# Progress in simulating the optical properties of ice clouds and graupel/Snow in support of the CERES Science Team

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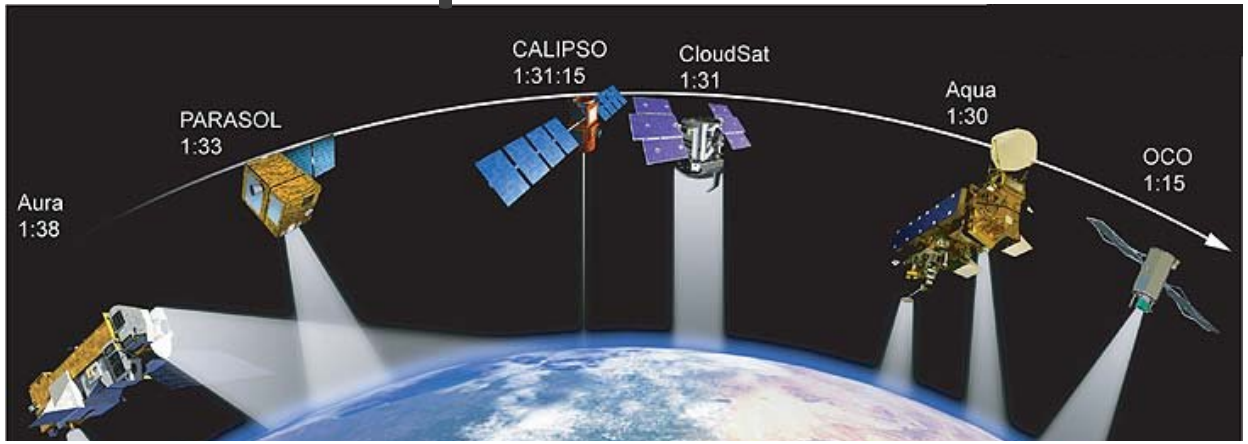
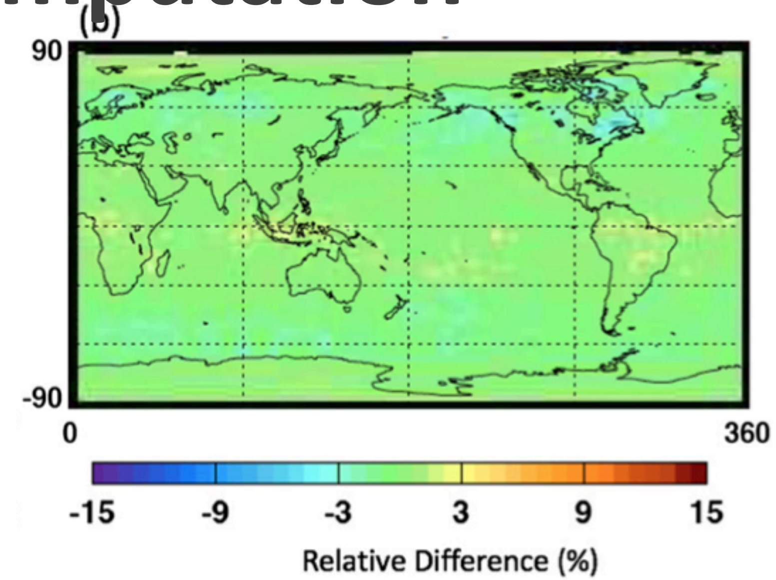
# An Ice clouds model is needed for remote sensing implementation and flux computation




A-Train satellite constellation




Loeb, Yang et al., 2018 JClim

**A consistent Ice optical property model is essential to a reliable estimation of fluxes at the surface and TOA from satellite observations.**

Ice cloud property retrieval

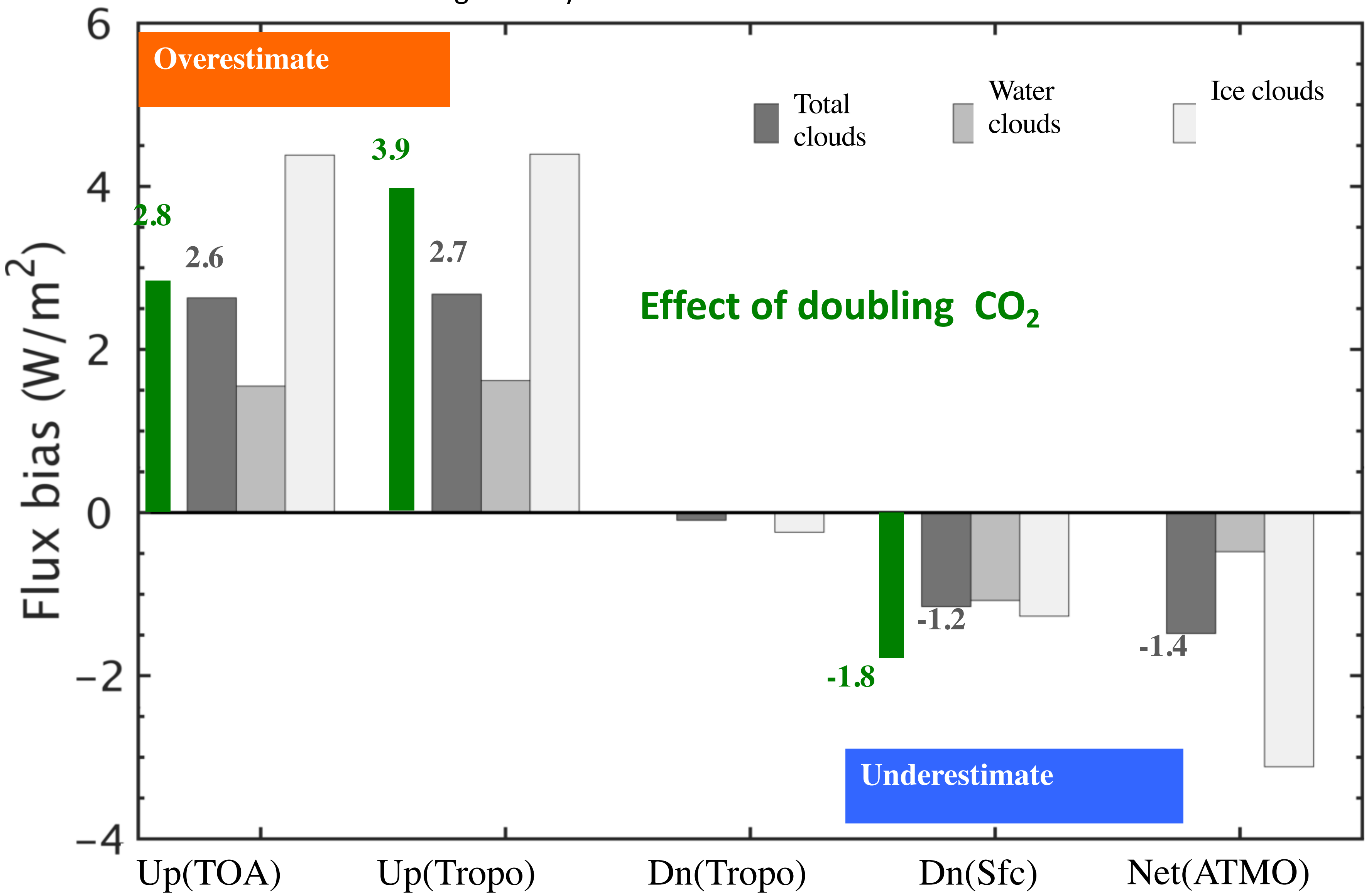
Broadband RT calculation

- Passive shortwave measurements
- Passive thermal infrared measurements
- Lidar measurements

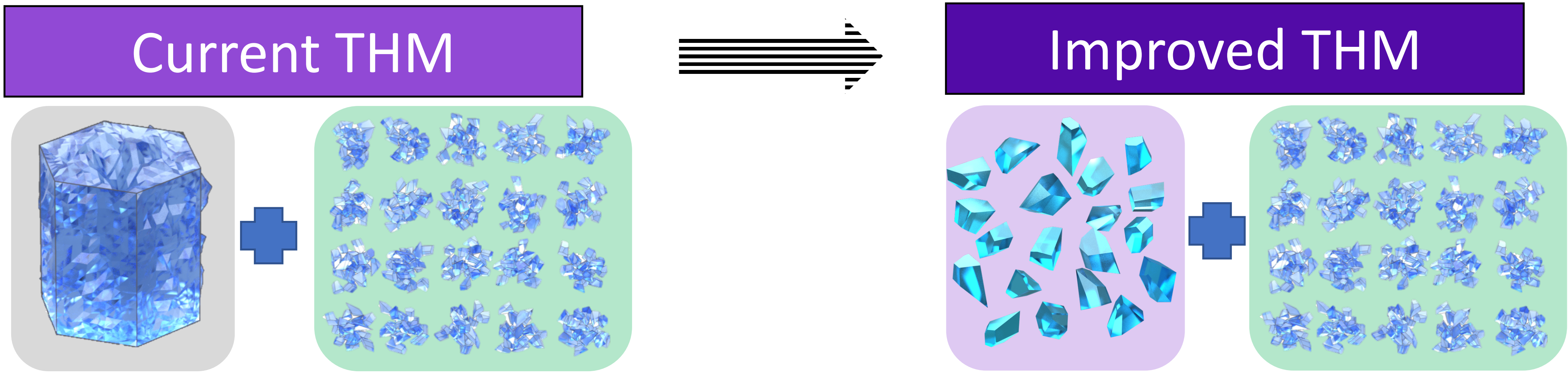
- Radiative parameterization
- Mass-diameter relationship

# Flux Biases due to neglecting LW scattering

Kuo, C.-P., P. Yang, X. Huang, D. Feldman, M. Flanner, C. Kuo, and E. J. Mlawer, 2017: Journal of Advances in Modeling Earth Systems.



