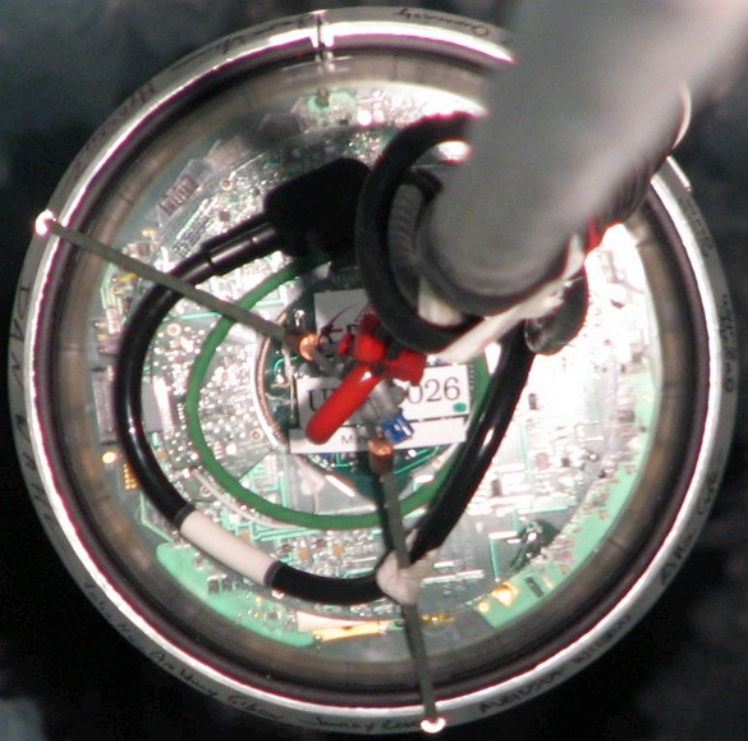
Particle Astrophysics at 90°S

Reports from the IceCube Neutrino Observatory



Kael Hanson for the IceCube Group

IAP Day 2012

Dec 20, 2012

IceCube
Neutrino Observatory

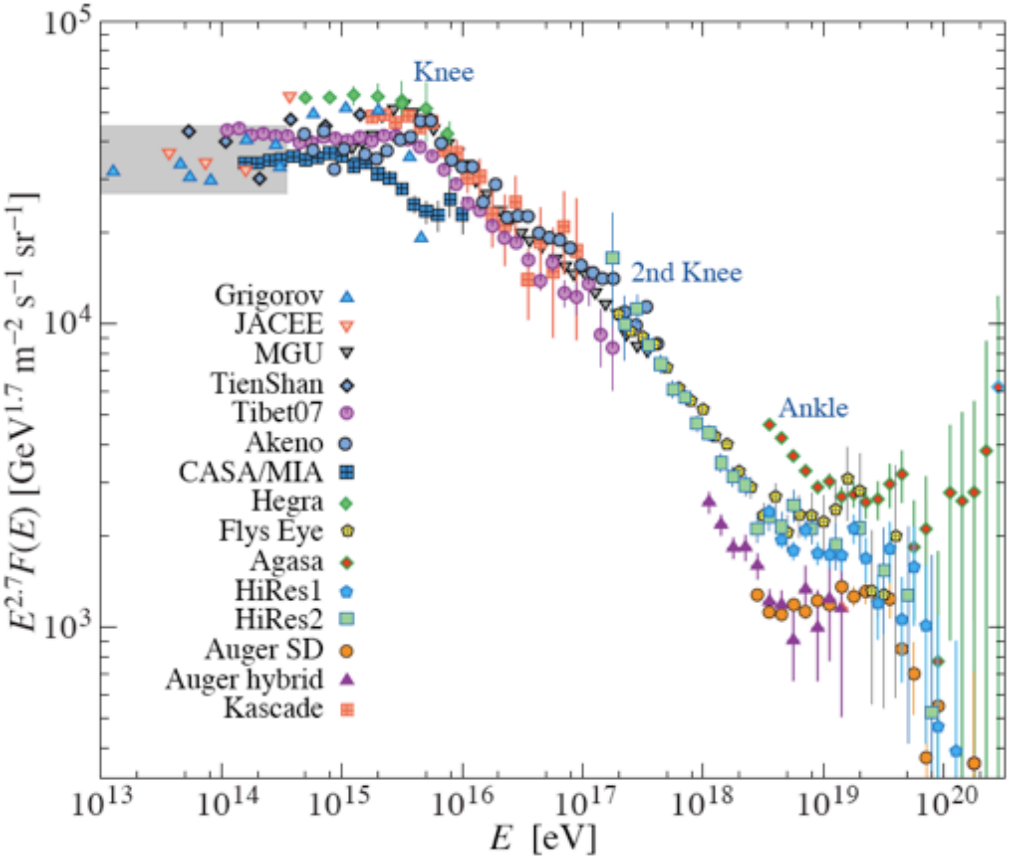
iihe
BRUXELLES BRUSSEL



Hunting Cosmic Neutrinos

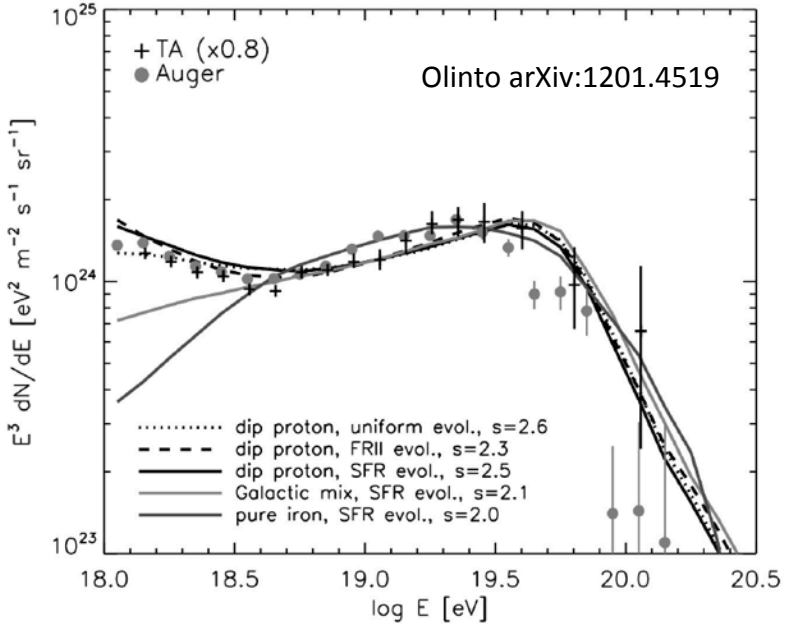
THE ICECUBE MISSION

Cosmic Rays



GZK Neutrinos

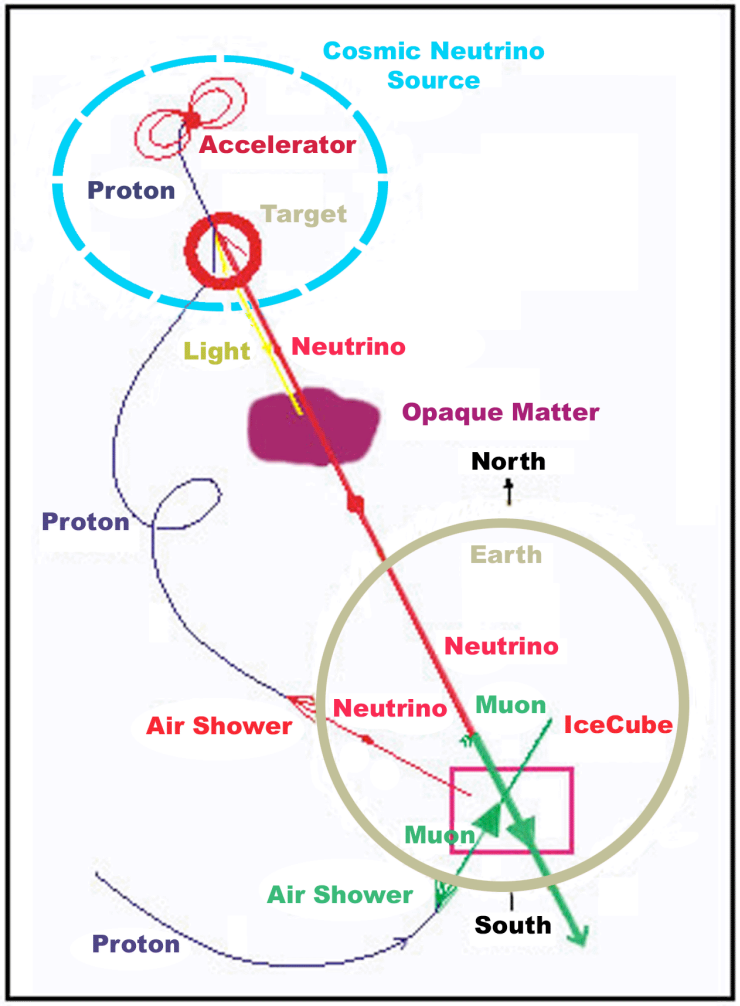
$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$
$$\rightarrow n + \pi^{+}$$



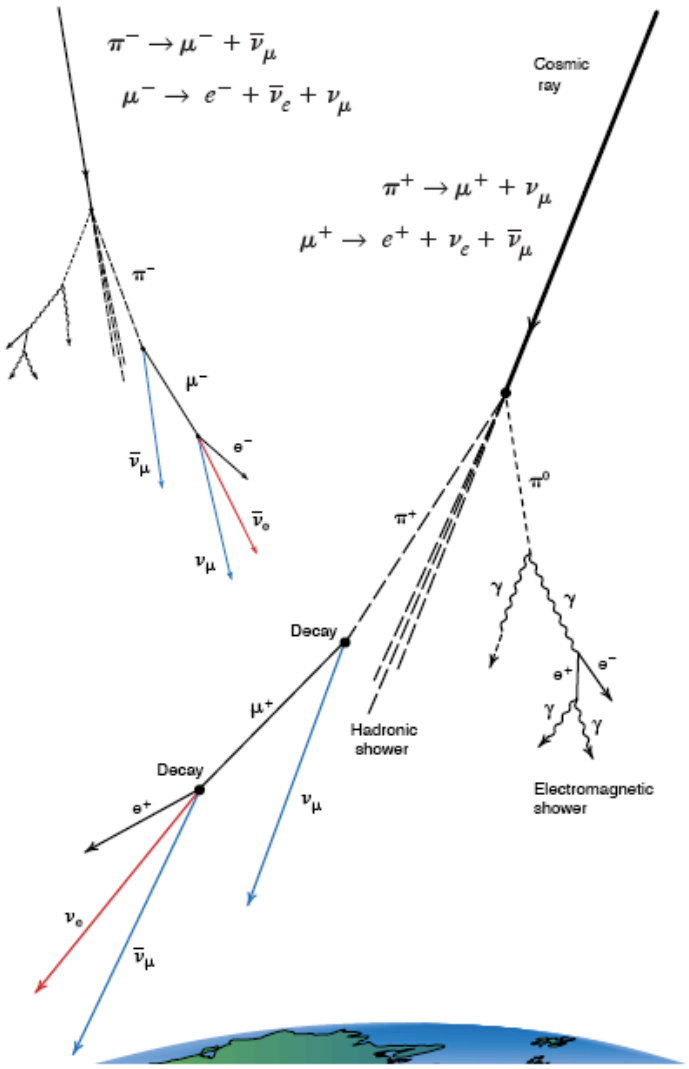
Neutrinos

Neutrinos, neutral and only weakly-interacting make perfect messengers to carry information from deep within the core of sources in a straight line to Earth based detectors. Neutrinos even pass through the Earth (up to 100 TeV). Earth often used as a screen and detectors intentionally look below horizon to discriminate neutrino-induced events from other more prevalent CR. Atmospheric neutrinos produced in the decay of charged mesons from CR-nucleus interactions in the Earth's atmosphere and constitute the main background for cosmic searches.

Observation of high-energy neutrino fluxes from an object would conclusively prove the existence of a hadronic acceleration process as neutrinos can only be produced via this mechanism. Gammas on the other hand can come from purely EM processes not linked to CR acceleration.



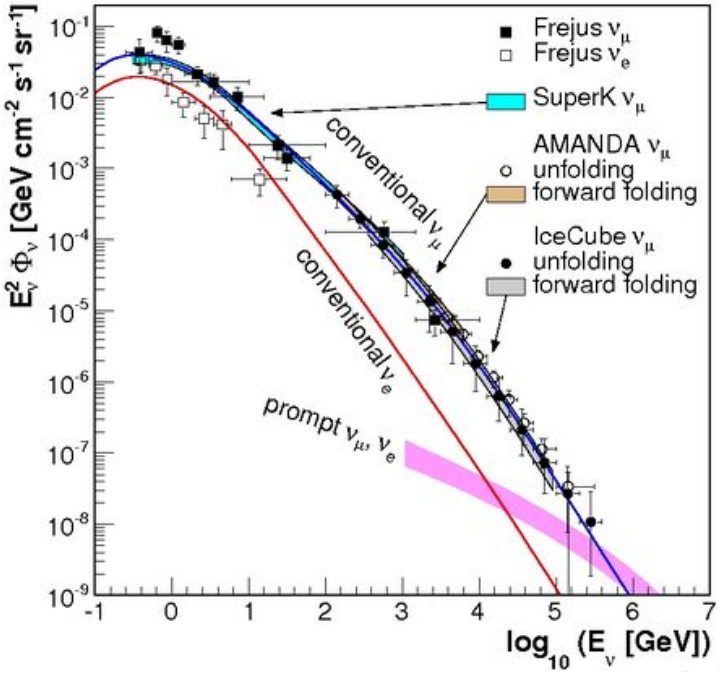
Atmospheric Neutrinos

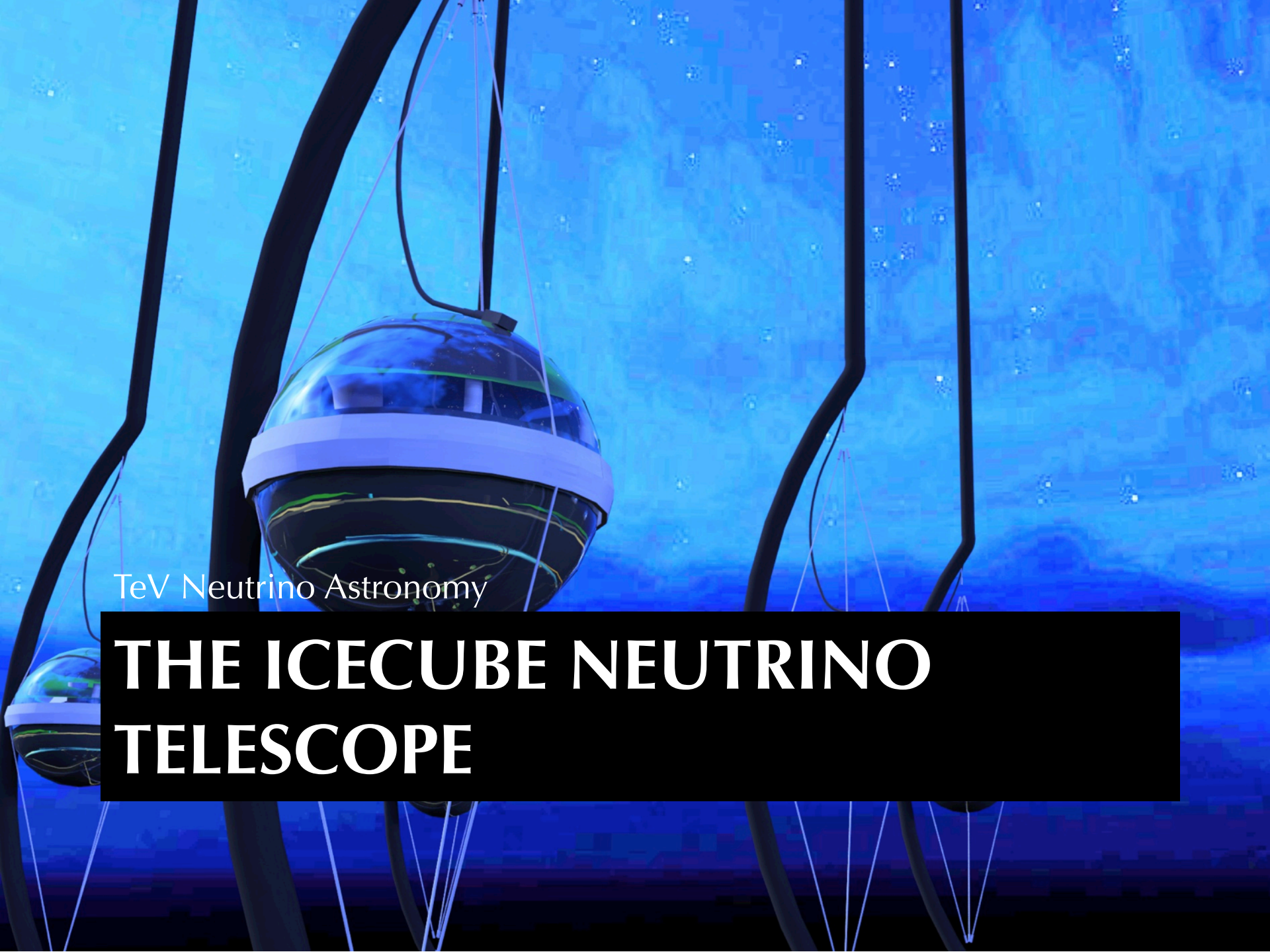


Neutrinos from meson decay in terrestrial atmosphere. Spectrum initially follows CR primary flux (-2.7) but quickly steepens due to muon energy loss. Electron neutrinos principally come from muon decay so much lower fluxes esp. at HE.

