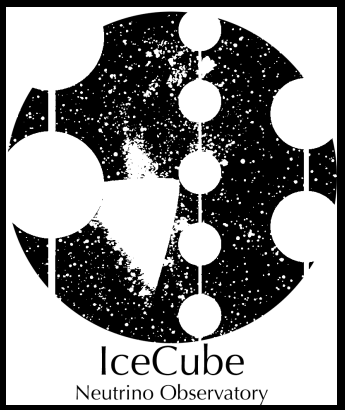
# Neutrino Astrophysics at the South Pole

Kael Hanson (ULB – IIHE)

Seminar given at Université Catholique de Louvain

Louvain-la-Neuve

2 December 2010



# Objectives of this Talk

- Motivation : why build IceCube detector – what questions will be answered by data from this facility?
- Detector description
- Results of the IC22 and IC40 data runs.
- Future of IceCube and neutrino astrophysics at the South Pole

# IceCube Collaboration

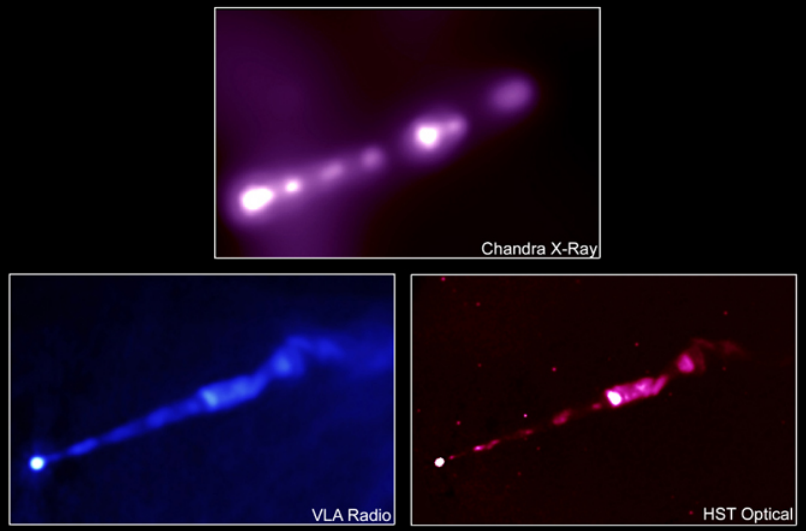
**IceCube Collaboration**: R. Abbasi[28], Y. Abdou[22], T. Abu-Zayyad[33], J. Adams[16], J. A. Aguilar[28], M. Ahlers[32], K. Andeen[28], J. Auffenberg[38], X. Bai[31], M. Baker[28], S. W. Barwick[24], R. Bay[7], J. L. Bazo Alba[39], K. Beattie[8], J. J. Beatty[18,19], S. Bechet[13], J. K. Becker[10], K.-H. Becker[38], M. L. Benabderrahmane[39], S. BenZvi[28], J. Berdermann[39], P. Berghaus[28], D. Berley[17], E. Bernardini[39], D. Bertrand[13], D. Z. Besson[26], M. Bissok[1], E. Blaufuss[17], J. Blumenthal[1], D. J. Boersma[1], C. Bohm[34], D. Bose[14], S. Böser[11], O. Botner[37], J. Braun[28], A. M. Brown[16], S. Buitink[8], M. Carson[22], D. Chirkin[28], B. Christy[17], J. Clem[31], F. Clevermann[20], S. Cohen[25], C. Colnard[23], D. F. Cowen[36,35], M. V. D'Agostino[7], M. Danninger[34], J. Daughhetee[5], J. C. Davis[18], C. De Clercq[14], L. Demirörs[25], O. Depaepe[14], F. Descamps[22], P. Desiati[28], G. de Vries-Uiterweerd[22], T. DeYoung[36], J. C. Díaz-Vélez[28], M. Dierckxsens[13], J. Dreyer[10], J. P. Dumm[28], R. Ehrlich[17], J. Eisch[28], R. W. Ellsworth[17], O. Engdegård[37], S. Euler[1], P. A. Evenson[31], O. Fadiran[4], A. R. Fazely[6], A. Fedynitch[10], T. Feusels[22], K. Filimonov[7], C. Finley[34], M. M. Foerster[36], B. D. Fox[36], A. Franckowiak[11], R. Franke[39], T. K. Gaisser[31], J. Gallagher[27], M. Geisler[1], L. Gerhardt[8,7], L. Gladstone[28], T. Glüsenkamp[1], A. Goldschmidt[8], J. A. Goodman[17], D. Grant[21], T. Griesel[29], A. Groß[16,23], S. Grullon[28], M. Gurtner[38], C. Ha[36], A. Hallgren[37], F. Halzen[28], K. Han[16], K. Hanson[13,28], K. Helbing[38], P. Herquet[30], S. Hickford[16], G. C. Hill[28], K. D. Hoffman[17], A. Homeier[11], K. Hoshina[28], D. Hubert[14], W. Huelsnitz[17], J.-P. Hülß[1], P. O. Hulth[34], K. Hultqvist[34], S. Hussain[31], A. Ishihara[15], J. Jacobsen[28], G. S. Japaridze[4], H. Johansson[34], J. M. Joseph[8], K.-H. Kampert[38], A. Kappes[9], T. Karg[38], A. Karle[28], J. L. Kelley[28], N. Kemming[9], P. Kenny[26], J. Kiryluk[8,7], F. Kislat[39], S. R. Klein[8,7], J.-H. Köhne[20], G. Kohnen[30], H. Kolanoski[9], L. Köpke[29], D. J. Koskinen[36], M. Kowalski[11], T. Kowarik[29], M. Krasberg[28], T. Krings[1], G. Kroll[29], K. Kuehn[18], T. Kuwabara[31], M. Labare[14], S. Lafebre[36], K. Laihem[1], H. Landsman[28], M. J. Larson[36], R. Lauer[39], R. Lehmann[9], J. Lünemann[29], J. Madsen[33], P. Majumdar[39], A. Marotta[13], R. Maruyama[28], K. Mase[15], H. S. Matis[8], M. Matusik[38], K. Meagher[17], M. Merck[28], P. Mészáros[35,36], T. Meures[1], E. Middell[39], N. Milke[20], J. Miller[37], T. Montaruli[28,a], R. Morse[28], S. M. Movit[35], R. Nahnhauer[39], J. W. Nam[24], U. Naumann[38], P. Nießen[31], D. R. Nygren[8], S. Odrowski[23], A. Olivas[17], M. Olivo[37,10], A. O'Murchadha[28], M. Ono[15], S. Panknin[11], L. Paul[1], C. Pérez de los Heros[37], J. Petrovic[13], A. Piegsa[29], D. Pieloth[20], R. Porrata[7], J. Posselt[38], P. B. Price[7], M. Prikockis[36], G. T. Przybylski[8], K. Rawlins[3], P. Redl[17], E. Resconi[23], W. Rhode[20], M. Ribordy[25], A. Rizzo[14], J. P. Rodrigues[28], P. Roth[17], F. Rothmaier[29], C. Rott[18], T. Ruhe[20], D. Rutledge[36], B. Ruzybayev[31], D. Ryckbosch[22], H.-G. Sander[29], M. Santander[28], S. Sarkar[32], K. Schatto[29], S. Schlenstedt[39], T. Schmidt[17], A. Schukraft[1], A. Schultes[38], O. Schulz[23], M. Schunck[1], D. Seckel[31], B. Semburg[38], S. H. Seo[34], Y. Sestayo[23], S. Seunarine[12], A. Silvestri[24], K. Singh[14], A. Slipak[36], G. M. Spiczak[33], C. Spiering[39], M. Stamatikos[18,b], T. Stanev[31], G. Stephens[36], T. Stezelberger[8], R. G. Stokstad[8], S. Stoyanov[31], E. A. Strahler[14], T. Straszheim[17], G. W. Sullivan[17], Q. Swillens[13], H. Taavola[37], I. Taboada[5], A. Tamburro[33], O. Tarasova[39], A. Tepe[5], S. Ter-Antonyan[6], S. Tilav[31], P. A. Toale[36], S. Toscano[28], D. Tosi[39], D. Turčan[17], N. van Eijndhoven[14], J. Vandenbroucke[7], A. Van Overloop[22], J. van Santen[28], M. Vehring[1], M. Voge[23], B. Voigt[39], C. Walck[34], T. Waldenmaier[9], M. Wallraff[1], M. Walter[39], Ch. Weaver[28], C. Wendt[28], S. Westerhoff[28], N. Whitehorn[28], K. Wiebe[29], C. H. Wiebusch[1], D. R. Williams[2], R. Wischnewski[39], H. Wissing[17], M. Wolf[23], K. Woschnagg[7], C. Xu[31], X. W. Xu[6], G. Yodh[24], S. Yoshida[15], P. Zarzhitsky[2] (262 authors)

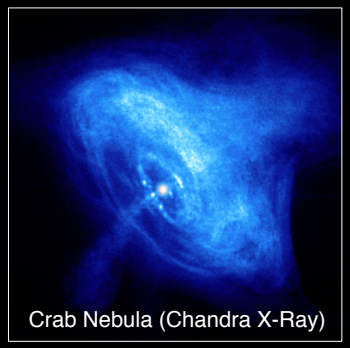
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39. DESY, D-15735 Zeuthen, Germany

Windup

# THE PHYSICS

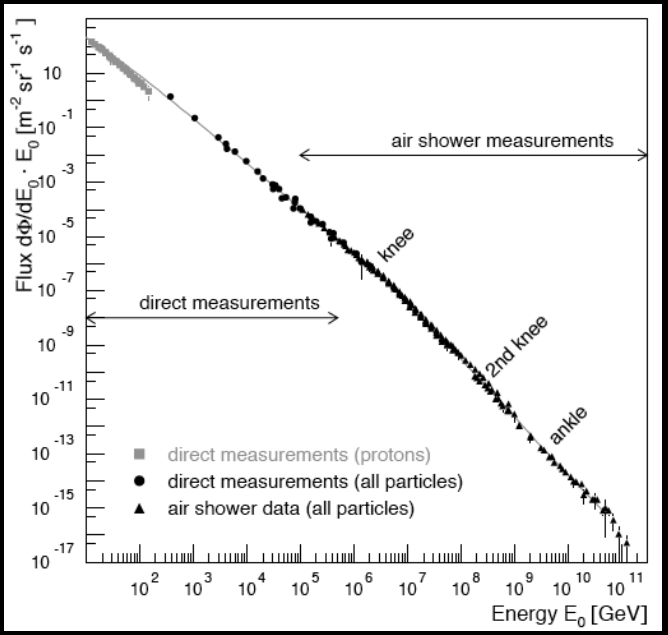
# Astrophysical Sources and Particles as Messengers





Crab Nebula (Chandra X-Ray)

- 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 20$^{th}$ 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.

# Cosmic Rays




The flux of cosmic rays has been known for 100 years: it extends from roughly 1 GeV where geomagnetic cutoff and atmospheric absorption screen low energy particles to above $10^{11}$ GeV when even the largest detectors such as PAO (Pierre Auger Observatory, Argentina) run out of events from the diminishing flux.

