Low-Cost IAQ Monitors:
Do you get what you pay for?

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Acknowledgements

- US Dept. of Energy Building America Program
- US Dept. of Housing & Urban Development Office of Healthy Homes
- US EPA Indoor Environments Division
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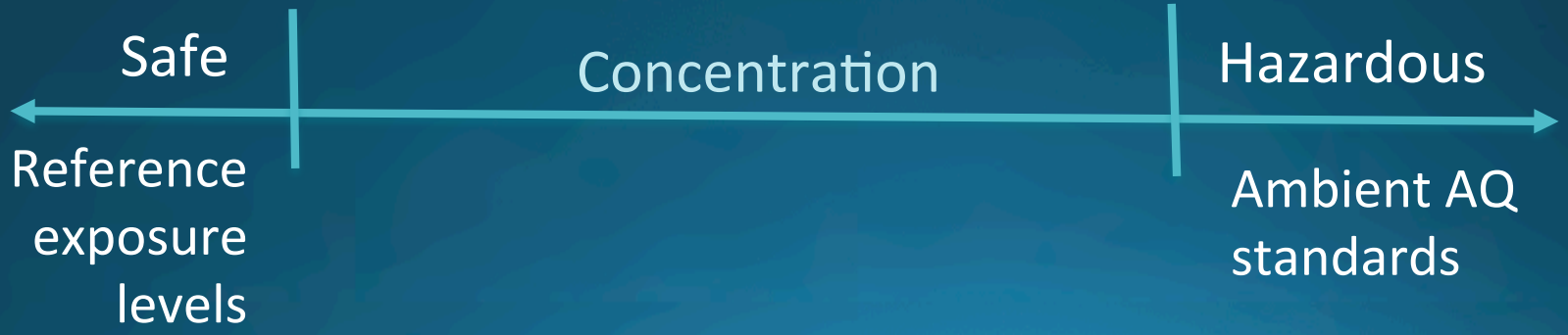
How do you rate the indoor air quality in your home?

- Excellent or very good
- Good / almost always acceptable
- Sometimes not acceptable
- Frequently not acceptable

What is the biggest problem or risk to indoor air quality in your home?

What is good indoor air quality?

- No unpleasant odors
- Air seems “fresh” and pleasant
- Comfortable temperature and humidity
- Allergens minimized
- No dampness or mold issues
- **Pollutant concentrations at safe levels**

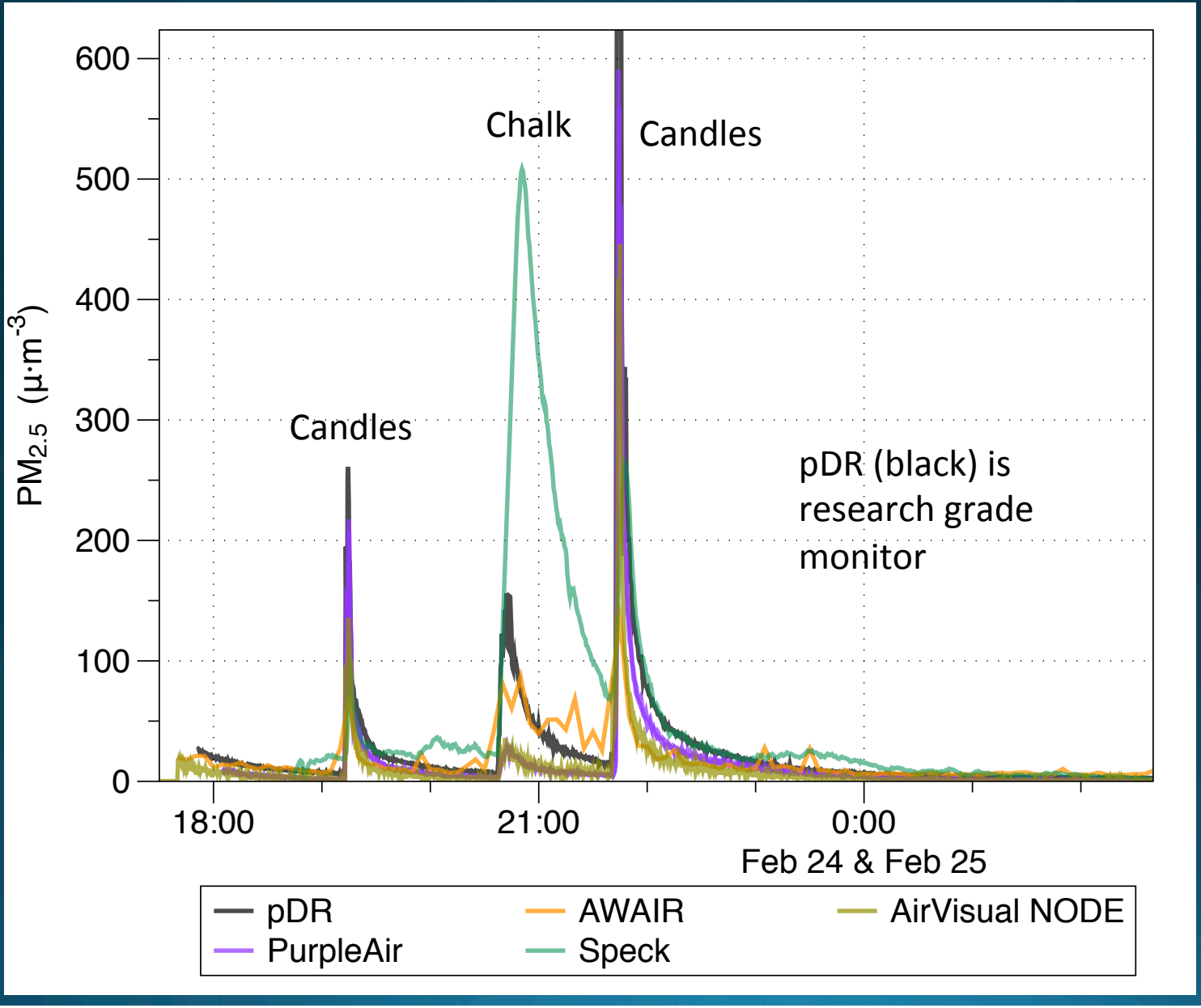


Why do we need IAQ monitors?

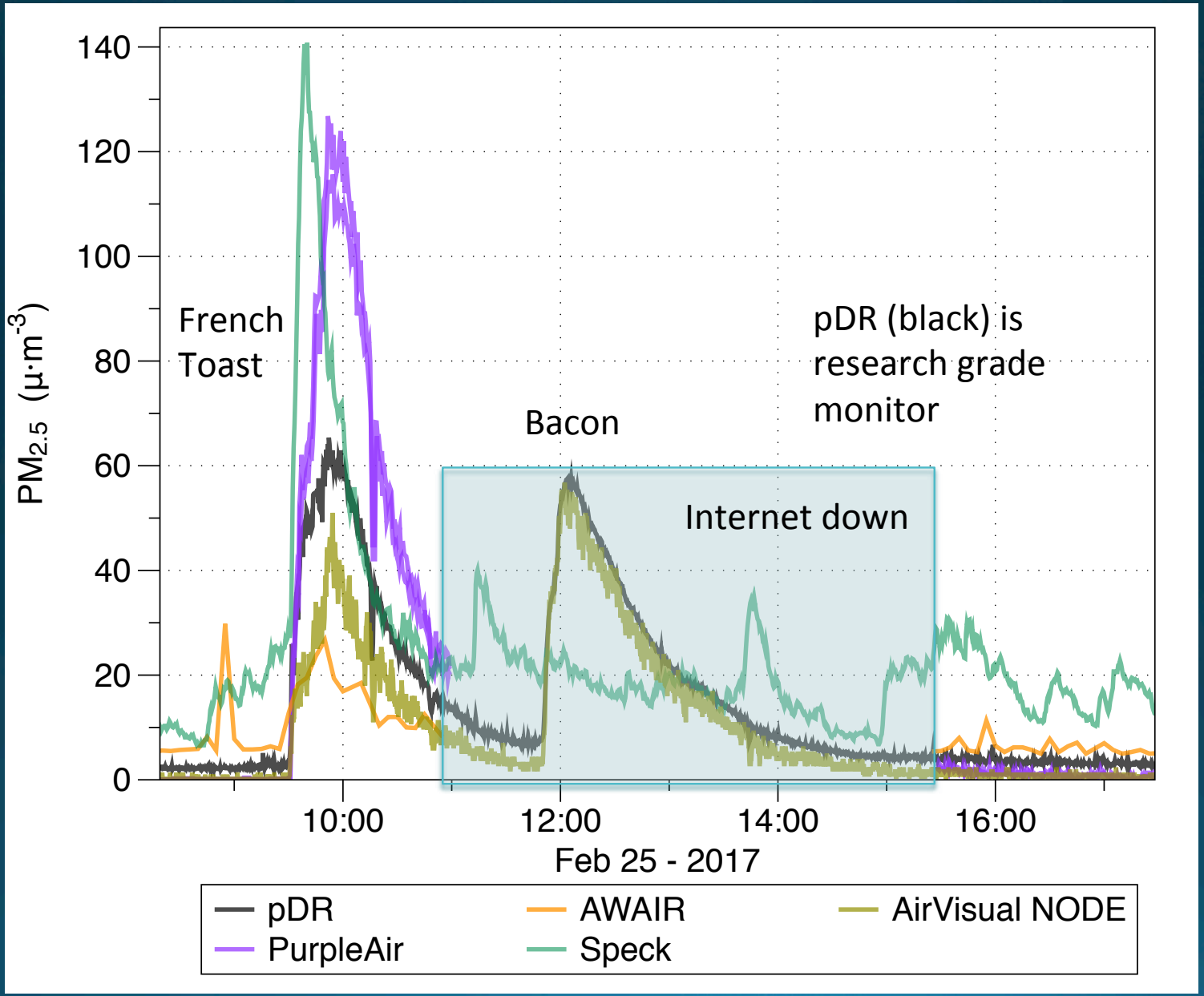
- Measure things we can't perceive
- Early warning of hazard
- Closed loop control

- Data to evaluate controls or pre / post retrofit
- Track system performance over time

