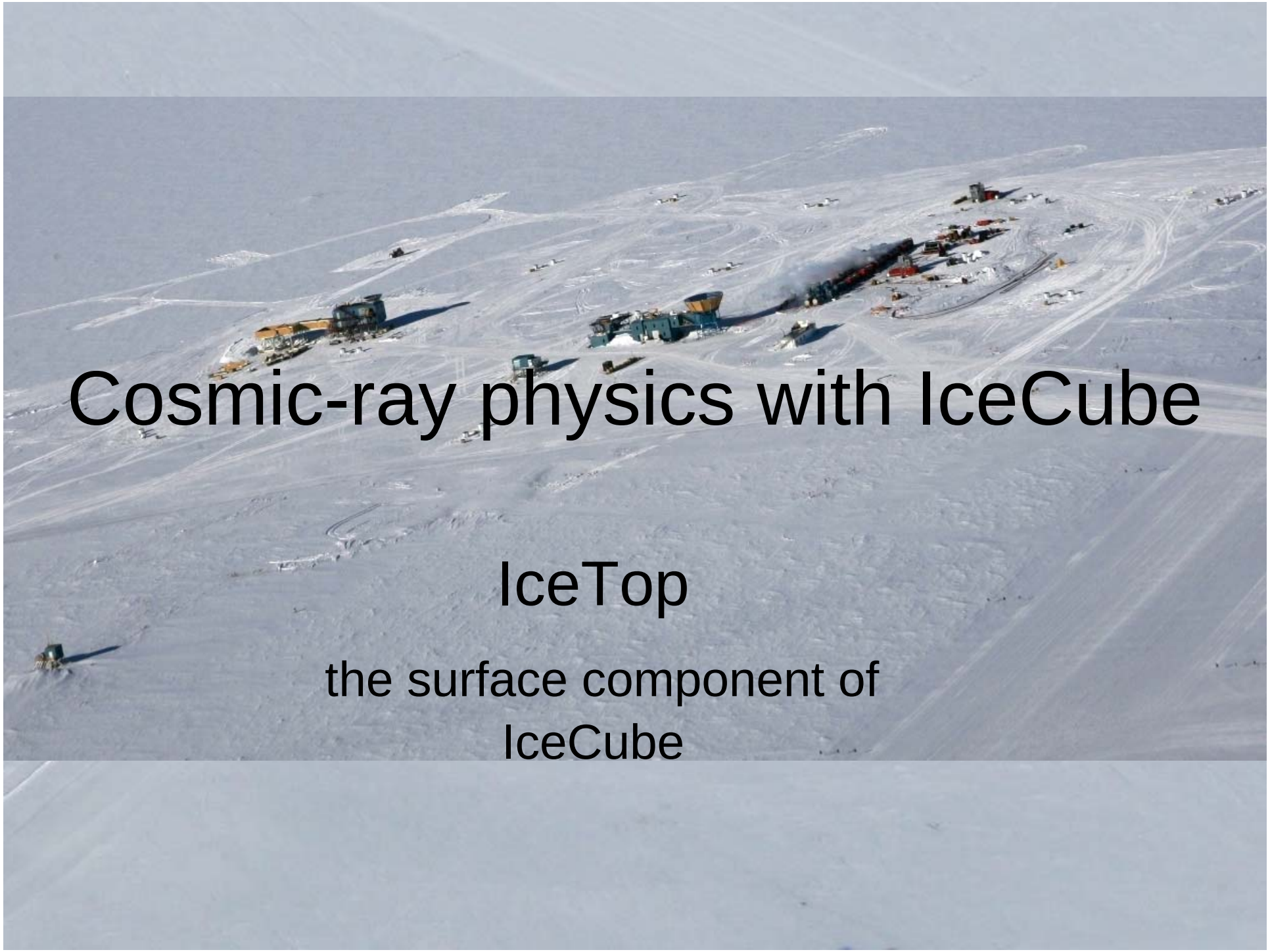


Cosmic-ray physics with IceCube

IceTop

the surface component of IceCube

Outline

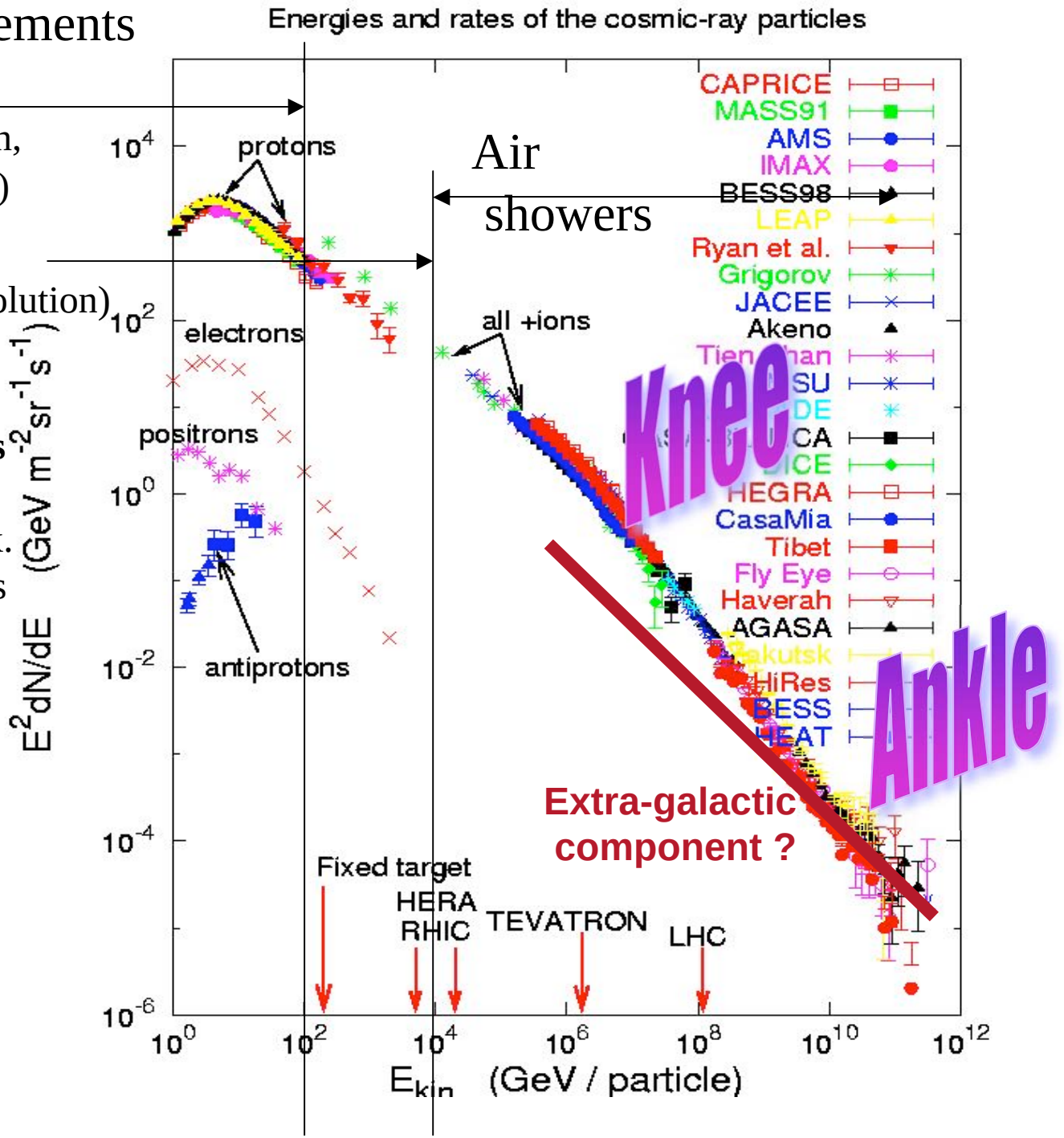
- Motivation: to understand
  - the end of the galactic cosmic-ray spectrum
  - the transition to extra-galactic cosmic rays
- Concept:
  - composition vs energy reflects sources
- Status:
  - 2005: data with 10^4 m^2 on surface & 1 string
  - 2006: running with 10^5 m^2 & 9 strings
- Plan: 10^6 m^2 & 80 strings in 5 years

Direct measurements

Spectrometers
(ΔA = 1 resolution, good E resolution)

Calorimeters
(less good resolution)

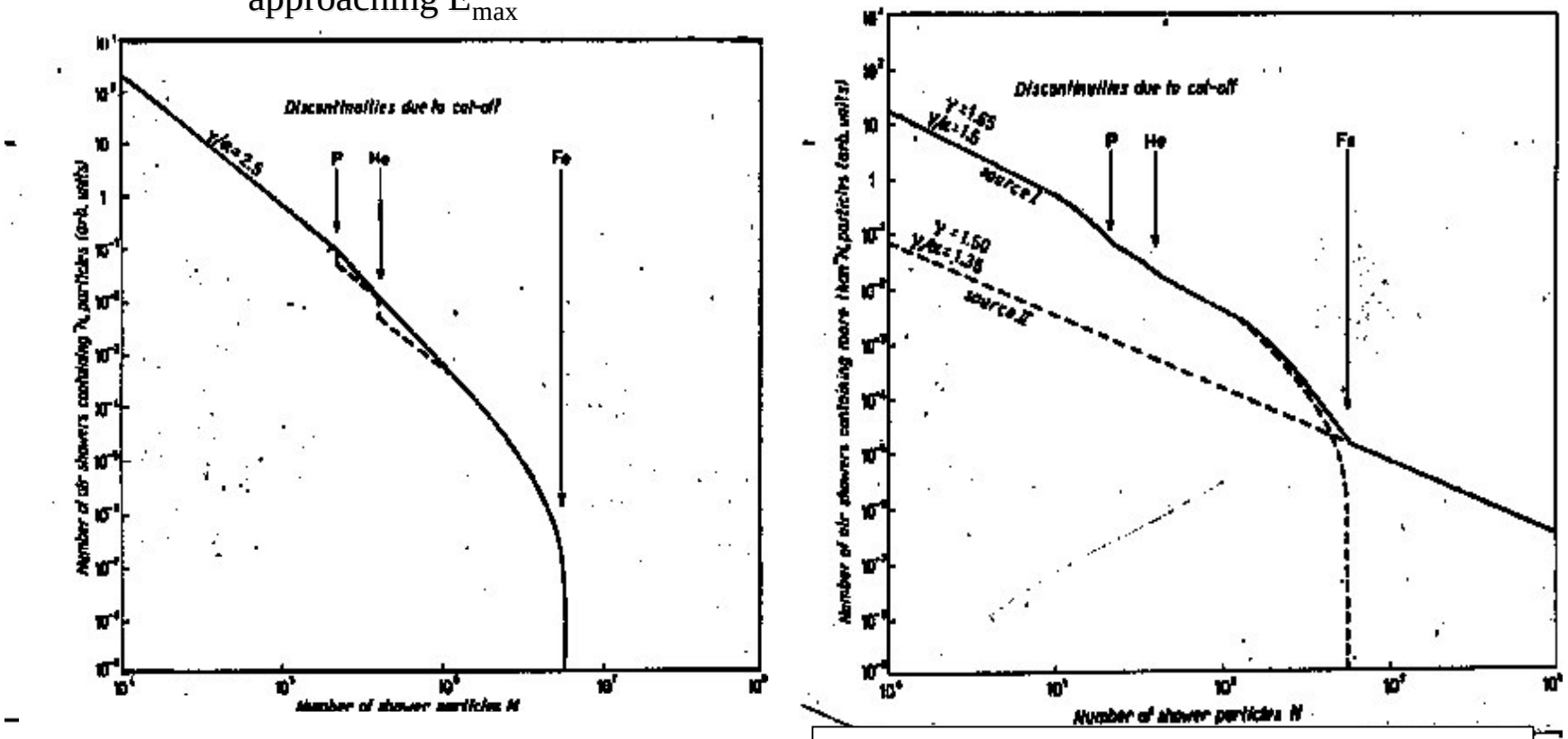
Air-shower arrays
on the ground to overcome low flux.
Don't see primaries directly.



B. Peters on the *knee* and *ankle*

Peters cycle: systematic increase of < A > approaching E_{max}

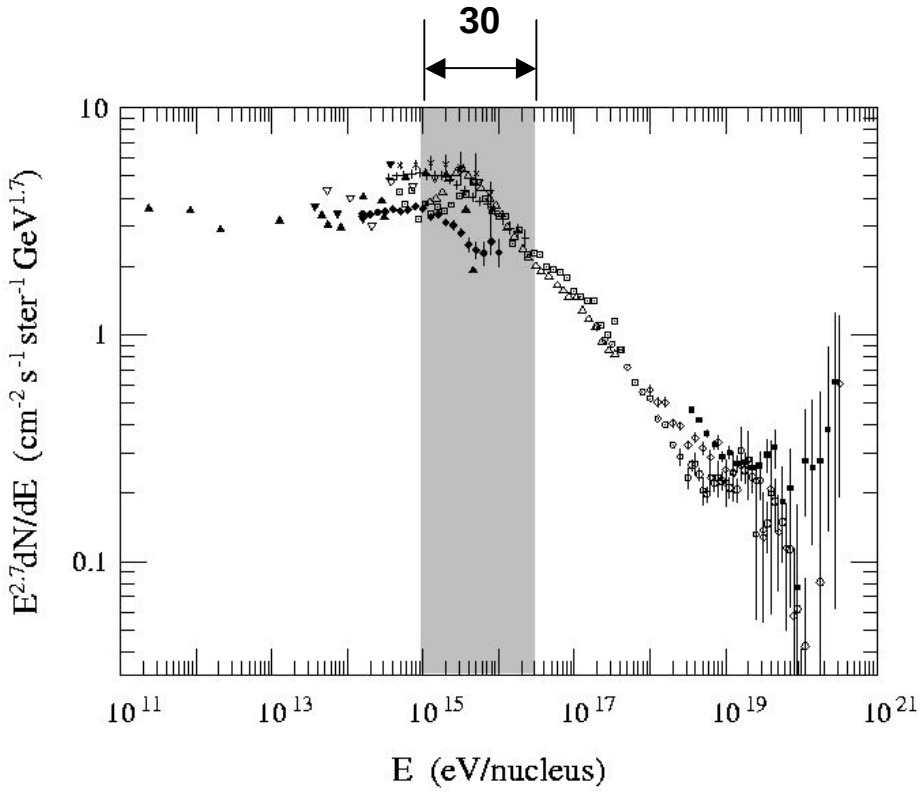
<A> should begin to decrease again for $E > 30 \times E_{knee}$



B. Peters, Nuovo Cimento 22 (1961) 800

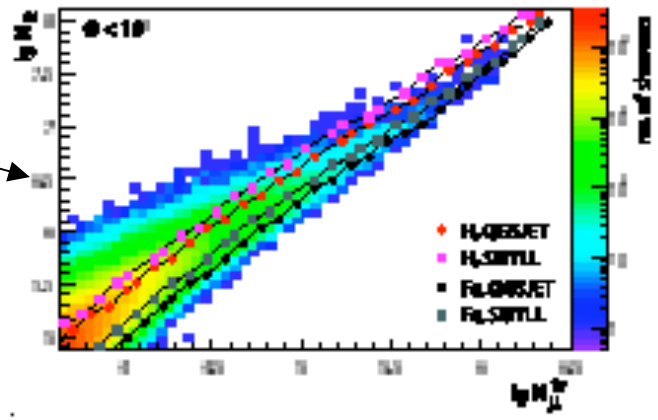
Rigidity-dependence

- Acceleration, propagation
  - depend on B: $r_{gyro} = R/B$
  - Rigidity, $R = E/Ze$
  - $E_c(Z) \sim Z R_c$
- $r_{SNR} \sim$ parsec
  - → $E_{max} \sim Z * 10^{15}$ eV
  - $1 \leq Z \leq 30$ (p to Fe)
- Slope change should occur within factor of 30 in energy
- With characteristic pattern of increasing A
- Problem: continuation of smooth spectrum to EeV



KASCADE measurement

Note model-dependence



Composition inferred from N_μ – N_e data

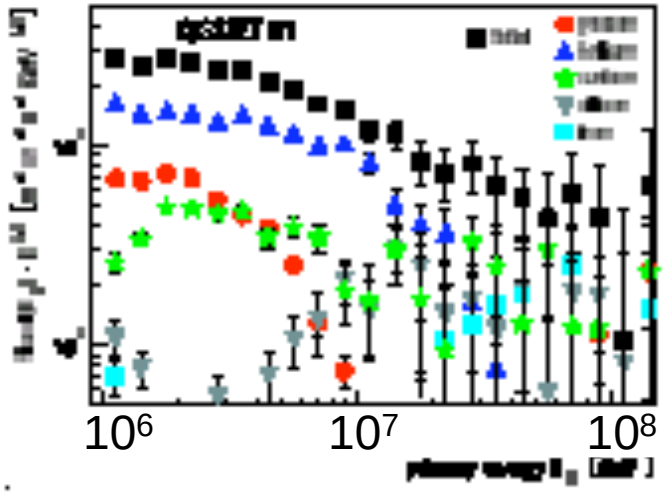


Figure 7. Result of the unfolding procedure based on QGSJET 01.

