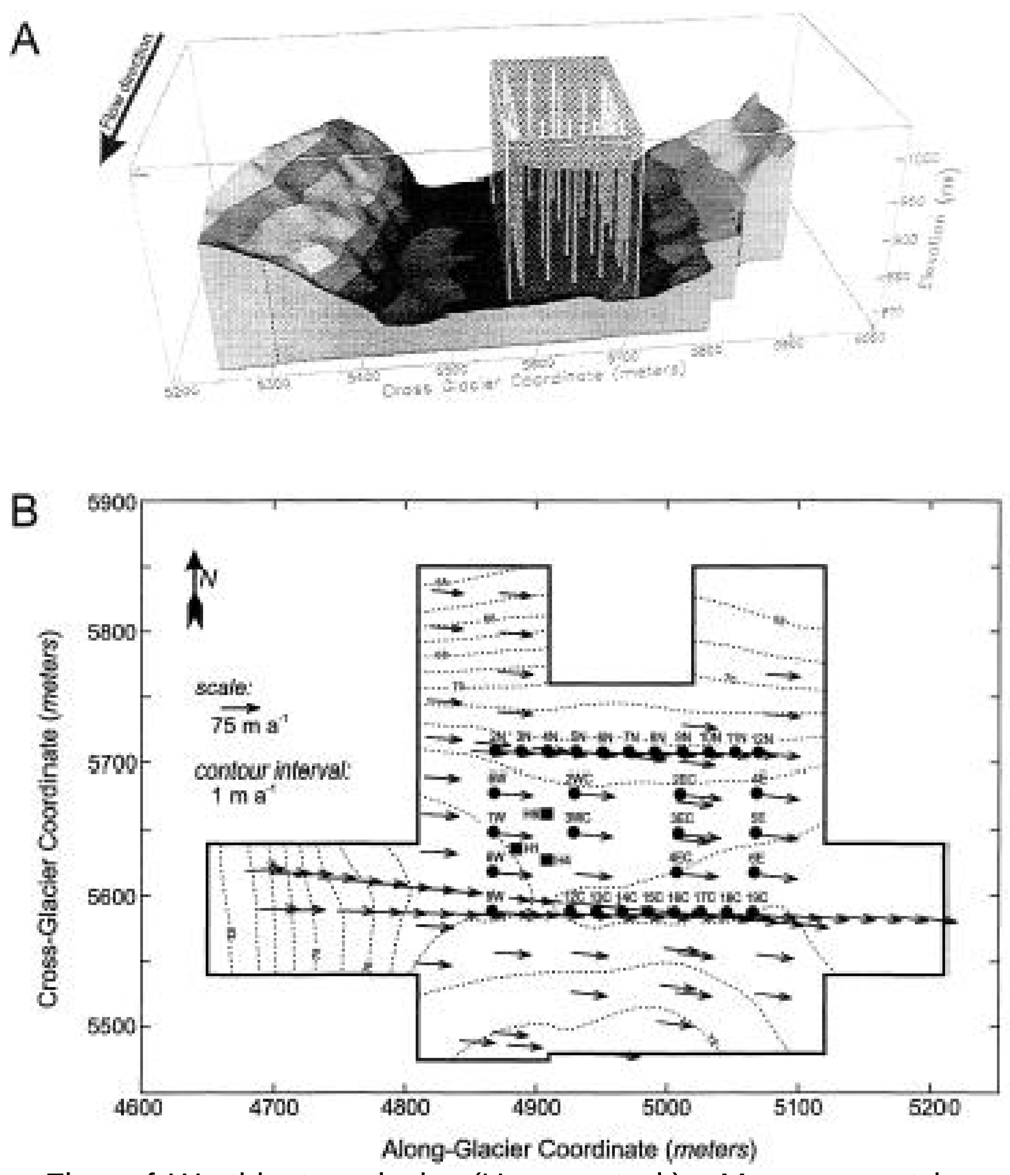
New Techniques: Muon Glaciology

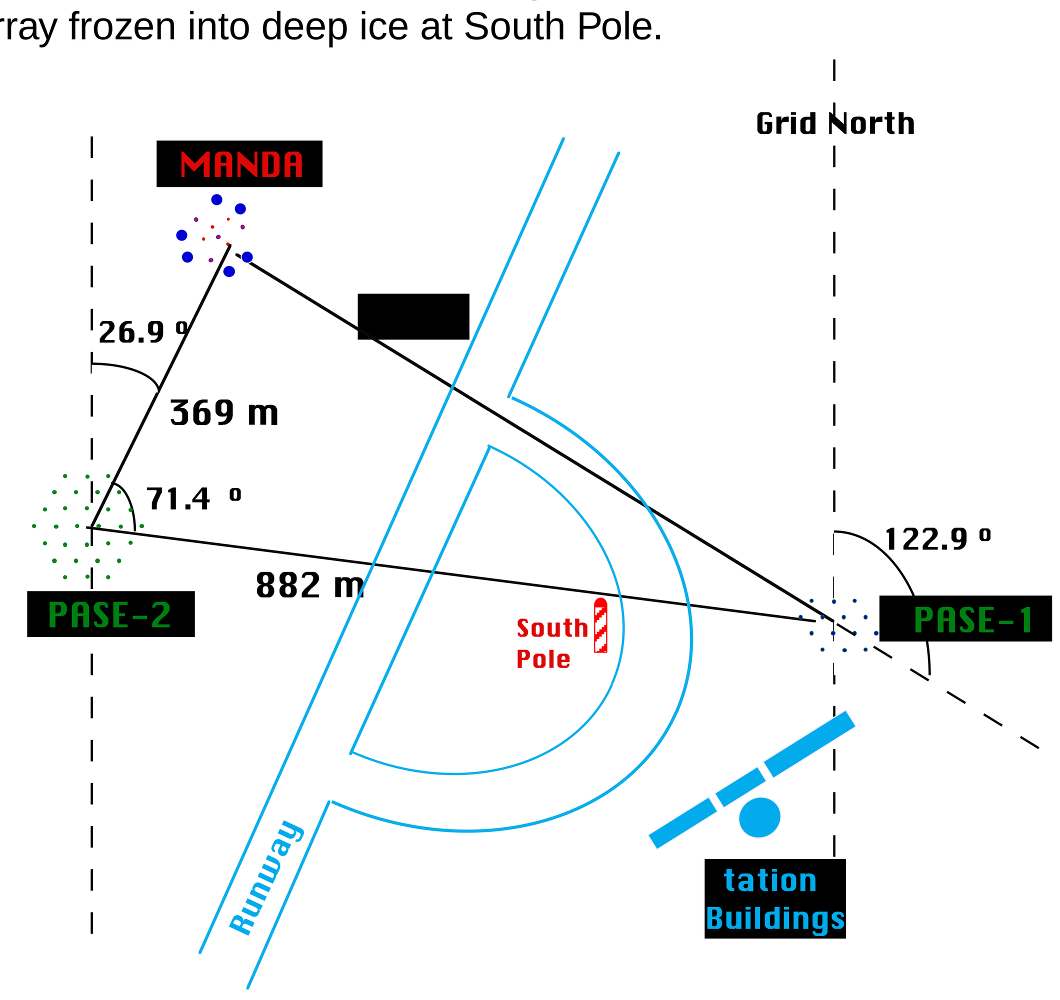
Dmitry Chirkin, Jeff Allen, Kurt Woschnagg, and P. Buford Price
Physics Department, University of California, Berkeley, CA 94720

The strain rate of cold glacial ice depends mainly on the stress tensor, temperature, grain size, and crystal habit. Lab measurements cannot be made at both the low stresses and low temperatures relevant to flow of cold glacial ice. Field studies with inclinometers measure only the horizontal components of flow, at T$\sim 0^\circ$ C.

