Impacts of orientation and morphology of small atmospheric ice crystals on in-situ aircraft measurements: scattering calculations

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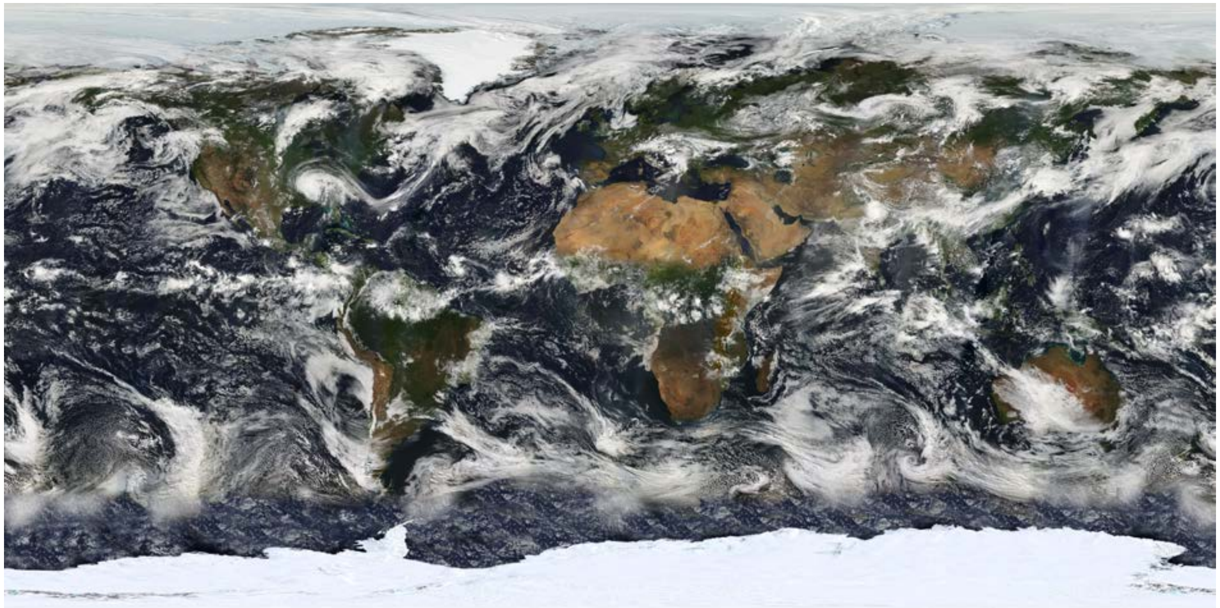
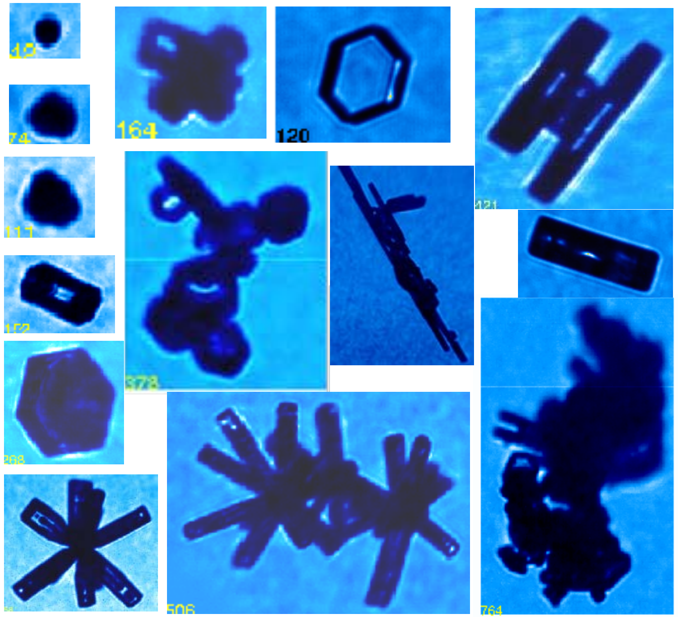
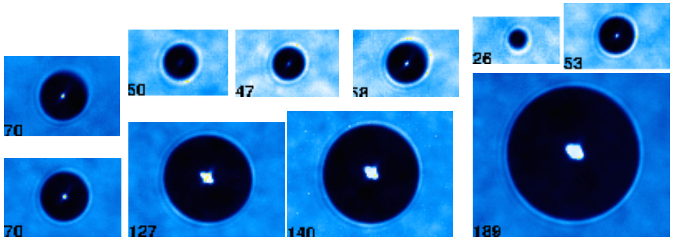
I. Introduction

Images from NASA



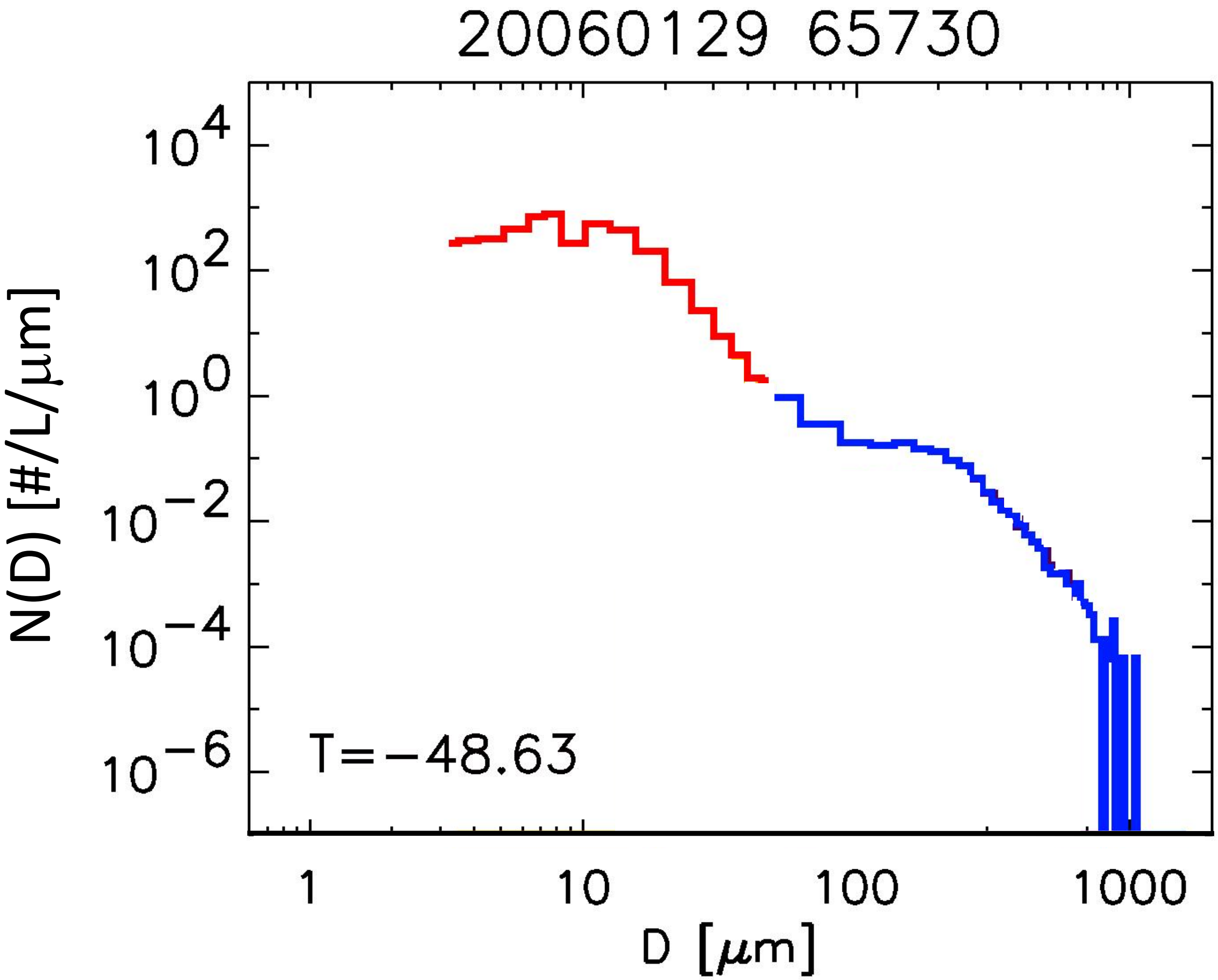
- Sun, energy source
- Sun – cloud interaction
  - reflection
  - absorption
  - transmission
- Cloud properties vary
  - space & time
- For climate system
  - knowledge of cloud radiative properties





