Understanding low-cost PM sensors: A “teardown” meets aerosol science

Overview of QA for PM sensors

Air Sensors Quality Assurance Workshop

U.S. Environmental Protection Agency

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Want more information?

Source material for this talk came from

- J. Volckens AAAR 2022 Plenary: https://www.youtube.com/watch?v=X95ZBl-_PCI
- Molina Rueda, E., Carter, E., L'Orange, C., Quinn, C., and J. Volckens. "Size-Resolved Field Performance of Low-Cost Sensors for Particulate Matter Air Pollution." (2023). *Environ. Sci. Technol. Lett.* https://doi.org/10.1021/acs.estlett.3c00030
- Tryner, J., Mehaffy, J. Miller-Lionberg, D., and J. Volckens. "Effects of aerosol type and simulated aging on performance of low-cost PM sensors." (2020). *J. Aerosol Sci.* https://doi.org/10.1016/j.jaerosci.2020.105654
- Ouimette, J. R., Malm, W.C., Schichtel, B.A., Sheridan, P.J., Andrews, E., Ogren, J.A., and W. P. Arnott. "Evaluating the PurpleAir monitor as an aerosol light scattering instrument." (2022). *Atmos Meas. Tech.* https://doi.org/10.5194/amt-15-655-2022
- Ouimette, J., Arnott, W.P., Laven, P., Whitweld, R., Radhakrishnane, N., Dhanivala, S., Sandink, M., Tryner, J., and J. Volckens "Fundamentals of low-cost aerosol sensor design and operation" (2023 submitted) *Aerosol Sci. Tech.*

Goal: Understand the physics governing particulate matter sensor operation to better understand the limitations of sensor performance as well as the quality assurance and correction approaches that are needed.

We'll answer questions like:

- Why does the PMS5003 sensor overestimate typical urban $PM_{2.5}$ concentrations in the U.S.?
- Why does the PMS5003 sensor overestimate wildfire smoke $PM_{2.5}$ concentrations even more?
- Why does the PMS5003 report a seemingly invariant particle number size distribution?
- Why do many PM sensors do such a poor job detecting particles larger than 1 µm?
- Why do mass concentrations reported by the PMS5003 increase linearly with relative humidity?

How are particles measured by regulatory-grade light scattering instruments?

Basic Optical Particle Counter (OPC)

Mie oh my: How much light would a particle scatter if a particle could scatter light?