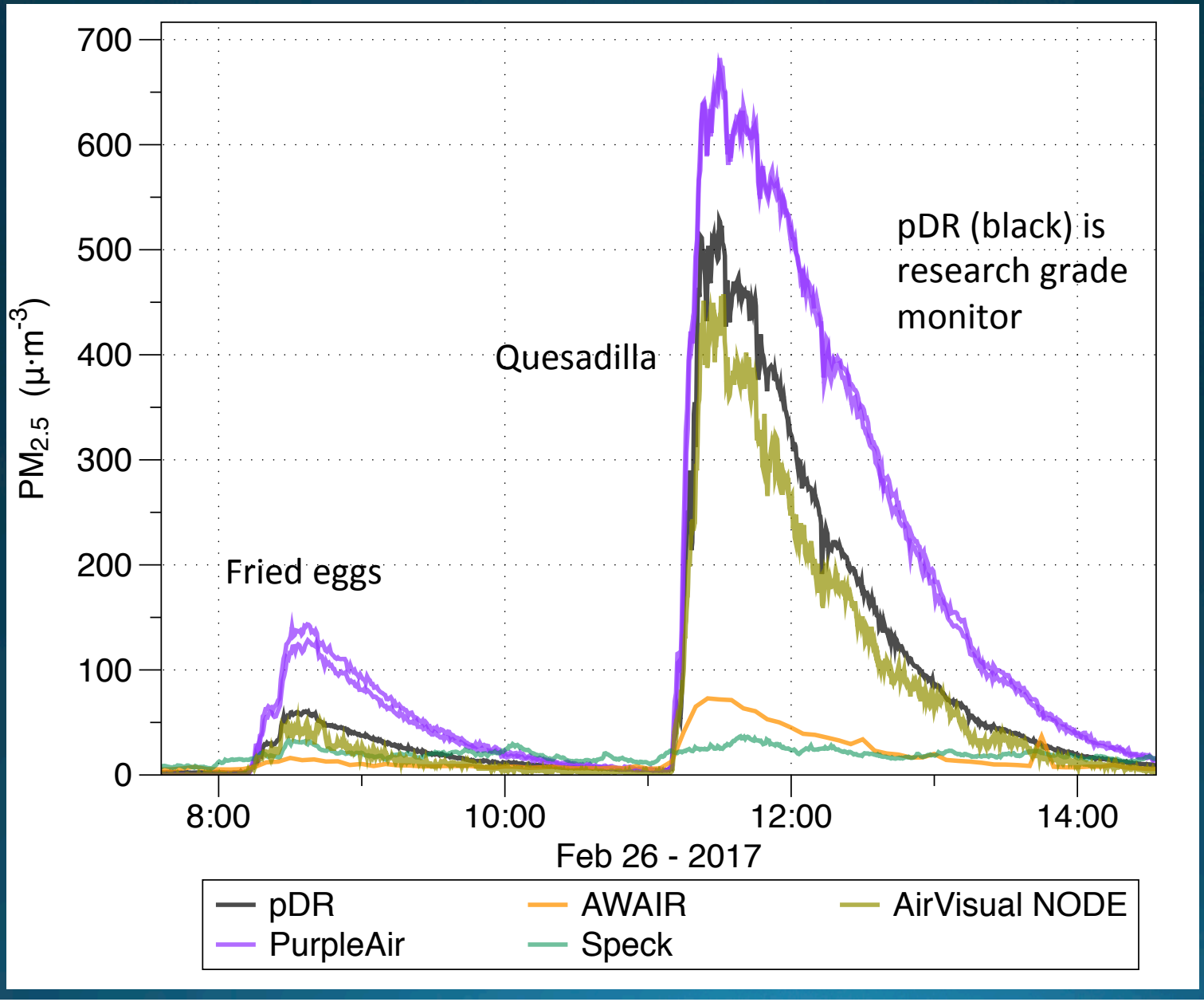
Example data low-cost particle monitors



Example data low-cost particle monitors



Example data low-cost particle monitors



Which IAQ parameters would we like to measure in homes?

- Temperature and humidity
- CO_2 for demand control ventilation
- Total VOC
- Odors

- Indoor pollutants
  - $PM_{2.5}$, PM_{10}, ultrafines
  - Acrolein, NO_2, CO
  - Formaldehyde, radon
  - Irritants
  - Allergens
- Outdoor pollutants
  - Diesel PM / black carbon
  - Ozone
  - $PM_{2.5}$, PM_{10}, ultrafines, NO_2
- Dampness & mold

Which IAQ parameters would we like to measure in homes?

- Temperature and humidity
- CO_2 for demand control ventilation
- TVOC
- Odors

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- Dampness & mold

Which IAQ parameters would we like to measure in homes?

- Temperature and humidity
- CO_2 for demand control ventilation
- TVOC
- ~~Odors~~

People detect these easily

- Indoor pollutants
  - $PM_{2.5}$, PM_{10}, ultrafines
  - Acrolein, NO_2, CO
  - Formaldehyde, radon
  - ~~Irritants~~
  - ~~Allergens~~
- Outdoor pollutants
  - Diesel PM / black carbon
  - Ozone
  - $PM_{2.5}$, PM_{10}, ultrafines, NO_2
- ~~Dampness & mold~~

Which IAQ parameters would we like to measure in homes?

- Temperature and humidity
- CO_2 for demand control ventilation
- TVOC
- ~~Odors~~

Nothing accurate and affordable is available

- Indoor pollutants
  - $PM_{2.5}$, PM_{10}, ~~ultrafines~~
  - ~~Acrolein~~, NO_2, CO
  - Formaldehyde, radon
  - ~~Irritants~~
  - ~~Allergens~~
- Outdoor pollutants
  - Diesel PM / black carbon
  - Ozone
  - $PM_{2.5}$, PM_{10}, ~~ultrafines~~, NO_2
- ~~Dampness & mold~~

Which IAQ parameters would we like to measure in homes?

- Temperature and humidity
- CO_2 for demand control ventilation
- VOCs
- ~~Odors~~

Can detect relevant levels, but expensive and requires frequent calibrations

- Indoor pollutants
  - $PM_{2.5}$, PM_{10}, ~~ultrafines~~
  - ~~Acrolein~~, NO_2, CO
  - Formaldehyde, radon
  - ~~Irritants~~
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Which IAQ parameters would we like to measure in homes?

- Temperature and humidity
- CO_2 for demand control ventilation
- VOCs
- ~~Odors~~

Relatively inexpensive time-integrated tests available

- Indoor pollutants
  - $PM_{2.5}$, PM_{10}, ~~ultrafines~~
  - ~~Acrolein~~, NO_2, CO
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  - ~~Irritants~~
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Which IAQ parameters would we like to measure in homes?

- Temperature and humidity
- CO_2 for demand control ventilation
- VOCs
- ~~Odors~~

Inexpensive sensors available, accurate enough and durable (2+y)

- Indoor pollutants
  - $PM_{2.5}$, PM_{10}, ~~ultrafines~~
  - ~~Acrolein~~, NO_2, CO
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- ~~Dampness & mold~~

Which IAQ parameters would we like to measure in homes?

- Temperature and humidity
- CO_2 for demand control ventilation
- VOCs
- ~~Odors~~

Inexpensive sensors available and accurate enough; durability uncertain

- Indoor pollutants
  - $PM_{2.5}$, PM_{10}, ~~ultrafines~~
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  - Formaldehyde, radon
  - ~~Irritants~~
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Which IAQ parameters would we like to measure in homes?

- Temperature and humidity
- CO_2 for demand control ventilation
- VOCs
- ~~Odors~~

Inexpensive and accurate enough sensors being used for research

- Indoor pollutants
  - $PM_{2.5}$, PM_{10}, ~~ultrafines~~
  - ~~Acrolein~~, NO_2, CO
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  - ~~Irritants~~
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Which IAQ parameters would we like to measure in homes?

- Temperature and humidity
- CO_2 for demand control ventilation
- VOCs
- ~~Odors~~

Inexpensive

Available, but costly

Coming soon

- Indoor pollutants
  - $PM_{2.5}$, PM_{10}, ~~ultrafines~~
  - ~~Acrolein~~, NO_2, CO
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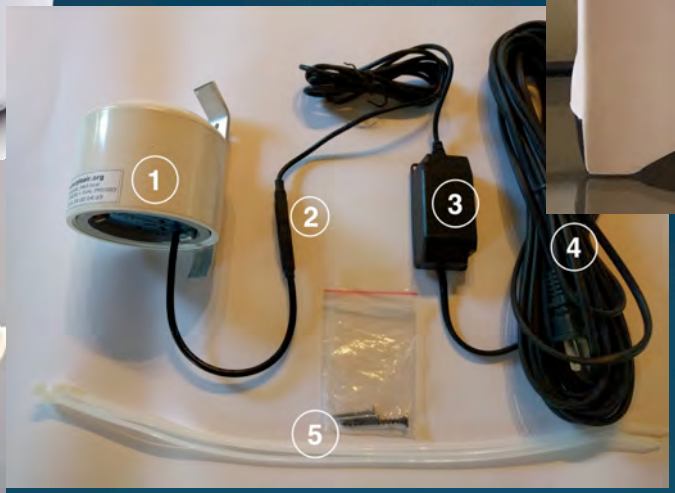
What's available to measure home IAQ?



What's available to measure home IAQ?

Device	Price	Temp	RH	CO_2	VOC	$PM_{2.5}$	PM_{10}	CO	Ozone	NO_2
Birdi (NA)	$119	●	●	●	●	●				
Koto Air Cubes	$139	●	●	●						
Netatmo	$149	●	●	●						
Speck	$149	●				●				
Airmentor	$183	●	●	●	●	●	●	●		
Awair	$199	●	●	●	●	●	●			
BlueAir-Aware	$199	●	●	●	●	●	●			
Foobot	$199	●	●	●	●	●		●		
Air Quality Egg	$280	●	●			●	●	●	●	
Dylos-DC 1100	$290					●	●			
uHoo (NA)	$299	●	●	●	●	●		●	●	

Is the specified range relevant?

