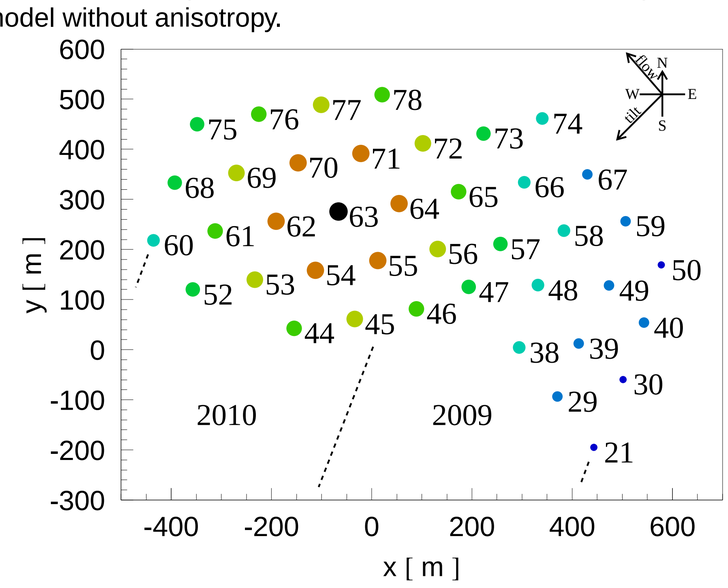
Evidence of optical anisotropy of the South Pole ice

The IceCube collaboration

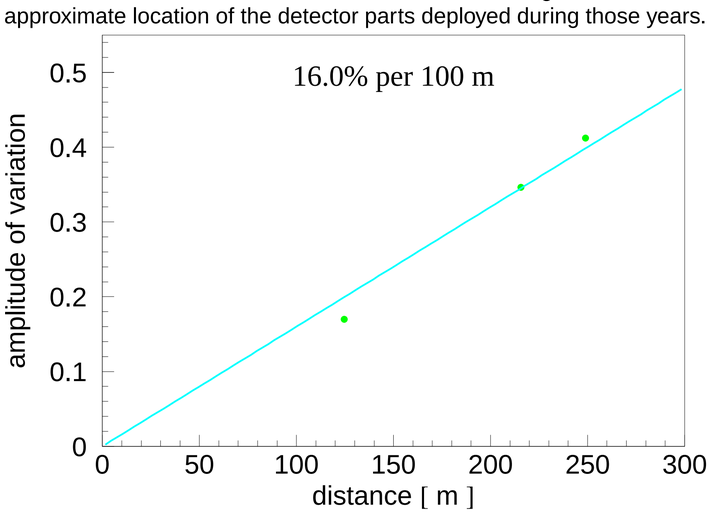
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Introduction

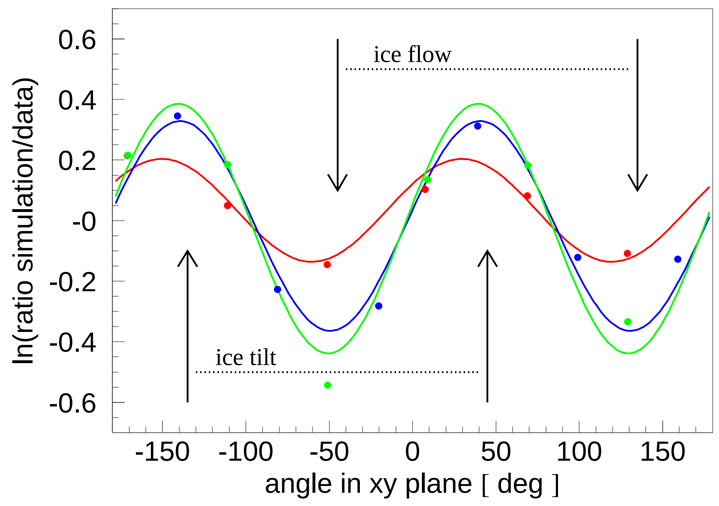
The IceCube collaboration has discovered evidence of a slight azimuthal dependence of the light propagation properties, which can be attributed to an apparently smaller amount of scattering in one direction. We developed a phenomenological model of such anisotropic scattering and fitted it to in-situ light source data. The model that includes the anisotropic scattering significantly improves the description of the calibration data when compared to a model without anisotropy.