Scattered light intensity at angle θ

Incident light Intensity

Wavelength

$$I(\theta) = \frac{I_o \lambda^2 (i_1 + i_2)}{8\pi^2 R^2}$$

distance away from particle

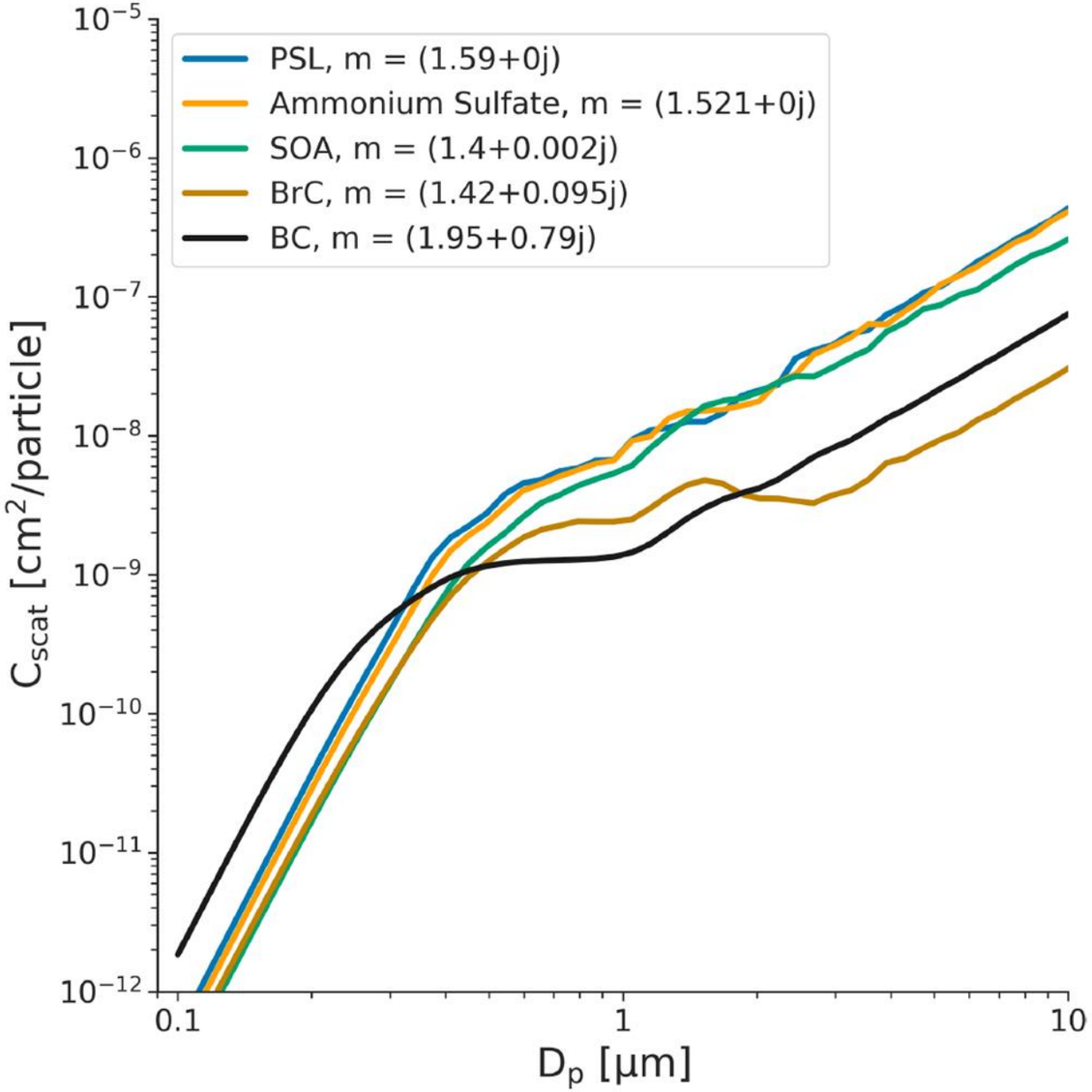
Mie intensity parameters

$i_1, i_2 = f(d_p, \lambda, \theta, m)$

particle diameter

particle refractive index

Retrieving particle size from an OPC



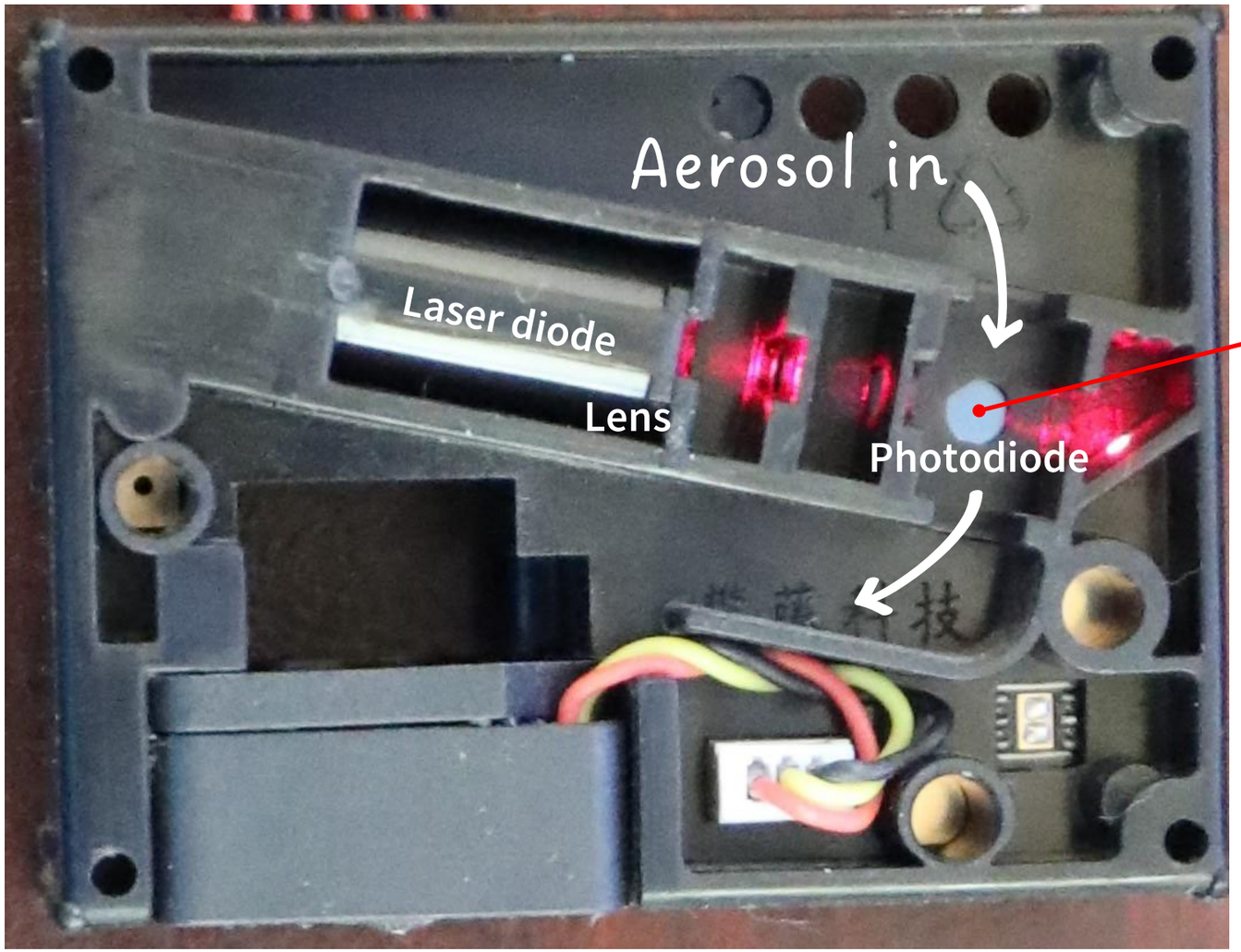
Hagan and Kroll Atmos. Meas. Tech. (2020) DOI: 10.5194/amt-13-6343-2020

Basic Optical Particle Counter (OPC)

Good for counting and sizing ~0.3-to-10-µm particles,
as long as particles pass through the focal point one at a time.

