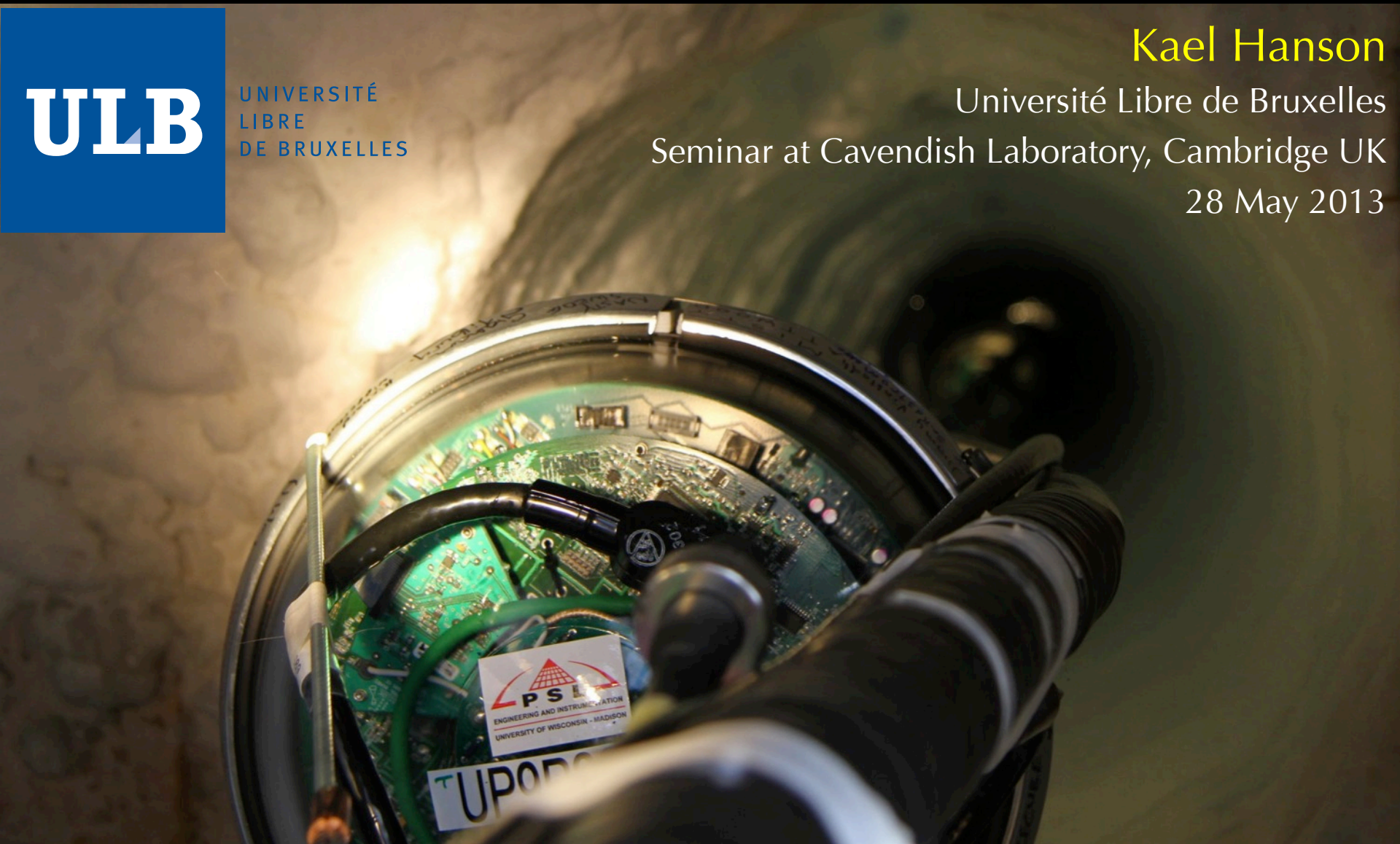
The IceCube HE Neutrino Events:
has neutrino astronomy finally arrived?



ULB UNIVERSITÉ LIBRE DE BRUXELLES

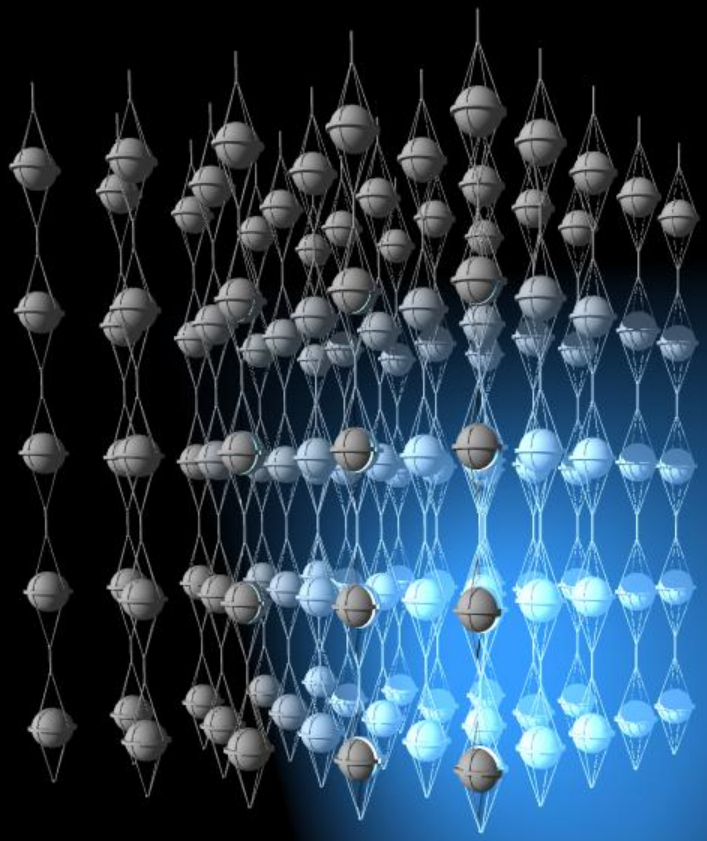
Kael Hanson
Université Libre de Bruxelles
Seminar at Cavendish Laboratory, Cambridge UK
28 May 2013



Outline of Talk



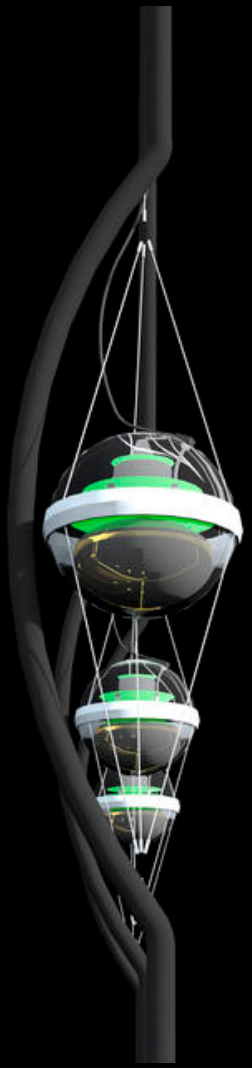
1. Motivation – why spend $300M and millions per year to support speculative detector facilities?
2. The IceCube detector
    1. Neutrino detection
    2. The optical instrument
    3. Deployment
3. IceCube results
    1. General results
    2. Bert and Ernie
    3. More muppets found in follow-up
4. Future initiatives at South Pole

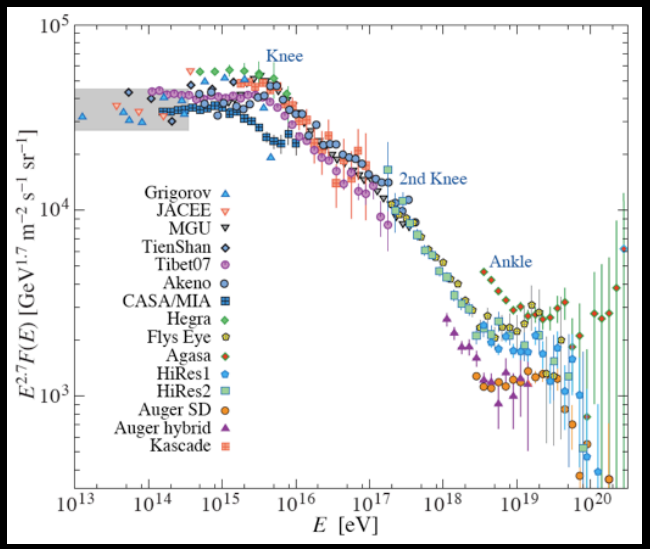


High-Energy Neutrino Astrophysics

INTRODUCTION

Cosmic Rays



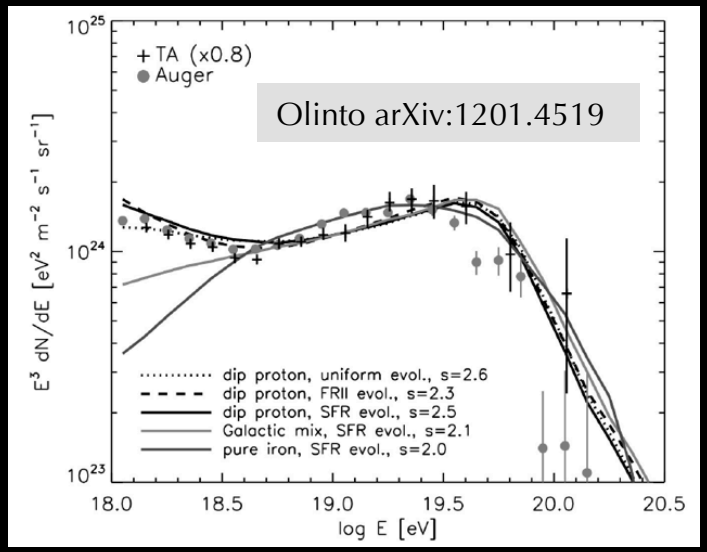


The flux of cosmic rays known for 100 years: it extends from roughly 1 GeV where geo. cutoff and atmospheric absorption screen particles to above 10^{11} GeV where flux ~1 UHECR / km^2 / century. Below knee at 1 PeV, flux is rather featureless $E^{-2.7}$ consistent with Fermi accel.

Composition mostly p below knee, getting heavier above it – the composition of UHECR is an outstanding question to resolve.

Above $10^{19.5}$ eV, protons interact with CMBR photons form pions through Delta resonance to give GZK cutoff now observed by PAO and TA experiments. Charged pions also give neutrinos.

$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$
$$\rightarrow n + \pi^{+}$$



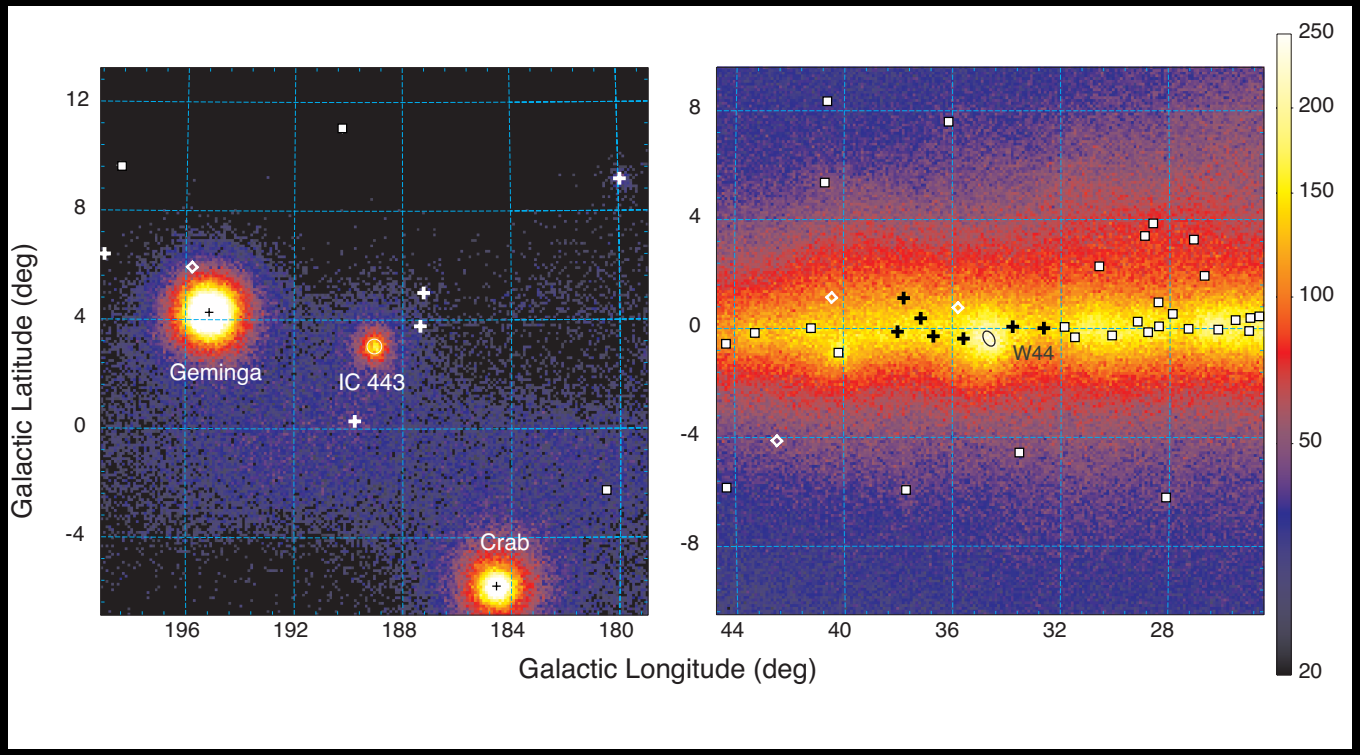
Astrophysical Sources and Messenger Particles



- What origin of galactic and extragalactic CR?
  - SNR abundant in galaxy, Fermi shock accel consistent with observations up to 1 PeV.
  - Beyond 1 PeV confinement in sources difficult.
  - Extra-galactic candidates, AGN and GRB, have highly boosted jets perhaps capable of achieving higher energies.
- Charged particle astronomy challenging due to directional, energy scrambling in GMF, IGMF.
- Photons > TeV energy absorbed by IR and CMBR photons on cosmological scales.
- Neutrinos are ideal astronomy particles: not deflected, absorbed even by great thicknesses.
- Small cross-sections demand very large detectors – O(km^n).
- Neutrinos, unlike photons, can resolve EM vs hadronic processes present at accelerator sites, but, …

Fermi IC443 and W44 – Signs of Pions!





Fermi finds two galactic SNR IC443 and W44 with spectra consistent with neutral pion decay –
Science **339**, 807 (15 Feb 2013)

Cosmic and Cosmogenic Neutrinos



Neutrinos produced in hadronic CR acceleration:

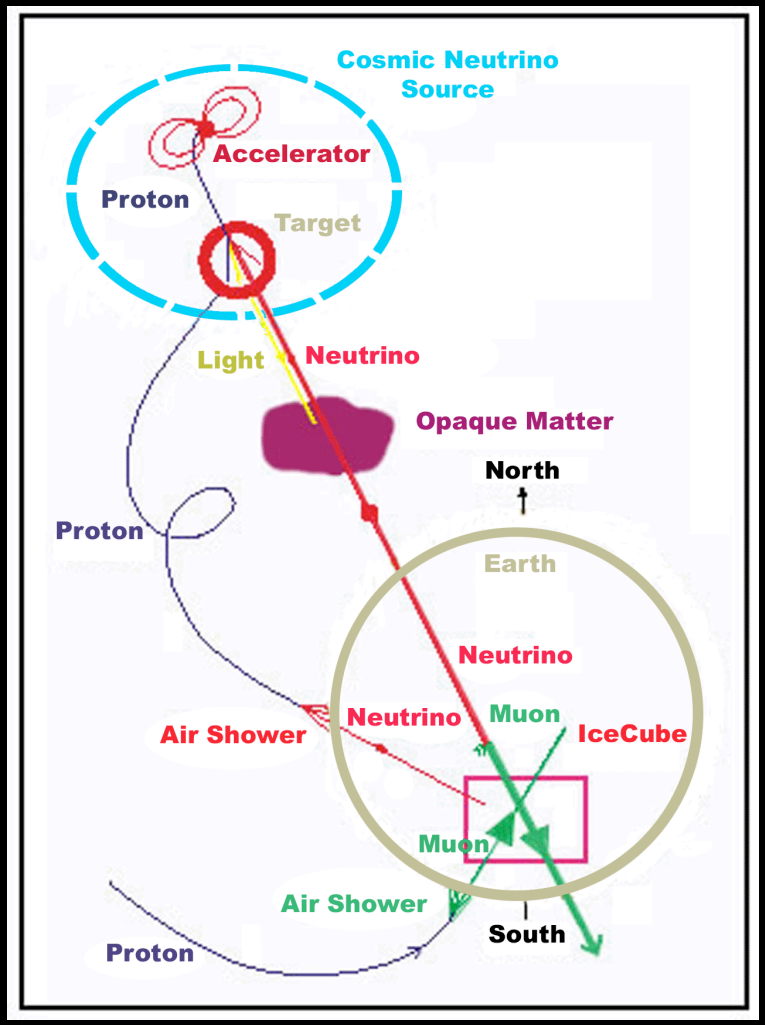
- From decay of π/K mesons
- Energies can be boosted by p+γ interactions in intense photon fields in AGN/GRB
- Fluxes of UHE neutrinos can be generically linked to total extra-galactic CR energy density → this gives WB (Waxman-Bahcall) benchmark flux:

$$2\text{-}4 \times 10^{-8}\ \mathrm{GeV/cm^2/s/sr}$$

Neutrinos from interaction of UHECR

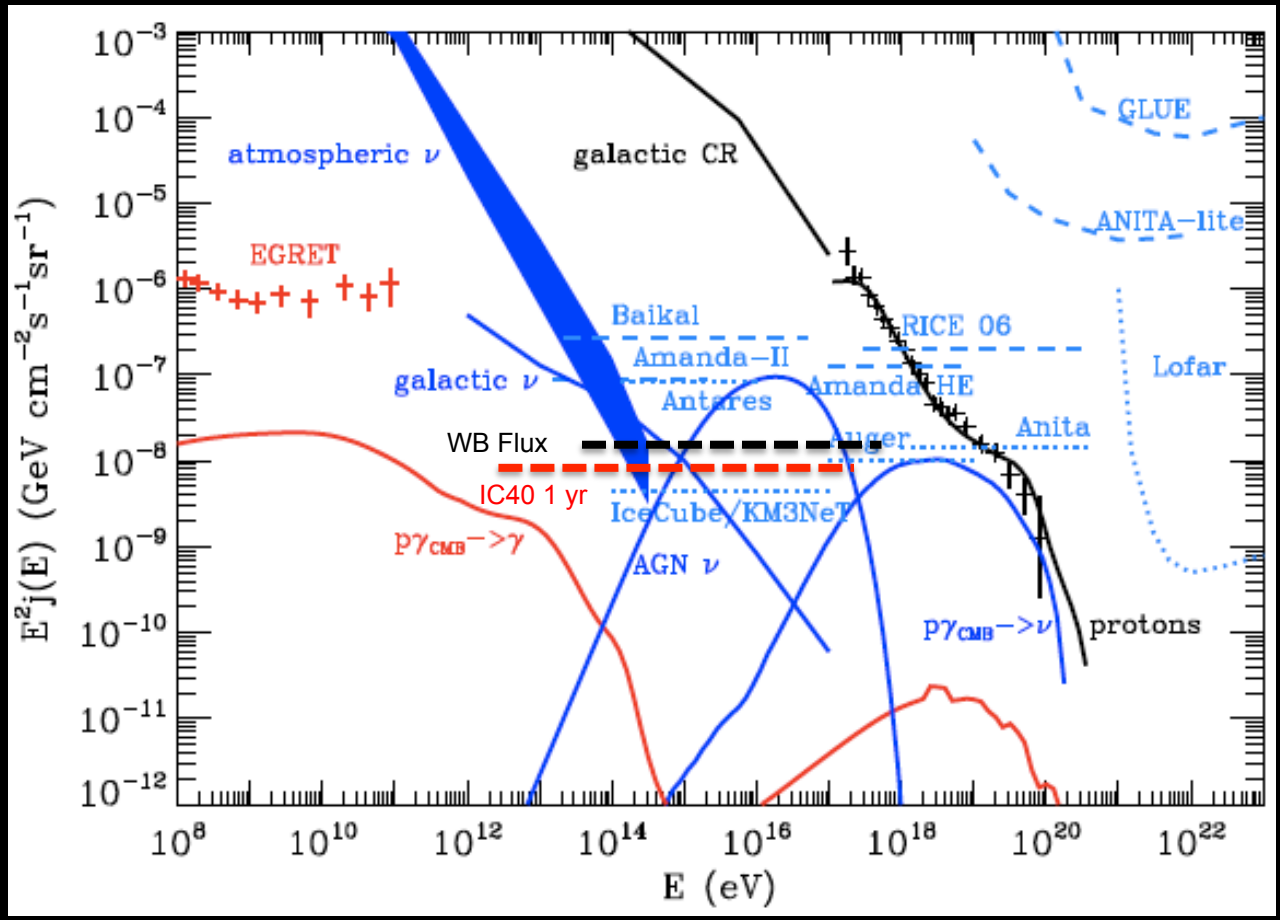
- *Guaranteed* flux – GZK effect observed, the neutrinos must be there
- Flux models depend on UHECR composition, constrained by gamma ray measurements.

