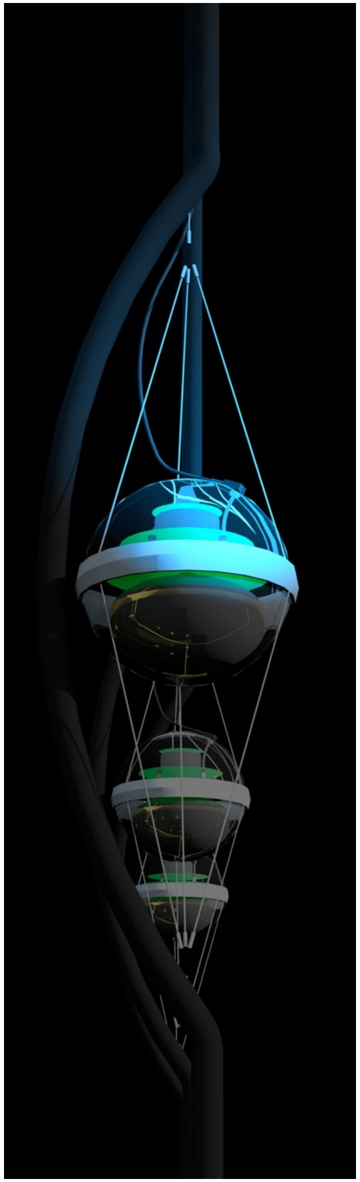
Neutrino Astronomy



This presentation is based on the excellent review of neutrino astronomy by Halzen & Klein 2010, and from one of his Plenary presentations in 2015.

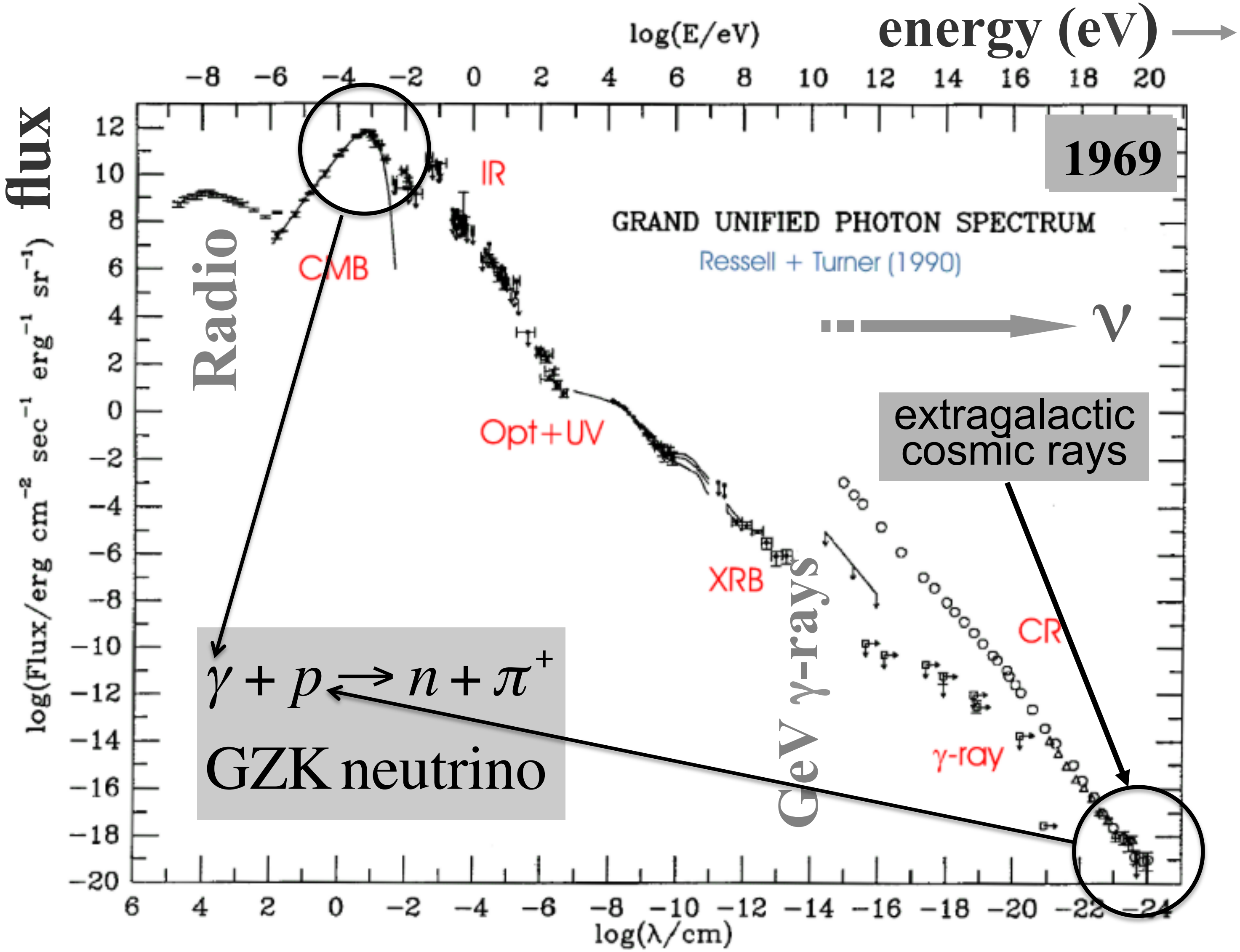
Neutrino Astronomy

- Neutrinos are ideal astronomical messengers. They travel from the edge of our observable Universe with little absorption and since they have no charge they are not deflected by magnetic fields.

- Unlike photons that are easily absorbed, high-energy neutrinos may reach us unscathed from cosmic distances, from the inner neighborhood of black holes.

- Because neutrinos are not easily absorbed they are very difficult to detect and large detector volumes of the order of a cubic-kilometer are required.

Photon Spectrum of the Universe



1969

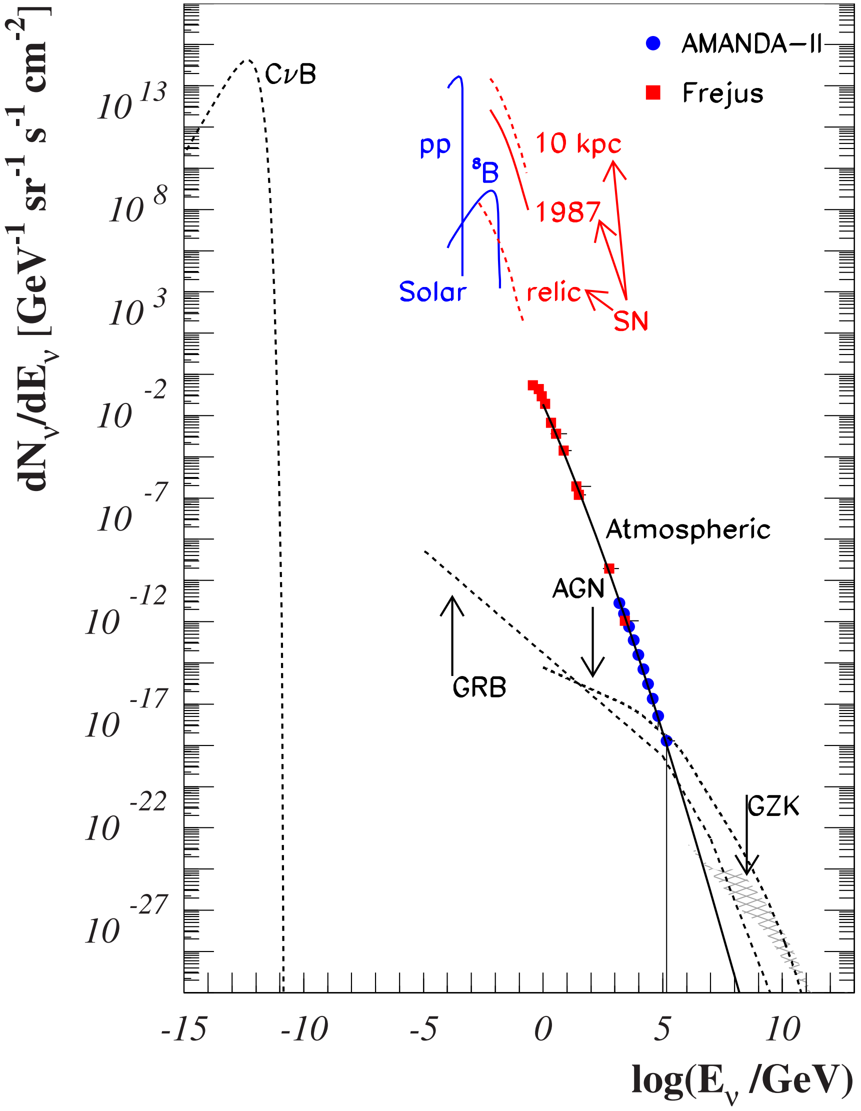
extragalactic cosmic rays

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

GZK neutrino

Neutrino Spectrum

- Solar neutrinos have energies of about 0.1 MeV to 10 MeV
- SN 1987A neutrinos (from the LMC) had energies ~100 GeV
- AGN and GRB neutrino flux is higher than the “background” for neutrinos with energies above 100 TeV



GZK Neutrinos

- Above a threshold of 4×10^{19} eV (1 TeV= 10^{12} eV, 1 PeV = 10^{15} eV) cosmic rays (energetic charged particles) interact with the cosmic microwave background photons introducing an absorption feature in the cosmic-ray flux, the Greissen–Zatsepin–Kuzmin cutoff.

