RoadMap
Workshop

Optical Properties of Martian Dust 1: Laboratory Measurements.

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Instituto de Astrofísica de Andalucía (IAA-CSIC)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101004052

Sep 19-21 2023

OUTLINE

- RoadMap.
- Definitions. Why experiments?
- The Cosmic Dust Laboratory (IAA-CODULAB).
  - Experiments.
  - Samples.
  - Results.

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RoadMap Animated Introduction

https://roadmap.aeronomie.be/index.php/public-outreach

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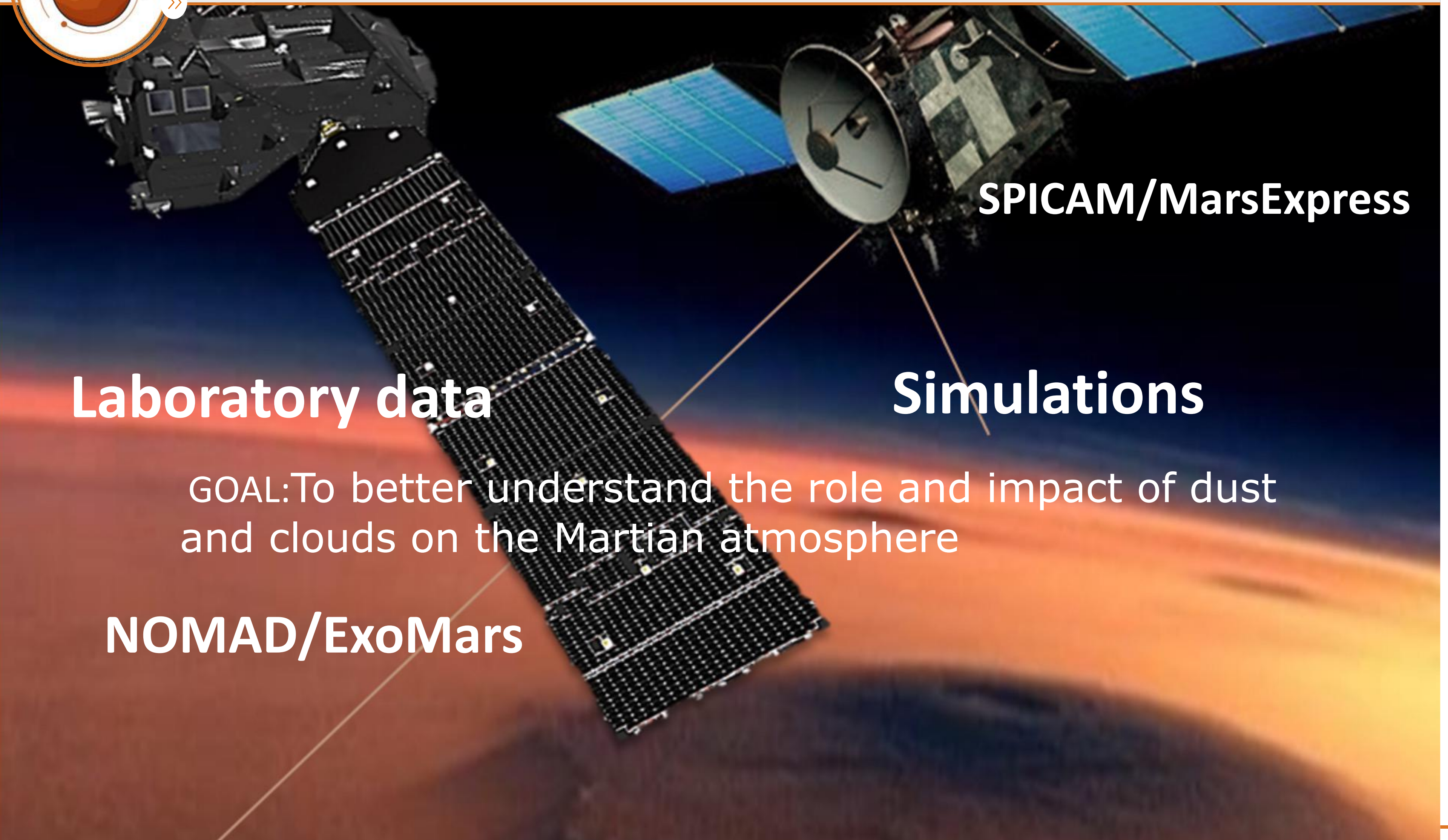
ROADMAP



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DUST STORMS I

Dust lifted into the atmosphere will eventually produce clouds and hazes, different spatial scales (local to global), and different timescales from (hour to seasons).

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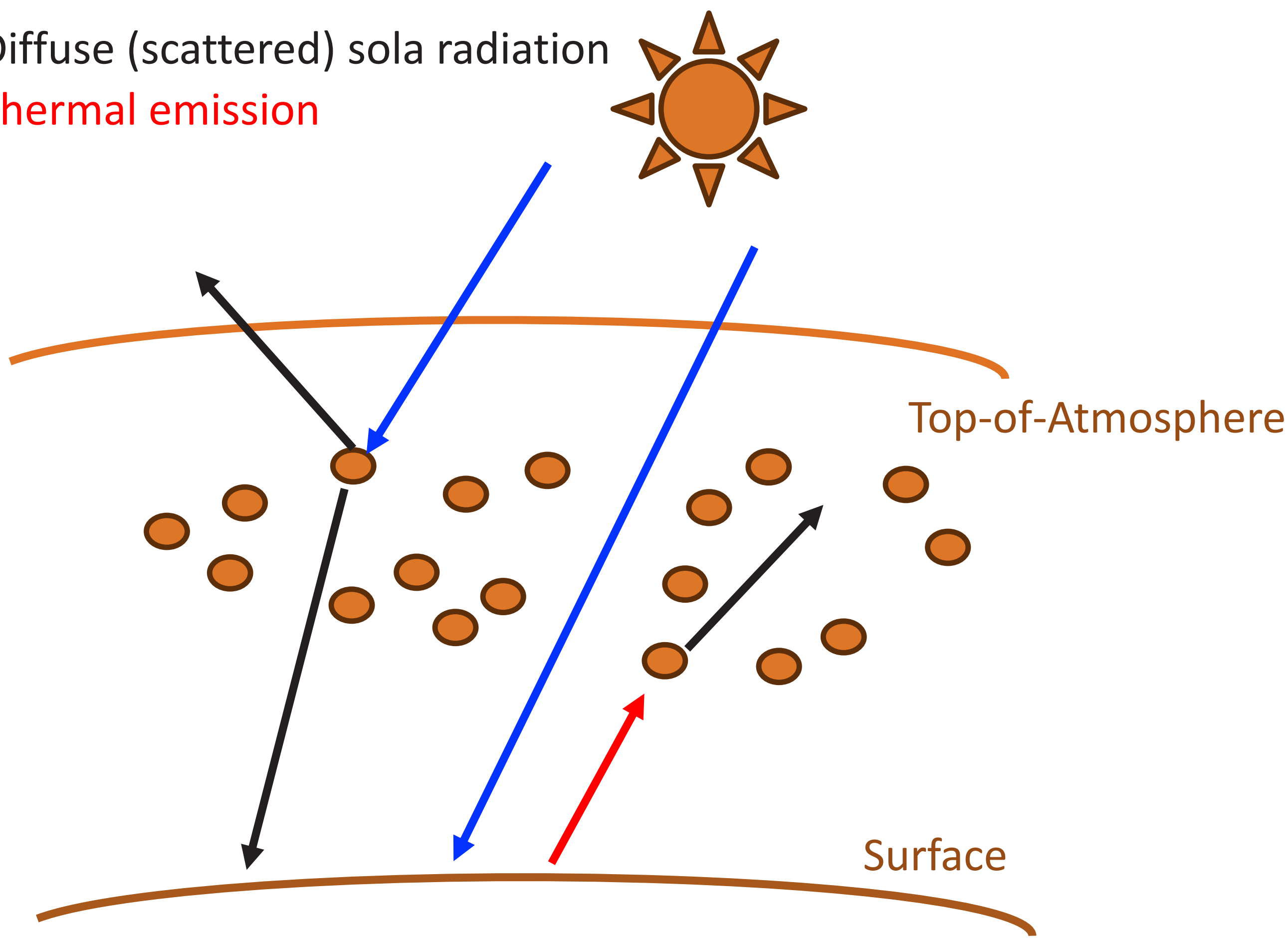
DUST STORMS II

Direct solar radiation

Diffuse (scattered) sola radiation

Thermal emission



Temperature profile
Radiative balance
Atmospheric dynamic

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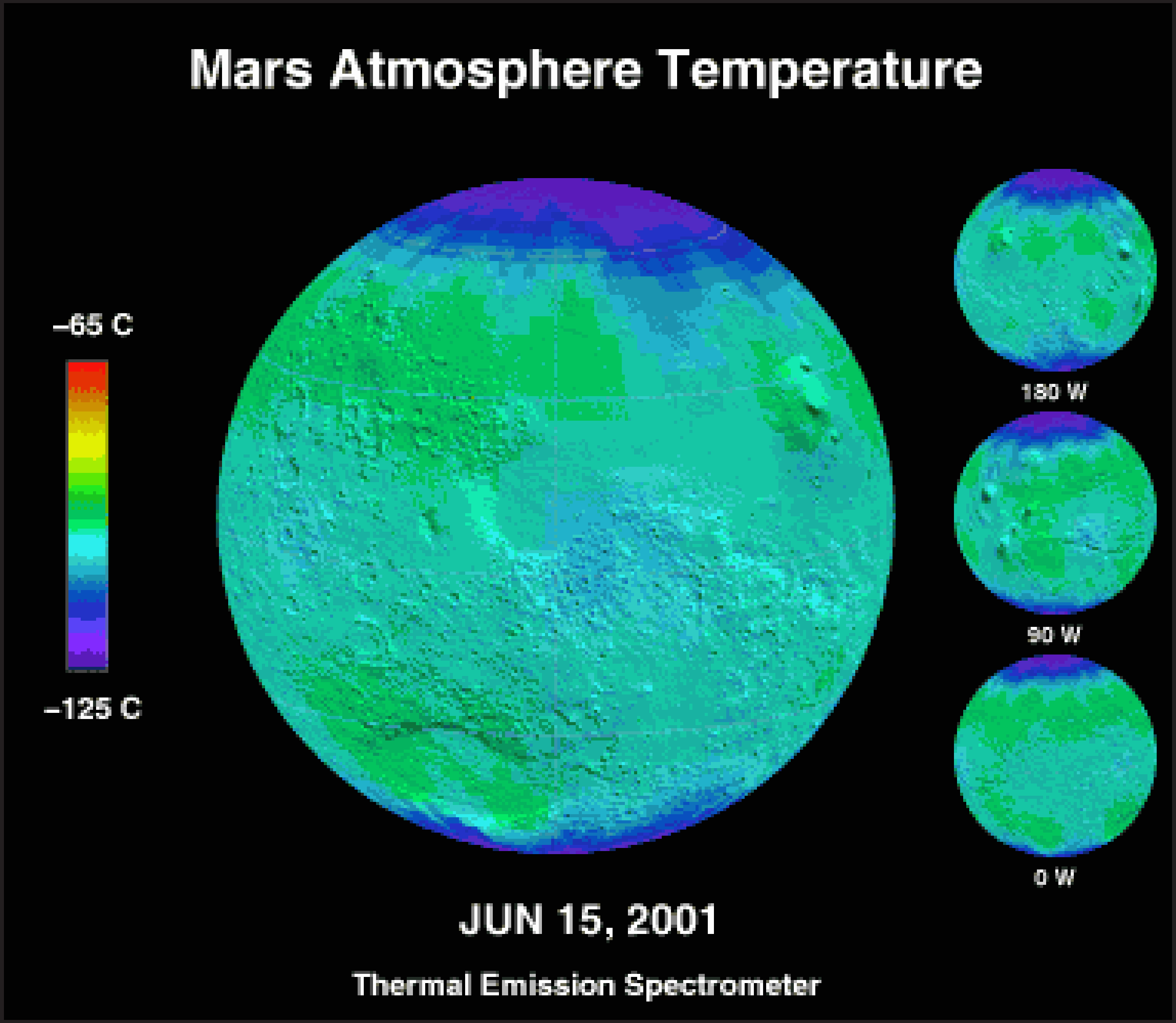
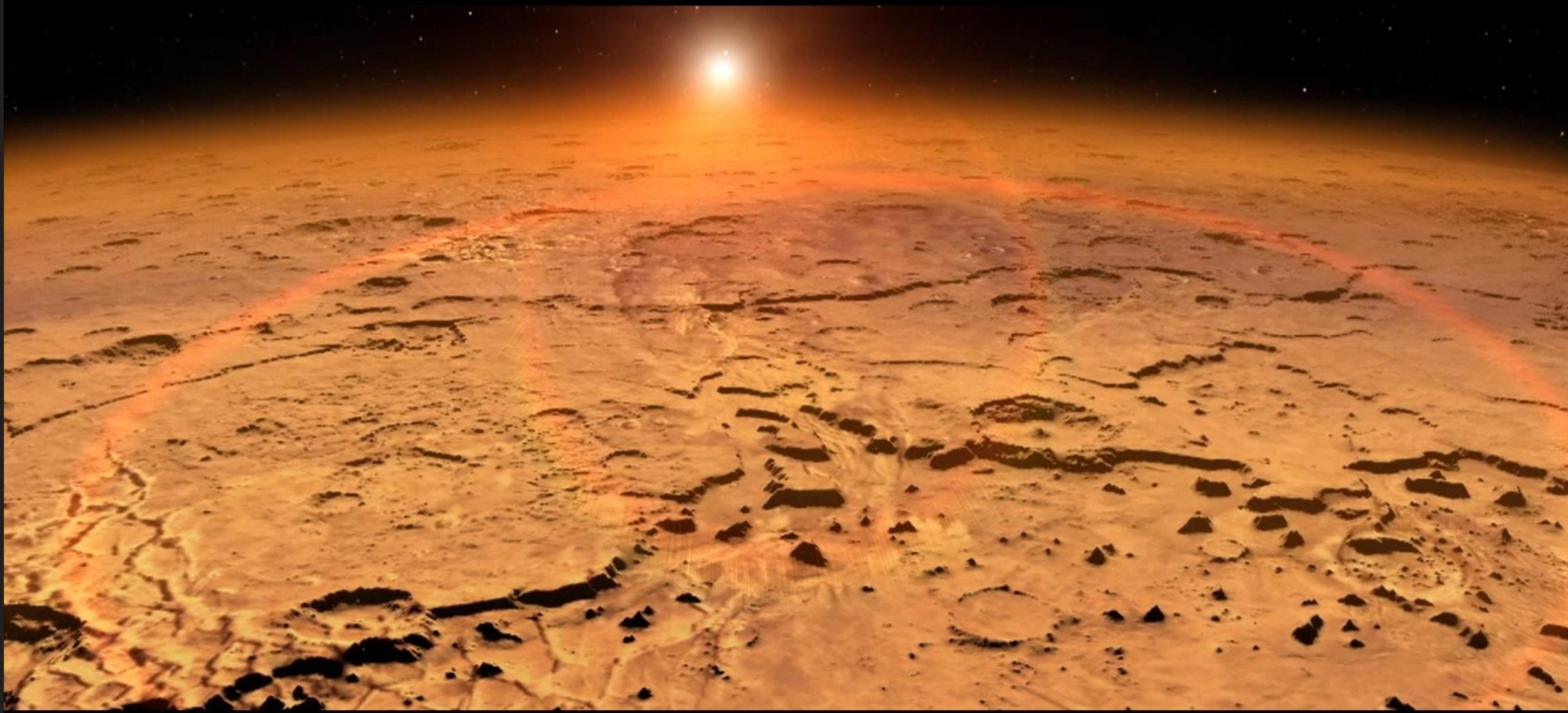
DUST STORMS III: EFFECT on TEMPERATURE PROFILE



TES@MGS CREDIT: The ASU Thermal Emission Spectrometer Team.

