Indoor exposures to outdoor air pollution

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The **Built Environment Research Group** at Illinois Tech is dedicated to investigating energy and air quality within the built environment

Research areas:

Indoor pollutant dynamics

Building science measurements and methods

Air cleaning and filtration

Human exposure assessment

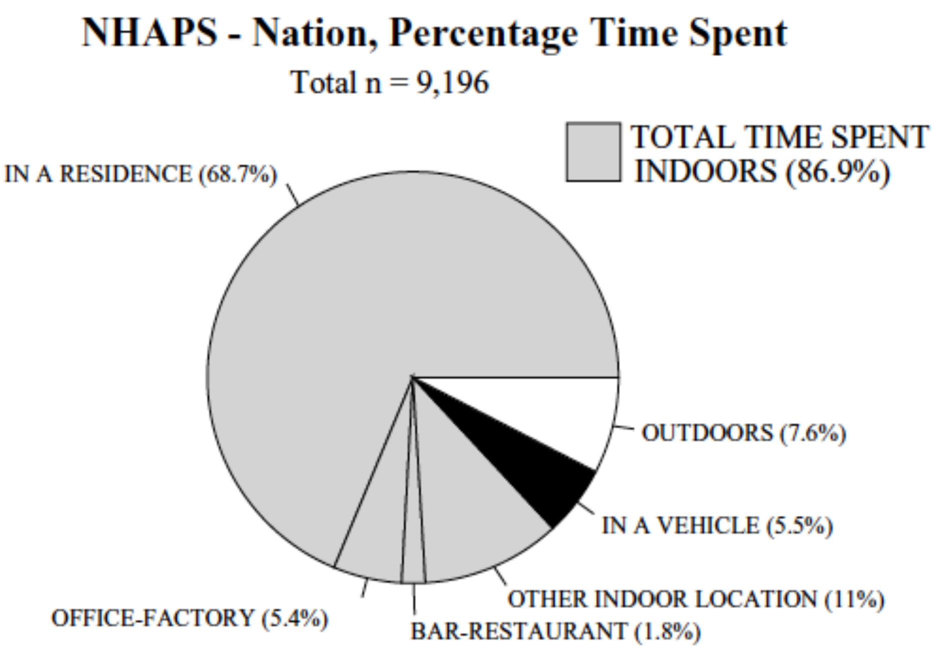
Building energy efficiency and energy simulation

INDOOR EXPOSURES TO OUTDOOR POLLUTANTS

Particulate matter and gas-phase pollutants (e.g., ozone)

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 indoor & outdoor sources of indoor pollutants

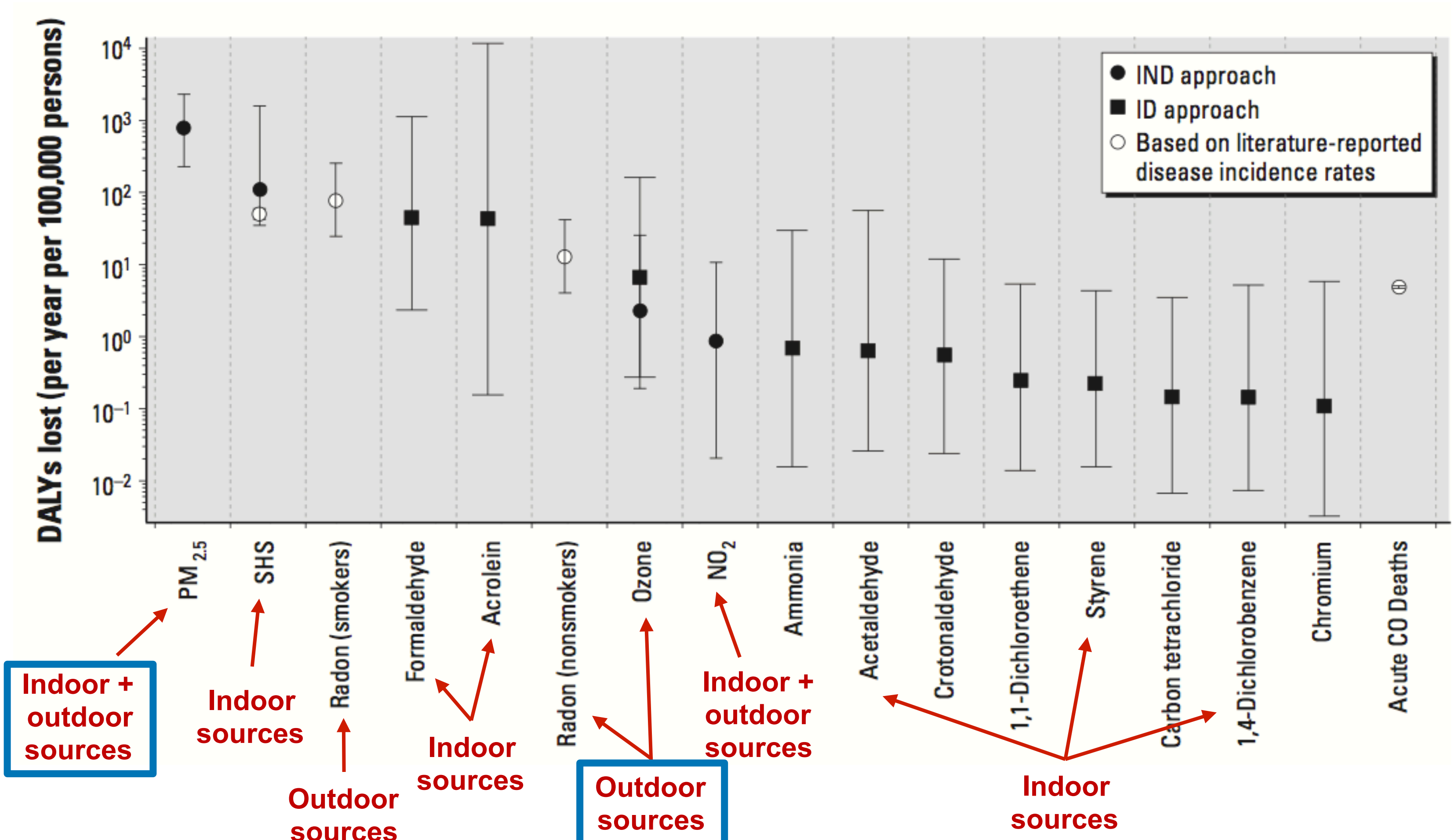
- Particulate matter
- Organic gases
- Inorganic gases

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

Residential indoor air and chronic health effects

Likely the **most harmful indoor air pollutants** inside residences:

- Accounts for **5 to 14%** of the non-communicable/non-psychiatric **U.S. disease burden**



Logue et al. **2012** *Environ Health Perspect* 120:216-222

A few outdoor airborne pollutants are regulated

National Ambient Air Quality Standards (NAAQS)

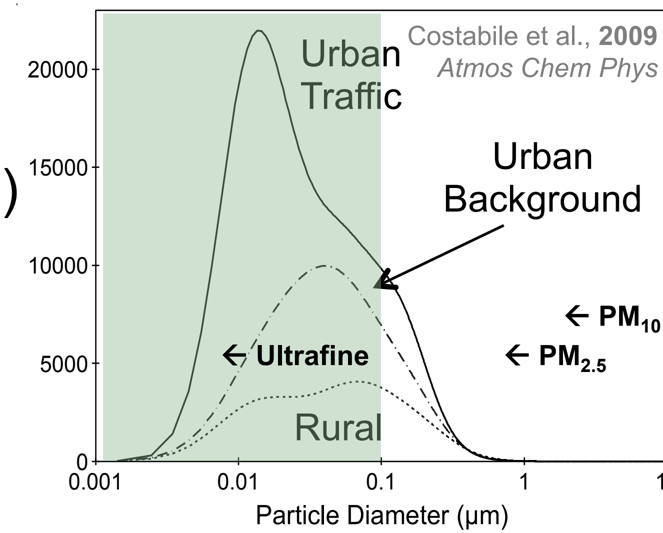
- US EPA and the Clean Air Act (1970)
- Set limits for 6 “criteria” air pollutants
  - World Health Organization (WHO) also maintains guidelines for 4 of these

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)

Outdoor particulate matter and ozone

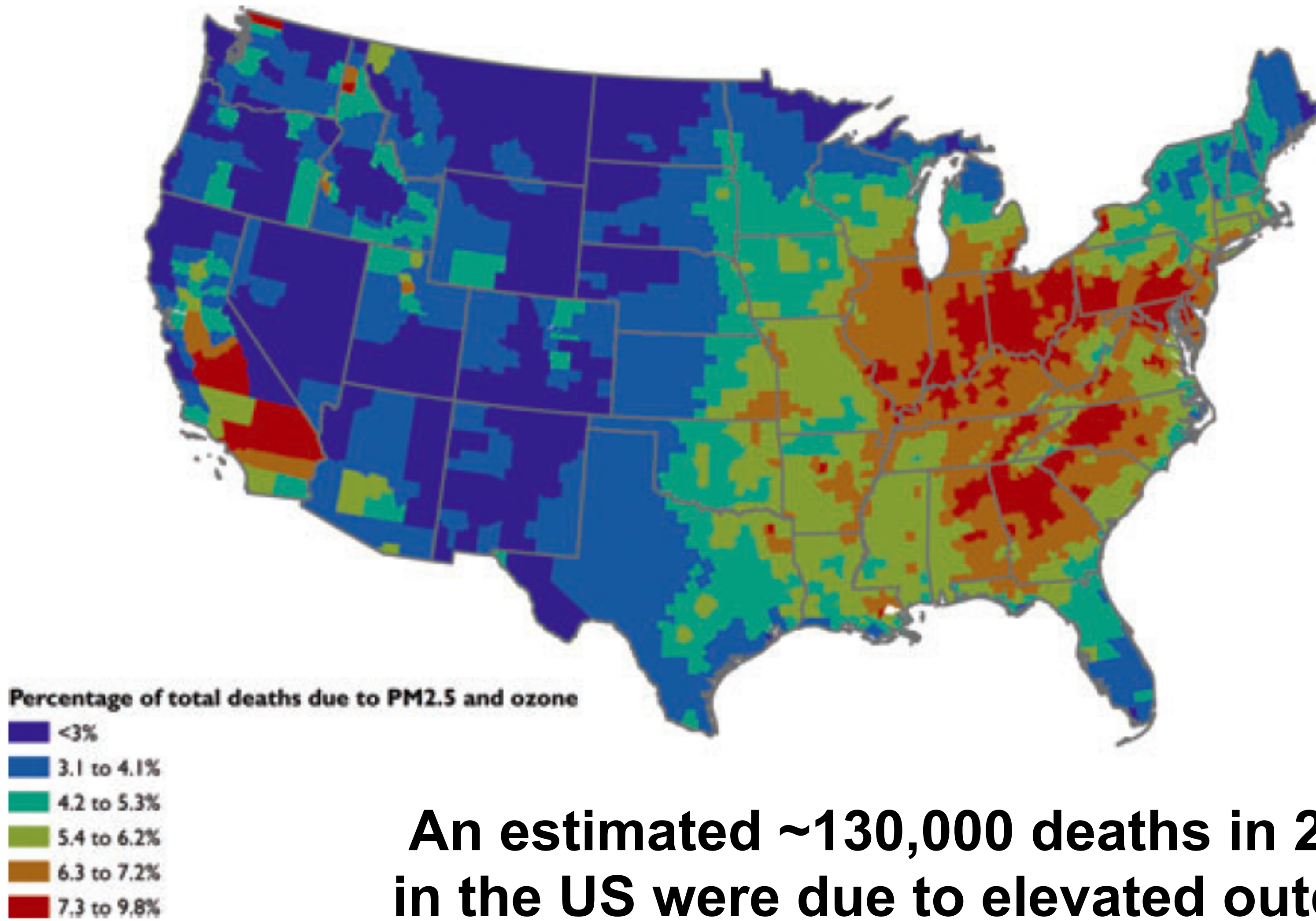
- **Particulate matter**
  - Solid and liquid particles suspended in air
  - Primary and secondary sources
    - Traffic, industry, natural, atmospheric rxns (SOA)
  - Wide range of sizes (a few nm to tens of µm) and constituents
    - Size governs deposition in the respiratory tract
  - Wide range of measurement methods and classifications
    - UFPs, $PM_{2.5}$, $PM_{2.5\text{-}10}$, PM_{10}, TSP, etc.

Most particles of outdoor origin are smaller than 100 nm



- **Ozone**
  - Formed through atmospheric reactions between hydrocarbons and nitrogen oxides in the presence of sunlight
  - Major contributor to smog

Outdoor particulate matter, ozone, and health

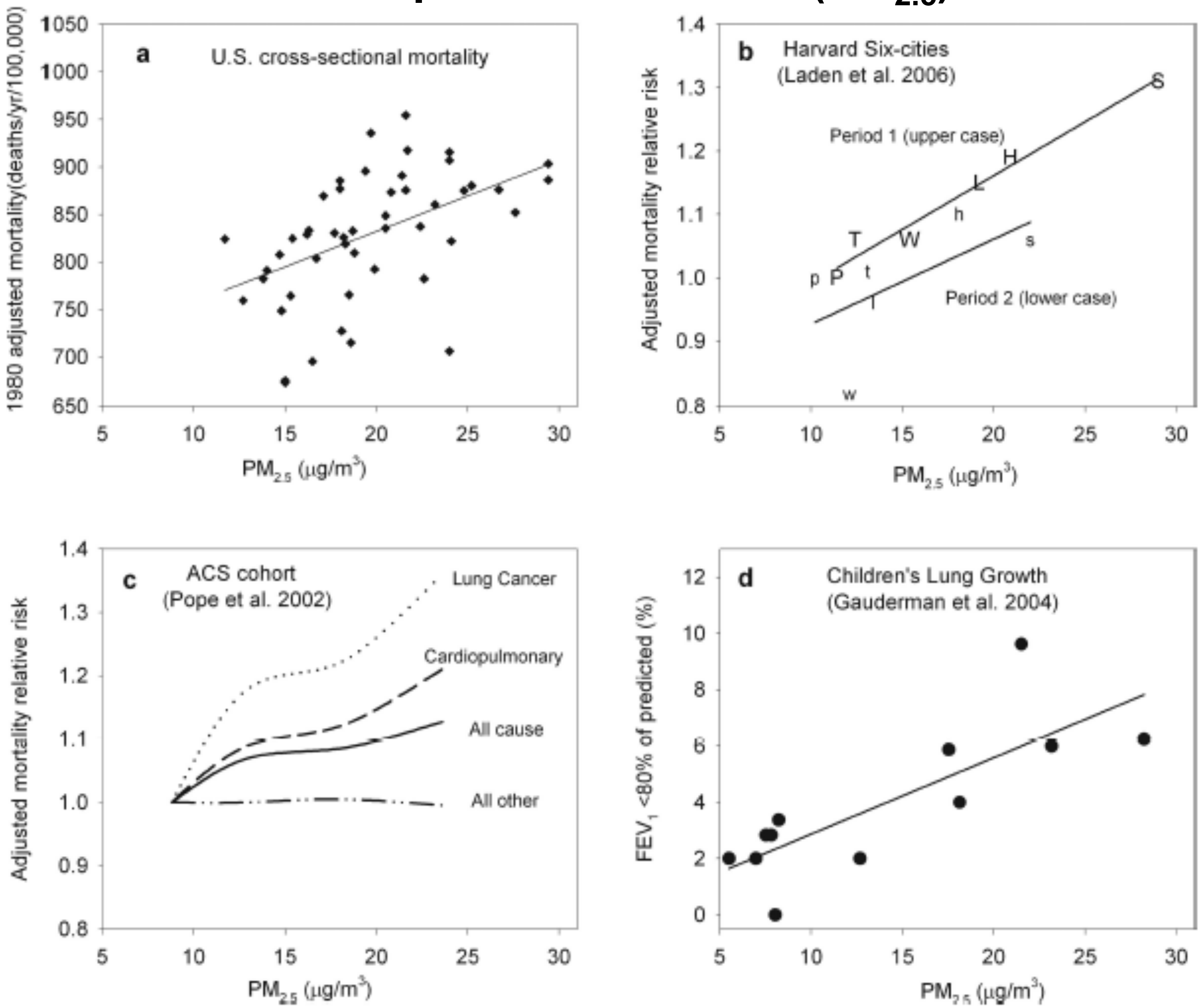


An estimated ~130,000 deaths in 2005 in the US were due to elevated outdoor $PM_{2.5}$ (and ~5,000 due to O_3)

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

Outdoor air epidemiology: A problem

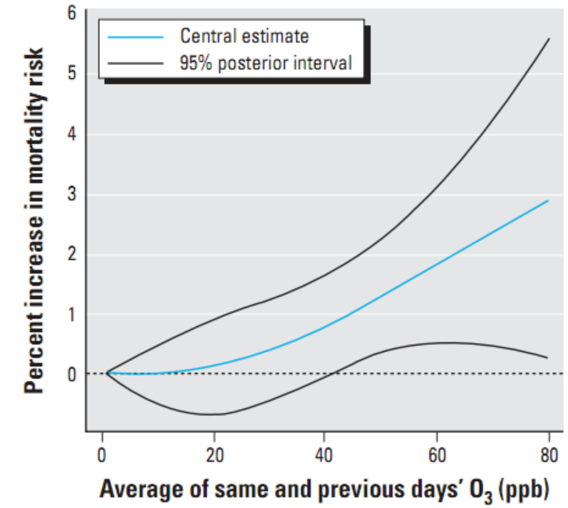
Fine particulate matter ($PM_{2.5}$)



Pope and Dockery, **2006** *J Air Waste Manage Assoc*

$$\Delta y_i = y_0[\exp(\beta_i \times \Delta E_i) - 1]$$

Ozone (O_3)



Bell et al., **2006**
Environ Health Persp

Nearly all outdoor air pollution epidemiology studies neglect an important point…

We spend most of our time indoors!