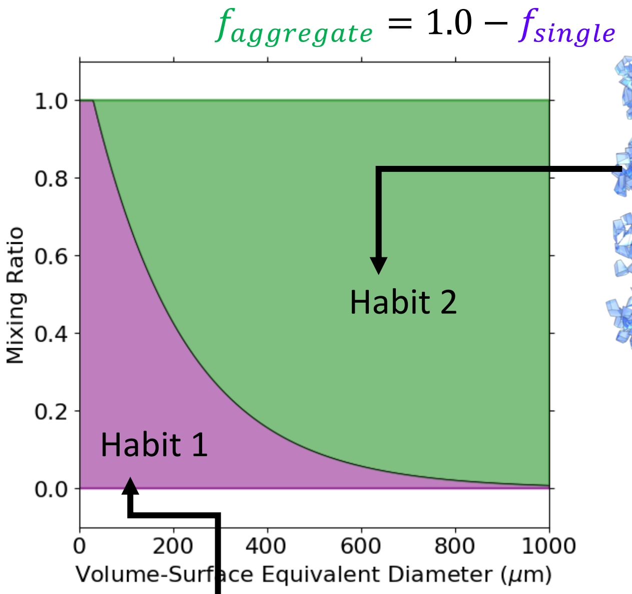
# An Improved Two Habit Model (THM)

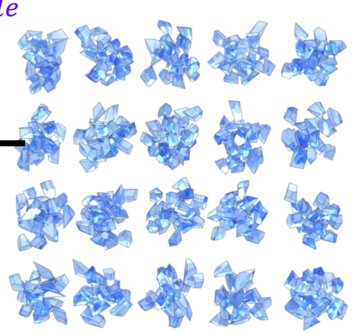


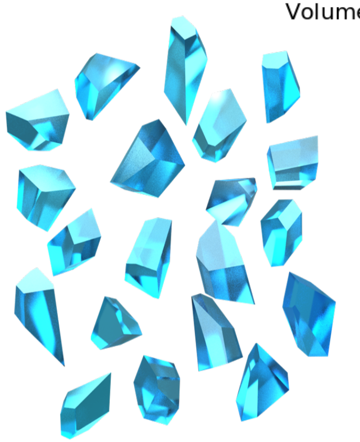

Loeb, Yang et al., 2018 JClim

- **Major updates in the improved THM**
  1. The improved THM uses an ensemble of 20 irregular hexagonal columns with a tilting parameter ($\sigma_t$) of 0.15 instead of a severely roughened hexagonal column ($\sigma_r = 0.5$) used in current Current THM (Loeb, Yang et al., 2018). This choice is to avoid some challenges in light scattering computations concerning ice crystal's surface roughness.
  2. Substantial improvement in backscattering resulting from using rigorous calculations.
  3. Refined the geometry of 20-column aggregates.

# An Improved Two Habit Model (THM)





- Same size-dependent, a continuous mixing ratio similar to the current THM (Loeb et al., 2018).
- A preliminary **version of an improved THM** database has been developed.
- Uses Volume-Projected Area Equivalent Diameter ($D_{VA}$) size characterization.

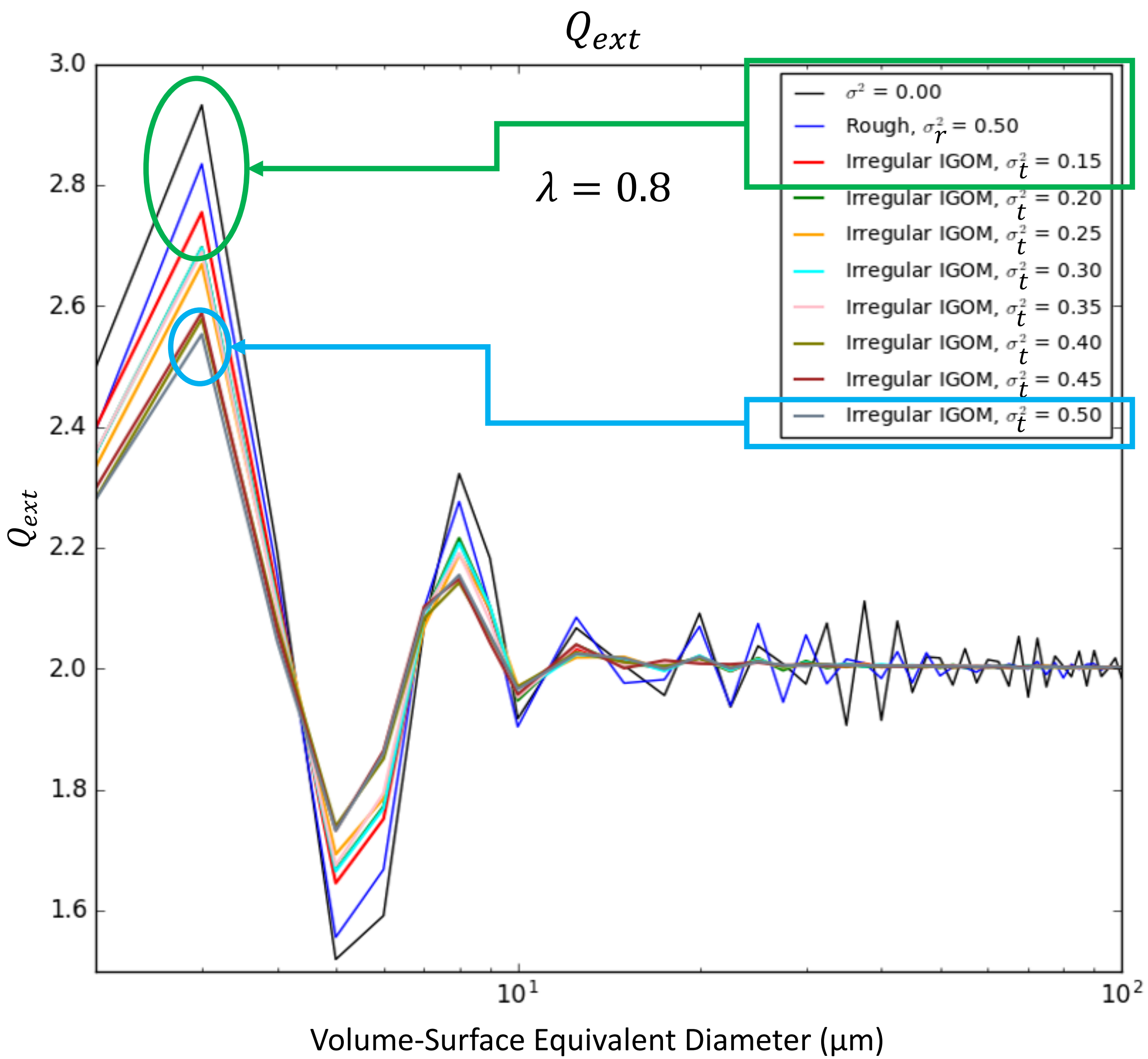
$$D_{VA} = \frac{3V_p}{2A_s}$$

$V_p$: Particle volume
$A_s$: Projected area

$$f_{single} = \begin{cases} e^{-0.005(D_{VA}-30)}, & D_{VA} \geq 30 \\ 1, & D_{VA} < 30 \end{cases}$$

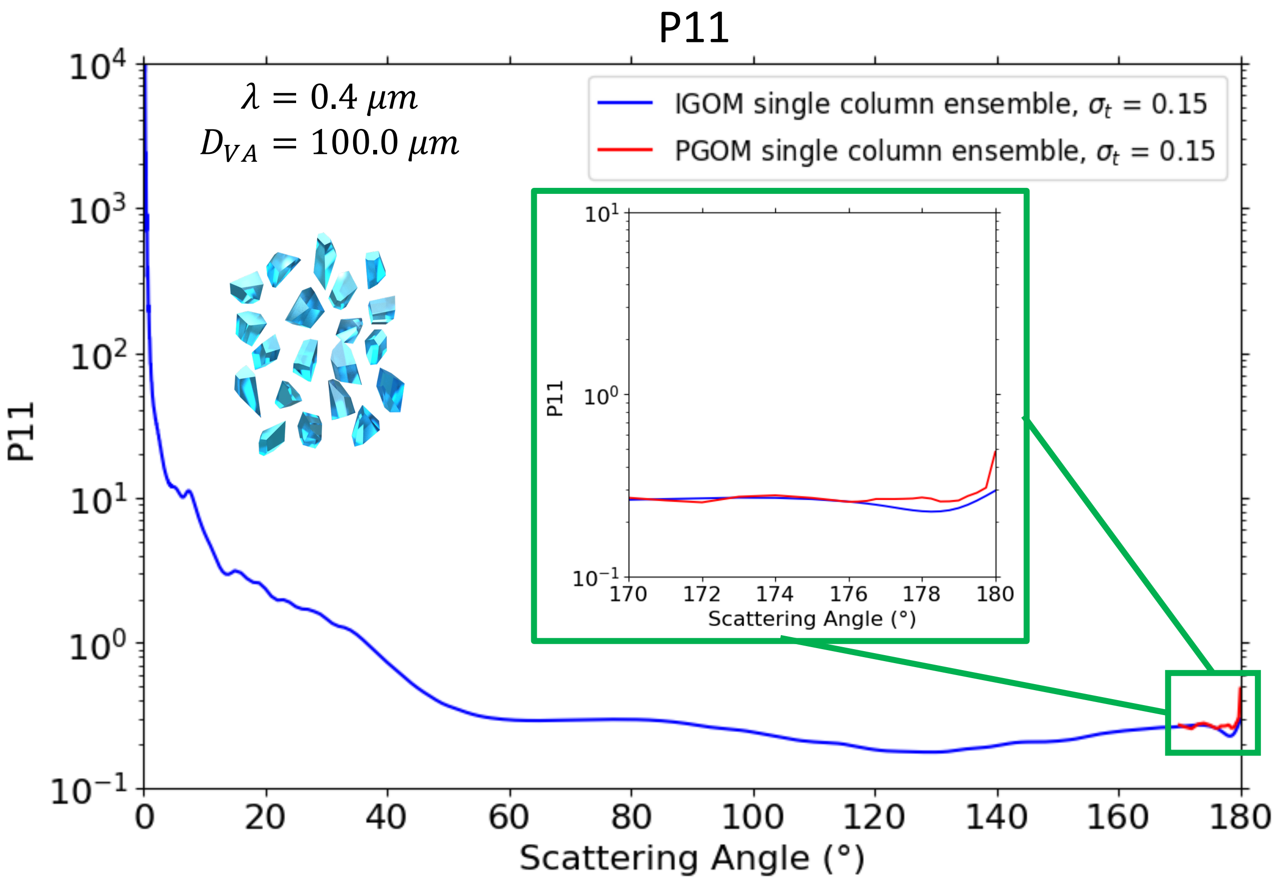
| | Current THM | Improved THM (preliminary version) | Improved THM (final version) |
|---|---|---|---|
| Wavelength | 470 bins (0.2 – 200 µm) | 42 bins (0.2 – 20 µm) | 470 bins (0.2 – 200 µm) |
| Size | 189 bins (2.0 – 10000.0 µm) | 59 bins (2.0 – 1000.0 µm) | 189 bins (2.0 – 10000.0 µm) |

# Updates 1: Single Column Tilting Parameter Optimization




- The single column ensemble of the improved THM has $\sigma_t = 0.15$.
  - $\sigma_t = 0.50$ results in inconsistent magnitudes of the extinction efficiency ($Q_{ext}$) compared to severely roughened hexagonal columns ($\sigma_r = 0.50$ ).
  - A smaller $\sigma_t$ results in more consistent magnitudes of $Q_{ext}$.
- Further investigation would need to further optimize $\sigma_t$ for irregular single column ensemble.