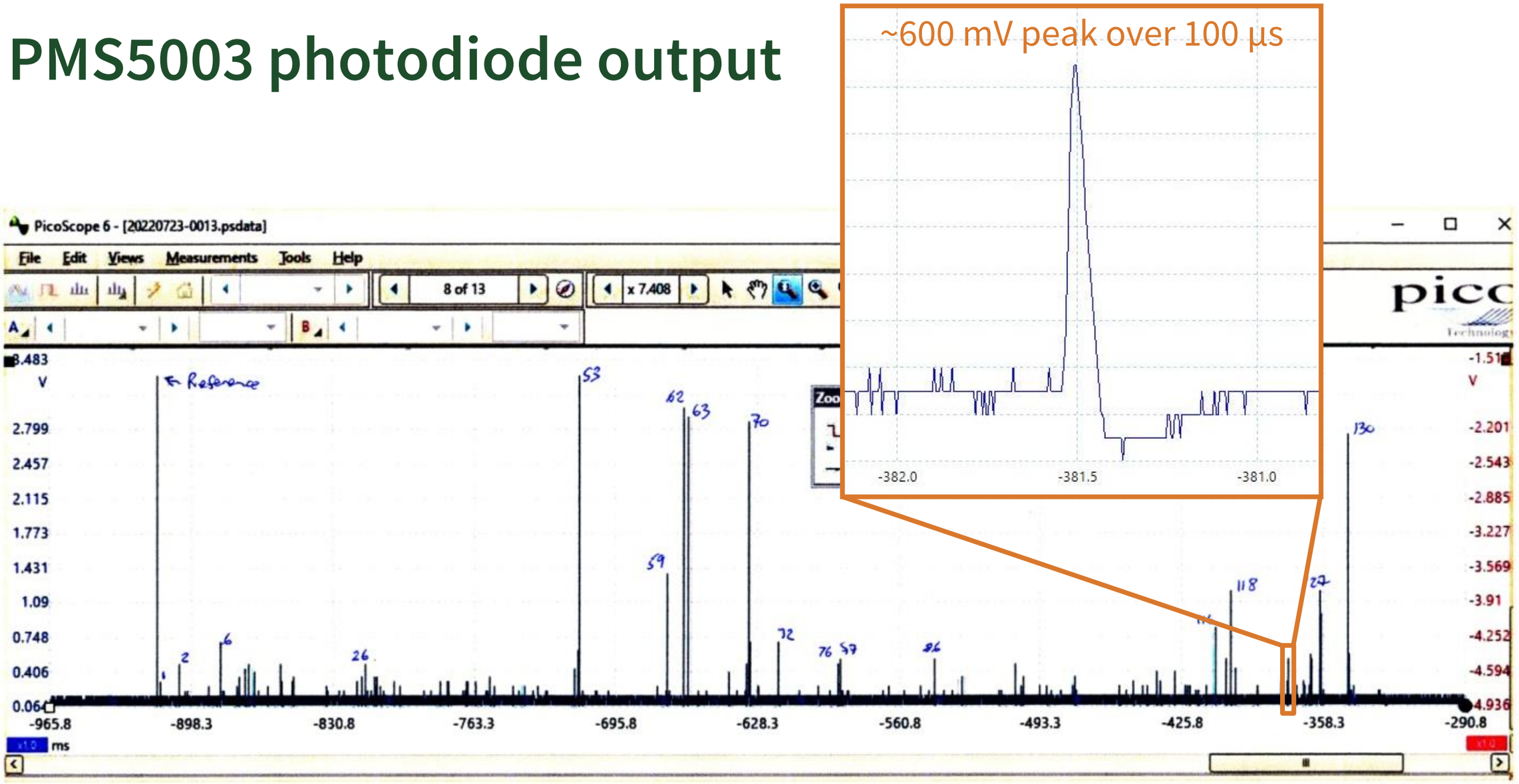
To what extent do PM sensors that cost ≤ $50 operate like conventional optical particle counters? Are they able to count and size individual particles?

Example: Plantower PMS5003 (used in PurpleAir monitor)