MARS IN THE PAST?



There are plenty of hints on today's Mars showing that the planet harboured in its past a more Earth-like environment with liquid water and warmer temperatures.

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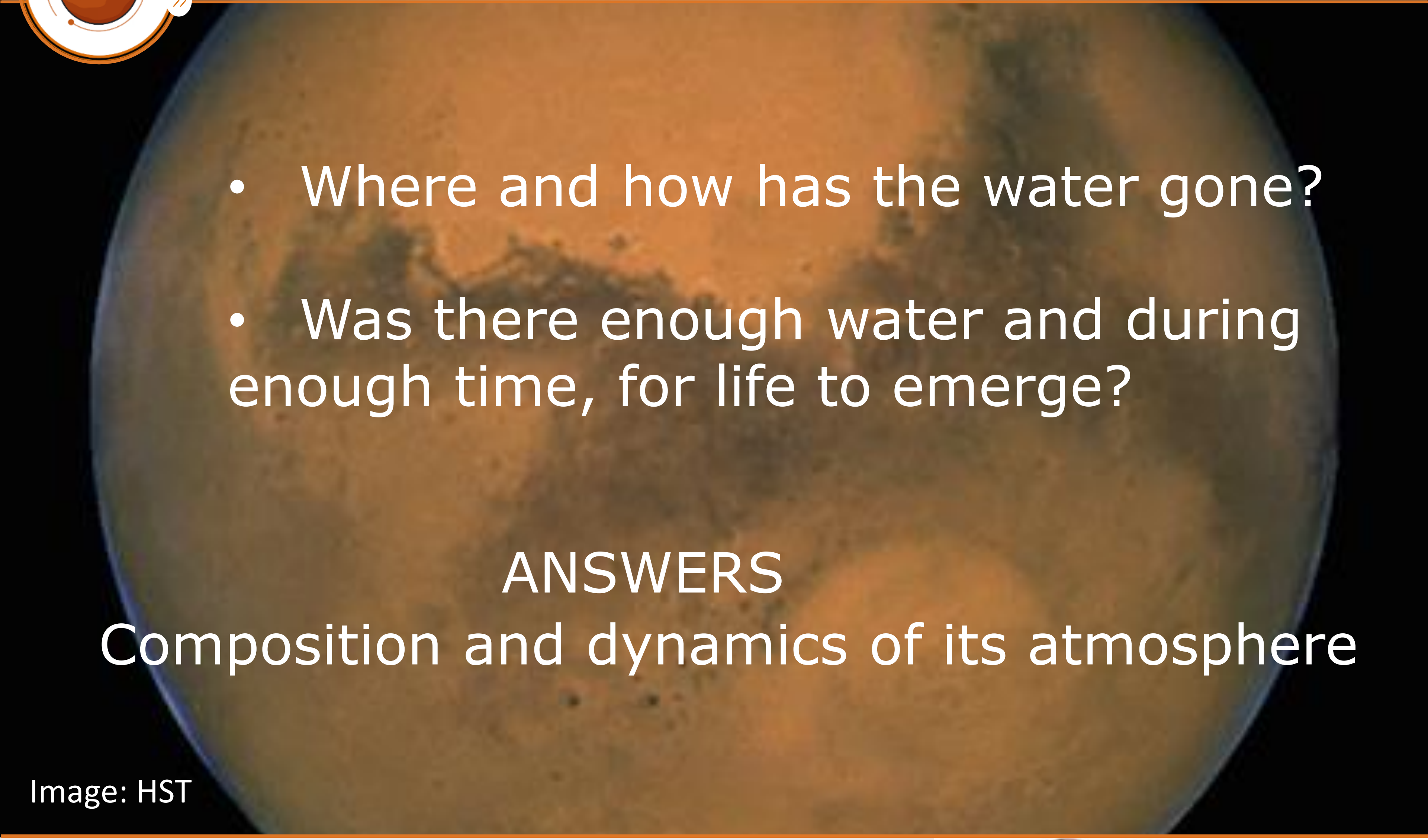

- Where and how has the water gone?
- Was there enough water and during enough time, for life to emerge?

ANSWERS

Composition and dynamics of its atmosphere

Image: HST

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SOME DEFINITIONS

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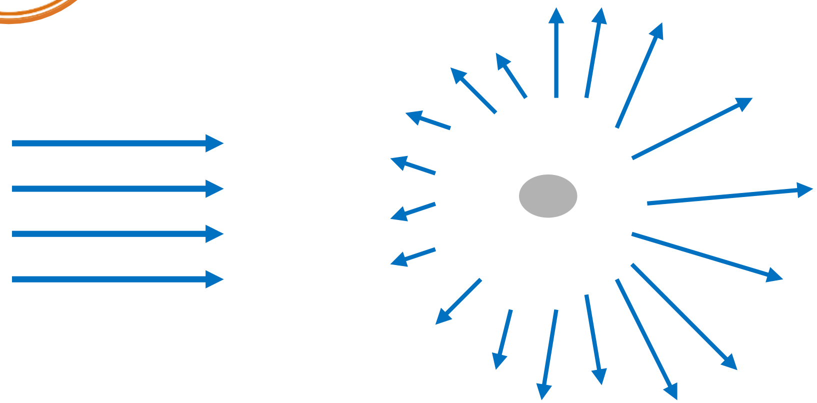
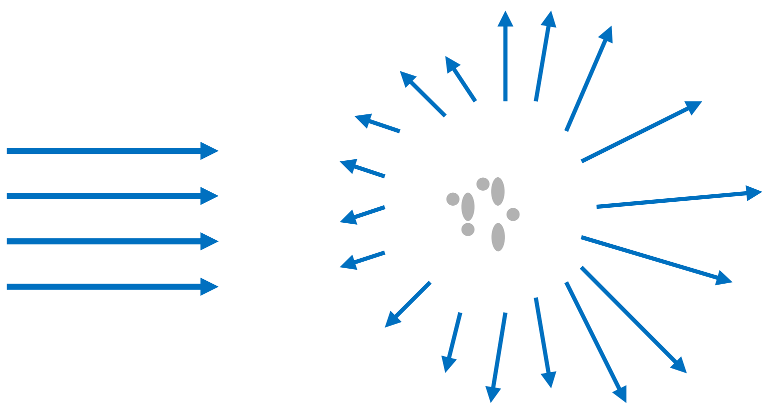
Our tool: Electromagnetic Light Scattering



DIRECT INTERACTION

INCIDENT LIGHT

ABSORPTION + SCATTERING + THERMAL EMISION



Single scattering approximation

Total field = Σ *single fields*

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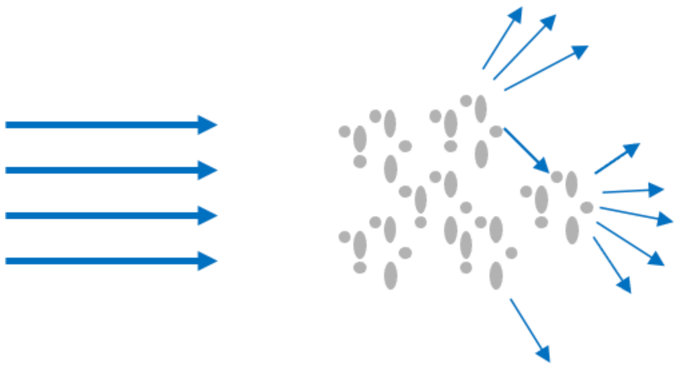
RADIATIVE BALANCE OF THE ATMOSPHERE



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

Scattering matrix

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

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

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

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

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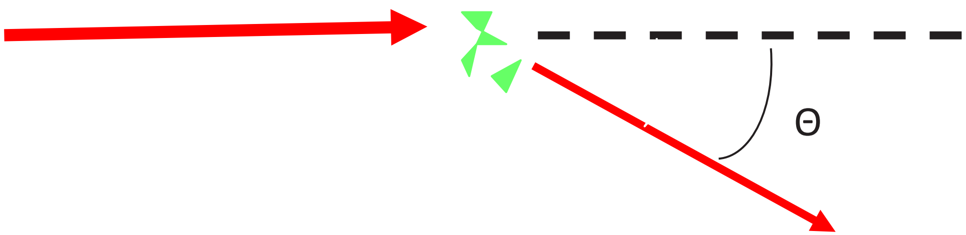
THE SCATTERING MATRIX



Intensidad

Pol. lineal

Pol. circular

$$\begin{pmatrix} I_{sc} \\ Q_{sc} \\ U_{sc} \\ V_{sc} \end{pmatrix} \propto \begin{pmatrix} F_{11} & F_{12} & 0 & 0 \\ F_{12} & F_{22} & 0 & 0 \\ 0 & 0 & F_{33} & F_{34} \\ 0 & 0 & -F_{34} & F_{44} \end{pmatrix} \begin{pmatrix} I_{in} \\ Q_{in} \\ U_{in} \\ V_{in} \end{pmatrix}$$

Depends on :
Shape
size
Composition (refractive index)
Wavelength

Stokes vector *Scattering Matrix* *Stokes vector*

Randomly oriented particles => all sattering planes equivalent F (λ,θ)
Mirror symmetry (6 independent elements)
van de Hulst, Light scattering by small particles, 1957

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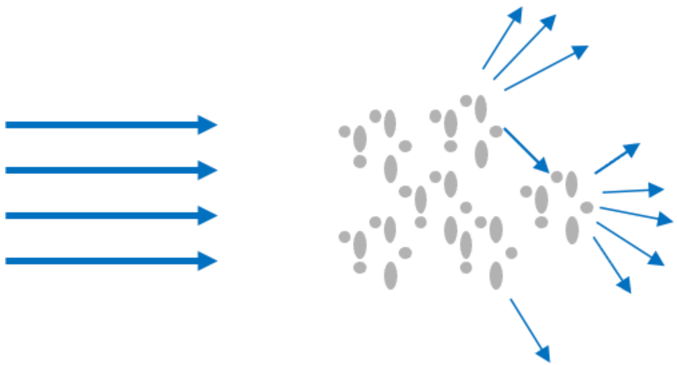

Multiple Scattered Diffuse component

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 along the direction of propagation $\hat{n}$

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

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

Scattering, Absorpion and Emission of light by small particles
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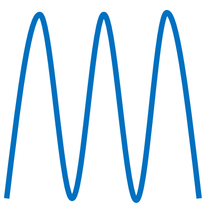
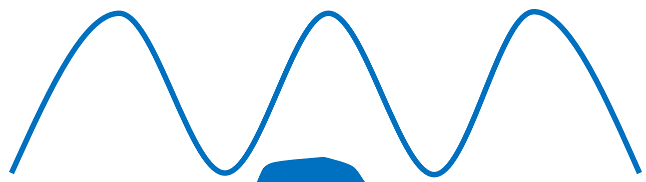
SIZE (r) vs SIZE PARAMETER (x)

VISIBLE $\lambda 1$

RADIO $\lambda 2$



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



r=2μm ≡ r=3.3mm

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

If m(λ1)=m(λ2)

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

r<<λ r~λ r>>λ

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Required dust optical properties:

- Spectral optical thickness
- Spectral single scattering albedo
- Spectral phase function (scattering matrix)
- Chemical composition

Dust size distribution and refractive index
r_{eff}; v_{eff}; $m(\lambda)$

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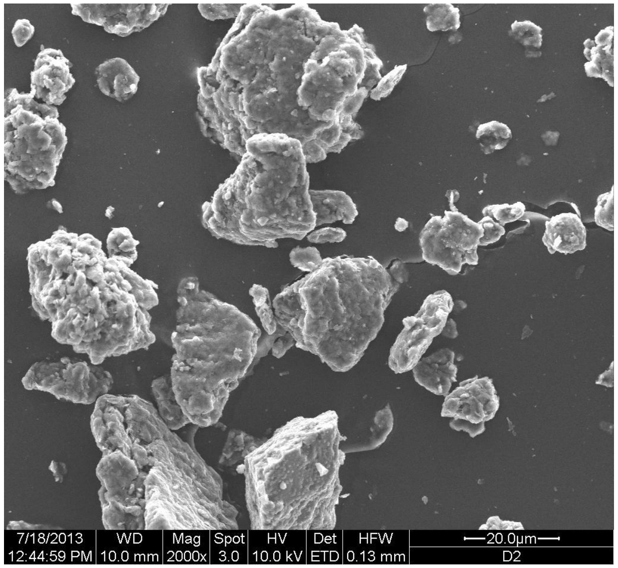
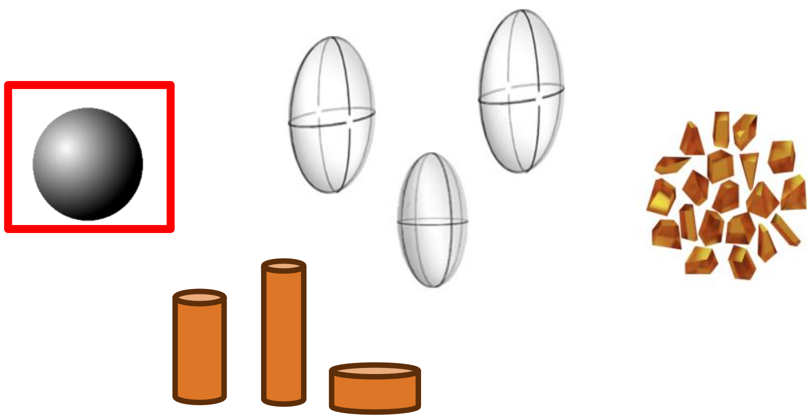
THE PROBLEM



- Complicated shapes
- Mixture compositions
- Broad size distributions

Complex computations

Simplified model particles;
Limited shapes and/or shapes



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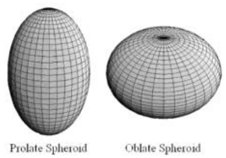
The problem: modelling scattering properties of dust grains

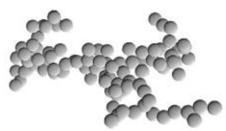
SIZE PARAMETER $x=2\pi r/\lambda$

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)

(Muinonen et al. JQSRT, 2009)

x>50 **Ray Optics Approximation**

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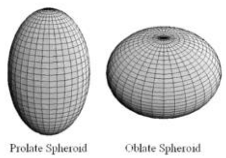

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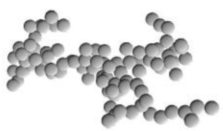

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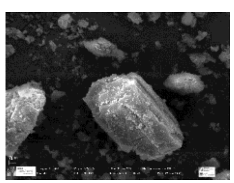
x>50 **Ray Optics Approximation**



LABORATORY DATA: ALL SHAPES AND SIZES

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Experimental Data

Advantages:

- Well characterized dust samples. (Composition, Size distribution, Morphology).

Drawbacks:

- Limited optical properties; samples, and wavelengths.