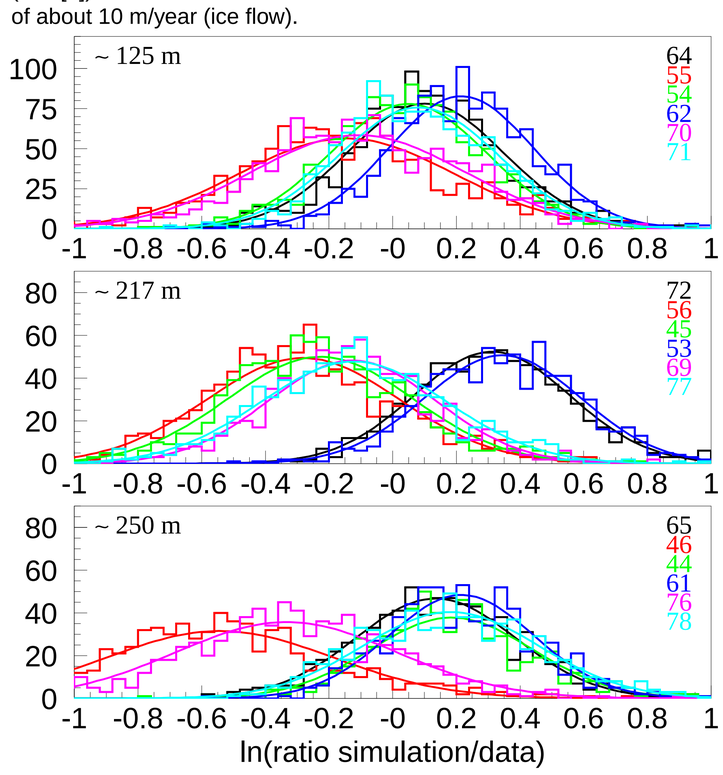
Top view layout of IceCube in the 40-string configuration in 2008. String 63, for which the DOMs emitted flashing light in the study presented here, is shown in black. The nearest 6 strings are shown in brown. The dashed lines and numbers 2009 and 2010 in the left figure indicate the approximate location of the detector parts deployed during those years.



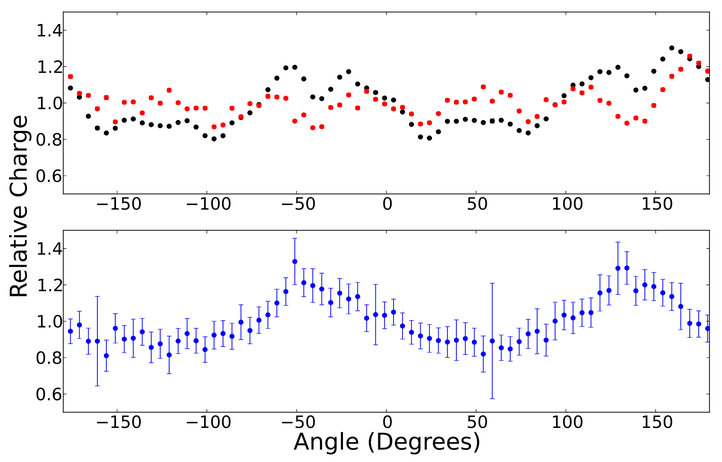
The amplitude of anisotropy as observed in charge ratio vs. distance. The 16% per 100 m fitted here describes the average behavior at all depths in the detector. This value, when computed for various depths, ranges from 10% in the clearest ice to 23% at the top of the detector.