Important still unknown VHE component is prompt neutrinos from decay of heavier charmed mesons.

The atmospheric neutrino flux is background for cosmic neutrino searches but is itself interesting for study of neutrino properties.

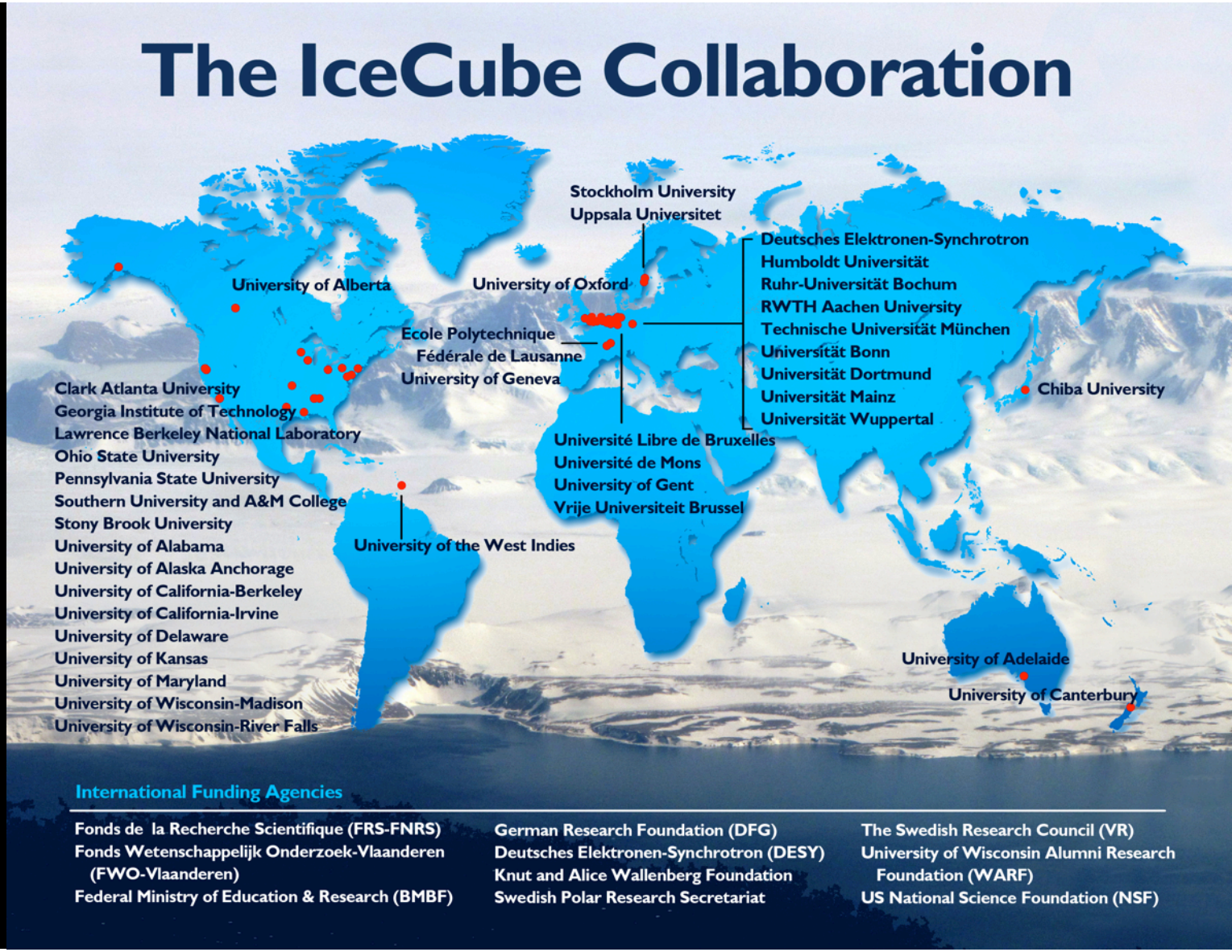




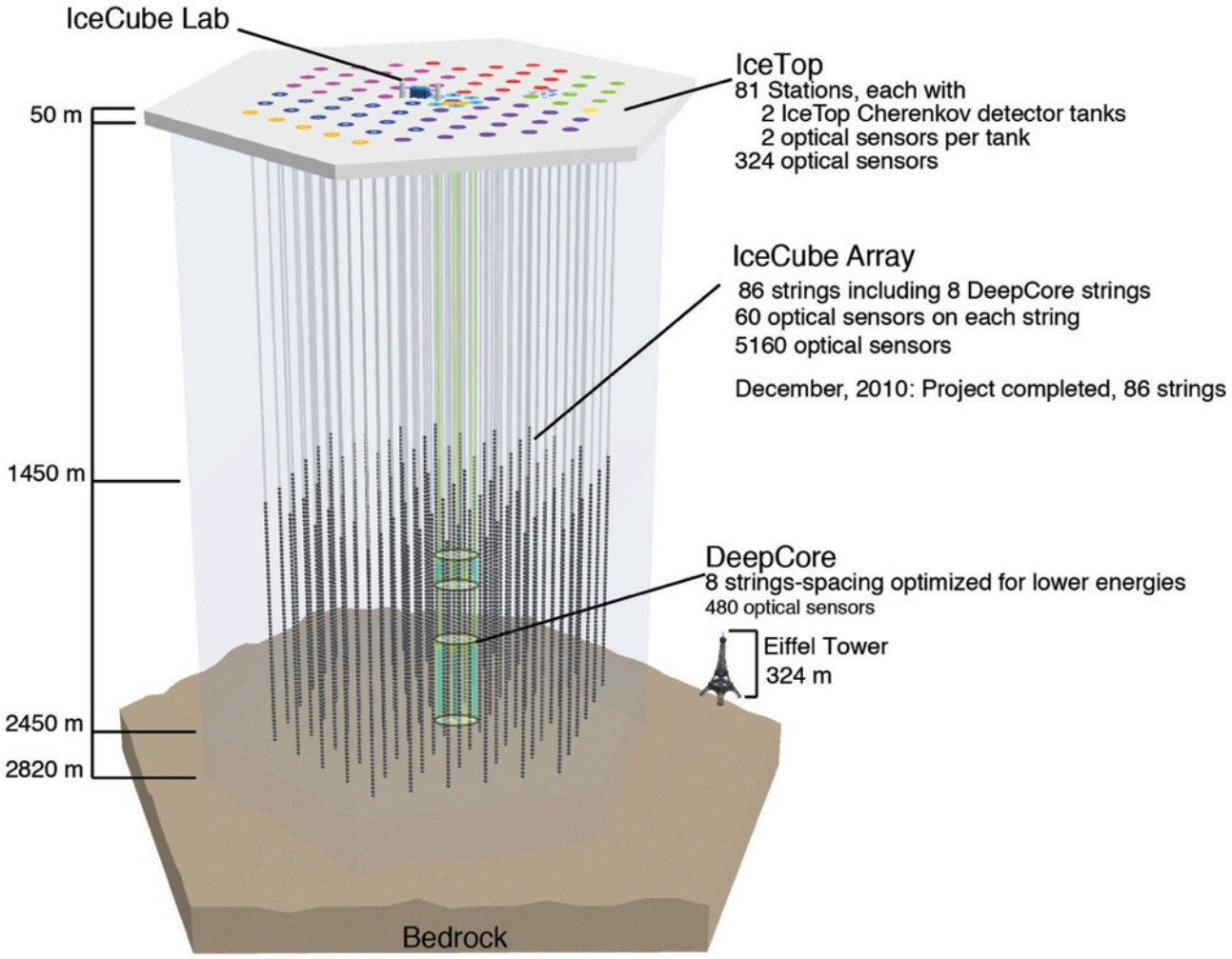
TeV Neutrino Astronomy

THE ICECUBE NEUTRINO TELESCOPE

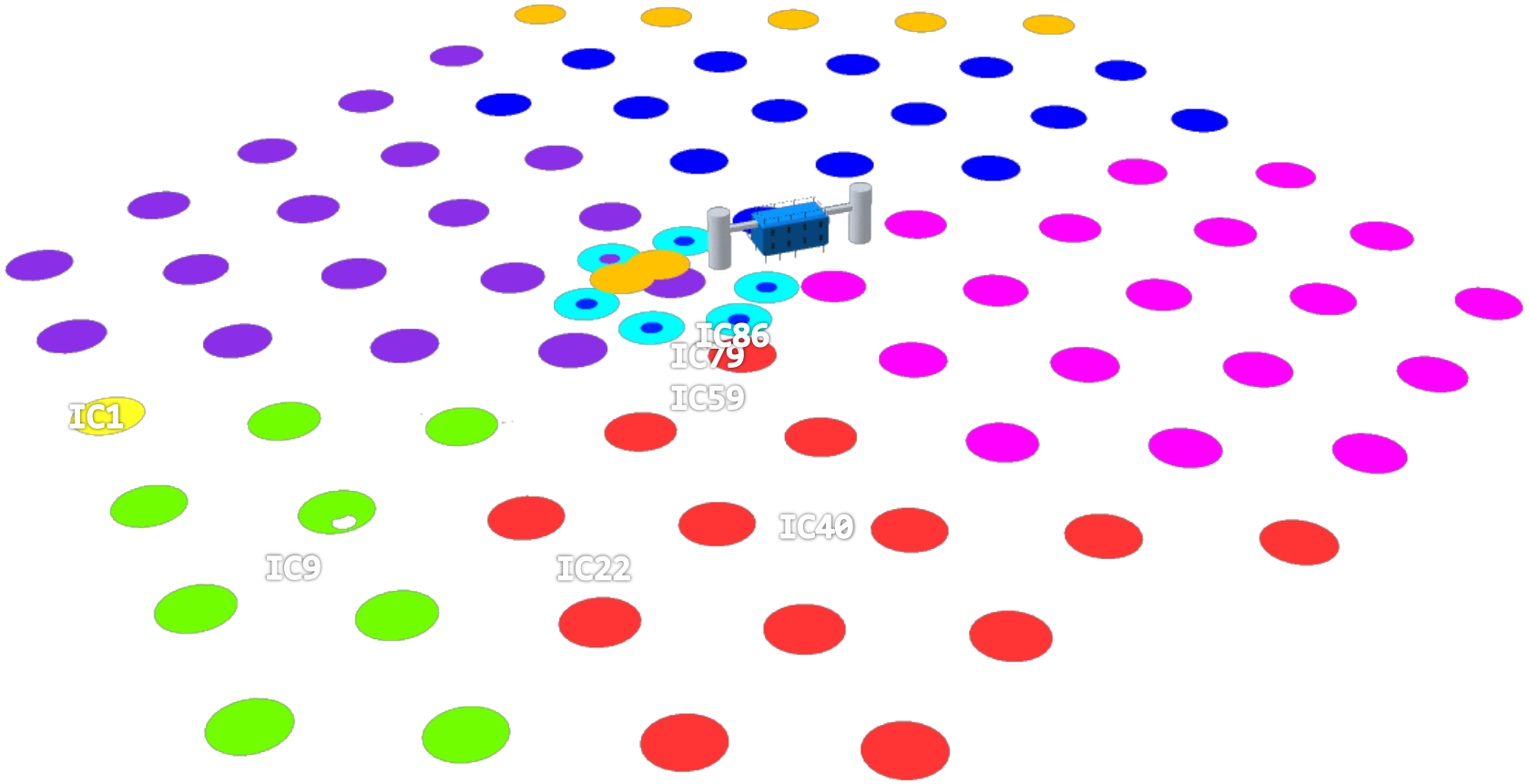
Collaborating Institutions and Financial Support



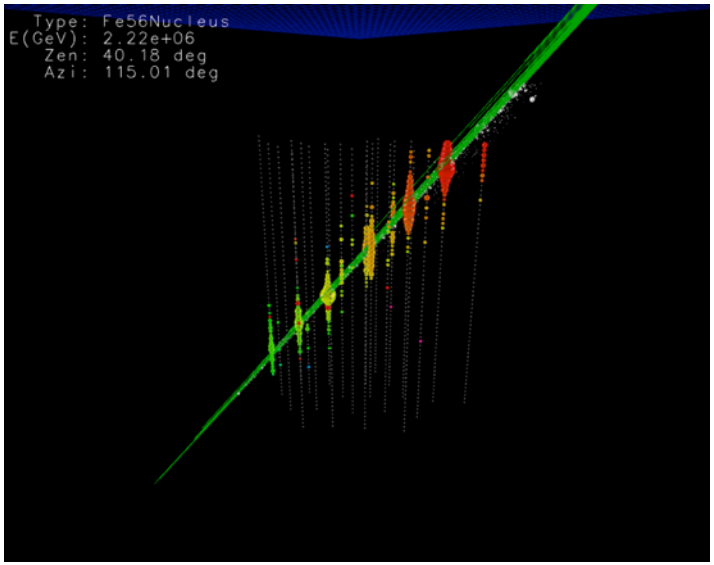
The IceCube Detector



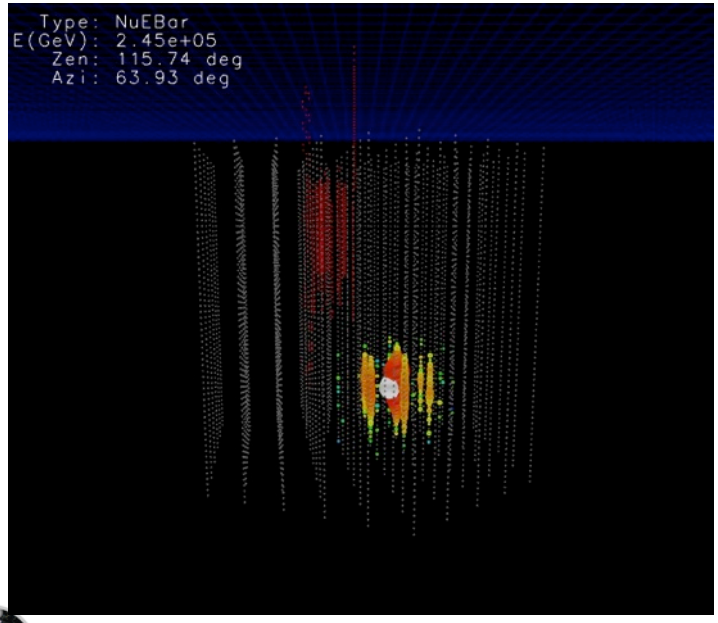
IceCube Configuration Jargon Decoder Slide

