How to constrain snow particle scattering models?
A first approach using triple-frequency radar Doppler spectra

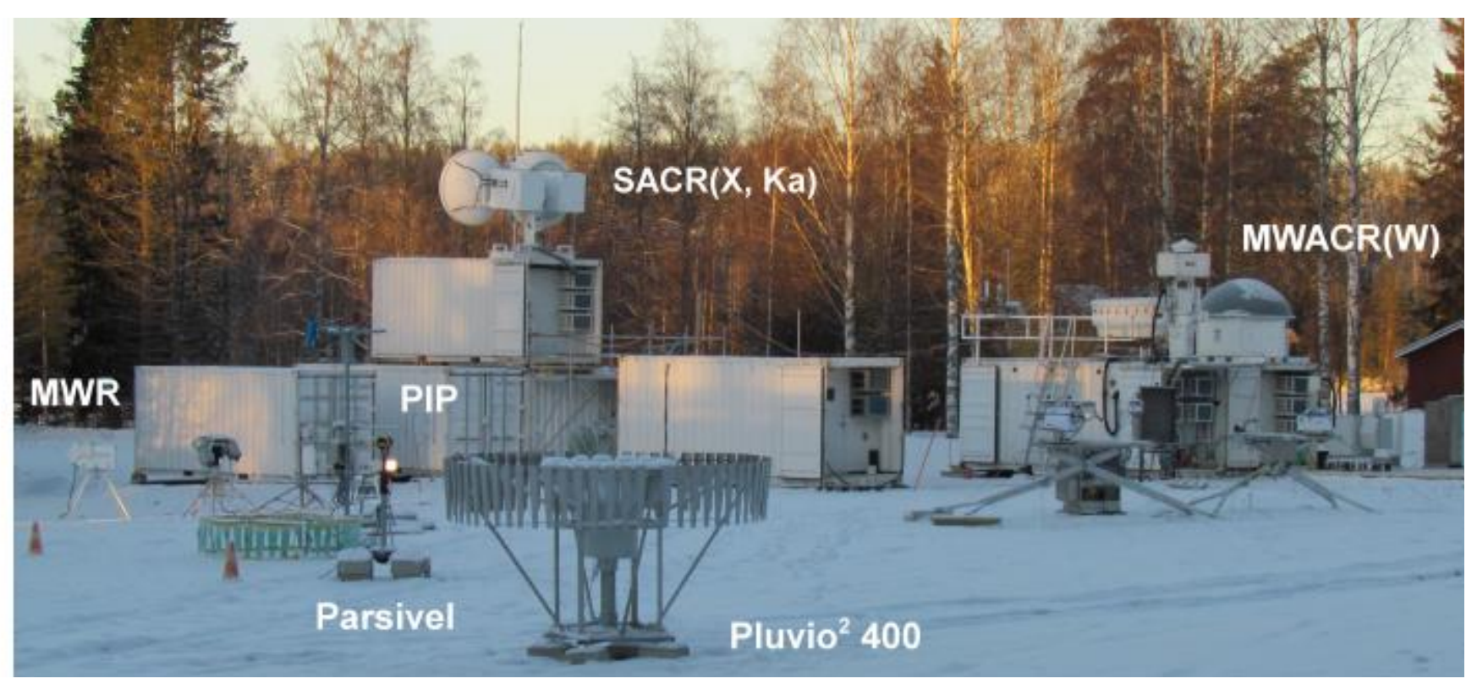
Kneifel[1], Stefan, A. Battaglia[2], P. Kollias[3], J. Leinonen[4], M. Maahn[5], H. Kalesse[6], and F. Tridon[2]
[1]University of Cologne, Germany; [2]University of Leicester, UK; [3]Stony Brook University, USA; [4]JPL, USA; [5]CIRES/NOAA, USA; [6] TROPOS, Germany

1. Motivation

- Fortunately, the **number of available scattering databases** for ice and snow particles in the microwave is **continuously growing**.
- Debates are ongoing whether approximations (T-Matrix, Rayleigh Gans, etc.) provide similar results compared to expensive, complex calculations assuming explicit particle structure (e.g. DDA).
- However, **how can we evaluate these scattering calculations?**
- In most measured variables, like radar reflectivity, backscattering properties and e.g. particle size distribution (PSD) or particle shape properties are difficult to separate.
- Multi-frequency radar observations are a step forward to better constrain PSD and density of snowflakes (e.g. *Kneifel et al., 2015*).
- However, **triple-frequency Doppler spectra provide a unique scattering signature which is nearly independent of PSD**.

