Indoor exposures to outdoor air pollution

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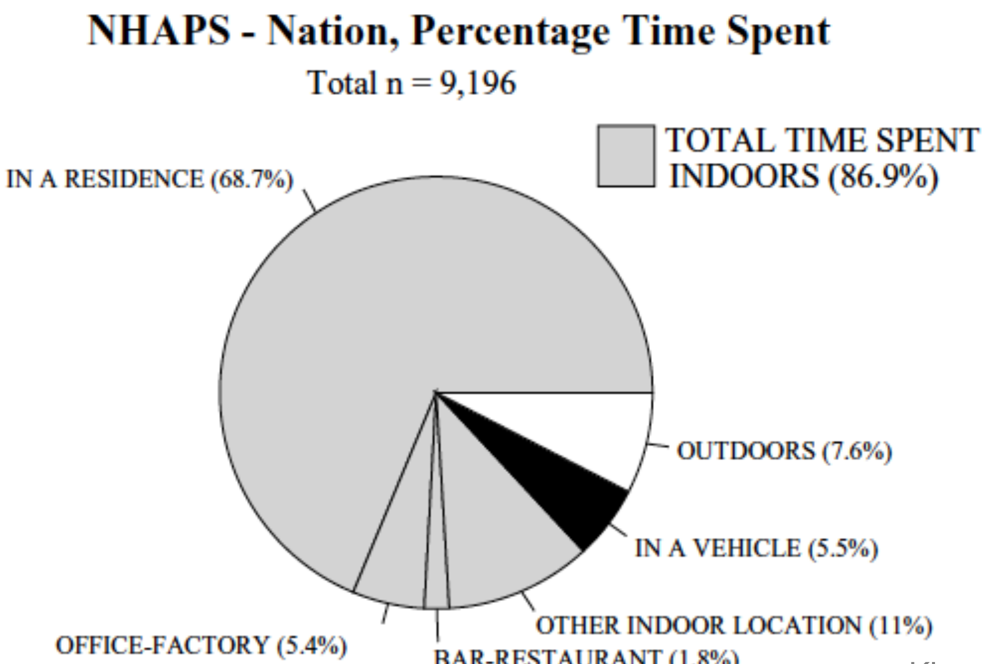
What do you think of when you hear "air pollution?"




What do I think of when I hear “air pollution?”



Americans spend almost 90% of their time indoors

~75% at home or in an office

Klepeis et al., *J Exp. Anal. Environ. Epidem.* **2001**, 11, 231-252

Indoor vs. outdoor air pollution

Air pollution is both an indoor and an outdoor issue

- Many indoor pollutant sources
- Outdoor pollutants also infiltrate indoors

Much of our exposure to outdoor air pollution occurs indoors

Health effects of indoor exposures are difficult to assess

- Time-consuming, invasive, and costly

Many connections are already made with outdoor pollutants

- There remains a need to **advance knowledge of indoor exposures**
  - Can improve connections to health effects
  - Can inform how building design and operation impacts exposures

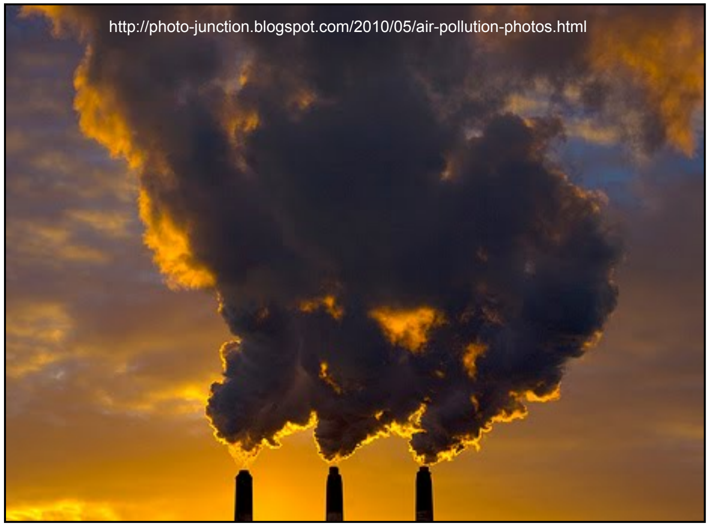
Some outdoor airborne pollutants are regulated

National Ambient Air Quality Standards (NAAQS)

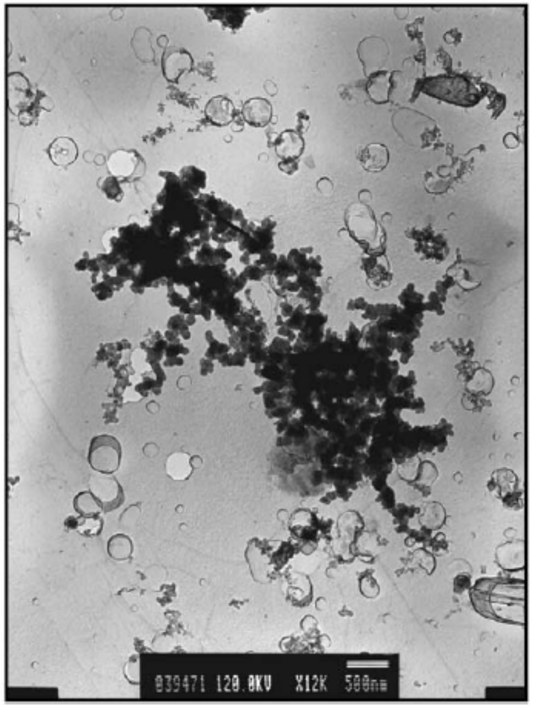
- US EPA and the Clean Air Act (1970)
- Set limits for 6 “criteria” pollutants

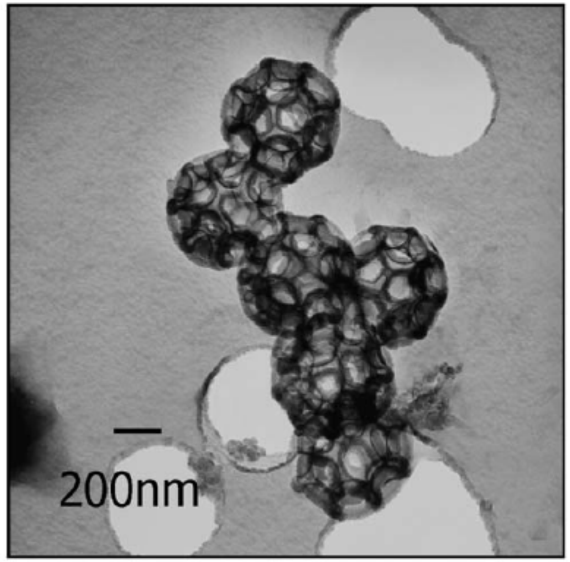
Pollutants Regulated Outdoors
Carbon monoxide (CO)
Lead (Pb)
Nitrogen dioxide (NO_2)
Ozone (O_3)
Particulate matter $PM_{2.5}$ and PM_{10}
Sulfur dioxide (SO_2)