# Improvement in Backscattering using a combination of the Improved Geometric Optics Method (IGOM) and the Physical-Geometric Optics Method (PGOM)




- Development of an improved THM involves a huge burden from the perspective of numerical computation; in particular, PGOM is computationally expensive for 20-column aggregate calculations.
- Combination of IGOM calculations and PGOM-based backscattering parameterizations
  - IGOM calculations: Entire scattering angle range.
  - Parameterization: Correct IGOM calculations for $170° - 180°$ scattering angles.

# Improvement in Backscattering

- The **backscattering enhancement ($\xi_{PGOM}(\theta)$)** is parameterized with the **Cauchy distribution ($F(\theta)$)**:

$$\xi_{PGOM}(\theta) = \frac{P_{11,PGOM}(\theta)}{P_{11,PGOM}(170°)} = 1 + F(\theta) - F(170°), \tag{1}$$

where

$$F(\theta) = c_1 \frac{1}{\left\{c_2 \pi \left(1 - \frac{\theta}{180°}\right)\right\}^2 + 1}. \tag{2}$$

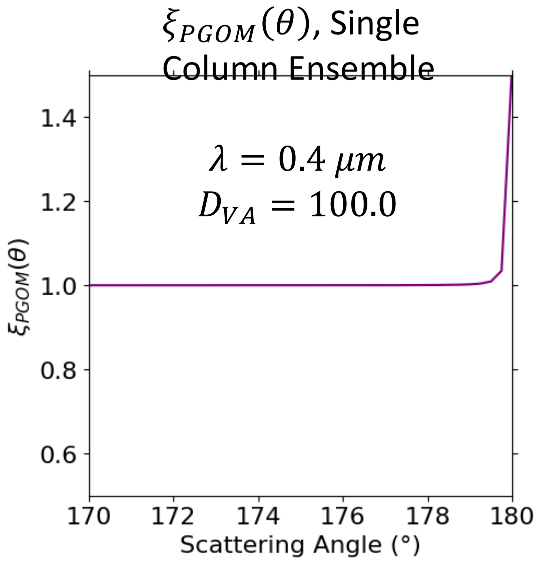
- $\theta$ is the scattering angle, ranged from $170° - 180°$; $P_{11,PGOM}$ is the PGOM calculated $P_{11}$ phase function; and $c_1$ and $c_2$ are parameters represented as:

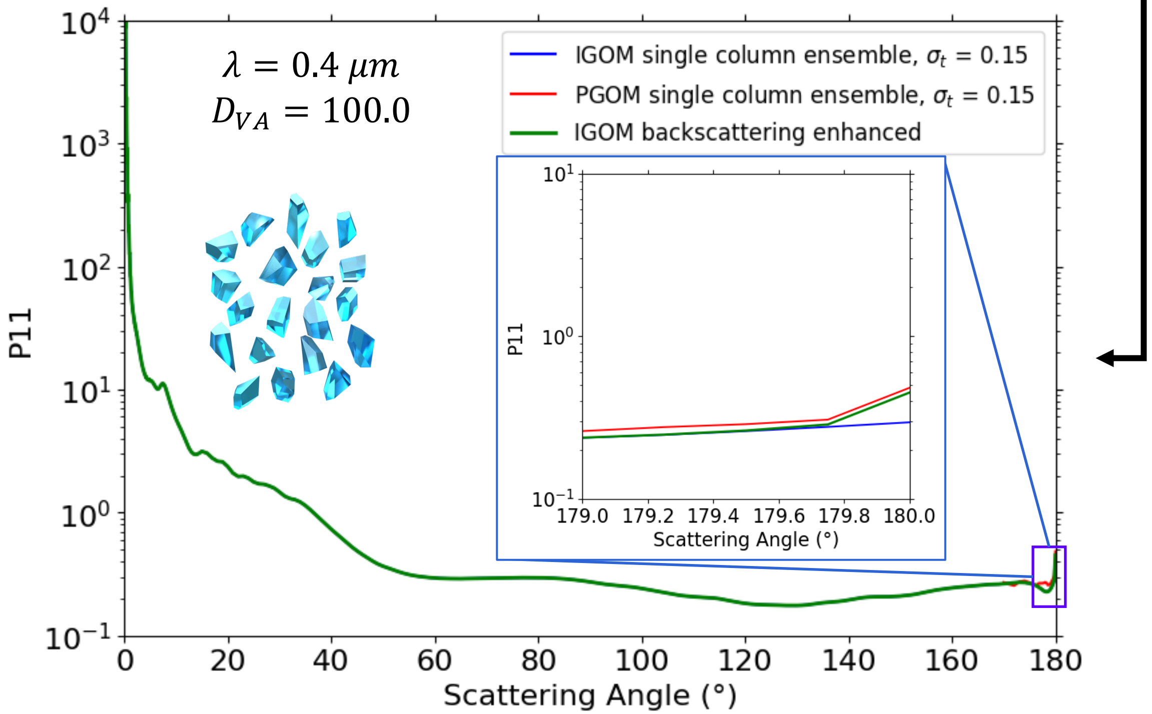
$$c_1 = d_1 * [1 - \tanh(a_0 * V_{abs} + a_1)] \tag{3}$$

$$c_2 = d_0 * kD \tag{4}$$

- $kD$ is the size parameter and $\boldsymbol{V_{abs}}$ is dependent on the imaginary part of the refractive index ($\mathrm{m}_i$) and $kD$.
- $d_0$, $d_1$, $a_0$, and $a_1$ are constants estimated from regressions.

# Improvement in Backscattering



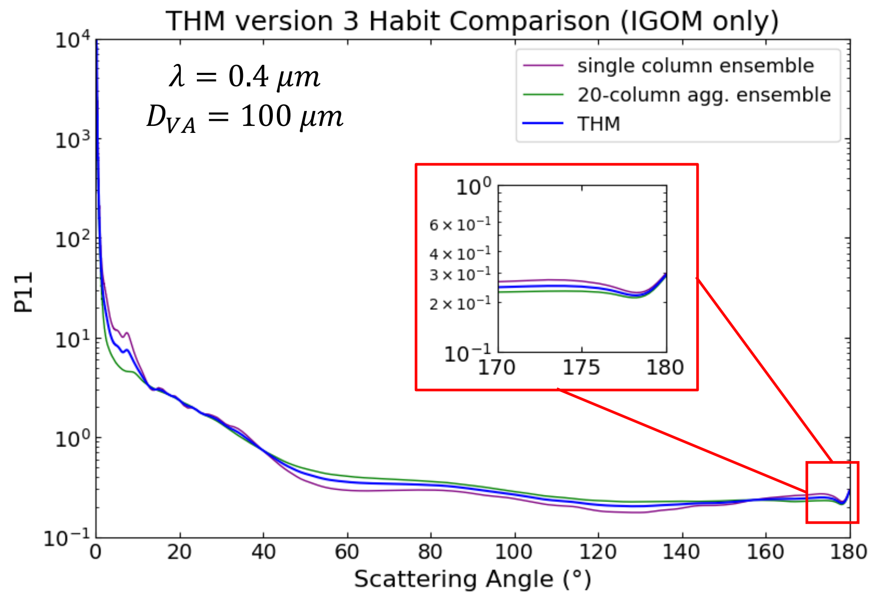

- With optimized coefficients of the parameterization, the phase function is obtained from

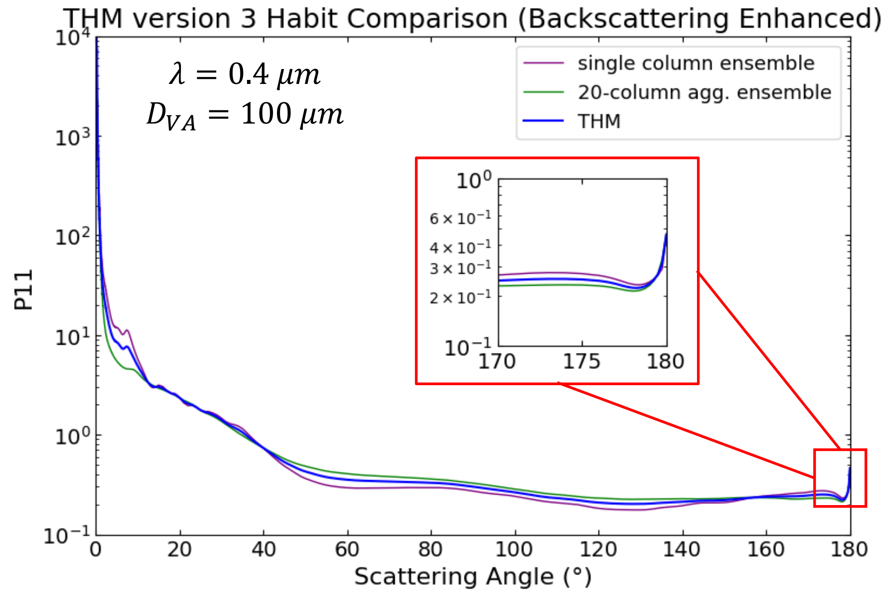
$$P_{11,,enhanced}(\theta) = \xi_{PGOM}(\theta) * \mathrm{P}_{11,\mathrm{IGOM}}(\theta) \quad (5)$$

- $P_{11,enhanced}$ has been shown to be fairly consistent with PGOM calculations.
- Reduced substantial computational burden

→ Feasible to develop the future THM single-scattering property database that covers entire size and spectral ranges.