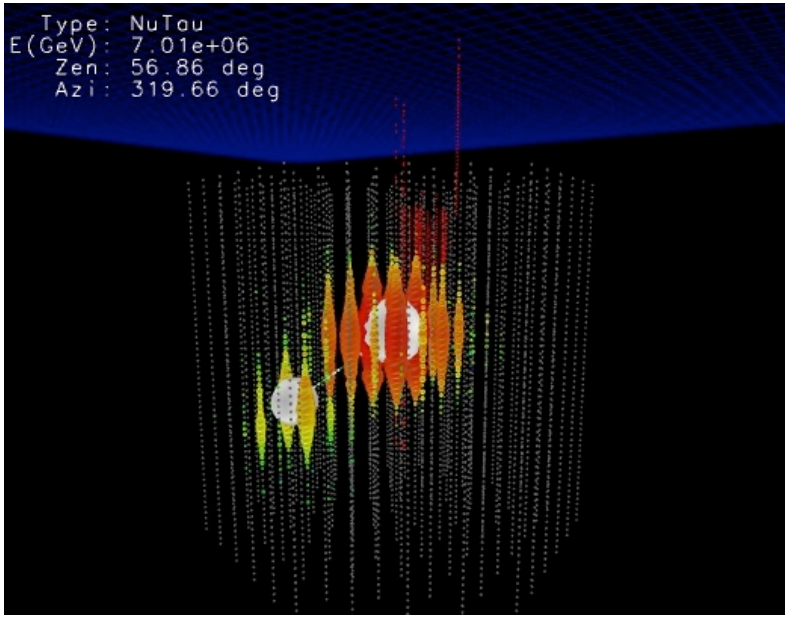


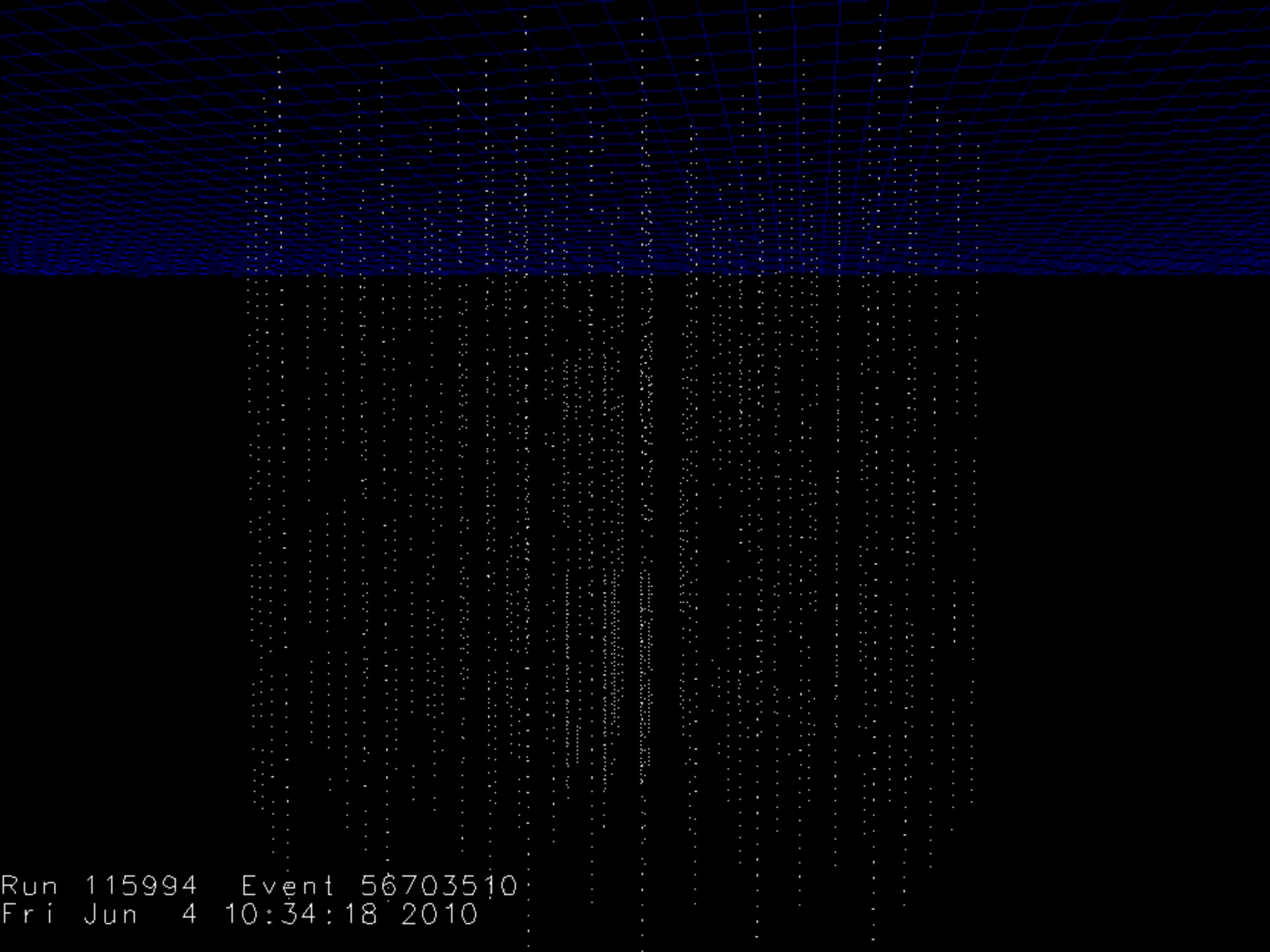
Detection of Neutrinos in the Ice



- About 25000 detectable Cherenkov photons per GeV of energy deposited within the detector – linear with E_{cas}
- Muons leave track-like deposit.
- EM / Hadronic showers more or less ball-like but anisotropic so it is possible to achieve some angular resolution even on cascades.

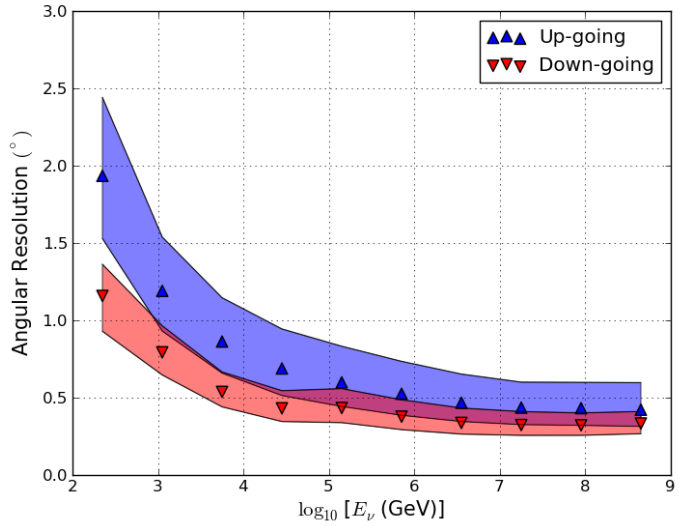




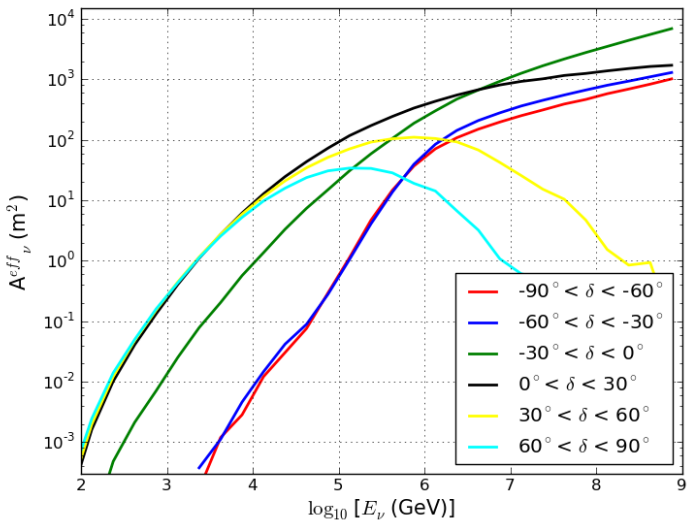

Run 115994 Event 56703510
Fri Jun 4 10:34:18 2010

IceCube Reconstruction Performance

Point sources angular resolution

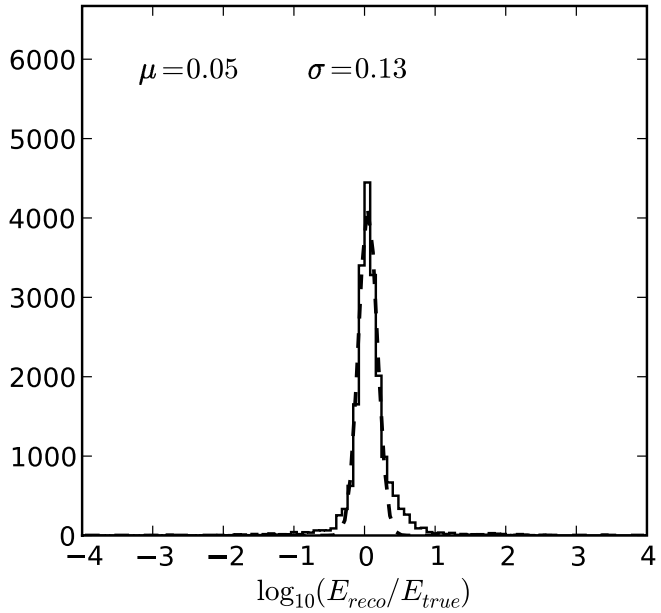


Point sources neutrino effective area



- 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. Extremely hard to get good neutrino energy for through-going muons.
- Cascade angular reconstruction poor but has improved quite a bit – now O(10°).

HE cascade E resolution

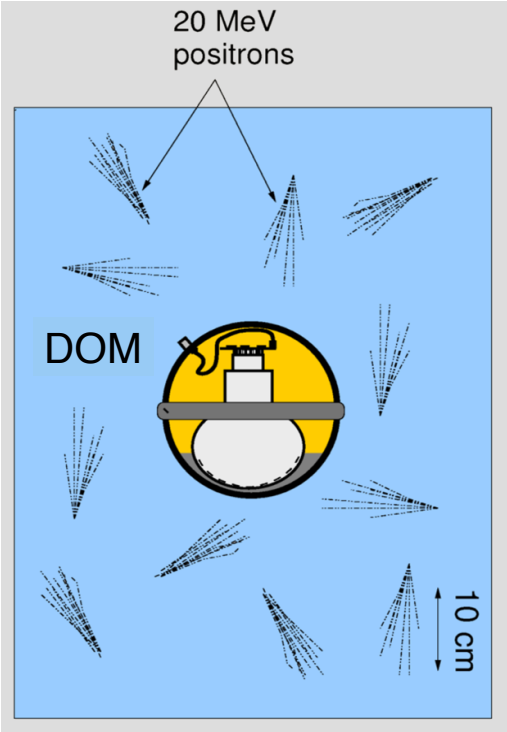




Neutrino astronomy at 1 MeV

SUPERNOVA NEUTRINO DETECTION IN LARGE CHERENKOV TELESCOPES

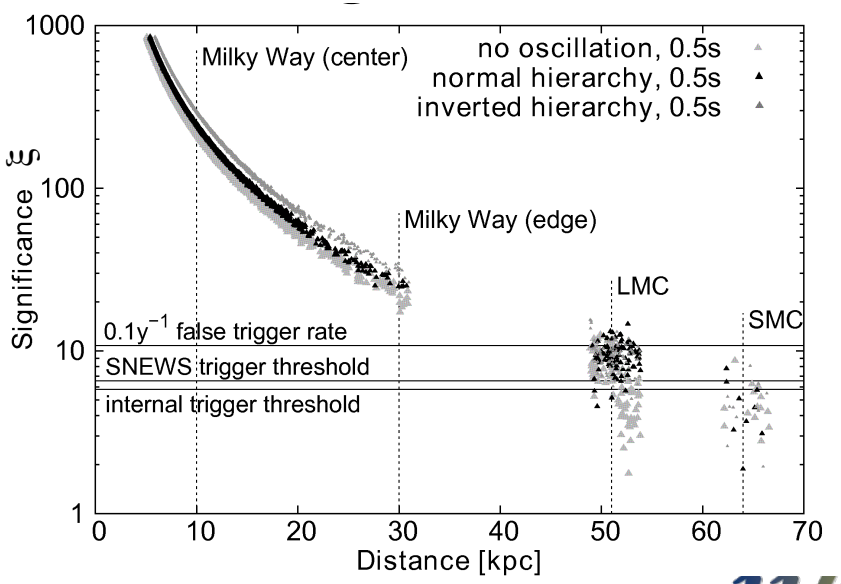
Detection of MeV-scale positrons in IceCube



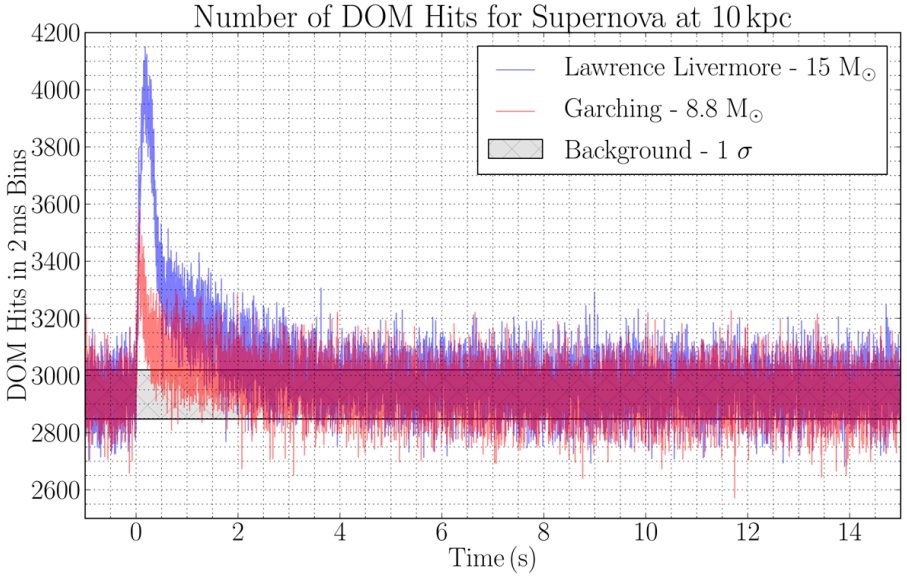
Principal detection channel inverse β decay antineutrinos → O(20) MeV e^+. Each interaction too weak to detect individually but SN burst yields 500k – 1M events in IceCube over 10s (4 Mton eff volume). Due to low background rate of IceCube PMTs this gives high significance detection. With artifical deadtime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

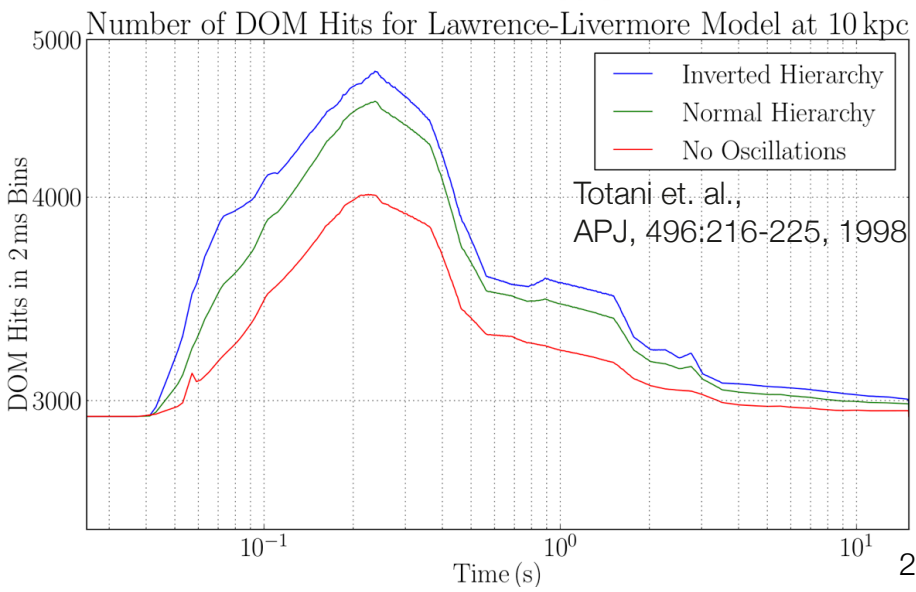
Each DOM has 1.6 ms integrating firmware counter and transmits this data separately to SN online trigger.

- 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.

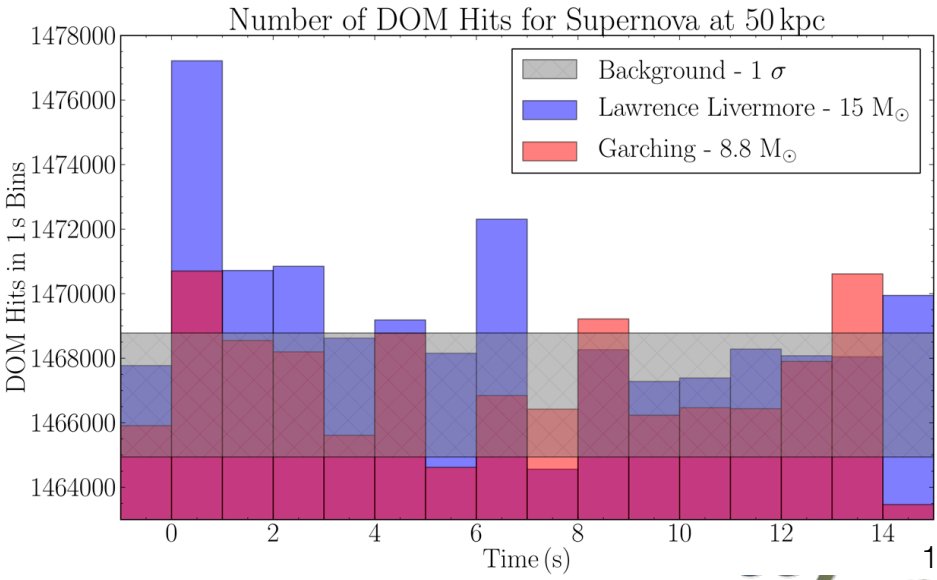


Expected Signal from GC / LMC





- 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.



