SPP2115: **P**olarimetric **R**adar **O**bservations meet Atmospheric **M**odelling (**PROM**)

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

Davide Ori
Jana Mendrok
Ulrich Blahak

PRISTINE

Who we are

Uni Köln

- Davide Ori

- ?

DWD

- Ulrich Blahak

- Jana Mendrok

Polarimetric extension of EMVORADO

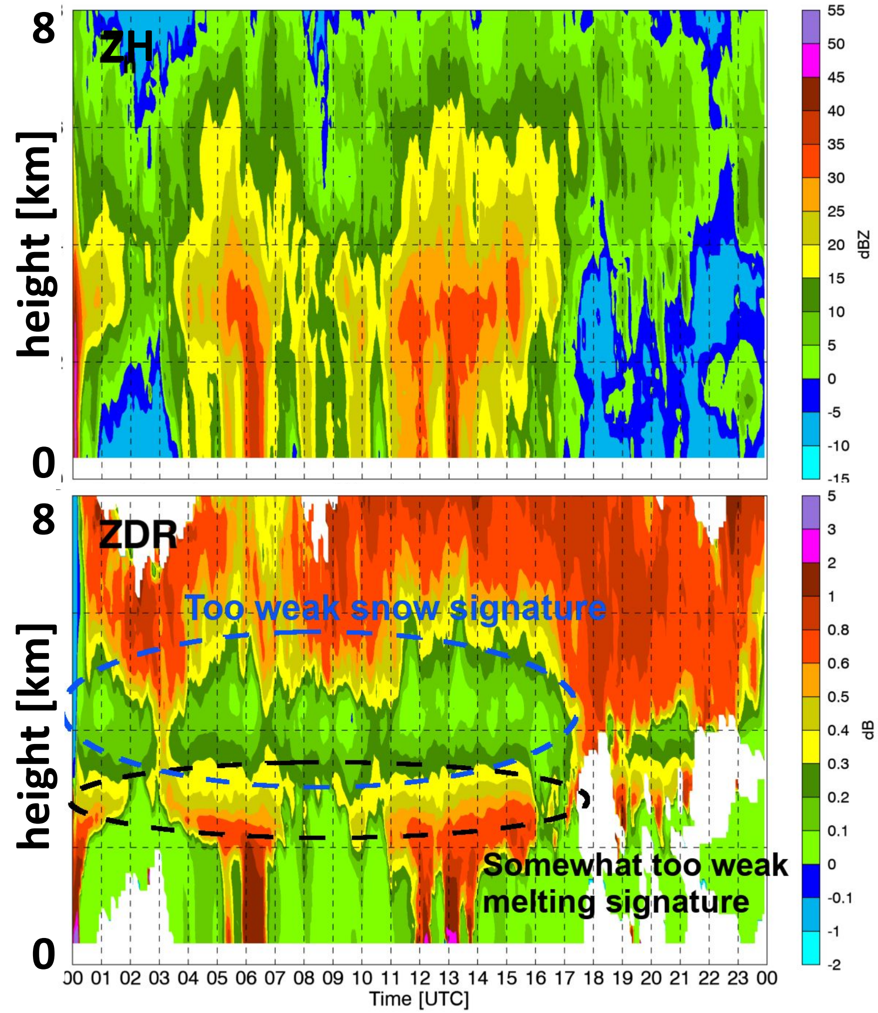
Based on T-matrix oblate soft spheroids:
ZH, ZDR, KDP, PhiDP, LDR, RhoHV, AH

Volume scans (range, azimuth, elevation)

Values on model grid as intermediate step

- PSDs and mass-size-relations consistent to model microphysics
- “Realistic” assumptions on Particle shapes / canting angles
- Volume scans include propagation effects: attenuation, beam blockage, beam smoothing
- Efficiency by use of look-up tables and parallelisation (MPI, OpenMP)
- Online coupled to COSMO and ICON, offline version available

24h timeseries of synthetic QVPs of ZH and ZDR from ICON-D2 (free) forecast



“All models are wrong, but some of them are useful”

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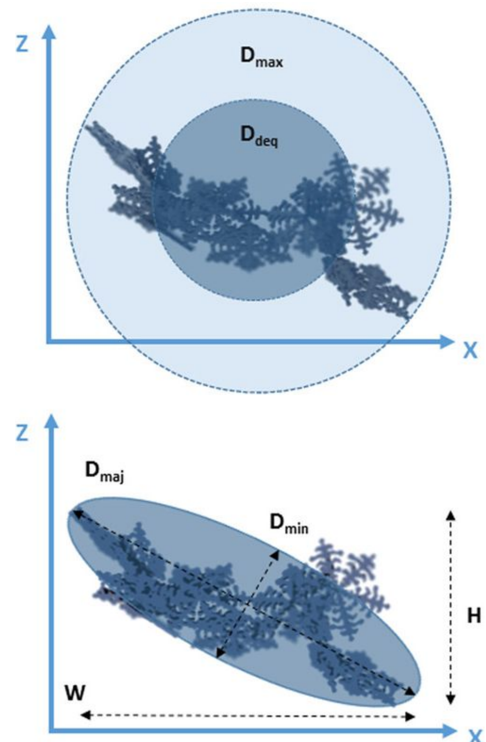
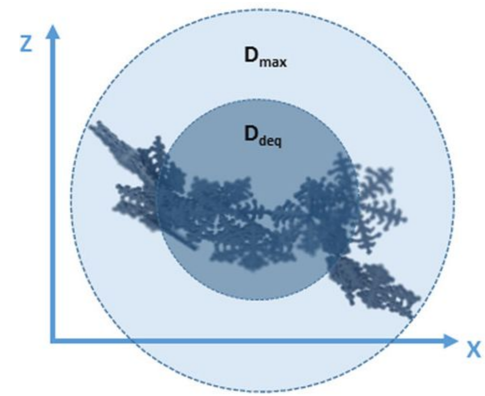
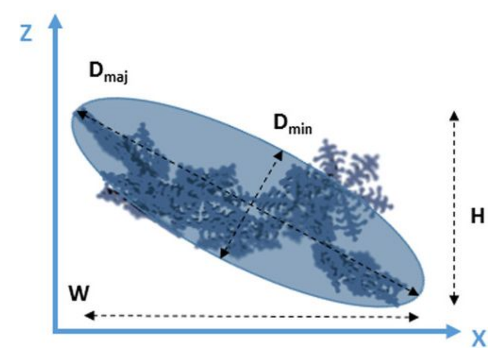
- Complex **hydrometeor models** exist and they have been extensively validated
- **Microphysical schemes** need to make simplifications



"All models are wrong, but some of them are useful"

- Complex **hydrometeor models** exist and they have been extensively validated
- **Microphysical schemes** need to make simplifications
- <u>Spheroidal scattering approximation fit well to microphysics</u>





Tmatrix accuracy various approaches

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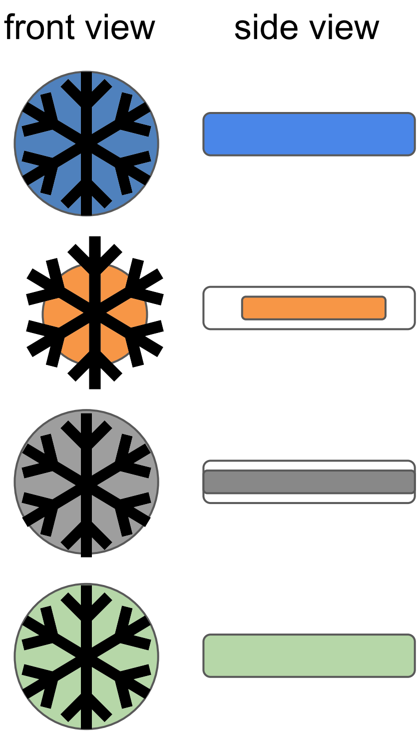
spheroidal or cylindric approximation of shape

4 tunables: D, m, ar, *density*

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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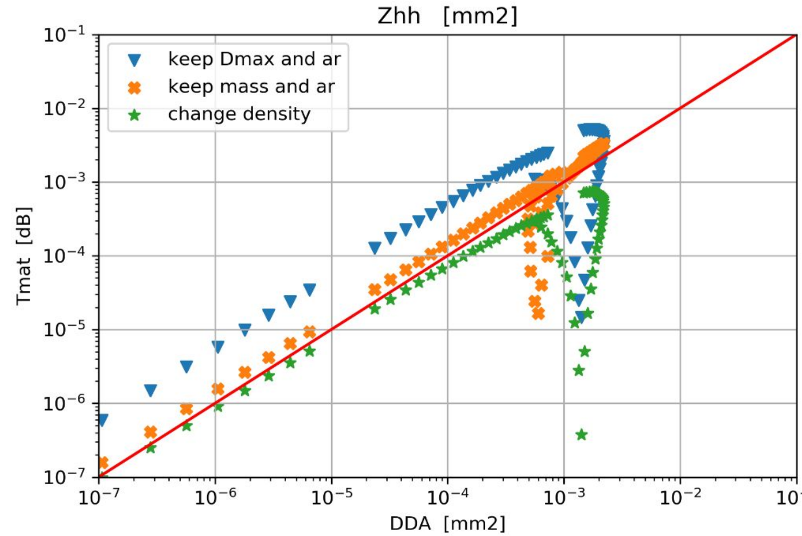
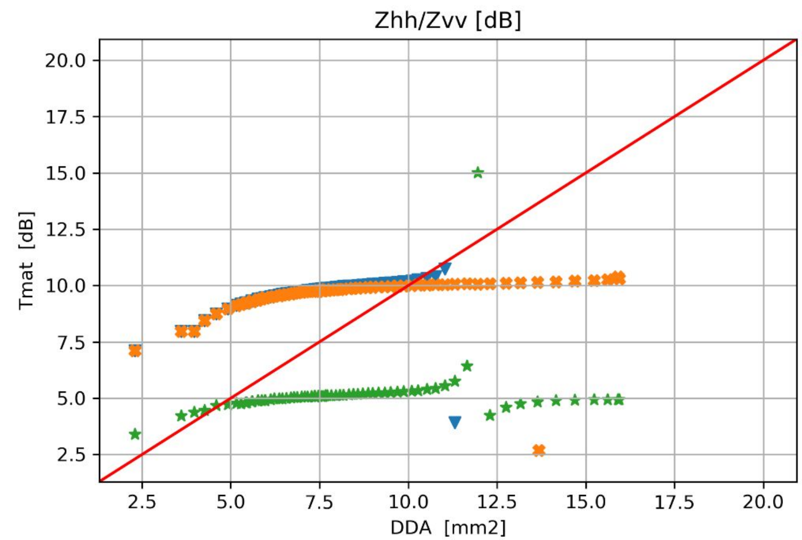
DENDRITES





