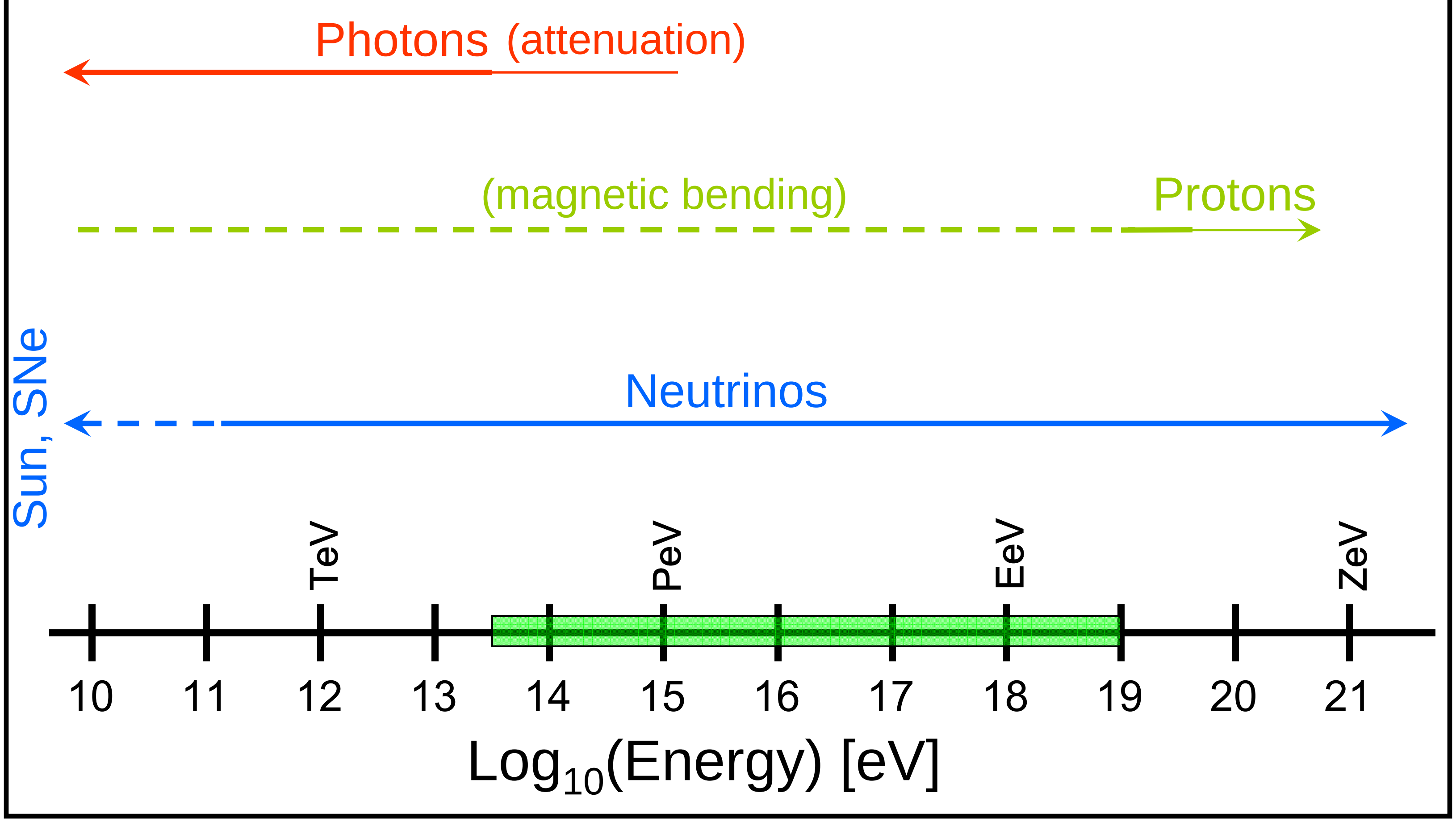
IceCube: First Light

Doug Cowen
IceCube Collaboration
Pennsylvania State University
cowen(at)phys.psu.edu

Astrophysical Messengers



Note: every time we open a new window on the heavens, we discover something interesting.

Neutrino Detection

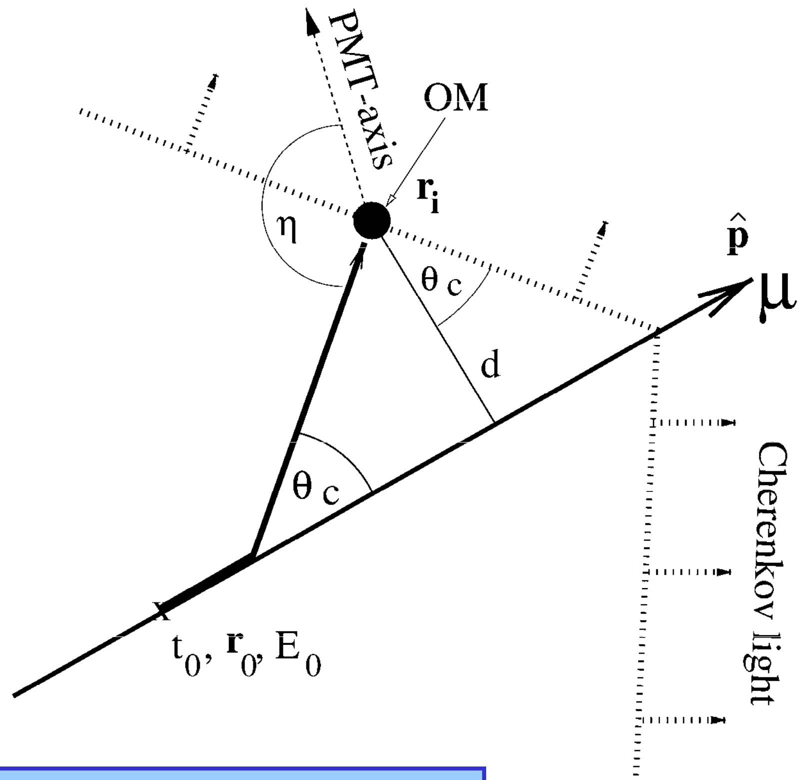
Detecting UHE Neutrinos

- Pathologically antisocial particles
  - Good: They can emerge from ultra-dense regions of space, conveying information to us that no other astronomical messenger can provide
  - Bad: They are fiendishly difficult to detect
  - Not So Ugly: Can use the earth as a filter to block backgrounds

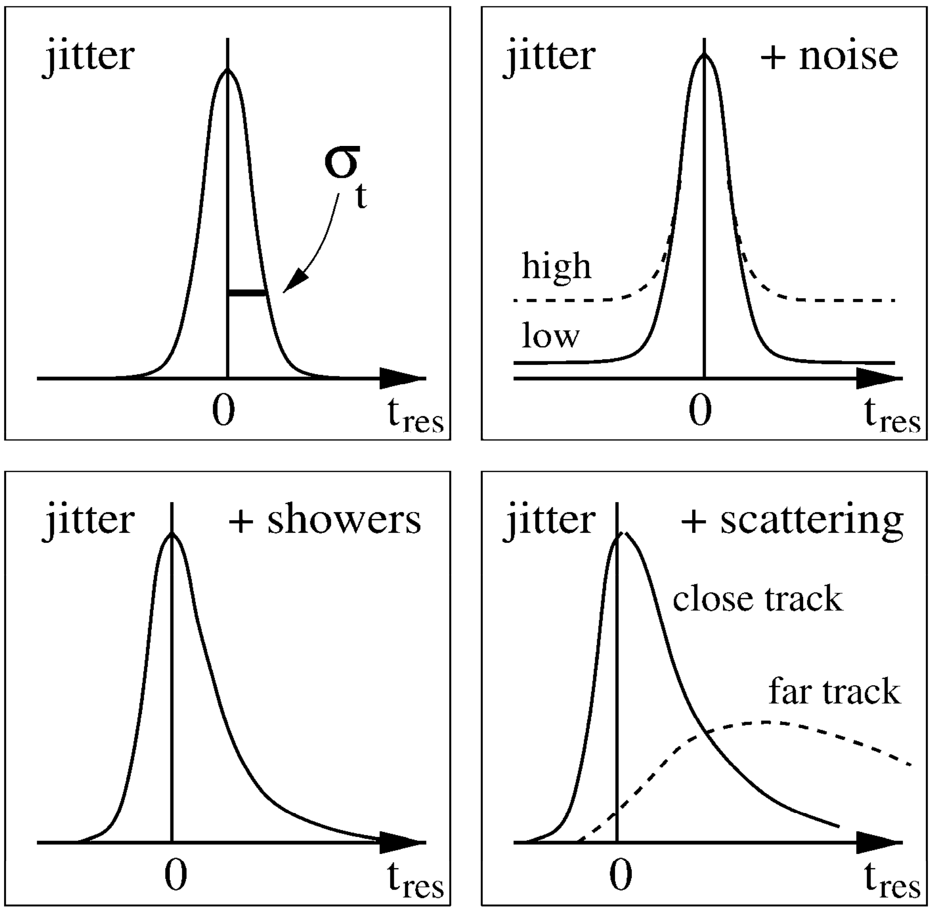
Detecting UHE Neutrinos

- On the rare occasion that a UHE neutrino crashes into normal matter, its enormous energy is imparted to many charged particles
  - These charged particles will move faster than light in the interaction medium ($v > c/n$, where n is the refractive index). They will emit Cherenkov light.
  - Cherenkov light can be detected by photomultiplier tubes (PMTs)
    - N.B.: Must have thorough knowledge of propagation medium for event reconstruction to work

Reconstructing Neutrino Events

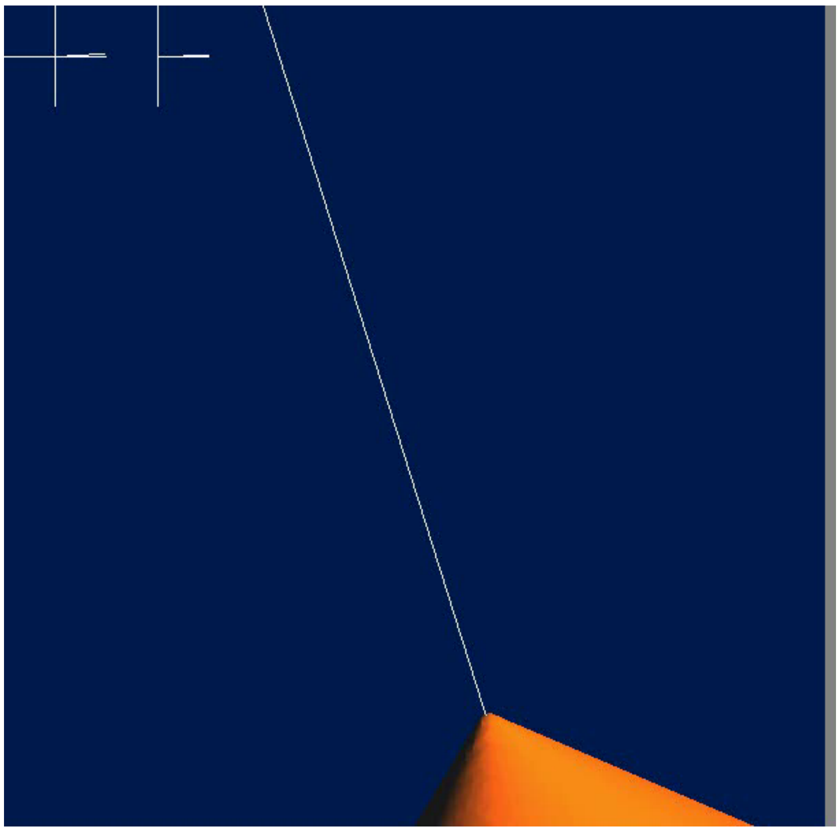


J. Ahrens et al.,
Nucl. Inst. & Meth.
*A***524**, 169 (2004).

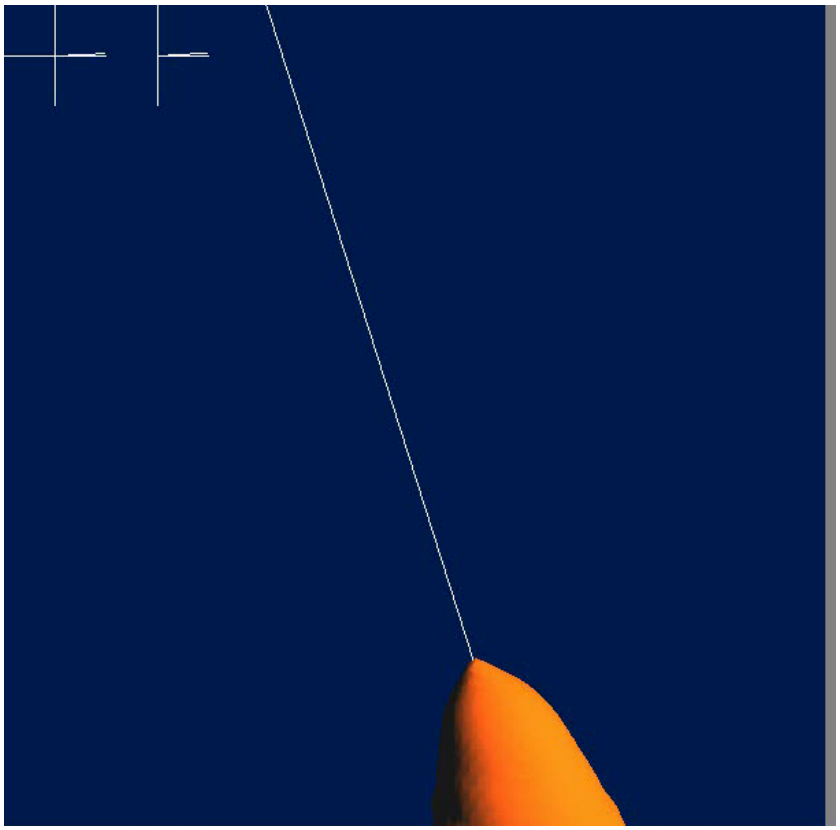


Relative PMT-to-PMT timing w/ns accuracy is absolutely vital.

Cherenkov Light in Ice: Ice Properties Matter!



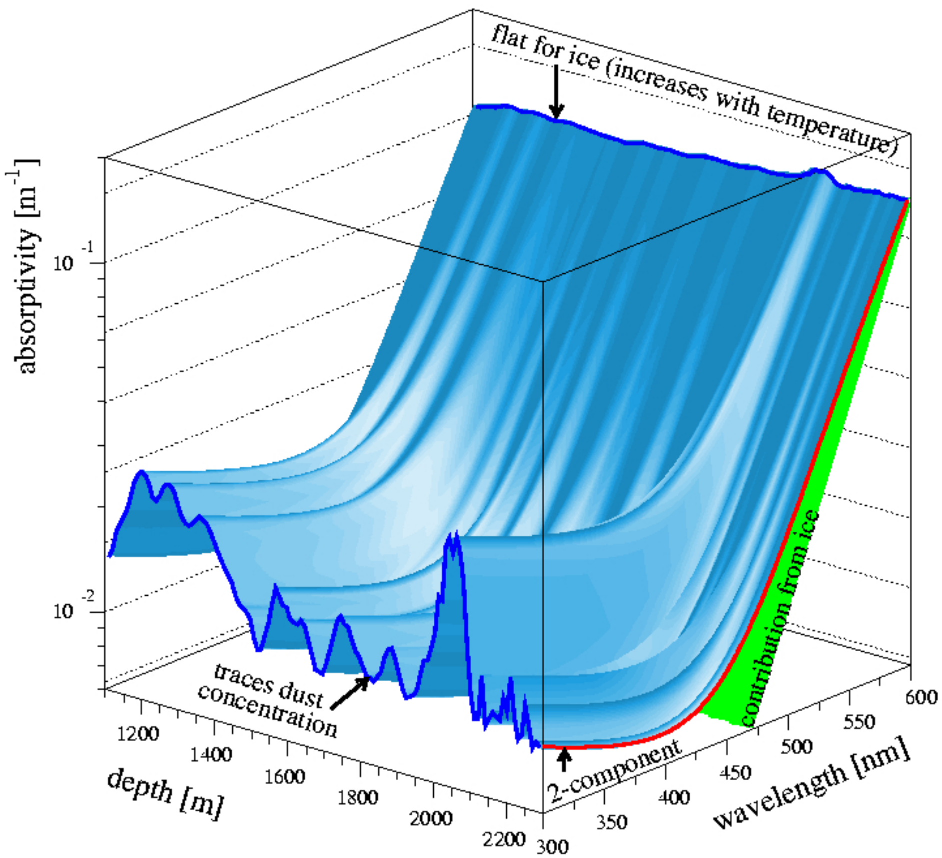
Perfect Cherenkov cone



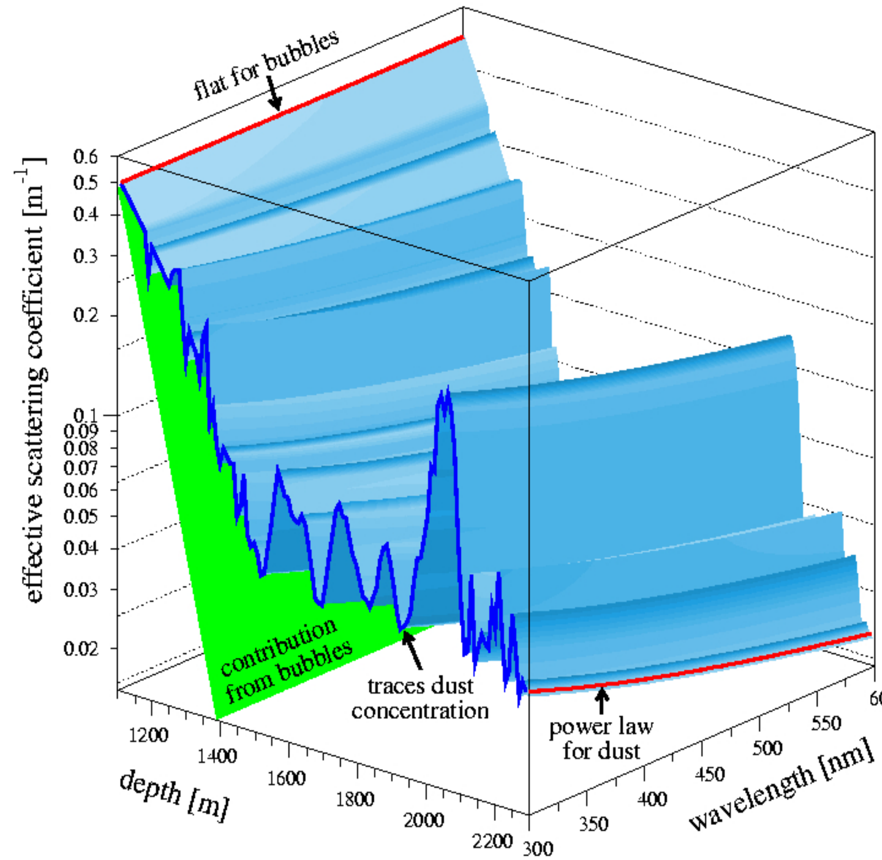
With scattering (dust, acid, crystal boundaries)

