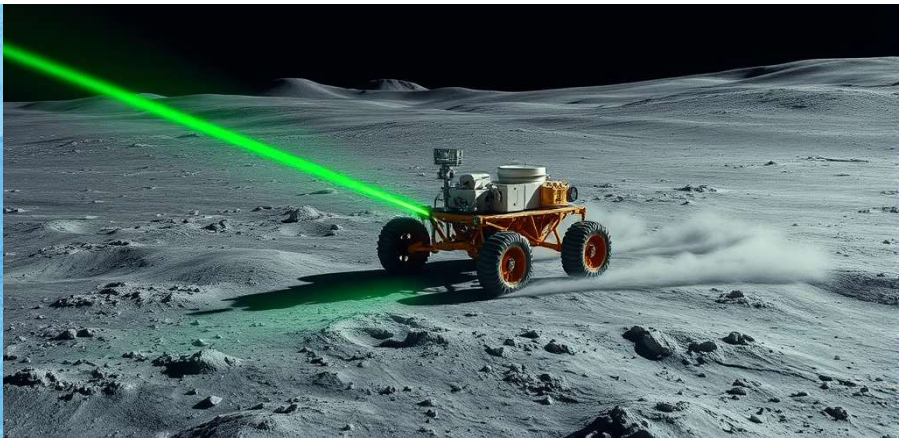
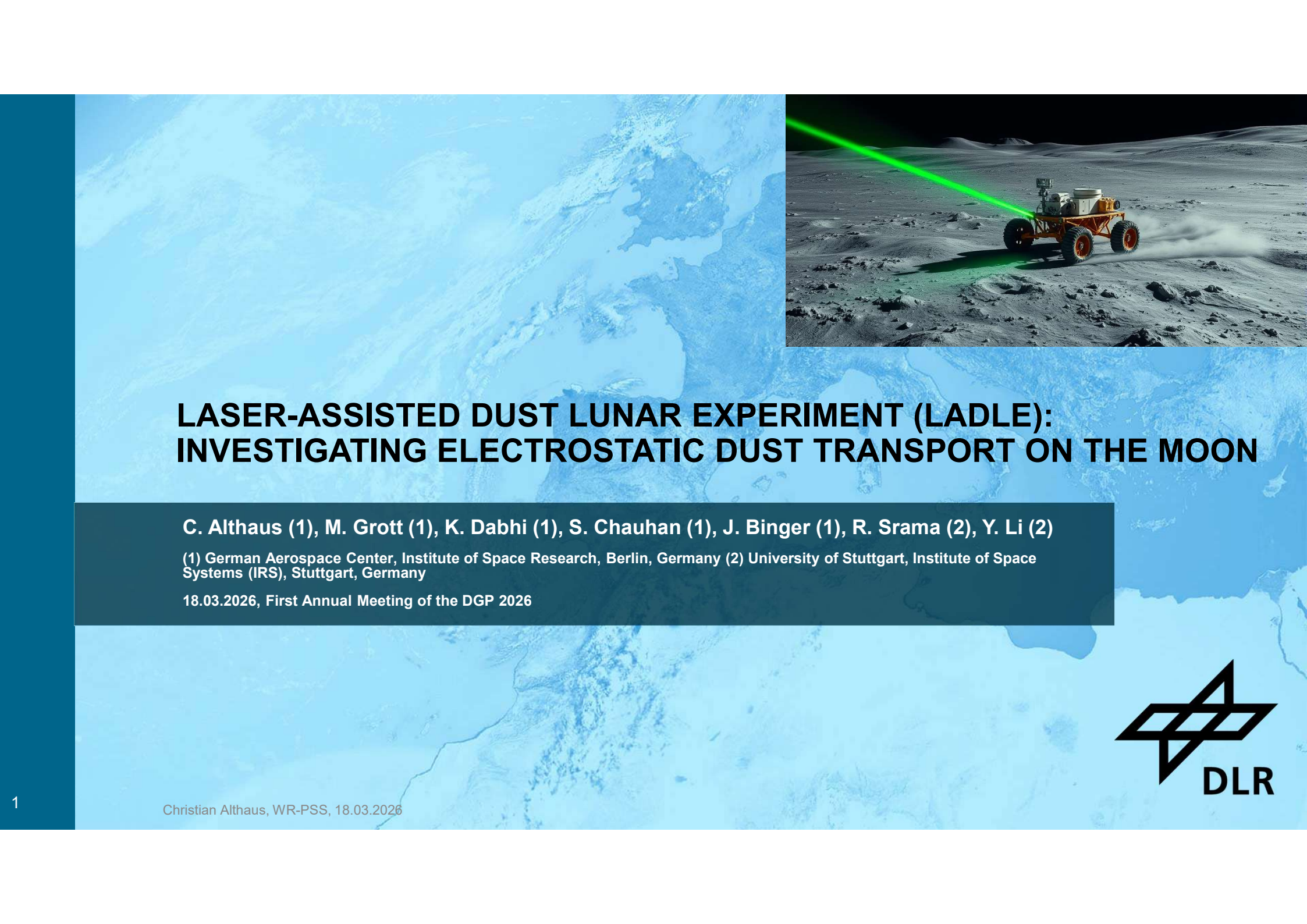




LASER-ASSISTED DUST LUNAR EXPERIMENT (LADLE): INVESTIGATING ELECTROSTATIC DUST TRANSPORT ON THE MOON

C. Althaus (1), M. Grott (1), K. Dabhi (1), S. Chauhan (1), J. Binger (1), R. Srama (2), Y. Li (2)

(1) German Aerospace Center, Institute of Space Research, Berlin, Germany (2) University of Stuttgart, Institute of Space Systems (IRS), Stuttgart, Germany

18.03.2026, First Annual Meeting of the DGP 2026

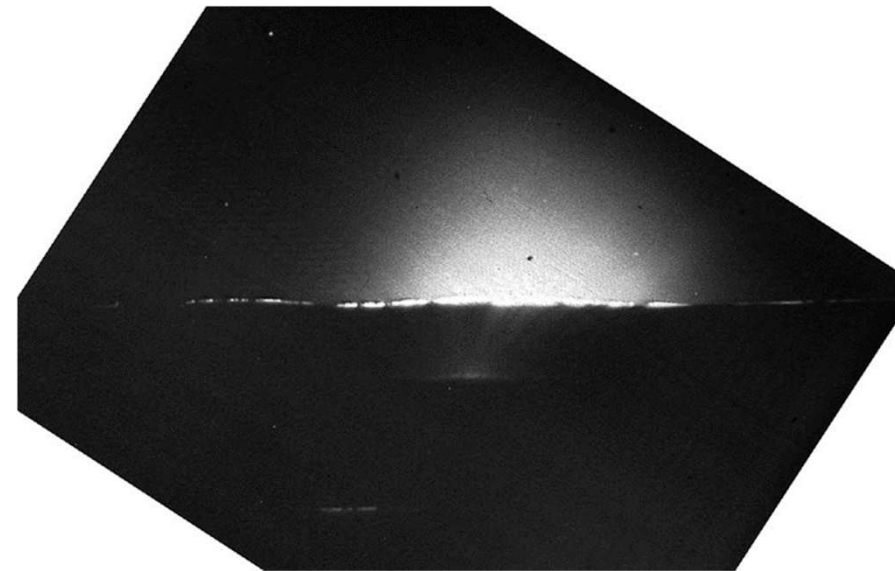


Lunar Regolith and Dust

- Lunar regolith : loose deposit of rock (Si, Fe, O₂)
- ranges from large boulders to ultrafine dust, < 1 cm in size.
- finest components < 20 micron make up Lunar dust environment
- HORIZON GLOW (HG) at the terminator by Surveyor and Apollo missions
- HG is mainly because of forward scattering of sunlight
- Dust is abrasive, sticky, health risky, technology threat
 - critical for instruments, vehicles, humans
 - dynamics not understood



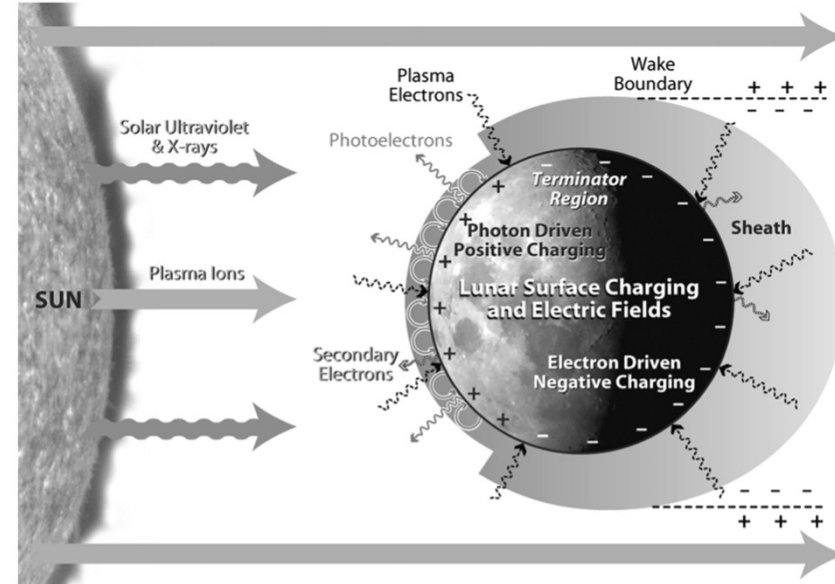
Footprint of Buzz Aldrin in Lunar Regolith
(Credits: NASA Public Domain)



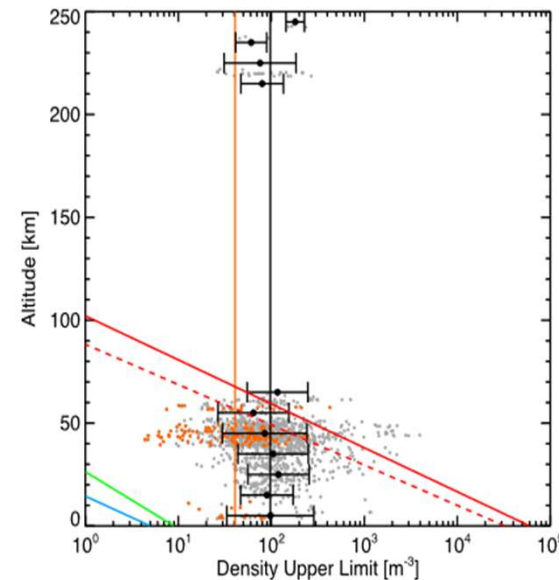
Surveyor 6 image showing a glow on the western lunar horizon after sunset (Credits: NASA Public Domain)

Lunar Dust: Charging Mechanisms

1. photoemission of electrons by UV rays and light X-rays
2. plasma electrons and ions
3. secondary electrons
4. electrons and ions of magnetosphere plasma (variable)
 - Clementine – 1 / m³ # density
 - LDEX (LADEE) – 100 / m³ # density
 - LADEE did not find dust levitation at 20-60 km (ballistic ejecta, interplanetary meteoroids)
 - Chang'E-3: ~ 28 cm (no dust at higher altitudes)

