Can you trust the data from a $200 IAQ Monitor?

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Building AMERICA
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UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

U.S. DEPARTMENT OF HOUSING AND URBAN DEVELOPMENT

Acknowledgements

Dr. Woody Delp did most of the work

Dr. Brett Singer planning and coordination with EPA and HUD project

Simon Walker helped with experiments and data downloads

Dr. Yang-Seon Kim weighed filters for gravimetric measurements

Have you used any IAQ monitors?

For what purpose?

Was the information helpful?

Results

Winners

FOB

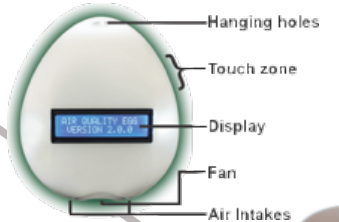
PA

AVN

AB

AWA

AQE



SPK

Losers

What are uses for IAQ monitors?

- Hazard identification
  - Alarm at problem concentrations
- Ventilation/filtration system control
- Diagnose problems in homes
- Assess benefits of retrofits
- Quantify IAQ

What characteristics do IAQ monitors need?

- Accuracy
  - Do they report correct concentrations
  - How good is their time response
  - False positive/negatives
  - Sensitive to environmental conditions: temperature or humidity
  - Repeatability
  - Need for calibration
- Durability
- Ease of use
- Real-time measurement
  - Real-time display
  - Recording data
  - Could be used as a controller
- Integrated – none of the above

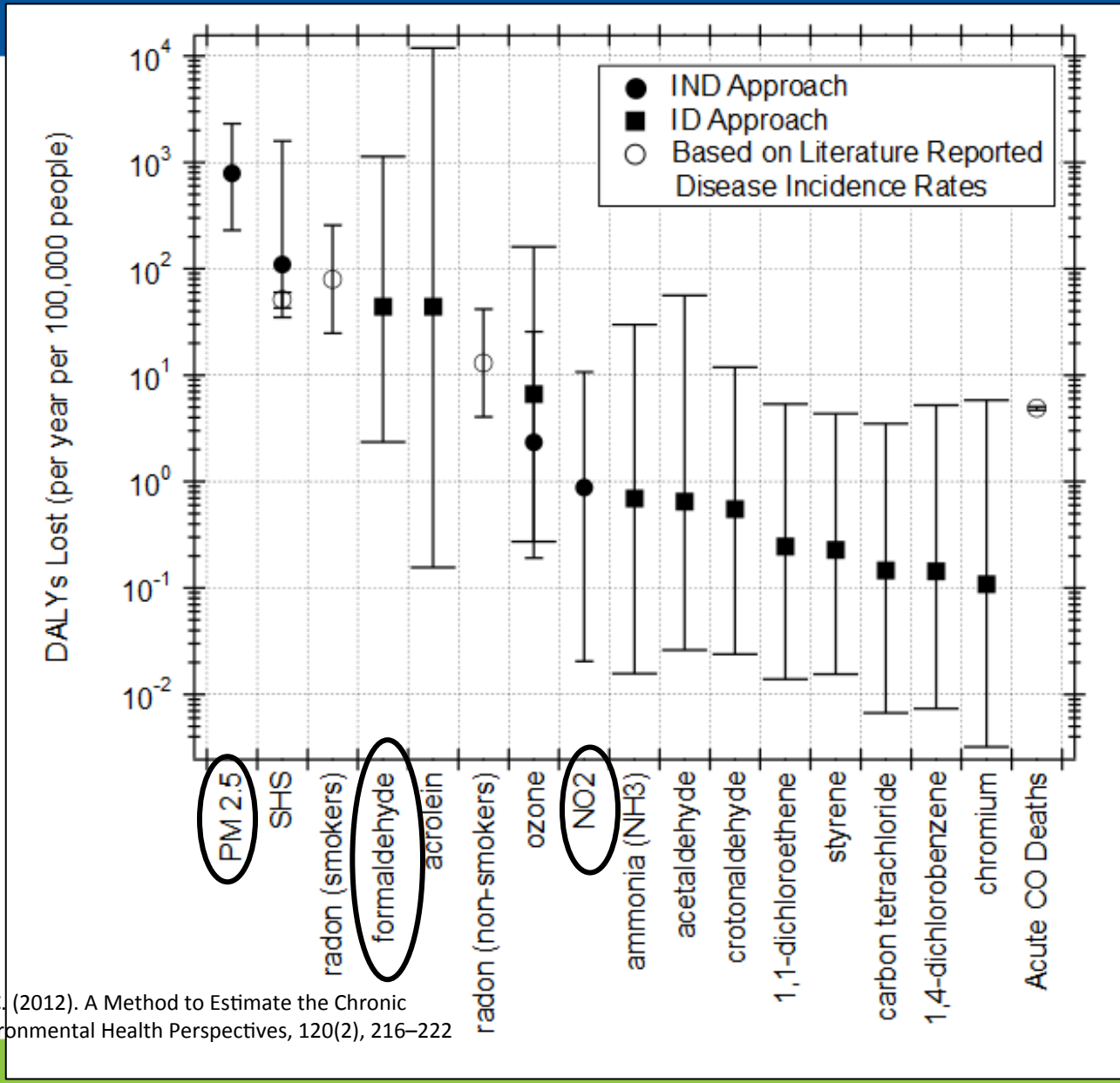
What should IAQ monitors detect?

- Odors
  - Sensed/acted on by people
  - We have no odor monitor – possibly use CO_2 as a surrogate. E.g., in Demand Controlled Ventilation
- Humidity
  - Can be sensed by people
  - We have readily available RH monitors
  - Visible mold easy to detect
  - Mold spores readily sampled for later analysis but not in real time
- Health
  - Not sensed by people
  - This is the critical thing we need monitors for

Identifying Contaminants of Concern

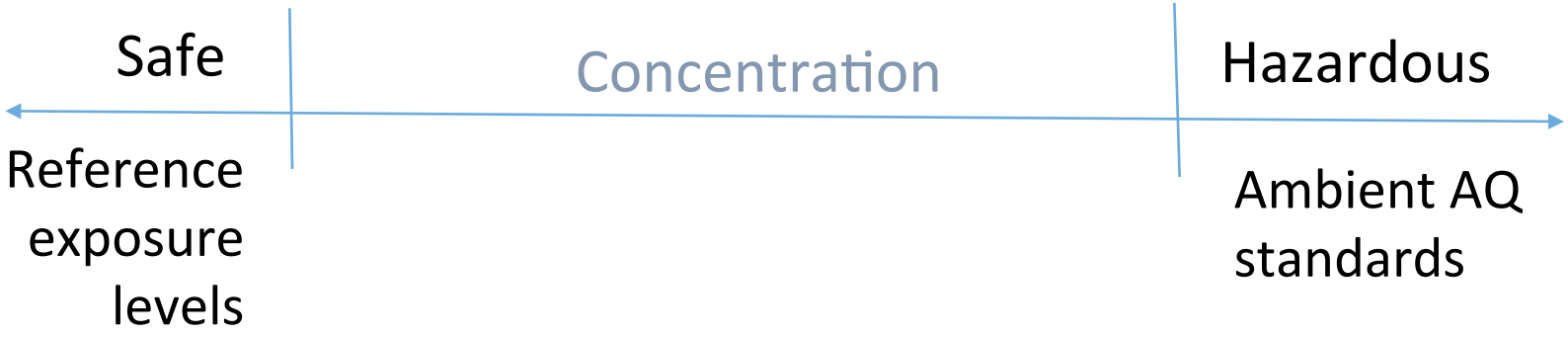
We live in a complex soup of many agents - which ones have the biggest health impact?

Disability Adjusted Life Years: DALYs



Logue, J. M., Price, P. N., Sherman, M. H., & Singer, B. C. (2012). A Method to Estimate the Chronic Health Impact of Air Pollutants in U.S. Residences. Environmental Health Perspectives, 120(2), 216–222

What are the target pollutant levels?



- **Ambient Air Quality Standards – Above is hazard**
  - Set to protect sensitive sub-populations, e.g. **asthmatics**
  - Mostly based on human exposure data
  - CO, NO_2, $PM_{2.5}$, PM_{10}, Ozone, Lead, SO_2
- **Reference Exposure Levels (RELs) – Below is safe**
  - Level below which **no adverse effects expected**
  - **Acute (hours)** and **Chronic (years to lifetime)**

Chronic vs. Acute

- Chronic – long term – like a year or more
- Acute – short term – immediate effect – 1 hour time scale

Concentration [µg/m^3]				
COMPOUND	**Chronic**	**Acute**		
		24 h	**8 h**	**1 h**
Formaldehyde*	**1.67E+00**	-	**9.00E+00**	5.50E+01
NO2*	**4.00E+01**	-	-	**1.89E+02**
PM2.5*	**1.00E+01**	**2.5E+01**	-	-
Lowest Acute-to-Chronic Ratio [-]	**-**	**2.5**	**5.4**	**4.7**

Monitoring: principally for chronic but we might want an alarm for acute?

Monitors do NOT have this acute alarm capability

Not just accuracy…

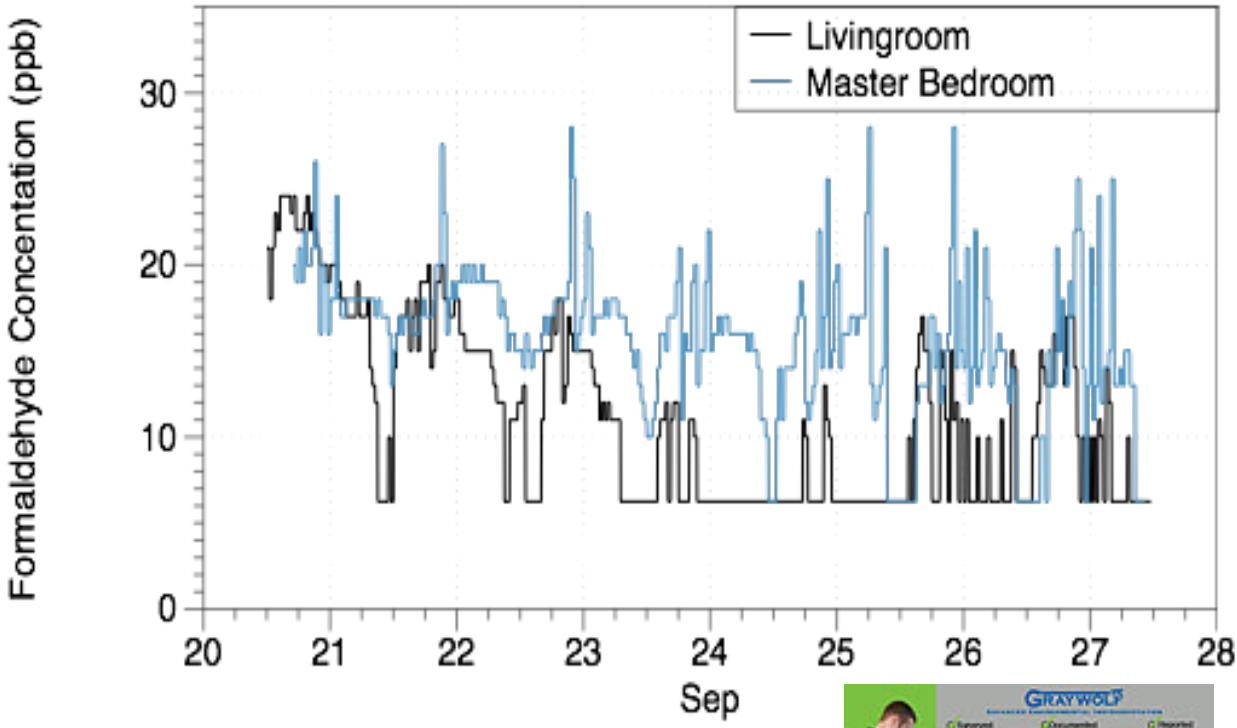
- Time resolution: can we capture short term events? E.g., cooking
- Re-calibration: is this an extra cost (current low cost devices don't have any capacity to do this)
- Materials cost for each sample
  - Passive samplers:
    - NO2 $45
    - Formaldehyde $95 (includes lab charges)

Formaldehyde

Time resolution might matter

Allows us to better understand what's going on:

Formaldehyde has a strong temperature-driven diurnal cycle



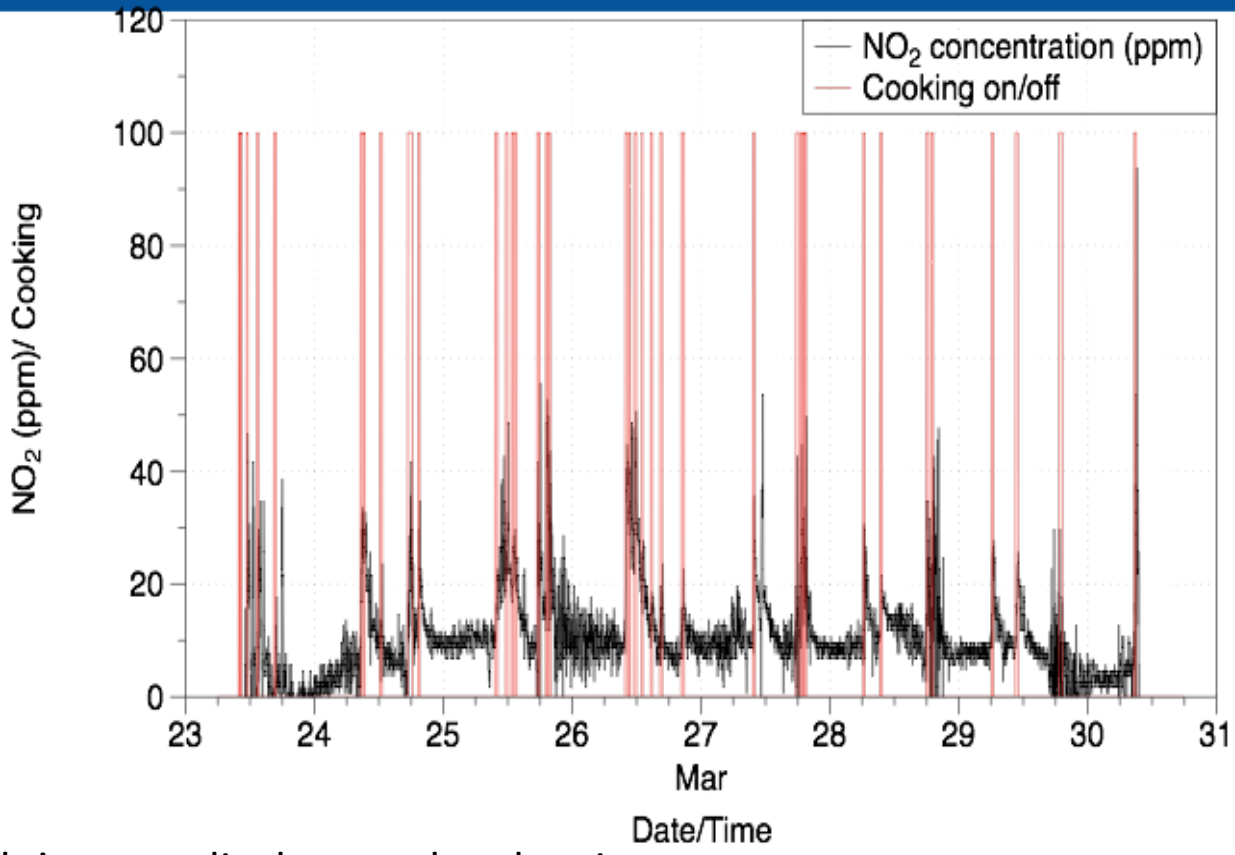
Passive: SKC UMEx-100 $100-$130, not real time integrated over a week no visual display, chronic only

Active: Shinyei $1500-$2000 30 minute samples, visual display, logged data. Chronic & acute

NO_2

NO2 low average but spikes with cooking

Need to capture the spikes?



Passive: Ogawa - $150, not real time, no display, no data logging

Active: Aeroqual − 1 minute, $1500, lots of drift, not recommended

Acrolein + other contaminants

- Acrolein: No reasonable sensor- could use gas chromatography: $100,000's
- Other VOCs:
  - TVOC not meaningful?
    - What pollutant at what level?
    - Is there harm being done?
    - If VOC unidentified we can't act on the information (is from cleaning products, carpet, furnishings, finishes, wood products, etc.
- Radon:
  - Inexpensive Passive samplers
  - Real-time for $200
  - Good monitor for $1000*
  - Exisiting evaluation infrastructure
    - E.g. http://radongasdetectorreviews.com/

* http://www.gastechnology.org/Solutions/Documents/BAPARR-Reports/Low-Cost-Radon-Reduction-Pilot-Study.pdf

Particles: PM2.5

$PM_{2.5}$

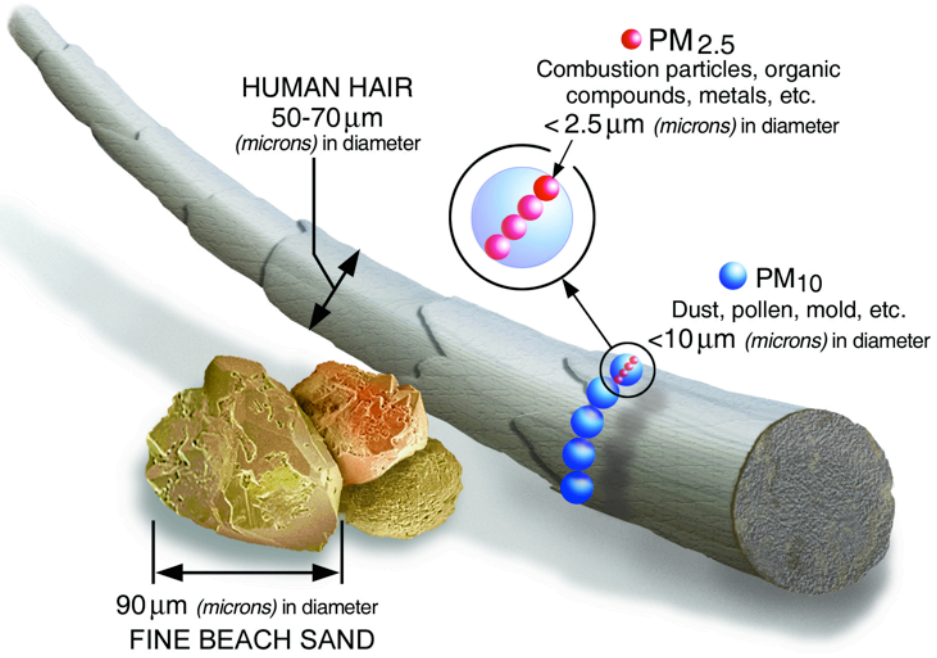
…causes increased cardiovascular morbidity and mortality;

…is associated with and likely causes respiratory illness.[1]

In-home exposure to $PM_{2.5}$ causes more health damage than any other non-biological air pollutant.[2]

Most consumer "IAQ Monitors" include PM2.5

$PM_{2.5}$ detection can enable control by ventilation or filtration



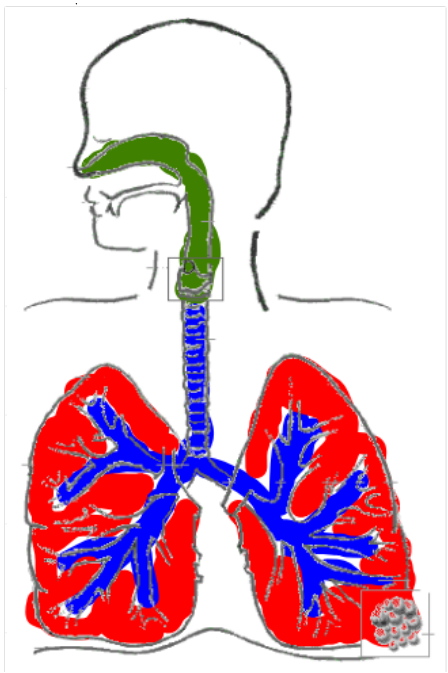
www.epa.gov/pm-pollution/particulate-matter-pm-basics#PM

1. EPA, *Integrated Science Assessment for Particulate Matter*. Washington, DC: U.S. Environmental Protection Agency; 2009.
2. Logue, *Environ Health Perspect.* 2012;120:216-222.

