Neutrino Astronomy in Antarctica

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Why neutrino astronomy: Cosmic-rays

Neutrino Hunting at the South Pole

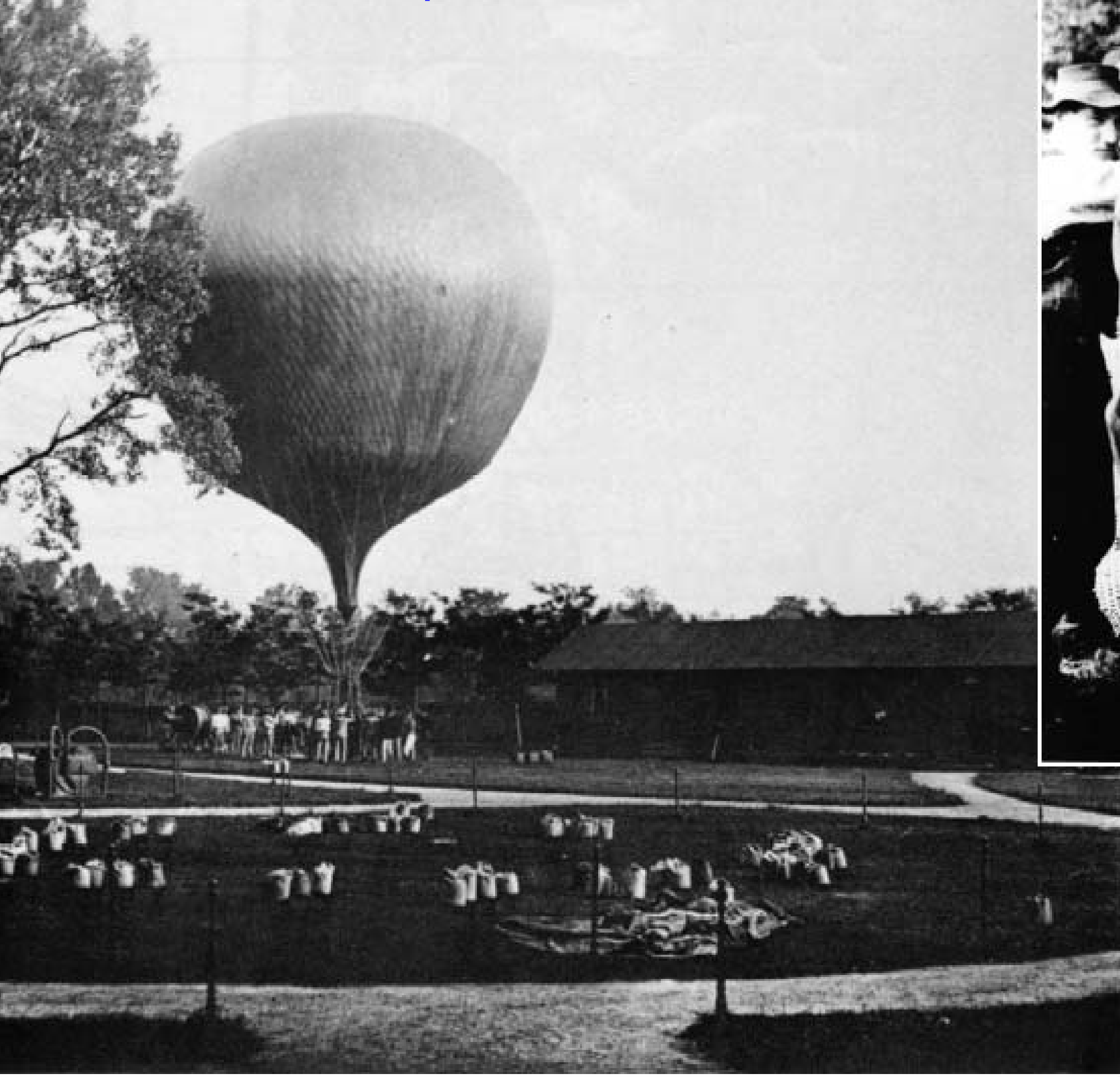
ARIANNA – a 100 km^3 detector

Conclusions

(n.b. a strong experimental emphasis)

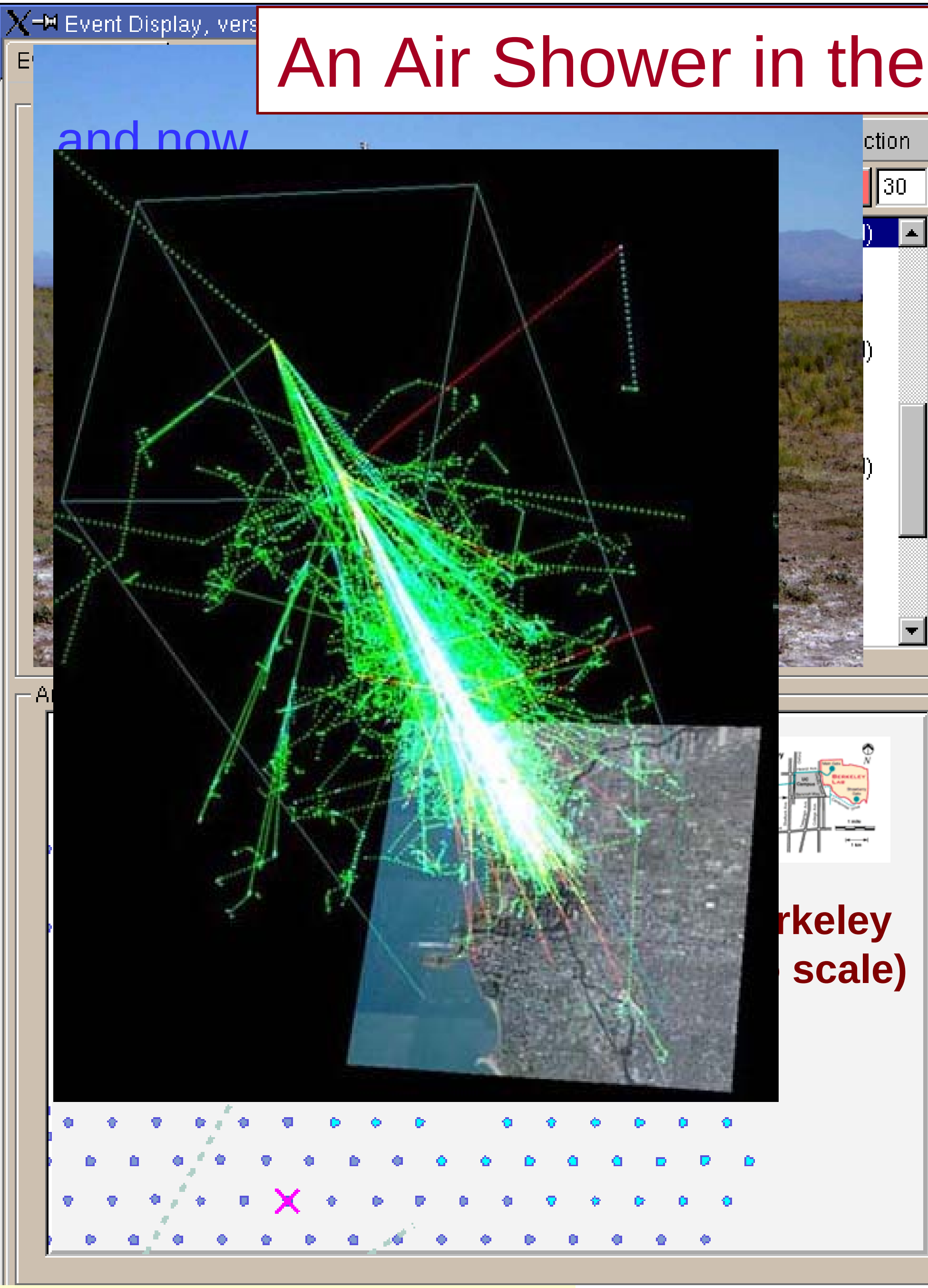
Cosmic rays then…

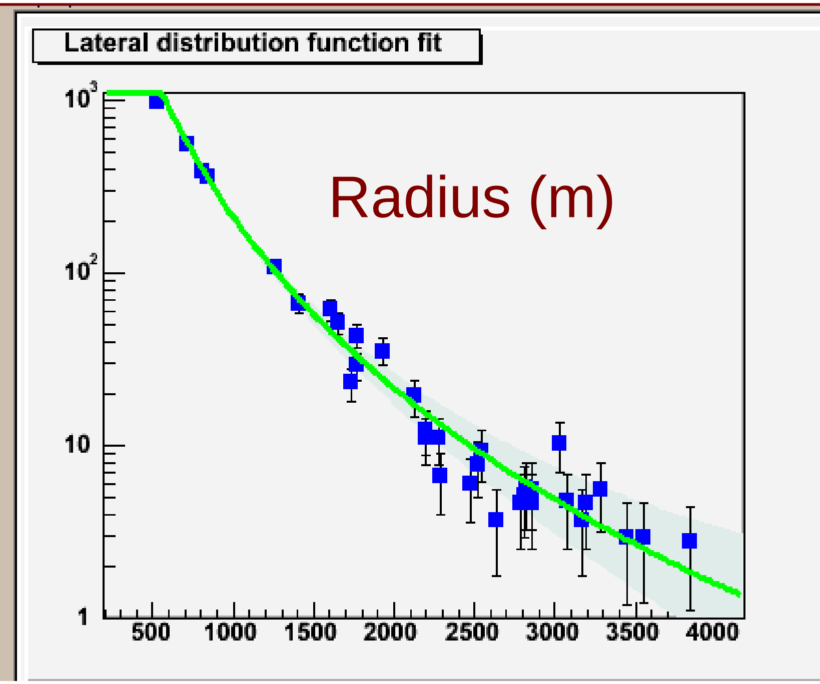
Mysterious radiation
from space



Discovery:
Victor Hess 1912
(Nobel Prize 1932)

An Air Shower in the Pierre Auger Observatory





One particle with enough energy to light a 50 watt bulb for one second

Where do they come from??

Needs a giant particle accelerator

One possibility: Supernovae Remnants

- A supernova occurs when a heavy star runs out of fuel (hydrogen/helium/carbon…) to burn, and then explodes.
- It leaves a neutron star, which may have a strong magnetic field which could 'power' the accelerator
- Hard to explain the most energetic cosmic-rays

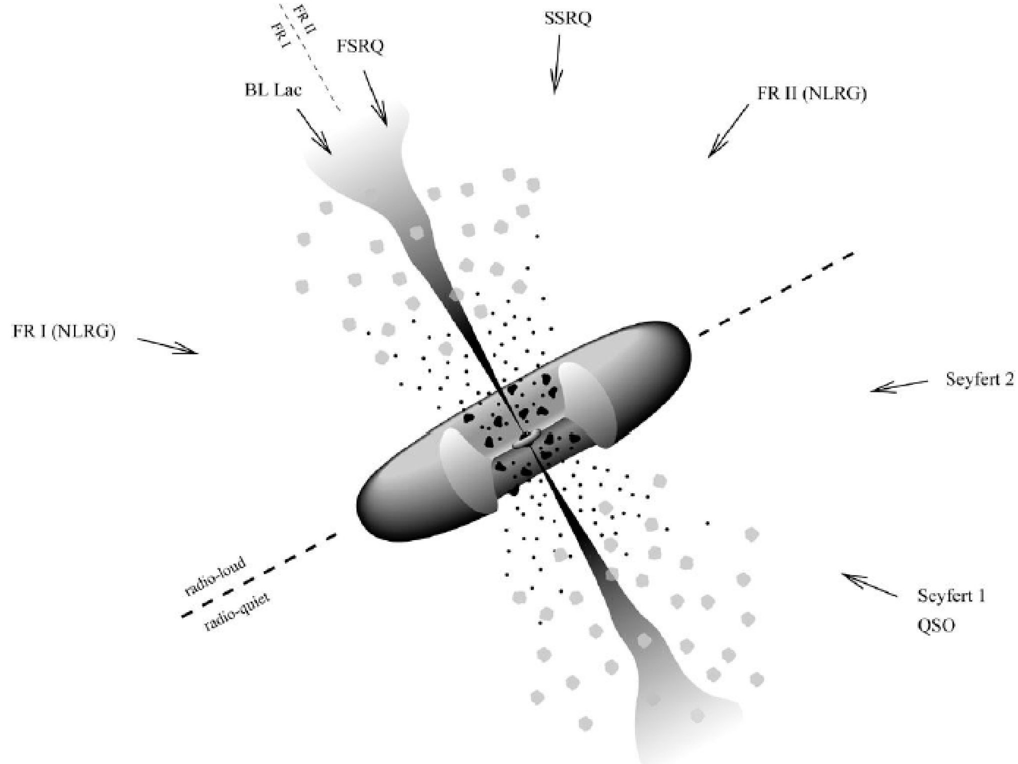
The Crab Nebula in Taurus (VLT KUEYEN + FORS2)

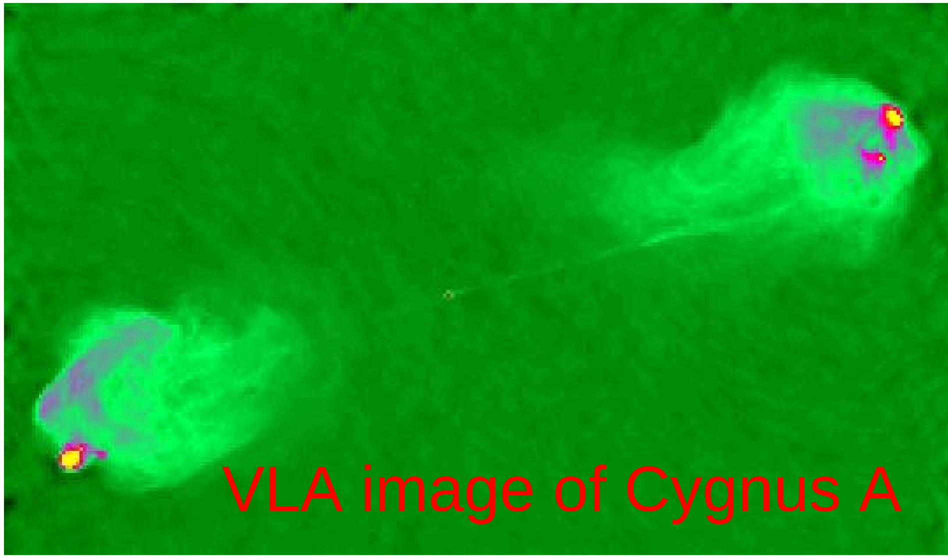
ESO PR Photo 40f/99 (17 November 1999)

Or…
Active Galactic Nuclei

- Galaxies with supermassive black holes at center
- Emits a narrow jet of relativistic particles