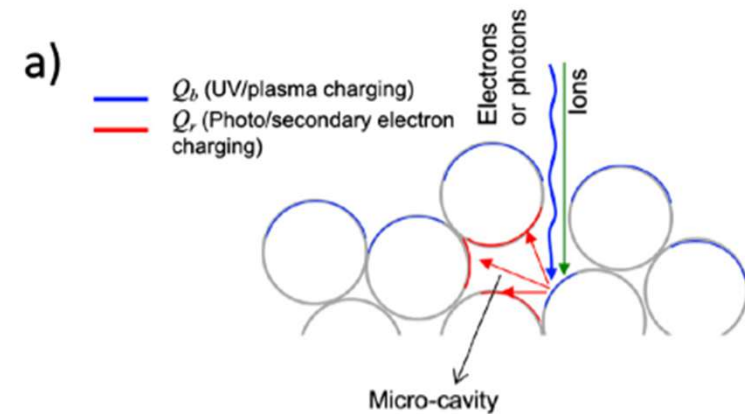
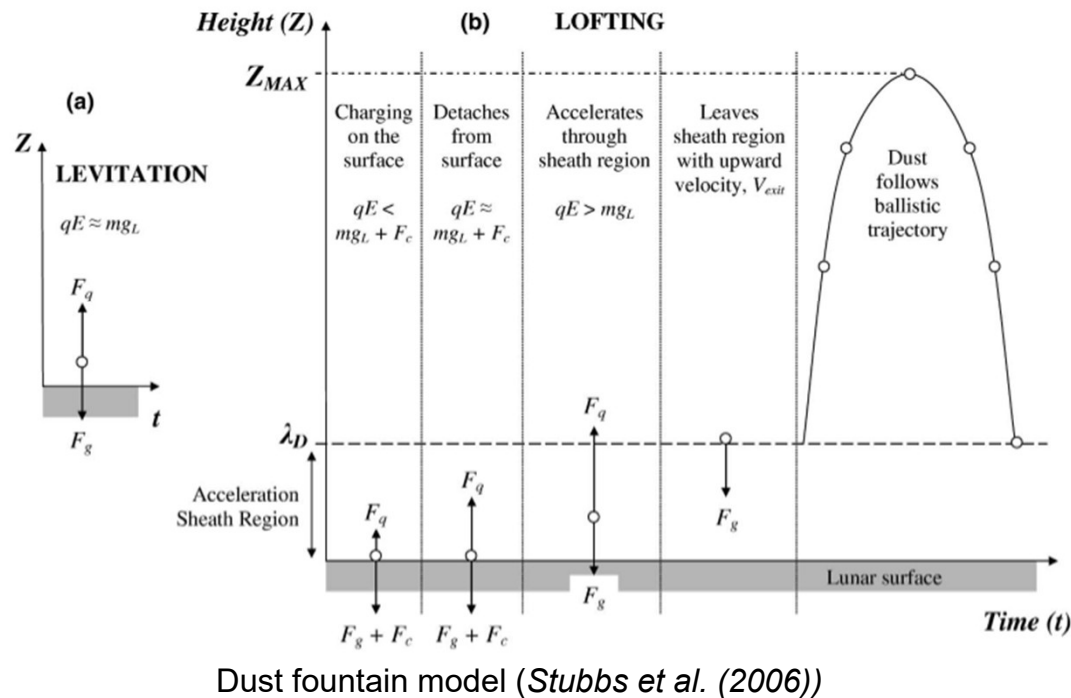


Lunar Surface Charging (Stubbs et al. (2014))



Number Density of Dust Particles measured by LDEX (Horiyani, Szalay (2015))

Dust Lofting Mechanism



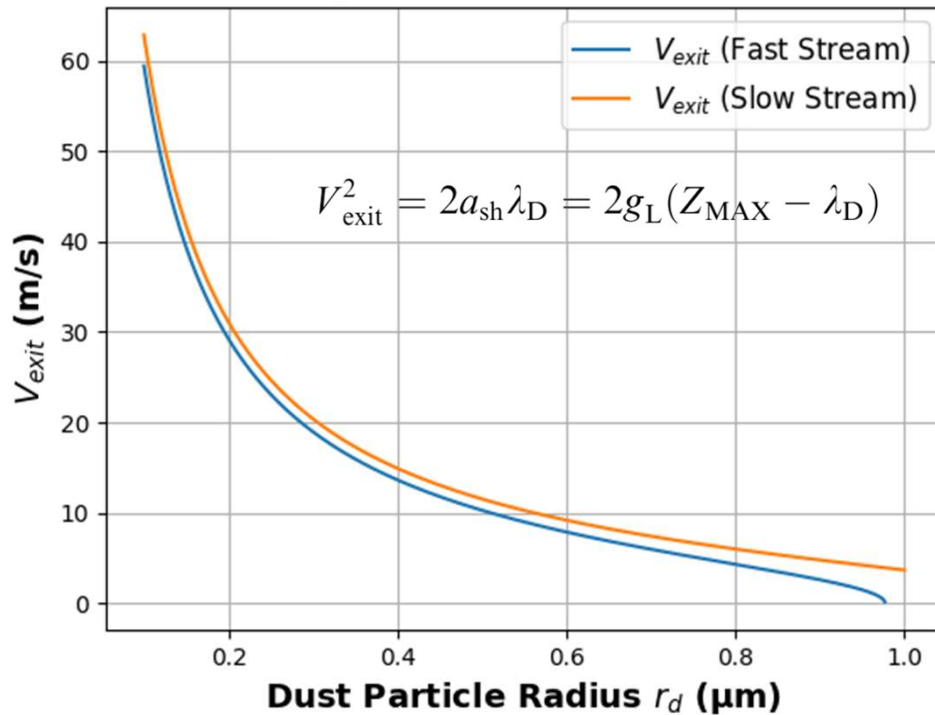
Patched charge model (Wang et al. 2016)

- dust fountain model explains the levitation simplified, but well enough for a 1st order assessment
- 'Coulomb Explosions' makes initial lift-off happen

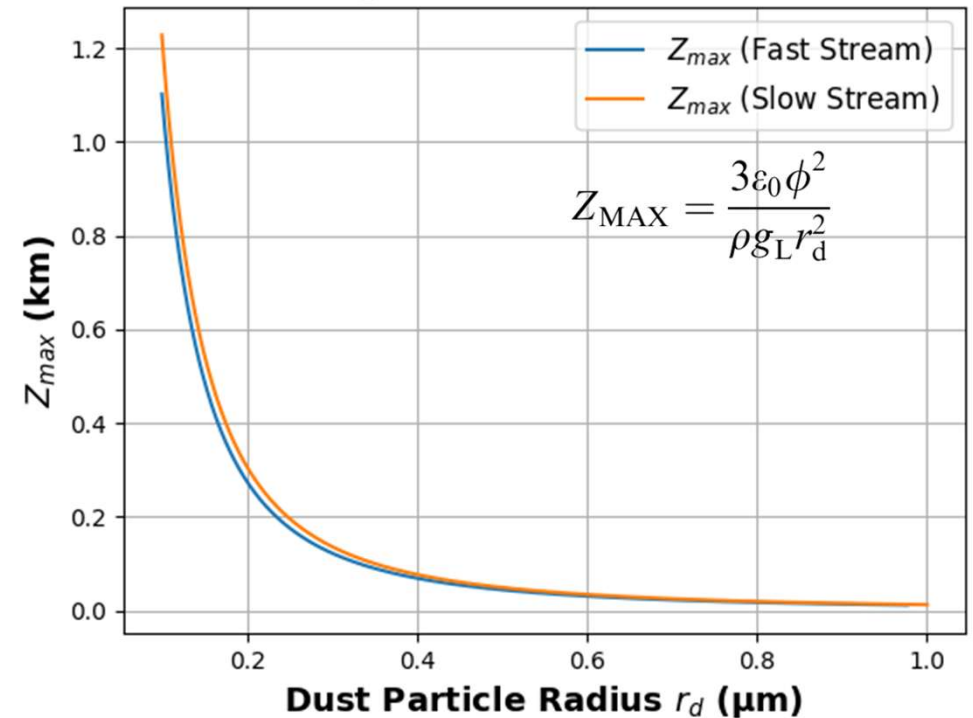
Dynamic behaviour of dust particles



Exit Velocity of Dust Particles vs. Radius



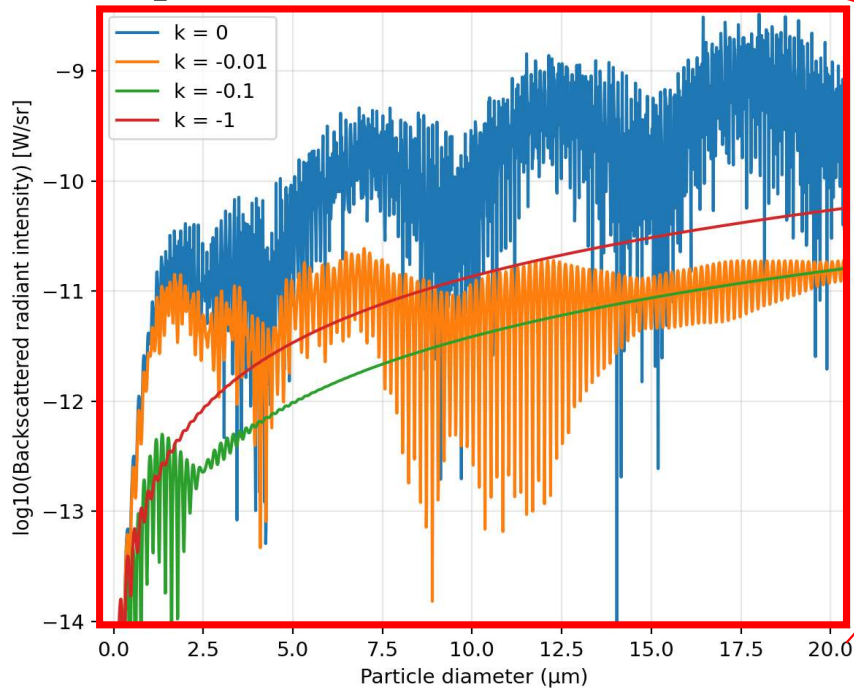
Maximum Height of Dust Particles vs. Radius



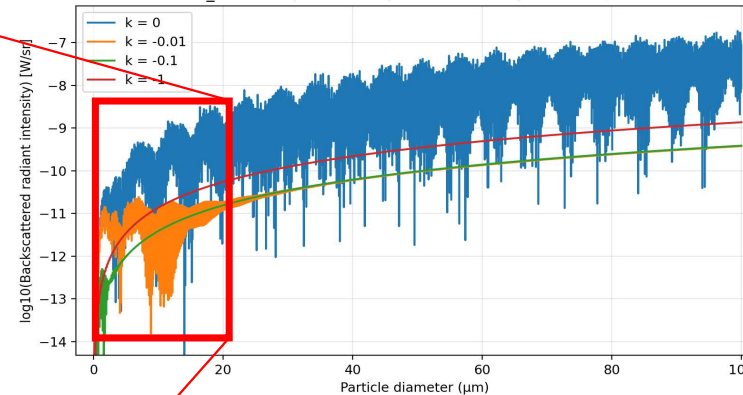
- μm sized particles are accelerated in the Debye sheet to velocities of $< 10 \text{ m/s}$
- the heights they reach are up to 50 m, and significantly lower for particles larger than some μm

Dust Backscattering – Mie Theory

Backscattered radiant intensity vs diameter (constant irradiance
 $n_{\text{real}}=1.56$, $\lambda=532$ nm, medium $n=1.0$, $E_0=1.0$ W/m²)



Backscattered radiant intensity vs diameter (constant irradiance
 $n_{\text{real}}=1.56$, $\lambda=532$ nm, medium $n=1.0$, $E_0=1.0$ W/m²)



Real lunar dust grains are **NOT** spherical.
Mie scattering is inaccurate. We
 present **more realistic “Irregular”**
 grains.

