Airborne Particulate Matter in Residences: Challenges and Opportunities for Control

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Learning Objectives & AIA disclaimer

1. Understand the importance of limiting exposure to ultrafine particles in homes
2. Describe effective options for limiting exposure to $PM_{2.5}$ and ultrafine particles in homes
3. Distinguish between structural and behavioral sources of water waste in residential applications
4. Implement cost-effective water control strategies that strive for and achieve elegant simplicity

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Acknowledgments

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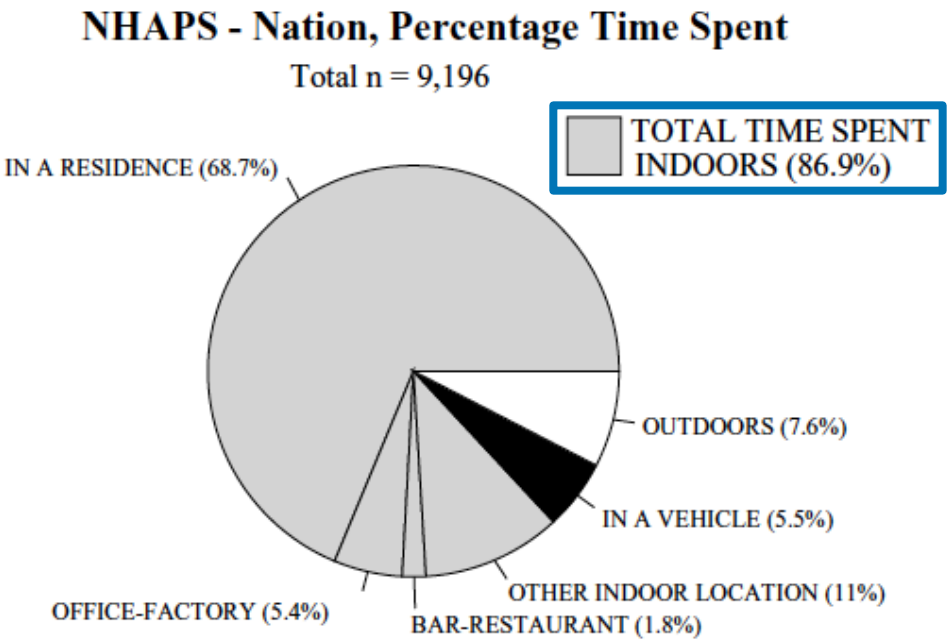
- **People**
  - Jeffrey Siegel, Atila Novoselac, Michael Waring, Lew Harriman, Terry Brennan, Laura Kolb, Cristina Cordova, Vito Ilacqua
  - Current and former members of the Built Environment Research Group:

Outline

- Introduction to indoor air pollution in residences
- Importance of indoor particulate matter for health
- Indoor and outdoor PM in residences
- Strategies for controlling indoor PM
- Challenges and limitations for controlling indoor PM

What do you think of when you hear "air pollution?"

What do I think of when I hear "air pollution?"



Klepeis et al. **2001** *J Exp Anal Environ Epidem*

Americans spend almost 90% of their time indoors

- Almost 70% at home

There are many <u>indoor</u> & <u>outdoor</u> sources of indoor pollutants

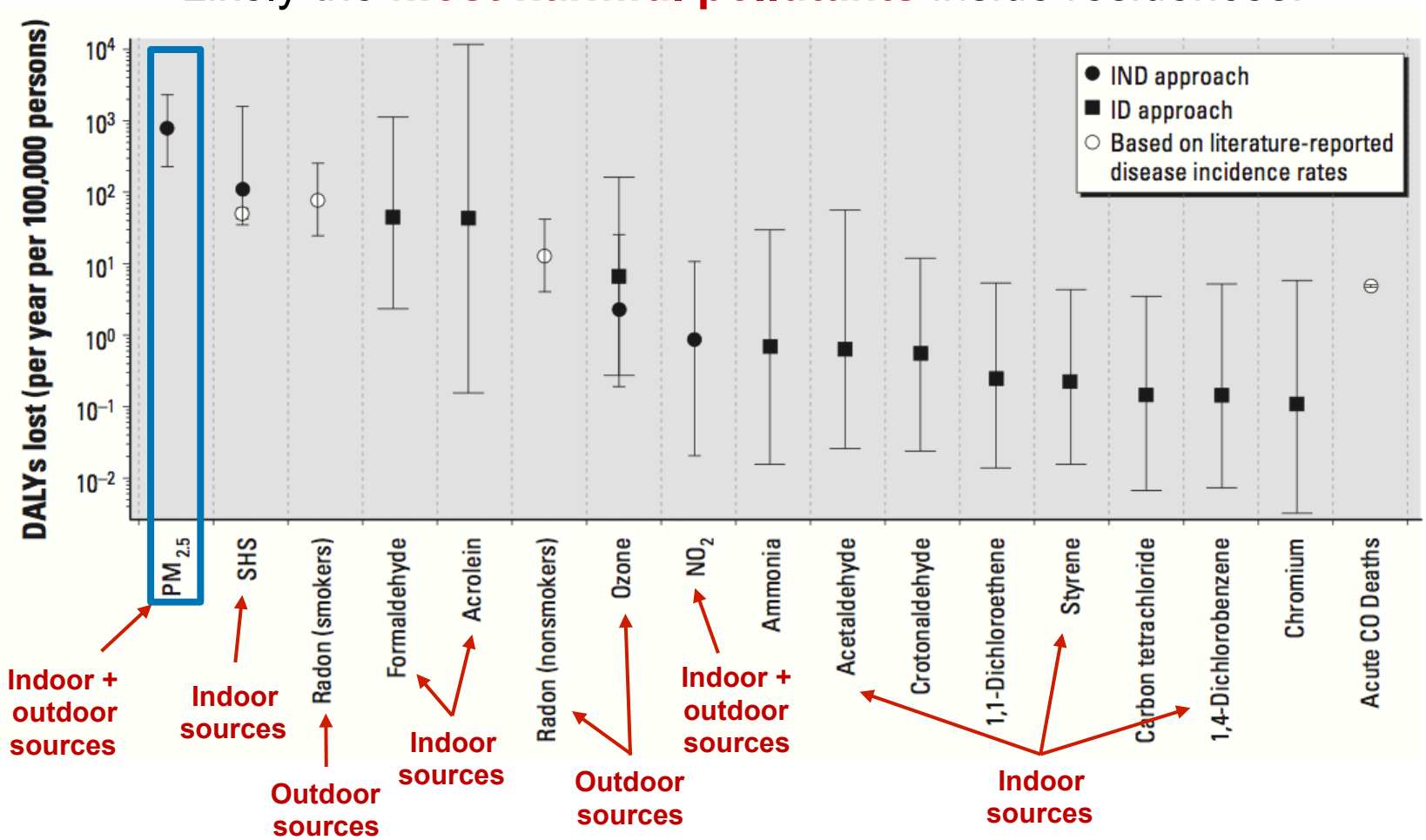
- Particulate matter (PM)
- Organic gases (e.g., VOCs, aldehydes)
- Inorganic gases (e.g., NO_x, CO, O_3)

Logue et al. **2011** *Indoor Air*

Residential indoor air and human health

Residential indoor air exposures account for **~5-14%** of the non-communicable/non-psychiatric **U.S. disease burden**

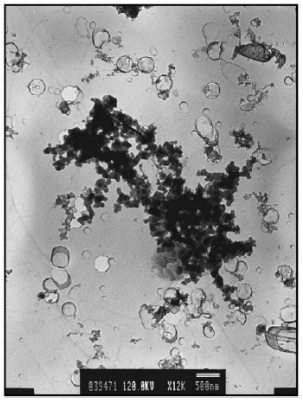
- Likely the **most harmful pollutants** inside residences:

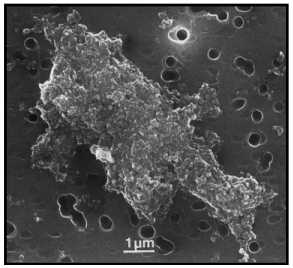


Logue et al. **2012** *Environ Health Perspect*

One of the biggest culprits: Particulate matter (PM)

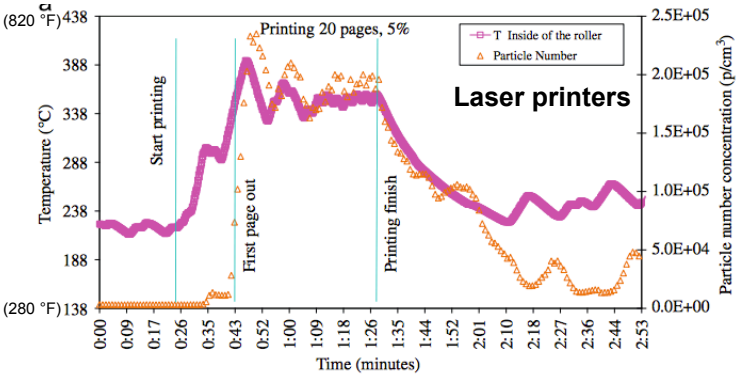
- Solid and liquid particles suspended in air
- Both indoor and outdoor sources
  - **Outdoors:** Traffic, industry, natural, atmospheric rxns
  - **Indoors:** Appliances, cleaning, combustion, others



