CHARACTERIZING COSMIC DUST PARTICLES WITH PHOTOPOLARIMETRY

Why we should care about the dust morphology

Olga Muñoz (olga@iaa.es)
Instituto de Astrofísica de Andalucía, CSIC
Granada, Spain

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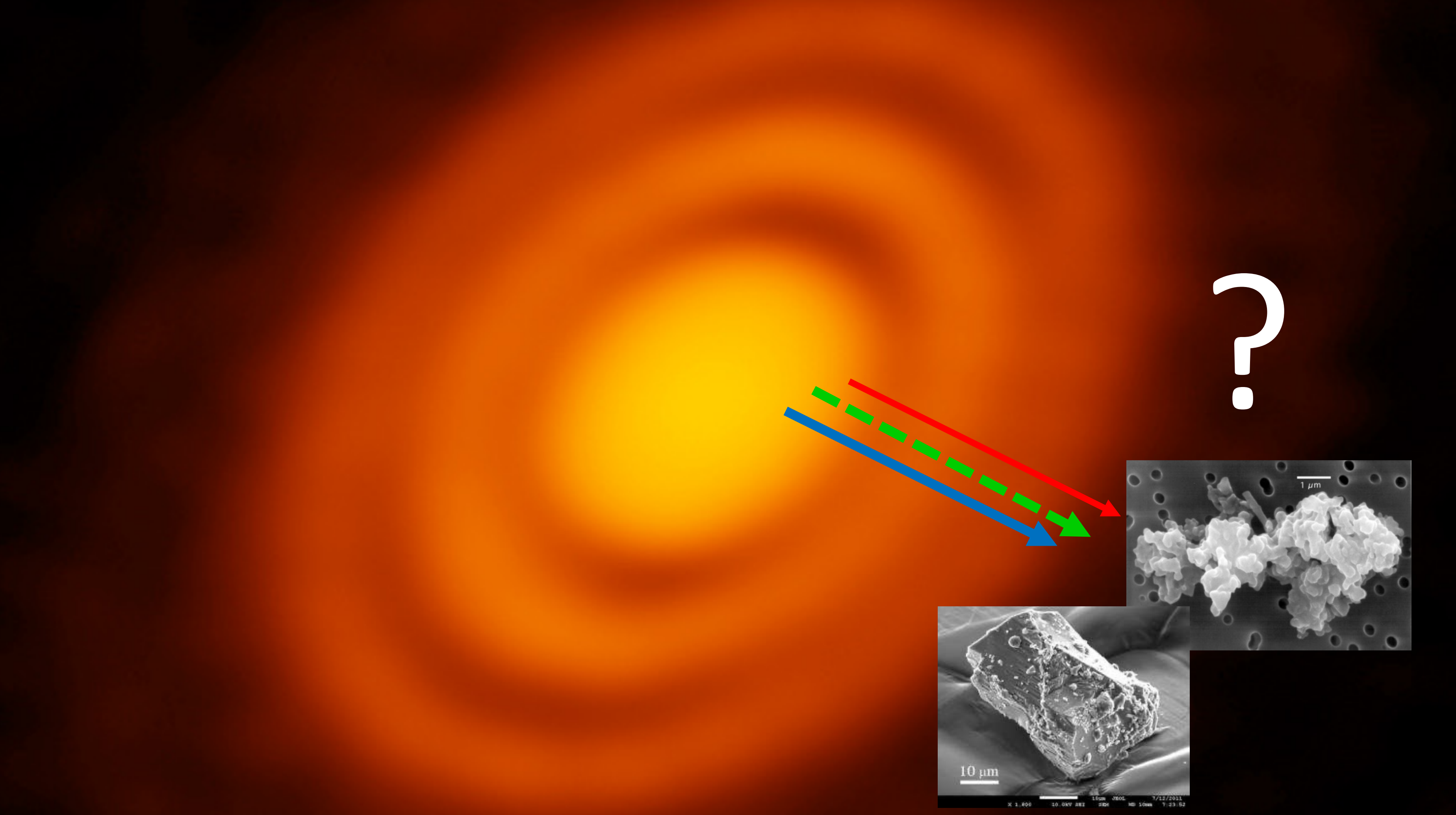
Characterizing the life cycle of dust



HL Tau Credit: ALMA(ESO/NAOJ/NRAO); C. Brogan, B. Saxton (NRAO/AUI/NSF)

GOALS

- Photopolarimetry as a tool for characterizing dust particles.
- Dust morphology matters

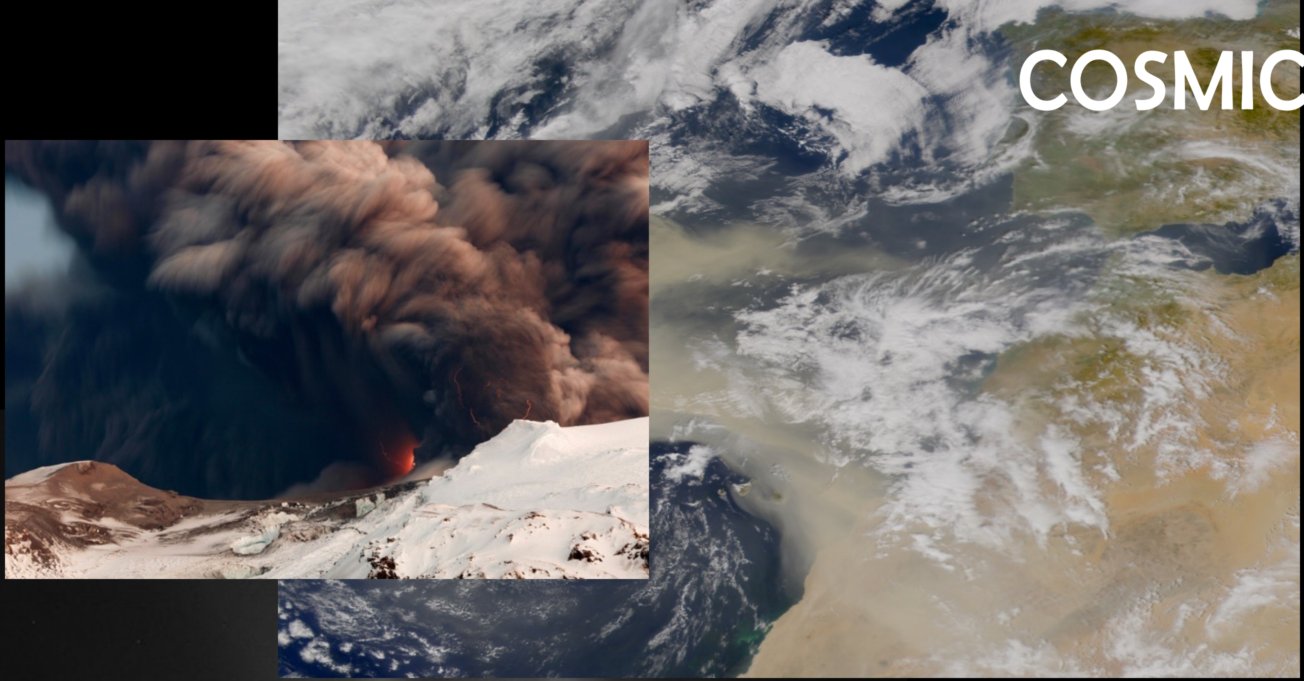
PART 1

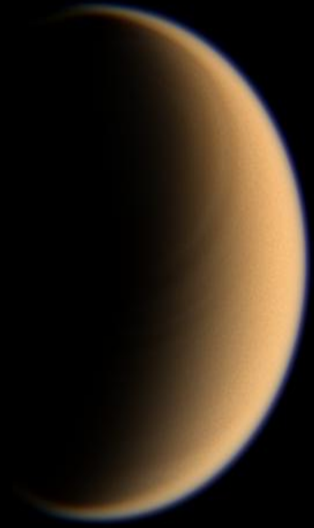
- Characterizing cosmic dust particles. Getting profit of Solar System research.
- Electromagnetic radiation. Definitions.
- Cosmic Dust Laboratory.
- Photopolarimetry as a tool for characterizing dust particles. Examples.

PART 2 (Practical Exercises)

- Dust morphology effect.
    1. Experimental data.
    2. Model/Scattering Databases.

COSMIC DUST...





... in the SOLAR SYSTEM

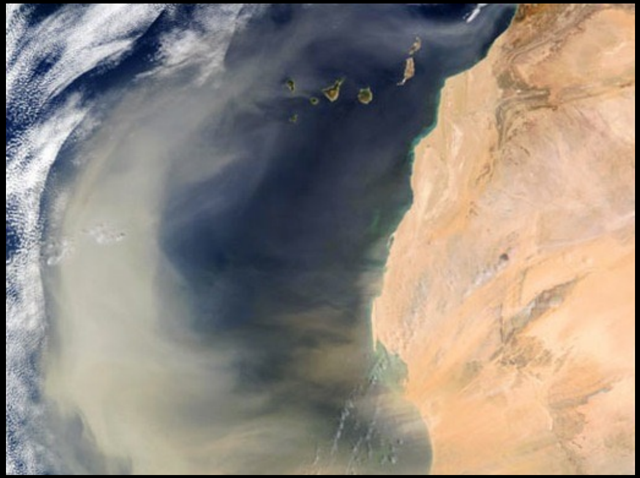
WHY?

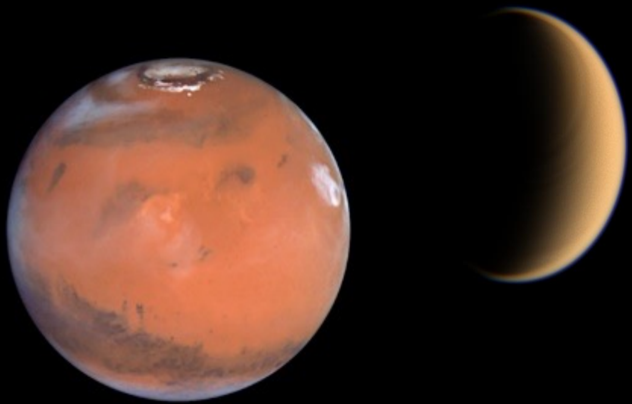
COMETARY DUST
BUILDING BLOCKS OF OUR PLANETARY SYSTEM

Comet 67P Churyumov-Gerasimenko

ESA/Rosetta/MPS for OSIRIS Team
MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA

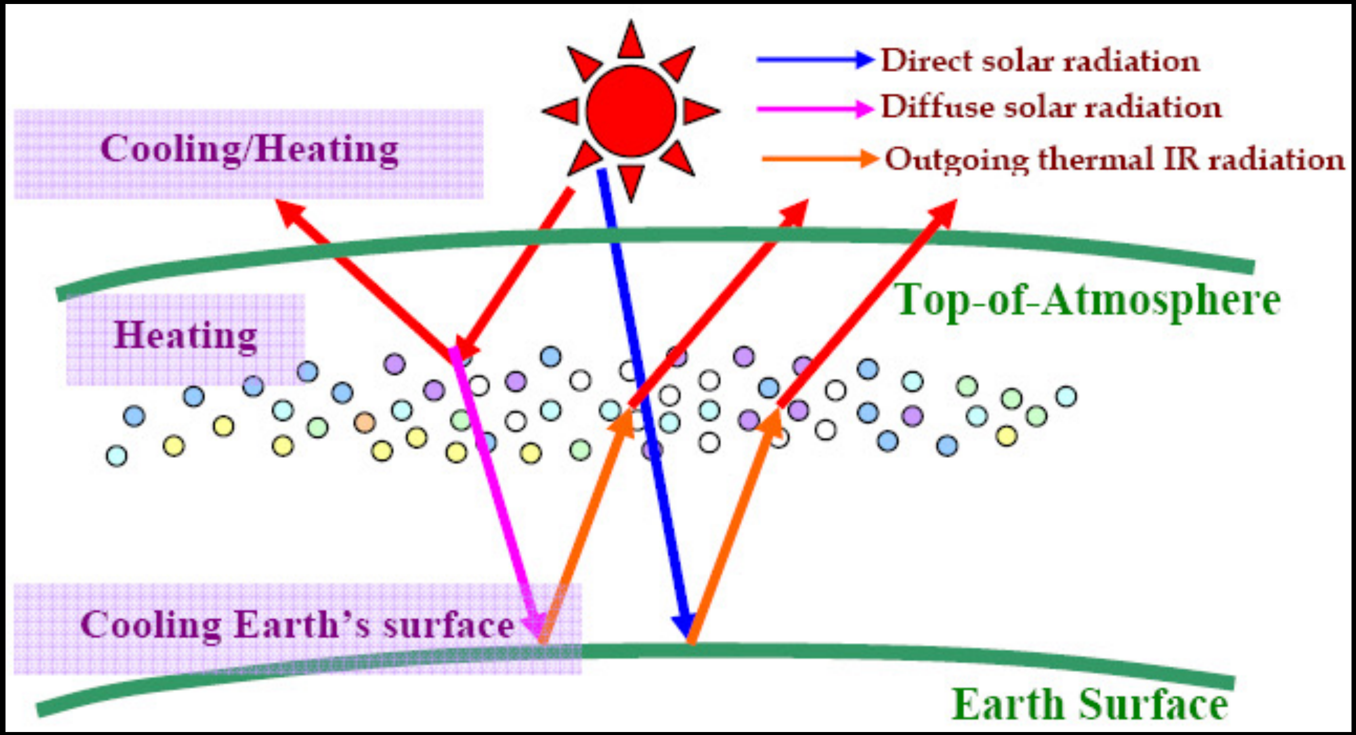
WHY?
PLANETARY ATMOSPHERES





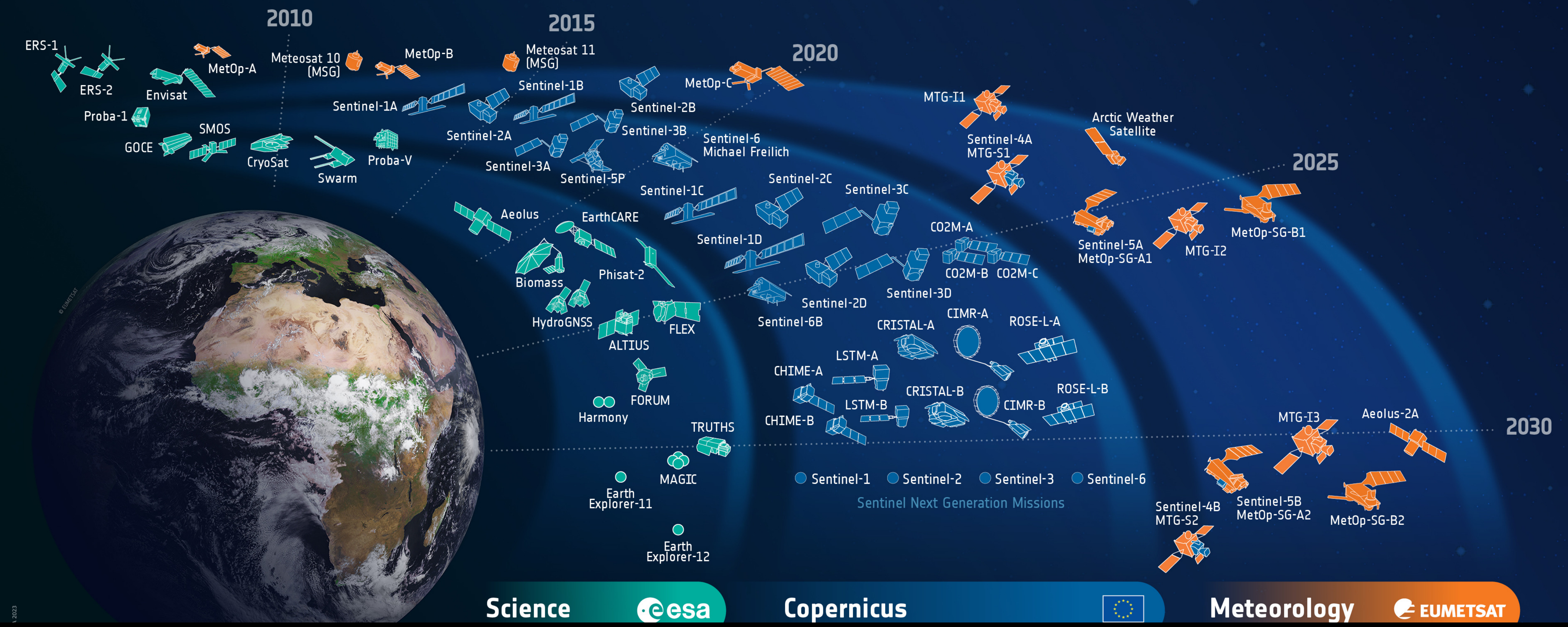
(KNOWLEDGE OF DUST SIZE AND COMPOSITION IS MANDATORY TO UNDERSTAND THEIR IMPACT ON CLIMATE)

Temperature profile
Radiative balance
Atmospheric dinamic



ESA

ESA-DEVELOPED EARTH OBSERVATION MISSIONS



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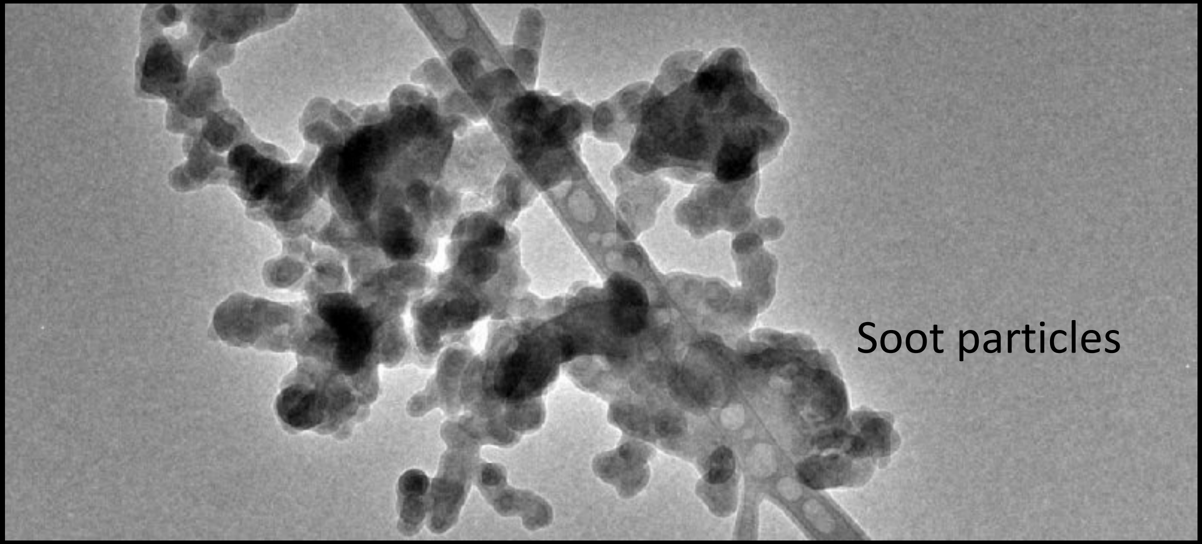
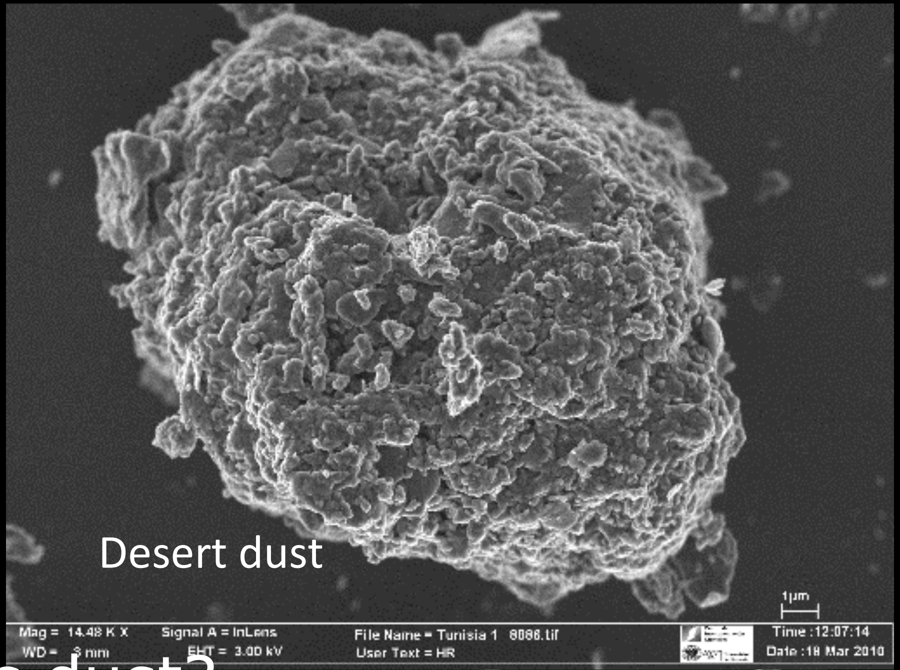
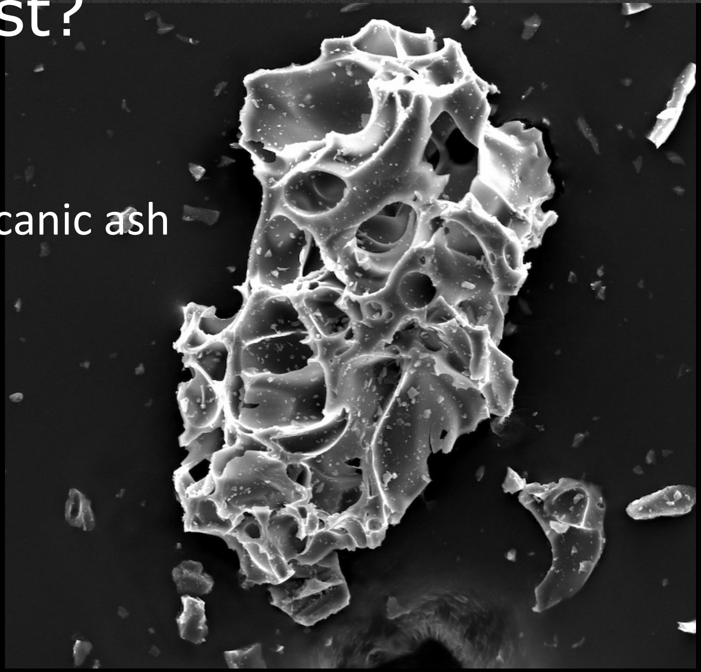
Terrestrial aerosols
Are they so different to cosmic dust?







www.scattering.iaa.es

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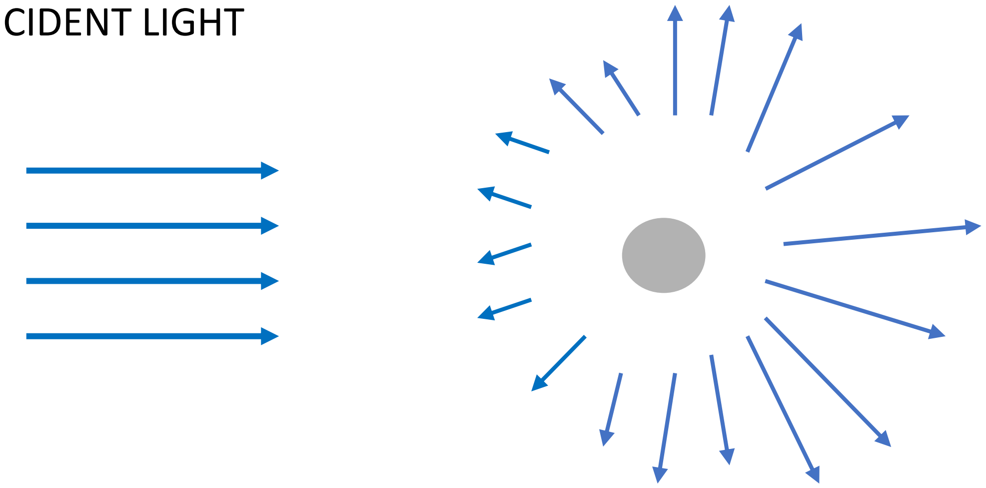
Some definitions