- Because of the GZK effect **cosmic rays with E >** 4×10^{19} eV **can only travel for about 75 Mpc before they get absorbed** in the interaction:

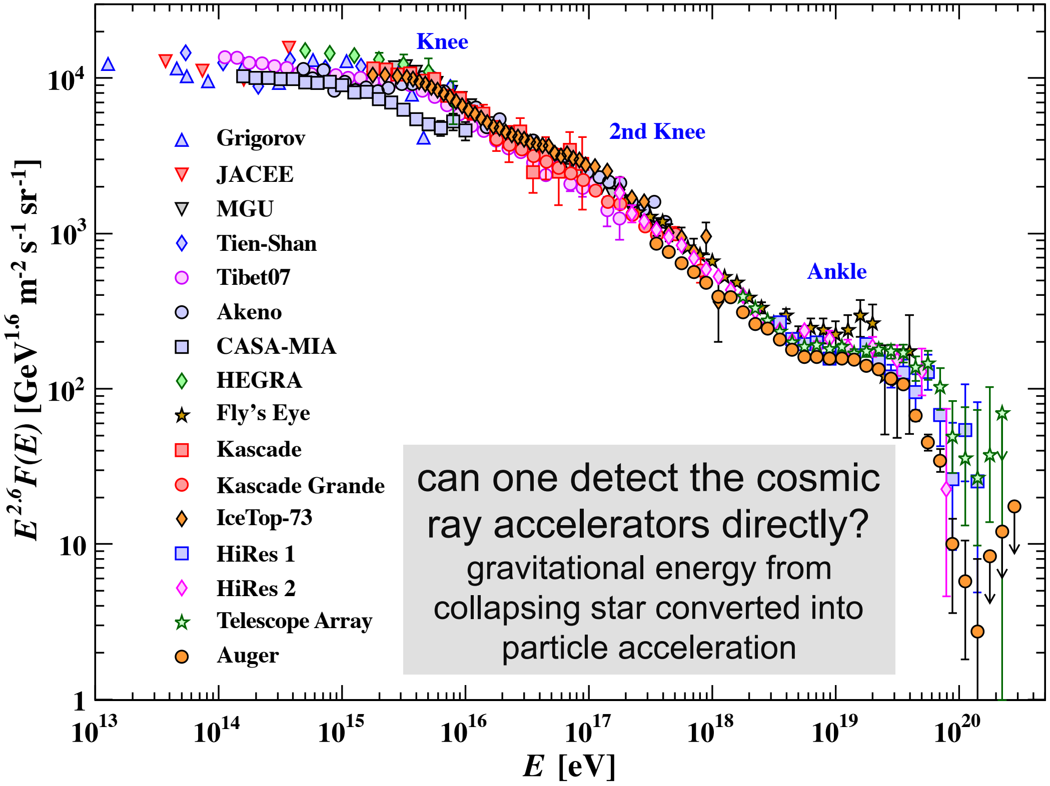
  COSMIC ray + CMB photon ➔ pion + neutron

- The charged pion will eventually decay into a GZK neutrino with an energy of $>10^6$ TeV

- The prediction is that the detection rate of GZK neutrinos is one per cubic kilometer per year. The direction of these neutrinos point back to the location of the source.

Cosmic Ray Spectrum

- Cosmic accelerators can produce particles with energies in excess of 10^8 TeV
- The cosmic ray energy spectrum follows a sequence of three power laws.
- The first two are separated by a feature dubbed the “knee” at an energy of approximately 3000 TeV.
- There is evidence that cosmic rays up to this energy are galactic in origin.
- Cosmic rays with energies near and above the "ankle" are thought to be extragalactic in origin.



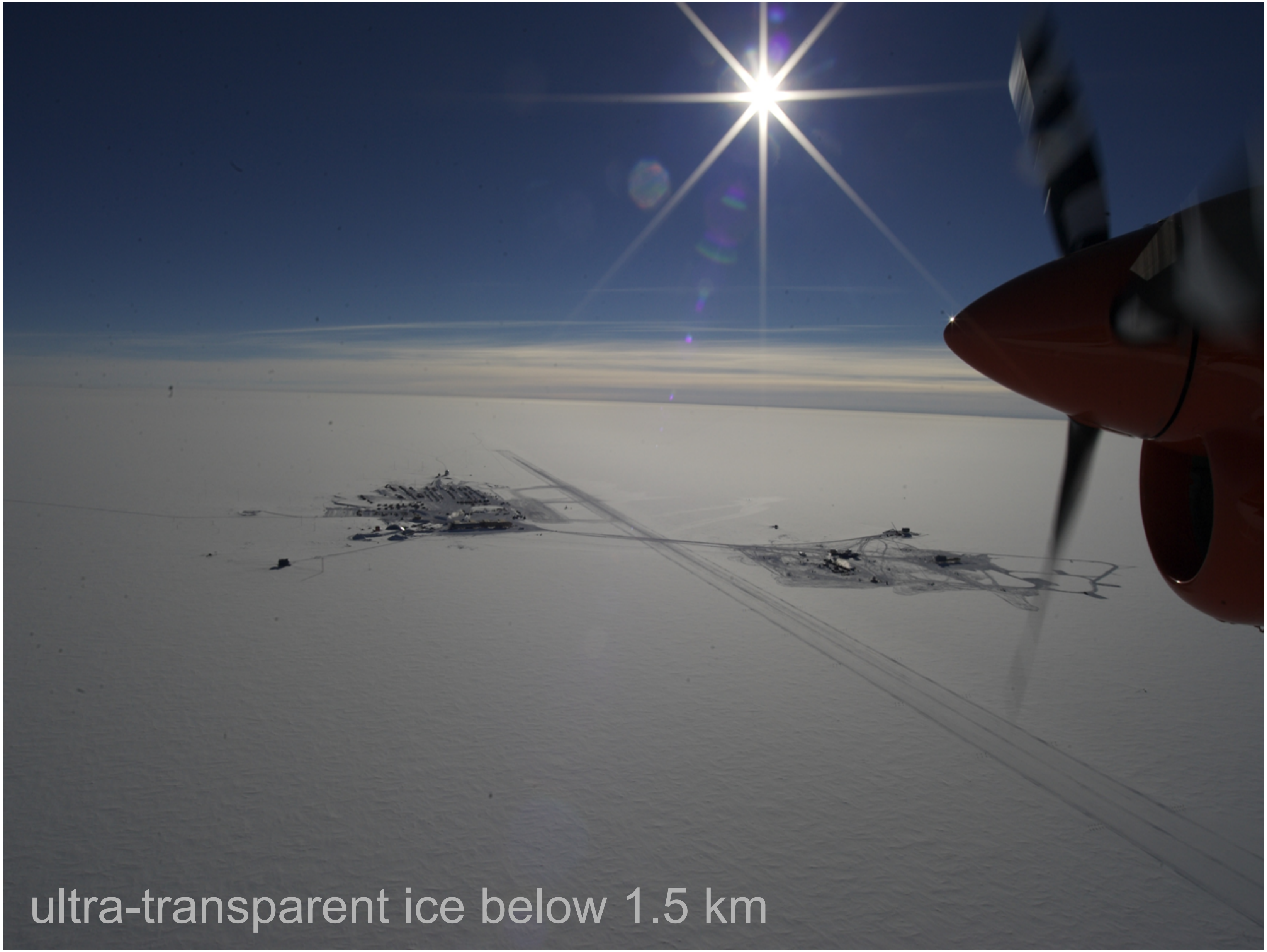
can one detect the cosmic ray accelerators directly?

gravitational energy from collapsing star converted into particle acceleration

Cosmic Ray Accelerators

- To produce cosmic rays requires protons to be accelerated to >TeV energies
- Cosmic Ray accelerators include Black Holes, Gamma Ray Bursts and Supernova Remnants
- The accelerated protons may interact with a photon to produce charged pions that latter decay into cosmic rays + neutrinos

