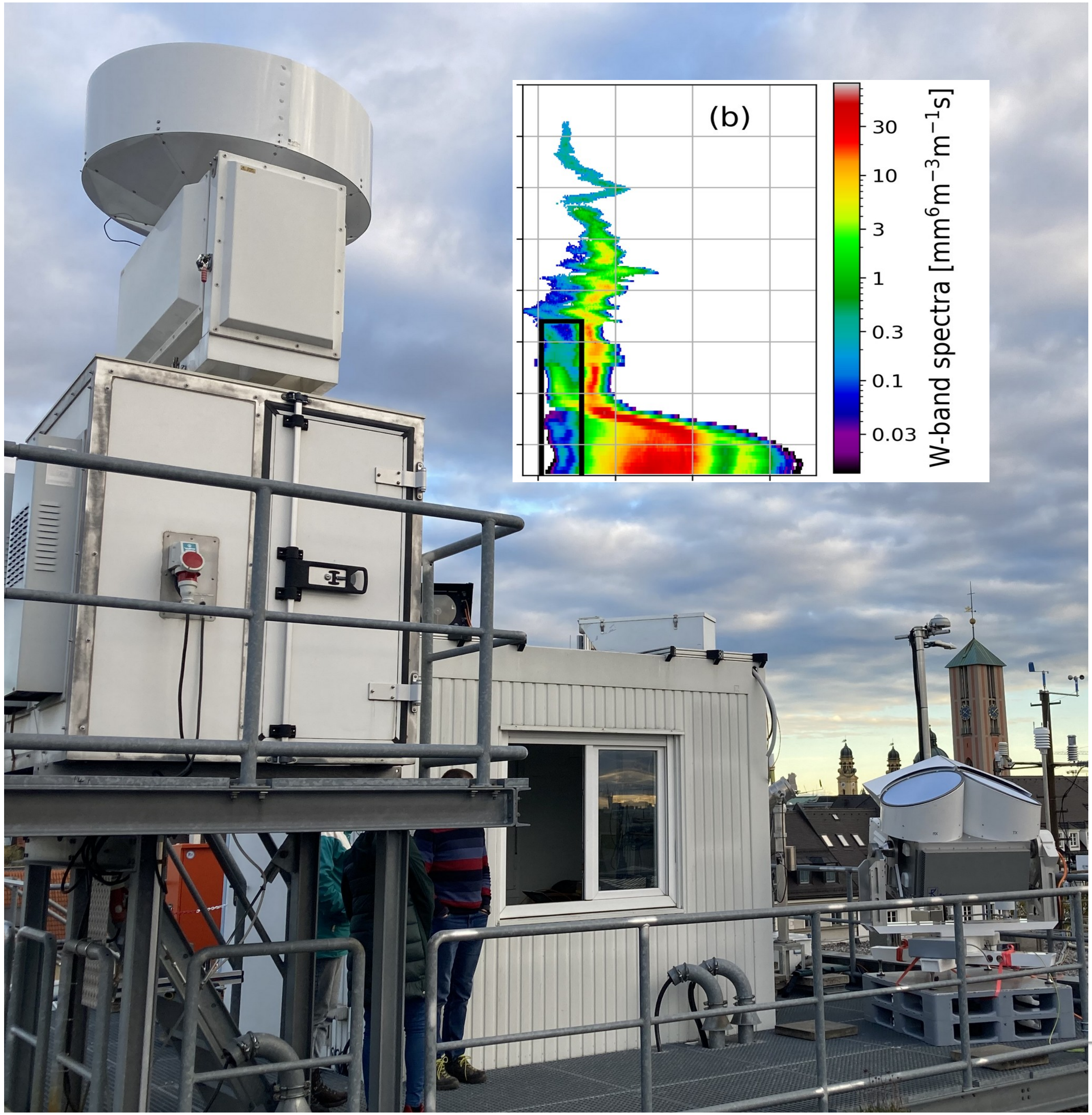

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Visualisation and Interpretation of Radar Doppler Spectra

Stefan Kneifel (LMU)

(with material from A. Battaglia, P. Kollias & E. Luke)

CCRES/CLU Training school, Munich, 2-5 Sept. 2025

Outline

- Motivation: From mean Doppler velocity to Doppler spectra
- The ideal quiet-air Doppler spectrum in rain
- Moving air: Spectral broadening and shifting
- Microphysical information in Doppler spectra
- Outlook

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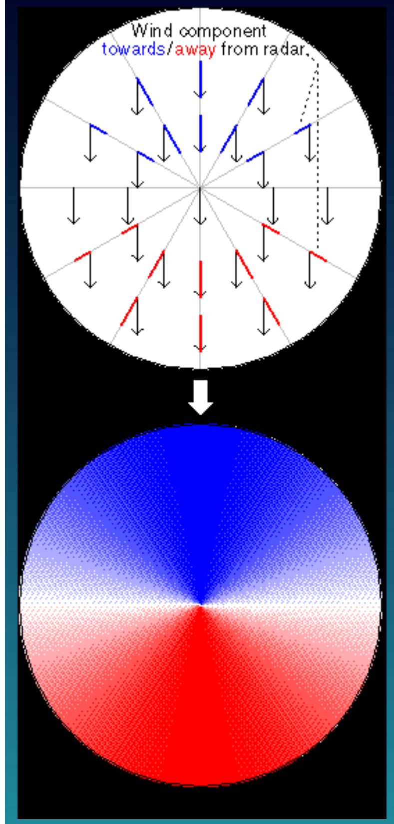
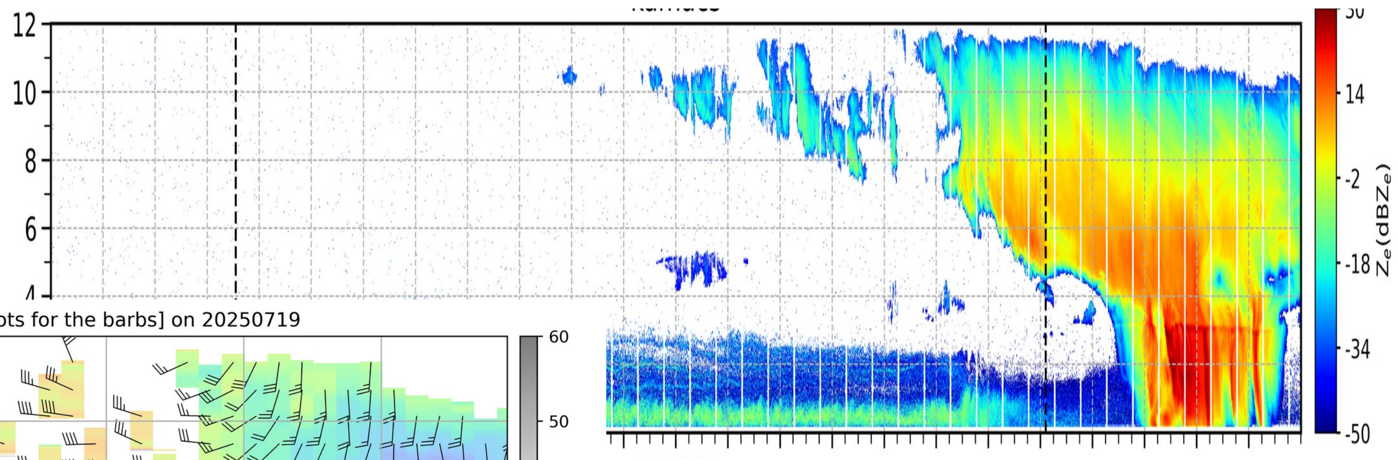
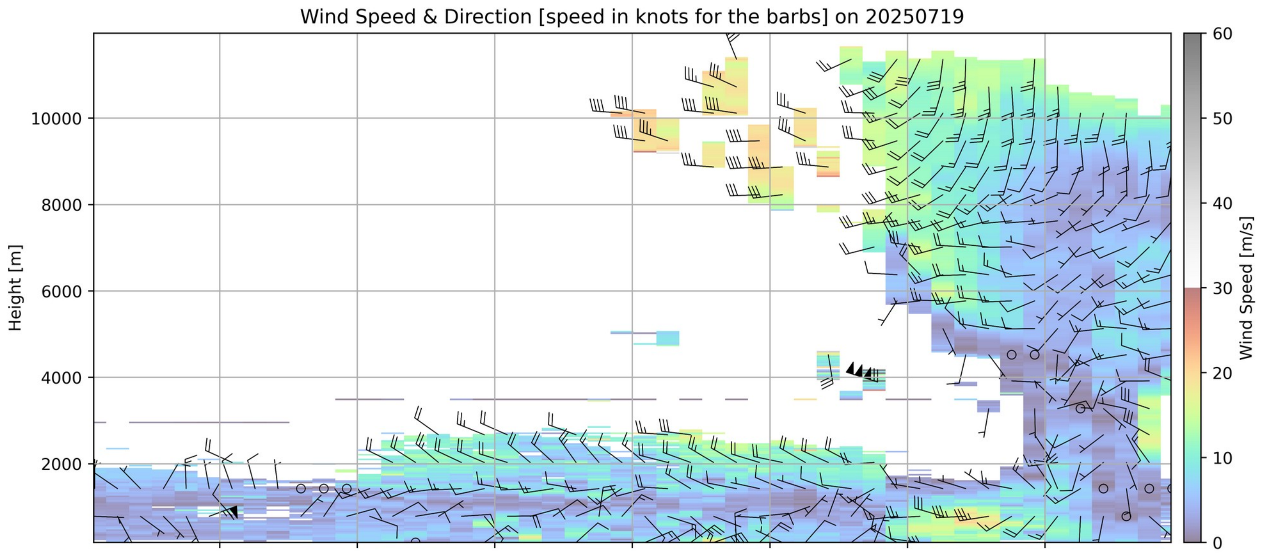
Doppler velocity measurement

- Essentially all cloud and precipitation radars (recently even satellite radars - EarthCare) can measure radial Doppler velocity
- At non-zenith elevation angles, the Doppler signal is usually dominated by the horizontal wind





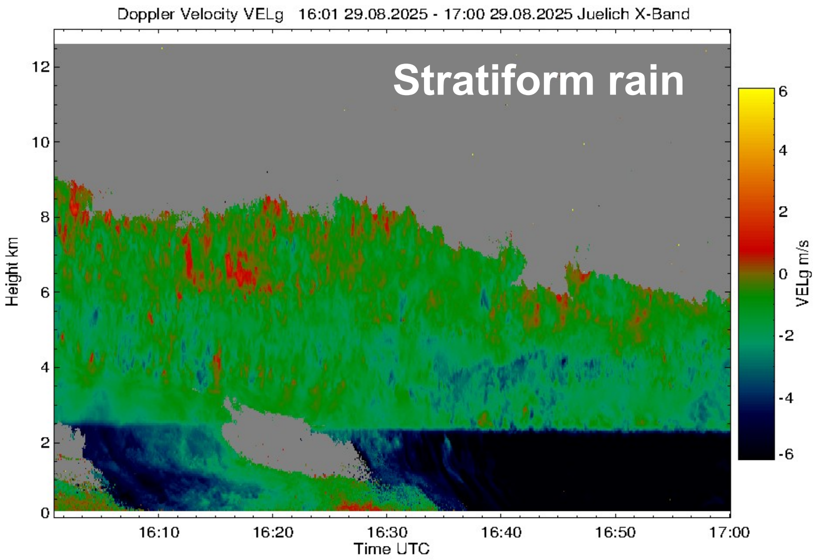


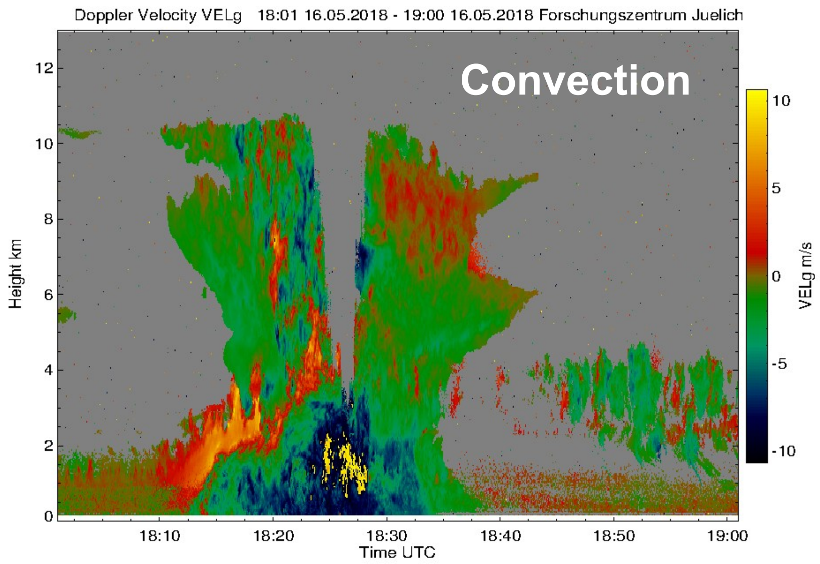
Horizontal wind speed and direction derived with LMU Ka-band (7° off-zenith PPI)

Doppler signal in vertically pointing radars

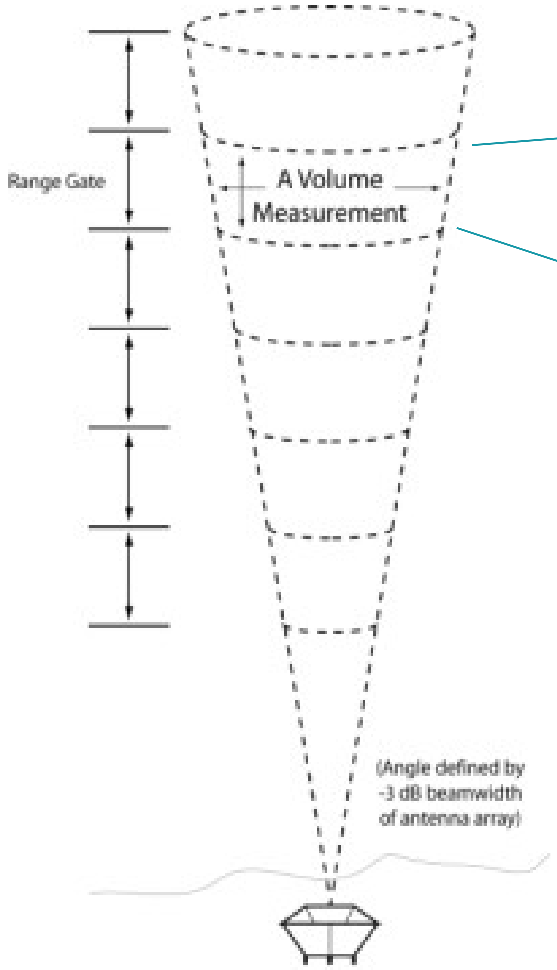
- For an exactly vertically pointing radar:
  - horizontal wind no effect (90° to beam axis)
  - maximum sensitivity to particle fall velocity
  - vertical wind

- (Vertical) Doppler velocity v_D is sum of particle's sedimentation velocity v_{sed} and vertical wind w: $v_D = v_{sed} + w$

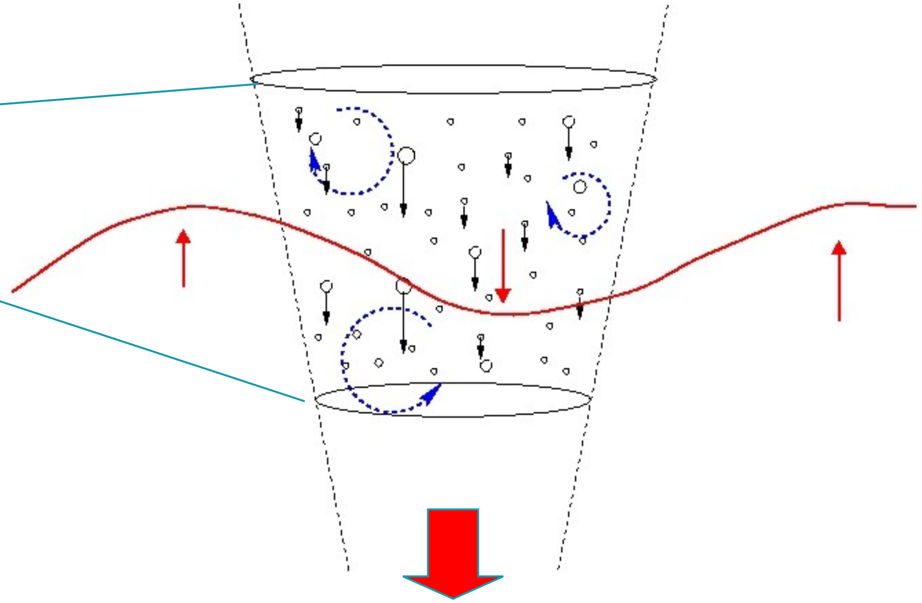


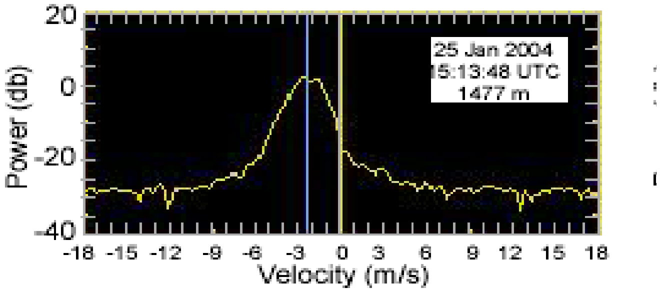


All Doppler radars measure Doppler spectra



A Wind Profiler is an example of a remote sensing instrument





The Doppler spectrum is the particle's reflectivity sorted by their radial velocities.