Optical Properties of South Pole Ice

Absorption in AMANDA ice



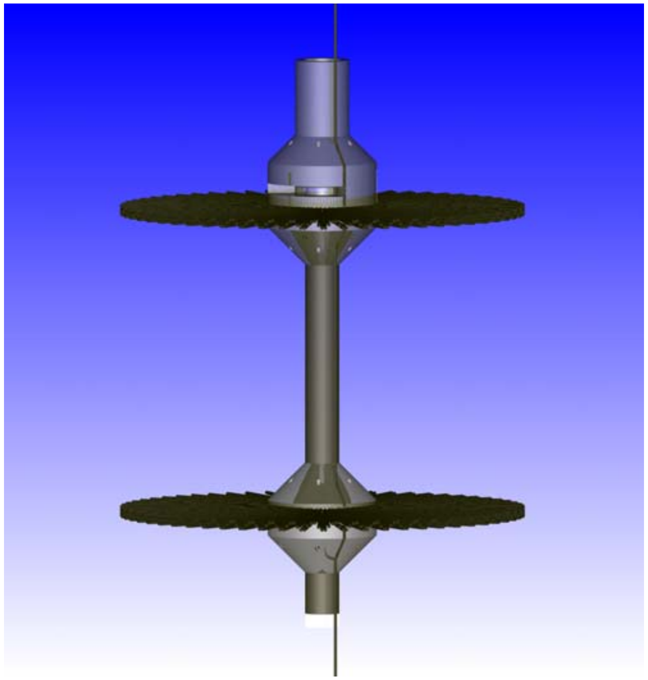
Scattering in AMANDA ice

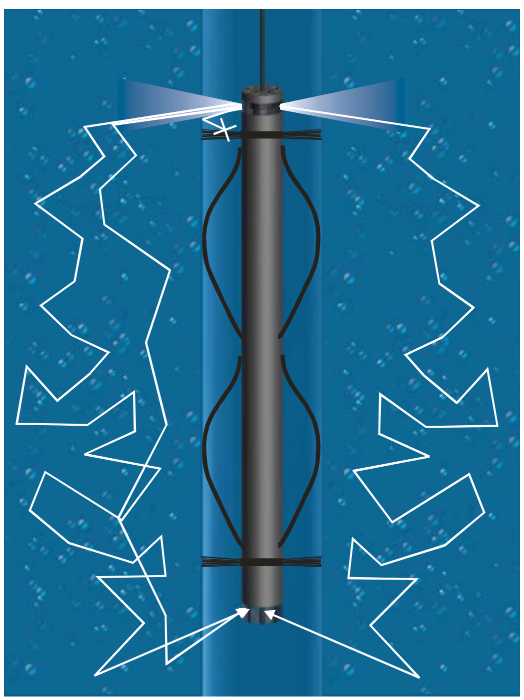


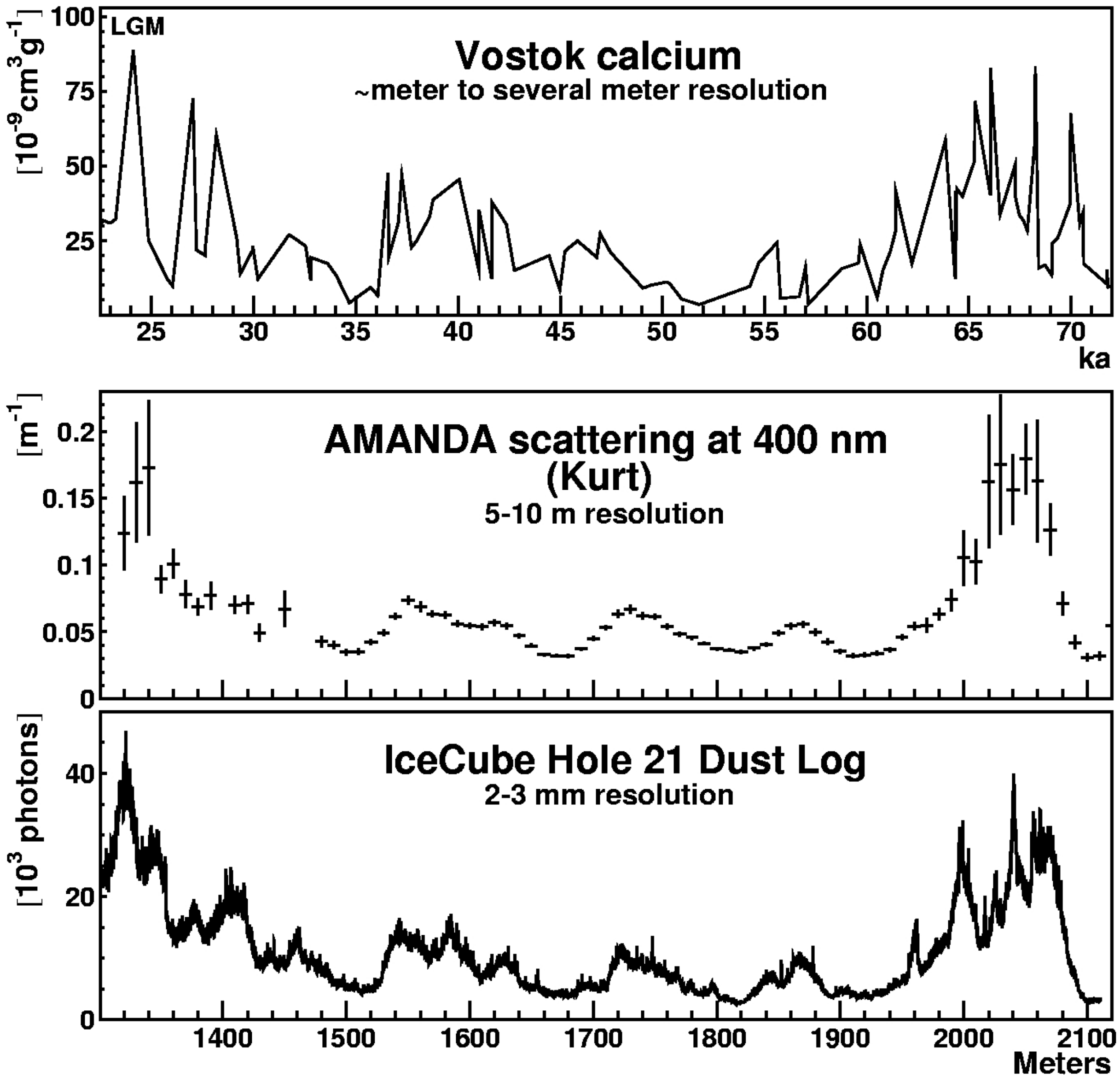
110 m absorption length!

20 m scattering length

The Dustlogger:
Are We Glaciologist Wannabes?







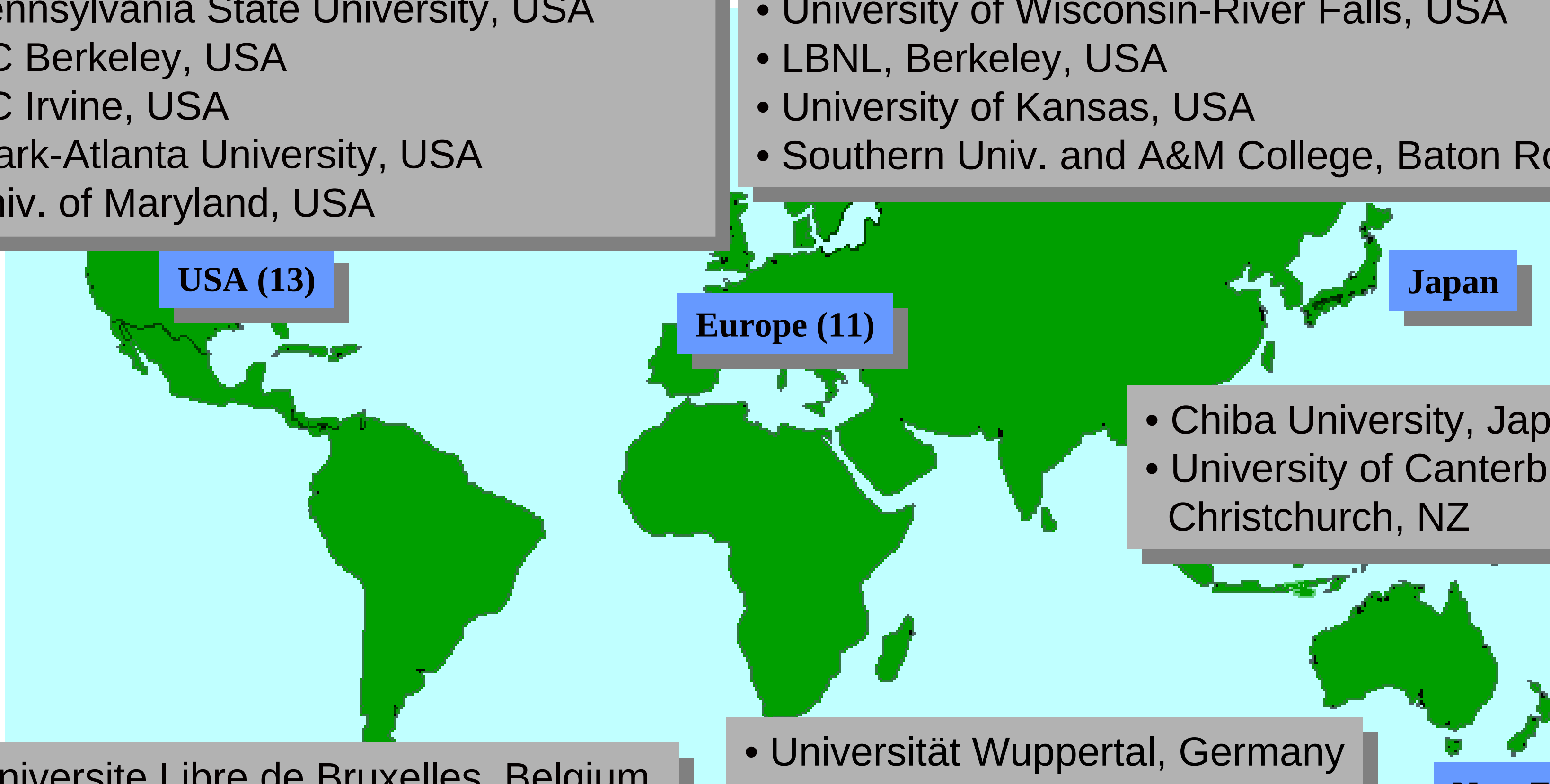
Detecting UHE Neutrinos

- To detect UHE neutrinos, therefore, we need:
  - Large instrumented volume
    - …but to keep costs reasonable, detector has to "barely work" (F. Halzen), i.e., should function with low pixelization density
  - Clear, well-understood medium
  - Lots of scientists willing to travel to a remote location for years on end with no guarantee of discovering anything

The AMANDA and IceCube Collaborations: >100-fold Proof that There's a Sucker Born Every Minute!

- Bartol Research Institute, Delaware, USA
- Univ. of Alabama, USA
- Pennsylvania State University, USA
- UC Berkeley, USA
- UC Irvine, USA
- Clark-Atlanta University, USA
- Univ. of Maryland, USA

- IAS, Princeton, USA
- University of Wisconsin-Madison, USA
- University of Wisconsin-River Falls, USA
- LBNL, Berkeley, USA
- University of Kansas, USA
- Southern Univ. and A&M College, Baton Rouge



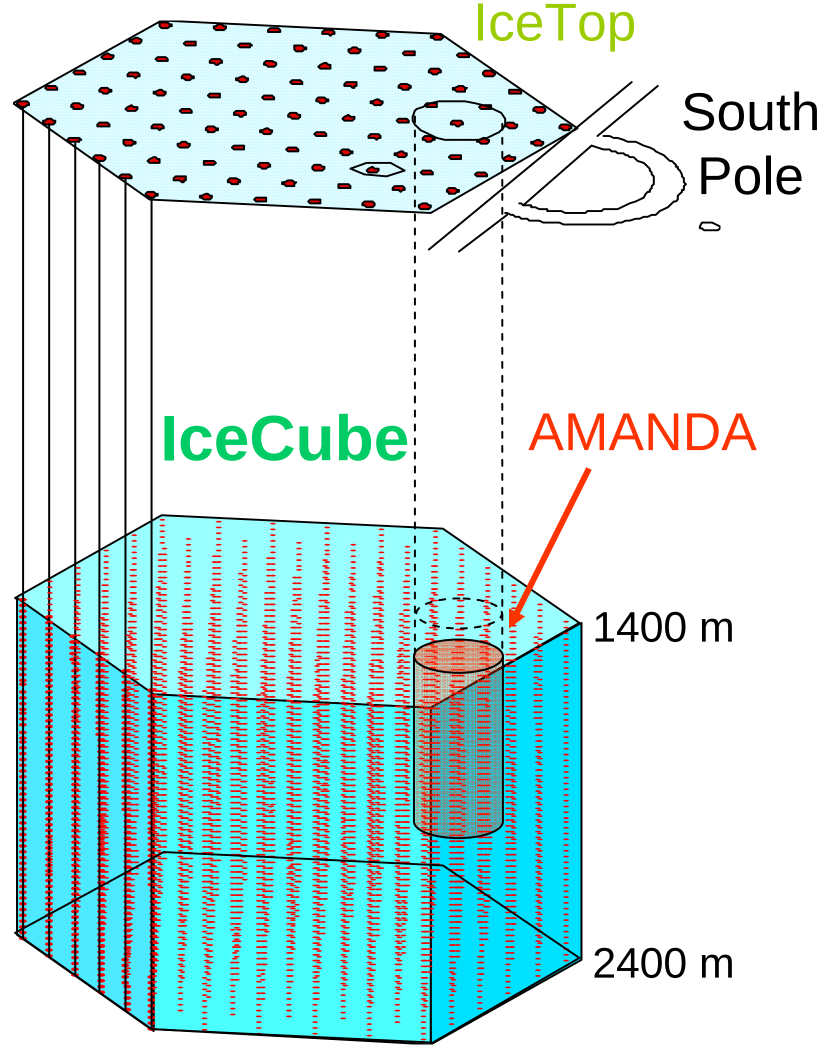
- Chiba University, Japan
- University of Canterbury, Christchurch, NZ

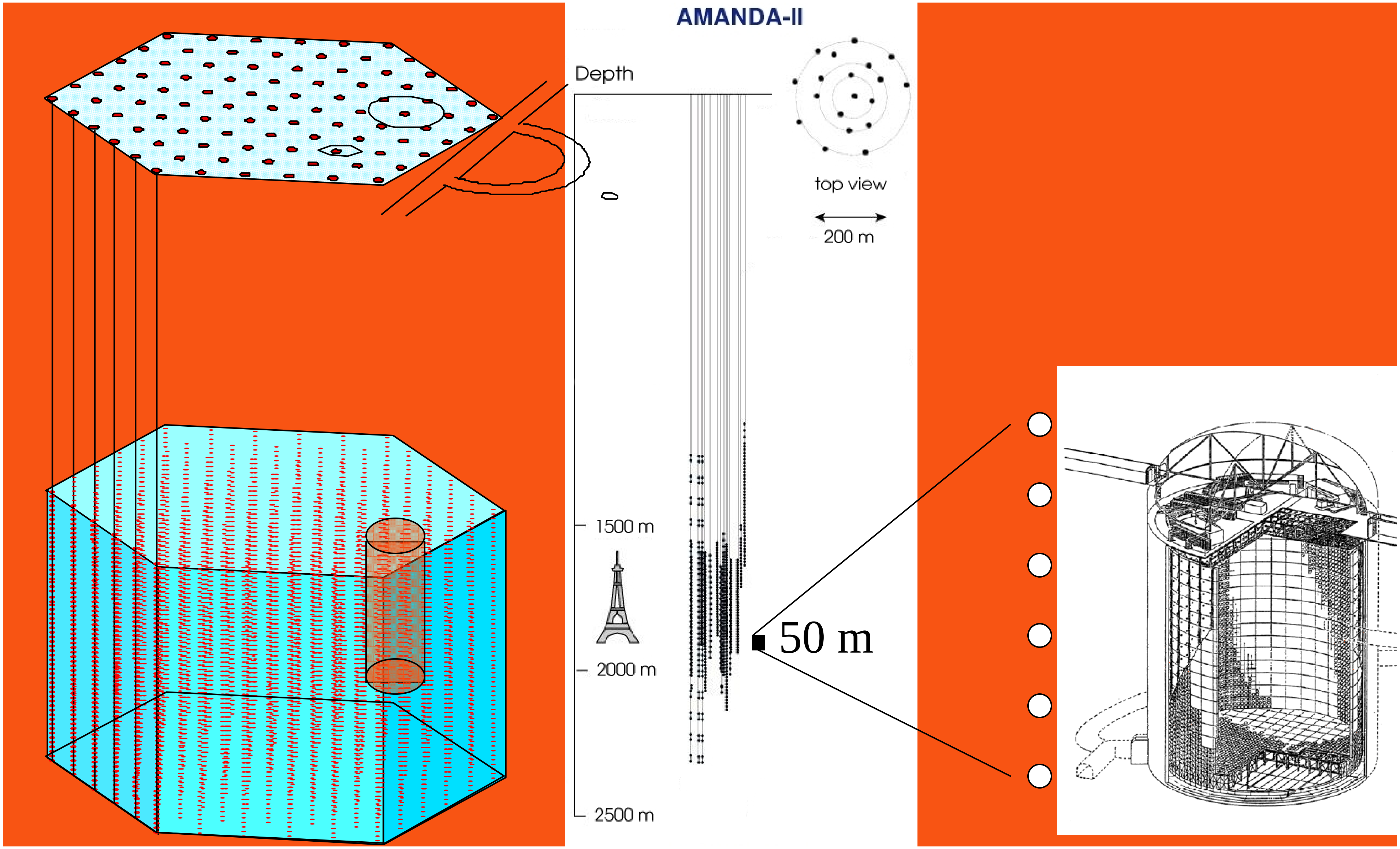
- Universite Libre de Bruxelles, Belgium
- Vrije Universiteit Brussel, Belgium
- Université de Mons-Hainaut, Belgium
- Universität Mainz, Germany
- DESY-Zeuthen, Germany

- Universität Wuppertal, Germany
- Uppsala University, Sweden
- Stockholm university, Sweden
- Imperial College, London, UK
- University of Oxford, UK
- NIKHEF, Utrecht, Netherlands

The IceCube Detector

- 1 km^3 instrumented volume: 1 Gton of ice
- 4800 digital optical modules (DOMs) on 80 strings.
- AMANDA will be enclosed within the array.
- An IceTop air shower station at the top of each string.



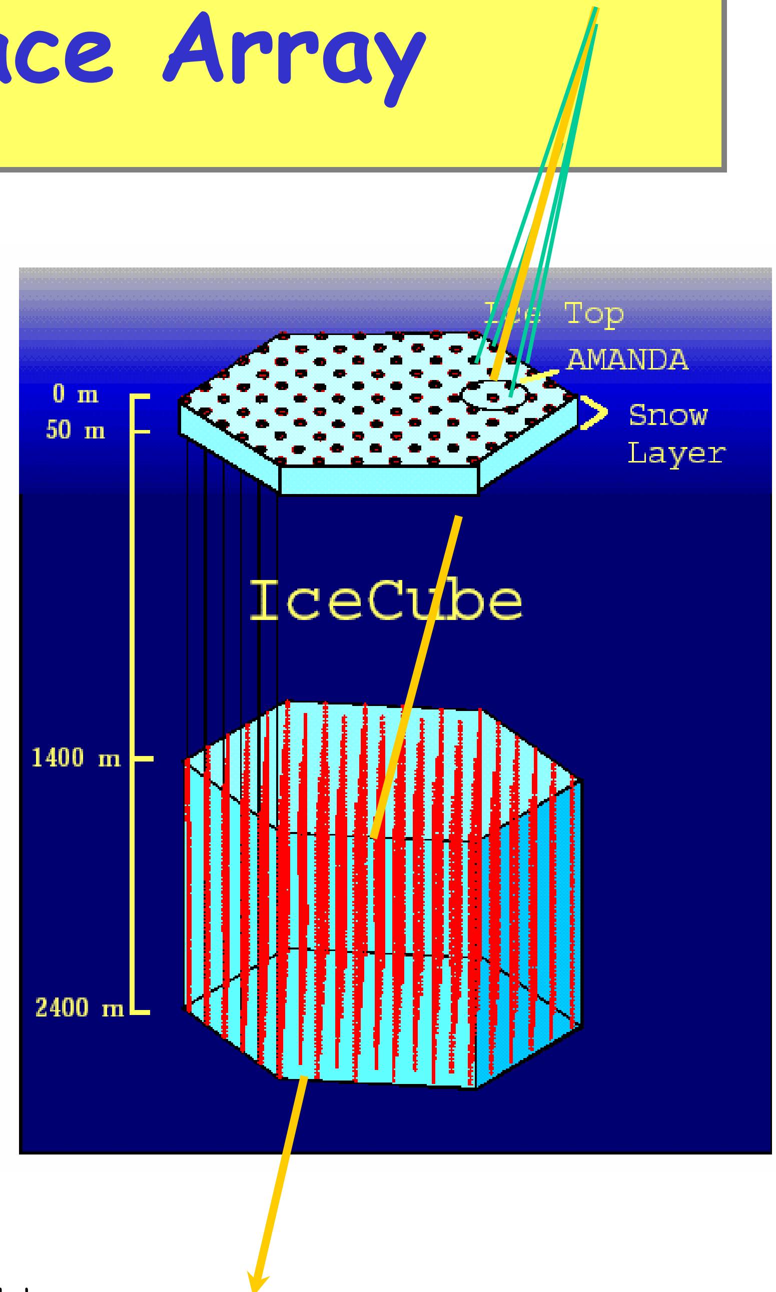


Volume = ~100 PSU Beaver Stadii
or, about 10^6 UCSB Gauchos Stadii

Size perspective

IceTop Surface Array

- One station (two tanks, four DOMs) above each IceCube string
- Used for calibration, veto, and cosmic ray composition studies
- Sensitive to showers above ~3 x 10^{14} eV



Building IceCube

Getting There: Almost as Much of an Adventure as Being There

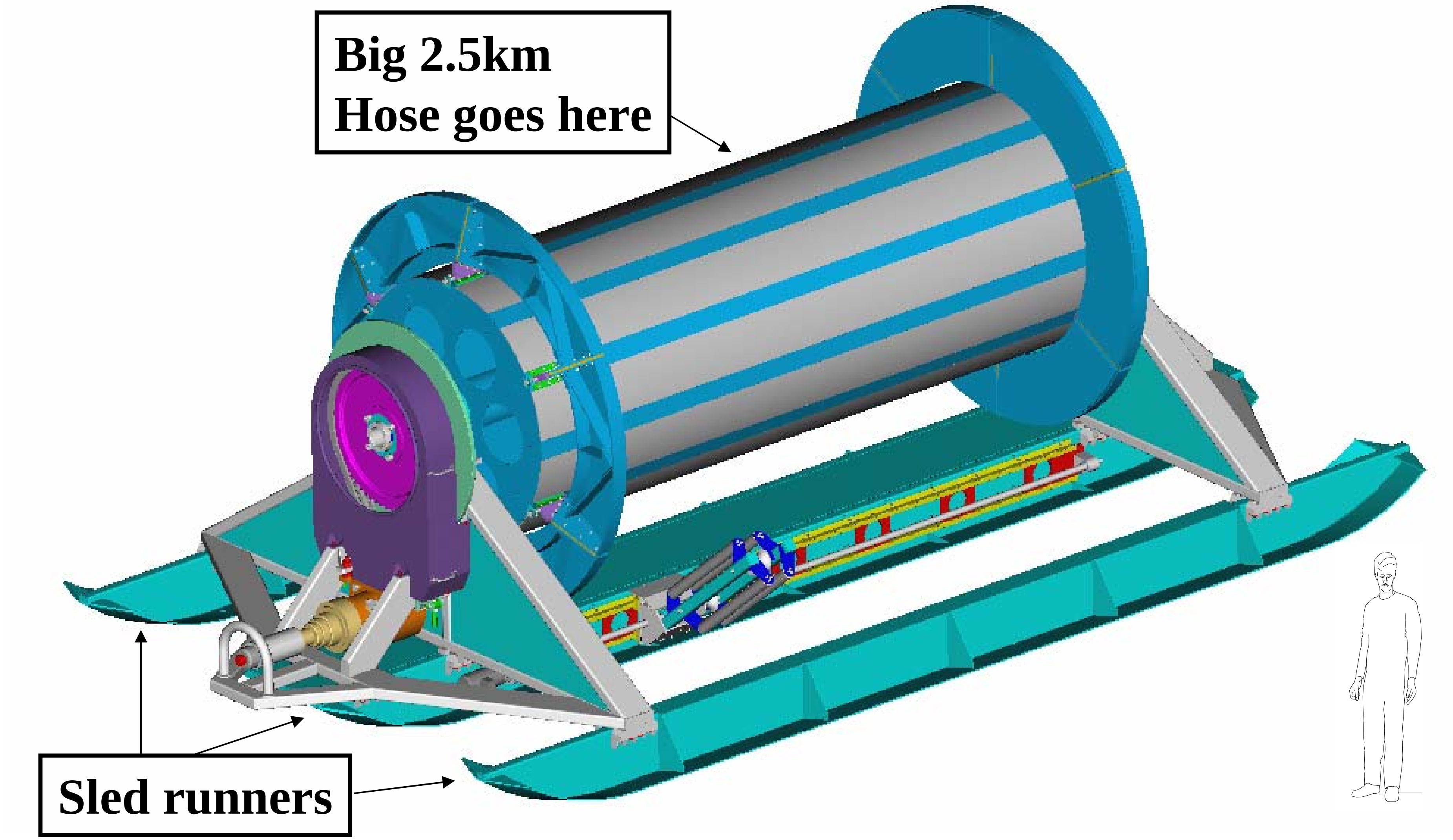
Flying First Class with the Air National Guard

Flying Economy Class: Fewer Windows!

