Radar to study clouds and precipitation

We have seen the main microphysical processes driving cloud and precipitation evolution.

In situ (aircraft) observations are nice and useful, but expensive and not exhaustive.

Remote sensing → larger coverage and range of conditions.

This session focuses on **how we can use radar to retrieve information about cloud and precipitation processes**. We will cover:

1. Radar basics
2. Polarimetric radar
3. Spectral radar measurements
4. Retrieval of microphysical processes using spectral radar data (A.-C. Billault--Roux)

Books (alphabetical order):
Fabry “Radar meteorology – Principles and practice”, 2015 → *F2015*
Ryzhkov and Zrnic, “Radar polarimetry for weather observations”, 2019 → *RZ2019*

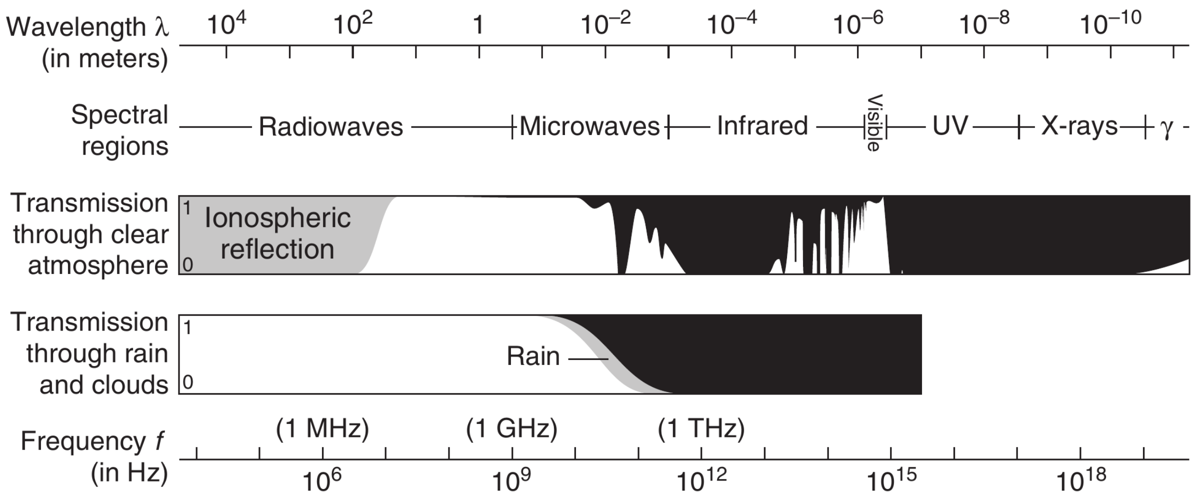
Radar = radio detection and ranging

Military technology developed during WWII

Weather radar is nowadays a key tool for meteorology, atm sciences…

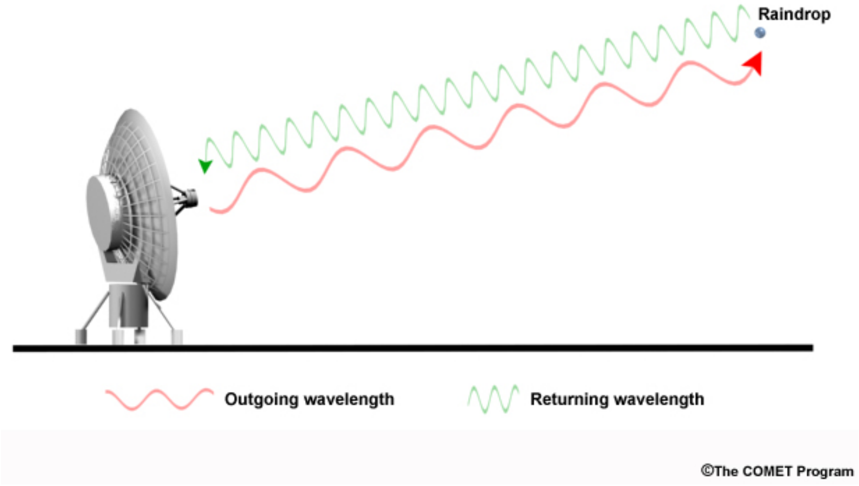
Frequency = trade-off between scattering and attenuation

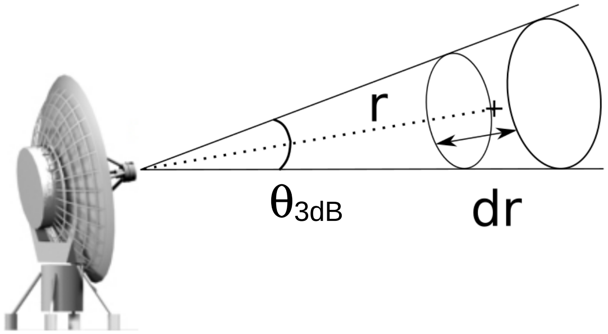
Naming convention	Nominal frequency	Nominal wavelength
LF	30–300 kHz	10–1 km
MF	0.3–3 MHz	1000–100 m
HF	3–30 MHz	100–10 m
VHF	30–300 MHz	10–1 m
UHF	300–3000 MHz	1–0.1 m
L	1–2 GHz	30–15 cm
S	2–4 GHz	15–8 cm
C	4–8 GHz	8–4 cm
X	8–12 GHz	4–2.5 cm
Ku	12–18 GHz	2.5–1.7 cm
K	18–27 GHz	1.7–1.2 cm
Ka	27–40 GHz	1.2–0.75 cm
W	75–110 GHz	4.0–2.73 mm
G	110–300 GHz	2.73–0.1 mm



F2015, fig 2.1

Radar transmits a pulse of energy at given freq, reflected by targets (drops)





Radar beam opening: **3 dB beamwidth**

$$\theta_{3dB} = 1.22 \frac{\lambda}{D}$$

λ	wavelength	[m]
D	antenna size	[m]

Radar measures travel time t → **range** $$r = \frac{ct}{2}$$

Pulse of duration τ → **range resolution** $$dr = \frac{c\tau}{2}$$

Doppler effect:
- transmitted freq f_0
- relative radial velocity v_r (radar - target)

$$\delta f = \frac{2v_r}{c} f_0$$

Scattering

Scattering properties of a hydrometeor depend on size, shape, physical composition, orientation, temperature and incident wavelength.

Physical composition, temperature, incident radar wavelength → relative permittivity ε_r

Scattering will depend on the electric interactions inside the particle (“internal dipoles”)

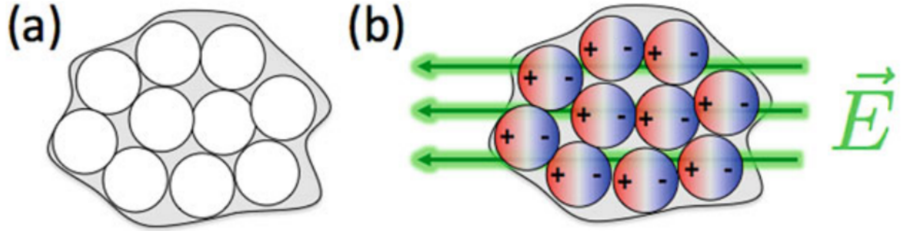


Fig. 1 (**a**) Schematic showing an arbitrary particle comprising tiny spherical finite scattering elements (white circles). (**b**) When an electric field (green vectors) is applied to the particle, a dipole moment is induced (red shading and plus signs indicate net positive charge; blue shading and minus signs indicate net negative charge), and dipoles align themselves in the direction of the electric field vector

Fig. 2 Schematic showing (**a**) a particle small compared the wavelength (traced out by the green line) in which the electric field (green vectors) is uniform throughout the particle, and (**b**) a particle large compared to the wavelength in which the electric field is nonuniform throughout the particle. In (**a**), the induced dipoles oscillate in phase with one another. In (**b**), the induced dipoles oscillate out of phase with one another

Kumjian 2018

Scattering

For radar applications: **backscattering cross-section** σ_b (towards radar) is important.