Potential for separating hydrometeors using spectra

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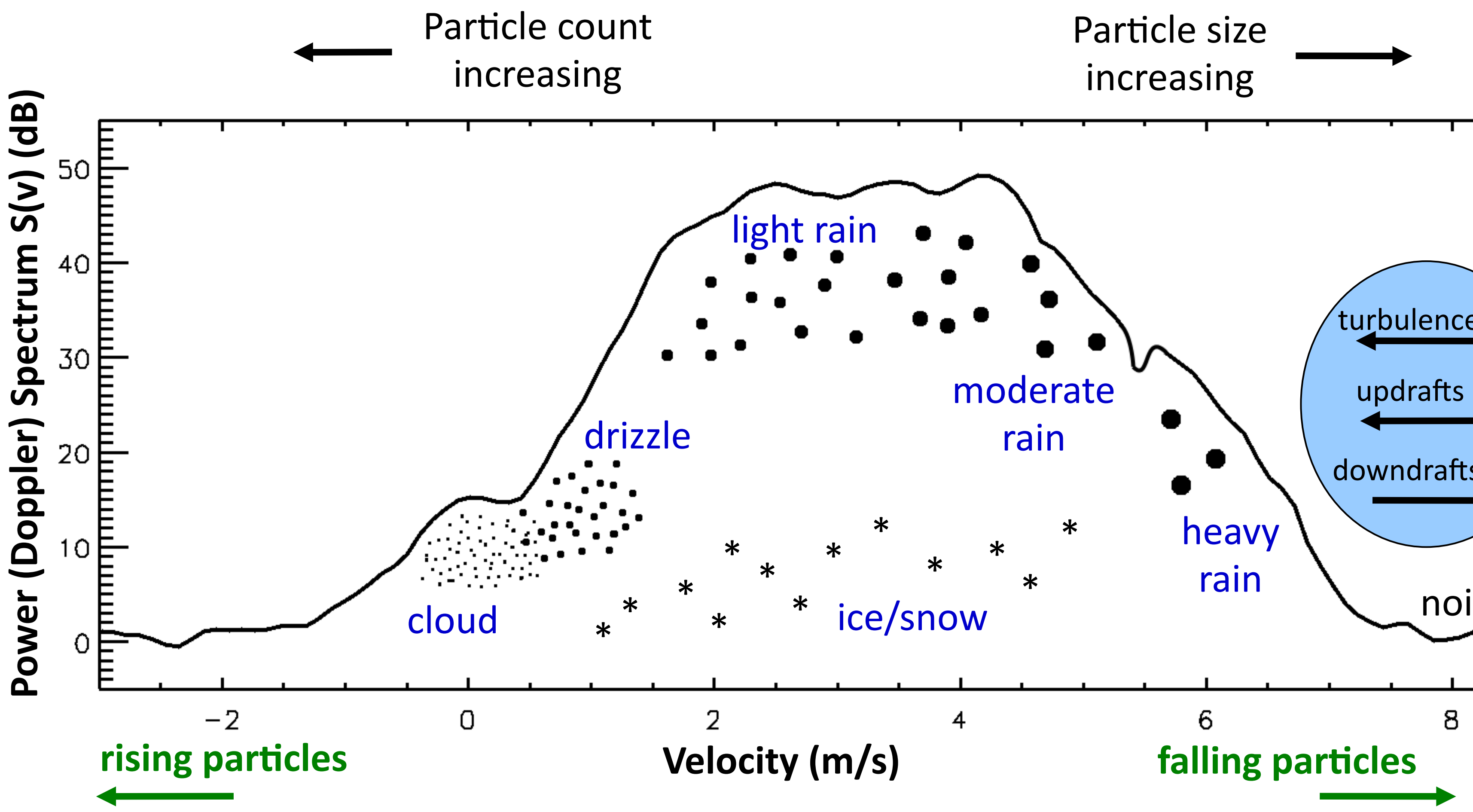

The Doppler spectrum can help to separate the signal of different hydrometeor types if they have distinct fall velocities

The potential of Doppler spectra was seen early on…

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REVIEWS OF GEOPHYSICS AND SPACE PHYSICS, VOL. 11, NO. 1, PP. 1–35, FEBRUARY 1973

Doppler Radar Characteristics of Precipitation at Vertical Incidence

D. ATLAS,[1] R. C. SRIVASTAVA, AND R. S. SEKHON

Department of Geophysical Sciences
University of Chicago, Chicago, Illinois 60637

A comprehensive review and extension of the theoretical bases for the measurement of the characteristics of rain and snow with vertically pointing Doppler radar are presented. The drop size distribution in rain can be computed from the Doppler spectrum, provided that the updraft can be estimated, but difficulties are involved in the case of snow. Doppler spectra and their moments are computed for rain by using various power law relations of fall speed v versus particle diameter D and an exponential fit to the actual fall speed data. In the former case, there is no sharp upper

The ideal quiet air Doppler spectrum in rain

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- Usually, a radar volume is filled with many particles having different sizes ***D***, fall velocities ***v***, and backscattering cross sections $\boldsymbol{\sigma_b}$
- Particles with a specific size *D* and number concentration ***N(D)*** produce a signal ***S(D)*** reflected back to the radar receiver

$$S(D) = \frac{\lambda^4}{\pi^5 |K|^2} N(D)\, \sigma_b(D)$$

only for Rayleigh scatterers: $\sigma_b(D) \propto D^6$

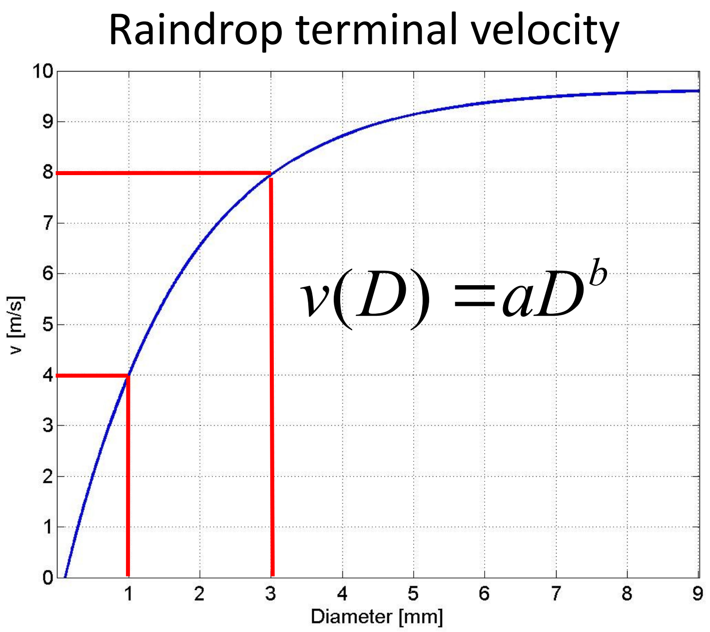
with the radar wavelength λ and $|K|^2$ being a constant related to the refractive index of liquid water (ca. 0.93).

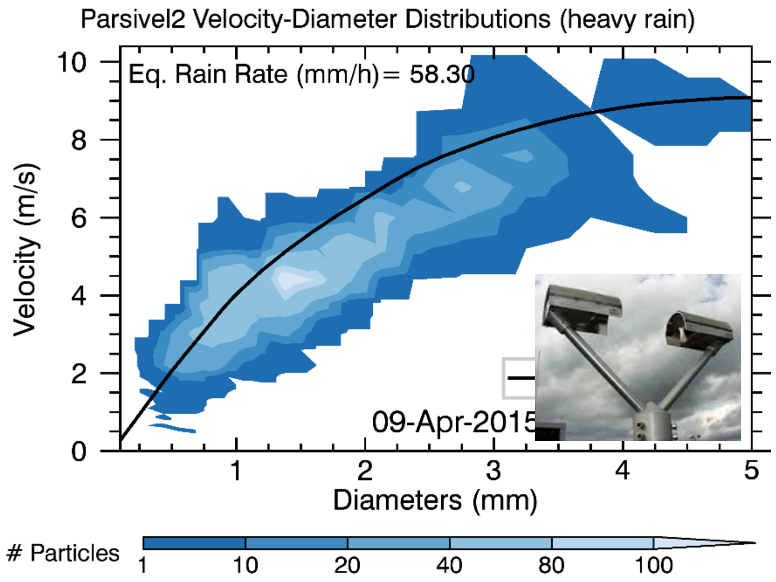
- The total reflected power from all different particle sizes is usually expressed as **radar reflectivity factor *Ze*** and is simply the integral over S(D):

$$Ze = \frac{\lambda^4}{\pi^5 |K|^2} \int_{D_{\min}}^{D_{\max}} N(D)\, \sigma_b(D)\, dD \quad [mm^6 m^{-3}]$$

Relation of fall velocity and rain drop size

- With a Doppler radar we do not only get the strength of the backscattered signal but also the (Doppler) velocity of the scattering particles.
- In case of quiet air (e.g. no vertical wind) this Doppler velocity is equal to the particle's fall velocity



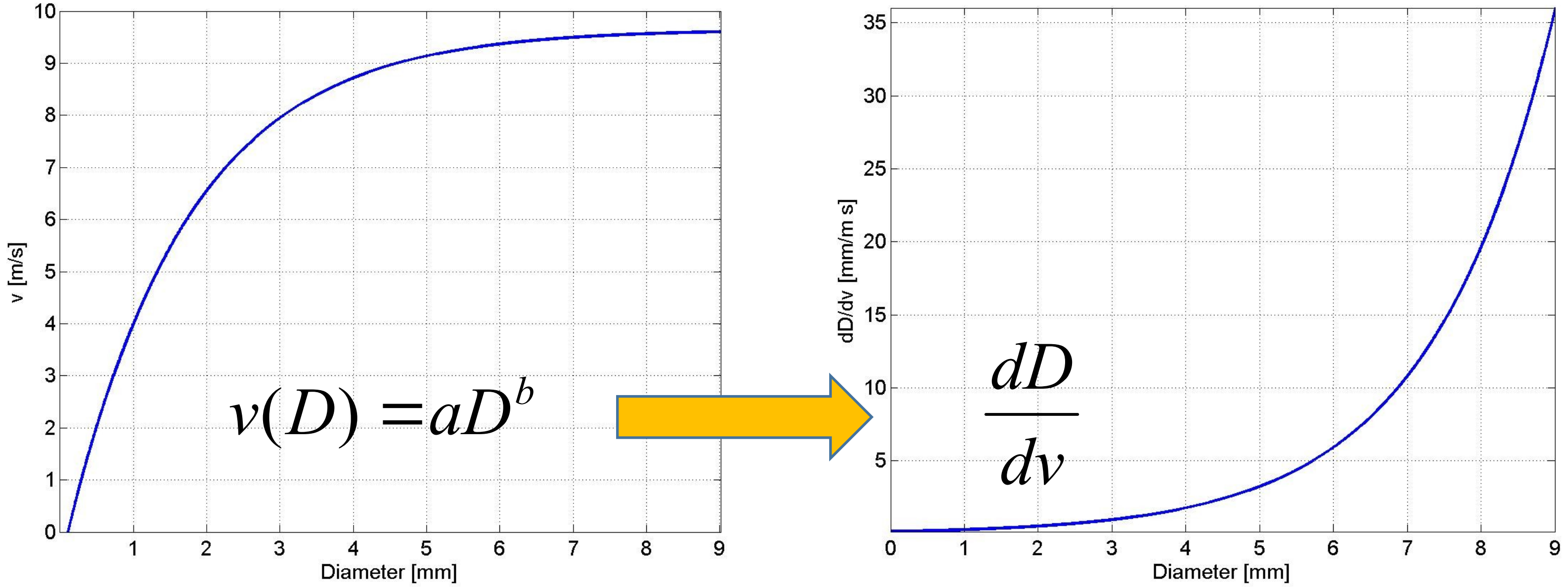


Left image: Real measured v(D) relation measured with an optical disdrometer (PARSIVEL)

Doppler spectrum *S(v)*

- With the v(D) relation, we can write S(D) also as function of velocity S(v):

$$Ze = \frac{\lambda^4}{\pi^5 |K|^2} \int_{D_{\min}}^{D_{\max}} N(D)\, \sigma_b(D)\, dD = \int_{v(D_{\min})}^{v(D_{\max})} \underbrace{\frac{\lambda^4}{\pi^5 |K|^2} N(D)\, \sigma_b(D) \frac{dD}{dv}}_{S(v)} dv$$



Ideal quiet air Doppler spectrum for rain

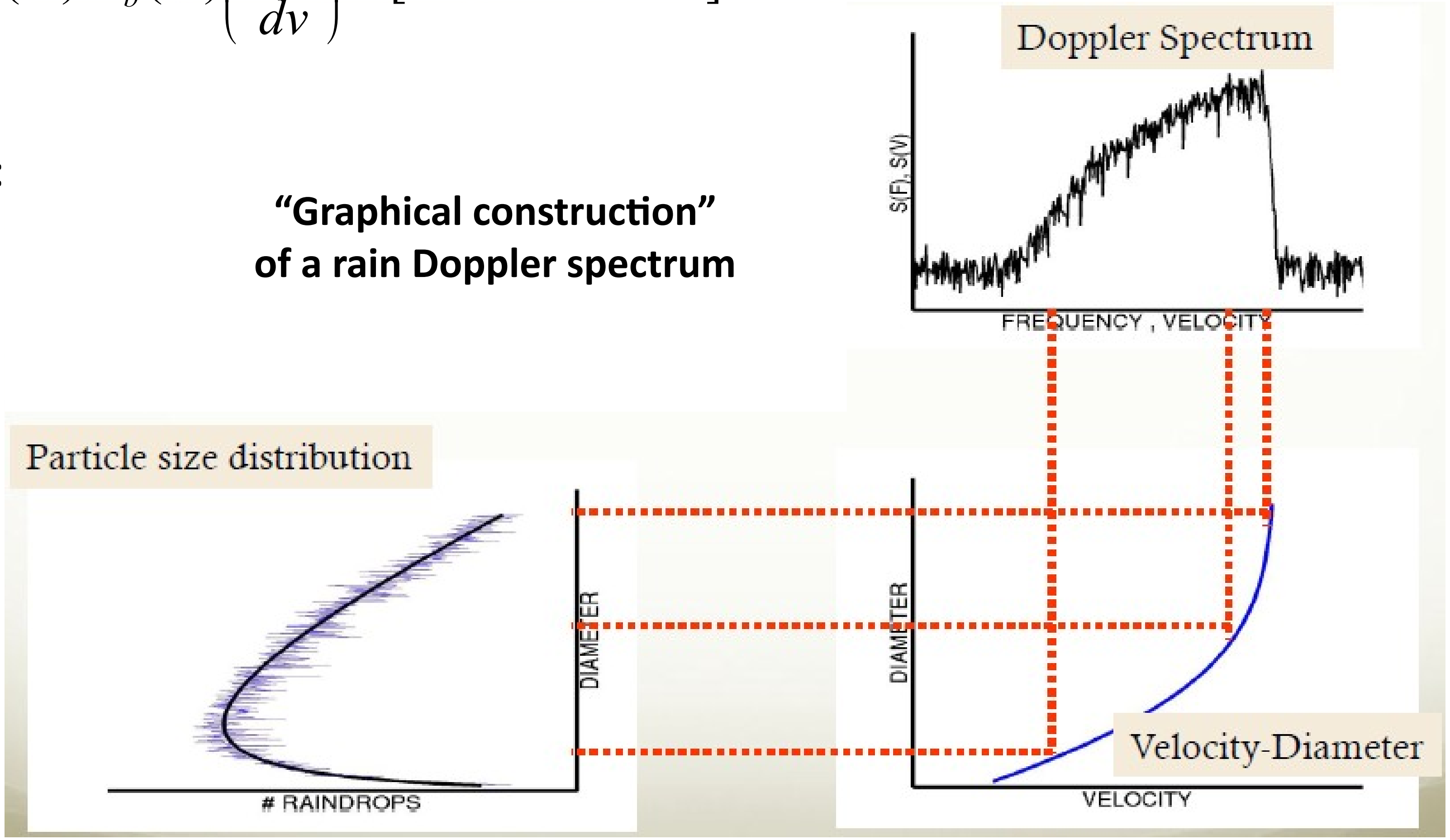
Spectral reflectivity factor:

$$S(v) = \frac{\lambda^4}{\pi^5 |K|^2} N(D)\, \sigma_b(D) \left(\frac{dD}{dv} \right) \quad [mm^6 m^{-3} / ms^{-1}]$$

