Dust Detection Challenges in Complex Environments

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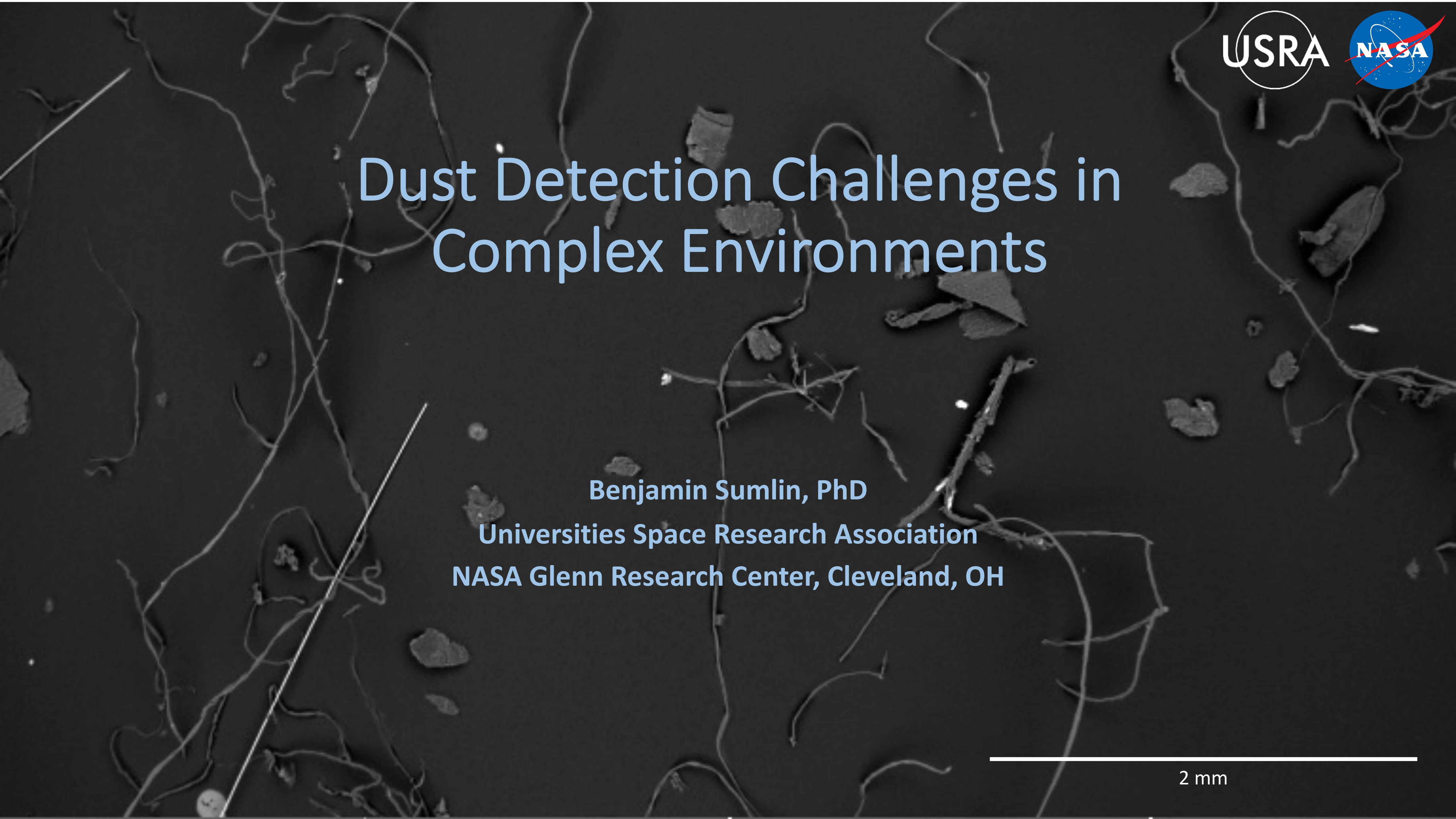


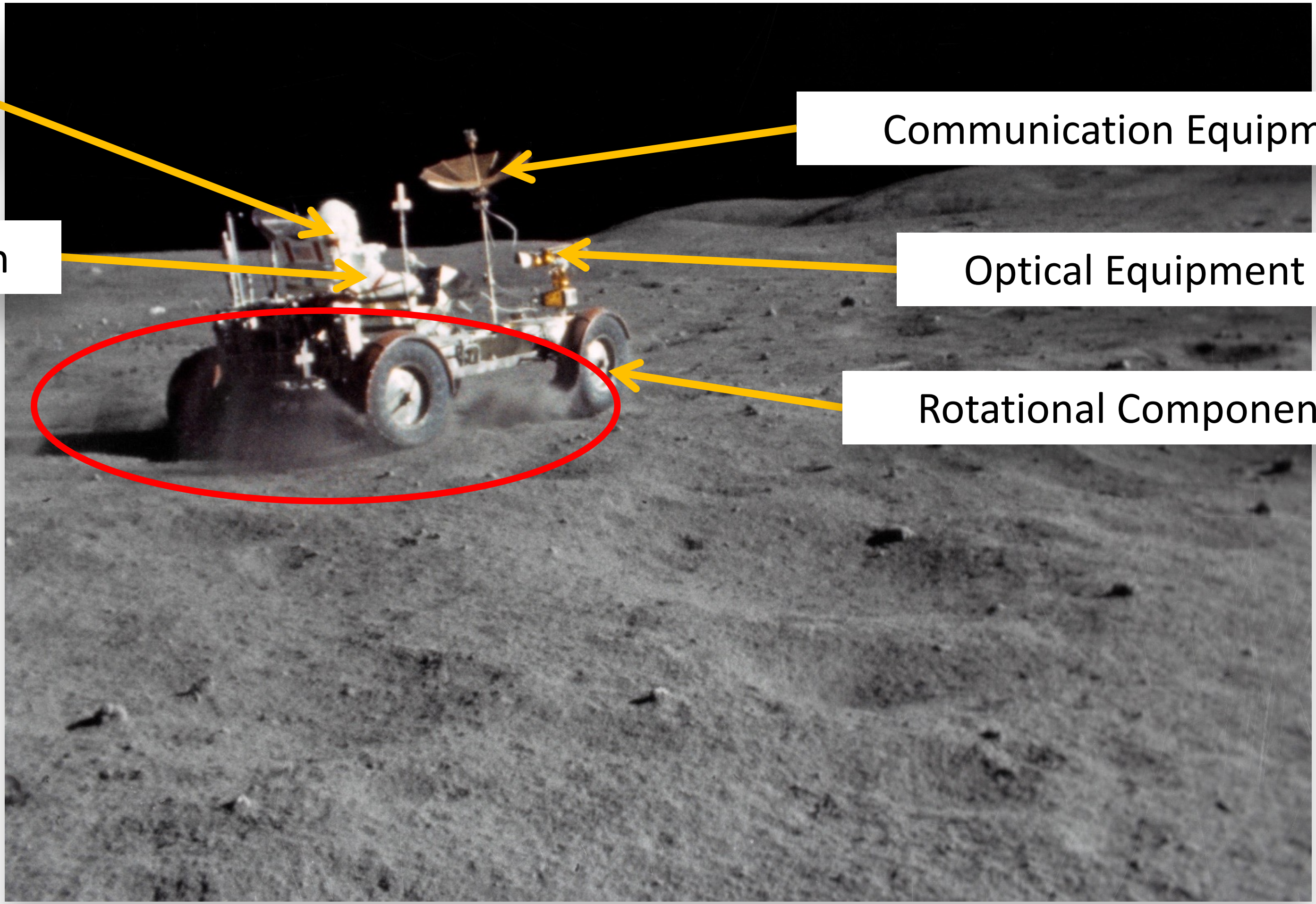
Outline

- What is “dust”?
- How do we detect dust?
- What else do we need to detect?
  - How does this interfere with dust detection?
- What devices are available for particulate matter sensing?