IceCube

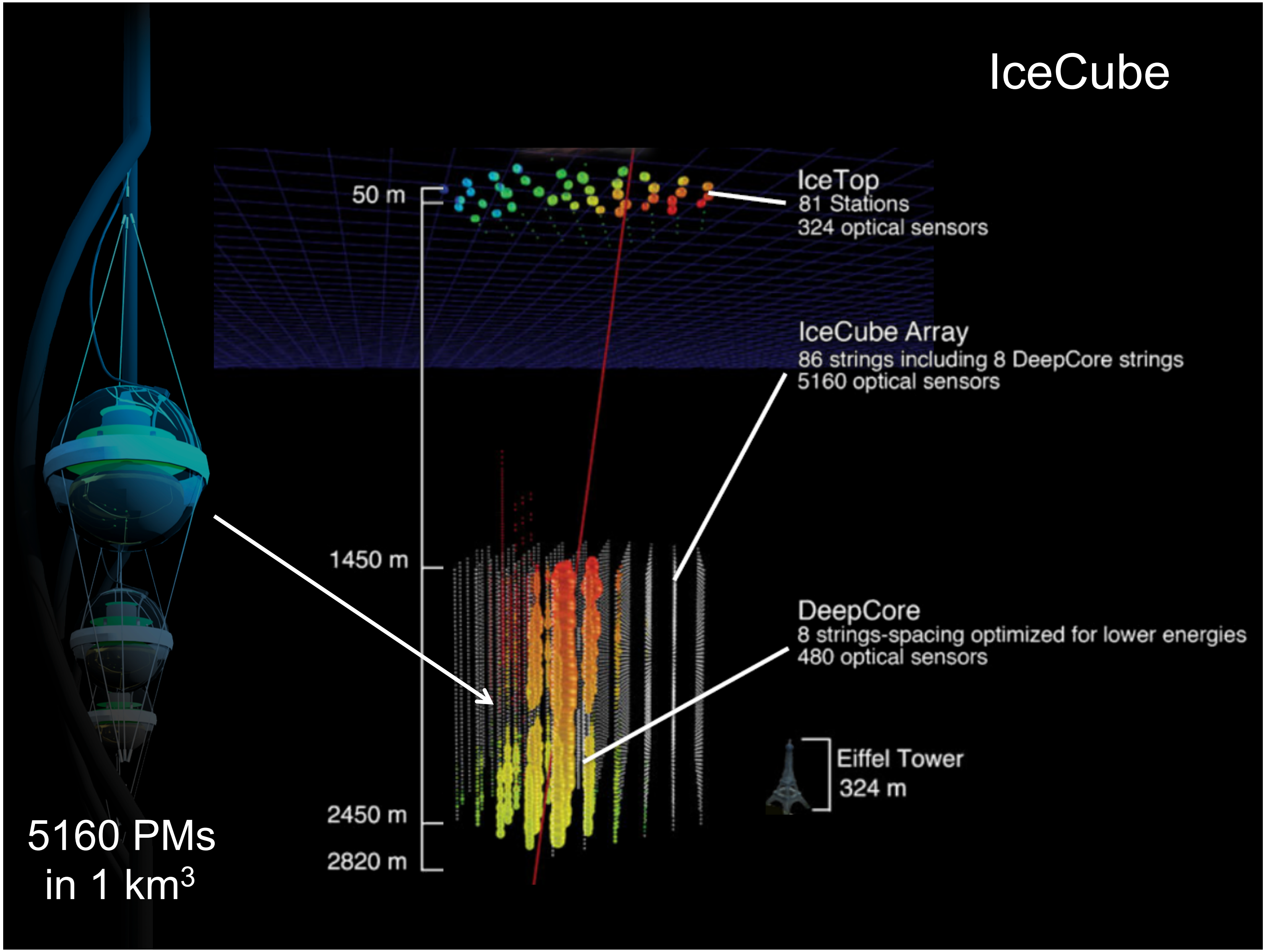


ultra-transparent ice below 1.5 km

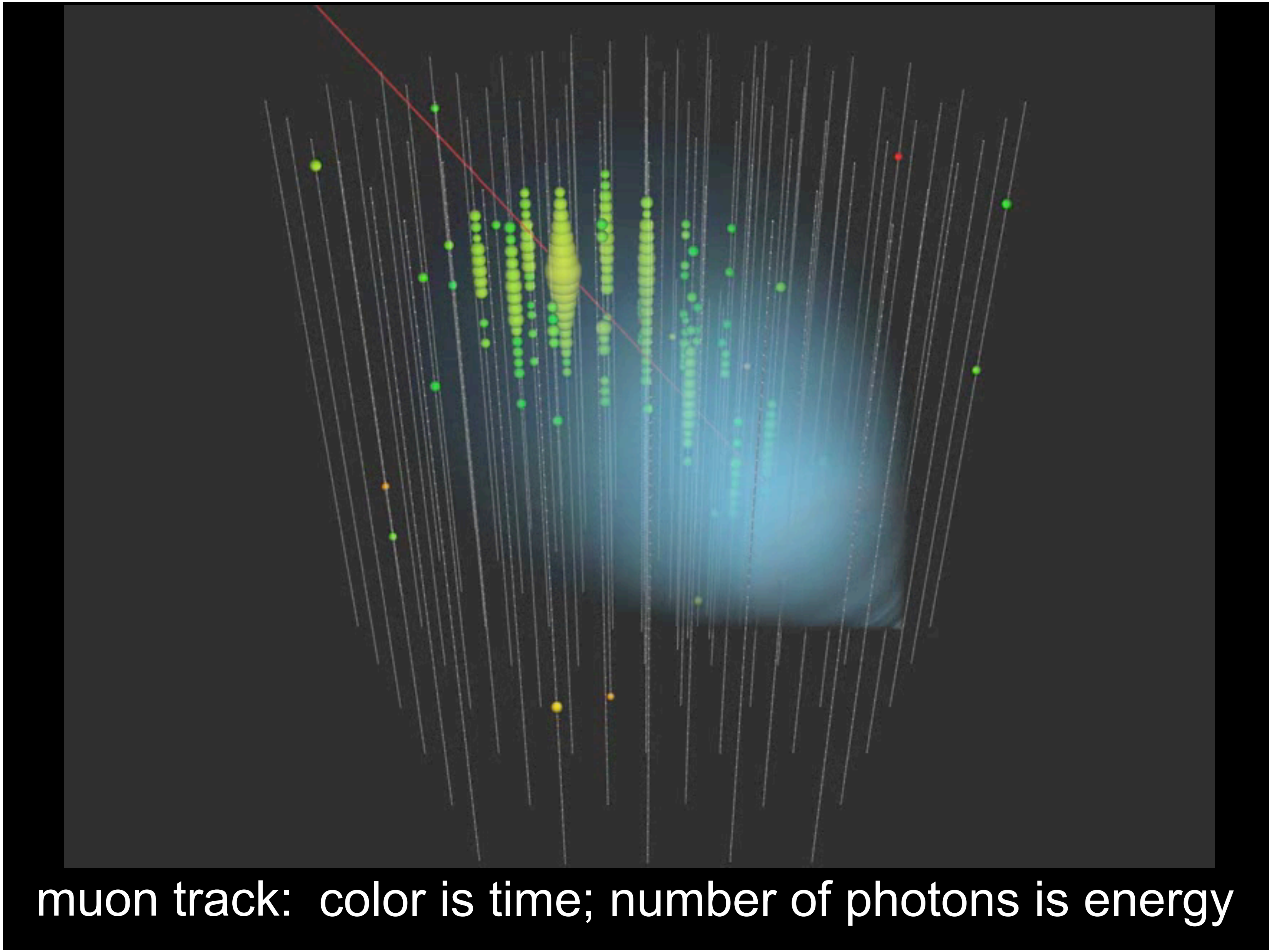
IceCube

- The few neutrinos that interact with a nucleus in the ice create muons as well as electromagnetic and hadronic secondary particle showers.
- The charged particles that are produced from the interaction of the neutrino with the ice produce Cherenkov Light that spreads through the transparent ice.
- Cherenkov light is radiated by charged particles moving faster than the speed of light in the medium; in ice, this is 75% of the speed of light in a vacuum.
- The Cherenkov light is captured by photomultipliers (that use the photoelectic effect).
- The absorption length of light in regular tap water is about 1 m. The absorption length of light in the south pole ice is > 100m.
- The direction of the incoming neutrino can be recovered from the track left in the detector array.
- All detected events in the photomultiplier tubes are time-stamped to ~ 2 nanoseconds precision.

IceCube

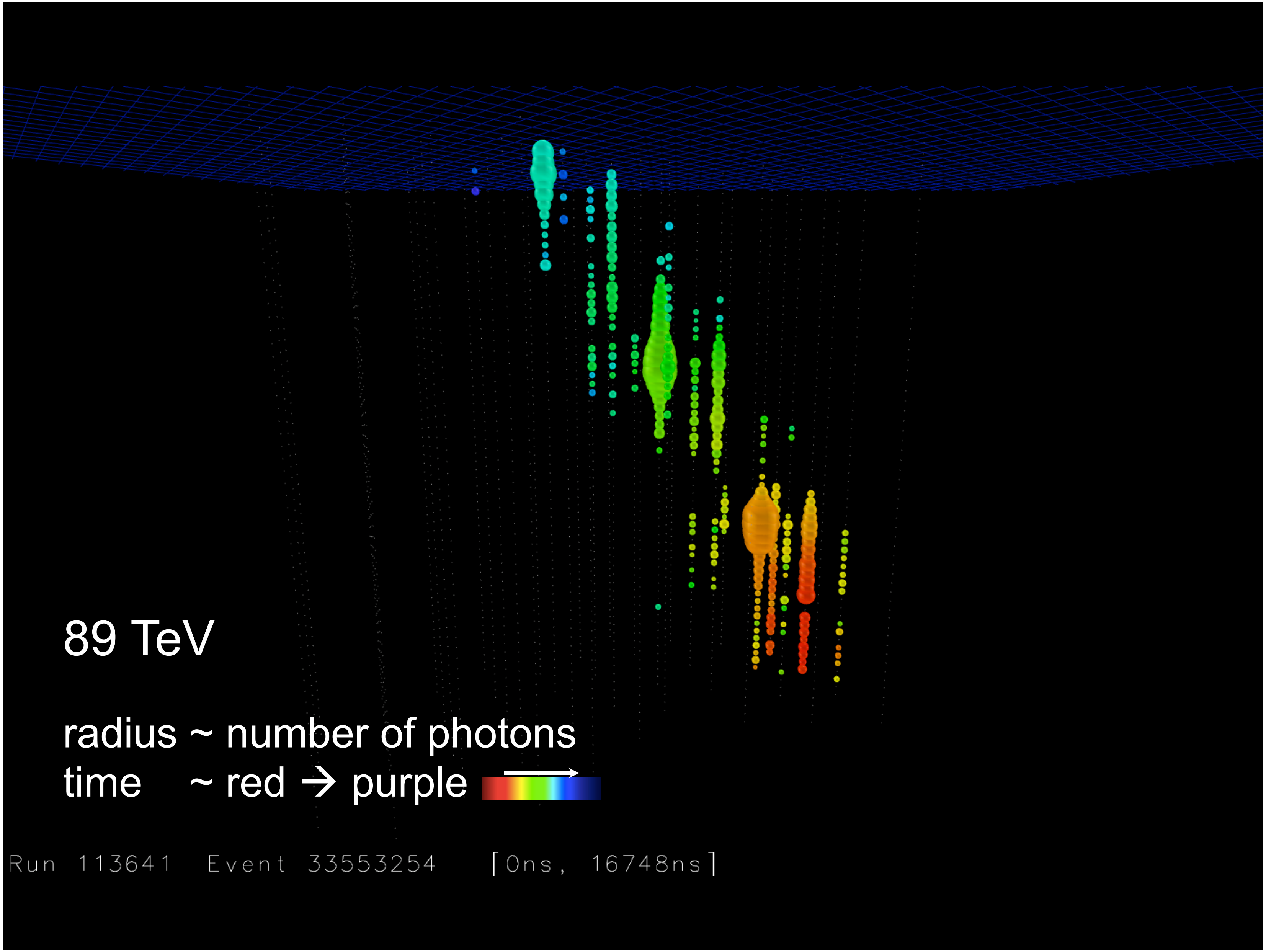

IceCube
50 m
1450 m
2450 m
2820 m
IceTop
81 Stations
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
5160 PMs
in 1 km³

