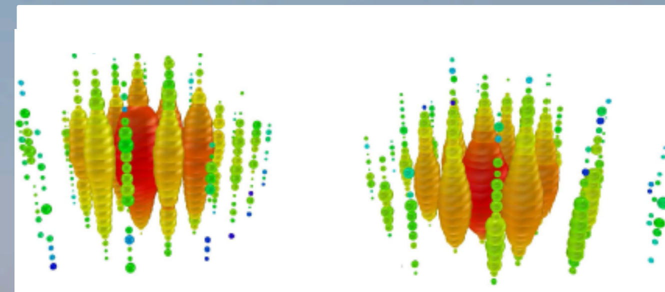


First astrophysical neutrinos?

Neutrino astroparticle physics

Joanna Kiryluk
for the IceCube Collaboration

Stony Brook University

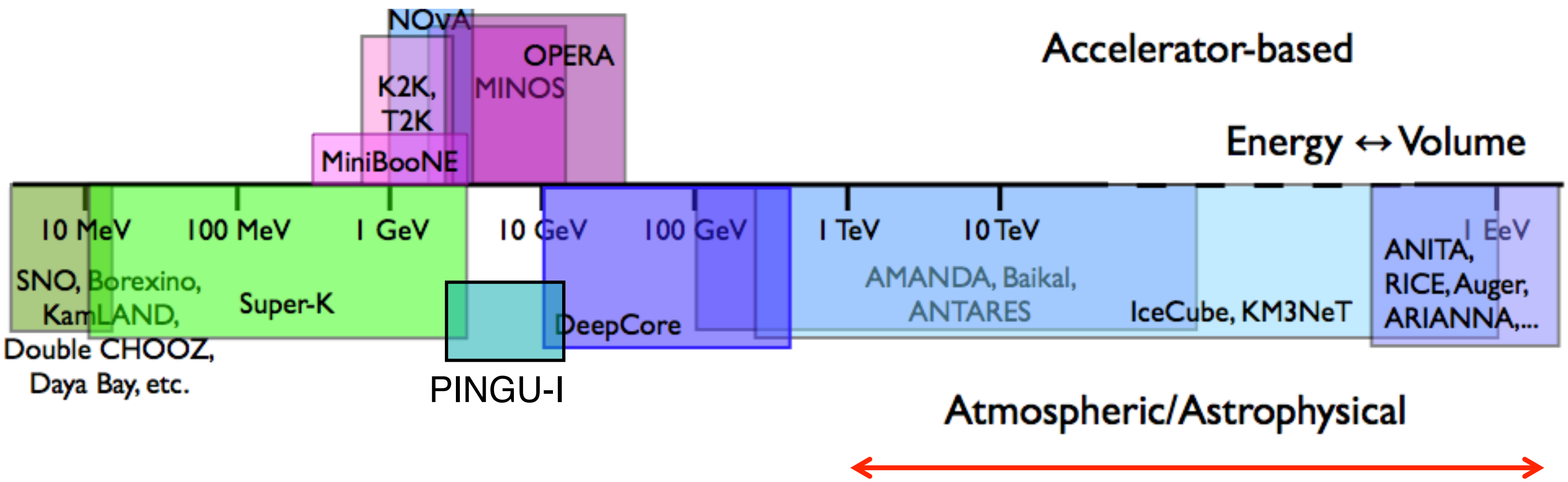
PIC 2013
IHEP, Beijing, September 3 - 7, 2013

Neutrino Astroparticle Physics

Topics of Astroparticle Physics:

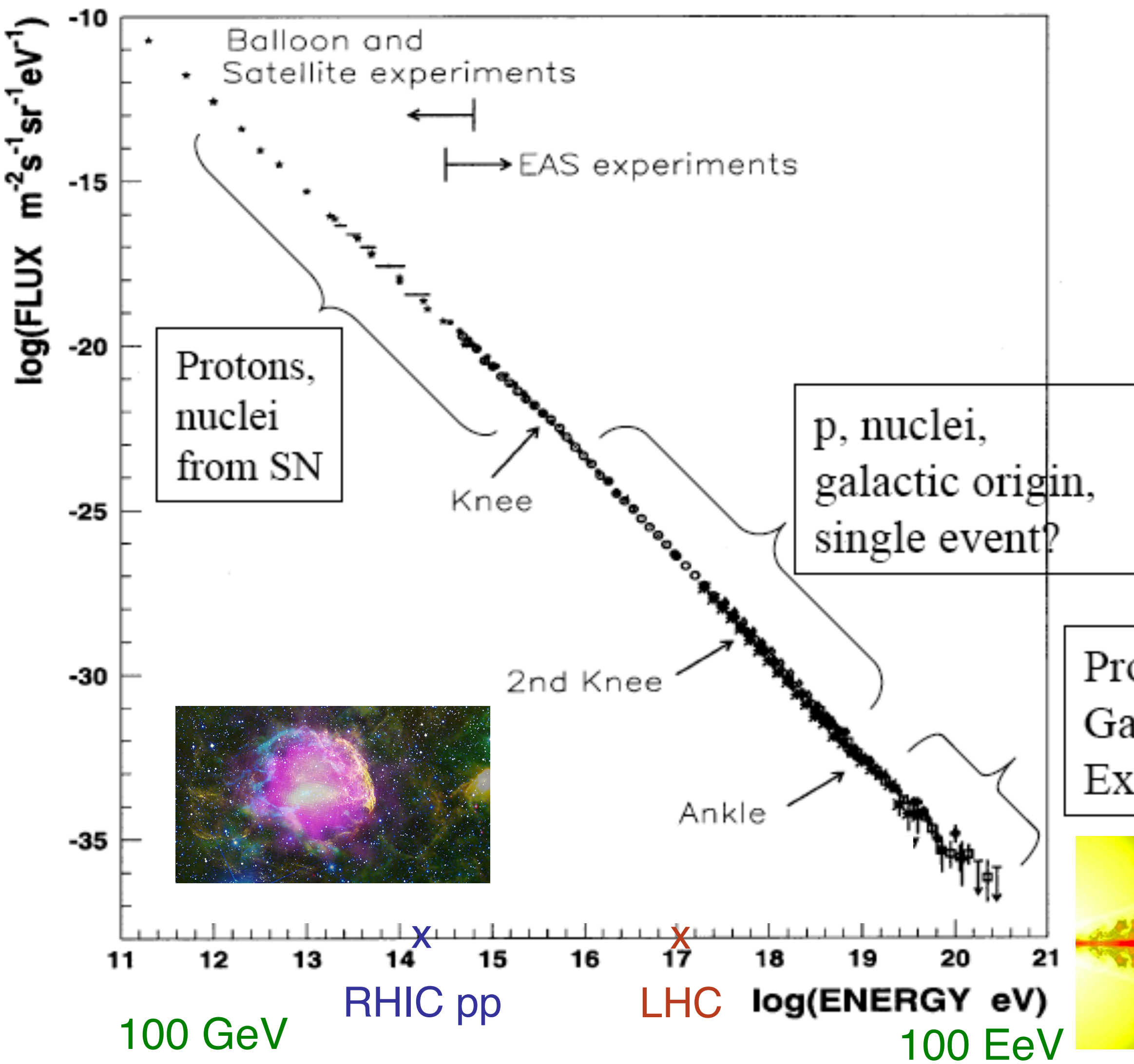
- Dark Matter
- Charged Cosmic Radiation
- Gamma-Ray Astronomy
- High-Energy Neutrino Astrophysics
- Low-Energy Neutrino Astrophysics
- Neutrino Properties
- Gravitational Waves
- Theoretical Astroparticle Physics
- Nuclear Astrophysics

$E_\nu \sim$ MeV - EeV

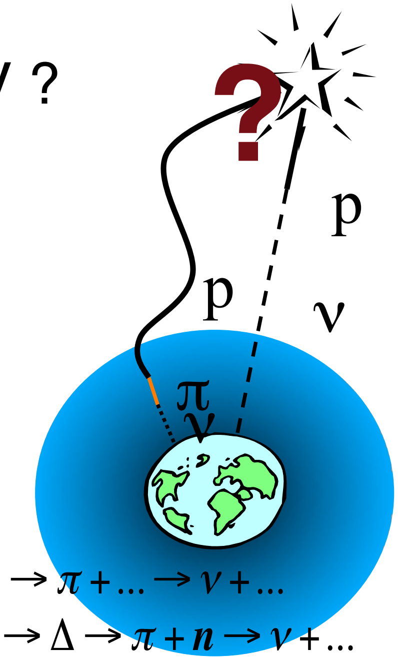


Neutrino Astroparticle Physics: Motivation

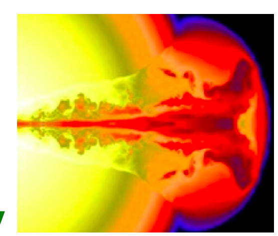
What is the origin of Cosmic Rays with E up to 10^{20} eV ?

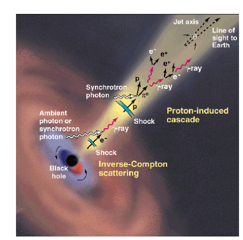


Protons? Nuclei?
Gammas? Exotics?
Extra-galactic origin



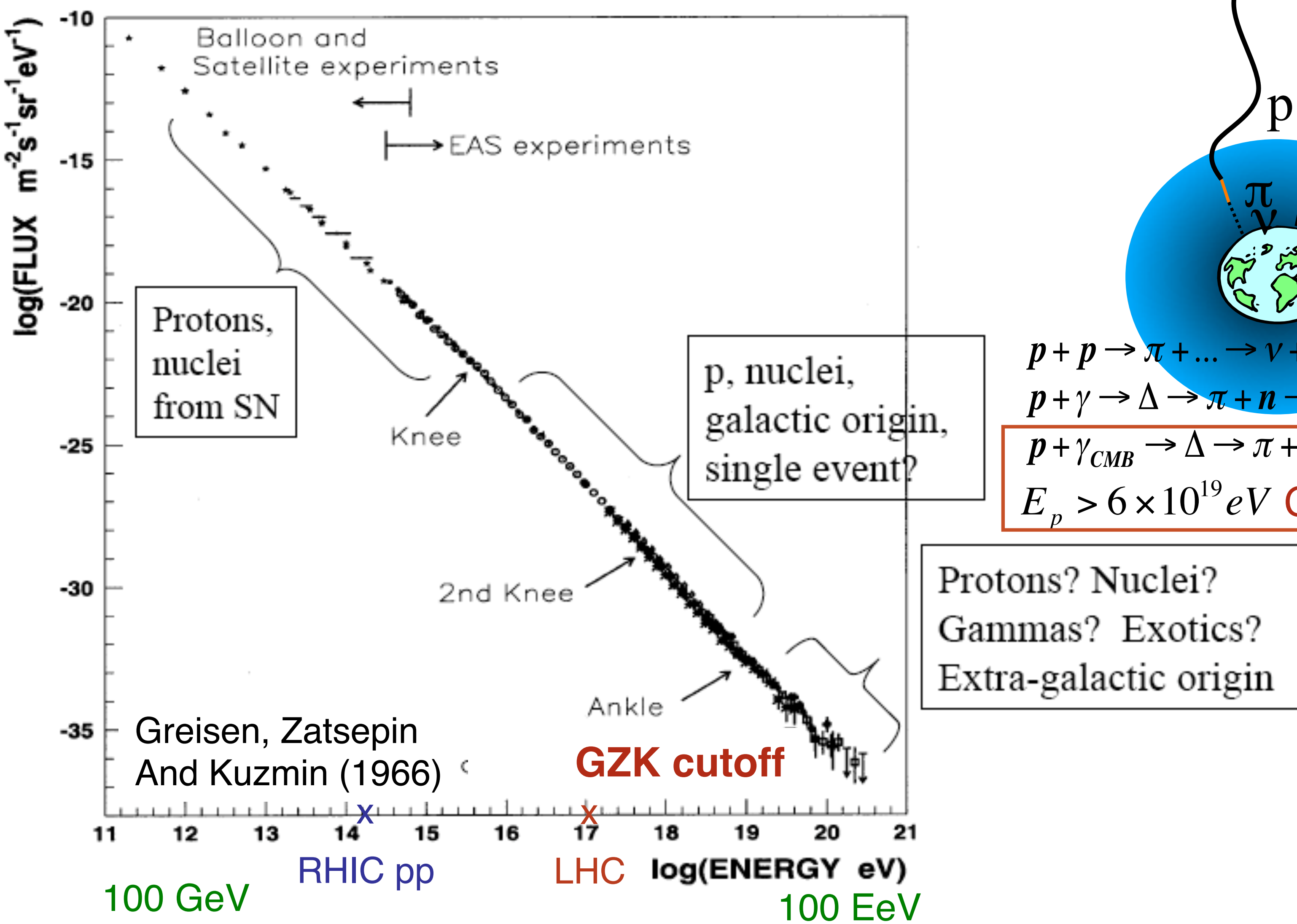
$$p + p \rightarrow \pi + \ldots \rightarrow \nu + \ldots$$
$$p + \gamma \rightarrow \Delta \rightarrow \pi + n \rightarrow \nu + \ldots$$

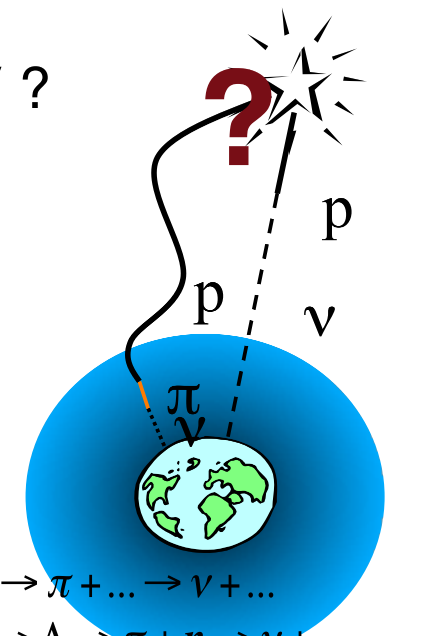




Neutrino Astroparticle Physics: Motivation

What is the origin of Cosmic Rays with E up to 10^{20} eV ?





$p + p \rightarrow \pi + ... \rightarrow \nu + ...$

$p + \gamma \rightarrow \Delta \rightarrow \pi + n \rightarrow \nu + ...$

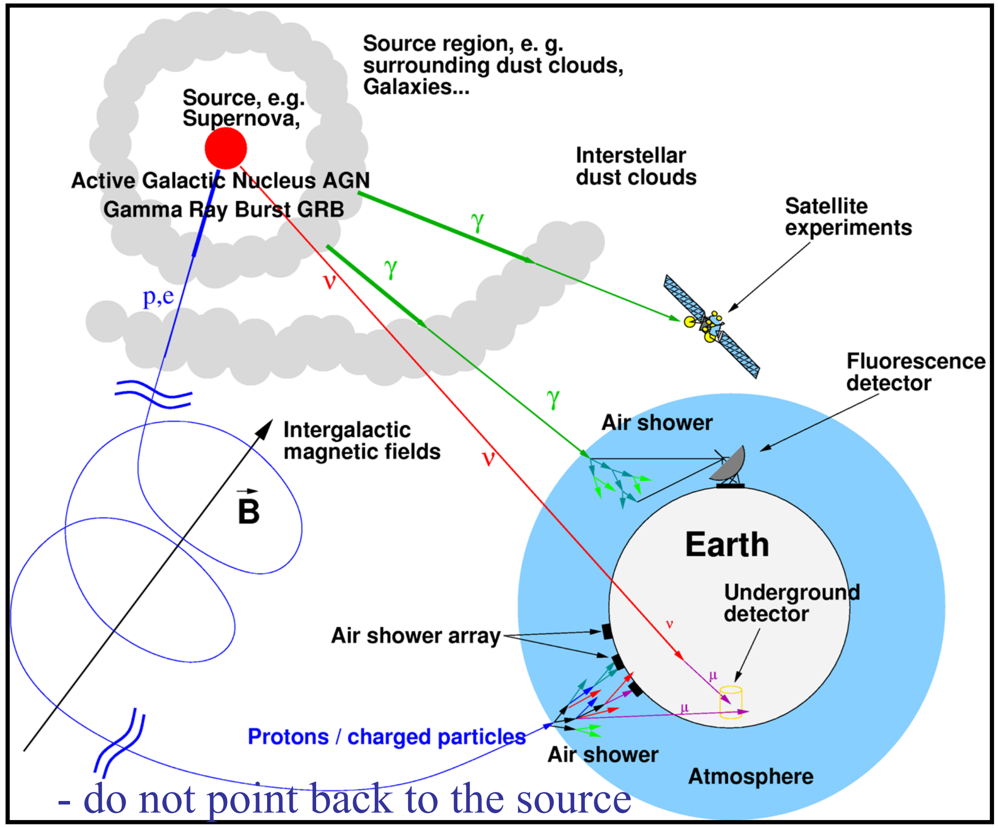
$p + \gamma_{CMB} \rightarrow \Delta \rightarrow \pi + n \rightarrow \nu + ...$

$E_p > 6 \times 10^{19} eV$ GZK cutoff

Neutrino Astroparticle Physics: Motivation

Neutrinos as probes of the high-energy Universe

- Protons with $E_p < 10$ EeV directions scrambled by magnetic fields
  - Initial Pierre Auger Collaboration result, Science 318 (2007) 938, linking CR and AGN's, weaken after new data analyzed
- γ-rays: straight-line propagation but reprocessed in the sources; TeV γ−ray astronomy: many newly discovered (galactic and extragalactic sources)
  - Fermi-LAT confirms SNR as sources of CR Science vol. 339 (2013) 807. Does not explain the highest energy CR

