Light scattering laboratories

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Experimental single scattering matrices from aerosols

Chronological evolution

1. A new polarization-modulated light scattering instrument. **Hunt & Huffman, 1973.**
2. Measuring scattering matrices of small particles at optical wavelengths (In Mishchenko *et al*. Light scattering by nonspherical particles) **Hovenier, 2000.**
3. Experimental determination of scattering matrices of dust particles at visible wavelengths: The IAA light scattering apparatus. **Muñoz *et al.* 2010.**

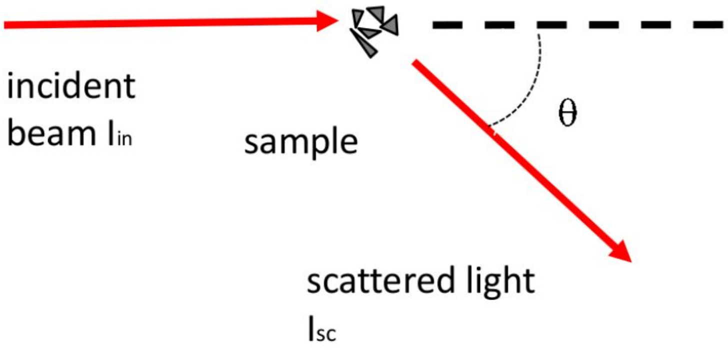
Scattering matrix

$$\begin{pmatrix} I_{sc} \\ Q_{sc} \\ U_{sc} \\ V_{sc} \end{pmatrix} = \frac{\lambda^2}{4\pi^2 D^2} \begin{pmatrix} F_{11} & F_{12} & F_{13} & F_{14} \\ F_{21} & F_{22} & F_{23} & F_{24} \\ F_{31} & F_{32} & F_{33} & F_{34} \\ F_{41} & F_{42} & F_{43} & F_{44} \end{pmatrix} \begin{pmatrix} \boxed{I_{in}} \\ \boxed{\begin{matrix} Q_{in} \\ U_{in} \end{matrix}} \\ \boxed{V_{in}} \end{pmatrix}$$

Intensity

Linear polarization

Circular polarization



Scattering matrix depends on:

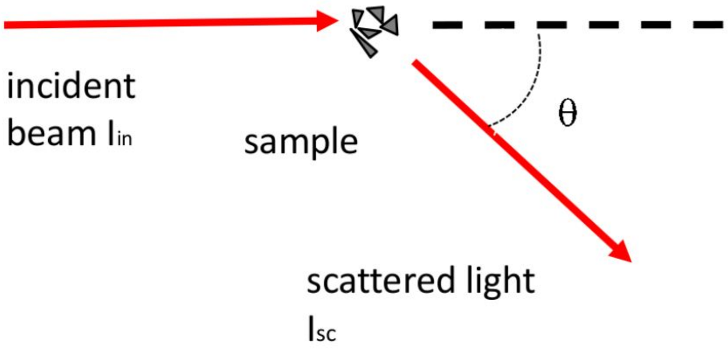
- ➢ Refractive index
- ➢ Shape
- ➢ Size distribution
- ➢ Wavelength

Size parameter

$$x = \frac{2\pi r}{\lambda}$$

Scattering matrix

$$\begin{pmatrix} I_{sc} \\ Q_{sc} \\ U_{sc} \\ V_{sc} \end{pmatrix} = \frac{\lambda^2}{4\pi^2 D^2} \begin{pmatrix} F_{11} & F_{12} & 0 & 0 \\ F_{12} & F_{22} & 0 & 0 \\ 0 & 0 & F_{33} & F_{34} \\ 0 & 0 & -F_{34} & F_{44} \end{pmatrix} \begin{pmatrix} I_{in} \\ Q_{in} \\ U_{in} \\ V_{in} \end{pmatrix}$$



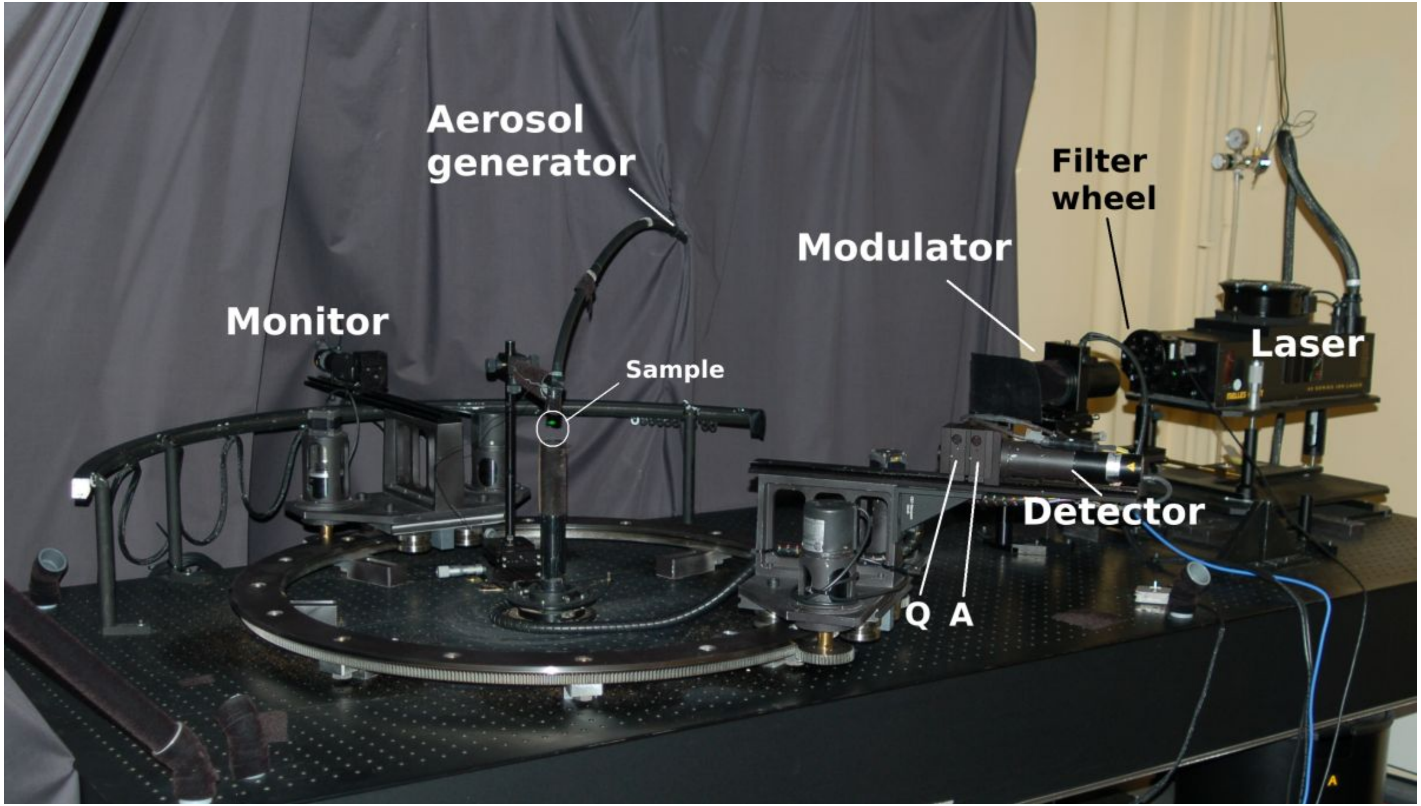
Scattering matrix depends on:

- Refractive index
- Shape
- Size distribution
- Wavelength

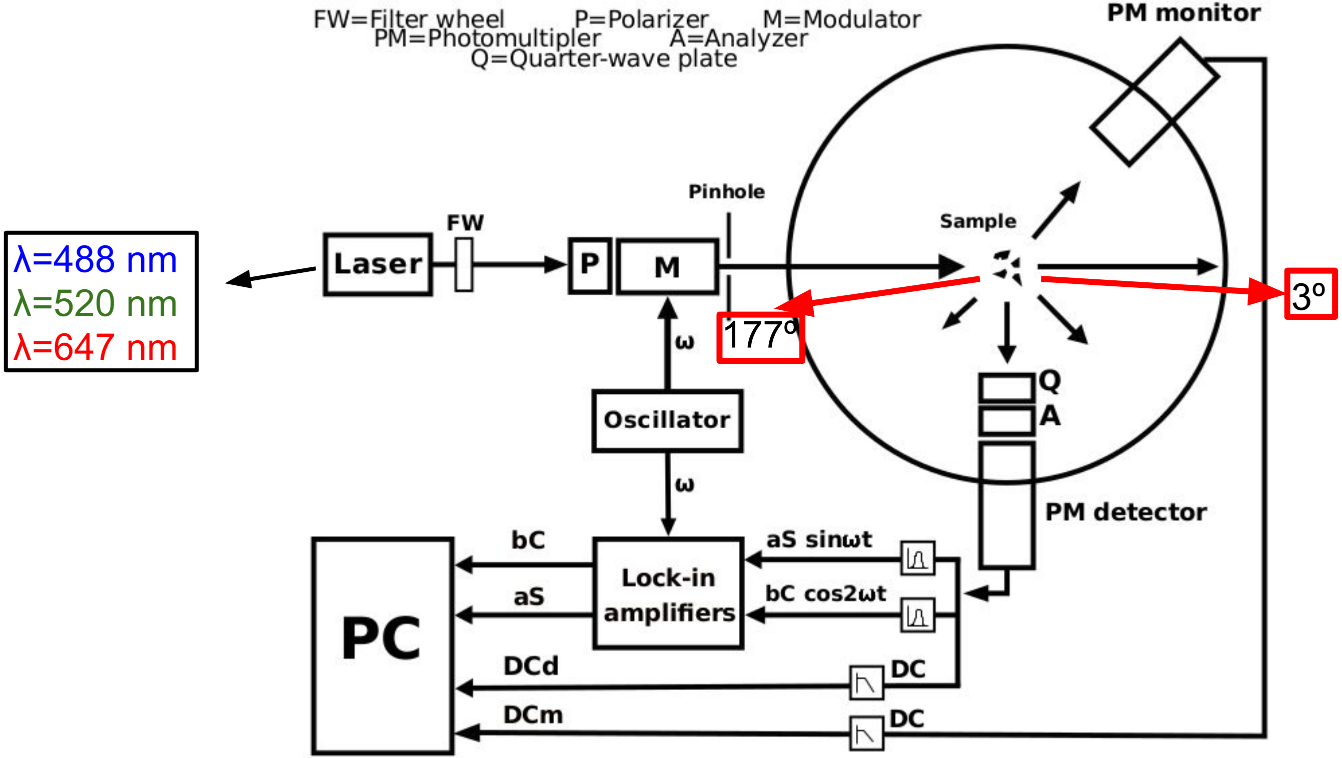
Size parameter

$$x = \frac{2\pi r}{\lambda}$$

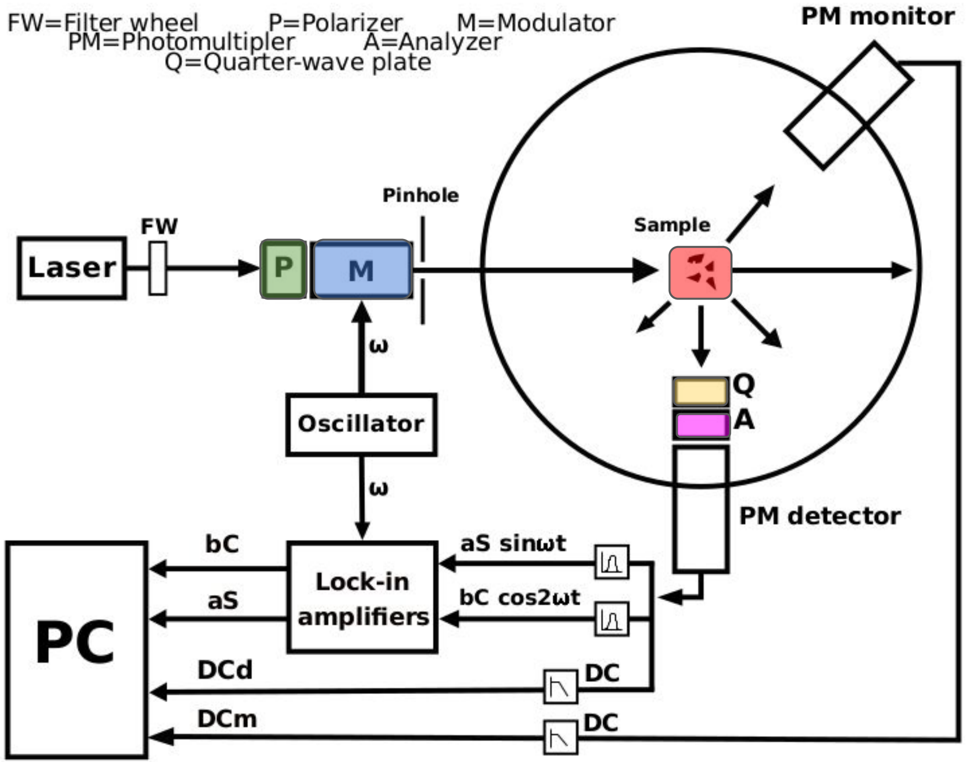
IAA-CODULAB experimental apparatus.