Antarctic Airways

NPX Airport Terminal

In 2003, We Built…the Drill Winch!



EHWD Hose Reel

Engineering model-Isometric View

The Sled You Wanted as a Child

21Jan04 at the Pole

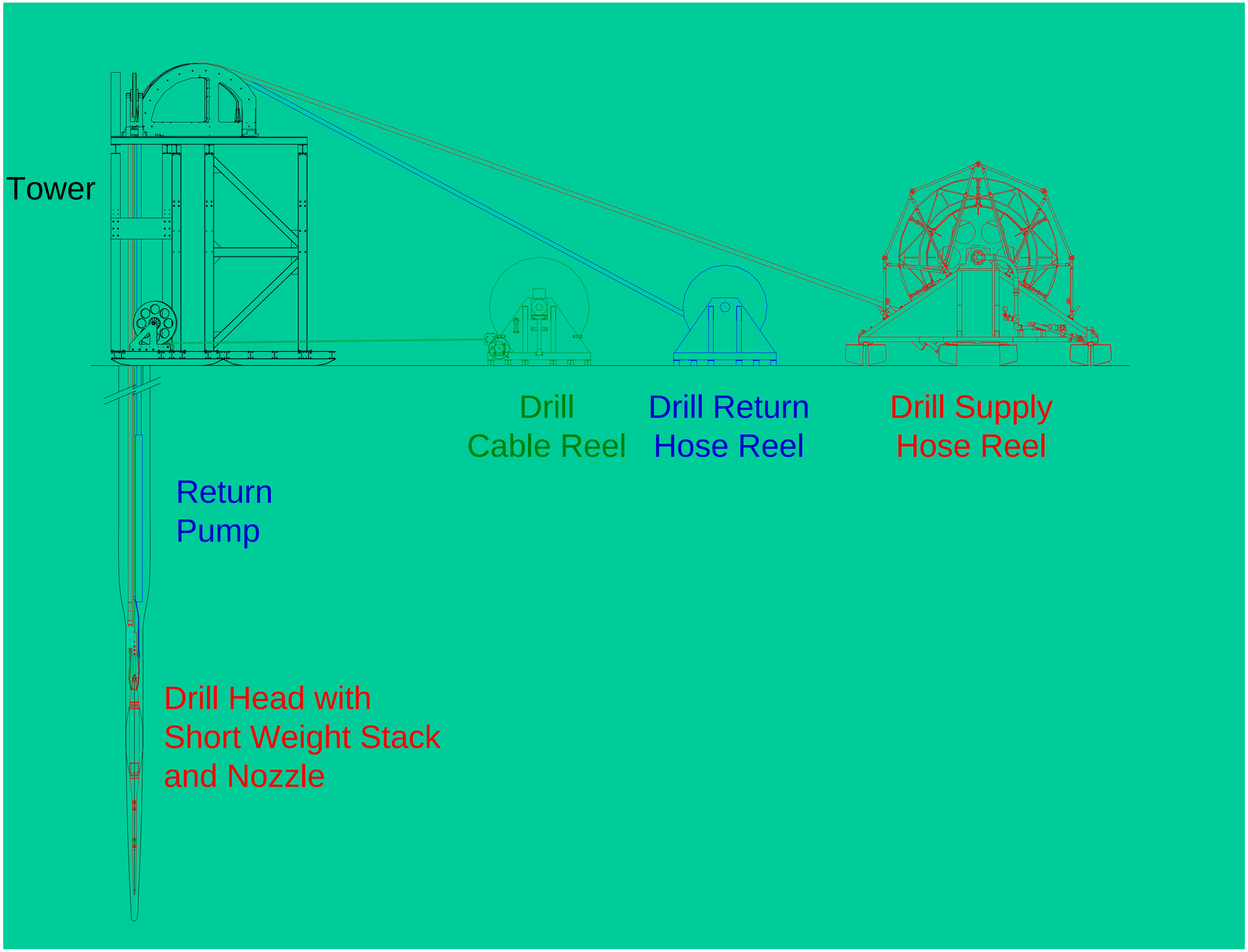
Non-Fragile Cargo Arrives at Pole: Nov 04

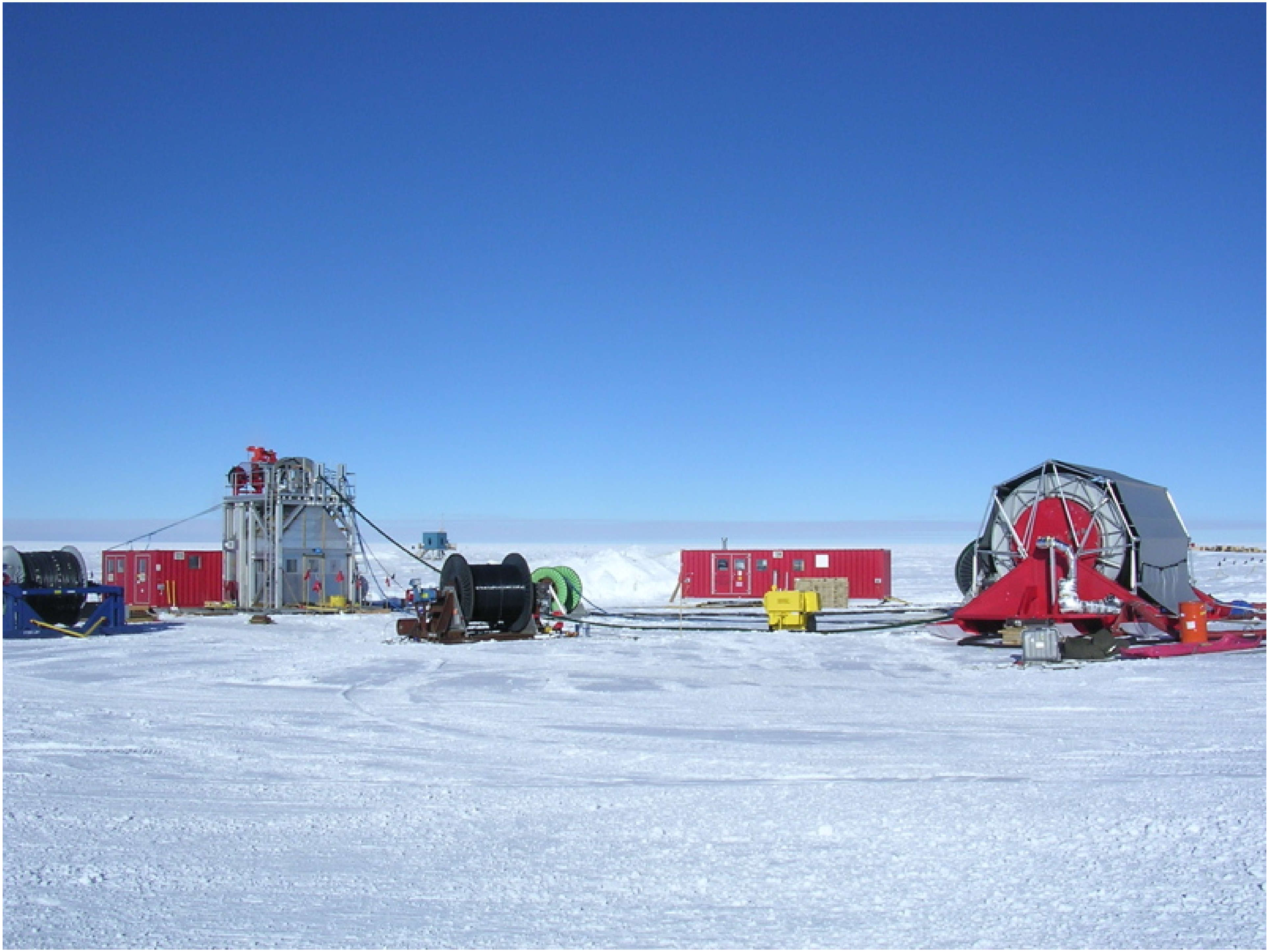
The "Counting House"

November 04: not very sunny yet

December 04: Sunnier!

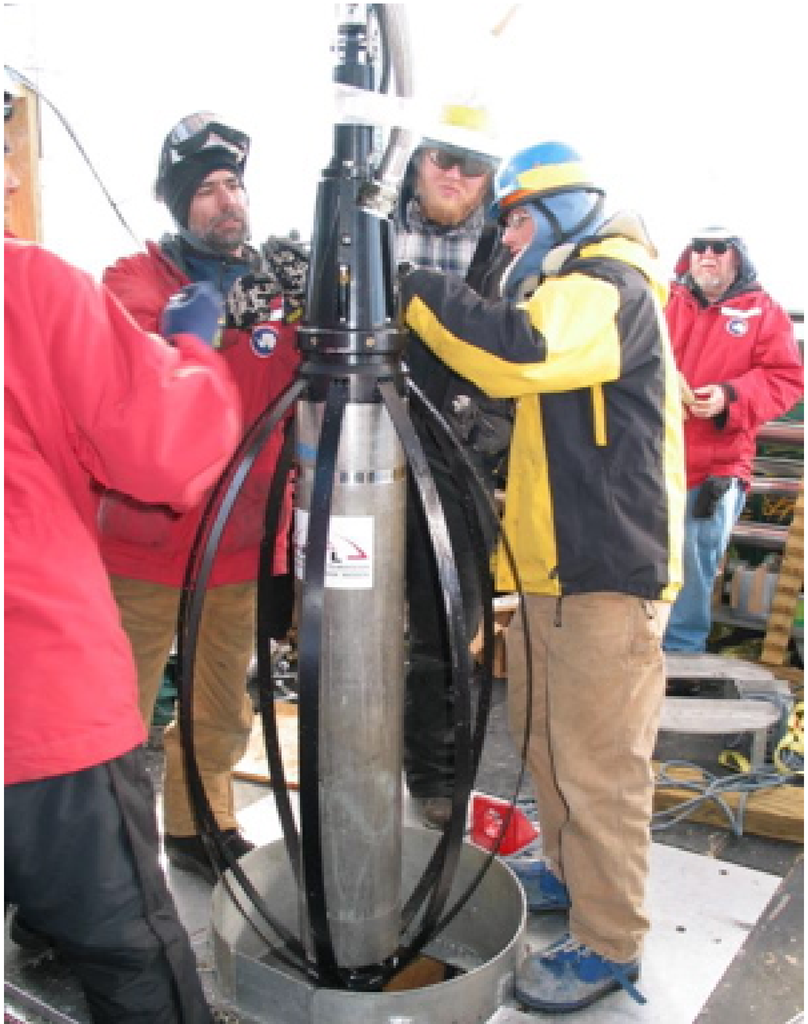
Melting the First IceCube Hole





Melting the First IceCube Hole

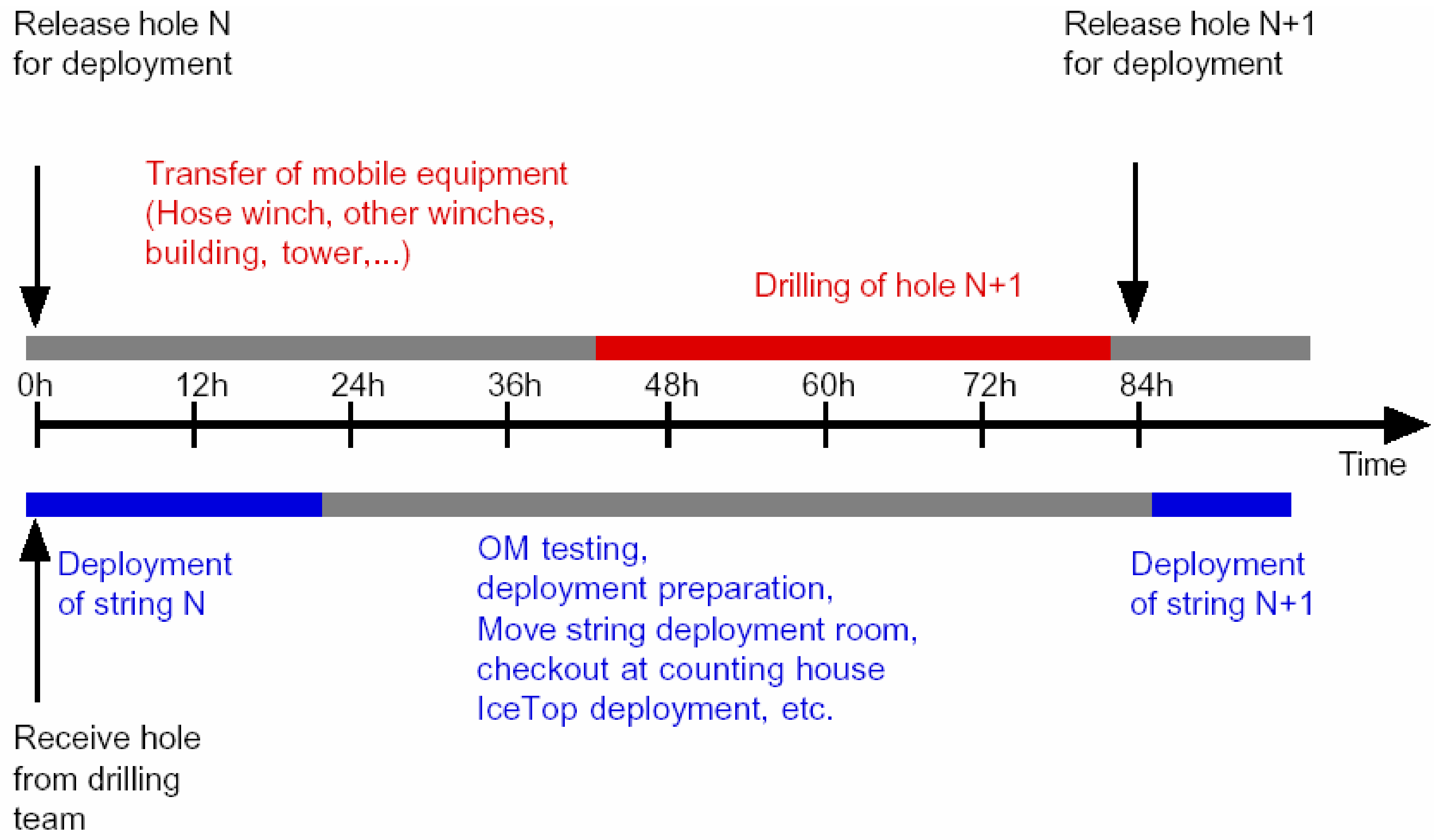
Building IceCube: Drilling Holes with Hot Water



Drill Upgrades for Next Season

- Firn drill with better heat transfer--design is nearly complete, out for bids
- Stronger weight stack with insulation--design is nearly complete, out for bids
- Simpler and larger crescent--have concept, working on details
- Working on hose strain relief concept--could work with present drum and crescent
- Sheaves for TOS (Tower Operating Structure) designed
- Designing brakes for reels that do not have any--replacing solenoid valves on some others
- Combo cable for RW and RWS--design complete out for bids
- Adding accelerometer and internal pressure gauge for drill head, design of daughter board complete
- Heated hoses designed and ordered
- Replacement motors for submersible pumps ordered--adding better cooling
- Design of MECC unit (for workshop, DNF, breaks, etc) complete

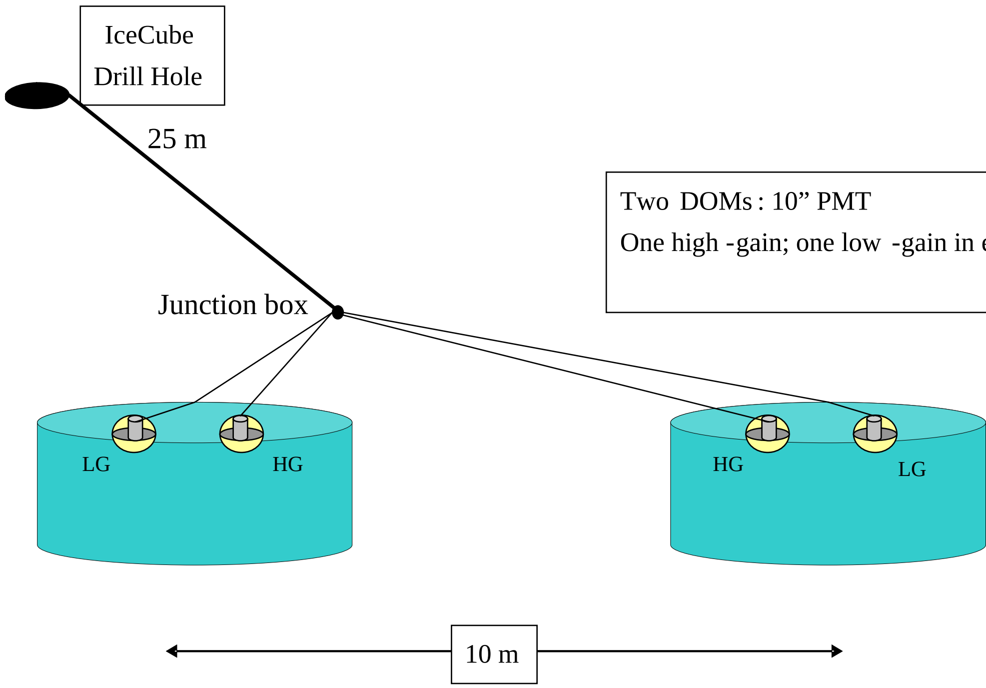
Deployment Cycle



The Surface Array Sub-detector: IceTop

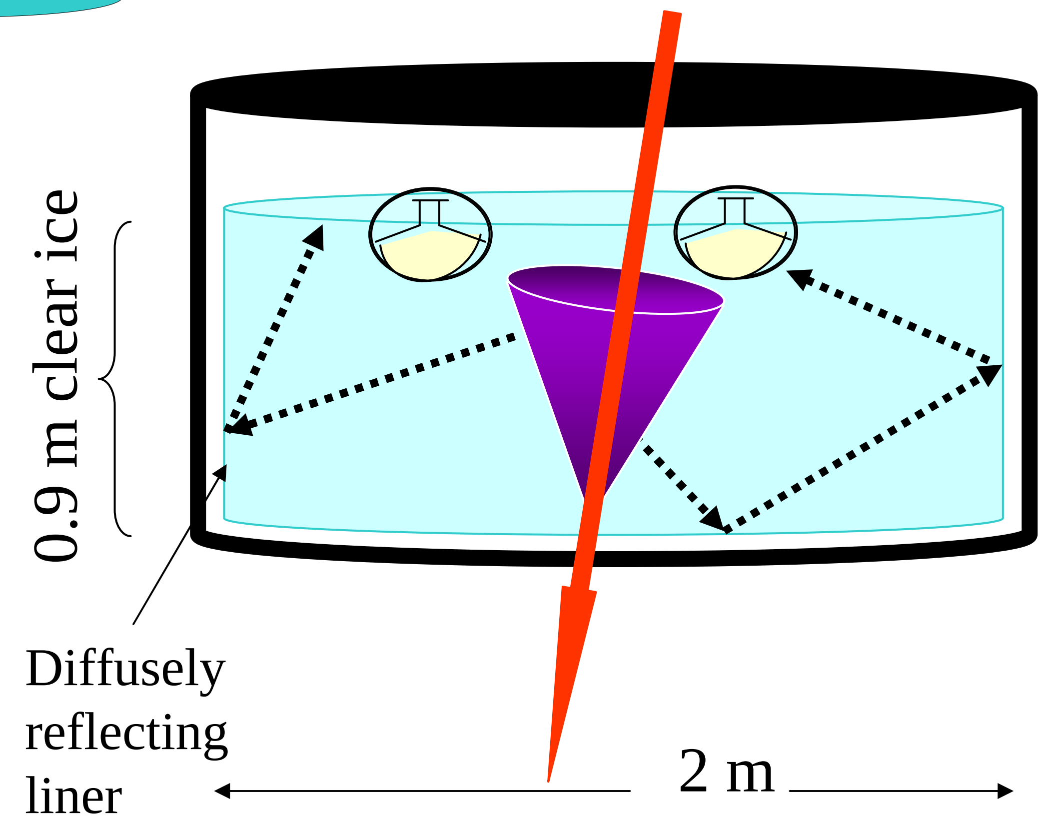
Serap Tilav, Bartol/U.Delaware (First Turkish woman @ Pole in the history of the world)

