Simulation of the lidar returns from clouds with a Monte Carlo radiative transfer model

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Background

- Clouds play an important role in weather and climate
  - Precipitation
  - Cloud-aerosol-radiation interactions
- Uncertainties on clouds are large
  - Cloud and climate change: clouds radiative effect enhance global warming by 0%-100% (large uncertainty).
- Lidar are widely used to detect clouds
- Simulation of lidar signals from clouds would help understand the cloud properties, and improve the lidar retrieval algorithms.

Simulation processes

- 1. Calculate single scattering properties.
- 2. Simulate the lidar signals from clouds with Monte Carlo radiative transfer model。

  (Why is a RTM needed? Multiple scattering.)
- 3. Compare with observations, and analyze the optical properties of ice clouds.

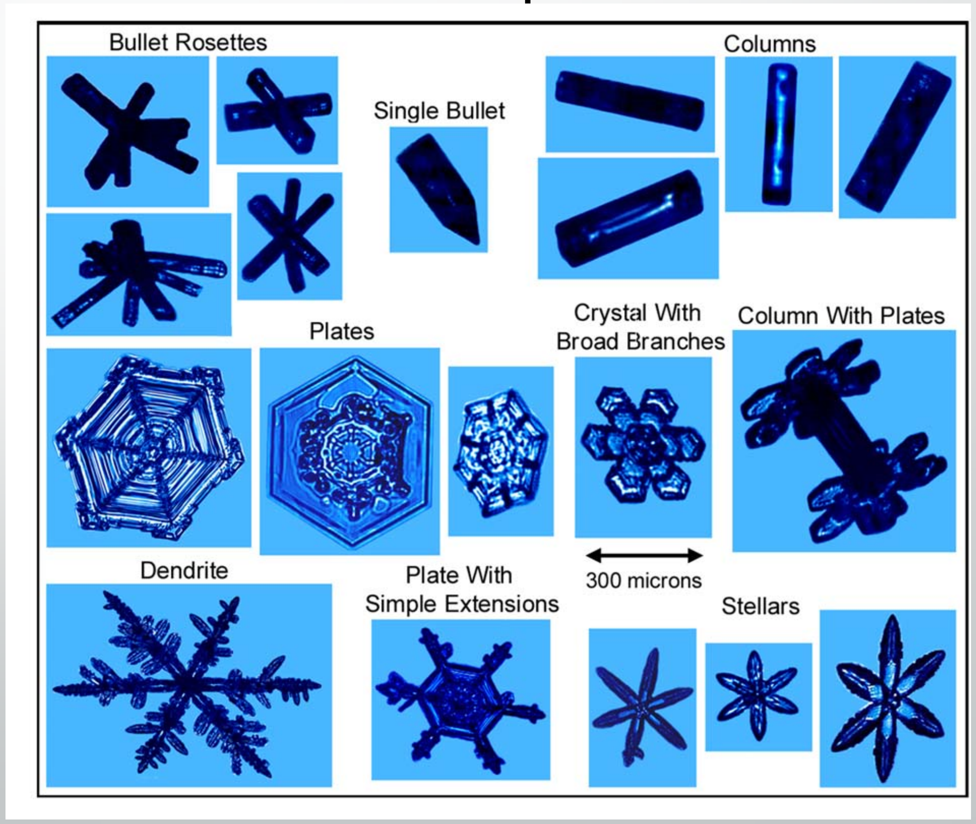
Single scattering properties

Single scattering properties are especially important for lidar signals, especially for backscattering properties.

- 1. Shape of cloud particles
- 2. Orientation of cloud particles
- 3. Calculation with scattering models

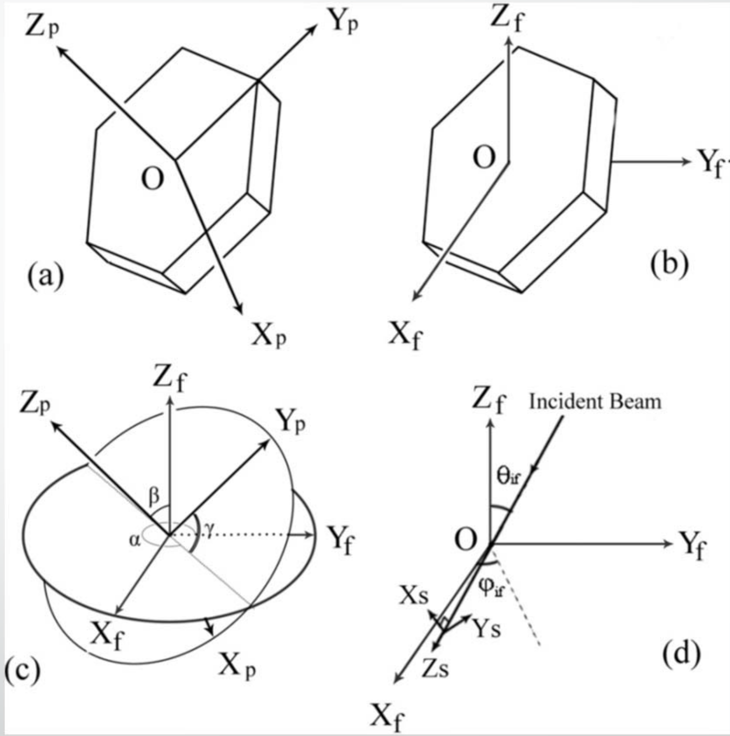
Shape of cloud particles

- Water cloud droplets: spheres
  - Note: very larger ones might be considered as spheroids
- Ice clouds:
  - Columns
  - Plates
  - Column/plate aggregates
  - Bullet rosettes
  - Droxtels
  - Irregular (rough) shapes