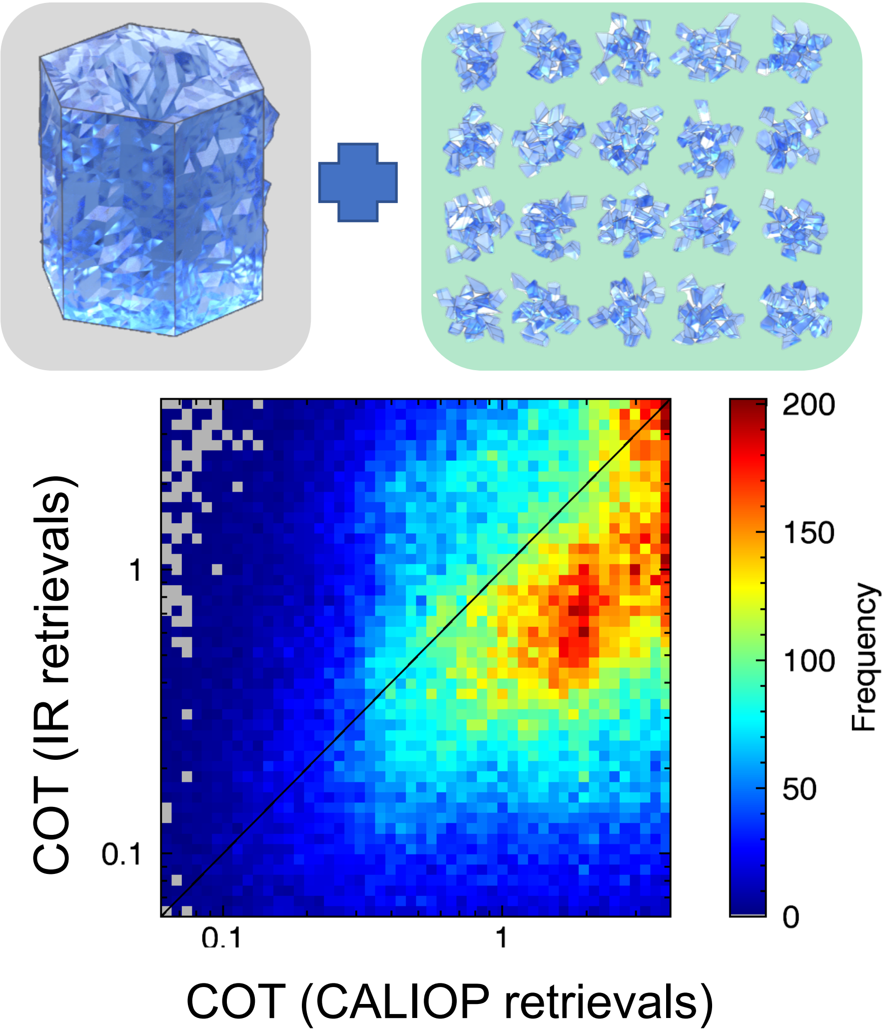
# Geometry of 20-column aggregates

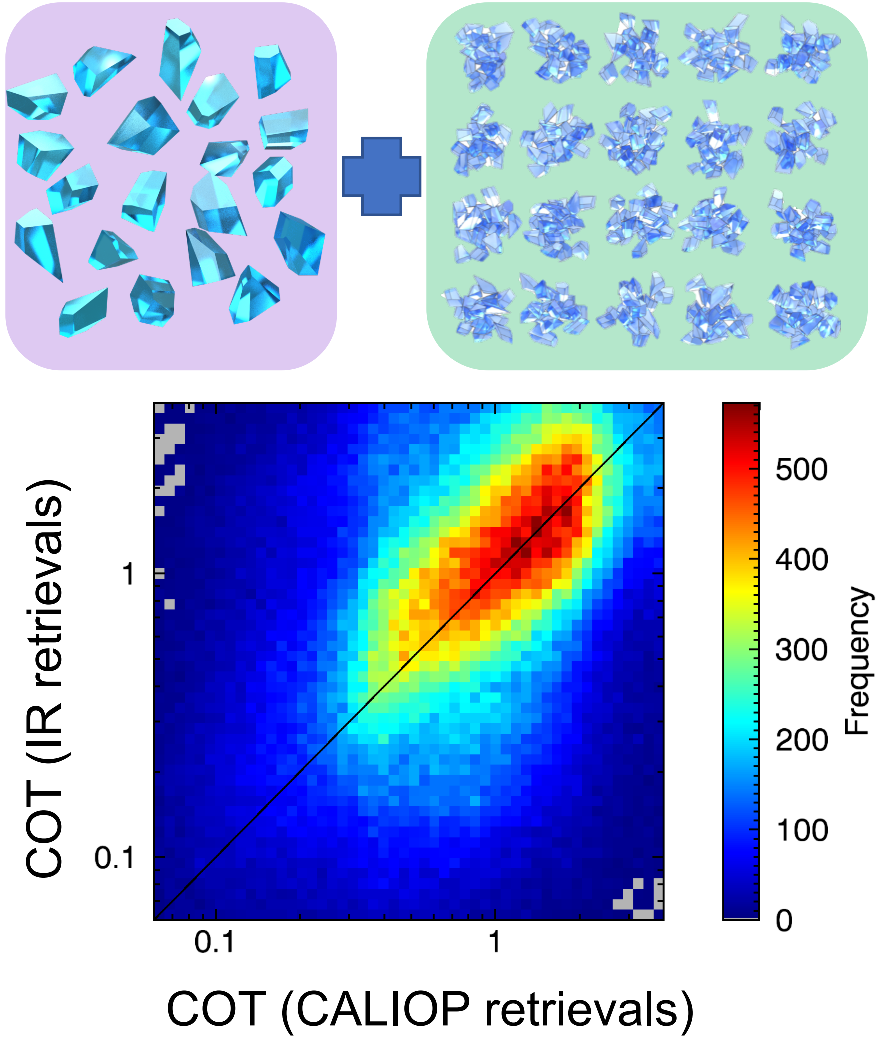



- The backscattering enhancement is applied to single column and 20-column aggregate ensembles separately.
- After the application, the THM database calculations are conducted.
- Bottom figure shows THM $P_{11}$ between single column and aggregate $P_{11}$s at $D_{VA} = 100\ \mu m$.
  - THM backscattering is shown to be enhanced compared to IGOM-only.

# Active–Passive Consistency Check



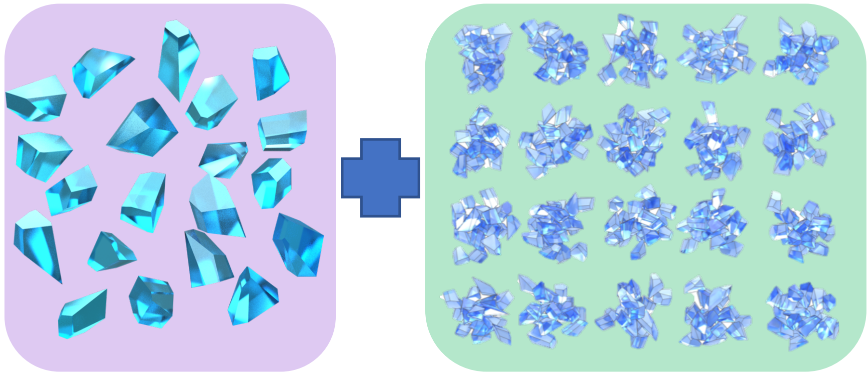




IIR=Imaging Infrared Radiometer; COT=Cloud Optical Thickness

Improved THM has reasonably robust backscattering, leading to consistency between passive and active COT retrievals.

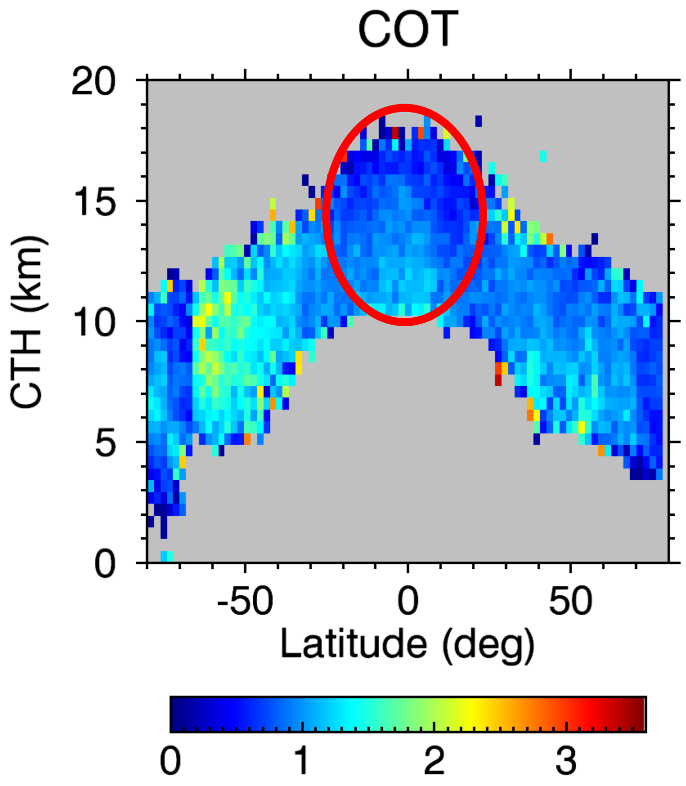
# Cirrus cloud climatology

CTT < -40°C
COT < 3.6
Single-layer ice

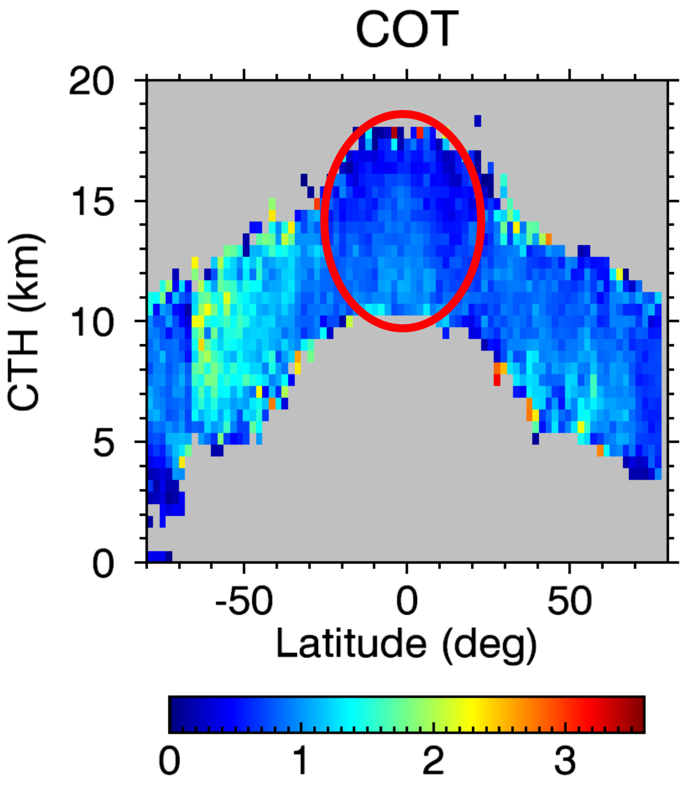


Physics-based active-passive synergistic retrievals of ice cloud properties

**IR-only retrievals**




**IR + lidar retrievals**




- Lidar + IR signals show sensitivity to the whole range of cirrus cloud COT (e.g., $\tau$ = 0–3.6).
- Decreased average COT for cirrus clouds where optically thin clouds ($\tau < 0.1$) are dominant due to sufficient sensitivity of lidar measurements to these optically thin clouds.