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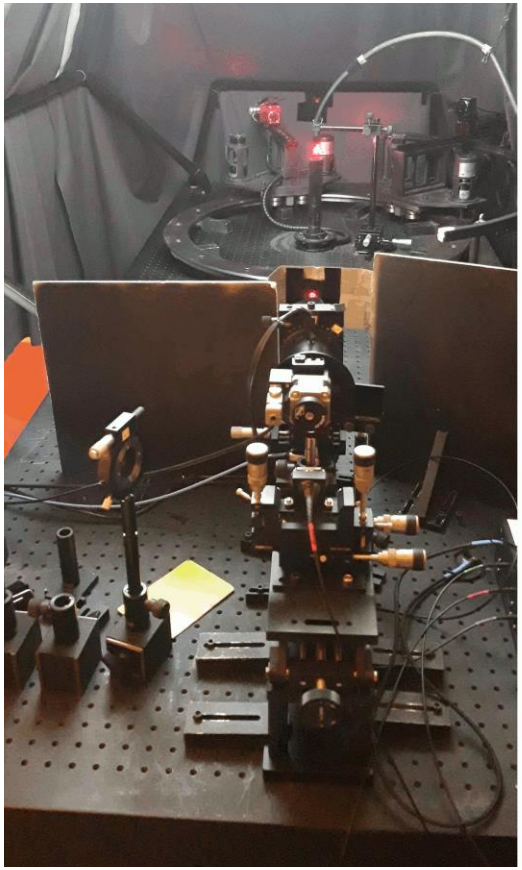
Experiments + Simulations



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IAA COSMIC DUST LABORATORY

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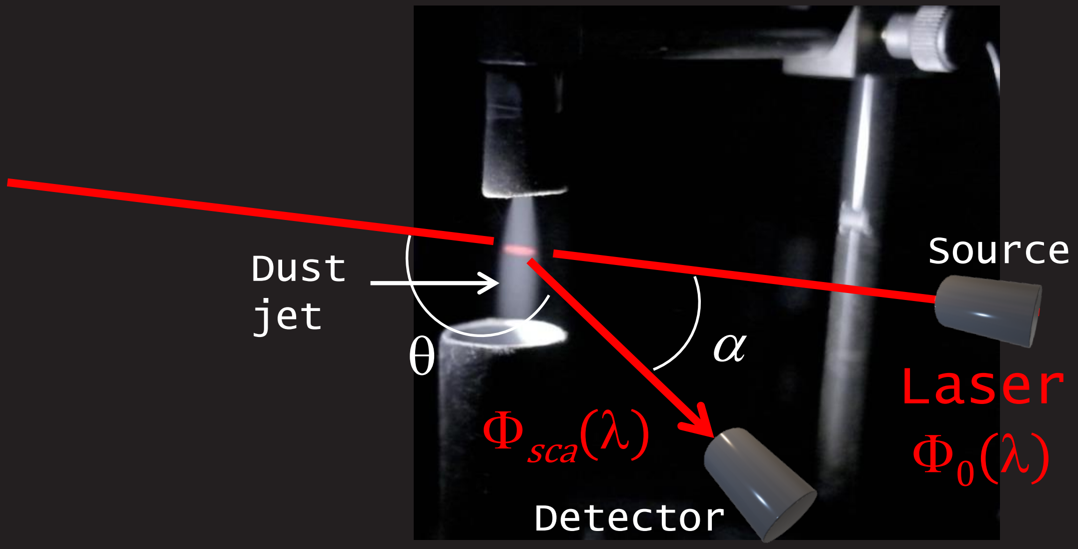
RoadMap



$$\mathbf{F}(\lambda,\theta) = \begin{pmatrix} F_{11} & F_{12} & F_{13} & F_{14} \\ F_{21} & F_{22} & F_{23} & F_{24} \\ F_{31} & F_{32} & F_{33} & F_{34} \\ F_{14} & F_{24} & F_{43} & F_{44} \end{pmatrix}$$

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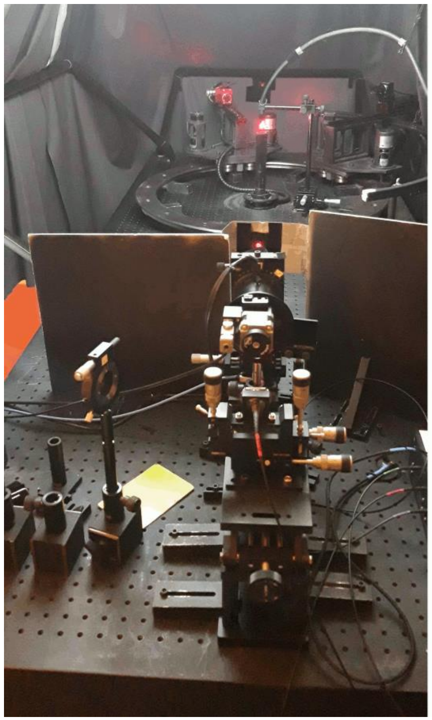
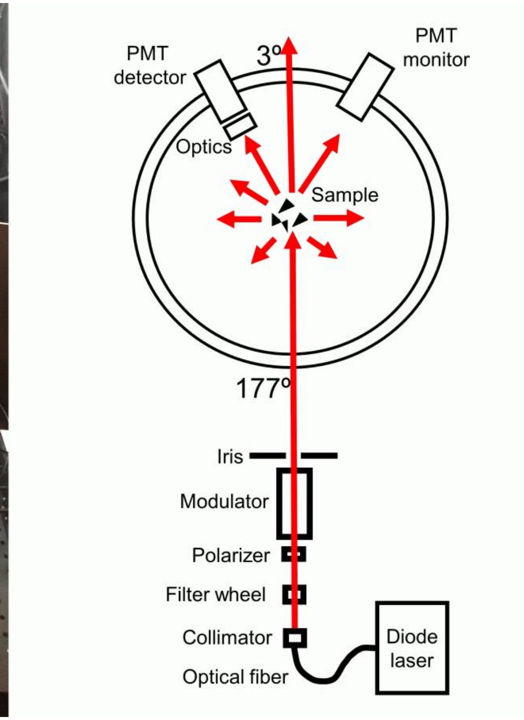
COSMIC DUST LABORATORY. SCATTERING.





λ=480 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

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

$$\delta_L = \frac{1 - F_{22}/F_{11}}{1 + 2F_{12}/F_{11} + F_{22}/F_{11}}$$

Randomly oriented particles => all sattering planes equivalent F (λ,θ)
Mirror symmetry (6 independent elements)
van de Hulst, Light scattering by small particles, 1957

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CODULAB: Spectrometer Varian Cary

Diffuse reflectance Spectra
200nm-2000 nm

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Experimental Data

I. Scattering matrices at 480 and 640 nm =>

- inputs radiative transfer models.
- testing the validity of numerical techniques.

II. Reflectance Spectra (200 nm-2000 nm) => retrieval of refractive indices.

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THE SAMPLES

Martian dust analog samples

Image: HST

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Dust samples: Composition

Wide range of spectral and compositional variabiliy


Johnson Space Center Mars-1

JSC Mars-1; palagonitic tephra

(Alen et al. 1998)


Mojave Mars Simulant 2- **MMS2**

Basalt chemically enriched Al:Fe

(Peters et al. 2008- Martian Garden)

Martian Global Simulant- **MGS1**

(Cannon et al. 2019)

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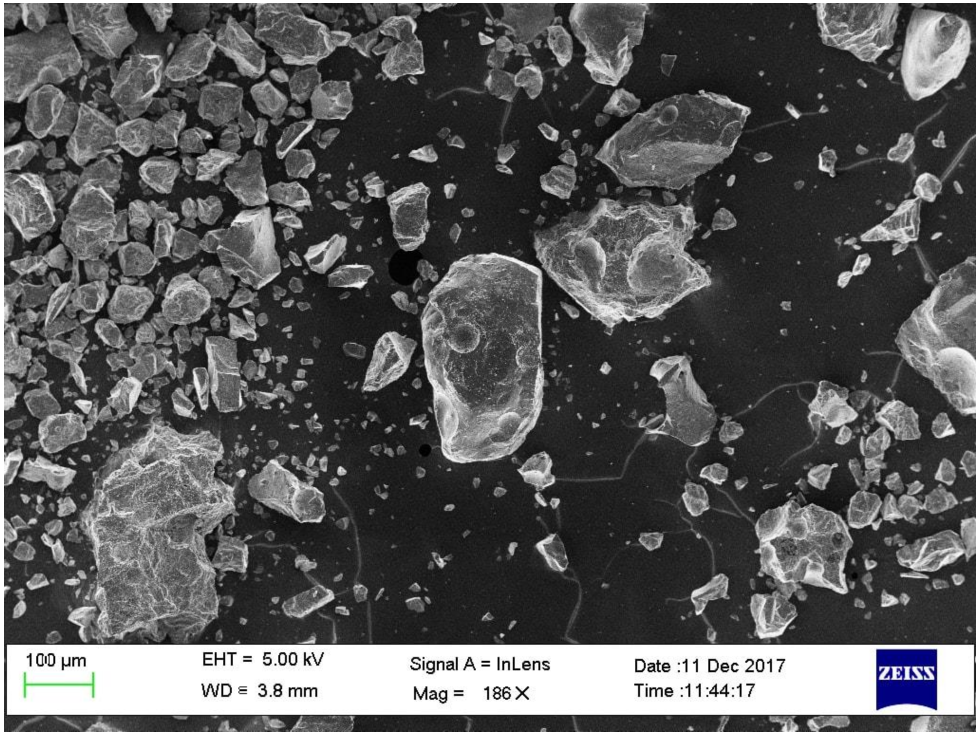
Dust samples: Size Distributions

We need narrow size distributions.



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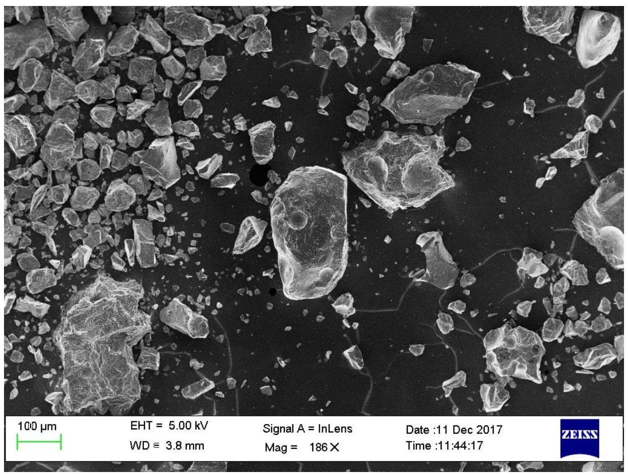
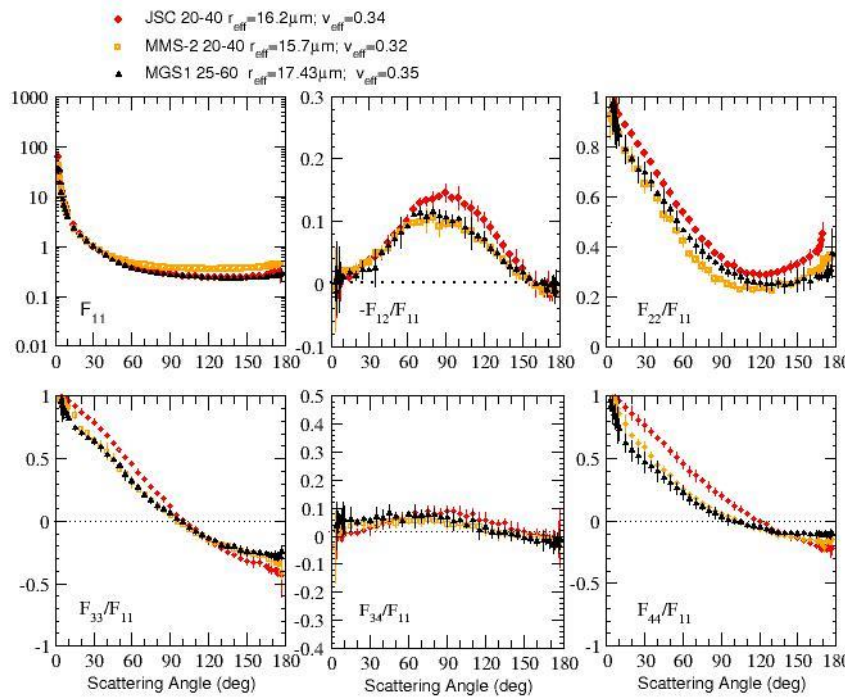
Dust samples: Size Distributions

We need narrow size distributions I.





Particle sizes should be representative for Martian atmospheric dust 1.4-1.7 µm; 3-7 µm (*e.g. Lemmon et al 2019, Chen-Chen et al 2019)*

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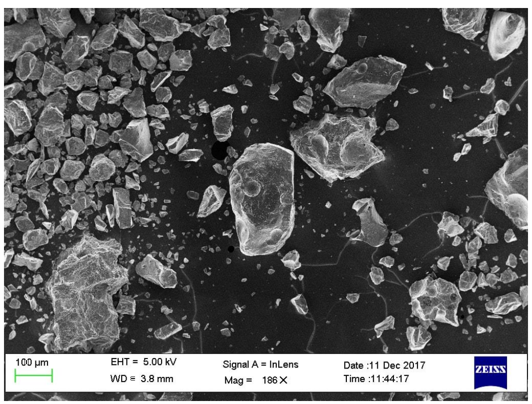
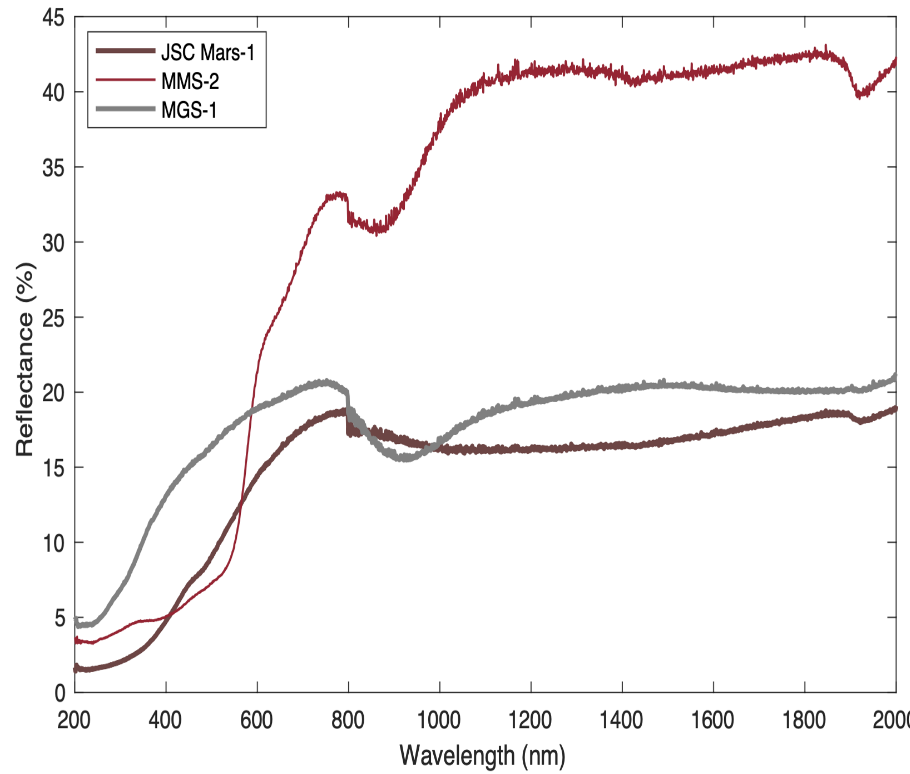
Dust samples: Size Distributions

We need narrow size distributions II.





Reflectance spectra does NOT depend on particle size.
BUT we need narrow SD in the geometric optics domain due to computational constraints (J Martikainen Lecture).