See also review by Anchordoqui & Montaruli [Ann. Rev. Nucl. Part. Sci 60: 129-62 (2010)]

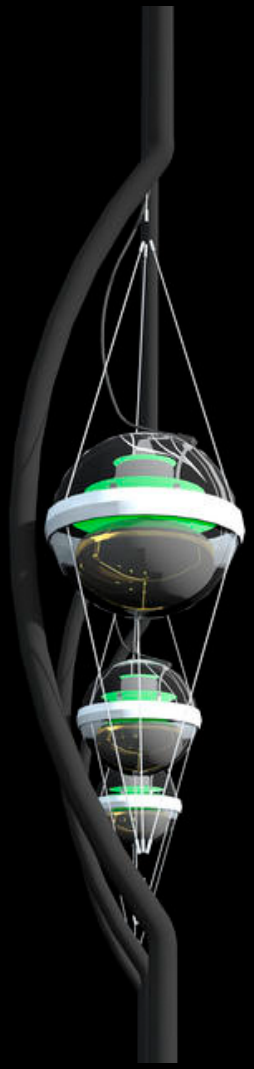


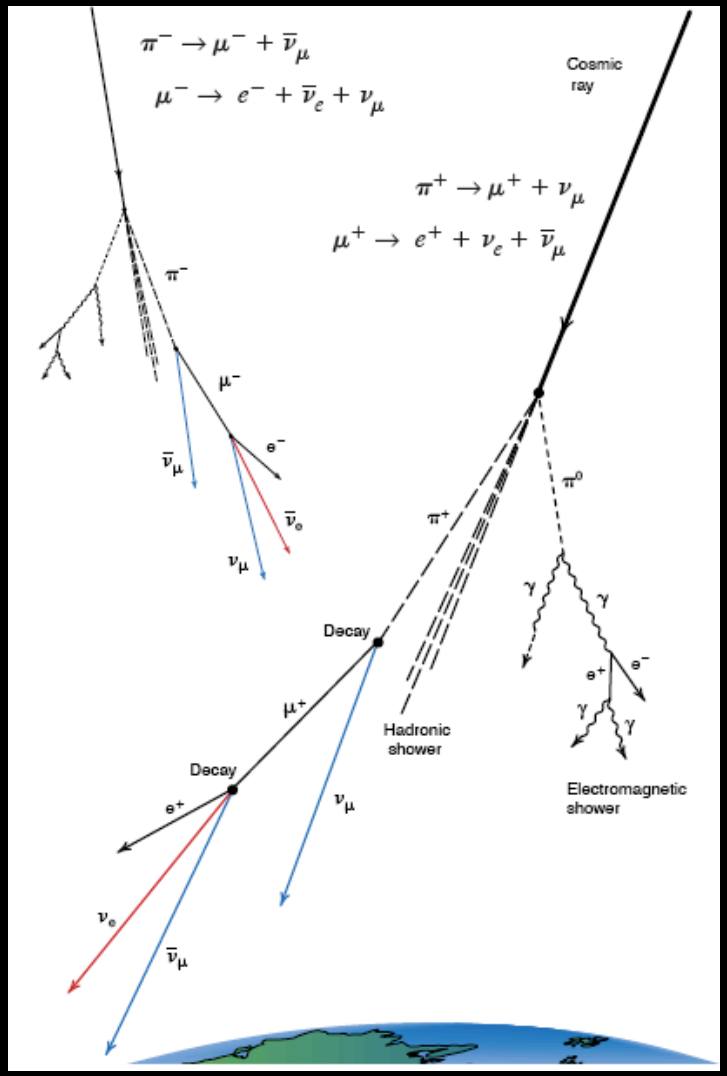
Neutrino Fluxes



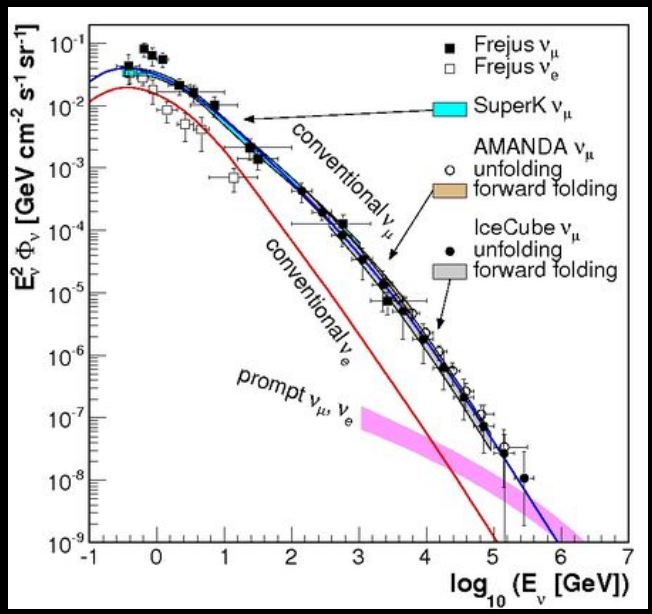


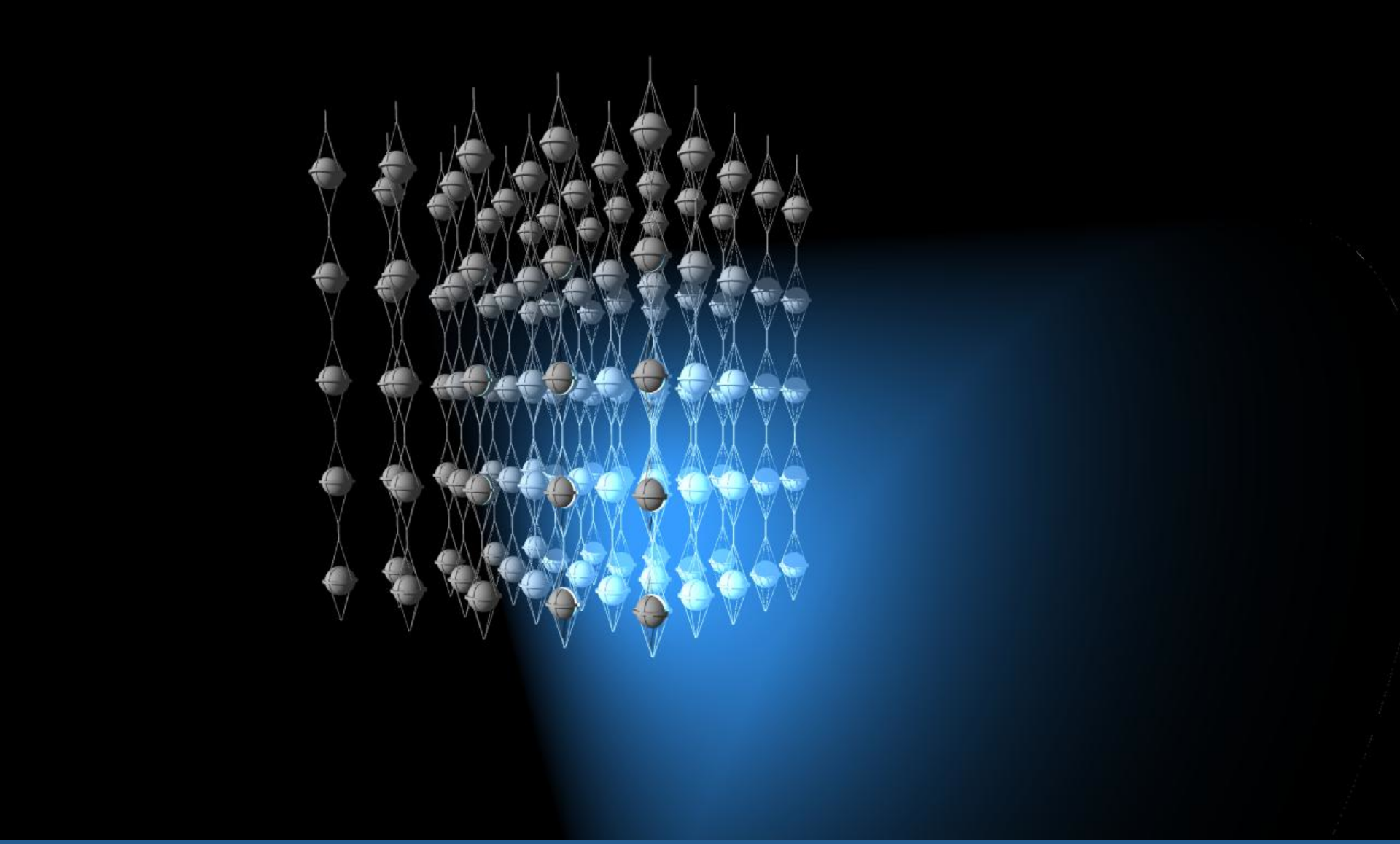
Atmospheric Neutrinos





- Neutrinos produced by meson decay in Earth's atmosphere – detected since 1960's.
- Tend to have harder spectra due to relatively long-lived meson – decay is overcome by energy loss in atmosphere giving spectrum 1 power harder than CR primaries
- Background for cosmic neutrinos – but interesting beam for oscillation studies





THE ICECUBE NEUTRINO OBSERVATORY

The IceCube Collaboration



Stockholm University
Uppsala Universitet

University of Alberta

University of Oxford

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

Chiba University

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

Université Libre de Bruxelles
Université de Mons
University of Gent
Vrije Universiteit Brussel

University of the West Indies

University of Adelaide

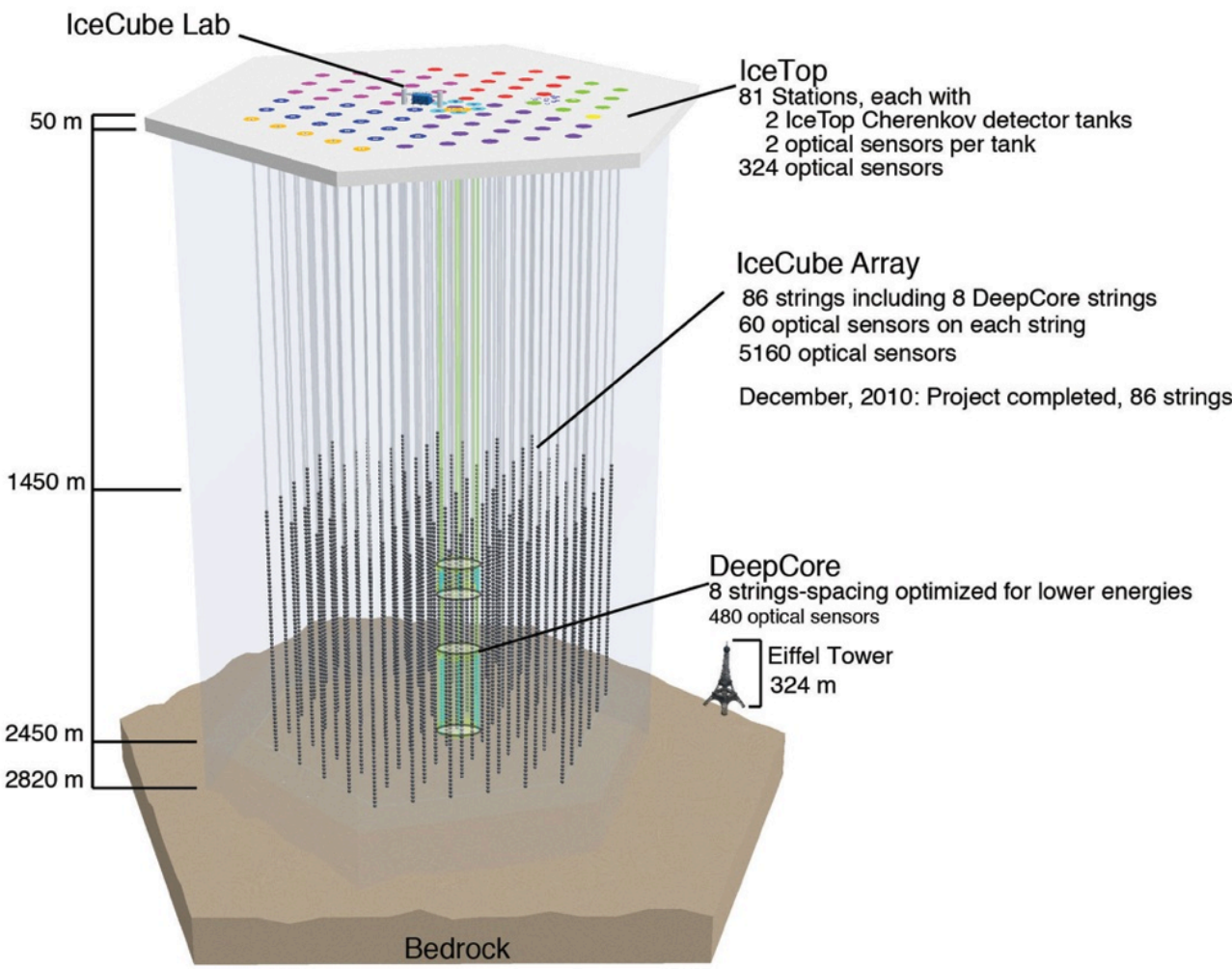
University of Canterbury

International Funding Agencies

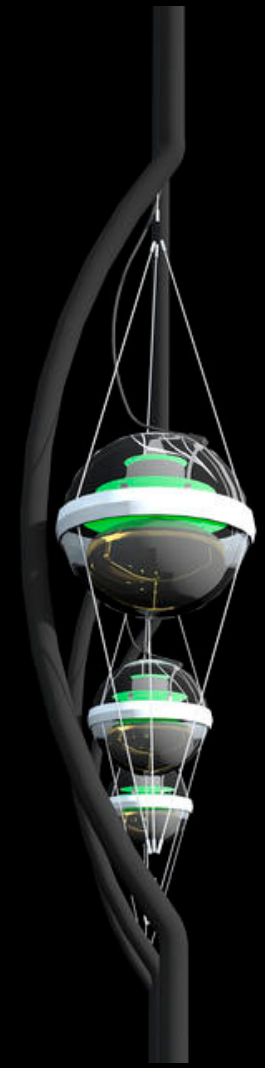
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

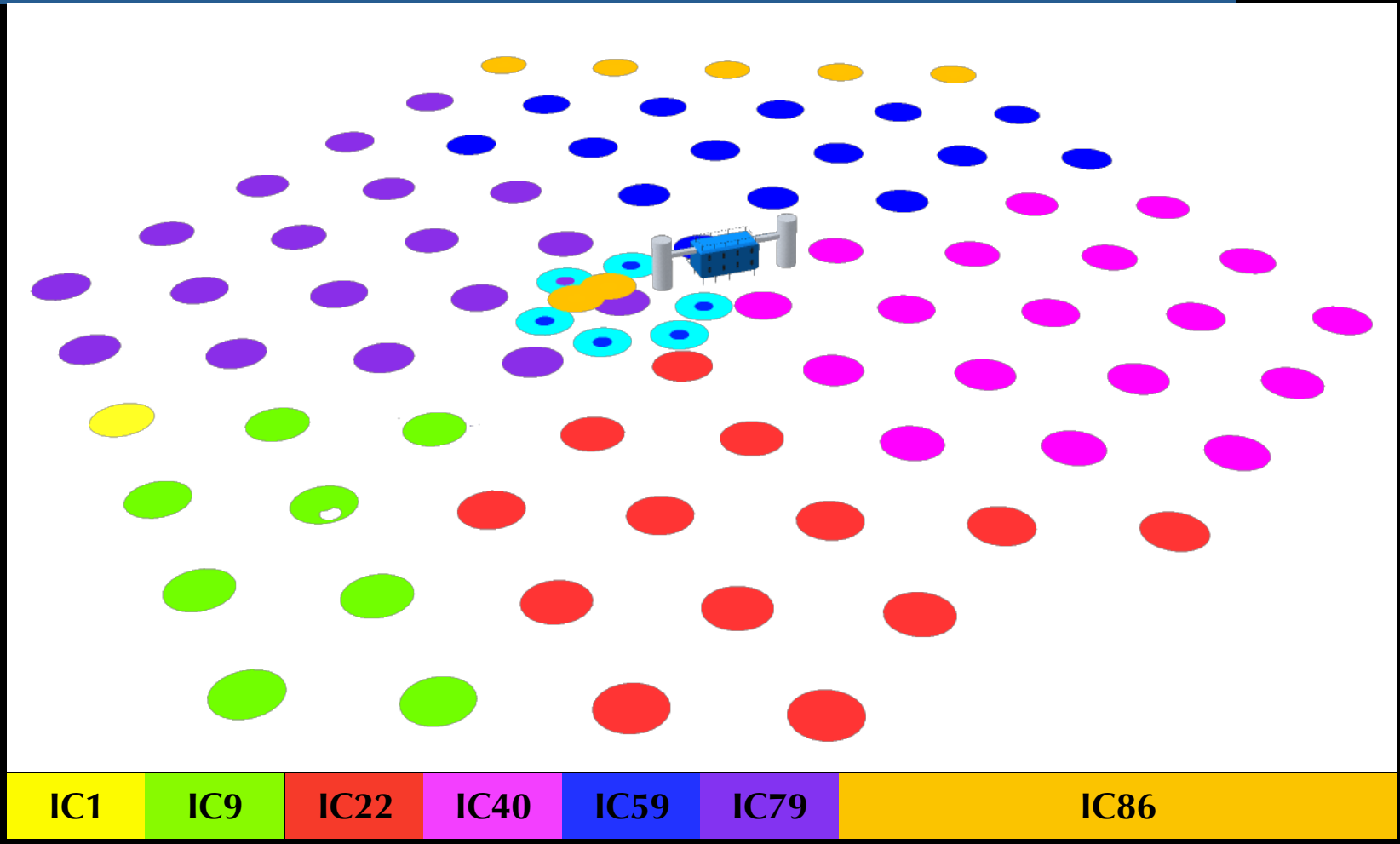
The IceCube Detector





Deployment Phases





Principle of Detection & Event Signatures



IceCube is a Cherenkov detector – sensitive to the light given off by charged particles transiting the optically transparent ice. n ~1.35, thus Cherenkov angle is approx 45°.

- With very large spacing, low photocathode coverage, and heavy scattering in ice, IceCube event reconstruction is fundamentally different from water Cherenkov facilities such as SuperK.
- Energy threshold for trigger is ~ GeV, practical event reconstruction with DeepCore begins around 20 GeV.
- No real upper limit to energy – DOMs' dynamic ranges can support 1000's of photoelectrons and always possible to move out of saturated core (would not swallow up km³ volume until very very very high energies) – but limited by flux intensities.

Track-like muons and UHE tau pass through detector leaving track. Actually track is sum of stochastic dE/dX linear in E for E > 1 TeV. Reasonably good determination of dE/dX, however, parent neutrino energy only known if interaction vertex in detector.

Cascade-like all neutrinos interacting via NC channel and electrons and tau decaying to hadrons or electrons will leave roughly spherical pattern around point like vertex. Good energy resolution, angular resolution ~ 10° with latest sophisticated (CPU intense) fits.

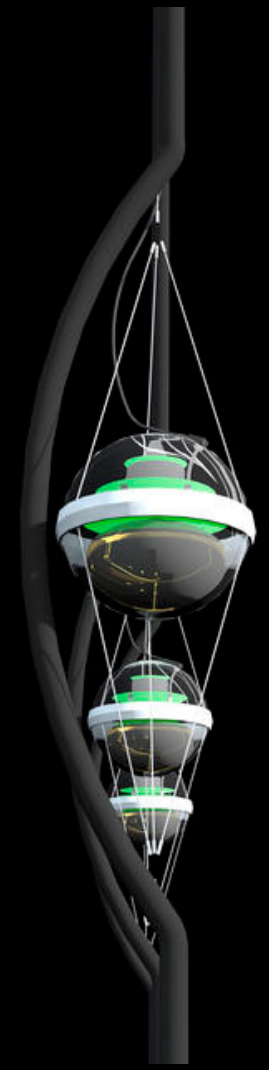
Hybrid event with CC muon and vertex in detector and taus present both track and ball. Taus which additionally decay in detector give nice "double bang" signature.