Exposures to outdoor particulate matter and ozone

- Elevated outdoor concentrations → health effects

$PM_{2.5}$/PM_{10}/ultrafine particles (UFPs)	**Ozone (O_3)**
Respiratory symptoms, cardiovascular mortality, lung cancer	Hospital admissions, respiratory illness, short-term mortality
Pope et al., **2002** *J Am Med Assoc*; Pope and Dockery, **2006** *J Air Waste Manag Assoc*; Miller et al., **2007** *New Engl J Med*; Ostro et al., **2010** *Environ Health Persp*	Gent et al., **2003** *J Am Med Assoc*; Bell et al., **2004** *J Am Med Assoc*; Hubbell et al., **2005** *Environ Health Persp*; Jerrett et al., **2009** *New Engl J Med*

- Americans spend most of their time indoors (nearly 90%)

  ~70% at home   Klepeis et al., **2001** *J Expo Anal Env Epi*

- Outdoor PM and O_3 infiltrate in buildings w/ varying efficiency

  PM: Chen and Zhao, **2011** *Atmos Environ*
  O_3: Avol et al., **1998** *Environ Sci Technol*; Weschler, **2000** *Indoor Air*

- Exposure to outdoor PM and O_3 (+ rxns) often occurs indoors

  PM: Meng et al., **2005** *J Exp Anal Environ Epidem*; Kearney et al., **2010** *Atmos Environ*
  O_3: Weschler, **2006** *Environ Health Persp*

- But we don't fully account for outdoor pollutant infiltration
  - Leads to "exposure misclassification"

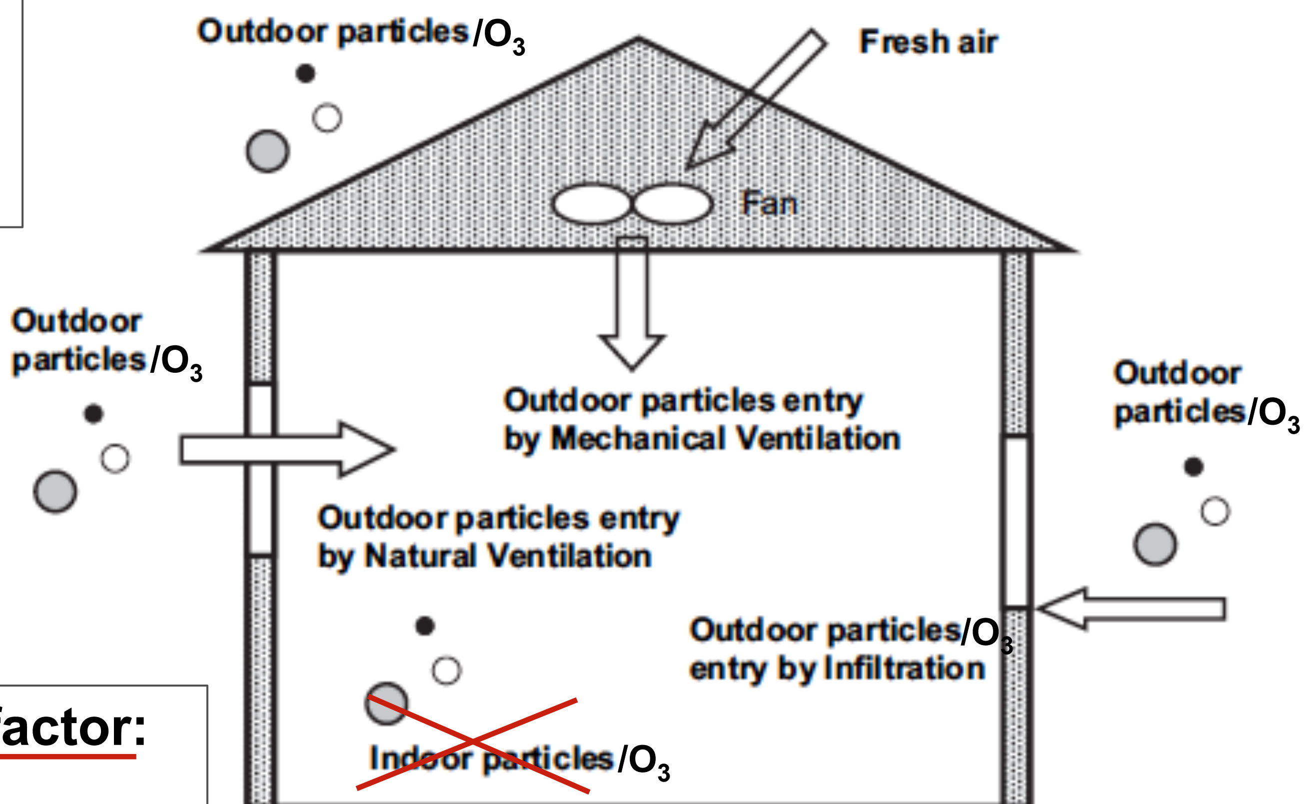
  Avery et al., **2010** *Environ Health Persp*; Baxter et al., **2013** *J Exp Sci Environ Epidem*; Hodas et al., **2013** *J Exp Sci Environ Epidem*

ACCOUNTING FOR OUTDOOR POLLUTANT INFILTRATION

Indoor sources of outdoor PM/O_3 and key definitions

I/O ratio:

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

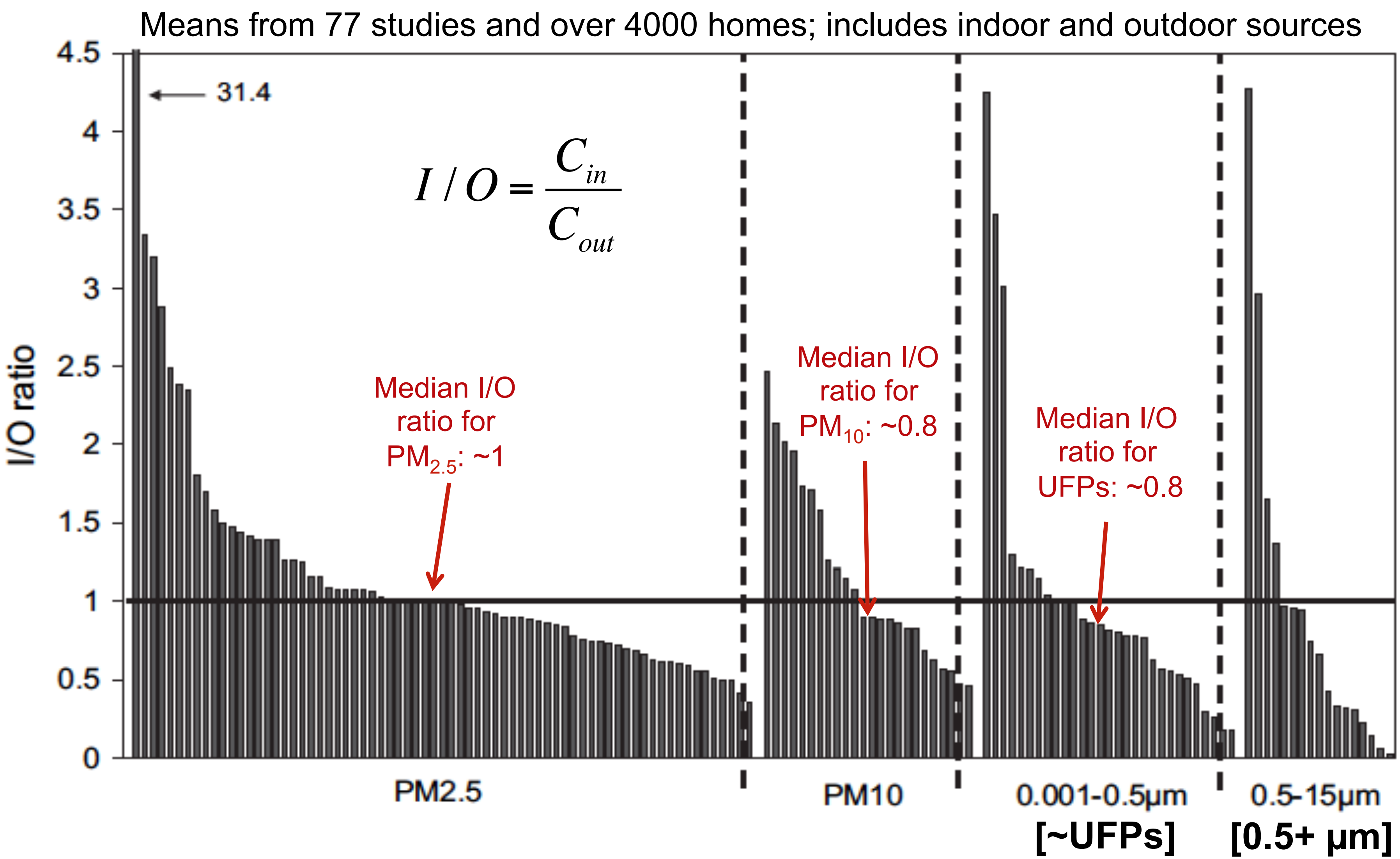


Chen and Zhao, **2011** *Atmos Environ*

Infiltration factor:

$$F_{\inf} = \left.\frac{C_{in}}{C_{out}}\right|_{no\,indoor\,sources}$$

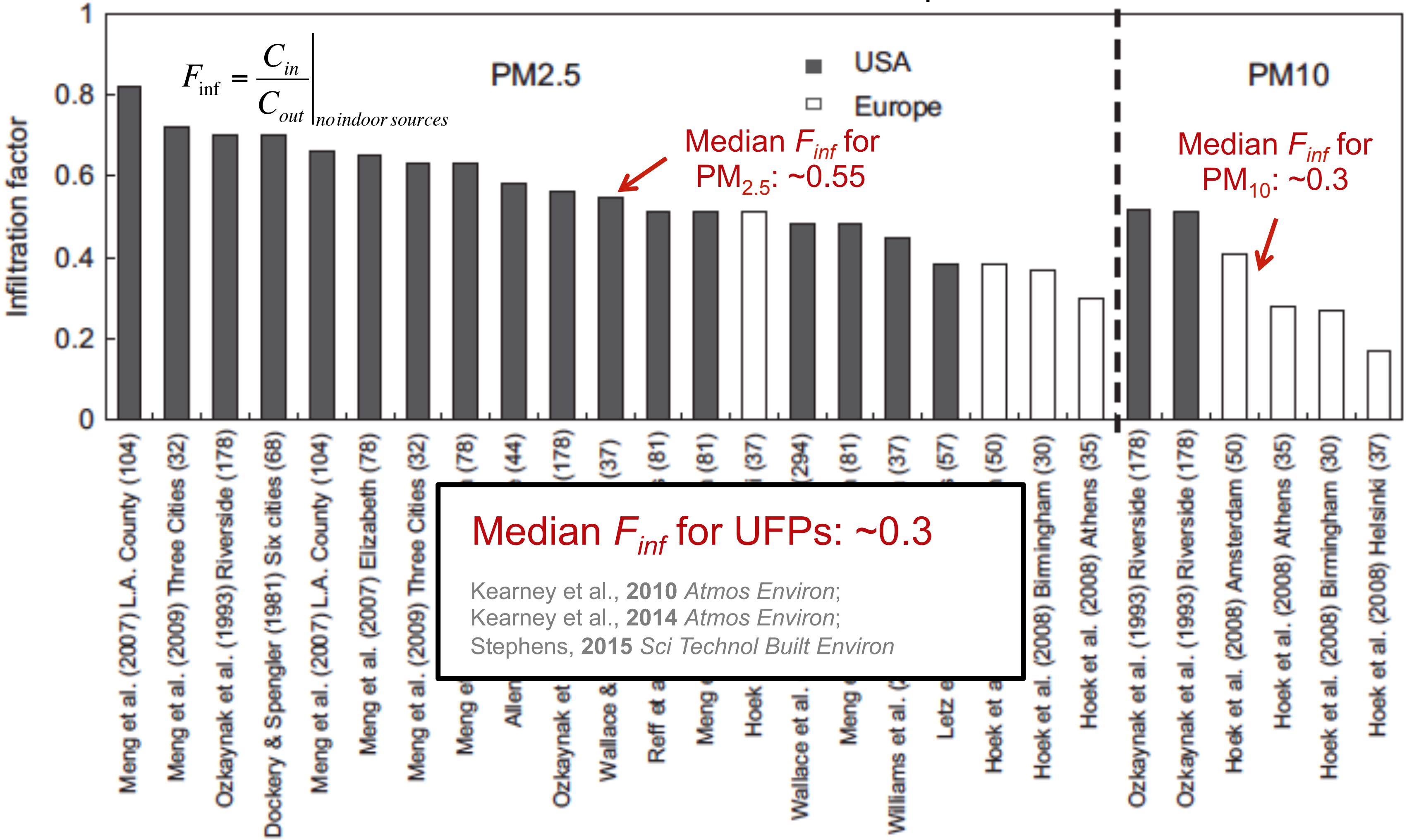
I/O PM ratios: Indoor + outdoor sources



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

PM Infiltration factors: Indoor PM of outdoor origin

Means from 21 samples of over 20 homes (includes only outdoor PM infiltration)
Total # of homes: ~1000 in the U.S. & ~150 in Europe



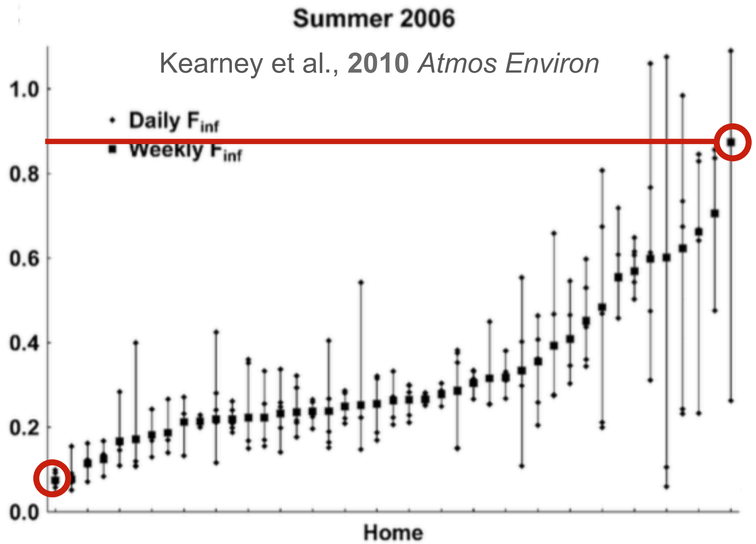
Median F_{inf} for UFPs: ~0.3

Kearney et al., **2010** *Atmos Environ*;
Kearney et al., **2014** *Atmos Environ*;
Stephens, **2015** *Sci Technol Built Environ*

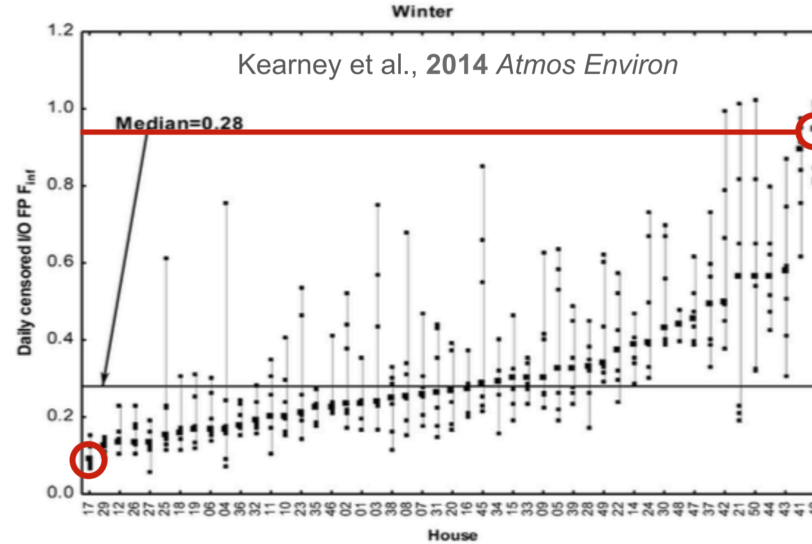
Chen and Zhao, **2011** *Atmos Environ*

Variability in residential $PM_{2.5}$ and UFP infiltration factors

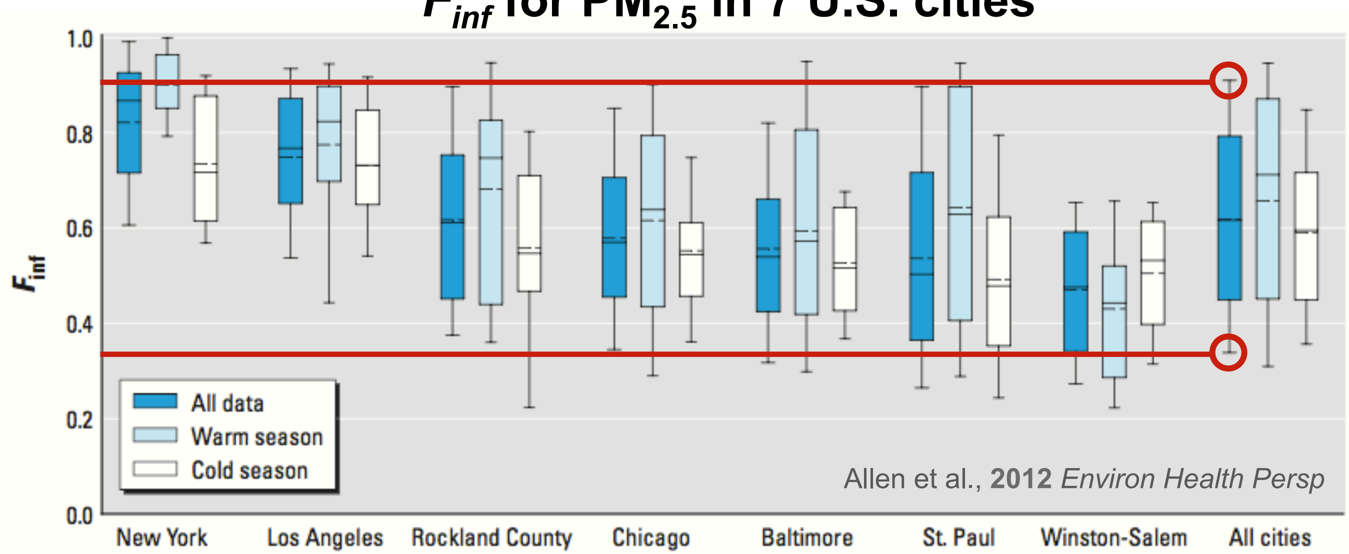
F_{inf} for UFPs in Windsor, ON



F_{inf} for $PM_{2.5}$ in Edmonton, AB



F_{inf} for $PM_{2.5}$ in 7 U.S. cities



Between-home variations for PM:

$0.1 < F_{inf} < 1$

Variability in ozone (O_3) infiltration factors

- I/O O_3 ratios also commonly range from <0.1 to ~1

Building	Location	I/O	Notes
Hospital	So. California	0.67	Thompson, 1971
Office/lab	So. California	0.80	Sabersky et al., 1973
Office/lab	So. California	0.65	Ibid.
Home	So. California	0.70	Ibid., natural ventilation
Hospital	So. California	0.5	Thompson et al., 1973
Indoor pool	So. California	0.5	Ibid.
2 Schools	So. California	0.3–0.7	Ibid.
Office/lab	So. California	0.5	Ibid.
Home	So. California	0.6	Ibid., evaporative cooing
2 Offices	So. California	0.66	Shair and Heitner, 1974; maximum ventilation
2 Offices	So. California	0.54	Ibid., minimum ventilation
Office/lab	So. California	0.62	Hales et al., 1974
5 Townhouses	Washington	0.5–0.7	Moschandreas et al., 1978
6 Apartments	Baltimore	0.5–0.7	Ibid.
2 Mobile homes	Denver	0.5–0.7	Ibid.
1 School	Chicago	0.5–0.7	Ibid.
1 Hospital	Pittsburgh	0.5–0.7	Ibid.
Homes	Medford, OR	0.1–0.3	Berk et al., 1981; weatherized homes
10 Homes	Boston, MA	0.2	Moschandreas et al., 1981
2 Offices	Boston, MA	0.3	Ibid.
Art gallery	So. California	0.5	Shaver et al., 1983
2 Museums	So. California	0.1	Ibid; activated carbon air filtration
Art gallery	England	0.7	Davies et al., 1984
41 Homes	Tucson, AZ	0.3	Lebowitz et al., 1984
12 Homes	Houston, TX	<0.1	Stock et al., 1985; conventional air conditioning

Weschler **2000** *Indoor Air*

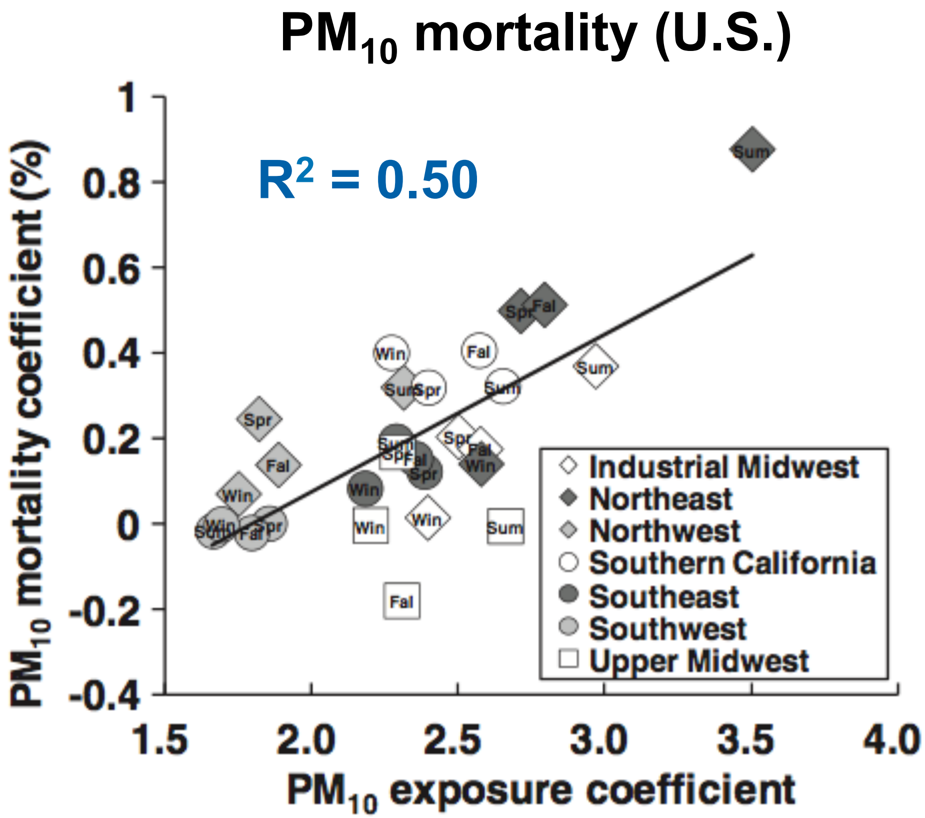
Key drivers of variability in infiltration factors

- Source of ventilation air
  - Infiltration (envelope leaks)
  - Mechanical ventilation
  - Natural ventilation
- Human behaviors
  - Window opening frequencies
  - Portable air cleaners
- Magnitude of the air exchange rate (AER)
  - Meteorological driving forces (e.g., I/O temperatures, wind speed/direction)
  - Building envelope characteristics (e.g., airtightness and possibly material)
- Pollutant characteristics
  - Sizes/classes/components of PM
  - Reactivity of O_3
- HVAC system design and operation
  - HVAC filtration and system runtime

Williams et al., **2003** *Atmos Environ*; Allen et al., **2012** *Environ Health Persp*; MacNeill et al, **2012** *Atmos Environ*; MacNeill et al., **2014** *Indoor Air*; El Orch et al., **2014** *Build Environ*; Chen et al., **2012** *Epidemiology*

How does variability in F_{inf} contribute to effect estimates?

