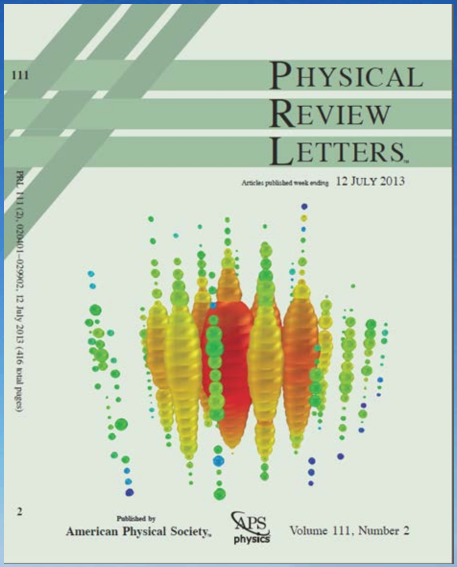
High Energy Astrophysics with Neutrino Detectors

Spencer Klein, *LBNL & UC Berkeley*



Cosmic-rays and Neutrinos

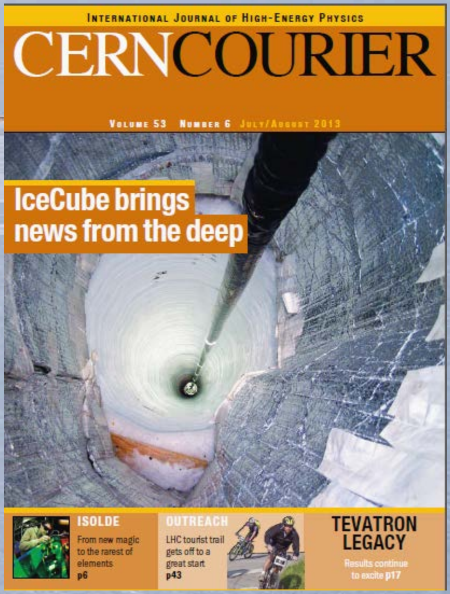
Detector Basics

- Ice and Water
- Finding and reconstructing neutrinos

Atmospheric and Extra-terrestrial neutrinos

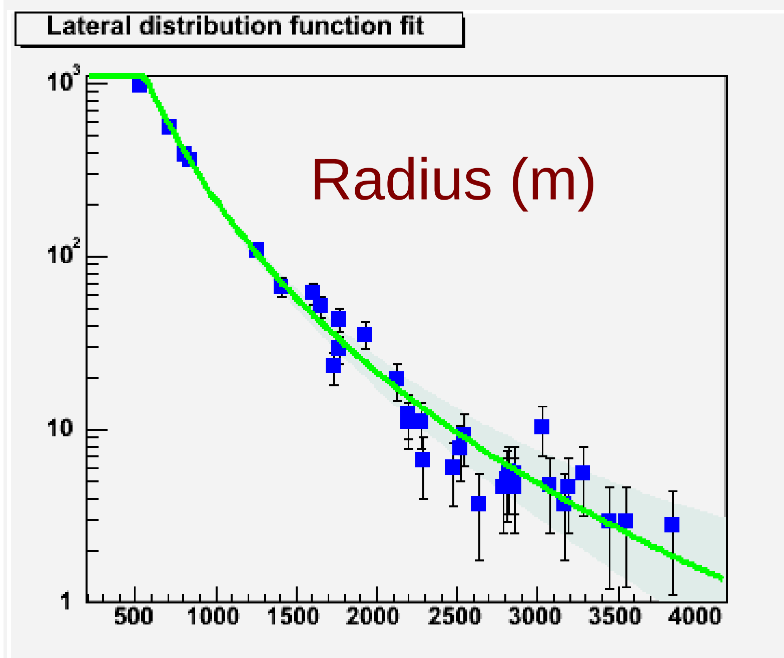
Other Physics

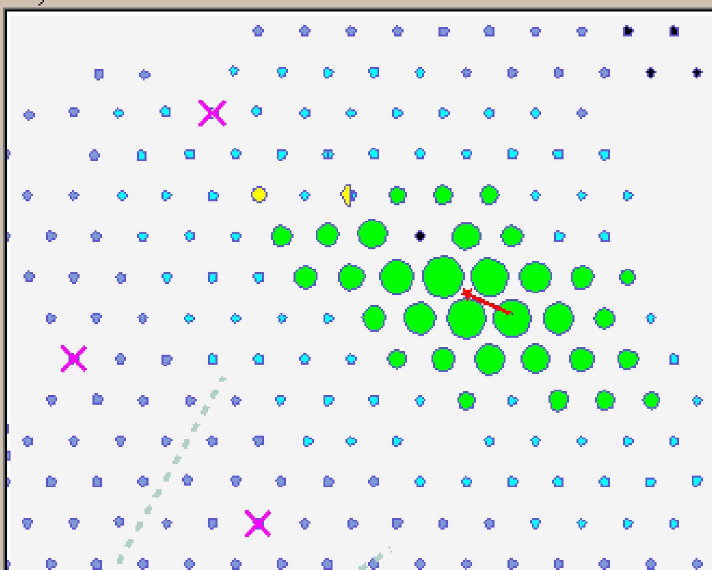
Conclusions



Many physics results are from 2013 ICRC

An Air Shower in the Pierre Auger Observatory





Asilomar (~ to scale)

Friday May 21, 2004

big event, 38 tanks

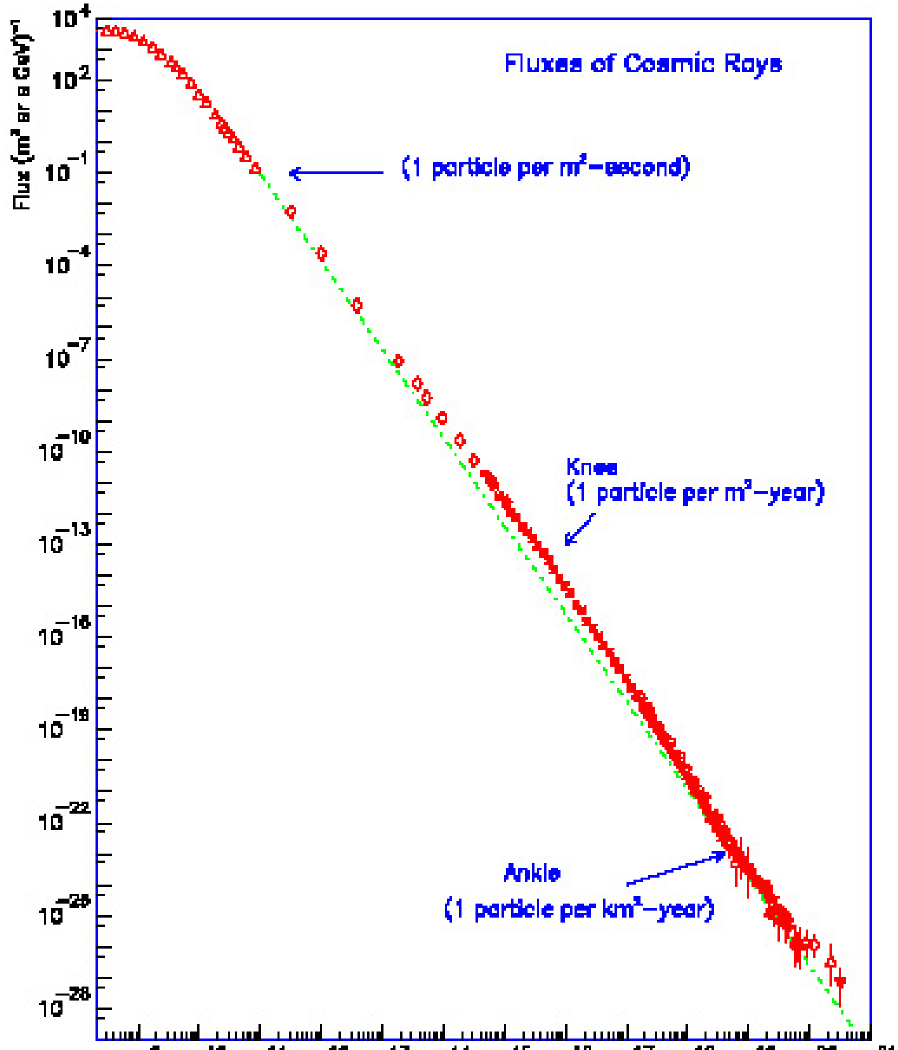
contained in the array

zenith angle ~60°

energy ~100 EeV

Cosmic Rays: An Unsolved Problem

- Observed over 13 decades in energy
- Energies up to $3*10^{20}$ eV
  - 48 Watt-sec
- Above $10^{16\pm1}$ eV, origin and composition are mysteries
  - Probably extra-galactic
- Only indirect composition measurements
  - Below the ‘knee’, <ln A> increases with energy.

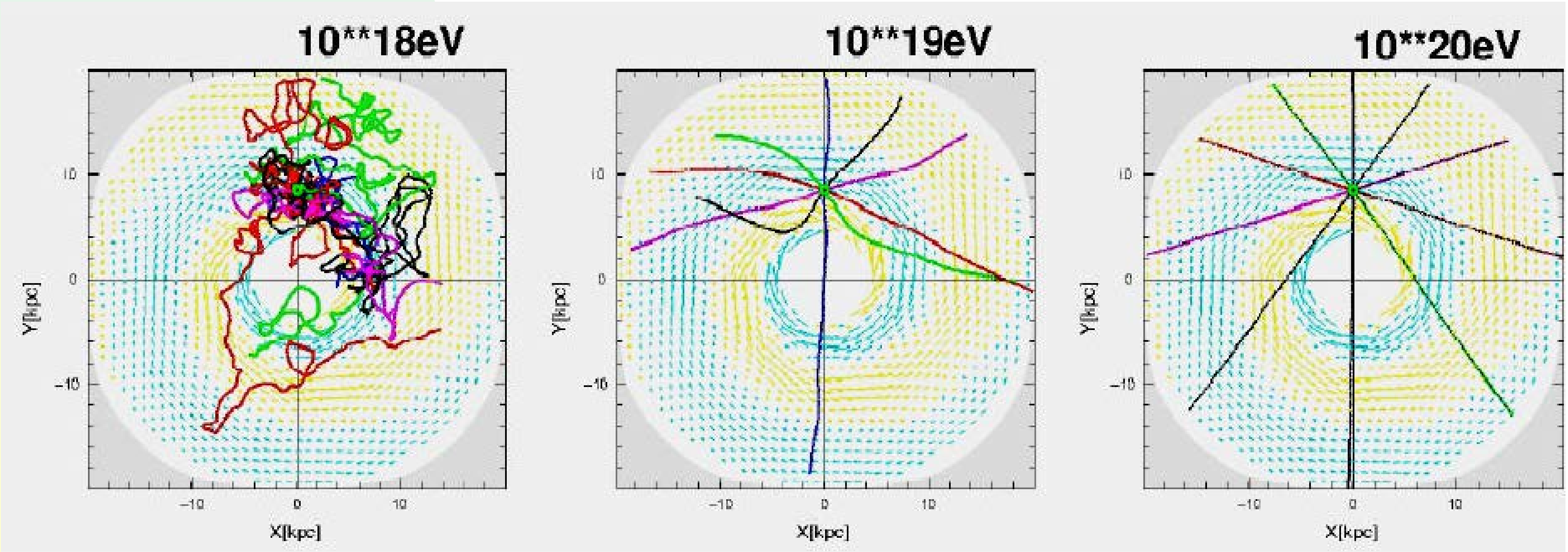


10^{8} eV

10^{21} eV

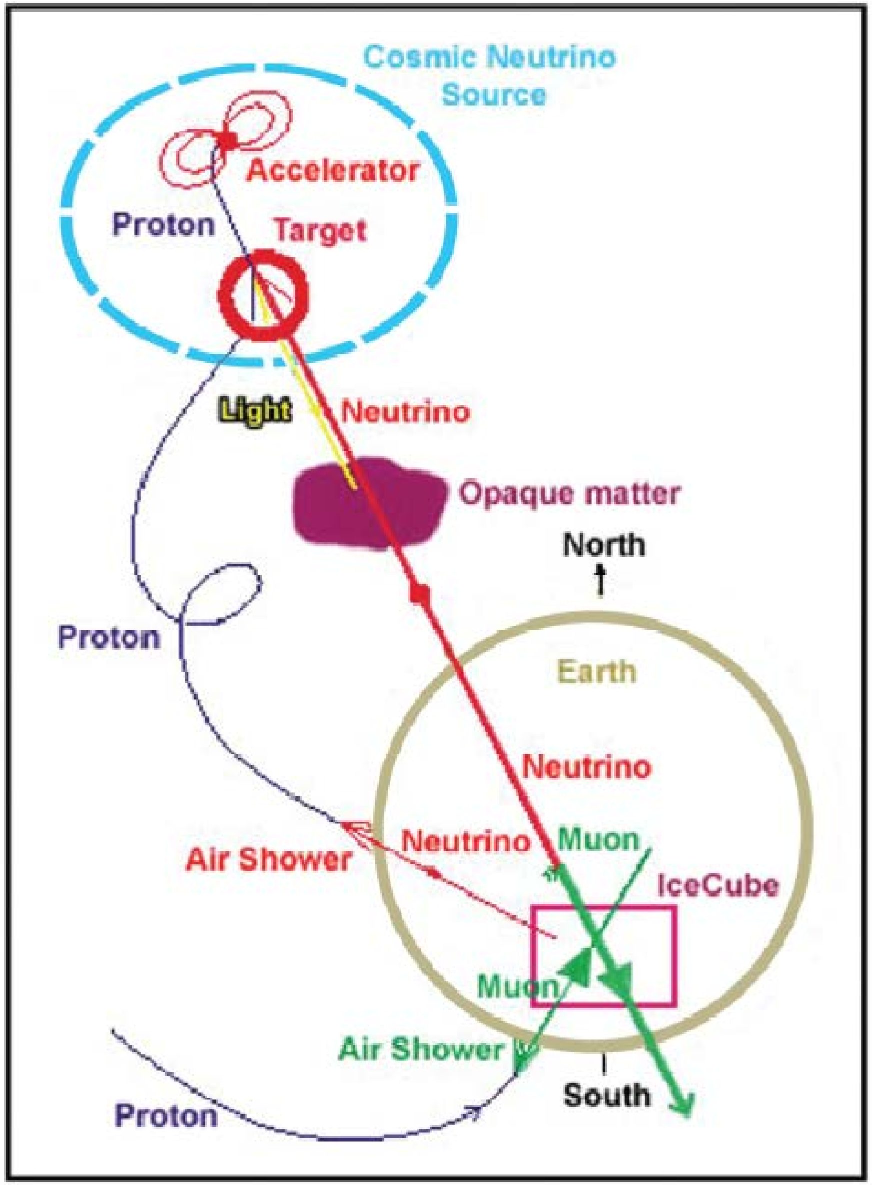
Cosmic Ray Propagation in the Galaxy

- Ions bend in the Galaxy's magnetic field
  - $\Theta \sim B/ZE$
- Below 10^{19} eV, cosmic rays do not point to their source
  - At higher energies, it depends on the simulation parameters, especially the assumed B field
  - EHECR searches have not observed any clear anisotropy

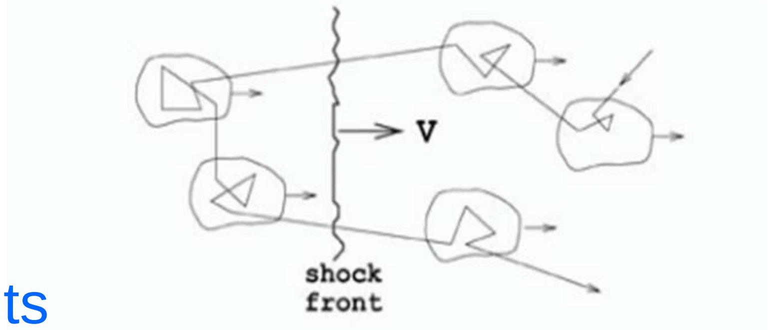


Neutrinos probe CR sources

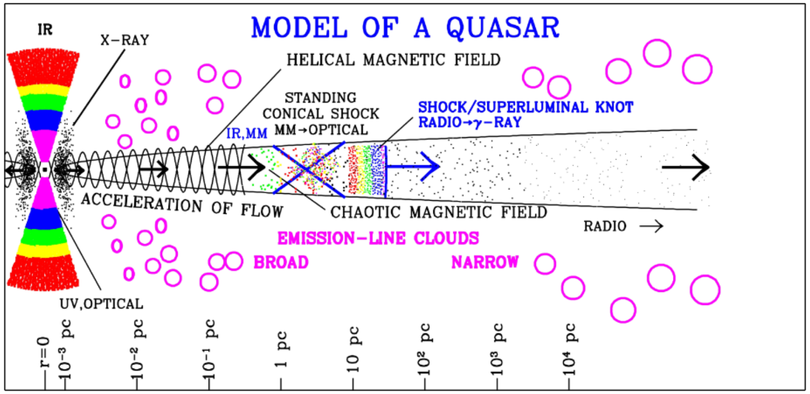
- Photons are absorbed by matter at the source and interact with cosmic microwave photons in transit
  - γ (TeV) γ (IR) --> e^+e^-
  - PeV photons interact w/ CMBR
- Charged cosmic rays are bent in transit
  - For E>40 EeV there is also absorption
- ν come straight to us
- Cross sections are small
  - A large detector is needed



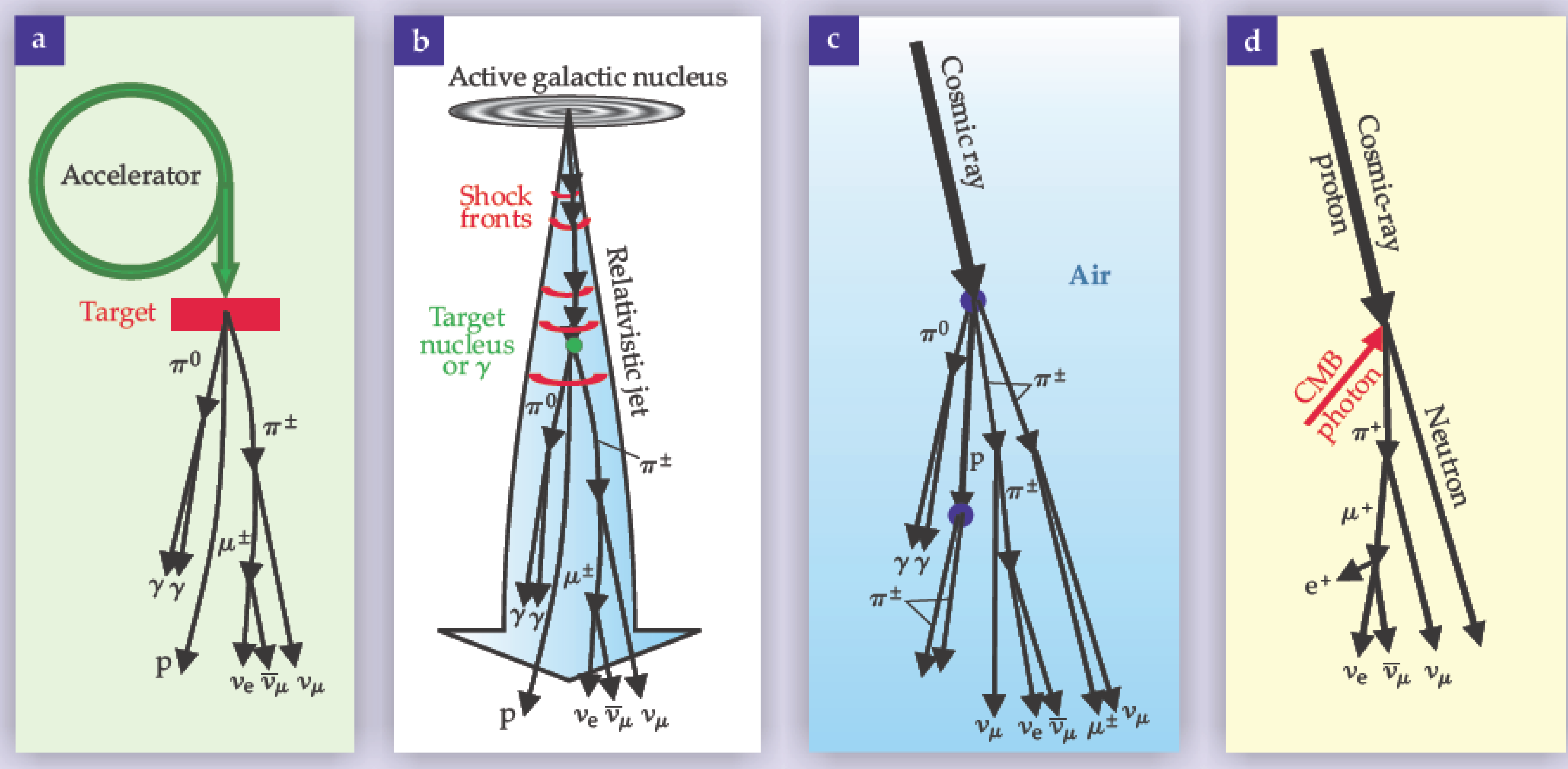
Acceleration Mechanisms



- Fermi shock acceleration
  - Repeated encounters with shock fronts
- Circular
  - A strong magnetic field confines particles while they are accelerated
    - B*L determines maximum energy
      - Hard to get energy $>10^{20}$ eV
  - e. g. in supernova remnants
    - Photons seen with E>10 TeV
- Linear
  - Acceleration in a relativistic jet
    - Lorentz boosted shock fronts allow very high accelerating gradients
  - e.g. in active galactic nuclei
  - Plasma wave acceleration also proposed



ν production



"GZK" neutrinos

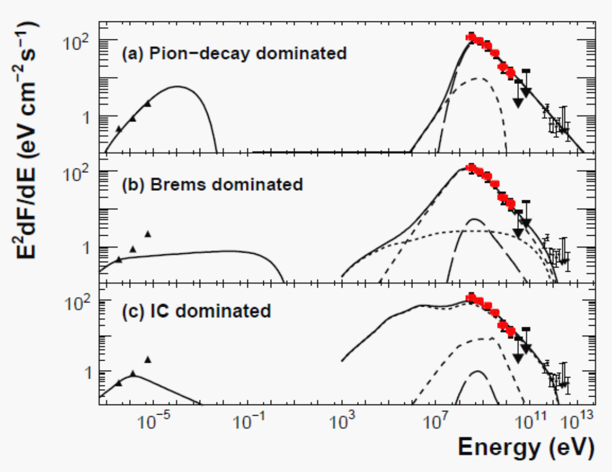
Prompt ν from charm also contributes at high energy

β decay of A>1 isotopes may also contribute

Most experiments can't distinguish between ν and anti-ν; I will lump them together here.

ν production in supernova remants

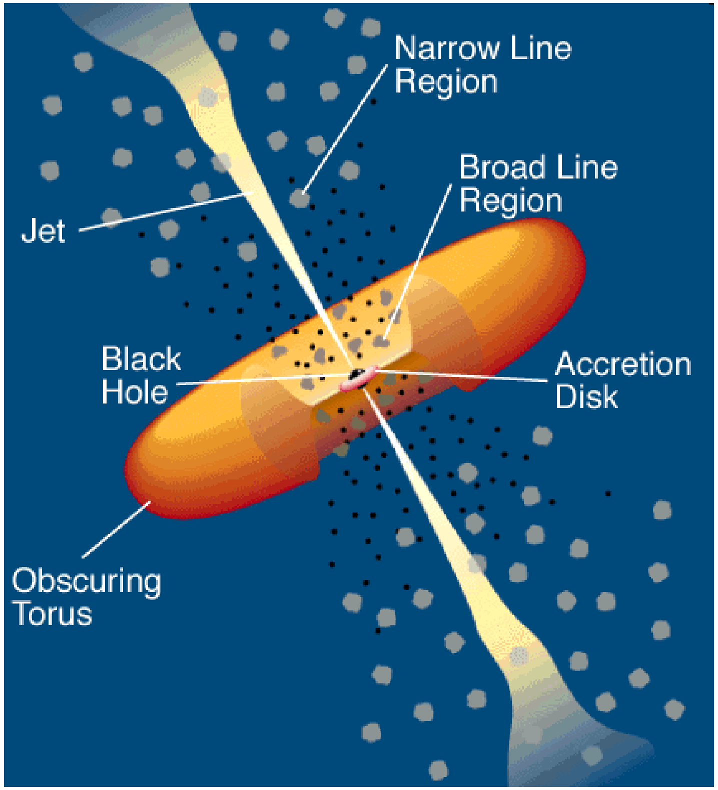
- Supernova remnants (SNR) have strong magnetic fields, surrounding plasma and accretion that can power acceleration.
- SNR are sources of TeV photons.
- Data from W28 & IC443 show a photon spectrum peaked at ~ 70 MeV, and consistent with π^0 decay.
  - Good evidence for hadron acceleration.
- The cosmic-ray composition is consistent with a SNR origin & leaky box model.
  - SNR are powerful enough to produce the cosmic-ray flux, at energies up to the knee.
- Magnetic fields allow confinement up to ~ $10^{16(\pm 1)}$ eV. SNR can probably not explain the highest energy cosmic rays.