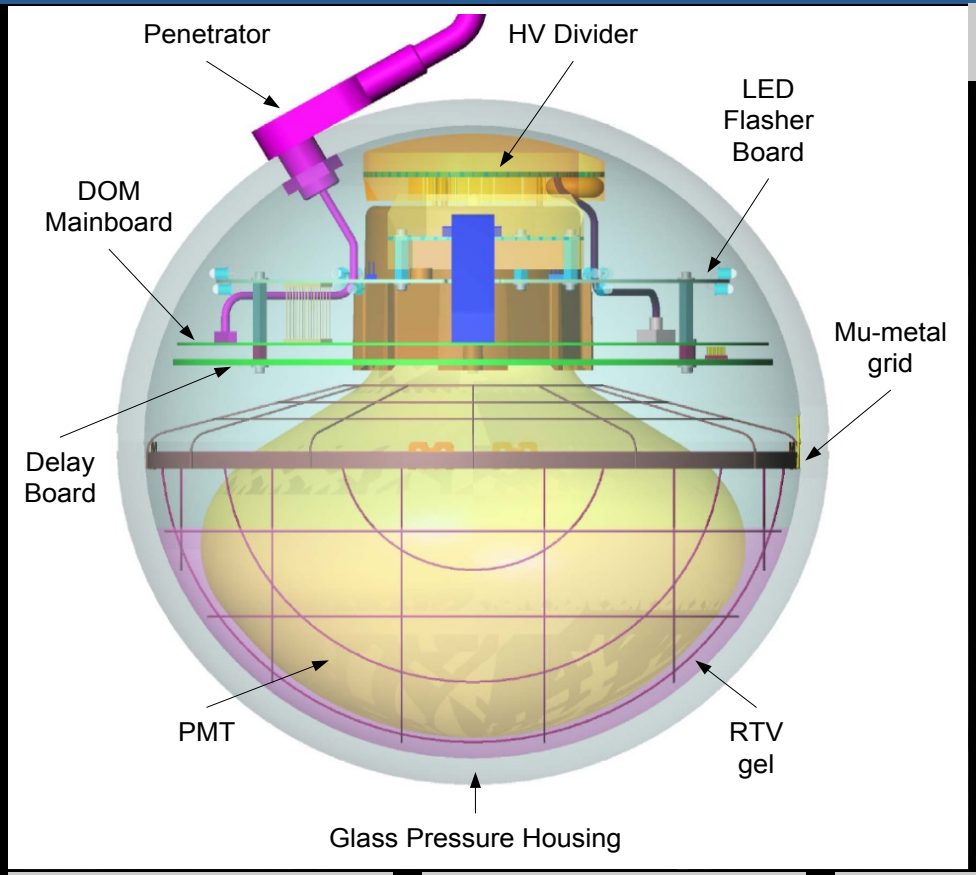


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The IceCube Digital Optical Module





DOM Optical

- **Large Area Photocathode** 10″ 10-stage Hamamatsu R7081-02 PMT (*QE* 24% @ 420 nm); High QE variant (*QE* 35% @ 420 nm) used in DeepCore DOMs
- **Low noise** 500 Hz bkg count rate in-ice @ 0.25 pe threshold.
- **Glass / Gel** 0.5″ thick Benthos pressure housing rated to 10,000 psi. Better transmission in 330 - 400 nm relative to AMANDA OM. Low radioactivity glass.
- **Optical calibration** Each DOM calibrated $\varepsilon(\lambda, T)$ in the lab to about 7%; *in-situ* flashers additionally permit in-ice optical measurements

Smart sensor

FPGA + ARM CPU SoC. 4k-hit deep memory buffer stores hits until readout over 1 Mbit digital link to surface.

Digitizer

300 MSPS ASIC 14-bit effective resolution. Slow pipelined ADC capture to 6.4 μs

Timing

1 ns time resolution thru automatic clock sync protocol embedded in 1 Mbit/s comms system.

Power

Power supplied by 18 AWG Cu pair to surface (3.5 km). 96 V, 3.75 W per channel (DOM)

The IceTop Surface Airshower Array





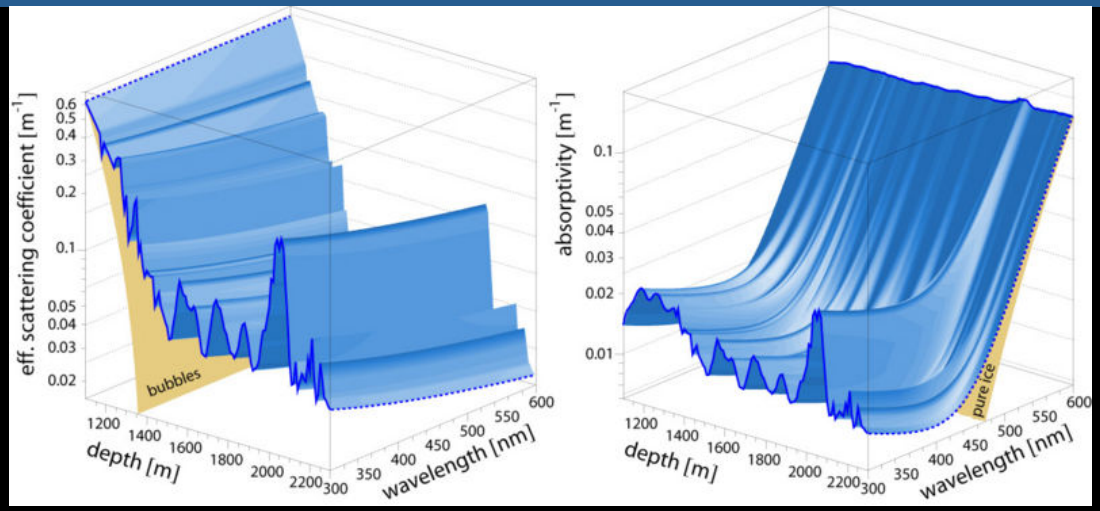
The IceTop array is air shower array composed of 2 frozen ice tanks at the top of every (non-DeepCore) hole. Each tank includes 2 standard DOMs (see picture at left). IceTop functions:

- Calibration point for deep ice array (air shower reconstruction independent and higher precision than in-ice track reconstruction).
- VETO for deep ice array – limited Ω.
- 3D air shower detector: by analysis of surface component (mainly EM) and deep component (muons) of air shower events, it is possible to reconstruct the energy and the composition of the primary CR.



Ice



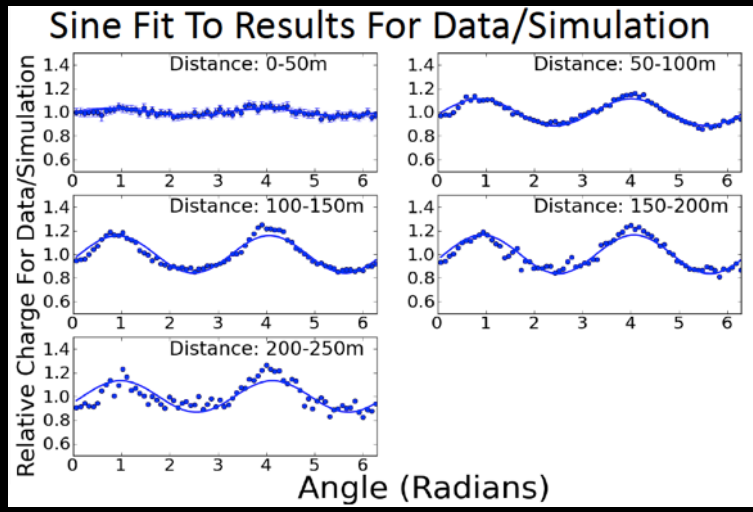


Ice properties measured with in-ice calibration sources:

- 12 high brightness 400 nm LEDs per DOM
- Handful of special calibrated sources

The complex ice structure deposited over 100 k-yr contains much structure and is prominent challenge for IceCube:

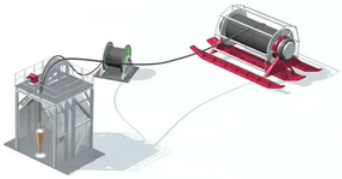
- Simulation of 10^{10} photons or more for high energy events now becoming possible with GPU acceleration
- Not only is there z structure, there is tilt and directional anisotropy!



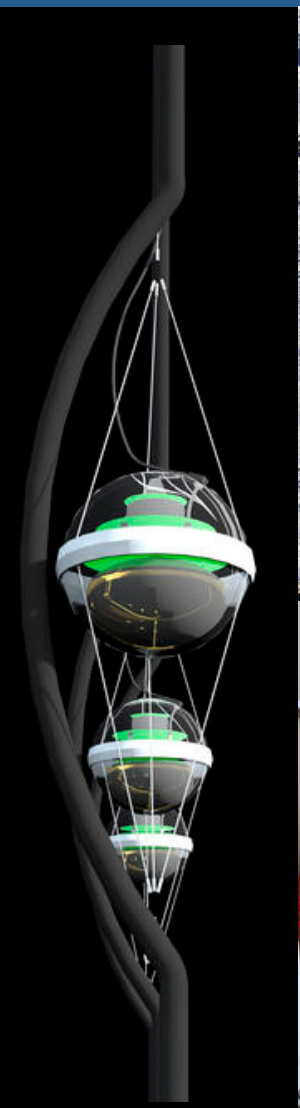
Hot Water Drilling

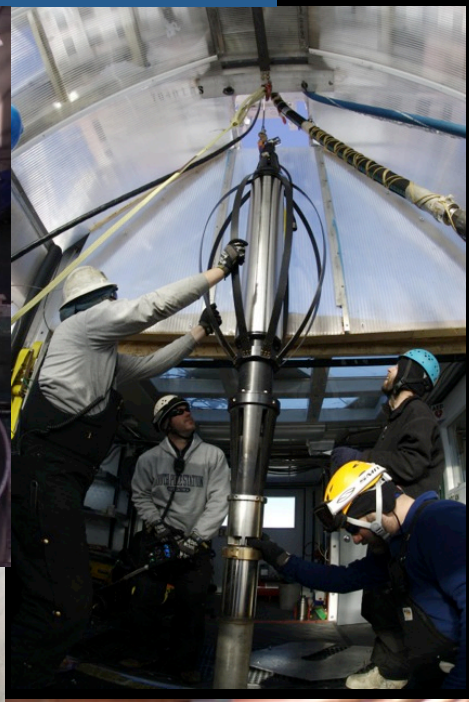


- 5 MW Drill power plant gives 195°F hot water in closed loop system.
- 5500 gallons AN-8 jet fuel / hole
- 30 man crew
- 30 h drilling – 3 day cycle time
- "Hole liftime" – 24hr
- DOM installation – 8 hr
- Typical freezeback times > weeks
- DOMs not operated in liquid under normal circumstances.



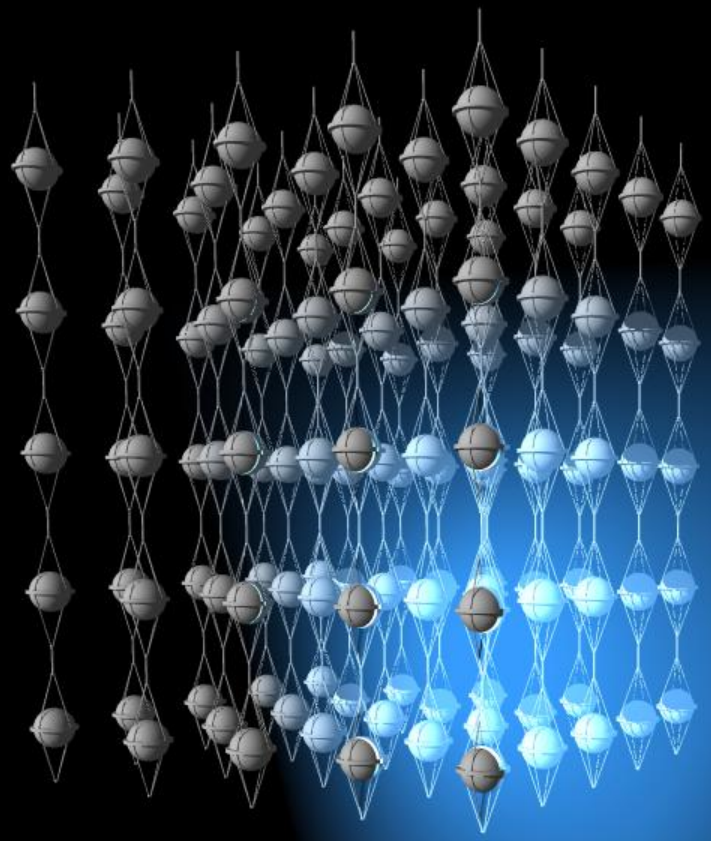
Drilling & Deployment Images





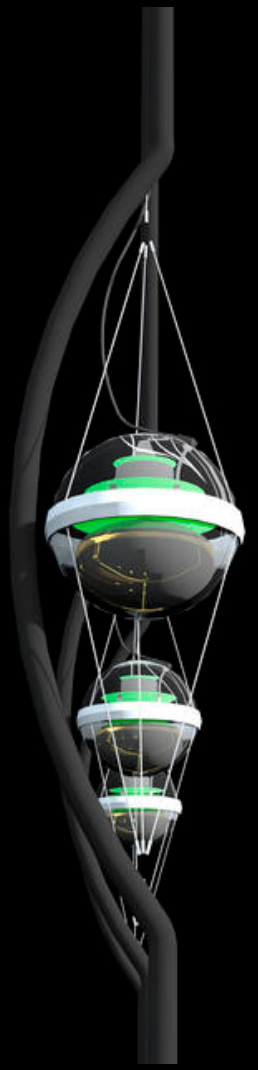




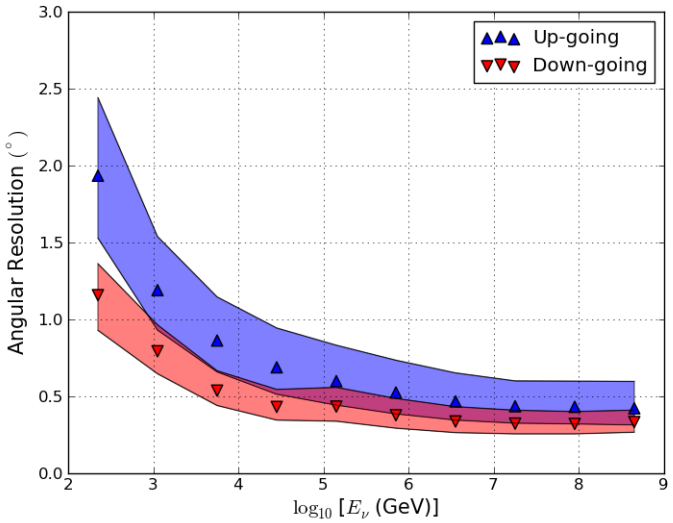
Performance and scientific product

ICECUBE RESULTS

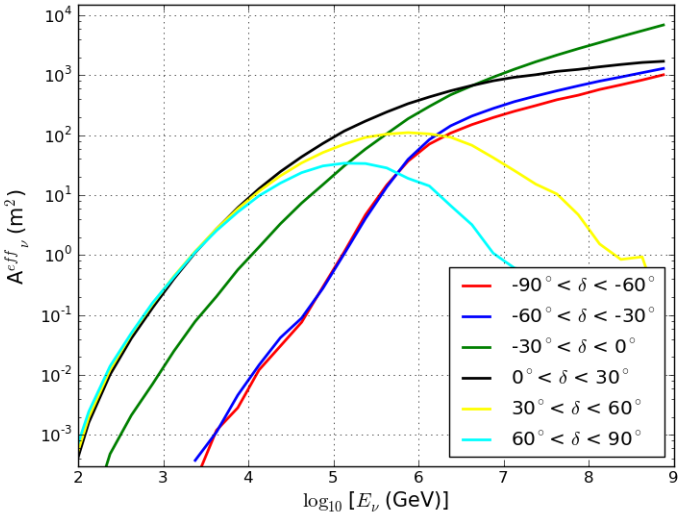
Reconstruction Performance



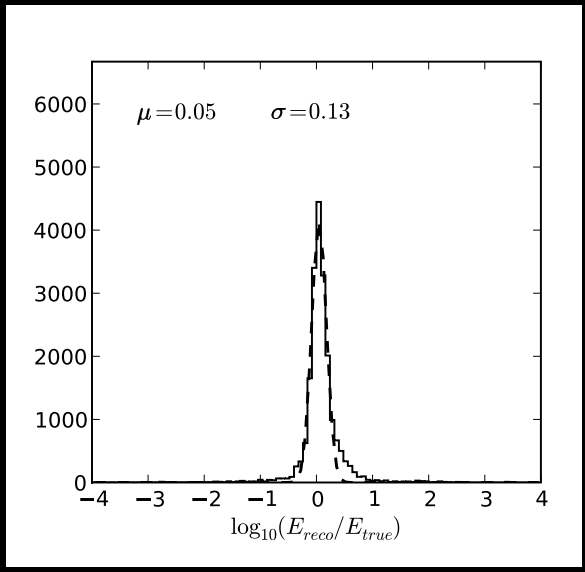
Point sources angular resolution



PS neutrino effective area



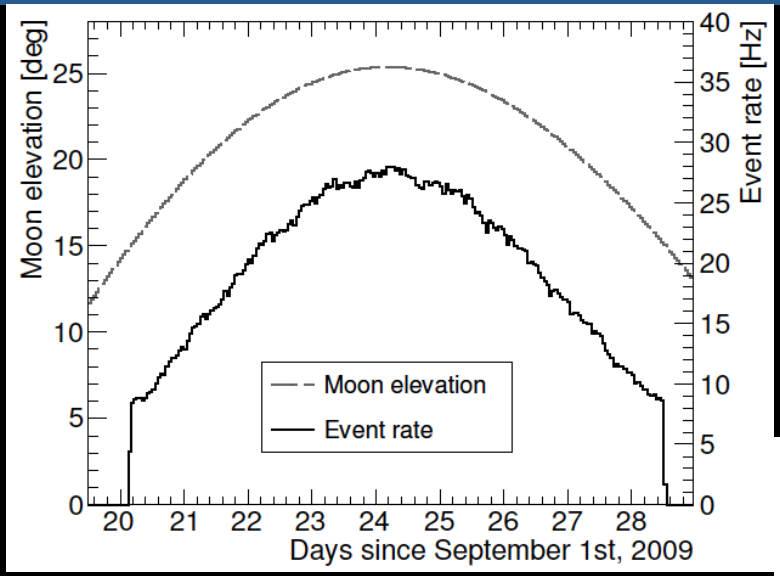
HE cascade E resolution



- Pointing and energy resolution *extremely* analysis dependent – these are only indicative plots
- Muon energy reco from dE/dX … but only gives the local energy of muon. <u>Extremely hard to get good neutrino energy for through-going muons.</u>
- Cascade angular reconstruction poor but has improved quite a bit – now O(10°).