$PM_{2.5}$ Benchmarks

Standard	Annual mean $\mu g/m^3$	24-h mean $\mu g/m^3$
US Ambient Standard (2012)	12	35
WHO Guideline Values (2005)	10	25
Canadian Ambient Standard 2015	10	28
Canadian Ambient Standard 2020	8.8	27

Size Matters for Particles



Deposition Fraction (%)

100
90
80
70
60
50
40
30
20
10
0

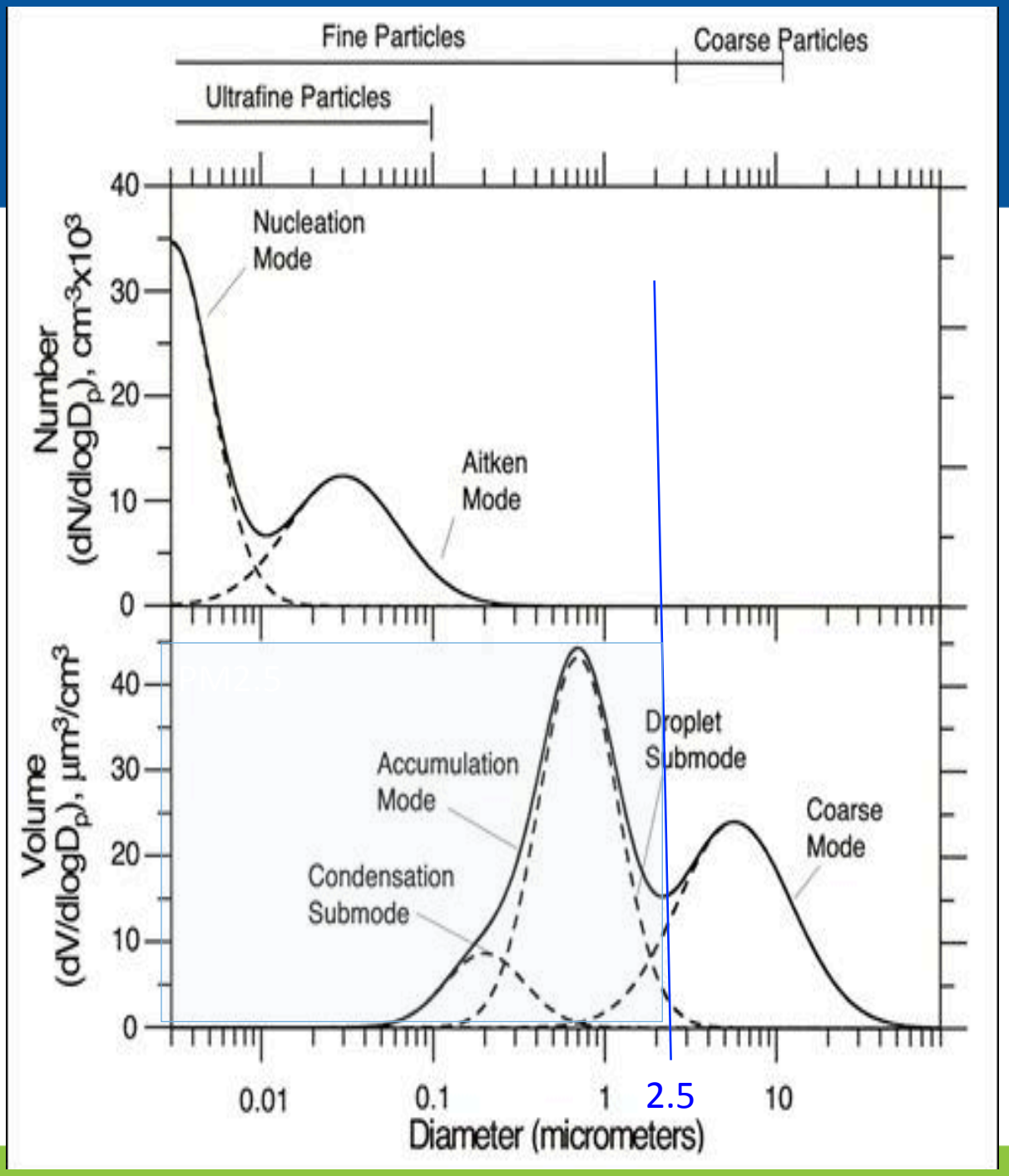
0.01
0.1
1
10

Particle Size (µm)

Developed from ICRP Publication 66. Human Respiratory Tract Model for Radiation Protection, 1994.

Particles 101

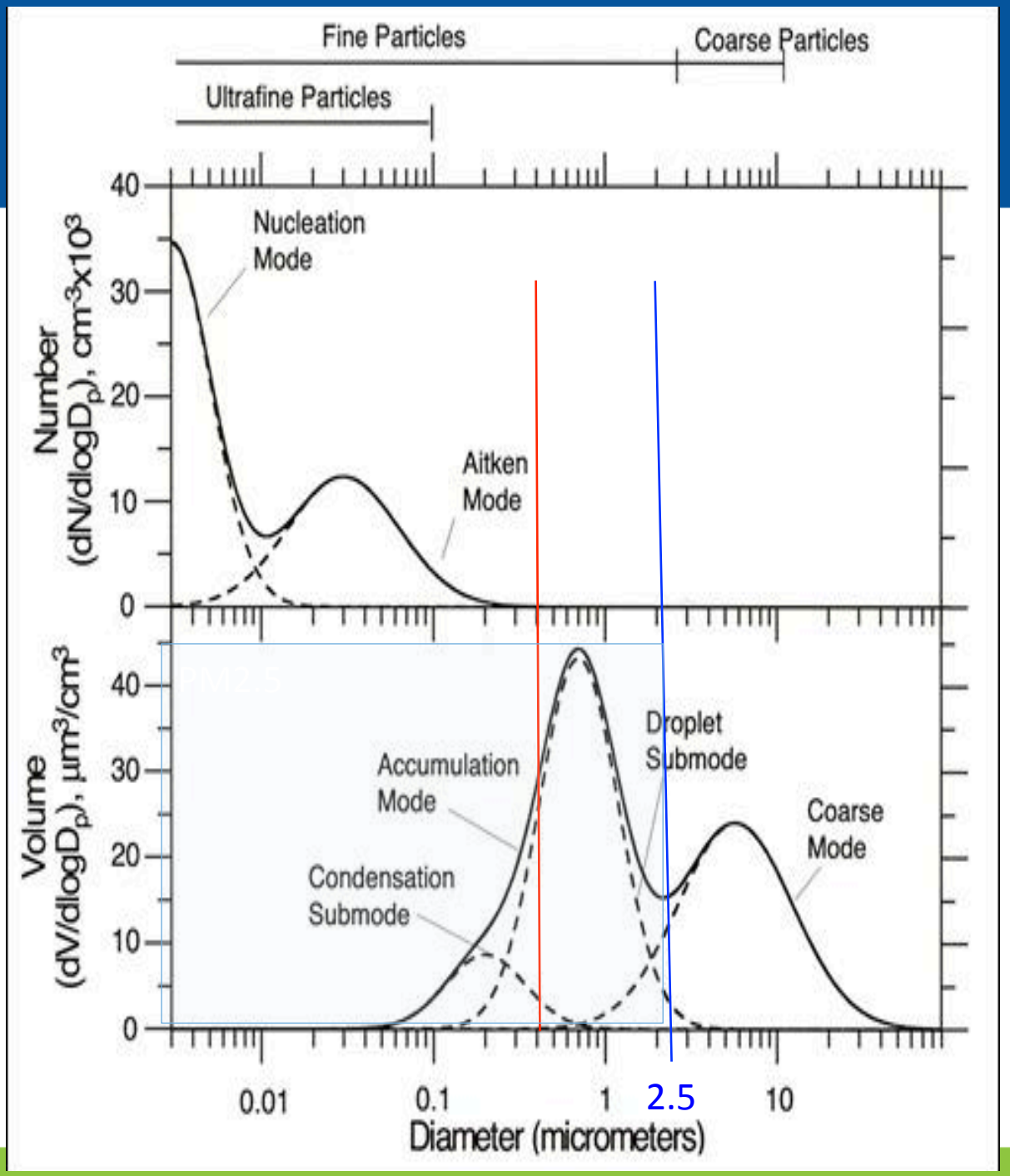
- "Particulate matter" or PM is comprised of particles with varied size & composition.
- Composition varies by source & changes w/ environment.
- Can describe PM by mass, volume or number of particles in volume of air.
- $PM_{2.5}$ is the mass concentration of particles smaller than 2.5 um diameter.



Source: NARSTO (2004)

Particles 101

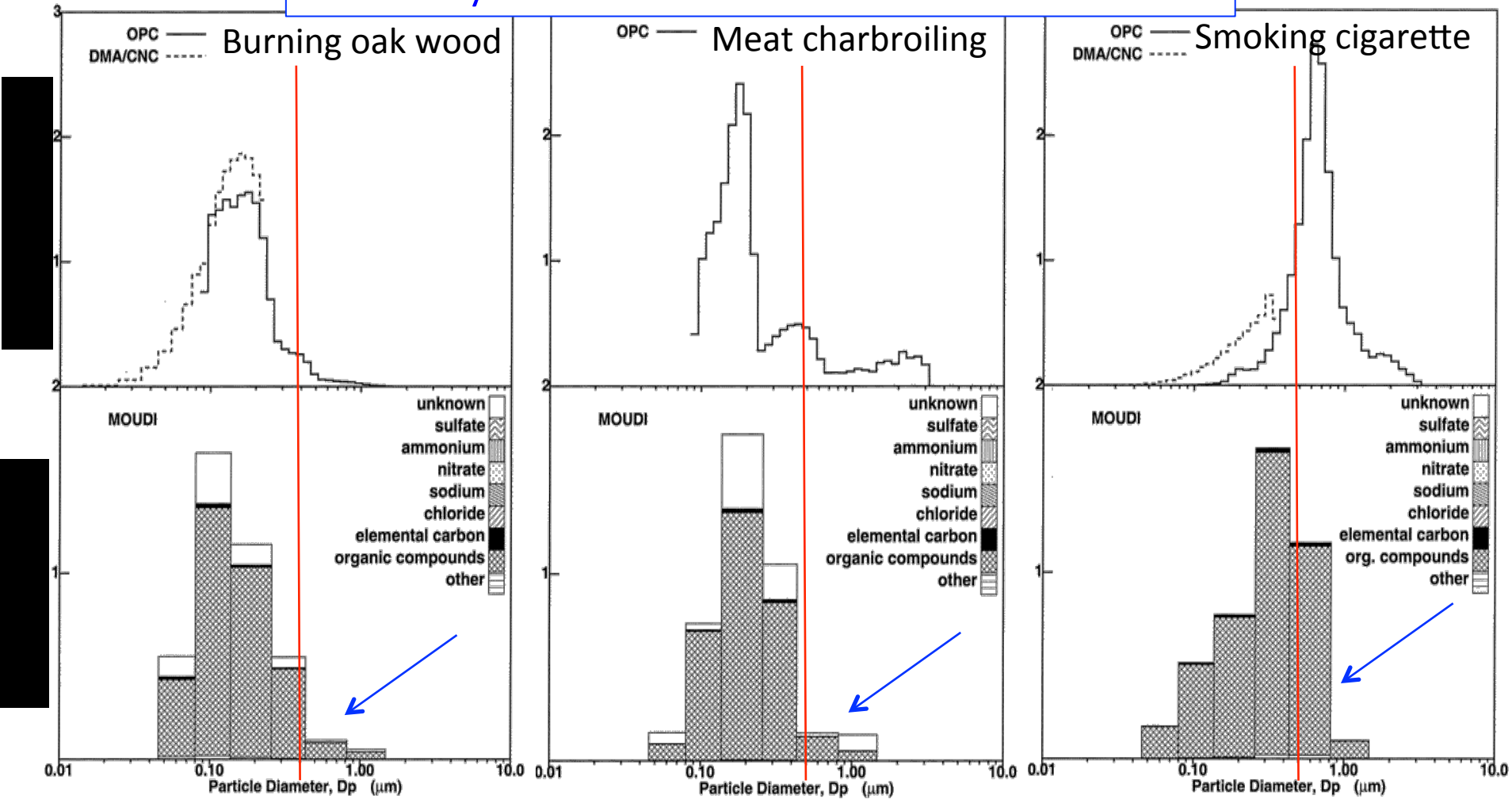
- Many low-cost sensors only see larger particles, e.g., >0.5 um or >1 um.
- Some see to 0.3 um.
- They estimate total PM based on what they see.
- Some sensors only provide particle counts. Some provide estimates of $PM_{2.5}$



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
Could they be "calibrated" to account for this?



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

Real-time
(seconds – hour)

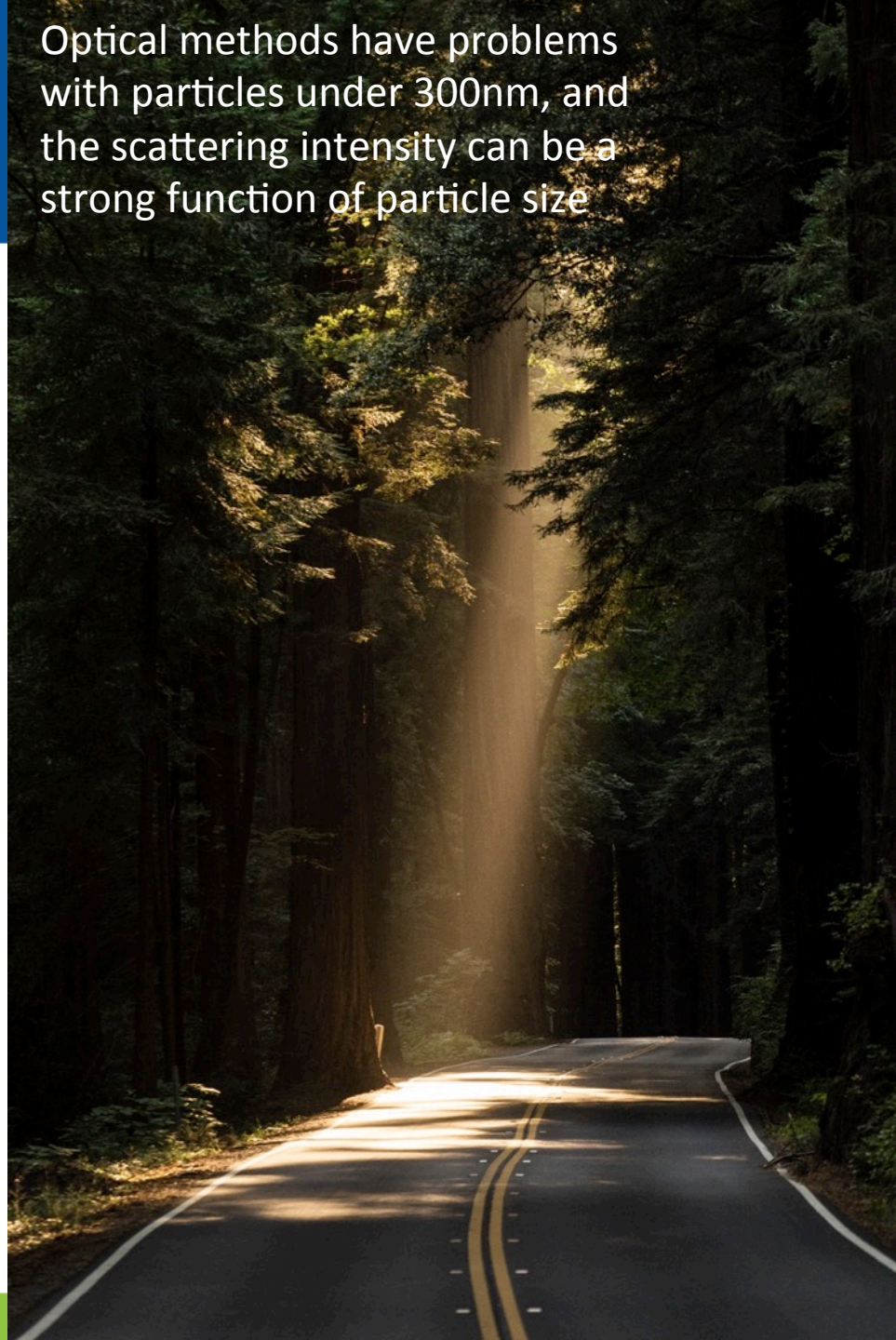
- Optical methods
  - **Scattering – in low cost monitors**
  - Laser particle counters

Scattering Light

The intensity of scattered light depends on:

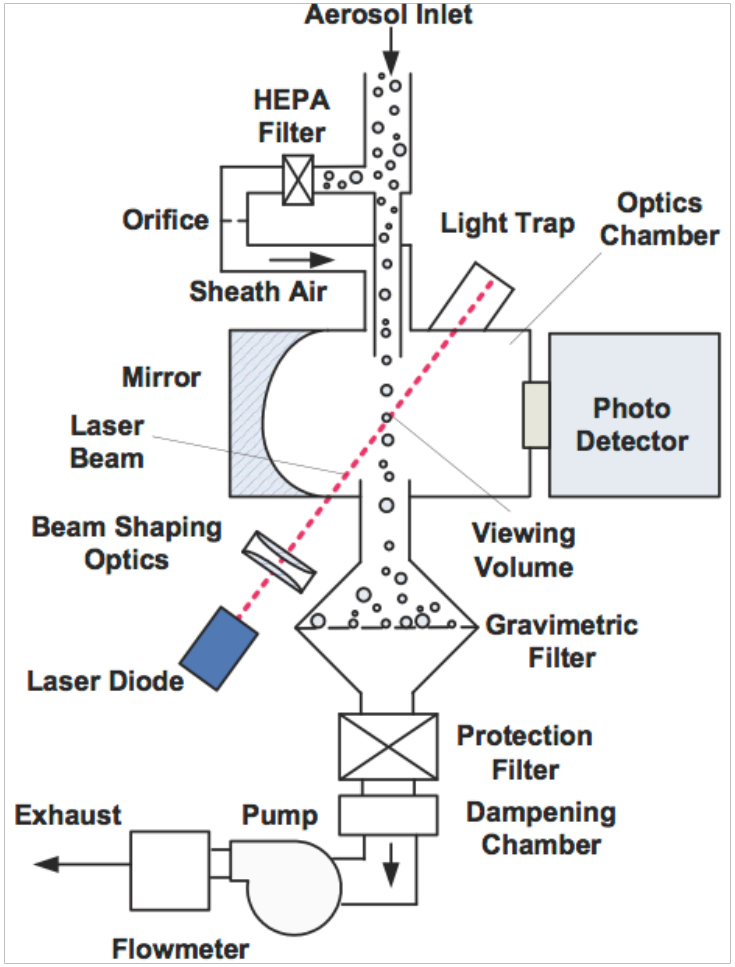
- Light wavelength
- Detection angle
- Particle size
- Refractive index

Approximately linear with mass



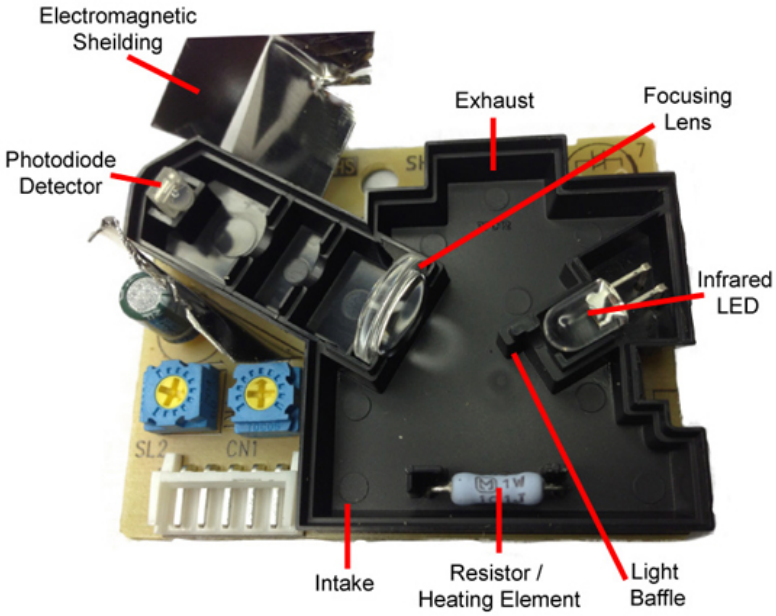
Heart of an optical sensor

Research grade



OEM pricing $100s

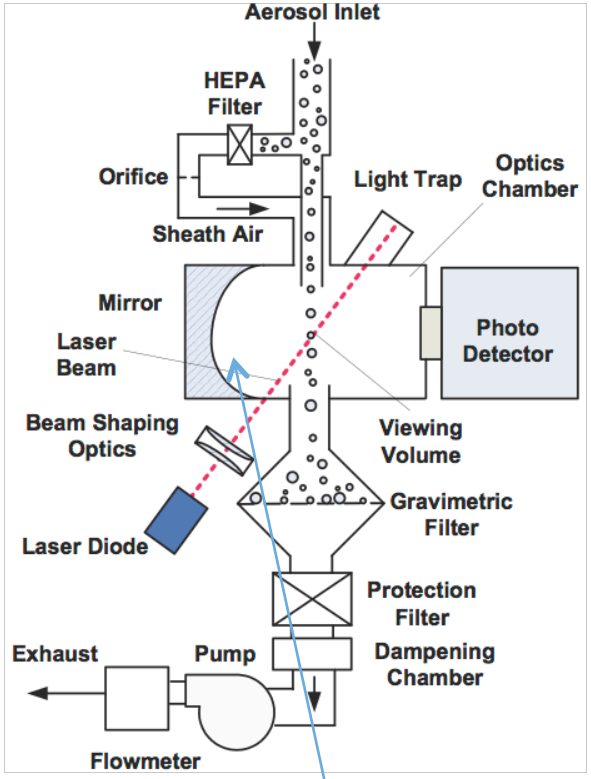
Low cost device



Bare sensor OEM pricing $4 - $15

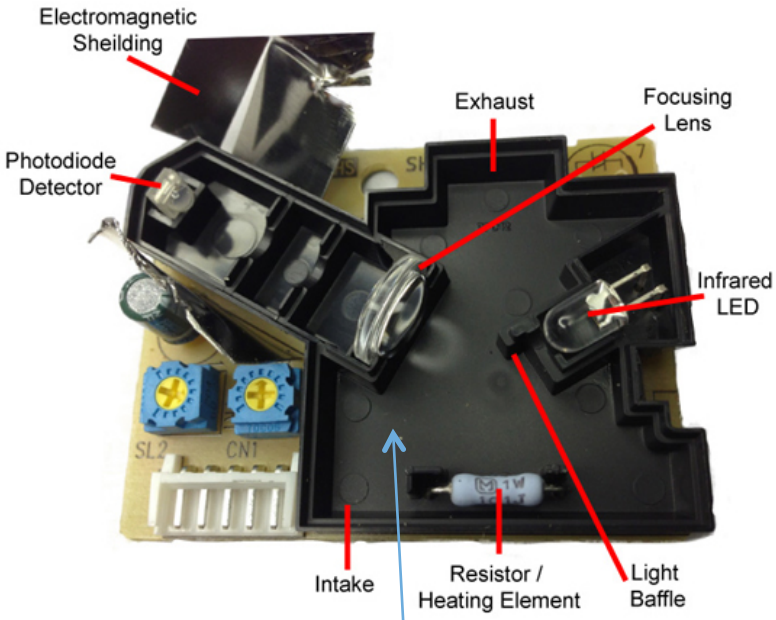
Heart of an optical sensor

Research grade



Machined housing
Close tolerances

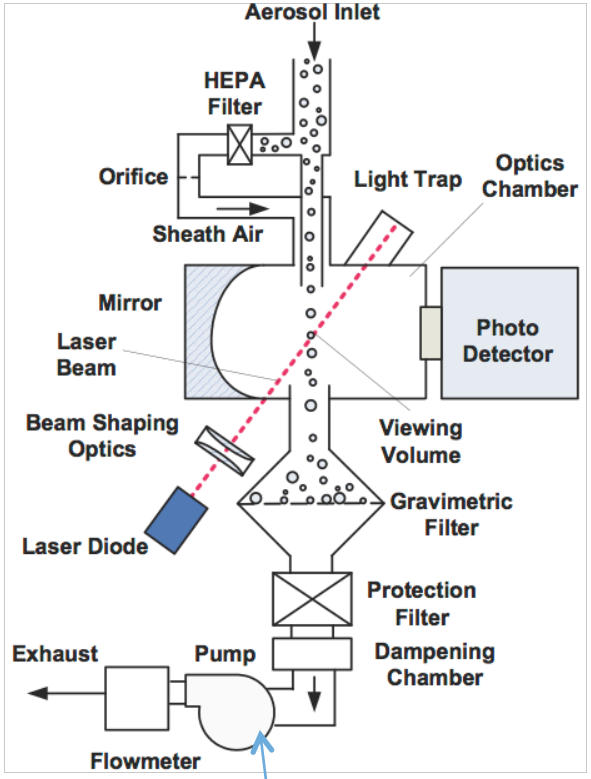
Low cost device



Molded plastic housing
Tolerances?

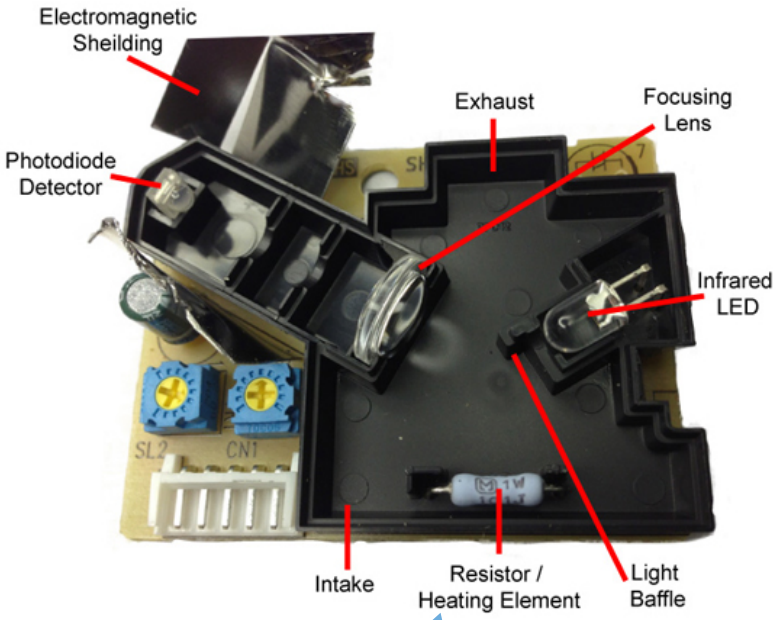
Heart of an optical sensor

Research grade



Pump for controlled flows

Low cost device

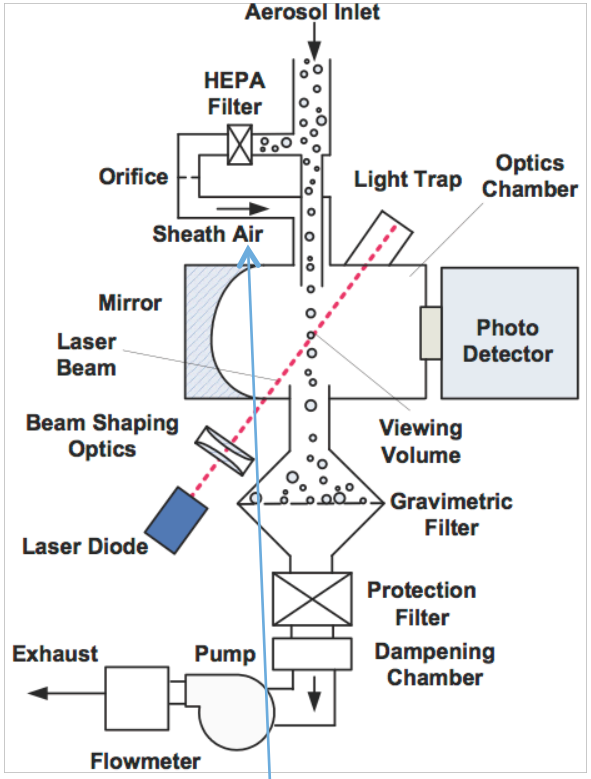


Heater induces a flow through the device

Control?

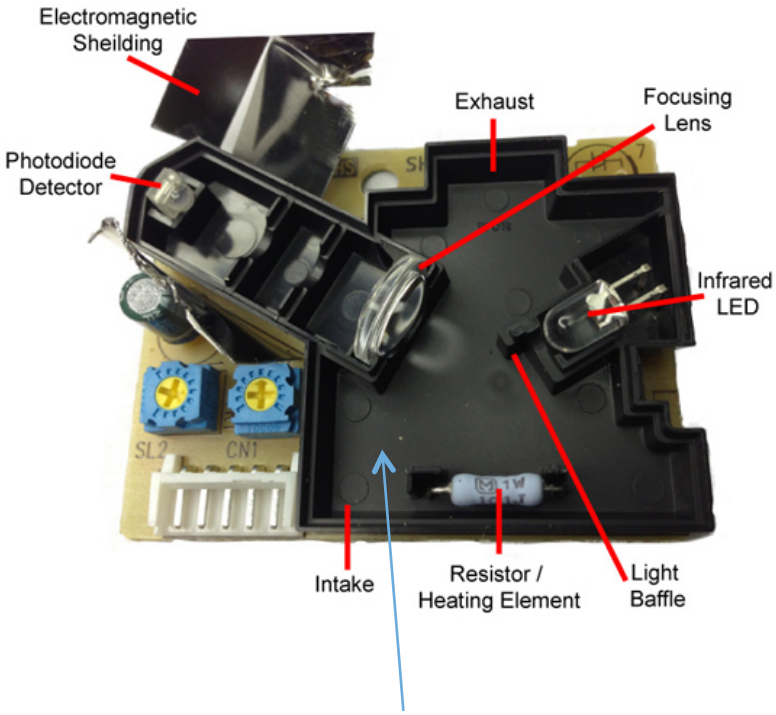
Heart of an optical sensor

Research grade



Sheath flow keeps the optical chamber clean

Low cost device



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

Reference $PM_{2.5}$ Measurements – adapting outdoor measurements for indoors

- U.S. federal reference method (FRM) is gravimetric: specifies pump, inlet, filter, and weighing procedures
- Alternative gravimetric sampling equipment designed for indoor spaces
- Federal equivalent methods (FEM)
  - Tapered Element Oscillating Microbalance
  - Beta attenuation
  - Specialized optical methods

- Designed for 24h integrated sample
- Too noisy for indoors

- Integrated
- $1500

1h or less
$10-25K per unit

$PM_{2.5}$ References

Thermo-Scientific TEOM-1405DF

ThermoFisher SCIENTIFIC

Direct Mass readings

$PM_{2.5}$, PM_{Coarse}

Grimm miniWRAS

GRIMM
DURAG GROUP

Aerosol Spectrometer

Particle size distribution in 41 channels from 10nm up to 35μm

About $35,000

BERKELEY LAB

Research PM Monitors

- Optical scattering devices developed for occupational health, used for residential research.
- Cost $4-10K for analyzer; $500 for OEM sensor unit.

In this study: Thermoscientific **PDR** 1500 & MetOne **BT** 645

Dylos – particles only

- Somewhere between reference and consumer grade
- Uses laser optics
- $200
- Not evaluated in our study
- Being used in some studies:
  - ROCIS
  - LBNL HENGH

Evaluating low-cost PM monitors

- Multiple units side-by-side
- Compare to reference monitor
- Controlled experiments
  - Standard sources
  - Varied environmental conditions
- Recent LBNL lab study + others…
- Not just particles.. CO2, T, RH, VOC
- Not just a sensor: packaged + power supply + wireless + display (in some cases) + storage (on-board and cloud)