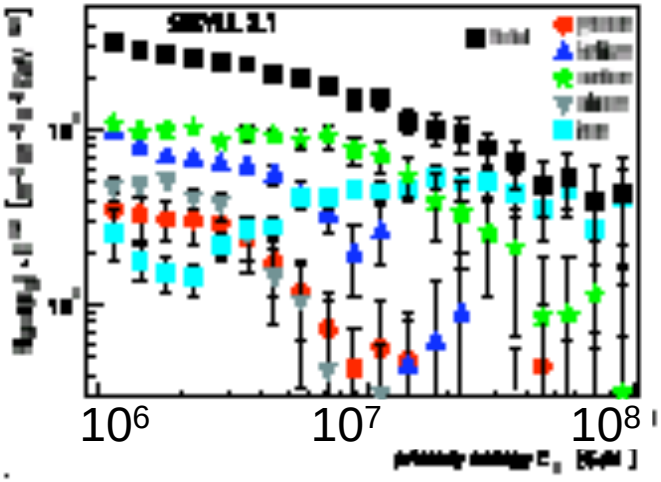
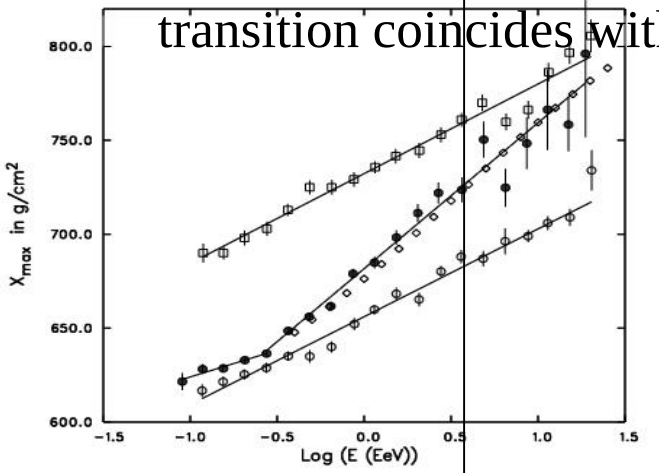


Figure 8. Result of the unfolding procedure based on SIBYLL 2.1.

Where is transition to extragalactic CR?

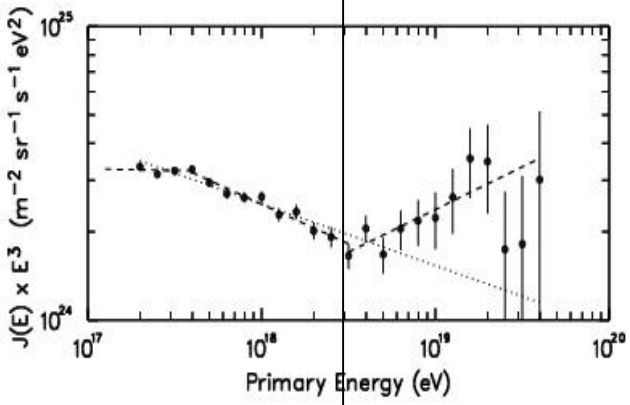
Original Fly's Eye (1993):
transition coincides with ankle



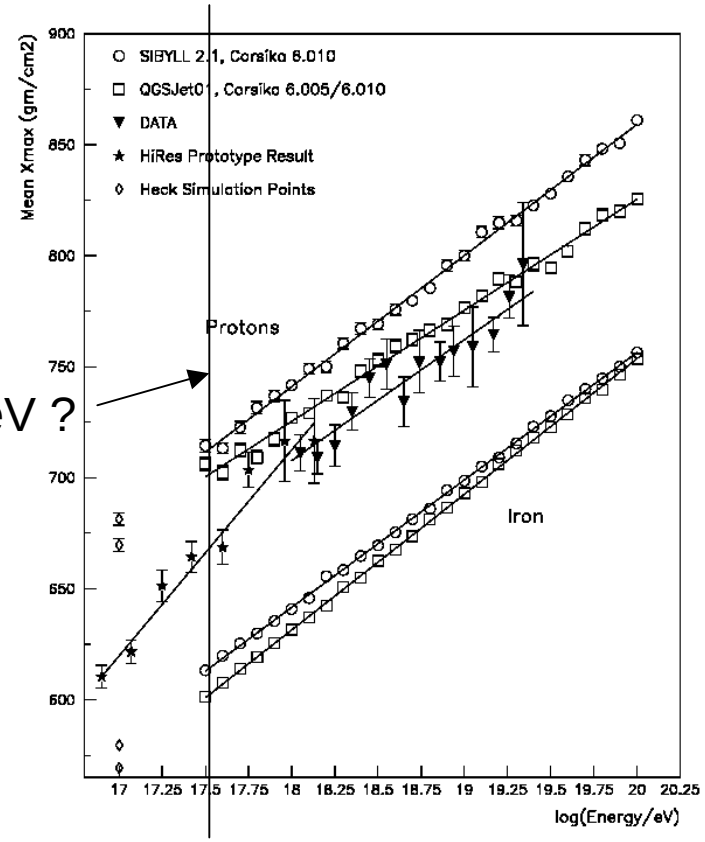
Stereo

3 EeV

or 0.3 EeV ?

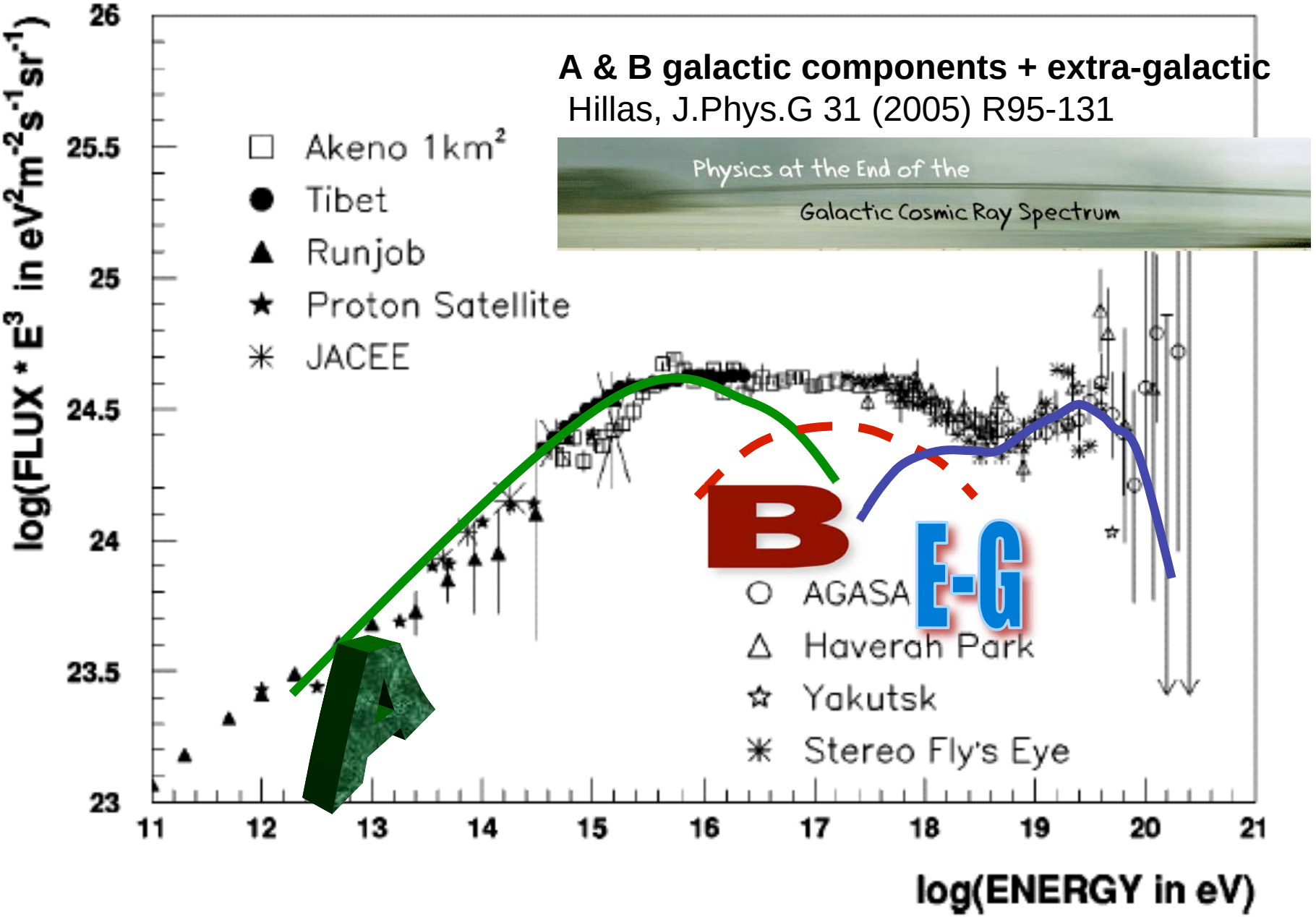


HiRes new composition result:
transition occurs before ankle



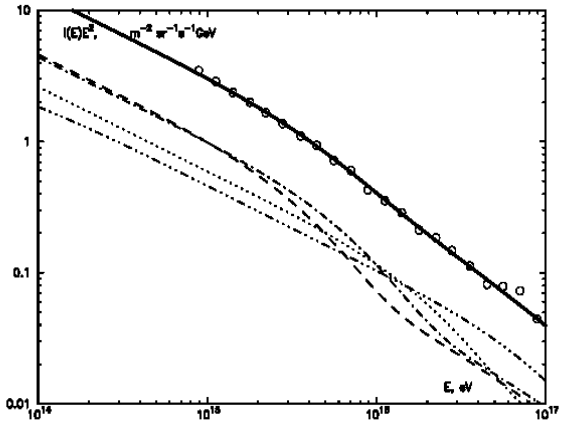
G. Archbold, P. Sokolsky, et al.,
Proc. 28th ICRC, Tsukuba, 2003

M. Nagano and A. A. Watson: Ultrahigh-energy cosmic rays

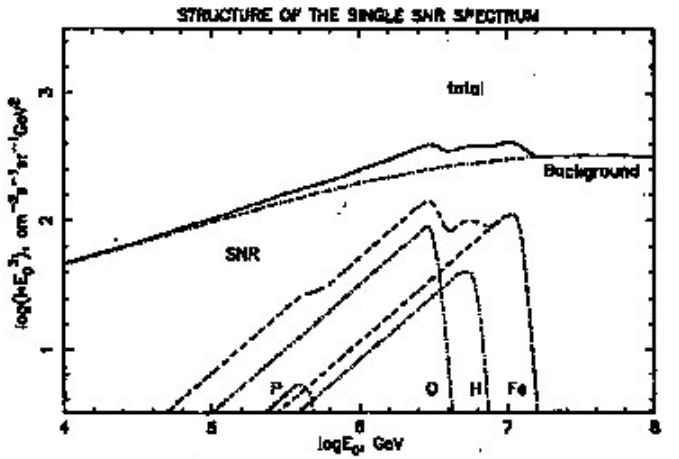


Models of galactic particles, E > knee

- Fine-tuning problem:
  - continuity of spectrum over factor 300 of energy implies relation between acceleration mechanisms
- Axford:
  - reacceleration by multiple SNR
- Jokipii & Morfill, Völk:
  - reacceleration by shocks in galactic wind (termination shock or CIRs)
- Erlykin & Wolfendale:
  - Local source at knee on top of smooth galactic spectrum
- **Need measurements of composition to $E > 10^{17}$ eV**



Völk & Zirakashvili, 28th ICRC p. 2031



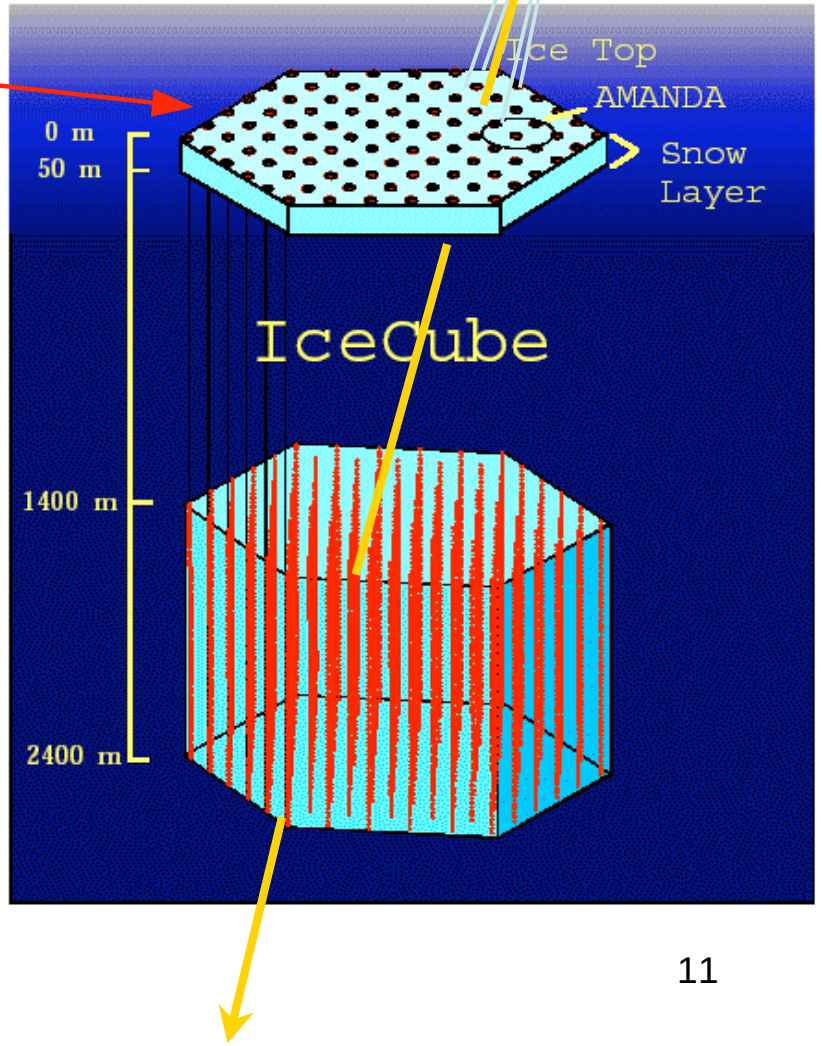
Erlykin & Wolfendale, J Phys G27 (2001) 1005

New experiments for knee to ankle

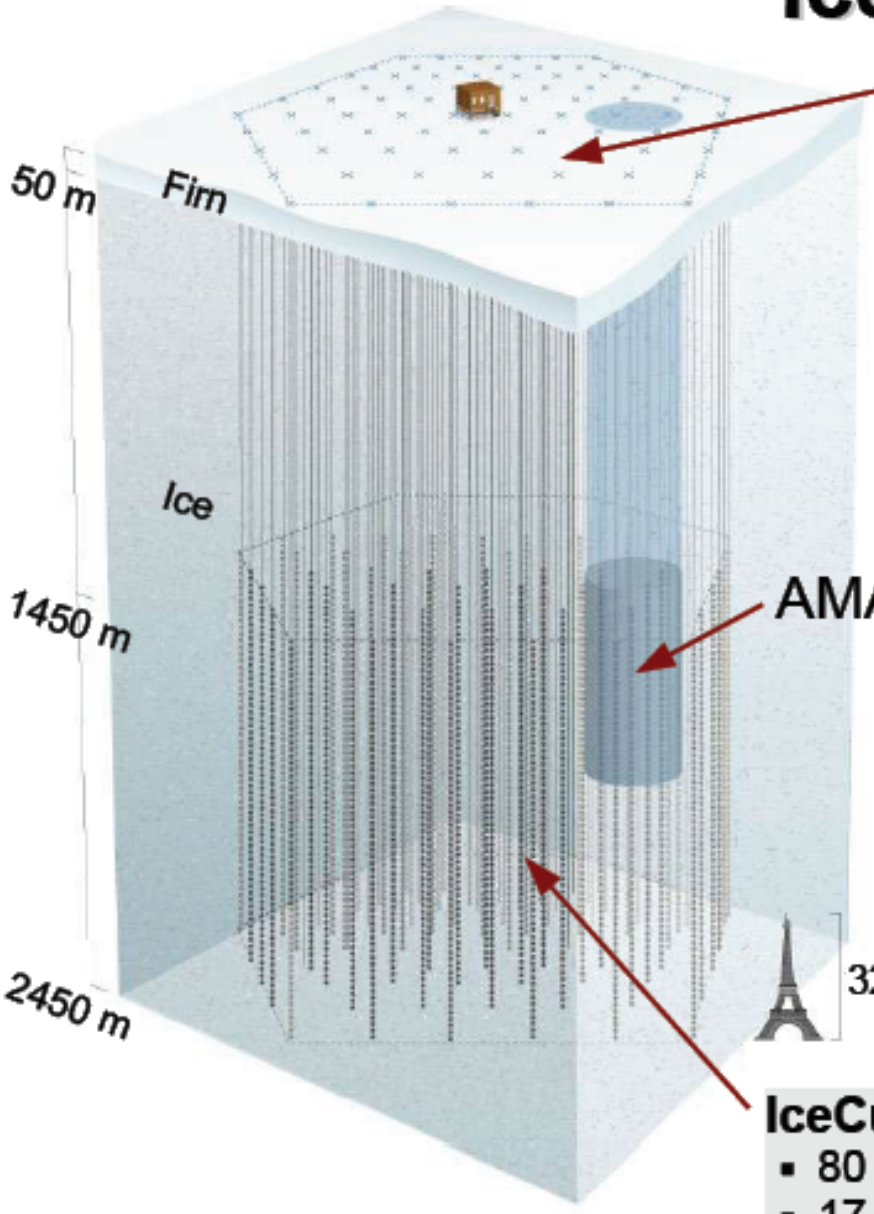
- KASCADE-Grande (e / μ)
- Tunka (air Cherenkov)
- TALE (hybrid)
- LOPES (radio)
- IceCube (e / energetic μ)
  - Primary E to ~10^{17} eV now
  - to ~10^{18} eV when complete