I might say the word “aerosol” a few times

An aerosol is a small piece of solid or liquid matter, suspended in a gaseous medium, such as smoke, dust, or haze. The term “aerosol” is *inclusive* of the medium.

The Moon is a dusty place



"Compared to the Apollo 11 landing, the degradation in visibility as a result of dust erosion was much more severe during Apollo 12. During Apollo 11, the crew likened the dust to a ground fog; that is, it reduced the visibility, but never completely obscured surface features. On Apollo 12 the landing was essentially blind for approximately the last 40 feet.

The Apollo 12 Mission report describes LM cabin atmosphere and associated health hazards to the crew, *"After ascent orbit insertion, when the spacecraft was again subject to a zero-g environment, a great quantity of dust and small particl... made breathing without the helmet difficult and hazard... present in the cabin atmosphere to affect vision."*[2]

Describing LM cabin atmospheric conditions at zero-g, Cernan says, *"The commander kept his helmet on throughout the rendezvous and docking. I took my gloves off after insertion and left them off. As soon as were hard docked, the commander took off his helmet. As I look back at that, ... LM spacecraft, I'm sorry I did. I could have left the helmet on, and ...e and mouth type of irritation. You knew you were in a very heavily ... LM because of the lunar dust. I don't know how much lunar dust ...ink we saved a great deal of grief by sweeping all the dust we could find in the floor into the holes and putting our tape covers over those holes. I think that had to help a great deal. There was an awful lot of dust on the floor that we didn't see."*[11]

The Apollo 12 Mission report adds, *"The transfer of equipment between both vehicles was impeded by the large amounts of dust and debris in the lunar module. Therefore, the timeline became very tight in meeting the schedule for lunar module jettison."*[2]

...olve any apparent problem ... the lunar environment."

Young responded, *"That didn't clear any dust out because you ... get any of that stuff in the suit loop to clean it out."*[8]

Unidentified Speaker, *"It just circulates around. It has a filter behind it."*[8]

Unidentified Speaker, *"Does it have a filter behind it? Well, it didn... out."*[8]

"We tried to vacuum clean each other down, which was a complete farce. In the first place, the vacuum didn't knock anything off that was already on the suits. It didn't suck anything, but we went through the exercise. It did clean the rock boxes, that much I'll say for it. I don't think it ... but it brushed the dirt off the boxes. We put them in their proper ...ed them.[3]

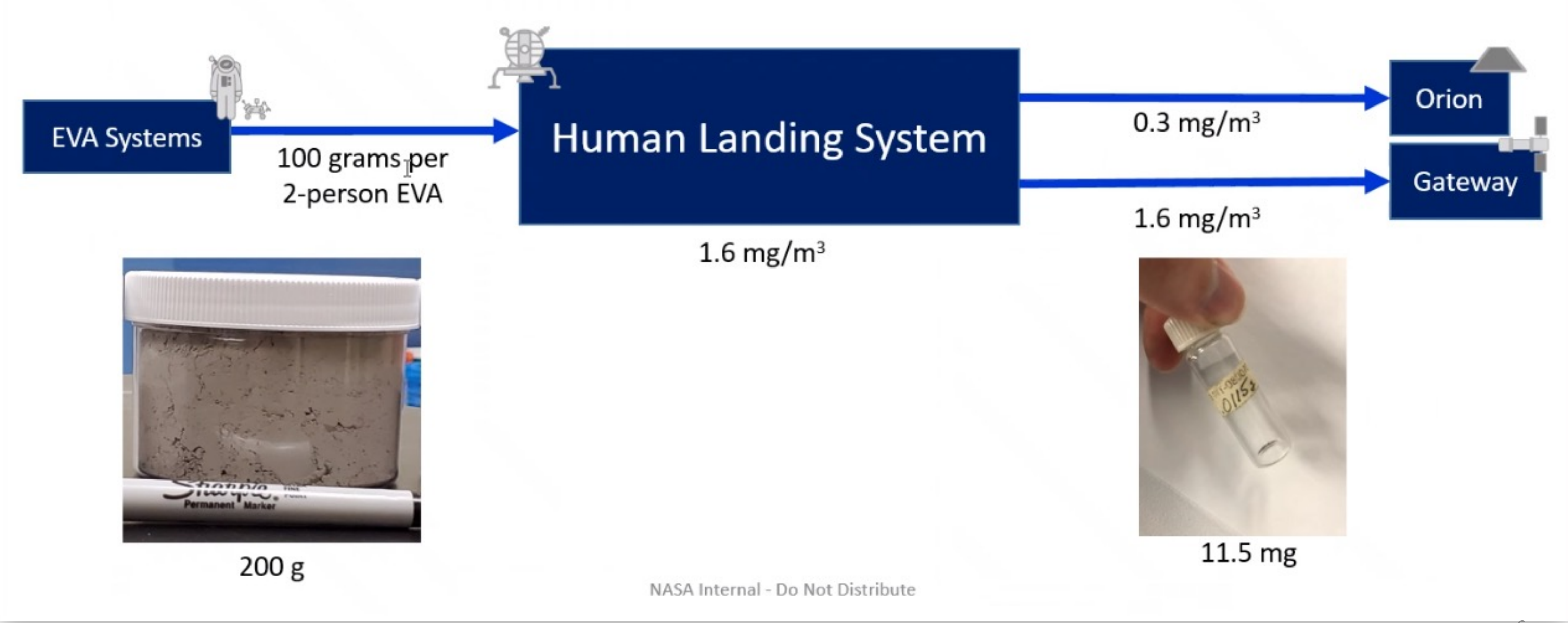
Duke answered, *"It did. The screen was covered with dust. It probably was so covered that it stalled out, and that's what failed it."*[8]

...says, *"Cabin repressurization after each extravehicular period was ...its became a significant*

Apollo 16 Mission report described the vacuum cleaner failure, *"The vacuum cleaner failed after becoming clogged with dust. The vacuum cleaner was cleaned postflight and it operated properly. The design of the vacuum cleaner is such that lunar dust can clog the impeller."*[9]

During the Apollo 16 Technica... *first EVA, and then from then on, it was really dirty."*[8]

That dust must go somewhere – just not to Gateway



Thanks to Kristen John (JSC)

But what IS dust?