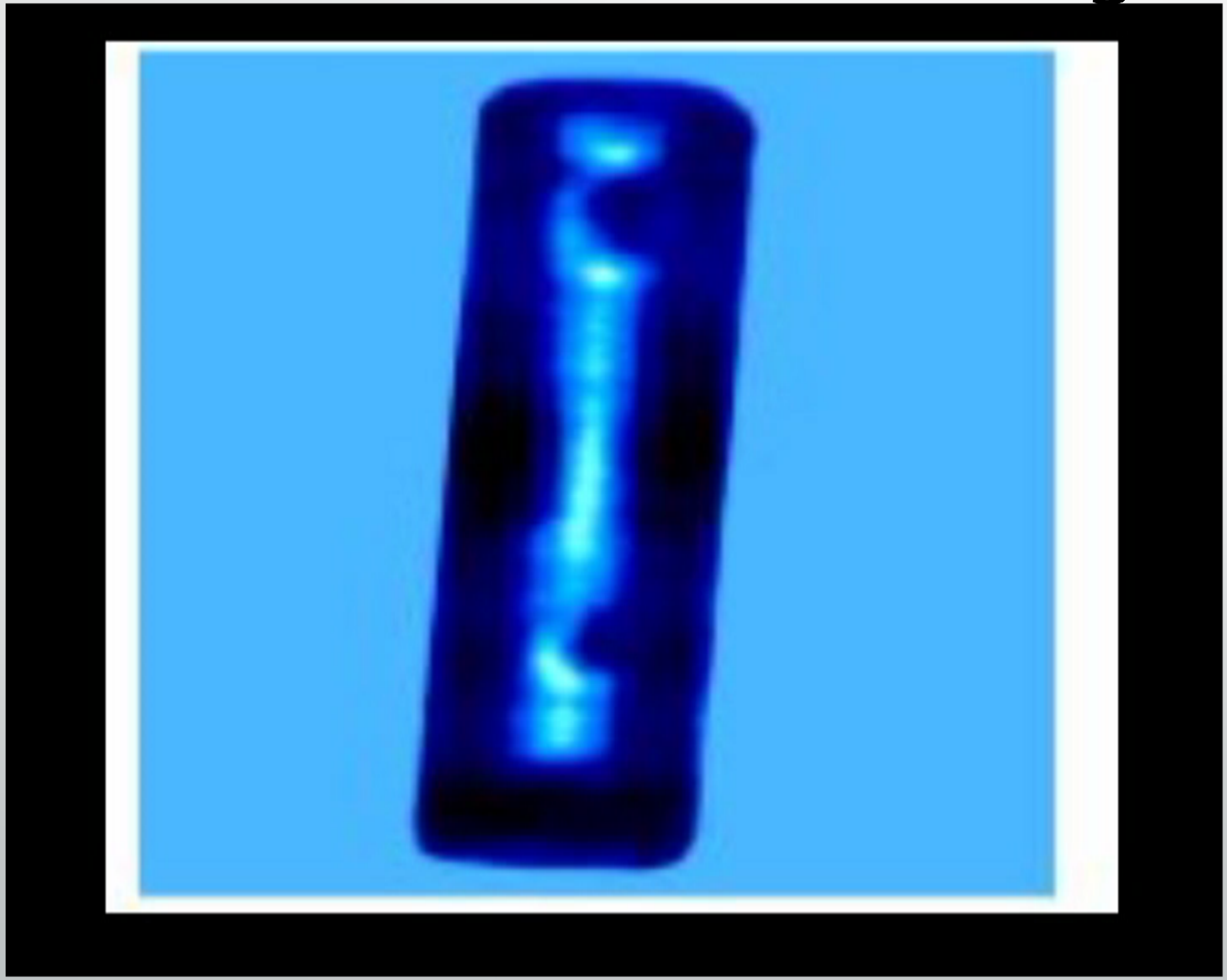


Orientation of ice cloud particles

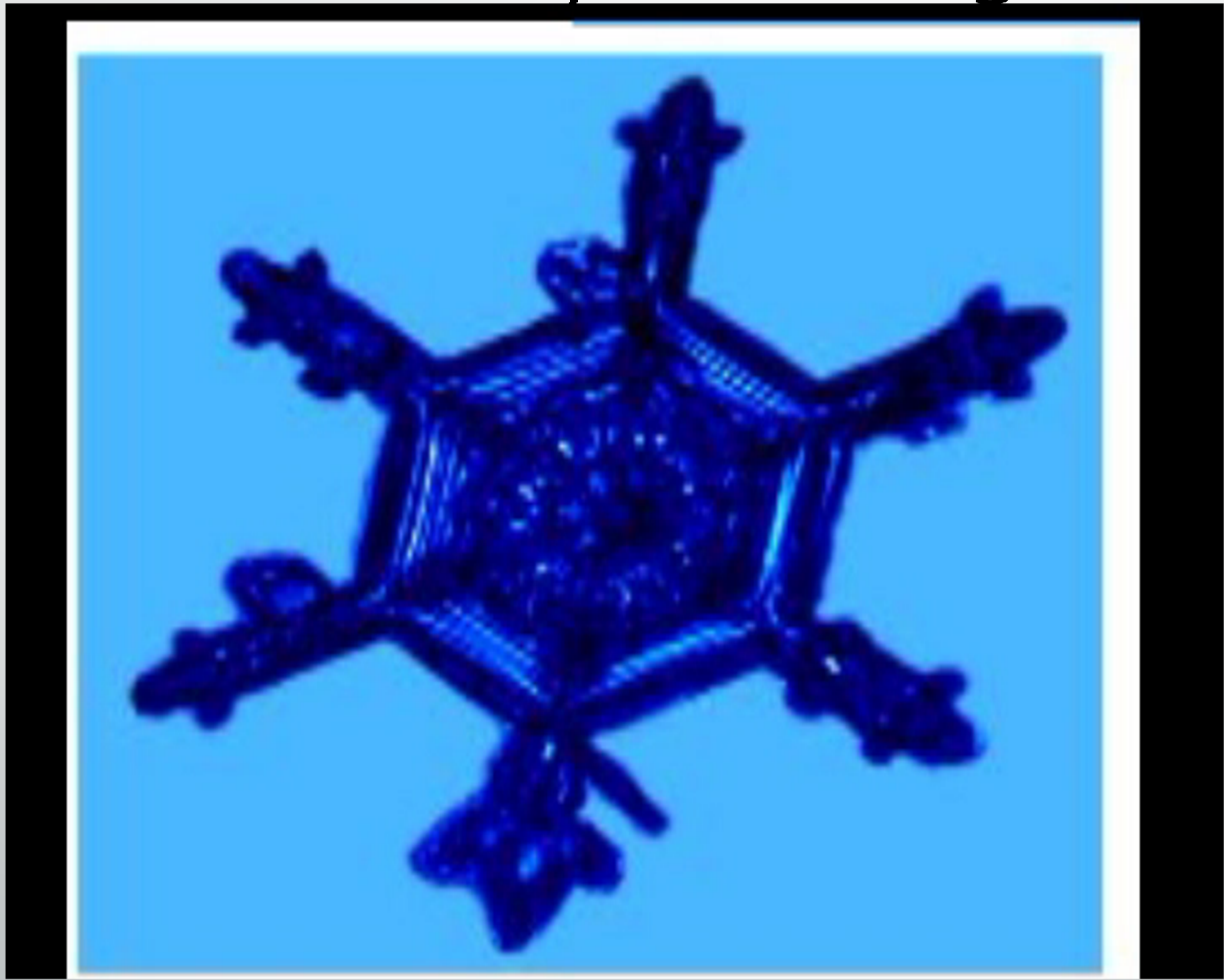
- Most radiative transfer models assume cloud particles are all randomly oriented.
- However, plates and columns might be horizontally oriented when they fall in fluid (air).



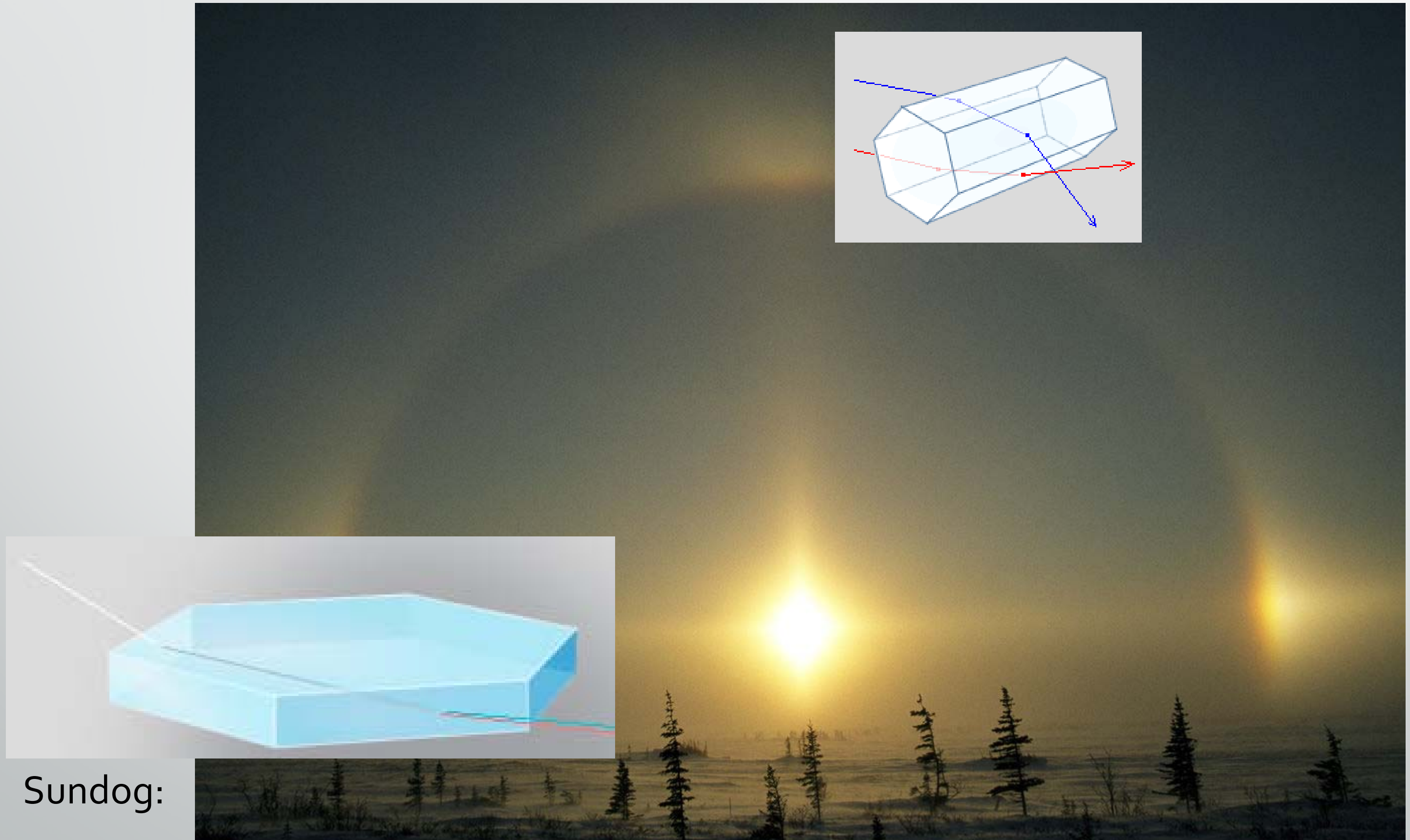
A simple experiment: orientation of a column falling in fluid



A simple experiment: orientation of a plate falling in fluid



Sundog: Horizontally oriented particles



Tangent arc:

Oriented columns

Sundog:

Oriented plates

Single scattering properties of ice cloud particles

- 1. Spherical water cloud droplets

  Lorenz-Mie theory
- 2. Randomly oriented particles (including 6 habits)

  IGOM (Yang et al. 2005)