2. Triple-frequency reflectivity signatures of (un)rimed snow

Triple-frequency (X, Ka, W-band) vertically pointing radar observations and ground-based in-situ data available from winter 2015 BAECC-SNEX campaign (Hyytiälä site, Finland).



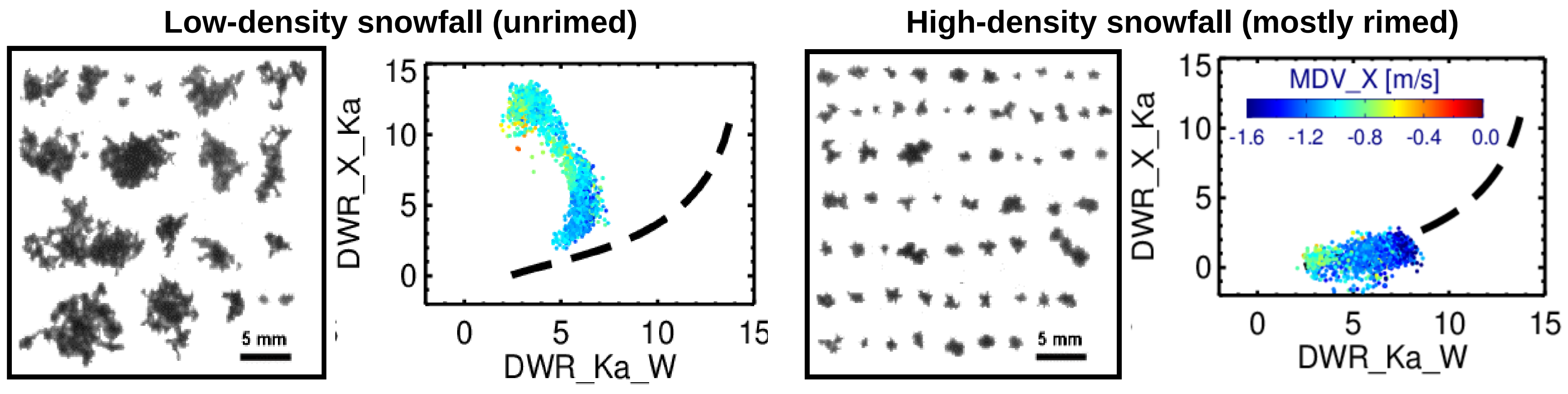
The dual-wavelength ratio is the ratio of the (linear) reflectivities which are the integrals of the Doppler spectra (*S(v)*) at both wavelengths (Eq. (2)). Hence, **PSD and scattering properties cannot be easily separated when looking at spectral moments only**.

$$S_\lambda(v) = \frac{\lambda^4}{\pi^5|K_w|^2}N(D)\sigma_{\mathrm{bsc}}(\lambda,D)\frac{\mathrm{d}D}{\mathrm{d}v} = \frac{\lambda^4}{\pi^5|K_w|^2}N(v)\sigma_{\mathrm{bsc}}(\lambda,v) \qquad (1)$$

$$\mathrm{DWR}_{\lambda_1,\lambda_2} = \frac{\int_{-v_{\mathrm{Nyq}}}^{v_{\mathrm{Nyq}}} S_{\lambda_1}(v)\mathrm{d}v}{\int_{-v_{\mathrm{Nyq}}}^{v_{\mathrm{Nyq}}} S_{\lambda_2}(v)\mathrm{d}v} = \frac{Z_{e,\lambda_1}}{Z_{e,\lambda_2}} \qquad (2)$$

λ: radar wavelength	N(D), N(v): Particle size distribution
v: Doppler velocity	Z_e: Effective radar reflectivity factor
D: Particle diameter	v_{Nyq}: Nyquist velocity of the radar
$\lvert K_w \rvert^2$: Dielectric constant of liquid water	σ_{bsc}: backscattering cross section

Comparison with in-situ data revealed that **pairs of DWRs show strong correlation to characteristic size of PSD but also particle bulk density** (*Kneifel et al., 2015*).


Low-density snowfall (unrimed)

High-density snowfall (mostly rimed)

Sample in-situ (PIP) images and DWRs (radar range gates closest to ground) derived from 6-min long periods of unrimed (left) and rimed (right) snowfall. Color denotes mean Doppler velocity in X-Band (from Kneifel et al., 2015).