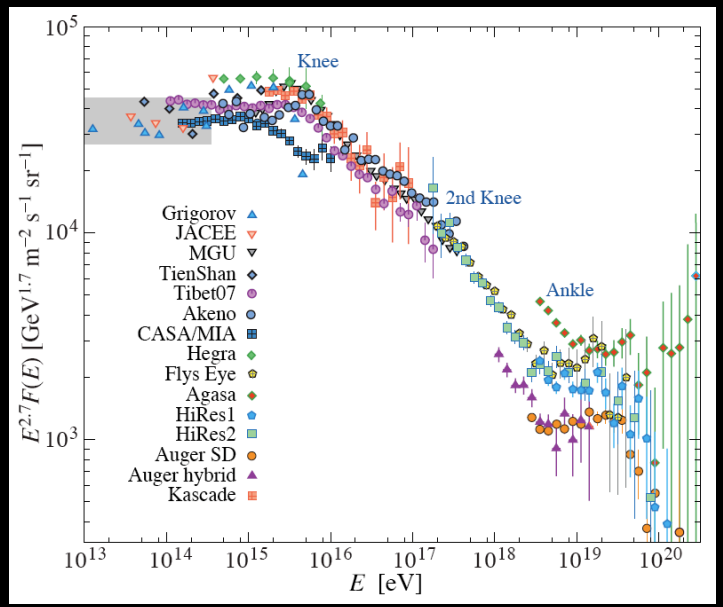
Composition is principally protons below the "knee" and appears to be getting heavier above it – the composition of UHECR is an outstanding question to resolve. It is also unknown exactly what gives rise to these knees: is our galaxy leaking particles or are the galactic accelerators running out of energy and the flux is being supplied by other, higher-energy extra-galactic objects?

see arXiV:0904.0725 for review on UHECR

At the extreme end of the spectrum, above 3E19 eV, the protons can interact with the photons of the CMBR (cosmic microwave background) and form pions through Delta resonances:

$$\gamma + p \rightarrow \Delta^+ \rightarrow p + \pi^0$$
$$\rightarrow n + \pi^+$$

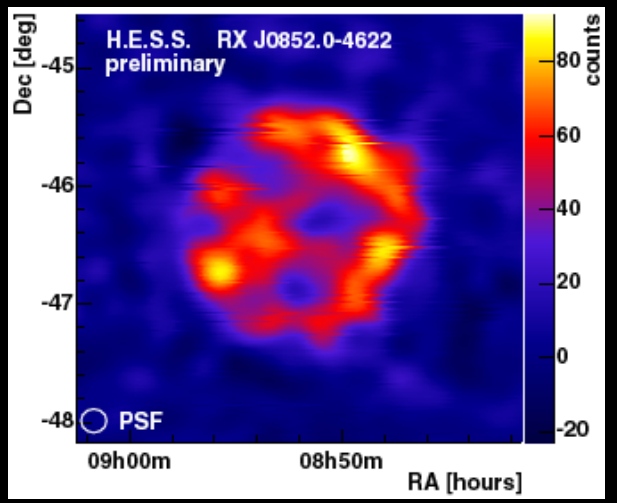
This effect – conventionally known as the GZK cutoff after Greisen, Zatsepin, and Kuz'min – severely limits the range of UHECR protons to 10's of Mpc, unfortunately just as the magnetic deflection begins to decrease to a point where particle astronomy is feasible. Notice however, that the short-lived charged pions will decay into neutrinos which we will get to in a second and then a bit later, too, so save this information.



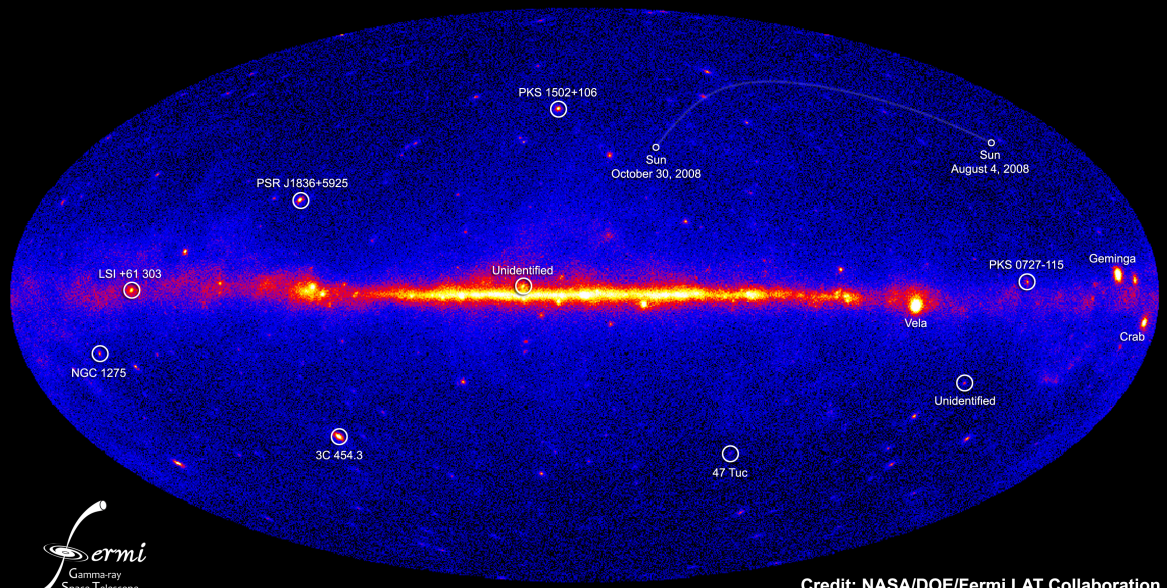
# Gamma Rays

Ground-based and satellite-based experiments from the past two decades have revolutionized the gamma sky. Galactic and extra-galactic sources including some of the most energetic events witnessed – GRB's – at cosmological distances continue to be found and studied leading to a better understanding of source physics. Despite these advances, gamma rays have not been able to either confirm or deny hadronic acceleration as gammas can be produced in EM-only processes.

The neutral gamma rays are not deviated by intergalactic fields and so are good particles for pointing back to sources. For very high energy gammas, the CMB field begins to get opaque limiting the travel distances to 10's – 100's Mpc.




**NASA's Fermi telescope reveals best-ever view of the gamma-ray sky**




Credit: NASA/DOE/Fermi LAT Collaboration

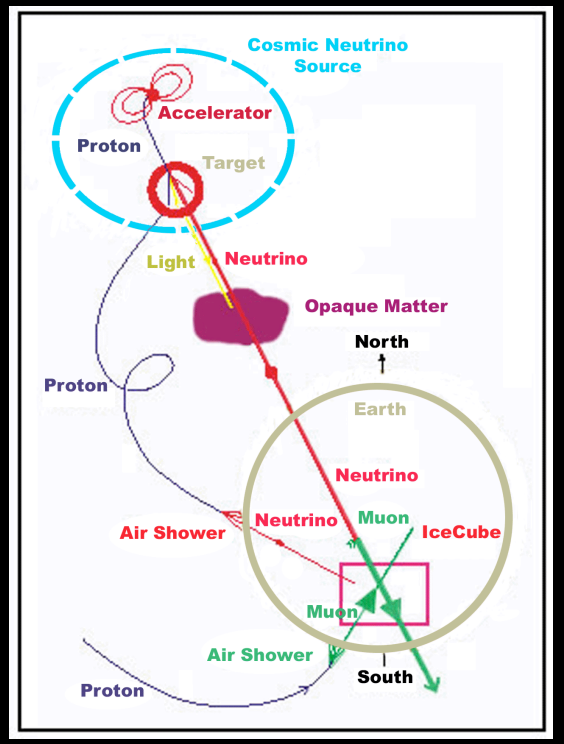
# Neutrinos

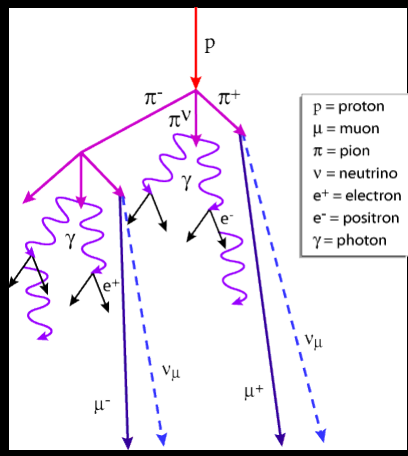
Neutrinos, being chargeless and only weakly-interacting make perfect messengers to carry information from deep within the core of sources in a straight line to Earth based detectors. The neutrinos even pass through the Earth (up to 100 TeV after which the Earth becomes opaque). The Earth is then often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

The small cross sections do demand that large target masses be instrumented. Typical theoretically predicted fluxes want cubic kilometers or square kilometers of muon effective area in order to produce viable event rates.

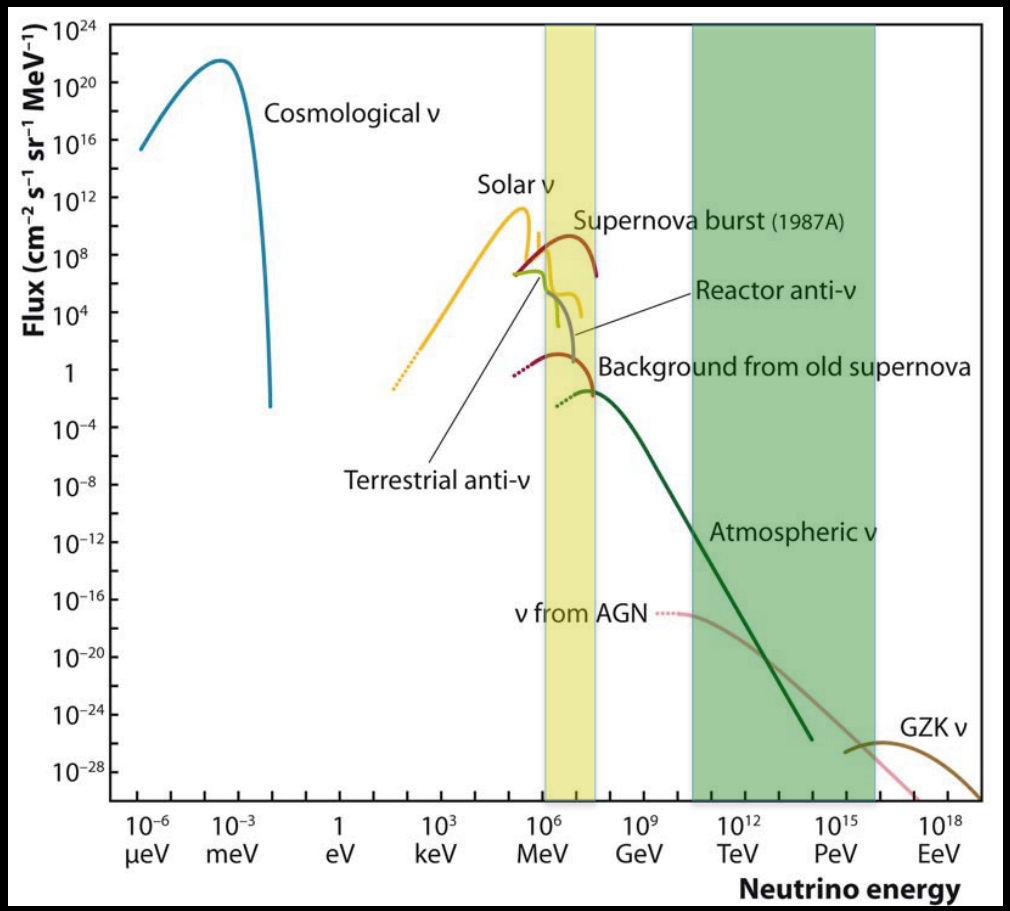
Observation of high-energy neutrino fluxes from an object would conclusively prove the existence of a hadronic acceleration process as neutrinos can only be produced via this mechanism.