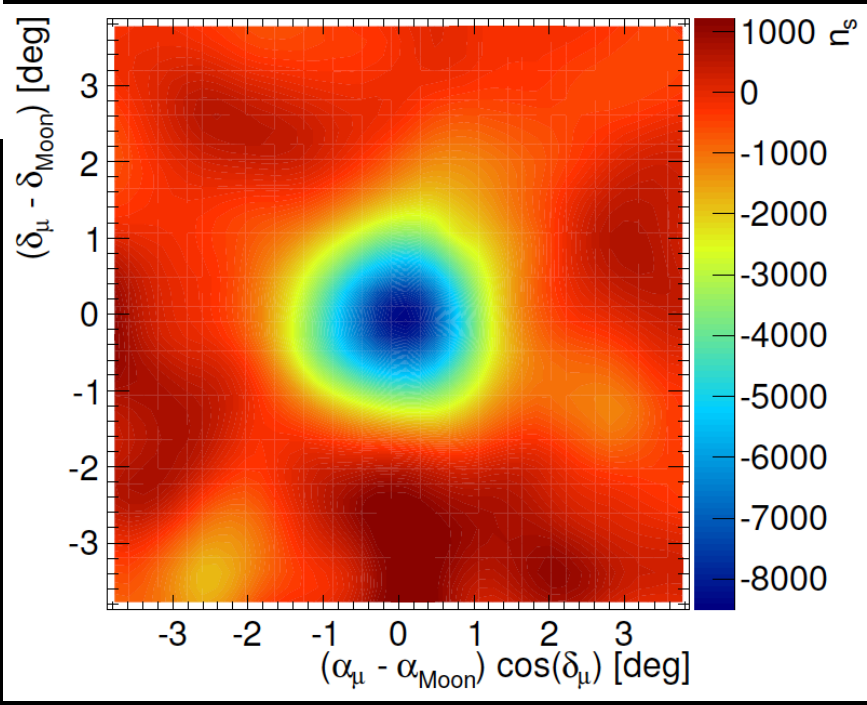
Moon Shadow – IC59





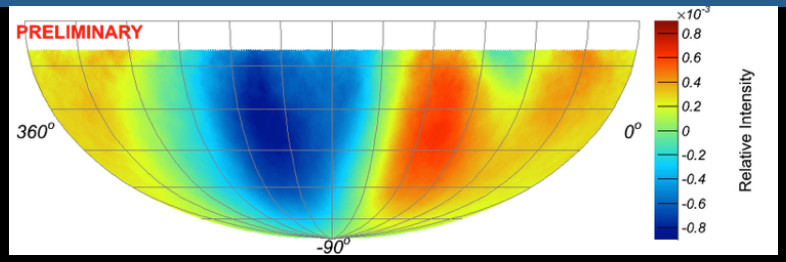
- Filter selects reco'd events with 10° in δ and 40°/cos(δ) in r.a.
- >11 DOMs on >2 strings
- 130 million events for IC40
- 180 million events for IC59
- Median E is about 40 TeV for selection in both IC40 & 59.

- Verifies timing accurate to minute scale (should be in fact 100 ns from GPS but nice to have cross-check)
- Detector resolution
  - 1.13° IC40
  - 0.98° IC59

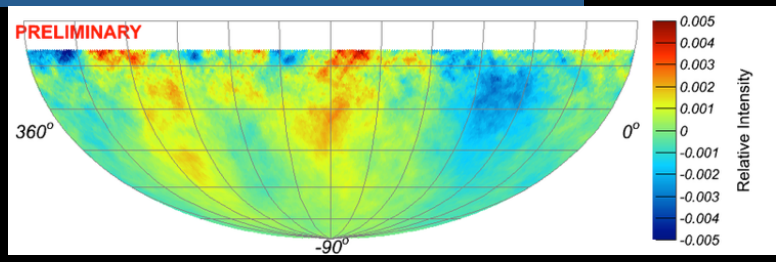


IC79 Cosmic Ray Anisotropy Measurements

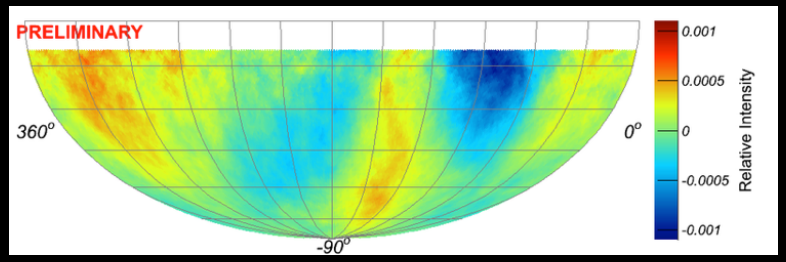




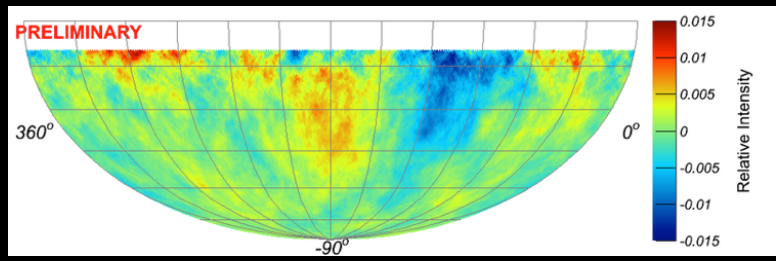
IC79 40 TeV 20° smoothing



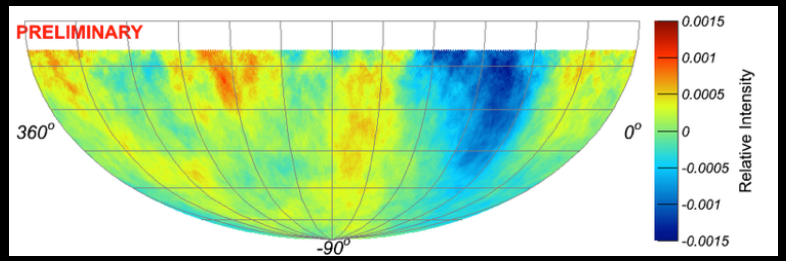
IC79 1 PeV 20° smoothing



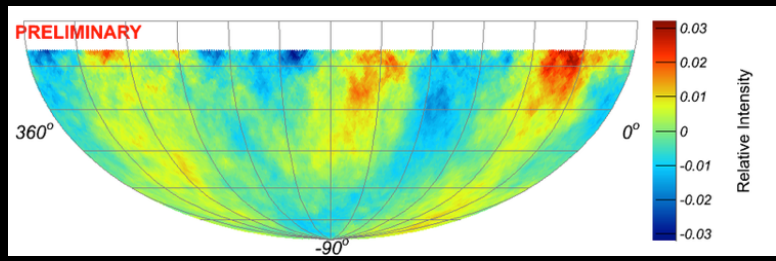
IC79 200 TeV 20° smoothing



IC79 5 PeV 20° smoothing

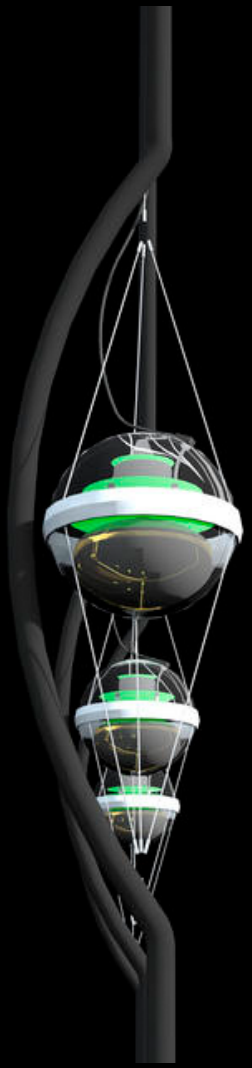


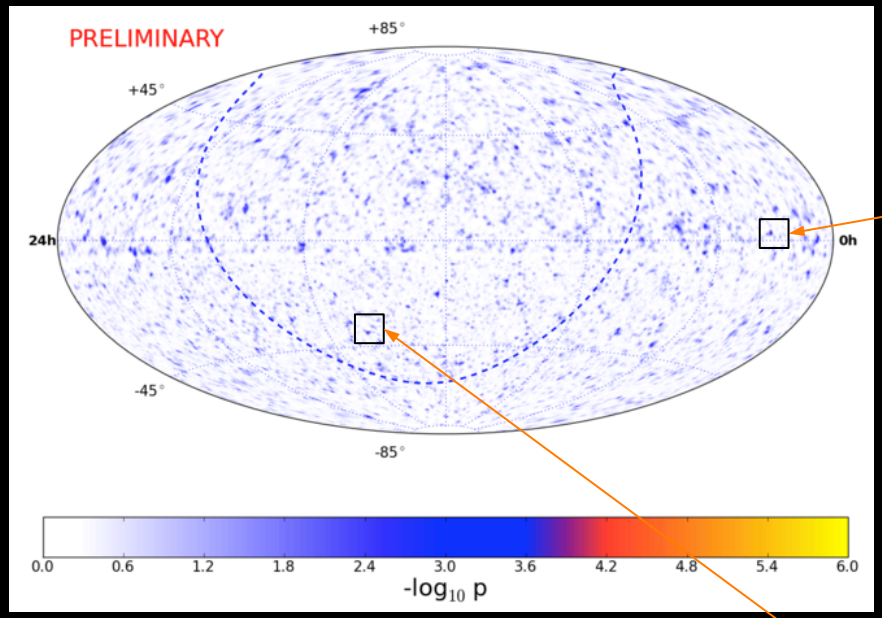
IC79 400 TeV 20° smoothing

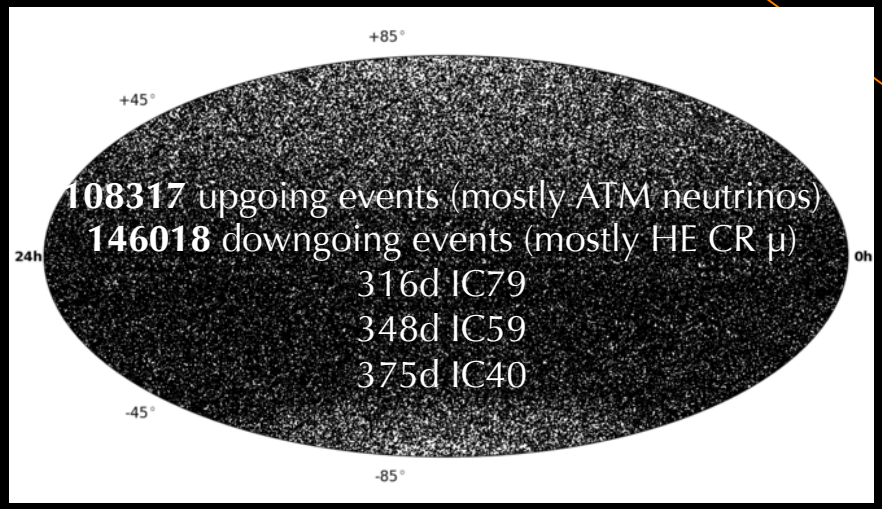


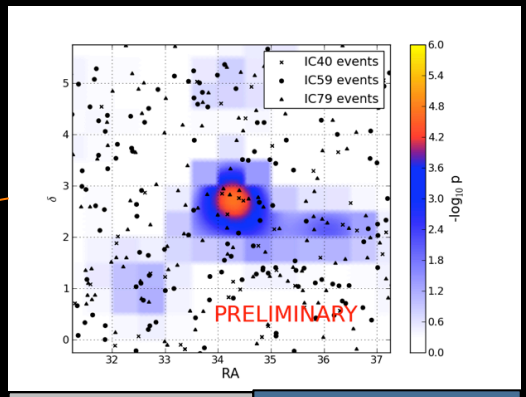
IC79 10 PeV 20° smoothing

Point Sources: IC40/59/79 Skymap



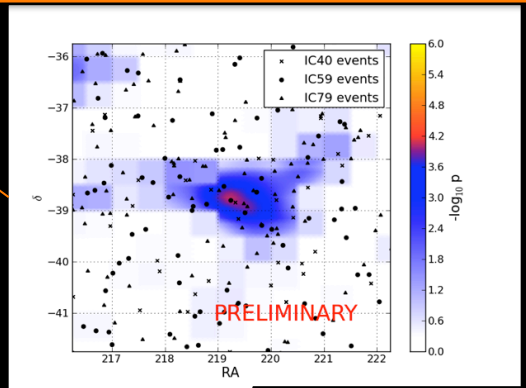






$-\log_{10}p = -4.7$
$\alpha = 34.25°$
$\delta = 2.75°$
$\gamma = -2.35$

57% of random skies had p-value equal or greater



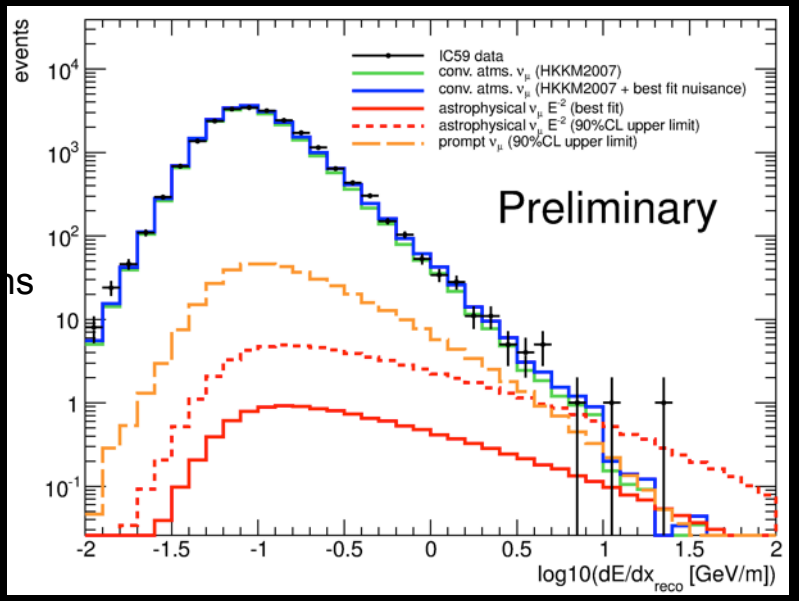
$-\log_{10}p = -4.7$
$\alpha = 34.25°$
$\delta = 2.75°$
$\gamma = -2.35$

57% of random skies had p-value equal or greater

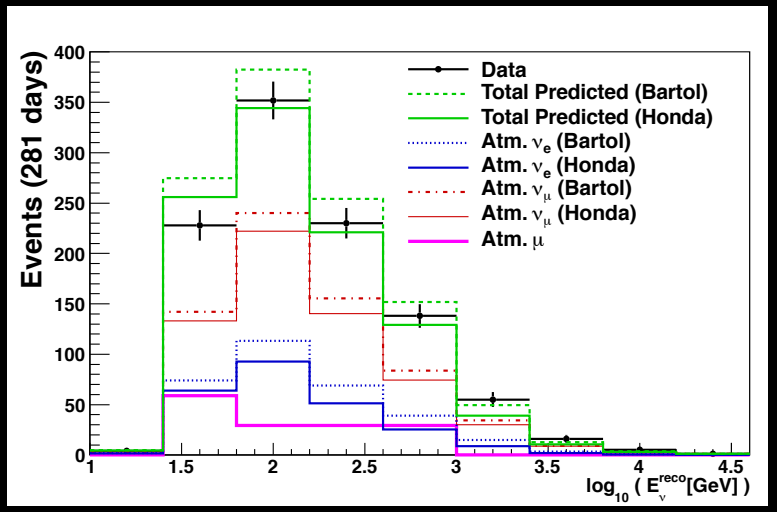
IceCube Atmospheric Neutrinos



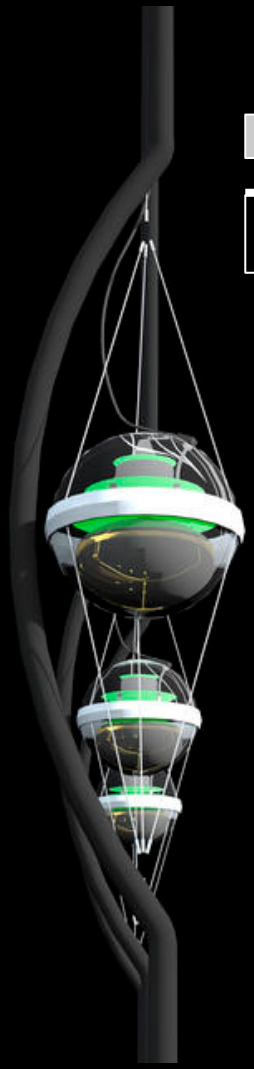
- Weak ~ 2σ excess observed from analysis of IC59 data
- Compatible with E^{-2} spectrum
- Flux limits got worse relative to IC40 because of excess

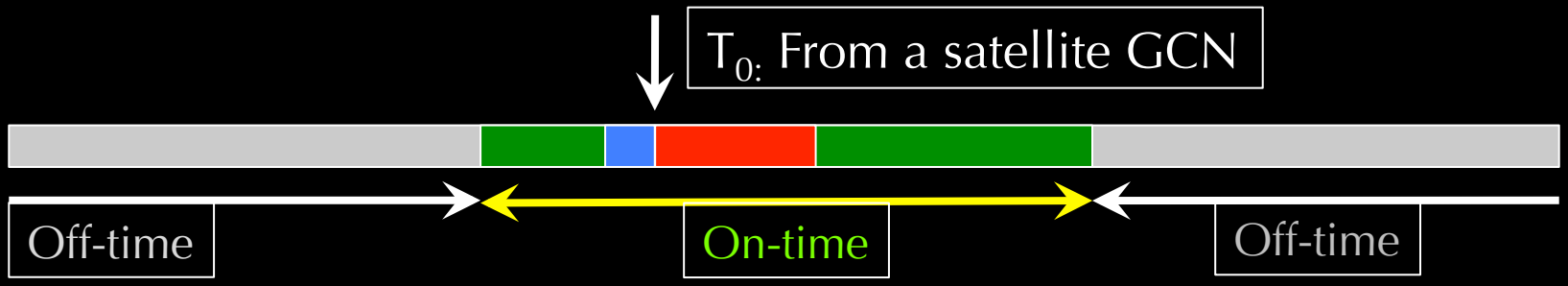


- Atmospheric cascade events
- PRL 110 (2013) 1511
- 1029 events observed
- 532 bkg evts from CRMU and muon neutrino CC
- 496 ± 66 ± 88 (syst)



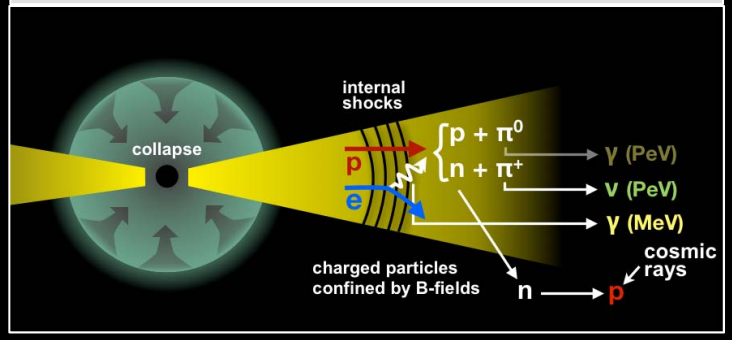
GRB Searches

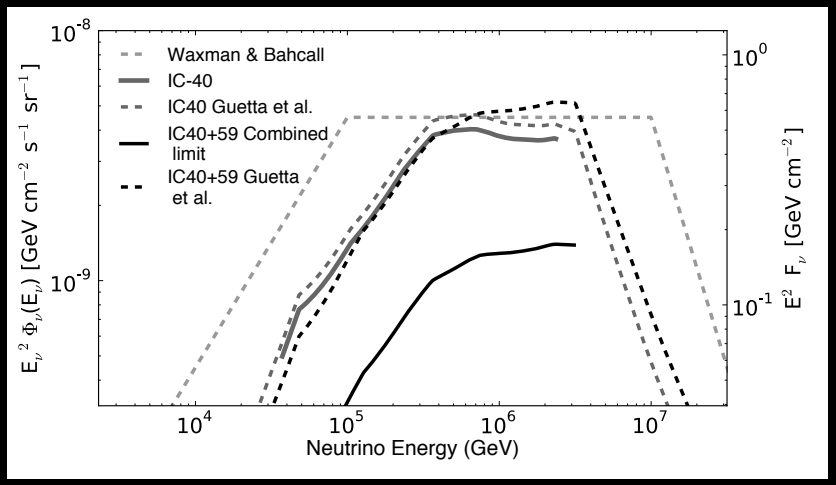




- Precursor (~100 s)
- Prompt (T_{90})
- Model Independent (±24 h)
- Off-time (full year)