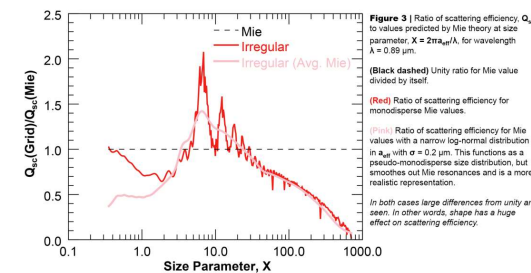
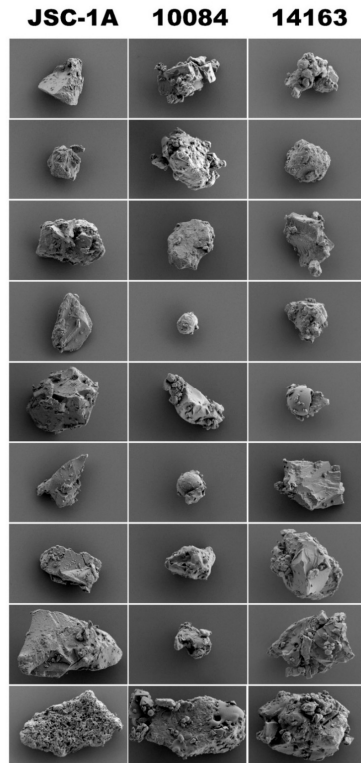


Figure 3 | Ratio of scattering efficiency, Q_{sc} , to values predicted by Mie theory at size parameter, $X = 2\pi a_{eff}/\lambda$, for wavelength $\lambda = 0.89$ μm .



Jay Goguen, Andrew Sharits, Ann Chiaramonti, Thomas Lafarge, Edward Garboczi (2024) *Three-dimensional characterization of particle size, shape, and internal porosity for Apollo 11 and Apollo 14 lunar regolith and JSC-1A lunar regolith soil simulant*

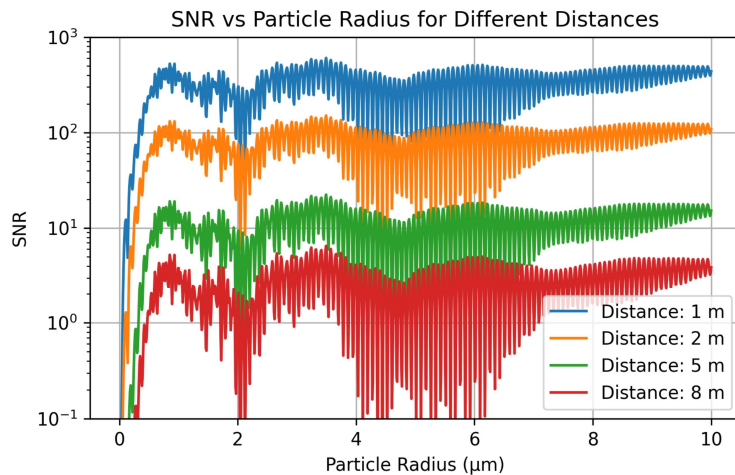
R. Lolachi, D.A. Glenar, T.J. Stubbs
 (2023)
*Optical monitoring of the dust
 environment at lunar surface
 exploration sites*

Camera Model and Signal Calculations

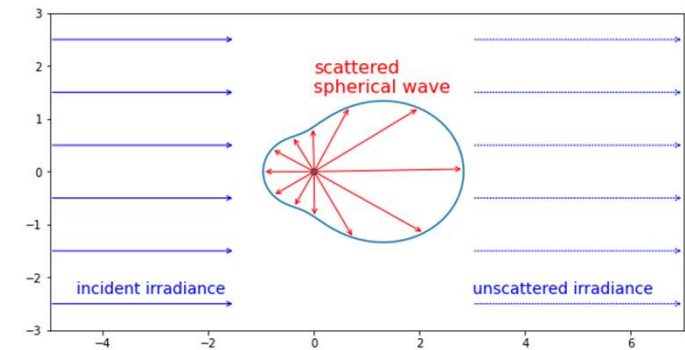
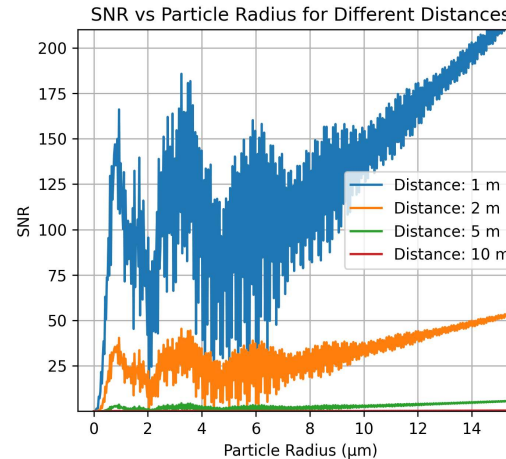
- SNR calculations were done for feasibility check
- Mie theory assumed for first assessment
- assuming a pulsed 0.1 mJ laser with full beam divergence of about 35 mrad
- SNR > 1 for particles larger 1 μm



Y-log scale



Y-linear scale



Credits: Scott Prahl/miepython

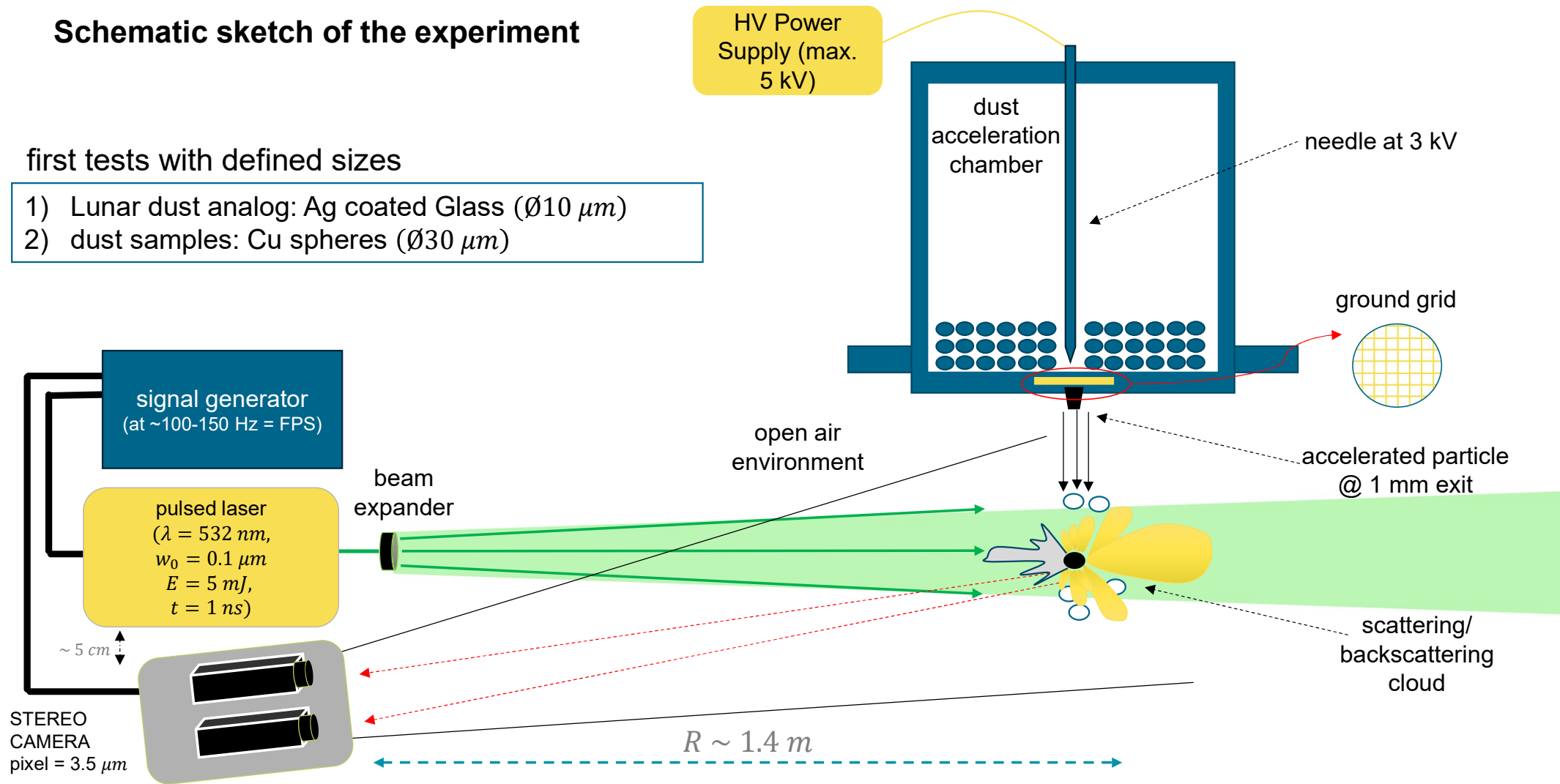
Assumptions for Mie Calculations

Refractive Index (lunar samples)	1.56 – 0.01j
Particle Radius	0.1 – 30 μm
Wavelength	532 nm
Scattering angle	-180 degree
Distance	1 – 10 m

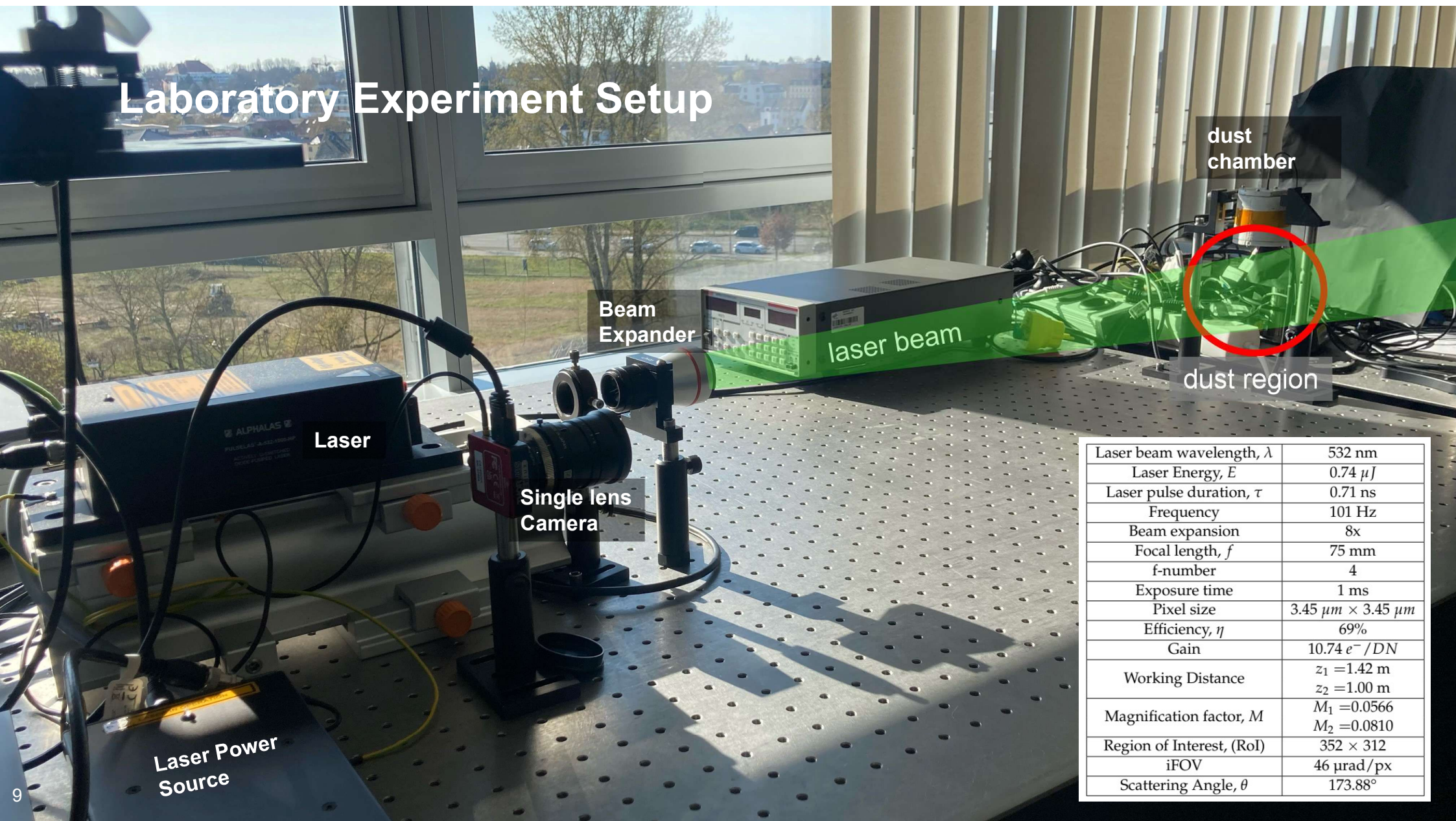
Schematic sketch of the experiment

first tests with defined sizes

- 1) Lunar dust analog: Ag coated Glass ($\varnothing 10 \mu m$)
- 2) dust samples: Cu spheres ($\varnothing 30 \mu m$)