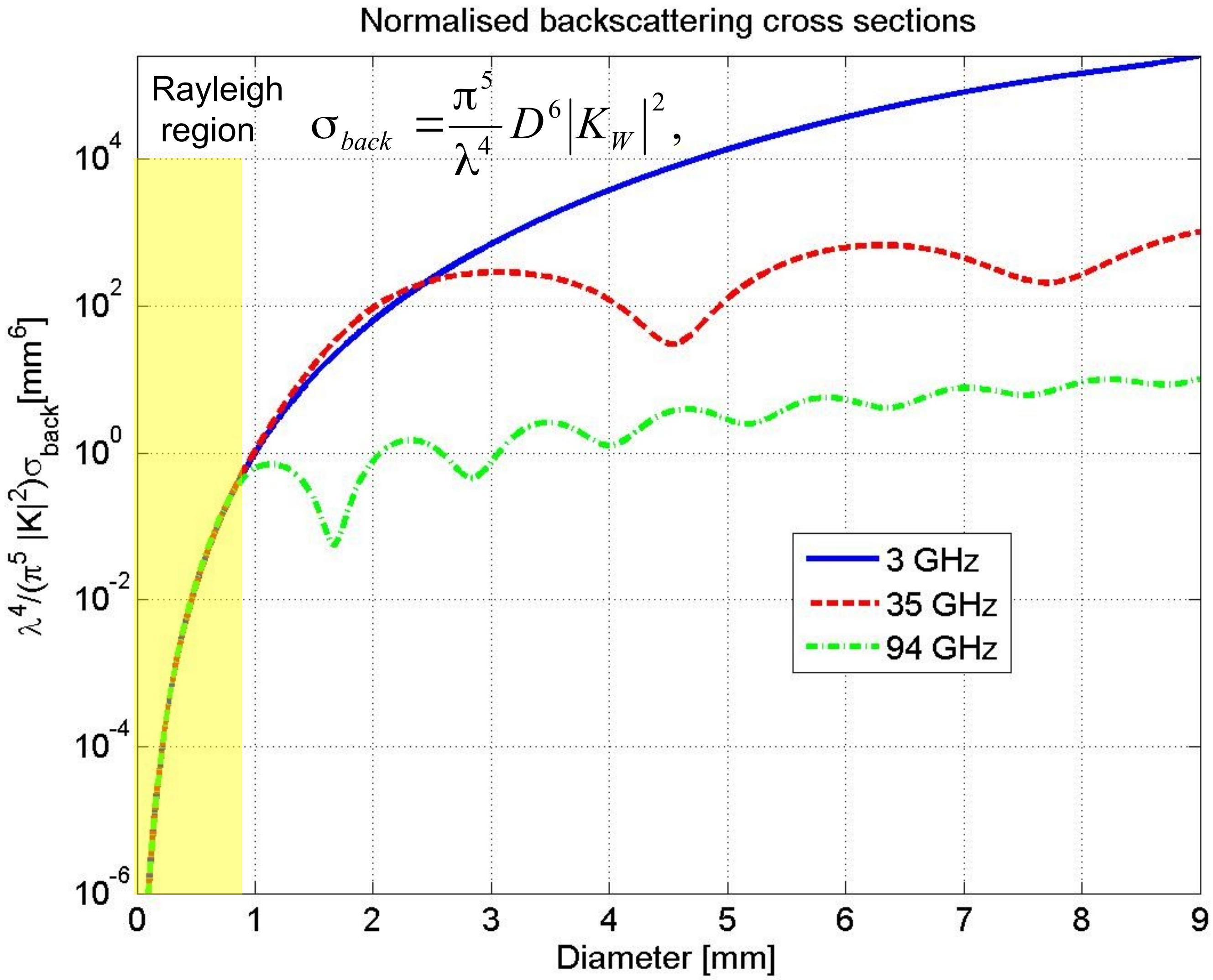
For C, S, X-band:

$$\sigma_b(D) \propto D^6$$

“Graphical construction” of a rain Doppler spectrum



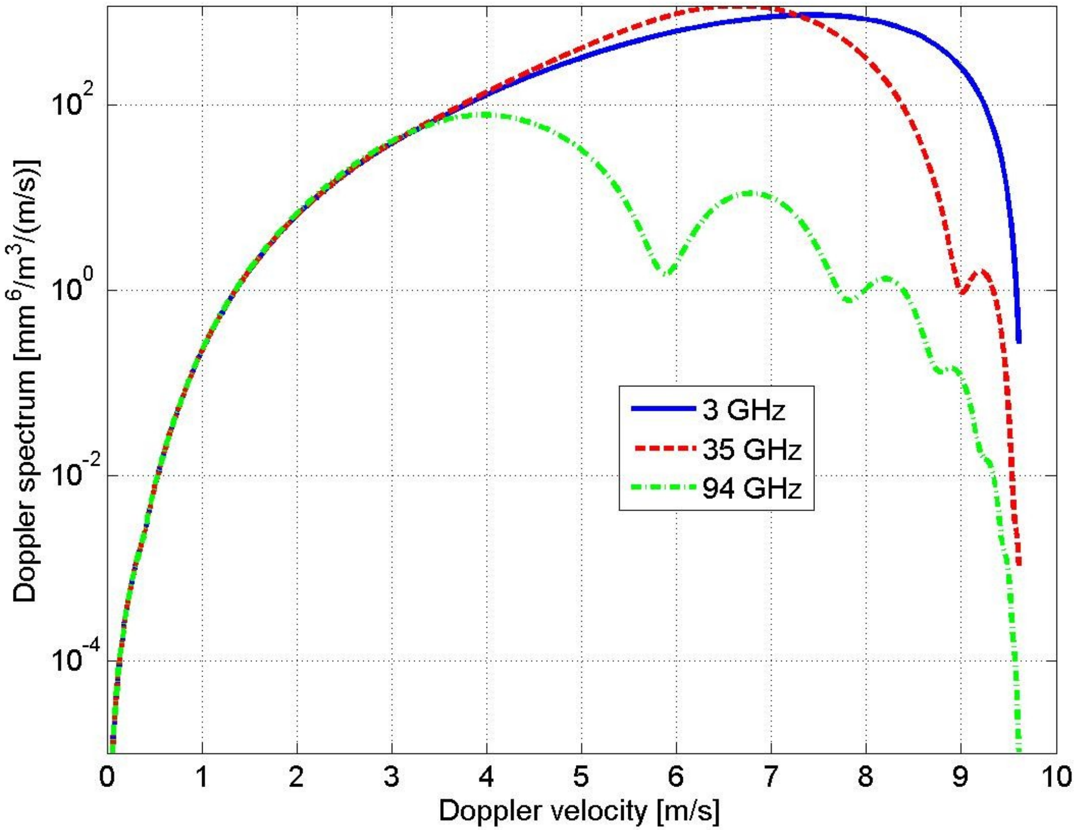
Backscattering at cloud radar wavelengths



- In general, the backscattering at lower wavelengths is lower than for pure Rayleigh scattering
- This is due to destructive intereference inside the drop which also causes specific dips at certain diameters
- However, the Mie-dips can be quite useful for determining/correcting for vertical wind (Kollias et a., 2002)

The most simple Doppler spectral rain DSD retrieval

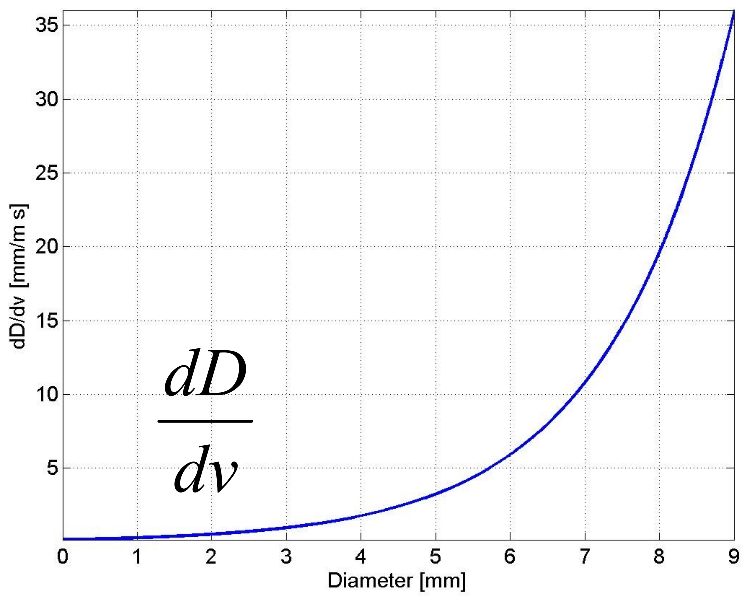
$$S(v) = \frac{\lambda^4}{\pi^5 |K|^2} n(D)\, \sigma_{back}(D) \left(\frac{dD}{dv} \right) \quad [mm^6 m^{-3} / ms^{-1}]$$

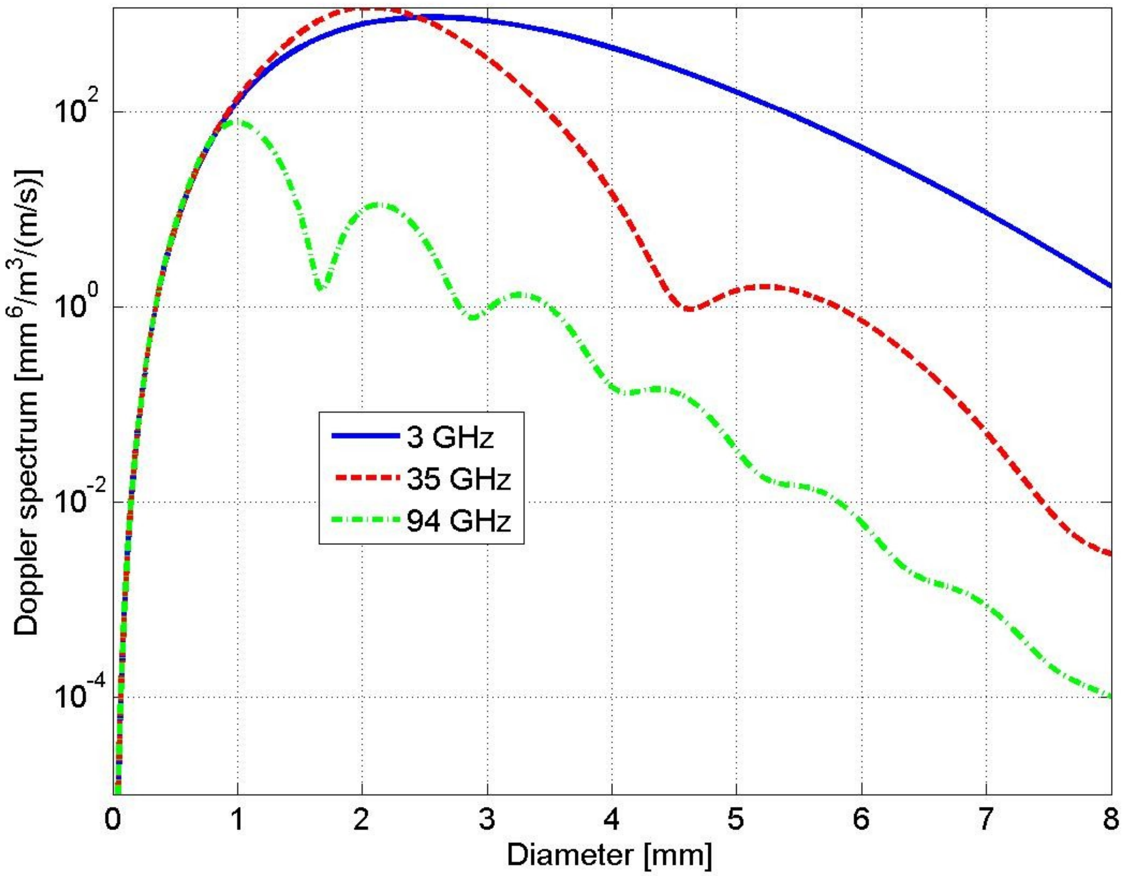


We measure the Doppler spectrum ***S(v)*** at one or multiple wavelengths with our radars…

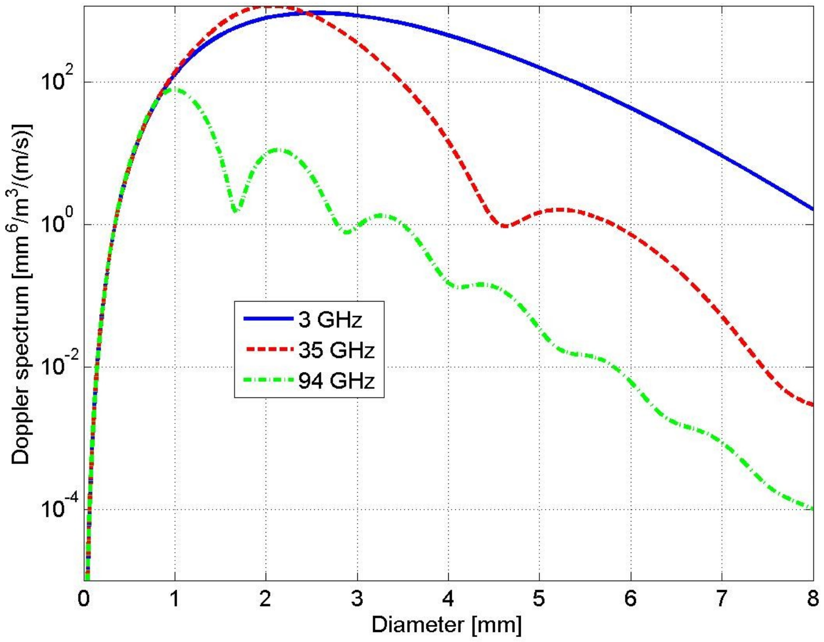
The most simple Doppler spectral rain DSD retrieval

We use a v(D) relation for rain to map the velocity space into diameters and **we obtain *S(D)***

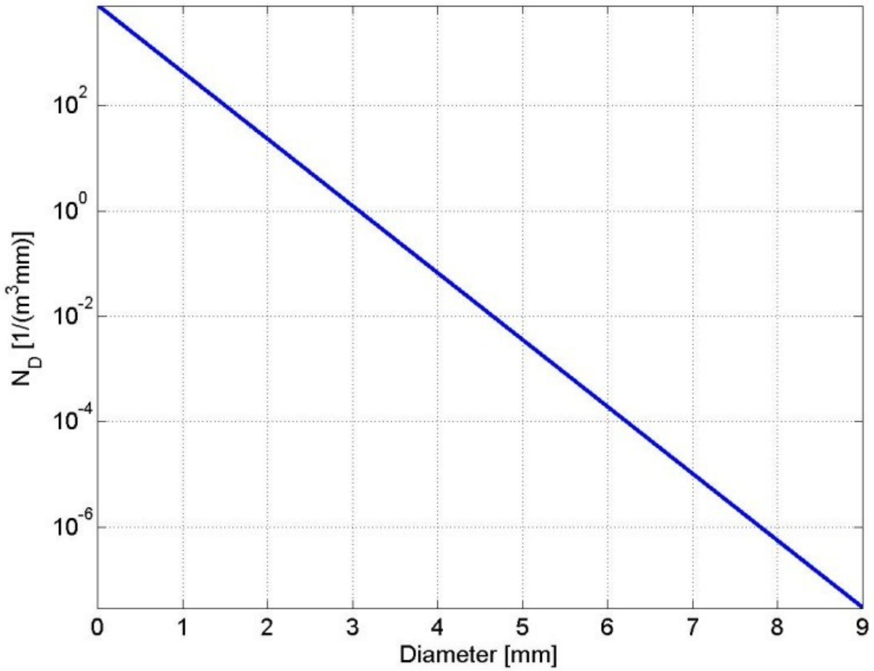




The most simple Doppler spectral rain DSD retrieval



$$N(D) = \frac{S(D)}{\sigma_{bsc}(D)}$$



Now, we just devide the signal in each velocity bin by its single-particle backscattering cross section and we obtain N(D)

(Basics of the MRR rain DSD approach)

What happens to our spectra if the air IS moving?