- Per NASA-STD-1008:

For the purpose of this NASA Technical Standard, we define "dust" pragmatically as the **regolith size fraction that poses any functional or longevity concerns or risks to hardware, components, or systems**. This is defined by an upper particle size bound and includes smaller particles. Estimates of source size fractions are given in this NASA Technical Standard for various dust transport mechanisms. The unit micrometer (μm) is used to define dust sizes in this NASA Technical Standard.

Note: The definition of "dust" can have ***different meanings*** *to* ***different scientific groups****, and the word "dust" has been used to characterize* ***anything from a very specific size particle distribution to nearly all of the particulate matter in a given sample/volume****. Various definitions of dust have been used widely in NASA official documents and in other scientific documents. However, when designing, developing, and testing technologies and systems for dealing with the particulate matter, it is not ideal to have two classes: one for dust and one for larger- or smaller-sized particles.*

But what IS dust?

Table 3—Planetary Pressurized Lunar Sources of Dust and Associated Dust Parameters

PP Lunar Sources of Dust	Particle Size (µm)	Surface Accumulated Loading (g/m^2)	Volumetric Loading (g/m^3)	Dust Velocity (m/s)	Charge to Mass Ratio (nC/g)
Extravehicular Activity (EVA) Suit Cross-Hatch Transported Dust	<500 µm [TBR] [1]	50 g per suit per EVA [2][3][5]	10 g/m^3 per suit per EVA [2][3][4]	Variable [6]	N/A
Hardware Cross-Hatch Transported Dust	<500 µm [TBR] [1]	Variable g/m^2 [2]	Variable g/m^3 [2]	Variable [6]	N/A

Notes:

1. Apollo 17 suit maximum particle size (NASA/TP-2009-214786). This value may change with new suit materials and/or designs.
2. These values may vary depending on program requirements. In some cases, the requirement for EVA suit cross-hatch transported dust and hardware cross-hatch transported dust may be combined.
3. Assuming 50 g of dust per crewmember per EVA based on EVA to Human Landing System (HLS) requirements.
4. Assuming dust concentration is 50 g spread evenly throughout 5 m^3 habitable volume. Value can be adjusted for different dust concentrations and habitable volumes. Assuming all dust on suit becomes airborne in habitable space, the concentration of airborne lunar dust would be 10 g/m^3 per suit per EVA. It is expected that post EVA remediation efforts will reduce the transferred dust loading on each individual EVA, but that a net buildup over multiple EVAs will occur.
5. This cell contains a mass rather than surface loading, which should be converted to an areal mass density before use in the Dust Class ID. This cell may be interpreted by: (1) dividing the dust mass by the surface area of the EVA suit, if suit loading is desired; or (2) dividing the mass by the affected interior surface area.
6. Aerosol particles travel with the same velocity as free airflow (in cabin or ducting). Particles impact onto surfaces at interruptions to free flow (e.g., sharp bends in the airstream).

But what IS dust?

Table 4—In-Space Pressurized Lunar Sources of Dust and Associated Dust Parameters

SP Lunar Sources of Dust	Particle Size (µm)	Surface Accumulated Loading (g/m^2)	Volumetric Loading (g/m^3)	Dust Velocity (m/s)	Charge to Mass Ratio (nC/g)
Microgravity Free Floating Dust	<100 µm [TBR] [1][2]	Variable [5]	0.0016 g/m^3 short duration; 0.0003 g/m^3 long duration [3][4]	N/A	N/A
Microgravity Surface Adhering Dust	<100 µm [TBR] [1][2]	Variable [5]	0.00001 g/m^3	N/A	N/A

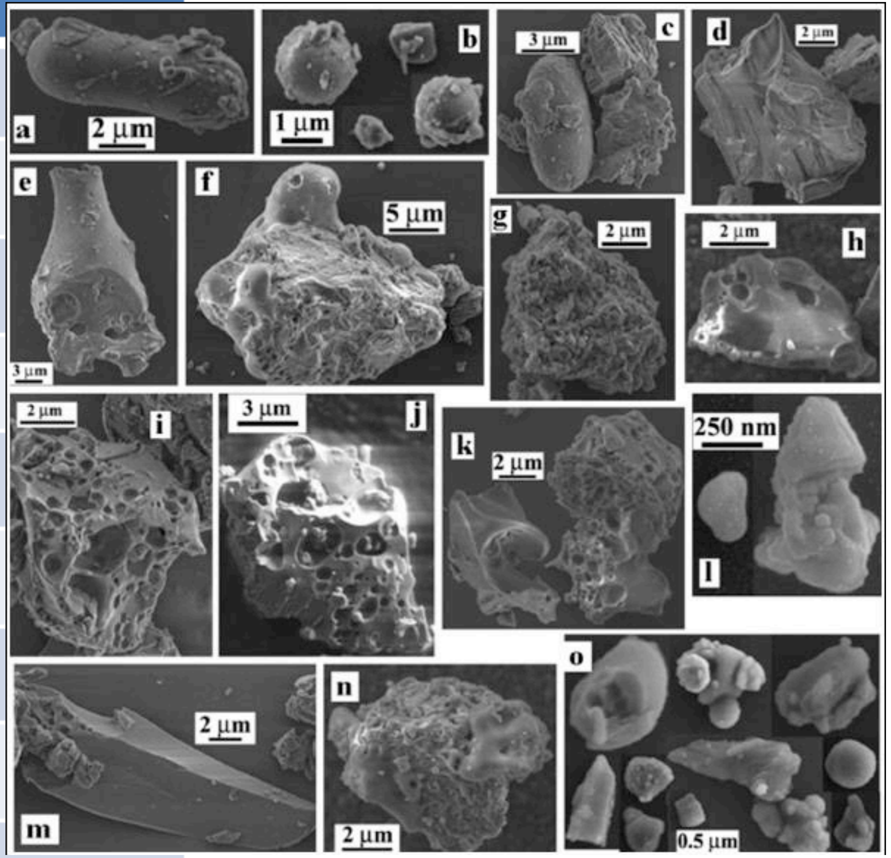
Notes:

1. Assumes pre-launch dust remediation. Particle size varies depending on application. For human health, inhalable particles are considered <10 µm, with the respirable range being <2.5 µm. NASA STD-3001, Volume 2 outlines allowable dust mass concentrations for human exposure.
2. Future missions will verify this value.
3. Lunar Atmosphere Dust Toxicity Assessment Group (LADTAG) Report. These values are typically time-weighted averages. Peak initial values may be higher.
4. Ranges from 0.3 mg/m^3 for long duration (30+ days) and 1.6 mg/m^3 for short duration (~7 days).
5. Surface accumulated loading for in-space pressurized assets is likely to be driven by mission architecture.