IAA-CODULAB

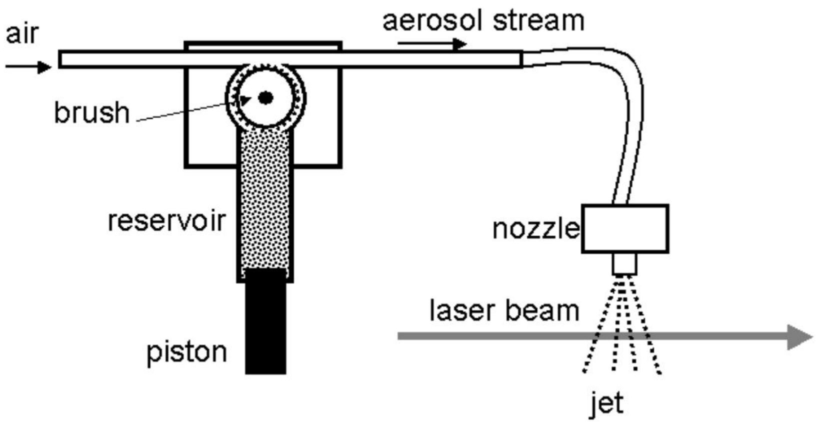


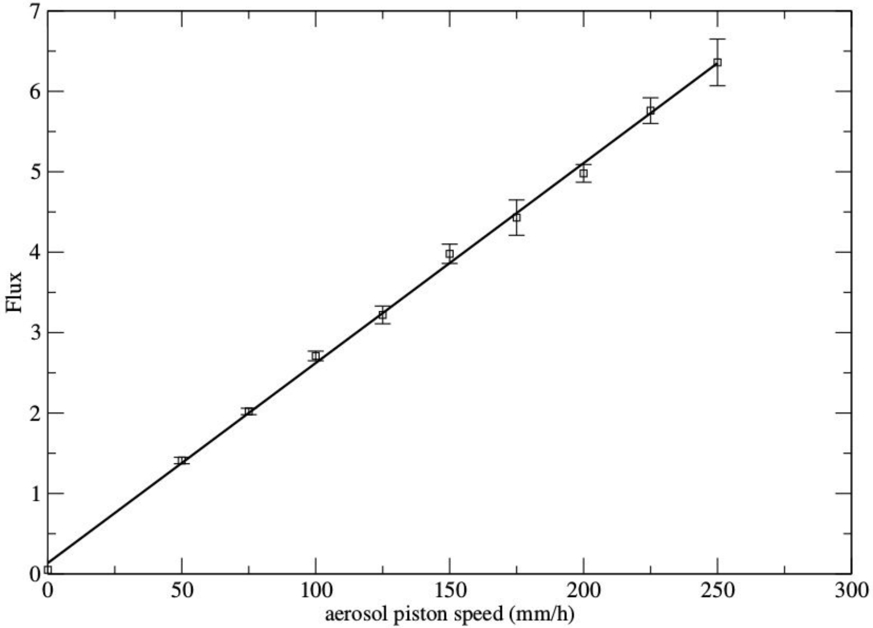
λ=488 nm
λ=520 nm
λ=647 nm
FW=Filter wheel
P=Polarizer
M=Modulator
PM=Photomultipler
A=Analyzer
Q=Quarter-wave plate
PM monitor
Laser
FW
P
M
Pinhole
Sample
177º
3º
ω
Oscillator
ω
Q
A
PM detector
PC
bC
aS
Lock-in amplifiers
aS sinωt
bC cos2ωt
DCd
DC
DCm
DC



$$\Phi_{sca}(\lambda, \theta) = c_1 \mathbf{A}_{\gamma_A} \mathbf{Q}_{\gamma_Q} \mathbf{F}(\theta) \mathbf{M}_{\gamma_M} \mathbf{P}_{\gamma_P} \Phi_{inc}(\lambda, \theta)$$

Aerosol generator and single scattering test.





Mueller matrices and optical configurations.

$$\mathbf{\Phi}_{sca}(\lambda,\theta) = c_1 \mathbf{A}_{\gamma_A} \mathbf{Q}_{\gamma_Q} \mathbf{F}(\theta) \mathbf{M}_{\gamma_M} \mathbf{P}_{\gamma_P} \mathbf{\Phi}_{inc}(\lambda,\theta)$$

$$\mathbf{A}_\gamma = \mathbf{P}_\gamma = \frac{1}{2}\begin{pmatrix} 1 & C & S & 0 \\ C & C^2 & SC & 0 \\ S & SC & S^2 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \qquad \mathbf{Q}_\gamma = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & C^2 & SC & -S \\ 0 & SC & S^2 & C \\ 0 & S & -C & 0 \end{pmatrix}$$

$$\mathbf{M}_{\gamma_M}(\phi) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & C^2 + S^2\cos\phi & SC(1-\cos\phi) & -S\sin\phi \\ 0 & SC(1-\cos\phi) & S^2 + C^2\cos\phi & C\sin\phi \\ 0 & S\sin\phi & -C\sin\phi & \cos\phi \end{pmatrix}$$

$C = \cos 2\gamma$ and $S = \sin 2\gamma$ $\qquad$ $\phi = \phi_c + \phi_0 \sin \omega t$

Mueller matrices and optical configurations.

$$
M_{\gamma_M}(\phi) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & C^2 + S^2 \cos\phi & SC(1-\cos\phi) & -S\sin\phi \\ 0 & SC(1-\cos\phi) & S^2 + C^2\cos\phi & C\sin\phi \\ 0 & S\sin\phi & -C\sin\phi & \cos\phi \end{pmatrix}
$$

$$
\sin\phi = \sin(\phi_0 \sin\omega t) = 2\sum_{k=1} J_{2k-1}(\phi_0)\sin(2k-1)\omega t
$$

$$
\cos\phi = \cos(\phi_0 \sin\omega t) = J_0(\phi_0) + 2\sum_{l=1}^{\infty} J_{2l}(\phi_0)\cos(2l)\omega t
$$

Mueller matrices and optical configurations.

$$\Phi_{sca}(\lambda,\theta) = c[DC(\theta) + 2J_1(\phi_m)S(\theta)\sin\omega t + 2J_2(\phi_m)C(\theta)\cos 2\omega t]$$

Configuration	$\gamma_P(deg)$	$\gamma_M(deg)$	$\gamma_Q(deg)$	$\gamma_A(deg)$	DC(θ)	S(θ)	C(θ)
1	45	0	-	-	F_{11}	-F_{14}	F_{13}
2	45	0	-	45	F_{11} + F_{31}	-F_{14}-F_{34}	F_{13}+F_{33}
3	45	0	0	45	F_{11} + F_{41}	-F_{14}-F_{44}	F_{13}+F_{43}
4	0	-45	-	-	F_{11}	-F_{14}	F_{12}
5	0	-45	-	0	F_{11} + F_{21}	-F_{14}-F_{24}	F_{12}+F_{22}

$$\Phi_{sca}(\lambda,\theta) = c_1 A_{\gamma_A} Q_{\gamma_Q} F(\theta) M_{\gamma_M} P_{\gamma_P} \Phi_{inc}(\lambda,\theta)$$

Mueller matrices and optical configurations.

$$\Phi_{sca}(\lambda,\theta) = c[\boxed{DC(\theta)} + 2J_1(\phi_m)\boxed{S(\theta)}\sin\omega t + 2J_2(\phi_m)\boxed{C(\theta)}\cos 2\omega t]$$

Configuration	$\gamma_P(deg)$	$\gamma_M(deg)$	$\gamma_Q(deg)$	$\gamma_A(deg)$	DC(θ)	S(θ)	C(θ)
1	45	0	-	-	F_{11}	-F_{14}	F_{13}
2	45	0	-	45	F_{11} + F_{31}	-F_{14}-F_{34}	F_{13}+F_{33}
3	45	0	0	45	F_{11} + F_{41}	-F_{14}-F_{44}	F_{13}+F_{43}
4	0	-45	-	-	F_{11}	-F_{14}	F_{12}
5	0	-45	-	0	F_{11} + F_{21}	-F_{14}-F_{24}	F_{12}+F_{22}

$$\Phi_{sca}(\lambda,\theta) = c_1 A_{\boxed{\gamma_A}} Q_{\boxed{\gamma_Q}} F(\theta) M_{\boxed{\gamma_M}} P_{\boxed{\gamma_P}} \Phi_{inc}(\lambda,\theta)$$

Alignment example

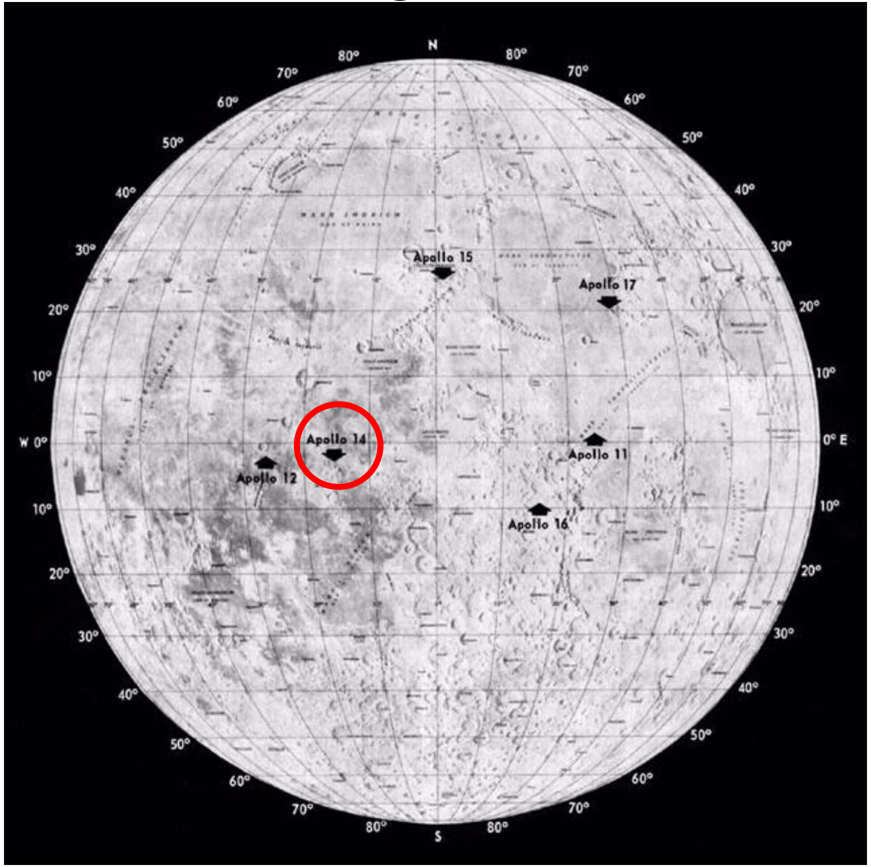
Configuration	$\gamma_P(deg)$	$\gamma_M(deg)$	$\gamma_Q(deg)$	$\gamma_A(deg)$	DC(θ)	S(θ)	C(θ)
1	45	0	-	-	F_{11}	-F_{14}	F_{13}
2	45	0	-	45	F_{11} + F_{31}	-F_{14}-F_{34}	F_{13}+F_{33}
3	45	0	0	45	F_{11} + F_{41}	-F_{14}-F_{44}	F_{13}+F_{43}
4	0	-45	-	-	F_{11}	-F_{14}	F_{12}
5	0	-45	-	0	F_{11} + F_{21}	-F_{14}-F_{24}	F_{12}+F_{22}

$$\mathbf{\Phi}_{sca}(\lambda,\theta) = c_1 \mathbf{A}_{\gamma_A} \mathbf{Q}_{\gamma_Q} \mathbf{F}(\theta) \mathbf{M}_{\gamma_M} \mathbf{P}_{\gamma_P} \mathbf{\Phi}_{inc}(\lambda,\theta)$$

$$\mathbf{I}_{sca} = \mathbf{F}(\theta)\cdot\mathbf{M}_{0^\circ}\cdot\mathbf{P}_{45^\circ}\mathbf{I}_{in} = \left(\frac{I_{in}+U_{in}}{2}\right) \begin{array}{c} \left[\begin{array}{c} F_{11} - F_{14}\sin\phi + F_{13}\cos\phi \\ F_{21} - F_{24}\sin\phi + F_{23}\cos\phi \\ F_{31} - F_{34}\sin\phi + F_{33}\cos\phi \\ F_{41} - F_{44}\sin\phi + F_{43}\cos\phi \end{array}\right] \end{array} \begin{array}{c} \mathrm{I} \\ \mathrm{Q} \\ \mathrm{V} \\ \mathrm{U} \end{array}$$