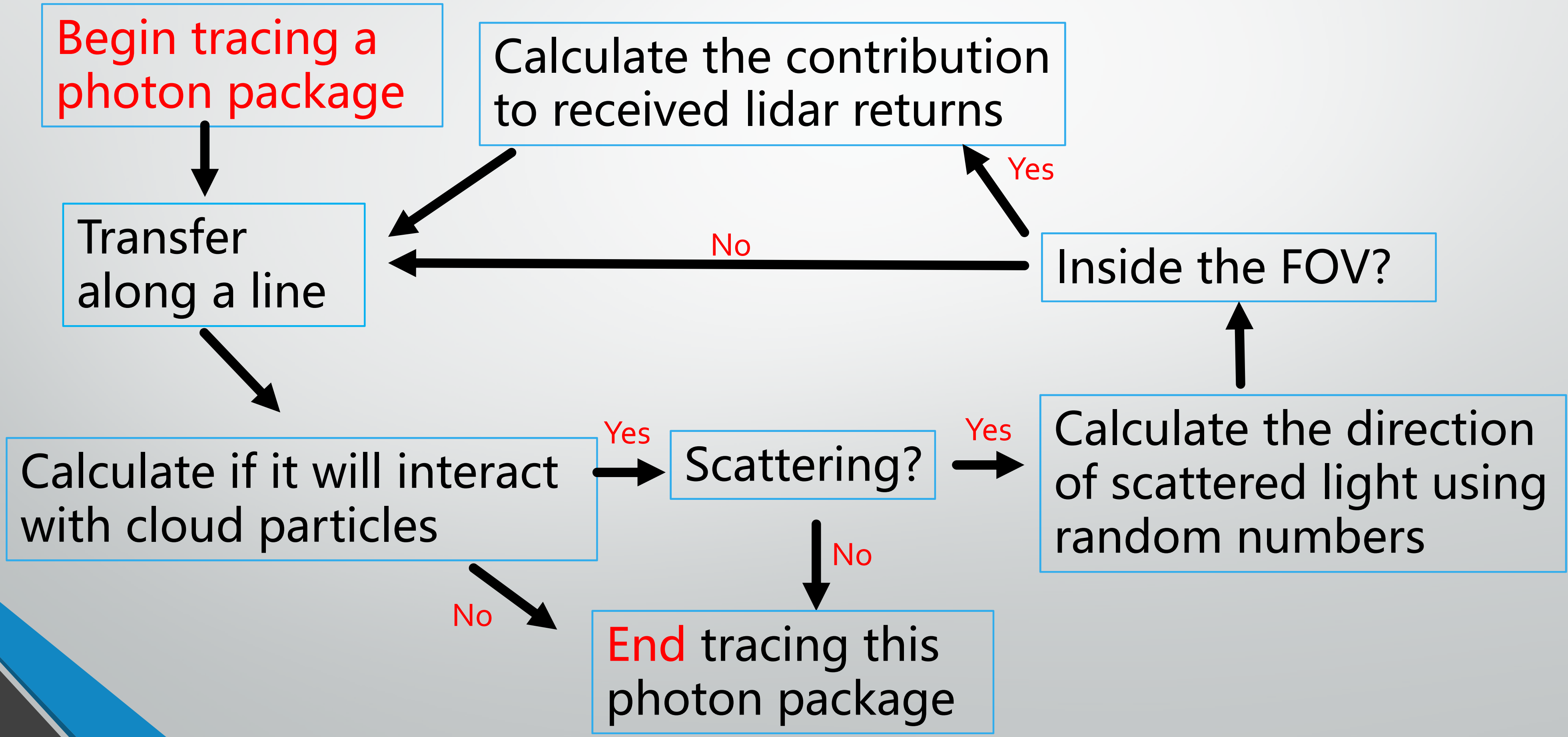
  Phase function $\mathbf{P}=\mathbf{P}(\theta_s)$
- 3. Horizontally oriented plates and columns

  PGOH (Bi et al. 2011)

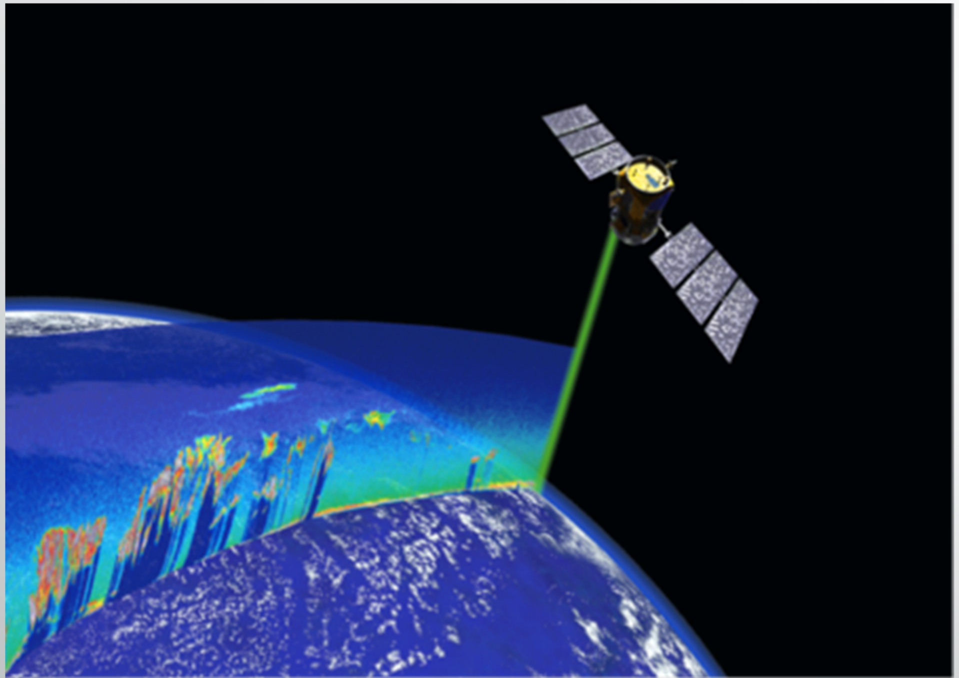
  Phase matrix $\mathbf{P}=\mathbf{P}(\theta_i, \varphi_i, \theta_s, \varphi_s)$

Monte Carlo radiative transfer model

Simulate N photon packages（N=200 million），and then calculate their contribution to lidar returns.

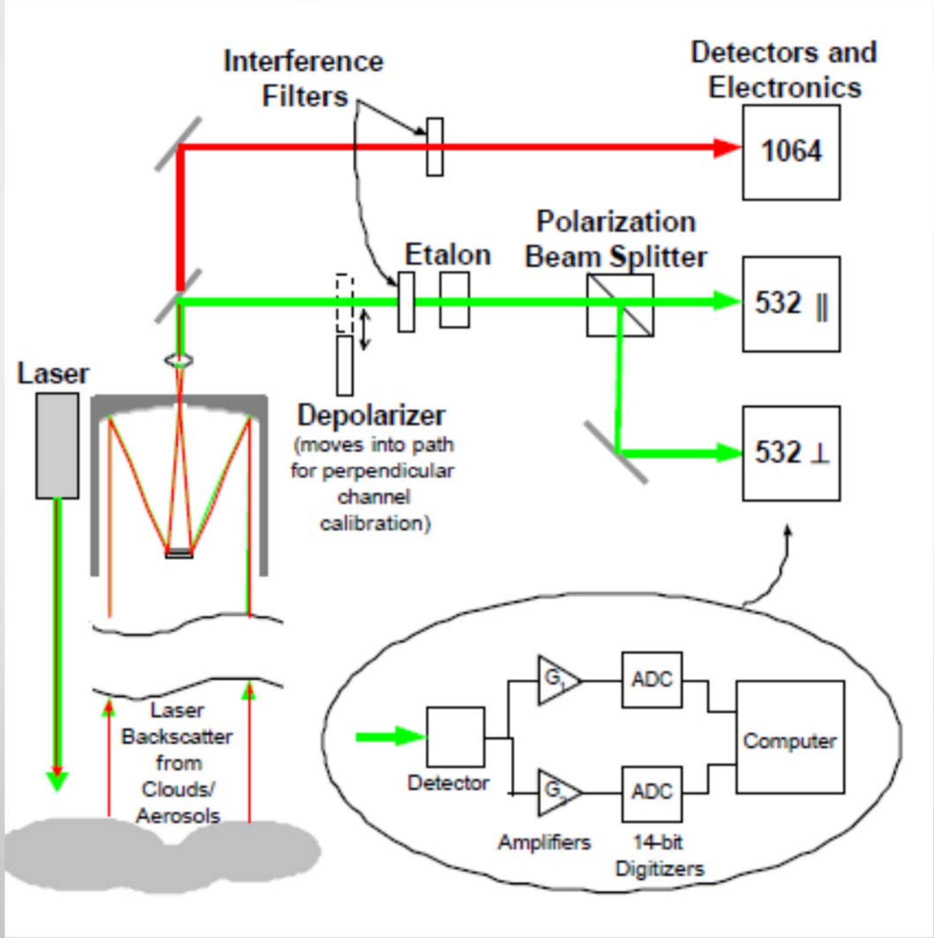


Simulation: CALIPSO - CALIOP



- Altitude： ~700km
- Wavelength：532nm; 1064nm
- FOV：130μrad
- Diameter： 1m
- Time： 2006年-今
- Off-nadir angle: 0.3°/3°
- Horizontal resolution:333m
- Vertical resolution： 30m

CALIPSO



Interference Filters
Detectors and Electronics
1064
Polarization Beam Splitter
Etalon
532 ||
Laser
Depolarizer
(moves into path for perpendicular channel calibration)
532 ⊥
Laser Backscatter from Clouds/ Aerosols
Detector
ADC
ADC
Computer
Amplifiers
14-bit Digitizers

Simulated variables

- Attenuated backscatter

$$\gamma' = \int_{\text{cloud\_base}}^{\text{cloud\_top}} \frac{\beta'_{\perp}(z)}{\cos\theta_{\text{off-nadir}}} dz + \int_{\text{cloud\_base}}^{\text{cloud\_top}} \frac{\beta'_{\parallel}(z)}{\cos\theta_{\text{off-nadir}}} dz$$