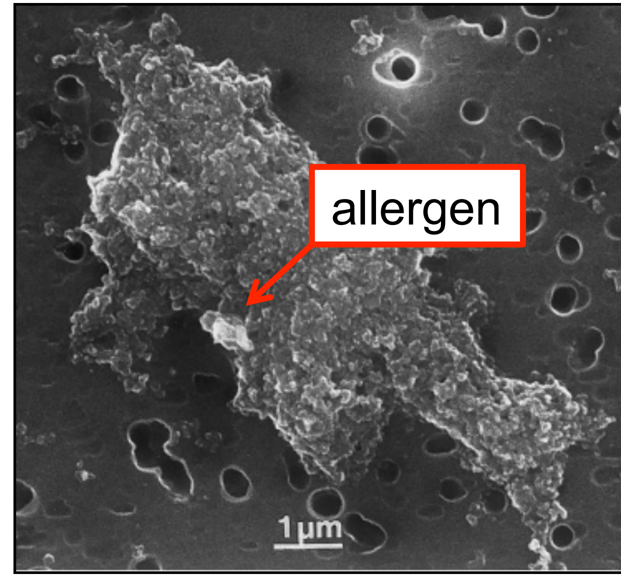
Sources of particulate matter

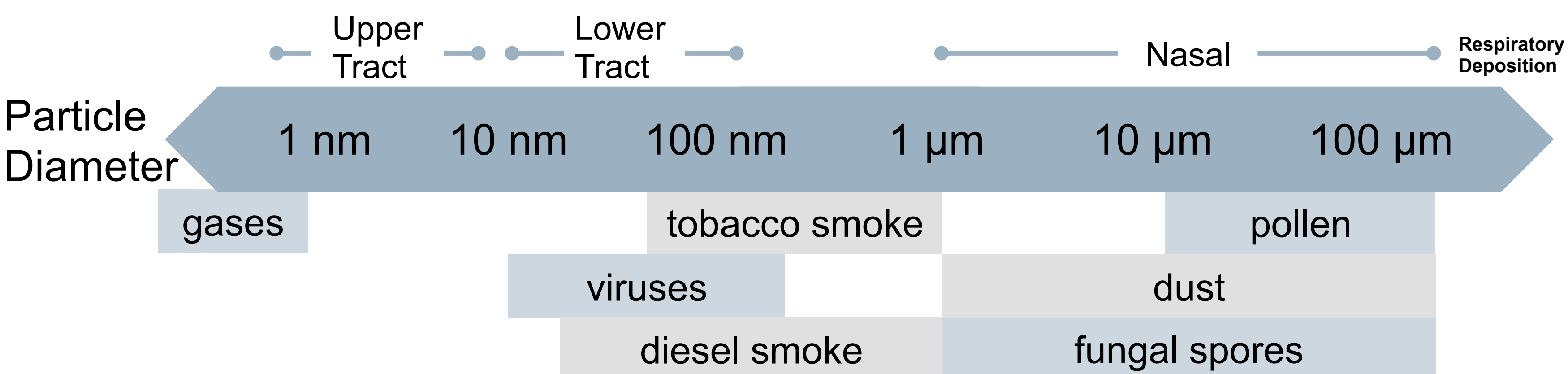


Particulate matter: Up close



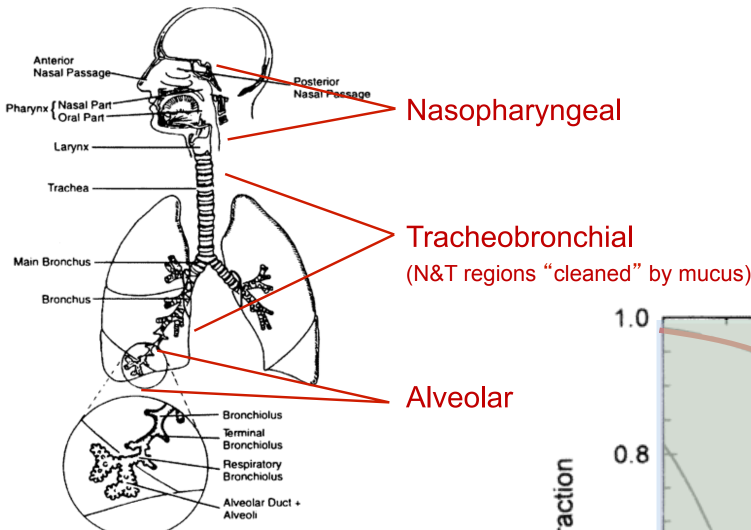


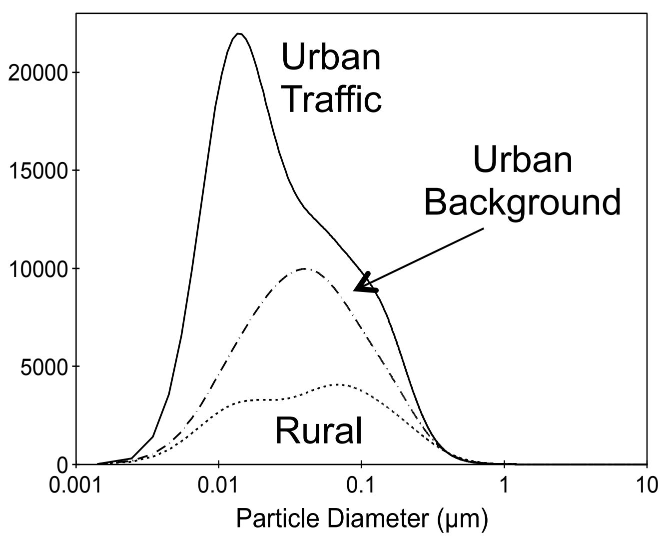




Casuccio et al., **2004** *Fuel Process. Technol.*; Ormstad, **2000** *Toxicol.;* Hinds, **1999** *Aerosol Technol.*

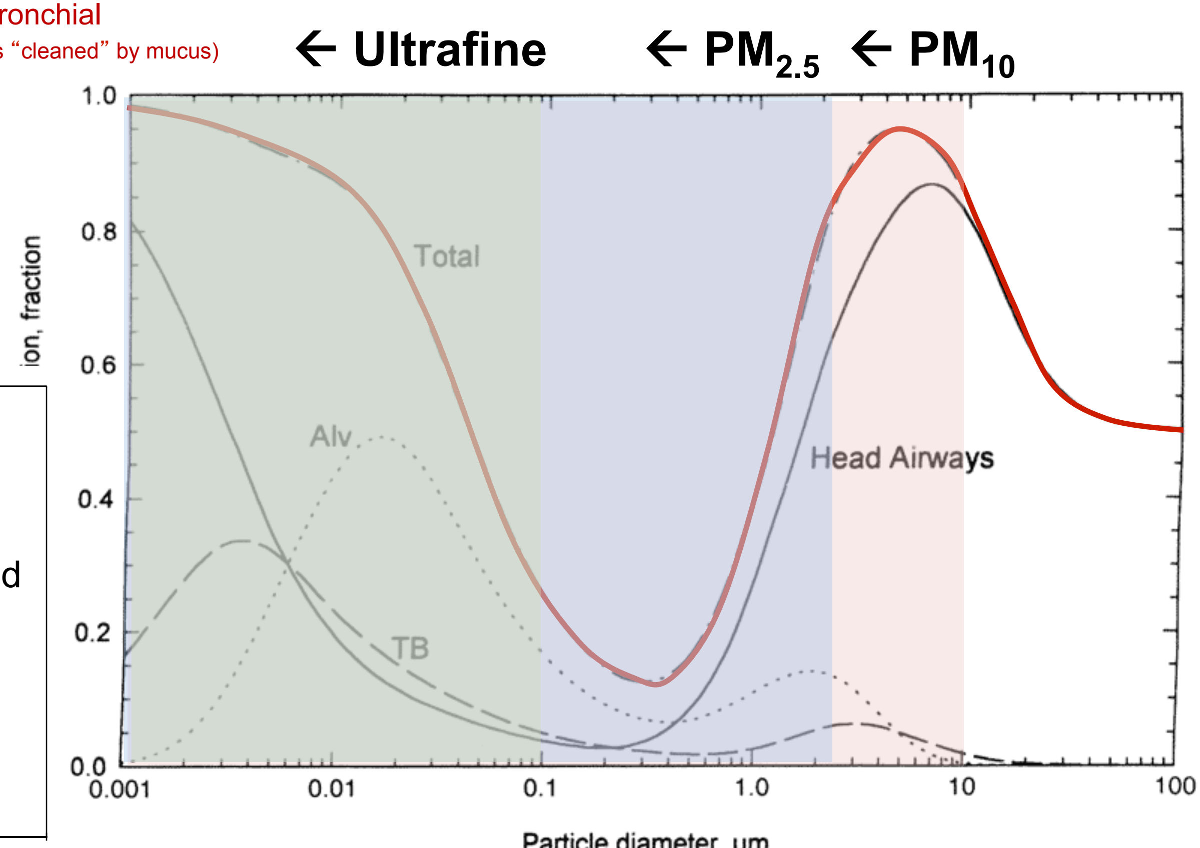
Particle deposition in the respiratory system





Costabile et al., **2009**
Atmos Chem Phys

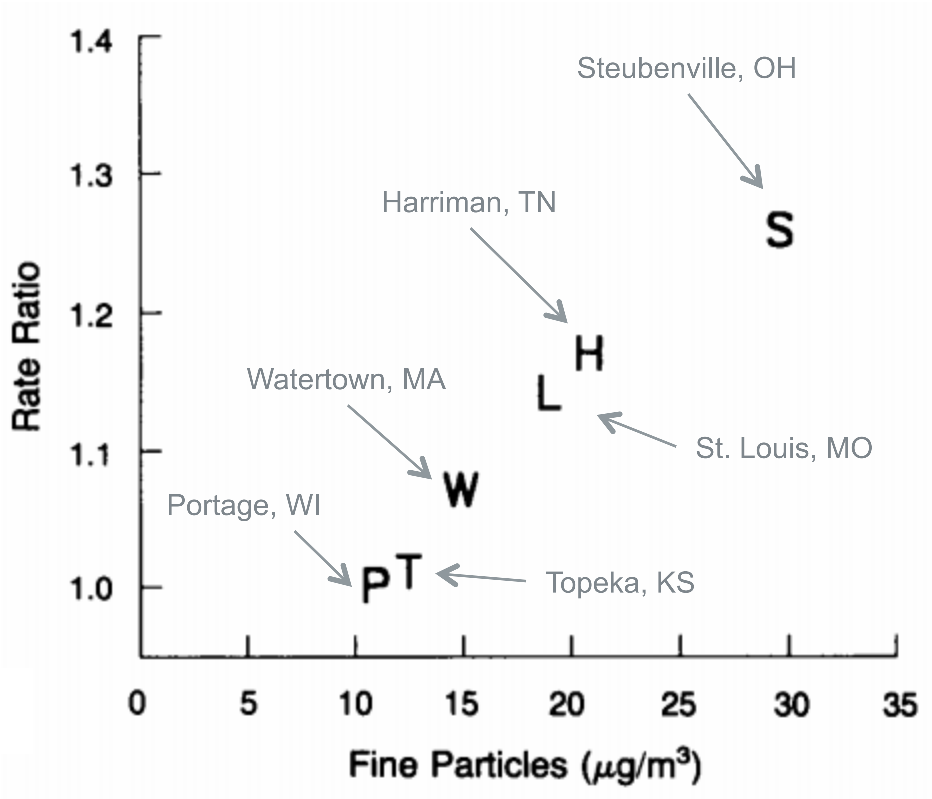
Hinds, 1999 Ch. 11



Most particles of outdoor origin are smaller than 100 nm

Outdoor PM and health effects

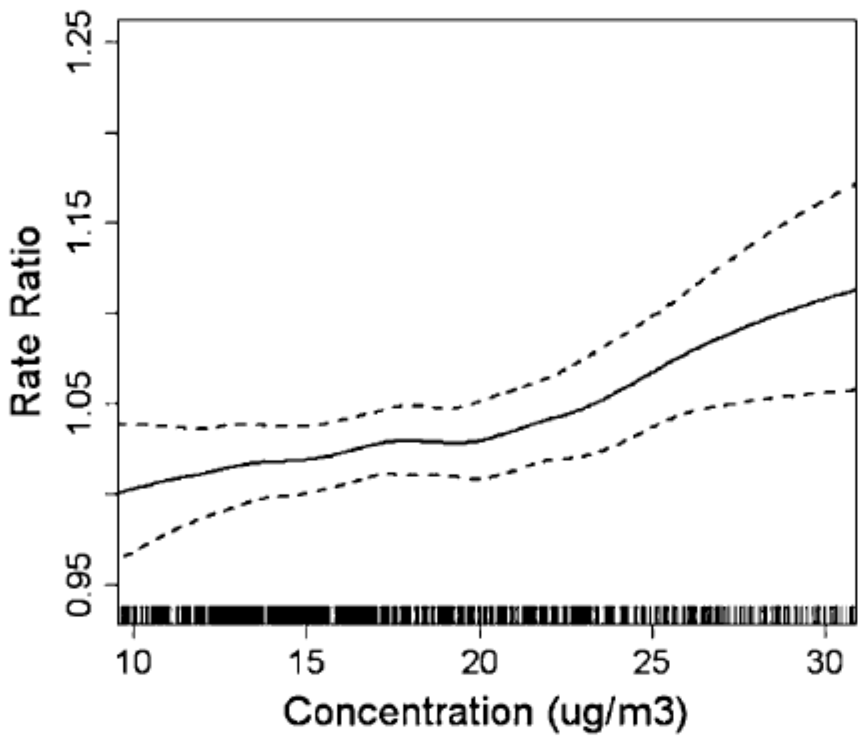
$PM_{2.5}$ and mortality



Mean $PM_{2.5}$ concentration measured outdoors in six cities over several years in the 1980s