Accounting for variations in AERs and window opening:



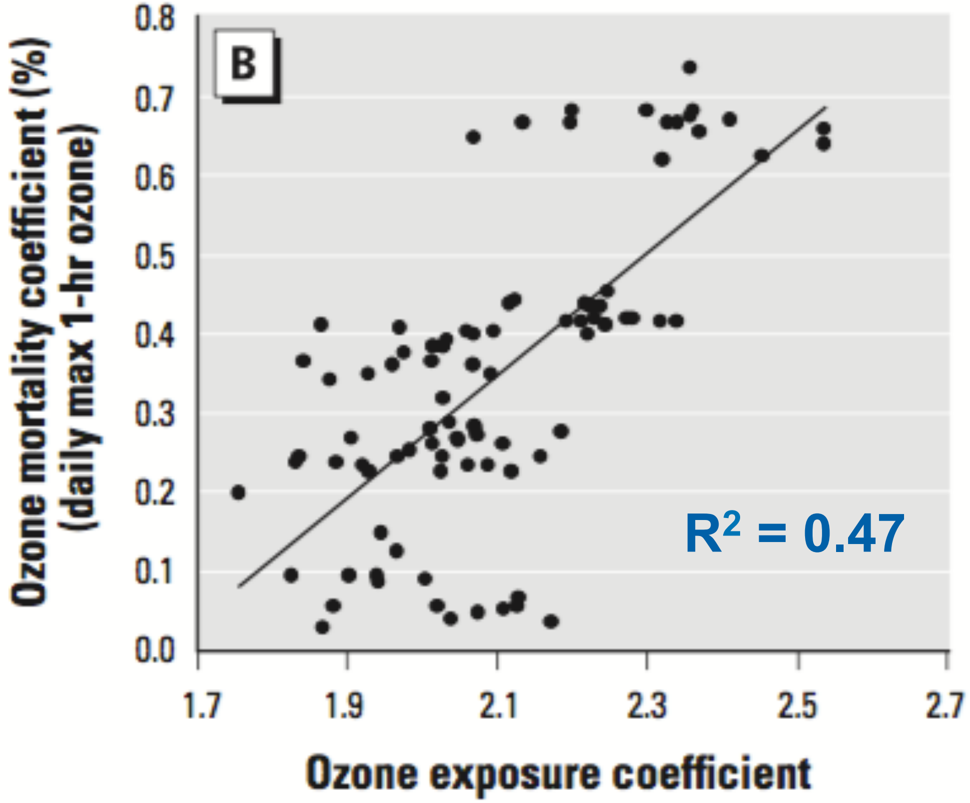
Chen et al., **2012** *Epidemiology*

$$\beta_{\exp} = \left\{\frac{\Delta C_{in}}{\Delta C_{out}}\right\}_{total} = f_{windows\_closed}\left\{\frac{\Delta C_{in}}{\Delta C_{out}}\right\}_{windows\_closed} + f_{windows\_open}\left\{\frac{\Delta C_{in}}{\Delta C_{out}}\right\}_{windows\_open} + f_{AC\_on}\left\{\frac{\Delta C_{in}}{\Delta C_{out}}\right\}_{AC\_on}$$

How does variability in F_{inf} contribute to effect estimates?

Accounting for variations in AERs and window opening:

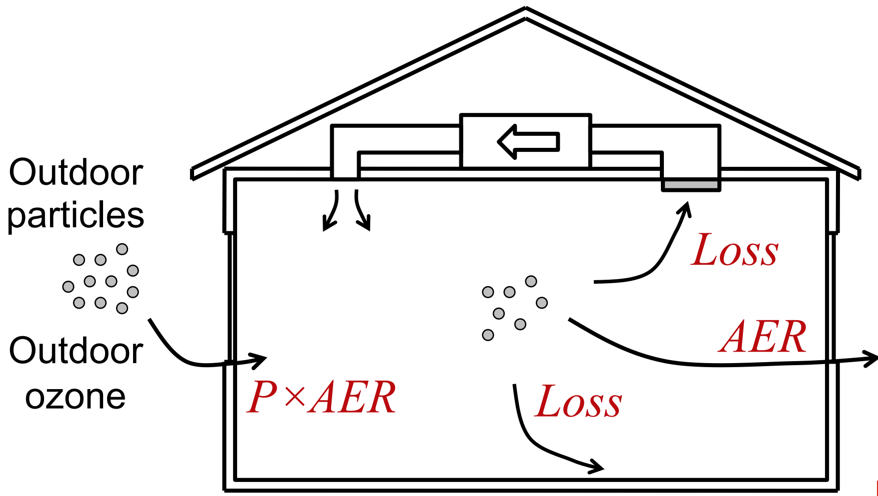
O_3 mortality (U.S.)



Chen et al., **2012** *Environ Health Perspect*

$$\beta_{\exp} = \left\{\frac{\Delta C_{in}}{\Delta C_{out}}\right\}_{total} = f_{windows\_closed}\left\{\frac{\Delta C_{in}}{\Delta C_{out}}\right\}_{windows\_closed} + f_{windows\_open}\left\{\frac{\Delta C_{in}}{\Delta C_{out}}\right\}_{windows\_open} + f_{AC\_on}\left\{\frac{\Delta C_{in}}{\Delta C_{out}}\right\}_{AC\_on}$$

Underlying mechanisms that govern F_{inf}



Penetration from outdoors

$$F_{inf} = \frac{P \times AER}{AER + Loss}$$

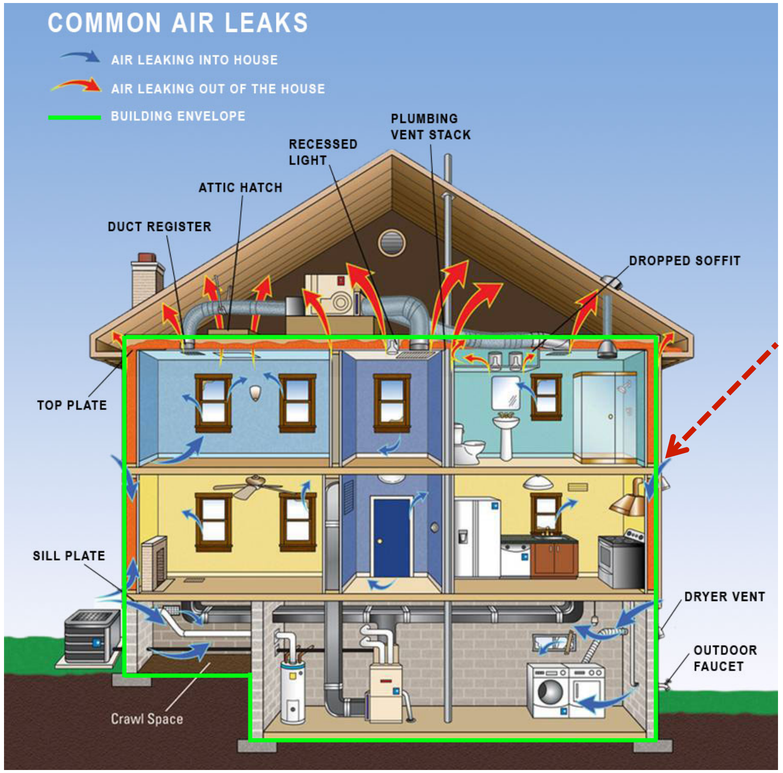
Removal by air exchange

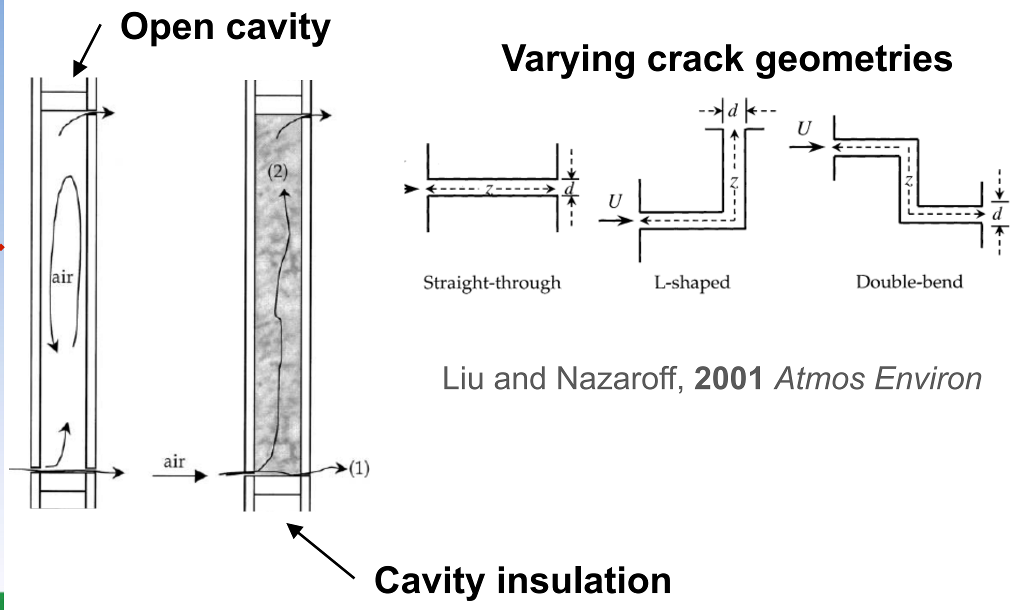
Removal by deposition to surfaces, phase changes, or control by filters or air cleaners

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

Envelope penetration factors

- O_3 and PM can penetrate through leaks in building envelopes
  - Ozone can react with envelope materials
  - Particles can deposit in envelope cracks
- Measurements are challenging
  - Need test methods to solve for 2 unknowns with 1 equation



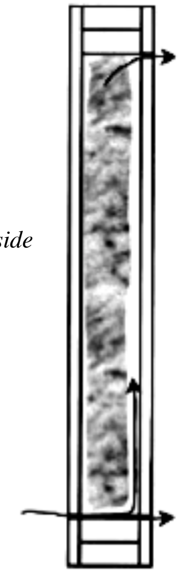


Liu and Nazaroff, **2001** *Atmos Environ*

Envelope penetration factors for PM

$$P_{envelope} = \frac{C_{inside}}{C_{outside}}$$

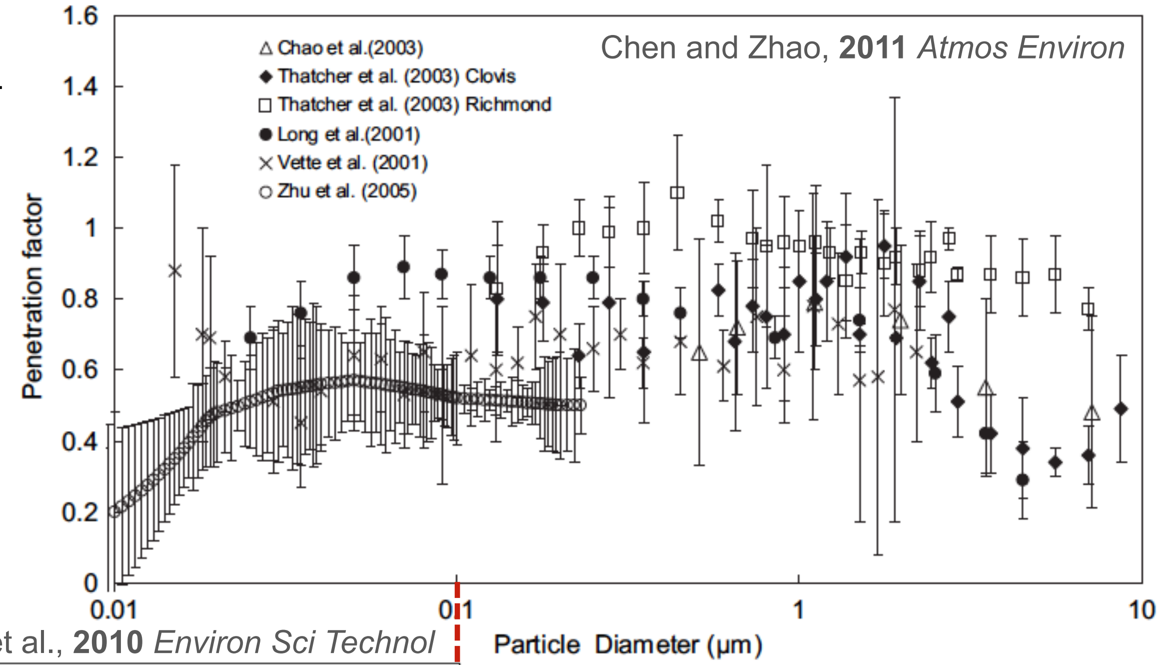
$C_{outside}$



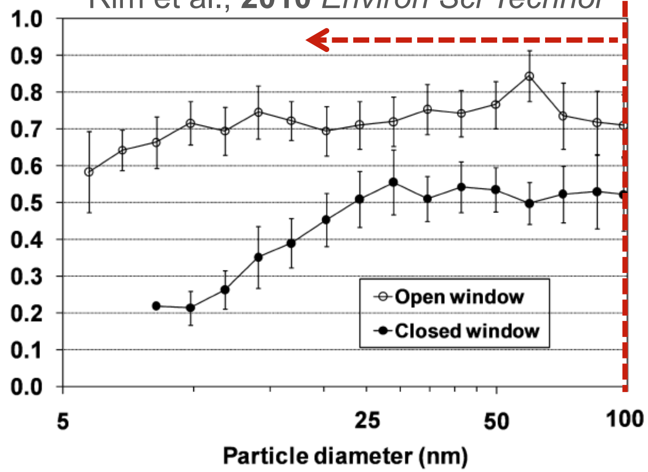
C_{inside}

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

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



Rim et al., **2010** *Environ Sci Technol*



# of homes with penetration factors measured:

Size-resolved PM: <20 homes

UFPs: ~30-50 homes

$PM_{2.5}$: *estimated* in 100s of homes

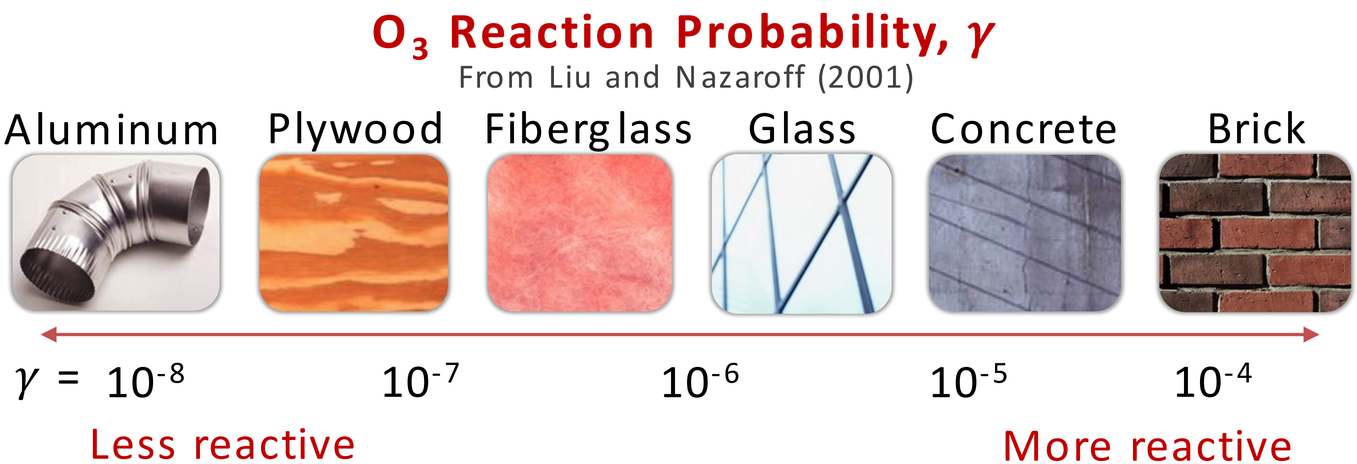
- But seldom (never?) *measured*

Envelope penetration factors for ozone (O_3)

- Typically assumed that O_3 penetration factor = 1

Weschler, **2000** *Indoor Air*; Weschler, **2006** *Environ Health Persp*

- But O_3 reacts with common envelope materials:

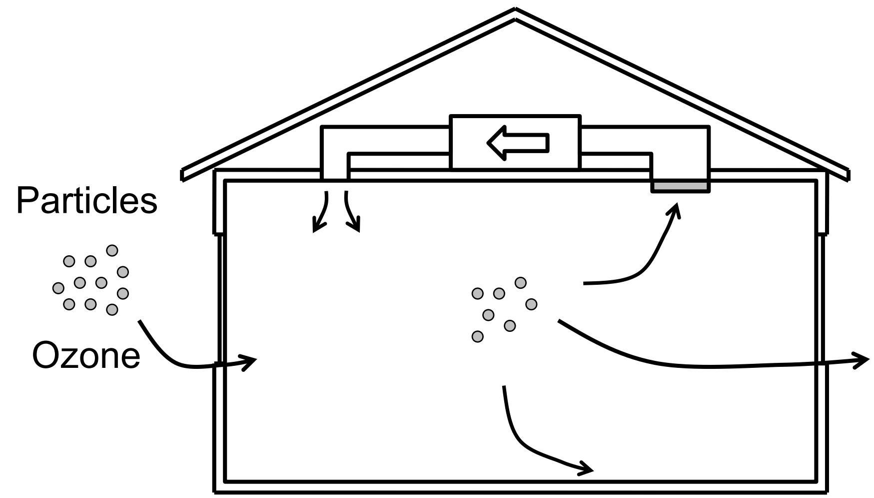


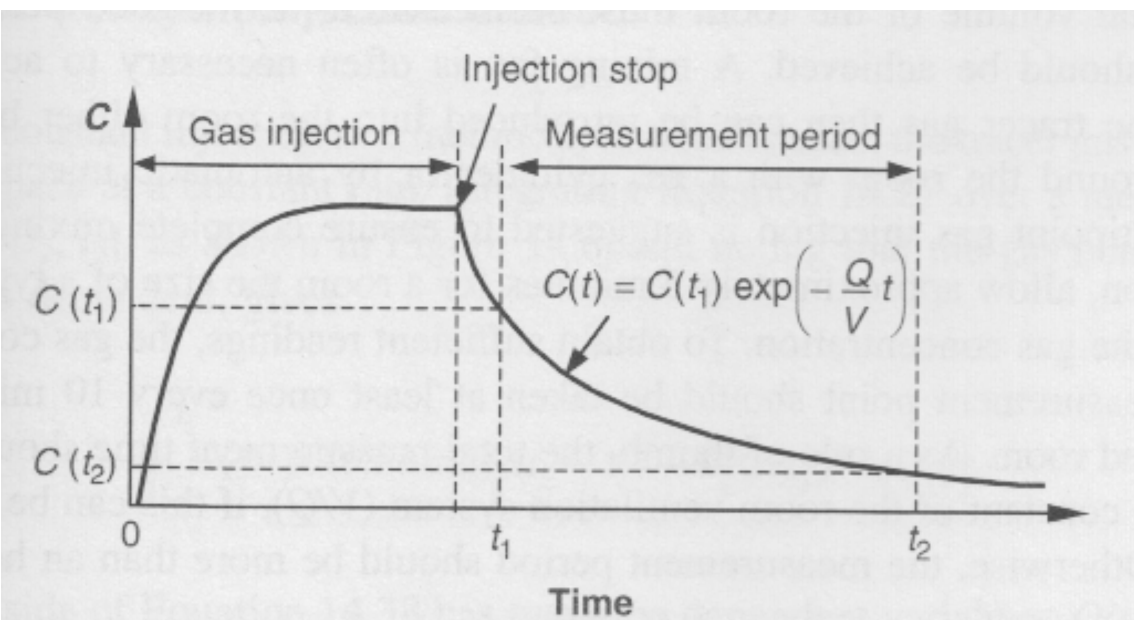
- No known measurements of O_3 penetration factors until 2012

Pollutant penetration into buildings: Challenges

There are some challenges with estimating *AER*, *P*, and *Loss*

- How do we measure each?
  - Or estimate from measured data?