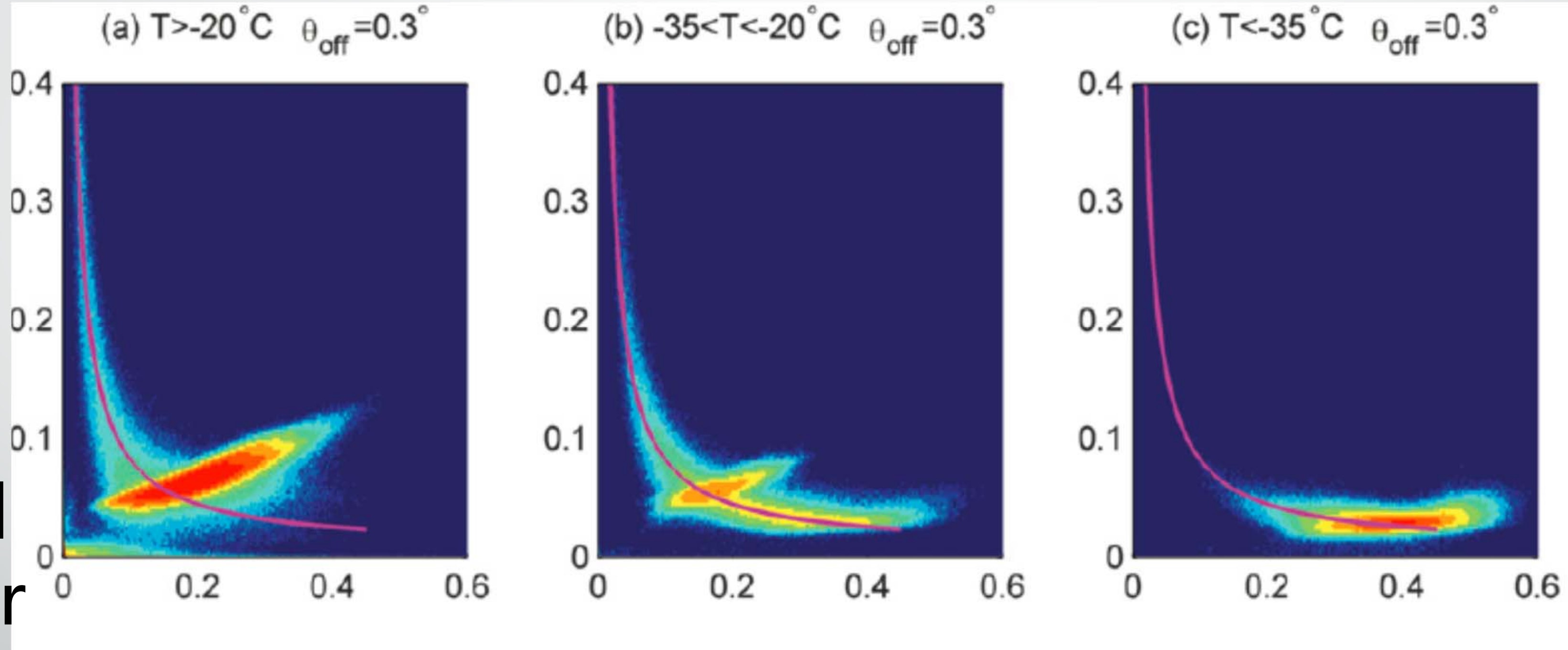
- Depolarization

$$\delta = \frac{\int_{\text{cloud\_base}}^{\text{cloud\_top}} \beta'_{\perp}(z)\, dz}{\int_{\text{cloud\_base}}^{\text{cloud\_top}} \beta'_{\parallel}(z)\, dz}$$