Dockery et al., **1993** *New Engl J Med*

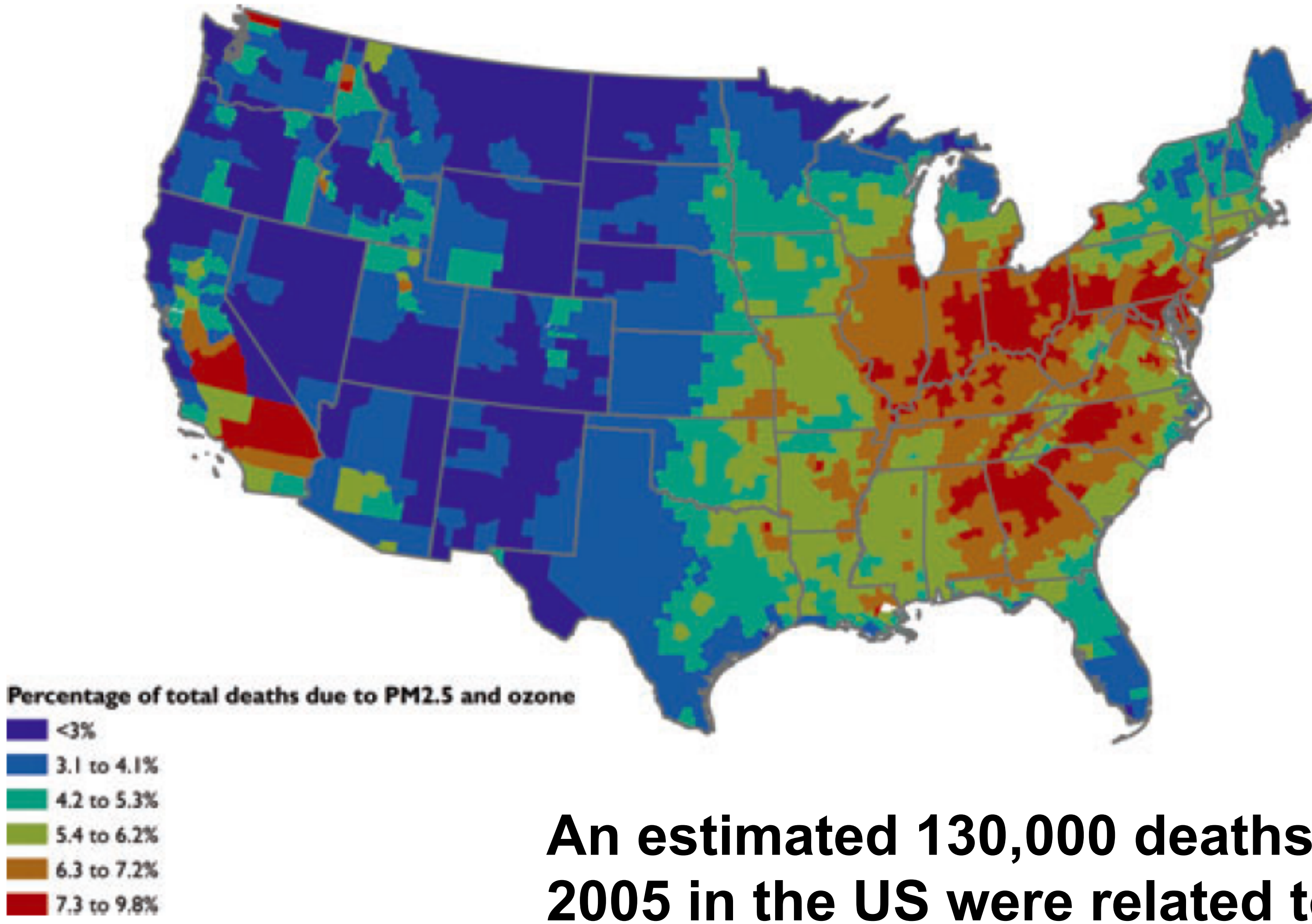
$PM_{2.5}$ and pediatric ER visits



3-day average $PM_{2.5}$data measured outdoors in Atlanta, GA from 1993 to 2004

Strickland et al., **2010** *Am J Respir Crit Care Med*

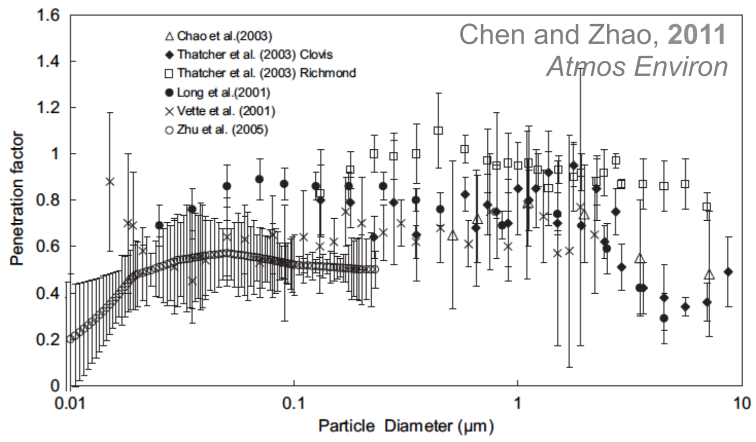
Health effects: Outdoor air pollution and mortality

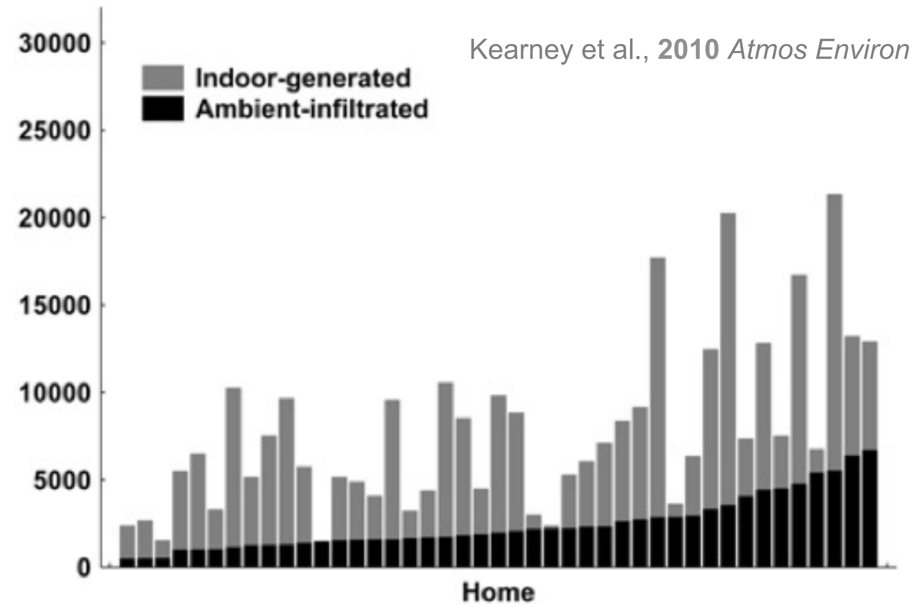


An estimated 130,000 deaths in 2005 in the US were related to outdoor $PM_{2.5}$

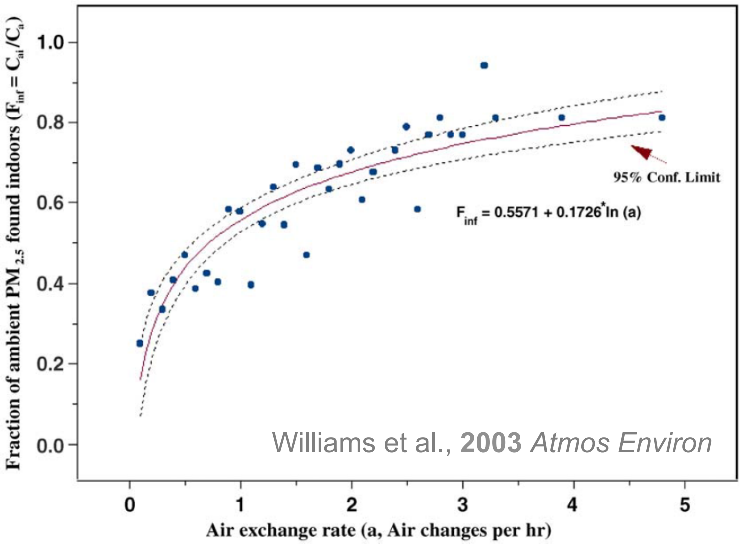
Fann et al., **2012** *Risk Analysis*

Indoor proportion of outdoor particles





Outdoor particles infiltrate into and persist within buildings with varying efficiencies

