Understanding the mechanistic drivers of indoor exposures to outdoor air pollution

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Talk outline

1. Primer on energy and air quality in the built environment

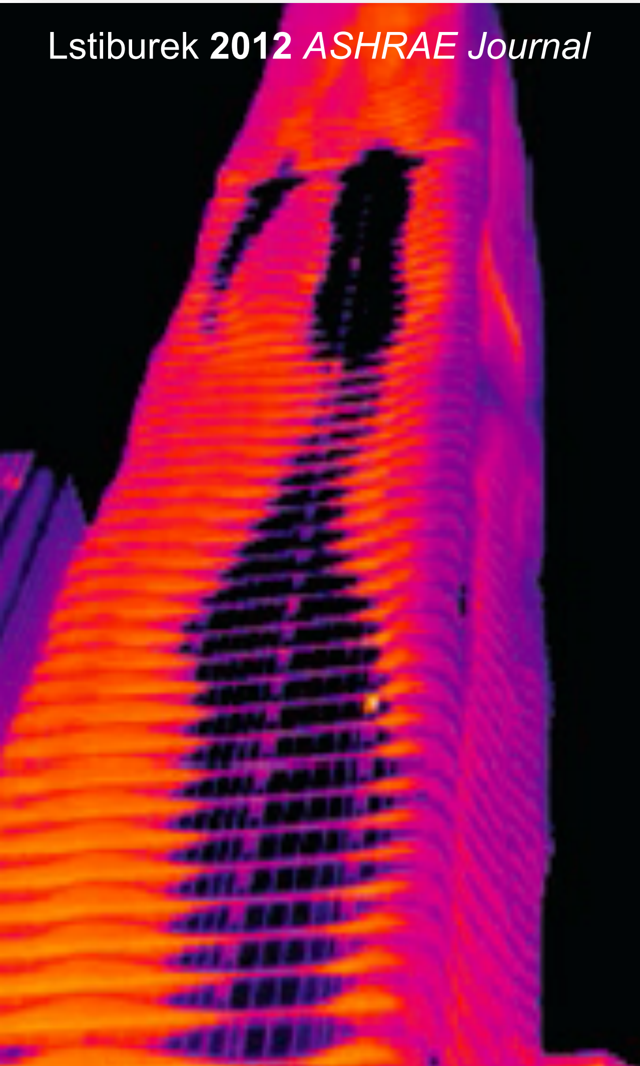
2. Indoor proportions of outdoor pollutants

3. Experimental characterizations of mechanistic drivers of indoor exposures to outdoor pollutants

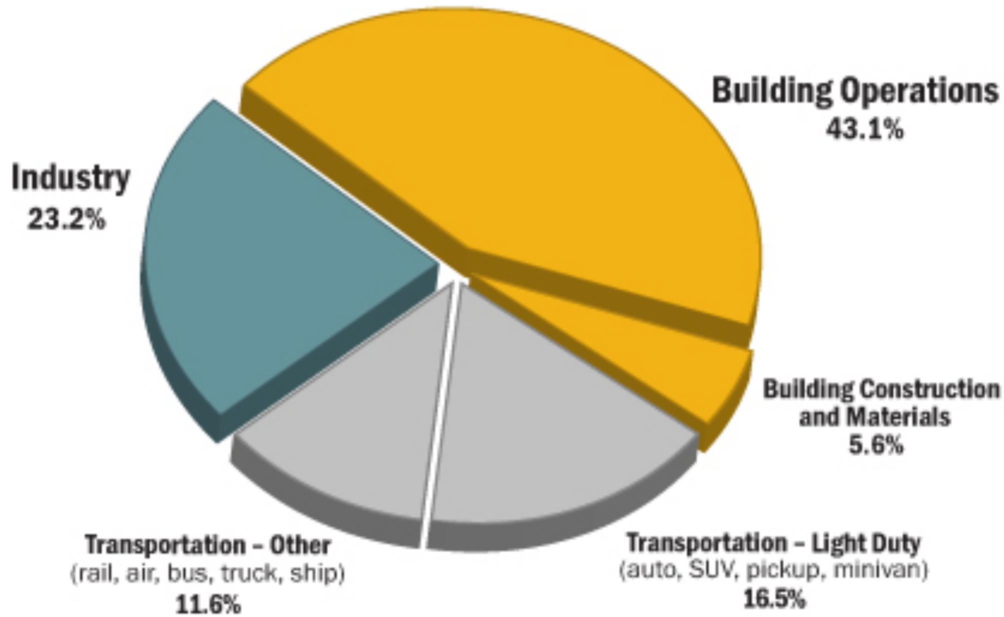
4. New(ish) related project: Climate change, indoor air, and health

What do you think of when you hear "energy"?

What do I think of when I hear "**energy**"?



Buildings

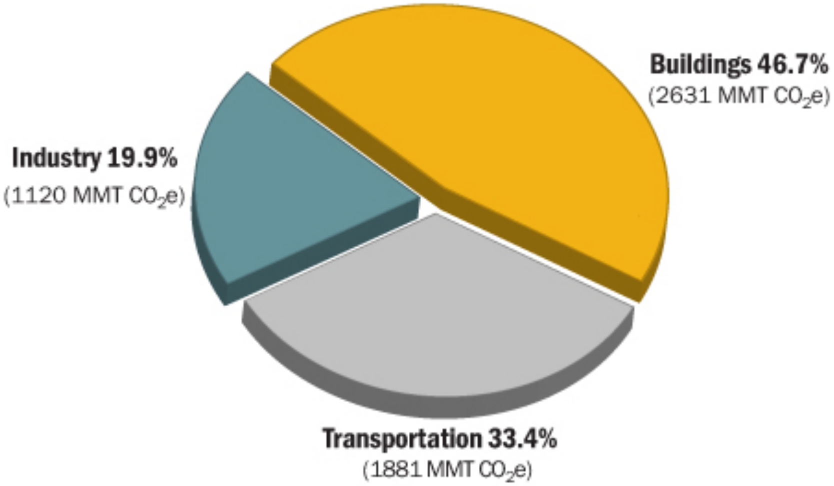


Buildings account for ~43-48% of total U.S. energy consumption

Buildings in the U.S. account for **~7%** of the total amount of energy used in the **world**

Buildings account for *a lot* of GHG and pollutant emissions

Contribution to GHGs



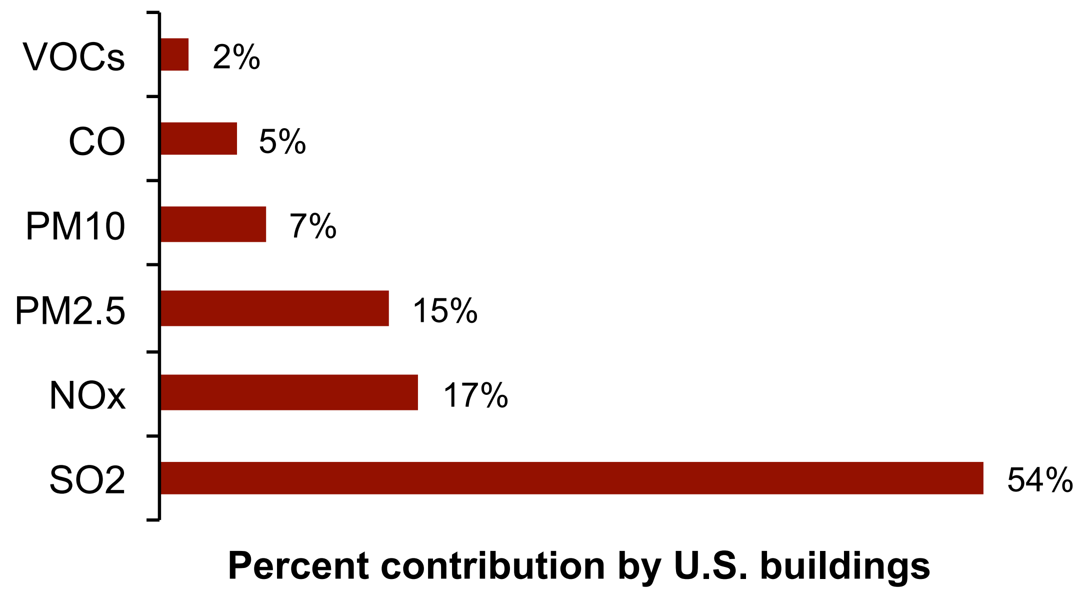
U.S. CO_2 Emissions by Sector

Data Source: U.S. Energy Information Administration (2011).

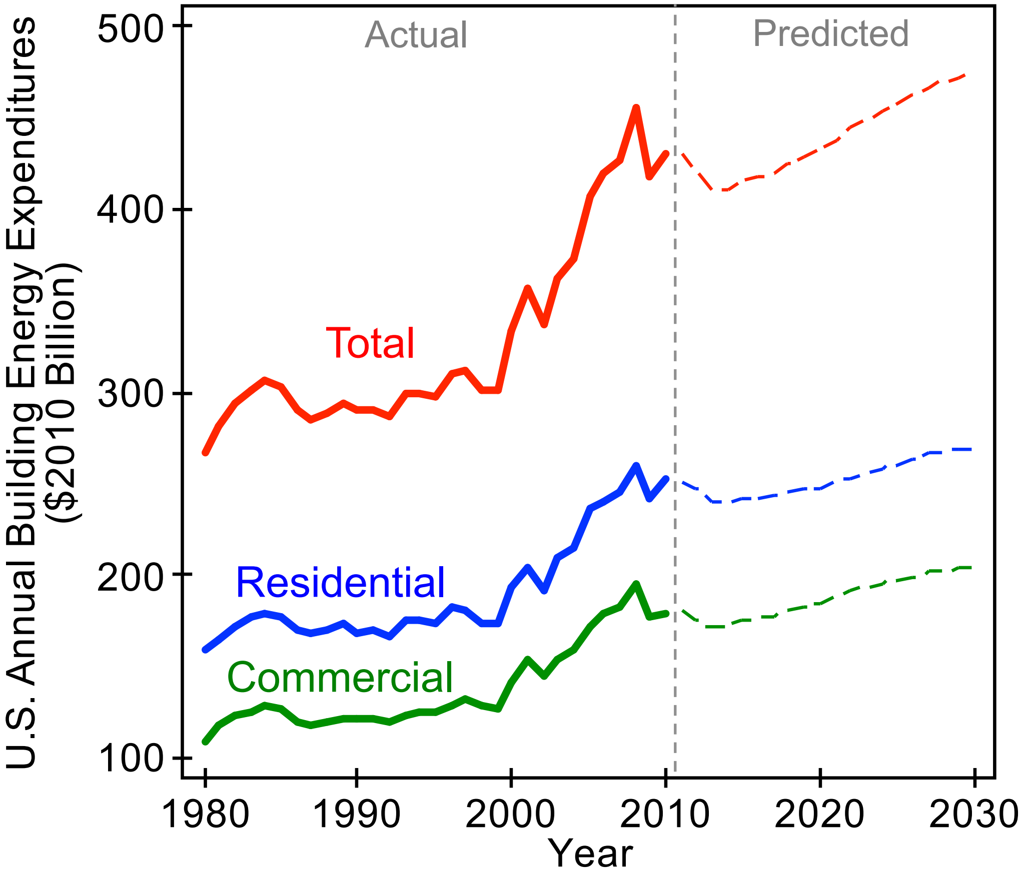
Major uses

1. Heating
2. Cooling
3. Lighting
4. Water heating

Contribution to outdoor air pollution

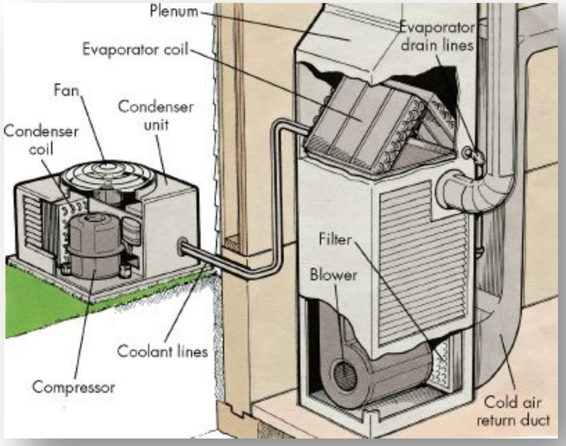


Building energy use costs *a lot* of money



U.S. building energy expenditures totaled ~$430 billion in 2010

Approximately 3% of our GDP



Approximately 1/3 of building energy use is for space conditioning

~1% of our GDP is spent on heating and cooling buildings

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

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

Formaldehyde and Other Volatile Organic Chemical Emissions in Four FEMA Temporary Housing Units

Maddalena et al., *Environ. Sci. Technol.* **2009**, 43, 5626-5632

Formaldehyde in the Indoor Environment

Salthammer et al., *Chem. Rev.* **2010**, 110, 2536-2572

Emission Rates of Formaldehyde from Materials and Consumer Products Found in California Homes