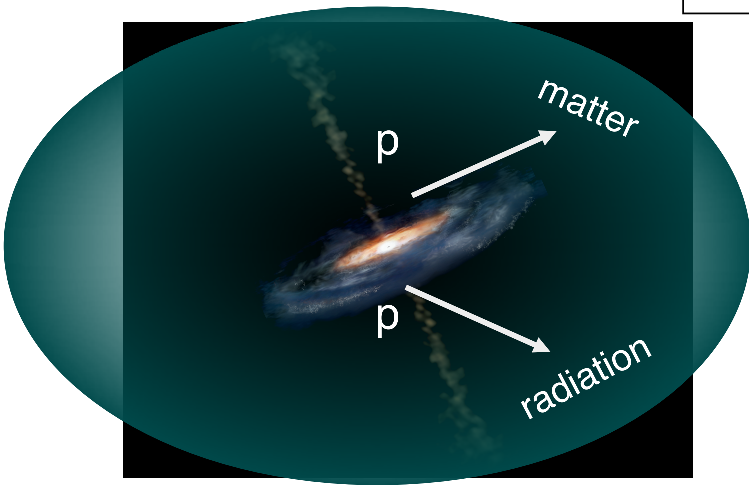


- Neutrinos: straight-line propagation, unabsorbed, not GZK suppressed, but difficult to detect

The Cosmic Neutrinos Production Mechanisms

- "On-source" astro-ν

TeV - PeV

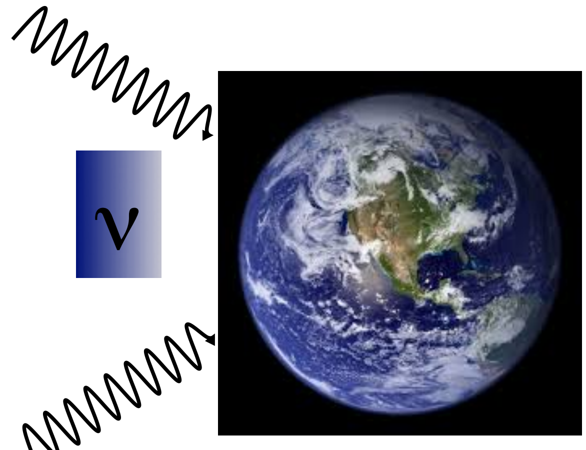


$$p + p \rightarrow \pi + ... \rightarrow \nu + ...$$

hadro production

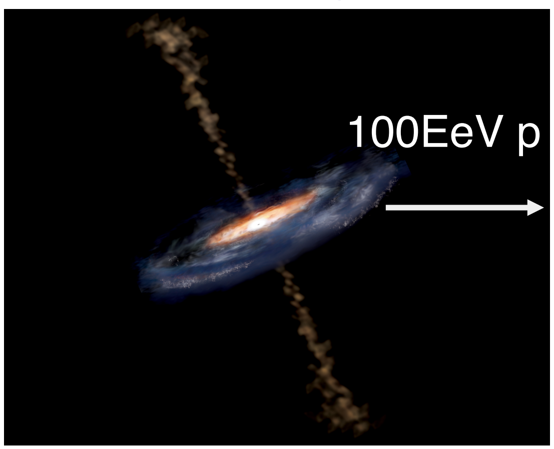
$$p + \gamma \rightarrow \Delta \rightarrow (p + \pi \rightarrow p + \gamma\gamma)$$
$$\rightarrow n + \pi \rightarrow n + \nu + ...$$

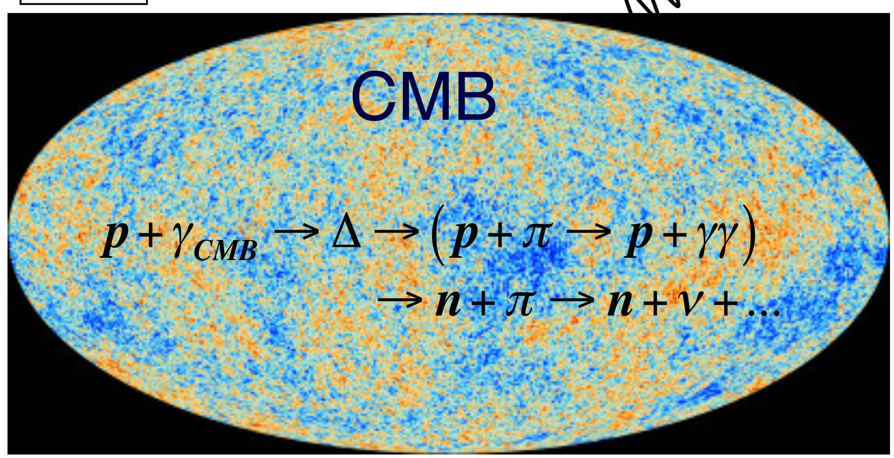
photo production



- "GZK" cosmogenic ν

EeV





$$p + \gamma_{CMB} \rightarrow \Delta \rightarrow (p + \pi \rightarrow p + \gamma\gamma)$$
$$\rightarrow n + \pi \rightarrow n + \nu + ...$$

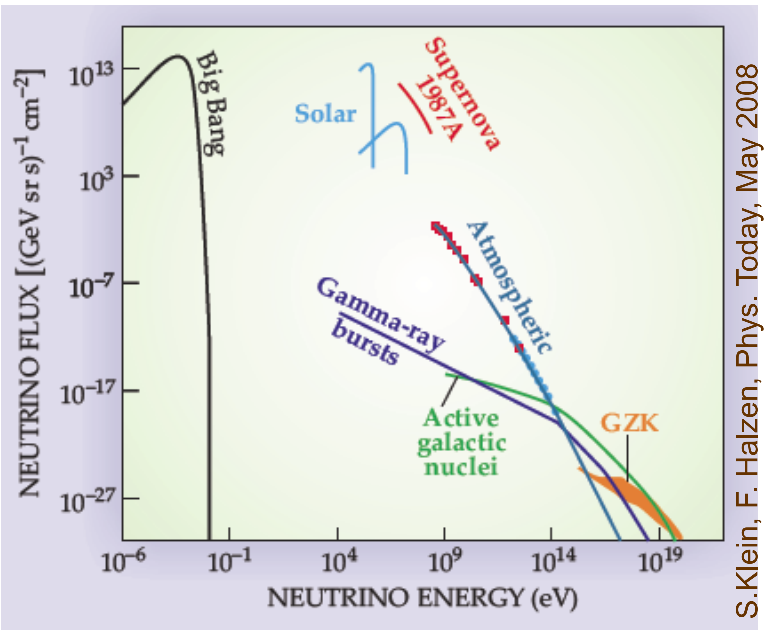
Source: S. Yoshida (TeVPA2013)

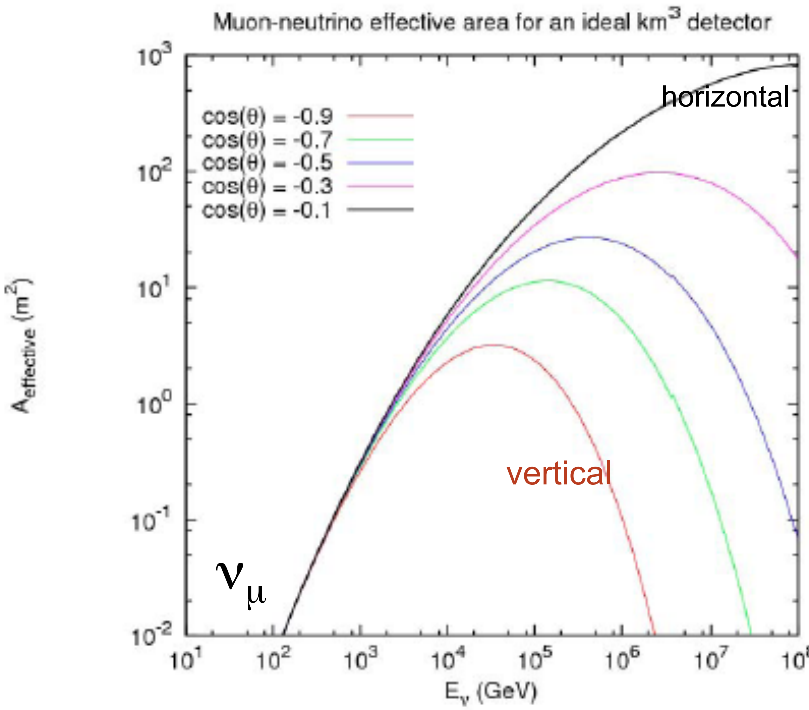
Need for a 1 km^3 Neutrino Detector

Rate = Neutrino flux x Neutrino Effective Area

= Neutrino flux x Neutrino Cross Section x Absorption in Earth

x Size of detector x (Range of muon for ν_μ)





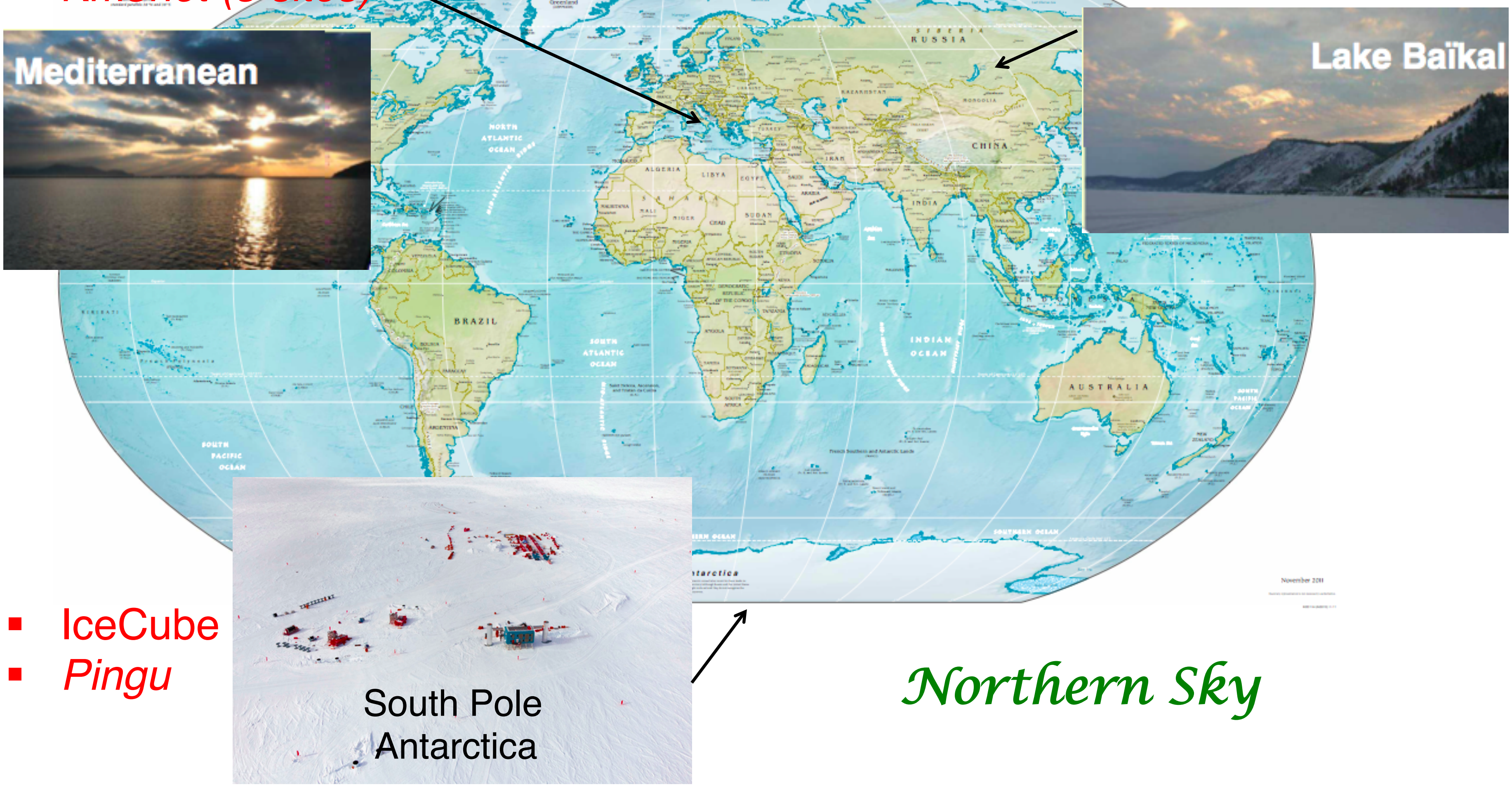
Expected GZK neutrino rates in 1 km^3 detector: ~ 1 per year

Neutrino Telescopes

Techniques: ▪ optical detection

Southern Sky

- Antares
- *Km3net (3 sites)*
- Lake Baikal

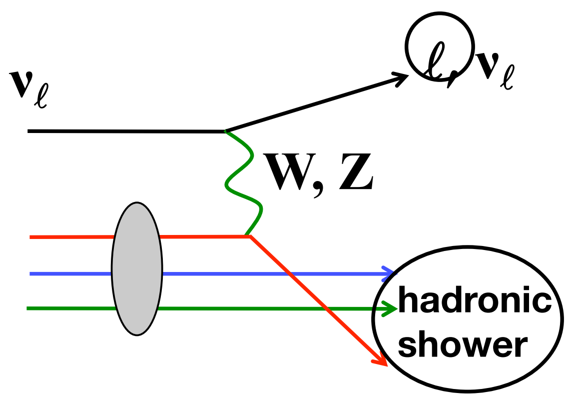


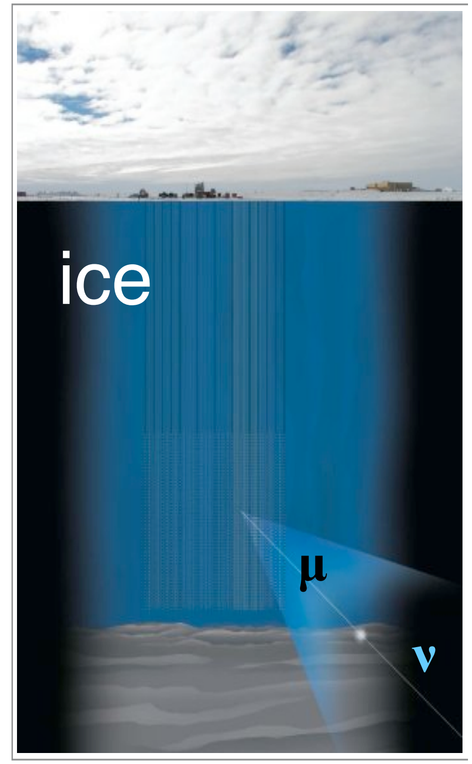
- IceCube
- *Pingu*

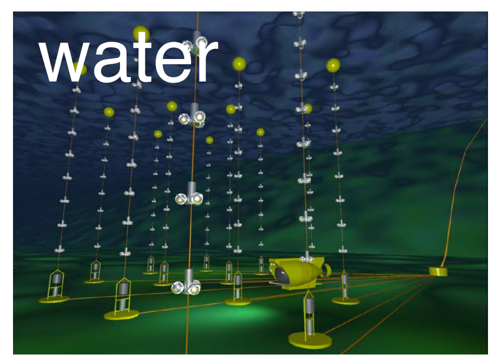
Northern Sky

Neutrino Telescopes: optical detection principle

Neutrinos of all flavors interact in or near the detector through charged current (CC) or neutral current (NC) weak interaction:







Neutrino interaction identification method: Observe the secondaries

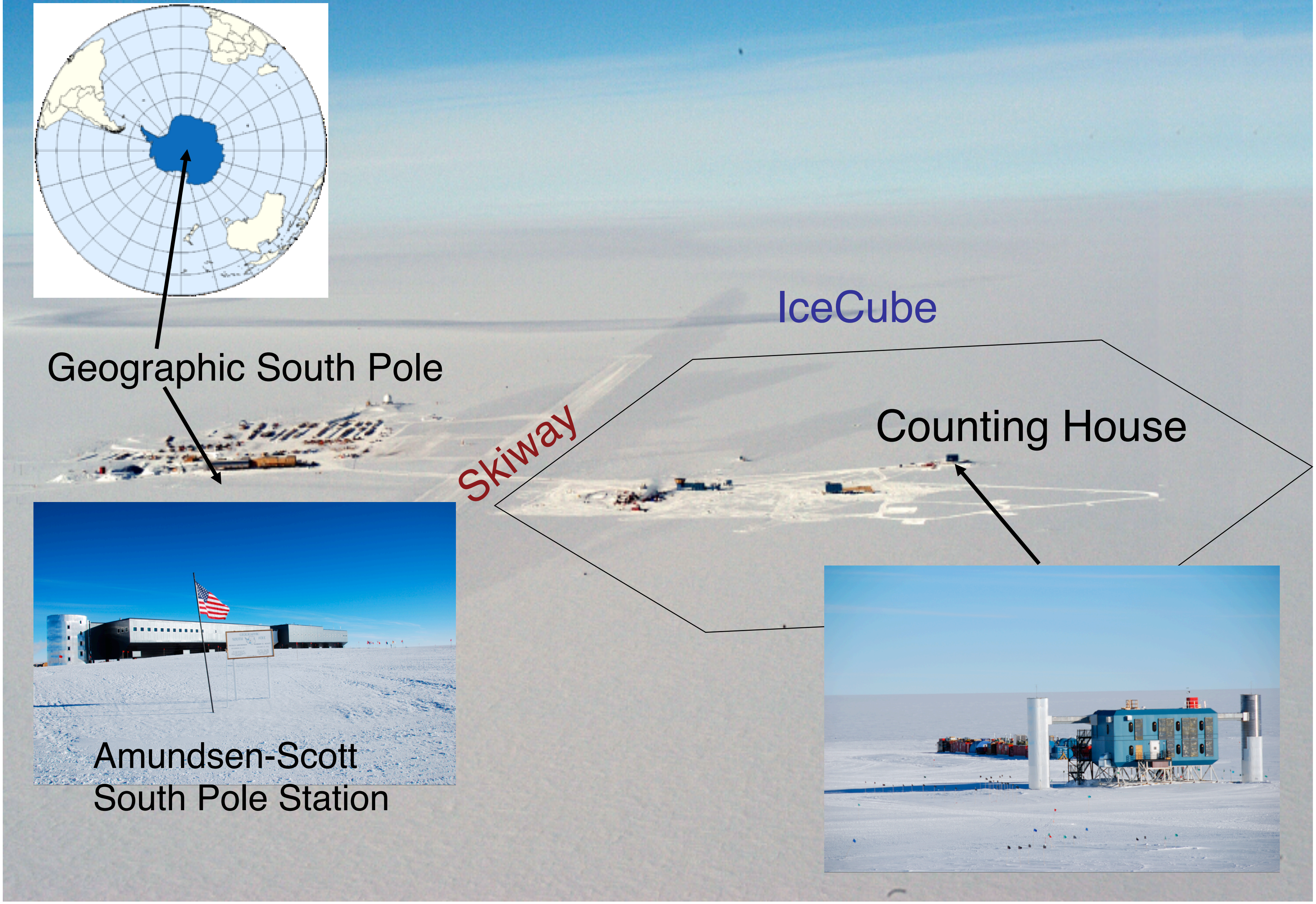
- O(km) muon tracks from ν_μ CC

  1 TeV ~ 2.5 km, 1PeV ~ 15 km

- O(10 m) e-m and/or hadronic cascades from ν_e CC, low energy ν_τ CC, and ν_x NC

via Cherenkov radiation detected by a 3D array of optical sensors

IceCube at the South Pole

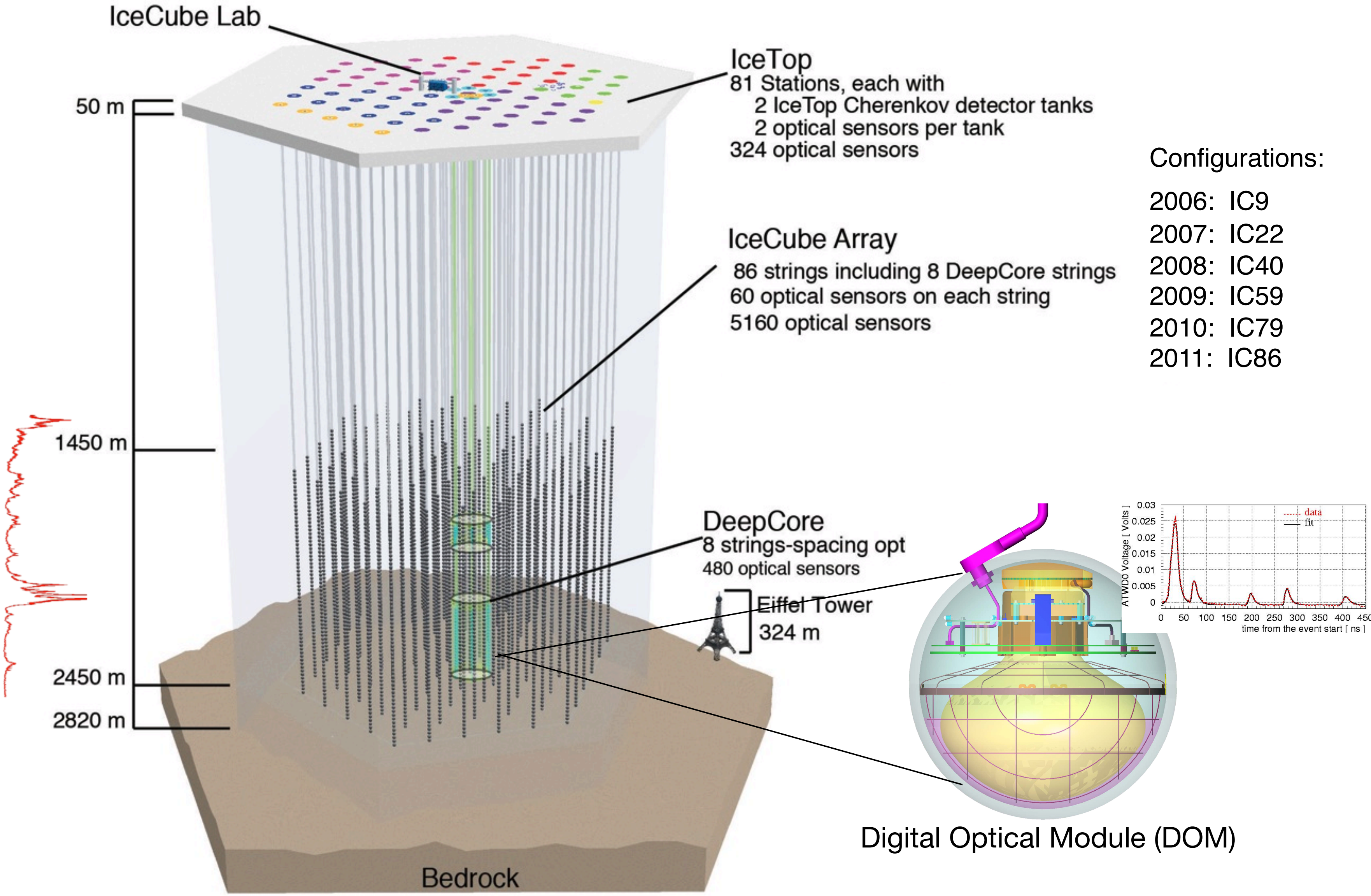



The IceCube Collaboration
10 countries, 40 institutions, ~260 collaborators
University of Alberta
Clark Atlanta University
Georgia Institute of Technology
Lawrence Berkeley National Laboratory
Ohio State University
Pennsylvania State University
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California-Berkeley
University of California-Irvine
University of Delaware
University of Kansas
University of Maryland
University of Wisconsin-Madison
University of Wisconsin-River Falls
Chiba University
Sungkyunkwan University
University of Oxford
Université Libre de Bruxelles
Université de Mons
University of Gent
Vrije Universiteit Brussel
University of Adelaide
University of Canterbury
Stockholm University
Uppsala Universitet
Deutsches Elektronen-Synchrotron
Humboldt Universität
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität München
Universität Bonn
Universität Dortmund
Universität Mainz
Universität Wuppertal
Ecole Polytechnique
Fédérale de Lausanne
University of Geneva
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)

The IceCube Detector

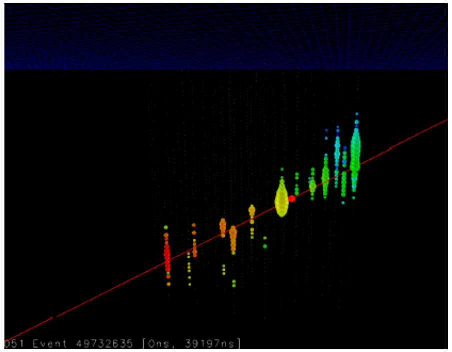
Configurations:

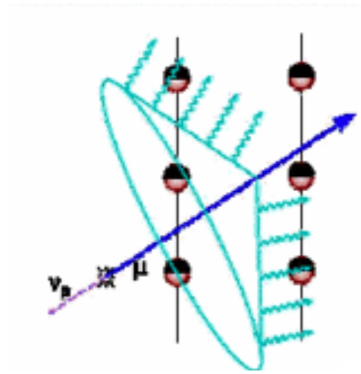
2006: IC9
2007: IC22
2008: IC40
2009: IC59
2010: IC79
2011: IC86



Event Signatures

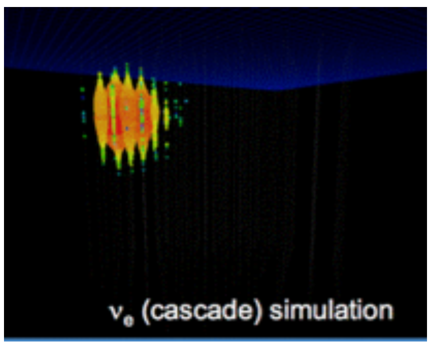
Neutrino interaction identification method: observe the secondaries (tracks, cascades) via Cherenkov radiation detected by a 3D array of optical sensors

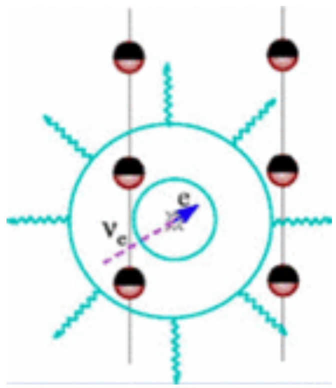




Tracks:

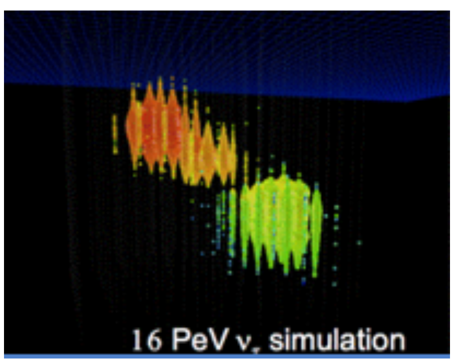
- $\nu_\mu + N \rightarrow \mu + X$
- through-going muons
- pointing resolution <1°





Cascades:

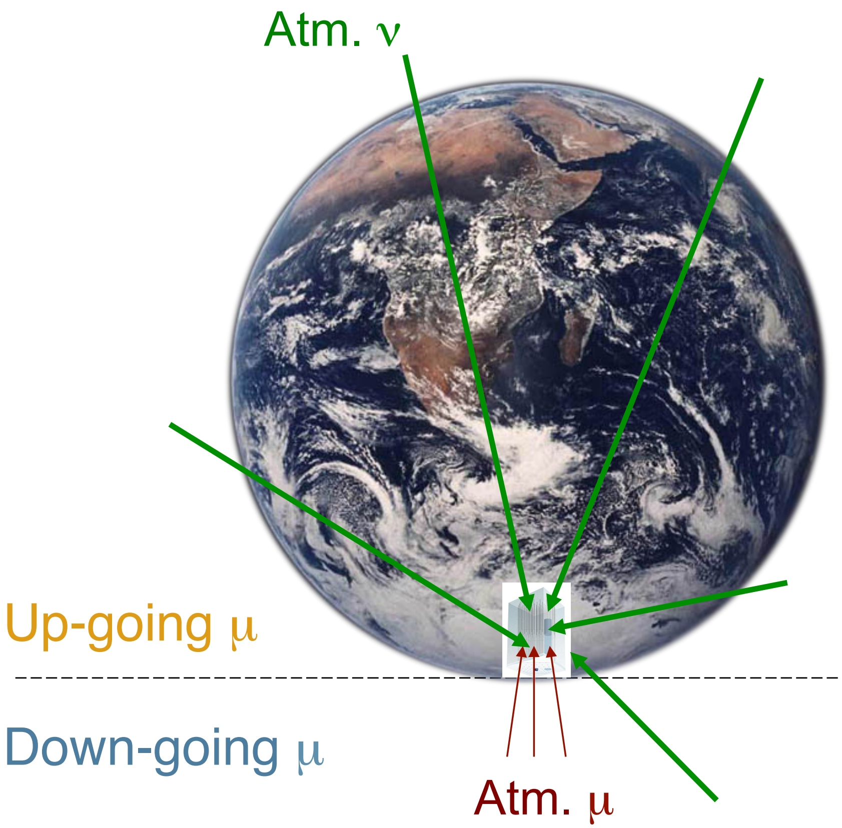
- e-m and hadronic cascades
- $\nu_{e(\tau)} + N \rightarrow e(\tau) + X$
  $\nu_f + N \rightarrow \nu_f + X \quad f = e, \mu, \tau$
- good energy resolution for cascades contained in the detector ~10%

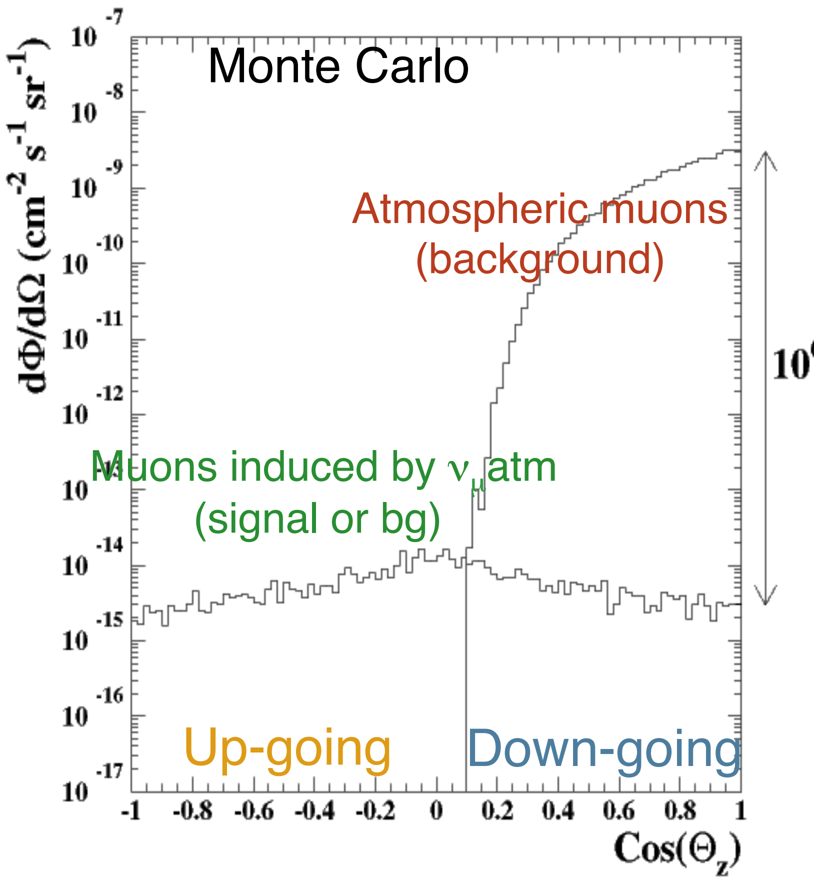


Composites

- starting tracks
- tau double bangs
- good directional and energy resolution

Cosmic Rays Background Rejection

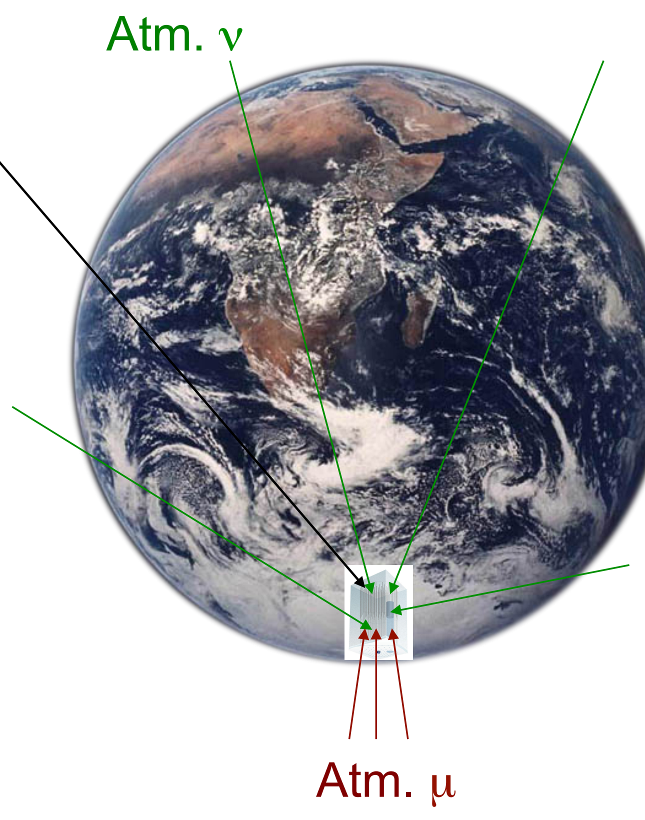




Reconstruct μ tracks and identify their origin (Cosmic Rays vs atm. ν_μ) by their direction

