An efficient polarimetric radar forward operator for NWP model validation and data assimilation

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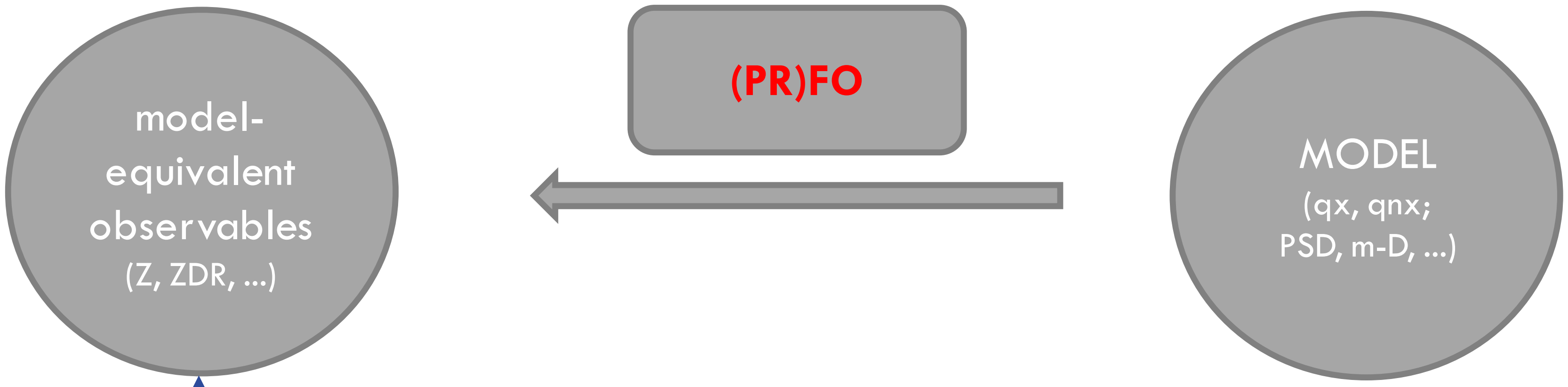
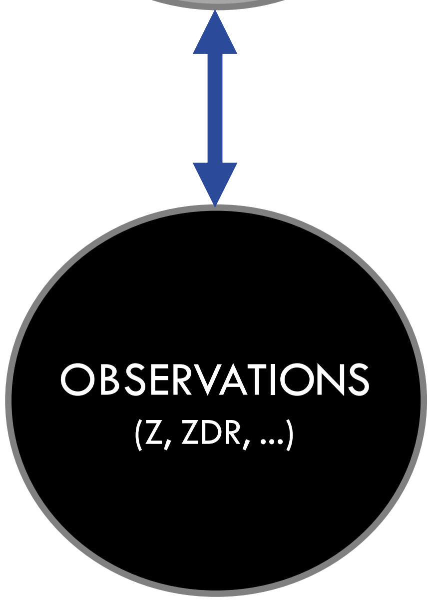
((Polarimetric) Radar) Forward operators





adapted from Pejcic'20

→ Forward operators are **centrals tools** in many applications:

- Retrieval development or retrievals
- OSSE
- Data assimilation
- Model evaluation / validation

((Polarimetric) Radar) Forward operators

model-equivalent observables
(Z, ZDR, …)

(PR)FO

MODEL
(qx, qnx;
PSD, m-D, …)

OBSERVATIONS
(Z, ZDR, …)

adapted from Pejcic'20

- Incomplete info from model → assumptions by FO required, e.g. on:
  - Melting state (→ brightband)
  - Dielectric properties: air-ice and water-air-ice mixtures
  - Polarimetry: Shape, orientation, internal structure of hydrometeors

  → **FO uncertainties**
- Tuning parameter ↔ Characterize & disentangle from model uncertainties

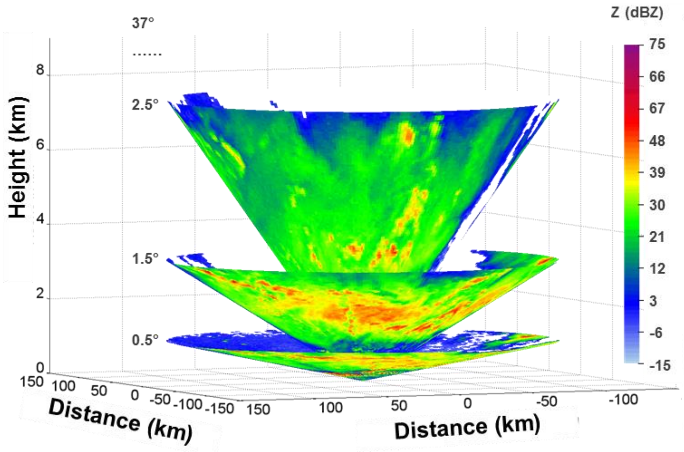
Efficient Modular Volume scan RaDar Operator (EMVORADO)

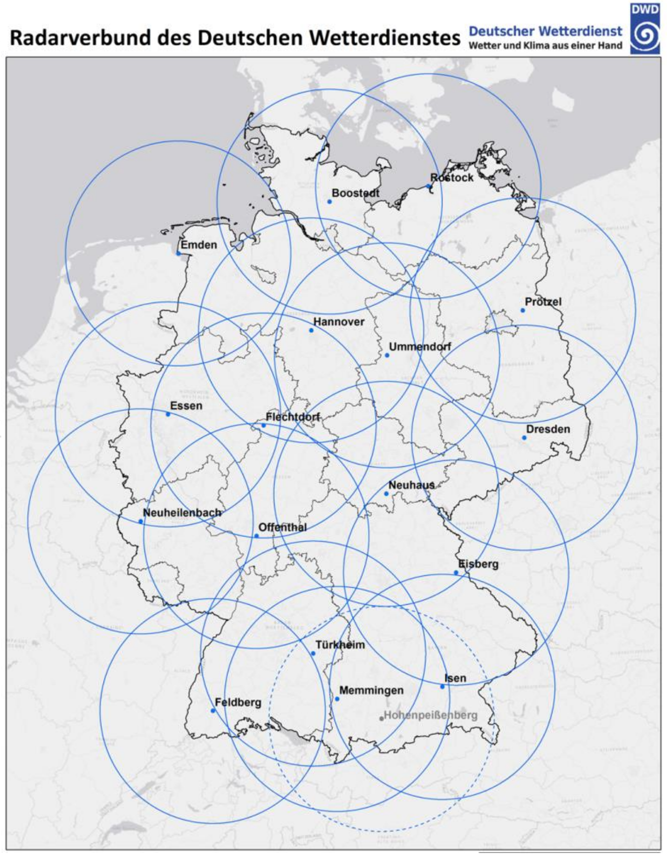
Deutscher Wetterdienst
Wetter und Klima aus einer Hand