Kelly et al., *Environ. Sci. Technol.* **1999**, 33, 81-88

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

Association between gas cooking and respiratory disease in children

Melia et al., *British Medical Journal* **1977**, 2, 149-152

Indoor Air Pollution and Asthma

Ostro et al., *Am. J. Respir. Crit. Care. Med.* **1994**, 149, 1400-1406

Respiratory Symptoms in Children and Indoor Exposure to Nitrogen Dioxide and Gas Stoves

Garrett et al., *Am. J. Respir. Crit. Care. Med.* **1998**, 158, 891-895

Pollutant Exposures from Natural Gas Cooking Burners

Logue et al., *Environ Health Perspect.* **2014**, 122, 43-50

Association of domestic exposure to volatile organic compounds with asthma in young children

Rumchev et al., *Thorax* **2004**, 59, 746-751

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

Cleaning products and air fresheners: exposure to primary and secondary air pollutants

Nazaroff and Weschler, *Atmos Environ.* **2004**, 38, 2841-2865

Frequent use of chemical household products is associated with persistent wheezing in pre-school age children

Sherriff et al., *Thorax* **2005**, 60, 45-49

The Use of Household Cleaning Sprays and Adult Asthma

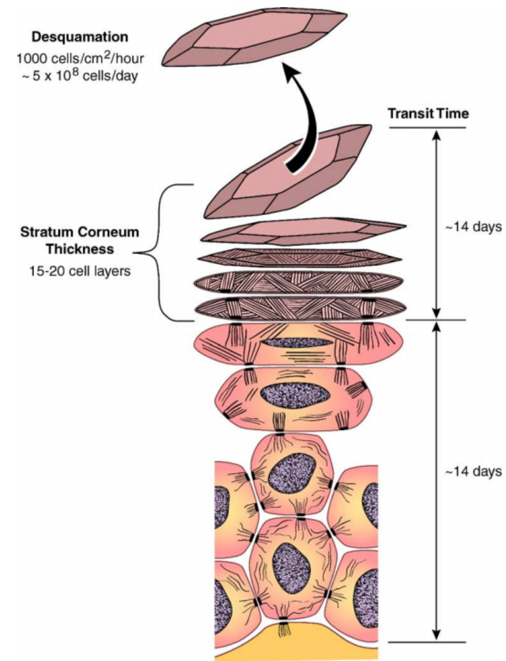
Zock et al., *Am. J. Respir. Crit. Care. Med.* **2007**, 176, 735-741

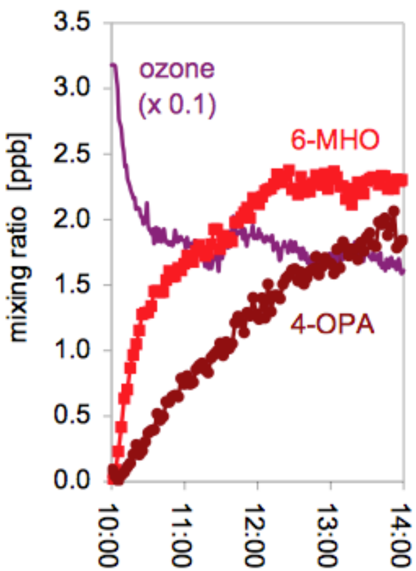
What do I think of when I hear "air pollution"?

Epidermal desquamation

Milstone, *J. Dermatol. Sci.* **2004**, 36, 131-140

We shed our entire outer layer of skin every 2-4 weeks





Reactions of ozone with human skin lipids: Sources of carbonyls, dicarbonyls, and hydroxycarbonyls in indoor air

Wisthaler and Weschler, *Proc Nat Acad Sci.* **2010**, 107, 6568-6575

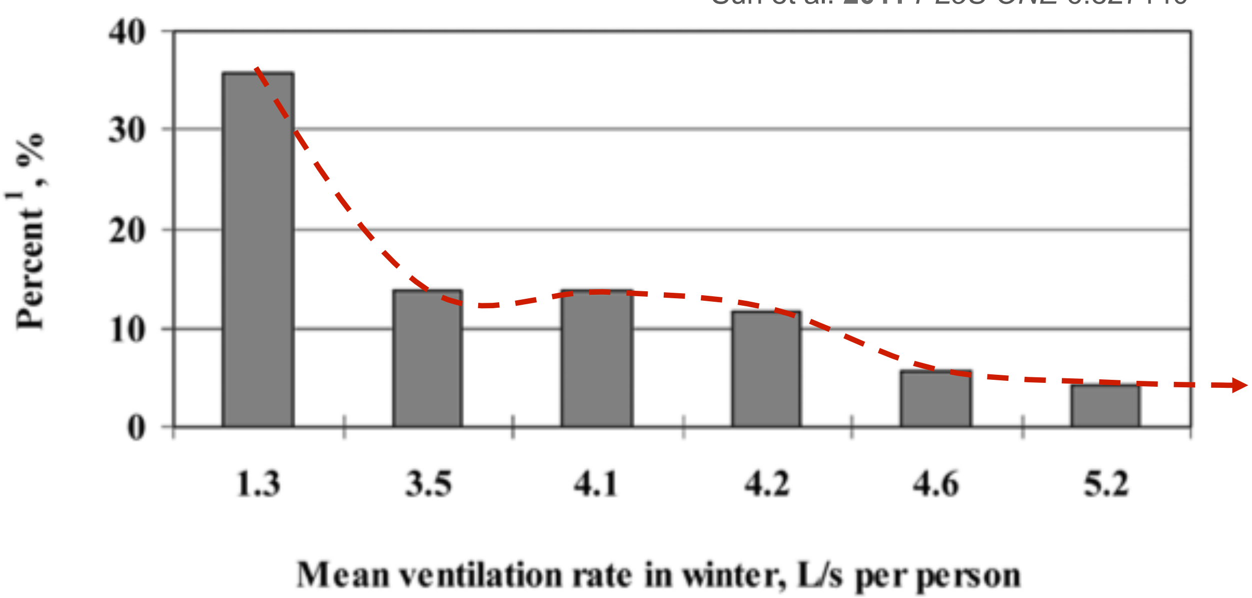
What do I think of when I hear "air pollution"?

Evidence of Airborne Transmission of the Severe Acute Respiratory Syndrome Virus

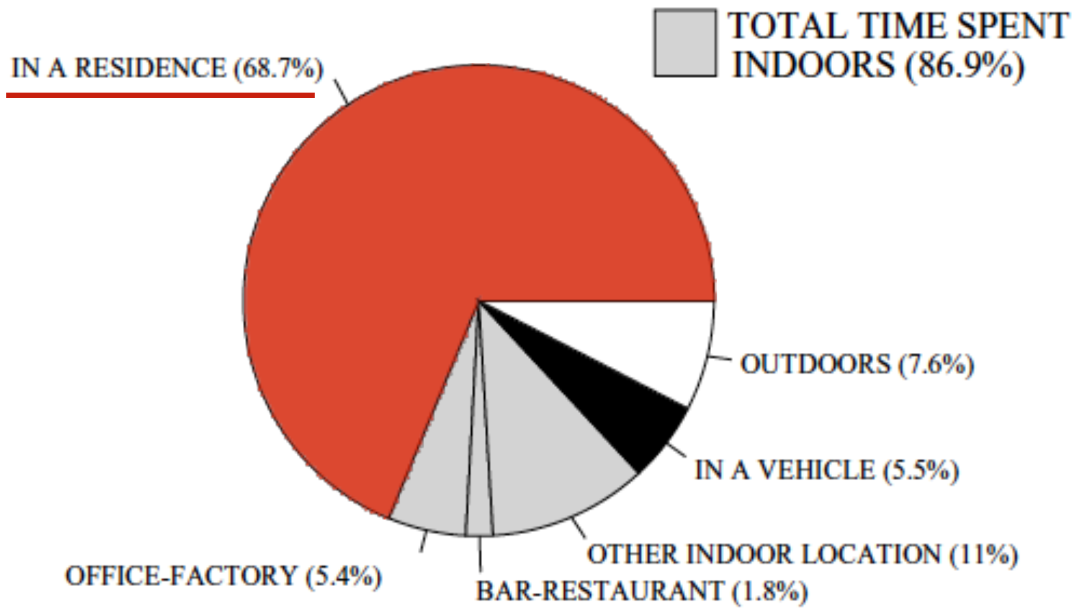
Yu et al., *New Engl. J. Med* **2004**, 350, 1731-1739

In China, Students in Crowded Dormitories with a Low Ventilation Rate Have More Common Colds: Evidence for Airborne Transmission

Sun et al. **2011** *PLoS ONE* 6:e27140



We spend *a lot* of our time in buildings



- 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
- Residential indoor air pollution is estimated to result in **5-14%** of the annual non-communicable, non-psychiatric **disease burden** in the U.S.
  - Excludes SHS and radon — Logue et al., *Environ. Health Perspect.* **2012**, 120, 216-222
- Cumulative lifetime **cancer risks** of **1-10** excess cases **per 10,000** people

Wallace et al., *Environ. Health Perspect.* **1991**, 95, 7-13
Sax et al., *Environ. Health Perspect.* **2006**, 114, 1558-1566
Hun et al., *Environ. Health Perspect.* **2009**, 117, 1925-1931

Buildings impact people, energy, and the environment



The design, construction, and operation of buildings greatly affect their contribution to energy use, greenhouse gas emissions, financial expenditures, human exposures to airborne pollutants, and human health

The **Built Environment Research Group** at IIT
is dedicated to investigating problems and solutions related to energy and air quality within the built environment

Research areas:

Indoor air quality

Building science measurements and methods

HVAC filtration and air cleaning

Human exposure assessment

Building energy efficiency and energy simulation

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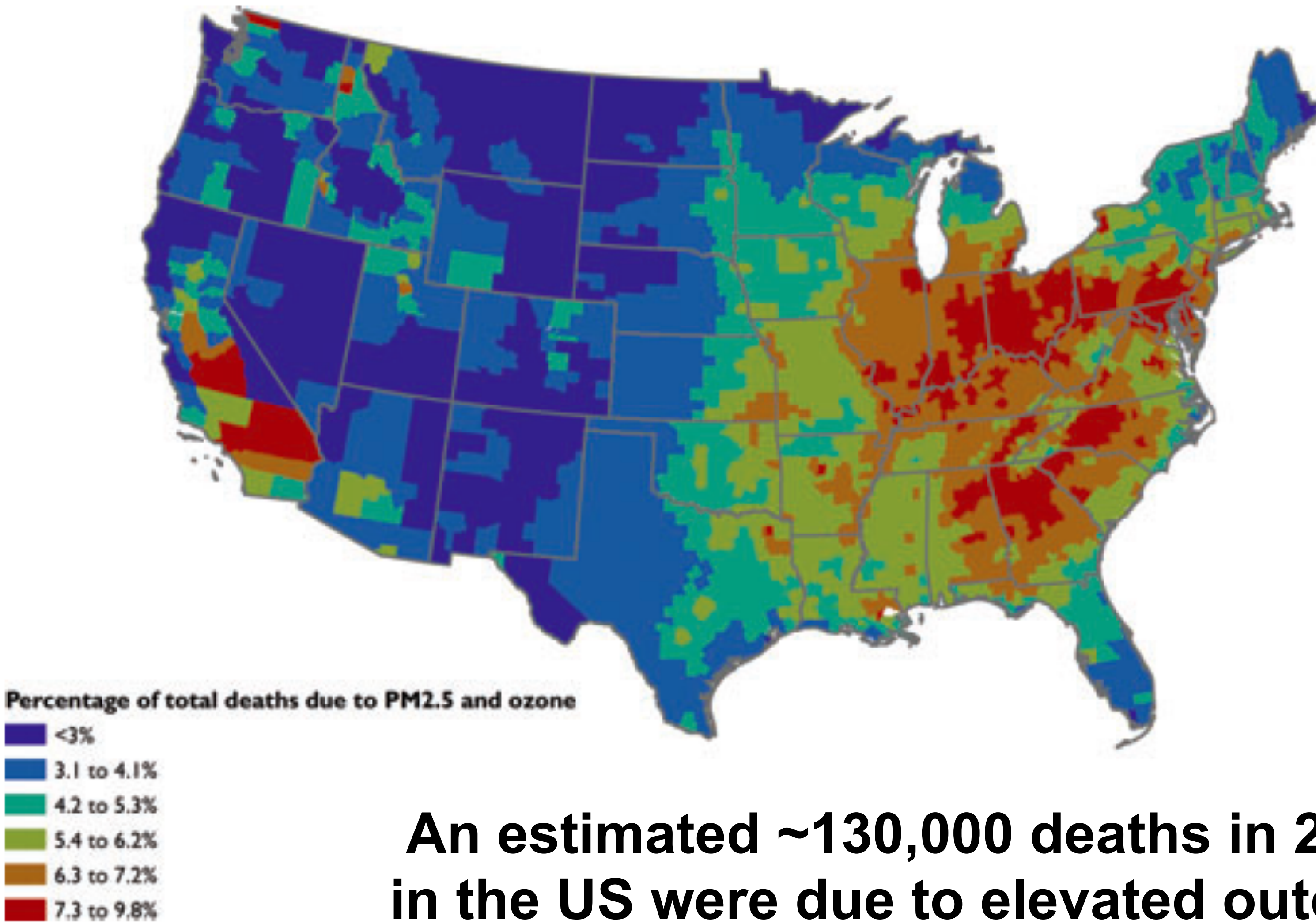
INDOOR EXPOSURES TO OUTDOOR POLLUTANTS