References:

Kneifel S., P. Kollias, A. Battaglia, J. Leinonen, M. Maahn, H. Kalesse, and F. Tridon (2016): First Observations of Triple Frequency Radar Doppler Spectra in Snowfall: Interpretation and Applications, *Geophys. Res. Lett.*, 43, 2225–2233, doi: 10.1002/2015GL067618.

Kneifel S., A. von Lerber, J. Tiira, D. Moisseev, P. Kollias, and J. Leinonen (2015): Observed Relations between Snowfall Microphysics and Triple-frequency Radar Measurements, *J. Geophys. Res.*, 120, 6034-6055, doi: 10.1002/2015JD023156.

Leinonen, J., and W. **Szyrmer** (2015): Radar signatures of snowflake riming: A modeling study, *Earth and Space Science*, 2, 346–358, doi:10.1002/2015EA000102.

Hogan, R. J., and C. D. **Westbrook** (2014): Equation for the microwave backscatter cross section of aggregate snowflakes using the Self-Similar Rayleigh-Gans Approximation, **J. Atmos. Sci.**, 71, 3292-3301.

3. Using Doppler spectra to get rid of N(D) influence

Under certain conditions we can directly relate the ratio of the real measured Doppler spectra (*Sr(v)*) at two wavelengths to the ratio of backscattering coefficients of the underlying particles (*Kneifel et al., 2016*).

$$\mathrm{DSR}_{\lambda_1,\lambda_2}(v) = \frac{Sr_{\lambda_1}(v,r)}{Sr_{\lambda_2}(v,r)} \approx \left(\frac{\lambda_1}{\lambda_2}\right)^4 \frac{\sigma_{\mathrm{bsc}}(\lambda_1,v)}{\sigma_{\mathrm{bsc}}(\lambda_2,v)} \qquad (3)$$

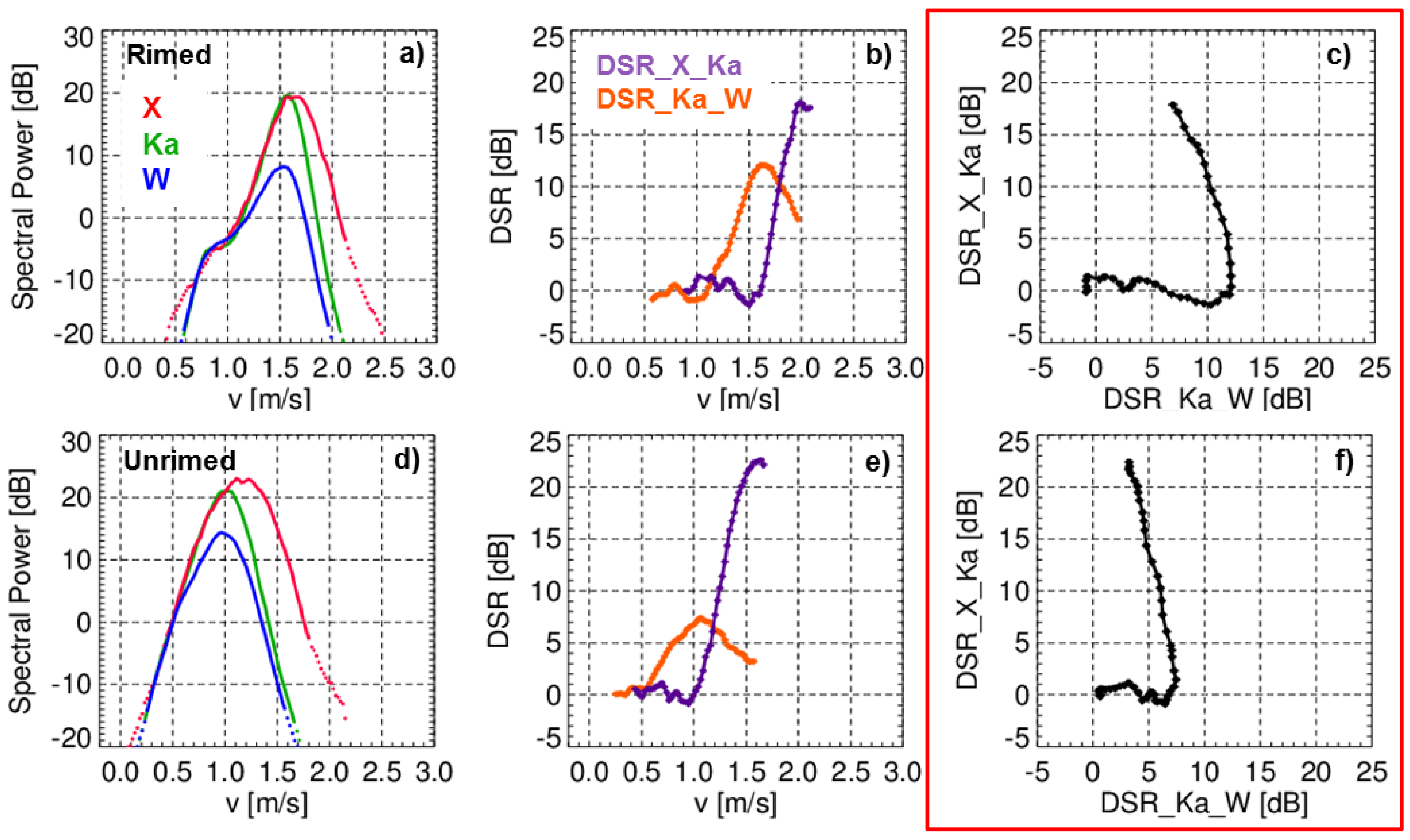
The Dual spectral ratio (DSR) is only equal to the backscattering ratio if