Scattering regime will depend on the size of the particle / incident wavelength

Radiometric size $x = \frac{\pi D}{\lambda}$

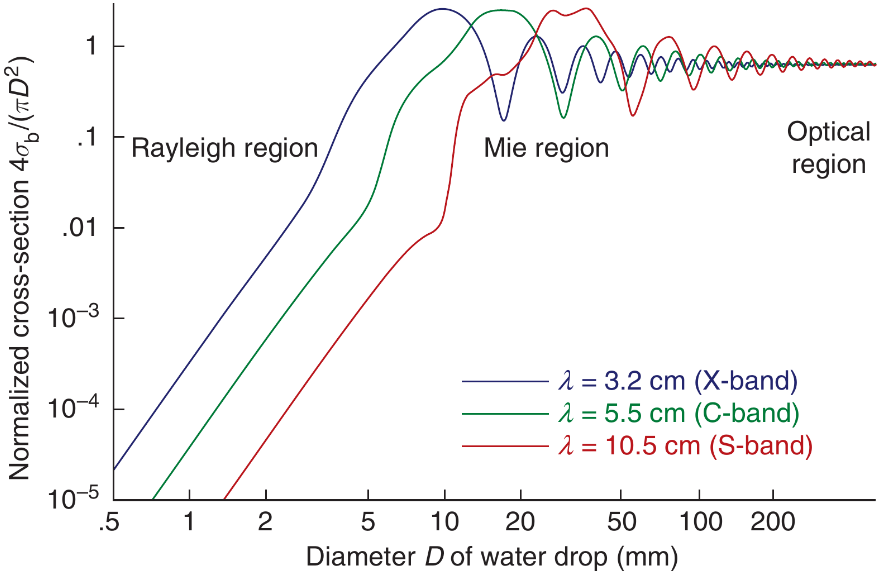
F2015, fig 2.2

If x << 1: Rayleigh regime ; $\sigma_b(D) = \frac{\pi^5}{\lambda^4} D^6 |K|^2$

$$|K|^2 = \left| \frac{\epsilon_r - 1}{\epsilon_r + 2} \right|^2$$

If x ~ 1: Mie regime (exact solution for spheres)

If x >> 1: nonselective or optical regime



Radar reflectivity

Let's consider distributed scatterers inside the radar sampling volume.

Radar reflectivity η = sum of backscattering cross-sections of all particles inside volume

$$\eta = \int_0^{+\infty} N(D)\sigma_b(D)\, dD$$

In Rayleigh regime $\eta = \frac{\pi^5}{\lambda^4}|K|^2 \int_0^{+\infty} N(D) D^6\, dD = \frac{\pi^5}{\lambda^4}|K|^2 Z$

Z = radar reflectivity factor [$mm^6\ m^{-3}$] or dBZ (10 $\log_{10}$ (Z/1))

$$Z = \int_0^{+\infty} N(D) D^6\, dD$$

Z_e = equivalent radar reflectivity factor ($|K|^2$ ~ 0.93 for liq water at usual weather radar freq)

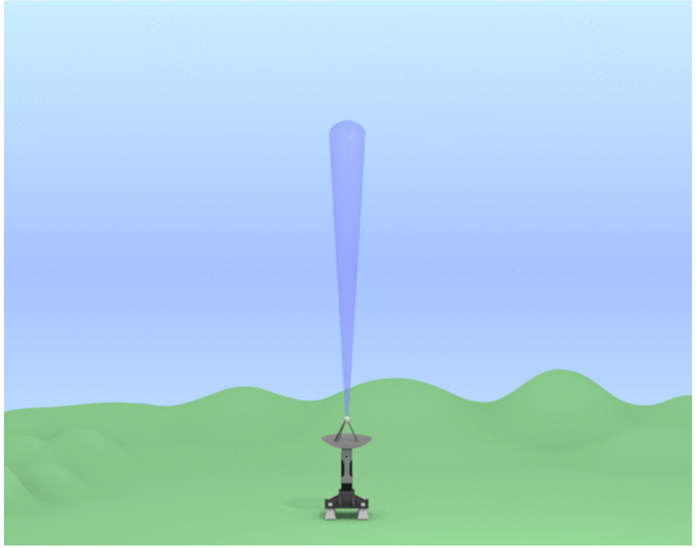
Radar equation: $P_r = C\frac{Z_e}{r^2}$ where P_r is the (measured) power received at the radar
C is a constant depending on radar features

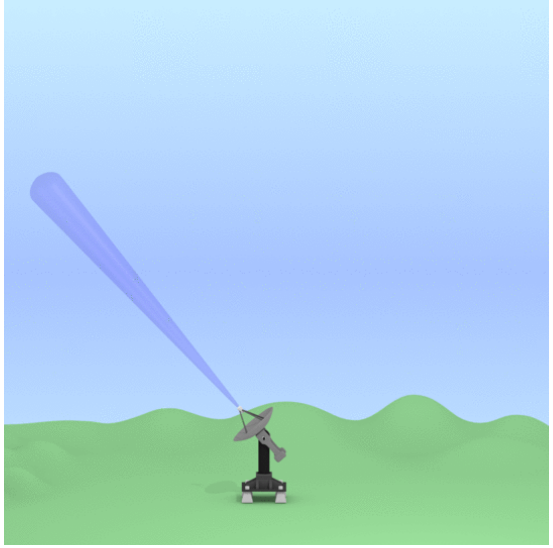
Radar scans

For radar system with a physical antenna and mechanical pedestal, we have

Range height indicator (**RHI**) scan: given azimuth, range of elevation

Plan position indicator (**PPI**) scan: given elevation, range of azimuth





Questions

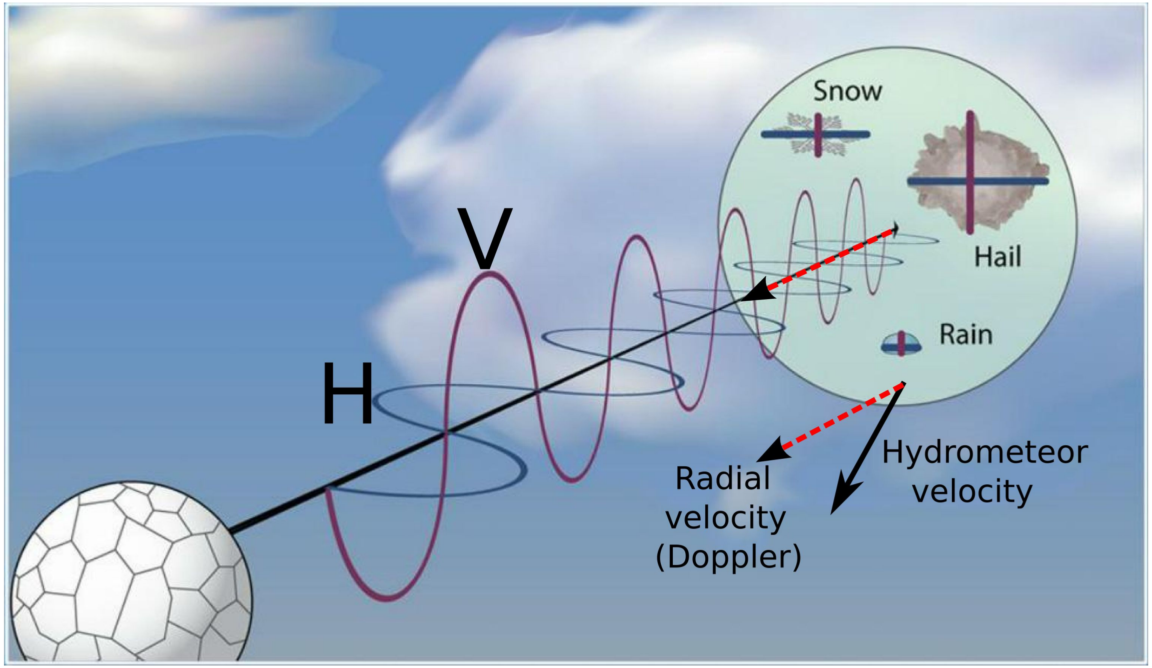
1. Why does the term “ranging” appear in the radar acronym?

2. What are the main scattering regimes?

3. What is the equivalent radar reflectivity (factor)?

Polarimetric radar

Precipitating hydrometeors are not spherical + their largest dimension ~ horizontal →
- Propagation in horizontal and vertical polarization planes is different
- **Dual-polarization Doppler (polarimetric) radar** → info on hydromet types and shapes!