Low cost (~$200) consumer grade monitors

AirBeam: AB

PM, T, RH

1 sec

Air Visual Node: AVN

$PM_{2.5}$, PM_{10}, CO_2,
T, RH

10 sec – 15 min

Air Quality Egg: AQE

PM, T, RH

1 min

AWAIR: AWA

PM, CO_2, VOC,
T, RH,

10 sec – 5 min

Foobot FOB

PM, CO_2, VOC,
T, RH,

5 min

Purple Air PA

$PM_{1.0}$, $PM_{2.5}$, PM_{10},
T, RH

80 sec

Speck: SPK

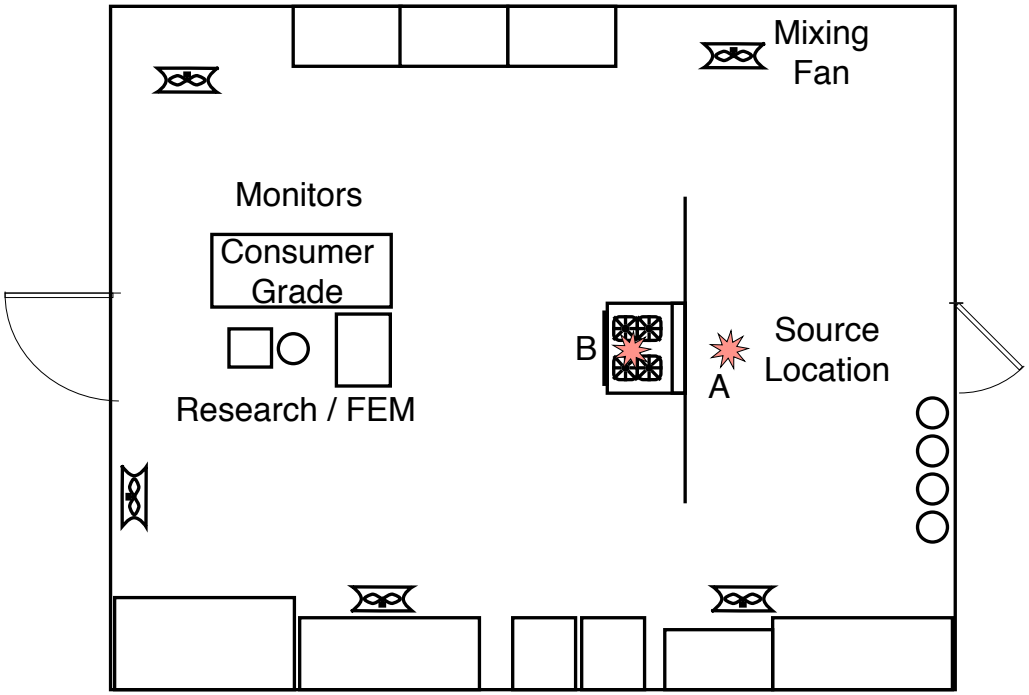
PM, # particles
T, RH

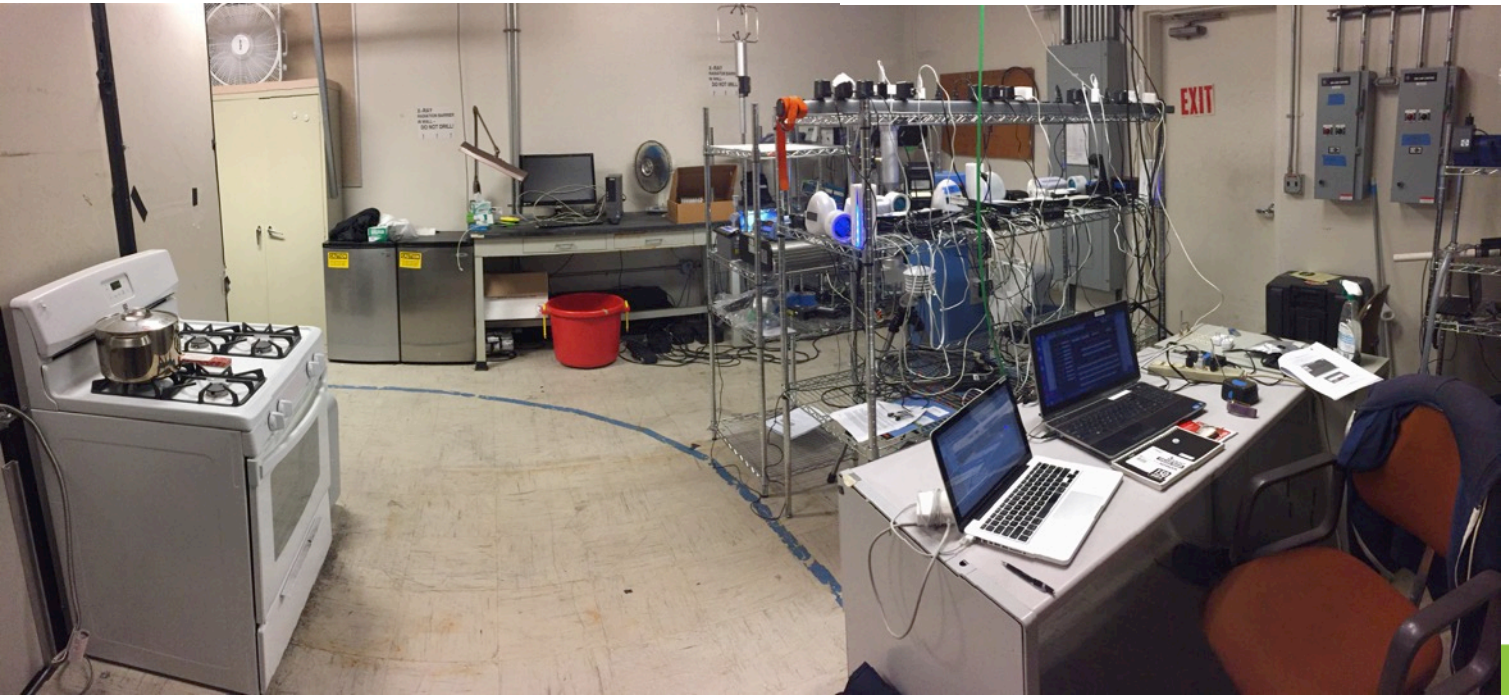
1 min

These use mass-produced particle sensors that cost <$10 to $35

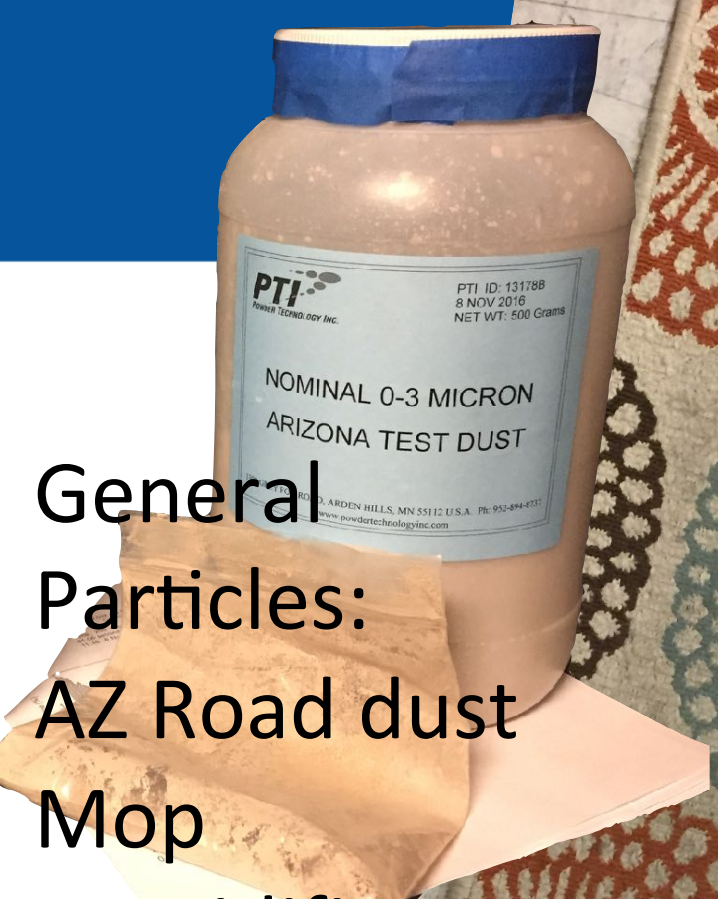
Test Lab

450 ft^2
~126 m^3





General Particles:
AZ Road dust
Mop
Humidifier



Hot surfaces

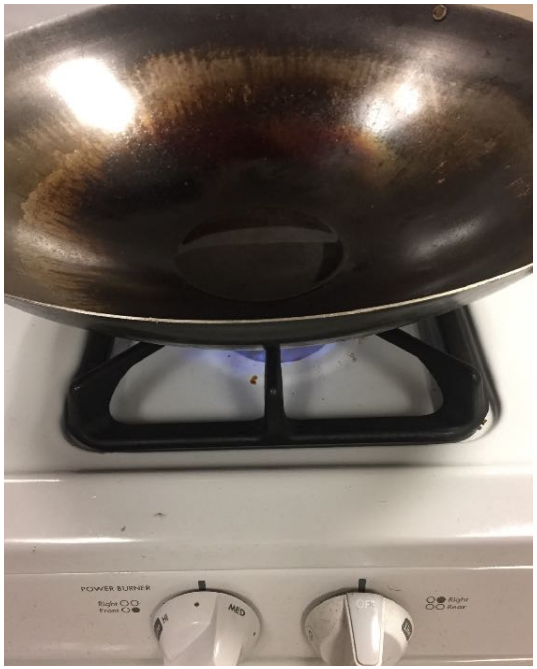
Hair Dryer

Oven

Electric Elements, Pots of hot water

Combustion
Natural Gas
Candles
Cigarettes
Incense

Cooking



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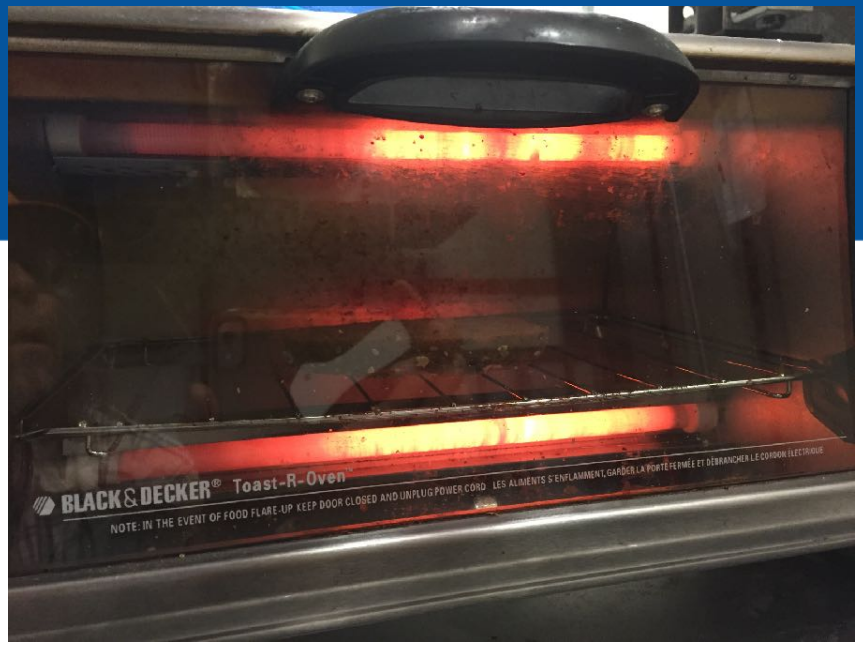
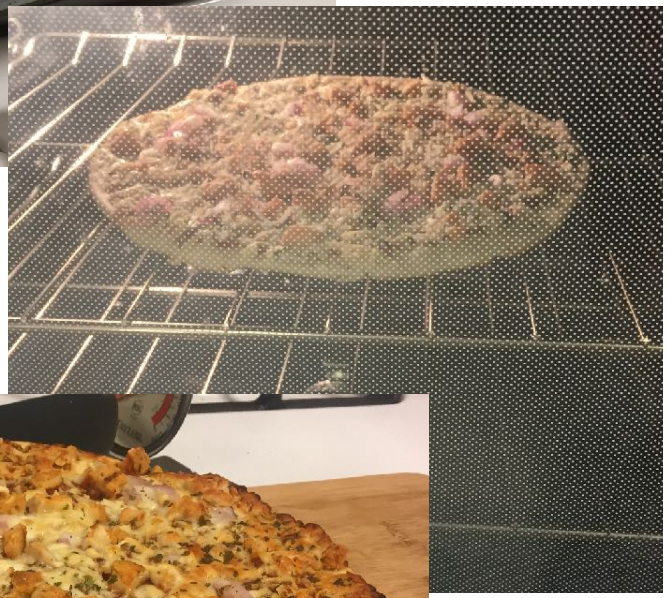
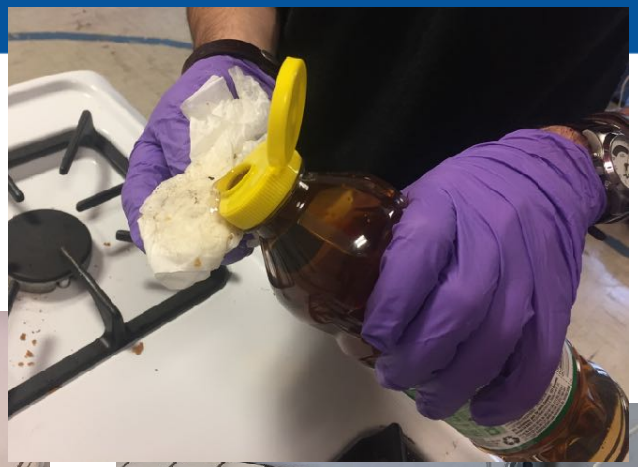

BLACK&DECKER® Toast-R-Oven
NOTE: IN THE EVENT OF FOOD FLARE-UP KEEP DOOR CLOSED AND UNPLUG POWER CORD LES ALIMENTS S'ENFLAMMENT, GARDER LA PORTE FERMÉE ET DÉBRANCHER LE CORDON ÉLECTRIQUE

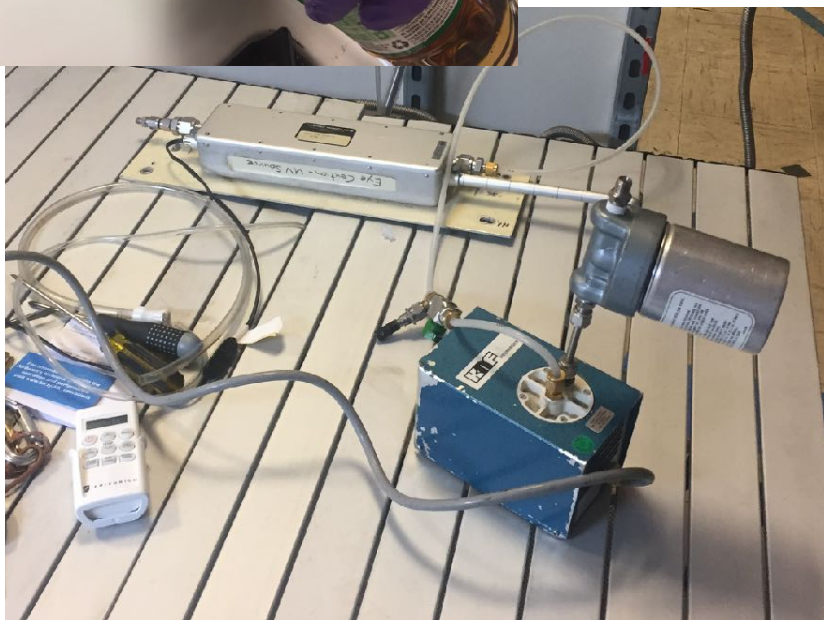

ARROWHEAD MILLS
BUTTERMILK
PANCAKE & WAFFLE MIX



Cooking

Chemistry – cleaning products and ozone



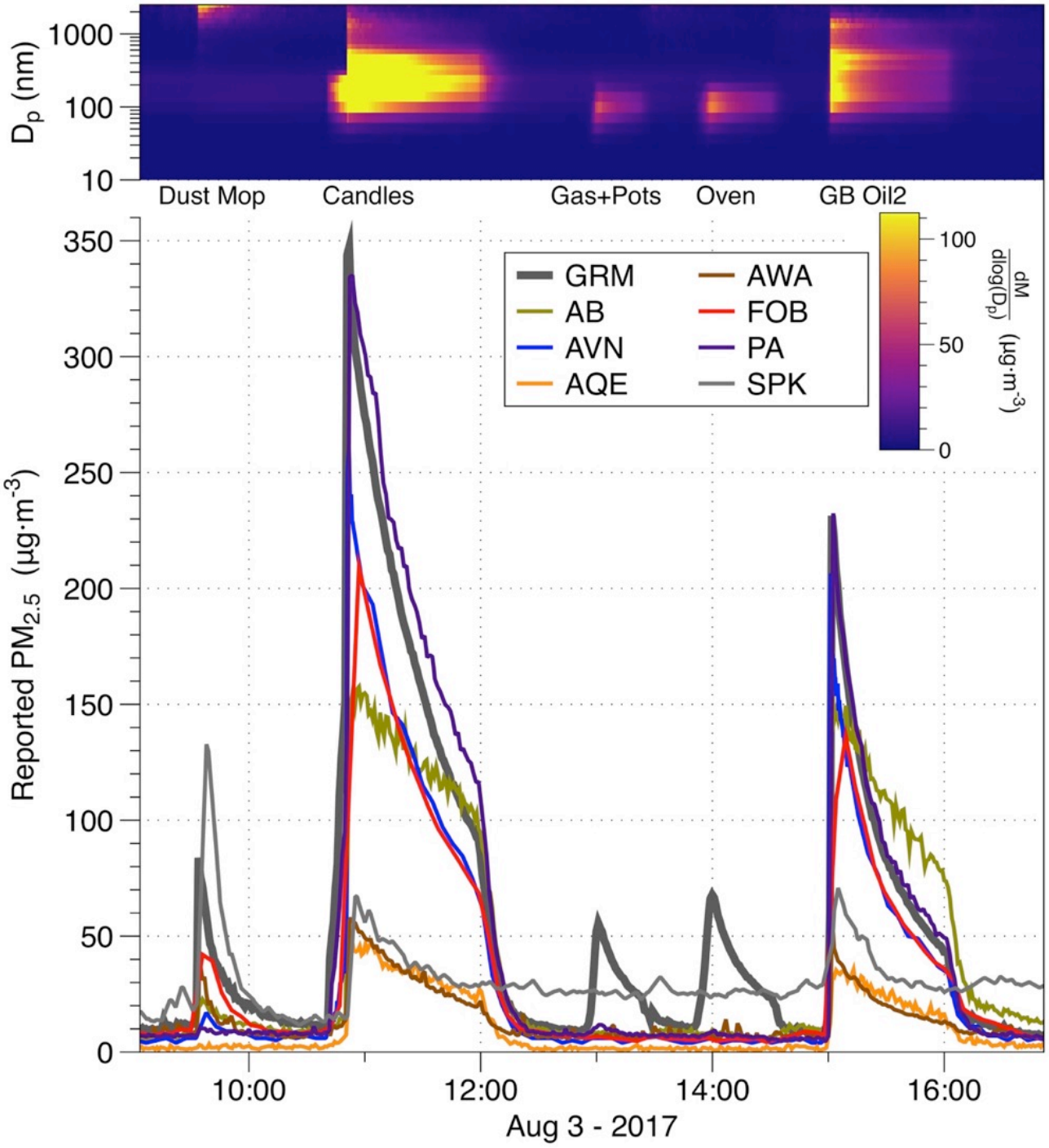


Lab Results

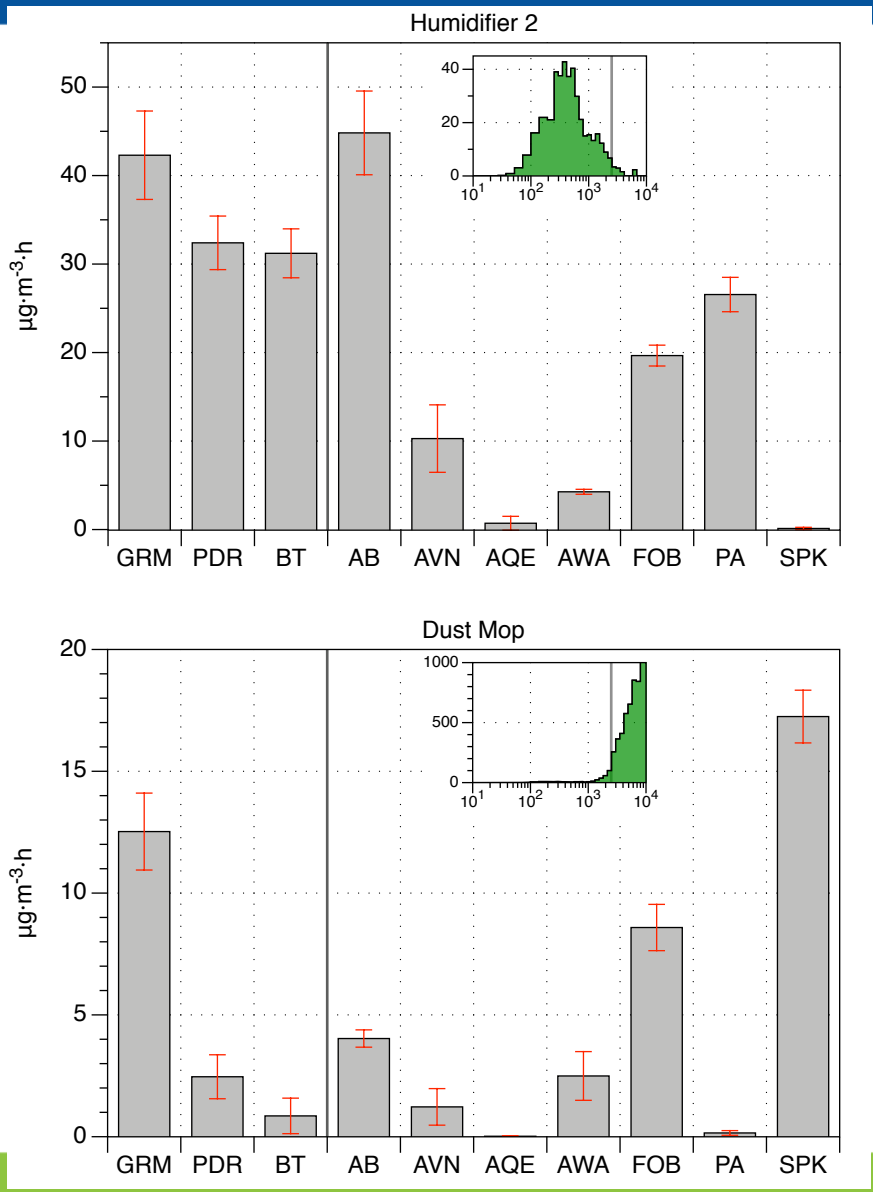
Event detection:
- Some better than others