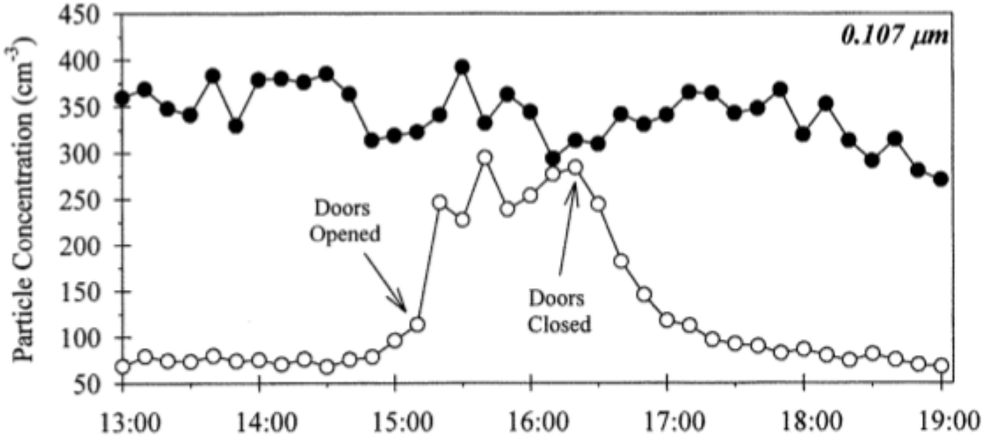
$$\frac{C_{in}}{C_{out}} = \frac{P \times AER}{AER + Loss}$$

✓ AER: Tracer decay
Inject an inert tracer gas, and measure the decay from C(t=0) after time t=0

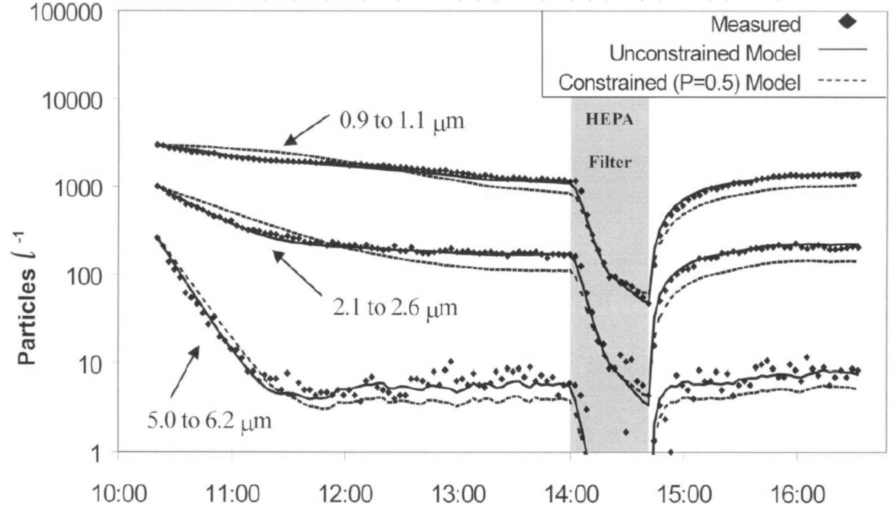
What about *P* and *Loss*?

How would you measure pollutant penetration factors?

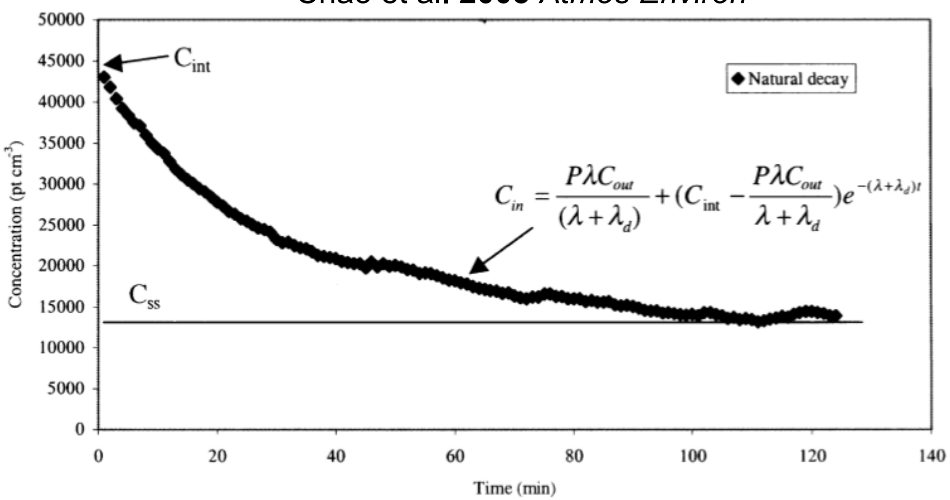
Vette et al. **2001** *Aerosol Sci Technol*



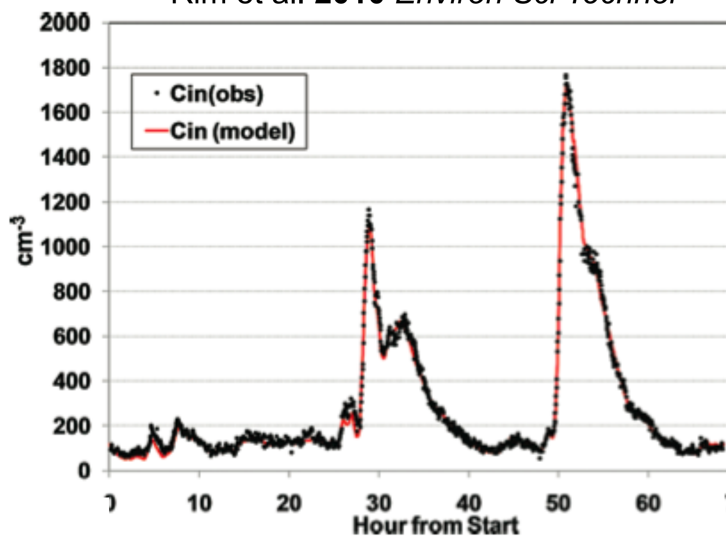
Thatcher et al. **2003** *Aerosol Sci Technol*



Chao et al. **2003** *Atmos Environ*



Rim et al. **2010** *Environ Sci Technol*

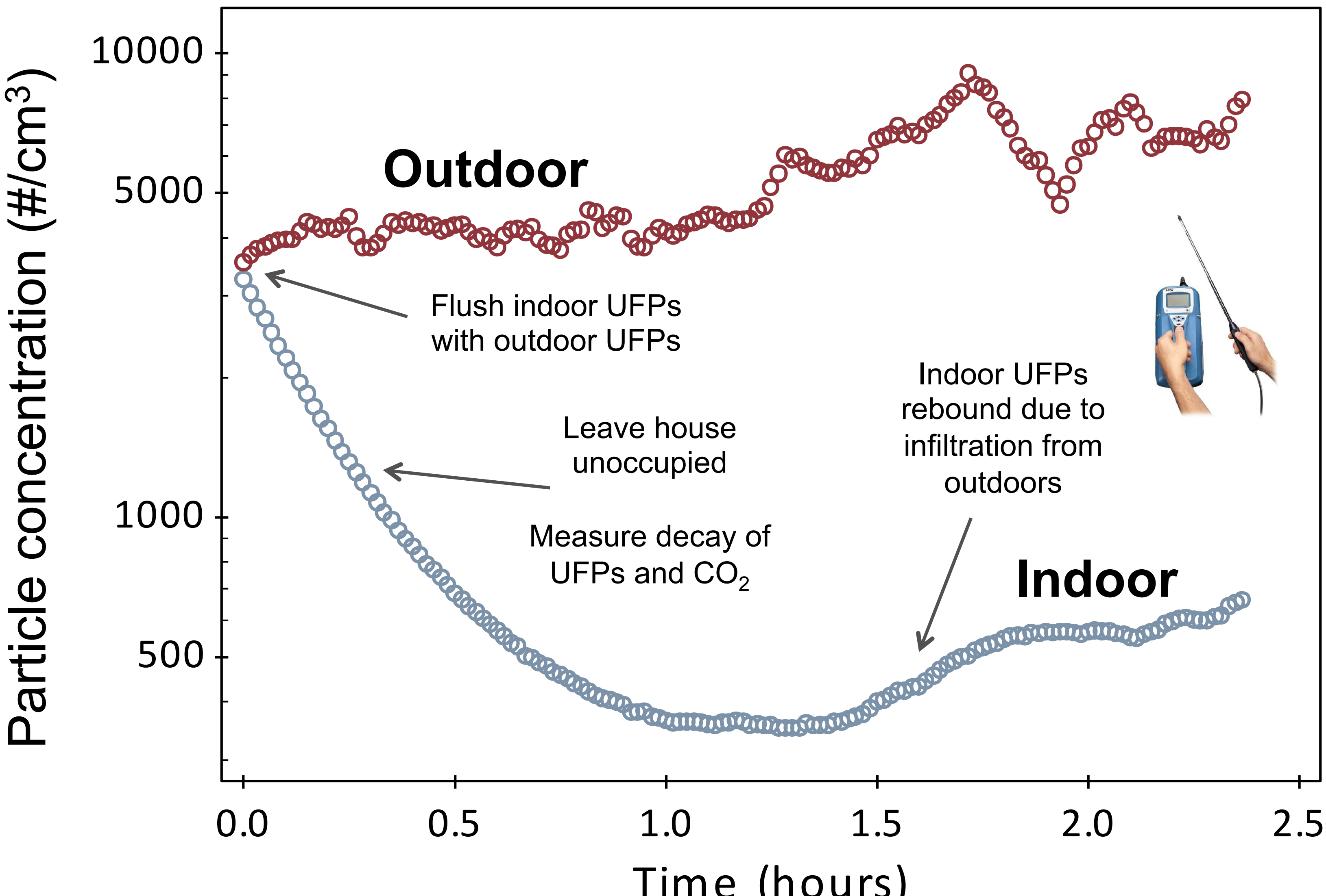


$$\frac{dC_{in}}{dt} = PaC_{out} - (a + k_{comp})C_{in}$$

MEASUREMENTS OF PARTICULATE MATTER AND OZONE PENETRATION FACTORS IN RESIDENCES

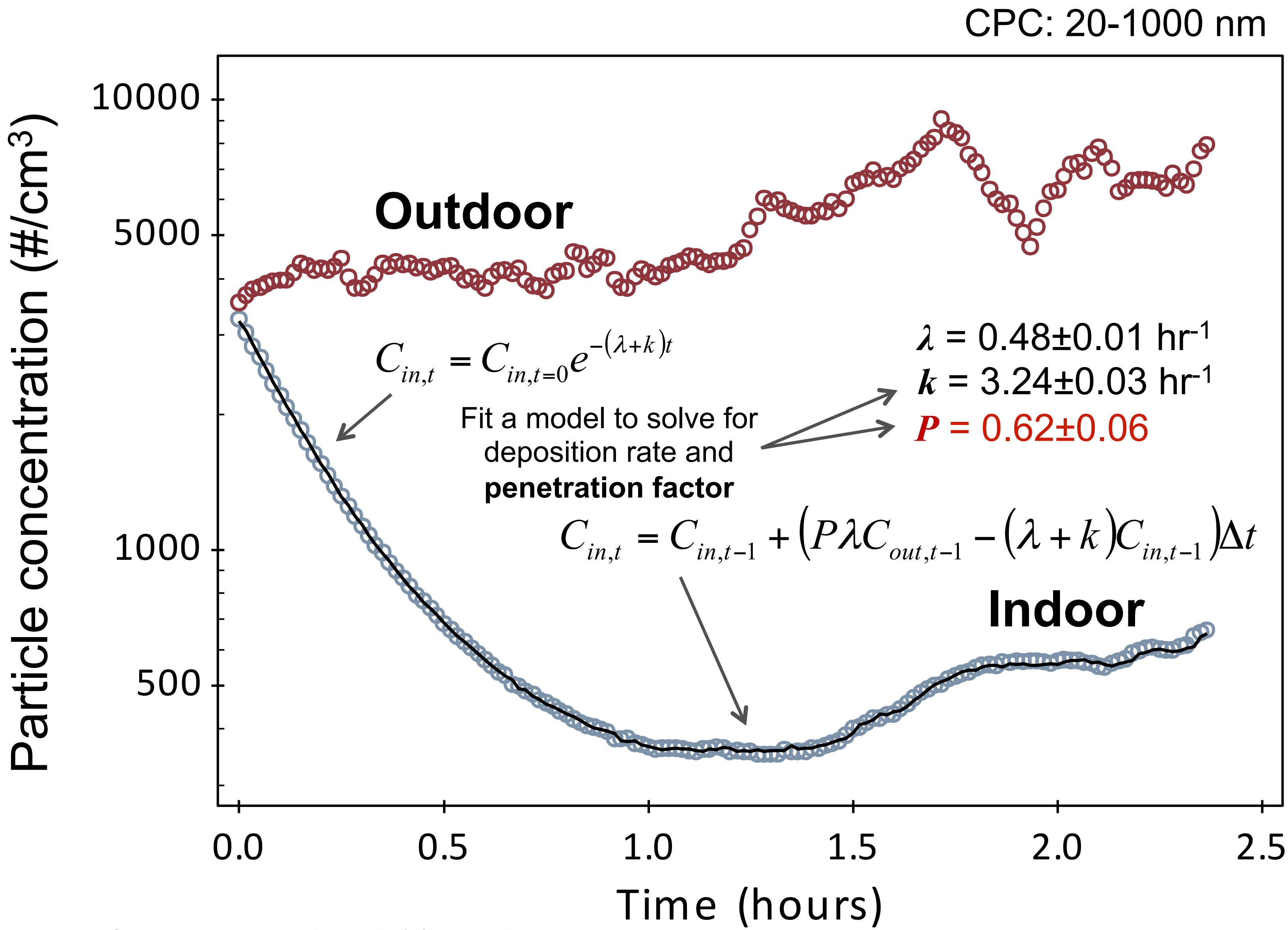
UFP penetration tests in Austin, TX (c. 2010)

CPC: 20-1000 nm



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

UFP penetration tests in Austin, TX (c. 2010)

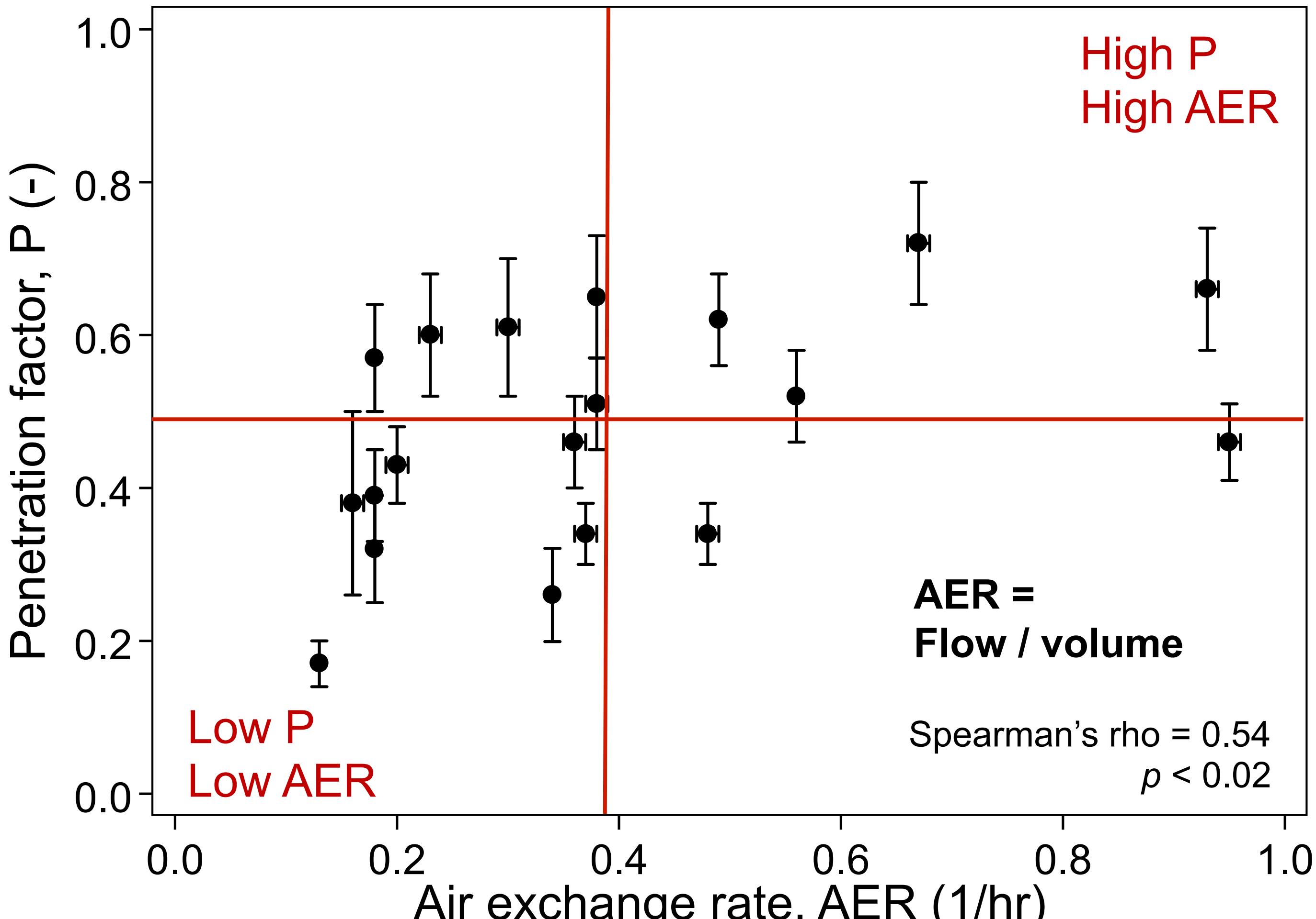


Stephens and Siegel, *Indoor Air* **2012** 22(6):501-512

UFP penetration tests in Austin, TX (c. 2010)