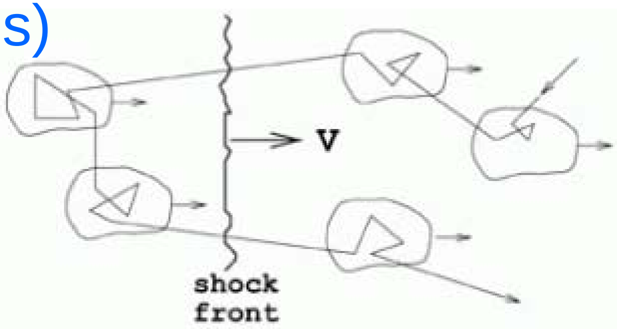
- Other possibilities exist
  - Gamma-ray bursters
    - (black hole/neutron star collisions)
    - Collapsing supermassive stars





Accelerating Charged Particles

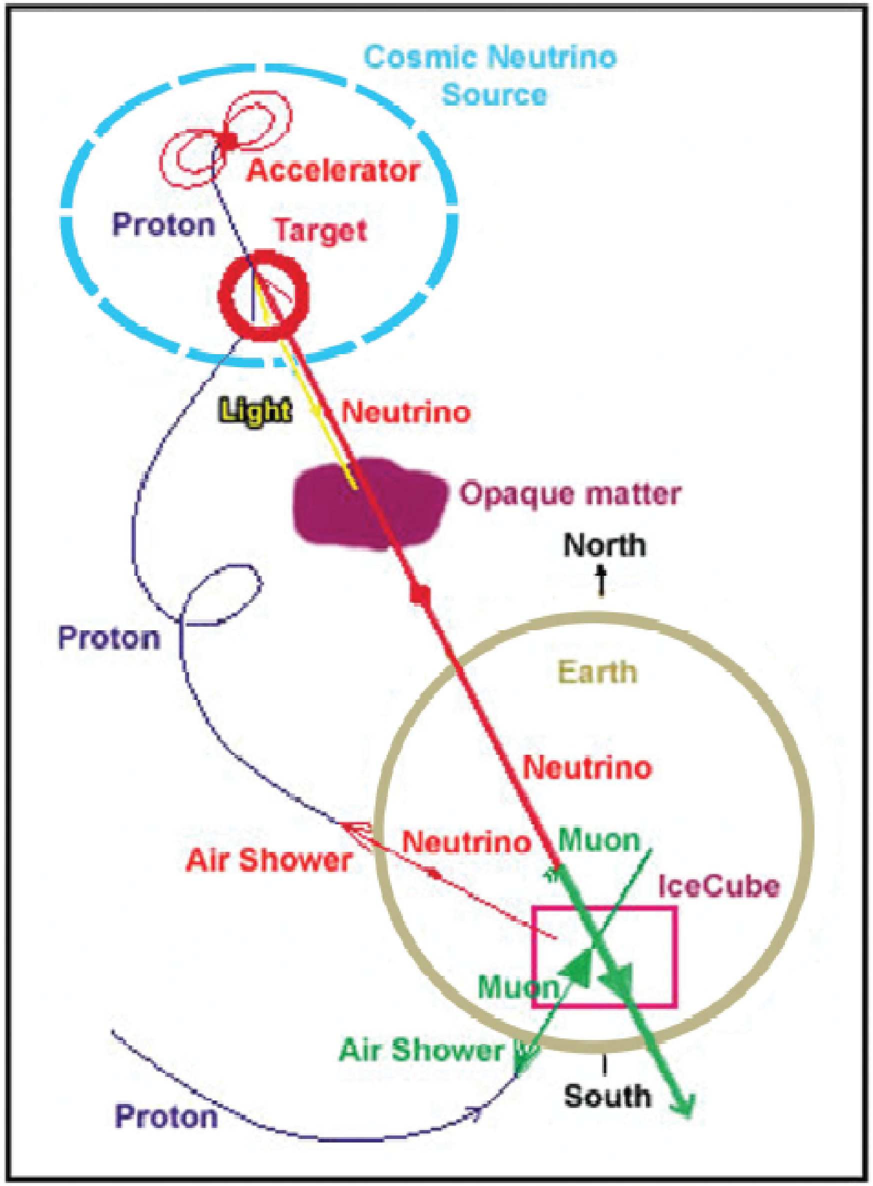
- Terrestrial method: strong microwave fields in conducting cavities
  - Lasers (also strong electromagnetic fields) can also be used
- Most likely astrophysical method: shock waves
  - Encounters with moving magnetized plasma (dissociated electrons and nuclei)



- Magnetic fields bend charged particles in circles, allowing for repeated encounters, and so repeated acceleration

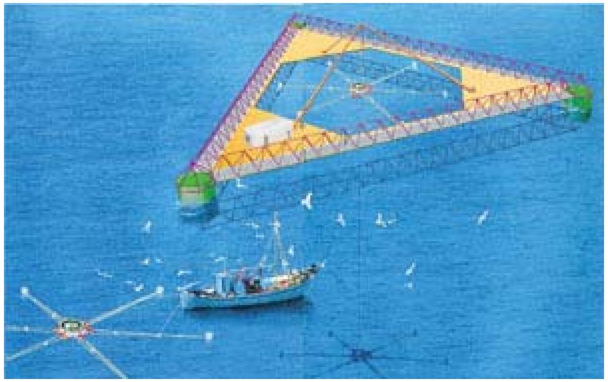
Neutrinos probe the sources of cosmic rays

- Neutrinos (ν) are particles that barely interact at all
  - No electrical charge
  - They only interact via the 'weak' interaction
    - Most pass through the earth without interacting
- ν are ideal to look for astrophysical accelerators
  - Charged cosmic rays (e.g. protons) are bent in transit
  - Gamma-rays are absorbed with the accelerator or in transit
- ν come straight to us

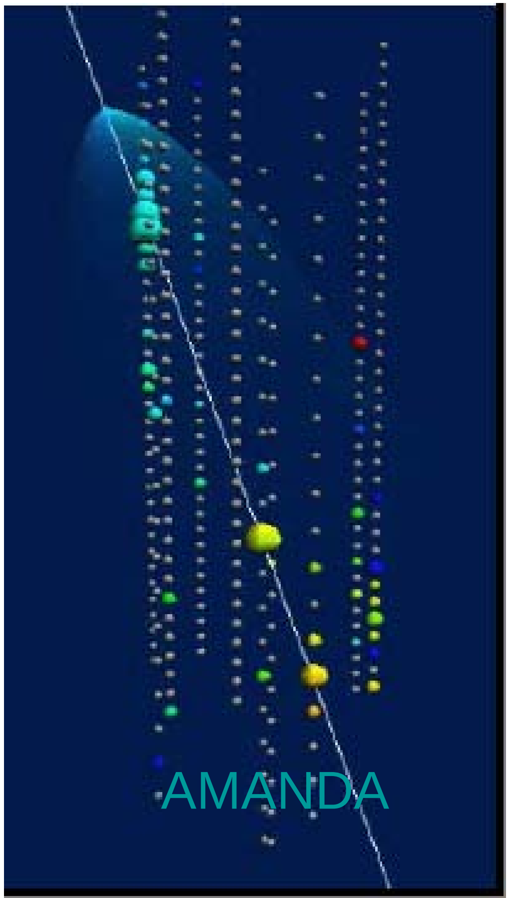


Detector Basics

- Because neutrinos interact so weakly, a giant detector is needed to see them
  - ~ 1 km^3 detector for 100 GeV < 10^{15} eV
- Only natural media are affordable
  - Water or ice
- Neutrinos interactions produce electrically charged particles, like electrons
  - If these charged particles move fast enough, they emit light, called Cherenkov radiation
    - Sort of like a sonic boom
- Both deep ocean or deep ice both bring many challenges.

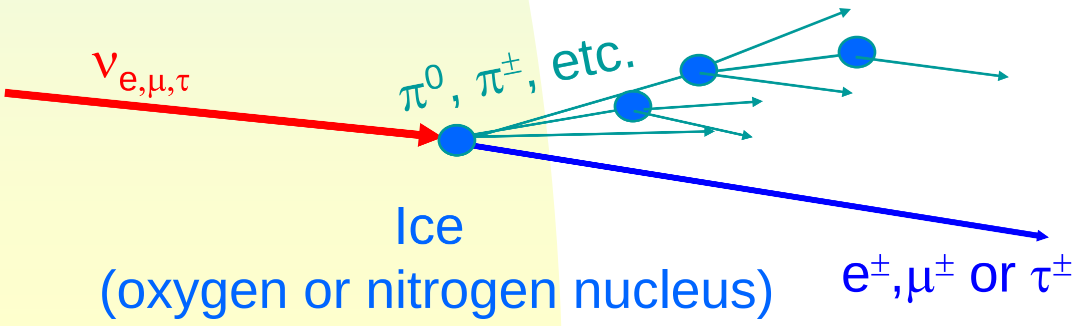


NESTOR



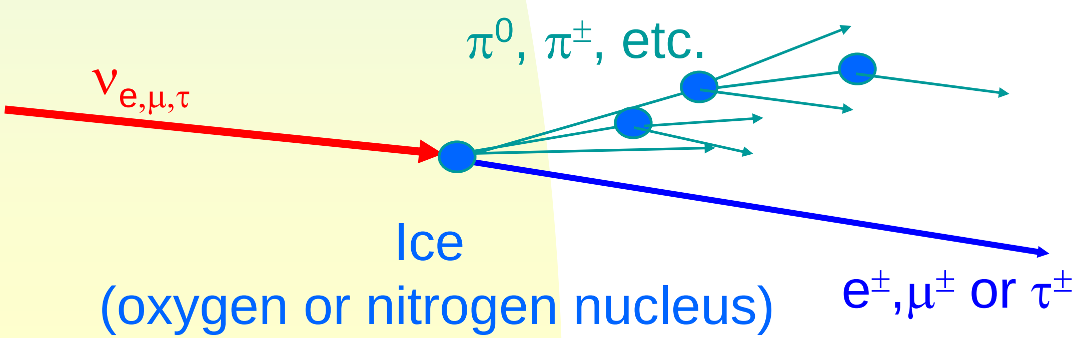
How to detect neutrinos

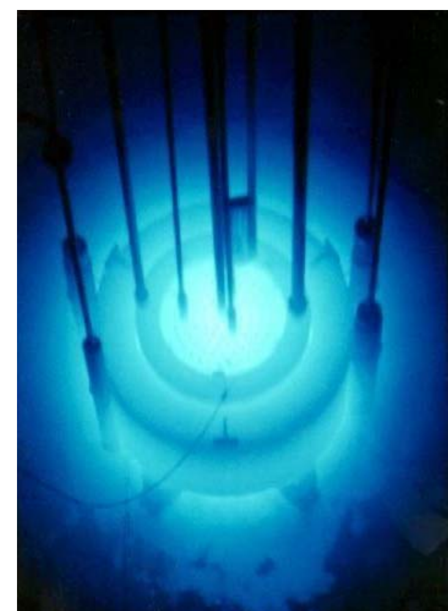
- Neutrinos interact with oxygen or nitrogen nuclei in the ice.
  - They use their energy to produce particles like pions (π), plus, usually, an electron, muon or tau
    - The three leptons act differently in the ice
      - Muons can travel long distance (km) in ice
  - The produced particles may themselves interact with the ice, producing more particles
  - These particles may then produce more charged particles, etc., until the energy runs out.
- This shower may contain billions to trillions or particles.



Observing Neutrino Interactions

- Charge particles moving quickly (more than 2/3 of the speed of light) will emit light (known as Cherenkov radiation)
- Showers have more negative charged particles than positive
  - Net negative charge, moving
  - This net charge leads to copious radio wave emission from energetic showers.





The IceCube Collaboration

IceCube

University of Alabama
University of Alaska, Anchorage
University of California, Berkeley
University of California, Irvine
Clark-Atlanta University
Bartol Research Institute, University of Delaware
Georgia Institute of Technology
University of Kansas
Lawrence Berkeley Natl. Laboratory
University of Maryland
Ohio State University
Pennsylvania State University
Southern University and A&M College
University of Wisconsin, Madison
University of Wisconsin, River Falls

RWTH Aachen
Ruhr-Universität Bochum
Universität Bonn
DESY, Zeuthen
Universität Dortmund
MPIfK Heidelberg
Humboldt Universität, Berlin
Universität Mainz
BUGH Wuppertal