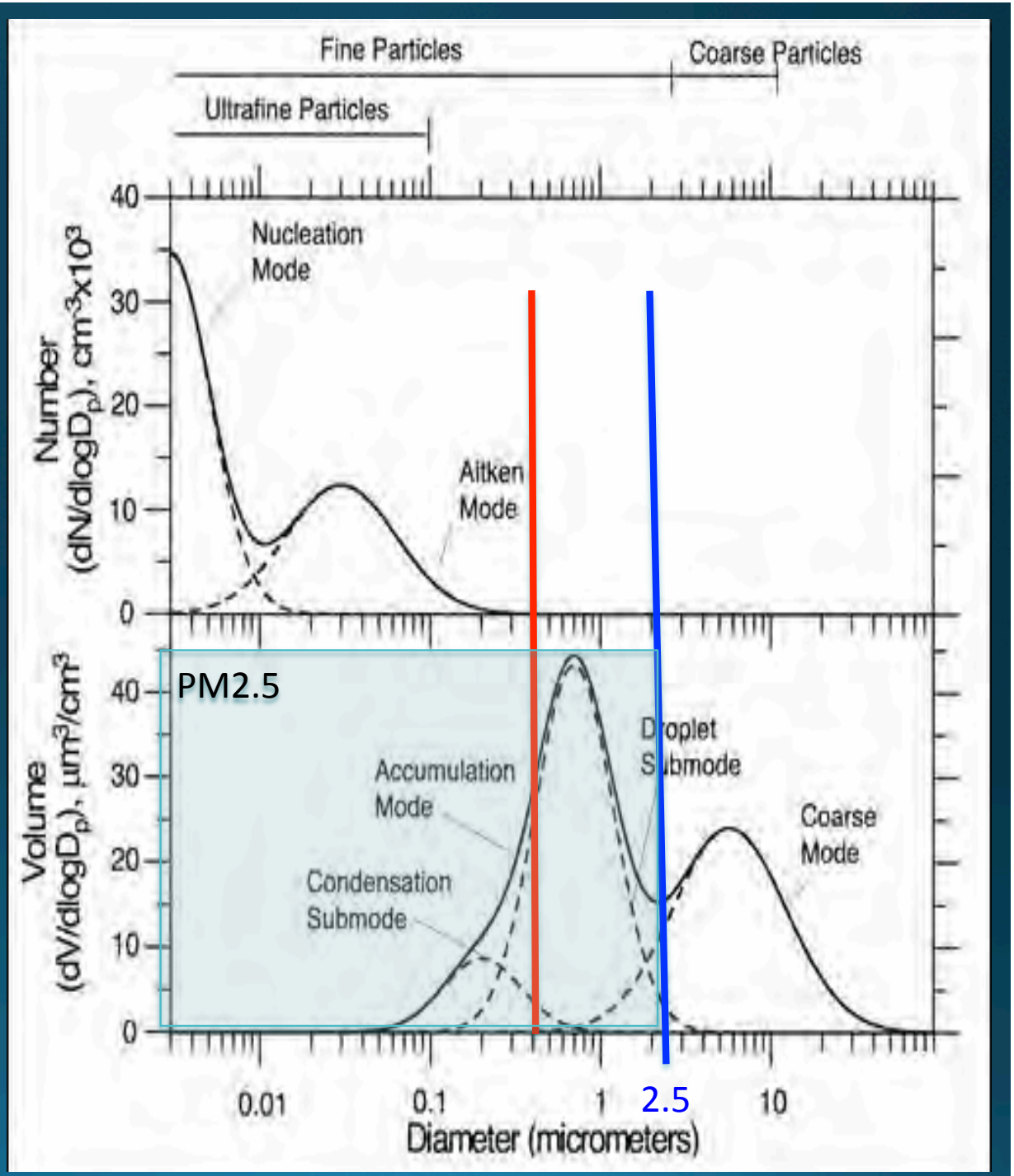
Device	Price	Temp	RH	CO_2	VOC	$PM_{2.5}$	PM_{10}	CO	Ozone	NO_2
Birdi (NA)	$119	●	●	●	●	●				
Koto Air Cubes	$139	●	●	●						
Netatmo	$149	●	●	●						
Speck	$149	●				●				
Airmentor	$183	●	●	●	●	●	●	●		
Awair	$199	●	●	●	●	●	●			
BlueAir-Aware	$199	●	●	●	●	●	●			
Foobot	$199	●	●	●	●	●		●		
Air Quality Egg	$280	●	●			●	●	●	●	
Dylos-DC 1100	$290					●	●			
uHoo (NA)	$299	●	●	●	●	●		●	●	

● Yes ● Somewhat ● No ● Not clear from product literature

Credit: Lauren Lawson

Particles 101

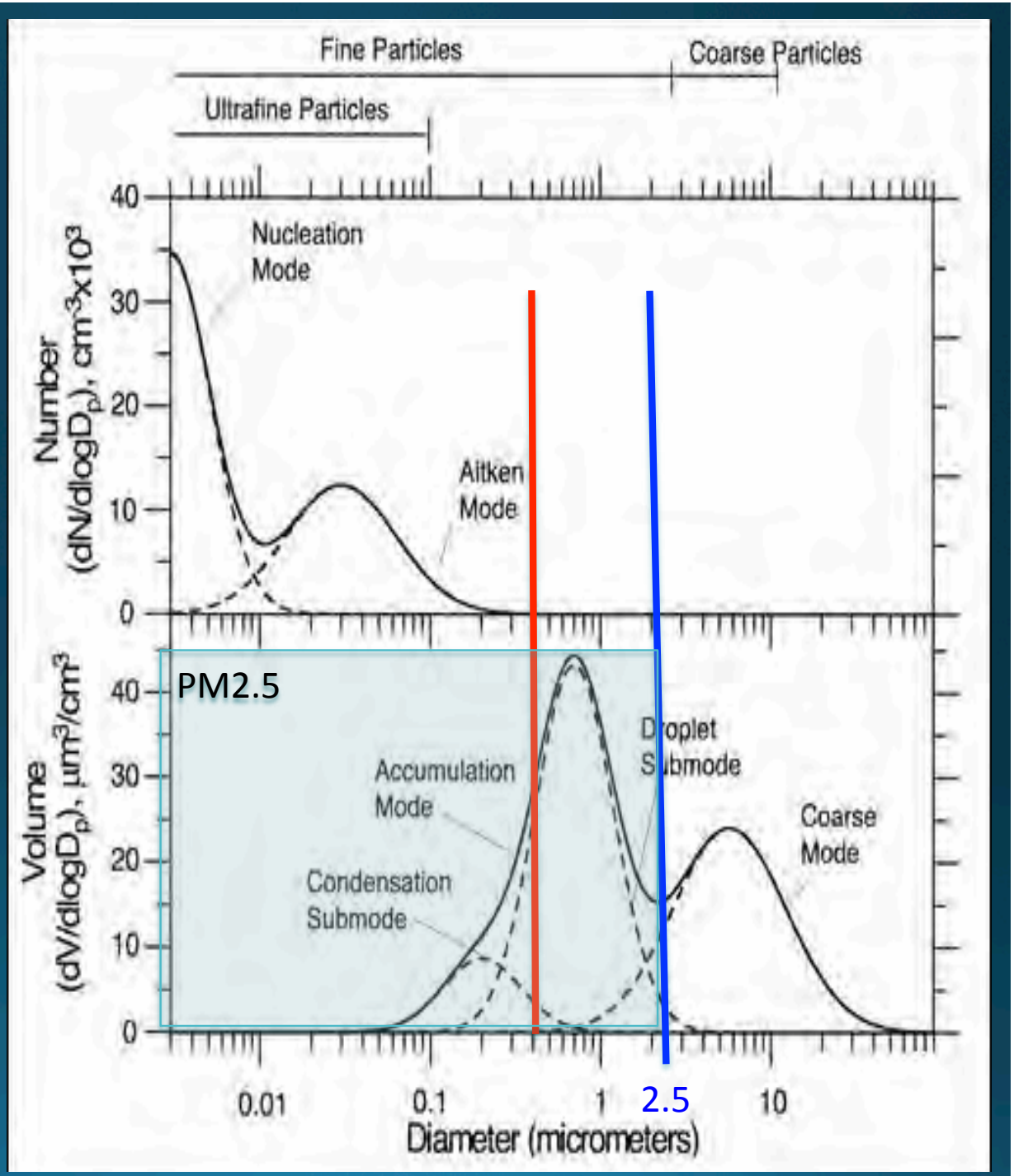
- "Particulate matter" or PM is comprised of particles with varied size & composition.
- Composition varies by source & changes w/ environment.
- Can describe PM by mass, volume or number of particles in volume of air.
- $PM_{2.5}$ is the mass concentration of particles smaller than 2.5 um diameter.



Source: NARSTO (2004)

Particles 101

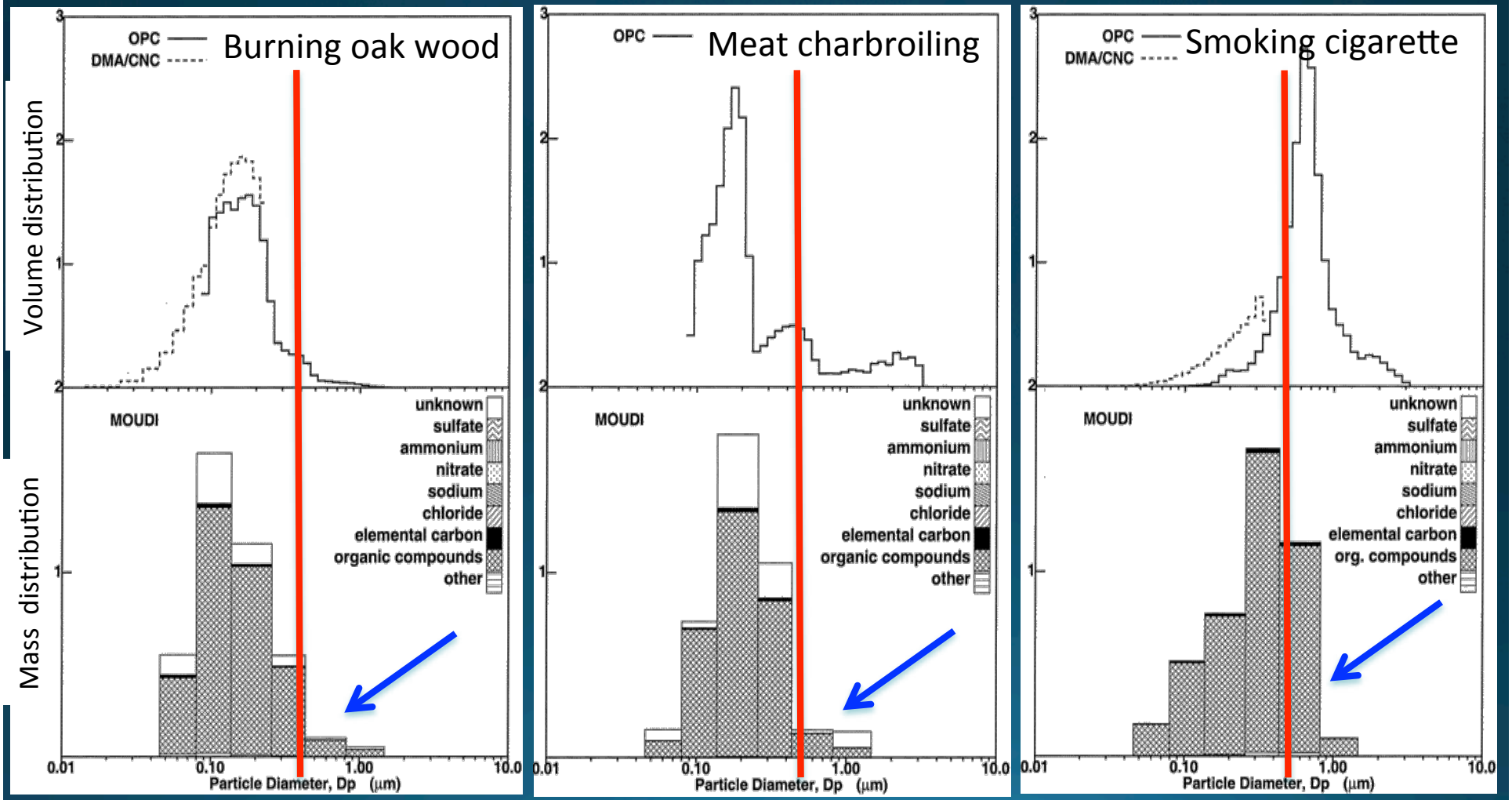
- Many low-cost sensors only see larger particles, e.g., >0.5 um or >1 um.
- Some see particles <0.3 um.
- They estimate total PM based on what they see.
- Some sensors only provide particle counts. Some provide estimates of $PM_{2.5}$