Particulate matter and gas-phase pollutants (e.g., O_3)

Motivation: Outdoor pollutants 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*

Exposures to outdoor O_3 and PM

- 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*

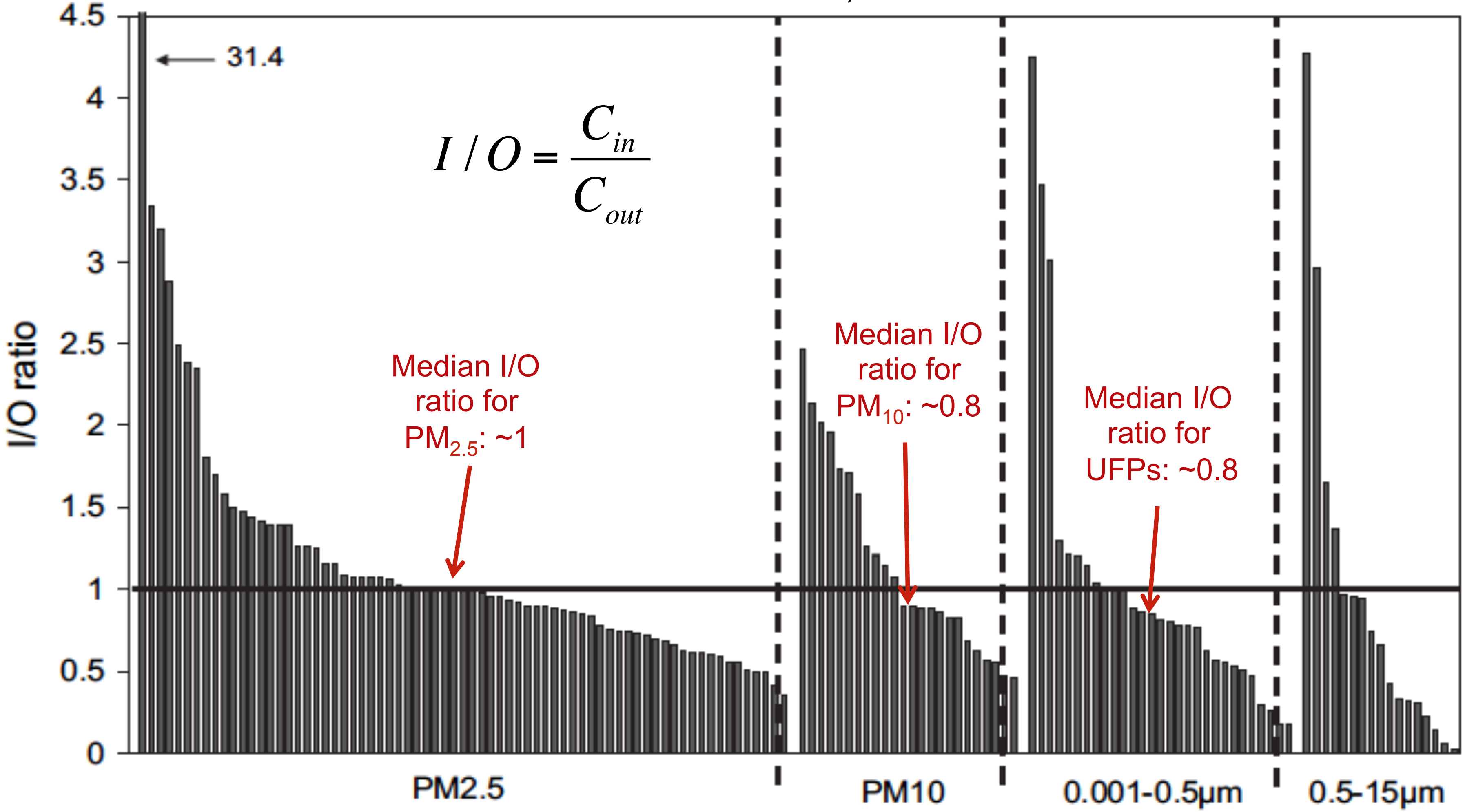
- Exposure to outdoor PM and O_3 (+ rxns) often occurs indoors

  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"