# Graupel and Snow Particles

**Hydrometeors**

WV

Cloud Water

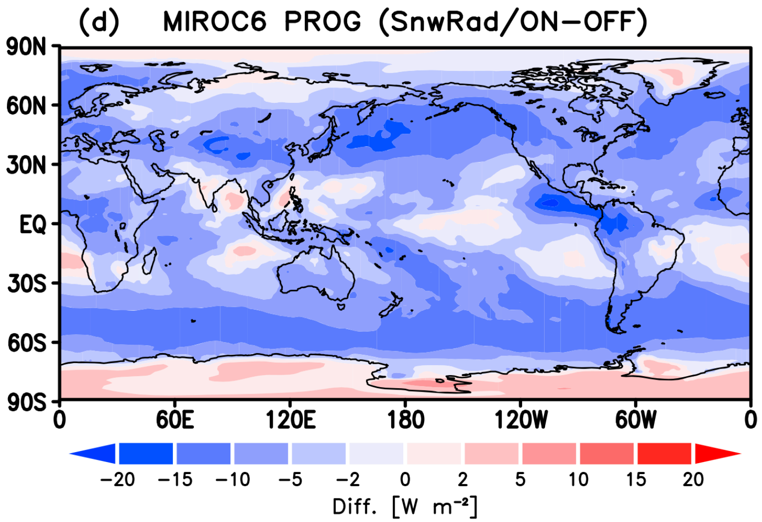
Cloud Ice

Rain

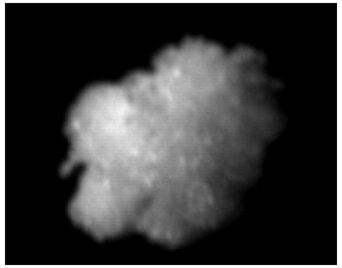
Graupel

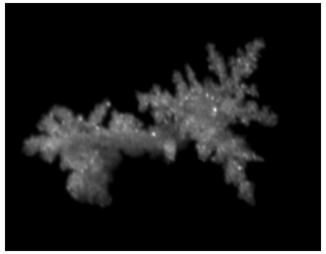

Snow


Ice crystal models are used for bulk optical property parameterizations for snow and graupel particles




Radiative effects of graupel/snowflakes are not negligible (Michibata et al., 2019).





Example images of in-situ measured graupel/snowflakes (Gergely et al., 2017).

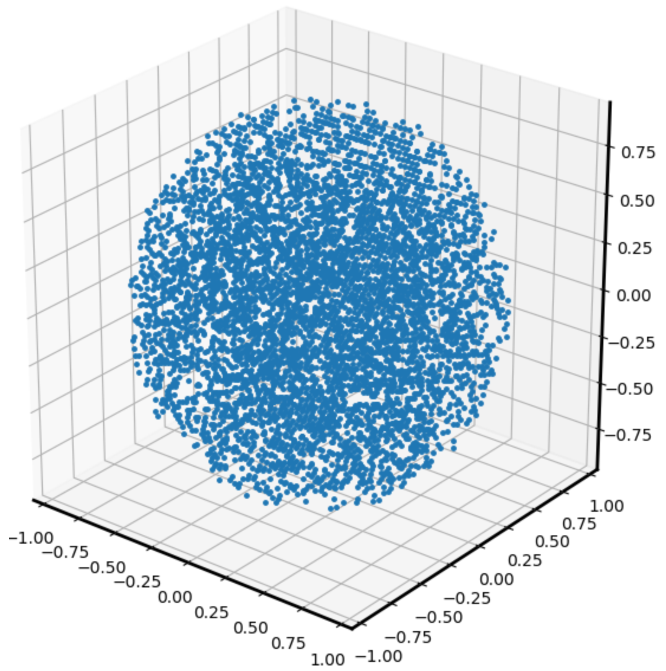
**Question:**

**Are ice cloud optical property models applicable to graupel/snowflakes?**

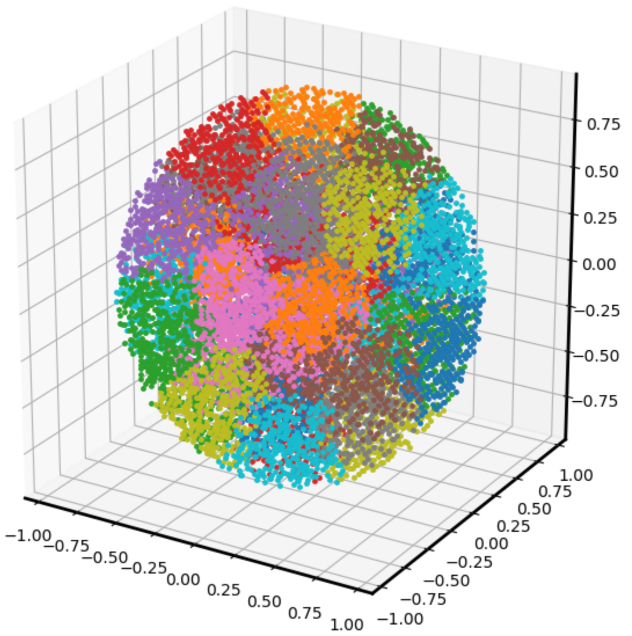
**→No, they are not applicable due to various ice mass density values. We need to develop realistic graupel/snow models.**

# Random points-clustering-convex hull algorithm

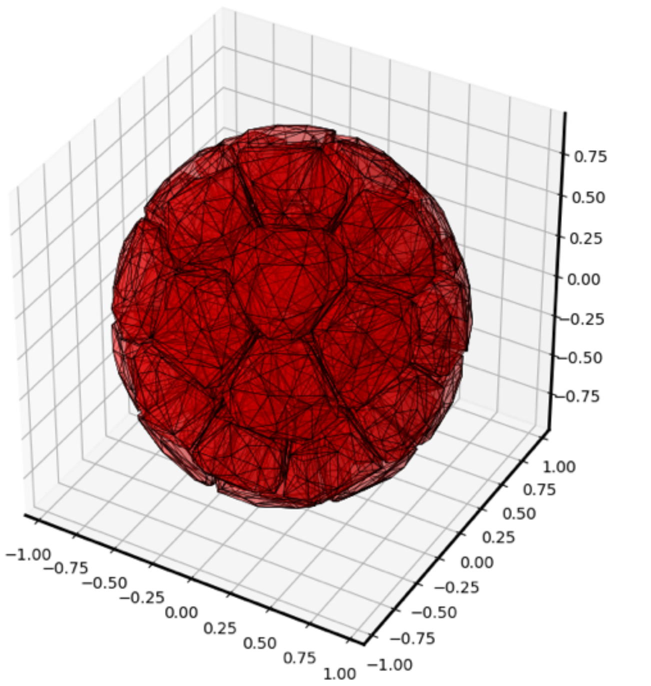
Step 1: generate random points in a certain shape




