Dependence of the directional intensity and polarization of light scattered by small ice crystals on their shape and size: Applications for airborne cloud probes

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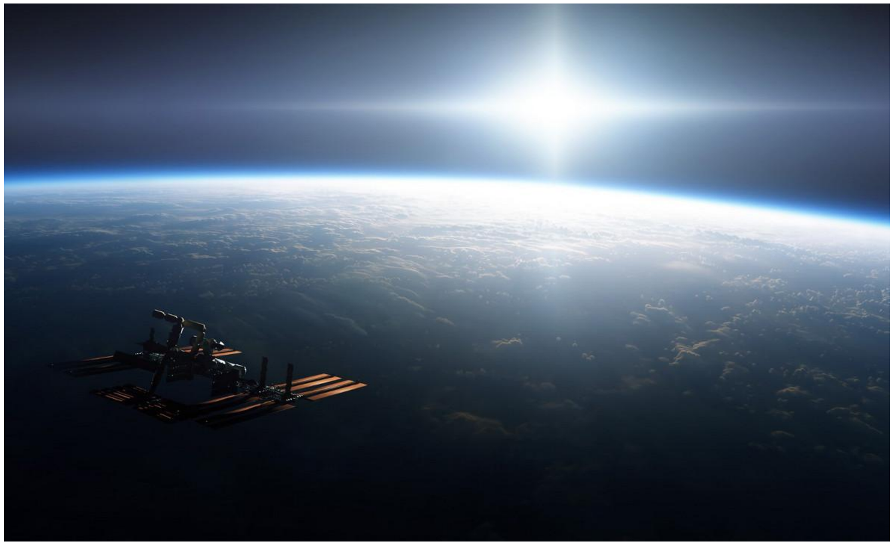
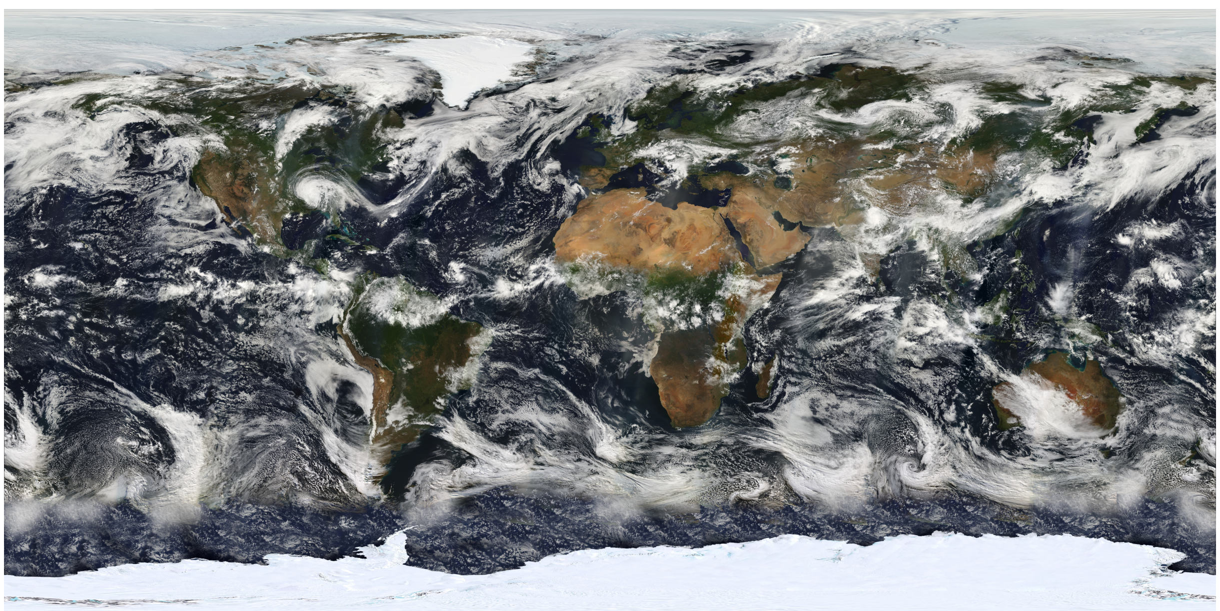
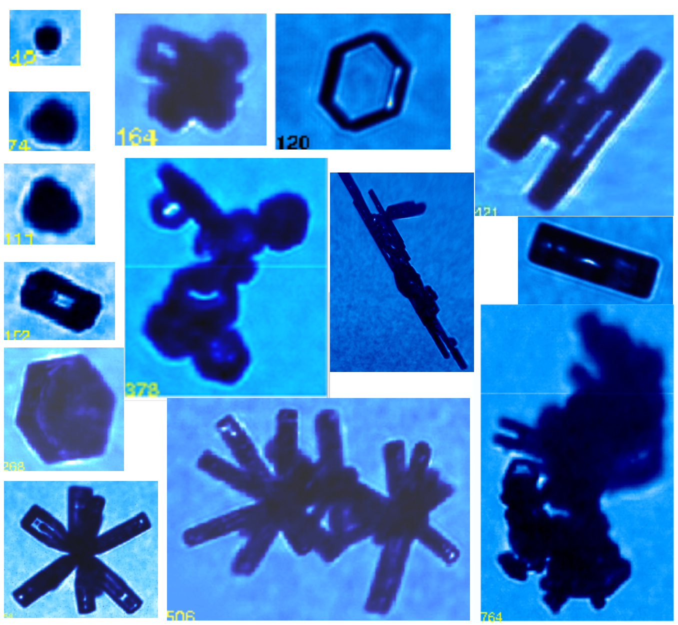
I. Introduction

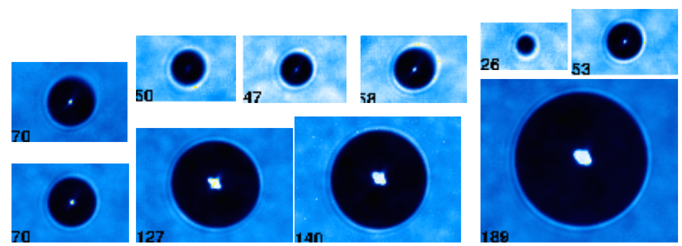


Images from NASA



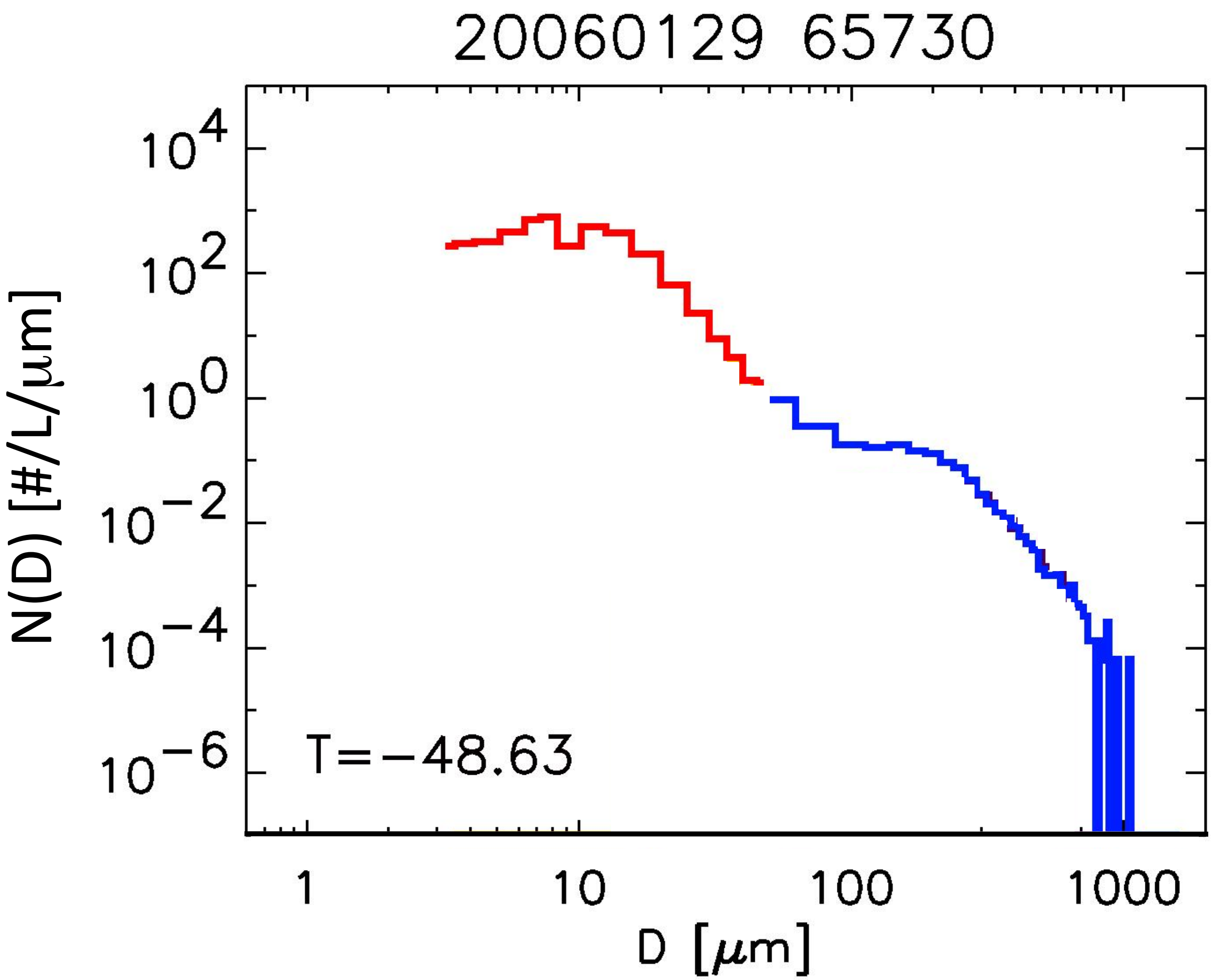
- Sun, energy source
- Sun – cloud interaction
  - reflection
  - absorption
  - transmission
- Cloud properties vary
  - space & time
- For climate system
  - knowledge of cloud radiative properties