IceCube



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

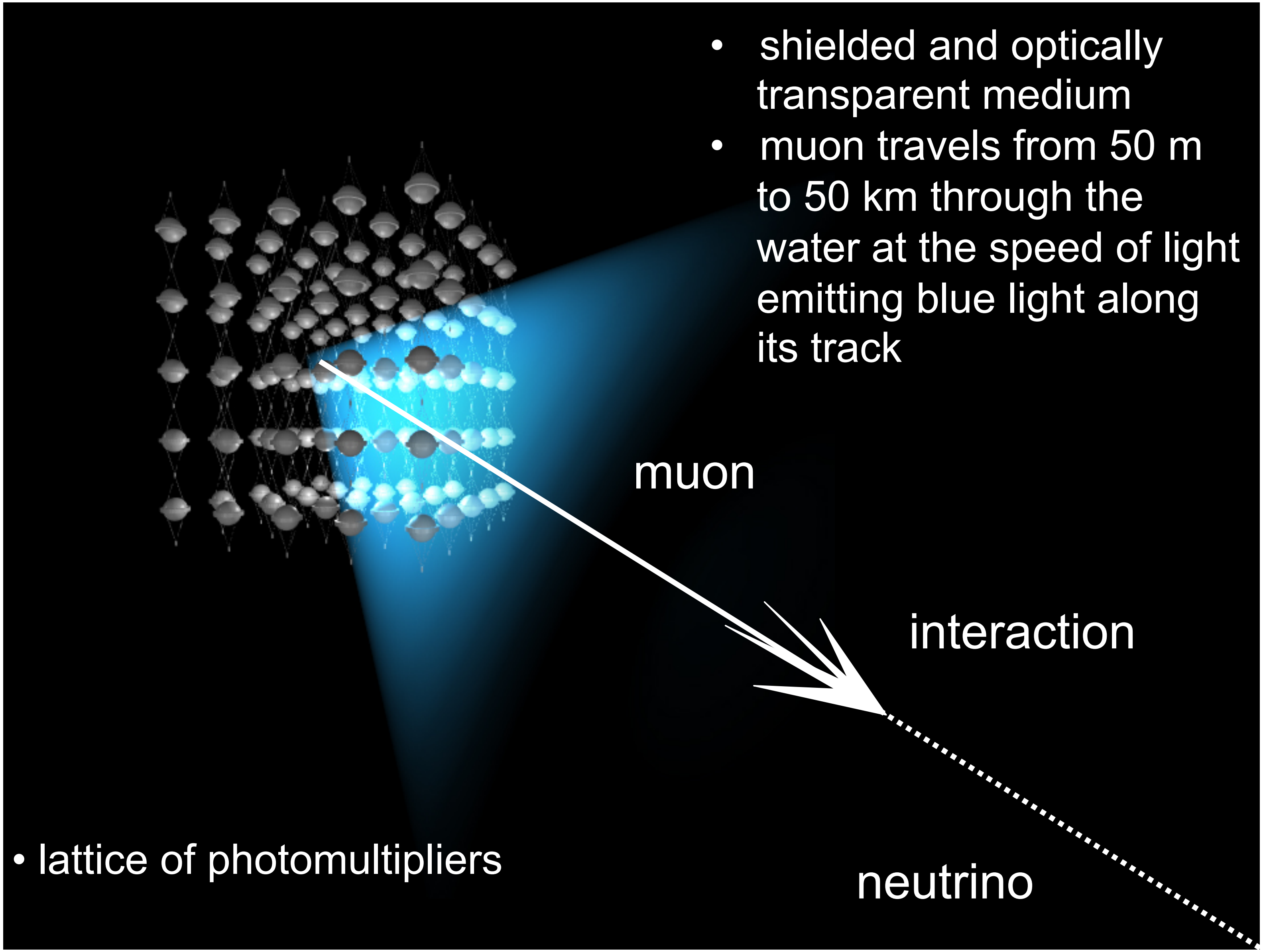
IceCube



89 TeV

radius ~ number of photons
time ~ red → purple

IceCube



- 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

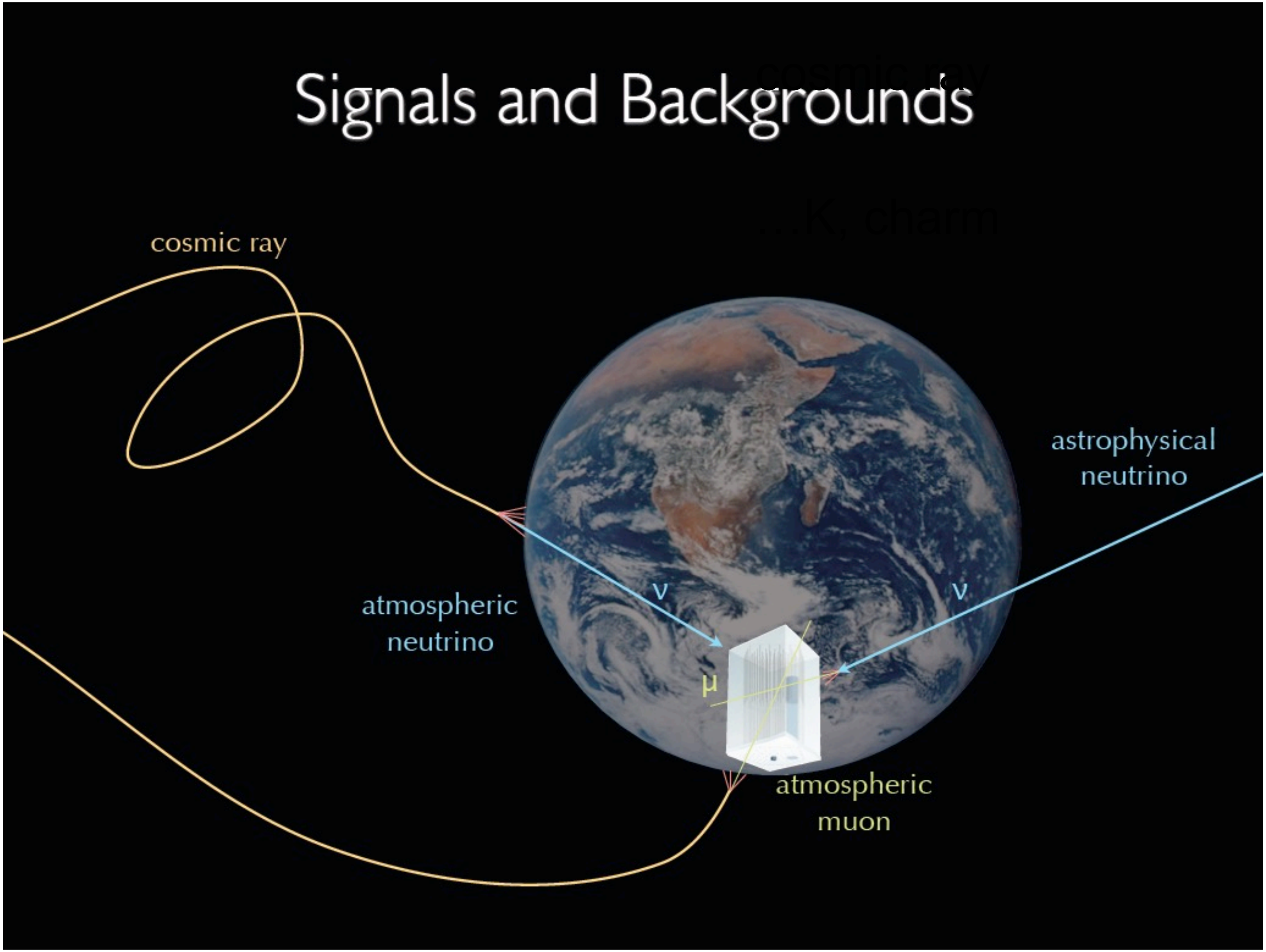
- lattice of photomultipliers

IceCube

“Noise sources”: Atmospheric Neutrinos and Atmospheric Muons

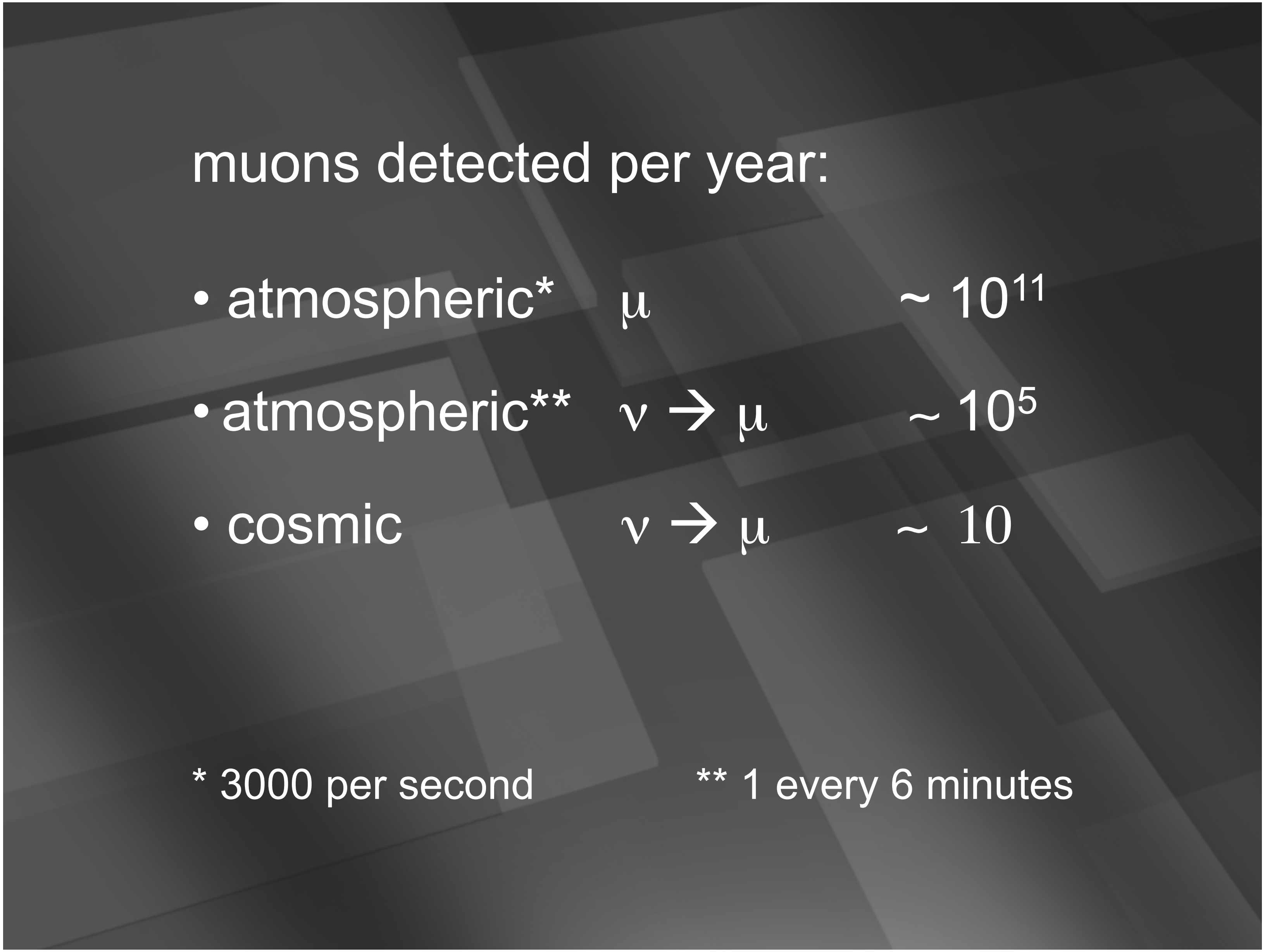
- IceCube detects about 100 atmospheric neutrinos per day with energies above 100 GeV.
- Cosmic rays that collide with nitrogen and oxygen in our atmosphere create pions and kaons. The decay of charged pions and kaons produces the atmospheric neutrinos.
- Cosmic ray showers above IceCube will generate atmospheric muons and atmospheric neutrinos
- Cosmic ray showers in the atmosphere distant from IceCube will produce atmospheric neutrinos in IceCube (the muons decay before they get to IceCube into e^- and 2 neutrinos of different type)