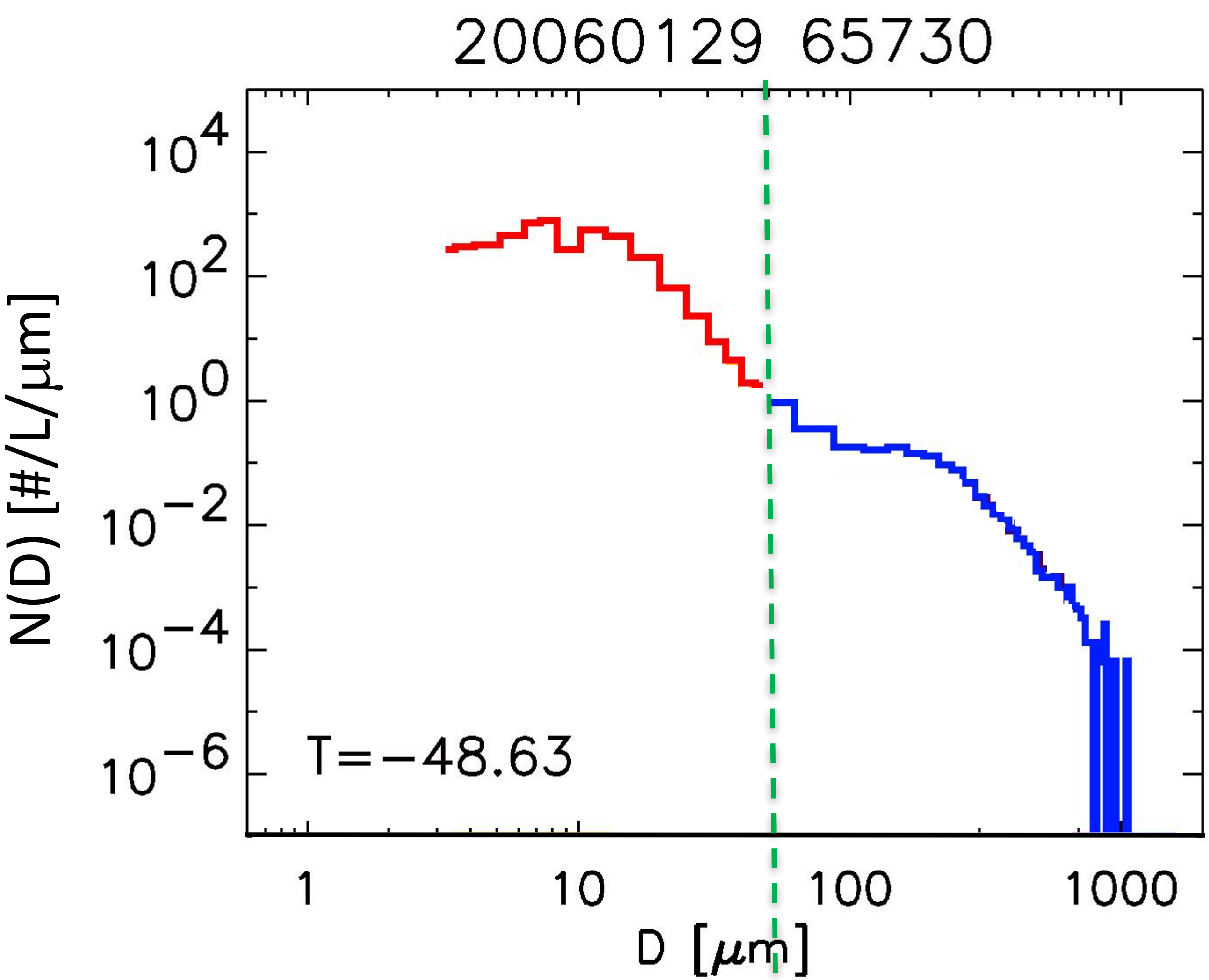
- Cloud radiative properties depend on particle shape & size
- Low warm clouds, liquid particles spherical
- High cold clouds, ice particles non-spherical
- Mixed clouds, ice & water coexist

II. Background



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

Fundamental input for numerical models & retrieval algorithms!



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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 (e.g., 4-12º and/or 168-176º) 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

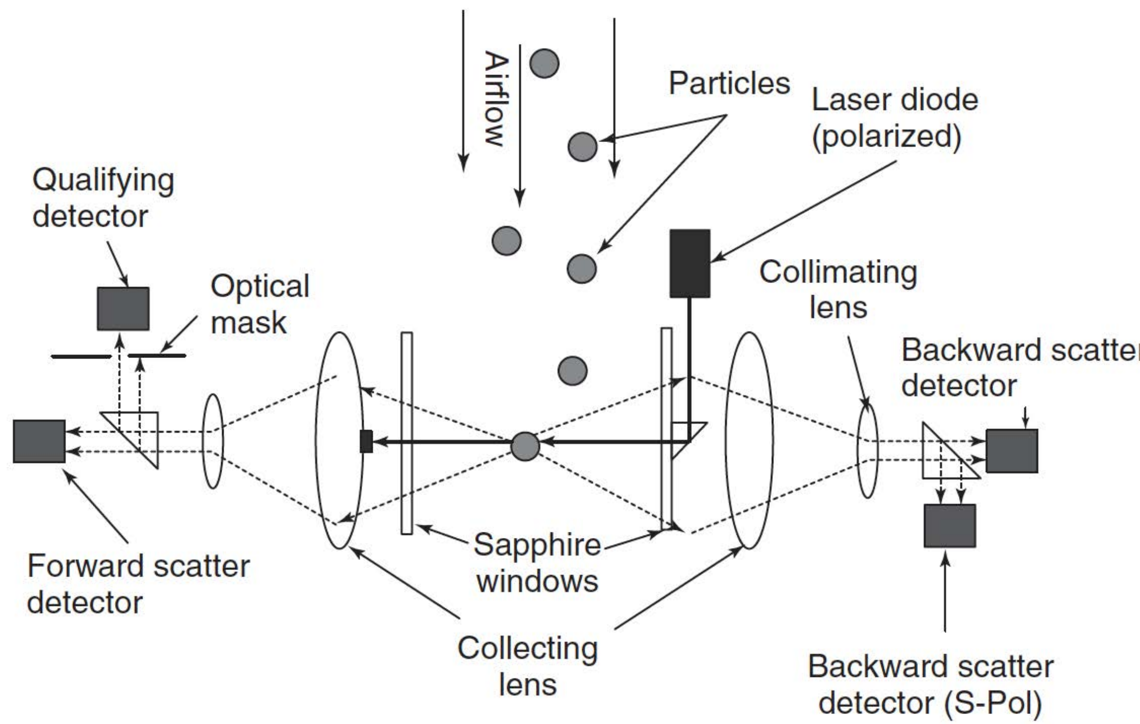
FSSP, CDP, CAS,

CAS-DPOL,

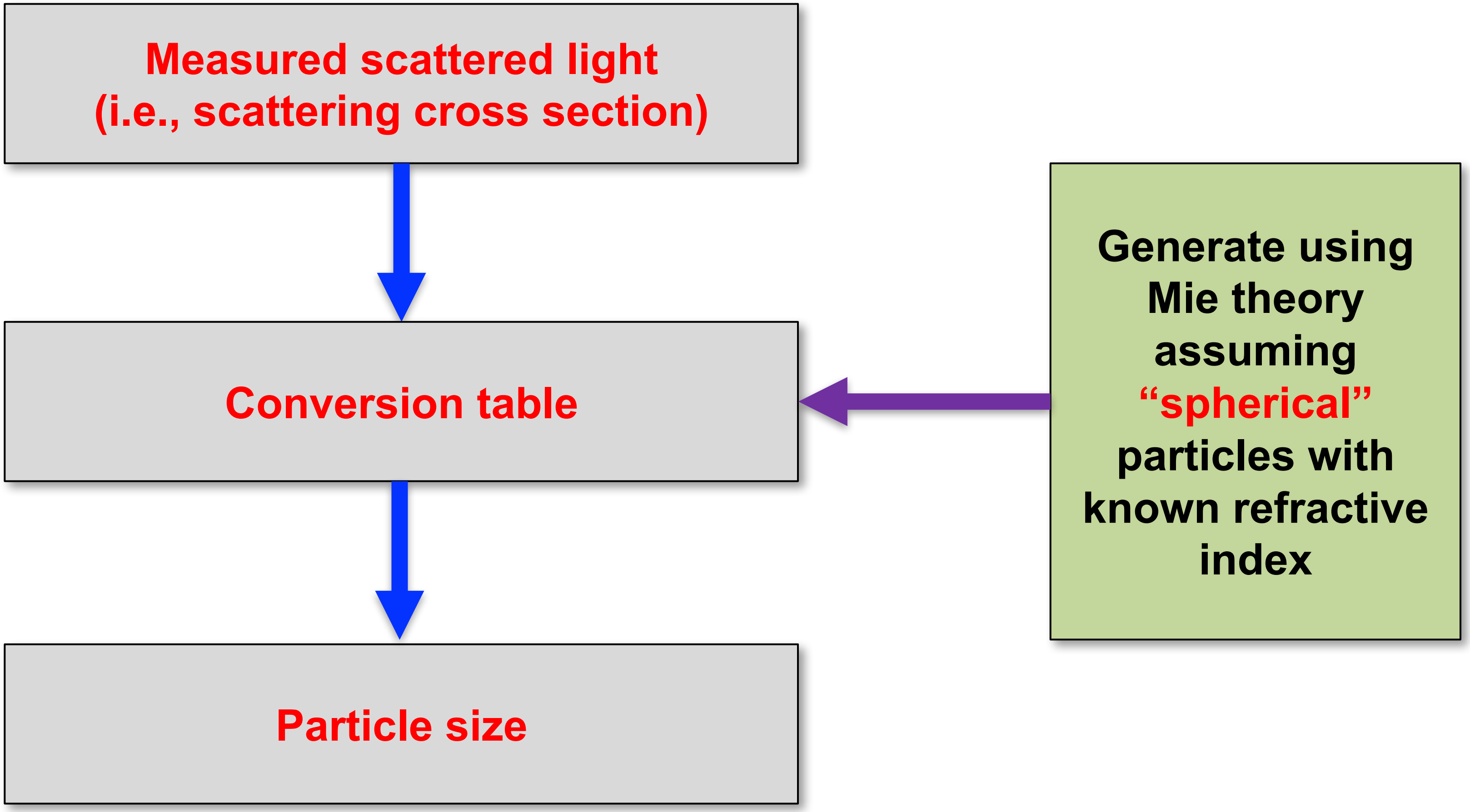
CPSPD,

Fast FSSP (FFSSP),

Fast CDP (FCDP)