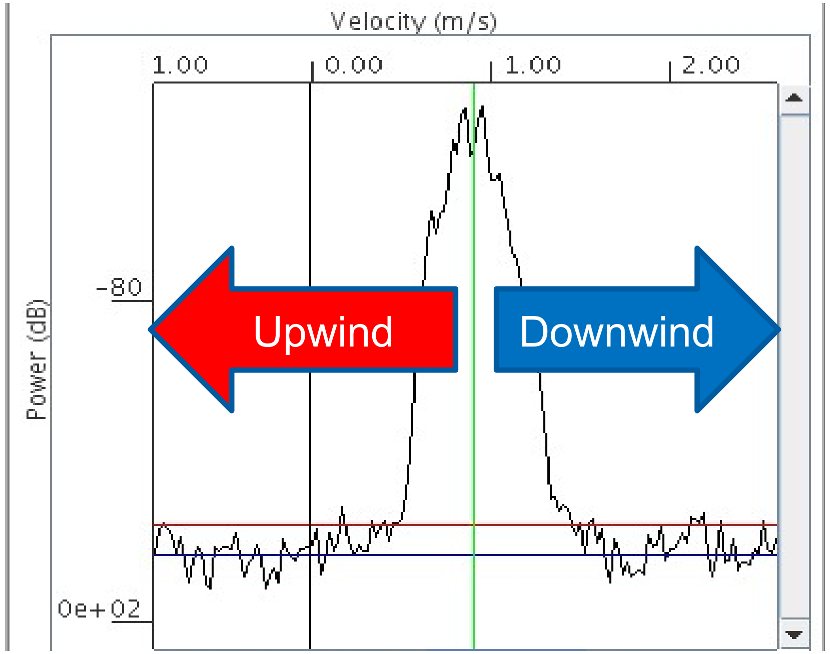
Spectral broadening and shifting

(see e.g., Doviak and Zrnic textbook for deeper reading)

Spectral shifting due to vertical wind

- If we assume that all particles in the volume are affected by the vertical wind in the same way, **vertical wind will simply shift the spectrum left or right**

- The shape of the spectrum does not change



How to correct for vertical air motion?

- Use signal of air tracer: Super-cooled liquid cloud droplets (ca. 0 m/s)
- Use scattering signature (Mie-dip of rain) related to specific diameter (velocity)
- Use statistical relation between Ze and MDV (only ice cloud)

Spectral shifting due to attenuation

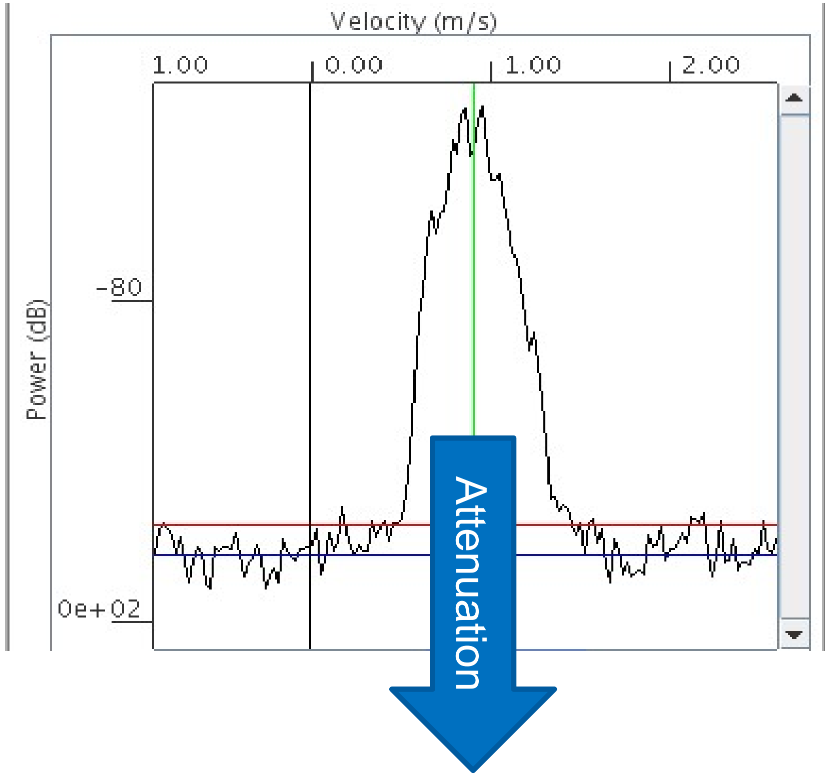
- As attenuation is affecting all particles in the same way (propagational property), attenuation will shift the spectrum „downwards“

- Shape of spectrum unaffected

- Most relevant at W-band; rain, melting layer and super-cooled liquid main contributors

<u>How to correct for attenuation?</u>

- Use collocated low-frequency radar (X-Band) which is unaffected by attenuation
- Use low-velocity spectral region (Rayleigh pleateau) for dual-wavelength (Ka-W) radars (only relative attenuation correction)

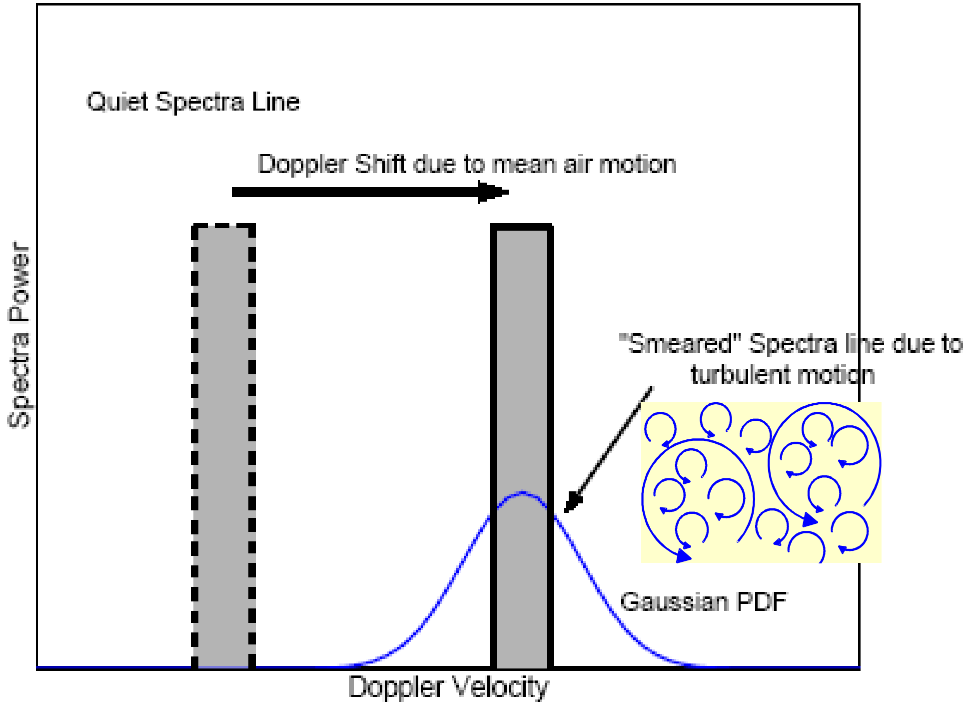


Effect of turbulence

1. Let‘s assume we have a mono-disperse (only one size for all particles) PSD: This would produce a Doppler velocity peak in still air, since all particles have the same fall velocity.

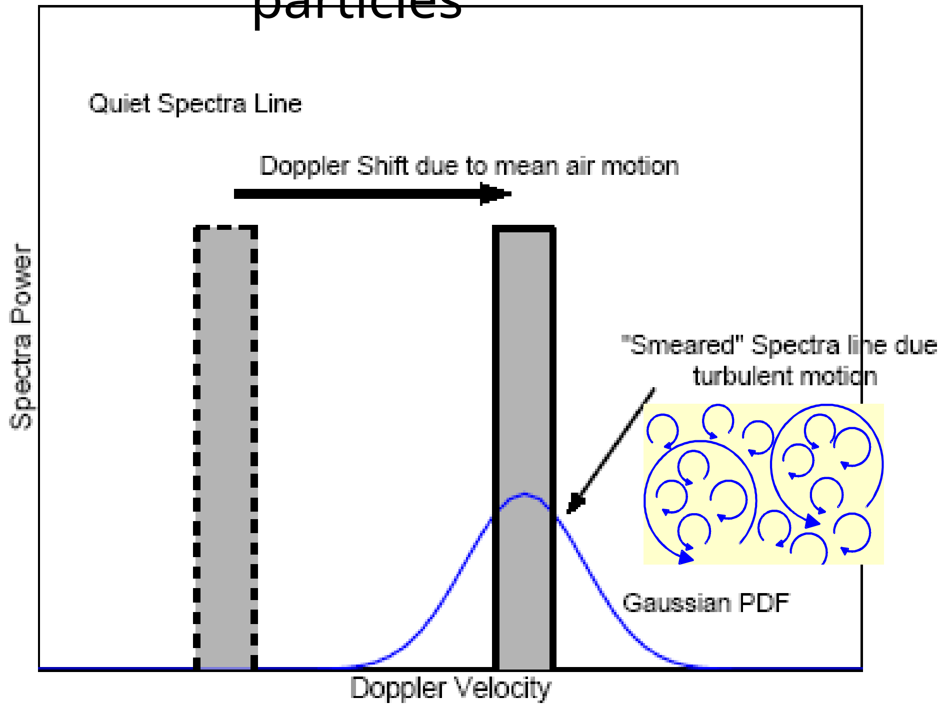
2. Turbulent air motions will slow down some droplets due to turbulent upward motions, others might accelerate due to downward motions.

3. Since the turbulent fluctuations are random (assuming normal distribution), our peaks gets transformed into a gaussian spectrum even though we have still just one particle size!

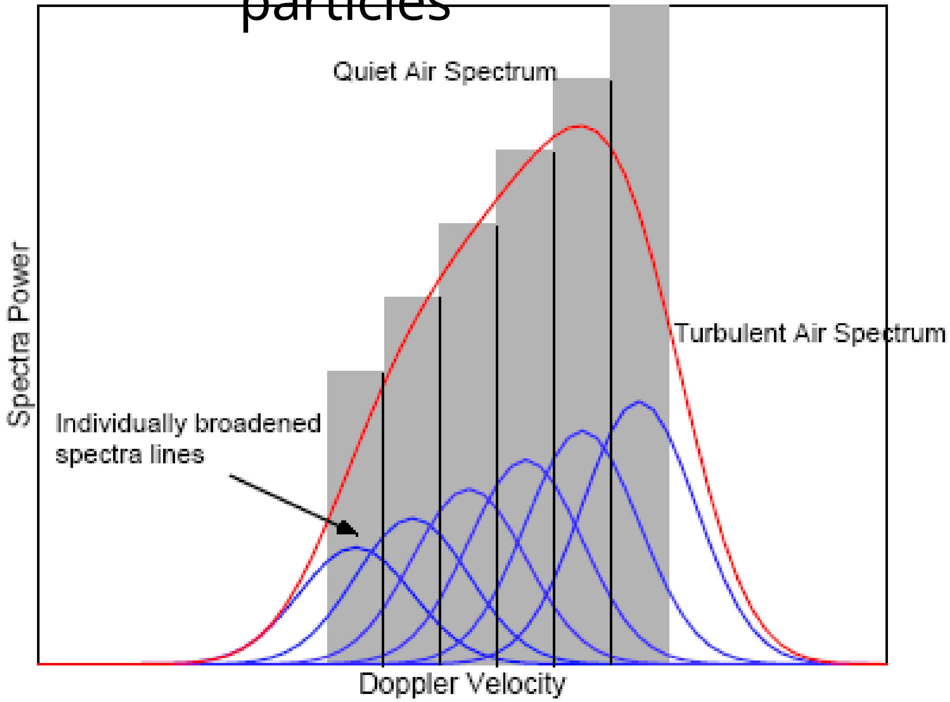


Effect of turbulence

One size particles

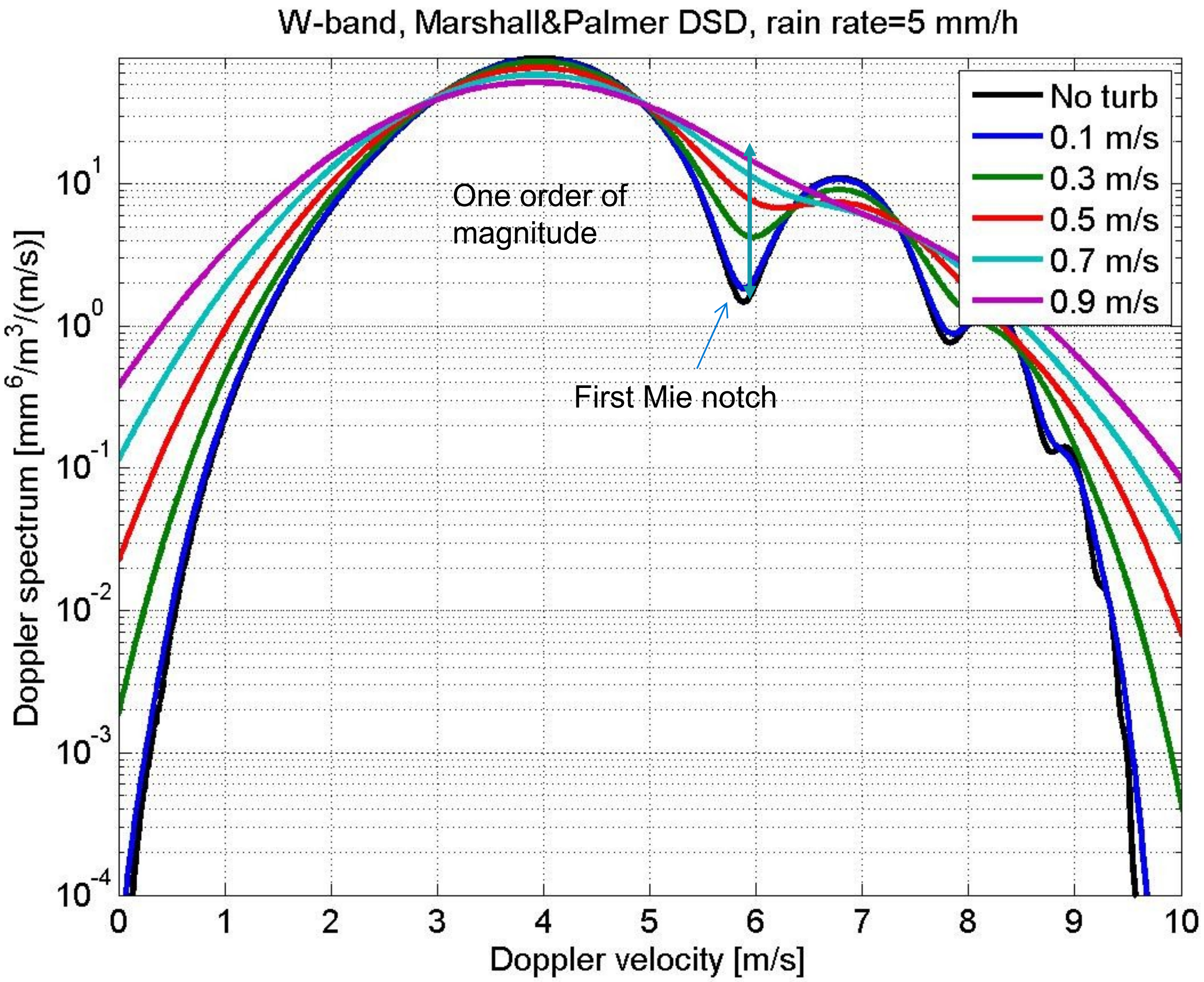


Different size particles



Turbulence broadens the spectrum and smears out microphysical features!