Laboratory Experiment Setup

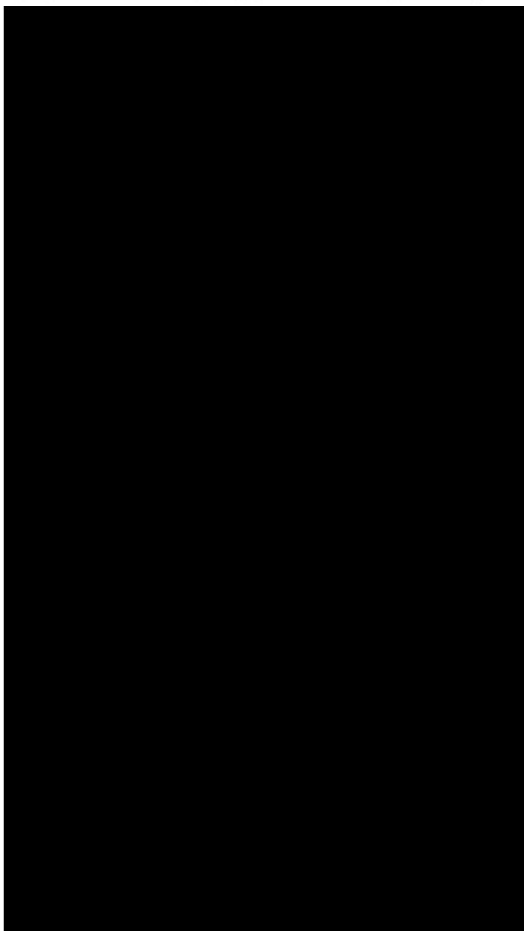


Laser beam wavelength, λ	532 nm
Laser Energy, E	$0.74 \mu\text{J}$
Laser pulse duration, τ	0.71 ns
Frequency	101 Hz
Beam expansion	8x
Focal length, f	75 mm
f-number	4
Exposure time	1 ms
Pixel size	$3.45 \mu\text{m} \times 3.45 \mu\text{m}$
Efficiency, η	69%
Gain	$10.74 e^- / \text{DN}$
Working Distance	$z_1 = 1.42 \text{ m}$ $z_2 = 1.00 \text{ m}$
Magnification factor, M	$M_1 = 0.0566$ $M_2 = 0.0810$
Region of Interest, (RoI)	352×312
iFOV	$46 \mu\text{rad}/\text{px}$
Scattering Angle, θ	173.88°

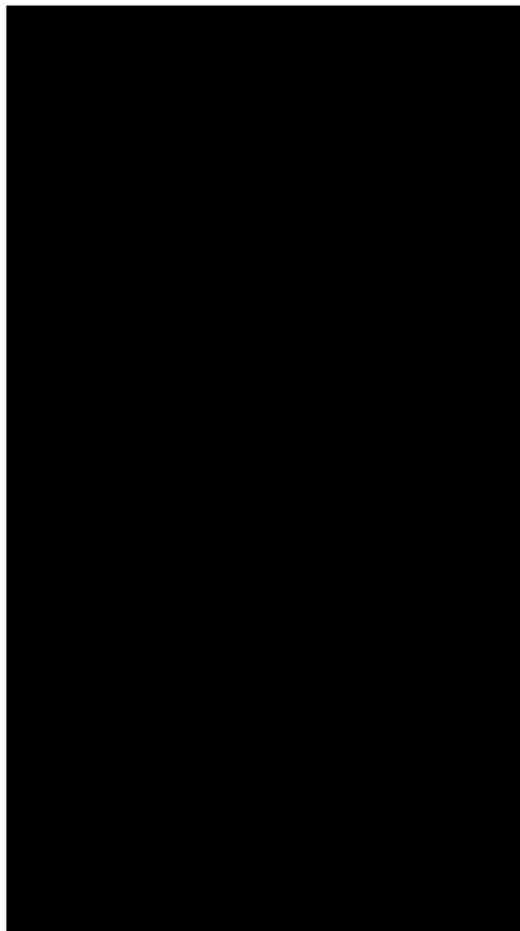
Laboratory Experiment Examples



(a) Silica (Ag coated) $10\ \mu\text{m}$



(b) Copper $30\ \mu\text{m}$



Camera settings

Detector Resolution	1080 x 1440
ROI	312 x 352

Frames per second	100
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Exposure time	1.6 ms
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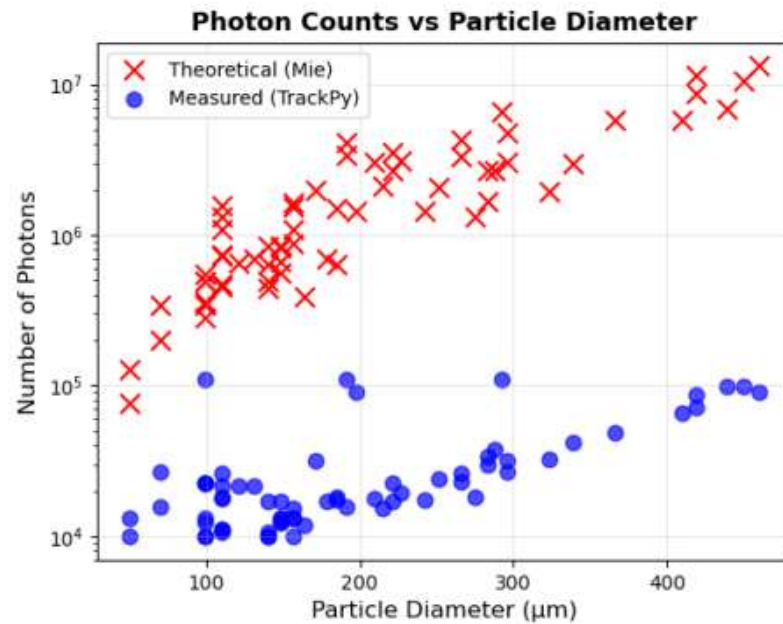
Gain	0
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Triggering	Hardware
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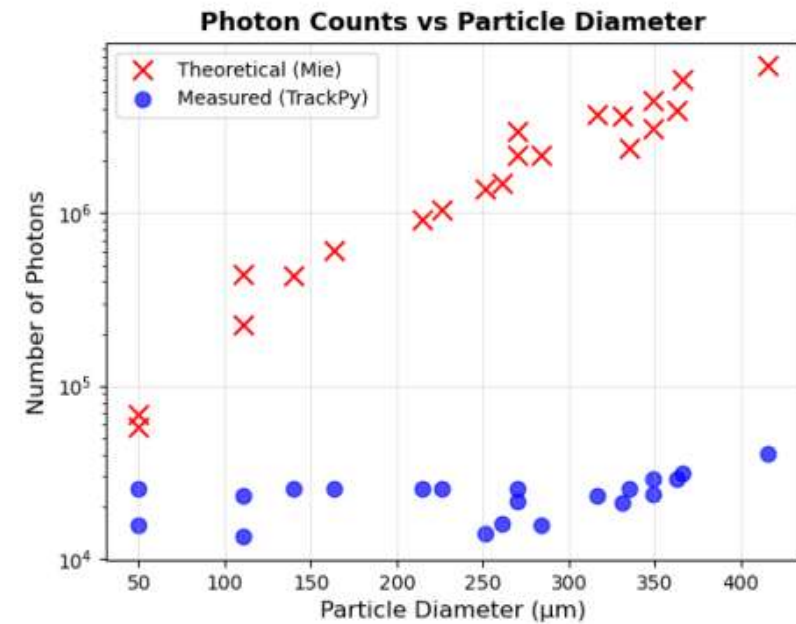
Pixel pitch	$3.5\ \mu\text{m}$
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Magnification	0.06
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Backscattering Results