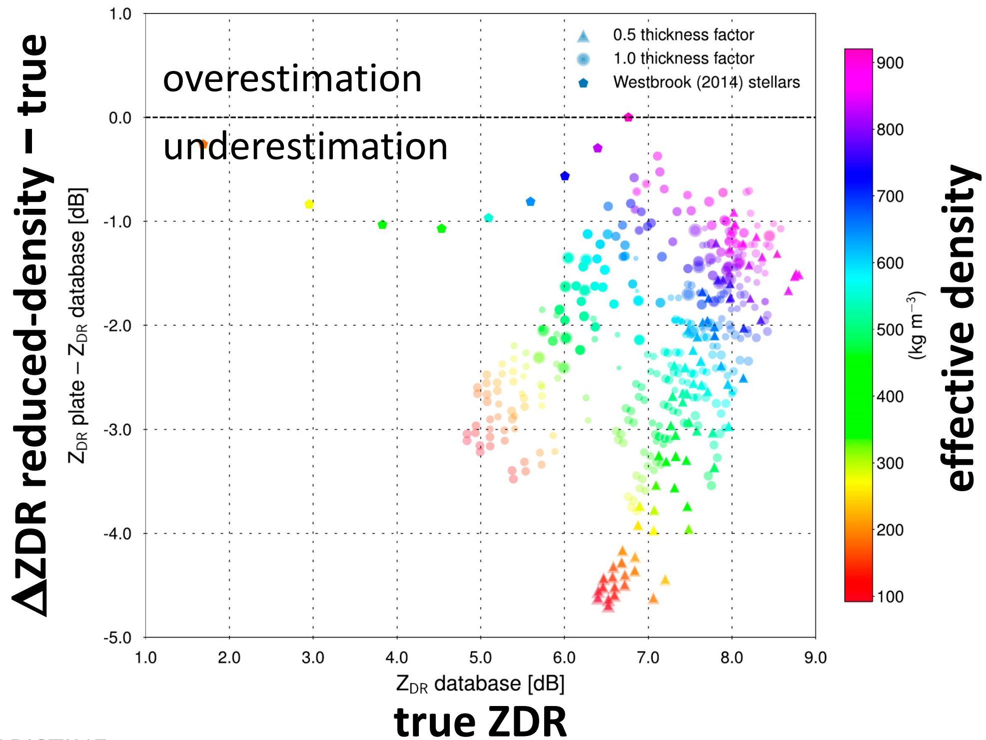
Reduced density approach

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



Worse for aggregates

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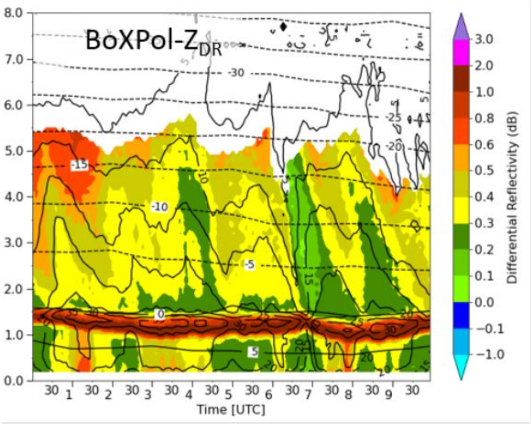
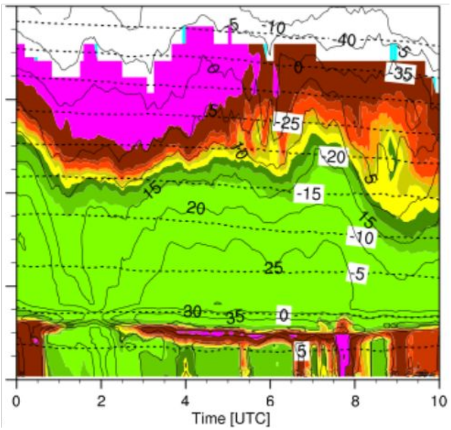
Observations



Model

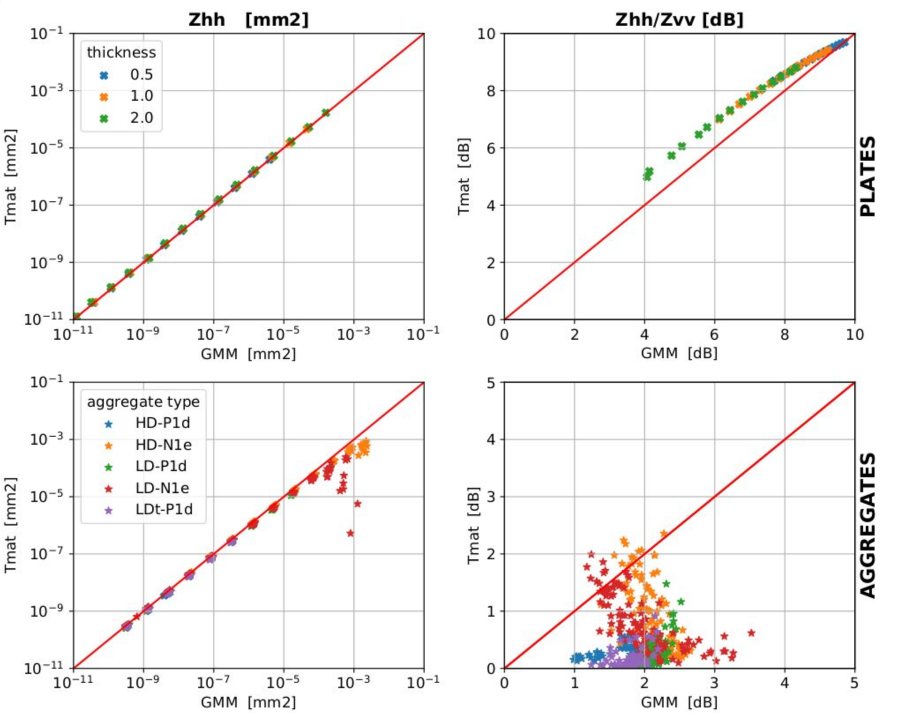


T-Matrix based simulations show a **consistent deficit** in terms of **polarimetric response** in the dendritic growth layer where large, “fluffy” particles prevail.

Polarimetric response much lower in spheroids (Tmatrix) compared to realistically shaped aggregates (DDA).

Aggregates dominate reflectivity signal, hence also ZDR, when present.

Sparse scattering data for oriented realistic shapes & existing DBs difficult to use consistent with model microphysics.



How to go forward?

Why not just use the scattering databases?

- Well… people (some of them are in this room) did use them. Mostly for microphysical evaluation

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  - You get 1 or 2 moments (if you are lucky), pre-defined PSD
  - maybe bulk riming degree (e.g. P3), bulk aspect-ratio (e.g. Harrington)
  - Little to no information about the ensemble variability