Source: NARSTO (2004)

Particle mass distribution varies by source
Many indoor sources mostly <0.5um

Low cost sensors see only the part to right of red line



Kleeman, Schauer, Cass (1999) ES&T

Multiple ways to measure PM

- Collect on a filter

Integrated number
(hours – day)

- Beta-attenuation
- Real-time micro balance
- Optical methods
  - Scattering
  - Laser particle counters

Real-time
(seconds – hour)

Research devices:
$1000s to >$10K

Laser-based particle counters

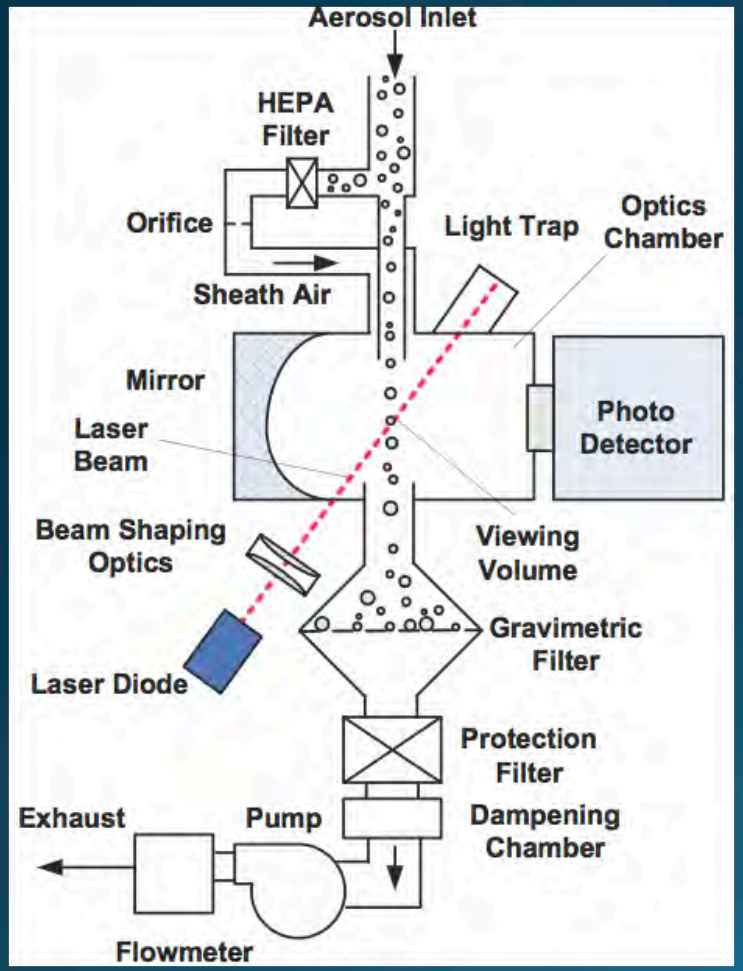
- Is like looking out a narrow doorway
- Something passes by and blocks the doorway generating a pulse
- Longer / bigger pulse is a bigger particle

Scattering Light

Mie scattering due to fog (water droplets)

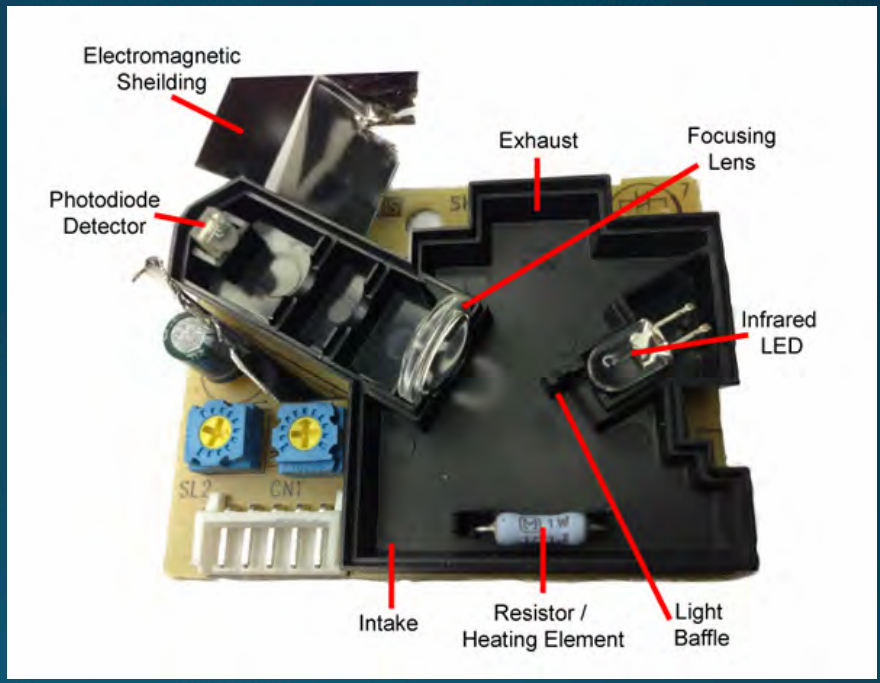
Heart of an optical sensor

Research grade



OEM pricing $100s

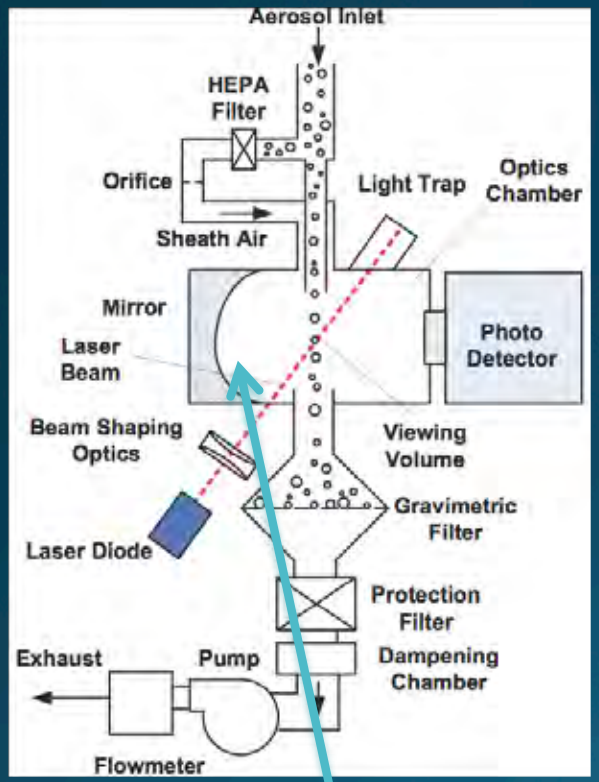
Low cost device



Bare sensor OEM pricing $4 - $15

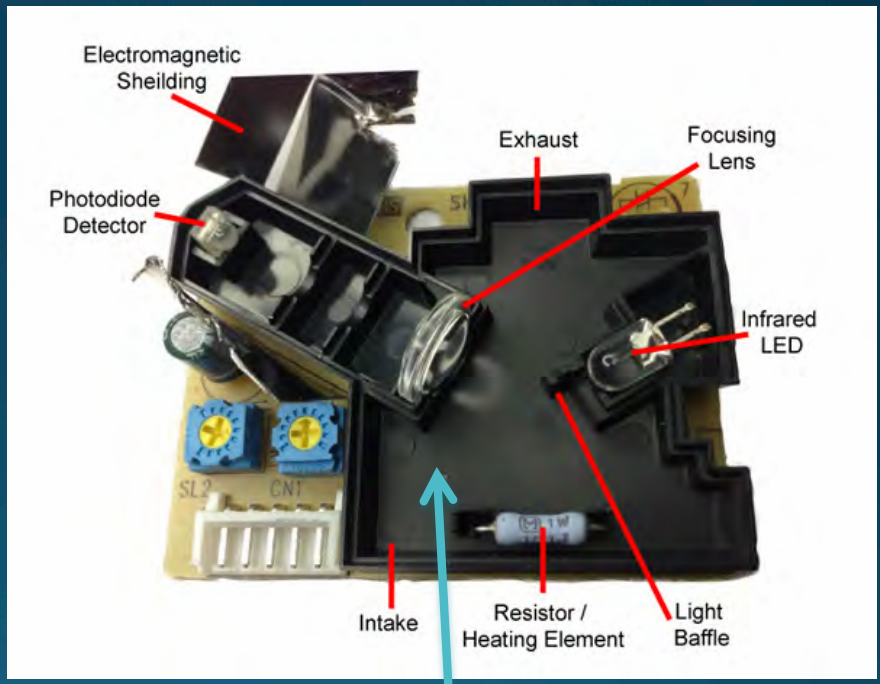
Heart of an optical sensor

Research grade



Machined housing
Close tolerances

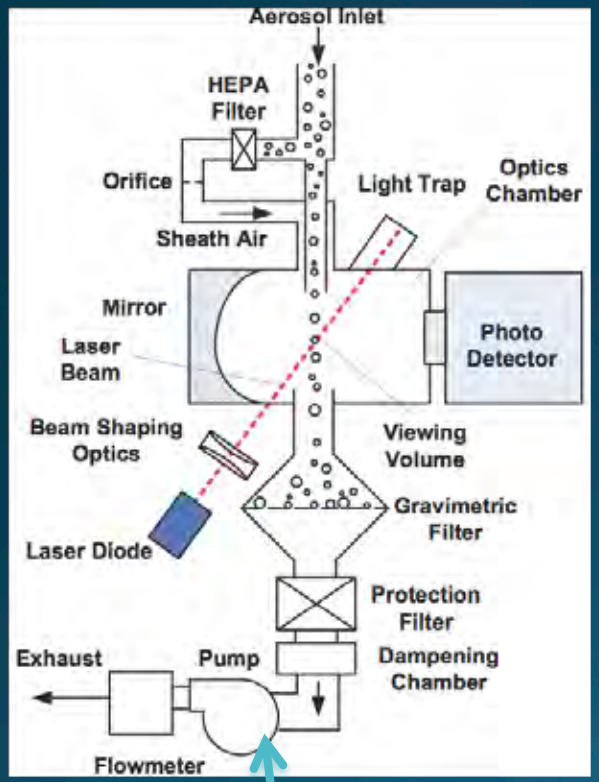
Low cost device



Molded plastic housing
Tolerances?