Stockholms Universitet
Uppsala Universitet

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

University of Alberta

Chiba University

University of Canterbury

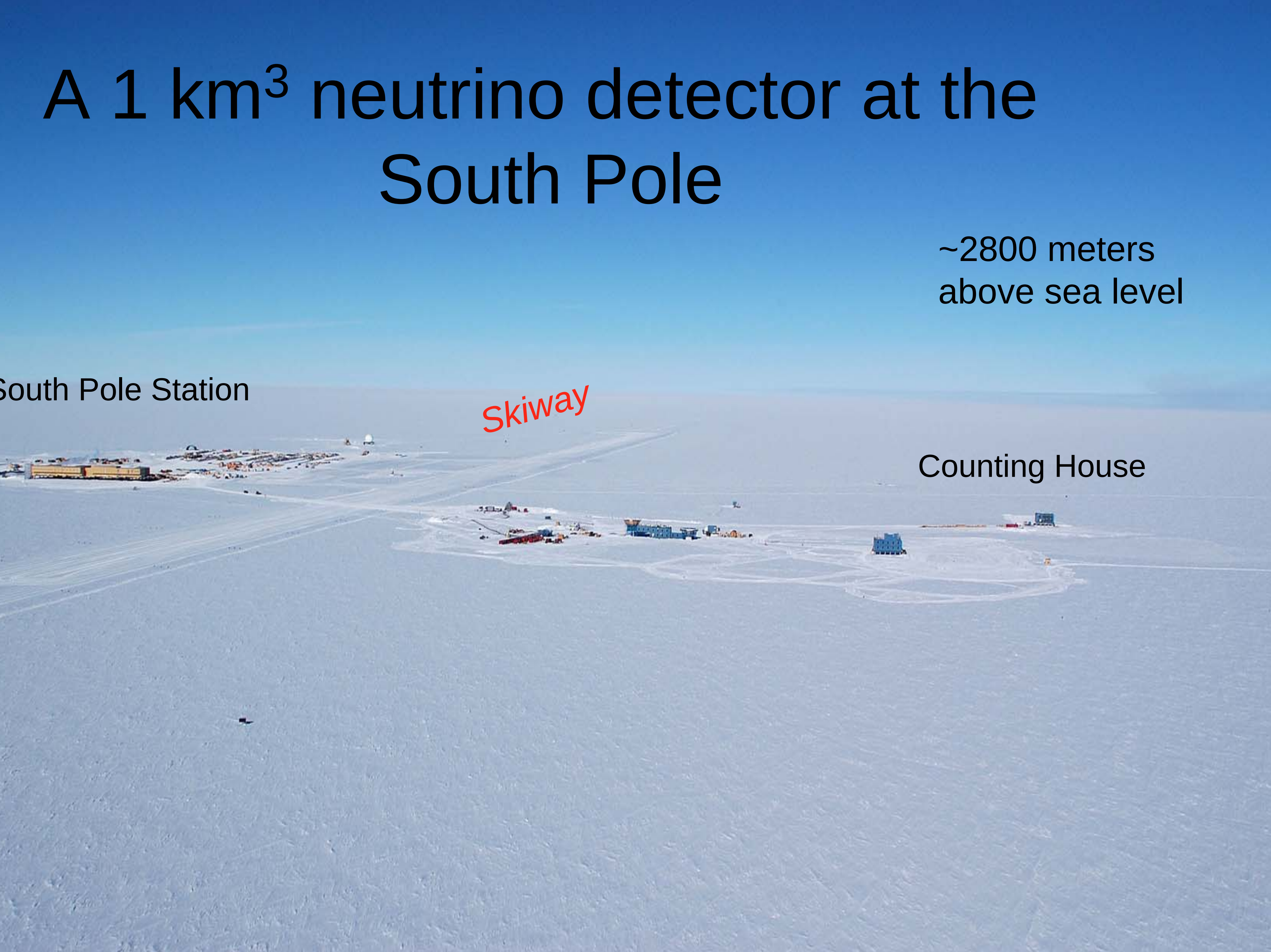
EPF Lausanne

Oxford University

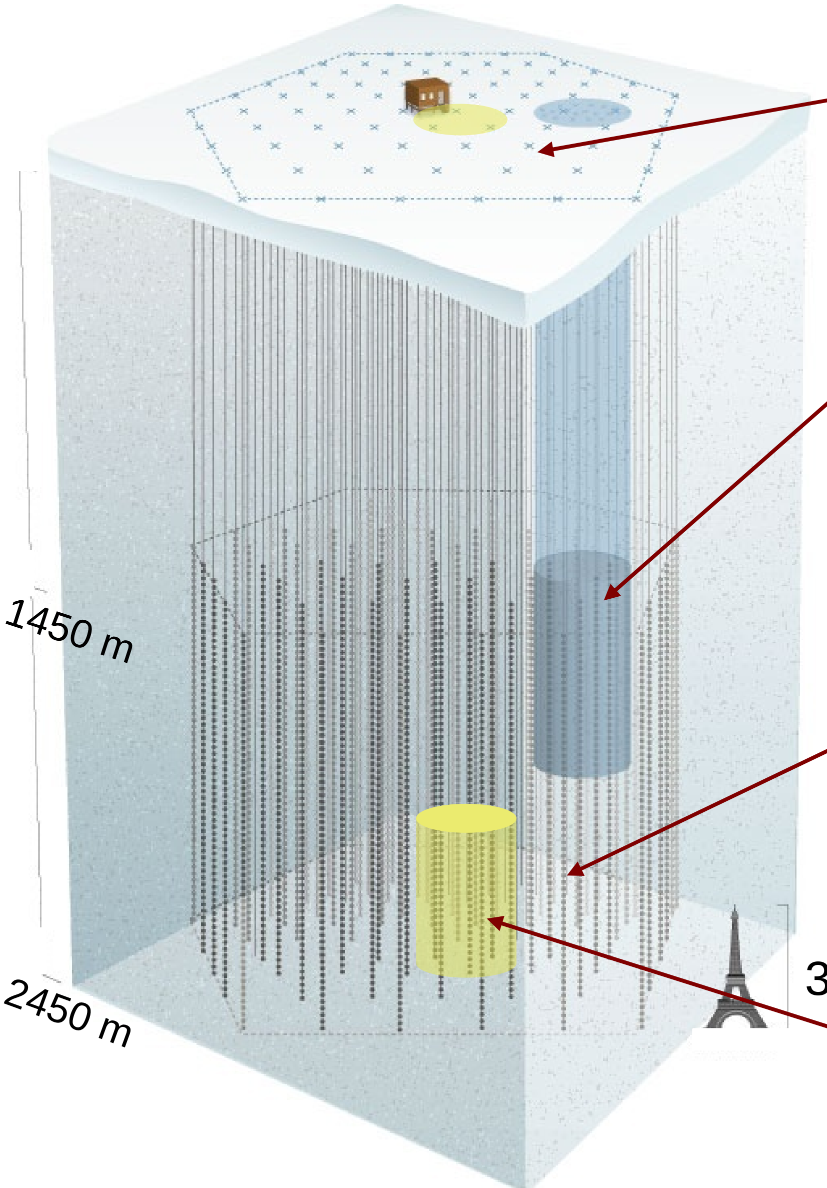
University of the West Indies

A 1 km^3 neutrino detector at the South Pole

~2800 meters
above sea level



IceCube Detector



IceTop: Surface Air Shower Array
320 1.8 m diameter ice tanks
1 km^2 area

AMANDA
(predecessor/
Prototype)

IceCube: (“Main Instrument”)
80 Strings / 60 optical sensors each
1 km^3 instrumented

Deep Core:
(Low energy extension)
6 strings/ 60 optical sensors each

Current status: 79 of 86 strings deployed

The practical aspects of building sophisticated detectors in Antarctica

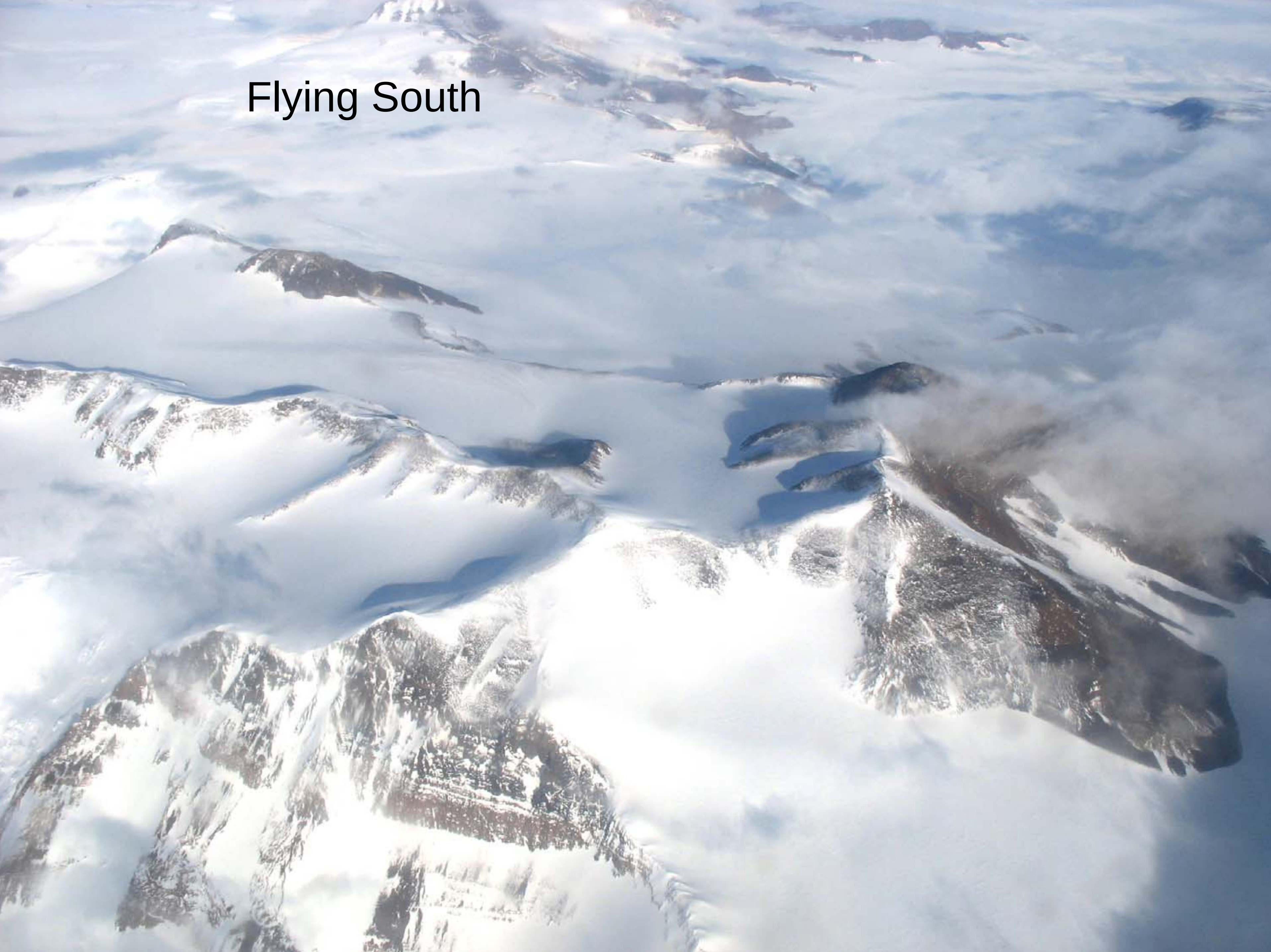
How do you actually build IceCube?


CAT


IVAN THE
TERRA BUS
FOREMOST

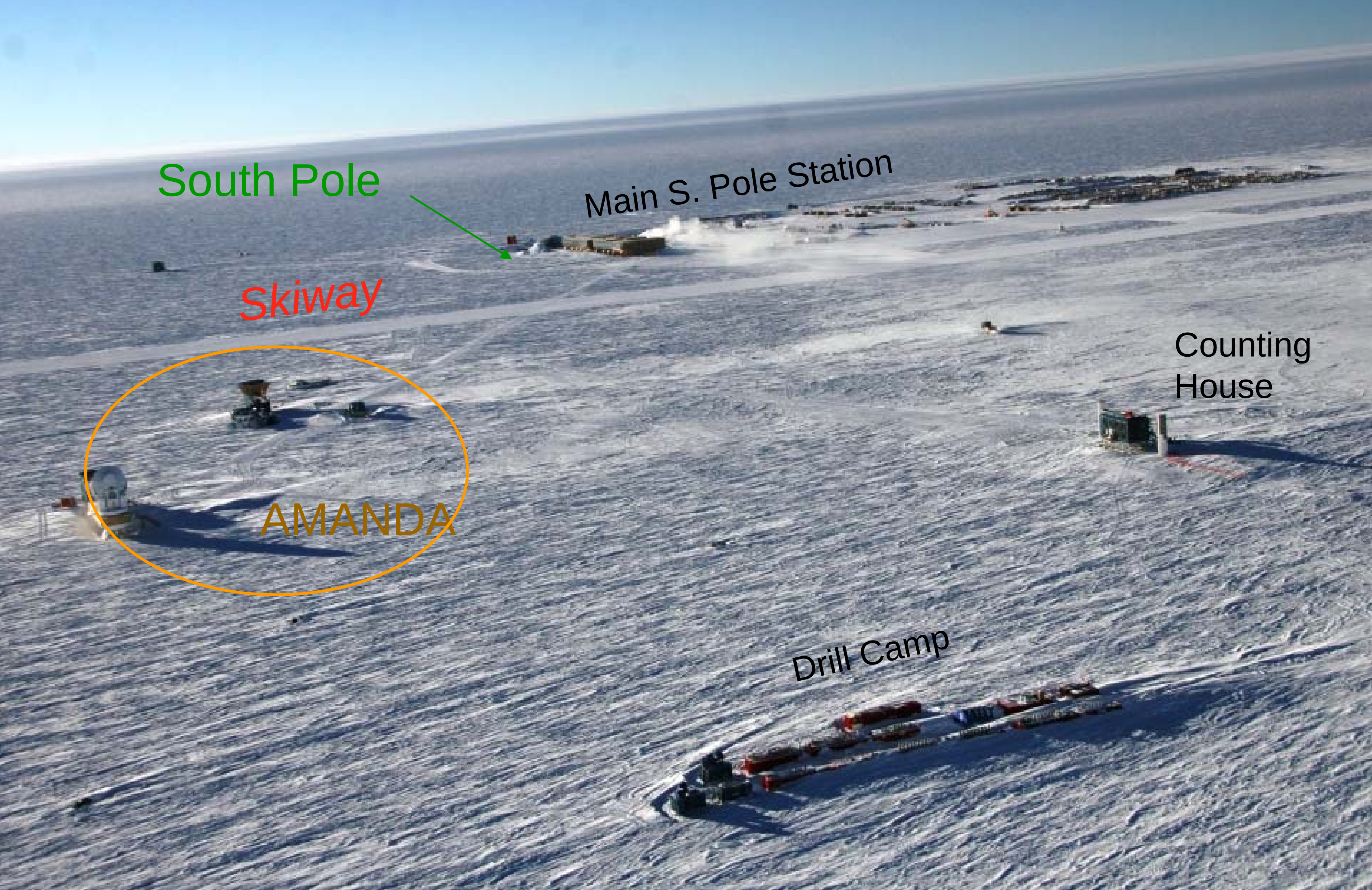
McMurdo Station – the main logistics base in Antarctica