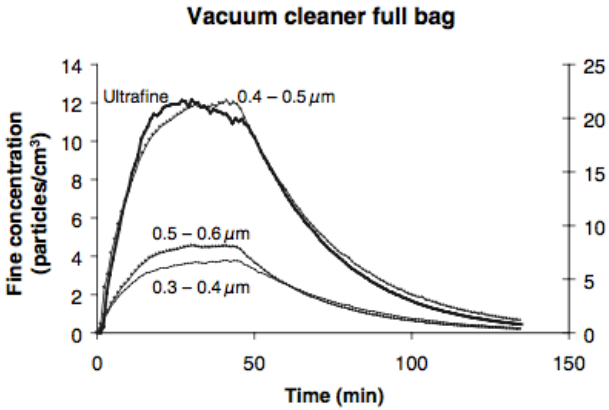


Casuccio et al. **2004** *Fuel Process Technol*
Ormstad **2000** *Toxicology*

Indoor sources

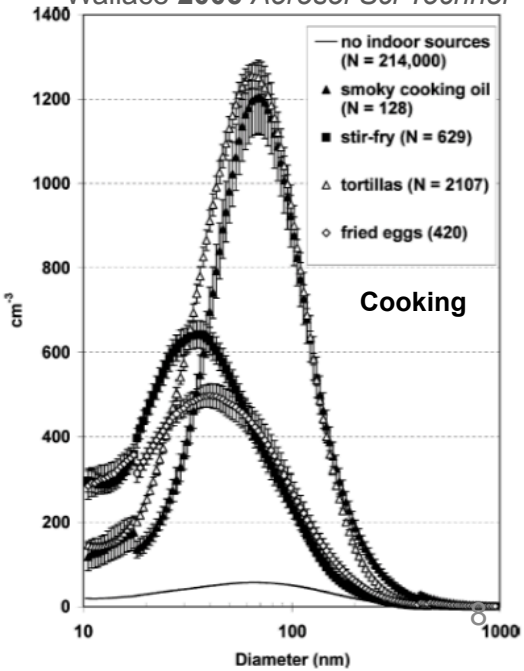


He et al. **2010** *J Aerosol Sci*



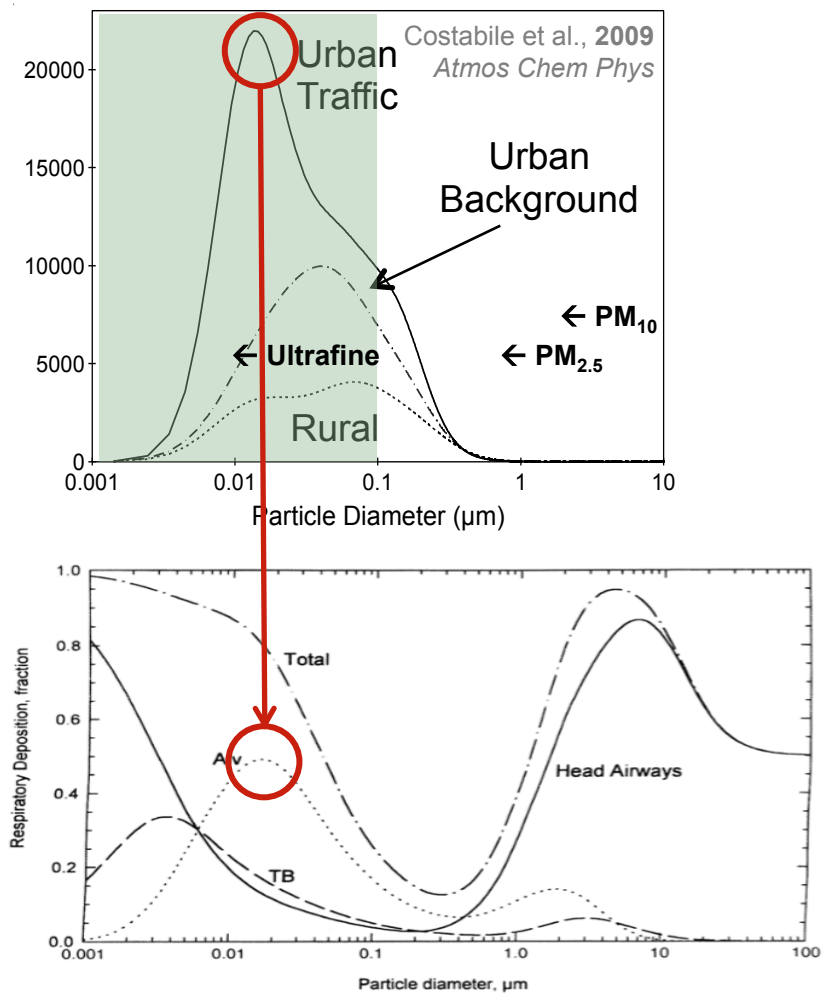
Afshari et al. **2005** *Indoor Air*

Wallace **2006** *Aerosol Sci Technol*



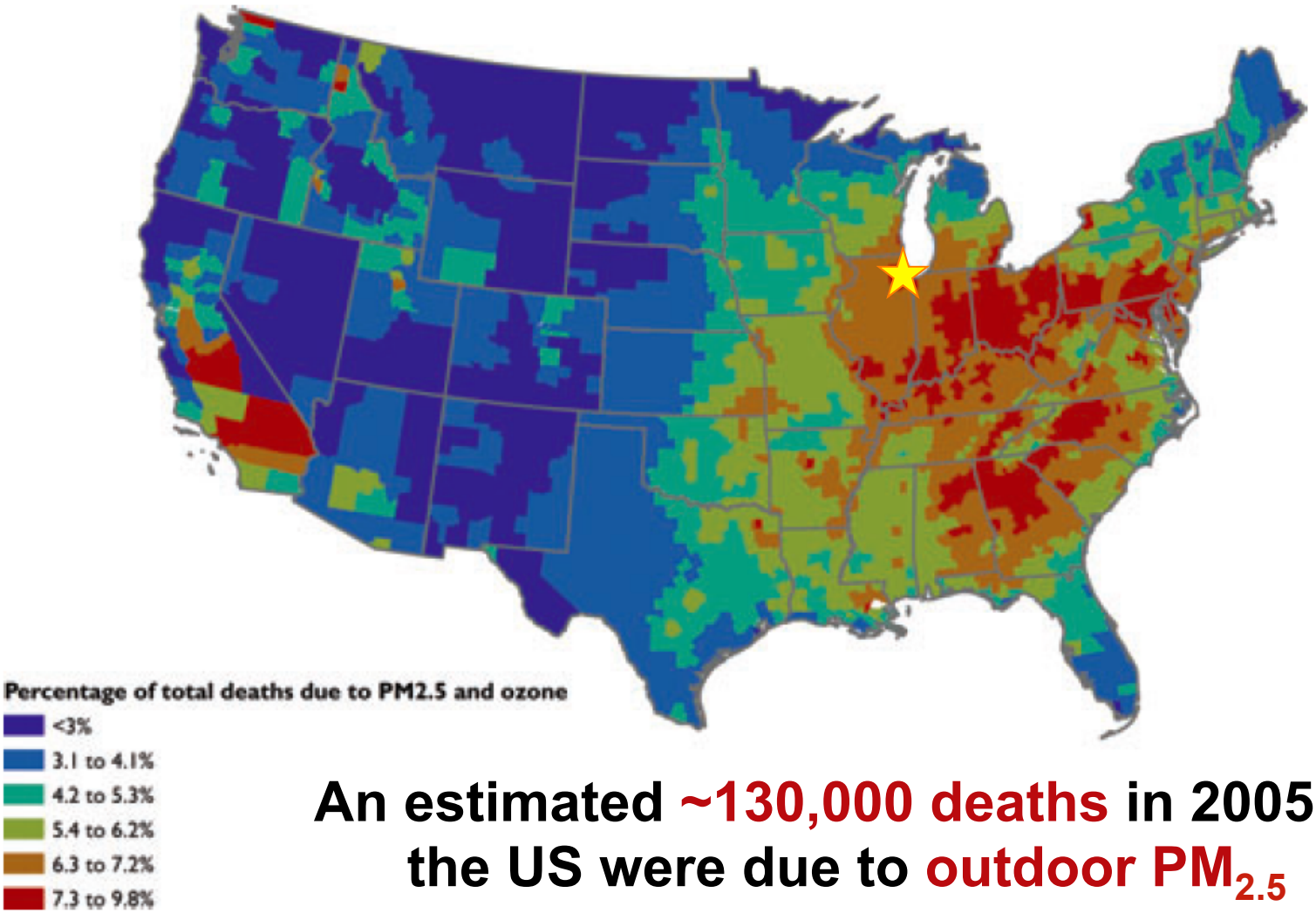
One of the biggest culprits: Particulate matter (PM)

- Wide range of sizes and constituents
  - From a few **nm** to tens of **µm**
  - Size governs deposition in the respiratory tract
  - Most particles of outdoor origin are smaller than 100 nm
- Wide range of measurement methods and classifications
  - UFPs, $PM_{2.5}$, PM_{10}, etc.
  - $PM_{2.5}$ and PM_{10} are regulated in the U.S. as part of the National Ambient Air Quality Standards (NAAQS)
- We know ***much more*** about the health effects associated with outdoor PM sources than indoor PM sources



Hinds **1999** *Aerosol Technol*

Outdoor particulate matter and human health



An estimated ~130,000 deaths in 2005 in the US were due to outdoor $PM_{2.5}$

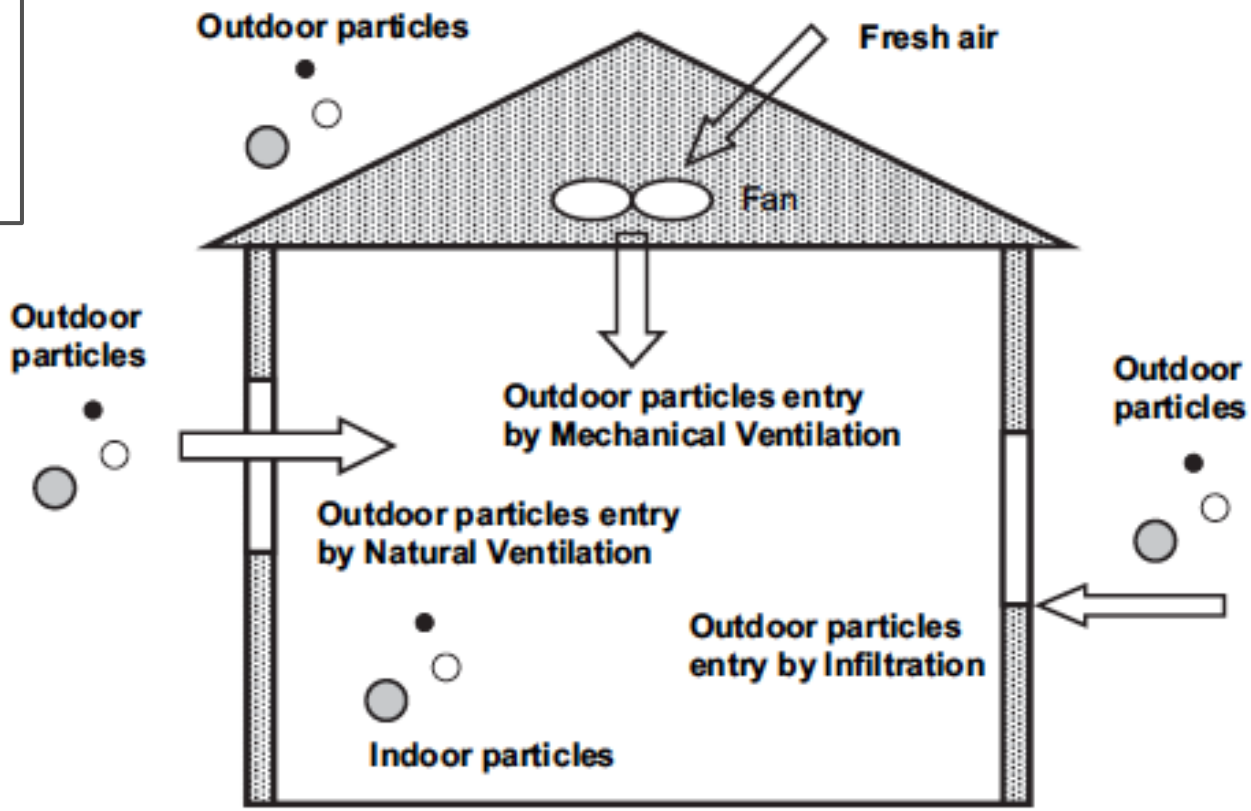
But most of this exposure occurs indoors (mostly at home)

Fann et al. **2012** *Risk Analysis*

Sources of indoor PM

I/O ratio:

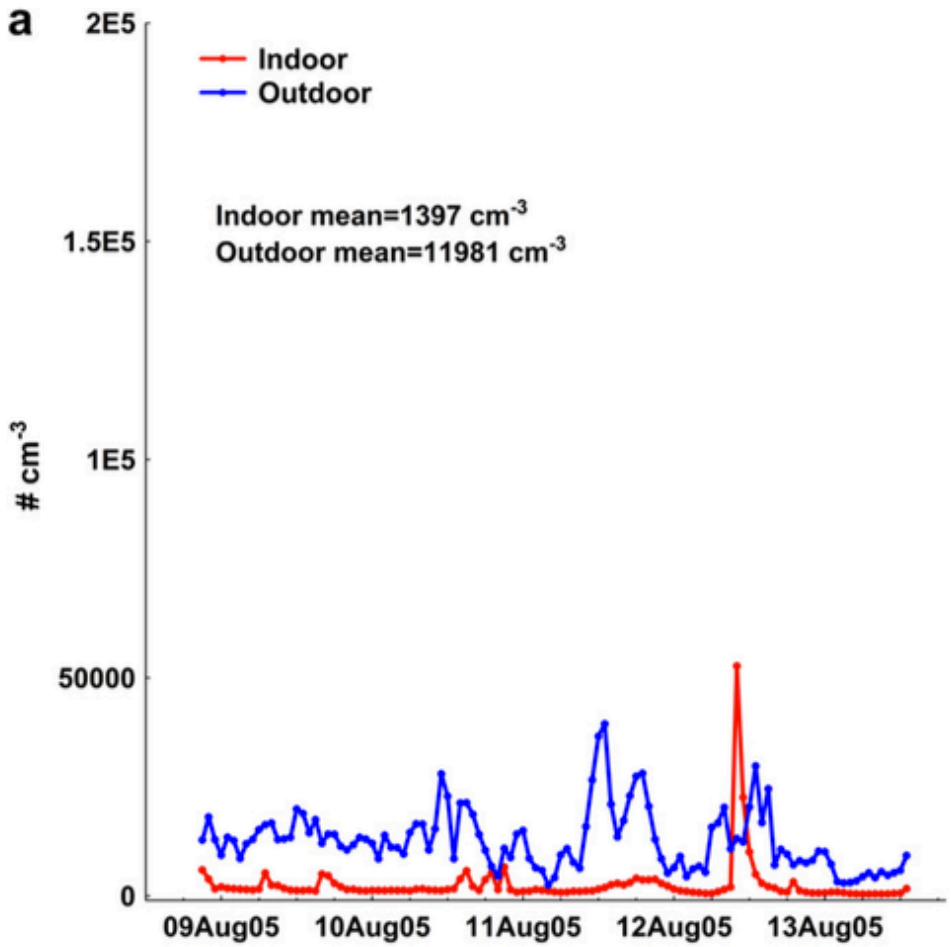
$$I/O = \frac{C_{in}}{C_{out}}$$



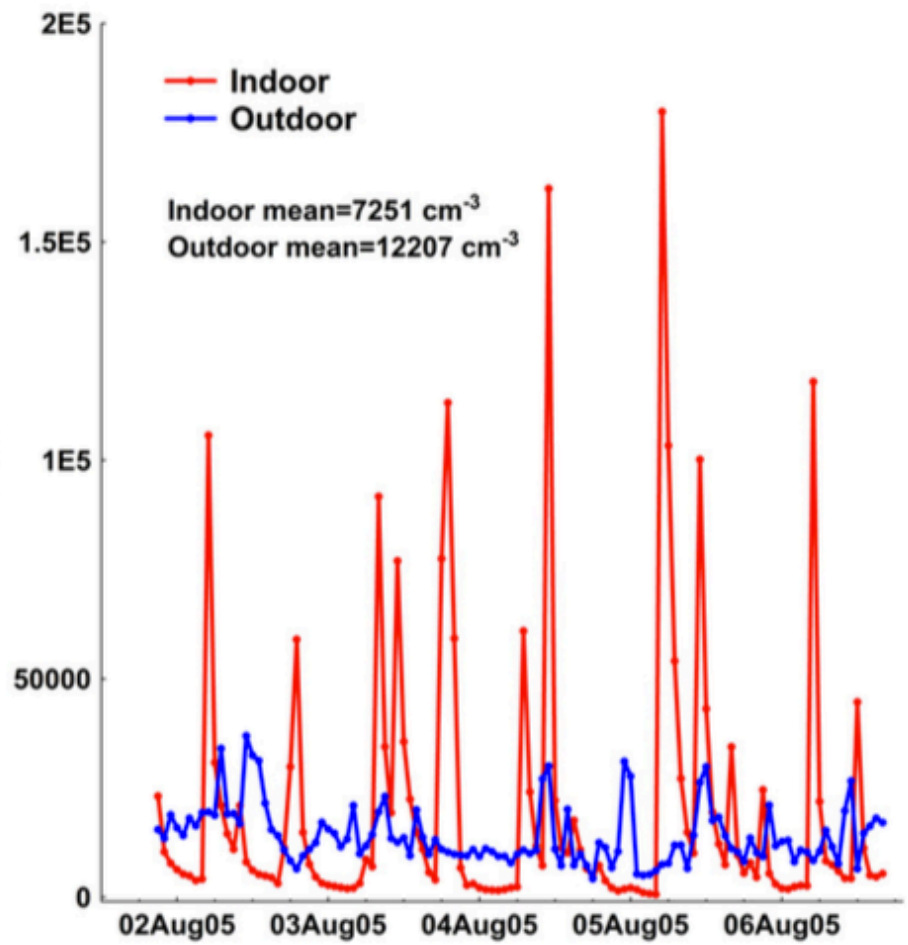
Chen and Zhao, **2011** *Atmos Environ*

Residential indoor PM profiles

Ultrafine particles (UFPs) in Canadian homes



Minimal indoor sources

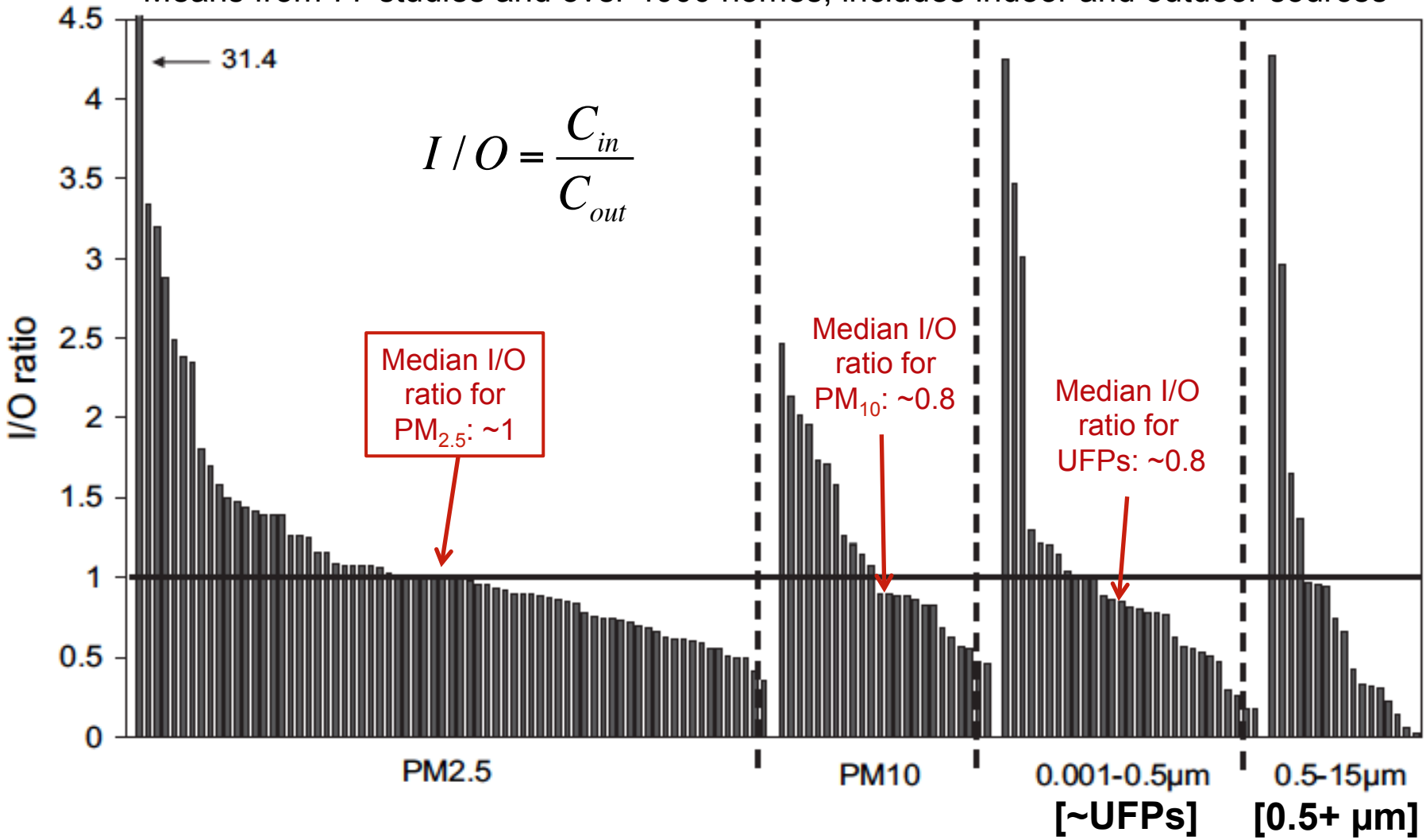


Numerous indoor sources

Kearney et al. **2010** *Atmos Environ*

I/O PM ratios: Indoor + outdoor sources

Means from 77 studies and over 4000 homes; includes indoor and outdoor sources



Chen and Zhao, **2011** *Atmos Environ*

REDUCING INDOOR PM EXPOSURES

Methods of reducing indoor air pollution

1. Eliminate pollutant sources
   - Do this first

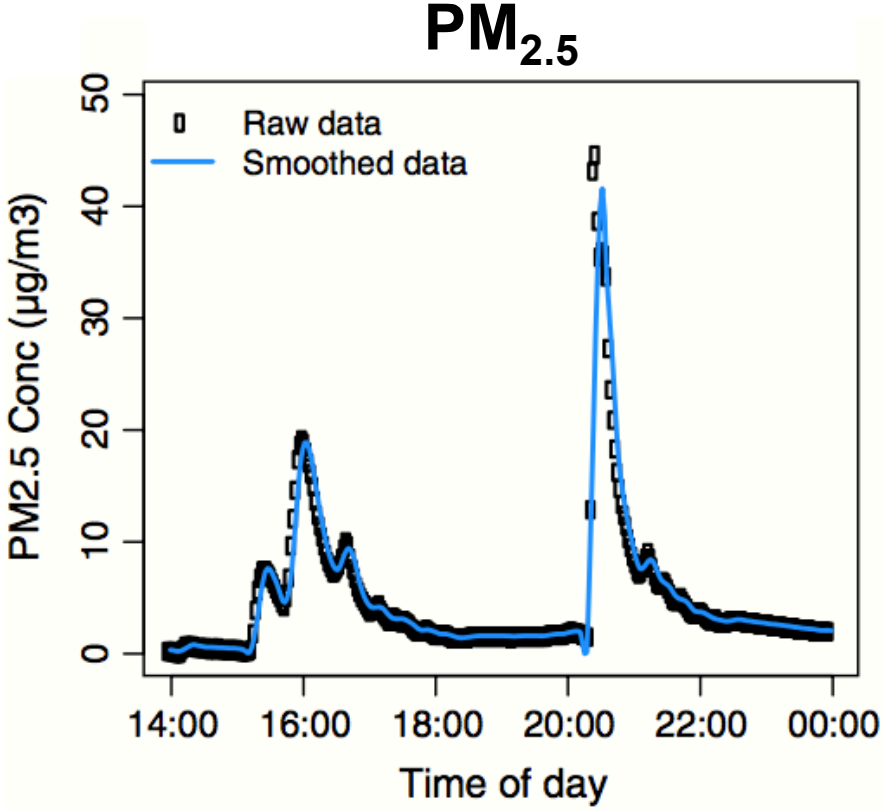
2. Exhaust pollutants to the outdoors
   - Do this second

3. Air cleaning and filtration
   - Do this third

1. Eliminate sources

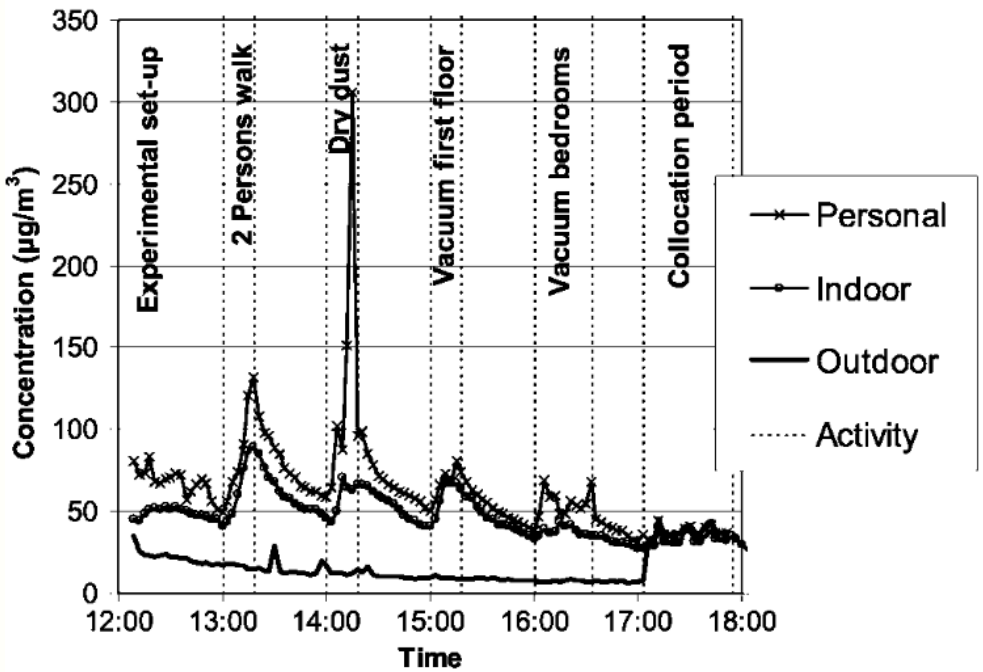
- Difficult to achieve practically

$PM_{2.5}$



Chan et al. **2018** *Indoor Air*

PM_5

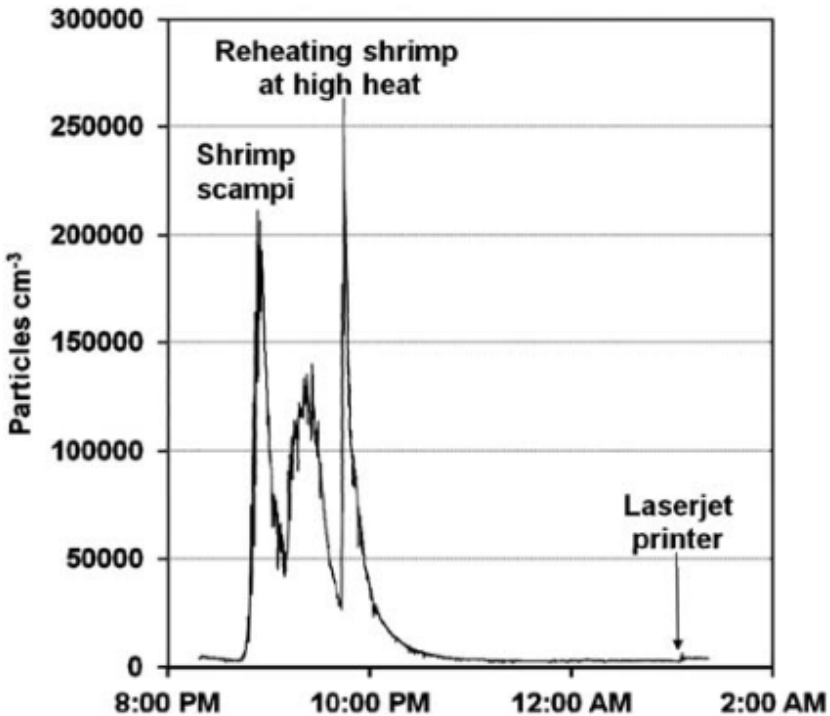


Ferro et al. **2004** *J Expo Anal Environ Epidem*

1. Eliminate sources

- Difficult to achieve practically

UFPs



Wallace and Ott **2011** *J Expo Sci Environ Epidem*

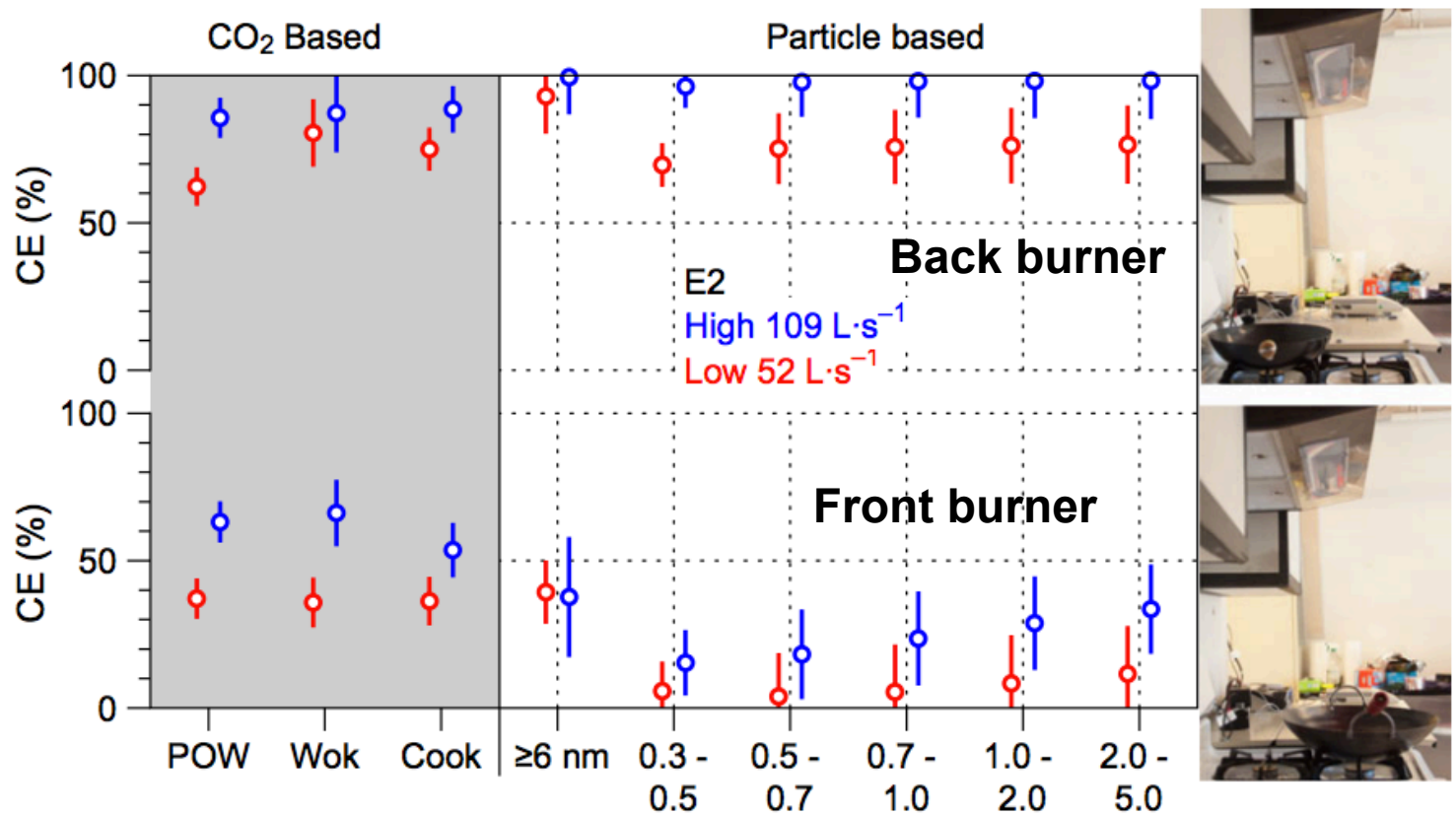
Appliance	Event	N	Mean emission rate ($\times 10^{12}$) (particles/min^{1})
Gas stove and toaster oven	Cooking	23	5.11
Gas clothes dryer	Drying clothes	6	4.40
Air popper	Popping corn	4	4.26
Electric toaster	Toasting	1	3.8
Match	Lighting candles	3	3.65
Spray cleaner	Housecleaning	6	2.60
Electric toaster oven	Cooking	54	2.11
Gas stove	Cooking	95	1.89
Electric stove	Cooking	21	1.25
Cigarette	Smoking	13	0.48
Electric mixer	Preparing food	5	0.57
Candles	Burning candles	10	0.56
Curling irons	Grooming	3	0.29
Steam iron	Ironing	6	0.24
Hair dryers	Grooming	8	0.23
Space heater	Heating	3	0.13
Hair straightener	Grooming	1	0.11
Laser printer	Printing 10 pages	3	0.06
Vacuums	Housecleaning	2	0.06
Fireplace	Fire lit	1	0.003

2. Exhaust pollutants to the outdoors

1. Natural ventilation (open windows)
2. Spot ventilation
3. Whole-house mechanical ventilation

2. Exhaust pollutants to the outdoors

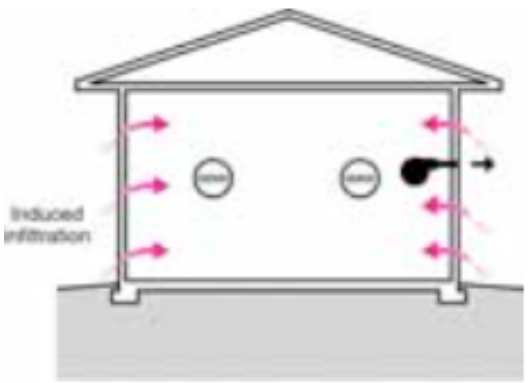
- **Spot ventilation**
  - Can work well for known sources (e.g. cooking)
  - Capture efficiency depends on burner location & flow rate



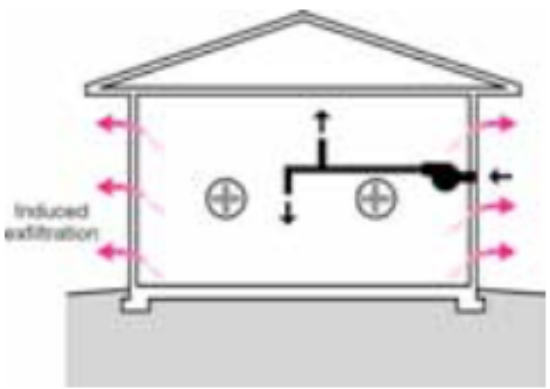
Lunden et al. **2015** *Indoor Air*

2. Exhaust pollutants to the outdoors

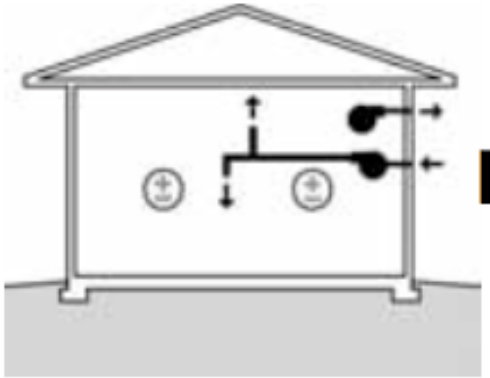
- **Whole-house mechanical ventilation**
  - Can dilute indoor sources
  - But can introduce outdoor sources
  - Which strategy is most effective (and most efficient)?



