Response to Reviewer #2

We thank the reviewer for the critical comments. We appreciate the emphasis on the importance of accurate asymmetry parameter (g) retrievals. However, we strongly disagree with the assertion that our methodology is "flawed" or that the scientific value of our results is significantly reduced. Below we address the points raised.

1. Validity of GO–diffraction separation

The reviewer expresses concern that our retrieval follows the methodology of Xu et al. (2022), which separates diffraction and geometric-optics (GO) contributions. We note that such a separation is not unique to our work but is inherent to all retrieval approaches based on in situ polar nephelometer data, since near-forward scattering cannot be directly measured. Earlier methods (e.g., Gerber et al., 2000; Auriol et al., 2001) assigned a fixed fraction of forward-scattered energy, derived from idealised hexagonal crystal calculations, to compensate for the missing range. Our approach represents a significant improvement: instead of prescribing the missing contribution a priori, we reconstruct the GO part of the phase function using a Legendre polynomial expansion of the measured scattering pattern, and only parameterise the diffraction peak. This makes our retrieval data-driven rather than model-imposed.

We acknowledge that the separation of diffraction and geometric optics (GO) is not exact from the perspective of electromagnetic theory. Nevertheless, for particles with large size parameters ($x > 100$), this decomposition is well established in atmospheric optics (e.g., Takano and Liou, 1989; Macke et al., 1996) and provides the only practical framework for reconciling theoretical scattering calculations with in situ measurements. Although improved GO methods have been developed to avoid this artificial separation, they have been shown to converge toward conventional ray-tracing results for the large size parameters relevant to our study (Yang and Liou, 1996), which further justifies the use of this approach. Importantly, the GO–diffraction separation is not unique to interpretation of in situ measurements but underlies many conventional ray-tracing schemes and remains the foundation of widely applied parameterisations and retrieval algorithms (e.g., Baran and Labonnote, 2007; van Diedenhoven et al., 2012). Rejecting this separation would therefore not only undermine our methodology, but also invalidate a large body of established research in atmospheric light scattering.

2. On forward peak and delta-transmission

The reviewer raises the concern that a narrow forward peak, caused by so-called delta rays in smooth crystals, could bias the retrieved values of g. We note that such features require pristine, plane-parallel crystal surfaces. Our measured phase functions, however, show no indications of smooth-surface scattering such as distinct 22° halos or strong specular reflections. Instead, the measured orientation-averaged angular scattering functions (Fig. 1) are consistent with complex or roughened surfaces. As demonstrated in Fig. 1, the delta-transmission peak is even more sensitive to surface roughness than halo or specular features, and it disappears at comparatively low levels of distortion. Consequently, it is highly improbable that delta-transmission features were present in the observed angular scattering functions, and thus unlikely that our retrievals of g are biased by this effect.