Probability density function of opaque clouds

Off-nadir angle： 0.3 degree

γ′ Layer-integrated backscatter

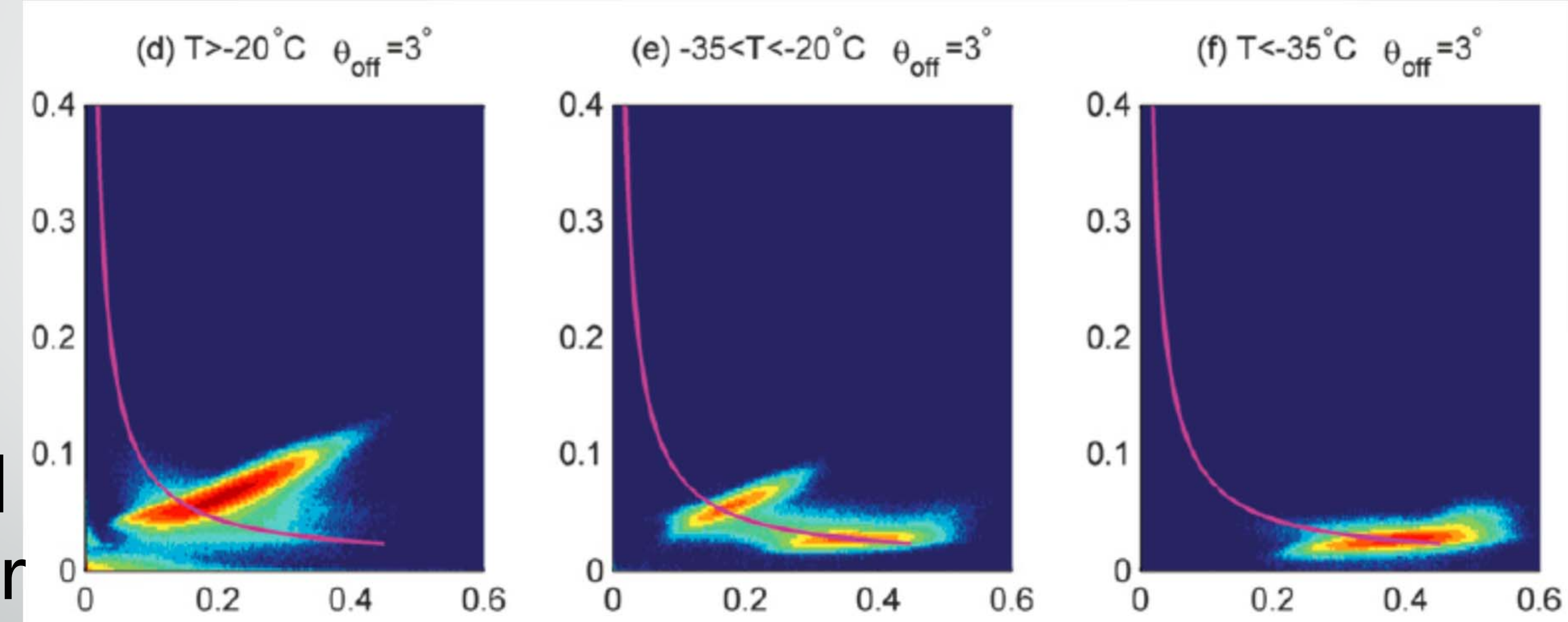


Layer integrated depolarization δ

Probability density function of opaque clouds

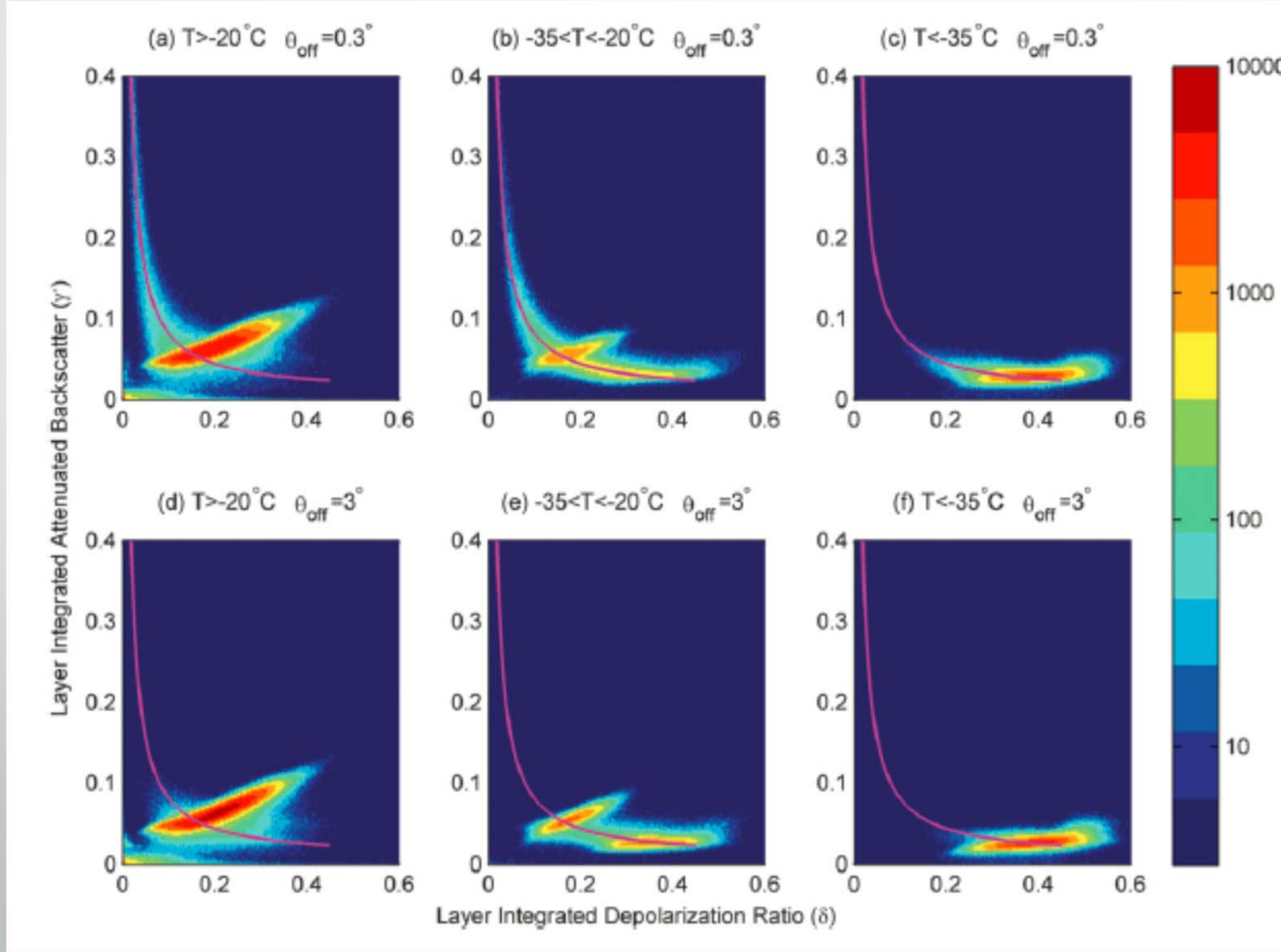
Off-nadir angle： 0.3 degree

γ′
Layer-integrated backscatter



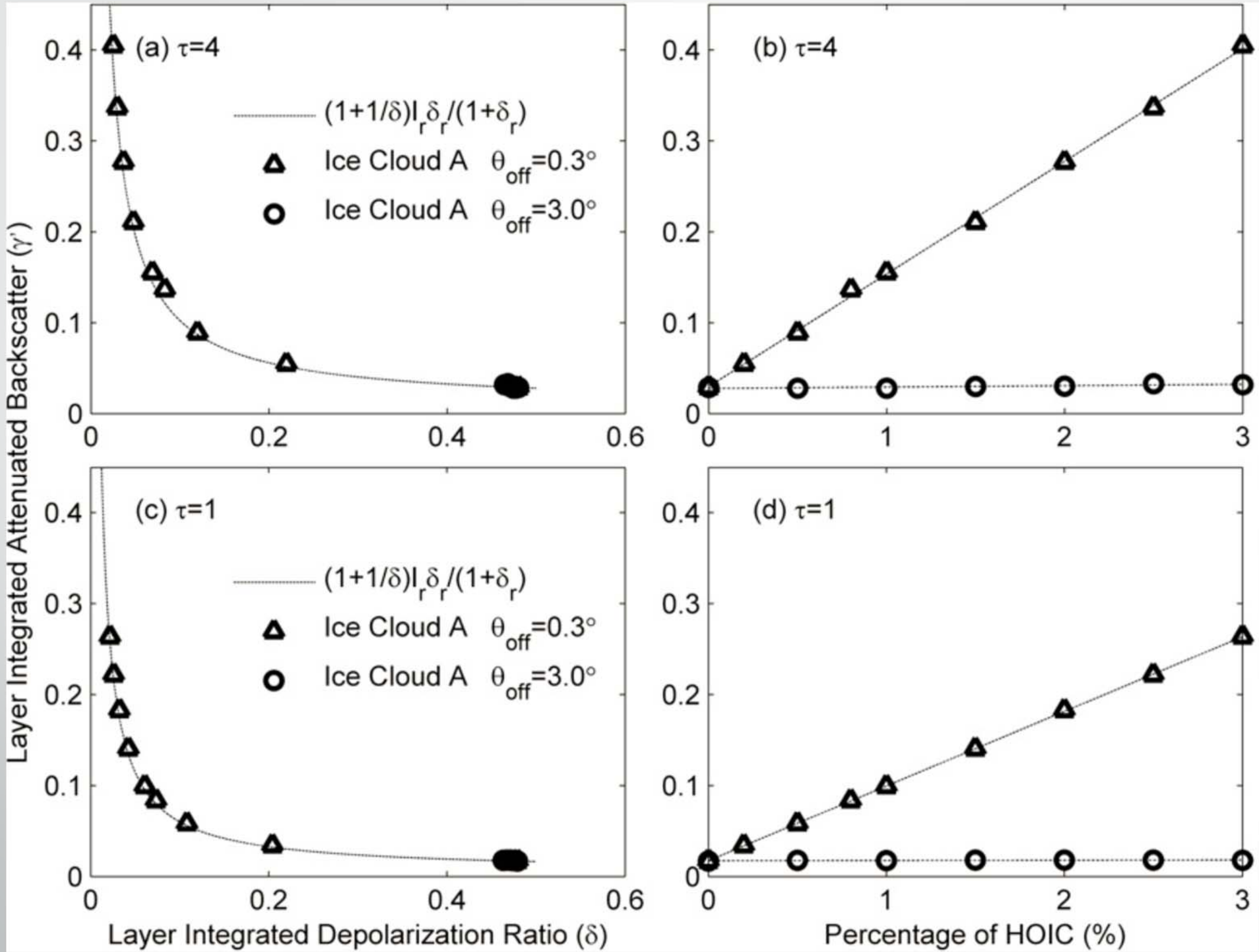
Layer integrated depolarization δ

Why does the “tail” disappear when the off-nadir angle changes from 0.3 to 3 degrees?



