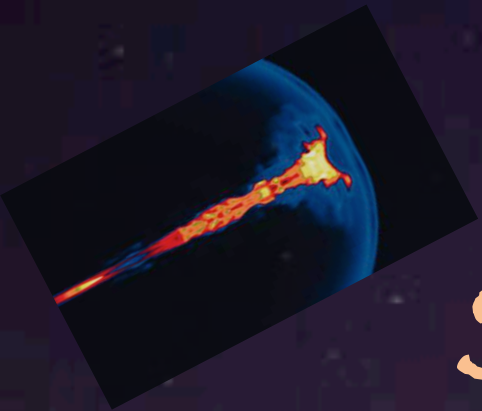
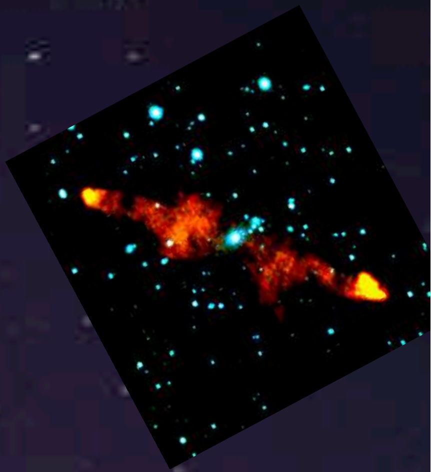


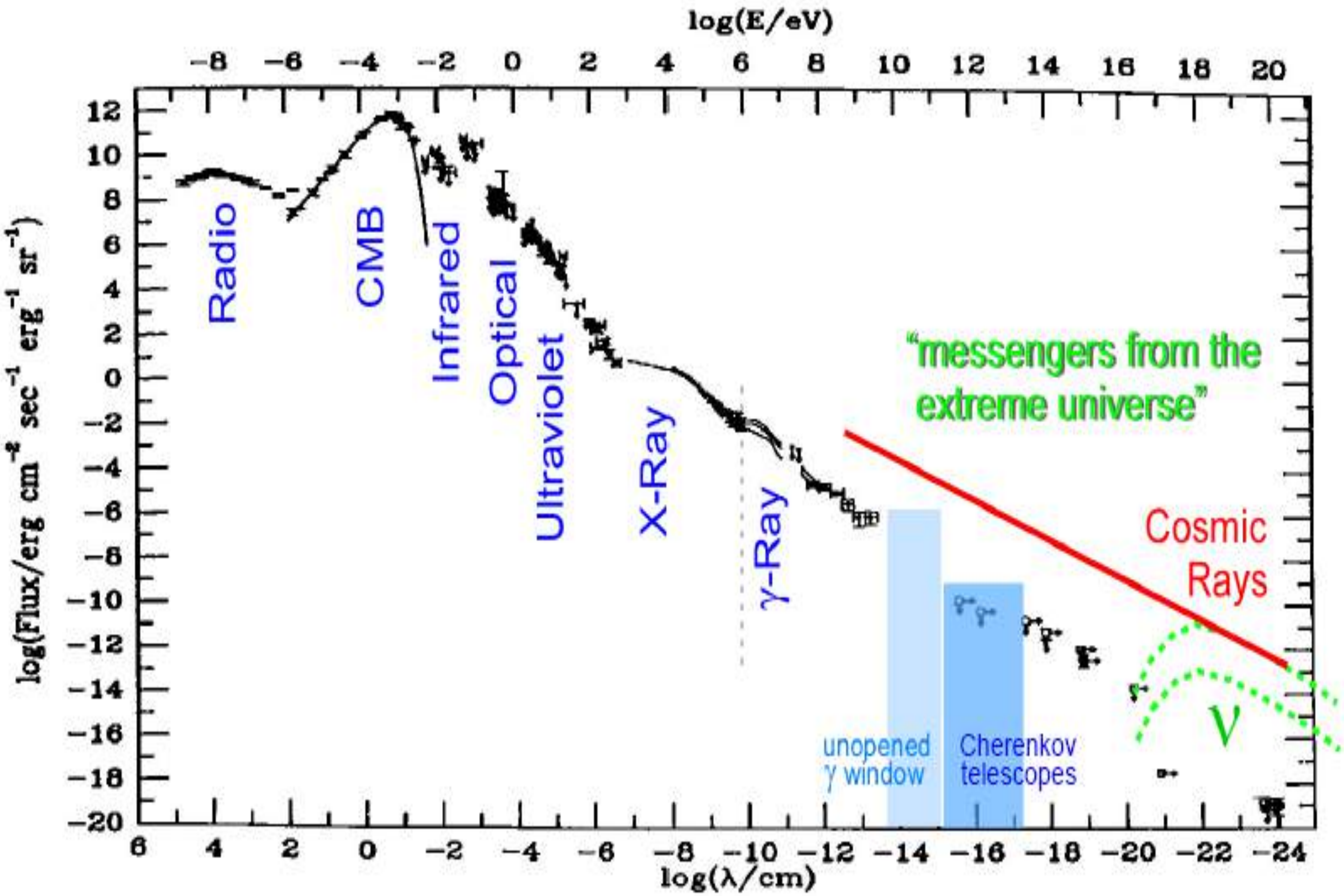




Seeing the high energy universe with IceCube

Subir Sarkar
Rudolf Peierls Centre

We can *see* the high energy universe directly with **photons** up to a few TeV
Beyond this energy they are attenuated through $\gamma\gamma \rightarrow e^+e^-$ on the infrared bkgd



But using **cosmic rays** we should be able to 'see' up to ~ 6 x 10^{10} GeV (before they get attenuated through $p\gamma \rightarrow \Delta^+ \rightarrow n\,\pi^+$ … on the CMB)

… and the universe is transparent to **neutrinos** at nearly *all* energies

The Origin of Cosmic Rays

Extraordinary cosmic particle accelerators ***somewhere***, but still **poorly identified** a century after the discovery of cosmic rays …

- Supernova remnants ✓
- Active galactic nuclei?
- Gamma ray bursts?
- Radio galaxy jets?
- …?

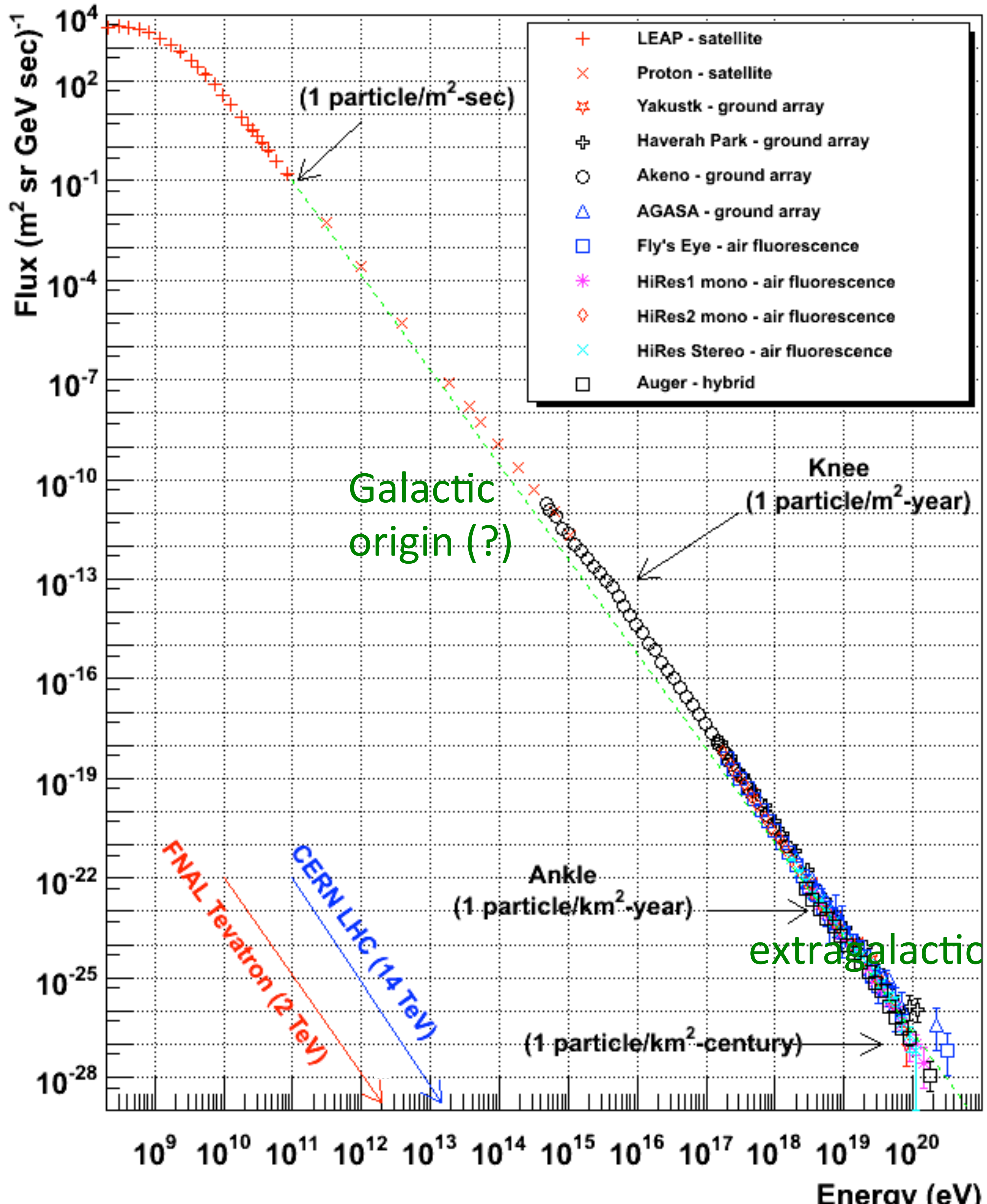
Cosmic ray interactions with matter and photons, near source or during propagation, produce neutrinos:

$$p + N \rightarrow X + \{\pi^+, \pi^-, \pi^0\}$$

$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

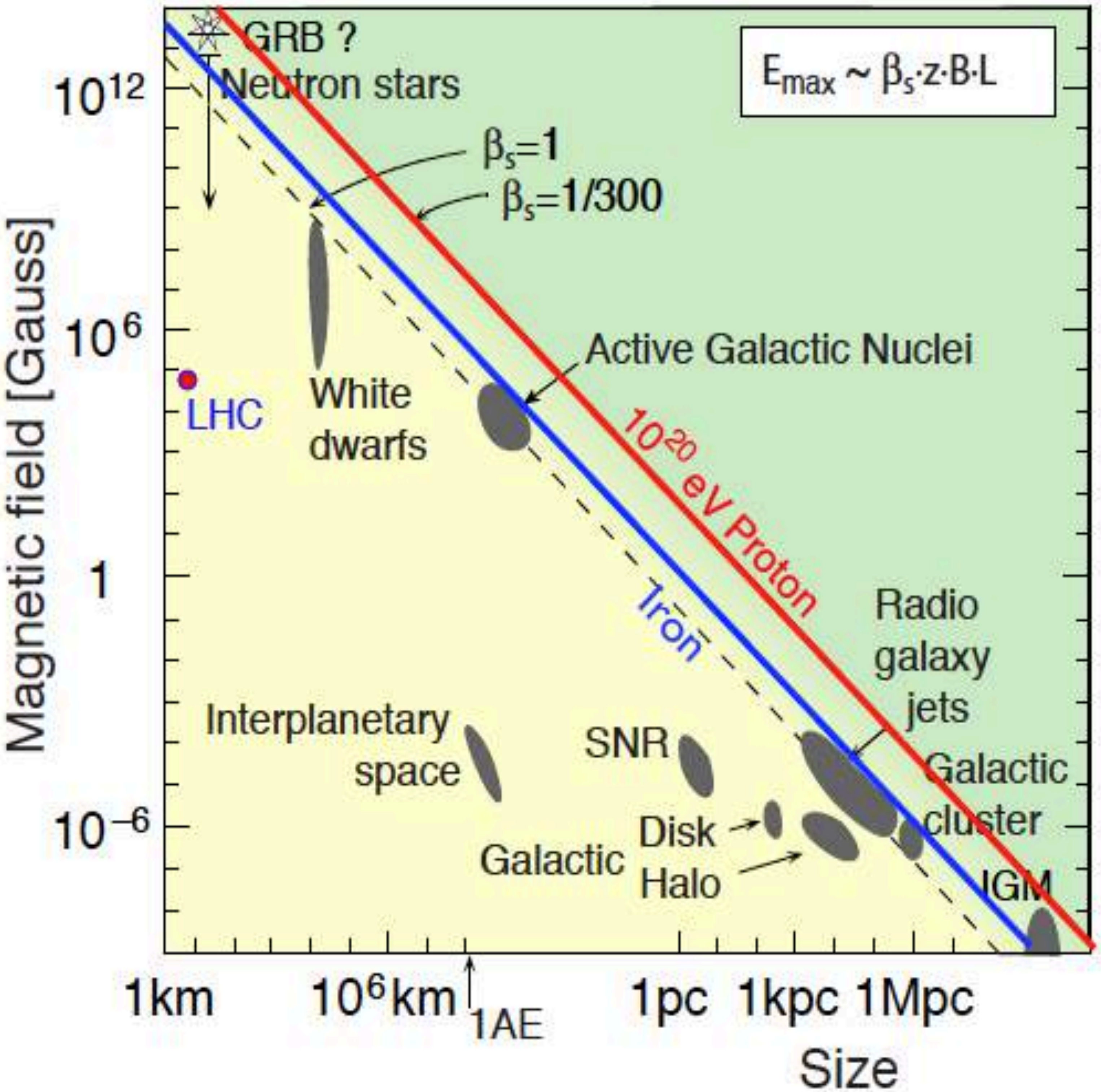
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

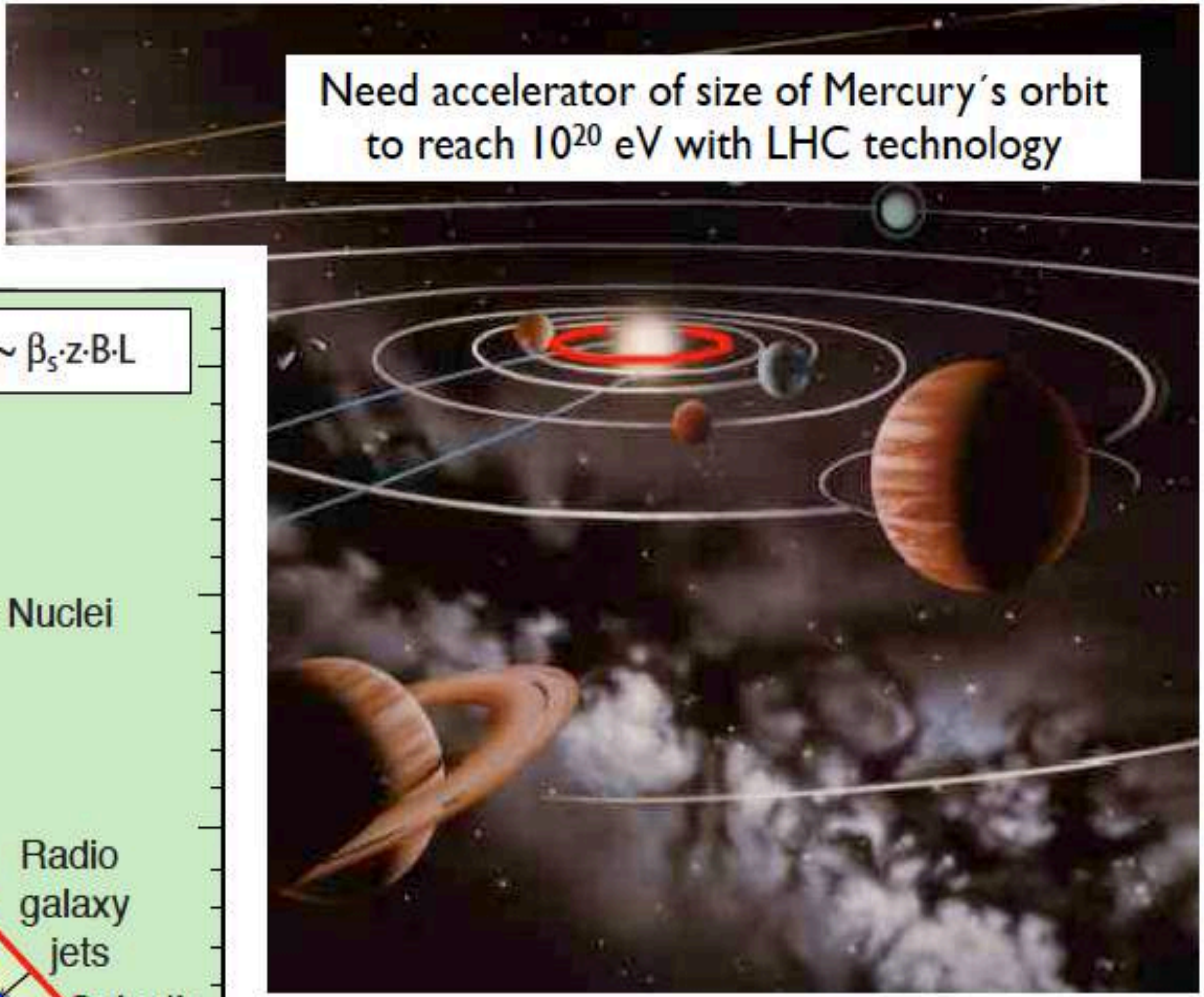


Neutrino scillations en-route to Earth equlibrate flavours

How does Nature manage to accelerate particles to ~ZeV energies?

Hillas plot (1984)





Realistic constraints more severe

- small acceleration efficiency
- synchrotron & adiabatic losses
- interactions in source region

The sources of cosmic rays *must* also be neutrino sources

Waxman-Bahcall Bound :

- $1/E^2$ injection spectrum (Fermi shock).
- Neutrinos from photo-meson interactions in the source.
- Energy in ν's related to energy in CR's :

$$[E_\nu^2\Phi_\nu]_{\rm WB} \approx (3/8)\,\xi_Z\,\epsilon_\pi\,t_{\rm H}\,\frac{c}{4\pi}\,E_{\rm CR}^2\,\frac{d\dot{N}_{\rm CR}}{dE_{\rm CR}}$$

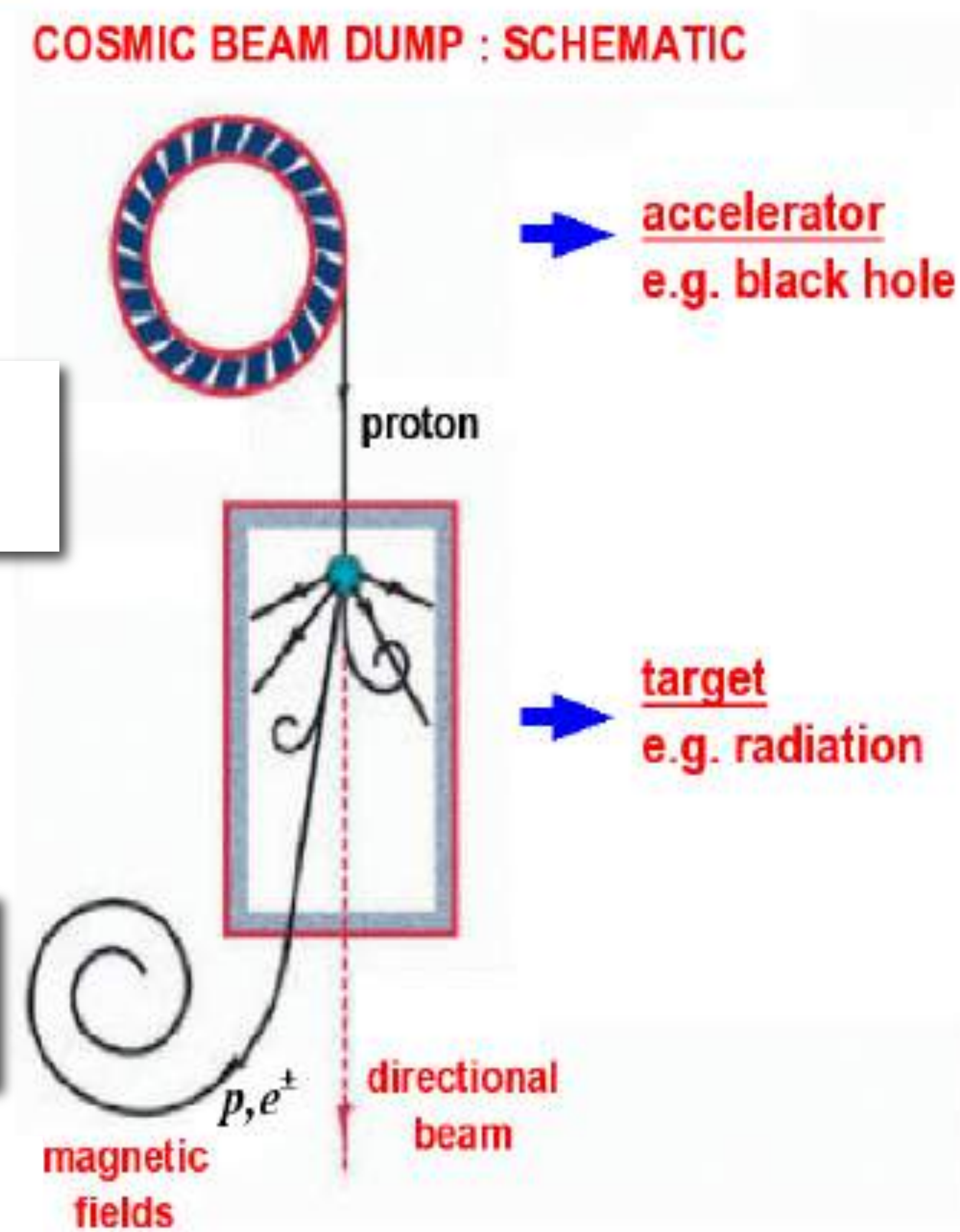
Fraction of CR primary energy converted to neutrinos