- differential attenuation is small or possible to correct
- turbulence-induced spectral broadening is small
- N(v) ≈ N(v+δv) and $\sigma_{\mathrm{bsc}} \approx \sigma_{\mathrm{bsc}}(v+\delta v)$ (valid if spectral resolution of Doppler spectra is high)

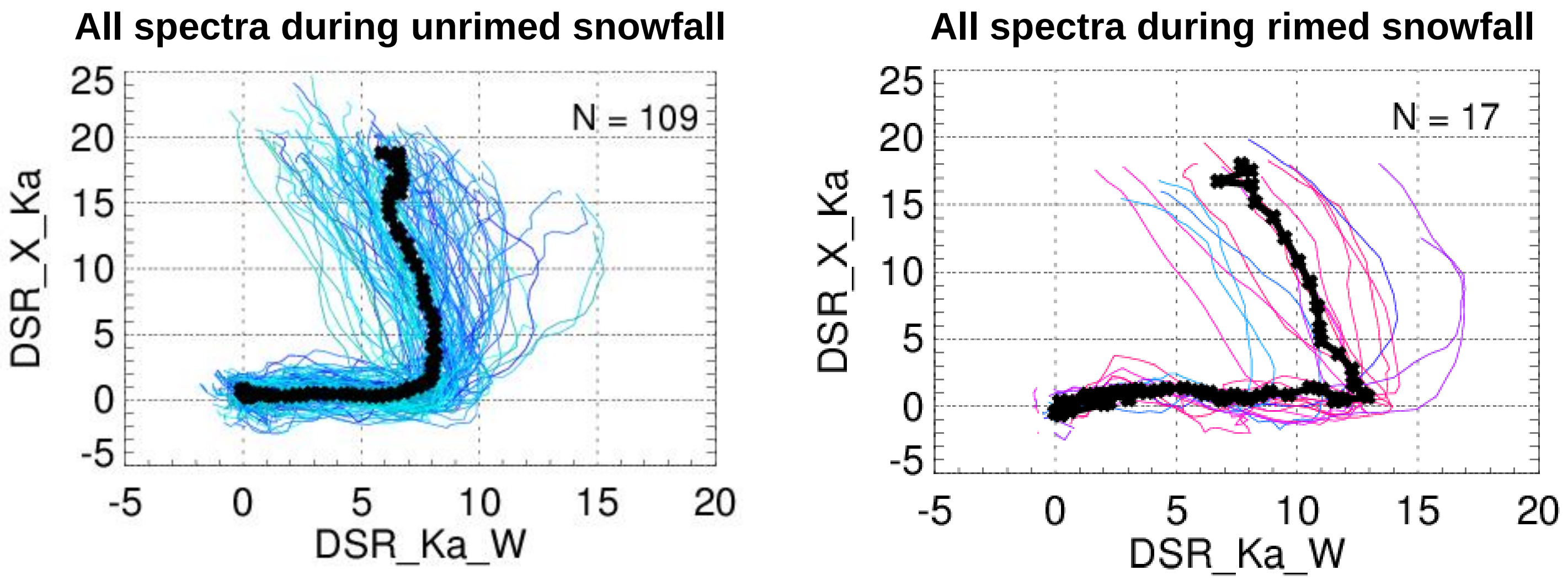
DSR derived from multi-frequency Doppler spectra is nearly independent of N(D) and can be directly compared to the backscattering ratio from scattering databases.

