PRISTINE

–

Polarimetric Radar simulations with realistic Ice and Snow properties and mulTI-frequeNcy consistency Evaluation

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Outline

- Motivation
- Making EMVORADO fit for external scattering data
  - Bulk scattering lookup tables from external data sources
  - Orientation averaging
- Outlook

Polarimetric radar operator: Pre-PRISTINE status

➔ Approach: add polarimetry to EMVORADO, but **keep existing core features & characteristics**

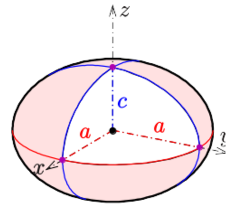
- consistent model coupling, sensor (network) modelling
- hydrometeor property assumptions (e.g. hydrometeor morphology & melting state)
- speed (→bulk scattering lookup-tables)

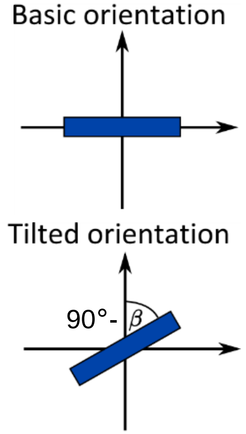
➔ Added scattering model option: **T-Matrix** + **angular moments**

*state-of-the-art, but **has its issues***

- **default:** shape (AR), orientation (σ_β), melt fraction dependence from **Ryzhkov et al. (2011)**

liquid	rain	ice	snow	graupel, hail	
Rayleigh	oblate spheroids	oblate spheroids	oblate spheroids	oblate spheroids	shape
-	Brandes (2002) f(deg4-in-D)	Matrosov (1996) thick plates aD^b	1.0-0.02*D 0.8 (D>10mm)	1.0-0.02*D 0.8 (D>10mm)	AR
-	10°	10°	40°	40°	σ_β
-	-	both: lin. in f_m to rain	both: lin in f_m to rain	AR: lin. in f_m between $AR_{wet}=[AR_{dry},0.8,0.48,AR_{rain}]$ for $f_m=[0,0.2,0.8,1]$ σ: lin. in f_m to rain	melting behaviour (f_m=mass melt fraction)

