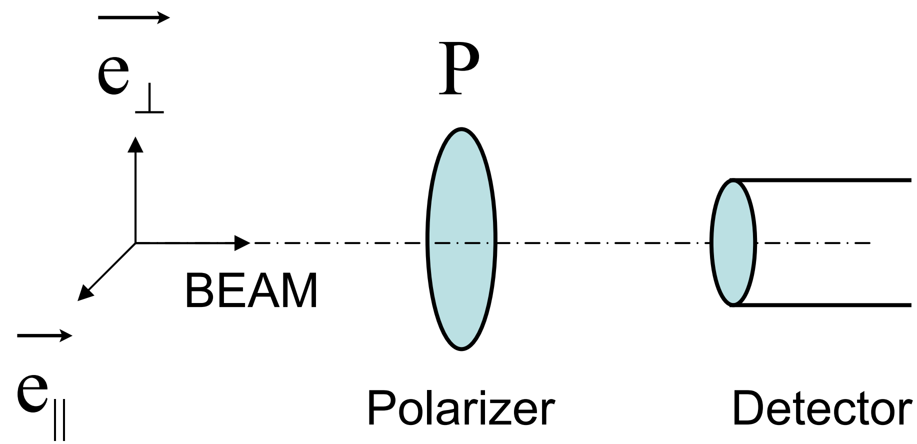
SIMONE
in situ light scattering and depolarization measurements

Stokes Vector

Advantage: Definition in terms of measurable quantities

$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} \quad \begin{matrix} \text{Intensity} \\ I_{\parallel} - I_{\perp} \\ I_{+} - I_{-} \\ I_{R} - I_{L} \end{matrix}$$



$$\begin{pmatrix} 1 \\ 1 \\ 0 \\ 0 \end{pmatrix} \quad \begin{pmatrix} 1 \\ -1 \\ 0 \\ 0 \end{pmatrix} \quad \begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix} \quad \begin{pmatrix} 1 \\ 0 \\ 0 \\ -1 \end{pmatrix}$$

0° 90° linear 45° left-handed circular

Scattering Matrix – Spheres

$$\begin{pmatrix} I_s \\ Q_s \\ U_s \\ V_s \end{pmatrix} = \frac{1}{\mathrm{k}^2 r^2} \begin{pmatrix} S_{11} & S_{12} & 0 & 0 \\ S_{12} & S_{11} & 0 & 0 \\ 0 & 0 & S_{33} & S_{34} \\ 0 & 0 & -S_{34} & S_{33} \end{pmatrix} \begin{pmatrix} I_i \\ Q_i \\ U_i \\ V_i \end{pmatrix}$$

Example: incident light is 100% polarized perpendicular to the scattering plane

$$\begin{pmatrix} I_i \\ -I_i \\ 0 \\ 0 \end{pmatrix} \Rightarrow I_s = (S_{11} - S_{12}) I_i \,, \quad Q_s = -I_s \,, \quad U_s = V_s = 0 \quad \Rightarrow \quad P_l = 1$$

Scattered light is also 100% polarized perpendicular to the scattering plane

Scattering Matrix – Ensemble of non-spherical particles

$$\begin{pmatrix} I_s \\ Q_s \\ U_s \\ V_s \end{pmatrix} = \frac{1}{\mathrm{k}^2 r^2} \begin{pmatrix} S_{11} & S_{12} & 0 & 0 \\ S_{12} & S_{22} & 0 & 0 \\ 0 & 0 & S_{33} & S_{34} \\ 0 & 0 & -S_{34} & S_{44} \end{pmatrix} \begin{pmatrix} I_i \\ Q_i \\ U_i \\ V_i \end{pmatrix}$$

Example: incident light is 100% polarized parallel to the scattering plane

$$\begin{pmatrix} I_i \\ I_i \\ 0 \\ 0 \end{pmatrix} \Rightarrow I_s = \left(S_{11} + S_{12}\right) I_i \,, \quad Q_s = \left(S_{12} + S_{22}\right) I_i \,, \quad U_s = V_s = 0 \quad \Rightarrow \quad P = -\frac{S_{12} + S_{22}}{S_{11} + S_{12}}$$

Scattered light is in general partially polarized, i.e. the incident light is depolarized

How to measure depolarization?

$$\Delta = 1 - \frac{S_{22}}{S_{11}}$$

light at detector | analyzer | particles | incident light

0° linear polarizer:

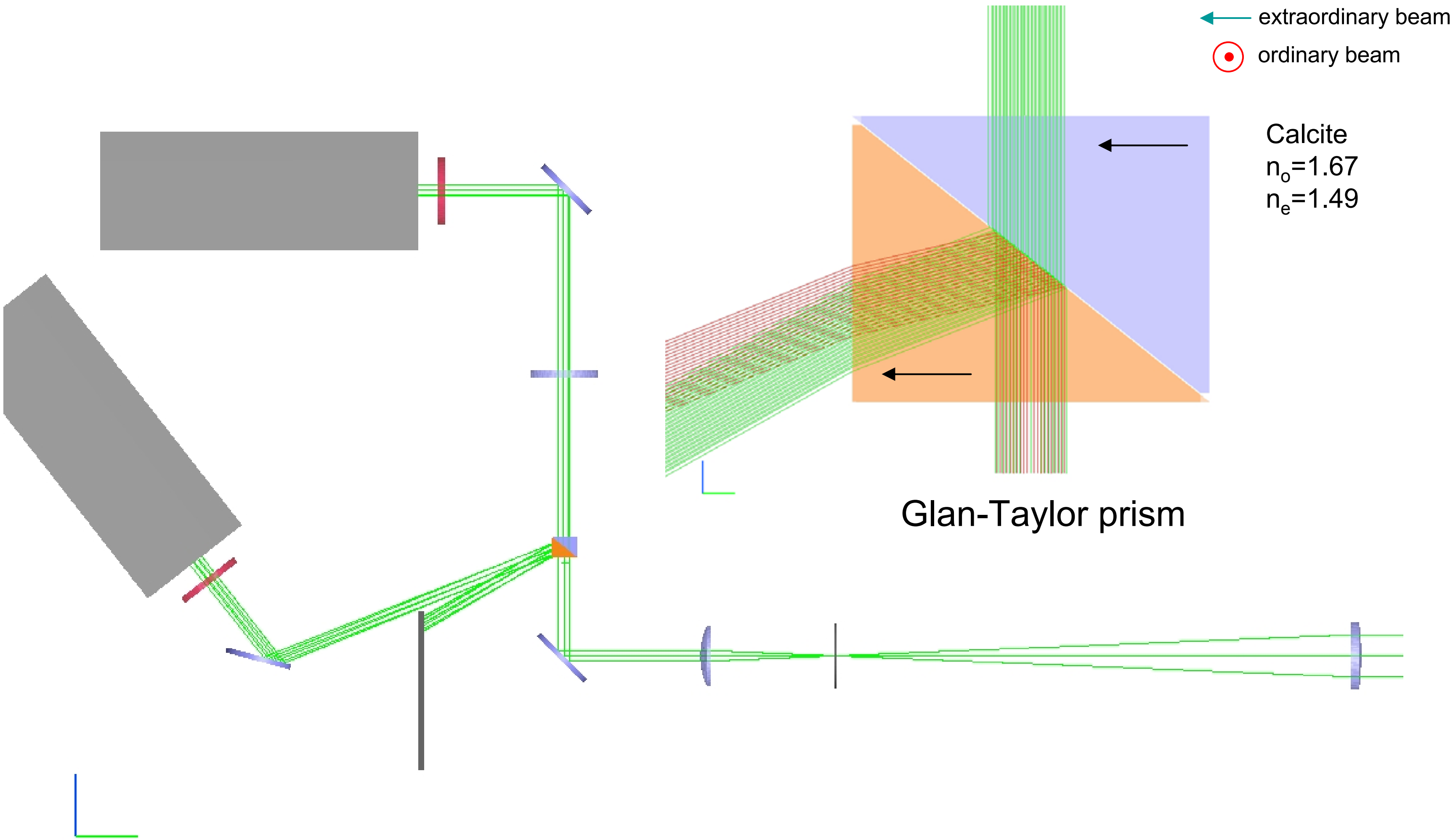
$$\frac{1}{2} I_i \begin{pmatrix} S_{11} + 2S_{12} + S_{22} \\ S_{11} + 2S_{12} + S_{22} \\ 0 \\ 0 \end{pmatrix} = \frac{1}{2} \begin{pmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} S_{11} & S_{12} & 0 & 0 \\ S_{12} & S_{22} & 0 & 0 \\ 0 & 0 & S_{33} & S_{34} \\ 0 & 0 & -S_{34} & S_{44} \end{pmatrix} \cdot \begin{pmatrix} I_i \\ I_i \\ 0 \\ 0 \end{pmatrix}$$

90° linear polarizer:

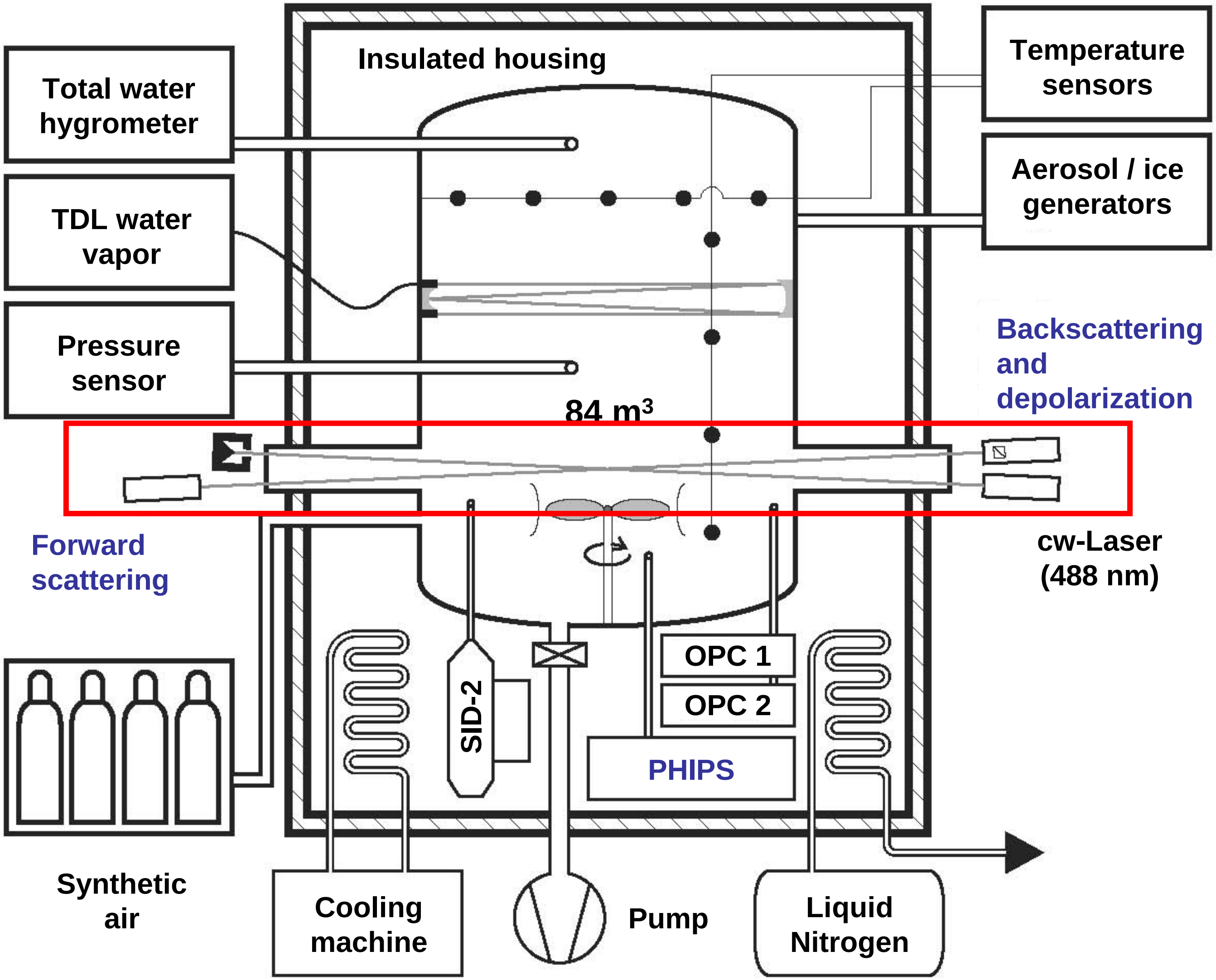
$$\frac{1}{2} I_i \begin{pmatrix} S_{11} - S_{22} \\ S_{22} - S_{11} \\ 0 \\ 0 \end{pmatrix} = \frac{1}{2} \begin{pmatrix} 1 & -1 & 0 & 0 \\ -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} S_{11} & S_{12} & 0 & 0 \\ S_{12} & S_{22} & 0 & 0 \\ 0 & 0 & S_{33} & S_{34} \\ 0 & 0 & -S_{34} & S_{44} \end{pmatrix} \cdot \begin{pmatrix} I_i \\ I_i \\ 0 \\ 0 \end{pmatrix}$$

$$\delta_H = \frac{I_\perp}{I_\parallel} = \frac{S_{11} - S_{22}}{S_{11} + 2S_{12} + S_{22}} \xrightarrow[\text{LIDAR}]{S_{12}=0 \text{ at } 180°} \frac{S_{22}}{S_{11}} = \frac{1-\delta_H}{1+\delta_H}$$

For scattering angles ≠180° δ_H is a mixture of S_{11} and S_{12}



extraordinary beam
ordinary beam
Calcite
n_o=1.67
n_e=1.49
Glan-Taylor prism

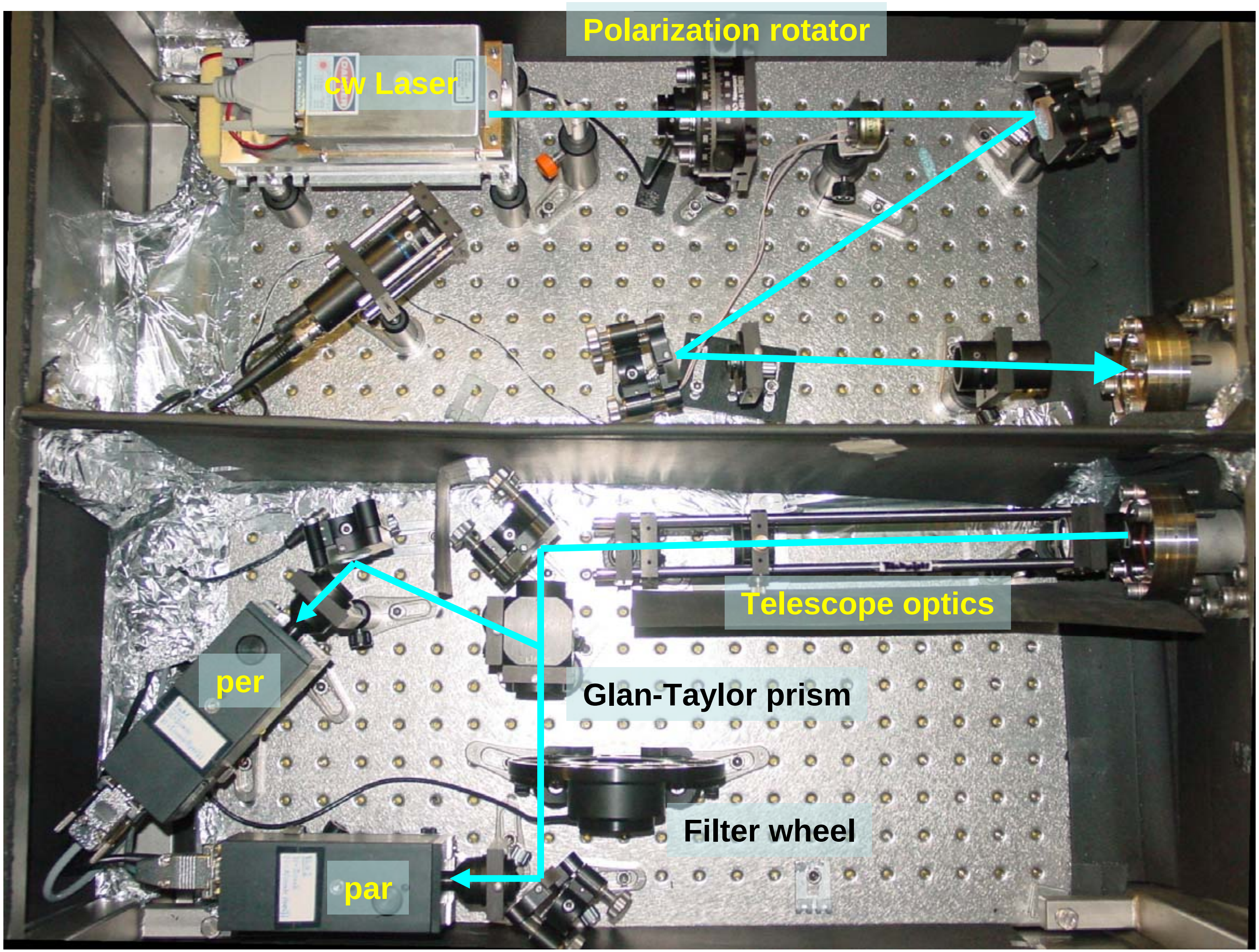


Insulated housing
Total water hygrometer
TDL water vapor
Pressure sensor
Temperature sensors
Aerosol / ice generators
Backscattering and depolarization
84 m³
Forward scattering
cw-Laser (488 nm)
SID-2
OPC 1
OPC 2
PHIPS
Synthetic air
Cooling machine
Pump
Liquid Nitrogen