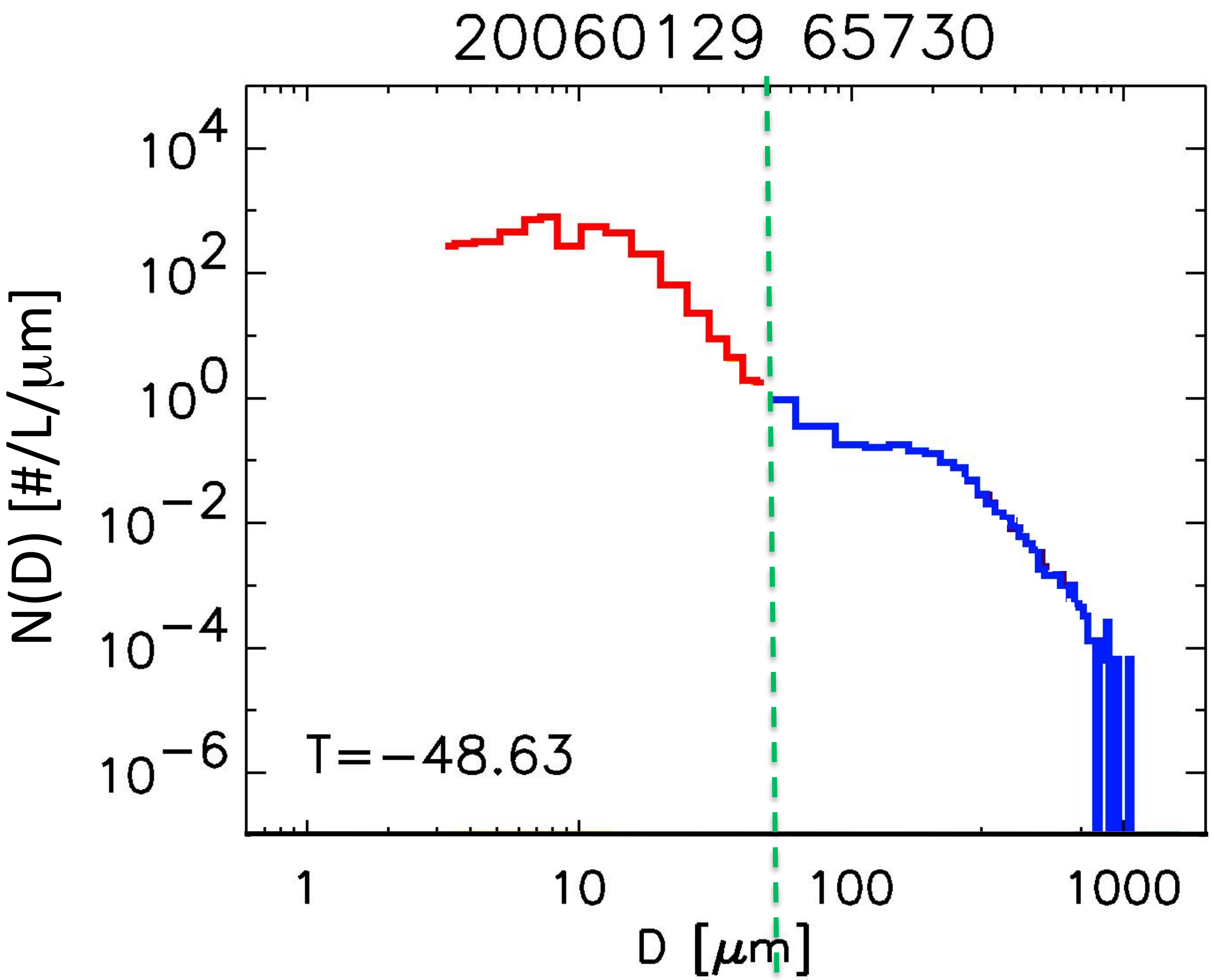
- Cloud radiative properties depend on particle shape & size
- Low warm clouds, liquid particles spherical
- High cold clouds, ice particles non-spherical
- Mixed clouds, ice & water coexist

II. Background



- **Size distribution [#/L/μm]**
  # of particles in given sample volume & size range (bin),

Fundamental input for numerical models & retrieval algorithms!



- Size distribution [#/L/μm]
  \# of particles in given sample volume & size range (bin),

Fundamental input for numerical models & retrieval algorithms!

Forward scattering probe ← → Optical array probe

FSSP, CDP, CAS, CPSPD, …

~50 μm

2D-C/P, CIP, 2DS, PIP, …

Forward scattering probes

- convert intensity of scattered light measured in specific angles to particle size (Mie scattering)
- shape (sphere) and refractive index of particle
- forward scattering spectrometer probe (FSSP), Knollenberg (1972)
- 1 – 50 μm
- Many different probes