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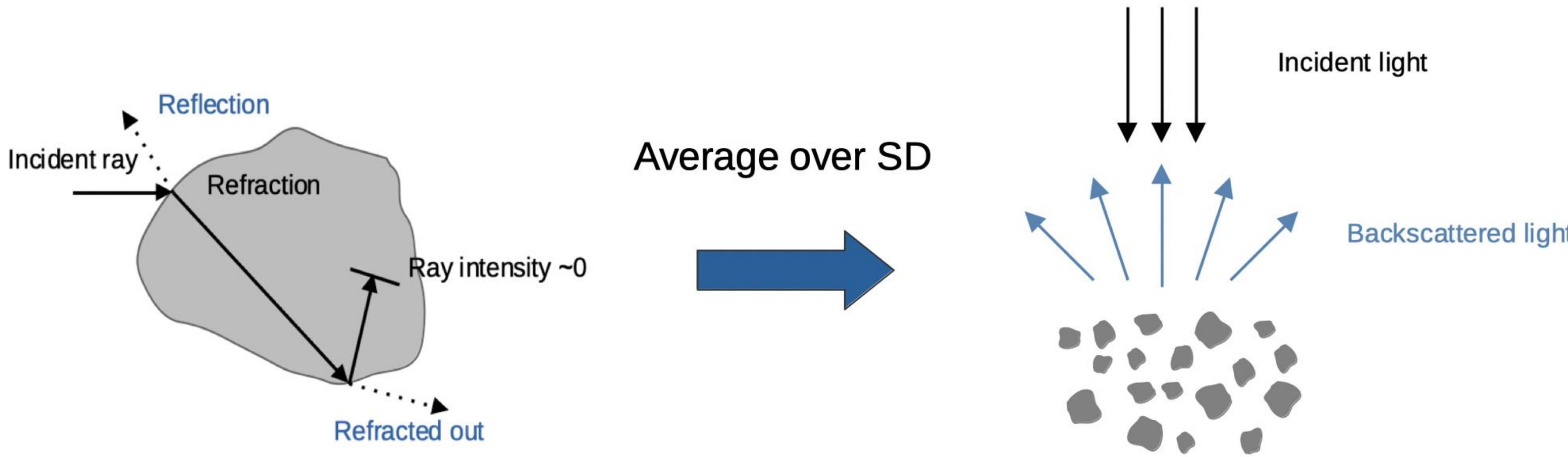
Optical constants retrieval: methods

SIRIS4 (Muinonen et al. 2009, Lindqvist et al. 2018)

RT-CB (Muinonen et al. 2004)



Approach: compute scattering properties for individual sizes, average over the measured size distribution and use the averaged particles in RT-CB to simulate the surface → compare the retrieved reflectance with the measured spectral value → iterate (Julia Martikainen lecture)

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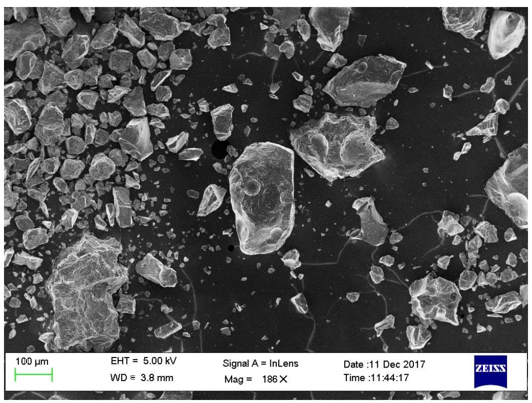
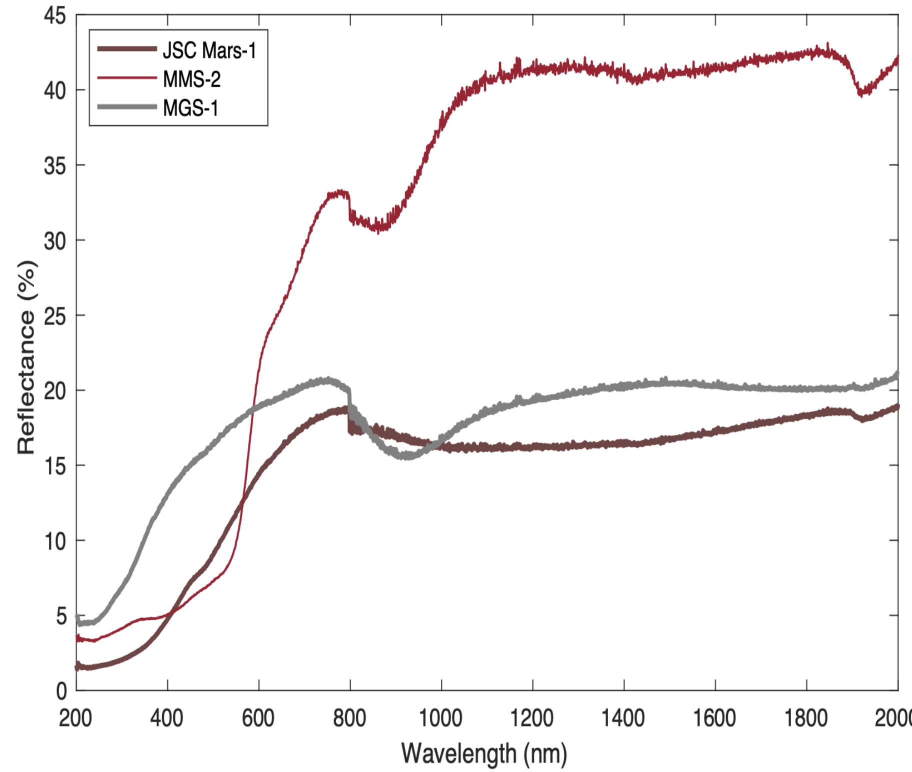
Dust samples: Size Distributions

We need narrow size distributions II.





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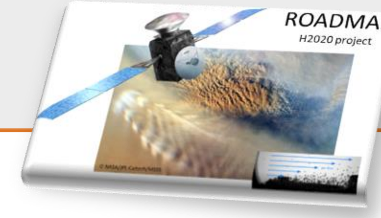
CSIC-ICV TEAM

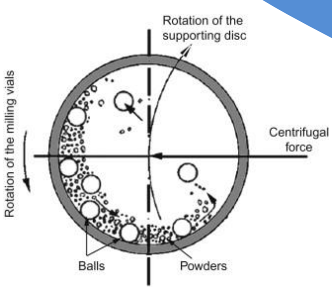
- Analogue Synthesis:



MILLING

Crushed powders

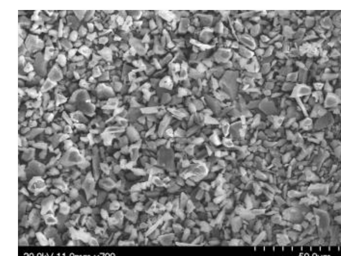
SIEVING, DECANTATION (gravitational separation) CENTRIFUGATION



Attrition mill

Grinding balls

Powder sieves (500 – 5 μm)



High energy planetary mill

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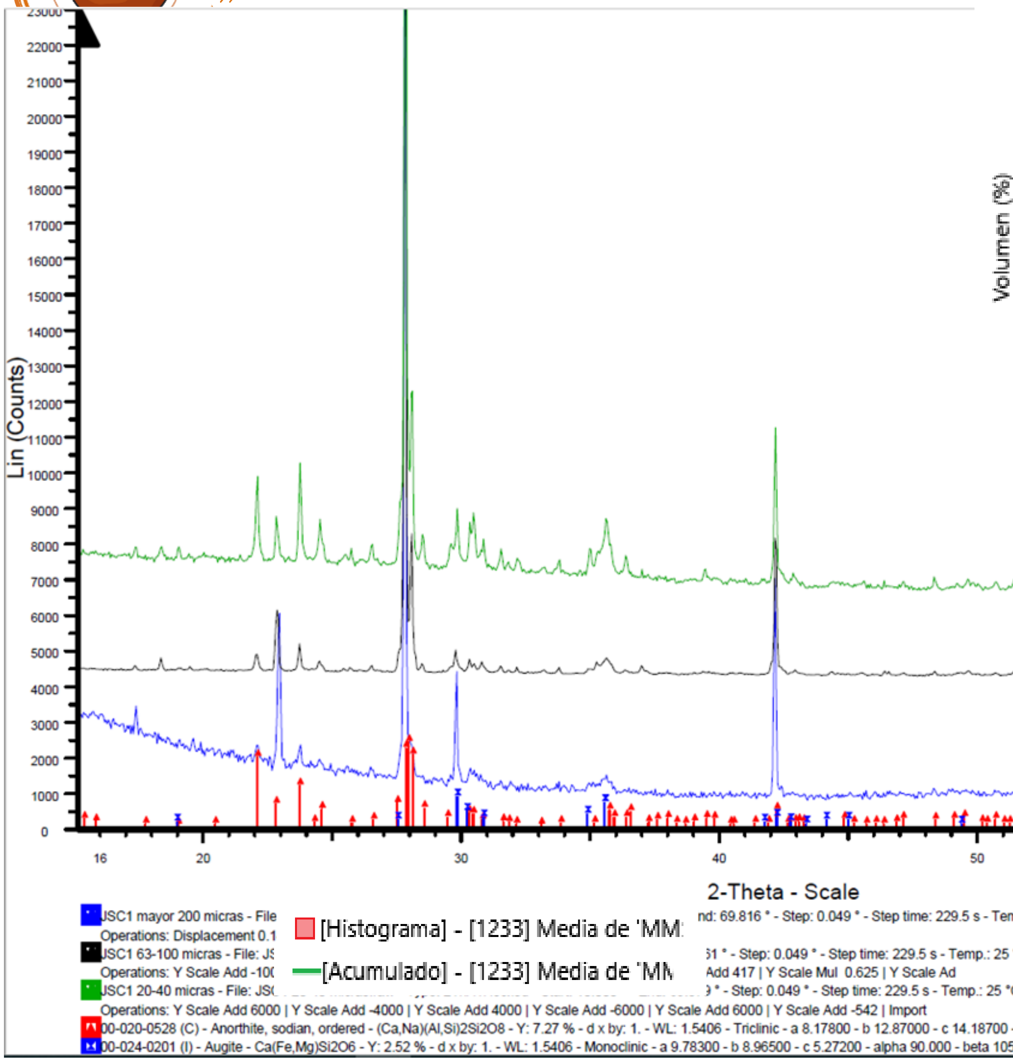
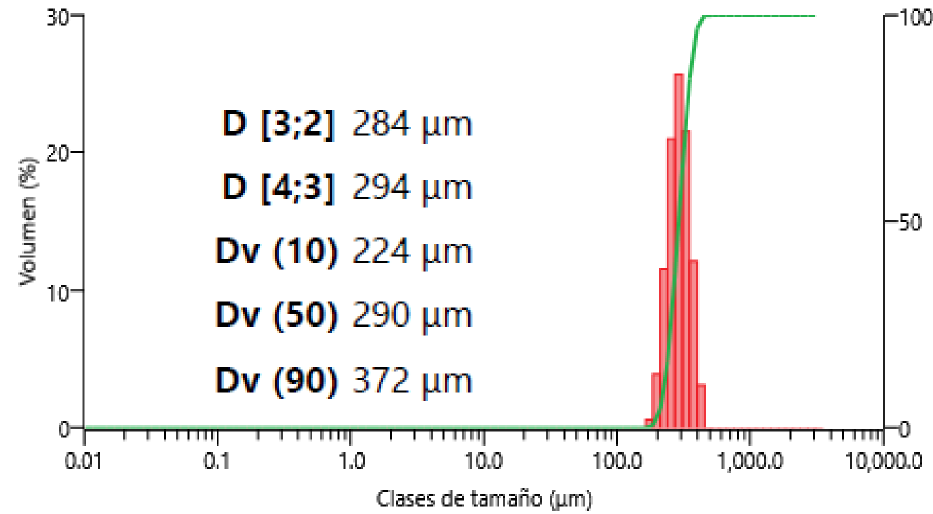
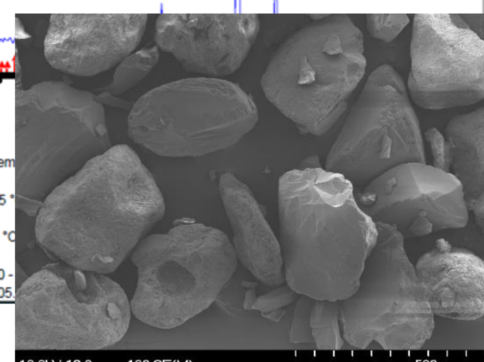
SAMPLES PRODUCTION PROCESS







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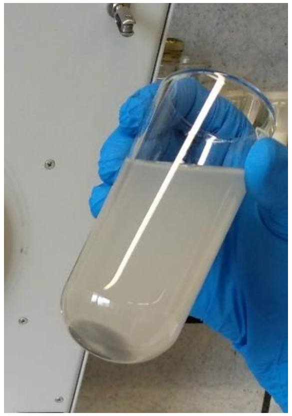
CSIC-ICV TEAM

CSIC-ICV TEAM

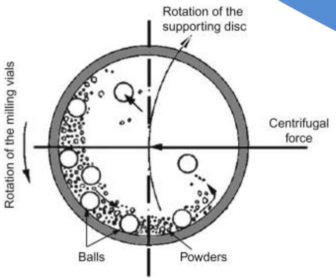
- Analogue Synthesis:



MILLING

Crushed powders

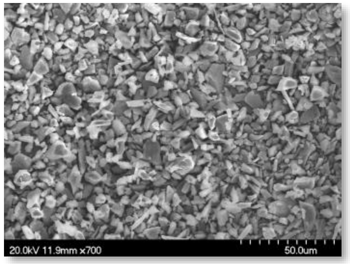
SIEVING,
DECANTATION
(gravitational separation)
CENTRIFUGATION



Attrition mill

Grinding balls

Powder sieves (500 – 5 μm)



High energy planetary mill

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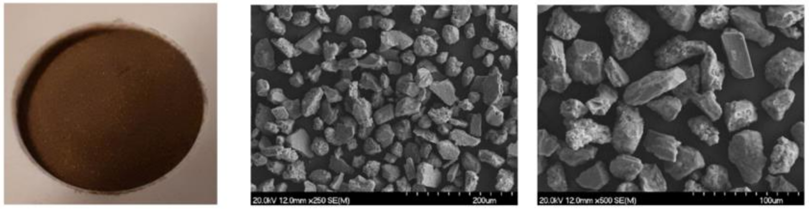
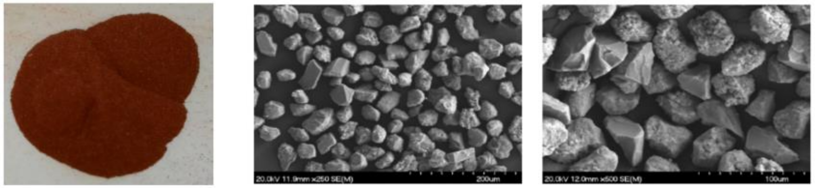
Union's Horizon 2020 research a
programme under grant agreeme

Narrow size distributions I: reflectance Spectra measurements

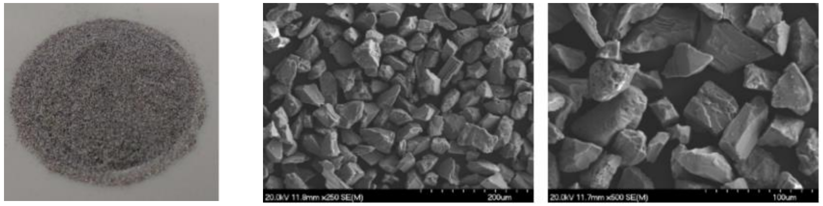
- Samples processed at the ICV: a 20-40 μm narrow size distribution in the geometric optics domain (r>>λ)



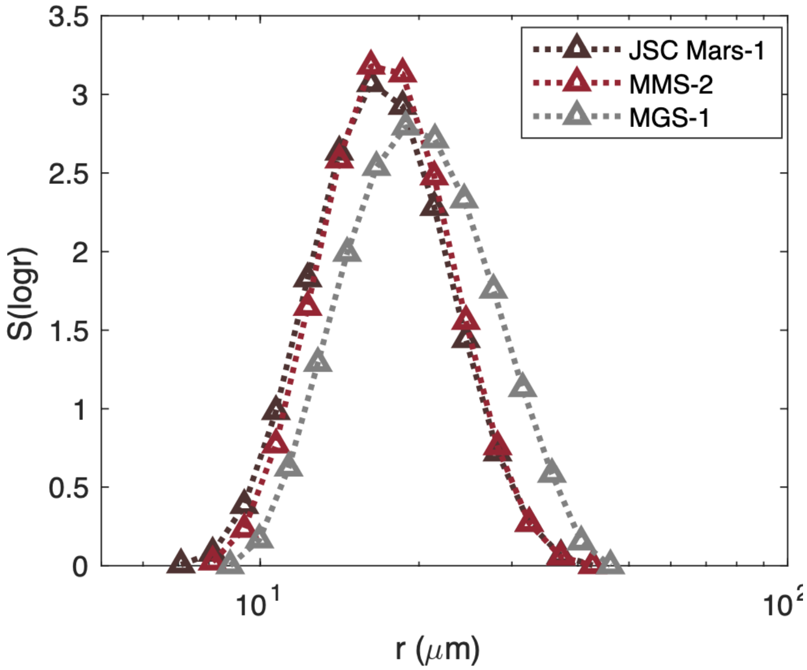
- JSC Mars-1 (Allen et al. 1997)