Air Showers with IceCube

IceTop



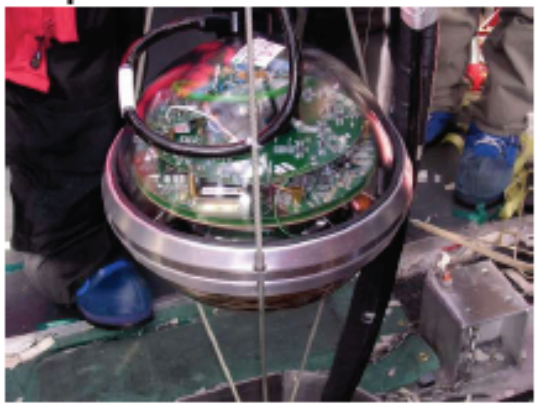
IceCube



IceTop: air shower array

- 80 Stations / 2 Tanks each
- 2 DOMs each per tank
- 125 m grid, 1 km^2 at 690 g/cm^2
- E_{thres} ~ 300 TeV for ≥ 4 stations
- Useful rate up to ~EeV

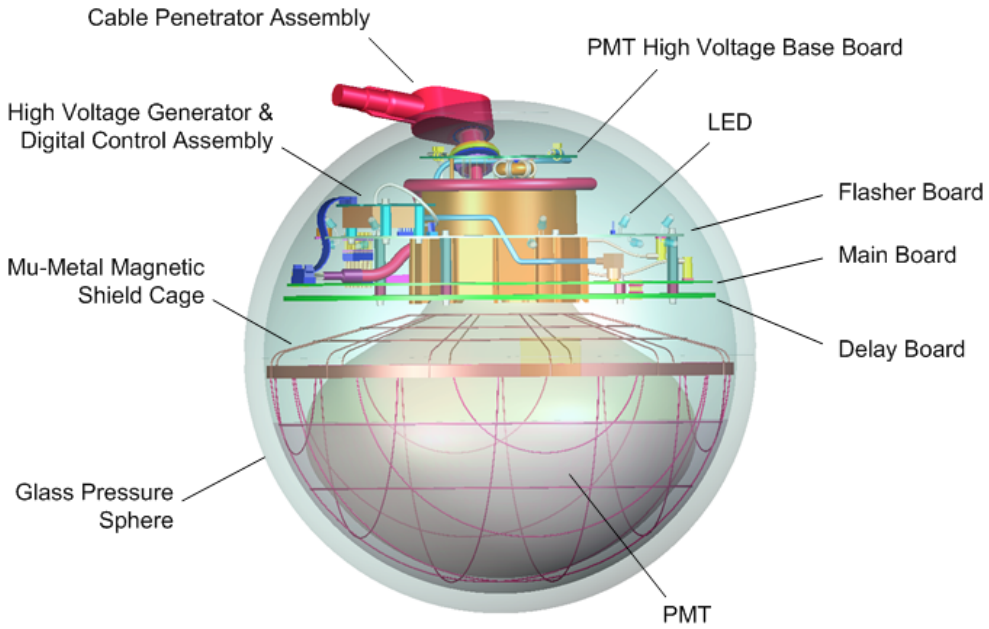
Digital **O**ptical **M**odule



IceCube: deep ice array

- 80 Strings / 60 DOMs each
- 17 m DOM spacing
- 125 m between strings
- 1 km^3 instrumented

IceCube
Digital Optical Module



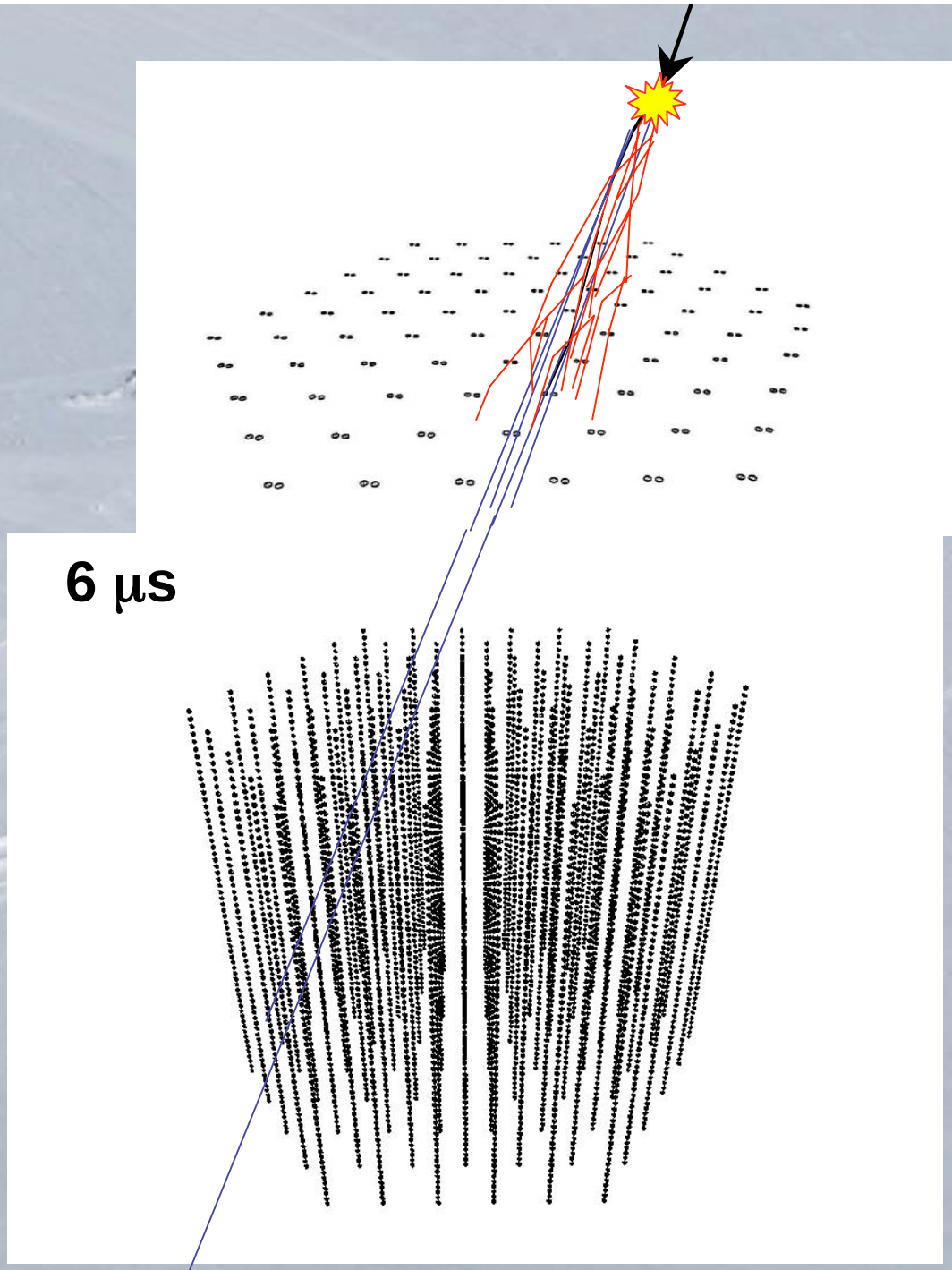
25 cm PMT

33 cm Benthosphere

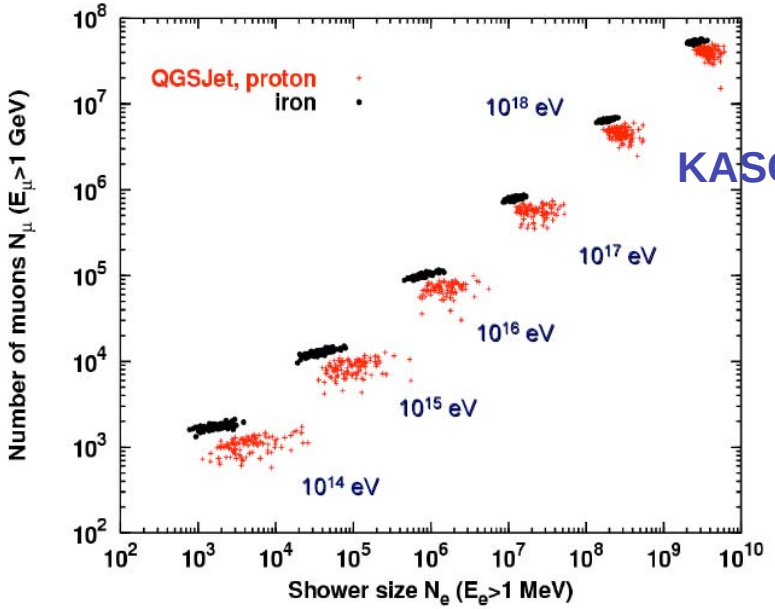
Science with IceCube/IceTop

- IceCube neutrino astronomy
  - Looks for neutrinos from interesting objects like accreting black holes
- IceTop makes IceCube a 3D air shower array
  - Origin of high-energy cosmic rays
  - Controls background for neutrinos
- Ratio surface/deep signal sensitive to nuclear composition of primary cosmic rays

- Calibration
  - pointing
  - $\Delta\theta/\theta$
  - E deposition
- Tag background
  - Reconstruction
  - rejection
- Cosmic-rays
  - $3 \times 10^{14} - 10^{18}$ eV
  - 'knee' to 'ankle'
  - galactic to extragalactic?



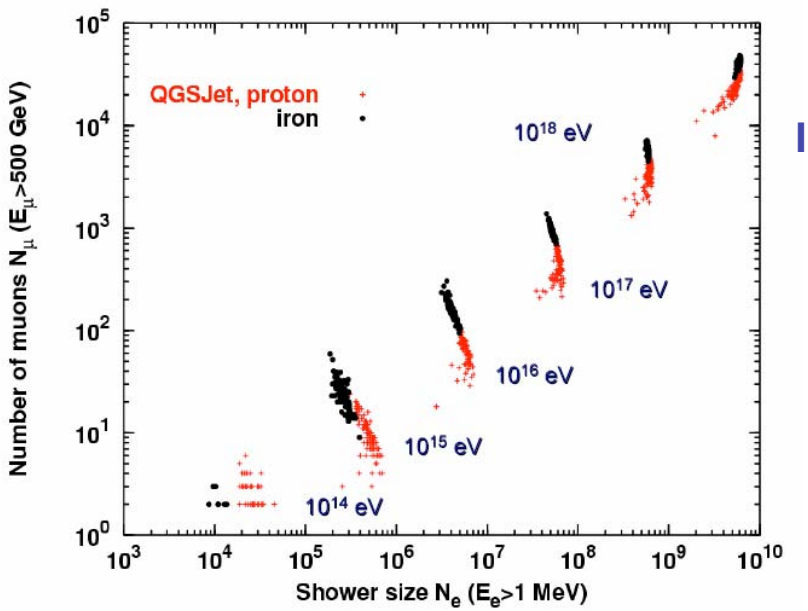
Muon / electron ratio reflects nuclear composition of primaries



KASCADE-Grande

- Sea level
- Low-energy muons

Calculations of Ralph Engel, presented at Aspen, April, 2005

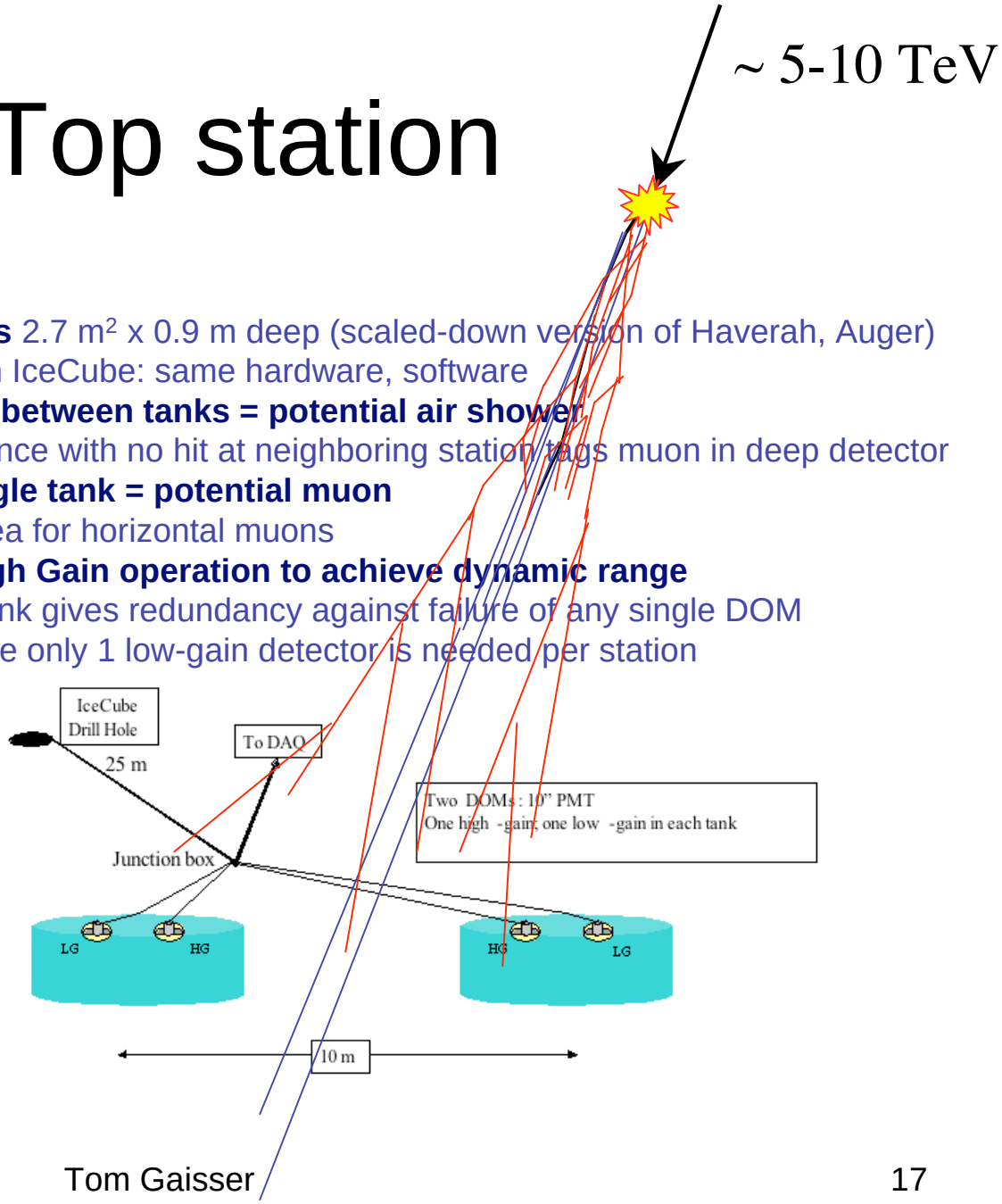


IceCube

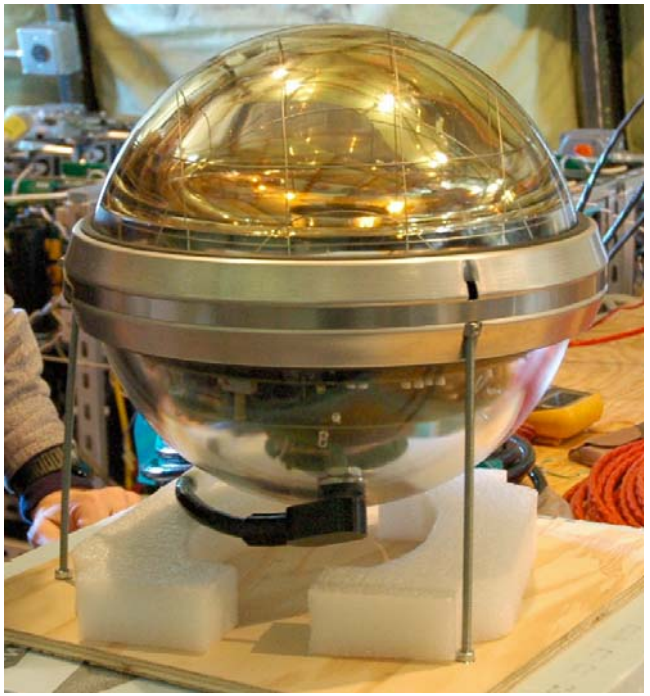
- Mountain altitude
- High-energy muons
- Single model

IceTop station

- **Two Ice Tanks** 2.7 m^2 x 0.9 m deep (scaled-down version of Haverah, Auger)
- Integrated with IceCube: same hardware, software
- **Coincidence between tanks = potential air shower**
- Local coincidence with no hit at neighboring station tags muon in deep detector
- **Signal in single tank = potential muon**
- Significant area for horizontal muons
- **Low Gain/High Gain operation to achieve dynamic range**
- Two DOMs/tank gives redundancy against failure of any single DOM
  because only 1 low-gain detector is needed per station