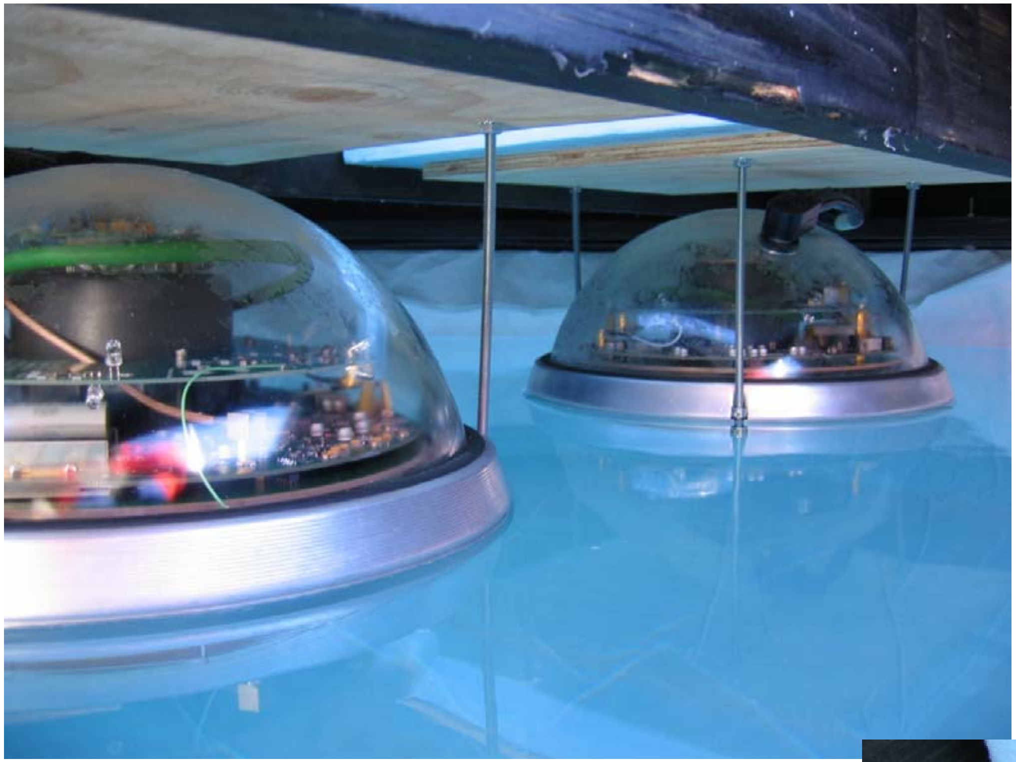
IceTop Design



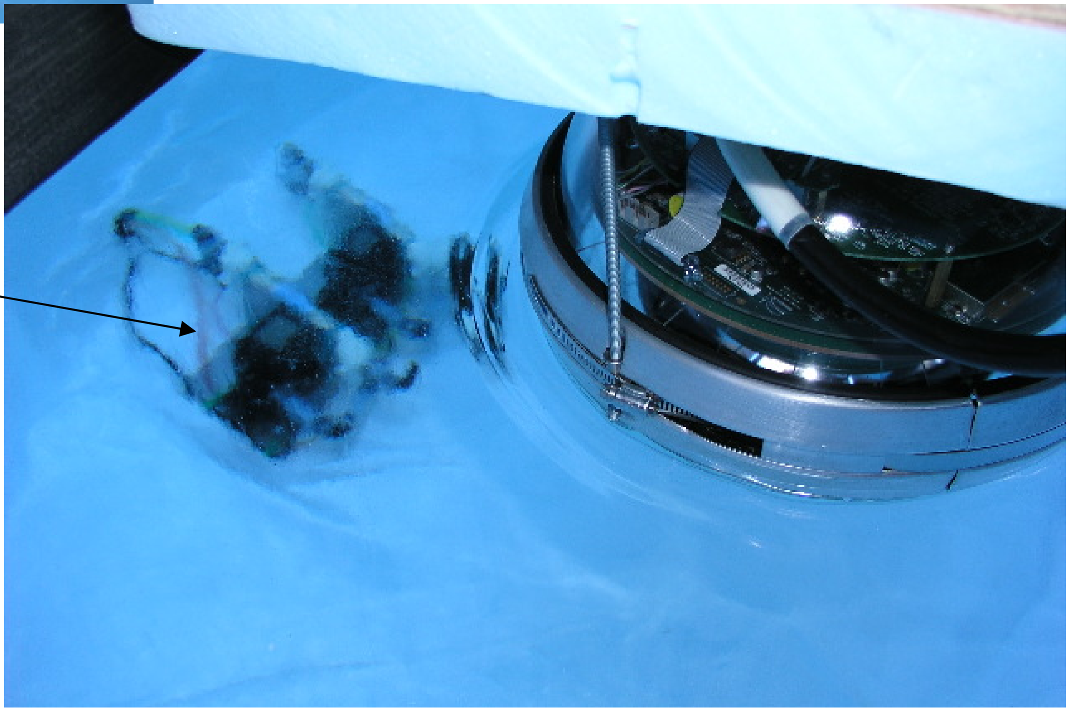
Two DOMs : 10” PMT
One high -gain; one low -gain in each tank

Ice Cherenkov Tank

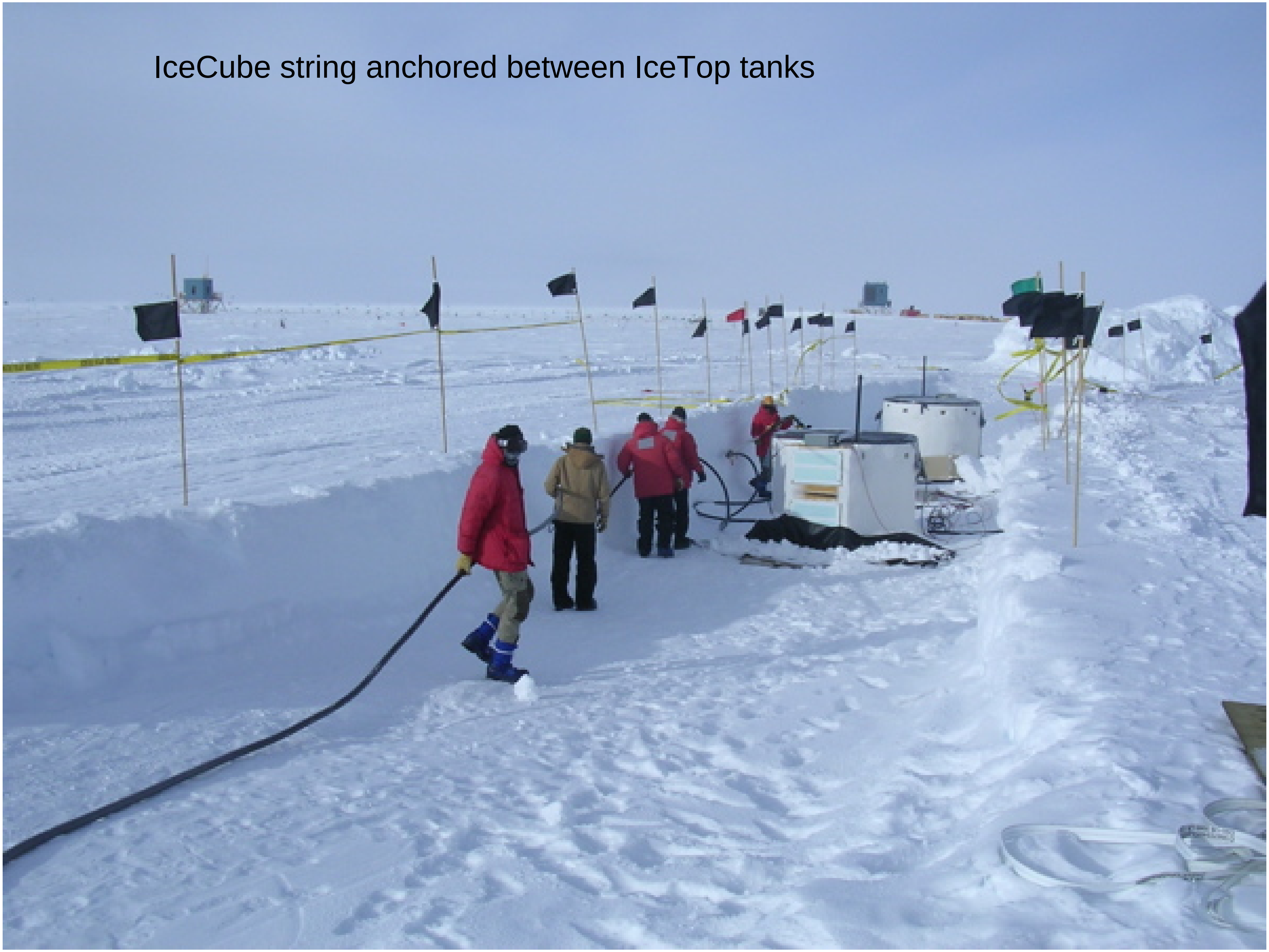




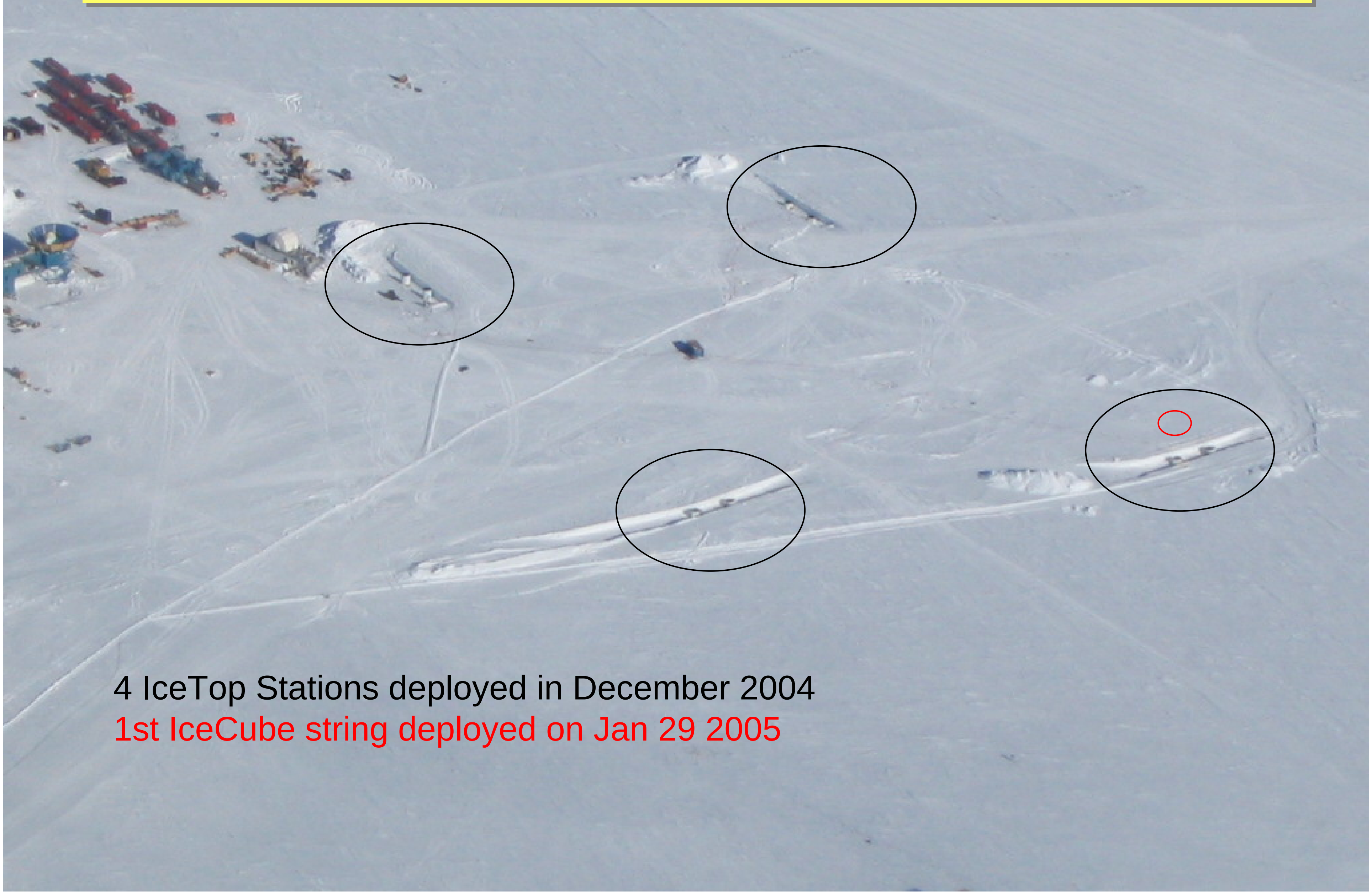
2 DOMs in liquid water in IceTop Tank



Freeze control unit
under ~75cm clear ice


IceCube string anchored between IceTop tanks

What We Did Over Winter Vacation



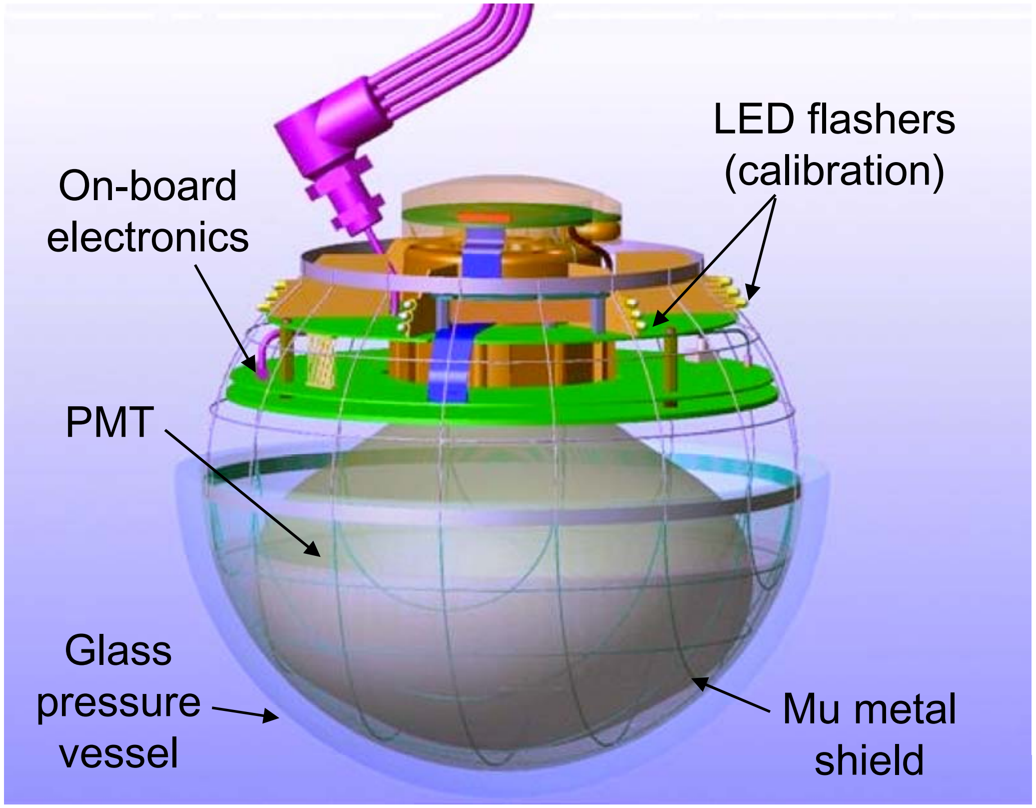
4 IceTop Stations deployed in December 2004

1st IceCube string deployed on Jan 29 2005

The Digital Optical Module (DOM): The Heart of IceCube

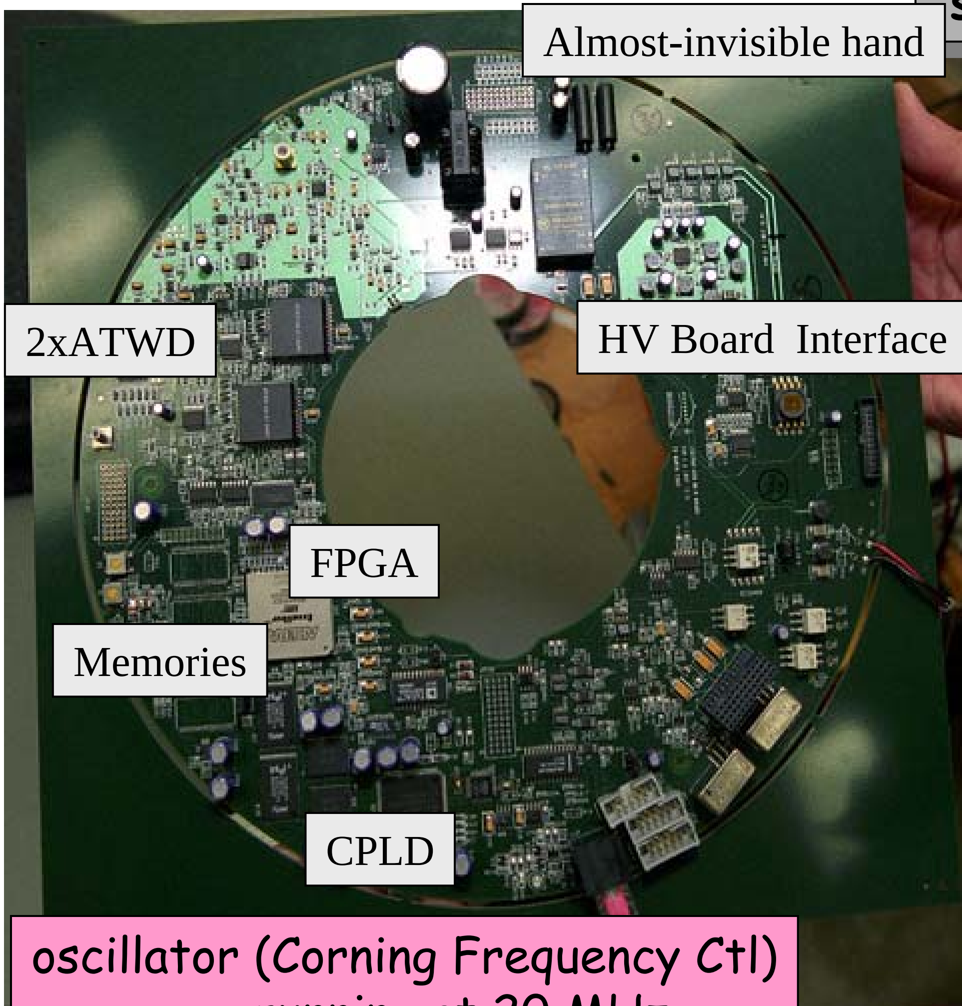
Digital Optical Modules (DOMs)

- 10" Hamamatsu PMT
- Glass pressure sphere
- Time resolution: < 5 ns
- Dynamic range:
  - 200 photoelectrons / 15 ns
  - 2000 PE integrated / 5 μs
- Digitization rate:
  - 300 MHz for first 300 ns
  - 40 MHz for 6.4 μs
- Noise rate *in situ* < 1 kHz
- Deadtime < 1%



- All waveforms captured by on-board digitizers
  - Full digitized amplitude series transmitted for complex waveforms
  - Summary info extracted from simple waveforms

DOM Mainboard



- 2 four-channel ATWDs
  Analog Transient Waveform Digitizers
  low-power ASICs
  recording at 300 MHz over first 0.5μs
  signal complexity at the start of event

- fast ADC
  recording at 40 MHz over 5 μs
  event duration in ice

- Dead time < 1%

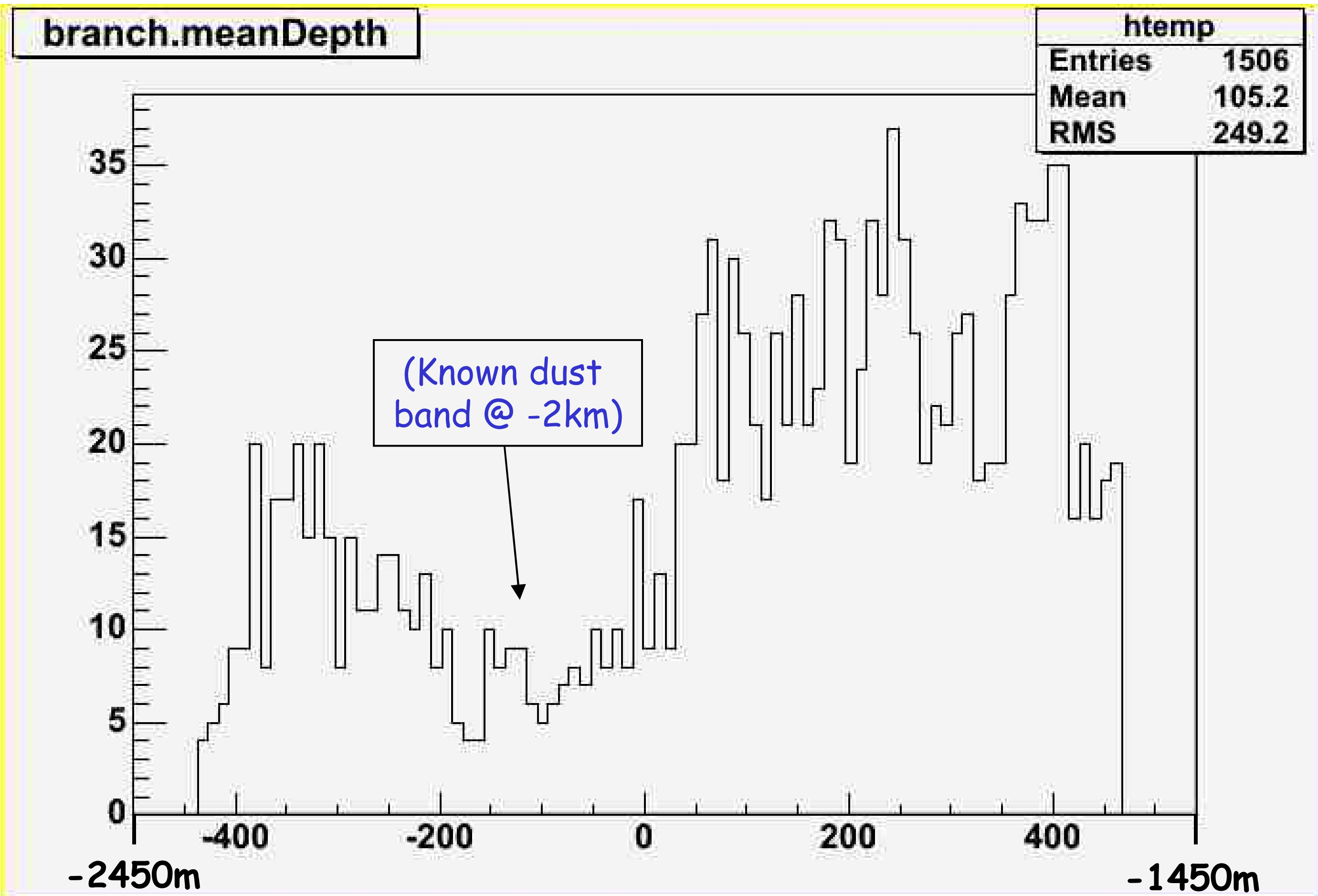
Dynamic range
- 200 p.e./15 ns
- 2000 p.e./5 μs

energy measurement (TeV – PeV)