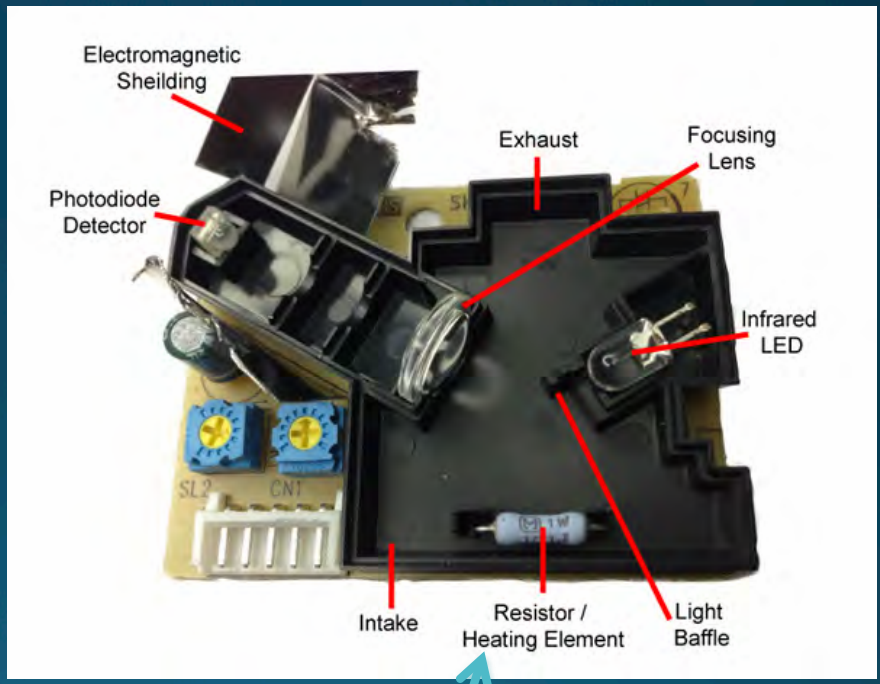
Heart of an optical sensor

Research grade



Pump for controlled flows

Low cost device

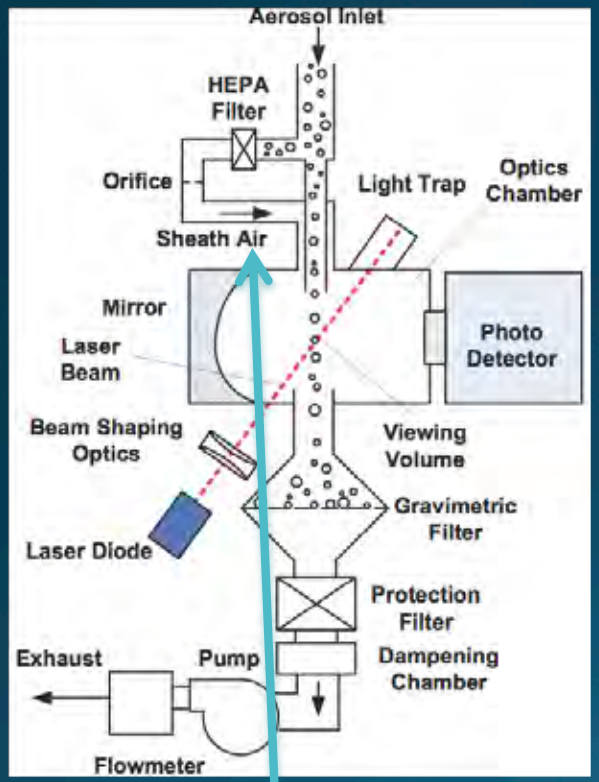


Heater induces a flow through the device

Control?

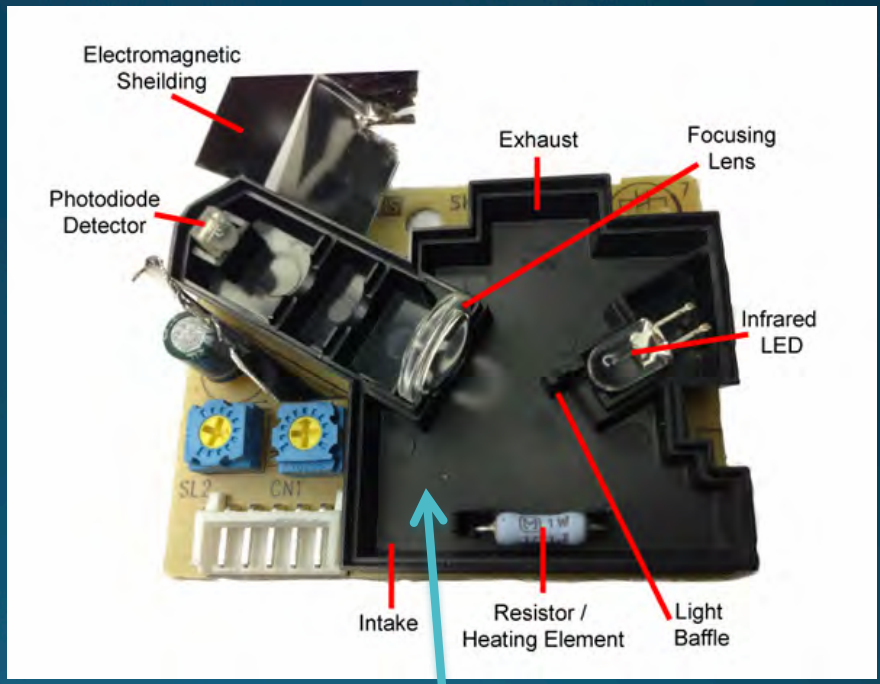
Heart of an optical sensor

Research grade



Sheath flow keeps the optical chamber clean

Low cost device



Optical chamber gets loaded with dust, potentially changing the flow and response

Packaged devices ~$200

- A pleasing box that may have a display or glow according to the perceived IAQ
- May have additional sensors (CO_2, VOC, …)
- Cloud storage 

- Possibility of controlling things

Build your own monitor (BYOM)

- **UPOD: Open source platform for mobile air quality monitoring**

  University of Colorado, Boulder

  http://mobilesensingtechnology.com/

  T, RH, P, CO_2, O_3, NO_2; slots for 4 e2v MOx sensors

- **Open Source Building Science Sensors**

  Illinois Institute of Technology

  http://www.osbss.com/

  T, RH, CO_2, Particles,

  delta–P, equilibrium RH, light

  state, proximity, occupancy

DIY / Maker offerings

- Perhaps a robust sensor, and the ability to do what you want
- A community is springing up offer parts lists and plans for devices
- ~$50

Performance Considerations

Sensor Characteristics

- Sensitivity & accuracy
- Reliability & durability
- Stability
- Selectivity
- Fault detection

Device Characteristics

- Cost
- Smart home platform
- Data accessibility
- Data visualization
- Dashboard
- Ease of setup

How to check a monitor or sensor

- Multiple units side-by-side
- Deploy alongside or nearby to reference monitor
- Controlled experiments
  - Standard sources
  - Varied environmental conditions

This is most difficult for most users.
Need manufacturers and standards to ensure quality.

Do they work?

- EPA has done some work focusing on outdoors
  https://www.epa.gov/air-sensor-toolbox
- South Coast AQMD is working on outdoor and chamber tests
  http://www.aqmd.gov/aq-spec/home
- Carnegie Mellon has done some work and developed the SPECK