▪ Forward scattering probes

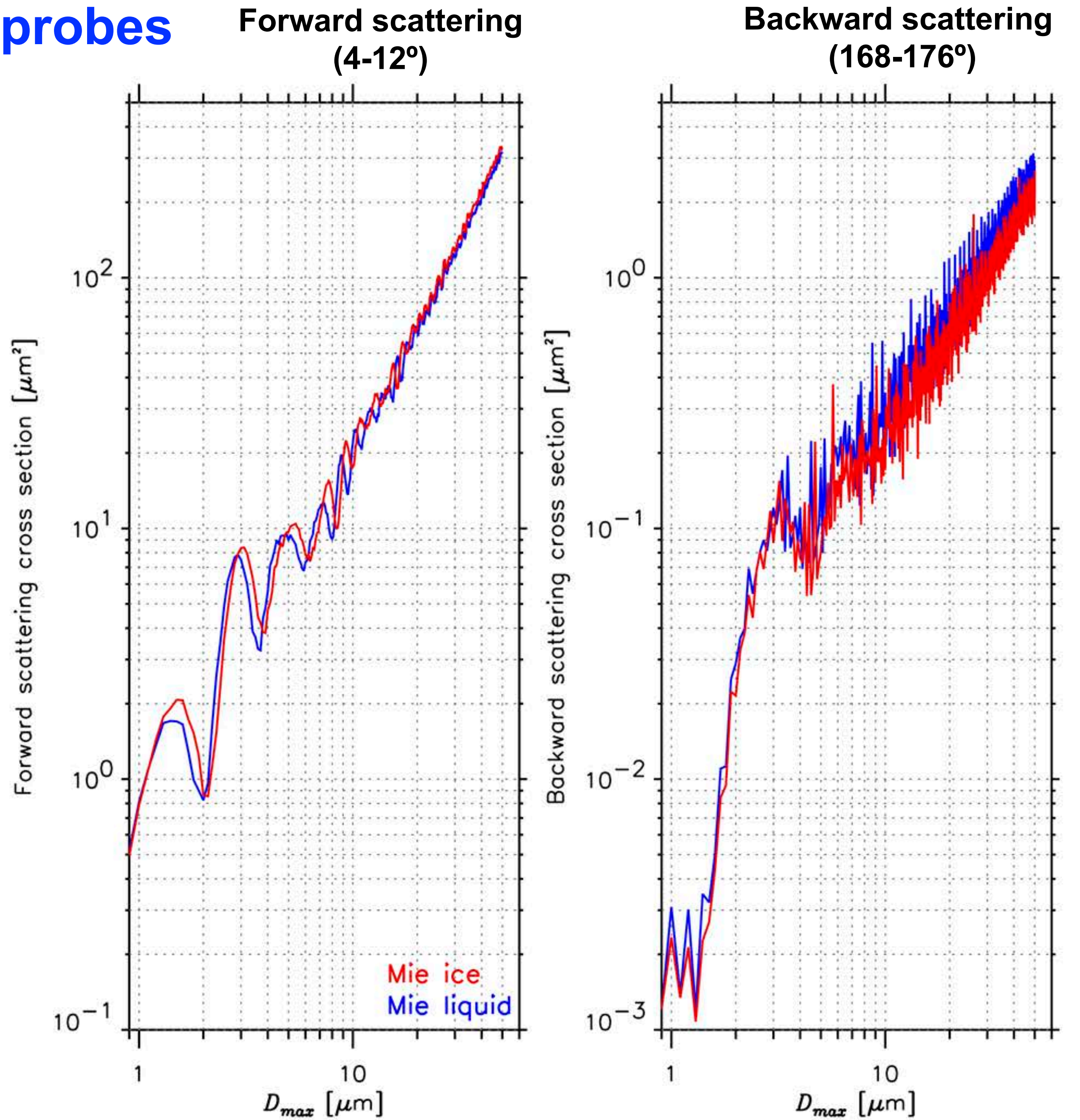


▪ Forward scattering probes

- Spherical shape
- Different refractive index

  ice (n_r=1.31) &

  liquid (n_r=1.33)



▪ Forward scattering probes

- Spherical shape
- Different refractive index

  ice (n_r=1.31) &

  liquid (n_r=1.33)

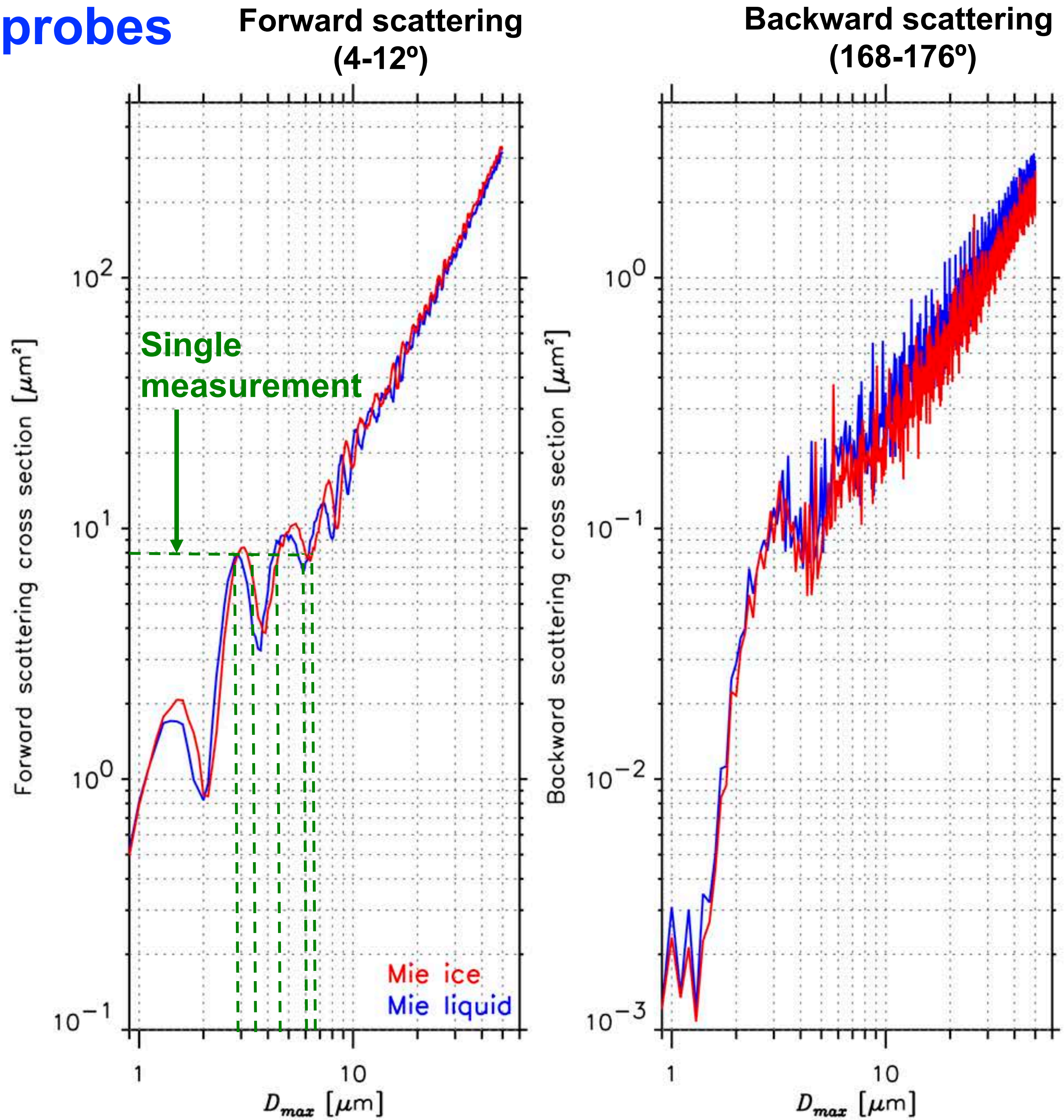
- Multiple solutions

  (i.e., D_{max})

  for scat. cros. sec.

This is known problem (<50%) due to spherical shape.

Nonspherical shape?