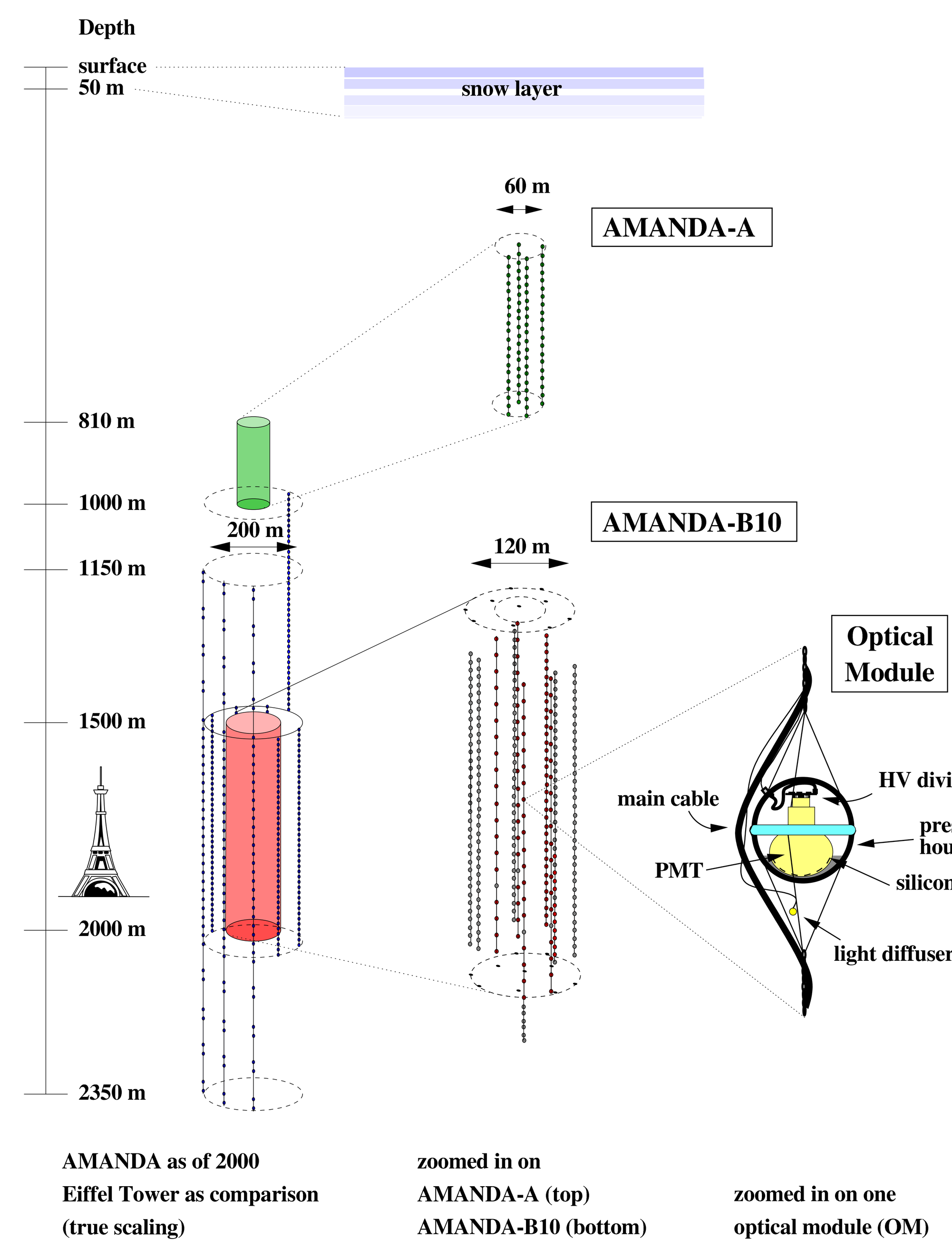


Flow of Worthington glacier (Harper et al.). Measurement is done with inclinometers to a depth of 180 m; T$\approx 0^\circ$ C in 31 boreholes during a 70-day period.

We have developed a new method for measuring the 3D strain-rate field at -40° to -15° C, using the AMANDA neutrino-detecting array frozen into deep ice at South Pole.

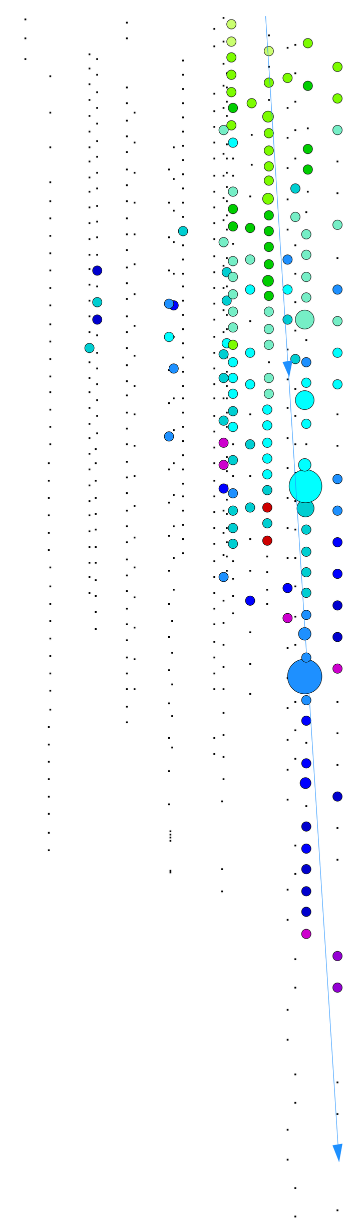


Location of AMANDA at the South Pole.