NOAA

Polarimetric radar variables

1. Radar reflectivity factor in both polarizations Z_H and Z_V (~conventional radar)

From definitions on p.6, we can define the radar reflectivity factor at hor and ver polarizations:

$$Z_h = \frac{\lambda^4}{\pi^5 |K|^2} \int_0^\infty \sigma_{bh}(D) N(D)\, dD$$

σ_{bh}: backscattering cross section at h pol

$$Z_v = \frac{\lambda^4}{\pi^5 |K|^2} \int_0^\infty \sigma_{bv}(D) N(D)\, dD$$

σ_{bv}: backscattering cross section at v pol

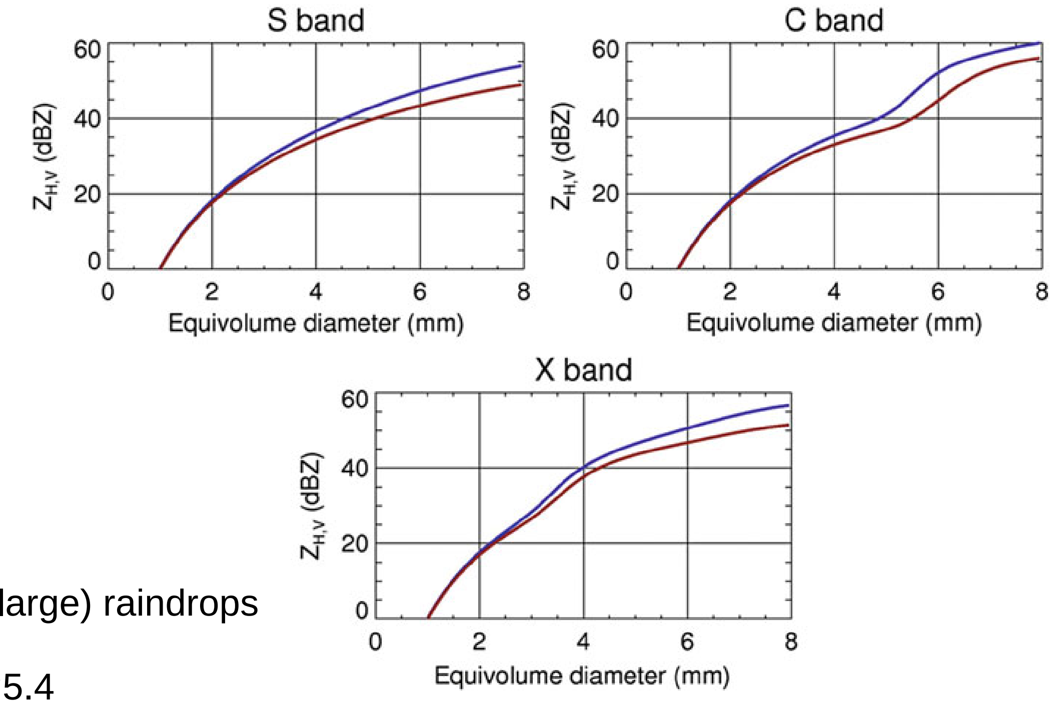
$[\lambda]$ = mm, $[\sigma]$ = mm^2 → $[Z]$ = $mm^6 m^{-3}$

Strong link between Z and DSD/PSD (N(D))

Polarimetric radar variables

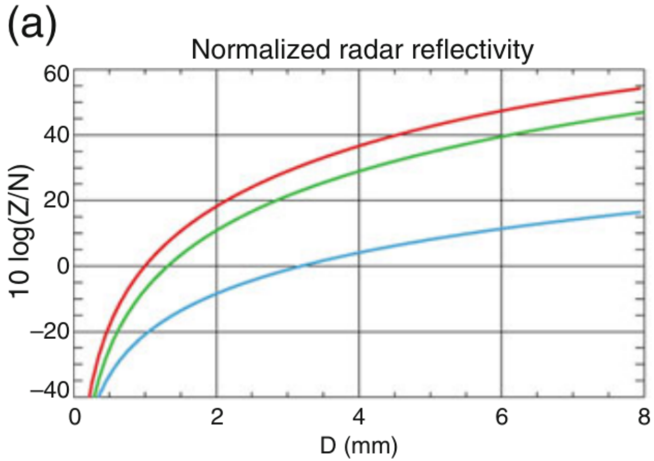
1. Radar reflectivity factor in both polarizations Z_H and Z_V (~conventional radar)

Z is mostly influenced by size, concentration and phase (Re(ε_r) ice < Re(ε_r) liquid water)



$Z_h > Z_v$ for (large) raindrops

RZ2019, fig5.4



$Z_{liq} > Z_{ice}$

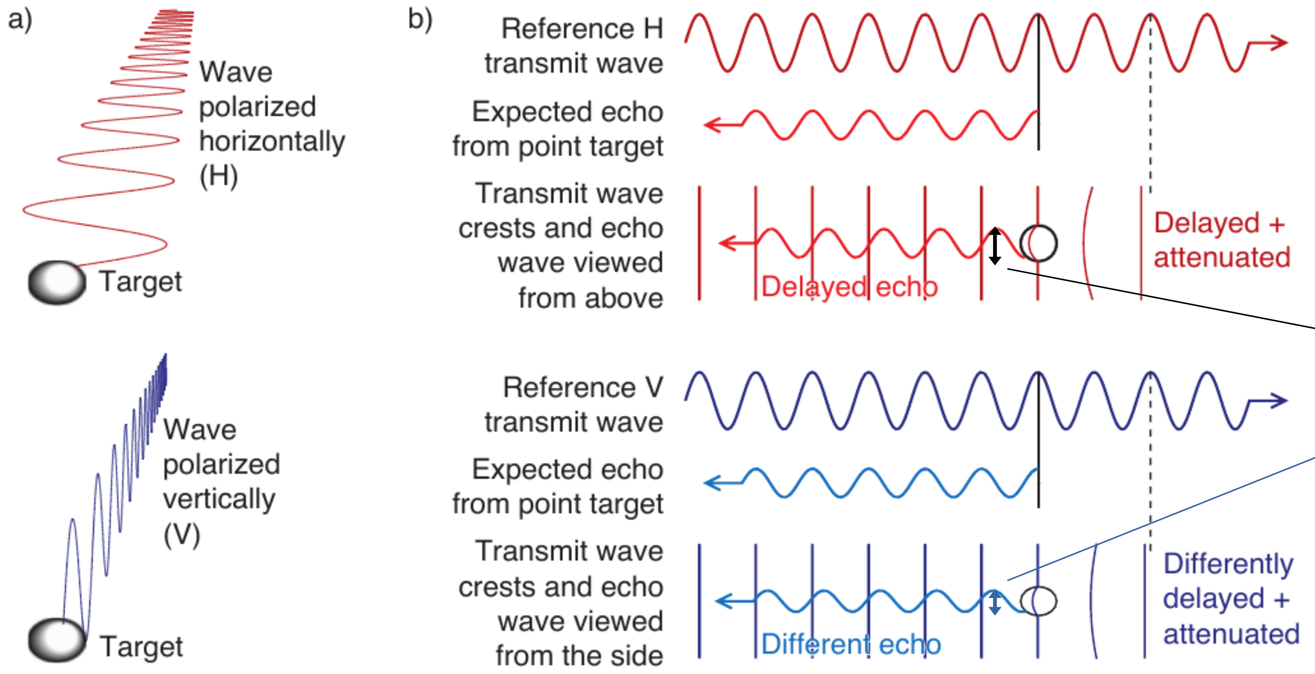
RZ2019, fig5.5.a

Polarimetric radar variables

2. Differential reflectivity Z_{DR}

$$Z_{DR} = 10\log_{10}\left(\frac{Z_h}{Z_v}\right) = Z_H - Z_V$$

Z_{DR} is mostly influenced by shape and relative permittivity of large particles, indep of their conc



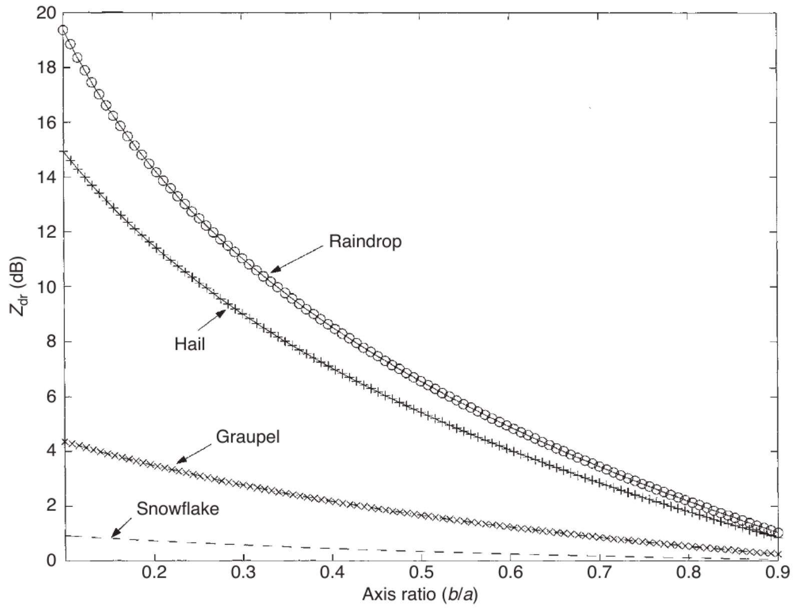
Amplitude in H > V
→ Z_{DR} > 0 [dB]