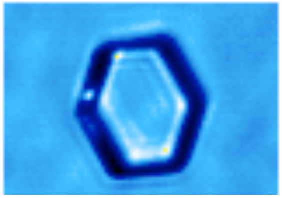
III. Key Challenge

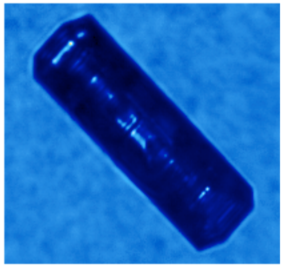
- **Nonspherical ice crystals**

- 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)





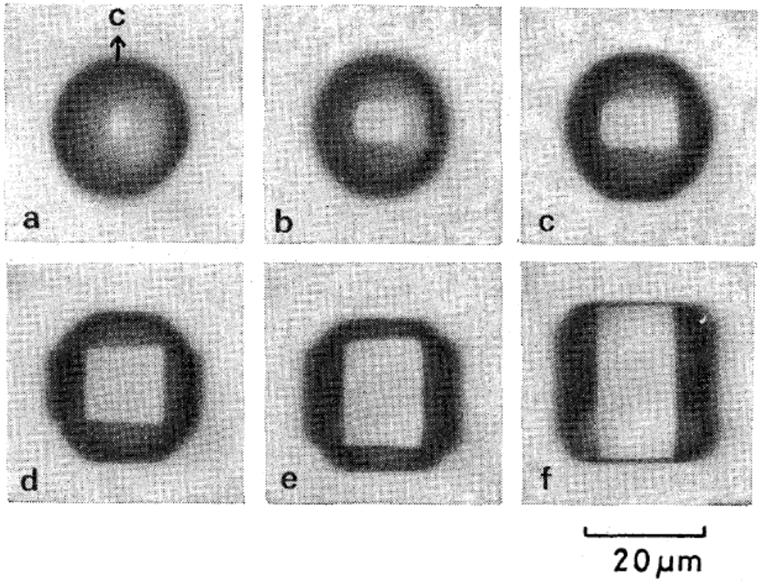


Fig. 1 An example of ice crystals grown from frozen cloud droplets at −15°C and a supersaturation of 1–2%. (a) 2.0, (b) 2.2, (c) 2.7, (d) 3.2, (e) 4.0, (f) 4.7 min.

- **Spherical frozen droplet becomes hexagonal column crystal**
- **Aspect ratio (*L/W*) depends on *T***
- **Gonda and Yamazaki (1984)**

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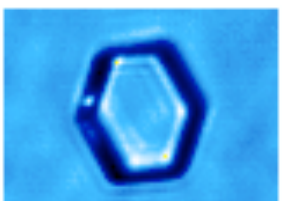
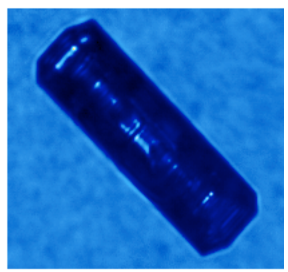
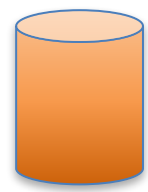
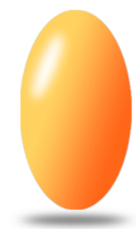






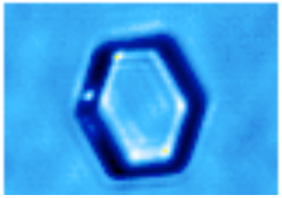


- Few studies (Borrmann et al. 2000; Meyer 2012) have tested uncertainty in forward scattering probes due to nonsphericity of ice crystals, show < 20% error based on *T*-matrix calculations using cylinder or spheroid!

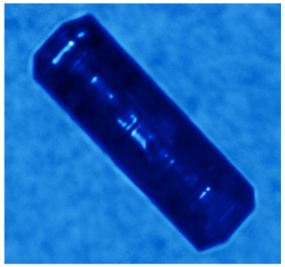
DDA cal.

- **Impact of nonsphericity have to be quantified with realistic shape!**

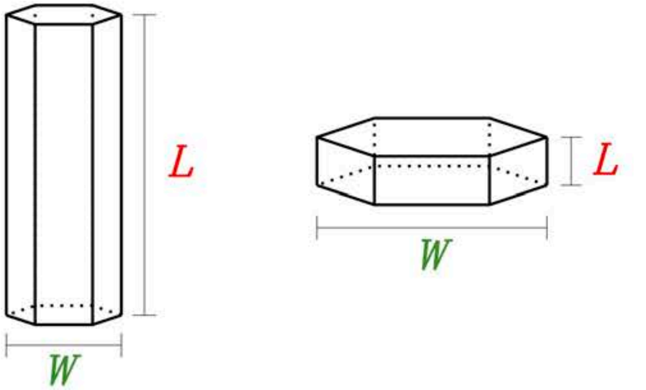
Aspect Ratio (*AR*) = *L* / *W*
***AR* = 0.10, 0.25, 0.50, 1.00, 2.00, 4.00**



Thin Plate



Long Column

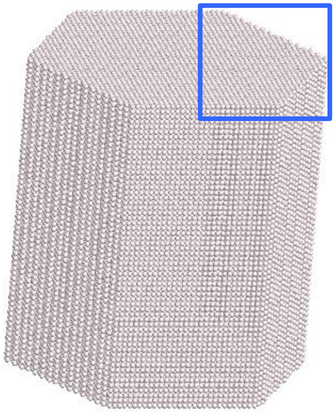


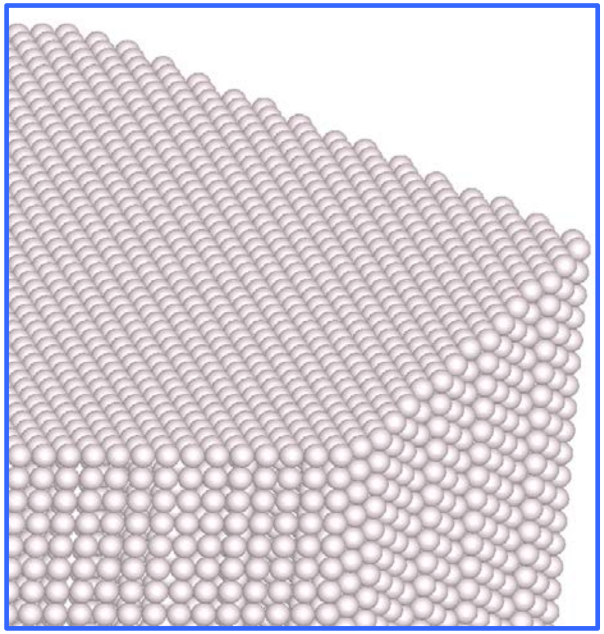
width, *W* : up to 20 μm
length *L*: up to 48 μm

- 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**



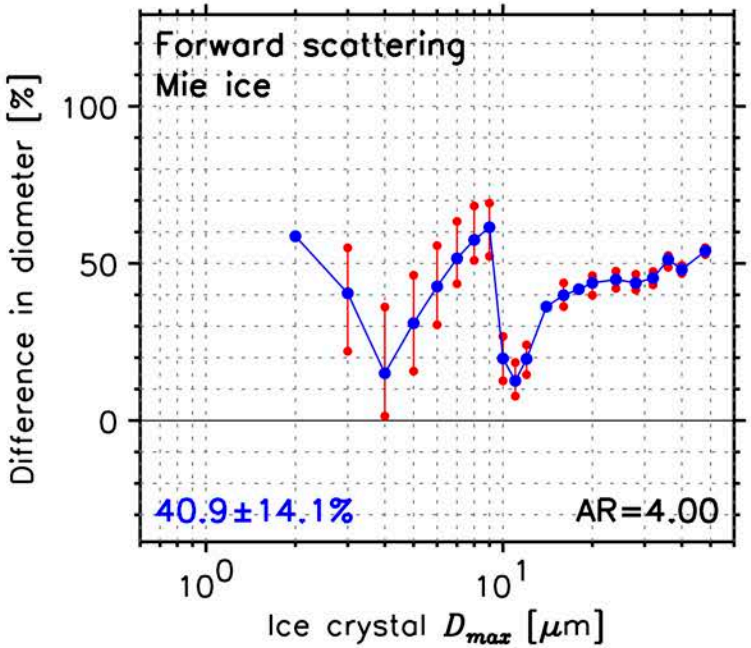


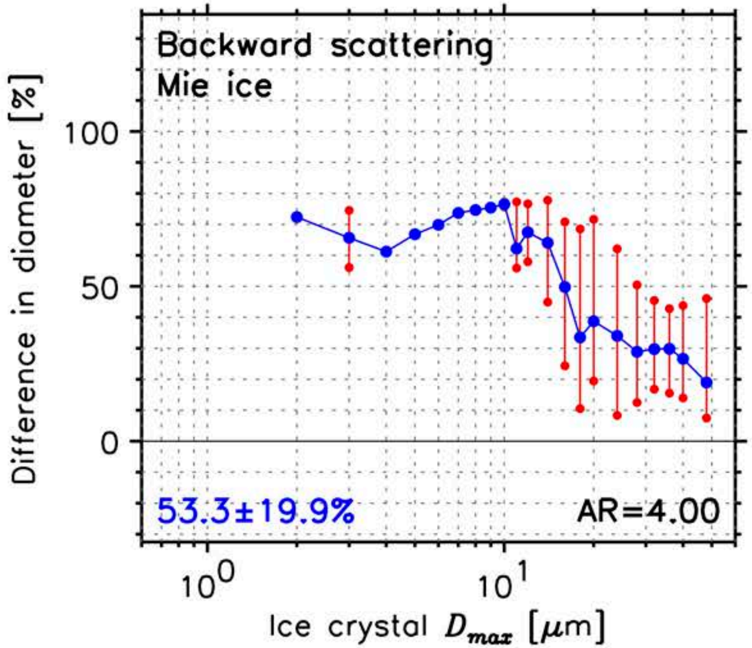
IV. Accomplishments

New conversion tables
Impact of orientation

Forward scattering (4-12º)