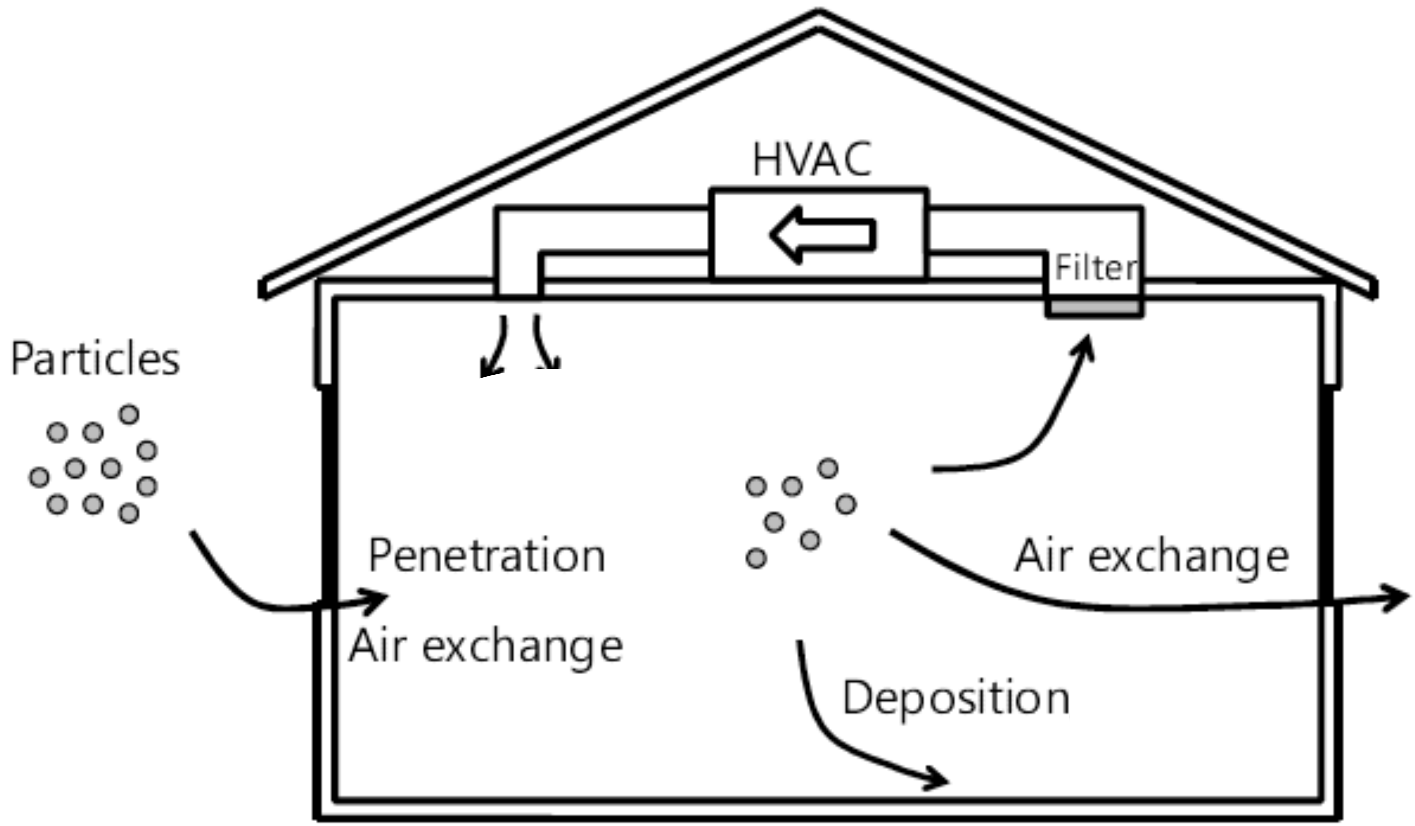


Exposure to outdoor PM often occurs indoors

Often at home

Meng et al., **2005** *J Expo Anal Environ Epidem*
Kearney et al., **2010** *Atmos Environ*
Wallace and Ott **2011** *J Expo Sci Environ Epidem*
MacNeill et al. **2012** *Atmos Environ*

Mechanisms that impact indoor exposures to outdoor PM



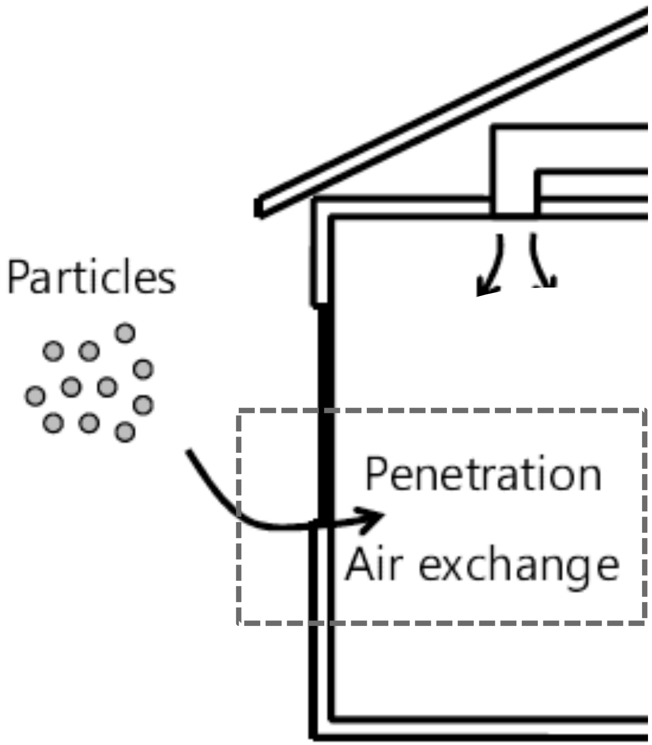
C_{in} = indoor concentration (#/m^3)
C_{out} = outdoor concentration (#/cm^3)
P = penetration factor (-)
λ = air exchange rate (1/hr)
k = surface deposition rate (1/hr)
f = fractional HVAC runtime (-)
η = filter removal efficiency (-)
Q = HVAC airflow rate (m^3/hr)
V = indoor air volume (m^3)

$$\frac{C_{in}}{C_{out}} = F_{\text{inf}} = \frac{P\lambda}{\lambda + k + f\frac{\eta Q}{V}}$$

Penetration from outdoors

Air exchange
Deposition
HVAC filter removal

Mechanisms that impact indoor exposures to outdoor PM



“Penetration Factor”
If *P* = 1:
The envelope offers no protection
If *P* = 0:
The envelope offers complete protection

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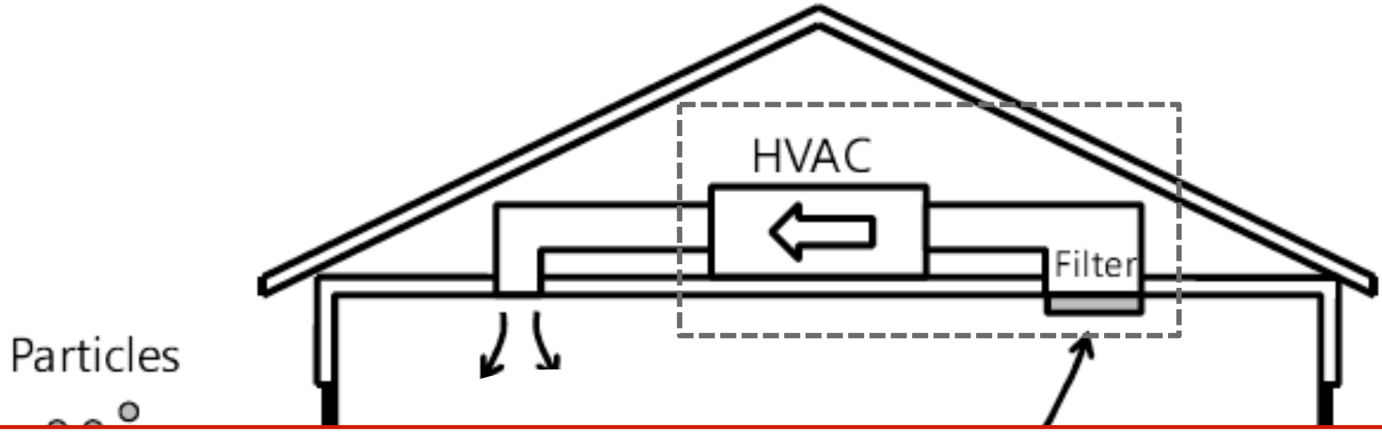
Penetration from outdoors

Mechanisms that impact indoor exposures to outdoor PM



"Filter efficiency"

If η = 1:

The filter offers complete protection (when the system operates)

If η = 0:

The filter offers no protection (ever)

C_{in} = indoor concentration (#/m^3)
C_{out} = outdoor concentration (#/cm^3)
P = penetration factor (-)
λ = air exchange rate (1/hr)
k = surface deposition rate (1/hr)
f = fractional HVAC runtime (-)
η = filter removal efficiency (-)
Q = HVAC airflow rate (m^3/hr)
V = indoor air volume (m^3)

$$\frac{C_{in}}{C_{out}} = F_{\text{inf}} = \frac{P\lambda}{\lambda + k + f\frac{\eta Q}{V}}$$

Filter removal
HVAC operation

Importance of source and removal mechanisms

- **Building envelope penetration**
  - Only recently has varying particle infiltration been implicated in observed health disparities with outdoor PM
    - Largely by varying AER, not penetration factor

Hodas et al., **2012** *J Expo Sci Environ Epidem*; Chen et al., **2012** *Epidemiology*

- **HVAC removal**
  - Prevalence of air-conditioning has been shown to be a modifier in $PM_{2.5}$ and PM_{10} mortality
    - Little information on filter removal efficiency and HVAC system runtime

Janssen et al., **2002** *Environ Health Persp*; Franklin et al., **2007** *J Expo Sci Environ Epidem*; Bell et al., **2009** *Epidemiology*

Goals of this work

- Further explore the impacts of building envelopes and HVAC filters on indoor PM of outdoor origin

  Key parameters:
  - Particle penetration factor, P
  - Particle removal by HVAC filter, $\eta Q/V$
  - HVAC system runtime, f

- Using measured data from recent studies on residential (and some small commercial) buildings

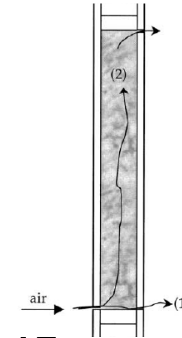
- Can we also **predict** these impacts?