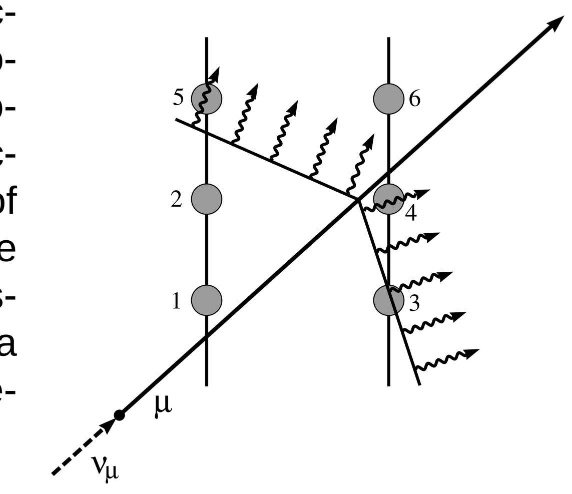


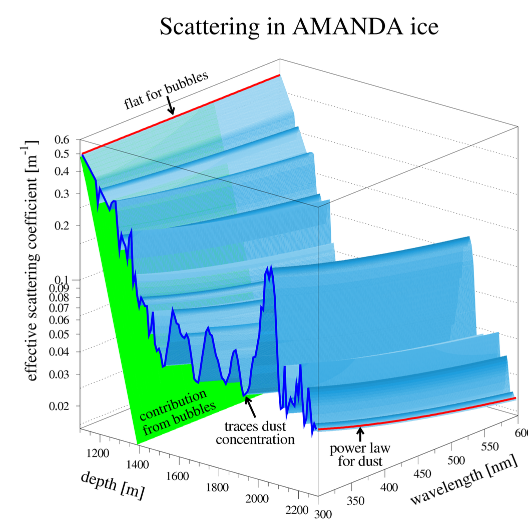
AMANDA-II: Antarctic Muon and Neutrino Detector Array.

Each strain detector consists of a photo-multiplier tube (PMT) in its pressure vessel. AMANDA has 677 PMTs at depths 1000 to 2350 m in a ~0.02 km^3 volume. The coordinates of each PMT relative to a coordinate system moving down slope at 9 m yr^{-1} can be measured with s.d. $<$1 m in 1 day by mapping trajectories of down-going cosmic-ray muons that pass through the array. The PMTs record the arrival times of the Cherenkov light emitted along the muon trajectory. Use of maximum likelihood for 10^5 muon tracks allows PMT positions to be determined; their positions are then updated at six-month intervals. We report results of strain-rate measurements in three dimensions, made in 2000 and 2001 at T$\approx -30^\circ$ C. Applying the same technique to the future 1 km^3 IceCube array, by averaging over subsets of the 4800 detectors, values of the strain-rate tensor as small as $3 \cdot 10^{-5}$ yr^{-1} can be measured as a function of temperature and lateral position. The vertical strain rate due to snow accumulation, estimated to be $\sim 3 \cdot 10^{-5}$ yr^{-1}, can be measured and serves as a check on the method.