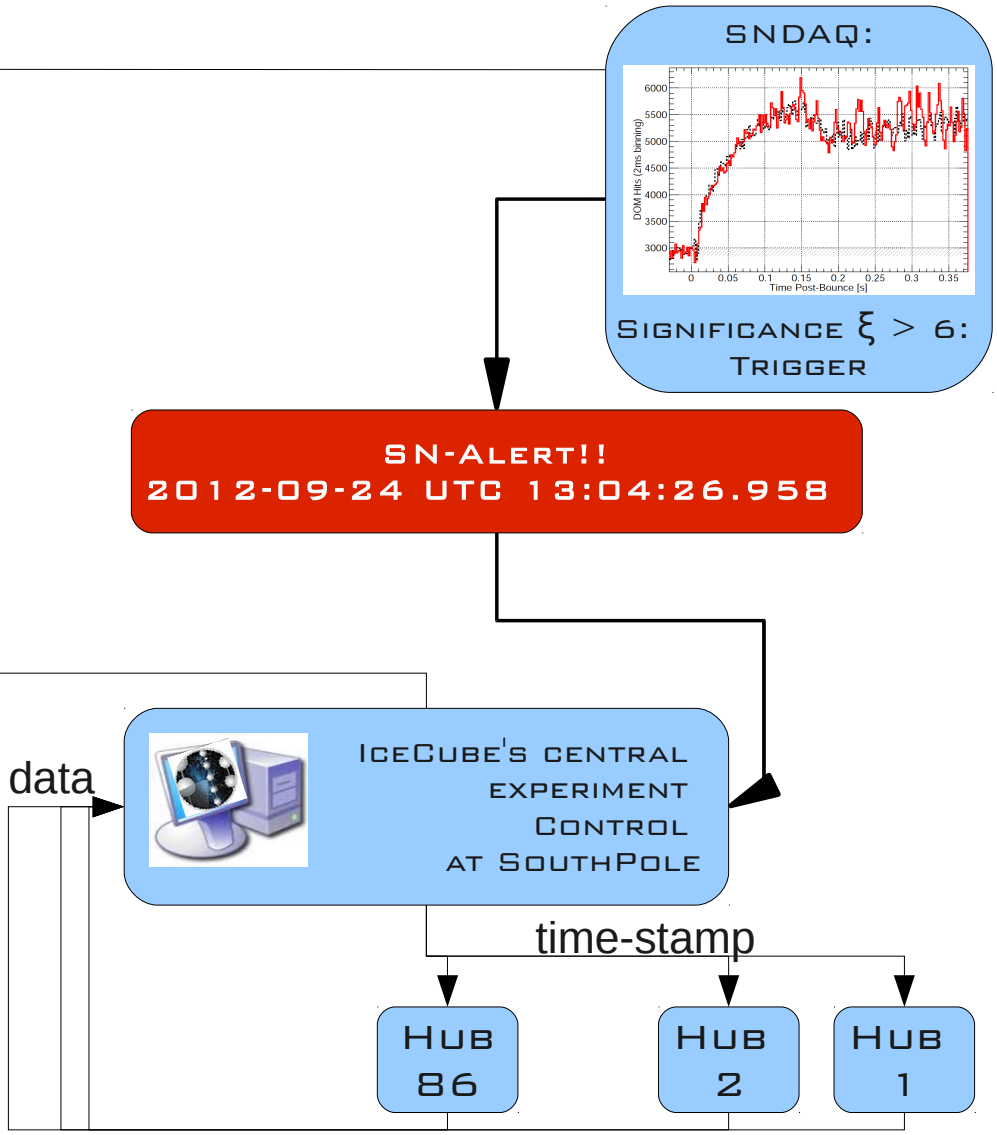
HitSpooling – Improvements to Supernova System

- Requirements:
  - Automated process for message forwarding when supernova alert triggered
  - Calculate from time-stamp which data chunks are needed. Do that simultaneously on 86 machines
  - Send it north

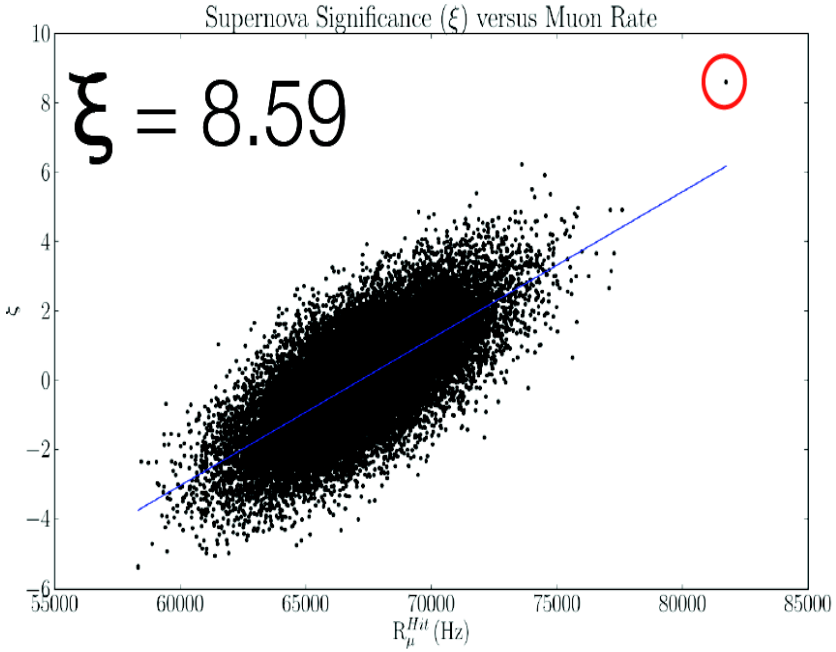


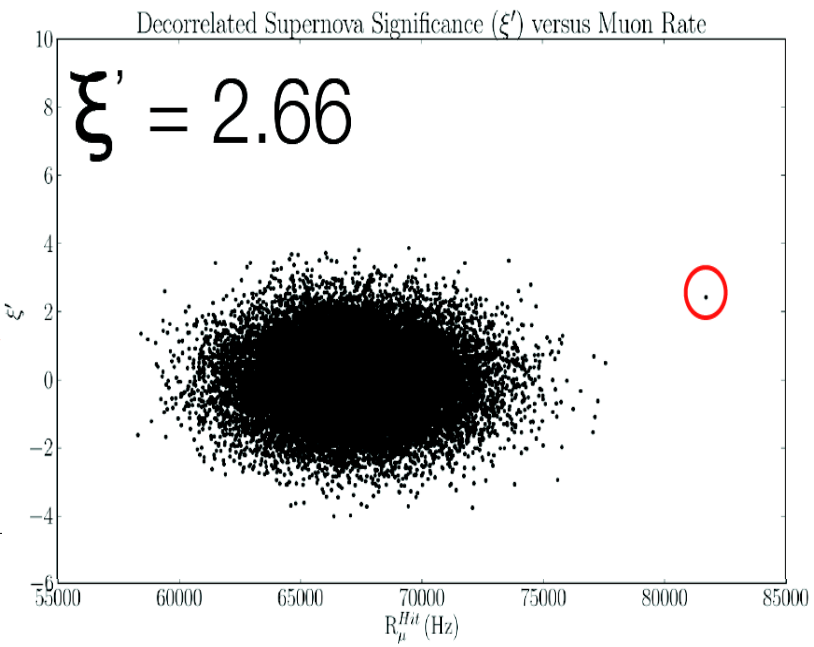
Data ware house
UW Madison





Removal of CR Muons from SN Trigger





- SN counting is not counting just Poisson noise of PMTs but CR muon activity too (note PMT noise **not** just Poisson but I digress…)
- This has the effect of broadening the distribution of the SN test statistic → we must place alarm threshold about 40% higher due to this effect.
- Currently can subtract some CR offline using muon DST
- With HitSpooling will be able to subtract, online, sub-threshold CR muons too.

Implementation

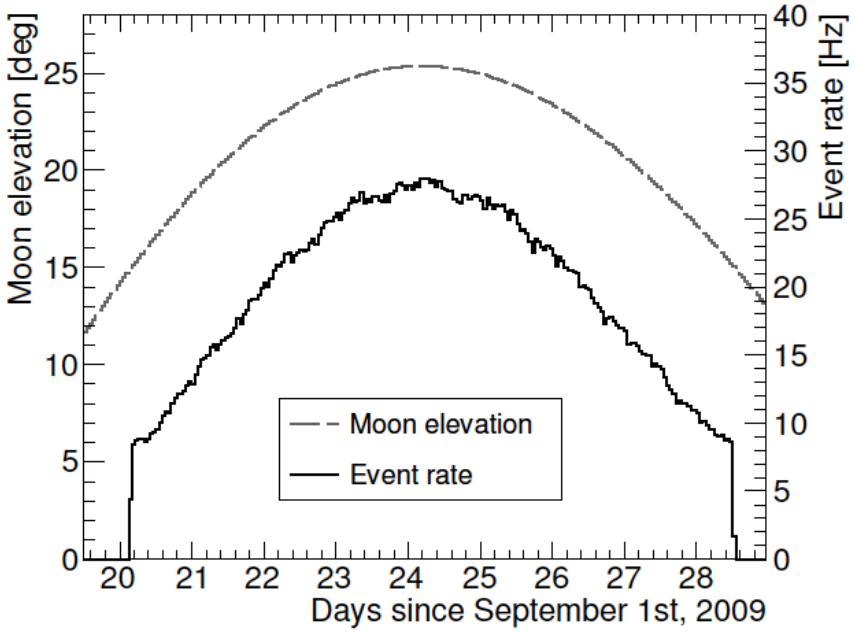
- **Data production**: readout computers write 200 MB/sec data to disk spool files
- **Data handling**: distributed framework to receive trigger messages, extract data from spool files, send to consumer
- **Status**: As of Nov 2012 the DAQ release with full support for HitSpooling tested at Pole. Expecting to turn on by end of 2012.



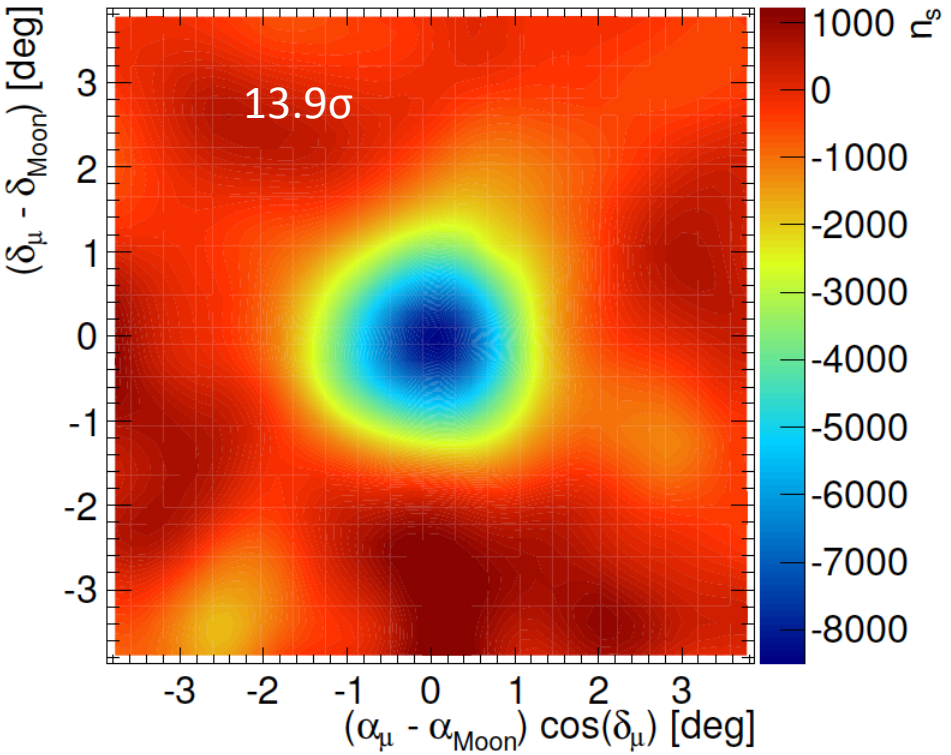
Neutrino astronomy at > 100 GeV

ICECUBE SCIENCE RESULTS

Shadow of the Moon IC40+IC59

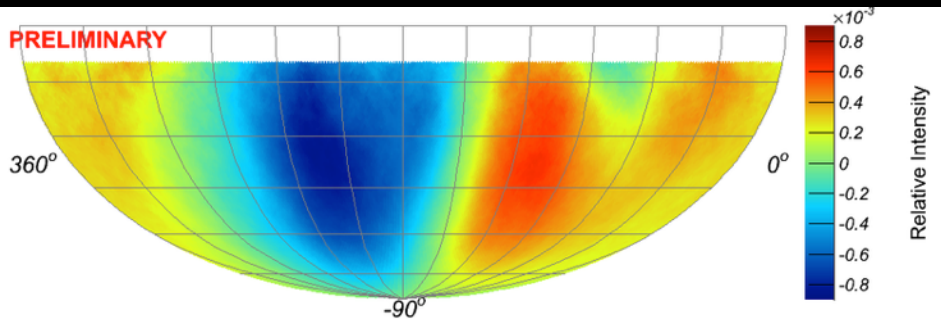


- Filter selects reco'd events with 10° in δ and 40°/cos(δ) in r.a.
- >11 DOMs on >2 strings
- 130 million events for IC40
- 180 million events for IC59
- Median E is about 40 TeV for selection in both IC40 & 59.

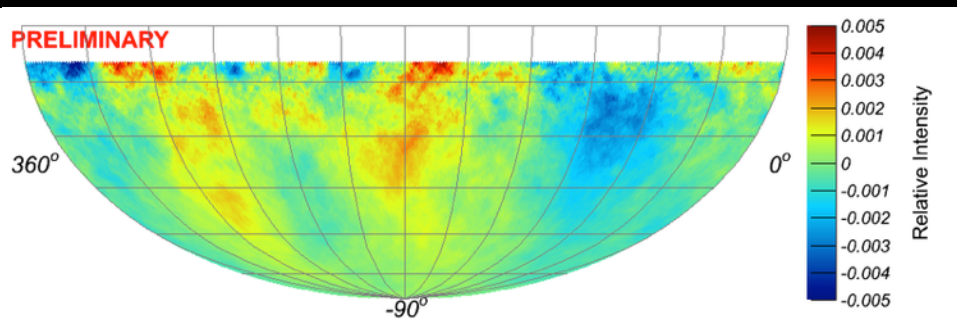


- Verifies timing accurate to minute scale (should be in fact 100 ns from GPS but nice to have X-check)
- Detector resolution
  - 1.13° IC40
  - 0.98° IC59