PARTICLE INFILTRATION MEASUREMENTS

Measuring particle infiltration

- Particles can penetrate through cracks in building envelopes
  - Theoretically a function of:
    - Crack geometry
    - Air speed through leaks

Liu and Nazaroff, **2001** *Atmos Environ*



- Are building details and particle penetration factors correlated?
  - e.g., air leakage parameters or building age
  - Need a better test method for measuring *P* quickly
- Applied a particle penetration test method in 19 homes

Stephens and Siegel, **2012** *Indoor Air*

Particle Diameter: 1 nm | 10 nm | 100 nm | 1 µm | 10 µm | 100 µm

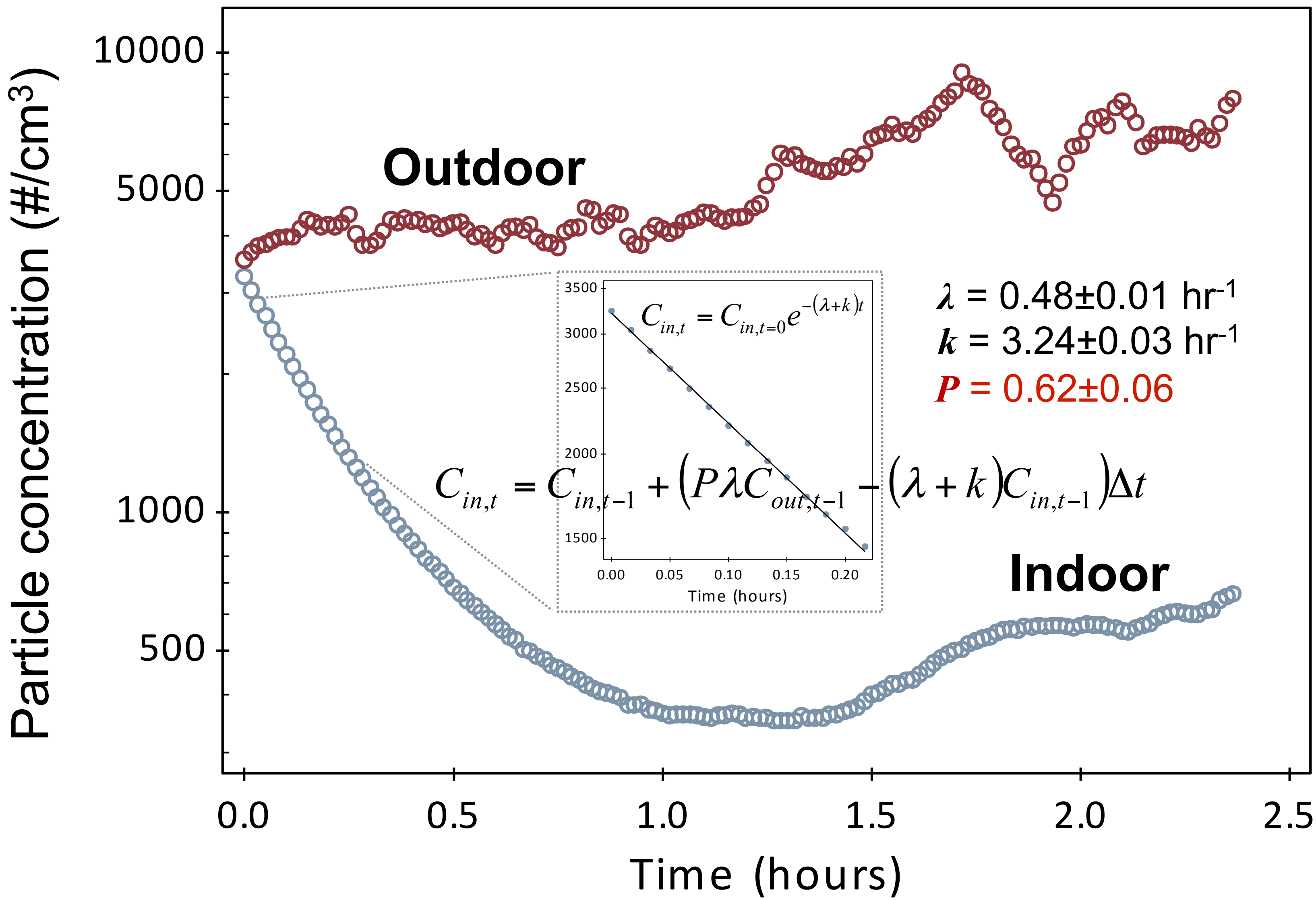
- gases
- tobacco smoke
- pollen
- viruses
- dust
- diesel smoke
- fungal spores

20 – 1000 nm

PM infiltration: Test homes

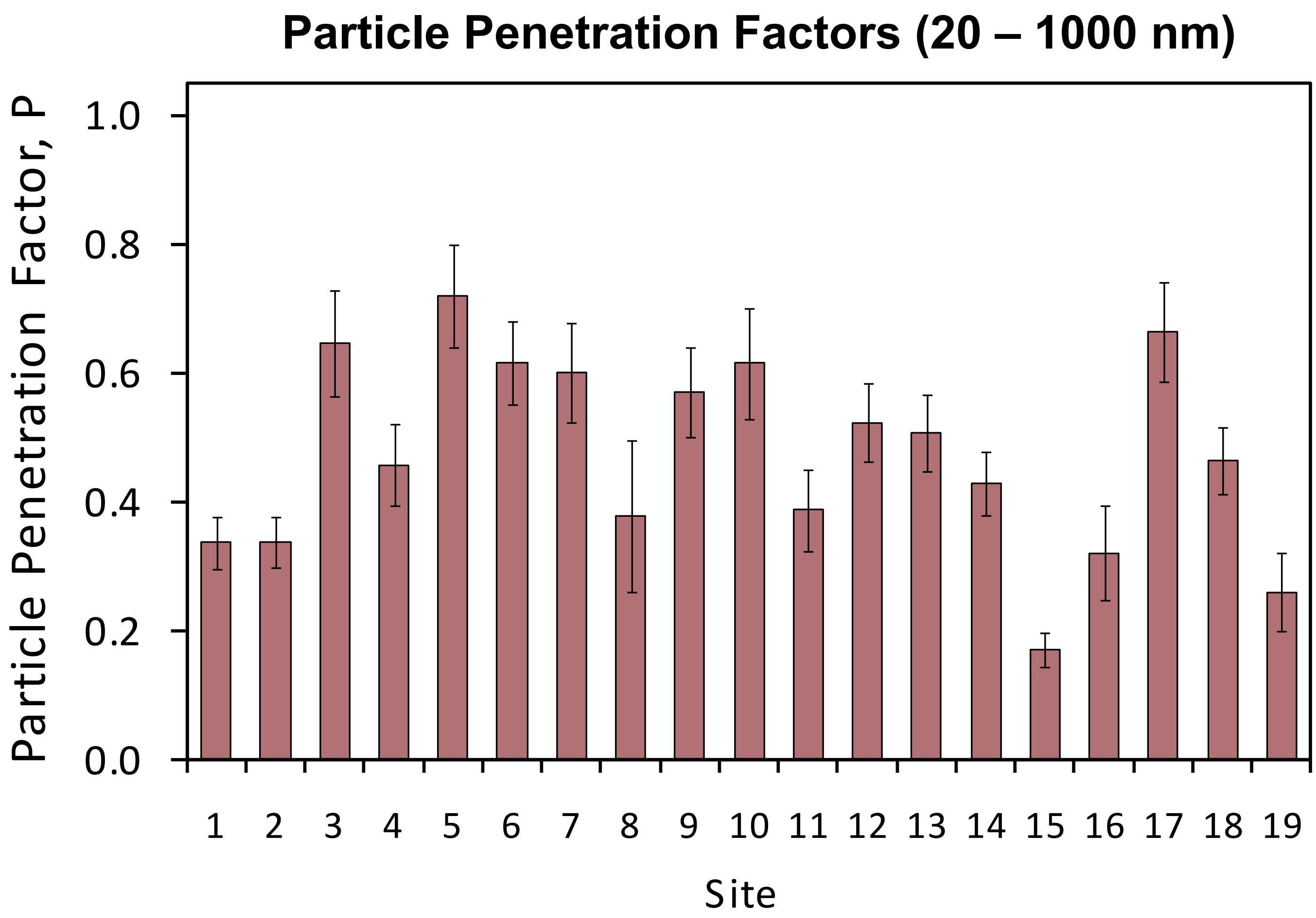
Stephens and Siegel, *Indoor Air* **2012** 22(6):501-512

Test method | Particulate matter (20-1000 nm)