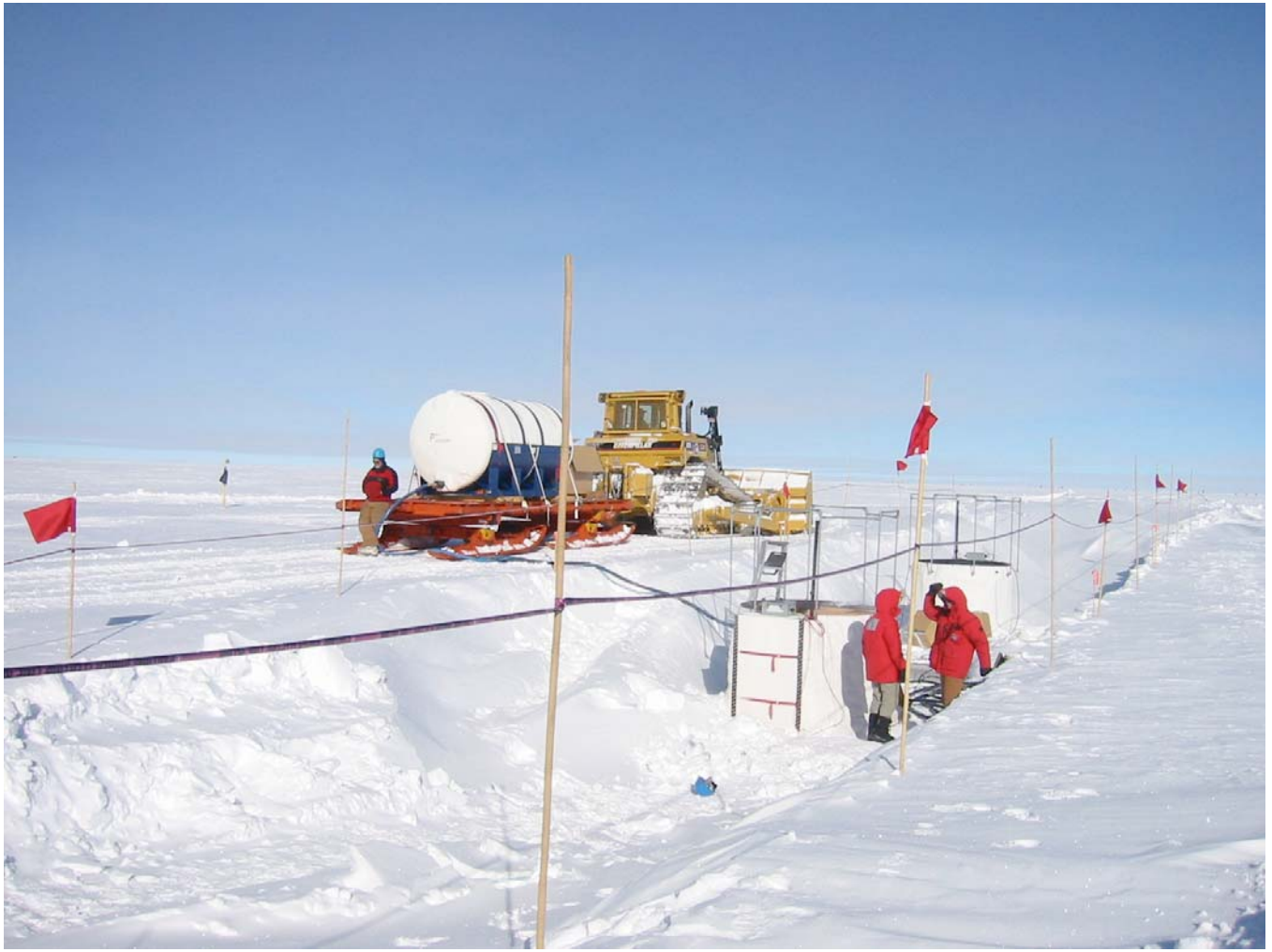


DOMs in IceTop

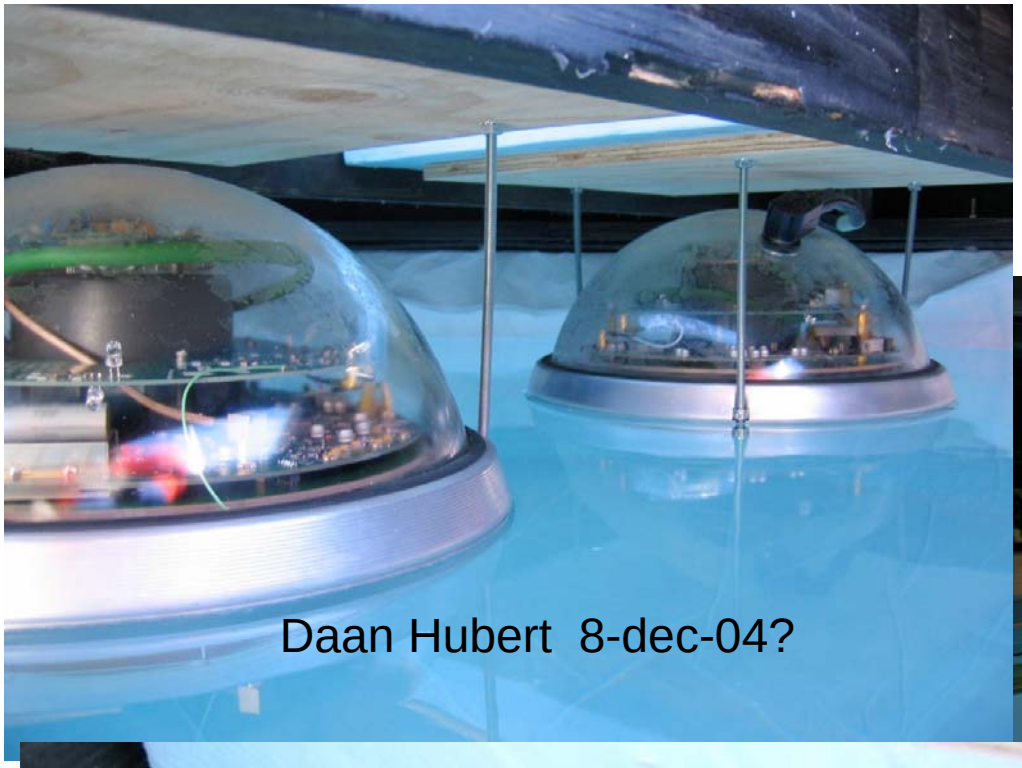


Filling tanks (Dec 2005)

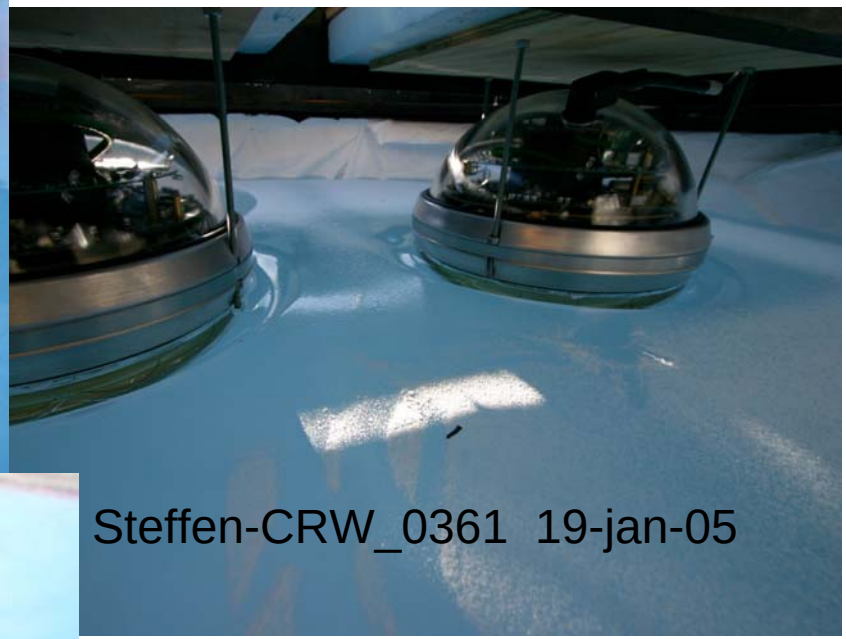
Use filtered water from drill system



Station 39



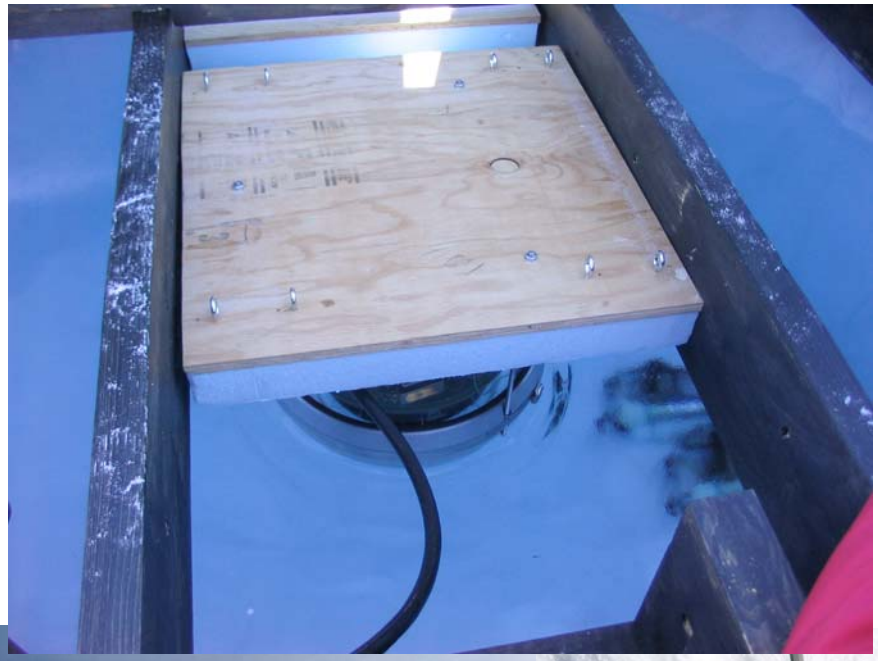
Daan Hubert 8-dec-04?