Step 2: cluster points into some random groups



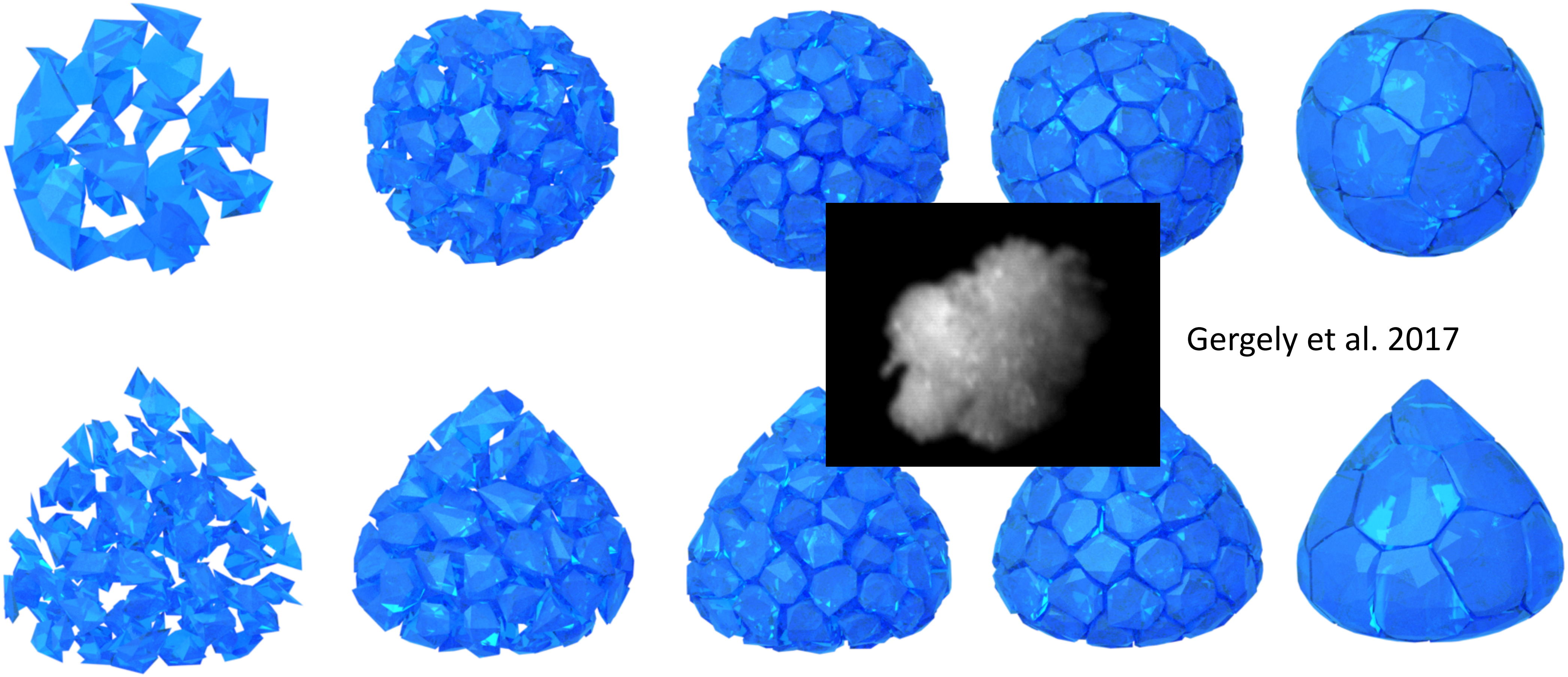

Step 3: create a convex polyhedron for each point group



# Examples: Graupel

Spherical

Conical



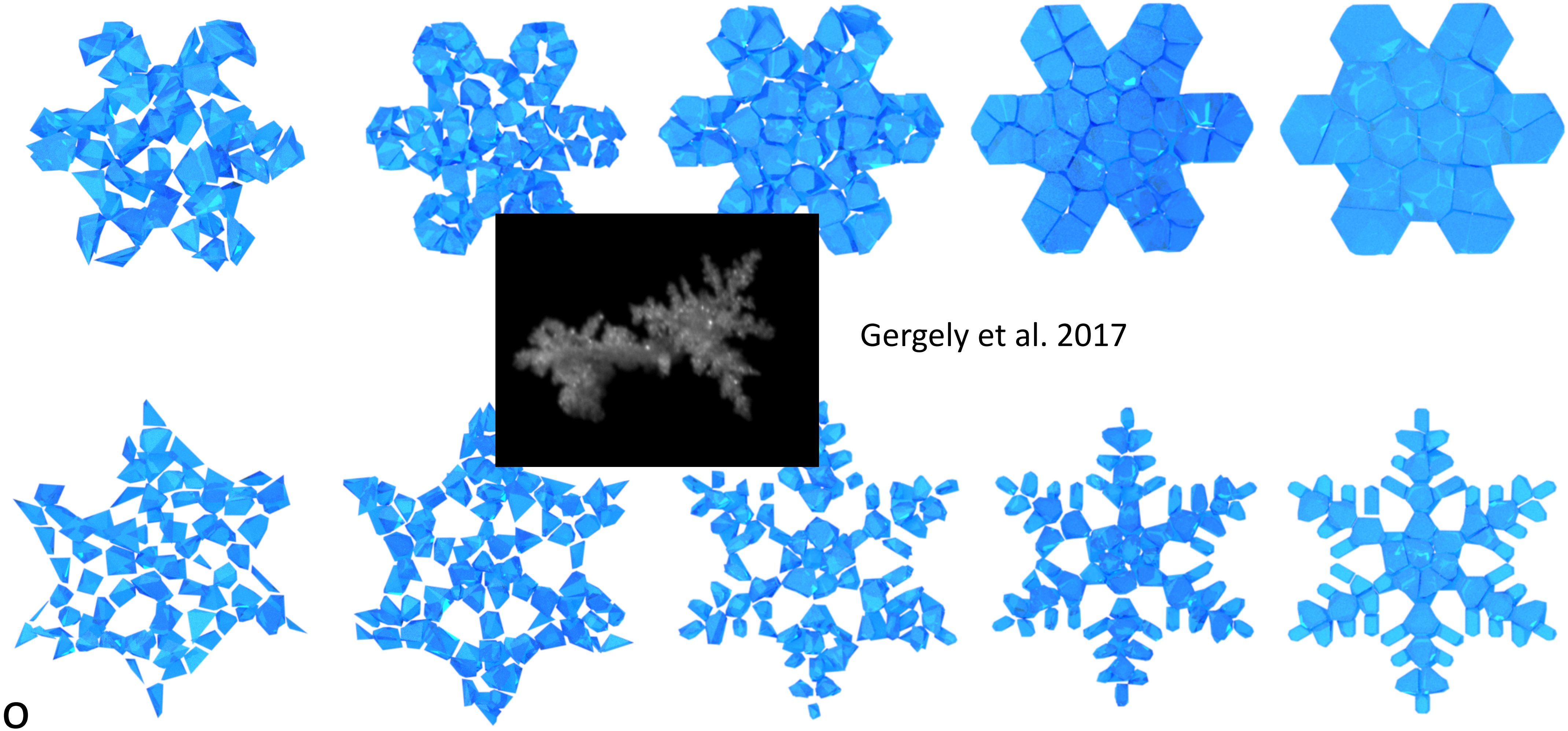
Gergely et al. 2017

Ice mass ratio (MR): 0.1 0.3 0.5 0.7 0.9

# Examples: Snowflake

Plate

Dendrite



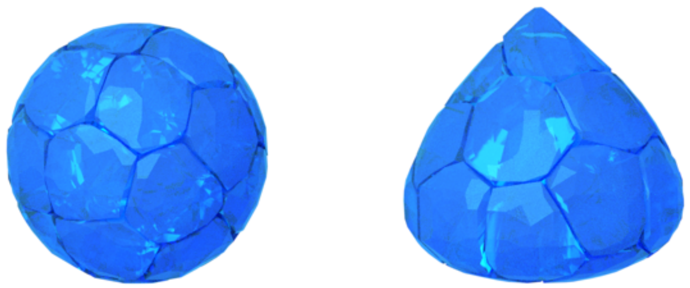
Gergely et al. 2017

Ice mass ratio (MR): 0.2 0.3 0.5 0.7 0.9

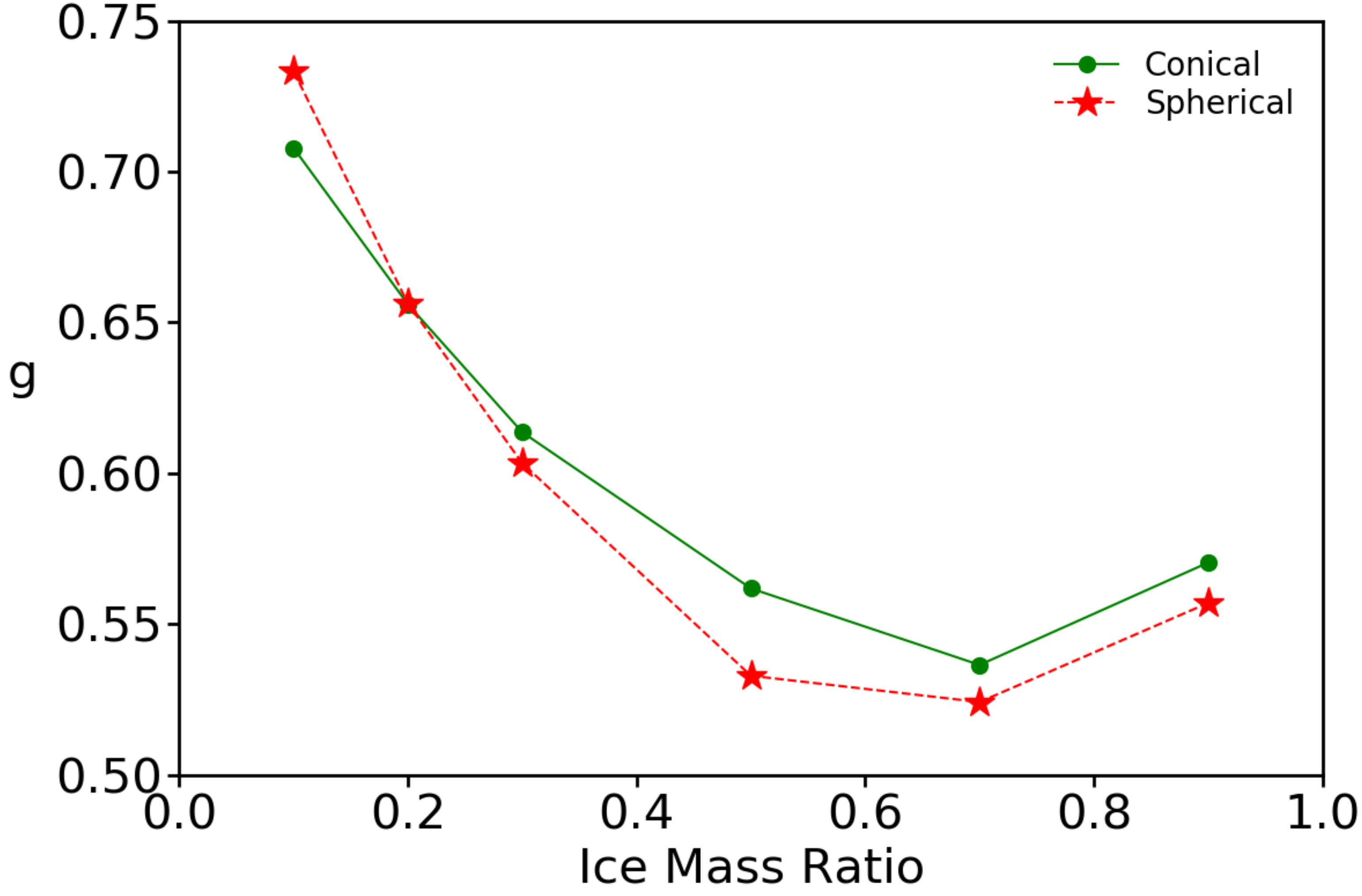