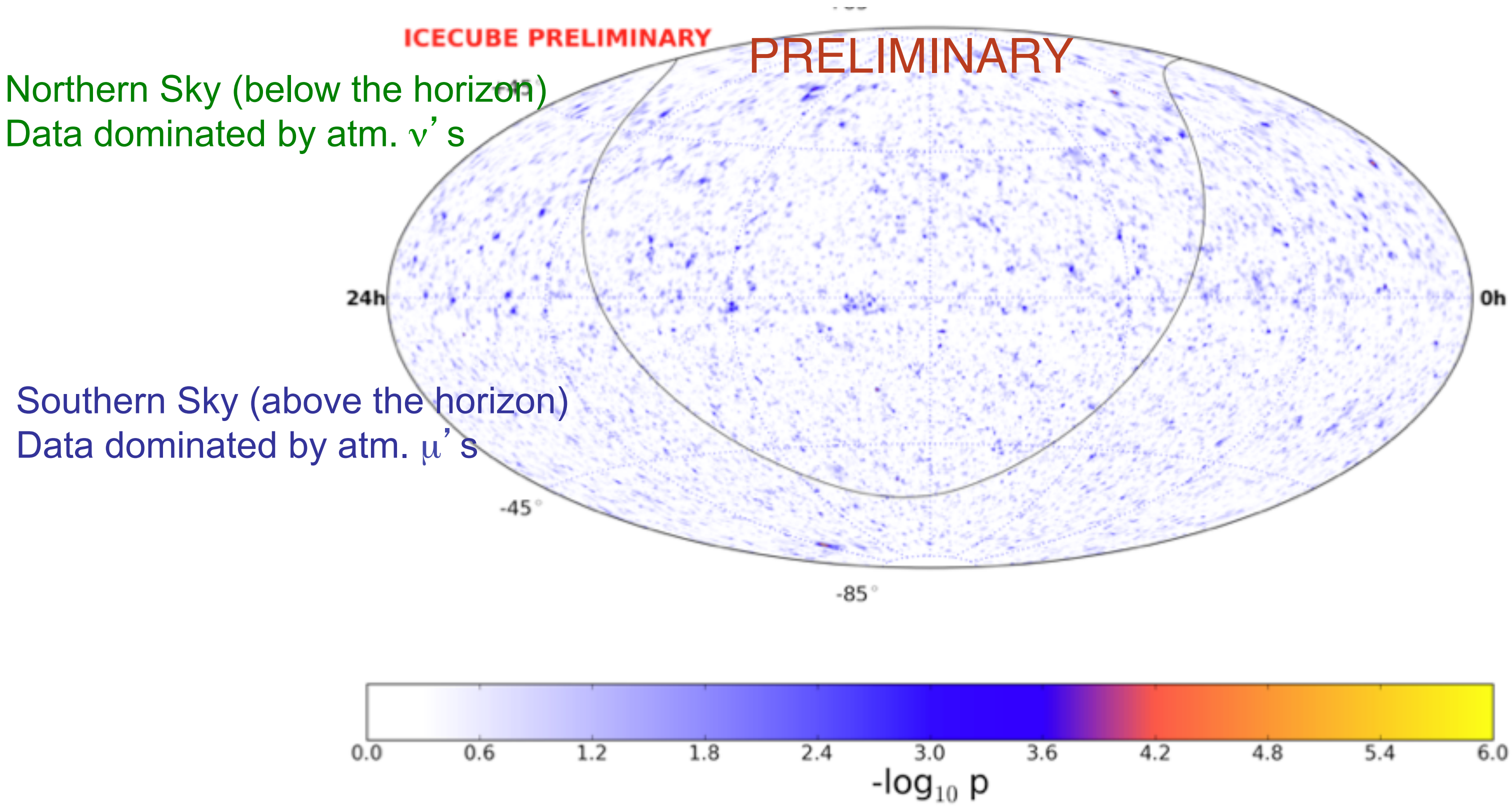
Point Source Neutrino Search

Search for excess of astrophysical neutrinos from a common direction over the background of atmospheric neutrinos



IceCube: 4 Years Point Source Search: Skymap

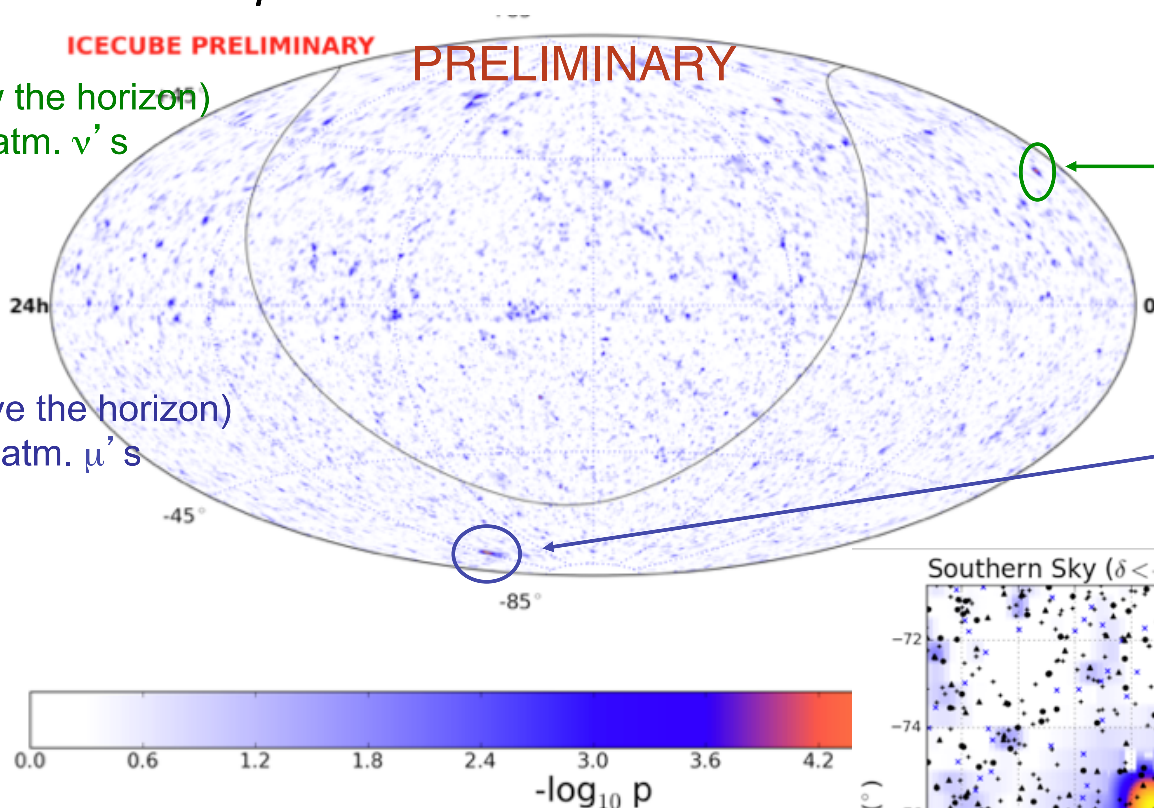
- *Search for excess of astrophysical neutrinos from a common direction over the background of atmospheric neutrinos*
- *All-sky search and a priori source list*

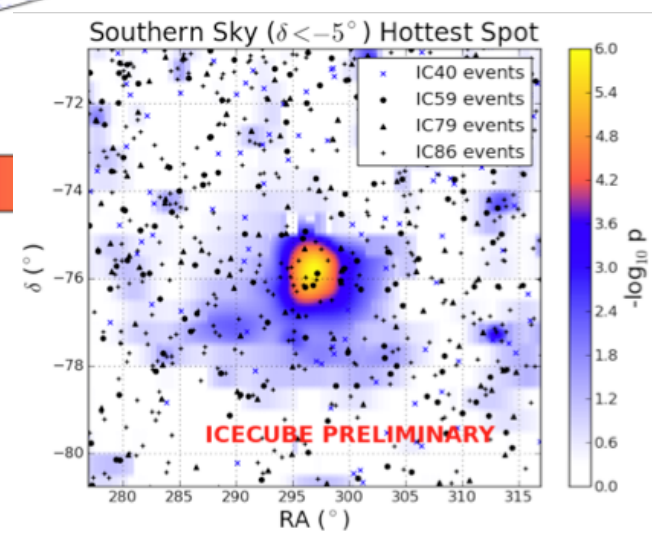


- 4 years of data: IC40+IC59+IC79+IC86, Livetime: 1371 days
- Total number of events: 178k (upgoing) + 216 (downgoing)

IceCube: 4 Years Point Source Search: Skymap

- *Search for excess of astrophysical neutrinos from a common direction over the background of atmospheric neutrinos*
- *All-sky search and a priori source list*



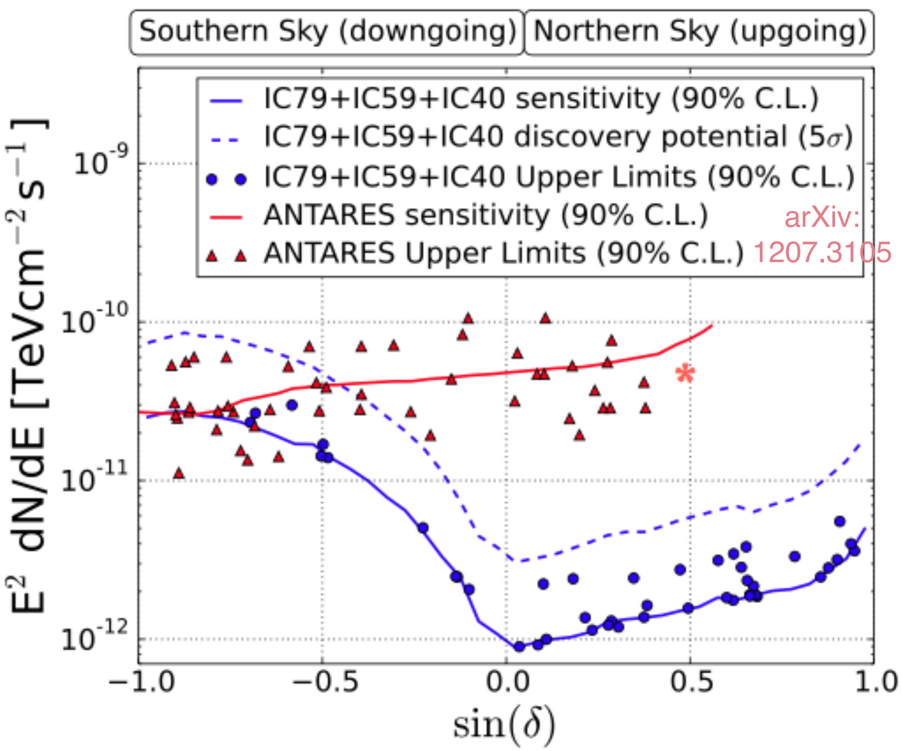


- 4 years of data: IC40+IC59+IC79+IC86, Livetime: 1371 days
- Total number of events: 178k (upgoing) + 216 (downgoing)
- Hottest spots and post-trial p-values:
- Nothern sky: Ra=11.45deg, Dec=31.35deg, 37.6 % (not significant)
- Southern sky: Ra=296.95deg, Dec=-75.75deg, 9.3 % (not significant)

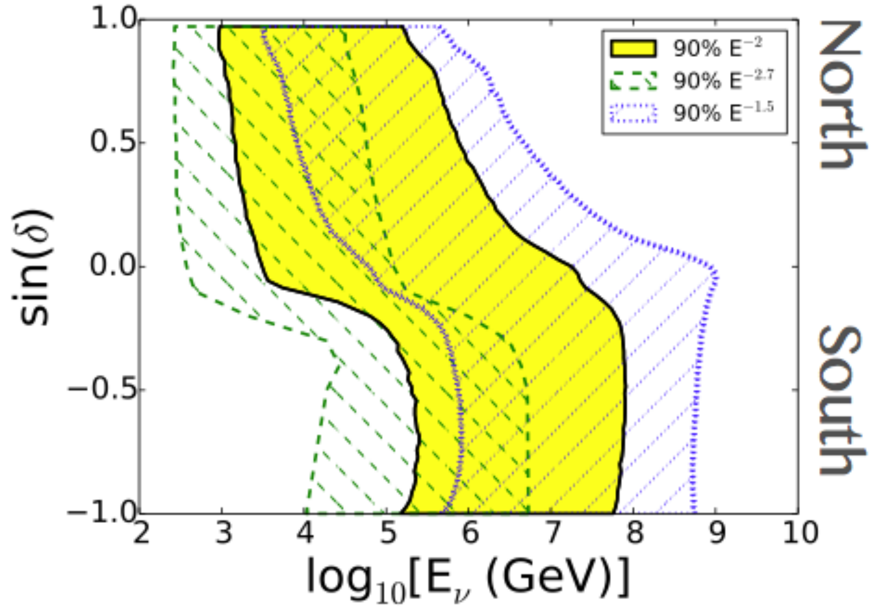
No evidence for point sources

IceCube: 3 Years Point Source Search: Upper Limits

- *Search for excess of astrophysical neutrinos from a common direction over the background of atmospheric neutrinos*
- *Stacking analyses*

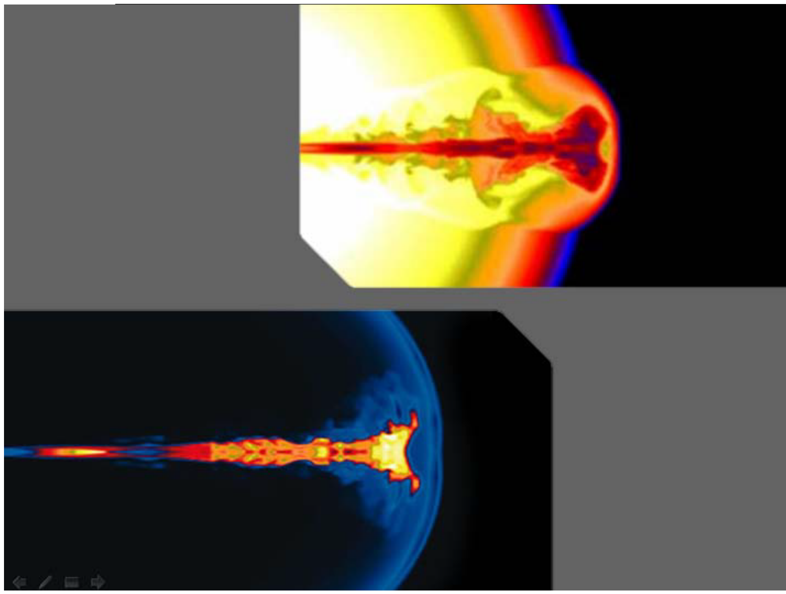


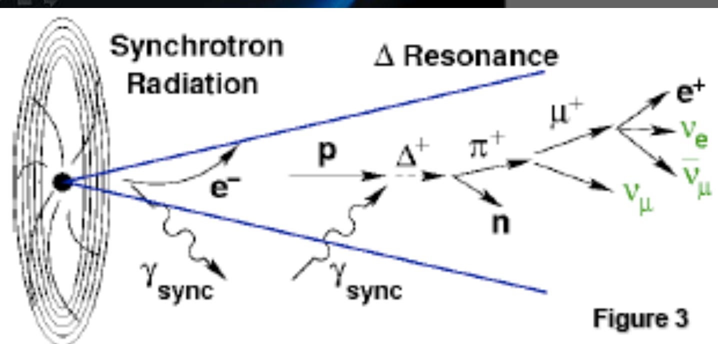
- Northern sky: 1 TeV – 1 PeV
- Southern sky: 100 TeV – 100 PeV