Effect of turbulence



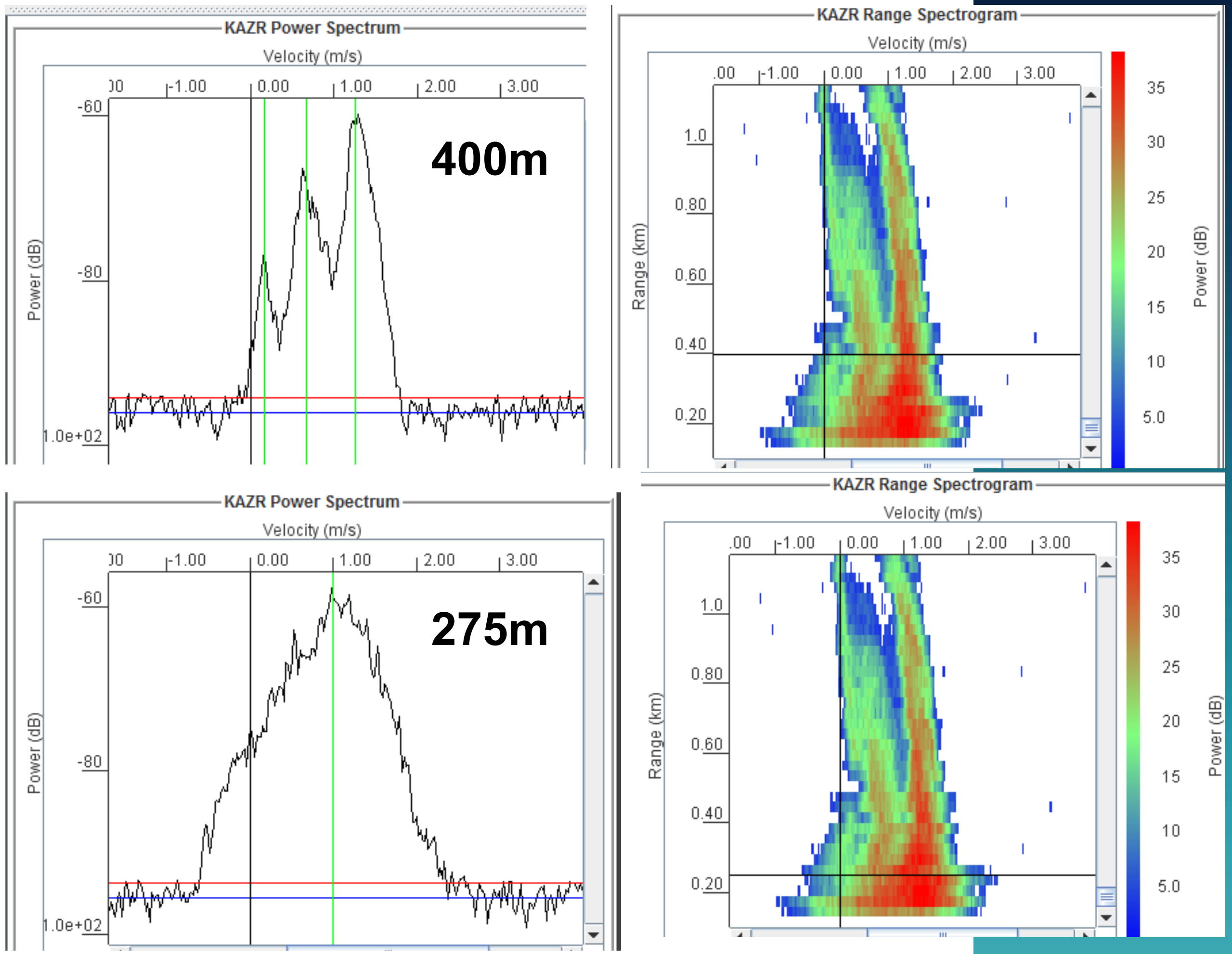
Effect of turbulence

Higher turbulence and associated broadening effects are usually found:

- Lowest few hundred meters above surface
- Regions with strong wind shear
- Convective regions
- Cloud boundaries (evaporation/sublimation)
- Melting layer (latent heat releases)

<u>Turbulence broadening depends also on:</u>

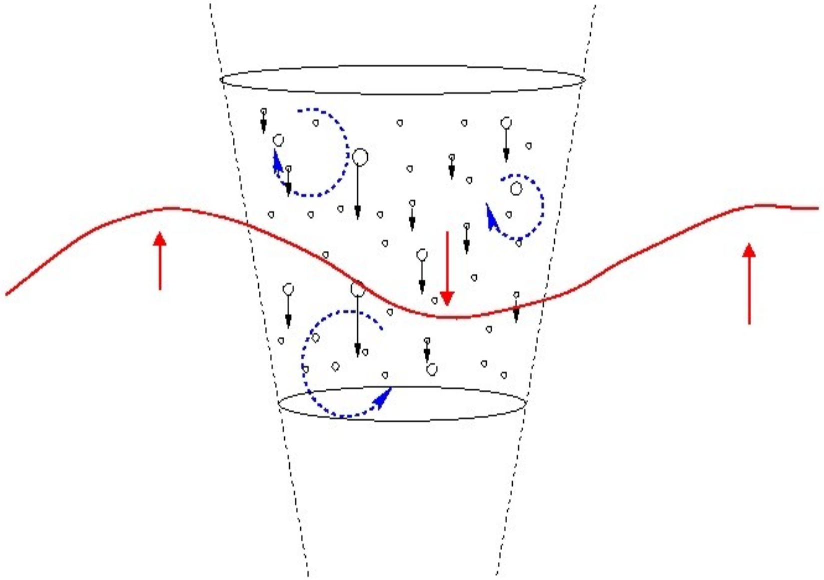
- radar beam width
- wavelength
- range, pulse length



Broadening due to wind shear (inside the beam)

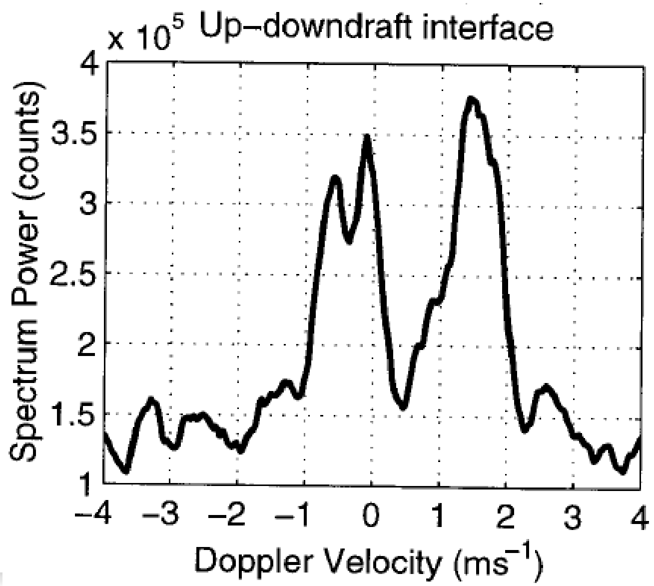
If the vertical wind is changing inside the radar volume (red curve in the sketch) this will add extra broadening to the spectrum.

It can also lead to bi-modal spectra (see spectrum on the lower right) although the quiet-air spectrum is a single Gaussian spectrum!



Wind shear broadens spectrum or even produces multi-modal spectra

Similar to turbulence, broadening depends on several radar parameters



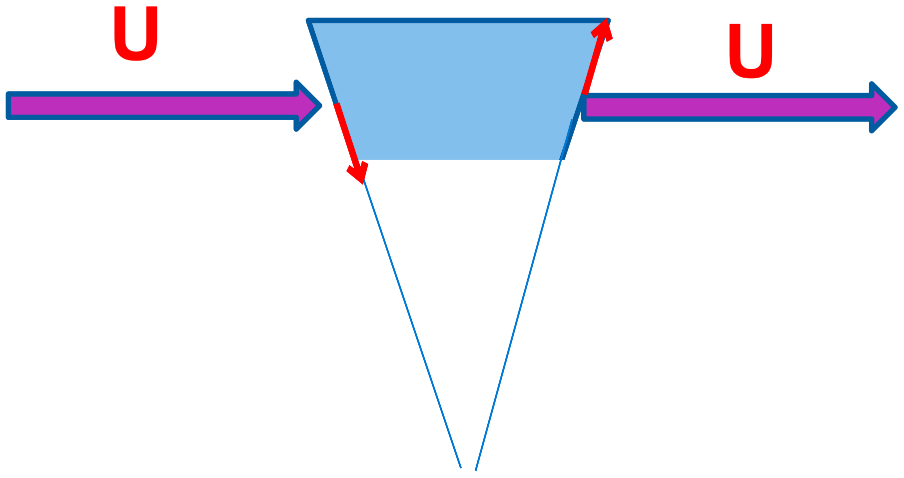
Kollias et al., JAS, 2001

Finite beam width broadening

Even for perfectly homogenuous horizontal wind, a radial velocity component will be induced in the beam regions which are not perfectly zenith

For ground-based, narrow-beam cloud radars, this effect is usually very small.

Large beamwidth wind profilers or cloud radars on fast-moving aircrafts or even satellites are substantially affected.



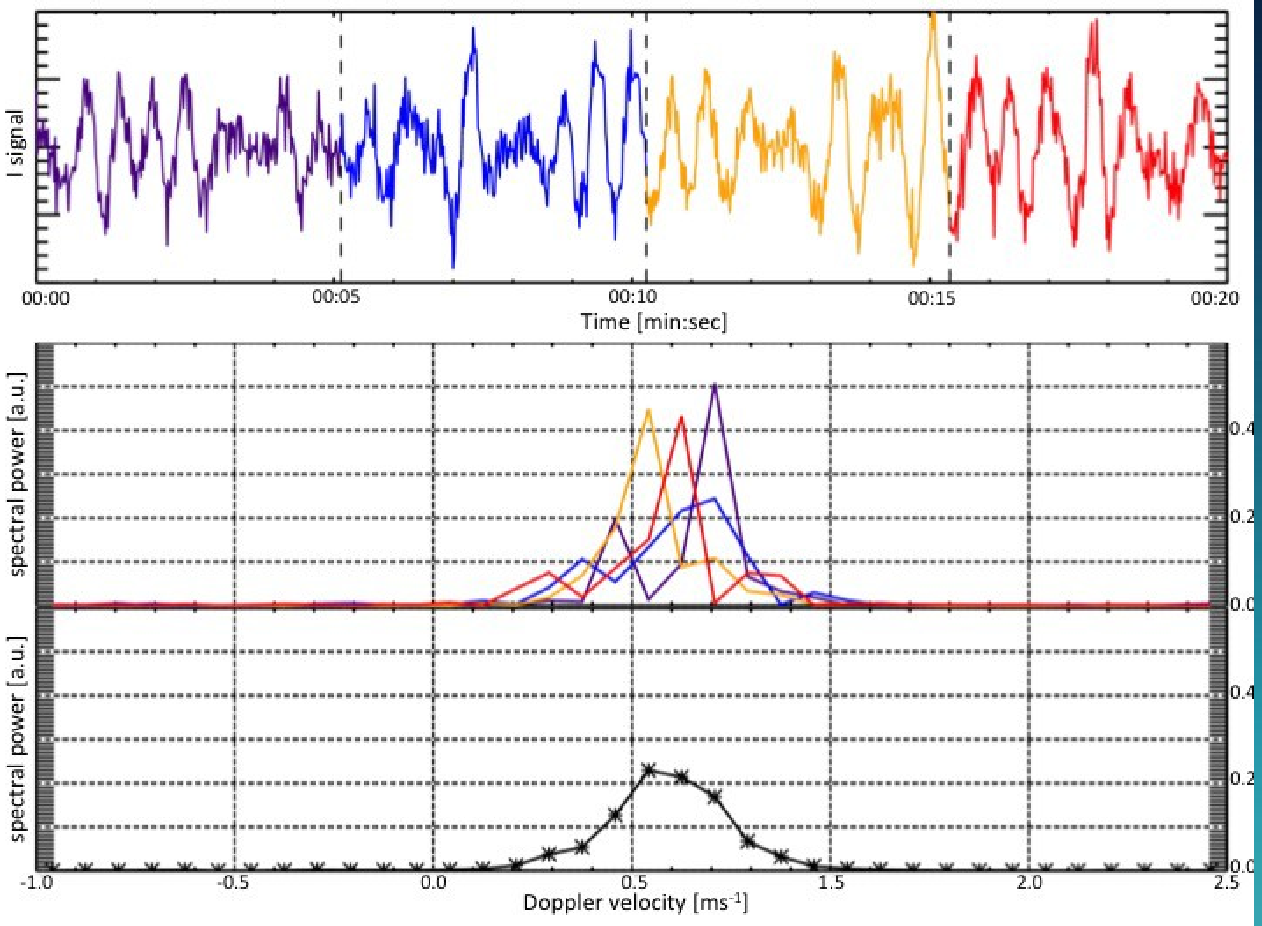
$$\sigma_B = \frac{U \cdot \theta_{3dB}}{4 \cdot \sqrt{\ln 2}}$$

Impact of spectral averaging

- Longer integration (averaging) time:
  - Less disk space
  - better SNR
  - Loss of microphysical information (shape becomes more Gaussian)

- Should you store single spectra (no averaging)?
  - No! Spectra very noisy
  - bad SNR

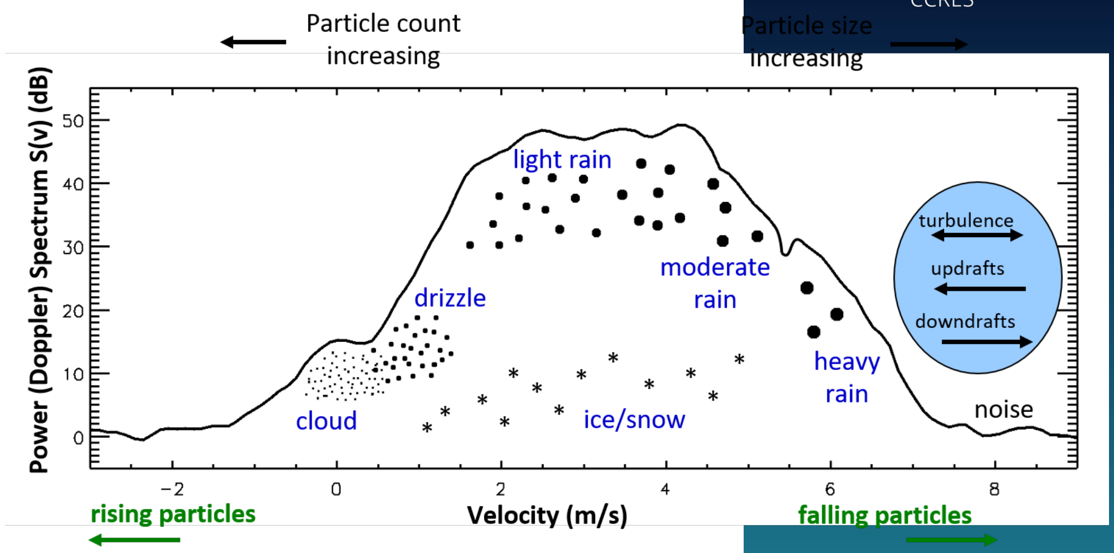
Spectral averaging of 2-4 seconds seems to be good compromise to maintain most microphysical information