IceCube



Signals and Backgrounds

IceCube



muons detected per year:

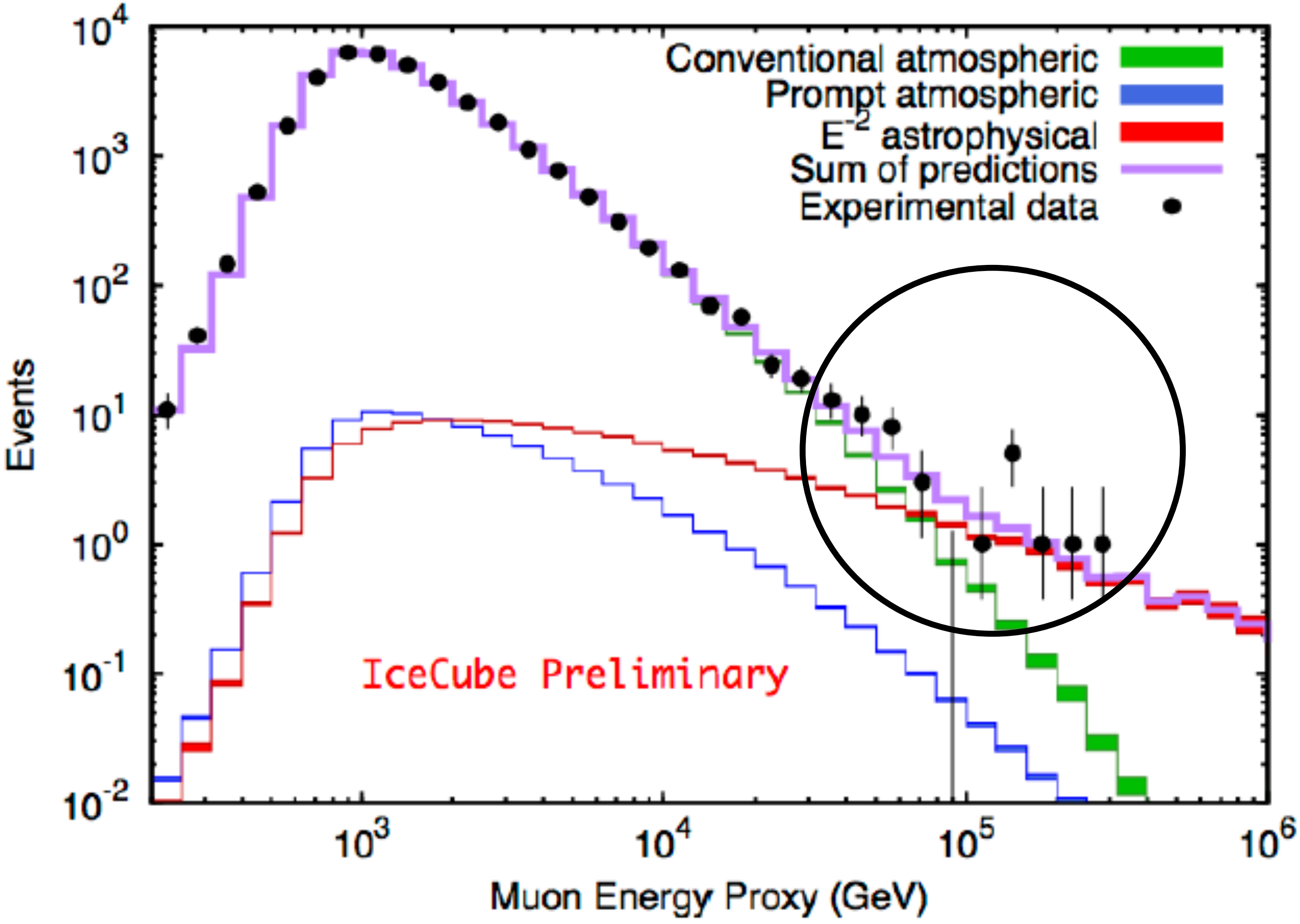
• atmospheric*	μ	$\sim 10^{11}$
• atmospheric**	$\nu \rightarrow \mu$	$\sim 10^{5}$
• cosmic	$\nu \rightarrow \mu$	~ 10

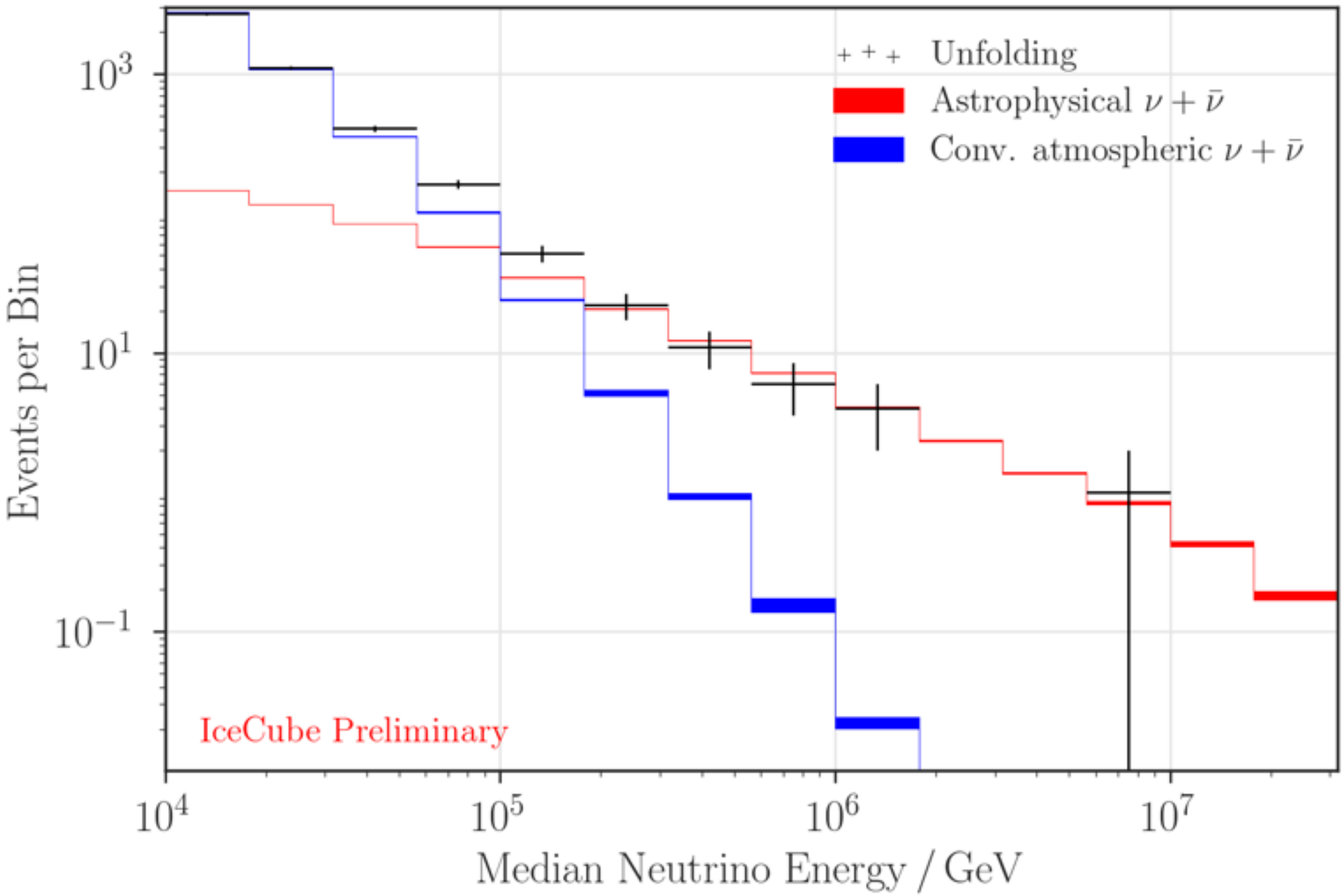
* 3000 per second

** 1 every 6 minutes

Discovery of Cosmic Neutrinos

cosmic neutrinos in 2 years of data at 3.7 sigma





Distribution of the median expected neutrino energy assuming the best-fit spectral index of 2.16. The black crosses correspond to experimental data and blue/red to the conventional atmospheric/astrophysical expectation weighted to the best-fit spectrum.