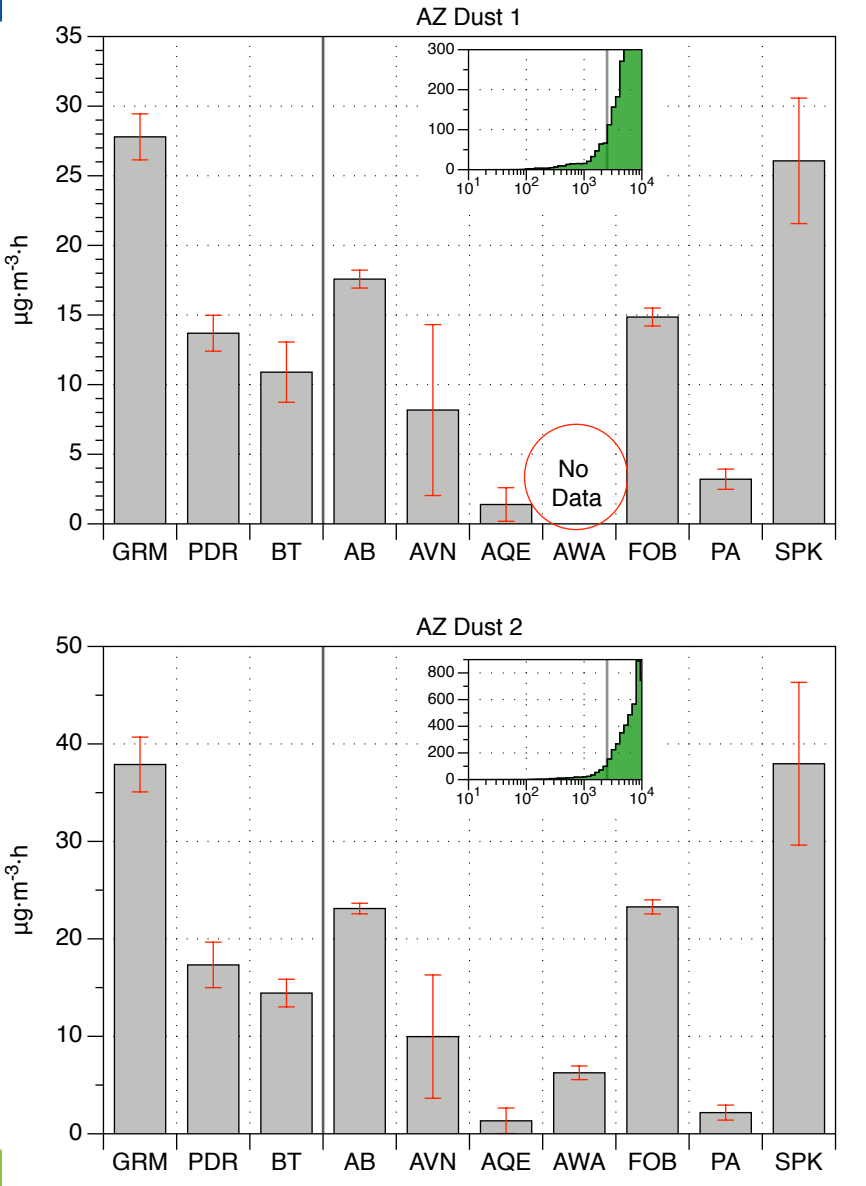
Magnitude
- Some better than others

Depends on “event” = depends on particle size distribution

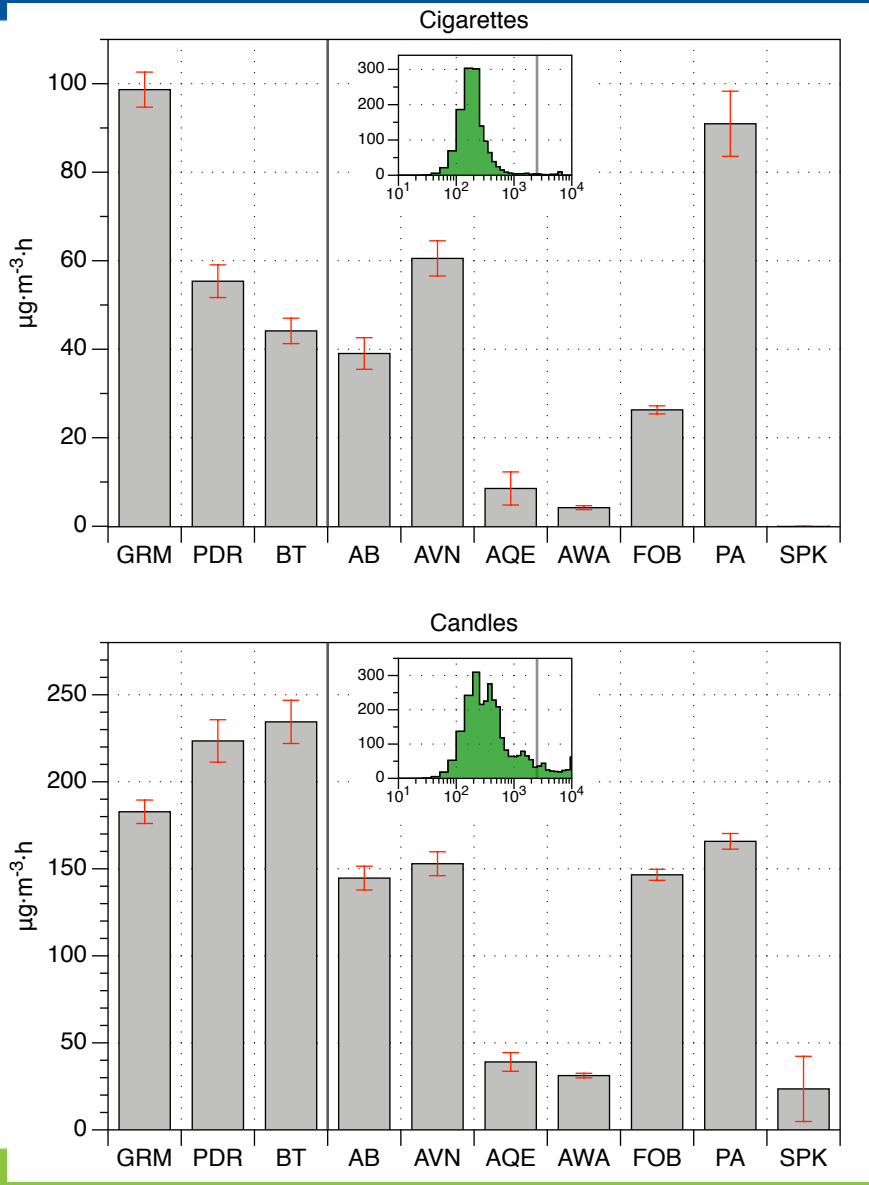


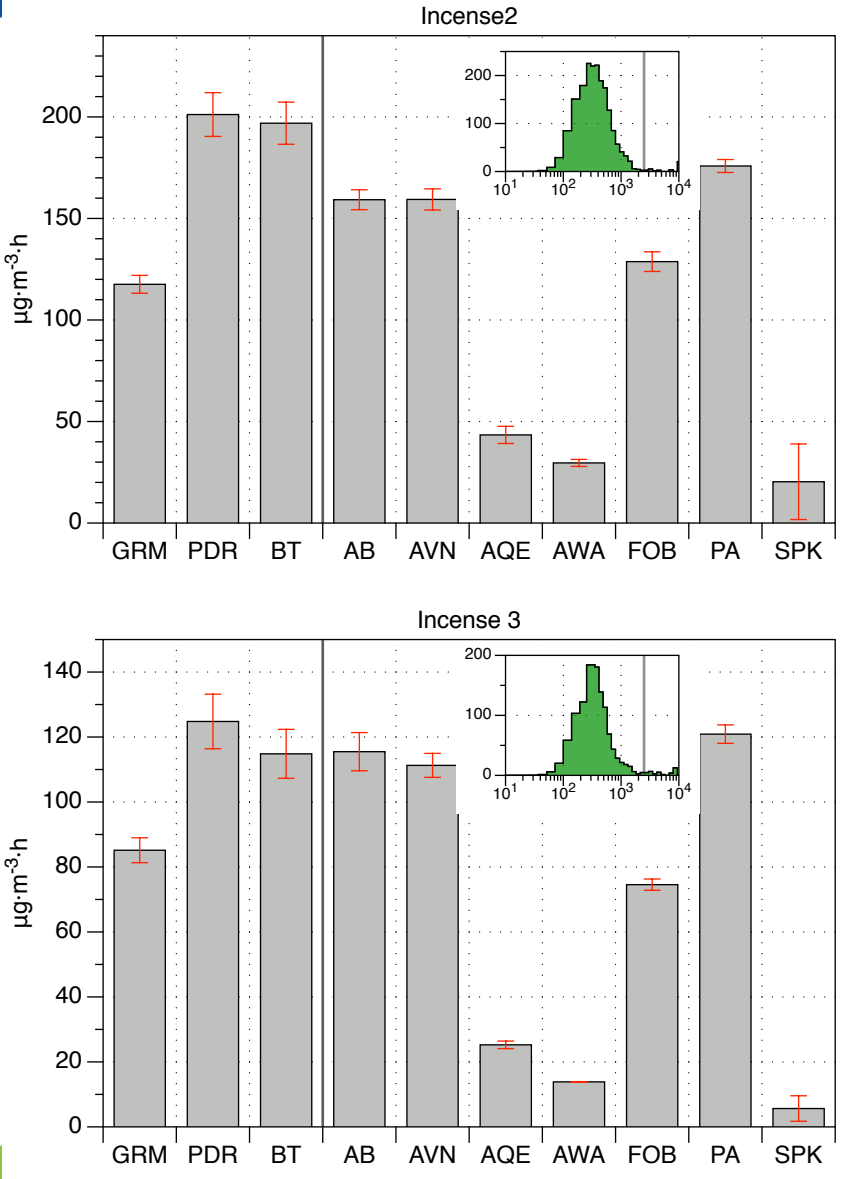
Humidifier and Dust



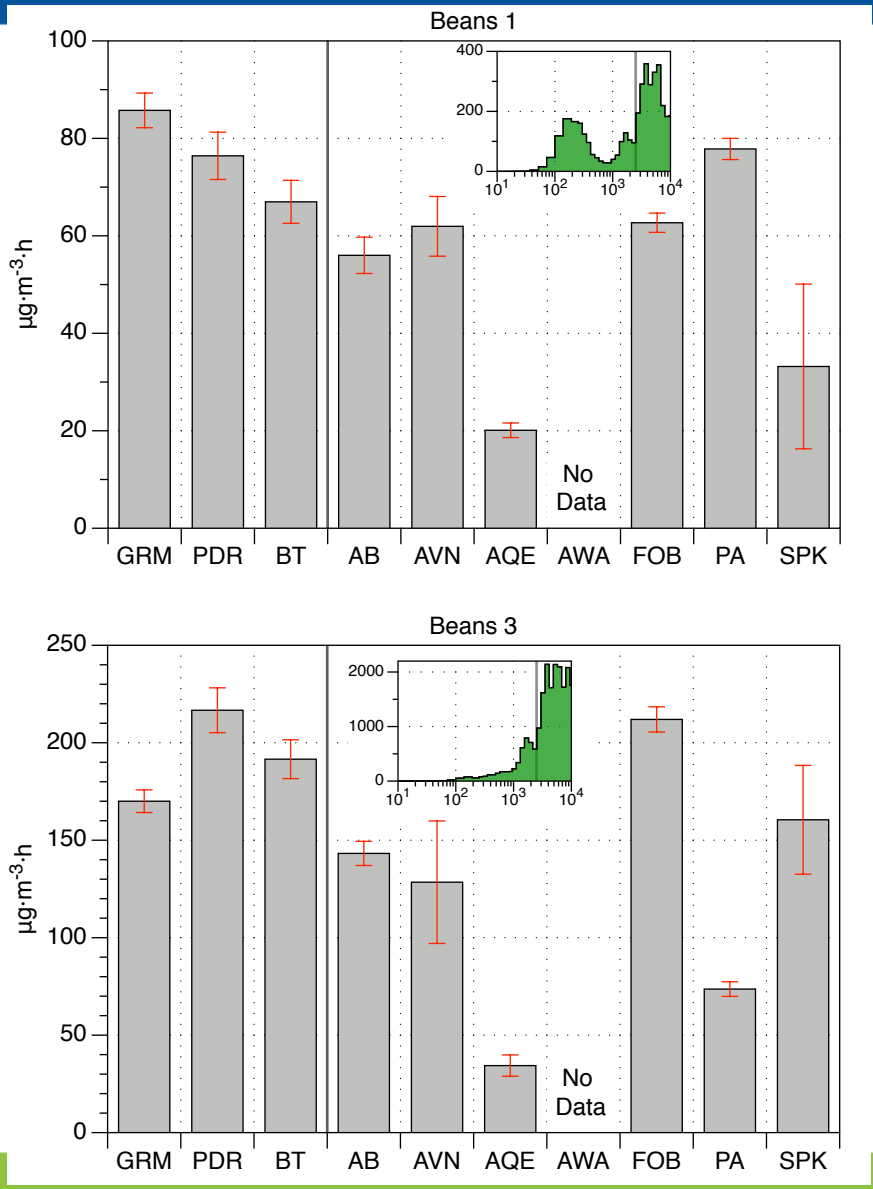


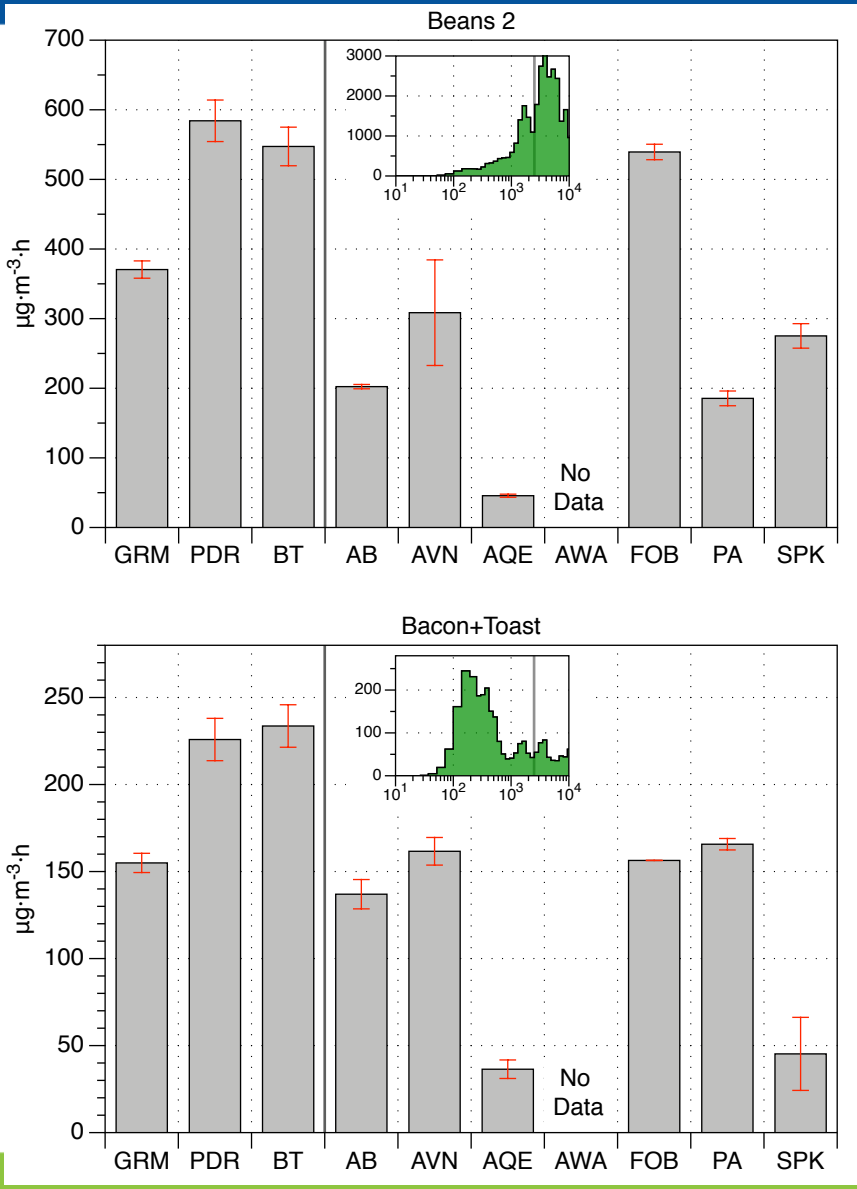
Recreational Combustion



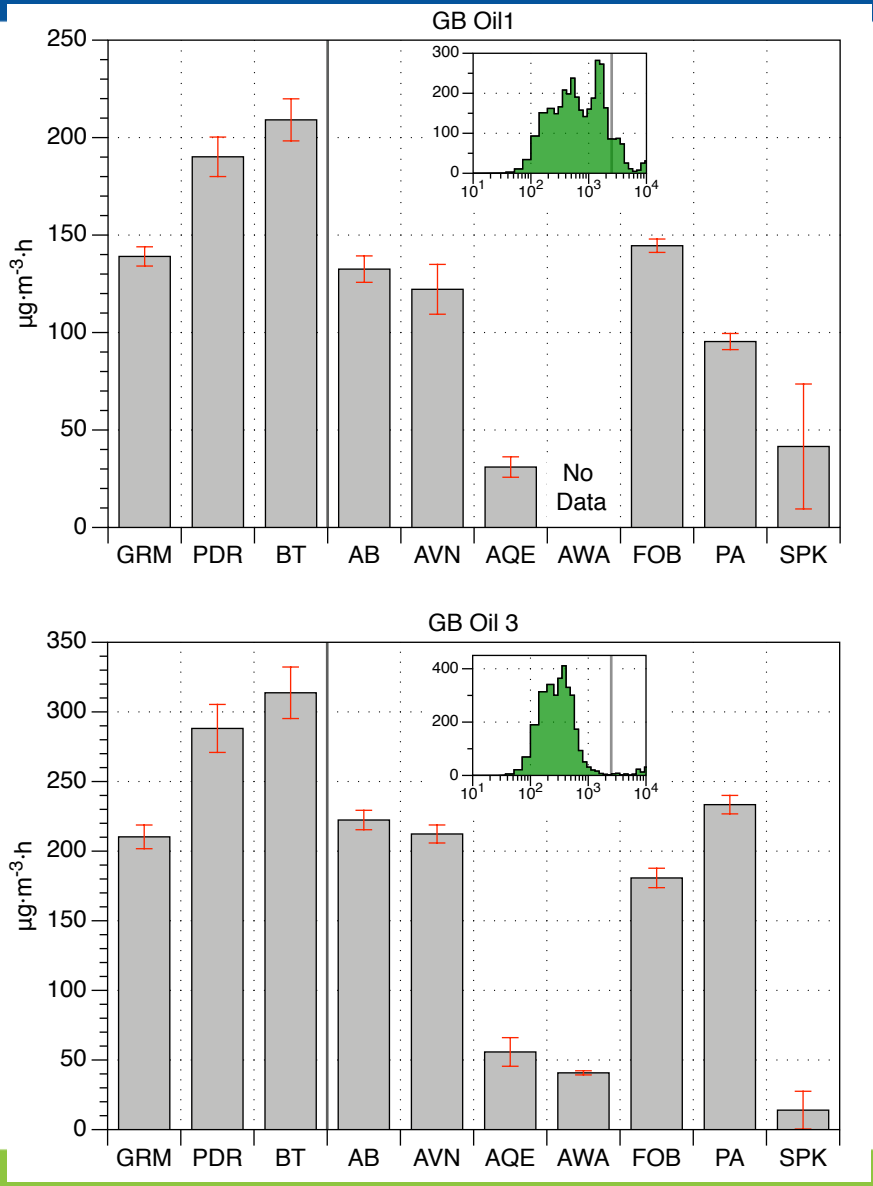


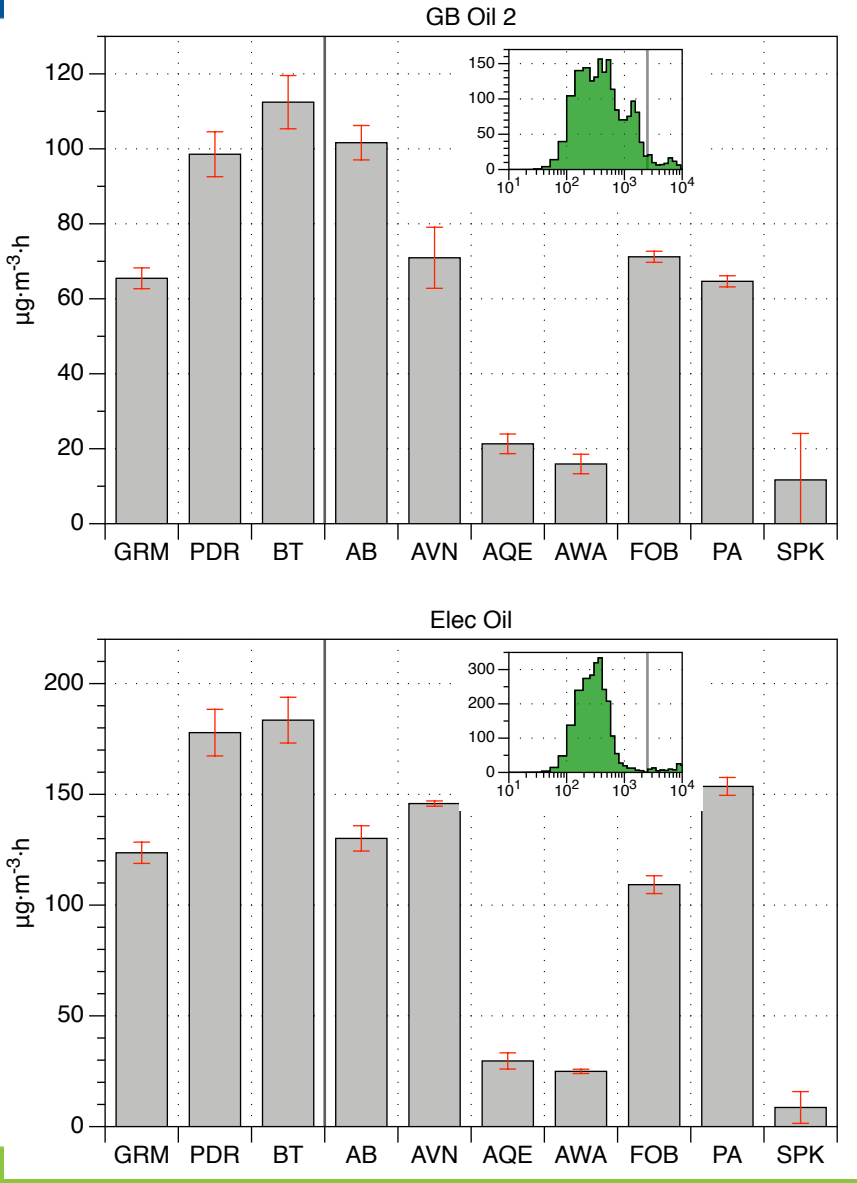
Stir-Frying and Frying + Toasting



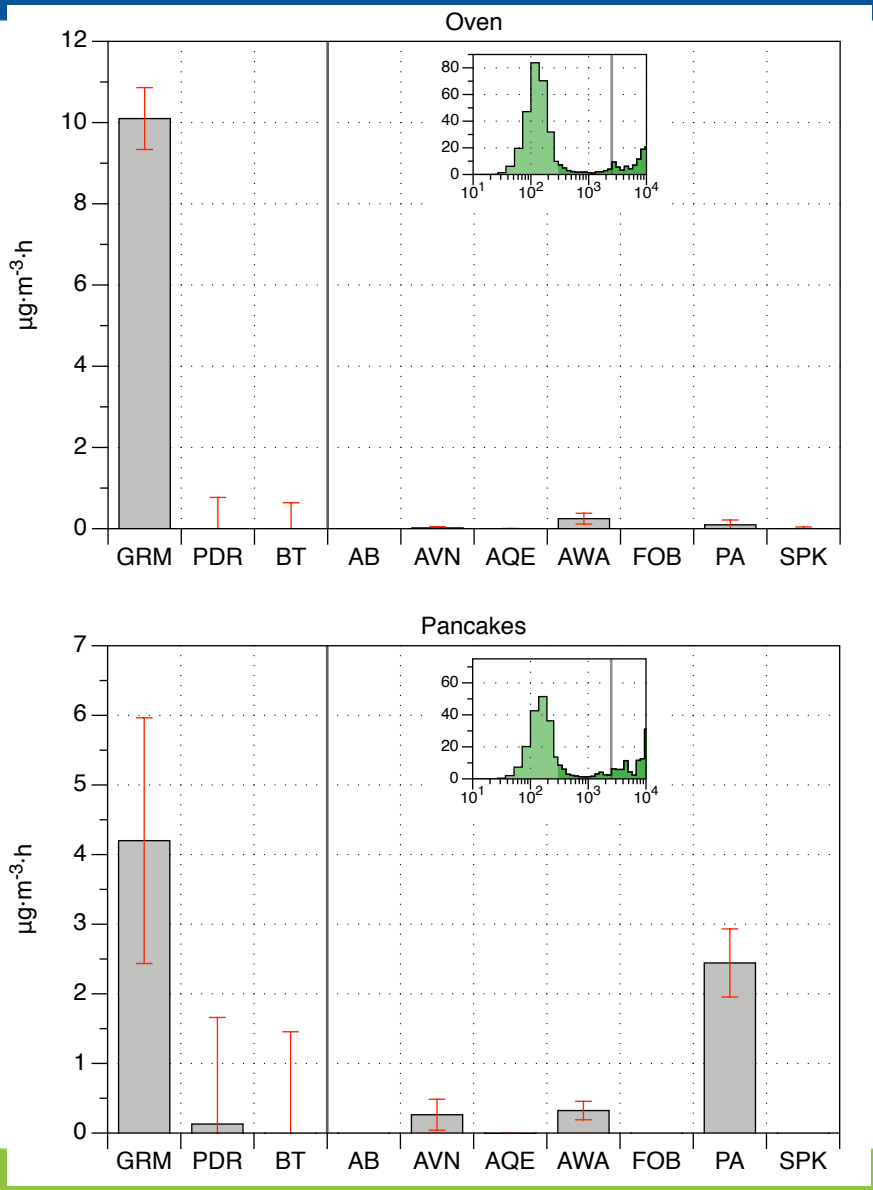