Emitting

Unit

488 nm



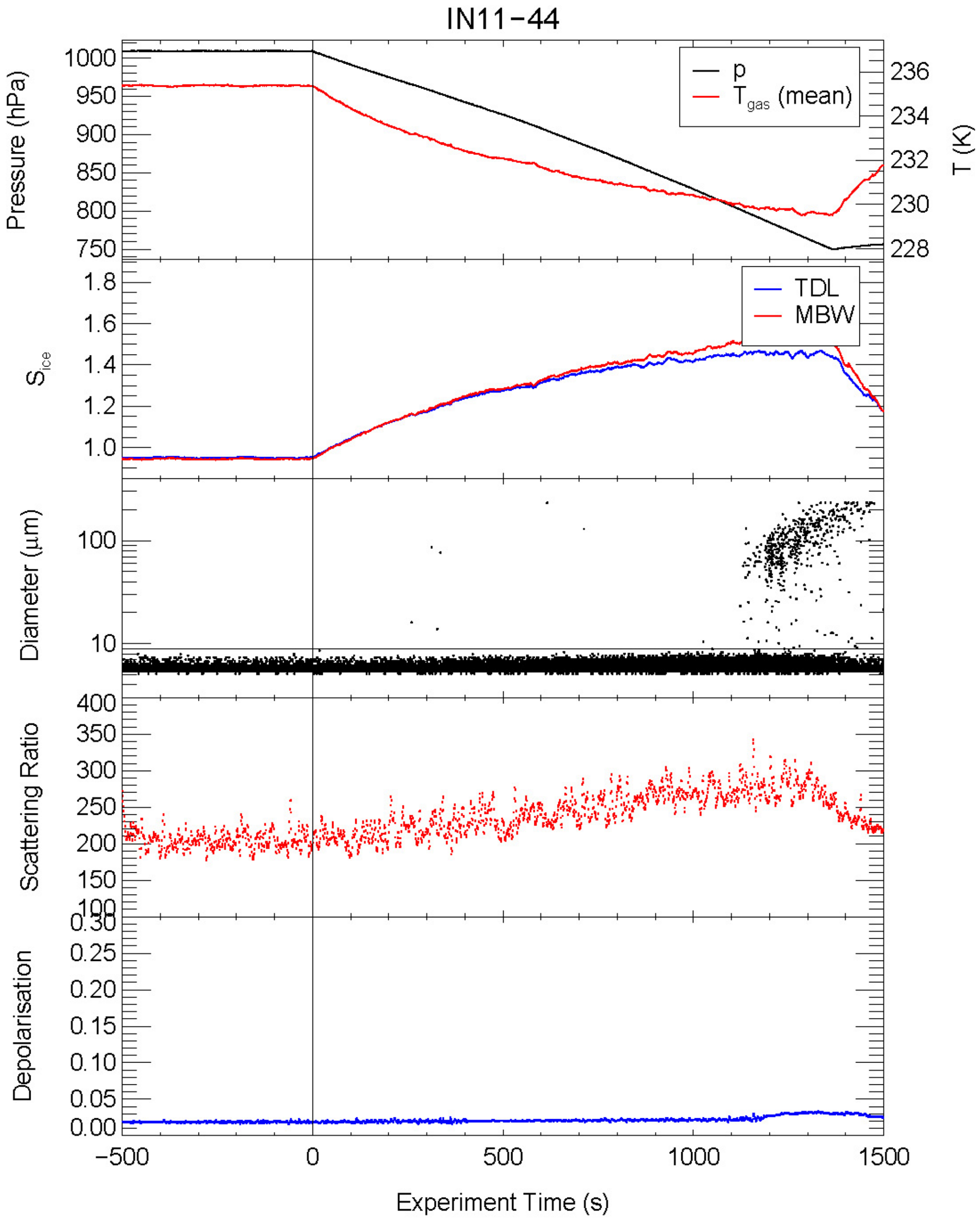
AIDA

Receiving

Unit

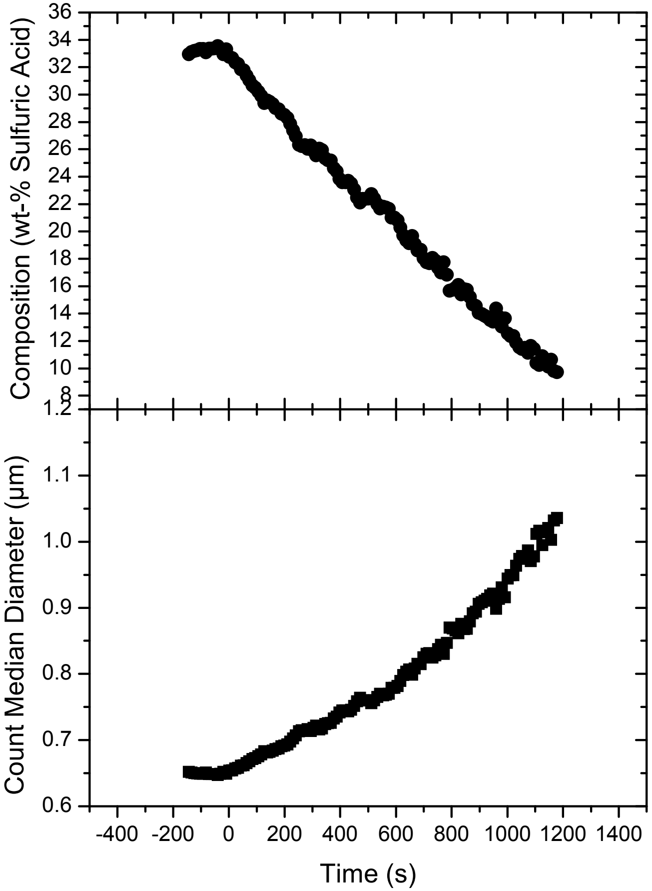
178.2°

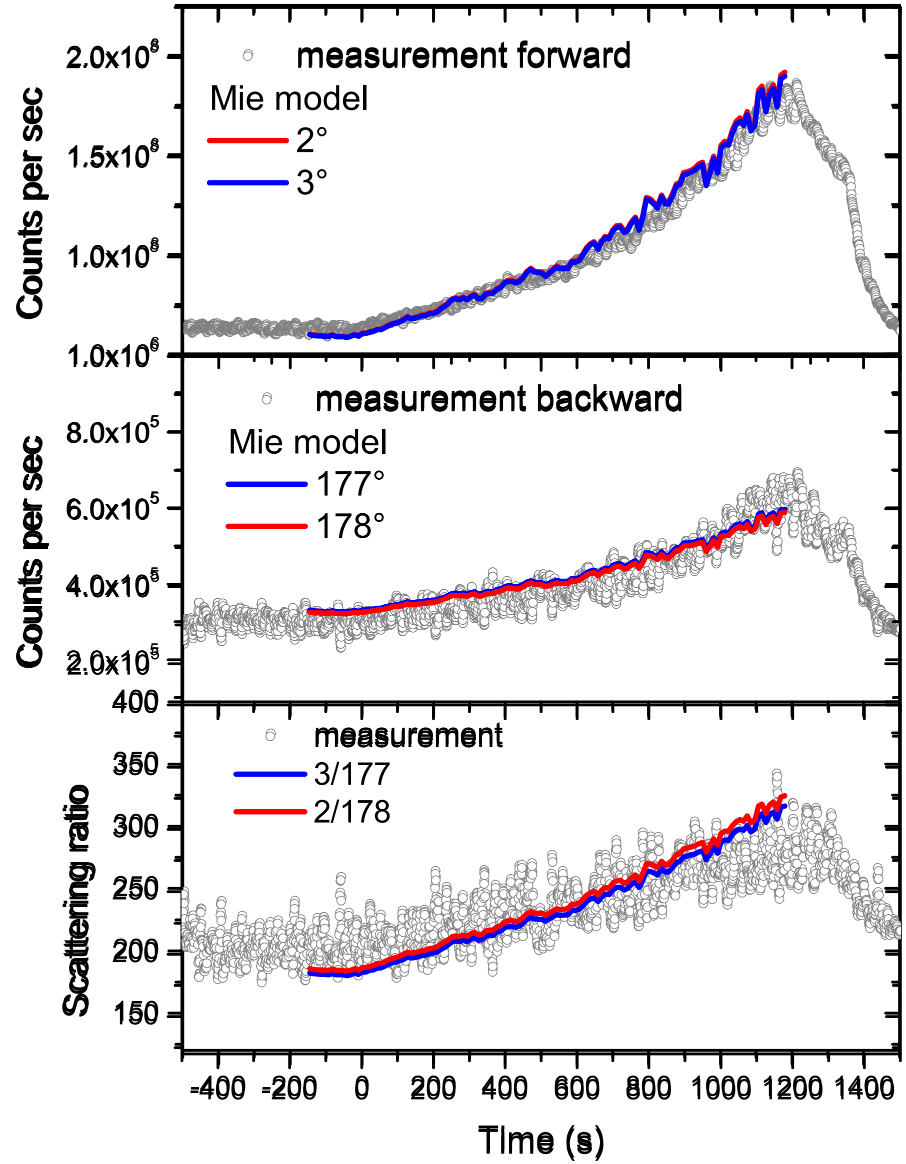
Growth of sulfuric acid aerosol by water uptake



IN11-44

FTIR results



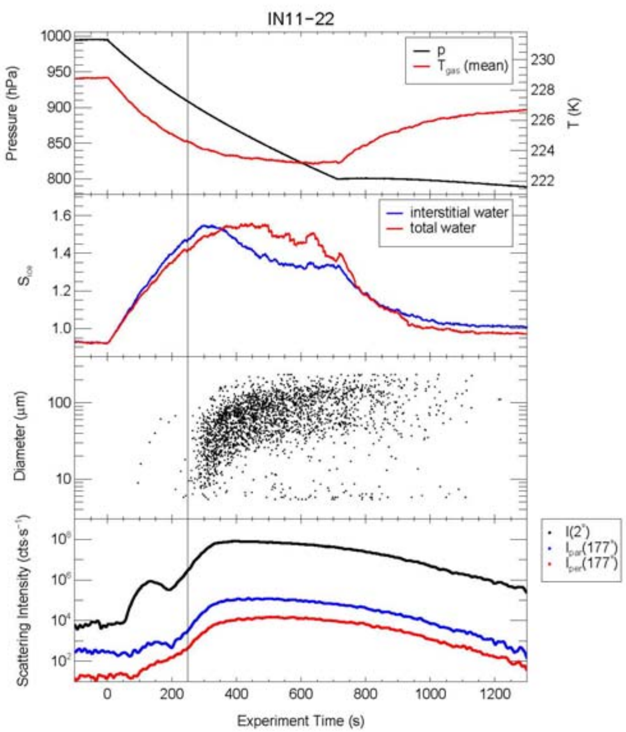


Ice nucleation on flame soot (CAST) of different organic carbon contents

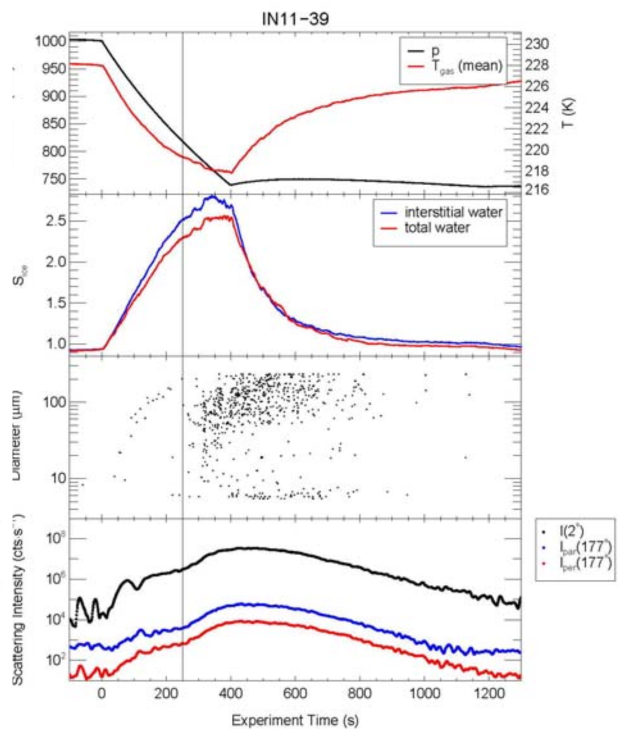
Min OC (C/O: 0.28) | Med OC (C/O: 0.39) | Max OC (C/O: 0.54)