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



# Neutrino Fluxes

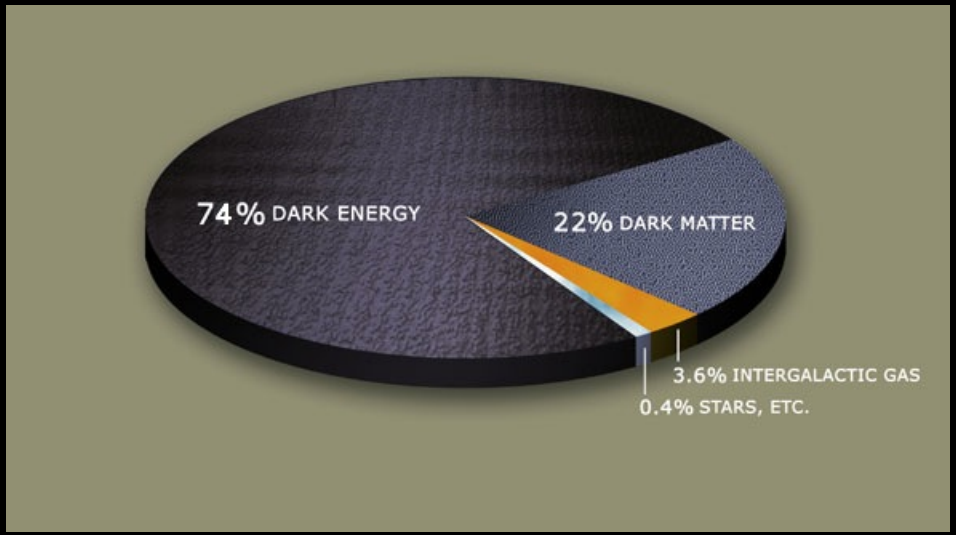



IceCube HE

IceCube SN

# Dark Matter

Only 4% of the gravitating mass of the Universe is luminous baryonic matter. 74% is a mysterious repulsive field or vacuum energy term in the FLRW metric to account for the apparent expansion of today's Universe. This entity is completely unknown so I move on from here. The remaining 22% is called **dark matter**. This ΛCDM model of the Universe uses a combination of measurements from CMB, large-scale structure, and Type Ia supernovae.




A fraction of this dark matter is non-luminous baryonic material locked up in MACHOs, however, most is thought to be non-baryonic. Candidate particles for DM must be massive, stable, and have weak interactions with matter – generically termed WIMPs. The favored particles come from SUSY the lightest supersymmetric partner, LSP, also called the neutralino or extra dimensions, the lightest KK particle, LKP.

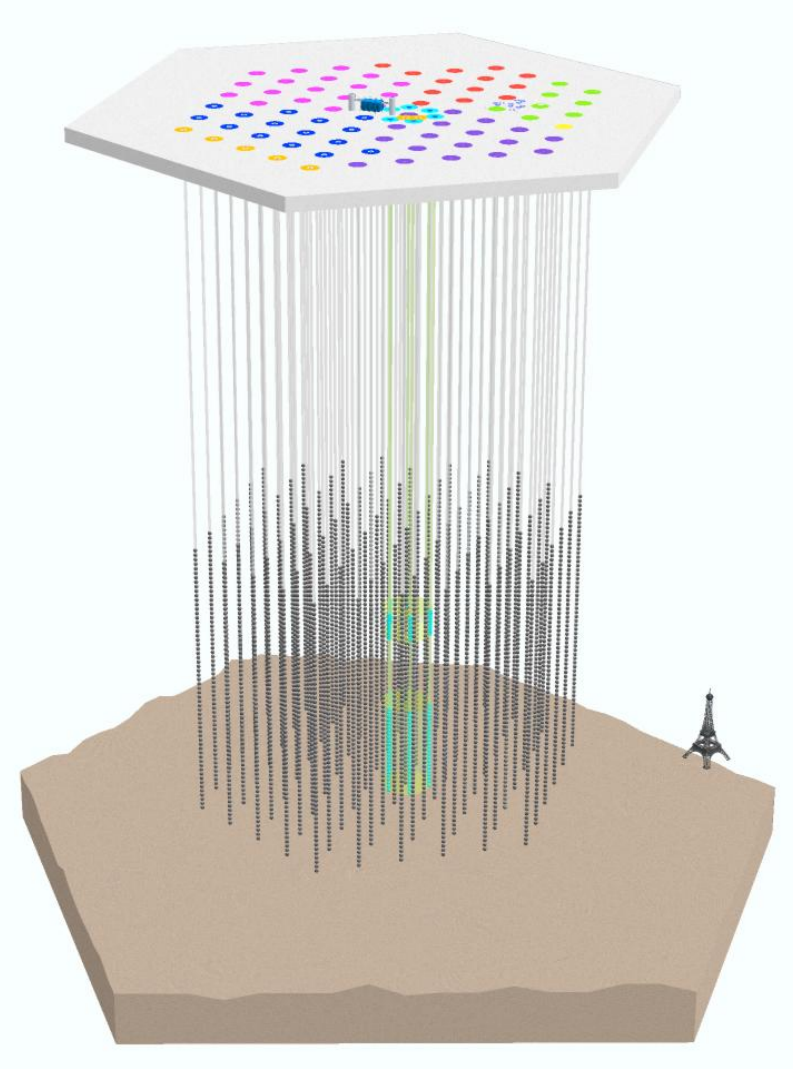
Experimental evidence for DM is strong: first it has been observed for decades that galactic rotation curves and galactic motion within clusters of galaxies does not follow simple Newtonian dynamics. Therefore, it has been proposed that galaxies possess large, invisible WIMP halos. In addition the CMB measurements give more precise, albeit more indirect indications that DM must exist.

Searches for dark matter include direct and indirect. Direct search detectors look for events where the WIMP interacts with a nucleus which recoils and is detected using semiconductors, crystal or noble gas scintillators, or cryogenic crystals. Indirect detection of WIMPs assumes particle-antiparticle annihilation either from WIMPs in galaxy halos or WIMPs gravitationally trapped in massive objects like Sun. The decay products are gammas and/or neutrinos.

The Pitch

# THE ICECUBE NEUTRINO DETECTOR AT THE SOUTH POLE

# IceCube



## Technical Details

80 strings each containing 60 digital optical modules (DOMs) spaced 17 m apart from 1450 m to 2450 m depth below South Pole surface. Strings are spaced on (roughly) hexagonal grid with spacing 125 m. At top of each string are 2 IceTop tanks each containing 2 DOMs.
6 DeepCore strings at center of array: 10 DOMs spaced 10 m at depths of 1750 m to 1840 m, 50 DOMs at 7 m spacing from 2107 m to 2450 m depth.

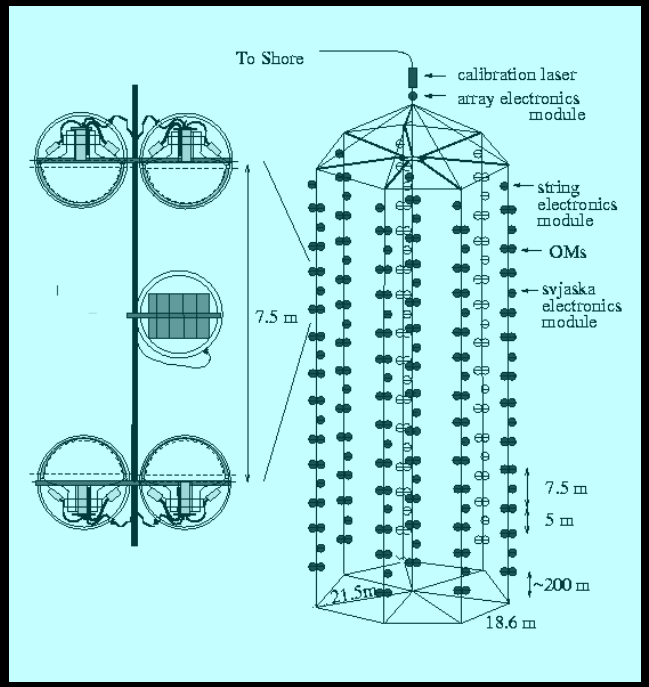
**Total 5480 Channels**

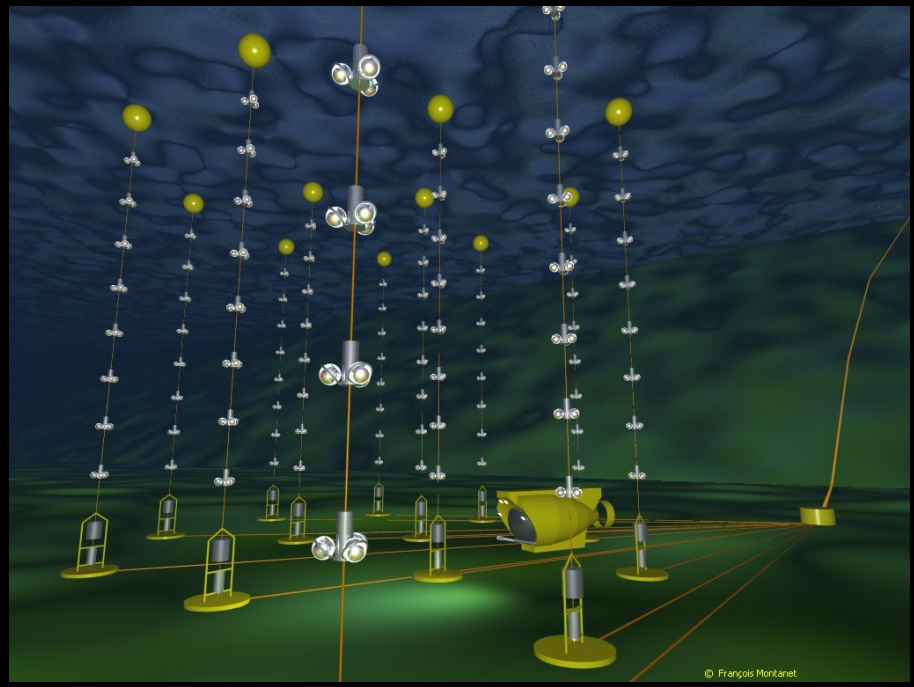
Primary design optimization: TeV muons from neutrinos. Also a capable galactic SN neutrino observatory. Builds on experience from AMANDA detector R.I.P. May 2009

## Construction History

2005 First string deployed – String 21 – IC1
2006 Eight strings deployed – IC9, atmospheric neutrino measurement published
2007 13 strings deployed – IC22, point sources, EHE, GRB
2008 18 strings deployed – IC40, official begin of IceCube operations.
2009 19 strings deployed, 1 DeepCore – IC59
2010 20 strings deployed, 5 DeepCore – IC79
2011 (Actually end of 2010) end of deployments – IC86

# Very Large Volume Cherenkov Neutrino Detectors



# Neutrino Detection in the Ice

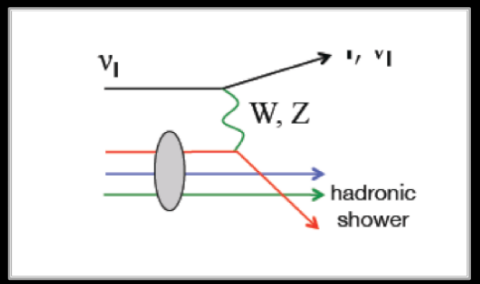
Neutrinos are only indirectly detected in Cherenkov detectors; they produce charged leptons (CC) or recoiling hadrons (NC) which emit Cherenkov light or produce secondaries which emit Cherenkov light. In some cases the neutrino-nucleus interaction happens quite a distance from the detector and it is only the muon or tau which traverses the active volume.