I/O PM ratios: Indoor + outdoor sources

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

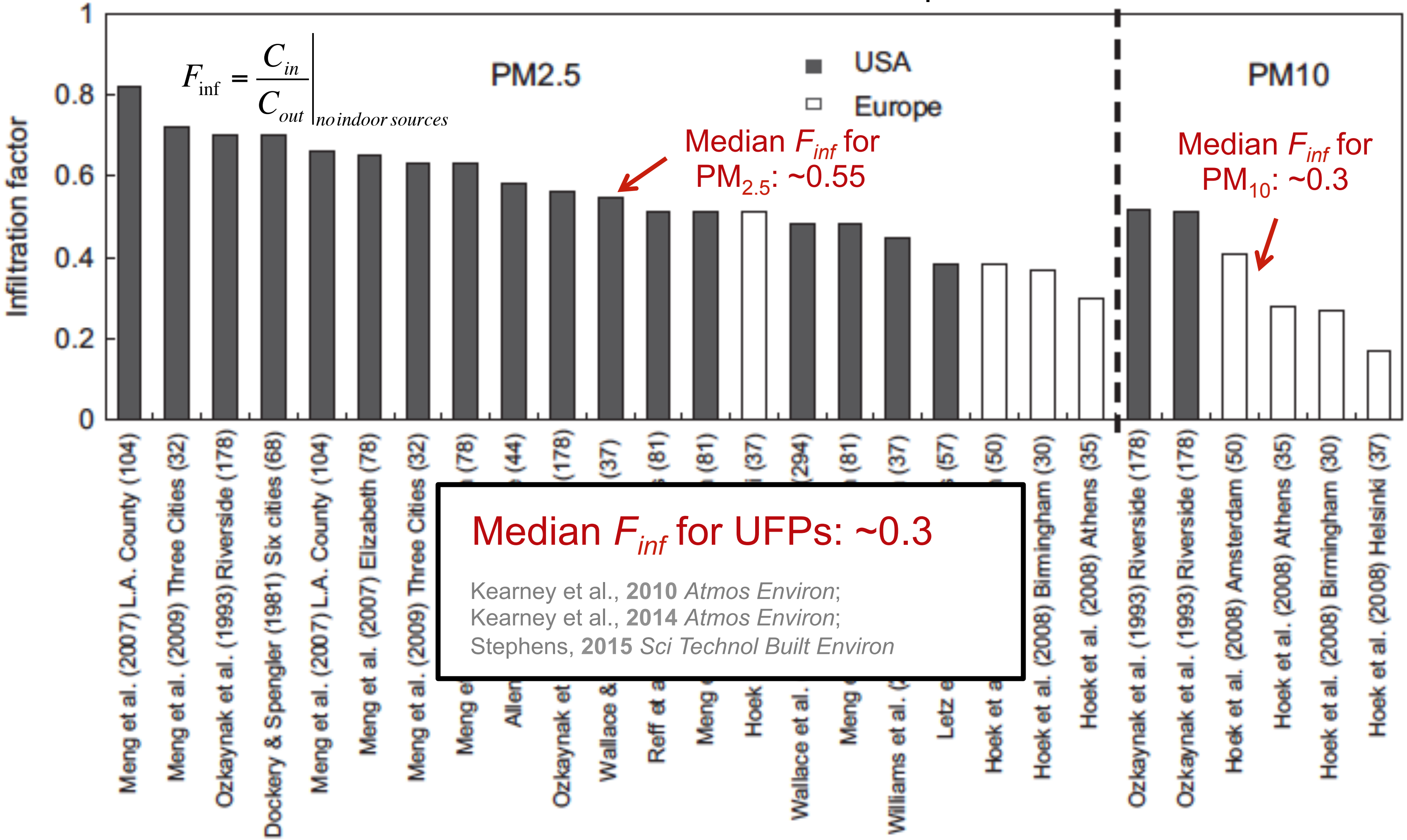


[~UFPs] **[0.5+ μm]**

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



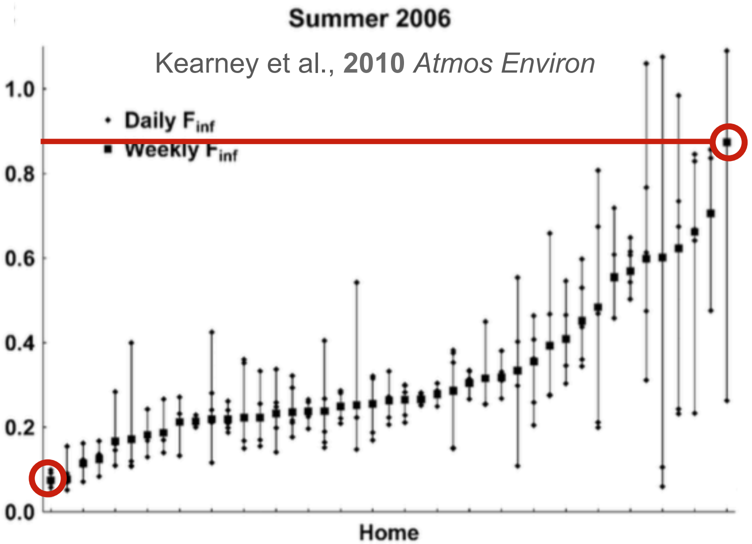
Median F_{inf} for UFPs: ~0.3

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

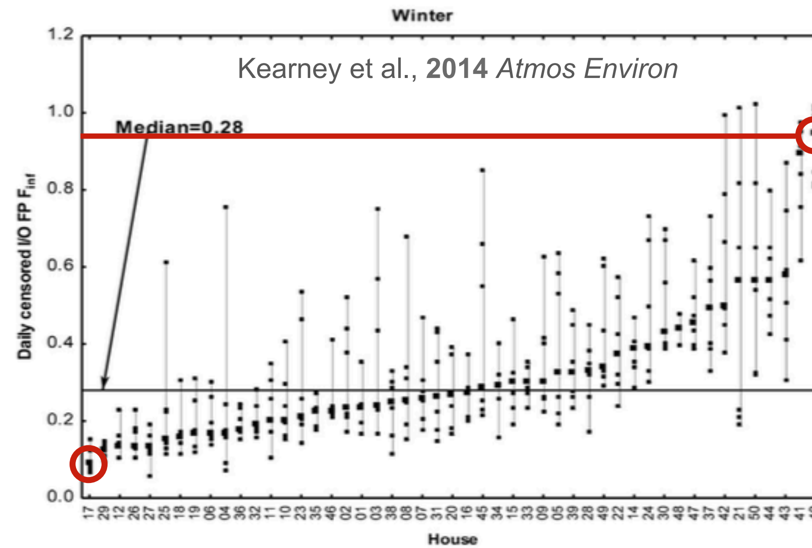
Chen and Zhao, **2011** *Atmos Environ*

<u>Variability</u> in residential $PM_{2.5}$ and UFP infiltration factors

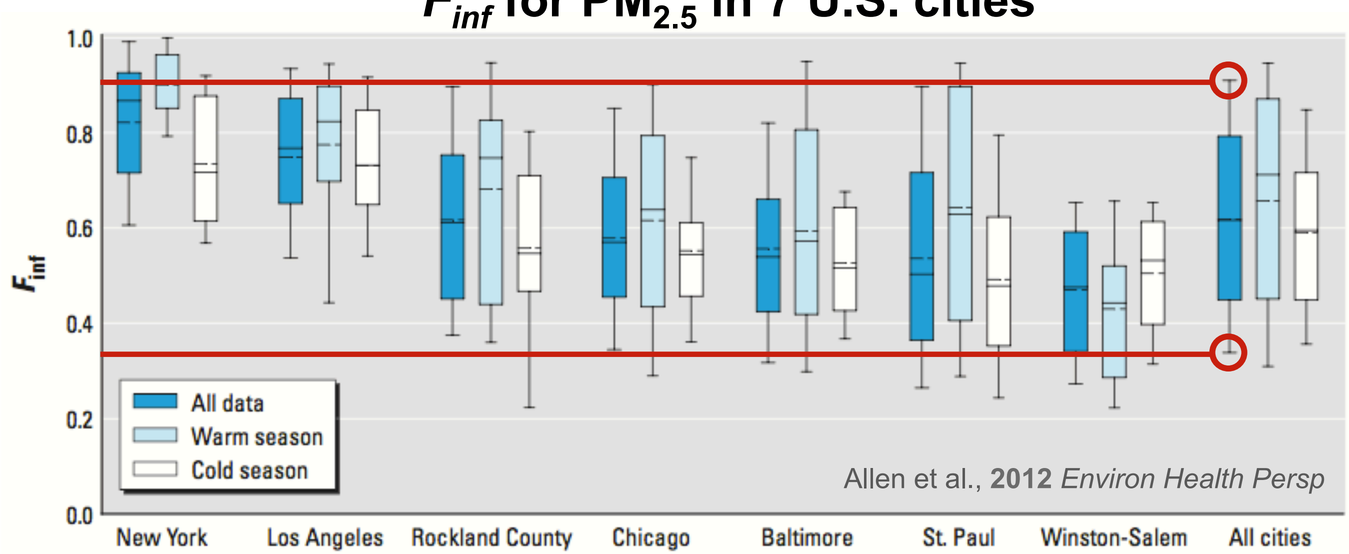
F_{inf} for UFPs in Windsor, ON



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



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



Between-home variations:
$0.1 < F_{inf} < 1$

Variability in O_3 infiltration factors

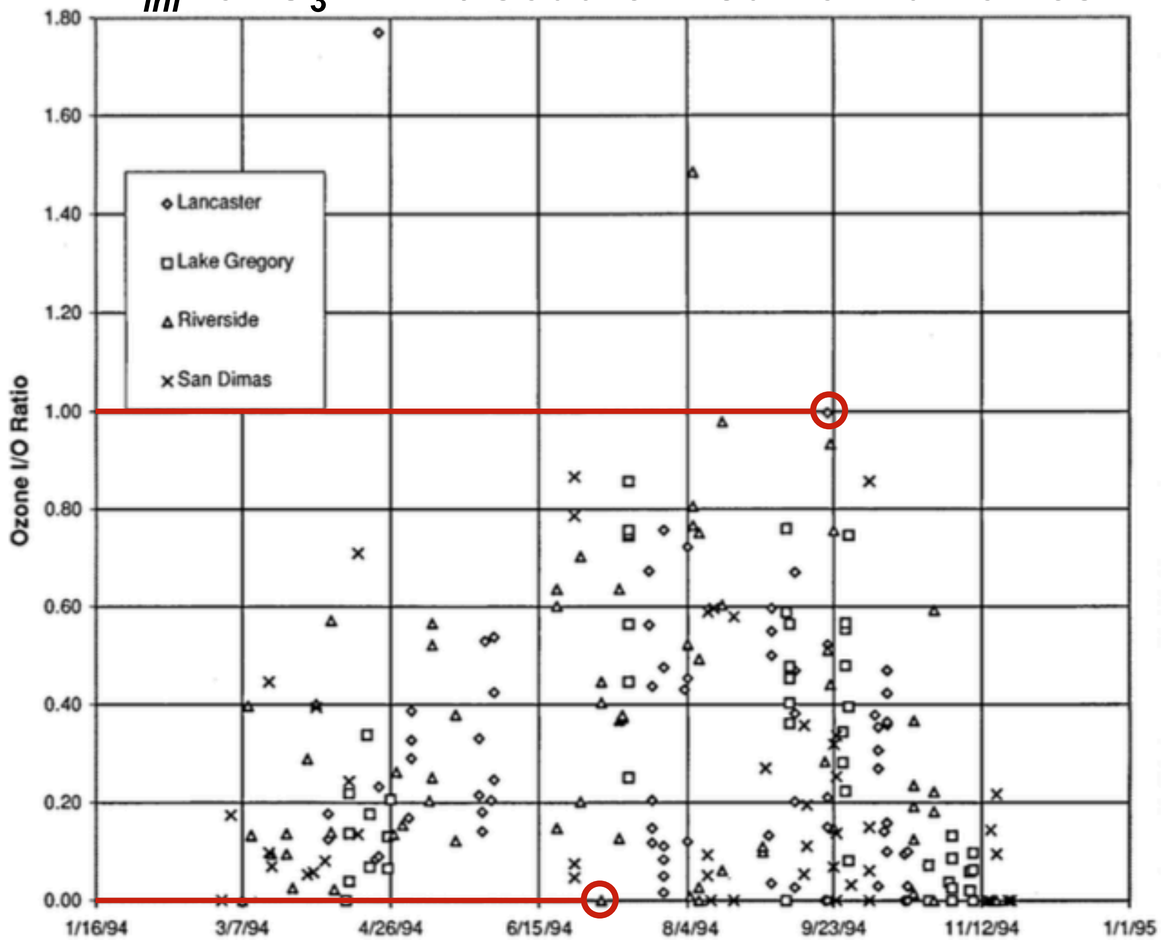
- I/O O_3 ratios commonly range from <0.1 to ~1

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*

<u>Variability</u> in O_3 infiltration factors

F_{inf} for O_3 in 126 southern California homes



Between-home variations:
$0 < F_{inf} < 1$

Avol et al., **1998** *Environ Sci Technol*

Key drivers of variability in infiltration factors

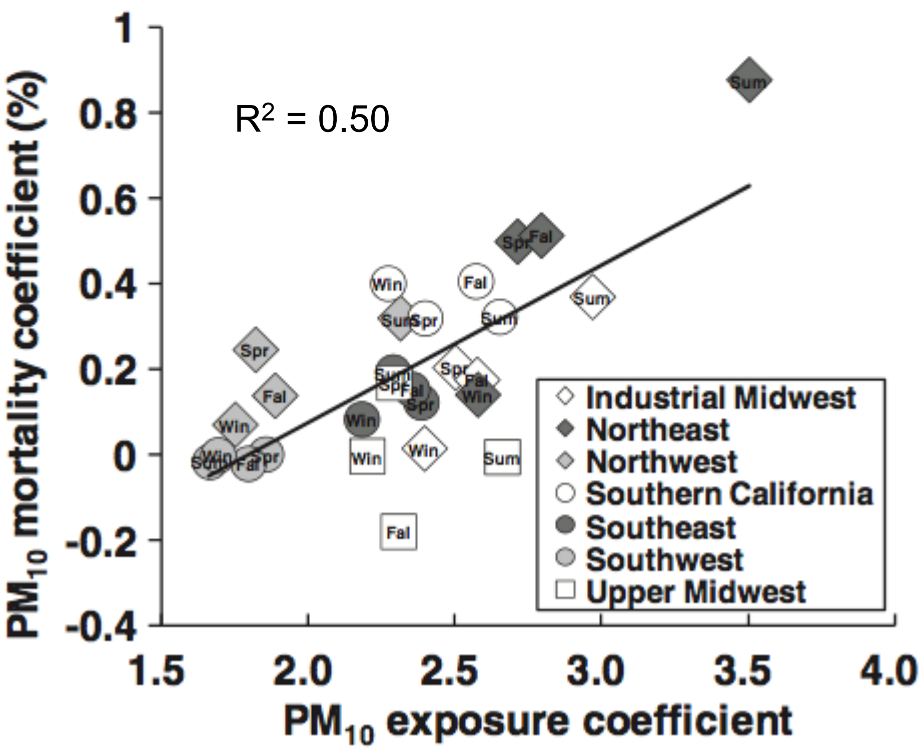
- Source of ventilation air
  - Infiltration (envelope leaks)
  - Mechanical ventilation
  - Natural ventilation
- Human behaviors (e.g., window opening frequencies)
- Magnitude of the air exchange rate (AER)
  - Meteorological driving forces
- Pollutant characteristics
  - Sizes/classes/components of PM
  - Reactivity of O_3
- Building characteristics (e.g., airtightness)
- HVAC system design and operation

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?

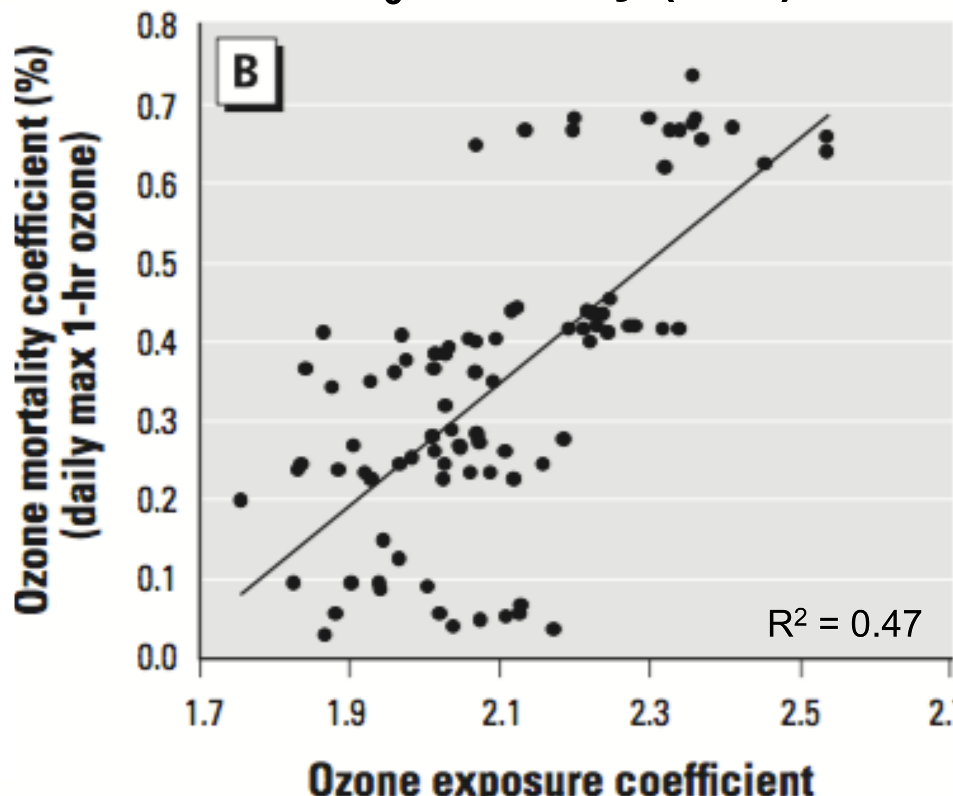
Accounting for variations in AERs and window opening

PM_{10} mortality (U.S.)



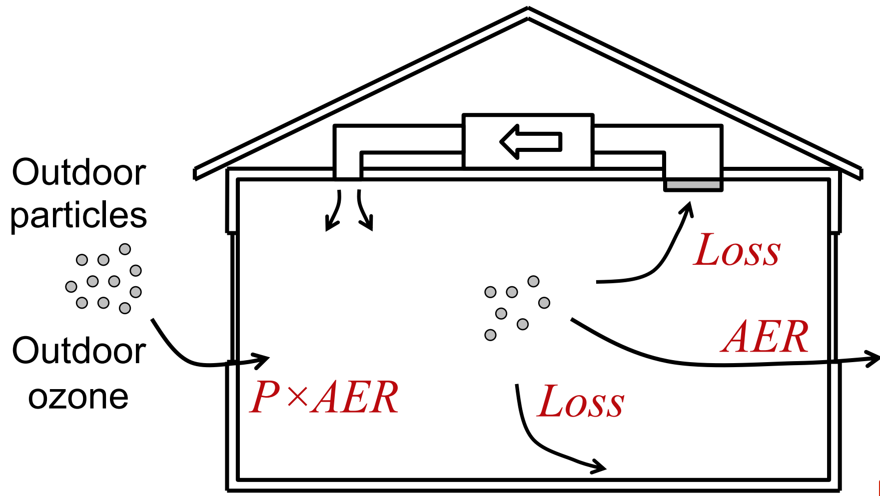
Chen et al., **2012** *Epidemiology*

O_3 mortality (U.S.)