- FPGA (Excalibur/Altera)
  reads out the ATWD
  handles communications
  time stamps events
  system time stamp resolution 7 ns wrt master clock

oscillator (Corning Frequency Ctl)
running at 20 MHz
maintains $\delta f/f < 2\times10^{-10}$

Buried Array Works

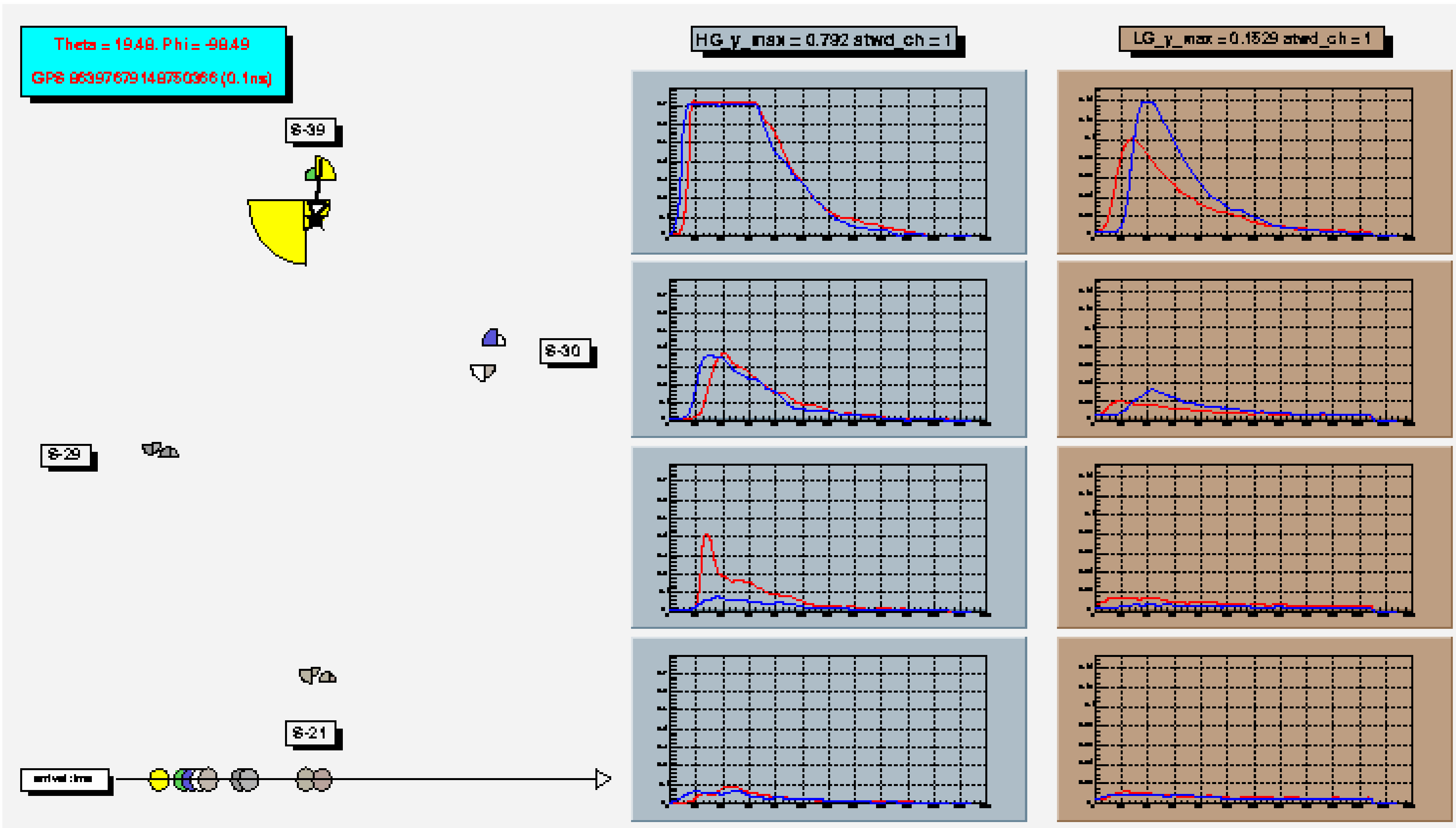


Plot of the <z> of the DOMs participating in a triggered event.

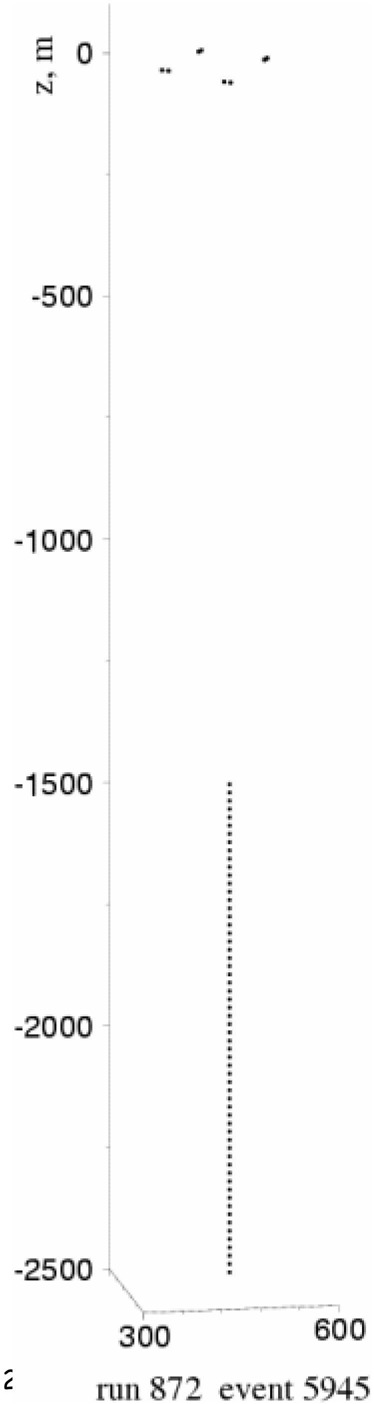
Not terribly meaningful…

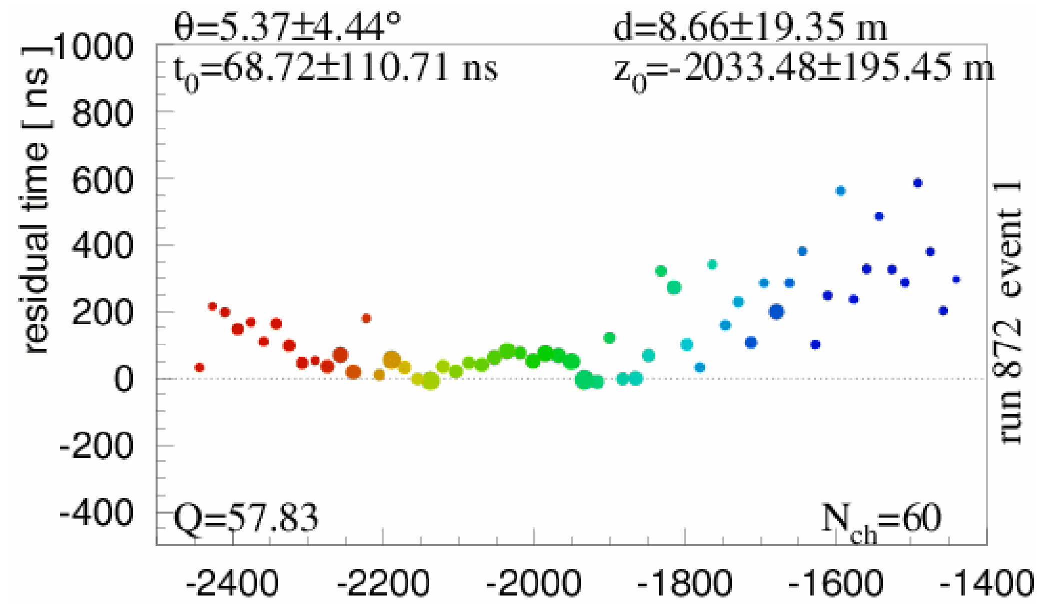
Dr. G. Marx

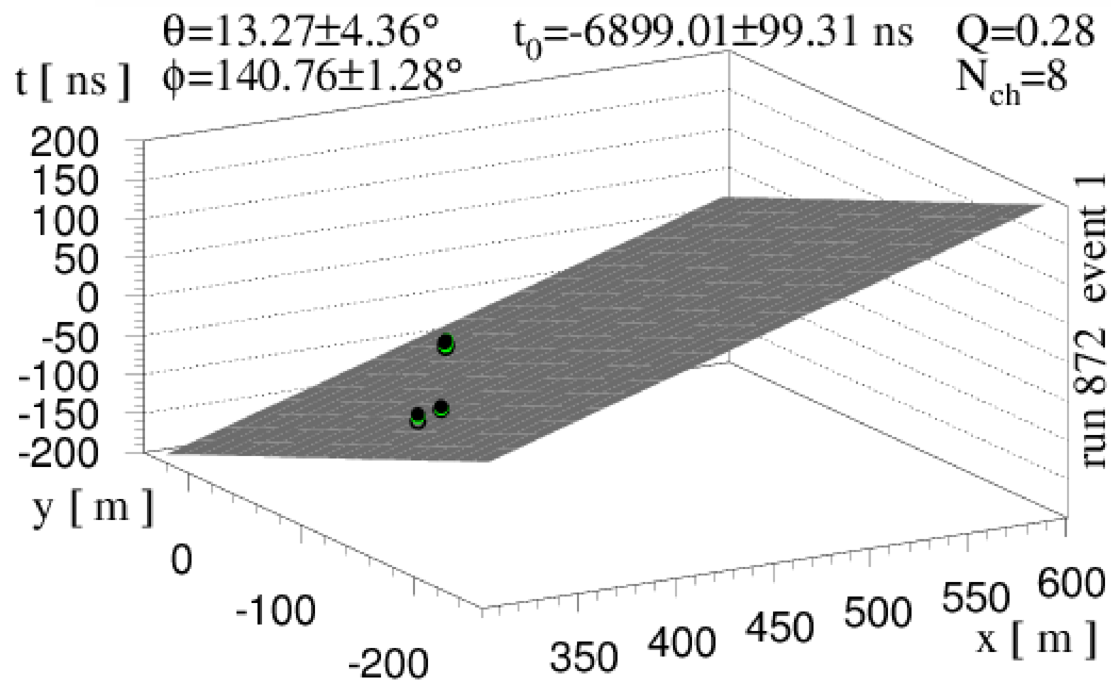
Surface Array Works



Run 872 Event 5945







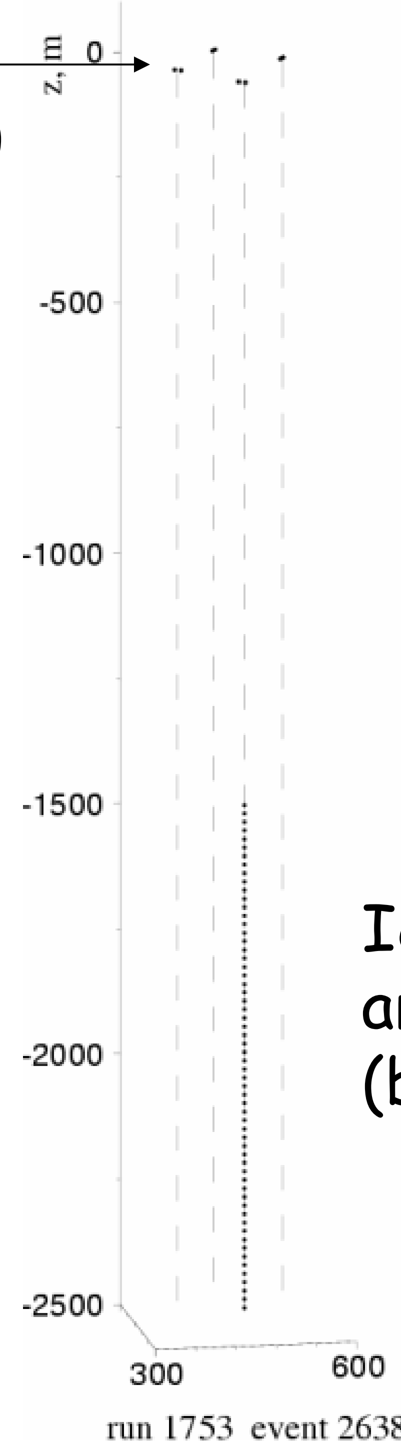
Monitoring Page from Yesterday

It All Works!

Please hold your applause:
it is only run-of-the-mill cosmic-ray muon. Possibly the longest one ever reconstructed, though…

Still, to be able to do this only a few weeks after deployment is (if we do say so ourselves) VERY impressive!

IceTop
(on surface)



IceCube
array
(buried)

Anticipated IceCube Performance

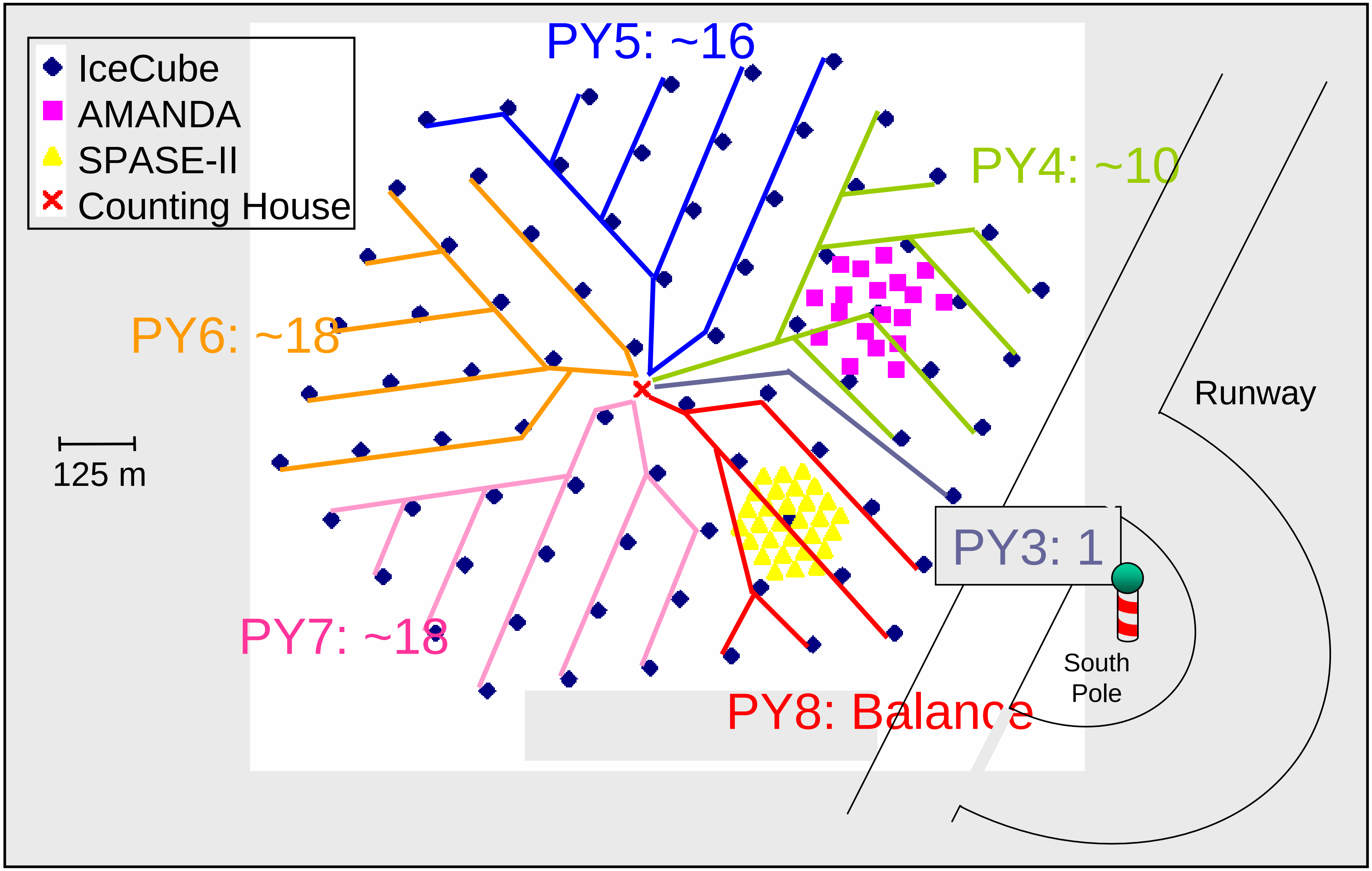
1. versus topic
2. versus time
3. versus flavor

IceCube Physics Topics

- Neutrino point sources (AGN, microquasars, magnetars, SNRs,…)
- Neutrinos from GRBs (afterglow, precursors, collapsars, supranovæ)
- Diffuse extraterrestrial neutrino fluxes
- Ultrahigh energy cosmogenic neutrinos (GZK interactions)
- Supersymmetry and Dark Matter (WIMPs, sleptons,…)
- Atmospheric neutrino spectrum & oscillations(?)
- Cosmic ray composition above the knee
- Sources of ultrahigh energy cosmic rays
- Galactic supernovæ (SNEWS)
- Ultralong baseline neutrino oscillations
- Tests of Lorentz invariance, weak equivalence principle
- Exotic massive particles (topological defects, relic particles)
- TeV-scale extra dimensions, electroweak instantons,…
- Magnetic monopoles, nuclearites, Q-balls,…

…and new discoveries!