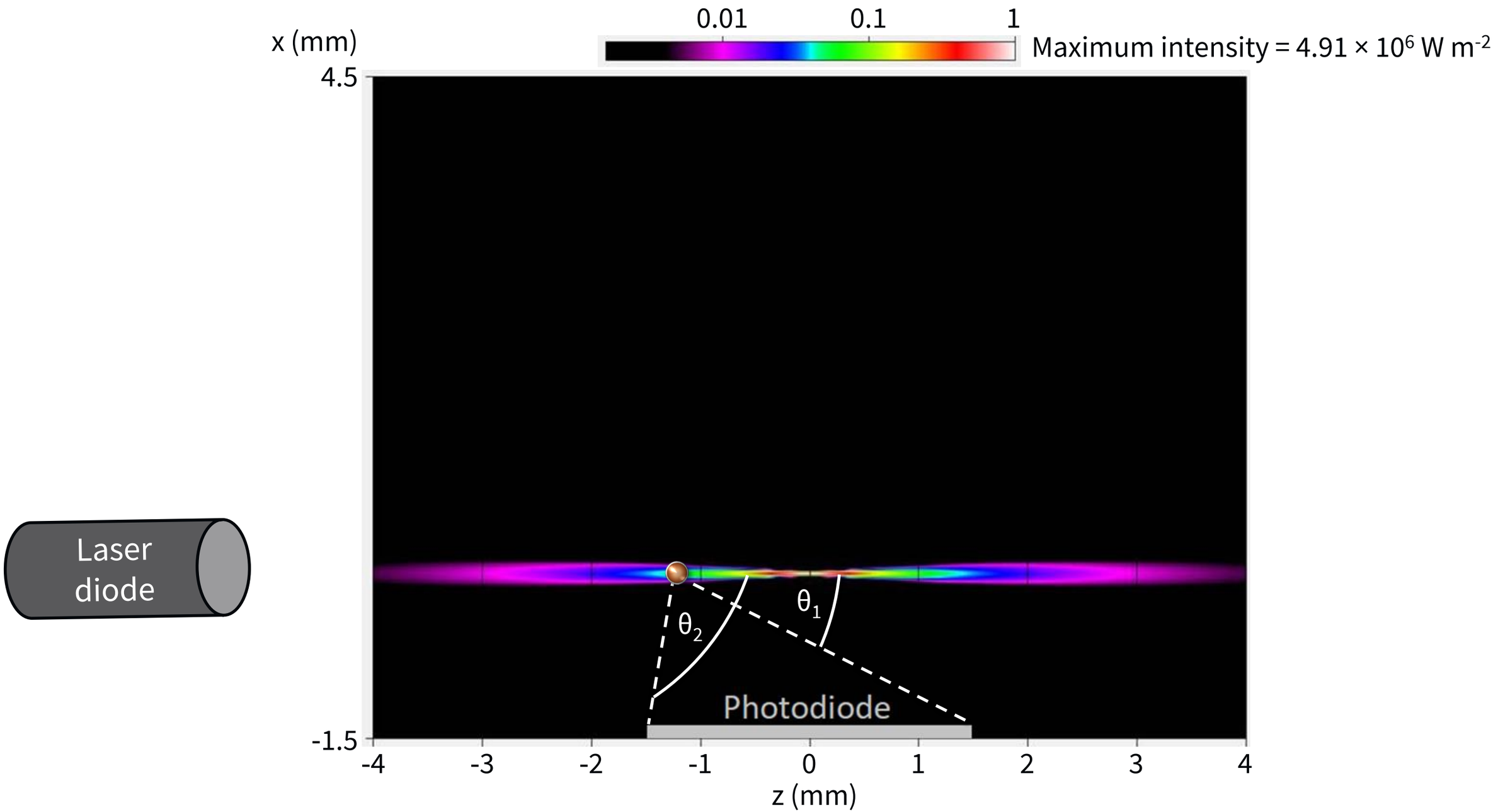


Ouimette et al. AS&T (submitted 2023)