4. Unique spectral triple-frequency scattering signature

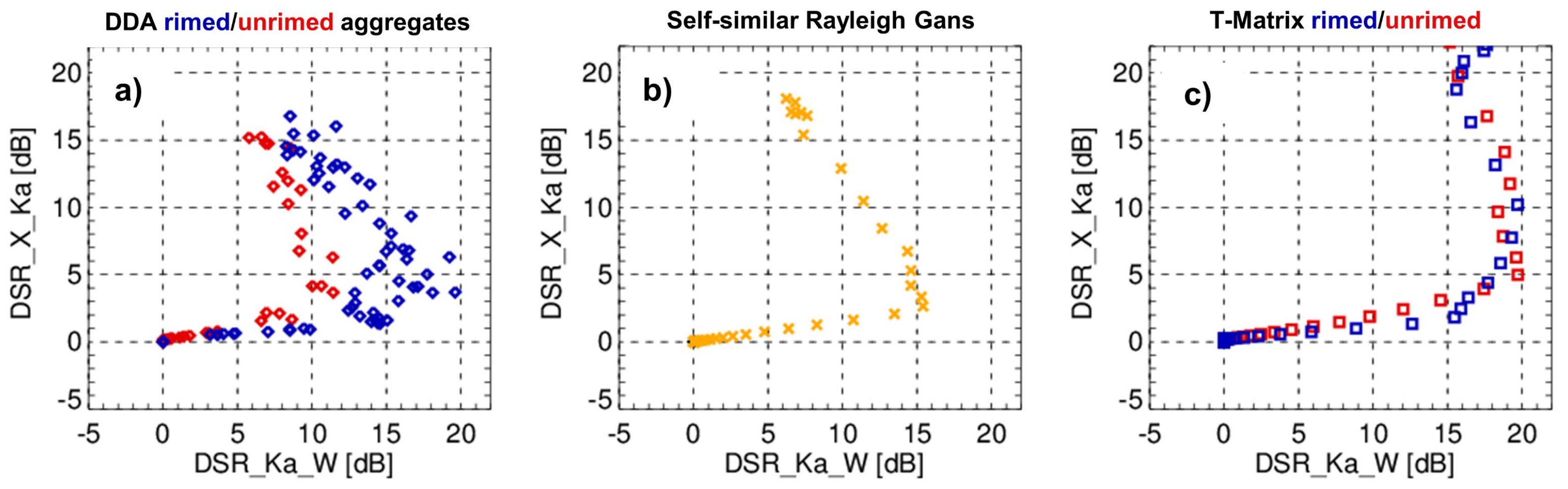
We saw that DSR(v) is independent of N(D). However, **DSR is still a function of the Doppler velocity v**. In order to compare with scattering databases, we still have to convert from the particle size space into the velocity space which is not trivial (Eq. (1)). With triple-frequency spectra, we can **derive a signature which does not depend on v** anymore:

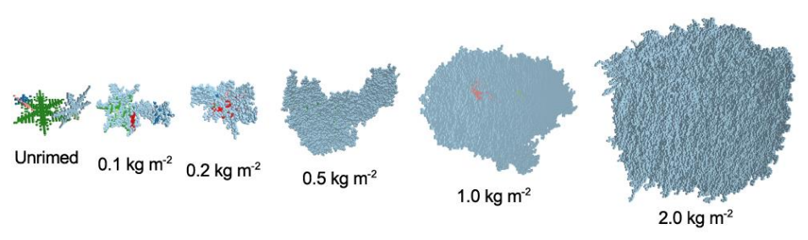


From left to right: Collocated radar Doppler spectra at X, Ka, and W-band (positive velocity means downward). Derived dual spectral ratios (DSR, Eq. (3)) of frequency pairs. Resulting DSR-DSR curve (independent of velocity) when plotting one DSR as function of the other frequency pair. Upper panels show period of rimed snow while lower panel is from a period of unrimed snowfall (from Kneifel et al., 2016).

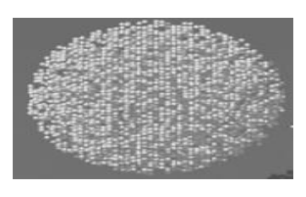

All spectra during unrimed snowfall

All spectra during rimed snowfall





Scattering calculations:
DDA/T-Matrix: Leinonen and Szyrmer, 2015
SS-Rayleigh Gans: Hogan and Westbrook, 2014



Contact: skneifel@meteo.uni-koeln.de