Experimental measurements of the JSC-1A lunar analog

JSC-1A lunar analog



Apollo landing sites (Smithsonian Institution)

JSC-1A sample (By ArnoldReinhold - Own work, CC BY-SA 3.0)

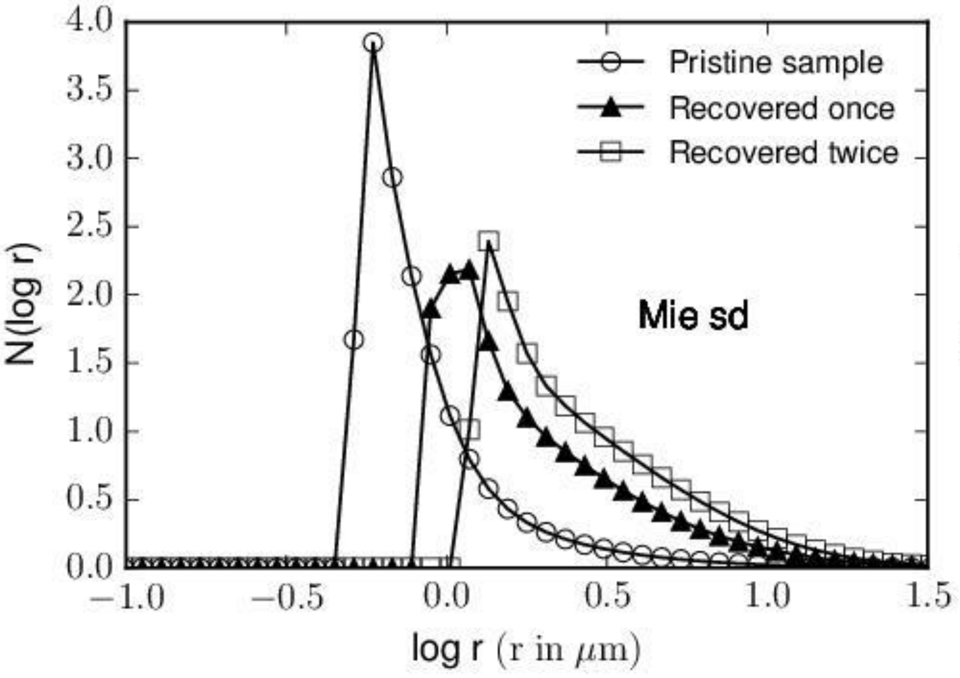
JSC-1A lunar analog

Constituent oxides	Apollo 14 sample 14163 (Papike et al. 1982)	JSC-1A (Ray et al. 2010)
SiO_2	47.3 %	45.7 %
Al_2O_3	17.8 %	16.2 %
CaO	11.4 %	10.0 %
FeO	10.5 %	-
Fe_2O_3	-	12.4 %
MgO	9.6 %	8.7 %
TiO_2	1.6 %	1.9 %
Na_2O	0.70 %	3.2 %
K_2O	0.55 %	0.8 %
MnO	0.135 %	0.2 %

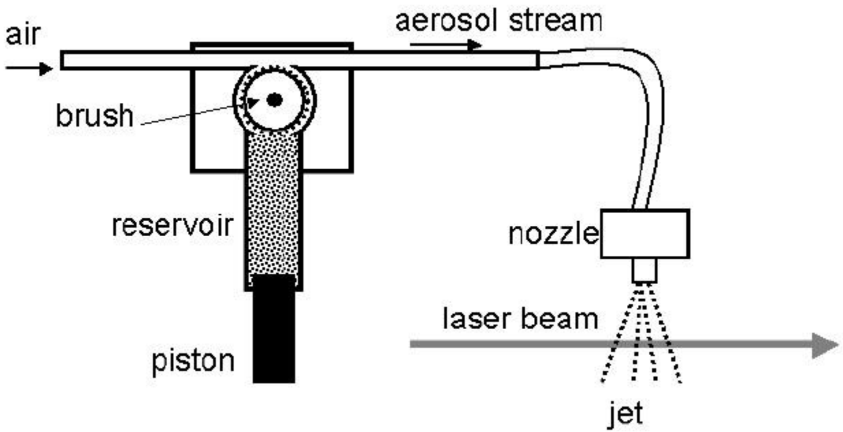
Escobar-Cerezo et al. (ApJSS, 2018)

JSC-1A size distribution

Size distribution



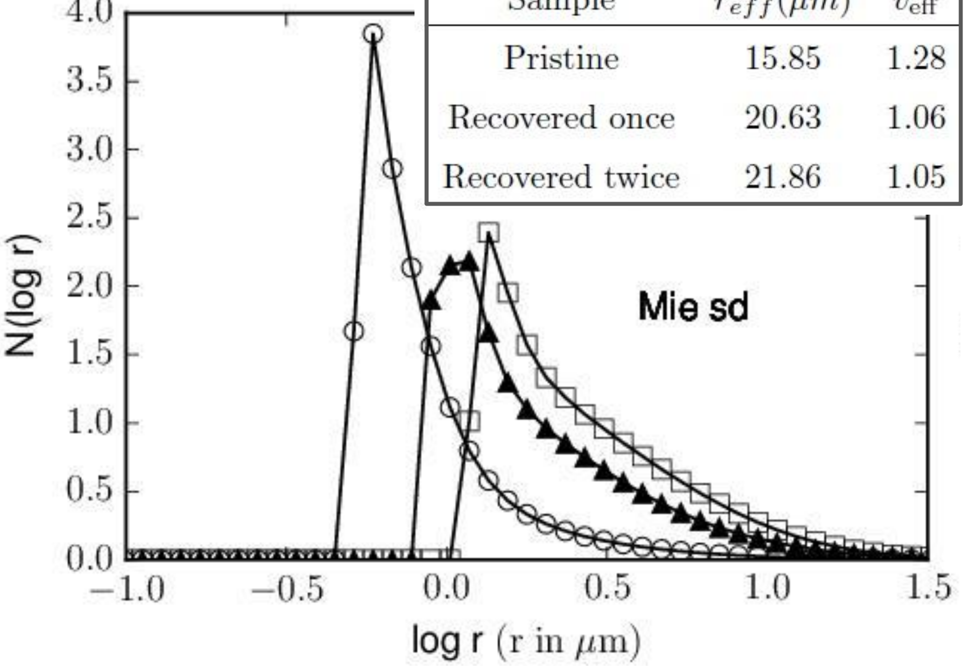
Aerosol generator



Escobar-Cerezo et al. (ApJSS, 2018)

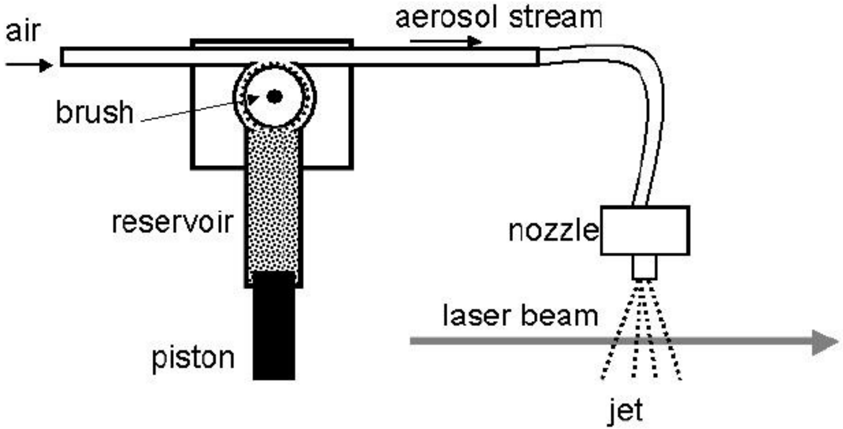
JSC-1A size distribution

	Mie	
Sample	$r_{eff}(\mu m)$	v_{eff}
Pristine	15.85	1.28
Recovered once	20.63	1.06
Recovered twice	21.86	1.05

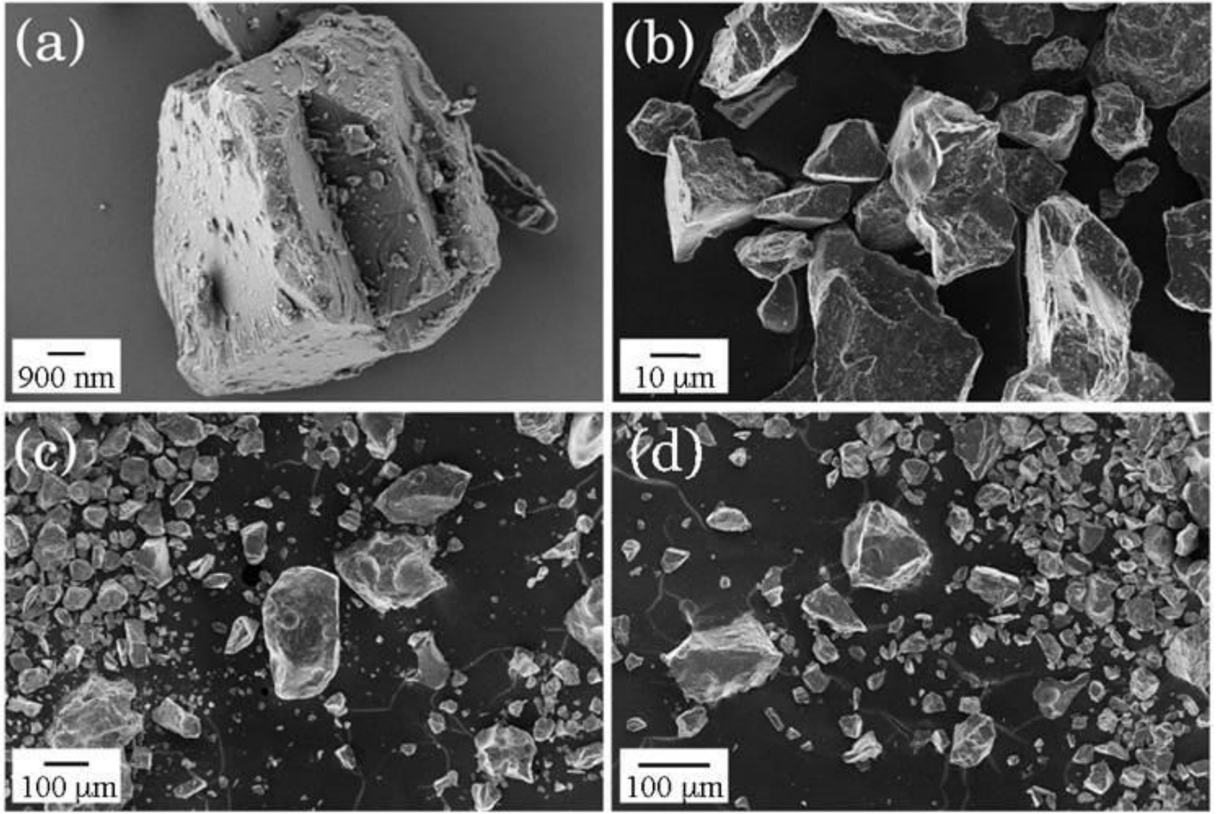


Escobar-Cerezo et al. (ApJSS, 2018)