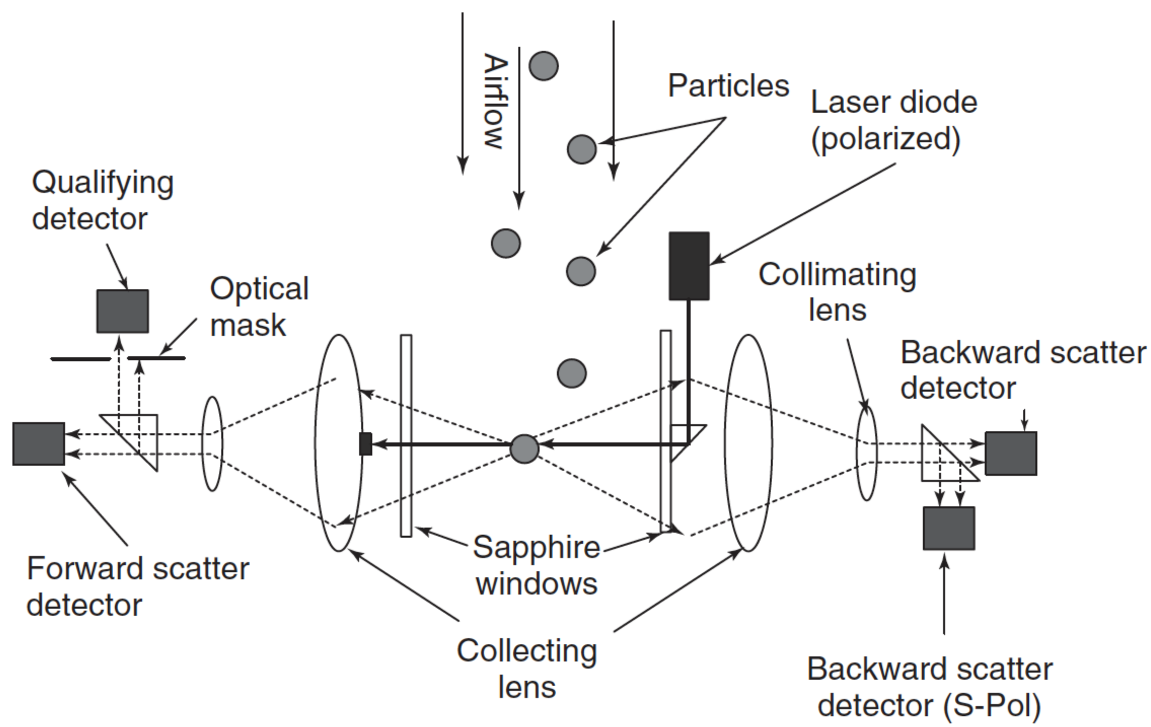
FSSP, CDP, CAS,

CAS-DPOL,

CPSPD,

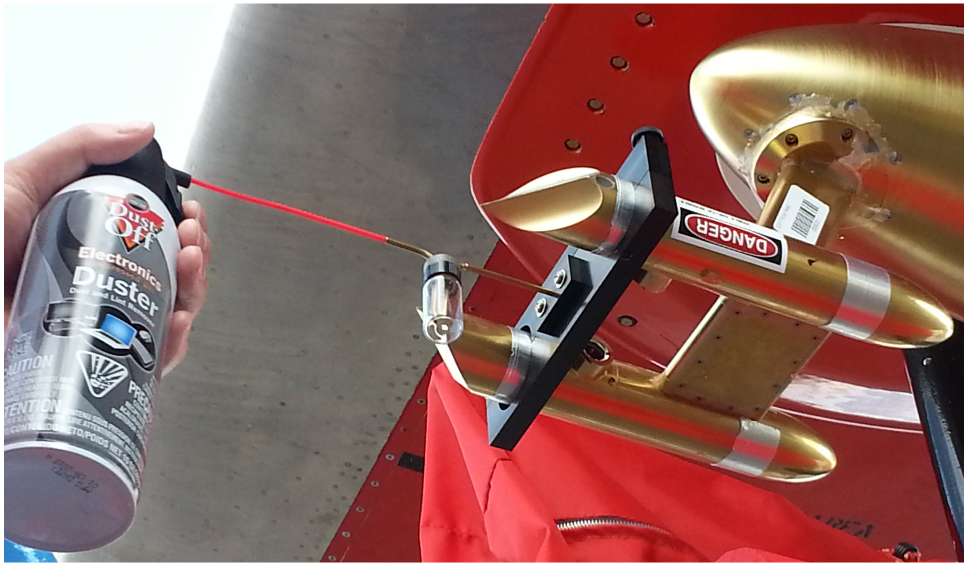
Fast FSSP (FFSSP),

Fast CDP (FCDP)



Forward scattering probes

- measure intensity of scattered light in forward and/or backward direction
- CDP in forward (4º-12º)
- CAS in forward (4º-12º) and backward (168º-176º)
- forward scattering probe was developed to measure "spherical liquid water droplet" -> errors for non-spherical ice crystals



CDP & calibration tool during High Ice Water Content (HIWC) field campaign @ Cayenne, French Guiana

▪ Forward scattering probes

- measured intensity of scattered light is "differential scattering cross section"

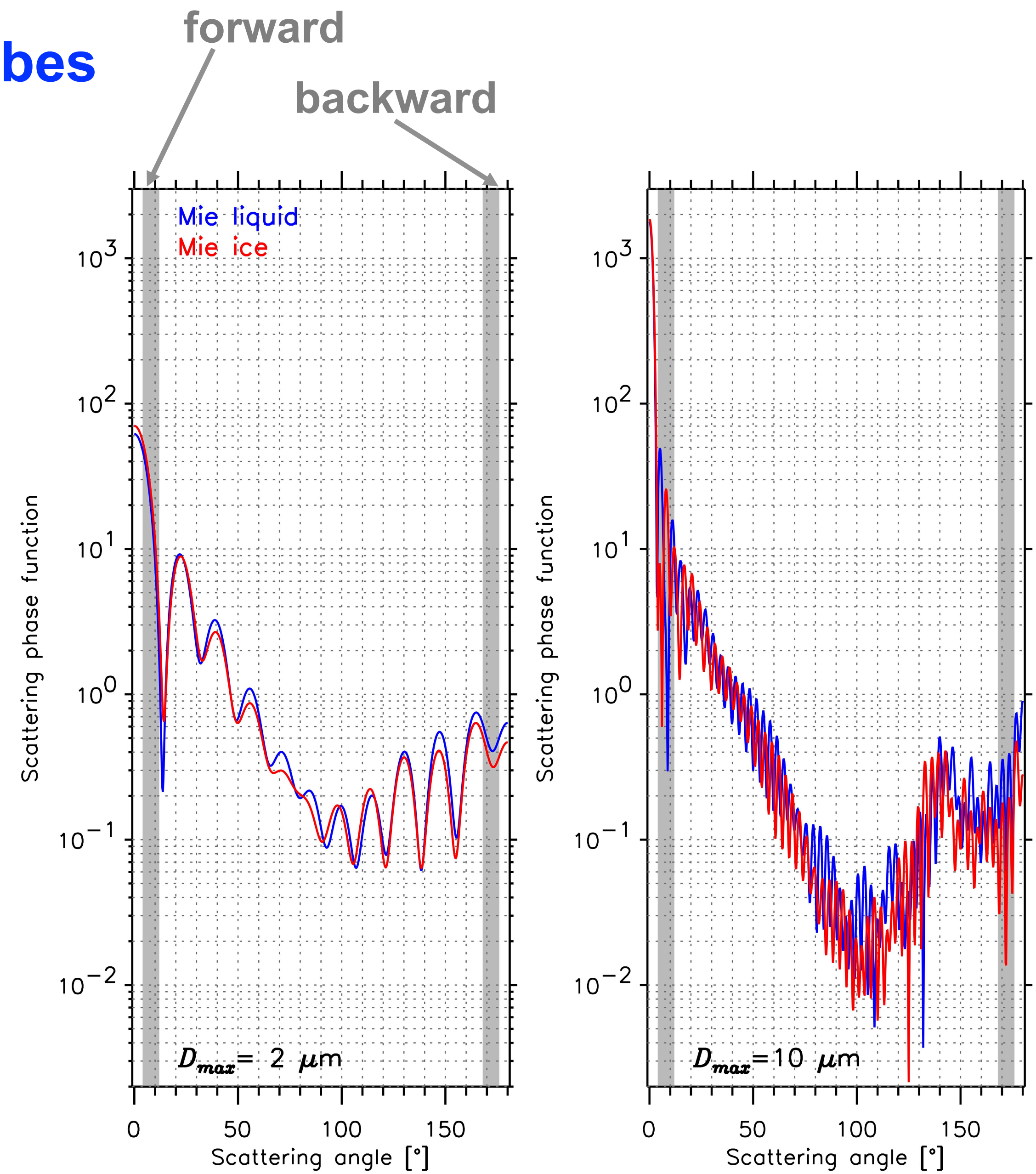
$$C_{sca,\theta} = \frac{1}{k^2} \int_0^{2\pi} \int_{\theta_1}^{\theta_2} P_{11} \sin(\theta) \, d\theta \, d\phi$$