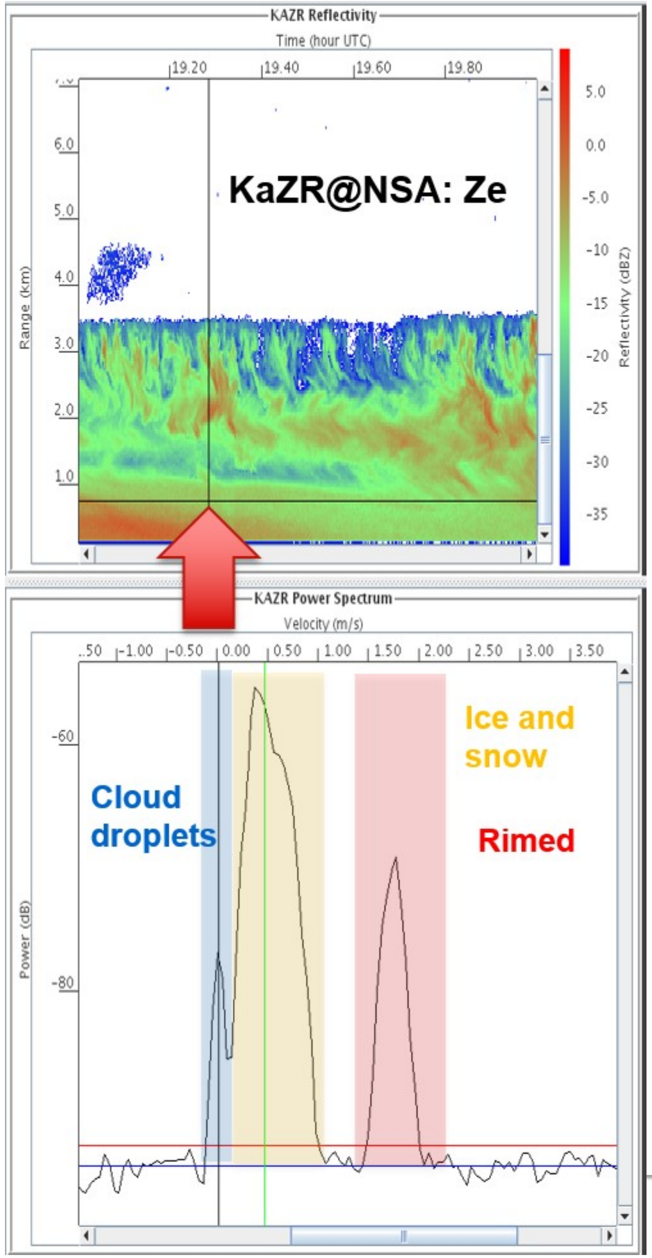
Optimal radar settings for drizzle detection
Acquistapace et al., AMT, 2017

Microphysical information in Doppler spectra

- The potential to differentiate various hydrometeors in Doppler spectra is based on their difference in fall velocity.
- If two particles have identical fall velocity, they cannot be separated in the spectra
- Auxiliary knowledge about the cloud often helps to constrain the problem, e.g.
  - Super-cooled liquid water detected by lidar
  - Polarimetric information
  - Information about temperature regime



Detection of super-cooled liquid water (SLW)

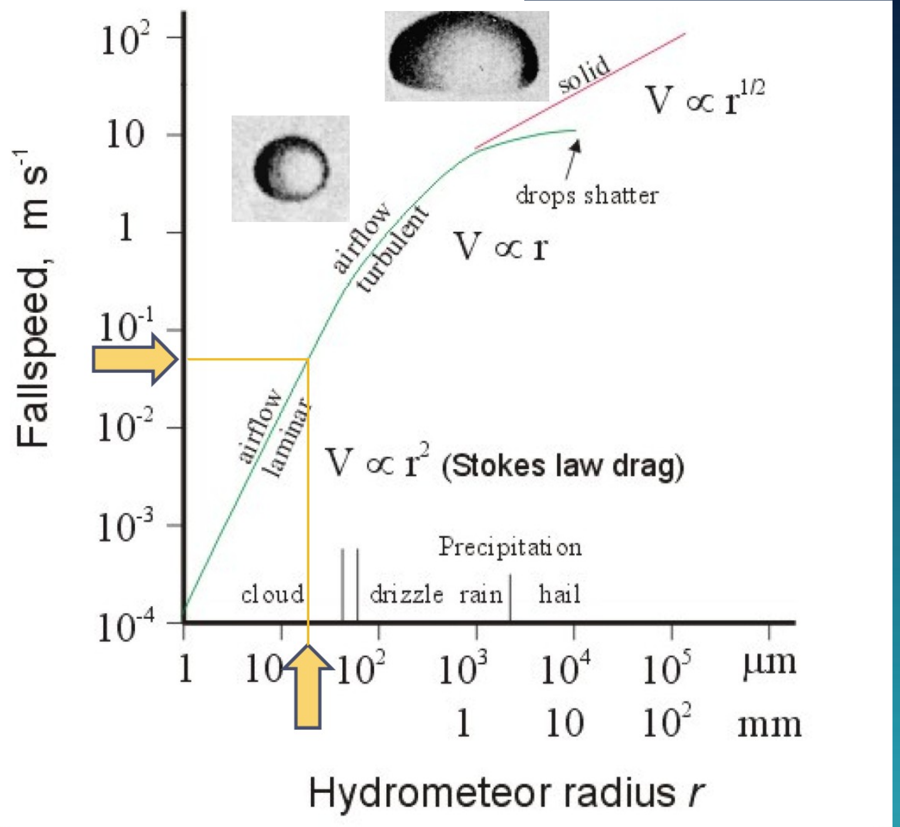


Main characteristics:

- Peak around 0 m/s
- Very narrow peak < 0.1 m/s
- Often close to regions with signatures of rimed particles

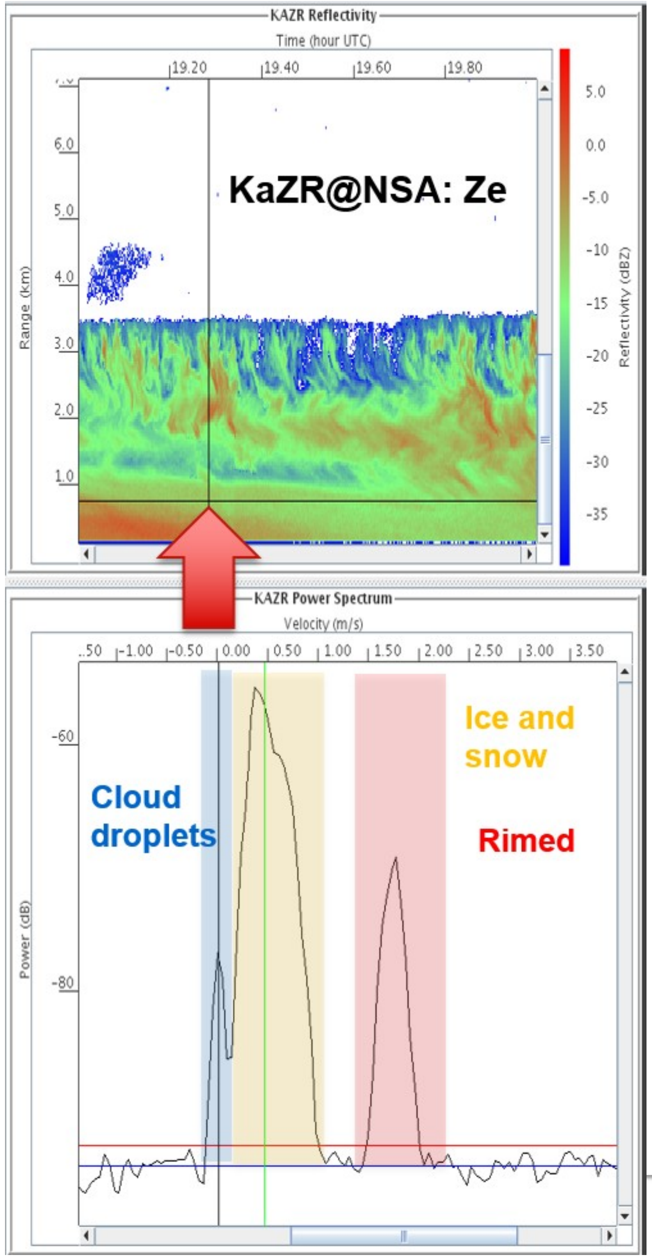
Challenges:

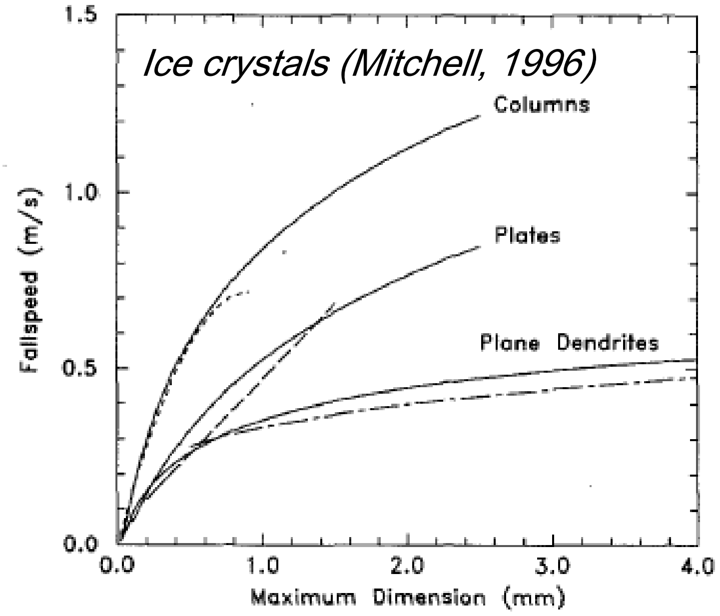
- Newly growing, small ice might „obscure“ SLW signal
- Turbulence broadening can merge SLW peak with ice/snow peak

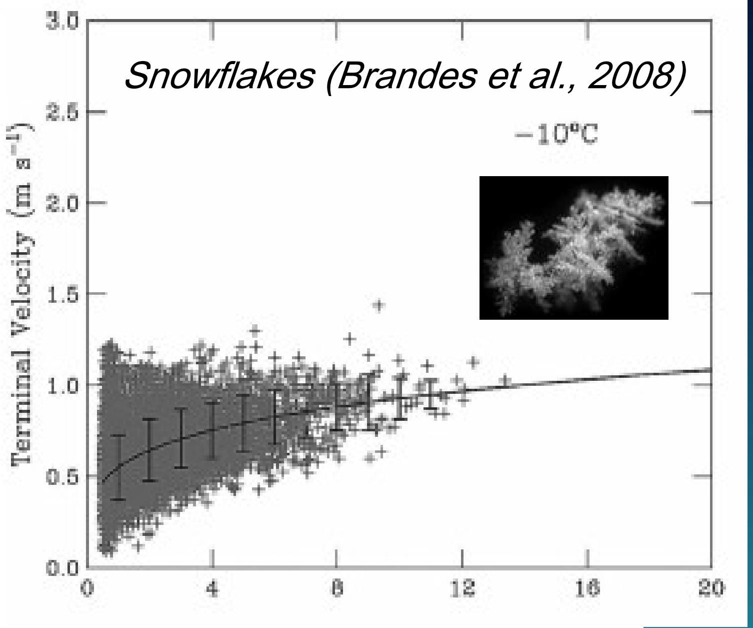


Adapted from McIlveen (1992)

Ice crystals and snowflakes

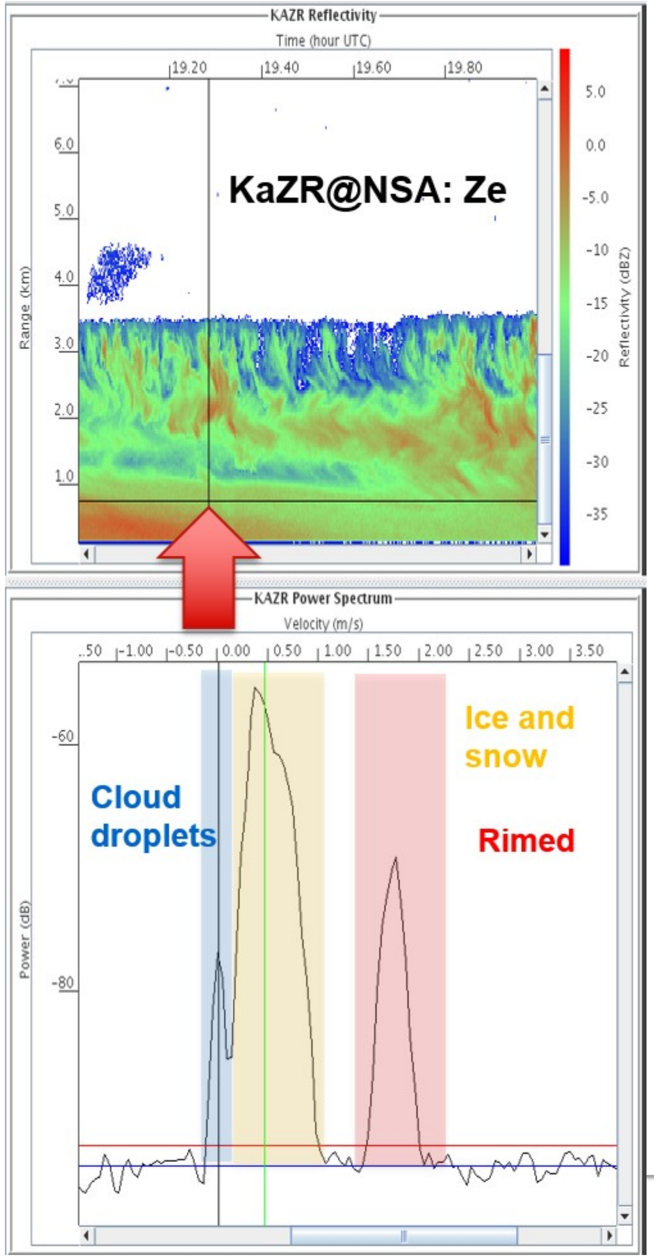


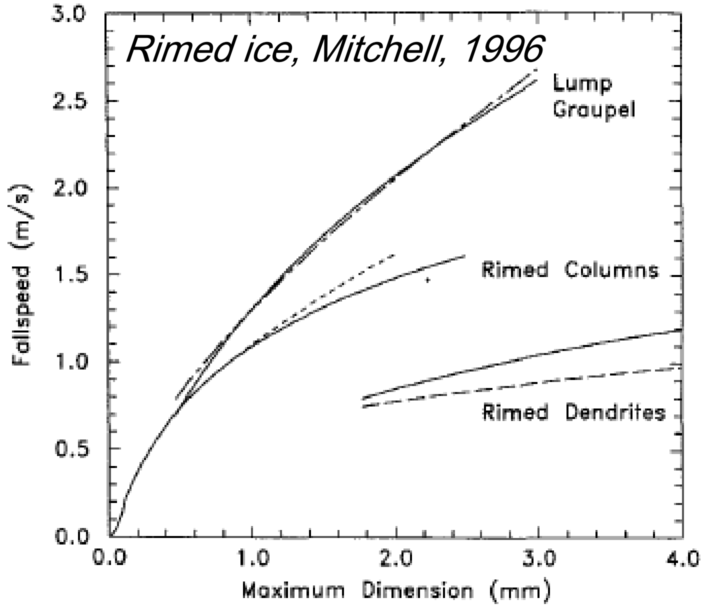




- Ice crystals even at 100µm fall already with 0.3 m/s
- Large dependence on particle shape
- Snowflakes approach 1.0-1.3 m/s at cm-sizes
- Often signatures of ice crystals and aggregates are mixed together in same spectral mode

Rimed ice





- Riming enhances mass but very weakly the cross sectional area of the particle
- Graupel can reach up to 4 m/s (faster modes most likely hail)