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

Underlying mechanisms that govern F_{inf}



Penetration from outdoors

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

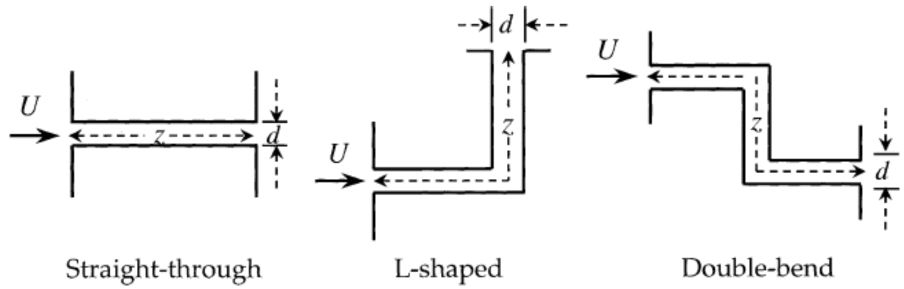
Removal by air exchange

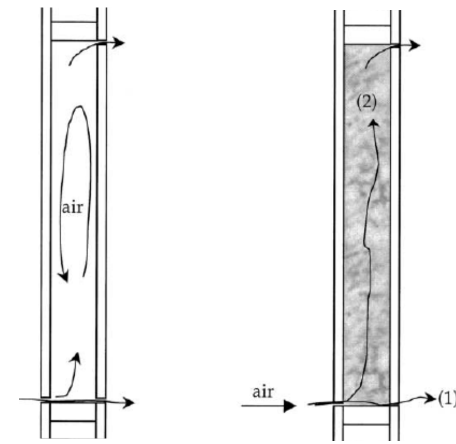
Removal by deposition to surfaces, phase changes, or control by filters or air cleaners

"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 on envelope materials



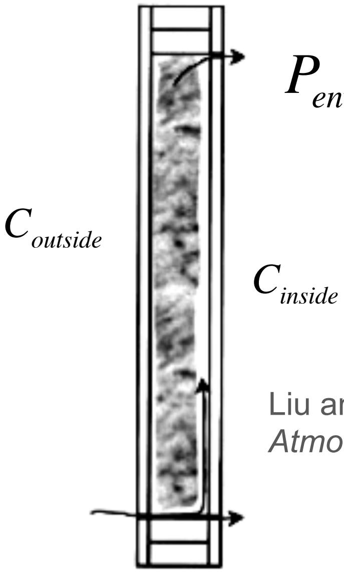


Liu and Nazaroff, **2001** *Atmos Environ*

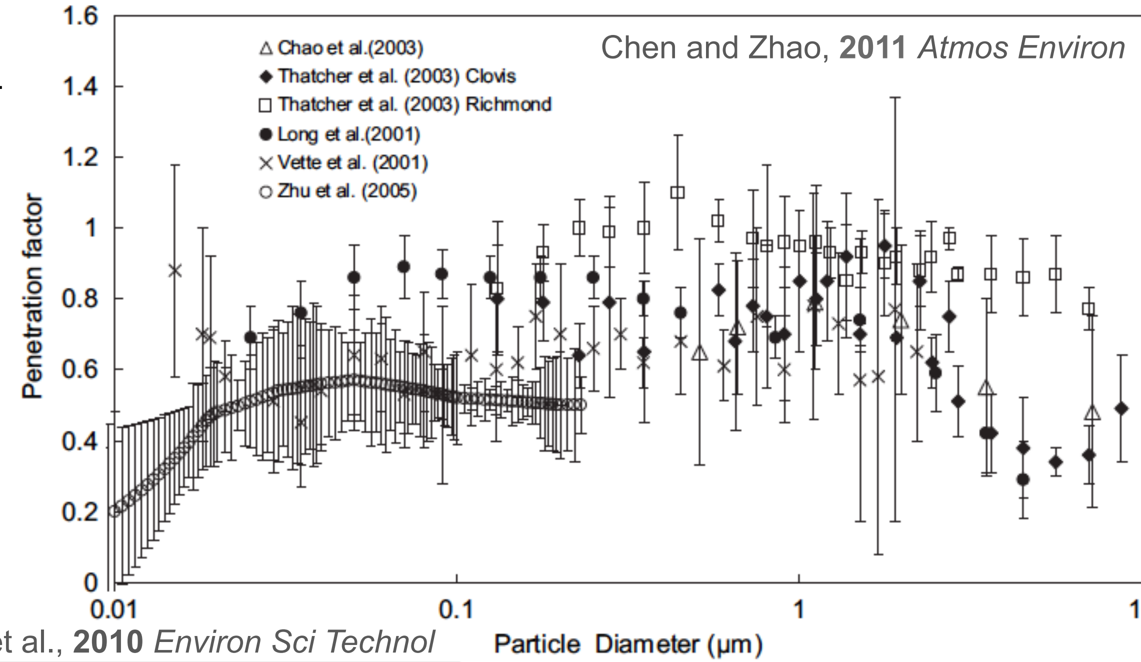
- No one has ever measured natural ozone penetration factors
  - Some modeling, some somewhat unrealistic measurements (by me)
- A few groups have measured PM penetration factors
  - Limited in number and size-resolution
- Measurements are challenging
  - Need test methods to solve for 2 unknowns with 1 equation

Envelope penetration factors for PM

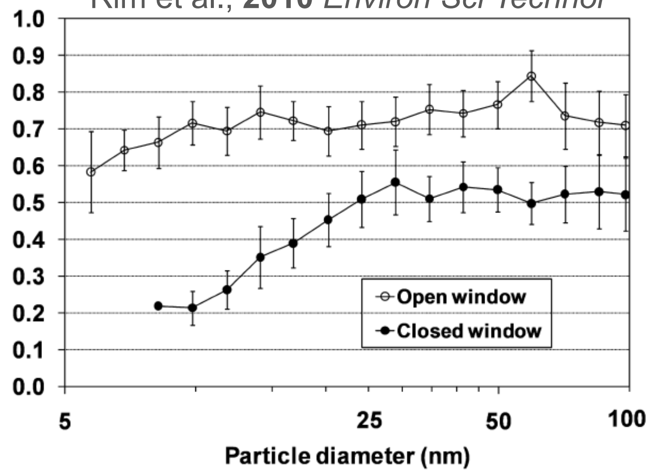
$$P_{envelope} = \frac{C_{inside}}{C_{outside}}$$



Liu and Nazaroff **2001** *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

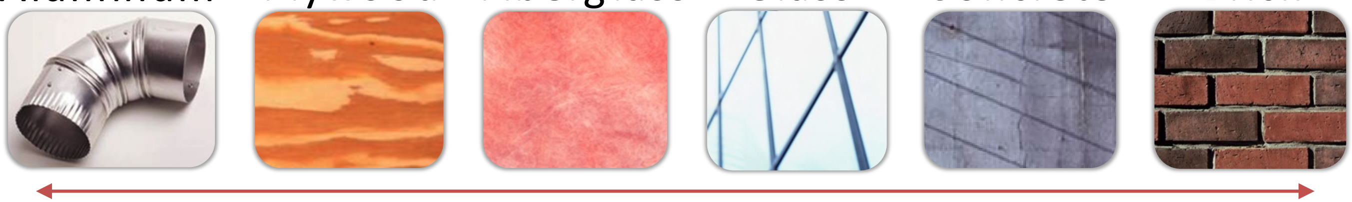
Weschler, **2000** *Indoor Air*; Weschler, **2006** *Environ Health Persp*

- But O_3 reacts with common envelope materials:

O_3 Reaction Probability, γ

From Liu and Nazaroff (2001)

Aluminum Plywood Fiberglass Glass Concrete Brick



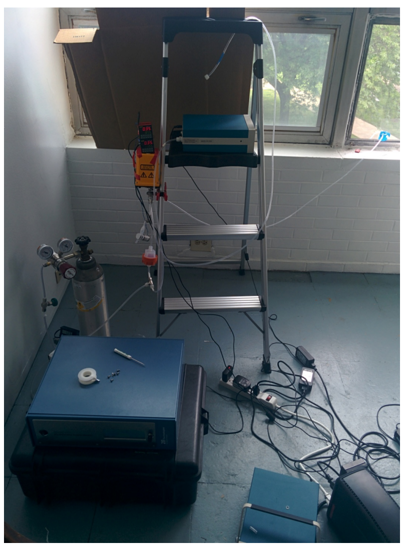
γ = 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4}

Less reactive More reactive

- No known measurements of O_3 penetration factors until 2012

Measuring envelope penetration factors

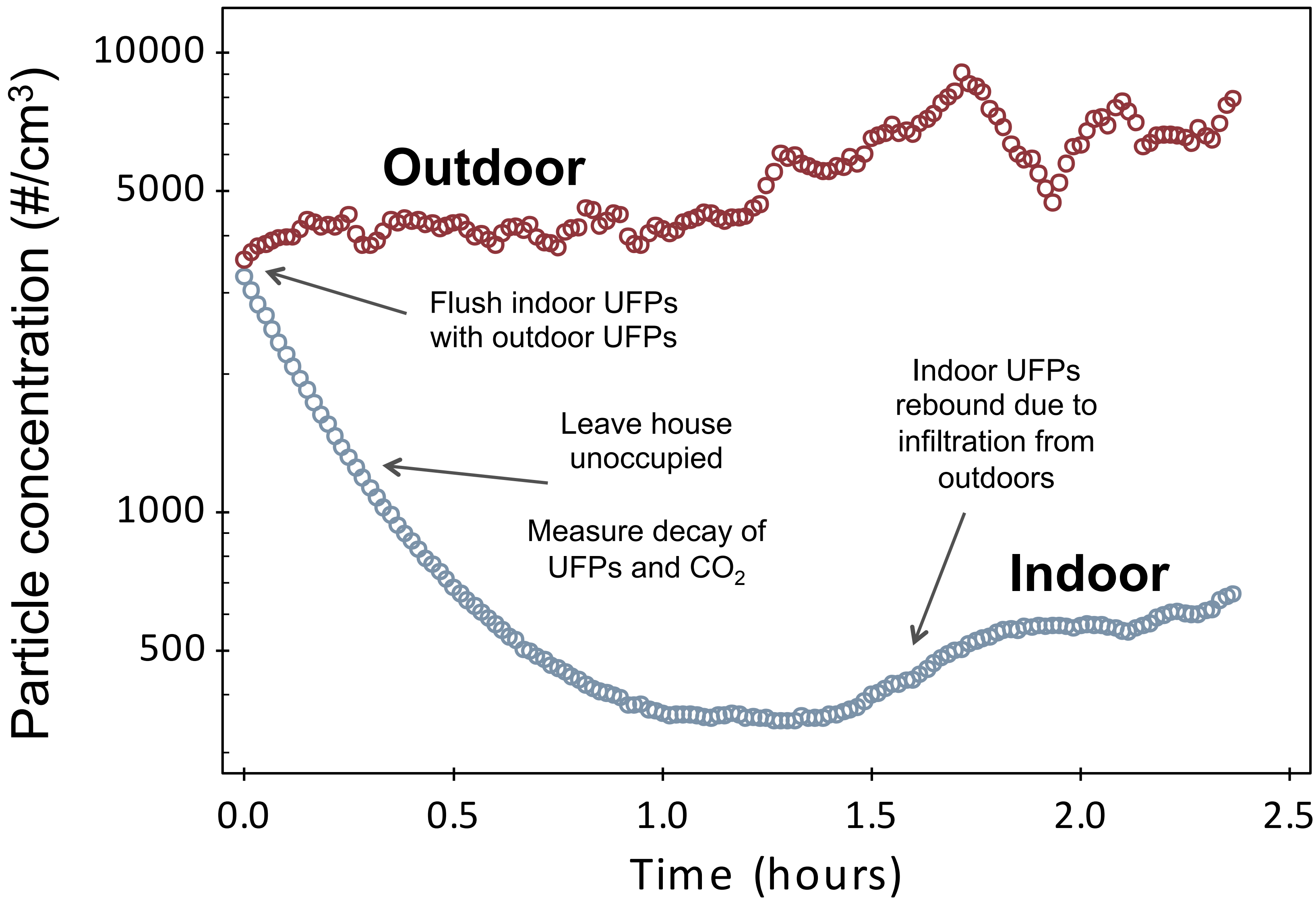
We have been working on novel methods to rapidly measure envelope penetration factors in order to characterize the ability of building envelopes to prevent the transport of outdoor pollutants indoors



- Size-resolved PM 0.01-10 μm
- $PM_{2.5}$
- Ultrafine particles (UFPs < 100 nm)
- Black carbon
- O_3
- NO_x