Lunar Dust Composition Comparison

Element Chemistry	Apollo 14 (Intermediate,LADTAG Testing)[2]	Estimate of Feldspathic Highlands Composition[1] (prevalent at Lunar South Pole)
SiO_2	47%	45%
TiO_2	2%	0.2%
Al_2O_3	20%	28%
FeO	9%	4%
MgO	8%	5%
CaO	12%	16%
Other	2%	2%
Total	100%	100%

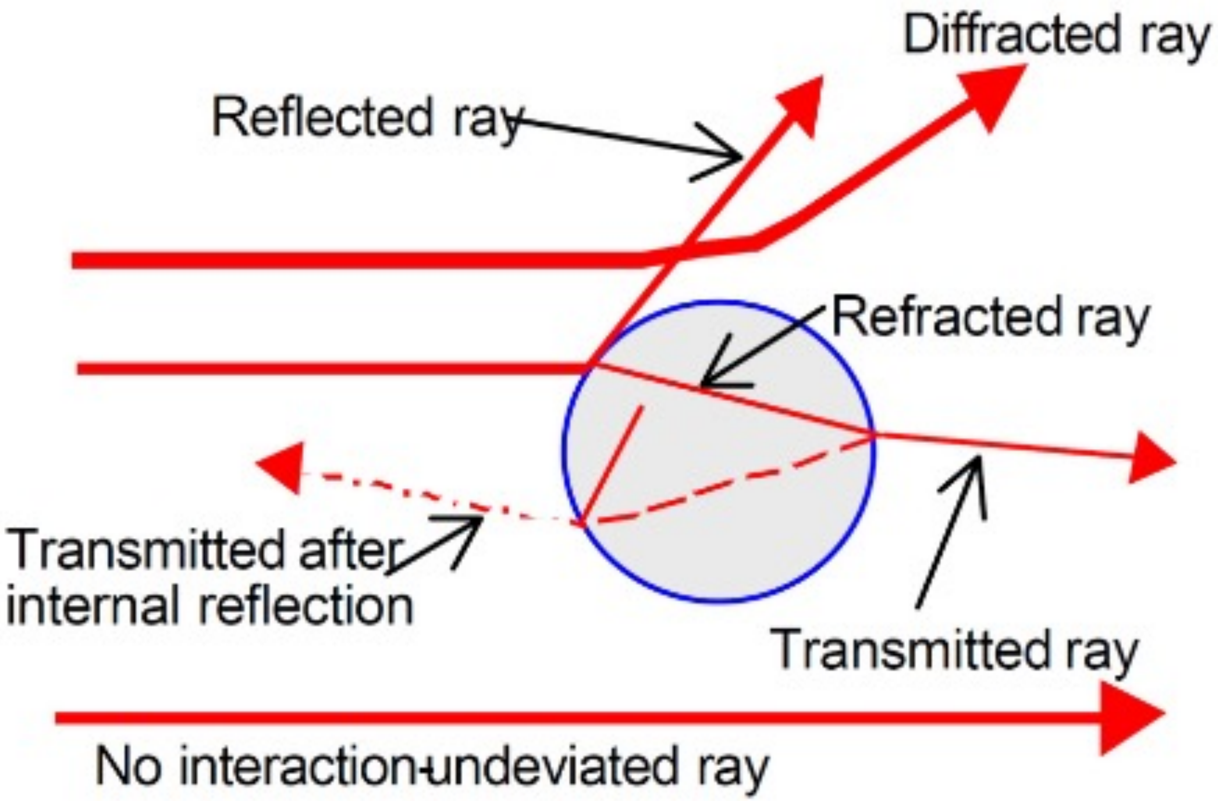
[1]Korotev et al. 2003
[2]McKay et al. 2015



How do we Detect Dust?

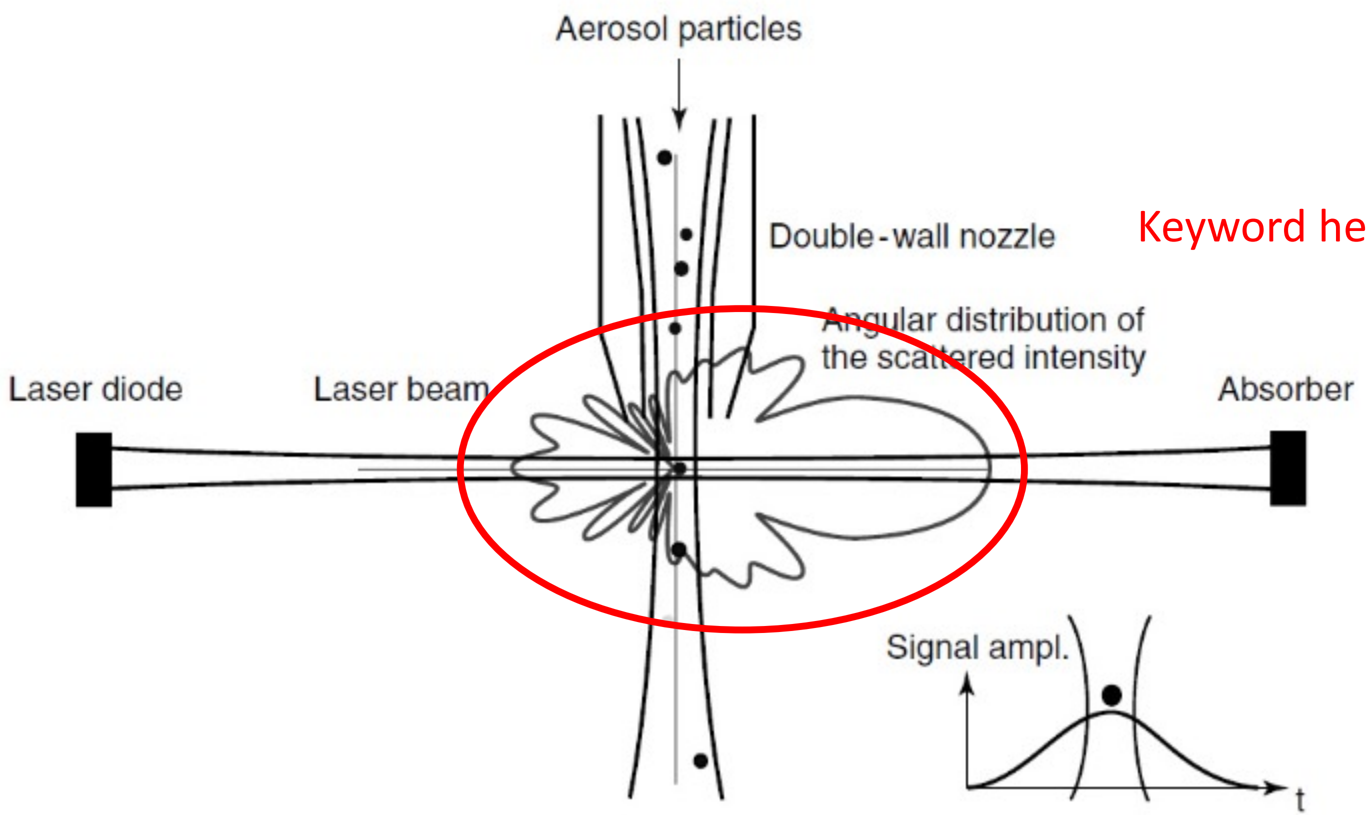
- Passive vs active sampling
  - ~~Passive~~
    - ~~Filters, bottles, tubes, etc~~
    - ~~Requires offline analysis (sample return)~~
  - Active
    - Light scattering~~, light absorption~~
    - Requires calibrations, assumptions, and maintenance