Spectral modes **> 1.5 m/s** are most likely due to rimed particles

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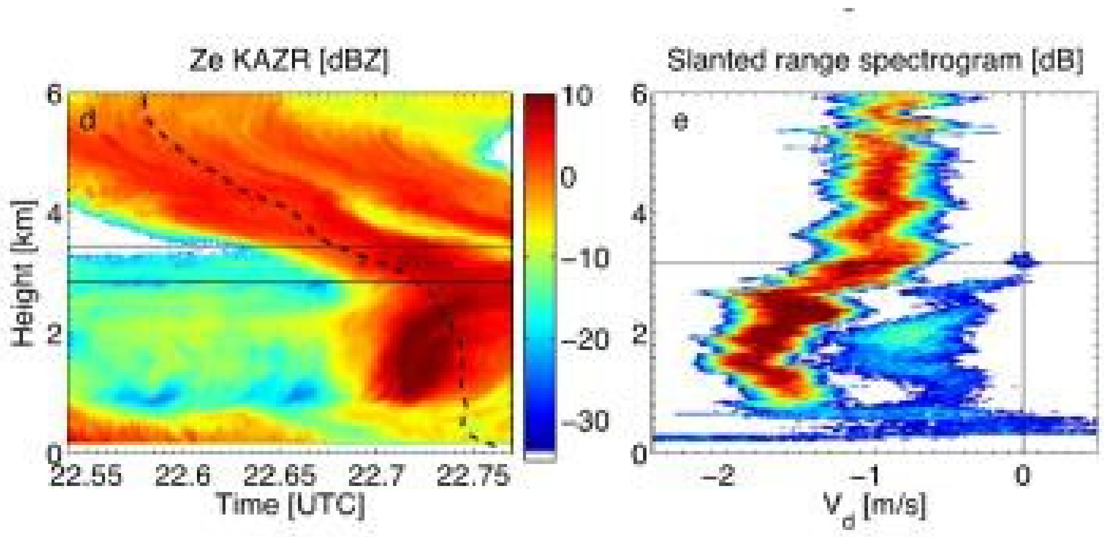
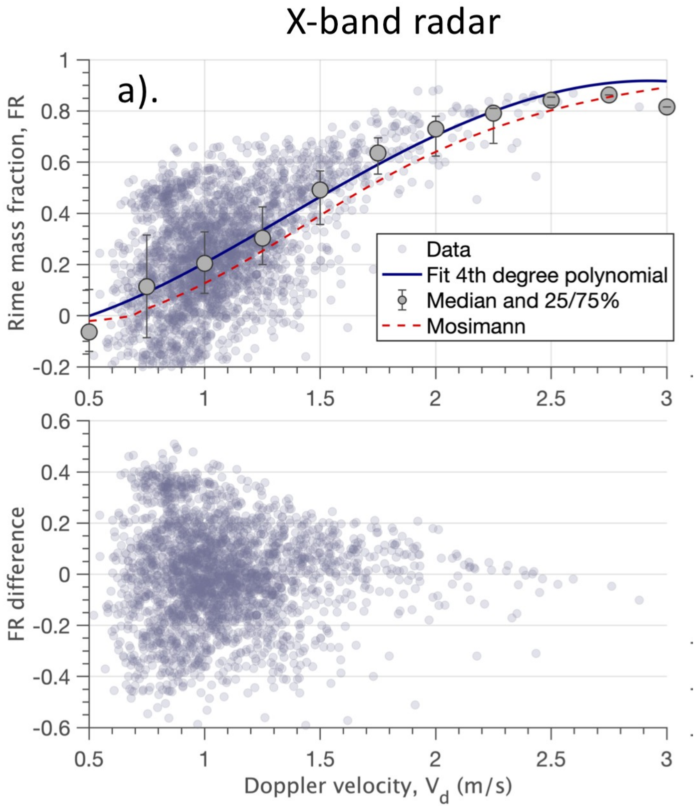
Rimed ice



Riming case study: Kalesse et al., ACP, 2016



Statistics of riming:

- *Kneifel and Moisseev, JAS, 2020*
- *Ockenfuß et al., JGR, 2025*

Secondary ice and super-cooled liquid

Billault-Roux et al., ACP, 2023

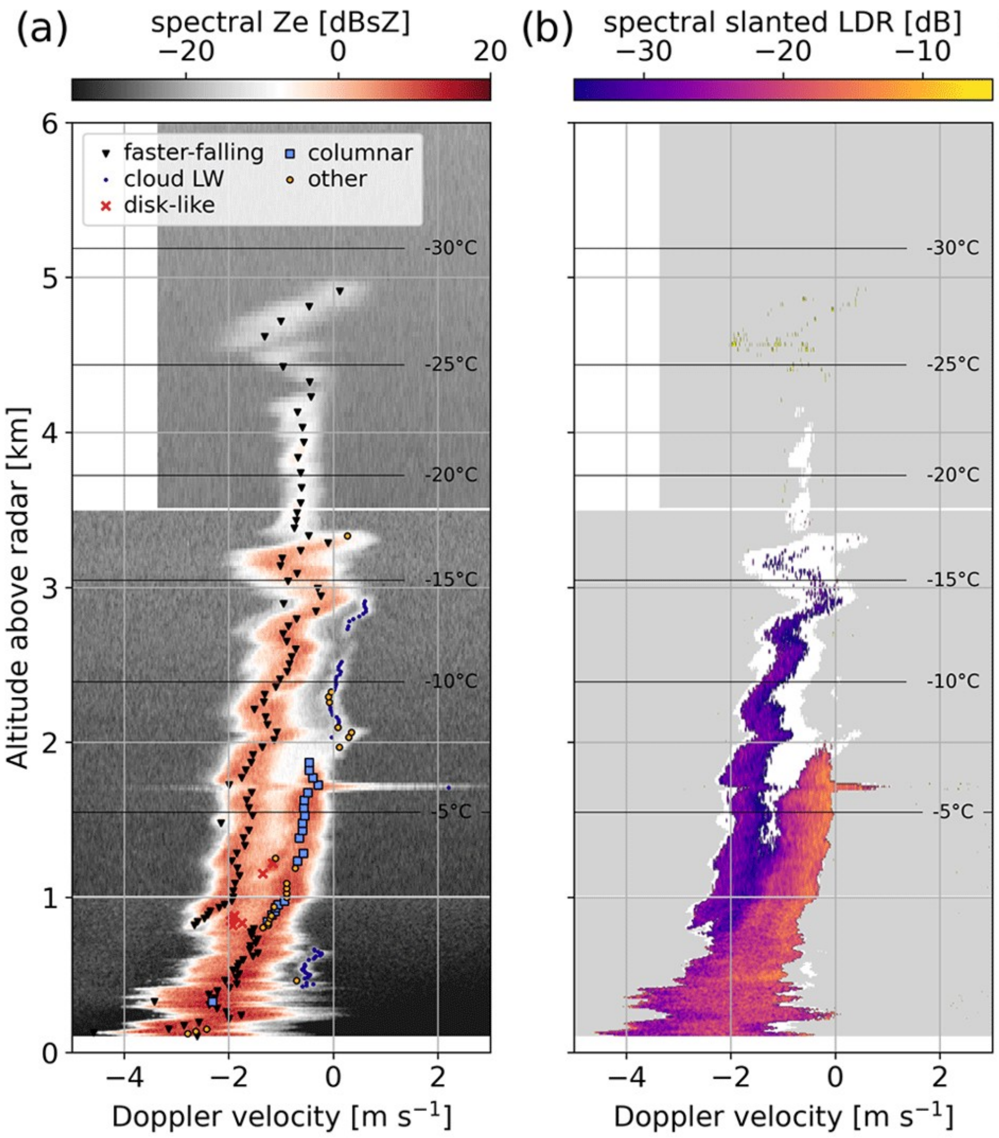
- In order to distinguish newly growing ice from super-cooled drizzle (similar vel.), we can use LDR-spectra

$$LDR = \frac{Ze_{cross}}{Ze_{co}}$$

- In general, LDR is large for columnar ice crystals. But if looking at the usual LDR moment, the large aggregates dominate the LDR and mask the signal from asymmetric ice crystals

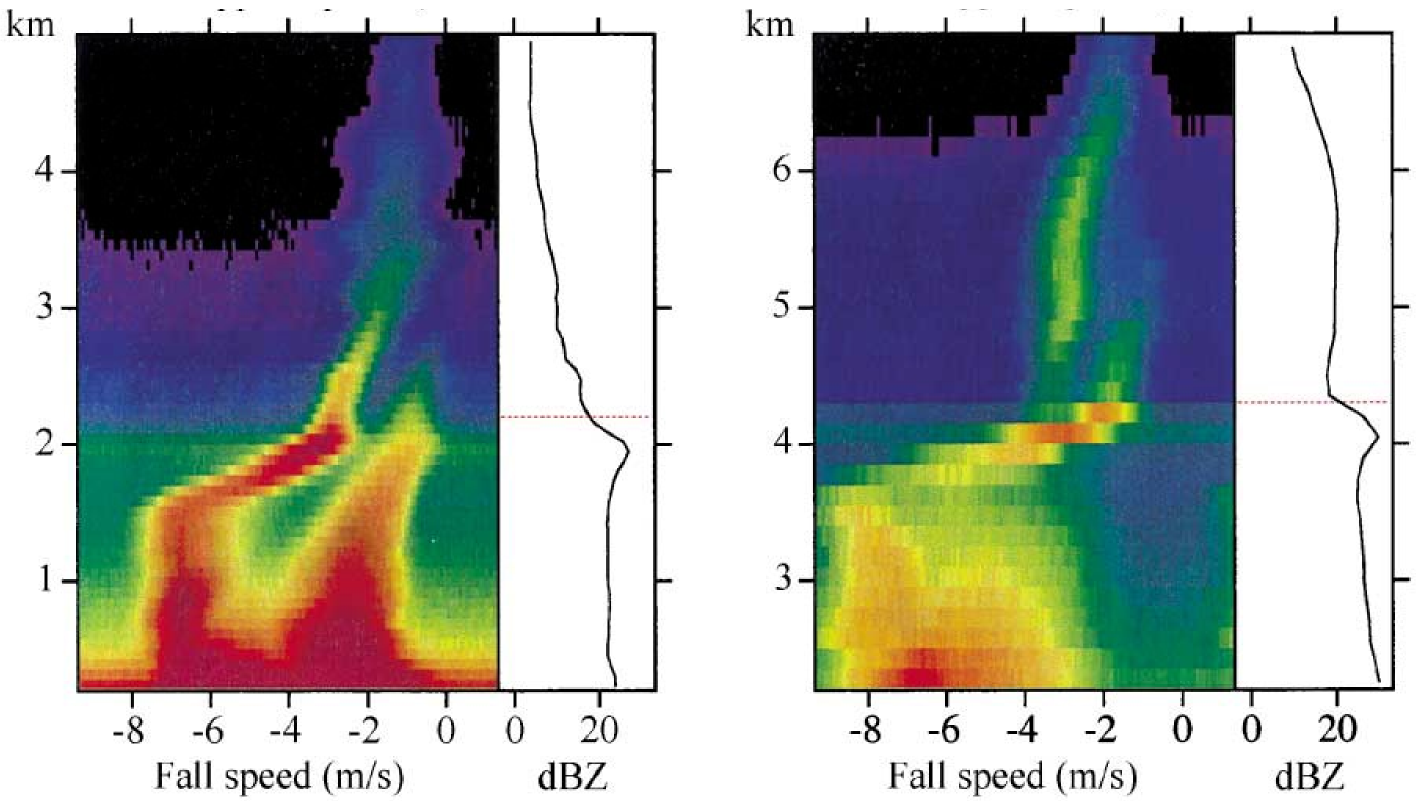
- In the spectral LDR their presence becomes obvious.

- Problem: Signal must be strong enough to cause a signal in the cross-channel. Plate like crystals have low LDR.



Melting layer signatures

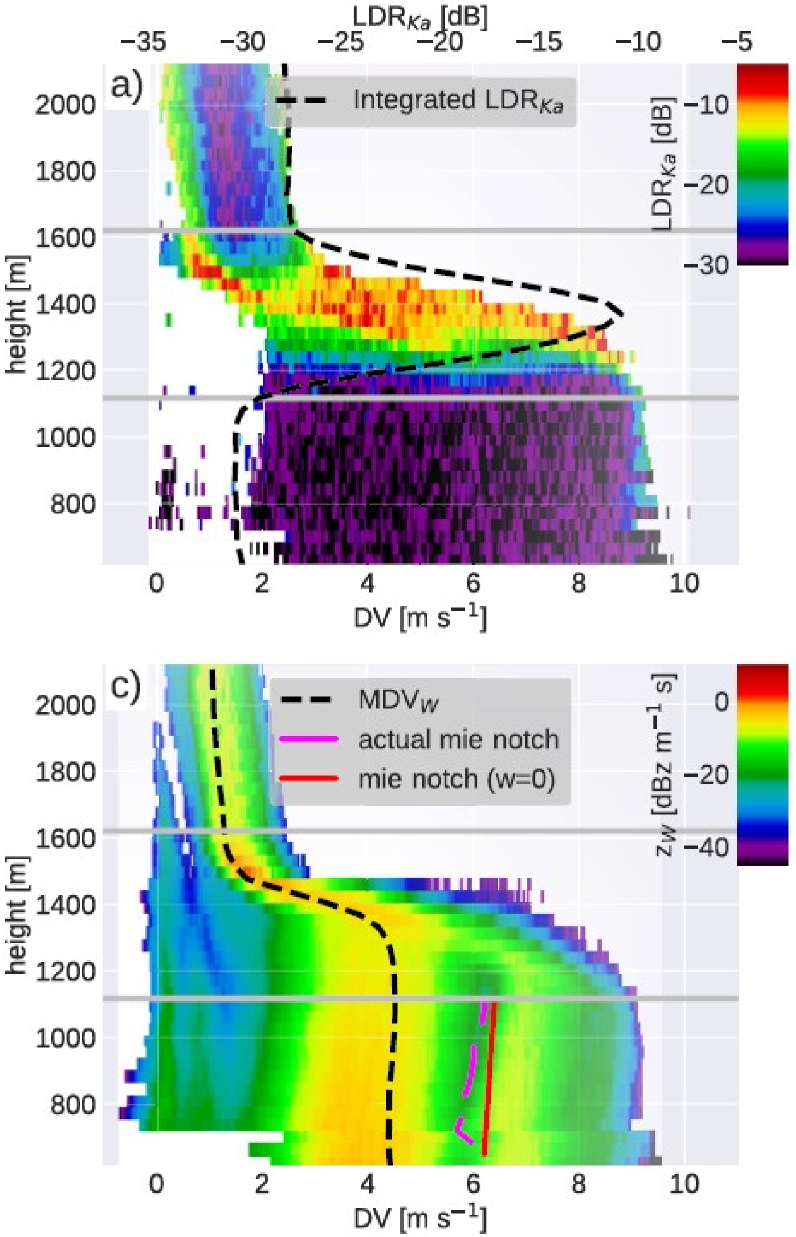
Zawadzki et al., AR, 2001



Super-cooled drizzle and melting snow

Melting rimed particles and small ice

Outlook



Combine polarimetric (LDR) and multi-frequency capabilities:

- Use Mie-notch in Rain and super-cooled liquid peak to correct for vertical air motion
- Use LDR information in Ka-band
- Use X-Band spectra for attenuation correction

Use new spectral tools (Peako, PeakTree) to analyze complex spectra

Agree on best practices within ACTRIS on how to store and process spectra

Karrer et al., JGR, 2022

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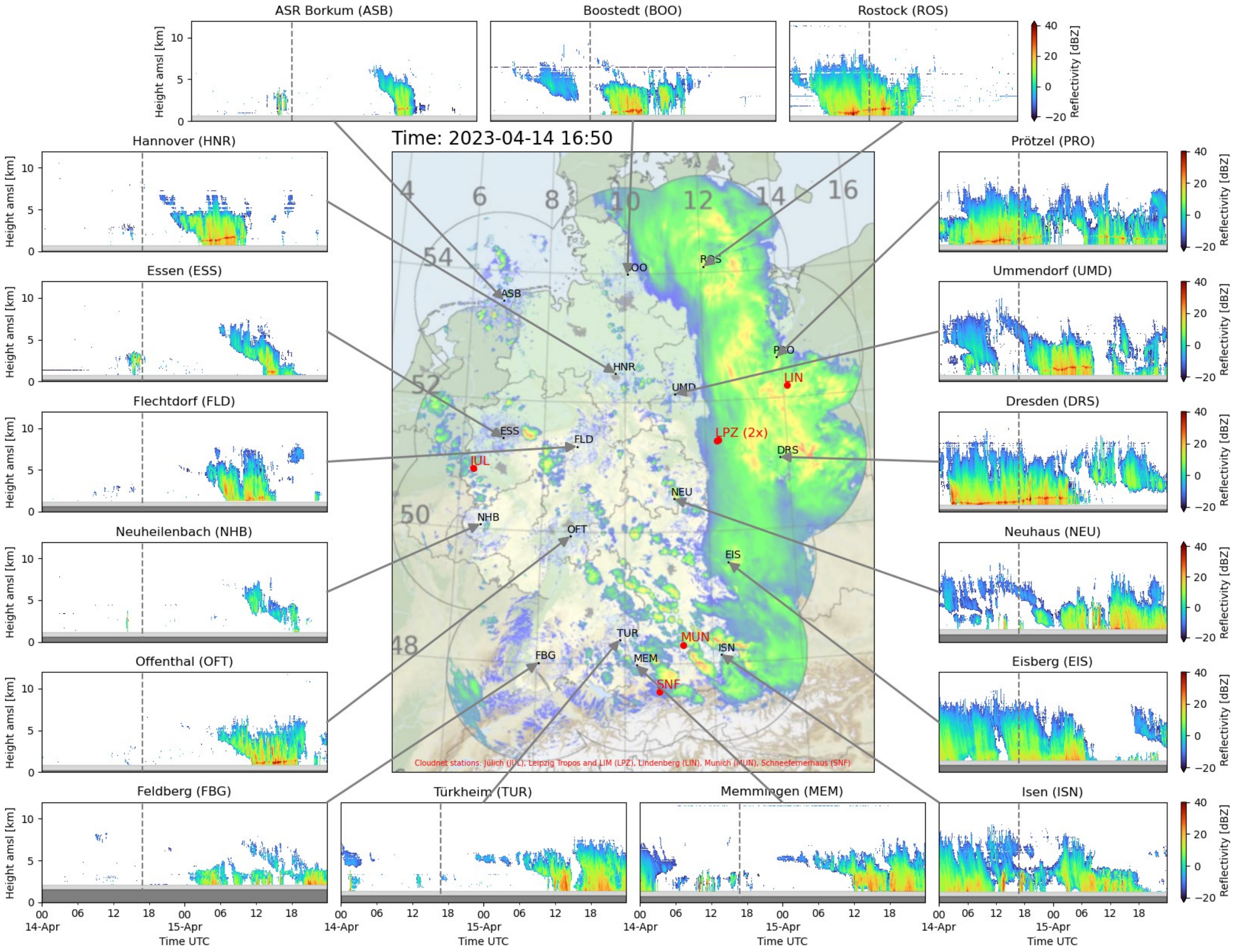
Doppler spectra from operational C-Band radars

European C-Band precipitation radars perform regular (Germany every 5 minutes) vertical scan (birdbath).