T = -45°C

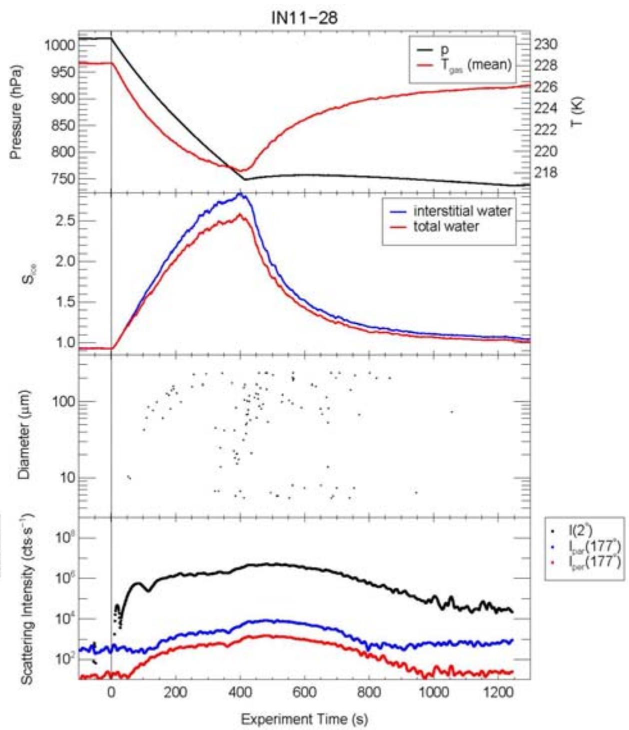
IN11-22, P2 40%



IN11-39, P2 95%



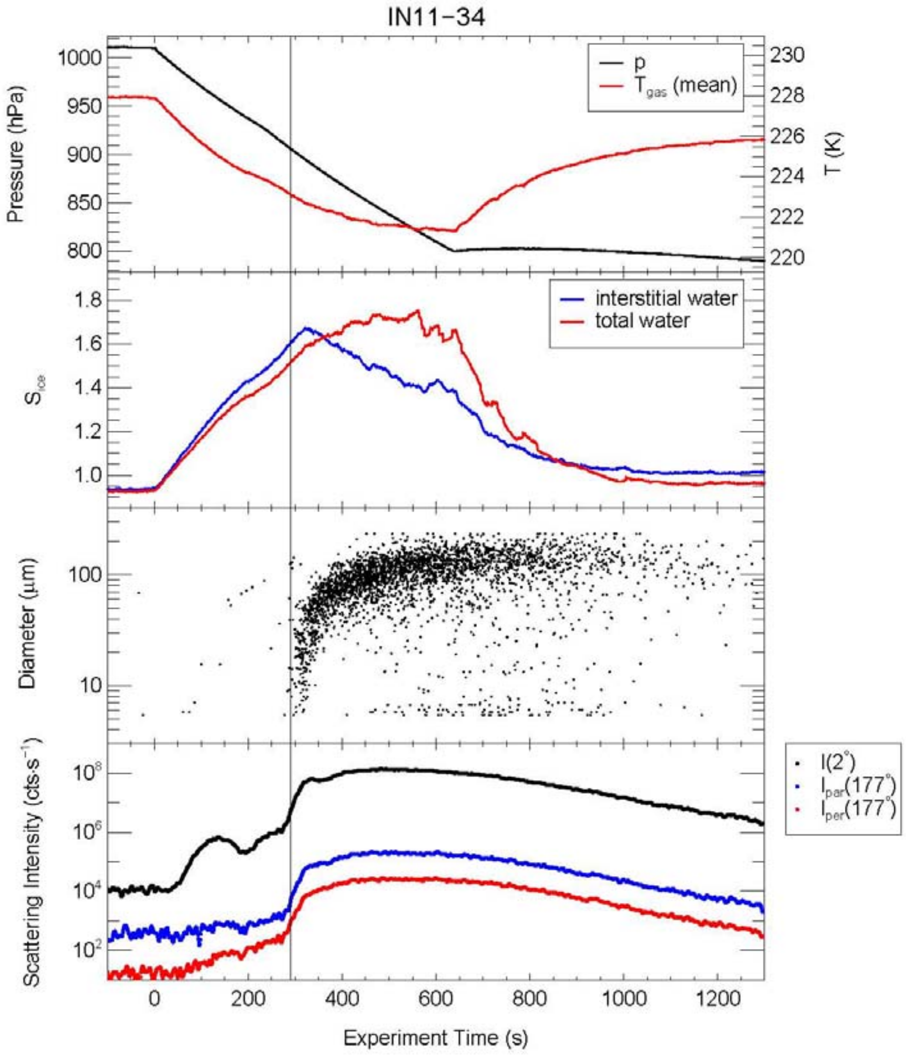
IN11-28, P2 90%

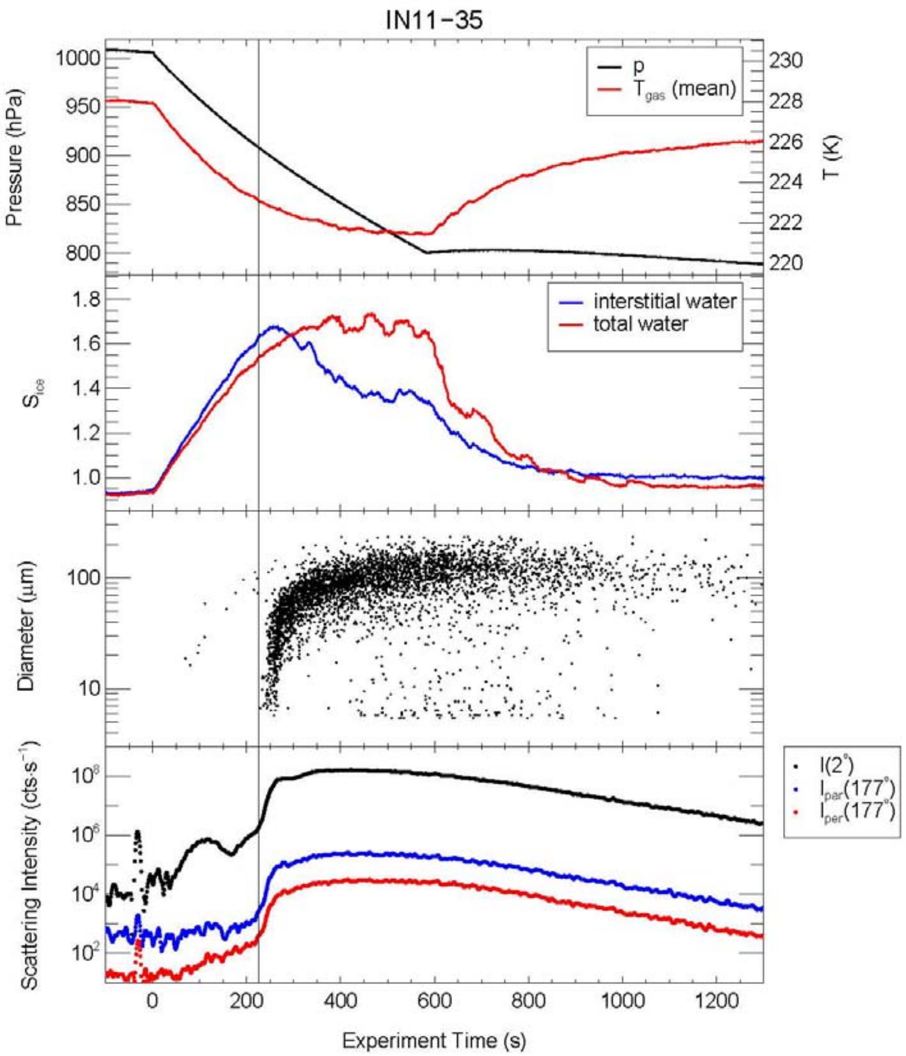


Organic carbon content →

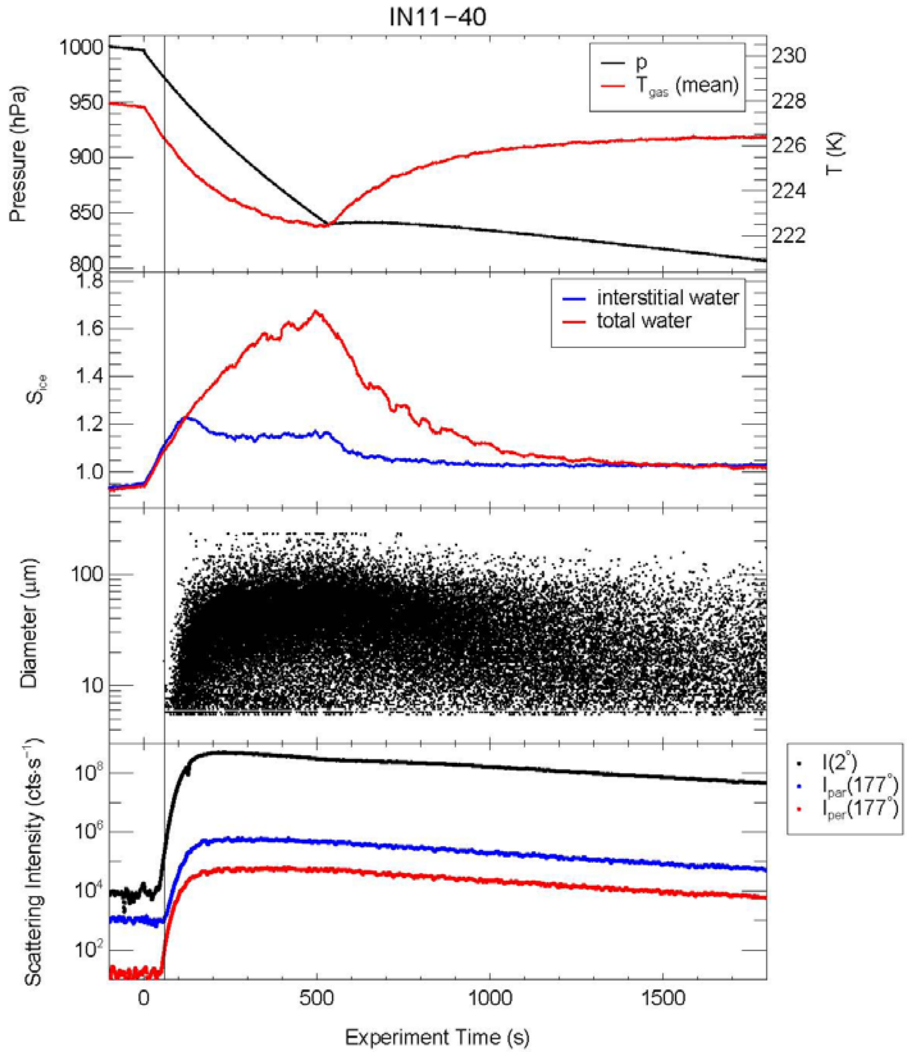
← Ice nucleation activity

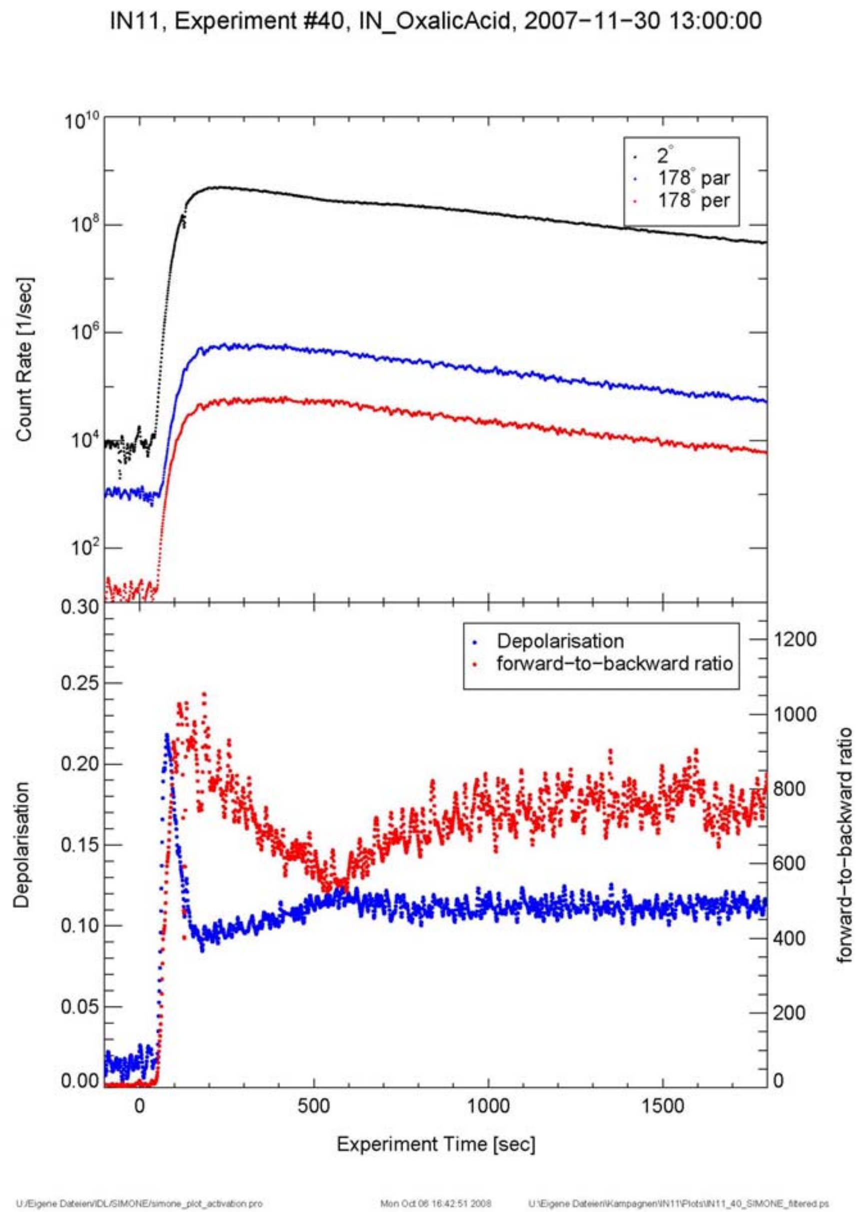
CAST soot (medium organic content), coated by sulphuric acid