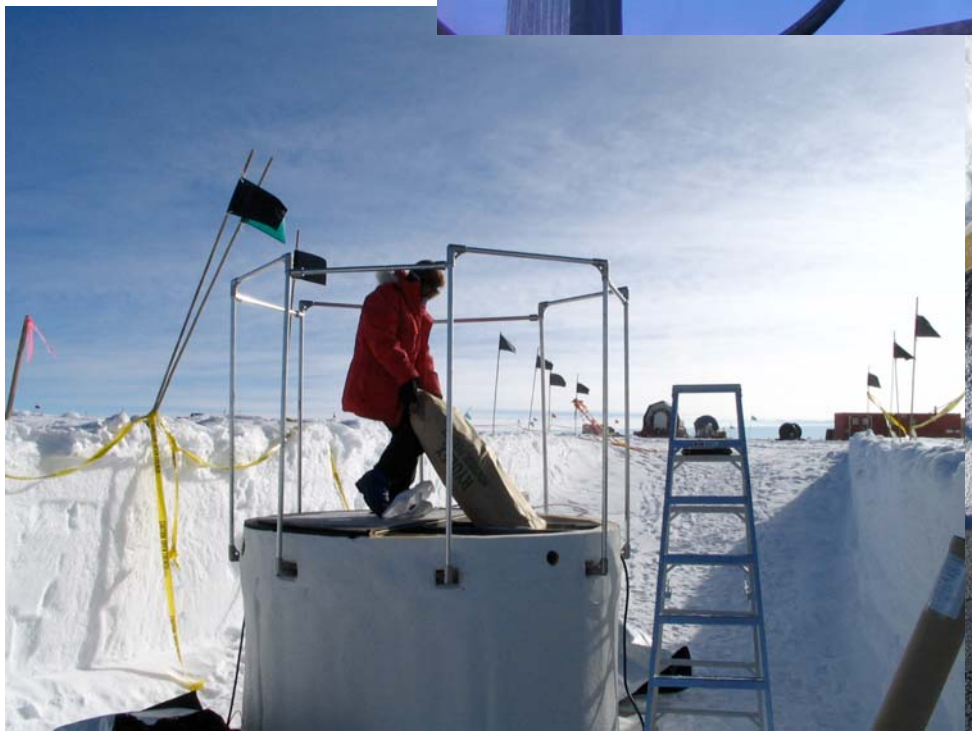


Steffen-CRW_0361 19-jan-05

JohnKelley 02-jan-05

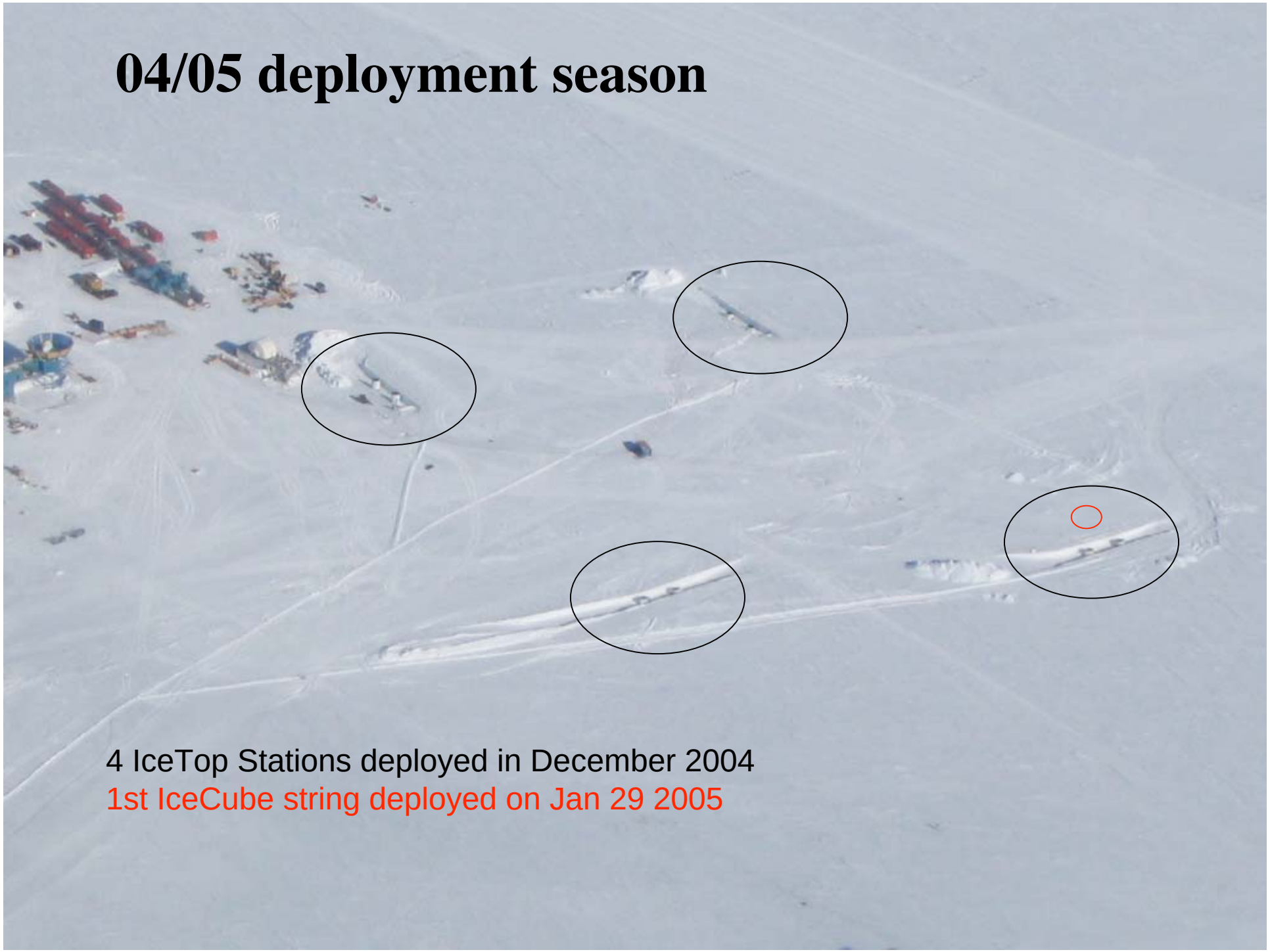
Insulate & darken tanks





IceCube string anchored between IceTop tanks

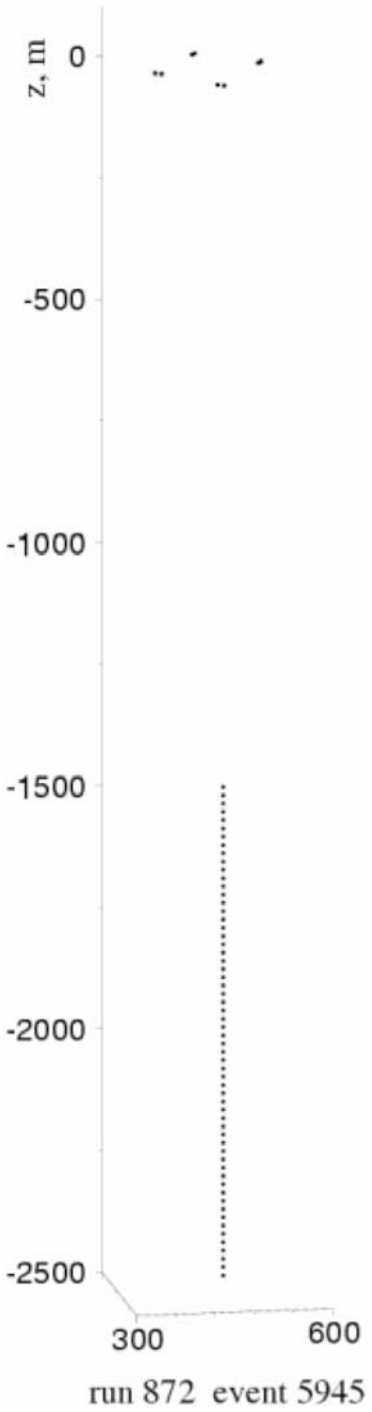
04/05 deployment season

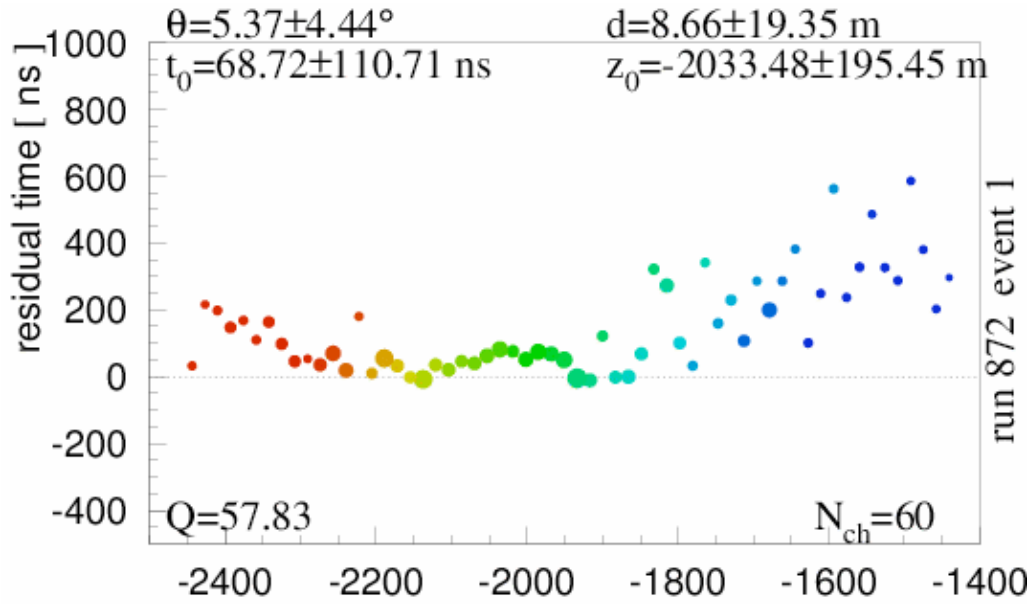


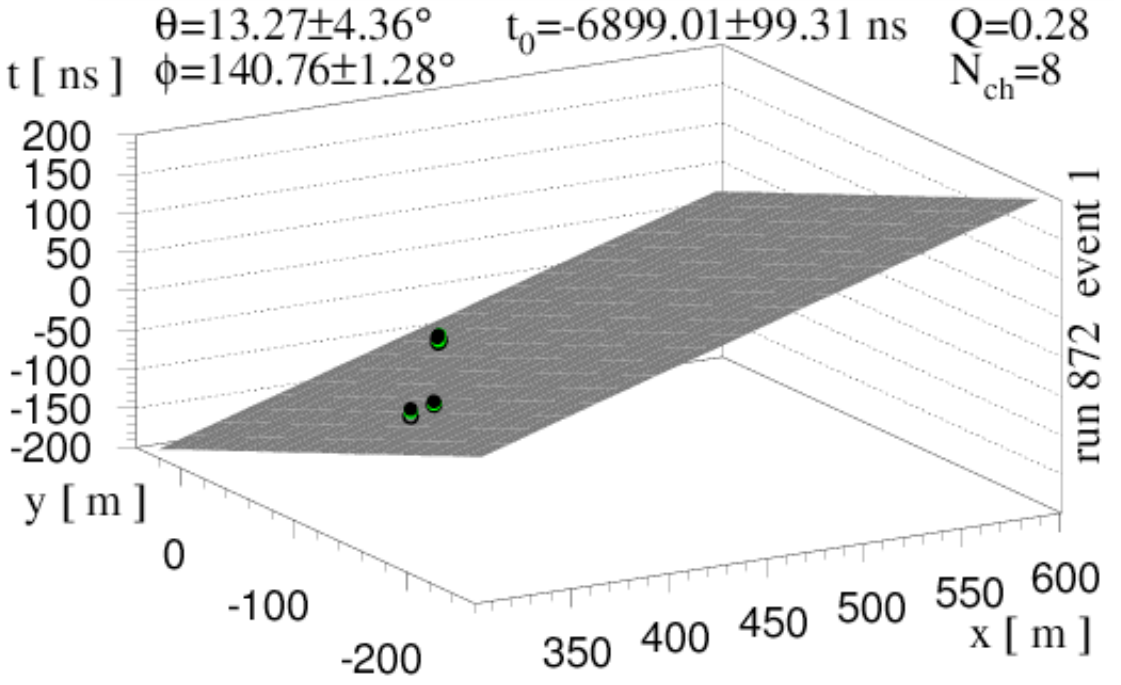
4 IceTop Stations deployed in December 2004

1st IceCube string deployed on Jan 29 2005

Run 872 Event 5945



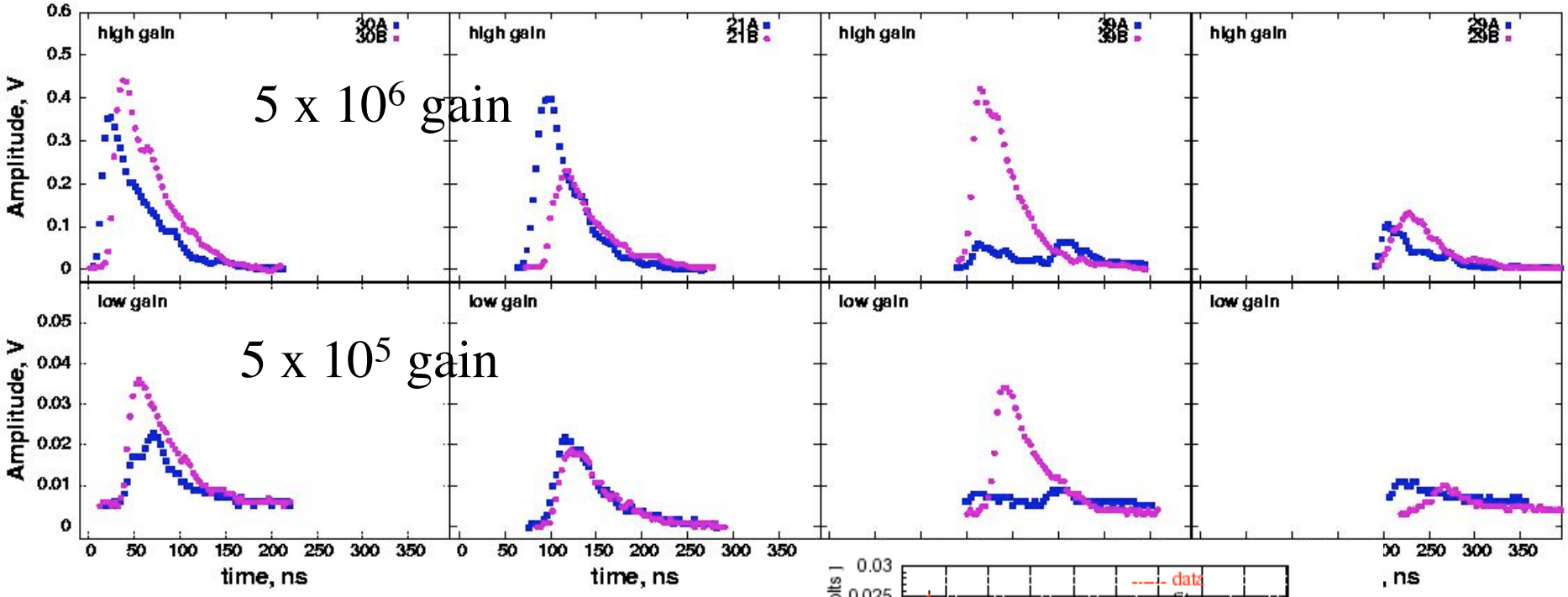




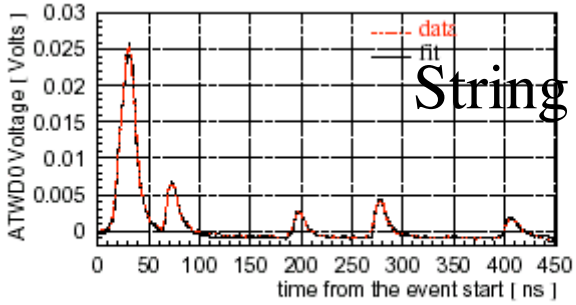
KEK,

Waveforms in a 4-fold shower

Station: 30 21 39 29



Sample every 3.4 ns

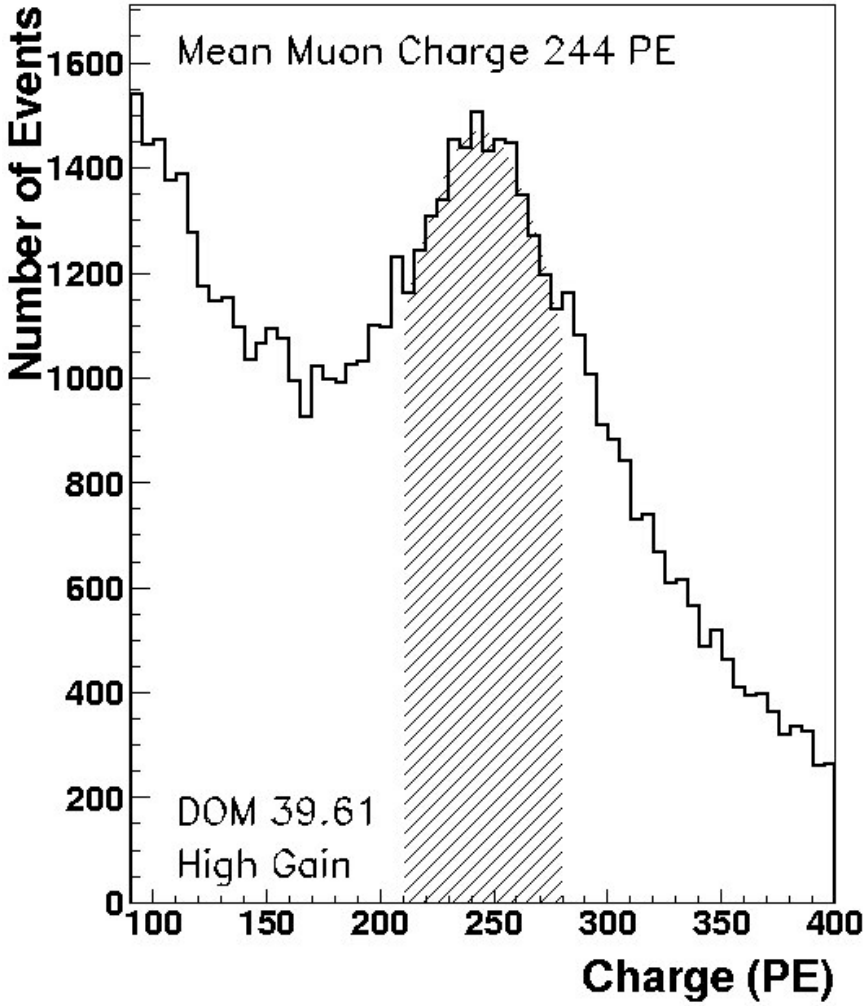


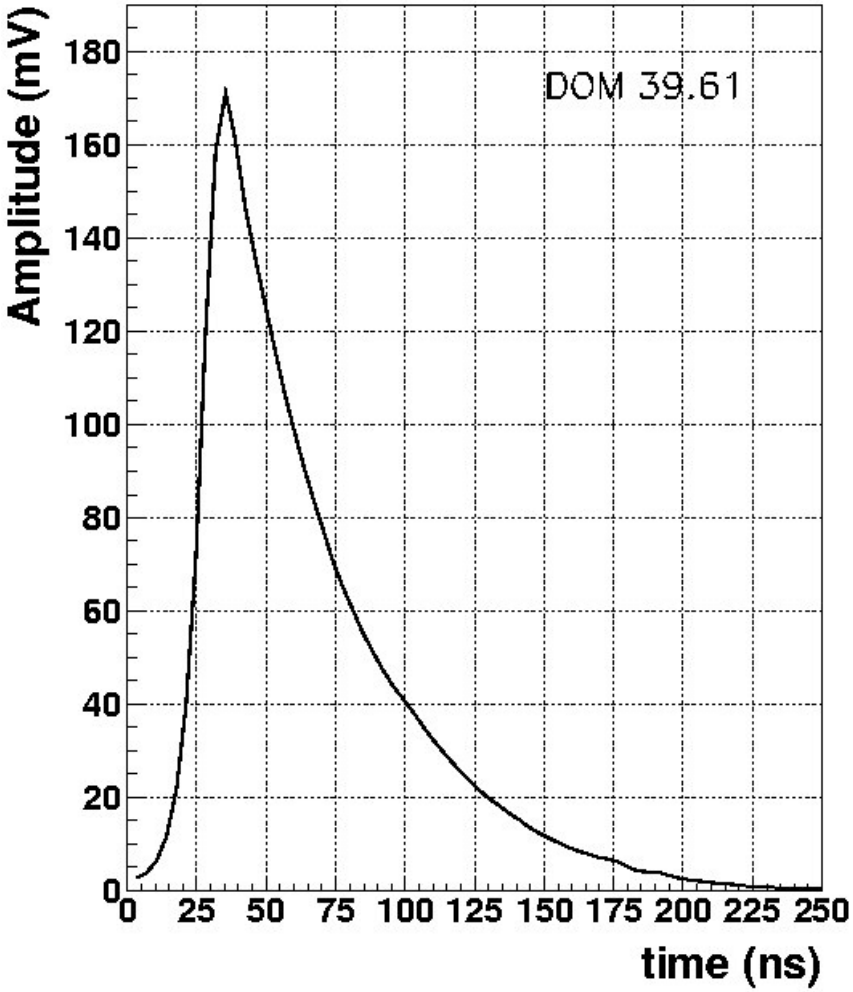
String 21

10^7 gain

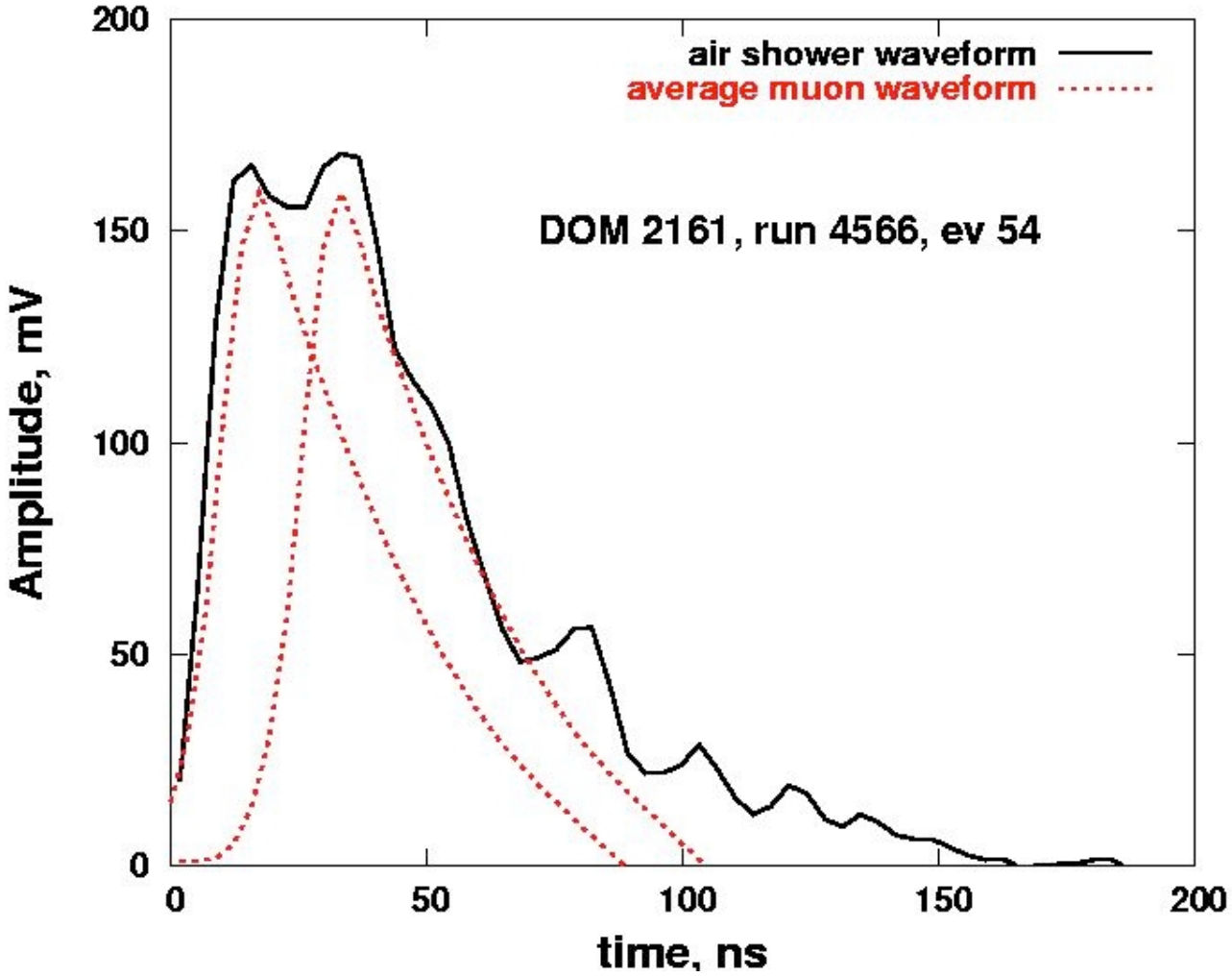
Fig. 27. Captured hit event waveform

Calibration with muons





How to interpret waveforms?