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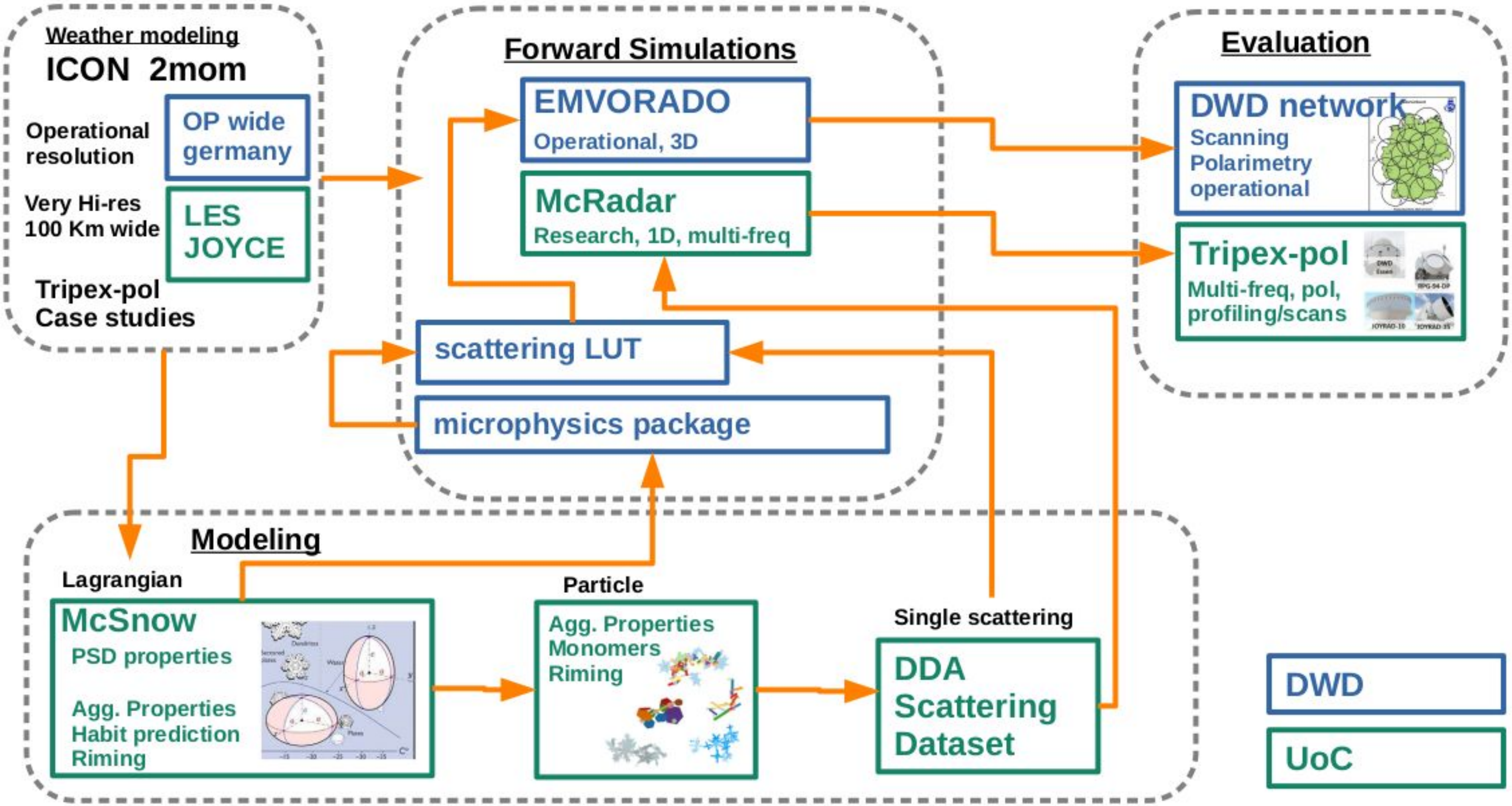
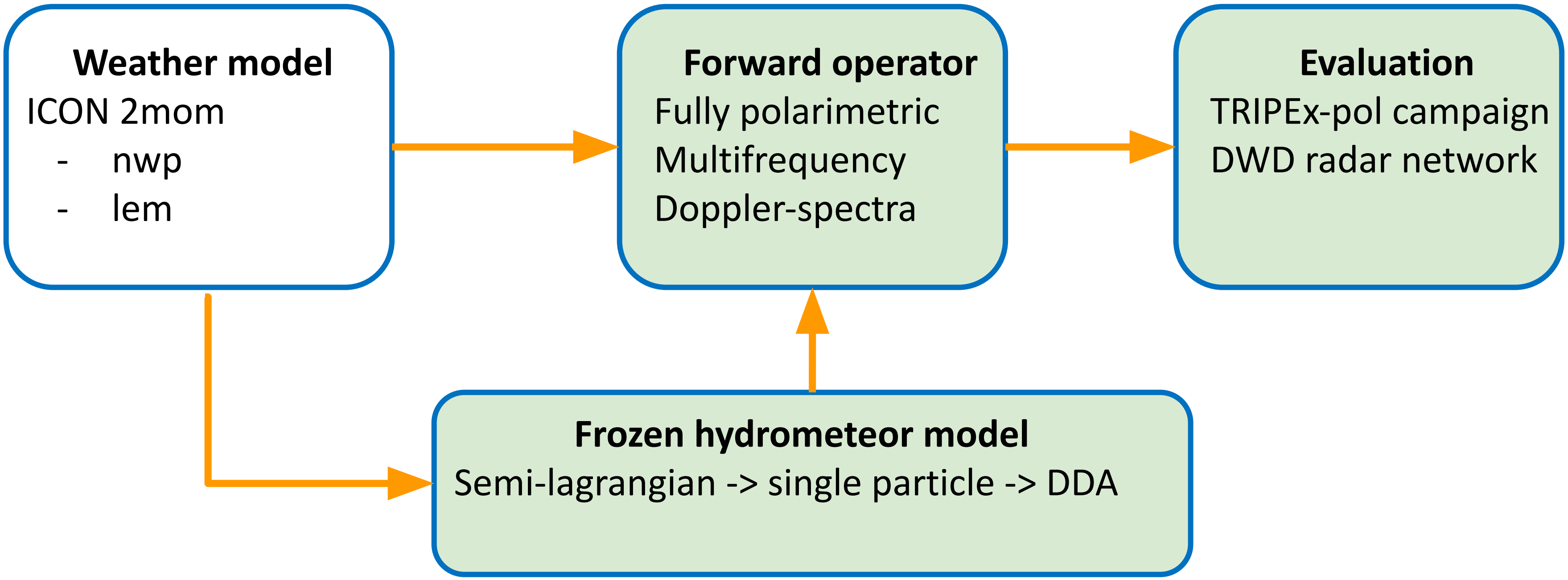
How to get this detailed information?

How to implement it back in a “coarser” NWP model?

Project schematics



How ? Work program



Multiple iterations:

- First iteration is short to allow for a fast deliverable of the FO
- Each iteration enlarge the variance of the simulated snow properties
- Allow for more accurate results and evaluation of uncertainties

Frozen hydrometeor model

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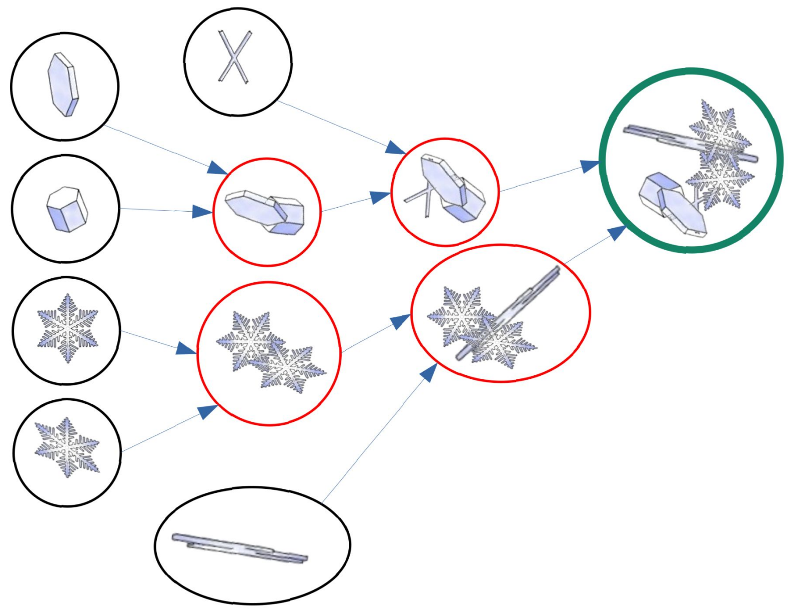
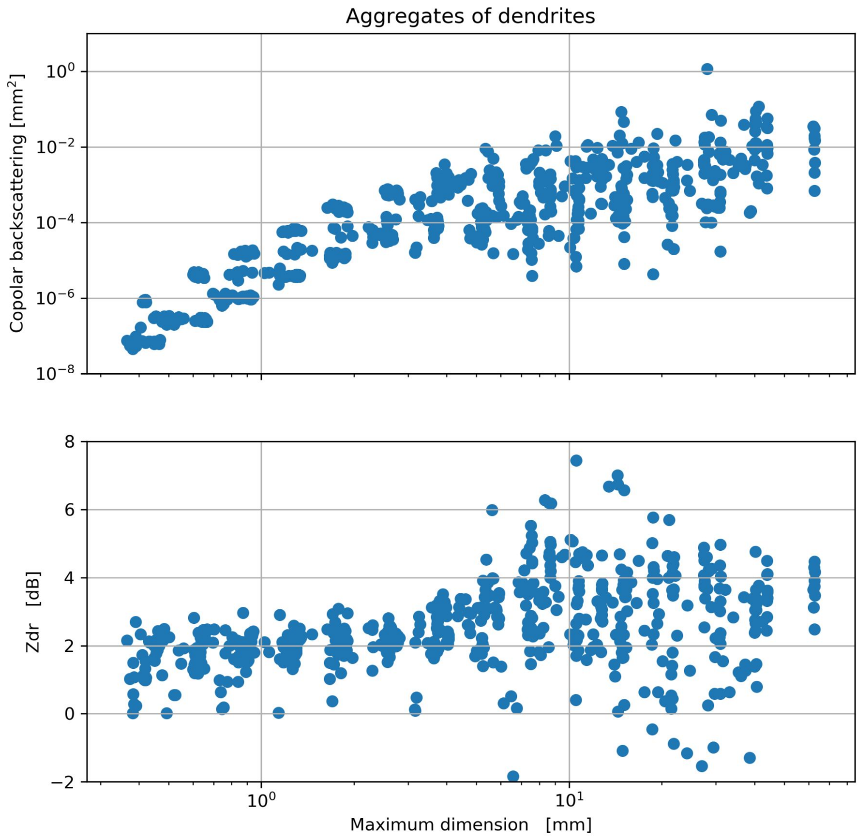




Single particle simulation:

1) McSnow predicts the properties of the monomers of each snowflake
2) By reconstructing the history of aggregation it is possible to precisely know the composition of each aggregate
3) The aggregate simulator realizes the shape that will be used for scattering calculations

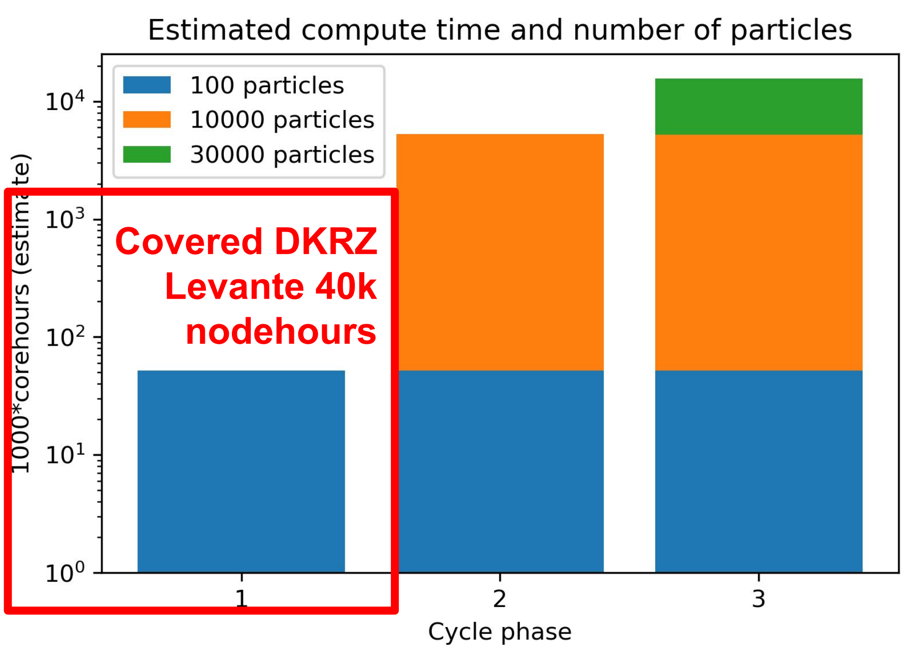
Computational cost - prioritize&update approach