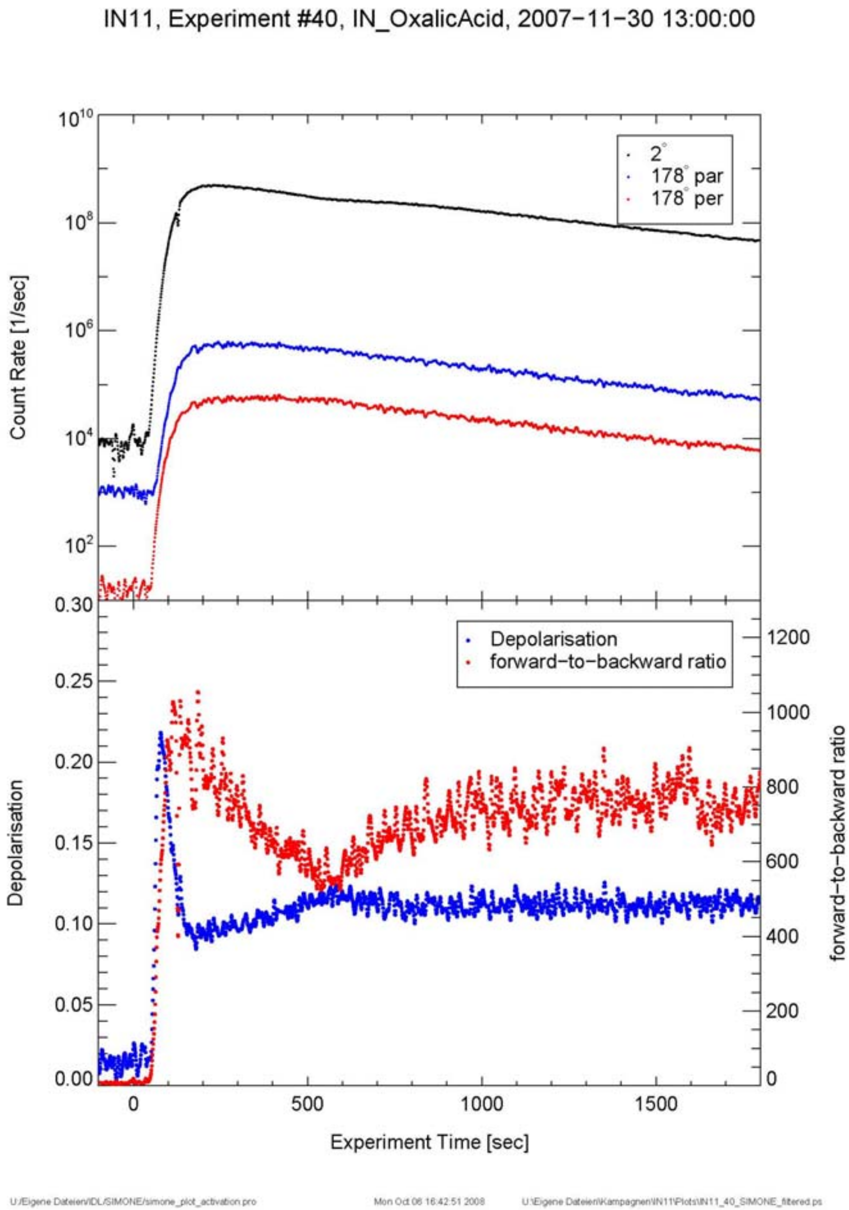


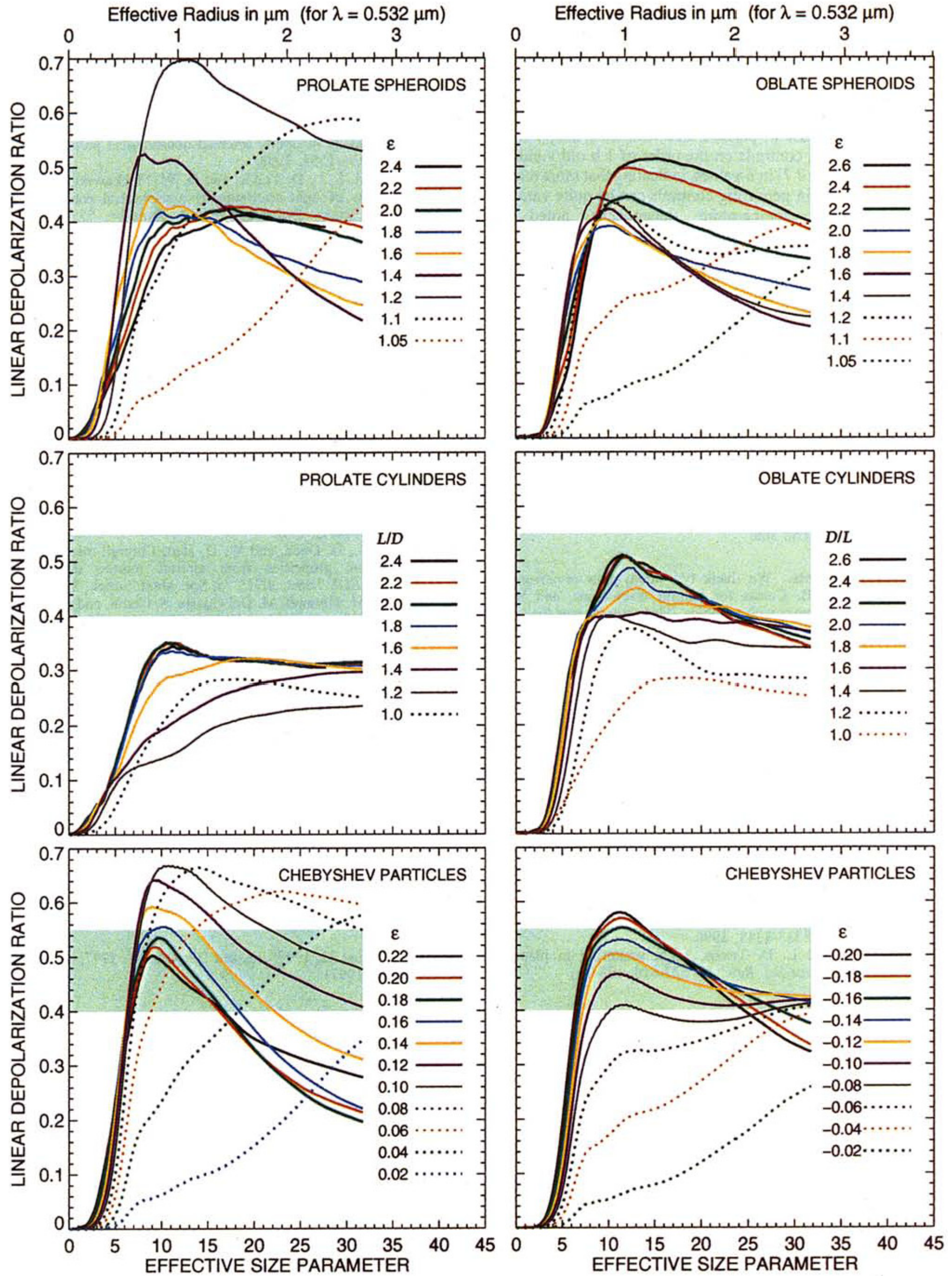
First experiments with oxalic acid (30/11/07)





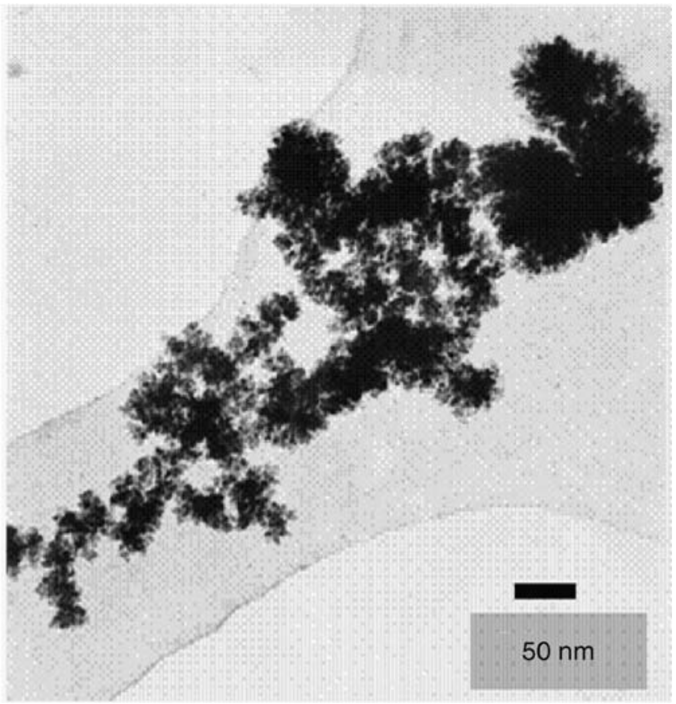
microphysical properties of slowly growing ice crystals





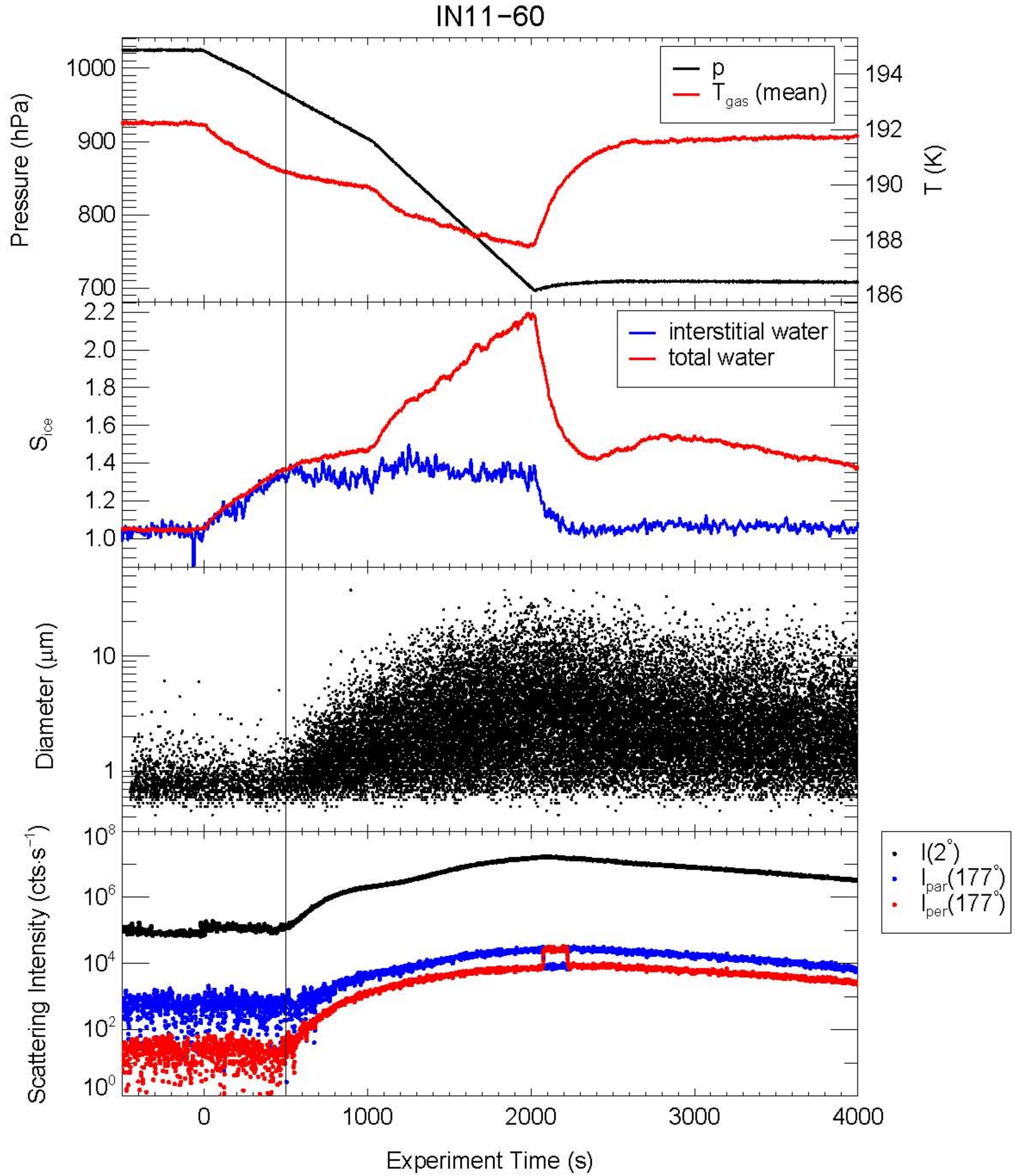
Mishchenko & Sassen, 1998

Ice Nucleation on Meteoric Smoke Analogues

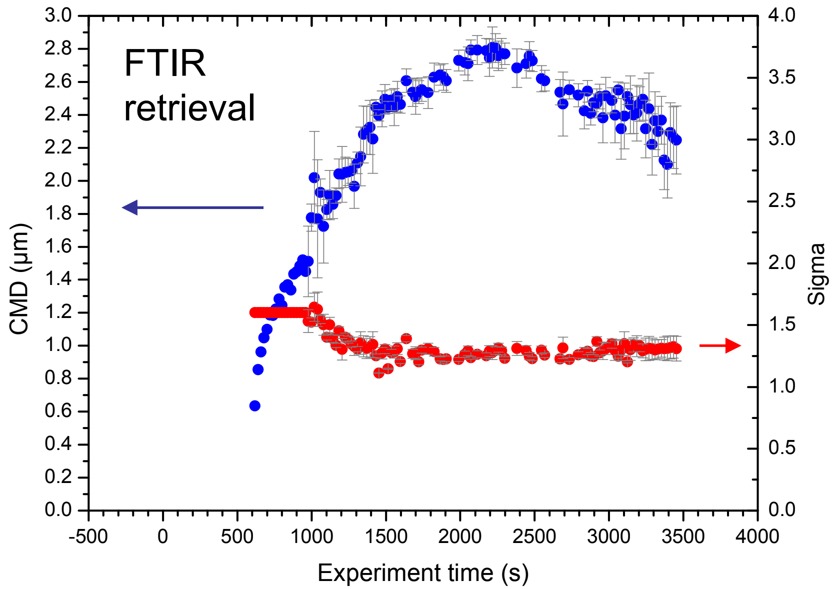


Meteor smoke analogue particle generated by the photo-oxidation of iron pentacarbonyl

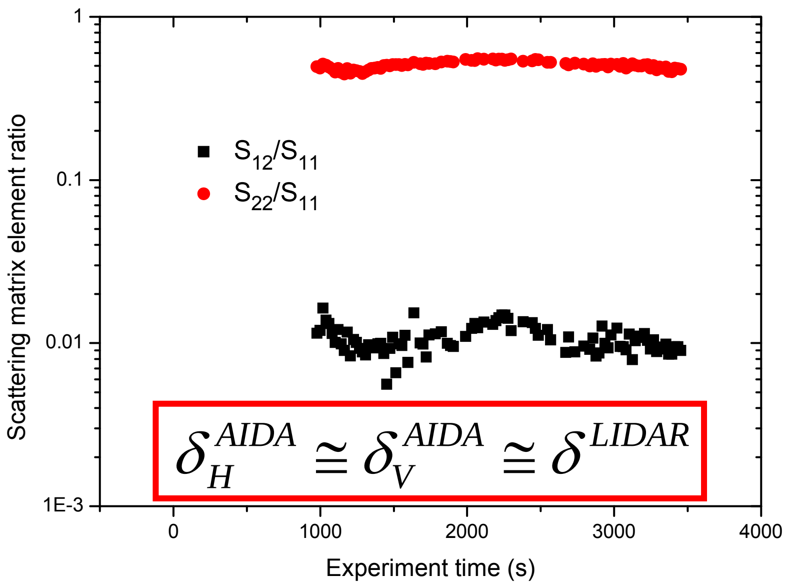
(Saunders and Plane, 2006)



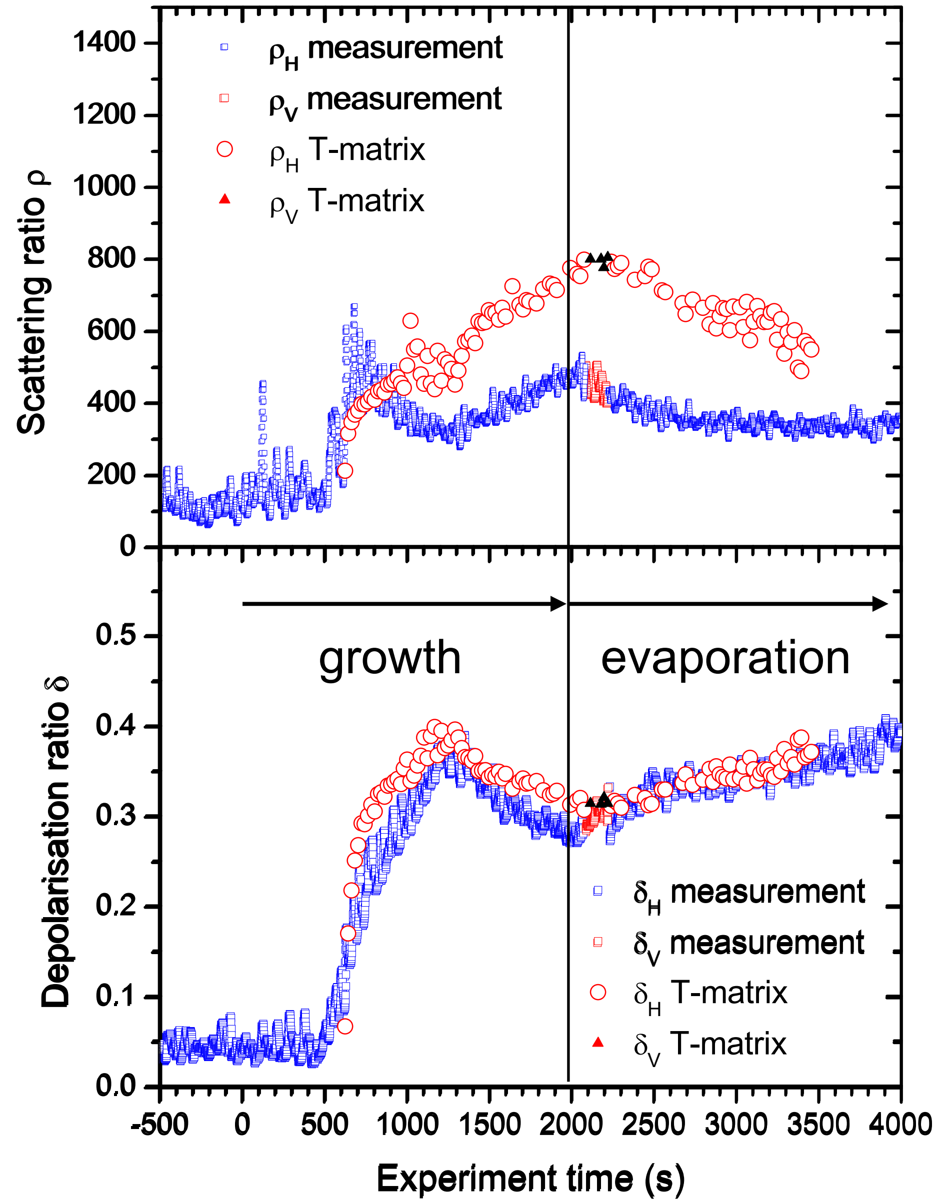
IN11-60



FTIR
retrieval
CMD (µm)
Sigma
Experiment time (s)