Fluctuations in tank response

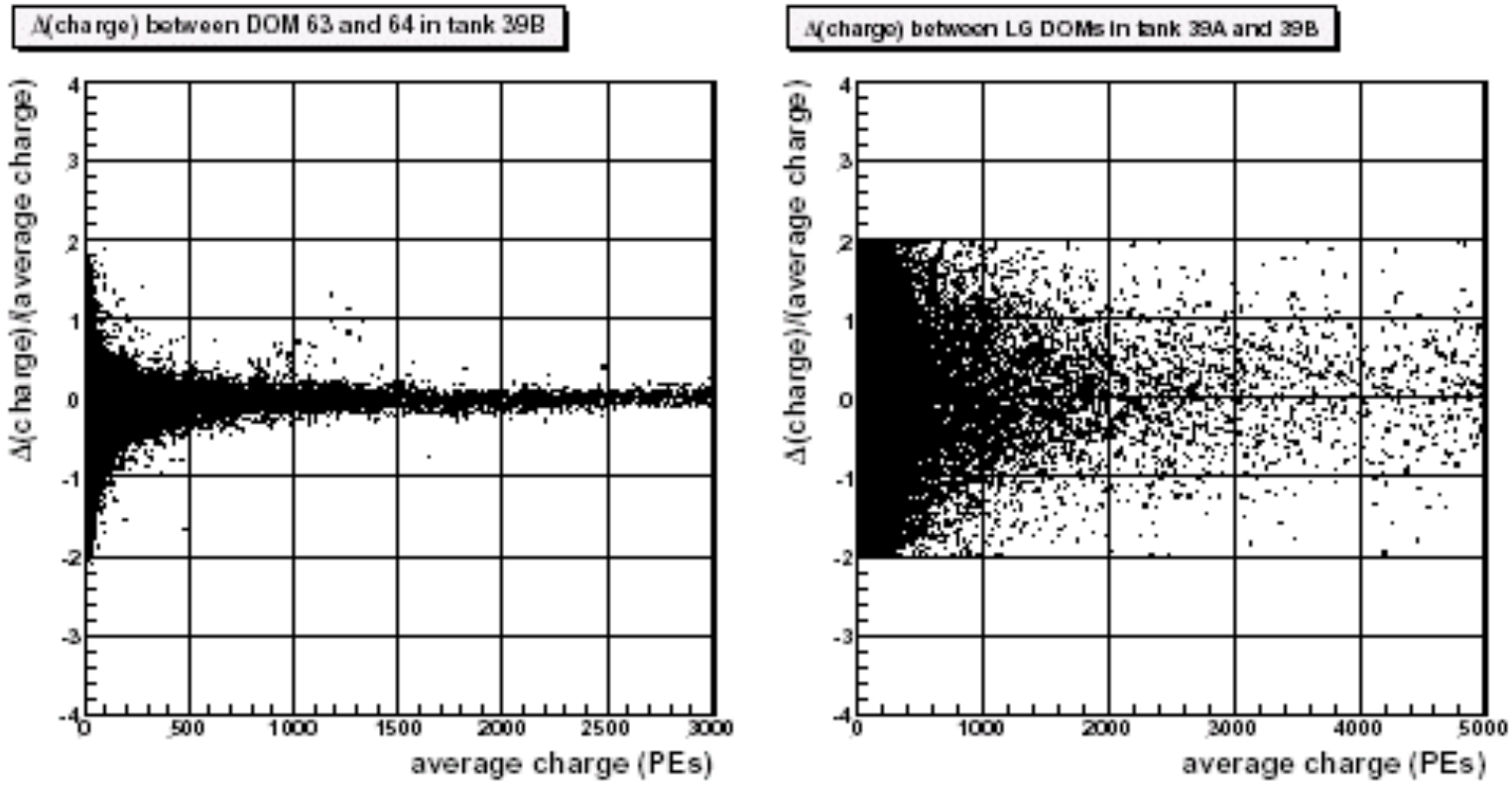
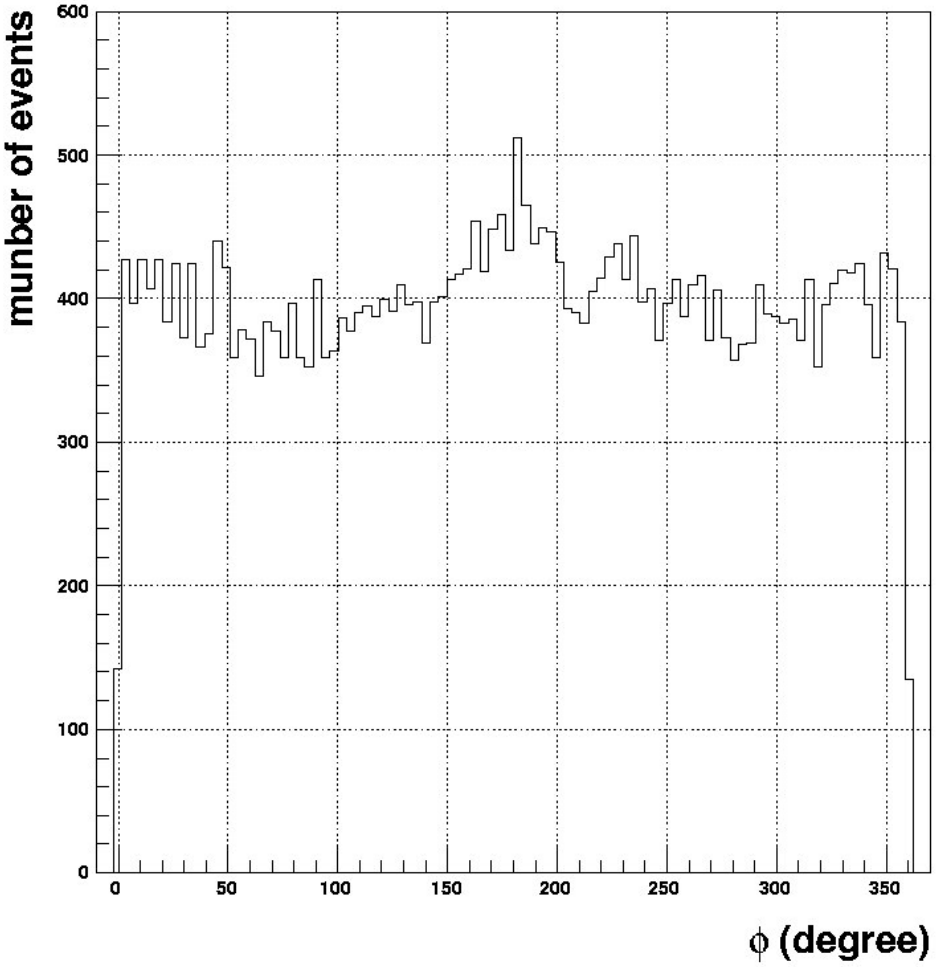


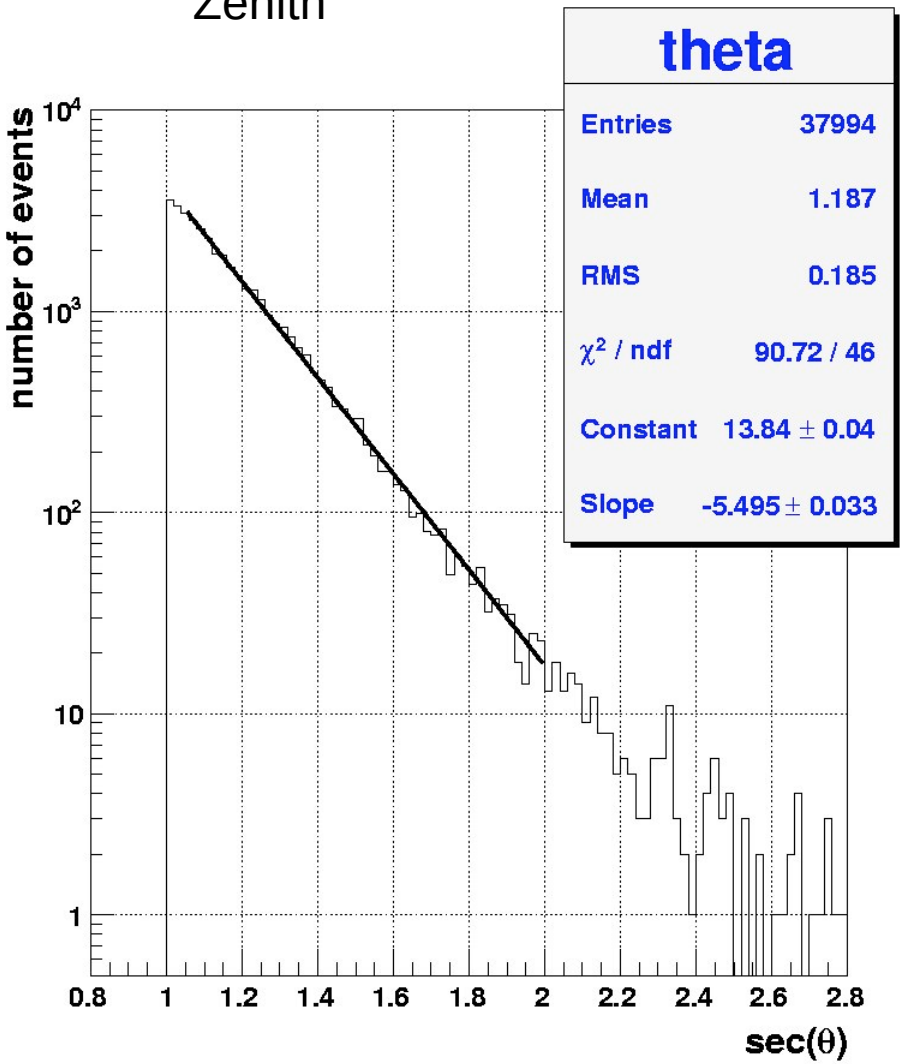
Fig. 38. Left panel: Fluctuations in tank response to signals measured by comparing the response of two DOMs in the same tank to air showers. Right panel: Shower-front fluctuations measured by comparing response of two tanks at the same station to air showers.