- Enhanced Mojave Mars Simulant (MMS-2, The Martian Garden)

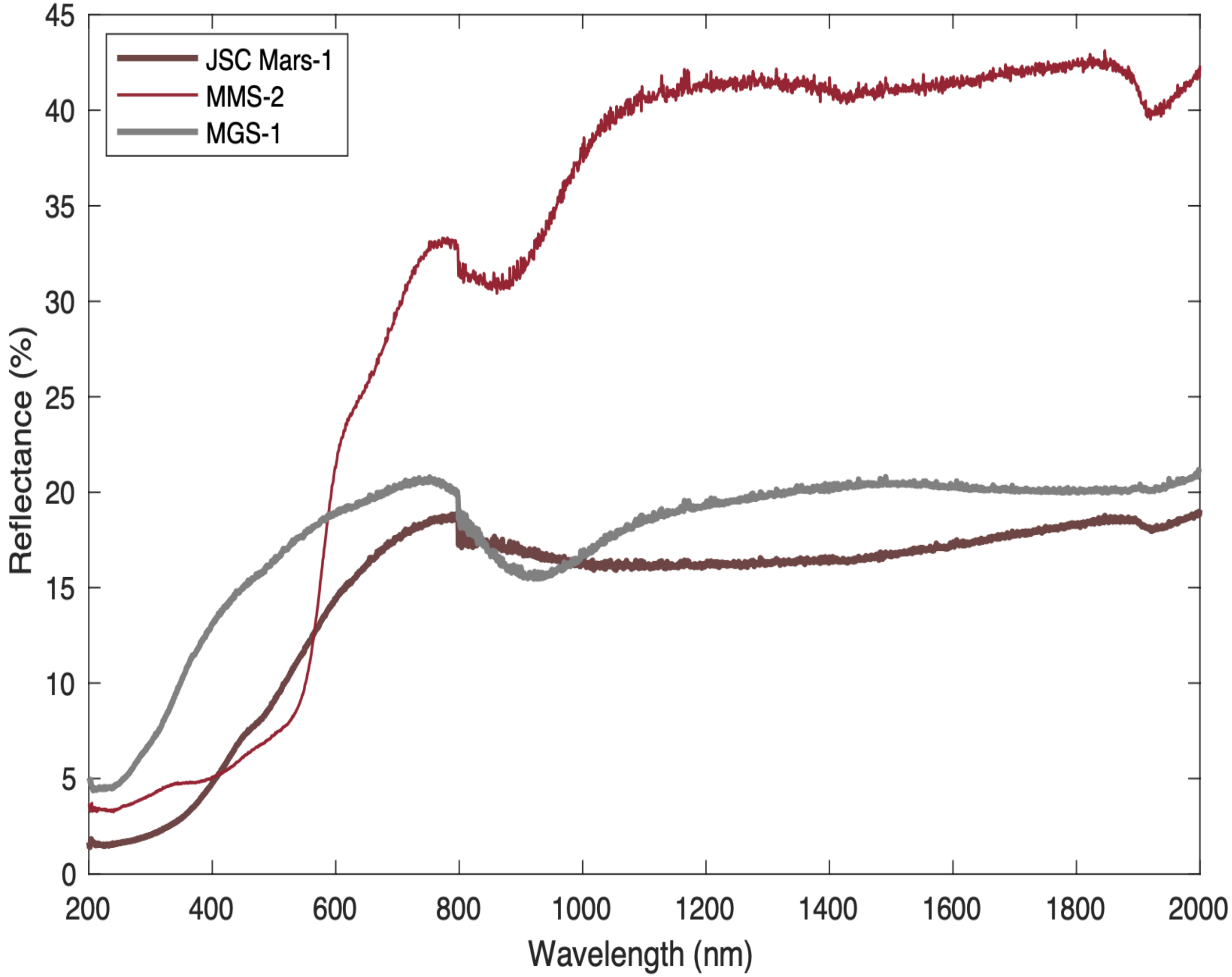


- Mars Global Simulant (MGS-1, Cannon et al. 2019)



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101004052

Experimental Data I. Reflectance Spectra.



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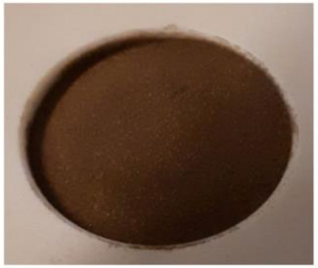
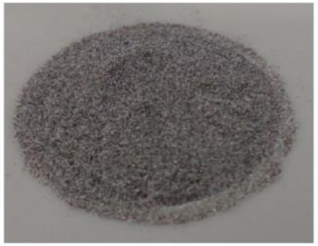
Narrow size distributions II: Scattering matrices

JSC Mars-1

L reff=**16.5** μm; σeff=0.3

M reff=**2.7** μm; σeff=0.5

S reff=**0.4** μm; σeff=0.2

MMS2

L reff= **16.2** μm; σeff=0.3

M reff=**1.9** μm; σeff=0.6

S reff=**0.34** μm; σeff=0.4

MGS1

L reff =**17.42** μm, σeff=0.4

M reff=**1.6** μm; σeff=0.9

S reff= **0.4** μm, σeff=0.2

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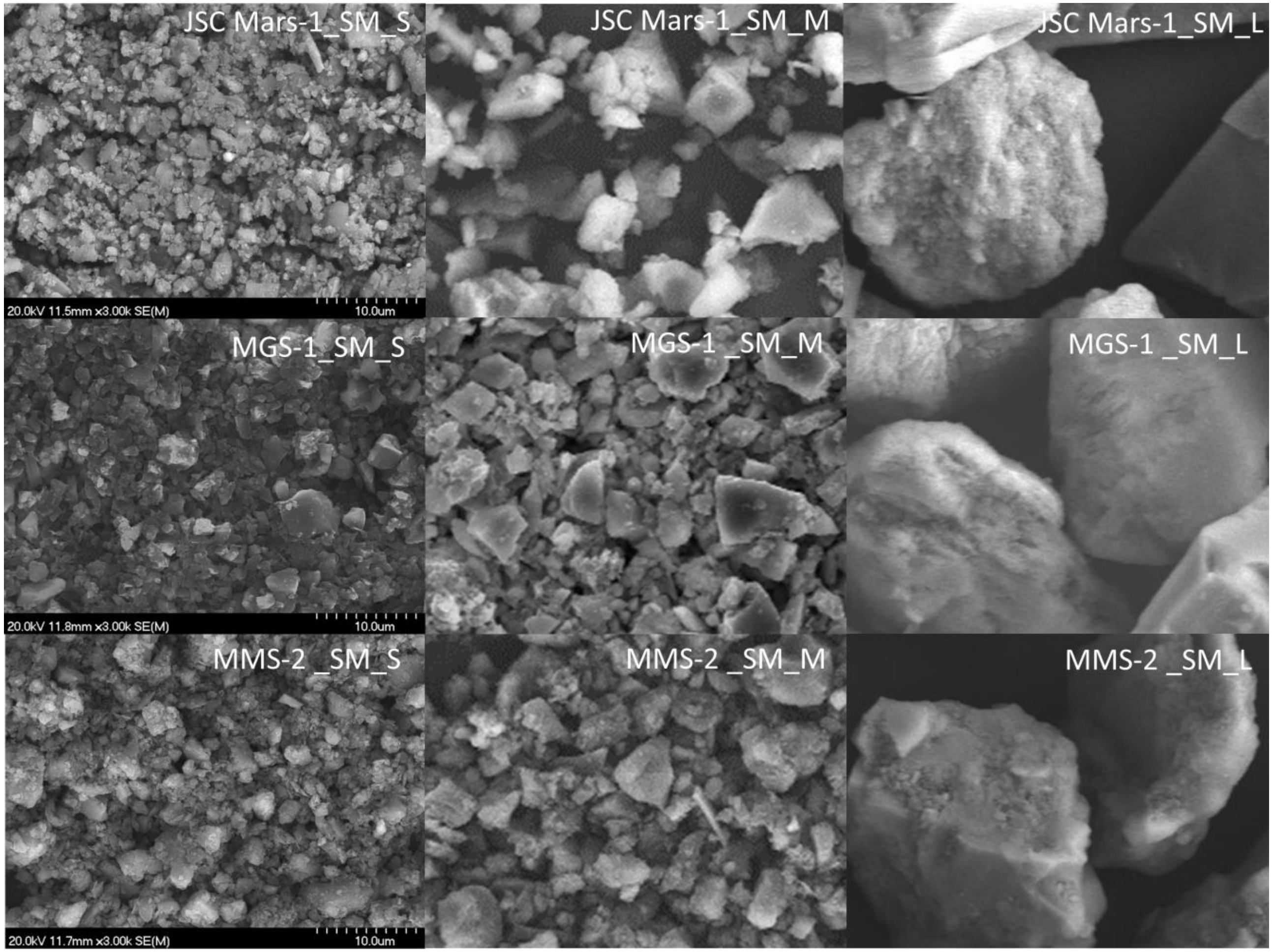
Optical Properties. Samples III



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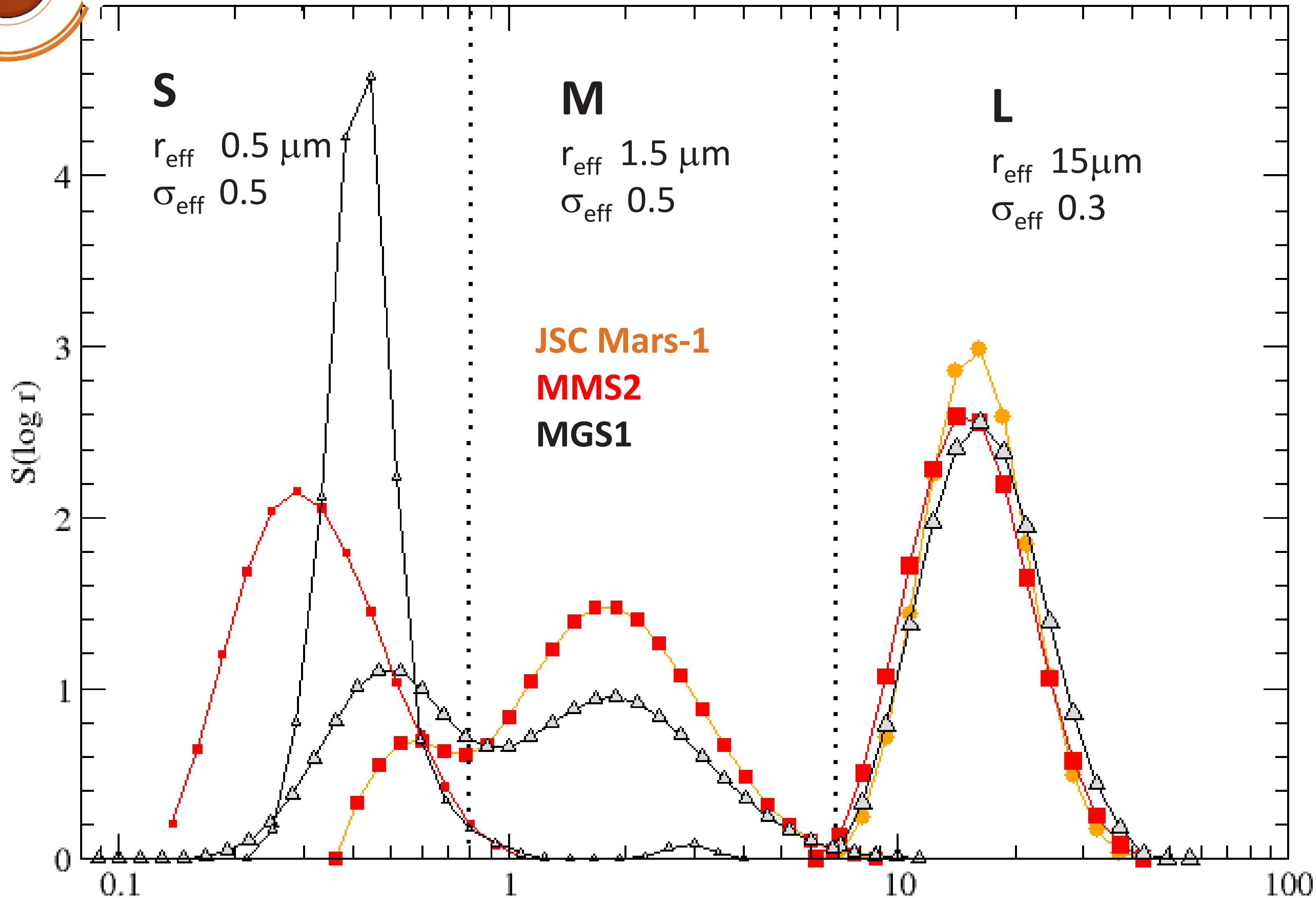
Optical Properties. Samples III



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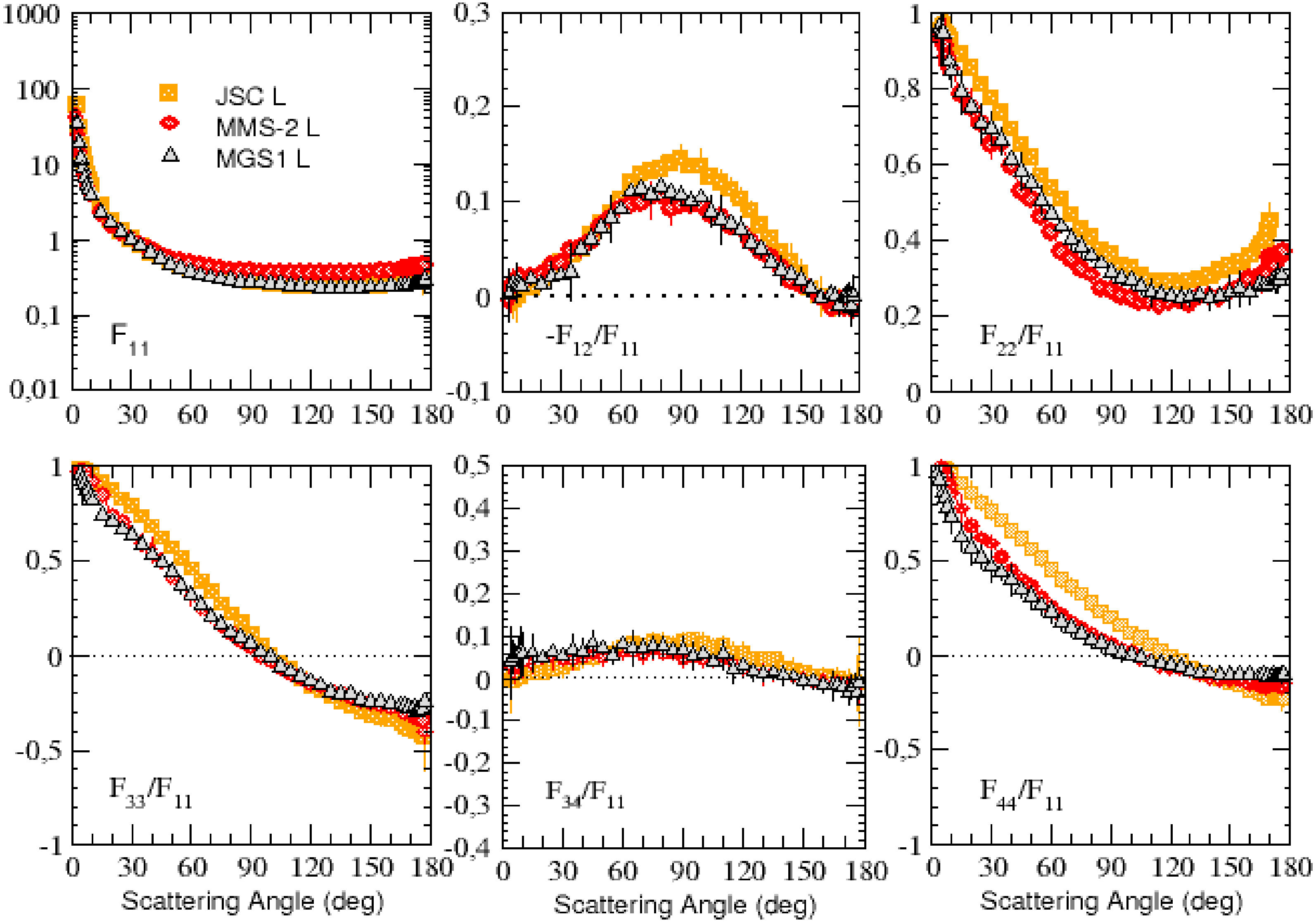
Scattering matrices @640 nm