Hubble time

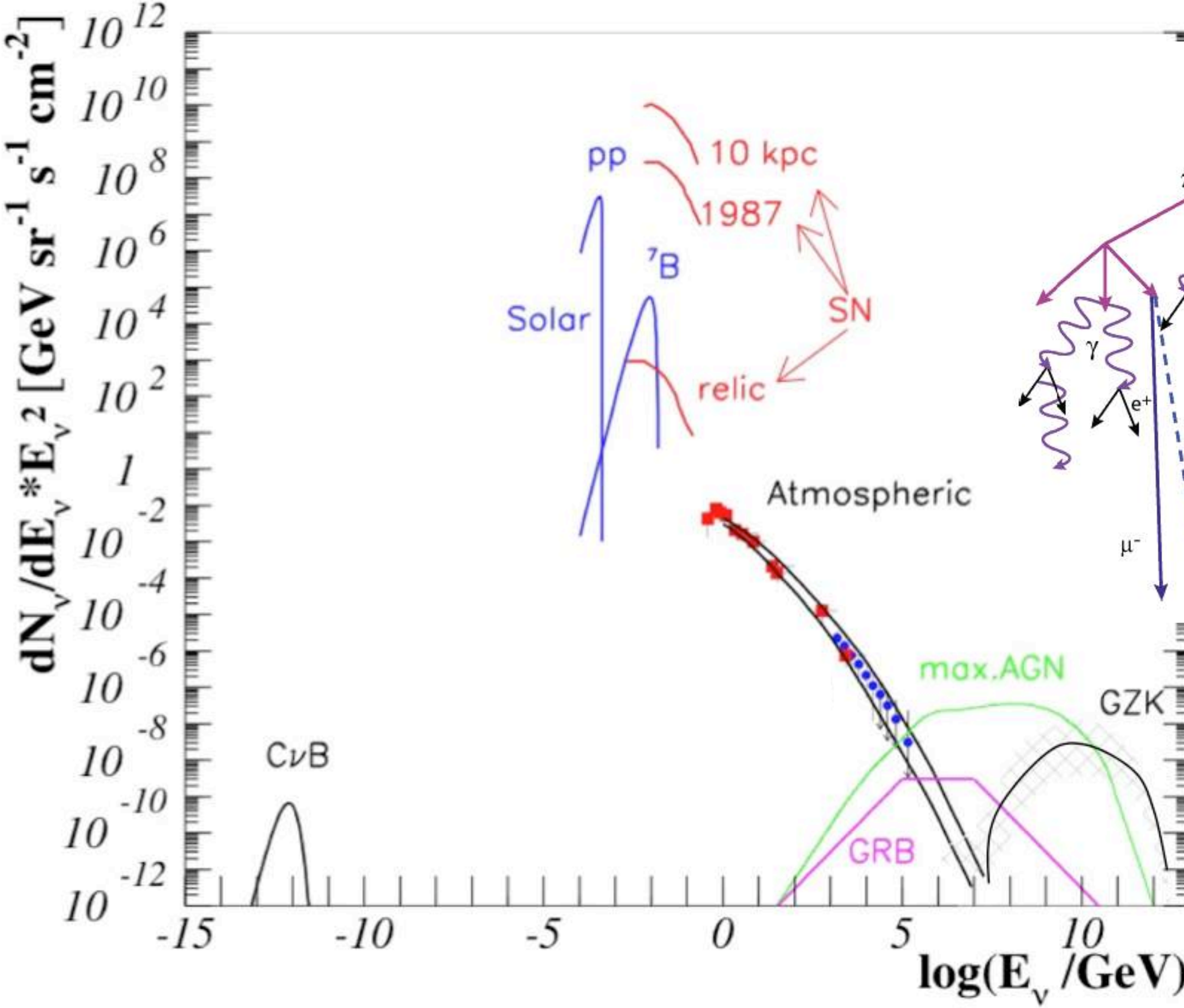
From rate of UHE CR's (10^{19}-10^{21} eV)

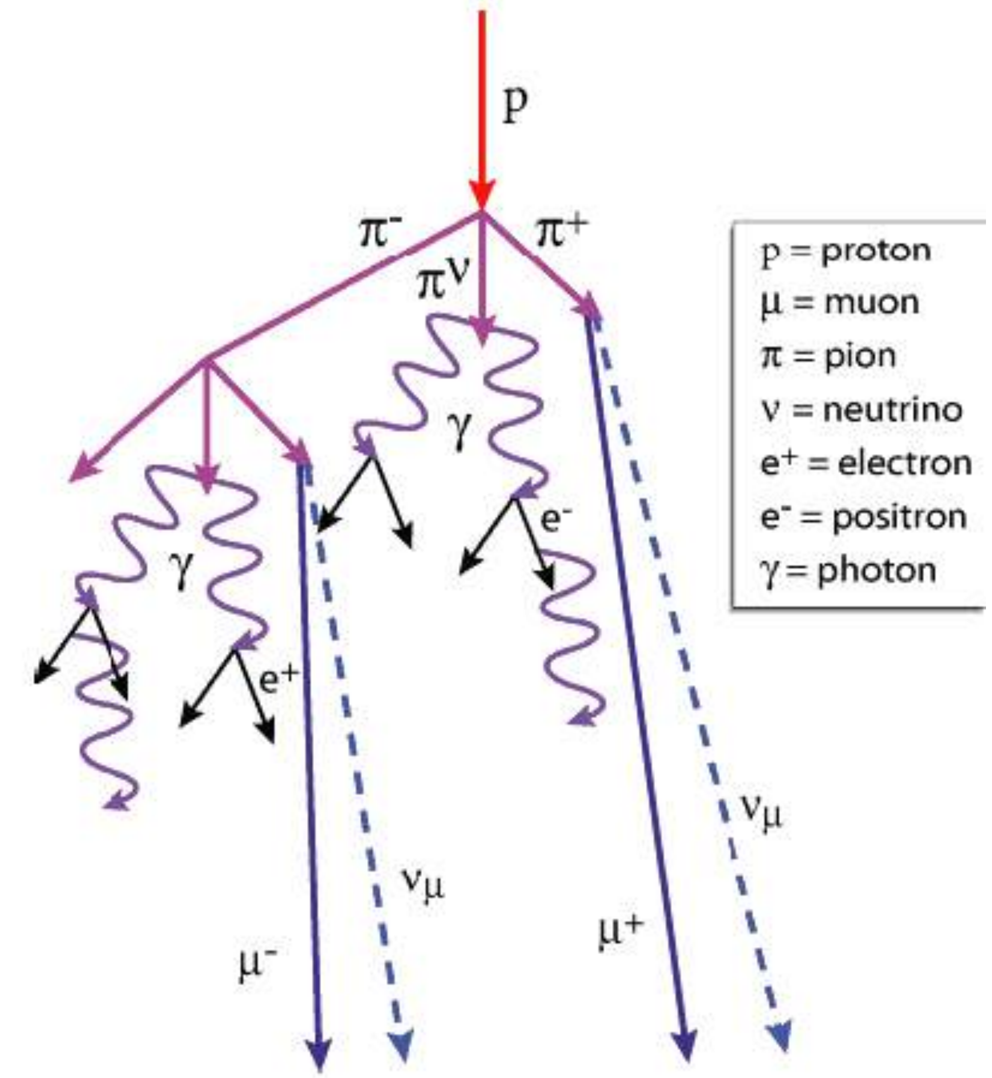
$$\approx\ 2.3\times10^{-8}\,\epsilon_\pi\,\xi_Z\,{\rm GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

➡Making a reasonable estimate for ϵ_π etc allows this to be converted into a flux prediction



Natural Sources of Neutrinos



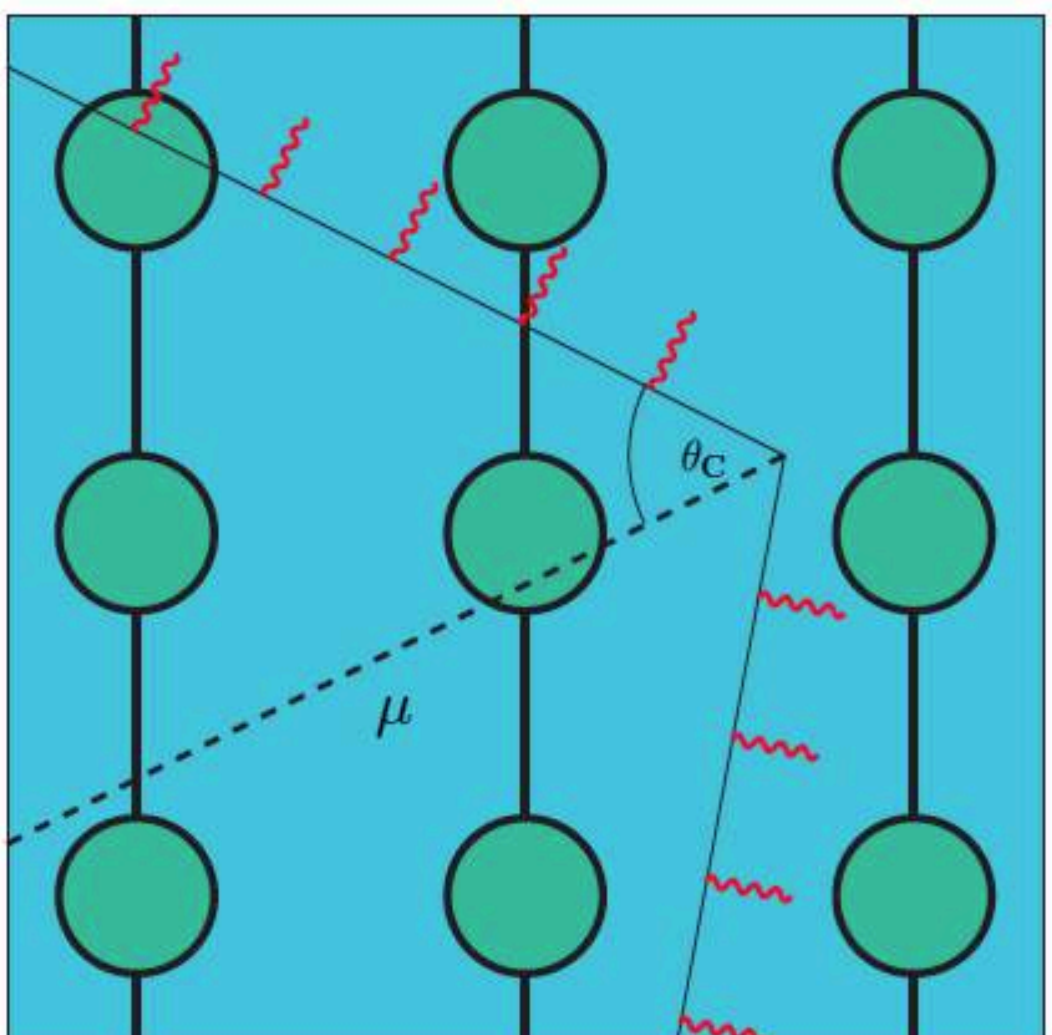


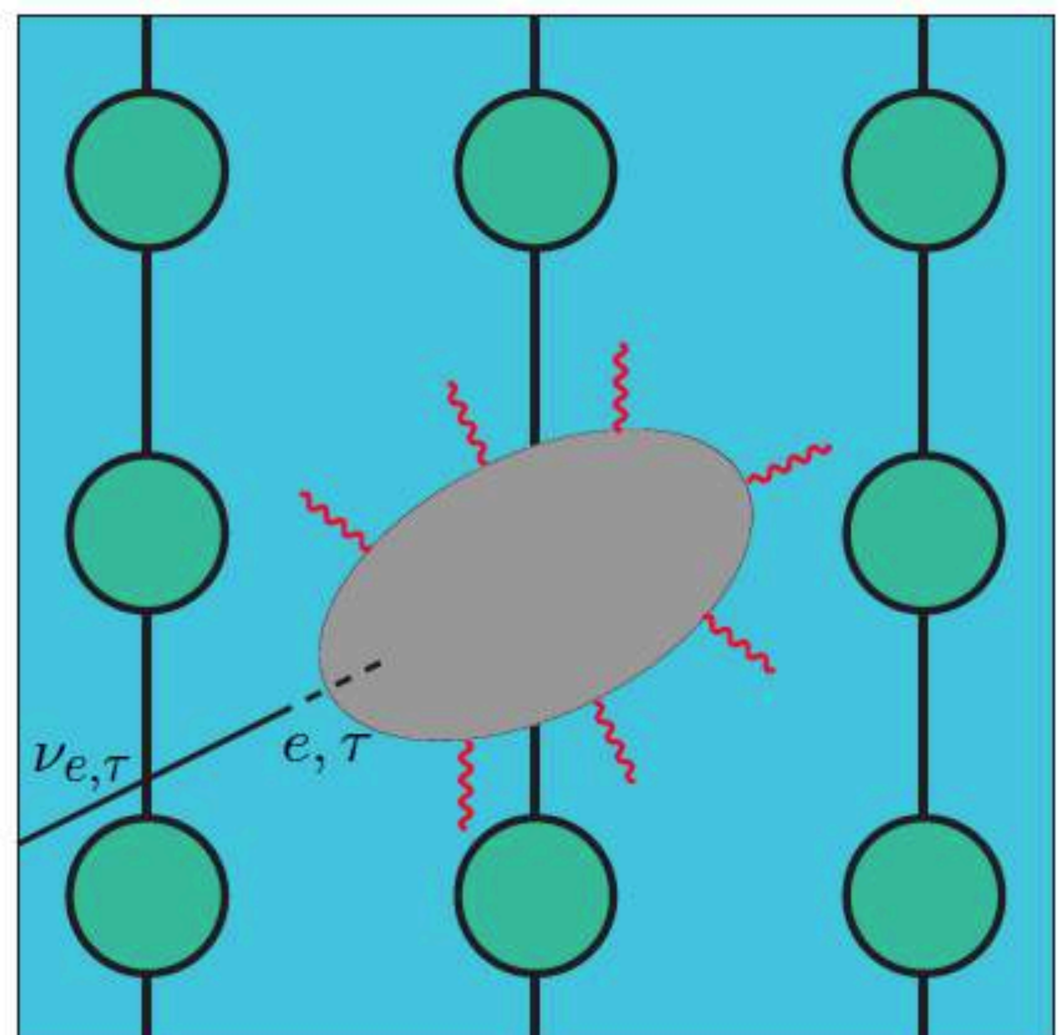
back-of-the-envelope ($E_\nu \sim 10^{15}$ eV):

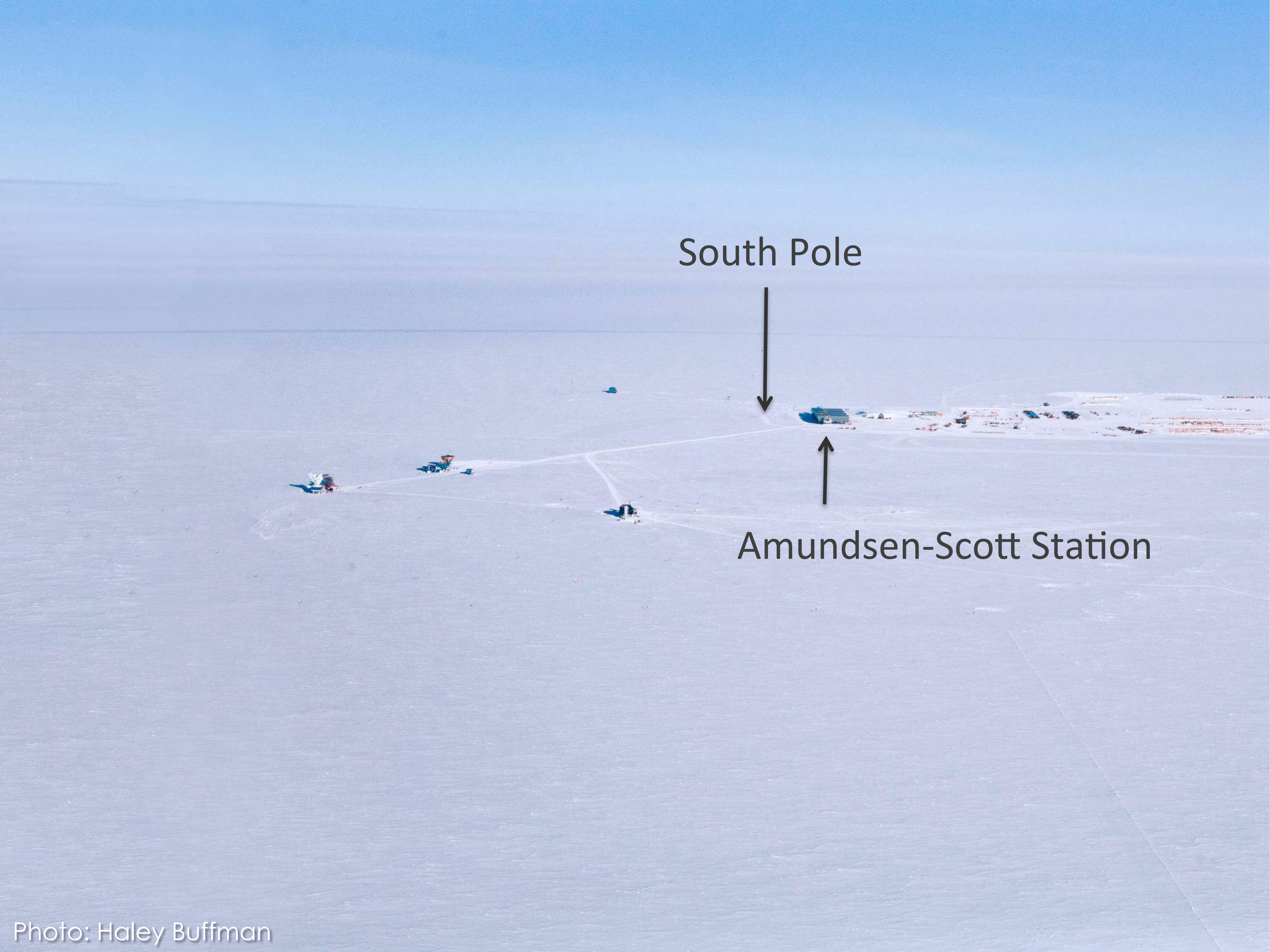
- **flux of neutrinos** : $\frac{\mathrm{d}^2 N_\nu}{\mathrm{d}t\,\mathrm{d}A} \sim \frac{1}{\mathrm{cm}^2 \times 10^5 \mathrm{yr}}$
- **cross section** : $\sigma_{\nu N} \sim 10^{-33} \mathrm{cm}^2$
- **targets**: $N_N \sim N_A \times V/\mathrm{cm}^3$

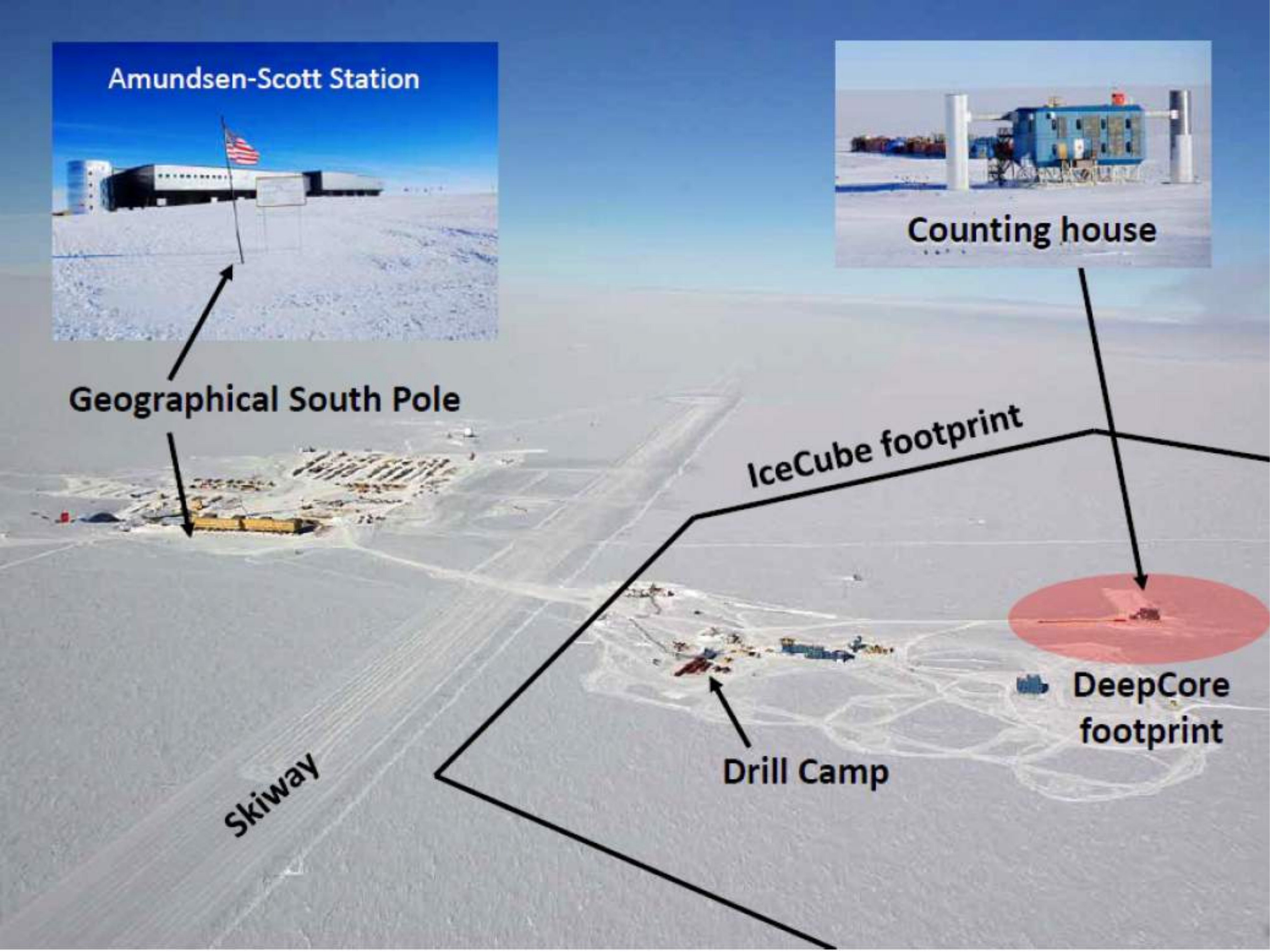
→ **rate of events** :

$$\dot{N}_\nu \sim N_N \times \sigma_{\nu N} \times \frac{\mathrm{d}^2 N_\nu}{\mathrm{d}t\,\mathrm{d}A} \sim \frac{1}{\mathrm{year}} \times \frac{V}{1\mathrm{km}^3}$$






South Pole
Amundsen-Scott Station
Photo: Haley Buffman



Amundsen-Scott Station
Counting house
Geographical South Pole
IceCube footprint
DeepCore footprint
Drill Camp
Skiway

The IceCube Collaboration

~250 scientists
40 institutions
11 countries

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
- Swedish Polar Research Secretariat
- The Swedish Research Council (VR)
- University of Wisconsin Alumni Research Foundation (WARF)
- US National Science Foundation (NSF)