Shower reconstruction with IceTop4

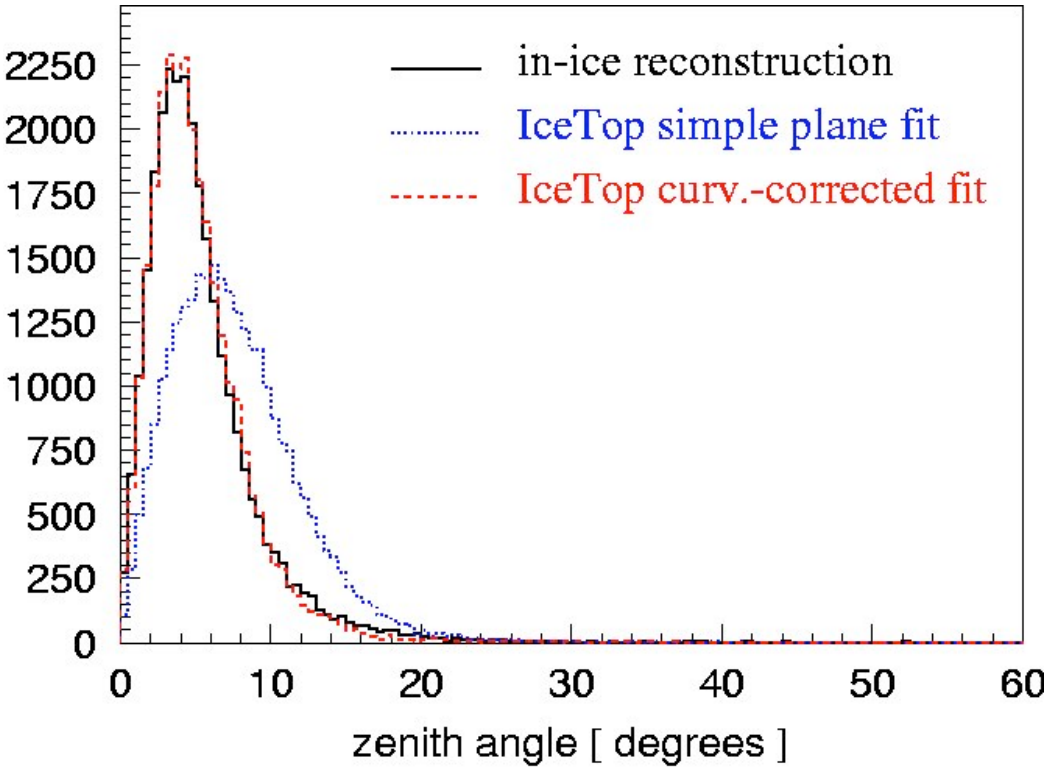
Azimuth

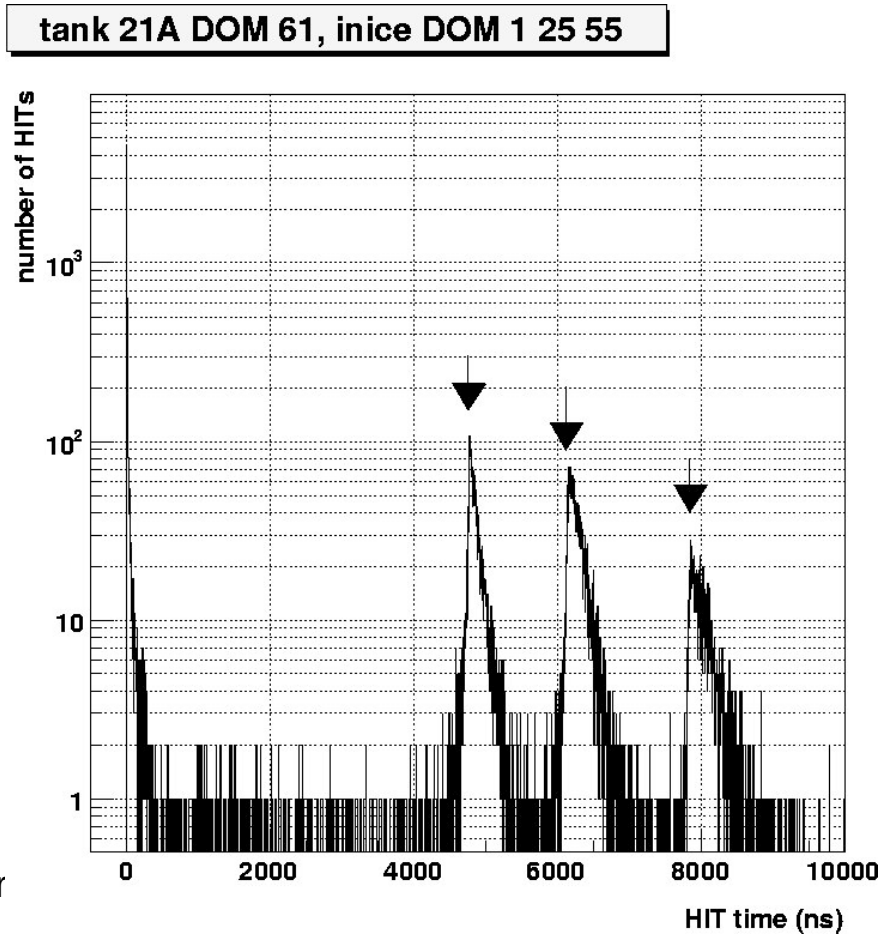


Zenith

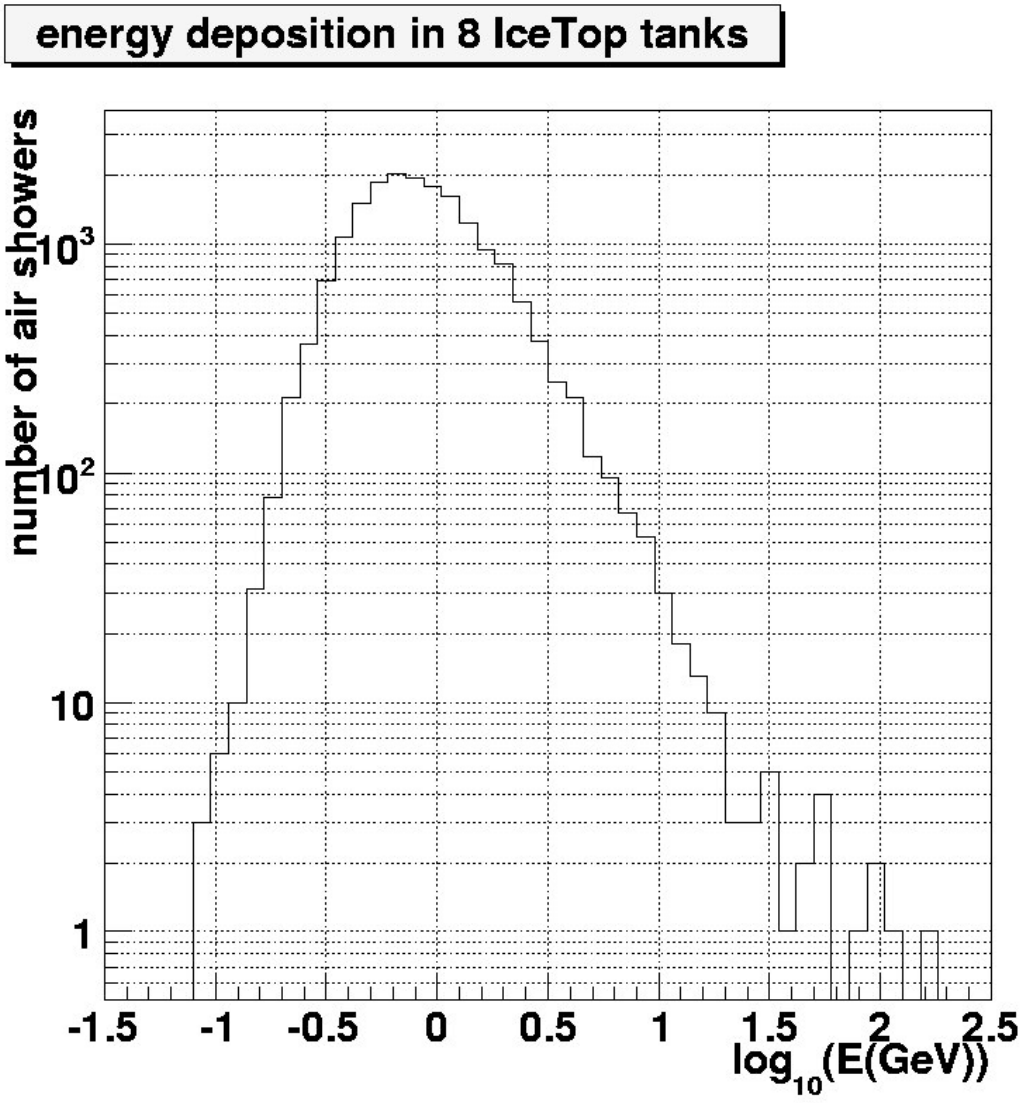


String21-IceTop coincidences

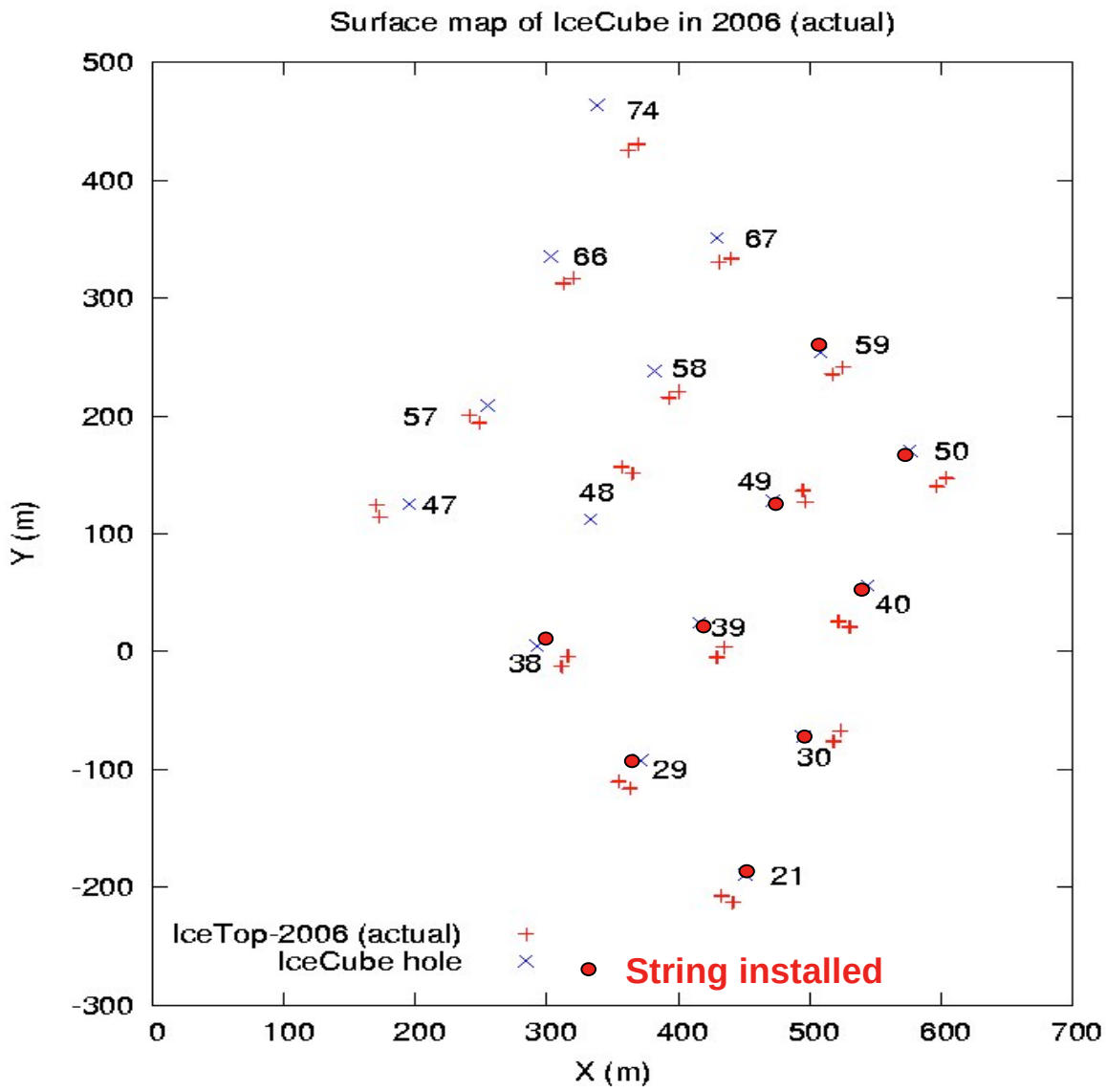




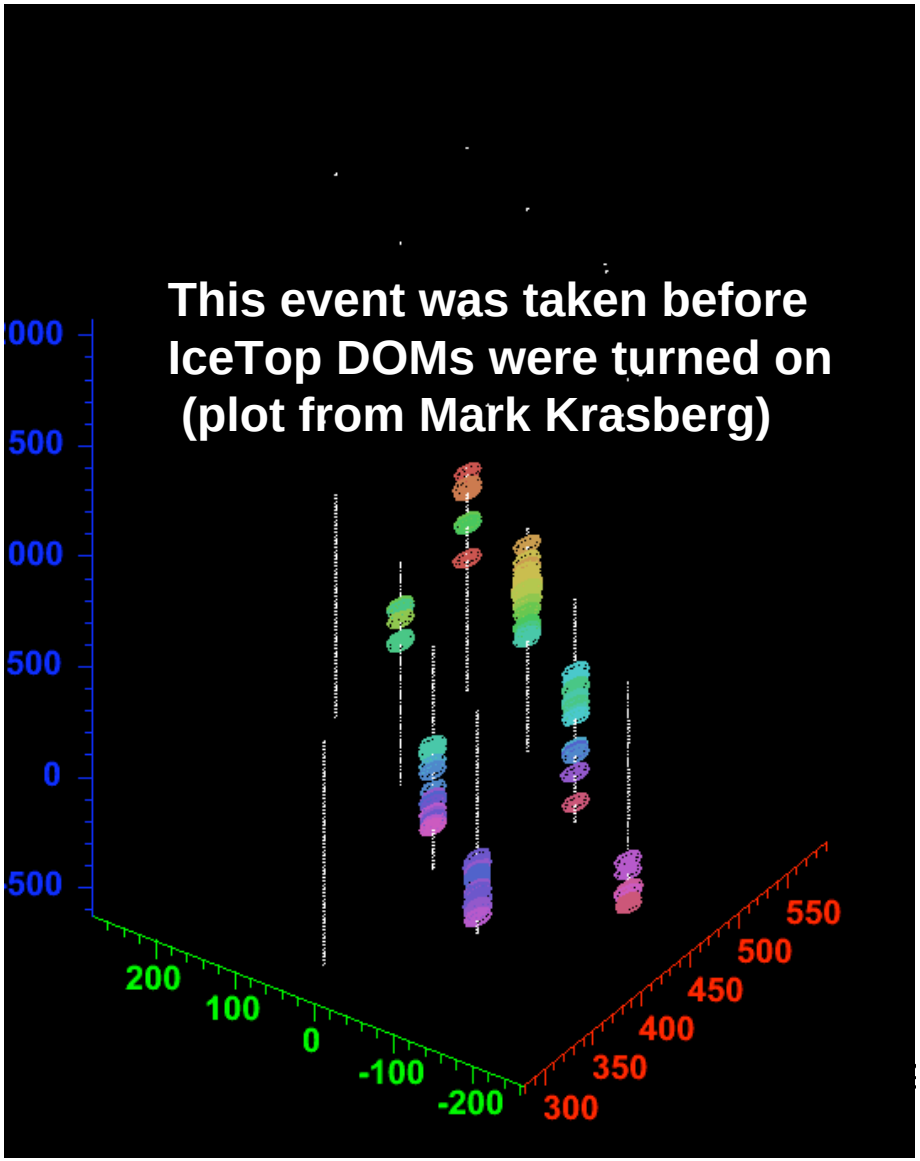
Spectrum of visible energy

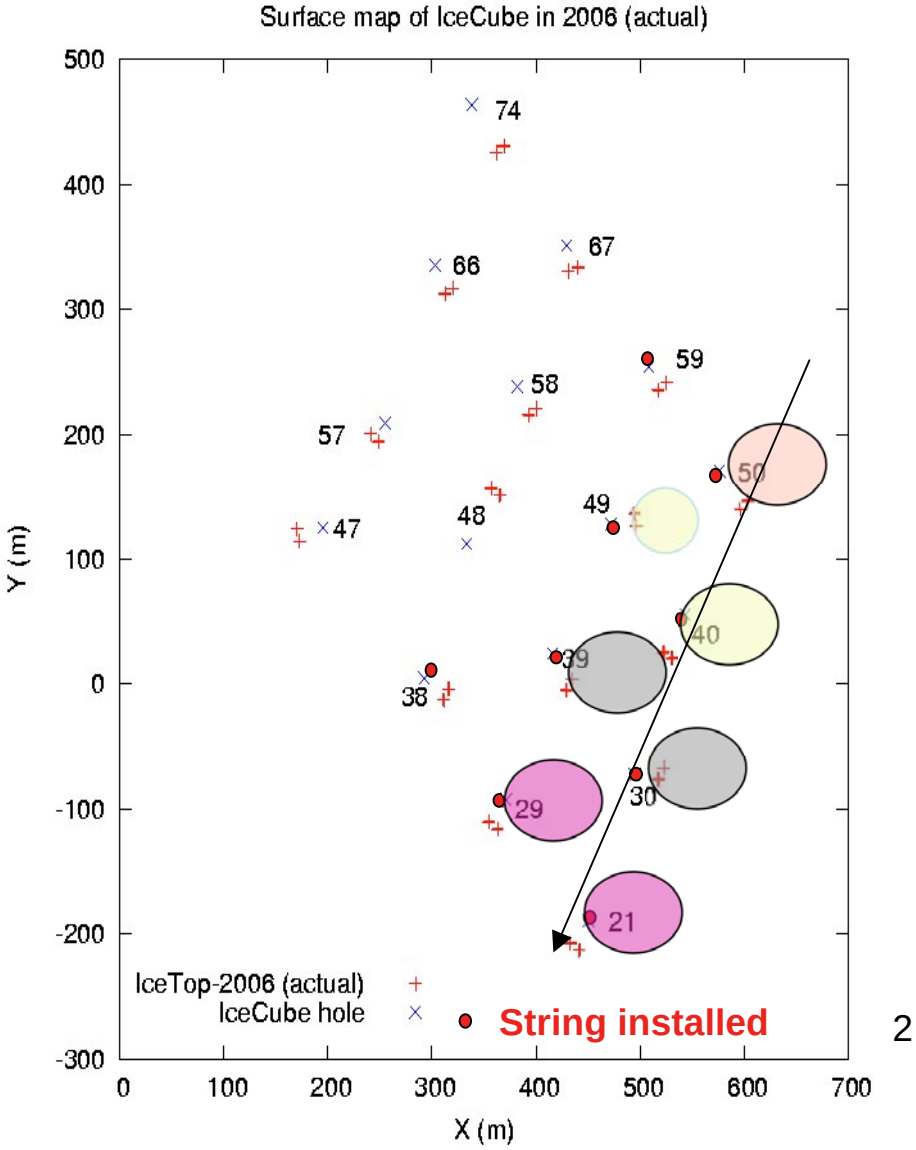


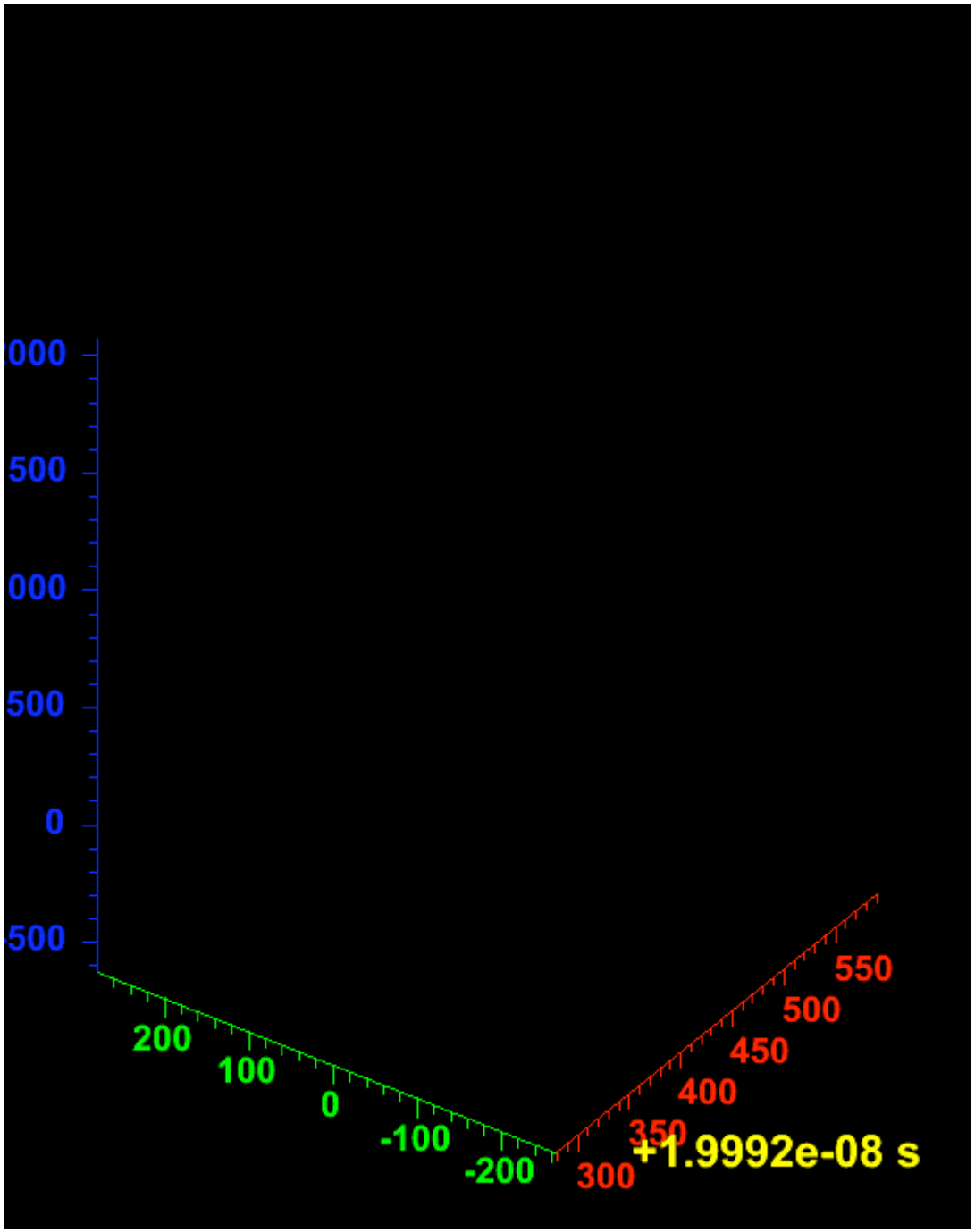
IceTop in 2006



Now running in IceTop: 16 stations, 32 tanks, 64 DOMs

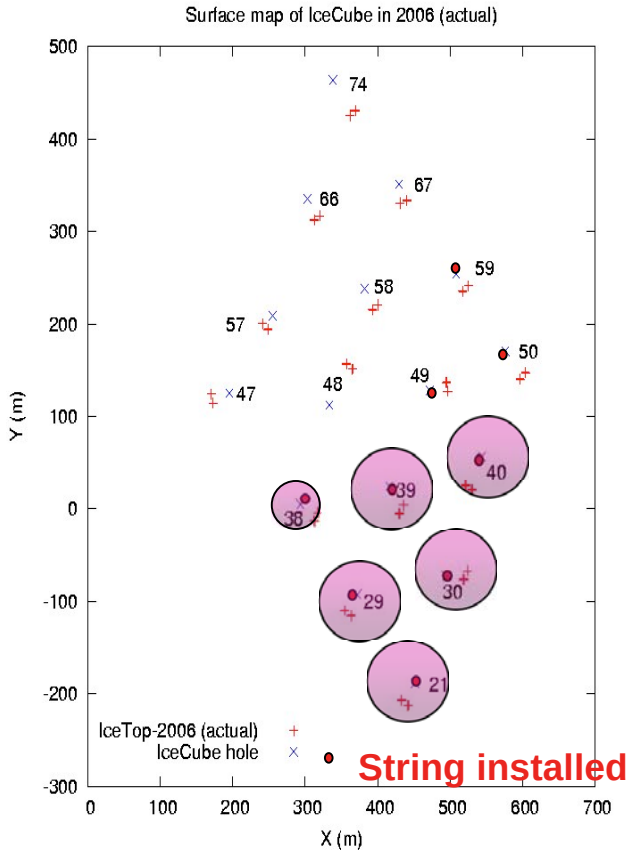


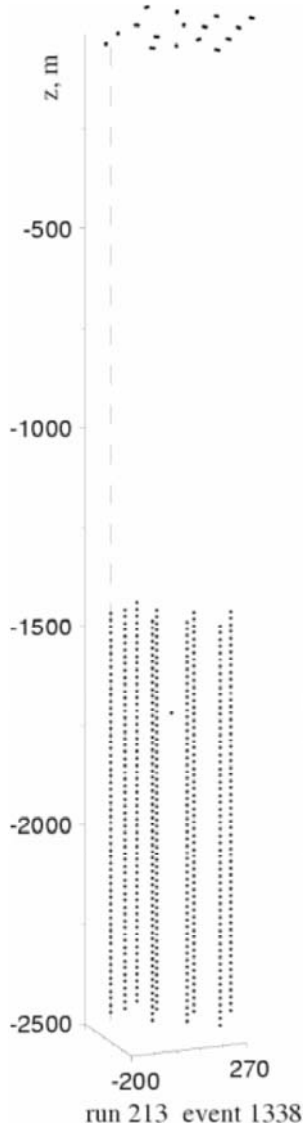



000
500
000
500
0
500
200
100
0
-100
-200
300
350
400
450
500
550
+1.9992e-08 s

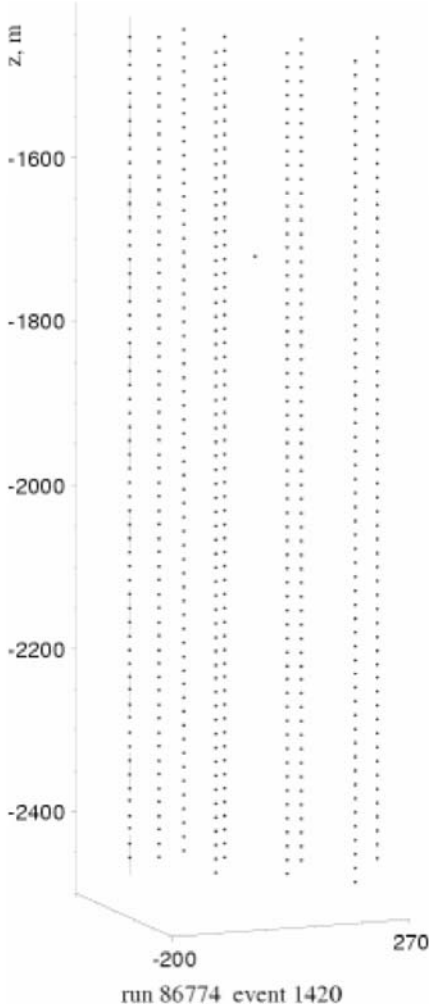
A coincident event

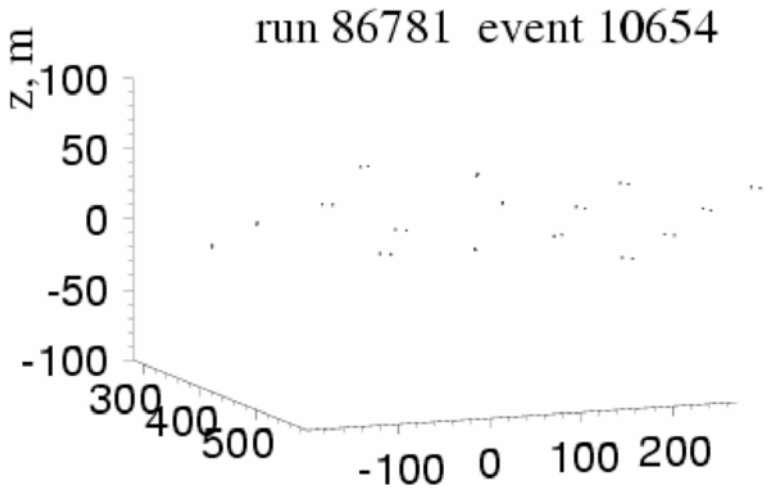
(taken with RealDAQ, animation by Dima)

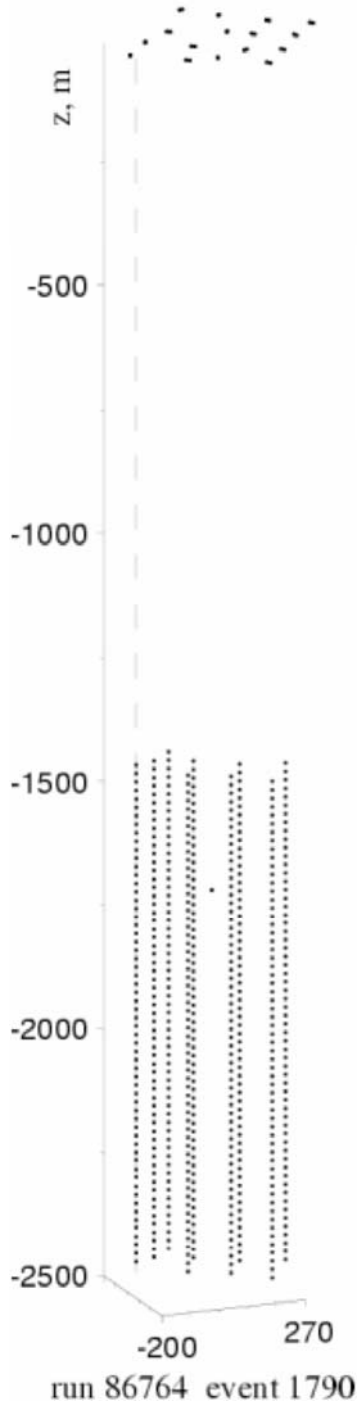




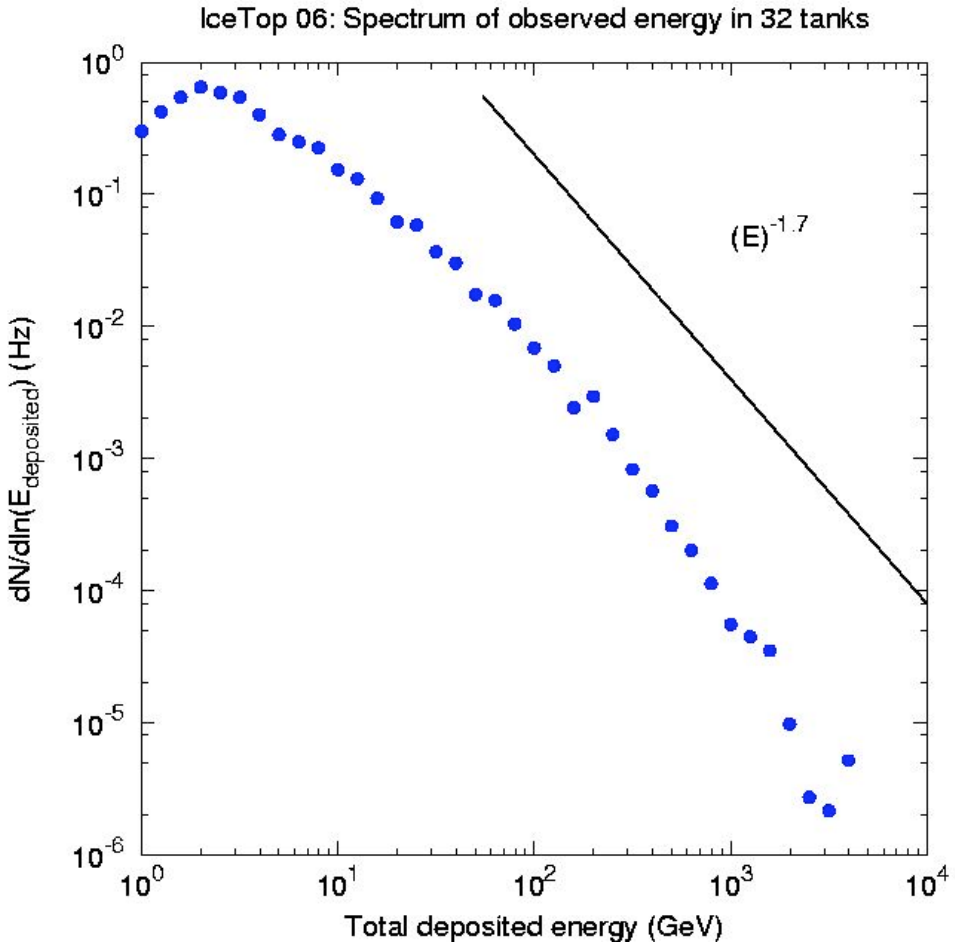
More events, Feb 2006



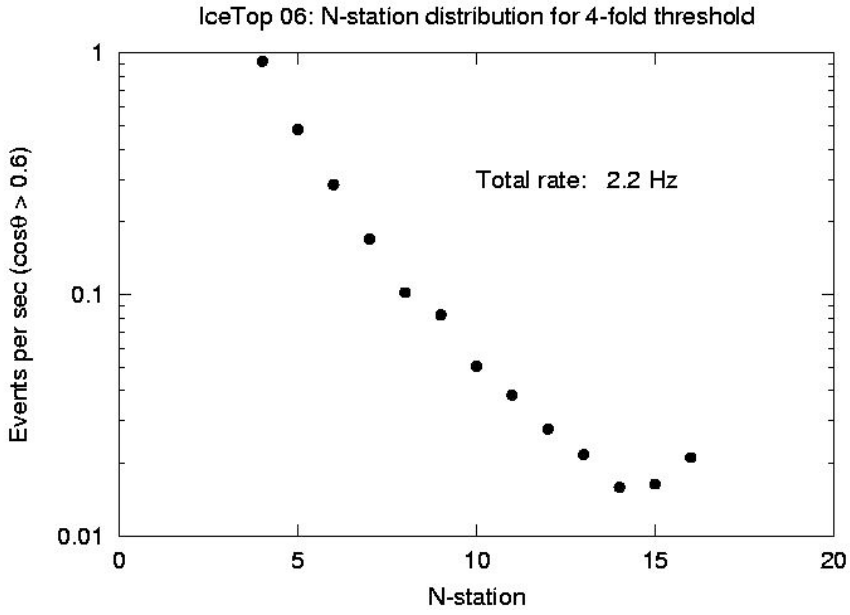




Expectations for IceTop16



Coincidence rate of >=4-folds with 9 strings expected to be approximately 0.02 Hz



IceCube Collaboration

Alabama University, USA

University of Alaska, Anchorage, USA

Bartol Research Institute, Delaware, USA

