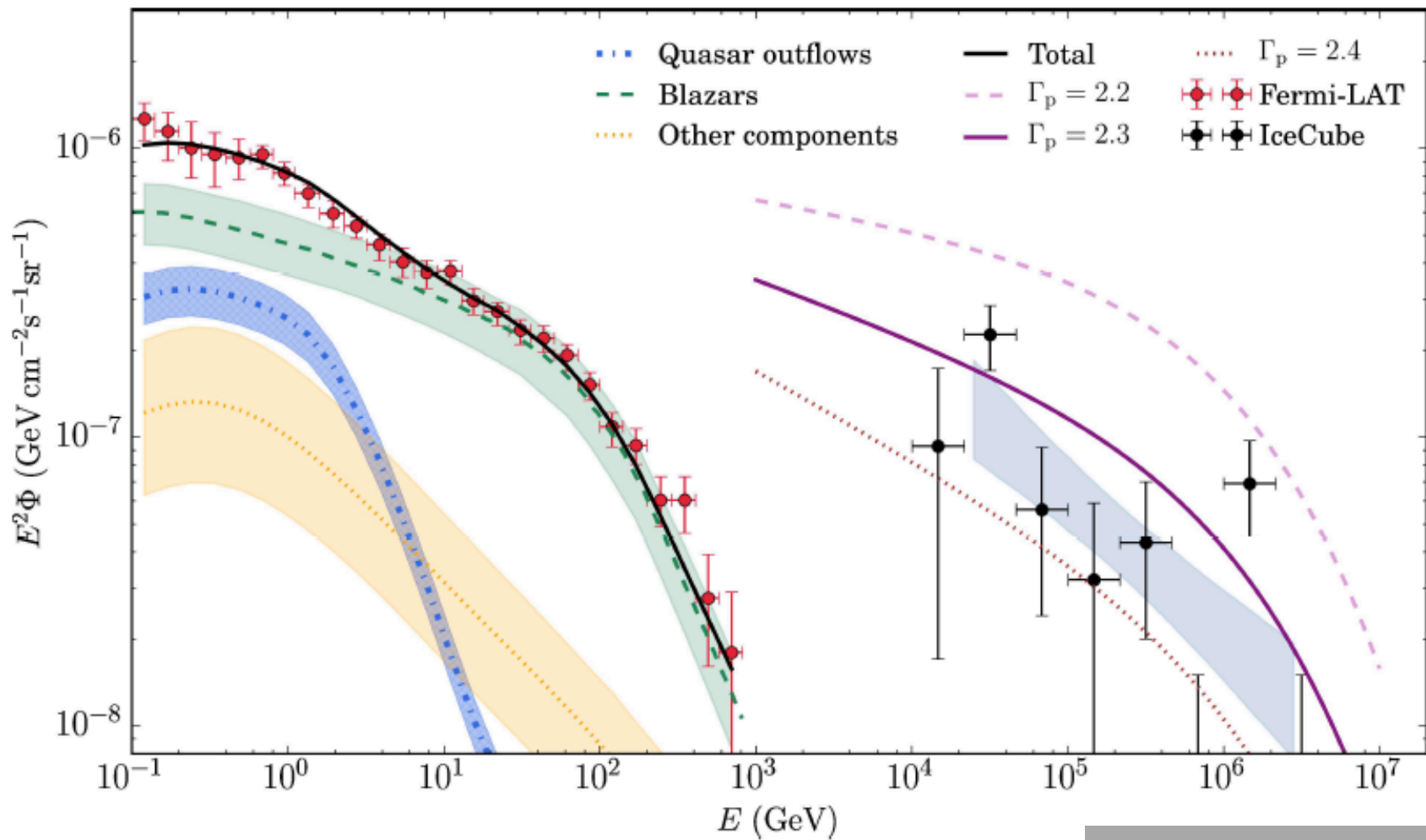
particle flows near  
supermassive  
black hole



radiogalaxies

Tjus et al.