- CAS

  θ_1=4° & θ_2=12° forward

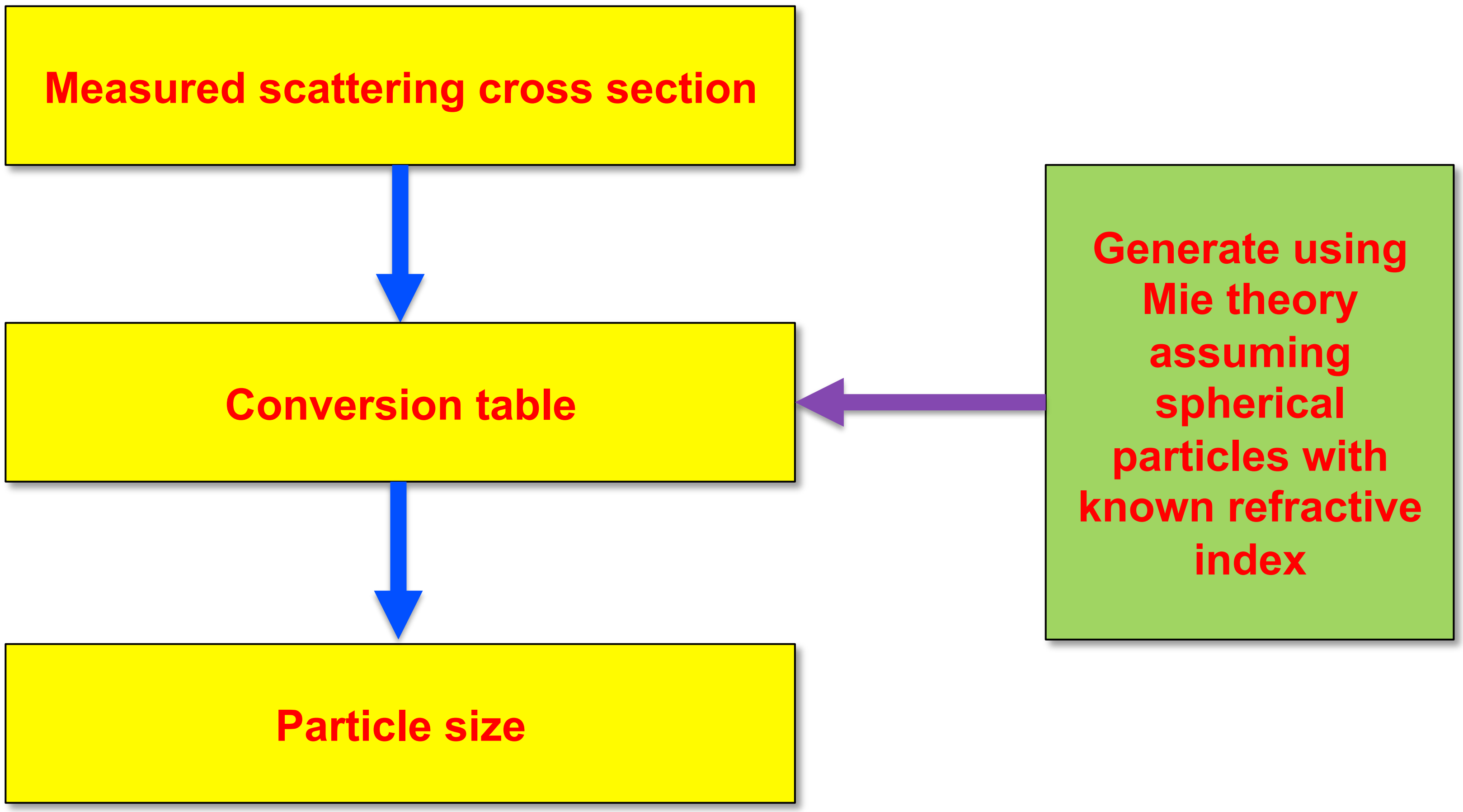
  θ_1=168° & θ_2=176° backward

- P_{11}: scattering phase function



Forward scattering probes

Operating principle



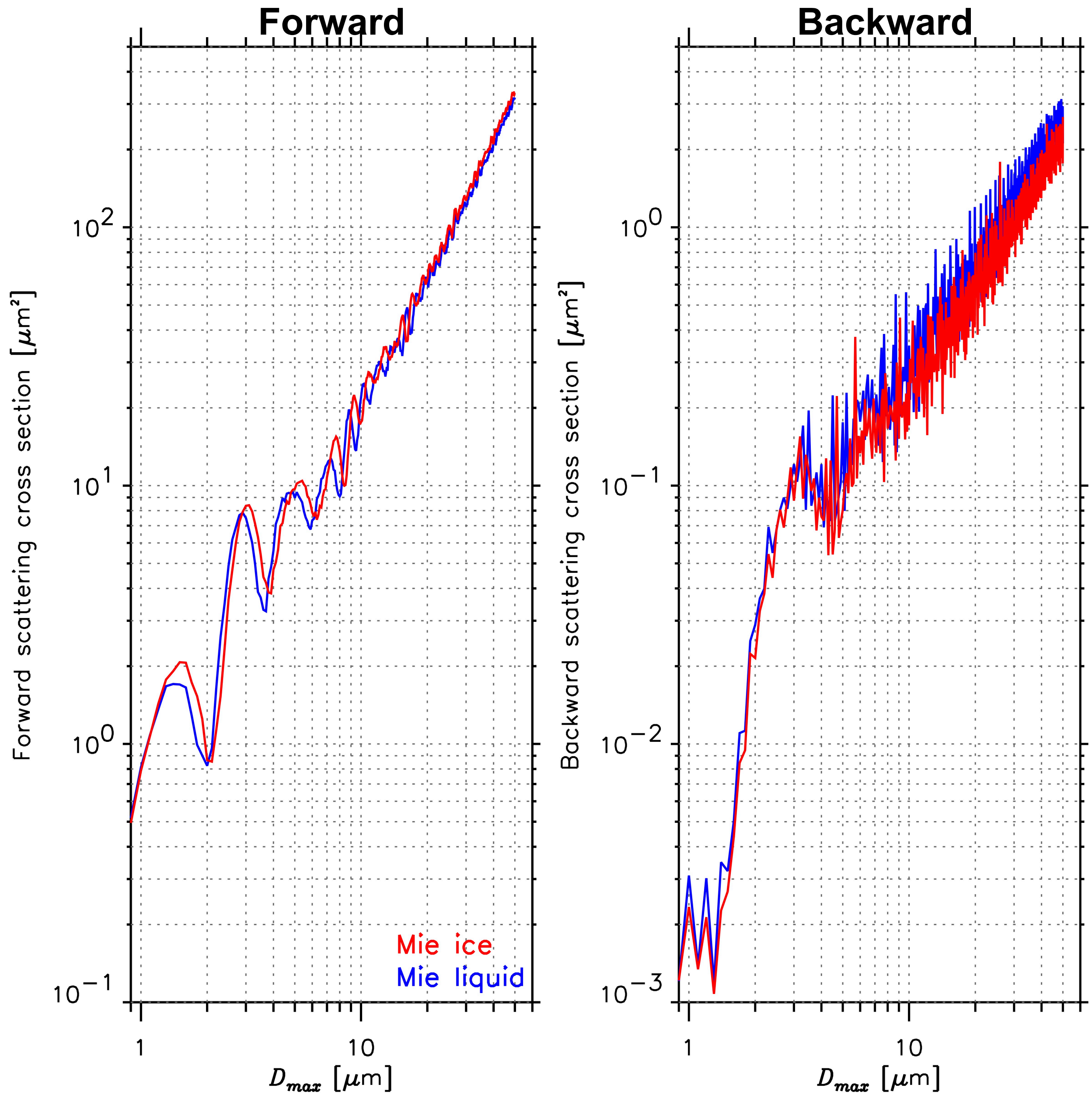
▪ Forward scattering probes

Convs. table

- spherical shape
- different refractive index

  ice (n_r=1.31) &

  liquid (n_r=1.33)



▪ Forward scattering probes

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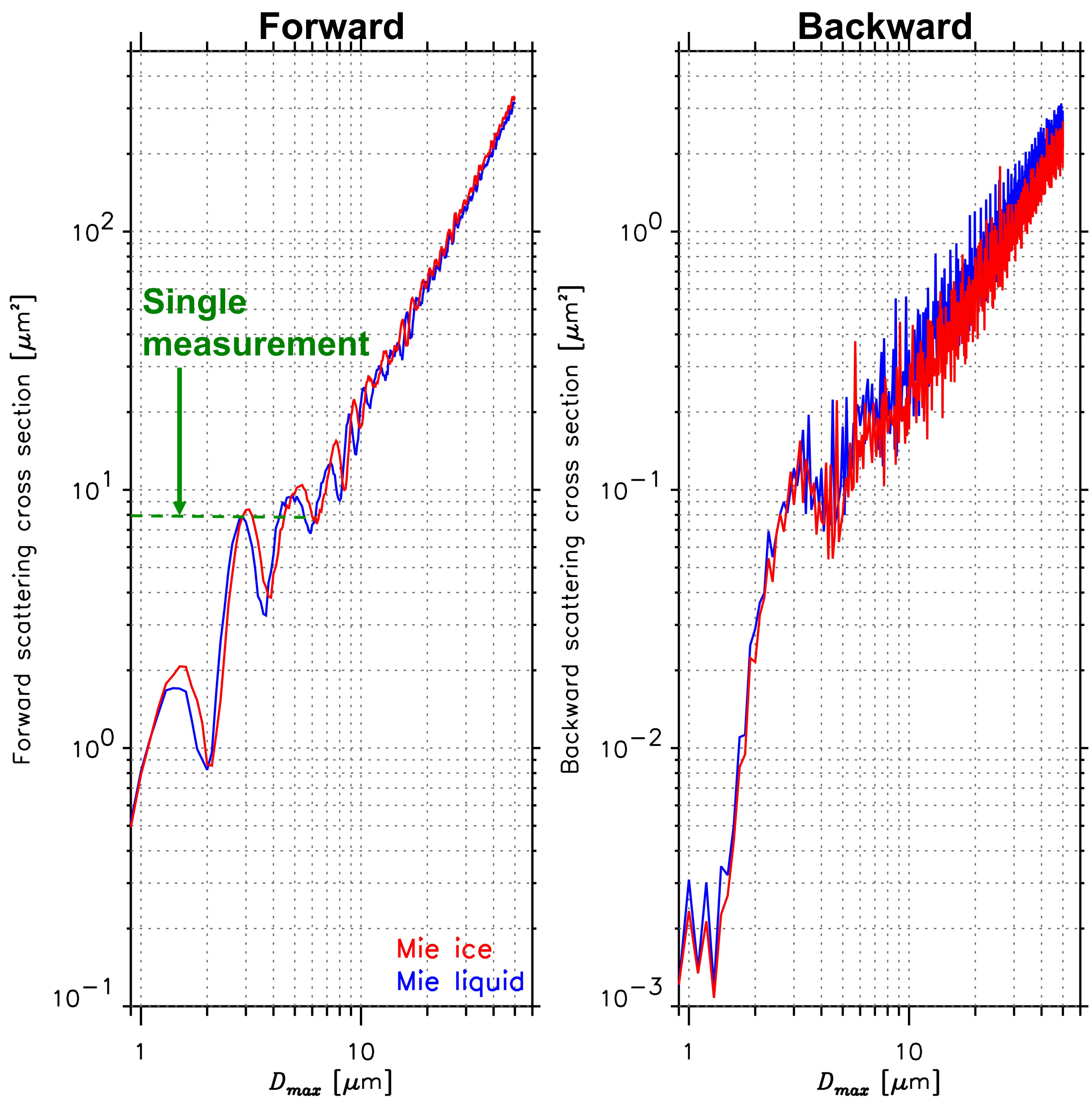