# IGOM computations

Maximum dimension: 5 mm

Wavelength: 355 nm



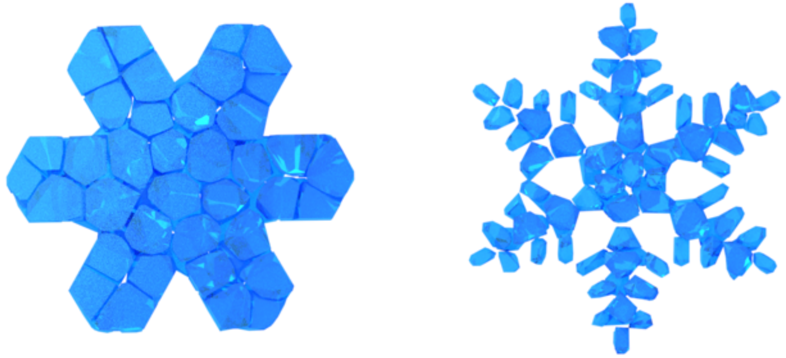
Asymmetry factor-Graupel



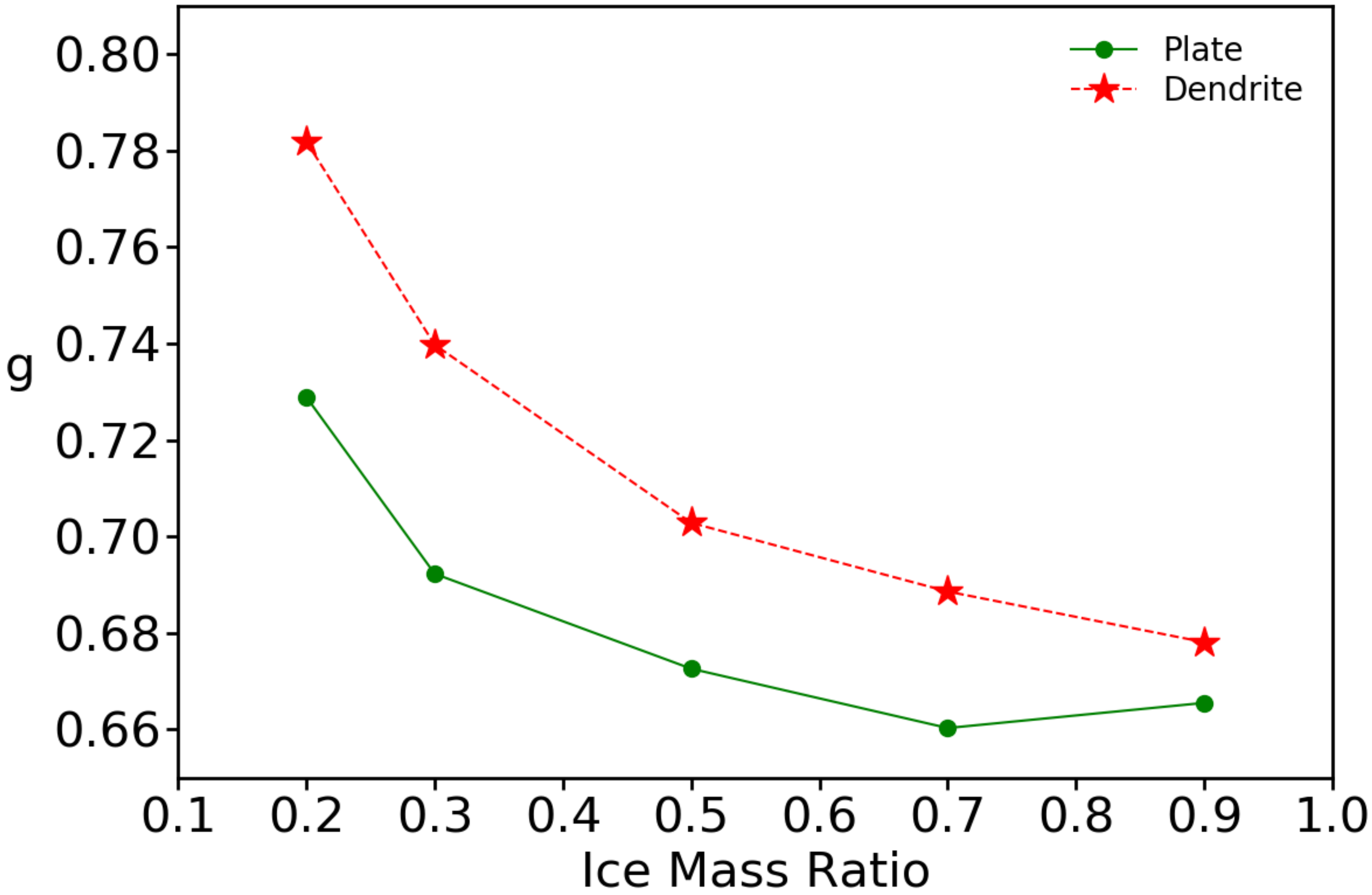
# IGOM computations

Maximum dimension: 1 mm

Wavelength: 355 nm



Asymmetry factor-Snowflake



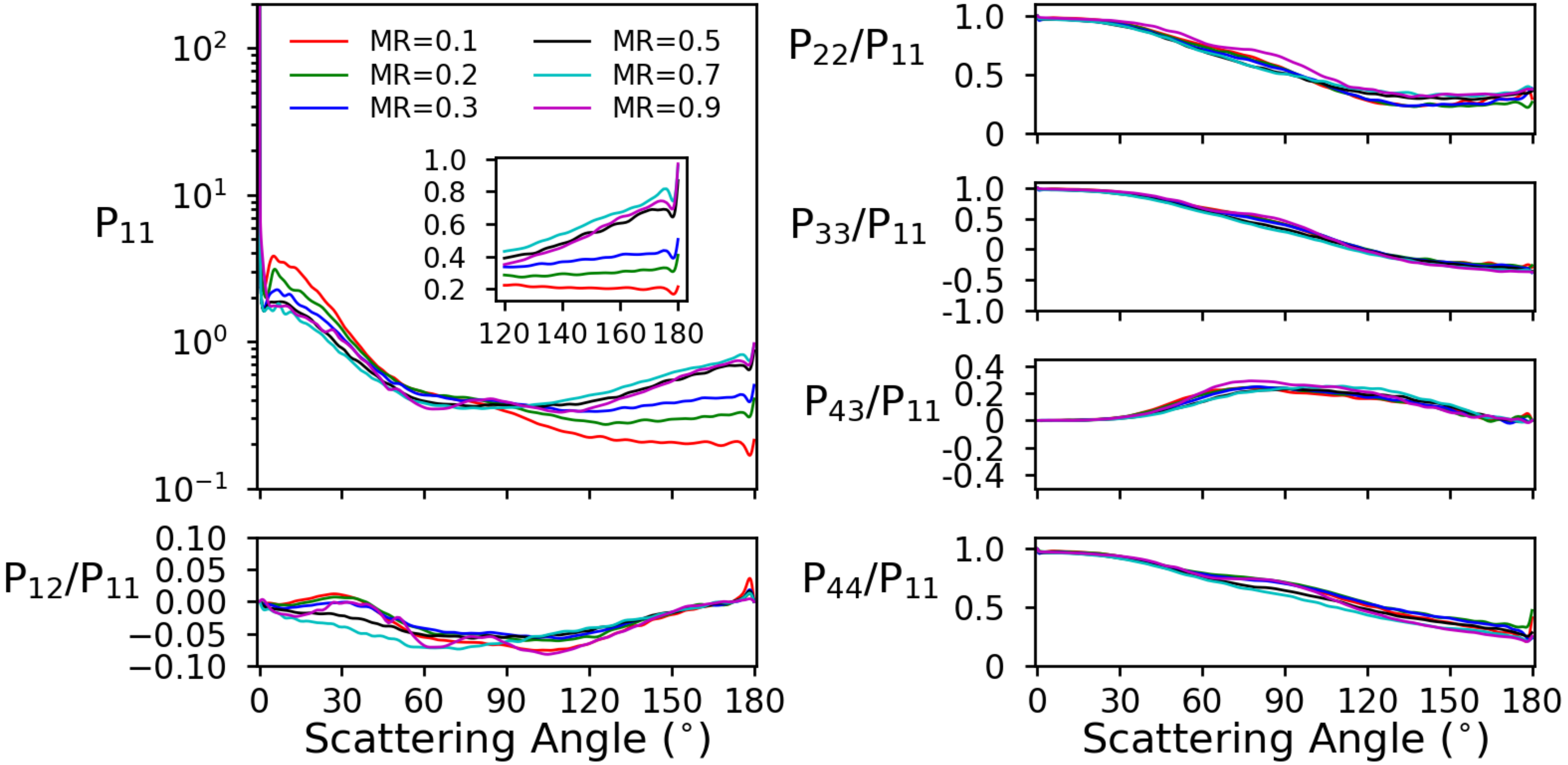
# Different Ice Mass Ratio (MR)

Maximum dimension: 5 mm

Wavelength: 355 nm

Conical shapes

Phase matrix



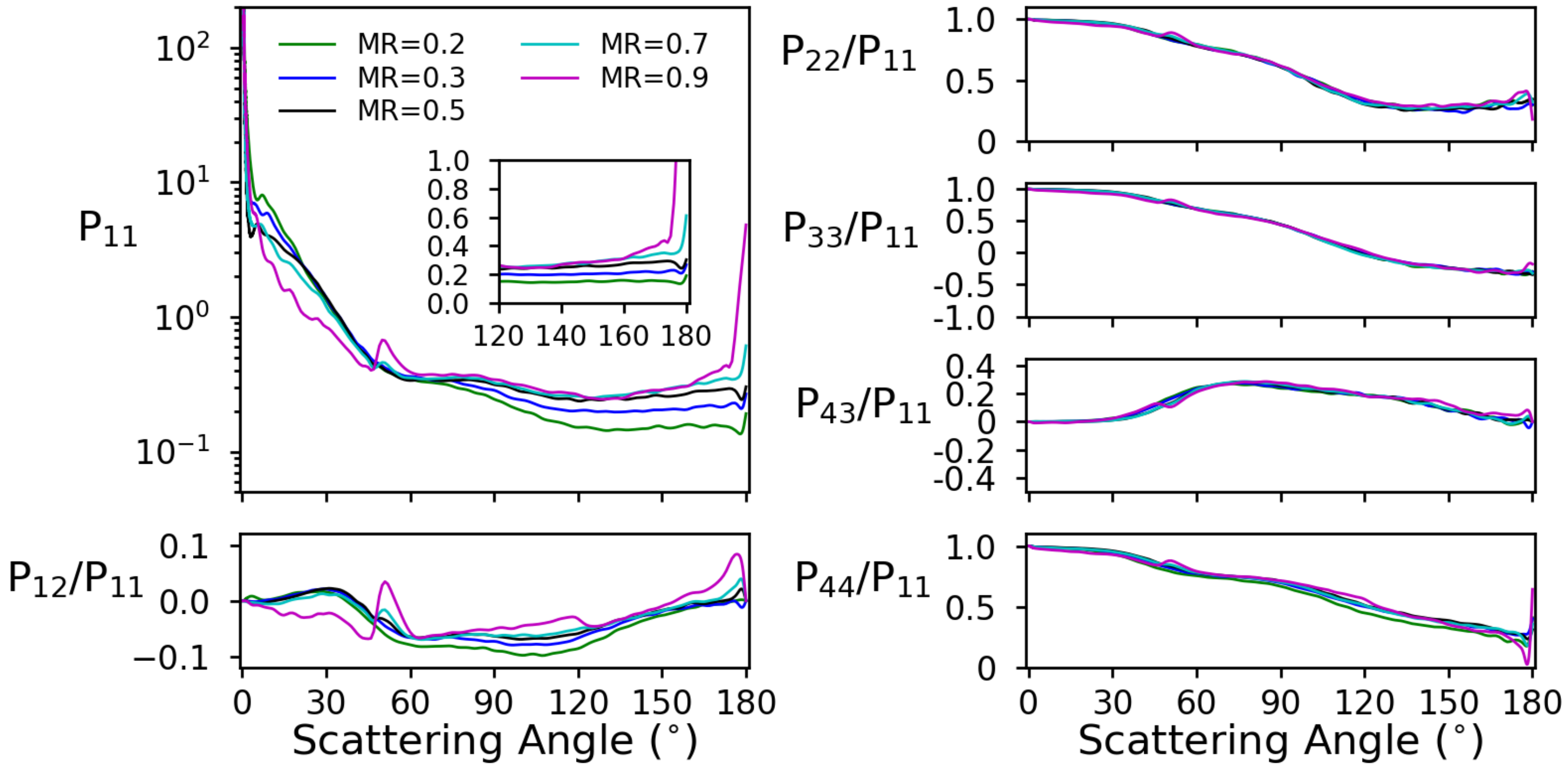
# Different Ice Mass Ratio (MR)