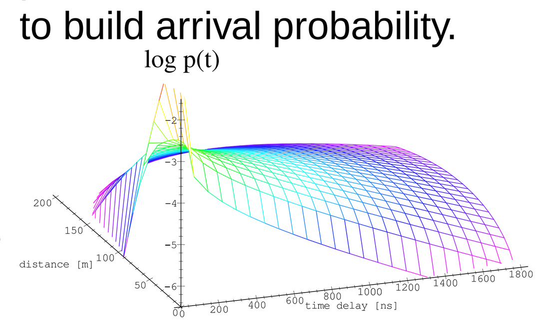


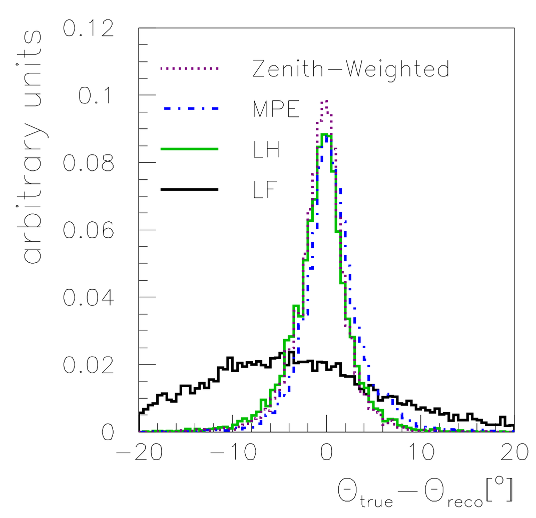
Muon moving through the detector generates Cherenkov photons. Arrival times of these photons at the PMTs of the detector depend on the amount of scattering in the ice. A precise knowledge of the arrival time distribution of the photons as a function of distance and time delay is necessary.





Optical properties of ice have been measured with AMANDA with very high precision, which allows one to build arrival probability.



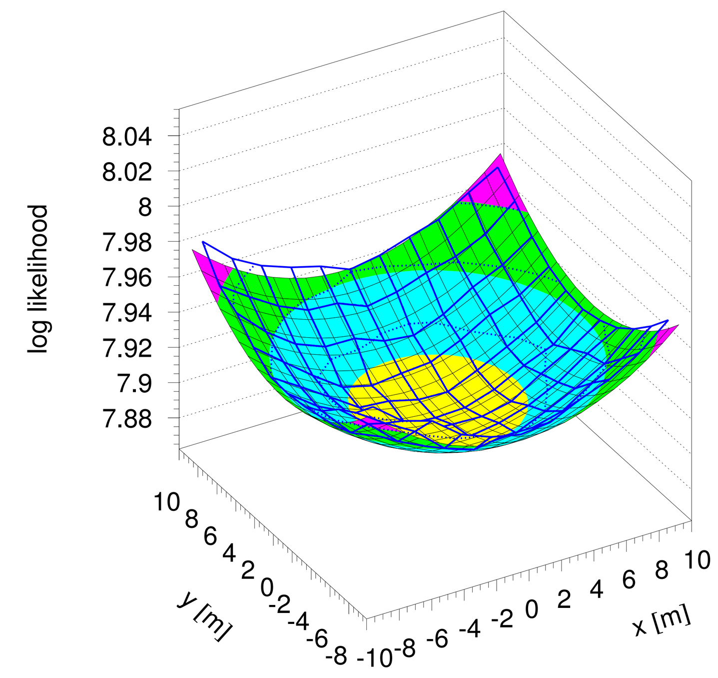


Because of the uncertainties contributed by Cherenkov photon scattering in ice and stochastic nature of muon propagation itself, it is possible to reconstruct the tracks with only $\approx 2^\circ$ angular precision. Reconstruction is performed by minimizing the likelihood

$$\mathcal{L} = \prod_{i=1}^{N_{\text{hits}}} p_i(t_{\text{res},i}|a = d_i, \eta_i, ...).$$

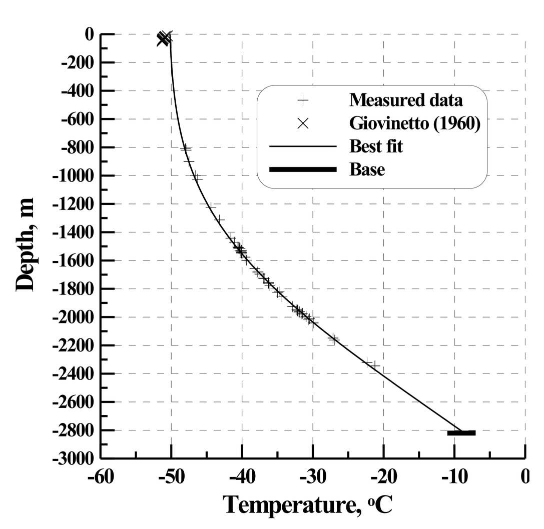
To estimate the position of an OM, $\gtrsim 10^5$ muon tracks are reconstructed using the rest of the array. The contribution of the OM to the log likelihood is averaged over these events. The minimum of the resulting function gives an estimate of the true position of the OM.