Frequencies: S, **C**, **X**, Ku, **Ka**, **W**, G

Elevation angles: from 0 to 90 every 10 deg

Azimuth averaging

Horizontally aligned initially
    vary canting angles later (at least for monomers)

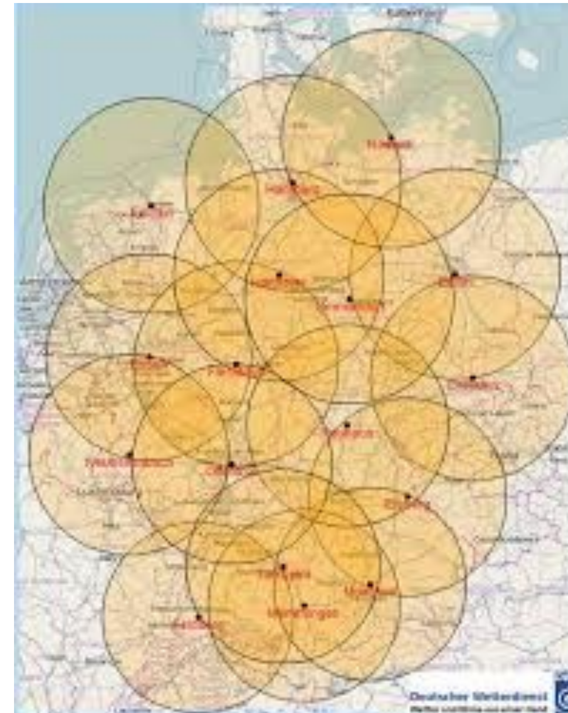


3 STAGES OF SIMULATIONS

I. First fast implementation
   A. Idealized shapes (match ICON)
   B. Substitute Tmat LUT with DDA
II. Explicit particle prediction
   A. nest McSnow + snow simulation
   B. connect snow shapes with environmental properties
   C. Evaluate sensitivity to snow shape
III. Add variability
   A. Sample the variance of snow formation processes
   B. Ensemble snow particles
   C. Evaluate uncertainty due to snow

1) LARGE-SCALE statistical evaluation:

a) DWD C-band pol radar network



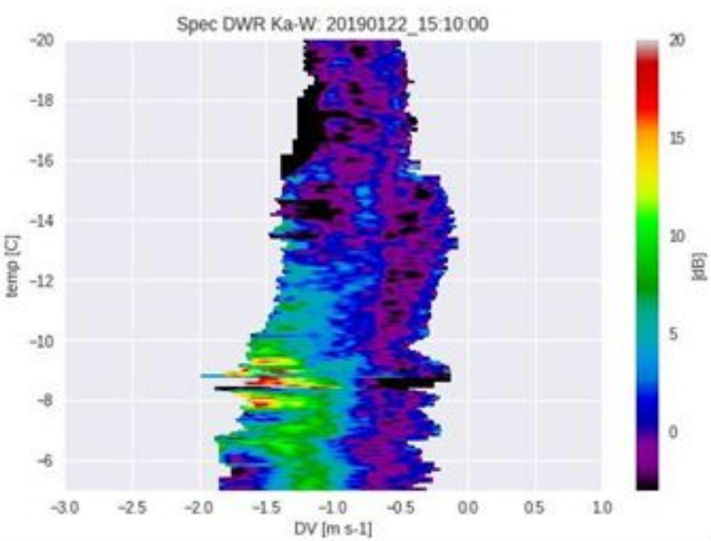
1) HIGH-RES campaign (TRIPEx-pol)

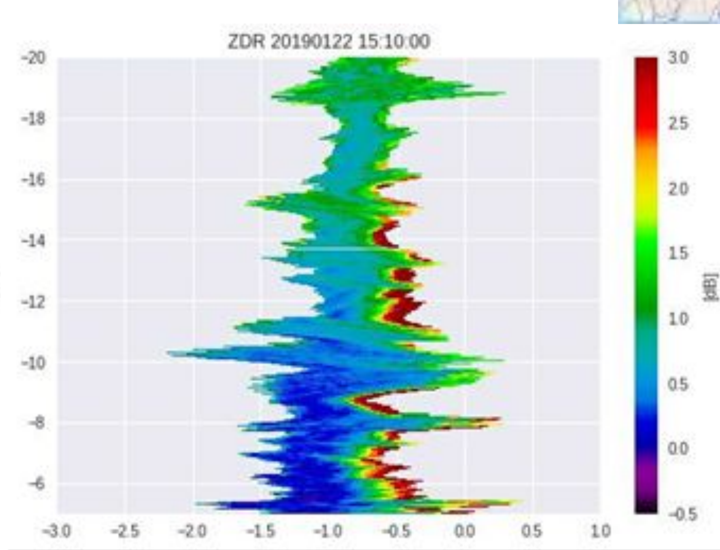
b) X-Ka-W Doppler VP radars

c) Pol-Doppler W-band

d) X/C band scanning

e) Great microphysical constrain





Collaborations

Particle modeling

FRAGILE
- \+ Lab. study particle shape
- − model snow properties

CORSIPP
- \+ field particle imaging

Forward Operator

CORSIPP / FRAGILE
- ± develop & intercompare pol-FO

Operation Hydrometeors / IcePolCKa
- − apply advanced FO in retrievals, DA, model evaluation, etc.

Single Scattering properties

FRAGILE
- ± coordination

IcePolCKa / CORSIPP / FRAGILE
- − enhanced scattering properties

openSSP (I. Adams, K-S Kuo)
ARTS-DB (M. Brath, P. Eriksson)

Evaluation

IcePolCKa
- \+ independent validation

CORSIPP
- \+ SAIL campaign

FRAGILE
- \+ TRIPEx-pol campaign

Backup slides

Why?

- Accurate **polarimetric Forward Operators (FO)** required by, e.g., QPE, retrievals, DA, model evaluation
- Uncertainties in scattering properties of frozen hydrometeors
  - variety in microphysical properties: which to use?
  - morphology is important, but usually strongly simplified

How?

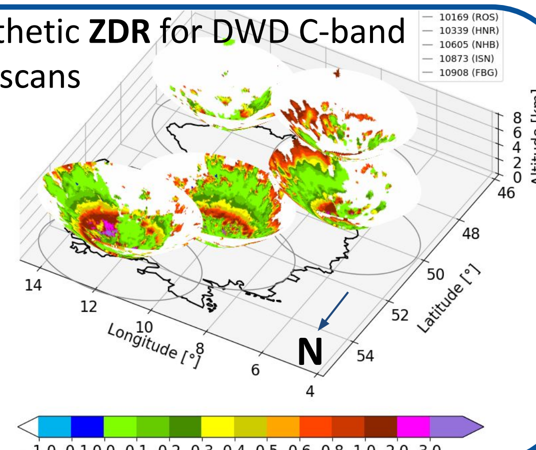
- **Explicitly model** frozen hydrometeor (HM) **shape** and **scattering properties**: Lagrangian super-particle + aggregation/riming model + DDA
- Infer statistical connections between scattering and atmospheric state
  - Ensure **consistency** with weather model assumptions
- **Evaluate** with multi-frequency polarimetric observations

Preliminary work

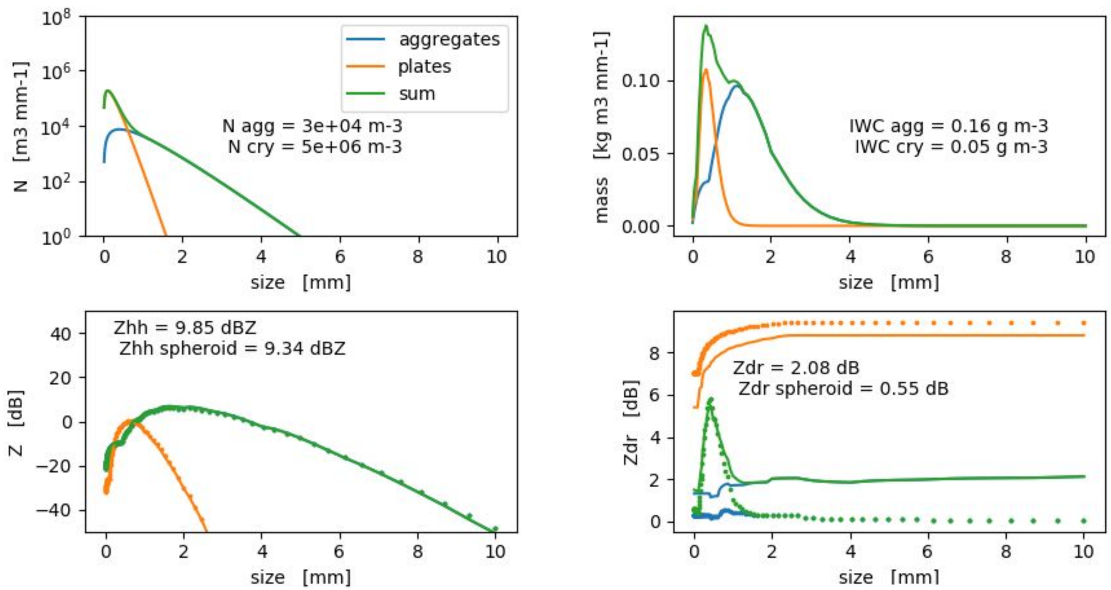
- Polarimetric extension of ICON-coupled FO EMVORADO:

- Scattering properties of complex-shape HMs
- Connecting NWP and Lagrangian particle models
- Aggregation model for particle mixtures
- Acquisition & analysis of observations (e.g. TRIPEx)

synthetic **ZDR** for DWD C-band PPI scans



Tmatrix/DDA closure study



Example size spectra of mixtures of plates and aggregates

Aggregates dominate the signal

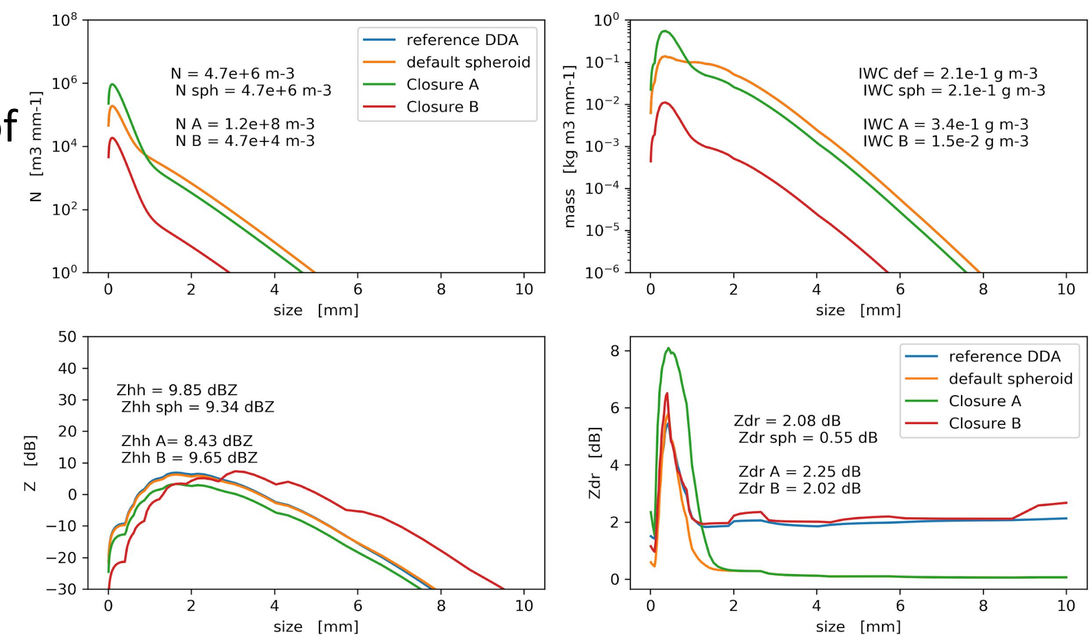
When simulated with soft spheroids Zdr drops

CLOSURES:

A - Increase the number concentration of plates -> N 100x larger, IWC 2x larger

B - Adjust aggregates density (aspect ratio) -> N 10x smaller, IWC 10x smaller

Scattering biases are reflected in microphysical retrievals



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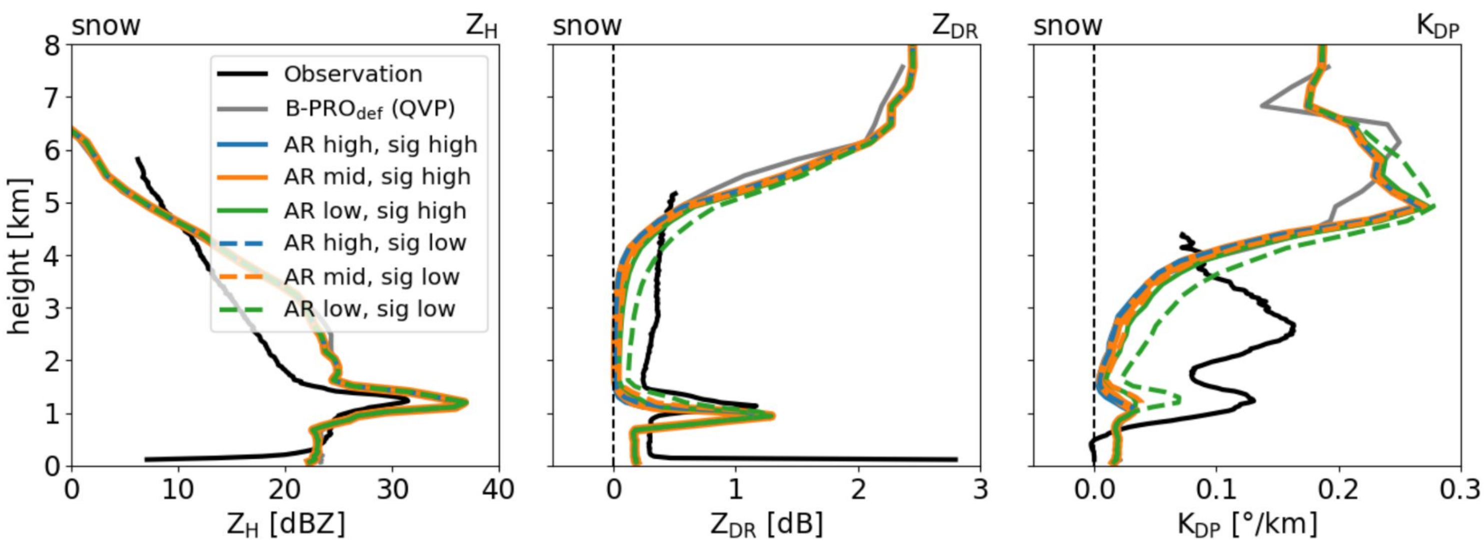
DGL signatures in PFOs

... **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

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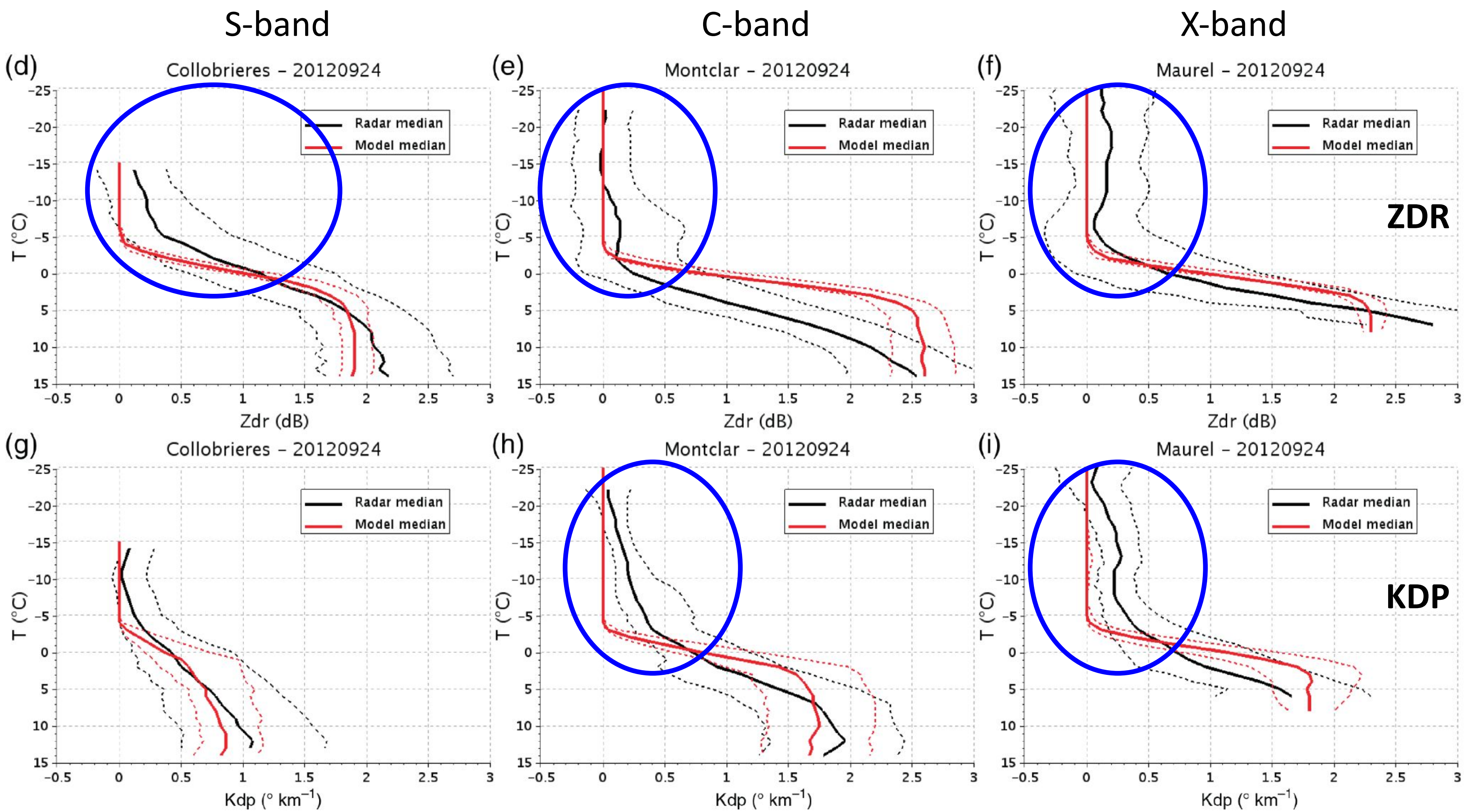
... **consistent deficit** in terms of **polarimetric response** ...