SNR W-28
Fermi-LAT, arXiv:1005.4474

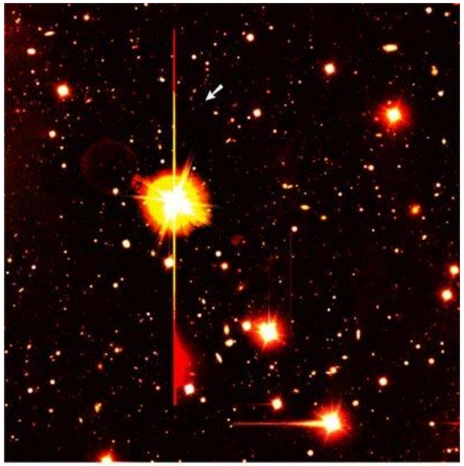
ν production in active galactic nuclei

- Galaxies containing supermassive black holes
  - Accretion powers a relativistic jet
- Scale TeV photon data to estimate ν spectra
  - Estimate γ absorption
  - ν attenuation in earth
  - Assume γ come from π^0
- Total of ~ 1,000 upward ν_μ/year from all AGNs
  - with E_ν > 1 TeV
  - Diffuse Flux
  - Are individual AGNs visible?



R. Gandhi, C. Quigg, M Reno and I. Sarcevic, 1996

ν production in gamma-ray bursters



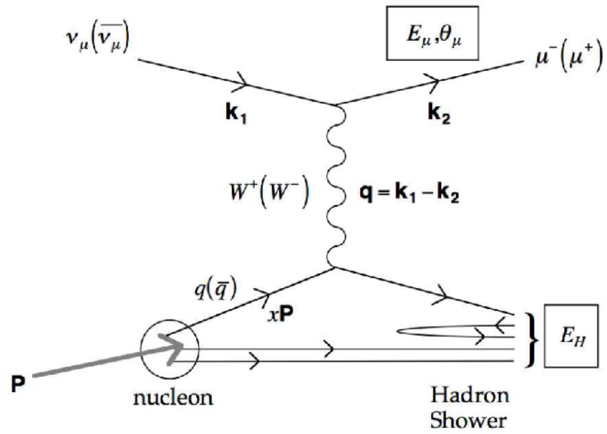
- Burst of γs with energies up to at least 10 GeV
  - Durations from seconds to minutes
    - Allows nearly background-free searches
- Colliding compact objects (e.g. neutron stars/black holes)
  - Short duration (<2 s)
- ‘hypernova’ – collapse of a supermassive star
  - Long duration (>2 s) (modulo some recently seen bursts)
- γ and ν emission predicted up to very high energies
- Estimate rate on a burst-by-burst basis using measured burst characteristics
  - IceCube ruled out circa 2012 models, but there are new ones

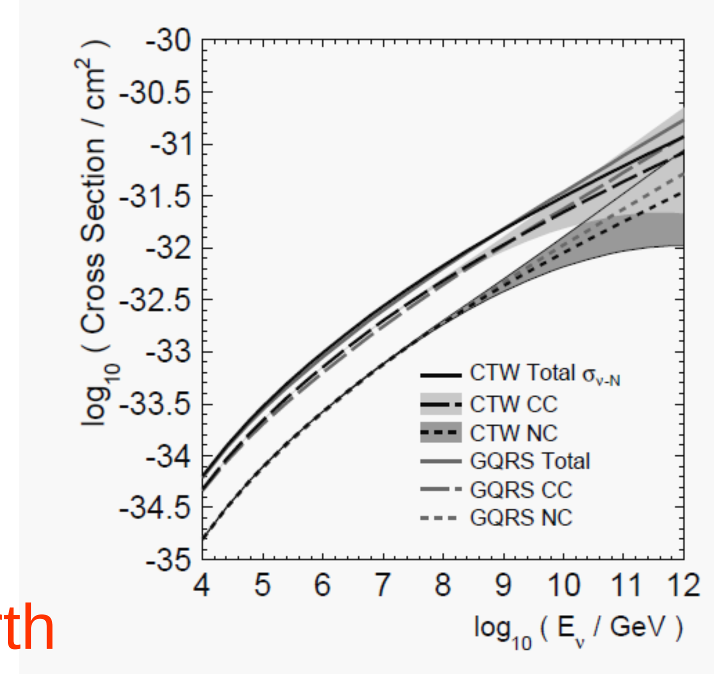
ν flux predictions

- Cosmic-ray acceleration occurs in low-density matter
  - 'beam-gas' or beam-photon interactions
- Produced π and K decay before they can interact
  - $\pi^{\pm}, K^{\pm} \rightarrow \mu\nu_\mu$, $\mu \rightarrow e\nu_e\bar{\nu}_\mu$
    - ν vs ν-bar difference usually neglected
    - c, b --> $l\nu X$ is often neglected
- Two approaches to calculate ν flux:
  - CR spectrum & target source density
    - N(ν) <= N(CR)
      - Except for 'quenched' sources, not visible as CR
      - Maximum ν energy is a few % of ion energy
  - Assume photon production from $\pi^0 \rightarrow \gamma\gamma$
    - Use measured photon flux & equality of $\pi^{\pm}$ & π^0 production
      - Avoids uncertainty due to CR composition
      - Complications from photon absorption

ν reactions and cross-sections

- Charged-current & neutral current deep inelastic scattering
  - In high-energy CC, 80% of energy goes lepton, 20% to hadronic shower
  - In NC, fraction deposited in target, rest escapes
- Cross section rises linearly with energy up to E_ν ~ few PeV, then rises more slowly
  - Acceptance increases rapidly with energy
- Main uncertainties are in the parton distribution functions at small Bjorken-x
- Measure, via neutrino absorption in Earth



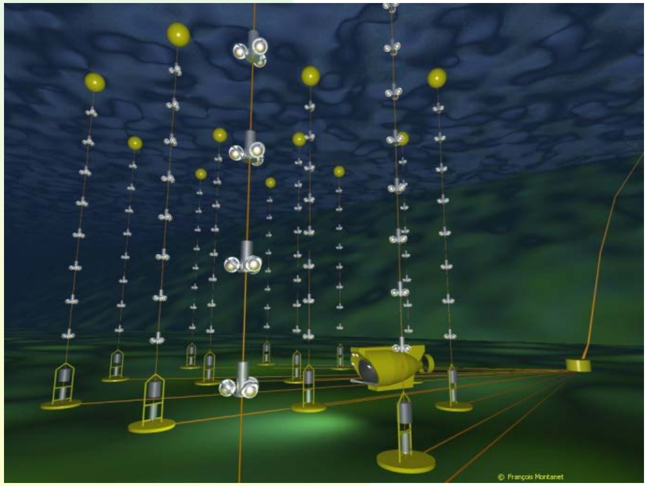


Connolly, Thorne & Waters, PRD 83, 113009 (2011)
Similar calcs by Cooper-Sarkan, Mersch & Sarkar

Detector Basics

- A 1 km^3 detector has a good chance to see extraterrestrial signals
- Only natural media are affordable
  - Water or ice
- Cherenkov radiation from charged particles
  - Sparse sampling optical detectors
  - Spare sampling radio for $E>10^{17}$ eV

NESTOR



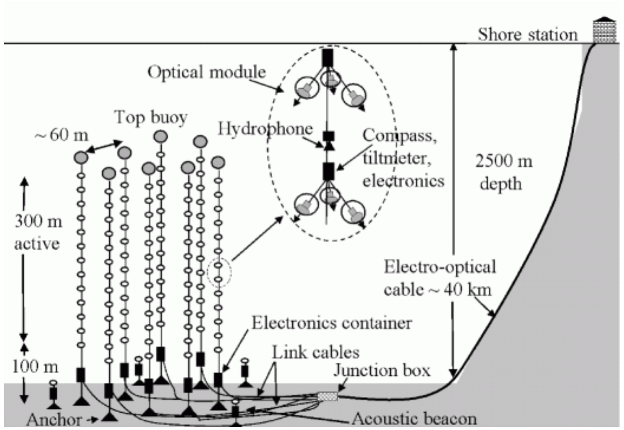
ANTARES

AMANDA

Ice vs. Water

Property	**Ice**	**Water**
Noise Rate	Low (300 Hz)	High (>30 kHz)
Homogeneity	Dust layers	Ocean currents
Purity	High	40K, bioluminescence
Scattering Length	Lower (30 m)	Higher
Angular Resolution	$< 1^0$ at high energy	$<0.3^0$ at high energy
Absorption Length	Higher	Lower
Deployment	Hot water drill	Remotely operated underwater vehicle or winches (Baikal)
Location	South Pole	French Riviera
Example	IceCube, AMANDA	DUMAND, Lake Baikal, NESTOR, NEMO, ANTARES, NESTOR

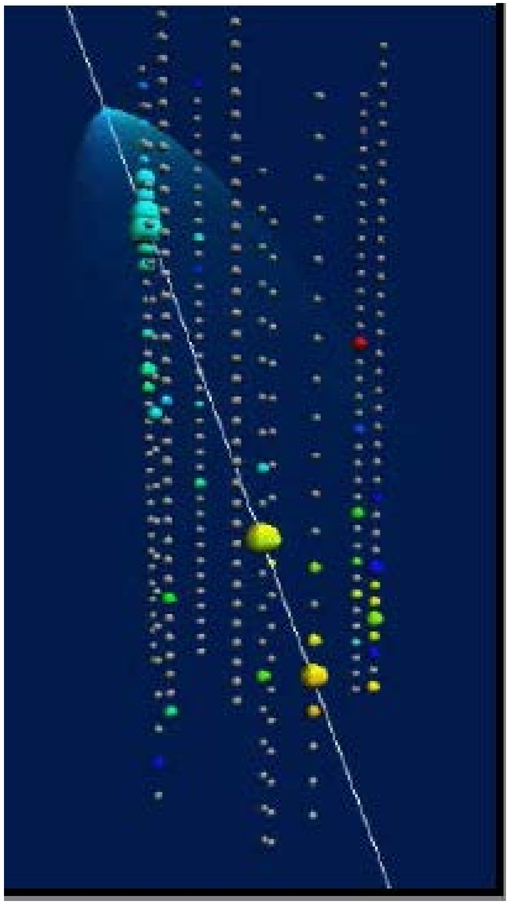
Water detectors



- Very high (> 10 kHz) rates from ^{40}K and bioluminescence.
  - Additional noise hits complicate reconstruction
  - Dead times during strong bioluminescence
- Longer scattering length gives more ‘direct’ (unscattered) light, allowing for better angular resolution
- Detectors are (marginally) accessible, using remotely operated vehicles
- ANTARES is taking data with 12 strings
  - 2500 m deep, 40 km off the coast of Nice, France.
- Proposed KM3NeT will instrument 5-6 km^3 in Mediterranean
  - Northern hemisphere provides ‘overhead’ view of galactic center.

Ice Detectors

- Pioneered by AMANDA (1992)
  - Observed atmospheric ν_μ
  - Learned many lessons
- Ice is inhomogenous
  - Air bubbles @ < 1,000 m deep
  - Dust layers cause scattering
- Ice has a long absorption length
  - But scattering is significant
- Cold & Dark --> Low Dark rates (1 kHz)
- Transmission to surface nontrivial



A μ in AMANDA

The IceCube Collaboration

International Funding Agencies

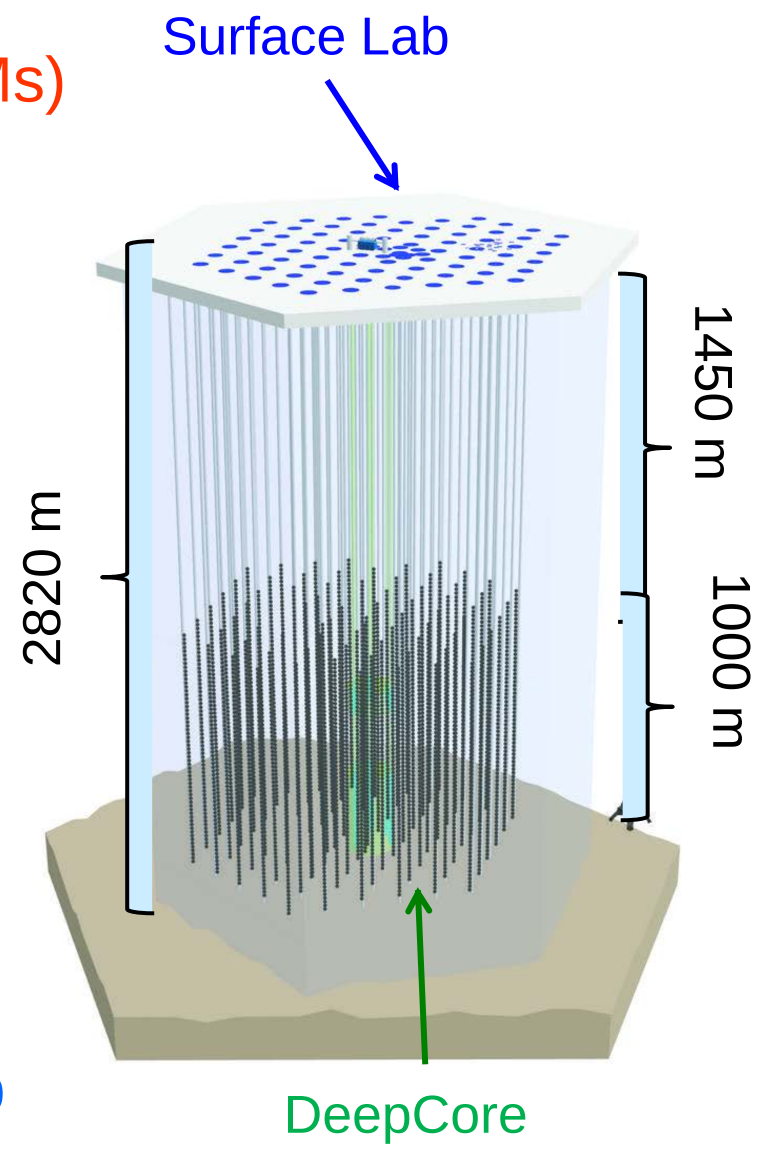
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)

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)

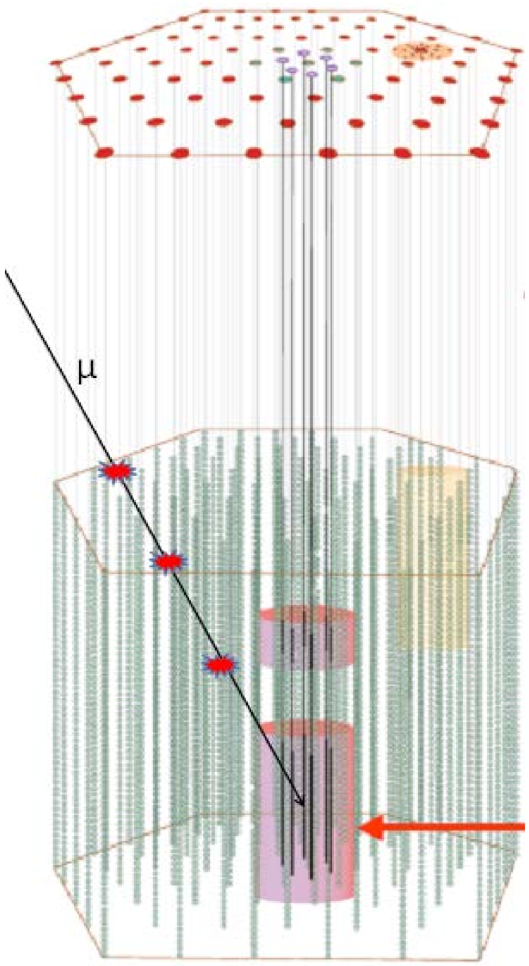
IceCube

- 1 km^3 neutrino observatory
- ~5160 digital optical modules (DOMs)
  - 10" phototube in a 13" sphere
  - 86 strings with 60 modules
    - 78 on a 125 m hexagonal grid
  - 1450 to 2450 m deep
- 160 station - 1 km^2 surface array
- Construction completed December, 2010
- 98% of DOMs working perfectly
  - Another ~ 1% functional
  - Only 2 DOMs failed in 2012
- 99% live time
  - No physicists around to mess up hardware.

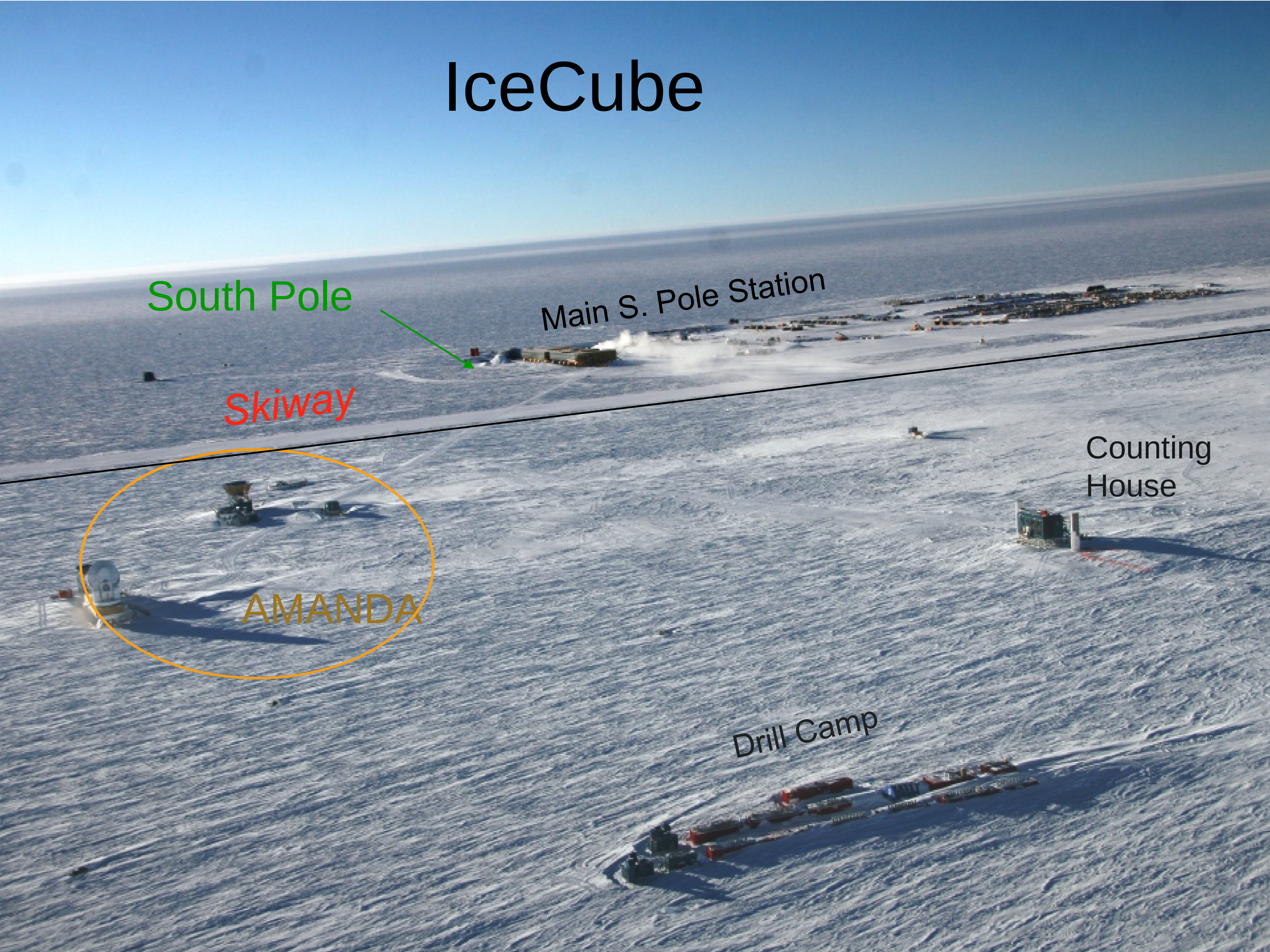


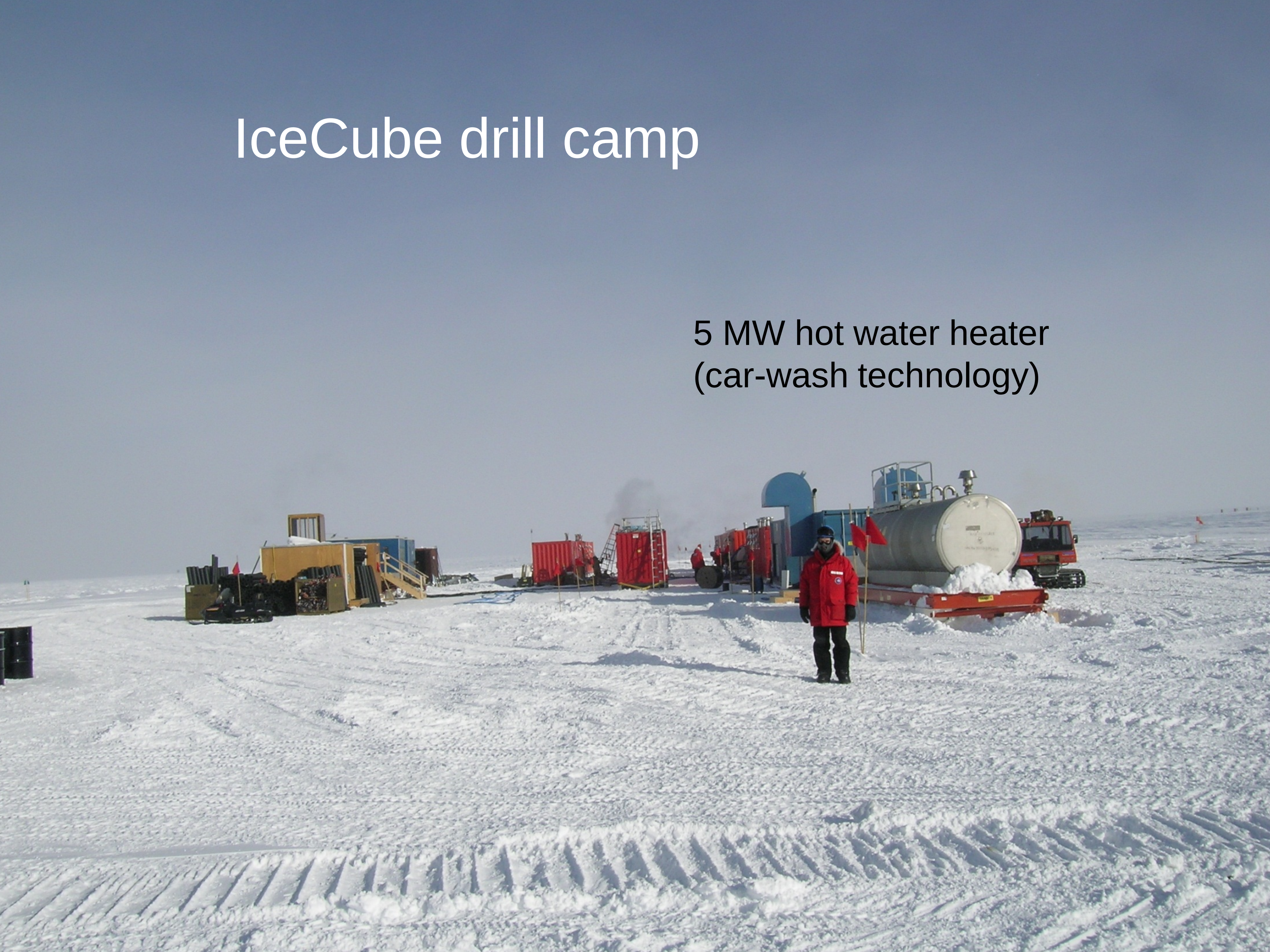
“DeepCore” low-energy infill

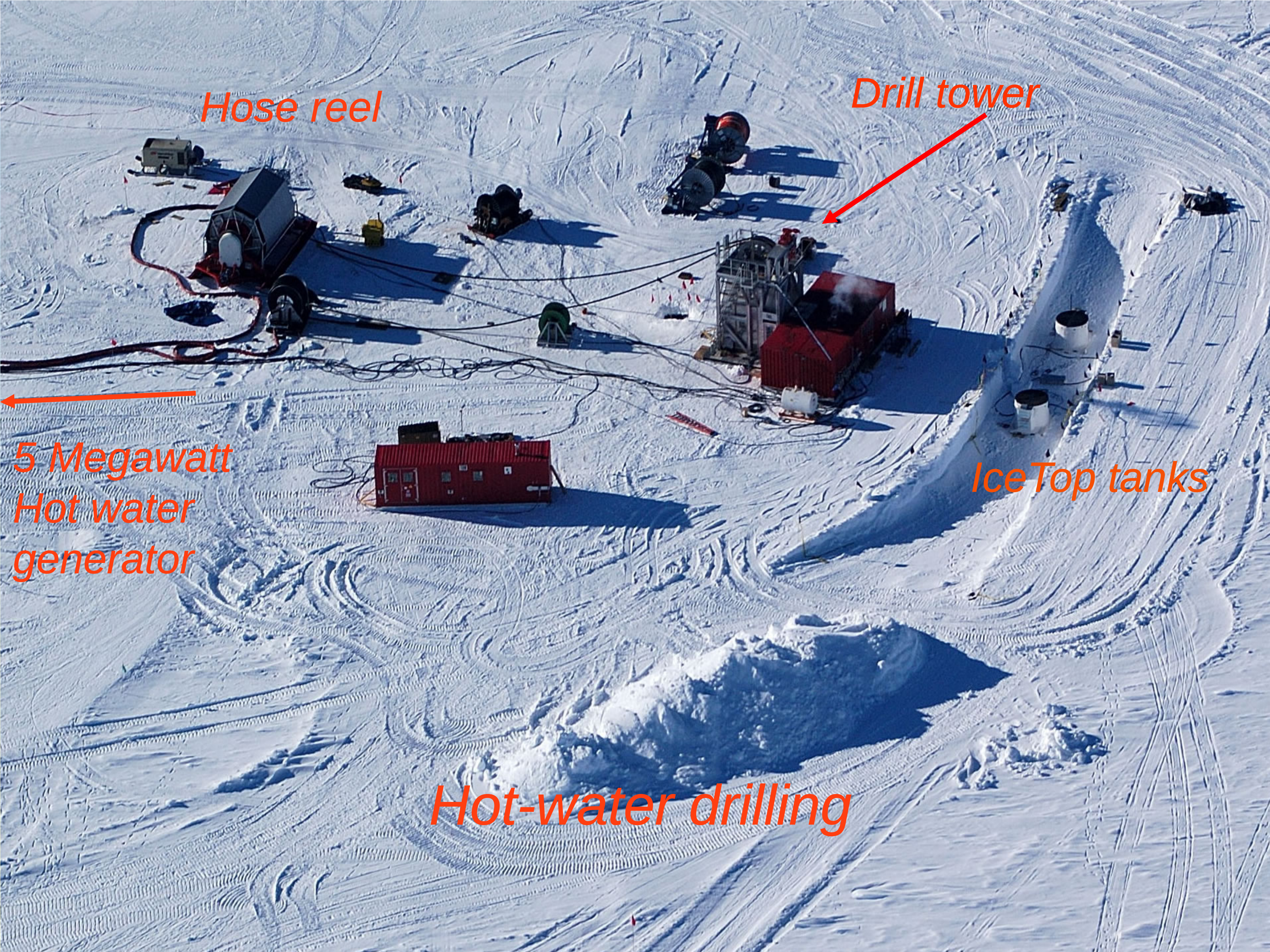
- A small, higher-density subarray
- Energy threshold down to ~ 10 GeV
- 6+2 new strings with high quantum efficiency DOMs on a 7 m spacing near the bottom of the detector
- Uses the rest of IceCube as a veto
  - DeepCore top DOMs also contribute
  - Reject cosmic-ray events
  - Look for events that start in the detector