Aerosol generator

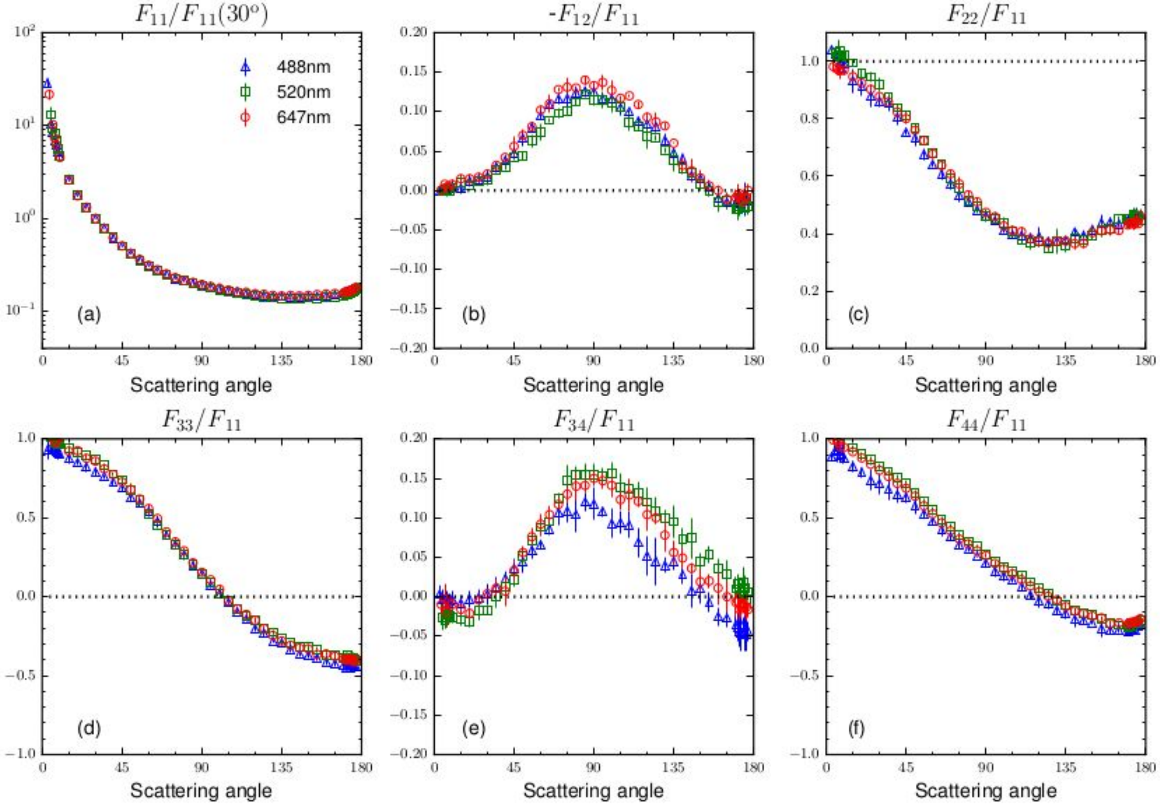


JSC-1A SEM images



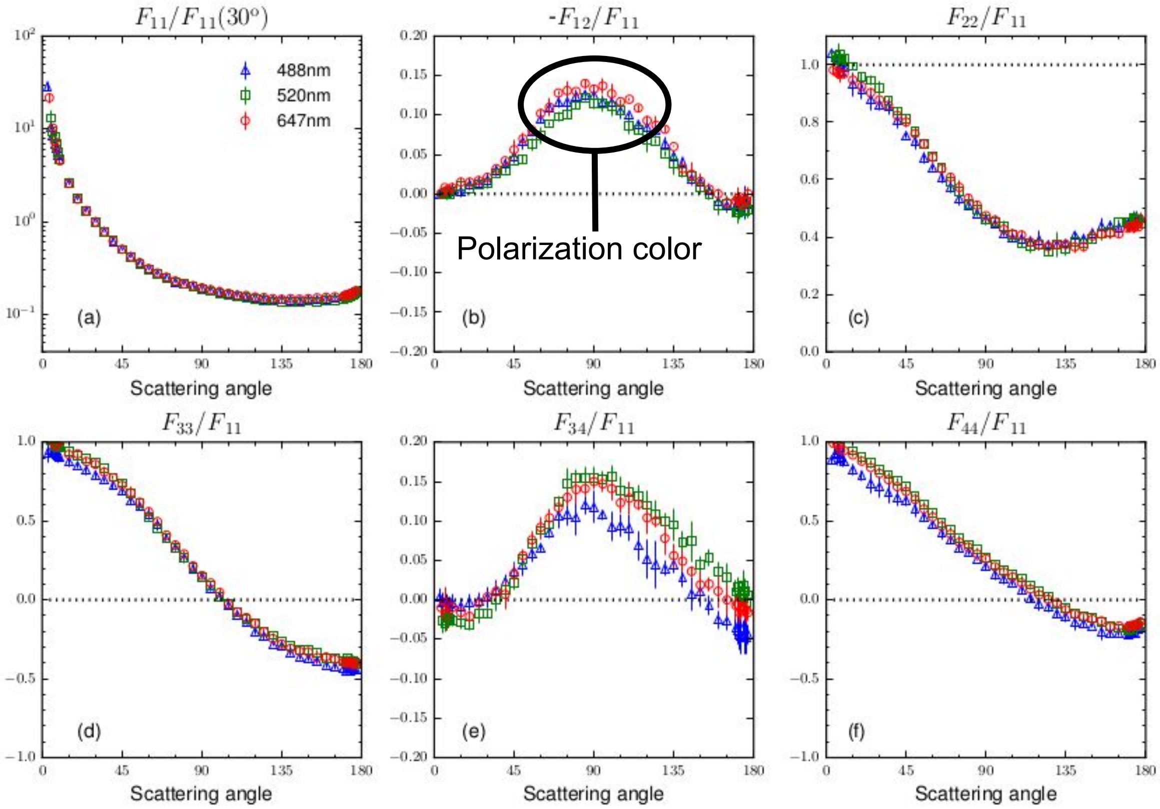
Escobar-Cerezo et al. (ApJSS, 2018)

Experimental measurements of the JSC-1A lunar analog



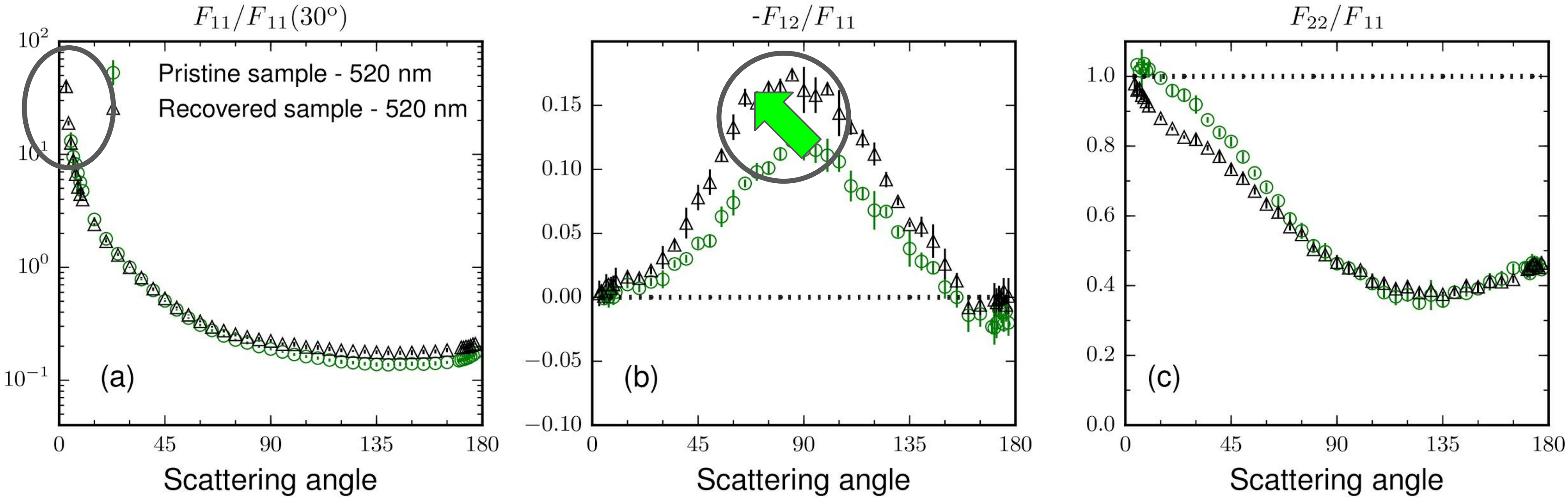
Escobar-Cerezo et al. (ApJSS, 2018)

Experimental measurements of the JSC-1A lunar analog



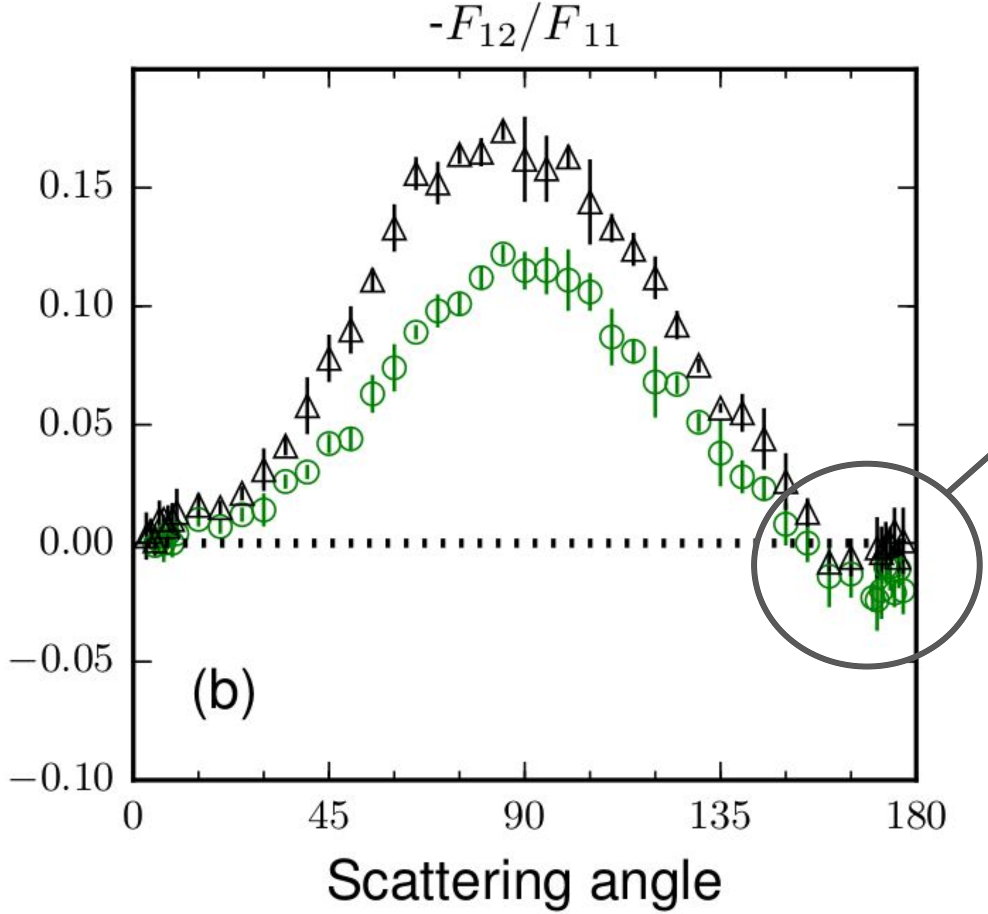
Escobar-Cerezo et al. (ApJSS, 2018)

Comparing pristine and recovered sample



Escobar-Cerezo et al. (ApJSS, 2018)