IceCube Neutrino Observatory

86 strings

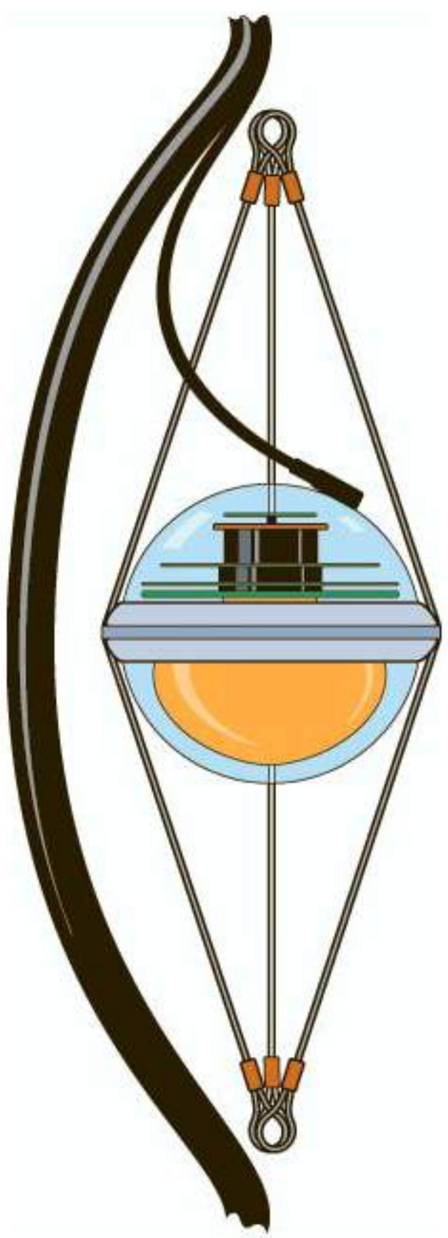
60 Optical Modules per string

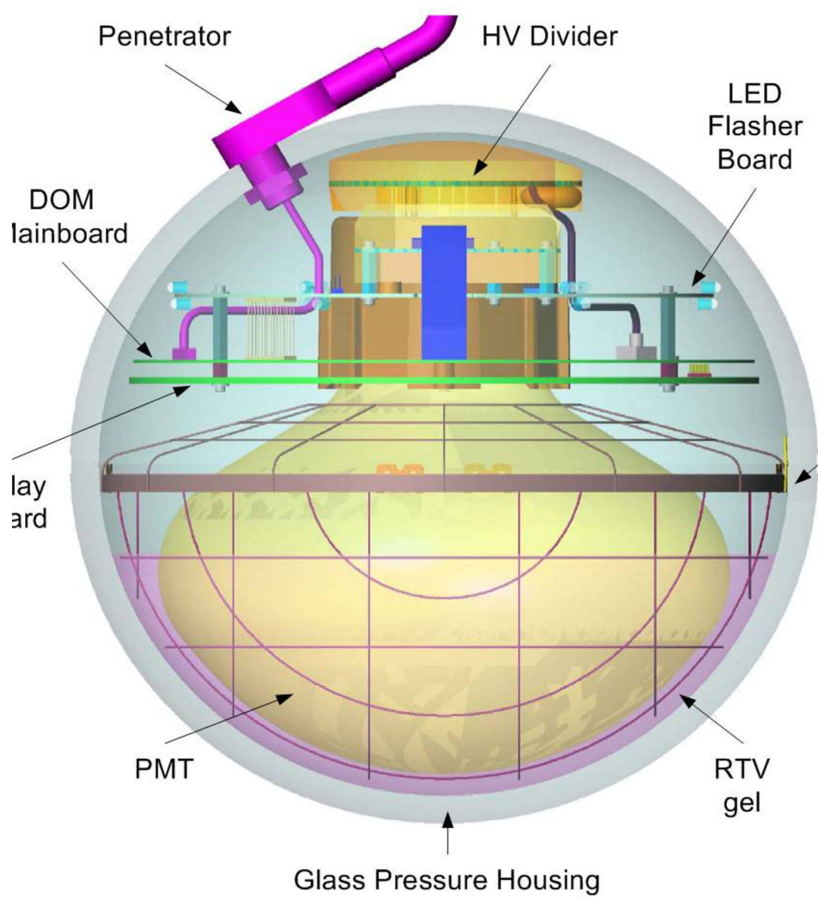
5160 Optical Modules in Ice

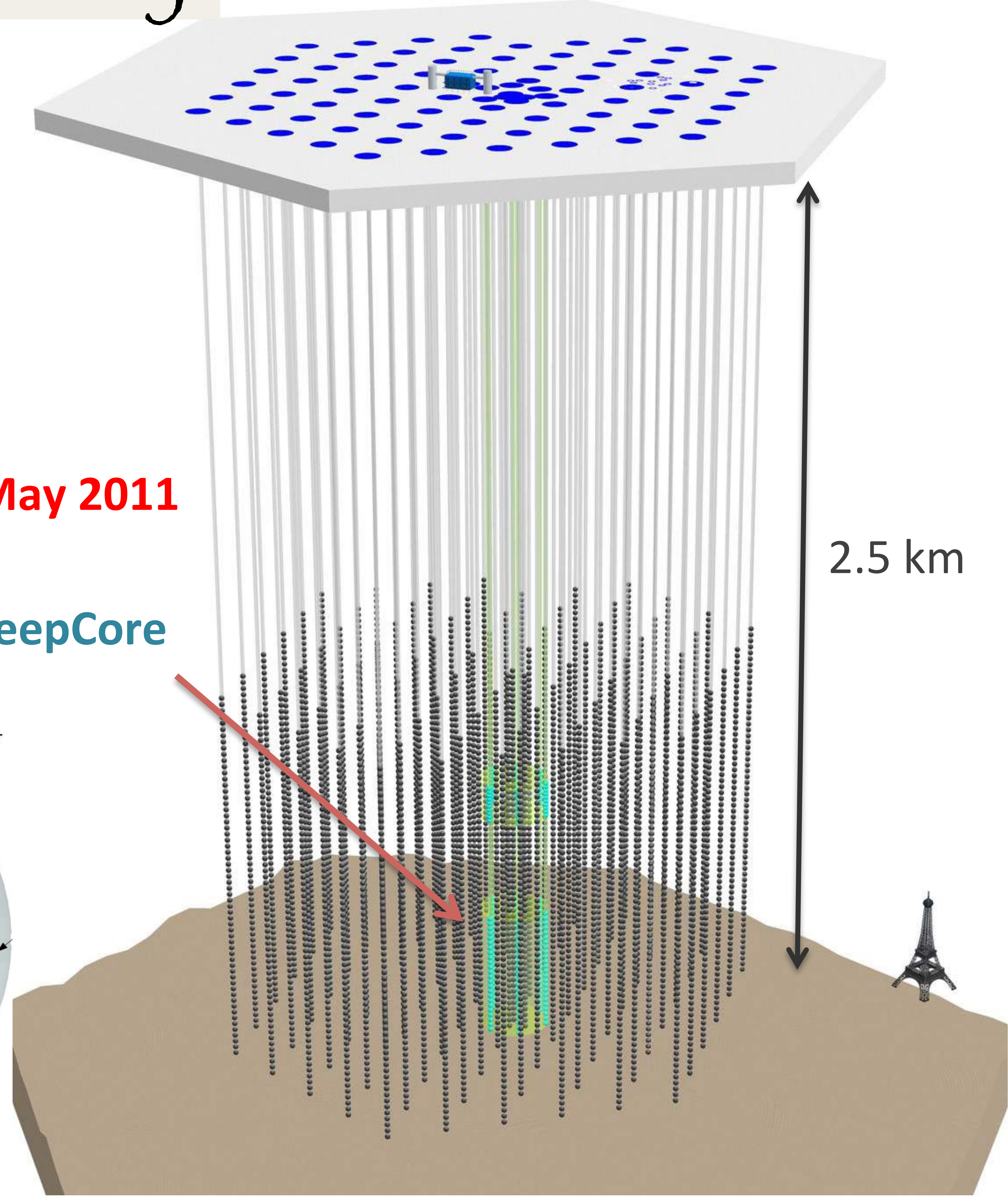
1 km^3 = Gton instrumented volume

Completed, began full operations May 2011

IceTop: 1 km^2 surface array

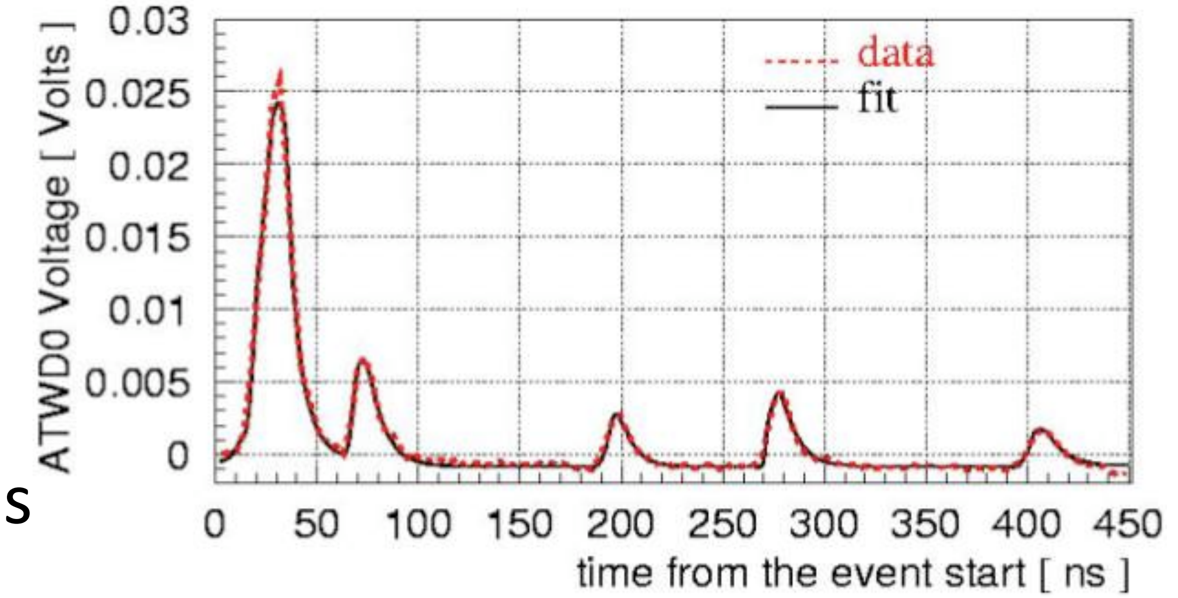


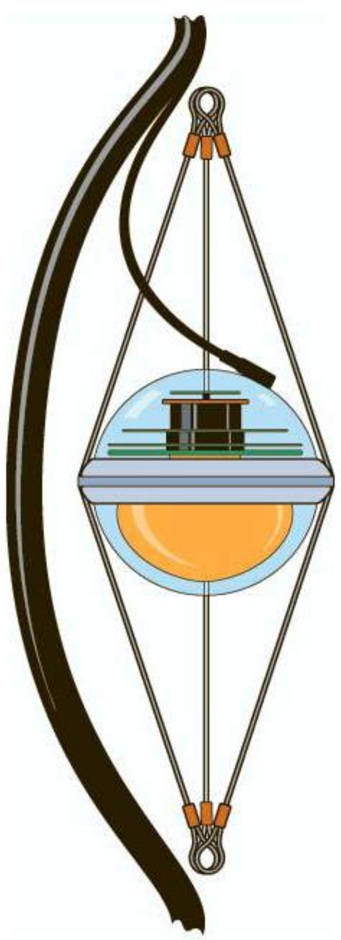


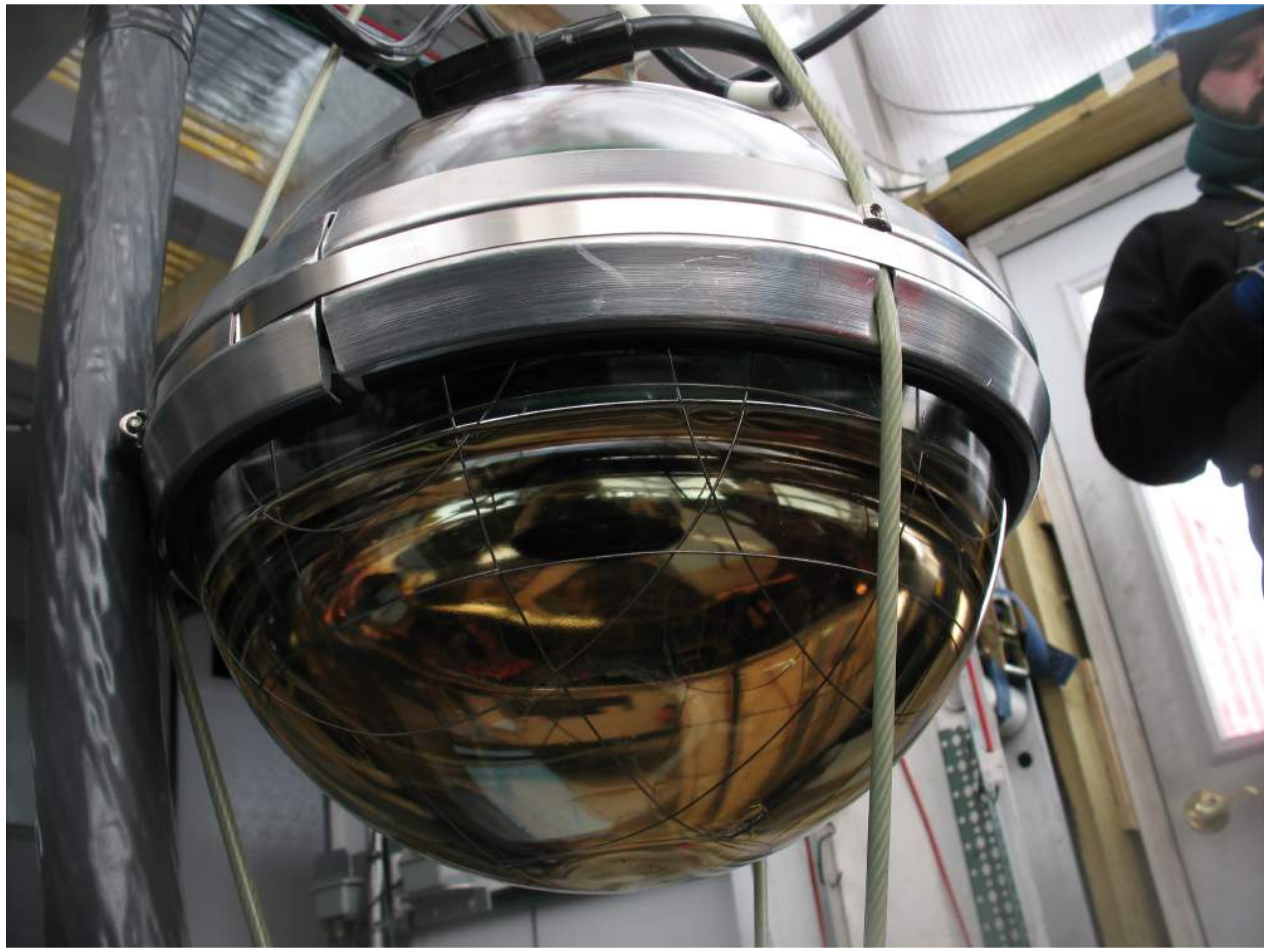


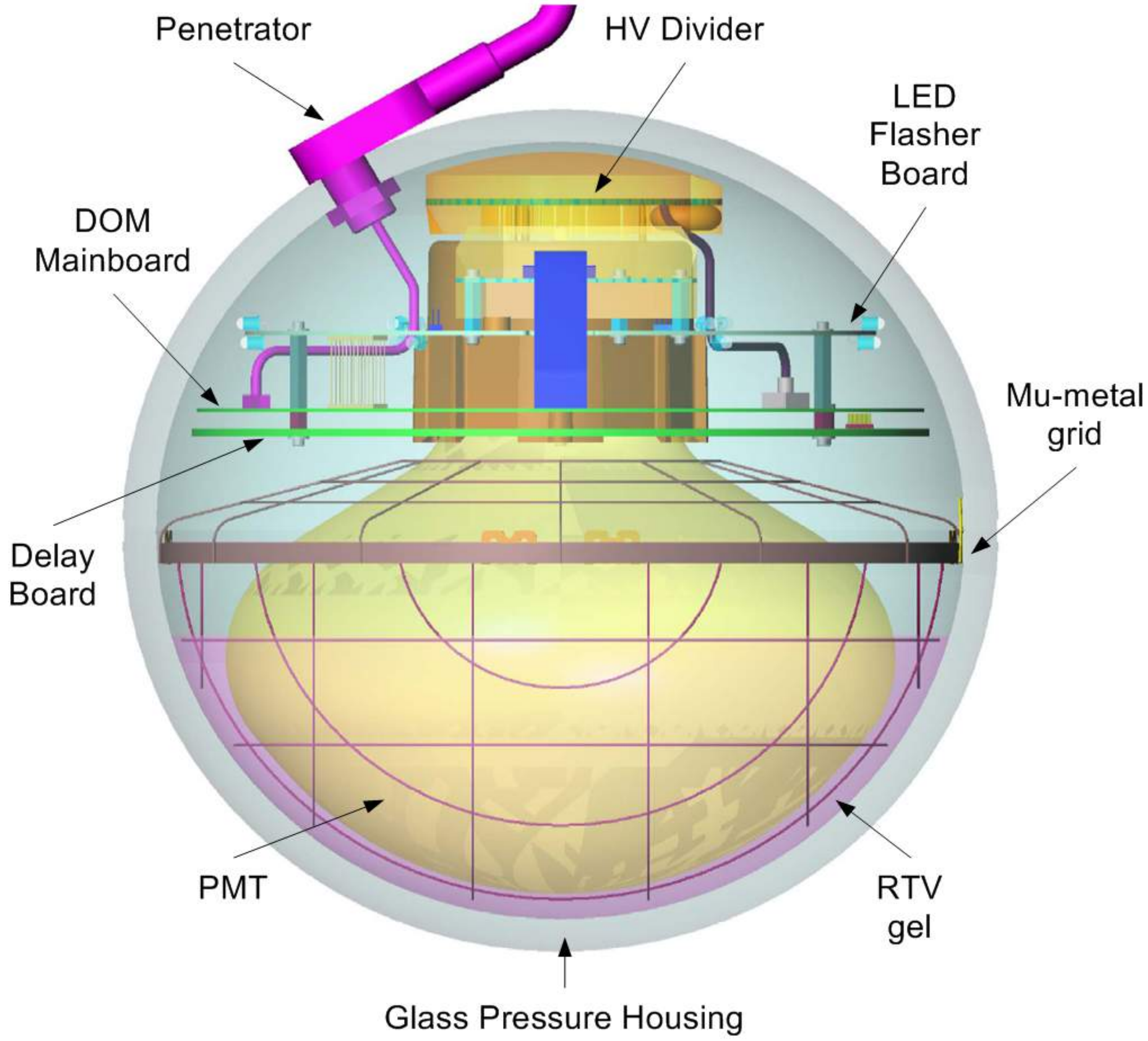
Digital Optical Modules

10” Hamamatsu Photomultiplier tubes (PMT)
3.5 W Power
Internal digitization and timestamping:
 ATWD: 300 MHz (400 ns)
 fADC: 40 MHz (6400 ns)
Dynamic range: from one to thousands of photo-electrons
Transmit digital data to surface