Stephens and Siegel, *Indoor Air* **2012** 22(6):501-512

Particle infiltration results

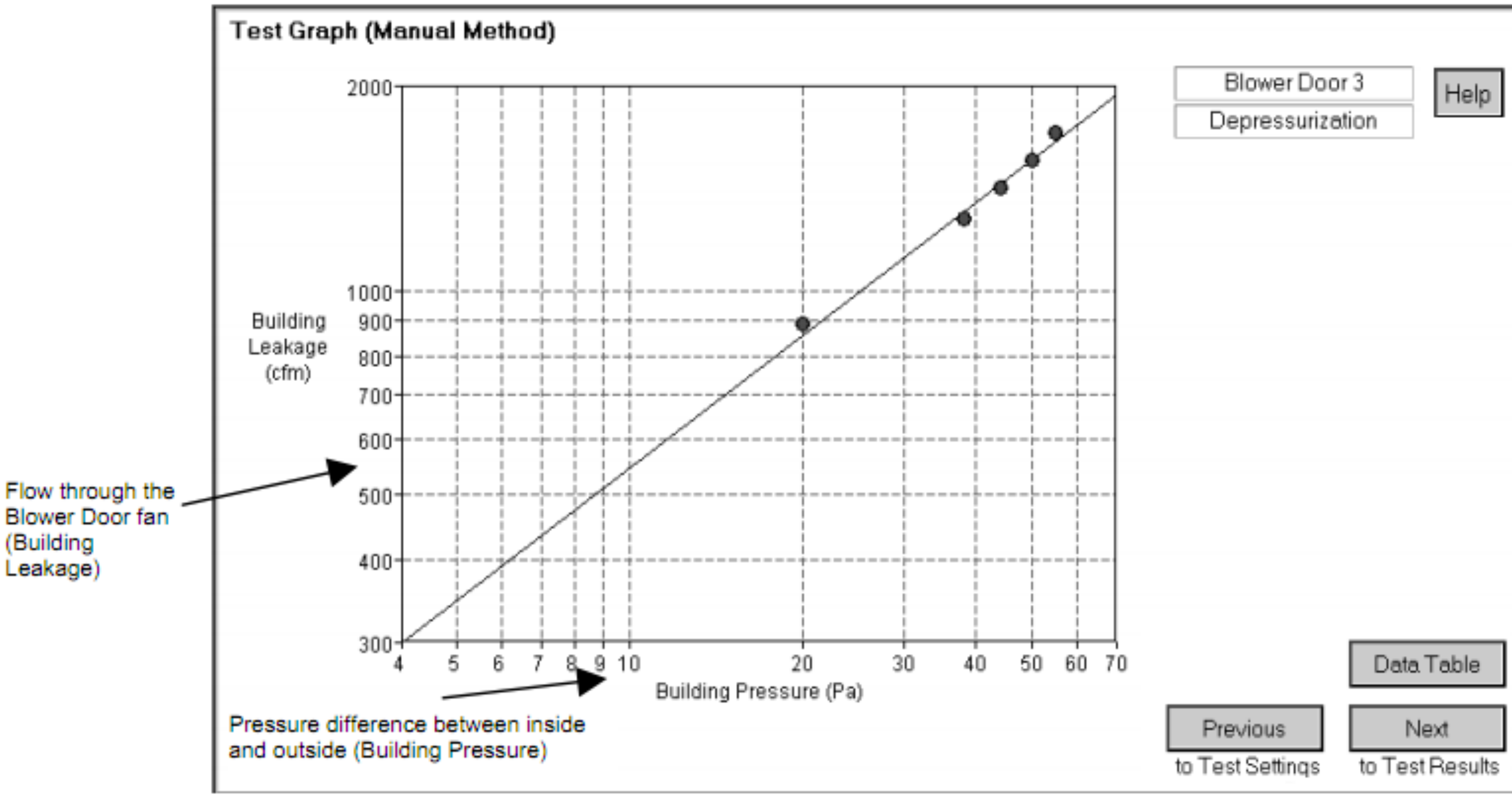


Mean (± SD) = 0.47 ± 0.15 | Range = 0.17 ± 0.03 to 0.72 ± 0.08

Stephens and Siegel, *Indoor Air* **2012** 22(6):501-512

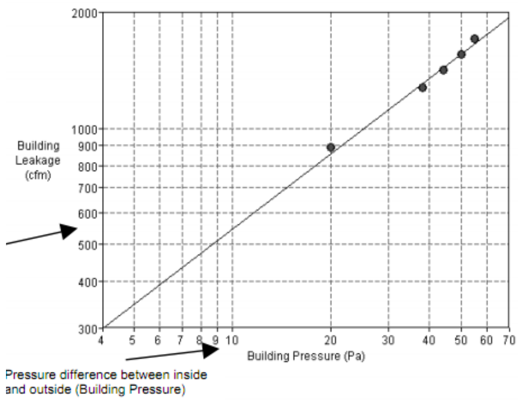
PM infiltration: What can we learn?

- Blower doors



Source: Energy Conservatory Blower Door Manual

Blower door tests



$$Q = C\Delta P^{n}$$

Airflow ($m^3\ s^{-1}$)

Leakage Coefficient ($m^3\ s^{-1}\ Pa^{-n}$)

I/O Pressure Difference (Pa)

Leakage Exponent (dimensionless)

$$ELA = C\Delta P_{ref}^{n-0.5}\sqrt{\frac{\rho}{2}}$$

Estimated Leakage Area (cm^2)

$$NL = 1000\frac{ELA}{Af}\left(\frac{H}{2.5m}\right)^{0.3}$$

Normalized Leakage, NL (dimensionless)

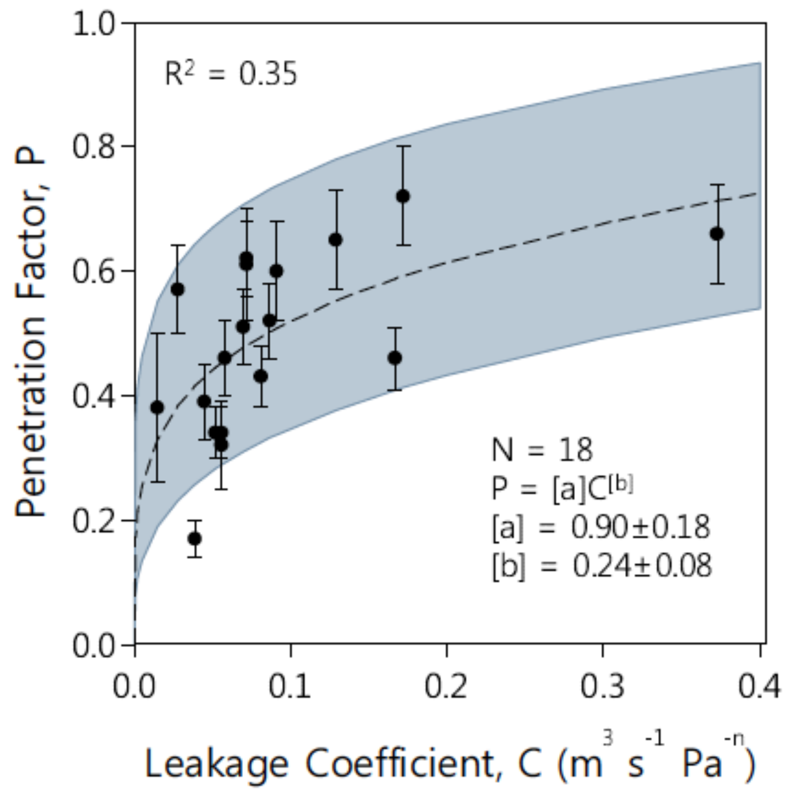
$$ACH_{50} = \frac{Q_{50\ Pa}}{V}$$

Air Changes per Hour @ 50 Pa (hr^{-1})

Source: ASTM E 779 and ASHRAE Standard 119

PM infiltration and air leakage

- Particle penetration factors (P for 20-1000 nm particles)
  - Significantly correlated with coefficient from blower door tests (C)
  - Spearman's $\rho = 0.71$ ($p < 0.001$)