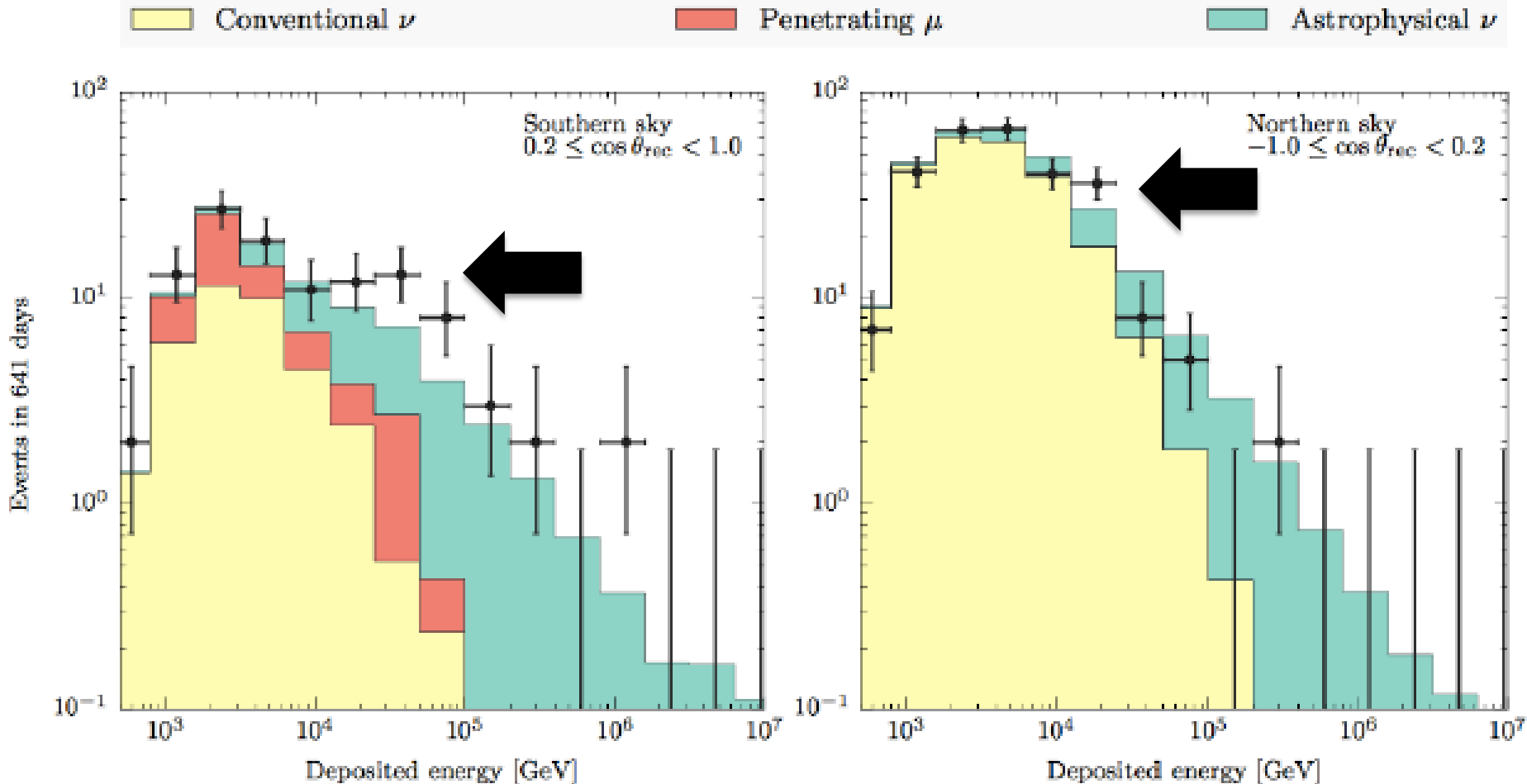
Hooper



**QUASARS**  
 Loeb

- there is more

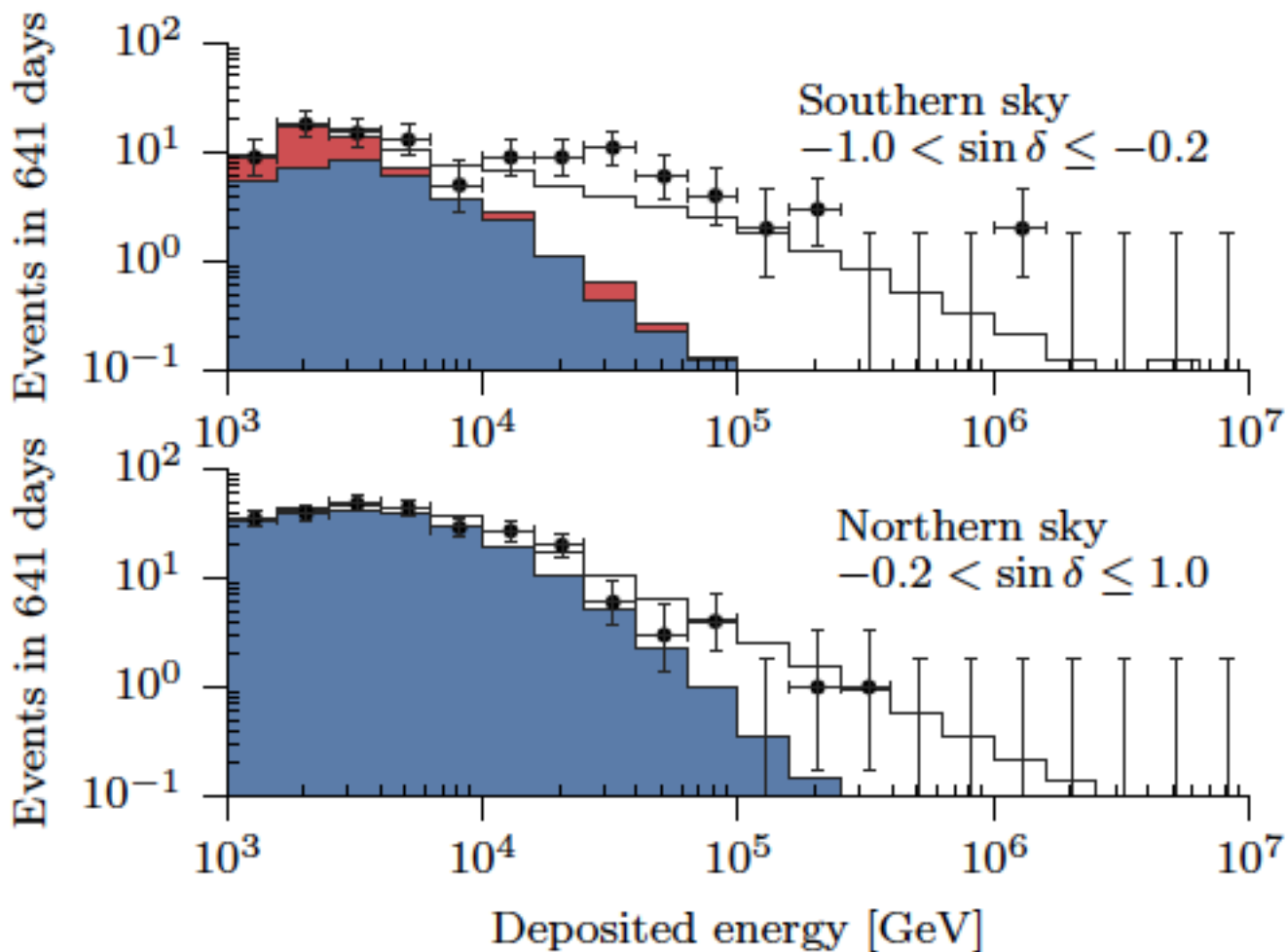
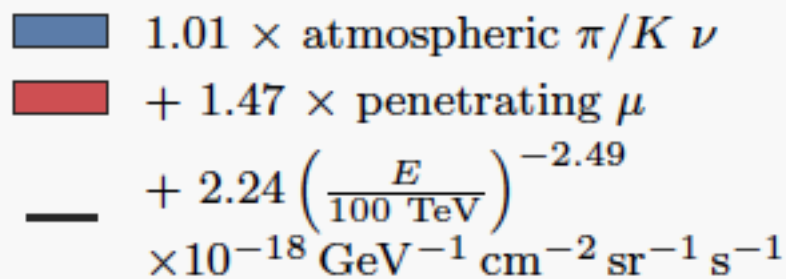
# towards lower energies: a second component?



warning:

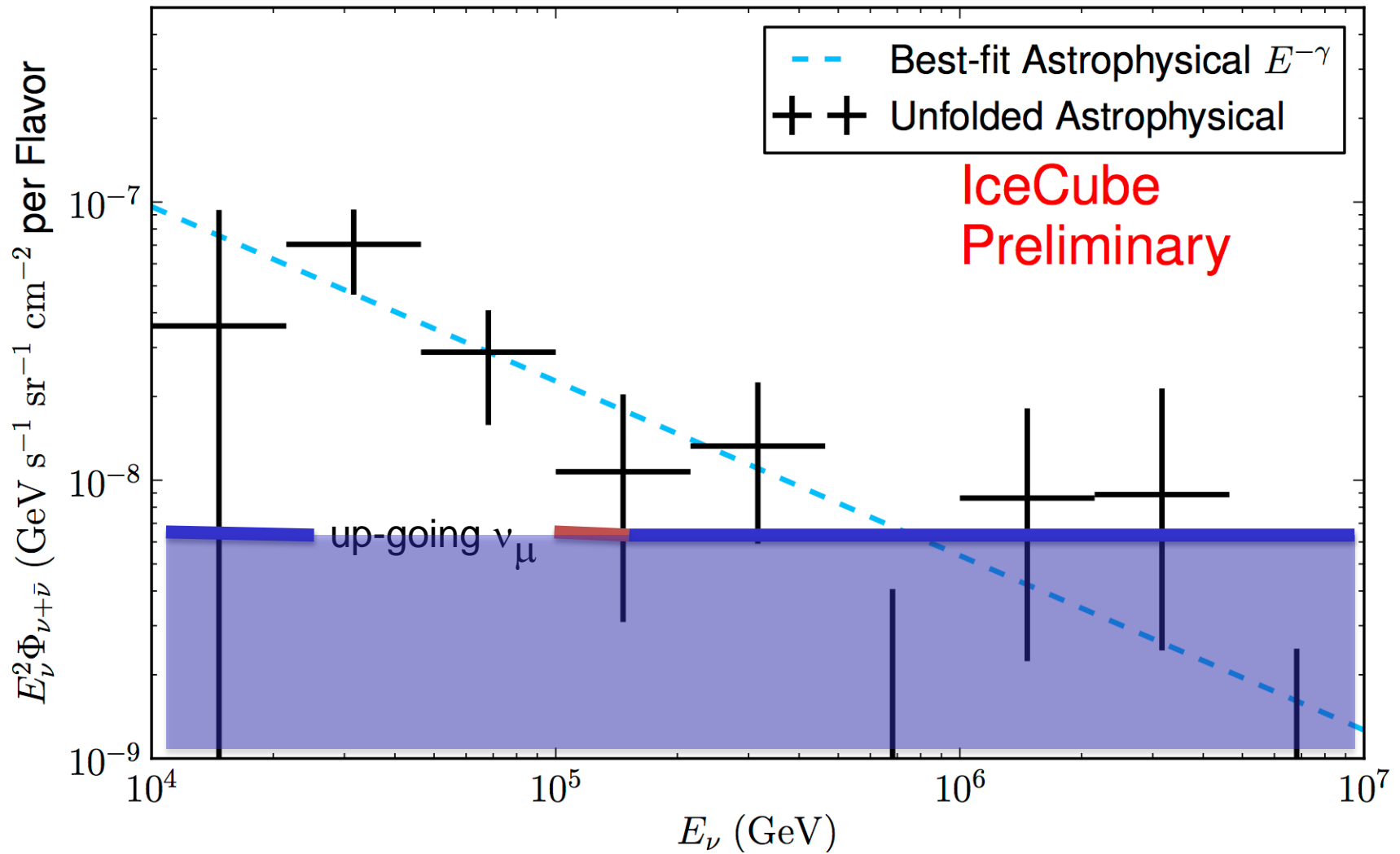
- spectrum may not be a power law
- slope depends on energy range fitted

PeV neutrinos  
absorbed in the Earth





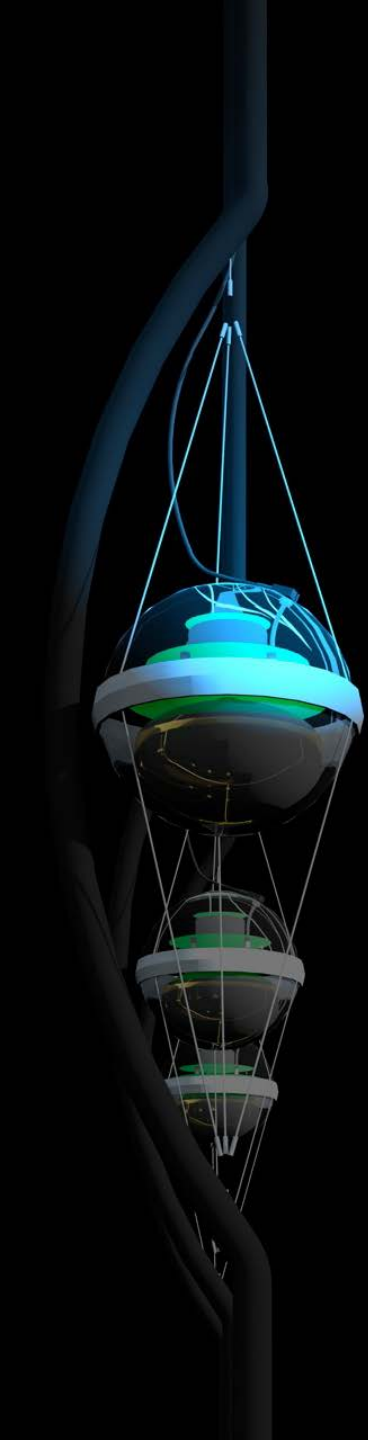
yet lower energies.....