Backward scattering (168-176º)

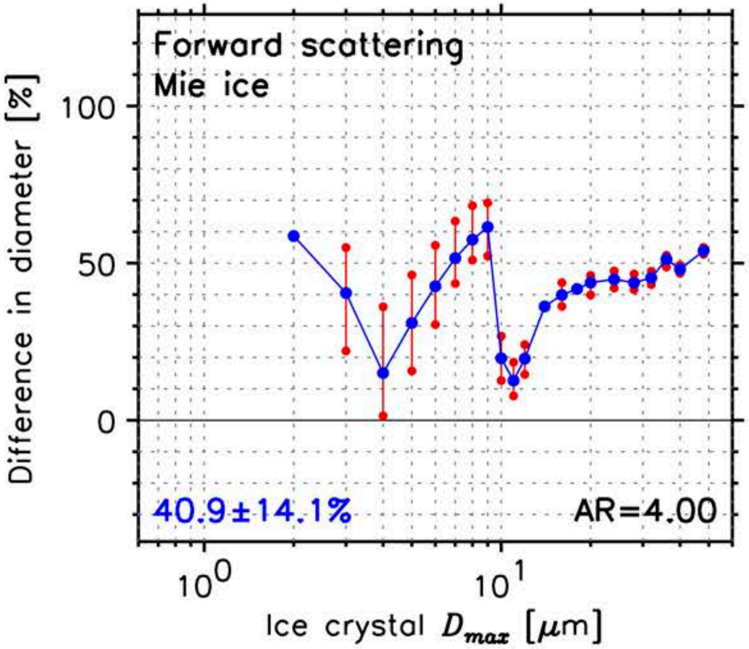




Baumgardner et al. (2017)

- **Difference in diameter b/n Mie ice and nonspherical crystals, mean+-stddev**
- **Up to 72% (170%) in forward (backward) scattering direction**
- **Increase with nonsphericity (i.e., departure from compact shape)**
- **Larger than those (<20%) with spheroid or cylinder**

Forward scattering (4-12º)



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- **Impact of particle orientation**
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- **Measurement < 1.0 μsec**
- **Certain orientation!**

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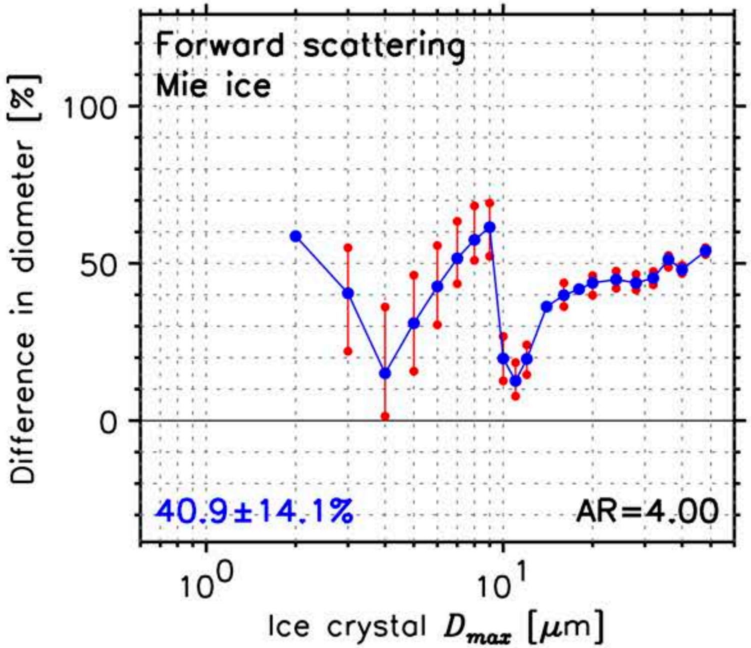

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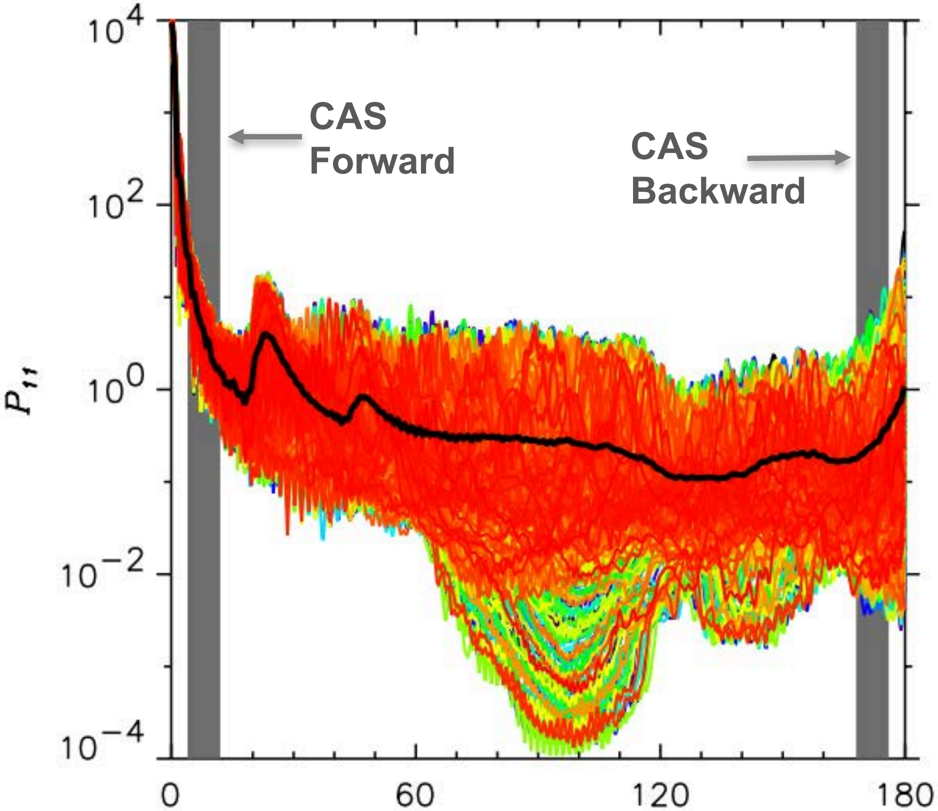
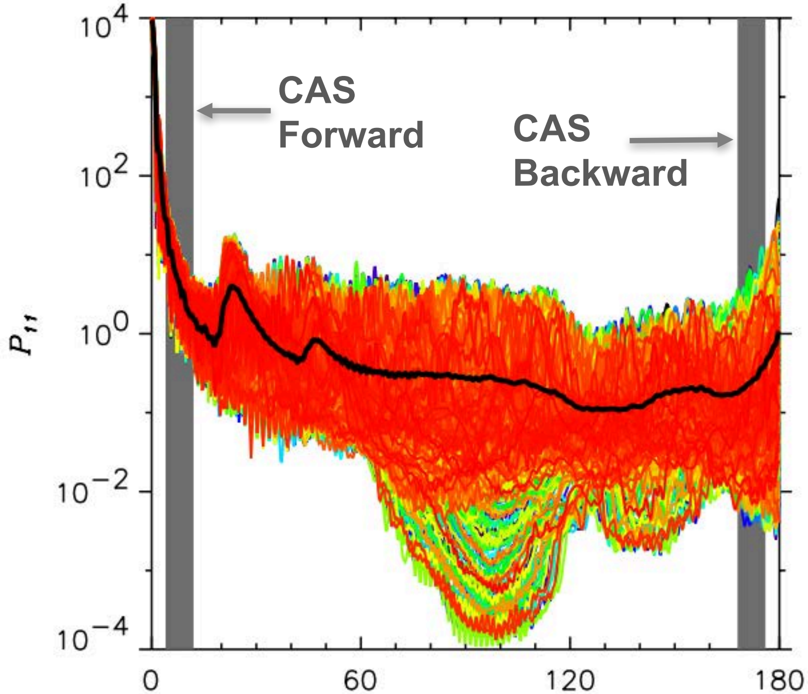
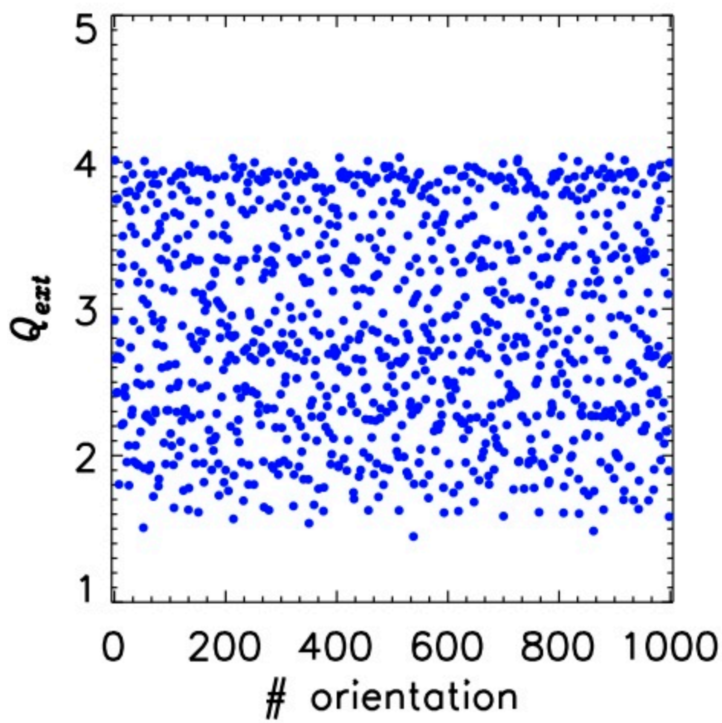
- **Certain orientation!**
- **Large variations in P_{11}**