Exhaust



Supply



Balanced

+ whole-house ventilation
+ high efficiency filtration
= most effective

Singer et al. **2016** *Indoor Air*

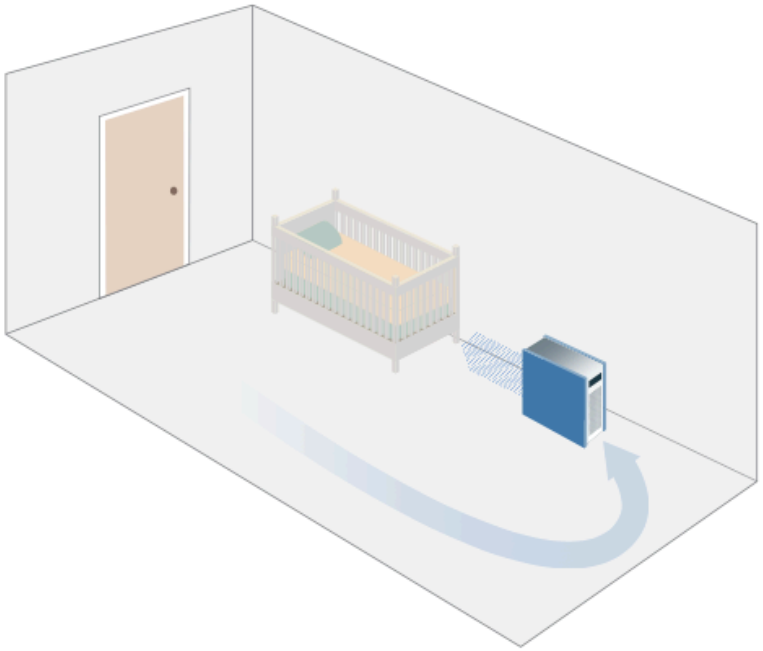
3. Air cleaning and filtration

- EPA guidance documents for air cleaners in homes include:
  - A short consumer-friendly *Guide to Air Cleaners in the Home* (2008)
  - A more in-depth technical summary: *Residential Air Cleaners (2nd Edition): A Summary of Available Information* (2009)
  - **Goal:** To provide consumers with information on different types of air cleaning devices, how they work, and how to evaluate their effectiveness for use in the home
  - **Note:** I have been working with colleagues to revise these documents

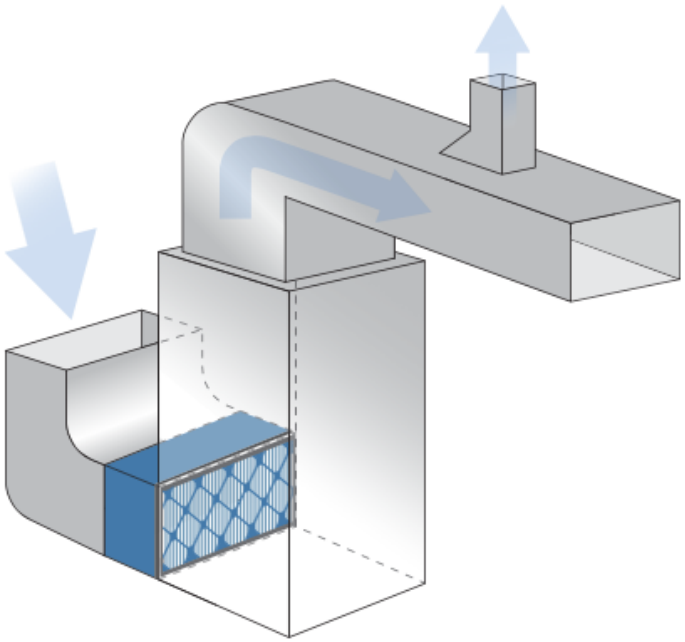
https://www.epa.gov/indoor-air-quality-iaq/guide-air-cleaners-home

General air cleaning strategies

- Two general categories of air cleaners
  1. Portable air cleaners
  2. Furnace filters and other duct-mounted air cleaners



Portable Air Cleaner



Furnace Filter

Air cleaning technologies

Air-cleaning technology	Targeted pollutant(s)	Test standards (rating metrics)
Fibrous filter media	Particles	Filters: ASHRAE 52.2 (MERV) ISO 16890 (ePM) ISO 29463 (HEPA) Proprietary test standards (FPR, MPR) Portable air cleaners: AHAM AC-1 (CADR)
Electrostatic precipitation (ESP)	Particles	No rating; some ozone emission standards (ANSI/ UL 867)
Ionizers	Particles	None specifically
Ultraviolet germicidal irradiation (UVGI)	Microbial particles	Air: ASHRAE 185.1 Surfaces: ASHRAE 185.2

Air cleaners and health

Health benefits of particle filtration

Fisk **2013** *Indoor Air*

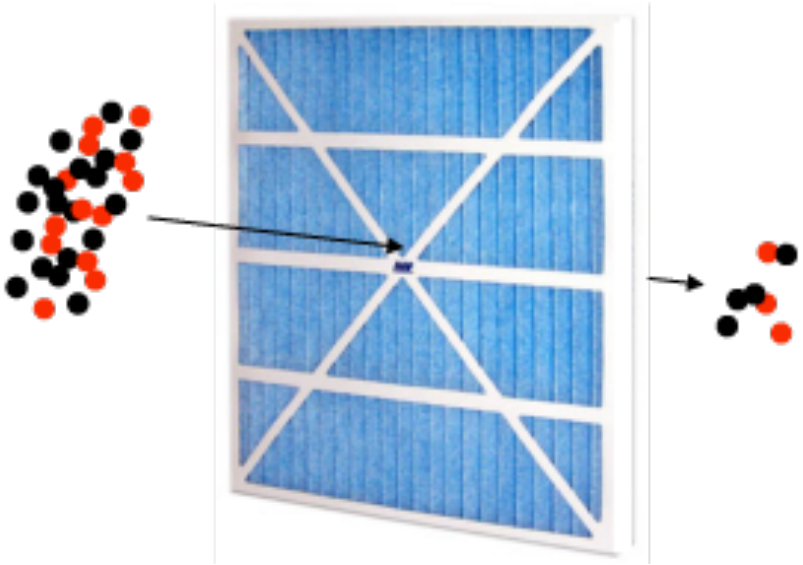
Photo from M.S. Waring and J.A. Siegel

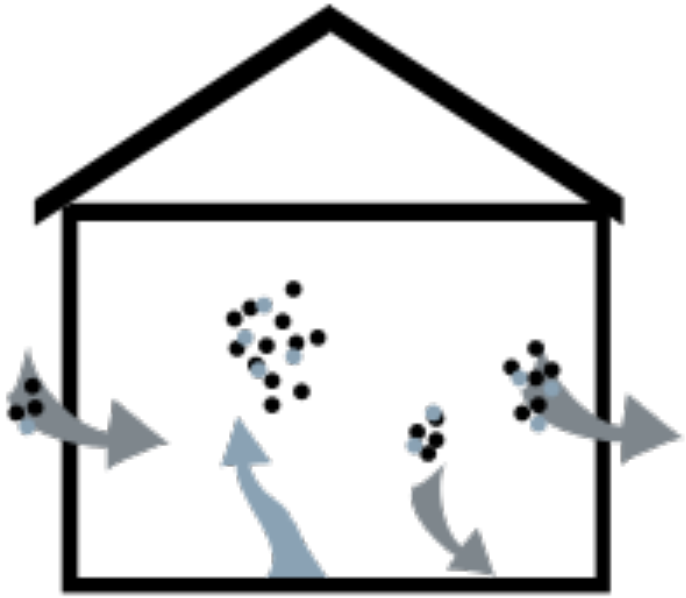
Air cleaners typically reduce indoor PM concentrations by ~50%

Documented health improvements with air cleaners include:

- Improvements in lung function in asthmatics
- Fewer asthma-related doctor visits
- Improvements in cardiovascular and pulmonary function
- HEPA and near-HEPA portable air cleaners most studied to date

Evaluating air cleaners and filters

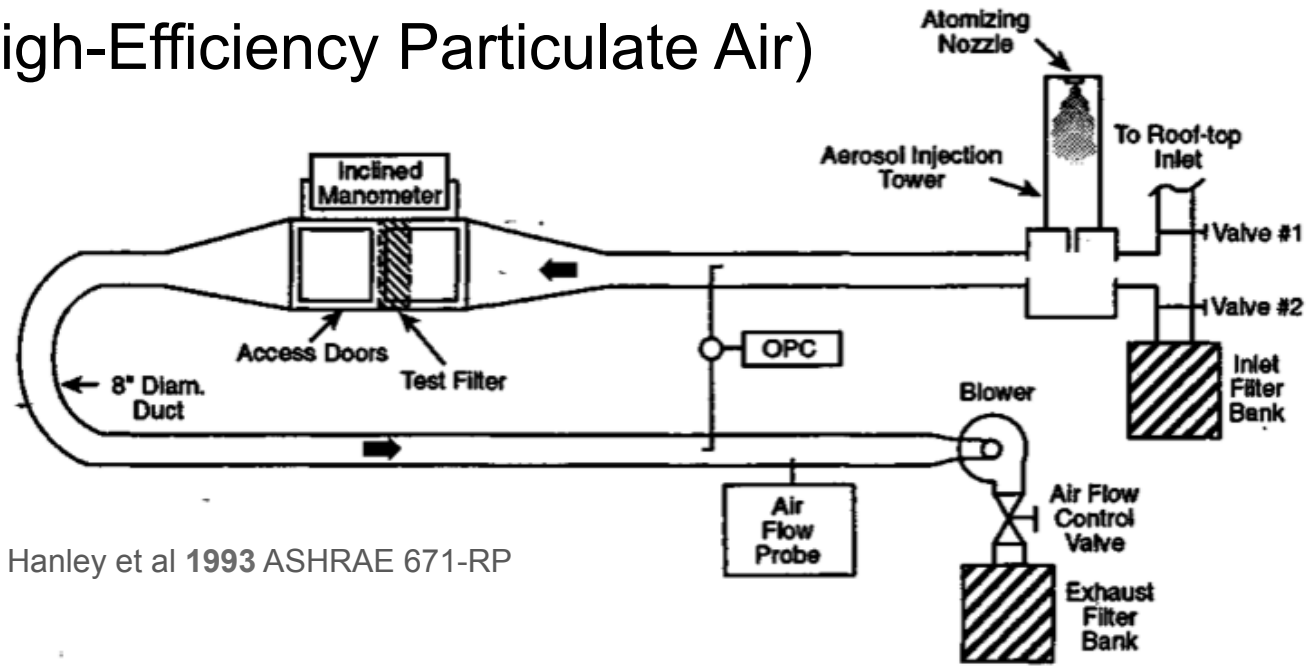




Efficiency vs. **Effectiveness**

Evaluating (single-pass) removal efficiency

- For particle removal:
  - MERV (Minimum Efficiency Reporting Value)
    - ASHRAE Standard 52.2
  - MPR (Micro-particle Performance Rating)
  - FPR (Filter Performance Rating)
  - HEPA (High-Efficiency Particulate Air)



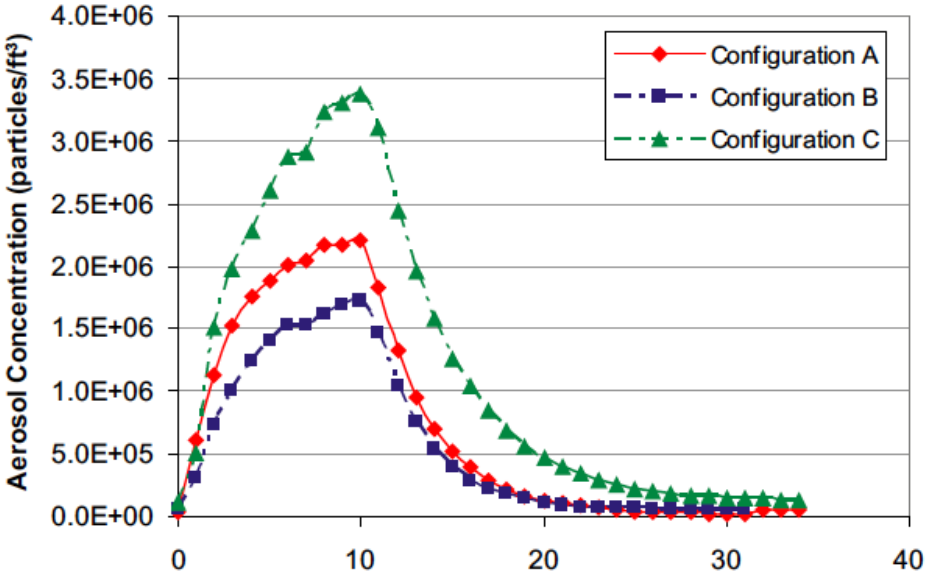
Hanley et al **1993** ASHRAE 671-RP

Evaluating effectiveness

- Clean air delivery rate (CADR)
  - Flow rate × removal efficiency
  - First dates back to 1985 Offermann et al. **1985** *Atmos Environ*
  - Basic procedure involves elevating aerosol concentrations
    - Measuring subsequent decay w/ and w/out air cleaner operating