Comparing pristine and recovered sample

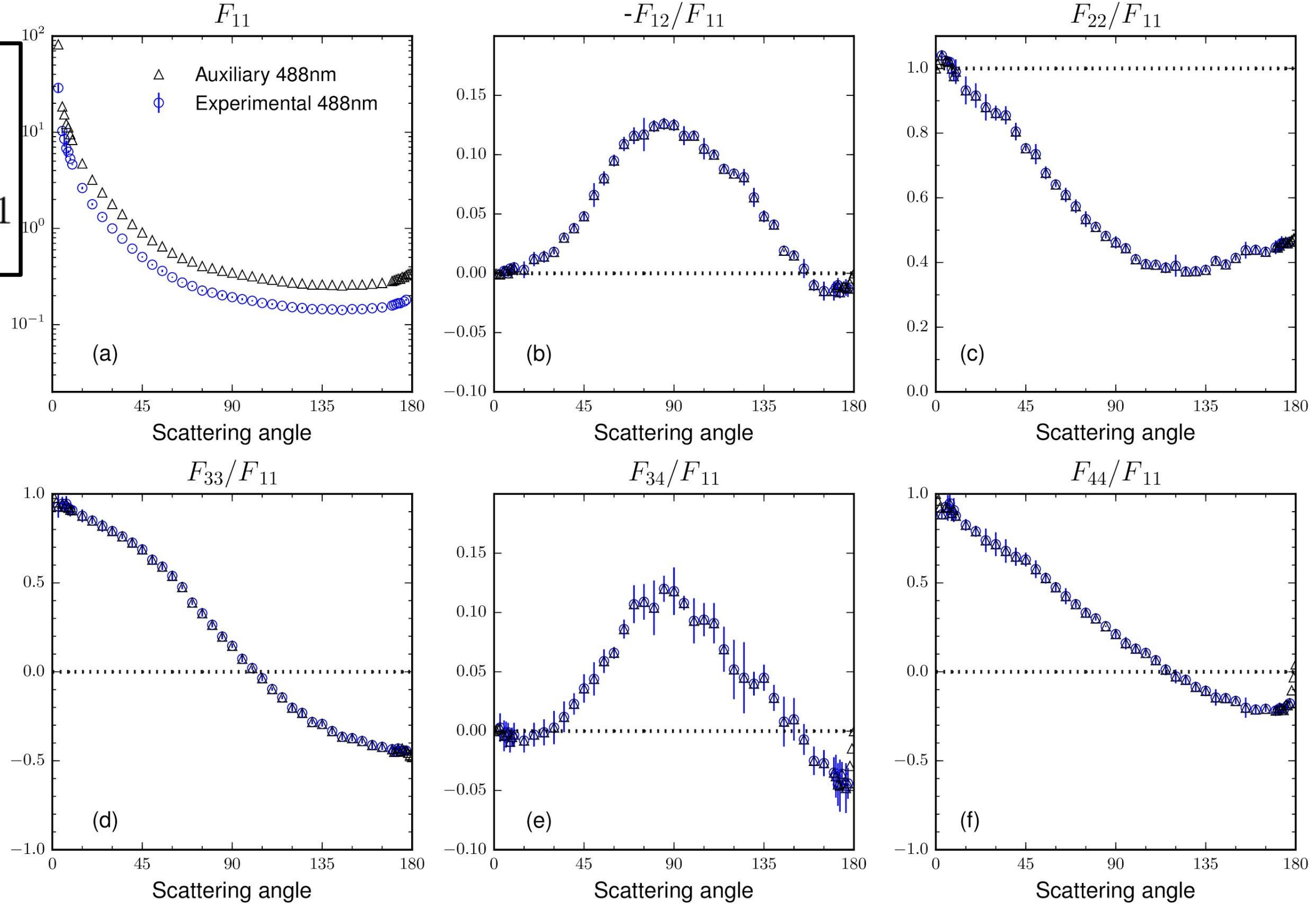


Submicron-size particles seem to be responsible for the measured negative branch !!!

Extrapolated matrix for JSC-1A lunar analog

Normalization condition

$$\frac{1}{2}\int_0^\pi d\theta \sin\theta F_{11}^{\mathrm{syn}}(\theta) = 1$$



Escobar-Cerezo et al. (ApJSS, 2018)

Computed asymmetry parameter and depolarization factor

Asymmetry parameter g

Wavelength λ	Mie
488 nm	0.74
520 nm	0.75
647 nm	0.74

Back-scattering depolarization factor $\delta_L(180°)$

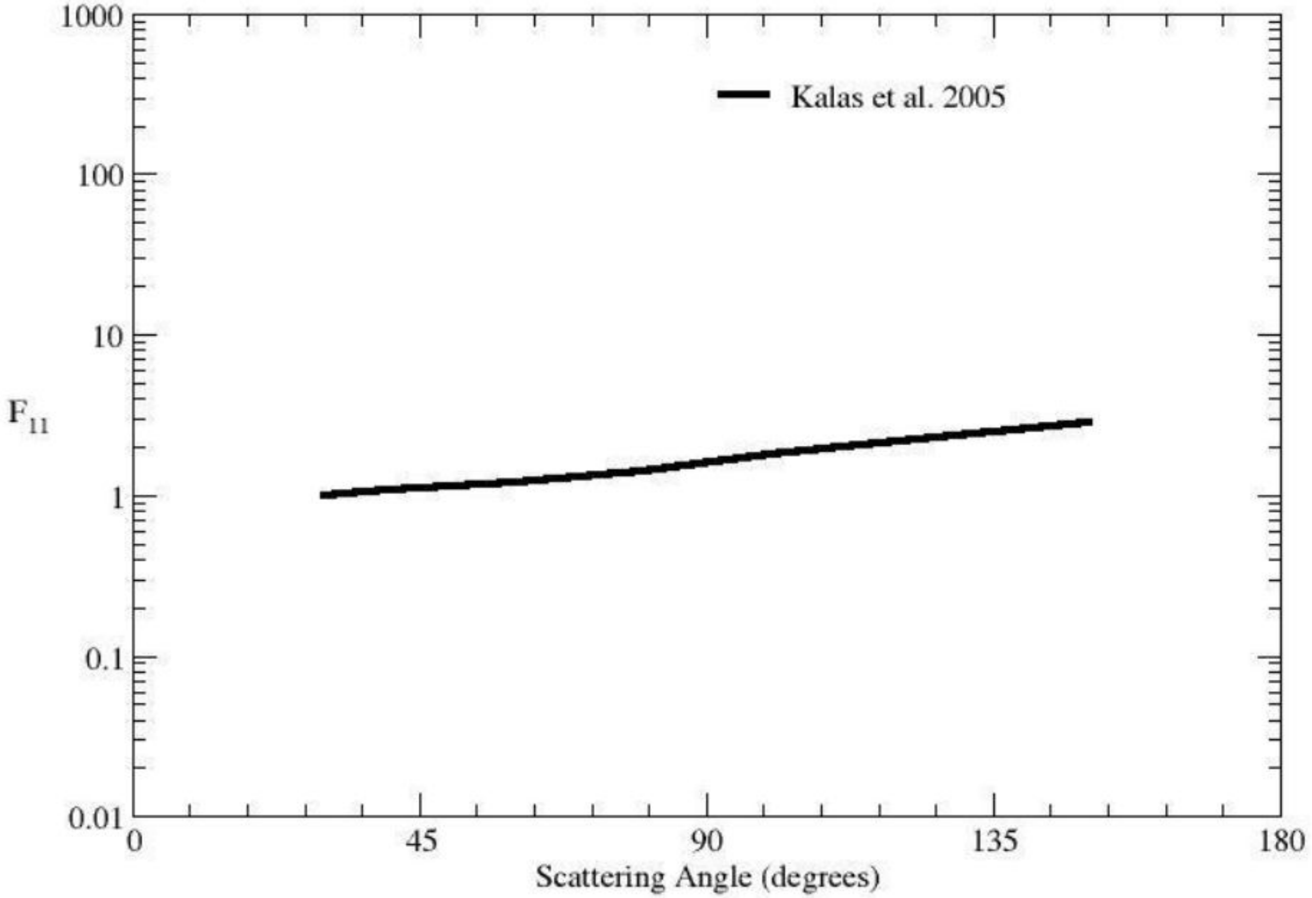
Wavelength λ	Mie
488 nm	0.35
520 nm	0.42
647 nm	0.31

Sterzik et al. assumed that the regolith depolarizes the light by a factor of 3.3 at 550nm (i.e. 0.3 as expressed on the table).

Escobar-Cerezo et al. (ApJSS, 2018)

Experimental Phase Functions of Millimeter-sized Cosmic Dust Grains

Experimental Phase Functions of Millimeter-sized Cosmic Dust Grains



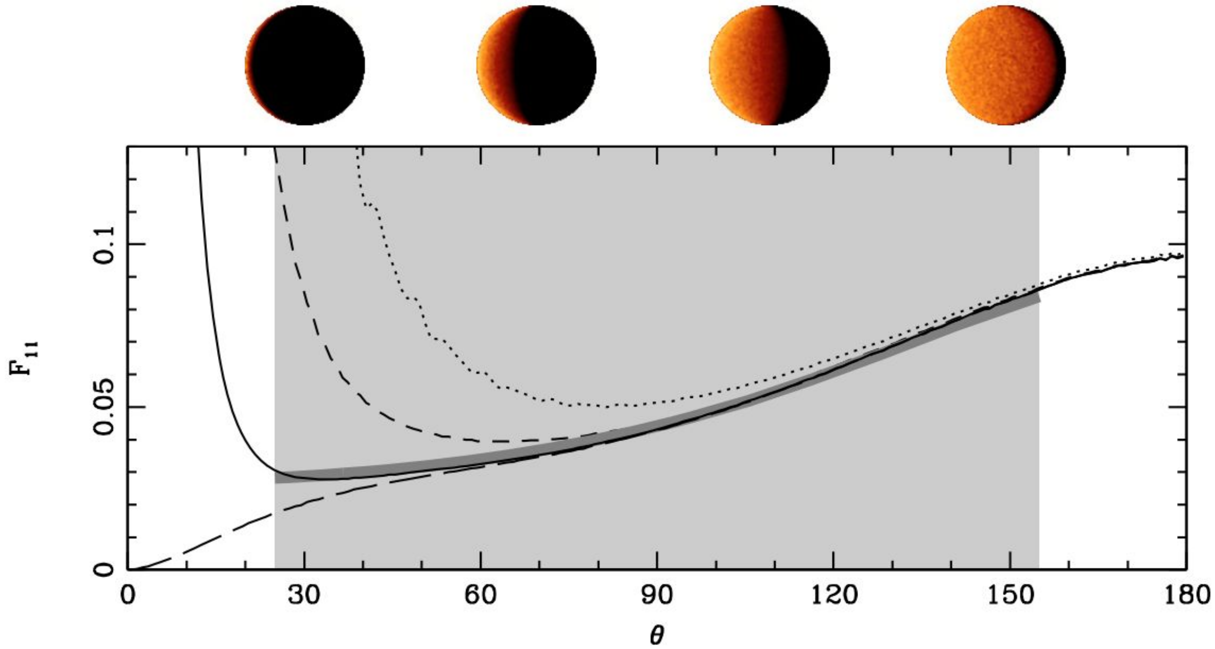
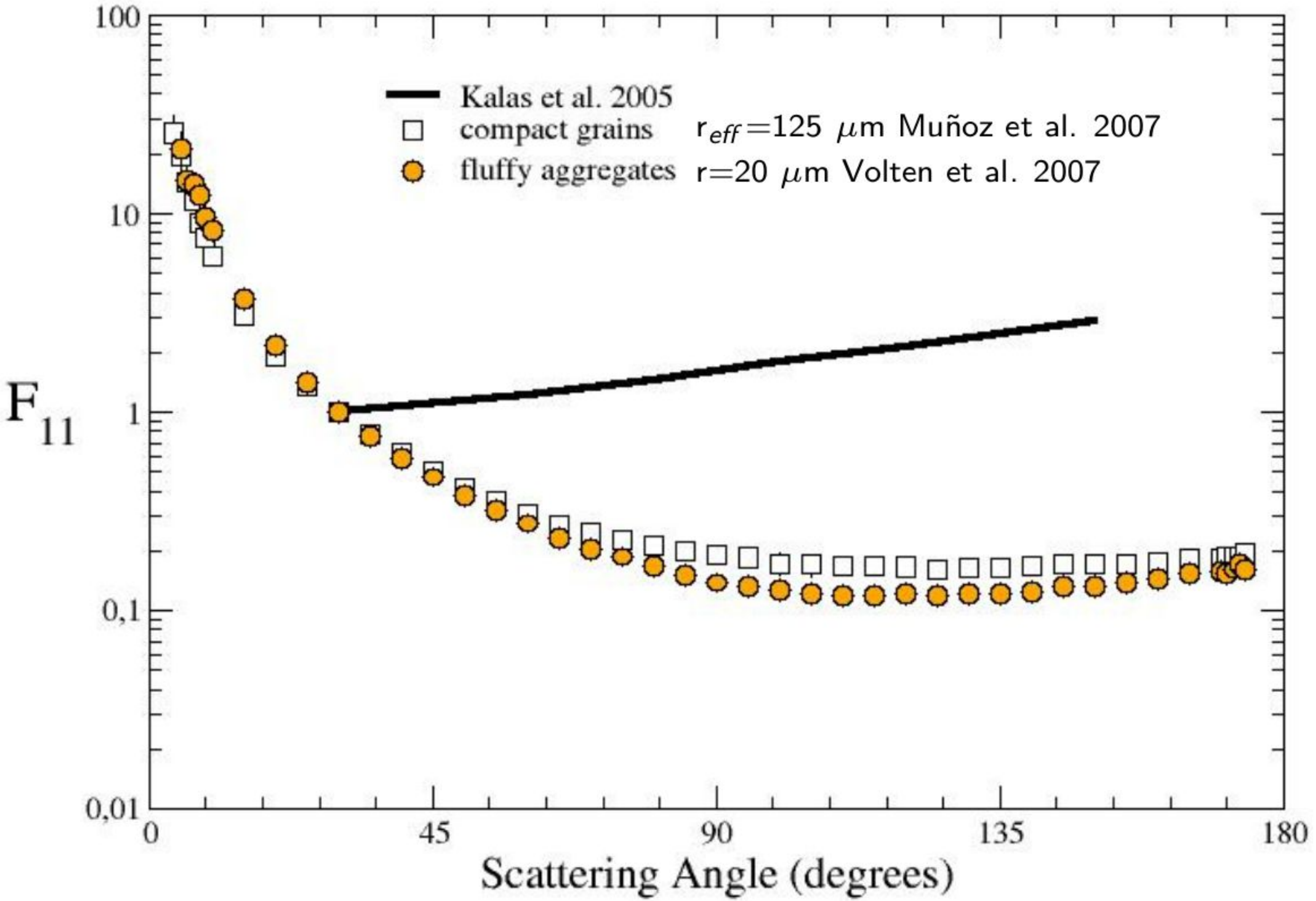