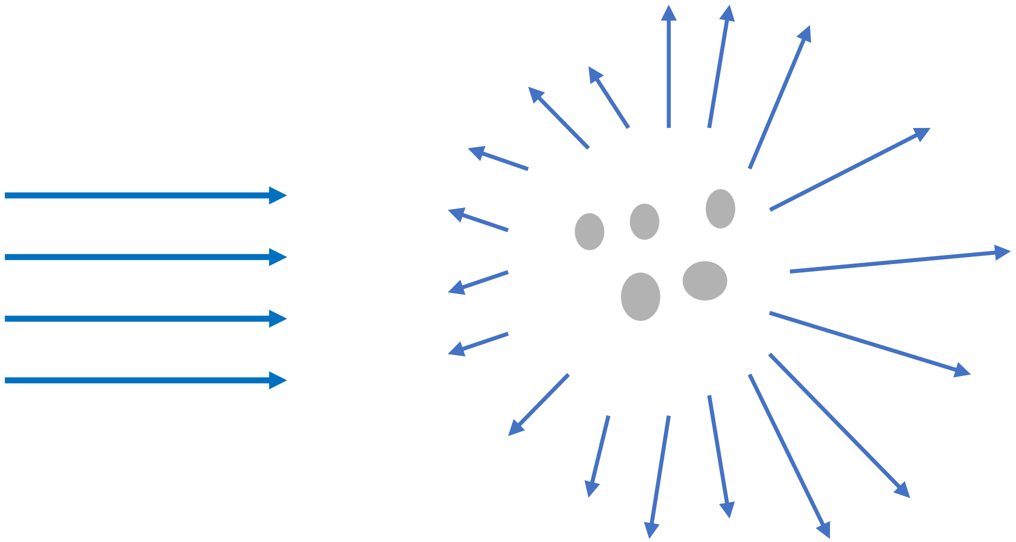
OUR TOOL: ELECTROMAGNETIC LIGHT SCATTERING

INCIDENT LIGHT



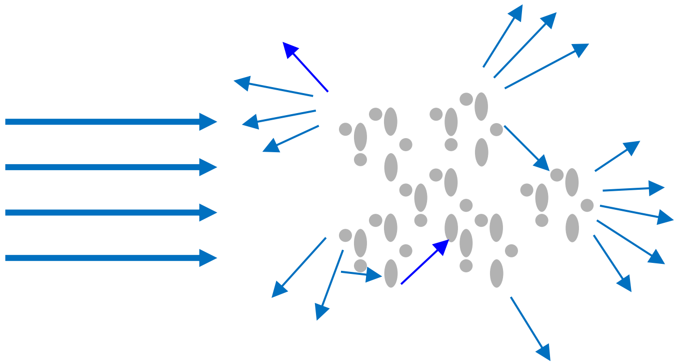
DIRECT INTERACTION

ABSORPTION + SCATTERING + THERMAL EMISION



Single scattering approximation
Total Field = Σ *single fields*

RADIATIVE BALANCE OF THE ATMOSPHERE



Multiple Scattered
Diffuse component

Intensity Vector $\boldsymbol{I}(\boldsymbol{r},\hat{\boldsymbol{n}},\mathrm{w}) = \begin{bmatrix} \mathrm{I}(\mathbf{r},\hat{\boldsymbol{n}},\mathrm{w}) \\ \mathrm{Q}(\boldsymbol{r},\hat{\boldsymbol{n}},\mathrm{w}) \\ \mathrm{U}(\boldsymbol{r},\hat{\boldsymbol{n}},\mathrm{w}) \\ \mathrm{V}(\boldsymbol{r},\hat{\boldsymbol{n}},\mathrm{w}) \end{bmatrix}$

Radiative Transfer Equation

Change in the intensity vector along the direction of propagation $\hat{n}$

$$\frac{d}{ds}\mathbf{I}(r,n,\omega) = -n_0(r)\underbrace{\langle K(\mathbf{r},n,\omega)\rangle \mathbf{I}(r,n,\omega)}_{\text{Absorption}} + n_0(r)\int_{4\pi} dn' \underbrace{\langle \overbrace{F(r,n,n',w)}^{\text{Scattering matrix}}\rangle \mathbf{I}(r,n',\omega)}_{\text{Scattering}}$$

$$+\, n_0(r)\underbrace{\langle K_e[r,n,T(r),\omega]\rangle}_{\text{Thermal Emission}}$$

Absorption

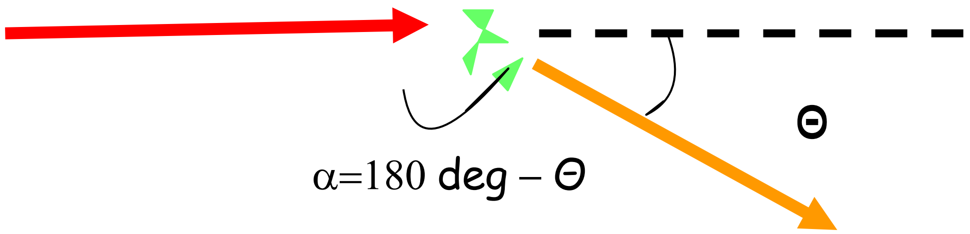
Scattering matrix

Scattering

Thermal Emission

Scattering, Absorption and Emission of light by small particles
Mishchenko, Larry & Travis, 2002
Transfer of polarized light in Planetary atmosphere
Hovenier, Van der Mee & Domke, 2004

THE SCATTERING MATRIX



Phase function

- F_{21}/F_{11} Deg. Lin. Pol.

$$\begin{pmatrix} I_{sc} \\ Q_{sc} \\ U_{sc} \\ V_{sc} \end{pmatrix} \propto \begin{pmatrix} F_{11} & F_{12} & F_{13} & F_{14} \\ F_{21} & F_{22} & F_{23} & F_{24} \\ F_{31} & F_{32} & F_{33} & F_{34} \\ F_{41} & F_{42} & F_{43} & F_{44} \end{pmatrix} \cdot \begin{pmatrix} I_{in} \\ Q_{in} \\ U_{in} \\ V_{in} \end{pmatrix}$$

Intensity (I_{sc}); Lin. Pol. (Q_{sc}, U_{sc}); Circular Pol. (V_{sc})

Stokes vector · *Scattering Matrix* · *Stokes Vector*

Depends on:
Shape
porosity
size
refractive index
orientation
wavelength

Degrees of polarization

Degree of linear polarization

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

Extended degree of linear polarization

$$EDLP = \frac{-Q}{I}$$

$U = 0 \Rightarrow |EDLP| = DLP$
$EDLP > 0 \Rightarrow$ vibration $\perp$scattering plane.

Degree of circular polarization

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

In case of single scattering of natural incident light, i.e., $(I_0, Q_0, U_0, V_0) \propto (1, 0, 0, 0)$:

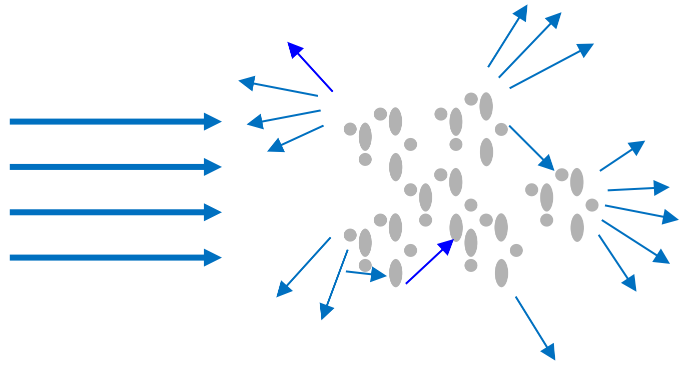
EDLP for natural incident light

$$EDLP(\theta) = -\frac{F_{21}(\theta)}{F_{11}(\theta)}$$

DCP for natural incident light

$$DCP(\theta) = \frac{F_{41}(\theta)}{F_{11}(\theta)}$$

RADIATIVE BALANCE OF THE ATMOSPHERE



Multiple Scattered
Diffuse component

Intensity Vector

$$\boldsymbol{I}(\boldsymbol{r},\hat{\boldsymbol{n}},\mathrm{w}) = \begin{bmatrix} \mathrm{I}(\mathbf{r},\hat{\boldsymbol{n}},\mathrm{w}) \\ \mathrm{Q}(\boldsymbol{r},\hat{\boldsymbol{n}},\mathrm{w}) \\ \mathrm{U}(\boldsymbol{r},\hat{\boldsymbol{n}},\mathrm{w}) \\ \mathrm{V}(\boldsymbol{r},\hat{\boldsymbol{n}},\mathrm{w}) \end{bmatrix}$$

APPROXIMATION
Radiative Transfer Equation neglecting polarization

Change in the intensity vector along the direction of propagation $\hat{n}$

$$\frac{d}{ds} I(\mathbf{r},\mathbf{n},\omega) = -n_0(\mathbf{r}) \underbrace{< K(\mathbf{r},\mathbf{n},\omega) > I(\mathbf{r},\mathbf{n},\omega)}_{\textit{Absorption}} + n_0(r) \int_{4\pi} \underbrace{dn' < F_{11}(\mathbf{r},\Theta,w) > I(\mathbf{r},\mathbf{n}',\omega)}_{\textit{Scattering}}$$

$$+ n_0(r) \underbrace{< K_e[r,n,T(r),\omega] >}_{\textit{Thermal Emission}}$$

Scattering, Absorption and Emission of light by small particles
Mishchenko, Larry & Travis, 2002
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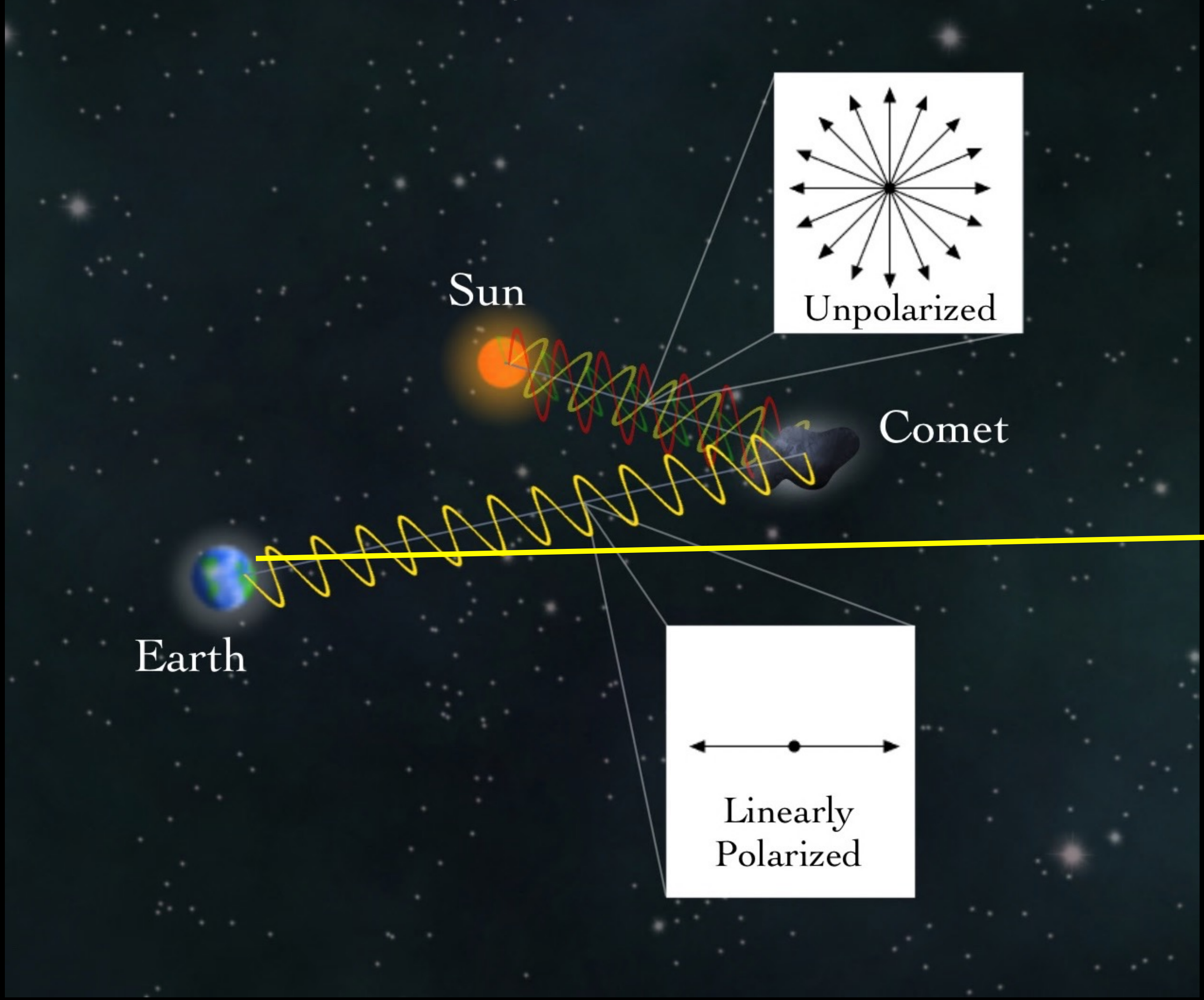
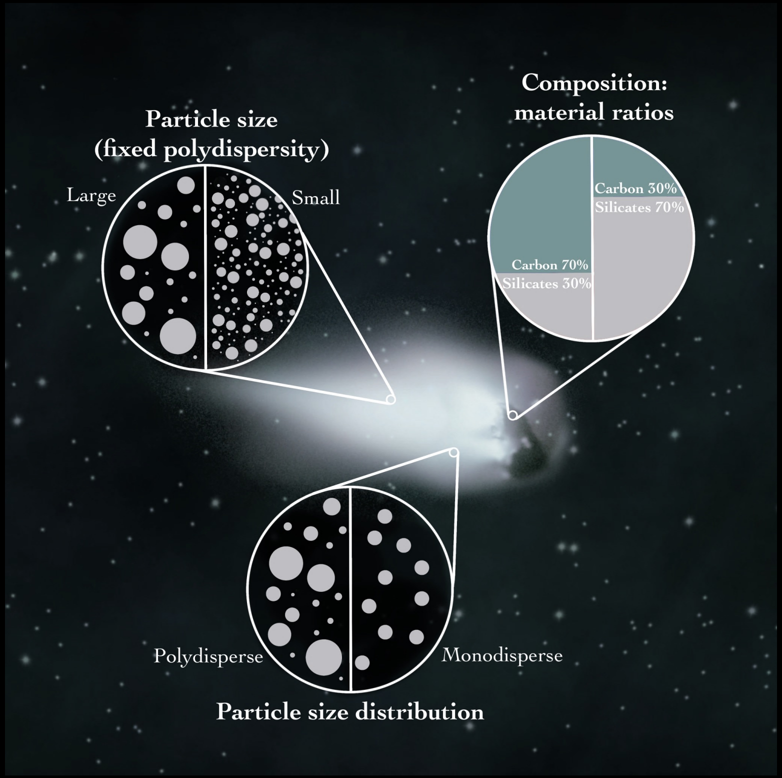
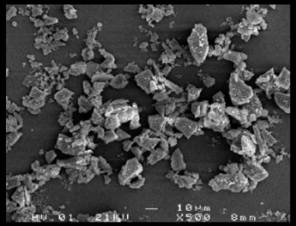
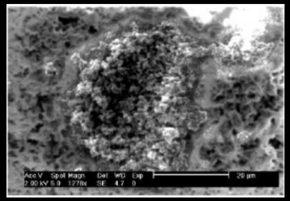
HOW: Polarimetry

Stellar light becomes linearly polarized when scattered by a dust cloud and/or reflected by a regolith



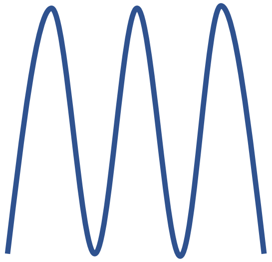






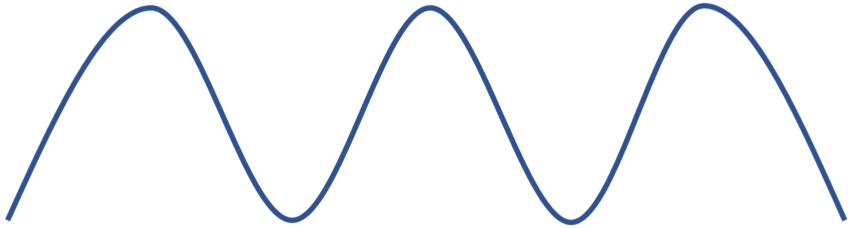
SIZE (a) vs SIZE PARAMETER (x)

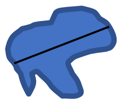
VISIBLE $\lambda 1$



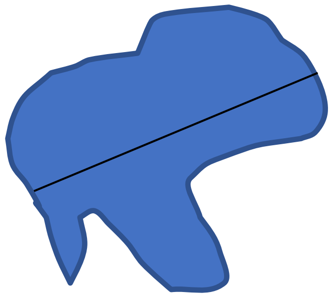
$$x = \frac{2\pi\, r}{\lambda}$$

RADIO $\lambda 2$





r=2μm ≡ r=3.3mm



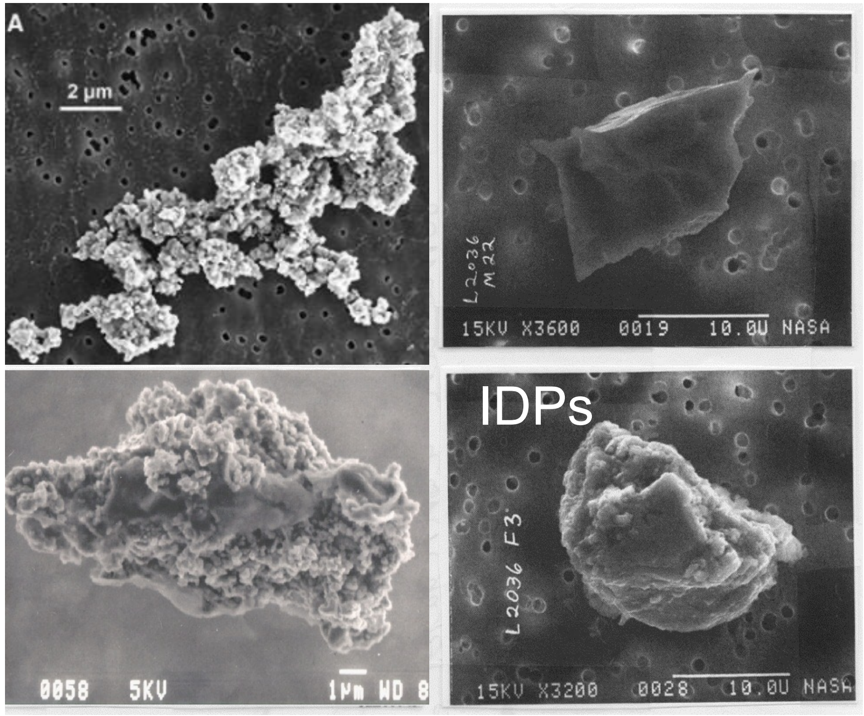
If m(λ1)=m(λ2)

$$X = \frac{2\pi * 2\mu m}{0.52\mu m} = 24$$

$$X = \frac{2\pi * 3346\mu m}{870\mu m} = 24$$

Rayleigh	Resonance/Mie	Geometric optics
r<<λ	r~λ	r>>λ

HOW?

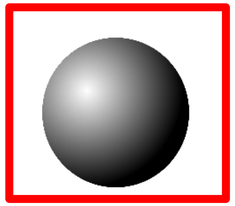


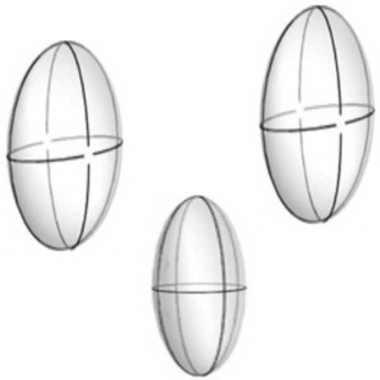
- Complicated shapes
- Mixture compositions
- Broad size distributions

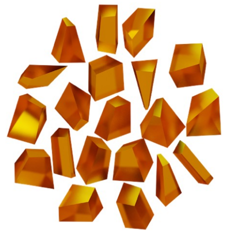
Complex computations

Simplified model particles;

Limited shapes and/or shapes





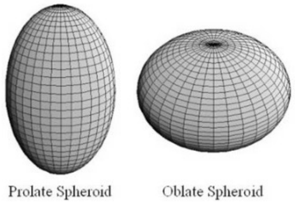


The Problem: Modelling scattering properties of dust grains

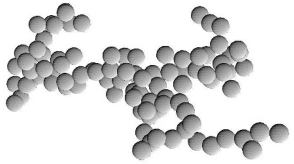
SIZE PARAMETER x=2π r/λ

Mie

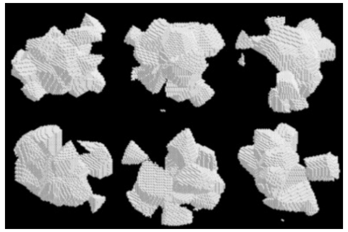
No restrictions x



x~30 (T-matrix: e.g. Mishchenko & Travis, JQSRT, 1998)

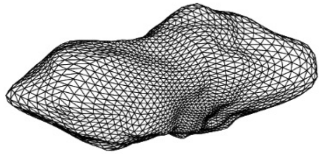


x~10-12 (DDA: Draine &Flatau, JOSA 1994; Yurkin & Hoekstra, JQSRT 2011) Mackowski &Mishchenko, JQSRT, 2011)



x~30 (Zubko et al. JQSRT, 2013)

(Muinonen et al. JQSRT, 2009)



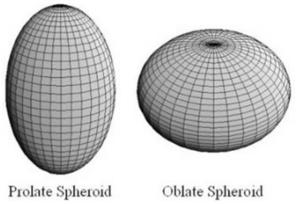
x>50 **Ray Optics Approximation**

The Problem: Modelling scattering properties of dust grains

SIZE PARAMETER $x=2\pi r/\lambda$

Mie

No restrictions x



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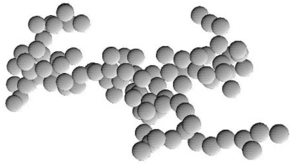

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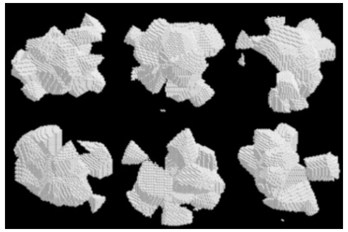

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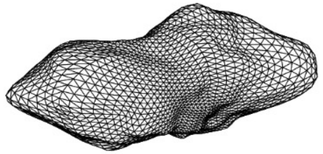
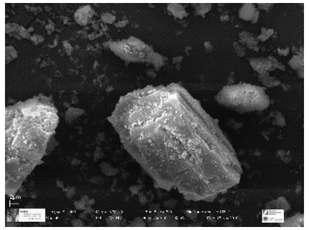


x>50 **Ray Optics Approximation**

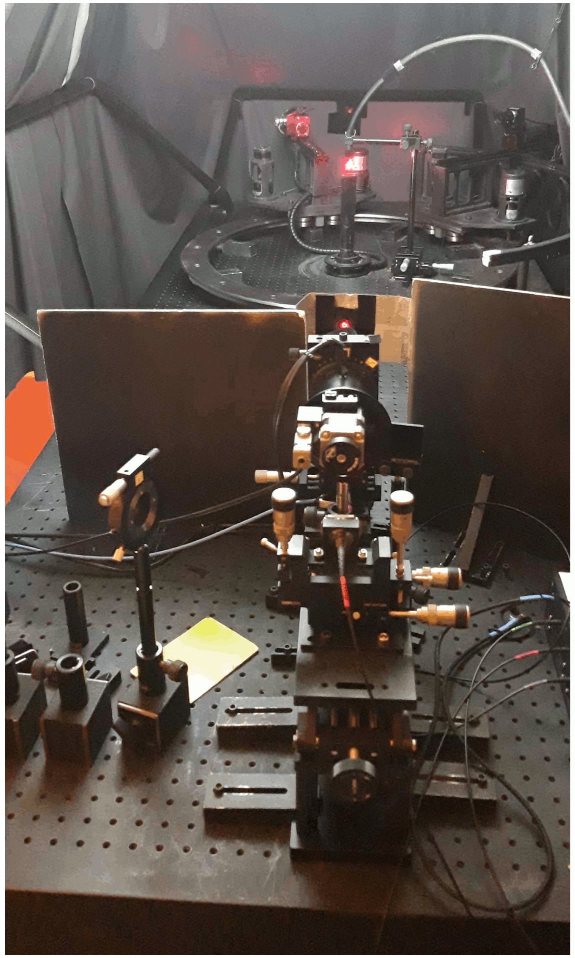


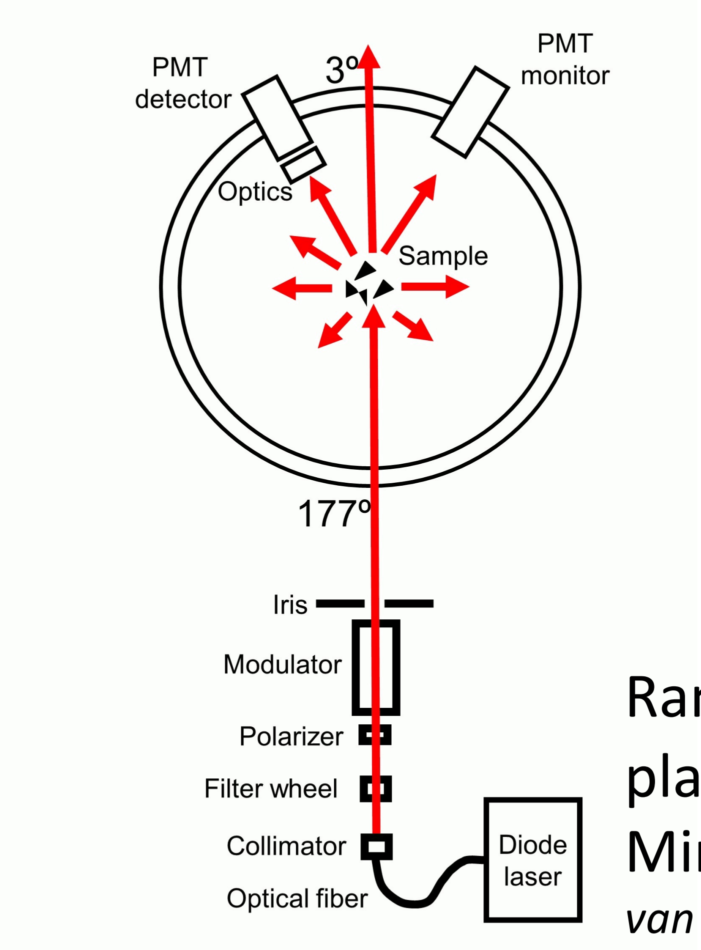
LABORATORY DATA: ALL SHAPES AND SIZES

THE EXPERIMENT
IAA COSMIC DUST LABORATORY

IAA- COSMIC DUST LABORATORY

λ=405 nm, 480 nm, 514 nm, 640 nm





$$\Phi_{sca} = \frac{\lambda^2}{4\pi^2 D^2} \mathbf{F}\, \Phi_0$$

Phase function

-F12/F11 degree of linear polarization

$$\mathbf{F}(\lambda,\theta) = \begin{pmatrix} F_{11} & F_{12} & 0 & 0 \\ F_{12} & F_{22} & 0 & 0 \\ 0 & 0 & F_{33} & F_{34} \\ 0 & 0 & -F_{34} & F_{44} \end{pmatrix}$$