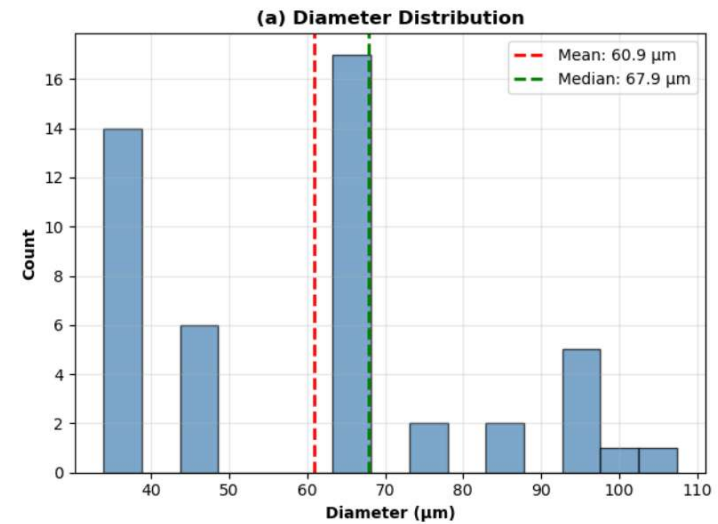
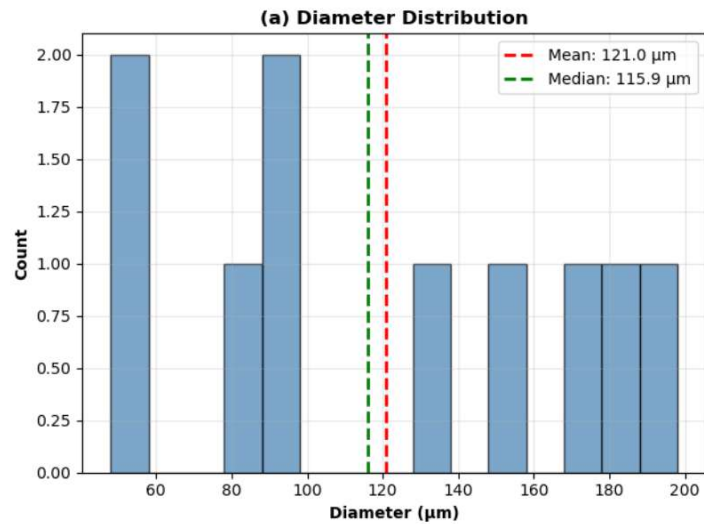
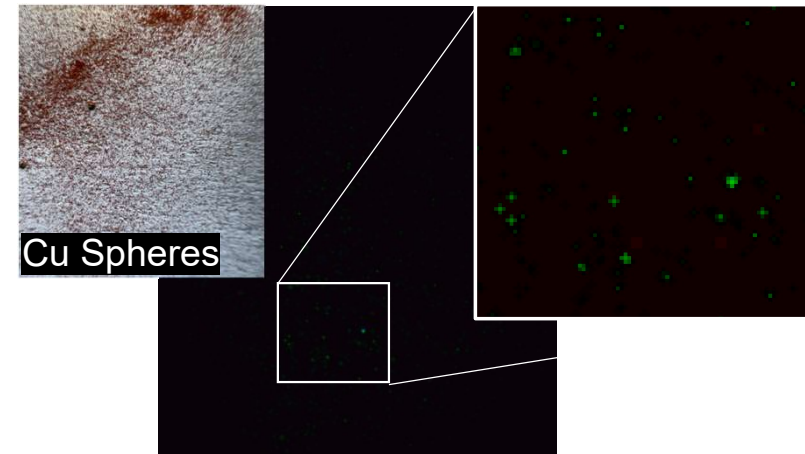
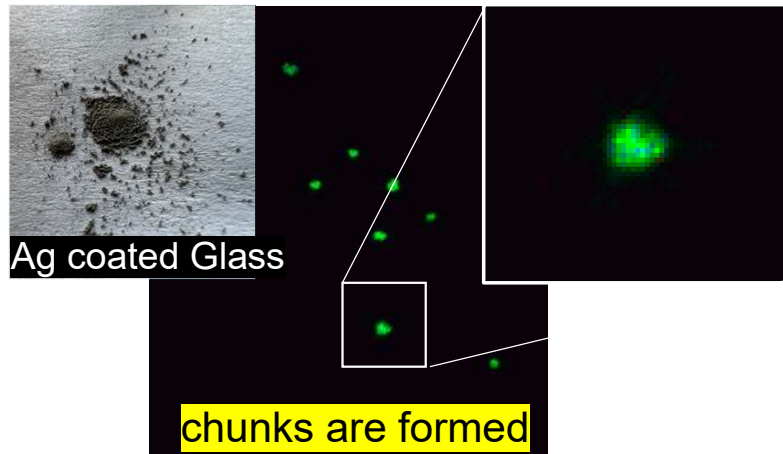
(a) Silica (Ag coated) 10 μm



(b) Copper 30 μm

Figure 3.12: Comparison of Theoretical and Recorded number of photons back at the detector $z = 1.42 \text{ m}$

Particle Statistics

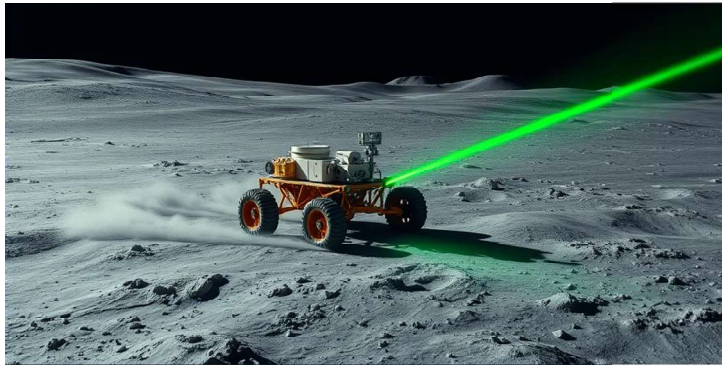


(a) Silica 10 μm

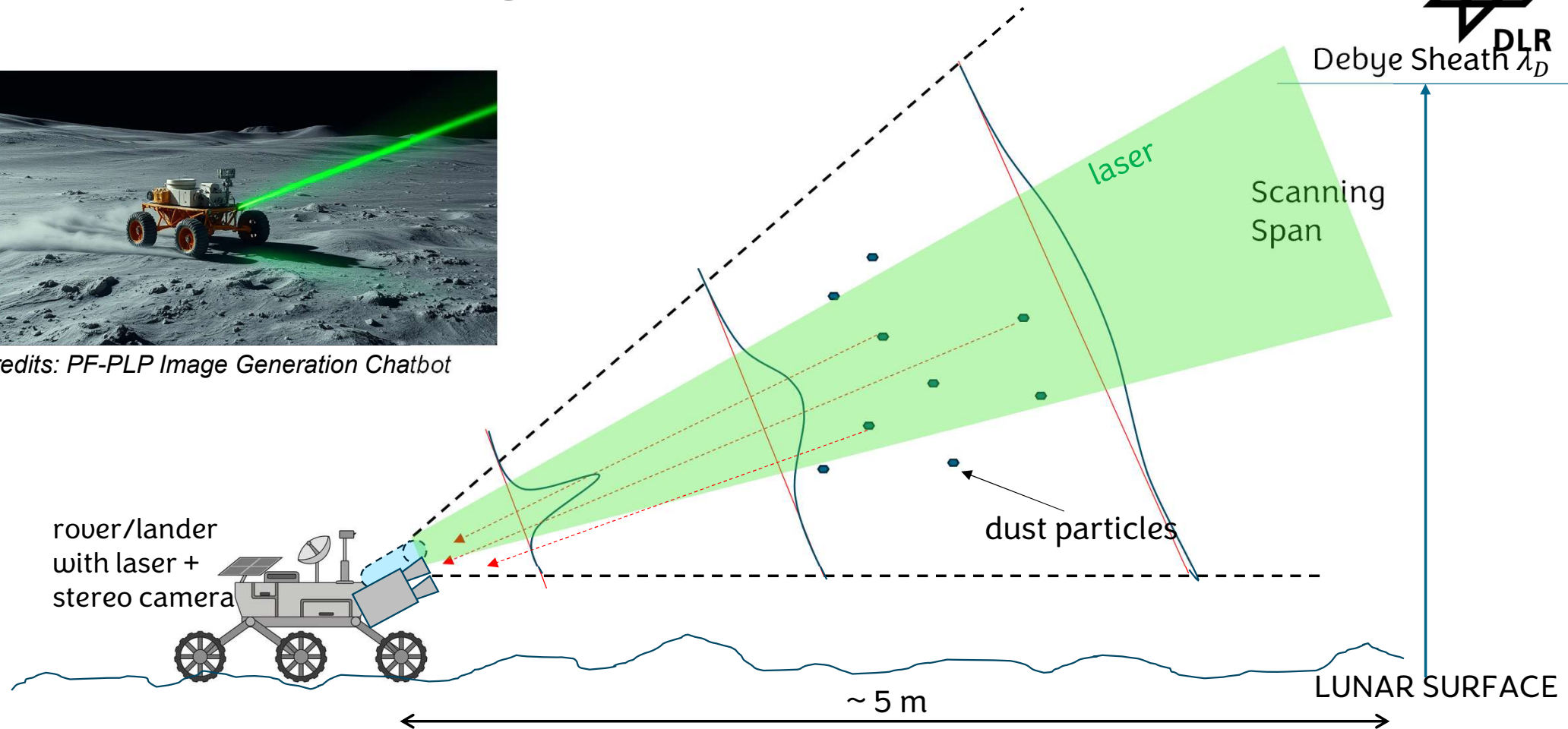
$z = 1.0 \text{ m}$

(b) Copper 30 μm

Visual of laser scattering with dust particles on Lunar surface



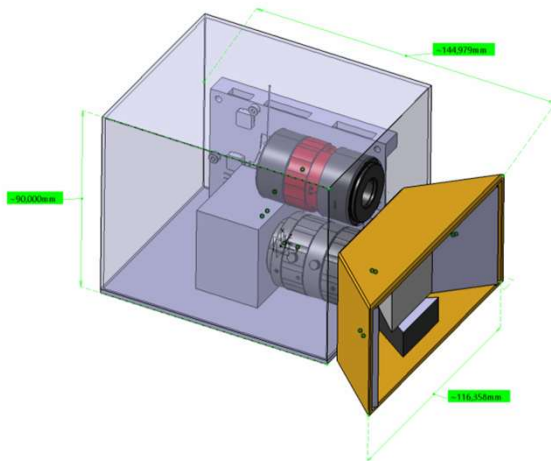
Credits: PF-PLP Image Generation Chatbot



Key Parameters of a model payload

Parameter

Parameter	Value	Unit
f	~25	mm
f/#	> 5.6	-
FOV	1 to 10	°
E pulse	100	μJ
t pulse	< 100	μs
Frequency	> 50	Hz
Detector 3d Plus Cube	12 pp 3.45 x 3.45	MP μm
Range	up to 5	m
Particle sizes	> 1	μm
Particle velocities	up to 10	m/s



Mass

Part	Value	Unit	Comment
Structure	400	g	incl. 20 % margin
BEX	80	g	incl. 20 % margin
Lens	110	g	incl. 20 % margin
Detector 3d Plus Cube	100	g	incl. 20 % margin
Laser Driver	120	g	incl. 20 % margin
TOTAL	810	g	incl. 20 % margin

Power

Part	Value	Unit	Comment
Detector 3d Plus Cube 12 MP	5 (12 peak)	W	
Detector 3d Plus Cube 4 MP	2 (5 peak)	W	alternative
Laser Driver	5	W	
TOTAL	10 (17 peak)	W	

Envelope

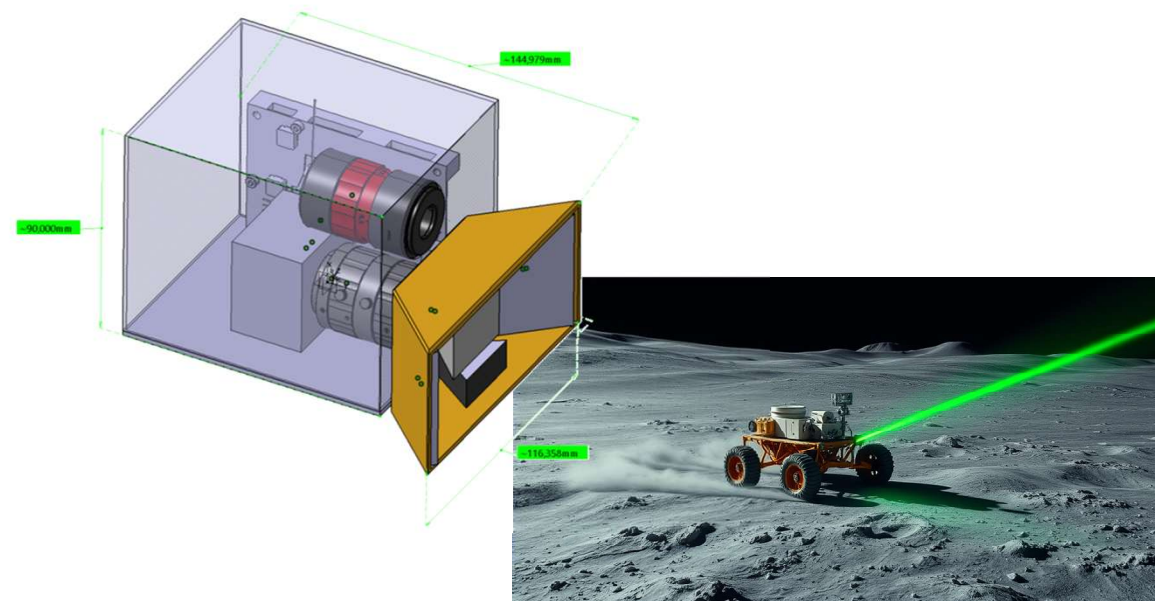
Part	Value	Unit	Comment
Height	90	mm	
Width	120	mm	
Length	150	mm	
TOTAL	1.6	l	

Conclusions & Outlook

- Electrostatic charging can levitate micron and sub-micron lunar dust, contributing to **horizon glow**.
- **Laser scattering** successfully detects particles and estimates **size, distribution and density** using (stereo) vision.
- Current testing uses **salt-pinch** due to limited dust chamber control; algorithms still need improvement for **backscatter and detector irradiance and size** modeling.
- Tracking ~ 10 m/s particles requires a **>100 FPS camera**.
- Better **refractive index data** and **controlled fine-dust testing** are needed for model validation.