https://explorables.cmucreatelab.org/explorables/air-quality-monitor-tests/

- Air quality in China
  http://aqicn.org/sensor/

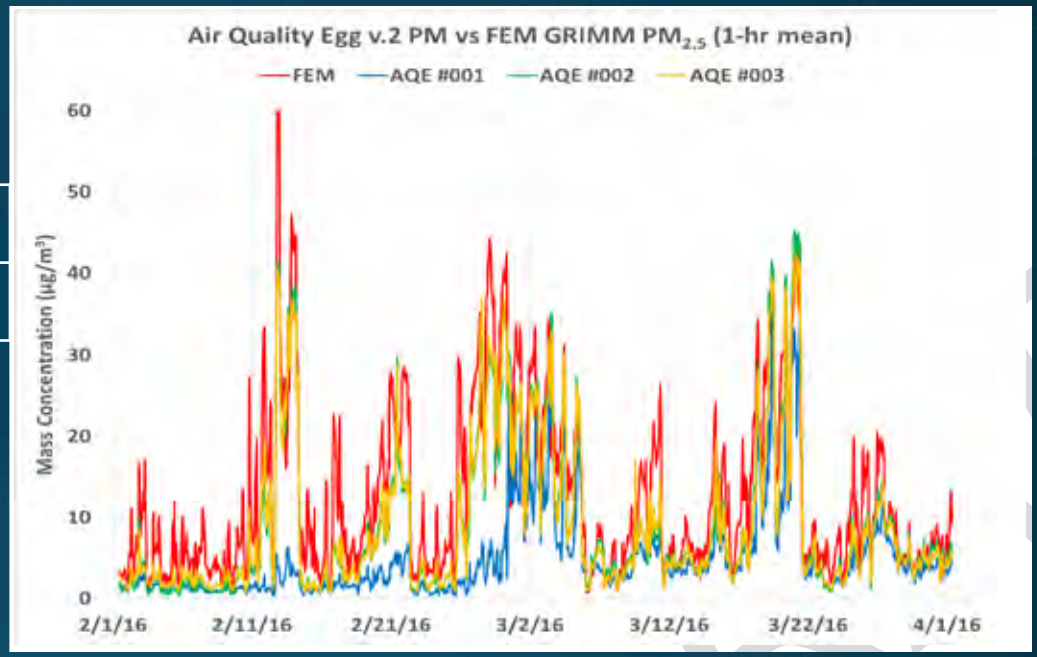
AirQuality Egg V2.0

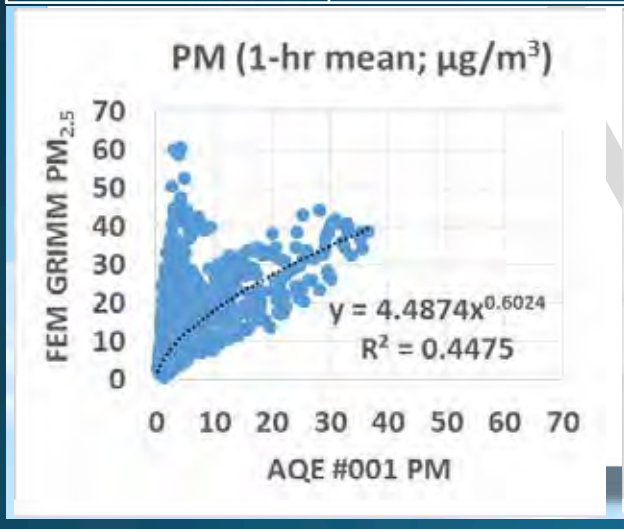
$280

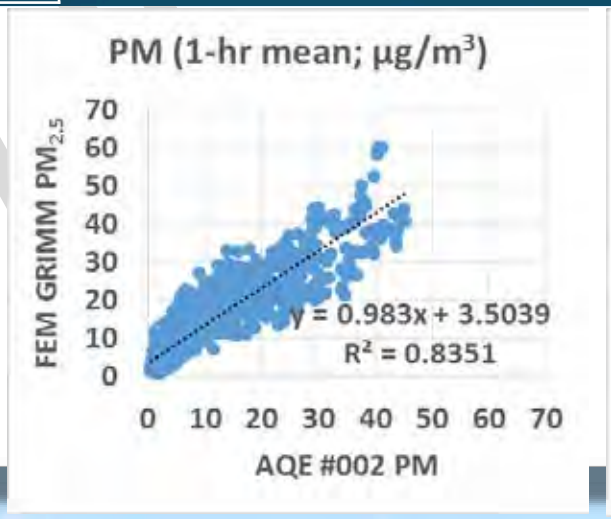
PM, T, RH

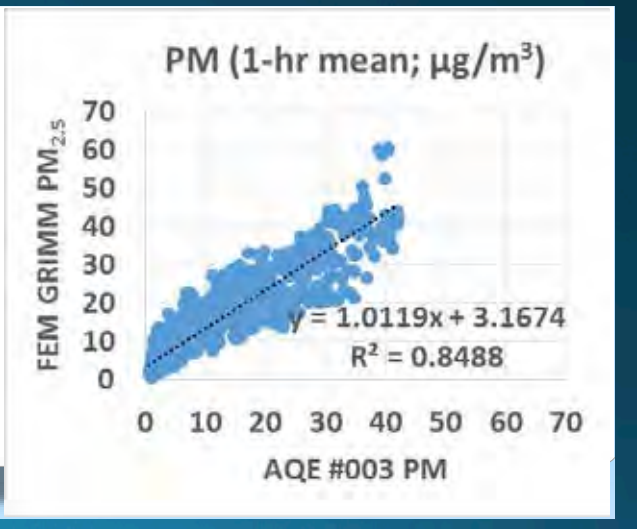
Cloud Storage	Yes
Devices	n/a

Group	R^2
EPA	-.06 to 0.40
SCAQMD	0.79 to 0.85
CMU	0.72









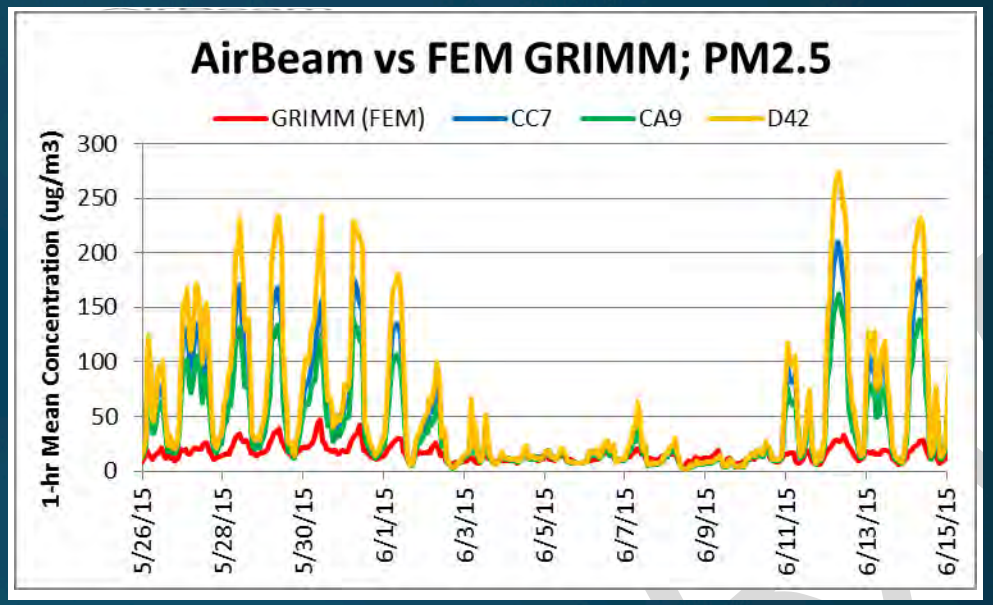
AirBeam

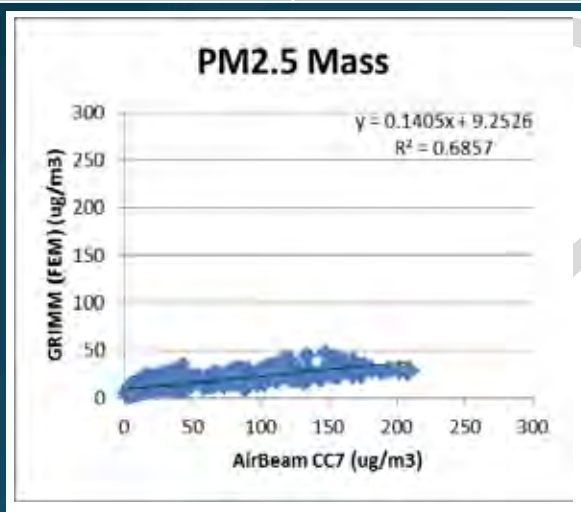
$250

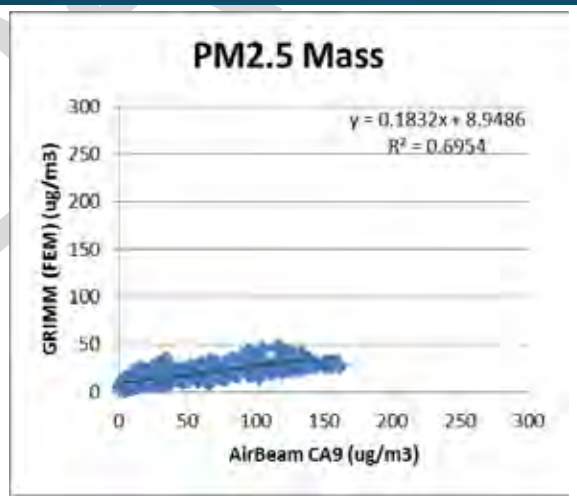
PM

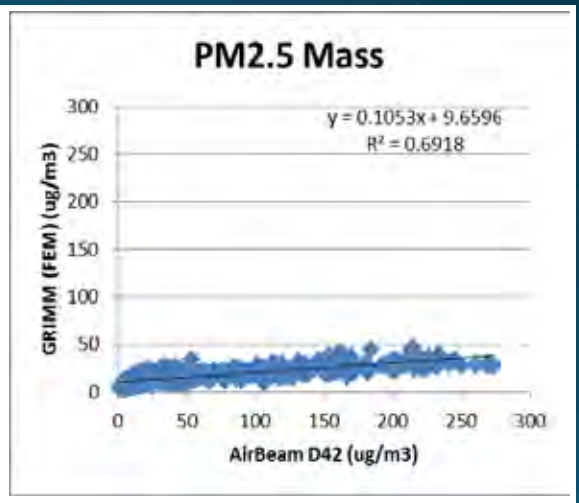
Cloud Storage	Yes