IceCube

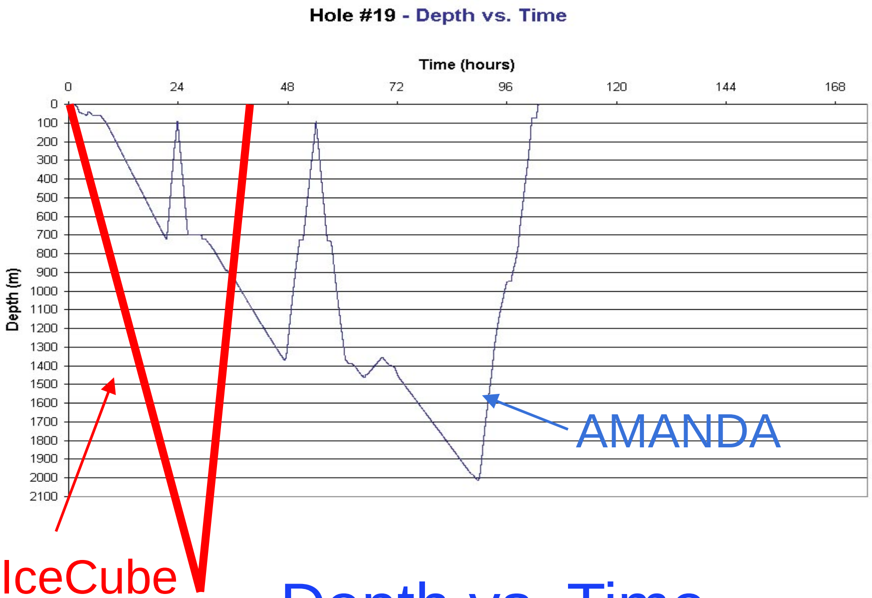

South Pole
Main S. Pole Station
Skiway
Counting
House
AMANDA
Drill Camp


IceCube drill camp
5 MW hot water heater
(car-wash technology)


Hose reel
Drill tower
5 Megawatt
Hot water
generator
IceTop tanks
Hot-water drilling

Hole Drilling

- 2500 m deep, 60 cm dia. holes
- 5 Megawatt hot water drill
  - (Mostly) reliable operation
- Single heater, hose, two towers
  - Set up one, drill with the other
- Speeds to 2.2 m/minute
  - ~40 hours to drill a hole

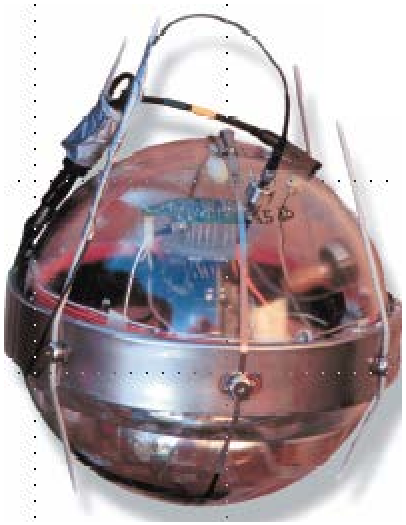


Depth vs. Time

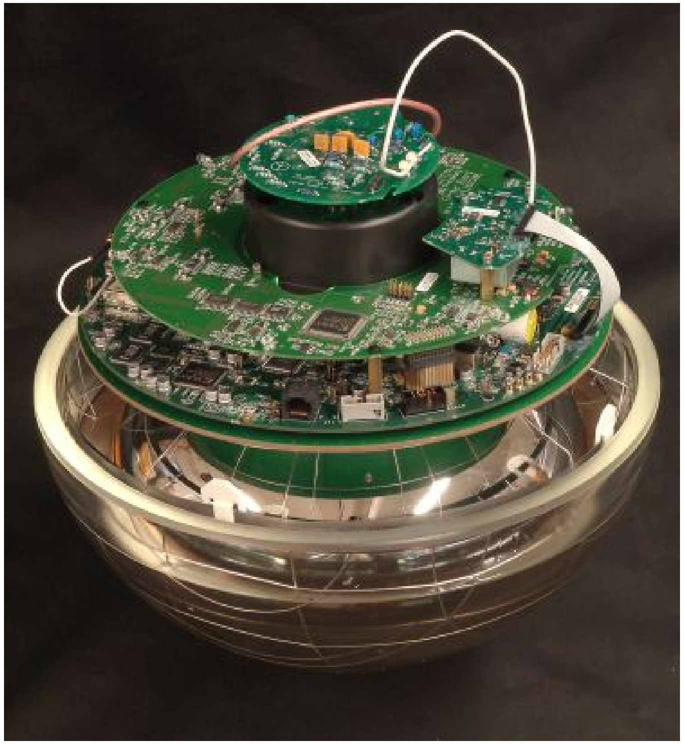
Deployment

- Attach DOMs to cable & lower
  - ~ 12 hours/string
- Special Devices (1 string each)
  - Dust Logger
  - Standard Candle – N_2 laser
  - Prototype Radio sensors
  - Prototype Acoustic sensors

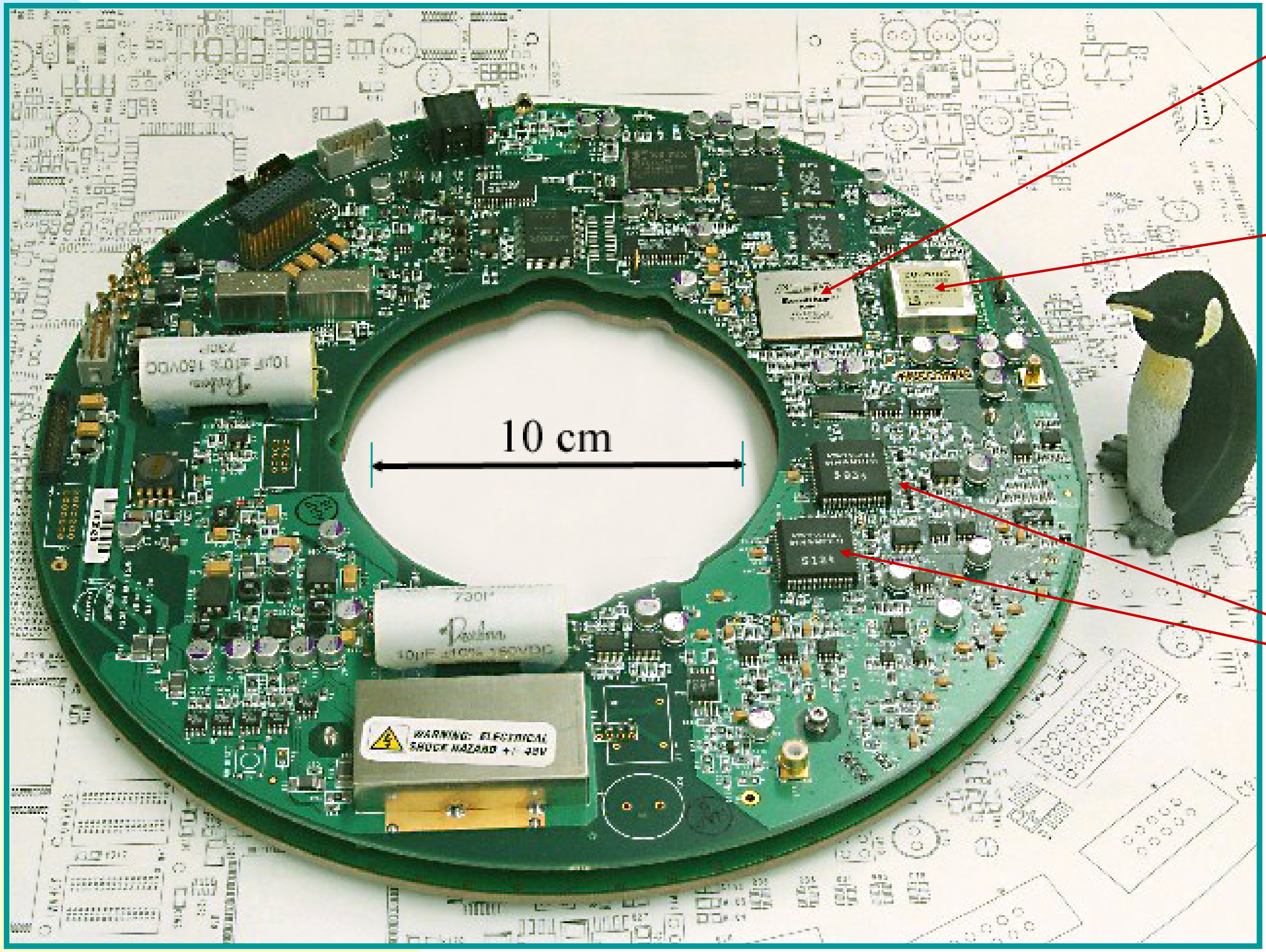
Optical Modules



- Each optical module collects data autonomously
  - ◆ 10” Photomultiplier w/ HV
  - ◆ 300 MHz waveform digitizer
    - Custom analog chip
  - ◆ 40 MHz fast ADC
  - ◆ Self triggering
    - ~1/4 photoelectron threshold
  - ◆ <5 Watts of power
  - ◆ 700 Hz Dark rate
    - 350 Hz w/ 51 μs deadtime
  - ◆ LEDs for calibration
- Packetized Digital data sent to surface



Digital Optical Module Mainboard



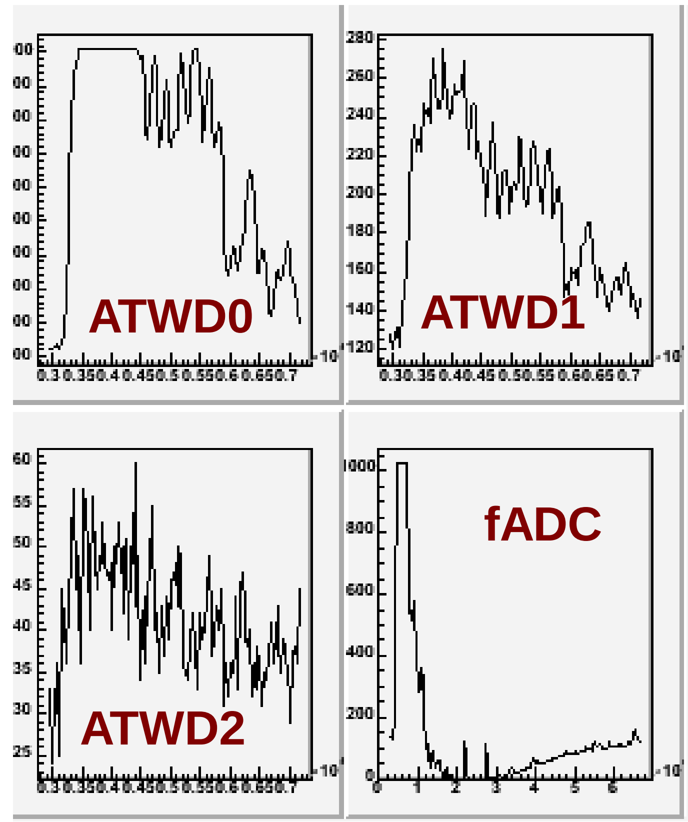
300kgate
FPGA w/
ARM 7 CPU

Crystal oscillator
Allen Variance
$< 5*10^{-11}$

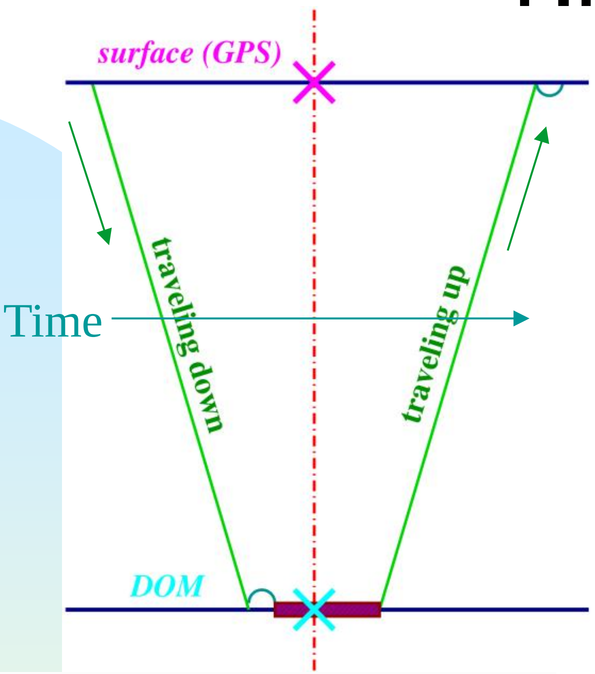
Custom
Switched
Capacitor Array
128 sample
300 MSPS
2/board

Data Acquisition

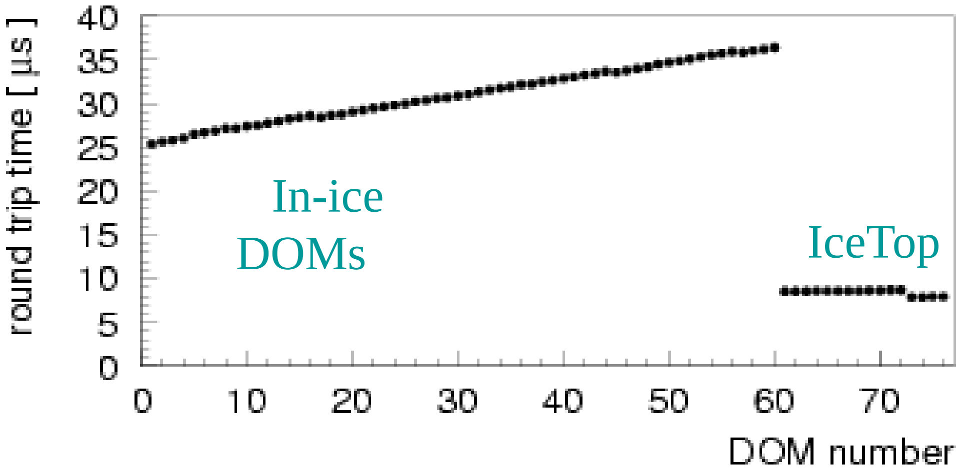
- Goal: Detect every photoelectron
- Record waveforms from non-isolated hits
  - ◆ 400 nsec @ 300 MSPS
    - 14 bit dynamic range
      - 3 10-bit channels
  - ◆ 6.4 μsec @ 25 MSPS
    - 10 bit dynamic range
  - ◆ Time Stamp isolated hits
- Trigger on multiplicity, topology
  - ◆ Frame (Event) = “All hits in a given time window”
- Commercial electronics on surface

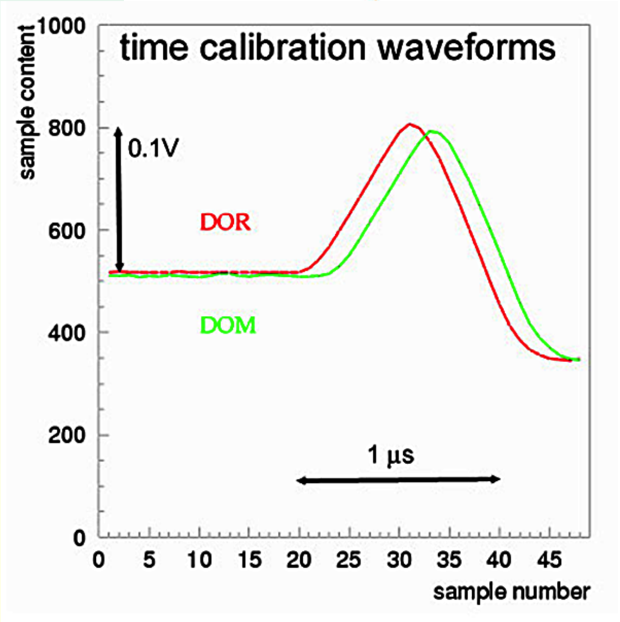


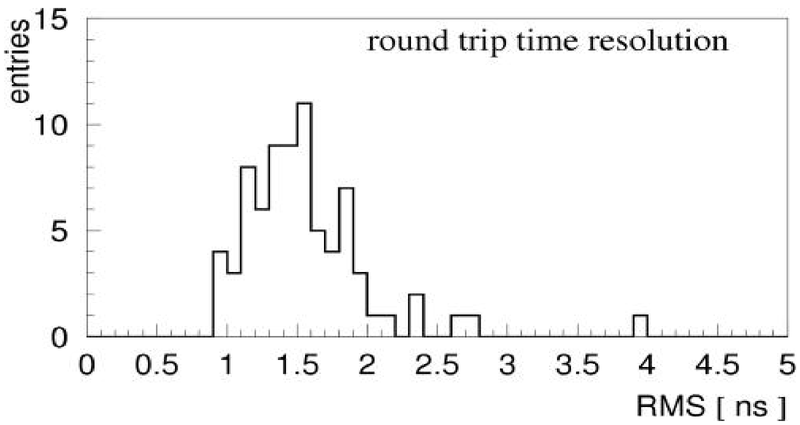
Time Calibration



Automatic recalibration every 3 1/2 seconds

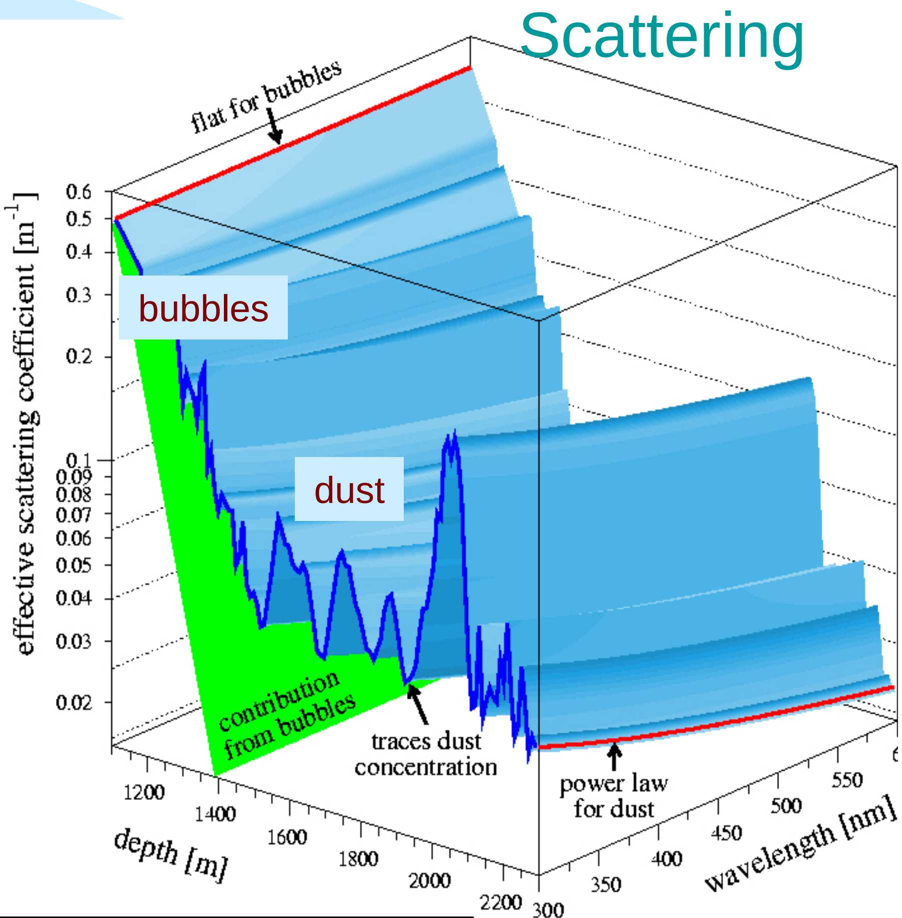


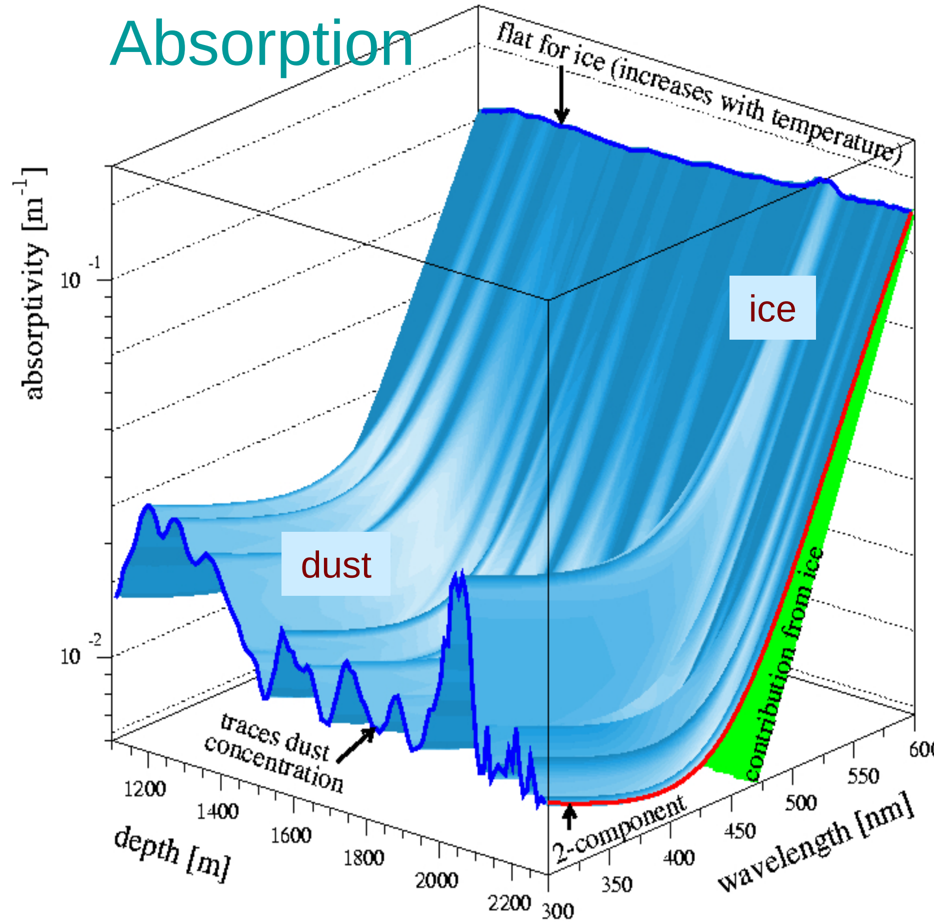




LED & muon studies show time resolution is ~ 2 ns

Optical properties of the ice





Measurements:

in-situ light sources

atmospheric muons

Dust Logger

Average optical ice parameters:

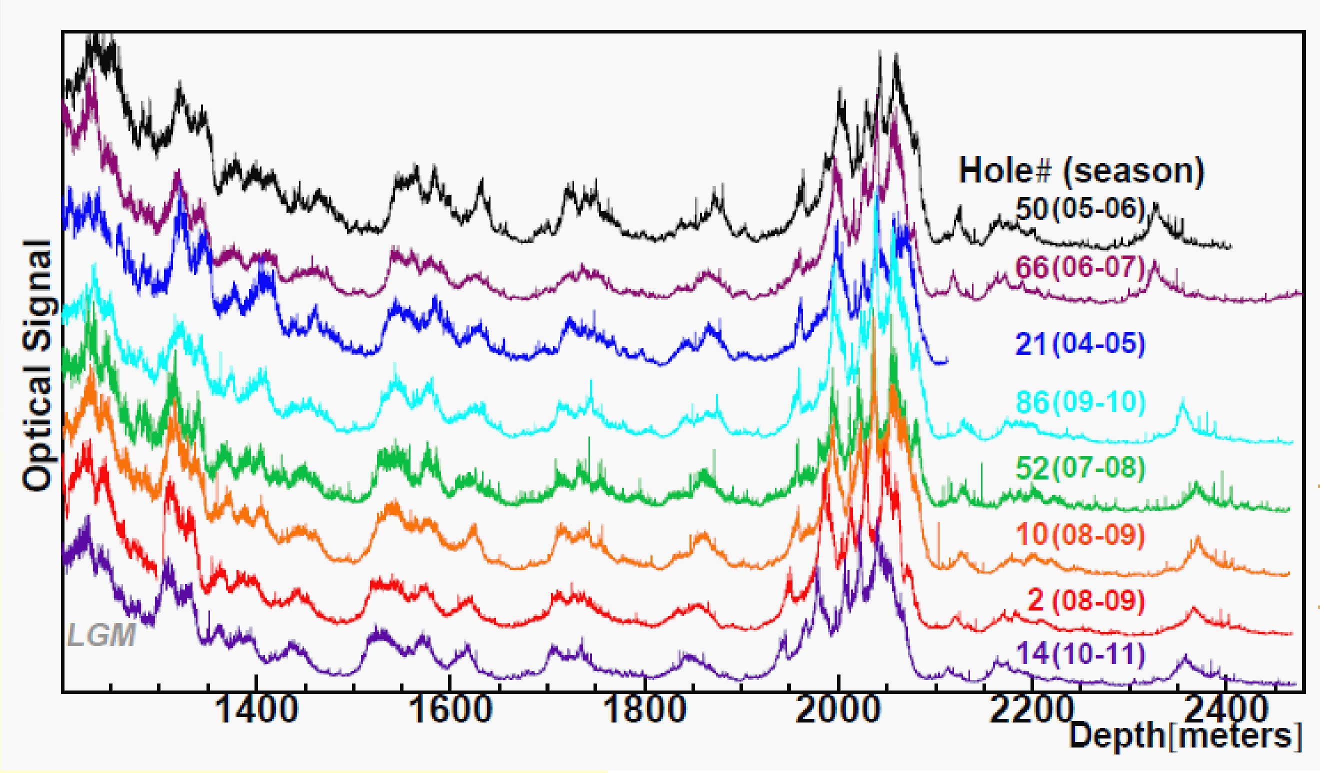
λ_{abs} ~ 110 m @ 400 nm
λ_{sca} ~ 20 m @ 400 nm

optical WATER parameters:

λ_{abs} ~ 50 m @ 400 nm
λ_{sca} ~ 200 m @ 400 nm

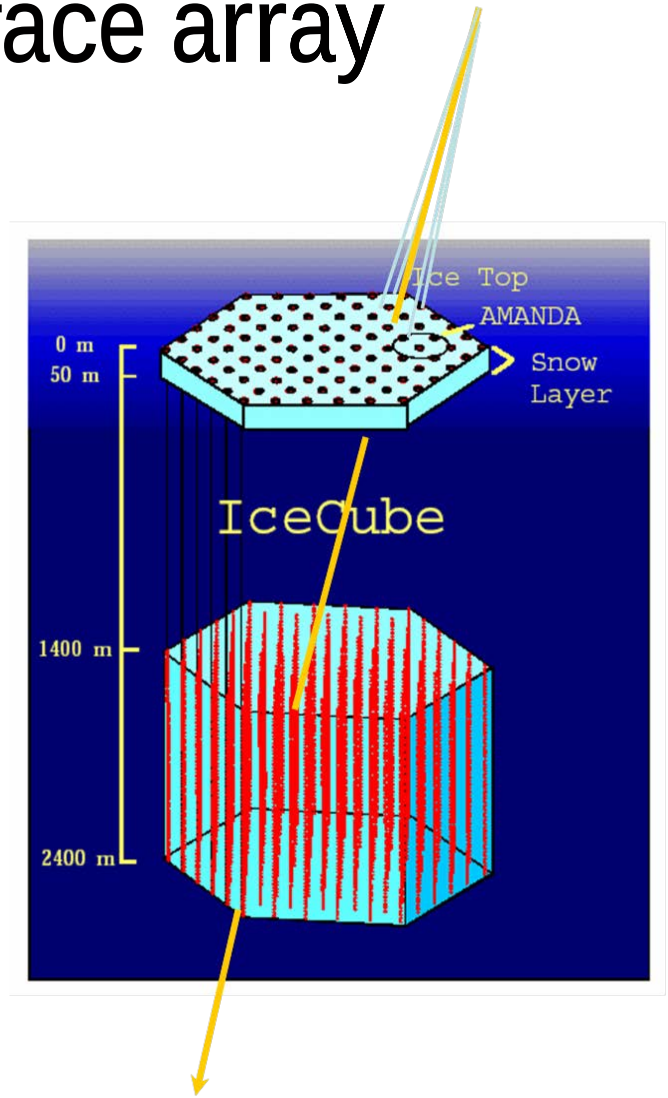
Dust Logger

- Measures optical properties of ice
- Emits light perpendicular to hole
  - Measures light scattered by dust
- Dust layer depths vary across IceCube
- LED studies show anisotropic scattering



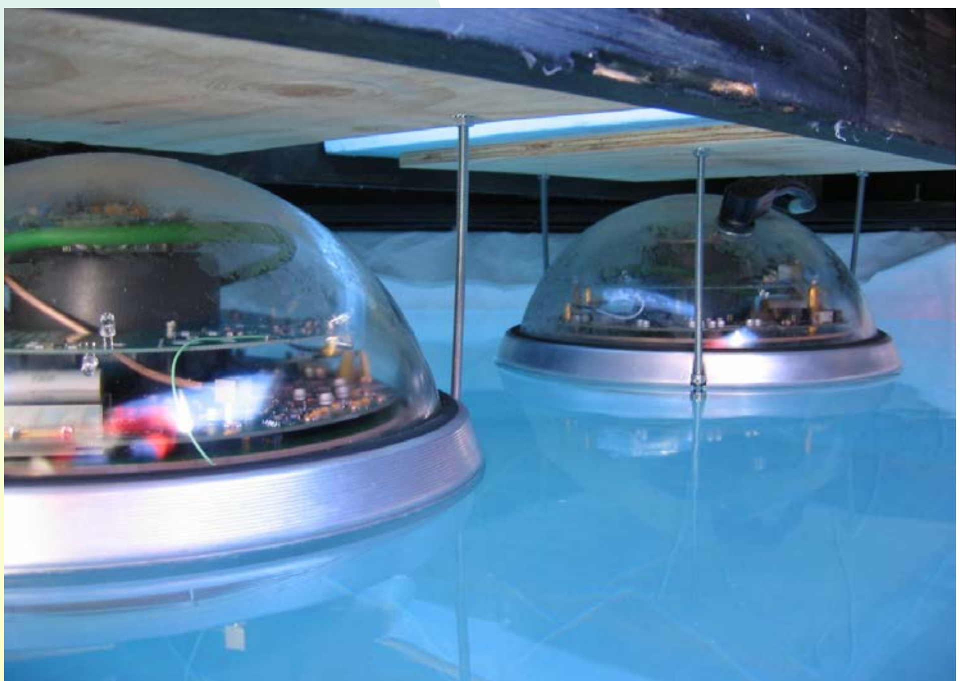
IceTop air shower surface array

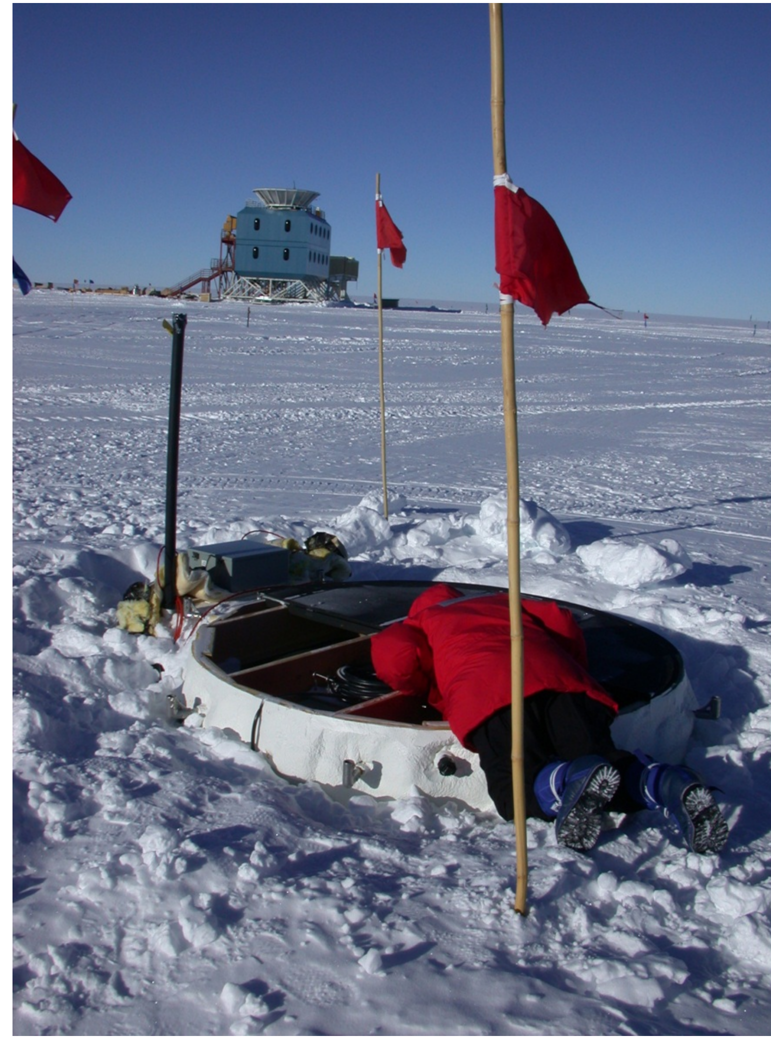
- 162 ice-filled tanks covering 1 km^2
  - 2 DOMs/tank observe the Cherenkov radiation from charged shower particles
- Shower energies from ~100 TeV to 10^{19} eV
- Cosmic Ray Flux & Composition
  - Surface particles : subsurface μ
  - High p_T muons in CR air showers
    - pQCD based composition studies
- Calibrate IceCube
- Veto downgoing cosmic rays
- γ detector (w/ IceCube as a veto)



IceTop Tanks

- Ice filled
  - Controlled freezing to eliminate bubbles
- 1.8 m diameter



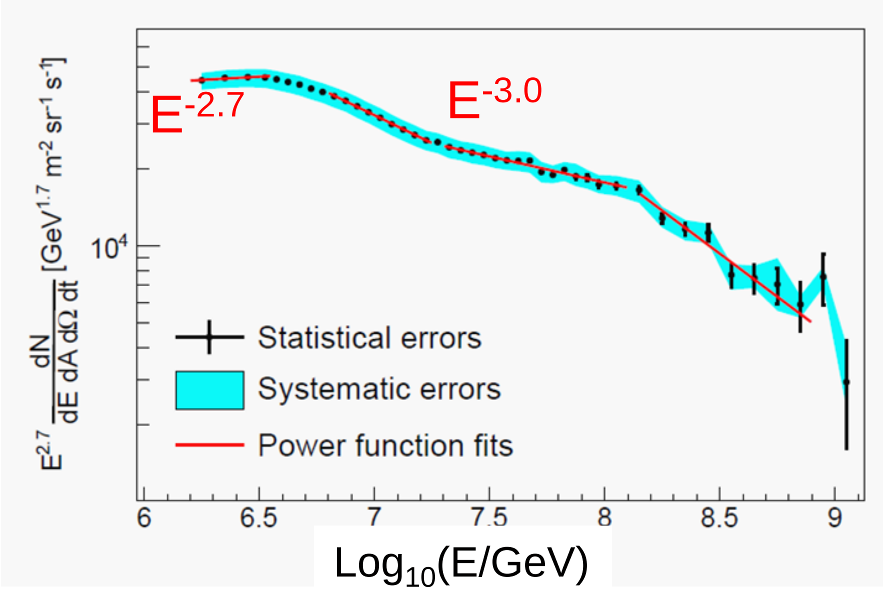


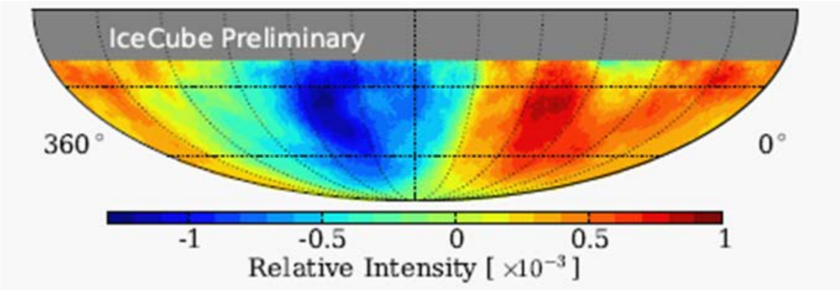
2 IceTop Tanks (= 1 station)

μ signals from IceTop DOMs

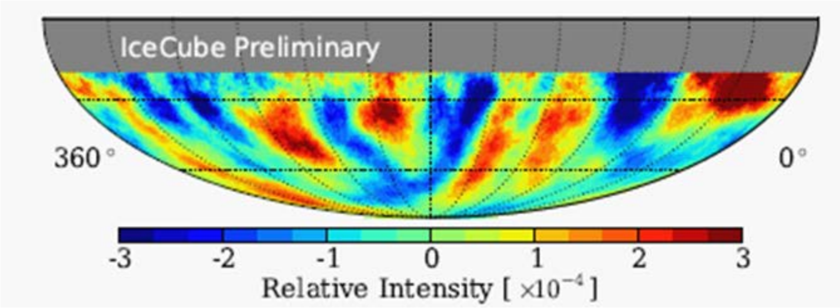
Cosmic-Ray spectrum & anisotropy

- CR spectrum with IceTop
  - 4 spectral components
  - 2 main ones
    - $E^{-2.7}$ below 4 PeV
    - $E^{-3.0}$ above 4 PeV
- CR anisotropy
  - 150 billion CR muons + IceTop
  - Anisotropy @ 10^{-3} level
  - Anisotropy @ 10-4 level after dipole, quadrupole removal
  - Persists up to 400 TeV
- Matches northern hemisphere results





Full anisotropy

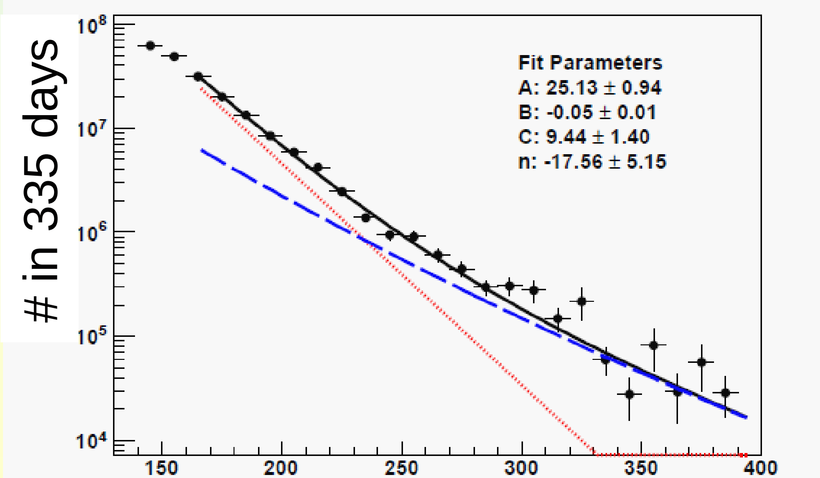


After dipole, quadrupole subtraction

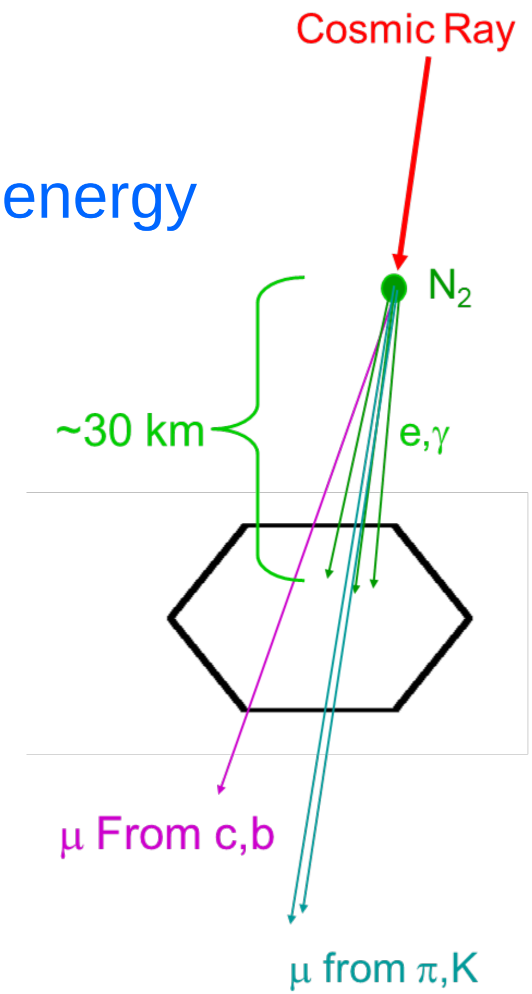
Isolated muons in IceCube: probing high transverse momenta

- Muons 135 m - 450 m from the shower core.
- Transverse momenta (p_T) of several GeV
  - p_T = interaction height/separation * muon energy
  - Magnetic bending, multiple scattering unimportant at large separations Perturbative QCD regime

exponential (soft) + power law (pQCD)



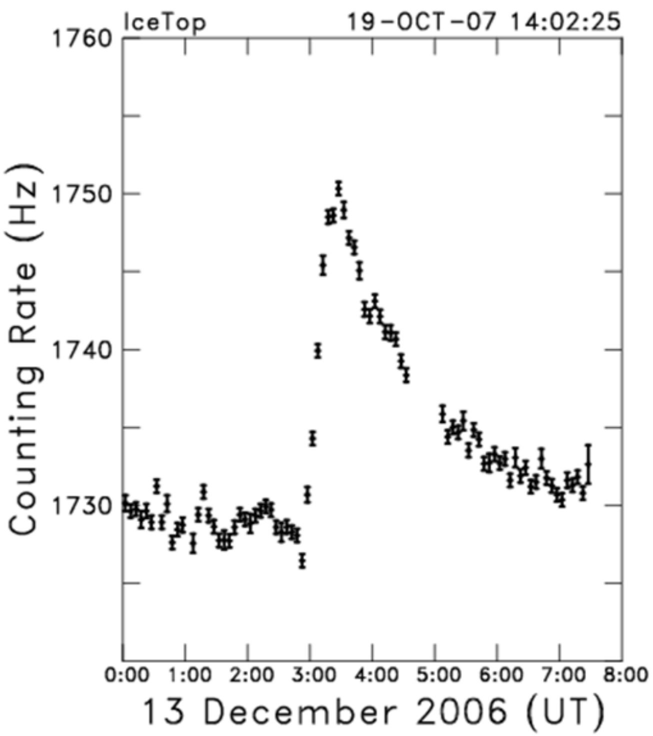
Separation between bundle & muon (m)



Phys. Rev. D87, 012005 (2013)

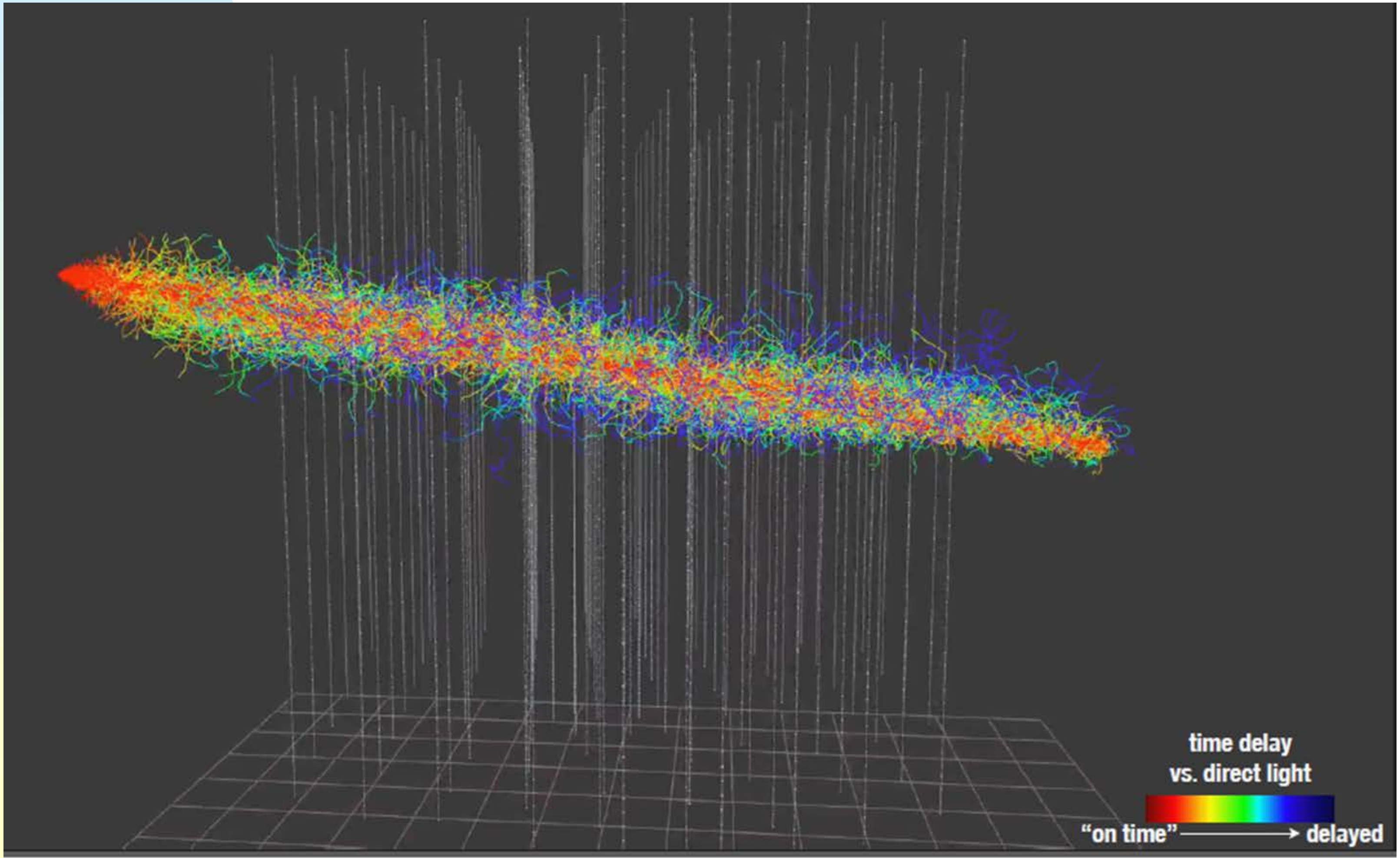
Solar physics with IceCube

- Low-energy (~ GeV) cosmic-rays occasionally produce secondary particles which reach the Earths surface.
- If the flux is high enough, this may be visible as an increase in the IceTop singles rates.
- Significant rate increase observed on Dec., 13, 2006 and May 17, 2012, due to solar flares.