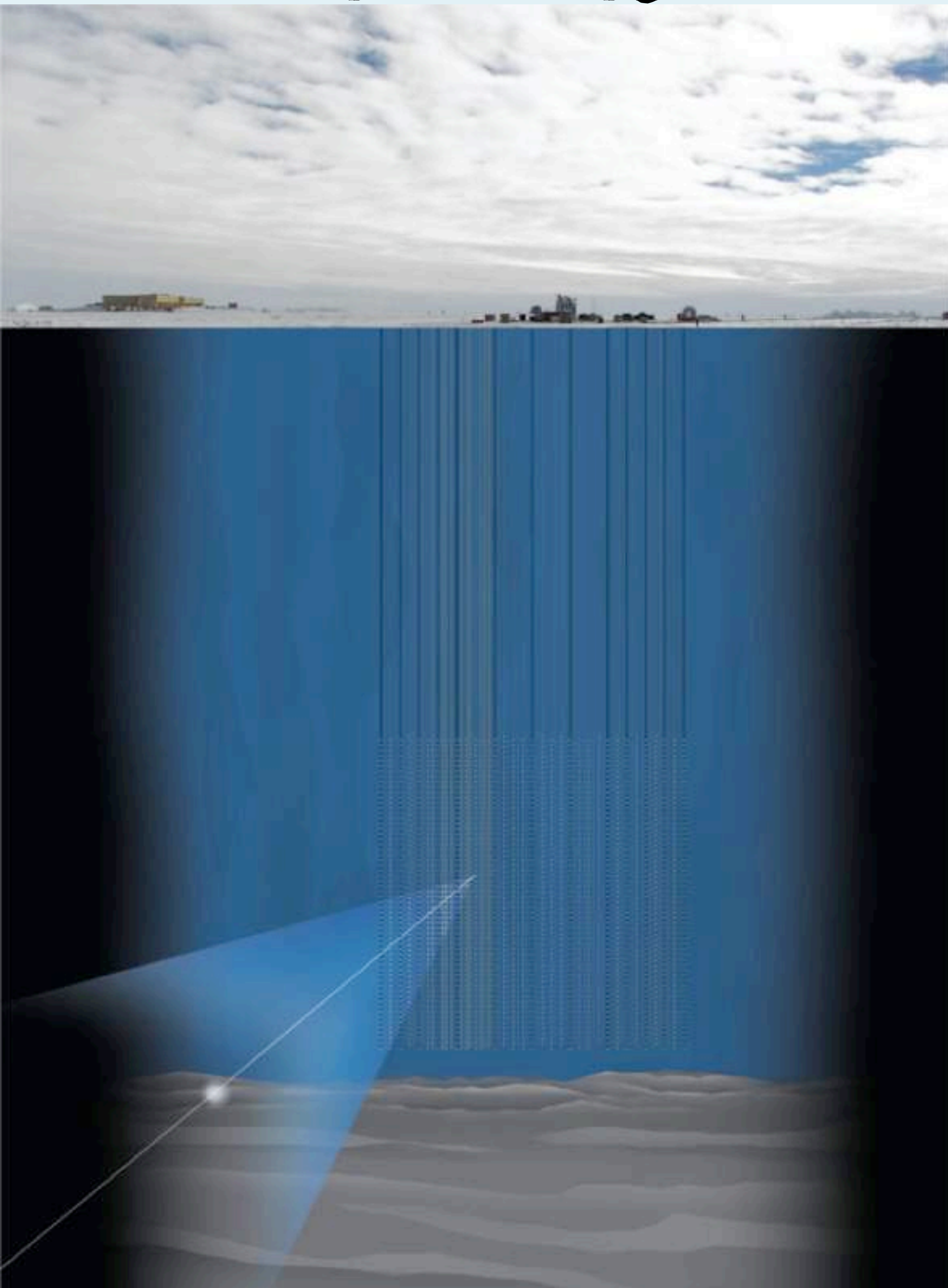


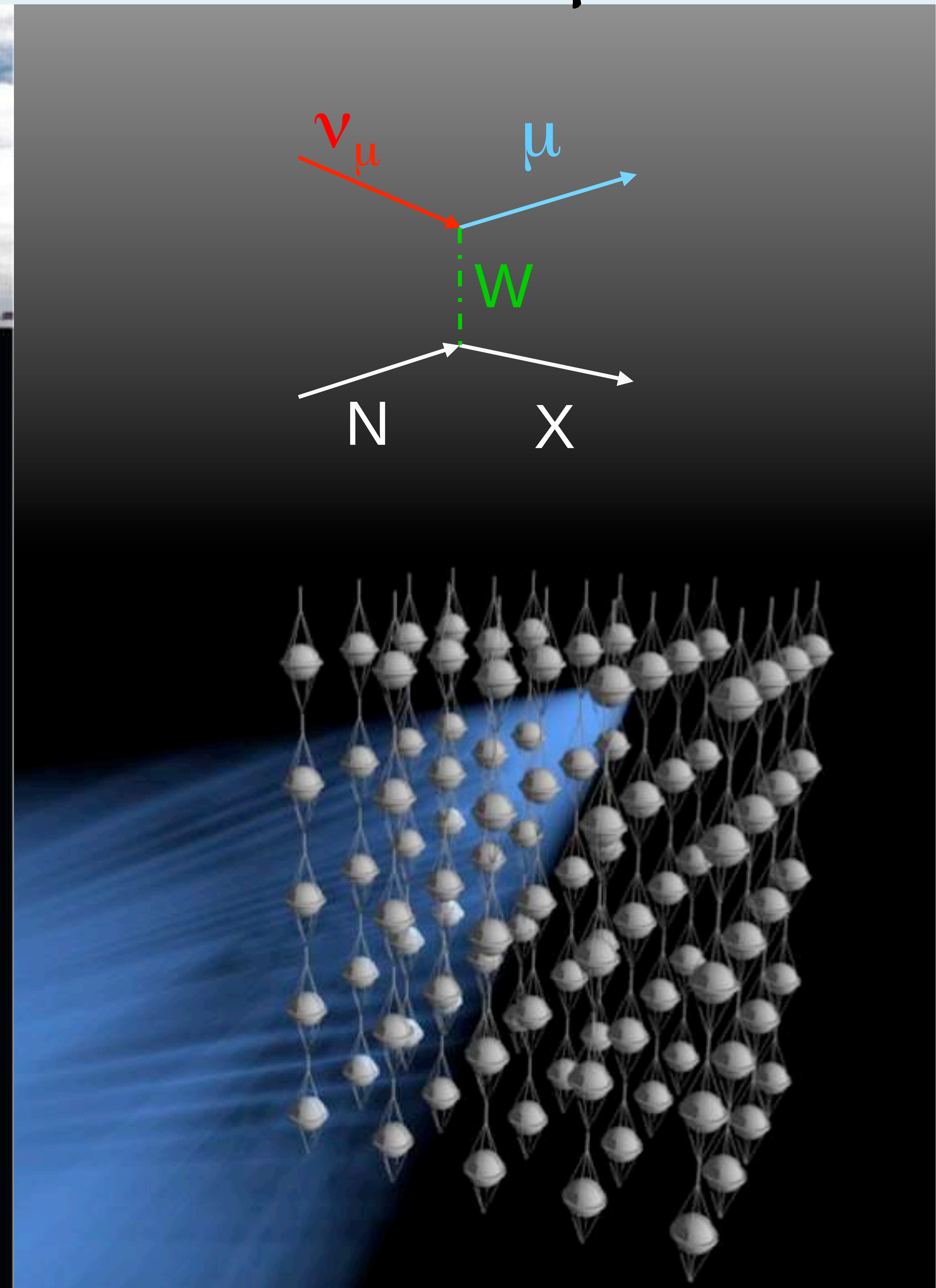






High Energy Neutrino Detection Principle



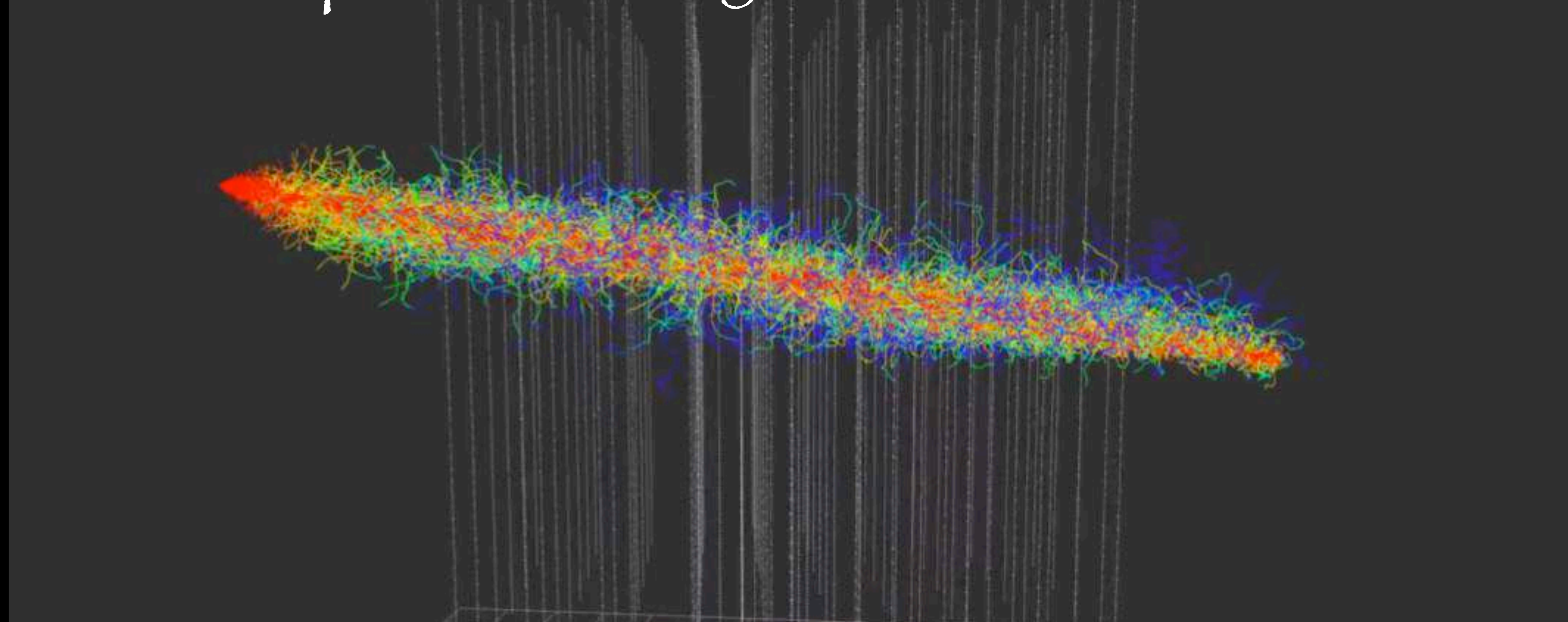


Photons produced by Neutrino Interactions

Track topology

(induced by muon neutrino)

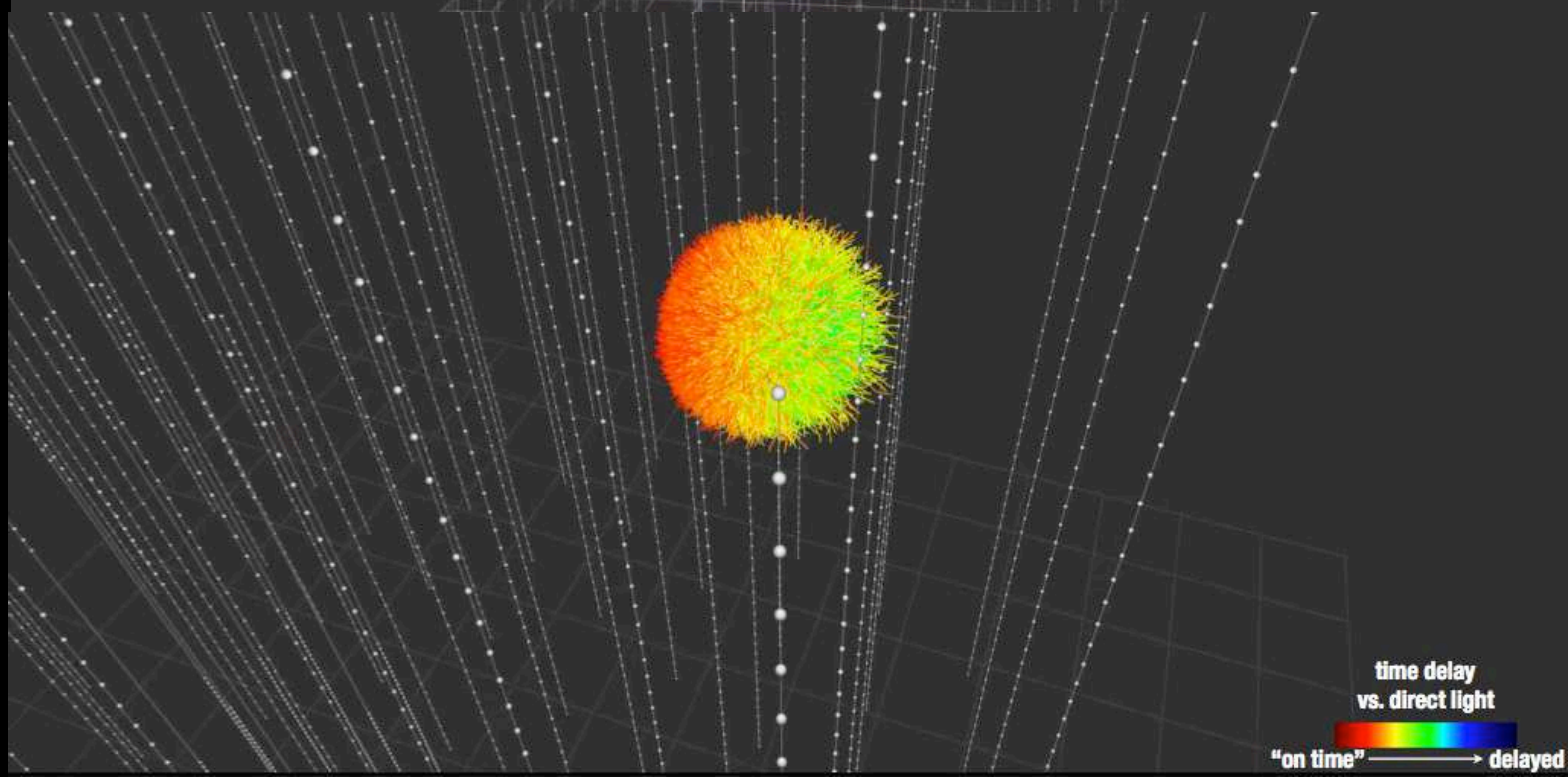
Good pointing (0.2° - 1°) but only *lower bound* on neutrino energy



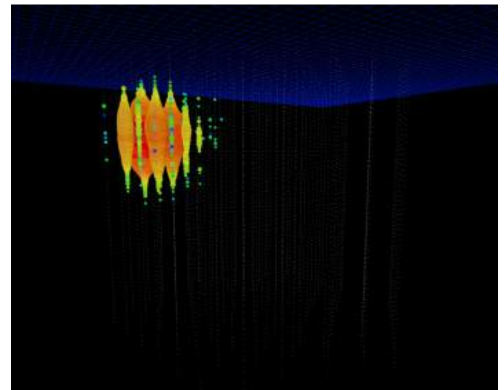
Cascade topology

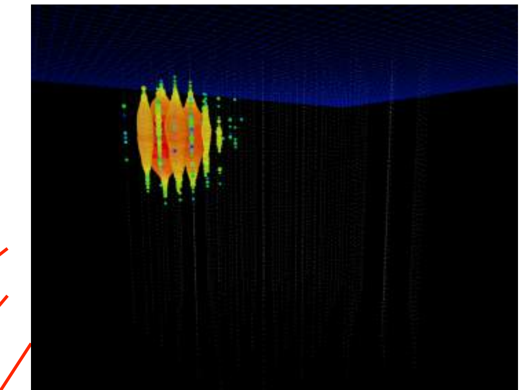
(induced by e.g. electron neutrino)

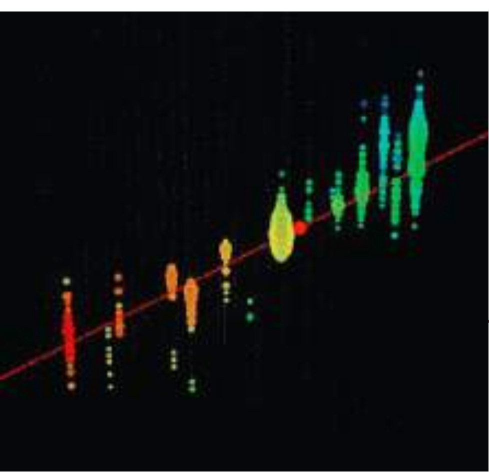
Good energy resolution (~15%) poor pointing (~10° - 15°)



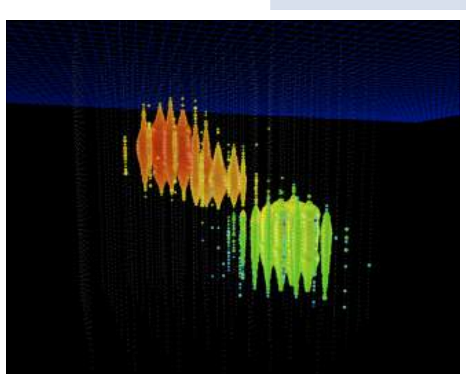
Neutrino signatures in IceCube



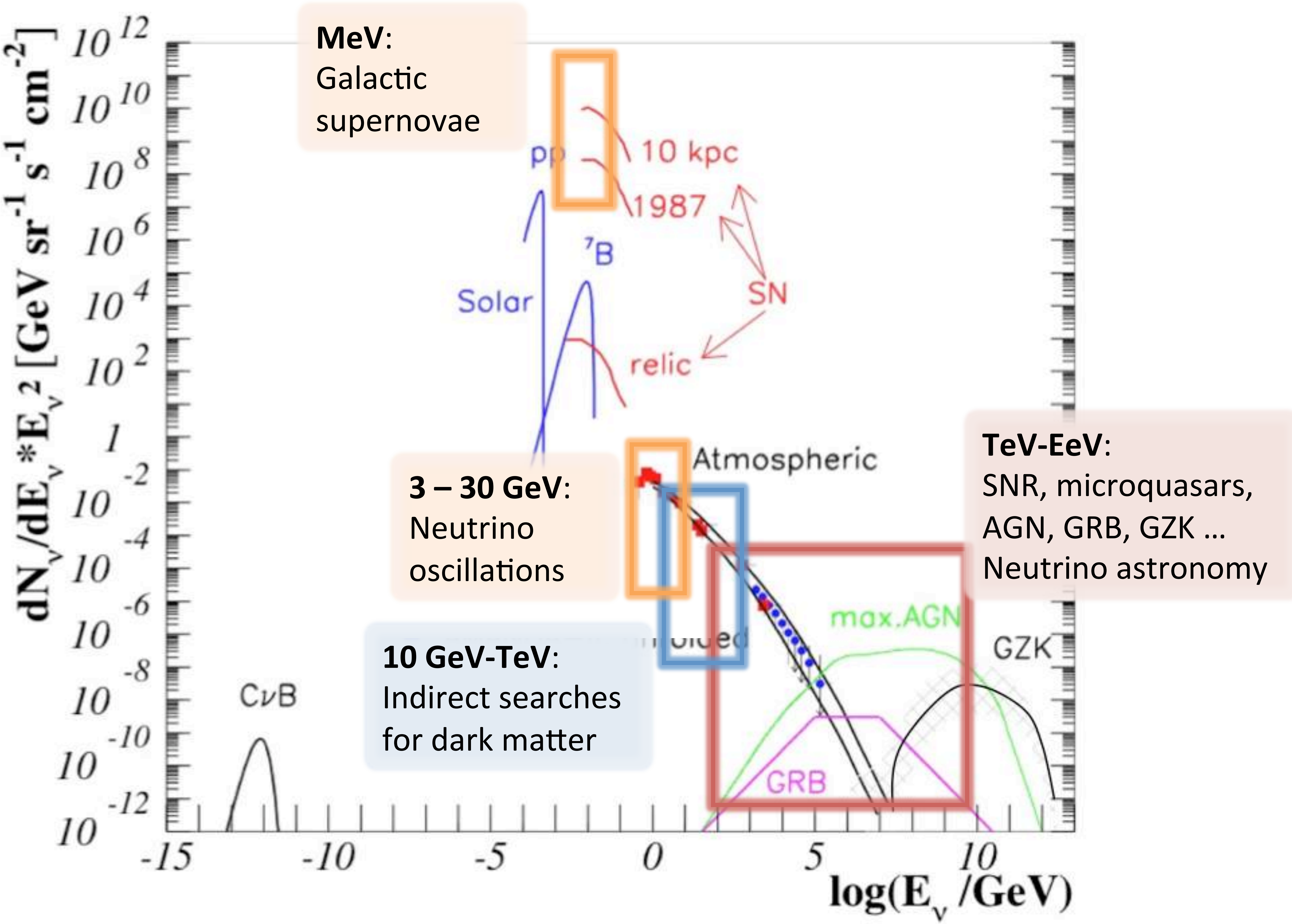




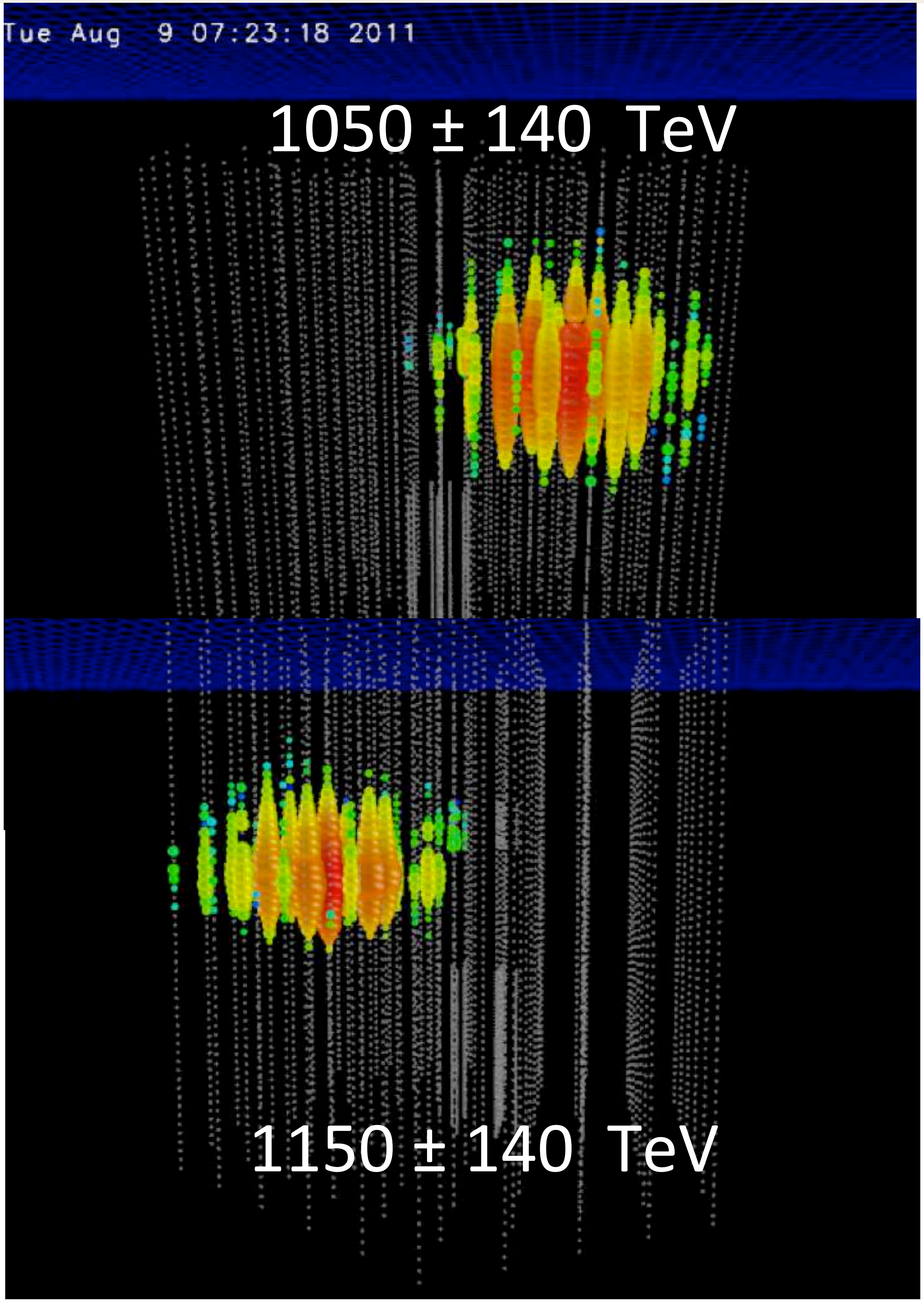
	Charged Current ($W^{+/-}$)	Neutral Current (Z^0)
ν_e	$\nu_e + N \rightarrow e^- + X$	$\nu_e + N \rightarrow \nu_e + X$
ν_μ	$\nu_\mu + N \rightarrow \mu^- + X$	$\nu_\mu + N \rightarrow \nu_\mu + X$
ν_τ	$\nu_\tau + N \rightarrow \tau^- + X$	$\nu_\tau + N \rightarrow \nu_\tau + X$



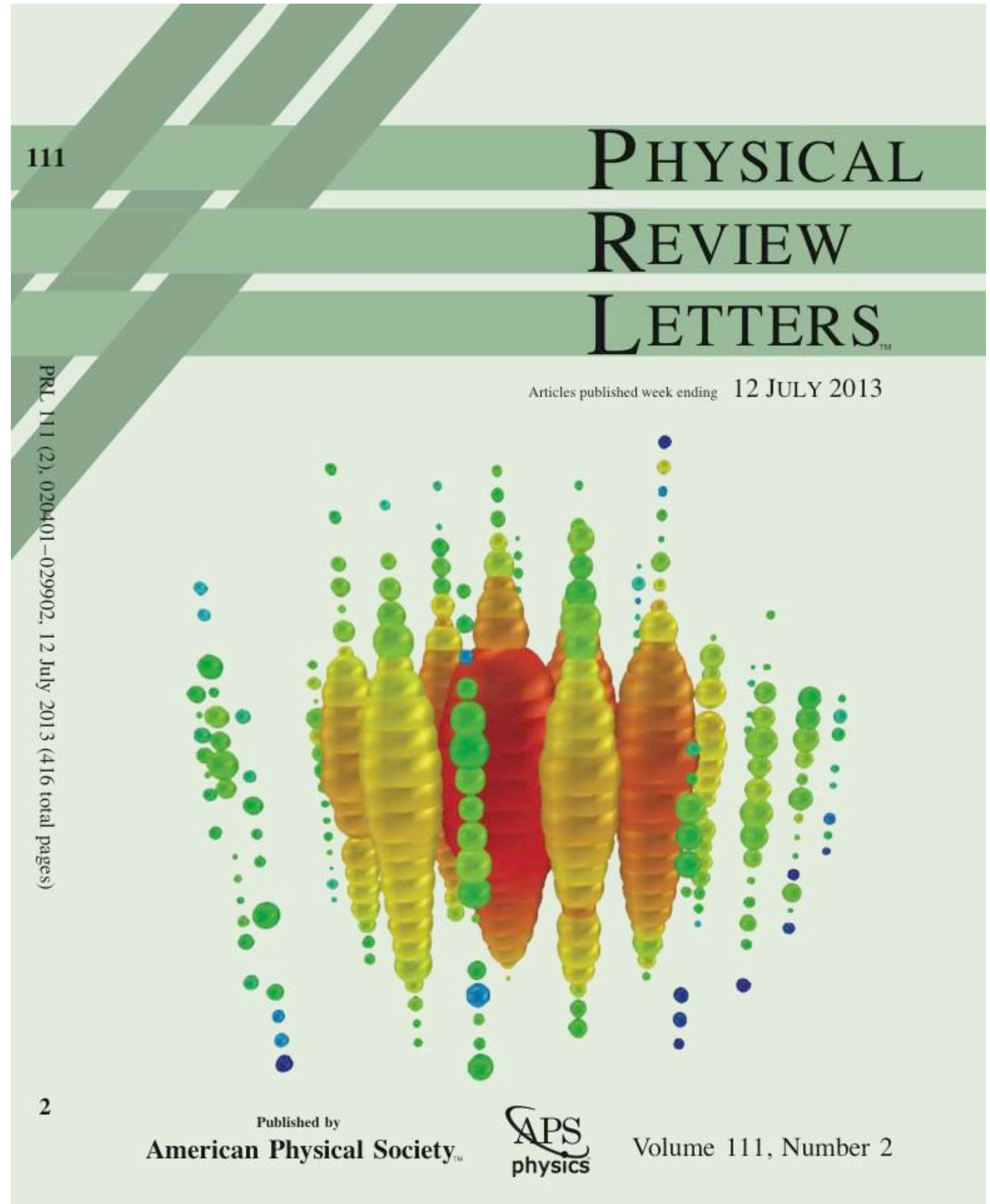
Sensitivity of IceCube



First Observation of PeV-energy Neutrinos



… discovered in search for GZK neutrinos



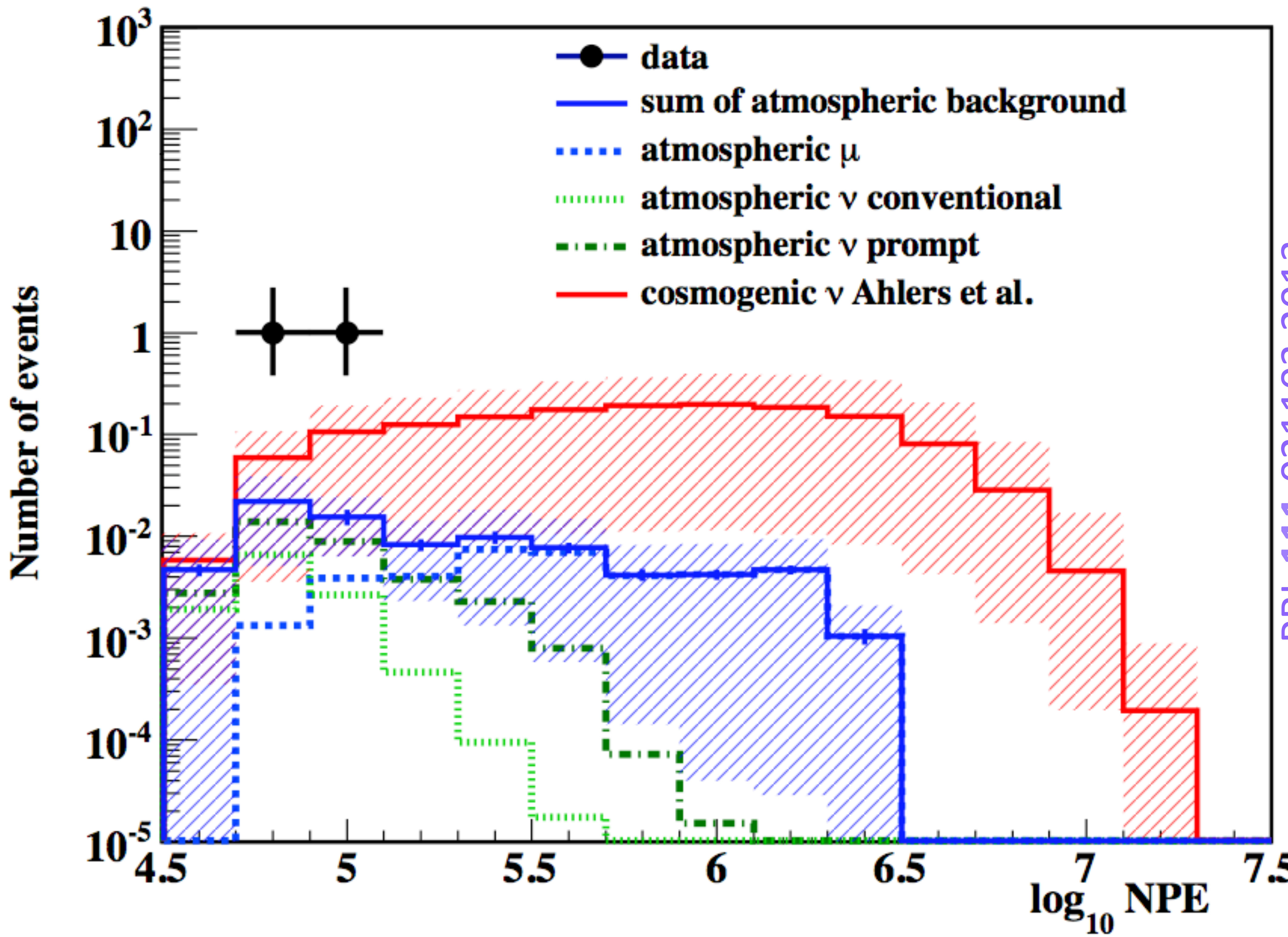
First Observation of PeV-Energy Neutrinos