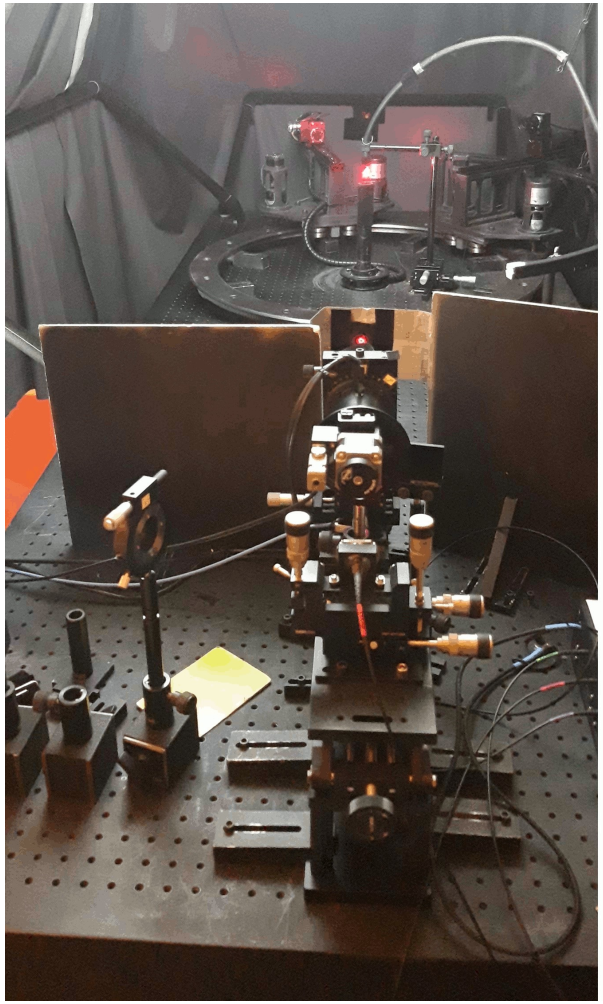
Randomly oriented particles => all sattering planes equivalent F (λ,θ)

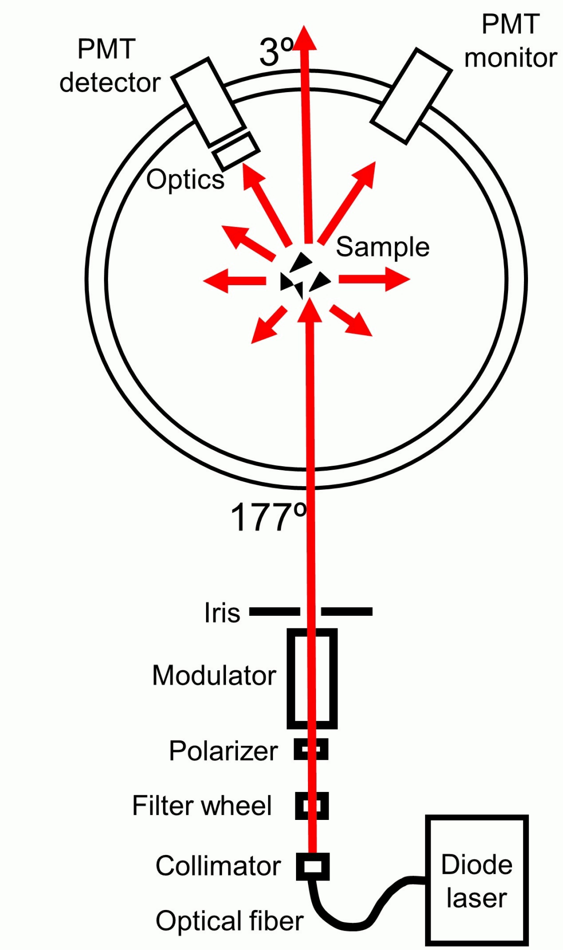
Mirror symmetry (6 independent elements)

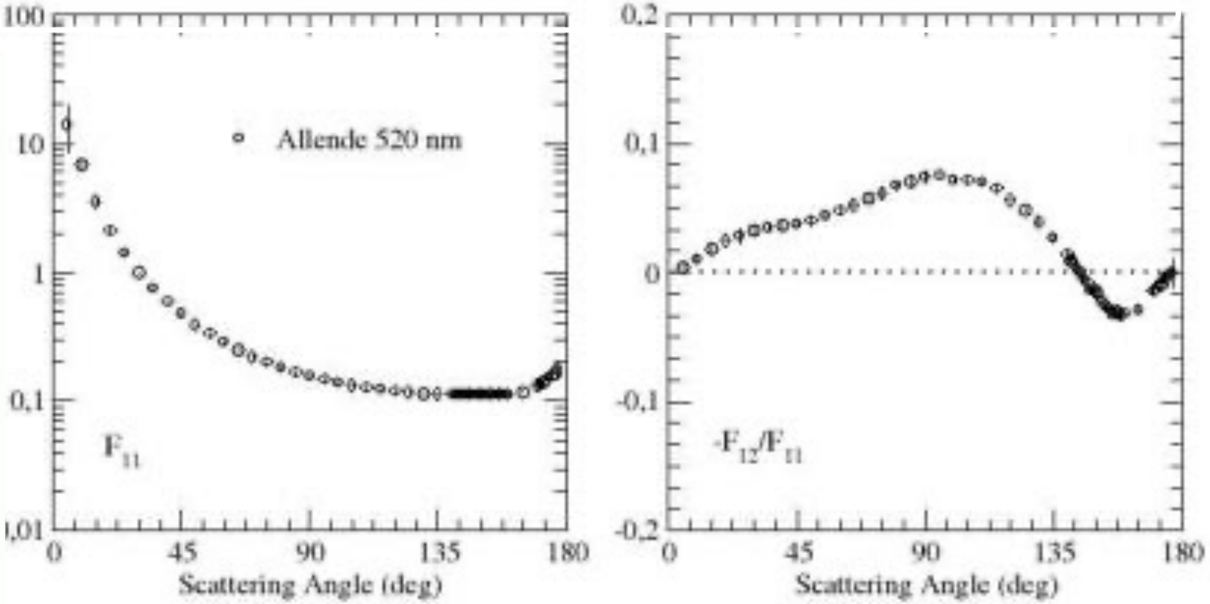
van de Hulst, Light scattering by small particles, 1957

Muñoz et al. JQSRT, 2010; Muñoz et al. Icarus 2011

IAA- COSMIC DUST LABORATORY





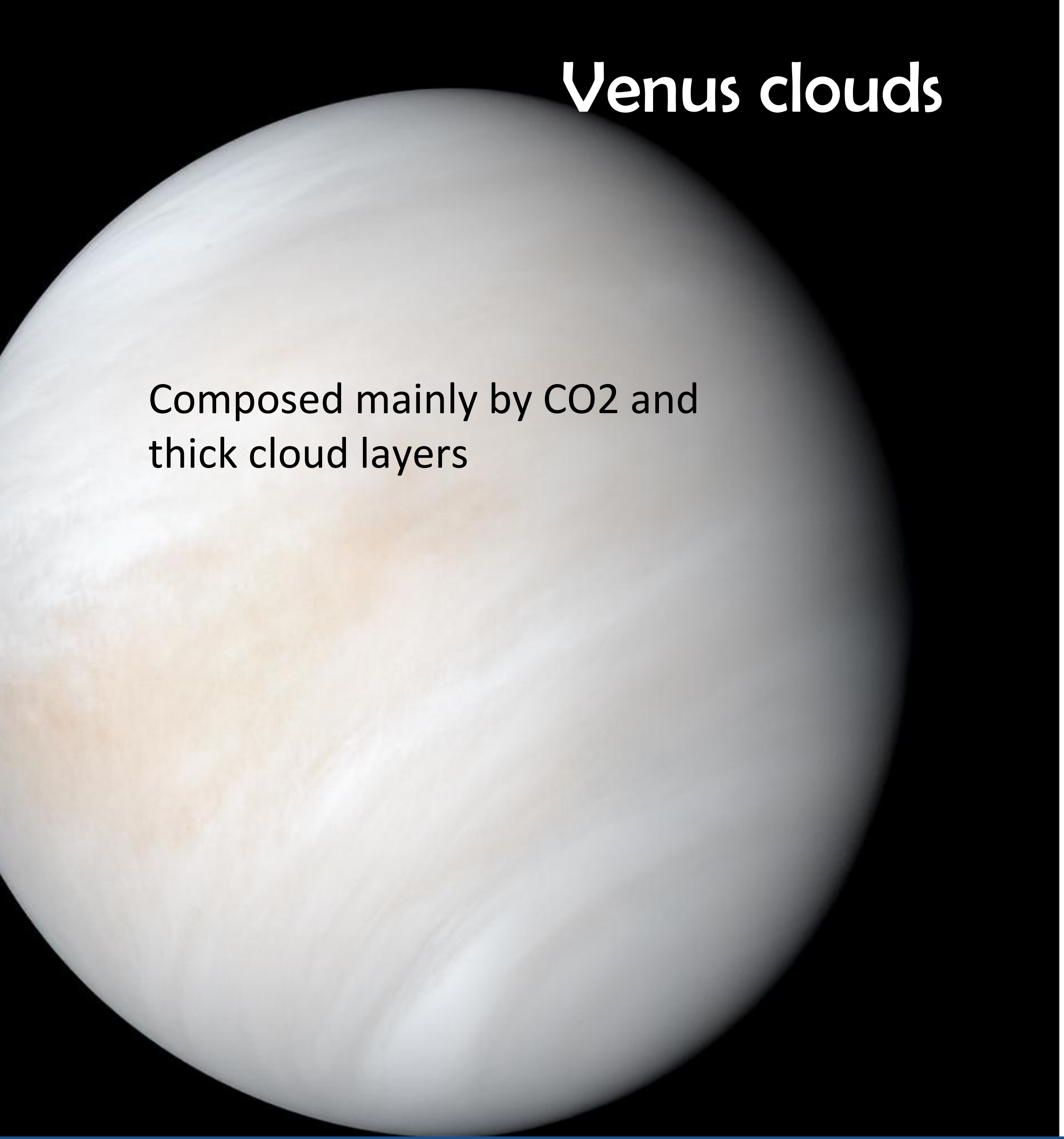


Data from Frattin et al, MNRAS, 484, 2019

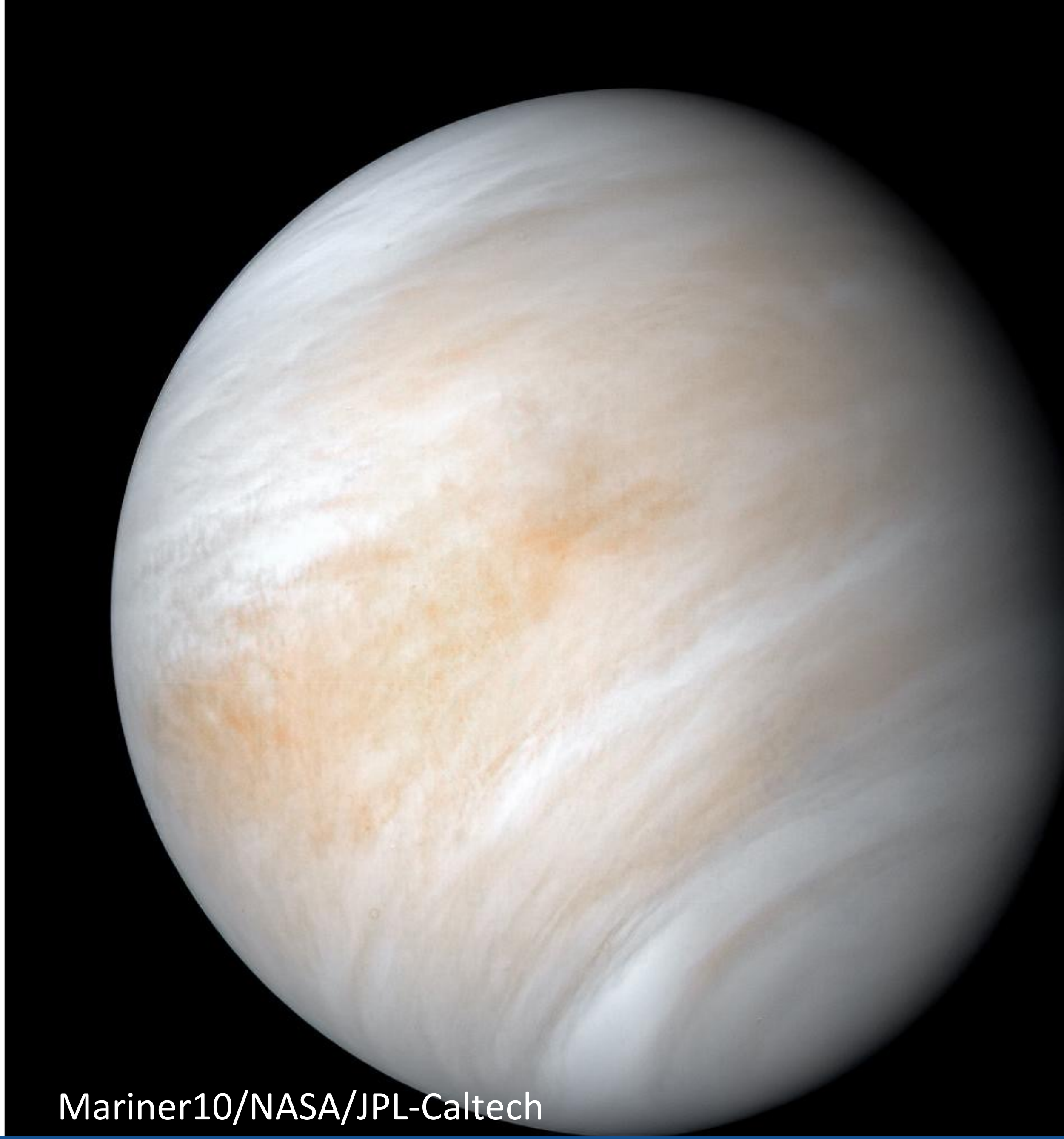
The simplest combination of optical elements (polarizer + modulator) gives the F_{11} and DLP

Photopolarimetry as a powerful tool
SOME EXAMPLES

Venus clouds



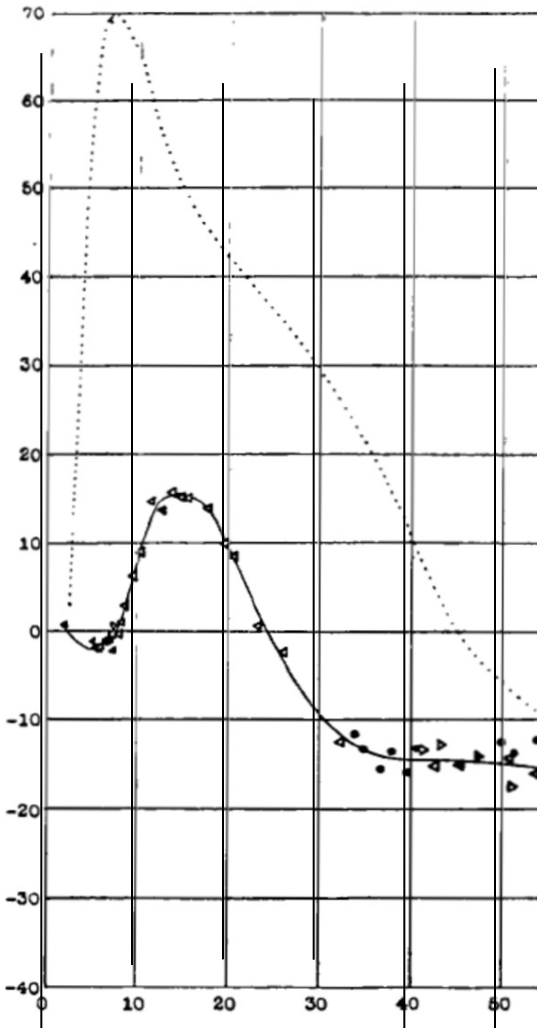
Composed mainly by CO_2 and thick cloud layers



Mariner10/NASA/JPL-Caltech

What is the composition of the clouds of Venus?

Several suggestions, water, H_2O ice, carbon suboxide (C_3O_2), solid CO_2…



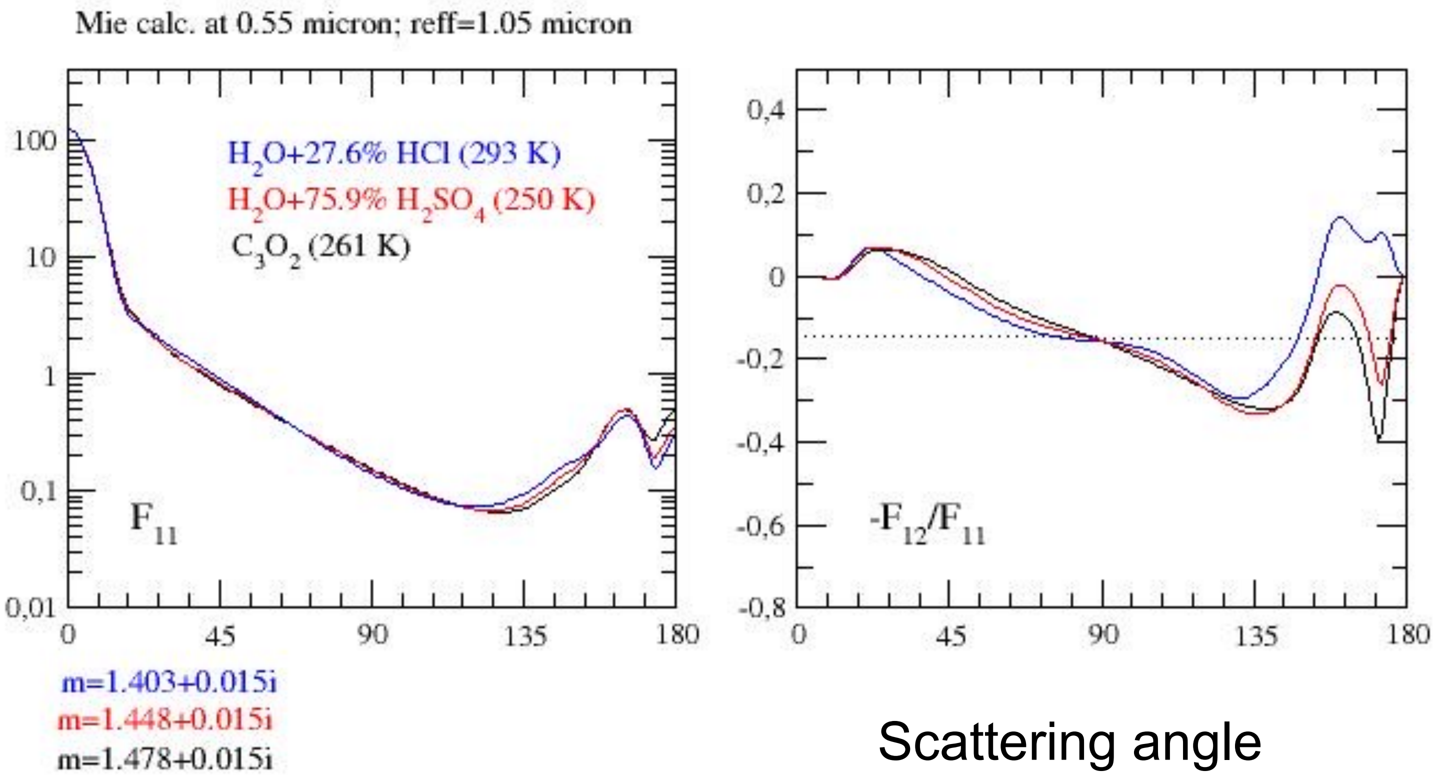
Degree of linear polari

Hansen & Hovenier (J. *Atmos. Sci. 31* **(1974)** *1137-1160)*

- Cloud particles are spherical (rainbow feature!).
- Effective radius= 1.05 ± 0.10 μm.
- Refractive index 1.46 at 0.365 μm
  1.44 at 0.55 μm
  1.43 at 0.99 μm
- Composition H_2SO_4.
- Top of cloud layer at about 50 millibar.

WHY POLARIZATION

Information on the refractive index of the particles
(spherical particles)



Scattering angle

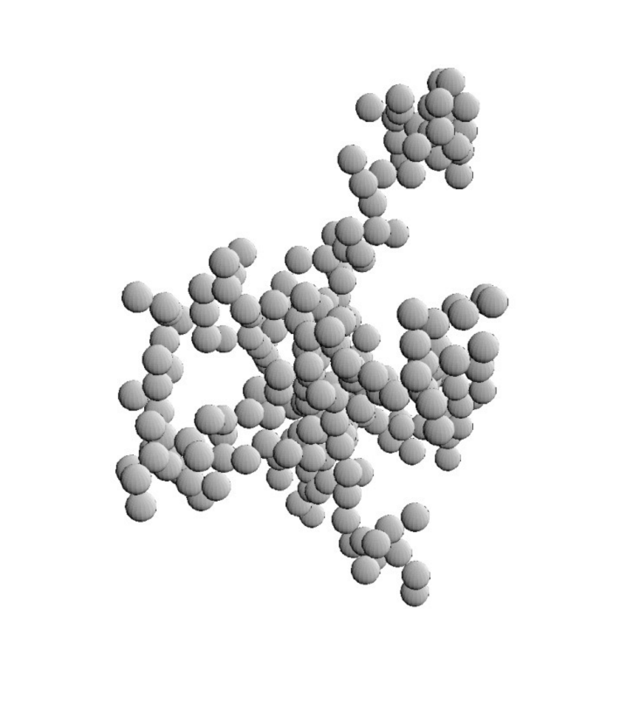
Calculations based on results by Hansen & Hovenier, 1974

TITAN

- The only natural satellite in the Solar System with a thick atmosphere.
- The atmosphere of this moon may resemble that of our planet in its early days, before primitive living organisms enriched it with oxygen via photosynthesis.
- Resembling that of Earth (N_2 ;94%) but small traces of oxygen and water. Methane (CH_4) plays a similar role to that of water in Earth's atmosphere.