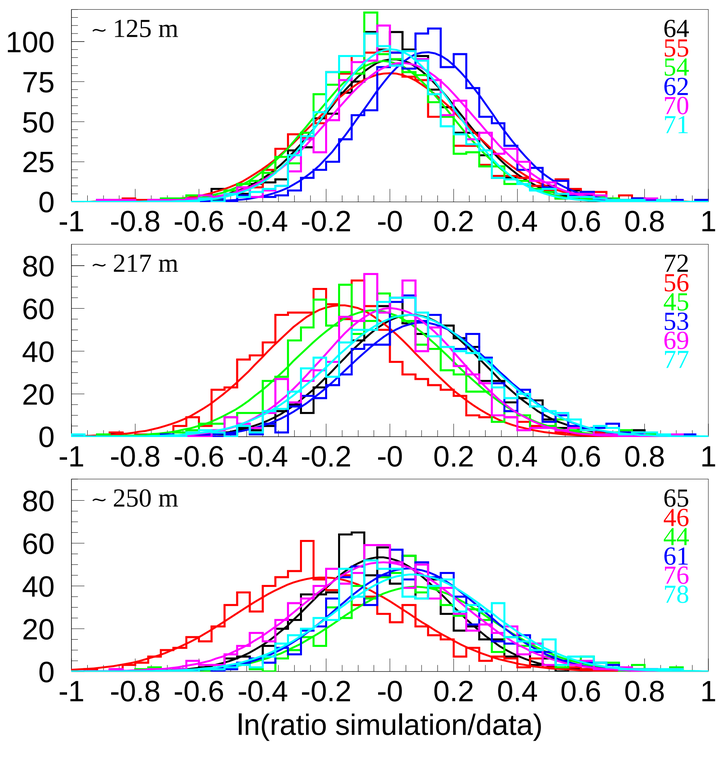
The maxima of histograms in figure below is plotted vs. azimuth of the direction from the emitting string 63 to the corresponding receiving strings. The points approximately fall on the fitted sines of twice the azimuth angle with phase that is approximately the same for all 3 curves and amplitude that increases with distance to the corresponding strings ($\sim$ 125 m, 217 m, or 250 m). Also shown are the gradient direction of the ice tilt (see [1]) and direction in which the ice moves at the South Pole at a rate of about 10 m/year (ice flow).



Ratio of (old) simulation that lacks anisotropy to data of total charge collected in DOMs on strings surrounding string 63: nearby strings $\sim$ 125 m away, next-to-near strings $\sim$ 217 m away, and even further ring of strings $\sim$ 250 m away. Each histogram contains entries for all emitters on string 63 and receivers on the denoted string such that the total received charge is greater than 10 photoelectrons.



Top: Variations in charge collected 100-150 m away from the reconstructed muon tracks in data (black) and simulation (red) based on ice model lacking anisotropy (for which some variation is expected due to hexagonal detector geometry). Bottom: ratio of data to simulation curves of the plot above. The main axis of anisotropy was fitted to 126 (and -54) degrees, which is within 5 degrees of the direction of the ice flow.



Ratio of (updated) simulation to data of total charge collected in DOMs on strings surrounding string 63, same notations as in figure to the left. The ice model used in this simulation includes the anisotropy fit result of this report.

Anisotropy of South Pole Ice

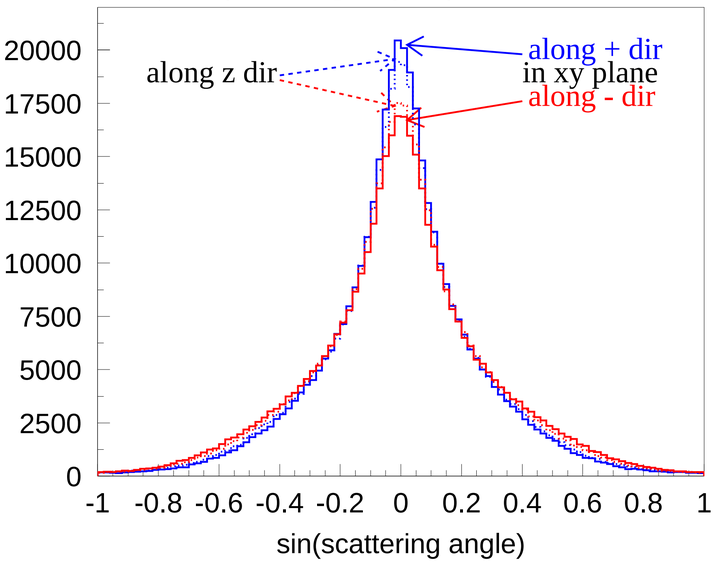
The anisotropy is implemented via a modification to the scattering function $f(\cos\theta)$, which describes the probability that the photon changes direction by an angle θ when scattered:

$$f(\vec{n_{in}} \cdot \vec{n_{out}}) \to f(\vec{k_{in}} \cdot \vec{k_{out}}), \quad \vec{k}_{in,out} = \frac{A\vec{n}_{in,out}}{|A\vec{n}_{in,out}|}.$$

The matrix A can be diagonalized to

$$A = \begin{pmatrix} \alpha & 0 & 0 \\ 0 & \beta & 0 \\ 0 & 0 & \gamma \end{pmatrix} = \exp \begin{pmatrix} \kappa_1 & 0 & 0 \\ 0 & \kappa_2 & 0 \\ 0 & 0 & \kappa_3 \end{pmatrix}$$

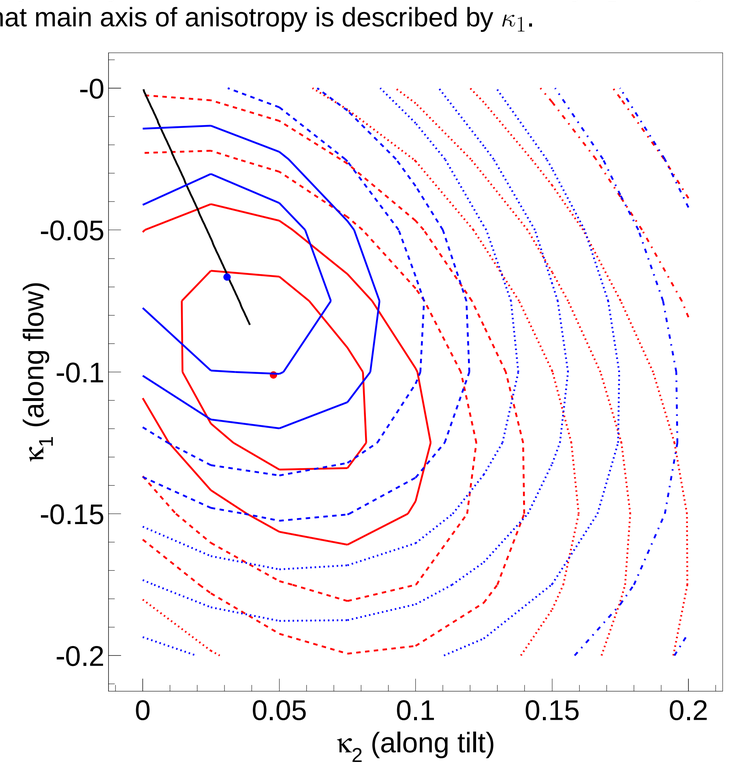
in a basis of the direction of the largest scattering in the xy plane, the direction of the smallest scattering in the xy plane, and z. If the ice is isotropic, $\alpha = \beta = \gamma = 1$, and we get back the scattering function that only depends on a product $\vec{n}_{in} \cdot \vec{n}_{out}$. We can always assume that $\alpha\beta\gamma = 1$ (or $\kappa_1 + \kappa_2 + \kappa_3 = 0$).