▪ Forward scattering probes

Convs. table

- spherical shape
- different refractive index

  ice (n_r=1.31) &

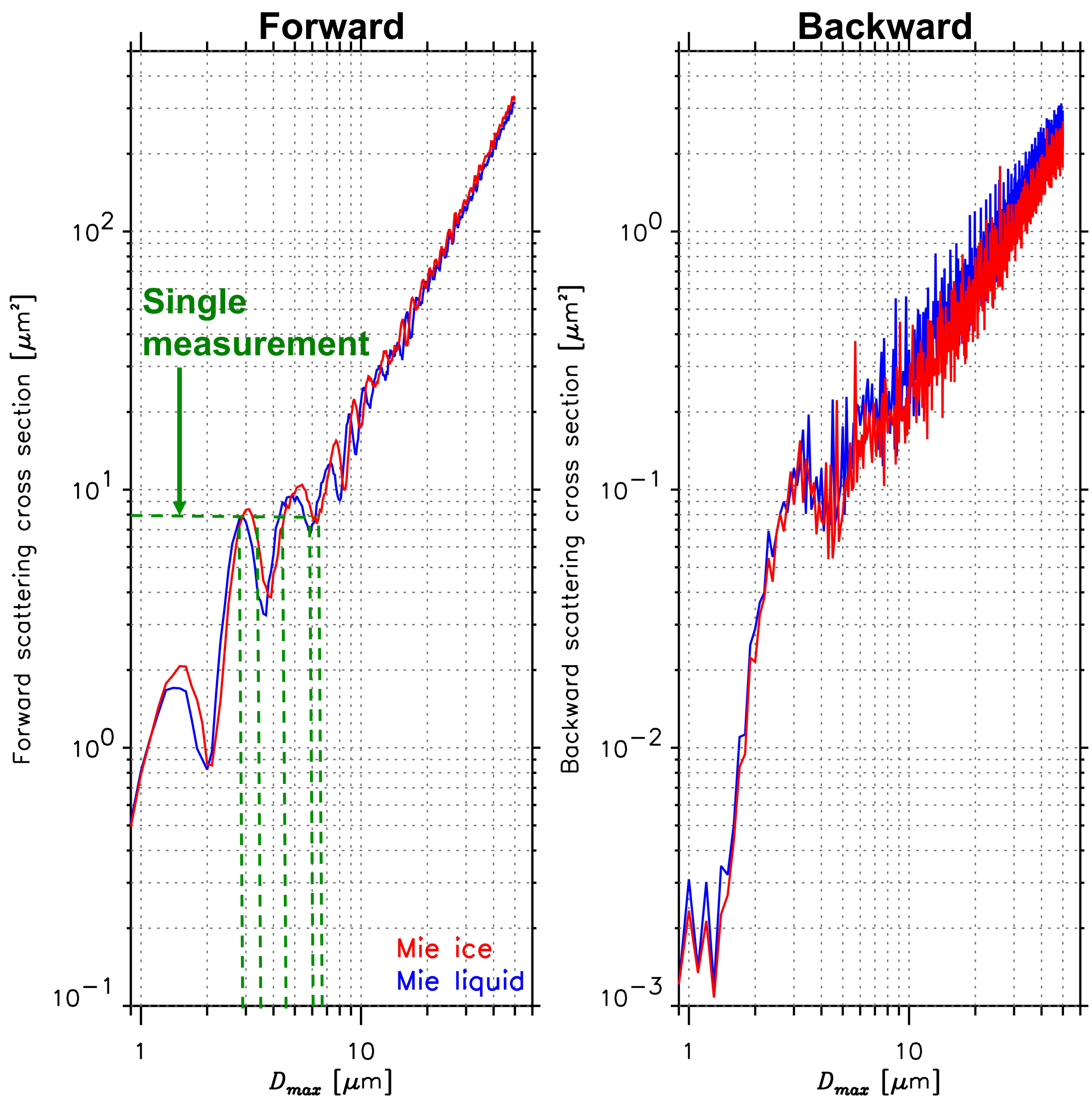
  liquid (n_r=1.33)

- multiple solutions

  (i.e., D_{max})

  scat. cros. sec.

  D_{max} < 10 μm



▪ Forward scattering probes

Convs. table

- spherical shape
- different refractive index

  ice (n_r=1.31) &

  liquid (n_r=1.33)

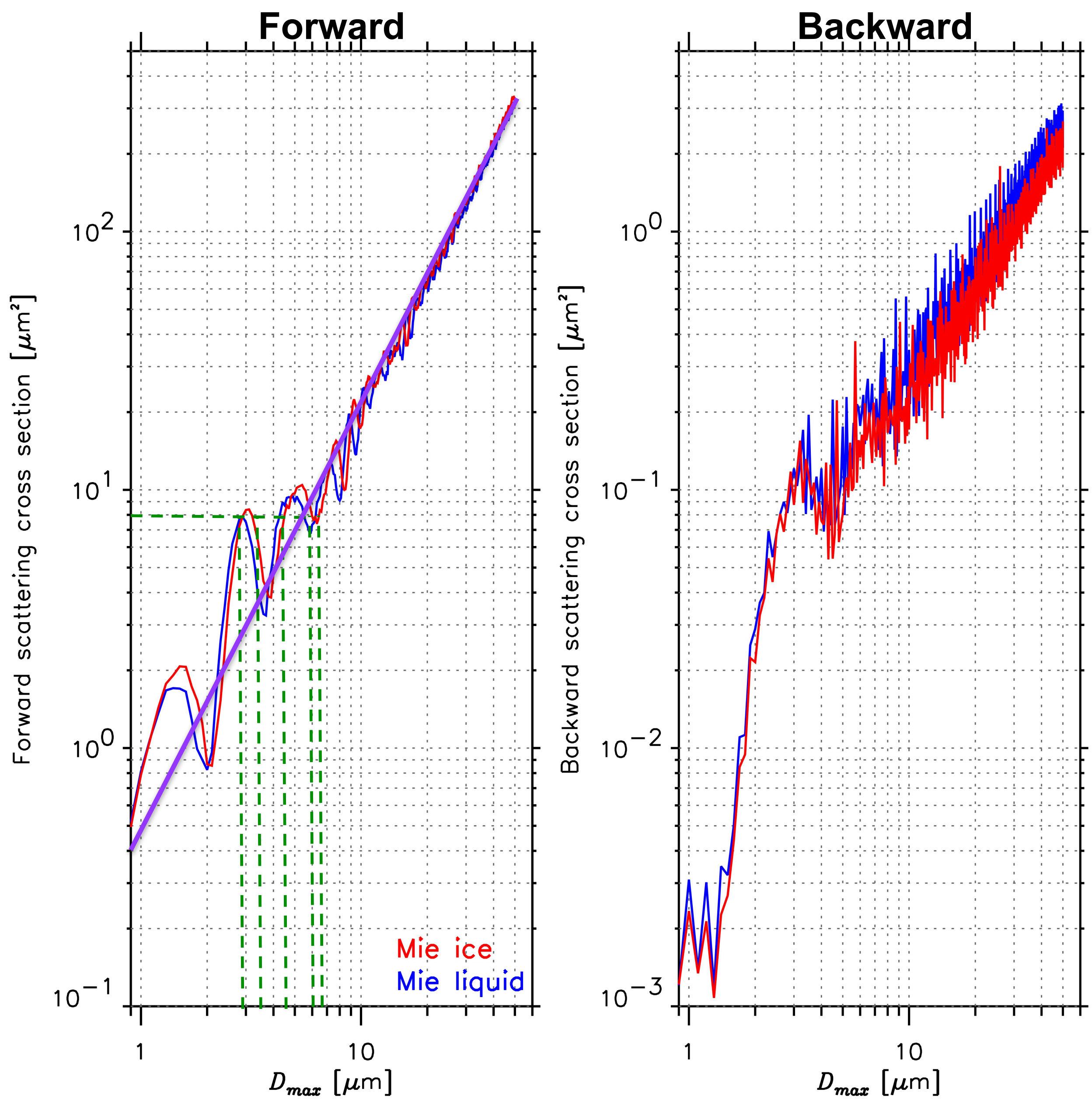
- multiple solutions

  (i.e., D_{max})

  scat. cros. sec.