SAMPLES L reff=16.5μm; σeff=0.3

JSC k=6.5E-04
MMS2 k=3.5 E-04
MGS1 k=4.3 E-04

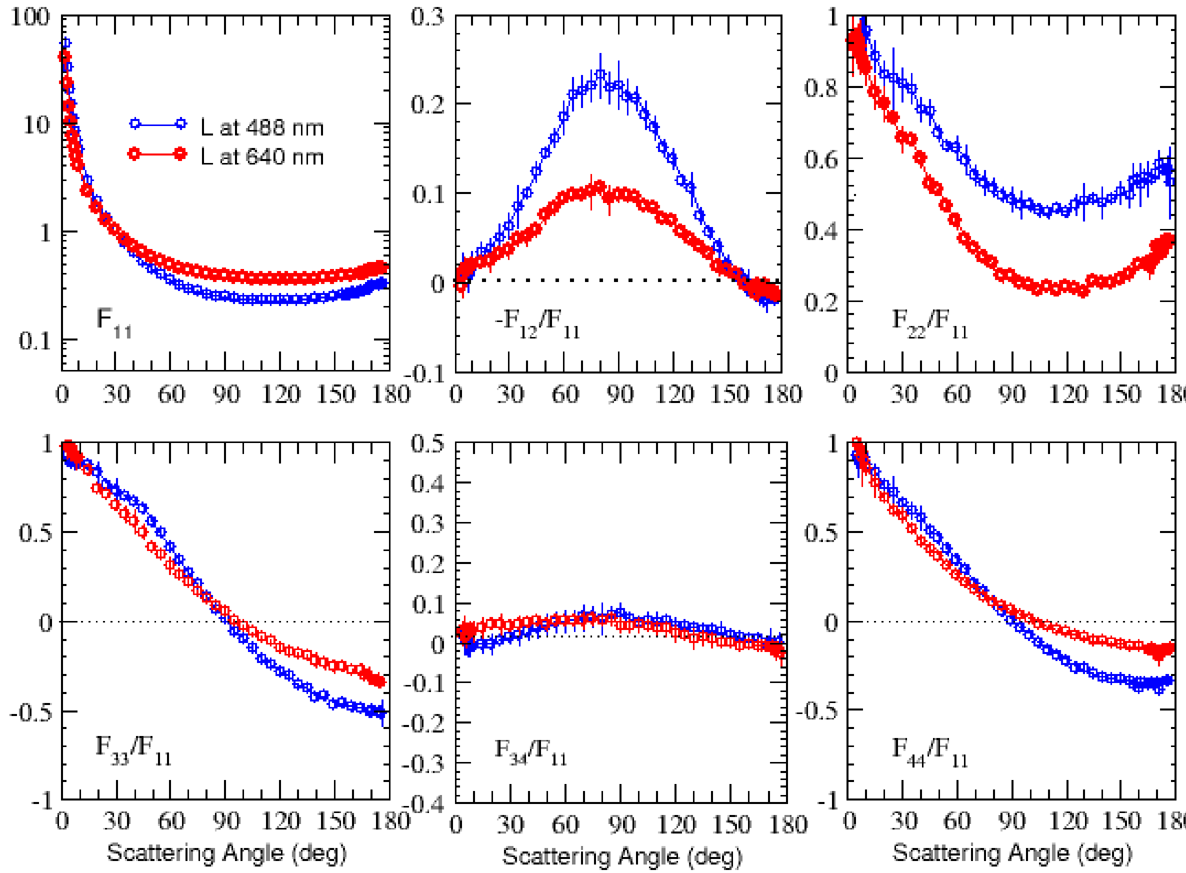


Scattering Matrices (refractive index effect) MMS2 L @488 and 640 nm

Refractive index effect: higher absorption at 488 nm

k(488 nm)=i1.1 E-03
k(640 nm)=i3.5 E-04

Martian analogue MMS2
L reff= **16.15** μm; σeff=0.34



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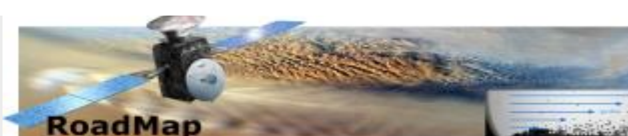
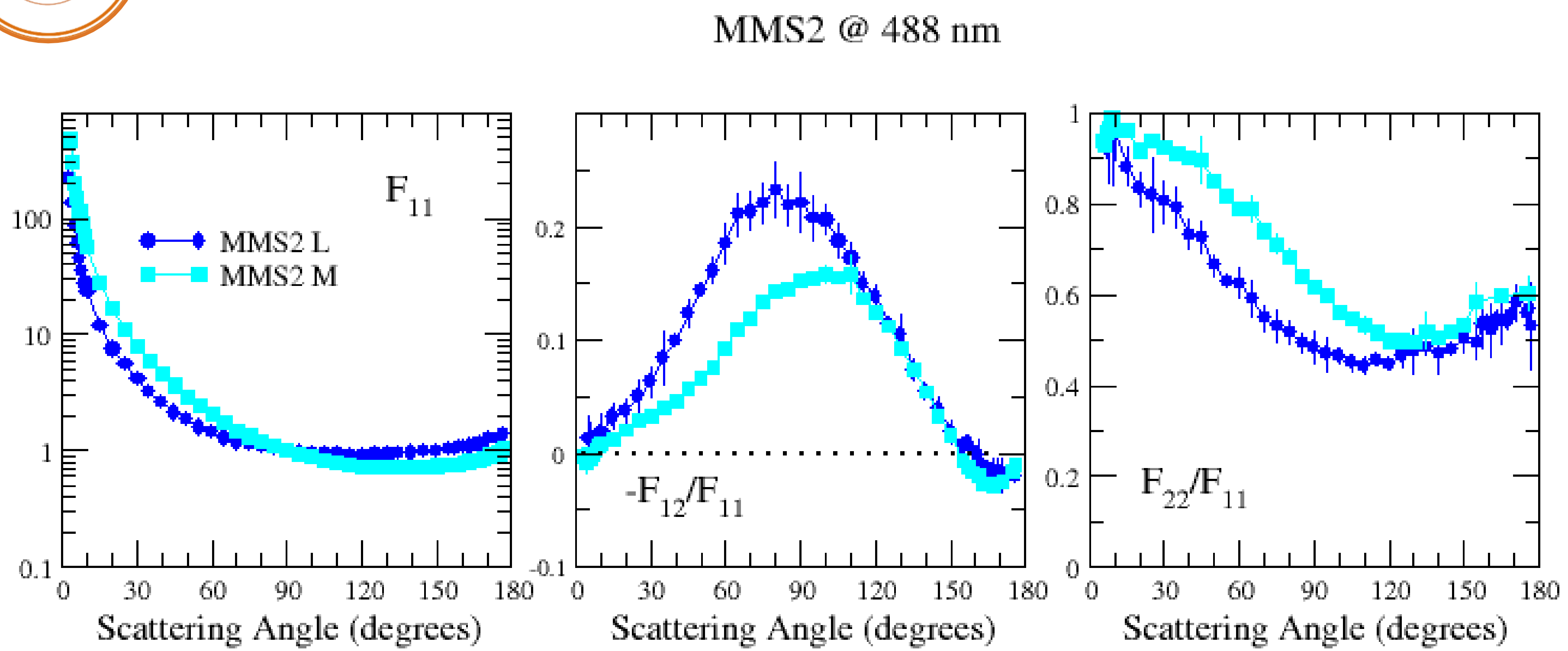


Scattering Matrices (size effect)
MMS2 @488 nm



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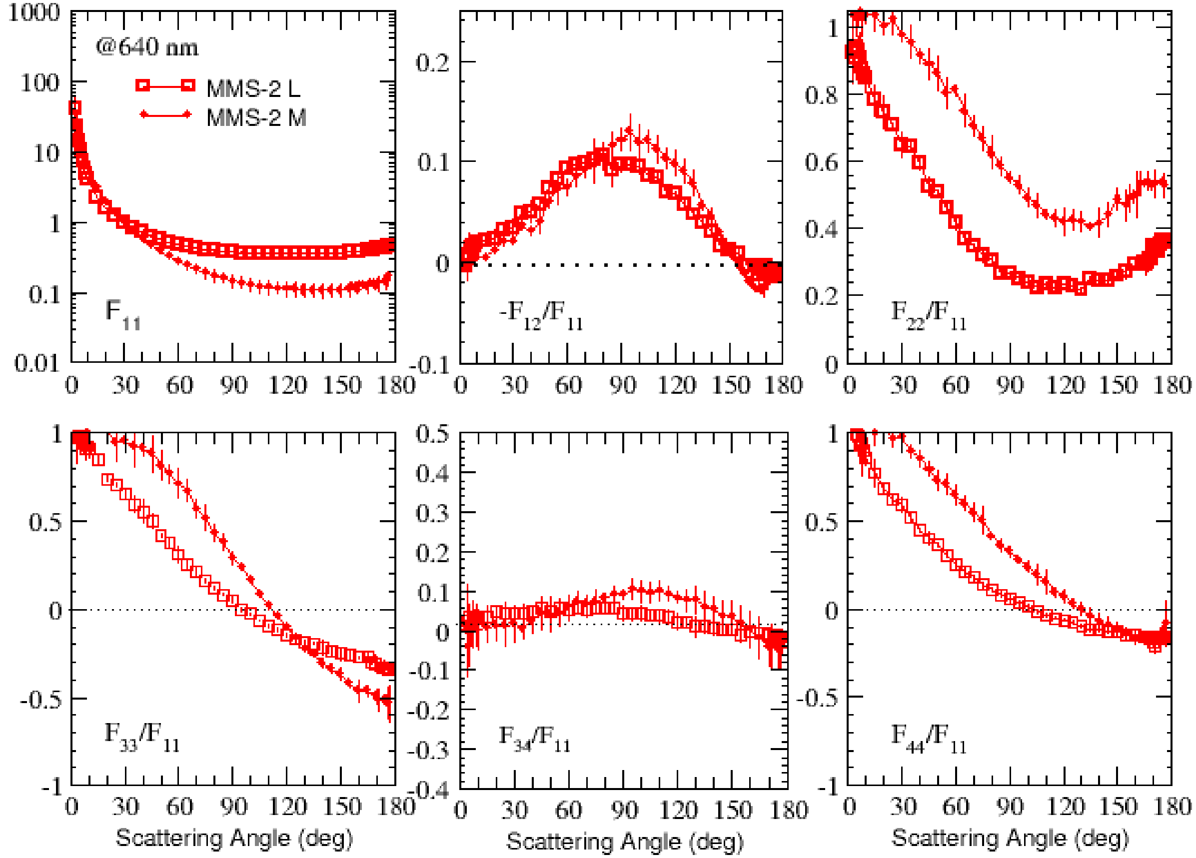
Scattering Matrices (size effect) MMS2 L & M @640 m



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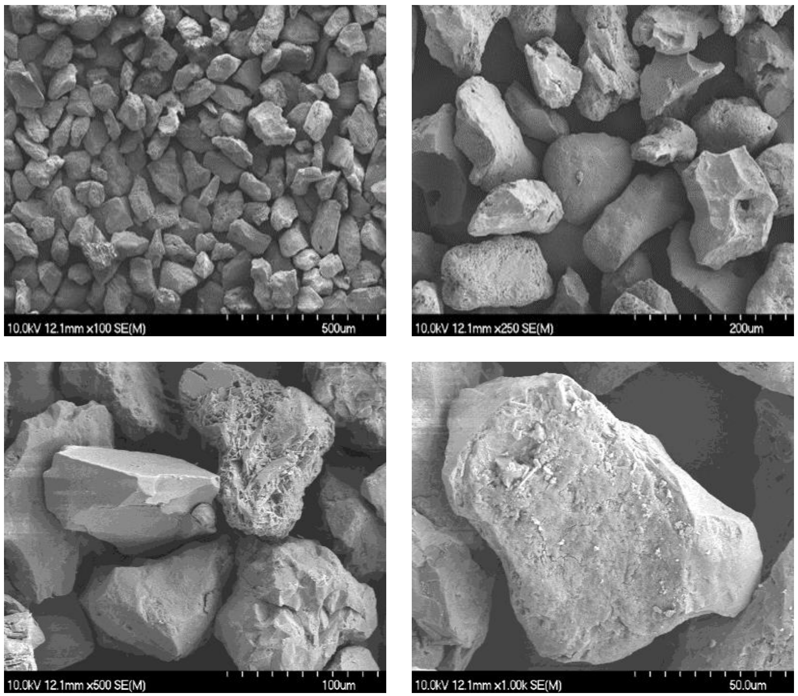
SPHERICAL MODEL vs MARTIAN DUST



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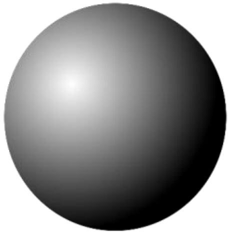

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SPHERICAL MODEL vs dust

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SPHERICAL MODEL vs dust

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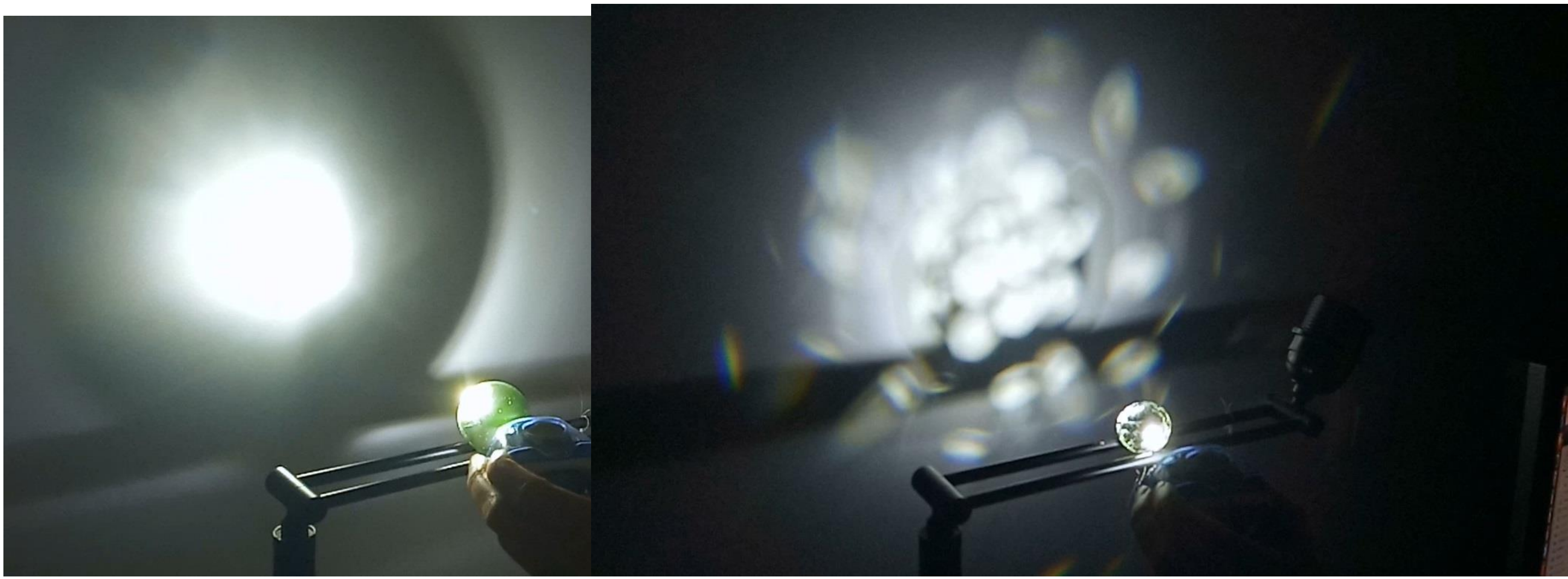
SPHERICAL MODEL vs dust