Planned Deployment Schedule



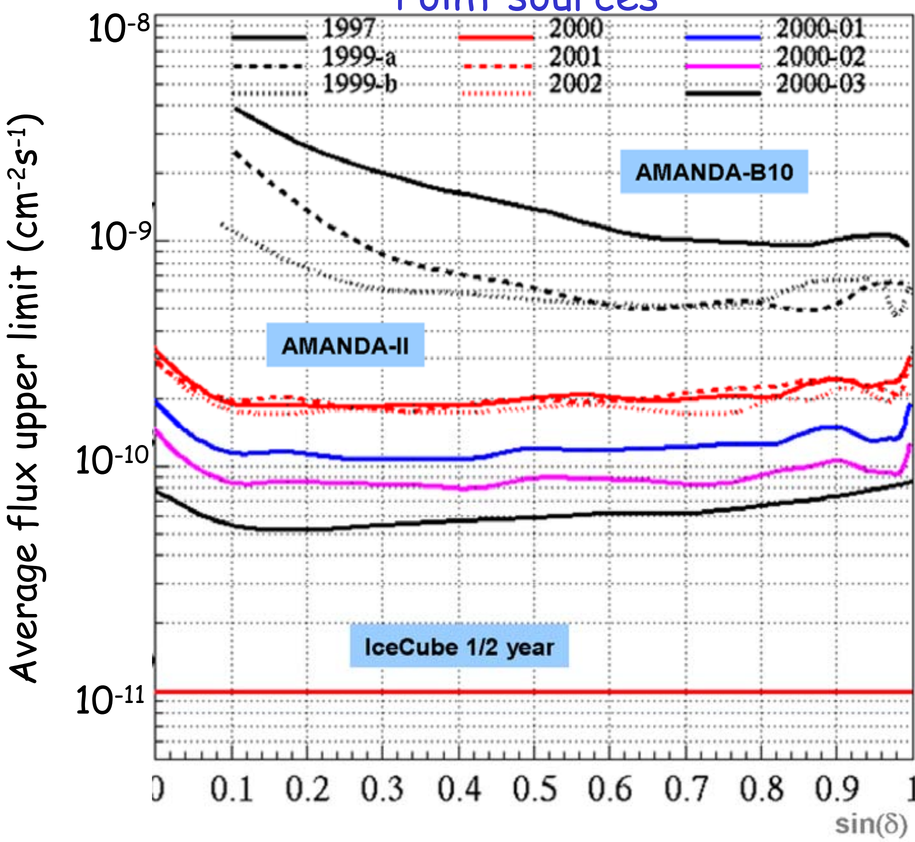
Physics Reach vs. Time

Diffuse sources

Date	New Strings added	Accumulated string-yrs/yr	total accumulated string-yrs	total accumulated km3-yrs	diffuse UHE muons @1e-7	diffuse UHE cascades @1e-7
Feb-05	1	0	0			
Feb-06	10	1	1			
Feb-07	16	11	12	0.15	8	4
Feb-08	18	27	39	0.49	24	13
Feb-09	18	45	84	1.05	53	28
Feb-10	18	63	147	1.84	92	49

Point sources

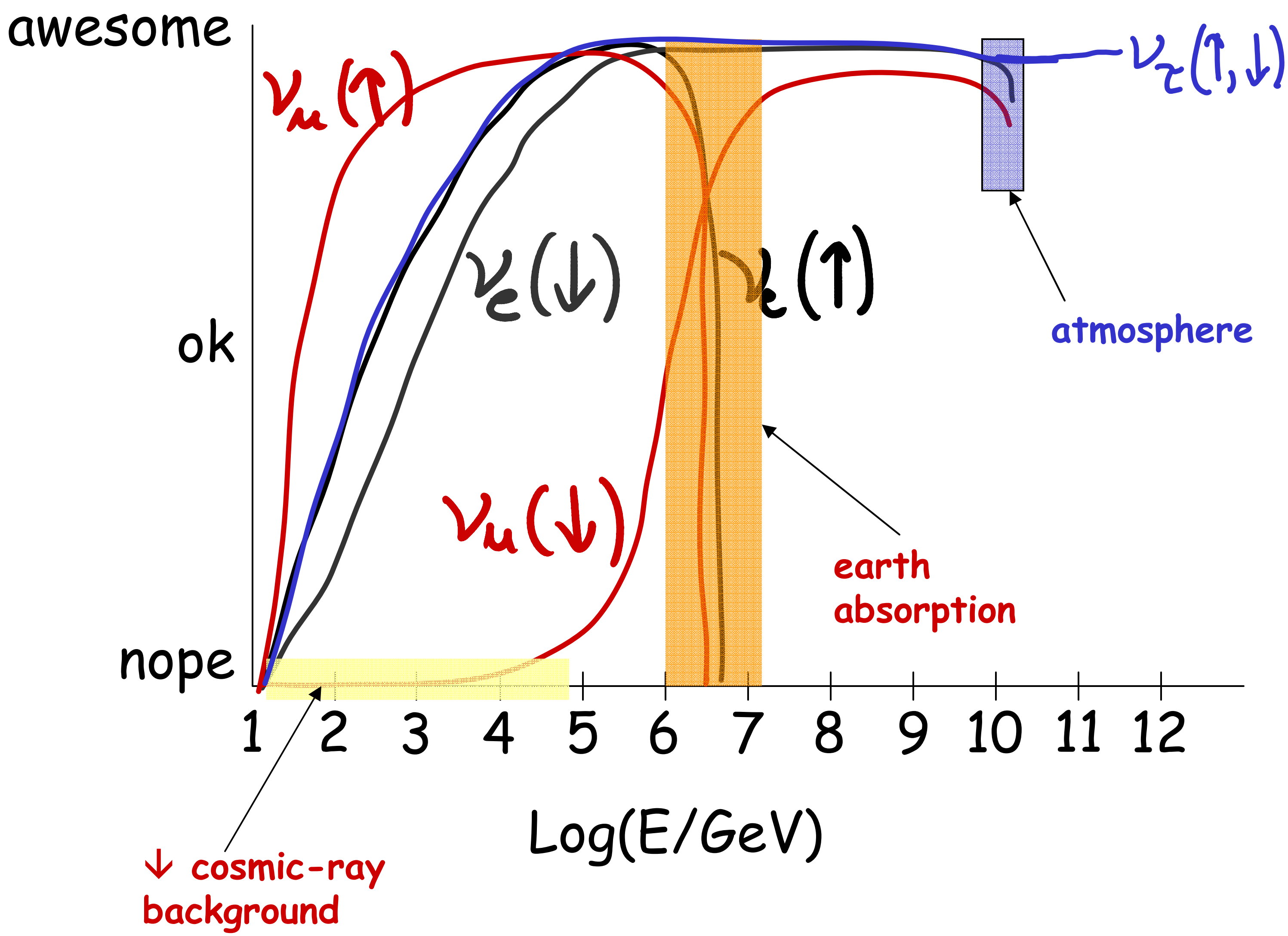
Note: Conservative estimates, AMANDA efficiencies assumed



Calculated for pure ν_μ+anti-ν_μ E^{-2} spectrum integrated above 1 TeV

~1 Crab

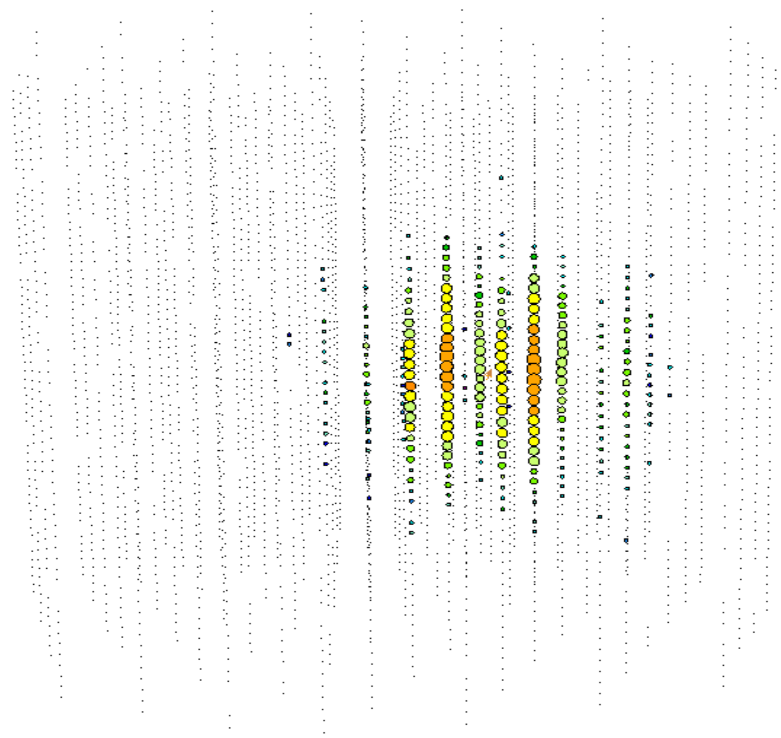
IceCube Neutrino Sensitivity vs. Energy vs. Flavor & up/down



Electron Cascades

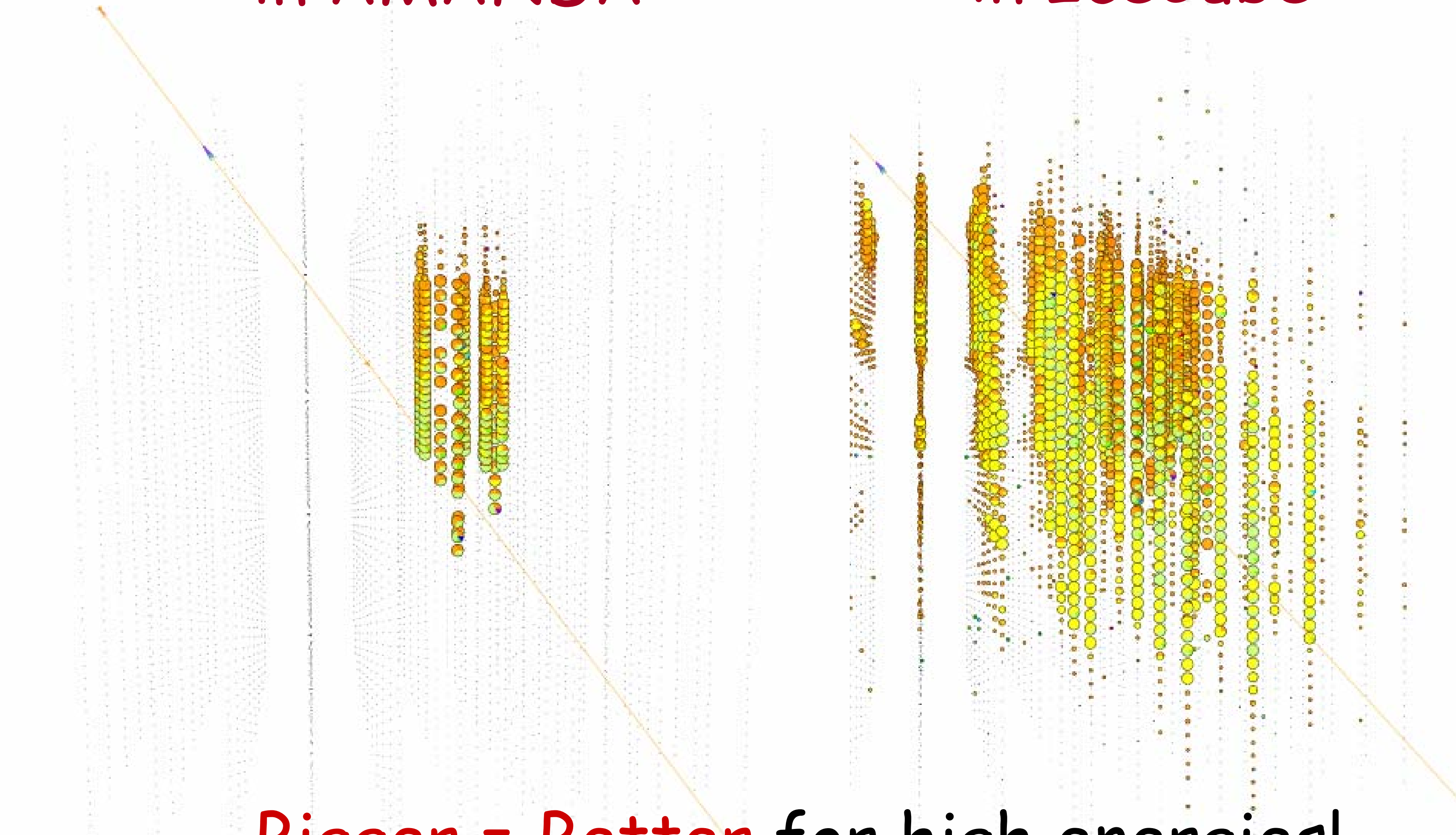
- Electron cascades over ~10 m: pointlike
- Roughly spherical distribution of light
  - 500 m diameter at 1 PeV
  - 100 m per decade of energy
- Energy resolution currently 10% in log(E)
- Angular resolution currently 27°

ν_e at 375 TeV



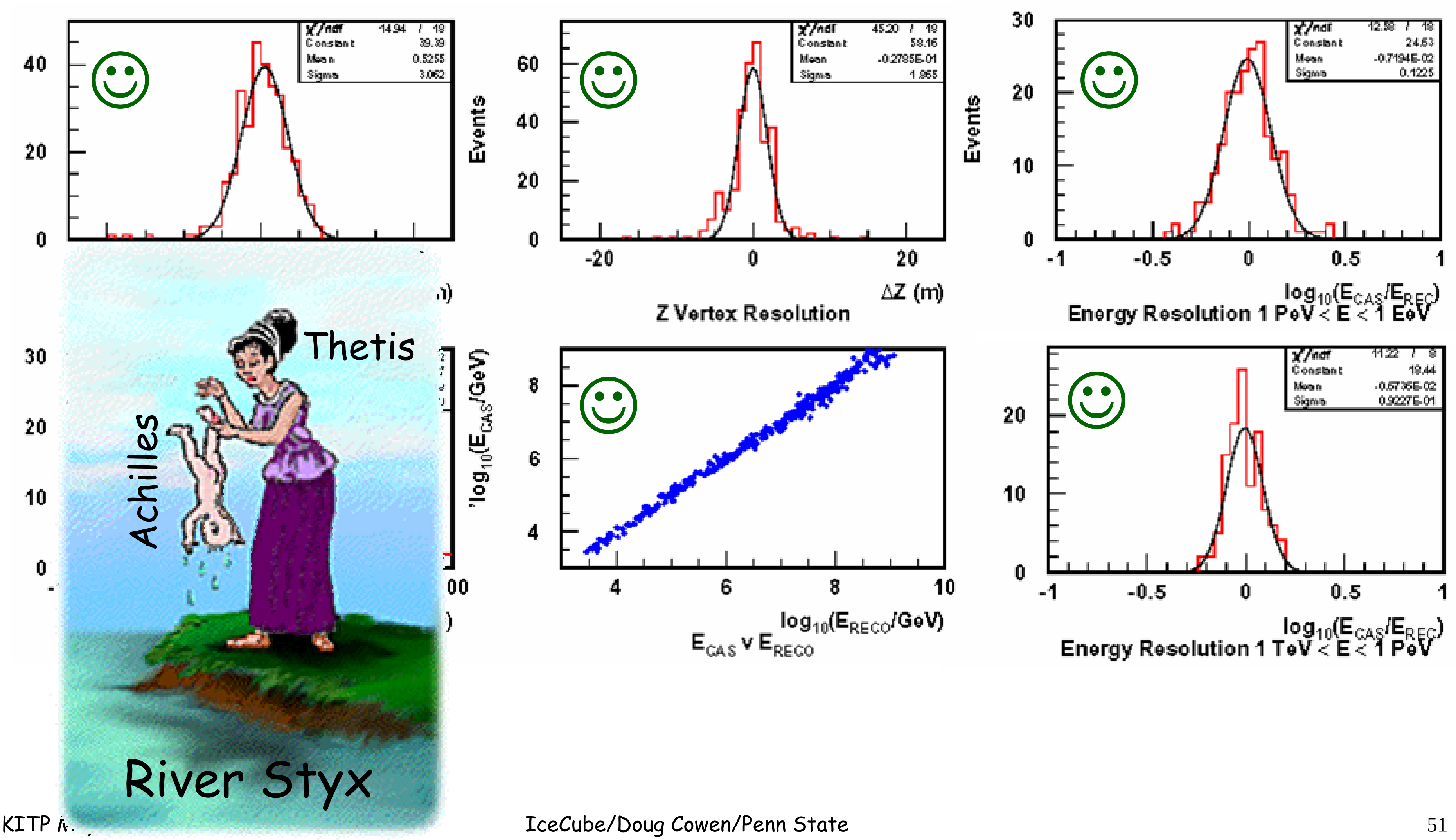
Simulated 2×10^{19} eV neutrino event

in AMANDA in IceCube

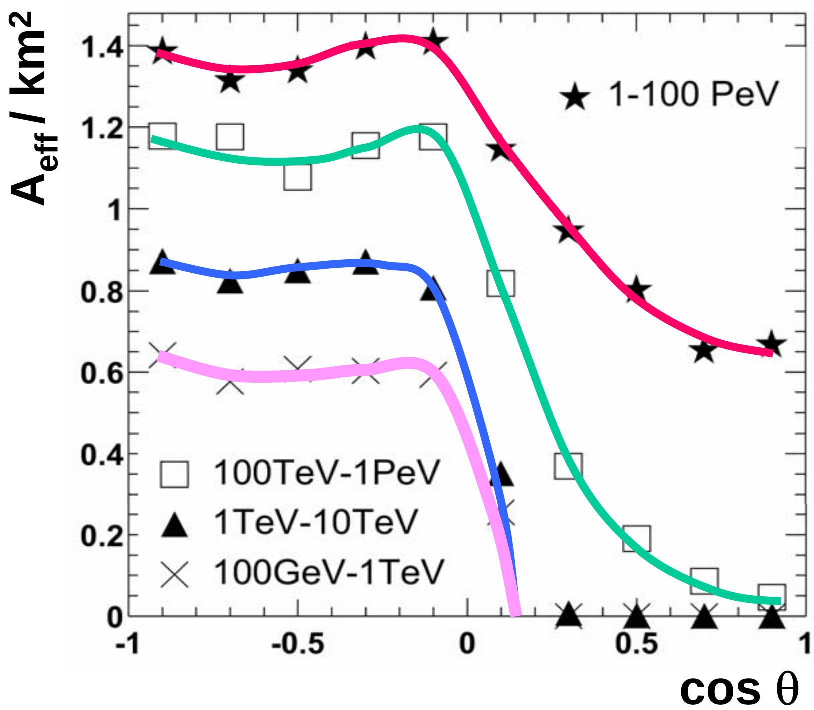


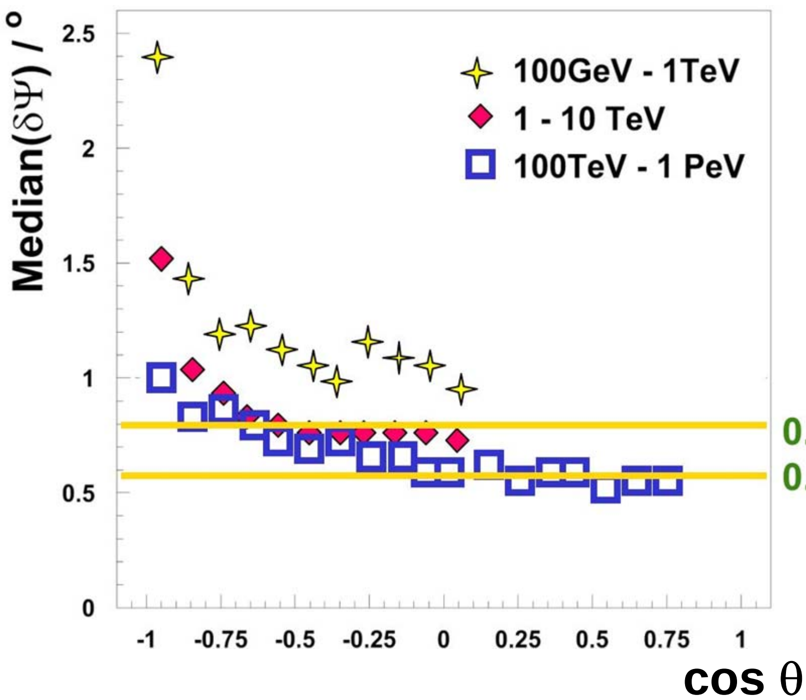
Bigger = Better for high energies!

AMANDA Cascade Response



IceCube Muon Response

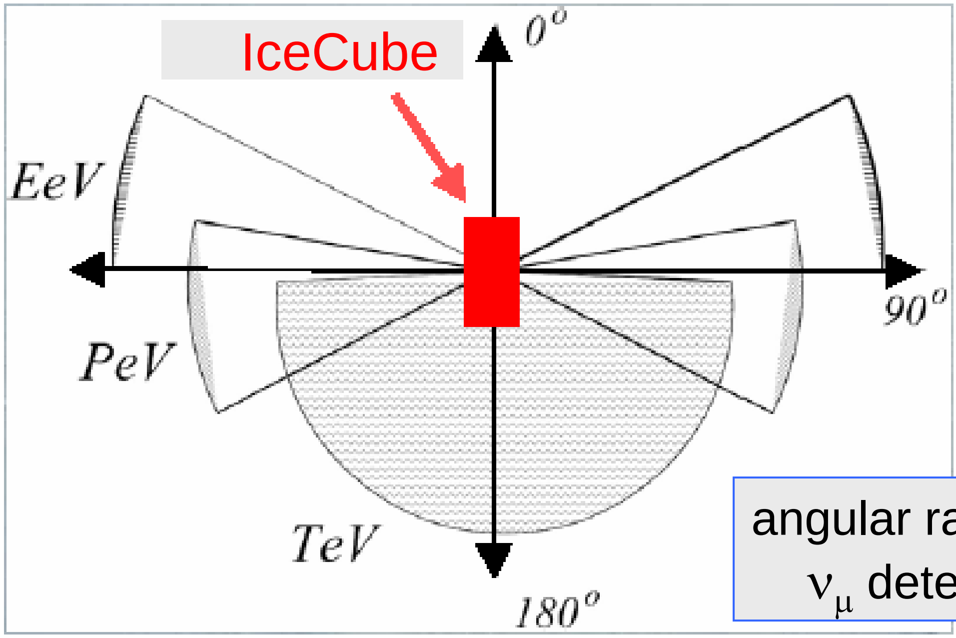




- Results with simulated AMANDA hardware, software
- Big improvements possible – waveforms, more hits, better noise reduction, reconstruction techniques

IceCube Muon Field of View

- TeV: look down to avoid atmos. muons
- PeV: Earth opaque, look horizontally
- EeV: Can look above horizon – atmospherics are at lower energy

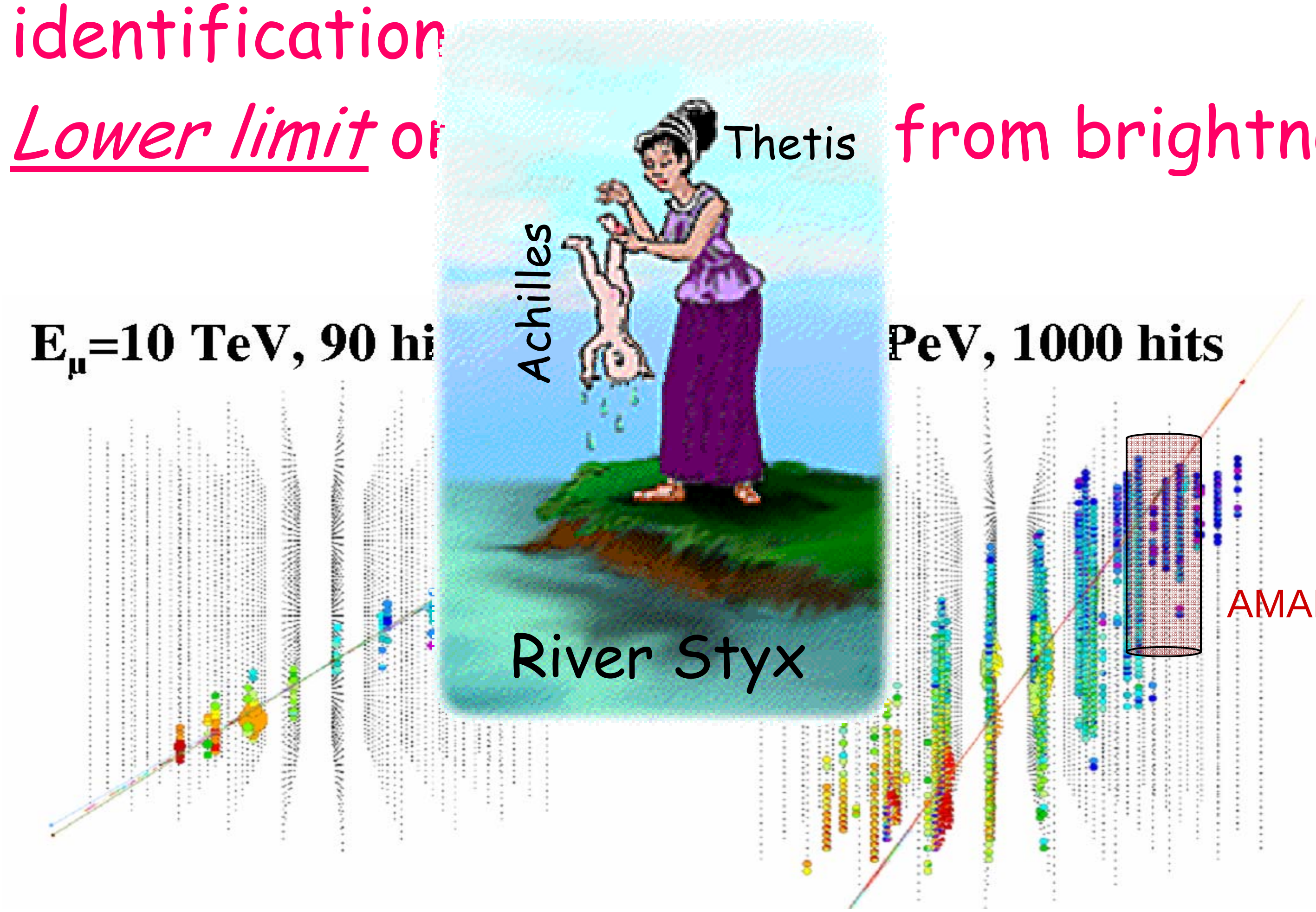


angular range for ν_μ detection

Cascades: 4π, except for absorption at high energies (with muons vetoed!)