Flying South


Flying South

Unloading IceCube Cargo

IceCube


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

Working at 10,000 feet
And -40^0 (C or F) is hard

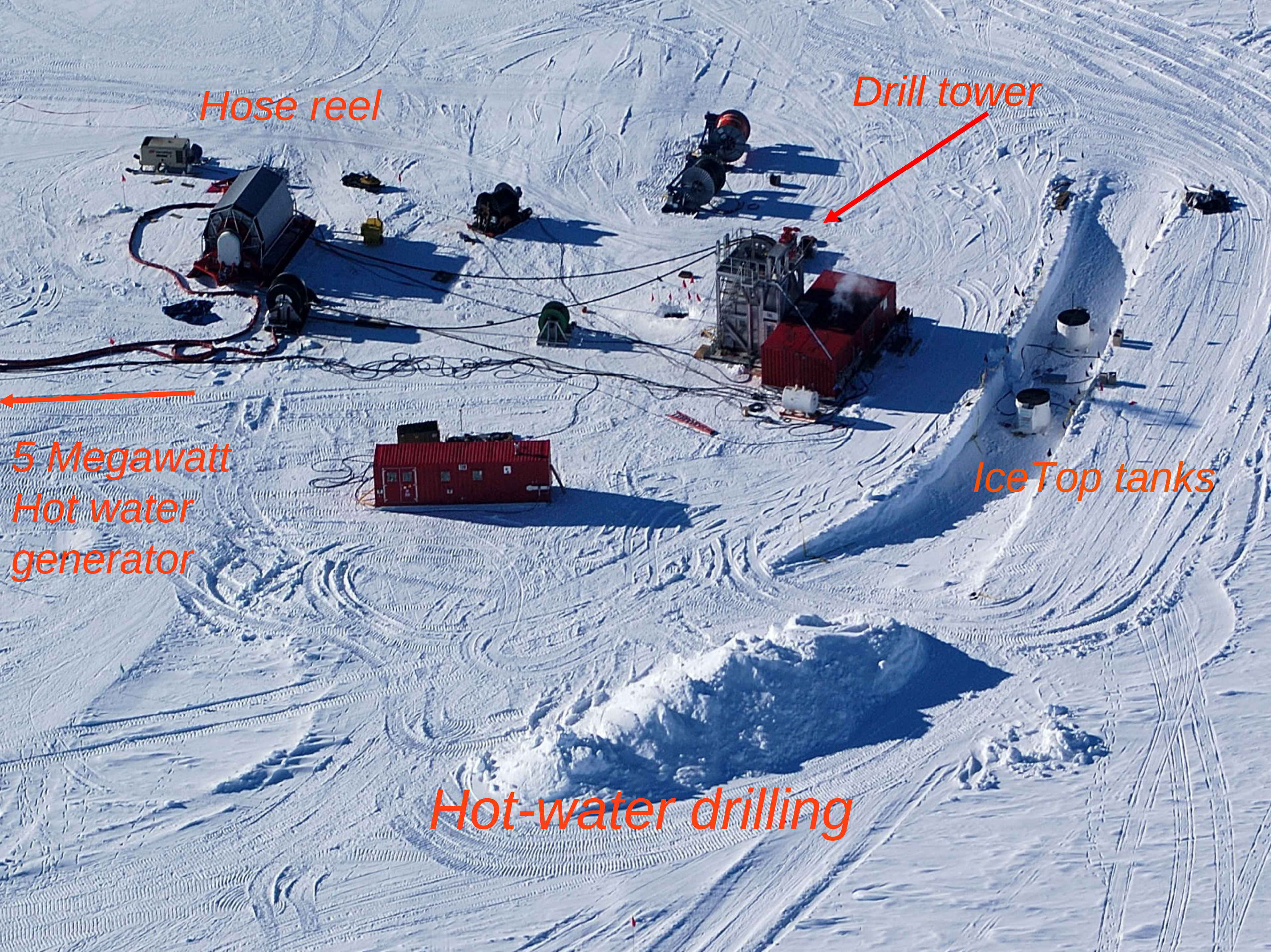
The new station… central laboratory++++

The old station


DANGER
HARD HAT AREA
Buried
Fuel Lines

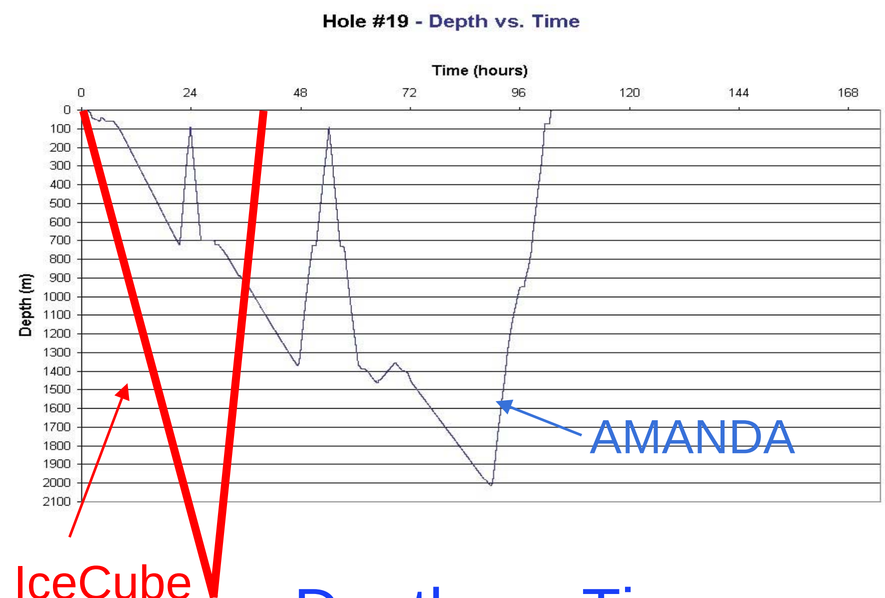
Transportation

Drilling holes for the IceCube String
With a hot-water drill


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

Hole Drilling

- 1 ½ mile 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 7 feet/minute
  - ~40 hours to drill a hole



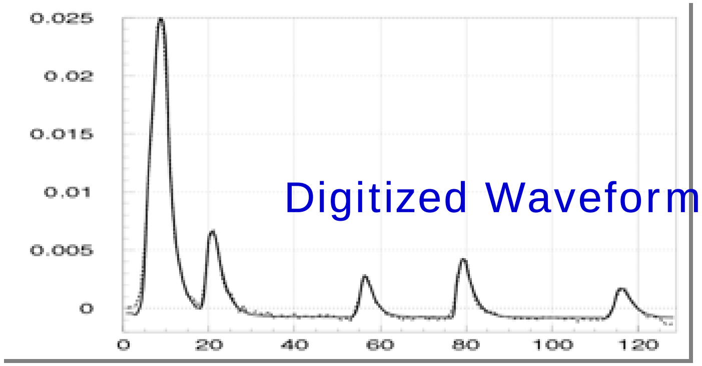
Depth vs. Time

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

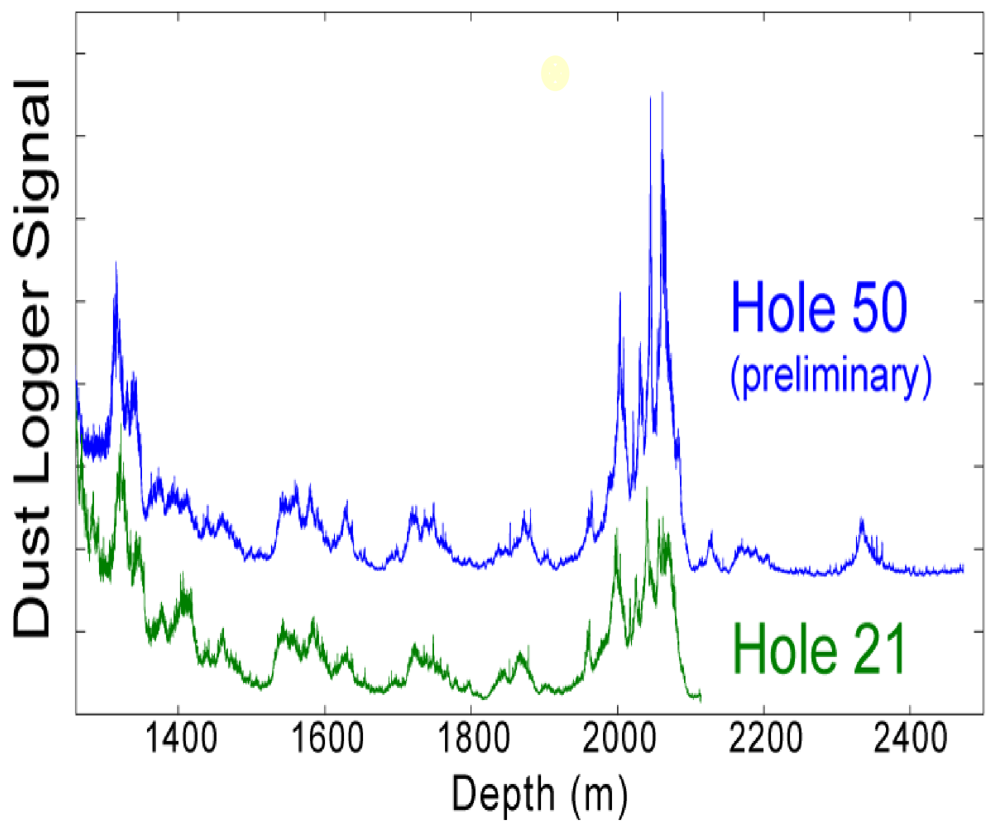
- Each optical module acts independently, like a small satellite
- It contains a photomultiplier tube (sensitive light detector)
- Electronics records the arrival times of observed photons (light)
  - Accuracy $2*10^{-9}$ s
- LEDs produce calibrated light pulses
- Transmits digital data packets to the surface.
- More than 98% of the deployed DOMS are functioning to spec.



3.3 ns/sample
1 ns =0.000000001 s

Probing the Ice

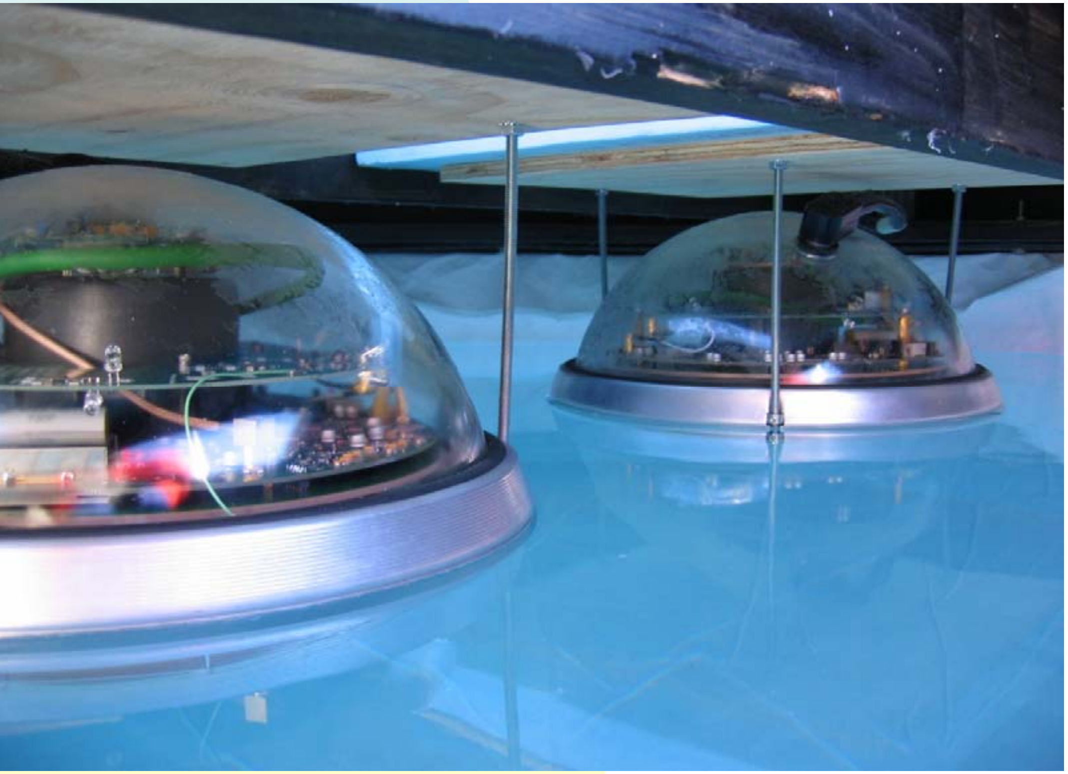
- Measures optical properties of Ice
- Emits light perpendicular to hole
  - Measures light scattered by dust
  - Studies the weather over the past ~ 70,000 years



2 IceTop Tanks (= 1 station)

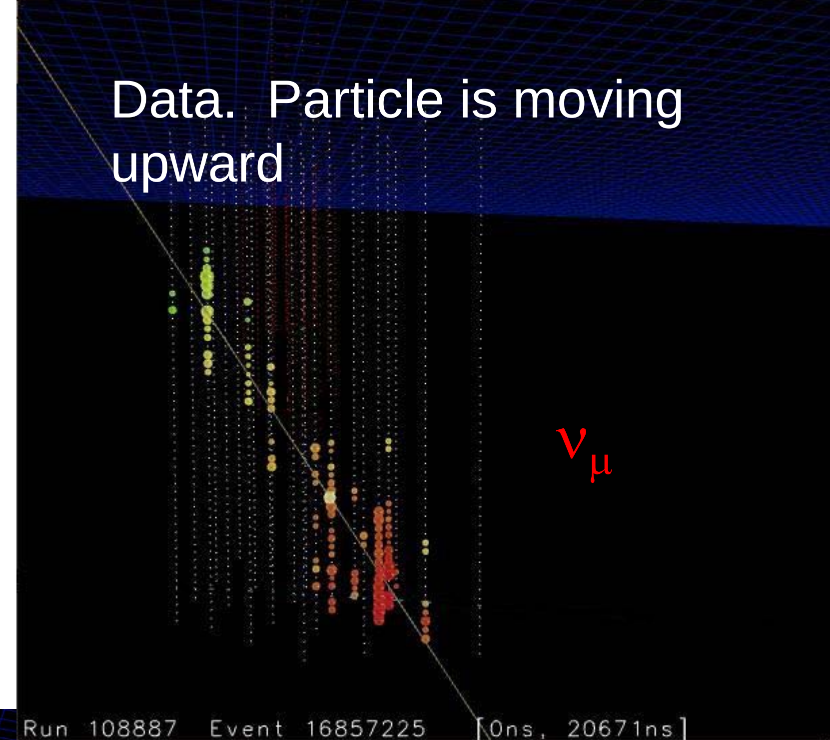
IceTop Surface array

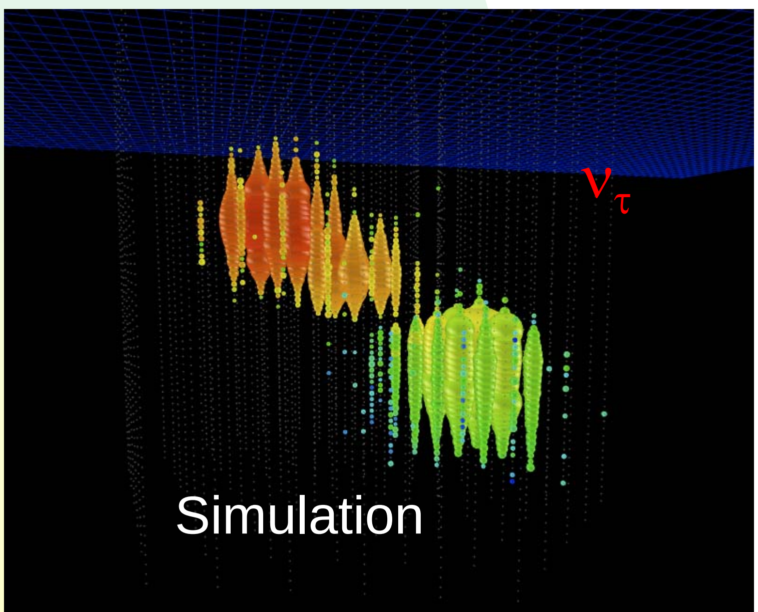
- Detects cosmic-ray air showers
  - ◆ Like Auger
- 160 water-filled tanks
  - ◆ Two optical modules in a tank of water look for Cherenkov light in the water

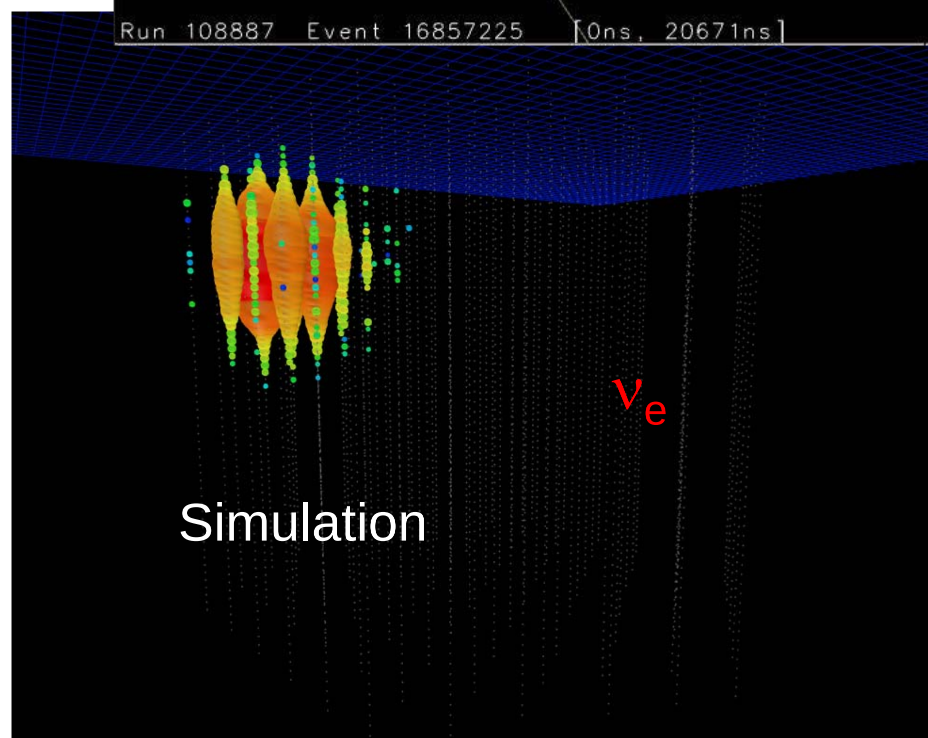


What do neutrino events look like?