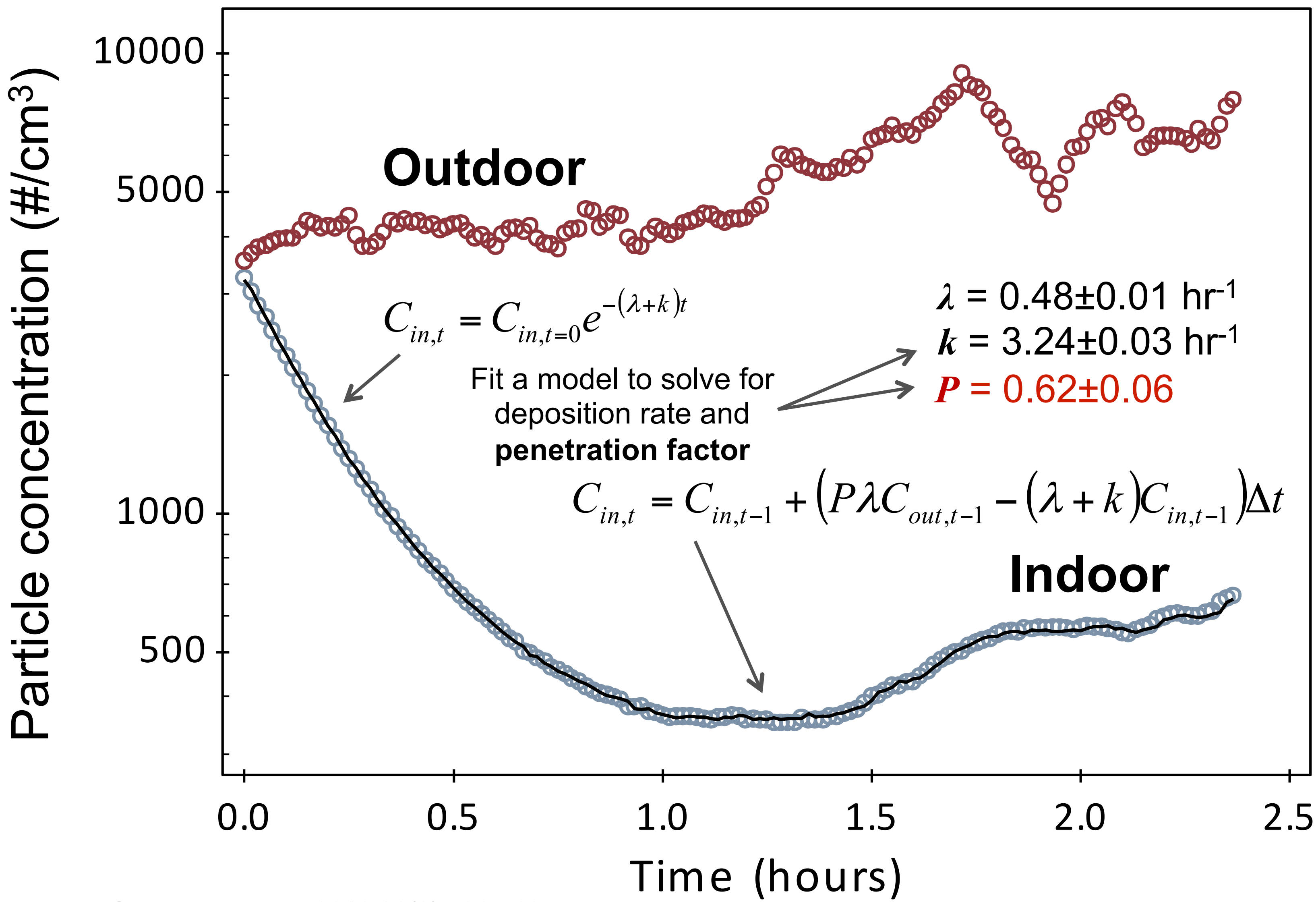
MEASUREMENTS OF PARTICLE PENETRATION FACTORS

UFP penetration tests in Austin, TX



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

UFP penetration tests in Austin, TX

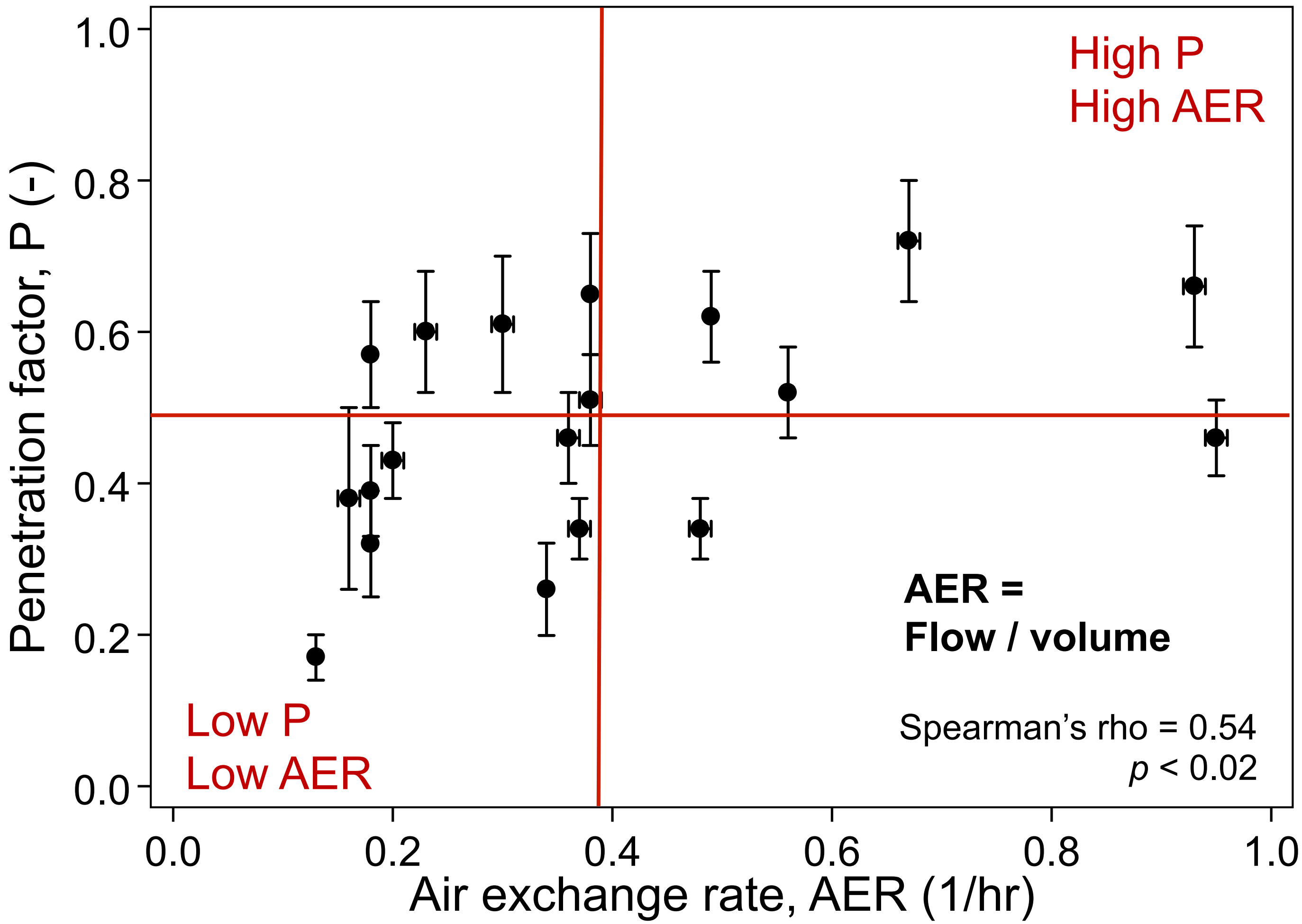


Stephens and Siegel, *Indoor Air* **2012** 22(6):501-512

UFP penetration tests in Austin, TX

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

UFP penetration results: P vs. AER



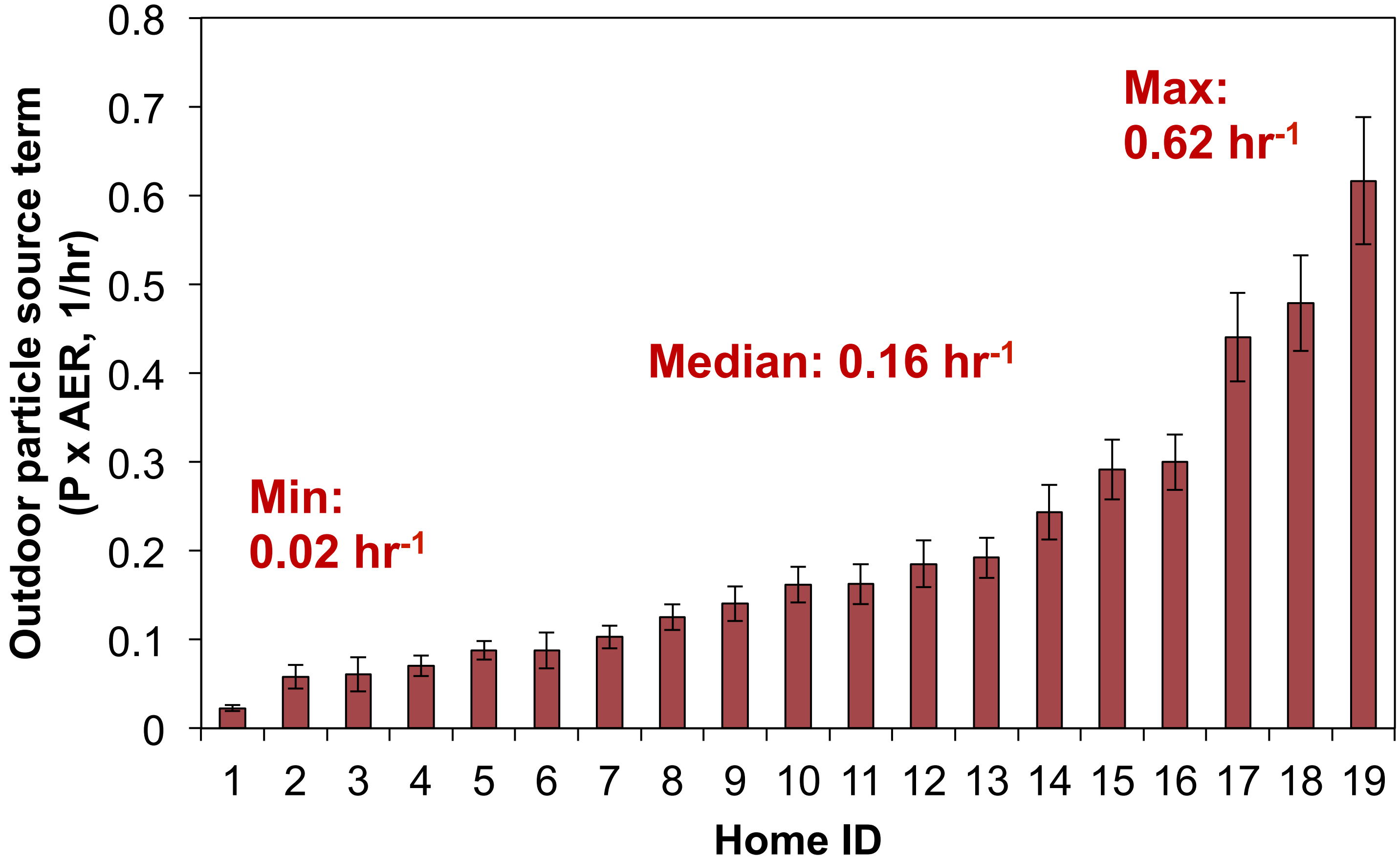
Penetration factors: Mean = 0.47 Range = 0.17 to 0.72

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

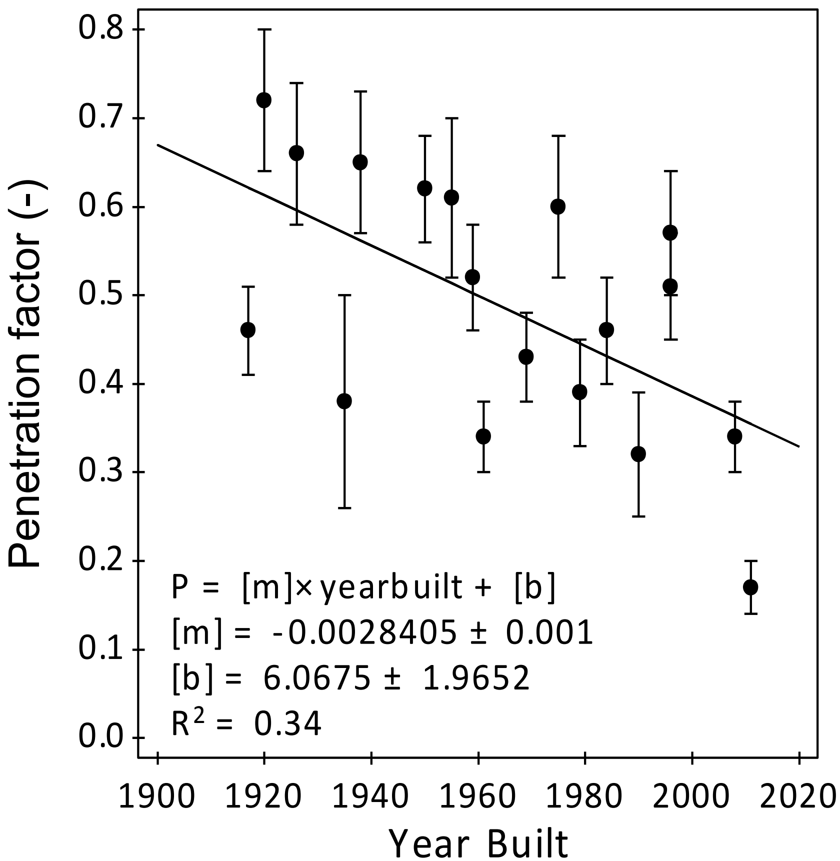
$$\frac{C_{in}}{C_{out}} = \frac{P \times AER}{AER + Loss}$$