log likelihood for OM 344 at 2345 m

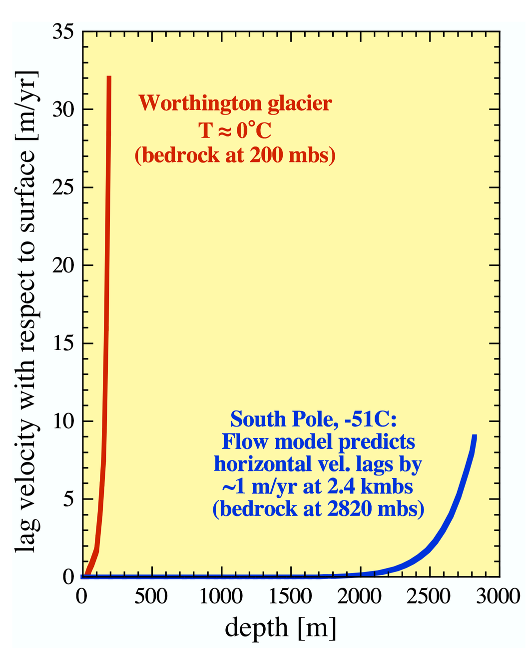


$x_{min} = -0.006 \pm 1.673$ [m]	$\delta x_{min} = 34.10 \pm 4.03$ [m]
$y_{min} = -0.281 \pm 1.844$ [m]	$\delta y_{min} = 35.63 \pm 3.98$ [m]
$z_{min} = -0.094 \pm 0.145$ [m]	$\delta z_{min} = 35.67 \pm 596.36$ [m]

Model Predictions

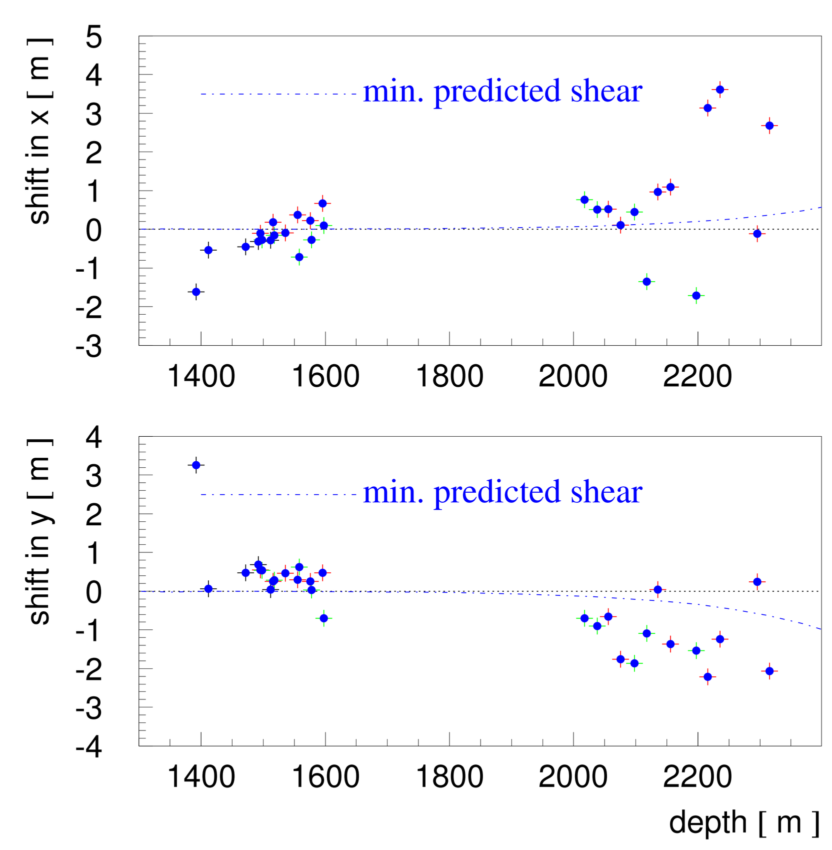


Temperatures measured in deep AMANDA boreholes (B. Price et al., 2002) and in a shallow borehole (M. Giovinetto, 1960)



Using the measured and extrapolated data for the temperature depth profile at the South Pole (using a geothermal flux of 61 mW/m^2 and a vertical advection model), the plot shows the prediction of a horizontal shear of ice of as much as 1 m/yr at a depth of 2400 m (assuming $U_{act} = 1.3$ eV, strain rate according to Glen's law with exponent $n = 3$).