➔ FO in DWD's **operational assimilation** of reflectivities and radial winds from C-Band **radar network**

➔ **Central requirements:**

- Computational **speed**
- Synthetic observations from sensor networks
- Model consistency





➔ **Central features:**

- Online coupled to ICON (and COSMO)
- Bulk (Mie) scattering lookup tables
- Observation modelling: incl. beam smoothing, scan pattern, …

Assumptions on unconstraints (→ tuning parameters):

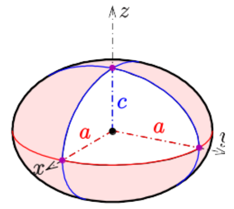
- Melting scheme: $f_m = f(T,D)$
- Choice of effective dielectrics index approaches

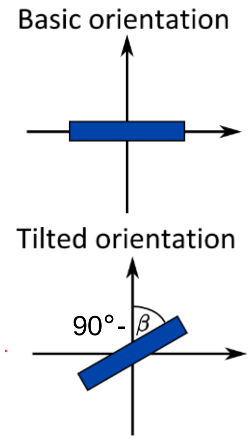
Polarimetric extention of EMVORADO

- Approach: extend & adapt where necessary, but **keep existing features & characteristics**
- Added scattering model option: **T-Matrix** + angular moments
  - shape (AR), orientation (σ_β), melt fraction dependence from **Ryzhkov et al. (2011)**
- Lookup tables extended & adapted for polarimetry
- Polarimetric output: ZDR, (LDR), KDP, RHV, ADP

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

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)





Result example: Computational speed

➔ **Parallelization + bulk scattering lookup tables**

- tabulation of additive components per hydrometeor class
- over total (1mom) or mean (2mom) bulk mass q_x + ambient temperature T + max. melting temperature T_m

➔ **Example: online in ICON-LAM** on DWD‘s NEX-SX Aurora HPC (128 vector processors)

- D2-domain, 2-mom microphysics, 6 hydromet. classes
- 24h free forecast with 5‘ output of 10-elev. volume scans for 16 DWD C-band radars (= 289 radar output times)

Configuration	EMVORADO time [s] (incl. MPI comm.)	Total model time [s]	Increase [%]
CTRL (no EMVORADO)	-	680	-
E1: **Mie** (look-up), pencil beam, dBZ + v_r	15*	695	2.2
E2: T-matrix (look-up), pencil beam dBZ + all dualpol moments + v_r	**28***	**708**	**4.1**
E3: E2 + **vertical beam function smoothing** (5 auxiliary rays for quadrature)	51*	736	8.2

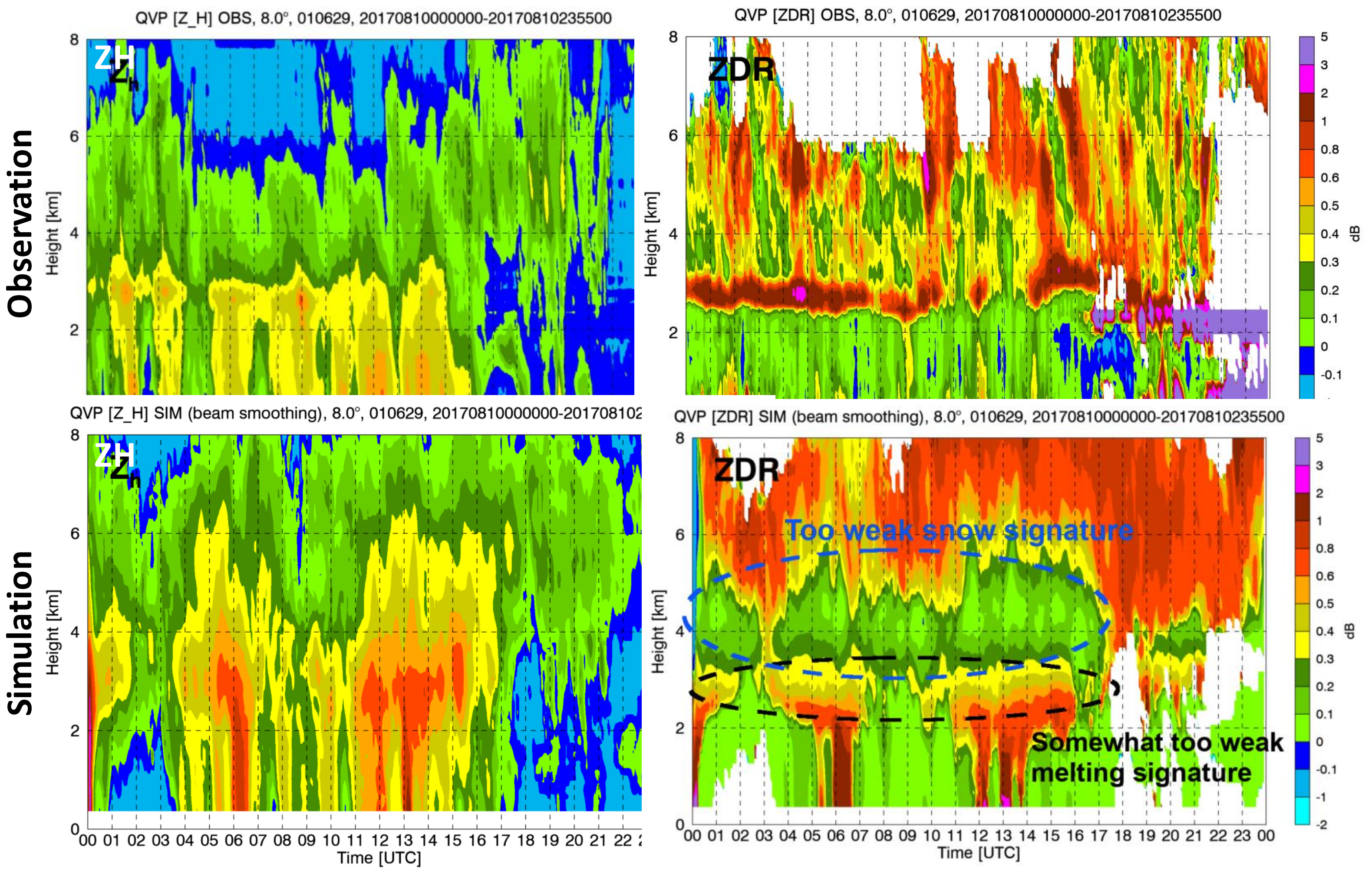
➔**Computing time polarimetry (E2),**
➔**one 5’-step,**
➔**all 16 German C-band stations:**
28 s / 289 = 0.1 s