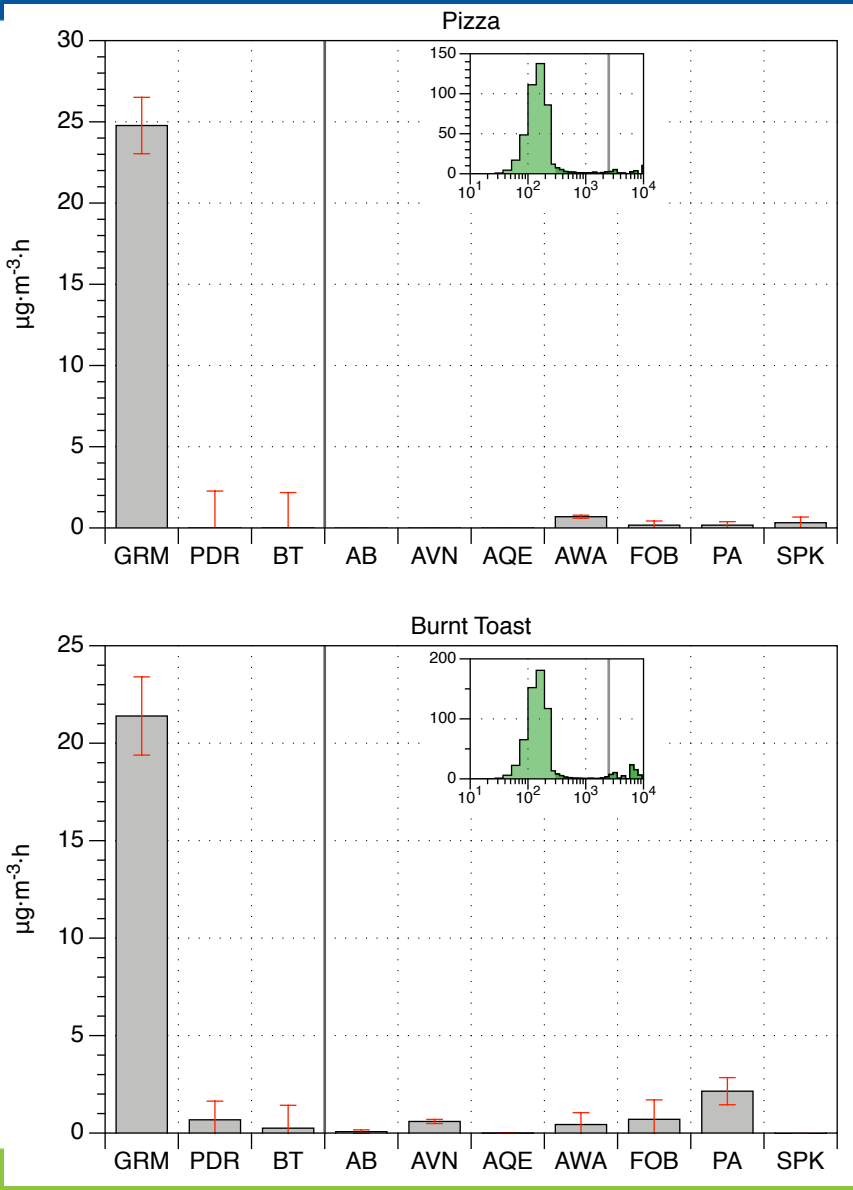
Heating Oil on Gas or Electric Burners



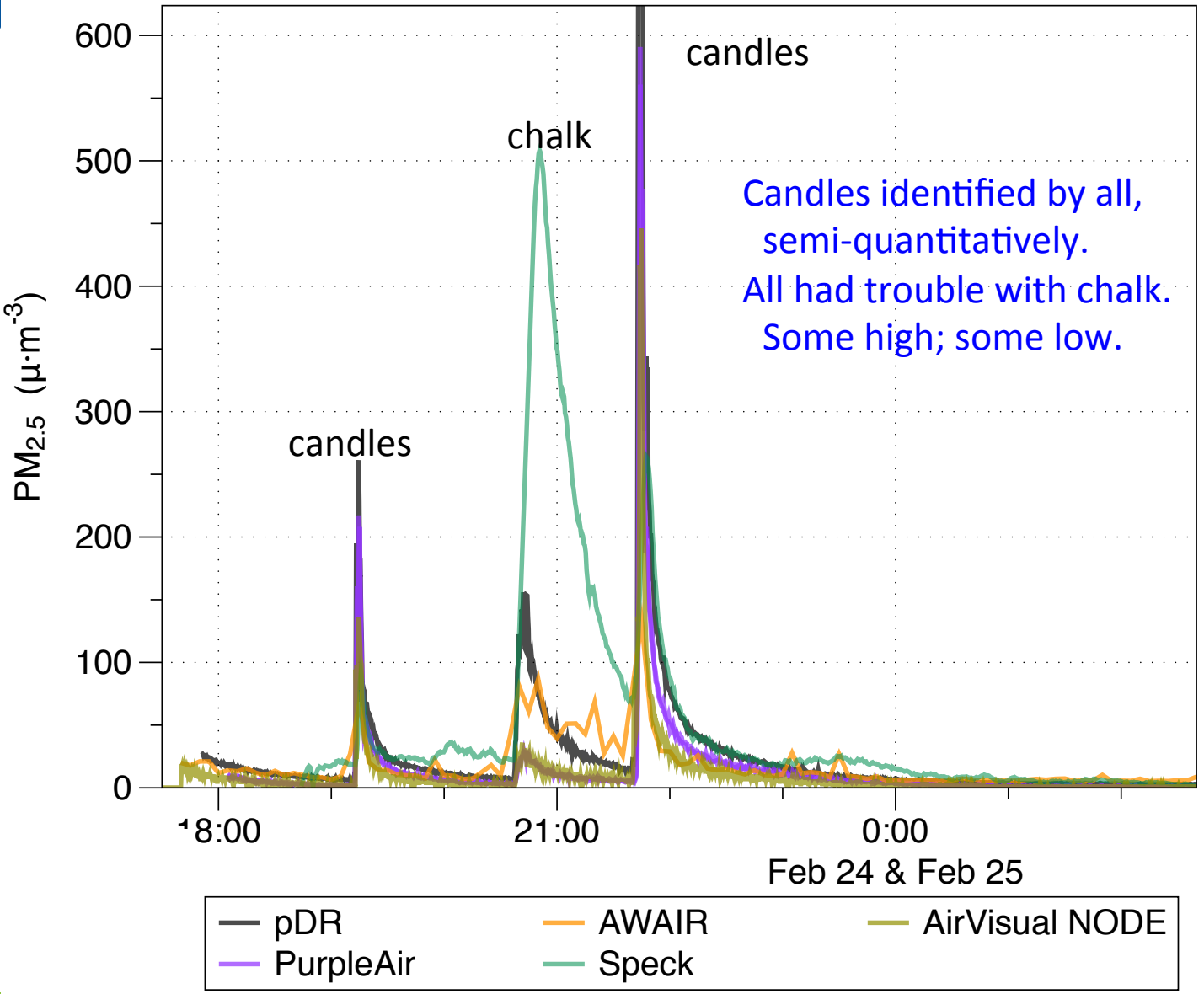


Cooking that Emits Mostly <0.3 um Particles

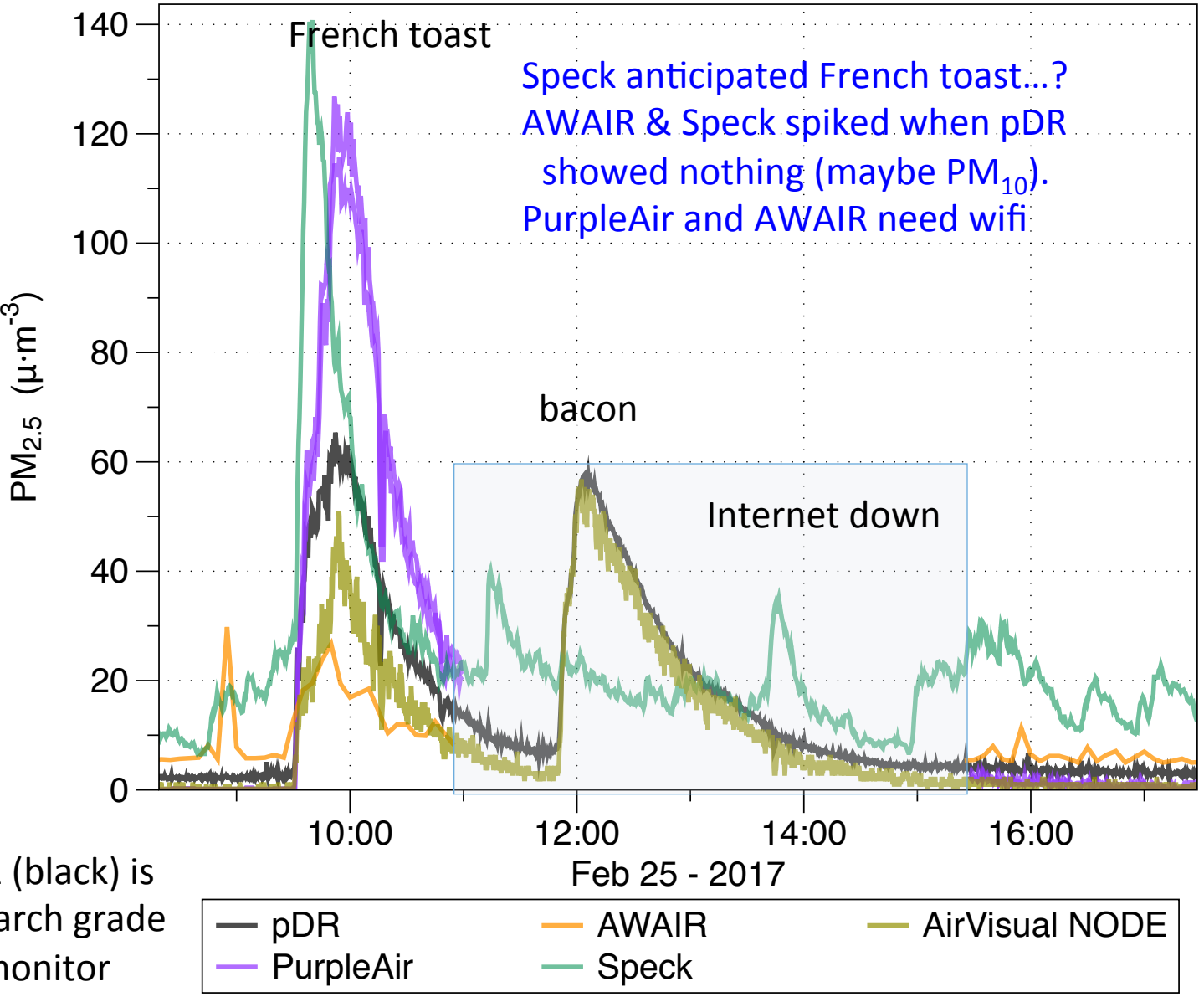




In-Home Test

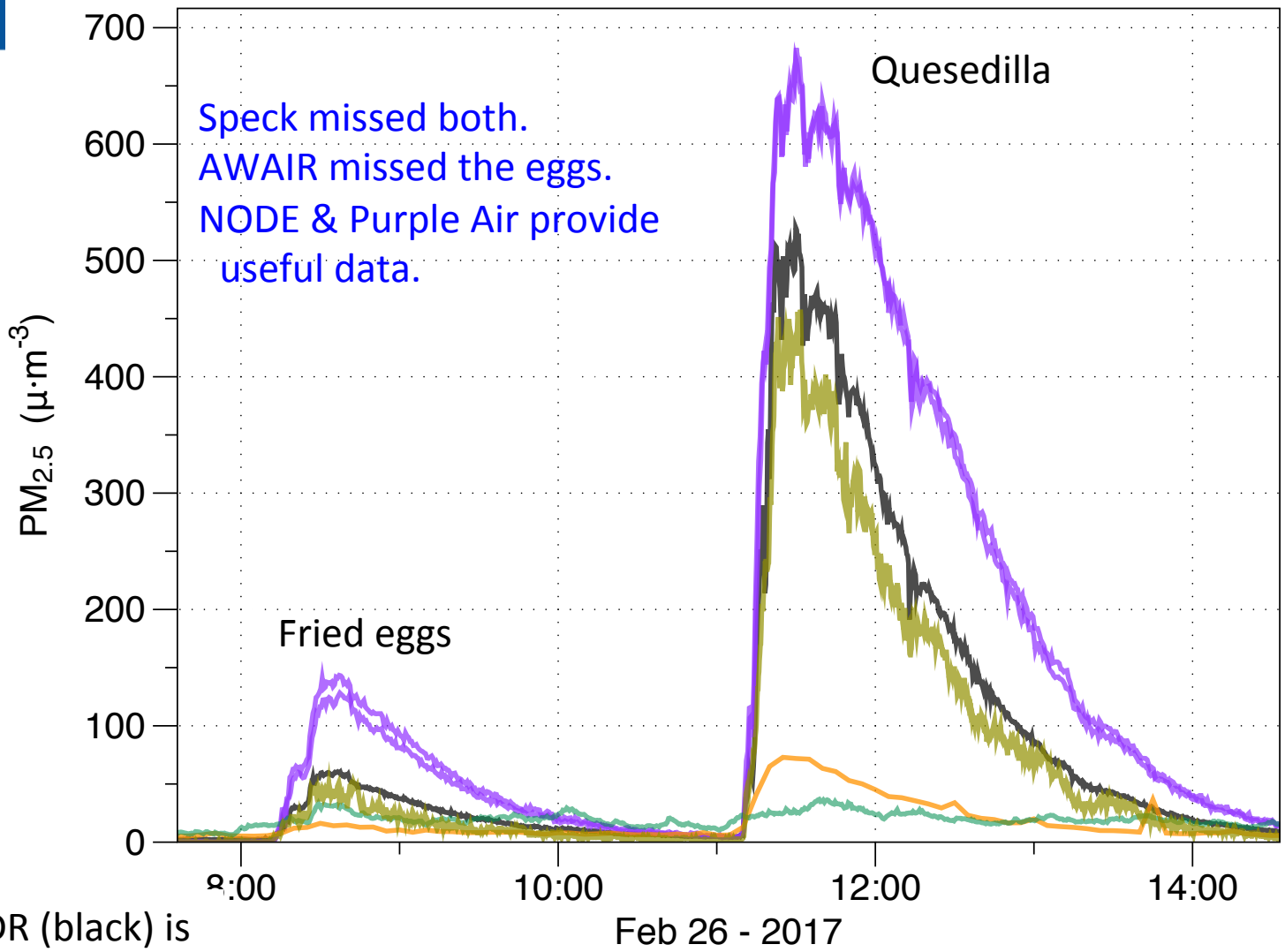

600
500
400
300
200
100
0
PM2.5 (µ·m-3)
candles
chalk
candles
Candles identified by all, semi-quantitatively.
All had trouble with chalk.
Some high; some low.
18:00
21:00
0:00
Feb 24 & Feb 25
pDR
PurpleAir
AWAIR
Speck
AirVisual NODE