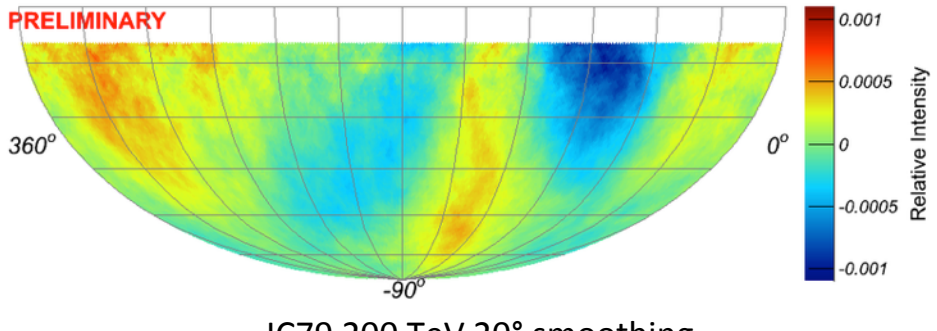
IC79 Cosmic Ray Anisotropy Measurements



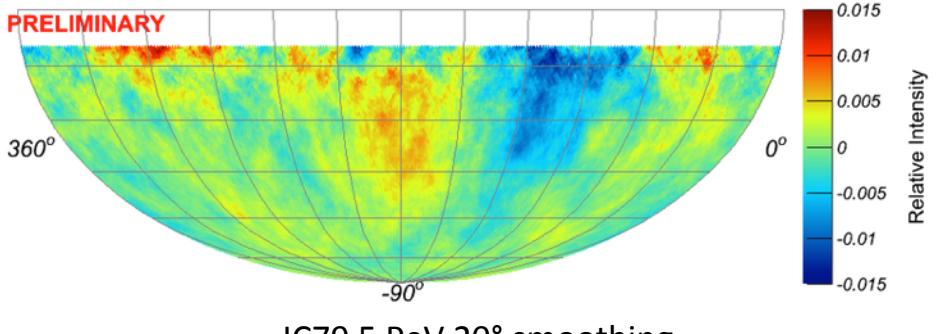
IC79 40 TeV 20° smoothing



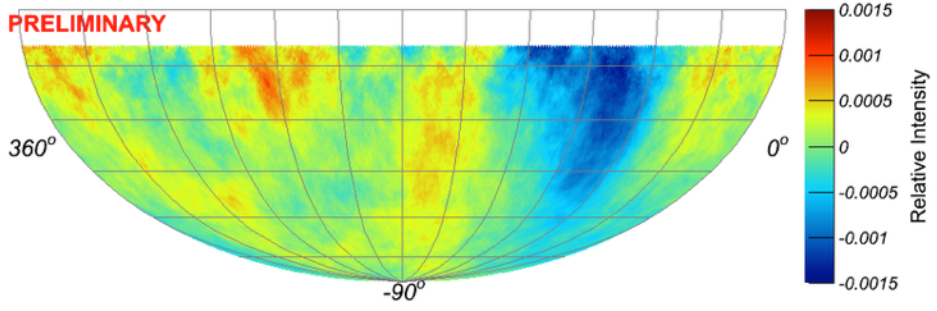
IC79 1 PeV 20° smoothing



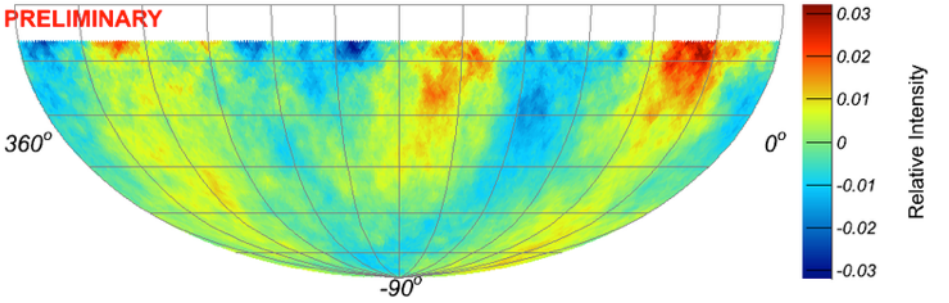
IC79 200 TeV 20° smoothing



IC79 5 PeV 20° smoothing



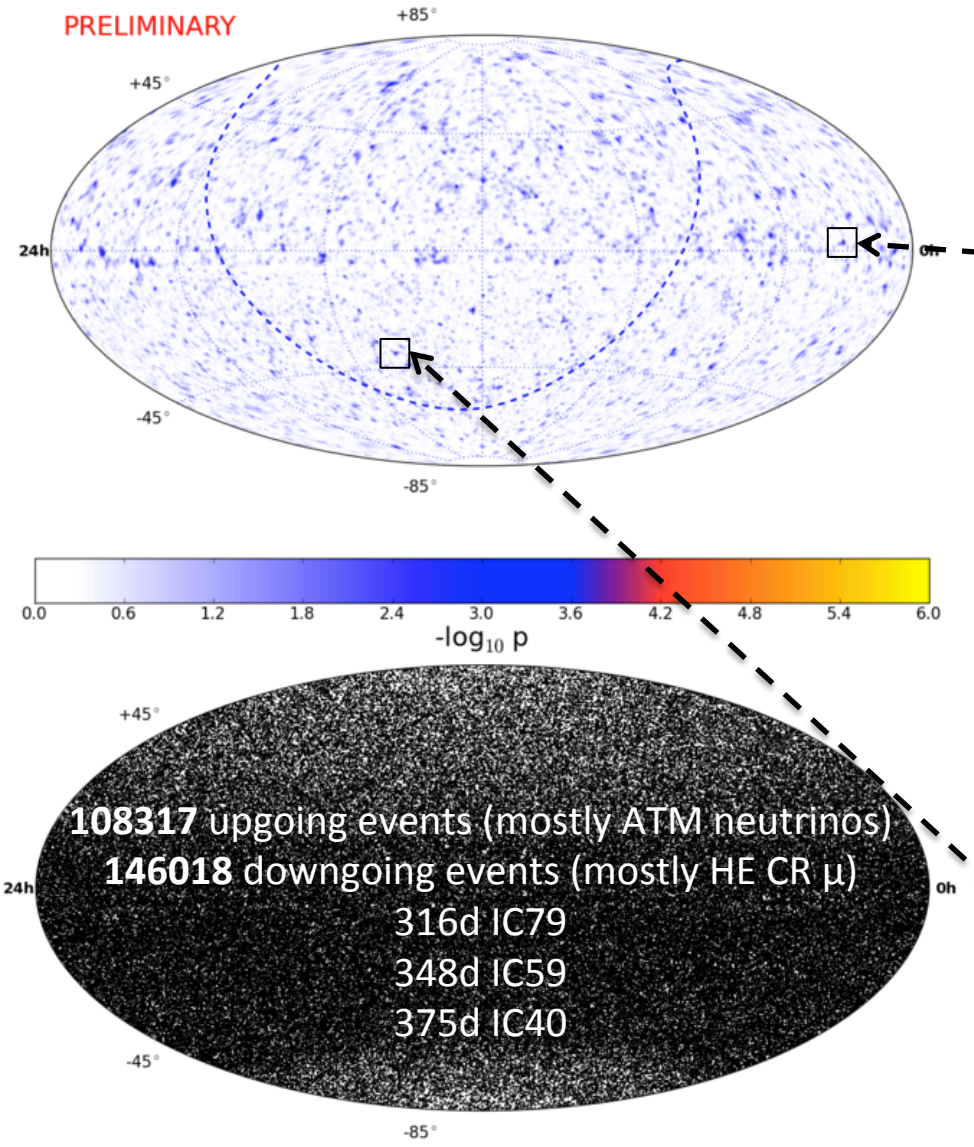
IC79 400TeV 20° smoothing

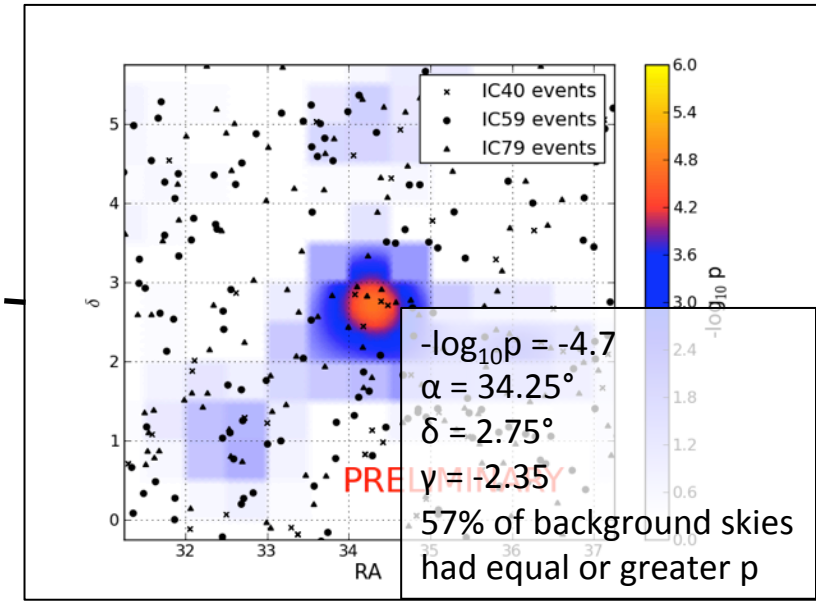


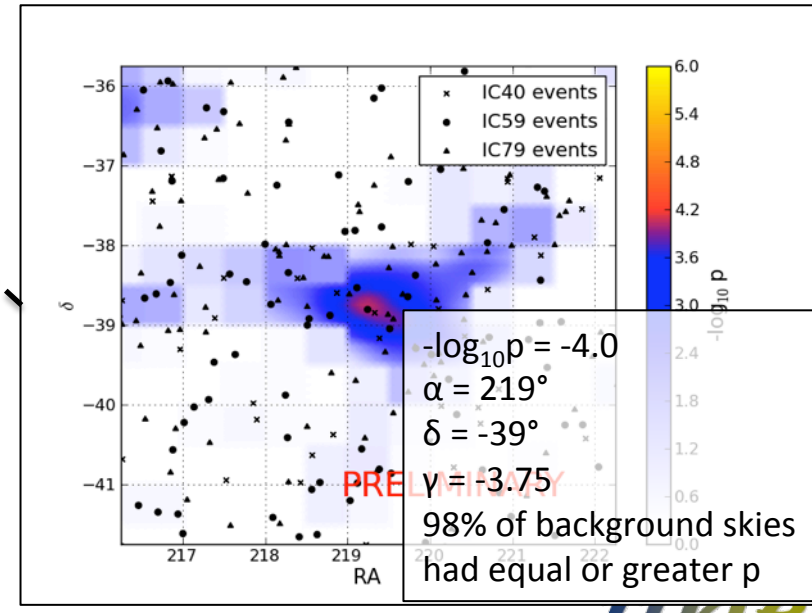
IC79 10 PeV 20° smoothing

See ApJ **746** (2012) 33 or arXiv:1109.1017 for IC59 published results

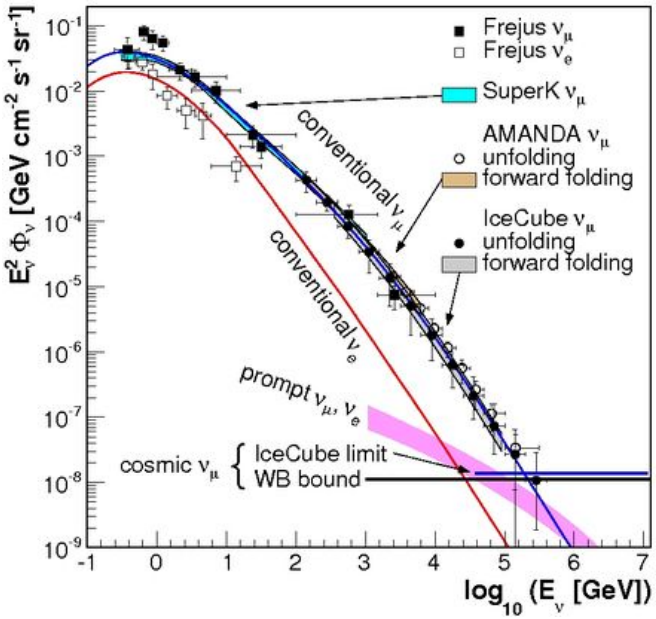
IC79+59+40 Skymap

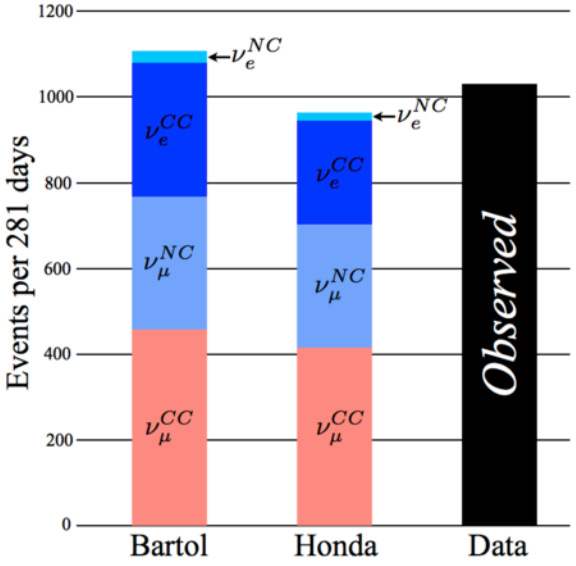




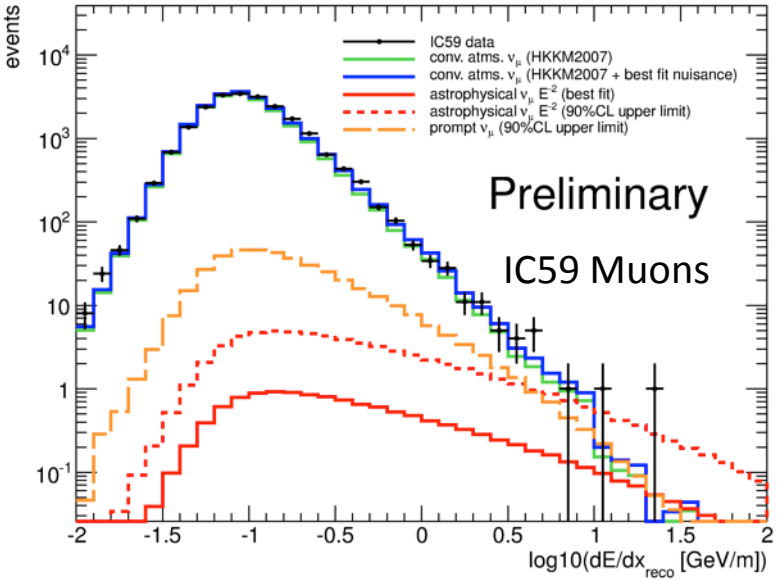


Atmospheric Neutrinos and Cascades in IceCube





IC59 Cascades



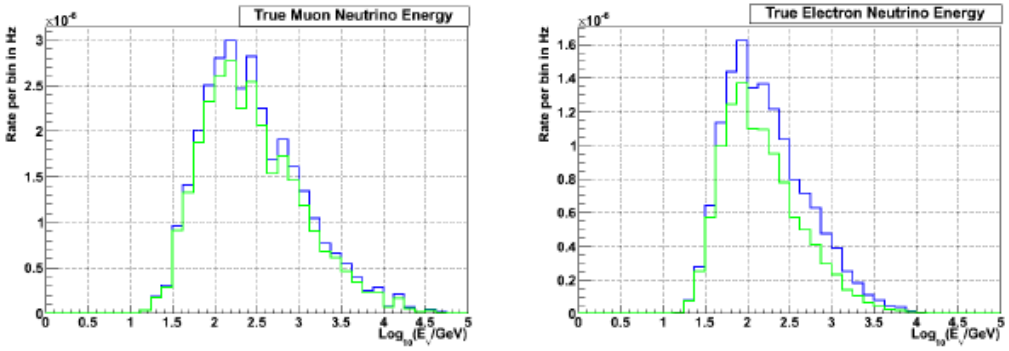
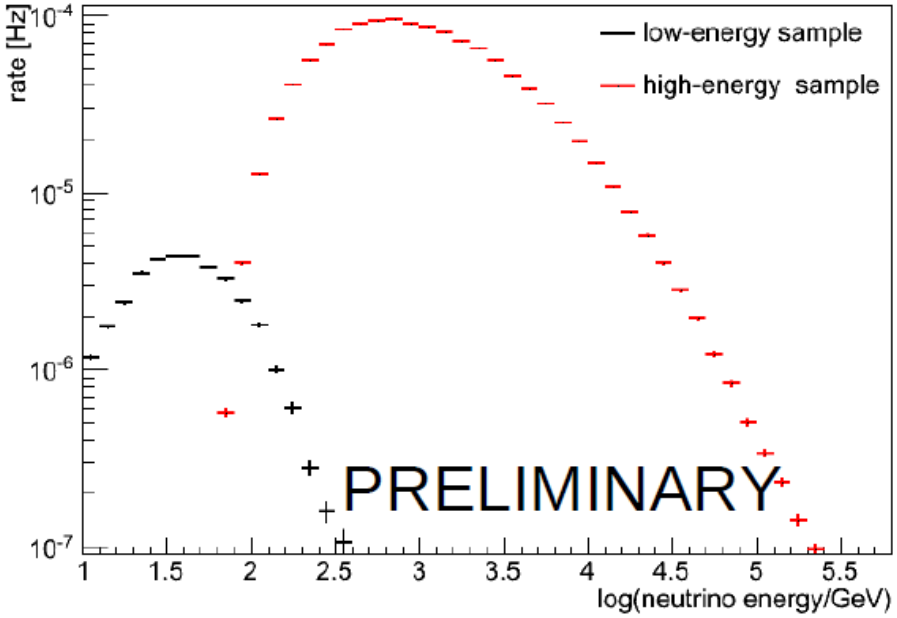
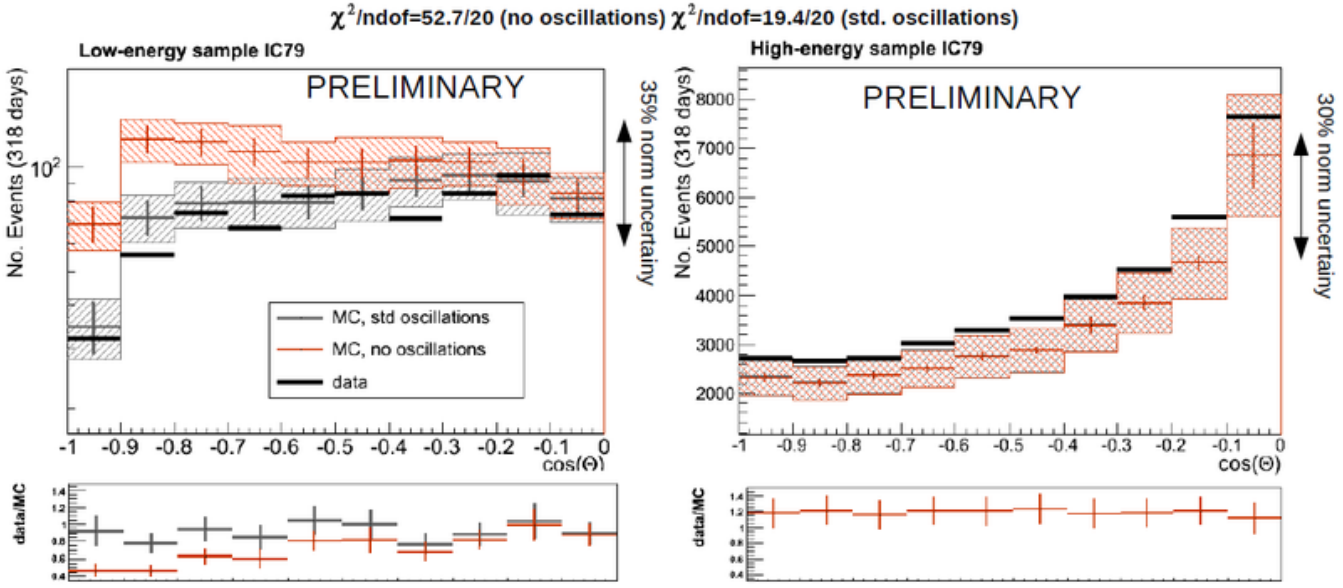


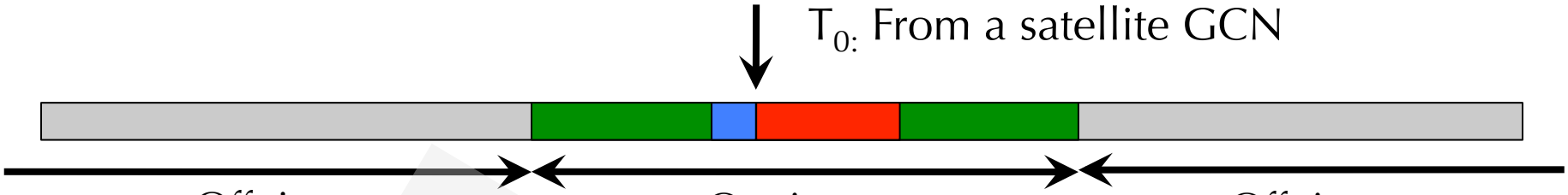
Figure 10.2. Atmospheric neutrino spectrum at final Hard Cut level (MC true energy). Left: true ν_μ energy spectrum is shown. with the Bartol model (blue) and Honda 2006 model (green). Right: true ν_e energy spectrum is shown. Large difference (40% at 1 TeV) is shown at higher energies though relatively small difference is shown at lower energies.