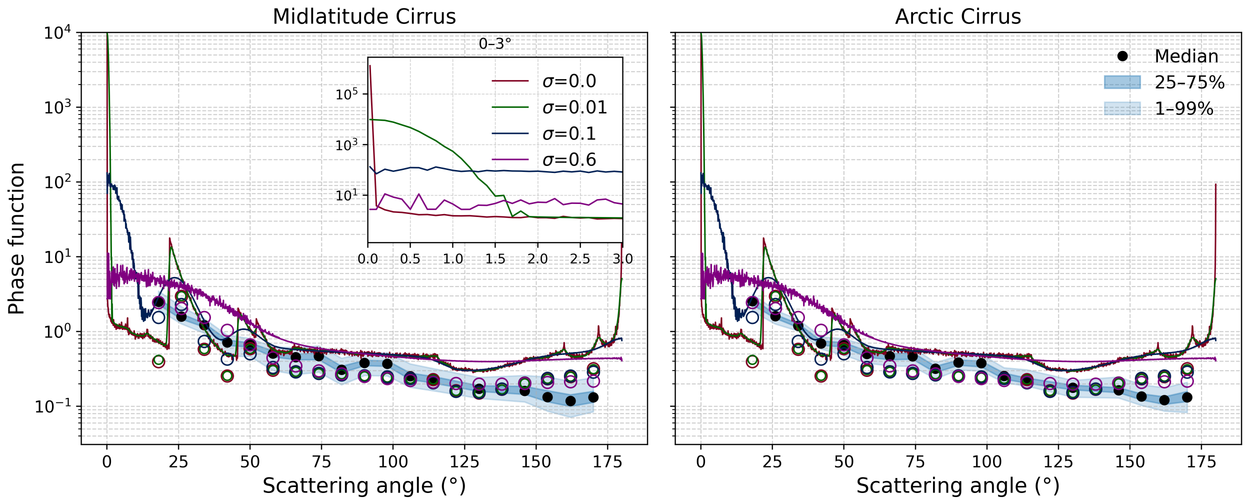

Figure 1: Statistical analysis of all PHIPS-measured orientation averaged phase functions that were used to retrieve g. The median function (shown as black circles) shows smooth angular behavior and no sharp delta features are present in the inter-quartile or in the 1 to 99 percentile range (shown as shaded areas), consistent with roughened ice particles. Overlaid are ray tracing simulations of the geometrical optics part of the phase function (without diffraction) for a hexagonal crystal with a unity aspect ratio and the length of 100 µm. The solid lines show the full phase function and circular markers show the phase function integrated over the PHIPS detection geometry. It can be seen that the delta peak vanishes at roughness of σ=0.1, whereas measurable halo-features are still seen. The unity model is not the best fit to the measurement data but demonstrates that σ values above 0.1 are needed to reproduce the measured featureless function.

3. Use of truncated Legendre expansion

The reviewer is concerned that truncation of the Legendre expansion may bias the results by excluding narrow forward peaks associated with smooth, pristine crystals, which would in turn lead to underestimation of g. We stress that this is not the case for our analysis. Truncation is not an arbitrary choice but a necessary step to avoid overfitting the limited angular range covered by PHIPS. More importantly, Xu et al. (2022) showed with ray-tracing simulations (their Figures 5 and 6) that when the expansion is truncated at orders consistent with the measurement range, the reconstruction error in g remains typically below 0.001 for roughened hexagonal crystals.

Crucially, our measurements do not contain smooth planar crystals. Instead, the measured phase functions are consistent with rough or complex particle surfaces. This is further supported by the C_p values in our dataset, which exceed 0.4 in nearly all cases (Fig. 2), indicating that the method is being applied well within its validity range.

Thus, while we fully acknowledge that the Legendre expansion is not applicable to smooth particles with narrow forward peaks, we explicitly do not need to worry about this regime in our analysis. Within the relevant parameter space of our measurements, the associated error in g is small and quantitatively constrained.

4. Diffraction approximation

The reviewer is concerned that our use of scalar diffraction for circular apertures underestimates the effect of noncircular particle shapes. However, orientation-averaged diffraction is primarily a

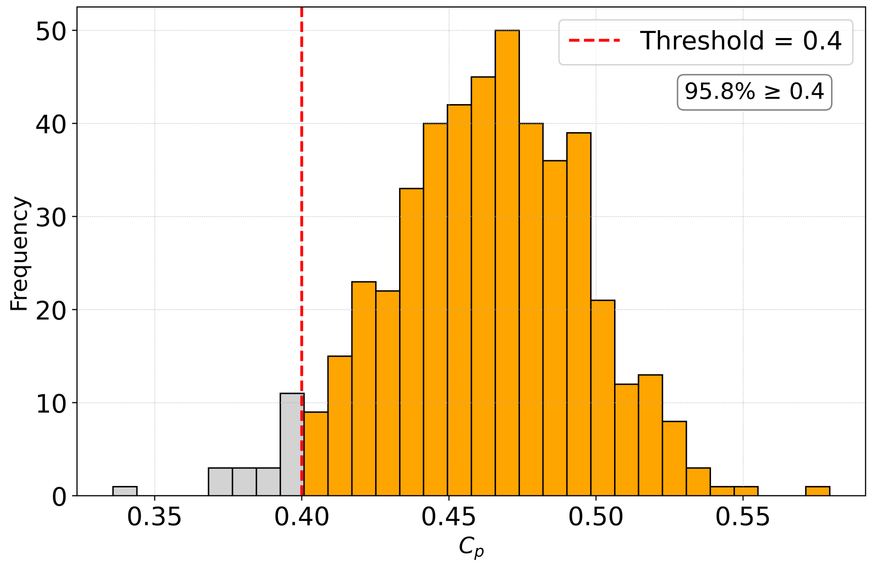

Figure 2: Distribution of C_p values from the PHIPS dataset. The vertical dashed line marks the decay rate of the expansion coefficients $C_p = 0.4$. Nearly all observations lie above this threshold, implying g retrieval errors below 0.001.

function of the projected area (Babinet's principle), and differences between circular and hexagonal apertures average out for large, randomly oriented ice crystals. Numerous studies (Liu and Yao, 1996; Hesse, 2008, and references therein) have shown that the diffraction peak is confined to angles well below the PHIPS cutoff of 18°, such that its detailed shape does not influence our retrieval of g. We therefore maintain that the circular-aperture approximation introduces only negligible error into the asymmetry parameter.