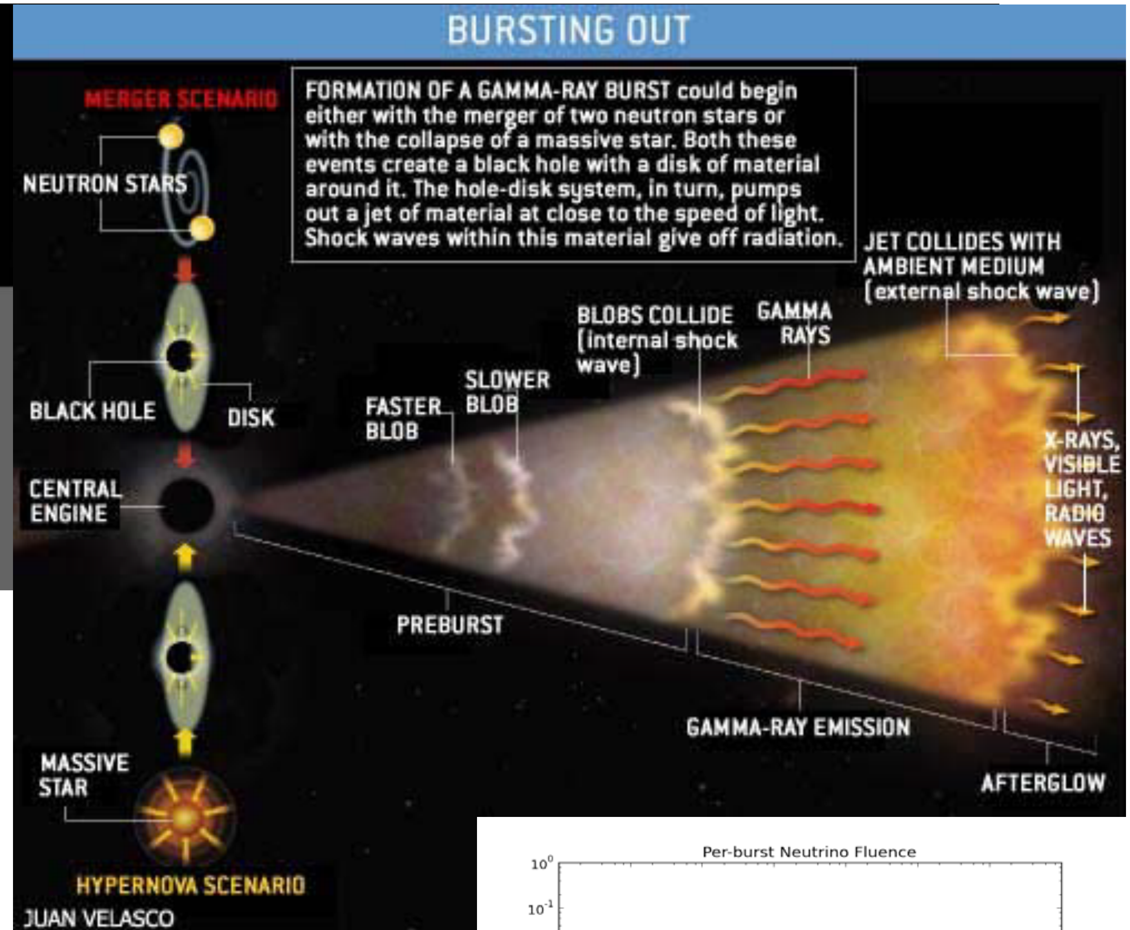


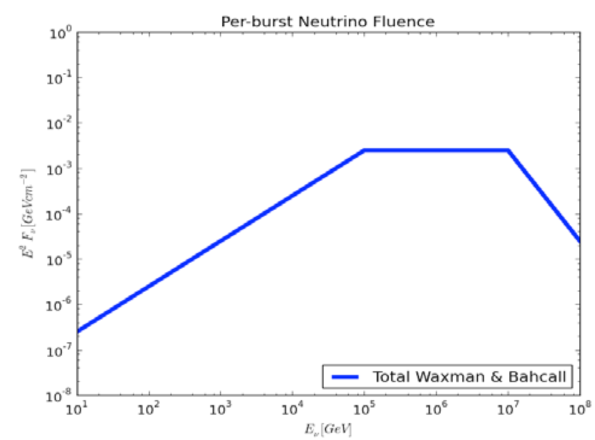
No evidence for point sources

Neutrinos From Gamma Ray Bursts





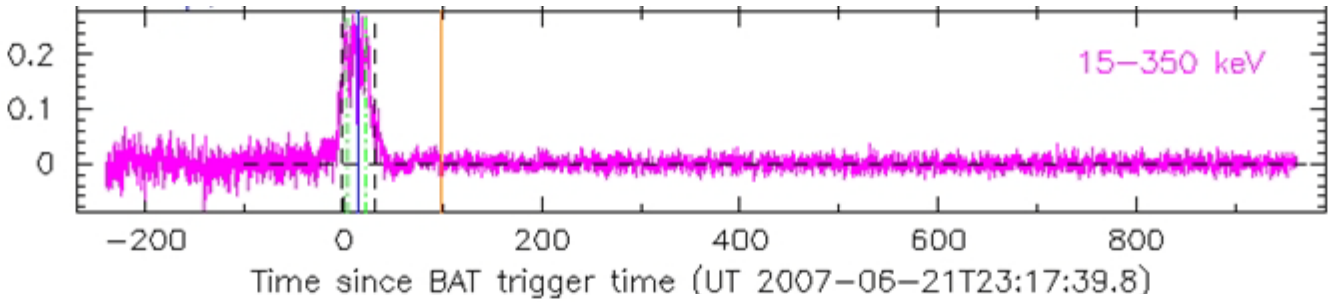




Fireball model:
Internal shocks in GRBs → acceleration for UHECRs
Neutrino production in p-γ interactions in fireball

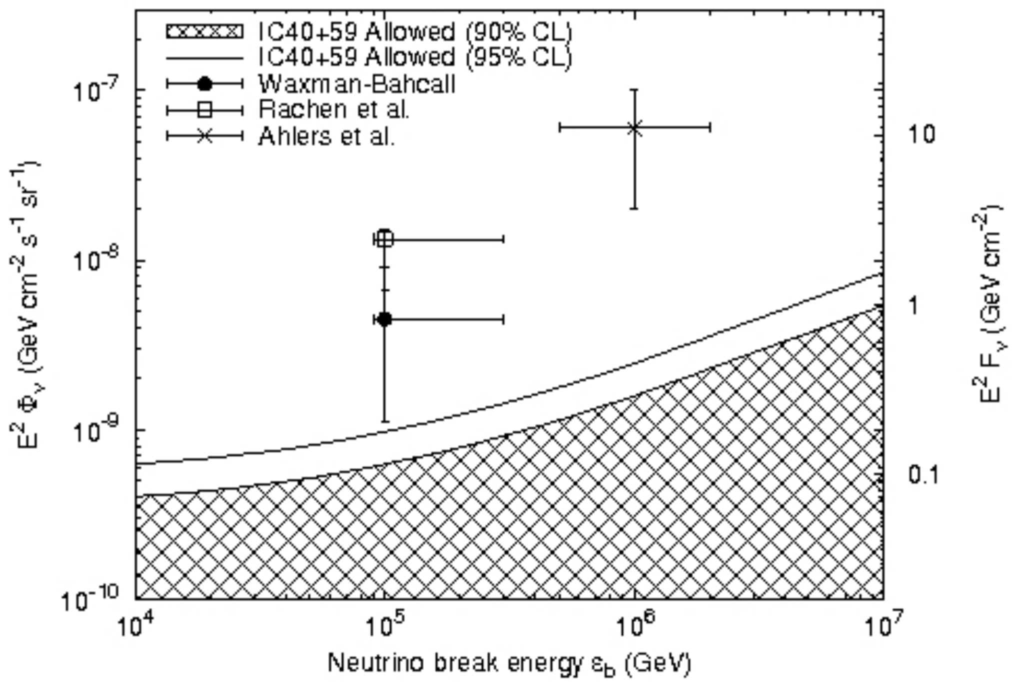
IC40+IC59 Neutrinos From Gamma Ray Bursts

Search for neutrinos from direction of GRB in short time window (<±1 day) around trigger time (=satellite measurement of GRB):



Results:

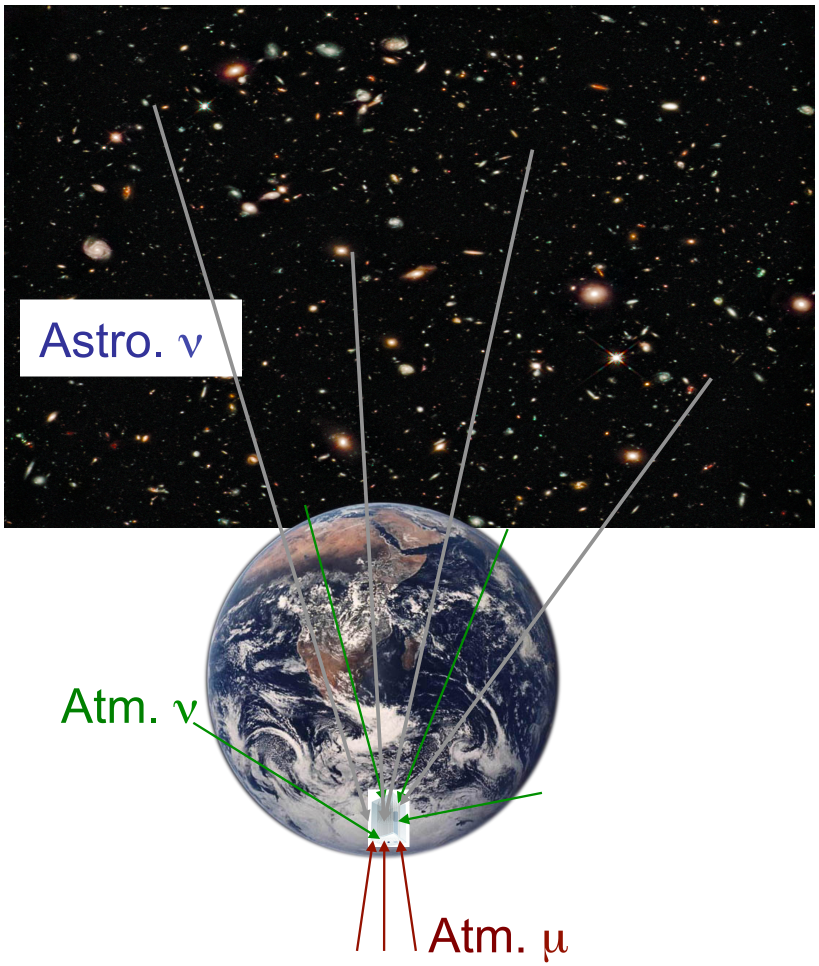
- 215 GRBs in Northern sky
- 2 events observed:
  both trigger IceTop, likely atm. muons
- Neutrino flux limits in tension with fireball model



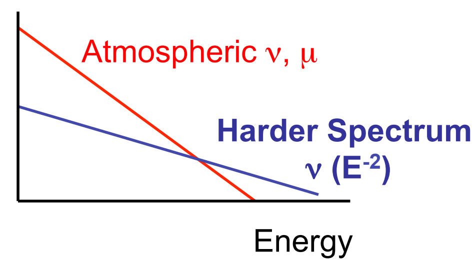
***Nature* 84, 351 (2012)**

Search for Diffuse Neutrino Fluxes

Diffuse flux = effective sum from all (unresolved) extraterrestrial sources (e.g.AGNs)
Possibility to observe diffuse signal even if flux from an individual source is too small to be detected by point source techniques.

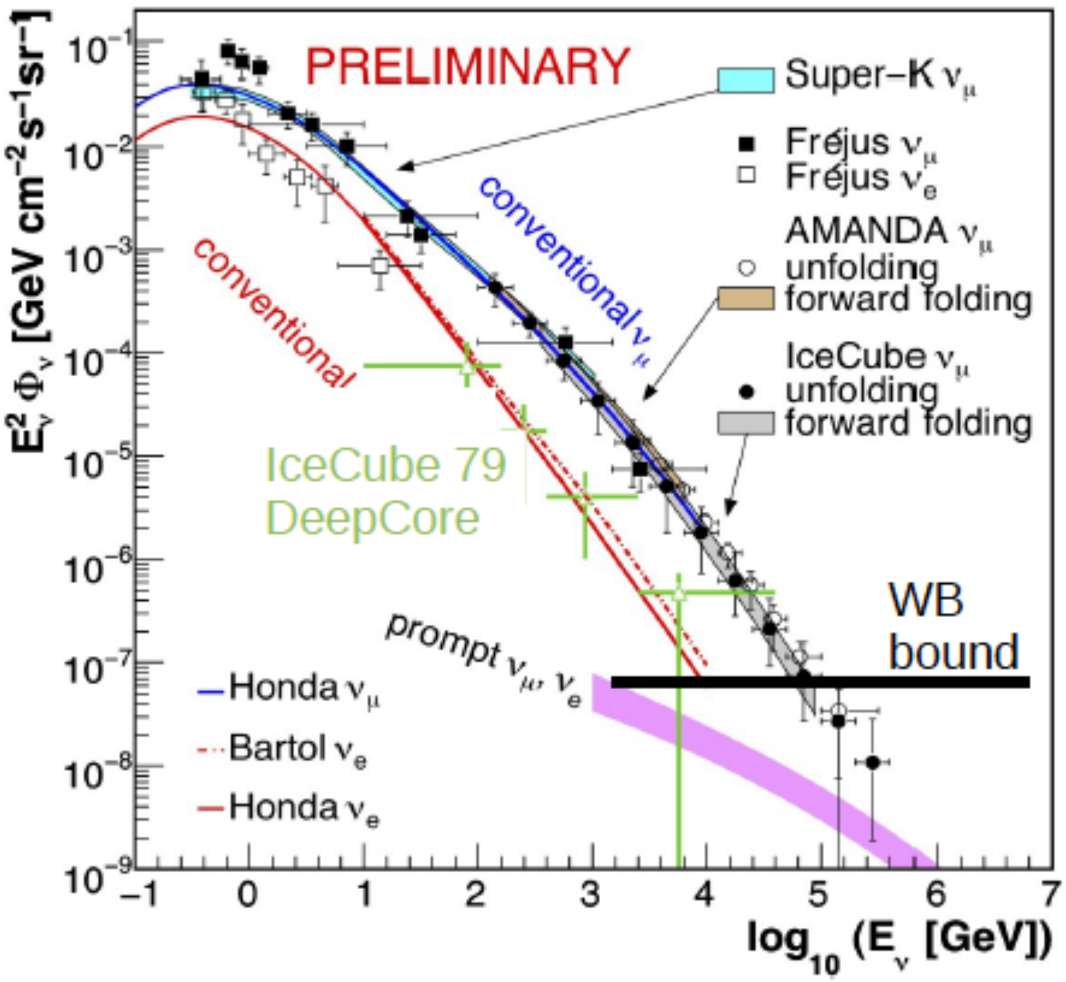


- Search for excess of astrophysical neutrinos with a harder spectrum than background atmospheric neutrinos



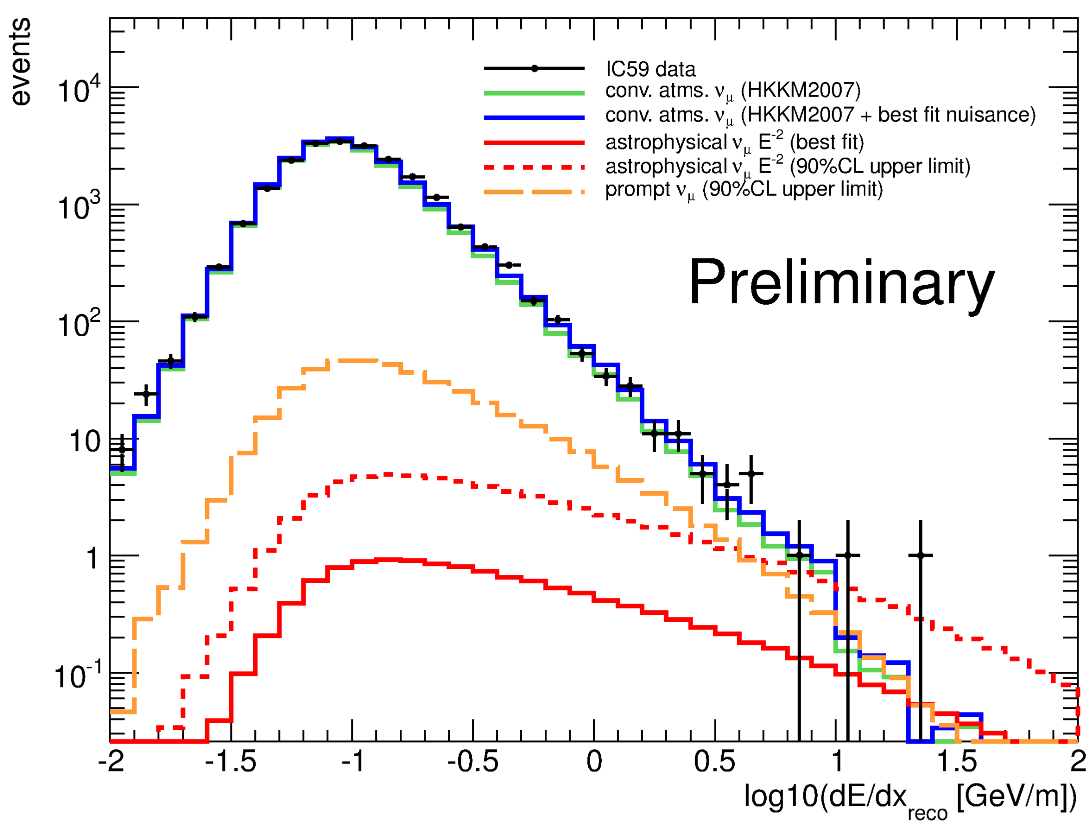
- Advantage over point source search: can detect weaker fluxes
- Sensitive to all three flavors of neutrinos
- Disadvantage: high background

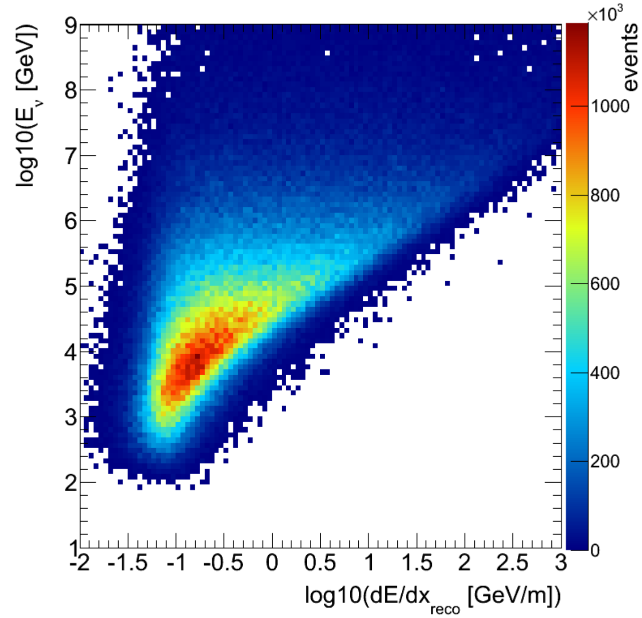
Atmospheric Neutrinos



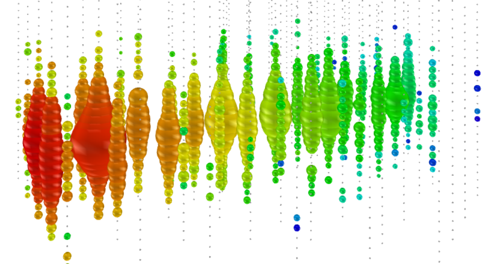
- atmospheric ν_μ spectrum, measure in IC40
- atmospheric ν_e spectrum, measured in IC79 (Deep Core)
- predicted prompt atmospheric ν-fluxes from charmed meson decays, Enberg et al (not yet measured)
- WB (Waxman-Bahcall) theoretical limit on diffuse astrophysical ν_μ