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

UFP penetration results: P vs. AER



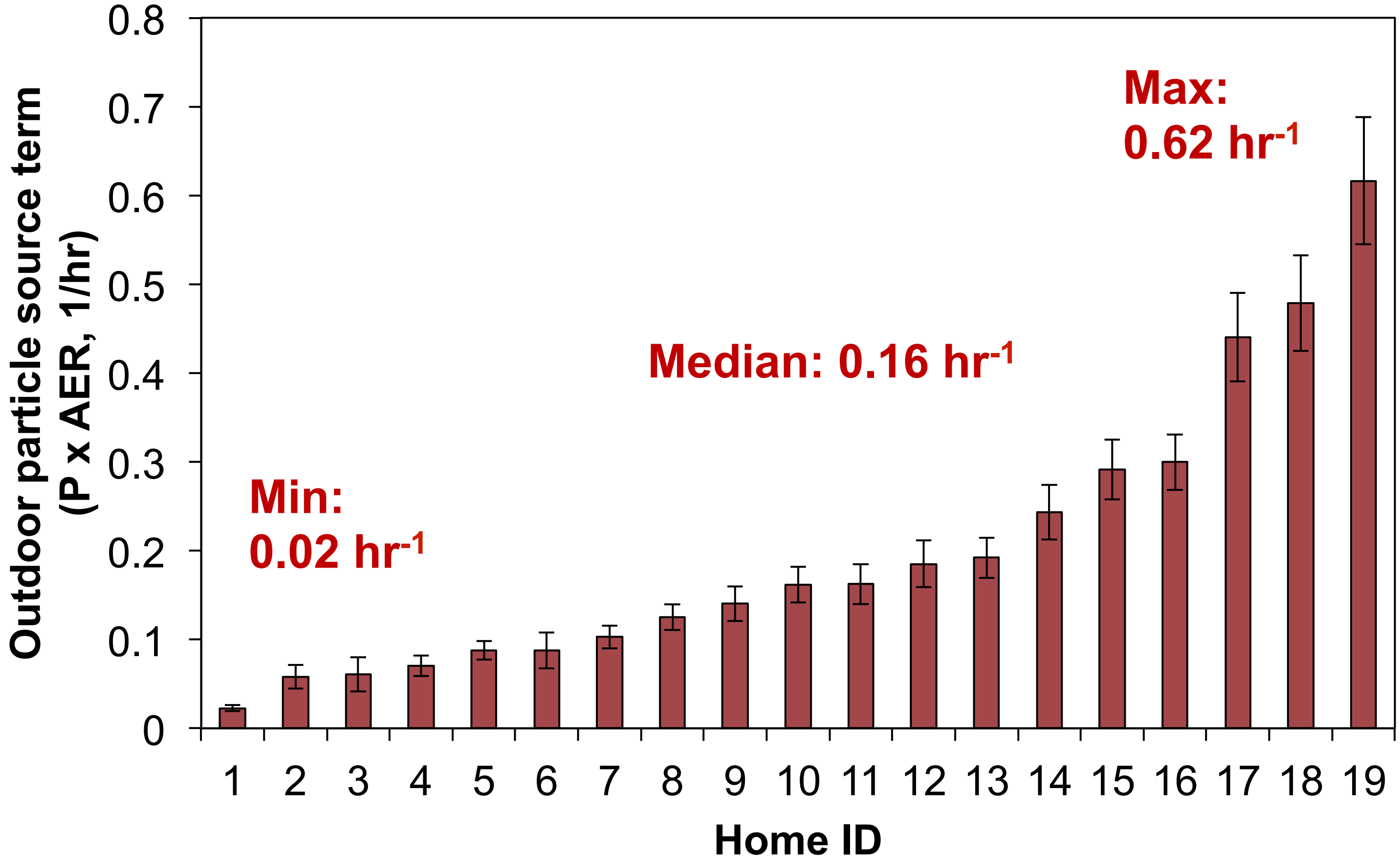
Penetration factors: Mean = 0.47 Range = 0.17 to 0.72

Air exchange rates: Mean = 0.39 hr^{-1} Range = 0.13 to 0.95 hr^{-1}

Stephens, *Science and Technology for the Built Environment* **2014** 21:3-13

Outdoor UFP source terms: Penetration × AER

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

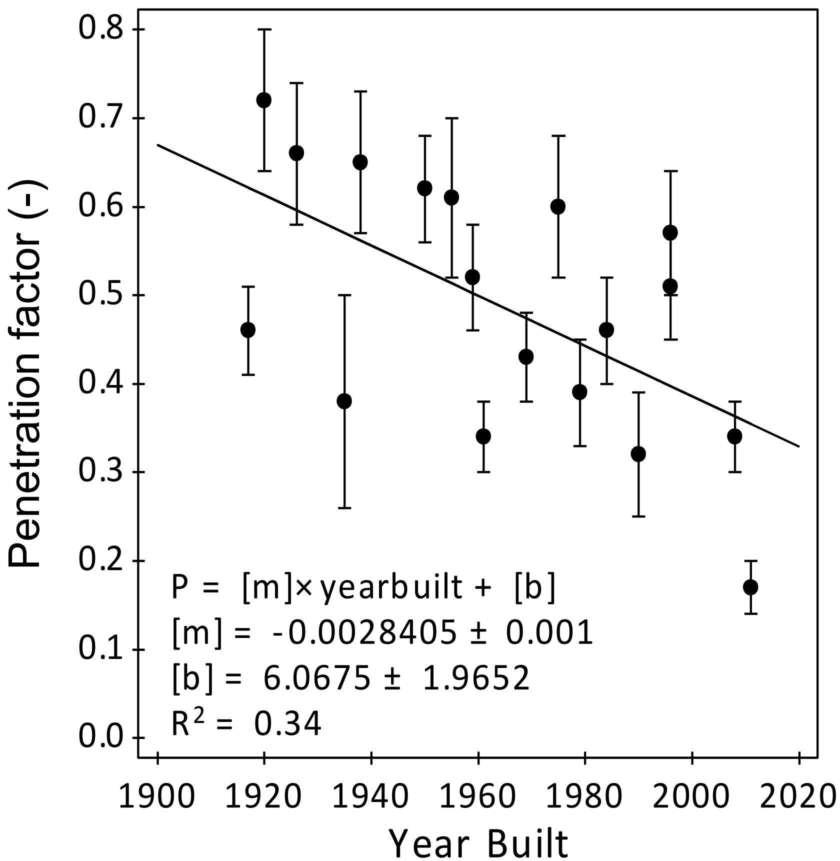


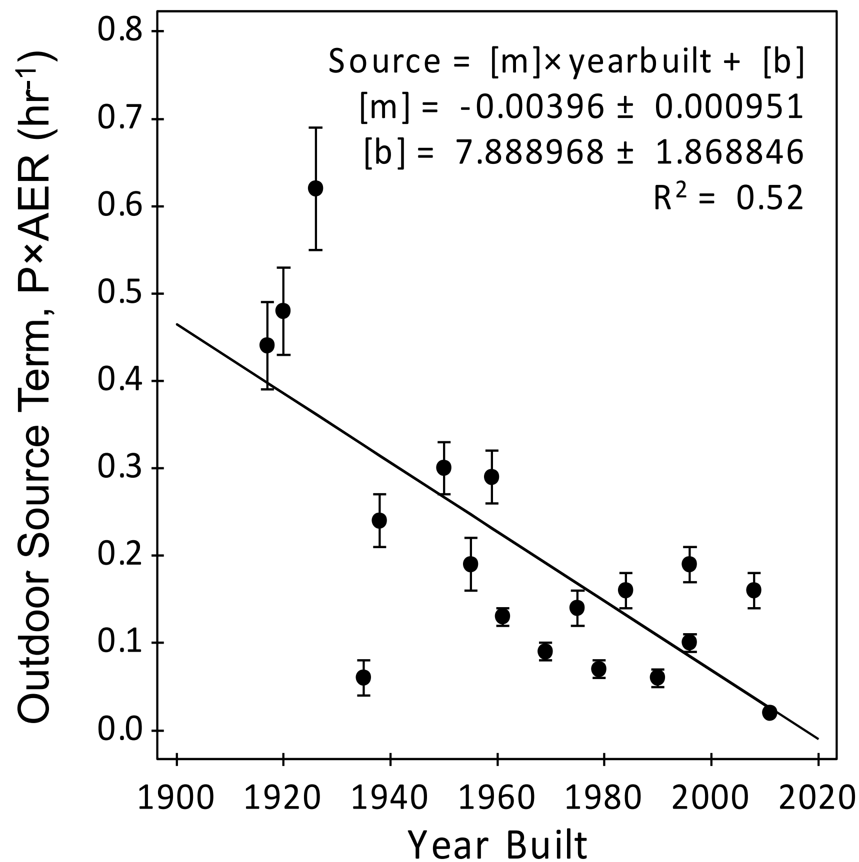
Stephens, *Science and Technology for the Built Environment* **2014** 21:3-13

UFP infiltration and age of homes

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

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



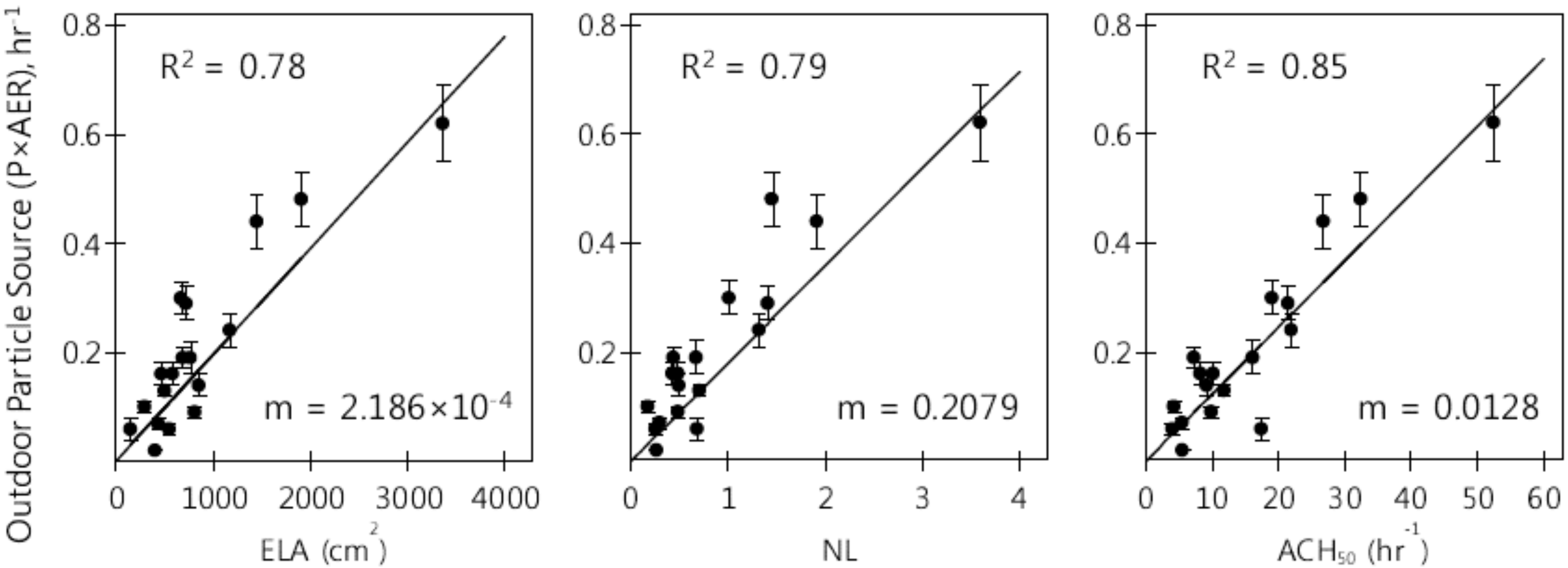


Older homes also had much higher outdoor particle source rates

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

Outdoor UFP source terms and airtightness (blower door)

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



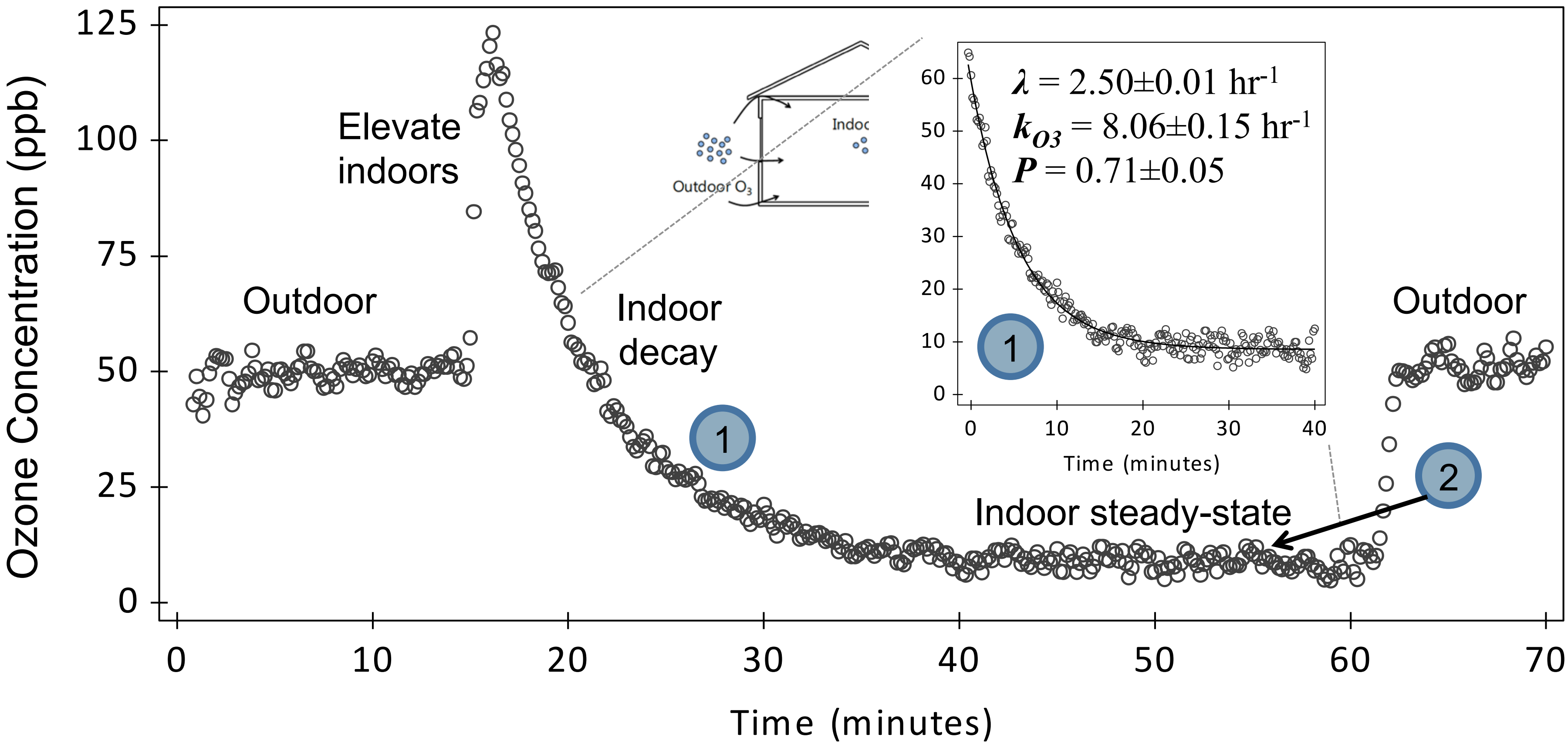
Leakier homes had much higher outdoor particle source rates

- Leaky homes are also older – predictive ability?
- Potential socioeconomic implications: low-income homes are also leakier

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

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

Ozone penetration tests in Austin, TX (c. 2010)



1 $$\frac{dC_{in}}{dt} = P\lambda C_{out} - (\lambda + k_{O3})C_{in}$$

Ozone

2 $$P = \frac{C_{in}}{C_{out}} \frac{\lambda + k_{O3}}{\lambda}$$

Ozone

λ $$\frac{dC_{t,in}}{dt} = P\lambda C_{t,out} - \lambda C_{t,in}$$

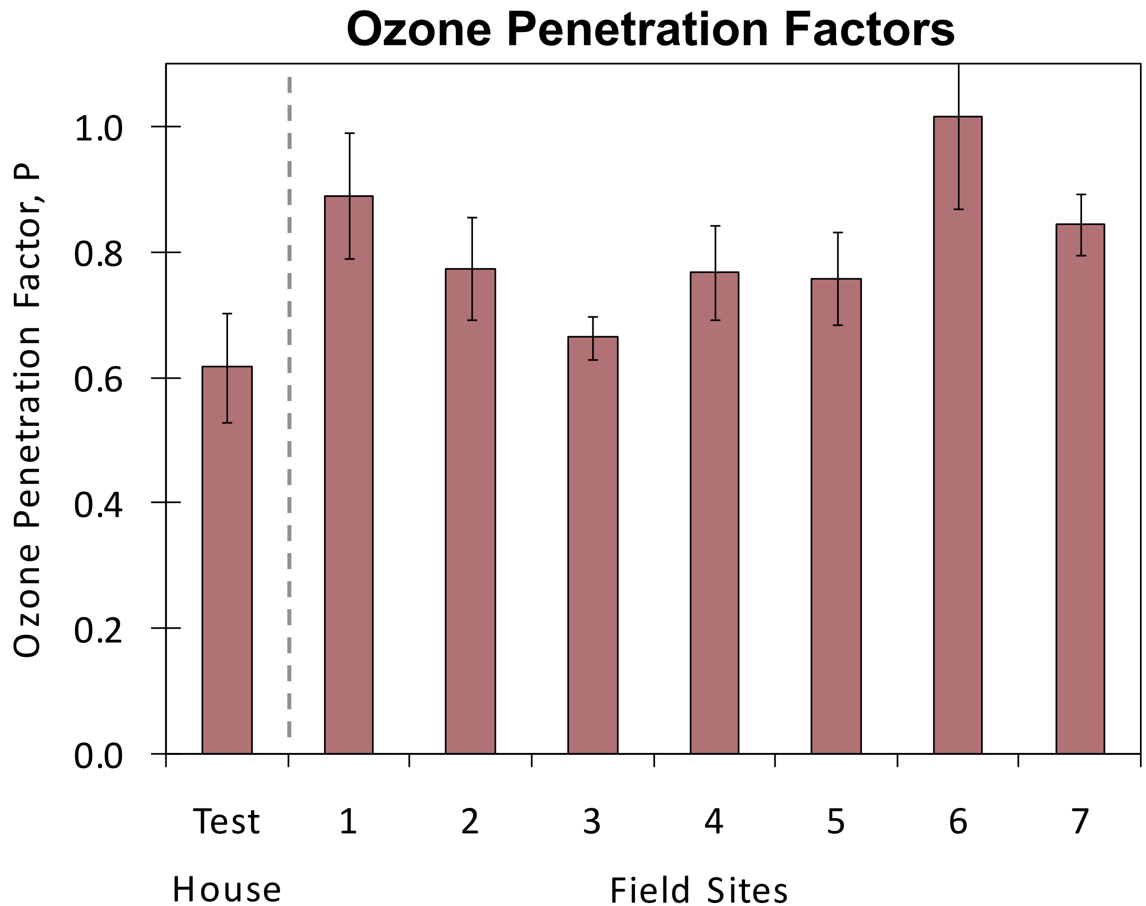
Tracer = CO_2

Stephens et al., *Environ. Sci. Technol.* **2012** 46(2), 929-936

Ozone penetration tests in Austin, TX (c. 2010)

Stephens et al., *Environ. Sci. Technol.* **2012** 46(2), 929-936

Ozone penetration tests in Austin, TX (c. 2010)



- Mean (± SD) = 0.79 ± 0.13 | Range = 0.62 ± 0.09 to 1.02 ± 0.15
- Usually assumed *P* = 1

Weschler, **2006** *EHP*; Gall et al., **2011** *Atmos Environ*; Chen et al., **2011** *Environ Health Persp*