High Energy Oscillations





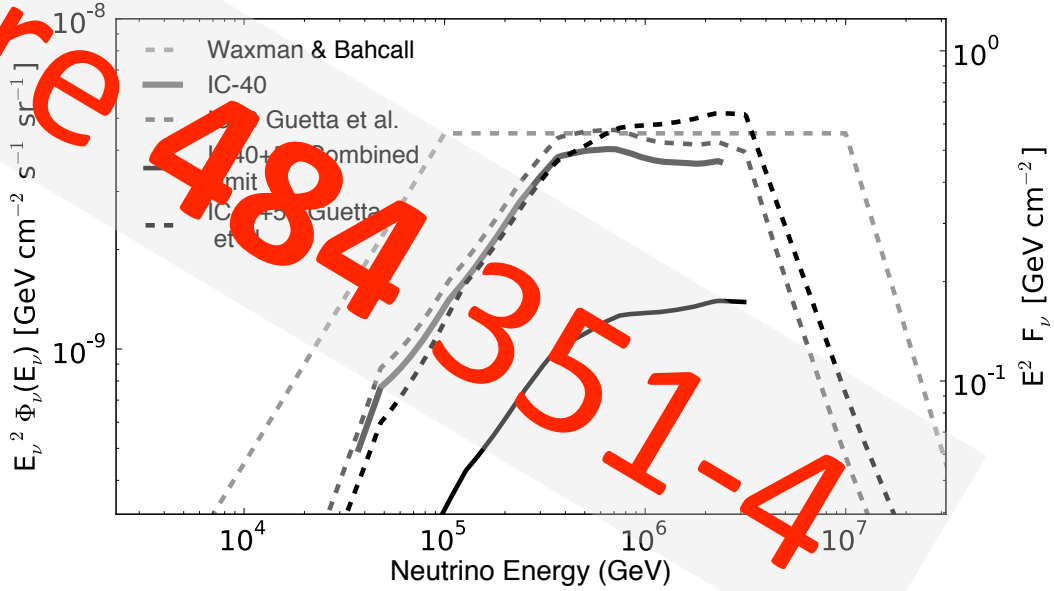
GRB Searches



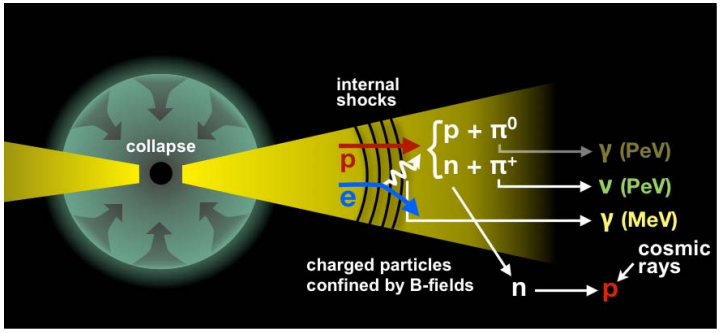
- Precursor (~100 s)
- Prompt (T_{90})
- Model Independent (±24 h)
- Off-time (full year)

Nature 484 351-4

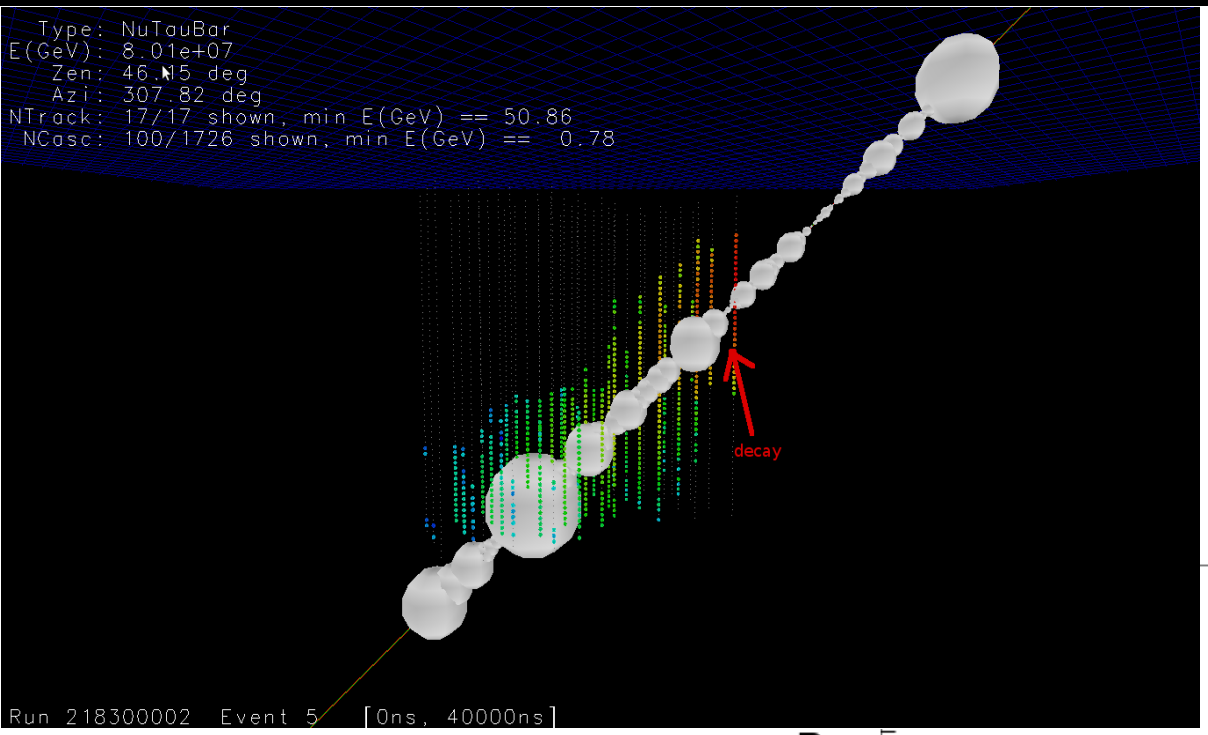
Model-dependent:
8.4 events expected
0 events observed



GRB *Fireball* Model



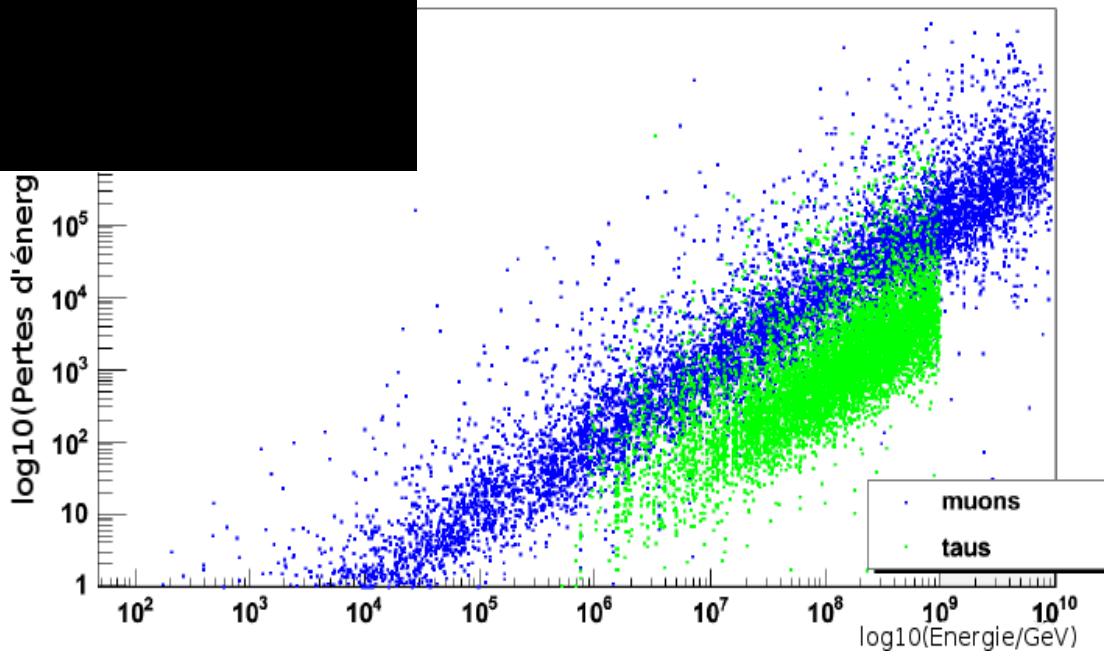
Search for UHE Tau Neutrinos



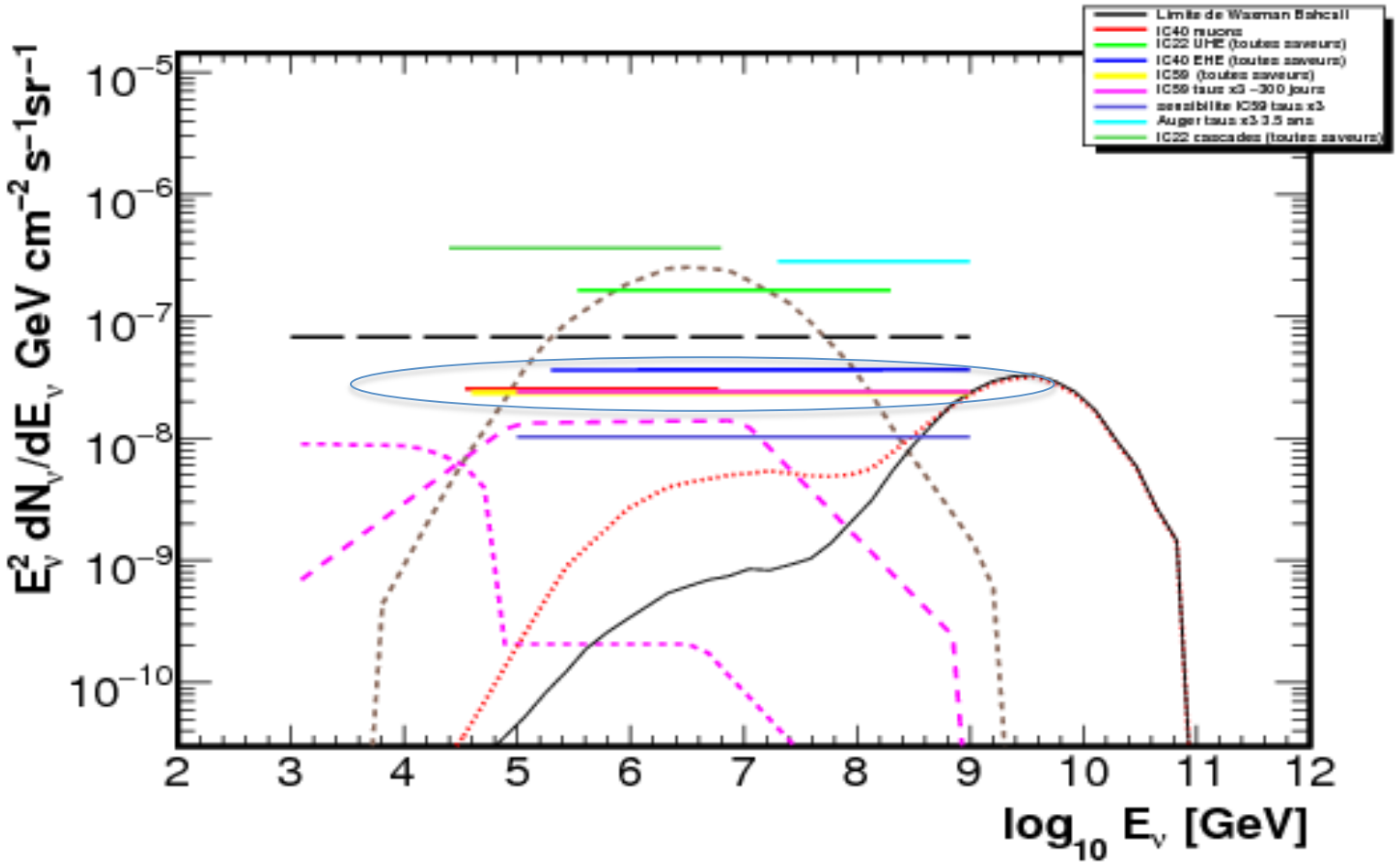


Sabrina Bechet successful Ph.D. defense
22 October 2012

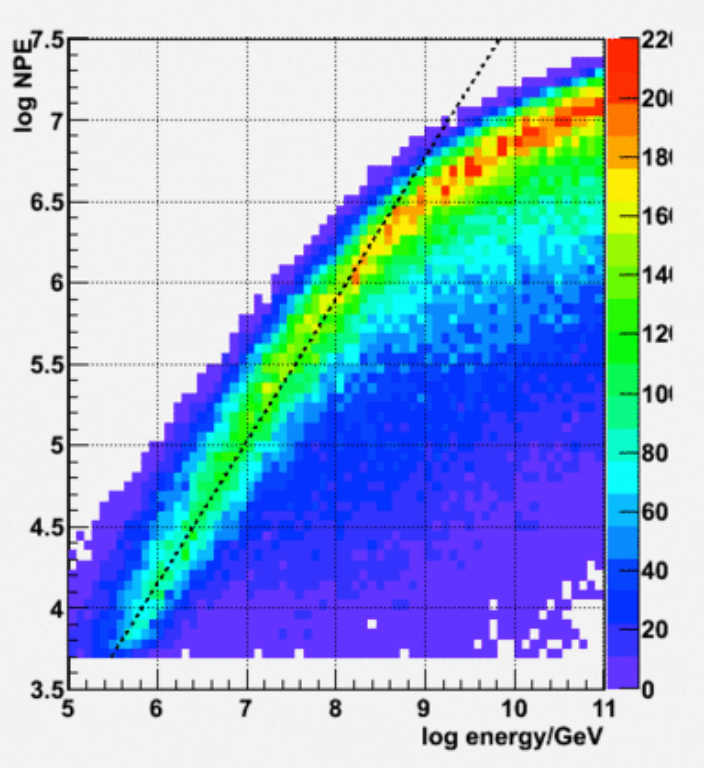
Tau dE/dX is less than muon of equivalent energy. Look for track with abrupt increase in brightness.



IC59 Tau Limit



EHE Diffuse Analysis

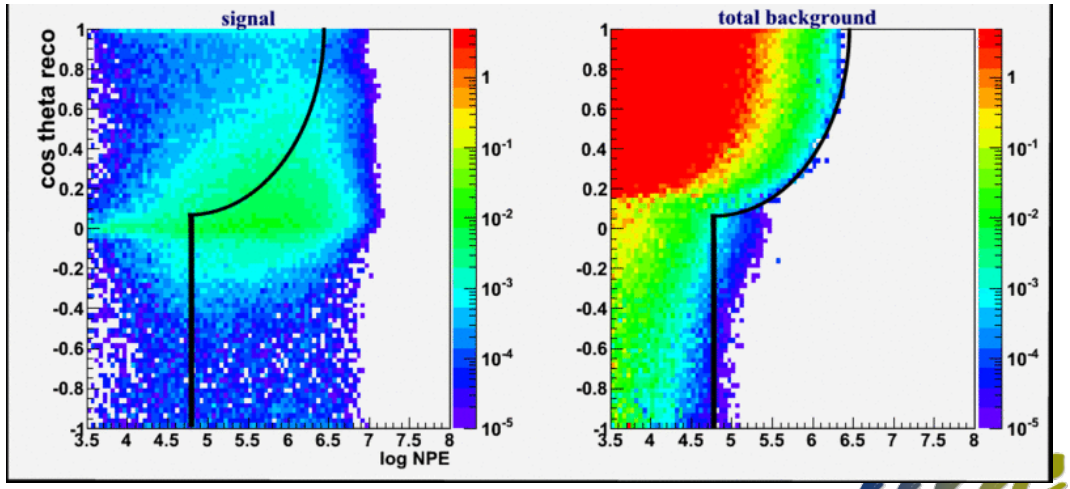


EHE event filter uses *energy proxy* NPE (# photo-electrons detected) and reconstructed zenith angle as discriminating variables. NPE is robust and fairly accurate for contained events up to almost 100 PeV. Above 100 PeV photons escape and PMT saturation becomes important.