Combined analysis of **79-string data (1 year)** and **first** analysis of **86-string data (1 year)**

2 PeV events found in a search targeting much higher energy neutrinos (related to GZK cutoff)

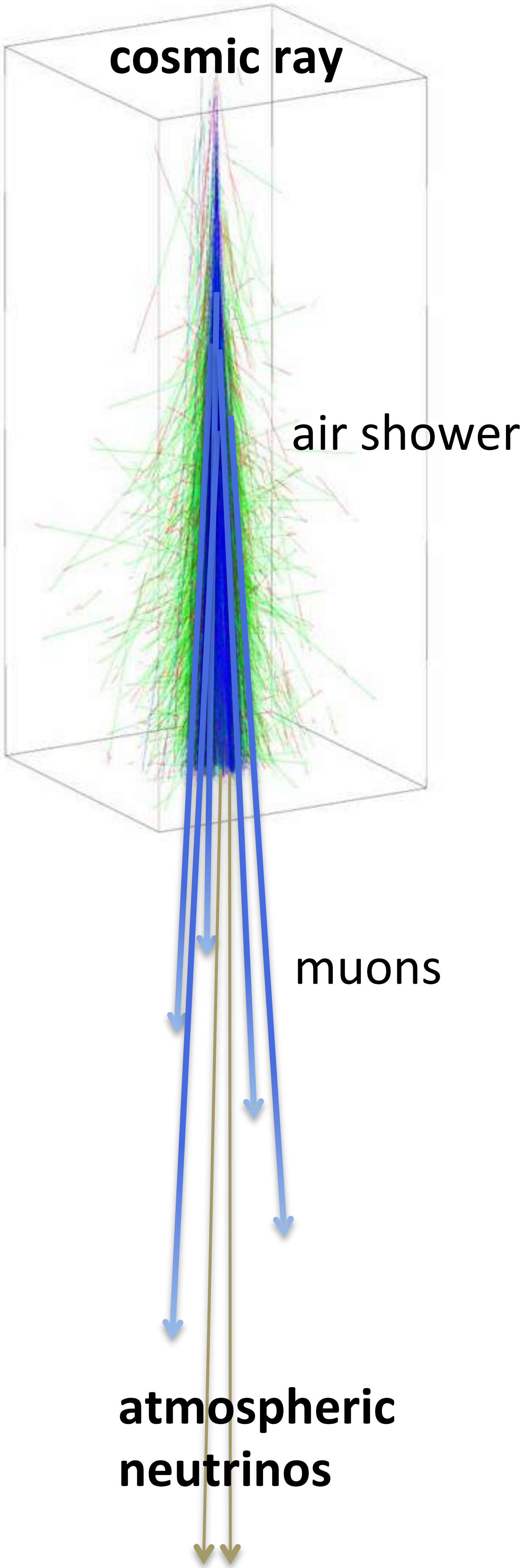
Expected background: **0.08 ± 0.05 events**

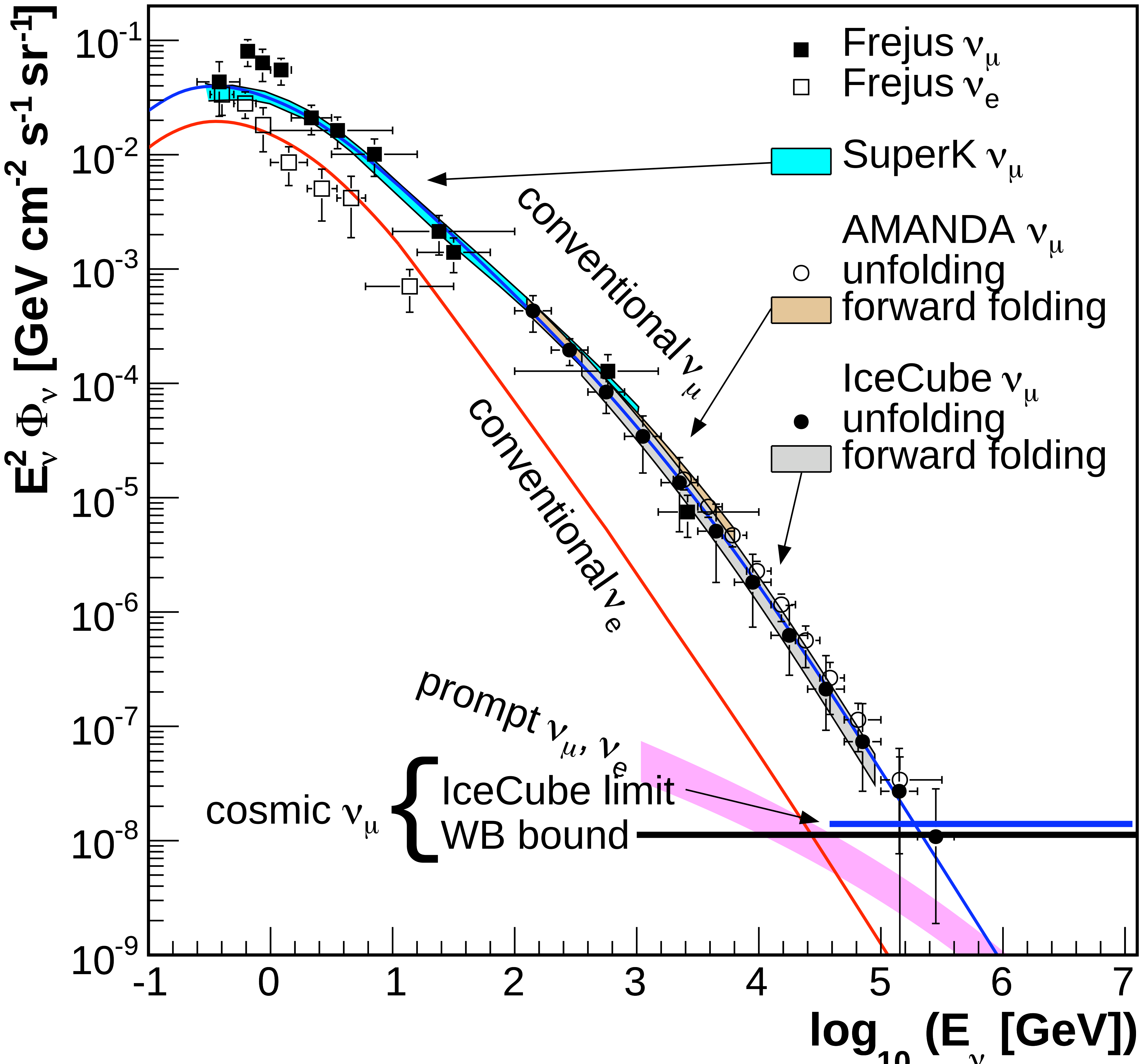
⇒2.8σ excess

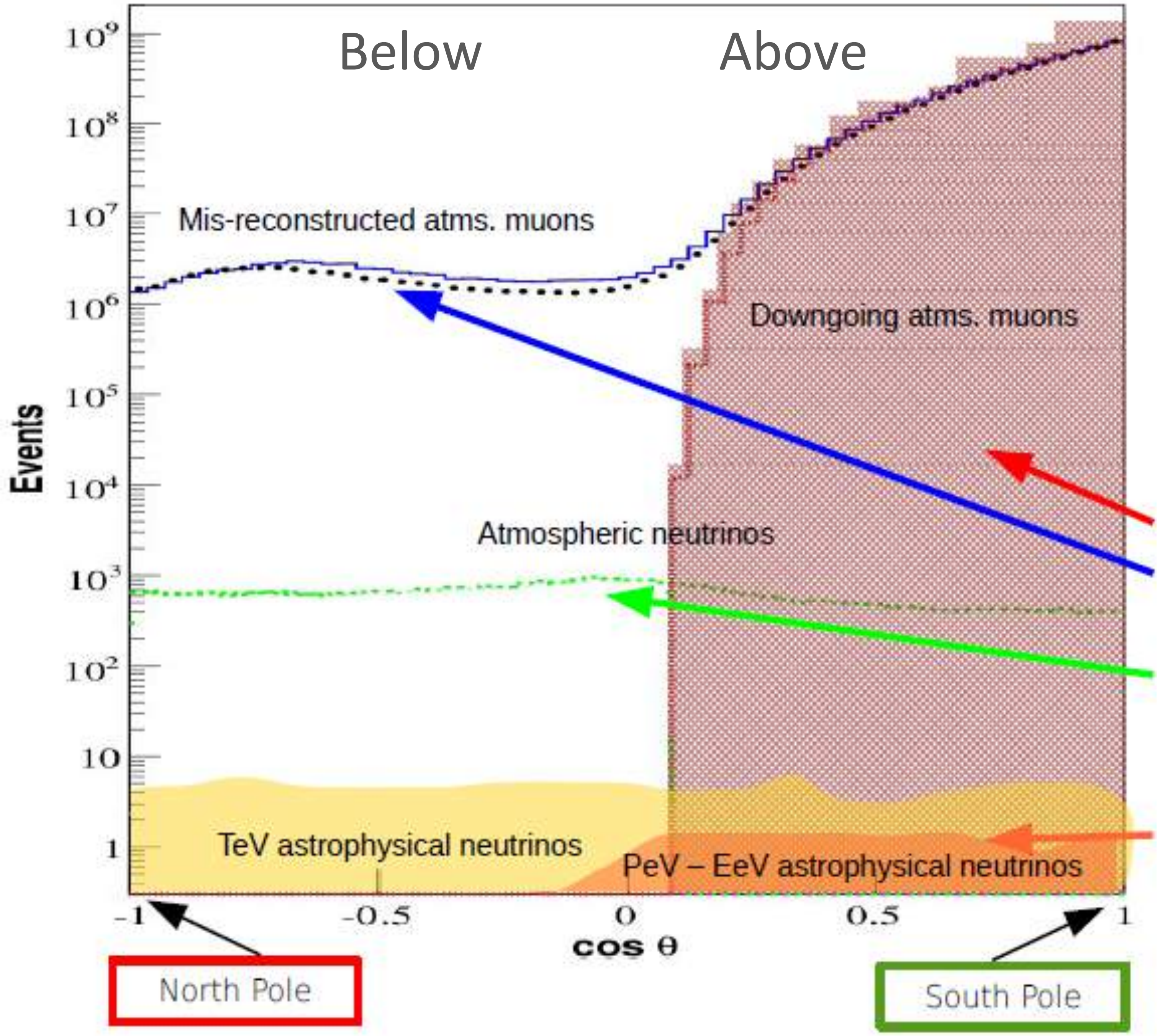


PRL 111:021103,2013

Atmospheric Neutrino Spectrum

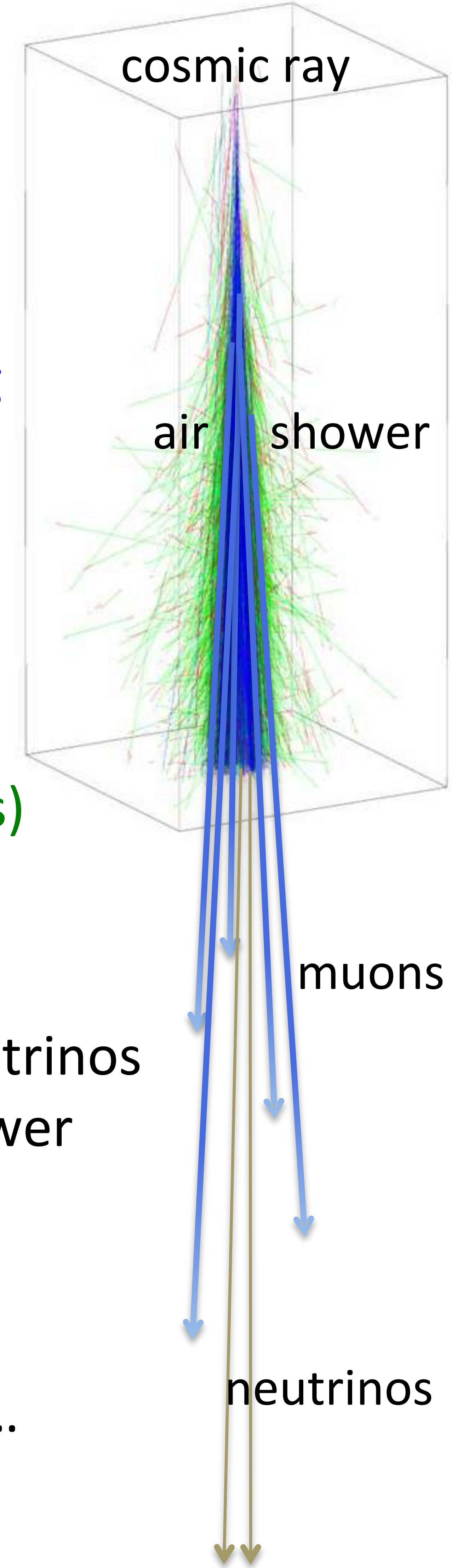






There is an enormous background of cosmic ray muons going *down* (only *misreconstructed* muons apparently going up since muons are all absorbed in the Earth)

Atmospheric neutrinos come from the *same* showers (1 in 10^6 events)



Using a veto for downgoing events, we remove the atmospheric neutrinos … by removing the muons coming from the *same* cosmic ray air shower

What's left is: PeV-EeV astrophysical neutrinos coming from above

NB: Doesn't work for upgoing, since the Earth absorbed the muons … so southern sky (*downgoing* events) becomes the best channel.

'High Energy Starting Events' analysis

Follow-up based on PeV events

1. **Lower** energy threshold, from ~PeV down to ~40 TeV

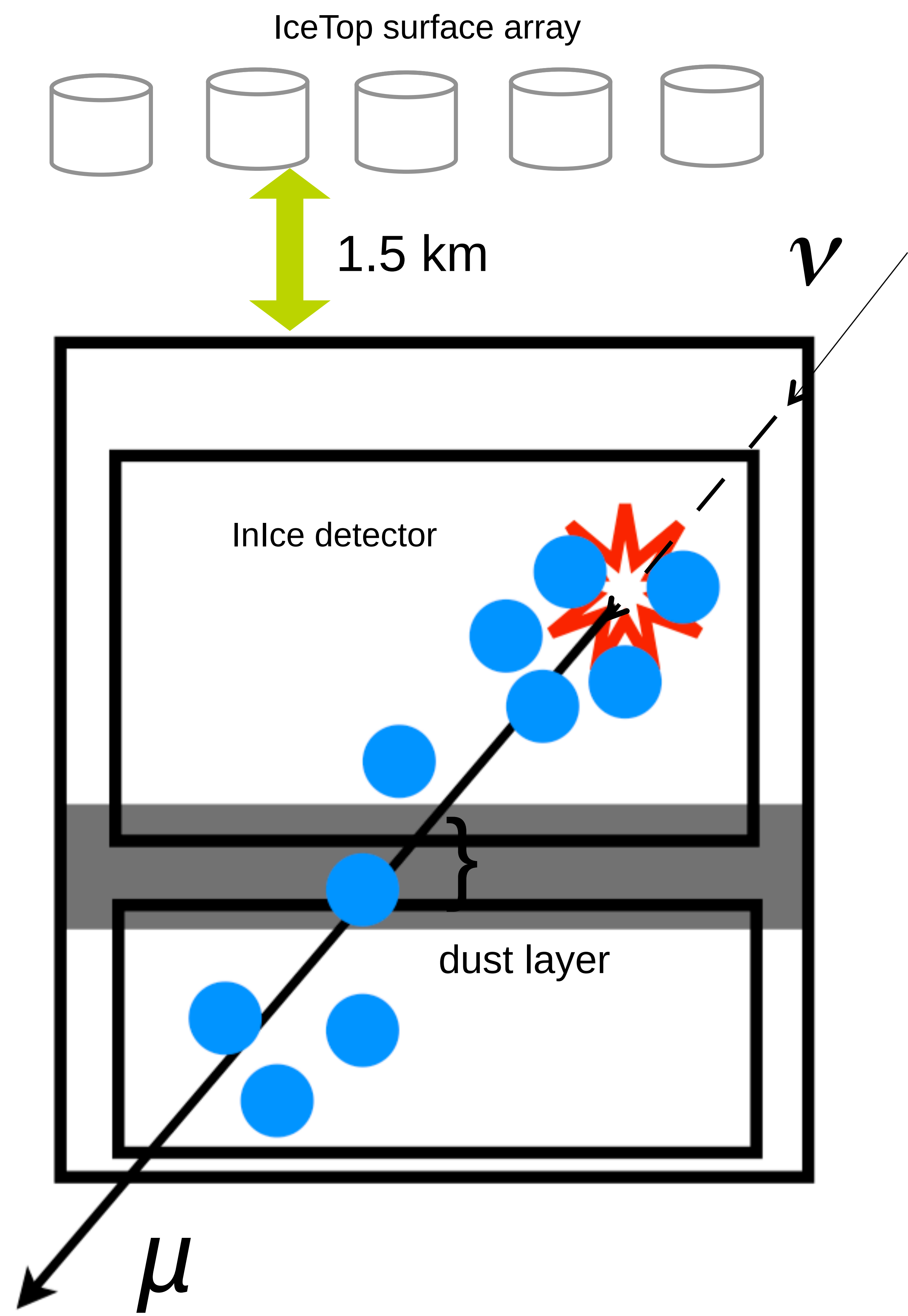
(Still very bright events … require > 6000 photo-electrons for trigger)

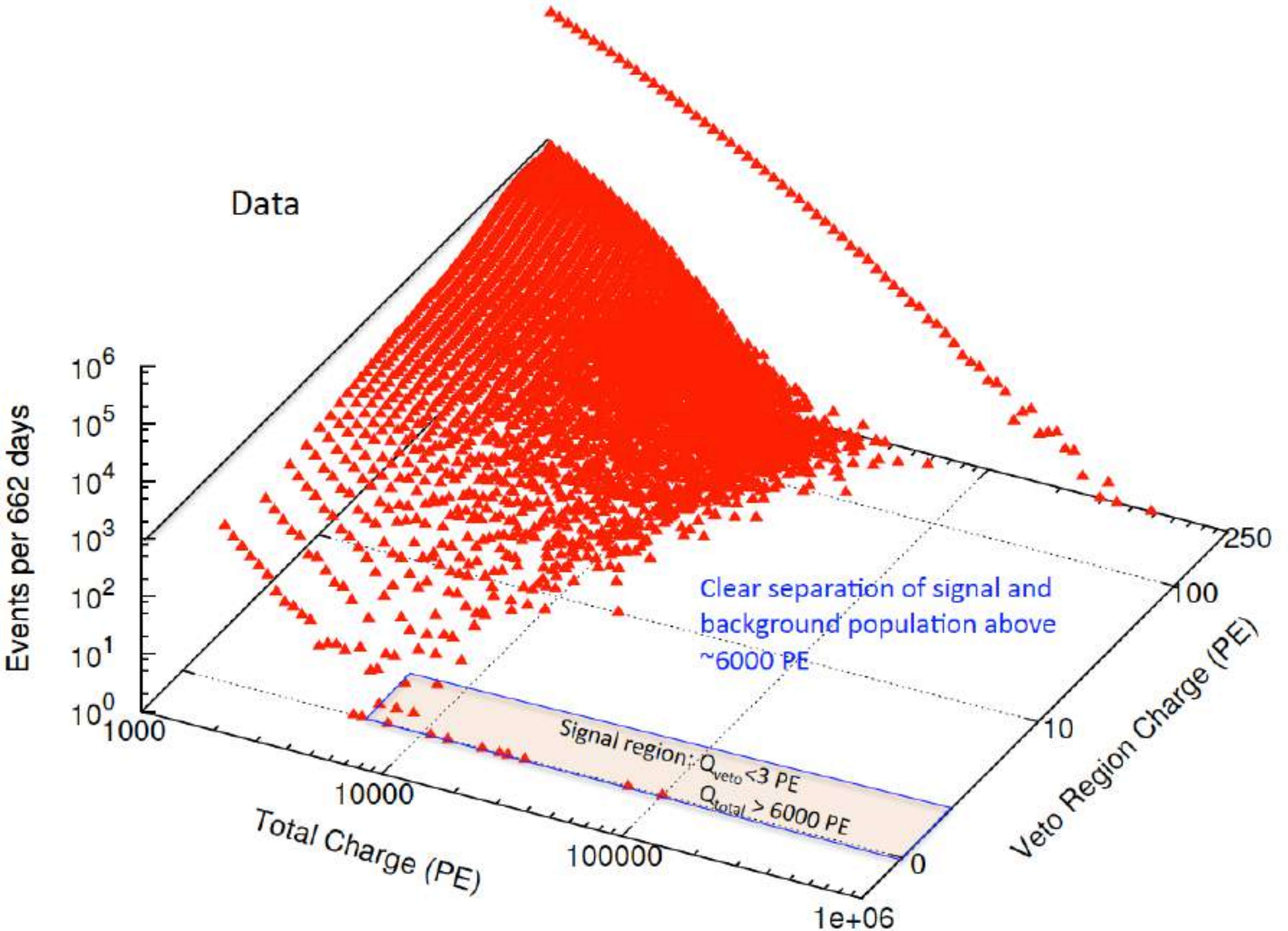
2. Use outer-most layer of IceCube as a **veto**