- Neutrinos come in 3 different ‘flavors’, which interact differently

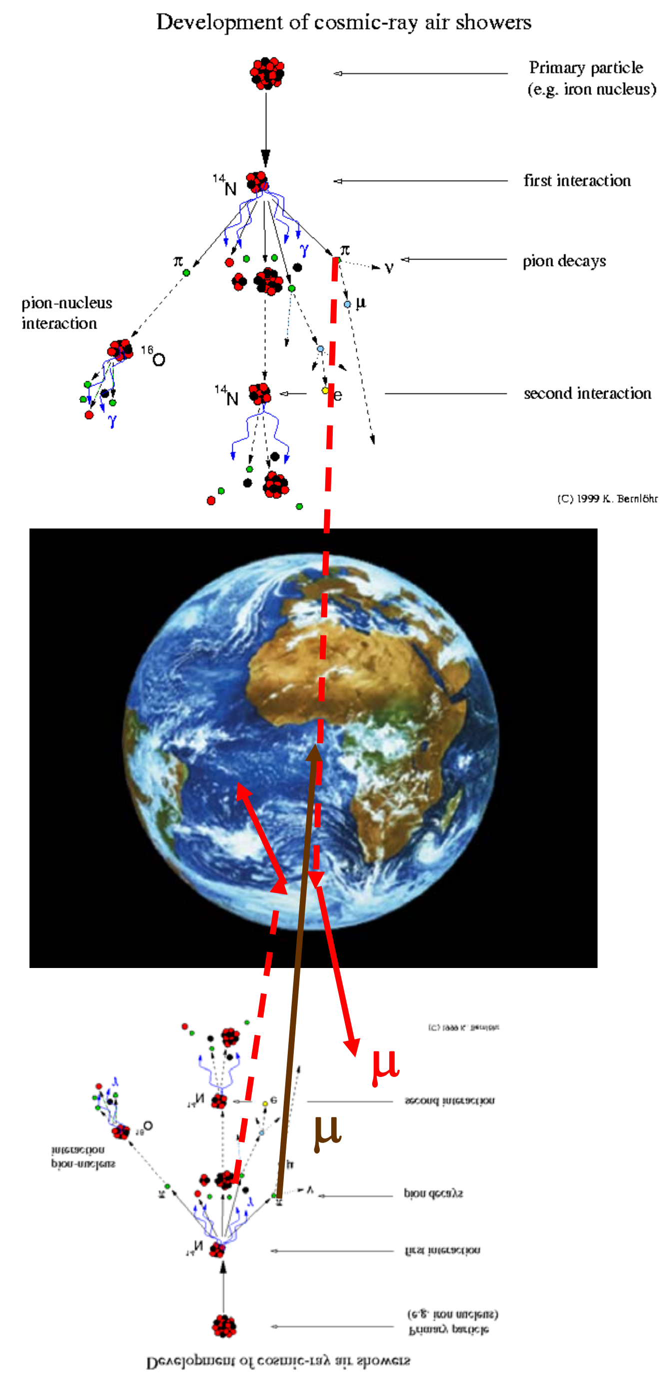




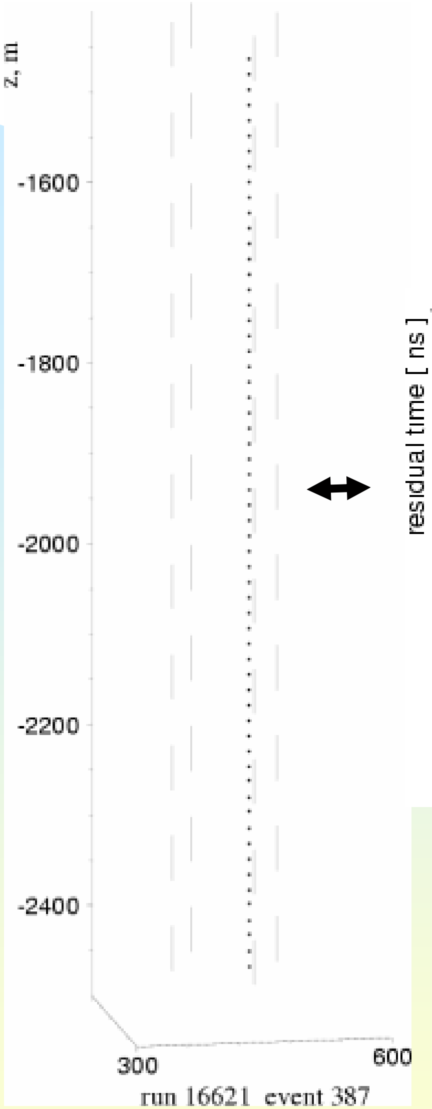


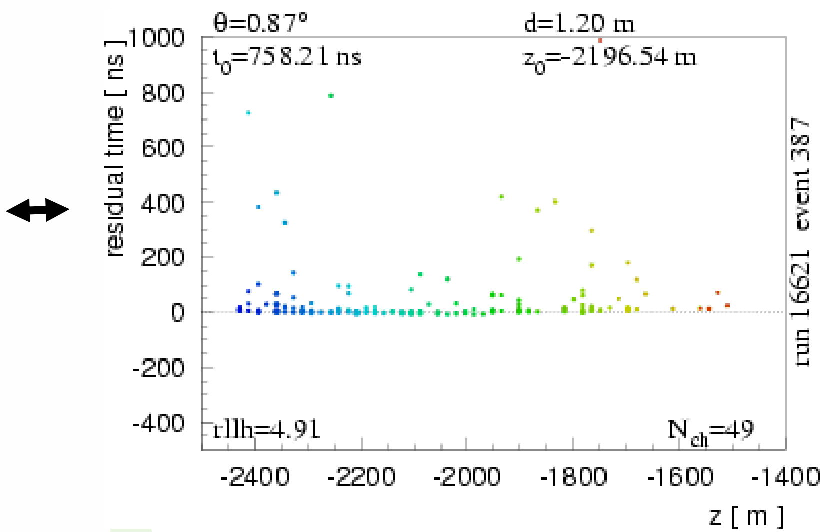
Backgrounds to extra-terrestrial ν

- Cosmic-ray air showers produce muons
  - These muons can penetrate 1.5 km of ice
  - 1,000,000 times as numerous as μ from neutrino interactions
  - Eliminate by selecting only upward-going events
- Upward & downward going ν
  - Irreducible background
  - Can avoid by selecting only very high-energy (above 1 PeV) events

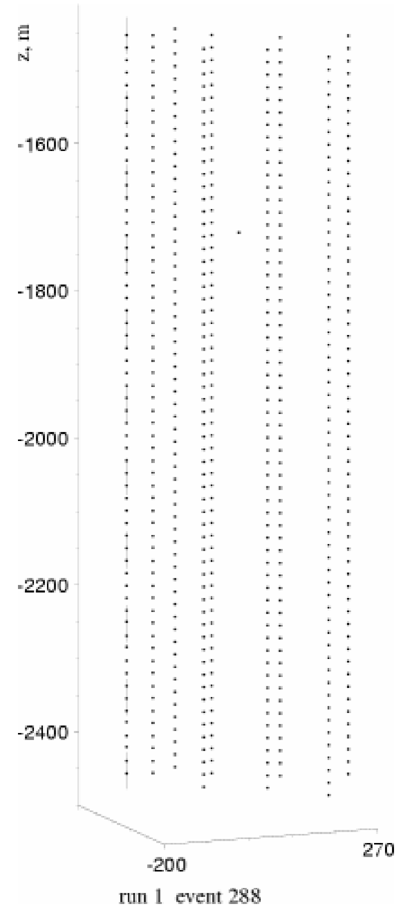


Neutrinos Observed





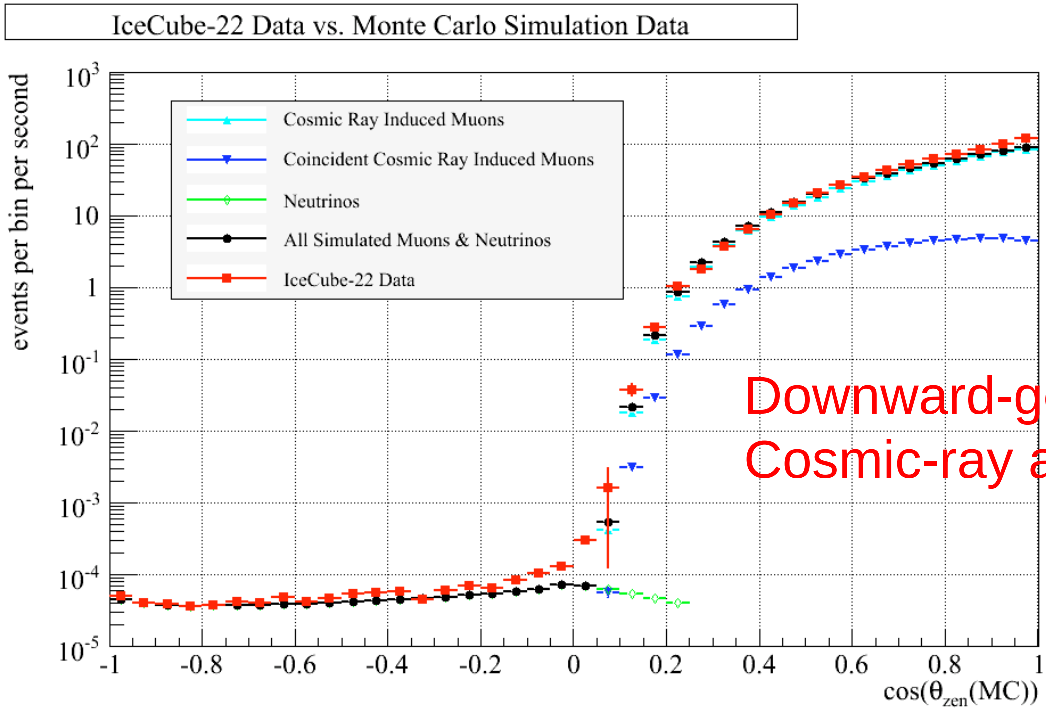
Time residuals from fit
Direct & scatted photons



A 2005 Neutrino candidate
49 DOMs hit in String 21

2006 Neutrino candidate
24 DOMs hit in 2 strings

Neutrino angular studies



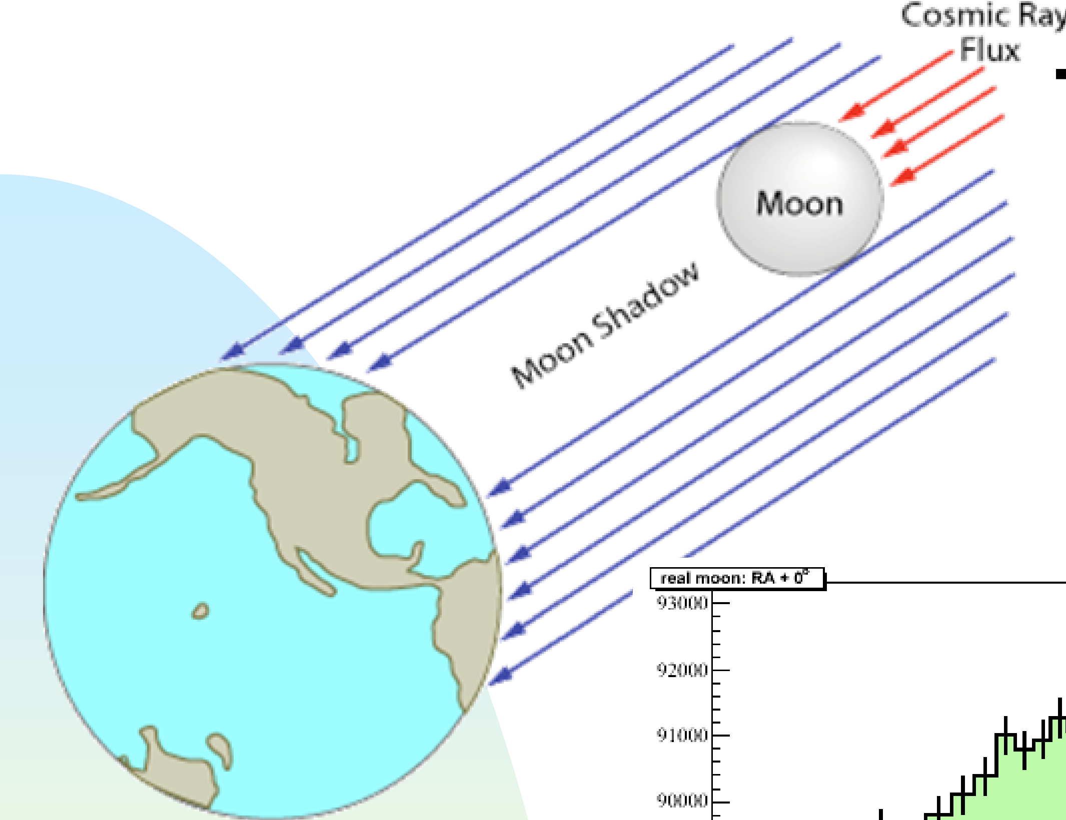
Downward-going muons from
Cosmic-ray air showers