IC59 Search for a Diffuse Flux of Muon Neutrinos





Energy estimator: reconstructed energy loss dE/dx



the highest energy event

<u>Best-fit results:</u>

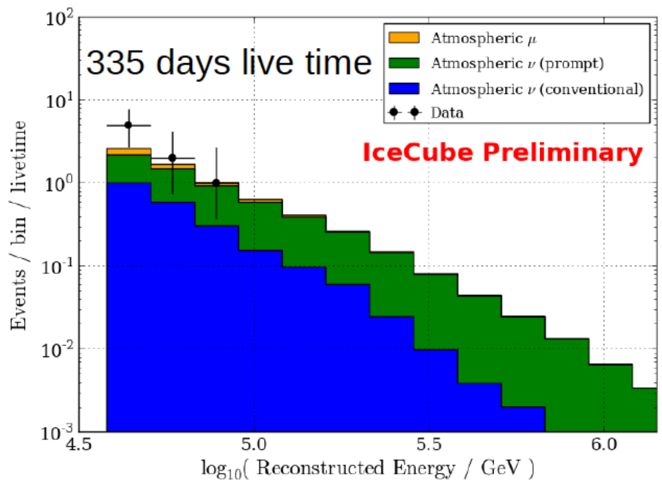
E^{-2} norm = (2.7 +/- 5.9) ×10^{-9} E^2 GeV cm^{-2} s^{-1} sr^{-1}

Prompt norm = (0 +/- 1.216) × [Enberg et al. + Gaisser knee]

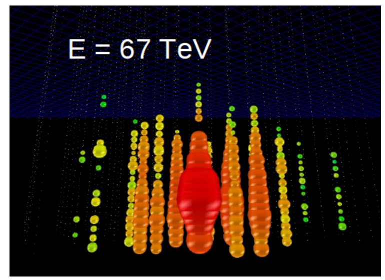
IC59 Neutrino-Induced Cascade Search Results

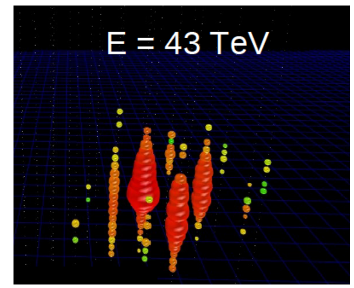
- (contained) cascade search analysis in IceCube, 335 days (2009-2010)
- Energy range 43 TeV < E_ν < 6 PeV (central 90% ν signal events)

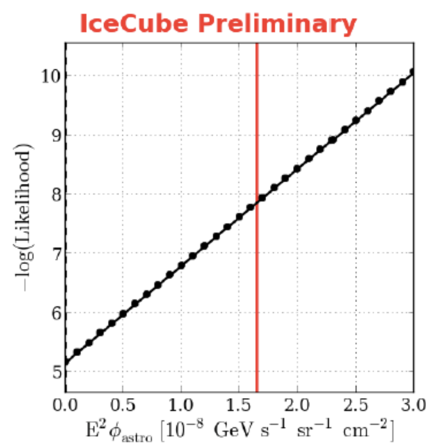
A. Schoenwald et al, for the IceCube Coll., ICRC2013 paper 0662

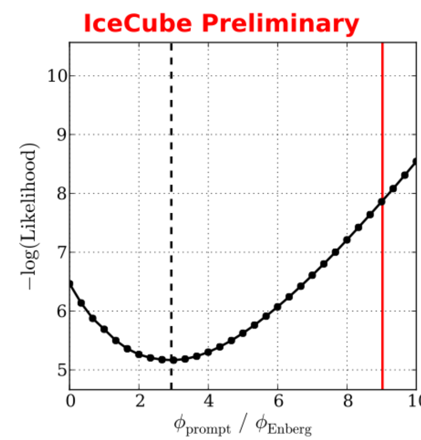


- After final selections (including E_{reco} > 38TeV) 8 data events were found (4 bg events expected)









Likelihood fit results:

- Flux limit (per flavor)

$\Phi_{90\%}$= 1.7x10^{-8} (E/GeV)^2 (GeV^{-1} s^{-1} sr^{-1} cm^{-2}

43 TeV < E_ν < 6 PeV

- Prompt neutrinos:

$$2.9^{+3.2}_{-2.6}\Phi_{Enberg}$$

- Nuisance parameters with no strong deviation from nominal value

parameter	pull	parameter uncertainty
ϕ_{conv}	0.16	$\sigma[\phi_{conv}] = 0.25$
ϕ_μ	0.16	$\sigma[\phi_\mu] = 0.5$
cosmic ray index	0.1	σ[index] = 0.5
energy scale	0.27	σ[energy scale] = 0.15

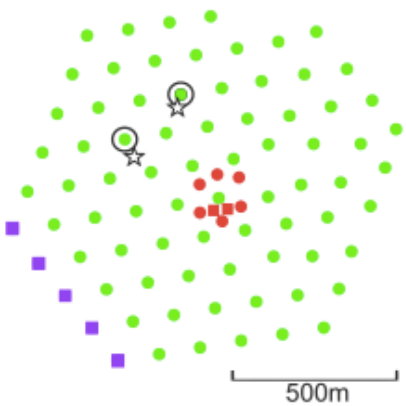
First observation of PeV-energy neutrinos with IceCube

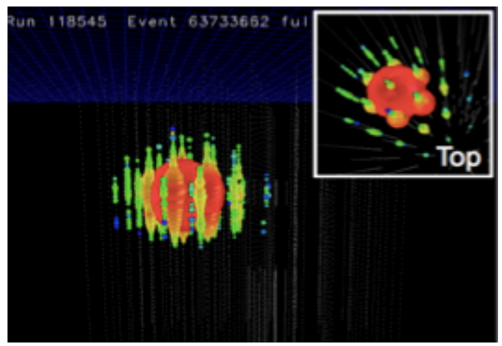
Phys. Rev. Let. 111 (2013) 021103

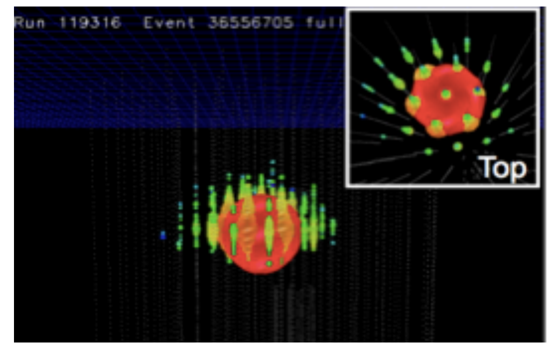
First observation of PeV-energy neutrinos with IceCube

Phys. Rev. Let. 111 (2013) 021103

IC79+IC86 analysis of *Extremely High Energy* filter data (670 days, 2010-2012) to search for cosmogenic or GZK all-flavor neutrinos (PeV-EeV)



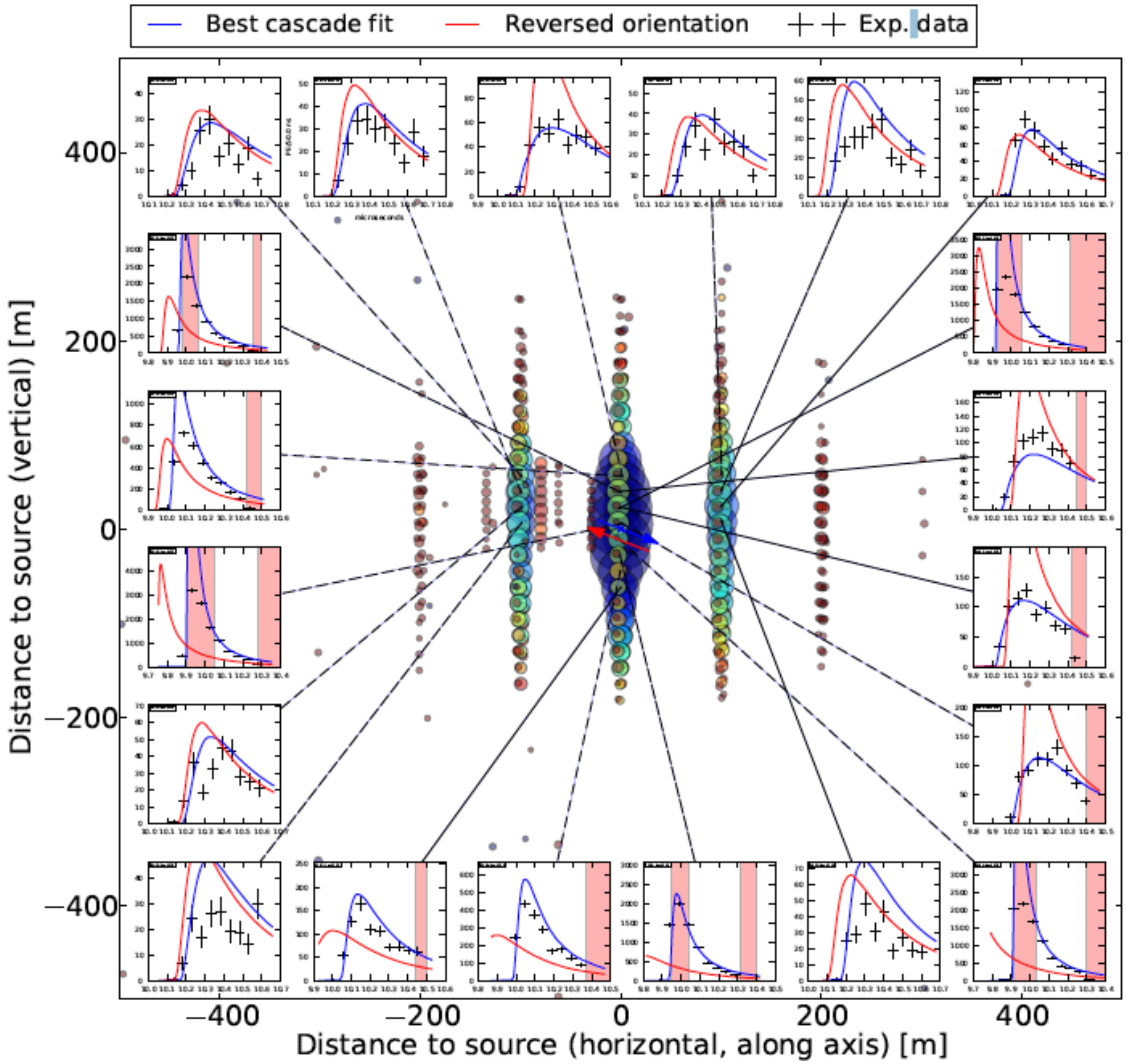




date (GMT)	Aug. 8, 2011	Jan. 3, 2012
NPE	7.0×10^4	9.6×10^4
number of recorded DOMs	354	312
reconstructed deposited energy (PeV)	1.04 ± 0.16	1.14 ± 0.17
reconstructed z vertex (m)	122 ± 5	25 ± 5

Two cascade like PeV events, found in an analysis dedicated to a search for bright events

Cascade Reconstruction



IC79+IC86 Contained Vertex Events Search

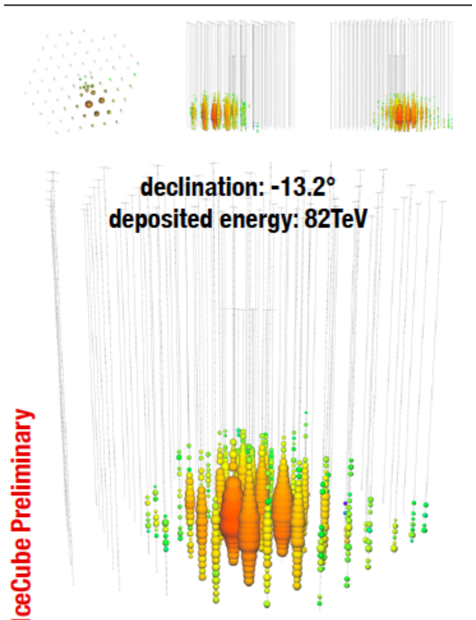
Accepted for publication in Science

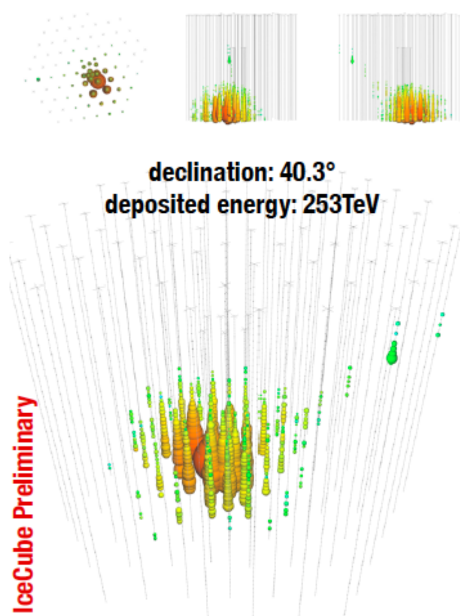
A follow up search on 2 PeV cascades:

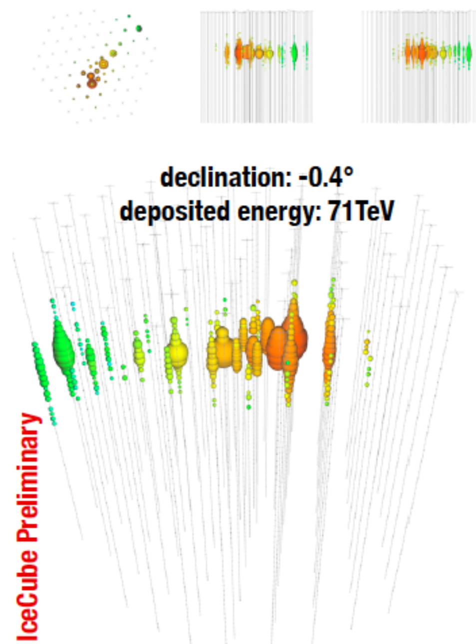
- Selecting for high energy neutrino events with vertices well contained in the detector volume (no flavor tagging, combination of neutrino induced muons and cascades)

Results:

Observed 28 events (21 cascade-like, 7 track-like) in 30 TeV < E_ν < 1.2 PeV, expected $10.6^{+4.7}_{-3.6}$ number of background μ and conv. ν events (12.1 ± 3.4 including prompt ν)



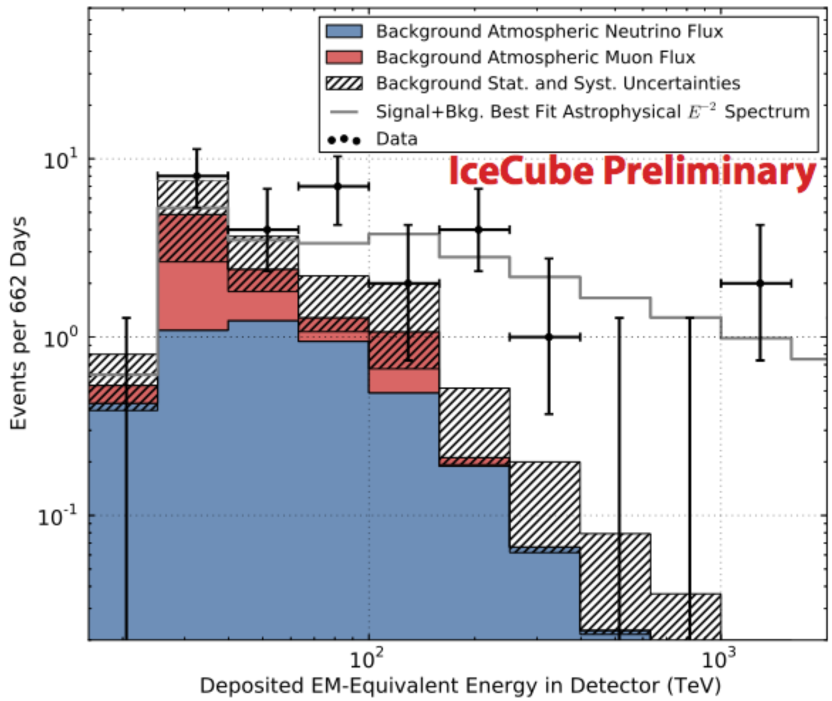


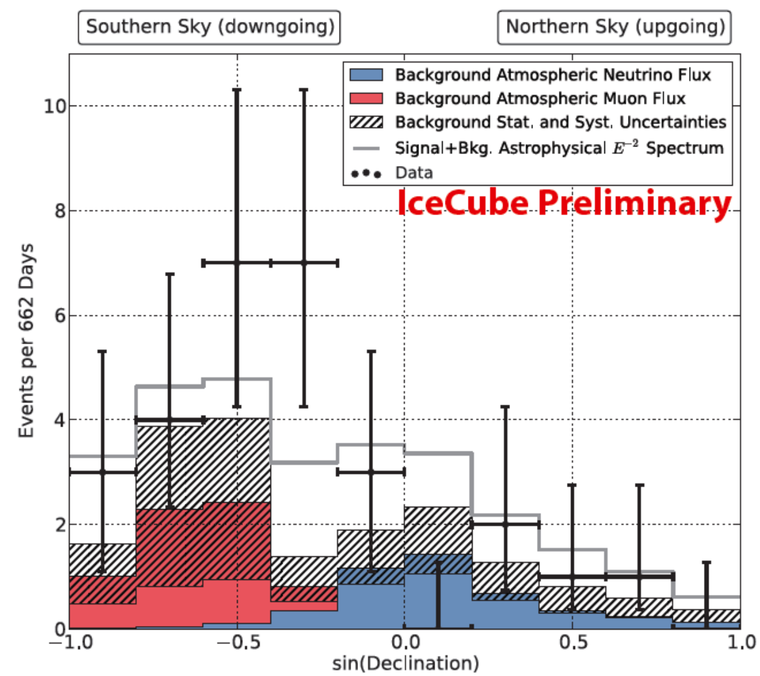


C. Kopper et al, for the IceCube Coll., ICRC2013 paper 0650

IC79+IC86 Contained Vertex Events Search

Accepted for publication in Science





Purely atmospheric origin (μ + atm. ν) of 28 events rejected at 4 σ level.