Phase matrix

Maximum dimension: 1 mm

Wavelength: 355 nm

Dendrite shapes

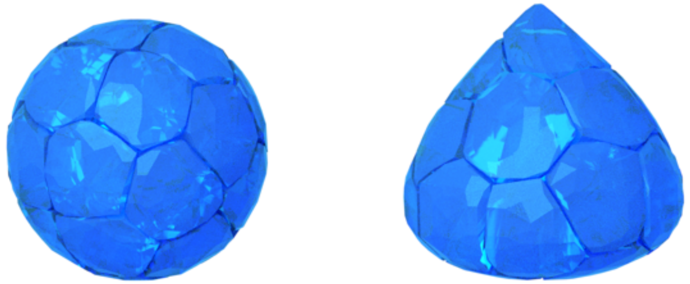


# Different Shapes-Graupel

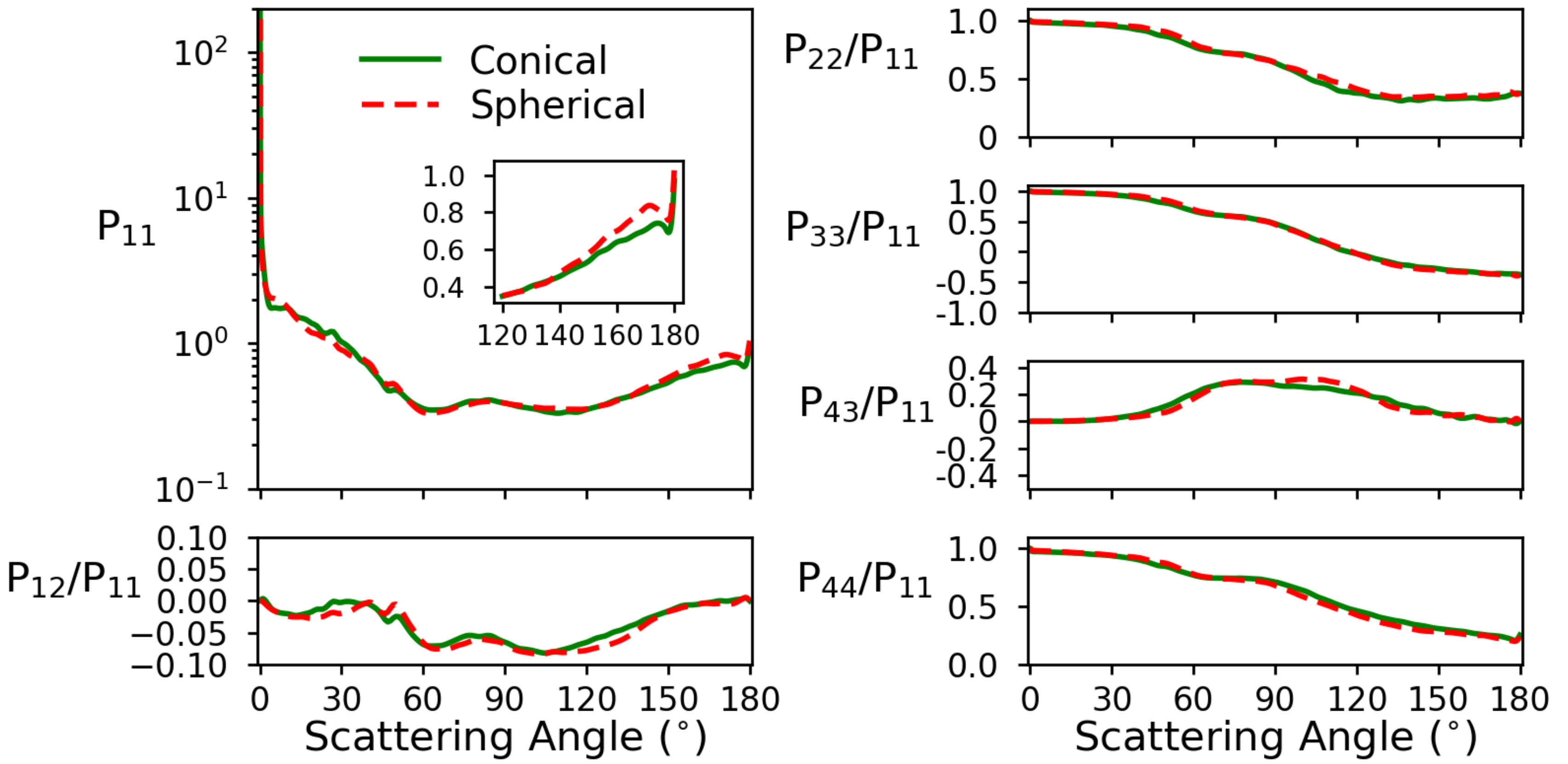
Maximum dimension: 5 mm

Wavelength: 355 nm

Mass ratio: 0.9



## Phase matrix

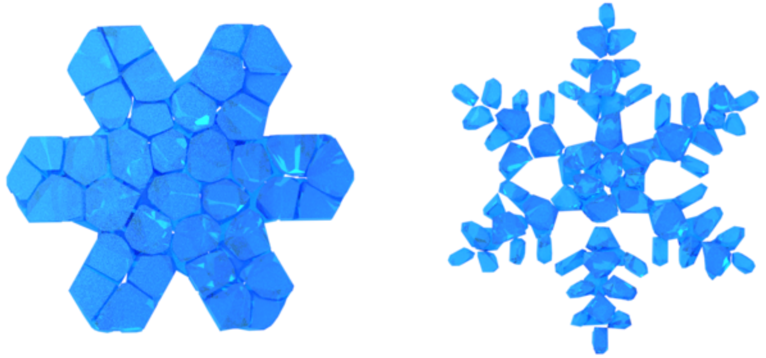


# Different Shapes-Snowflake

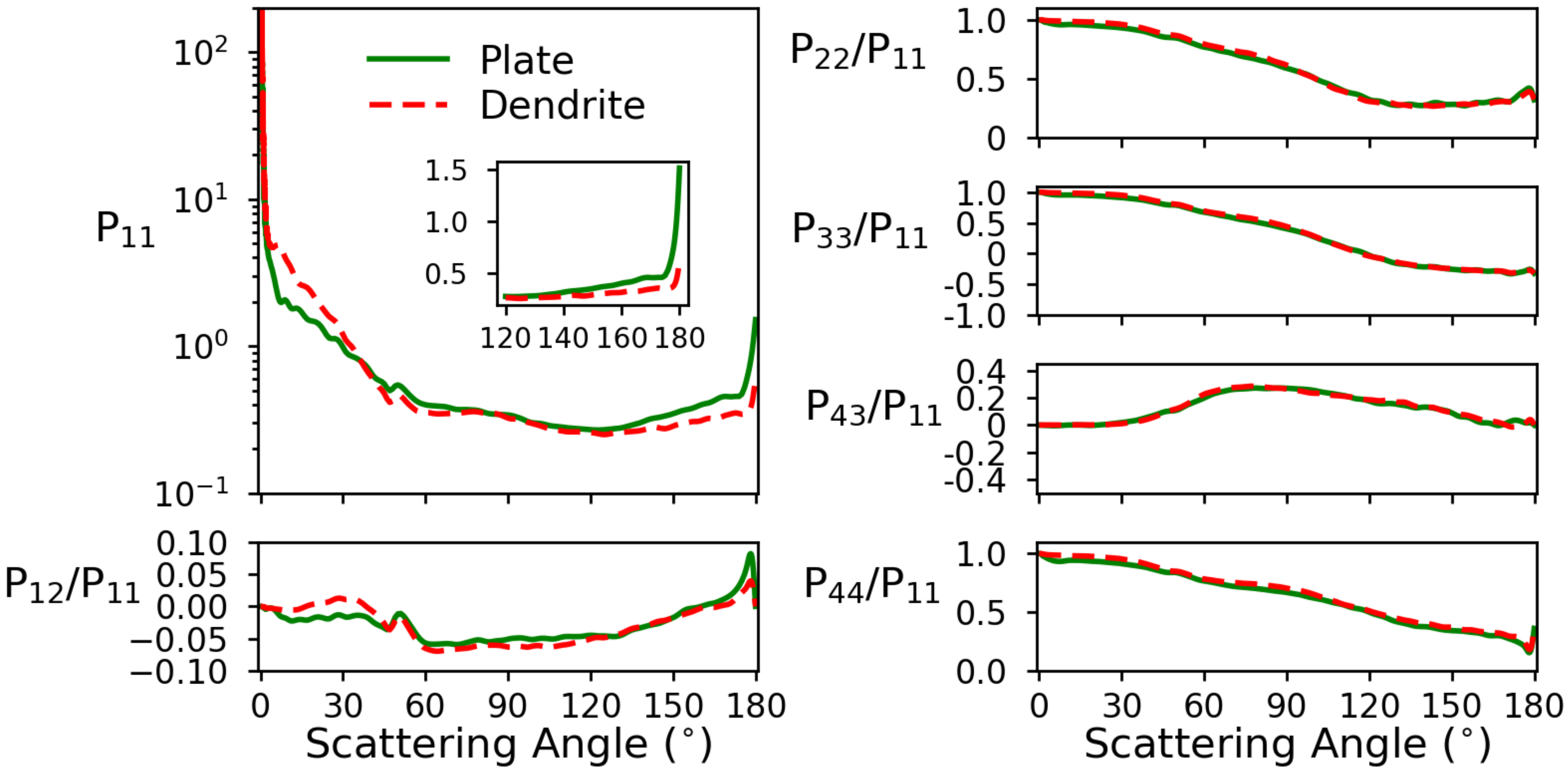
Maximum dimension: 1 mm

Wavelength: 355 nm

Mass ratio: 0.7



Phase matrix



# Summary and Future Plan

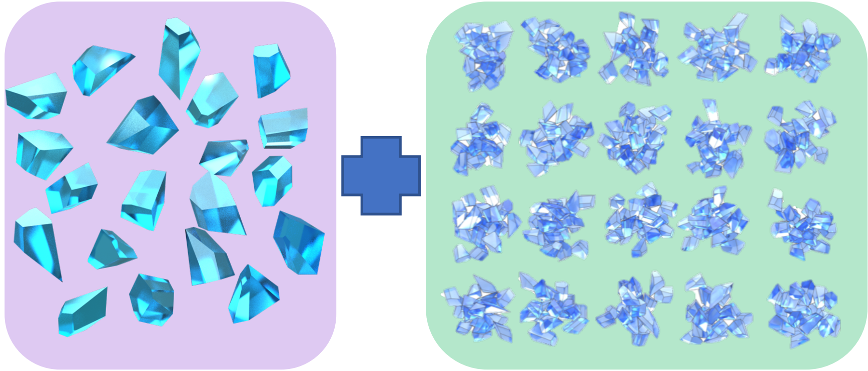
**Development of a new ice crystal optical property database is in progress:**

- An improved THM
  - Improved ice crystal shape models
  - Improved backscattering computations

  → Active–passive sensor-based retrieval consistency
- Graupel/Snow crystal model
  - Realistic graupel/snow particle shape models
  - Various ice mass density ratios

  → The single-scattering properties of graupel/snow are realistic.
- Near future plan:
  1. Deliver a preliminary improved THM database
  2. Extensive validations and application studies
  3. Develop a database of graupel/snowflakes

Improved THM



Graupel/Snow