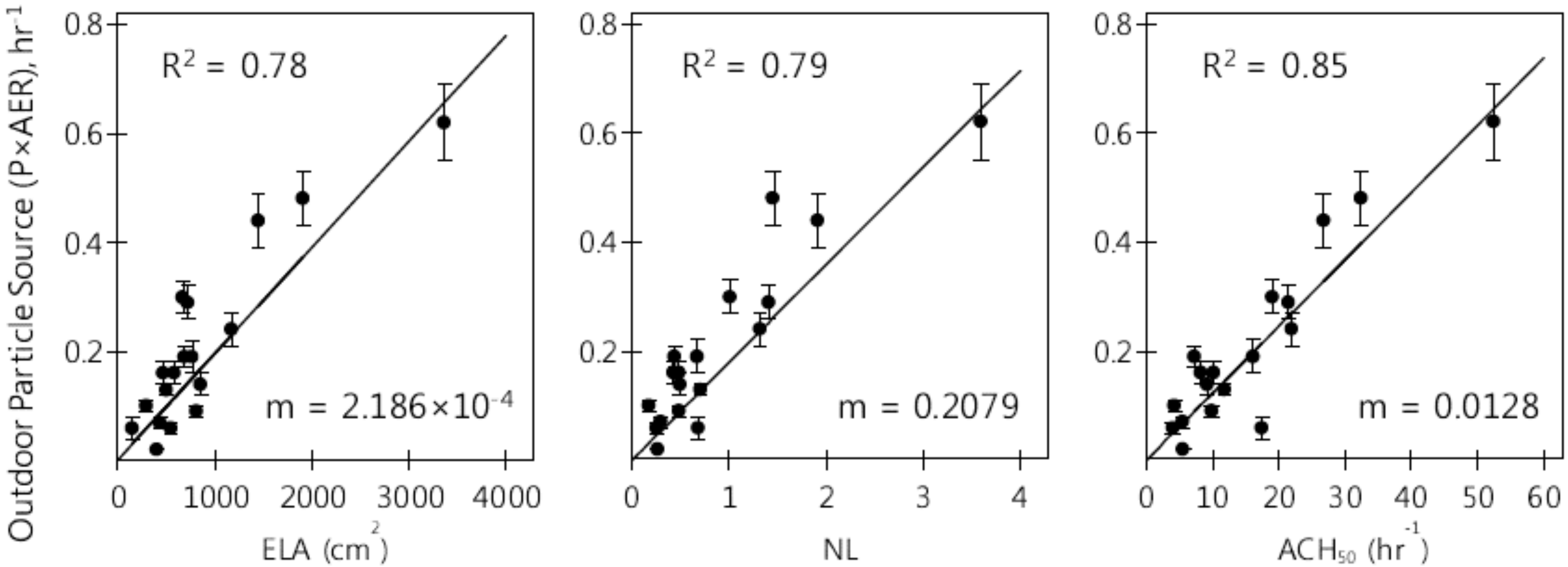


- Association is strong, but predictive ability is low

Stephens and Siegel, *Indoor Air* **2012** 22(6):501-512

PM infiltration: Outdoor particle source and air leakage

$$\frac{C_{in}}{C_{out}} = \frac{P \times AER}{AER + Loss}$$



Leakier homes had much higher outdoor particle source rates

- Potential socioeconomic implications: low-income homes are leakier

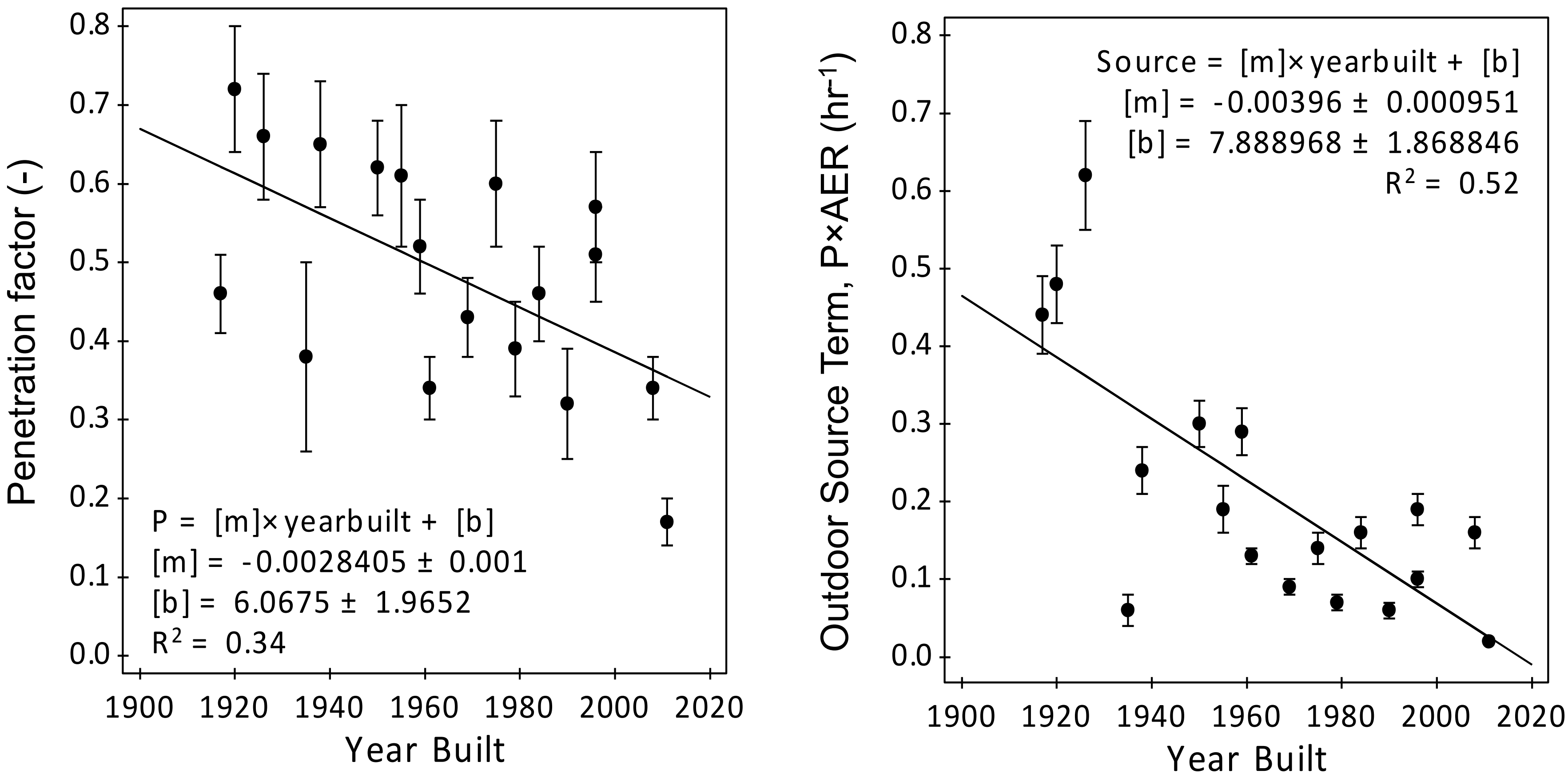
Chan et al., **2005** *Atmos Environ*

Stephens and Siegel, *Indoor Air* **2012** 22(6):501-512

PM infiltration and age of homes

$$\frac{C_{in}}{C_{out}} = \frac{P \times AER}{AER + Loss}$$

$$\frac{C_{in}}{C_{out}} = \frac{P \times AER}{AER + Loss}$$



Older homes also had much higher outdoor particle source rates

Stephens and Siegel, *Indoor Air* **2012** 22(6):501-512

MEASUREMENTS OF HVAC FILTRATION

HVAC filter performance

ASHRAE Standard 52.2 → MERV

- Filter efficiency for 0.3 to 10 μm particles

1-inch depth

MERV 4

MERV 6

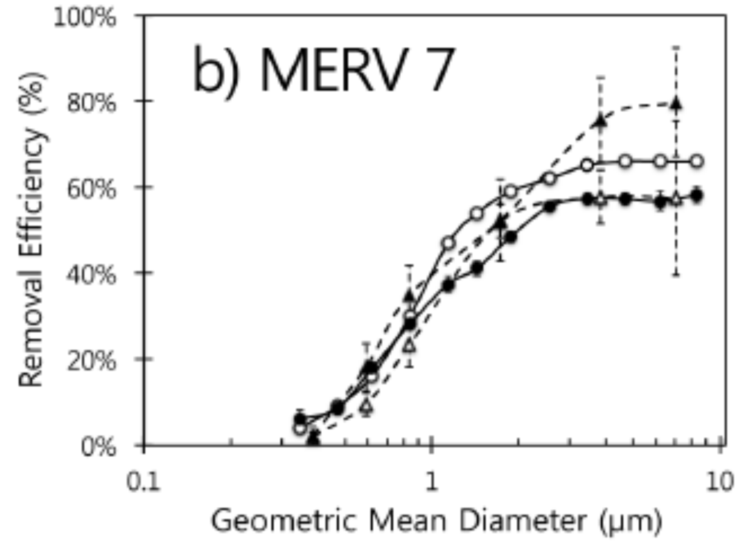
MERV 11

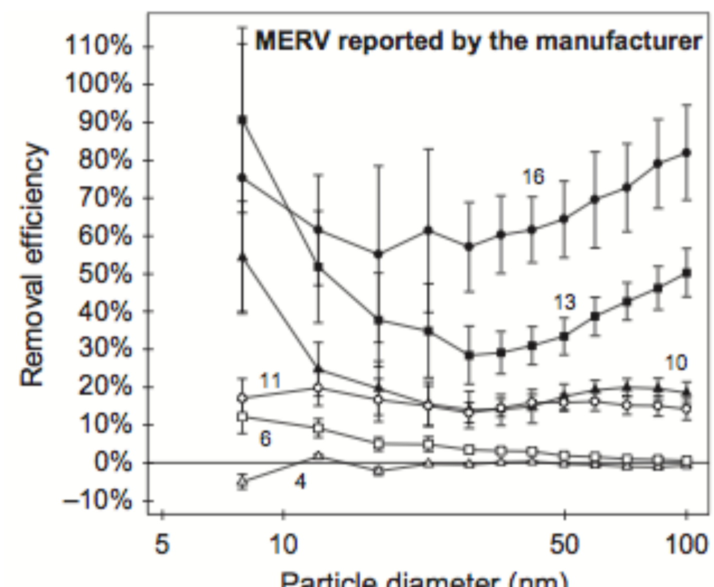
5-inch depth

MERV 10

MERV 13

MERV 16





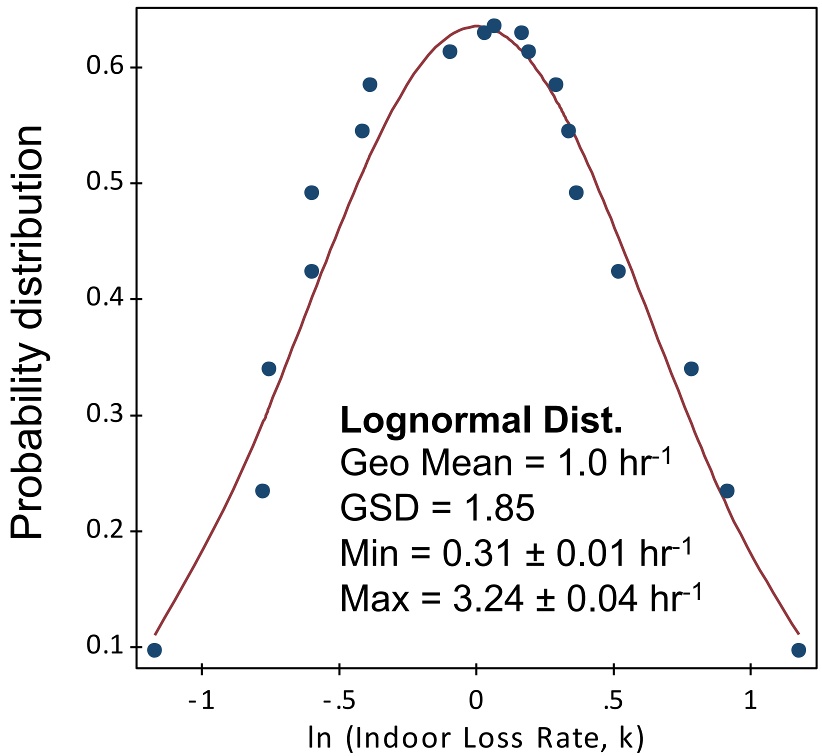
Stephens and Siegel, *Aerosol Sci. Technol.* **2012** 46(5), 504-513
Stephens and Siegel, *Indoor Air* **2013**

Indoor particle removal rates

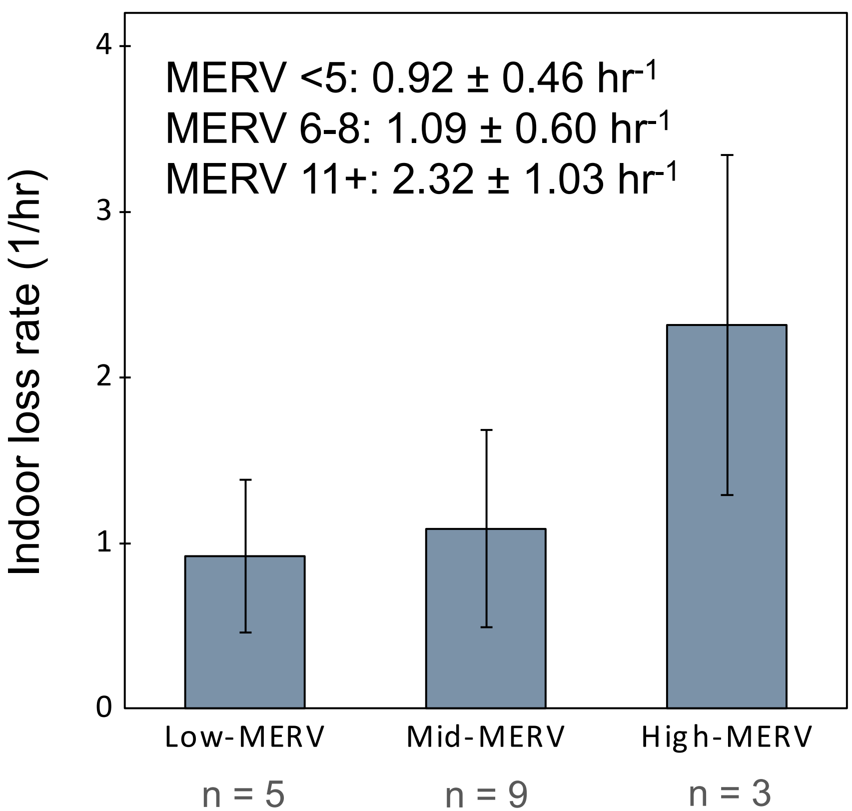
- Submicron particle loss with HVAC system operating 100%