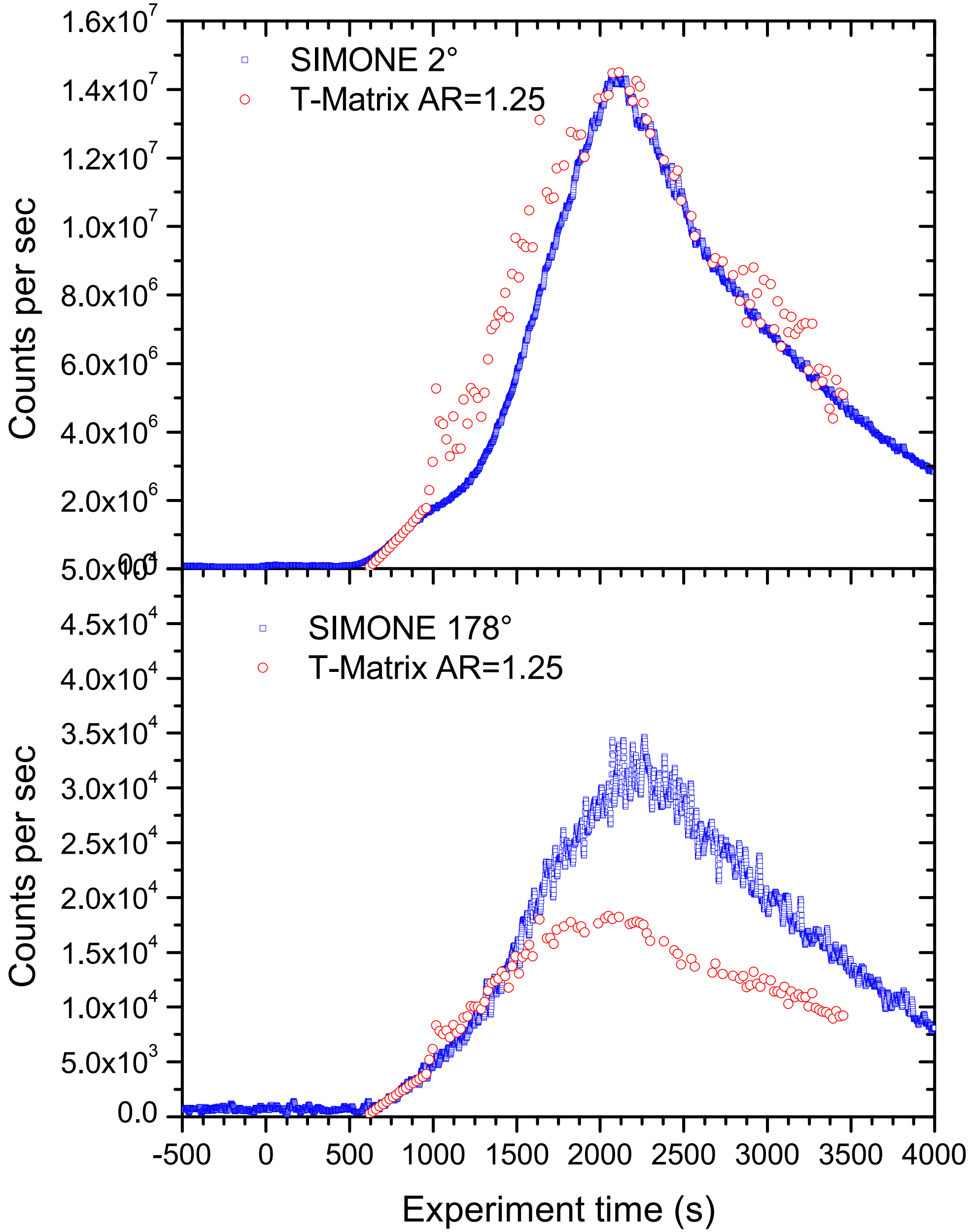


S_{12}/S_{11}
S_{22}/S_{11}
Scattering matrix element ratio
Experiment time (s)
$\delta_H^{AIDA} \cong \delta_V^{AIDA} \cong \delta^{LIDAR}$

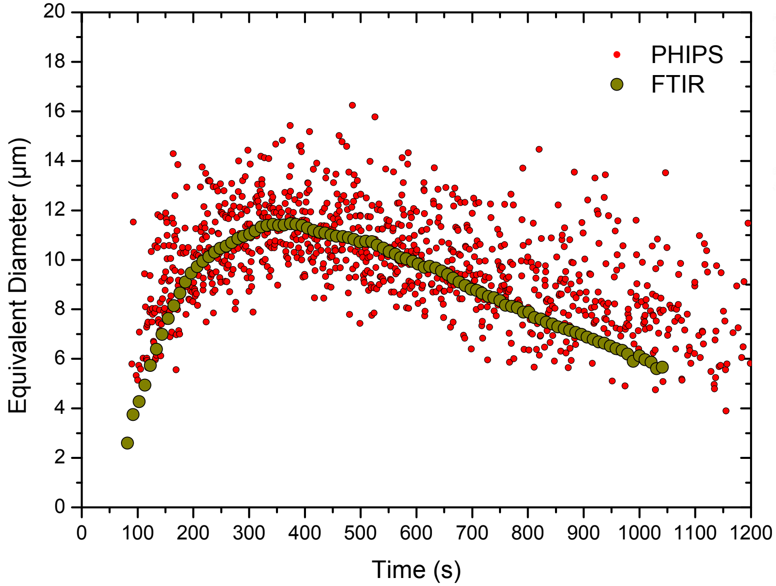


ρ_H measurement
ρ_V measurement
ρ_H T-matrix
ρ_V T-matrix
Scattering ratio ρ
growth
evaporation
δ_H measurement
δ_V measurement
δ_H T-matrix
δ_V T-matrix
Depolarisation ratio δ
Experiment time (s)

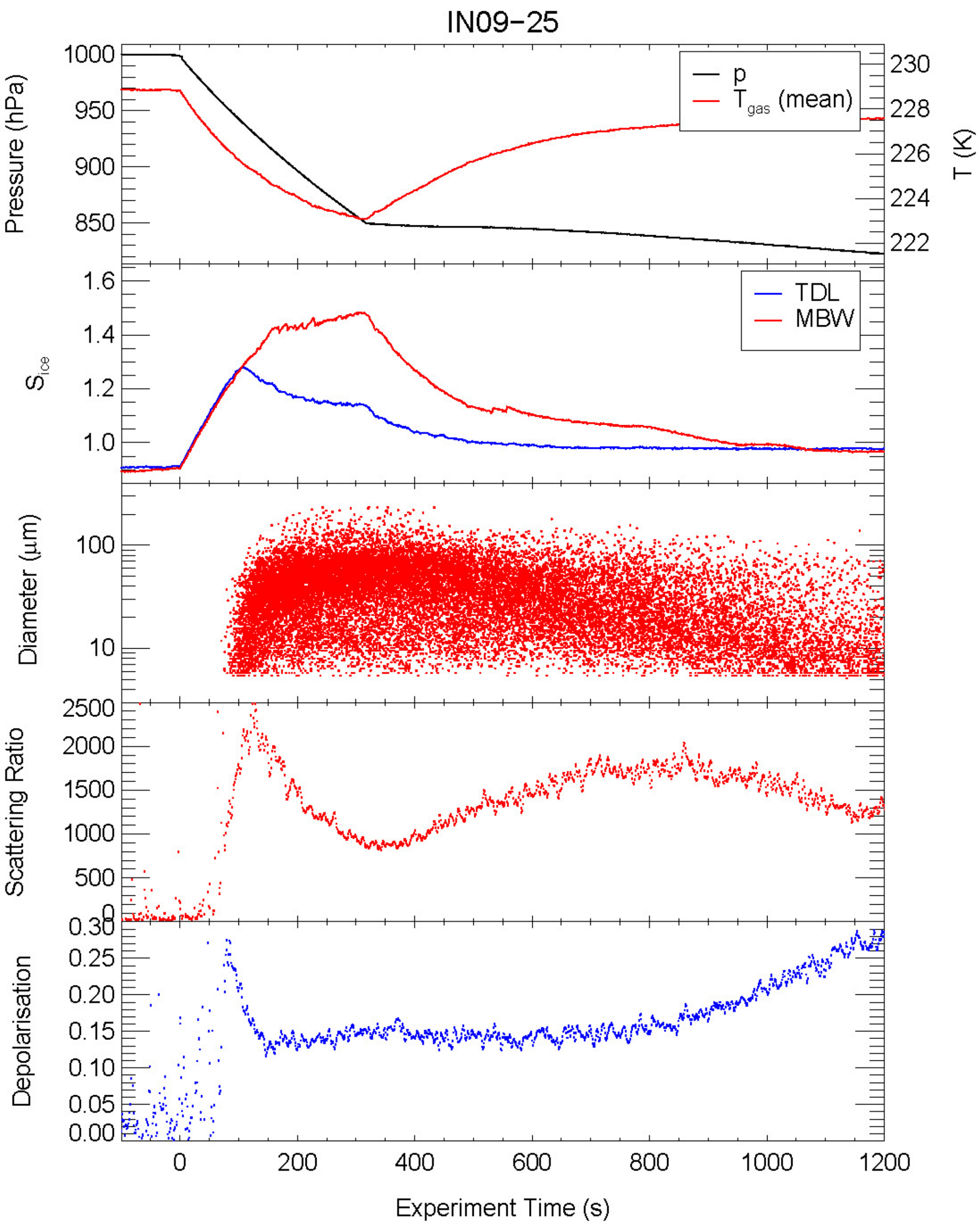
IN11-60



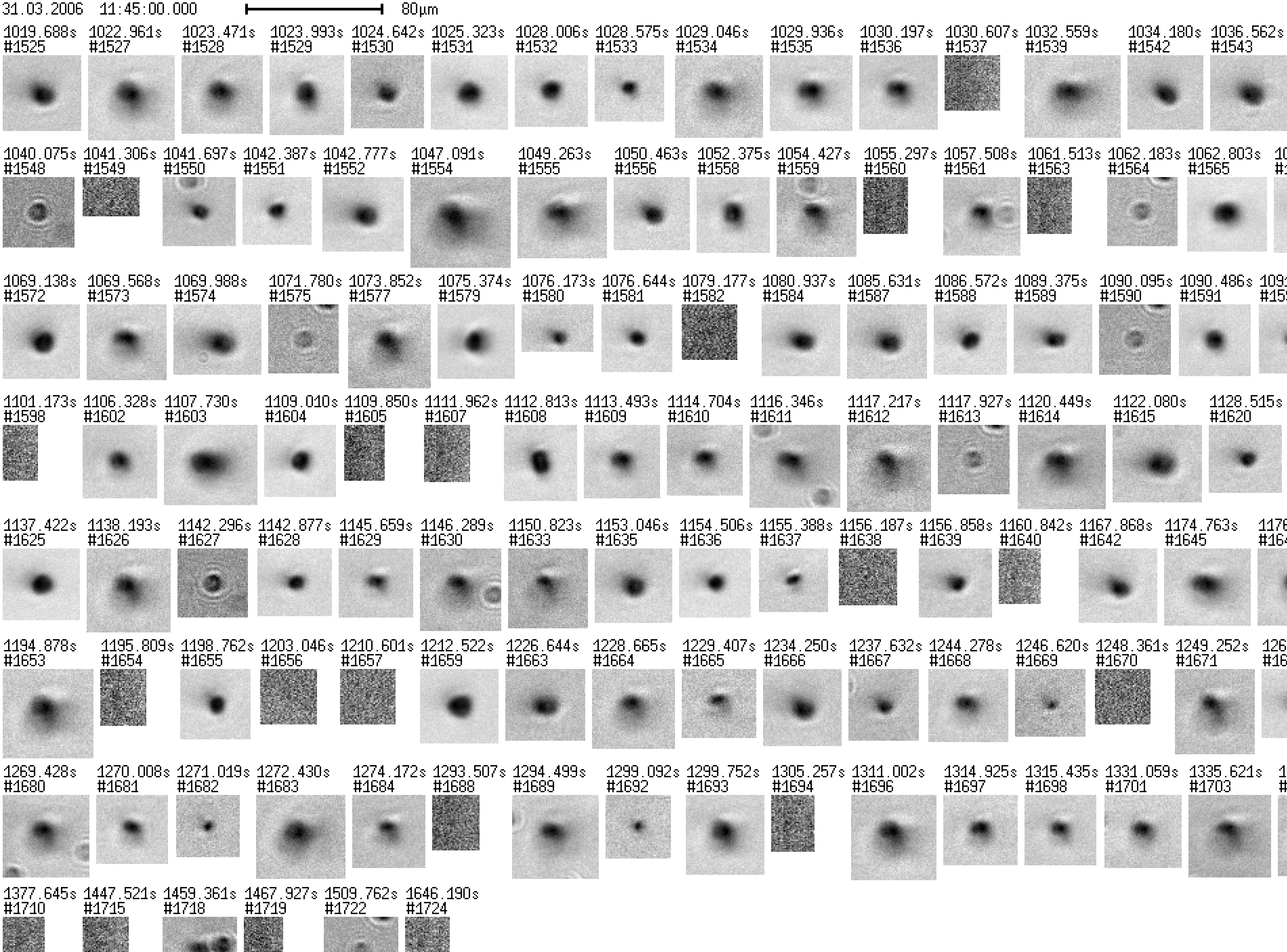
SIMONE 2°
T-Matrix AR=1.25
SIMONE 178°
T-Matrix AR=1.25
Counts per sec
Counts per sec
Experiment time (s)
1.6x10^7
1.4x10^7
1.2x10^7
1.0x10^7
8.0x10^6
6.0x10^6
4.0x10^6
2.0x10^6
0.0
5.0x10^4
4.5x10^4
4.0x10^4
3.5x10^4
3.0x10^4
2.5x10^4
2.0x10^4
1.5x10^4
1.0x10^4
5.0x10^3
0.0
-500 0 500 1000 1500 2000 2500 3000 3500 4000