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

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

118545:63733662 Aug 8, 2011 1.14 PeV
119316:36556705 Jan 3, 2012 1.29 PeV

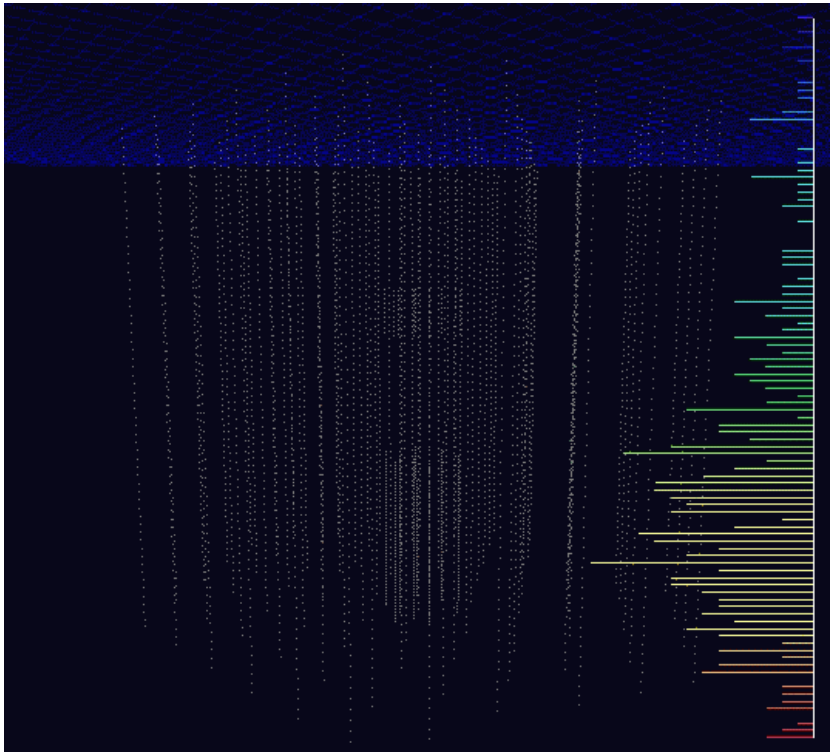


Hints of a signal? Too early to say but certainly interesting

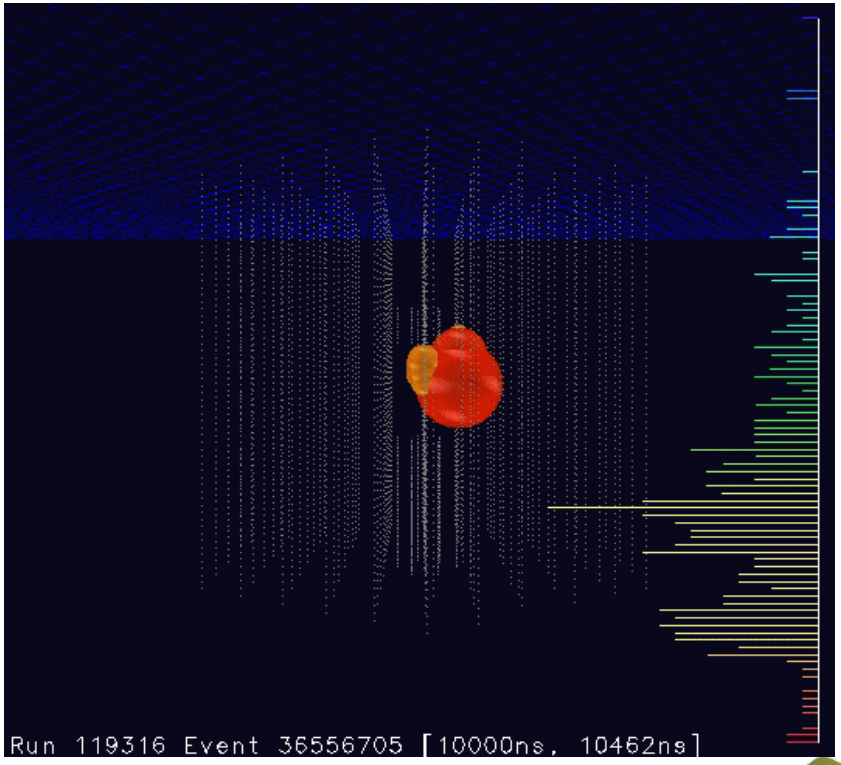
Systematics on Energy Reco ~ 35% currently but we are working to improve this.

Background estimates post-unblinding are moving target based on best available information but are all so far << 1. Follow up studies underway. Stay tuned.

EV118545:63733662 1.14 PeV 100k p.e.



EV119316:36556705 1.29 PeV 78k p.e.



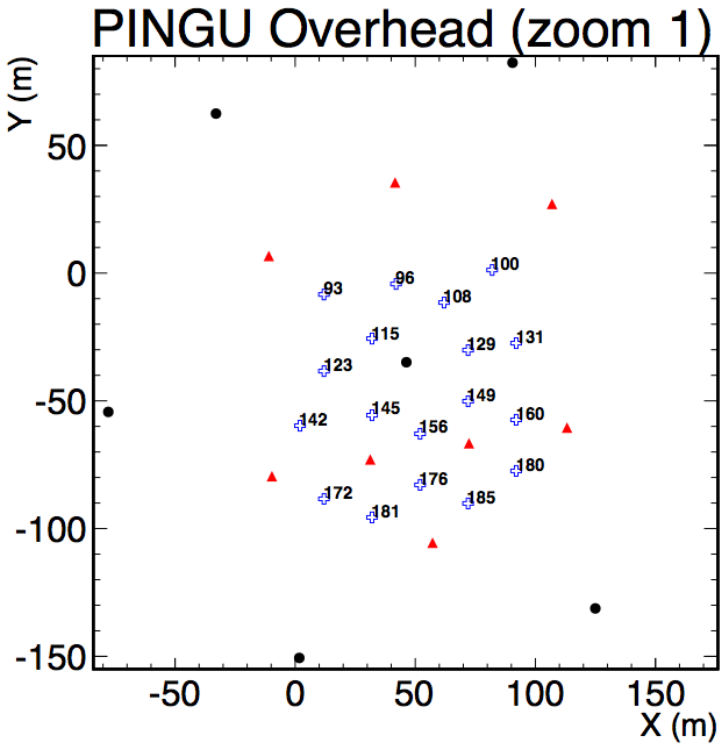


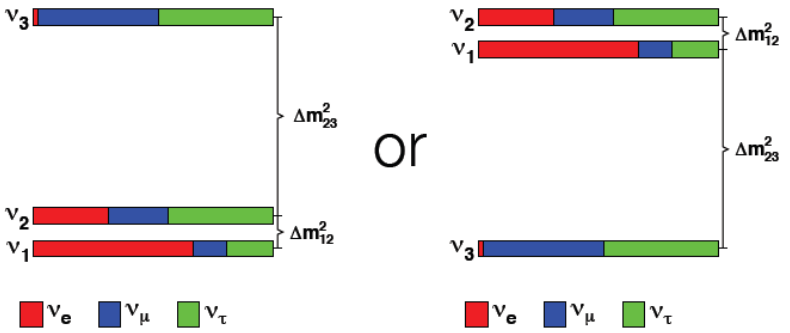
The Future of Optical Cherenkov Telescopes in the Ice

PINGU AND MICA

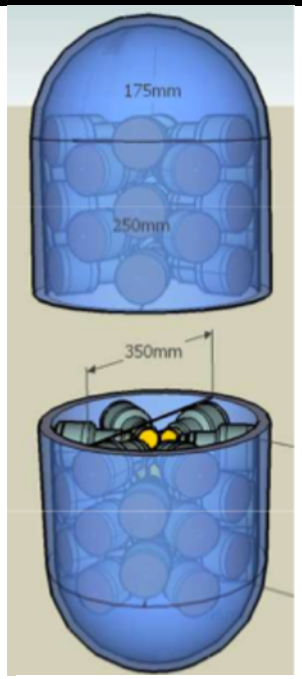
Precision IceCube Next-Generation Upgrade

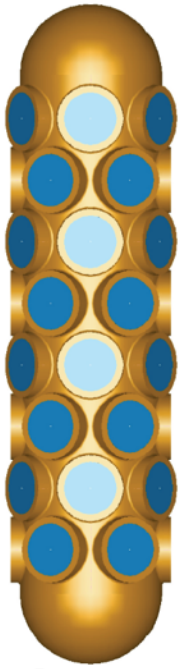
- **P**recision **I**ceCube **N**ext-**G**eneration **U**pgrade
- Motivation: Akhmedov, Razzaque, Smirnov arXiv:1205.7071 → PINGU detector has sensitivity at 3-10 σ level after 5 years to mass hierarchy due to matter effects in 5-10 GeV region.
- Detector still in concept phase but can probably predict that if it's constructed it will …
  - Be O(20) strings in-filled inside of IceCube DeepCore in deep clear ice
  - Be spaced along string in range 3-6 m
  - **Use basic DOM technology with tweaks to electronics (custom ASIC digitizers replaced by pipelined ADCs)**
  - Cost O(50 MUSD)
- Timescale is > 2016 for deployment of instrumentation
- Major logistical problem to revive IceCube EHWD which now somewhere on WAIS.

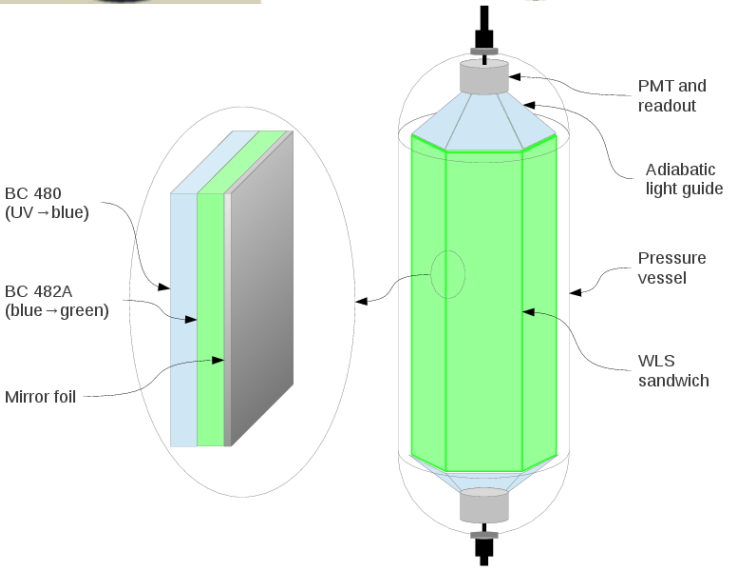




MICA





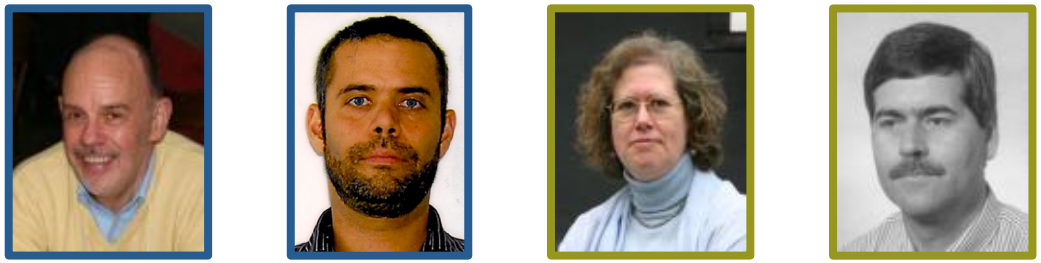
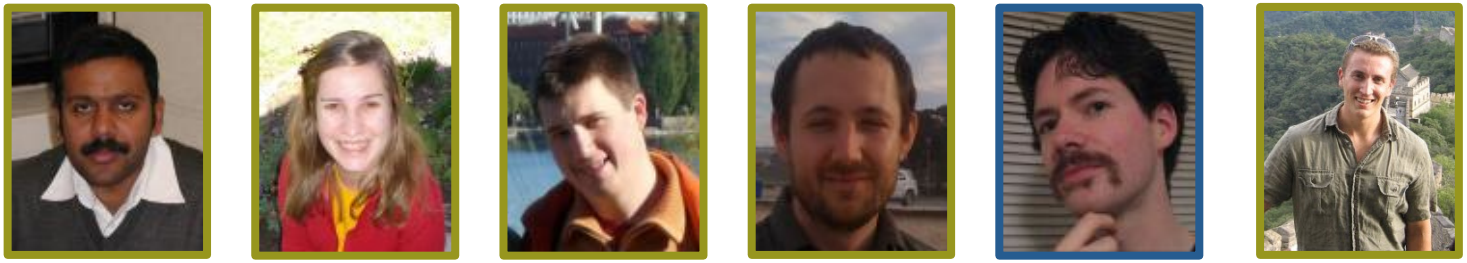
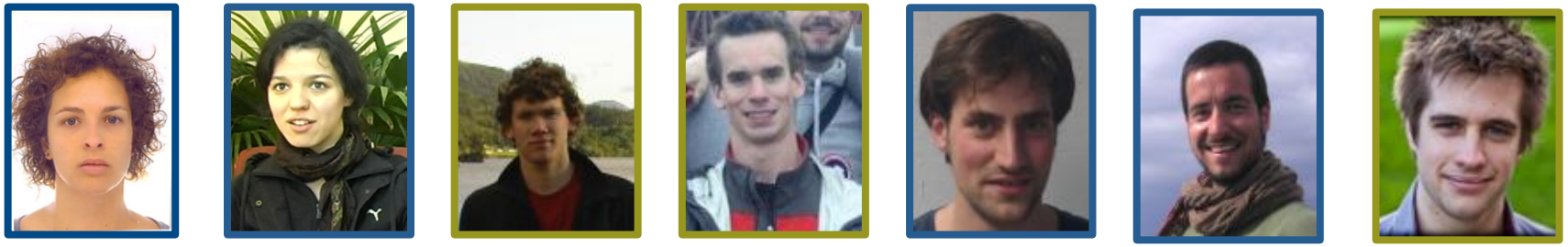


Multi-megaton Ice Cherenkov Array

- Far future project
- Main physics goal is to instrument deep quiet ice for megaton proton decay detector
- Also quite interesting for supernova physics
- 120 strings x O(100) large-area photo detectors per string
- 250 m x 40 m at bottom and center of IceCube Veto Array
- Developments to enhance effective photocathode area underway by several EU groups
  - Multi-anode PMT (30 small PMTs – no WF readout) (NIKHEF / Erlangen)
  - Wavelength shifters (Bonn)