Light Scattering is the Method of Choice



Webb, P.A. Particle Sizing by Static Laser Light Scattering, Technical Workshop Series Micromeritics; Micromeritics Instrument Corp: Norcross, GA, USA, 2000

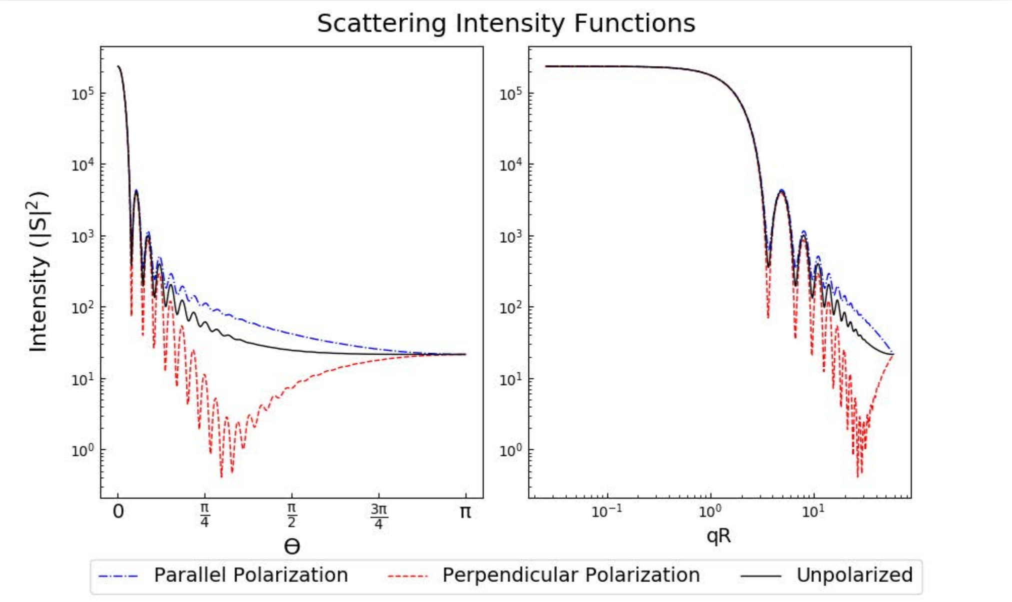
Light Scattering is the Method of Choice



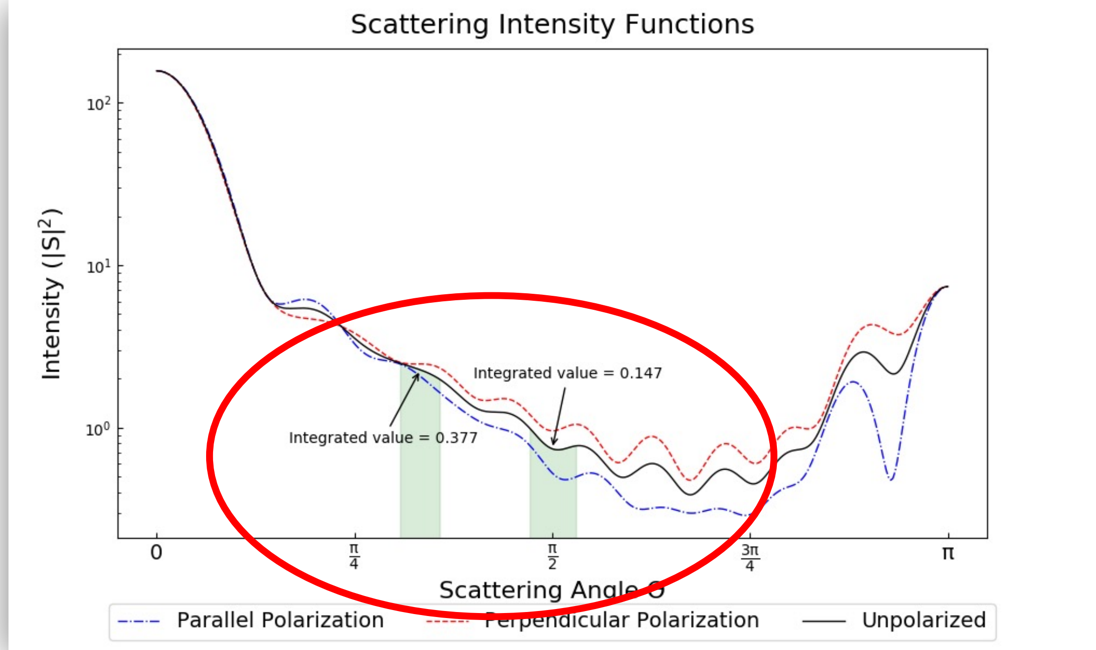
Keyword here is *angular*

Agranovski, I. Aerosols: Science and Technology; John Wiley & Sons: Hoboken, NJ, USA, 2011.

Angular distribution measurements carry massive uncertainty




```
>> import PyMieScatt as ps
>> import numpy as np
>> import matplotlib.pyplot as plt
>>
>> m=1.7+0.5j
>> w=532
>> d=5000
>>
>> theta,SL,SR,SU = ps.ScatteringFunction(m,w,d)
>> qR,SLQ,SRQ,SUQ = ps.ScatteringFunction(m,w,d,space='qspace',normed=False)
```




```
>> m = 1.536 # refractive index of NaCl
>> w = 405 # laser wavelength (nm)
>>
>> dp_g = 85 # geometric mean diameter (nm)
>> sigma_g = 1.5 # geometric standard deviation (unitless)
>> N = 1e5 # total number of particles (cm^-3)
>>
>> B = ps.Mie_Lognormal(m,wavelength,sigma_g,dp_g,N,returnDistribution=True)
>> S = ps.SF_SD(m,wavelength,B[7],B[8])
```

Sumlin, B. J. et al., Retrieving the aerosol complex refractive index using PyMieScatt: A Mie computational package with visualization capabilities. *Journal of Quantitative Spectroscopy and Radiative Transfer* **2018,** 205, 127-134.

Light scattering requires assumptions and carries uncertainties

- Light scattering does ***not*** measure mass, size, shape, etc. It only measures light scattering.
  - Q_{sca} – single particle scattering efficiency, unitless
  - β_{sca} – ensemble scattering coefficient, inverse length
- Light scattering can be used to ***estimate*** these quantities.
  - Most COTS (commercial off-the-shelf) instruments are **single-angle single-wavelength** instruments that use some transfer function to estimate particle size and number concentration.
    - This requires a calibration to some standard (typically Arizona Test Dust, ISO 12103-1)
    - Only strictly valid for estimating mass and number concentration of the calibration analyte. Requires some assumptions to use against other challenge materials.