Outlook

Develop a **compact breadboard system (2 Units)** using COTS, combining laser, a high-FPS camera and onboard processing, then integrate it onto a **demonstration rover** to validate mobile dust detection in controlled tests.

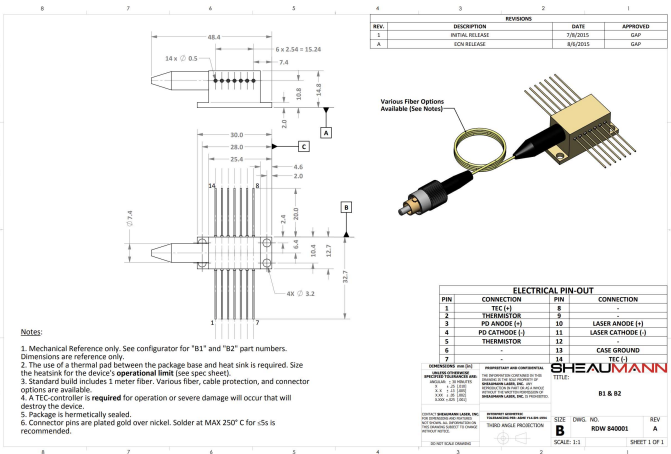


BACKUP

COTS for Elegant Breadboard



Butterfly Laser Diode:



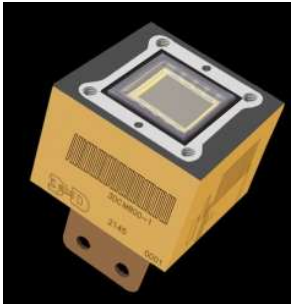
Driver Board:



Lens:

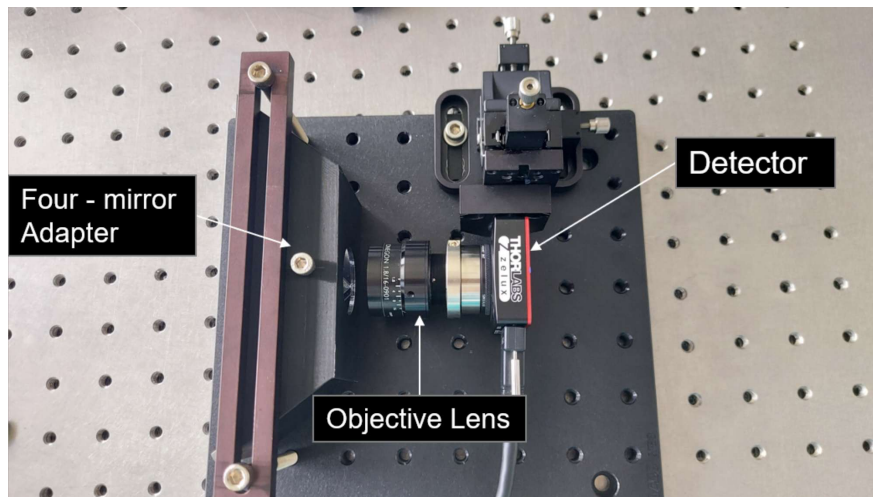


Detector:

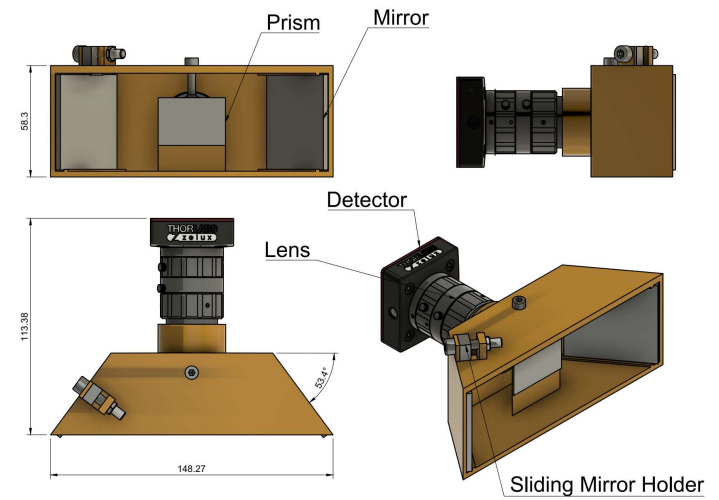


Later implementation of Stereo Camera

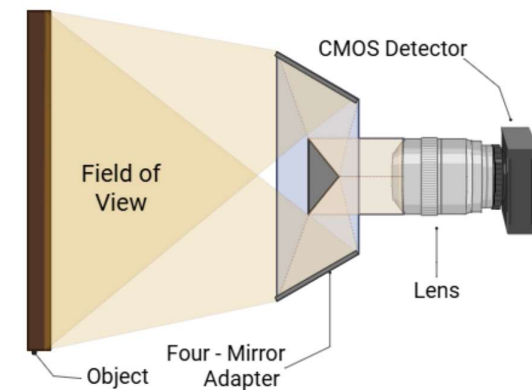
- implementation of stereo imaging planned
- knowledge of **position** of the particle in space (x, y, z)
- for deriving **number densities**
- for estimating **particle sizes** through **signal strength**
- for calculation of **velocity** components v_x , v_y , v_z



Credits: S. Chauhan



Credits: S. Chauhan



Particle Count and Size

Overall Particle Size and Shape Analysis Summary (Silicon 10 μm , $z=1.00$ m)

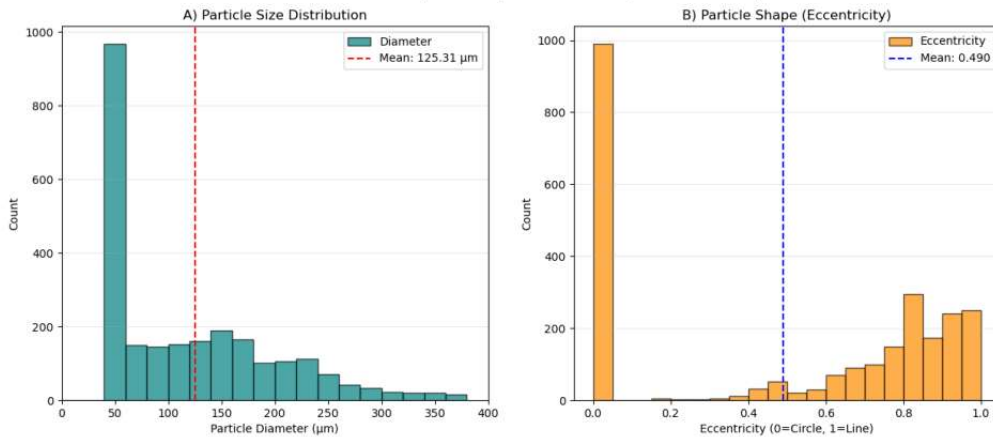


Figure 3.10: Batch Particle Analysis for Silica (Ag coated)
at $z = 1.00$ m

Overall Particle Size and Shape Analysis Summary (Copper 30 μm , $z=1.00$ m)

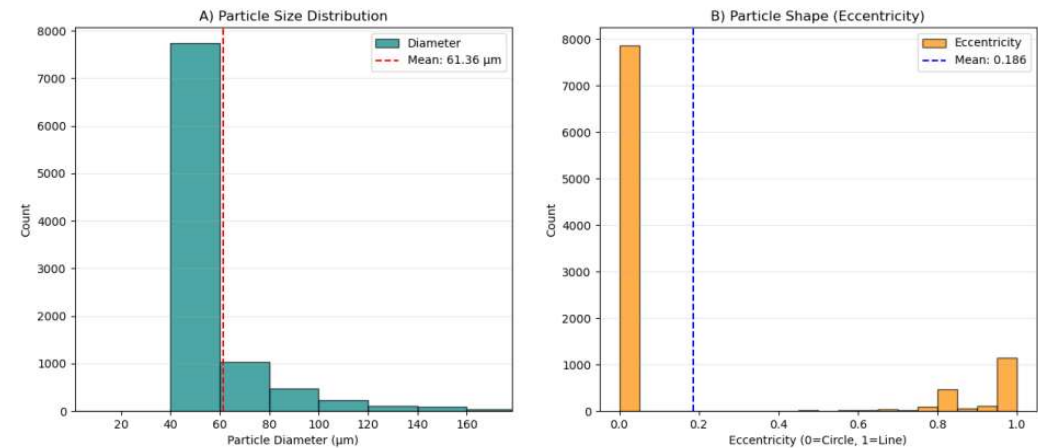
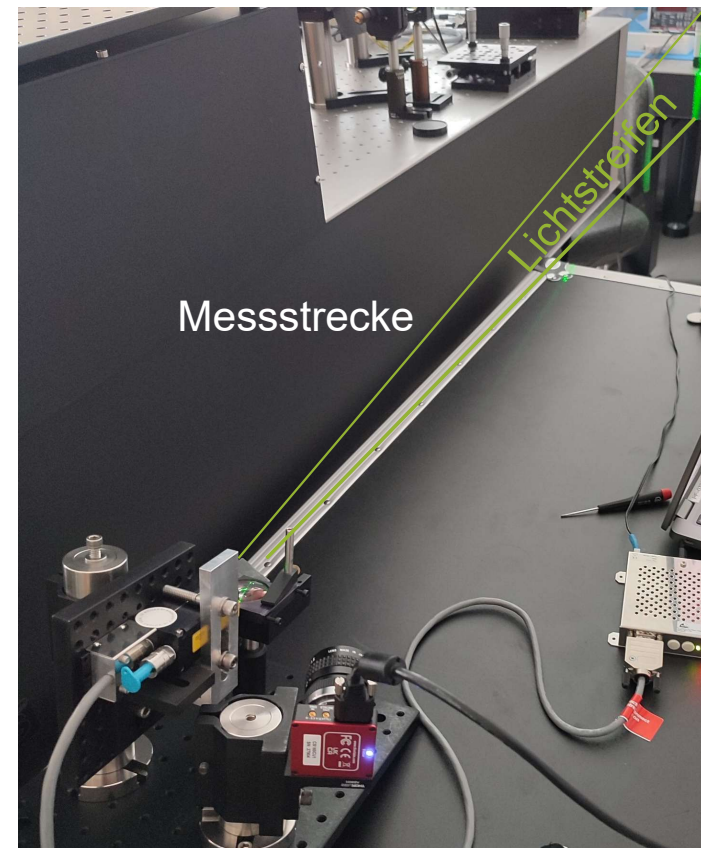
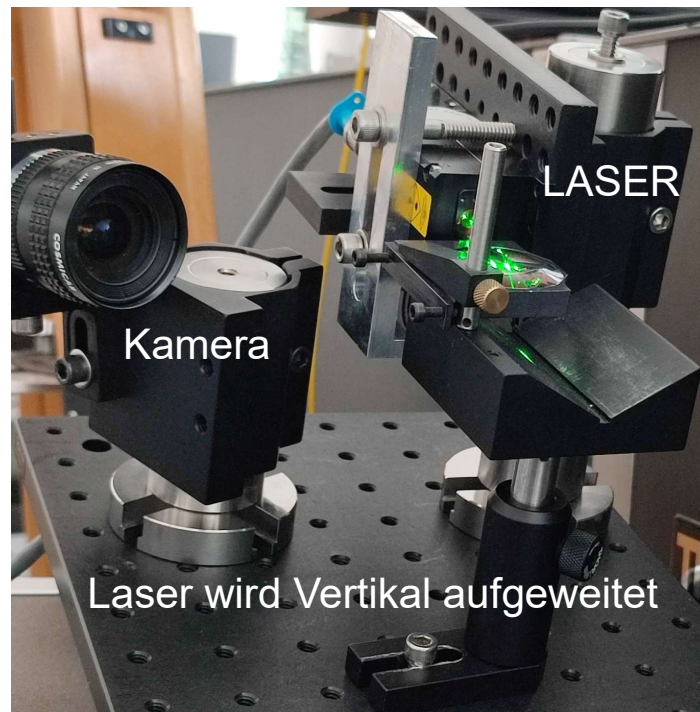