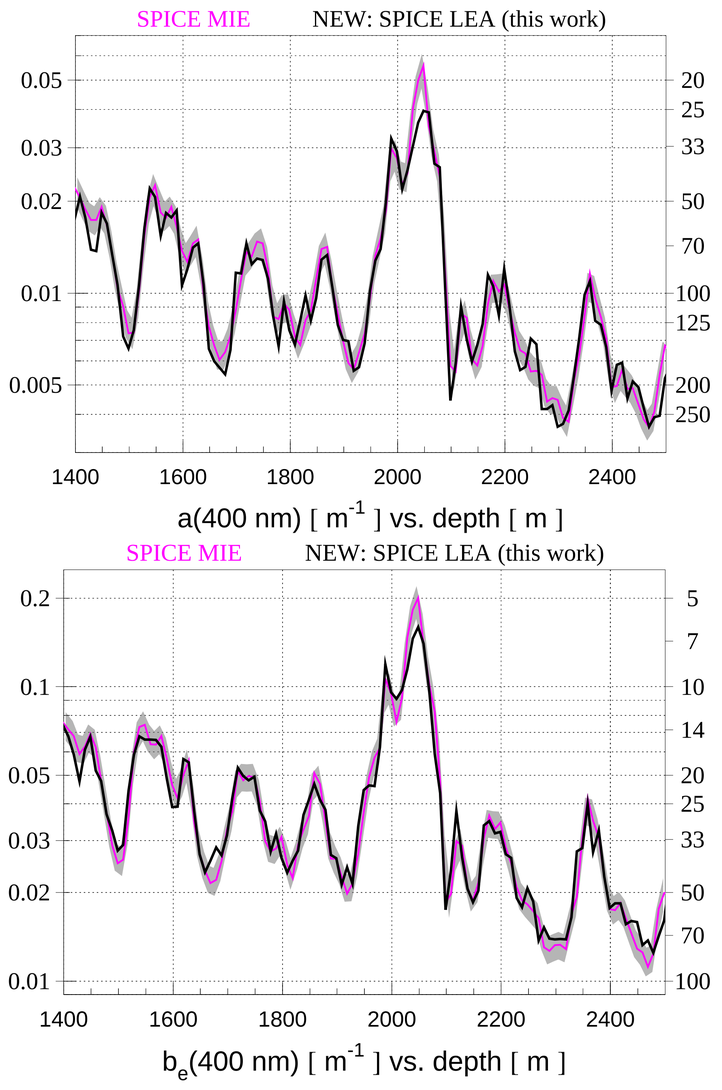
Distributions of the photon direction component after scatter along a direction perpendicular to the initial direction: either in xy plane (solid), or along the z axis (dashed). The -8% anisotropy along the main anisotropy axis ($\kappa_1 = -0.08$) is assumed. The photons with initial direction along the main anisotropy axis (the "-" direction) scatter less than the photons with initial directions along the minor axis (the "+" direction).

Result

We performed fits for the coefficients $\alpha = \exp(\kappa_1)$ and $\beta = \exp(\kappa_2)$. The main axes of the diagonalized matrix A describing anisotropy were chosen: one along the z-axis, and the other two in the xy plane. The azimuth angle of the axes in the xy plane was also fitted. The two methods shown in the figure below yield anisotropy coefficient values that are within 20% of their average: $\kappa_1 = -0.082$ and $\kappa_2 = 0.040$. Taking these as the result the third coefficient is $\kappa_3 = -\kappa_1 - \kappa_2 = 0.042$. Given the large discrepancy between the two methods we can assume that $\kappa_2 = \kappa_3$, and, thus, that there is a symmetry between the to directions described by κ_2 and κ_3, and that main axis of anisotropy is described by κ_1.



Likelihood function in the vicinity of the minimum using only charge information (red) and using time-binned data (blue). The two dots in each plot show positions of the minima in both cases. The line is drawn from (0,0) to the average of the two dots and shows that the ratio of κ_1/κ_2 is approximately the same in both cases.



New absorption and effective scattering parameters (LEA) compared with the result reported in [1] (MIE). The grey band around the MIE result shows the uncertainties reported in [1].

References

[1] M. Aartsen et al., NIM-A, 711 (2013) 73, arXiv:1301.5361.