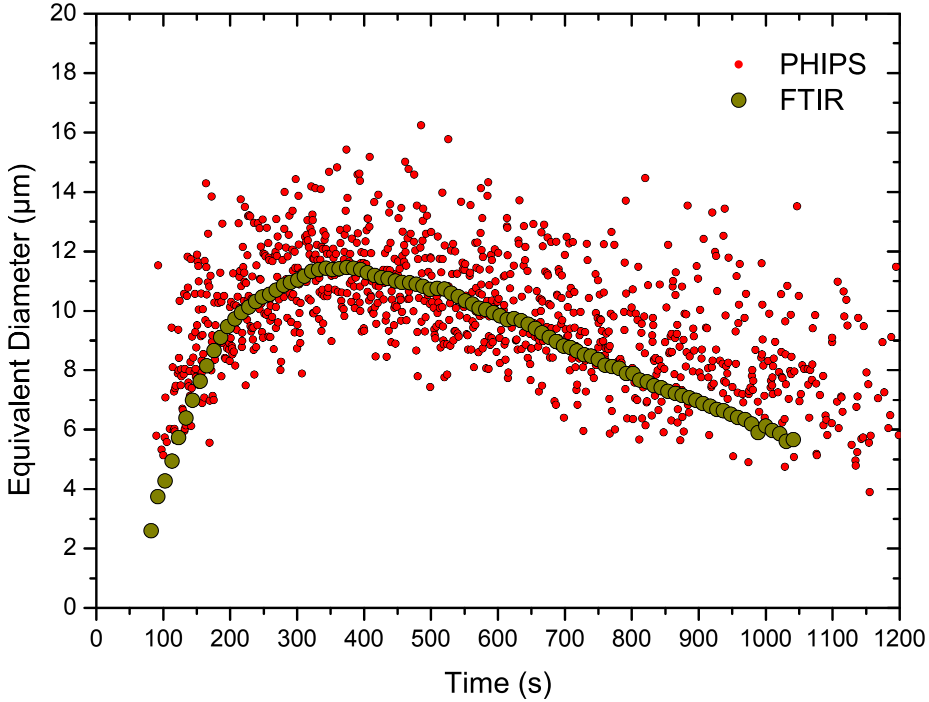


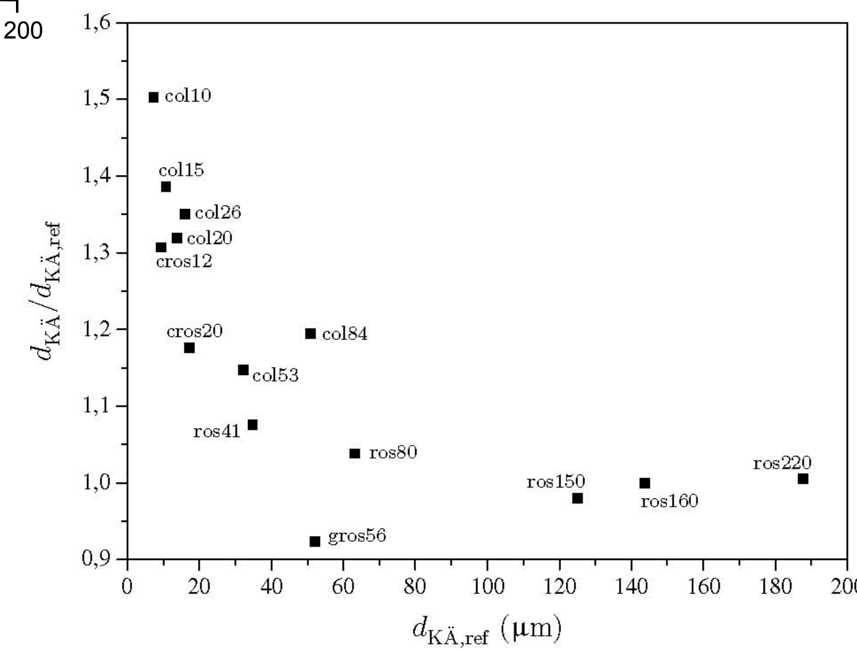
PHIPS
FTIR
Equivalent Diameter (μm)
Time (s)

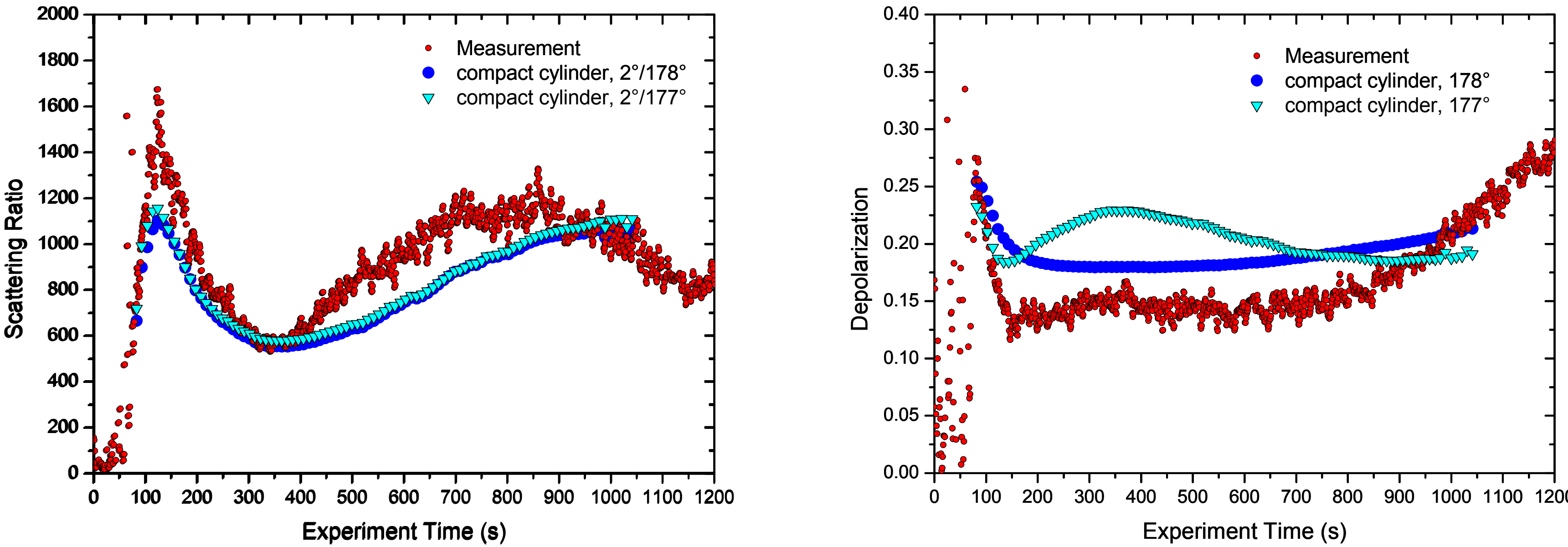


IN09-25
p
T_{gas} (mean)
Pressure (hPa)
T (K)
TDL
MBW
S_{ice}
Diameter (μm)
Scattering Ratio
Depolarisation
Experiment Time (s)

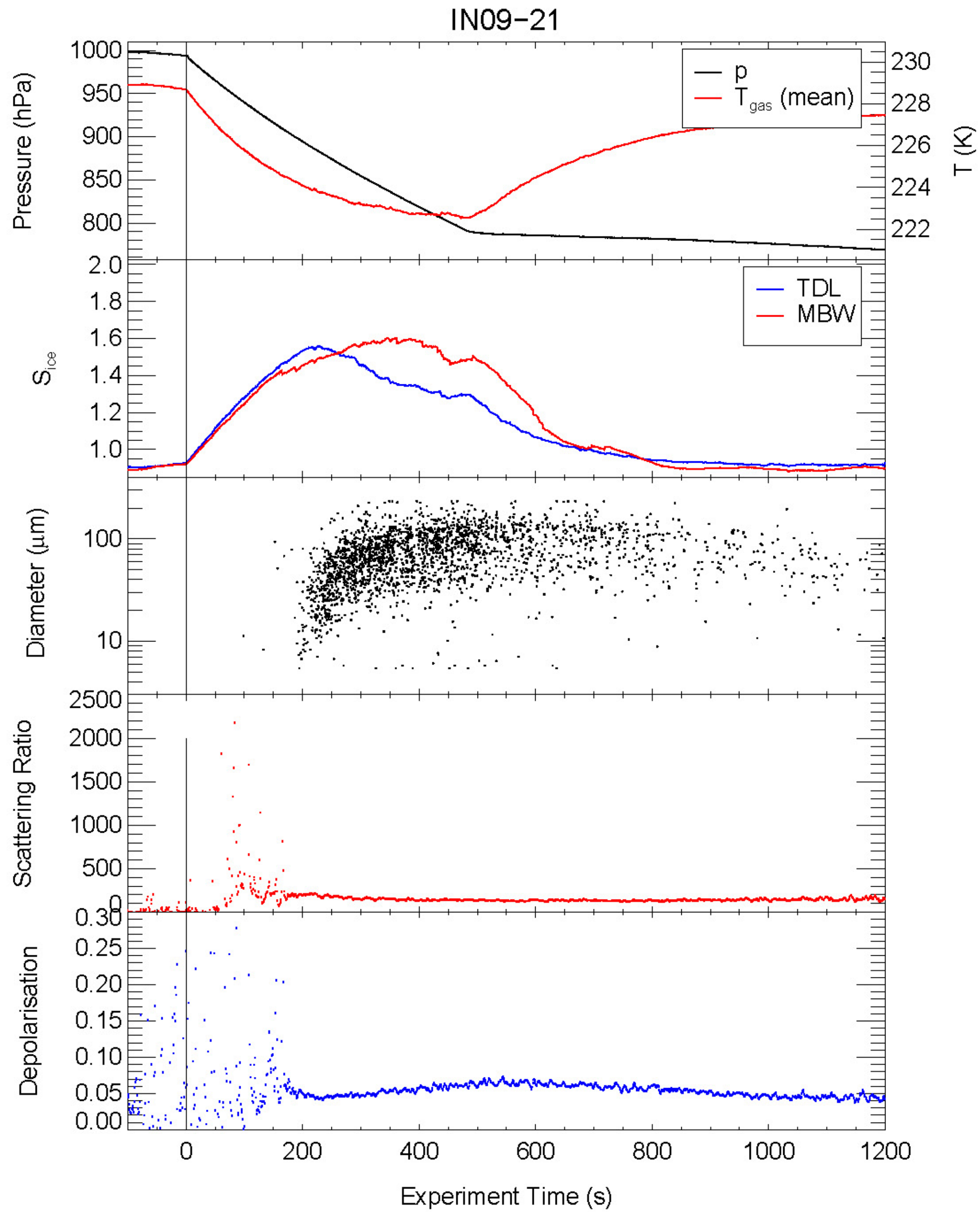

31.03.2006 11:45:00.000
80µm
1019.688s #1525
1022.961s #1527
1023.471s #1528
1023.993s #1529
1024.642s #1530
1025.323s #1531
1028.006s #1532
1028.575s #1533
1029.046s #1534
1029.936s #1535
1030.197s #1536
1030.607s #1537
1032.559s #1539
1034.180s #1542
1036.562s #1543
1040.075s #1548
1041.306s #1549
1041.697s #1550
1042.387s #1551
1042.777s #1552
1047.091s #1554
1049.263s #1555
1050.463s #1556
1052.375s #1558
1054.427s #1559
1055.297s #1560
1057.508s #1561
1061.513s #1563
1062.183s #1564
1062.803s #1565
1069.138s #1572
1069.568s #1573
1069.988s #1574
1071.780s #1575
1073.852s #1577
1075.374s #1579
1076.173s #1580
1076.644s #1581
1079.177s #1582
1080.937s #1584
1085.631s #1587
1086.572s #1588
1089.375s #1589
1090.095s #1590
1090.486s #1591
1101.173s #1598
1106.328s #1602
1107.730s #1603
1109.010s #1604
1109.850s #1605
1111.962s #1607
1112.813s #1608
1113.493s #1609
1114.704s #1610
1116.346s #1611
1117.217s #1612
1117.927s #1613
1120.449s #1614
1122.080s #1615
1128.515s #1620
1137.422s #1625
1138.193s #1626
1142.296s #1627
1142.877s #1628
1145.659s #1629
1146.289s #1630
1150.823s #1633
1153.046s #1635
1154.506s #1636
1155.388s #1637
1156.187s #1638
1156.858s #1639
1160.842s #1640
1167.868s #1642
1174.763s #1645
1194.878s #1653
1195.809s #1654
1198.762s #1655
1203.046s #1656
1210.601s #1657
1212.522s #1659
1226.644s #1663
1228.665s #1664
1229.407s #1665
1234.250s #1666
1237.632s #1667
1244.278s #1668
1246.620s #1669
1248.361s #1670
1249.252s #1671
1269.428s #1680
1270.008s #1681
1271.019s #1682
1272.430s #1683
1274.172s #1684
1293.507s #1688
1294.499s #1689
1299.092s #1692
1299.752s #1693
1305.257s #1694
1311.002s #1696
1314.925s #1697
1315.435s #1698
1331.059s #1701
1335.621s #1703
1377.645s #1710
1447.521s #1715
1459.361s #1718
1467.927s #1719
1509.762s #1722
1646.190s #1724


PHIPS
FTIR
Equivalent Diameter (µm)
Time (s)

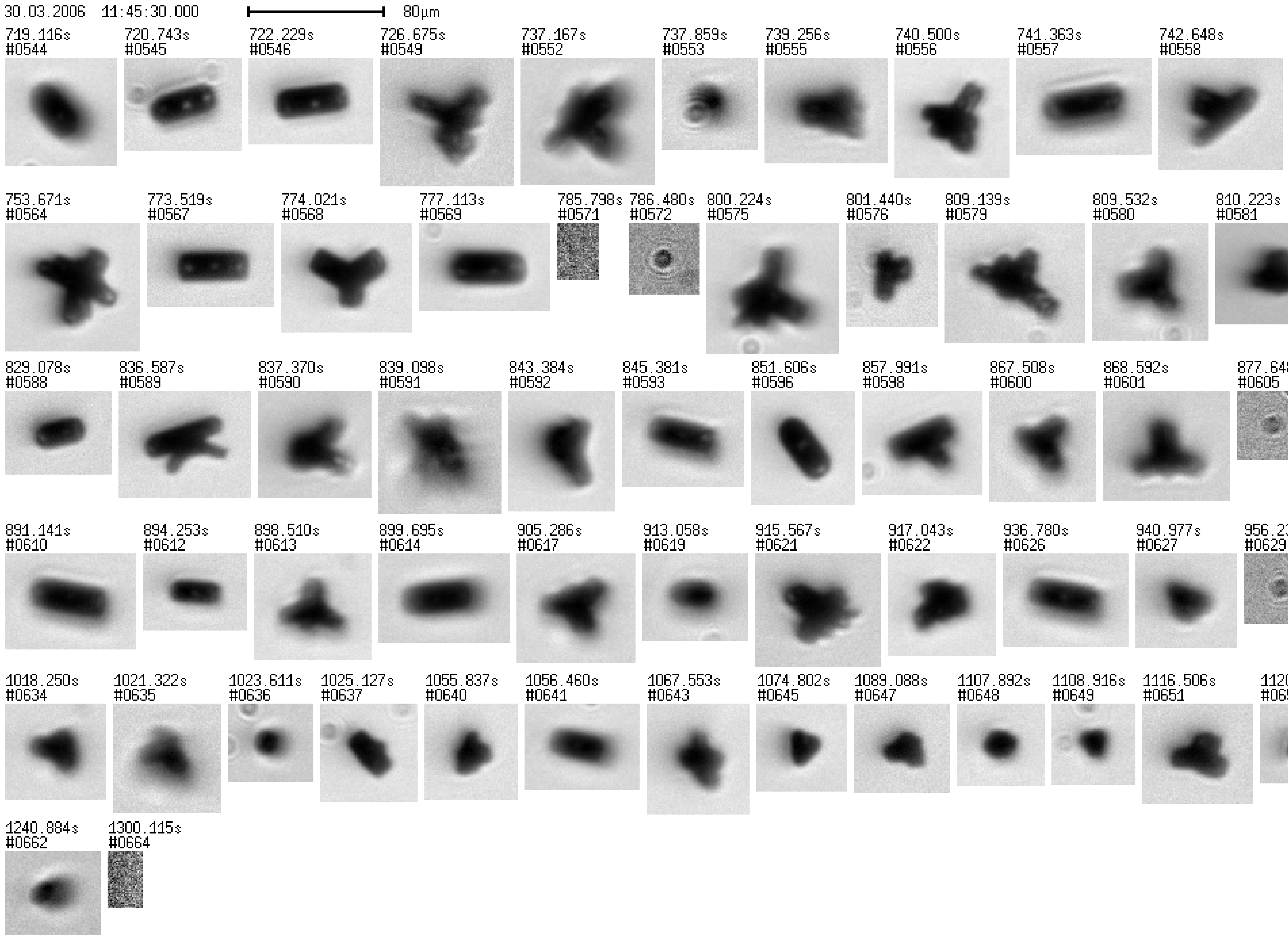

col10
col15
col26
col20
cros12
cros20
col84
col53
ros41
ros80
ros150
ros160
ros220
gros56
$d_{KÄ}/d_{KÄ,ref}$
$d_{KÄ,ref}$ (µm)