Removes atmospheric background (muon + neutrino) **from above**

Earth filters muon background **from below**

(NB: track-events will be suppressed when using veto so expect mainly shower-events)



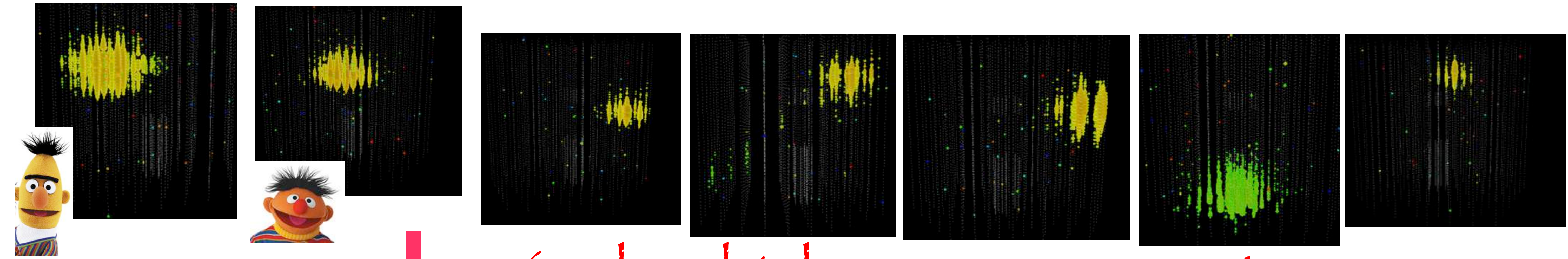


Data
Events per 662 days
10^6
10^5
10^4
10^3
10^2
10^1
10^0
1000
10000
100000
1e+06
Total Charge (PE)
Veto Region Charge (PE)
250
100
10
0
Clear separation of signal and background population above ~6000 PE
Signal region: Q_{veto} <3 PE
Q_{total} > 6000 PE

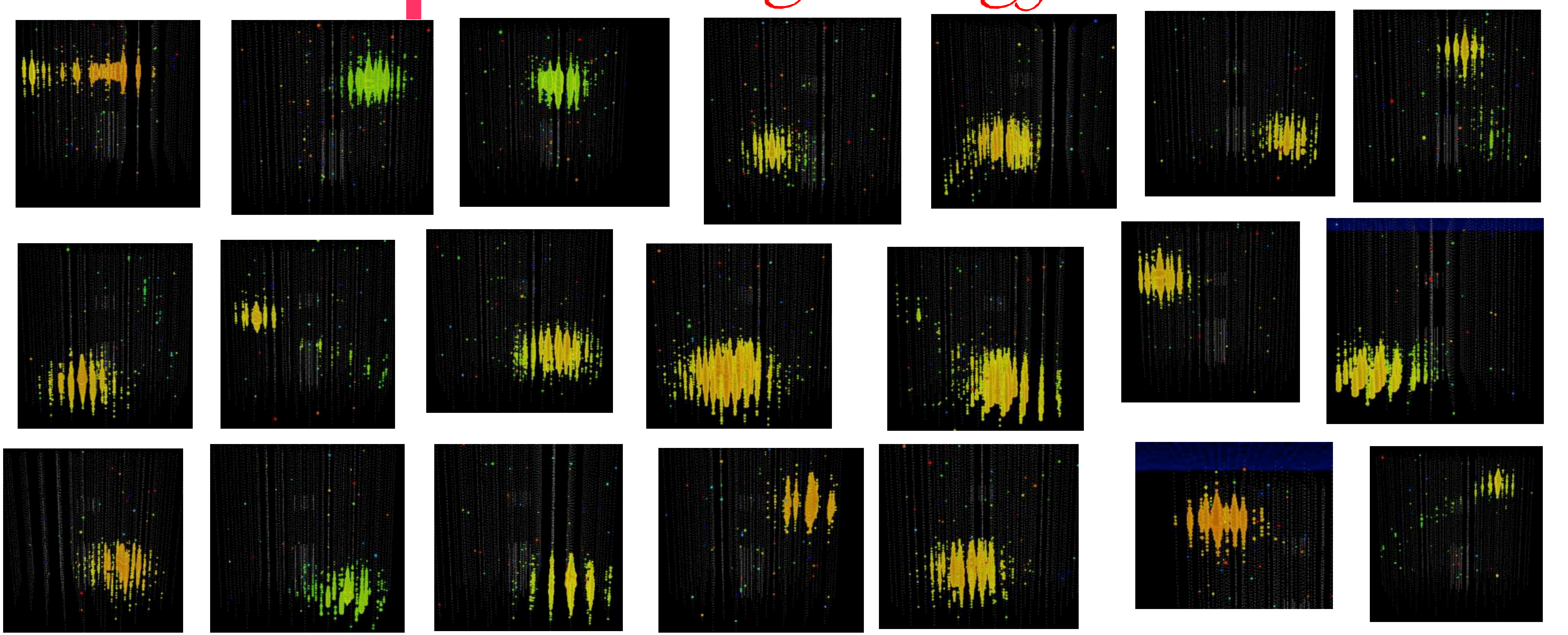
Re-discovery of Bert & Ernie

Atmospheric μ background: 6 ± 3.4

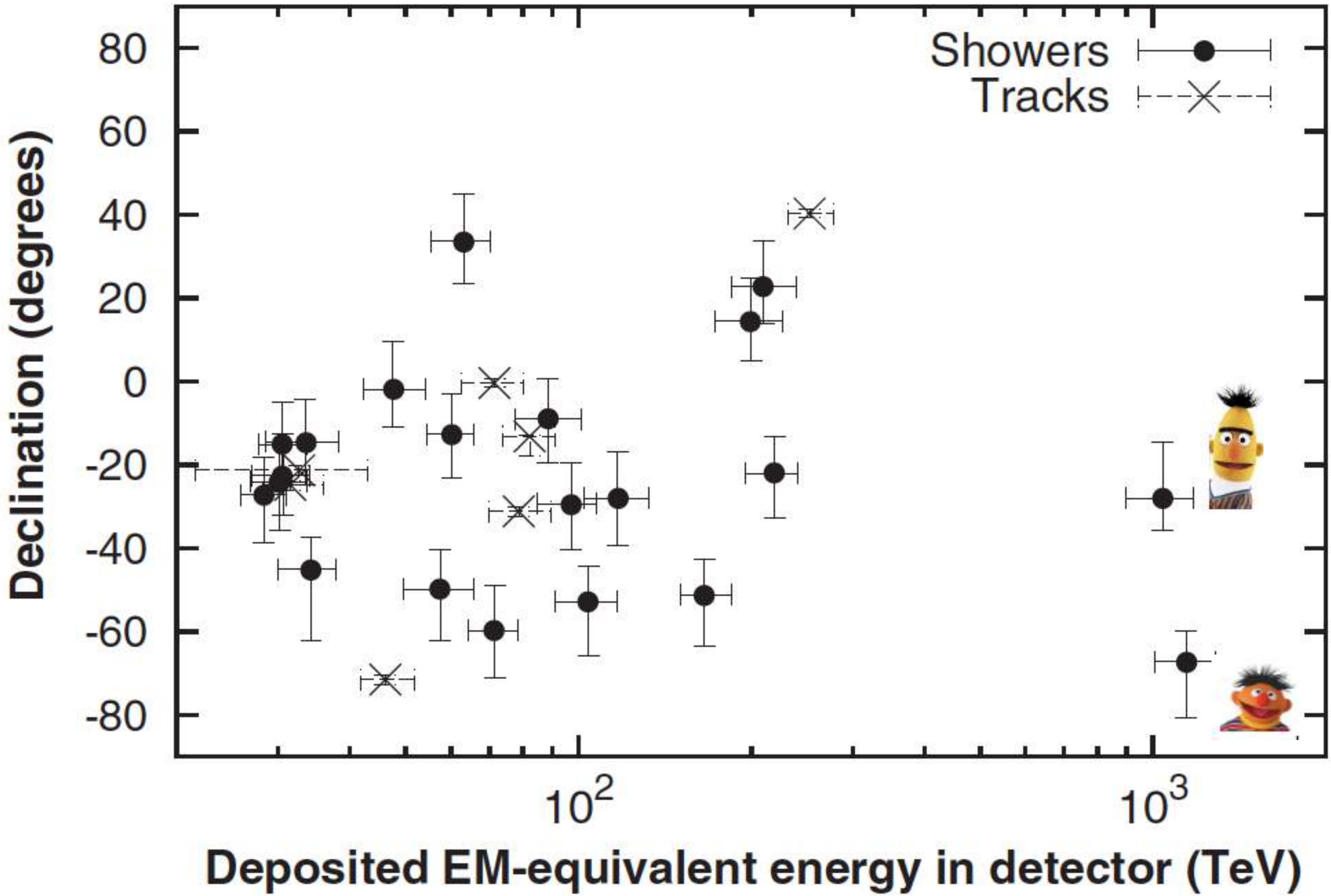
Atmospheric ν background: $4.6^{+3.7}_{-1.2}$



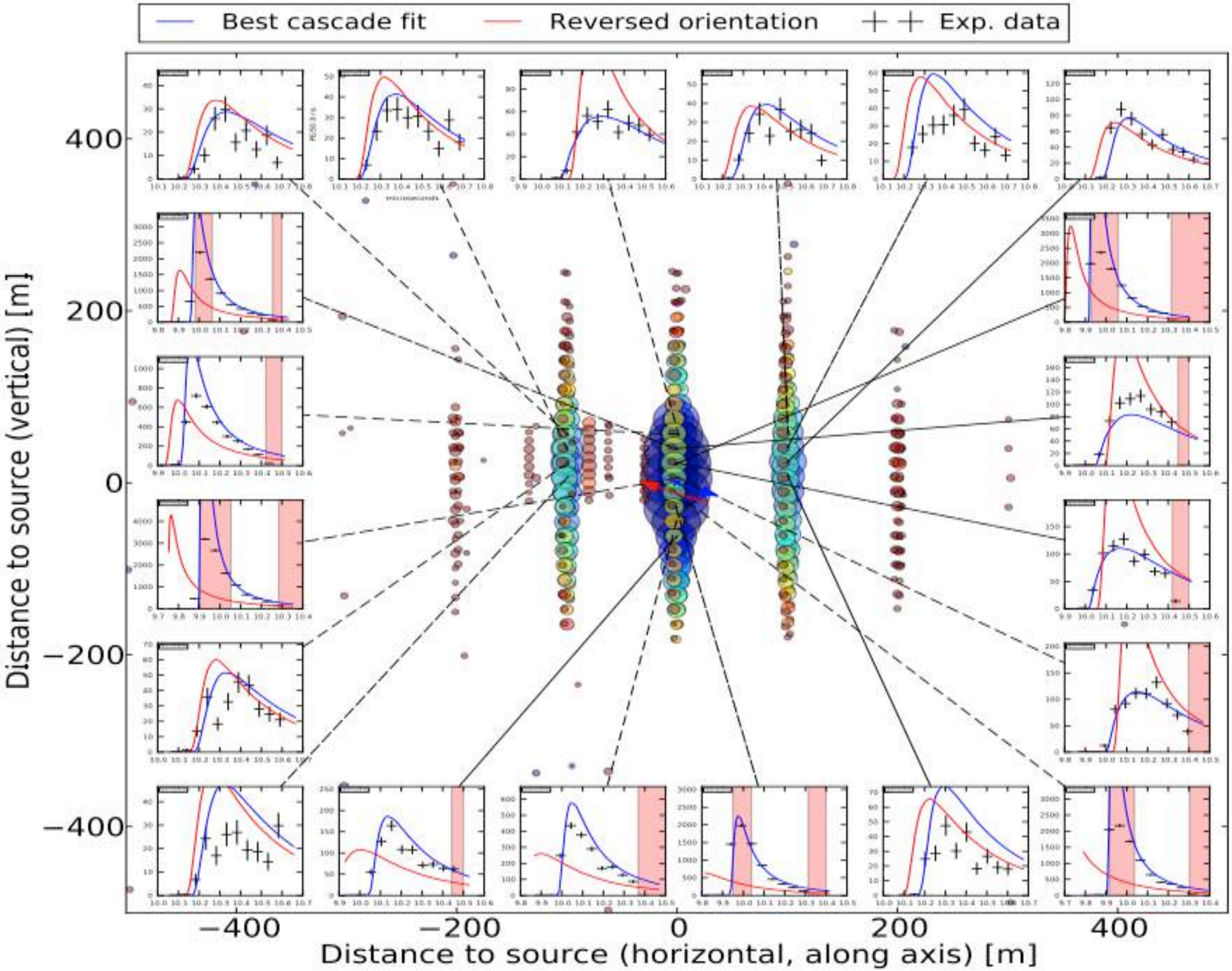
+ 26 other high-energy events!



Track events can have much *higher* true energies than deposited energies



The arrival directions of shower-like events can be determined from the waveforms



High Energy Starting Event Analysis: Results

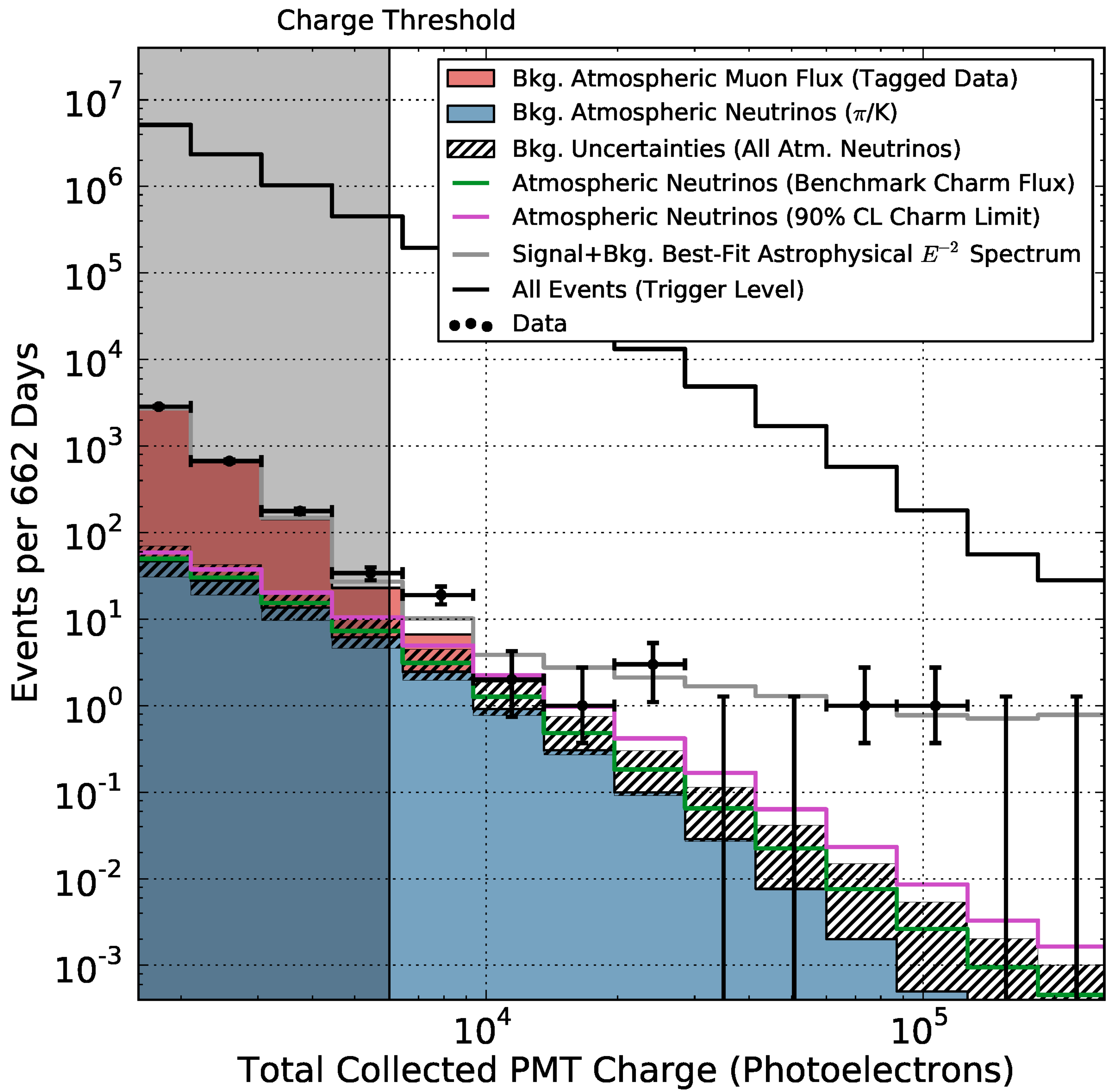
26 new events

Expected background:
10.6 ± 4 atm. events

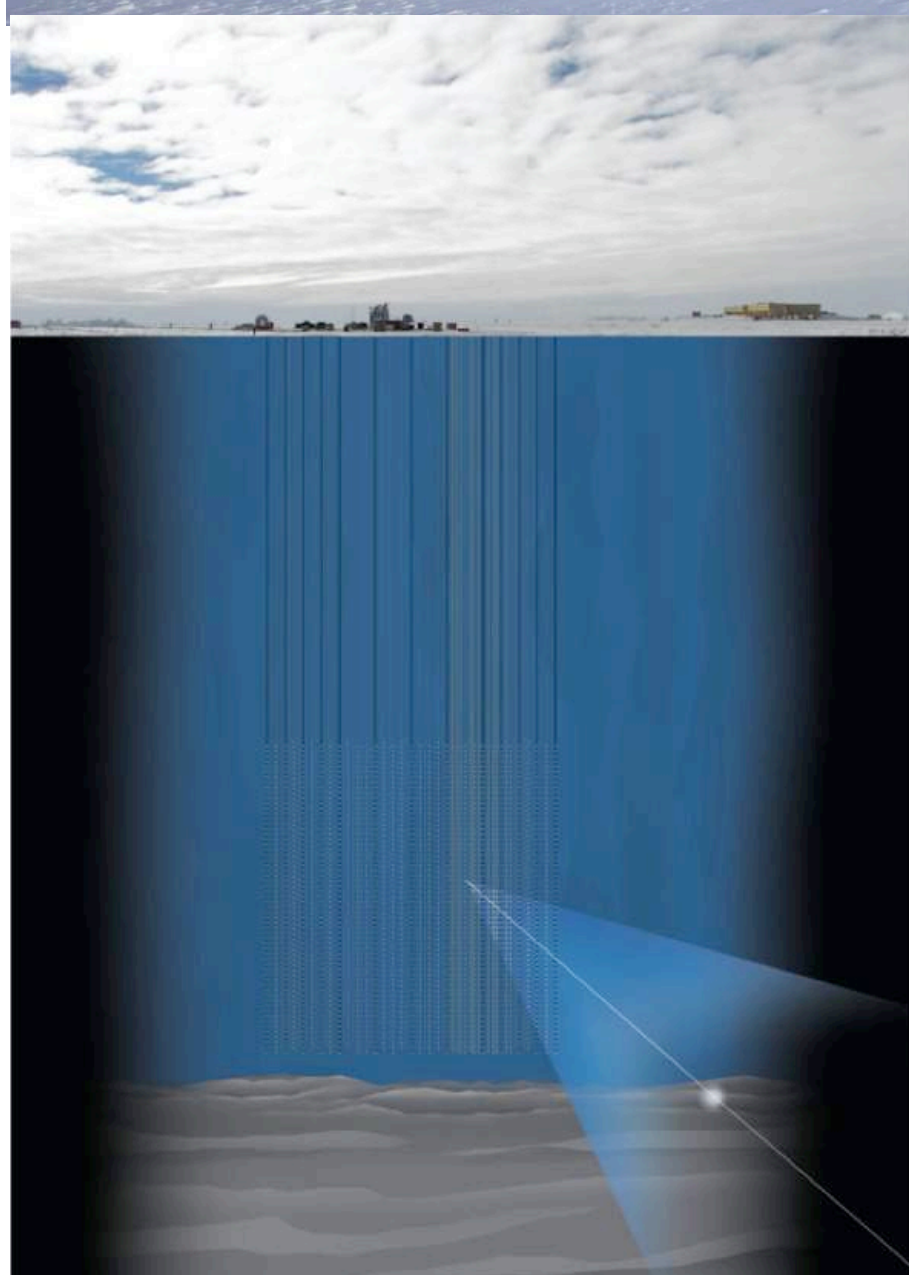
⇨ **4.1σ combining both analyses**

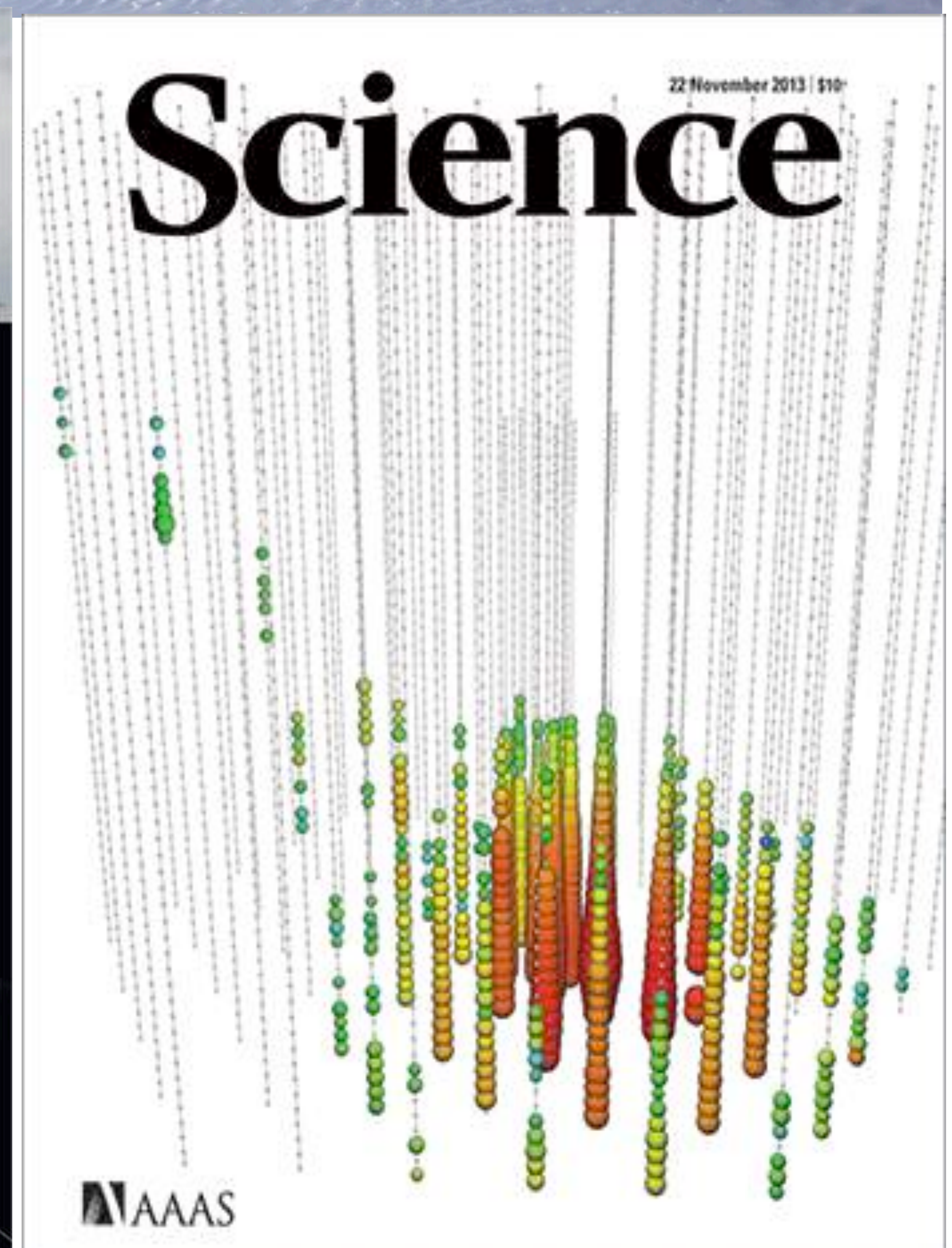
Cutoff beyond ~1 PeV?