  D_{max} < 10 μm

- linear fitting,
- avg. over solutions



▪ Forward scattering probes

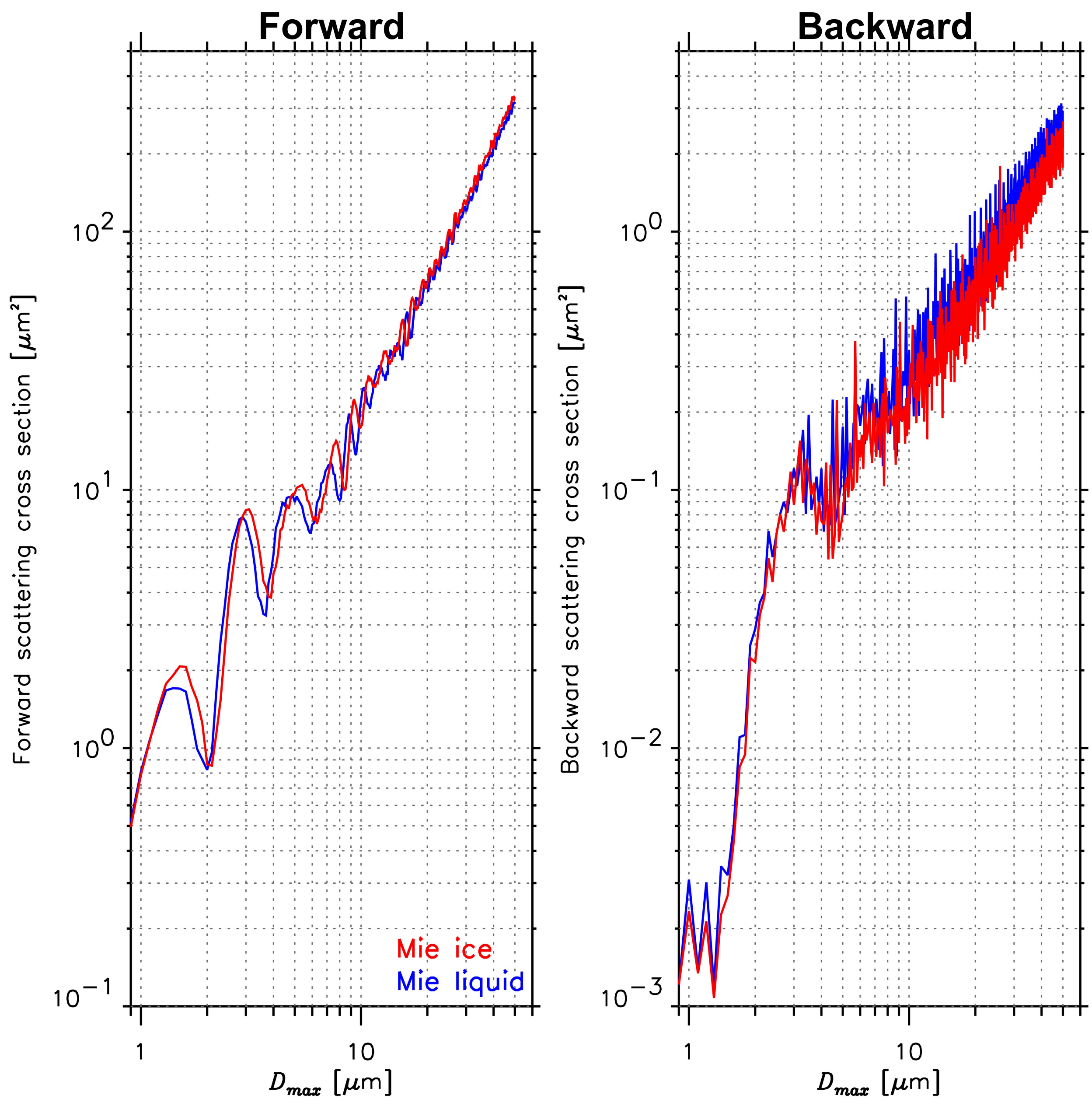
Convs. table

- Errors due to Mie scat.
  even for spherical shape
- $>\pm$20% (D_{max}<10 μm)
- < 10% (10< D_{max}<30 μm)
- < 15% (D_{max}>30 μm)

using "best fitting curve"

This is known errors due to Mie scattering of "spherical" particles.

What about ice crystals? "Non-spherical!"



III. Key Challenge

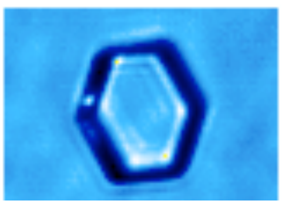
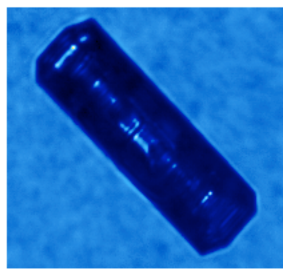
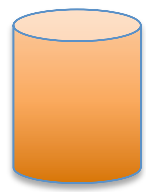
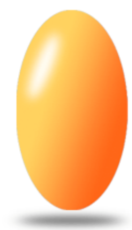
- **Nonspherical ice crystals**

- ice crystals can be spherical shape (fresh, homogeneous freezing),

most cases nonspherical shapes

- hexagonal shapes are fundamental (hexagonal lattice structure)

- 60% hexagonal shapes (AIDA chamber experiment, Schnaiter et al. 2012)

- Few studies (Borrmann et al. 2000; Meyer 2012) have tested uncertainty in forward scattering probes due to nonsphericity of ice crystals,

Show < 20% errors

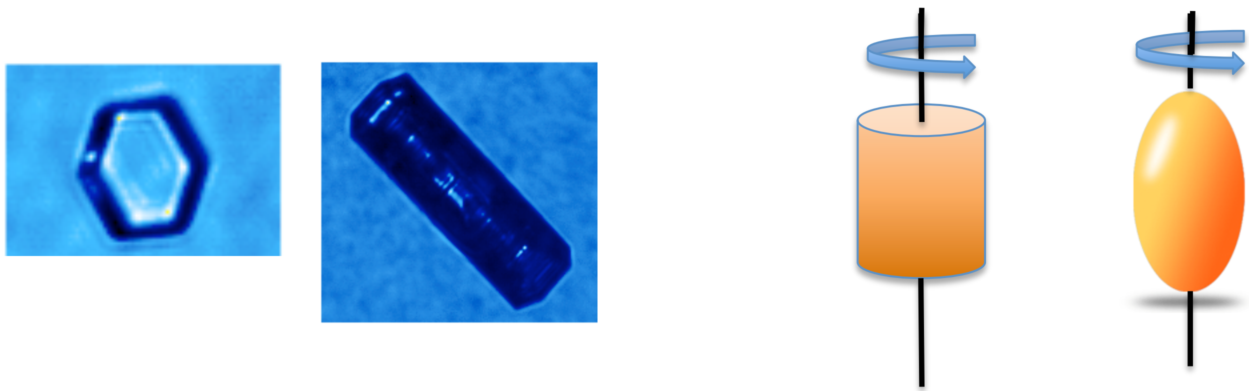
based on *T*-matrix calculations using cylinder or spheroid!

III. Key Challenge

- **Nonspherical ice crystals**

  - this is due to demanding computing computing power to obtain exact solutions of nonspherical particles based on Maxwell's equations

  - Less expensive *T*-matrix limited to axially symmetric particles



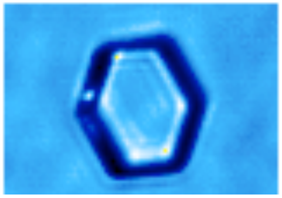
  - Discrete dipole approximation (DDA), exact solution for any shape

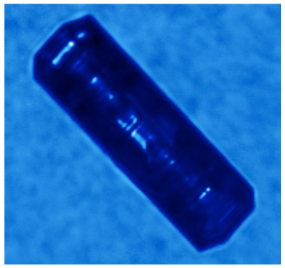
  - computing time & memory increase with particle size

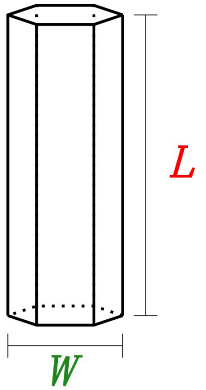
  - large computing resources needed (i.e., Blue Waters)

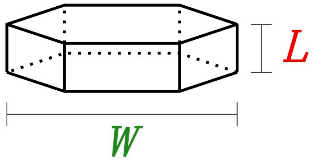
DDA cal.