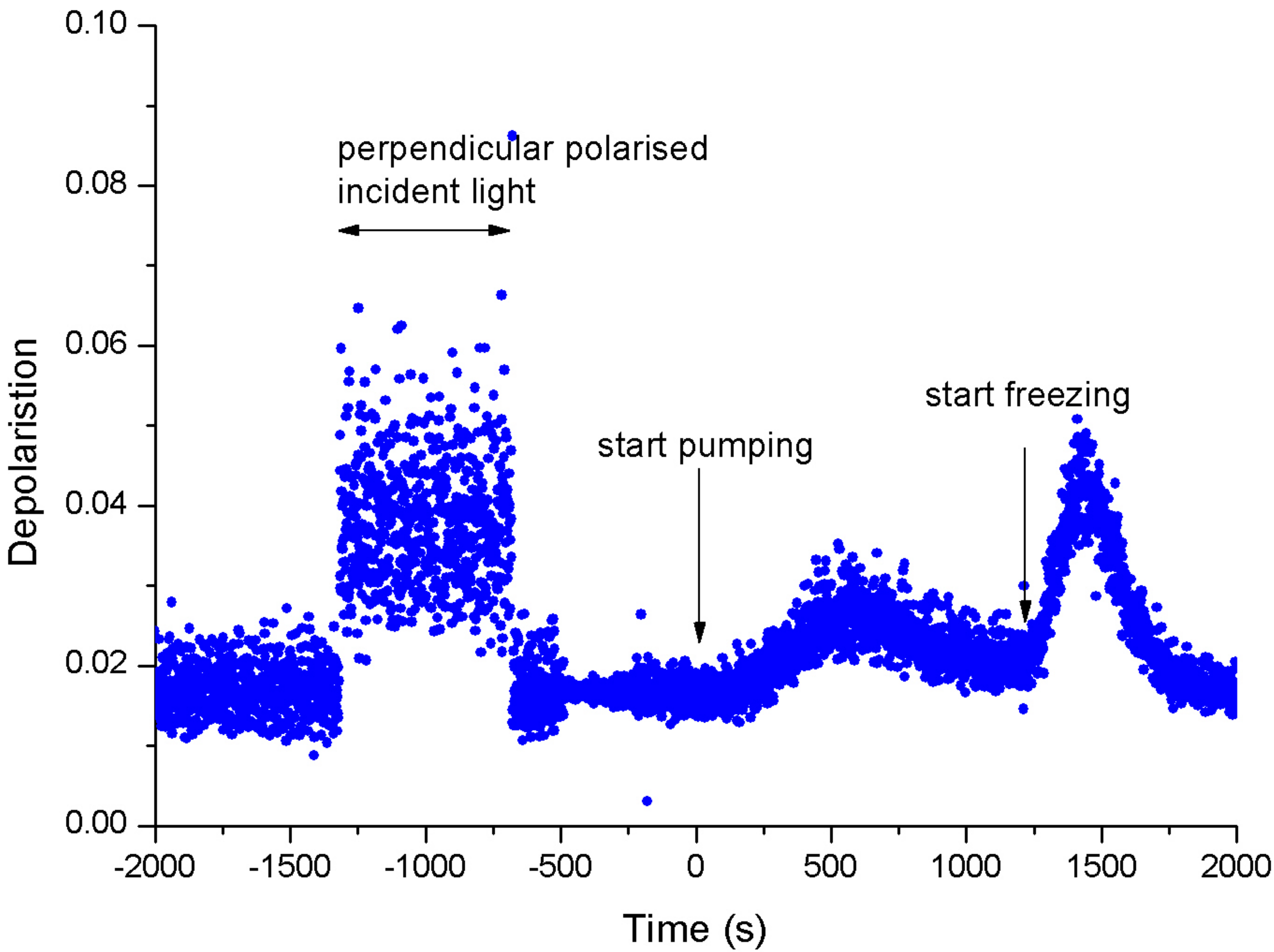
Scattering Ratio
Experiment Time (s)
Measurement
compact cylinder, 2°/178°
compact cylinder, 2°/177°
Depolarization
Experiment Time (s)
Measurement
compact cylinder, 178°
compact cylinder, 177°



IN09−21
1000
950
900
850
800
Pressure (hPa)
230
228
226
224
222
T (K)
p
T_{gas} (mean)
2.0
1.8
1.6
1.4
1.2
1.0
S_{ice}
TDL
MBW
100
10
Diameter (µm)
2500
2000
1500
1000
500
0
Scattering Ratio
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Depolarisation
0
200
400
600
800
1000
1200
Experiment Time (s)



30.03.2006 11:45:30.000
80µm
719.116s #0544
720.743s #0545
722.229s #0546
726.675s #0549
737.167s #0552
737.859s #0553
739.256s #0555
740.500s #0556
741.363s #0557
742.648s #0558
753.671s #0564
773.519s #0567
774.021s #0568
777.113s #0569
785.798s #0571
786.480s #0572
800.224s #0575
801.440s #0576
809.139s #0579
809.532s #0580
810.223s #0581
829.078s #0588
836.587s #0589
837.370s #0590
839.098s #0591
843.384s #0592
845.381s #0593
851.606s #0596
857.991s #0598
867.508s #0600
868.592s #0601
#0605
891.141s #0610
894.253s #0612
898.510s #0613
899.695s #0614
905.286s #0617
913.058s #0619
915.567s #0621
917.043s #0622
936.780s #0626
940.977s #0627
#0629
1018.250s #0634
1021.322s #0635
1023.611s #0636
1025.127s #0637
1055.837s #0640
1056.460s #0641
1067.553s #0643
1074.802s #0645
1089.088s #0647
1107.892s #0648
1108.916s #0649
1116.506s #0651
1240.884s #0662
1300.115s #0664



perpendicular polarised incident light
start pumping
start freezing
Depolaristion
Time (s)
0.10
0.08
0.06
0.04
0.02
0.00
-2000
-1500
-1000
-500
0
500
1000
1500
2000

Stokes Vector – Degree of Polarization

$$I^2 \geq Q^2 + U^2 + V^2$$

degree of linear polarization

$$P_l = -\frac{\sqrt{Q^2 + U^2}}{I}$$

degree of circular polarization

$$P_c = \frac{V}{I}$$

Mueller Matrix

matrix of optical element

$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{pmatrix} \begin{pmatrix} I_i \\ Q_i \\ U_i \\ V_i \end{pmatrix}$$

outgoing vector

incident vector

$$\frac{1}{2} I_i \begin{pmatrix} 1 \\ 0 \\ 0 \\ 1 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} \cdot \frac{1}{2} \begin{pmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \cdot I_i \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

λ/4 retarder

linear polarizer

Scattering Matrix

General matrix

$$\begin{pmatrix} I_s \\ Q_s \\ U_s \\ V_s \end{pmatrix} = \frac{1}{\mathrm{k}^2 r^2} \begin{pmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{pmatrix} \begin{pmatrix} I_i \\ Q_i \\ U_i \\ V_i \end{pmatrix}$$

for nonpolarized incident light:

$$\frac{I_s}{I_i} = S_{11} \, , \frac{Q_s}{I_i} = S_{21} \, , \frac{U_s}{I_i} = S_{31} \, , \frac{V_s}{I_i} = S_{41}$$

➔ light scattering in general induces polarization !

Scattering Matrix – Symmetry

- 4x4 matrix contains all information about angular scattering by a medium
- defined by size, shape and material of the particles
- Single-particle symmetry or media that are invariant under rotation and reflection reduces the number of non-zero and independent matrix elements

$$\begin{pmatrix} S_{11} & S_{12} & 0 & 0 \\ S_{12} & S_{11} & 0 & 0 \\ 0 & 0 & S_{33} & S_{34} \\ 0 & 0 & -S_{34} & S_{33} \end{pmatrix}$$

isotropic sphere

$$\begin{pmatrix} S_{11} & S_{12} & 0 & 0 \\ S_{12} & S_{22} & 0 & 0 \\ 0 & 0 & S_{33} & S_{34} \\ 0 & 0 & -S_{34} & S_{44} \end{pmatrix}$$

ensemble of non-spherical particles

Scattering Matrix – Spheres

$$\begin{pmatrix} I_s \\ Q_s \\ U_s \\ V_s \end{pmatrix} = \frac{1}{k^2 r^2} \begin{pmatrix} S_{11} & S_{12} & 0 & 0 \\ S_{12} & S_{11} & 0 & 0 \\ 0 & 0 & S_{33} & S_{34} \\ 0 & 0 & -S_{34} & S_{33} \end{pmatrix} \begin{pmatrix} I_i \\ Q_i \\ U_i \\ V_i \end{pmatrix}$$

Example: incident light is 100% polarized parallel to the scattering plane

$$\begin{pmatrix} I_i \\ I_i \\ 0 \\ 0 \end{pmatrix} \Rightarrow I_s = (S_{11} + S_{12}) I_i \,, \quad Q_s = I_s \,, \quad U_s = V_s = 0 \quad \Rightarrow \quad P_l = -1$$

Scattered light is also 100% polarized parallel to the scattering plane

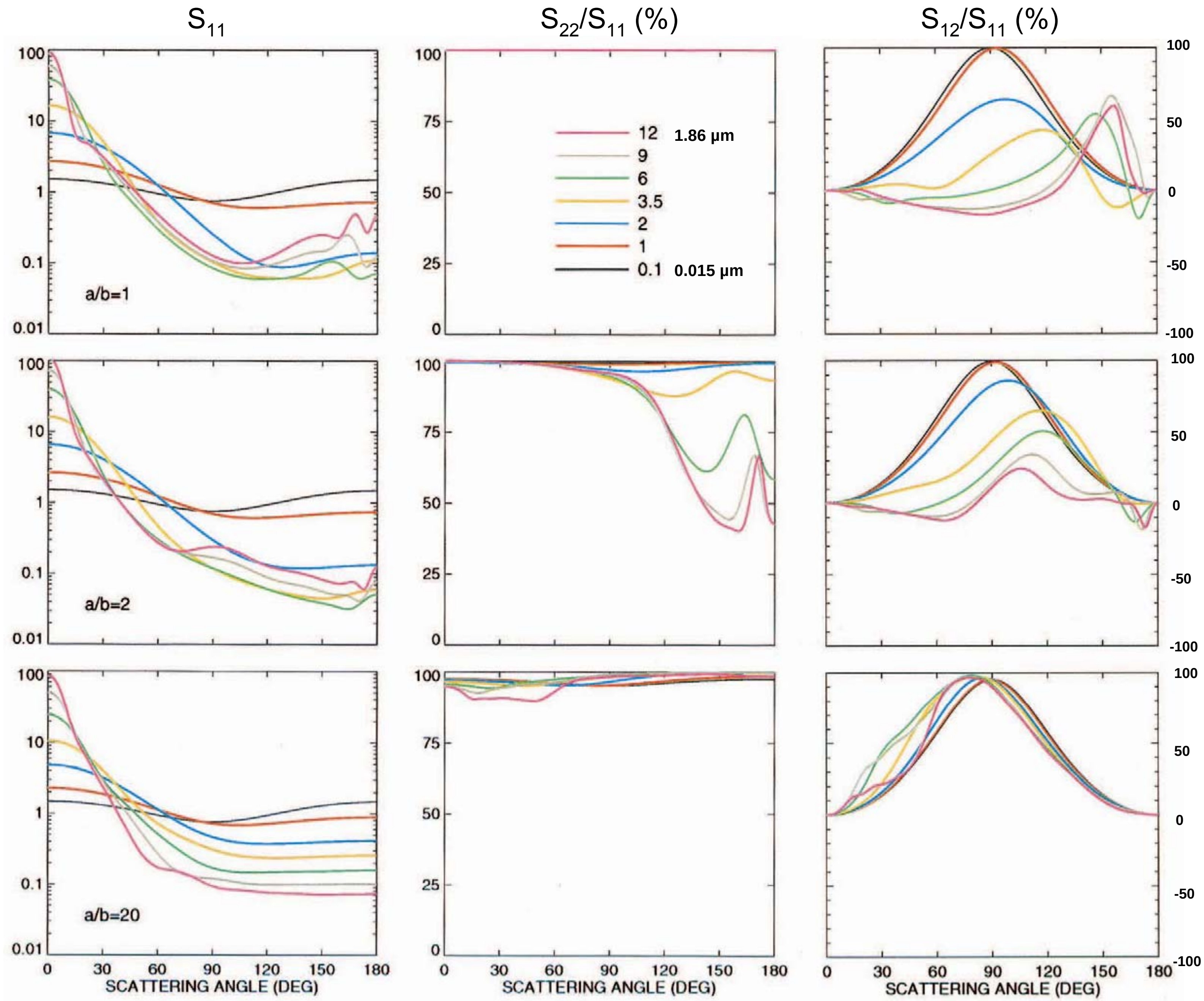
Scattering Matrix – Spheres

$$\begin{pmatrix} I_s \\ Q_s \\ U_s \\ V_s \end{pmatrix} = \frac{1}{k^2 r^2} \begin{pmatrix} S_{11} & S_{12} & 0 & 0 \\ S_{12} & S_{11} & 0 & 0 \\ 0 & 0 & S_{33} & S_{34} \\ 0 & 0 & -S_{34} & S_{33} \end{pmatrix} \begin{pmatrix} I_i \\ Q_i \\ U_i \\ V_i \end{pmatrix}$$