Stephens et al., *Environ. Sci. Technol.* **2012** 46(2), 929-936

CURRENT APPLICATIONS

Recent measurements of envelope penetration factors

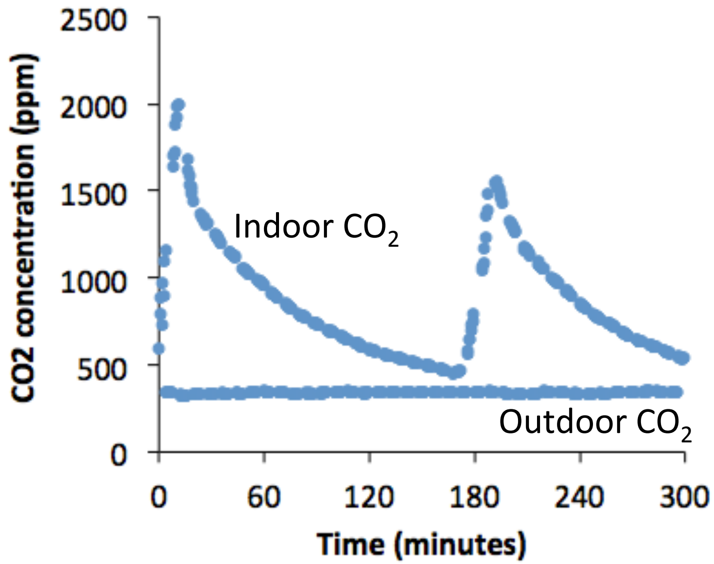
We have been working to develop methods to rapidly and accurately measure envelope penetration factors in order to characterize the ability of building envelopes to prevent the transport of outdoor pollutants indoors

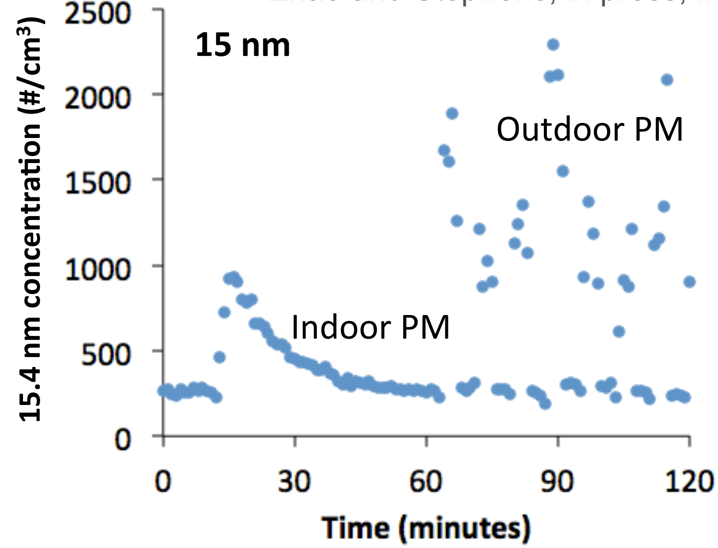
- Size-resolved particles 0.01-10 µm
- Integral measures of $PM_{2.5}$ mass and ultrafine particles (UFPs < 100 nm)
- Reactive gases: O_3 and NO_x

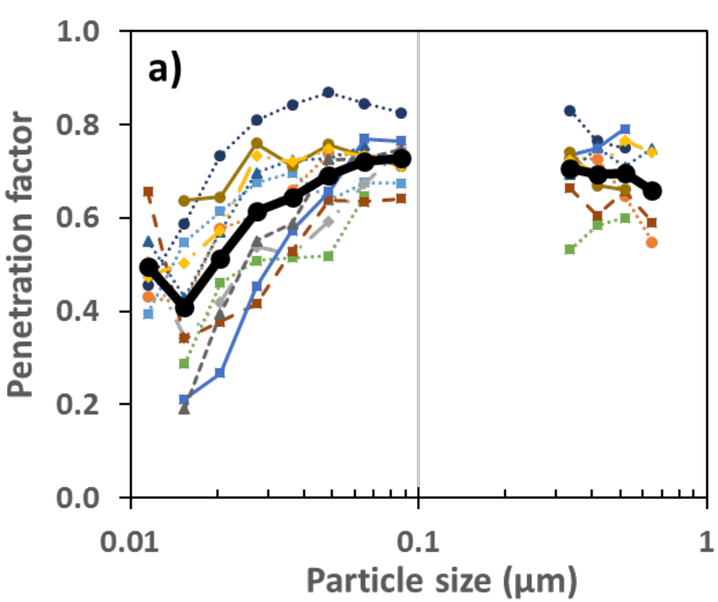
Recent measurements of envelope penetration factors

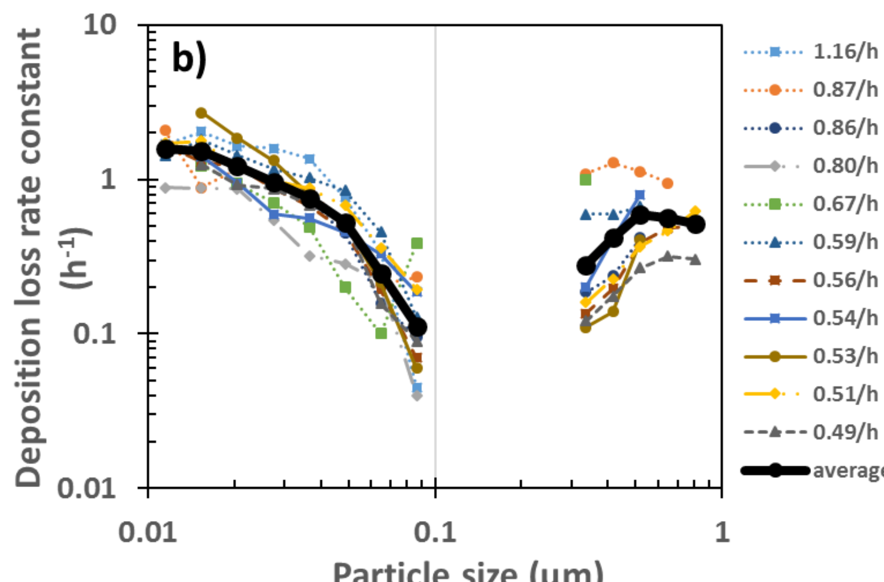
Particle penetration measurements in a test apartment unit

Zhao and Stephens, in press, *Indoor Air*



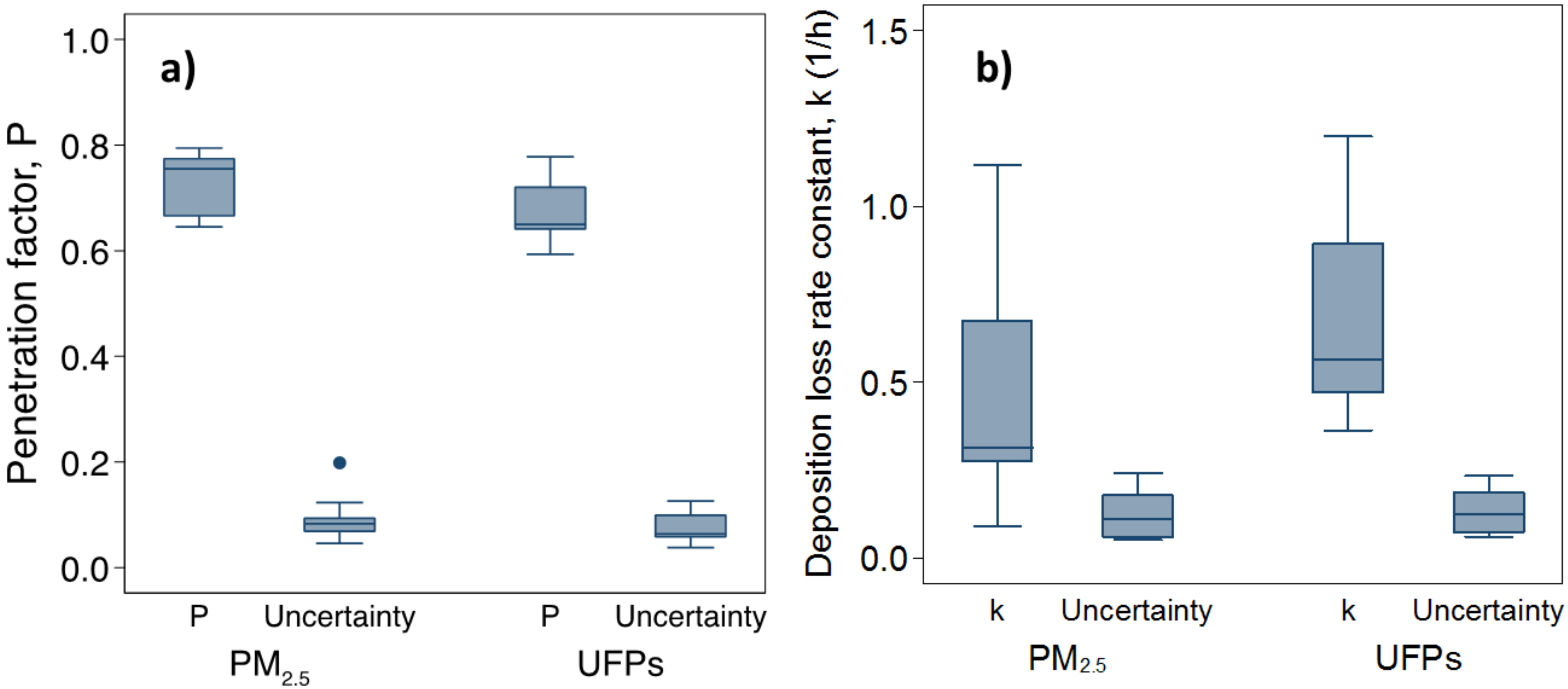






Particle penetration measurements in a test apartment unit

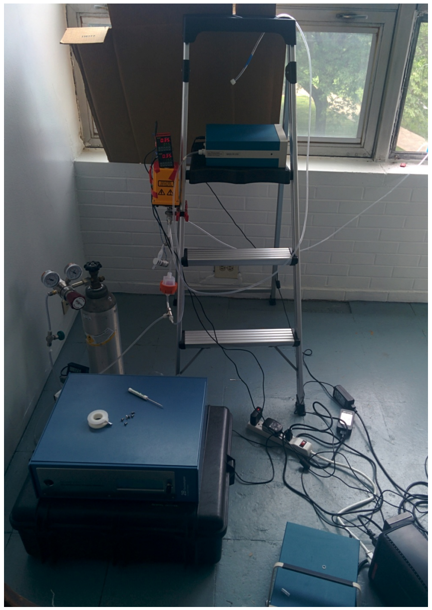
Penetration factors for integral measures of UFPs and $PM_{2.5}$



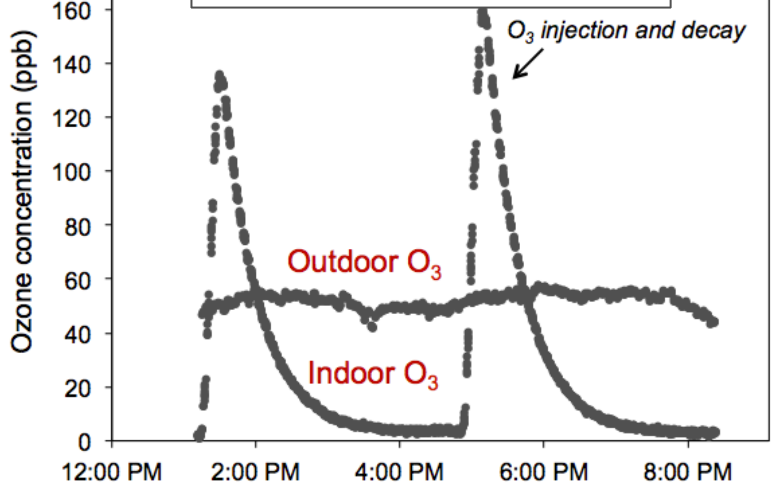
Mean (± SD) penetration factors:
- $PM_{2.5}$: 0.73 ± 0.05
- UFPs: 0.67 ± 0.05

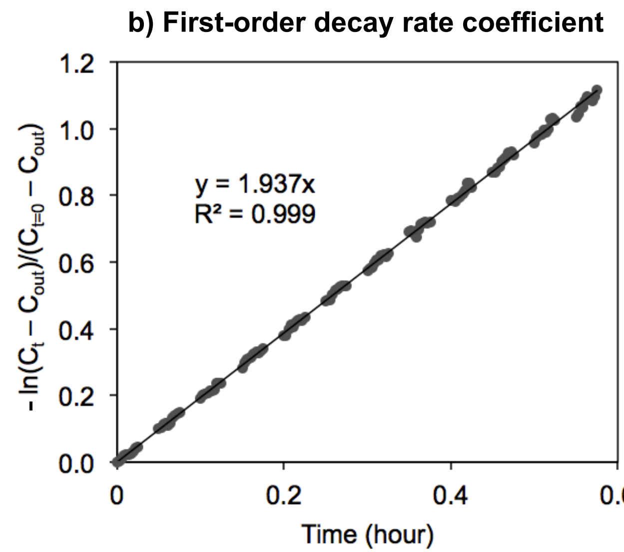
Zhao and Stephens, in press, *Indoor Air*

Ozone penetration measurements in a test apartment unit



$$\frac{dC_{in}}{dt} = P\lambda C_{out} - (\lambda + k)C_{in}$$

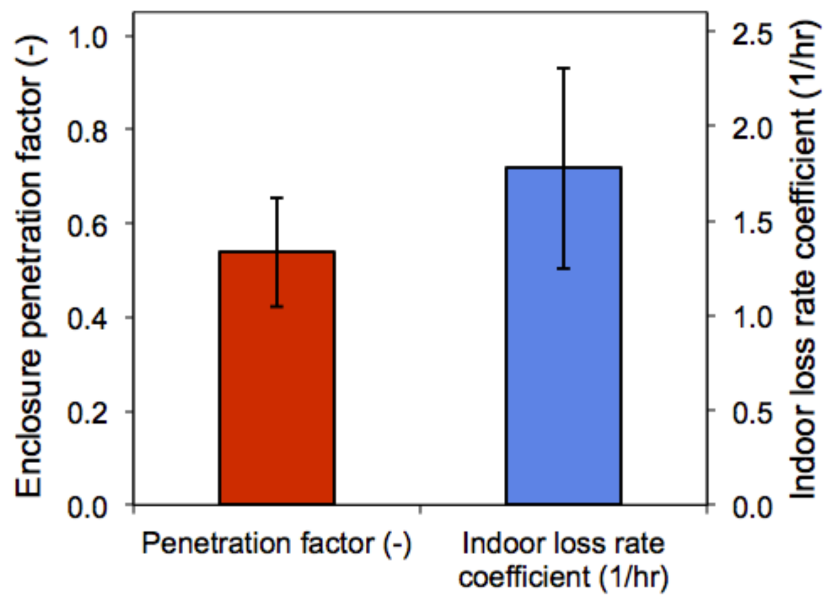




Mean (± SD) penetration factor for O_3: 0.54 ± 0.10

Approximately 45% of outdoor ozone reacted with the envelope during <u>natural</u> <u>infiltration</u> tests

- Only ~55% enters indoors



Zhao and Stephens, *Indoor Air* **2016** 26(4), 571-581

Recent field measurements in Chicago, IL (EPA IA+CC)

- **Goal:** Measure envelope airtightness, pollutant infiltration factors (F_{inf}) and, when possible, pollutant penetration factors (*P*) and deposition loss rate constants (*k*) in homes before and after energy retrofits are applied
  - Focus on outdoor pollutants: UFPs, $PM_{2.5}$, BC, O_3, and NO_x
  - Help fill important data gaps in the literature:
    - Initial penetration factors
    - How infiltration/penetration factors change after energy retrofits

Home recruitment status:

Target:	Completed to date:
30 homes pre/post retrofit	6 SF homes + 3 MF units - 1 failed MF test = 8 units pre/post retrofit complete + 5 non-retrofit MF homes = 13 tests complete

ELEVATE ENERGY
Smarter energy use for all

Recent **field measurements** in Chicago, IL (EPA IA+CC)

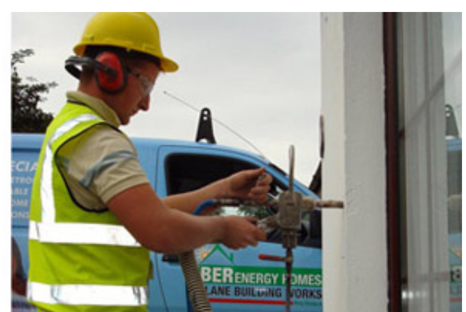
- Pre/post retrofit measurements in 6 SF + 2 MF units
  - Homes planning to undergo energy efficiency improvements

Homes built between 1894 and 1956 (avg = 1926)

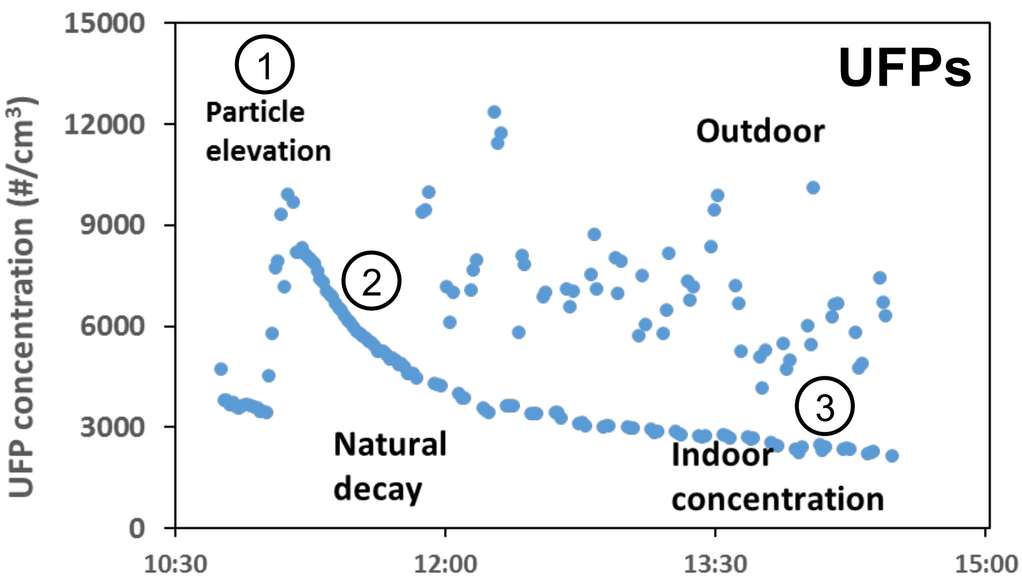
Typical retrofit measures

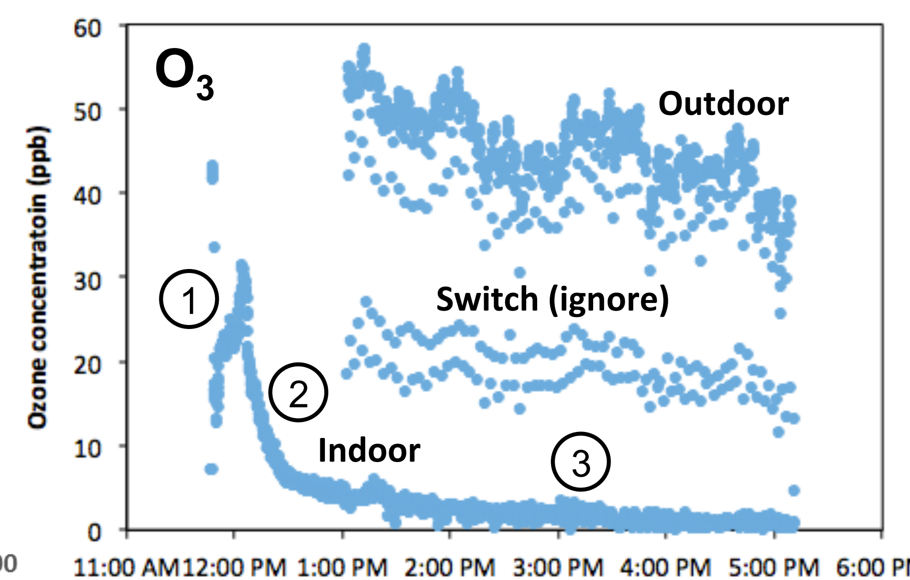
- All homes:
  - Attic air sealing and blown-in insulation for all homes
    - Typically to R-49
    - Typically with attic hatch insulation
  - Weather stripping on doors