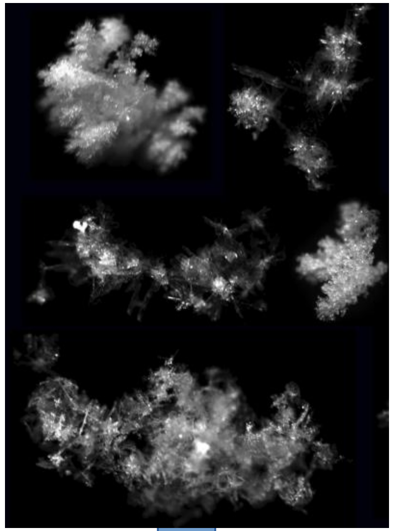


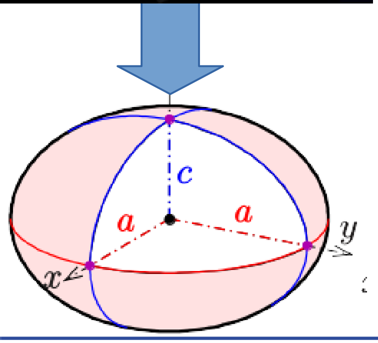


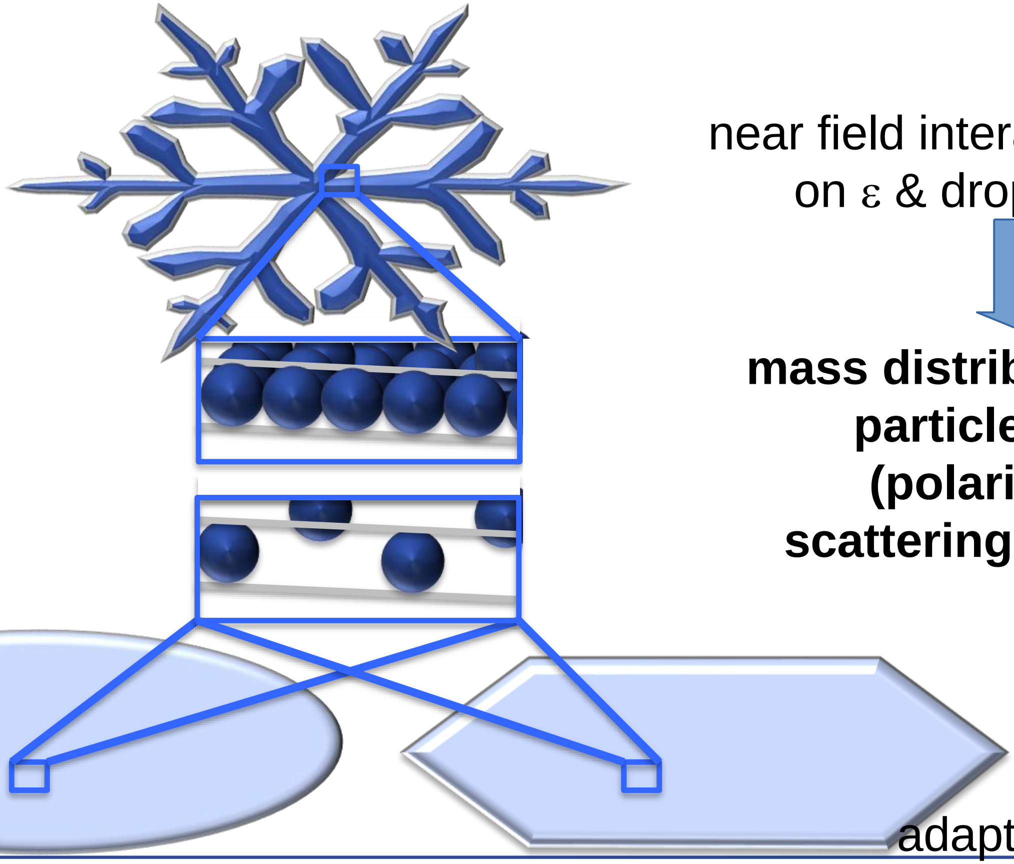
Polarimetric radar operator: [T-Matrix] Issues

➔ Polarimetric radar forward operator state-of-the-art:

- Assume regular-shaped, **homogeneous effective density** in Mie/T-Matrix calculations
  - (most?) popular: fix D_{max}, m, aspect ratio → derive effective **(reduced)** density of spheroid







near field interactions depend on ε & drop off as $1/r^3$

mass distribution within particle affects (polarimetric) scattering properties

adapted from Kumjian, 2019

Polarimetric radar operator: [T-Matrix] Issues

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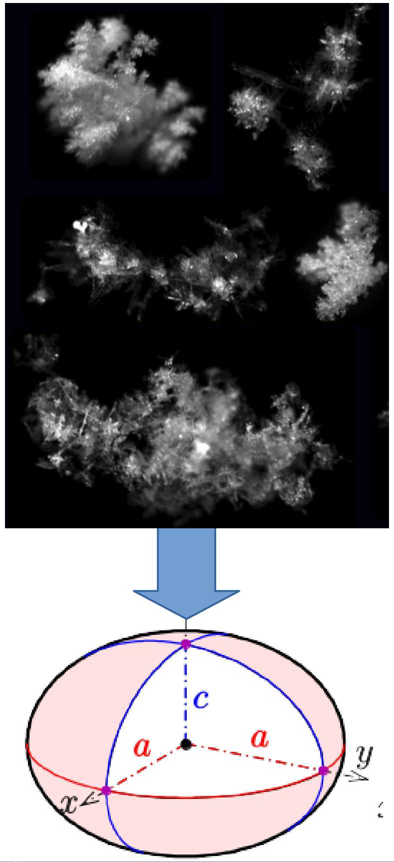