Upward

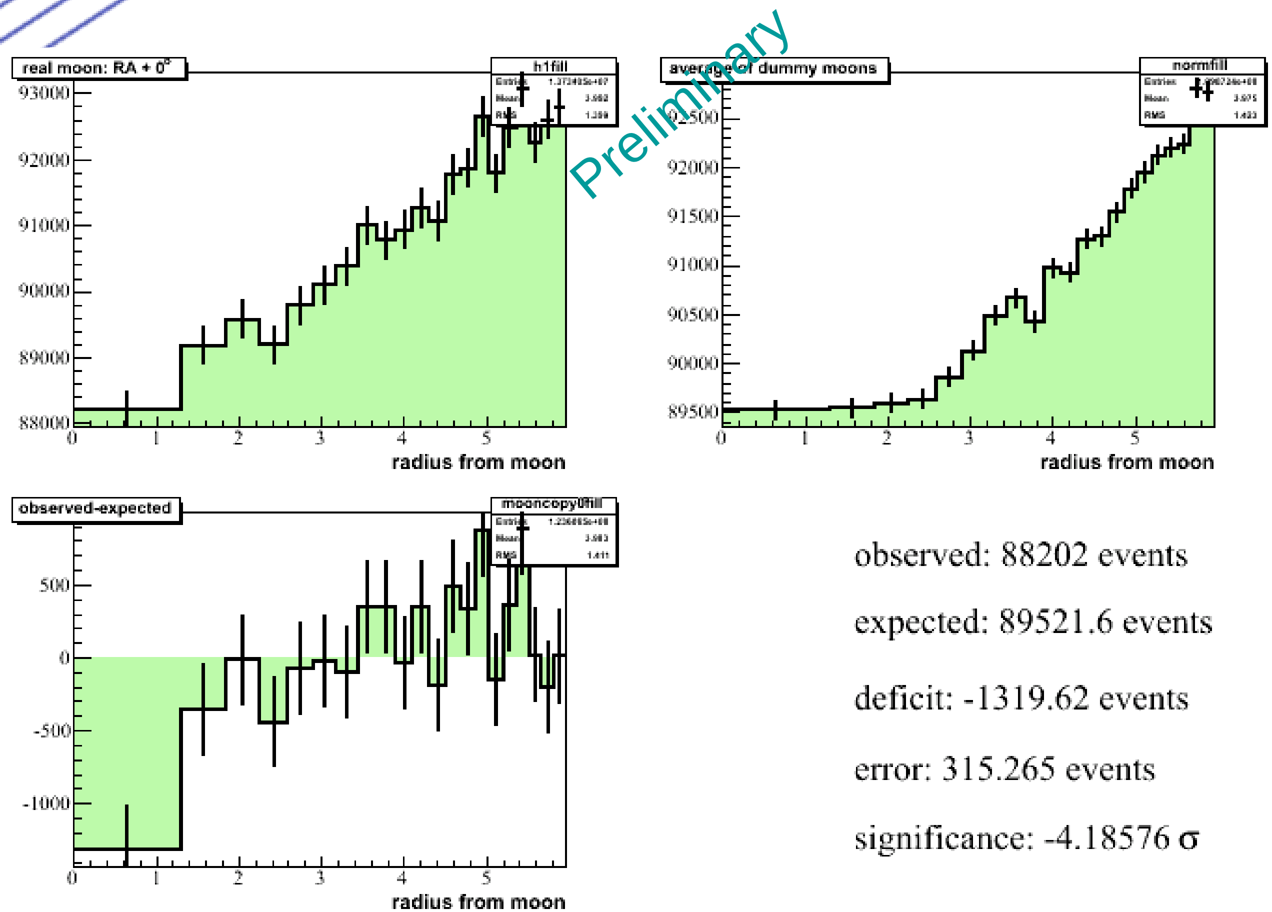
Downward

- Clear cutoff of cosmic-ray muons near horizon
- Angular directions well understood

The moon shadow in cosmic rays



Downward-going muons
1 months of 40-string data



Moon diameter ~0.5^0

IceCube Angular Resolution ~ 1^0

observed: 88202 events

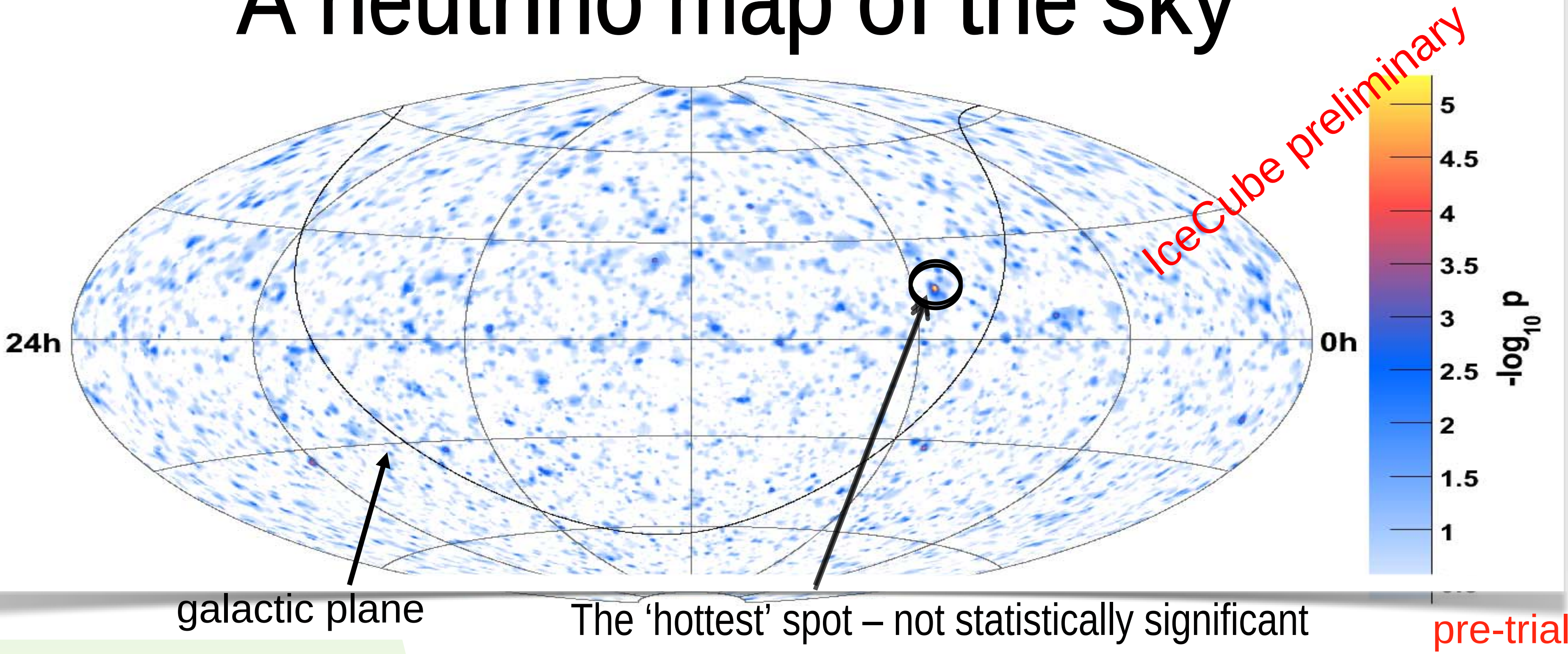
expected: 89521.6 events

deficit: -1319.62 events

error: 315.265 events

significance: -4.18576 σ

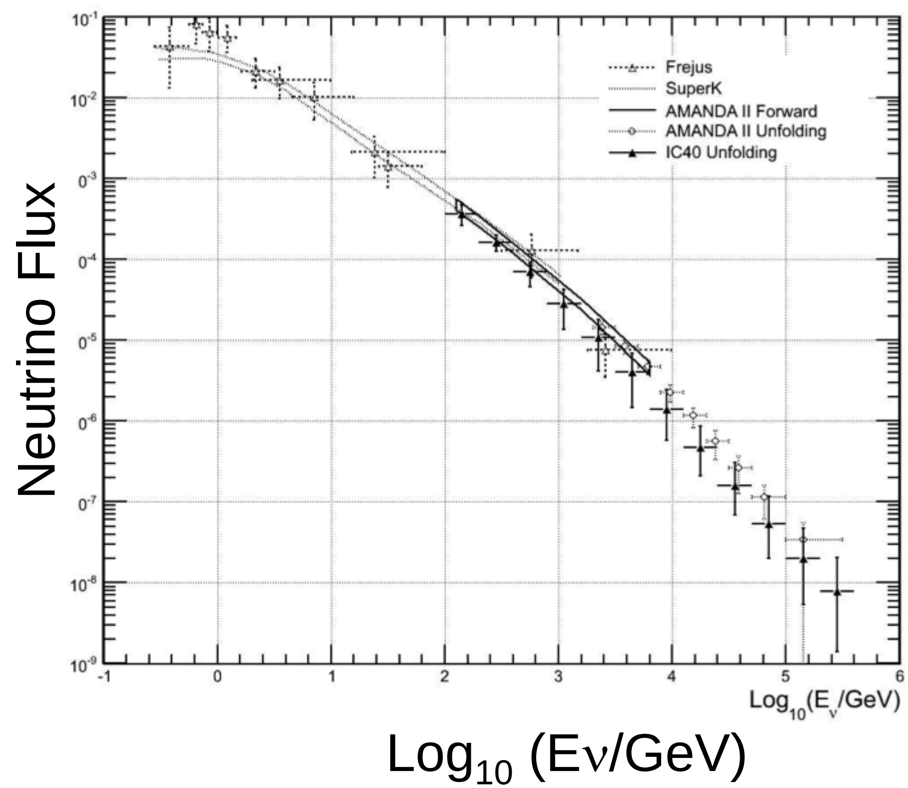
A neutrino map of the sky



- 375 days of data with 40 strings (1/2 full detector)
- Northern hemisphere – 14,121 upward-going events
  - ~ 90% neutrinos
- Southern hemisphere – 22,779 down going events
  - Very high energy muons selected
  - Mostly downward-going muons
- No statistically significant sources found (p=18%)

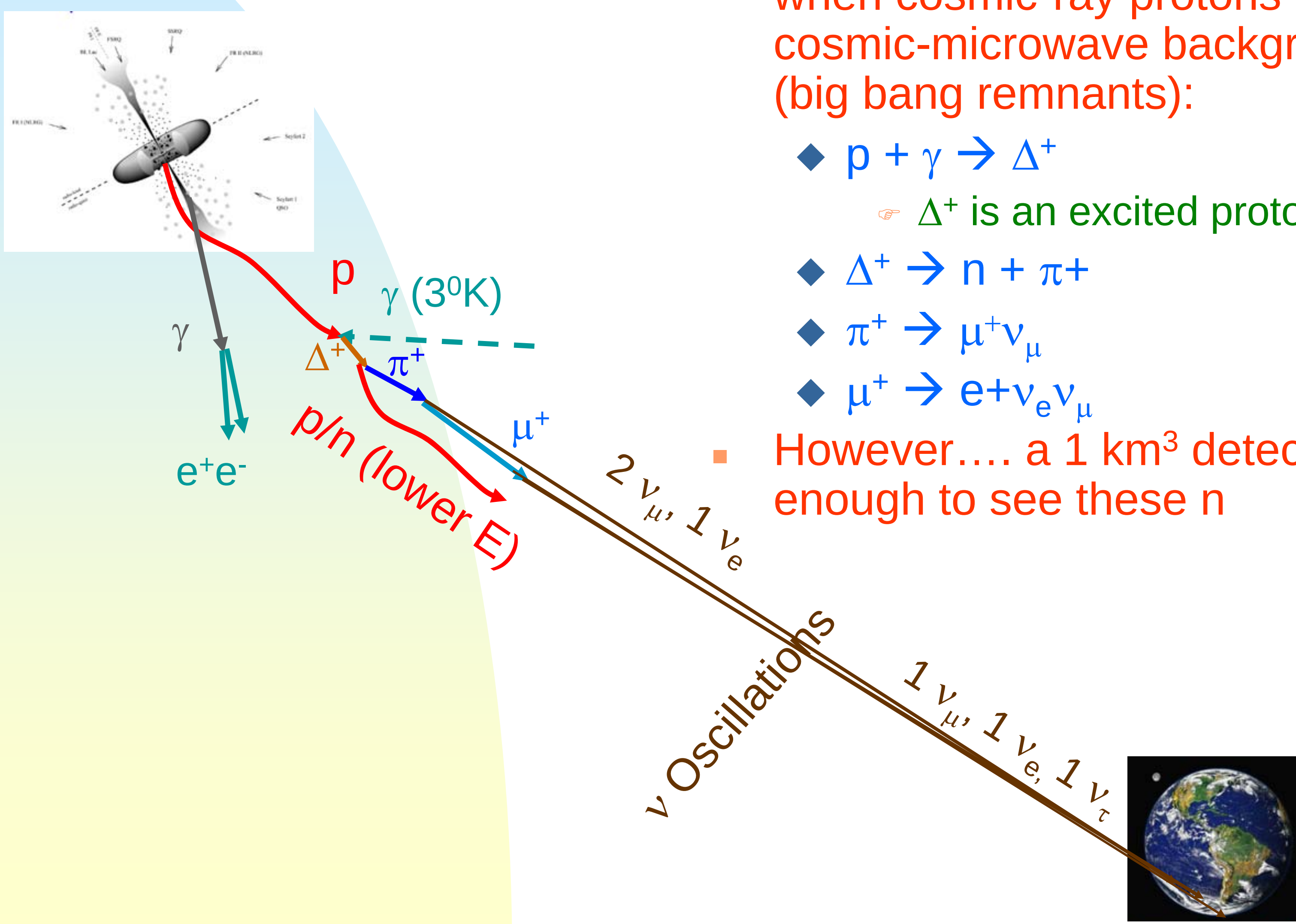
Diffuse Neutrinos?

- If there are many neutrino sources in the sky, it may not be possible to resolve individual point sources.
- This would be visible as an omnidirectional, diffuse flux.
- We search for this by looking for a flux of very high-energy neutrinos, beyond that due to atmospheric neutrinos
- So far, we haven't seen anything



Neutrinos at the highest energies

- Neutrinos with $E>10^{17}$ eV are produced when cosmic-ray protons interact with cosmic-microwave background radiation (big bang remnants):
  - $p + \gamma \rightarrow \Delta^+$
    - Δ^+ is an excited proton
  - $\Delta^+ \rightarrow n + \pi+$
  - $\pi^+ \rightarrow \mu^+\nu_\mu$
  - $\mu^+ \rightarrow e+\nu_e\nu_\mu$
- However…. a 1 km^3 detector is not big enough to see these n

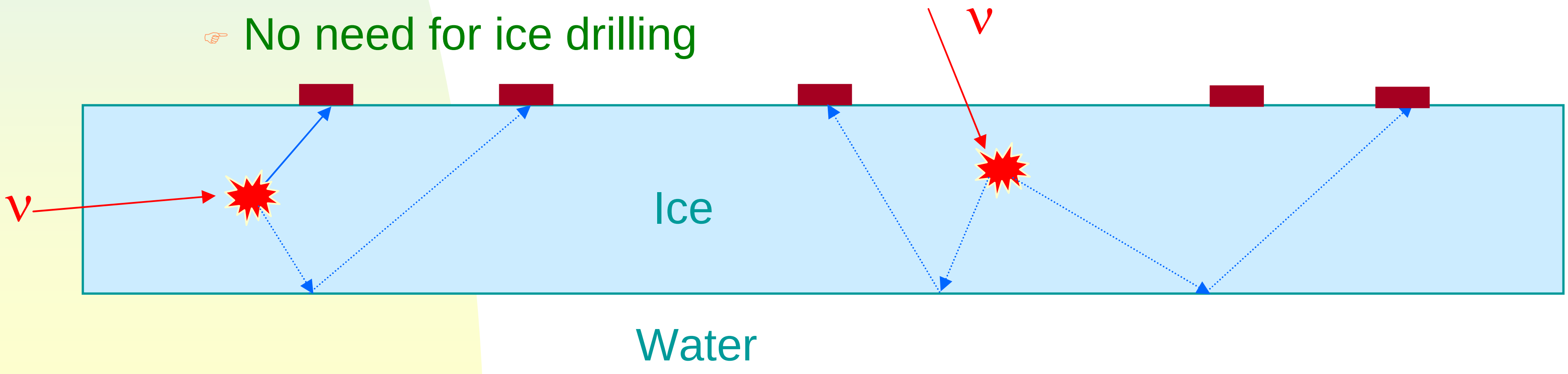


A 100 km^3 detector

- Optical (IceCube) technology does not scale
- Detect radio waves emitted by the shower as a whole
  - Coherent emission, so radio energy ~ E_ν^2
  - Radio waves can travel long distances in ice
    - Absorption length ~ 500 m – 1 km
      - For light, absorption length ~ 100-200 m
  - Can put stations on a 1 km grid