GZK neutrino search

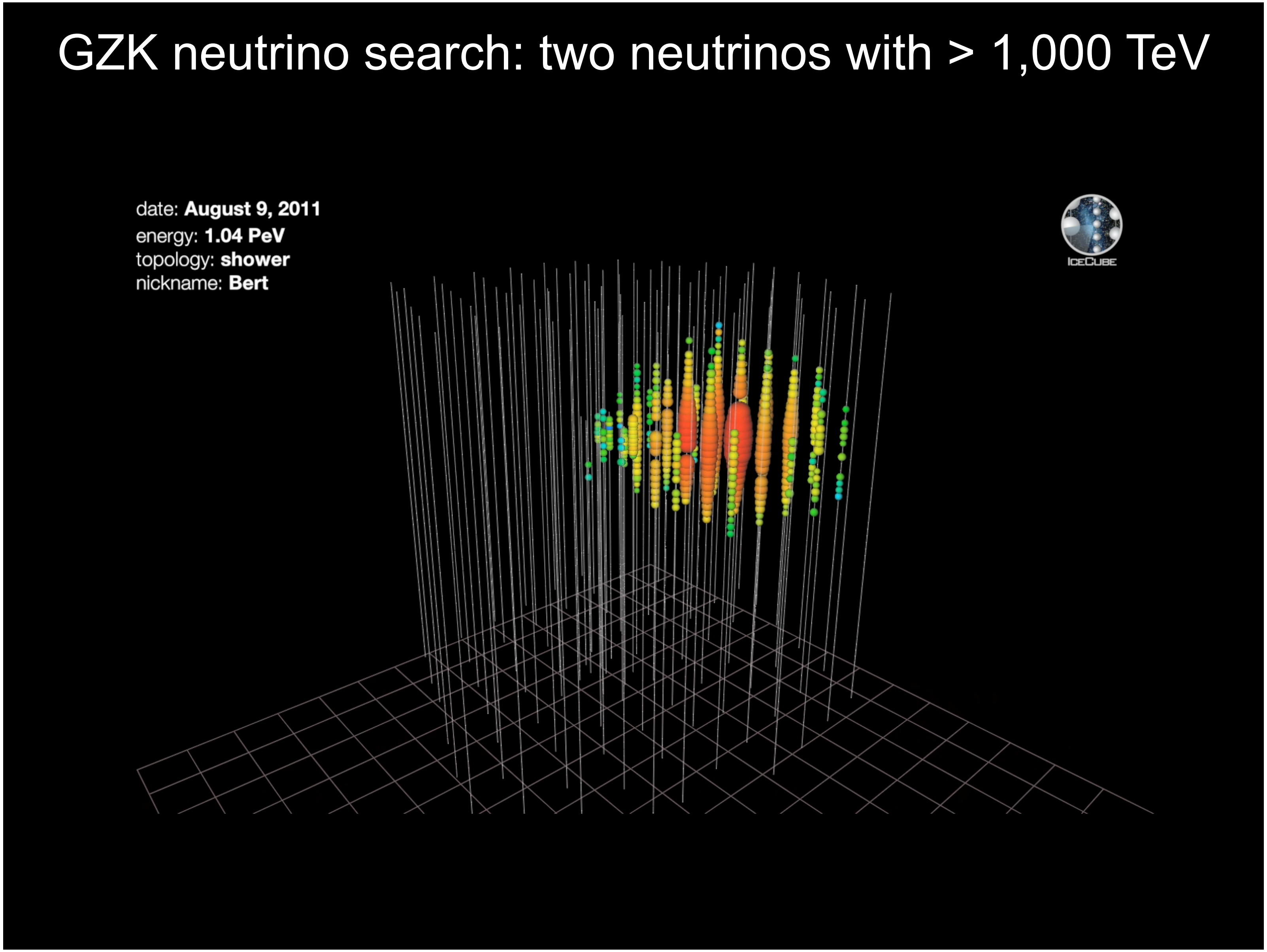
GZK neutrinos are produced from the following process:

A cosmic ray (*p*) with energy above ~4×10^{19} eV interacts with a CMB photon (γ) producing a pion (π). The charged pion will decay into a neutrino (ν) and the muon will decay into a positron (e^+) and neutrinos with ~10^6 TeV energy!

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

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

GZK neutrino search

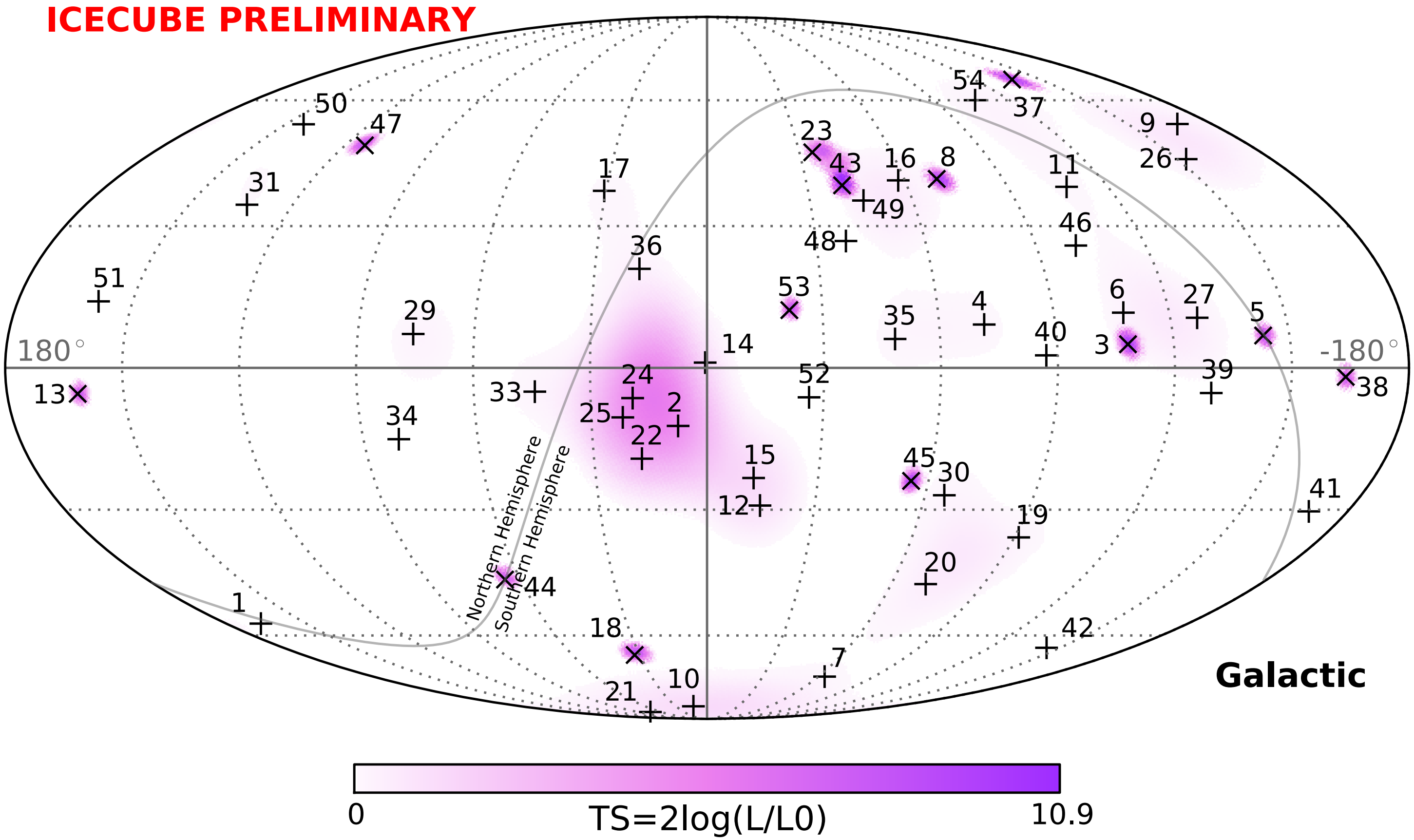


GZK neutrino search: two neutrinos with > 1,000 TeV

date: **August 9, 2011**
energy: **1.04 PeV**
topology: **shower**
nickname: **Bert**

Origin of Astrophysical Neutrinos

4 year HESE



where do they come from?

Origin of Astrophysical Neutrinos

- The 4 year IceCube results confirm the presence of astrophysical neutrinos and provide a measurement of the flux of astrophysical neutrinos.

- The sources of these neutrinos are expected to be black holes and massive exploding stars (GRBs). These sources are able to accelerate protons to > 10^6 TeV

- The map of the detected locations of the astrophysical neutrinos indicates that most are of extragalactic origin but a small fraction my be from our own galaxy.

- Neutrinos above 100 TeV cannot be produced in the Earths atmosphere indicating that these are astrophysical in origin.

- The neutrino-induced tracks are used to locate the position of the sources to an accuracy of less than a degree in the sky.

Where are the gamma rays that should accompany neutrinos?

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

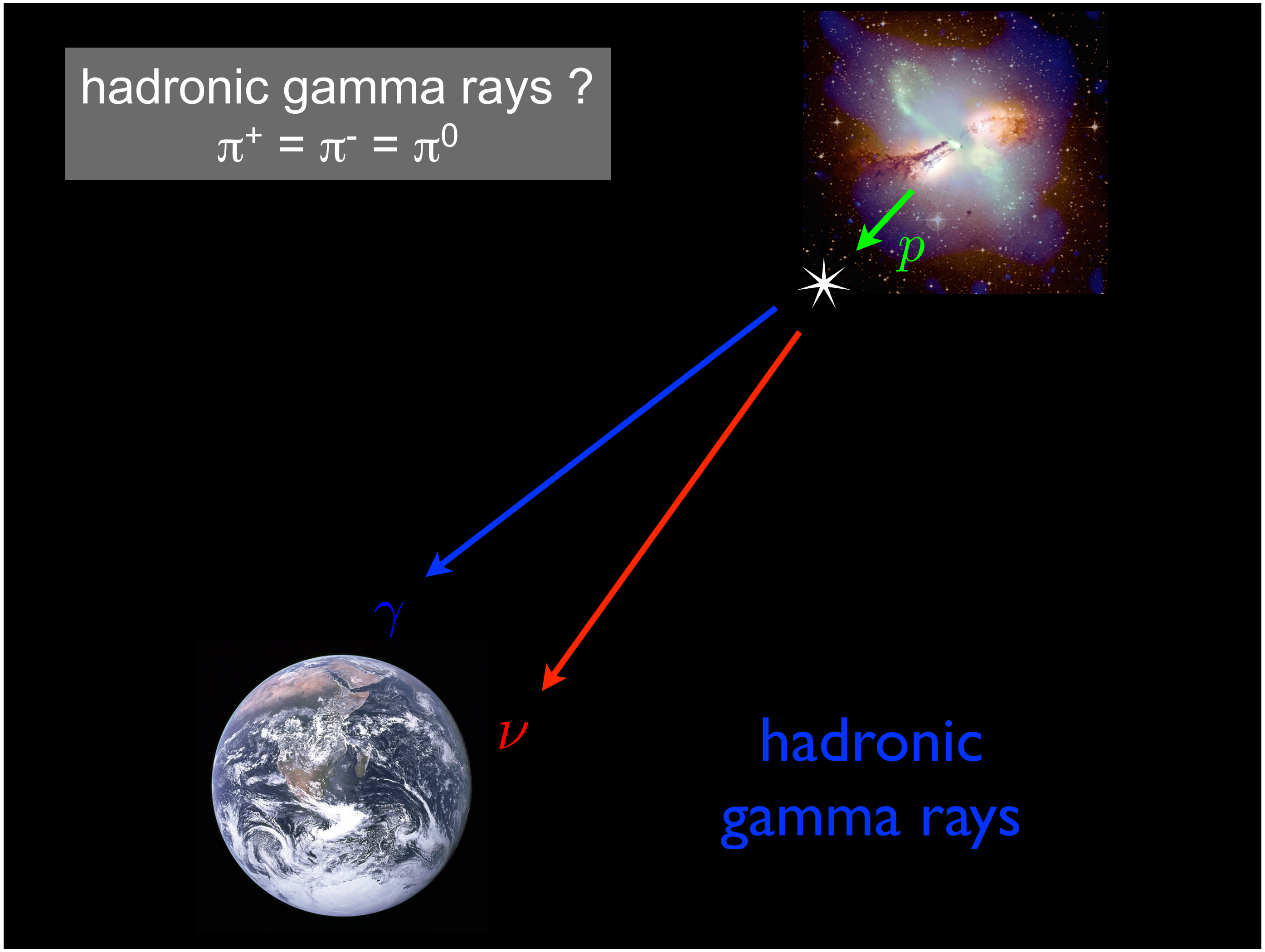
$\pi^{+} \rightarrow \mu^{+}+\nu_{\mu} \rightarrow \left\{e^{+}+\nu_{e}+\bar{\nu}_{\mu}\right\}+\nu_{\mu}$

(charged pion decays $\rightarrow$ cosmic rays and neutrinos)

$\pi^{0} \rightarrow e^{-}+e^{+}+\gamma$

(neutral pion decays $\rightarrow$ cosmic rays and gamma rays)

Where are the gamma rays that accompany neutrinos?