# IceCube: the discovery of cosmic neutrinos

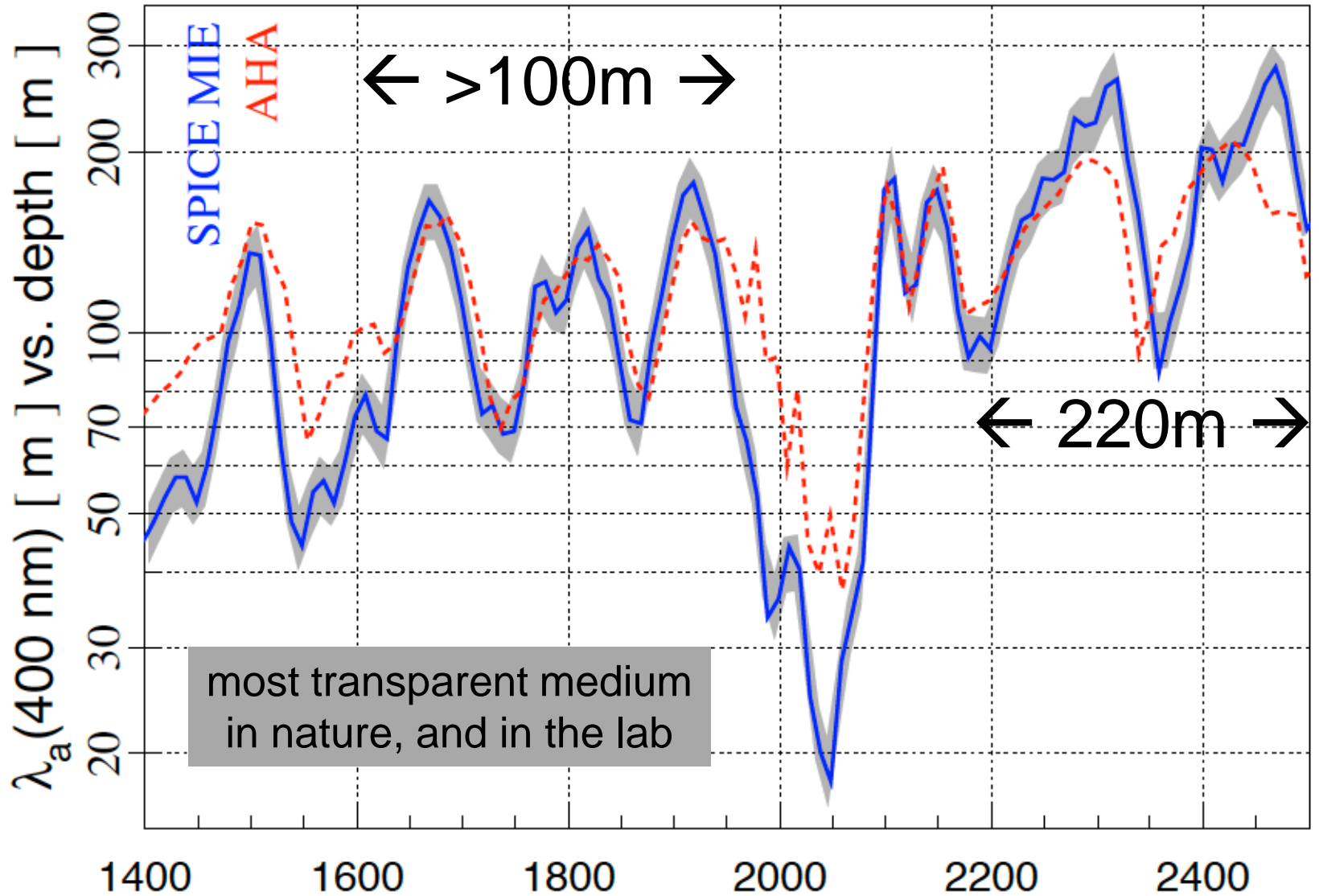
francis halzen

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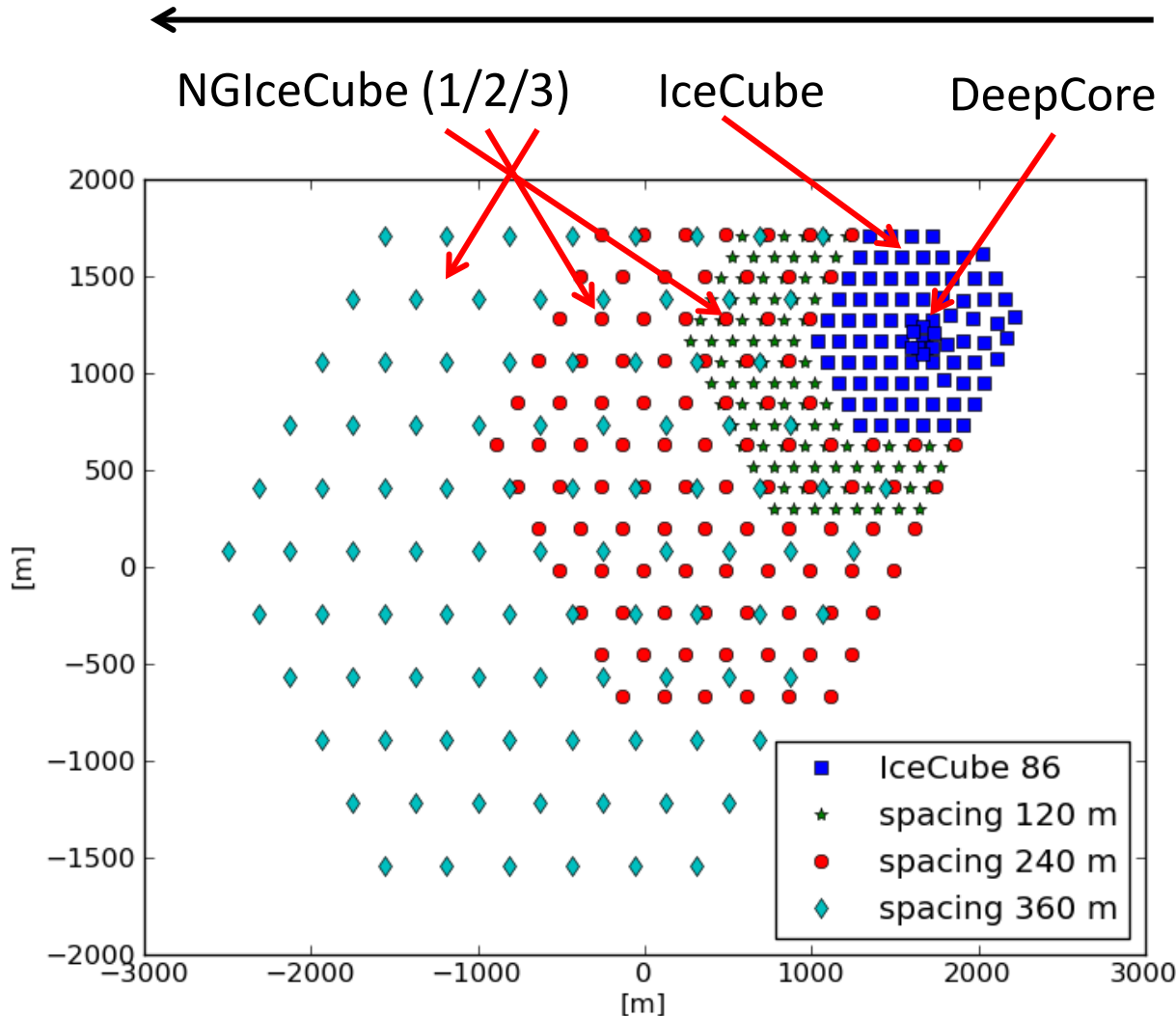
- a next-generation IceCube with a volume of  $10 \text{ km}^3$  and an angular resolution of  $< 0.3$  degrees will see multiple neutrinos and identify the sources, even from a “diffuse” extragalactic flux in several years
- need 1,000 events versus 100 now in a few years
- discovery instrument  $\rightarrow$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

# absorption length of Cherenkov light



# 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>**

## 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

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