5. On the request for a "health warning"

We respectfully disagree with the reviewer that our results require a warning label suggesting unreliability. Our methodology represents a well-founded improvement over previous approaches, is supported by numerical validation (Xu et al., 2022), and includes explicit uncertainty estimates. All approaches to ice cloud optics—whether based on theory, laboratory experiments, or in situ data—are necessarily approximate, given the complexity of real atmospheric ice. Our contribution lies in advancing the experimental basis for g, providing observational constraints that are otherwise sparse. We believe this substantially increases, rather than decreases, the scientific value of the manuscript.

6. Conclusion

In summary, the reviewer's criticisms appear to dismiss not only our approach but, by implication, all experimental efforts to derive g for large, irregular ice particles. We maintain that our method represents a significant advance: it combines measured scattering with a physically justified reconstruction framework, avoids the ad hoc assumptions of earlier retrievals, and provides explicit, quantitative error bounds. Our results therefore contribute an essential and meaningful step forward in establishing an experimental basis for cirrus radiative properties. We do not argue that our approach is the only way to derive g from our observations and welcome future modeling efforts to test and complement our in-situ data with methods beyond our current computational reach.

References

Xu, G., M. Schnaiter, and E. Järvinen, 2022: Accurate Retrieval of Asymmetry Parameter for Large and Complex Ice Crystals From In-Situ Polar Nephelometer Measurements. *J. Geophys. Res. Atmos.*, **127**, e2022JD036608, https://doi.org/10.1029/2022JD036608.

Auriol, F., J.-F. Gayet, O. Crepel, A. Fournol, and S. Oshchepkov, 2001: In situ observation of cirrus scattering phase functions with 22° and 46° halos: Cloud field study on 19 February 1998. *J. Geophys. Res.*, **106**, 17923–17931, https://doi.org/10.1029/2000JD900762.

Gerber, H., Y. Takano, T. J. Garrett, and P. V. Hobbs, 2000: Nephelometer measurements of the asymmetry parameter, volume extinction coefficient, and backscatter ratio in Arctic clouds. *J. Atmos. Sci.*, **57**, 3021–3034, https://doi.org/10.1175/1520-0469(2000)057<3021:NMOTAP>2.0.CO;2.

Macke, A., J. Mueller, and E. Raschke, 1996: Single scattering properties of atmospheric ice crystals. *J. Atmos. Sci.*, **53**, 2813–2825, https://doi.org/10.1175/1520-0469(1996)053<2813:SSPOAI>2.0.CO;2.

Takano, Y., and K.-N. Liou, 1989: Solar radiative transfer in cirrus clouds. Part I: Single-scattering and optical properties of hexagonal ice crystals. *J. Atmos. Sci.*, **46**, 3–19, https://doi.org/10.1175/1520-0469(1989)046<0003:SRTICC>2.0.CO;2.

Takano, Y., and K.-N. Liou, 1996: Geometric-optics–integral-equation method for light scattering by nonspherical ice crystals. *Appl. Opt.*, **35**, 6568–6584, https://opg.optica.org/abstract.cfm?URI=ao-35-33-6568.

Baran, A. J., and L.-C. Labonnote, 2007: A self-consistent scattering model for cirrus. I: The solar region. *Quart. J. Roy. Meteor. Soc.*, **133**, 1899–1912, https://doi.org/10.1002/qj.164.

van Diedenhoven, B., B. Cairns, I. V. Geogdzhayev, A. M. Fridlind, A. S. Ackerman, P. Yang, and B. A. Baum, 2012: Remote sensing of ice crystal asymmetry parameter using multi-directional polarization measurements—Part 1: Methodology and evaluation with simulated measurements. *Atmos. Meas. Tech.*, **5**, 2361–2374, https://doi.org/10.5194/amt-5-2361-2012.

Liu, C., and K. Yao, 1996: Calculation of ice crystal diffraction. *Adv. Atmos. Sci.*, **13**, 340–348, https://doi.org/10.1007/BF02656851.

Hesse, E., 2008: Modelling diffraction during ray-tracing using the concept of energy flow lines. *J. Quant. Spectrosc. Radiat. Transfer*, **109**, 1374–1383, https://doi.org/10.1016/j.jqsrt.2007.11.002.