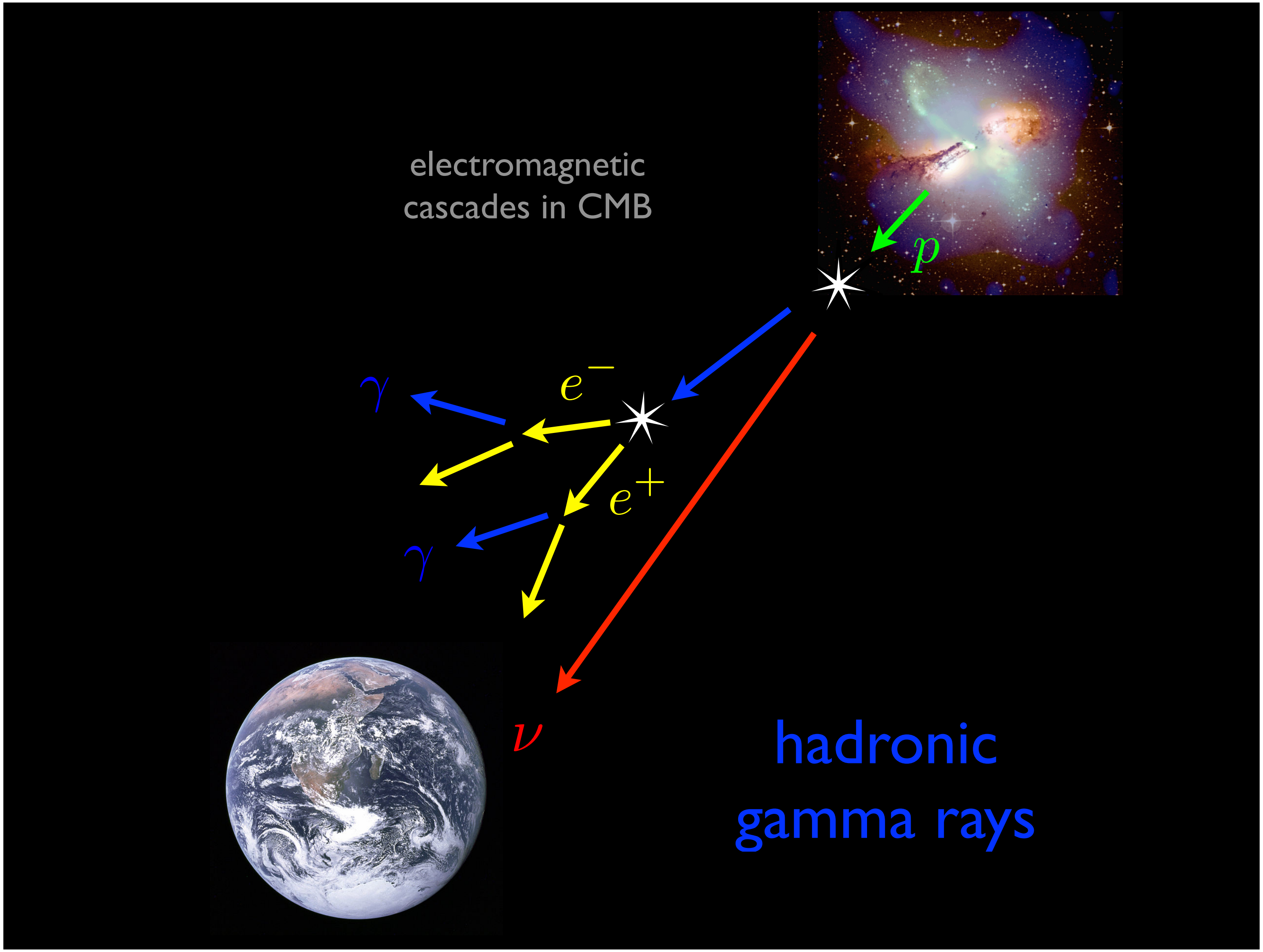


hadronic gamma rays ?
$\pi^+ = \pi^- = \pi^0$

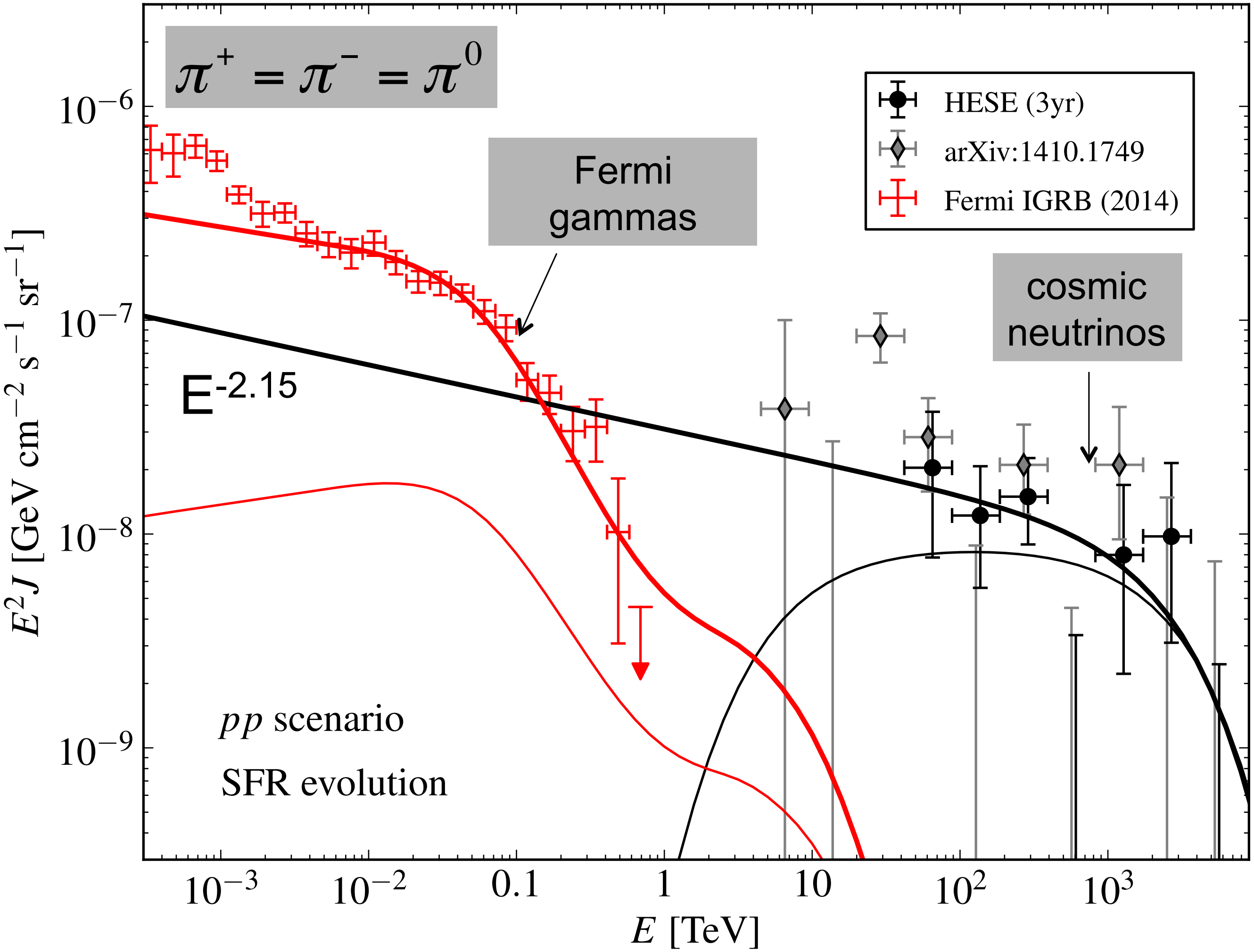
hadronic
gamma rays

Hadrons are particles made of two or more quarks held together by the strong force. Most of the mass of ordinary matter comes from two hadrons, the proton and the neutron (hadrons: pions, kaons, protons, neutrons…). Hadronic gamma rays are produced by the decay of neutral pions.