GRB *Fireball* Model





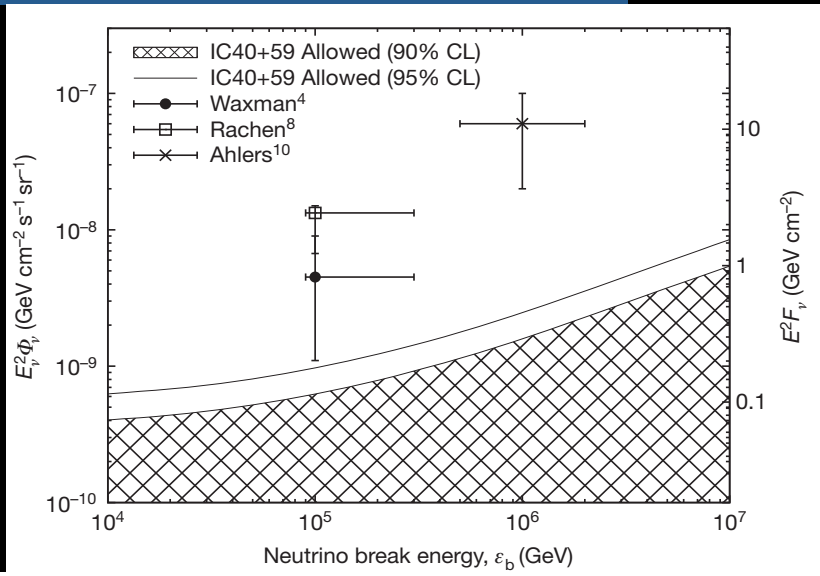
Model-dependent:
8.4 events expected
0 events observed

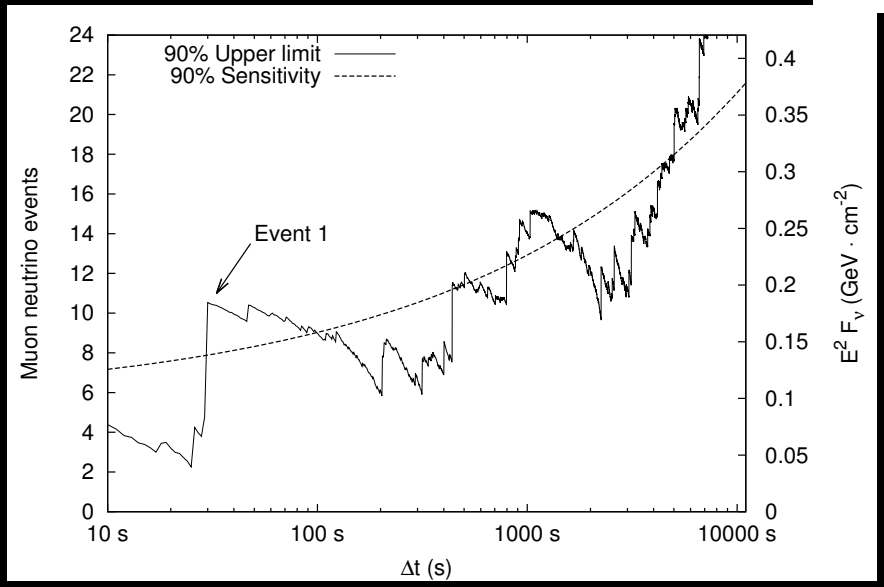
IC40 + IC59 GRB Results



No observation of GRB neutrinos:

- "fireball" theory must be significantly revised, or
- hypothesis of GRBs as the only source of UHE CRs excluded for some models

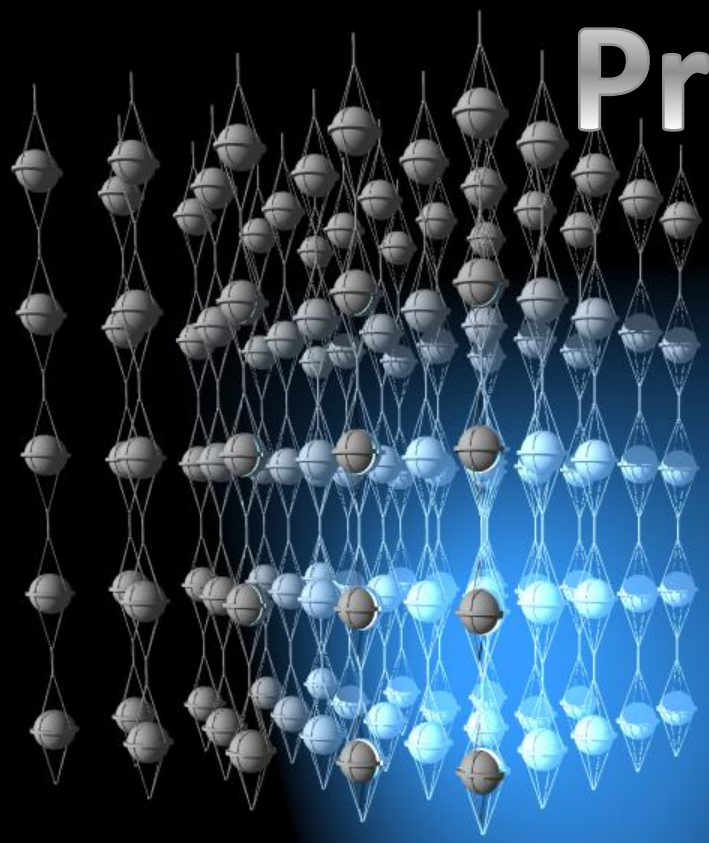




Read our article in …

Nature

Vol **484**, 351 (2012)



Preliminary!

Here come the muppets …

THE HIGH ENERGY EXCESS

Note difference between British and American English terminology here



muppet

Pronunciation

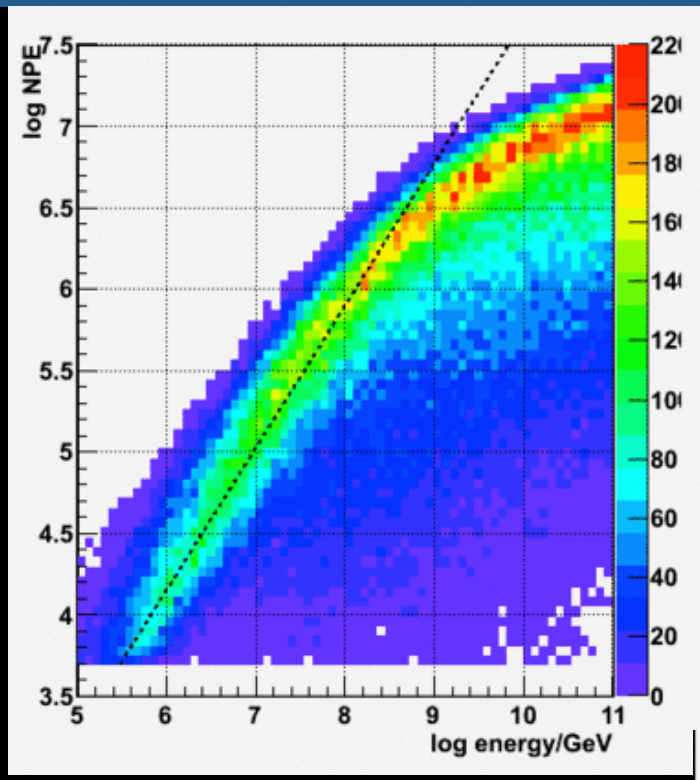
- /ˈmʌpɪt/, /ˈmʌpɛt/

Noun

1. *Brit.* Pejorative slang term used to describe an incompetent or foolish person.
2. *Amer.* One of a number of puppet characters known for an absurdist, burlesque and self-referential style of variety-show sketch comedy.
3. *Astrophys.* A very energetic neutrino event appearing in large-scale under-ice Cherenkov telescopes, most likely of cosmic origin.

EHE Diffuse Analysis



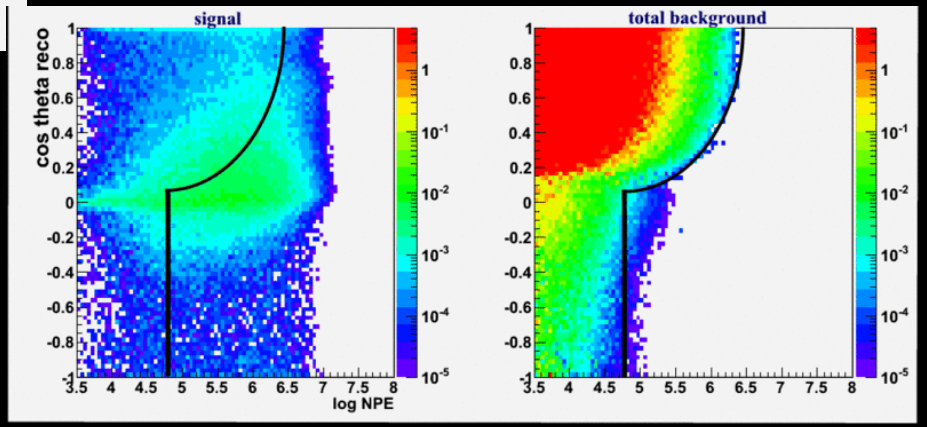


EHE event filter uses *energy proxy* NPE (# photo-electrons detected) and reconstructed zenith angle as discriminating variables. NPE is robust and fairly accurate for contained events up to almost 100 PeV. Above 100 PeV photons escape and PMT saturation becomes important.

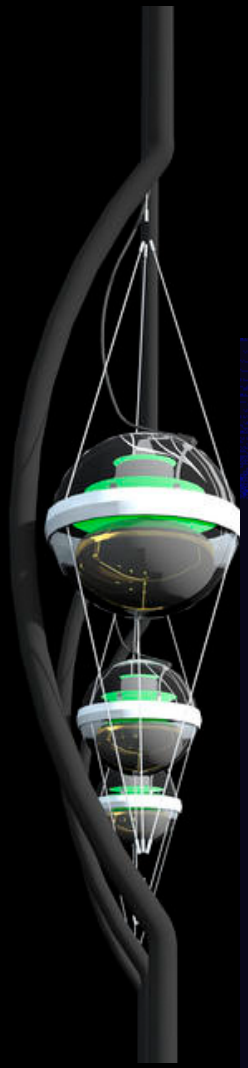
In addition the variability of the ice clarity enlarges spread at all energies.

Combined analysis of IC79 and IC86 yields 2 cascade-like events both from IC86 run:

118545:63733662 Aug 8, 2011 1.05 PeV
119316:36556705 Jan 3, 2012 1.15 PeV

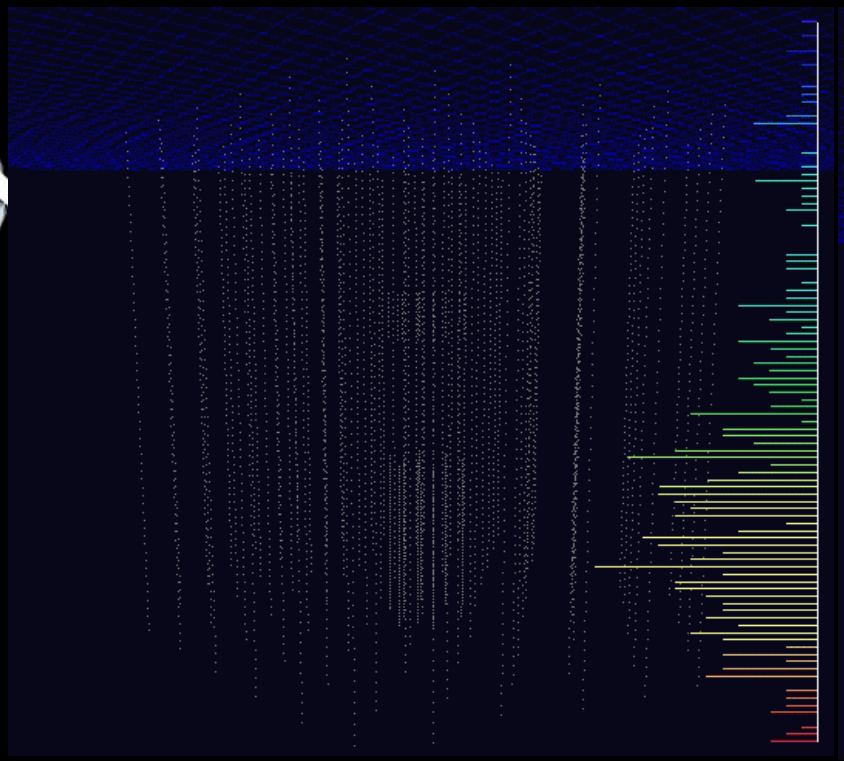


2x PeV Events Found

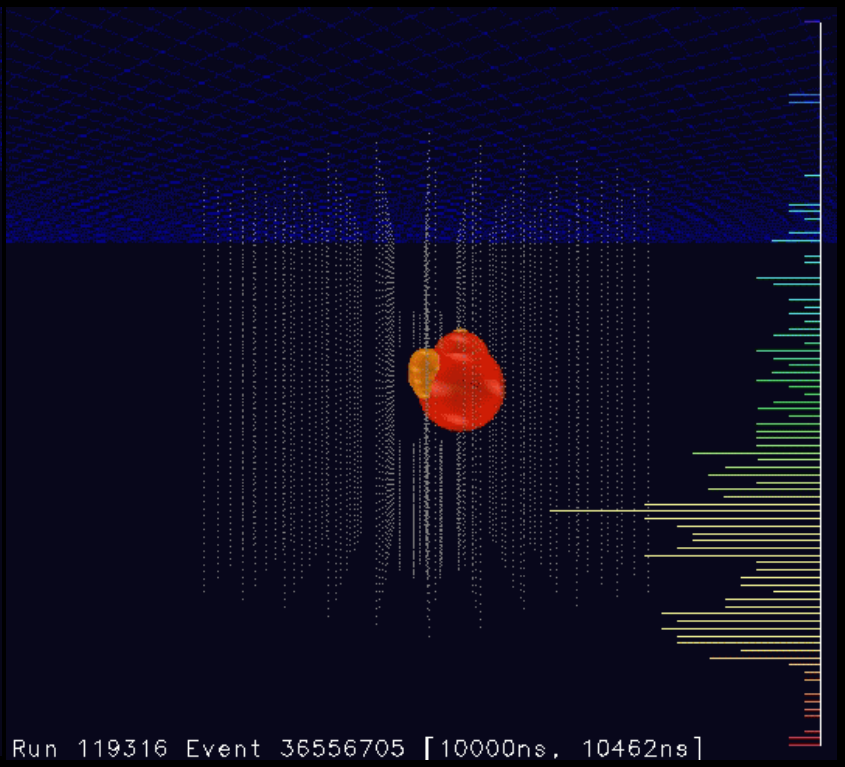


- Energy reconstruction error at these energies dominated by systematics: $\Delta E/E \sim 0.1$.
- Unexpected that EHE search would turn up 2 nicely contained cascade events? No.

EV118545:63733662 1.05 PeV 100k p.e.



EV119316:36556705 1.15 PeV 78k p.e.



Article on 2 PeV Events



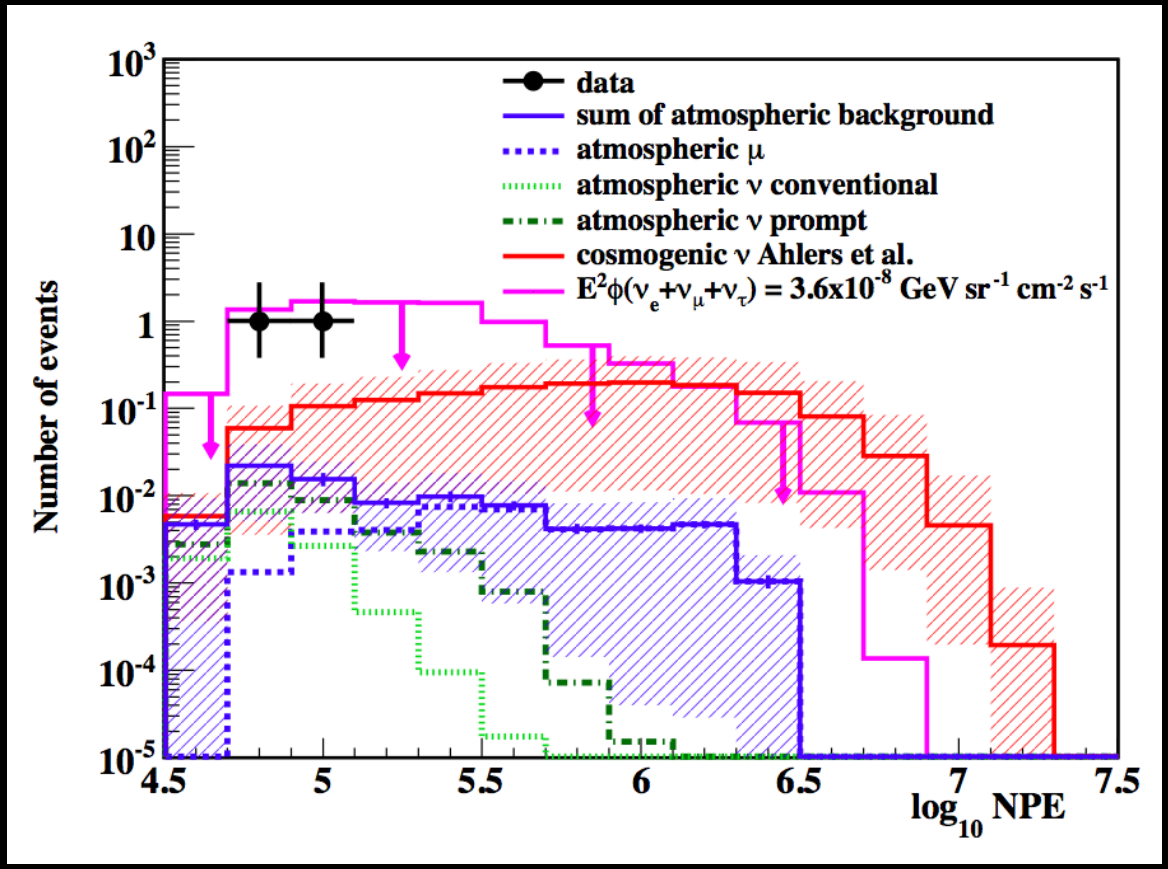
First Observation of PeV-energy Neutrinos with IceCube

arXiv:1304.5356

Submitted to PRL

What are they?

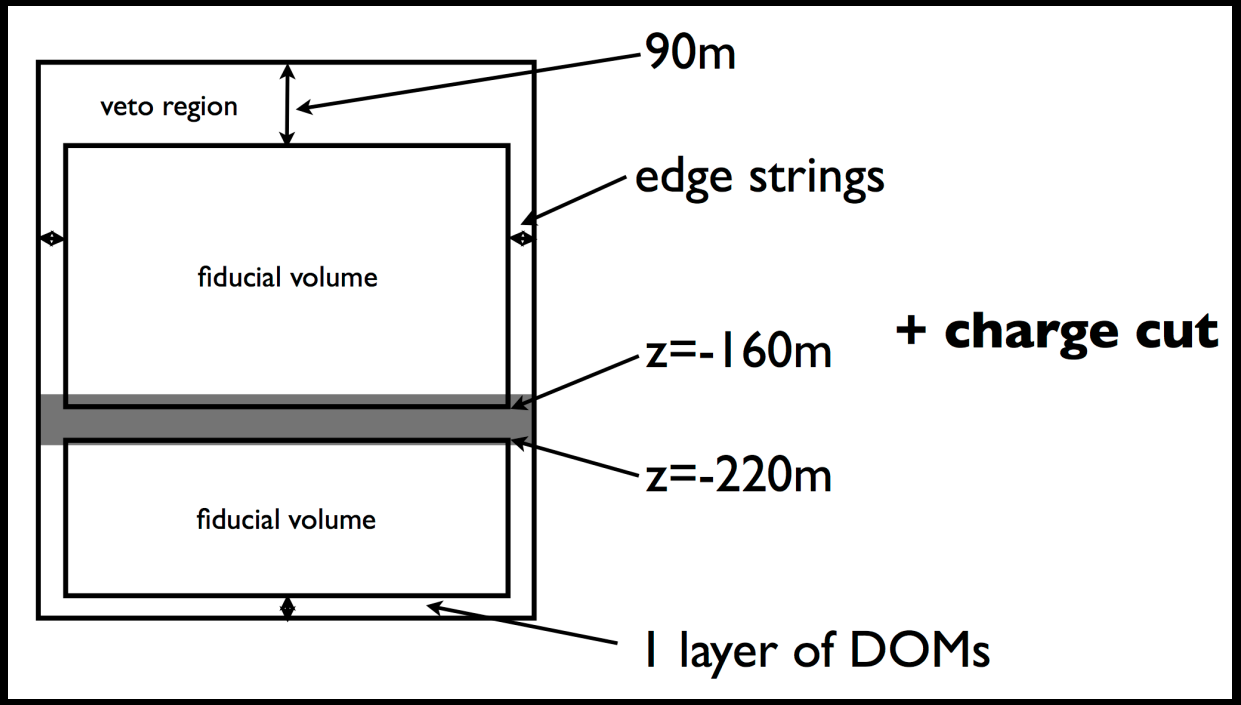




Preliminary!