Gap at ~0.5-1 TeV?




physicsworld
BREAKTHROUGH
OF THE YEAR
2013
ICECUBE
NSF

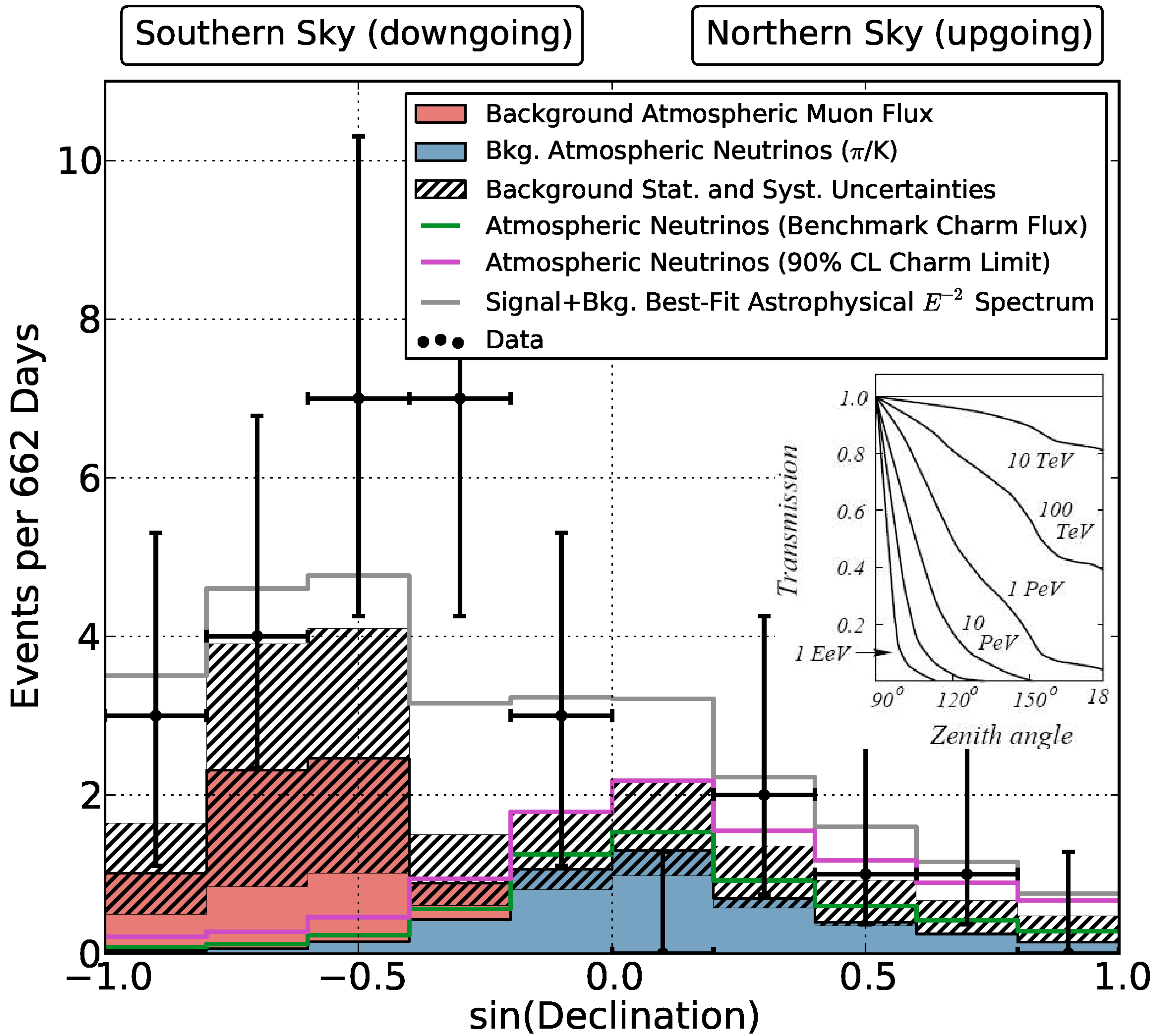



22 November 2013 | $10
Science
AAAS

High Energy Starting Event Analysis: Results

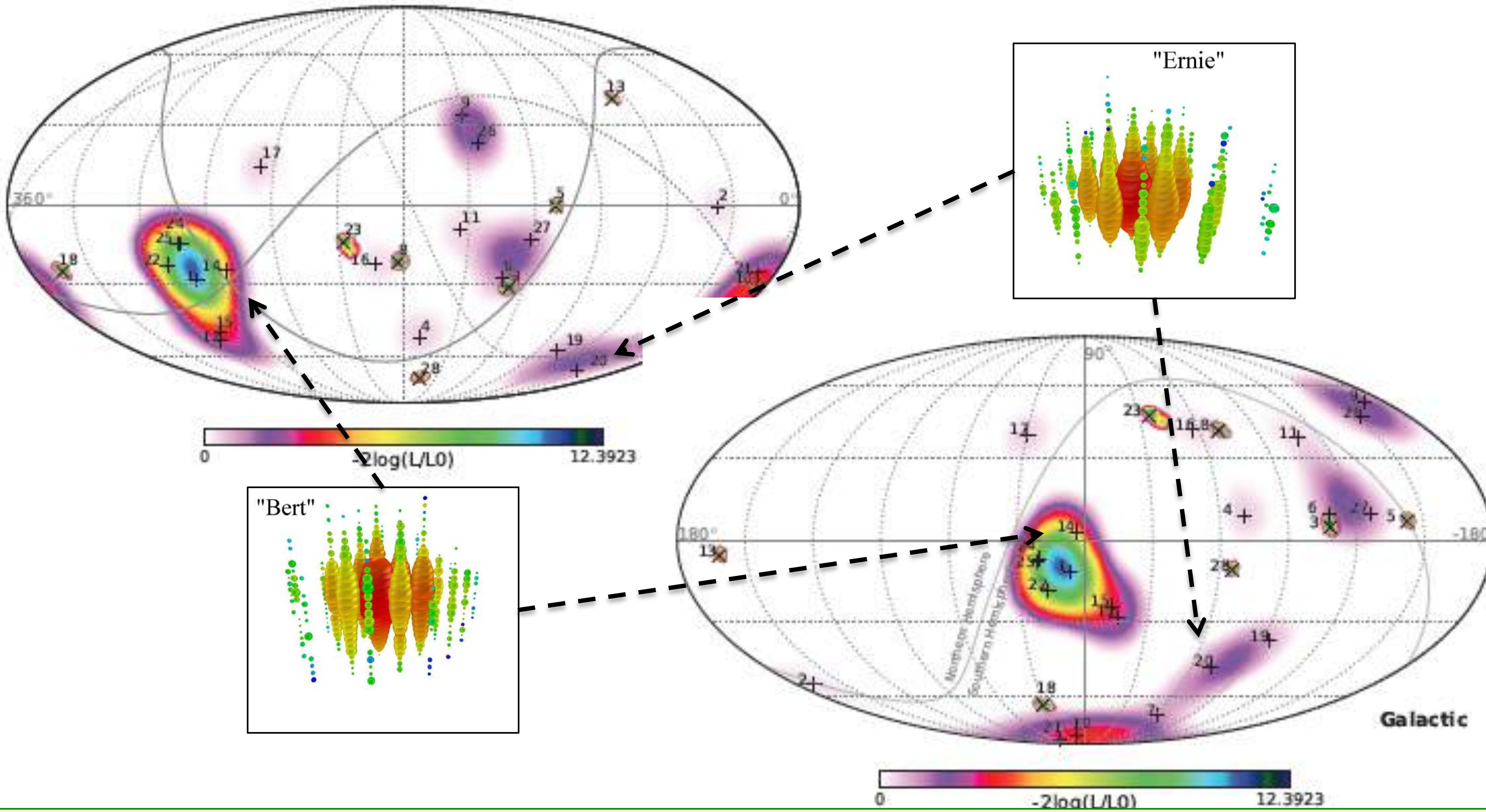
More astrophysical events expected *from above* (South) because of Earth absorption at high energies ….

The zenith angle distribution is consistent with an isotropic flux … *not* with production in the atmosphere



Arrival Directions & Clustering

Distribution of point-source likelihoods in equatorial and galactic coordinates

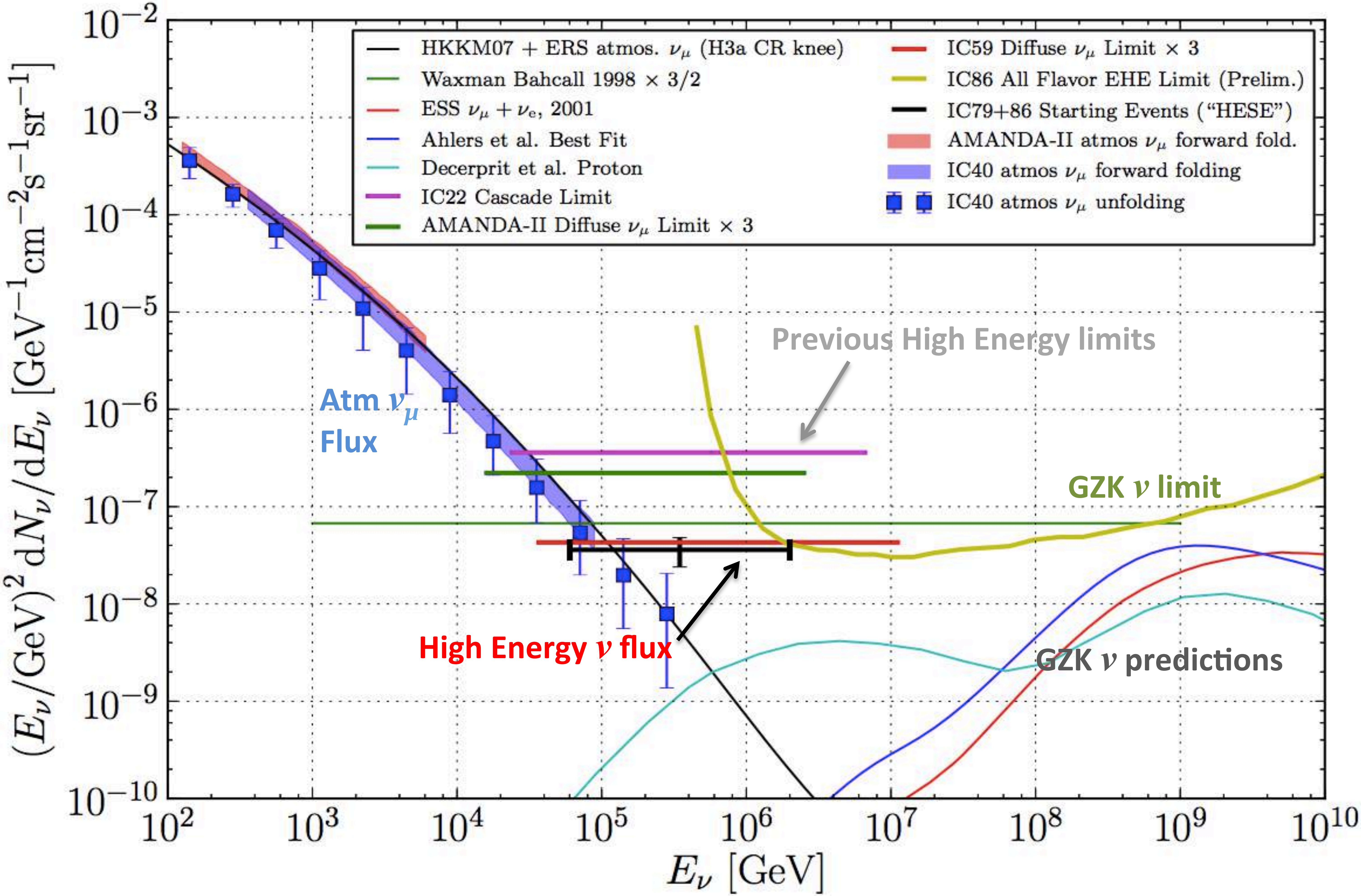


5 (shower) events observed in 30°×30° region, 2 more nearby (*#12, #15*), while 0.6 events are expected … in a randomized map, the chance of having such a cluster *anywhere* in the sky is ~ 8% (NB: no clustering in time either)

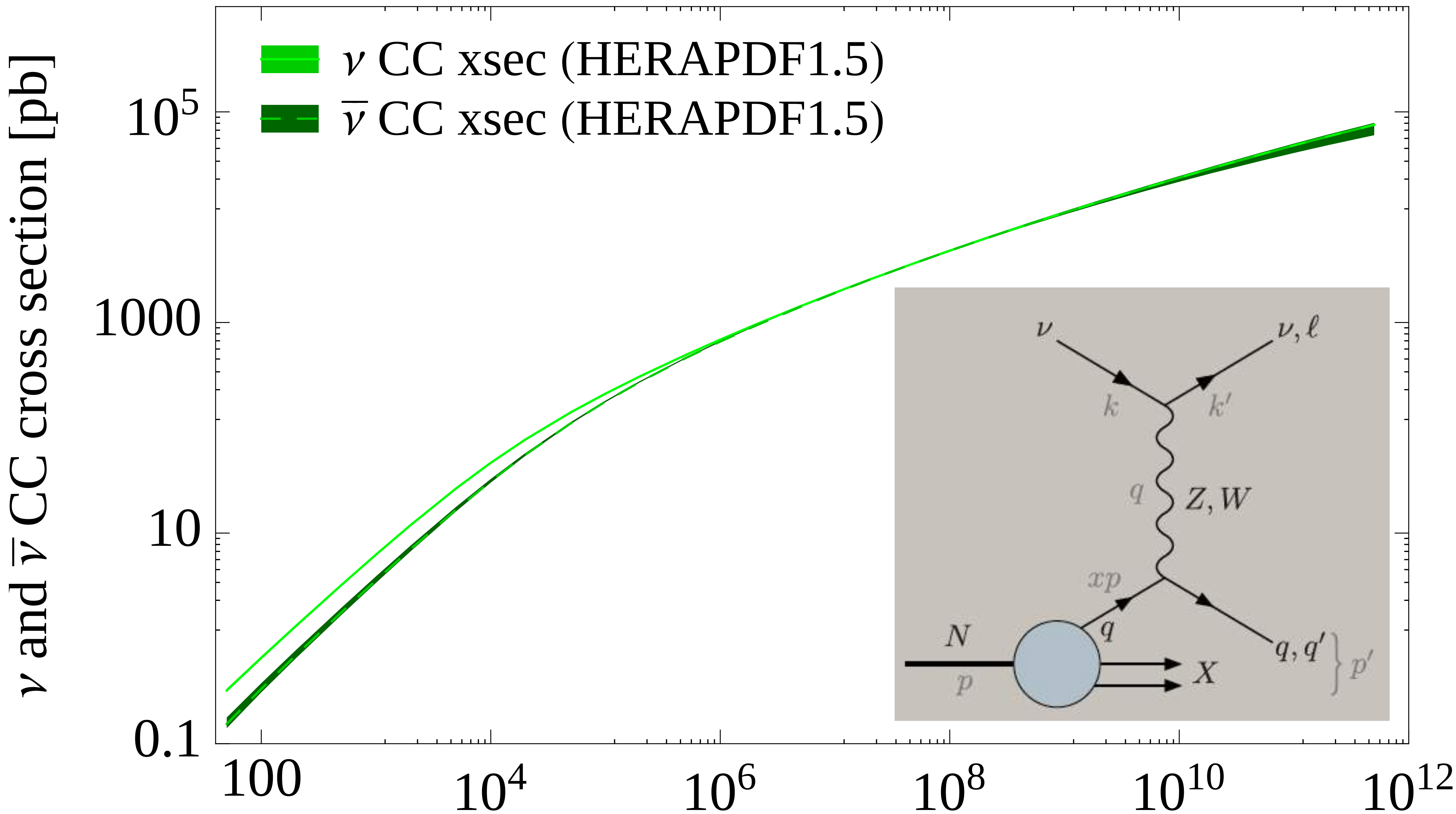
Title	Author(s)	Journal reference	ArXiv	Category
IceCube PeV cascade events initiated by electron-antineutrinos at Glashow resonance	Barger, Learned, Pakvasa	PRD 87, 037302 (2013)	1207.4571	Glashow resonance
Neutrino decays over cosmological distances and the implications for neutrino telescopes	Baerwald, Bustamante, Winter	JCAP10(2012)020	1208.4600	Neutrino decay; track deficit
On the interpretation of IceCube cascade events in terms of the Glashow resonance	Bhattacharya, Gandhi, Rodejohann, Watanabe	---	1209.2422	Glashow resonance
PeV neutrinos from the propagation of ultra-high energy cosmic rays	Roulet, Sigl, van Vliet, Mollerach	JCAP01(2013)028	1209.4033	GZK
Explanation for the Low Flux of High-Energy Astrophysical Muon Neutrinos	Pakvasa, Joshipura, Mohanty	PRL 110, 171802 (2013)	1209.5630	Neutrino decay; track deficit
On the origin of IceCube's PeV neutrinos	Cholis, Hooper	JCAP06(2013)030	1211.1974	Extragalactic (GRB)
Diffuse PeV Neutrinos from Gamma-ray Bursts	Liu, Wang	ApJ 766, 73 (2013)	1212.1260	Extragalactic (GRB)
Cosmic PeV Neutrinos and the Sources of Ultrahigh Energy Protons	Kistler, Stanev, Yuksel	---	1301.1703	Extragalactic
PeV Neutrinos from Intergalactic Interactions of Cosmic Rays Emitted by Active Galactic Nuclei	Kalashev, Kusenko, Essey	PRL 111, 041103 (2013)	1303.0300	Extragalactic (AGN)
Diffuse PeV neutrino emission from ultraluminous infrared galaxies	He, Wang, Fan, Liu, Wei	PRD 87, 063011 (2013)	1303.1253	Extragalactic (Infrared galaxies)
Stringent constraint on neutrino Lorentz invariance violation from the two IceCube PeV neutrinos	Borriello, Chakraborty, Mirizzi, Serpico	PRD 87, 116009 (2013)	1303.5843	Lorentz invariance
Neutrinos at IceCube from heavy decaying dark matter	Feldstein, Kusenko, Matsumoto, Yanagida	PRD 88, 015004 (2013)	1303.7320	Exotic (dark matter decay)
Galactic PeV Neutrinos	Gupta	APh 48, 75 (2013)	1305.4123	Galactic
Sub-PeV Neutrinos from TeV Unidentified Sources in the Galaxy	Fox, Kashiyama, Meszaros	ApJ 774, 74 (2013)	1305.6606	Galactic
Superheavy Particle Origin of IceCube PeV Neutrino Events	Barger, Keung	---	1305.6907	Exotic (Leptoquark)
PeV neutrinos observed by IceCube from cores of active galactic nuclei	Stecker	PRD 88, 047301 (2013)	1305.7404	Extragalactic (AGN)
The fraction of muon tracks in cosmic neutrinos	Vissani, Pagliaroli, Villante	JCAP09(2013)017	1306.0211	Future strategy
TeV–PeV Neutrinos from Low-Power Gamma-Ray Burst Jets inside Stars	Murase, Ioka	PRL 111, 121102 (2013)	1306.2274	Extragalactic (GRB)
Demystifying the PeV cascades in IceCube: Less (energy) is more (events)	Laha, Beacom, Dasgupta, Horiuchi, Murase	PRD 88, 043009 (2013)	1306.2309	Future strategy
Testing the Hadronuclear Origin of PeV Neutrinos Observed with IceCube	Murase, Ahlers, Lacki	---	1306.3417	Extragalactic
Pinning down the cosmic ray source mechanism with new IceCube data	Anchordoqui, Goldberg, Lynch, Olinto, Paul, Weiler	---	1306.5021	Galactic
Constraining Superluminal Electron and Neutrino Velocities using the 2010 Crab Nebula Flare and the IceCube PeV Neutrino Events	Stecker	---	1306.6095	Lorentz invariance
TeV-PeV neutrinos over the atmospheric background: originating from two groups of sources?	He, Yang, Fan, Wei	---	1307.1450	Two source populations
The Galactic Pevatron	Neronov, Semikoz, Tchernin	---	1307.2158	Galactic
Photohadronic Origin of the TeV-PeV Neutrinos Observed in IceCube	Winter	PRD 88, 083007 (2013)	1307.2793	Extragalactic
Pseudo-Dirac neutrinos via mirror-world and depletion of UHE neutrinos	Joshipura, Mohanty, Pakvasa	---	1307.5712	
Long-lived PeV-EeV Neutrinos from GRB Blastwave	Razzaque	---	1307.7596	Extragalactic (GRB)
Are IceCube neutrinos unveiling PeV-scale decaying dark matter?	Esmaili, Serpico	---	1308.1105	Exotic (dark matter decay)
Establishing the astrophysical origin of a signal in a neutrino telescope	Lipari	---	1308.2086	
Testing Relativity with High-Energy Astrophysical Neutrinos	Diaz, Kostelecky, Mewes	---	1308.6344	Lorentz invariance
A Simple Explanation of the Ultra-high Energy Neutrino Events at IceCube	Chen, Bhupal Dev, Soni	---	1309.1764	
Galactic Center origin of a subset of IceCube neutrino events	Razzaque	PRD 88, 081302(R) (2013)	1309.2756	Galactic
Probing the Galactic Origin of the IceCube Excess with Gamma-Rays	Ahlers, Murase	---	1309.4077	Galactic
Diffuse PeV neutrinos from hypernova remnants in star-forming galaxies	Liu, Wang, Inoue, Crocker, Aharonian	---	1310.1263	Extragalactic (star-forming galaxies)
Revolution at ICECUBE horizons	Fargion, Paggi	---	1310.3543	Track deficit
Diffuse Neutrino Flux from Cosmic Ray Interactions in the Milky Way	Joshi, Winter, Gupta	---	1310.5123	CR interactions
GeV - PeV Neutrino Production and Oscillation in hidden jets from GRBs	Fraija	---	1310.7061	Extragalactic (GRB)
Detection of ultra high energy neutrinos by IceCube: Sterile neutrino scenario	Rajpoot, Sahu, Wang	---	1310.7075	Exotic (sterile neutrinos)
Reevaluation of the Prospect of Observing Neutrinos from Galactic Sources in the Light of Recent Results in Gamma Ray and Neutrino Astronomy	Gonzalez-Garcia, Halzen, Niro	---	1310.7194	Galactic
Self-consistent neutrino and UHE cosmic ray spectra from Mrk 421	Dimitrakoudis, Petropoulou, Mastichiadis	---	1310.7923	Extragalactic (Blazar, Mrk421)

What are these events?