Fig. 2. Angular scattering functions for large dust grains, showing the relative intensity scattered at a scattering angle θ. The pure reflectance function (long-dashed curve) is given, and diffraction effects are added for 10, 30 and 100 μm grains (dotted, dashed and solid curves). The empirical scattering function of the Fomalhaut disk grains from Kalas et al. (2005) is also shown (thick grey curve, albedo chosen to match the computations). The grey area indicates the observable range of scattering angles for the Fomalhaut system.

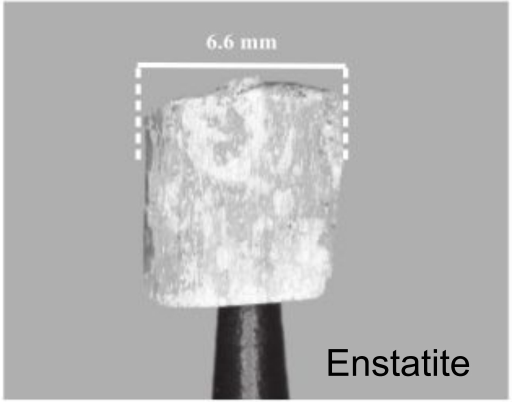
- Very large grains (>100 μm) to explain HST images (Min *et al*. 2010).
- Fomalhaut: Herschel far-IR spectra shows high temperature grains.
- Large (r ~ 15 μm) fluffy aggregates consisting of small monomers to explain far-IR Herschel data. (Acke et al. 2012).



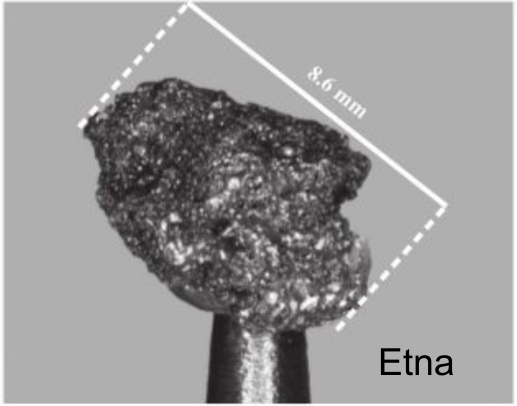
Kalas et al. 2005
compact grains
r_{eff}=125 μm Muñoz et al. 2007
fluffy aggregates
r=20 μm Volten et al. 2007
F_{11}
100
10
1
0,1
0,01
0
45
90
135
180
Scattering Angle (degrees)

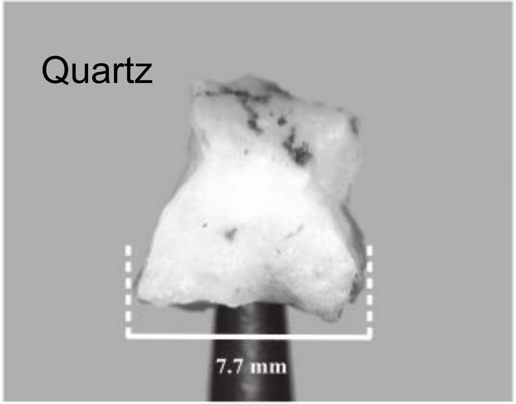
Experimental Phase Functions of Millimeter-sized Cosmic Dust Grains

$n=1.58 + i2.10^{-5}$



$n=1.59 + i0.01$

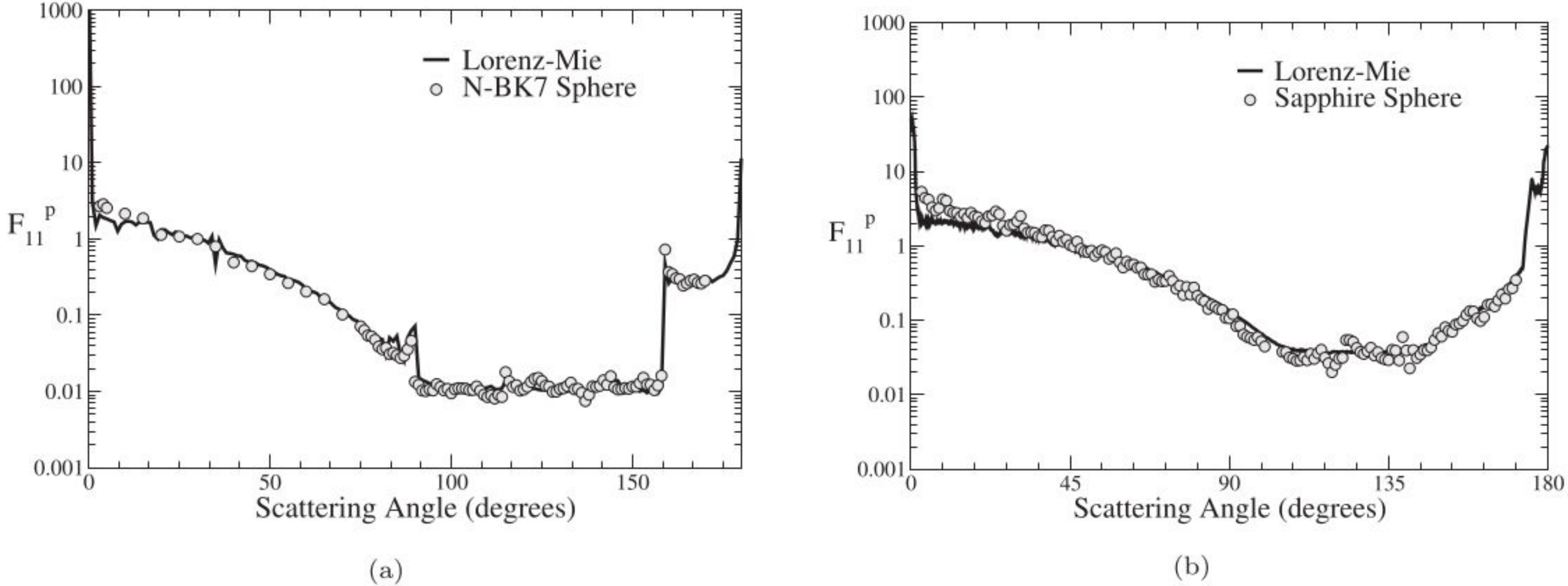




$n=1.54 + i0.0$

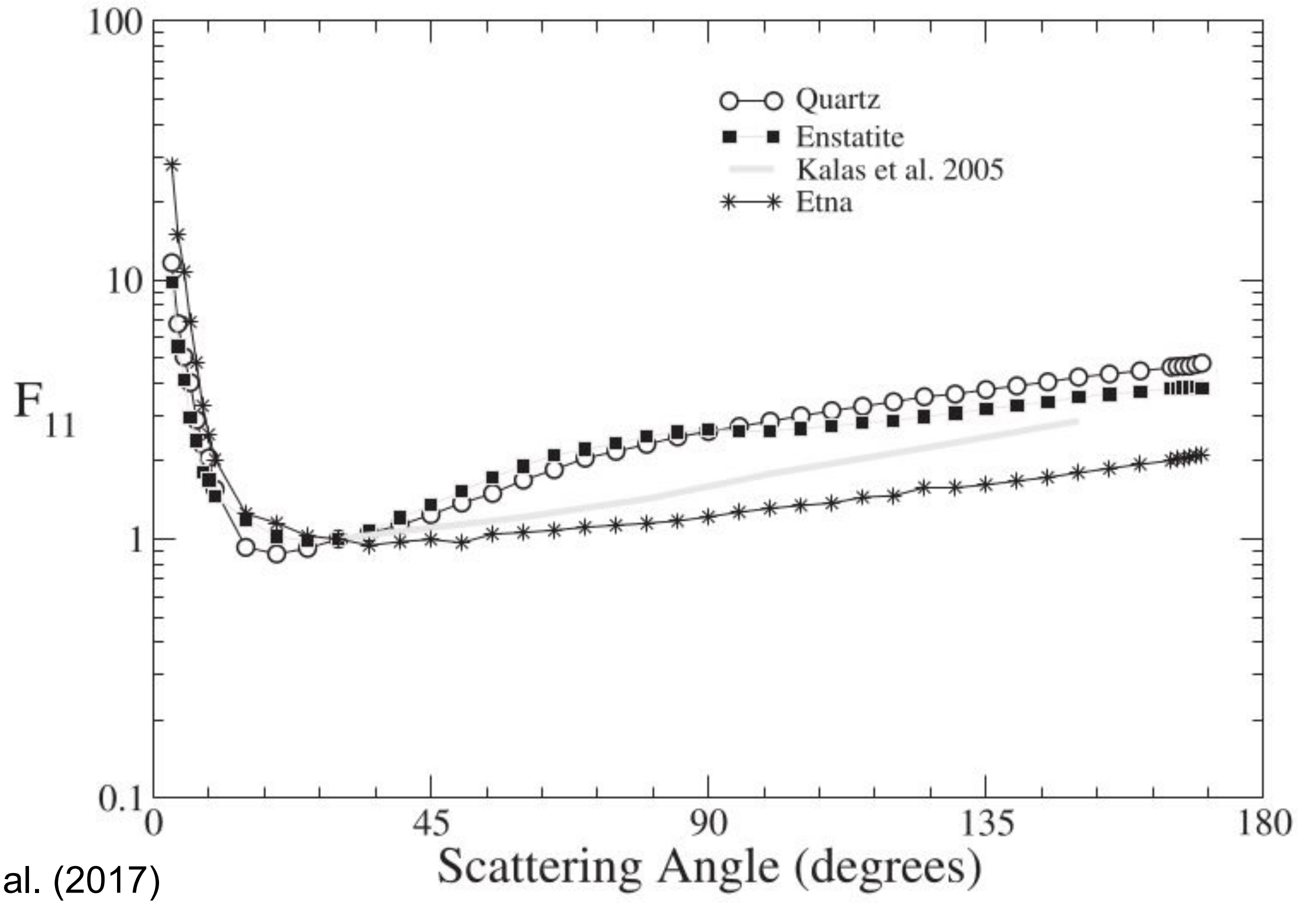
Muñoz et al. (2017)