The data can be used to derive cloud radar-like time-height plots.

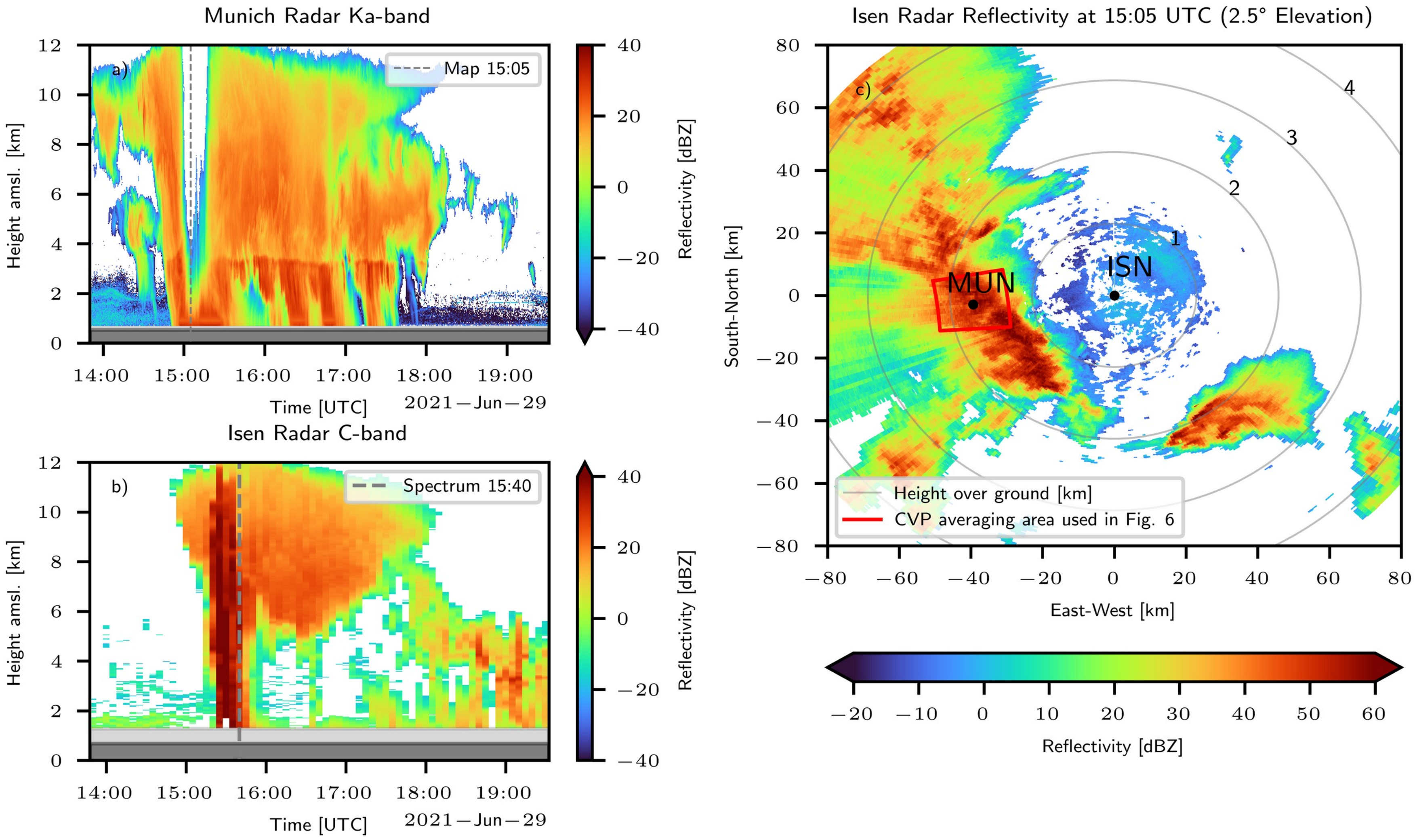
(Birdbath data stored for all 17 DWD C-Band radars at DWD since 2021)



Frech et al. subm. to BAMS

Doppler spectra from operational C-Band radars

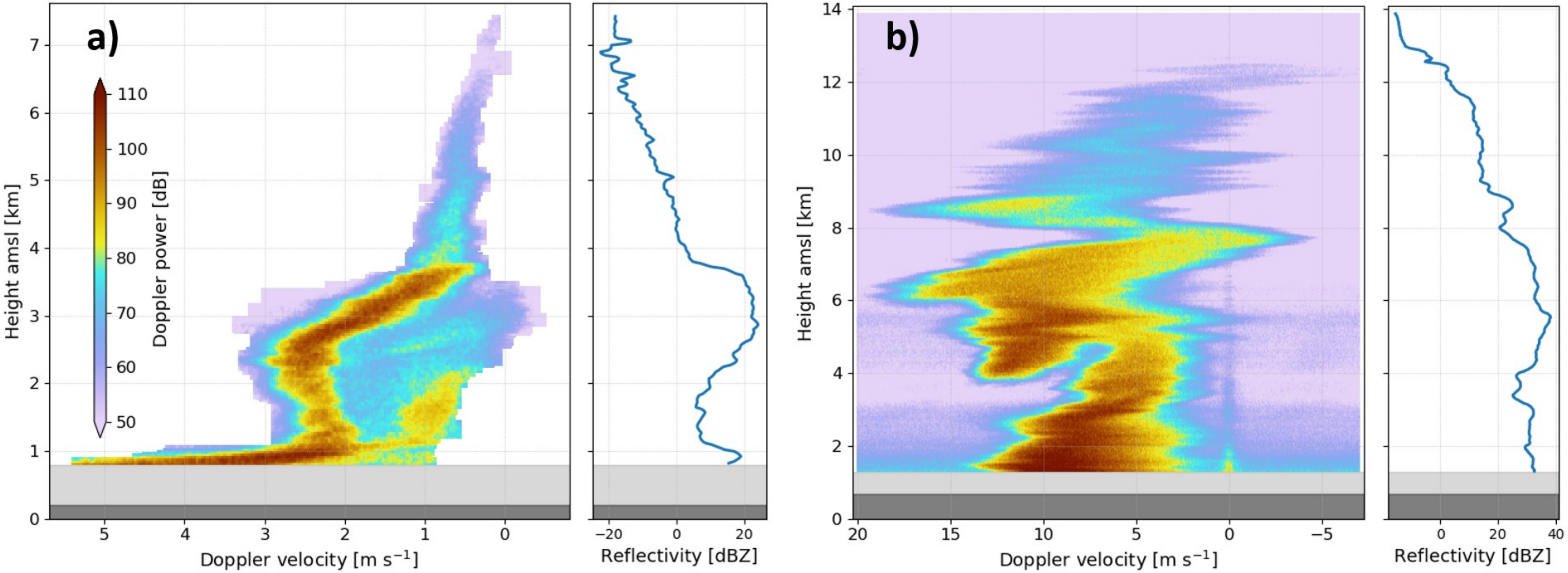
C-Band radars can easily penetrate through the thickest thunderstorm!



Frech et al. subm. to BAMS

Doppler spectra from operational C-Band radars

The vertical pointing C-band data can also be used to derive vertical Doppler spectra (stored for all 17 DWD C-Band radars at DWD since 2021)



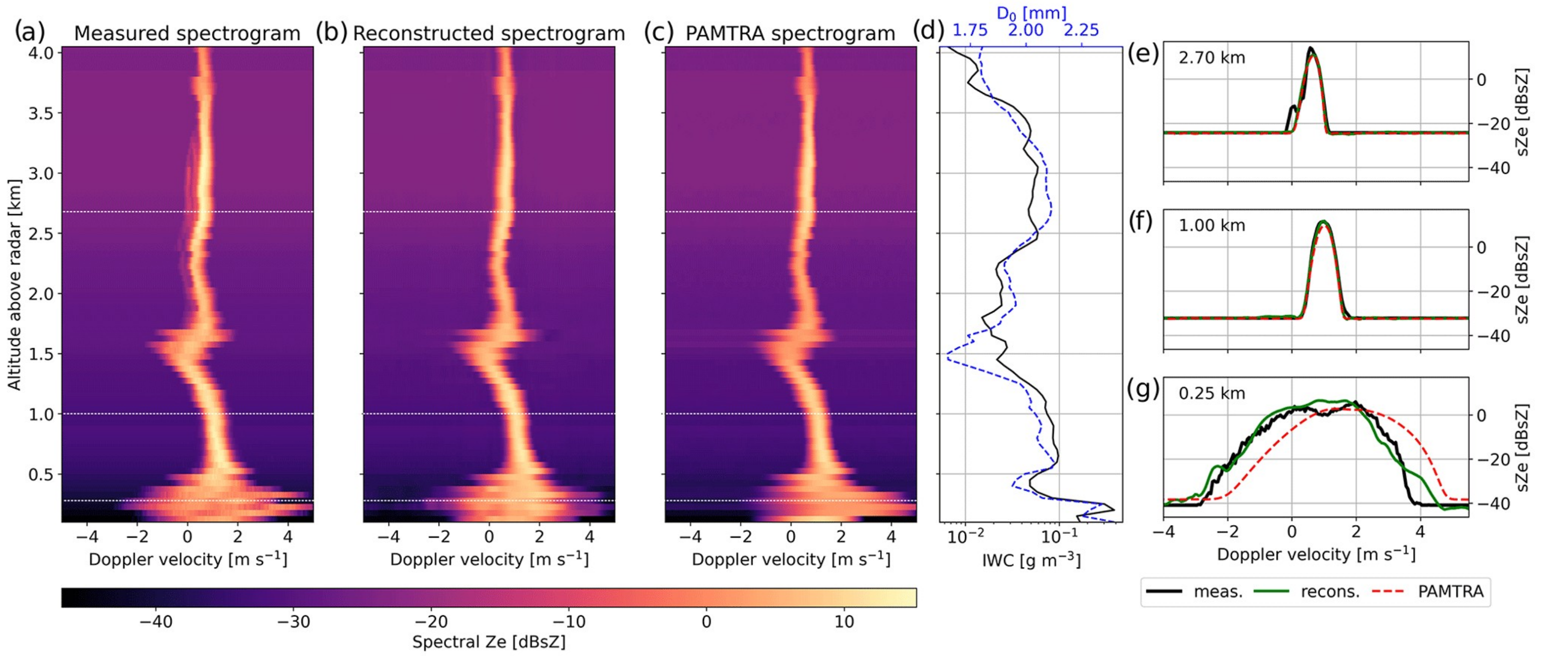
Rimed ice and secondary ice (Melting layer at 1km)

Convective hail storm (potential for hail size retrievals)

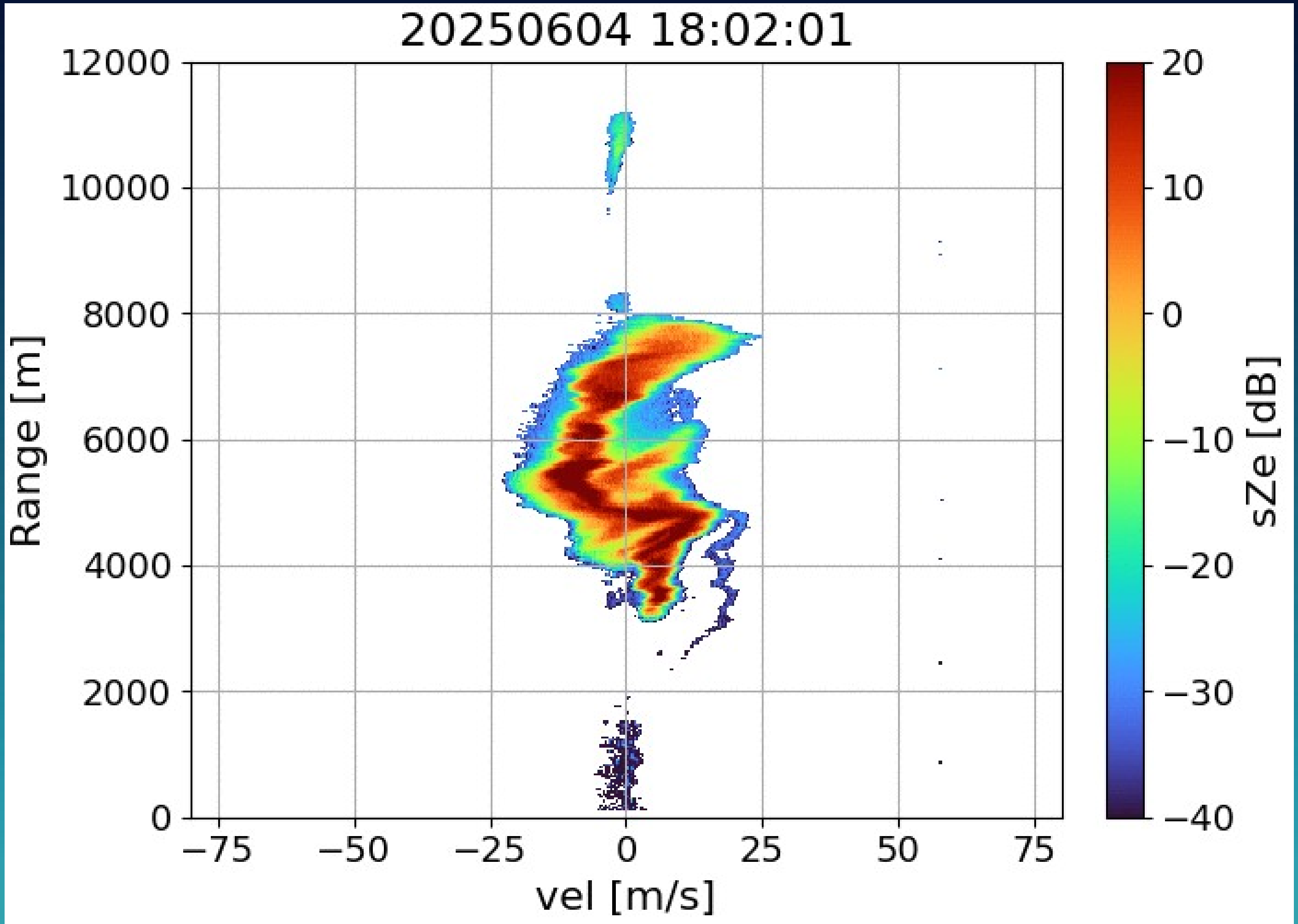
Frech et al. subm. to BAMS

AI based Doppler spectral retrievals

- Doppler spectra are difficult to use in „classical“ retrievals (e.g., optimal estimation), because lot of pre-filtering is needed
- Full separation/correction of dynamical effects often only possible for ideal cases
- However, our radar forward operators (e.g., PAMTRA, CR-SIM, McRadar) are able to accurately simulate Doppler spectra based on various microphysical and dynamical assumptions
- **AI based retrieval methods** are a very promising avenue to explore the full information content contained in Doppler spectra.



Billault-Roux et al., AMT, 2023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6000
4000
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−50
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0
25
50
75
vel [m/s]
sZe [dB]
20
10
0
−10
−20
−30
−40

Thank you !