Starting Event Follow-Up Search





(Partially) contained event search: require first light inside guarded volumes (420 Mton fiducial mass). This analysis is sensitive to *all* neutrino flavors > TeV with preference to cascade-like. The sensitivity is 3x that of EHE analysis above 1 PeV. Performed on same 2 year IC86 data.

Preliminary!

Results



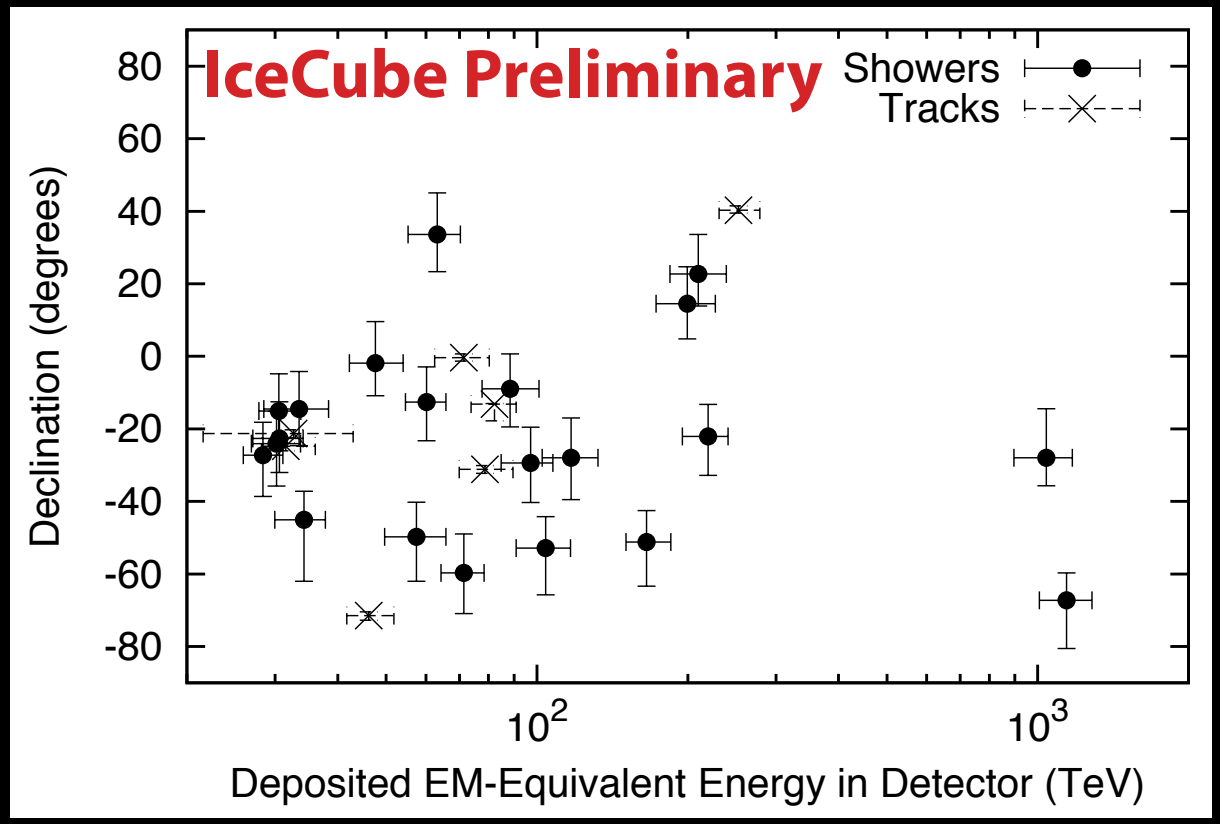
28 Events total:
7 muon like
21 cascade like
Background expectation 10.6 events

The original two events, Bert and Ernie, remain in this data sample, and remain the two highest-energy events of the sample.

Preliminary!

Zenith angle / event type

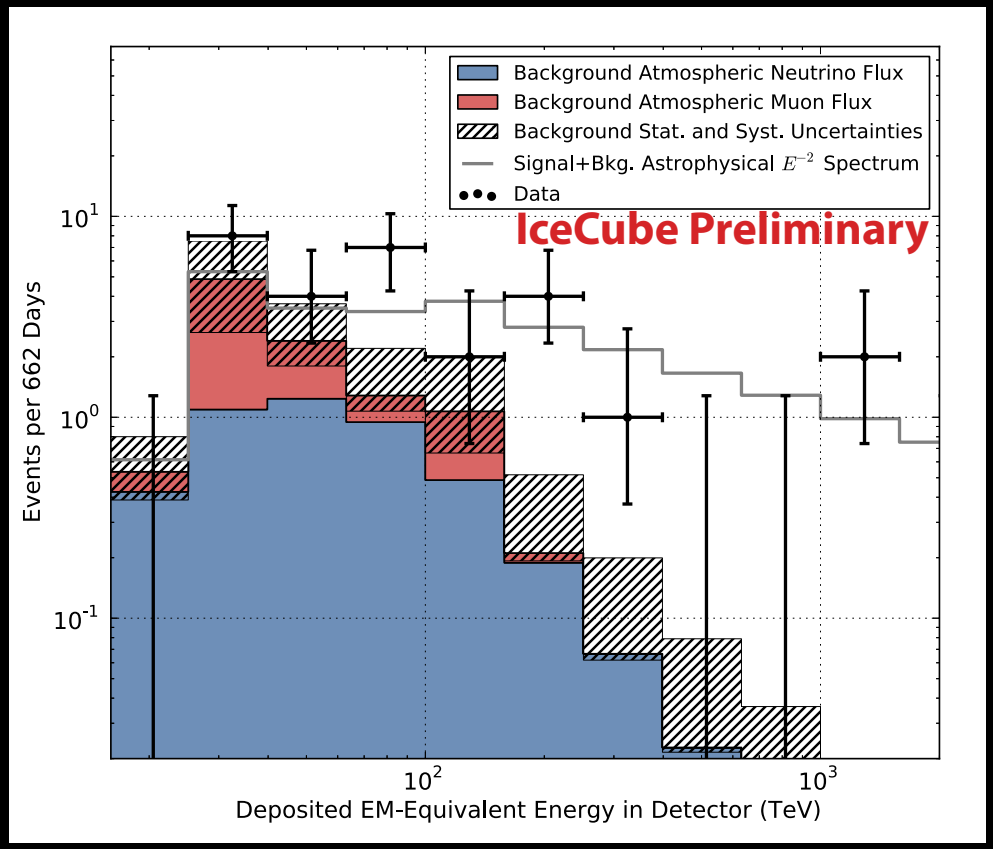




Preliminary!

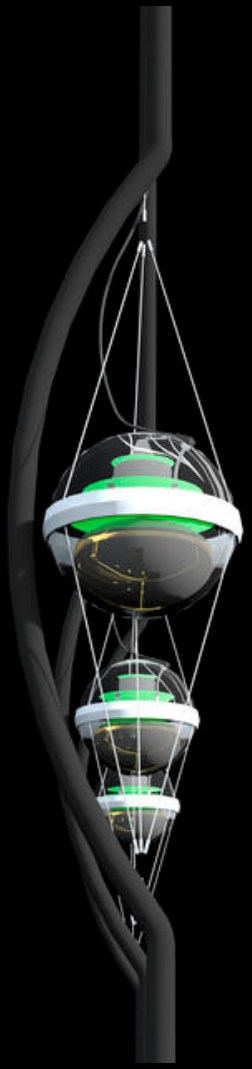
Energy

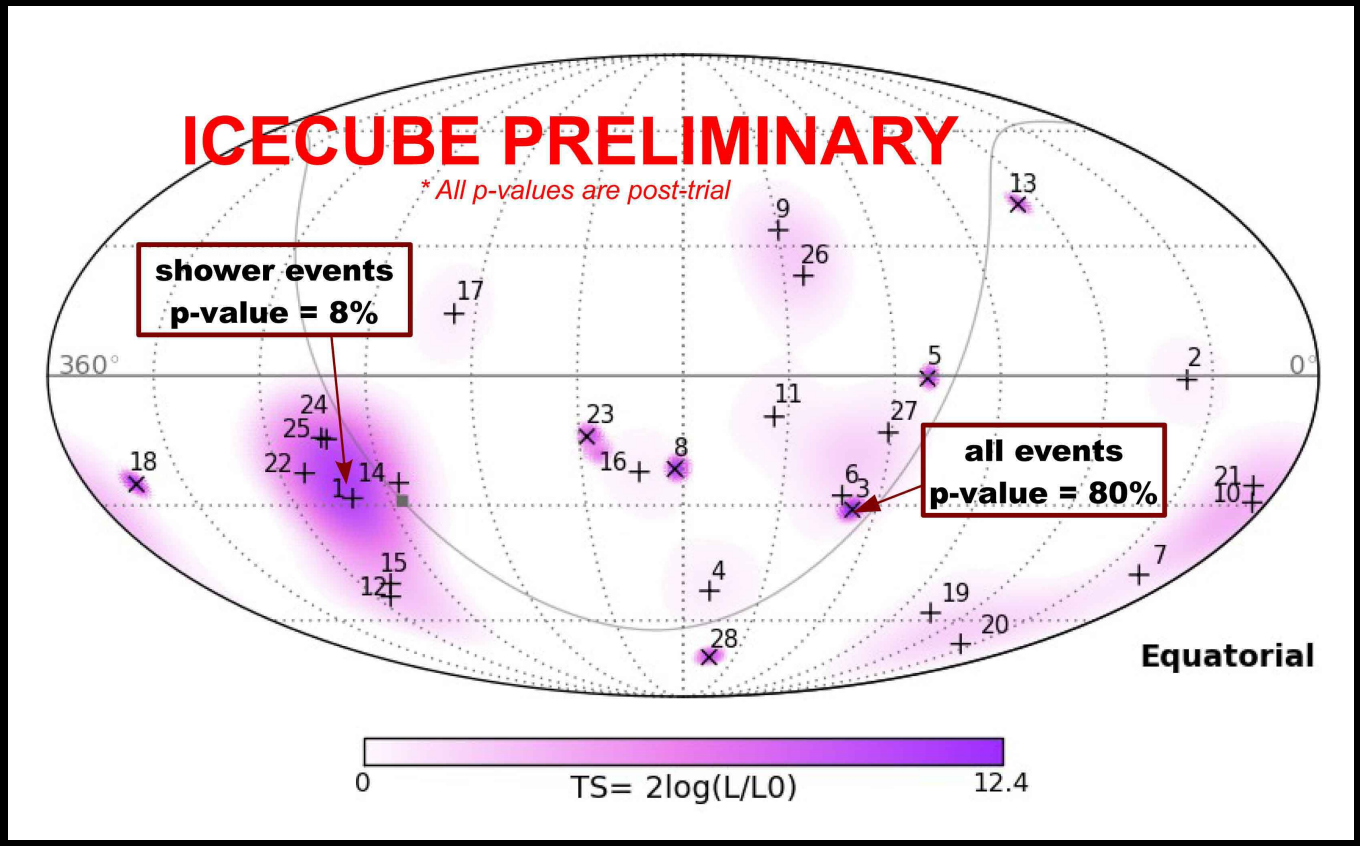




Preliminary!

HESE Skymap



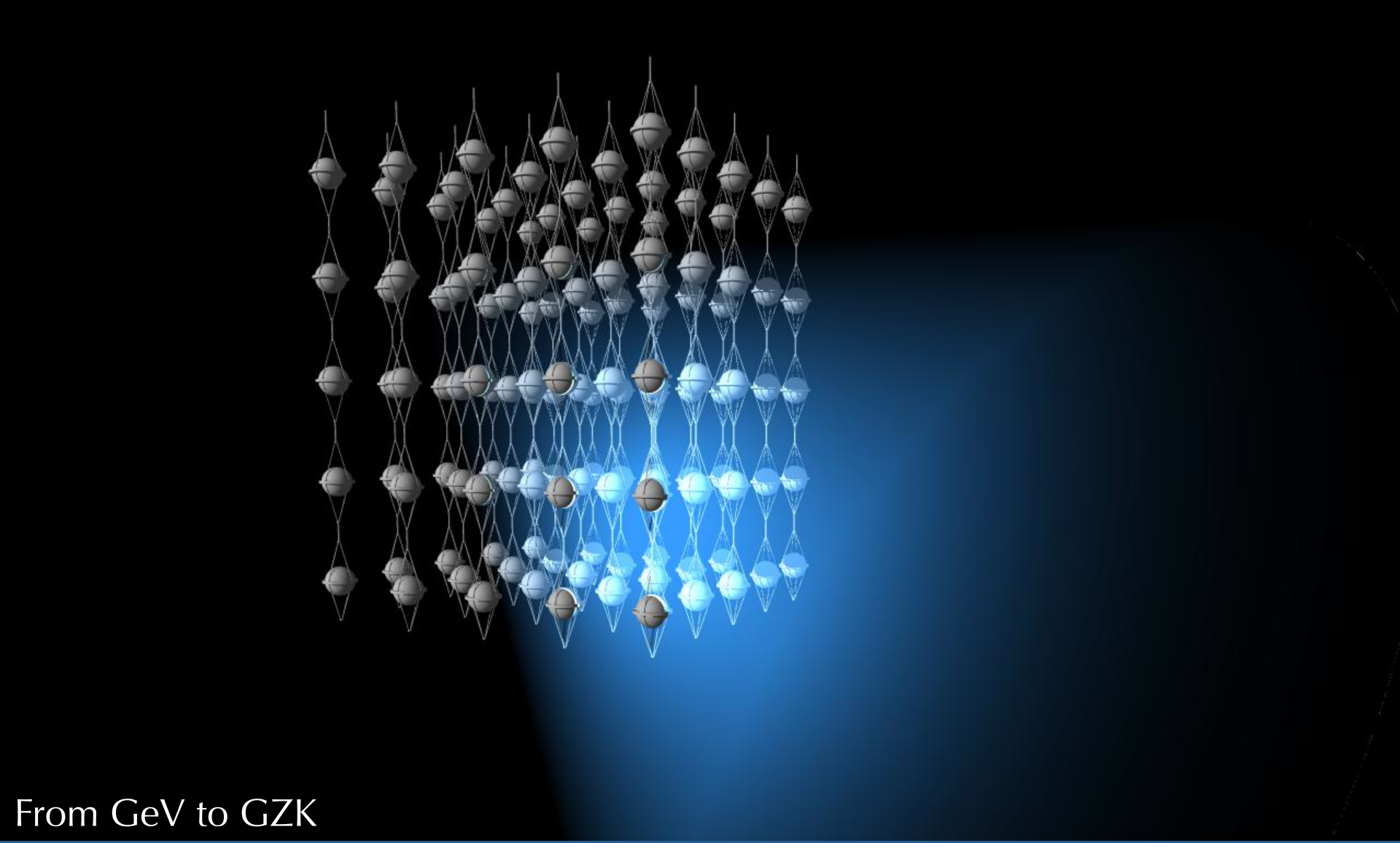


Cascade-like events marked with + and muons marked with x. While there appears to be a clustering near GC (grey dot on grey line marking galactic plane) – not significant at this point.

What are these events?



- Atmospheric CR background from above?
  - Extensive high statistics study of veto efficiency show sneak-through probability is extremely small – 10^{-9}
  - Neutrinos from airshowers above should have attendant muons + activity in IceTop
- High energy tail from below-horizon atmospheric neutrinos
  - Flavor ratios not right – would expect more muon-like events
  - Angular distribution wrong
- Cosmogenic neutrinos? No, flux too high, energy too low.
- Compatible with isotropic hard spectrum E^{-2} of cosmic neutrinos in energy, angular dist, event topology.
- It appears that there should be some cutoff or spectral break in the PeV region – extrapolating E^{-2} flux to infinity, one would expect ½ dozen additional PeV-scale events.