Experimental Phase Functions of Millimeter-sized Cosmic Dust Grains



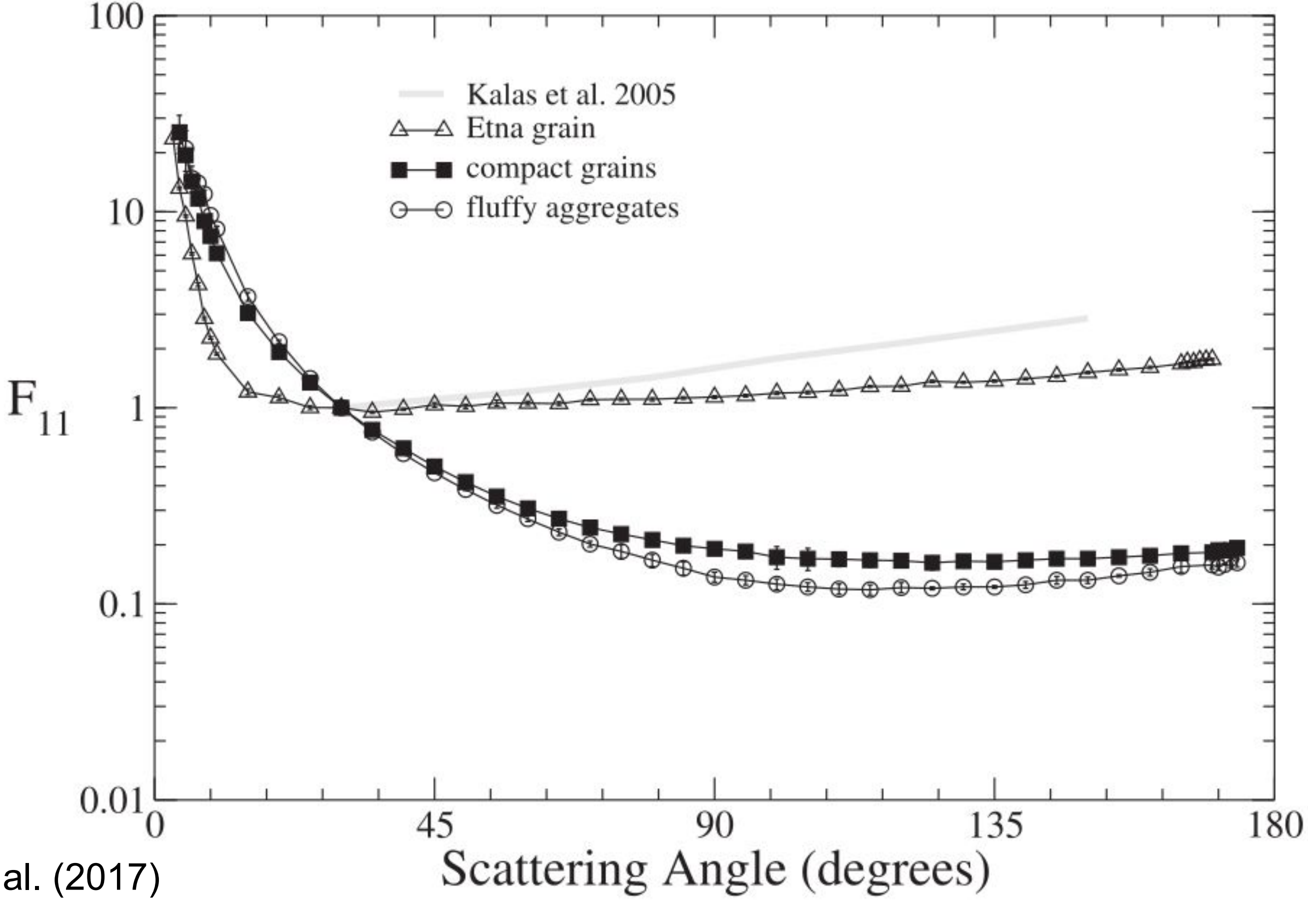
Muñoz et al. (2017)

Experimental Phase Functions of Millimeter-sized Cosmic Dust Grains



Muñoz et al. (2017)

Experimental Phase Functions of Millimeter-sized Cosmic Dust Grains



Muñoz et al. (2017)

Goniophotometers

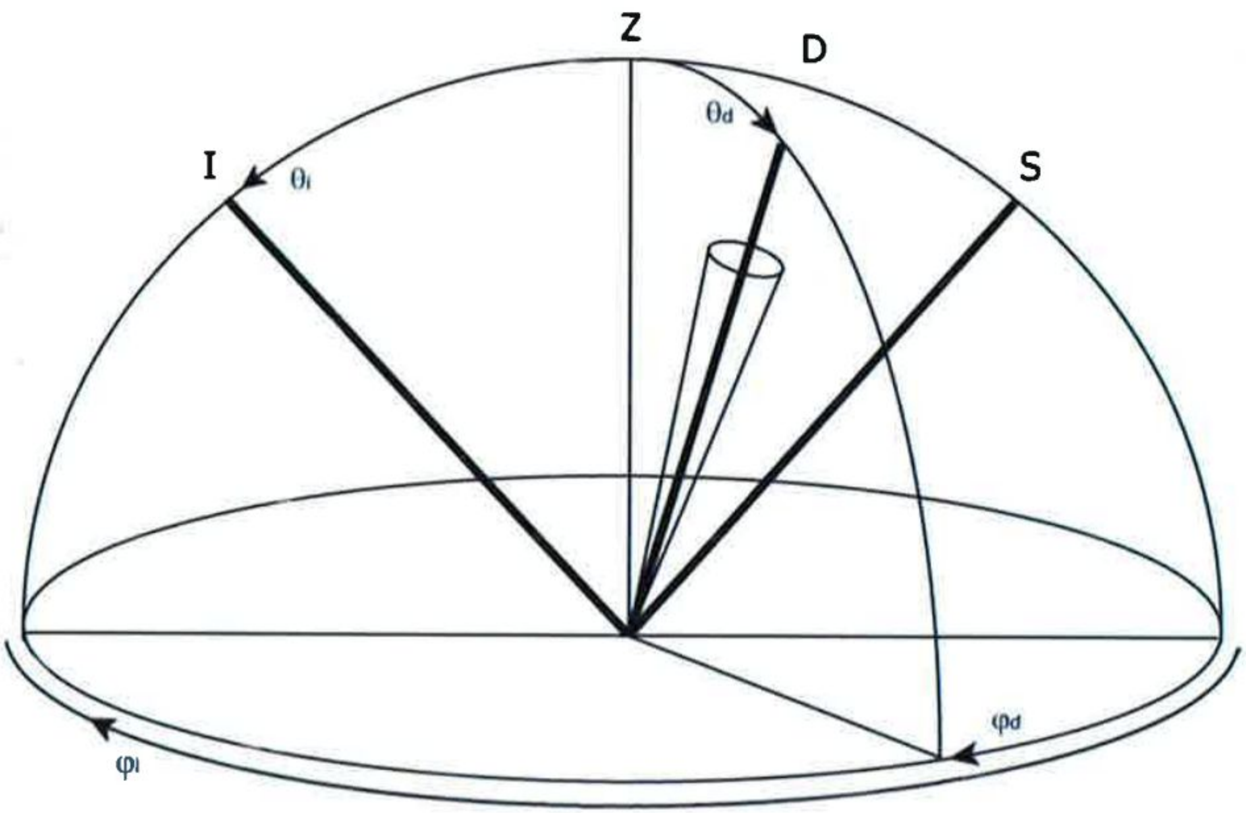
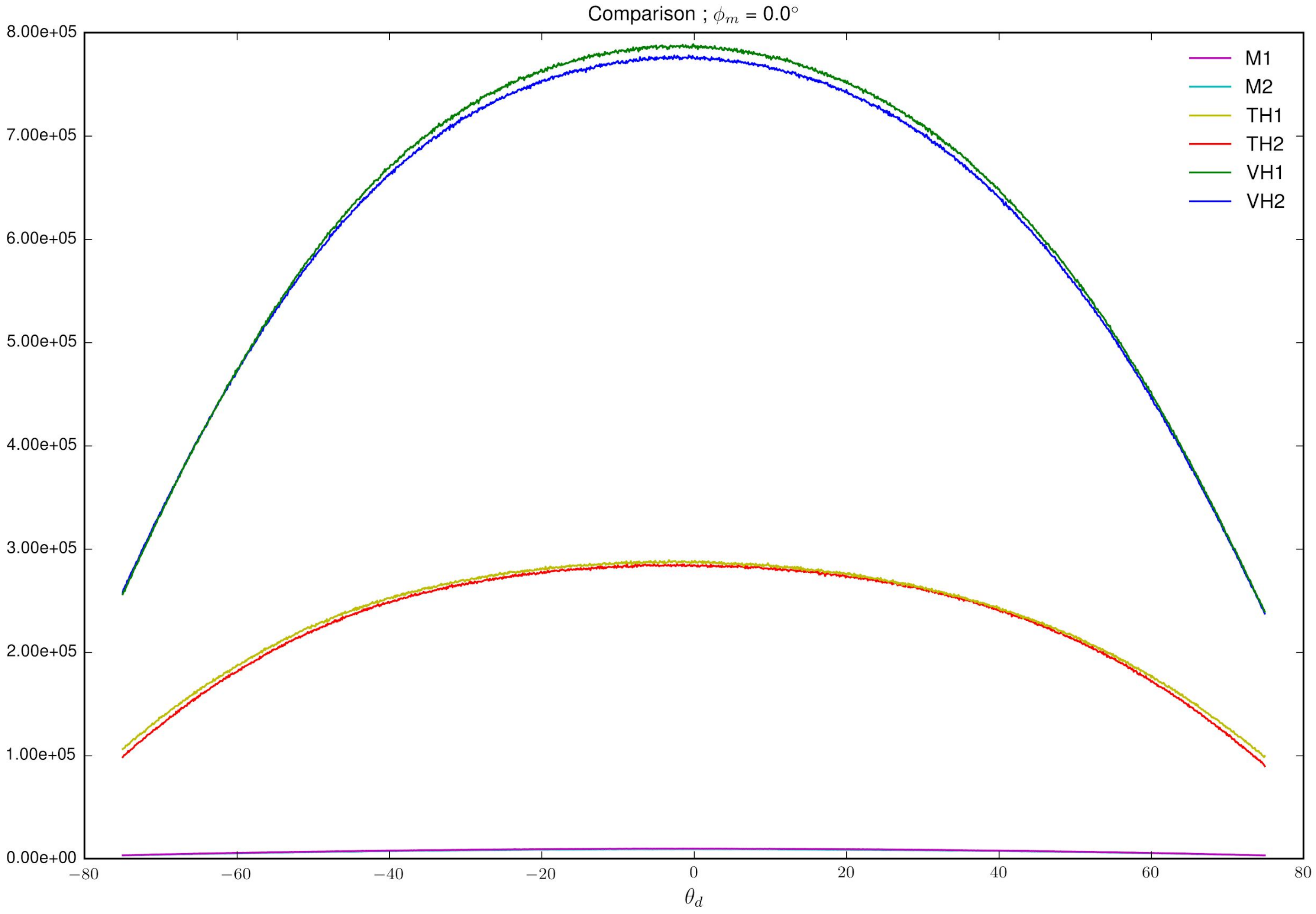
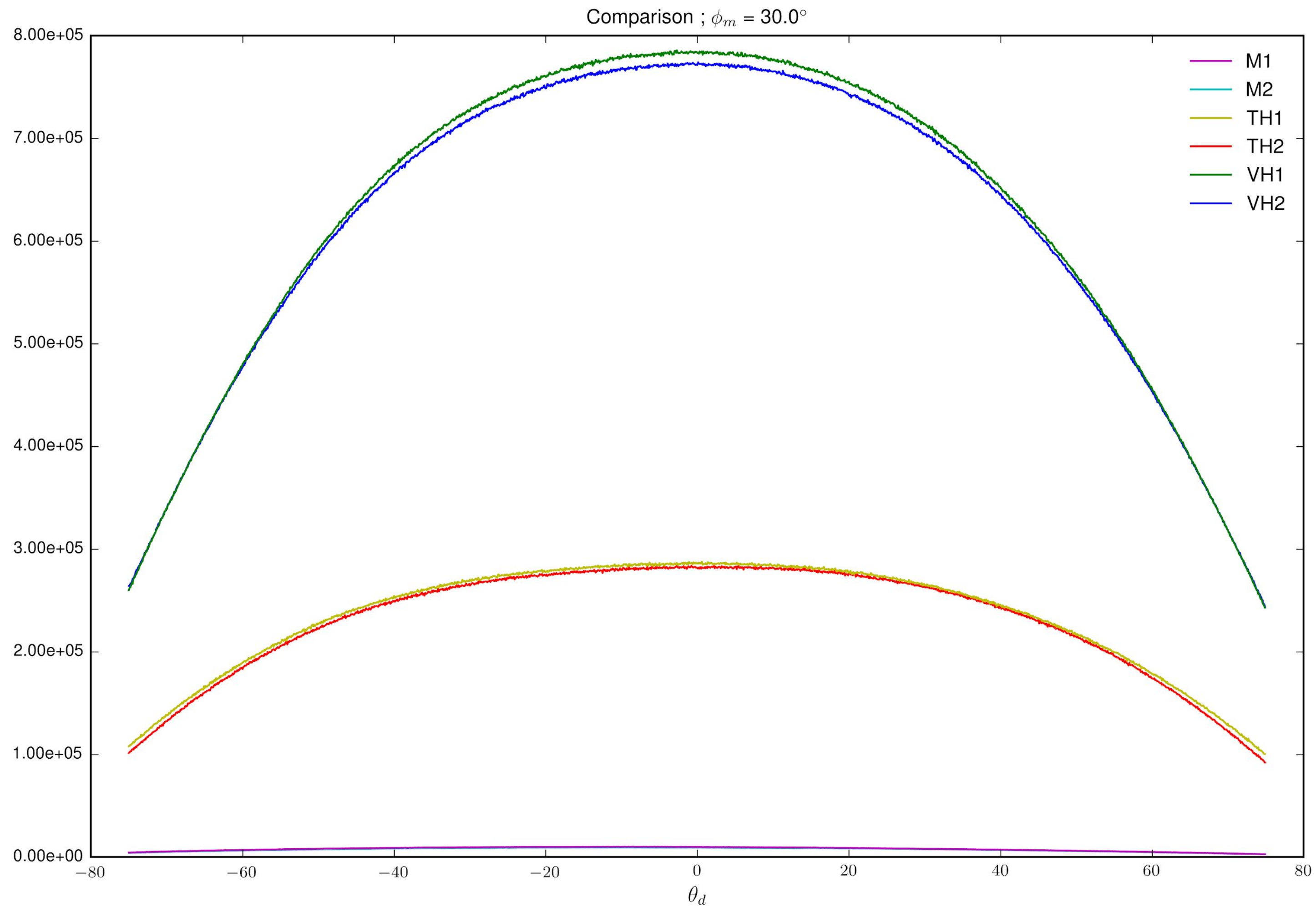
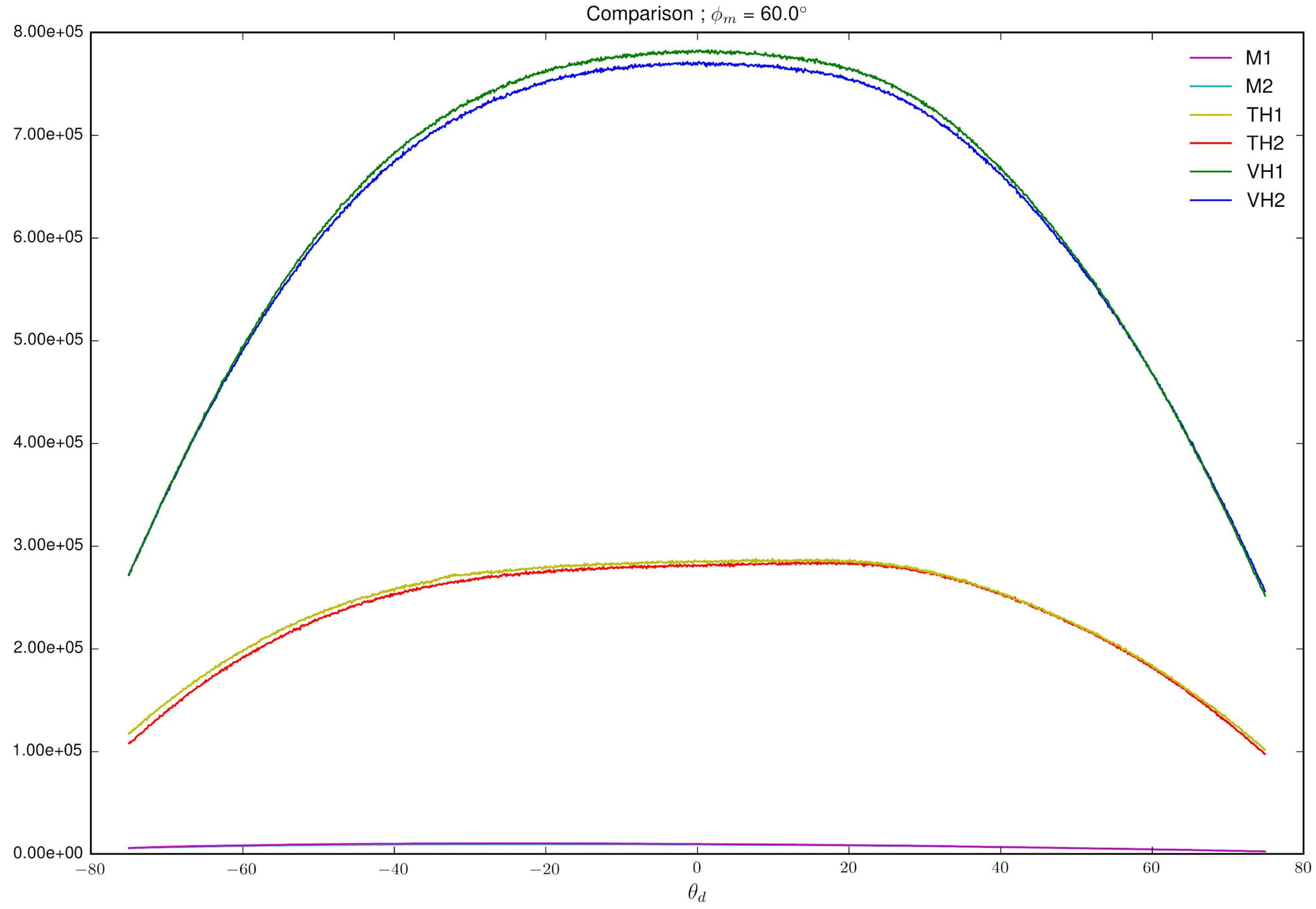