Likelihood fit: Energy range: $60\,\mathrm{TeV} \leq E_\nu \leq 2\,\mathrm{PeV}$

Results: $E_{cutoff} = 1.6^{+1.5}_{-0.4}\,\mathrm{PeV}$

$$E^2\Phi_{90\%} = (1.2 \pm 0.4) \times 10^{-8} \left[\mathrm{GeV^{-1} s^{-1} sr^{-1} cm^{-2}}\right]$$ (per ν flavor)

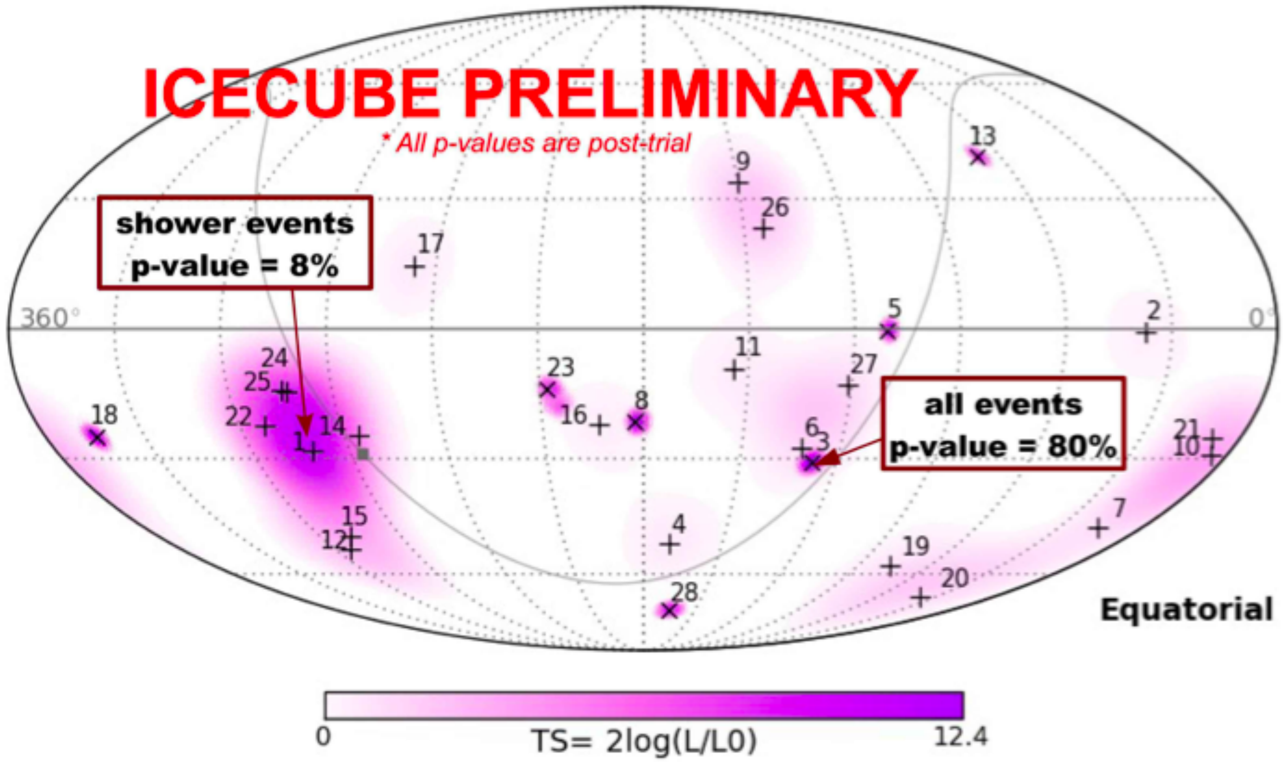
C. Kopper et al, for the IceCube Coll., ICRC2013 paper 0650

IC79+IC86 Contained Vertex Events Search

a follow up search on 2 PeV cascades

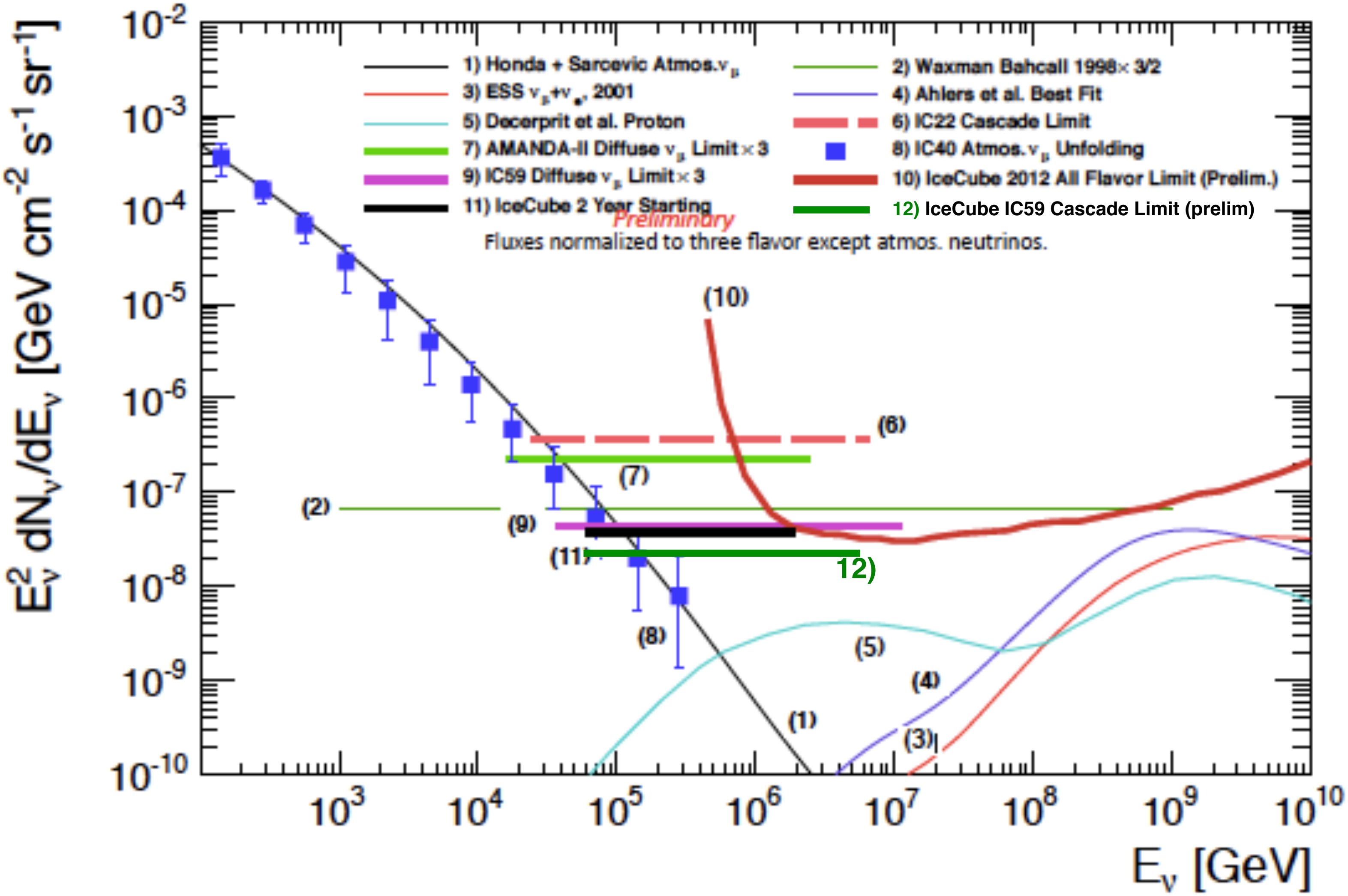
Searched for:

- Point source in sample of all 28 events
- Point source in subsample of 21 cascade events



No evidence of spatial clustering found

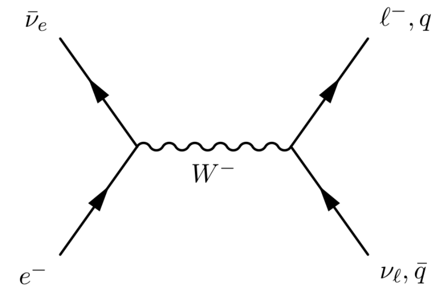
Diffuse Fluxes – Status



A. Karle, TeVPA2013

CR sources pp vs pγ collisions: Glashow Resonance

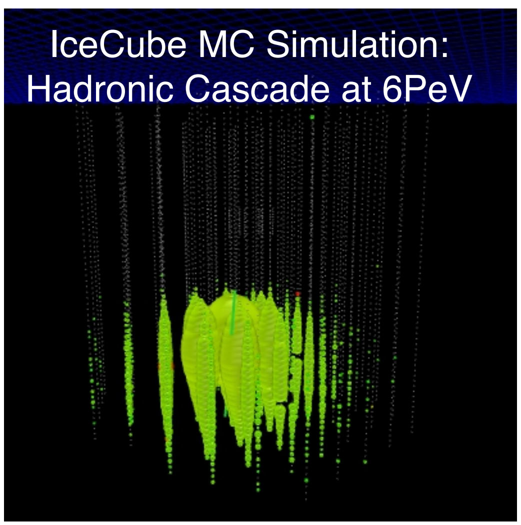
- Resonant W production $\overline{\nu_e} + e^- \rightarrow W^-$ at $E_\nu = 6.3$ PeV

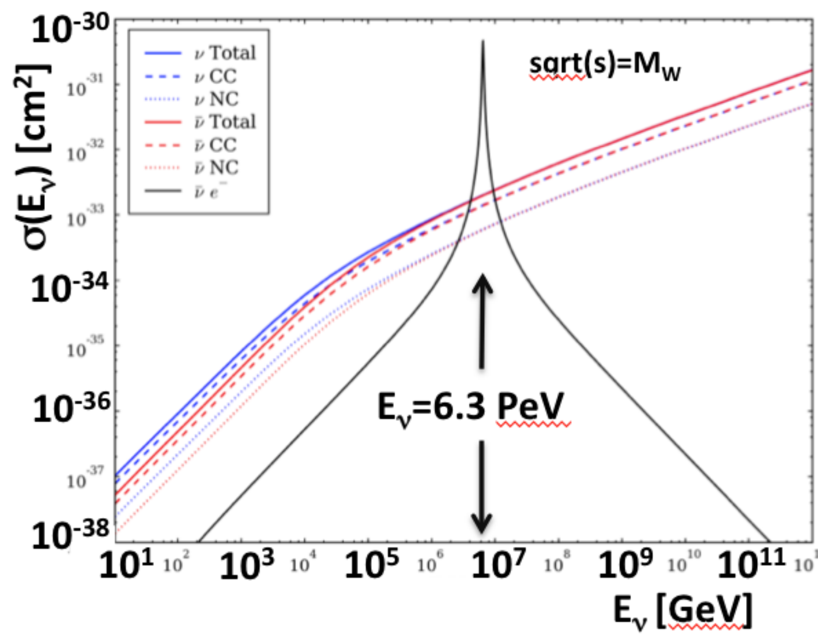


- Unique channel: sensitive to electron anti-ν flux

  IceCube does not distinguish ν and anti-ν induced DIS events

- Hadronic particle showers $W^- \rightarrow q\bar{q}$ are dominant: $\Gamma_{qq}/\Gamma_{tot} \sim 70\%$





CR sources pp vs pγ collisions: Glashow Resonance

$$\overline{\nu_e} + e^- \rightarrow W^-$$

- proton collisions - pp

$$p + p \rightarrow N\left(\pi^0 + \pi^+ + \pi^-\right) + \ldots$$

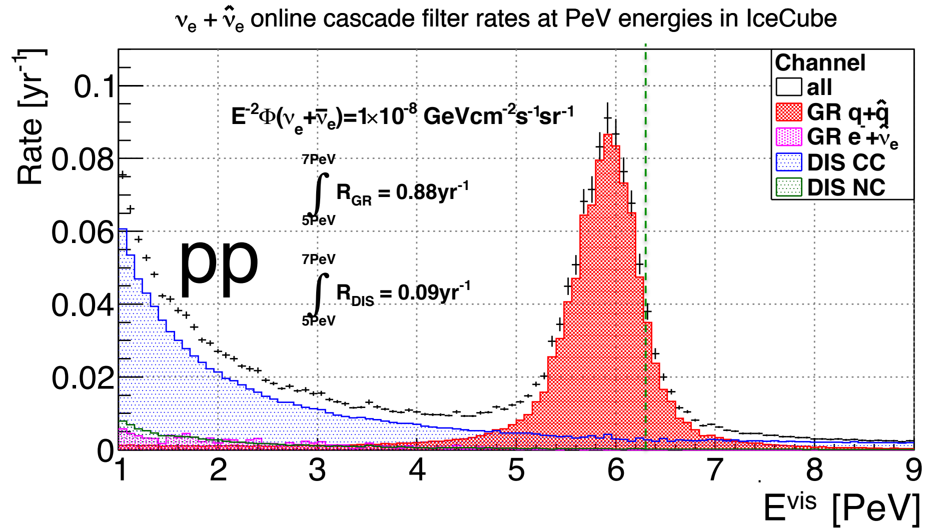
anti-ν_e and ν_e produced equally
at Earth: anti-ν_e : ν_e = 1 : 1*

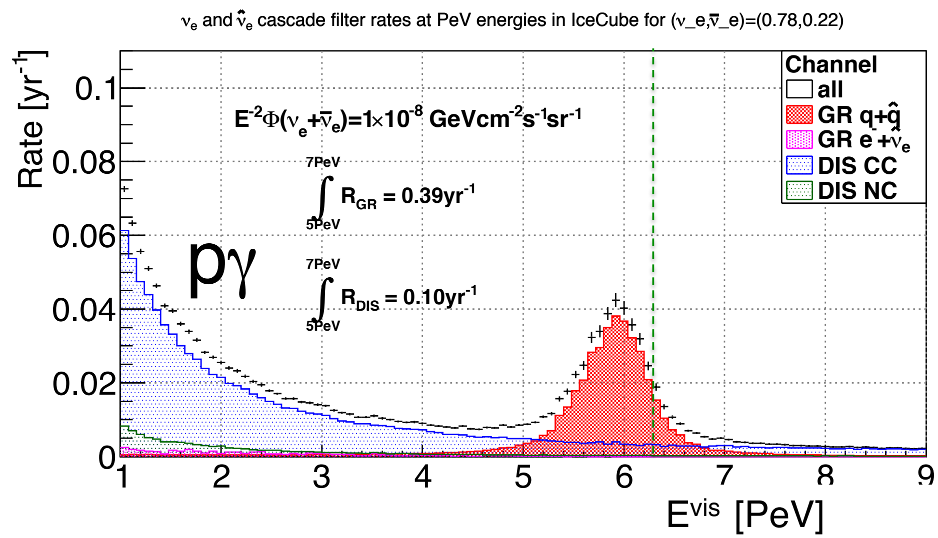
- proton photon scattering – pγ

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} \pi^+ + n \\ \pi^0 + p \end{cases}$$

no anti-ν_e produced at source
at earth: anti-ν_e : ν_e = 0.22 : 0.78*

(*)ratios at earth from Bhattacharya et. al., arXiv:1108.3163





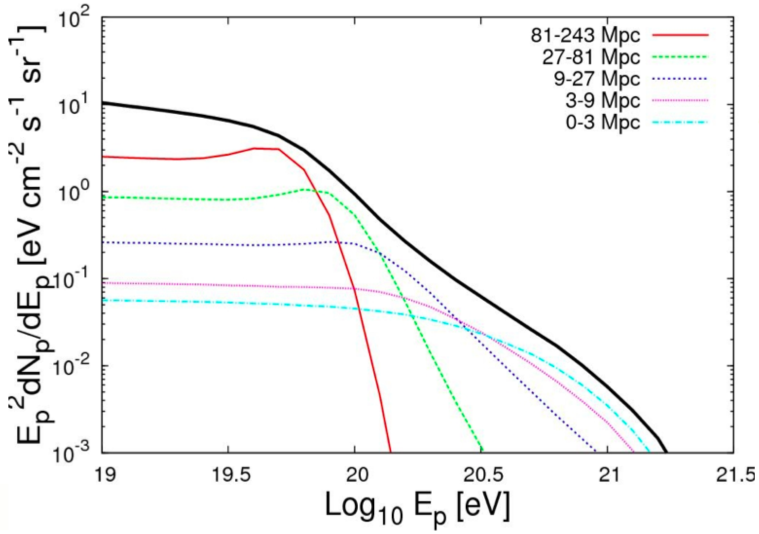
H. Niederhausen, J. Kiryluk for the IceCube Coll., ICRC2013 paper 0494