*if the look-up tables already exist; additional time to pre-compute look-up tables, depends on platform, may vary from few minutes to several days

Result example

➔ Time series of Quasi Vertical
- 24h at 5min resolution
- C-band (OFT), 8°elevation
- Stratiform summer event

➔ **Lack of polarimetric signatures** in dendritic growth/aggregation layers
- Persistent issue
- Model or FO?
  - **T-Matrix** approach (reduced density) **very likely contributes**
    → Schrom & Kumjian, 2018
    → **not unique to EMVORADO or ICON**
    e.g. Augros (2016), Matsui (2019), Köcher (2021), Shrestah (2022)

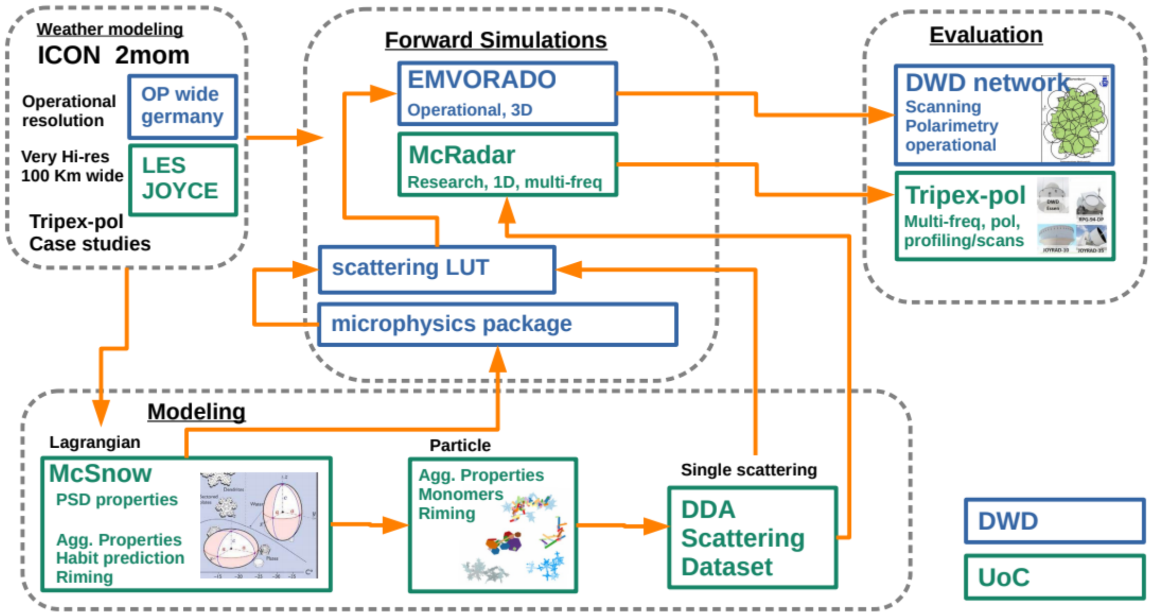


Outlook: PROM-2 PRISTINE

➔ FO uncertainties: **Particle model, shape & orientation**

➔ Issues:

- none-TMat approaches are costly
- scattering data with polarimetry & orientation is sparse
- availability of model-consistent habit & habit selection



➔ **Solution approach: a model-guided database**

- model shape & occurence of hydrometeors (snow primarily), derive scatt. props from DDA
  - **Lagragian particle model + aggregation/riming model**
  - starting from ICON model state
- **DDA-based bulk scatt LUTs** for EMVORADO
  - selection from scatt. DB **in dependence of model state („habit prediction“)**
  - consistent with model

Further reading

➔ Projekt Webpage of SPP-PROM 2115:
https://www2.meteo.uni-bonn.de/spp2115/doku.php

➔ EMVORADO User Manual:
http://www.cosmo-model.org/content/model/documentation/core/emvorado_userguide.pdf

➔ (non-pol.) EMVORADO reference paper: Zeng et al. (2016), QJRMS

➔ Polarimetric FO papers:

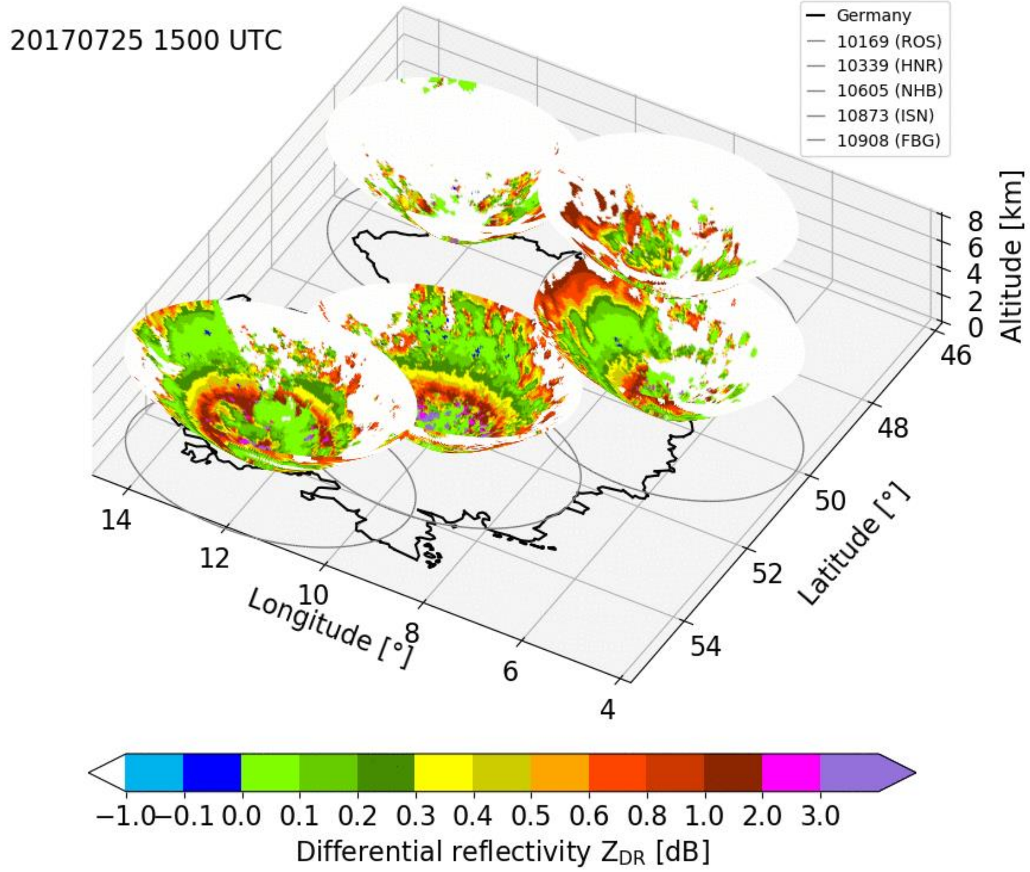
- Trömel et al. (2021), ACP
- Shrestha et al. (2022), GMD
- Shrestha et al. (2022), ACPD
- Mendrok et al. (in prep)