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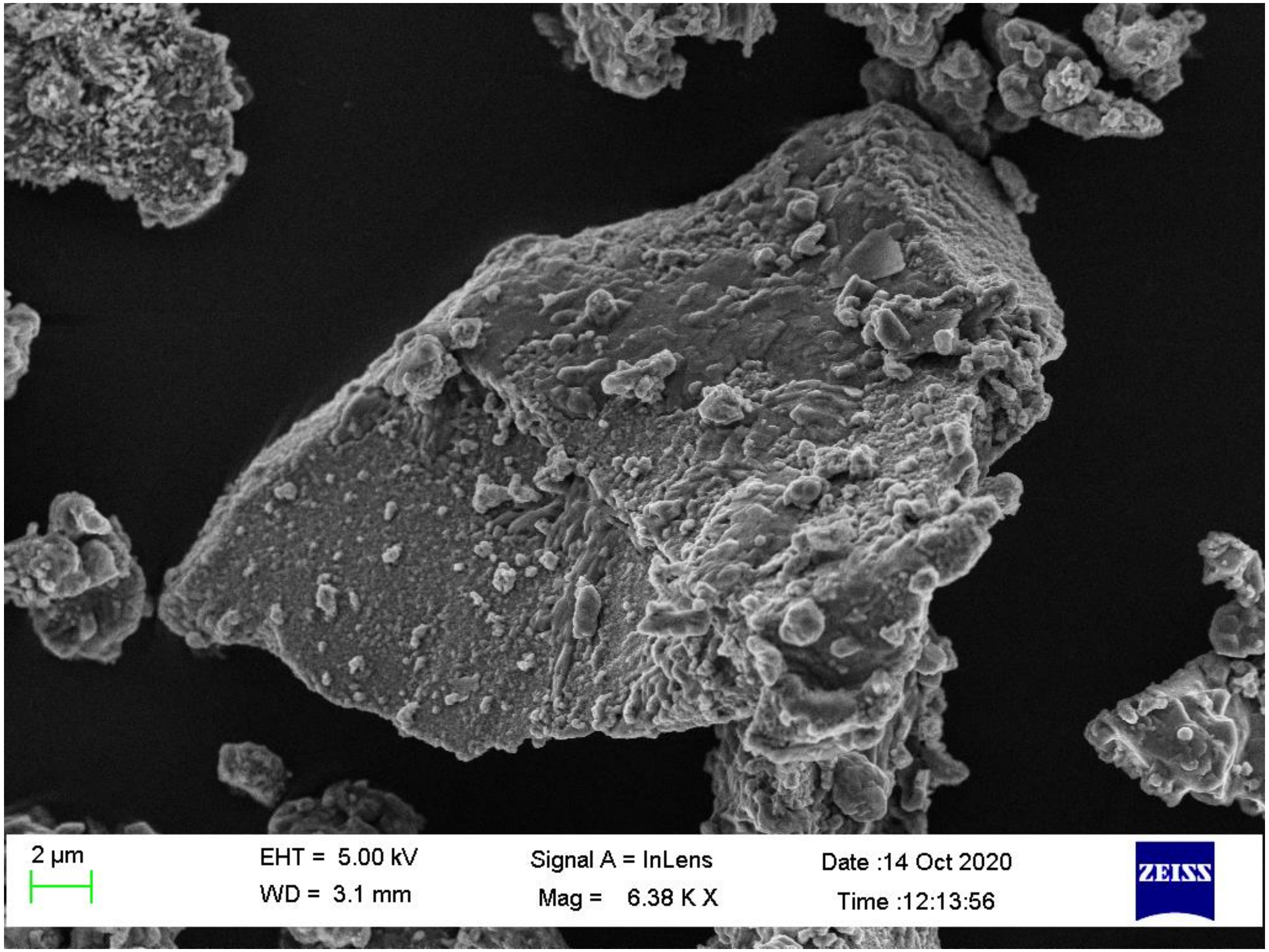
Martian Dust



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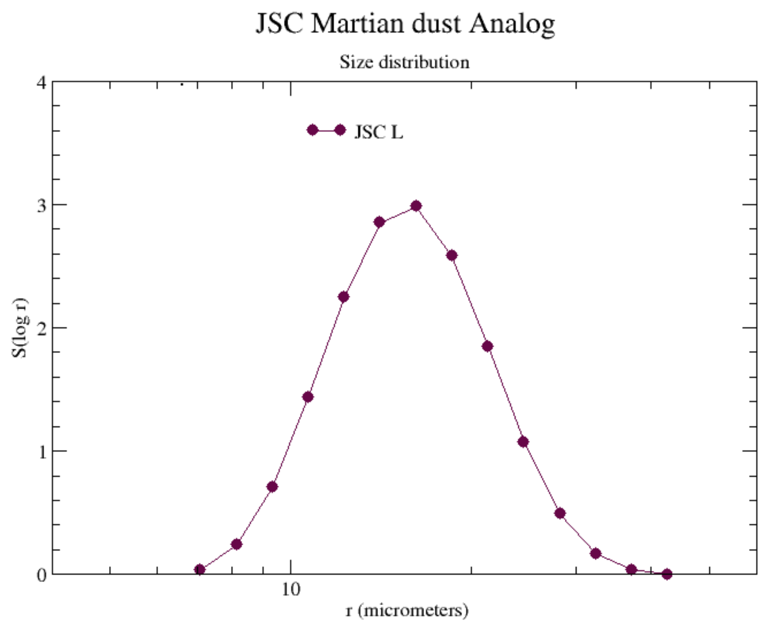
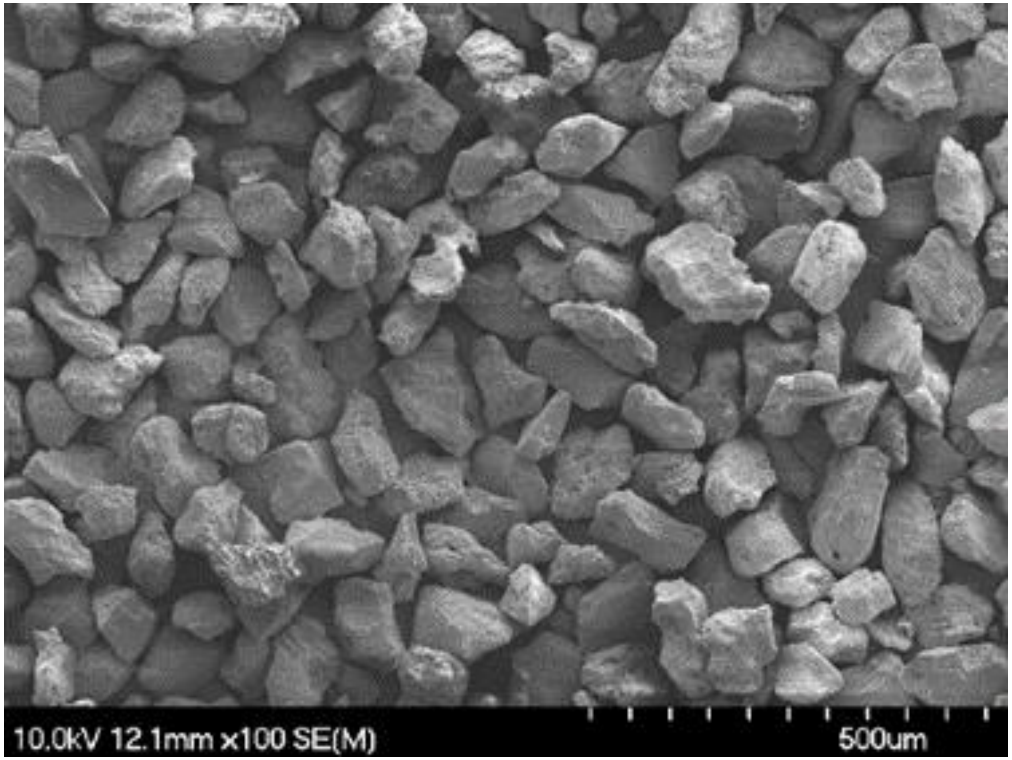
Testing the Spherical model (JSC L)





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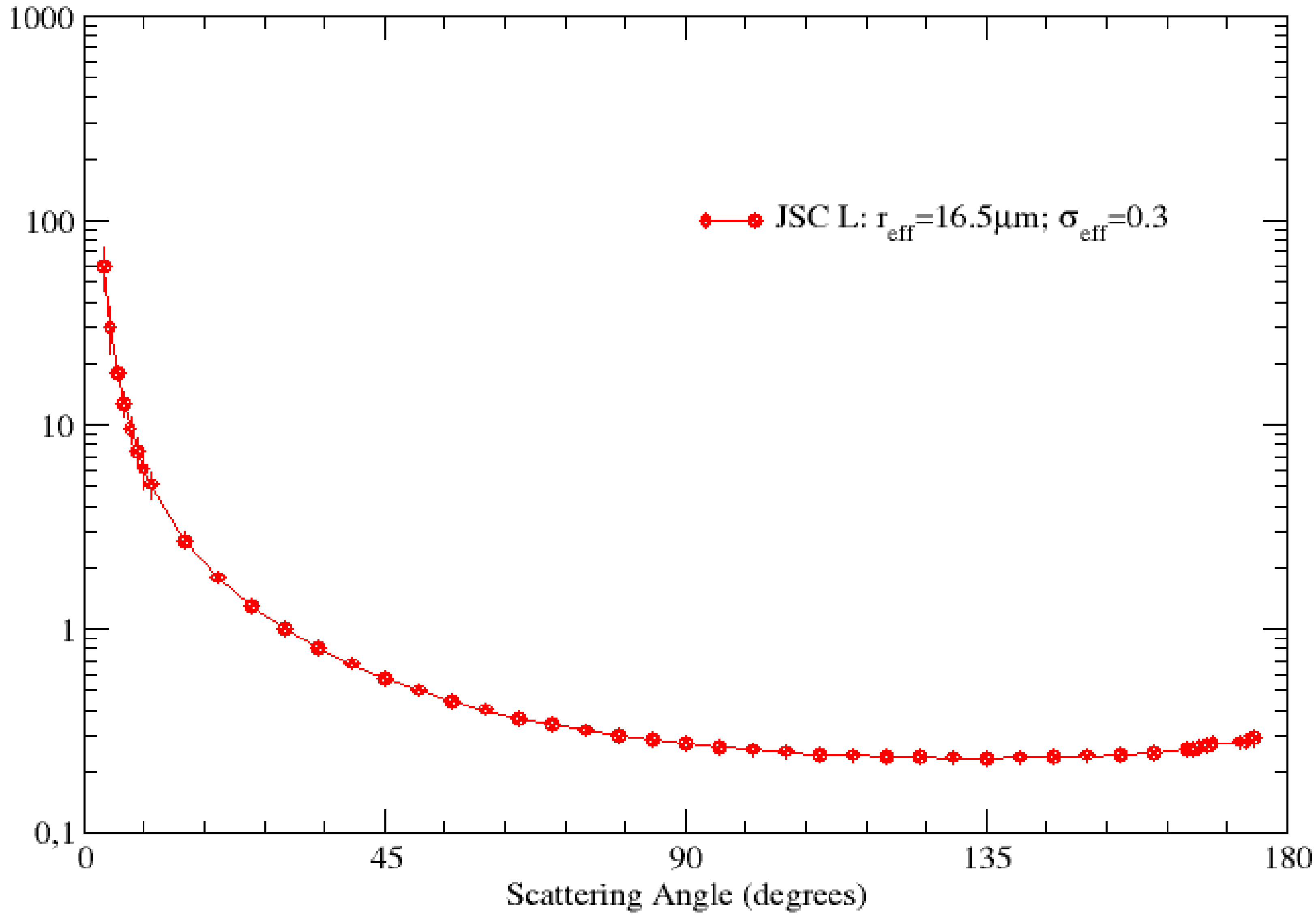
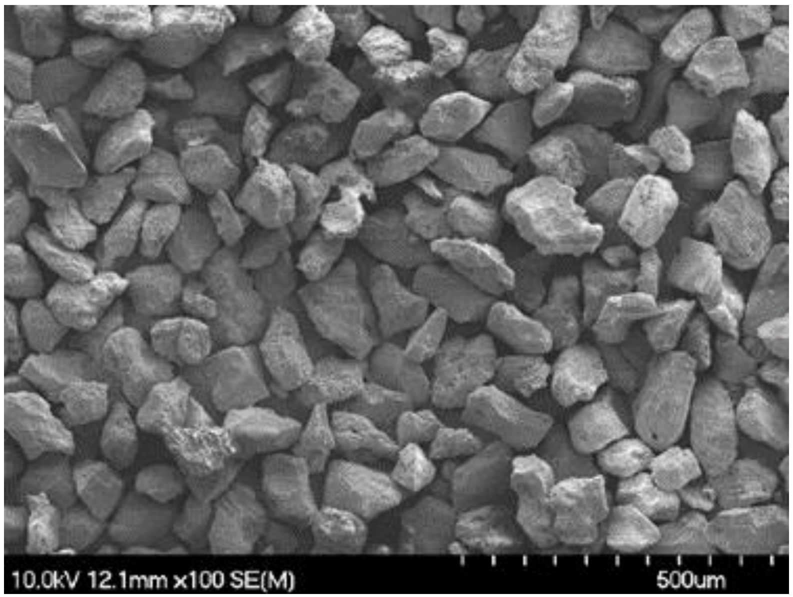
Phase Function JSC1 L @640 nm



Testing the Spherical model vs Martian dust



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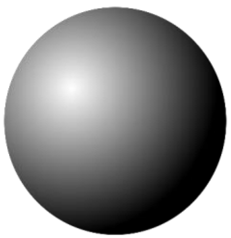

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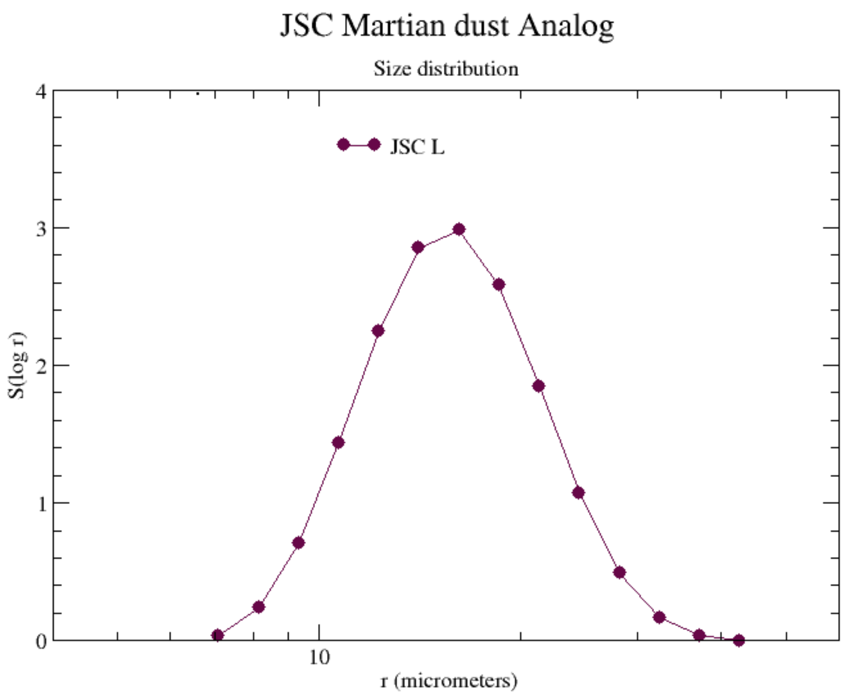
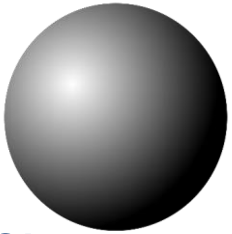
Testing the Spherical model (JSC L)