The Cosmic Neutrino Fluxes

- "GZK" cosmogenic ν
  - Production

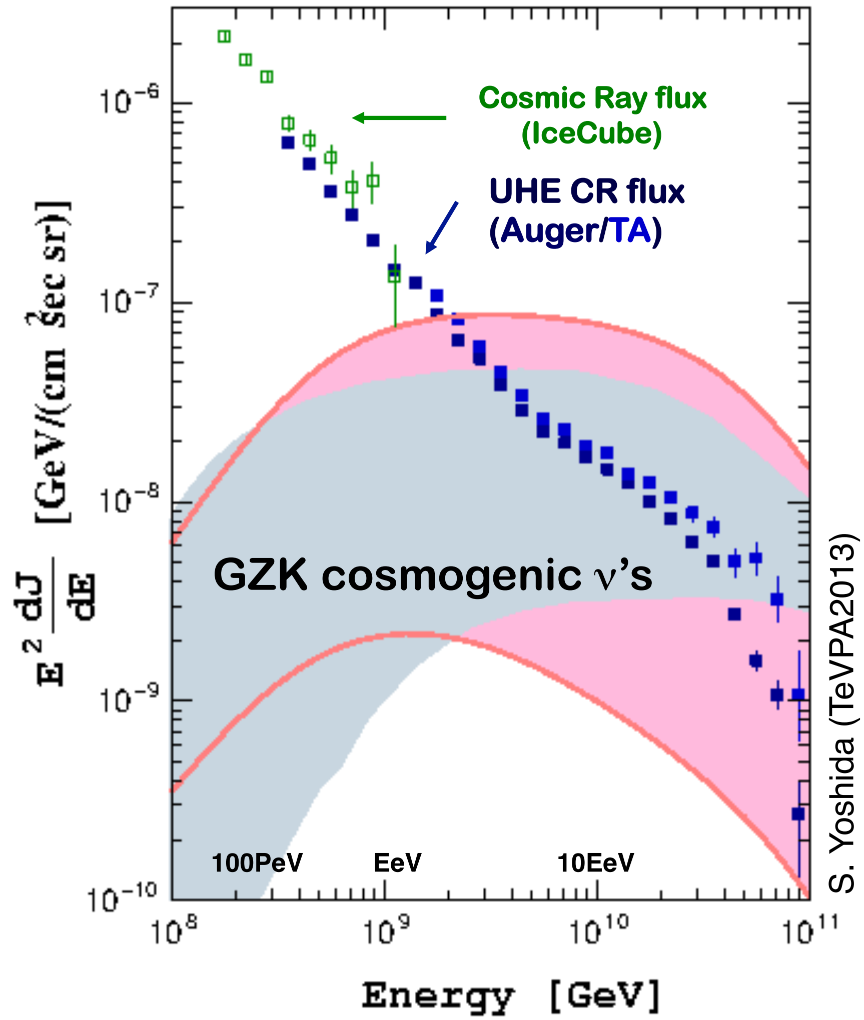
    $$p+\gamma_{CMB} \rightarrow \Delta \rightarrow \pi + n \rightarrow \nu + \ldots$$

  - CR spectrum:



$$E^{-\alpha}\exp\left(-E/E_{\max}\right)$$

$$E_{\max} \sim 10^{20.5} eV, \quad \alpha = 2.0$$



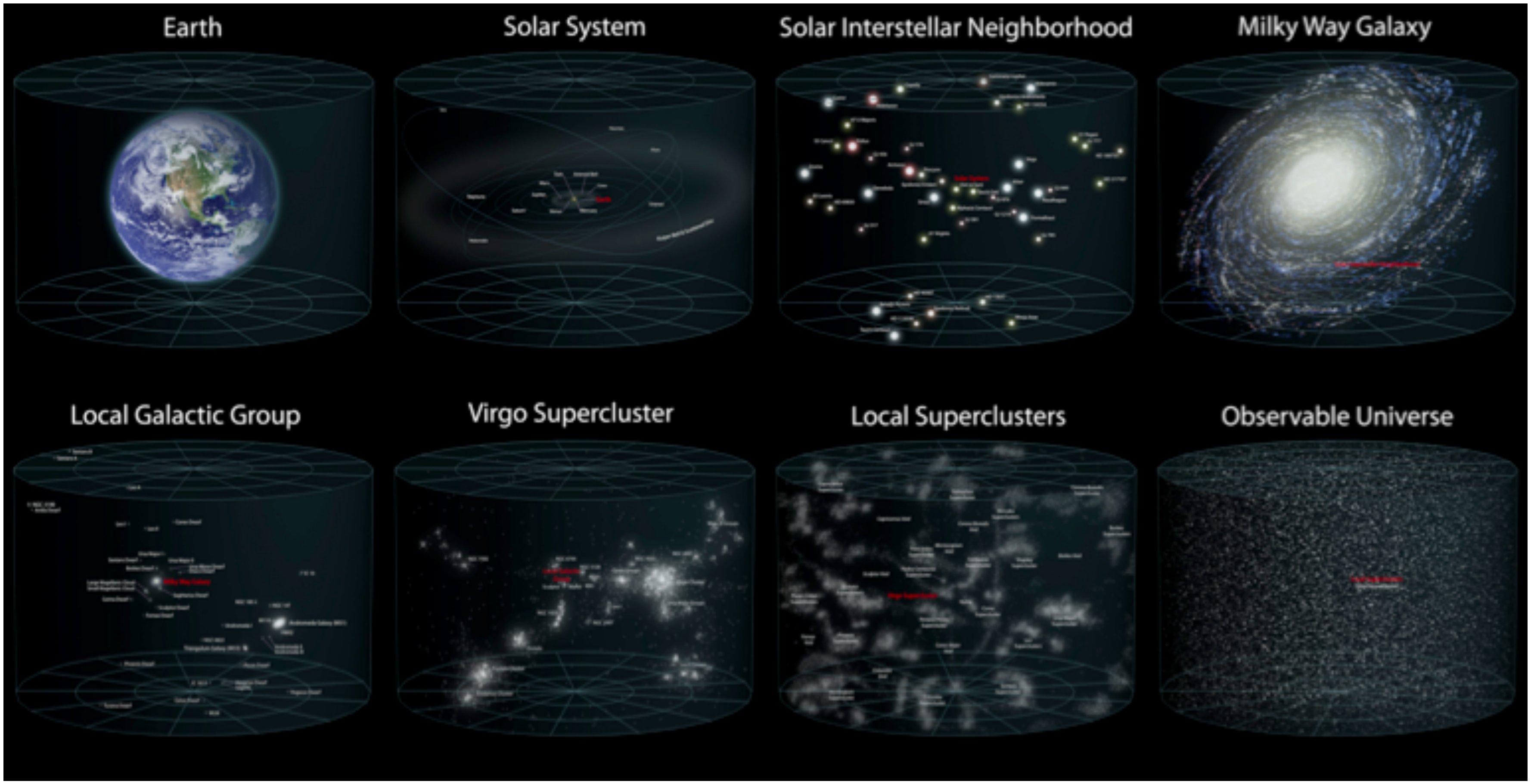
GZK cosmogenic ν's: calculations depend on:
Composition [p, mix], evolution of sources, highest energy E_{max}, injection spectrum, end of galactic CR

- allowed range of the ν flux
  Ahlers et al, Astropart.Phys. 34 106 (2010)
- **the ν fluxes from strongly evolved and no evolved**
  Yoshida et al, Prog.Theo.Phys. 89 833(1993)

Astronomical Distances

1 Mpc = 3.26 million light-years

0.037 Mpc



3 Mpc

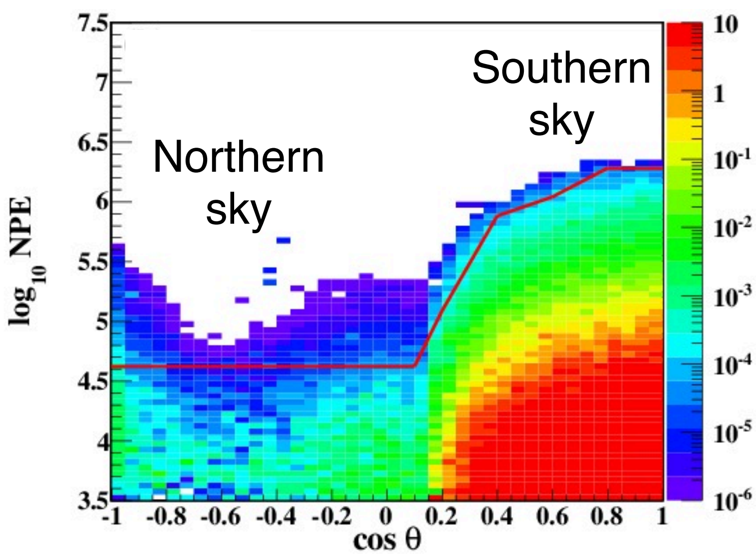
33 Mpc

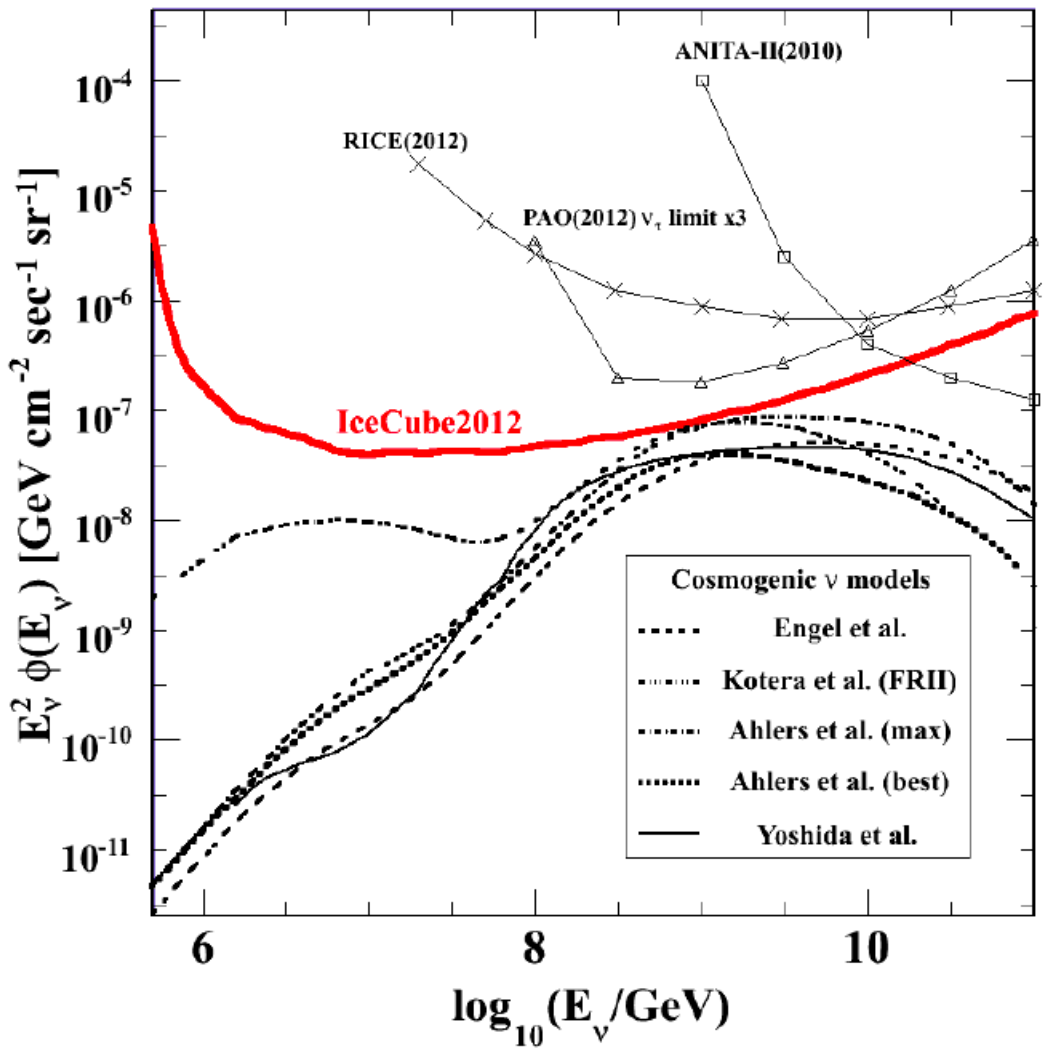
28000 Mpc

(IC79+IC86) Search for Cosmogenic GZK Neutrinos

Phys. Rev. Lett. 111, 021103 (2013)

- Data from 2010-2012
- Energy range PeV – EeV
  - no atmospheric background is expected
- Two neutrino-induced cascade events found at ~1 PeV.



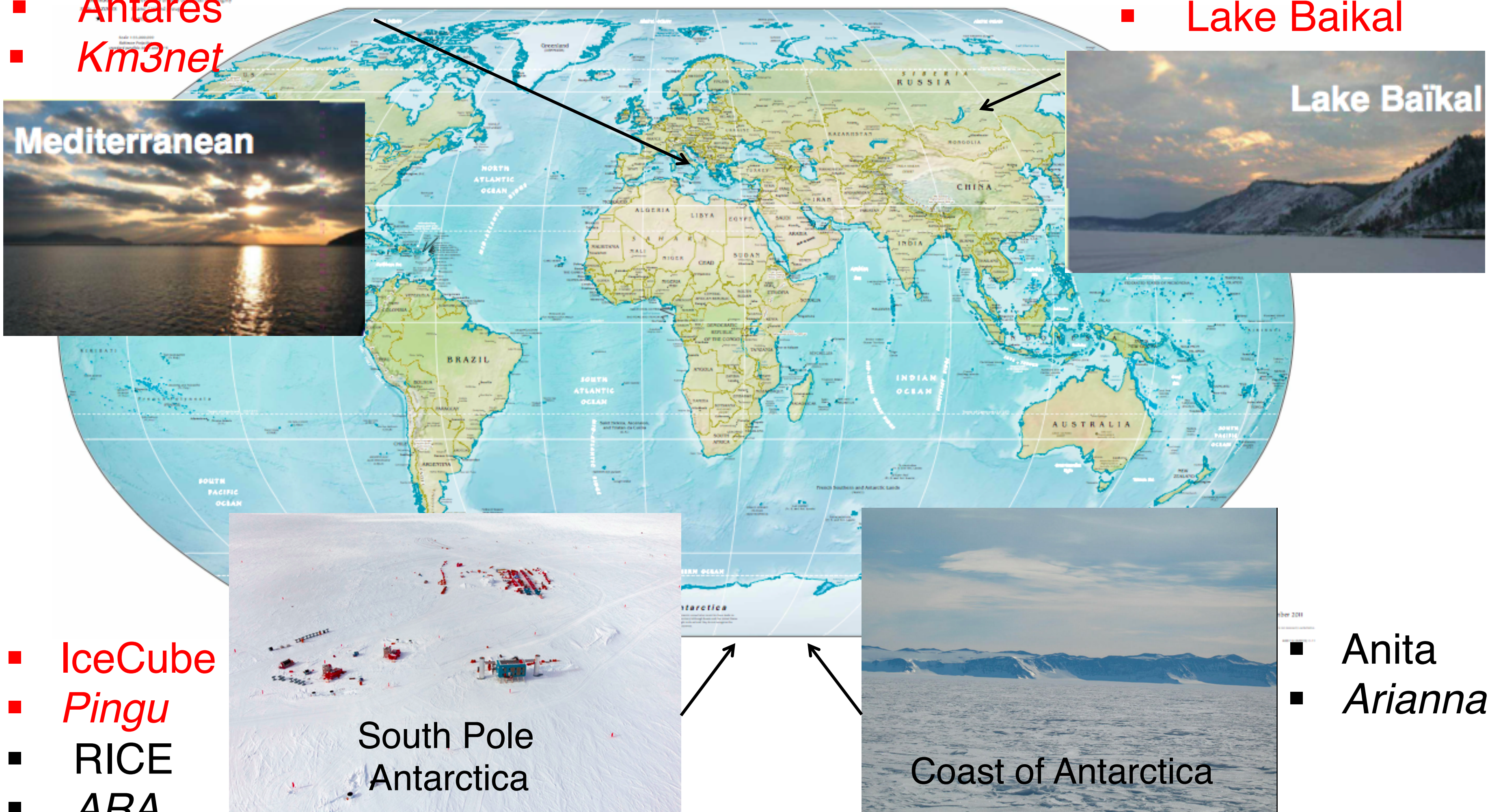


Neutrino Telescopes

Techniques:
- optical detection
- radio detection

- Antares
- *Km3net*

- Lake Baikal

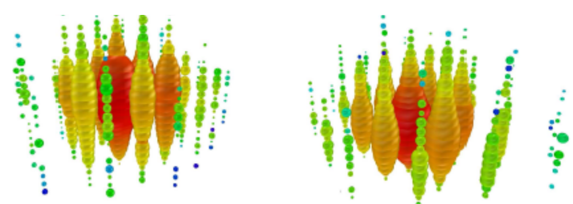


- IceCube
- *Pingu*
- RICE
- *ARA*

- Anita
- *Arianna*

Summary

- Era of km^3 neutrino astronomy has begun
  - 100,000+ high-energy neutrinos on the books
- Atmospheric neutrino flux measurements (cascade and muon channels)
- Prompt neutrino limits (cascade and muon channels)
- Two 1 PeV neutrino-induced cascades detected
  Evidence for astrophysical neutrinos !



- No astrophysical neutrino sources detected yet
- No neutrinos seen from GRBs
  - Setting limits on physics of fireball model
- Continued gains in sensitivity
  - Continuous data taking with full detector, improved analysis techniques