F2015, fig 6.1

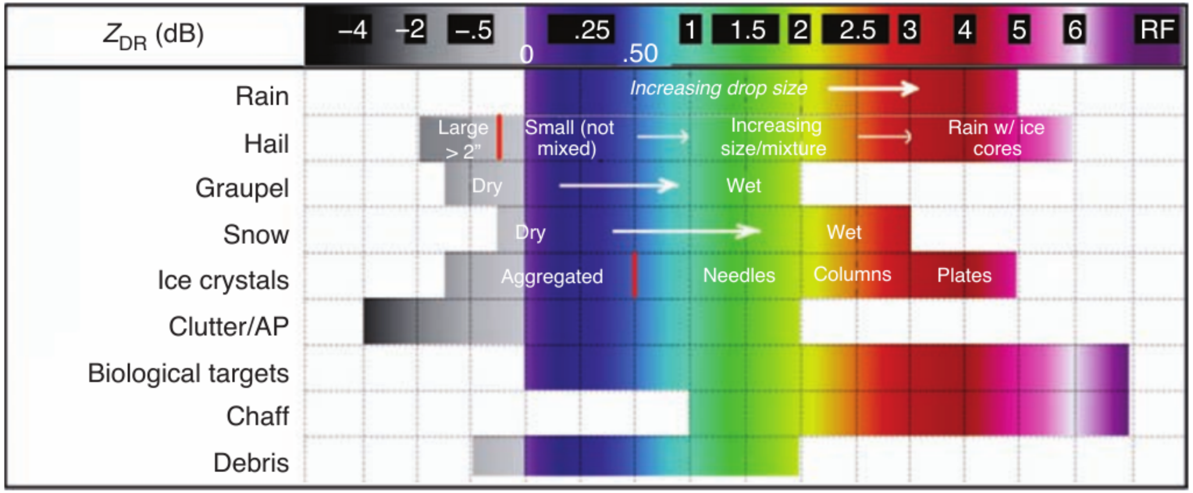
Polarimetric radar variables

2. Differential reflectivity Z_{DR}

Typical Z_{DR} values



F2015, fig 6.3

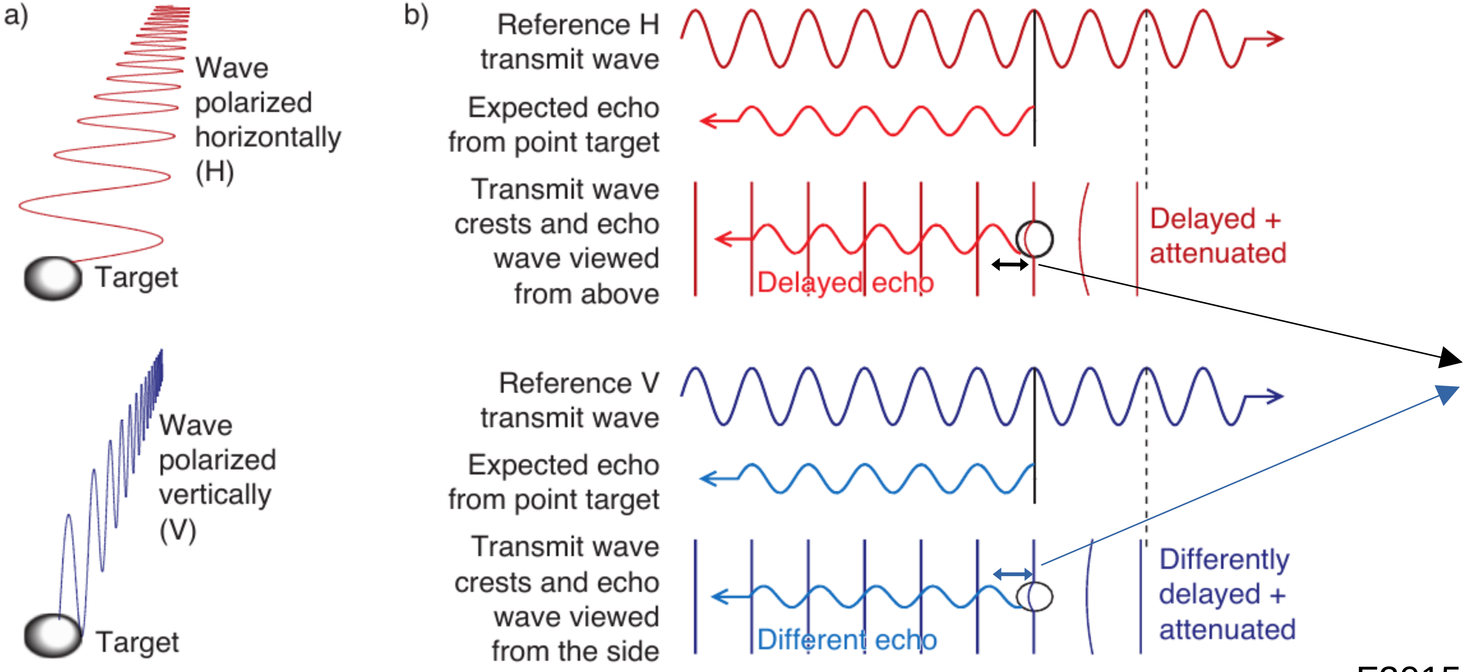


F2015, fig 6.4

Polarimetric radar variables

3. Specific differential phase shift (on propagation) K_{dp}

K_{dp} is mostly influenced by shape, concentration. Scale with frequency. Not affected by calibration, partial beam filling or attenuation.



Phase shift in H ≠ V

Total phase shift Φ_{dp}

$$K_{dp} = \frac{1}{2}\frac{d\phi_{dp}}{dr}$$

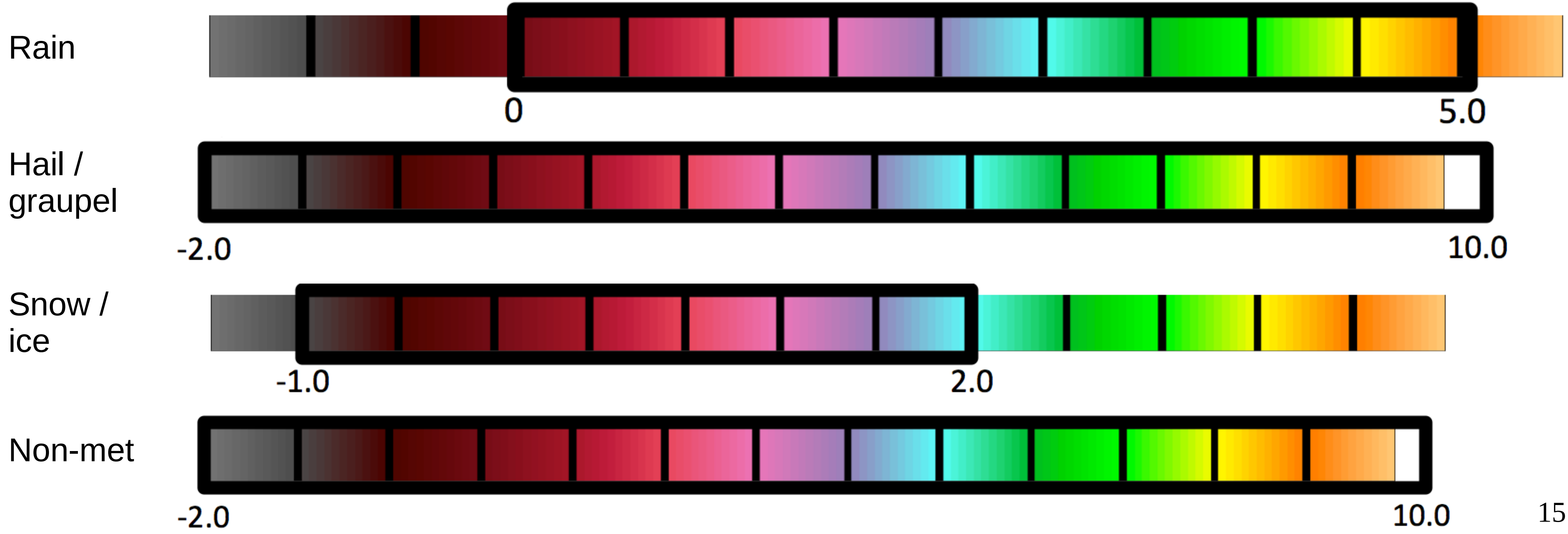
[° km^{-1}]