Kogan et al., **2008** EPA Report 600/R-08-012

$$CADR = V\left(L_{AC} - L_{noAC}\right)$$

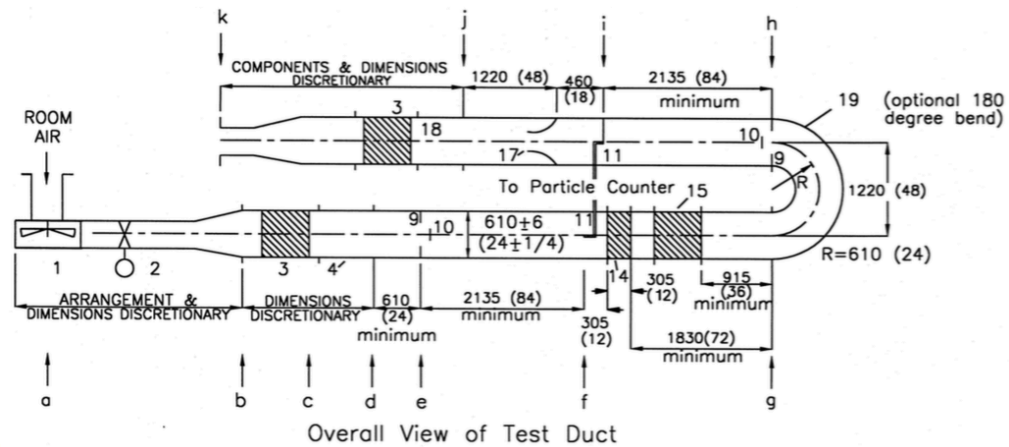


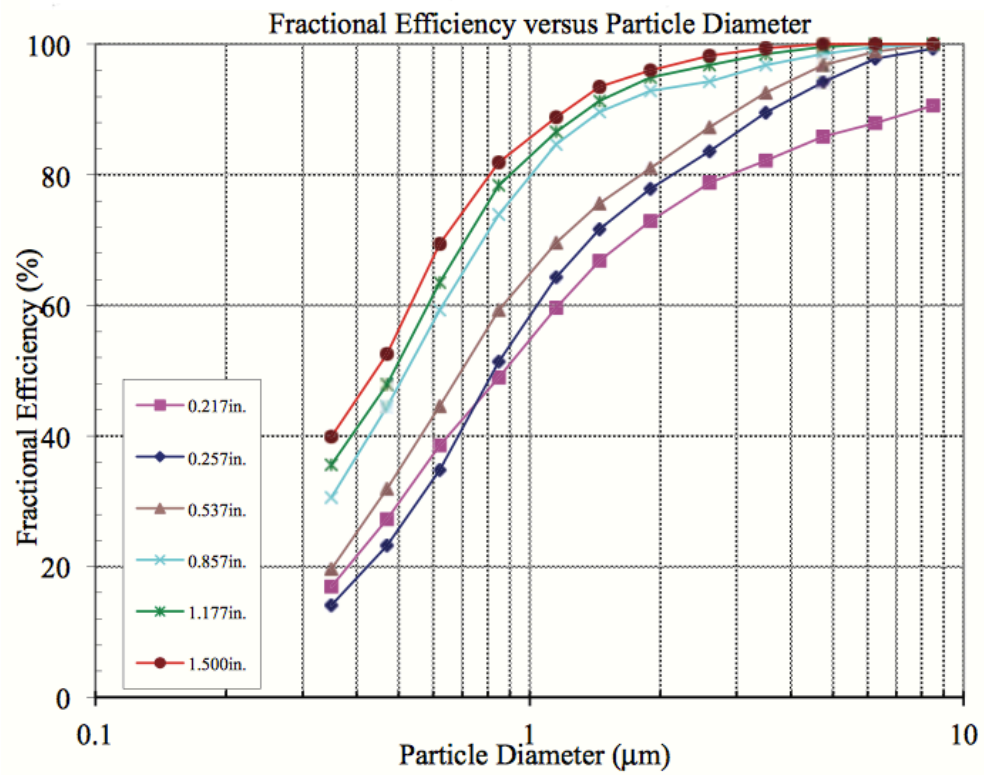
CHALLENGES/LIMITING FACTORS

FINE AND ULTRAFINE PM REMOVAL BY FILTERS/AIR CLEANERS

Filtration of indoor aerosols below 0.3 µm

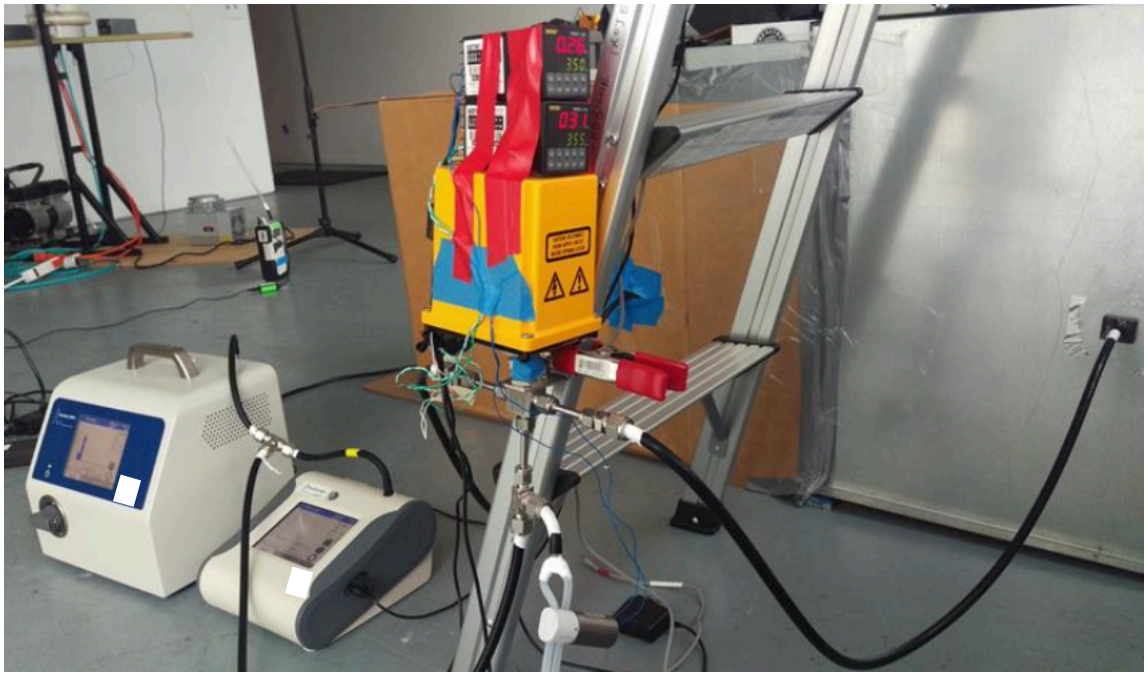
- Filters are evaluated only in laboratory tests
  - No in-situ test standard
- ASHRAE Standard 52.2 most widely used
  - MERV = Minimum Efficiency Reporting Value
  - Only from 0.3 to 10 µm
  - Same for MPR and FPR
- Remember:
  - Most particles (by number) are smaller than 0.3 µm



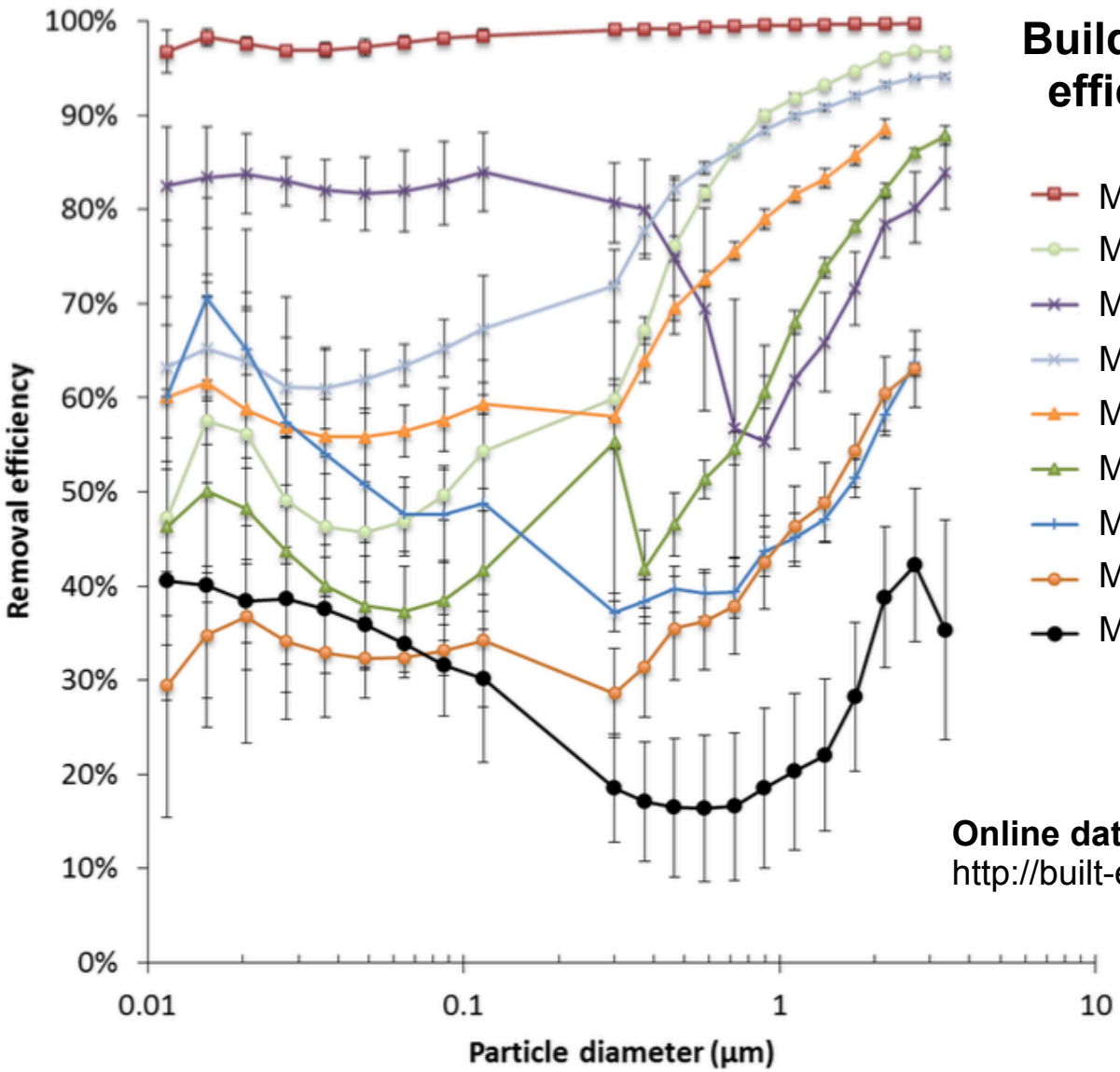


Fine and ultrafine particle removal efficiency

- We have been making measurements of in-situ particle removal efficiency of a large number of residential HVAC filters
- Particles from 10 nm to 10 μm



Fine and ultrafine particle removal efficiency



Building a database of filter efficiency measurements

- MERV 16 5”
- MERV 13 2”
- MERV 13 1”
- MERV 11 4”
- MERV 11 2”
- MERV 11 2”
- MERV 8 4”
- MERV 8 1”
- MERV <4 1”

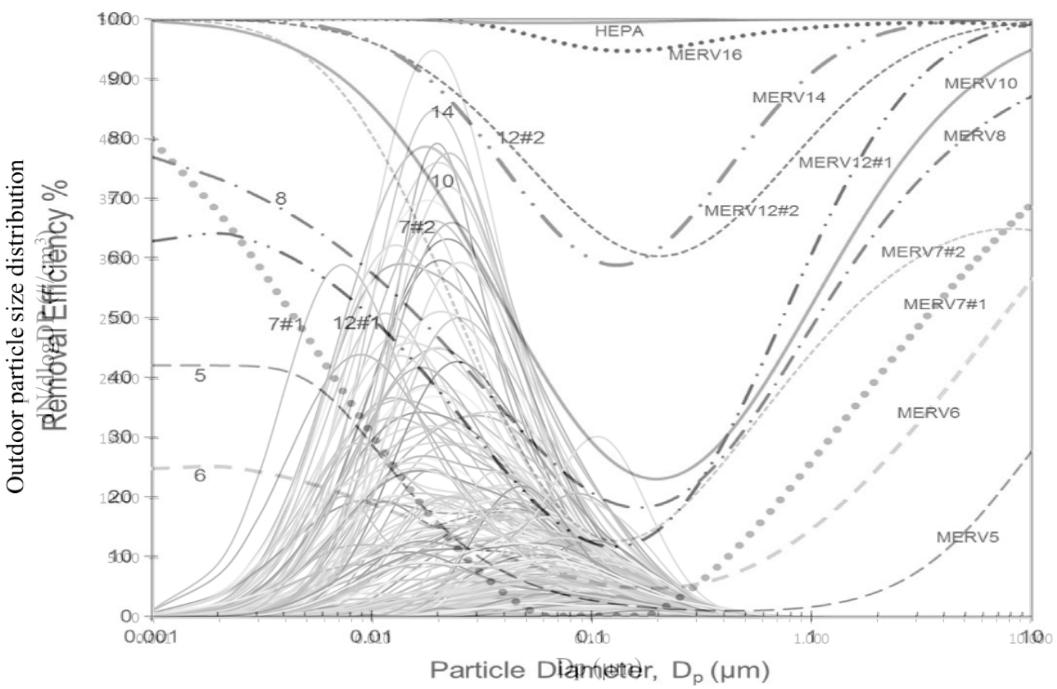
Online database:
http://built-envi.com/portfolio/filter-testing/

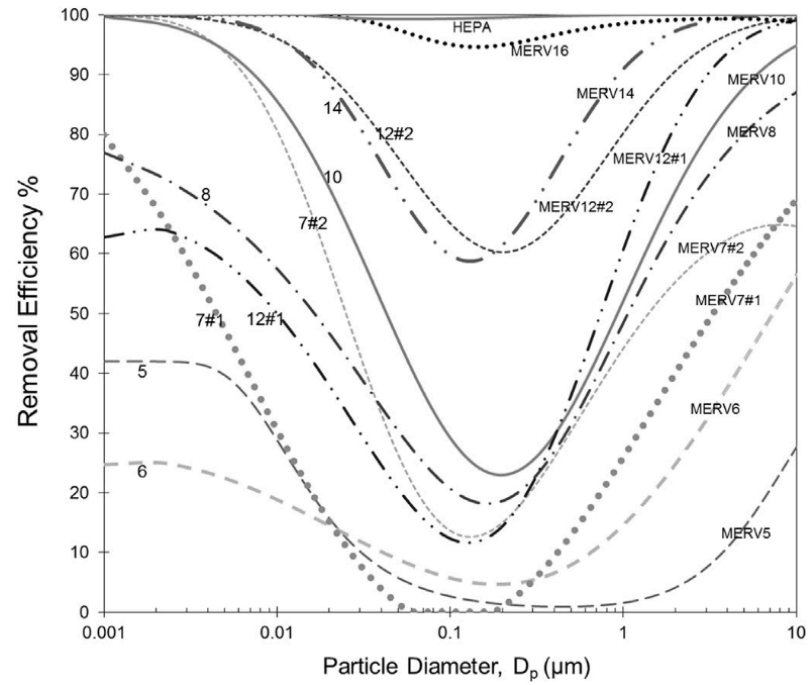
Fazli and Stephens **2016** *ASHRAE Conference*