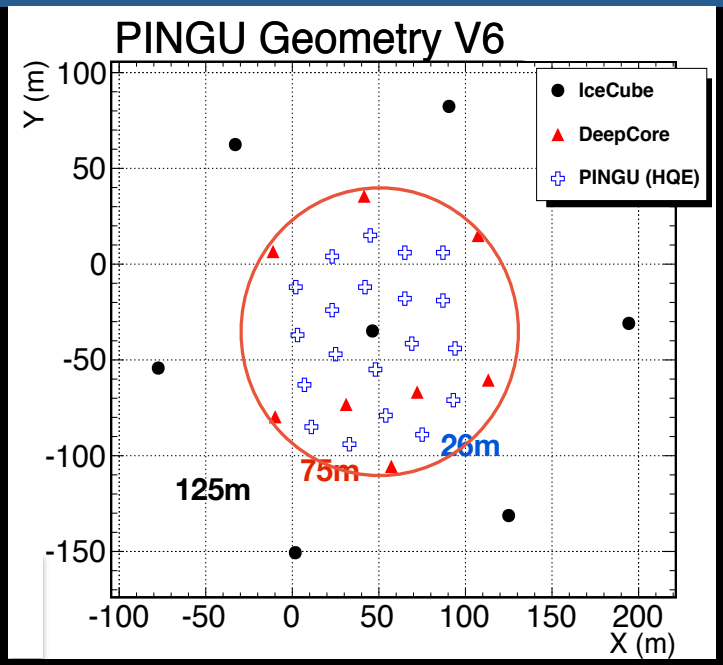


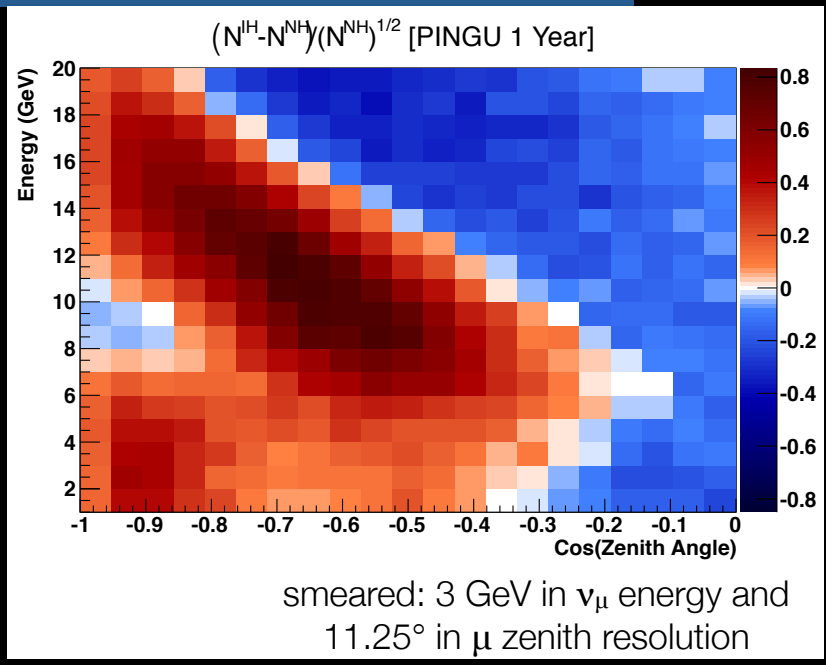
From GeV to GZK

NEUTRINO ASTROPHYSICS AT EXTREME ENERGIES

PINGU

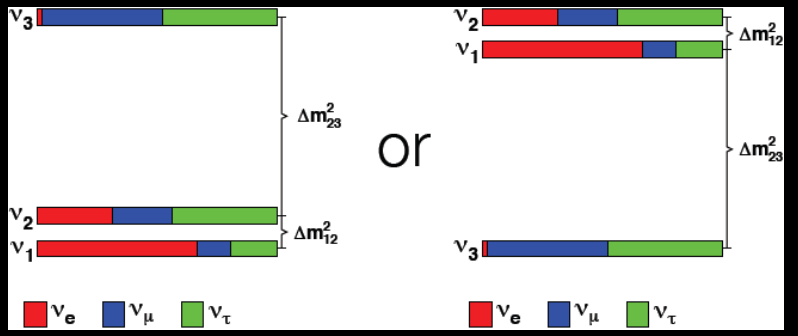






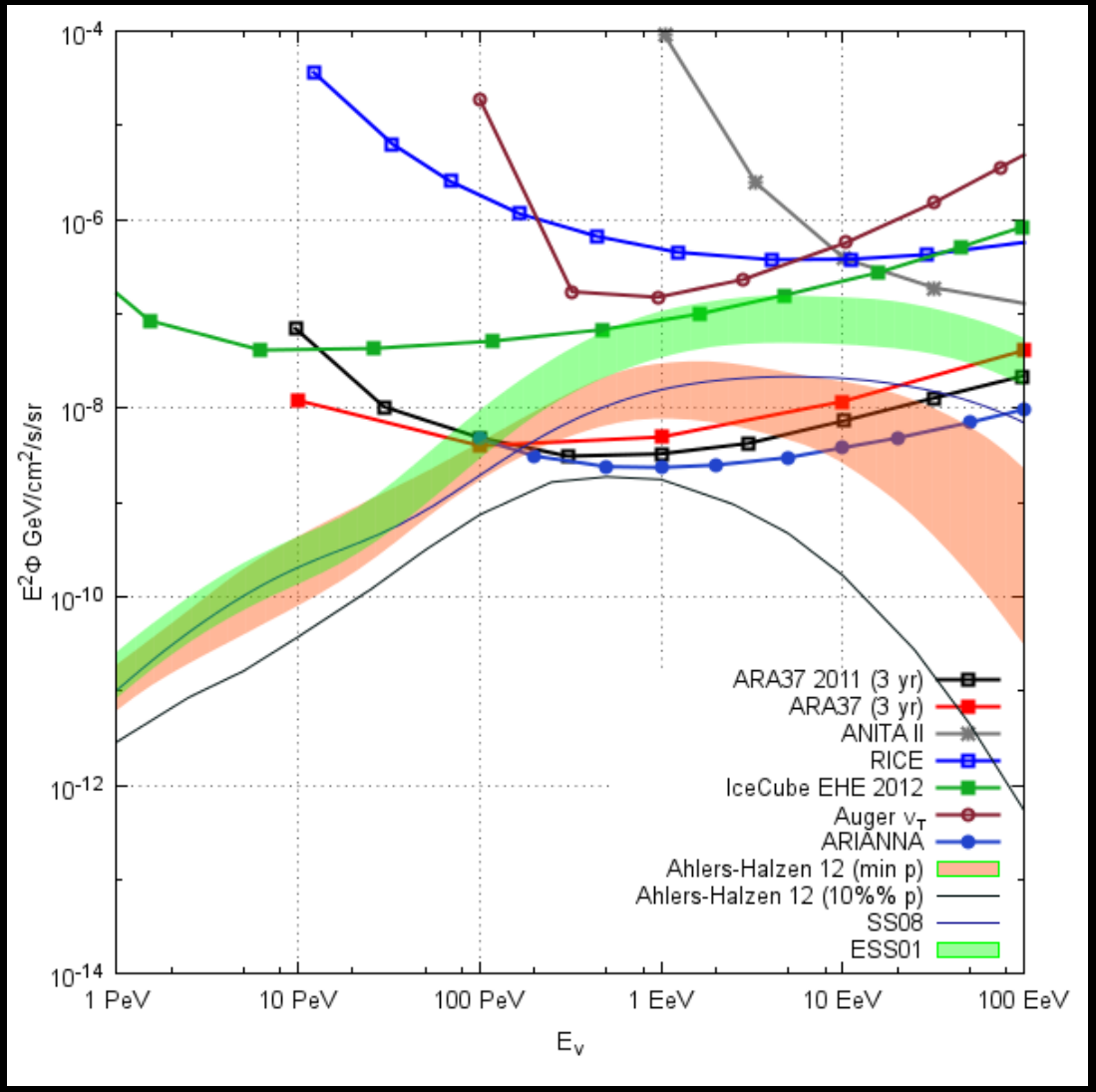
smeared: 3 GeV in ν_μ energy and 11.25° in μ zenith resolution

- Akhmedov, Razzaque, Smirnov arXiv:1205.7071 predict 3-10σ NH/IH discriminator after 5 yr
- 20 strings / $35-40M
- Using basic IceCube DOM technology, lightly upgraded



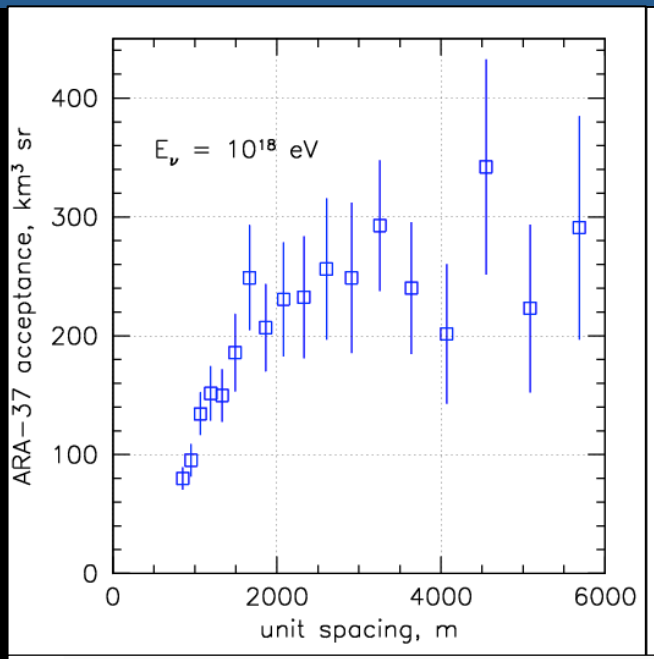
Cosmogenic Neutrinos

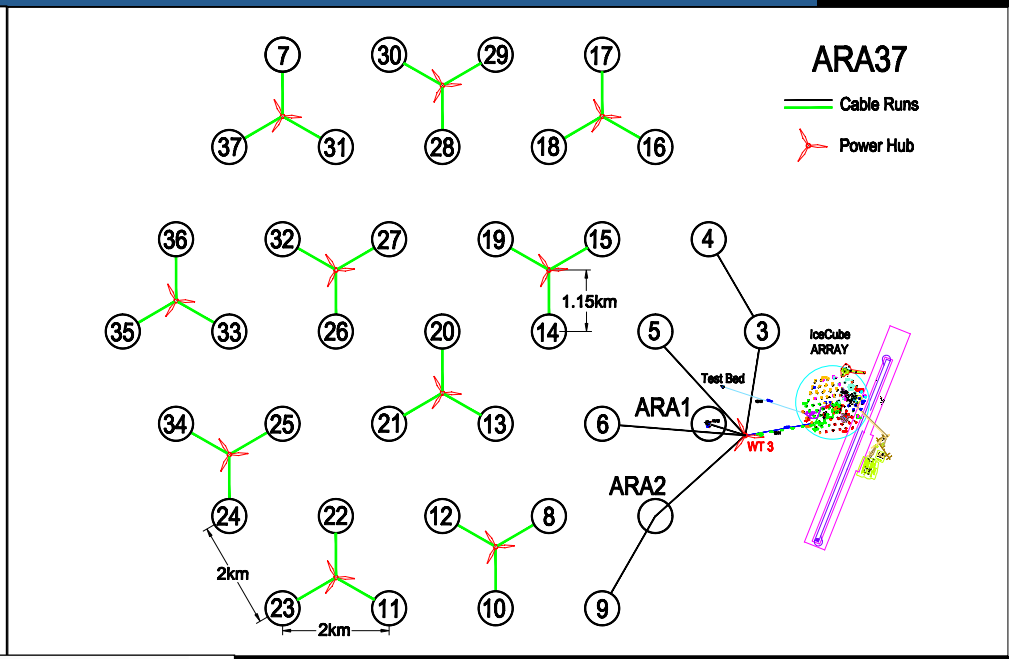


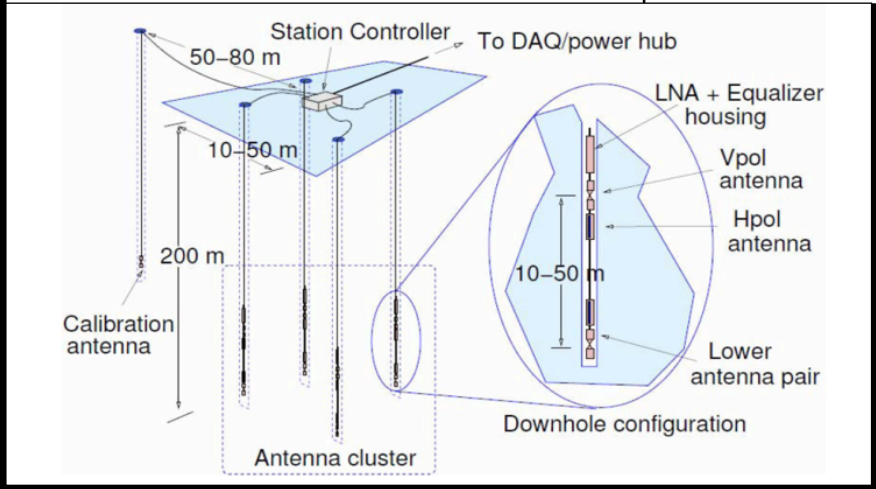


Radio Detection of Neutrinos - ARA









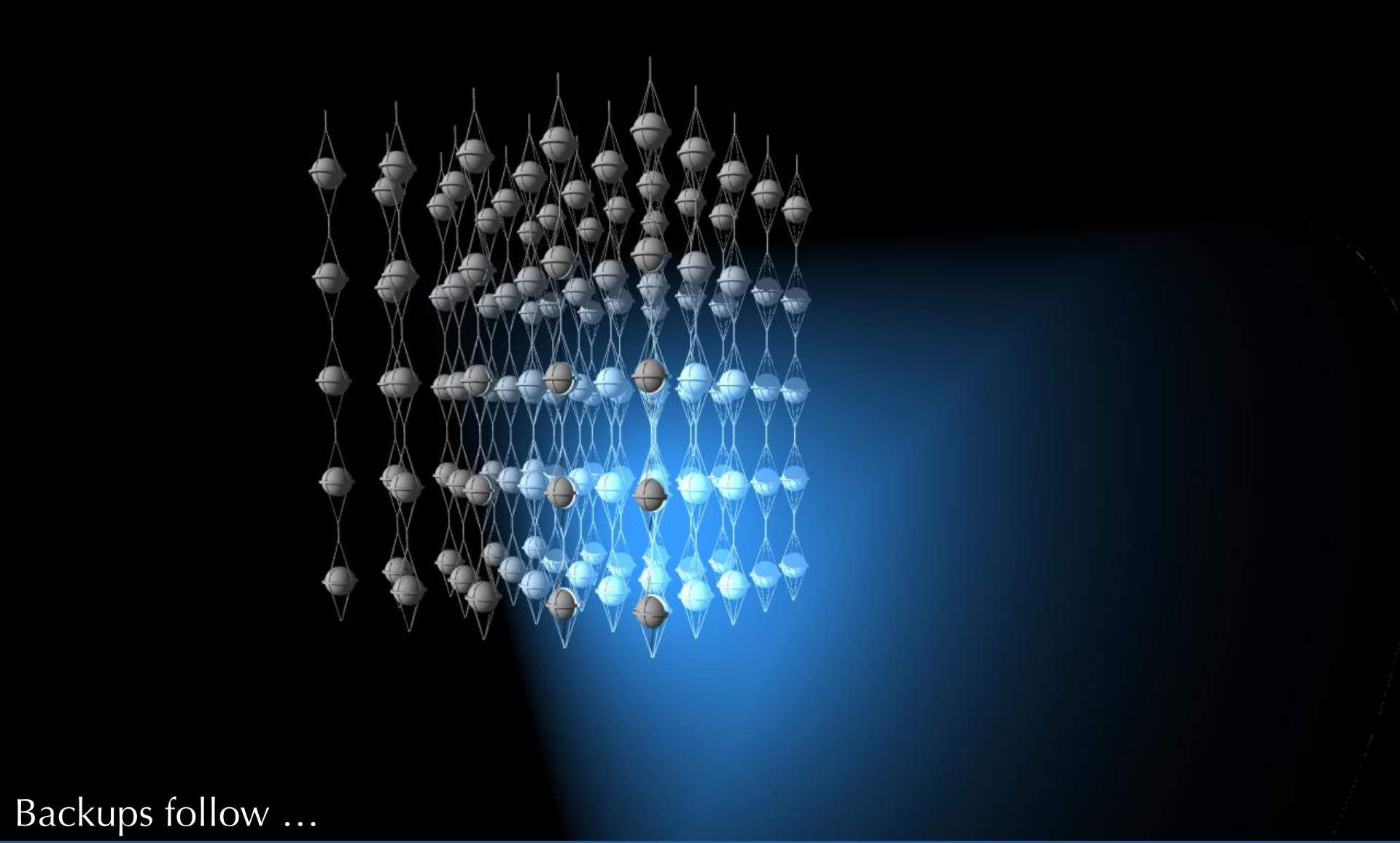
Status

- 1 TestBed deployed 2010-11
- 1 ARA station deployed 2011-12
- 2 ARA stations deployed 2012-13
- ¾ stations workin well – RF environment of Pole + atten length of ice favorable for GZK detector.
- No deployments 2013-14 due to NSF operations decrease
- Total 37 station array completion not likely until 2018

Summary



- Several interesting developments in cosmic ray and neutrino astrophysics
- HE neutrino astronomy in particular receives an envigorating boost with strong indications of extraterrestrial flux of HE neutrinos from first two years of full IceCube operation.
- Very exciting next year with IceCube as new revolutionary analysis techniques compound effectiveness of more data.
- Next steps with IceCube – go high or go low?
  - Neutrino oscillation physics with PINGU detector cost effective and fast alternative to long-baseline efforts.
  - Effective high-statistics study of signal at high energies requires IceCube extension or shift to new detector techniques such as RF detection.