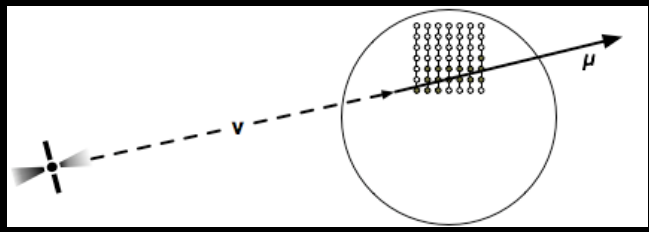
IceCube can distinguish only two event archetypes:

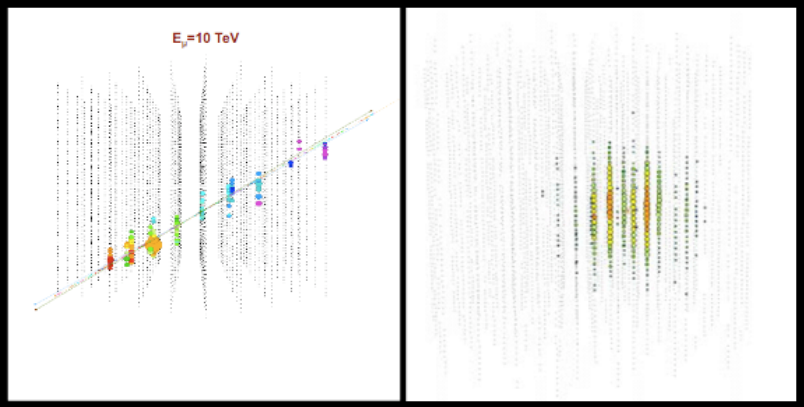
- Track-like events are passing muons or UHE taus which deposit energy dE/dX ∝ E and so the energy of the track may be estimated. Good angular resolution – O(1°). Muons and taus can travel many km before losing energy or decaying.
- Cascade-like events are anisotropic balls of light that come from EM or hadronic showers typically all of the energy is deposited in a few tens of meters.

Tau particles, depending on the energy can look like either or both. They are an interesting class to study as there is no atmospheric background.

Light deposition ranges from single photons to tens of thousands of photons depending on energy and event type.



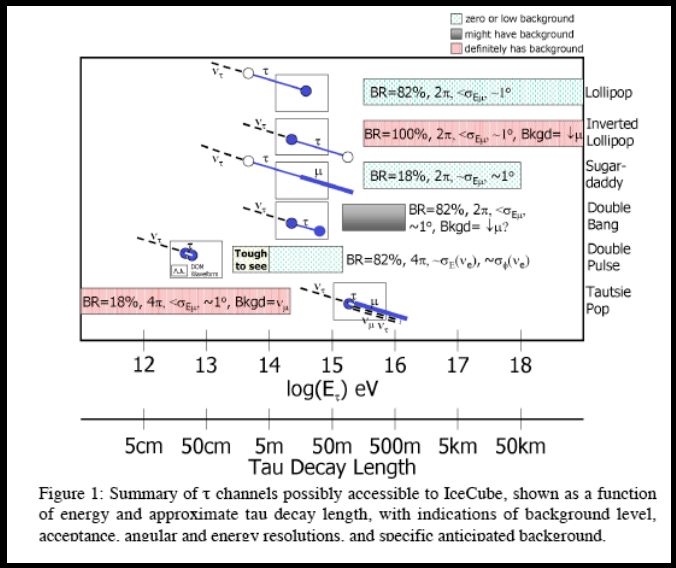
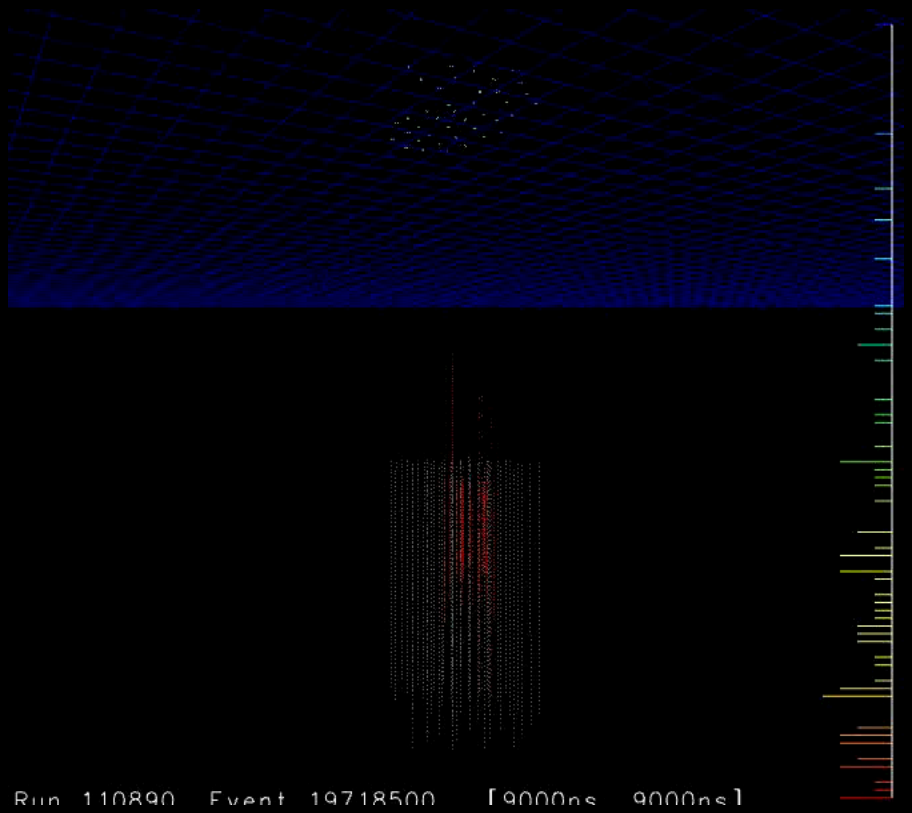



Figure 1: Summary of τ channels possibly accessible to IceCube, shown as a function of energy and approximate tau decay length, with indications of background level, acceptance, angular and energy resolutions, and specific anticipated background.

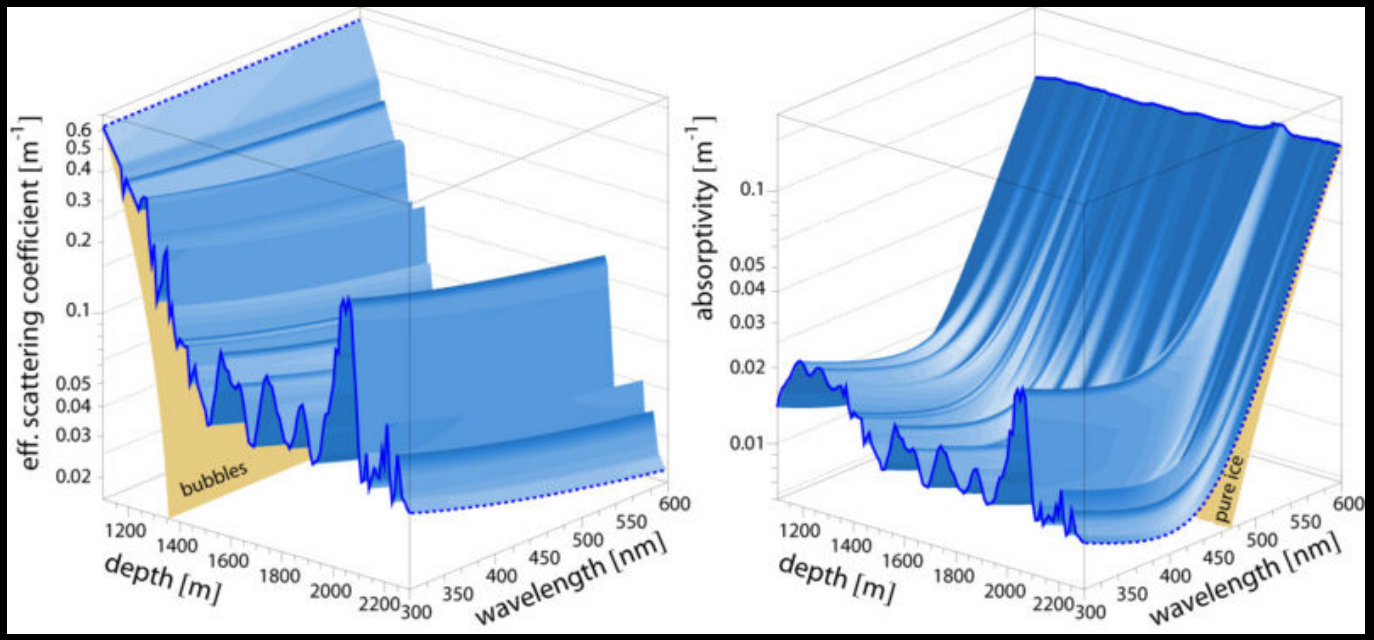
# Event Display

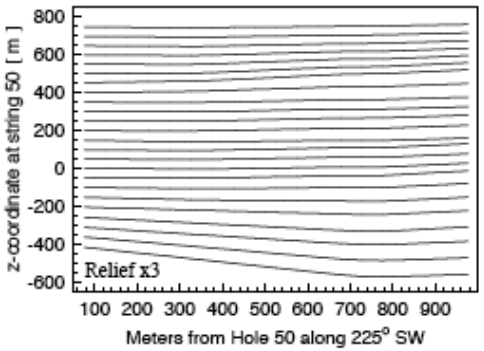



This event is a UHE CR reconstructed to have energy 900 PeV which strikes both IceTop and the in-ice detector. While only one muon track is reconstructed there are probably hundreds or thousands of muons in a bundle passing through the detector.