Fine and ultrafine particle removal efficiency

Using size-resolved removal efficiency to estimate removal of $PM_{2.5}$ and UFPs

- We gathered 194 long-term average (1-year or more) outdoor particle size distributions from the literature from all over the world
- And mapped them to size-resolved filtration efficiency for typical MERV filters

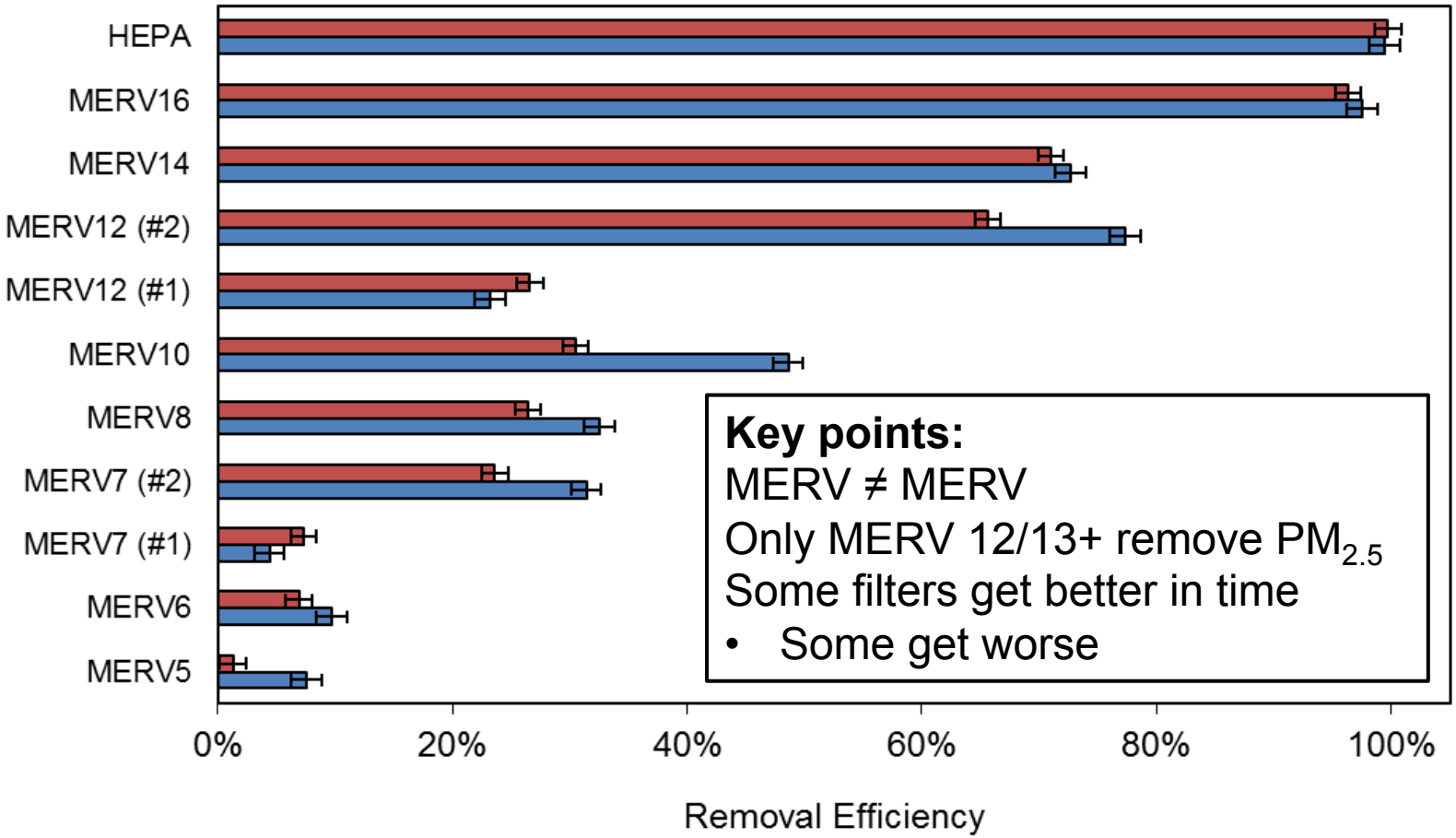




Azimi et al. **2014** *Atmos Environ*

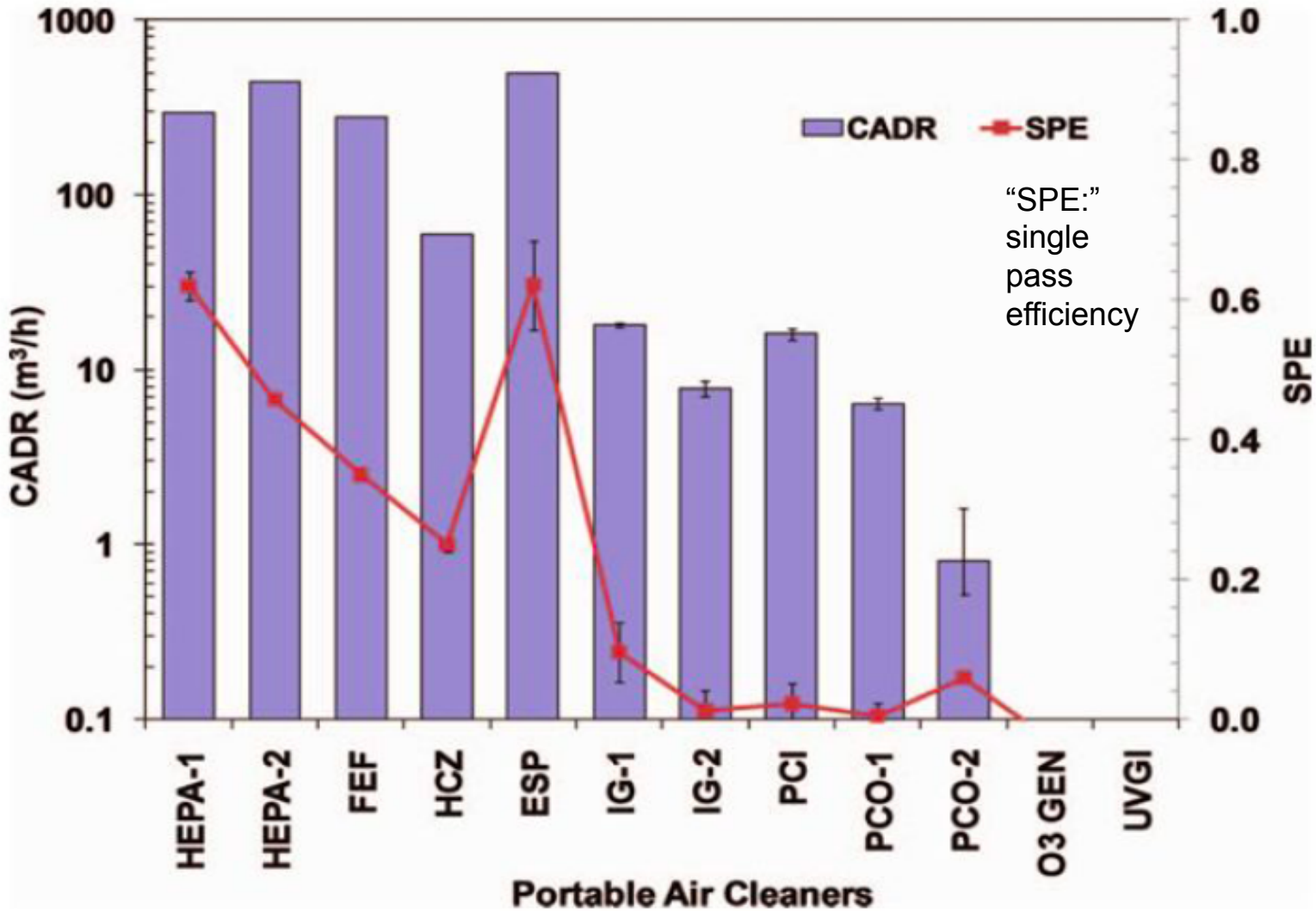
Fine and ultrafine particle removal efficiency

Using size-resolved removal efficiency to estimate removal of $PM_{2.5}$ and UFPs



Azimi et al. **2014** *Atmos Environ*

Fine and ultrafine PM removal by portable air cleaners

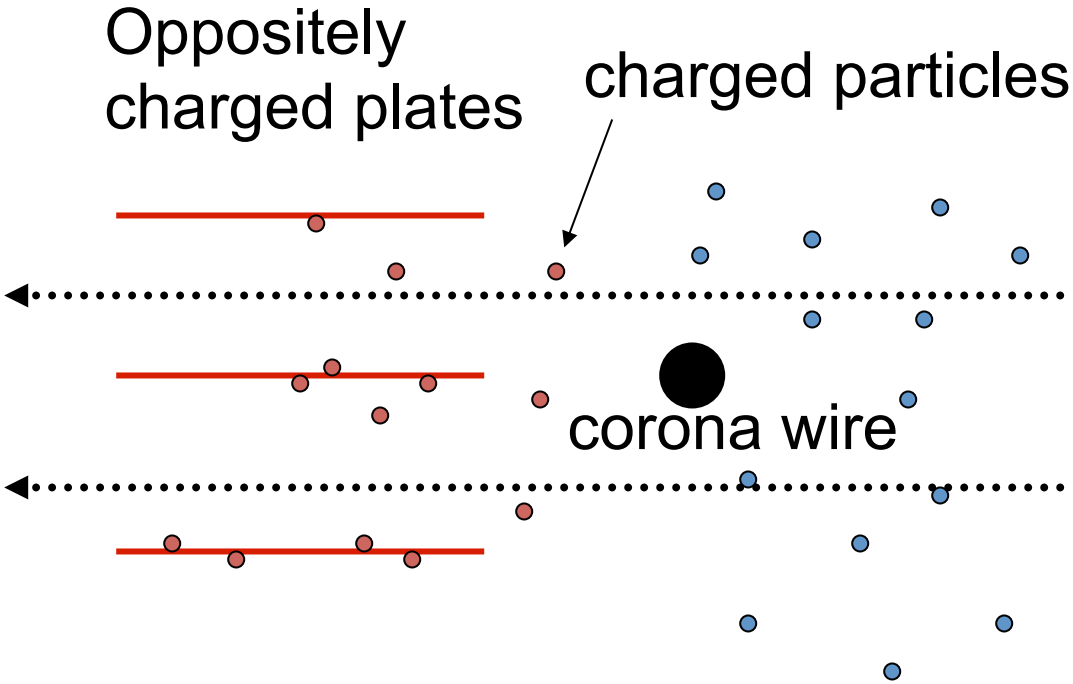


Sultan et al., **2011** *HVAC&R Research*

OZONE EMISSIONS FROM ELECTRONIC AIR CLEANERS

Ozone emissions from electronic air cleaners

- "Ion generating air cleaners" and electrostatic precipitators
  - Utilize high voltage to 'excite' oxygen (make singlet O out of O_2)
  - O_2 then forms with O to form O_3 (ozone)

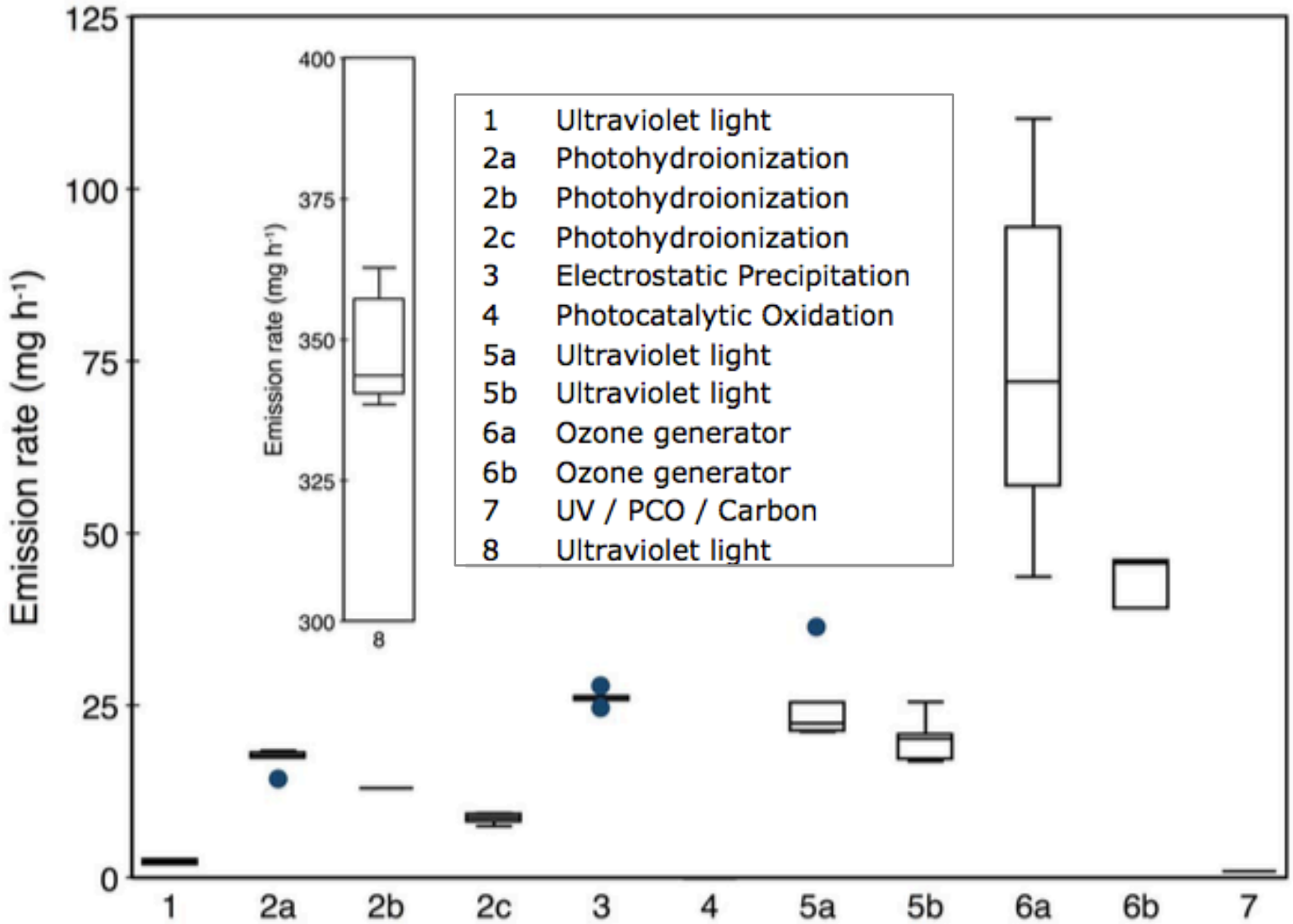


Waring et al. **2009** *Atmos Environ*

Ozone emissions from electronic air cleaners

Morrison et al. **2014** *CARB Report "In-duct air cleaning devices: Ozone emission rates and test methodology"*