PMS5003 photodiode output

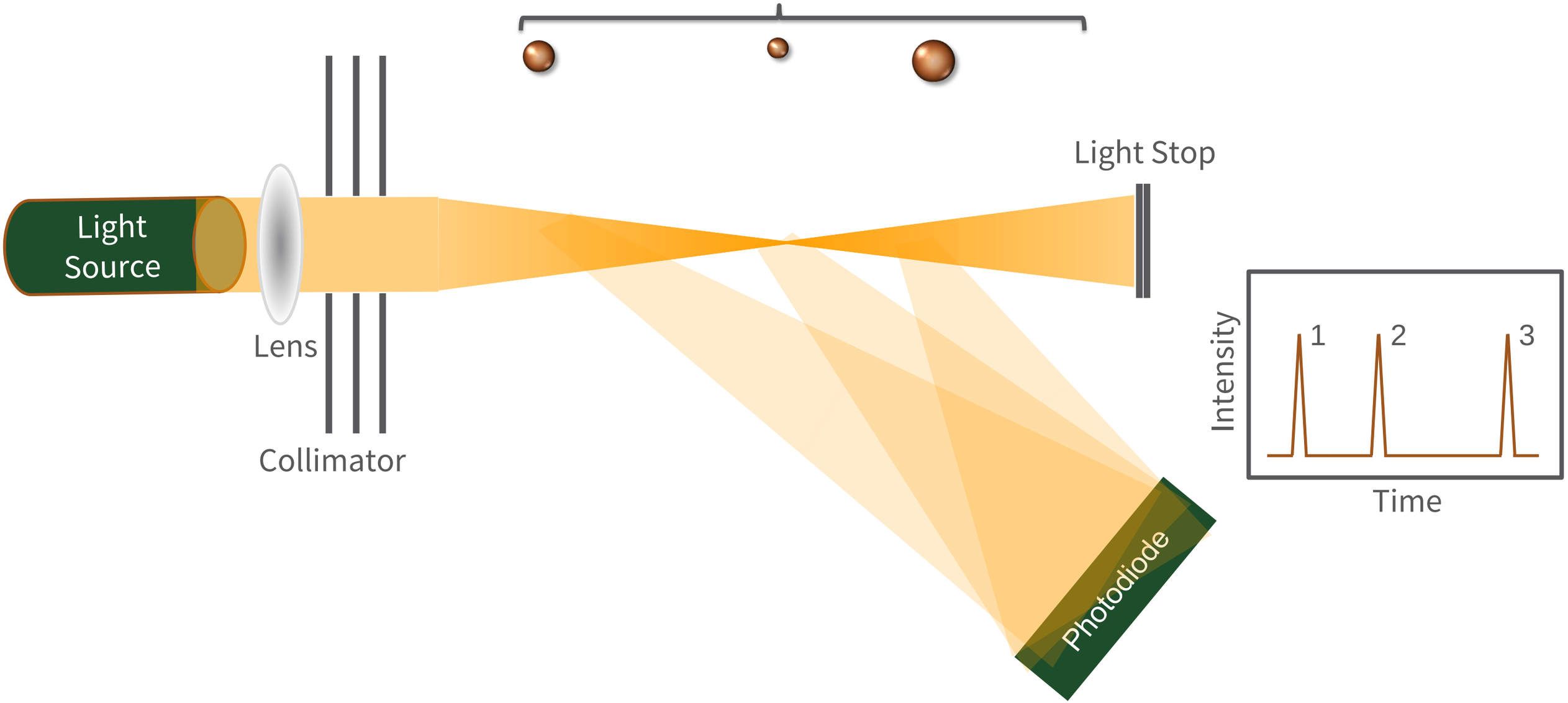


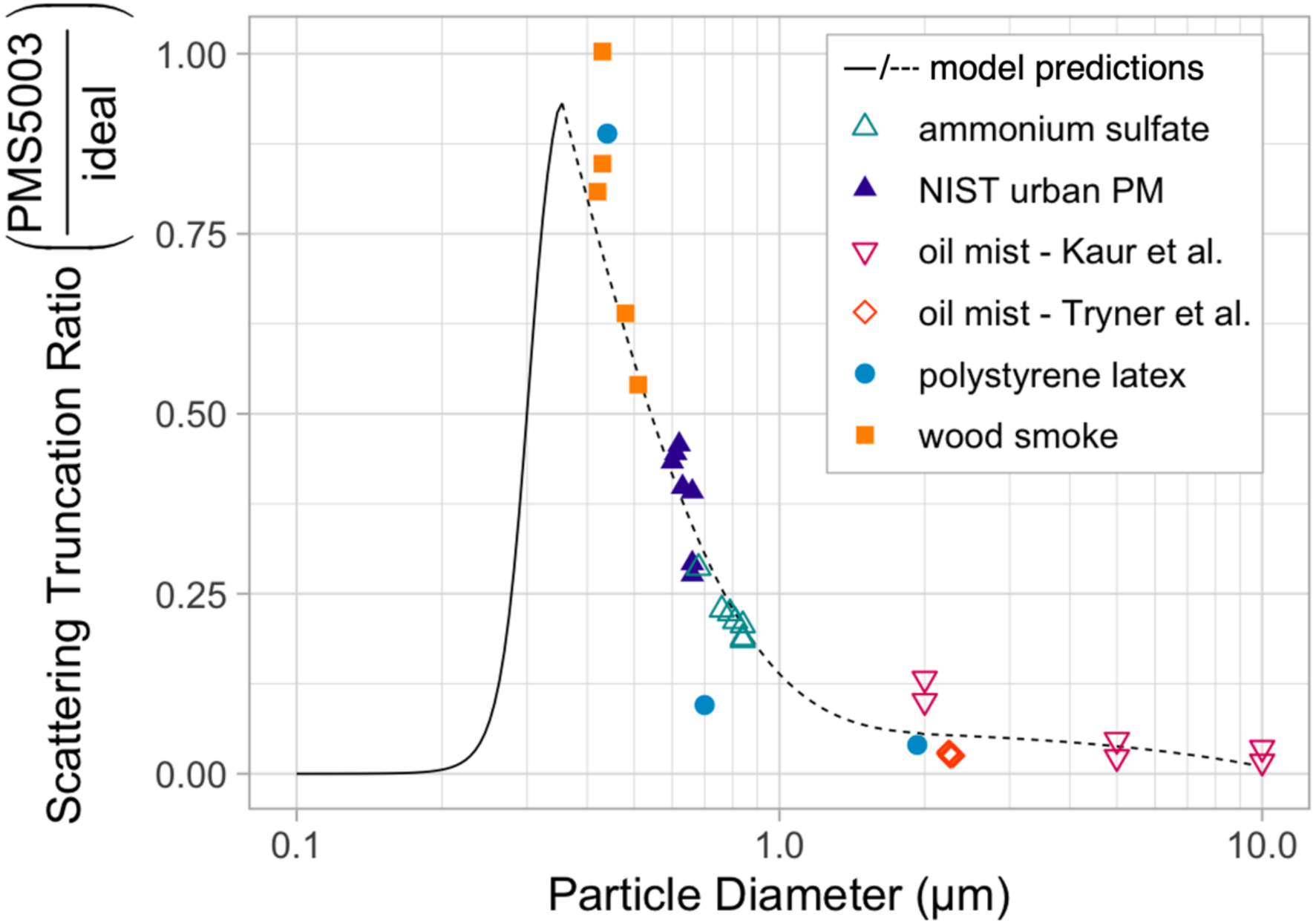
Ouimette et al. AS&T (submitted 2023)



Ouimette et al. AS&T (submitted 2023)