Light scattering requires assumptions and carries uncertainties

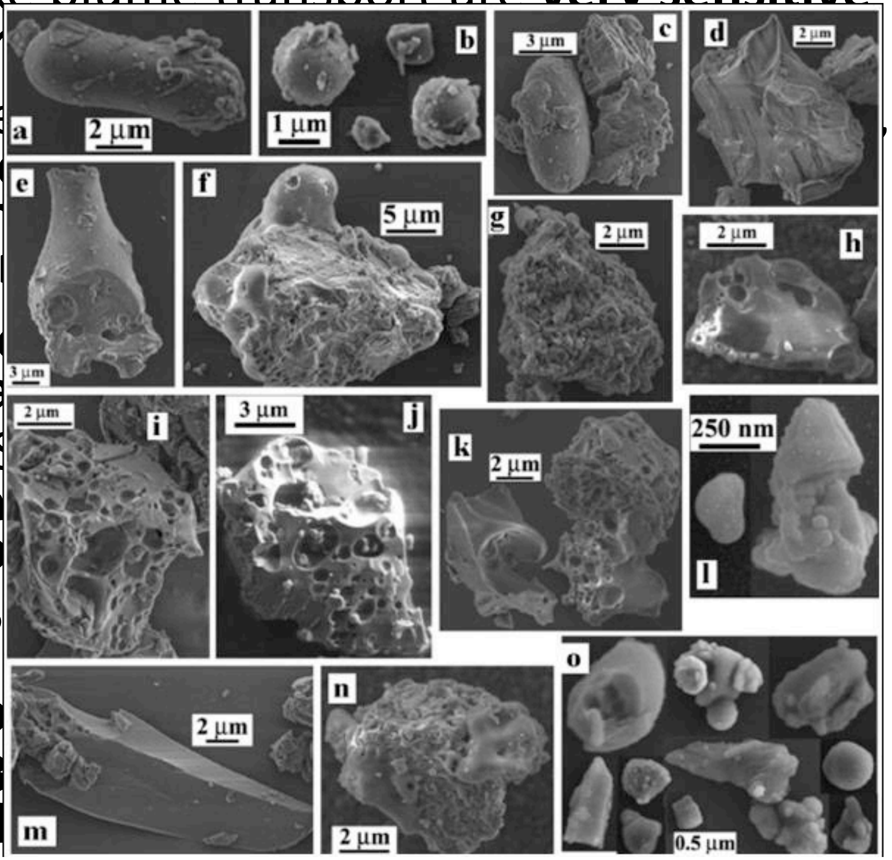
- Some instruments use multiple wavelengths or multiple angles
  - This is better, but still not perfect
    - Uncertainty in angular measurements
    - Small changes in the analyte can cause large changes in angular scattering distribution
    - Still requires calibration for a particular material in order to report mass
- In theory, three independent measurements can reconstruct a size distribution
  - **Still does not report mass, which requires a calibration**

Other Confounding Issues

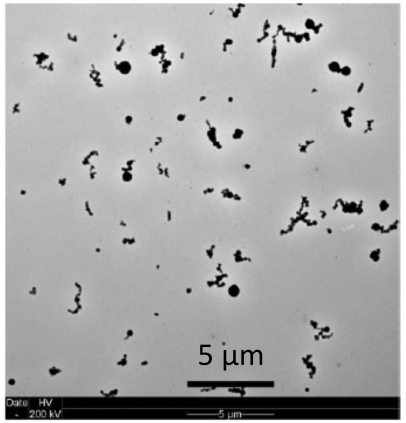
- Smoke, dust, and typical crew-generated cabin aerosols all interfere with each other when constructing a detection method.
- All aerosols scatter light in some way, and depending on the interaction of the analyte with the detector, can produce false alarms, or not alarm at all.
- ***<u>There currently exists no single light-scattering detector that can accurately discriminate between these different types of contaminants.</u>***

The Smoke Aerosol Measurement Experiment (SAME)

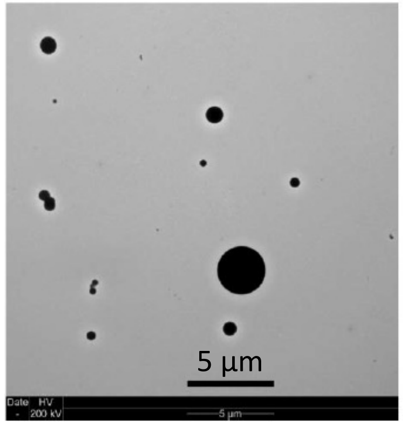
- In microgravity, particle formation and smoke plume transport are **very sensitive to ai**
- Howe
  parti
  reser
  expe
- **Dete**
  size a
  - IS
    h
    p
  - S
    s
    p
  - **B**
    d