F2015, fig 6.1

Polarimetric radar variables

3. Specific differential phase shift (on propagation) K_{dp}

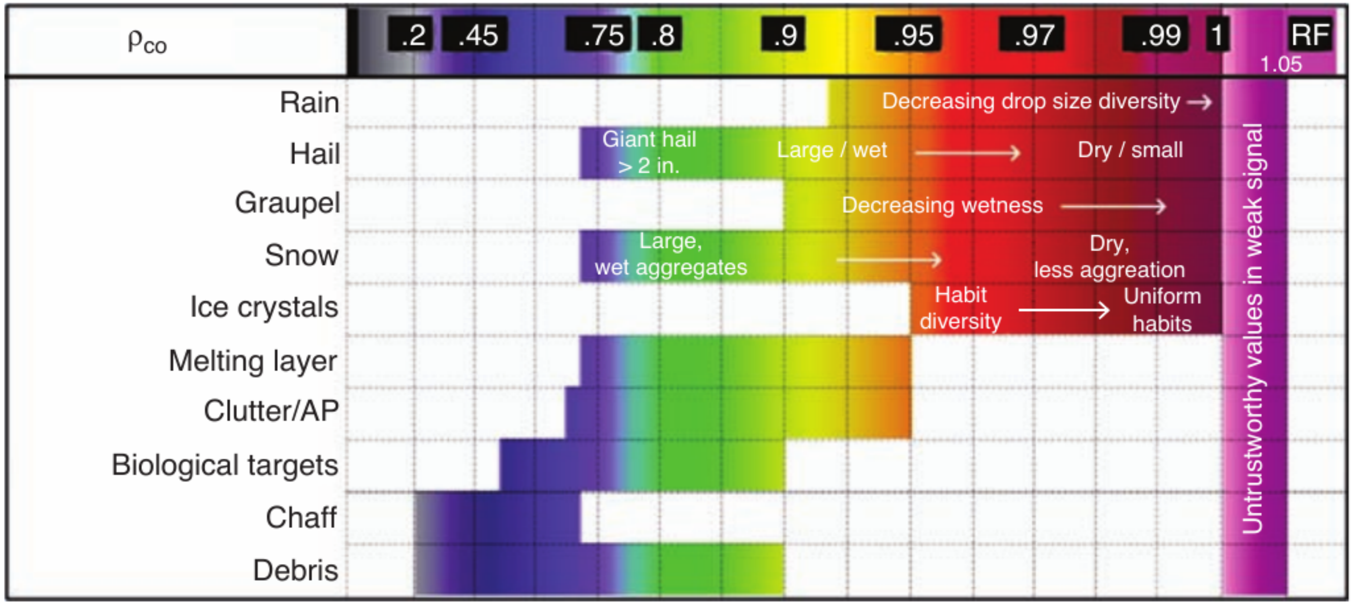
Typical K_{DP} values (from Kumjian JOM 2013, Part1)



Polarimetric radar variables

4. Copolar correlation coefficient ρ_{hv}

ρ_{hv} is the correlation between time series of Z_H and Z_V. It reflects the homogeneity of the particles (shapes, orientations, permittivity...) inside the radar volume.

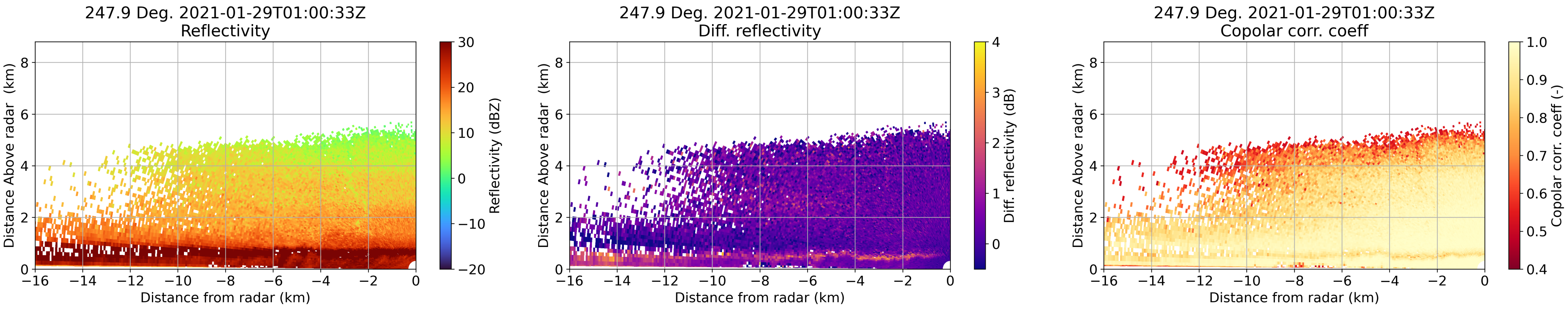


F2015, fig 6.9

Melting layer

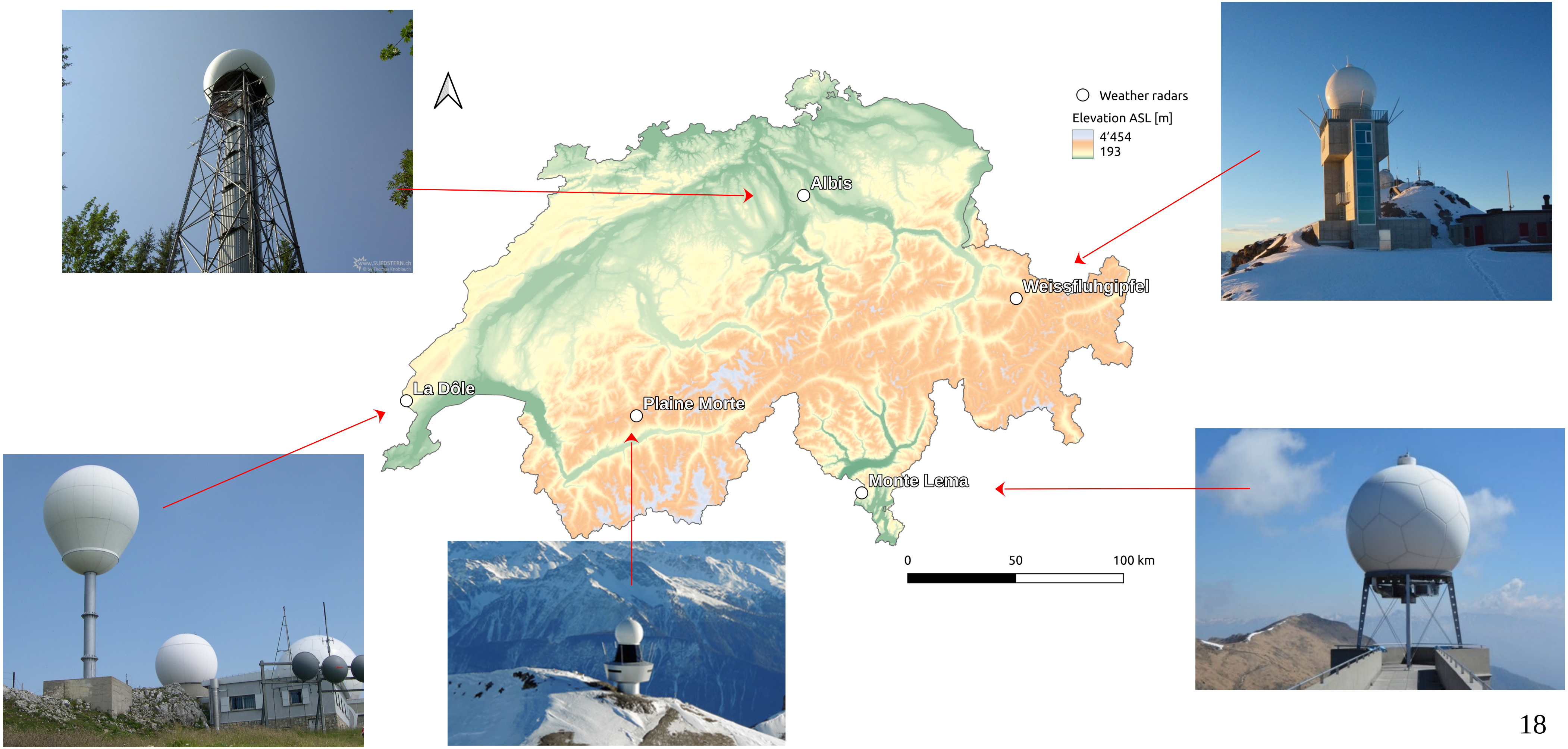
The transition from ice crystals / snowflakes to raindrops is called the melting layer.

This phase change has a strong impact on the polarimetric variables (cm-wavelengths).