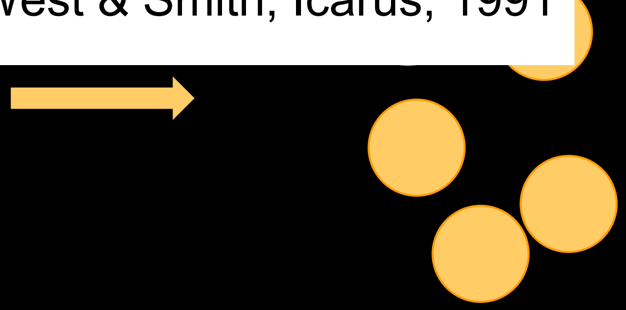
TITAN AEROSOLS

Pioneer 11 (Tomasko 1980;Tomasko & Smith 1982)
Voyager (West et al. 1983) strong polarization data near 90° => gradient of particles size very small spherical particles

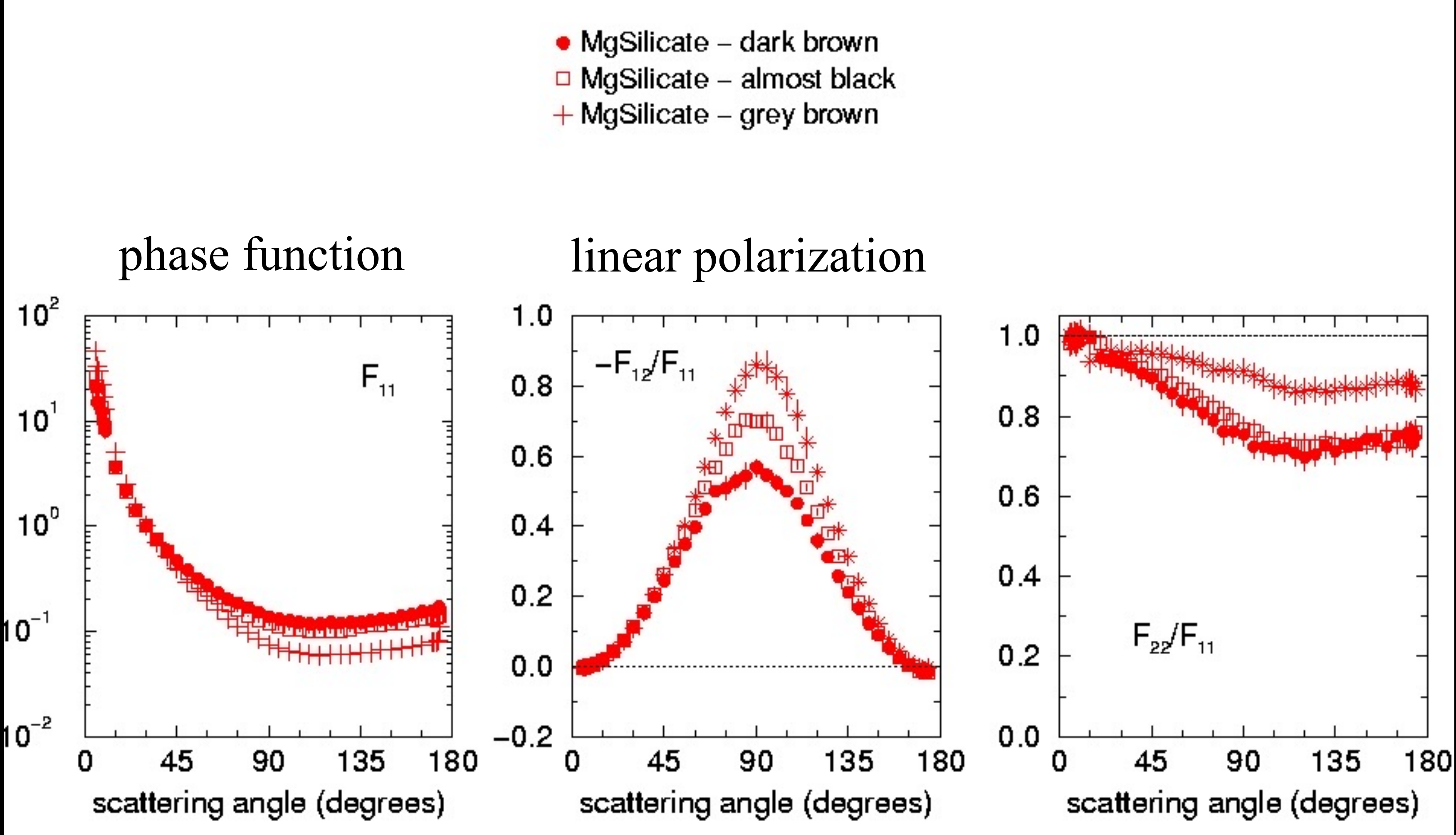


West & Smith, Icarus, 1991

Voyager intensity data strong forward peak
=> Large spherical particles (Rages & Pollack, 1981; West et al. 1983)

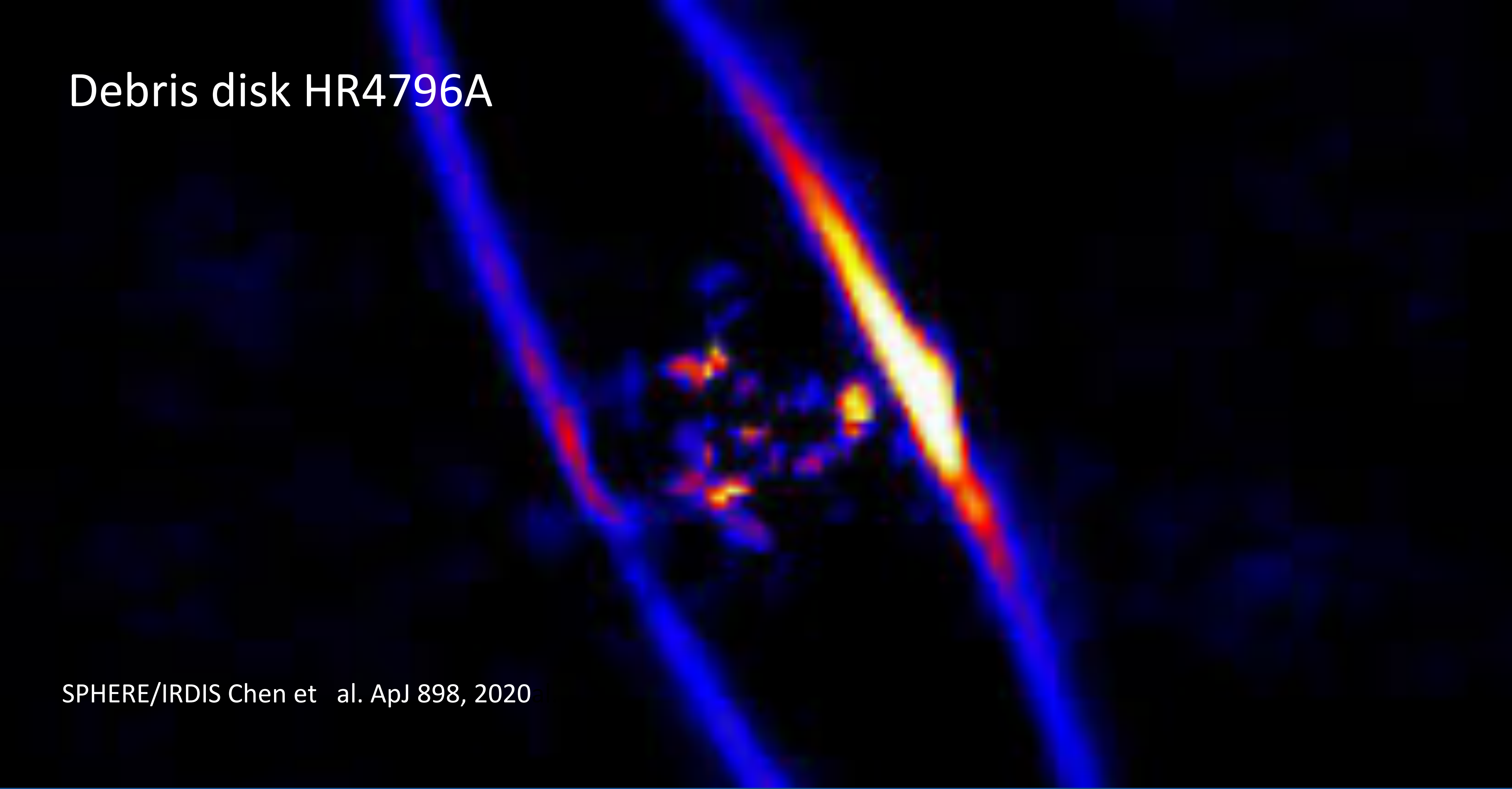


Fluffy MgSilicates



Volten et al. A&A, 470(1), 377,2007

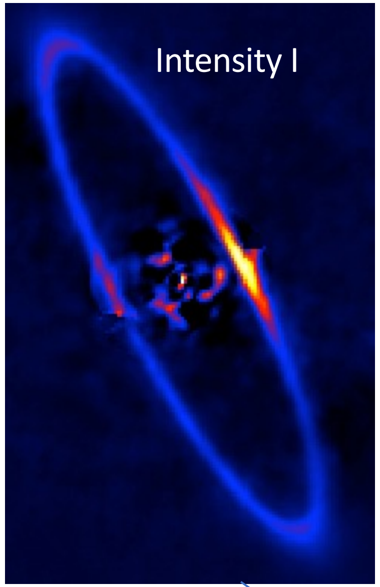
Debris disk HR4796A

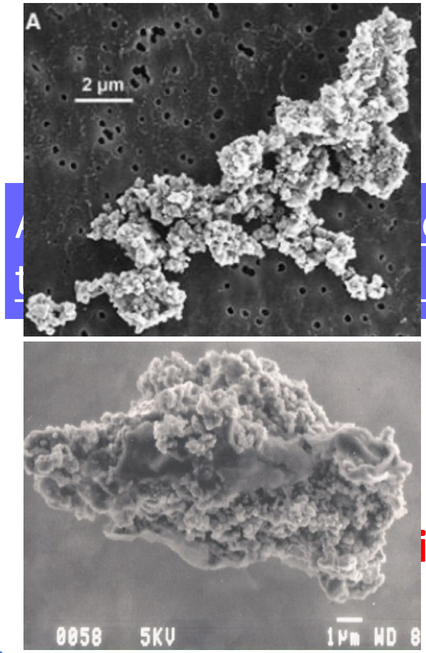


SPHERE/IRDIS Chen et al. ApJ 898, 2020

GROWING DUST GRAINS. PLANETESIMALS

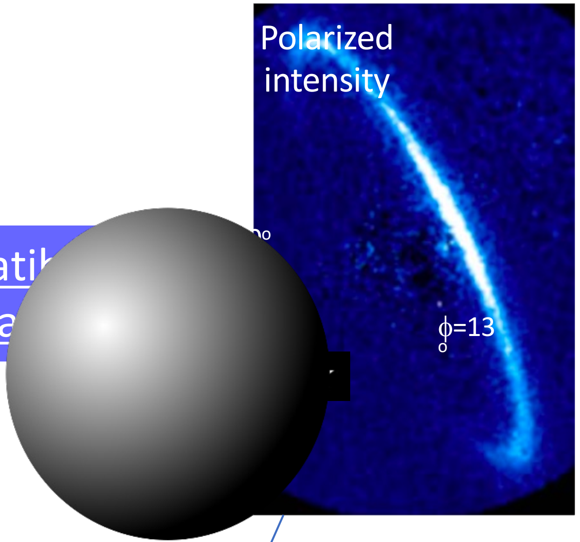
HR4796A debris disk (Gemini Planet Imager)





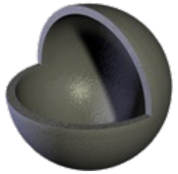
A ... o model compatib... t... AND in polariza...

≠



pI=$\sqrt{Q^2 + U^2}$

...ibility in optical indices



vs

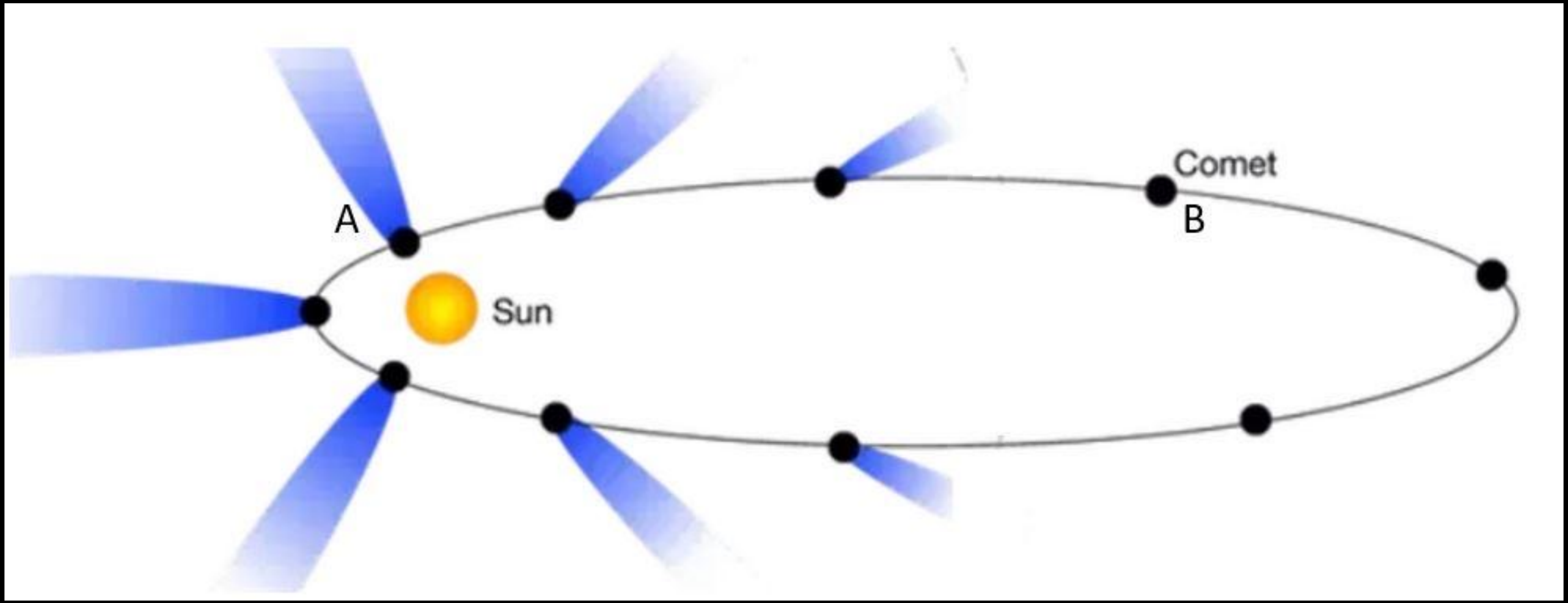
min size ~20-30μm

min size ~2-3μm

After J. Milli, Université Grenoble Alpes

POLARIMETRY FOR CHARACTERIZING COMETARY DUST.

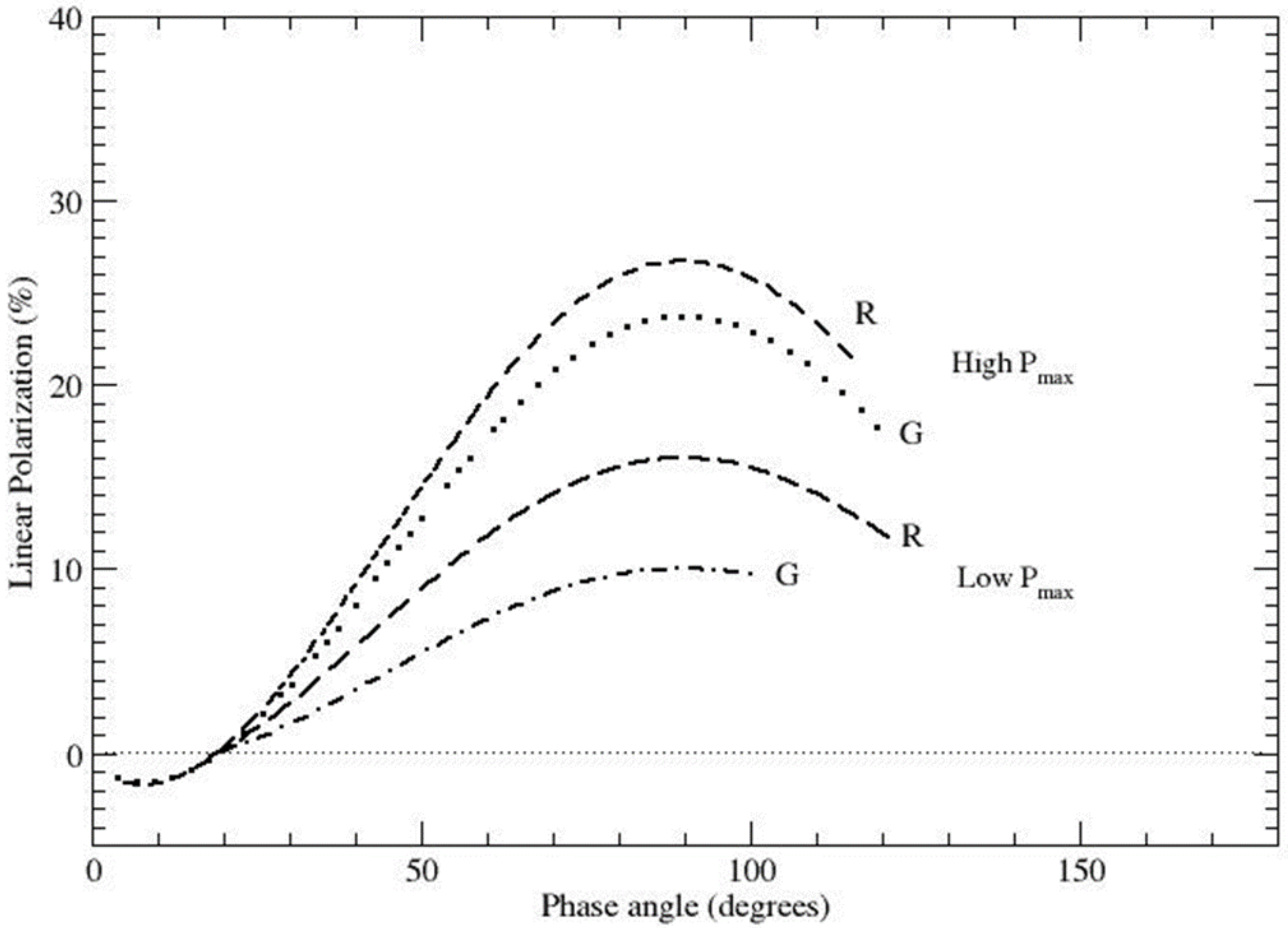
Polarimetry: Cometary Dust



Relative quantity
does not depend on the
number of particles

$$DLP = \frac{I_{par} - I_{per}}{I_{par} + I_{per}}$$

Ground-Based polarimetry of Comets



Bell-Shape

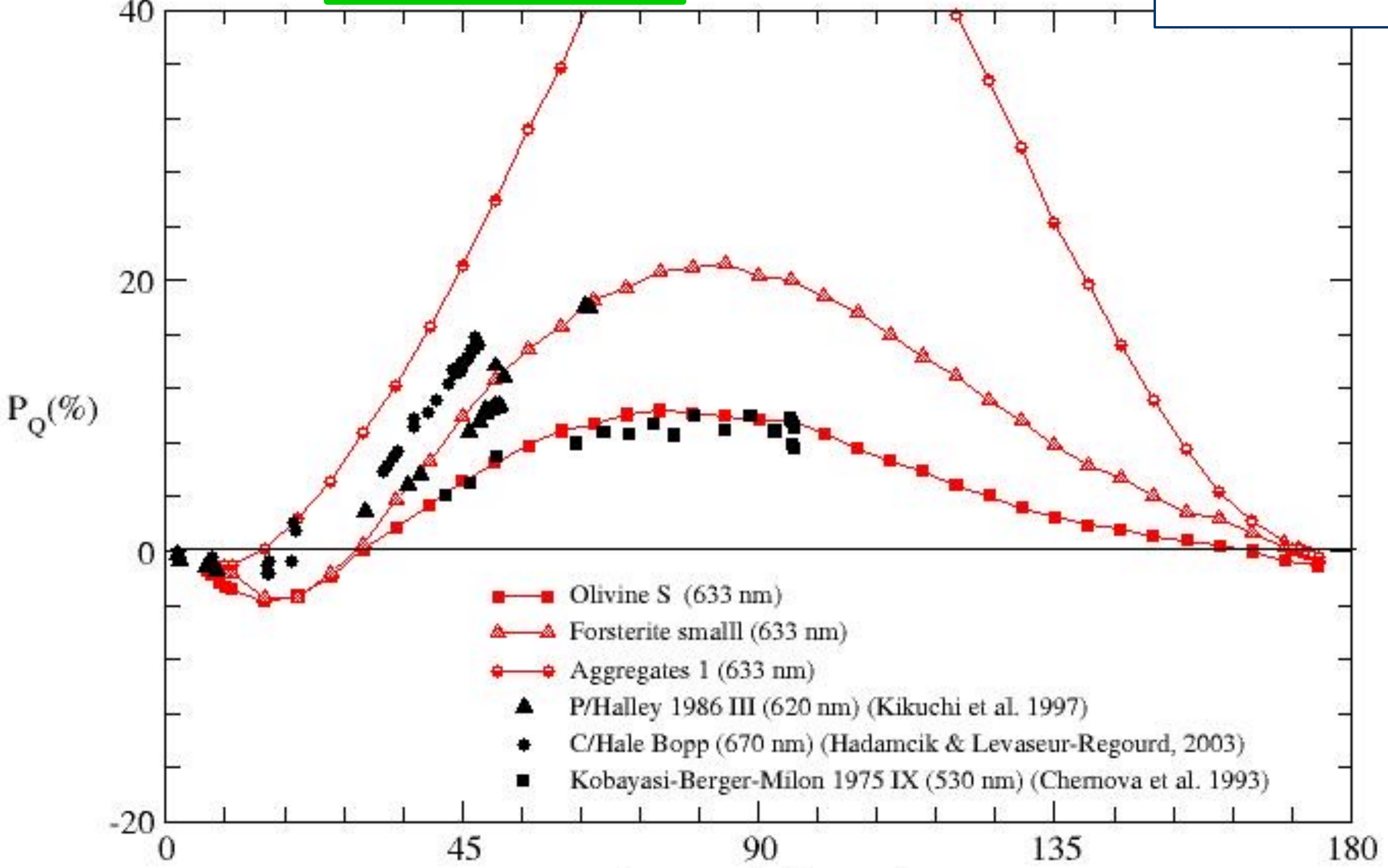
OBSERVATIONS & EXPERIMENTAL DLPs

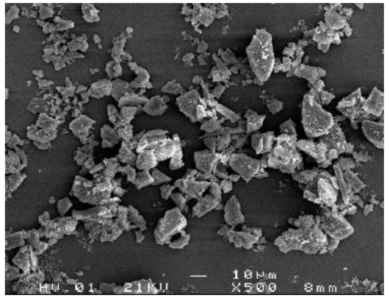
Rayleigh
$r \ll \lambda$

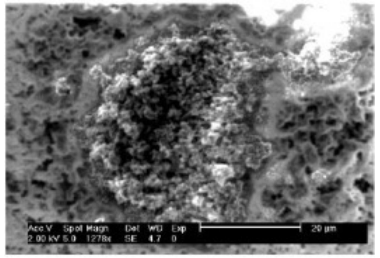
Resonance
$r \sim \lambda$

GO
$r \gg \lambda$

Bell-Shape







micron-sized particles

Observational data from **Database of Comet Polarimetry** (Kiselev et al. 2005)

Experimental data from **Granada-Amsterdam Light Scattering Database** (Muñoz et al. 2012)