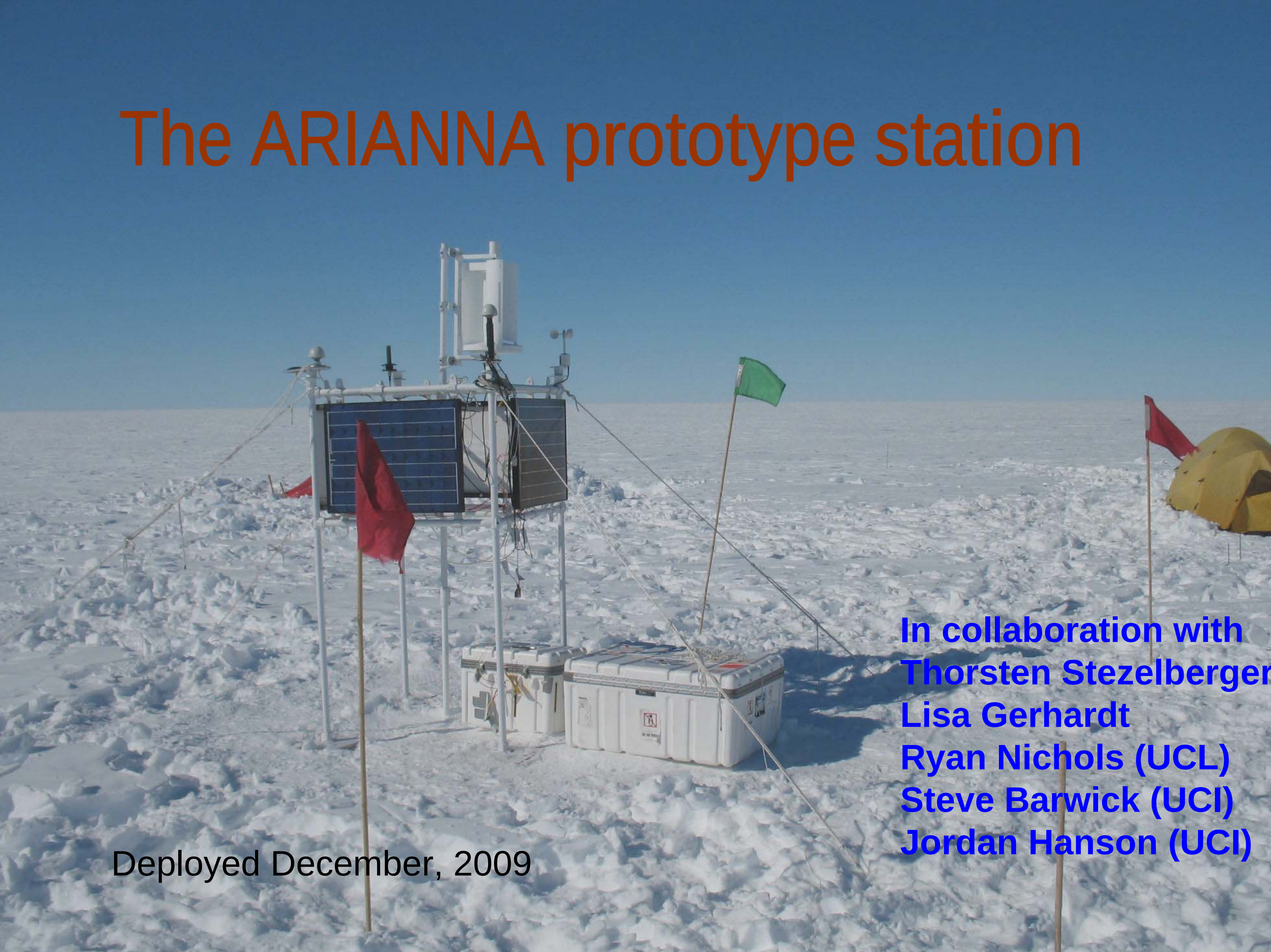
ARIANNA: Radio in the Ross Ice Sheet

- Downgoing ν produce downgoing Cherenkov cones.
  - Usually need buried detectors to observe
- The Ross ice shelf is a 650 m of ice atop water
  - Site is ~ 100 km south of from McMurdo station
- 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



Dotted lines show reflected signal

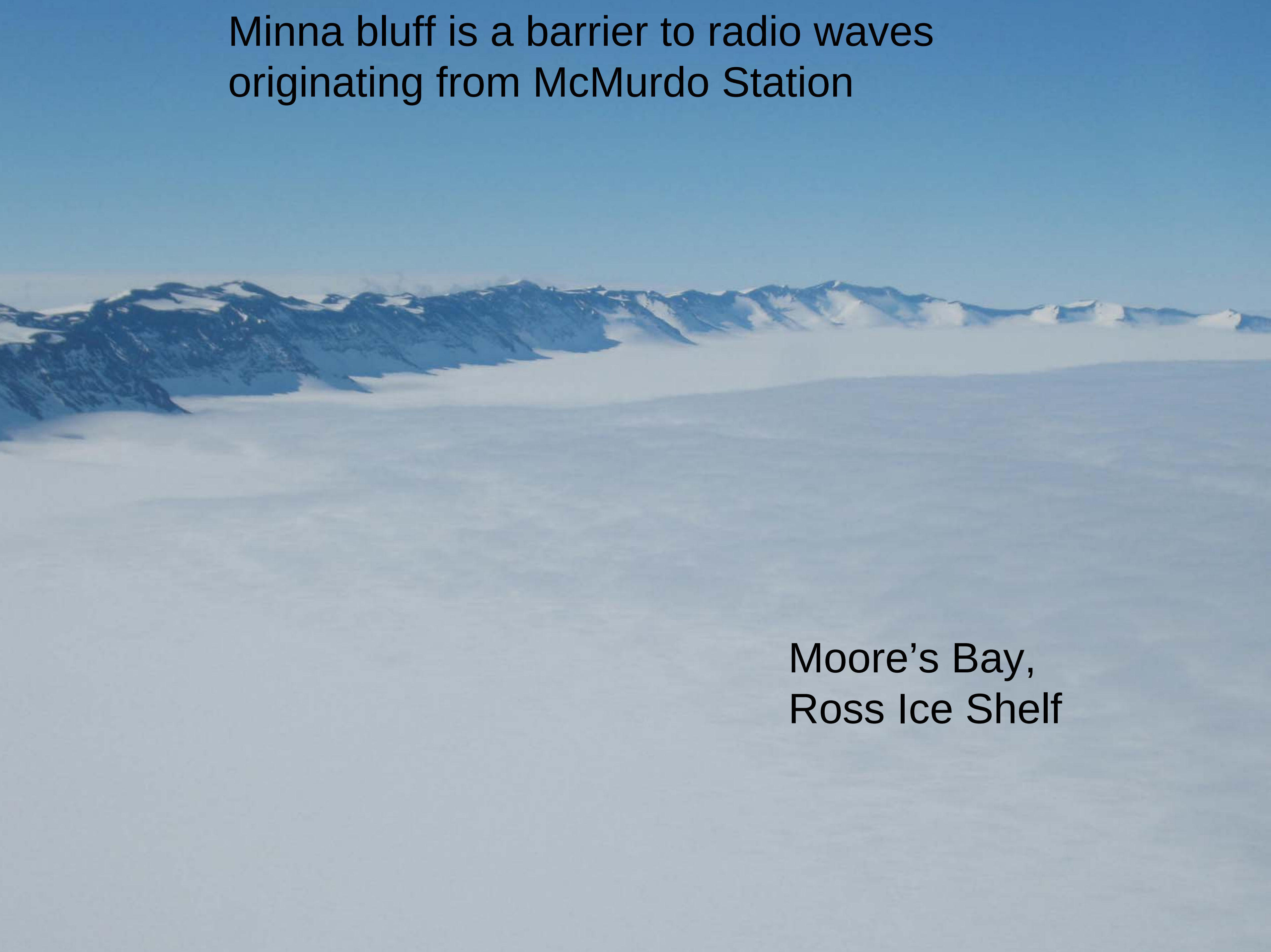
The ARIANNA prototype station



In collaboration with
Thorsten Stezelberger
Lisa Gerhardt
Ryan Nichols (UCL)
Steve Barwick (UCI)
Jordan Hanson (UCI)

Deployed December, 2009

For now, helicopter is the only way in


Minna bluff is a barrier to radio waves originating from McMurdo Station
Moore's Bay, Ross Ice Shelf

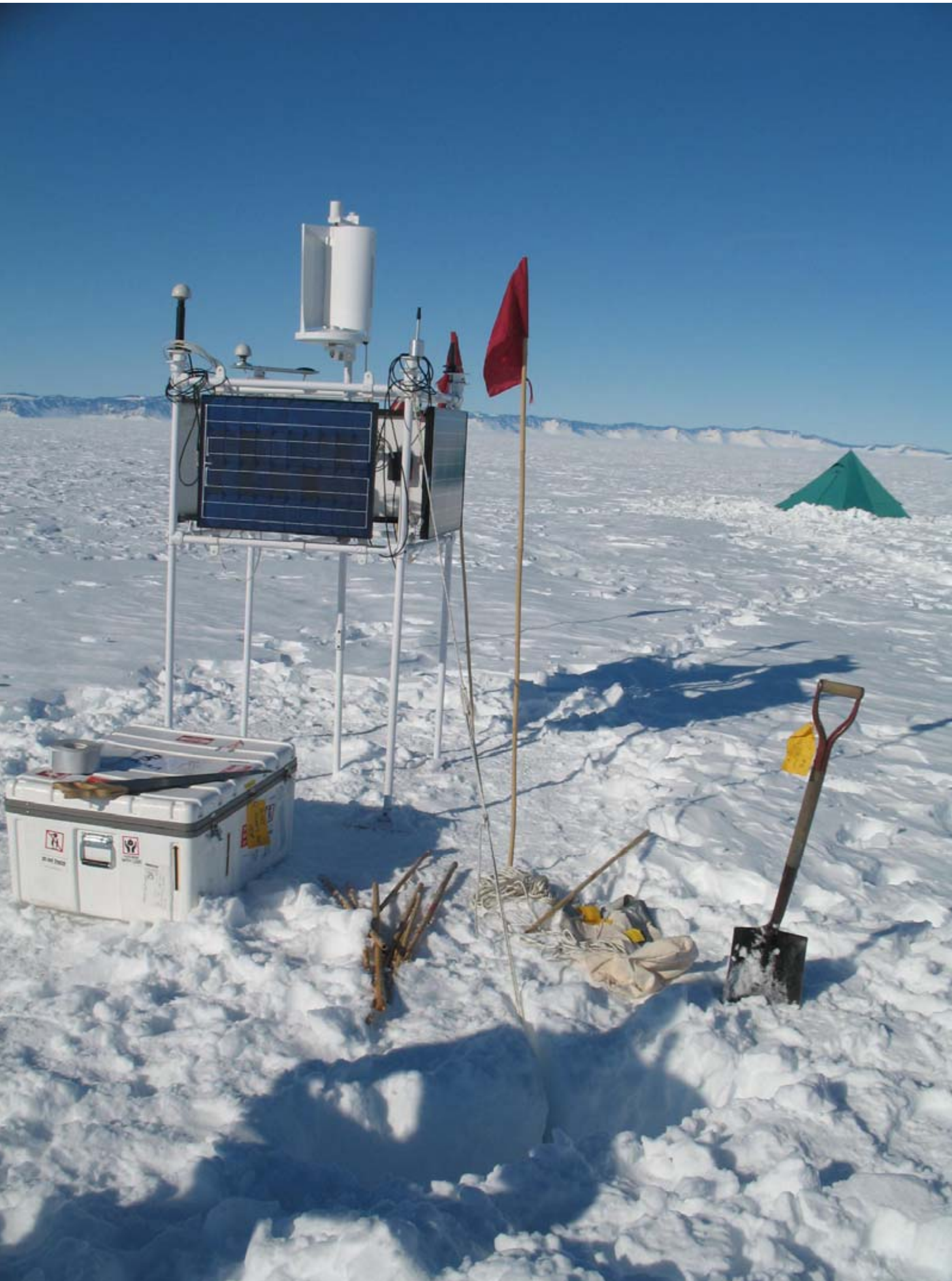
But …. we need internet access

The flank of Mt. Discovery, at about 5,000 feet
A good place for the internet repeater