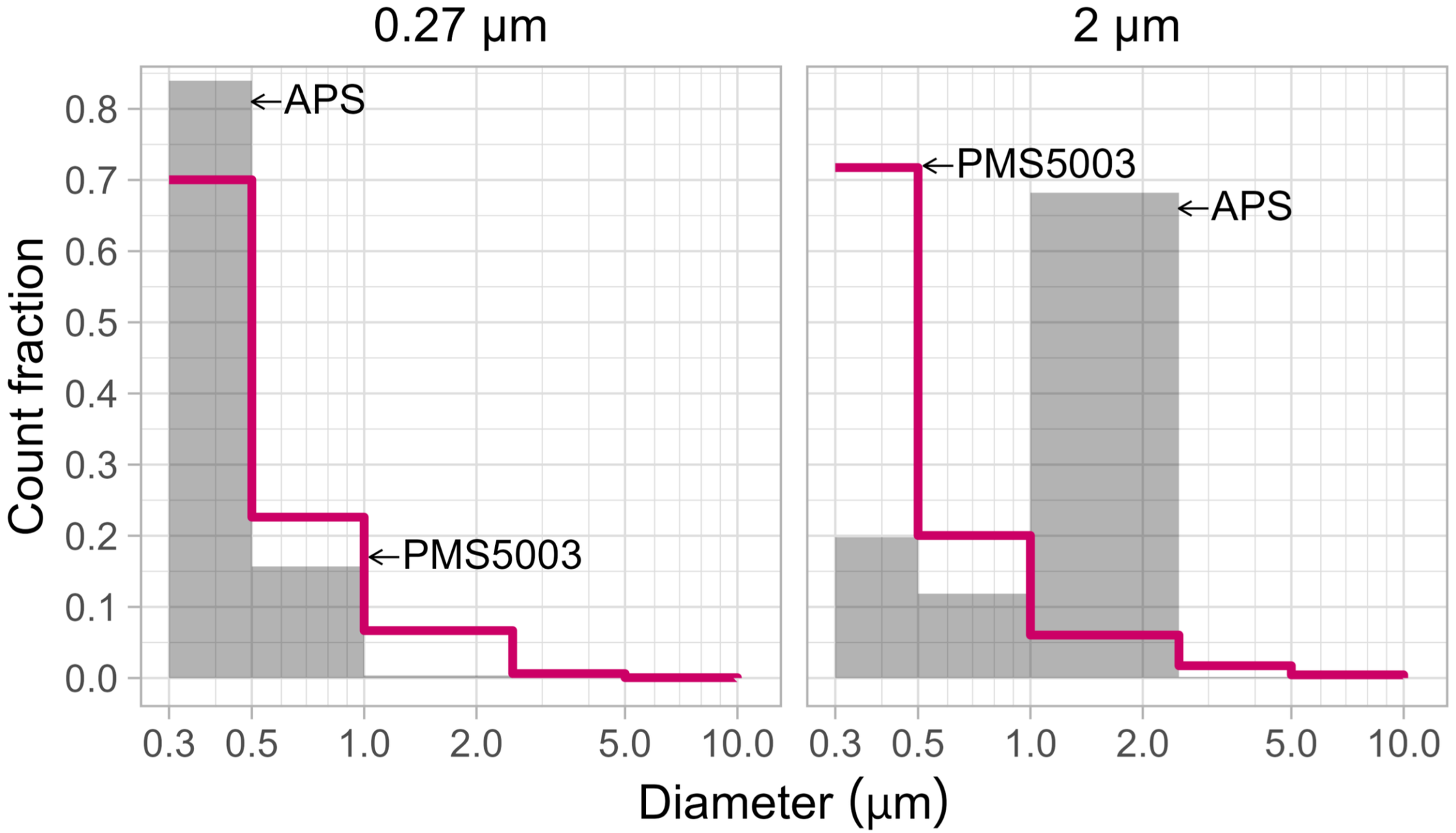
Aerosol flow is dispersed across the beam profile.
Most particles miss the laser focal point.