Aspect Ratio (*AR*) = *L* / *W*
AR = 0.10, 0.25, 0.50, 1.00, 2.00, 4.00


Thin Plate


Long Column



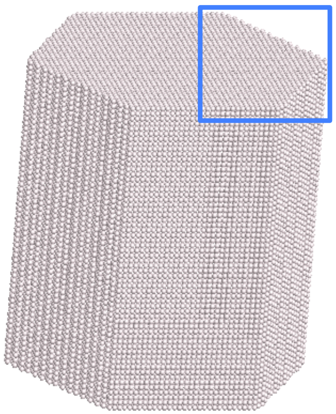


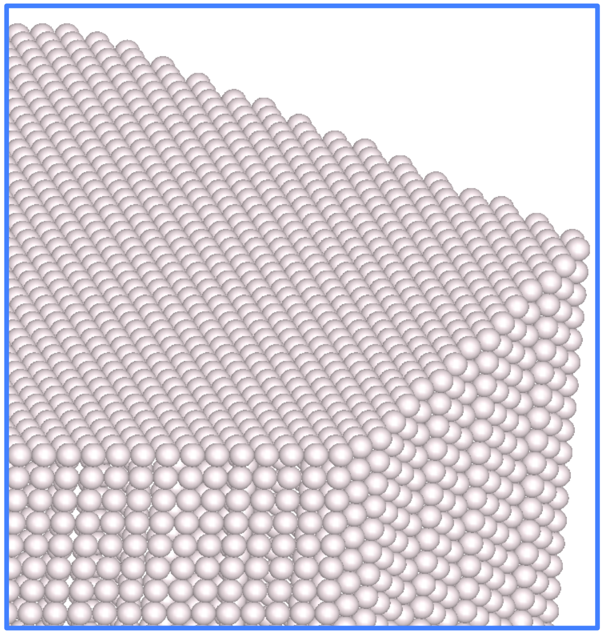
width, *W* : up to 20 μm
length *L*: up to 48 μm

- Amsterdam Discrete Dipole Approximation (ADDA)
- Um and McFarquhar (2015, JQSRT)
- Um et al. (2015, ACP)

- Scattering phase matrix
- Forward & backward scattering cross section of CAS

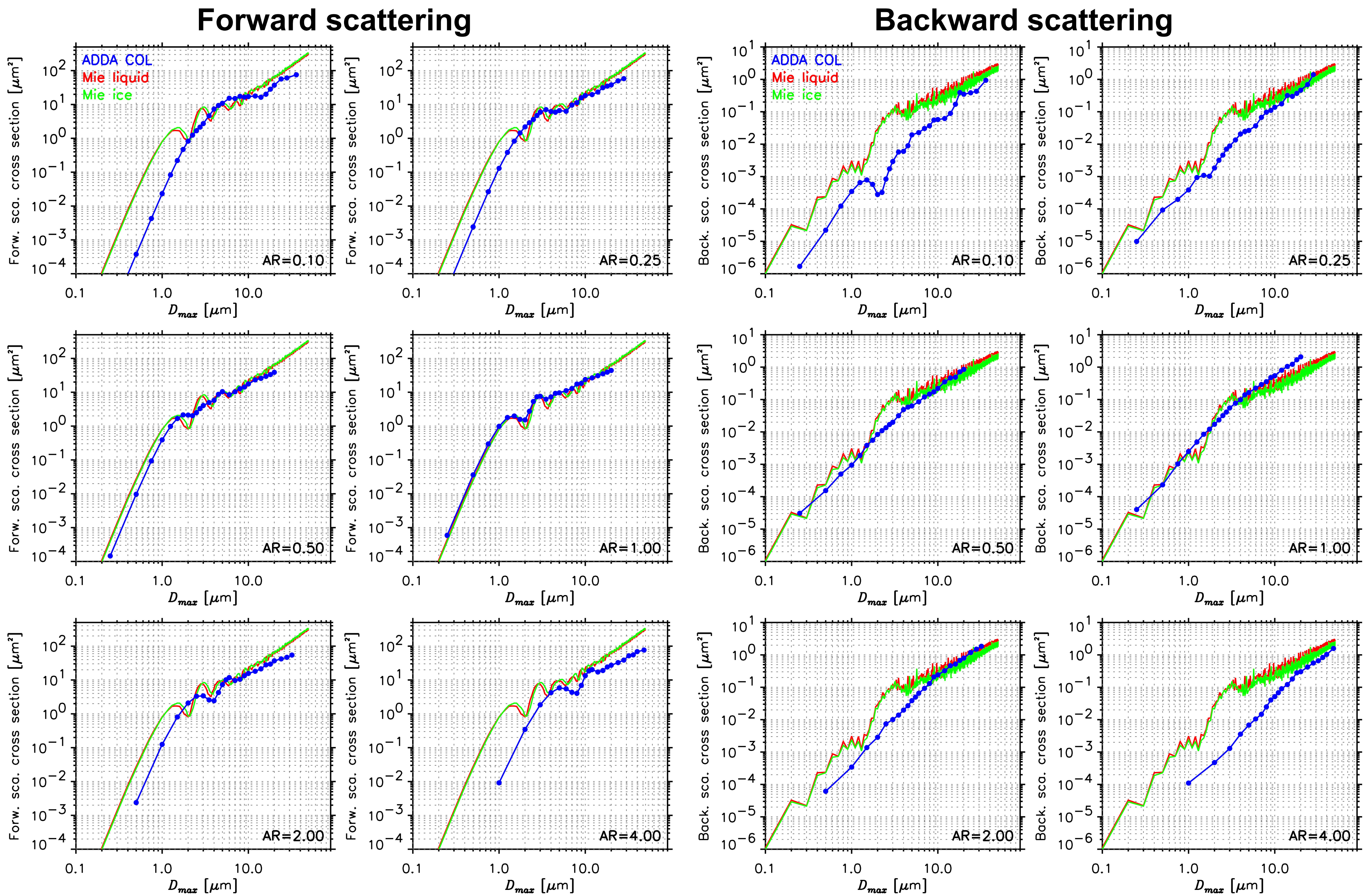
- Assign each or group of dipoles to cores of BW