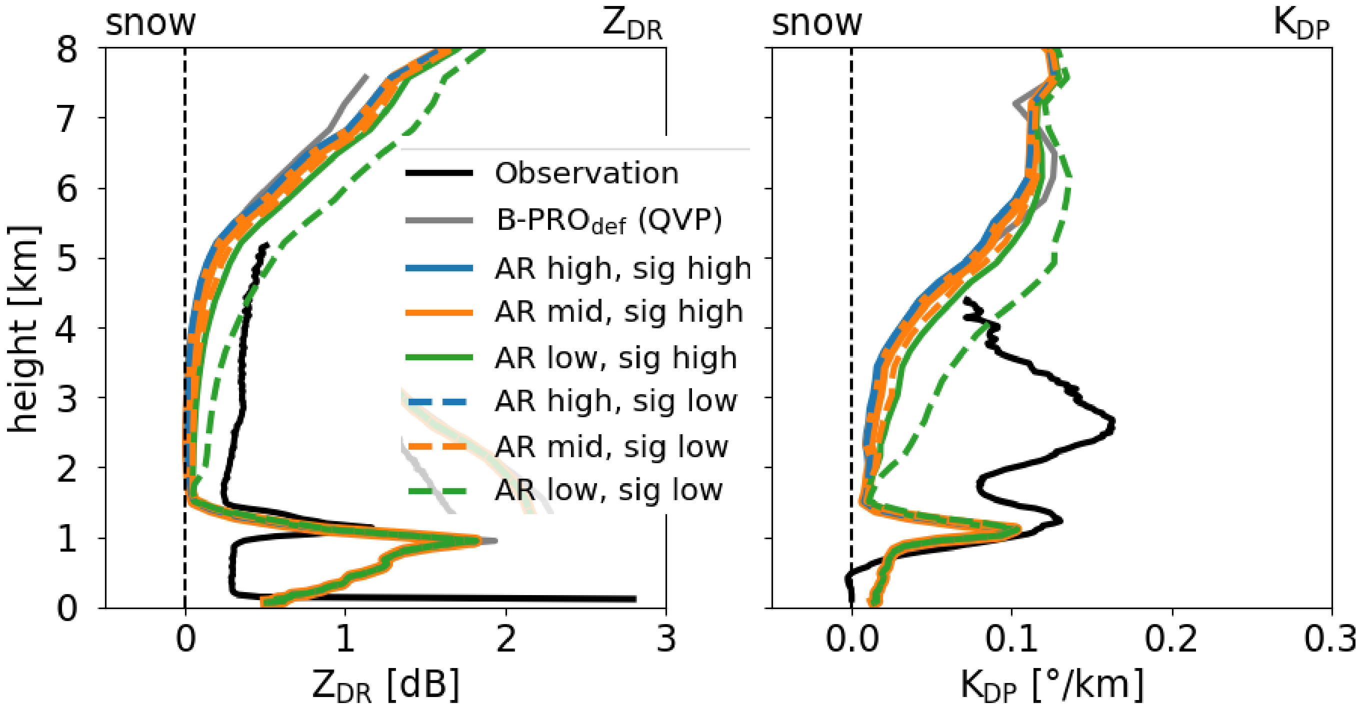

Shrestha et al., 2022

Polarimetric radar operator

- Approach: add polarimetry to EMVORADO, but **keep existing core features & characteristics**
  - consistent model coupling, sensor (network) modelling
  - hydrometeor property assumptions (e.g. hydrometeor morphology & melting state)
  - speed (→bulk scattering lookup-tables)
- Added scattering model option: T-Matrix + angular moments

- Add option to **use externally calculated scattering data**
  - interface to scattering DB(s)

DWD: Project aims

➔ **Improve DWD‘s radar operator EMVORADO**

- for (better) use in
  - **model evaluation:** O-B deviations due to NWP model or radar operator?
  - data assimilation: bias reduction (at the source, not post-proc)

- but keeping its capabilities
  - model consistency (esp. PSD, m-D relation)
  - calculation speed (eg. bulk scatt. lookup tables)
  - flexibility in instrument definition, e.g. frequency

Outline

- Motivation
- Making EMVORADO fit for external scattering data
  - **Bulk scattering lookup tables from external data sources**
  - Orientation averaging
- Outlook

Bulk scattering LUT

➔ Ensure consistency
- w/ model (PSD, m-D relation)
- w/ EMVORADO setup (e.g. melting scheme)

} ensured by file naming scheme using hash-based IDs
no user interaction required (nor possible)

➔ Phase 1: Externally prepared model-consistent LUT
- a) **Overrule/don't apply hash ID**
- b) Simplified hash number: only consider PSD & m-D

➔ Phase 2ff: in-EMVORADO LUT preparation
- Select particles from DB with consistent m-D
  - (& other constraints – here's the science part)
- Form & use equivalent hash ID

Outline

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- ➔ Making EMVORADO fit for external scattering data
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  - **Orientation averaging**
- ➔ Outlook

Orientation averaging

➔ So far: ***Angular moments approximation*** (Ryzhkov, e.g. 2011)

- Derive polarimetric scattering properties of particles with Gaussian canting distribution from scattering amplitudes of „uncanted“ particle

- **Pro:**
  - single orientation output from T-Matrix only (minimum effort & memory)
  - „quasi-analytical“ orientation weight factors (easy computation)

- **Con:**
  - rotationally symmetric particles only (?)
  - easy-to-calculate factors for elevation=0° and specific canting distributions only (oblate: random & Gaussian; prolate: horizontally aligned)

Orientation averaging

➔ Modification: ***Explicit orientation averaging***

- Derive polarimetric scattering properties for a set of fixed particle orientation & integrate/average over them
- Con:
  - more T-Matrix output (more memory; **comp. effort increases only marginally when done correctly**)
  - numerical integration, ie method and sampling point dependent
- Pro:
  - any desired orientation distribution (flexible)
  - any radar elevation (flexible)
  - arbitrary particle shapes (flexible)

➔ replace angular moments, also for in-EMVORADO SSP calculations from T-Matrix

Explicit orientation averaging

➔ Parameters to provide & average:

- Angular moments act on complex scattering amplitudes **S**
  - **S** are NOT additive! **(ie not usable in expl. orient. avg.!)**