Ozone emissions from electronic air cleaners

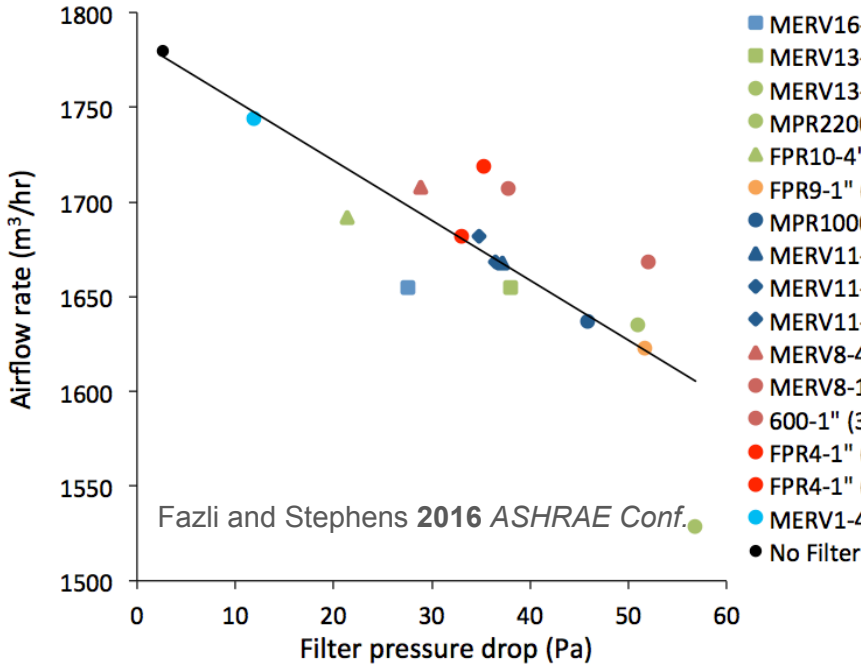


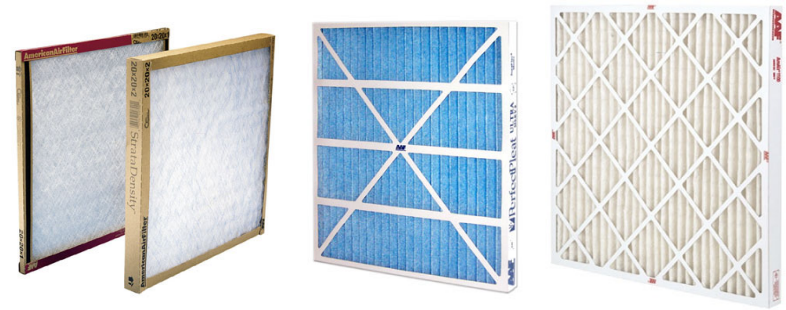
Morrison et al. **2014** *CARB Report "In-duct air cleaning devices: Ozone emission rates and test methodology"*

CONSIDERATIONS FOR IN-DUCT AIR CLEANERS AND FILTERS

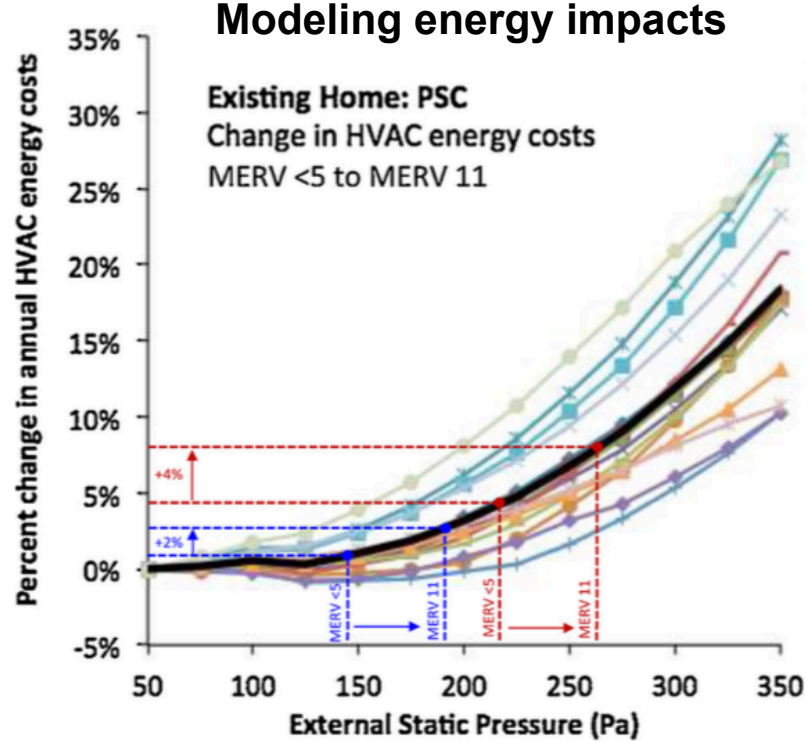
Pressure drop, airflow, and energy use of in-duct filters

Measurements of pressure drop and flow





Modeling energy impacts



Fazli et al. **2015** *Energy and Buildings*

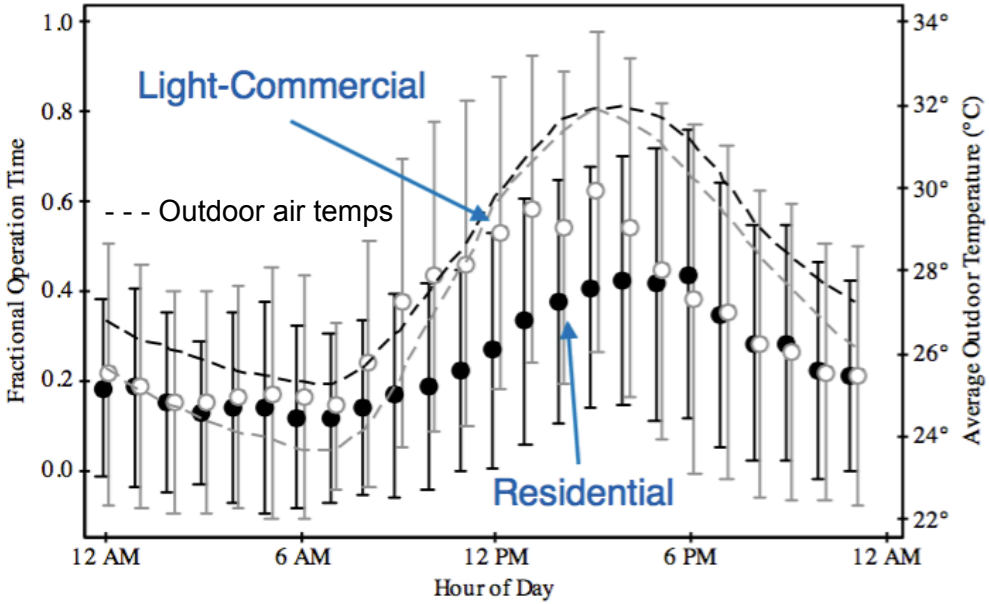
Key points:
Higher efficiency residential filters often have a higher pressure drop, which typically reduces airflow rates

But the energy impacts are usually small

Others: Stephens et al. **2010** *ASHRAE Trans*; Stephens et al. **2010** *HVAC&R Res*; Walker et al. **2012** *LBNL-6143E*

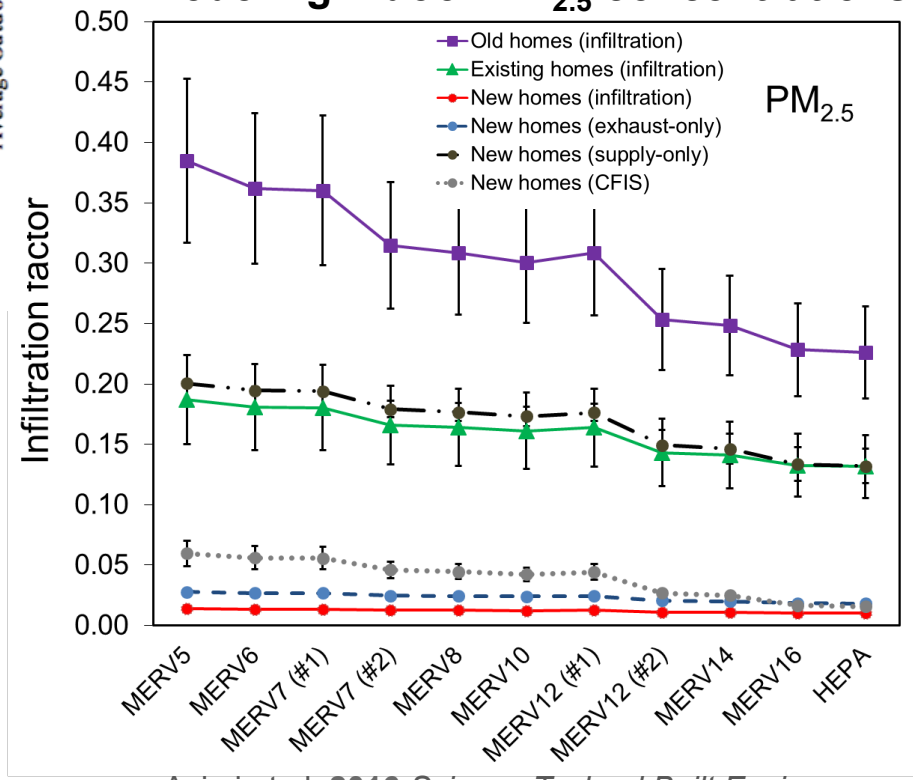
HVAC runtimes limit the effectiveness of in-duct devices

Measurements of HVAC runtimes



Stephens et al. **2011** *Build Environ*

Modeling indoor $PM_{2.5}$ concentrations



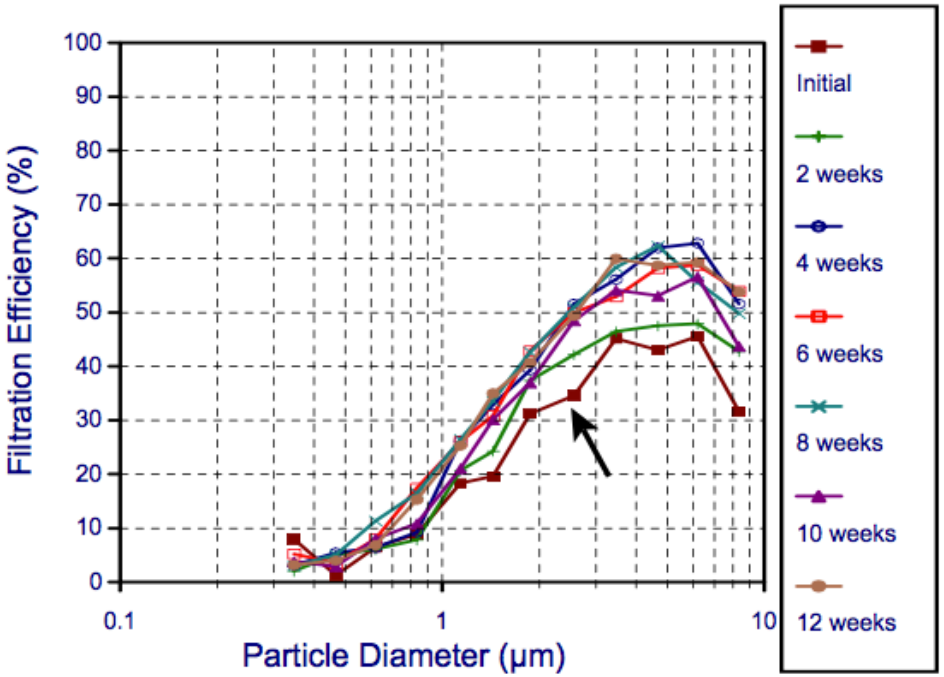
Azimi et al. **2016** *Science Technol Built Environ*

Key point:
Central heating and cooling systems typically don't run often enough to reduce indoor PM concentrations as much as you might think

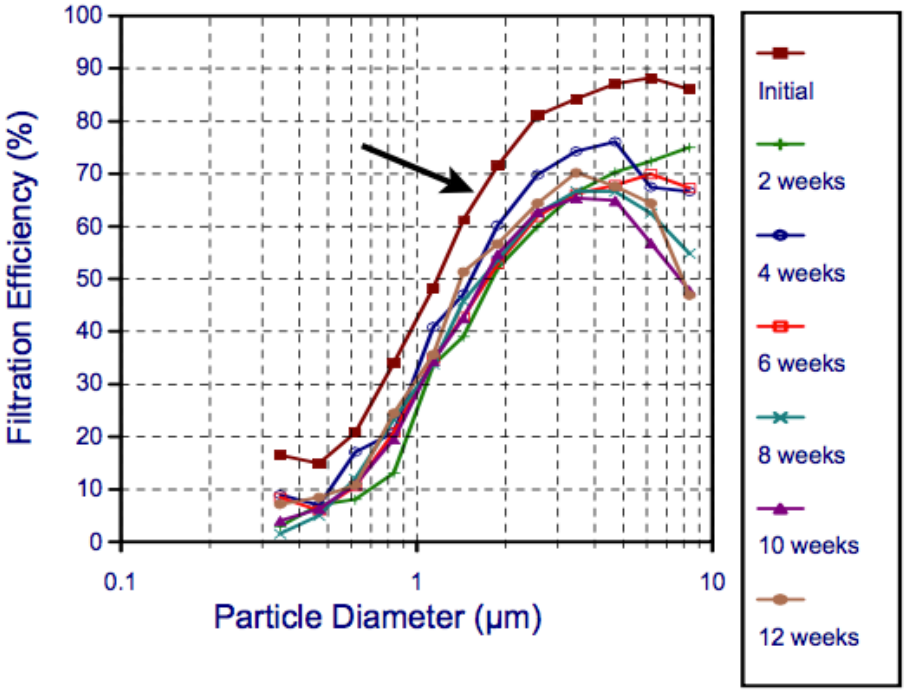
- Typically ~25% of the time or less

Dust loading affects removal efficiency of filters

Non-electret media filters (MERV 5 when clean)