Devices	Android

Group	R^2
EPA	0.65 to 0.66
SCAQMD	0.65 to 0.70
CMU	n/a









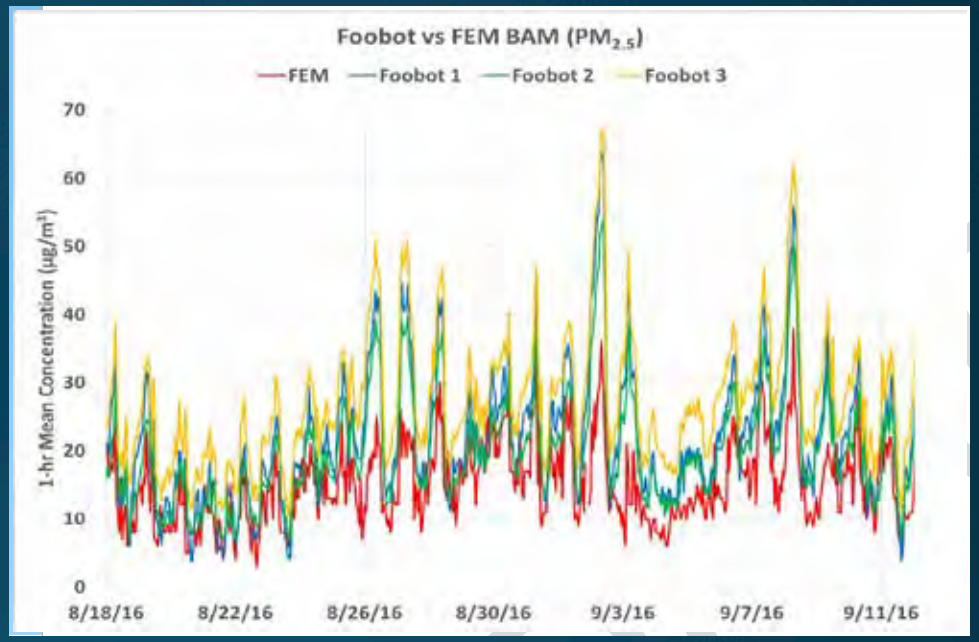
Foobot

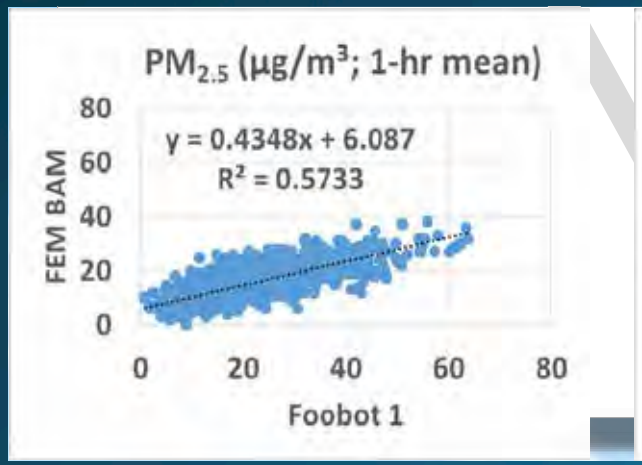
$199

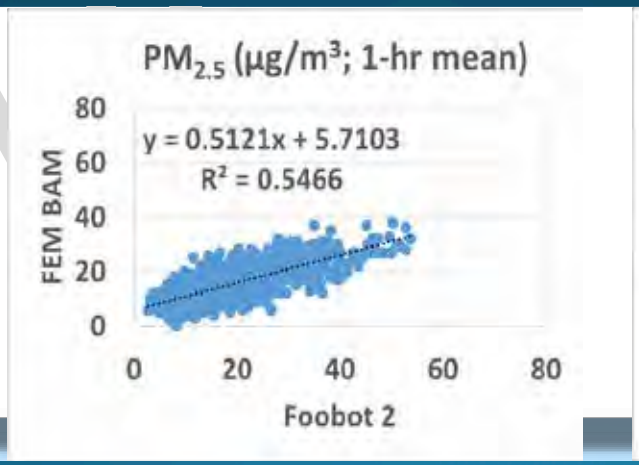
PM, T, RH, CO_2, CO, tVOC

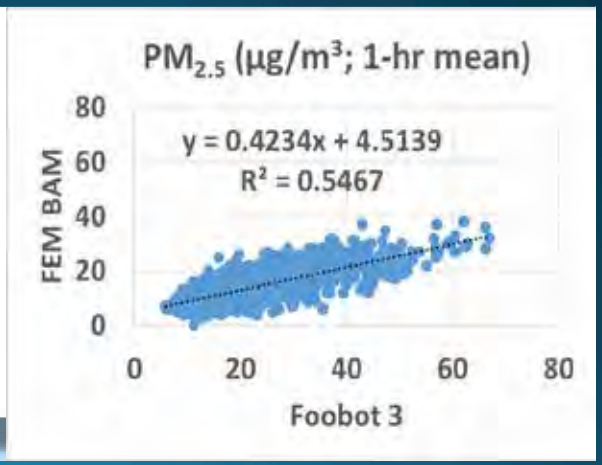
Cloud Storage	Yes
Devices	iOS, Android

Group	R^2
EPA	n/a
SCAQMD	0.55
CMU	0.25

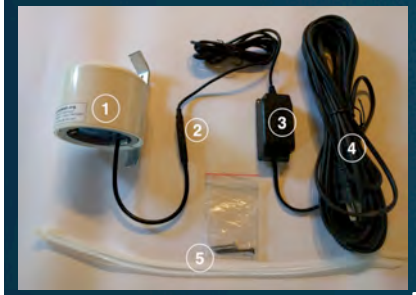








PurpleAir

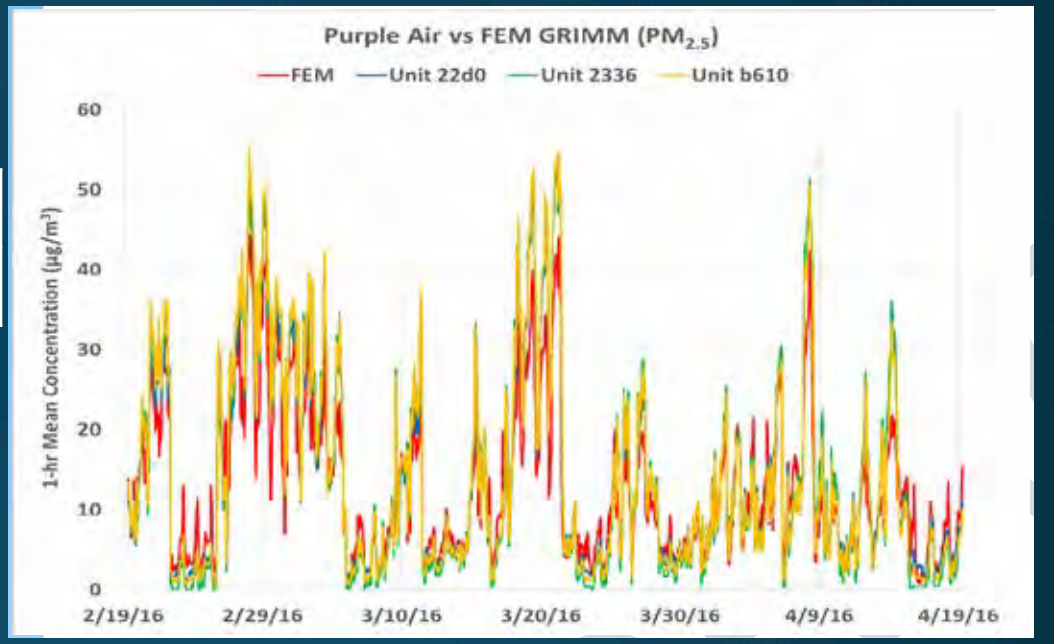


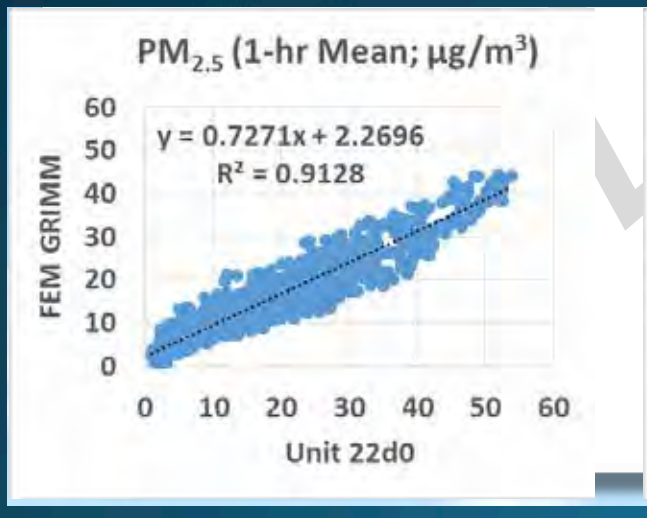
$199

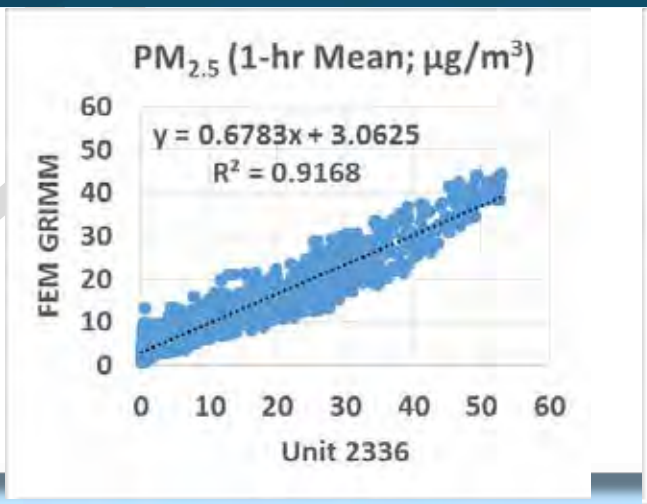
PM

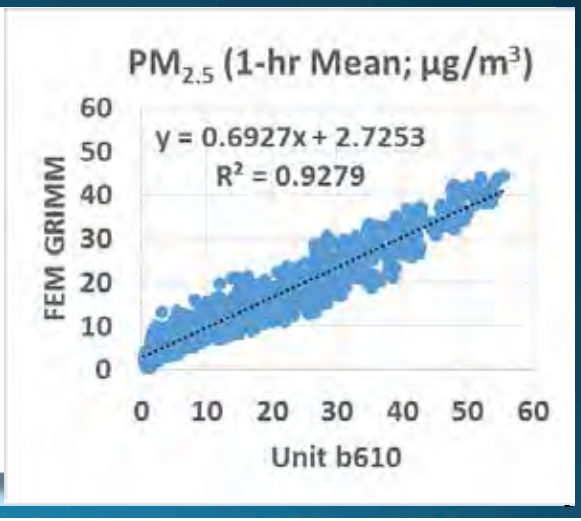
Cloud Storage	Yes
Devices	?