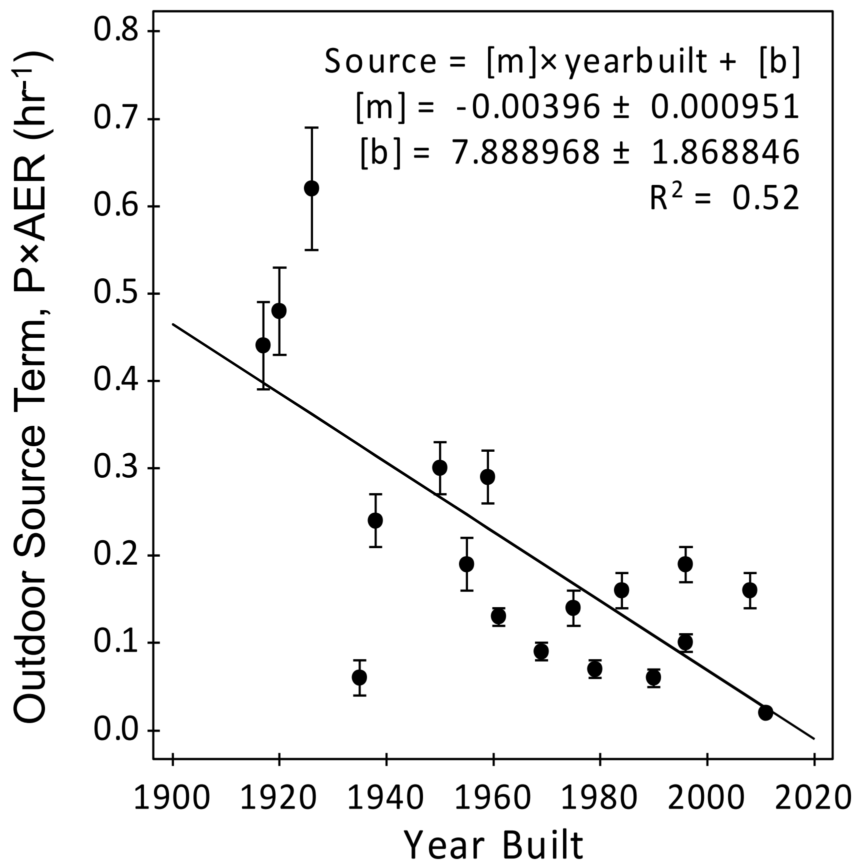
Stephens, *Science and Technology for the Built Environment* **2014** 21:3-13

PM infiltration and age of homes

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



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

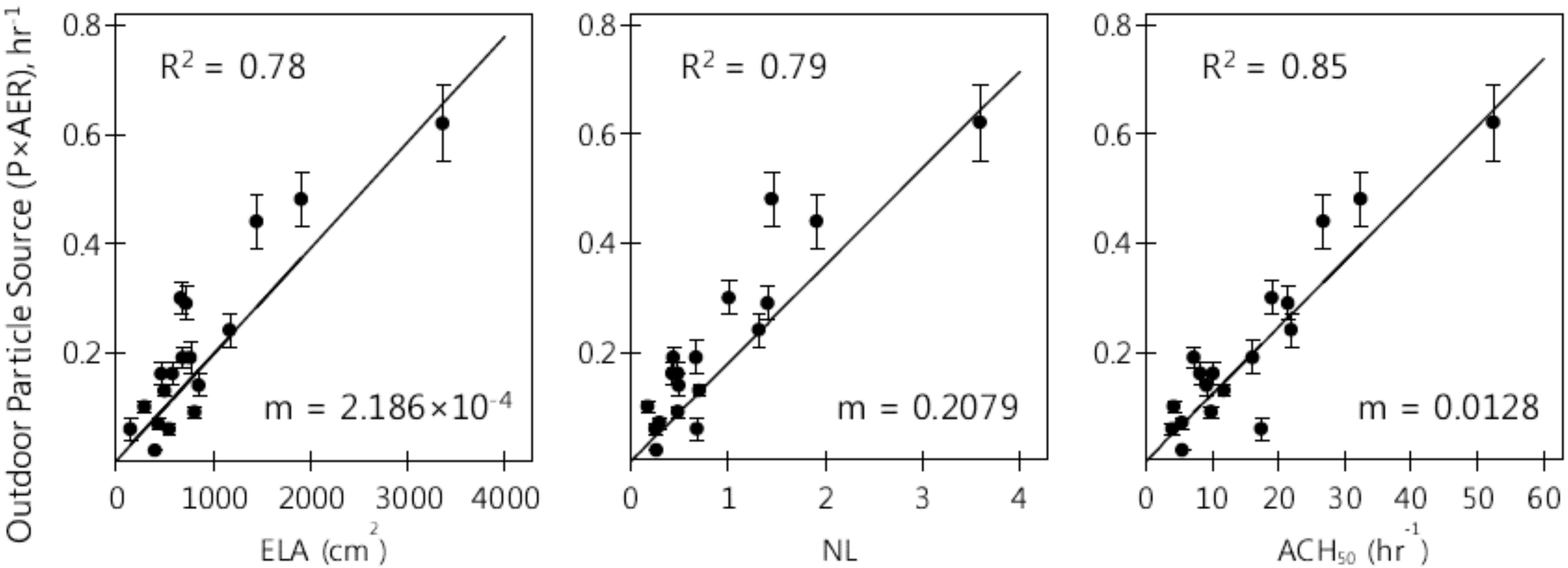


Older homes also had much higher outdoor particle source rates

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

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

Implications for UFP exposure

$$F_{inf} = \frac{C_{in}}{C_{out}} = \frac{P \times AER}{AER + Loss_{PM}}$$

- Assume mean $Loss_{UFP}$ = 1 hr^{-1}

Mean from this study

Least protective home, 1926

- P_{UFP} = 0.66 ± 0.08
- AER = 0.93 ± 0.01 hr^{-1}
- **I/O PM = 0.32**

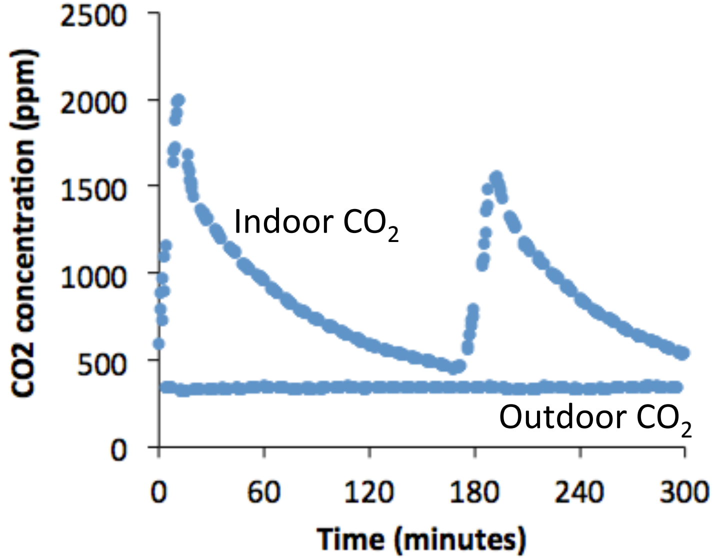
Factor of ~16

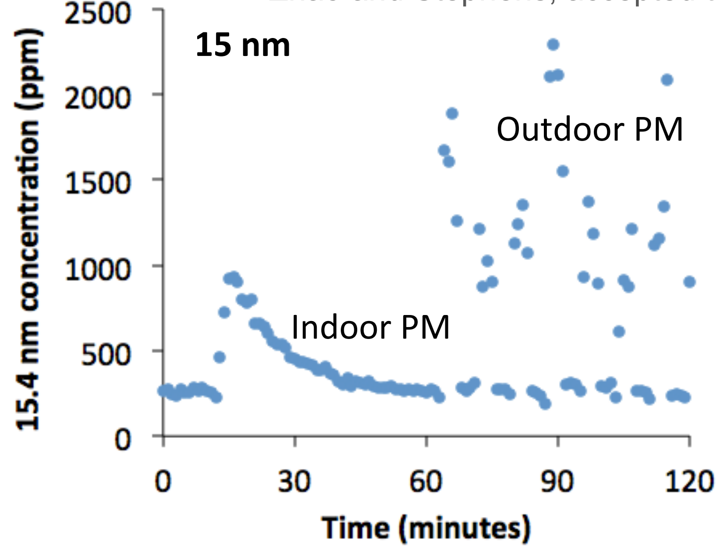
Most protective home, 2011

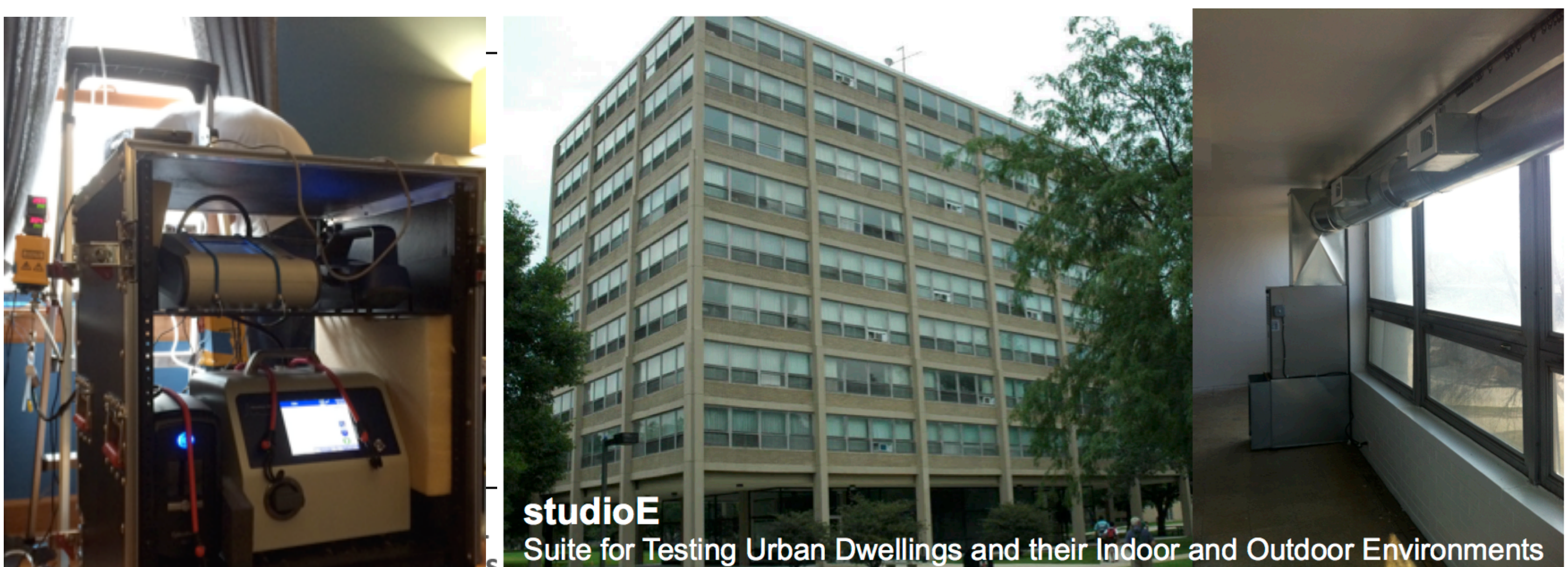
- P_{UFP} = 0.17 ± 0.03
- AER = 0.13 ± 0.01 hr^{-1}
- **I/O PM = 0.02**