And the rest is backups …
END

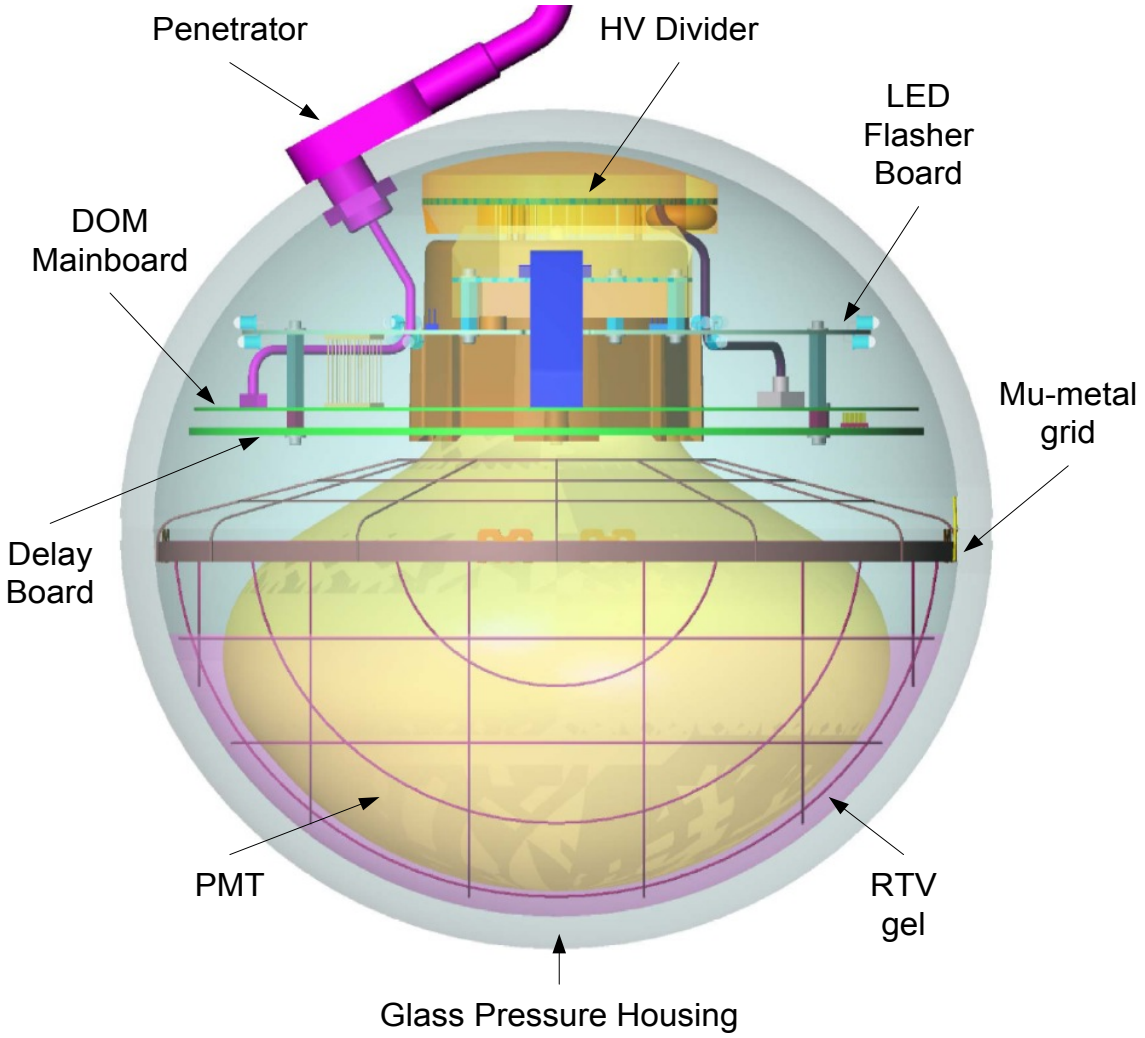
IIHE IceCube Group

Arriving in the near future

- Krijn de Vries
- Guiliano Maggi

The IceCube Digital Optical Module



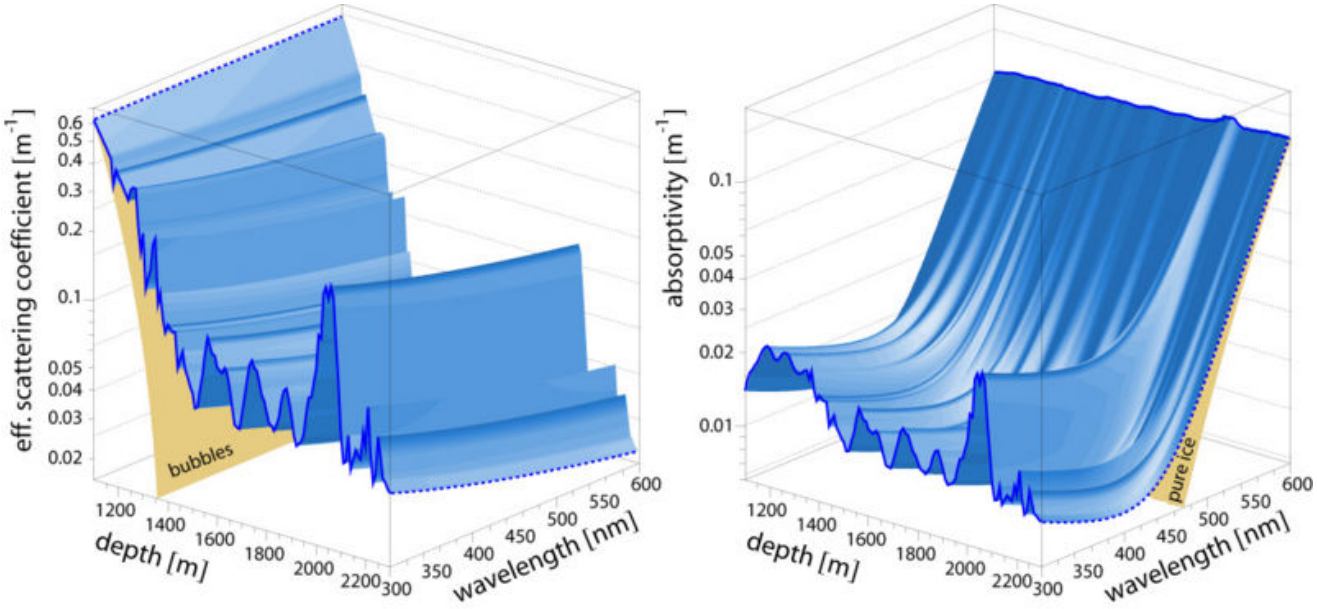
DOM Optical

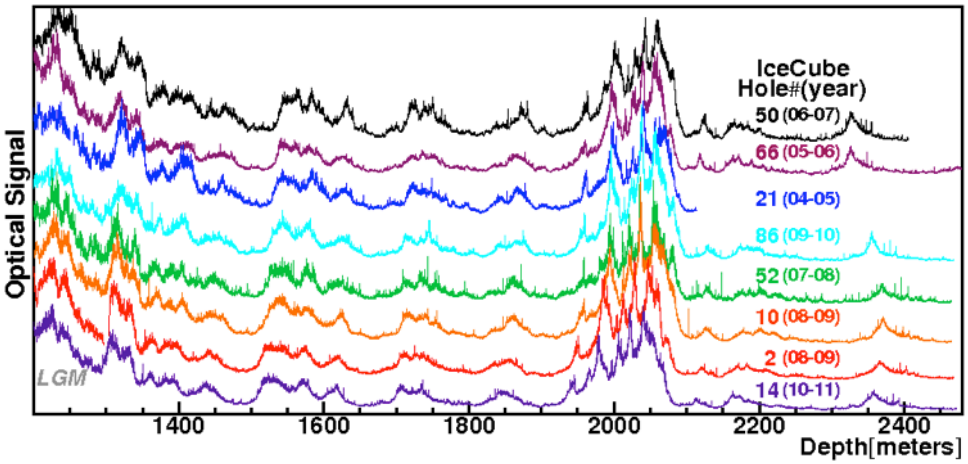
- **Large Area Photocathode** 10″ 10-stage Hamamatsu R7081-02 bialkali PMT (peak *QE* 24% @ 420 nm); High QE variant (peak *QE* 35% @ 420 nm) used in DeepCore DOMs
- **Low noise** 500 Hz background counting rate in-ice @ 0.25 pe threshold
- **Glass / Gel** 0.5″ thick Benthos pressure housing rated to 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

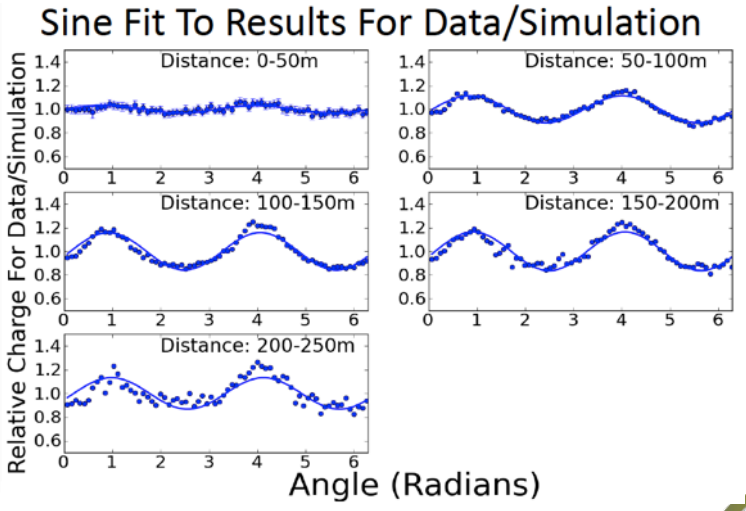
DOM Electronics

- **"Smart" autonomous digital sensor** FPGA with hardcore ARM CPU running embedded system. 4k-hit deep memory buffer stores hits until readout over 1 Mbit digital link to surface.
- **High-speed pulse digitization** Full waveform capture for hits which have coincidence trigger with neighbors. Waveform capture ASICs 14 bits effective @ 300 MSPS.
- **Array Timing** Handled in DOM comms protocol - DOM-to-DOM timing to 1-2 ns precision using *RAPCal* method.
- **Low power** - 3.75 W / DOM

The Ice

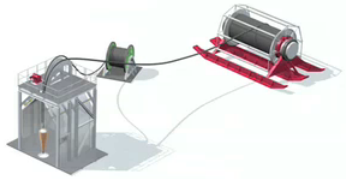

eff. scattering coefficient [m^{-1}]
0.6
0.5
0.4
0.3
0.2
0.1
0.05
0.04
0.03
0.02
bubbles
depth [m]
1200
1400
1600
1800
2000
2200
wavelength [nm]
300
350
400
450
500
550
600
absorptivity [m^{-1}]
0.1
0.05
0.04
0.03
0.02
0.01
pure ice
depth [m]
1200
1400
1600
1800
2000
2200
wavelength [nm]
300
350
400
450
500
550
600


Optical Signal
IceCube
Hole#(year)
50 (06-07)
66 (05-06)
21 (04-05)
86 (09-10)
52 (07-08)
10 (08-09)
2 (08-09)
14 (10-11)
LGM
1400
1600
1800
2000
2200
2400
Depth[meters]


Sine Fit To Results For Data/Simulation
Distance: 0-50m
Distance: 50-100m
Distance: 100-150m
Distance: 150-200m
Distance: 200-250m
Relative Charge For Data/Simulation
1.4
1.2
1.0
0.8
0.6
0
1
2
3
4
5
6
Angle (Radians)

Drilling with the EHWD

- Drill power plant 5MW
- 195°F pressurized hot water + closed loop water recovery system
- Drilling & deployment process
  - Drill 50 m with hot iron to get below hard packed snow layer called *firn*.
  - Drill 60cm hole to 2.5 km depth – takes approx 24h
  - Retrieve drill head and *ream* as you go out – takes another 6-8h
- Optical module deployment
  - DOMs attached to main cable – 5 min / DOM
  - String drop at 20 m / min after attach
  - Entire deployment is another 8h.



Drilling & Deployment



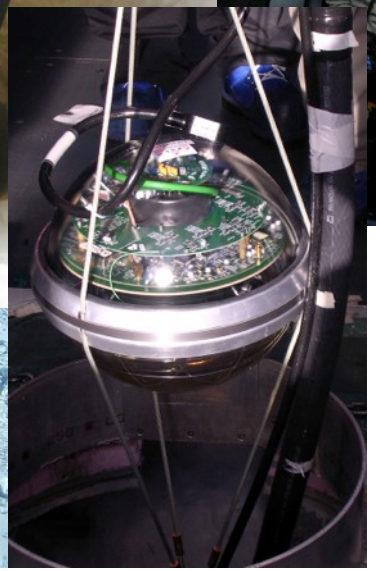








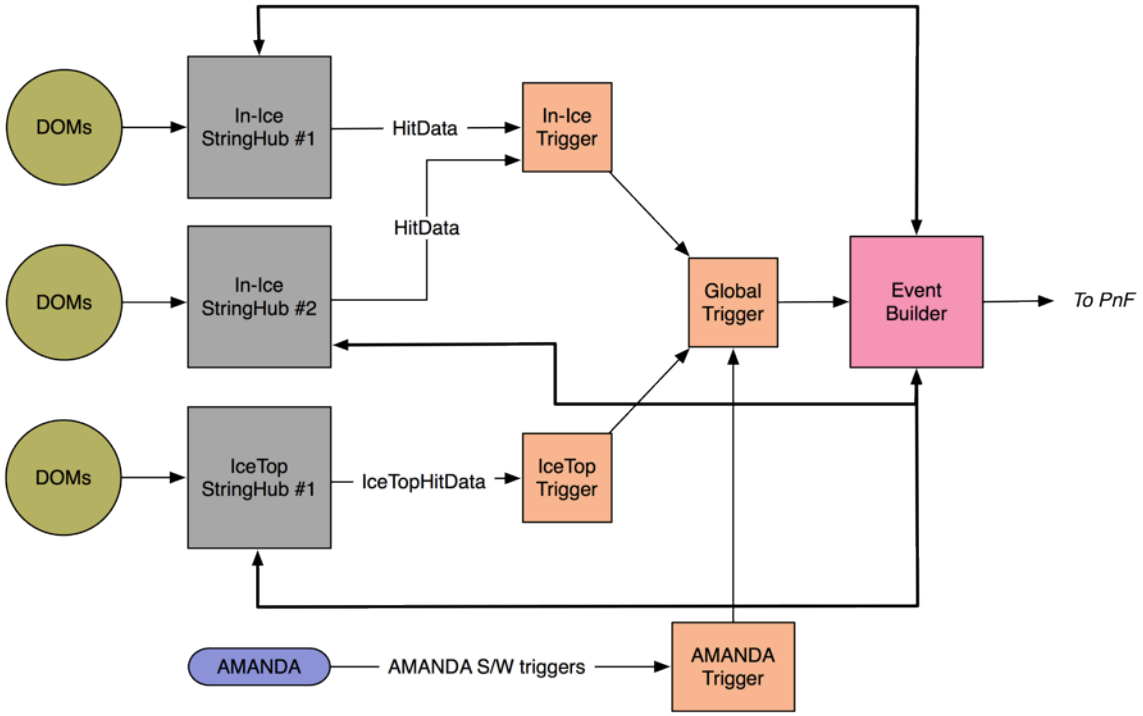


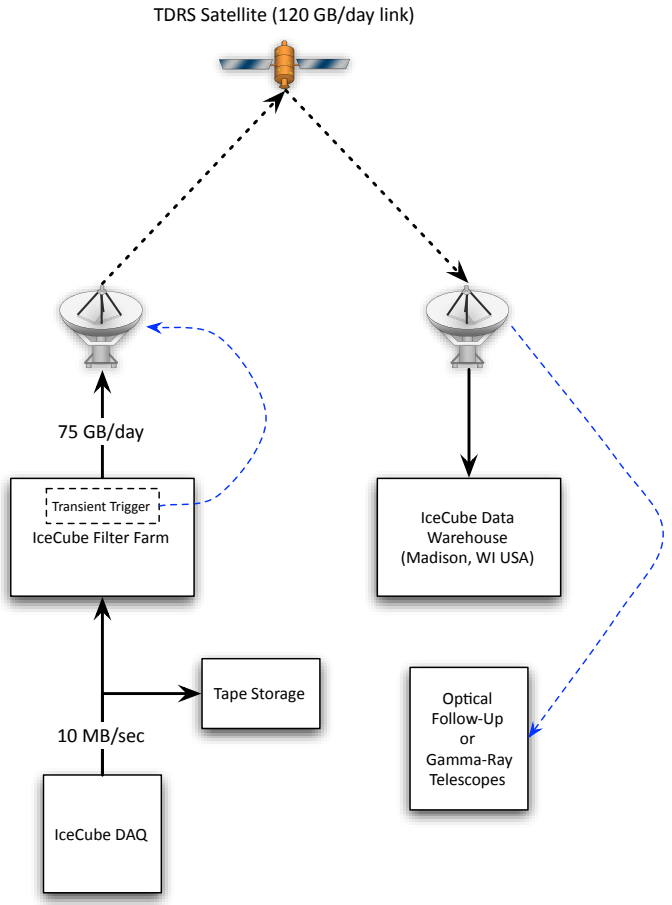


IceCube

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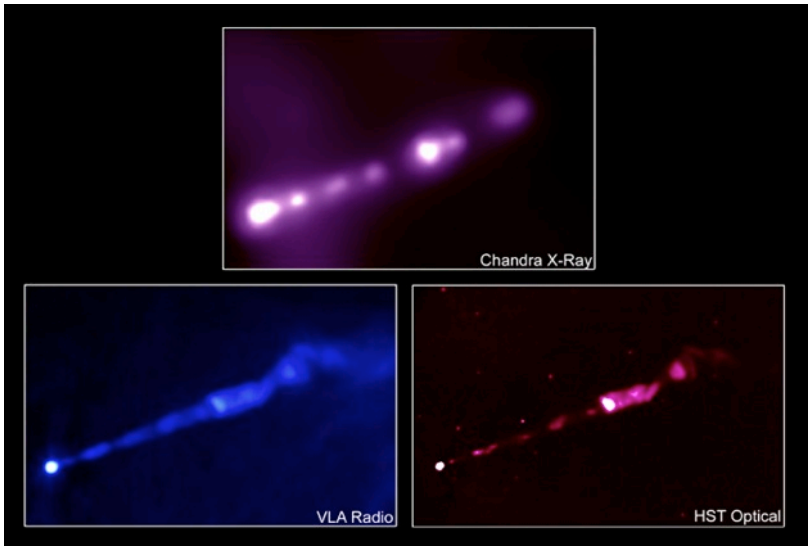
Triggering and Data Processing

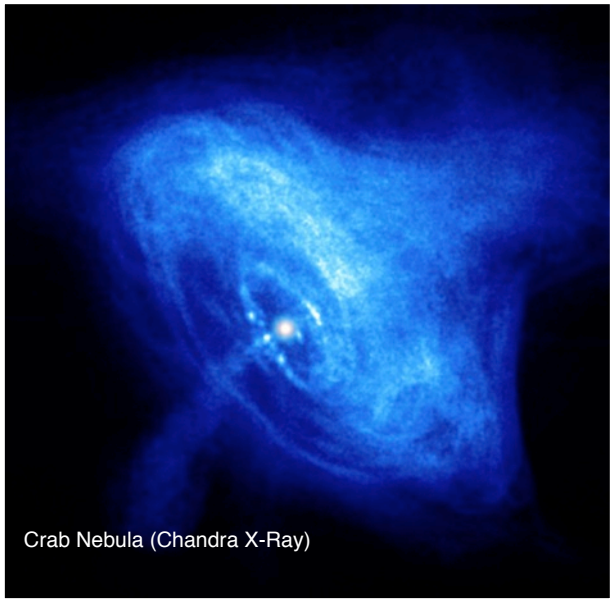




- Photon hits semi-autonomously time-stamped and digitized by DOMs (there is a local coincidence signal shared by near DOMs which determines how much information digitized).
- Readout via 3.5 km copper cable @ 1 Mbit → **250 MB/sec**
- Low-latency triggering (< 3s) and event assembly writes **3.5 kHz 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.

Astrophysical Sources and Messenger Particles

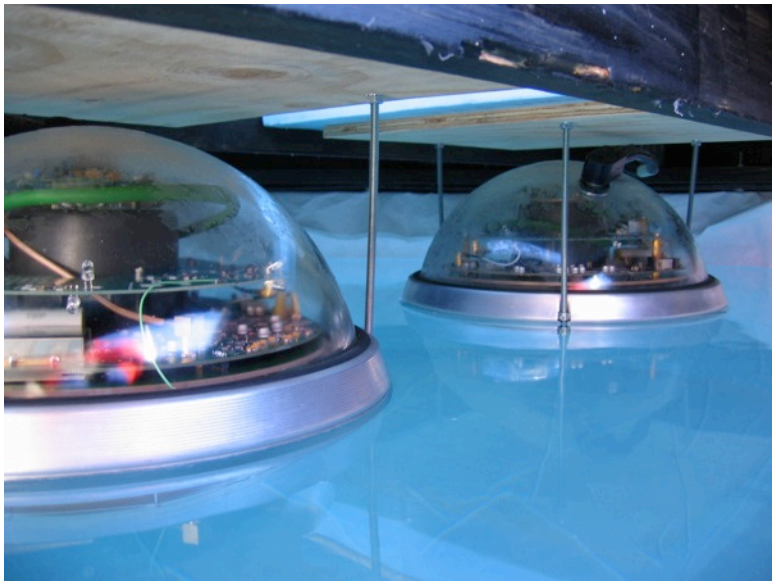




- Long-standing problem in (particle-) astrophysics: what is origin of cosmic rays?
  - Supernova remnants are abundant even in galaxy and Fermi shock acceleration is consistent with observations up to 1 PeV, but beyond 1 PeV it is hard to justify efficient energy transfer.
  - Gamma-ray binaries, microquasars, and pulsar wind nebulae are other galactic candidate accelerators
  - Extra-galactic candidates such as AGN and GRB
- Astronomy into the 20th century used only visible light as means of observation of celestial objects. The EM spectrum has opened up and now includes everything from radio waves to TeV gamma rays (dynamic range of 10^{20}).
- Any stable, preferably neutral, particle can carry information across vastness of space, essentially this leaves protons (and heavier nuclei), electrons and gammas, neutrinos, and gravitons.

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IceTop



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 with limited solid angle.
- 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.



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

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