Fig. 1: Coordinate system

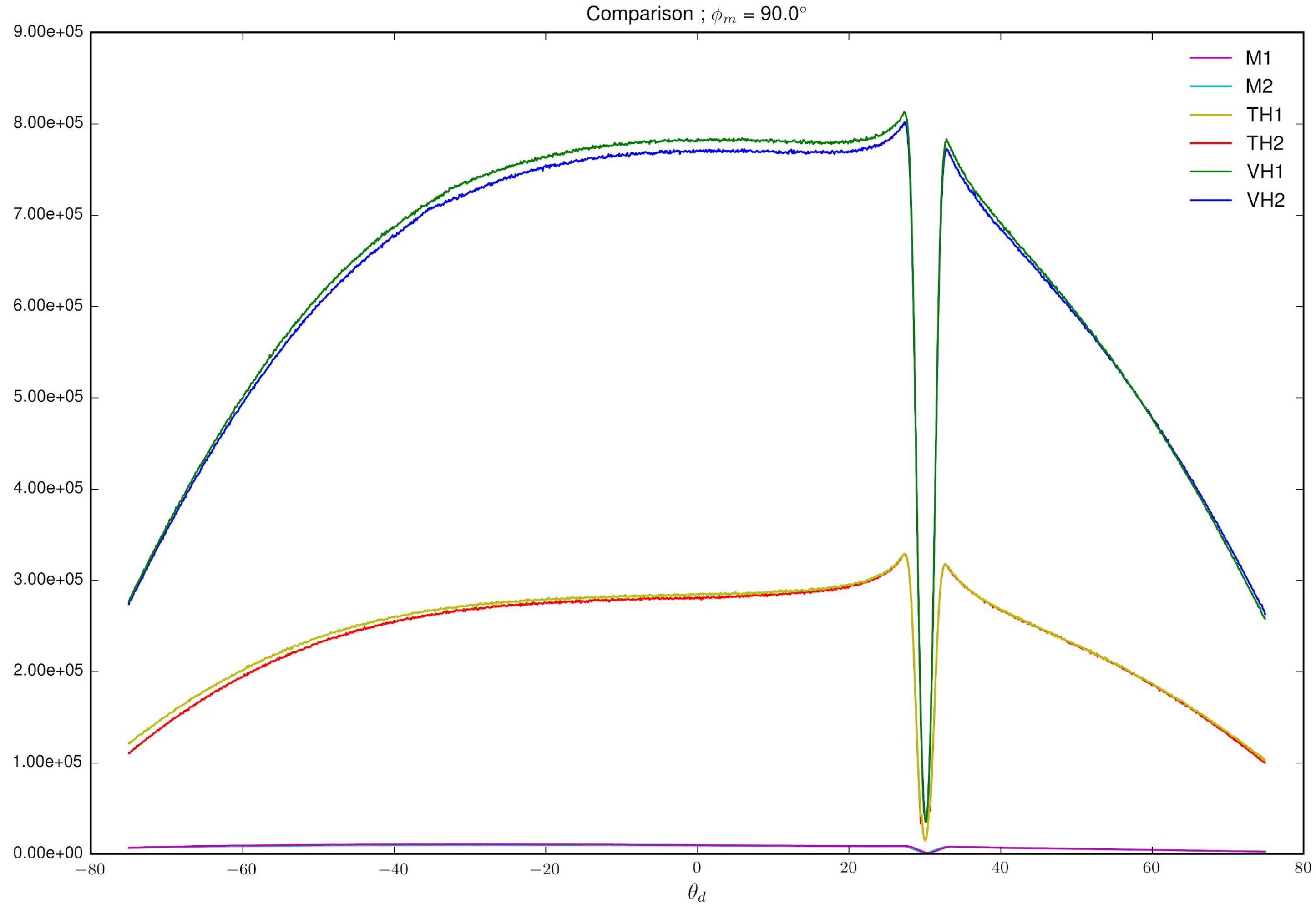

Comparison ; ϕ_m = 0.0°
8.00e+05
7.00e+05
6.00e+05
5.00e+05
4.00e+05
3.00e+05
2.00e+05
1.00e+05
0.00e+00
−80
−60
−40
−20
0
20
40
60
80
θ_d
M1
M2
TH1
TH2
VH1
VH2



Comparison ; ϕ_m = 30.0°
8.00e+05
7.00e+05
6.00e+05
5.00e+05
4.00e+05
3.00e+05
2.00e+05
1.00e+05
0.00e+00
−80
−60
−40
−20
0
20
40
60
80
θ_d
M1
M2
TH1
TH2
VH1
VH2



Comparison ; ϕ_m = 60.0°
8.00e+05
7.00e+05
6.00e+05
5.00e+05
4.00e+05
3.00e+05
2.00e+05
1.00e+05
0.00e+00
−80
−60
−40
−20
0
20
40
60
80
θ_d
M1
M2
TH1
TH2
VH1
VH2



Comparison ; ϕ_m = 90.0°
9.00e+05
8.00e+05
7.00e+05
6.00e+05
5.00e+05
4.00e+05
3.00e+05
2.00e+05
1.00e+05
0.00e+00
−80
−60
−40
−20
0
20
40
60
80
θ_d
M1
M2
TH1
TH2
VH1
VH2