FO: own unnamed, Caumont06-based

Model: Meso-NH

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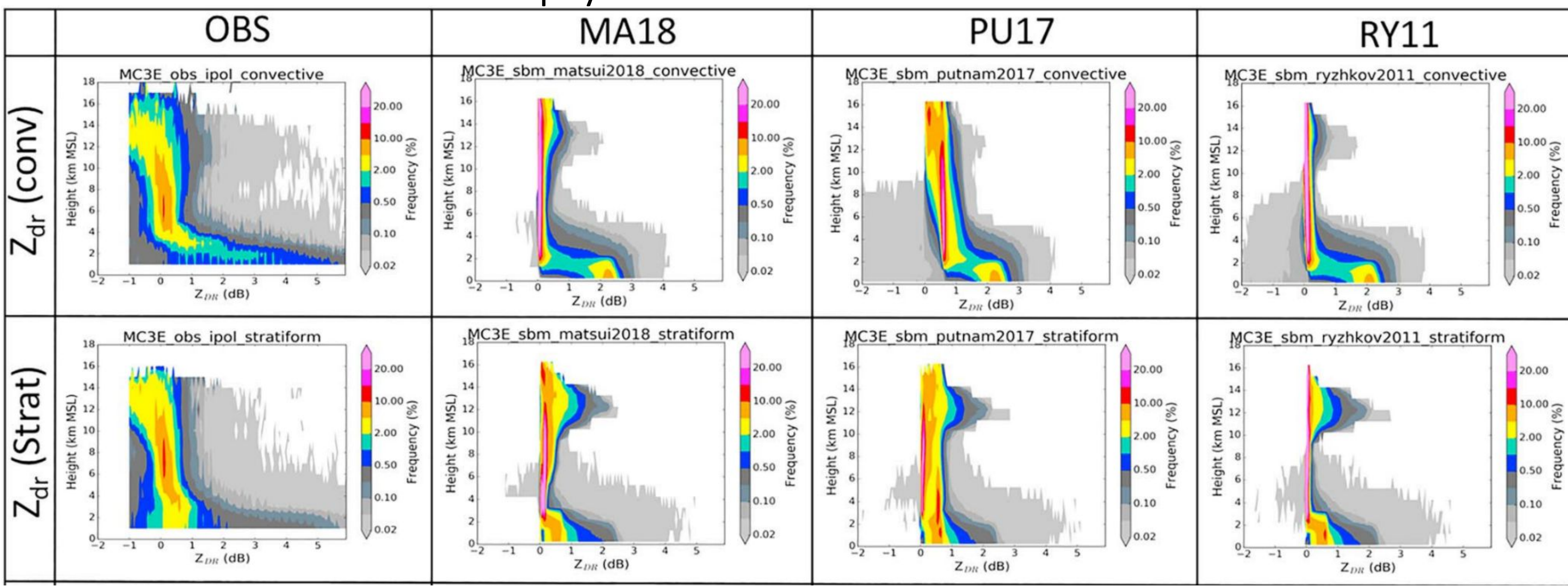
Augros et al. (2016), QJRMS

DGL signatures in other PFOs

... **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

Matsui et al. (2019), JGR

DGL signatures in other PFOs

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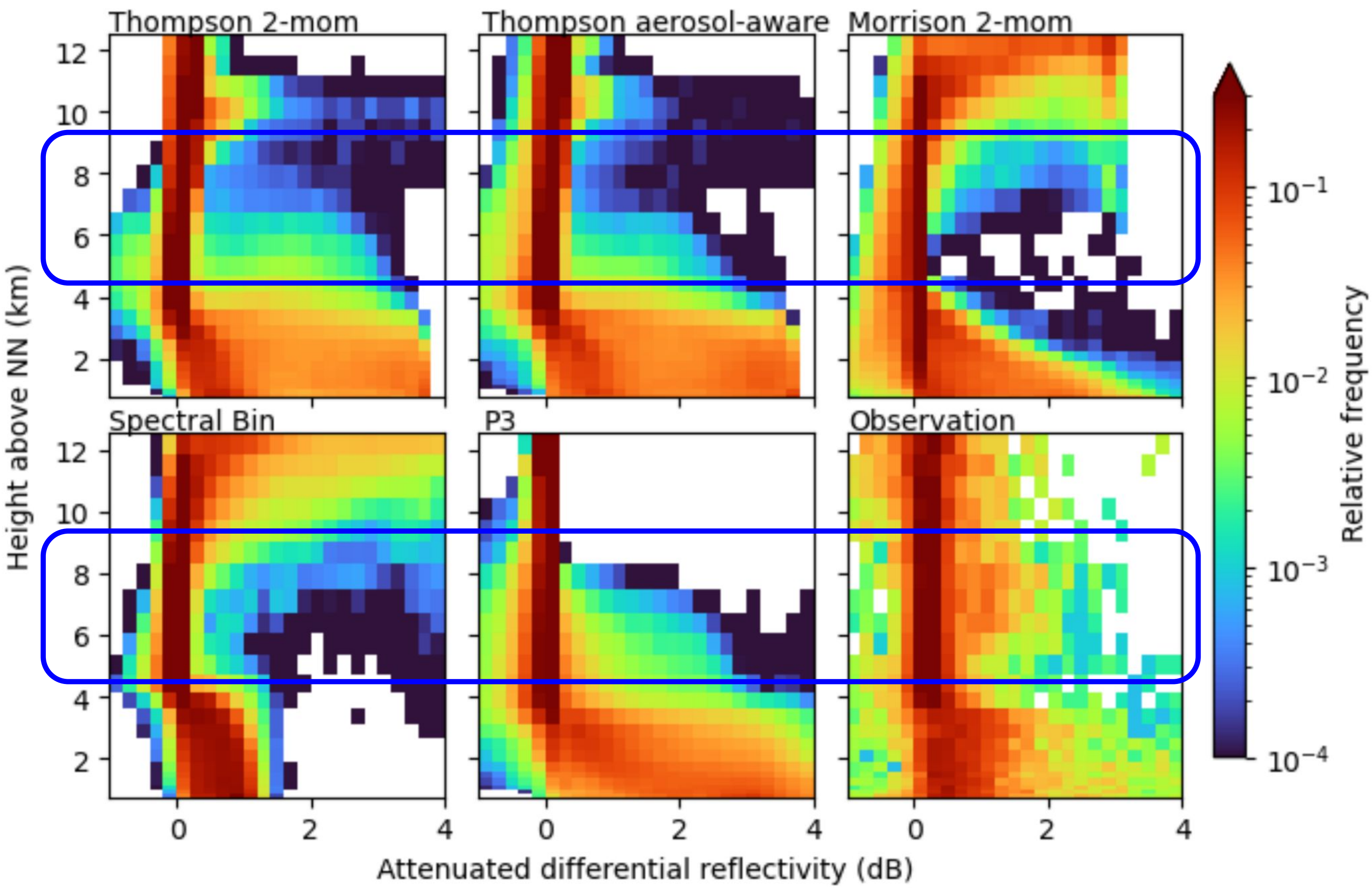
... **consistent deficit** in terms of **polarimetric response** ...



FO: CR-SIM
model: WRF

Köcher et al. (2021), AMTD

DGL signatures in other PFOs

... **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?

DFG

Project timeline

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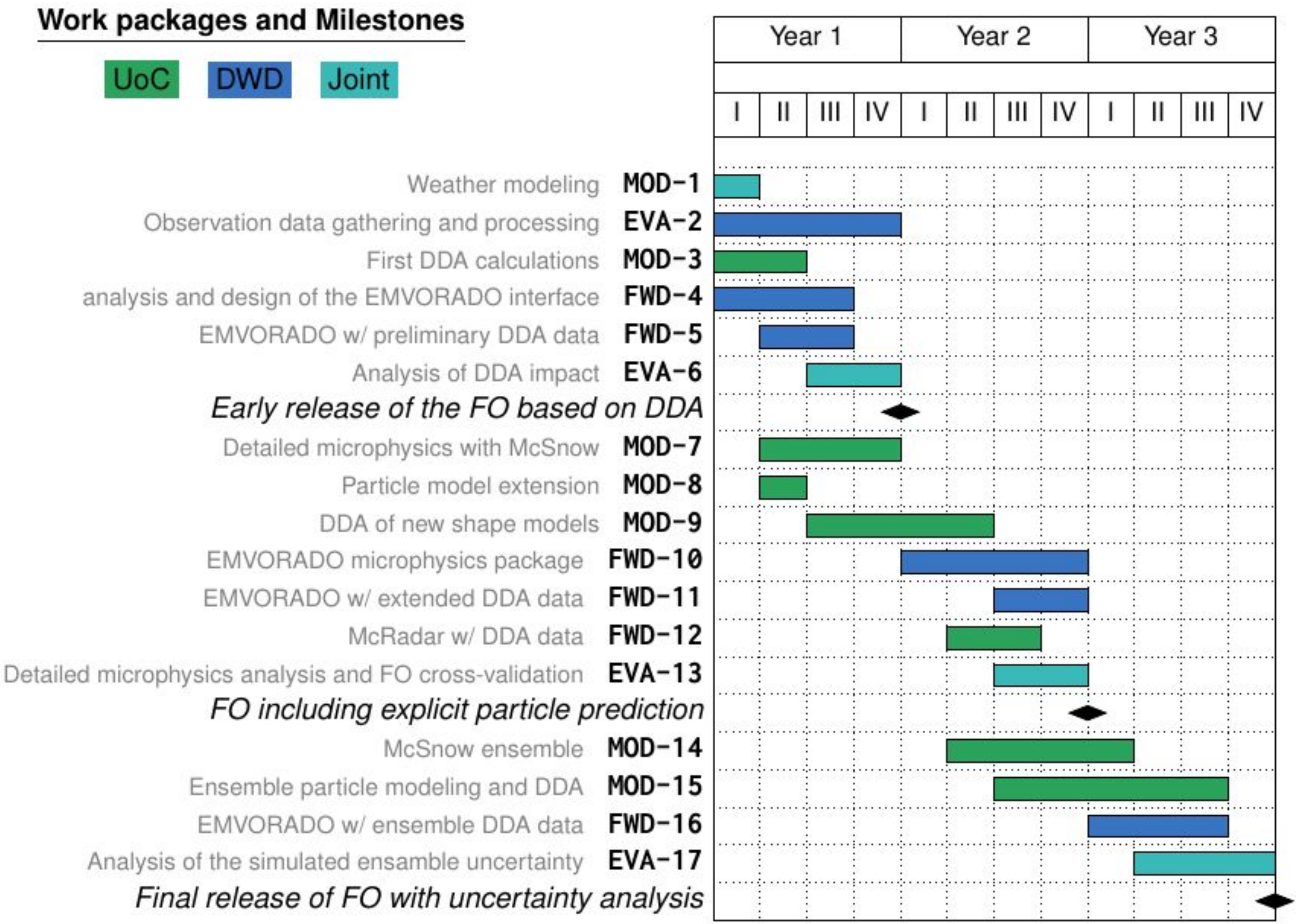