JSC m(640 nm)=1.6+ i6.5E-04



Mie model inputs:

SD JSC L sample

Refractive indez JSC sample

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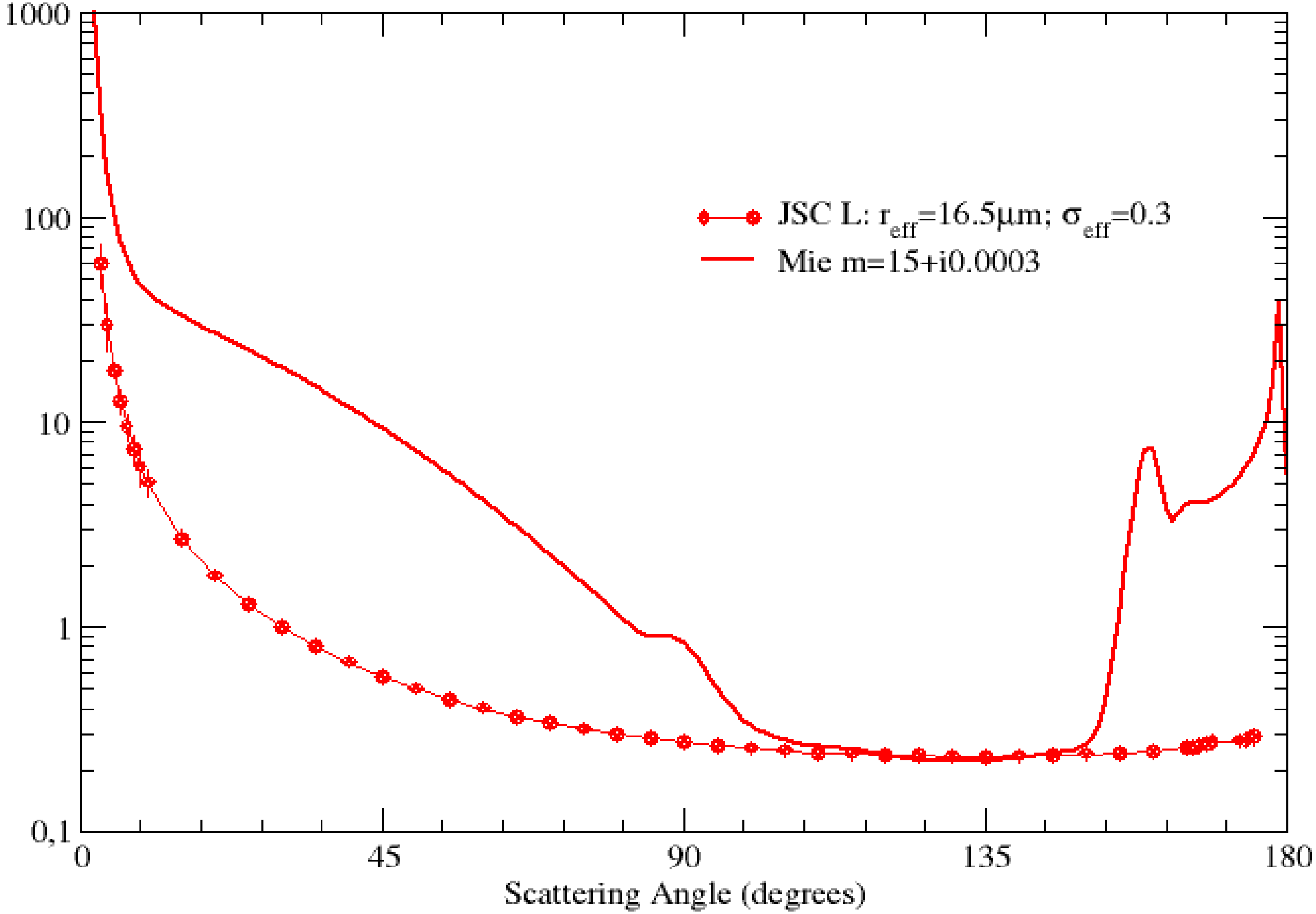
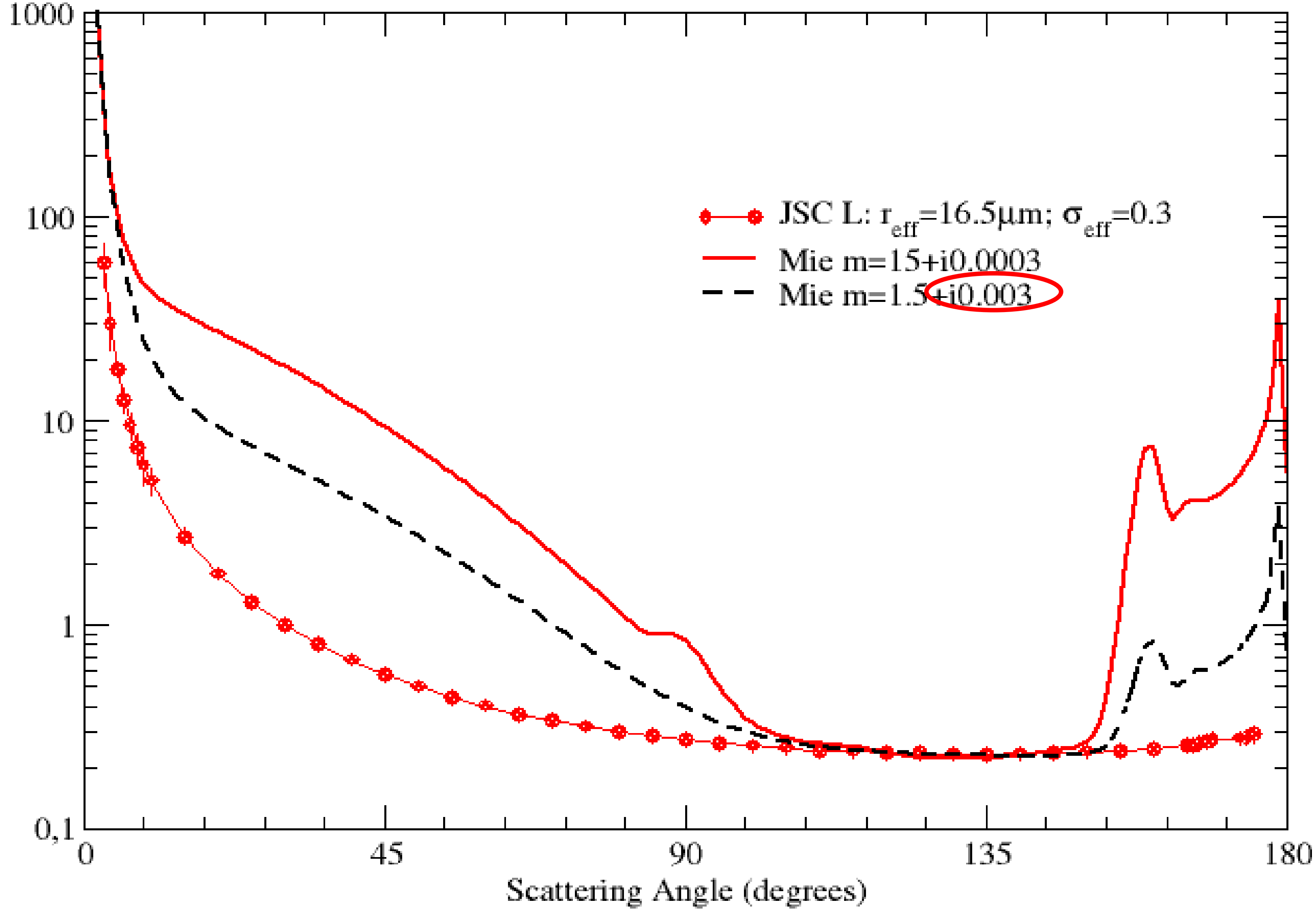
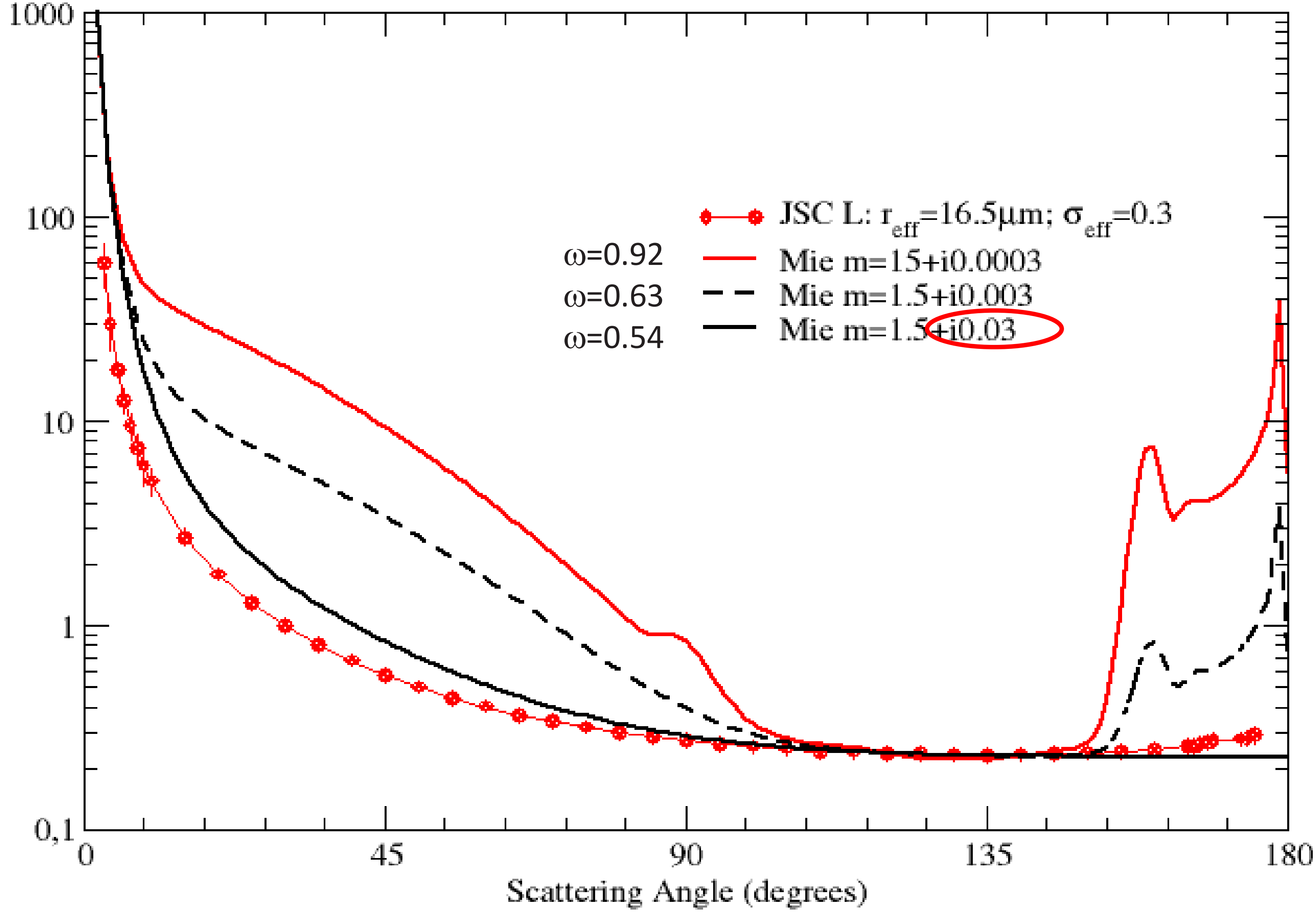
PF JSC1 L + Mie Computations @640 nm



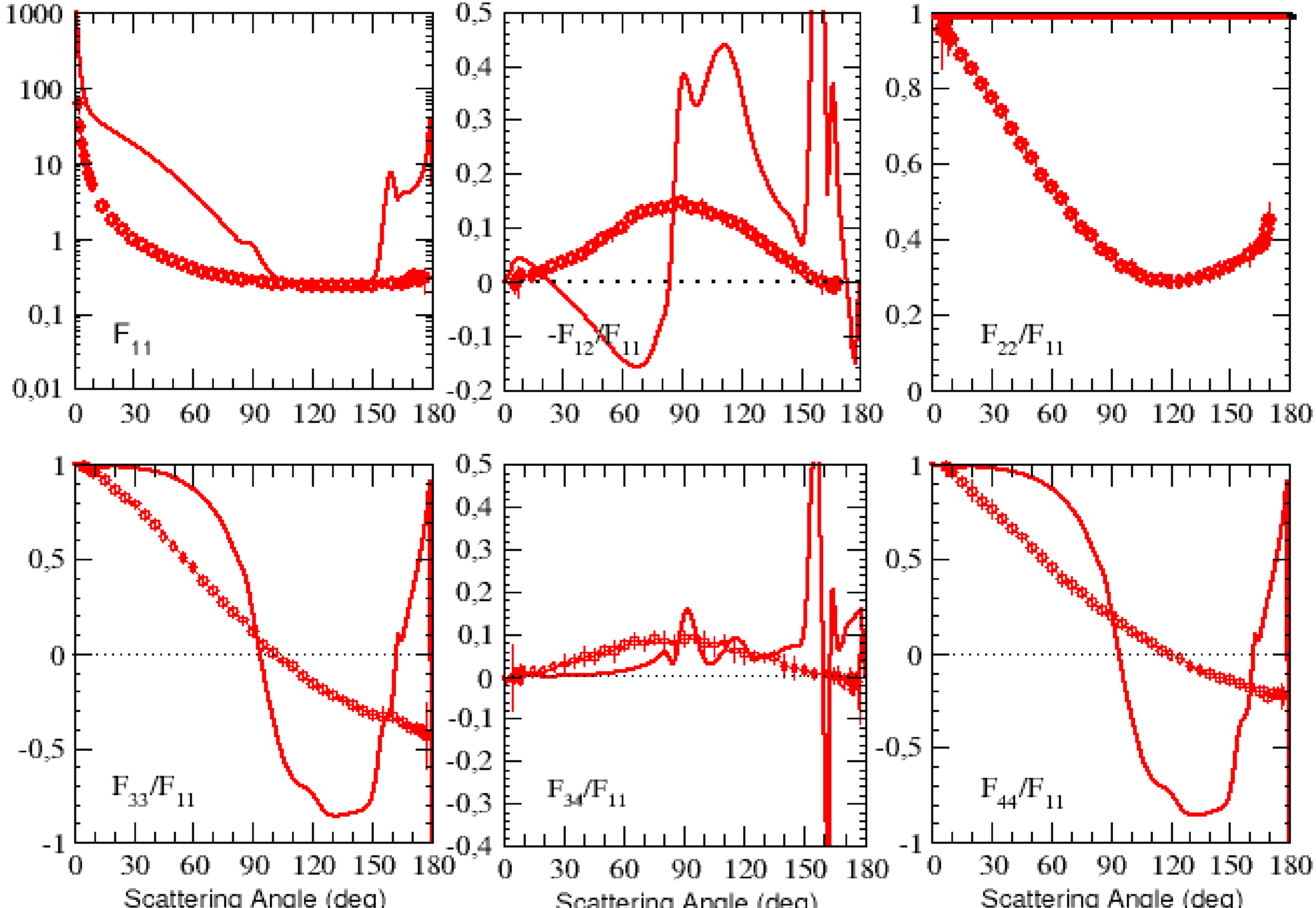
PF JSC1 L + Mie Computations



JSC1 L + Mie computations @640 nm



JSC1 L + Mie Computations @640 nm



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/