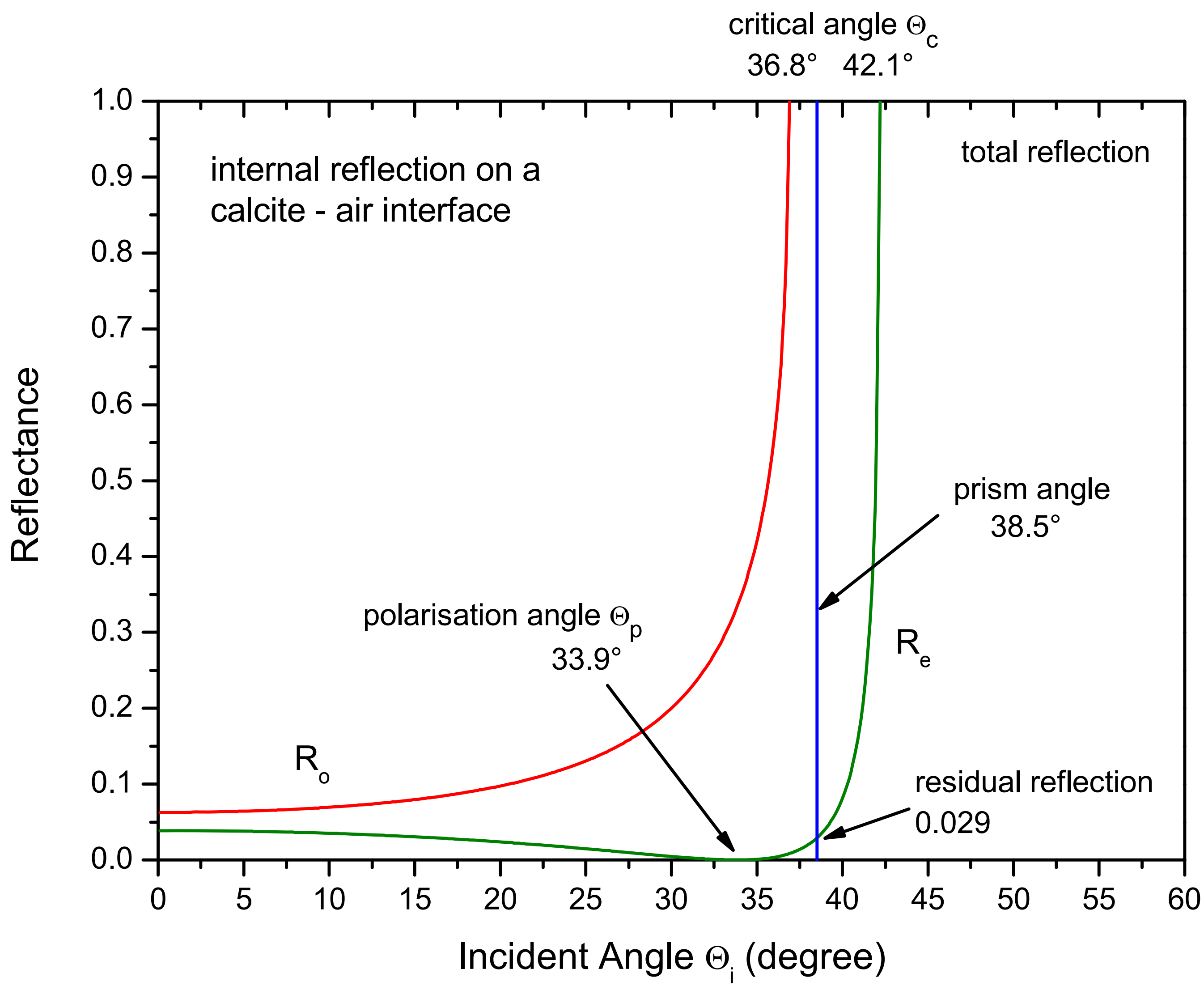
Example: incident light is nonpolarized

$$\begin{pmatrix} I_i \\ 0 \\ 0 \\ 0 \end{pmatrix} \Rightarrow I_s = S_{11} I_i \,, \quad Q_s = S_{12} I_i \,, \quad U_s = V_s = 0 \quad \Rightarrow \quad P = -\frac{S_{12}}{S_{11}}$$

Scattered light is partially polarized



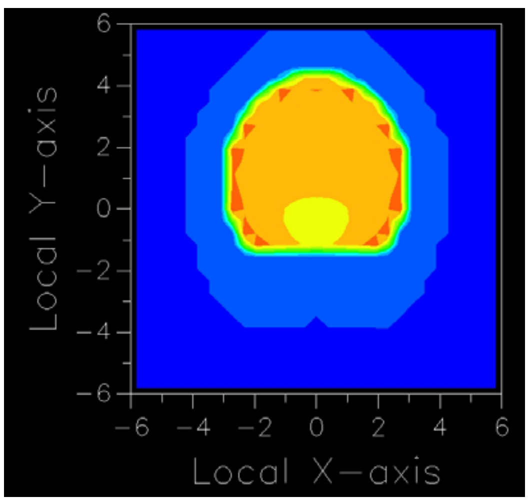
Zakharova & Mishchenko, 2000

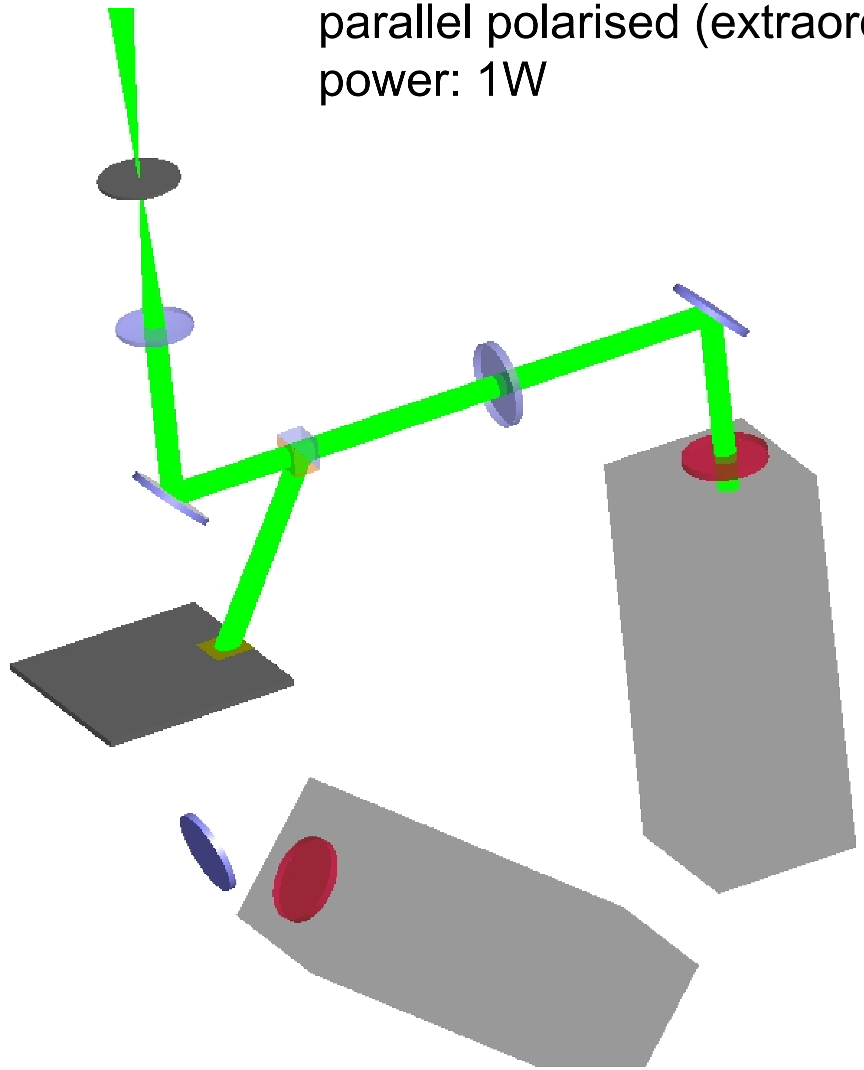


critical angle Θc
36.8°
42.1°
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
internal reflection on a
calcite - air interface
total reflection
prism angle
38.5°
polarisation angle Θp
33.9°
Re
Ro
residual reflection
0.029
Reflectance
0
5
10
15
20
25
30
35
40
45
50
55
60
Incident Angle Θi (degree)

parallel polarised (extraordinary) rays
power: 1W

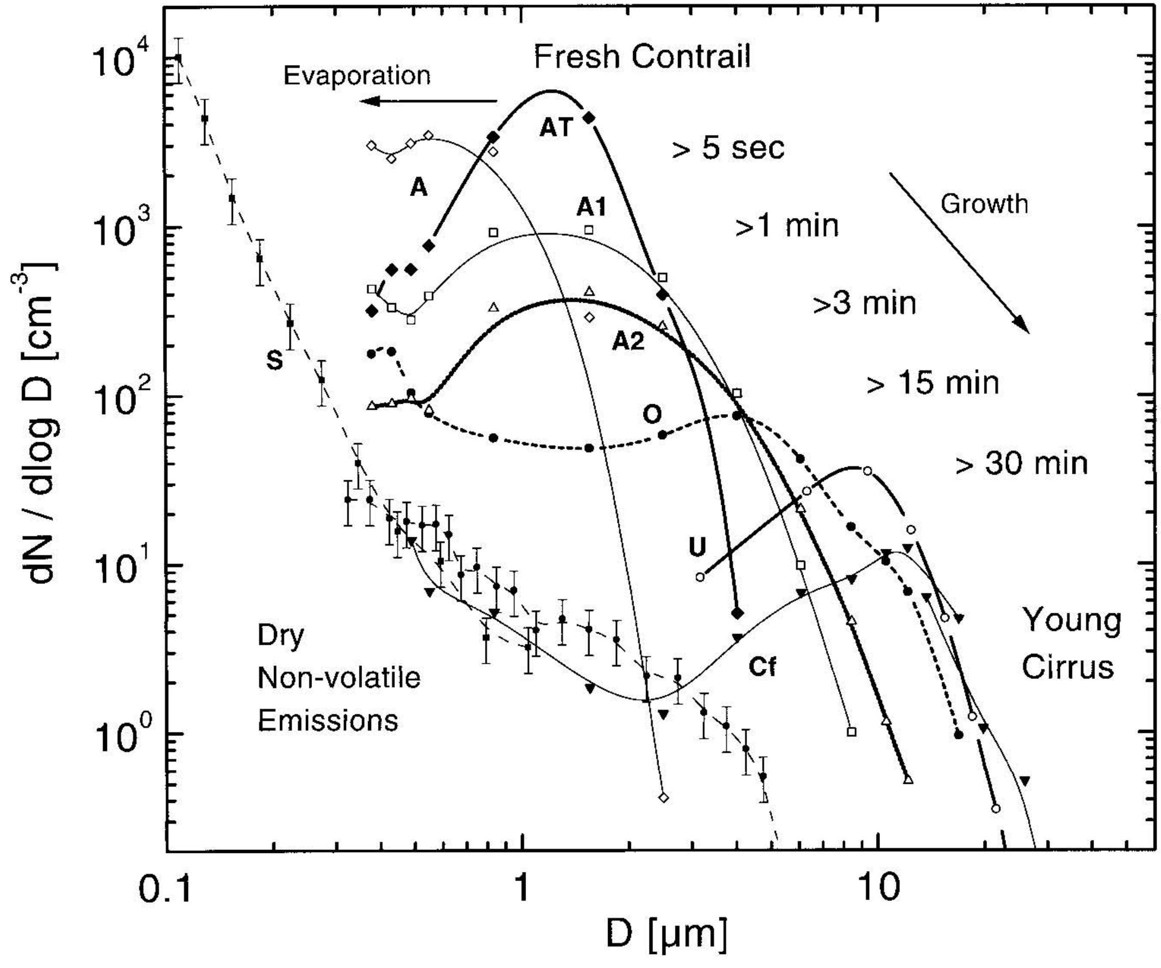
integrated power on
beam stop: 0.03W





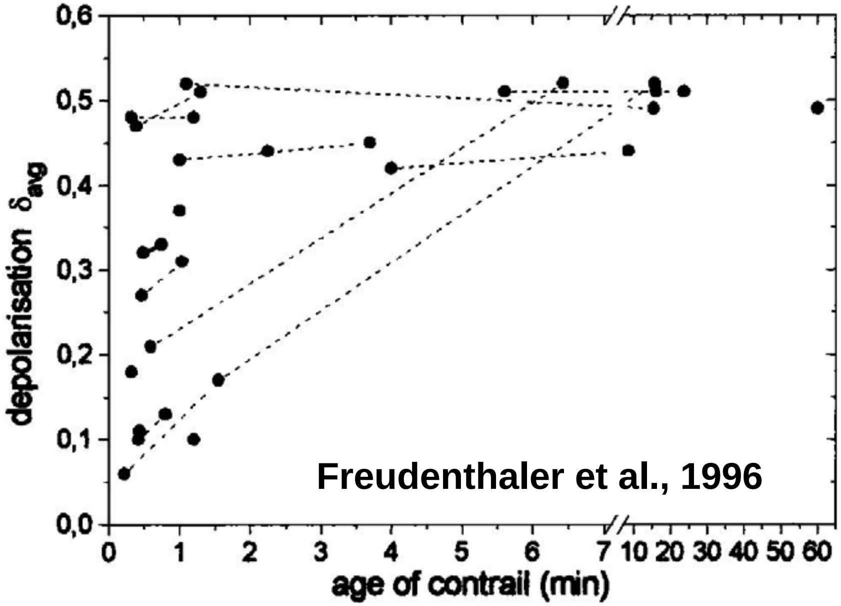
Transition of Contrails into Cirrus Clouds

In situ measurements of ice crystal number size distributions



Schröder et al., 2000

Evolution of contrails probed by polarization LIDAR



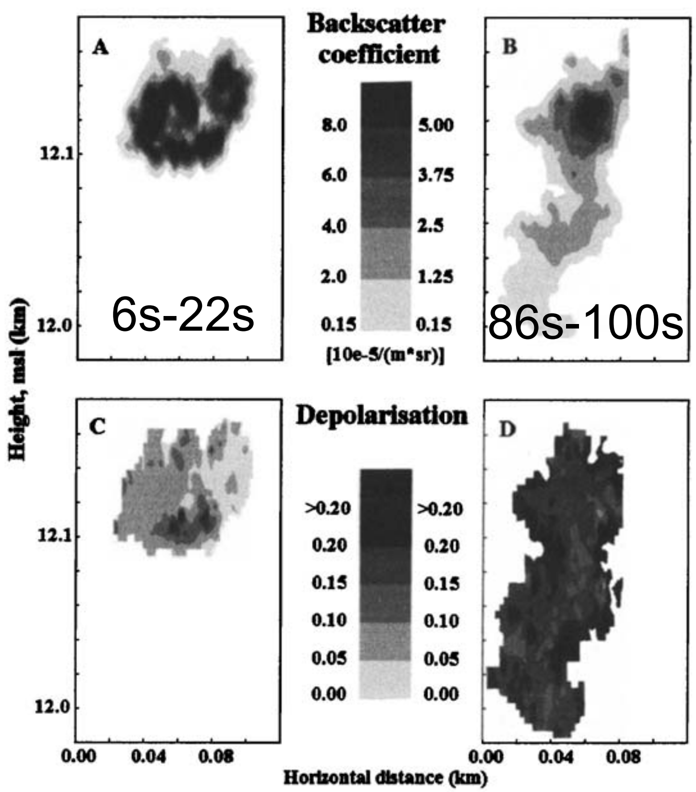


Table 1. Characteristics of selected SUCCESS contrails.

Date	Time UTC	Z_{ct} km	T_{ct} °C	ΔZ m	Age min	Δ	Comment
21 Apr	1948:00	11.26	-56.8	66	0.5	0.65	DC-8
21 Apr	1949:30	11.19	-56.3	114	2.0	0.49	DC-8
21 Apr	1953:30	11.38	-57.8	84	6.0	0.38	DC-8
23 Apr	1952:00	11.90	-67.4	582	≥60	0.38	Corona
23 Apr	2110:00	12.24	-65.7	462	≥60	0.34	Subvisual
23 Apr	2233:00	12.27	-67.0	282	≥60	0.61	Corona
23 Apr	2303:00	12.34	-67.4	138	≥60	0.68	Subvisual
23 Apr	2316:00	12.25	-67.2	162	≥60	0.62	Corona
2 May	2001:20	11.75	-61.3	246	≥45	0.33	Thin
2 May	2030:00	11.76	-61.3	90	≥45	0.31	Thin

Sassen & Hsueh, 1998