- currently, set of additive parameters used in PSD-integration, hydrometeor class add-up, and bulk LUT:
  - **zh** (=bsc-xs in h-h), **zv, zvh, rrhv** (=Re(nominator(RHV)), **irhv** (=Im(…)); **kdp, ah** (=ext-xs in h), **adp**

$$\rho_{hv} = \frac{2^2 |S_{hh} S_{vv}^*|}{\sqrt{|S_{hh}|^2 \cdot |S_{vv}|^2}} = \frac{\sqrt{(\bar{Z}_{33}+\bar{Z}_{44})^2 + (\bar{Z}_{43}-\bar{Z}_{34})^2}}{\sqrt{\sigma_{hh} \cdot \sigma_{vv}}}$$

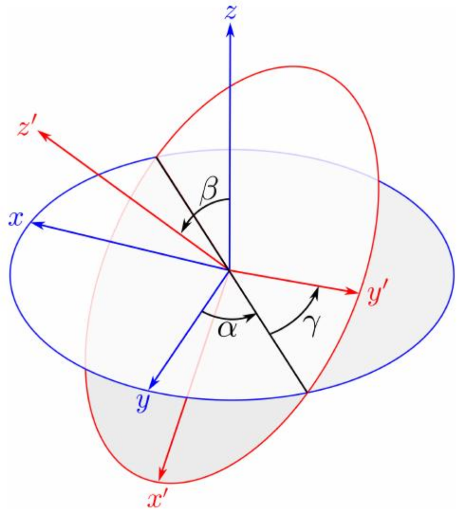
- (Stokes) Scattering and extinction matrices (Z and K) are an alternative representation of pol. scatt props
  - additive
  - bsc=f(Z(1:2,1:2)), nom(RHV)=f(Z(3:4,3:4)) & ext,kdp=f(K)

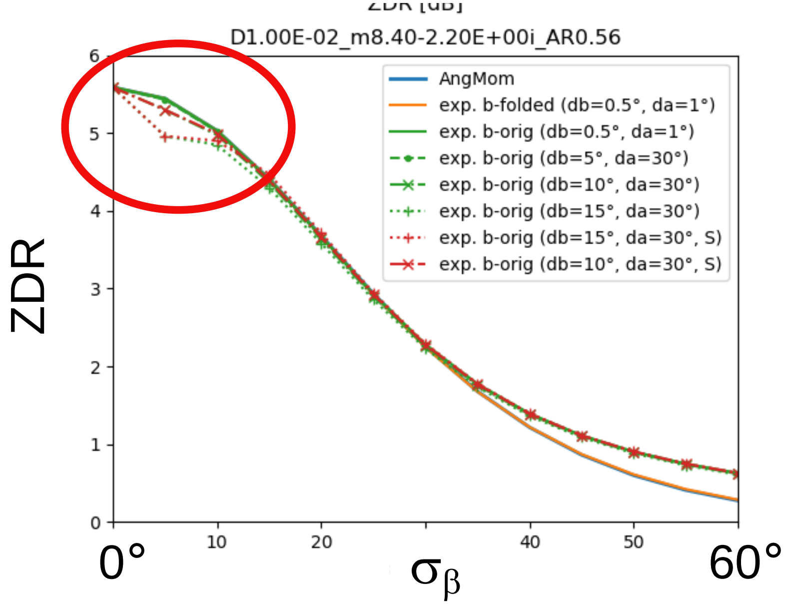
➔ **use LUT 8-parameter set in canting distrib calc & (already) as new TMat-(wrapper-)output**

Explicit orientation averaging

➔ Numerical integration:

- Over azimuthal (α) and canting (β) orientation angles
  (for oblate spheroids, γ not applicable due to rotat. symmetry w.r.t. z-axis)
- Which quadrature scheme?
  - Trapezoidal, Simpson; Gauss-Legendre, …?
- Which polar angle parameter to integrate over?
  - β or $\cos(\beta)=\mu$?
    $\rightarrow \int Z * p * \mathbf{\sin\beta}\, d\beta = \int Z * p\, d\mu$
- How many quadrature points?
  - not very critical, but β (variable) more than alpha (α)