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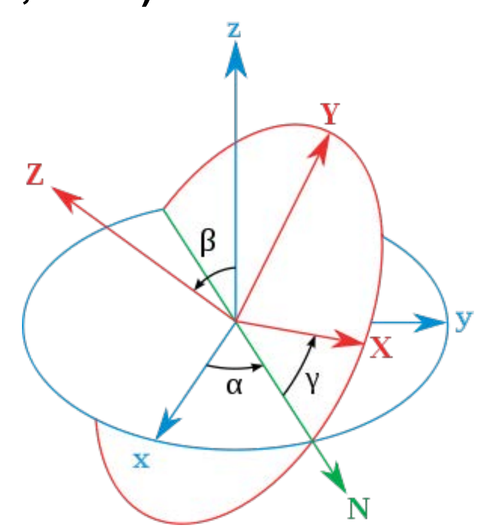
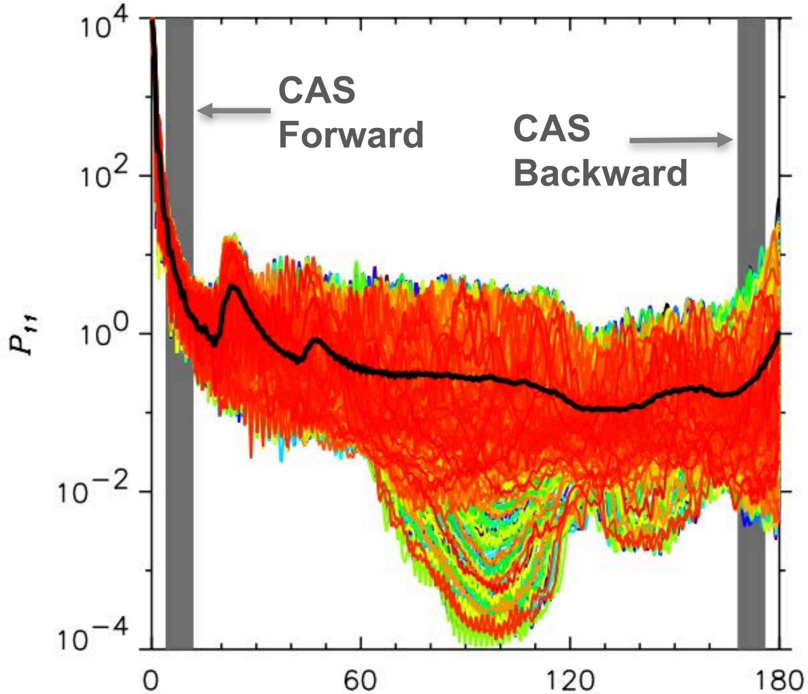
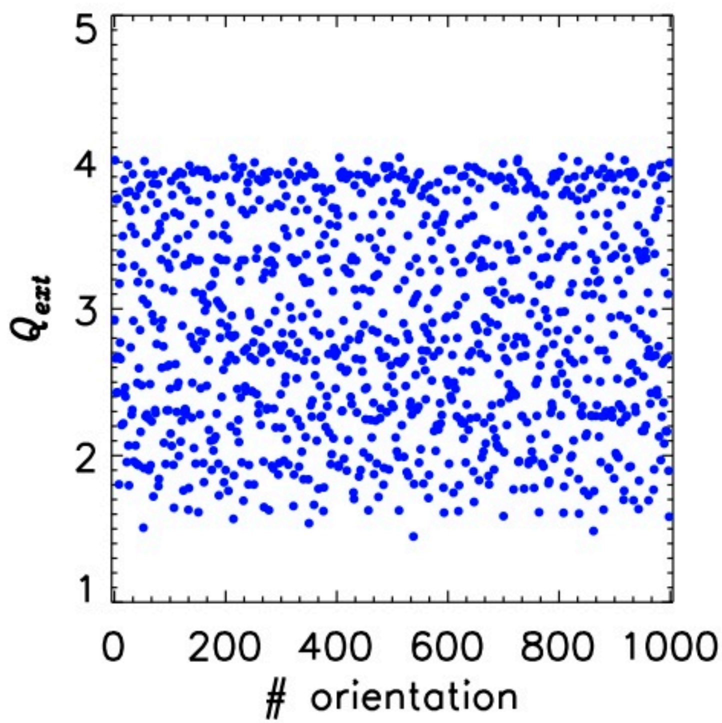
- **Large variations in scattering properties**

- **Euler α, β, γ for orientation**
- **Quasi Monte Carlo method**
- **1000 selections of β & γ**
- **Um and McFarquhar (2013; 2015)**







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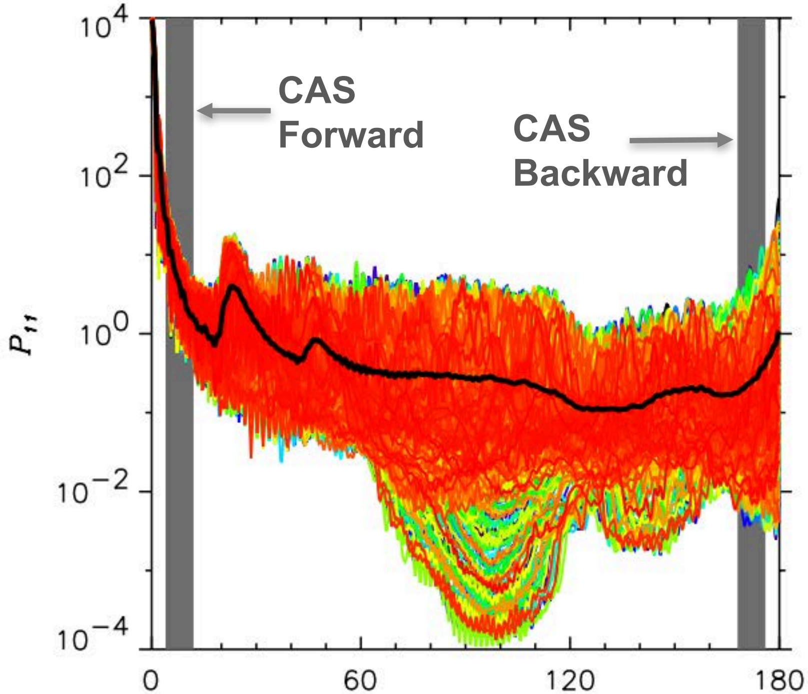
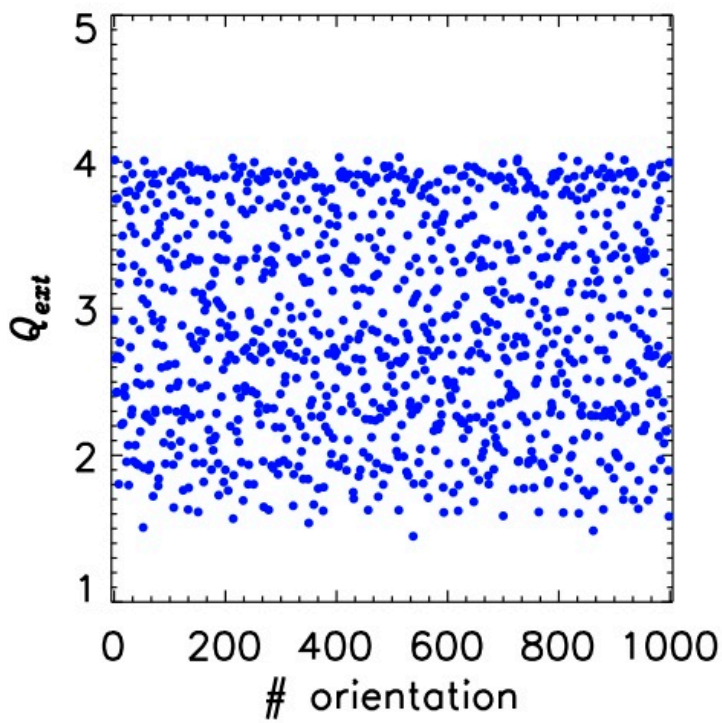
- ***L*=48 μm, *W*=12 μm**
- **45 BW XE nodes**
- **~28 hours/orientation (hard to get discount!)**
- **460 GB mem/orientation**
- **45 X 28 X 1000 = 1.26 M node hours**