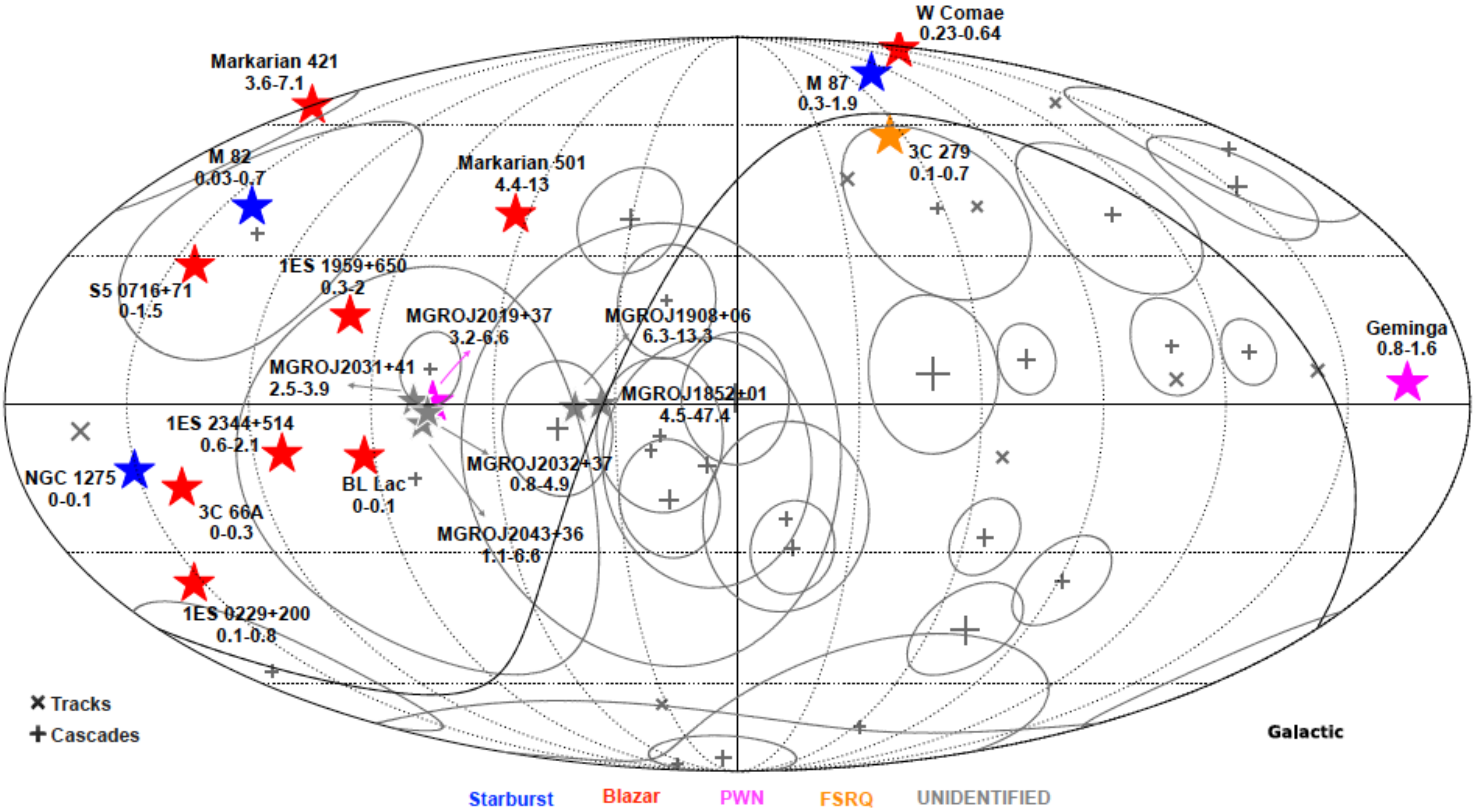
Where are the gamma rays that accompany neutrinos?

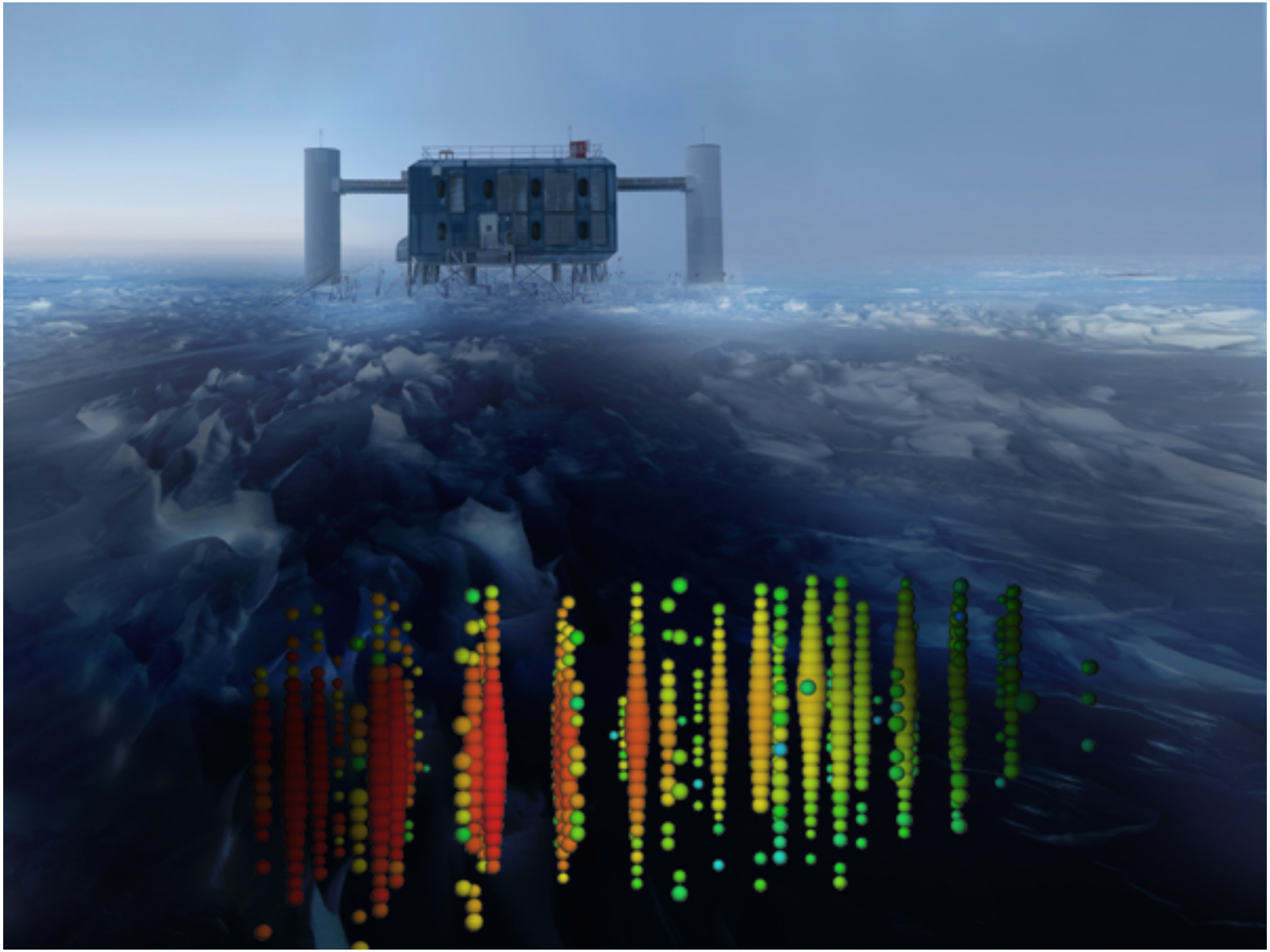


Where are the gamma rays that should accompany neutrinos? Answer: Fermi detects them



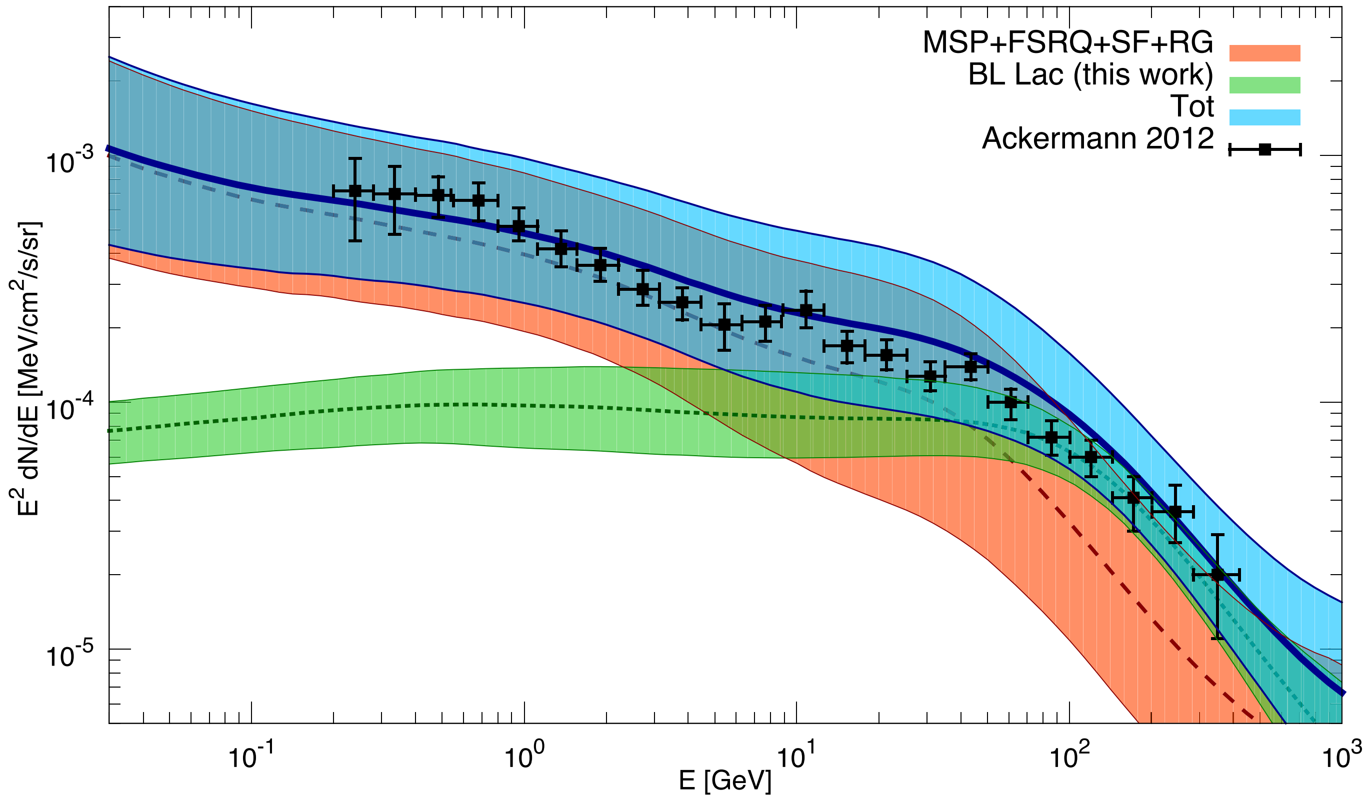
number of muon neutrino events from gamma ray sources in 5 years





This image shows one of the highest-energy neutrino events of this study superimposed on a view of the IceCube Lab (ICL) at the South Pole. Image: IceCube Collaboration

Where are the gamma rays that should accompany neutrinos? Produced mostly by Blazars above 50 GeV



Global view of the diffuse γ -ray predictions is displayed for unresolved **BL Lacs (dotted green)** and for the sum of misaligned AGNs, star-forming galaxies, FSRQs, and millisecond pulsars (orange dashed line and uncertainty band). IGRB data are also displayed with black points. The sum of all the predictions is displayed in a blue curve line and cyan uncertainty band (figure from Di Mauro et al. 2014)