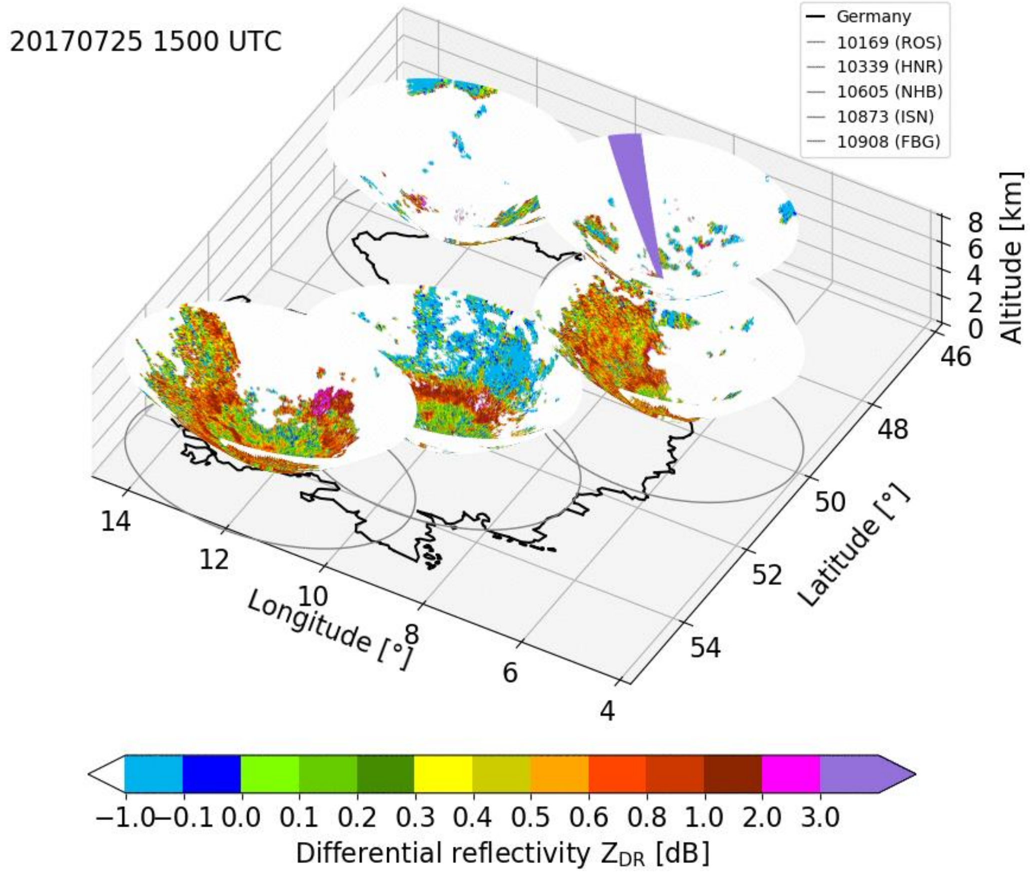
Extra slides

Application: Evaluate hydrometeor type representation

➔ Radar simulation output: Synthetic observations of polarimetric moments

- **equivalent to observations**: 10+1 elev. volume scans of 16 stations every 5' (**obs-governed, extendable**)
- shown: synthetic (left) vs. real (right) observations of ZDR (elev=1.5°) of a 2h forecast for 15UTC DA

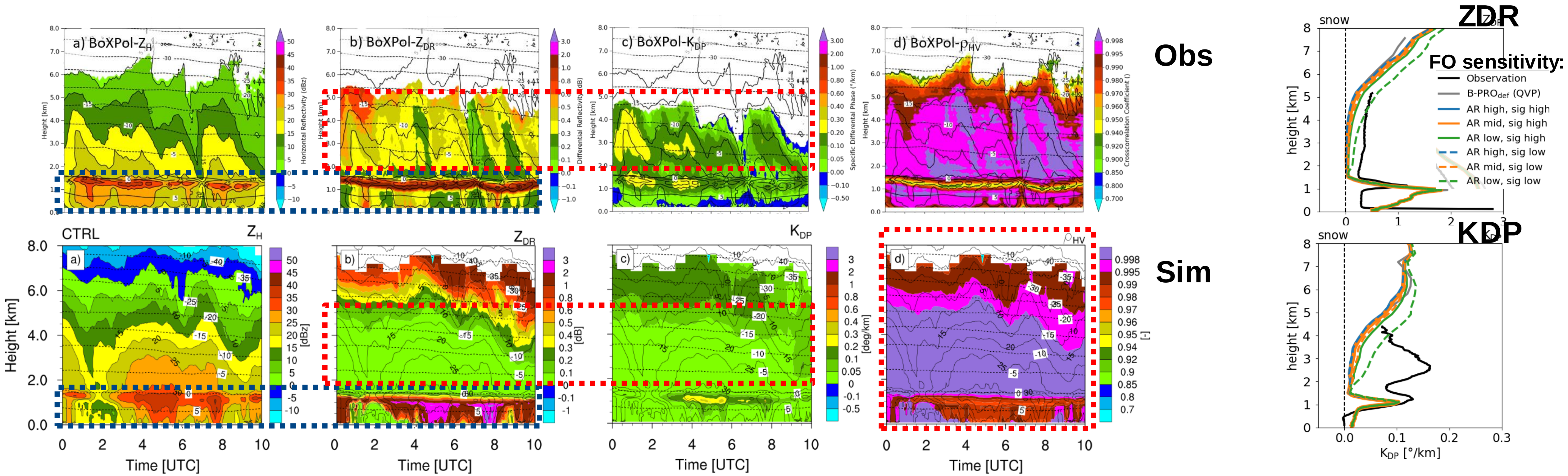




Polarimetric extention: Applications & Challenges

➔ Model evaluation (Shrestha et al., 2021):