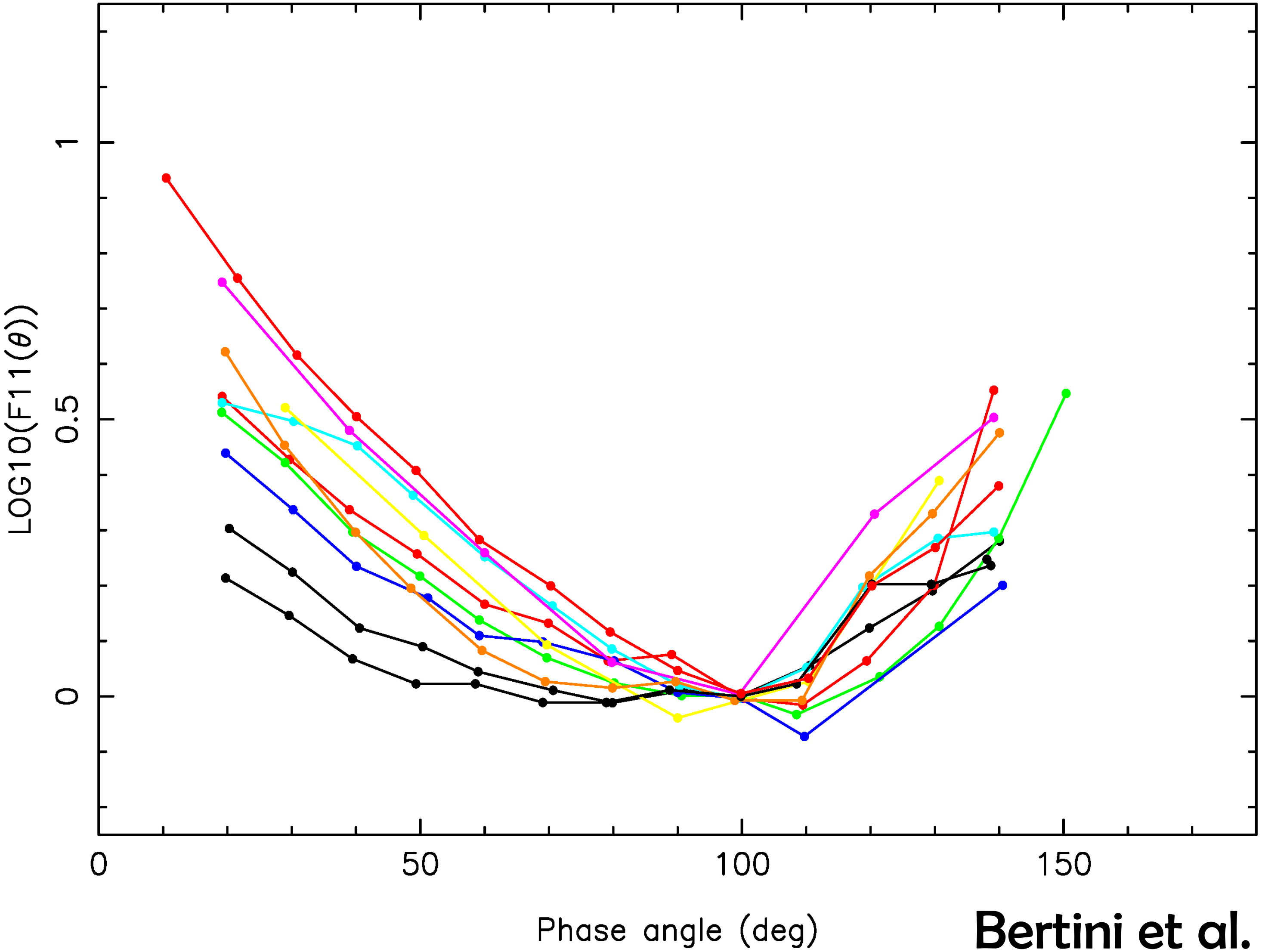
67P Churyumov-Gerasimenko (ESA)

2004-2017

ESA Rosetta

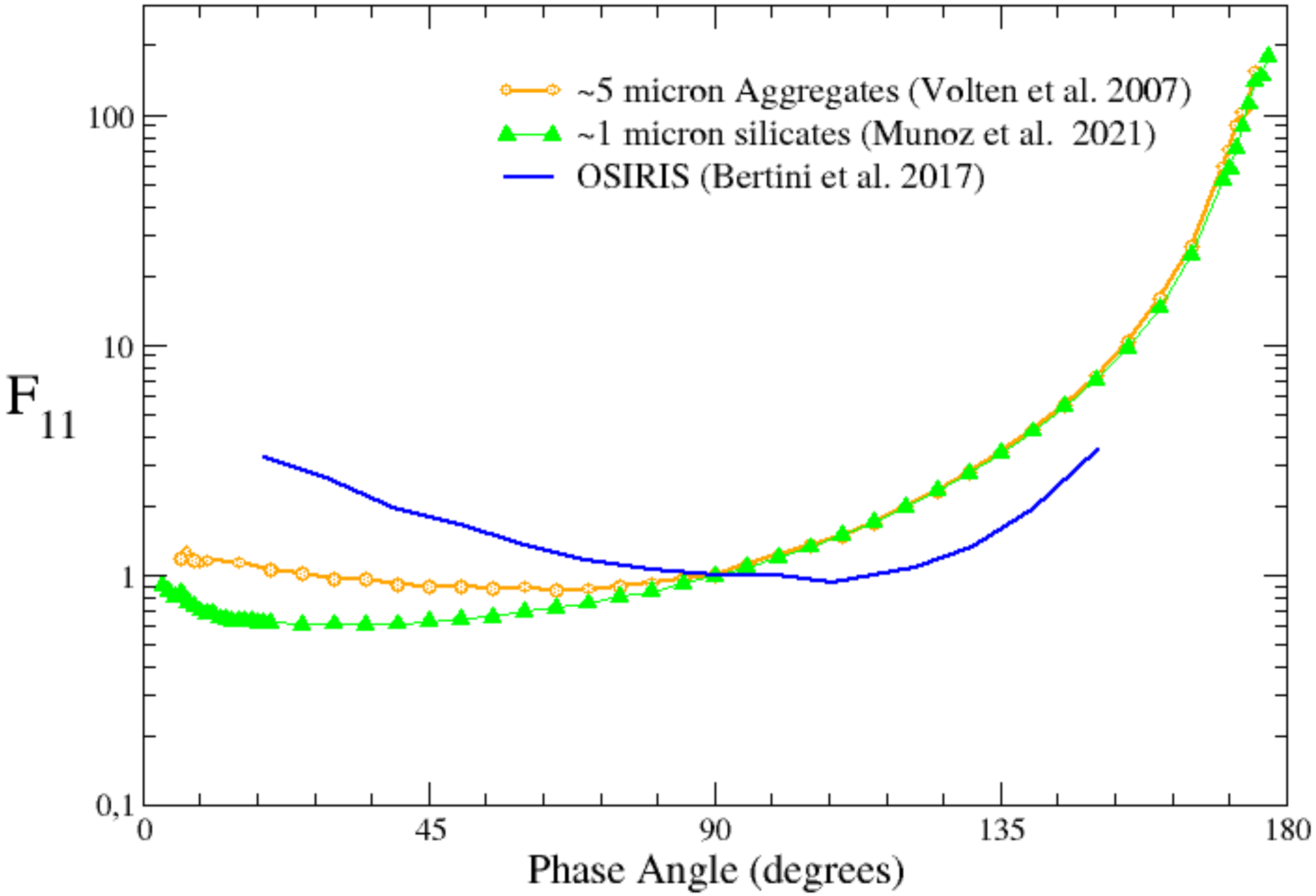
OSIRIS provides unique observations of intensity of the light scattered by dust within 67P coma.

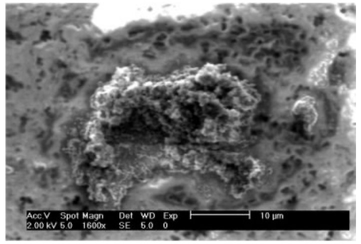
OSIRIS@ROSETTA U-Shaped Phase Functions

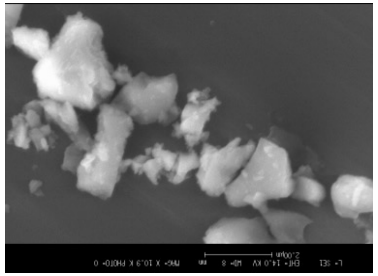


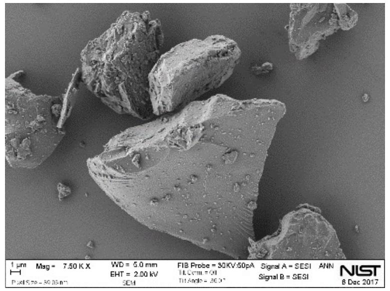
Bertini et al. MNRAS, 469 (2), 2017

OBSERVATIONS & EXPERIMENTAL
Phase Functions micron-sized dust grains

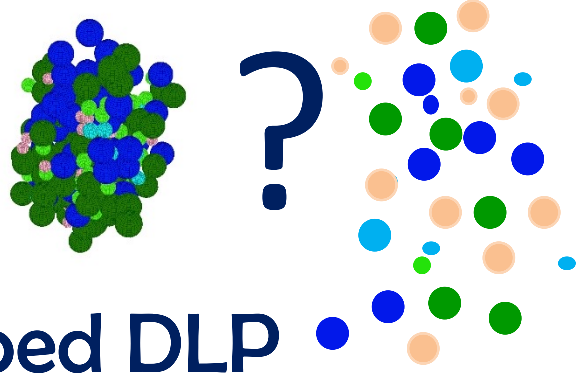




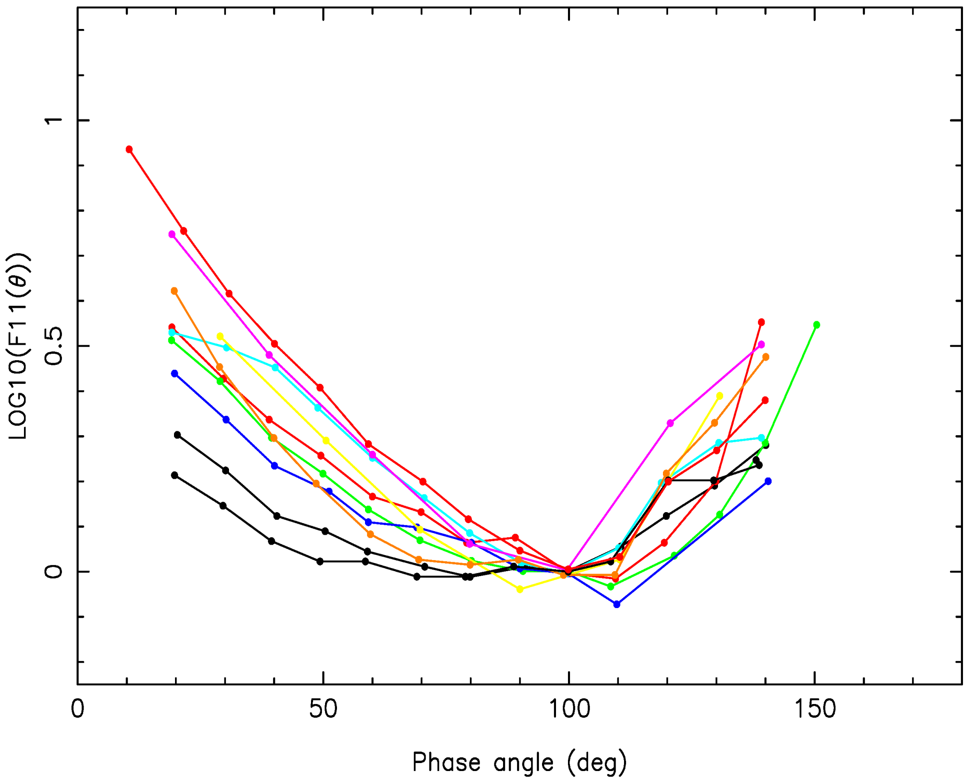


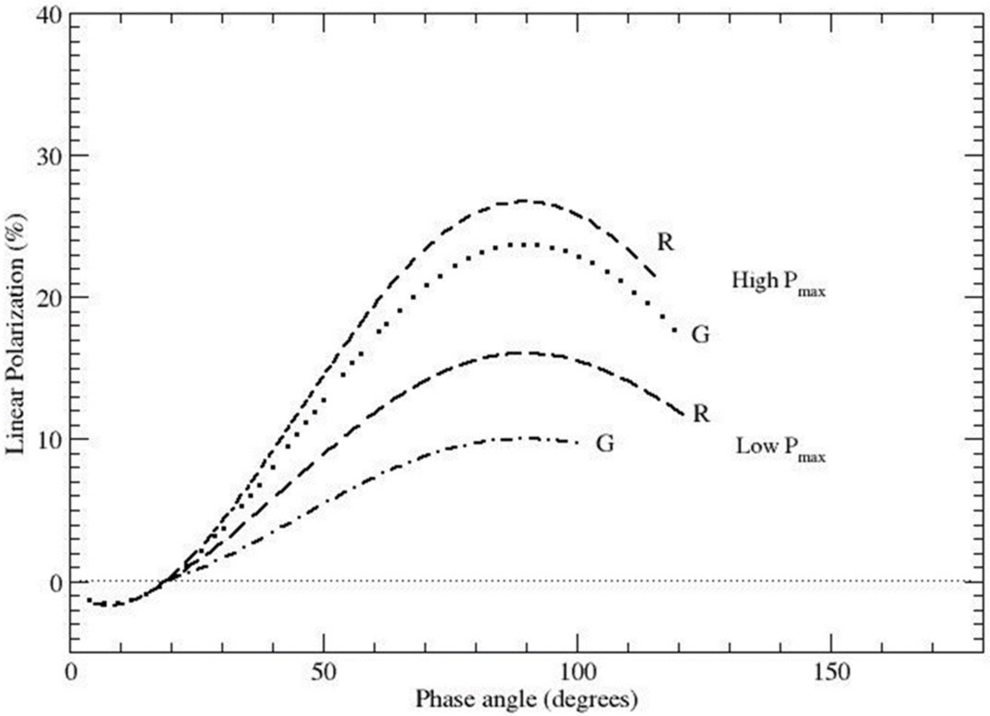


What type of dust particles



OSIRIS U-Shape PFs AND GB obs bell-shaped DLP



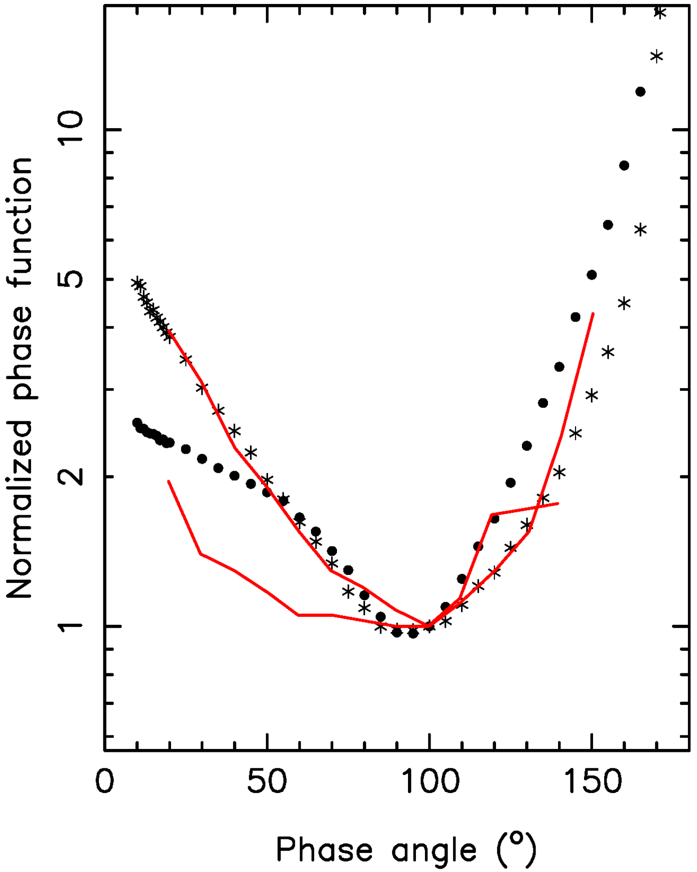


U-shaped phase functions produced for very large particles?

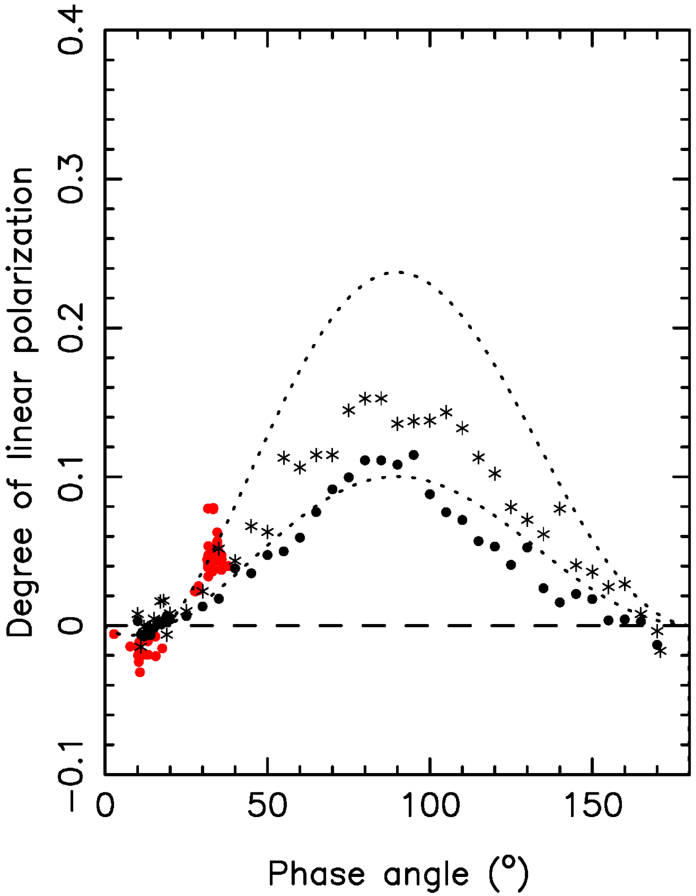
Rayleigh	Resonance	Geometric optics
r<<λ	r~λ	r>>λ

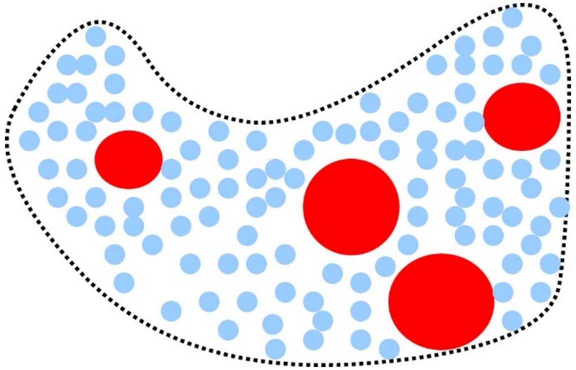
CONCLUSION: large absorbing porous particles can reproduce both sets of observations

OSIRIS U-Shape PFs



GB obs bell-shaped DLP





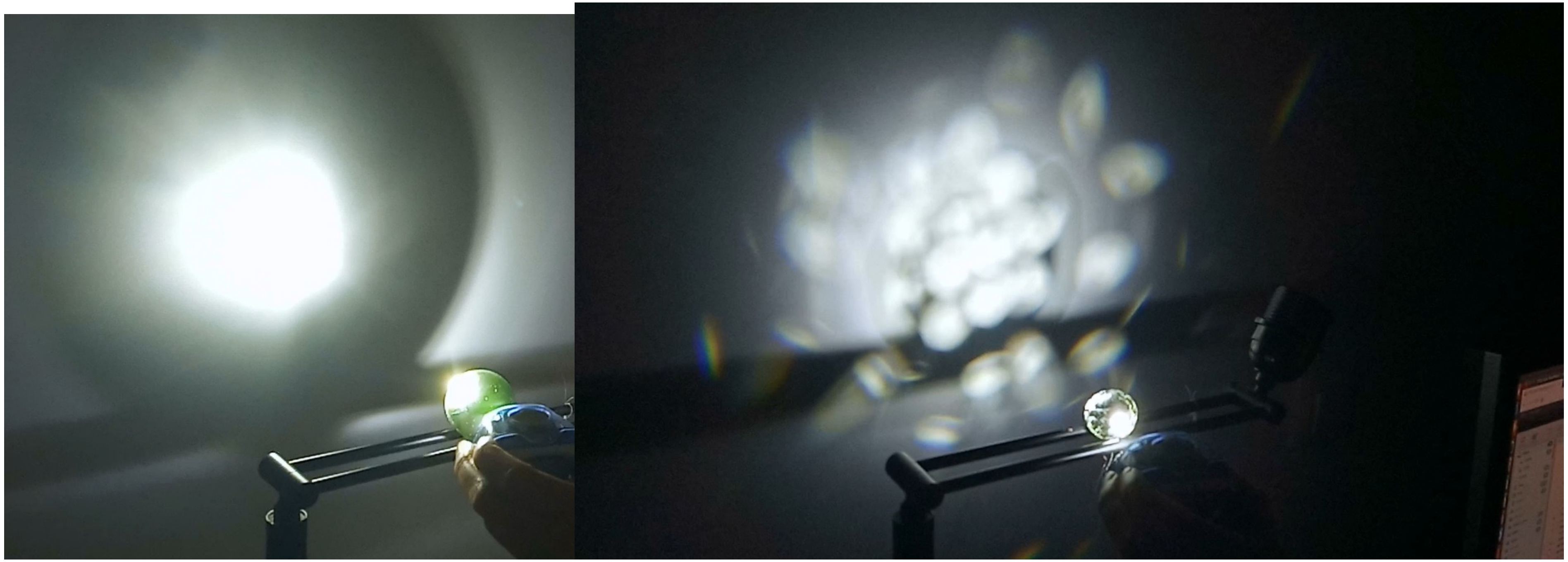
Markkanen et al. 2018;
Moreno et al. 2017;
Muñoz et al . 2020;

Observations: Bertini et al. 2017, Rosenbush et al 2017

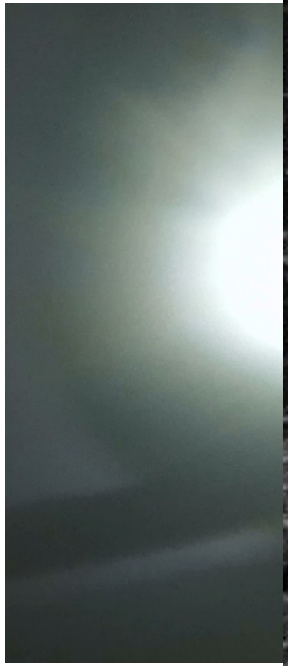
PART 2
Practical exercises using experimental data & Model/Scattering Databases