$$Loss = k + f\frac{\eta Q}{V}$$

where f = 1



Split by filter type



Stephens and Siegel, *Indoor Air* **2012** 22(6):501-512

HVAC system runtimes

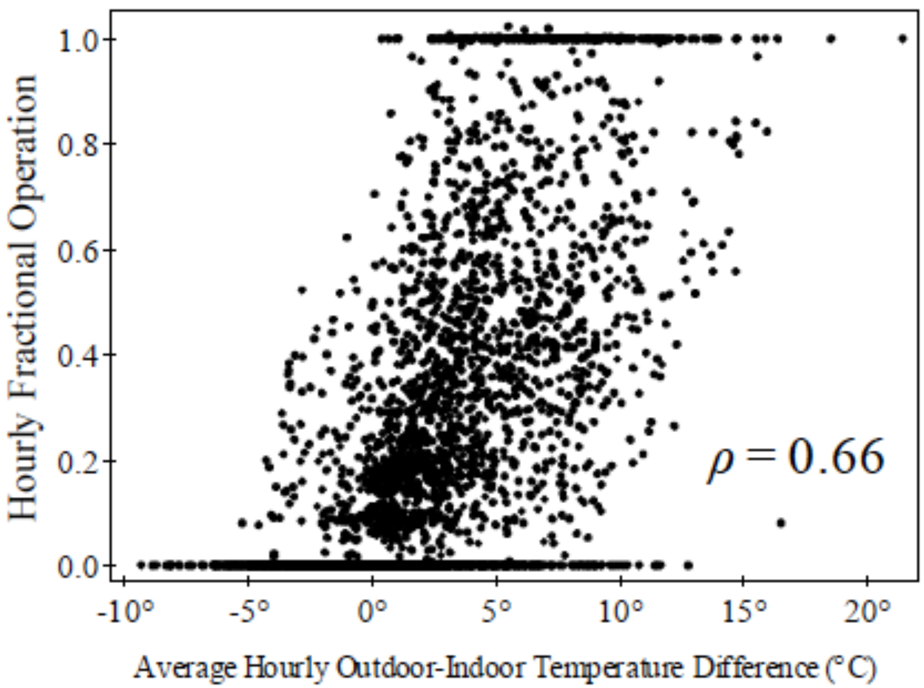
$$\text{HVAC Removal} = f\,\frac{\eta Q}{V}$$

- HVAC systems in U.S. homes typically only operate in response to indoor-outdoor climate conditions
  - f varies in time
- Previously collected dataset (ASHRAE RP-1299)
  - 8 residential systems and 9 light-commercial systems
  - Monitored 1 day per month for 1 year (cooling period only)
  - 3,100+ hours of cooling operation over 114 days
  - Explored data for system runtimes

Stephens et al., **2011** *Building and Environment*

HVAC system runtimes in 17 buildings

- Mean HVAC runtimes ranged 10.7% to 55.3%
  - Median $f \approx 21\%$
  - Increased with indoor-outdoor ΔT
    - Also with lower thermostat settings



Increase in hourly duty fraction per °C rise in average hourly indoor-outdoor temperature difference

Site	% per °C	R^2	N (hours)
1	6.0%	0.71	175
2	3.7%	0.33	180
3	2.9%	0.68	215
4	7.2%	0.68	226
5	9.3%	0.69	222
6	9.1%	0.80	161
7	4.7%	0.71	204
8	7.3%	0.62	164
9	6.0%	0.69	175
10	4.9%	0.73	171
11	11.3%	0.67	211
12	4.5%	0.68	91
13	7.9%	0.61	218
14	7.1%	0.78	173
15	9.2%	0.63	182
16	4.0%	0.41	152
17	2.4%	0.22	150
Average	6.3%	Total	3070
Median	6.0%		

Median increase in hourly runtime per °C rise in average indoor-outdoor temperature difference: ~6% per °C

Stephens et al., **2011** *Building and Environment*

VARIATIONS IN EXPOSURES

Across observed range of envelope penetration, filter efficiency, and runtimes

Implications for submicron PM exposure

- Penetration factors ranged 0.17 to 0.72
- AER ranged 0.13 hr^{-1} to 0.95 hr^{-1}
- Outdoor particle source terms ranged 0.02 hr^{-1} to 0.62 hr^{-1}
  - Factor of ~30 difference from lowest to highest
  - Higher in older, leakier homes

- Indoor removal rates ranged 0.31 hr^{-1} to 3.24 hr^{-1}
  - Factor of ~10 difference from least efficient to most efficient filter
  - Varied with rated filter efficiency (particularly for high-efficiency)

- HVAC fractional operation ranged 10.7% to 55.3%
  - Factor of ~5 difference
  - Varied with thermostat settings, occupancy, and outdoor climate

Implications for submicron PM exposure

- Combined effects: $F_{\text{inf}} = \frac{C_{in}}{C_{out}} = \frac{P \times AER}{AER + k + f\,\frac{\eta Q}{V}}$

	Lower bound	Upper bound
Penetration factor, P	0.17	0.72
Air exchange rate, AER (1/hr)	0.13	0.95
Outdoor source term, $P \times AER$ (1/hr)	0.02	0.62
Indoor loss rate, $k + \eta Q/V$ (1/hr)	3.24	0.31
Fractional HVAC operation, f	55.3%	10.7%
I/O submicron PM ratio (F_{inf})	0.01	0.70

Factor of ~60 to ~70 difference in indoor proportion of outdoor particles between:

- A new airtight home with a very good filter and high HVAC operation, and
- A leaky old home with a poor filter and low HVAC operation

- Some potential for predictive ability using:
  - Age of home
  - Building airtightness test results
  - Knowledge of HVAC filter type
  - I/O climate conditions

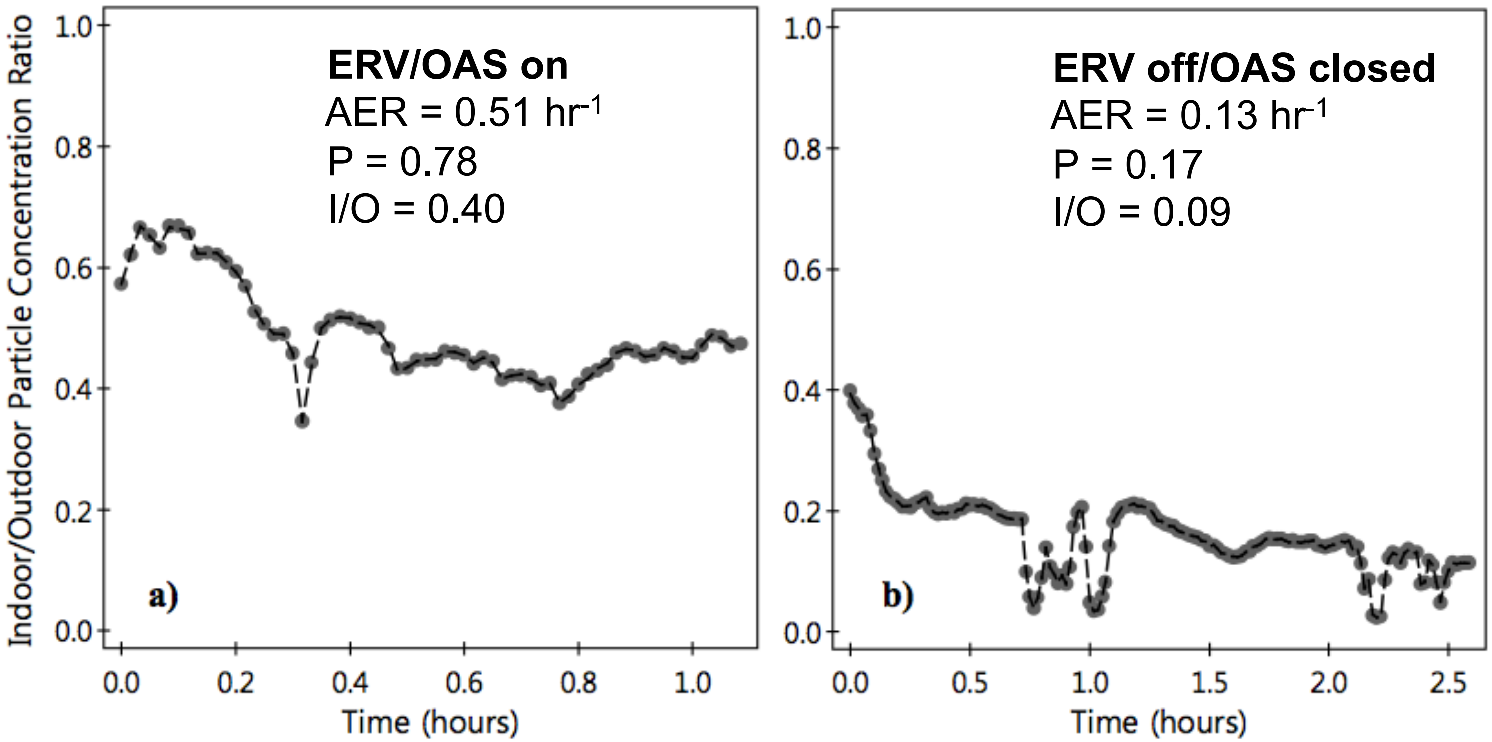
A CAUTIONARY TALE

In a net-zero energy capable home

Impacts of high-efficiency HVAC systems

- One of the test homes (Site 15) had a dedicated mechanical ventilation system
- Outdoor air supply duct ran through an energy recovery ventilator and was installed directly into the HVAC return plenum
- Previous results were only for natural infiltration, when the system was unplugged and capped
  - Relying on envelope leakage alone for ventilation air
- We repeated the test a second time with the ERV/OAS unit operating…

Impacts of high-efficiency HVAC systems



- This home was responsible for both the lowest and the highest envelope penetration factors!
  - Depending on whether or not the ERV was operating
- Problem: The ERV/OAS was ducted to directly ***downstream*** of the HVAC filter

Implications for design and construction

- Importance of performance testing
  - Blower door tests at a minimum
  - More advanced IAQ tests would be ideal
- Attention to detail
  - Envelope air sealing
  - HVAC system design and construction
  - HVAC filter choice
- Stay informed
  - Keep an eye on the researchers and publications mentioned herein
  - Plenty of opportunities to advance research in housing energy and IAQ

Acknowledgments

- Jeffrey Siegel at the University of Texas at Austin / University of Toronto
- All of our homeowners and occupants
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  - University of Texas at Austin Continuing Fellowship
  - NSF IGERT Award DGE #0549428
  - ASHRAE Grant-In-Aid
  - Thrust 2000 Endowed Graduate Fellowship

Questions/Comments

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