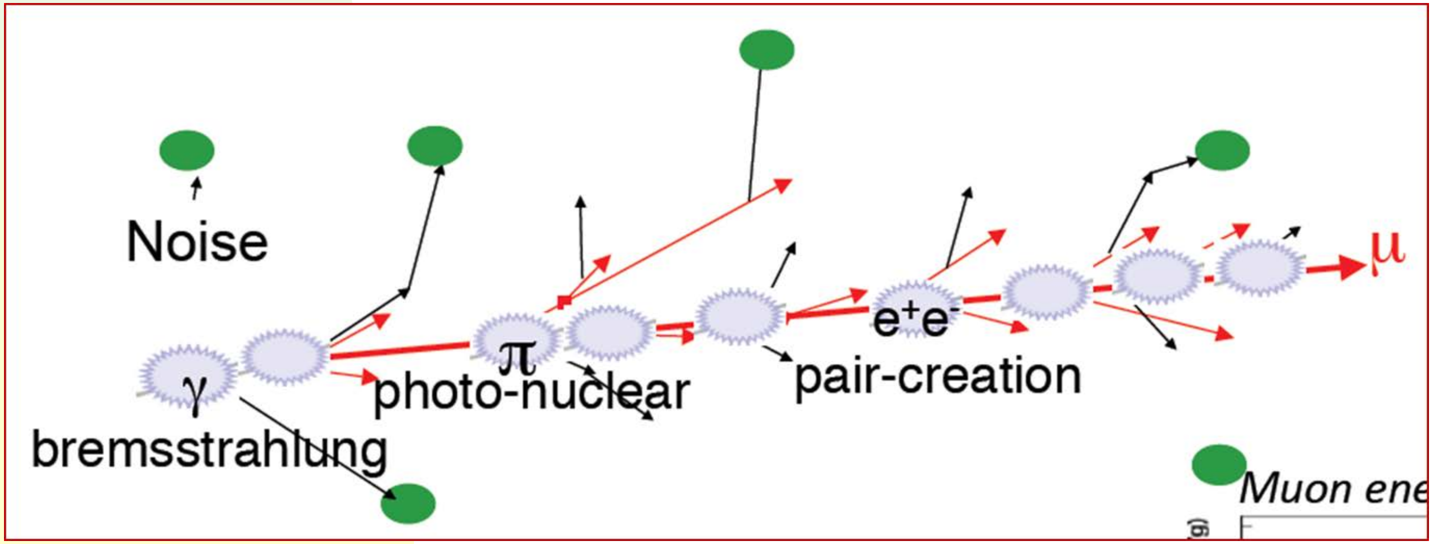
The Cherenkov light from a muon

- Color indicates time
- For simulation, ray tracing is extremely time consuming



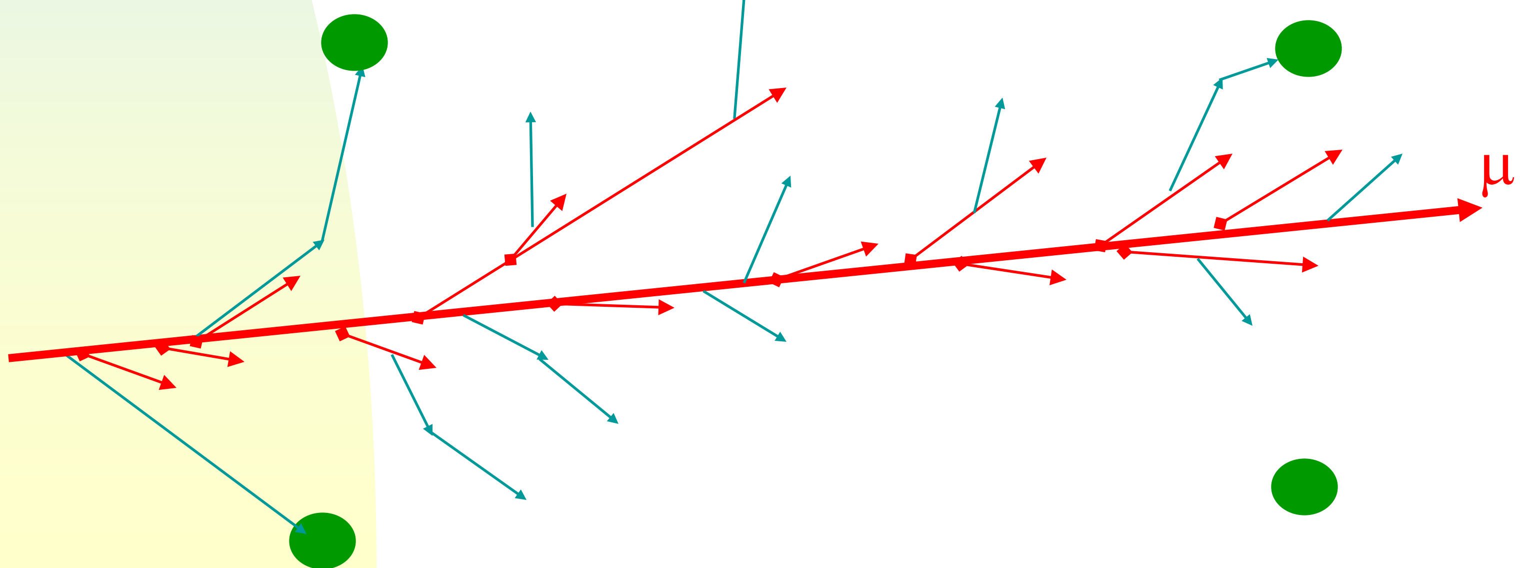
μ tracking

- μ tracks lose energy by emitting γ, e^+e^- pairs and hadronic interactions (via virtual γ)
  - Because of stochastic loss, light emission is not uniform
- Charged particles emit Cherenkov radiation
  - angle $\theta = \text{Cos}^{-1}(1/n) = 41^0$
  - The photons scatter (Λ ~ 25 m)
  - Some ($<10^{-6}$) photons are observed in DOMs
- We measure points 5-50 meters from the μ track



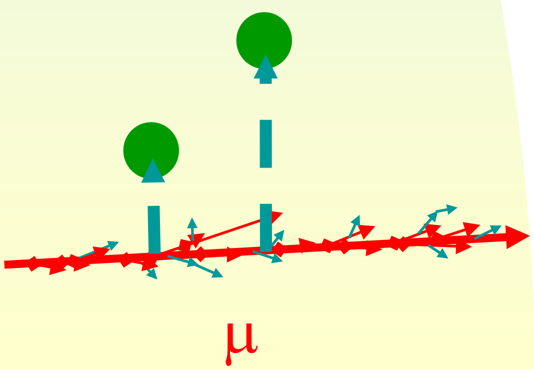
Muon – 1st Guess algorithms

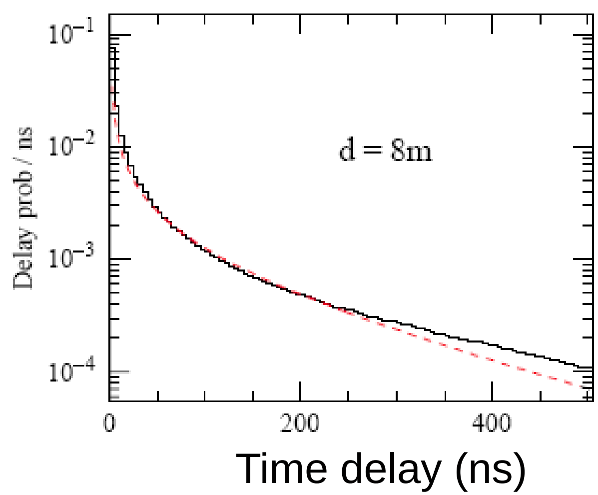
- Data includes all hits within a 2-10 μs window
  - Hit cleaning removes isolated hits as probable noise
- 1st guess algorithms
  - Fit moving plan to light pattern
  - Tensor of inertia – find long axis of cigar
- Maximum Likelihood fit gives final answer

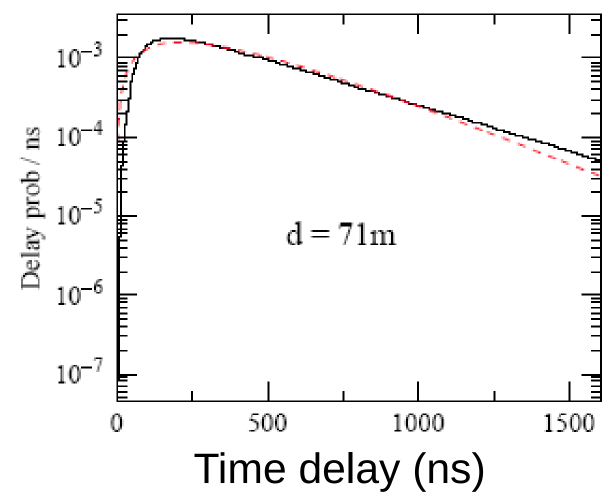


Muon Reconstruction Overview

- Maximum Likelihood method
  - Pandel distributions give arrival time distribution for photons from an infinite linear track $\vec{x}$ at a DOM at position $\vec{y}$
    - perpendicular distance, position, angles, depth
      - Depth dependent optical properties still a major issue
    - Include noise probability
  - Feed to minimizer
- Use multiple seeds and/or scan direction space to avoid false minima and/or shallow minima

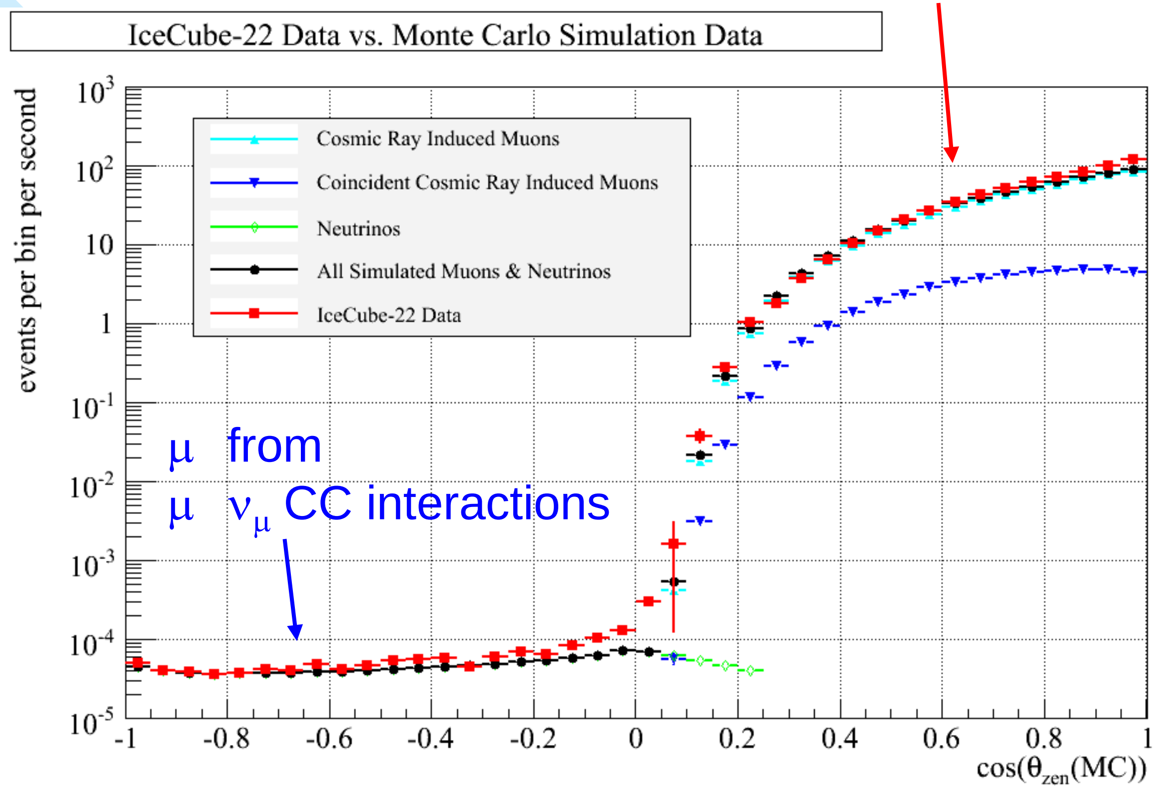






Muon Angular Distribution

μ from cosmic-ray air showers



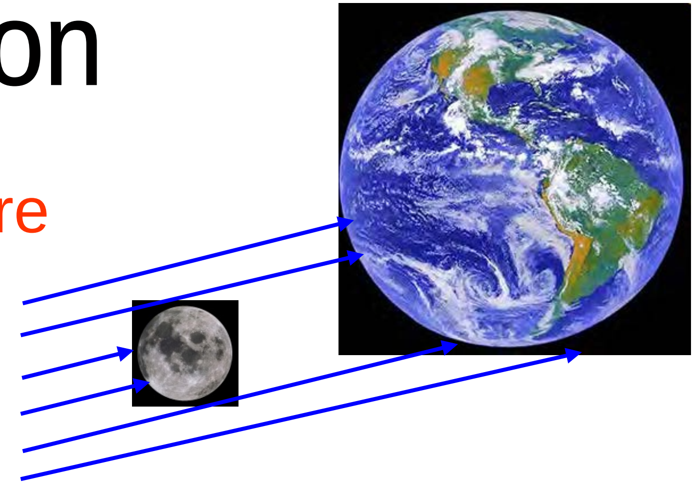
Upgoing

$\mathrm{Cos}(\theta_{Zen})$

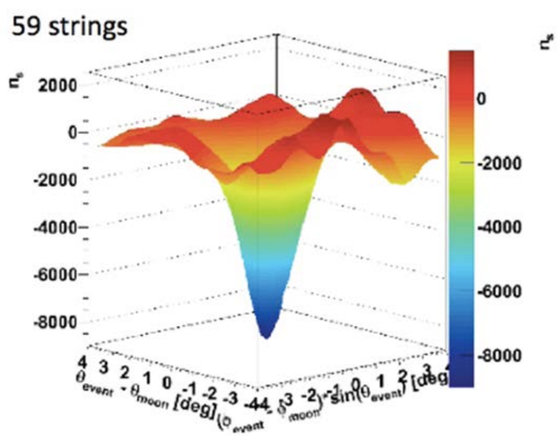
Downgoing

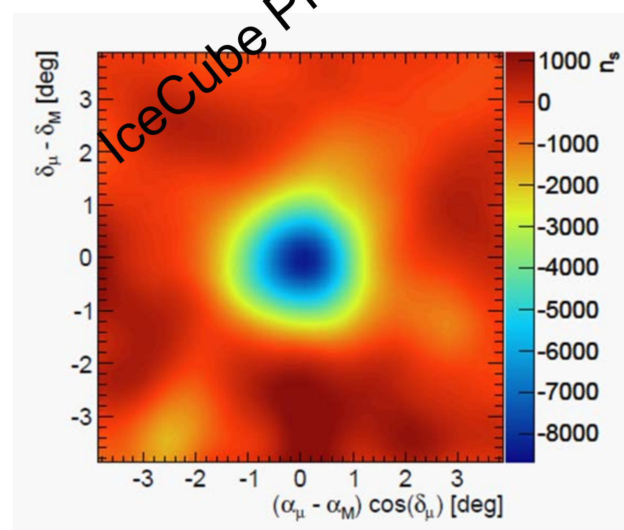
The sharp cutoff and data/Monte Carlo agreement shows that we understand our angular resolution

The Shadow of the Moon

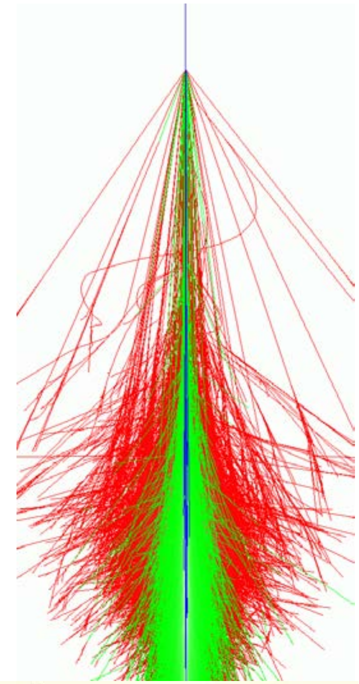


- The moon absorbs cosmic-rays, so there will not be any air showers/ atmospheric μ from its direction
- Maximum elevation 28^0 above horizon
- Deficit of 900 events/28,000 observed
  - ~ 12σ per year
- IceCube points within 0.2^0 of the moon
- Angular resolution better than 1^0 at high energies.

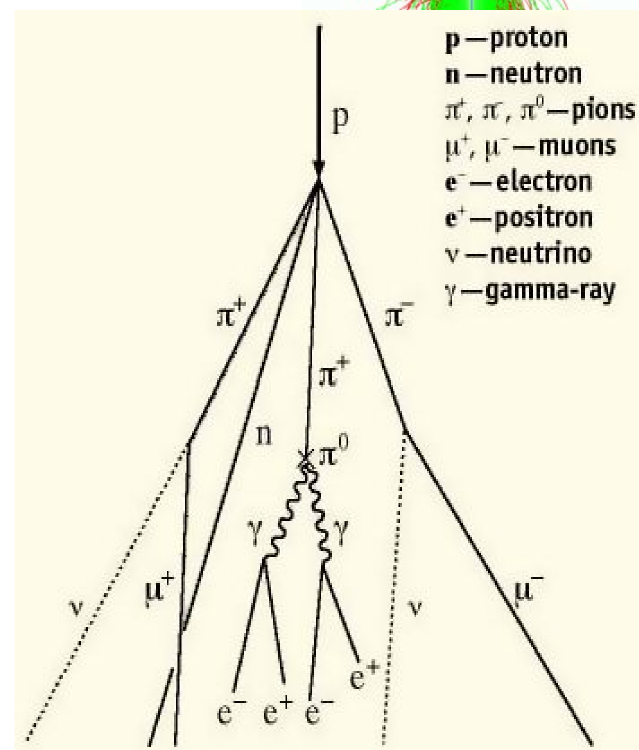




Atmospheric neutrinos



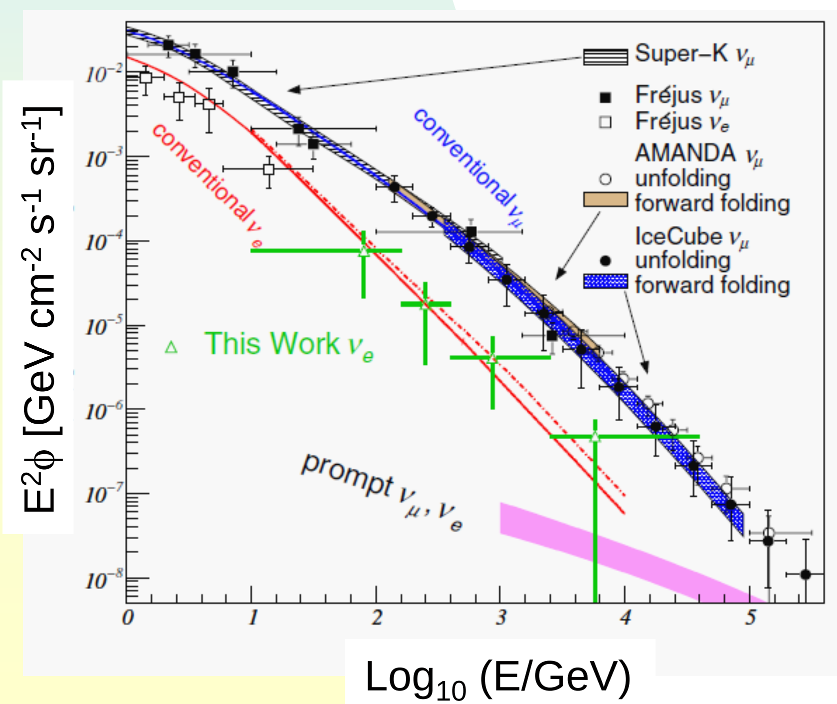
- "Conventional" from π/K decay
  - $\pi \to \mu\nu_\mu$, $\mu \to e\nu_\mu\nu_e$
    - I do not differentiate between ν & ν
  - High energy π interact before decaying
    - ν spectrum is harder than CR spectrum
      - $E^{-3.7}$ below knee, $E^{-4.0}$ above it
        - π knee is about 400 TeV
    - Flux known to ~ 20%
- "Prompt" from charm/bottom decay
  - ν spectrum follows CR spectrum
    - $E^{-2.7}$ below knee, $E^{-3.0}$ above it
    - Flux poorly known (factor of 2)
      - Forward production, non-perturbative component?
- Complex calculations predict spectrum

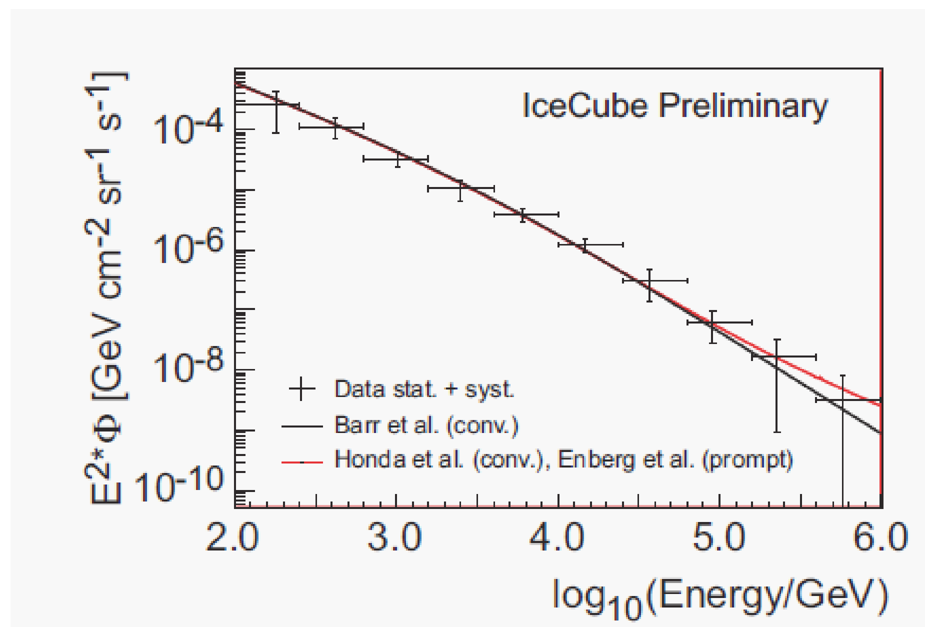


Atmospheric neutrinos measurements

- ν_e flux measured from 80 GeV to 6 TeV
  - Showers in DeepCore; rest of IceCube is veto
- ν_μ measured up to 1 PeV
  - Not yet sensitive to prompt component
  - Dominated by systematic uncertainties
- ~ 5% seasonal rate variation seen for ν_μ from Antarctica

PRL 110, 151105 (2013)

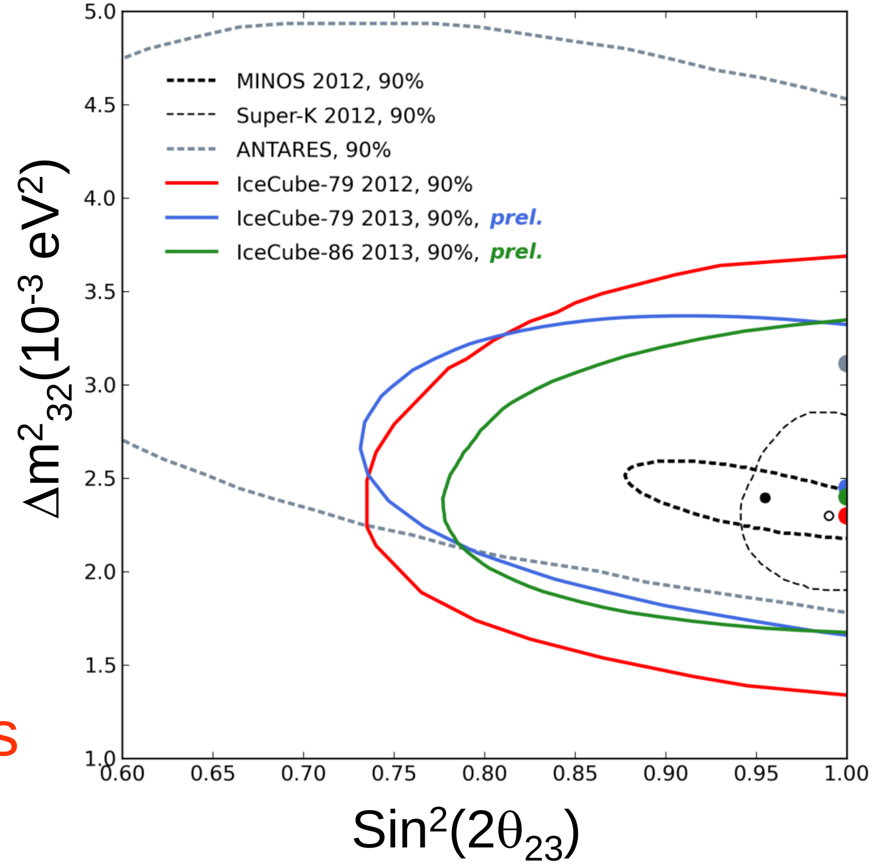




Atmospheric neutrino oscillations

- Vacuum oscillations
  - Depends on E_ν & zenith angle
  - 1^{st} oscillation minimum is at 28 GeV for vertical upgoing ν
- Multiple analyses select starting events in DeepCore
  - Different techniques to reconstruct events, determine energy and zenith angle
  - Tradeoff between accuracy and reconstruction efficiency
  - Different systematics
- Searches for sterile ν in progress

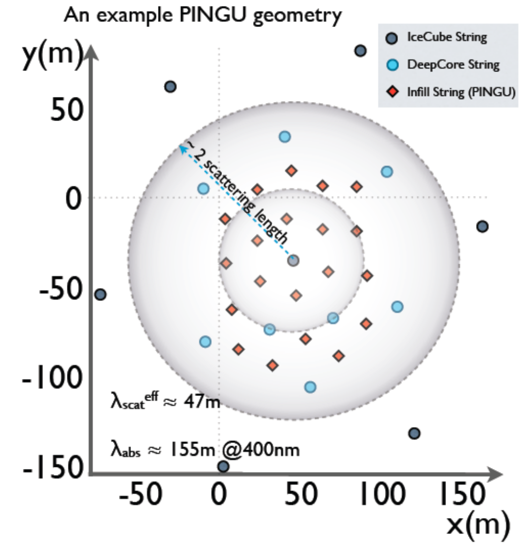
PRL 111, 081801 (2013)