As will be discussed in the next slide the ice is of varying quality and thus there is a high absorption in the lower middle which is clearly visible in this event.

# South Pole Ice



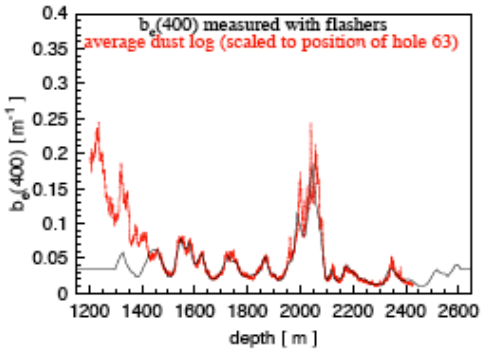




Figure 11: Left: extension of ice layers along the average gradient direction. Relief is amplified by a factor of 3 to enhance the clarity of the layer structure. Right: comparison of the average dust log with the effective scattering coefficient $b_e(400)$ measured with the flasher data.

# Drilling







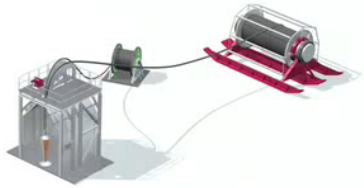









# The Drill Animation



# 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 reco).
- 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.



# DOMs




As of June 2009 all DOMs have been produced. Currently operating 4943 DOM channels of 5060 deployed – 98%. 0.5% of DOMs have experienced catastrophic failure.

## 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** 300-500 Hz background counting rate in-ice 0.25 pe discriminator threshold, 200 μs afterpulse suppression

**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 is calibrated ε(λ, T) in the lab to about 7%; *in-situ* flasher board additionally permits in-ice optical measurements

## DOM Electronics

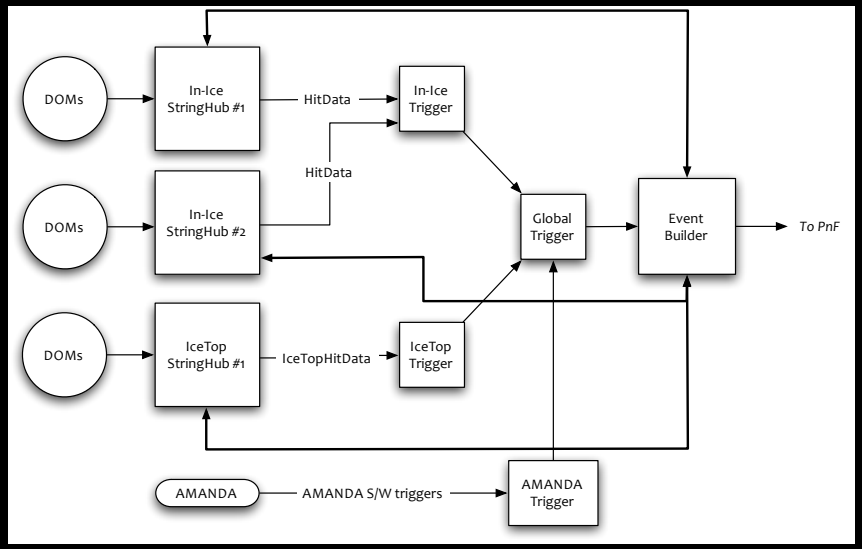
**"Smart" autonomous digital sensor** Versatile FPGA design (Altera Excalibur) with hardcore ARM CPU running embedded system. 4k-hit deep memory buffer stores hits until readout over 1 Mbit digital link to surface.

**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

# Data Acquisition / Triggers




| Trigger Name | Description |
|---|---|
| Simple Majority | Coincidence of M hits in time window T |
| Calibration | Form event around hits of specific type (flasher hits) |
| Cluster | Coincidence of M hits in N along string also in time window T |
| Cylinder | Coincidence of M hits in cylindrical volume in time window T |
| SlowMP | Slow particle trigger |

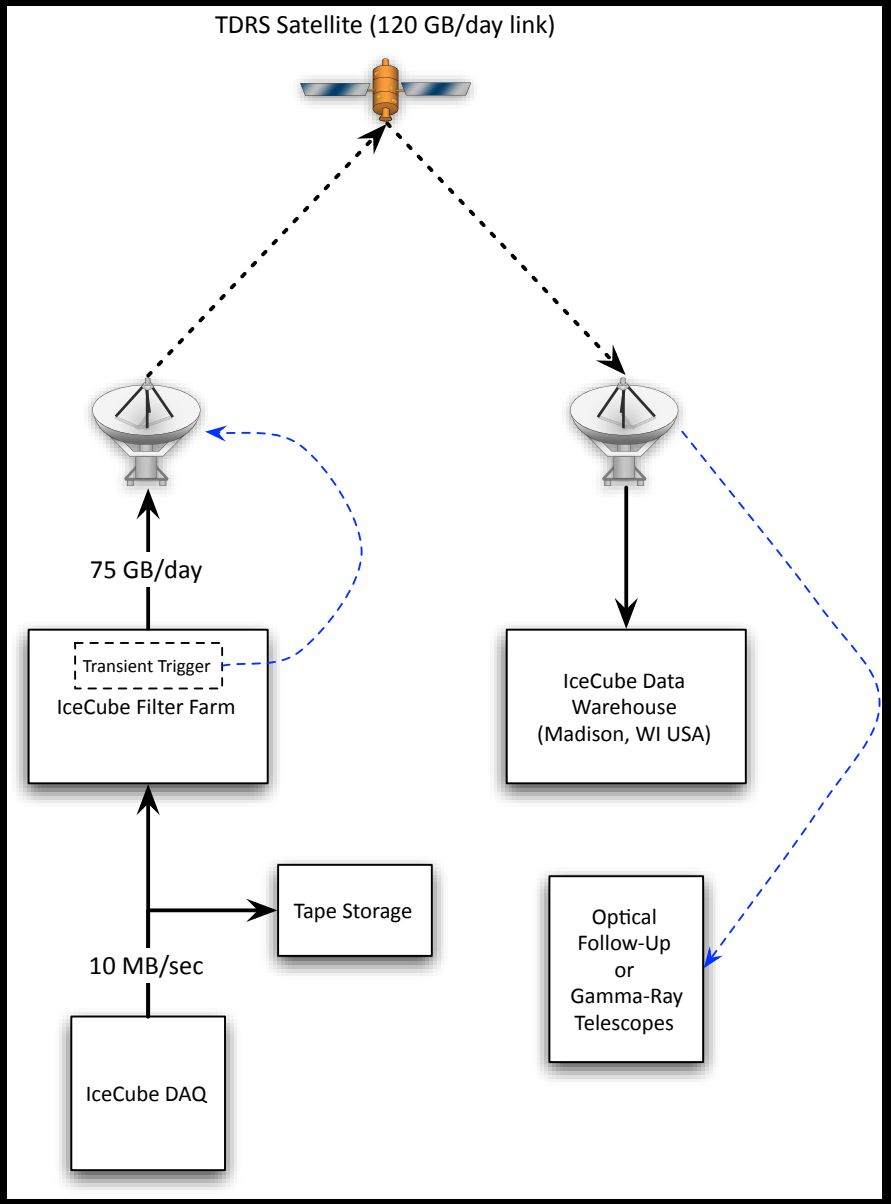
Surface DAQ is networked conglomerate of Java user-space applications except for Linux kernel driver to custom readout cards which talk to DOMs. DOMs send hits asynchronously: that is the hits are time-stamped to ns precision but can arrive milliseconds or even seconds later at the surface due to buffering in the ice. The surface software must re-assemble these O(5000) digital streams.

Each string is serviced by 1 host which reads out data, sends hit summaries to trigger system and buffers full hit data. The triggers may signal the event builder to readout a segment of the buffered data in which case the event builder will create new event, issue readout requests to each computer holding the buffered hit data on a given string, and assemble the fulfilled requests into the event structure which it then writes to disk for processing by downstream systems.

The triggers are software routines limited only by necessity to maintain sufficient throughput for the system. The workhorse trigger for the published analyses has been the trivially simple simple majority trigger (SMT). However, newer more complex triggers which contain reconstruction algorithms looking for specific physics signatures such as slow monopoles have been developed and are expected to deploy with IC86 next year.

Current trigger algorithms only examine those hits with in-ice neighbors (so called “HLC” hits) as they are predominantly not noise and down by 50x in rate. Future triggers (TrackEngine) are looking to mine the isolated hits to recover trigger volume at low energies (< 50 GeV).

# Data Filtering




## Data Filtering

Cluster at South Pole – O(100) cores – filters data in real time. While the raw data stream (>2.5 kEvent / sec, 10 MB/sec) is written to tape which becomes available at the end of the season, it is only used in emergency cases. IC59 / IC79 analyses are based on the SP filter output which arrives daily via TDRS satellite uplink.

Further filtering at the Data Warehouse occurs to produce reduced data products suitable for download by collaborating institutions.

## Supernova Trigger and Target-of-Opportunity

The IceCube online supernova trigger system sends triggers to SNEWS system – worldwide neutrino and gravity wave experiments share reporting of triggers in this manner.

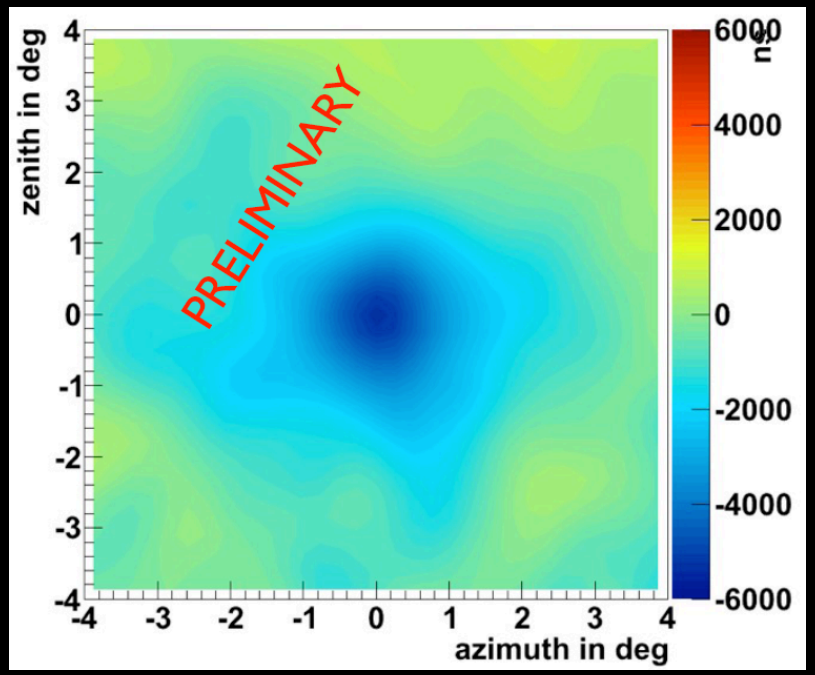
The TeV neutrino ToO program sends triggers to participating optical or gamma ray observatories upon finding well-reconstructed neutrino multiplets.

Strikeout!