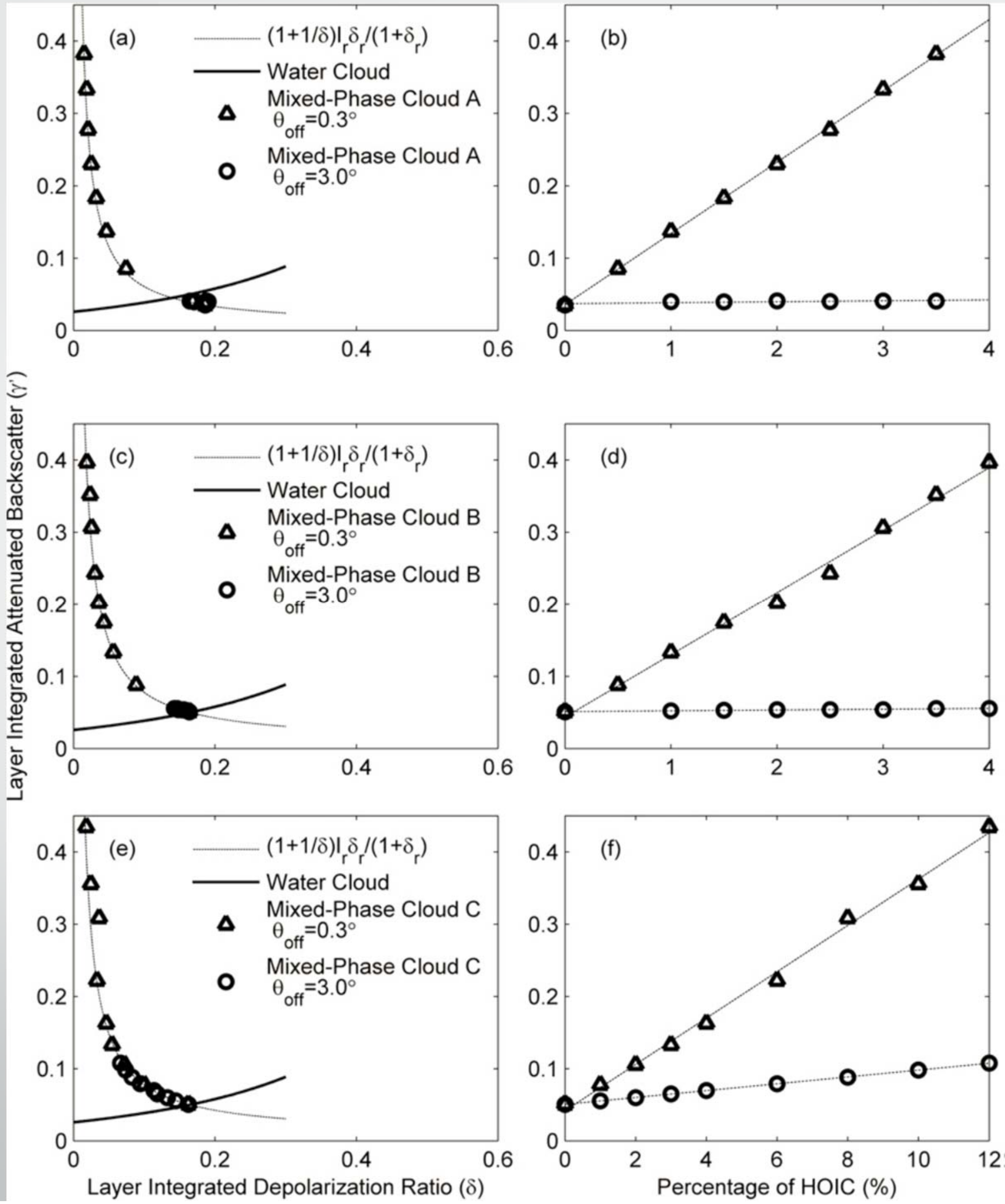
Horizontally oriented ice plates

Simulation results: Ice clouds



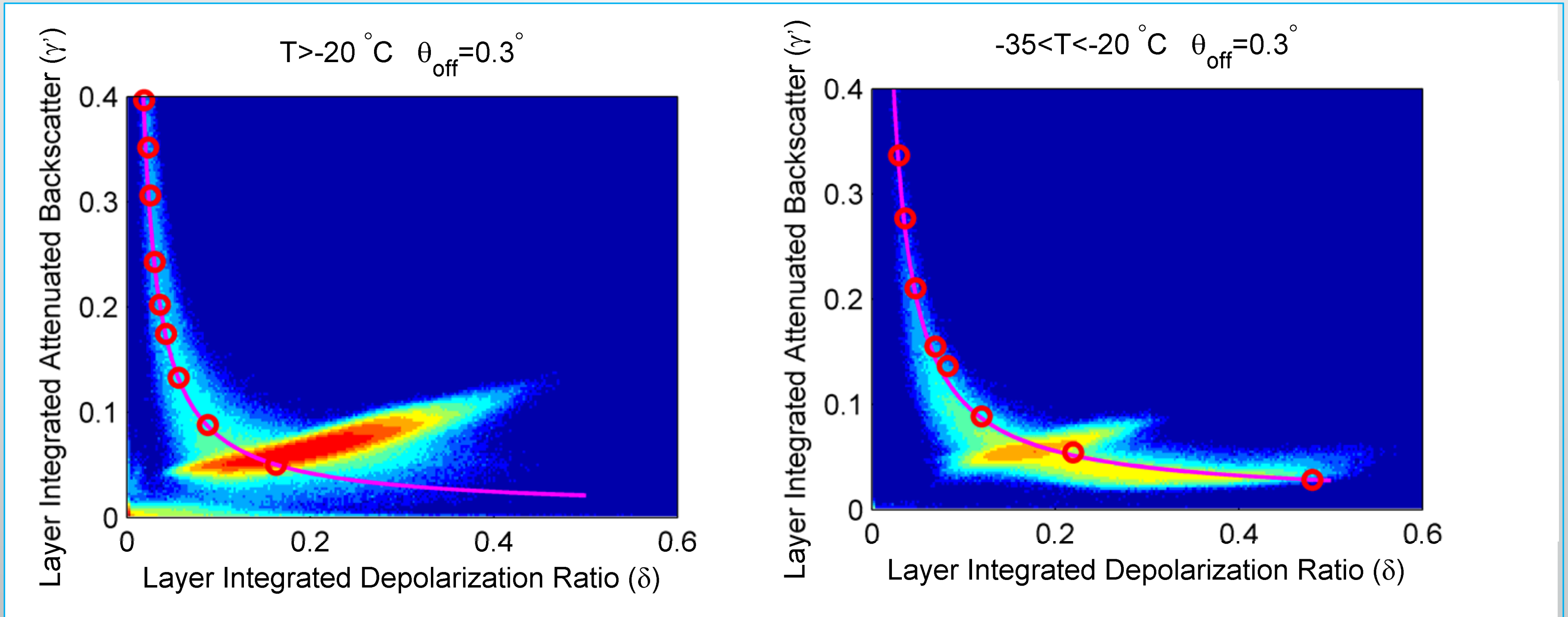
Zhou et al. (2012)

Simulation: Mixed-phase clouds



Zhou et al. (2012)

Comparison of simulations with observations (off-nadir=0.3)



Zhou et al. (2012)

Simulation results

- Horizontally oriented ice cloud particles：

  Consistent very well with observations

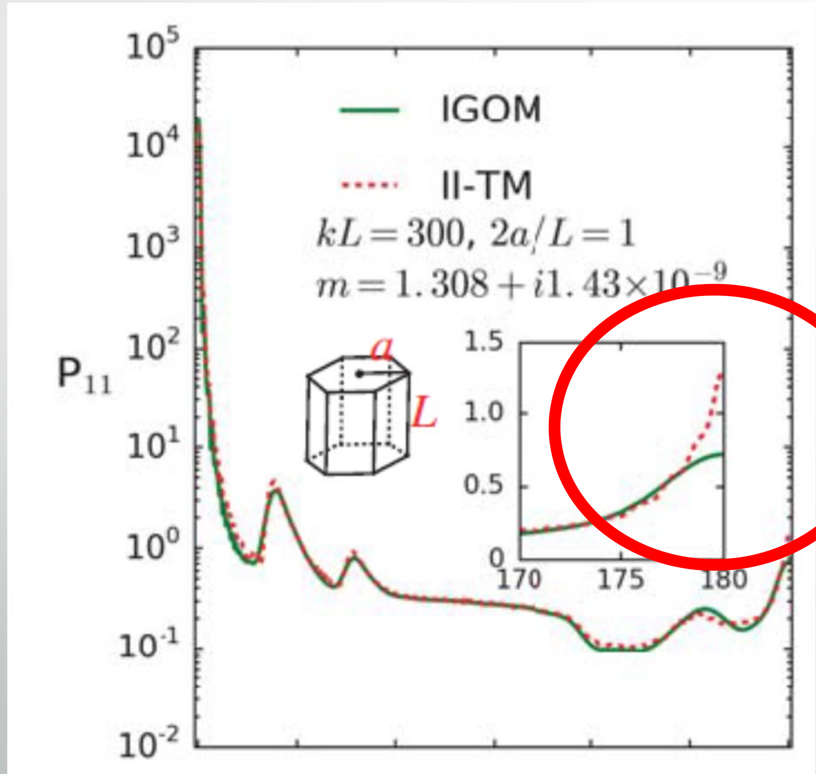
- Randomly oriented particles：

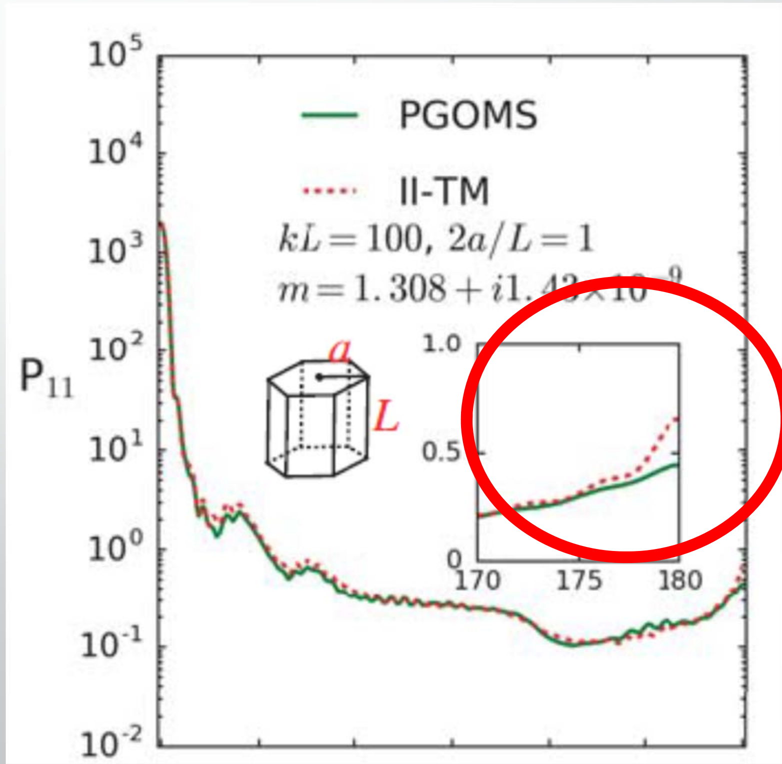
  The simulated backscatter is systematically lower than observations. (underestimated by ~40%)

Why is there an underestimation?

Problem with the Geometric methods?