The next step: PINGU

arXiV1306.5846

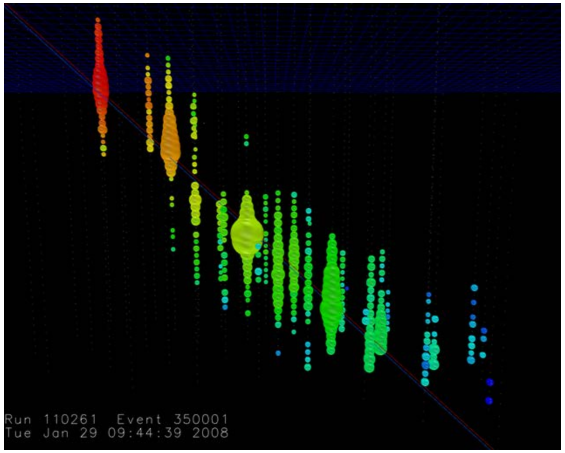
- Precision IceCube Next Generation Upgrade
- A DeepCore for DeepCore
  - Higher DOM density, lower threshold
    - 20 -40 strings on with ~ 20 m spacing
    - 60-100 Optical Modules per string
      - Similar to IceCube modules
  - Threshold ~ a few GeV
  - ~ 10 Mton effective target mass



- Main Physics Topic: the neutrino mass hierarchy
  - Which neutrino is heaviest?
  - Atmospheric neutrinos oscillations via resonant ν_e conversion in the high electron densities in the deep Earth
    - MSW Effect
- Studies of supernova neutrinos, etc.
- A future follow-on, MICA, will have an even lower threshold

Searching for extra-terrestrial ν

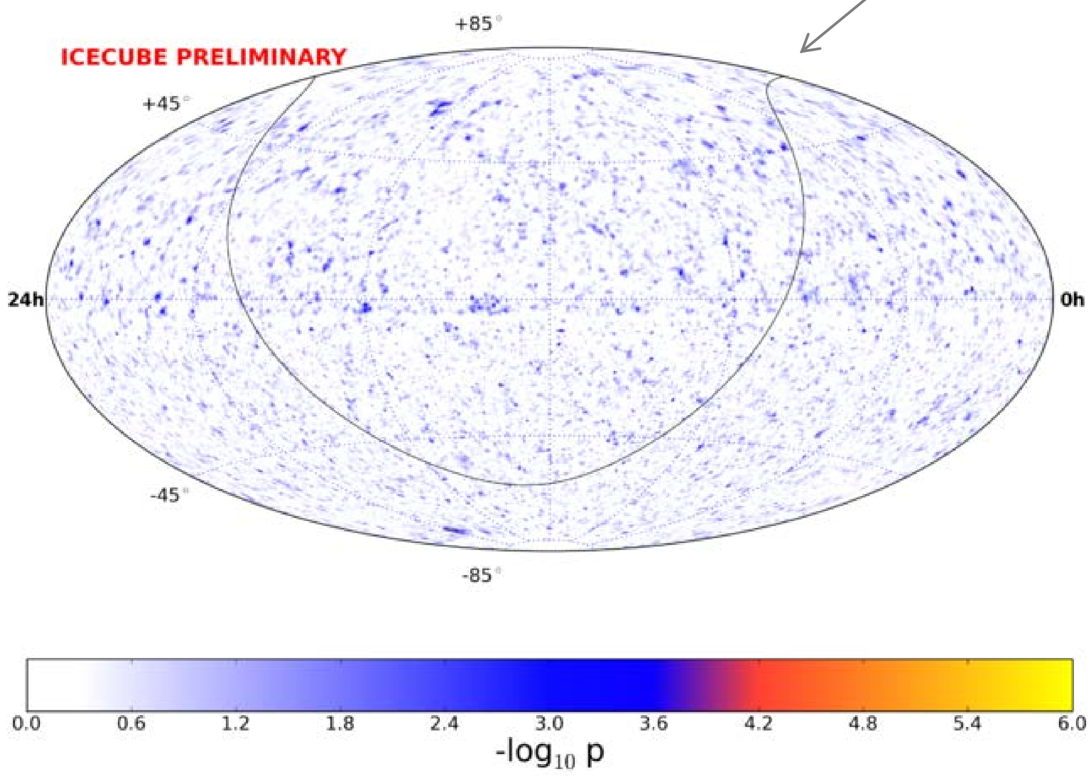
- Large atmospheric ν background
  - For Southern Searches, there is an even larger background of atmospheric μ
- Diverse strategies:
- Point sources
- High-energy ν_τ
  - Very low atmospheric flux
- Energetic downward-going neutrinos that are not accompanied by a muon/bundle or shower
- An excess of high-energy neutrinos
  - Extra-terrestrial neutrinos should have a harder energy spectrum than atmospheric ones



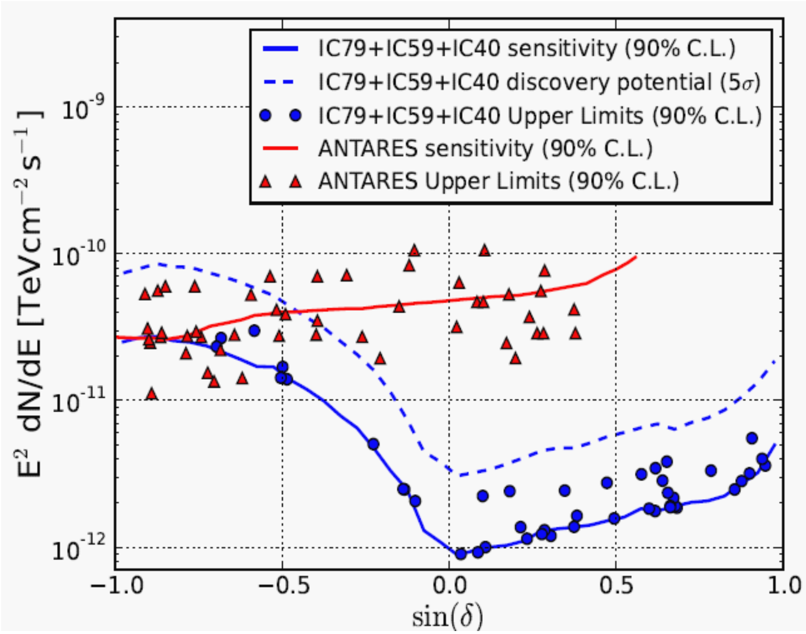
4 year neutrino sky map

- 1371 live days, with 390,000 events
  - ~90% ν purity in Northern Hemisphere; mostly μ in South
  - No significant excesses

galactic plane



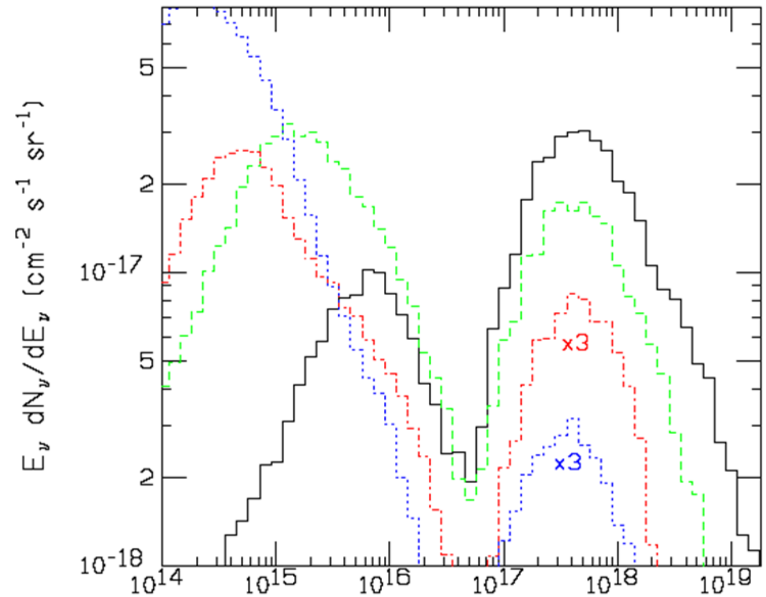
Point source searches



- Flux limits calculated for assumed E^{-2} energy spectrum
  - Limits depend on declination
    - == zenith angle in IceCube
  - $E^2\phi \sim 10^{-12}$ TeV cm^{-2} s^{-1} is 'interesting region'
- All sky survey, pre-selected sources and stacking by source classes
  - Classes: e.g. blazars, supernova remannts, etc.
- Searches for gamma-ray bursts, using GRB position/times determined from photon observations
- Periodic/flaring sources
  - Triggered (by other observations) and untriggered

Extremely high energy events

- 'GZK' neutrinos are produced when UHE cosmic-ray protons interact with the 3^0K microwave background radiation
  - $p + \gamma \rightarrow \Delta^+ \rightarrow p,n + \pi$
    - $\pi^\pm$ decays lead to ν
    - ν spectrum peaked $\sim 4*10^{17}$ eV
- Flux depends on composition
- Select events with high energy deposition in the detector
  - Cut depends on reconstructed zenith angle, assuming μ hypothesis
  - Energy deposition quantified by # of observed photoelectrons
    - Search in 2 years of data



E_ν (eV)

Hydrogen Helium
Oxygen Iron

PRL 111, 021103 5 (2013)

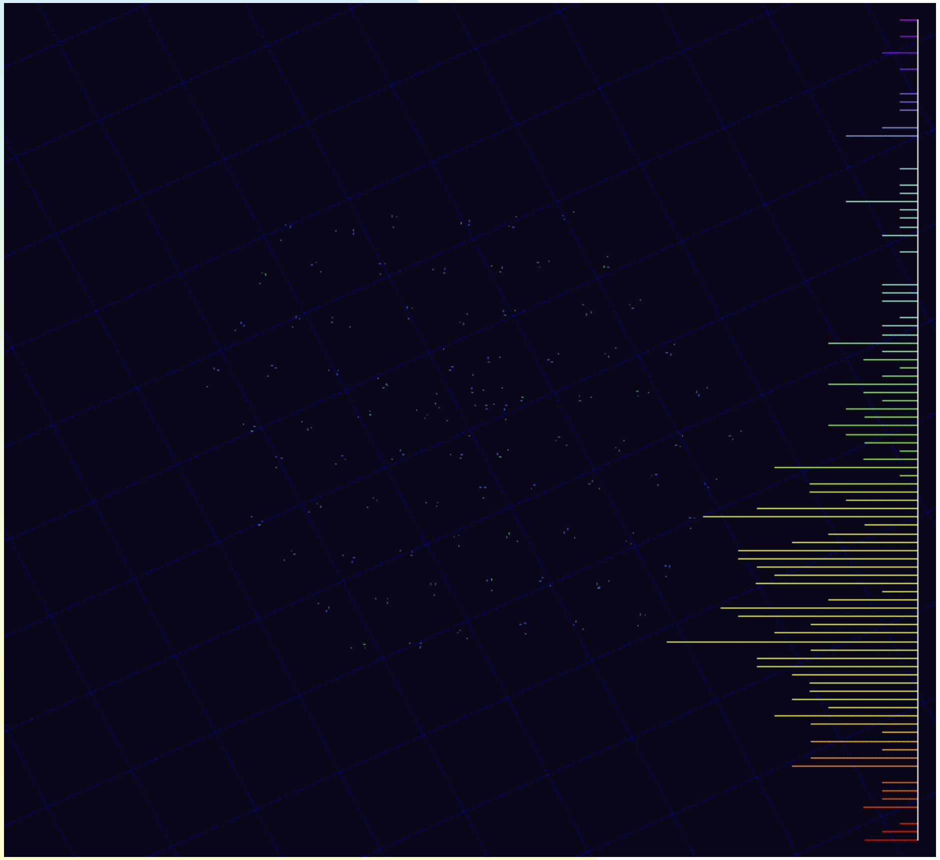
Bert: Aug-2011

354 hit DOMs

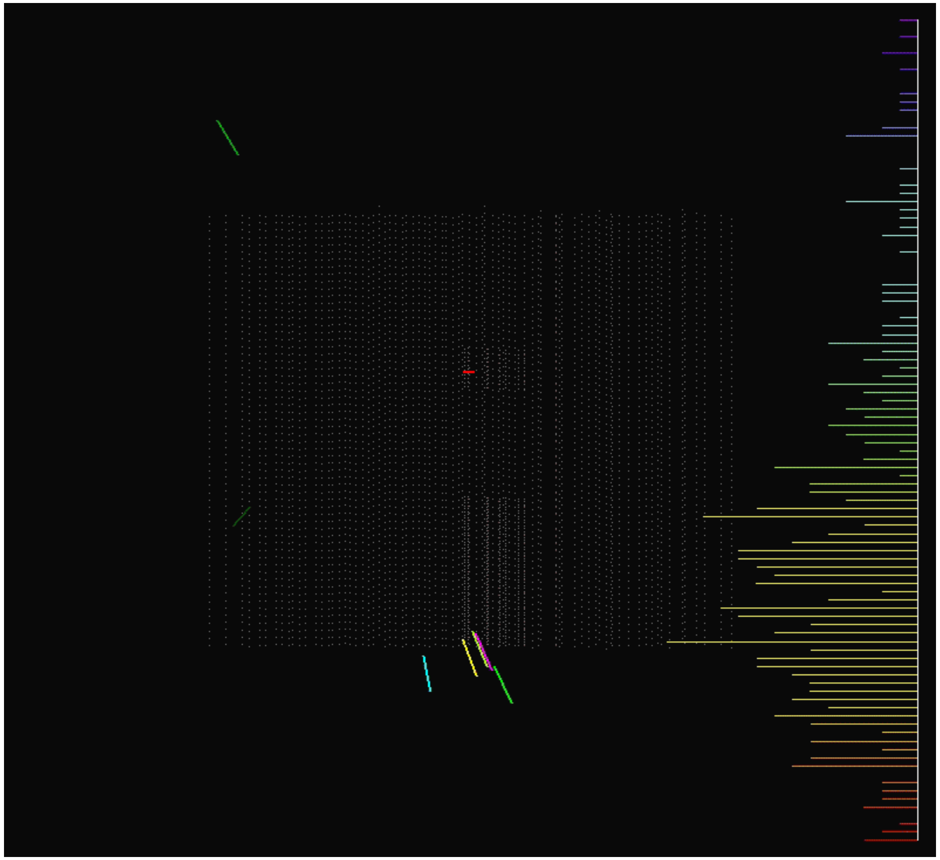
Energy = 1.04± 0.16 PeV

Zenith angle = 28^0 (downgoing)

TopView



Side View



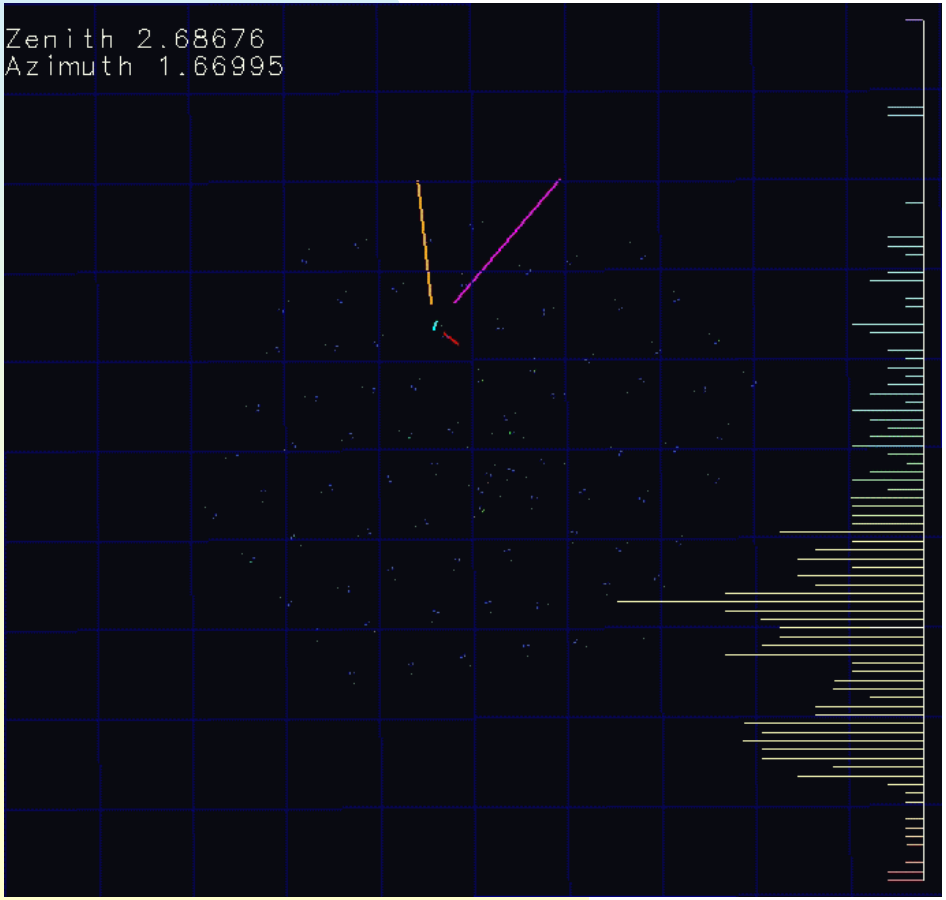
Ernie: Jan., 2012

312 Hit DOMs

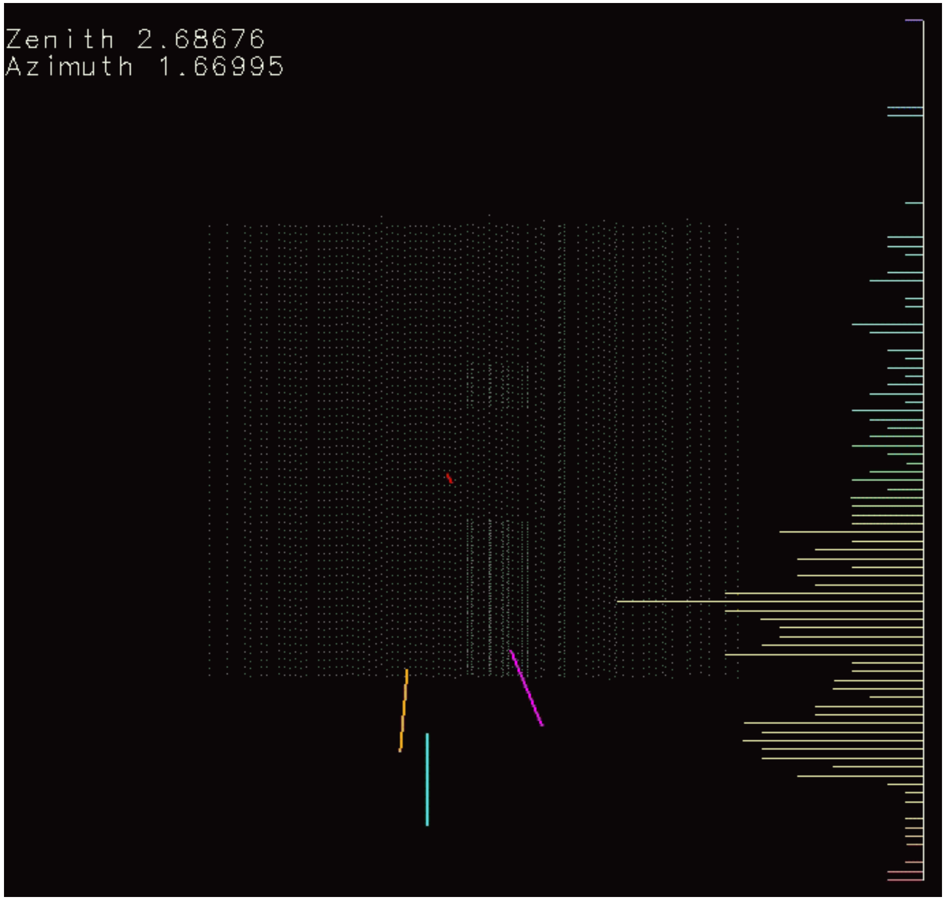
Energy = 1.14± 0.17 PeV

Zenith angle = 67^0 (downgoing)

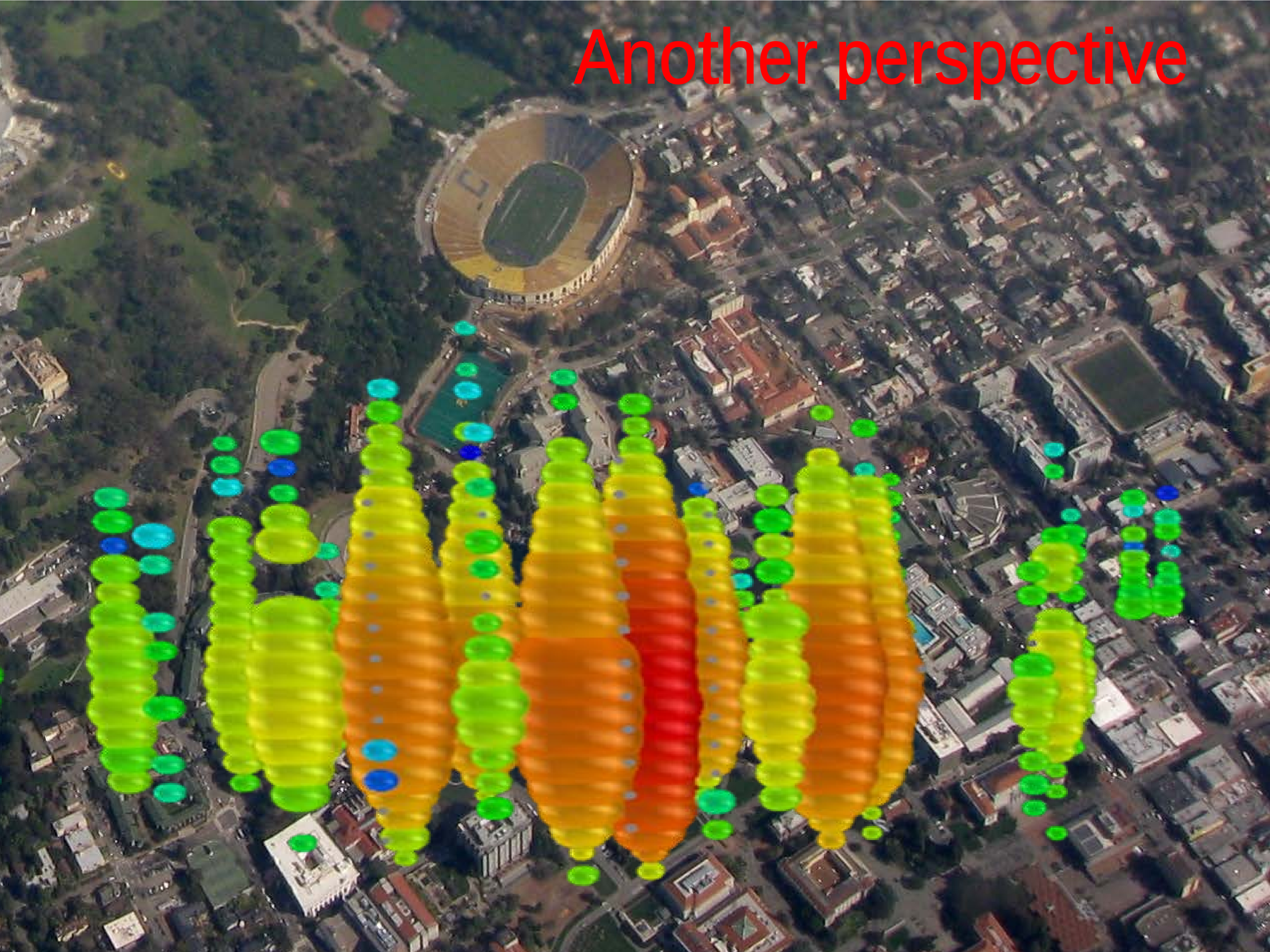
TopView



Side View

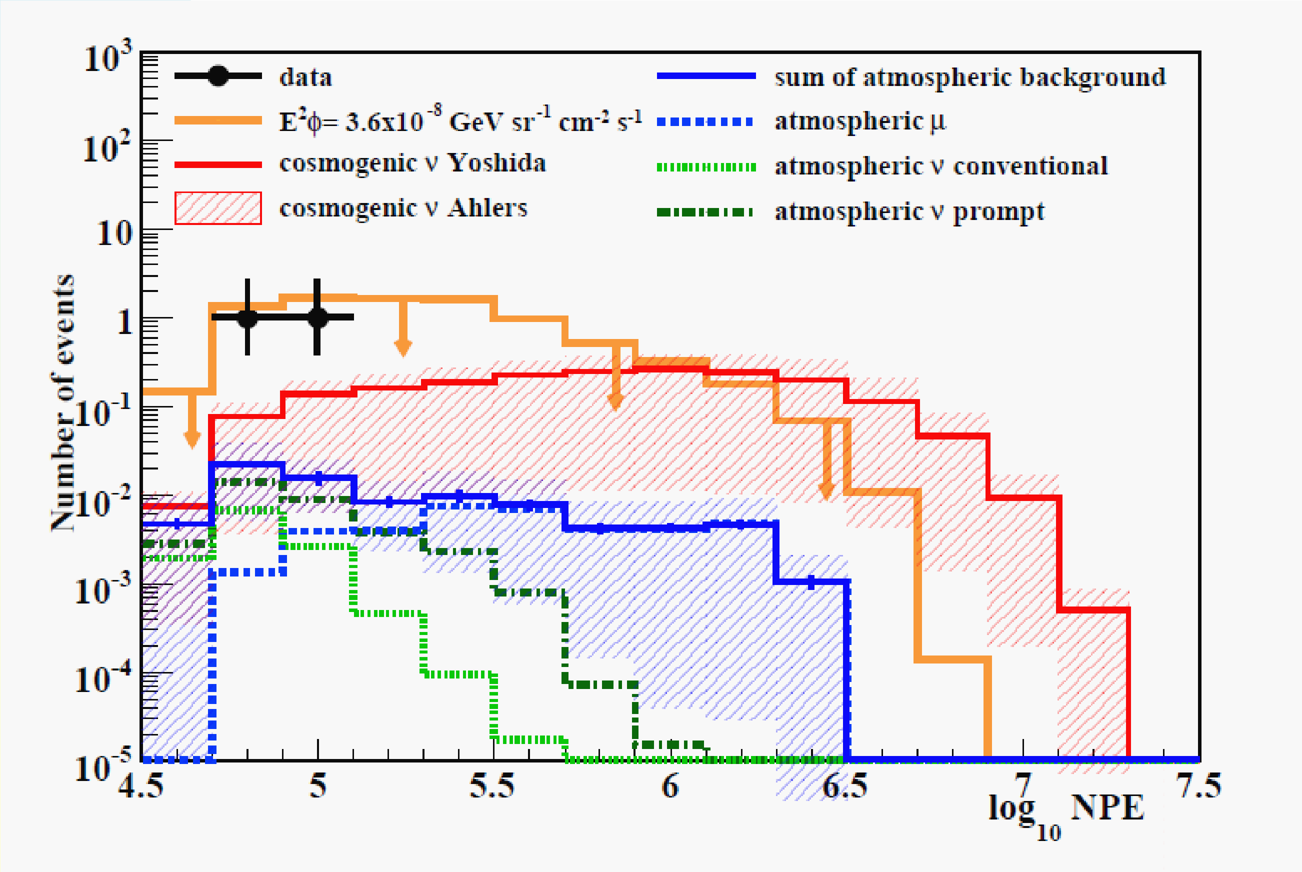


Another perspective



Bert and Ernie vs. the world

- Too low in energy to be GZK neutrinos
- Both events are 'golden' cascades, well contained in the detector, and with well reconstructed energies
  - No less-attractive events