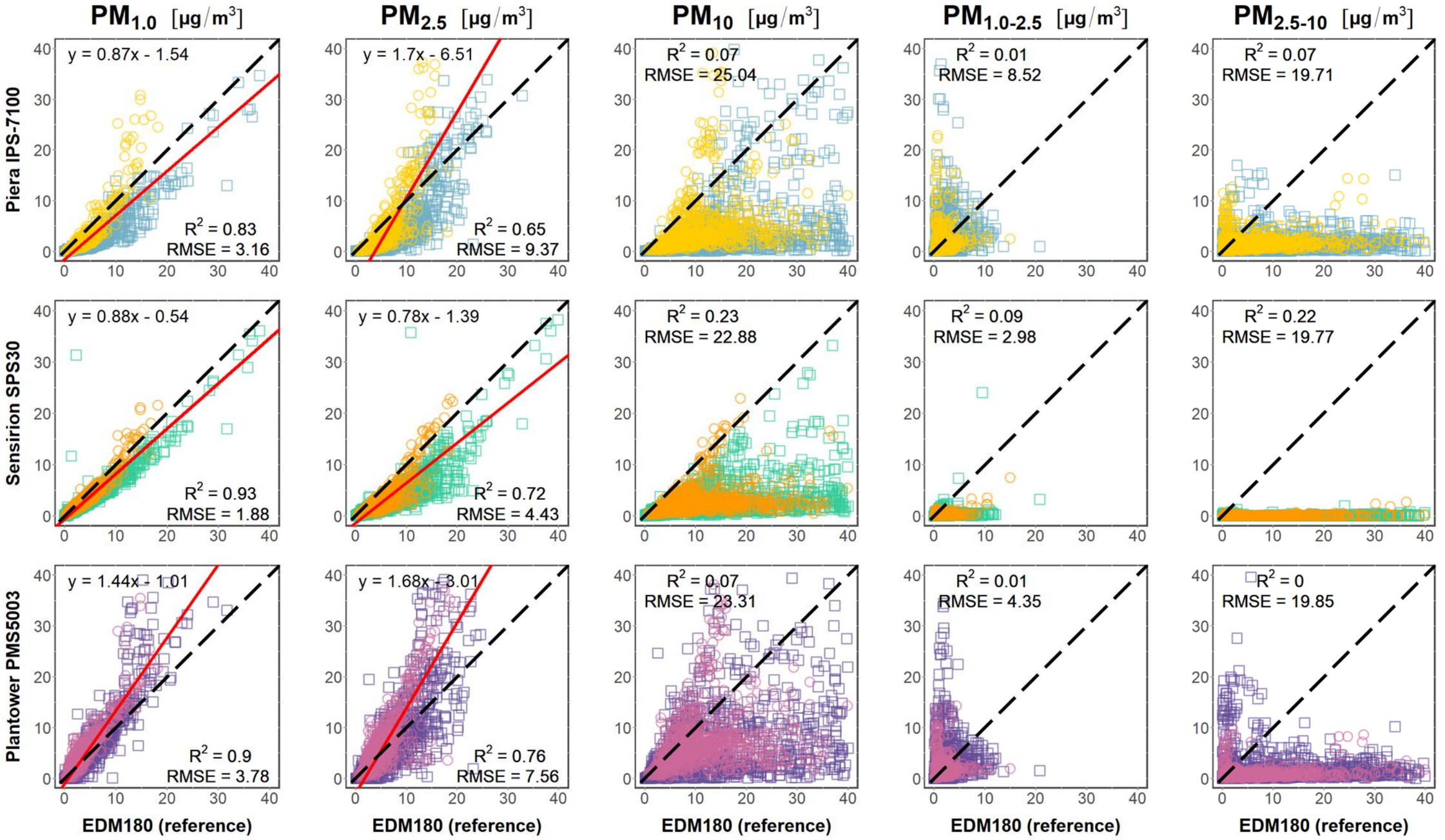


Ouimette et al. AS&T (submitted 2023)

What does this look like in practice?