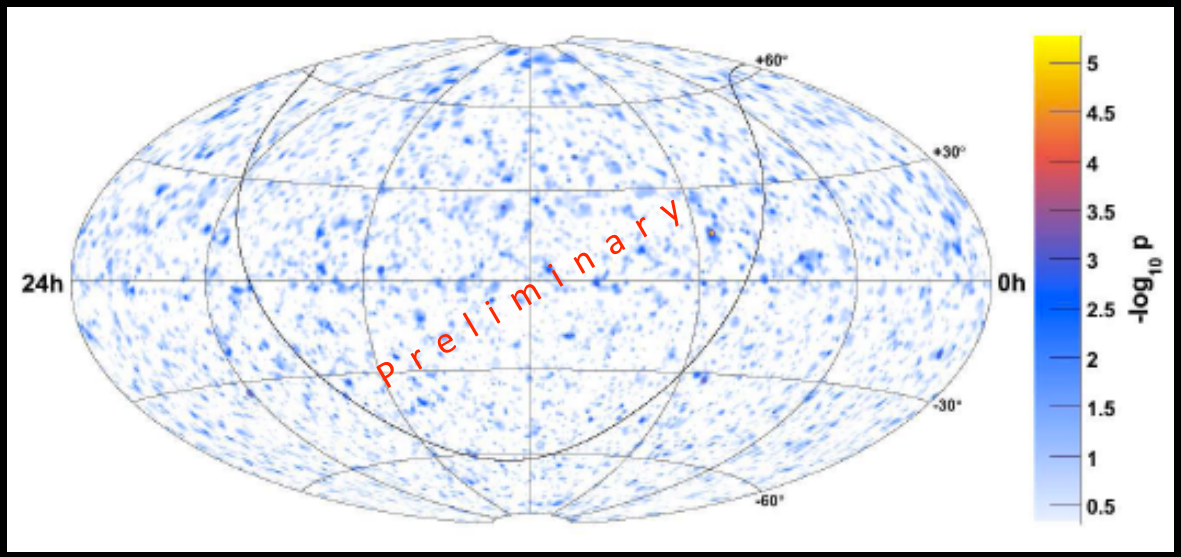
# THE RESULTS : IC-22 / IC-40

# Proof Positive – Measuring the Shadow of the Moon in CR

- The moon occupies 30' of sky and blocks CR. This shadow is often used by CR experiments to
  - Validate hardware and software chain from low levels (e.g. timekeeping) to analysis level: track reconstructions, astronomical coordinate transforms, &c
  - Study detector point-spread function using real data instead of simulation.
- IC40 data analyzed
- Cuts:
  - Moon >= 15° above horizon
  - # DOM >= 12
  - # STR > 2
  - NDIRC >= 6, LDIRC >= 400
  - "Paraboloid error" < 1.6 deg
  - Track reco ±10° in dec and ±40° in R.A. from moon
- 69 M events remain
- Median angular resolution is 1.27° (from sim)
- 10σ deficit of events observed
- Shape of deficit is consistent with input PSF.



# Point Sources IC40 - Results

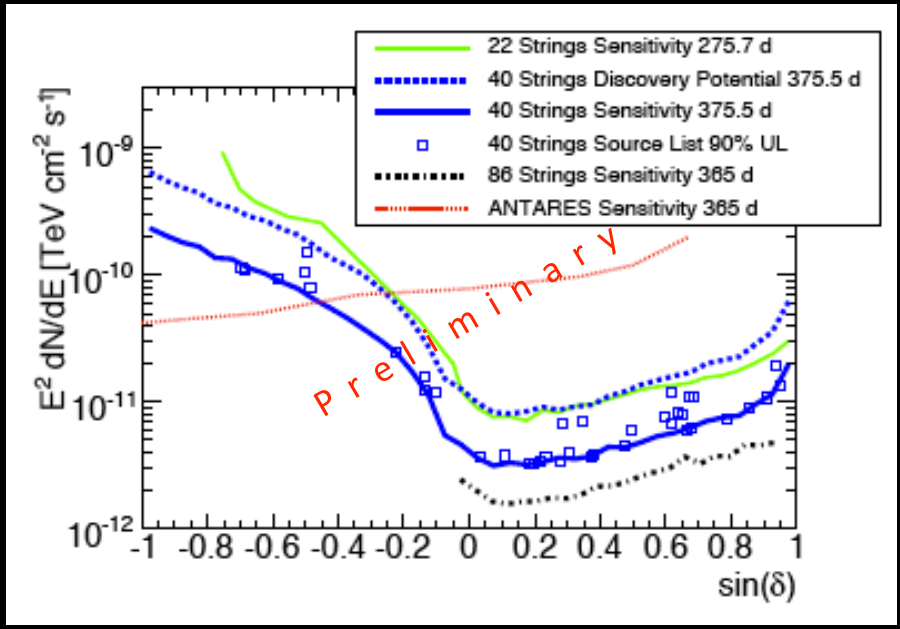



The final sample of events includes 37,000 events:

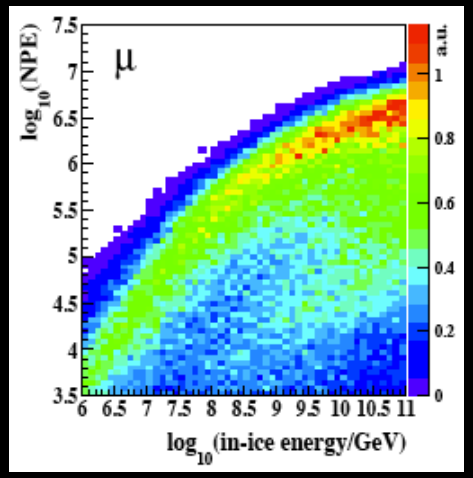
- 14,000 up-going (2.5% background contamination estimated) , and
- 23,000 down-going (mostly all background CR muons)

Skymap of p-values for final sample of events in IC40 PS analysis. Most significant point at RA, dec = (113.75°, 15.15°) is best fit to $E^{-2.1}$ but has post-trial significance of only 0.18 (you get a hotter spot 1/5$^{th}$ of the time for random skies)

This is equatorial coordinates – the galactic plane is indicated by thin black line.



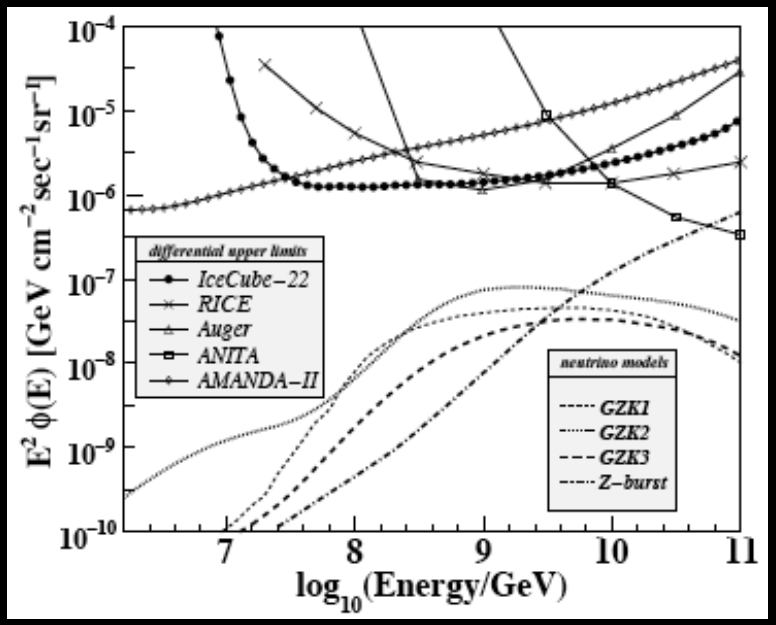
# UHE Neutrino Search – IC22




**Published in Phys. Rev. D82 072003 (2010)**

Results of IC22 EHE (> 10 PeV) search for neutrinos of GZK origin. Very basic track reconstruction and track energy estimation using only total # of detected photo-electrons in event as proxy for energy (see plot top right).

Nevertheless, the results are highly competitive in energy band (50 PeV to 500 PeV) even for limited size of IC22. More to come later with full detector analysis: IceCube could see GZK neutrinos after some years of operation, however better to pursue different techniques as statistics would be extremely limited even in optimistic GZK scenarios.

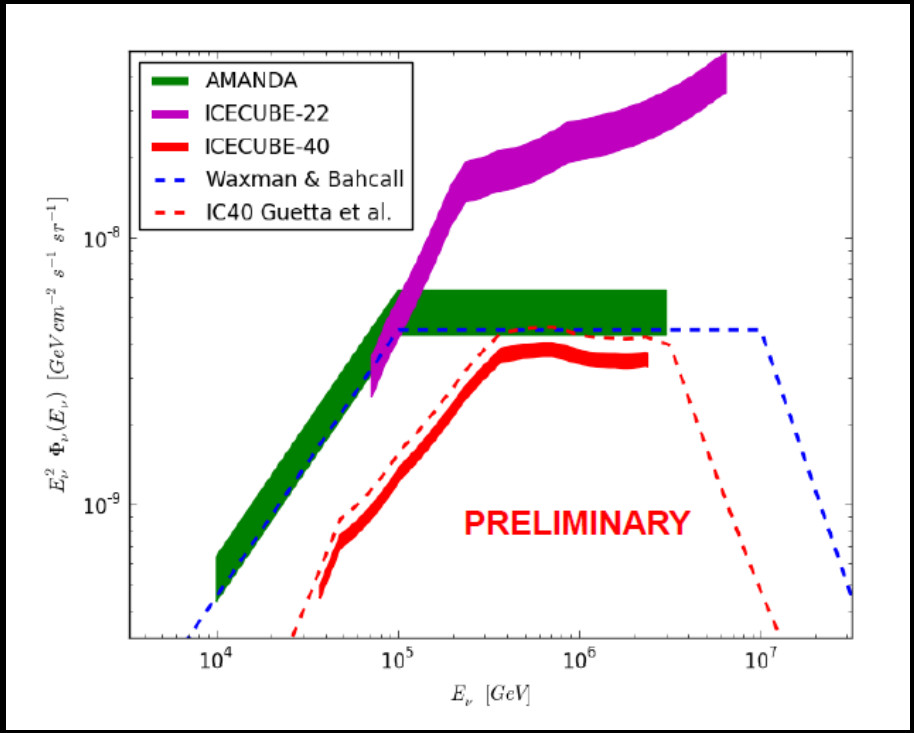


# Neutrinos Coincident with GRB Triggers

GRBs are extremely bright objects that are good candidates for high-energy neutrino production – so called fireball and cannonball models can produce neutrinos in excess of PeV energies. Unfortunately they are typically at redshifts of O(1).