IceCube Muon Energy Response

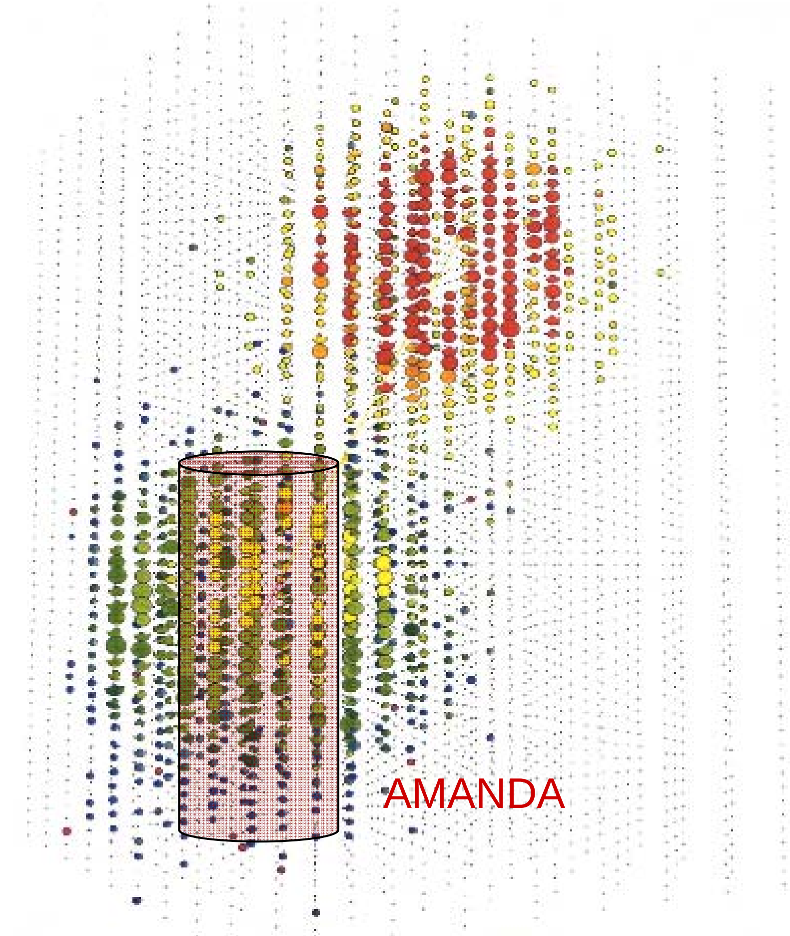
- Long tracks: Better resolution, flavor identification
- *Lower limit* o from brightness



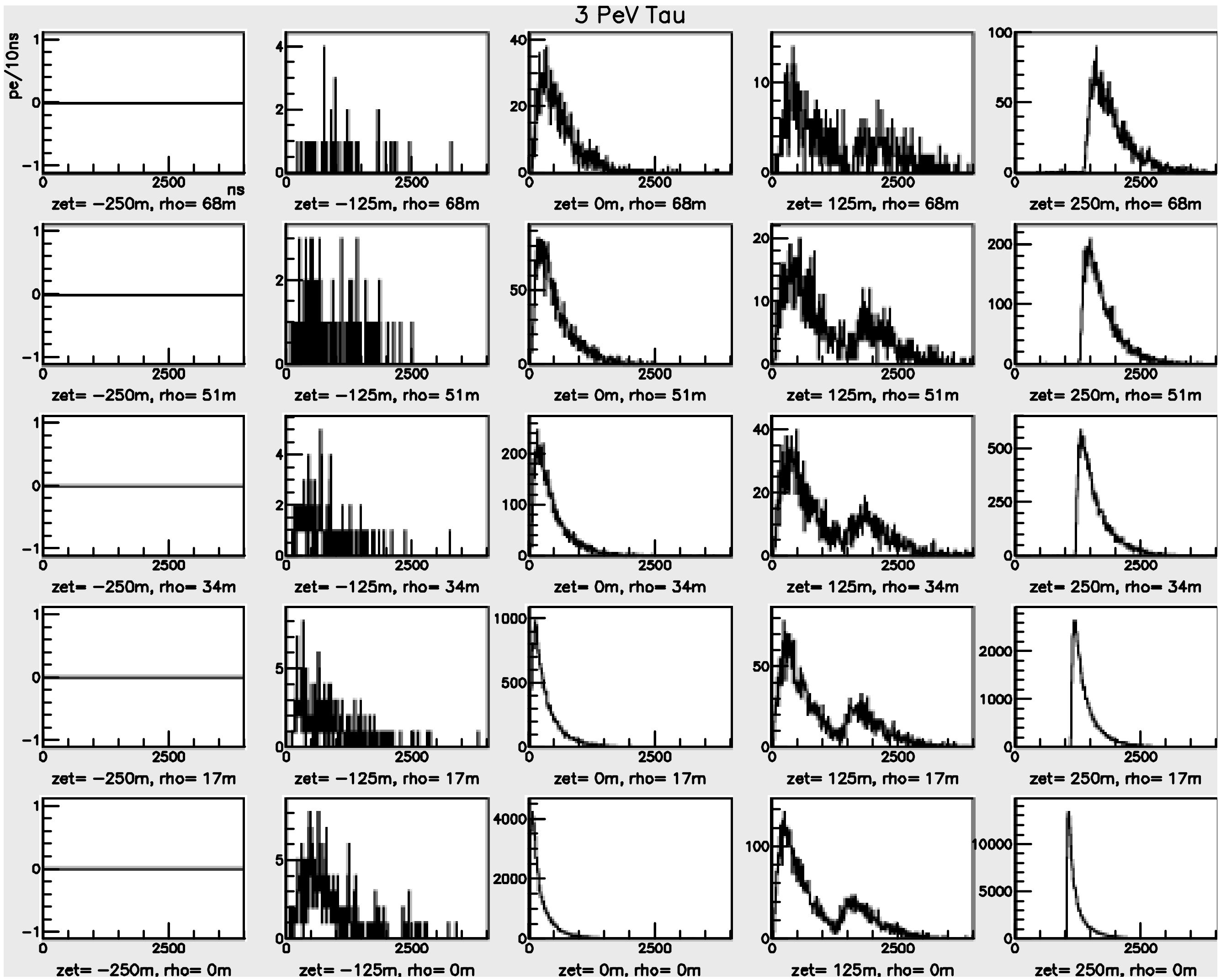
Tau Events

- Two cascades
  - νN interaction vertex
  - τ lepton decay
- Dim lepton track connects the vertices
  - ~50 m/PeV
  - Suppressed by $(m_\tau / m_\mu)^2$
- E » PeV: "Lollipop"
  - Dim track ending in a spectacular vertex

"Double Bang"
(Learned & Pakvasa 1995)



Tau Identification: Digitization is Good



IceCube Tau Neutrino Response

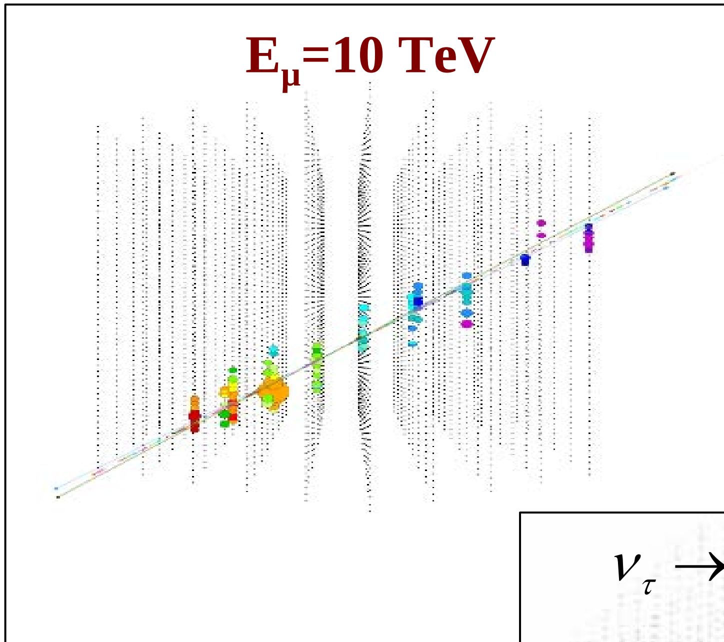
- Energy: ~same as for ν_e cascades when double bang is contained
- Directionality:
  - double bangs: connect the vertices!
    - 100s of meters separation
    - each vertex position known to several meters
    - find $\Delta\phi < \sim 1^o$
  - lollipops
    - sub-degree muon pointing accuracy from tau track
    - plus anchor point from single shower
    - almost certainly better than 0.5^o

Emoticonic Summary of IceCube Response vs. Flavor

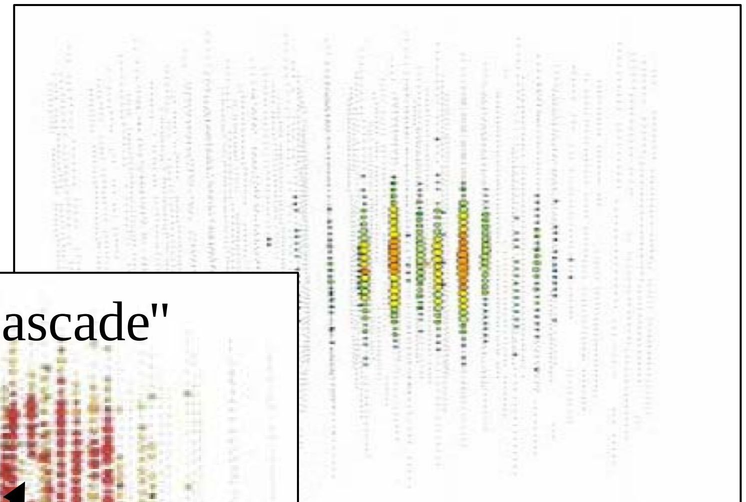
	Directional resolution		Energy Resolution		Effective volume or area		Background suscept-ibility		Acceptance	
E:	lo	hi	lo	hi	lo	hi	lo	hi	lo	hi
ν_e	☹	😐	☺	☺	☹	😐	☺	☺	☺ 4π	😐 $2\pi(\downarrow)$
ν_μ	☺	☺	☹	☹	☺	☺	☹	☺	😐 $2\pi(\uparrow)$	😐 $2\pi(\downarrow)$
ν_τ	☹	☺	☺	☺ 😐	☹	😐	☺	☺	☺ 4π	☺ 4π

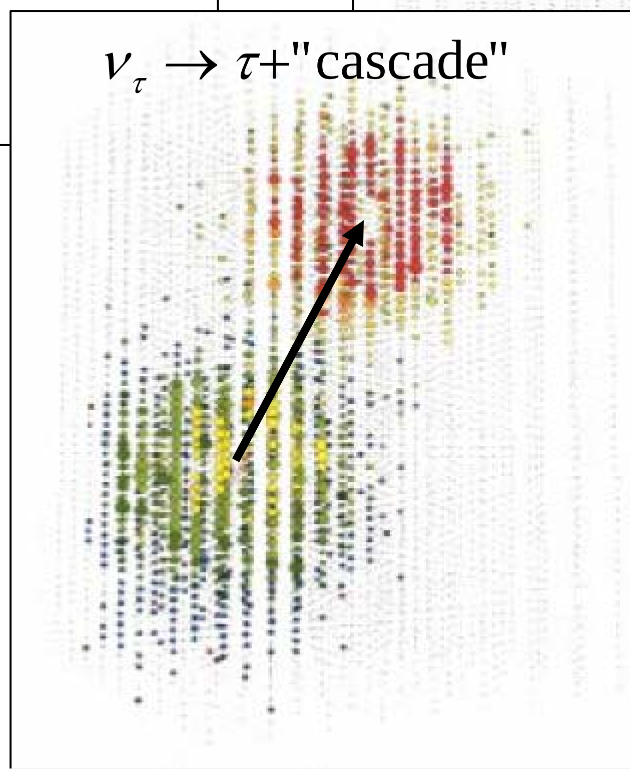
Neutrino Flavor Separation

IceCube All-Flavor Neutrino Detection

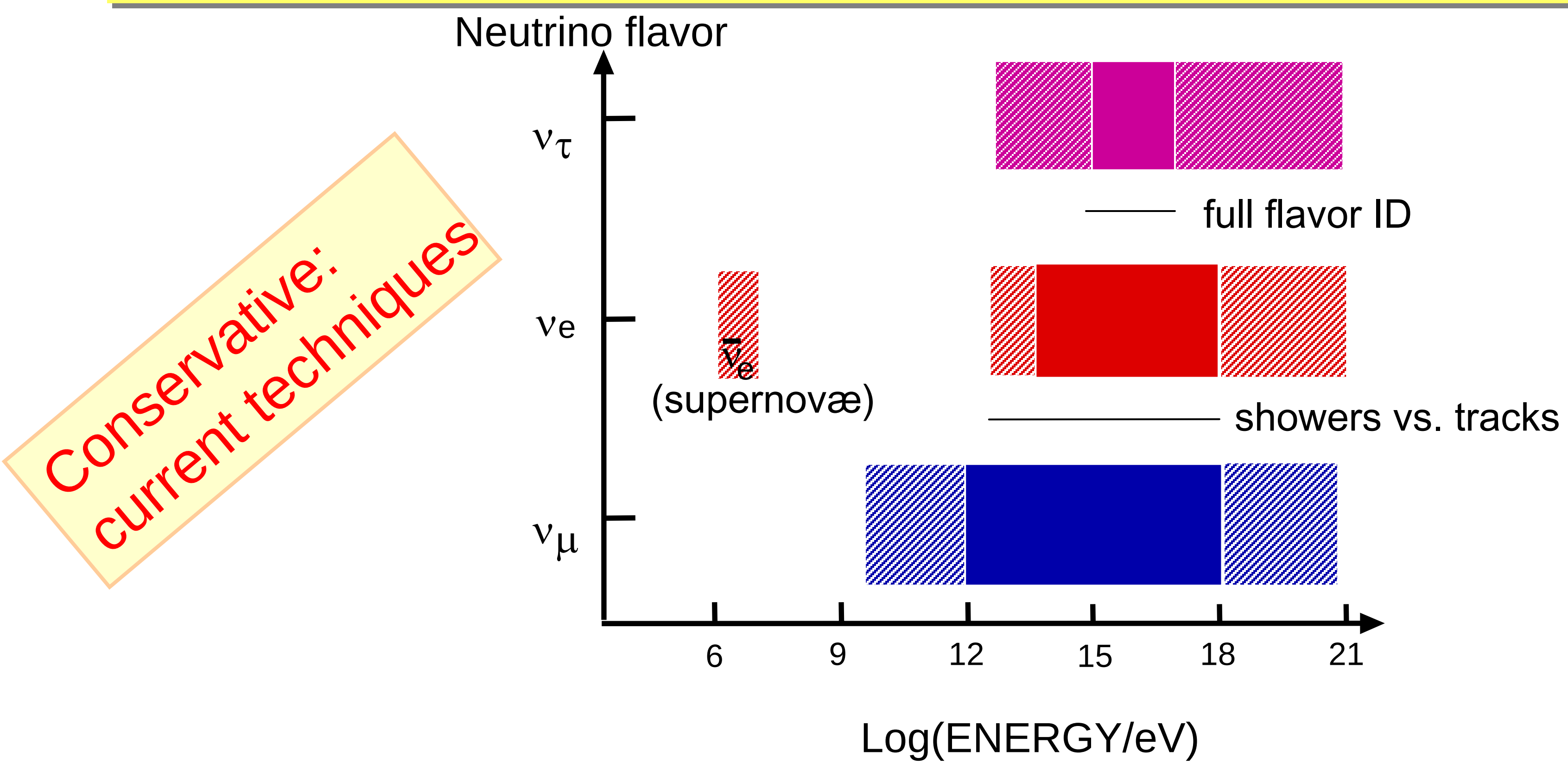


$\nu_e \rightarrow e$ E = 375 TeV





Neutrino Sensitivity



- Sensitive to all flavors of neutrinos
  - Solid areas show best reconstruction: flavor, direction, energy
  - Hatched areas show triggers, more difficult reconstruction.

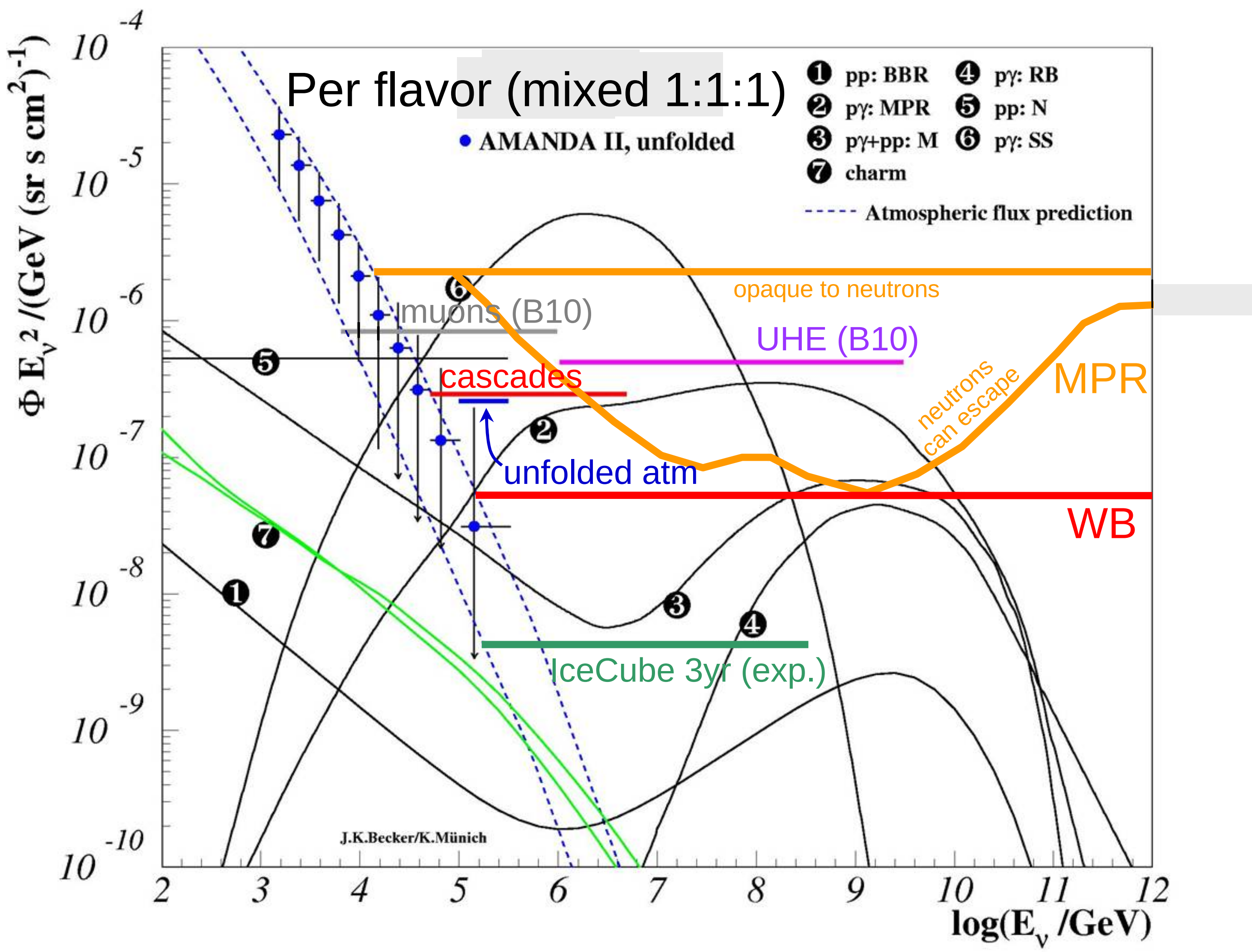
IceCube Signal Sensitivities

Atmospheric Neutrino Oscillations(?)