- Some homes:
  - Attic knee wall air sealing and insulation
  - Can light boxes
  - Crawlspace insulation and air sealing
  - Blown-in wall insulation in balloon framing wall cavities (2 homes)



Example data: Pollutant infiltration





Three distinct test periods to solve for *P* and *k*:

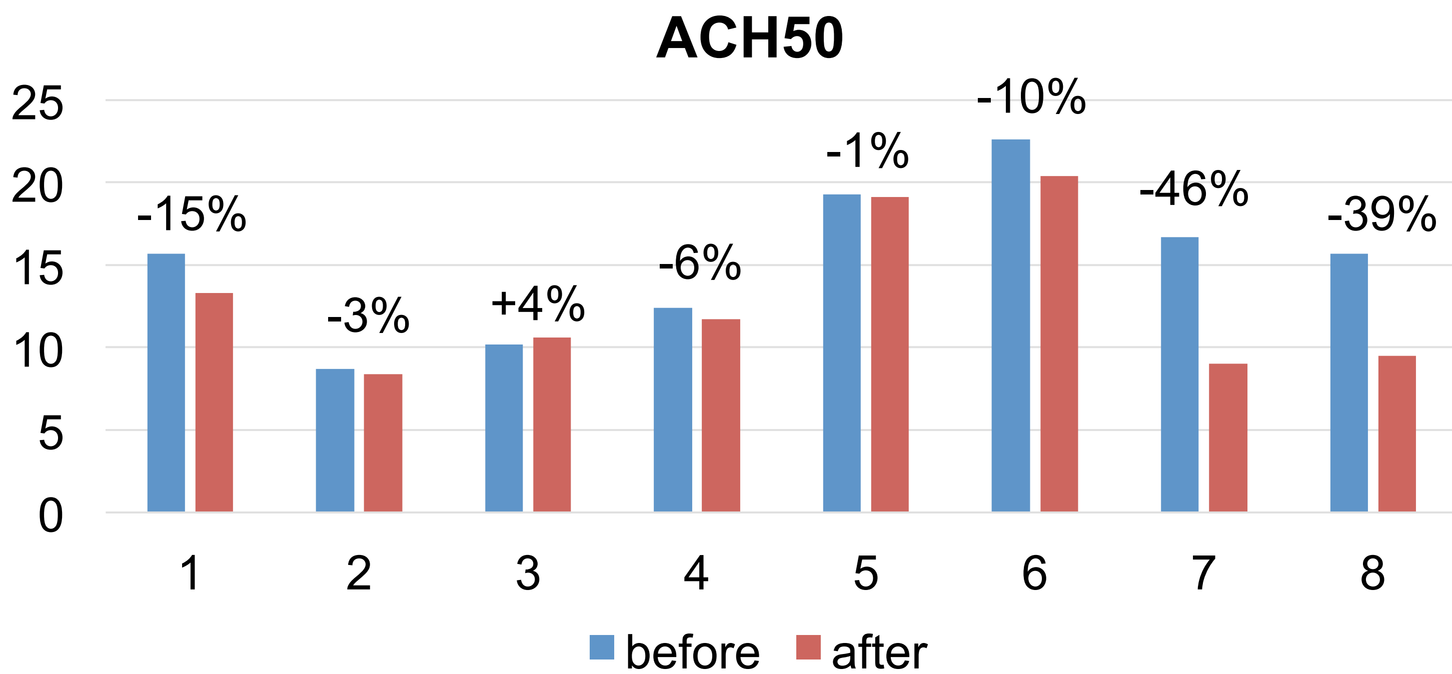
1. Elevation w/ open windows + blower door
   - Indoor only for ~15 minutes
2. Decay to background
   - Indoor only for ~45 minutes
3. Response/rebound period → infiltration factor
   - Alternating indoor/outdoor for ~3 hours

Houses are unoccupied during testing

Preliminary results: Blower door ACH_{50}

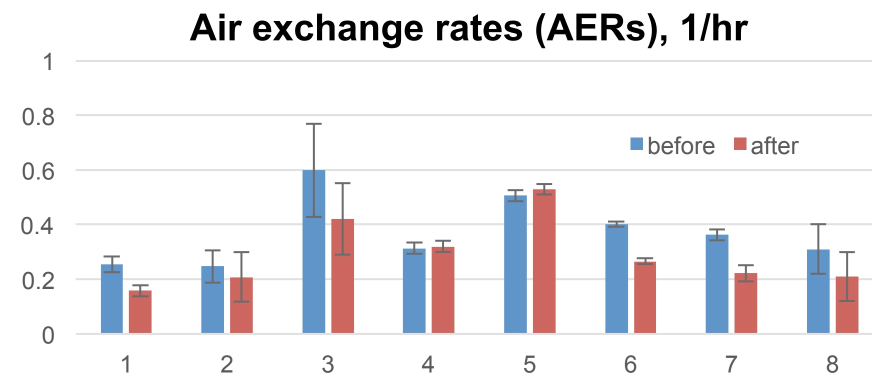
The retrofits reduced ACH_{50} by between -4% and 46%

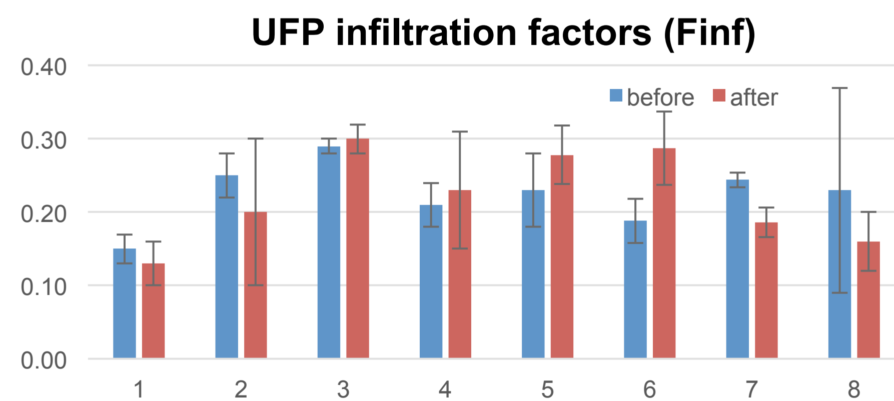
- Average change: -15%

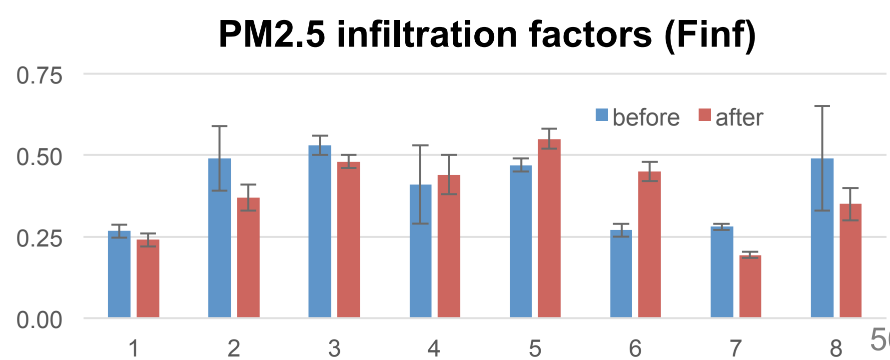


Preliminary results: AERs and infiltration factors

- Air exchange rates were between 39% lower and 5% higher during measurements before and after retrofits
  - Influenced by airtightness, temperature differences, and wind speed/direction
- Average UFP infiltration factors were 0.22±0.04 before retrofits and 0.22±0.06 after retrofits
  - No difference (some up, some down)
- Average $PM_{2.5}$ infiltration factors were 0.40±0.11 before retrofits and 0.39±0.12 after retrofits
  - No difference (some up, some down)
- F_{inf} influenced by multiple factors
  - Retrofits + climate conditions + PSDs

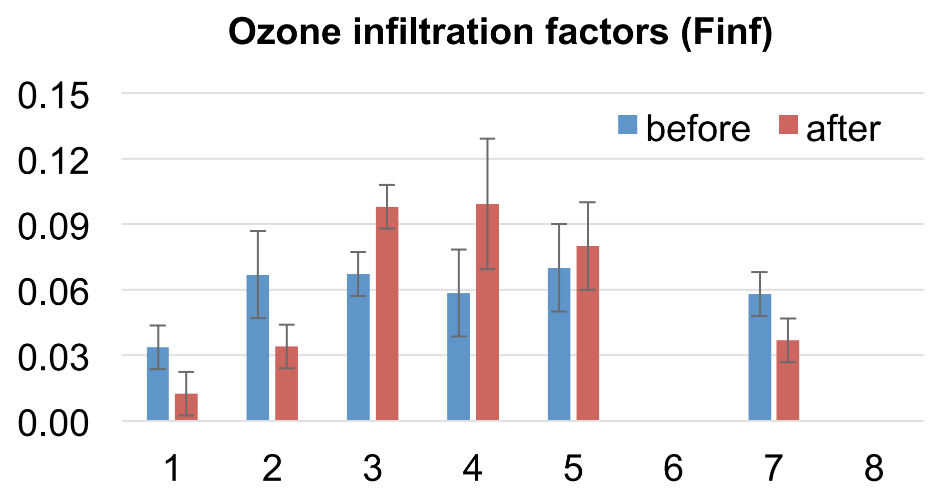




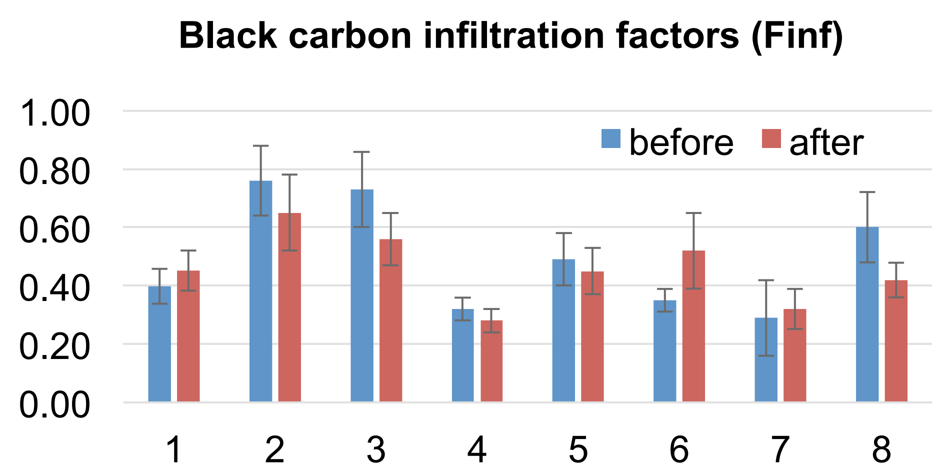


Preliminary results: AERs and infiltration factors

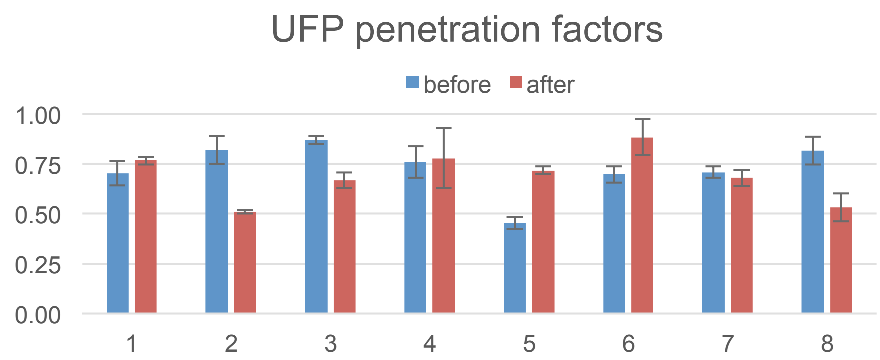
- Average ozone infiltration factors were 0.05±0.02 before retrofits and 0.06±0.03 after retrofits
  - No difference (some up, some down)



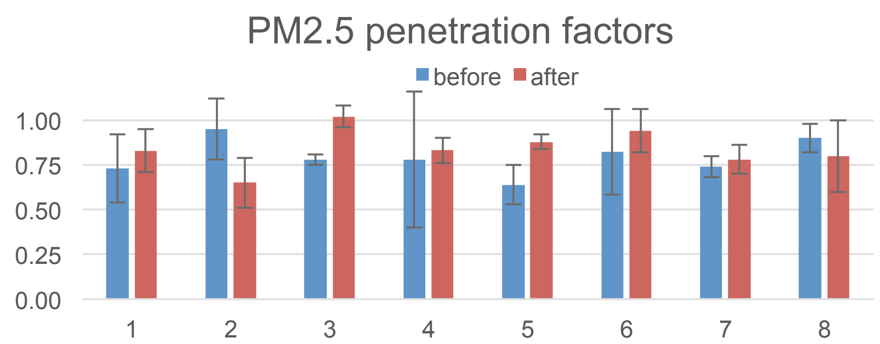
- Average black carbon infiltration factors were 0.48±0.18 before retrofits and 0.46±0.12 after retrofits
  - No difference (some up, some down)



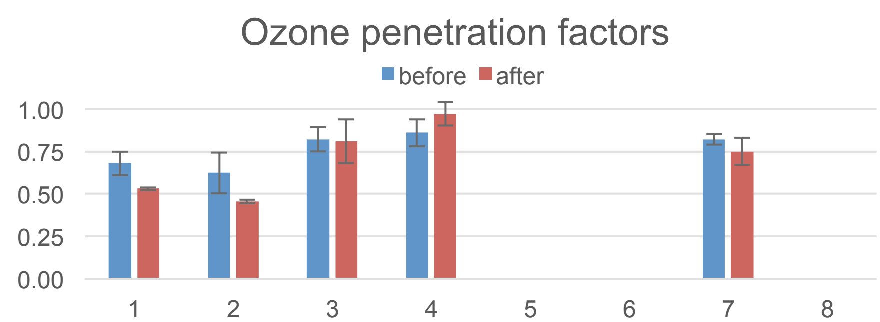
Preliminary results: UFP, $PM_{2.5}$, and O_3 penetration factors



- Estimates of UFP penetration factors (mean ± SD) were 0.72±0.12 before retrofits and 0.72±0.10 after retrofits
  - Ranging from 0.46±0.03 to 0.88±0.09

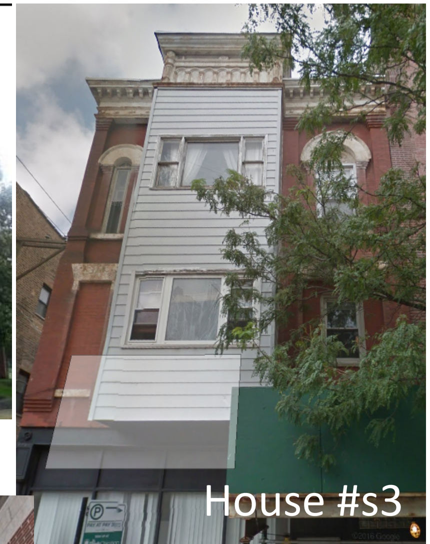


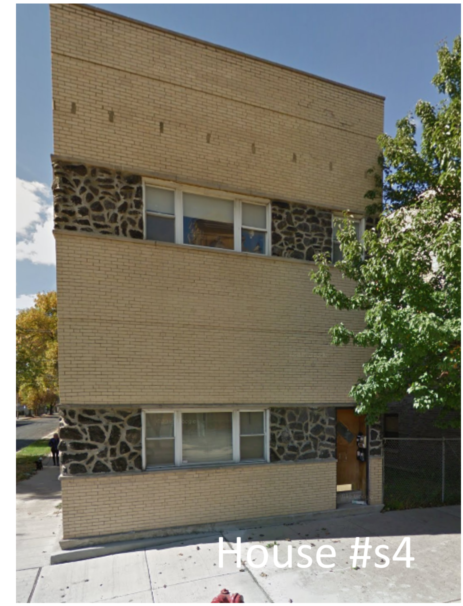
- Estimates of $PM_{2.5}$ penetration factors (mean ± SD) were 0.78±0.09 before retrofits and 0.85±0.11 after retrofits
  - Ranging from 0.64±0.11 to 1.02±0.06



- Estimates of ozone penetration factors (mean ± SD) were 0.76±0.09 before retrofits and 0.70±0.19 after retrofits
  - Ranging from 0.68±0.07 to 0.97±0.07

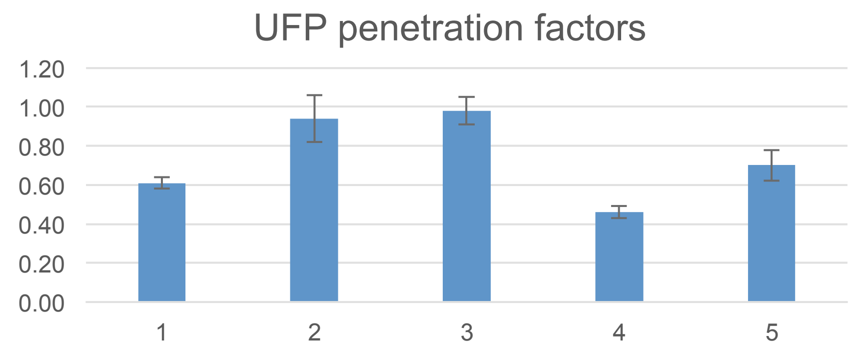
Non-retrofit homes (all multi-family)



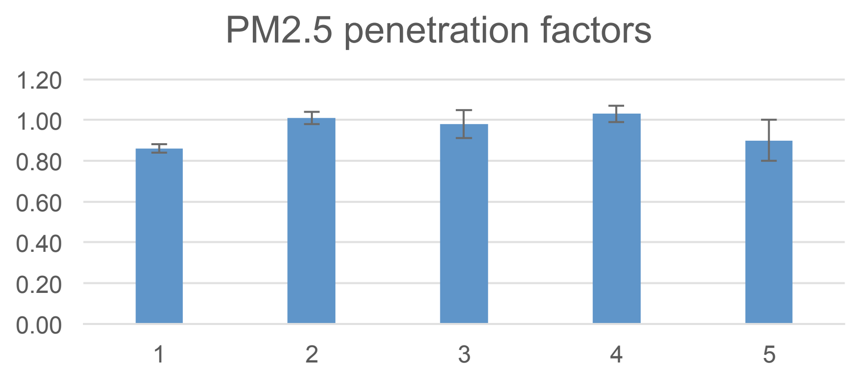


Preliminary results: Non-retrofit home penetration factors

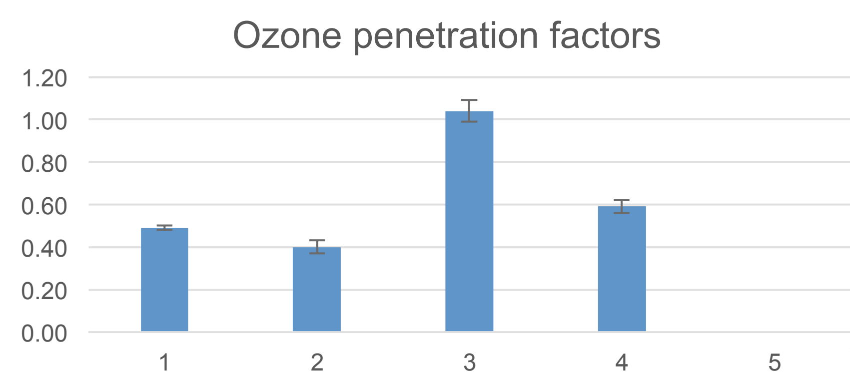
- Estimates of UFP penetration factors (mean ± SD) were 0.74±0.07
  - Ranging from 0.46±0.03 to 0.98±0.07



- Estimates of $PM_{2.5}$ penetration factors (mean ± SD) were 0.96±0.05
  - Ranging from 0.86±0.02 to 1.03±0.04



- Estimates of ozone penetration factors (mean ± SD) were 0.76±0.03
  - Ranging from 0.40±0.0 to 1.04±0.04



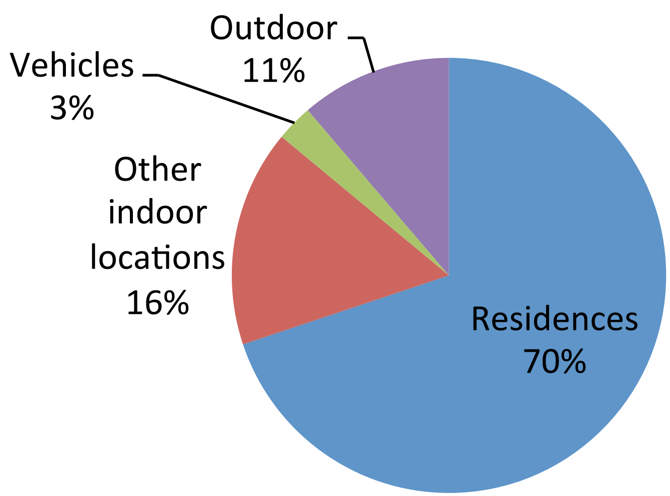
All homes were multi-family units

WHAT CAN YOU DO WITH THIS INFORMATION?