Tryner et al. J. Aerosol Sci. (2020) DOI: 10.1016/j.jaerosci.2020.105654

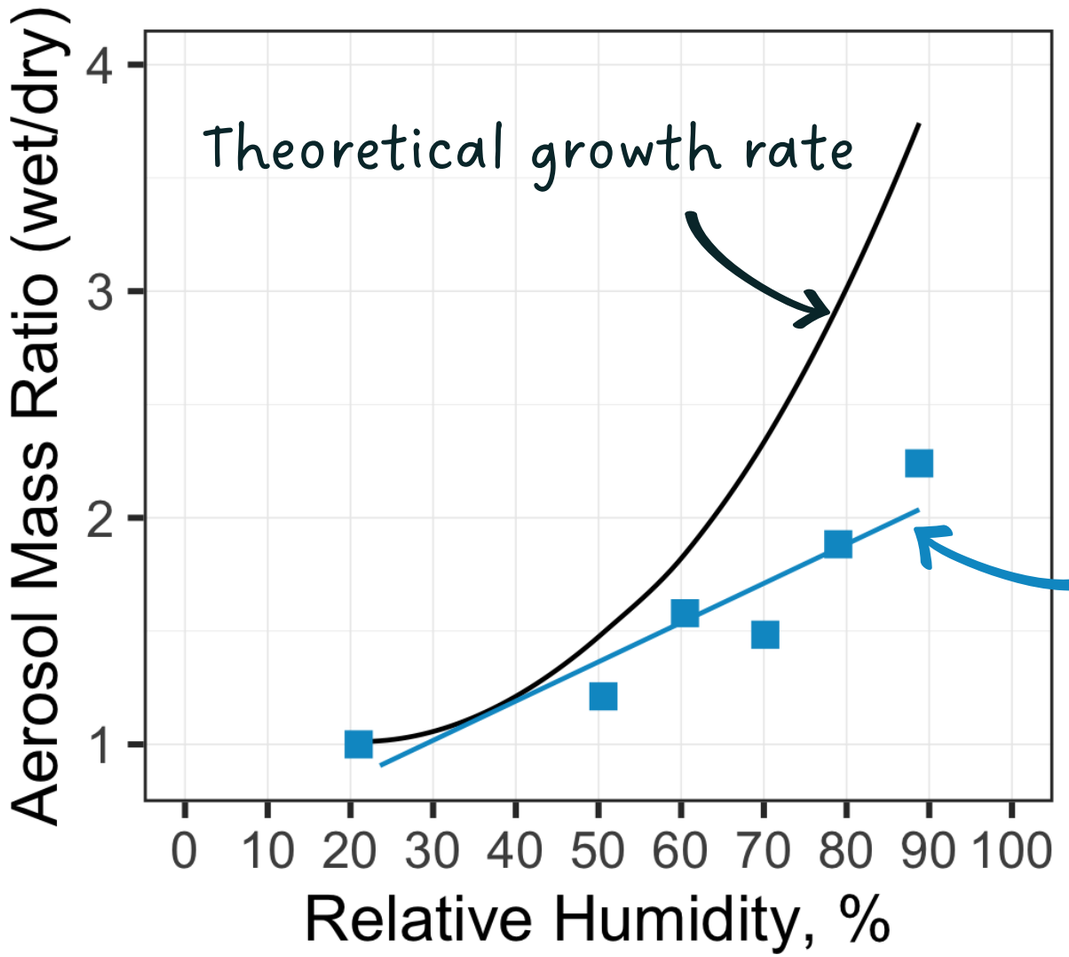


Fall/Winter conditions □ **Summer conditions** ○

Molina Rueda et al. ES&T Lett. (2023) DOI: 10.1021/acs.estlett.3c00030

$$PM_{2.5} = 0.52 \cdot PA_{raw} - 0.086 \cdot RH + 5.75$$

Barkjohn et al. (2021)
DOI: 10.5194/amt-14-4617-2021



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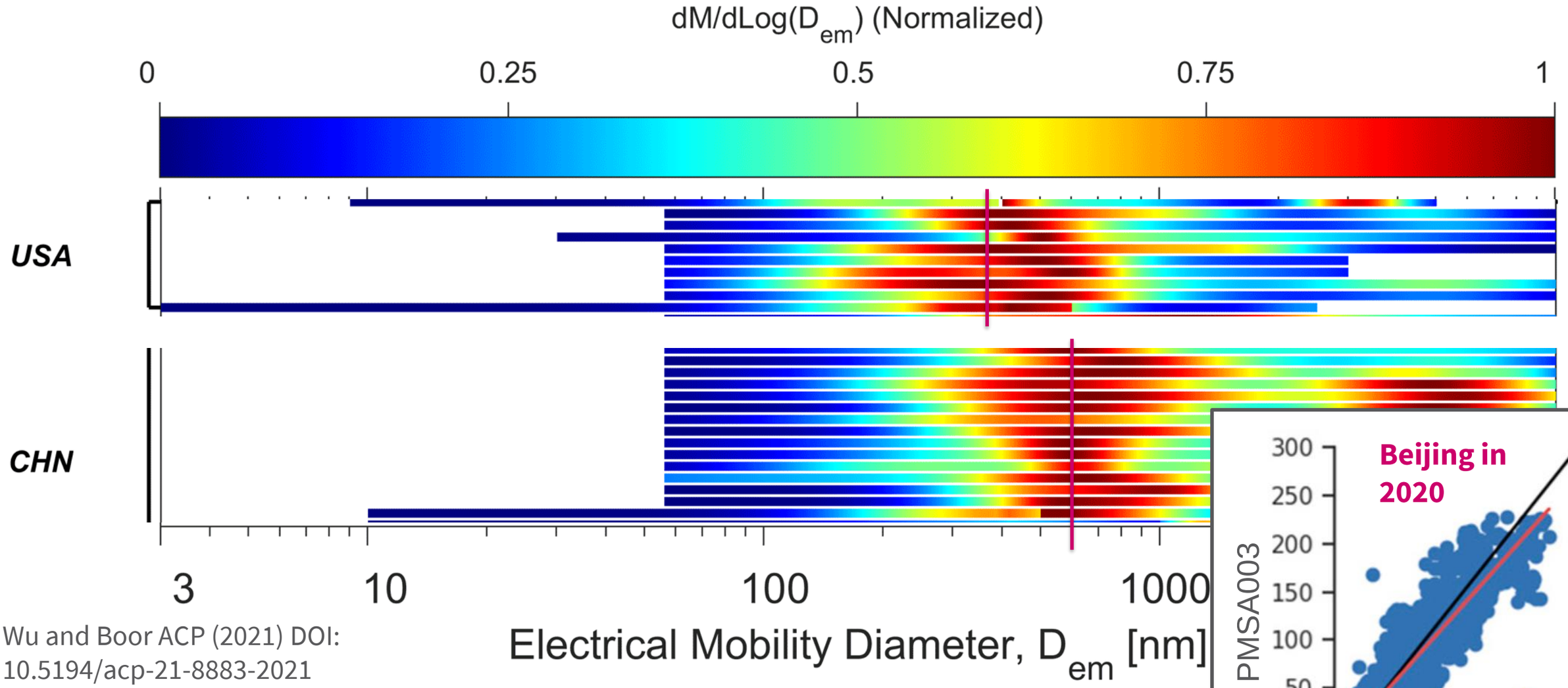

Wu and Boor ACP (2021) DOI:
10.5194/acp-21-8883-2021

Mei et al. Sensors (2020) DOI: 10.3390/s20164381

Take-home points

1. PM sensors that cost ≤$50 (e.g., Plantower PMS5003, Sensirion SPS30) are imperfect optical particle counters

2. They detect particles from 0.3 – 1 µm (with varying success).

3. Practical takeaways:
   - Particle number size distributions reported by PMS5003 are not accurate. Most particles are undersized by the sensor.
   - The U.S.-wide $PM_{2.5}$ correction developed at EPA for the PMS5003 sensor is consistent with the physics that govern sensor operation.
   - Efforts to calibrate sensors for $PM_{2.5}$ mass become more complicated when mass is dominated by supermicron particles (e.g., dust).
   - PMS5003, SPS30 sensors do not respond to the PM_{10}–$PM_{2.5}$ mass fraction.