Electret media filters (MERV 11 when clean)



Hanley and Owen **2003** ASHRAE Research Project Final Report 1190-RP
Owen et al. **2013** ASHRAE Research Project Final Report 1360-RP

Filter bypass is relatively common in homes

Filter bypass reduces filtration effectiveness

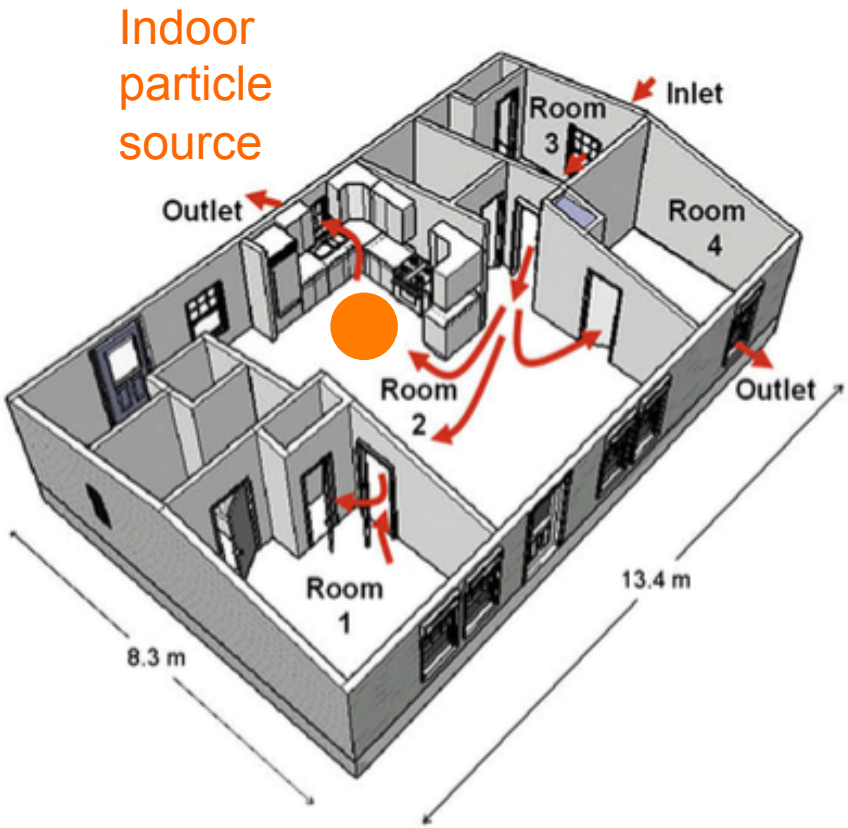
VerShaw et al. **2009** *ASHRAE Transactions*

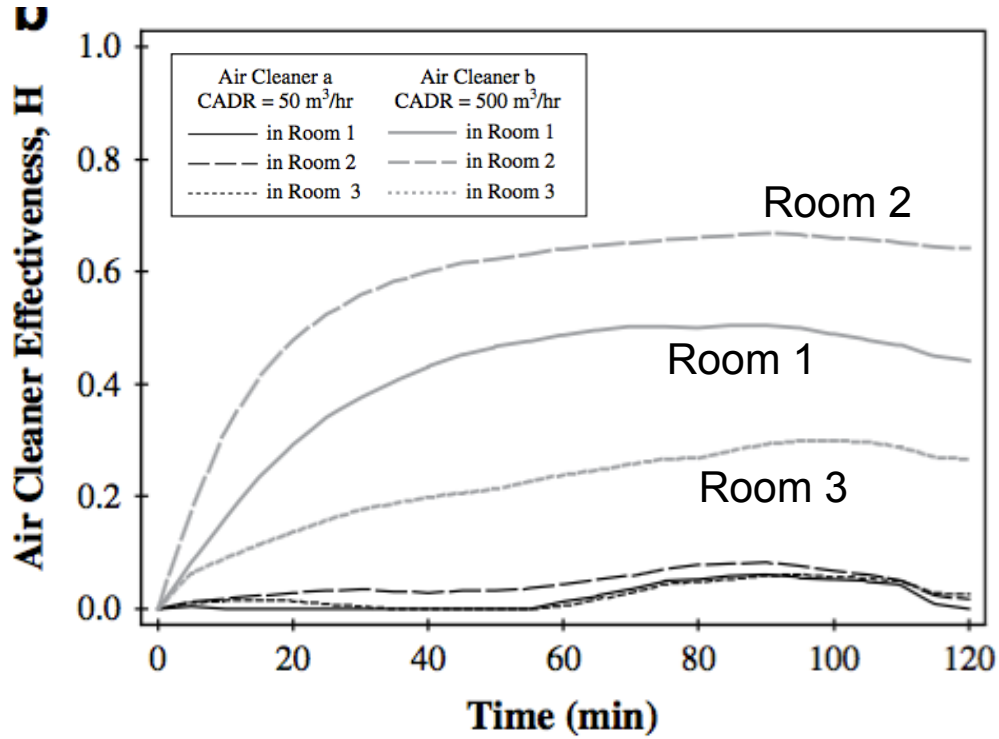
Photo credit: Brent Stephens

CONSIDERATIONS FOR PORTABLE AIR CLEANERS

Air cleaner effectiveness impacted by placement

- Air cleaner location will obviously influence its **effectiveness** in indoor environments
- We define effectiveness as follows: $1 - \frac{C_{ac}}{C_{no\ ac}}$

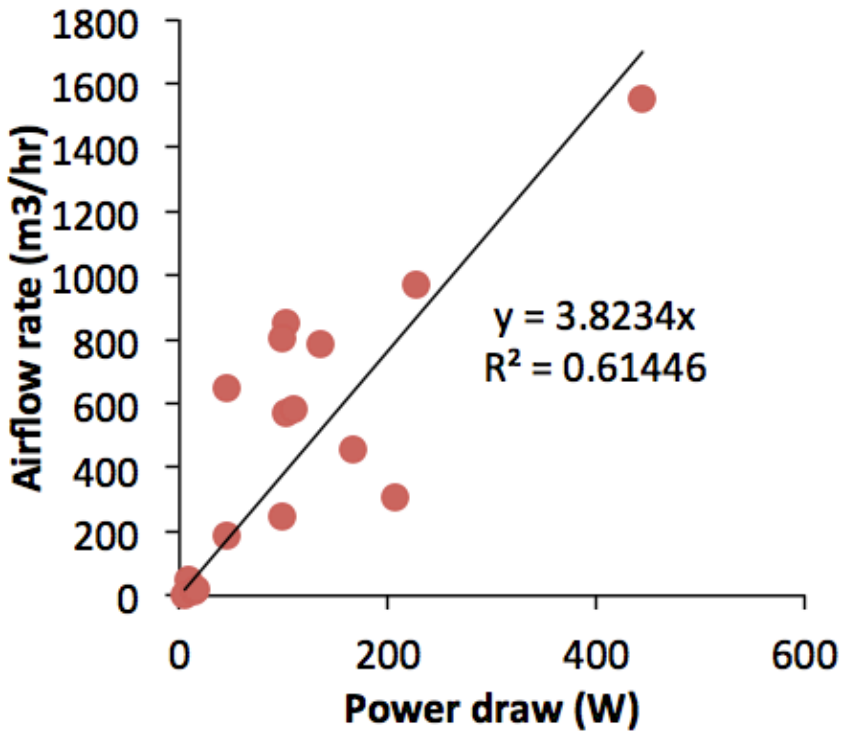




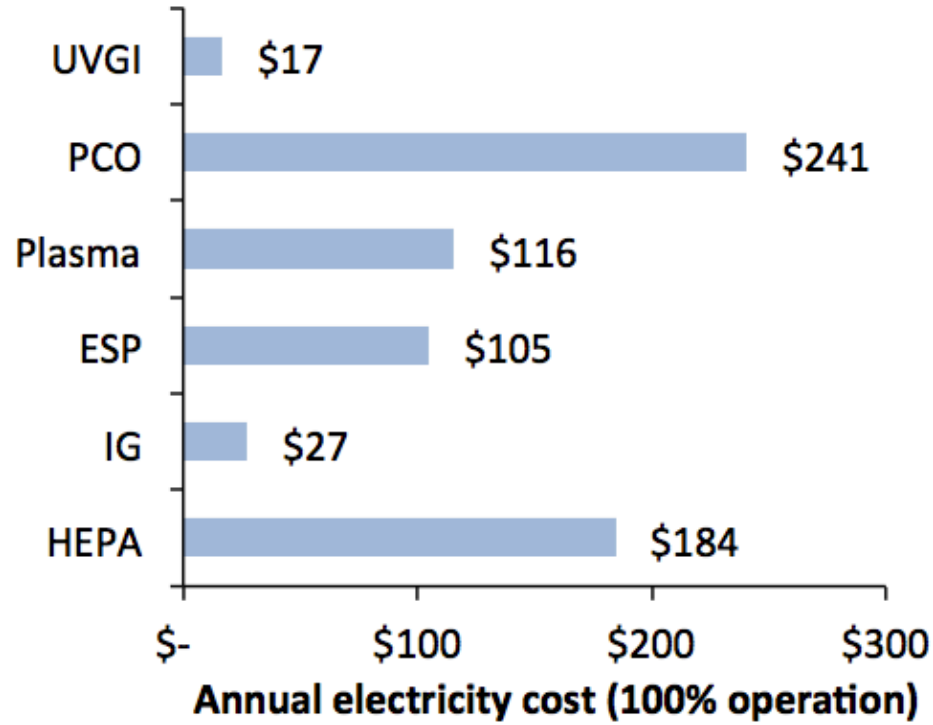
Siegel and Novoselac **2010** *Building and Environment*

Electricity costs of operating portable air cleaners

Airflow rate ↑ Power draw ↑



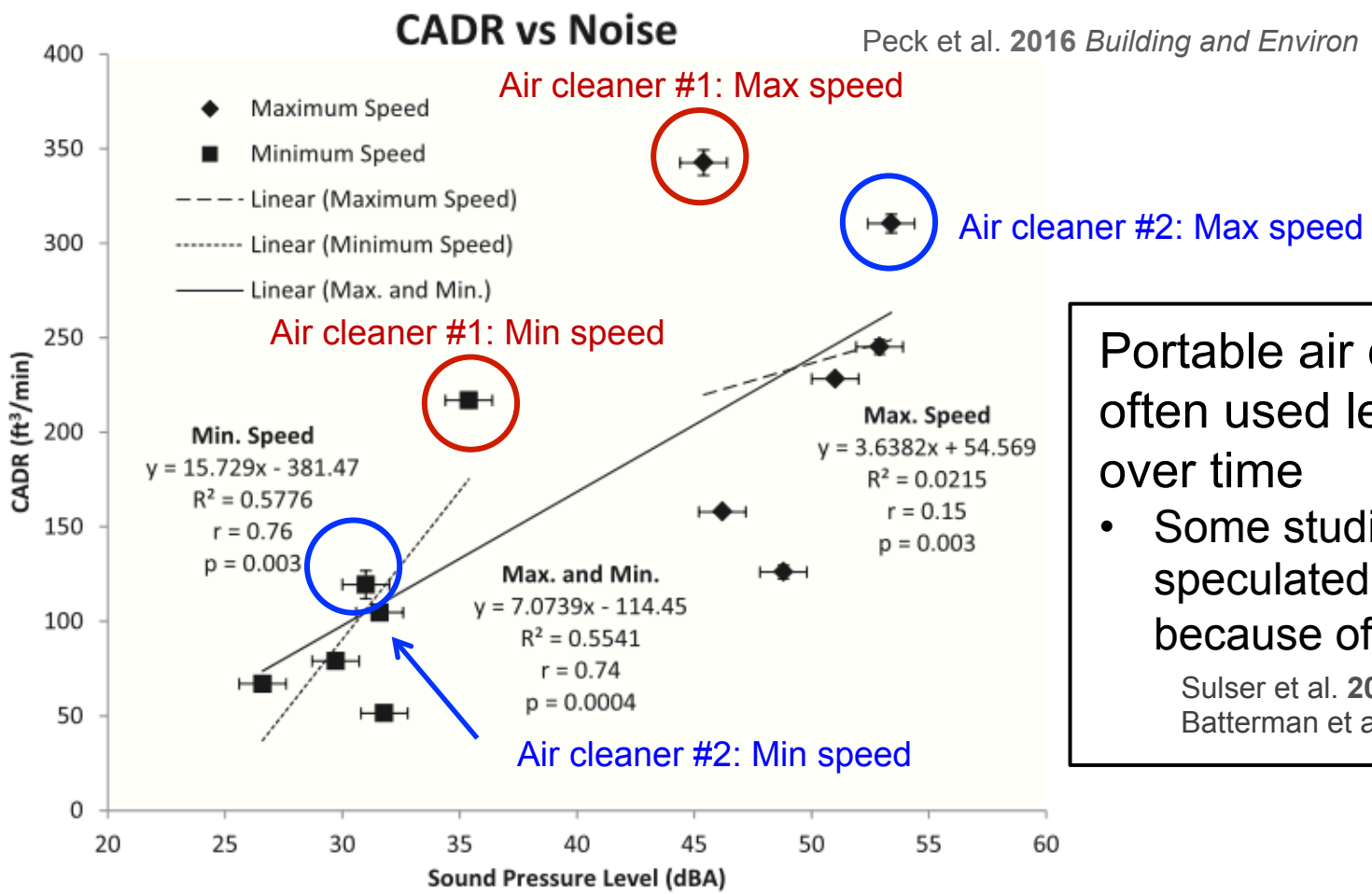
Annual cost of operation (Operating 100% of the time)



Data from: Waring et al. **2009** *Atmos Environ*; Sultan et al. **2011** *HVAC&R Research*
Cost calculations by Brent Stephens

Noise can affect the use of portable air cleaners

- Portable air cleaners are often loudest at their most effective setting (e.g., their highest flow setting)



Portable air cleaners are often used less frequently over time

- Some studies have noted/ speculated that may be because of noise

Sulser et al. **2009** *Int Arch All Immunol*; Batterman et al. **2012** *Indoor Air*

Summary

- Many indoor and outdoor sources of PM in homes
  - UFPs, $PM_{2.5}$, PM_{10}
- Ventilation can help, but can introduce outdoor PM
- Portable air cleaners can help (↑ CADR → better)
  - But they must operate (noise/power draw)
- HVAC filters can help
  - But HVAC systems often have low runtimes and other systemic issues (bypass/airflow/capacity/power draw)
- Other technologies can help too
  - But often have other drawbacks (e.g., ozone emissions, lack of standardization of testing)

Questions

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