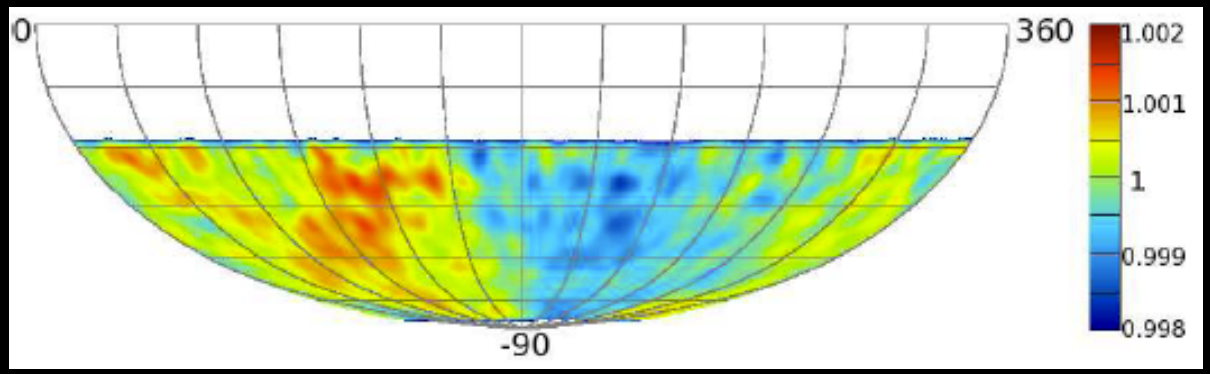
**Idea**: use satellite triggers to winnow down search to specific timeand space-angle interval surrounding burst as reported by satellites. Search only these windows and stack the on-source vs off-source to enhance S/N.

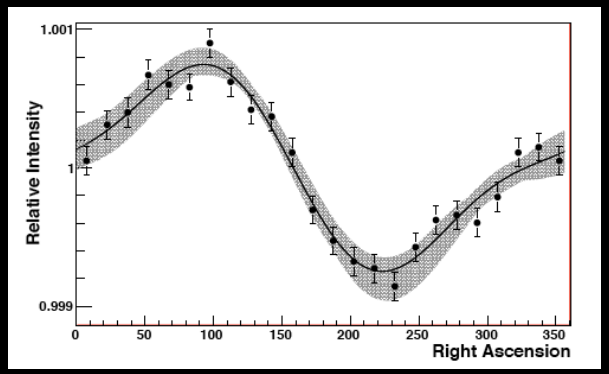
During IC40 run there were 117 bursts that were selected for analysis. Among these triggers there were no coincident neutrino events found within the on-source window within ± 2248 seconds yielding a combined limit which is below the Waxman-Bahcall benchmark flux (flux assuming GRBs were source of all UHE CR).



# Cosmic Ray Anisotropy

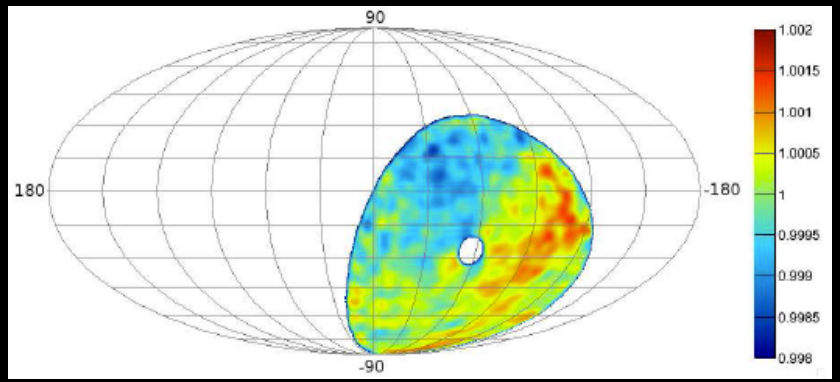
arXiV: 1005.2960 (ICECUBE Collaboration) Accepted by ApJ Letters



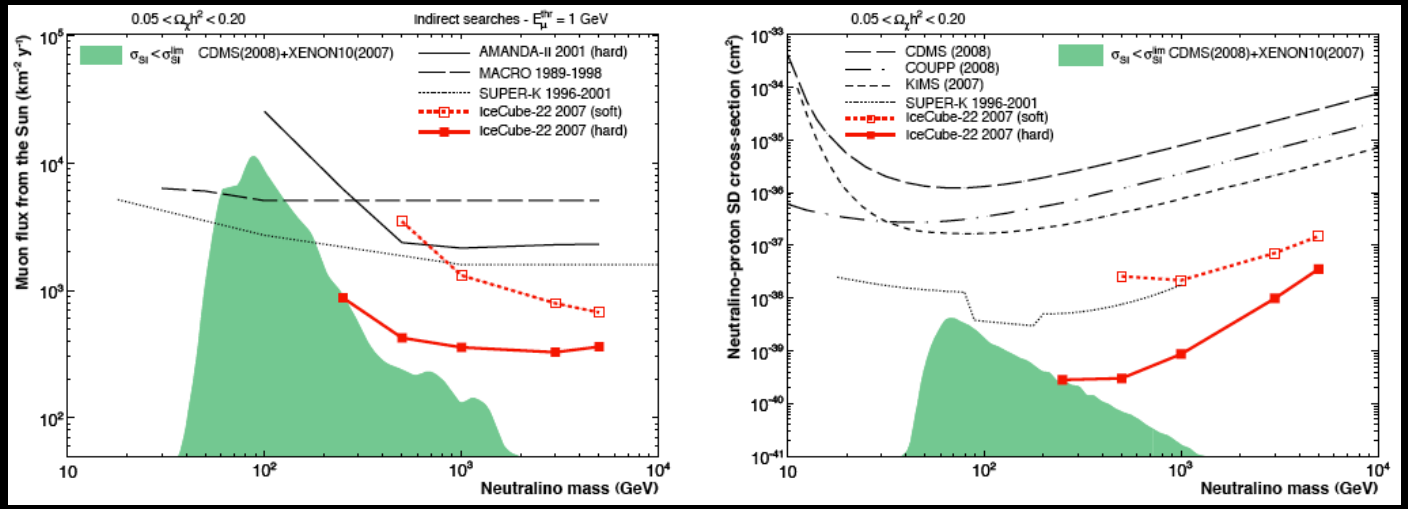



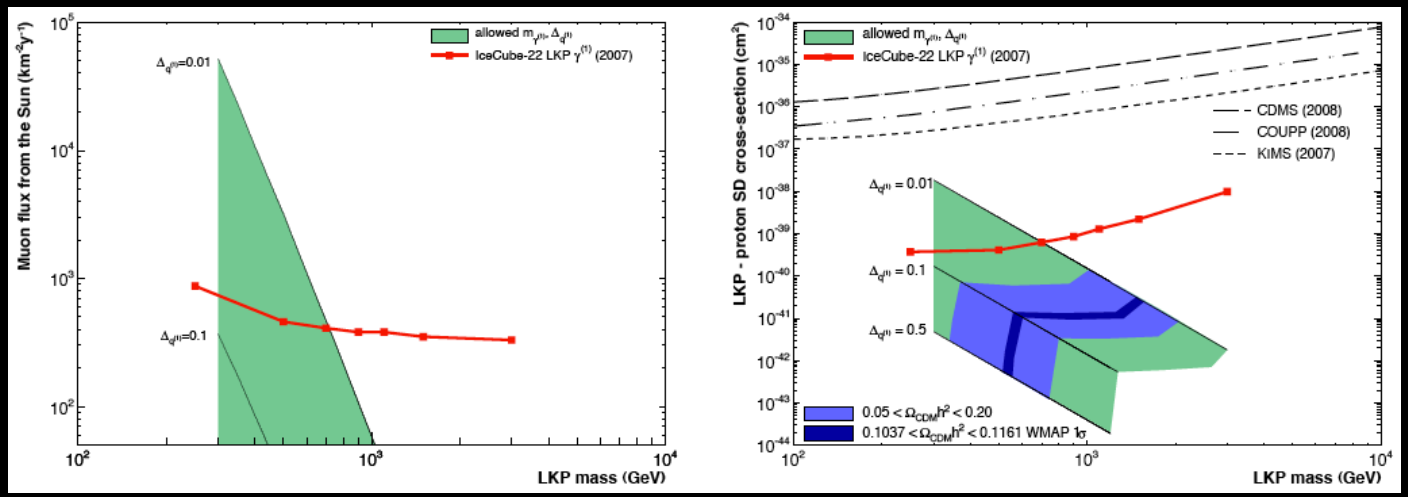

IC22 collected sample of 4.3 billion downward CR muon events with a median energy of 20 TeV – all tracked to median precision of 3°. After accounting for daily and seasonal variations in the rate of muons from changes in the temperature of the upper atmosphere and plotting the high statistics one obtains the partial skymap plotted in equatorial coordinates above and galactic coordinates to the right.

The nature of this anisotropy is unknown but confirms earlier measurements from the Northern Hemisphere (Amenori et. al., Science 314 (2006) 439 and Abdo et. al., ApJ 698 (2009) 2121). It is not due to Compton-Getting nor heliospheric magnetic fields. Possible explanations are galactic magnetic field structure and / or diffusive particle flows from a nearby source.