Group	R^2
EPA	n/a
SCAQMD	0.77 to 0.92
CMU	n/a









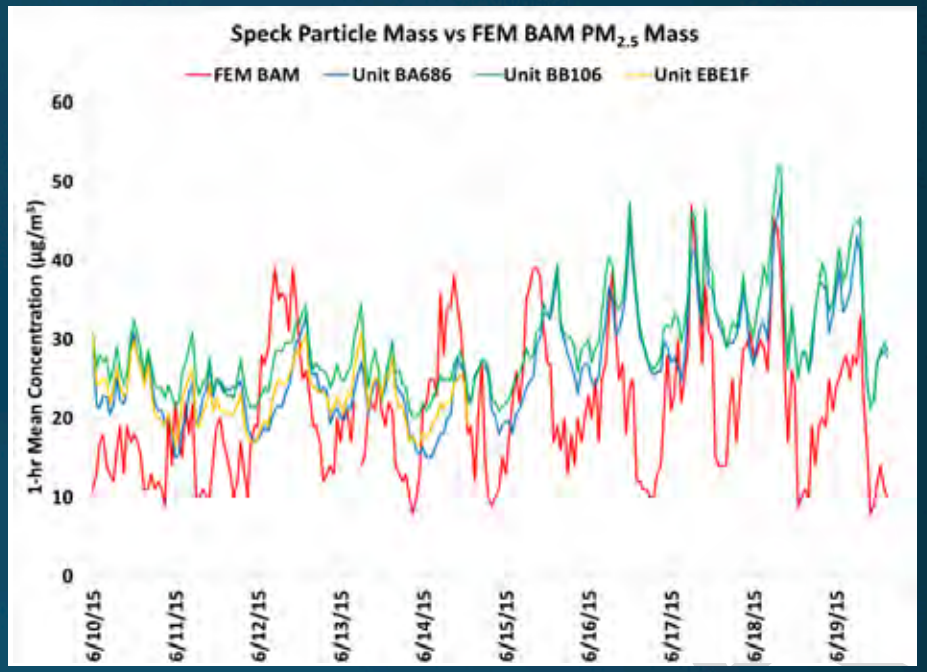
Speck V2.0

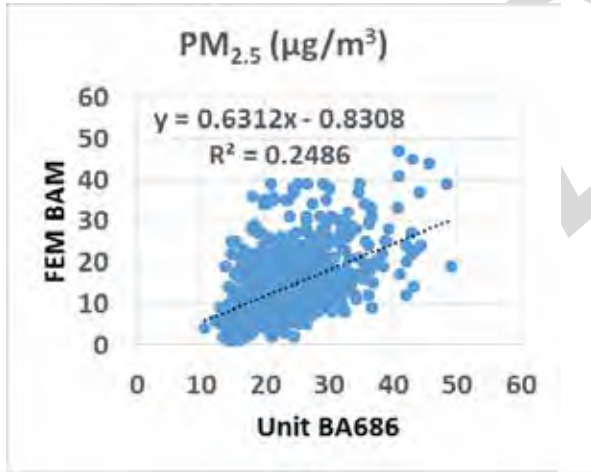
$199

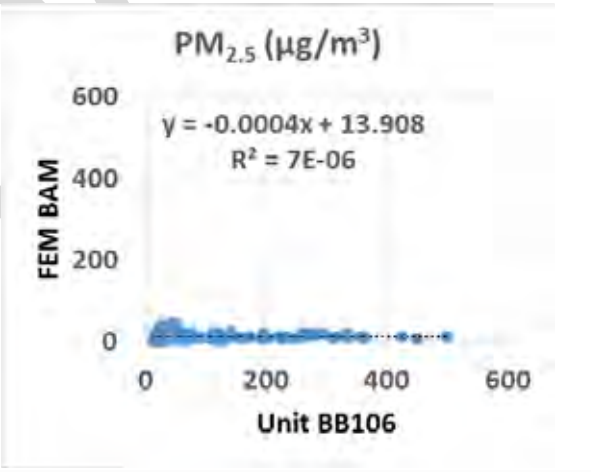
PM

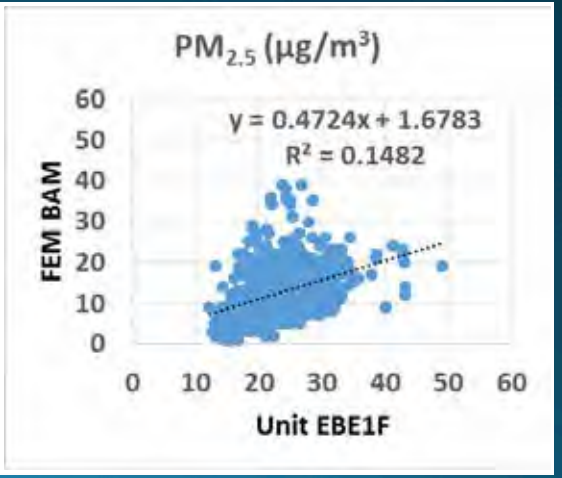
Cloud Storage	Yes
Devices	iOS, Android

Group	R^2
EPA	0.01
SCAQMD	0 to 0.25
CMU	0.61

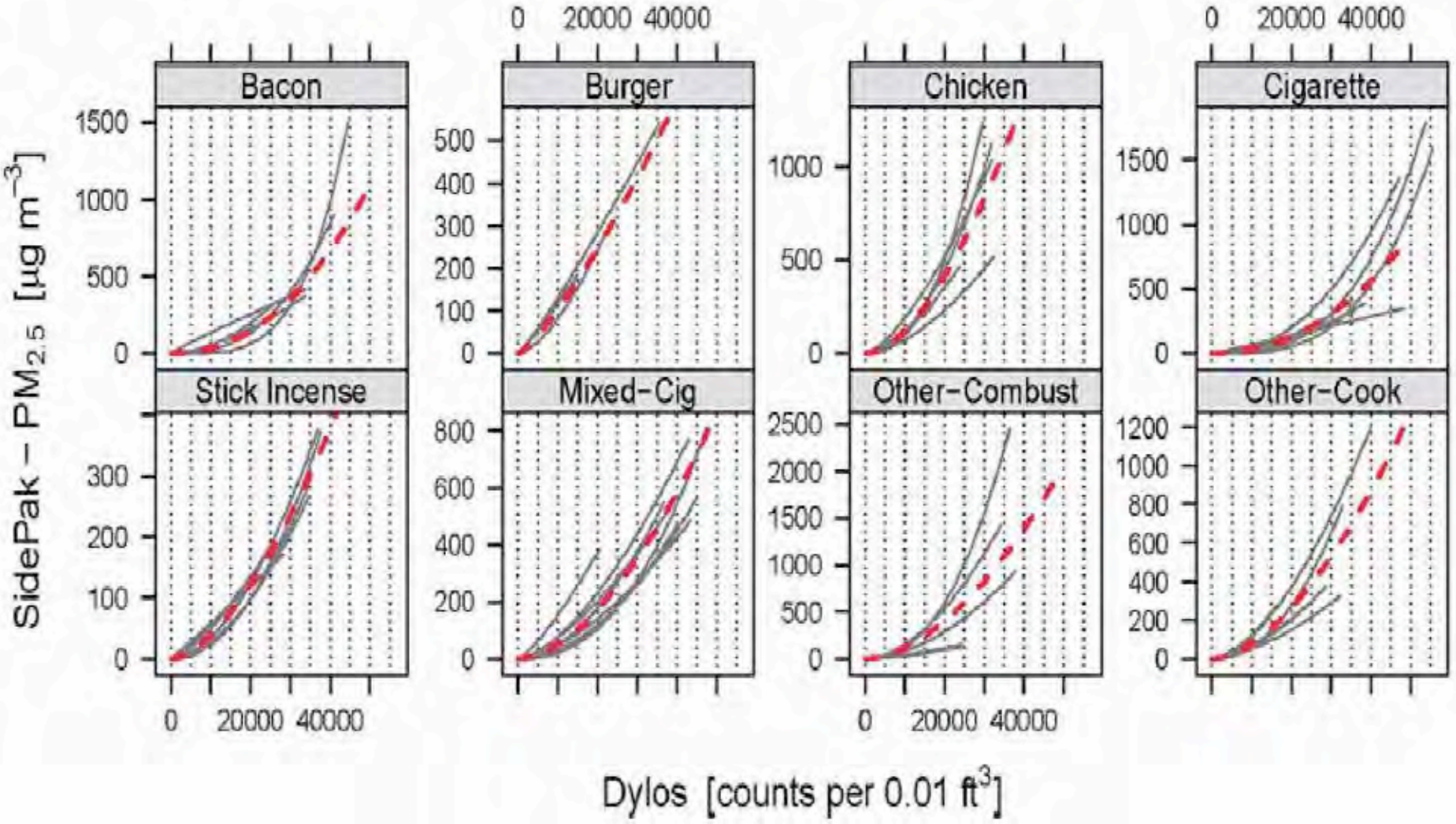






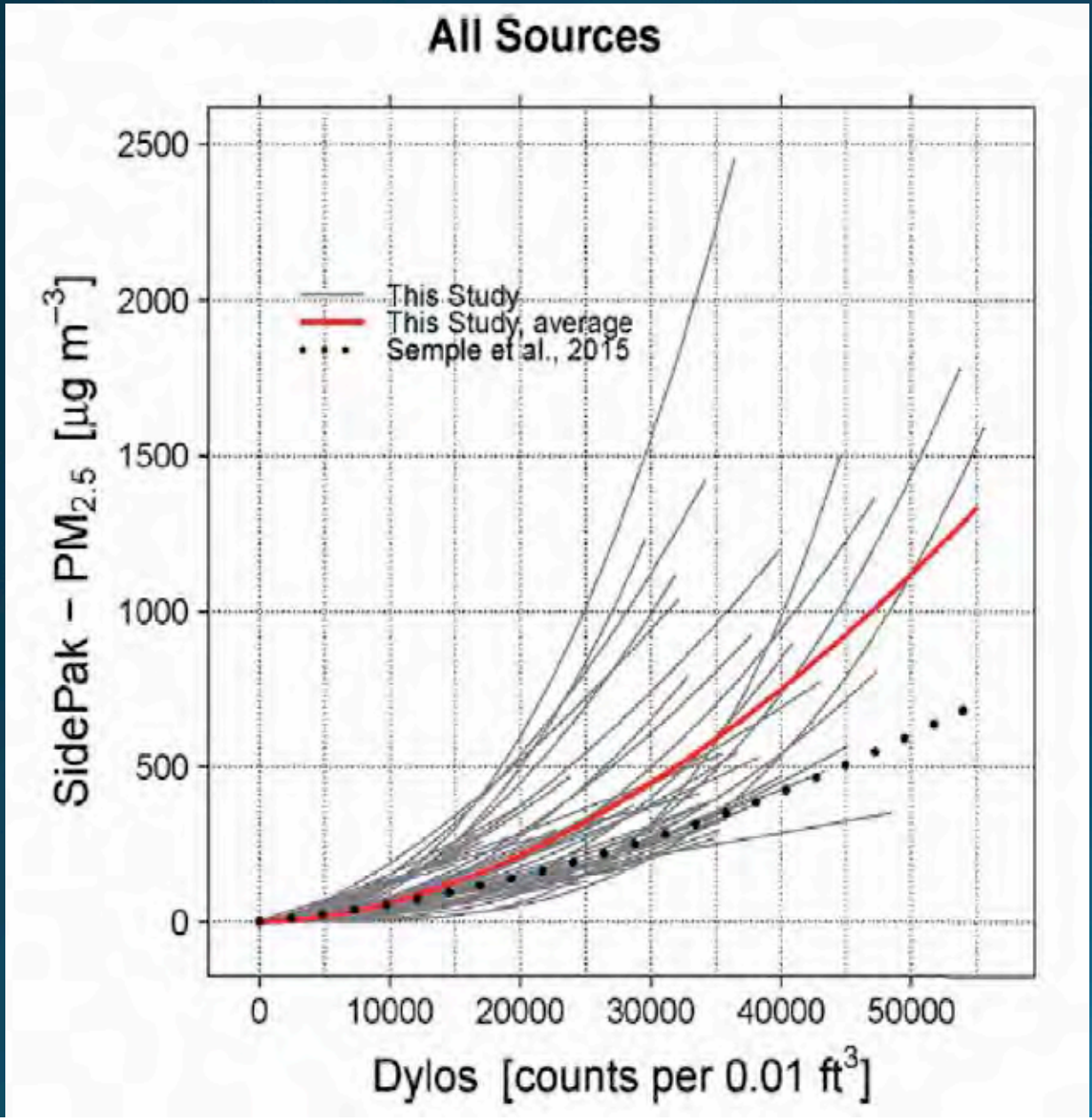


Responses vary for residential sources



Dacunto (2015)

Responses vary for residential sources



Dacunto (2015)

Yep. It's complicated.

Residential IAQ sensing – Feb 2017

- For many indoor sources, low-cost sensors cannot see the particles that comprise most of the mass.
- No low-cost sensors for ultrafine particles
- Target range for NO_2 is at low end of current sensor capabilities
  - The most common O_3 and NO_2 sensors are cross-sensitive
- Accurate CO_2 sensors cost $80-200+; confirmed stability only at top of cost range. Lower cost units may be okay.
- VOC sensors mostly measuring compounds that are not harmful at environmental levels. Also calibration and failure issues.

Particle measurements - Feb 2017

- Many products available for under $250
- Some appear to detect most significant indoor particle emission events. (Some don't). Useful for controls.
- Some can be used for semi-quantitative evaluation of improvements with control equipment. Most useful to compare when sources & environment are the same.
- Only a few appear to be sensitive and consistent enough to manage indoor exposures to outdoor particles.
- Without repeat calibration checks against reference instruments, none are good enough to make claims about improvements to $PM_{2.5}$.

The Future: Sensor Improvements

- Low-cost PM mass sensors
- Improved NO_2 reliability & sensing of NO
- Lots of people working on selective VOC sensors including formaldehyde
- Low-cost sensor for diesel PM (black carbon) being tested now

Tough Questions

- What are the most important parameters to measure?
- What threshold(s) to use for controls?
- What monitor should I buy?
- Can I use one of these monitors to prove to a client that their IAQ is good?
- If the monitor says things are bad, what should I do?

Literature Cited

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LBNL working on bibliography of scientific papers of sensor performance.

Questions?

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Extra Slides