RHI for Z_H, Z_{DR} and ρ_{hv} collected with an X-band radar

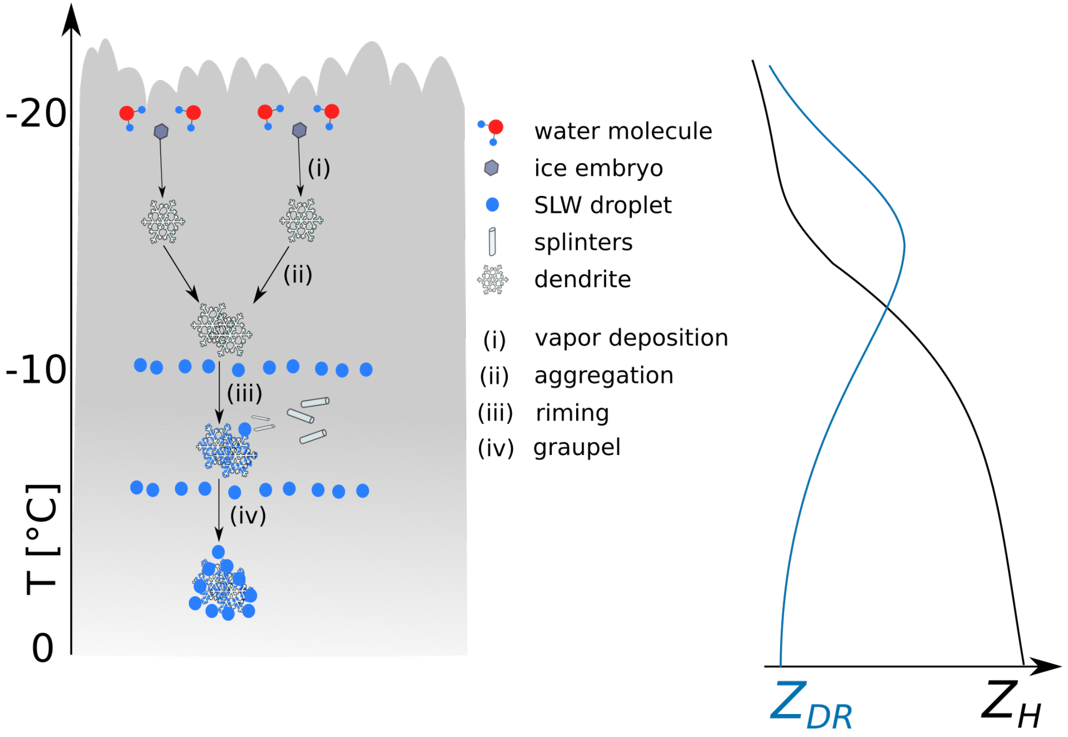
MeteoSwiss operational network of polarimetric C-band radars



Radar and microphysics (1) – Polarimetric signatures

Polarimetric signatures (Z_H and Z_{DR})

- Deposition: Z_H and Z_{DR} ↗
- Aggregation/riming: Z_H ↗ and Z_{DR} ↘



Limitations

- Beam elevation < 45°
- Calibration.

Questions

1. What is the basis of radar polarimetry for clouds and precipitation?

2. Which polarimetric radar variables are related to the amplitude or the phase of the backscattered signal?

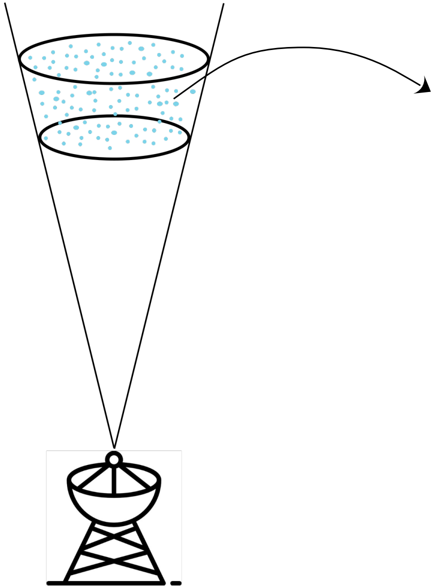
3. How can you relate polarimetric radar variables and microphyiscal processes?

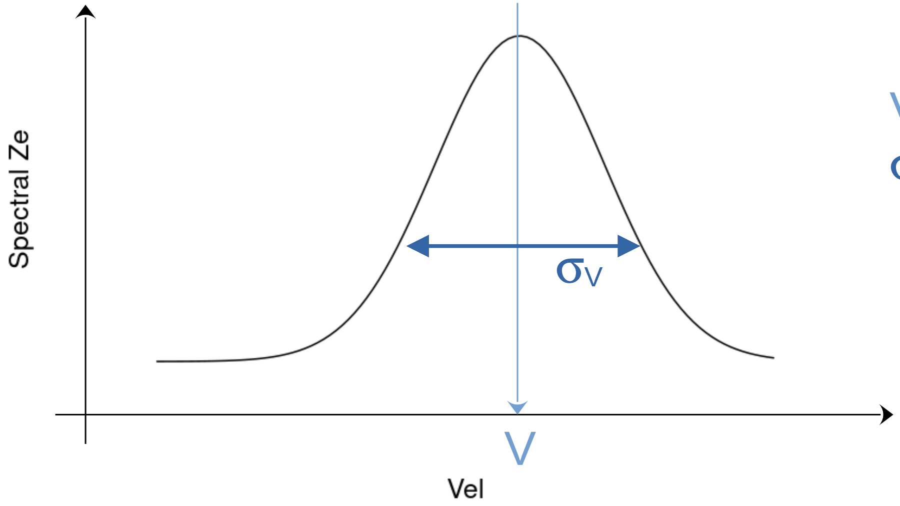
Doppler spectral data

Radar may record the full Doppler spectrum (i.e. values of Z at different frequencies/velocities)

Rich data because info about variability within the radar sampling volume!

Mostly used in vertical profiling configuration to limit influence of horizontal wind...



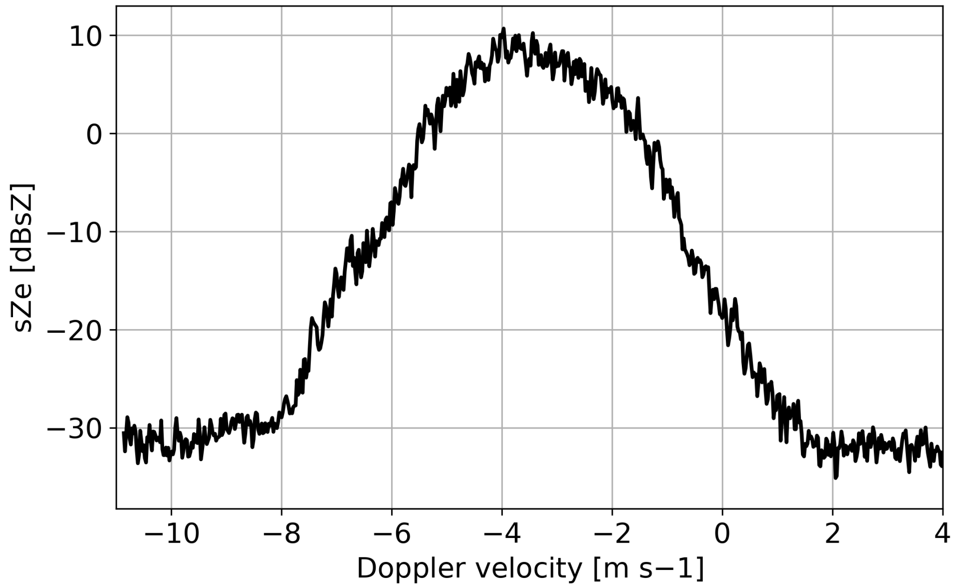


V = mean velocity
σ_V = spectral width

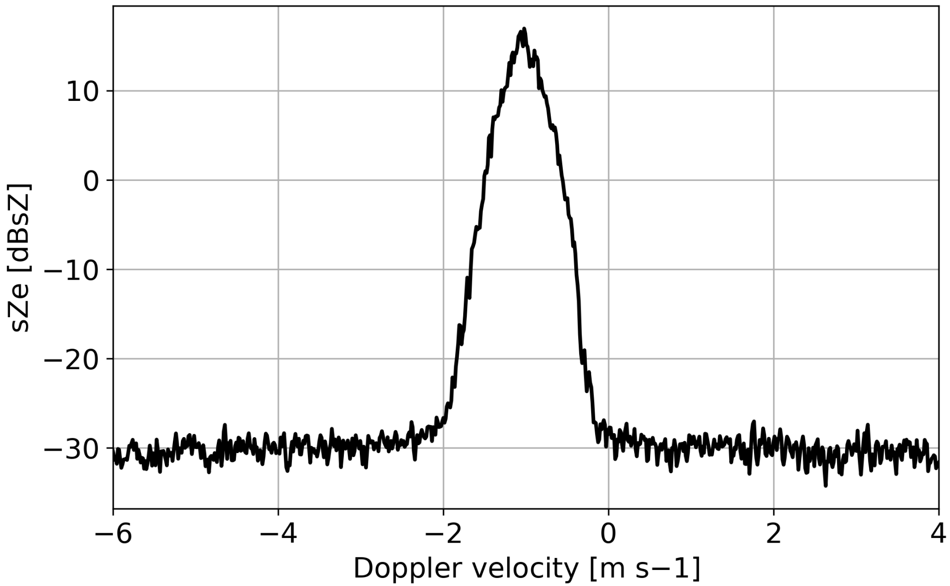
Doppler spectral data

Doppler spectrum influenced by hydrometeors (σ_b, v, concentration)
but also atm conditions (wind, turbulence) and radar characteristics (λ, θ_{3dB}, noise)