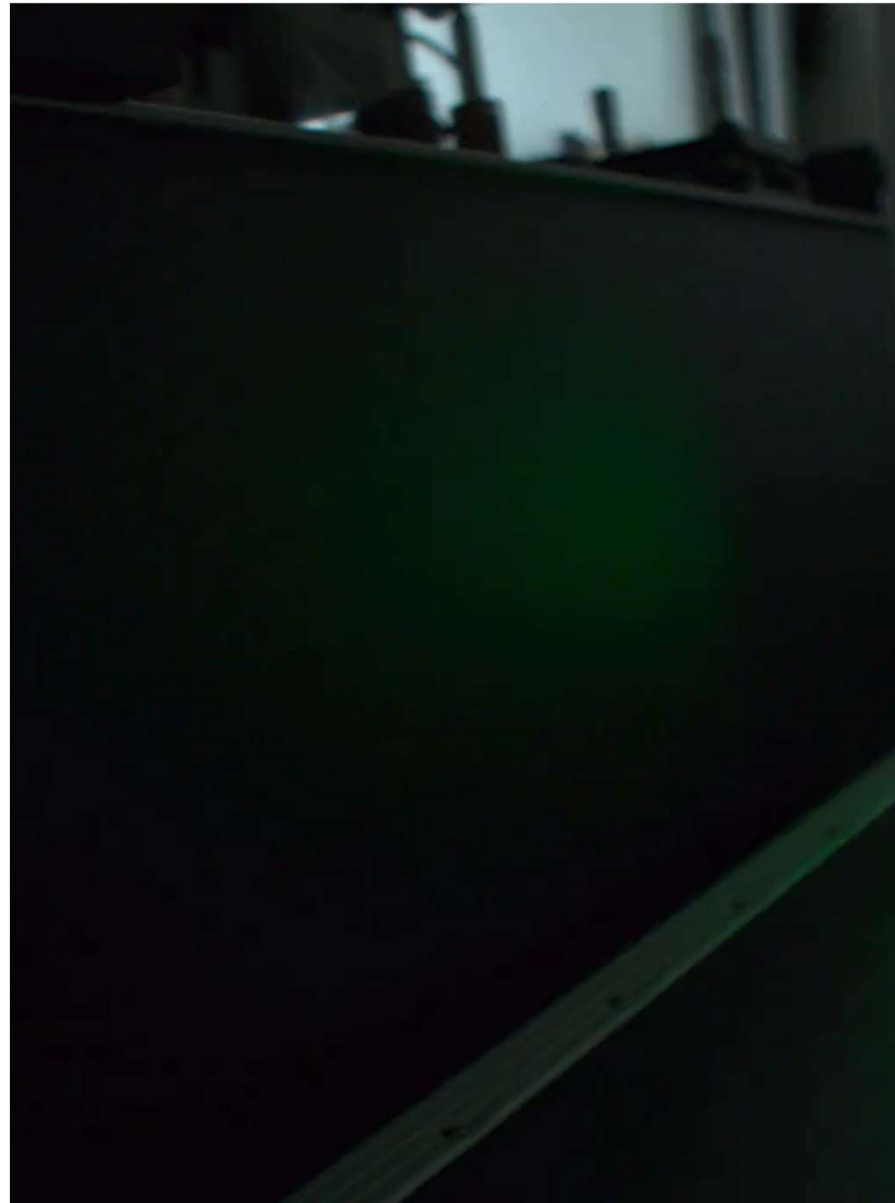
Figure 3.11: Batch Particle Analysis for Copper
at $z = 1.00$ m

Vorversuch

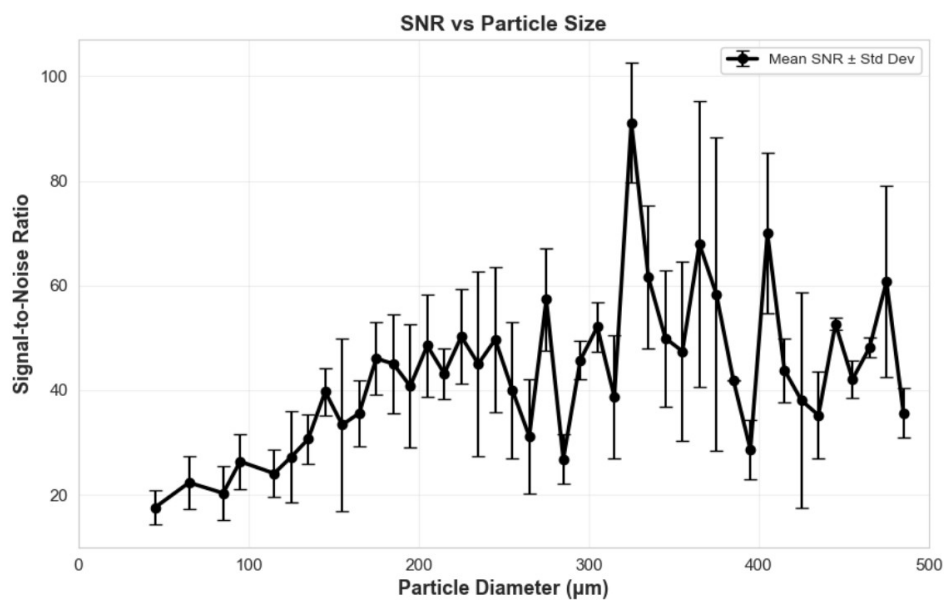


Kameraaufzeichnung

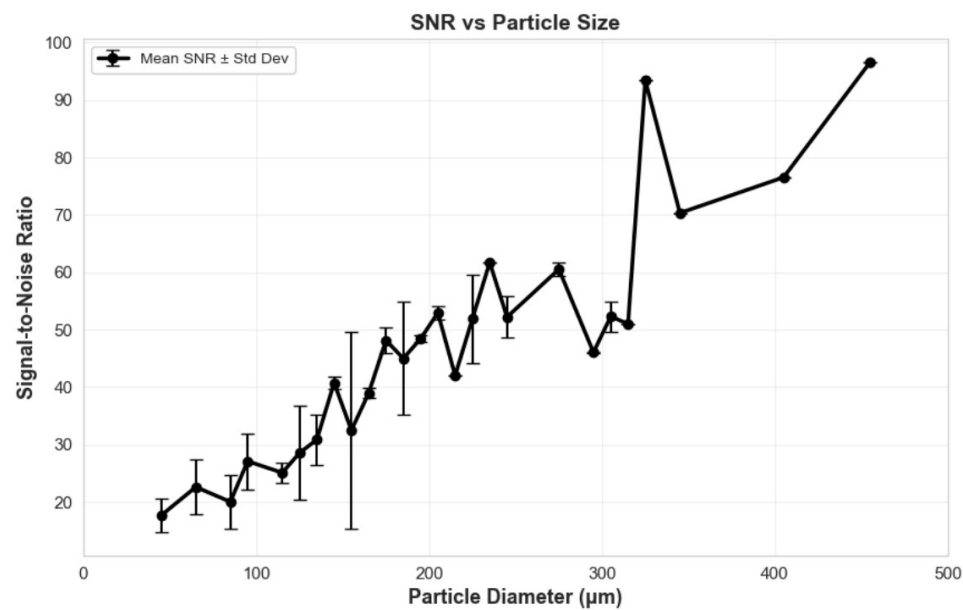
- Veranschaulichen der Messstrecke mit einem Schirm
- Staub in der Luft durch Aufblitzen erkennbar



Backscattering Results



(a) Silica (Ag coated) 10 μm



(b) Copper 30 μm

Backscattering – Mie theory

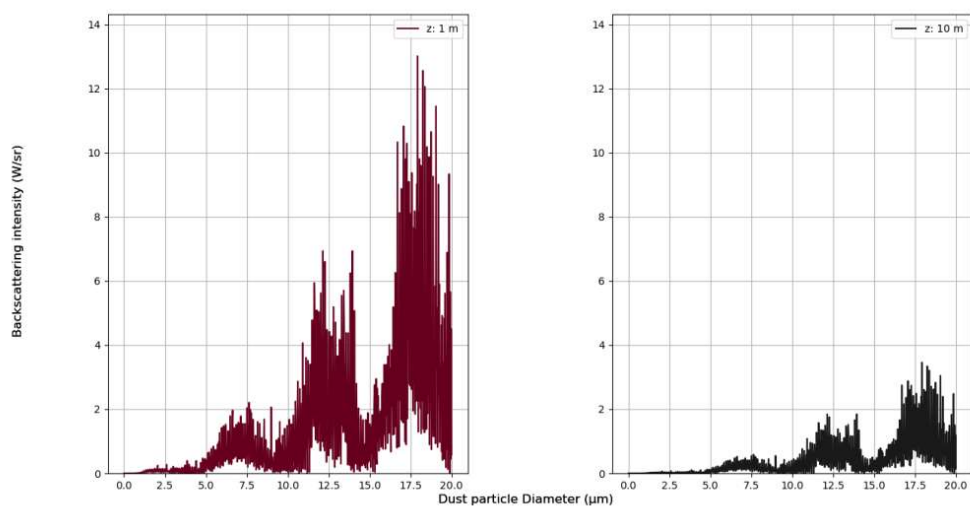


Figure 2.5: Backscattering Efficiency with no absorption.
(Refractive index $m=1.56$)