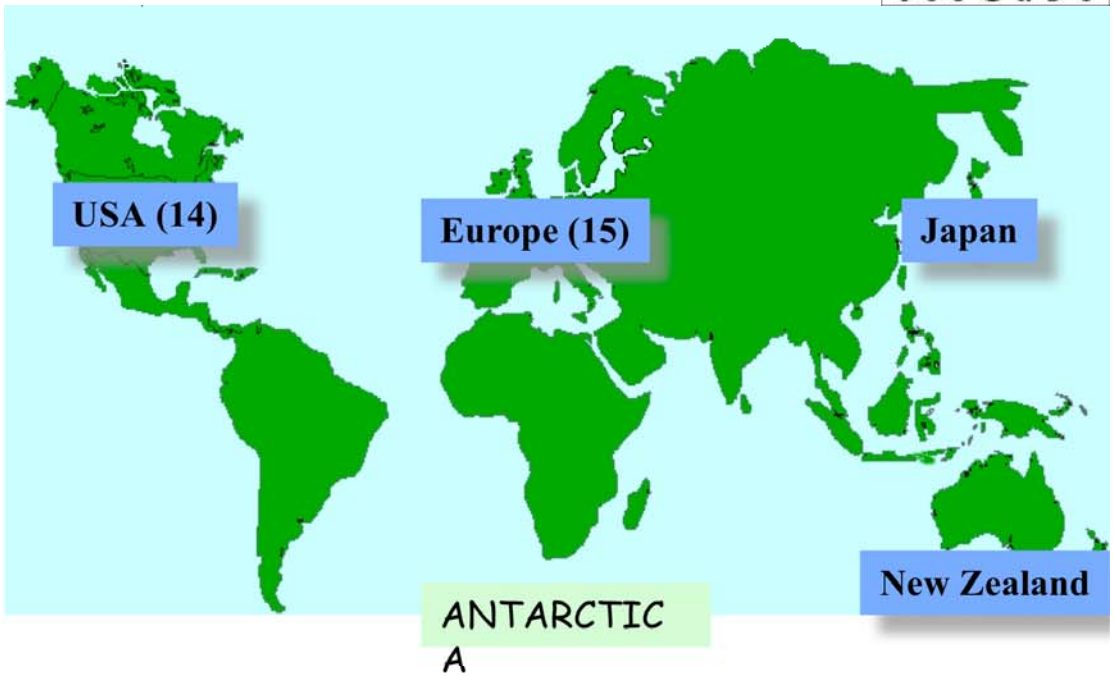
Pennsylvania State University, USA

UC Berkeley, USA

UC Irvine, USA

Clark-Atlanta University, USA

University of Maryland, USA

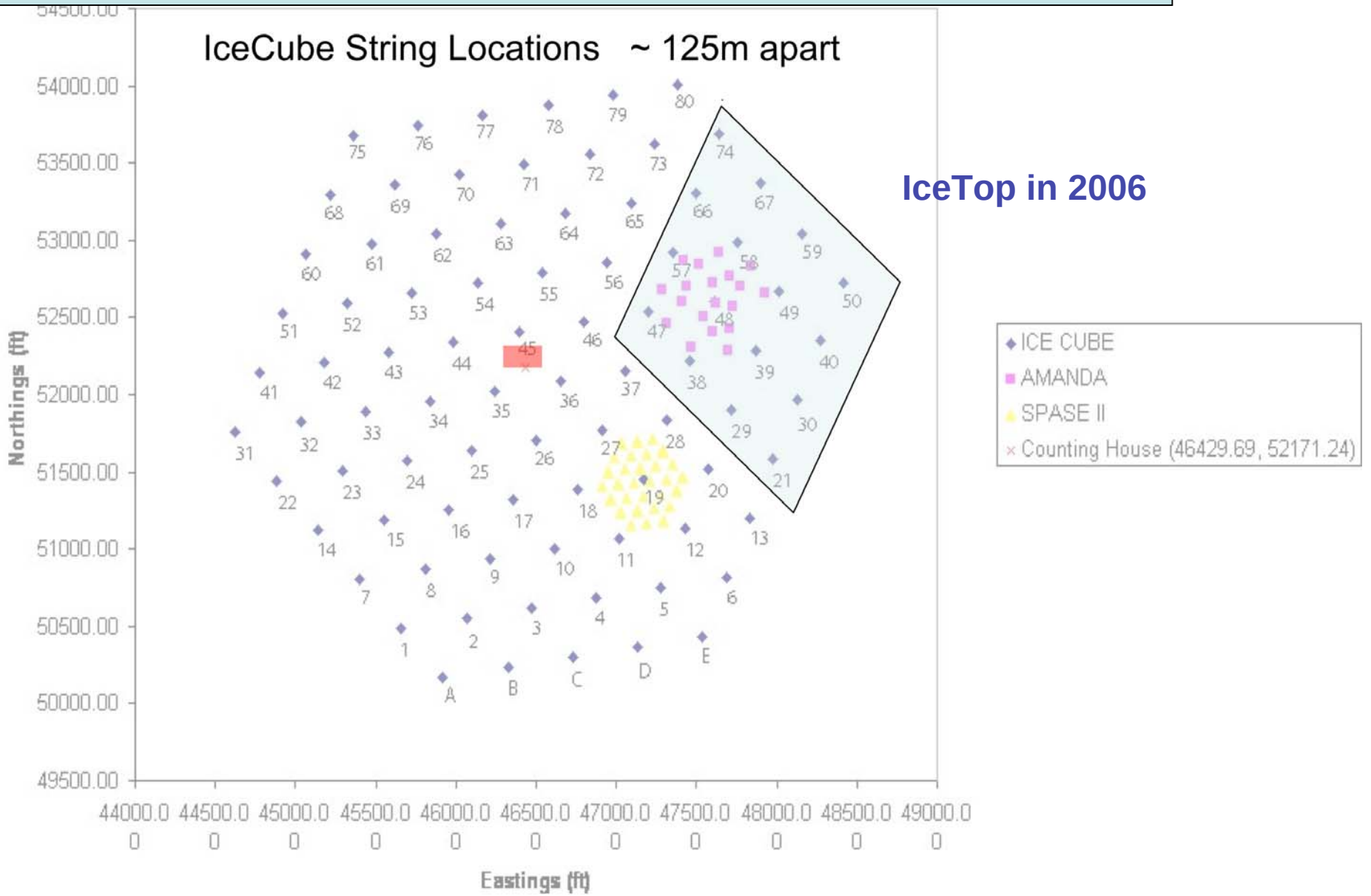


IAS, Princeton, USA
Universite Libre de Bruxelles, Belgium
University of Wisconsin, Madison, USA
Vrije Universiteit Brussel, Belgium
University of Wisconsin, River Falls, USA
Université de Gent, Belgium
LBNL, Berkeley, USA
Université de Mons-Hainaut, Belgium
University of Kansas, USA
Universität Mainz, Germany
Southern University and A&M College, Baton Rouge, USA
Humboldt Universität, Germany

Chiba University, Japan

University of Canterbury, Christchurch, New Zealand

Plan to complete IceCube in 2011



IceTop in 2006

Summary

- First year's operation (1 string, 8 tanks)
  - Timing accuracy maintained to 3 ns over 2.5 km
  - Demonstrates IceCube will work as planned
- 2006: 9 strings, 16 stations in operation
  - Hardware running since beginning of February
  - Verification and Commissioning in progress
- Plan for completion in five more years
- IceCube with IceTop:
  - Neutrino telescope & 3D air shower array
  - Coincident events from 300 TeV to 1 EeV