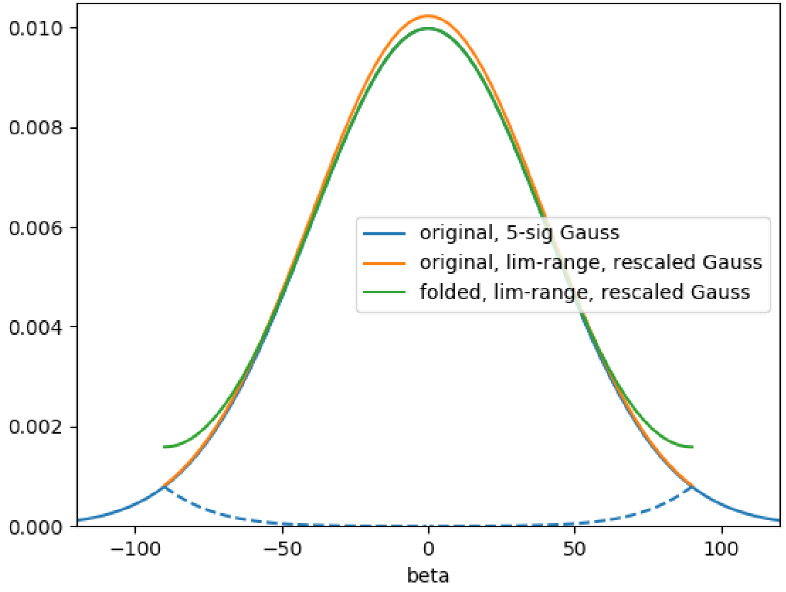


Explicit orientation averaging

➔ Numerical integration: Over **canting (β)** orientation angles

- **What about pdf-contributions from outside +/-90°?**
  - for large(r) σ_β, norm(Gaussian pdf) over [-90°,+90°] < 1.
  - What to do?
    - nothing? (not an option since not norm-conserving)
    - **renormalize**? (current implementation)
    - **fold**? (my earlier choice)

  Consider any of them „more“ (physically) correct?



Explicit orientation averaging: Conclusions I

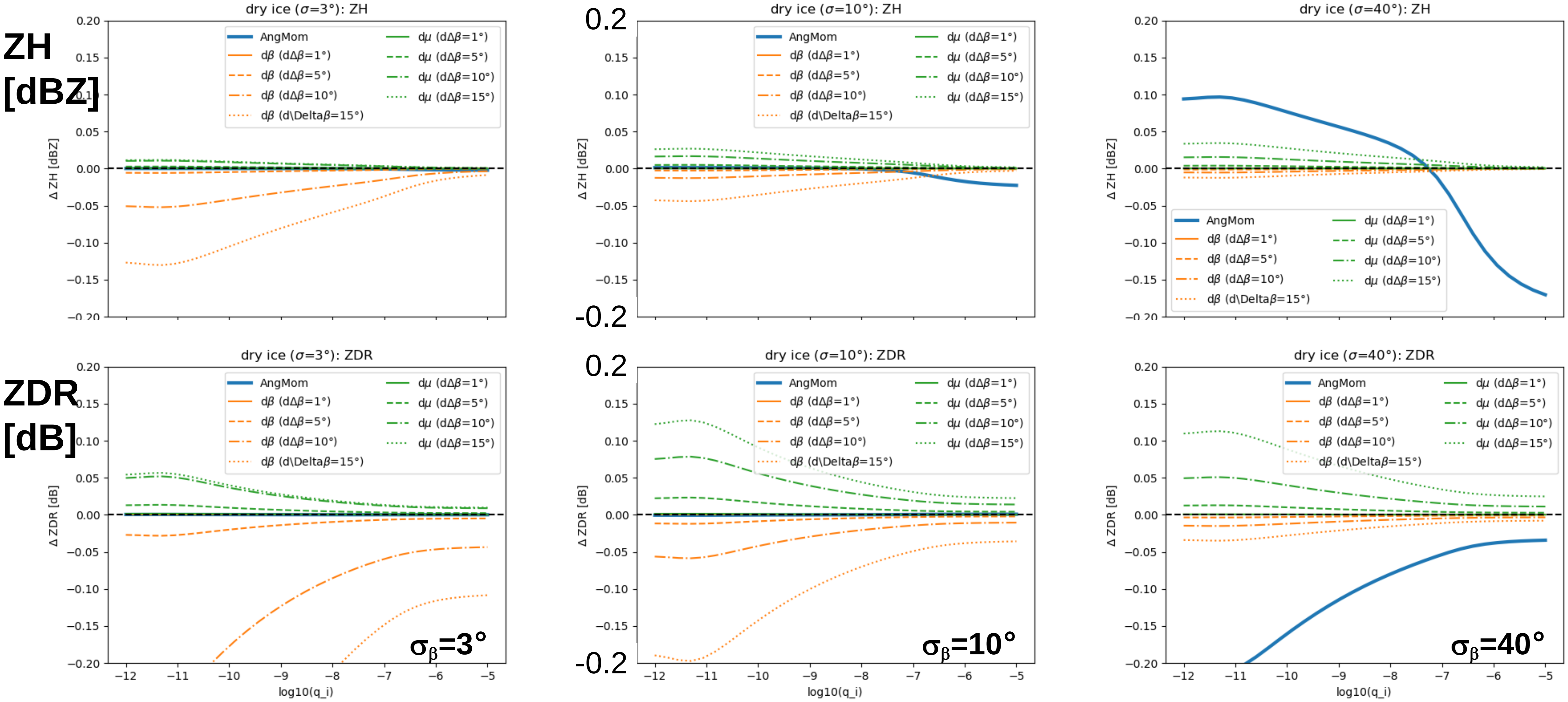
➔ From single particle tests:

- Simpson performs bad for polar angle integration
- Trapezoidal with $\Delta\mu$=const performs bad
- Gauss-Legendre better than $\Delta\beta$=const except for small σ_β

Explicit orientation averaging: Choice of dx & spacing

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

➔ Resulting EMVORADO bulk scattering LUT (dry ice example): Diff to **exp.orient.avg. high-res. reference**



Explicit orientation averaging: Choice of dx & spacing

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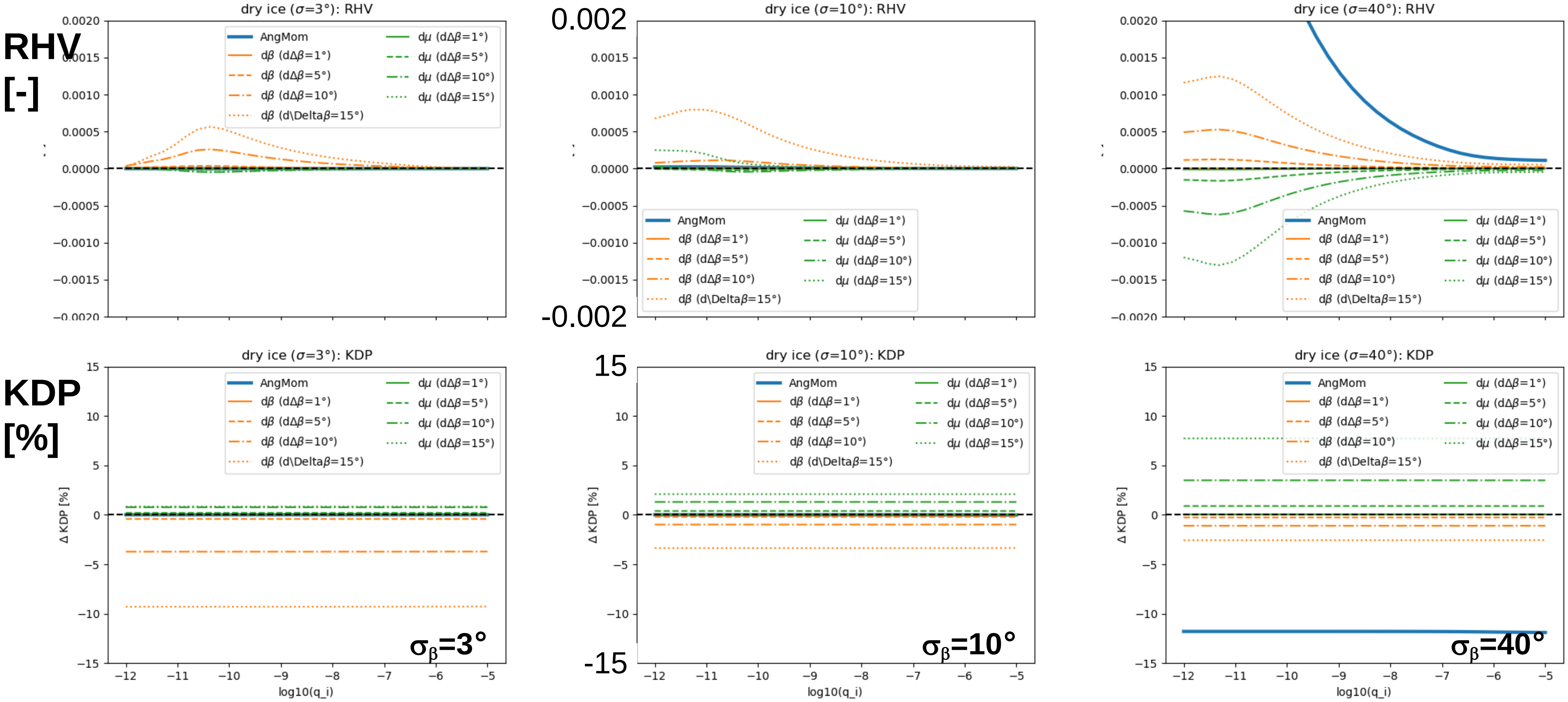

Explicit orientation averaging: Conclusions II

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

➔ From EMVORADO bulk LUT (dry ice example):