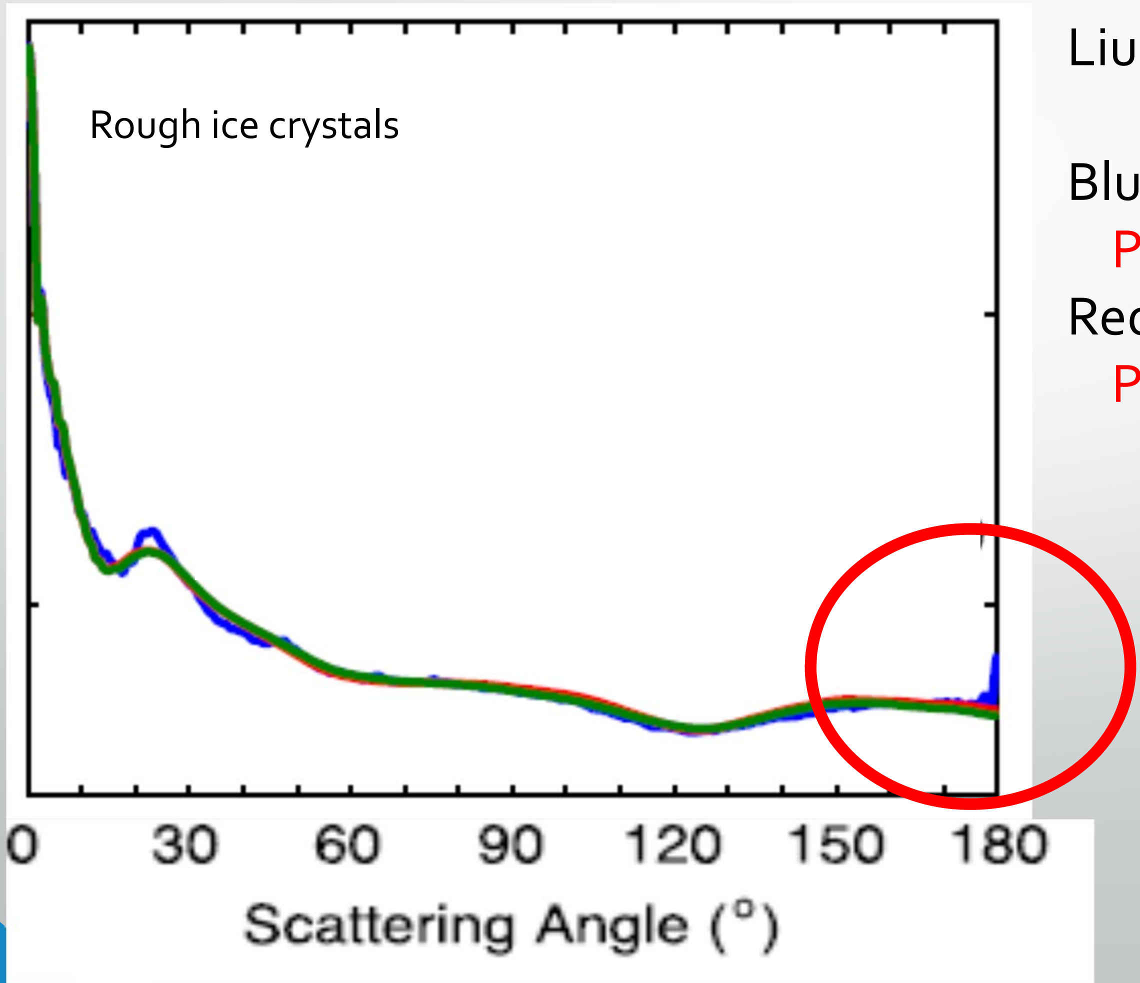
Geometric method simulate a backscatter much less than accurate models based on Maxwell's equations. A process might be missing.





Yang et al. (2019)

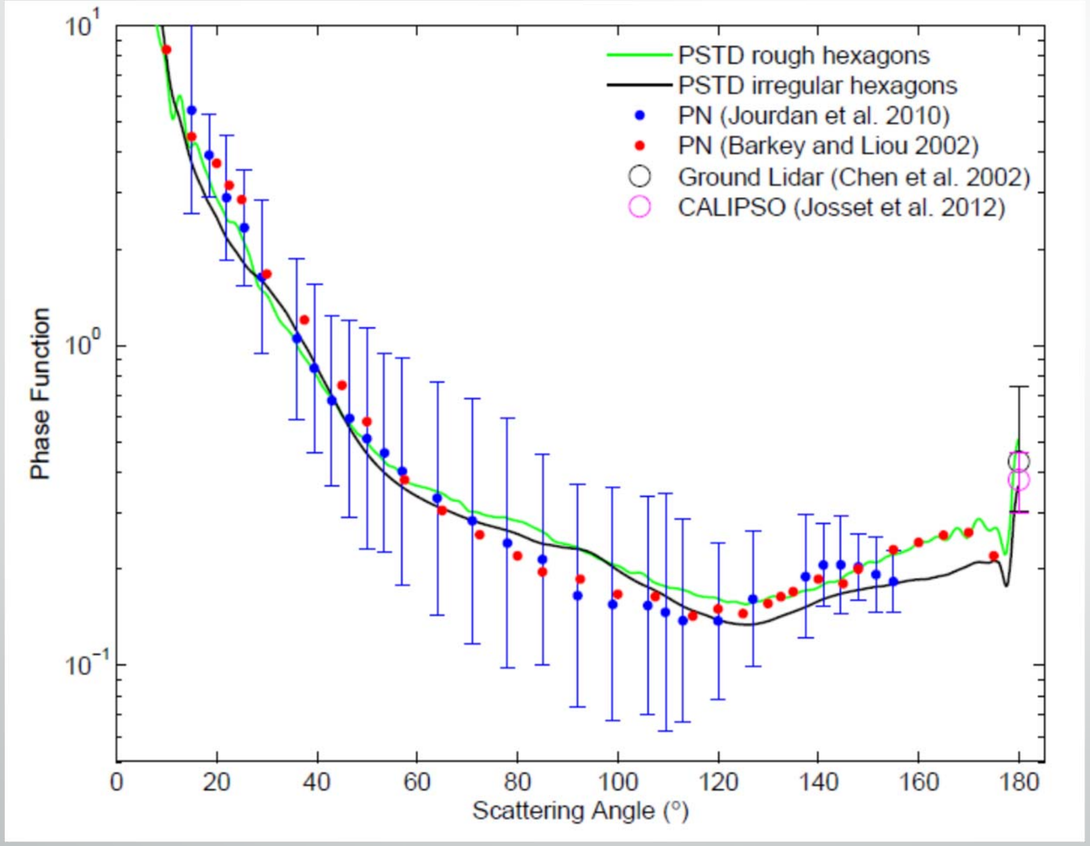
A backscattering peak for ice crystals?



Liu et al. (2013)

Blue: Rigid Method
Peak exist
Red/green: Geometric method
Peak not exist

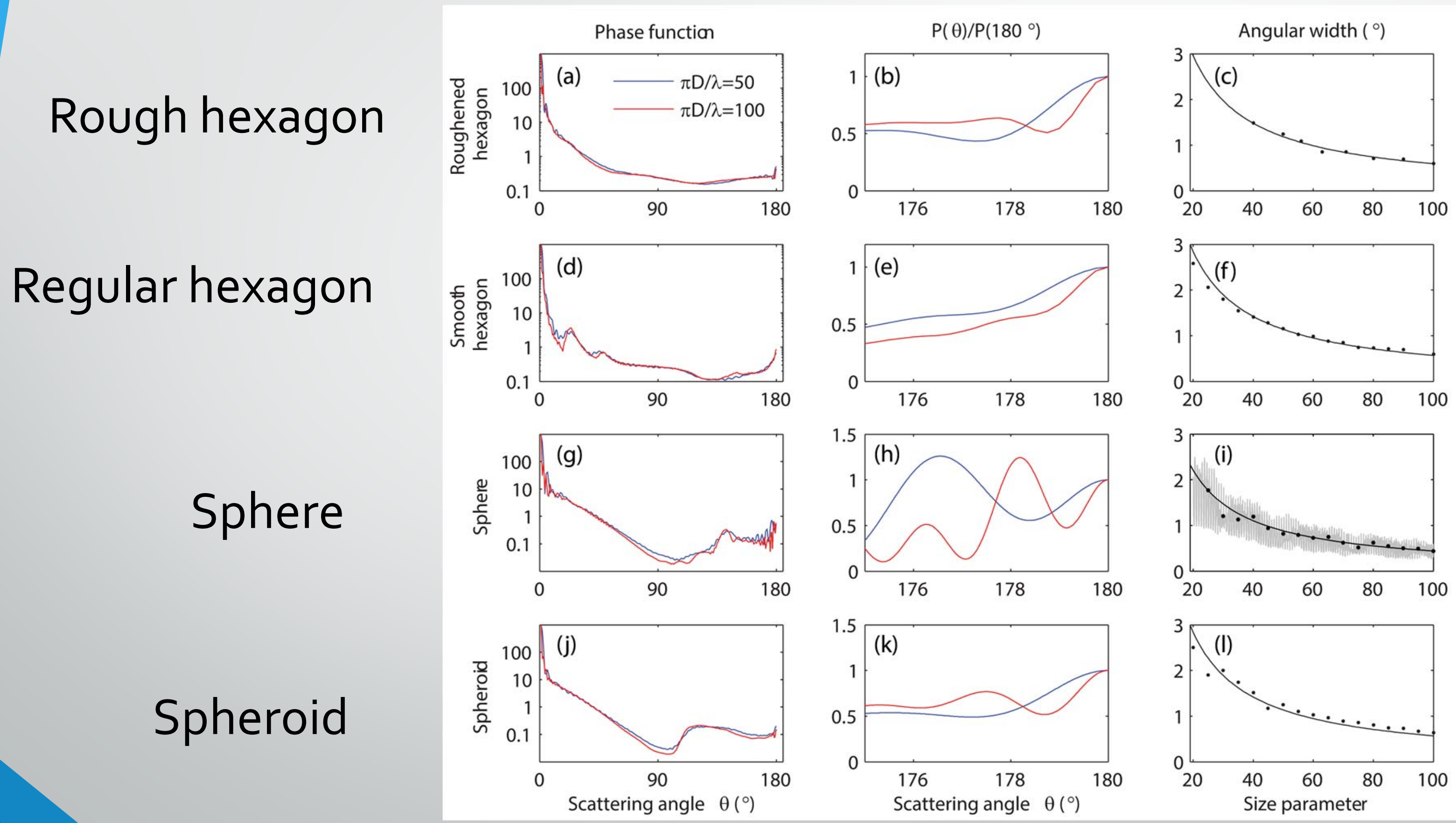
Observations: Backscattering peak exist



Why is there a peak?