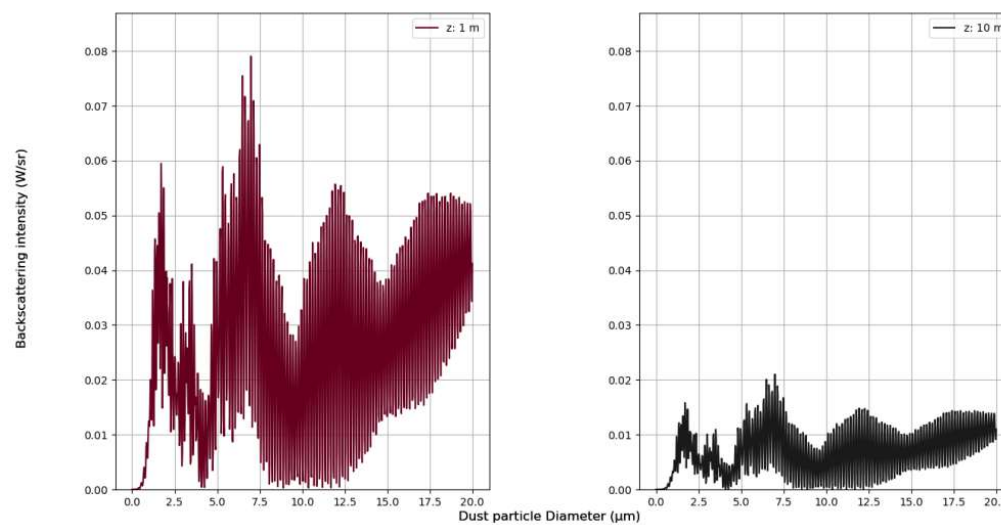
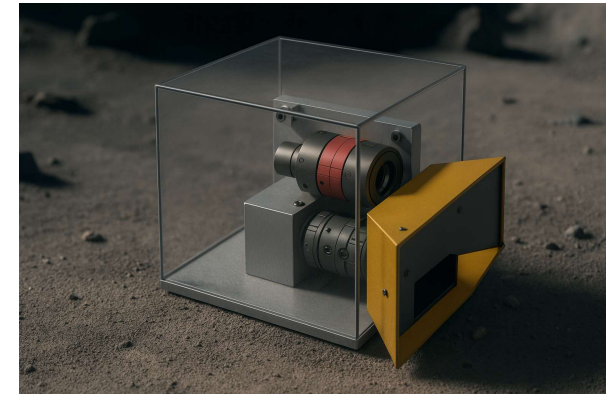
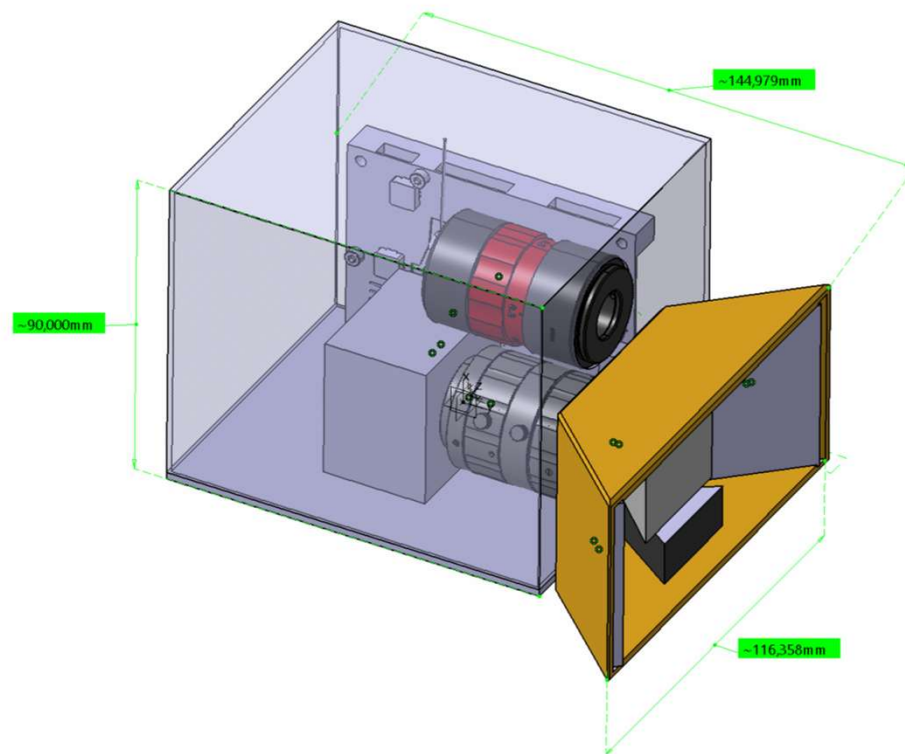
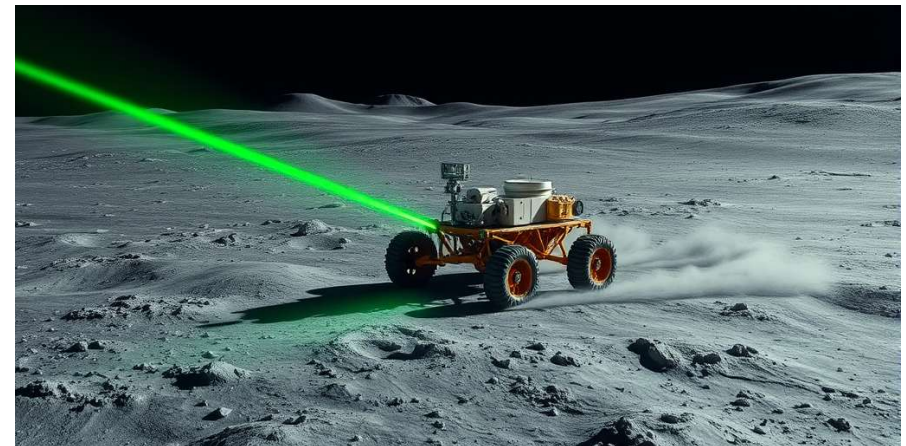


Figure 2.7: Backscattering Efficiency
(Refractive index $m=1.56-0.01j$)

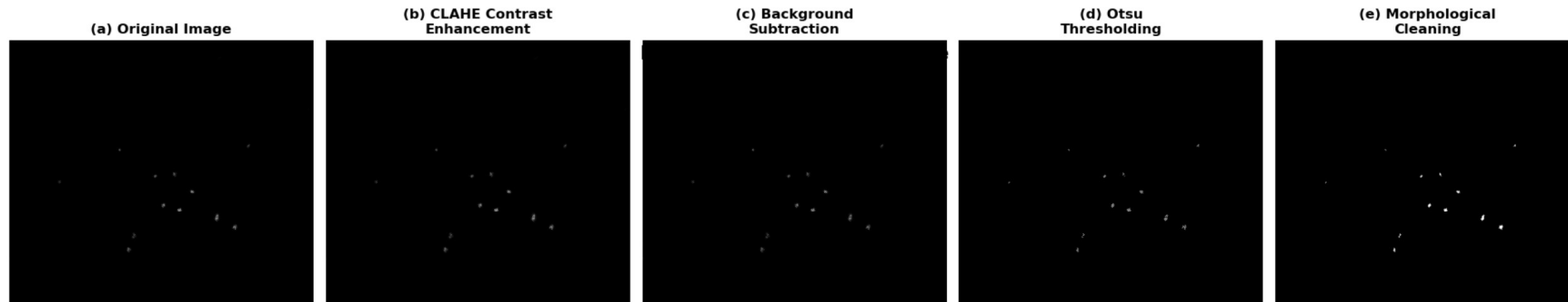
Visual impression of a model payload



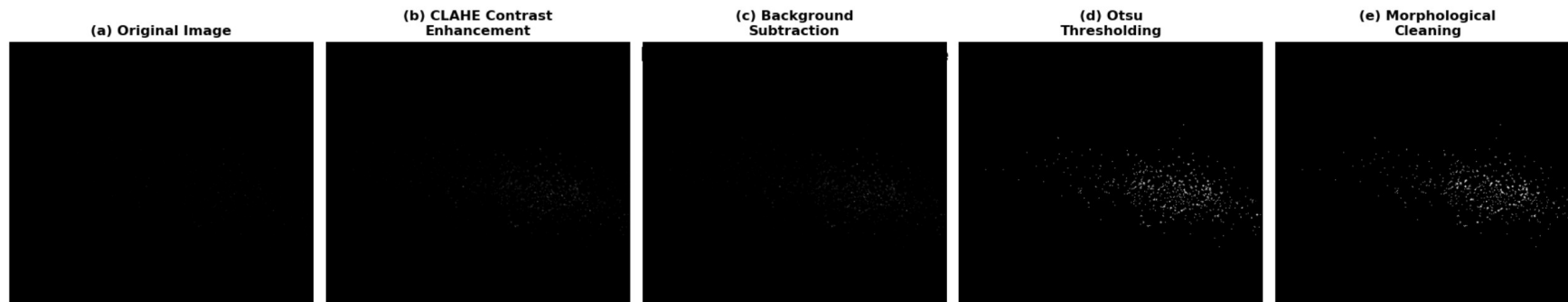
Credits: PF-PLP Image Generation Chatbot



Particle Detection Flow

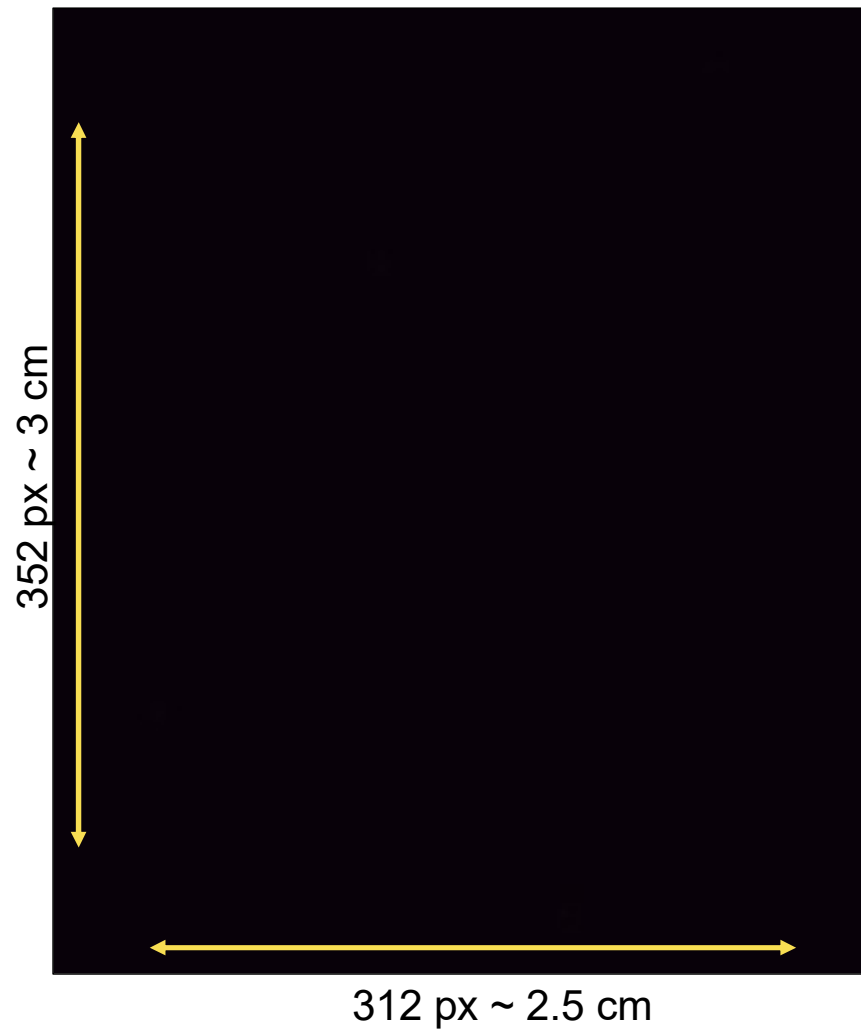


(a) Silica $10\ \mu m$



(b) Copper $30\ \mu m$

Laboratory Experiment Example



Camera settings

Detector Resolution	1080 x 1440
ROI	312 x 352
Frames per second	100
Exposure time	1.6 ms
Gain	0
Triggering	Hardware
Pixel pitch	3.5 μm
Magnification	0.06