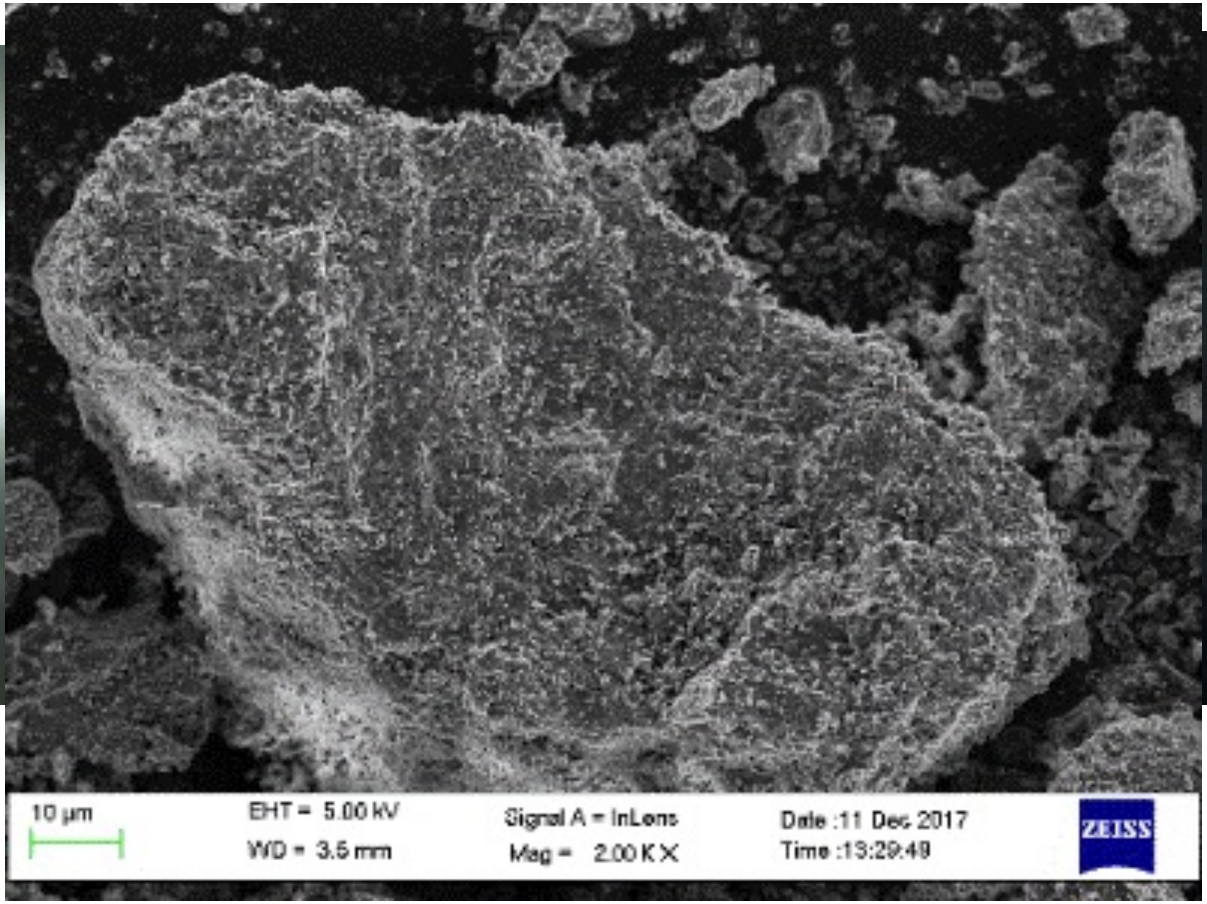
Spherical vs irregular

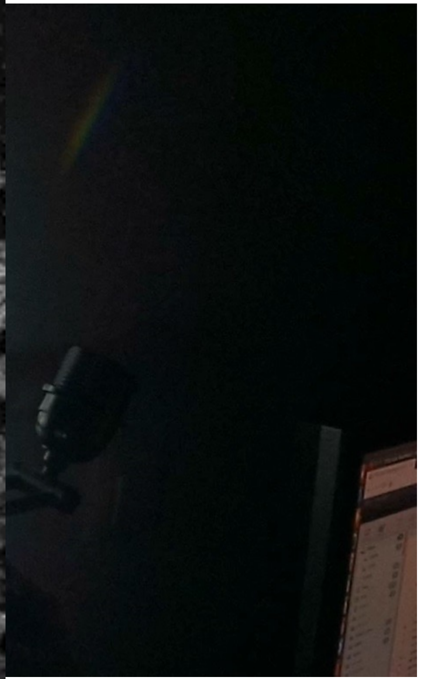
sphere vs irregular particle



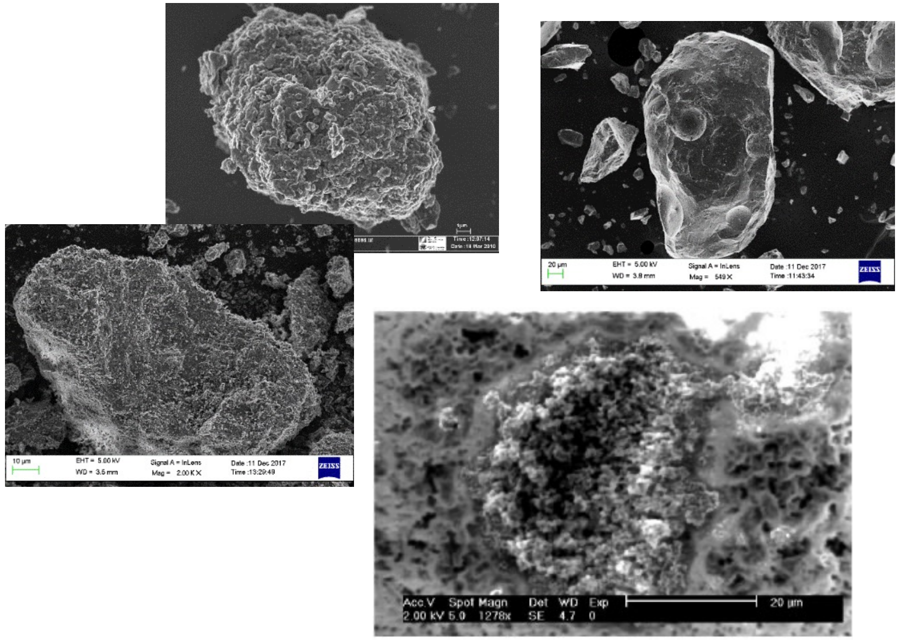
sphere vs irregular particle





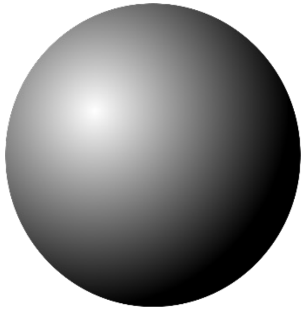


SPHERICAL MODEL vs COSMIC DUST FOR



?

≈



LABORATORY TEST
Testing the spherical model

Rayleigh	Resonance/Mie	Geometric optics
$r << \lambda$	$r \sim \lambda$	$r >> \lambda$

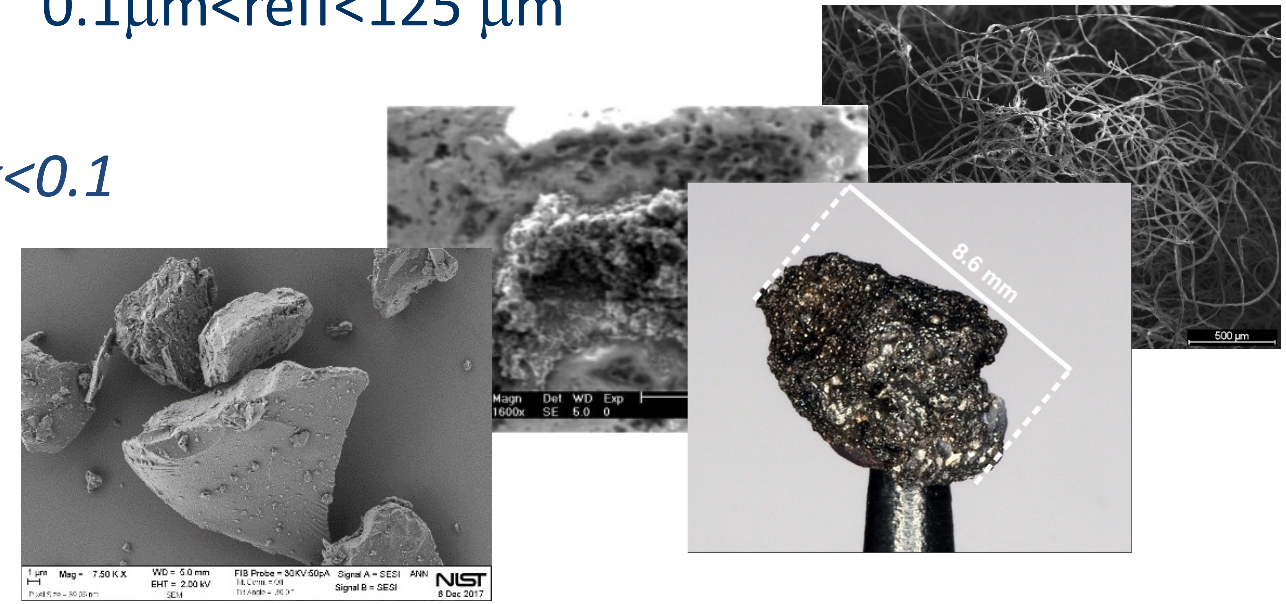
THE SAMPLES

r~3 mm

0.1µm<reff<125 µm

m=n+k*i*

1.5<n<3; 0.00001<k<0.1



SIZE REGIMES

r<<λ | r~λ | **CODULAB** | r>>λ

Rayleigh | Resonance/Mie | Geometric optics

Experimental data freely available at the Granada-Amsterdam Light Scattering Database

[*www.iaa.es/scattering*](http://www.iaa.es/scattering) *Muñoz et al. JQSRT, 113, 565-574, 2012.*

Granada - Amsterdam Light Scattering Database

What is in this database?

Data in this database are freely available under the request of citation of this paper and the paper in which the data were published

https://scattering.iaa.csic.es/

LIST OF ALL SAMPLES

SAMPLES CATEGORIES

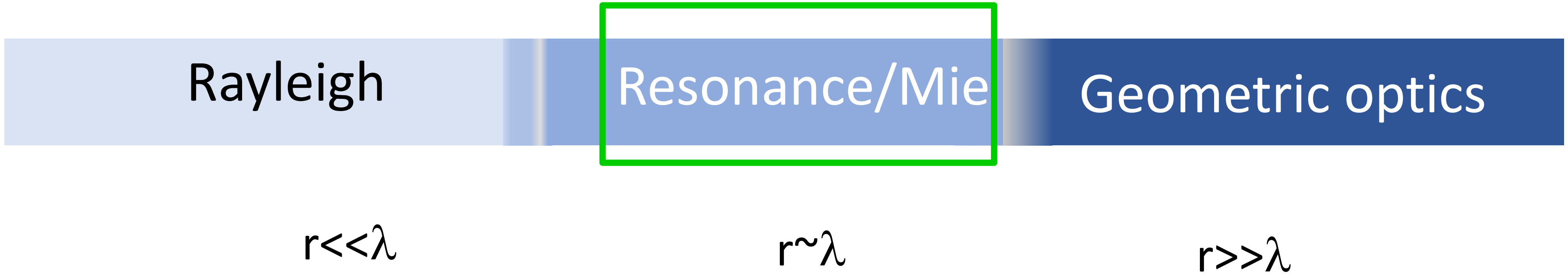
NEWS

PAPERS

THEORY

EXPERIMENTAL APPARATUS

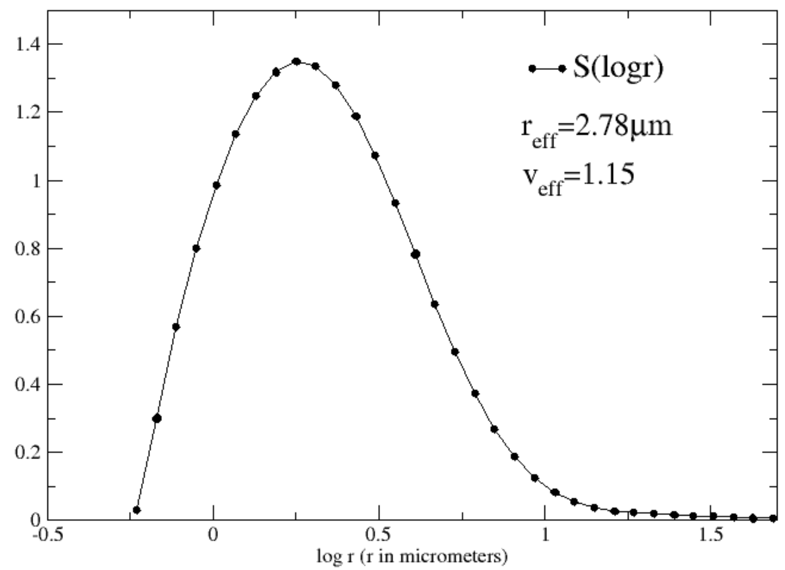
LABORATORY TEST
Testing the spherical model for retrieving grain sizes in resonance regimes
Experiments.



MARTIAN DUST ANALOG

SHAPES: SPHERICAL/NONSPHERICAL

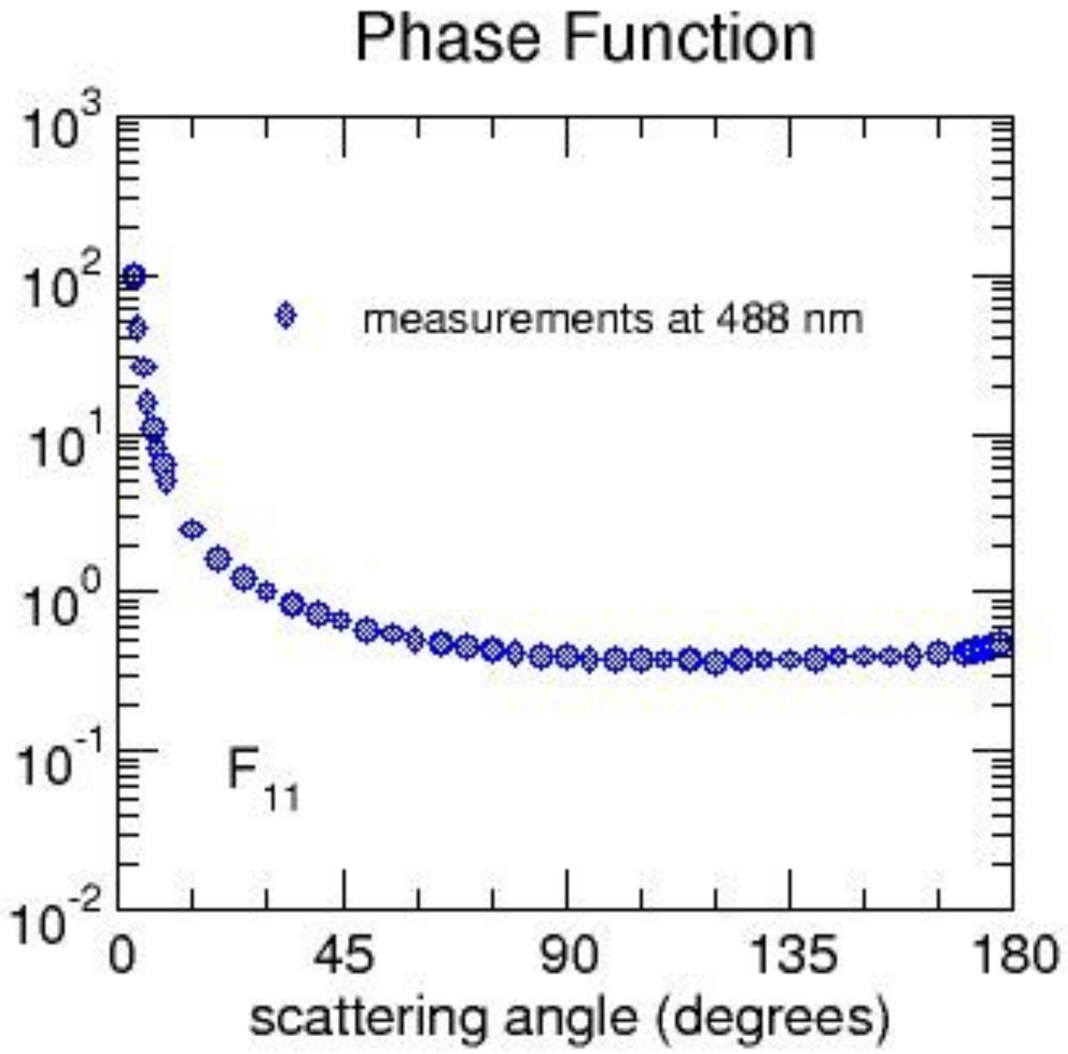
$r \sim \lambda$

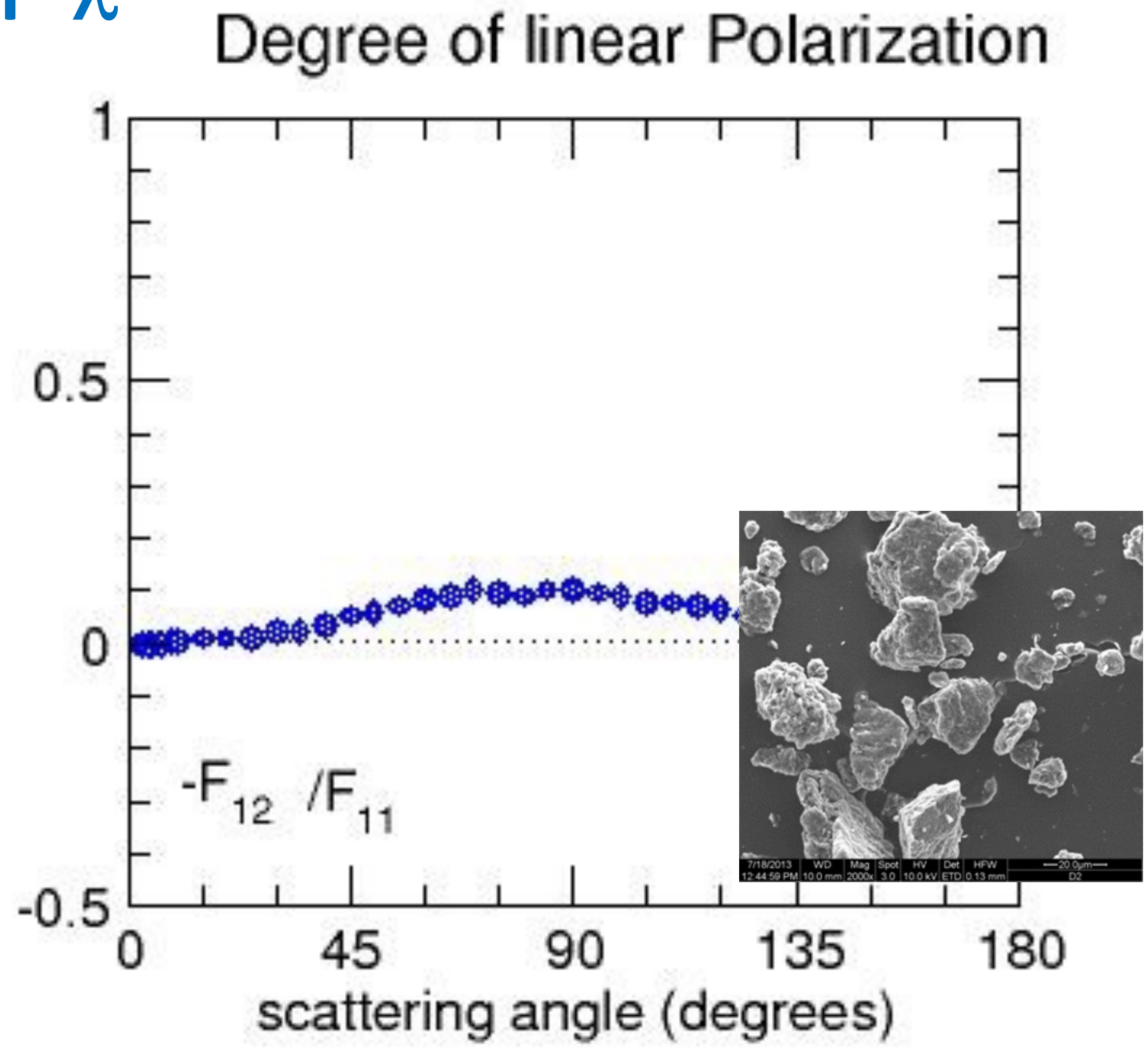


Dabrowska et al. Icarus, 250, 83-94, 2015.