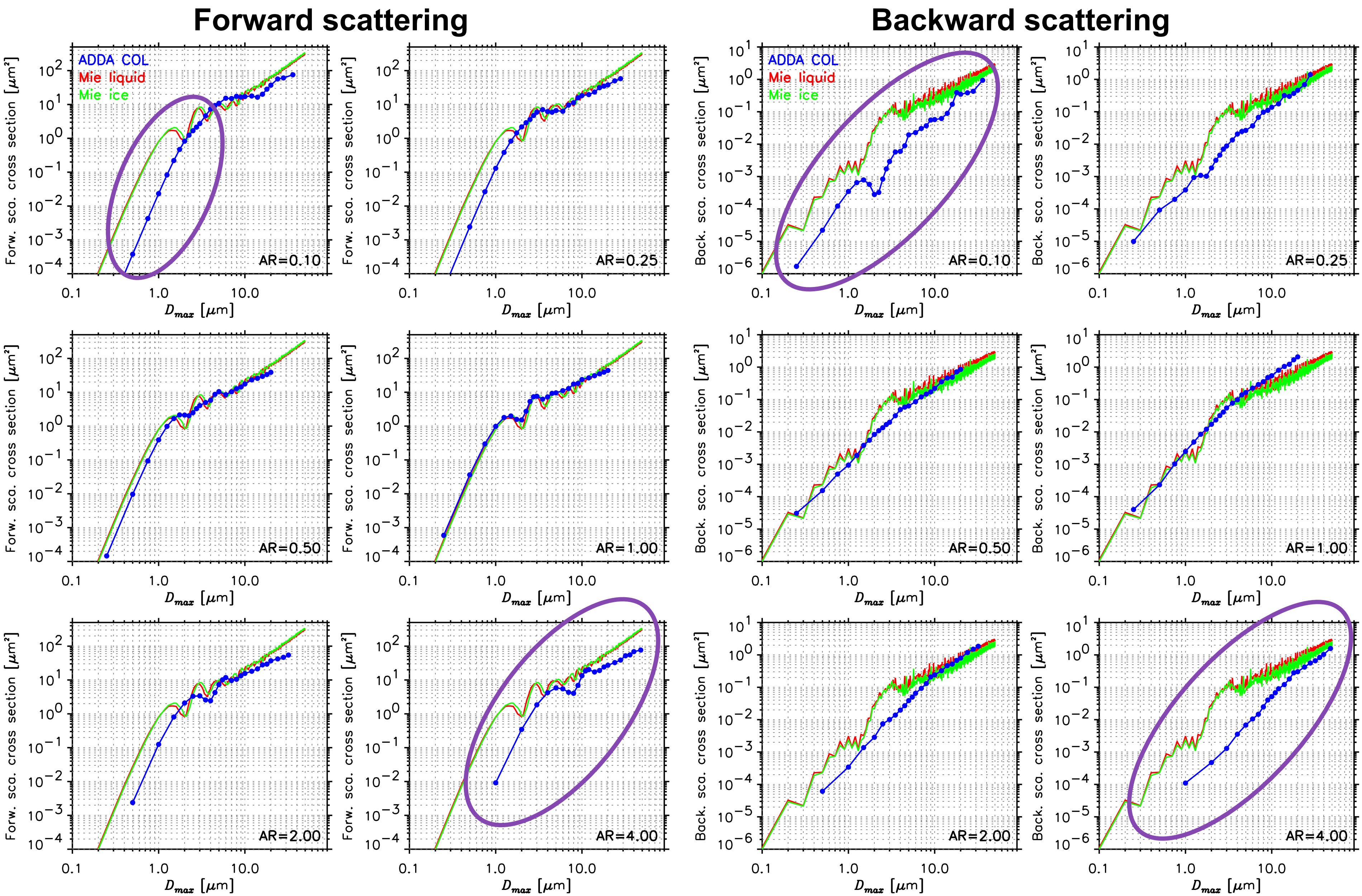


IV. Accomplishments

New conversion tables

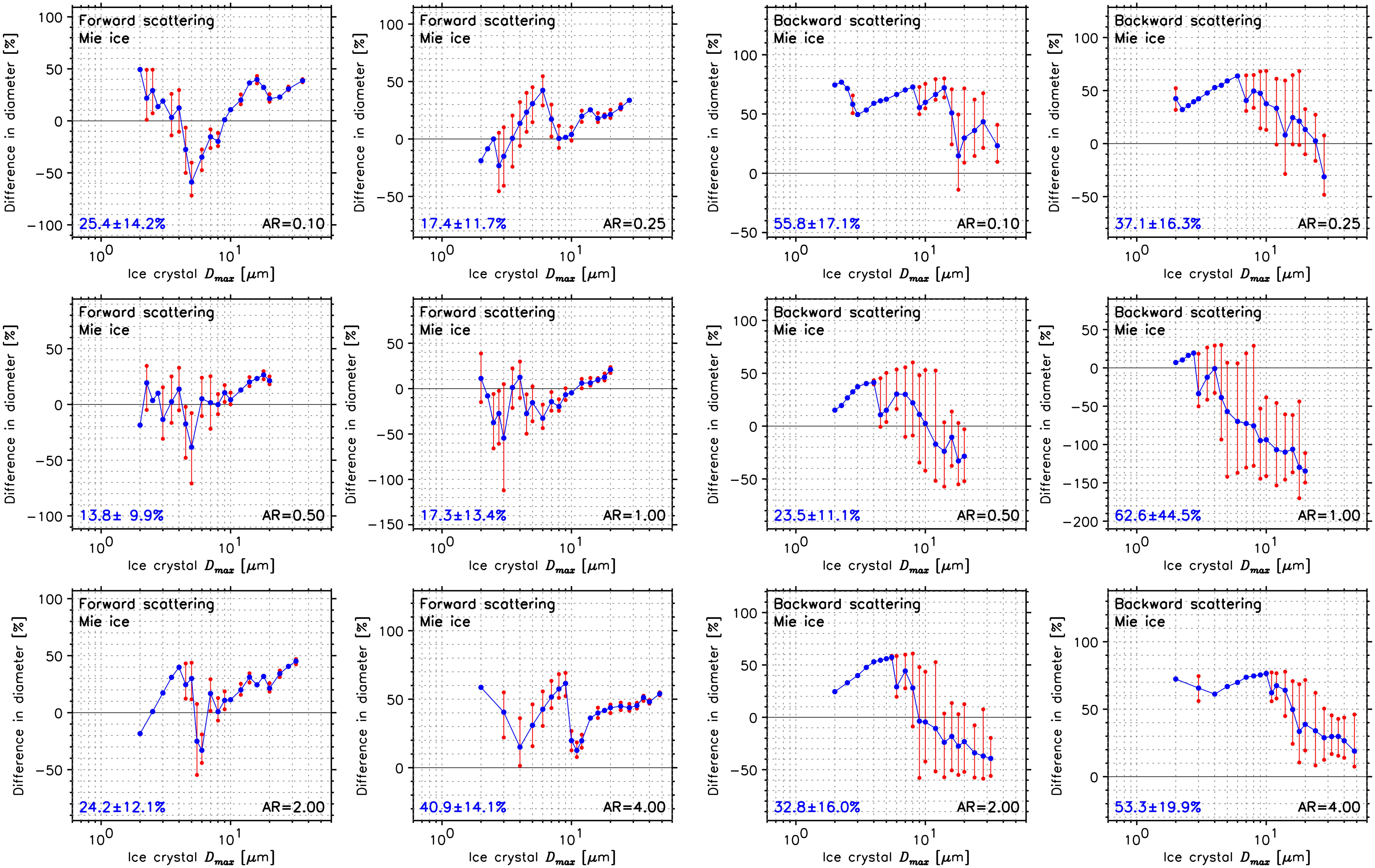


- Nonspherical crystal, Mie sph. liquid, Mie sph. ice, different *AR* for each panel



- **Nonspherical crystal**, **Mie liquid**, **Mie ice**, **different *AR* for each panel**
- **Errors increase with nonsphericity (i.e., either oblate or prolate shape)**

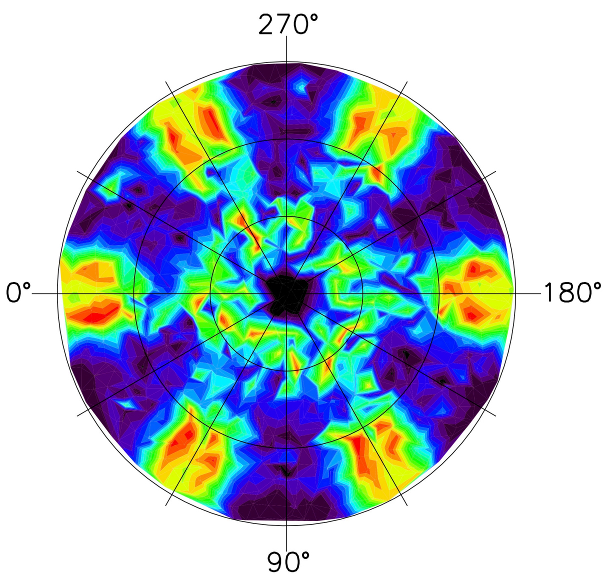
Forward scattering   Backward scattering



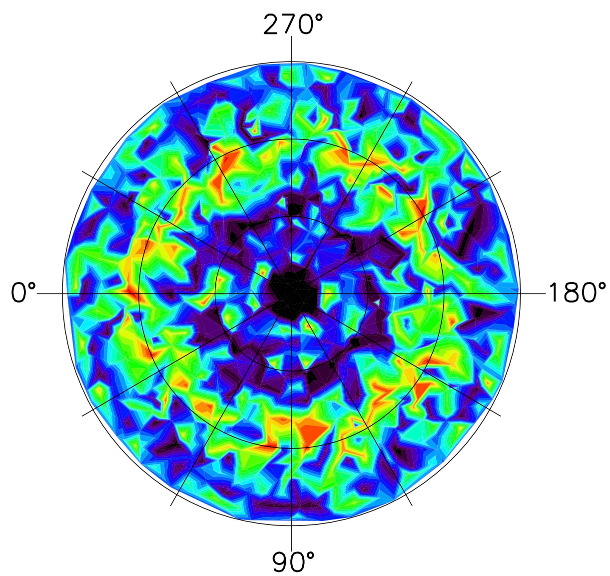
- **Difference in diameter b/n Mie ice and nonspherical crystals, mean+-stddev**
- **Average errors, up to 41% (63%) in forward (backward) scattering direction**

Summary & Future Work

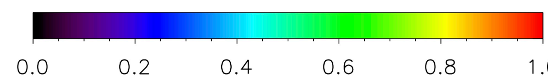
- **Errors in forward scattering probes due to nonspherical ice crystals are larger than those due to Mie scattering of spherical particles**
- **Up to 41% (63%) in forward (backward) scattering direction, increase with nonsphericity (i.e., departure from compact shape)**
- **Building new conversion tables (+ orientation & polarization) using BW**



Hexagonal column



Ellipsoid



Linear depolarization ratio

***AR*=4.0**
***L*=10 μm**
***W*=2.5 μm**