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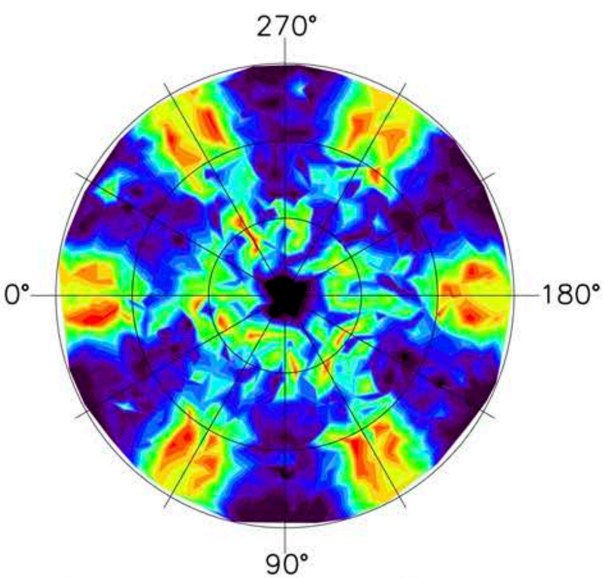
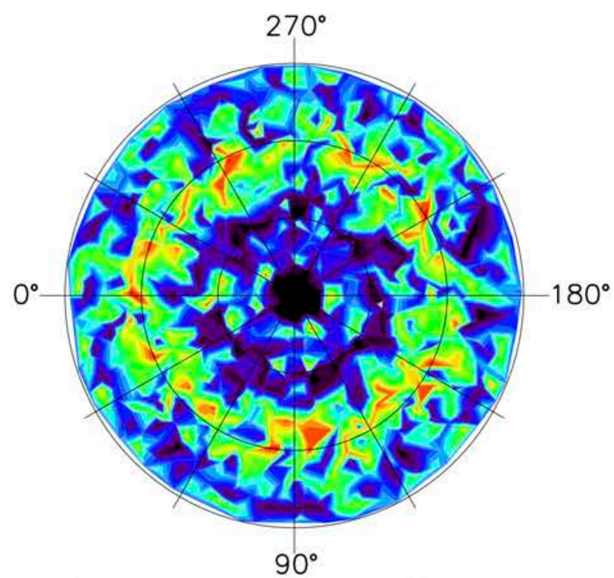
- **Errors, up to 515% (790%) in forward (backward) scattering direction due to impact of orientation!**

Summary & Future Work

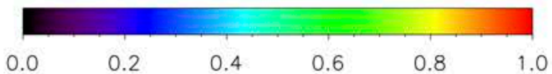
- Up to 72% (170%) in forward (backward) scattering direction, increase with nonsphericity (i.e., departure from compact shape)
- Up to 515% (790%) in forward (backward) scattering direction due to orientation of nonspherical shape
- New conversion table is required!
- Building new conversion table (+ polarization) using BW



Hexagonal column



Ellipsoid



Linear depolarization ratio

AR=4.0
L=10 μm
W=2.5 μm

▪ Forward scattering probes

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

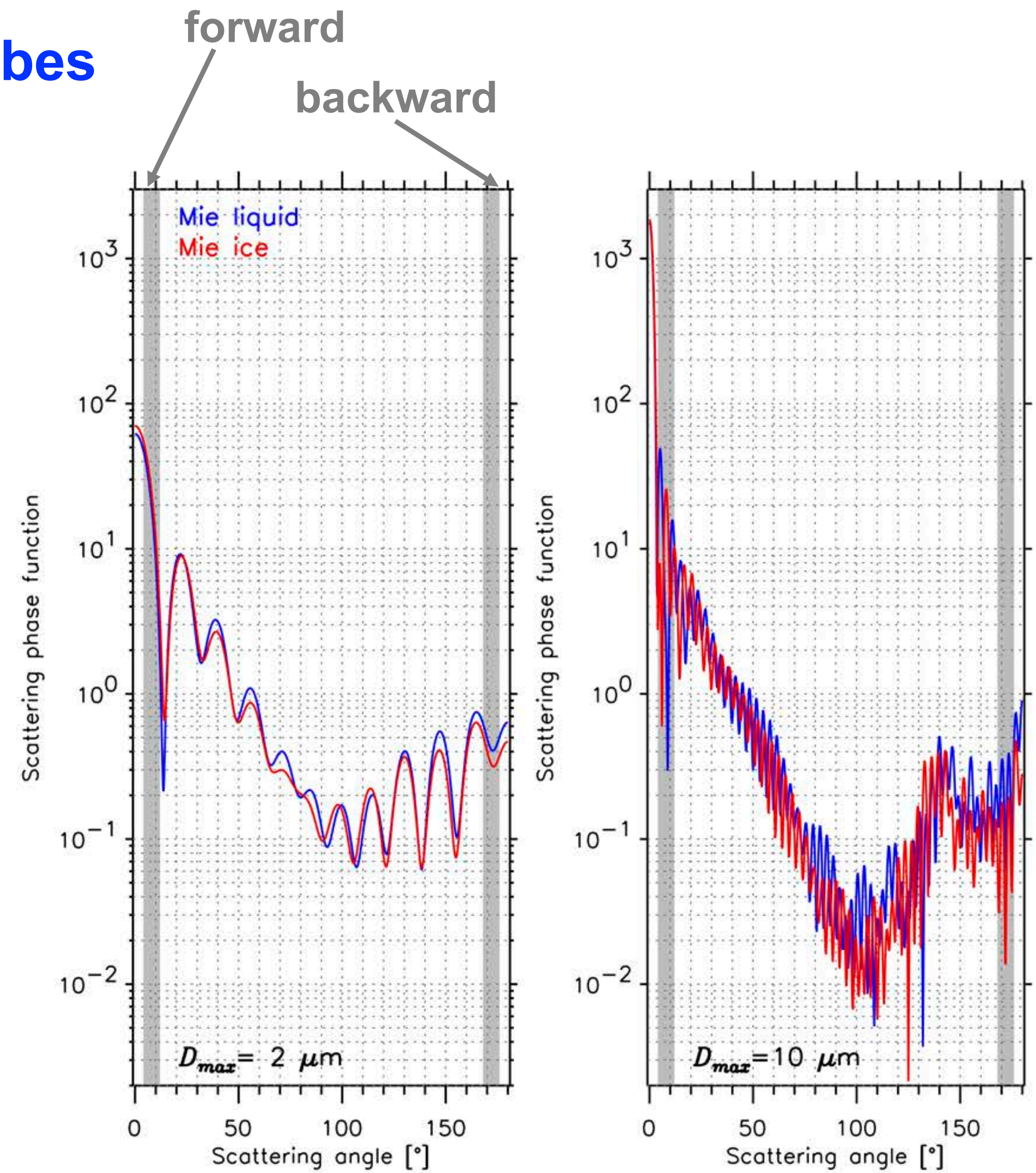
$$C_{sca,\theta} = \frac{1}{k^2}\int_0^{2\pi}\int_{\theta_1}^{\theta_2} P_{11} sin(\theta) d\theta d\phi$$

- CAS

  θ_1=4º & θ_2=12º forward

  θ_1=168º & θ_2=176º backward

- P_{11}: scattering phase function



▪ Forward scattering probes

Convs. table

- spherical shape
- different refractive index

  ice (n_r=1.31) &

  liquid (n_r=1.33)

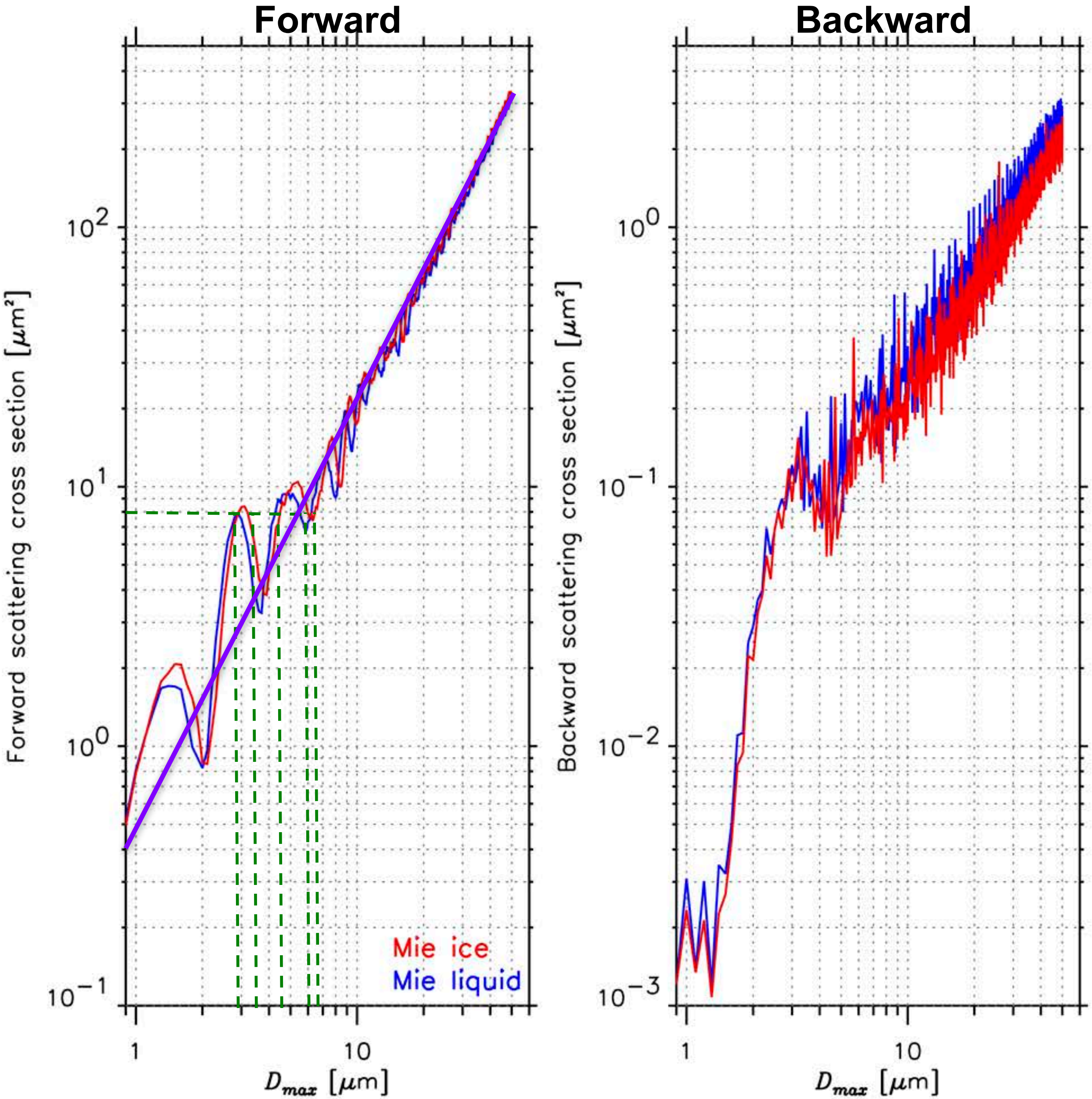
- multiple solutions

  (i.e., D_{max})

  scat. cros. sec.