SHAPES: SPHERICAL/NONSPHERICAL

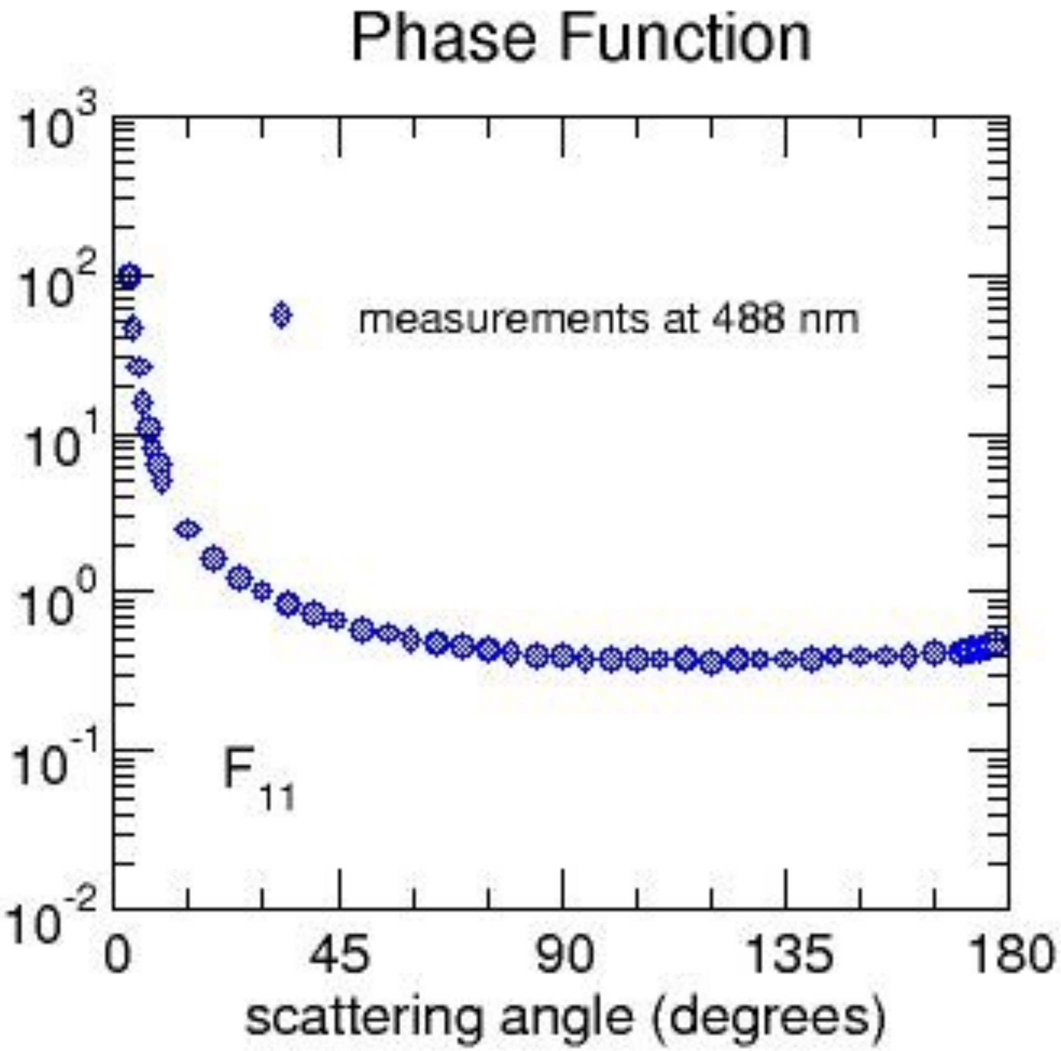
r~λ

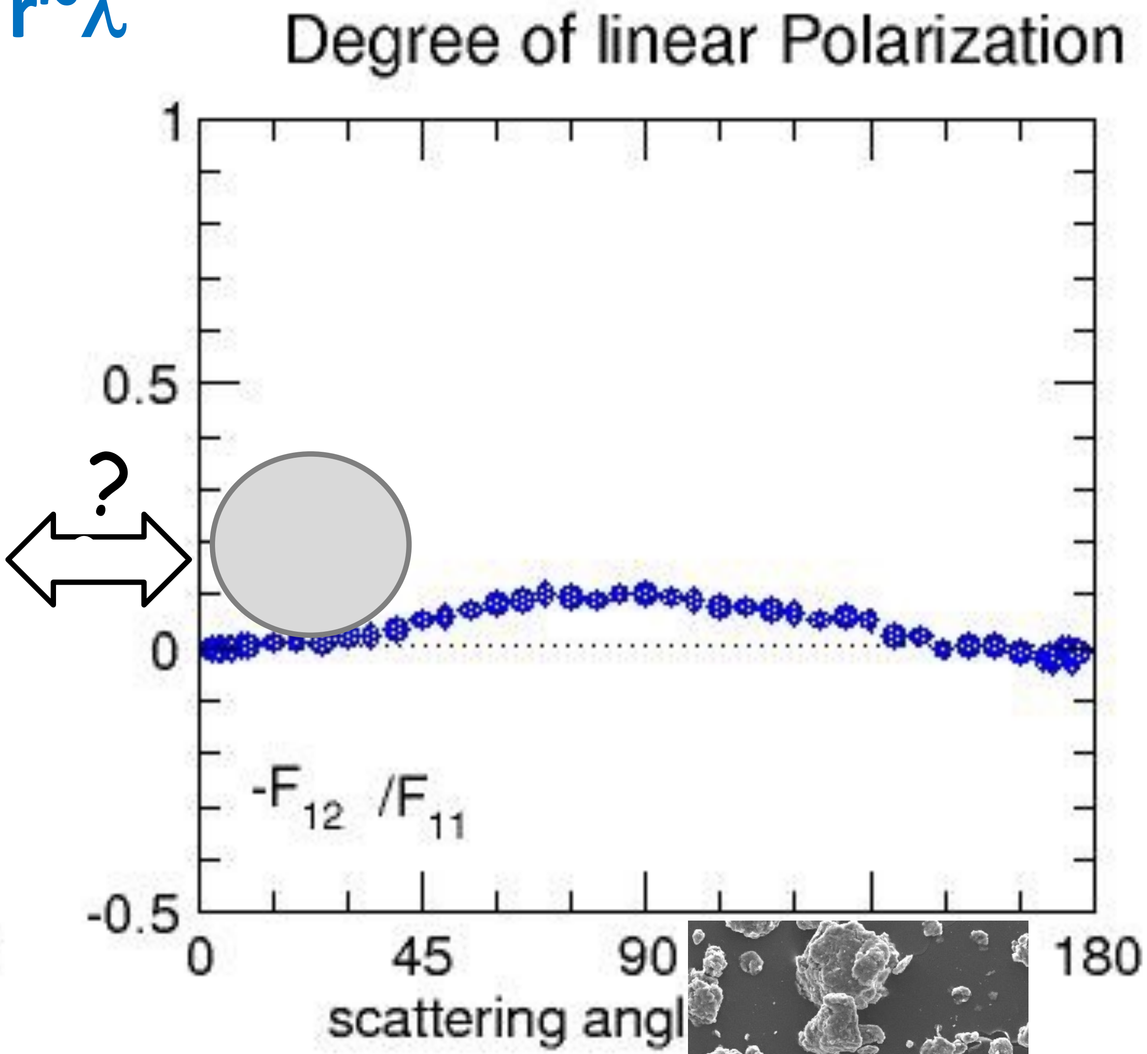


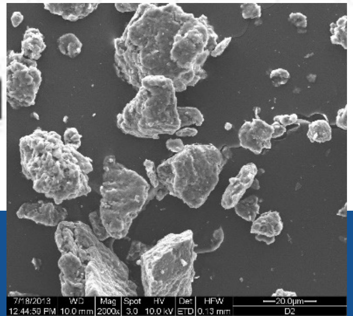


SHAPES: SPHERICAL/NONSPHERICAL

r~λ



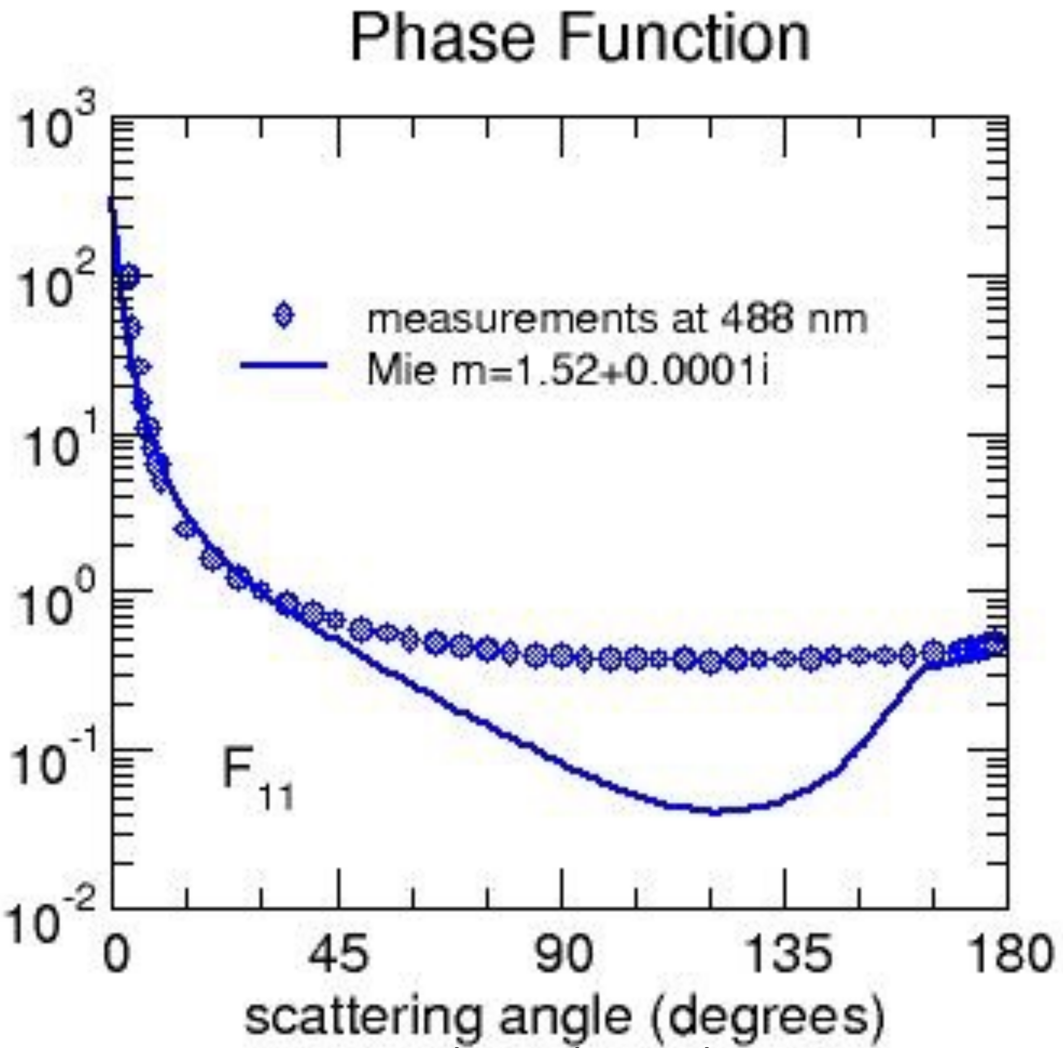


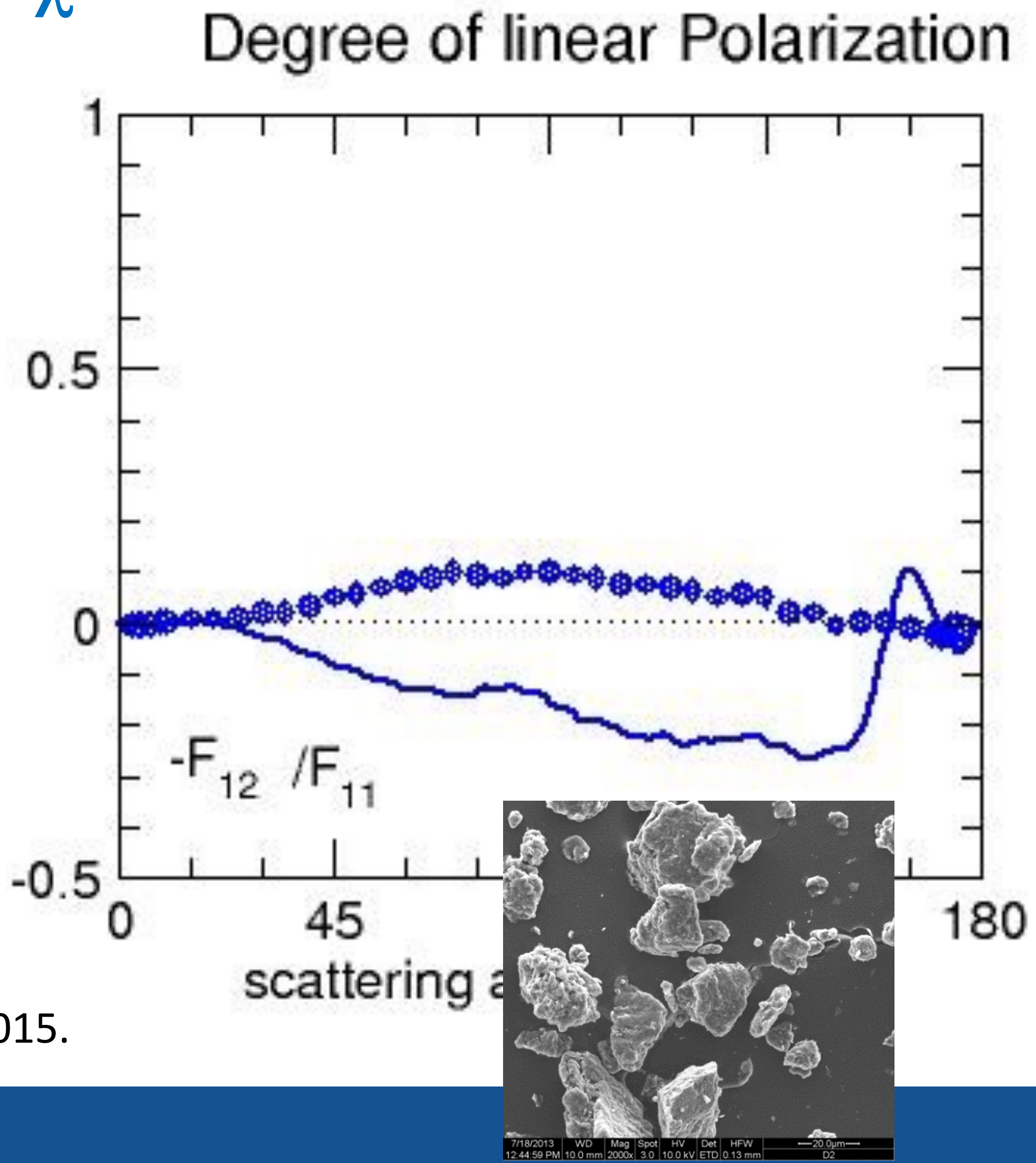


Dabrowska et al. Icarus, 250, 83-94, 2015.

SHAPES: SPHERICAL/NONSPHERICAL

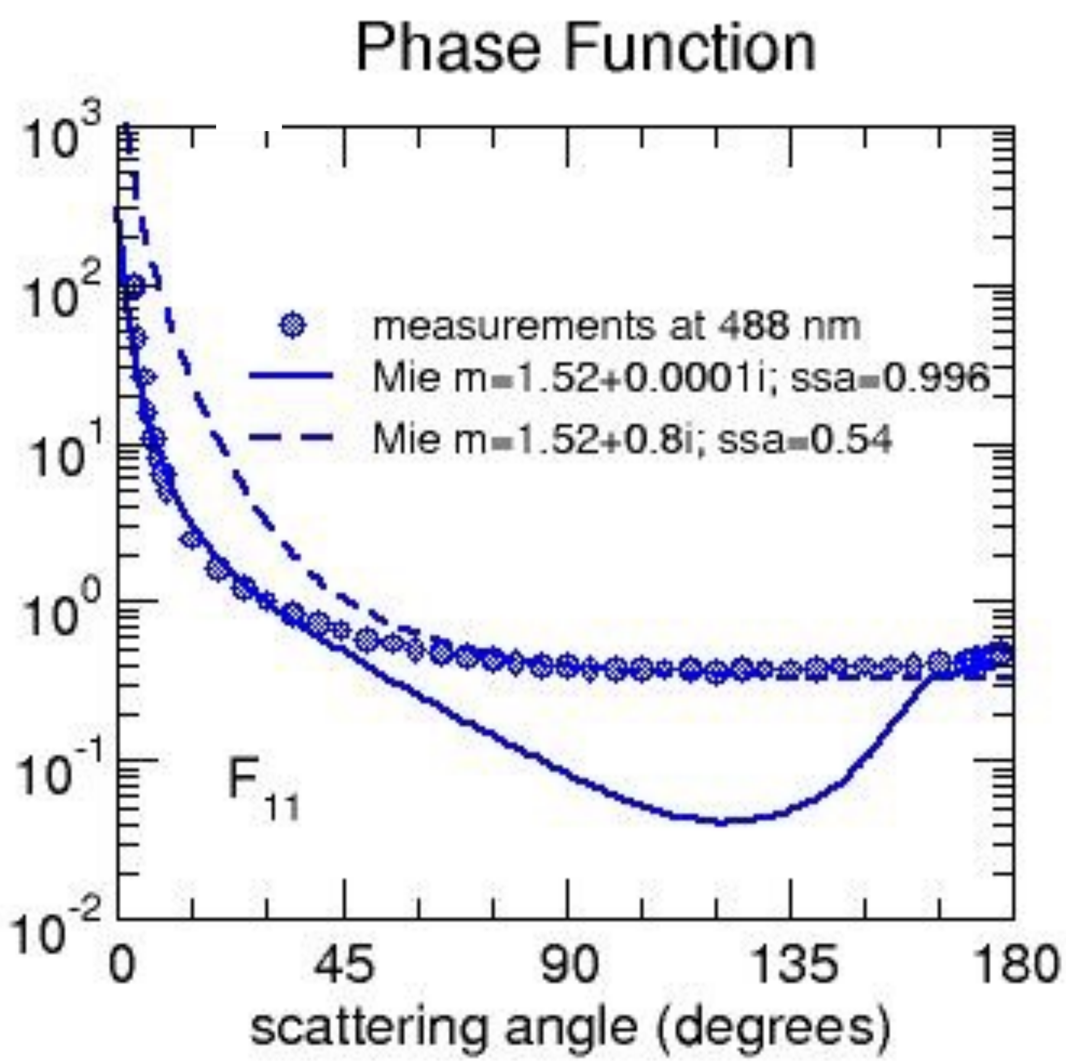
$r \sim \lambda$

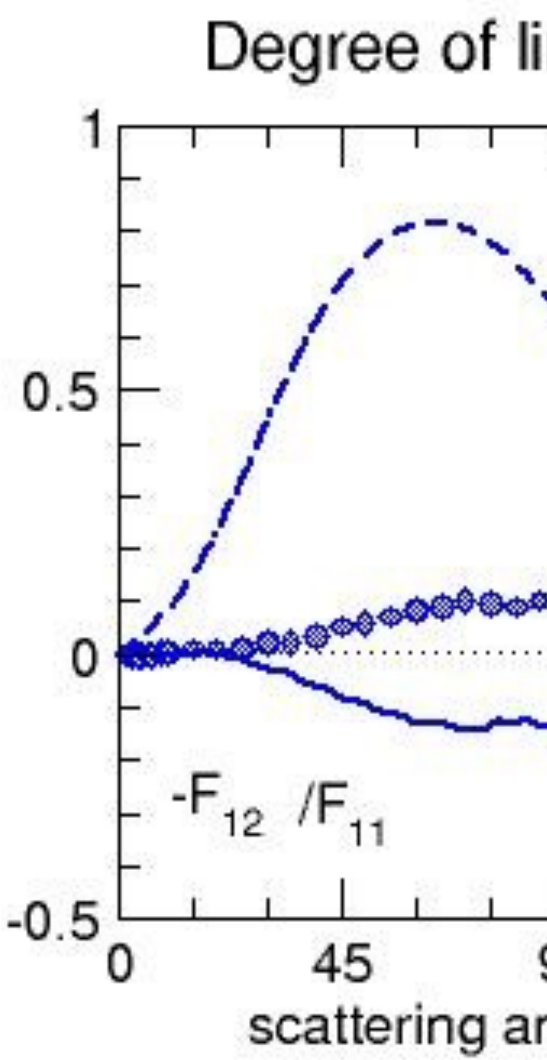


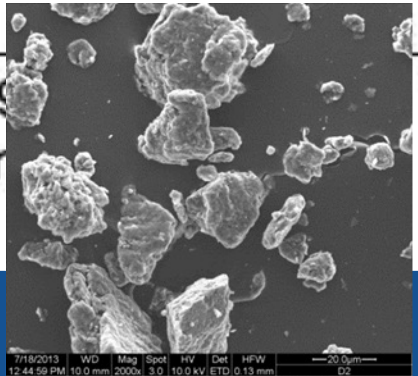


Dabrowska et al. Icarus, 250, 83-94, 2015.

SHAPES: SPHERICAL/NONSPHERICAL

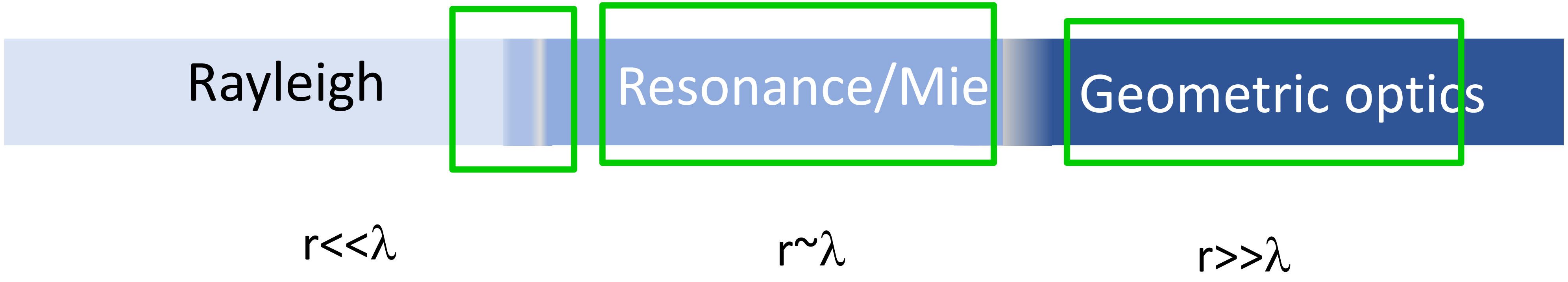




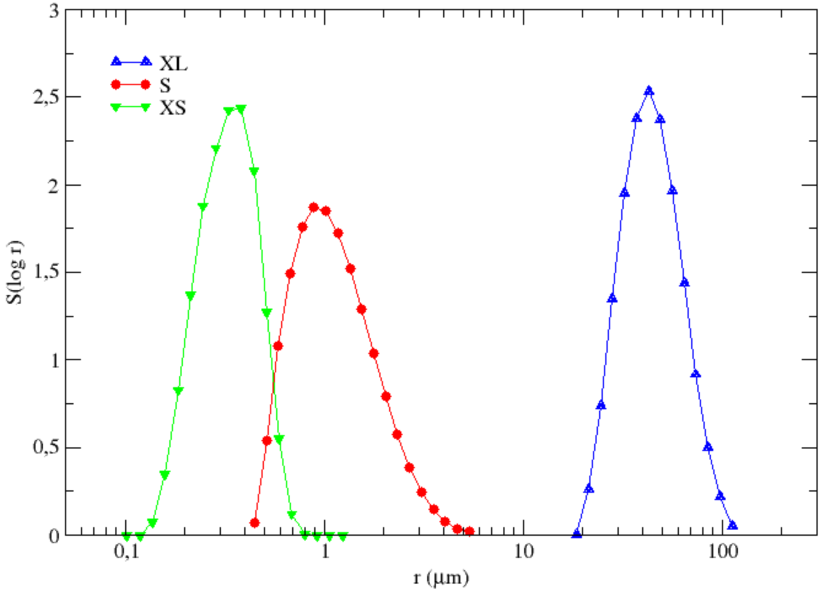


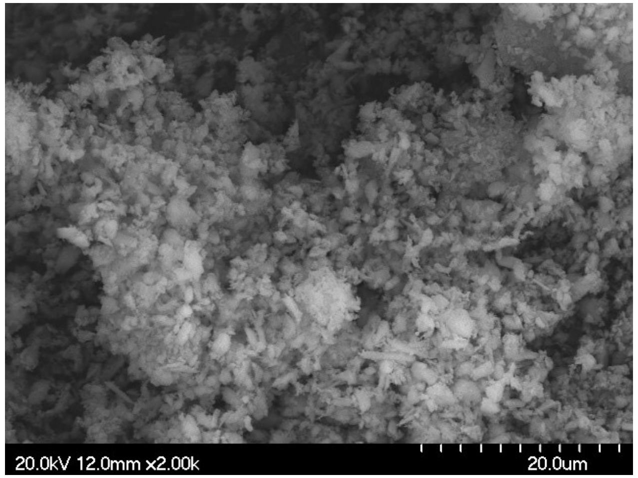
Dabrowska et al. Icarus, 250, 83-94, 2015.

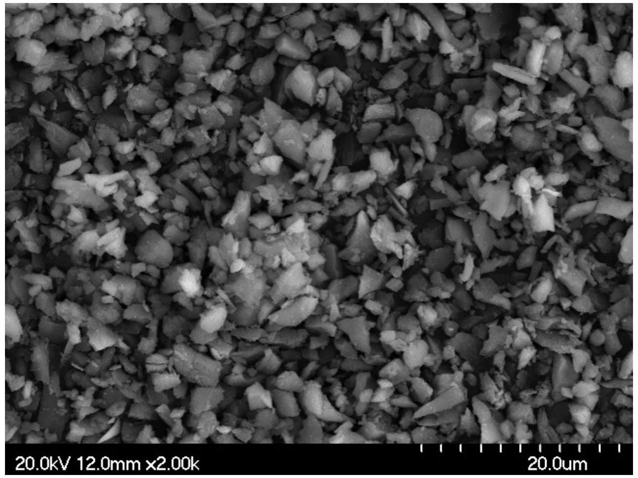
LABORATORY TEST
Testing the spherical model for retrieving grain sizes in the Rayleigh-resonance, resonance and Geometric Optics regimes. Experiments.

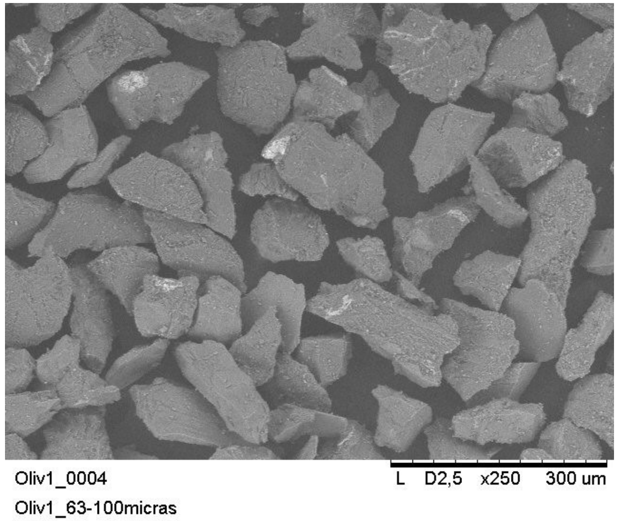


Forsterite samples
Spheres vs realistic dust



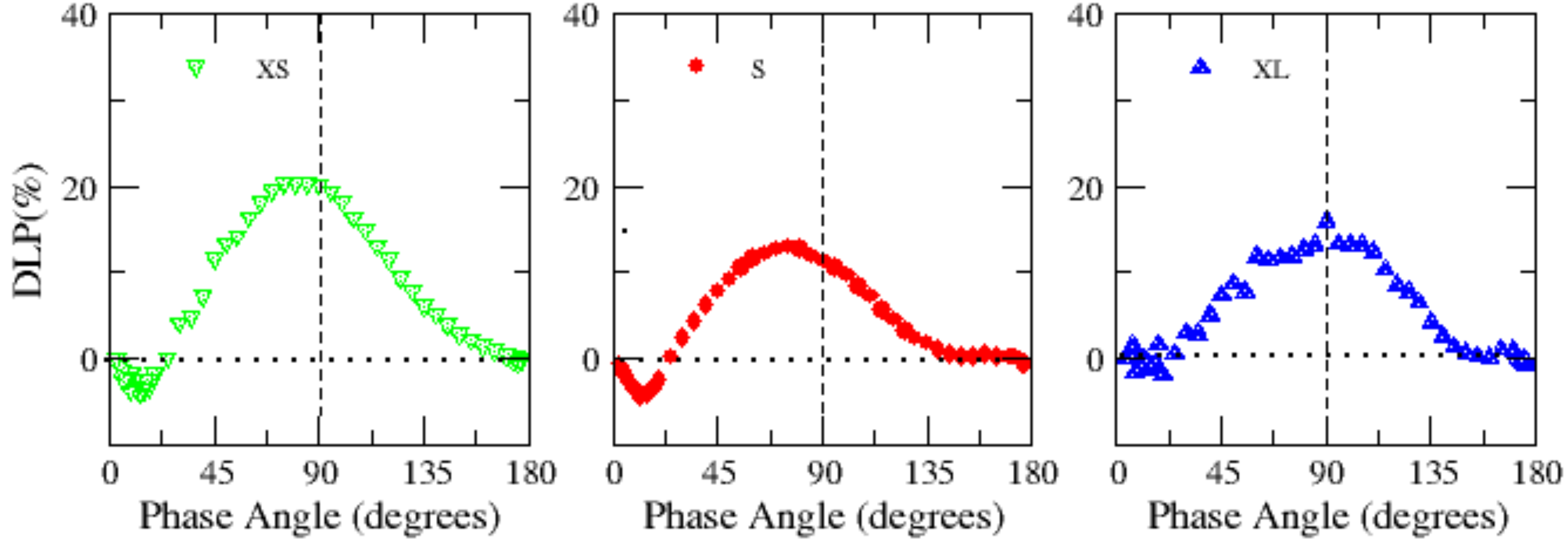


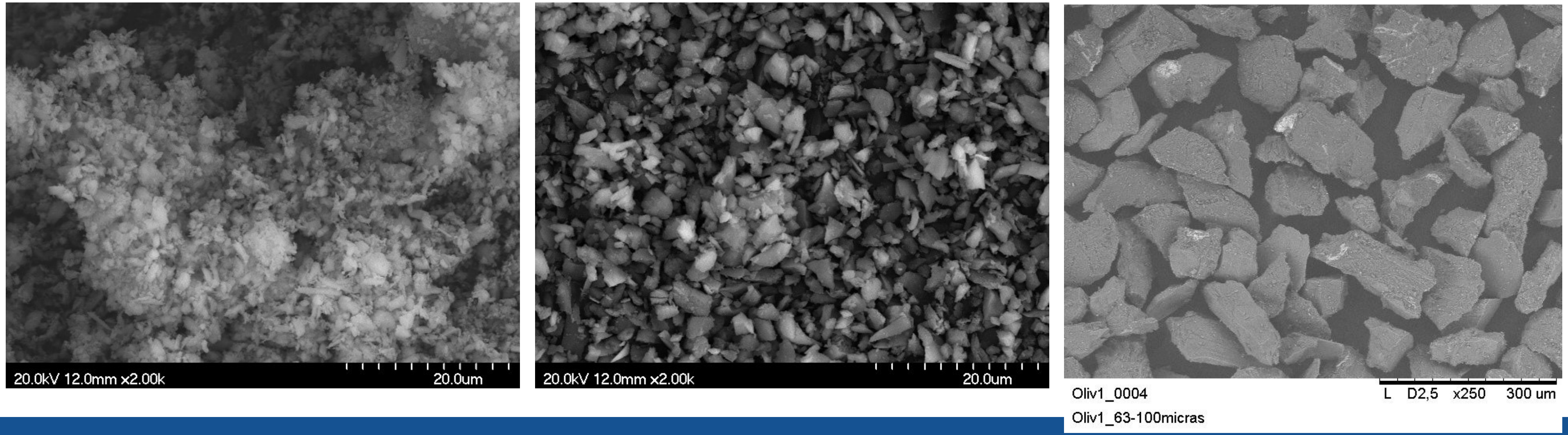




Muñoz et al. ApJS, 2021

Testing at CODULAB the effect of retrieving particle size by assuming the spherical model for natural dust particles