- ∫dμ might mitigates β=0° non-contribution issue of ∫sin(β)dβ
  - for μ(Δβ=const):
    - kinks at σ_β<Δβ removed in single particle example, but slightly larger offsets in general for same Δβ
    - dμ clearly better at σ_β<Δβ, similar performance at σ_β≈Δβ, slightly worse at σ_β>Δβ
    - dμ overestimates, dβ underestimates

- for large(r) σ_β, any Δβ and dx better than **angmom** (clearly underestimates pol. moments)

  → **gridding over β** on Δβ=const base that can easily be refined when/where needed

  dx=dμ or selection of dx dependent on σ_β

  partially refined grid or even mix of dμ (at small β) and dβ (at larger β) could be used

- from dry ice LUT, **Δα=30° & Δβ=10° seem sufficient**
  - but should be further tested for rain & melting hydrometeors

(More) Questions?

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Extra slides

∫ z(β) p(β) sinβ dβ ≡ ∫ z(β(μ)) p(β(μ)) dμ? YES!

$$\int_{x_1}^{x_2} f(x)\,dx = \int_{y_1(x_1)}^{y_2(x_2)} g(y)\,dy$$

$$f(x)\,dx = g(y)\,dy$$

$$g(y) = f(x)\,\frac{dx}{dy}$$

$$\int g(y)\,dy = \int f(x)\,\frac{dx}{dy}\,dy$$

$$= -f(x)/\sin\beta \; d\cos\beta$$

$$x = \beta$$

$$y = \cos\beta = \mu$$

$$\frac{d\beta}{d\cos\beta} = 1/\frac{d\cos\beta}{d\beta} = 1/-\sin\beta = -\frac{1}{\sin\beta}$$

$$f(x) = p(x)\cdot\sin\beta$$

$$g(y) = f(x)\,/\,\frac{dy}{dx}, \qquad \frac{dy}{dx} = \frac{d\cos\beta}{d\beta} = -\sin\beta$$

$$= p(x)\cdot\sin\beta \,/\!/\, -\sin\beta$$

$$= -p(x)$$

$$\int_1^0 -p(x)\,d\cos\beta = \int_0^1 p(x)\,d\cos\beta$$

$$y_1 = \cos\beta_1 = \cos 0^\circ = 1$$

$$y_2 = \cos\beta_2 = \cos 90^\circ = 0$$

Reduced density approach

SPP 2115

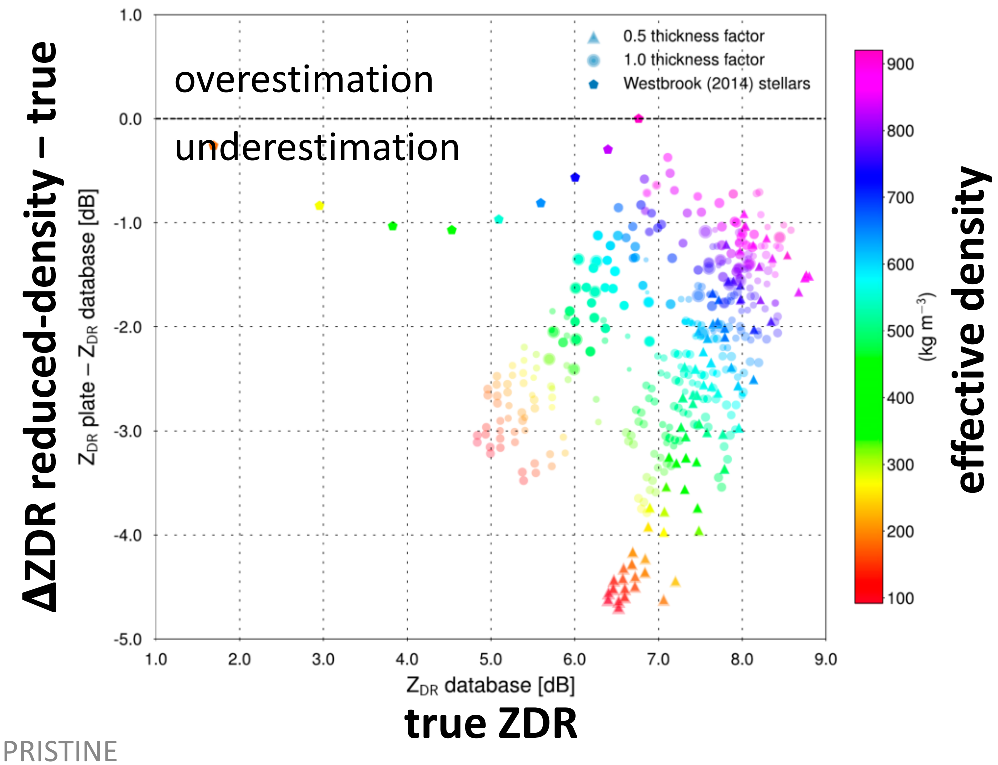
Probably the most popular approach to setup particles consistent to model constraints (keeping m, D, and aspect ratio unchanged) with T-Matrix suitable shapes.