Practical applications

- Improve exposure estimates for epidemiology studies
  - Ongoing U.S. $PM_{2.5}$ mortality analysis:

If outdoor $PM_{2.5}$ concentrations are linked to ~137,000 deaths annually in the U.S…



Exposure to ambient origin $PM_{2.5}$

Parham Azimi, PhD

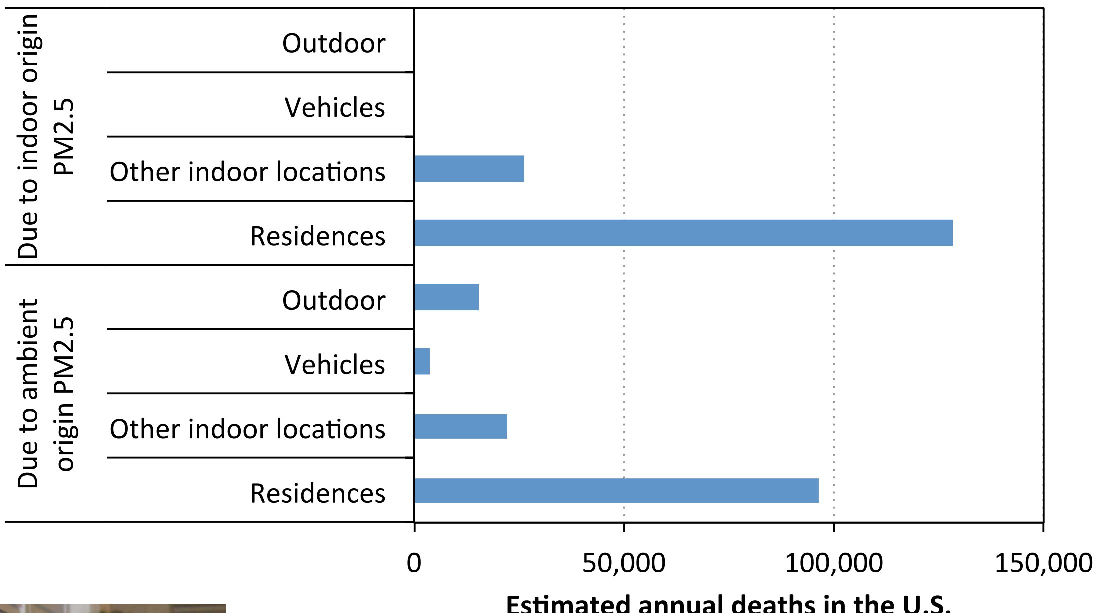
… then 70% of the outdoor $PM_{2.5}$ mortality burden is likely due to outdoor $PM_{2.5}$ exposure inside homes

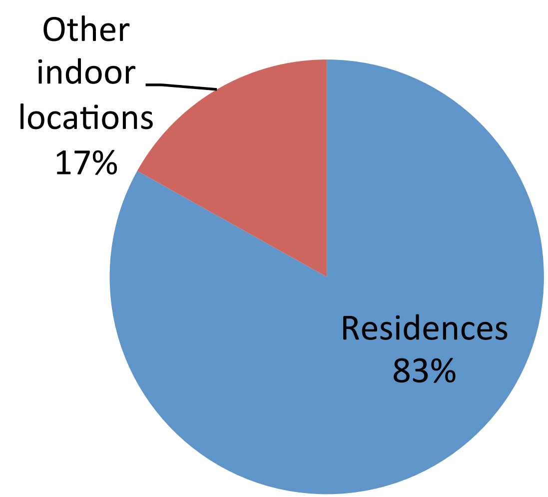
Azimi and Stephens *in preparation*

Practical applications

- Improve exposure estimates for epidemiology studies
  - Ongoing U.S. $PM_{2.5}$ mortality analysis:

If outdoor $PM_{2.5}$ concentrations are linked to ~137,000 deaths annually in the U.S…





Exposure to indoor origin $PM_{2.5}$

Parham Azimi, PhD

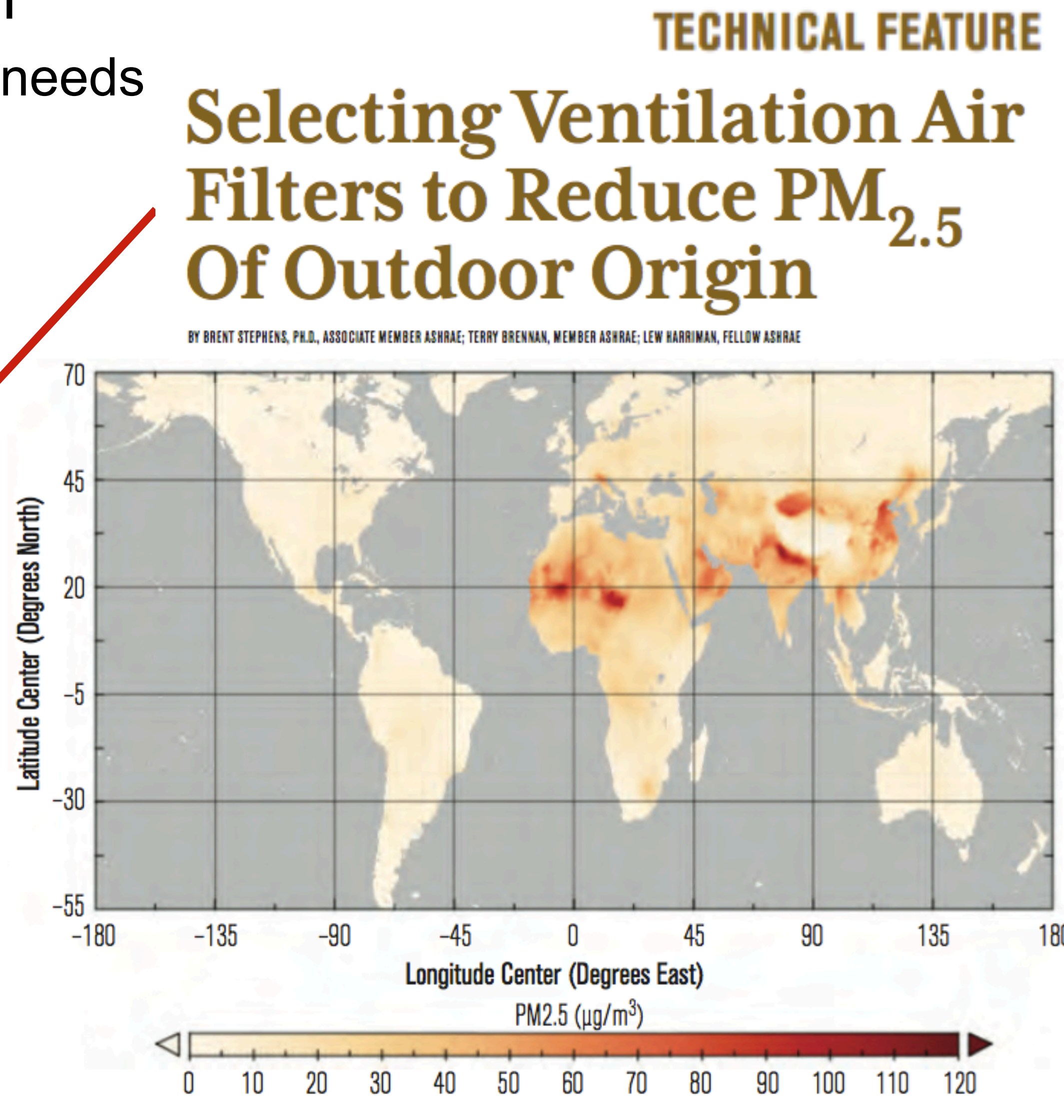
… then indoor sources of $PM_{2.5}$ may contribute to another ~154,000 deaths annually (with 83% attributed to indoor residential exposure)

Azimi and Stephens *in preparation*

Practical applications

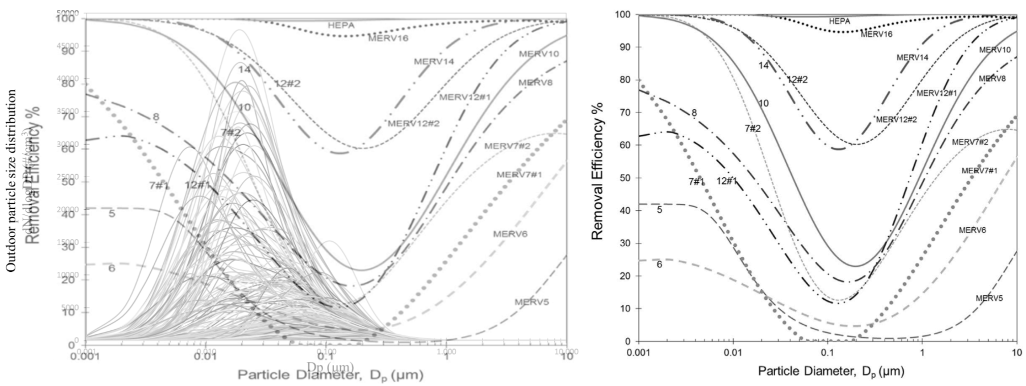
- Influence building design
  - Global OA $PM_{2.5}$ filtration needs

Stephens et al. *ASHRAE Journal* September 2016

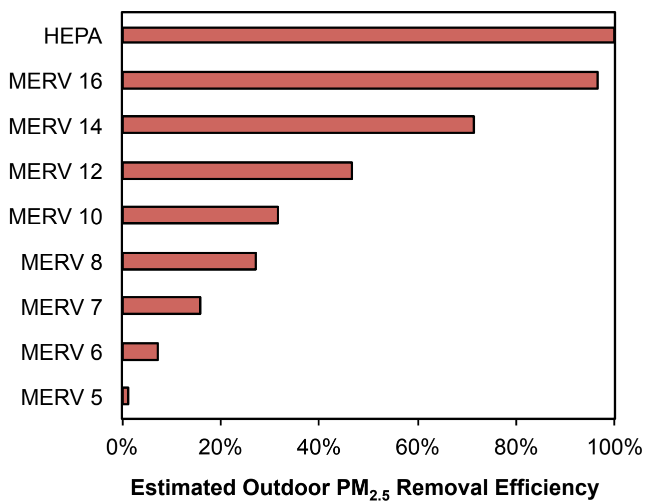


Practical applications

- Influence building design
  - Global OA $PM_{2.5}$ filtration needs



Azimi et al., *Atmos Environ* **2014** 98:337-346



Stephens et al. *ASHRAE Journal* September 2016

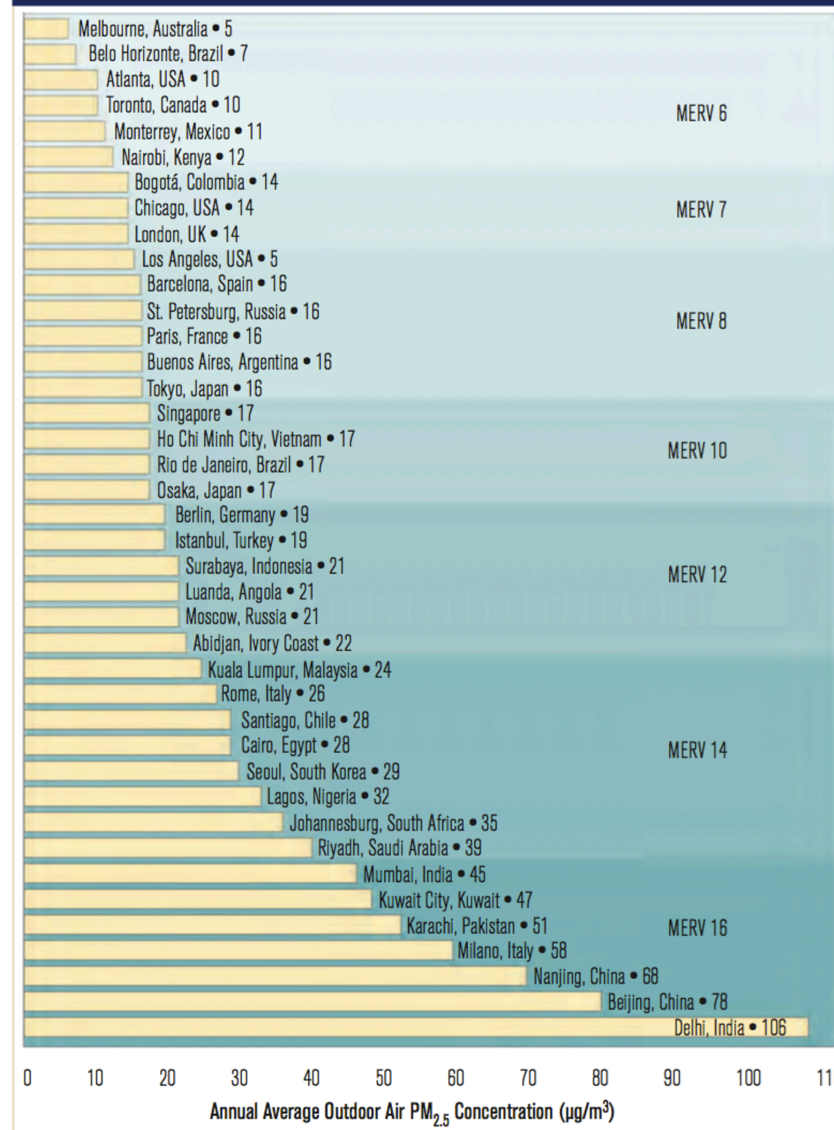
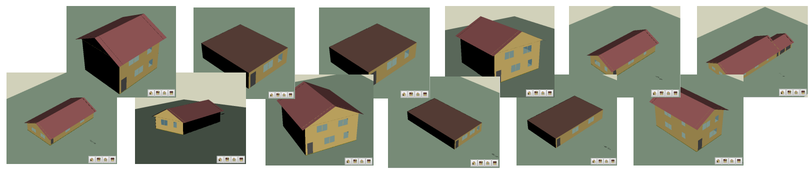
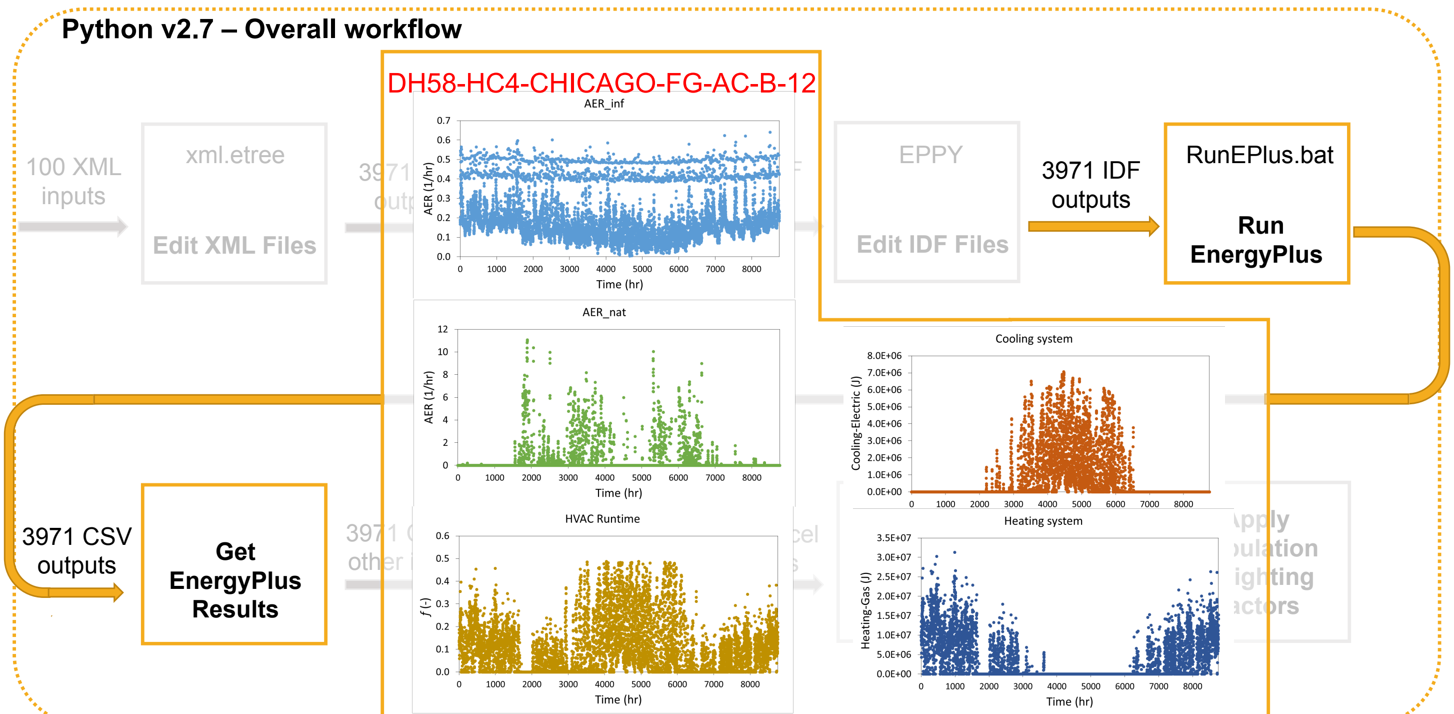


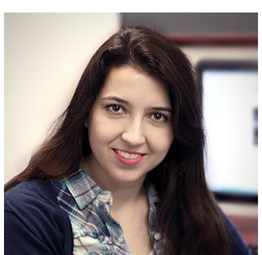
FIGURE 3 Ventilation air filtration levels (MERV) needed to reduce entering outdoor $PM_{2.5}$ concentrations to U.S. NAAQS maximum level of 12 μg/m^3.

Practical applications

- Improve our ability to model the indoor environment
  - Development of a nationally representative set of combined energy and indoor air quality models for U.S. residences







Torkan Fazli

Fazli and Stephens *in preparation*

Summary

- Much of human exposure to outdoor air pollution occurs indoors

- Failing to account for indoor exposures to outdoor air pollution can lead to exposure misclassification and errors in epidemiology studies

- We continue to improve our abilities to measure some of the fundamental drivers of outdoor pollutant infiltration
  - And translate to practical applications such as improving epidemiology studies, influencing the way we design and operate buildings, improving modeling capabilities to inform policy, and more

Acknowledgments

- Many thanks to all of the homeowners and occupants that have let us inside their buildings!
- **Funding sources**
  - UT: University of Texas at Austin Continuing Fellowship, NSF IGERT Award DGE #0549428, Thrust 2000 Endowed Graduate Fellowship (UT-Austin)
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- **People**
  - UT: Jeffrey Siegel, Elliott Gall, Clement Cros, Rich Corsi, and Atila Novoselac
  - IIT: Haoran Zhao, Parham Azimi, Torkan Fazli, Dan Zhao, Akram Ali, Zeineb El Orch, Jihad Zeid, Ben Wachholz, and staff at Elevate Energy

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