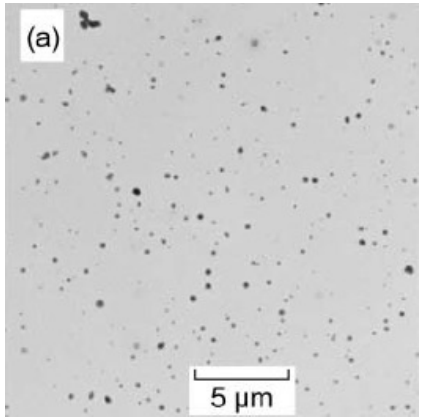
Pyrell, air flow = 8 cm s^{-1}



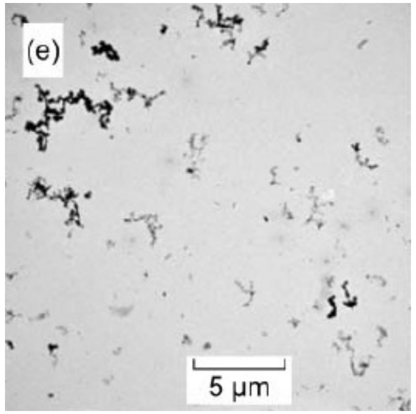
Pyrell, air flow = 0 cm s^{-1}



Kapton, unaged



Teflon, unaged

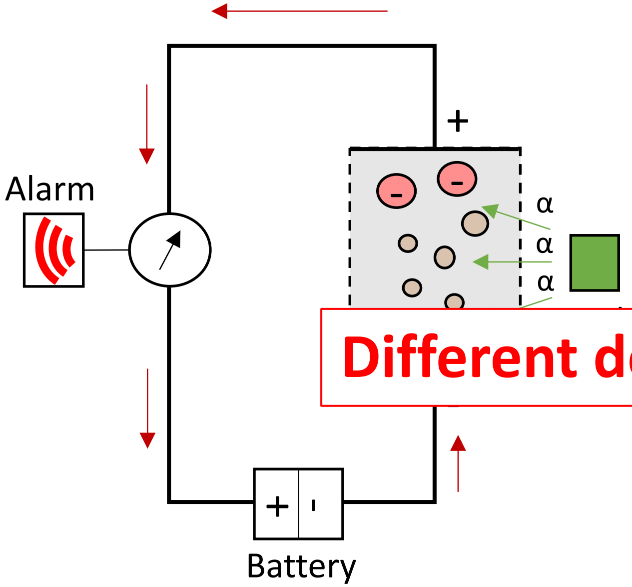


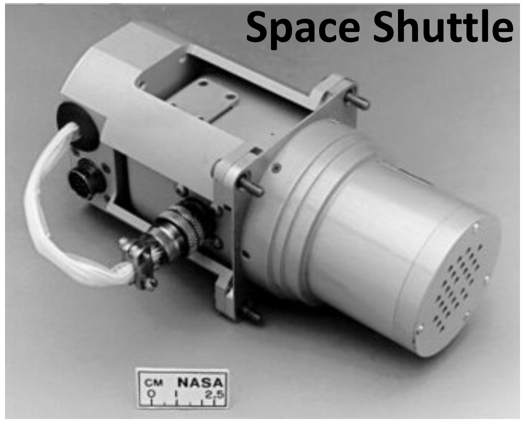
Mulholland et al., Aerosol Sci. Tech., 49:310-321, 2015.
Meyer et al., Fire Safety Journal, 98. 74-81, 2018.

Slide prepared by Claire Fortenberry (USRA/NASA GRC)

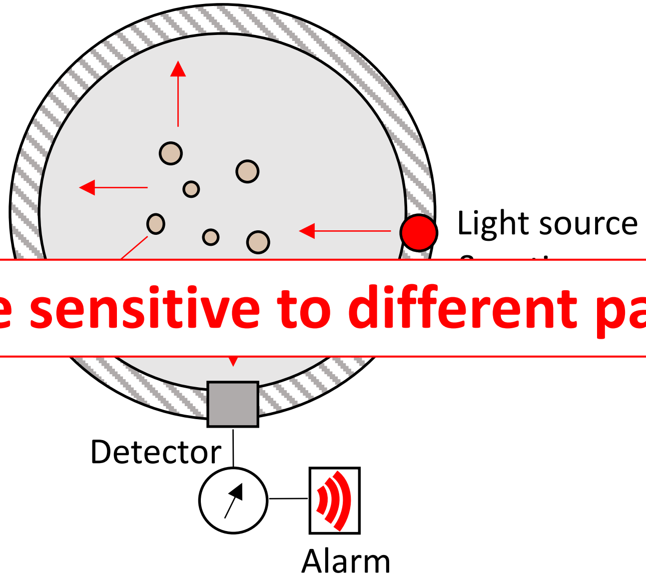
Smoke Detection Methods

Ionization

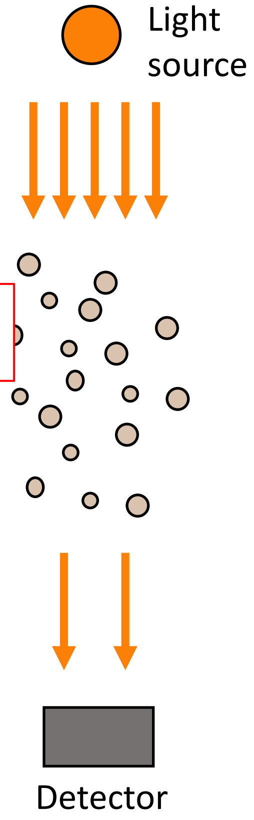




Light Scattering



Obscuration

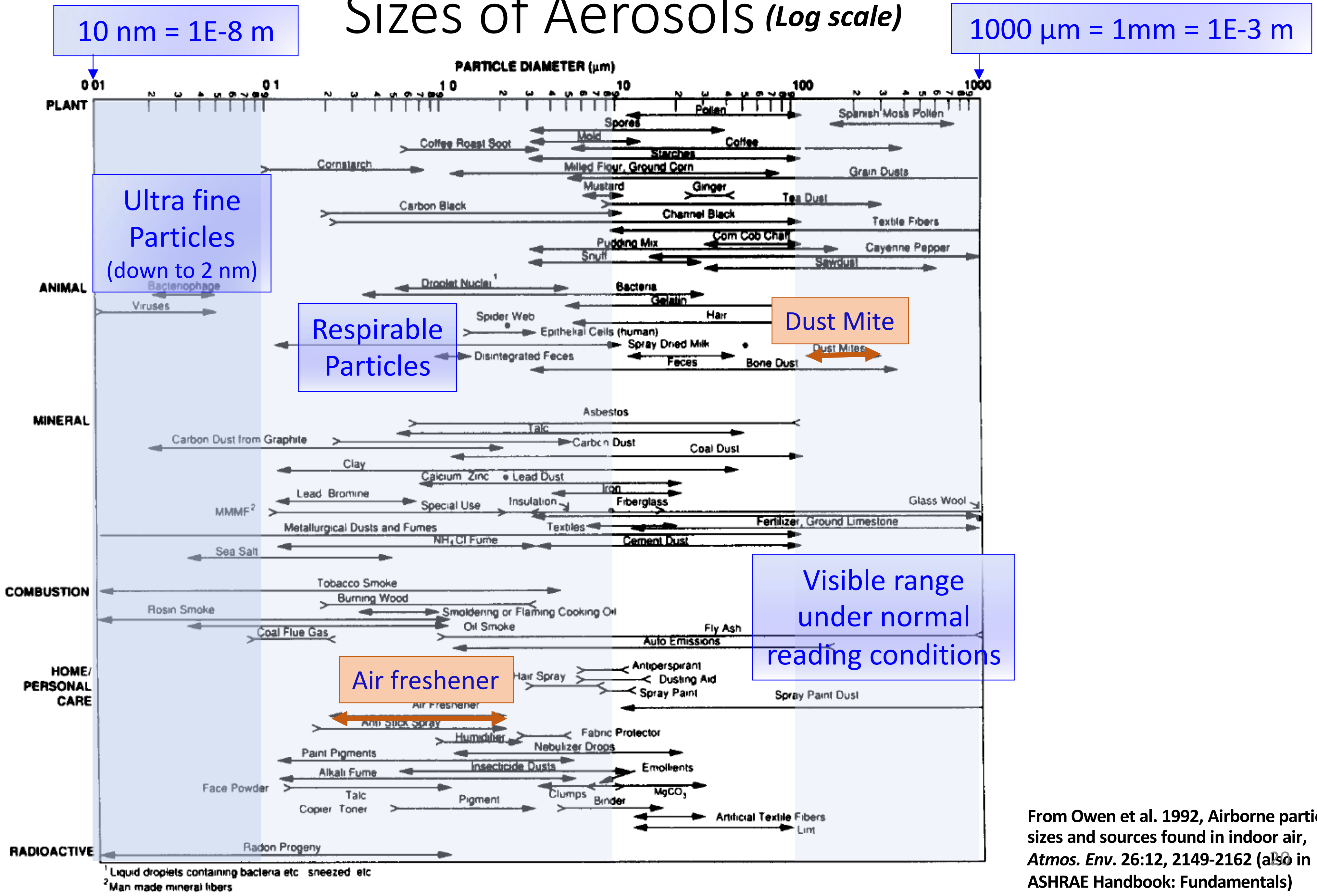


Smoke detector sensitivity standards

Different detectors are sensitive to different particle sizes!