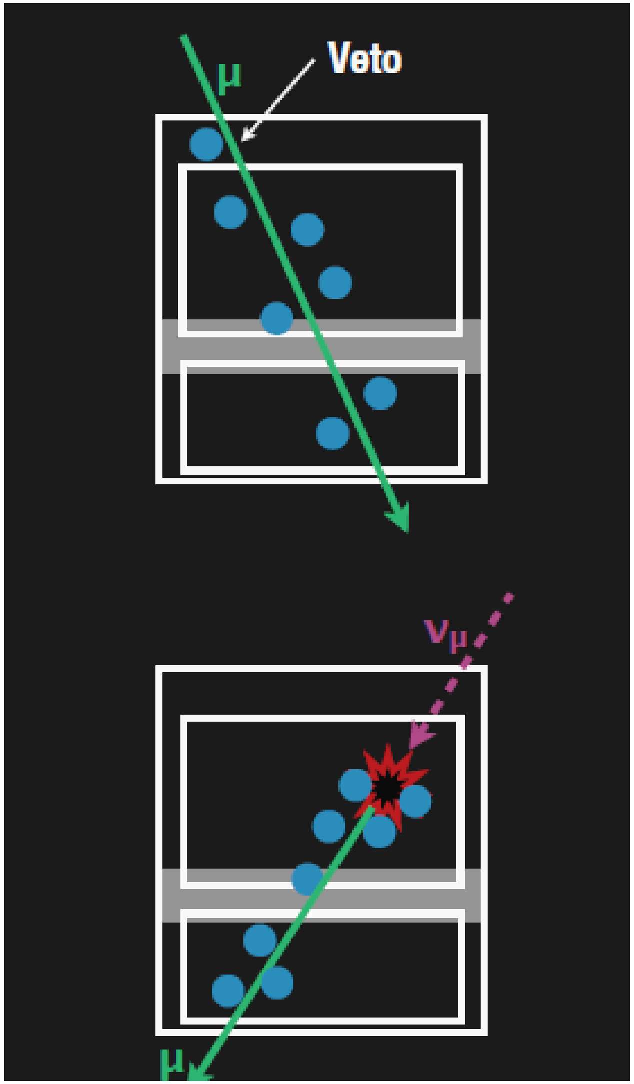


Background estimates

- Based on original cuts, for 3 flavors
- Atmospheric muons: 0.038 ± 0.004 (stat.) $^{+0.021}_{-0.038}$ (syst)
  - Based on simulations
    - We only expect ~ 100 1-PeV muons per year, most of them accompanied by additional muons
- Conv. Atm ν: 0.012 ± 0.001 (stat.) $^{+0.010}_{-0.007}$ (syst)
  - Based on simulations which are tied to data
- Prompt atmospheric ν: 0.032 ± 0.001 (stat.) $^{+0.03}_{-0.04}$ (syst.)
  - Based on the calculated flux, plus simulations
- Total: 0.082 ± 0.004 (stat.) $^{+0.04}_{-0.06}$ (syst.) events
- Two events is a 2.8 σ fluctuation

Contained event search

- Select high-energy events that originate inside the detector
  - Events with more than 6,000 observed photoelectrons (PE)
    - Fully sensitive for ν_e above 100 TeV
    - 400 Mton fiducial volume (~40% of detector)
- Sensitive to all three flavors
- Veto downward-going atmospheric ν accompanied by muons
- 28 events pass, including previously known “Bert & Ernie”

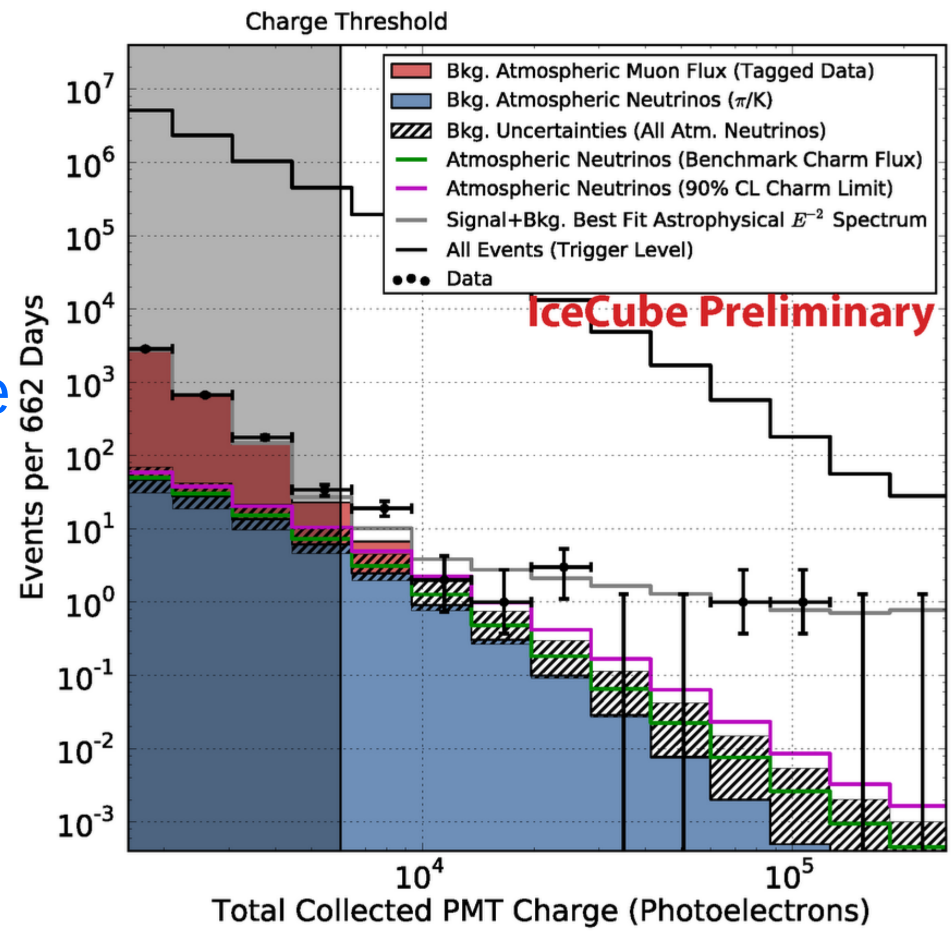


Contained event backgrounds

- Downgoing muon background estimated from data, using a two-layer veto w/ smaller fiducial volume
  - 3 event survive; extrapolate to 6 ± 3.4 events in active region
- Atmospheric neutrino background estimated from previous measurements + veto effect
  - High-energy downgoing atmospheric ν are generally accompanied by muons which will cause the event to be vetoed.
  - (Non-prompt) ν estimated 4.6 ±1.2 events
  - Prompt flux estimated per ERS to be 1.5 events

Event energies

- Number of observed photoelectrons used as energy proxy
- Below 6000 p.e., dominated by atmospheric backgrounds
  - Data and predictions agree
- Above 6,000 pe there is a clear neutrino excess, above expectations from the non-prompt flux (blue) + ERS charm (hatched)
- The events are evenly distributed throughout the detector.

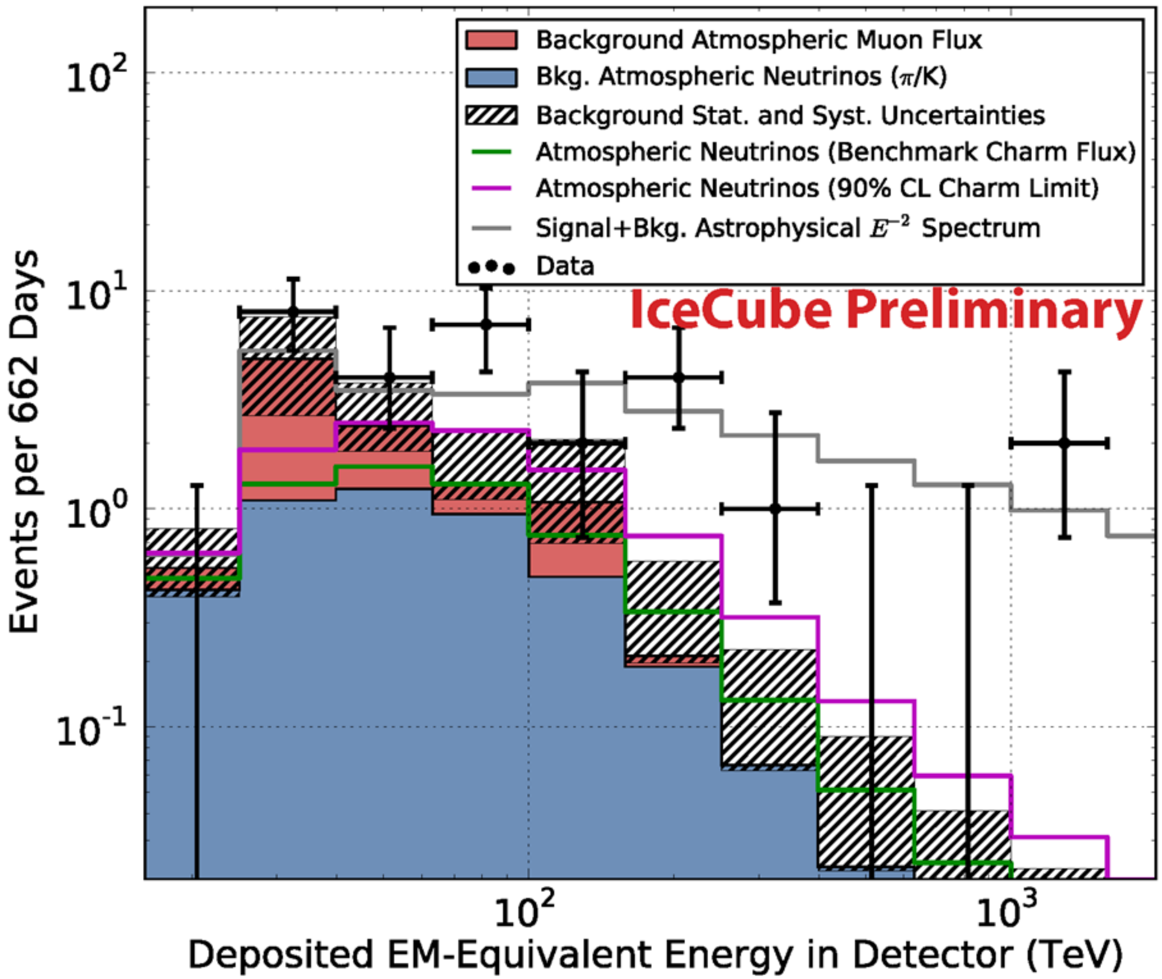


Quantifying the excess

- Select events with E > 60 TeV, to eliminate most atmospheric muon background.
- Fit data to a mixture of non-prompt atmospheric, prompt atmospheric and astrophysical neutrinos.
- Over the range 60 TeV < E < 2 PeV, the spectrum is consistent with an E^{-2} spectrum:
  - $E^2\phi \sim 1.2 \pm 0.4 \times 10^{-8}$ GeV/cm^2/s/sr **per flavor**
  - If the astrophysical component is set to zero, the prompt component rises to 4.5 times the current experimental limit.
- A cutoff is needed; without a cutoff, this spectrum predicts 3 - 6 events in the 2 - 10 PeV energy range
  - Alternately, compatible with an $E^{-2.2}$ energy spectrum.
  - Even for 100% ν (no $\bar{\nu}$), a cutoff is still needed.

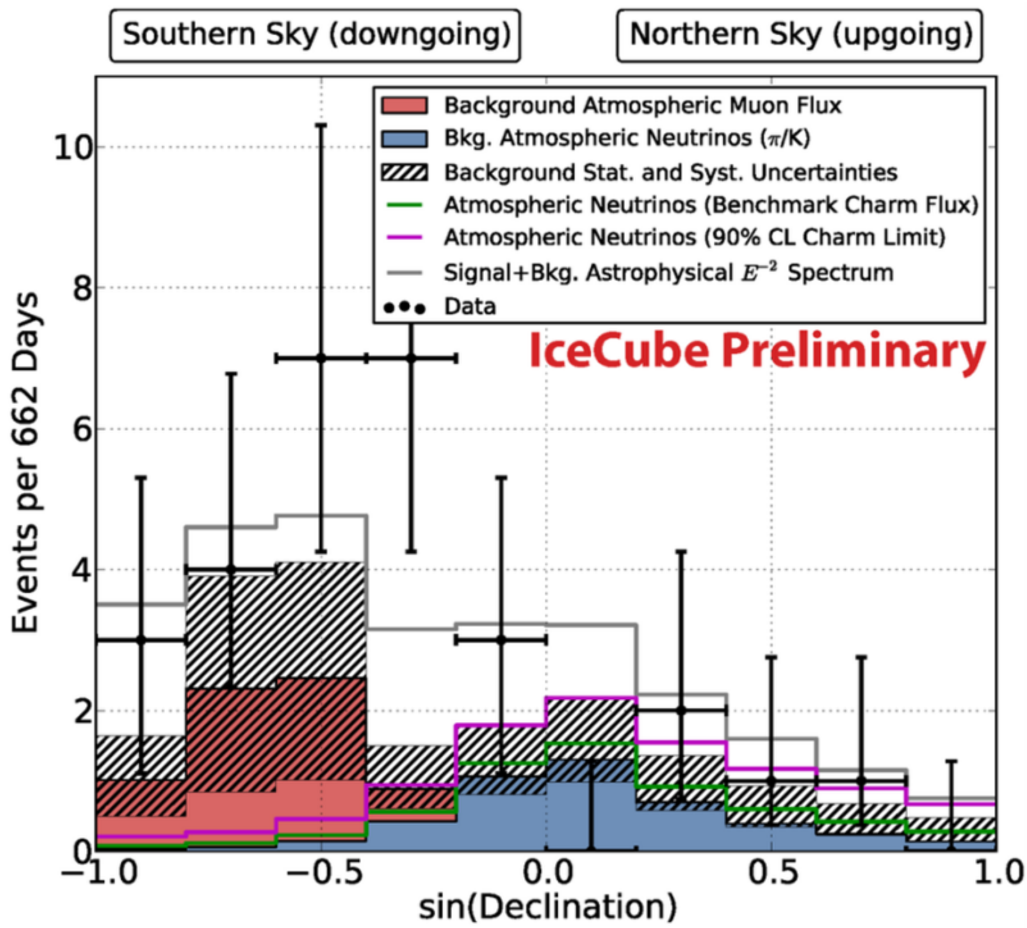
Energy spectrum & event characteristics

- Deposited energy
  - Electromagnetic process assumed
  - ~ 10-15% less light from hadronic showers
- 21 of 28 events are shower-like
  - Fraction is consistent with astrophysical or prompt ν



Zenith angle distribution

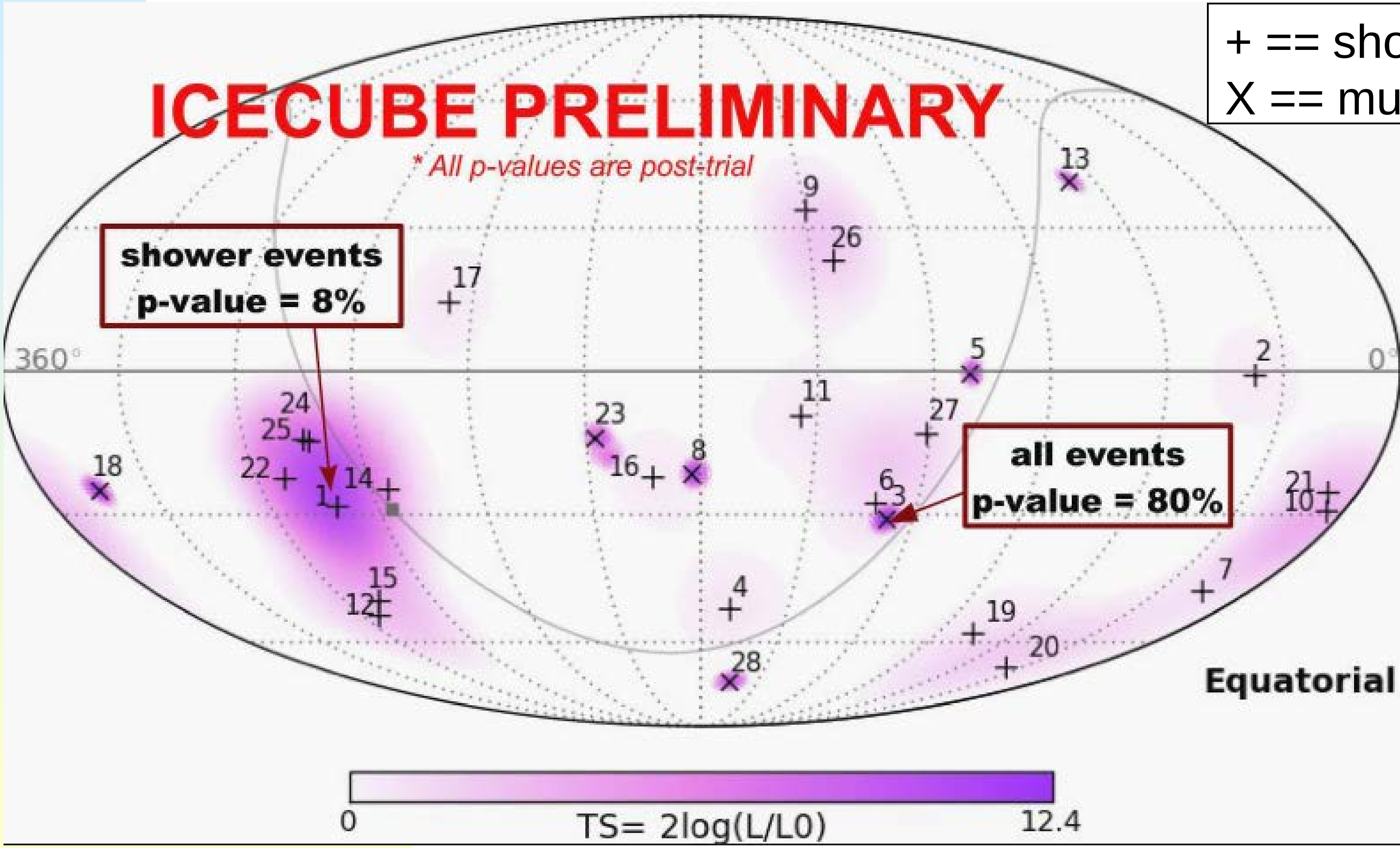
- 24 of 28 events are downward-going
- Most atmospheric ν should be upward-going
  - Effect of veto
- Astrophysical ν should be somewhat more downward-going
  - Acceptance and absorption
- 1.5 σ away from astrophysical prediction; inconsistent with atmospheric



Contained event sky map

Searches for clusters (source) & connection to galactic plane
p-values calculated for all 28 events & for 21 showers

+ == shower
X == muon track



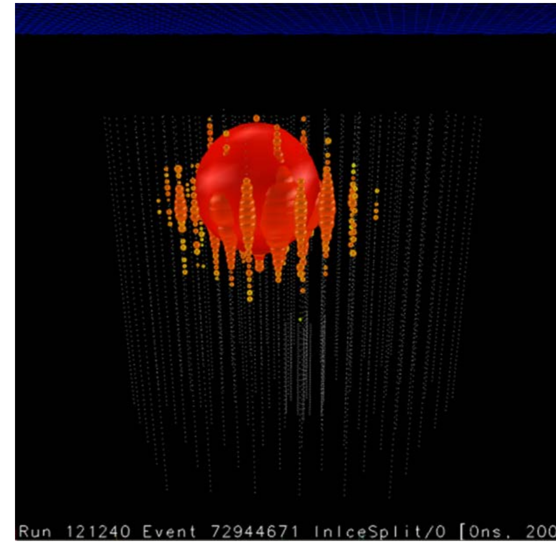
No significant source or connection to galactic plane seen

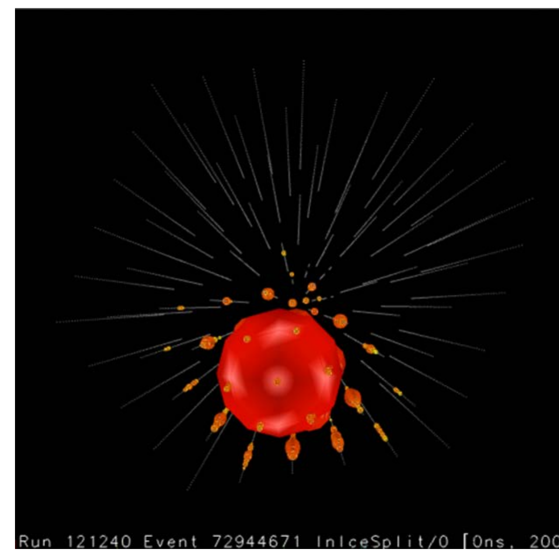
Looking ahead – more data

- IceCube continues to collect and analyze data
- One very high energy event appeared in the 10% of the 2012 data used to develop the analysis – “Big Bird”
- 378 hit DOMs
- Bert and Ernie are the not only PeV neutrinos

Energy	[illegible]
Zenith Angle	[illegible]

IceCube Top Secret



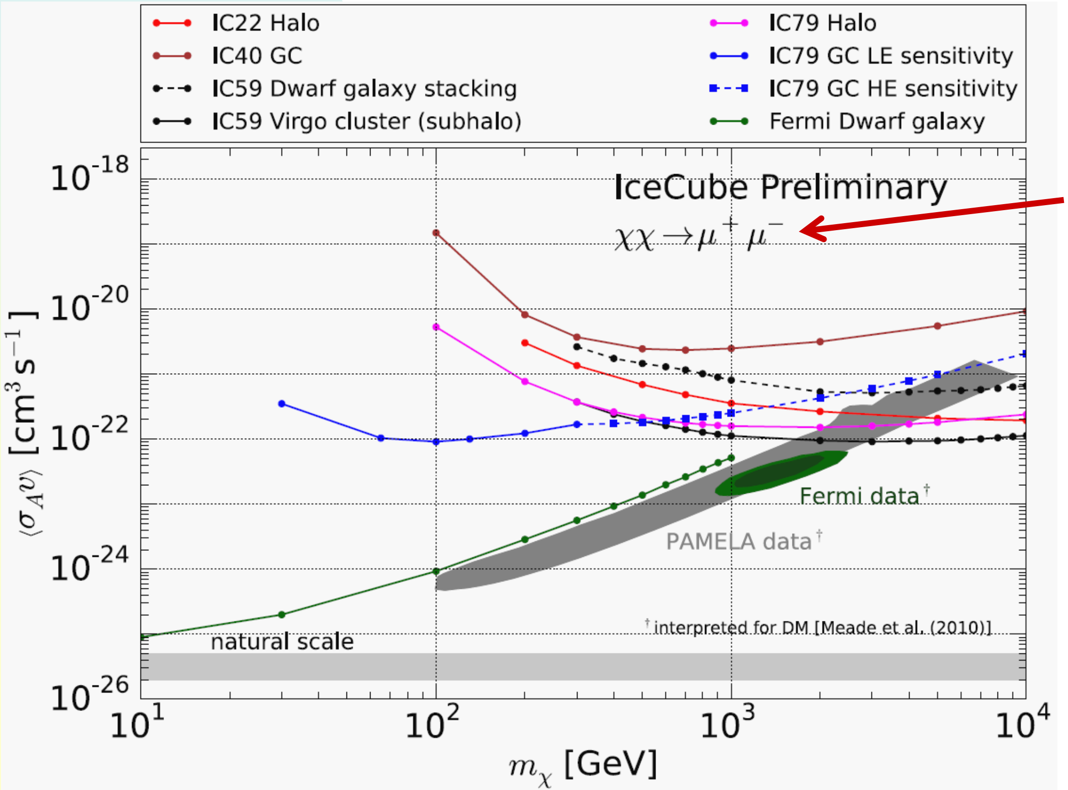


Some other IceCube physics

- Neutrinos from annihilation of particle dark matter
  - Annihilation in the Sun, the Earth, the galactic center or halo, or dwarf galaxies.
- Supernova monitor for our galaxy & Large Magellenic Cloud
- Pairs of upward going particles
  - Expects in some SUSY models with high mass scales
- Limits on magnetic monopoles and other exotica
  - Fast monopoles produce Cherenkov radiation
  - Slow monopoles may catalyze proton decay
- $\sigma_{\nu N}$ at PeV energies via absorption in the Earth
- Glaciology
  - Probe weather over last 100,000 years