- COSMO 2-mom of stratiform rain event, observed with X-band pol. radar at Bonn, Germany



➔ FO uncertainties & shortcomings:

- shape & orientation: choice of parametrizations, natural variability
- suitability of homogeneous models for fluffy, low effective density particles, eg snow aggregates

Polarimetric extention: (DA) Challenges

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

- FO uncertainties (non-**polarimetry** specific)
  - **Particle model, shape & orientation**
  - Effective medium approximation of refractive index
  - Melting scheme
  - Understanding of the measurement process: **beam smoothing of pol. parameters** (Z-weighted?)
- Technical
  - LUT calc time consuming (but: calculated once & re-used; then as fast as Mie/Rayleigh!)
  - Memory requirements (5-10 times Mie)
  - Lacking implementation of superobbing & feedback files

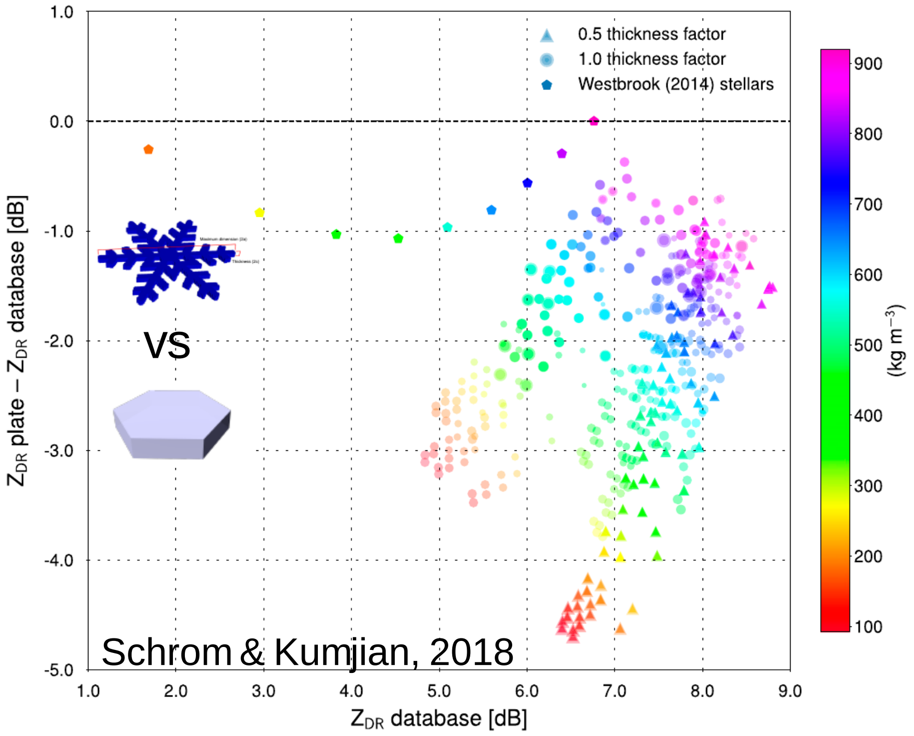


FIG. 3. As in Fig. 1, but for Z_{DR}. The size of the markers indicating the Westbrook (2014) particles are enlarged for the purposes of interpretation and therefore do not correspond in scale to the size of the markers depicting the Lu et al. (2016) branched planar crystals.

Tmatrix accuracy various approaches

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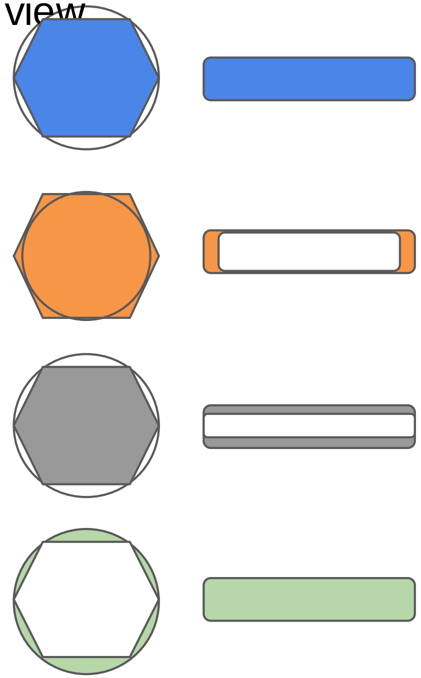
spheroidal or cylindric approximation of shape

4 extreme approaches (D, m, ar, density):

front view | side

1) increase mass
2) reduce max dimension
3) **change aspect** (make it thinner)
4) **reduce density**



There is no unique method.
It is possible to “tune” individual spheroids to match (some) scattering properties of complex shaped particles, but not consistently over size and wavelength ranges.