Slide prepared by Claire Fortenberry (USRA/NASA GRC)

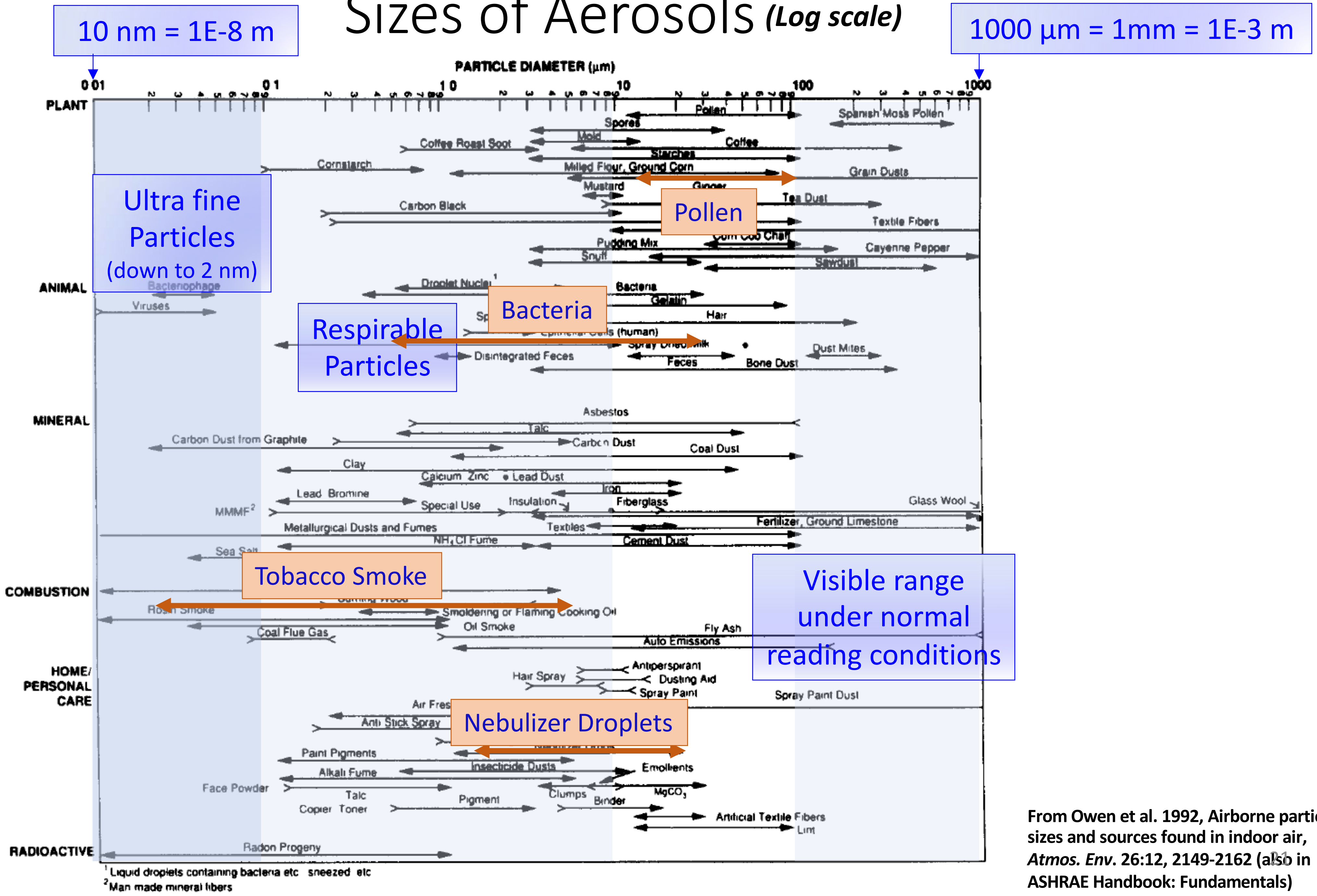
Sizes of Aerosols *(Log scale)*



Slide prepared by Marit Meyer (NASA GRC)

From Owen et al. 1992, Airborne particle sizes and sources found in indoor air, ***Atmos. Env.*** 26:12, 2149-2162 (also in ASHRAE Handbook: Fundamentals)

Sizes of Aerosols *(Log scale)*



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Aerosol Behavior in Low Gravity

- On Earth, our air quality is improved by gravitational settling
  - In µg, all particles remain airborne until deposited on surfaces, air inlet screens or ventilation system filters
- ‘Dusty air’ has been a complaint of astronauts
  - Indicates high concentrations of inhalable particles
- Filter inlets and fan intakes on equipment require regular vacuuming

Dirty avionics intake fan

Slide prepared by
Marit Meyer
(NASA GRC)

Different Levels of Fidelity and the Costs Associated with Them – you get what you pay for

- ~~Reference Quality~~
  - ~~First-principle measurement backed by a Federal Reference Method (FRM)~~
  - ~~Large physical footprint, high power consumption~~
- ~~Industrial Quality~~
  - ~~Modest footprint and power consumption~~
  - ~~Typically only good for measuring "one thing"~~
- Low-cost
  - Small footprint, low power consumption, cheap
  - Poor data quality, but can be improved with careful calibration and full knowledge of the drawbacks
  - Can be distributed to improve data quality

Low-cost and COTS Sensors

- Attractive due to their cost, small physical footprint, and low power consumption.
- Typically single- or multi-angle, single-wavelength light scattering with extra steps.
  - Various types of detection such as integrated signal and pulse counting
- Data quality is typically poor
- **Few (or none) independent publications and critiques**

Some Resources

- Alfano et al. reviewed some fifty low-cost sensors and summarized their data products, detection limits, working principles, and associated publications.
- doi:10.3390/s20236819


sensors MDPI

Review

A Review of Low-Cost Particulate Matter Sensors from the Developers' Perspectives

Brigida Alfano [1], Luigi Barretta [2,3], Antonio Del Giudice [1], Saverio De Vito [1,*], Girolamo Di Francia [1], Elena Esposito [1], Fabrizio Formisano [1], Ettore Massera [1], Maria Lucia Miglietta [1] and Tiziana Polichetti [1]

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check for updates

Some Resources

Some Resources

- http://www.aqmd.gov/aq-spec/sensors
- Independent testing efforts by the South Coast Air Quality Management District
- Tests instruments co-located with FRM or FEM instruments
- Provides field reports with the intercomparison results
- An excellent way to get independently-verified information on sensor performance!