  D_{max} < 10 μm

- linear fitting,
- avg. over solutions



▪ Forward scattering probes

Convs. table

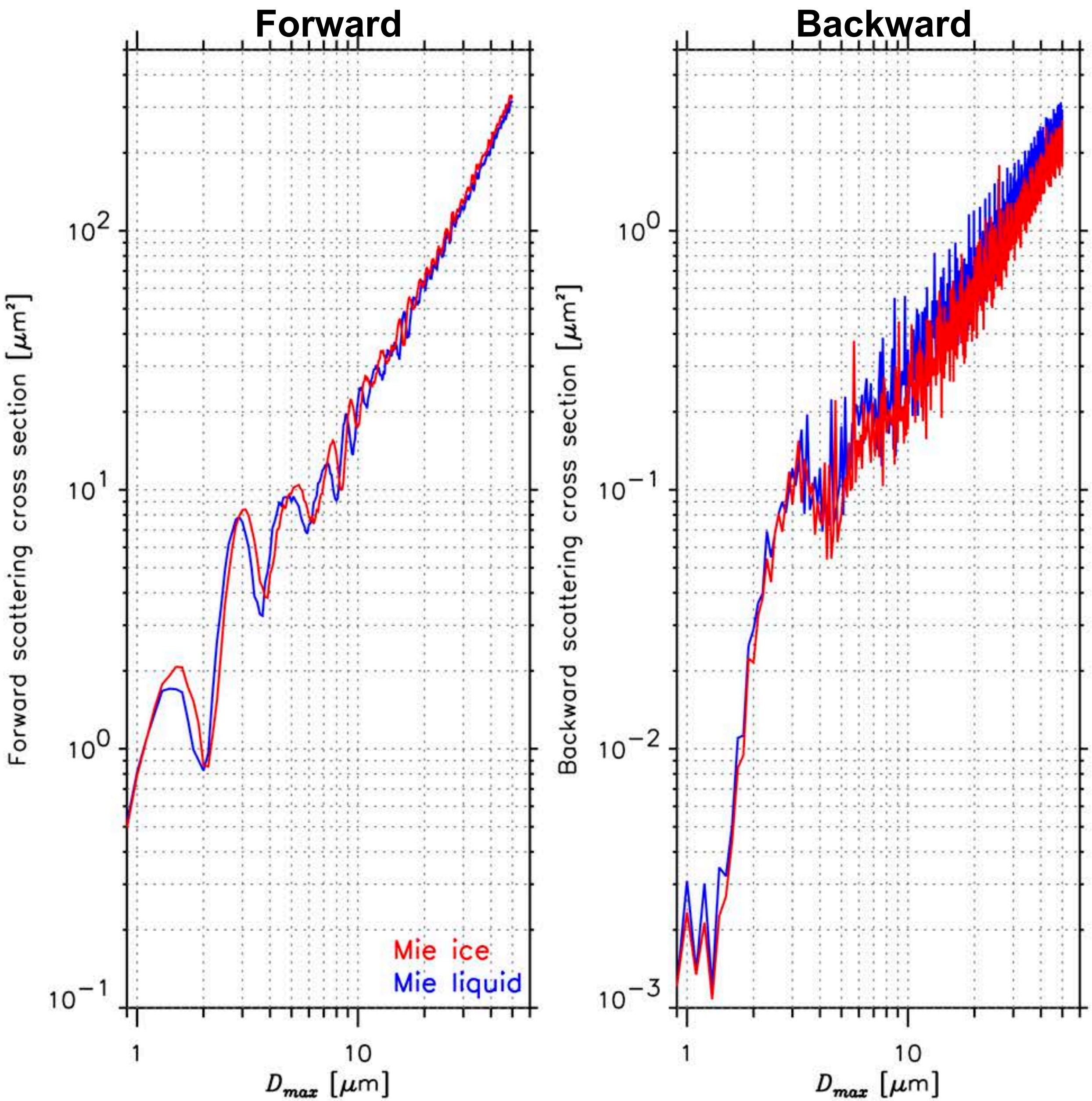
- Errors due to Mie scat. even for spherical shape
- $> \pm 20\%$ (D_{max}<10 μm)
- < 10% (10< D_{max}<30 μm)
- < 15% (D_{max}>30 μm)

using "best fitting curve"

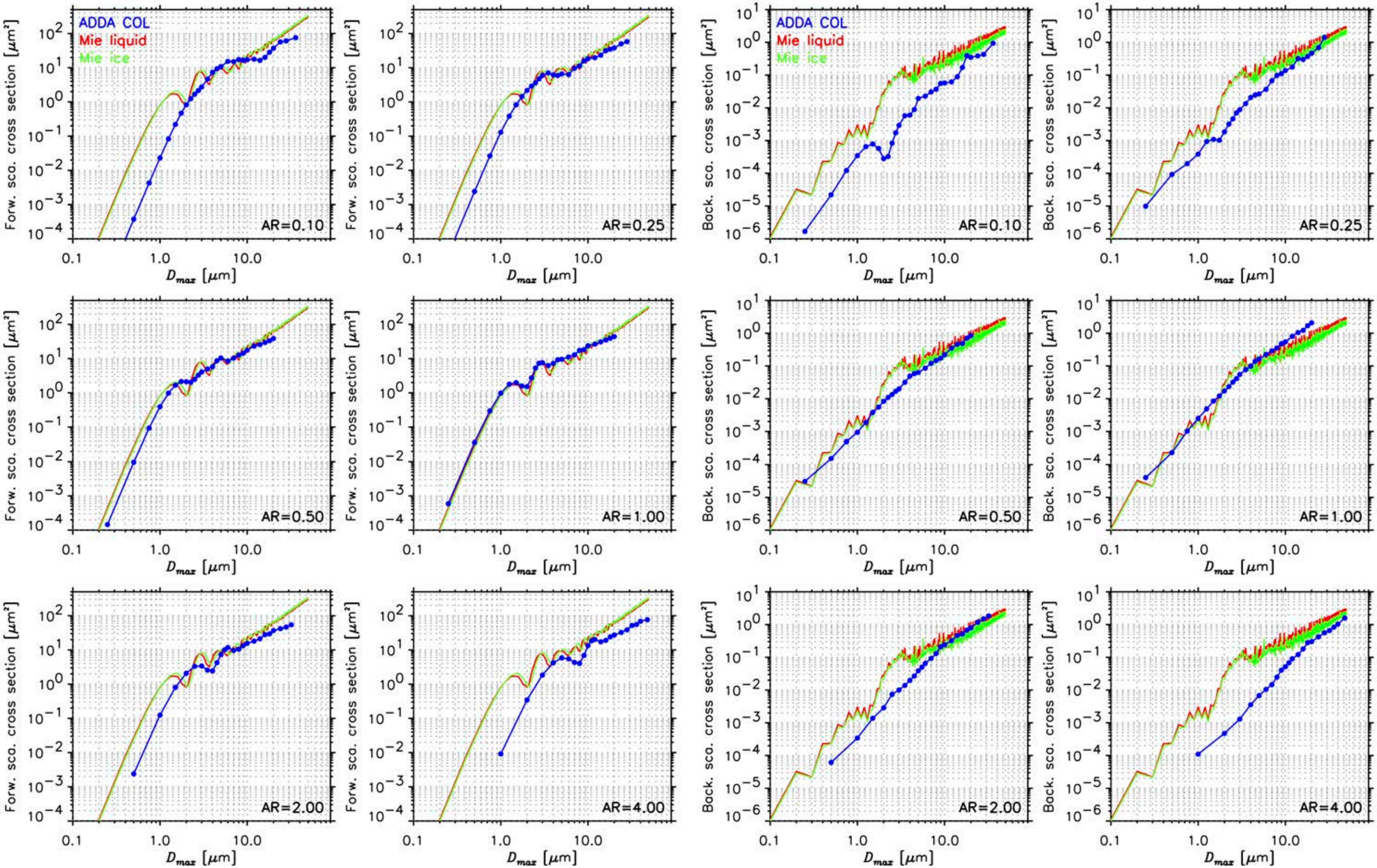
This is known errors due to Mie scattering of "spherical" particles.

What about ice crystals?

"Non-spherical!"



Forward scattering | Backward scattering



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