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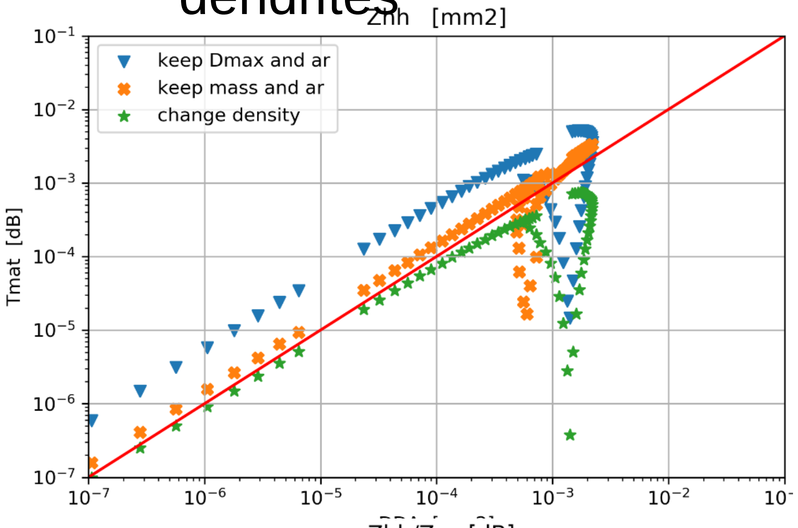
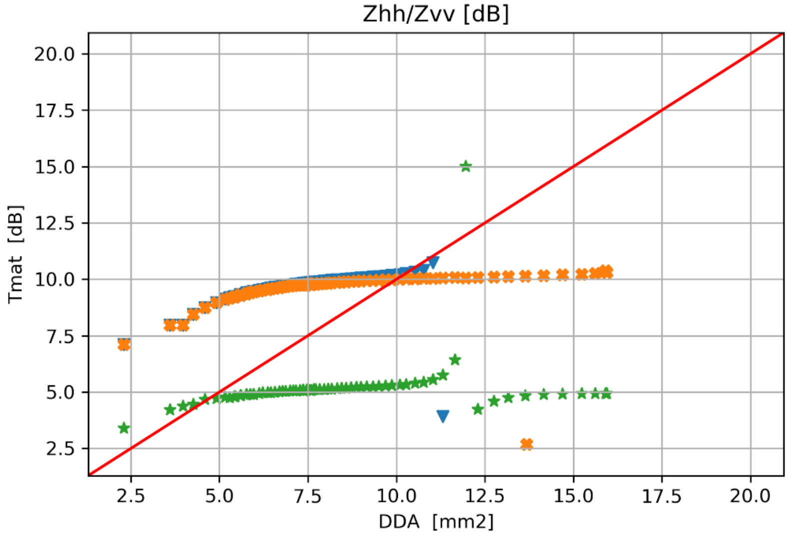
Example with dendrites





Reduced density approach

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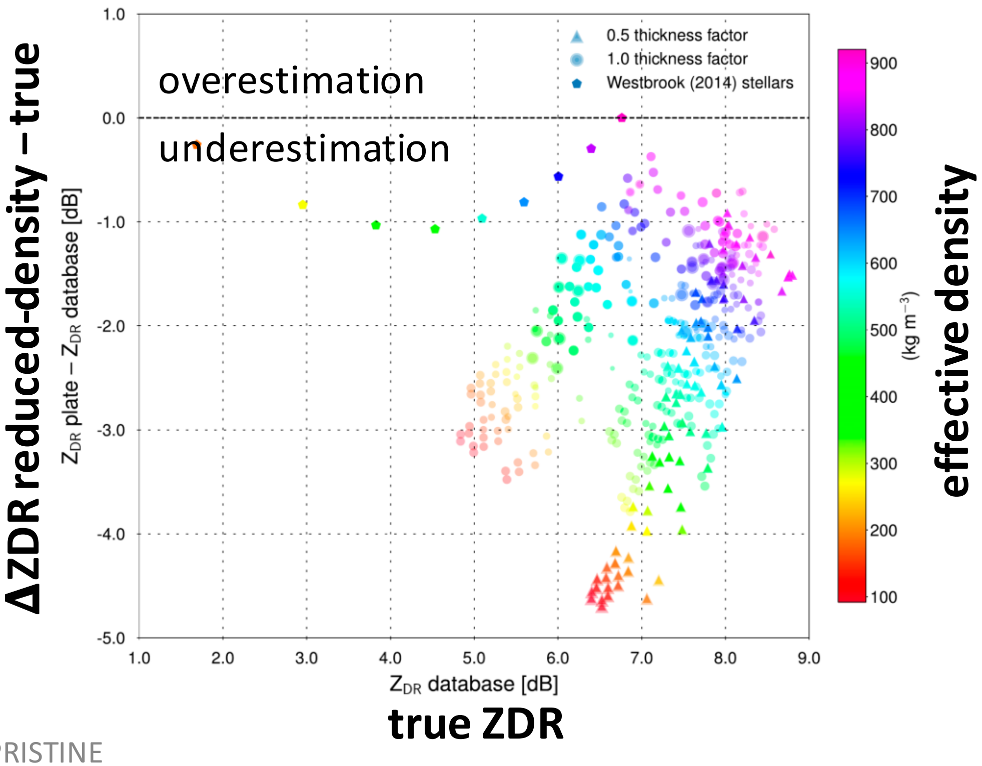
Probably the most popular approach to setup particles consistent to model constraints (keeping m, D, and aspect ratio unchanged) with T-Matrix suitable shapes.

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



PRISTINE

DGL signatures in PFOs

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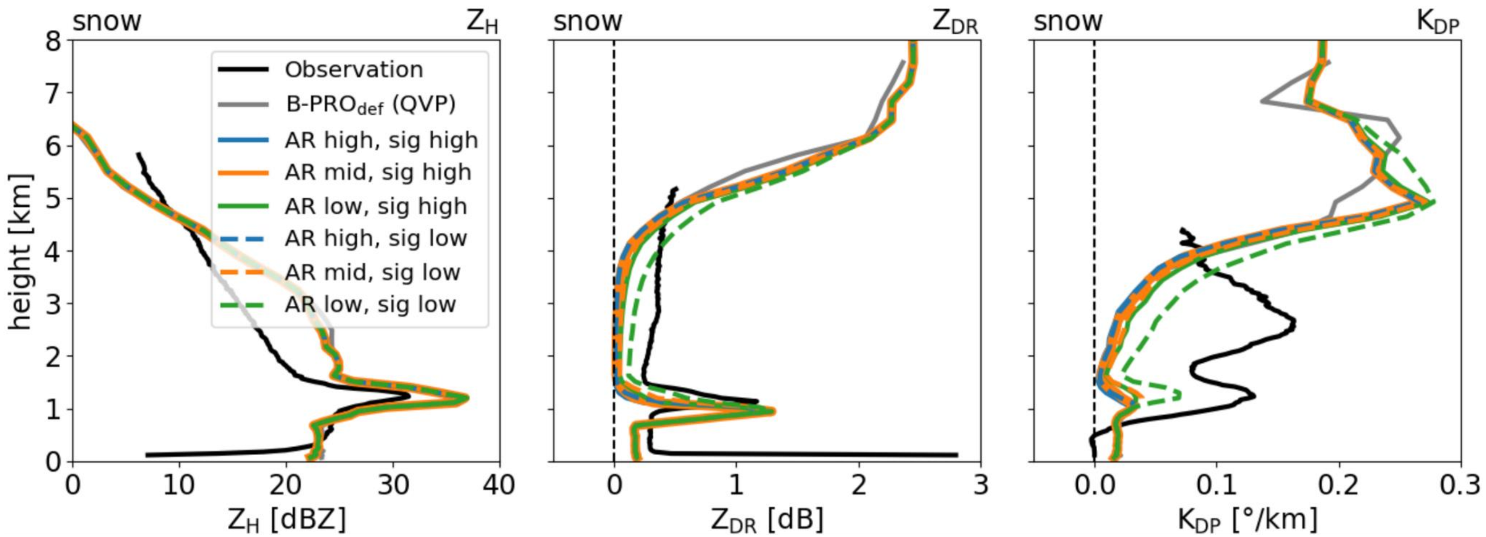
... consistent deficit in terms of polarimetric response ...