T-Matrix based simulations show a **consistent deficit** in terms of **polarimetric response** in the dendritic growth layer where large, "fluffy" particles prevail.

Schrom & Kumjian (2018)

- assessed errors in polarimetric scattering properties of homogeneous reduced-density particles as proxies of branched planar crystals (both from DDA)
- found persistent underestimation of ZDR, the worse the less dense

- provided detailed explanation for the **role of internal structure** from dipole interactions



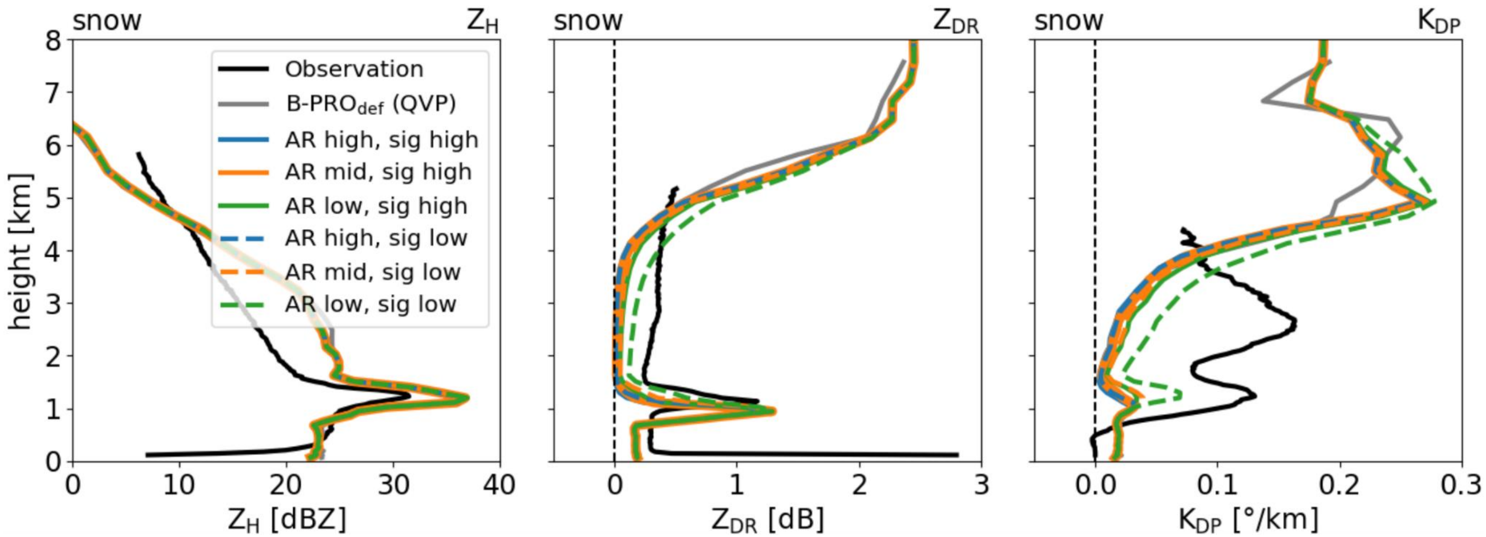
DGL signatures in PFOs

SPP 2115

... consistent deficit in terms of polarimetric response ...

There are further explanations for lack of polarimetric signals!

FO uncertainties that can contribute include, e.g.,
- melting models
- dielectric properties (primarily of air-ice(-water) mixtures)
- *shape and orientation assumptions*



	snow
AR_{high}	Ryzhkov et al. (2011) $max(1.0-20D, 0.8)$
AR_{mid}	**Xie et al. (2016)** $\mathbf{max(0.7-10D, 0.5)}$
AR_{low}	Dunnavan et al. (2019) 0.4
σ_{high}	**Ryzhkov et al. (2011)** **40°**
σ_{low}	Matsui et al. (2019) 20°

Shrestha et al. (2021), GMDD

DGL signatures in other PFOs

SPP 2115

... **consistent deficit** in terms of **polarimetric response** ...

There are **further explanations & reasons** for lack of polarimetric signals!

FO uncertainties that can contribute include, e.g.,

- melting models
- dielectric properties (primarily of air-ice(-water) mixtures)
- shape and orientation assumptions

Regarding **model microphysics** these include, e.g.,

- hydrometeor size distribution
- hydrometeor class partitioning
  - lack of secondary ice
  - wet growth processes
- mass-size relation
- mixed-phase hydrometeors

→ Can we draw robust conclusions about model microphysics from synthetic signals based on homogeneous particle approaches?