Limits on WIMP annihilation

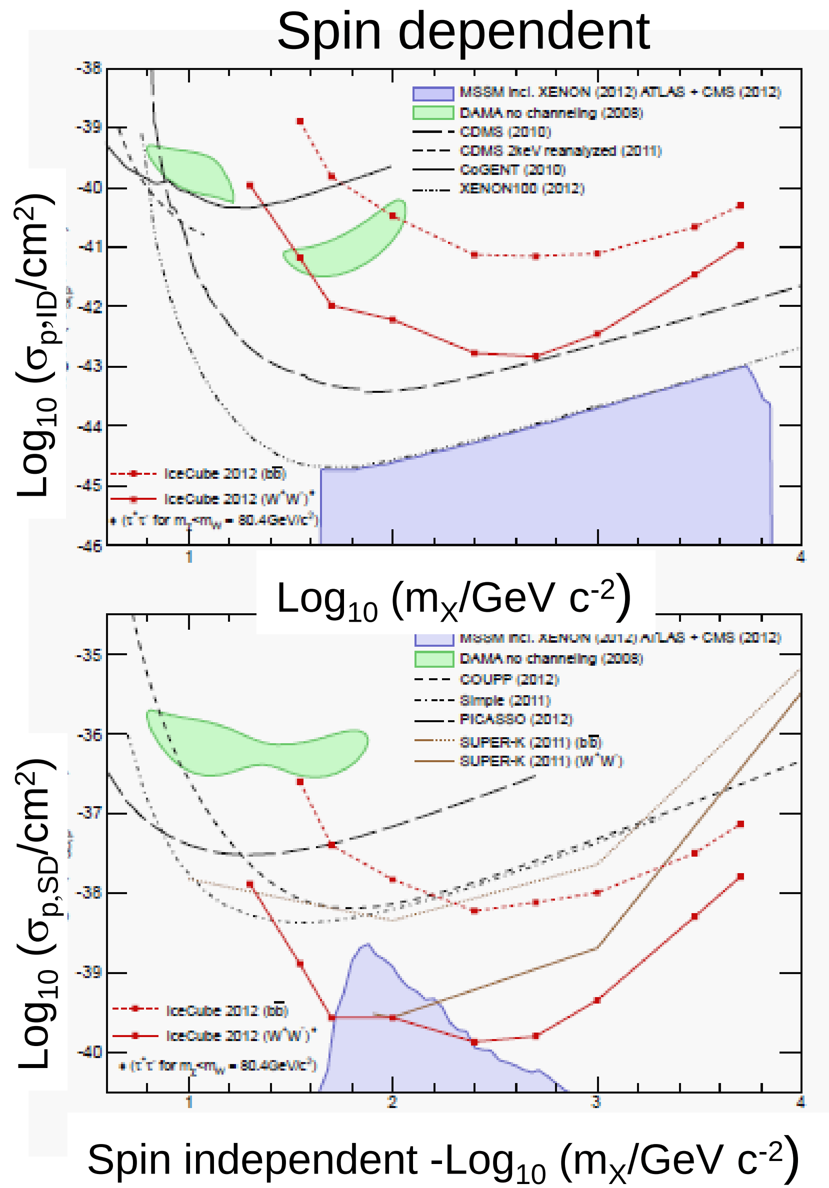
- Limits on ν from WIMP annihilation in the galactic halo and center, and in nearby galaxies
- Consider multiple final states:
  - W^+W^- ($\tau^+\tau^-$ below threshold), b-bbar, νν
  - Uncertainties due to mass profile of galaxy



final state

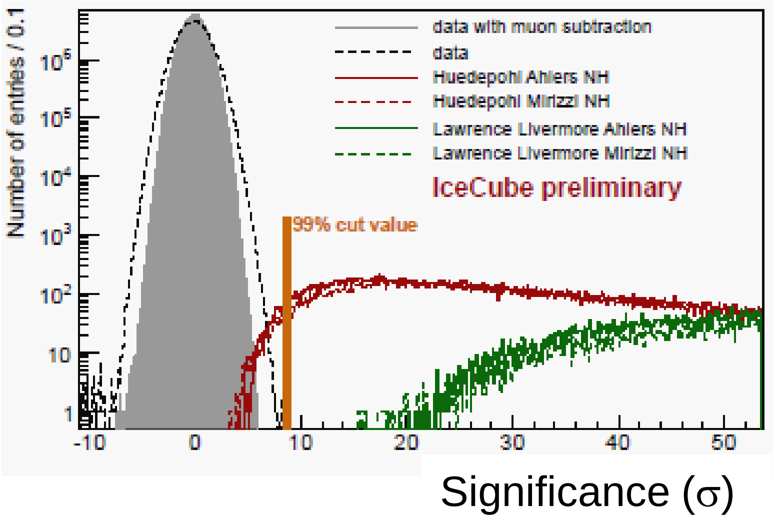
ν from WIMP annihilation in the sun

- Weakly interacting massive particles may be gravitationally captured in the sun, and annihilate, producing neutrinos
  - Capture in Earth and/or Galactic Halo also occurs
- Captured by spin-dependent interaction
  - Sun is mostly hydrogen
- Search for ν coming from the sun
  - No excess seen
- Cross-section limits set



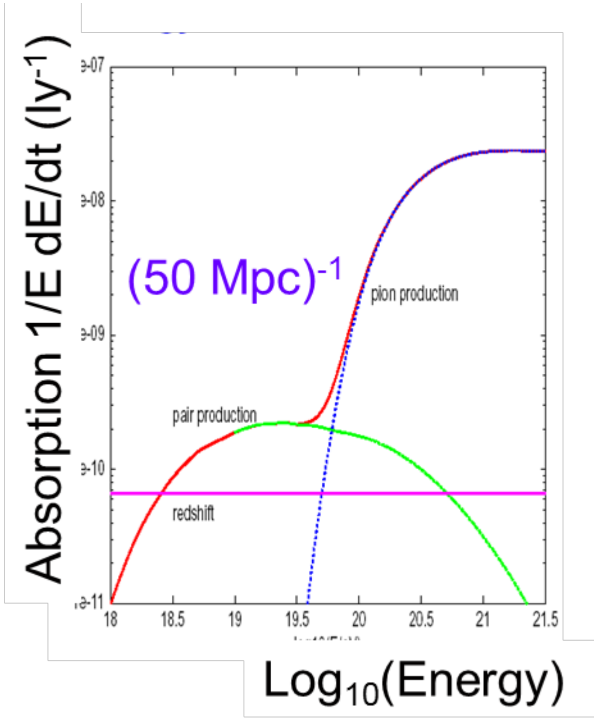
Supernova and exotics

- Search for a burst of O (MeV) ν
- These do not trigger IceCube, but are visible as a collective increase in the singles rates for all buried DOMs.
- Subtract hits from visible
- Sensitive to supernovae in our galaxy
    - Some sensitivity to Magellanic clouds



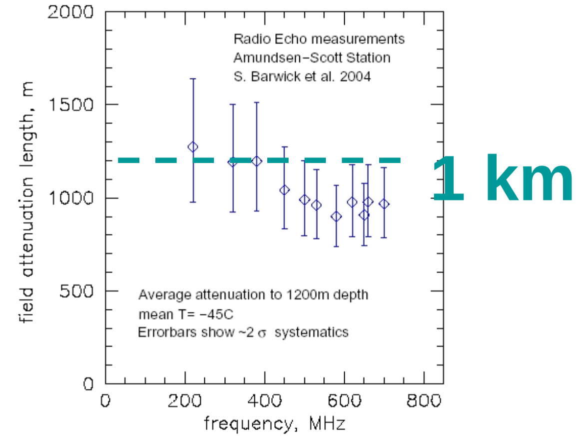
Searching for GZK ν

- CR with E> $4*10^{19}$ eV are absorbed by GZK interactions, and have a range of ~50 megaparsecs
  - $p + \gamma \rightarrow \Delta^+ \rightarrow$ lower energy $p + \nu$
  - Heavier CR are photodissociated
- ν from GZK interactions are the only way to probe the EHE universe at distances beyond ~75 megaparsecs
- IceCube is too small to see a clear signal.
  - Optical Cherenkov does not scale much further
- A new technique is needed
  - Coherent Radio-Cherenkov detection looks promising

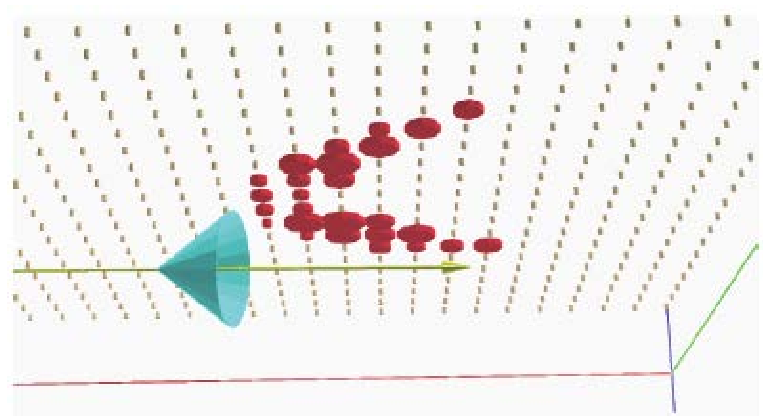


ν detectors: The next generation

- Require ~ 1 km ‘signal’ attenuation length
  - Radio waves!
- ν-induced showers have more e^- than e^+
  - Compton scattering of atomic e^-
  - e+ annihilation on atomic electrons
- Moving charges with v>c/ε
  - Cherenkov Radiation
- Coherent emission if λ_{radio}> shower width
  - $E_{radio} \sim E_\nu^2$
  - Threshold ~ 10^{17}-10^{20} eV
    - Depends on ν-interaction to receiver distance
- Attenuation length too short for acoustic detection



South Pole Ice



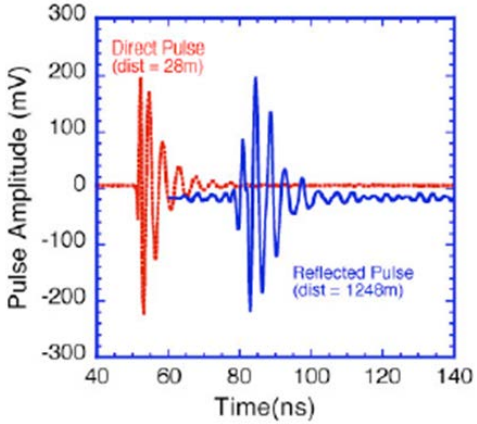
Experimental Efforts

- GLUE, LOFAR, Lunaska, SKA… – look for radio signals from moon
  - High threshold (> to >> 10^{20} eV)
  - Signal attenuation in regolith ~ 9 m/f[GHz]
- FORTE – satellite search for radio waves from Greenland
- ANITA – dedicated long-duration balloon that circled Antarctica twice
  - Horn antennas search for radio signals from Antarctic ice

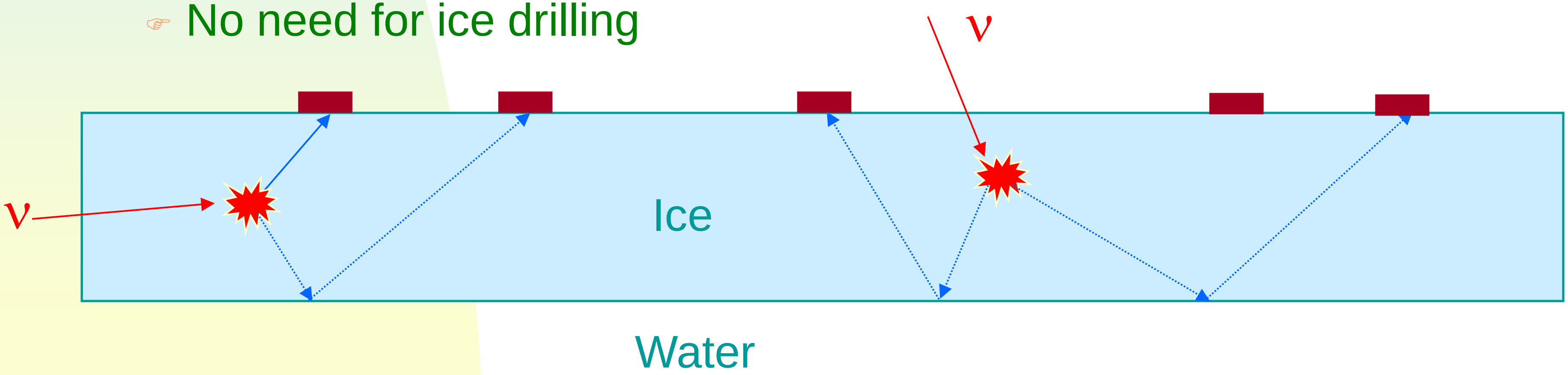
- RICE & (now) ARA at South Pole
  - Buried antennas
- ARIANNA – Ross ice shelf

ARIANNA: Radio in the Ross Ice Sheet

- Downgoing ν produce downgoing Cherenkov cones.
  - Usually need buried detectors to observe
- The ice-water interface reflects radio waves
  - Surface detectors can be sensitive to downward going Cherenkov photons
    - Large increase in solid angle
    - No need for ice drilling



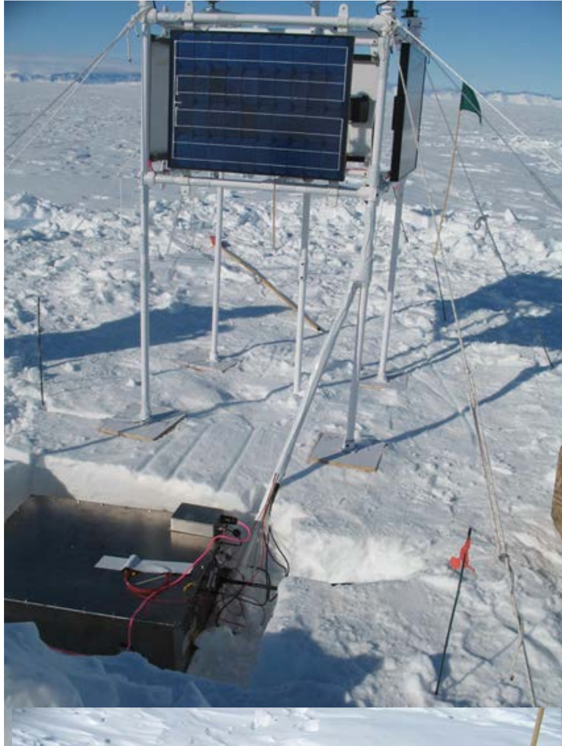
Signal reflection from interface



Dotted lines show reflected signal

ARIANNA status

- 7 station ‘hexagonal radio array’ prototype should be complete by Dec., 2013.
- Plan to propose a 900+ station array soon.
- Major issue: winter power



Logistics – home base

Logistics – Transportation

New C-17

Old C-141

Logistics – Transportation

Conclusions

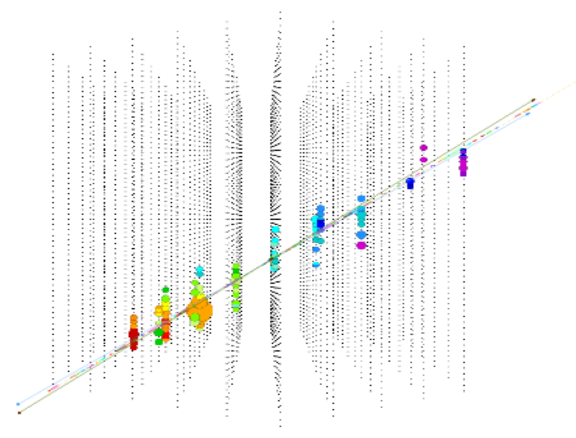
- UHE Cosmic Rays are one of the great unsolved problems in physics.
  - Extraterrestrial ν can shed light on the origin & composition of UHE cosmic rays. Many detectors are searching for these ν.
- The IceCube detector was completed in December, 2010, and is working very well.
- IceCube is pursuing many searches for extra-terrestrial neutrino.
  - We observe an diffuse ν excess, above the expected atmospheric background, with a significance of about 4 σ.
  - We observe three ν with E >1 PeV.
- IceCube is also studying many other topics: WIMPs, cosmic-rays, solar physics, magnetic monopoles….
- Next-generation experiments may search for radio waves from EHE ν interactions, with an active volume ~100 km^3.

Backup/storage

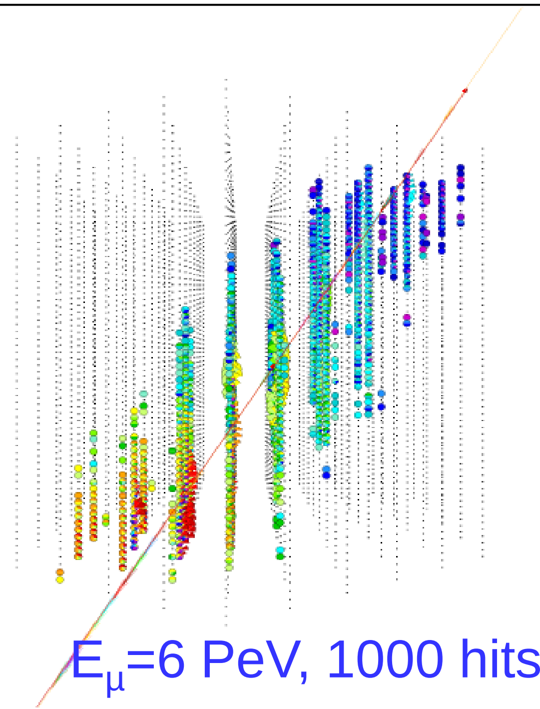
ν_μ interactions

- Good directional information
- Background from atmospheric ν
- μ lose energy by bremsstrahlung, direct pair production & photonuclear interactions
  - dE/dx ~ E for E> 1 TeV
- Range depends on energy
  - 1 TeV --> 1 km in ice
  - 1 PeV --> 20 km range
    - Effective area is much larger than detector volume

Measure range &/or 'dE/dx' to get energy

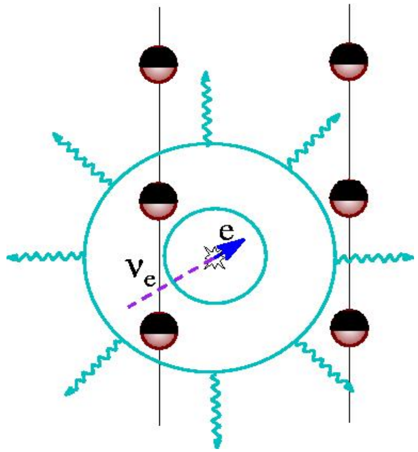


E_μ=10 TeV, 90 hits

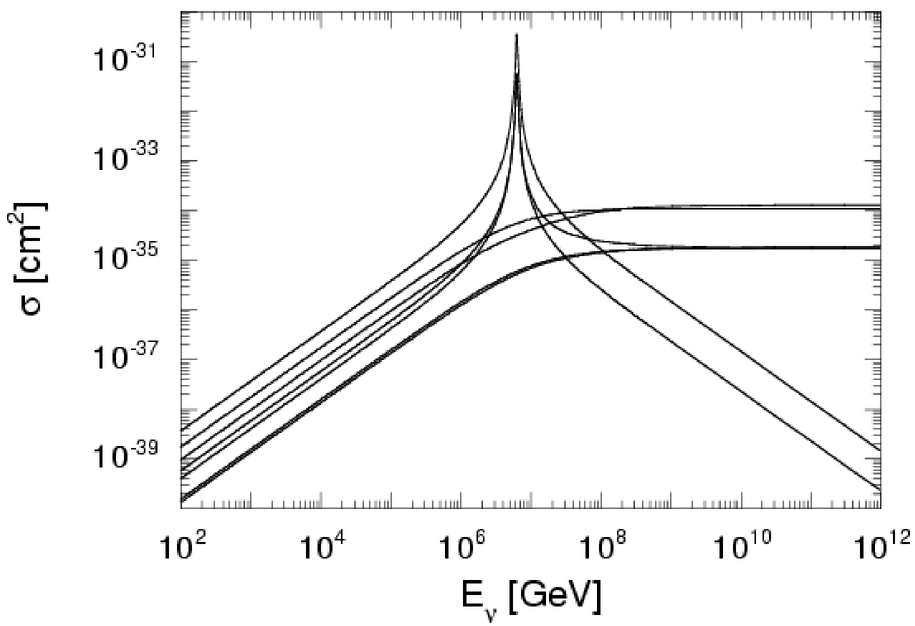


E_μ=6 PeV, 1000 hits

ν_e interactions: Electromagnetic Showers



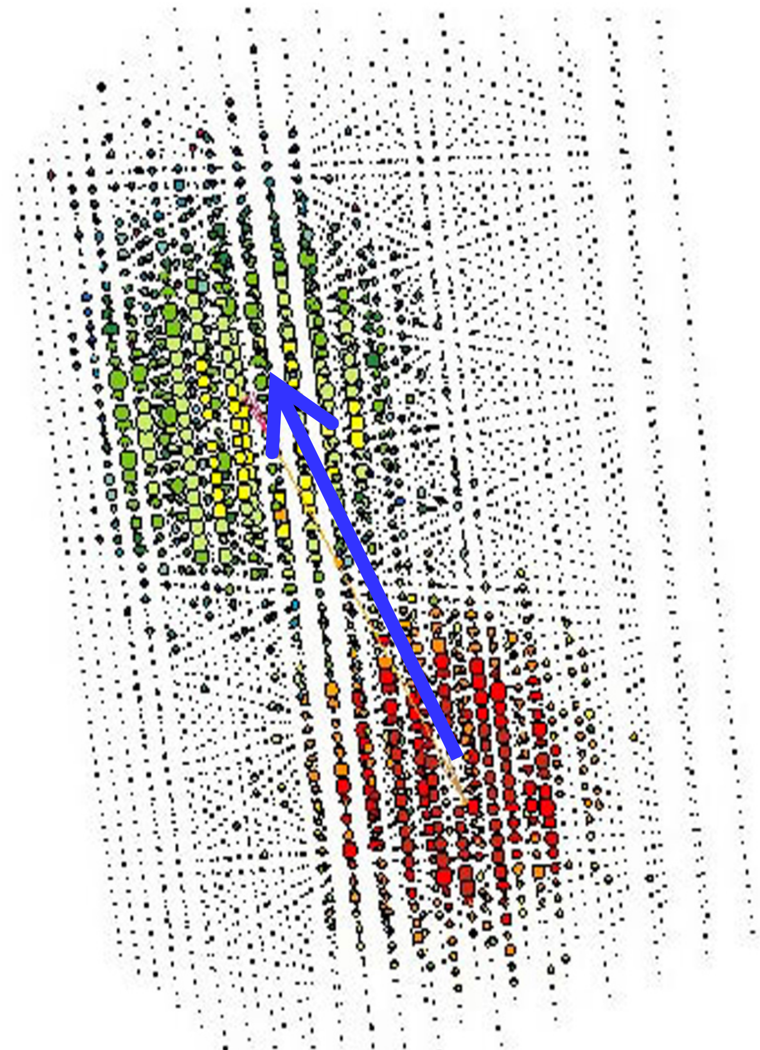
- Shower length ~ 10 m --> good energy resolution
- Bloblike --> poor directional determination
- Peak in cross section for νe >W --> $l\nu$, hadrons
  - ~ "Glashow Resonance"
- Techniques are much less developed than for ν_μ



Gandhi, Quigg, Reno & Sarcevic, 1996

ν_τ interactions

- $\nu_\tau N \dashrightarrow \tau X$
  - $\gamma\beta c\tau$ = 500 m at E=10^{16} eV
- Double-bang signature
  - 1 shower when the τ is produced
  - 2nd shower when the τ decays
  - A minimum ionizing track connects the showers



E_τ = few PeV

Learned and Pakvasa, 1994