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)** $\boldsymbol{max(0.7-10D, 0.5)}$
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

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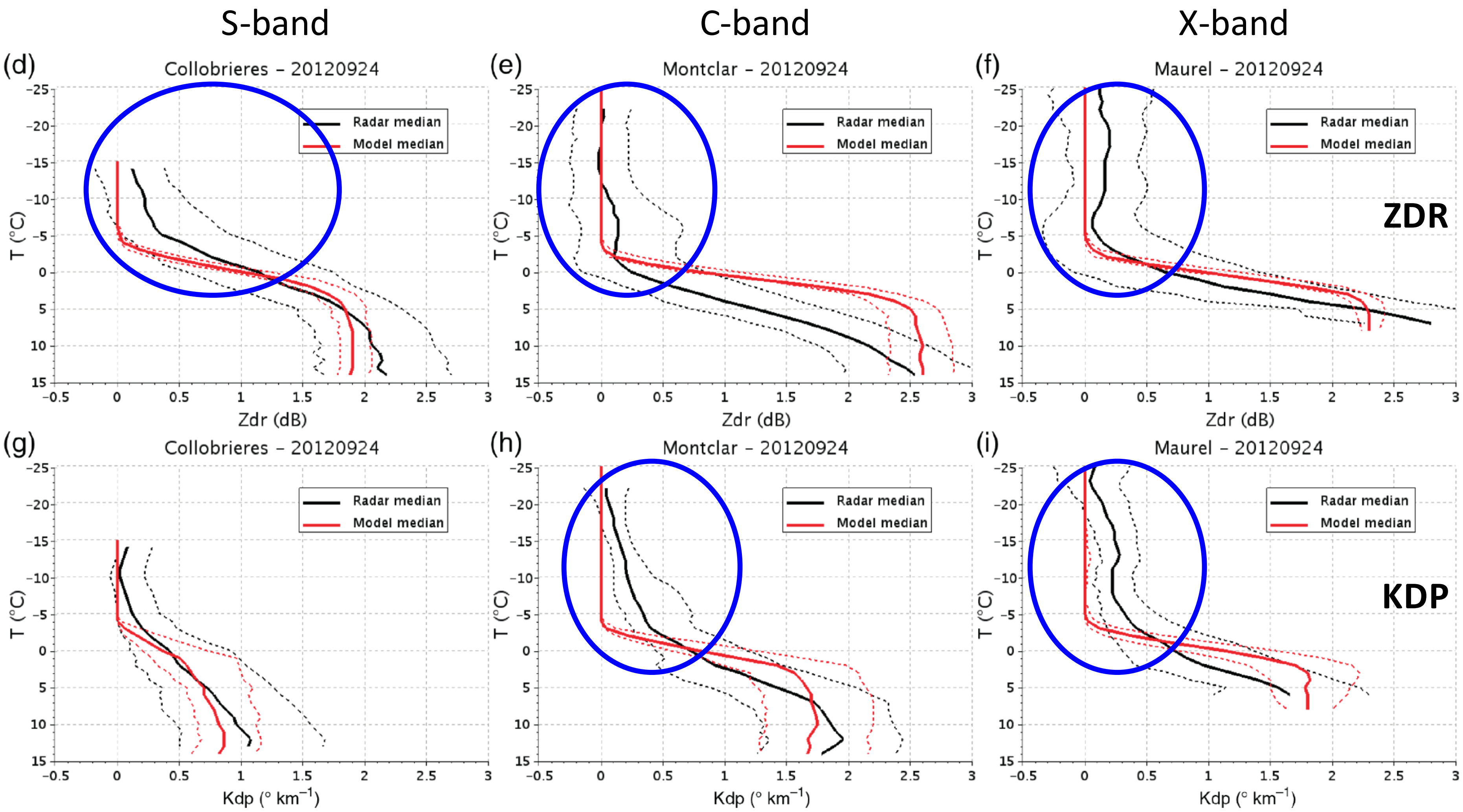
... **consistent deficit** in terms of **polarimetric response** ...