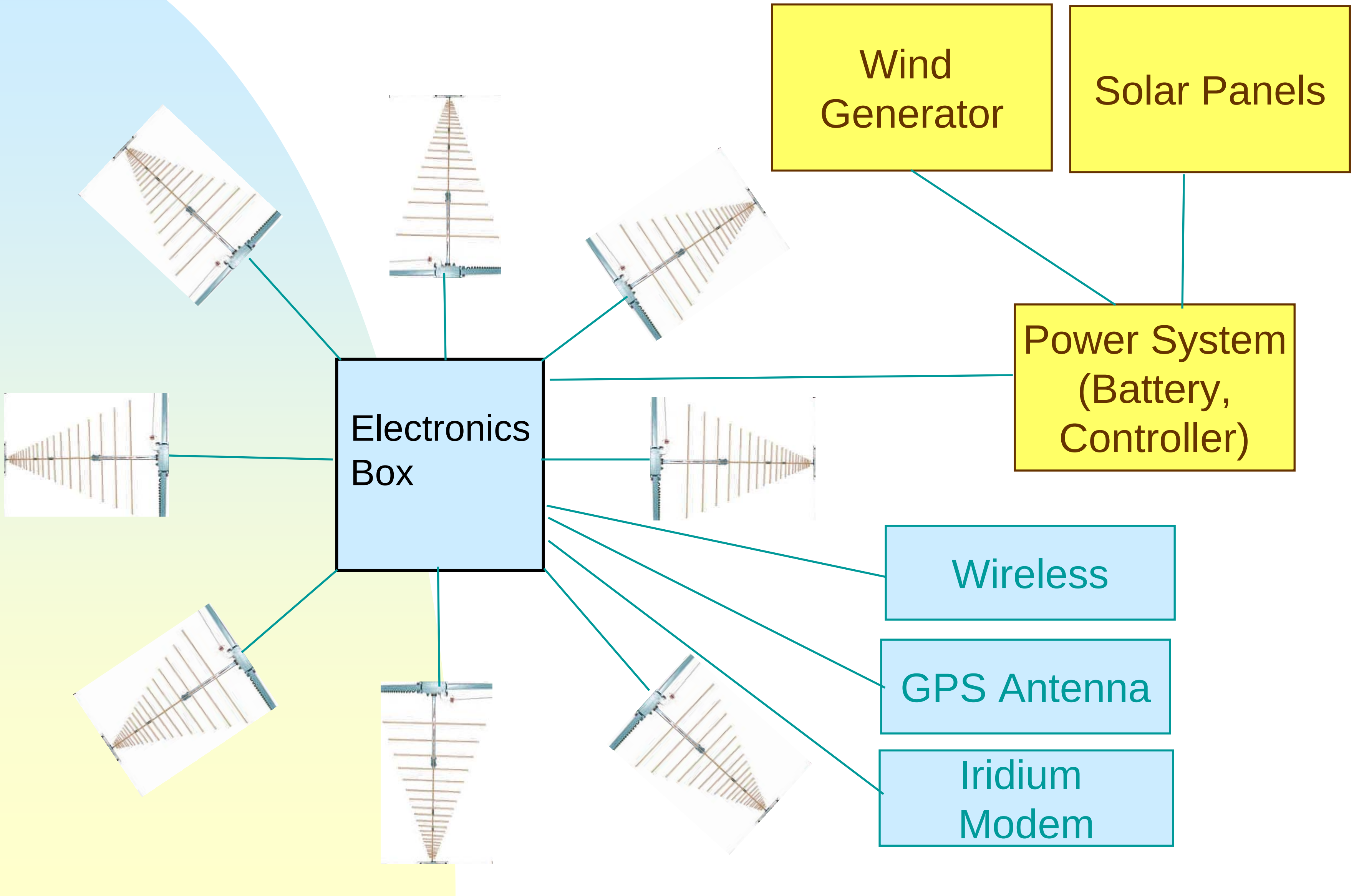
Setting up Camp

The rest of our supplies

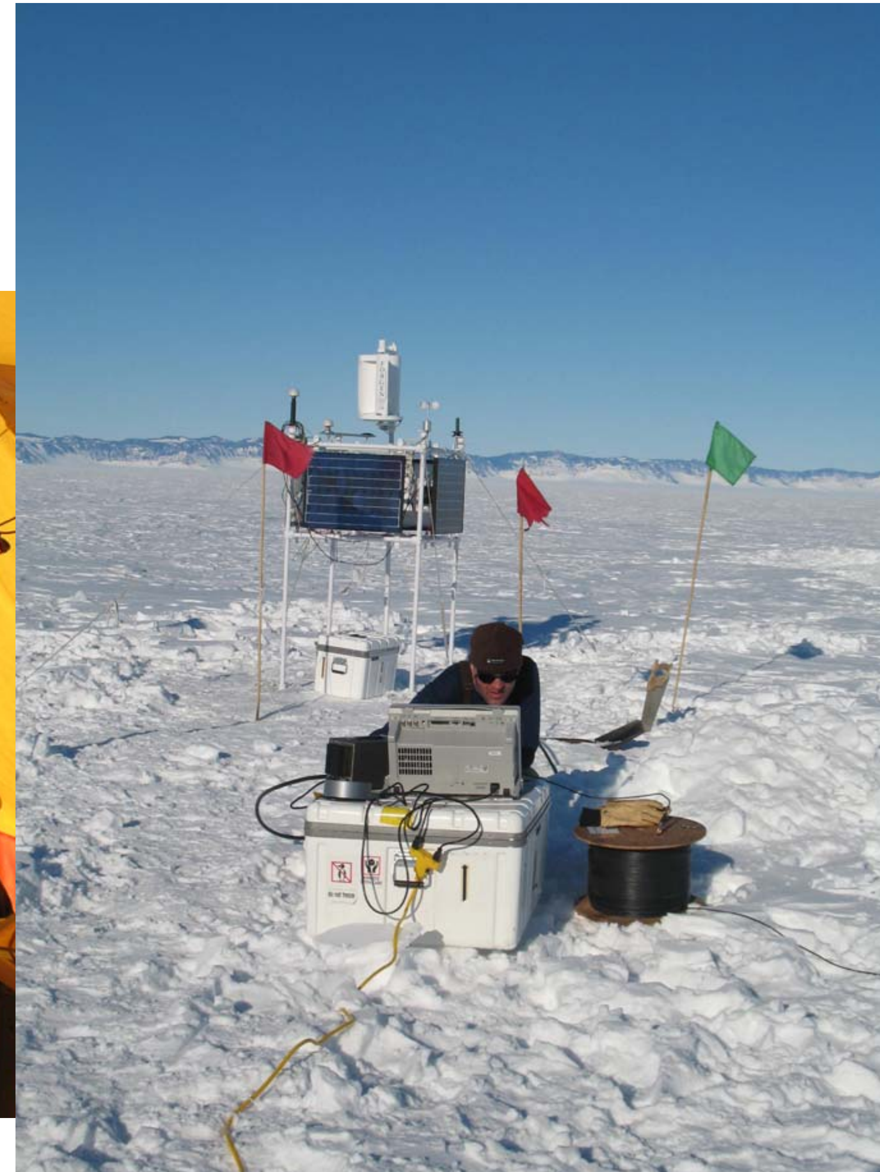
The prototype station



ARIANNA Setup

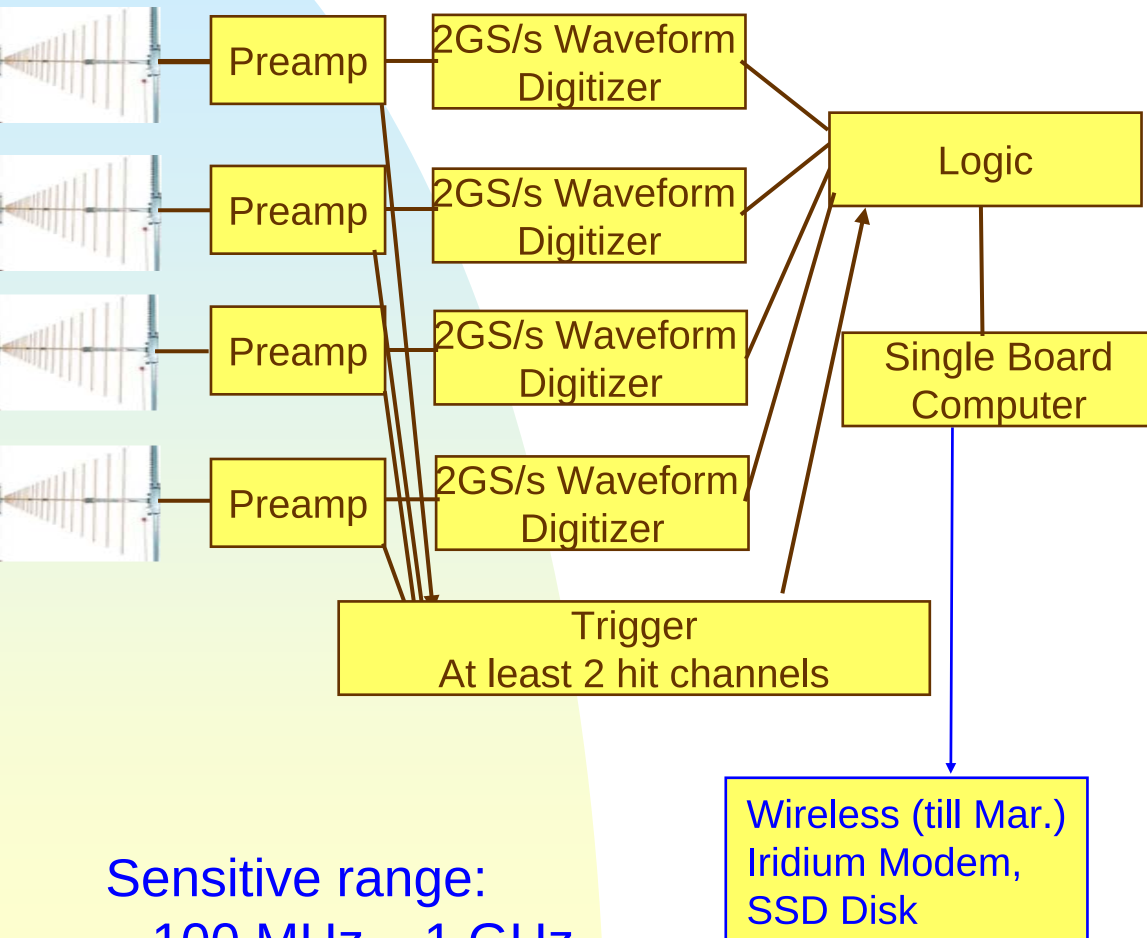


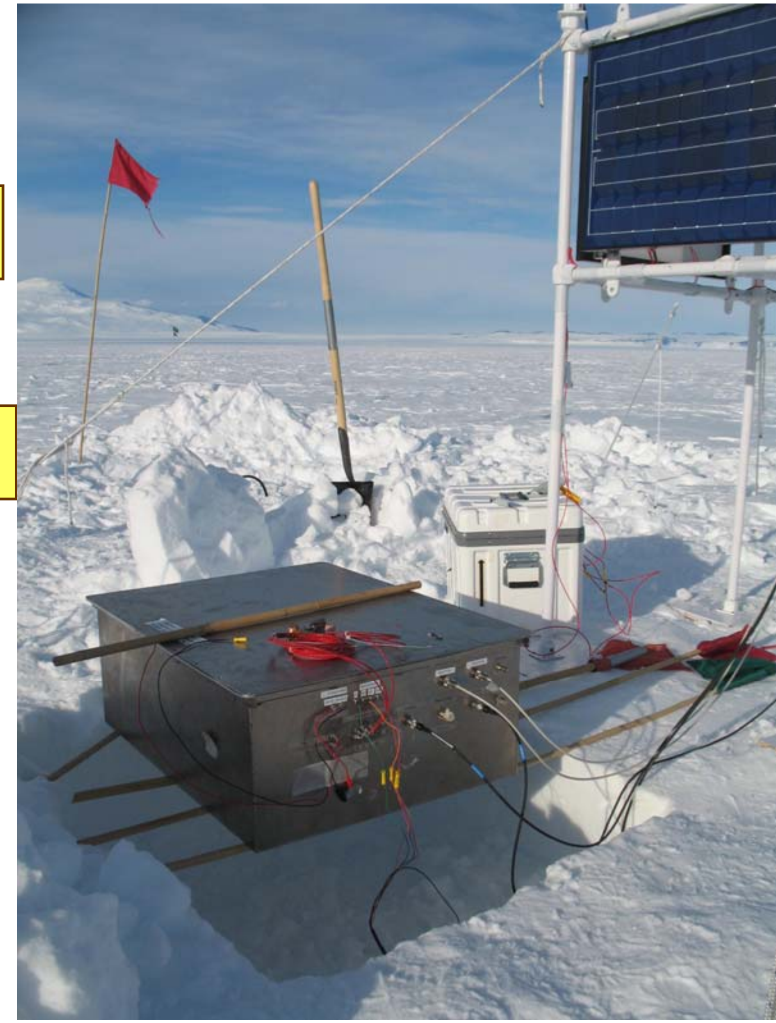
Working space



Internet tower

Data acquisition hardware

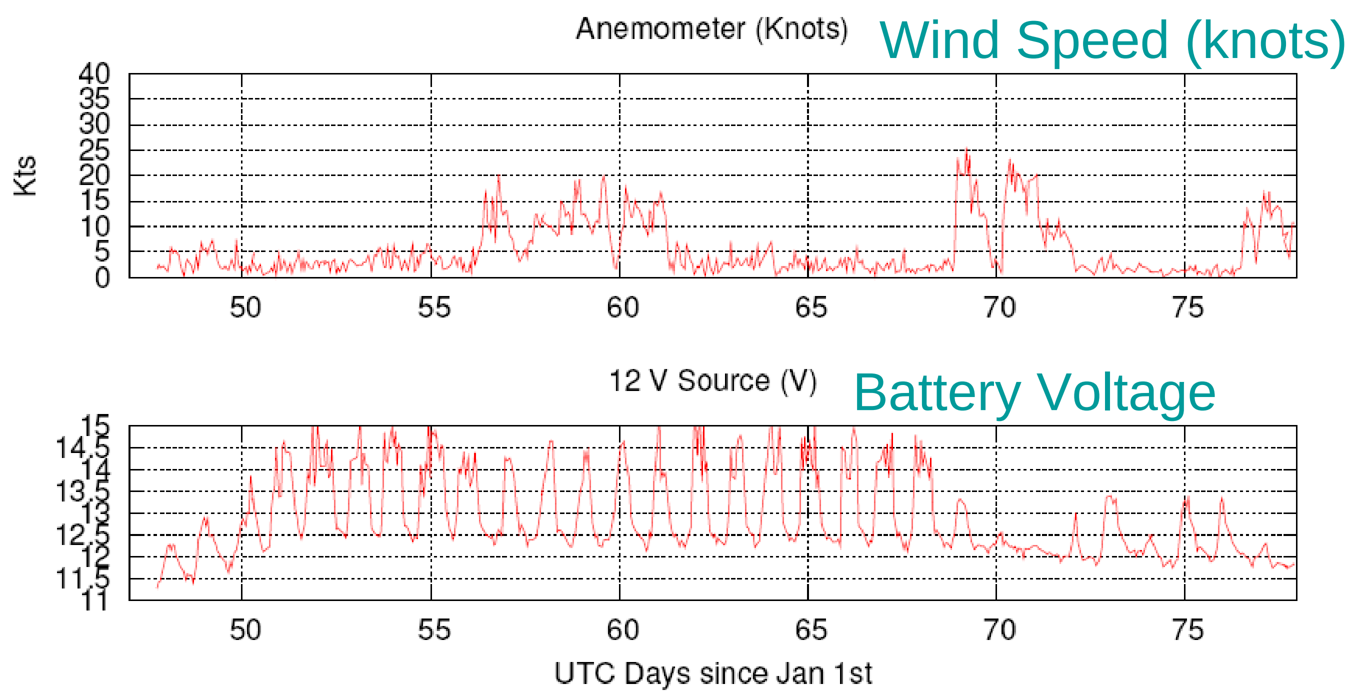




Sensitive range:
~ 100 MHz – 1 GHz

Station Status

- The station worked well until ~ March, when the sun got too low in the sky.
  - Not enough wind to power the station.
- Except for the Internet link, we saw no man-made noise.
  - We reached the natural (thermal) noise limit



ARIANNA – future plans

- Design of a 5-7 station array is in progress.
  - Deployment in 2011/2012?
- Eventual goal - ~ 1,000 stations, forming a 30 by 30 km array.

Conclusions

- The 1 km^3 IceCube neutrino observatory is nearing completion.
  - We are searching for point sources of neutrinos and a diffuse (omnidirectional) flux.
- IceCube should detect extra-terrestrial neutrinos. If it doesn’t, then it will put stringent limits on our theories about energetic objects in the cosmos.
  - IceCube is a general-purpose experiment, and many other studies are in progress.
- To study the highest energy cosmic-rays, a ~ 100 km^3 detector is needed.
- At very high energies (above 10^{17} eV), neutrino interactions produce a detectable pulse of radio waves.
- ARIANNA can detect these radio waves.
  - A prototype station is working well.
  - A 1,000 station array would cover 100 km^3.

Thank you for your attention

Any questions?