ex#1 of measured Doppler spectrum



ex#2 of measured Doppler spectrum

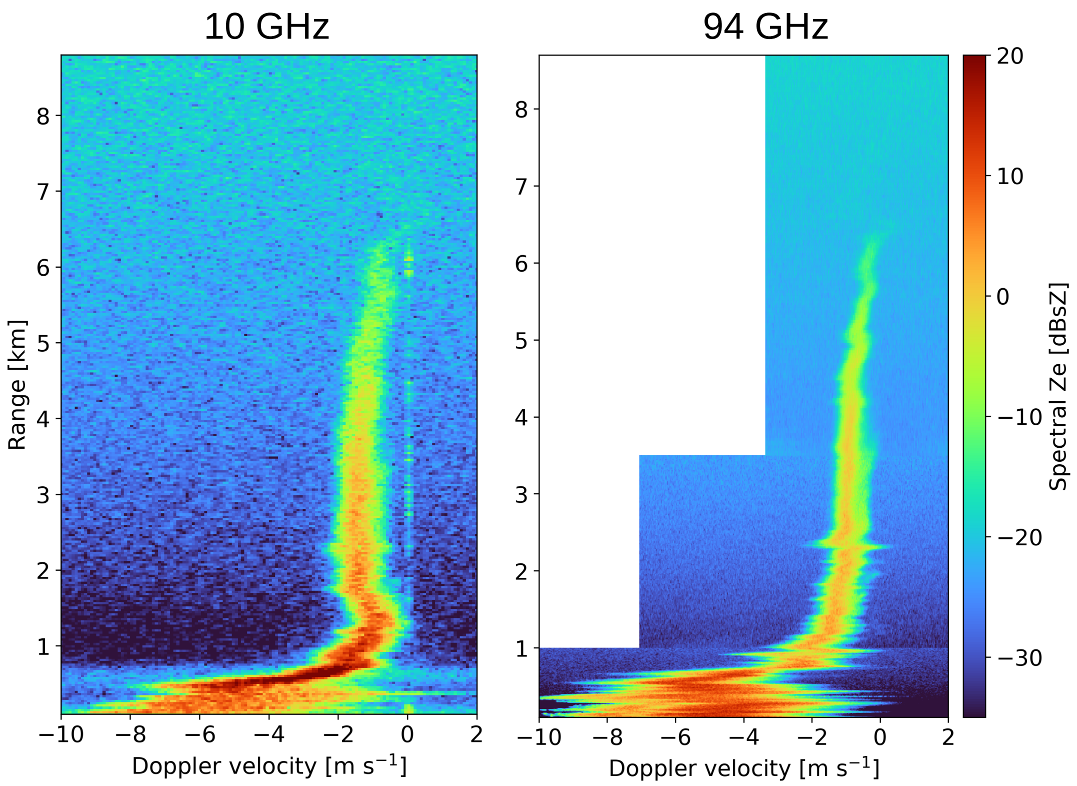


From LTE’s W-band profiler

Melting layer

The phase change also influences the shape and magnitude of the Doppler spectra

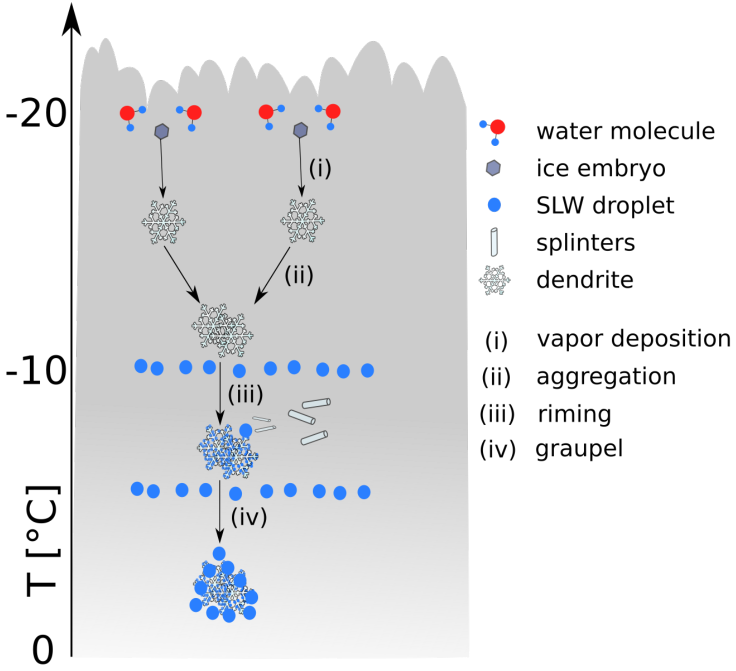
- Raindrops fall faster → increase in velocity
- Raindrops cover a large range of fall velocities → broader spectra
- Raindrops have larger σ_b → increase in Z

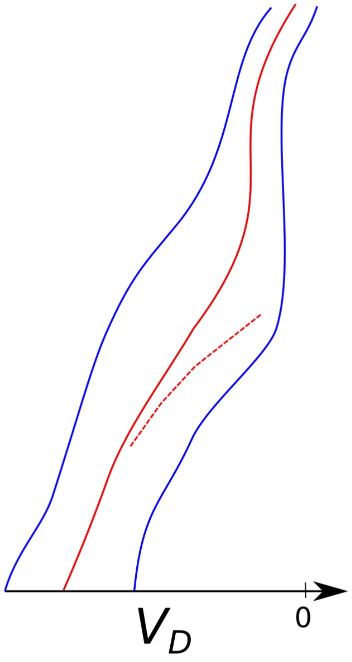


Radar and microphysics (2) – Doppler spectrum

Doppler spectral signatures

- Deposition: V_D and σ_D are low.
- Aggregation/riming: V_D and σ_D ↗
- Secondary ice production → bi-modality.
- Turbulence: σ_D ↗↗





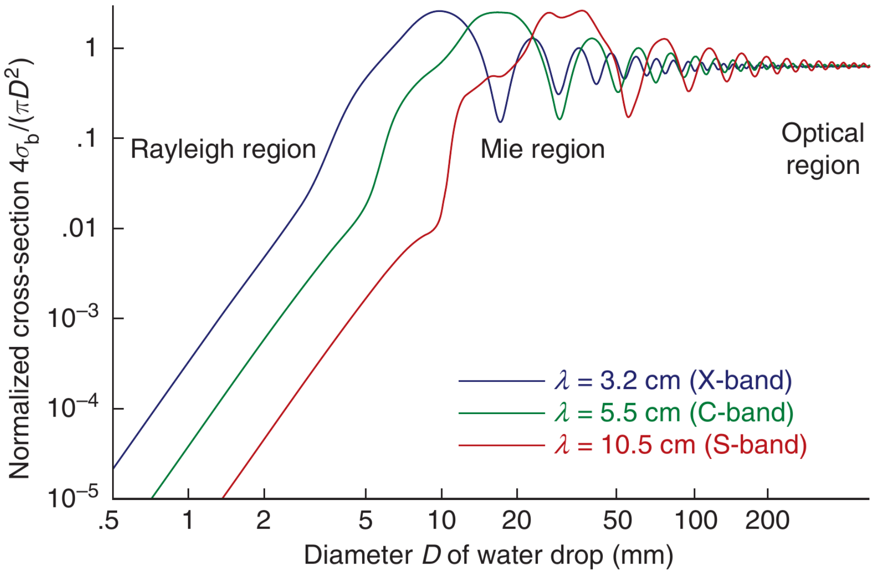
Limitations

- Contamination by vertical wind.
- Mixing by turbulence.