FO: own unnamed, Caumont06-based
Model: Meso-NH

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Augros et al. (2016), QJRMS

DGL signatures in other PFOs

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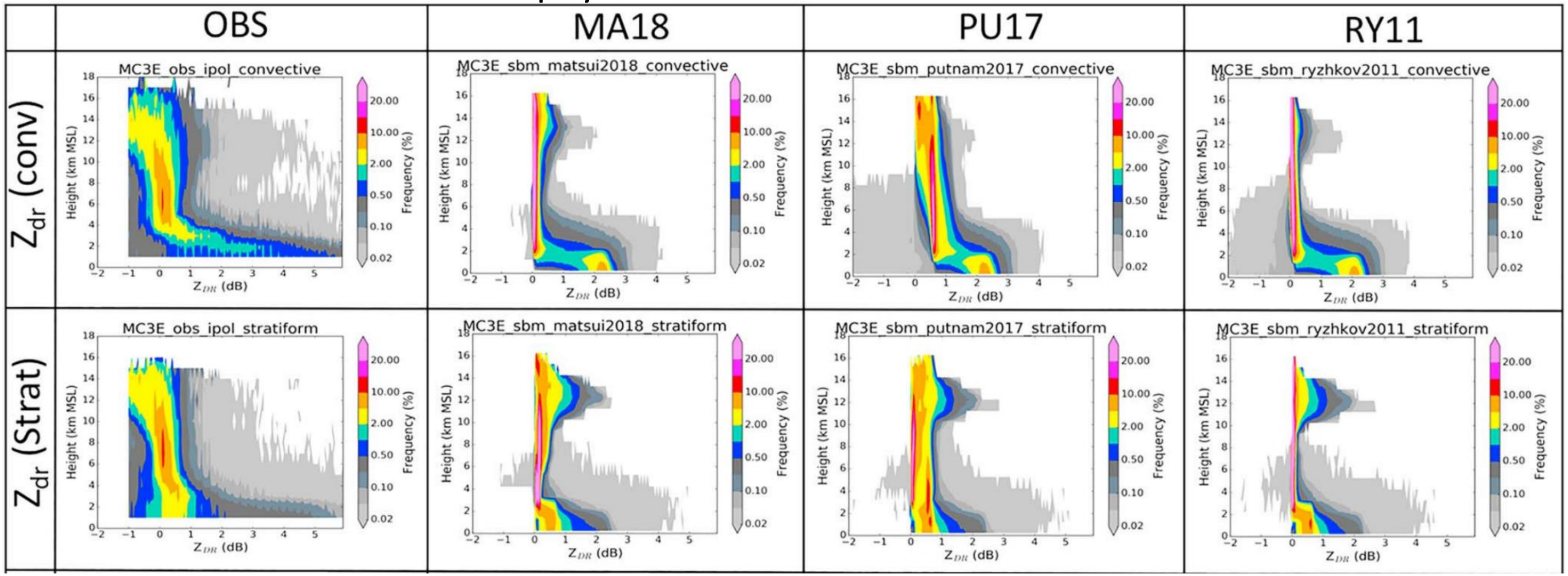
... **consistent deficit** in terms of **polarimetric response** ...

MA18, PU17, and RY11 refer to *different shape and orientation assumptions* in the PFO for the precipitating frozen hydrometeors. Atmospheric state from WRF simulations using HUCM spectral bin microphysics is identical between the cases.



strongly oriented graupel & hail

FO: POLARRIS
model: WRF-SBM

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Matsui et al. (2019), JGR

DGL signatures in other PFOs

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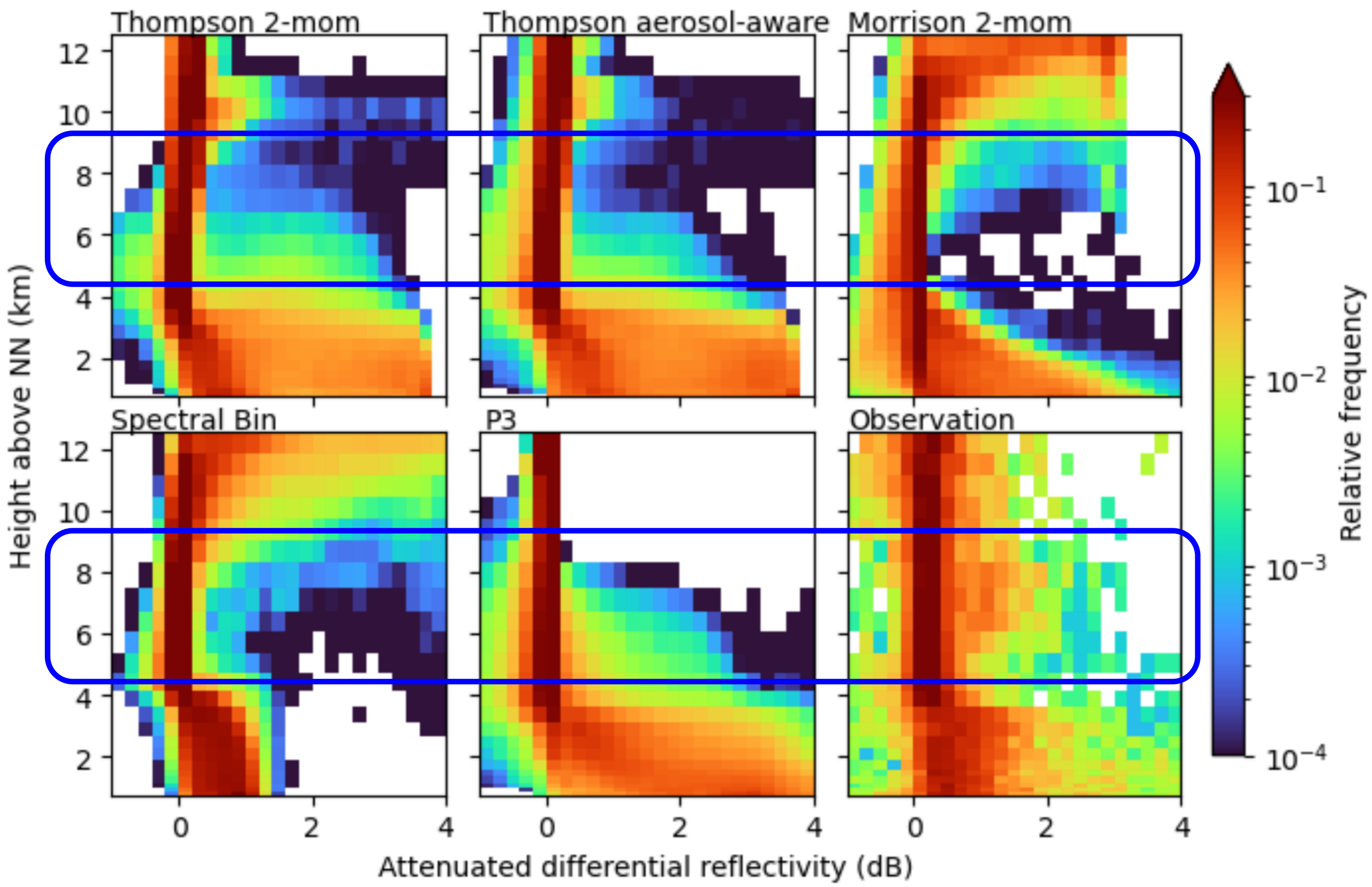
... consistent deficit in terms of polarimetric response ...



FO: CR-SIM
model: WRF

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Köcher et al. (2021), AMTD

DFG

DGL signatures in other PFOs

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... **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?