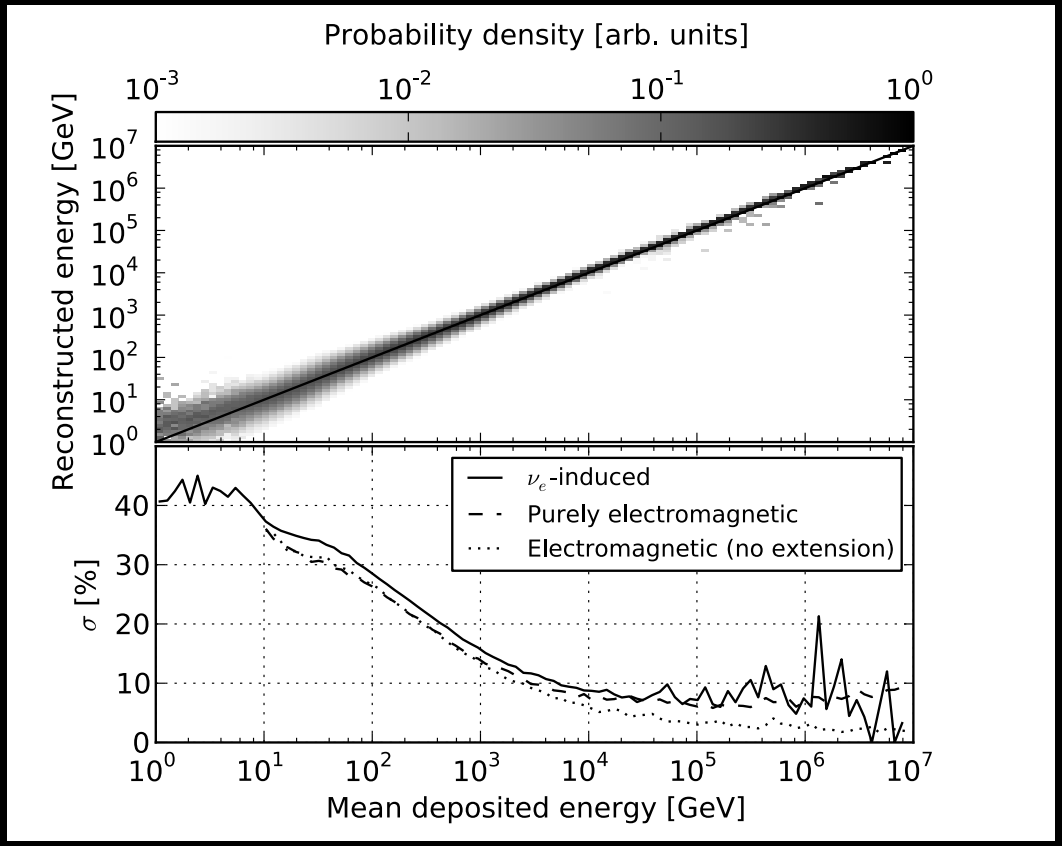


Backups follow …

THE END

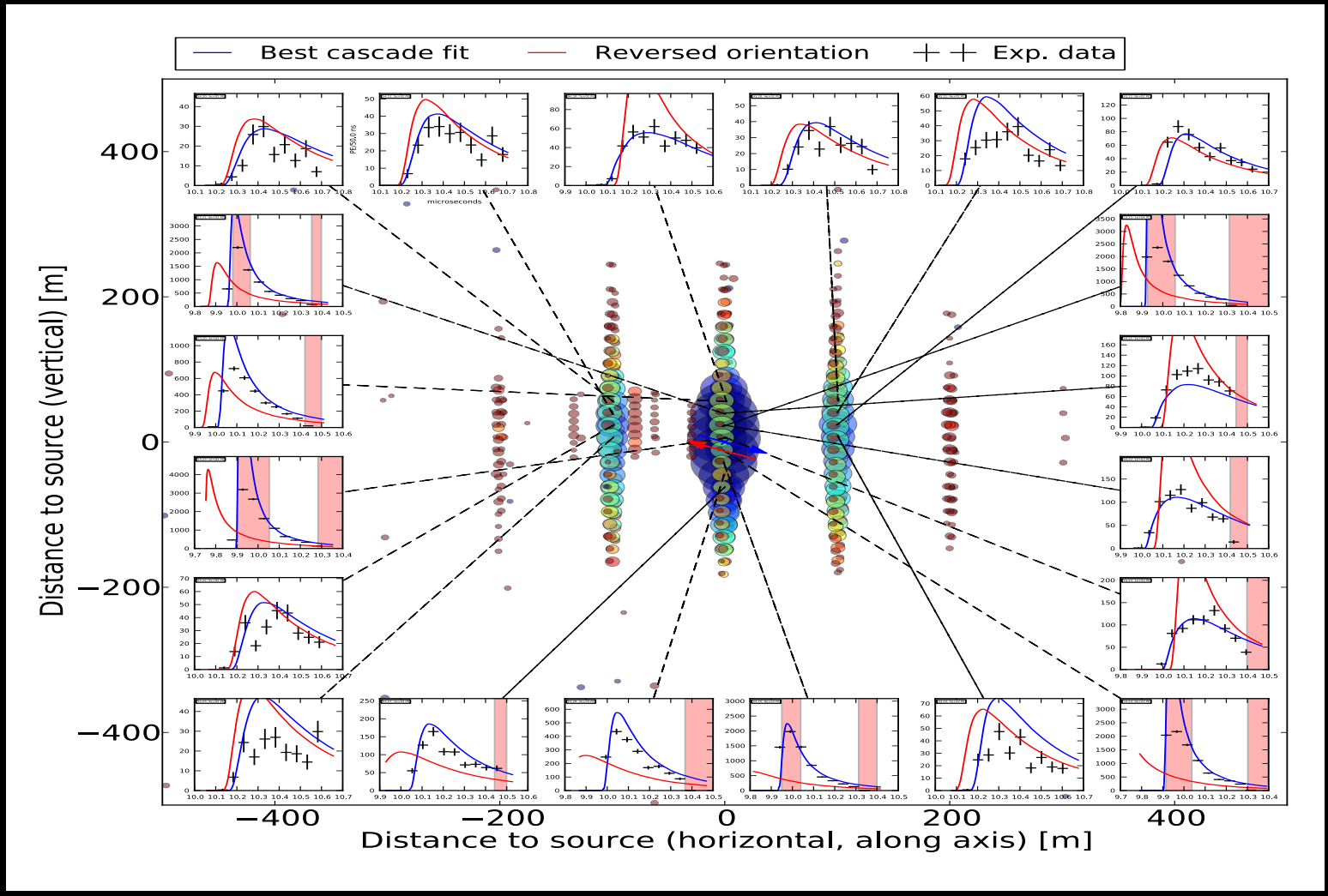
Energy Reconstruction





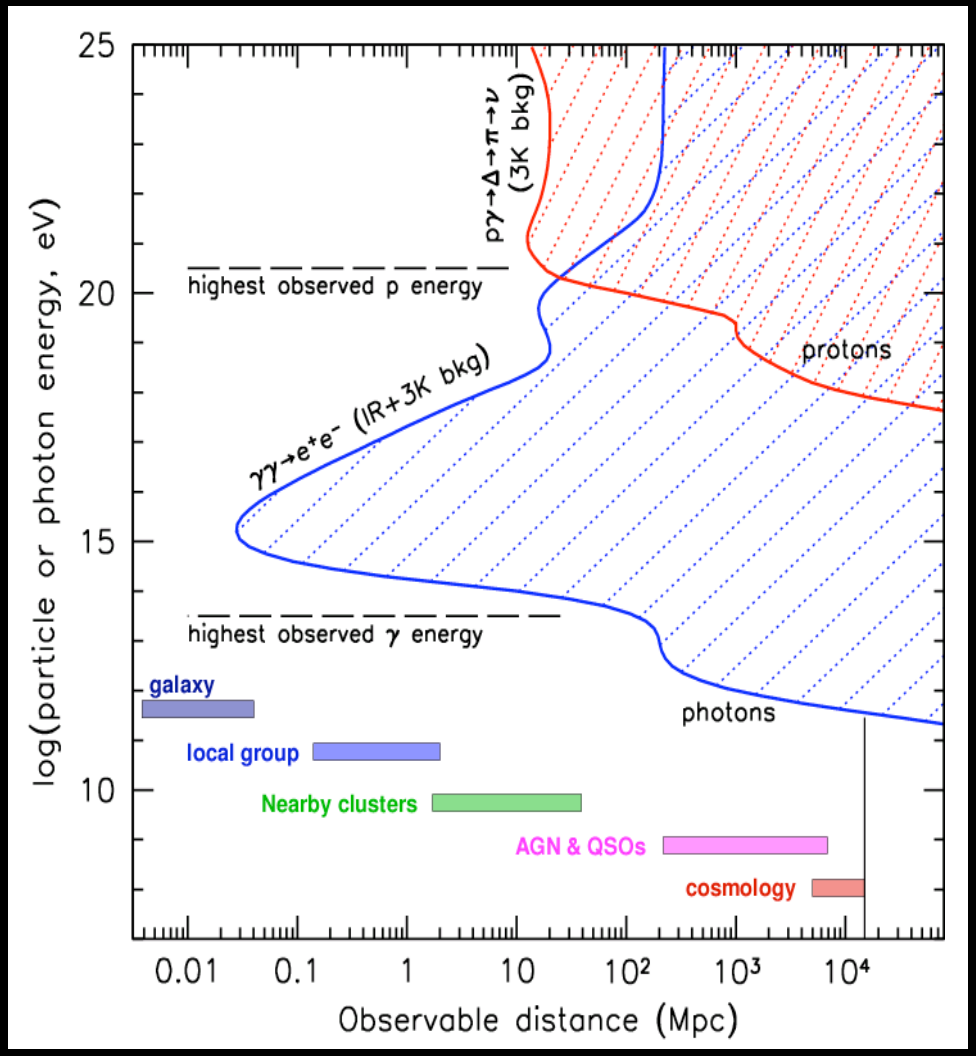
Bert Decomposed



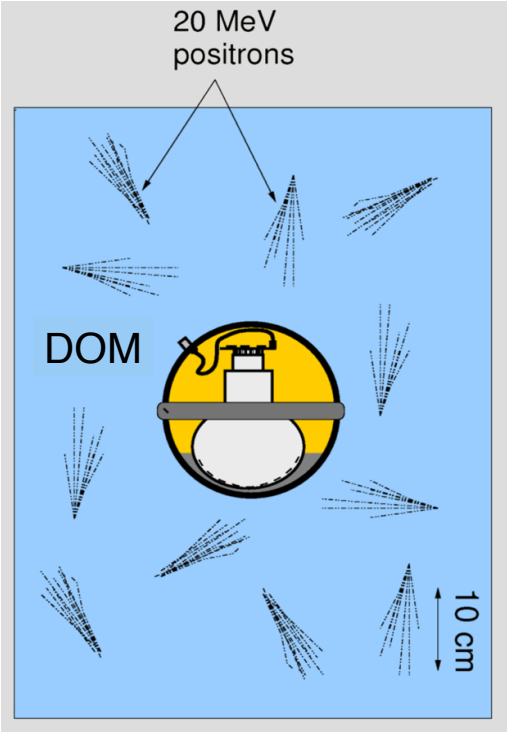


HE Photon Horizon





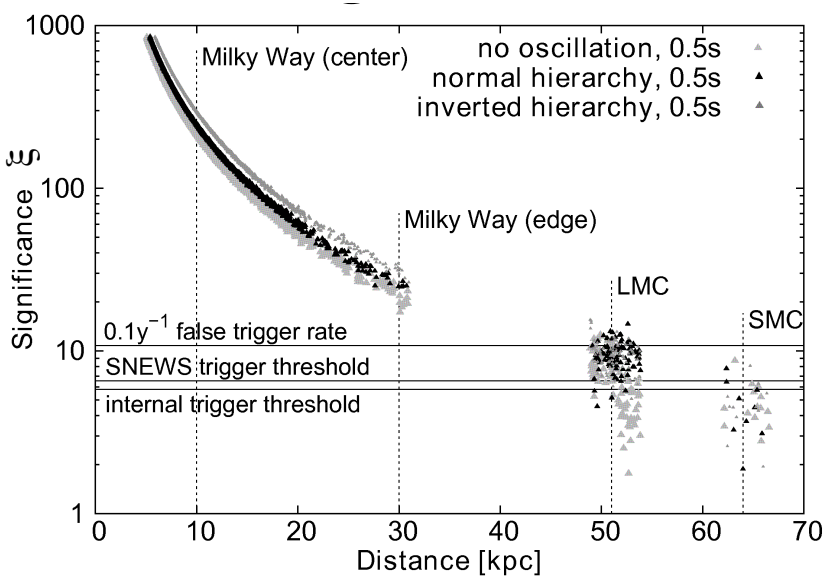
Detection of MeV-scale positrons in IceCube



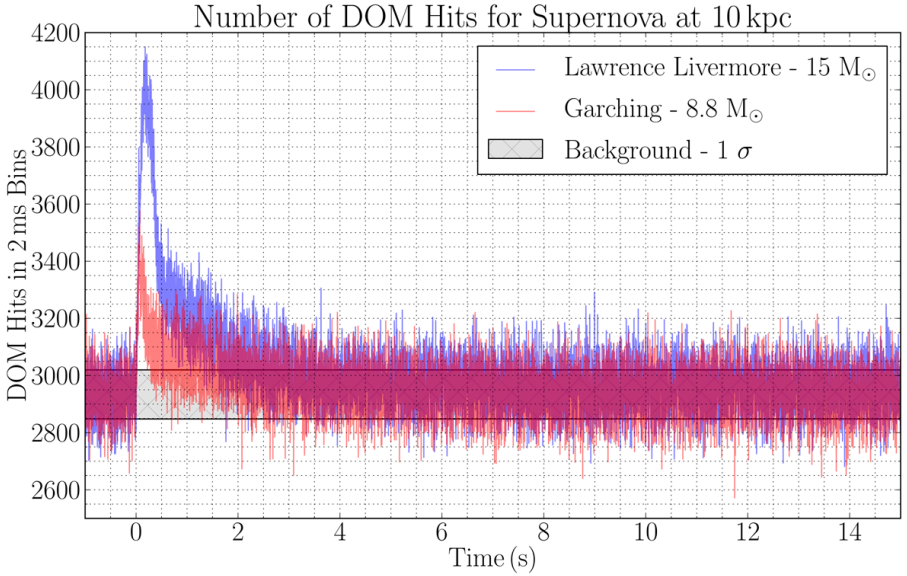
Principal detection channel inverse β decay antineutrinos → O(20) MeV e^+. Each interaction too weak to detect individually but SN burst yields 500k – 1M events in IceCube over 10s (4 Mton eff volume). Due to low background rate of IceCube PMTs this gives high significance detection. With artifical deadtime of 200 μs (PMT noise dominated by correlated late-light not ion afterpulsing) – background is 250 Hz / channel.

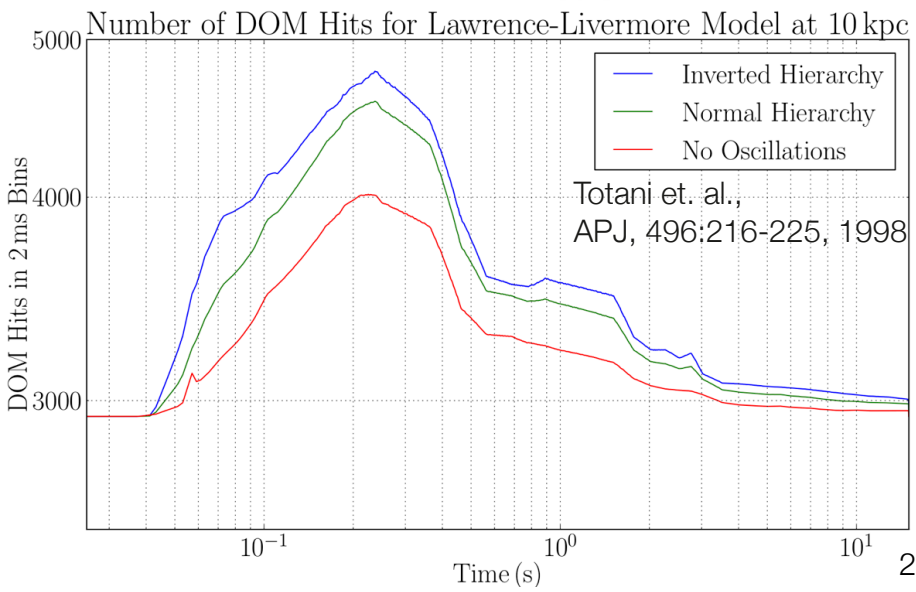
Each DOM has 1.6 ms integrating firmware counter and transmits this data separately to SN online trigger.

- Good time resolution but
  - No pointing
  - No energy resolution yet but feasibility studies with DeepCore DOMs indicate marginal possibility to obtain average neutrino energy.
- IceCube participating in the SNEWS global SN network since 2008.

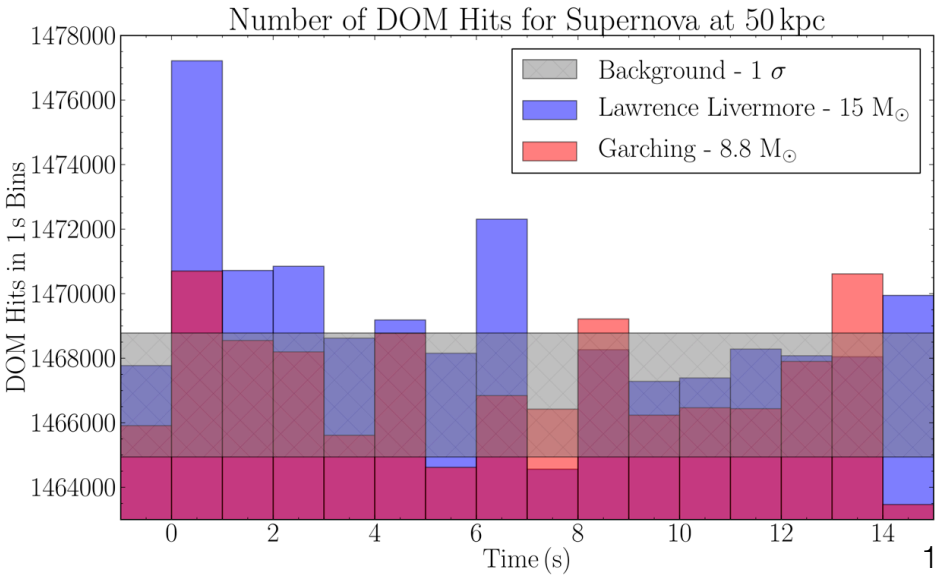


Expected Signal from GC / LMC

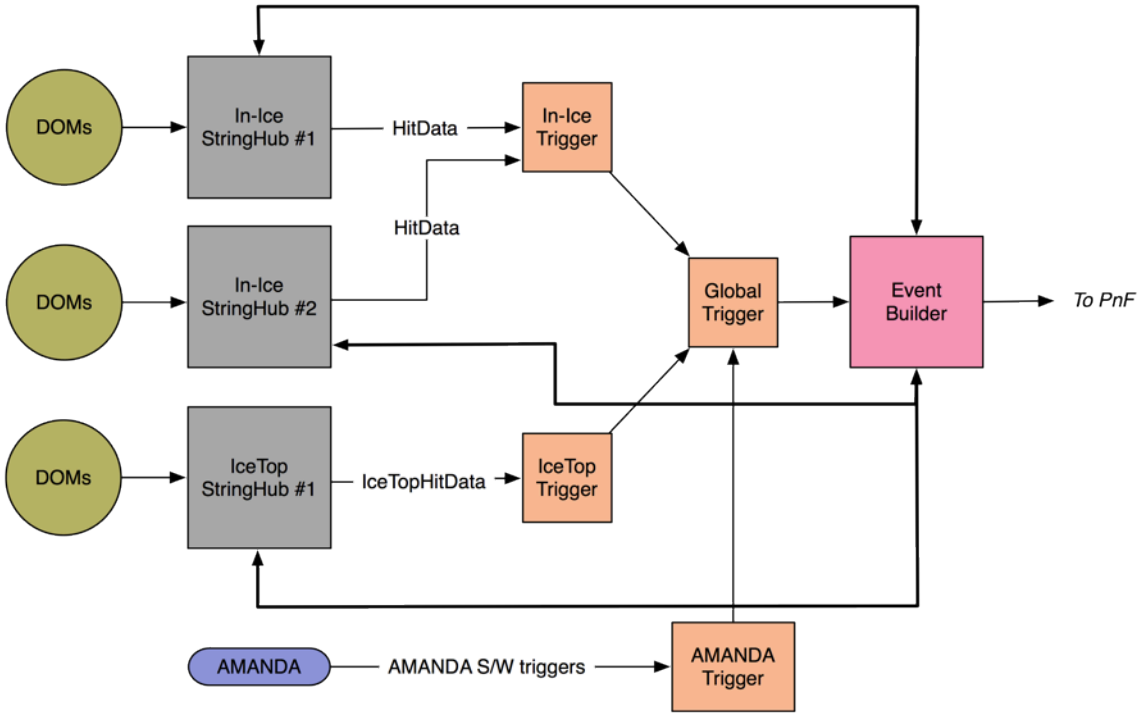


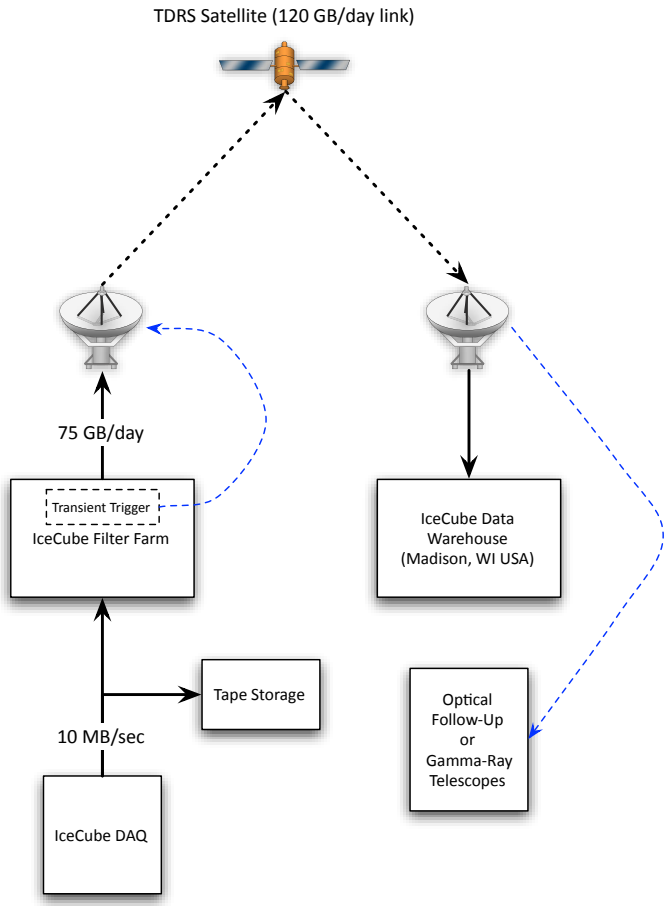


- For GC in galaxy enough statistics to in principle detect difference between NH and IH (MSW in PNS flavor changes higher-temperature flavors into electron anti-neutrinos).
- However these predictions are quite model dependent.
- Statistics marginal in LMC/satellite galaxies but completely sufficient for detection.



Triggering and Data Processing



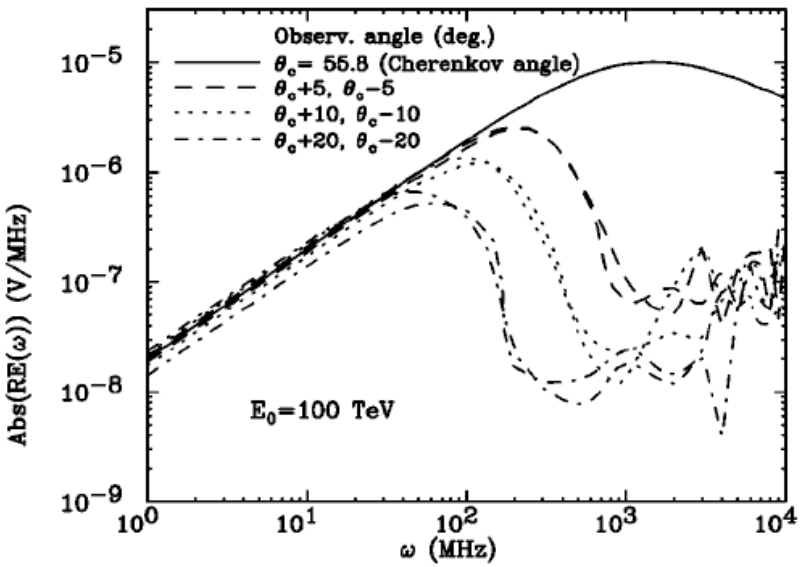


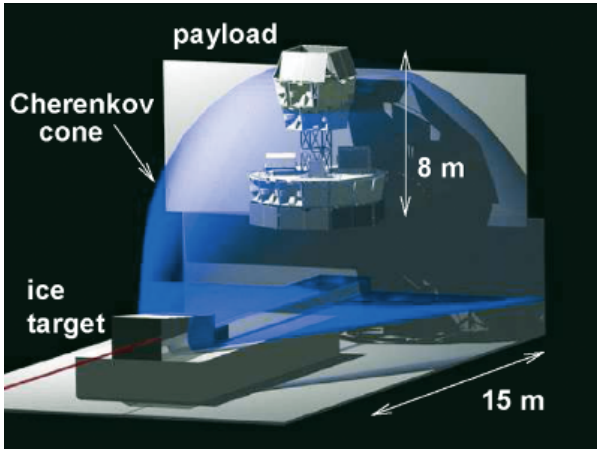
- Photon hits semi-autonomously time-stamped and digitized by DOMs (there is a local coincidence signal shared by near DOMs which determines how much information digitized).
- Readout via 3.5 km copper cable @ 1 Mbit → **250 MB/sec**
- Low-latency triggering (< 3s) and event assembly writes **3.5 kHz events/s (10 MB/s)**. Basic trigger condition is 8 hits in 5 μs but multiple triggers now running.
- Online cluster at Pole reconstructs and filters **100 GB/day** and sends over TDRS link.
- Fast triggers can be sent to optical follow-up instruments.

Principle of Detection

First proposed by G. Askaryan in 1960's the Askaryan effect occurs in energetic cascades due to slight excess of negative charge over positive charge; this leads to a coherent EM pulse, parameterized by ZHS (PRD 45 (1992) 362), AVZ (PRD 61 (1999), and others. General features of radiation include:

- Approx. linear scaling of impulse with cascade energy – $1/R^2$ in power ➔ 1/R E-field
- Peak power at GHz when detector near Cherenkov angle (55° in ice)
- At 10° off cone peak power at 200 MHz





- The Askaryan effect and the parameterizations have been experimentally verified at SLAC T460 test beam (Gorham et al PRL 99 (2007) 171101)
- **Why South Pole ice?** The colder the better - top cold part of glacier at -40° C to -50° C with RF attenuation lengths of over 1 km for f = 100's of MHz and 100's of m for f ~ 1 GHz
- Antennas should be buried in bulk ice below firn layer in order to avoid ray bending in index of refraction gradient in firn.