# Dark Matter Searches – IC22



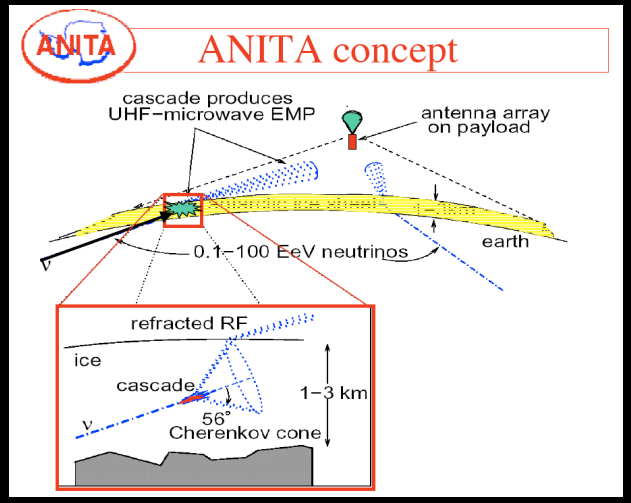



# FUTURE AND SUMMARY

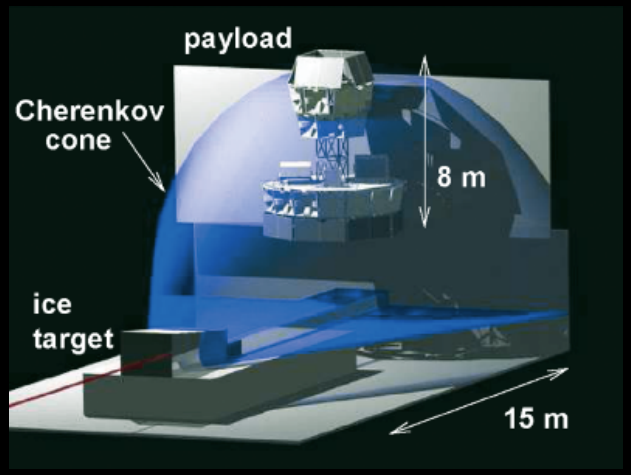
# IceCube Future

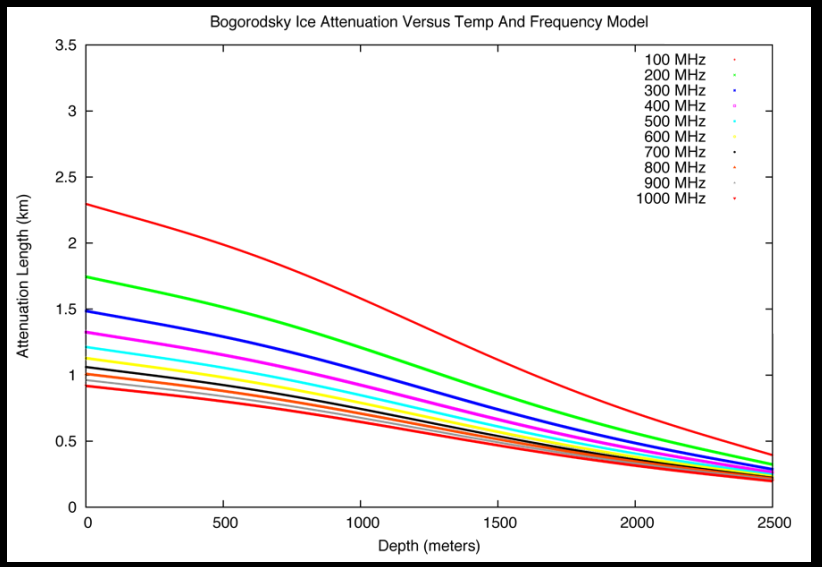
- The experiment has been designed to run for 15 years following completion of the deployment phase. By all accounts the hardware is working well and the failure rate is consistent with > 95% of the array still operational in 15 years.
- At this time there are no concrete plans to extend the array with deployment of additional PMTs, however, the European groups have started discussions to extend DeepCore (density or size).
- New triggers and analysis methods are being developed to increase the physics capability of the current detector. Some of this involves upgrades to the (surface) data acquisition system.
- Deep ice is a good laboratory for other low-background experiments: 2011 – "DM Ice" prototype to be deployed.
- IceCube EHWD will remain mothballed at South Pole for at least one more year. Final disposition of drill uncertain …

# Beyond IceCube : Radio

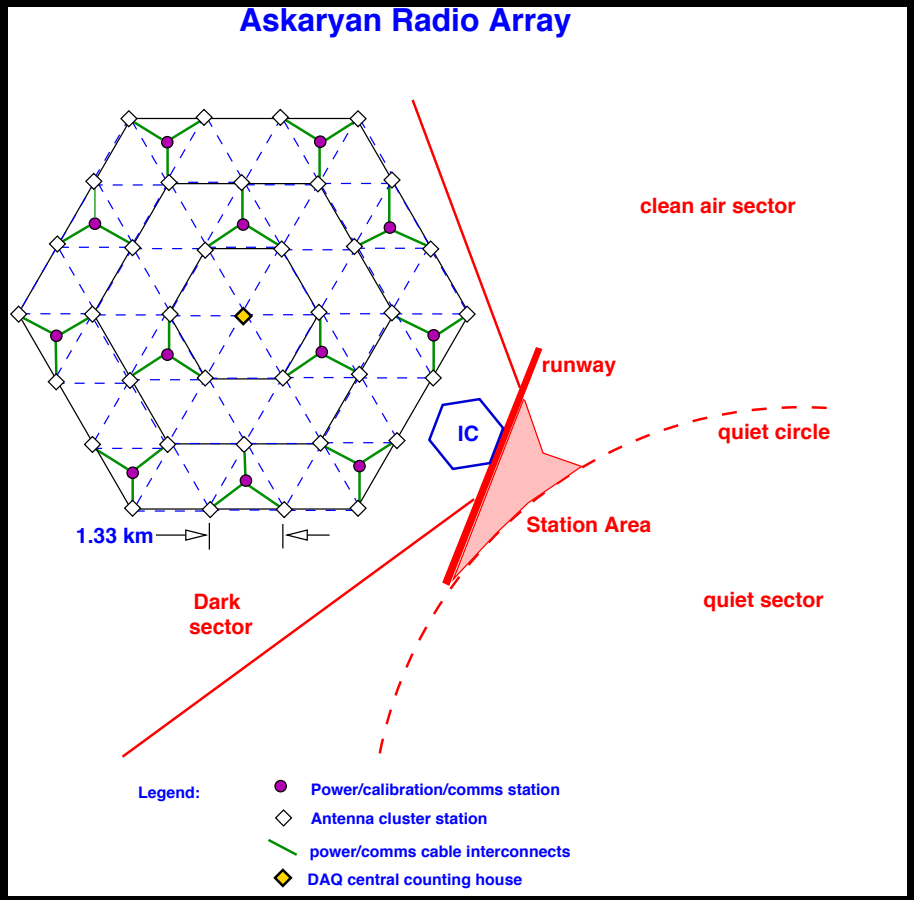



- Optical detection of neutrinos is limited by cost of densely instrumenting large > O(100 km$^2$) areas of ice: detector spacing is dictated by attenuation of optical photons in ice – max 200 m.
- G. Askar'yan predicts optical analog in radio (1960's)
- Effect verified in SLAC test beam – 2000.
- RF attenuation lengths in cold ice are beyond km. Thus possible to sparsely distribute detectors (antennas) across large areas to collect nu.
- ANITA experiment has taken this to the extreme – single cluster of antennas flown aboard balloon payload looking out over vast amounts of ice – has flown two full flights – 2 candidates remain from last flight.

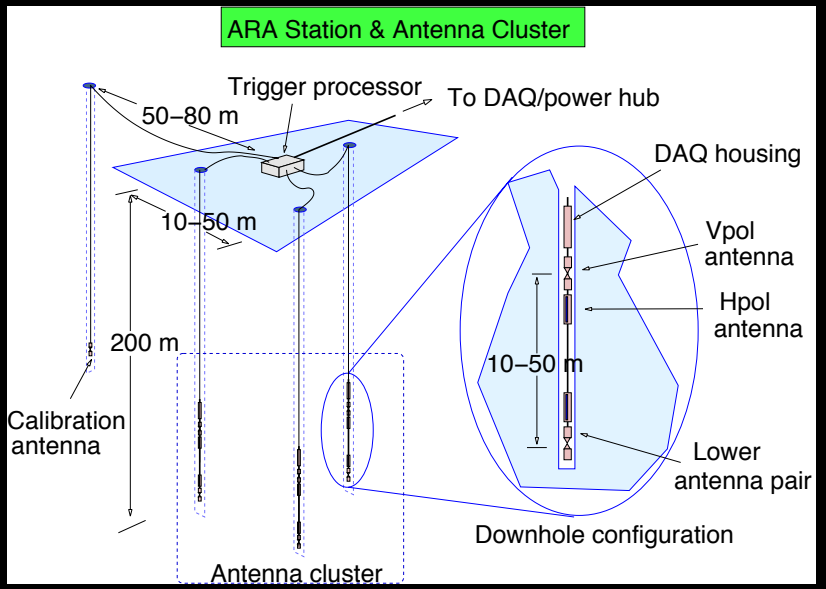


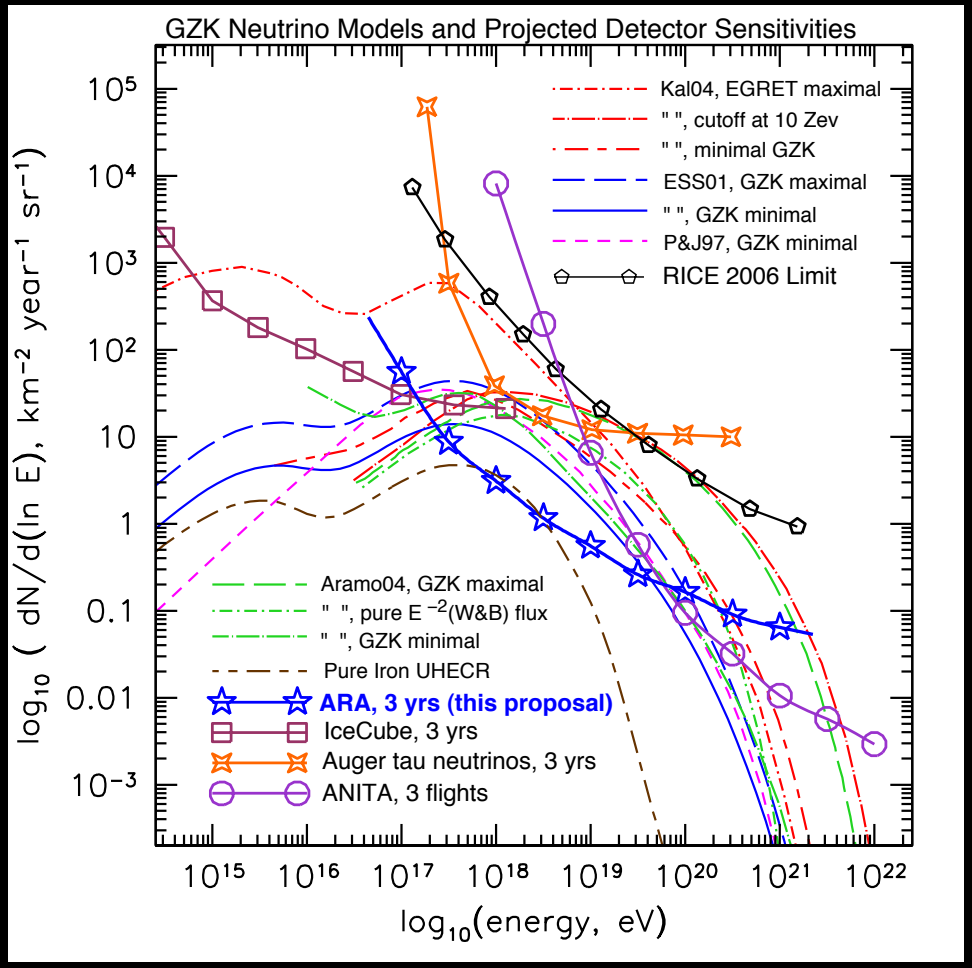
# The ARA Project




- ARA collaboration seeking to build 80 km2 prototype array 2012 – 2015 at South Pole. Consists of shallow array of RF antennas (100 MHz – 1 GHz) buried in hole clusters which lie along vertices of hexagonal lattice with 1.33 km spacing.
- Project is approved for deployment of 2 hole clusters (funds awarded to build up to 9 such prototypes) – in USA and Belgium (FNRS).
- First deployment of test bed station will happen 2010-11 as well as tests of new rapid shallow drill technologies.
- First of two holes 2011-12 season.



# ARA Performance Study



# Summary

- IceCube deployment will be completed in the coming weeks.
- Detector is working well and has proven that it can measure shadow of Moon to match expectations.
- IC22 and IC40 data analysis is producing publications
- IC59 data filtering underway and IC79 data run in progress until approx April 2011. IC86 thereafter.
- No extra-terrestrial neutrino sources identified to this point but (a) it's still early – we have only processed data for 50% detector. Still have yet to see data from DeepCore make it through final analysis level.
- Extensions to IceCube possible – taking unexpected shape thus far with DM Ice prototype
- In the future co-deployment of radio array to look for extremely energetic / extremely feeble GZK fluxes.