Current picture of neutrino energy spectrum



To calculate the flux given the event rate requires the ν-N scattering cross-section
… We have computed this with few % accuracy @ next-to-leading order in QCD



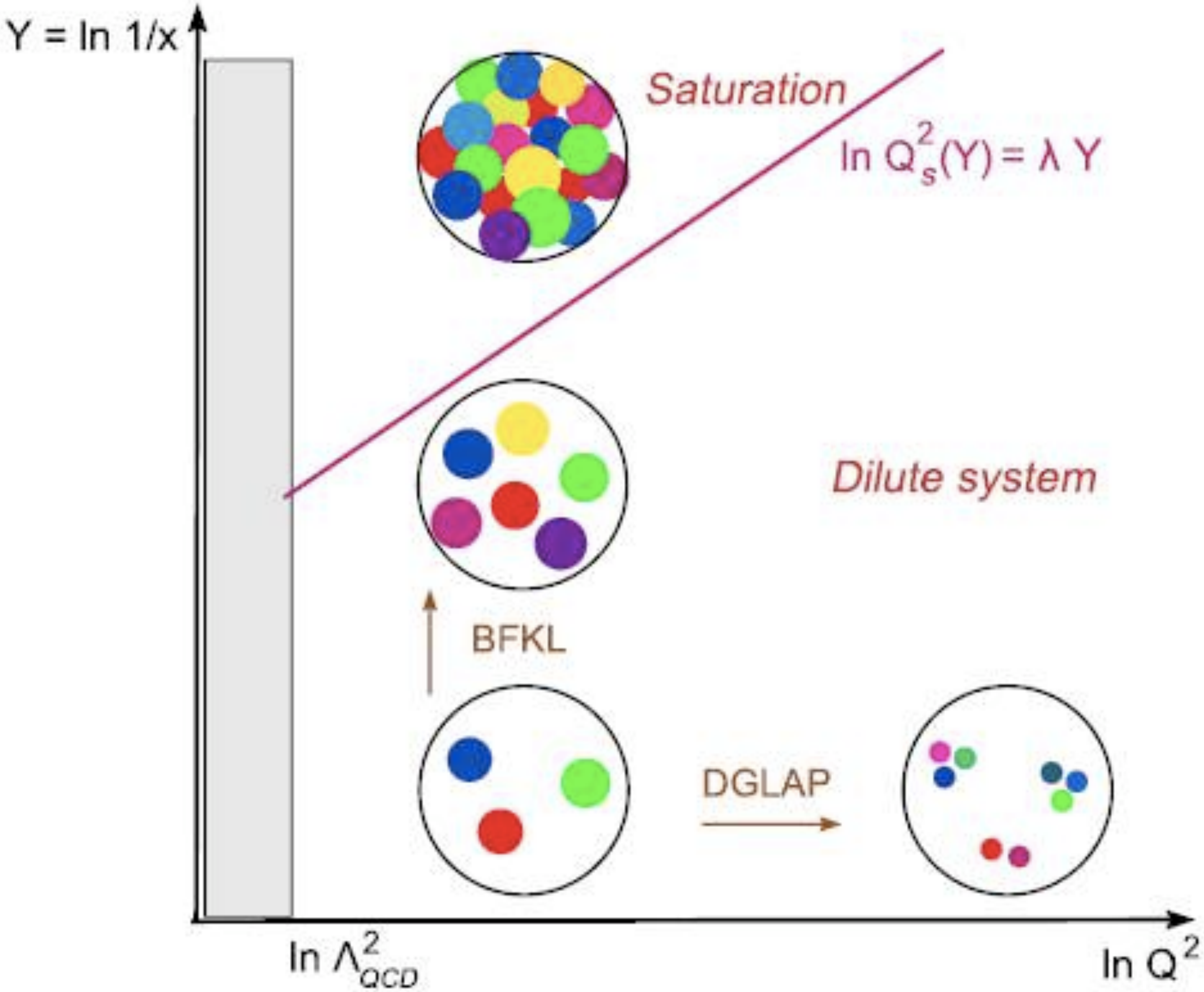
Cooper-Sarkar *et al*, JHEP 1108:042,2011

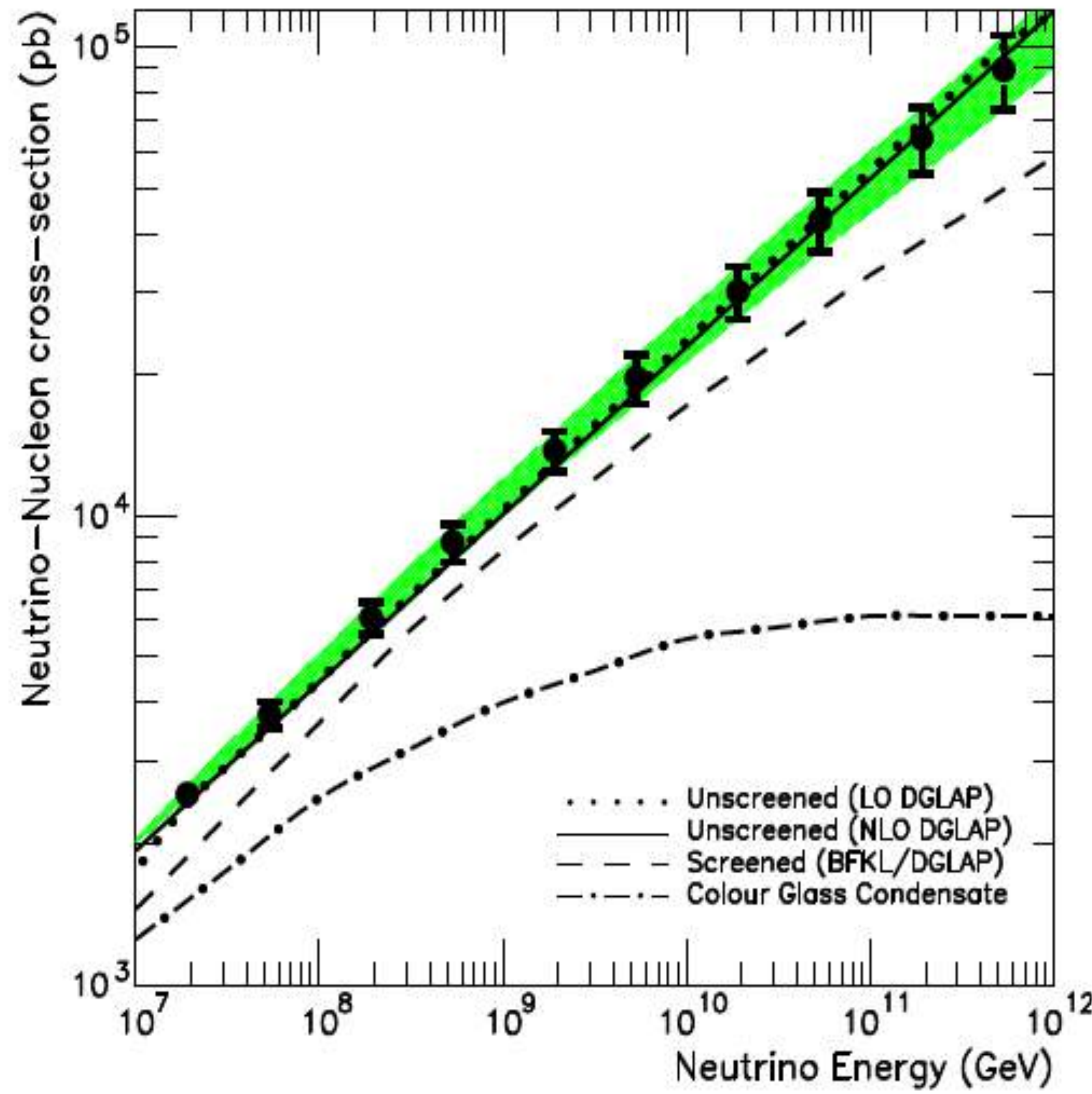
$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x\;\mathrm{d}Q^2} = \frac{G_F^2 M_W^4}{4\pi(Q^2+M_W^2)^2 x}\sigma_r$$

with reduced cross-section

$$\sigma_r = \left[Y_+ F_2^\nu(x,Q^2) - y^2 F_L^\nu(x,Q^2) \pm Y_- x F_3^\nu(x,Q^2)\right]$$

As the gluon density rises at low *x*, non-perturbative effects become important, and a new phase of QCD – Colour Glass Condensate – may form

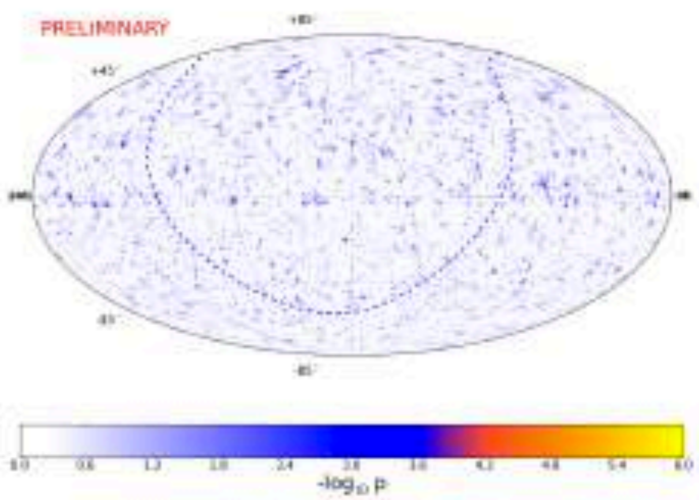




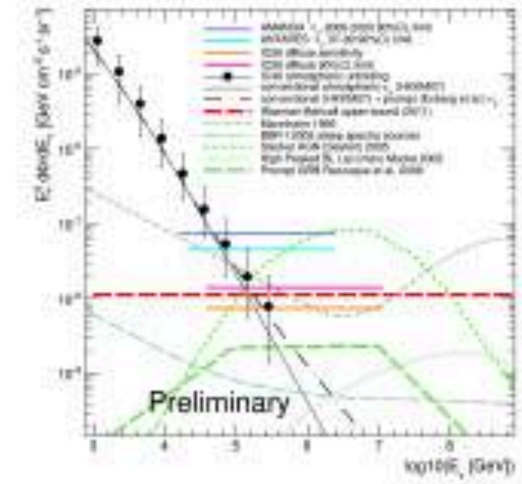
Anchordoqui *et al*, PR D74 (2006) 043008

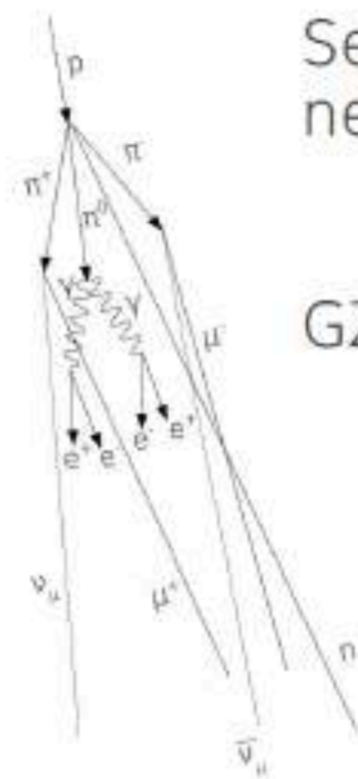
The observed zenith angle dependence of the neutrino flux can provide a measure of the DIS cross-section at ultra high energies where theoretical predictions are uncertain … and thus discriminate between theoretical models

The IceCube physics program



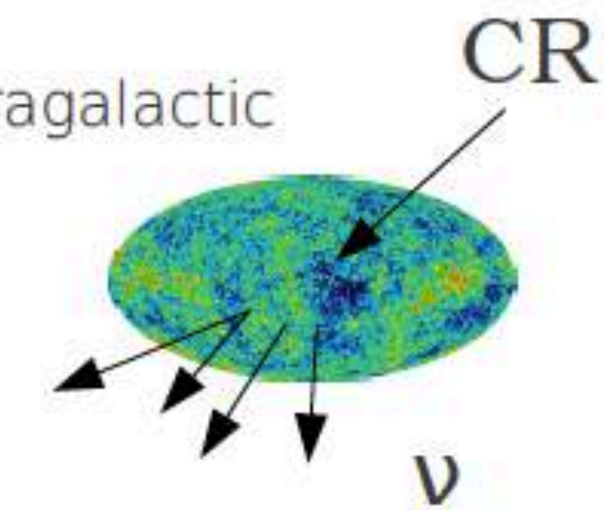
Diffuse/ atmospheric





Search for an extragalactic neutrino signal

GZK neutrinos



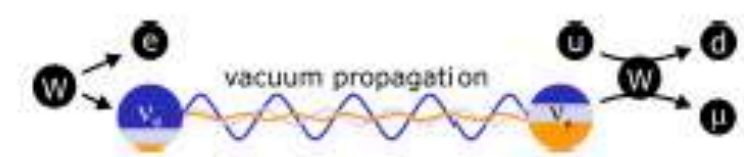
Point source

Search for point-like sources
→ galactic (e.g. SNR)
→ extragalactic (e.g. AGN)

Transient sources
→ GRB, flaring objects

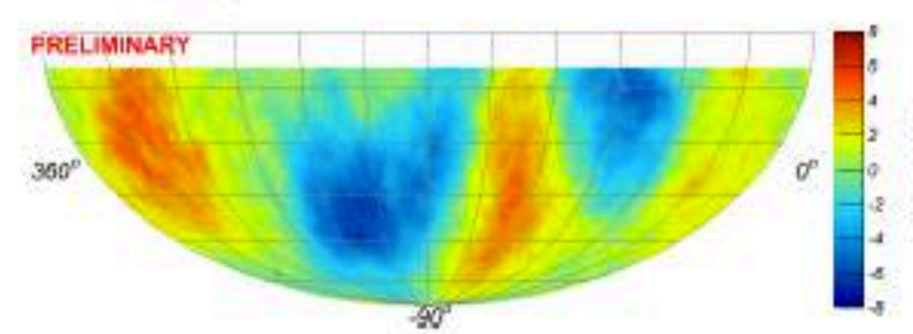
Optical follow-up programs

Prompt atms. neutrinos



Neutrino oscillations

Cosmic ray physics



Dark Matter

Exotic particles

Indirect Dark Matter Searches

$\chi + \chi \rightarrow W + W \rightarrow \nu + \nu$

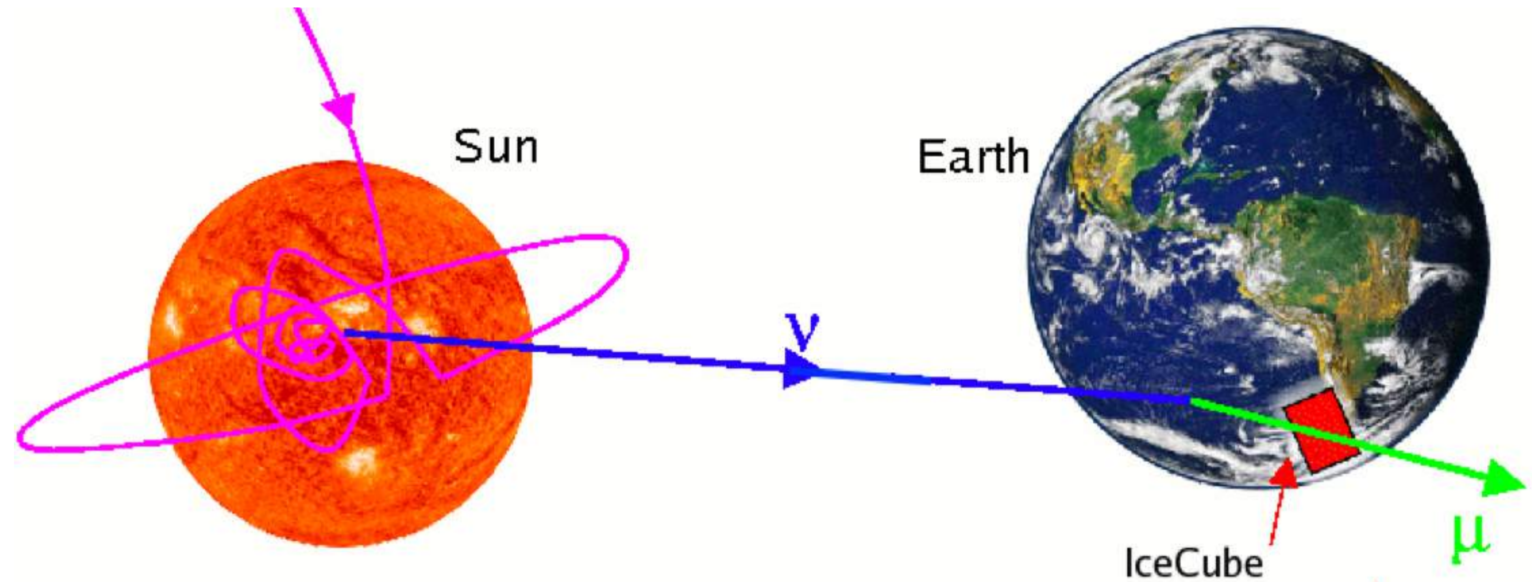
Neutrinos are typical end products of dark matter annihilation

High energy neutrinos from the Sun:

Dark matter particles scatter and get trapped in the Sun

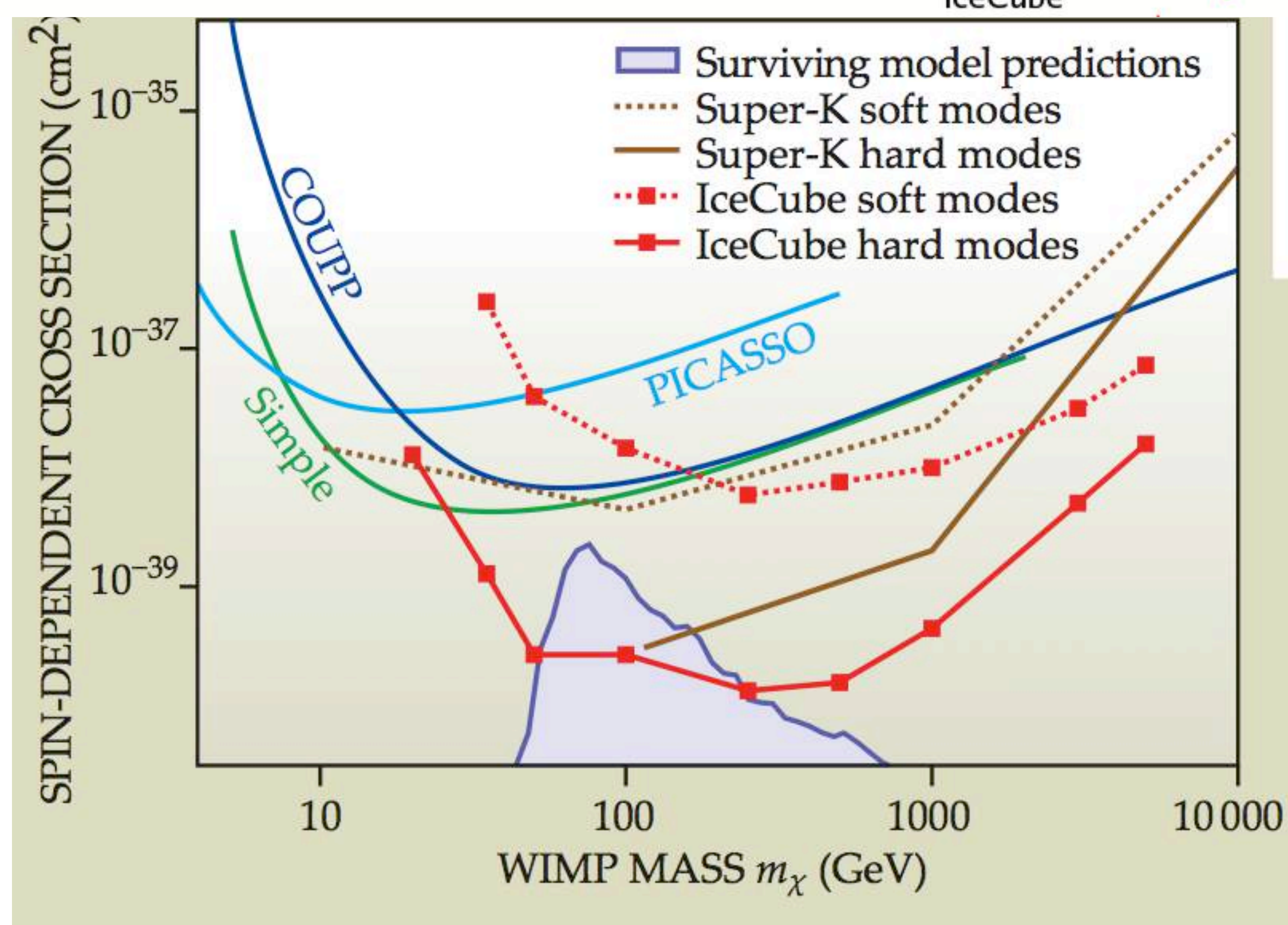
As trapped density grows, annihilation rate reaches equilibrium with capture rate

Annihilation neutrino flux is sensitive to the **dark matter scattering cross section**



Analysis of IceCube-79 Data:

"These are the most stringent *spin-dependent* WIMP-proton cross section limits to date above 35 GeV/c^2 for most WIMP models." PRL **110**:131302,2013

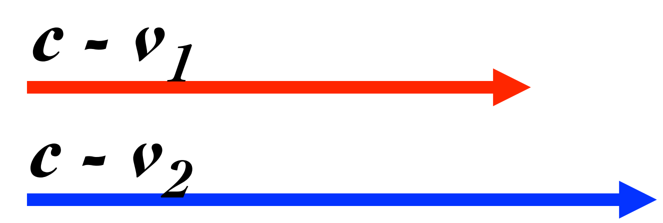


Probing Planck scale physics in neutrino oscillations

Astrophysical accelerators generate neutrinos through pion decay
so neutrinos produced in the ratio: $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$

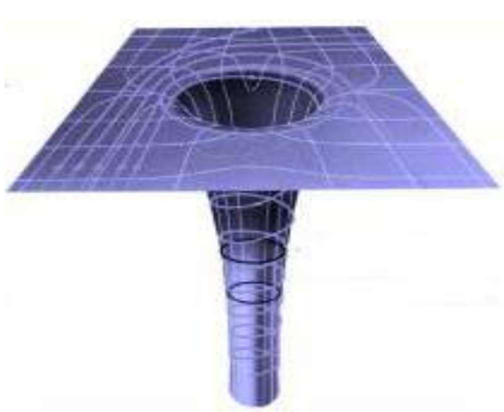
After flavour *equilibration* through oscillations, this becomes:
$\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1$
… any deviation in the measured ratios at Earth probes new physics:

- Lorentz invariance violation (LIV) in QG



- Violations of the equivalence principle (different gravitational coupling)

- Interaction of particles with 'space-time foam' (quantum decoherence of flavor states)



First analyses of data from completed detector:

Exceed predicted terrestrial backgrounds at > 4σ

Data consistent with first glimpse of astrophysical neutrino flux

Questions:

What is energy spectrum? Is there a cut-off? A gap (two source populations)?

Is there evidence for sources? Or is flux completely isotropic?

Coming next:

2x more High Energy Starting Event sample by spring

First analyses with upgoing muon neutrino tracks – is flux seen all-sky?

Significant improvement in reach for shower reconstruction

This is likely the beginning of a new astronomy and a new probe of physics beyond the Standard Model