Zhou and Yang (2015)

The backscattering peak width is inversely proportional to the size parameter.

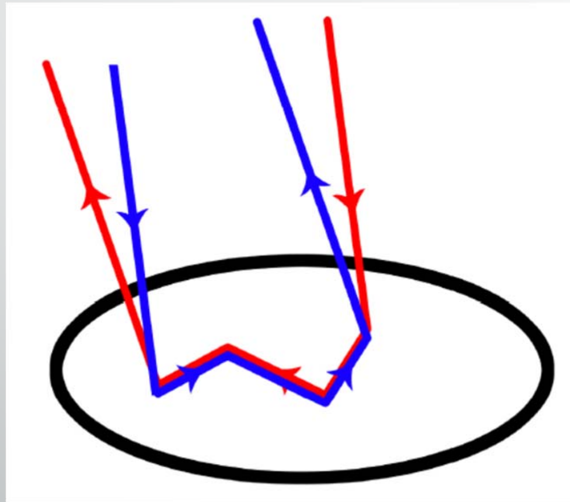


Zhou (2018)

Coherent backscatter enhancement

Interference between conjugate terms representing reversible sequences of elementary scatterers is constructive at the backscattering direction, resulting in a coherent backscatter enhancement.

$$\bar{E}^{sca}(\bar{r}_s,t)=\int_{V_{int}} d\bar{r}_1 k_1^{2}(\tilde{m}^2(\bar{r}_1)-1)\bar{G}(\bar{r}_s,\bar{r}_1)\cdot\bar{E}^{inc}(\bar{r}_1,t)$$
$$+\sum_{n=2}^{\infty}\int_{V_{int}}\cdots\int_{V_{int}} d\bar{r}_1..d\bar{r}_n k_1^{2n}\prod_{i=1}^{n}(\tilde{m}^2(\bar{r}_i)-1)\bar{G}(\bar{r}_s,\bar{r}_1)\bar{G}(\bar{r}_1,\bar{r}_2)...\bar{G}(\bar{r}_{n-1},\bar{r}_n)\cdot\bar{E}^{inc}(\bar{r}_n,t)$$

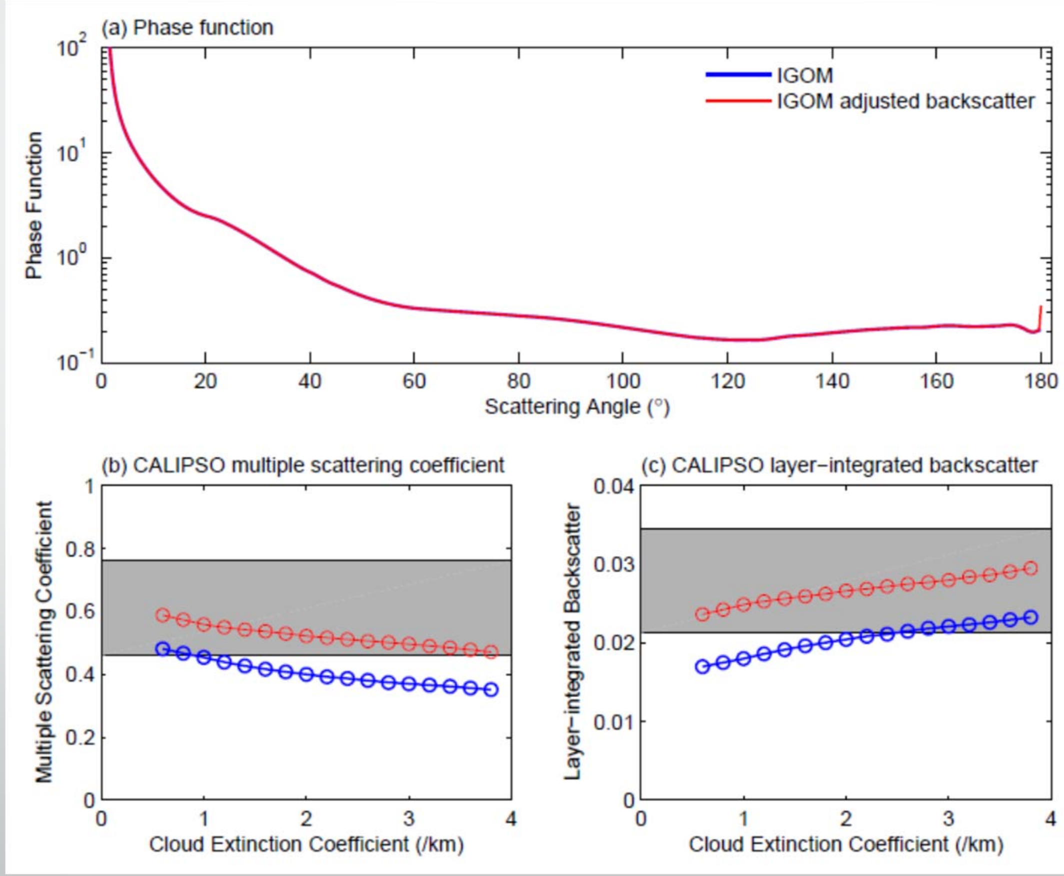


Zhou (2018)

$$\bar{E}_{c1,\parallel}(\bar{r}_s,t)+\bar{E}_{c2,\parallel}(\bar{r}_s,t)$$
$$=\sum_{n=2}^{\infty}\int_{V_{int}}\cdots\int_{V_{int},|\bar{r}_n|>|\bar{r}_1|} d\bar{r}_1..d\bar{r}_n k_1^{2n}\prod_{i=1}^{n}(\tilde{m}^2(\bar{r}_i)-1)$$
$$\cdot(\hat{r}_{\parallel}\otimes\hat{r}_{\parallel})\cdot\prod_{i=1}^{n-1}\{(\frac{3}{k_1^2 r_{i,i+1}^2}-\frac{3\mathrm{i}}{k_1 r_{i,i+1}}-1)\hat{r}_{i,i+1}\otimes\hat{r}_{i,i+1}+(1+\frac{\mathrm{i}}{kr_{i,i+1}}-\frac{1}{k^2 r_{i,i+1}^2})\bar{I}\}\cdot\hat{r}_0$$
$$G(\bar{r}_1,\bar{r}_2)...G(\bar{r}_{n-1},\bar{r}_n)\ E_0[\exp(\mathrm{i}\bar{k}_i\cdot\bar{r}_n-\mathrm{i}\omega t)G(\bar{r}_s,\bar{r}_1)+\exp(\mathrm{i}\bar{k}_i\cdot\bar{r}_1-\mathrm{i}\omega t)G(\bar{r}_s,\bar{r}_n)].$$

$$|\bar{E}_{c1,\parallel}(\bar{r}_s,t)+\bar{E}_{c2,\parallel}(\bar{r}_s,t)|^2=|2\bar{E}_{c1,\parallel}(\bar{r}_s,t)|^2$$
$$=2(|\bar{E}_{c1,\parallel}(\bar{r}_s,t)|^2+|\bar{E}_{c2,\parallel}(\bar{r}_s,t)|^2),[backscatter]$$

By adjusting the IGOM simulated phase function with the coherent backscatter theory, we are now able to simulate the observed backscatter for randomly oriented particles well.



Zhou and Yang (2015)

Conclusions

- 1. The lidar signals of ice cloud particles can be well simulated with a Monte Carlo radiative transfer model.
- 2. Horizontally oriented ice cloud particles exist in over 60% of thick ice/mixed-phase clouds. The equivalent fraction of regular horizontally oriented plates is only 0.2%, but the actual percentage can be much more.
- 3. There is a backscattering peak associated with the phase function of randomly oriented ice particles. The backscattering peak is largely induced by coherent backscatter enhancement in single scattering.

Discussion: Fast RTM for lidar simulations

Monte Carlo radiative transfer model is expensive:

- CPU time: 5 min for 1 case with pure randomly oriented particles. 50 min for 1 case with oriented particles.
- Storage: the phase matrix for a specific oriented particle is **10 GB**. $\mathbf{P}=\mathbf{P}(\theta_i, \varphi_i, \theta_s, \varphi_s)$

We may want a fast RTM for lidar

Discussion: How to build a fast RTM for lidar?

- 1. Plane parallel models (i. e., adding-doubling) could not be used. None-uniform incident beam.
- 2. Monte Carlo is too slow.
- 3. Simple lidar equations requires predetermined parameters to account for multiple scattering.

Proposed solution:

- Combine the Monte Carlo results, and simple lidar equations.

Discussion: Proposed fast RTM for lidar

- 1. Simulate the lidar signals of various clouds and aerosols with the Monte Carlo radiative transfer model, and build a database.
- 2. Retrieve statistical relationships between multiple scattering coefficient, depolarization, FOV, extinction coefficient, and particle type (including orientation) with the database.
- 3. For a specific volume, calculate the multiple scattering coefficient and depolarization from the above statistical relationship, and insert to the traditional lidar equation.