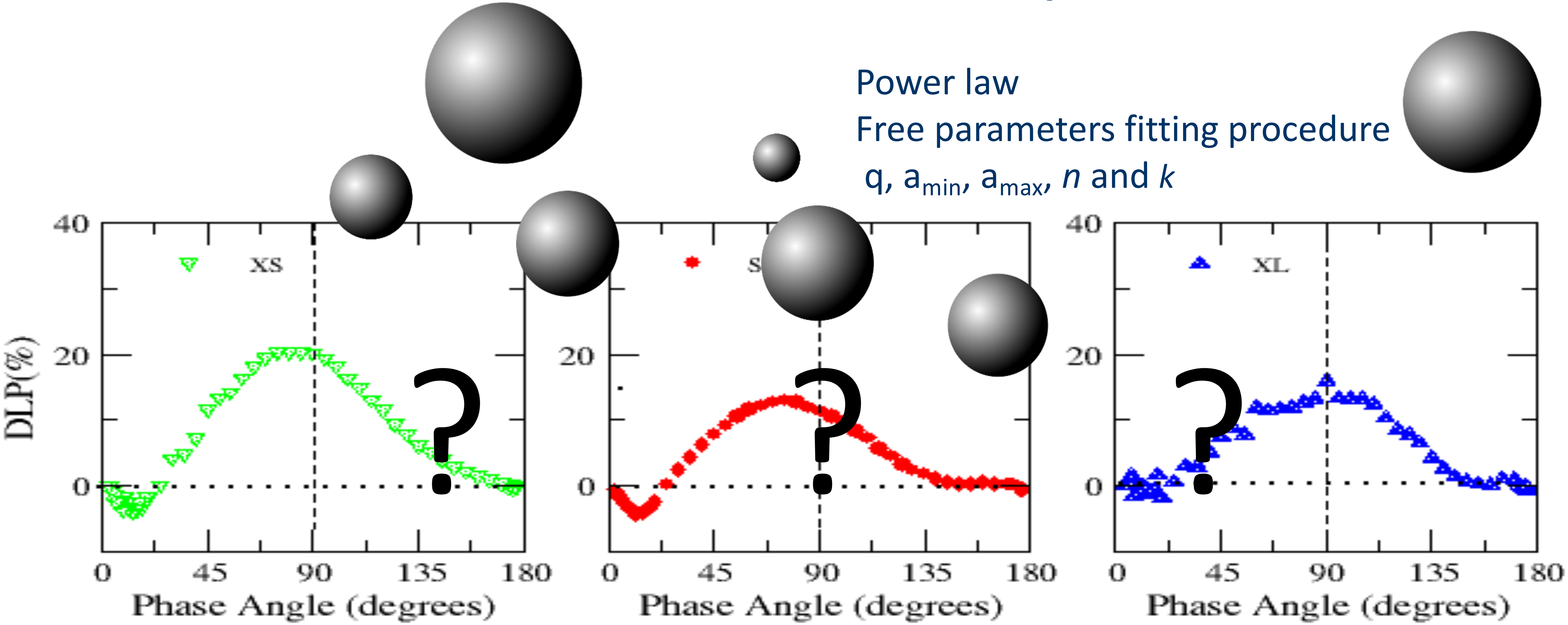
Muñoz et al. ApJS, 2021

Testing at CODULAB the effect of retrieving particle size by assuming the spherical model for natural dust particles

Power law

Free parameters fitting procedure

q, a_{min}, a_{max}, *n* and *k*

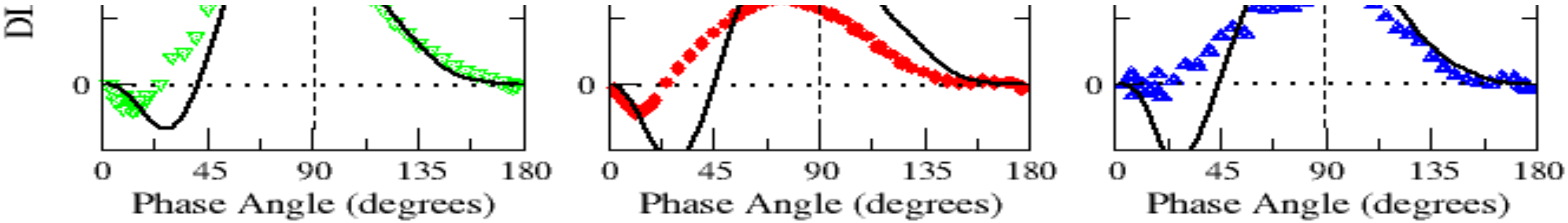


Muñoz et al. ApJS, 2021

Best fitted values (Mie theory) vs actual values

$m_{forsterite} = n + ik = 1.65 + i1E\text{-}5$

The use of the Mie model for analysing polarimetric observations might prevent locating dust particles with sizes of the order of or larger than the wavelength of the incident light.



a_{max}=0.8 μm

a_{max}=10.7 μm

a_{max}=112 μm

Mie { a_{max}=0.22μm; n=2.09; k=3E-2 }

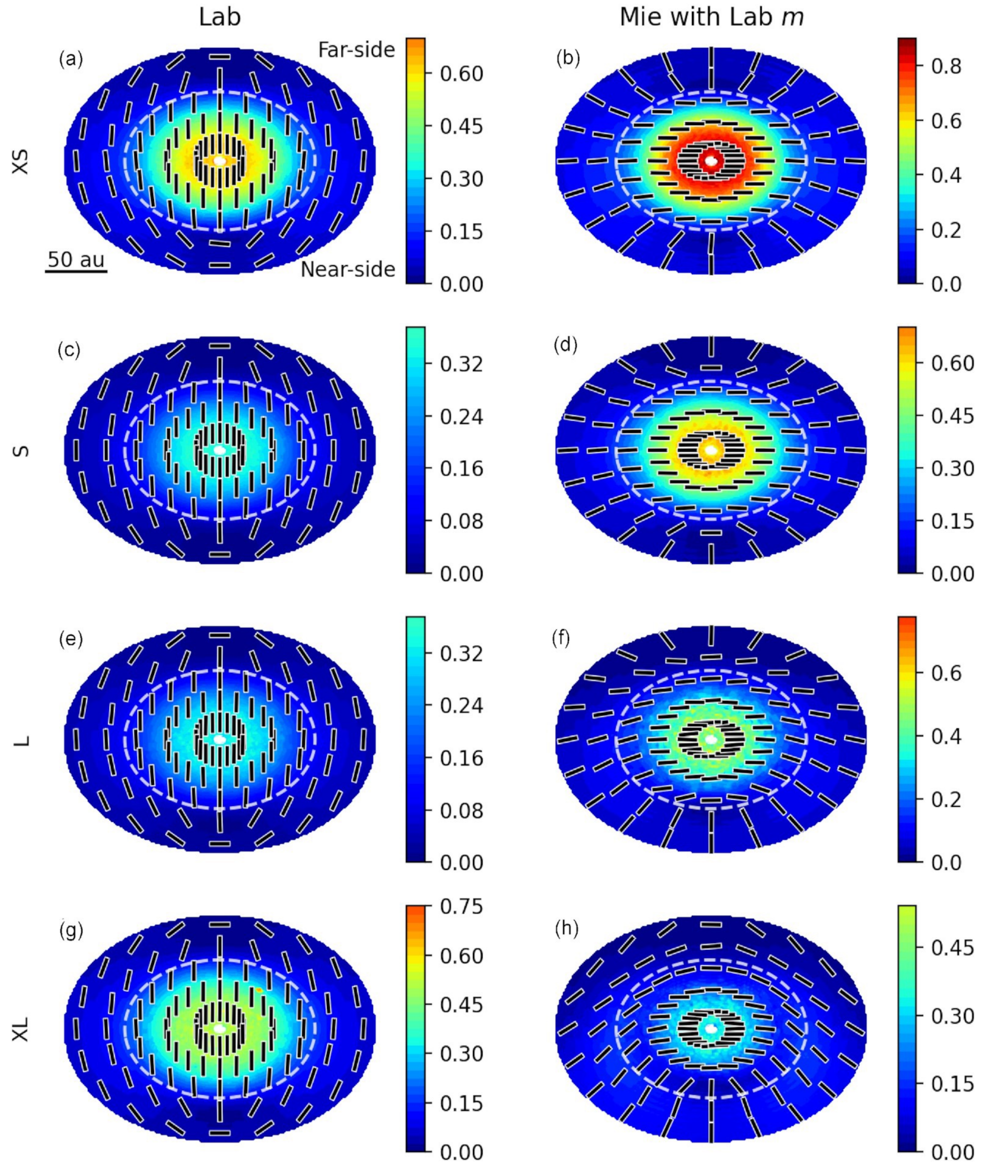
Mie { a_{max}=0.21μm; n=2.28; k=3E-3 }

Mie { a_{max}=0.21μm; n=2.13; k=8E-2 }

Muñoz et al. ApJS, 2021

Simulated (sub)millimetre disc polarization (spheres vs irregular dust)

Monte Carlo code RADMC-3D
Dullemond et al. 2012



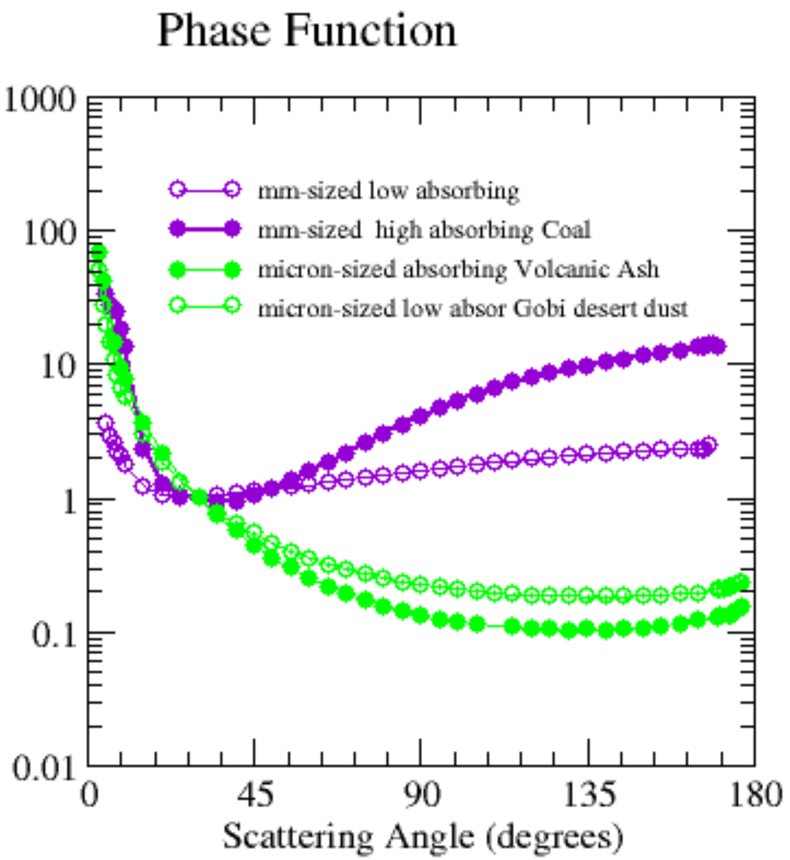
Polarization fraction
Pf (%) =P/I ; $P \equiv \sqrt{Q^2 + U^2}$
Dashed white contours
optical depth 0.1

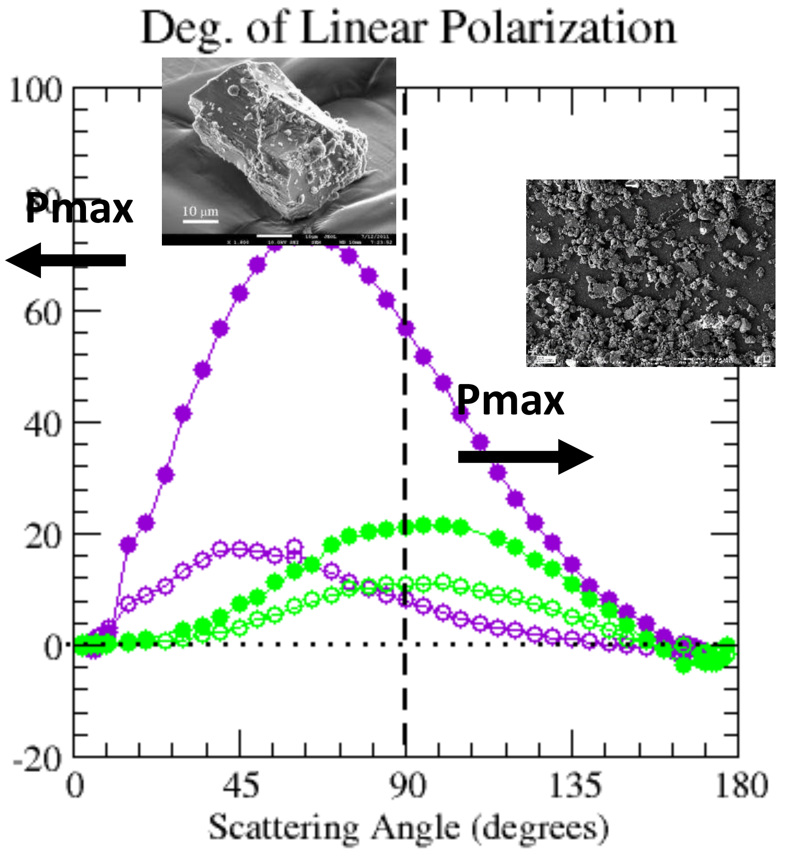
OXFORD UNIVERSITY PRESS

Lin et al. MNRAS, 520, 2023

4.3 SIZE EFFECT ON THE SCATTERING PATTERN. mm-sized vs μm-sized compact dust grains.

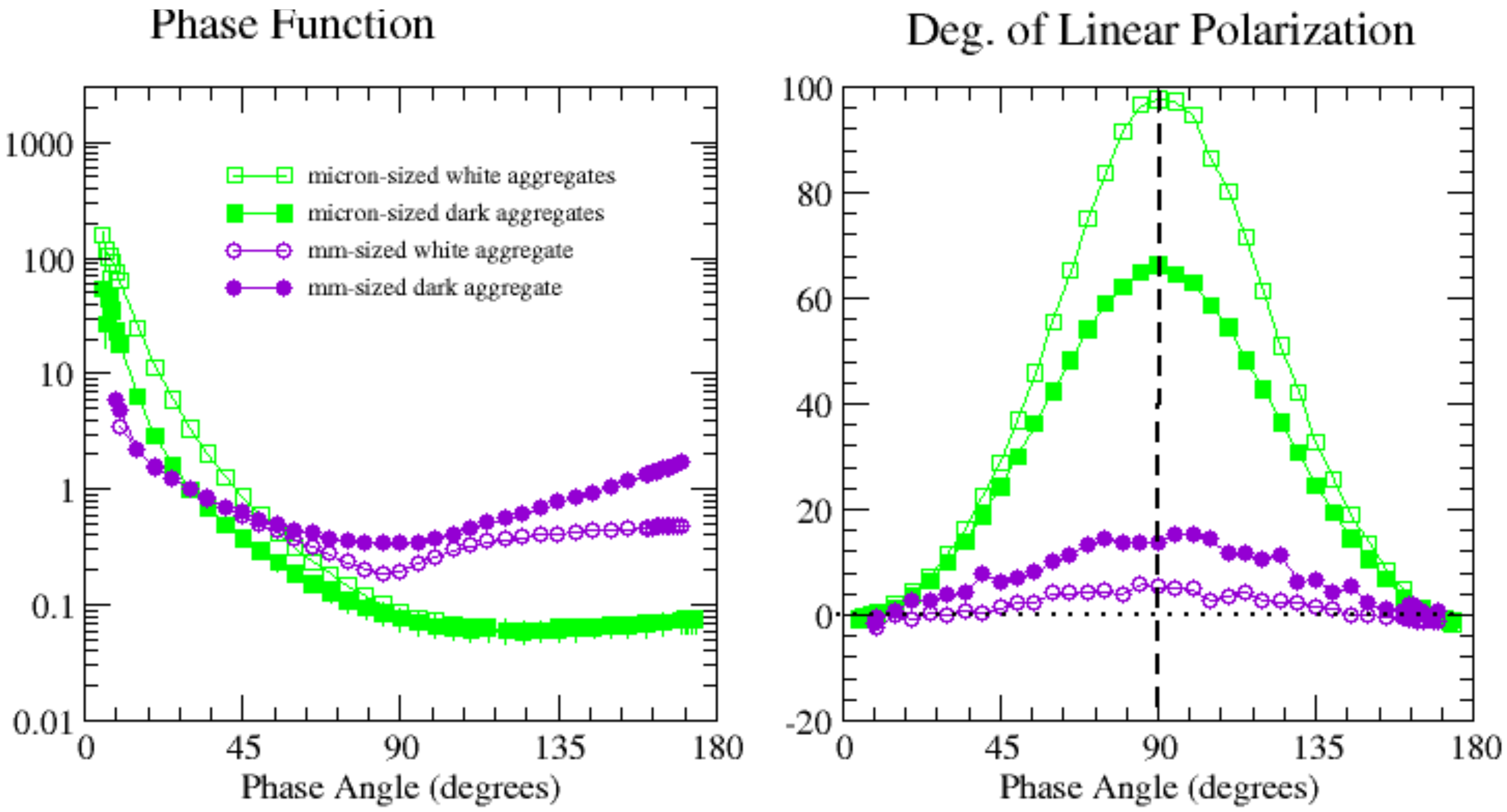
r>>λ
λ=520 nm





Muñoz et al. ApJ, 846 (1), 2017.
Muñoz et al. ApJS, 247, 2020.

SIZE EFFECT ON THE SCATTERING PATTERN.
mm-sized vs μm-sized **porous** dust grains.



Volten et al. et al. A&A, 470, 2007
Muñoz et al. ApJS, 247, 2020.

Practical Information for computing light scattering by spherical and nonspherical particles

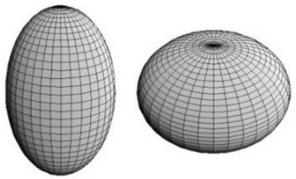
The Problem: Modelling scattering properties of dust grains

SIZE PARAMETER $x=2\pi r/\lambda$

Mie

No restrictions x

Double-precision Lorenz-Mie scattering code for polydisperse spherical particles: spher.f



Prolate Spheroid   Oblate Spheroid

x~30

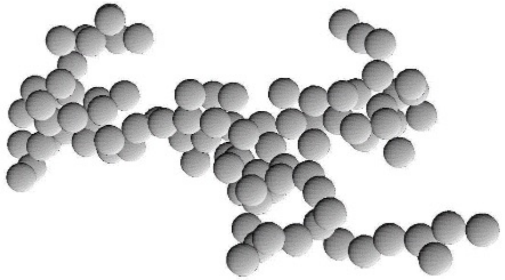
(T-matrix: e.g. Mishchenko & Travis, JQSRT, 1998)

T-matrix codes for computing light scattering by nonspherical particles

SCATTPORT

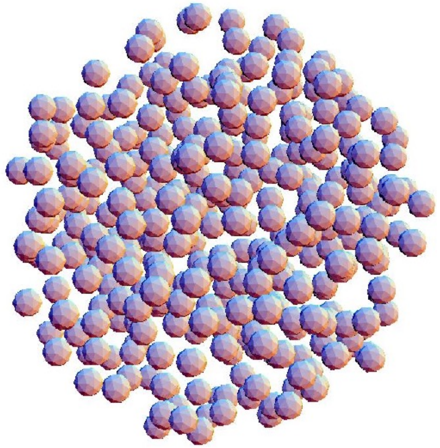
The Problem: Modelling scattering properties of dust grains

SIZE PARAMETER $x=2\pi\, r/\lambda$



x~10-12

(DDA: Draine &Flatau, JOSA 1994;
Yurkin & Hoekstra, JQSRT 2011)

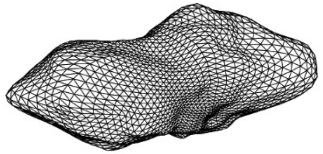


A multiple sphere T-matrix FORTRAN code for use on parallel computer clusters

The Problem: Modelling scattering properties of dust grains

SIZE PARAMETER $x=2\pi\ r/\lambda$

(Muinonen & Nousiainen 2003)

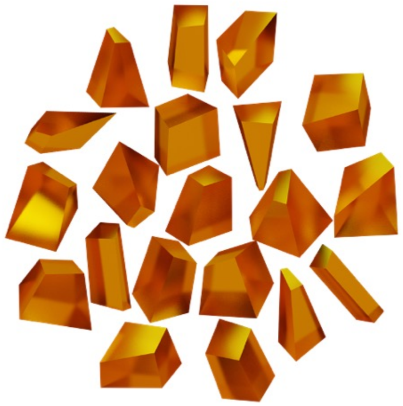


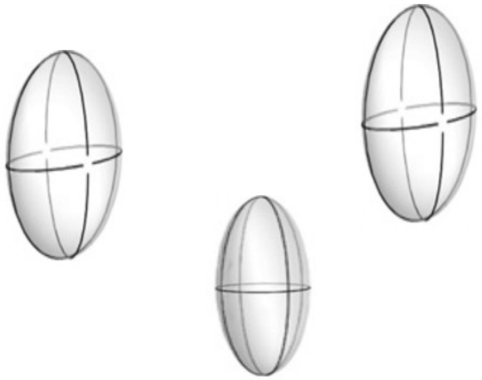
x>50

Ray Optics Approximation

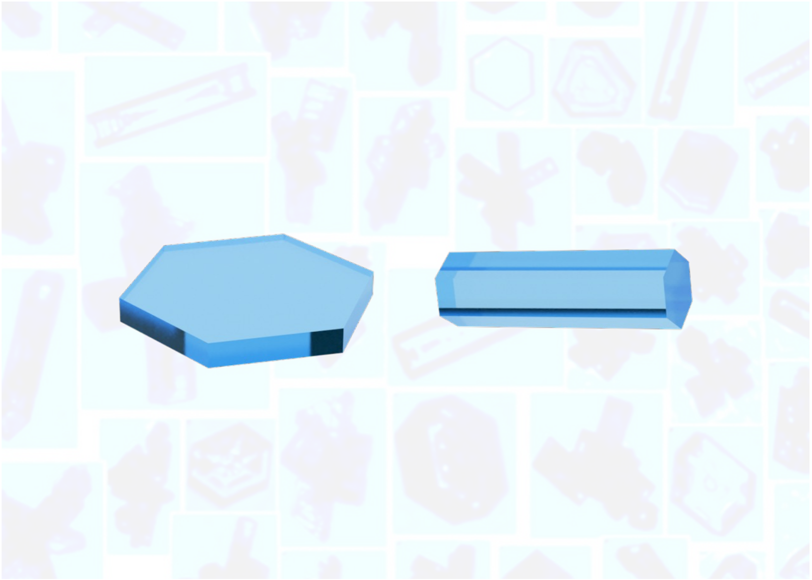
[Light scattering by large particles in the Ray Optics approximation]

COMPUTE SCATTERING PRPERTIES





[Scattering properties Databases]



Granada - Amsterdam Light Scattering Database

What is in this database?

Data in this database are freely available under the request of citation of this paper and the paper in which the data were published

https://scattering.iaa.csic.es/

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SAMPLES CATEGORIES

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