- 100,000 atmospheric neutrinos/yr with full IceCube
- Can we profit from the facts that
  - Although have unfavorable δm^2 at these energies, limiting $\nu_\mu \rightarrow \nu_\tau$ oscillations,
  - At high energies, atmospheric ν_e suppressed relative to ν_μ
    - Note: electron and tau neutrinos look the same at sufficiently low energies
- Conceivably, the small number of extra ν_τ due to $\nu_\mu \rightarrow \nu_\tau$ oscillations may be comparable to those from atmospheric ν_e...and measurable!

See Stanev astro-ph/9907018

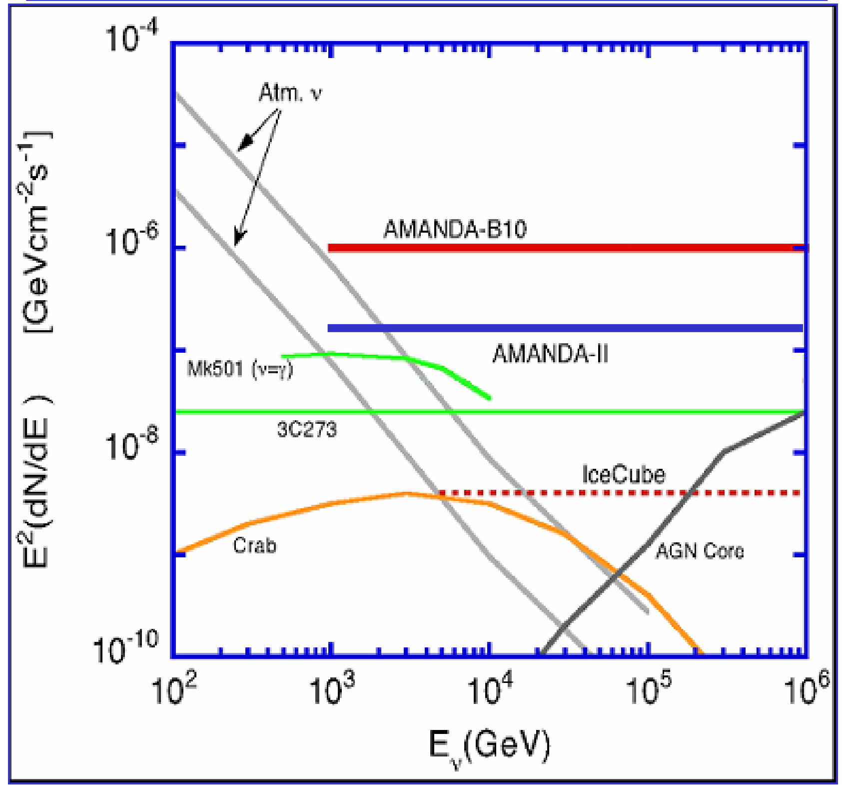
Diffuse Neutrino Fluxes



Steady & Transient Pt. Sources

Sensitivity point sources (1 y):

$5.5 \cdot 10^{-9}\ E^{-2}\ (cm^{-2}s^{-1}GeV)$



Steady Sources:
Search cone 1° opening half-angle
+ "soft" energy cut (< 1 TeV)

Transient Sources (e.g., GRB):
Essentially background-free search energy, spatial and temporal correlation with independent observation

For ~1000 GRB's observed/year expect (looking in Northern sky only)

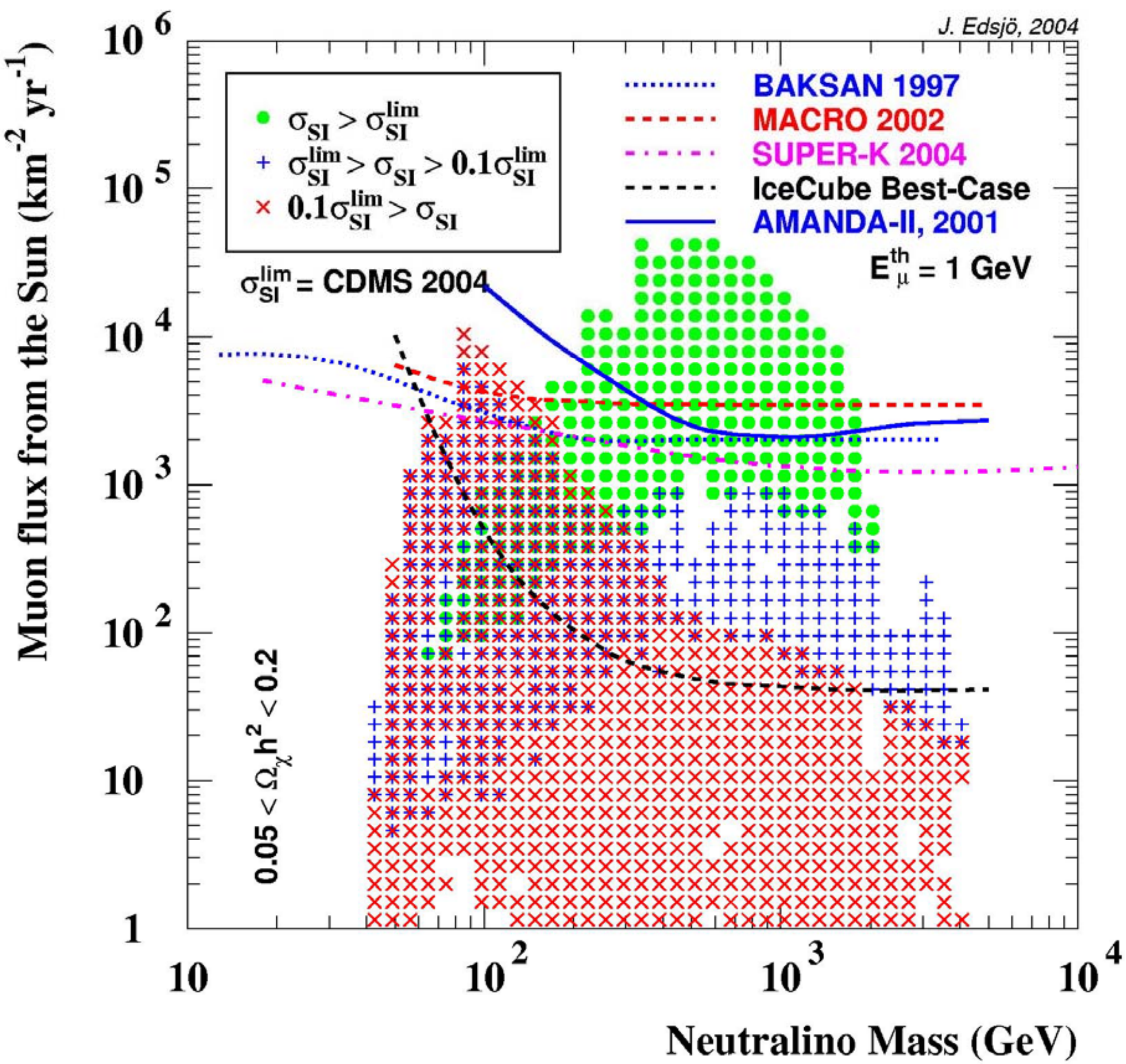
- signal: 12 ν
- background (atm ν): 0.1

Sensitivity GRB (1 y):
$\sim 0.2\ \phi_{WB}$

Excellent prospects for detection of GRB ν's within 1-2 km^3-years

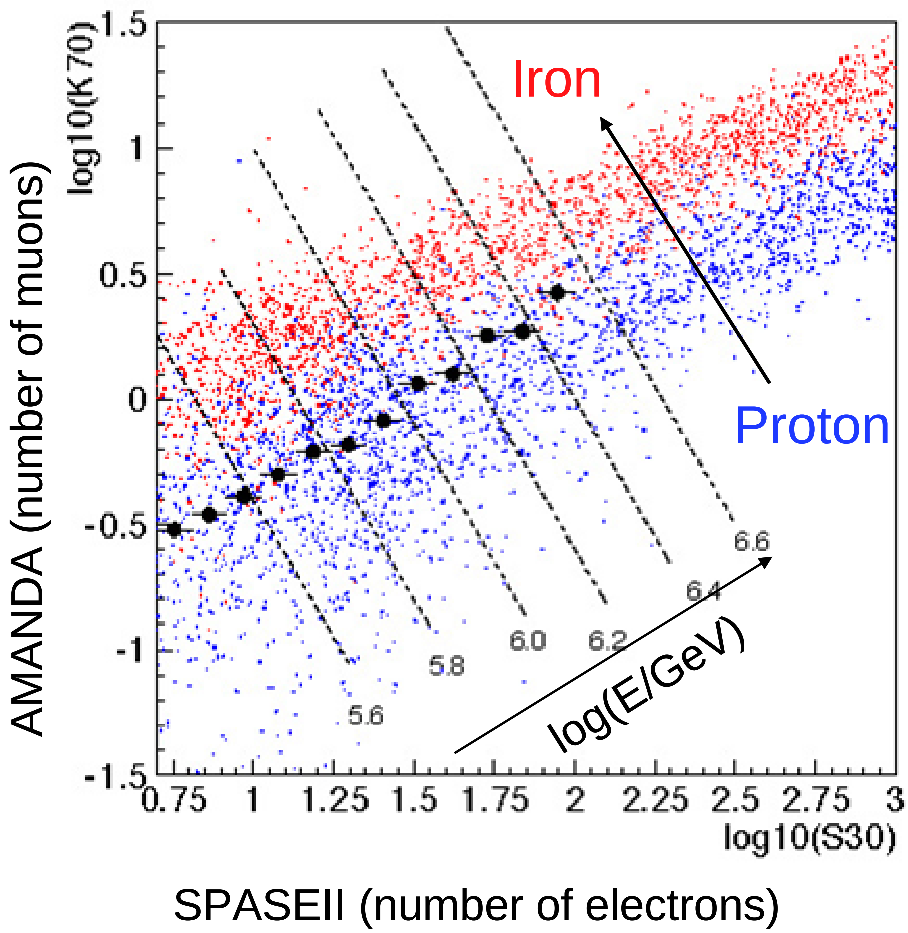
WIMPs from the Sun

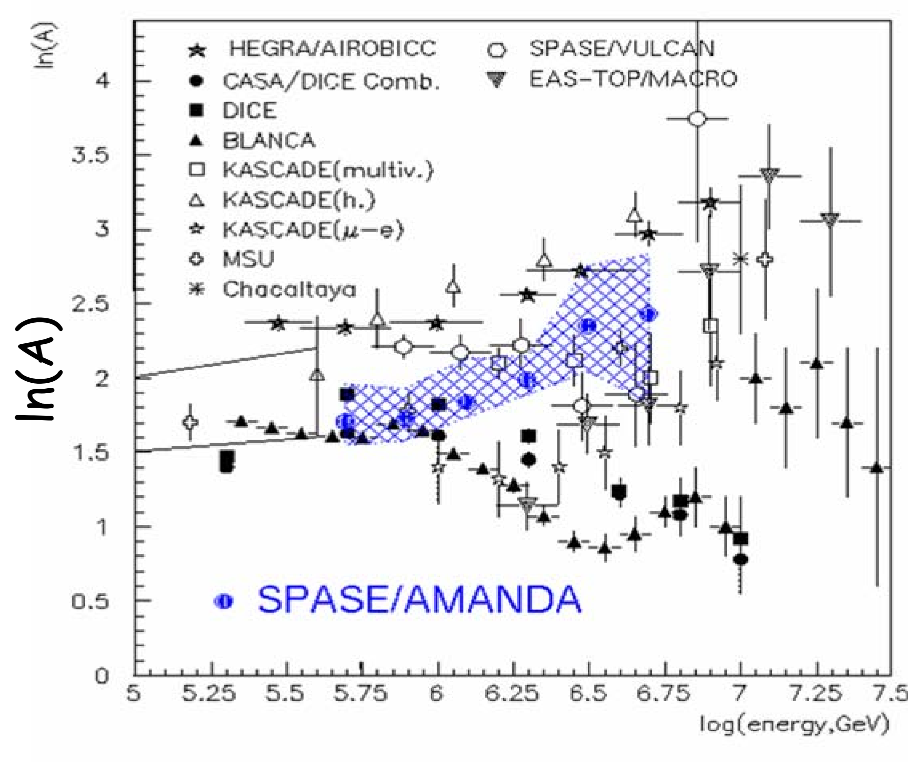
- ● disfavored by direct searches
- + near direct search sensitivity
- x inaccessible to direct searches



- Complementary to direct searches
- Best for high WIMP masses
- Depends on low energy muon response

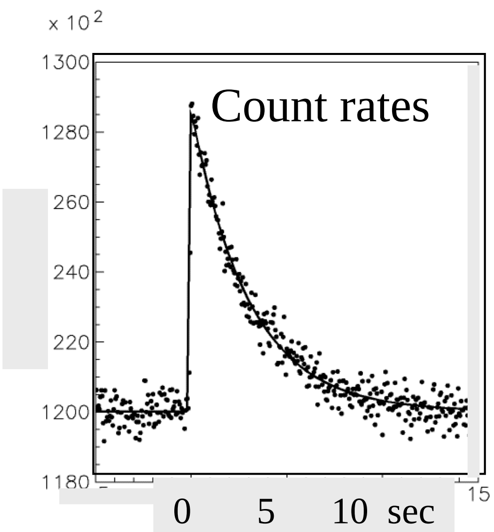
Cosmic Ray Composition

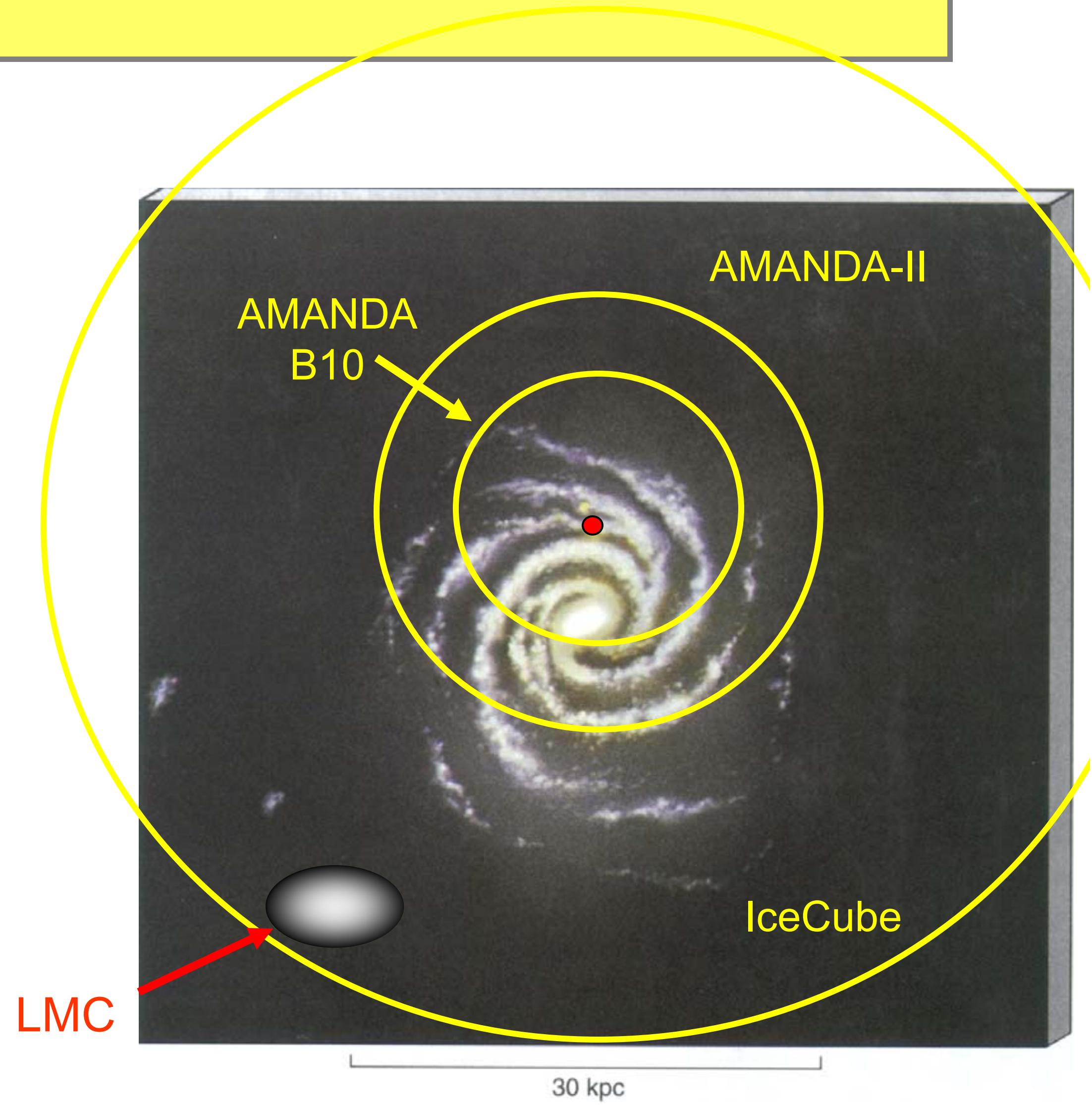




Supernova Detection

Detect MeV supernova neutrinos through overall increase in tube noise rates





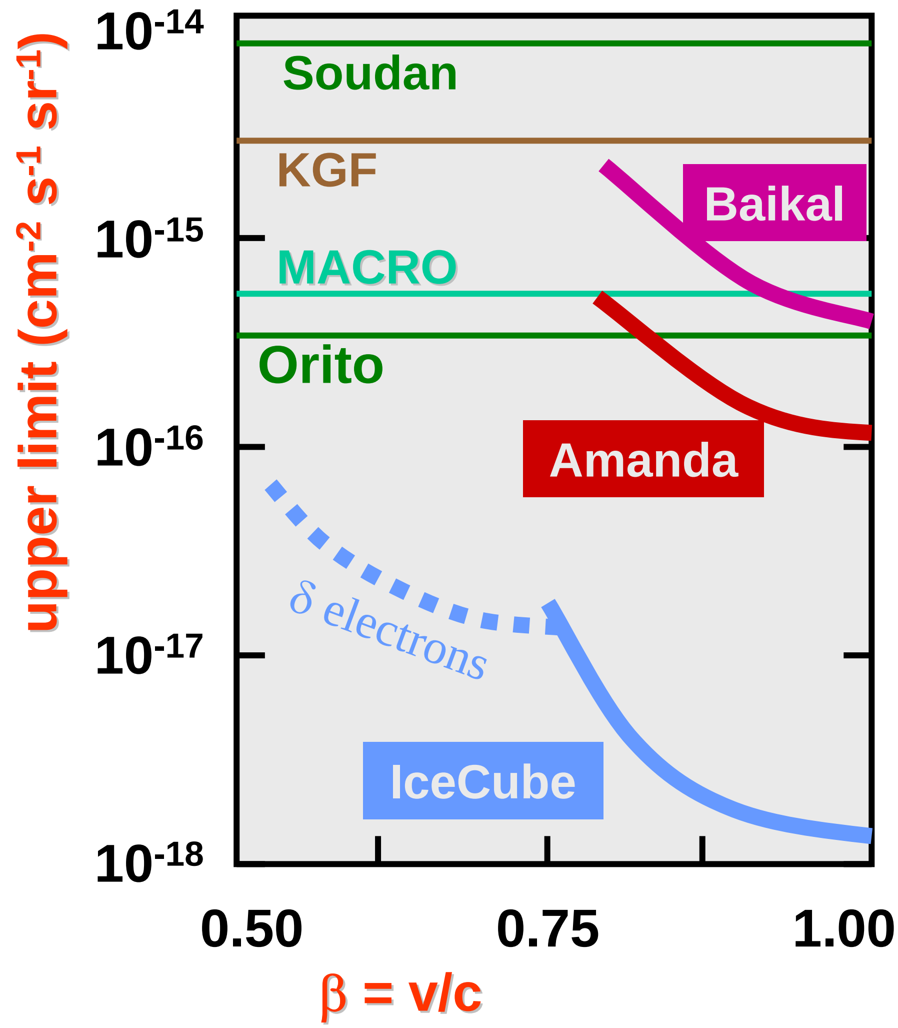
Magnetic Monopoles

Relativistic monopoles:
- Cherenkov emission enhanced by $(g/e)^2 \approx 8300$ compared to muons

May be able to look for slow monopoles through nucleon decay

Can also look for nuclearites, Q-balls,…

…and for stuff dimmer than muons, like staus

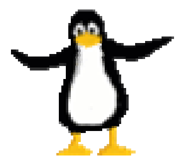


A Note on Nearby GRBs

- Gamma-rays create nitrous oxide (laughing gas) in atmosphere
  - We all die, but we all die laughing
- What if neutrinos arrive first, by a significant time margin?
  - May have enough time to write a paper before we die!
  - Also known as "publish *and* perish"

Endnote: In case you were wondering, there are no penguins at the South Pole.
So this, for example,
does not happen there:

THE END



I lied, but only about the penguin.

Thanks to Peter and Eli for organizing this excellent workshop!