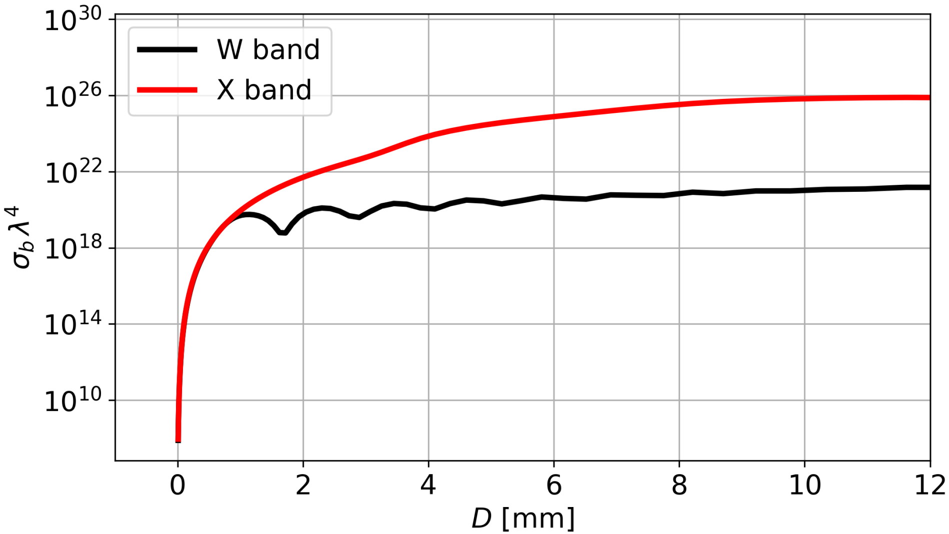
Combination of 2 (or more) frequencies

Typically X/W (10/95 GHz), Ka/W (35/95 GHz) or X/Ka (10/35 GHz) bands

Dual-frequency (reflectivity) ratio DFR = Z_{f1} / Z_{f2} ($f_1 < f_2$)



$\sigma_b\lambda^4$ (~réflectivité)



Small particles → Rayleigh regime at both freq → DFR ~1

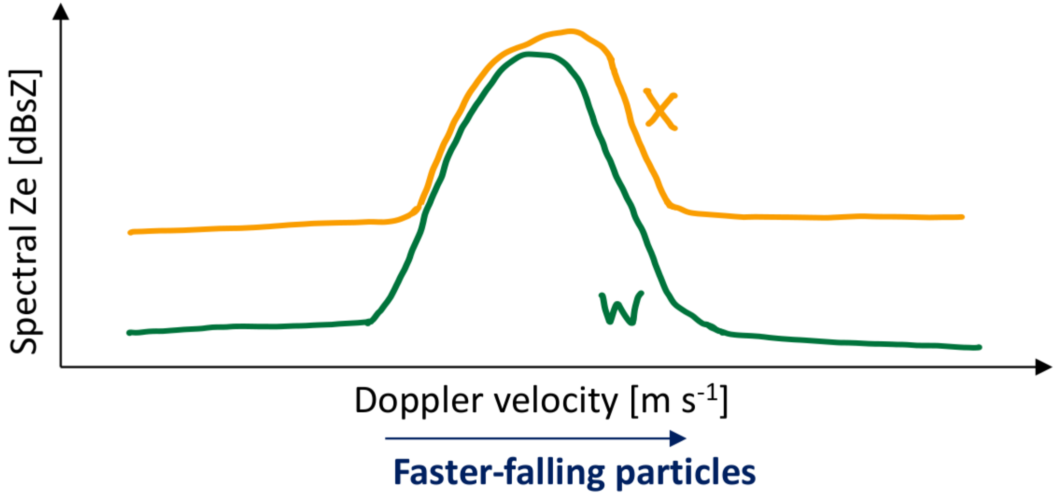
Large particles → Rayleigh at low, Mie at high freq → DFR >> 1

Combination of 2 (or more) frequencies + spectral data

DFR per spectral class...

X-band: $\lambda \approx$ 3 cm >> $D_{snowflake}$
(λ larger than most snow particles)

W-band: $\lambda \approx$ 3 mm ~ $D_{snowflake}$
(λ larger than small snow particles, but smaller than big ones!)



Combination of 2 (or more) frequencies + spectral data

DFR per spectral class...

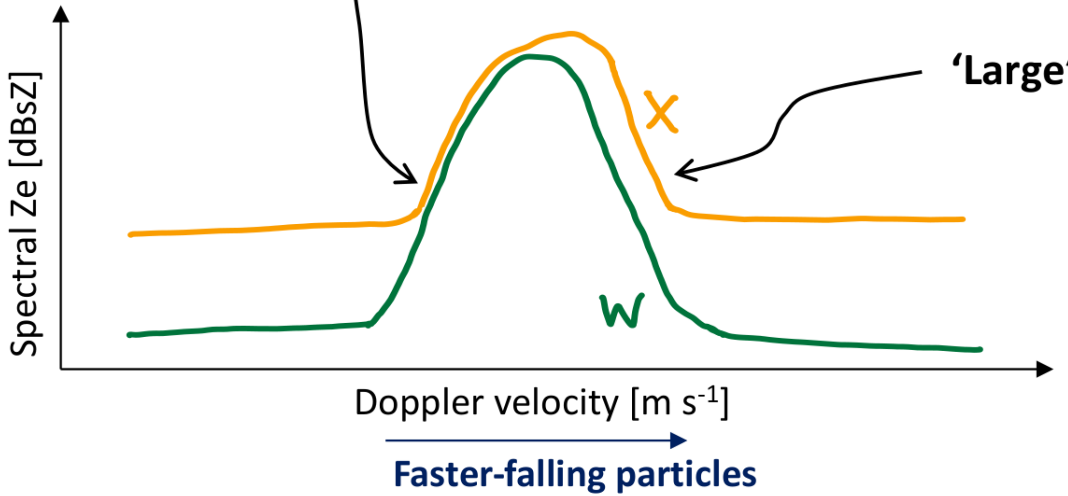
- Rayleigh/non-Rayleigh scattering regimes

X-band: $\lambda \approx$ 3 cm >> $D_{snowflake}$
(λ larger than most snow particles)

W-band: $\lambda \approx$ 3 mm ~ $D_{snowflake}$
(λ larger than small snow particles, but smaller than big ones!)

'Small' particles: $sZe_X \approx sZe_W$

'Large' particles: $sZe_X > sZe_W$



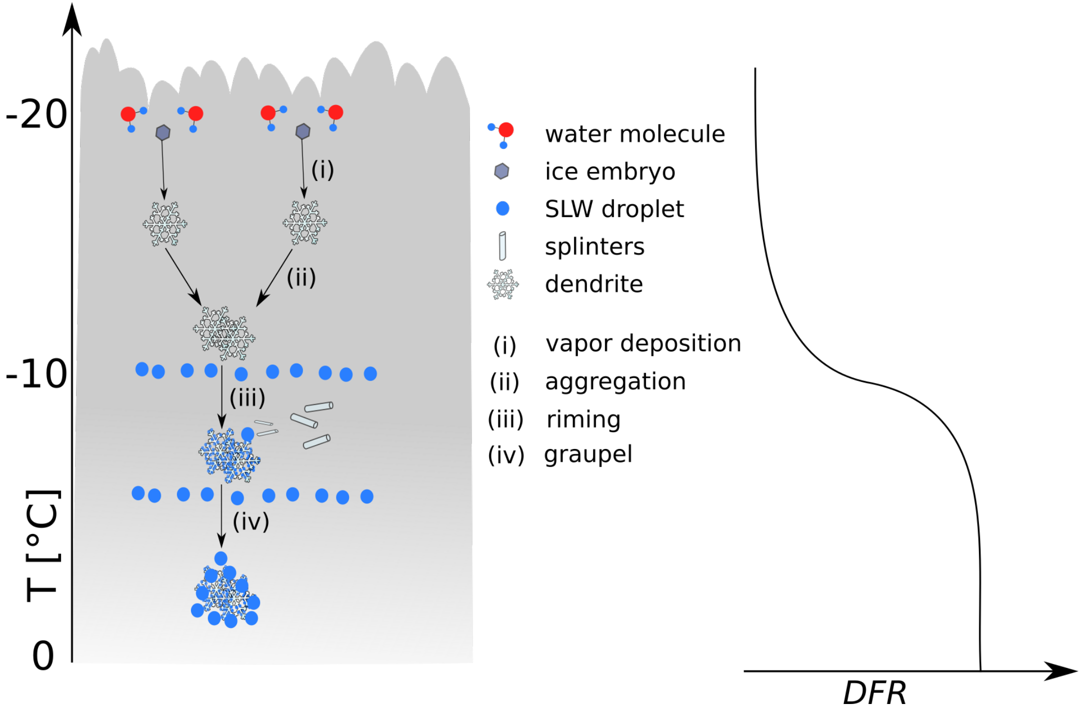
Radar and microphysics (3) – Multi-frequency

DFR signatures

- Deposition: DFR ~ 1.
- Aggregation/riming:
  size/density ↗ → DFR >> 1
- To distinguish agg/riming:
  triple-frequency approach

Limitations

- Beam matching.
- Accurate calibration.



Summary

Radar to study clouds and precipitation

1. Radar basics
   → Weather radars: 3 < freq < 100 GHz – 1 mm < λ < 10 cm
   → Active RS, measures signal backscattered by hydrometeors
   → 2 main scattering regimes for weather radar: Rayleigh and Mie
   → Radar reflectivity (factor)

2. Polarimetric radar
   → Backscattered signal at 2 linear polarization planes (H and V)
   → Additional variables → information about hydrometeor types/shape

3. Spectral radar meas.
   → Information about inside sampling vol + reflects microphys
   → Influenced by various factors not only related to hydromet

4. Multi-freq. radar meas.
   → Rayleigh or Mie scattering depending on particle size
   → Possibly spectral multi-frequency radar obs...