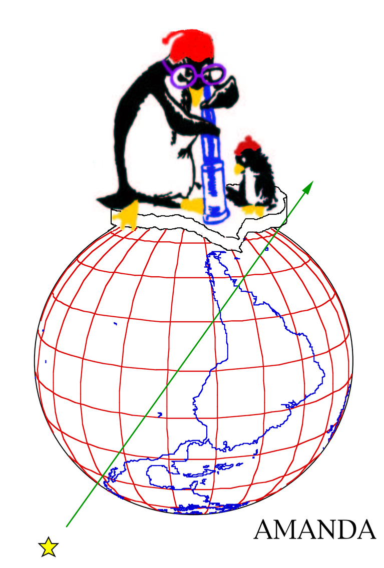
Preliminary Results

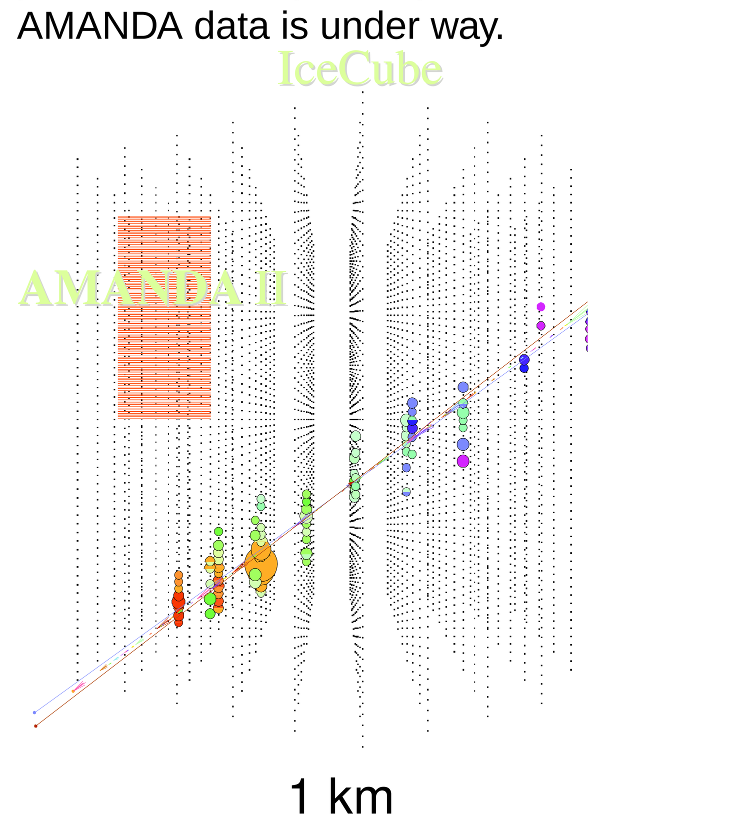


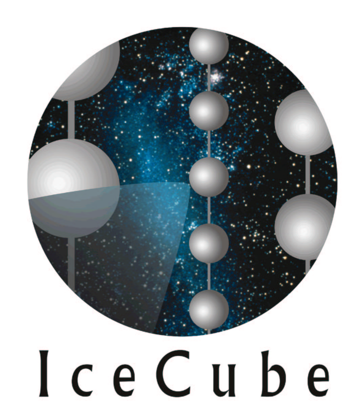
Sensor positions for years 2000 and 2001 were estimated with the muon method, and the shifts from year 2000 to 2001 are shown on the plot. It shows a hint of the ice shear in the direction of positive x and negative y. This is consistent with the ice flowing in the north-west direction.

Conclusions and Outlook

We have developed a method, which allows to monitor positions of the AMANDA sensors with time. So far, however, it was not possible to reliably observe the ice shear. The errors of the position measurement (~ 1 m) are comparable with the minimum predicted ice shear for a period of 5 years. The analysis of years 1998-2003 of AMANDA data is under way.







IceCube will comprise 80 strings with 4800 sensors and will be much more sensitive to the ice shear.