In-Home Test



pDR (black) is research grade monitor

In-Home Test



pDR (black) is research grade monitor

Other Studies

- 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/

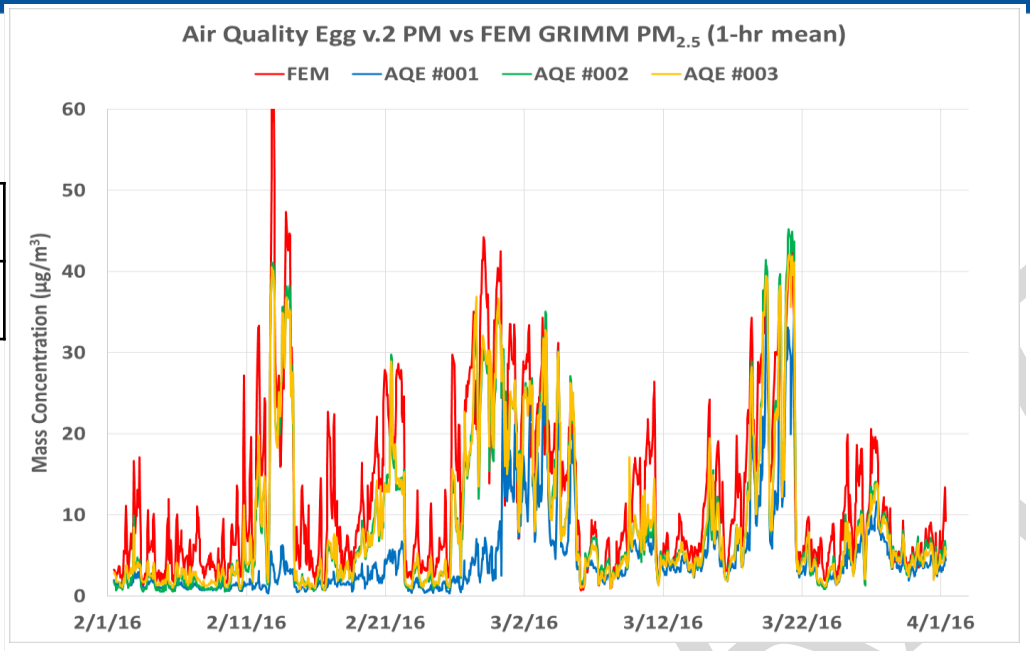
AirQuality Egg V2.0

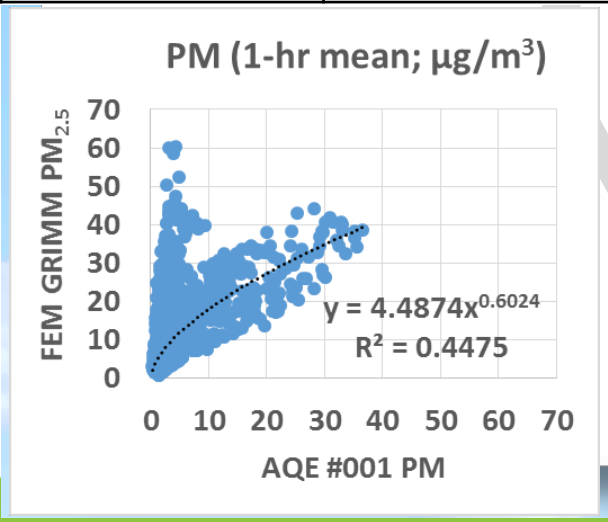
$280

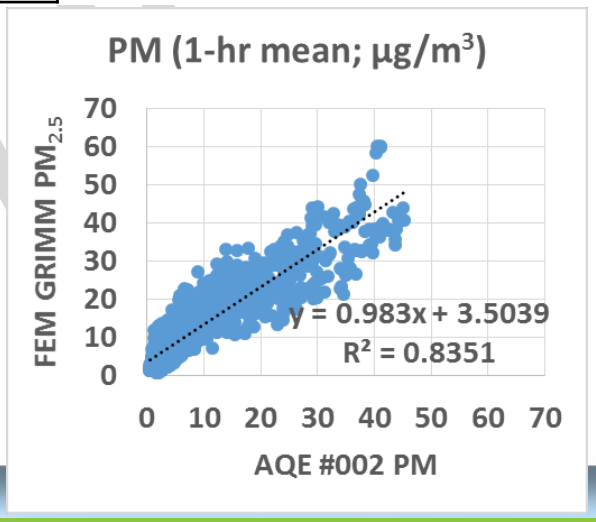
PM, T, RH

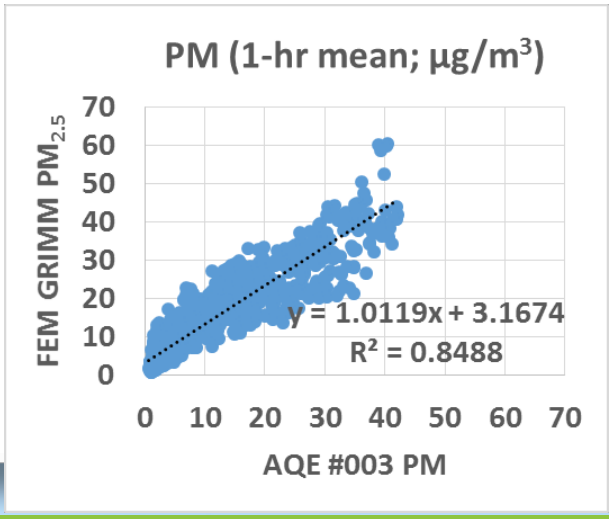
Cloud Storage	Yes
Devices	n/a

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









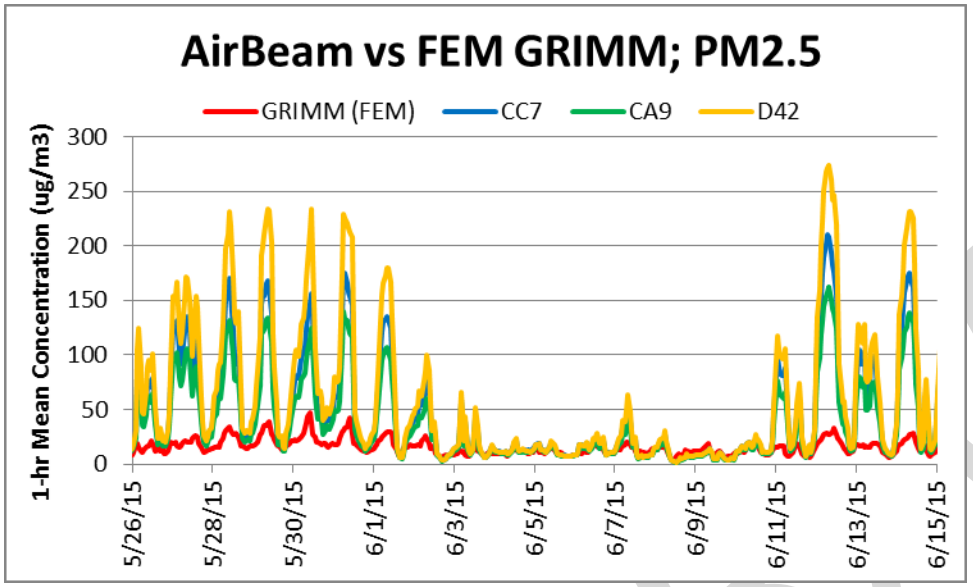
AirBeam

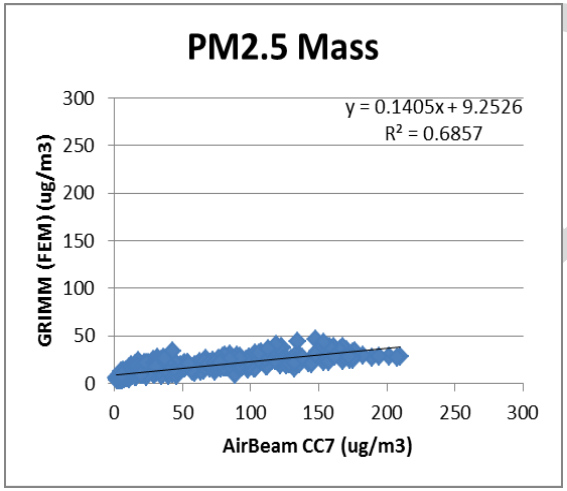
$250

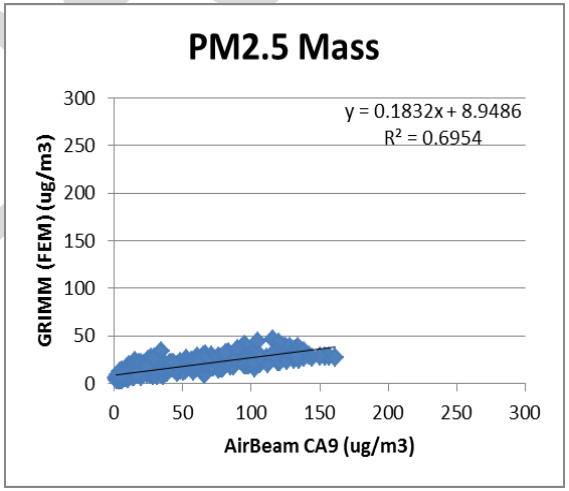
PM

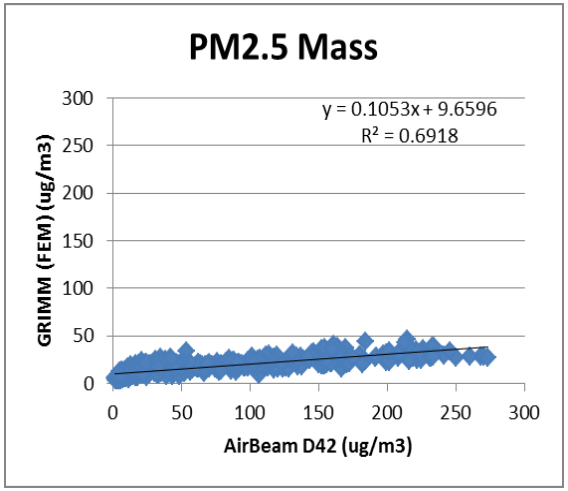
Cloud Storage	Yes
Devices	Android

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









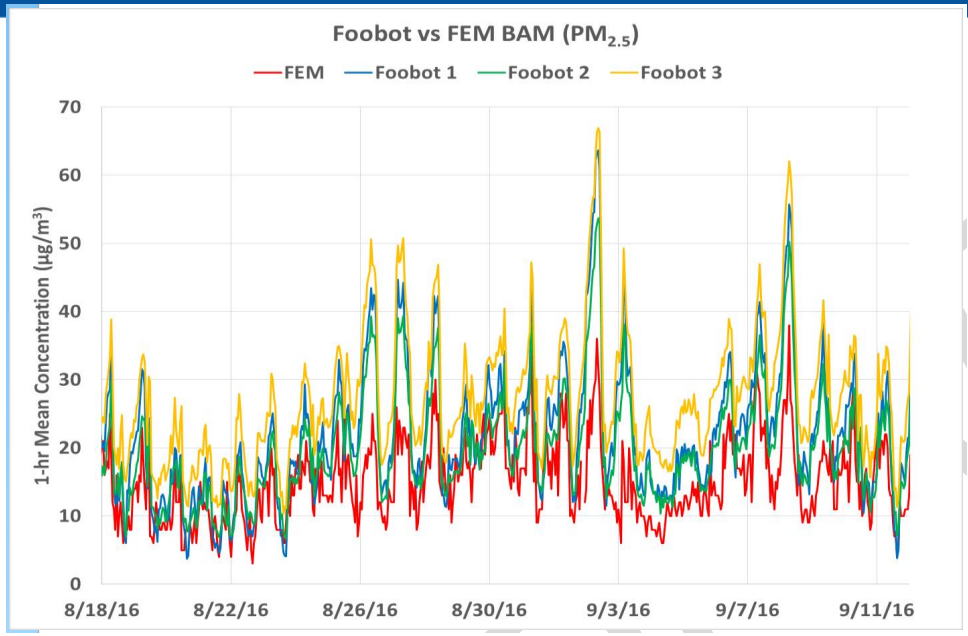
Foobot

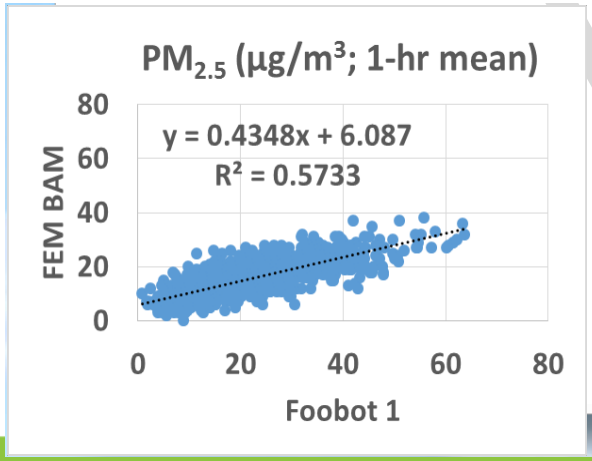
$199

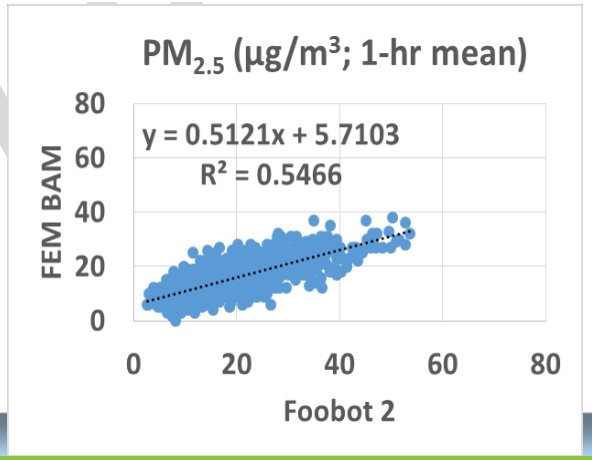
PM, T, RH, CO_2, CO, tVOC

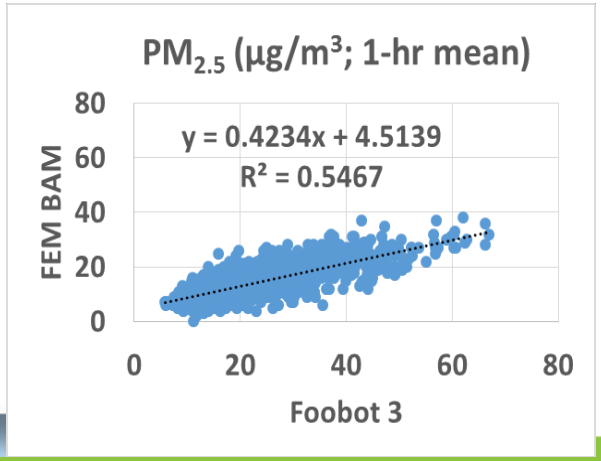
Cloud Storage	Yes
Devices	iOS, Android

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









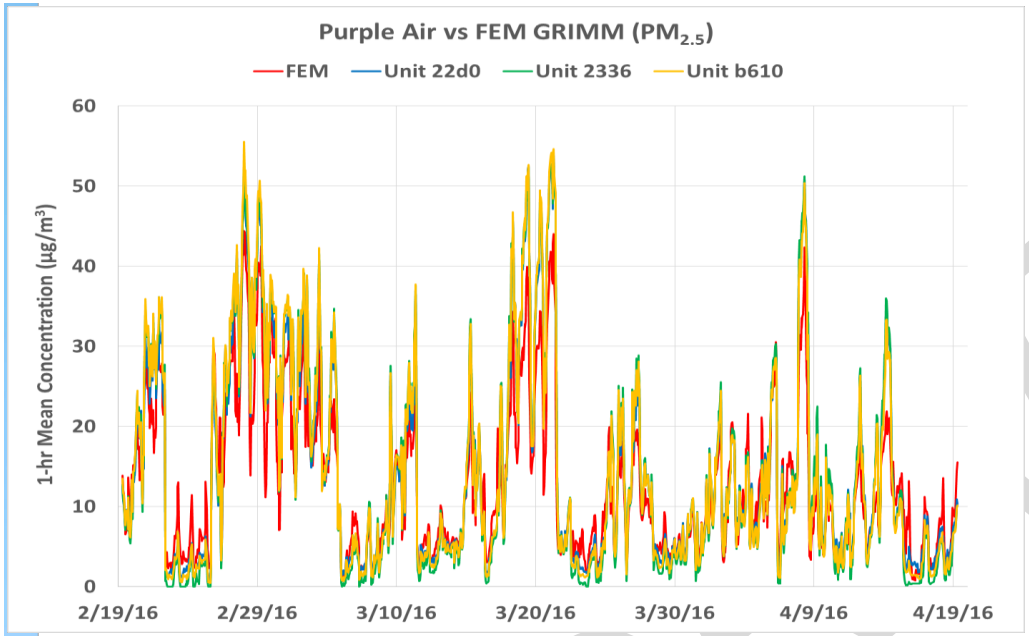
PurpleAir

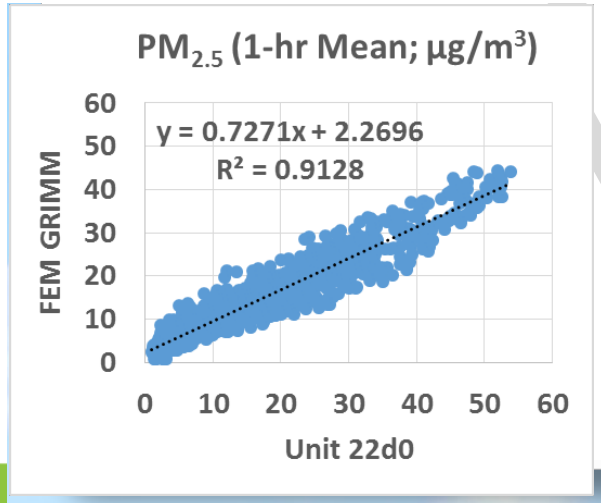
$199

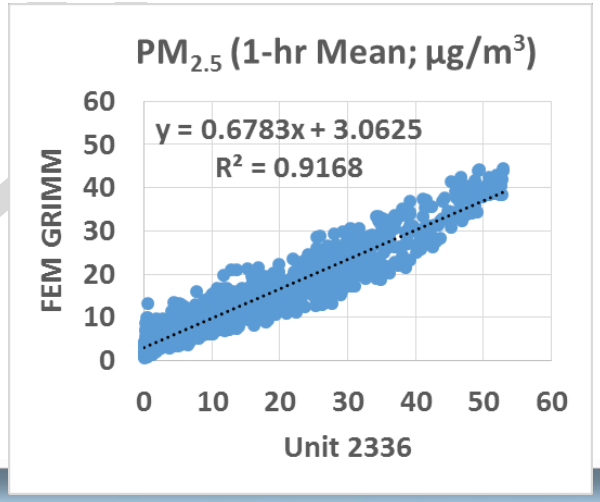
PM

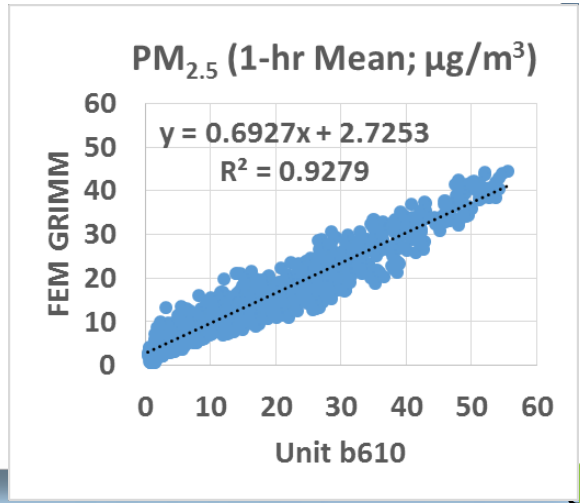
Cloud Storage	Yes
Devices	?

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









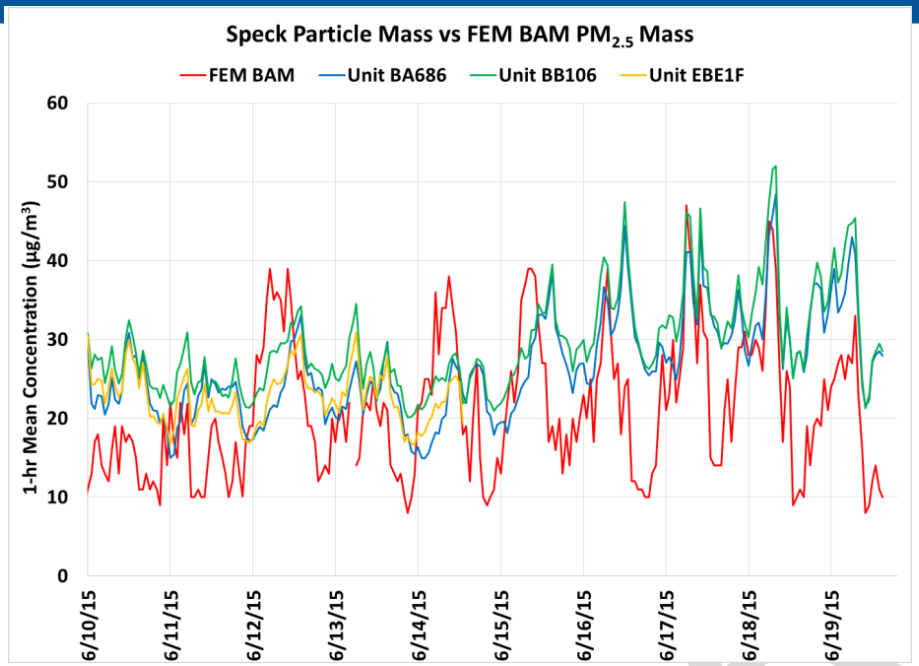
Speck V2.0

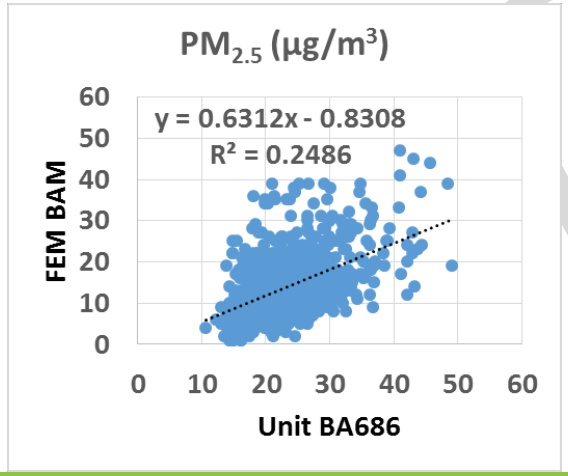
$199

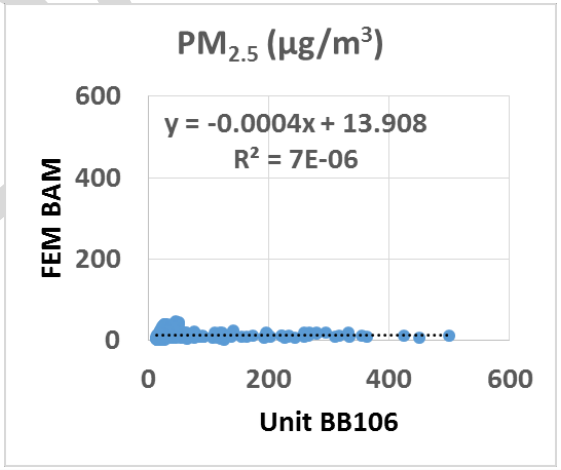
PM

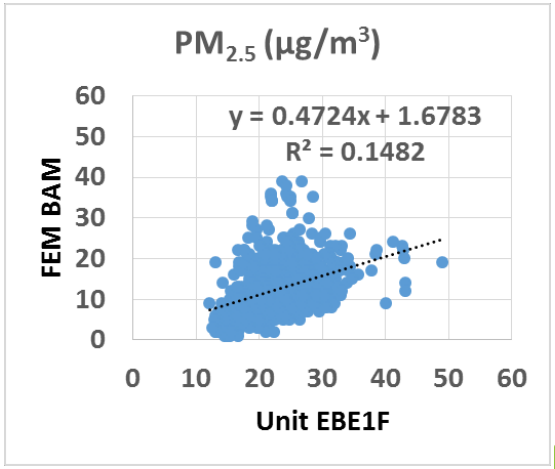
Cloud Storage	Yes
Devices	iOS, Android

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









Results

Winners

FOB

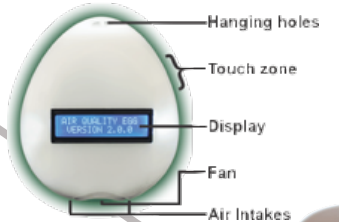
PA

AVN

AB

AWA

AQE



SPK

Losers

Conclusions

1. Four consumer monitors detected most sources and quantitatively* measured all large sources of $PM_{2.5}$.
   - Appear suitable to indicate IAQ.
   - Could control a filter for most situations.
   - PA could be used for health calculation

2. Two consumer monitors detected many sources but not quantitatively.

3. One monitor was not informative.

4. No consumer monitors suitable to detect & control ultrafine particles.