Explicit snow properties

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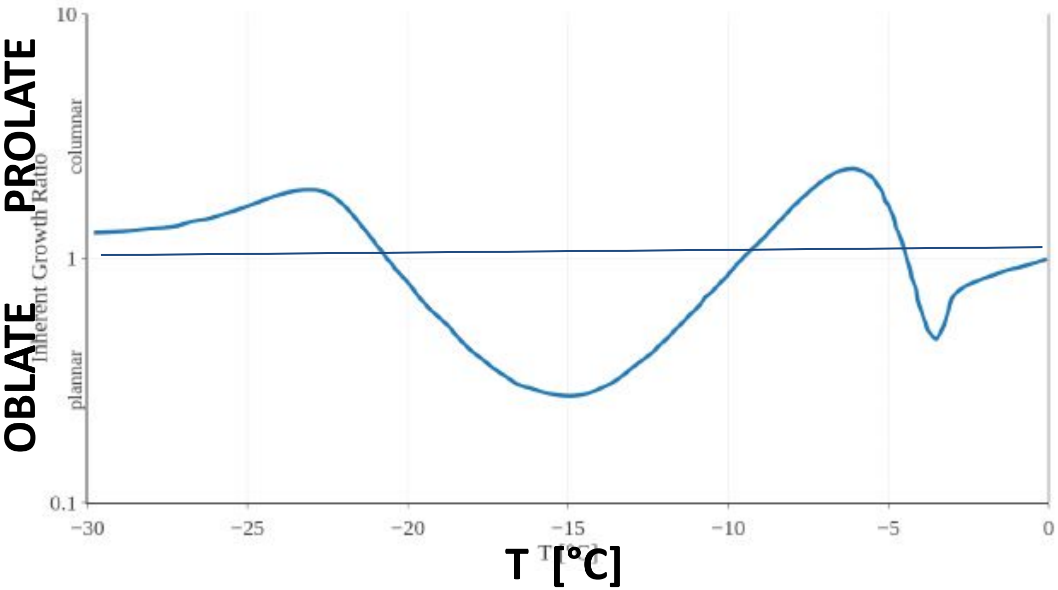
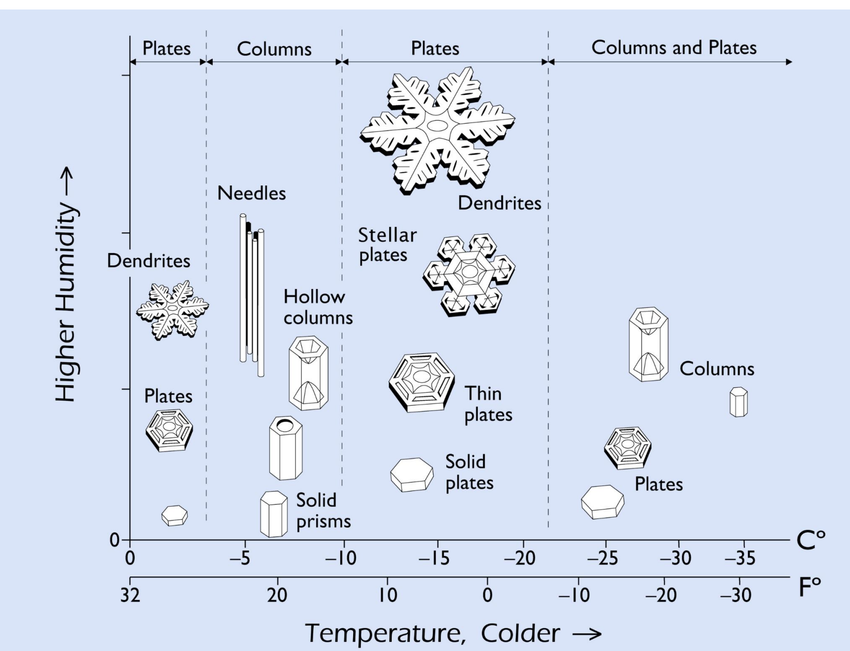


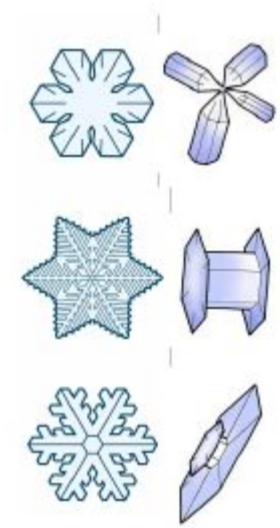
McSnow implements ice crystals **shape prediction** based on physical models of preferential growth rate

returns monomer **size**, **density** and **aspect ratio -> map into a monomer shape**



Only few monomer shapes are implemented in the aggregation model

Need to expand to **dendrites with diverse branching** and **capped columns.**



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EMVORADO - DWD's operational radar FO

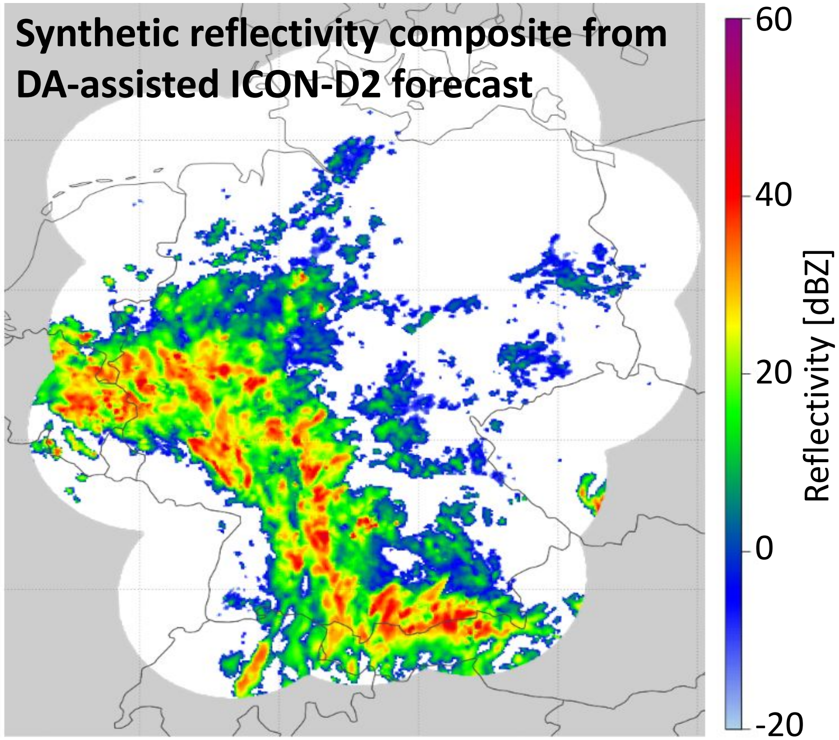
Targeting large-scale applications, particularly operational data assimilation

- Online-coupled to the host model (ICON/COSMO) ensuring microphysics consistency
- Very fast all-network simulations through bulk scattering lookup tables & parallelization

- arbitrary weather radar frequencies
- modular
- range of options for several modules (e.g., melting scheme, EMA, beam characterization)

Configuration	EMVO. time [s]	Total time [s]	Inc. [%]
CTRL (no EMVORADO)	-	680	-
E1: **Mie** (LUT), pencil beam, dBZ + v_r	15*	695	2.2

24h-long ICON-D2 (free) forecasts with 5-minutely radar simulations



Preliminary Work: polarimetric FO

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Bulk scattering lookup tables (LUT)

Principle:

- Precomputed, tabulated **additive radar moment** components as **function of** hydrometeor **mean mass** (=q/n)**, temperature, and melting state**
- Separate table **for each hydrometeor type**
- Separate tables for each model microphysics scheme and its different configurations
- Table look-up by **3rd order linear or log-linear interpolation** to actual model state, depending on radar moment and model state variable
- Summation over all hydrometeor types

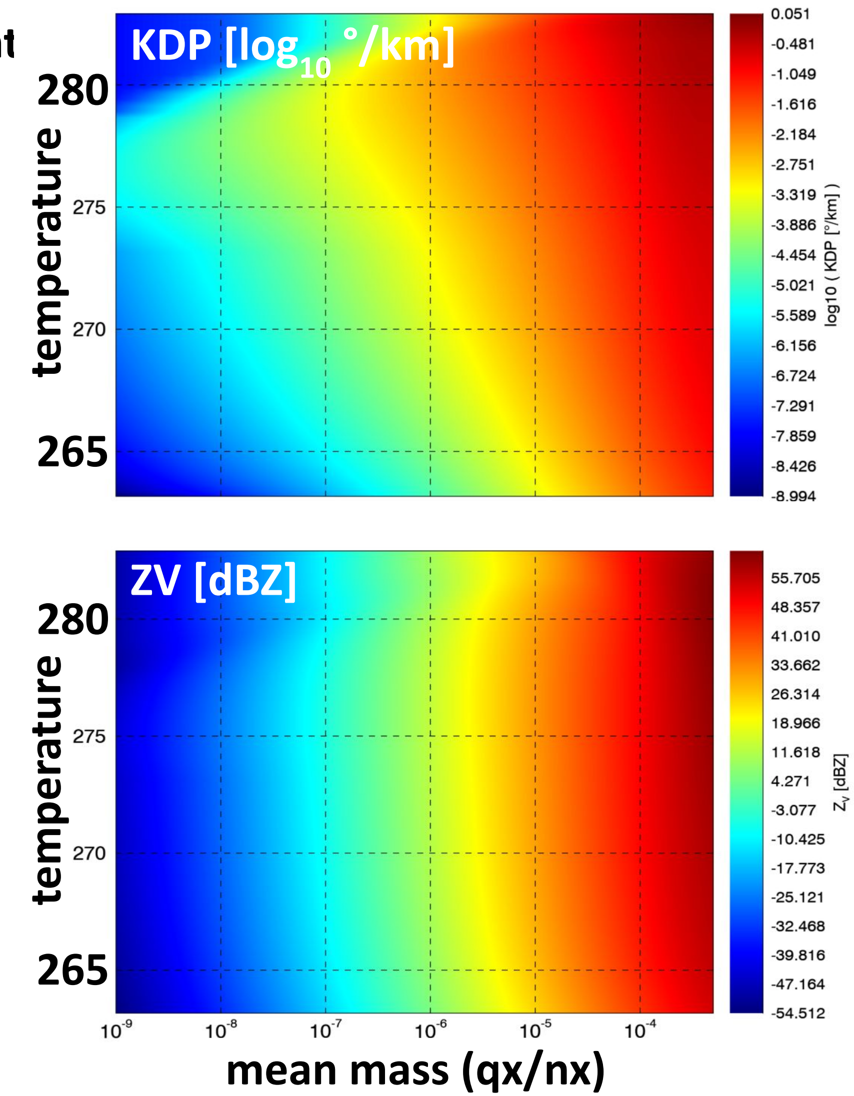
Stored in NetCDF files:

- **Cross-platform portable**
- **Exchange between users possible**

Table generation is automatically triggered when NetCDF file is not present

Example tables:

(2-mom scheme, wet graupel)



How? - Forward Operator

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Problem & Approach

- Morphology of frozen hydrometeors is highly diverse
- No constraints from NWP model (here: ICON)
- Correlations known to exist with certain parameters (e.g. thermodynamics variables)

→ **Connect the ICON variables to the snow scattering properties** (and their uncertainties) using, e.g., statistical inference or machine learning

→ **Select suitable set of particles based on model state variables**

General steps

- Extend bulk LUT preprocessor for handling external scattering data
  - explicit orientation „averaging“ instead of angular moments approach
  - size (+ shape?) distribution integration over unstructured grids
- Derive bulk LUTs from explicit-modelling-particle & DDA scattering data
  - relate explicit-modelling-particles with NWP atmospheric state (complexity reduction)
- Apply new LUTs & evaluate against DWD-network & TRIPEx-pol observations (individual cases & statistically)

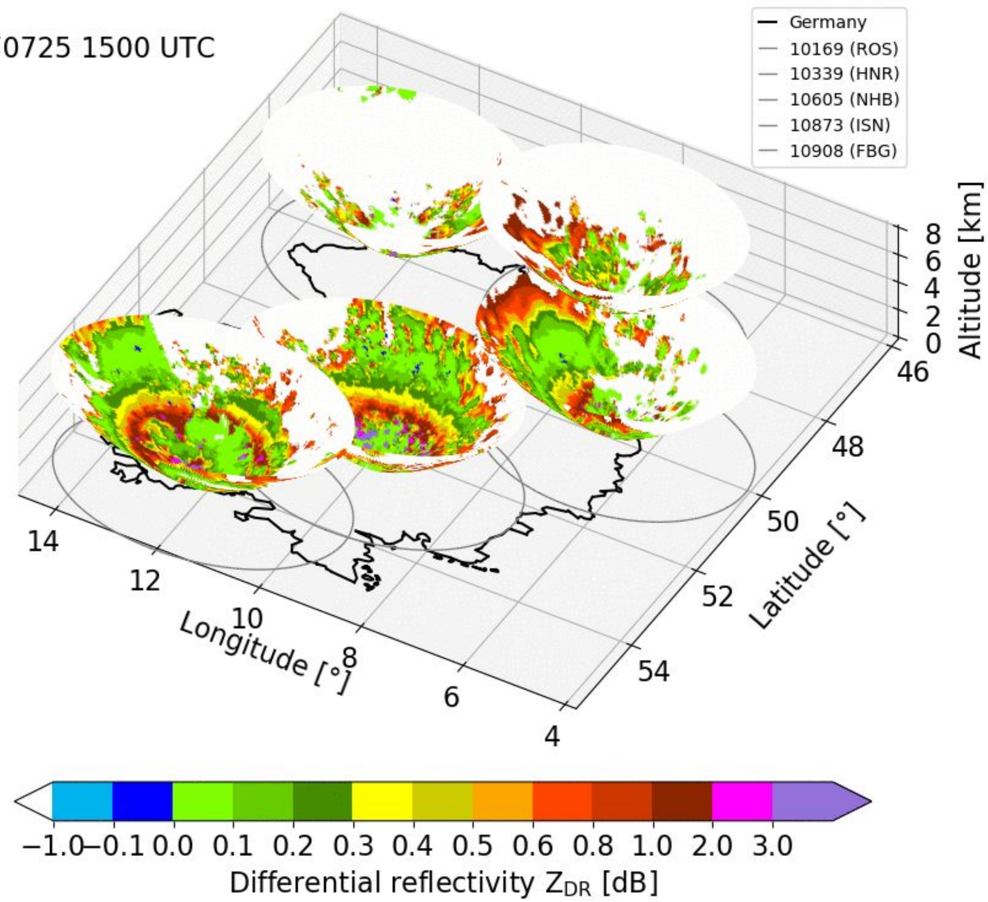
→ **Different focus in each work program iteration**

Polarimetric extension of EMVORADO

simulated ZDR scans from an ICON model run
(for clarity, only 5 of 16 radars and 1 of 10 elevations shown)

Configuration	EMVO. time [s]	Total time [s]	Inc. [%]
CTRL (no EMVORADO)	-	680	-
E1: **Mie** (LUT), pencil beam, dBZ + v_r	15*	695	2.2
E2: **T-matrix** (LUT), pencil beam dBZ + v_r + pol.mom.	**28***	**708**	**4.1**
E3: E2 + **vertical beam function smoothing** (5 rays)	51*	736	8.2

24h-long ICON-D2 (free) forecasts with 5-minutely radar simulations



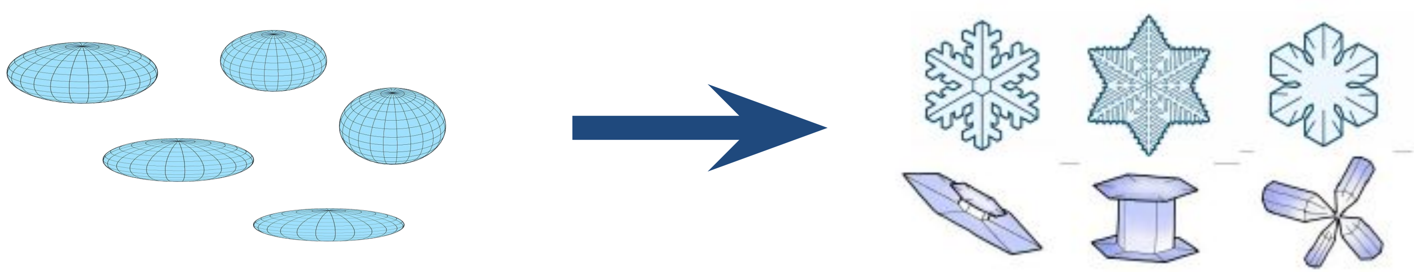
How? - Forward Operator

Iteration 1: **Realistic-shape (DDA) scattering data** instead of spheroids (TMatrix)

<u>Main aspect</u>: Preprocessor for LUTs from external scatt. data

- no changes to bulk LUT design & application (size-, shape-, & orientation (?) distributions, tab. parameters)
- allow hydrometeor class dependent LUT source (internal Mie, internal TMat, or external)
  - revised LUT name hashing to enforce microphysical consistency
- analyse preprocessor design options
  - internal or external tool?
  - particle / grid „selection“ approach

Outcome: rapidly available EMVORADO with DDA-based (dry snow & dry ice) LUTs fully consistent with ICON microphysics, based on realistic but not explicitly predicted shapes



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How? - Forward Operator

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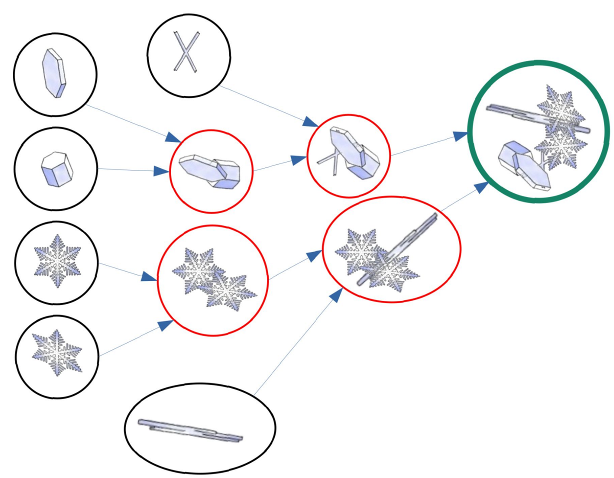
Iteration 2: **Explicitly modelled particle shapes**

<u>Main aspect</u>: Relating explicitly modelled particle properties to NWP atmospheric state

- Analyze relations between explicitly modelled particle properties and NWP atmospheric state (statistics, machine learning, ...)
- Identify suitable shape-prediction parameters from NWP model
  - expected good candidates: ambient T, Rh, cloud-top T
- LUT preprocessor with shape-prediction capability
  - e.g. additional tabulation parameters (revised LUT design)

Outcome: EMVORADO with shape-prediction based (dry snow & dry ice) LUTs



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How? - Forward Operator

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Iteration 3: **Uncertainty analysis**

<u>Main aspect</u>: Relating explicitly modelled particle properties to NWP atmospheric state

- Repeat relations analysis over extended set of explicitly modelled particle properties
- Derive & evalute new LUTs from diversified scattering data
  - Estimate radar signal uncertainties resulting from shape-prediction uncertainty
- Revise/refine shape-prediction approach in LUT preprocessor
  - e.g. retune prediction to ensemble mean

Outcome: uncertainty characterization; possibly also revised shape-prediction based (dry snow & dry ice) LUTs