PA

FOB

AB

AVN

AWA

AQE

SPK

* Within a factor of 10 for AirBeam… is this good enough?

PA quantitatively much better than others – but no nice packaging/display

Remaining issues

Need to test for durability − are they still OK 5, 10 years from now?

What about other key pollutants: formaldehyde, NO_2, etc.?

Almost all require an internet connection for cloud storage but will restart automatically if internet down and then reconnected.

- ALWAYS confirm upload otherwise data overwritten and lost
- AWAIR only kept data in cloud for limit time − if not downloaded lost forever

Almost all have an app for data viewing − particularly if they have no built-in display

Other considerations

- Purple Air: Best performance, buy no nice packaging/ display, no battery
- Foobot: Good performance, no direct display
- AirVisual Node: Good performance. Has battery power – will log w/o internet connection. Has better CO2 detection – looks at previous week for lowest reading and auto-calibrates. Has very good display.
- Air Beam: No display
- AWAIR: Stylish packaging
- Air Quality Egg: OK display
- Speck: Good Display

Ongoing Work

- Newport Partners with Building America: developing a standardized testing/evaluation protocol for IAQ sensors
- South Air Quality Management District:
- LBNL: working with manufacturers on product improvements

Build your own monitor (BYOM)

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

  University of Colorado, Boulder

  http://mobilesensingtechnology.com/

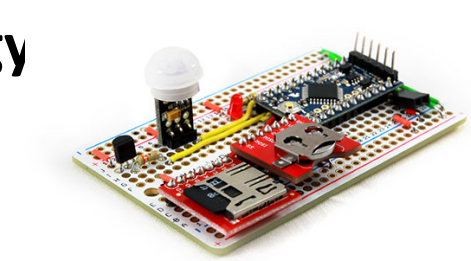
  T, RH, P, CO_2, O_3, NO_2; slots for 4 e2v MOx sensors

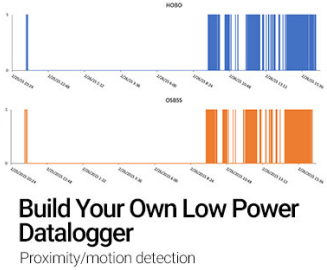
- **Open Source Building Science Sensors**

  Illinois Institute of Technology

  http://www.osbss.com/

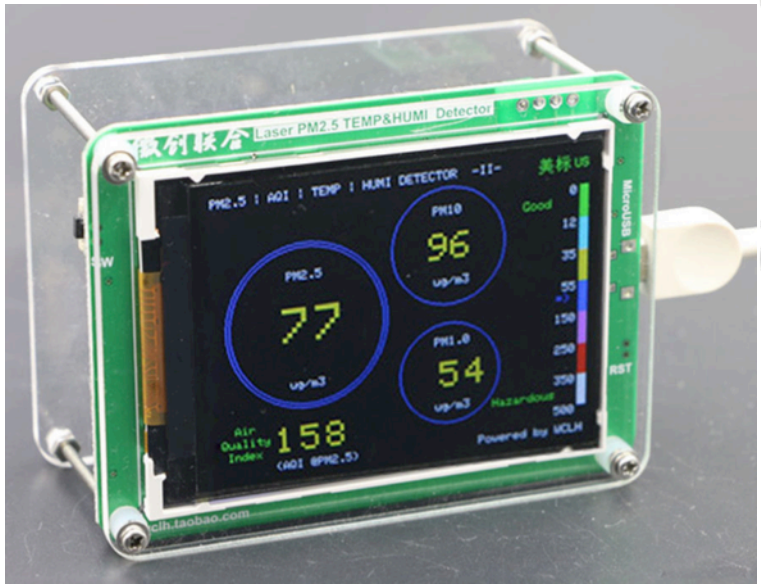
  T, RH, CO_2, Particles, delta–P, equilibrium RH, light state, proximity, occupancy

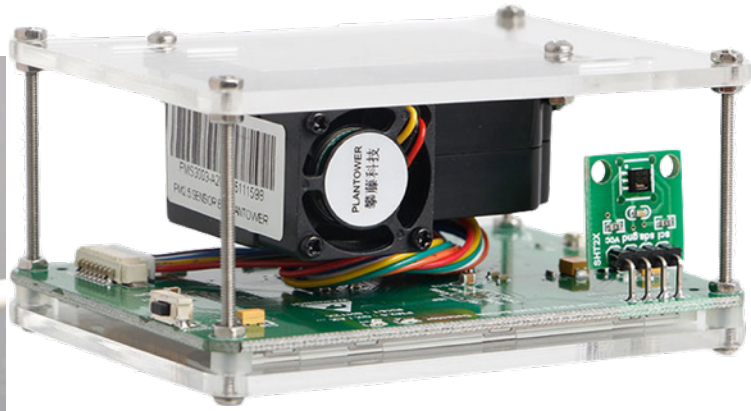




DIY / Maker offerings

- 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





What's coming… IAQ on a home performance dashboard

Center for Realtor Technology

https://crtlabs.org/2018/01/rosetta-home-beta-is-coming/