Ongoing size-resolved particle penetration measurements

Zhao and Stephens, accepted to *Indoor Air* **2016**

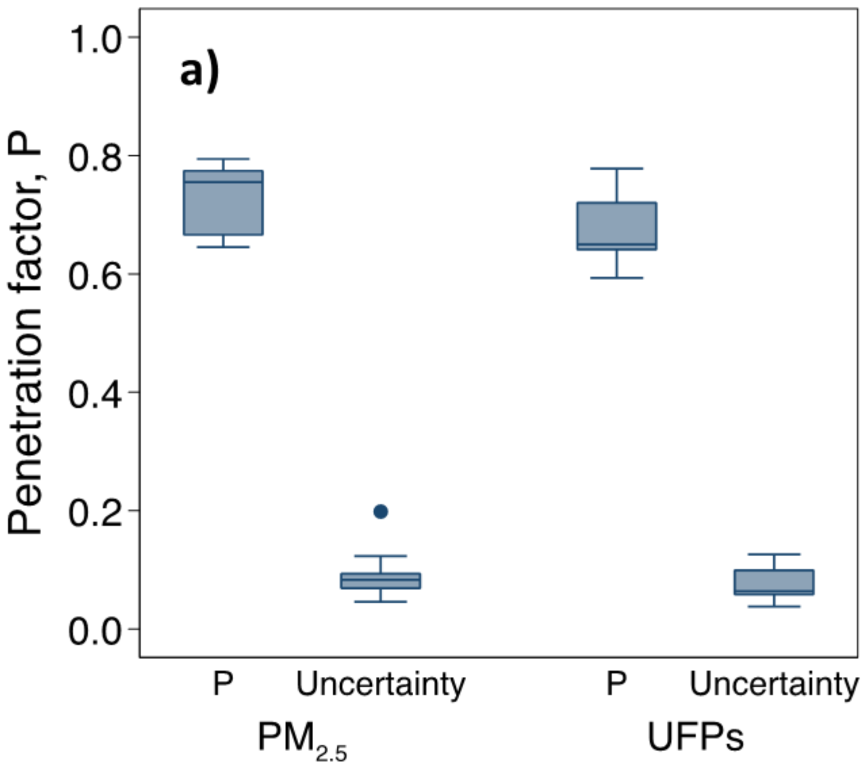


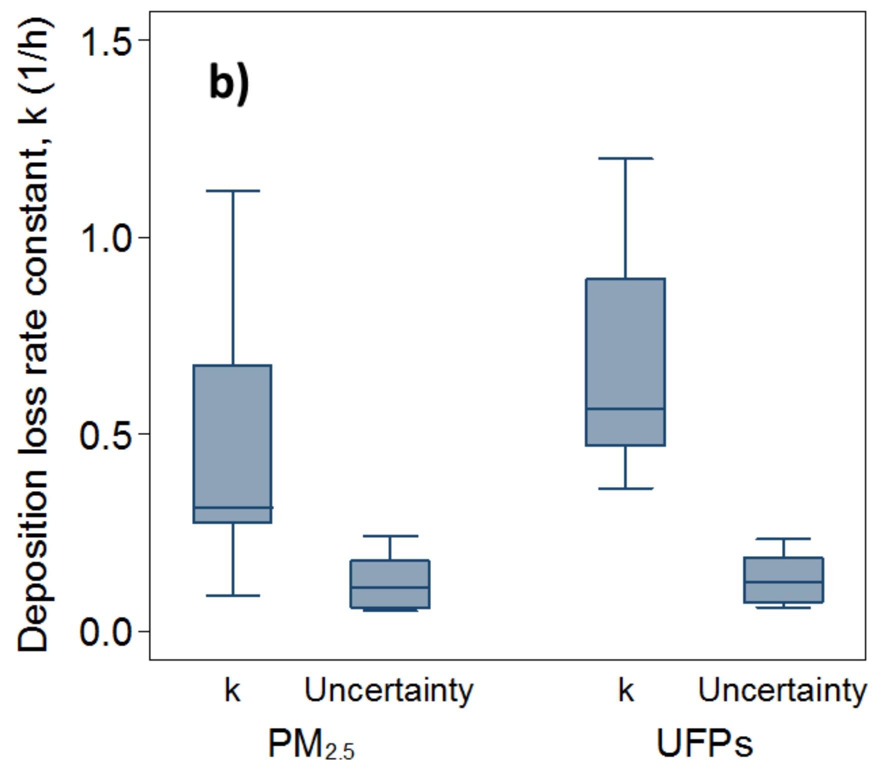




Ongoing size-resolved particle penetration measurements

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

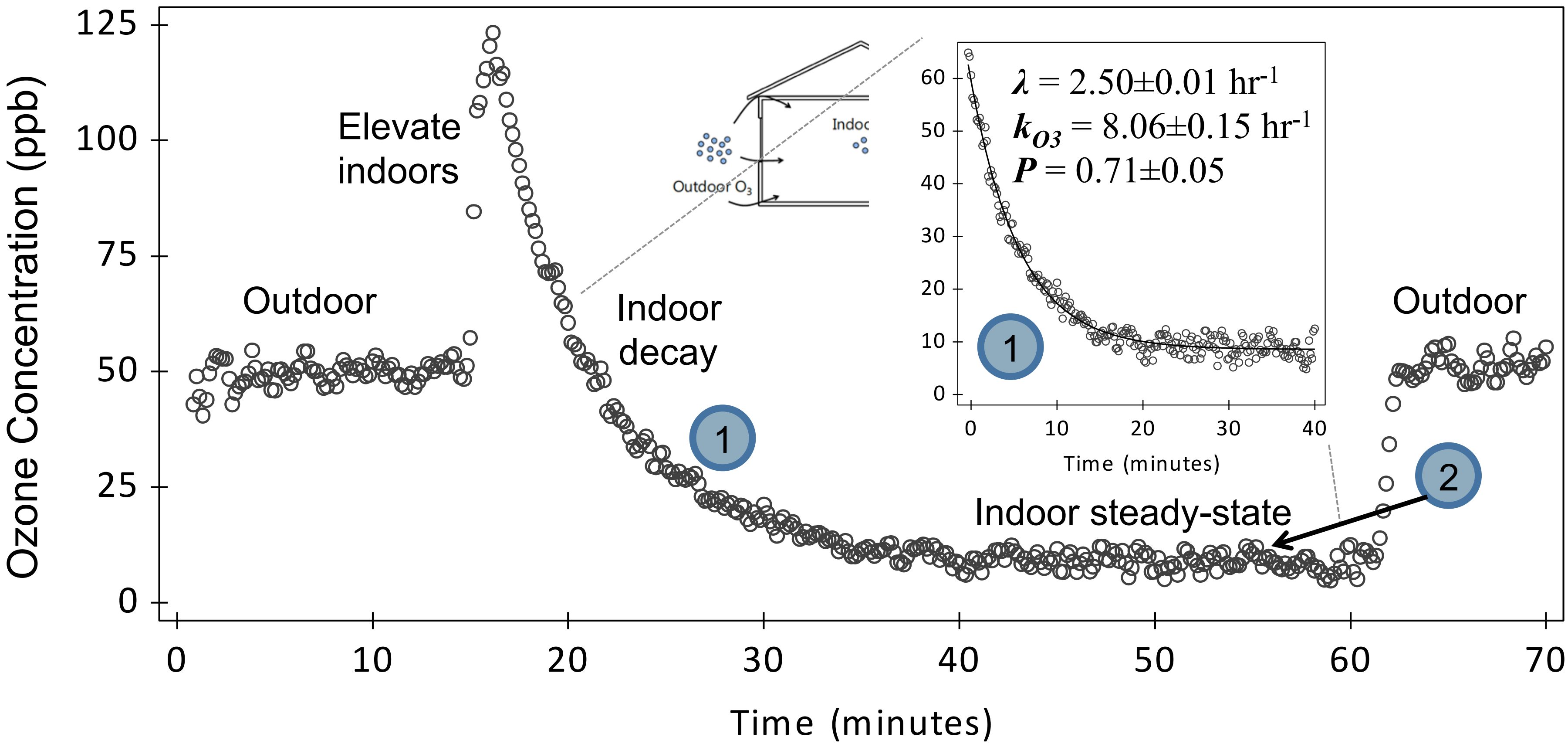




Zhao and Stephens, accepted to *Indoor Air* **2016**

MEASUREMENTS OF OZONE PENETRATION FACTORS

Ozone penetration tests in Austin, TX



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

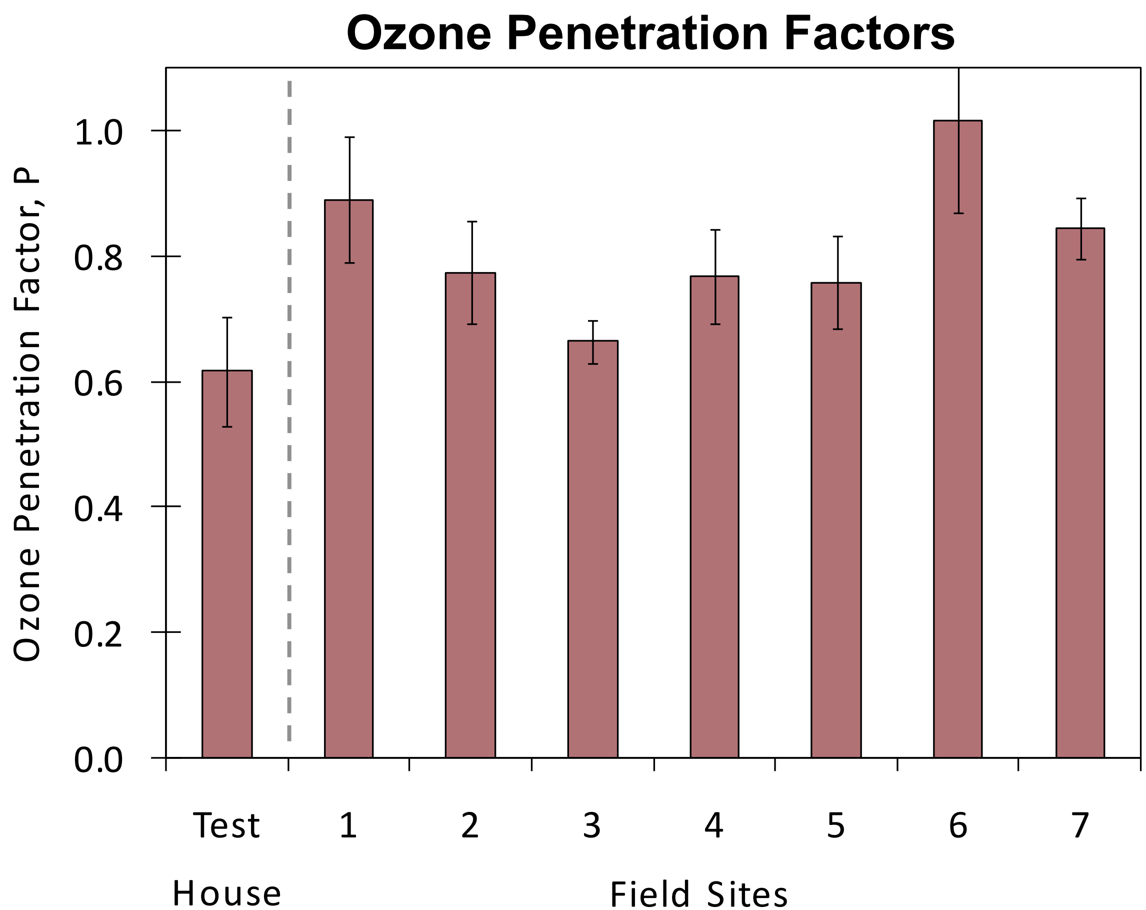
Tracer = CO_2

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

Ozone penetration tests in Austin, TX

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

Ozone penetration tests in Austin, TX



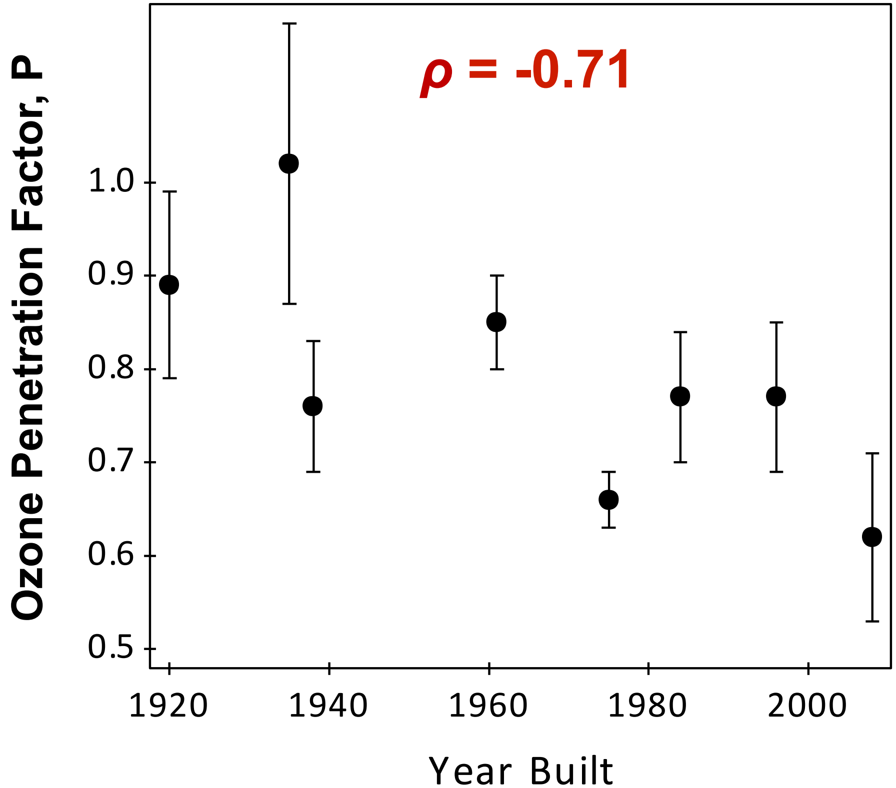
- Mean (± SD) = 0.79 ± 0.13 | Range = 0.62 ± 0.09 to 1.02 ± 0.15
- Usually assumed *P* = 1

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

Exploration of ozone results: What can we learn?

Spearman rank correlations ($p \leq 0.05$)



Ozone infiltration was lower in newer homes (small sample)

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

Implications for ozone exposure

$$F_{inf} = \frac{C_{in}}{C_{out}} = \frac{P \times AER}{AER + Loss_{O3}}$$

- Assume mean $Loss_{O3}$ = 2.8 hr^{-1}

Lee at al., **1999** *JAWMA*

Least protective home, 1920

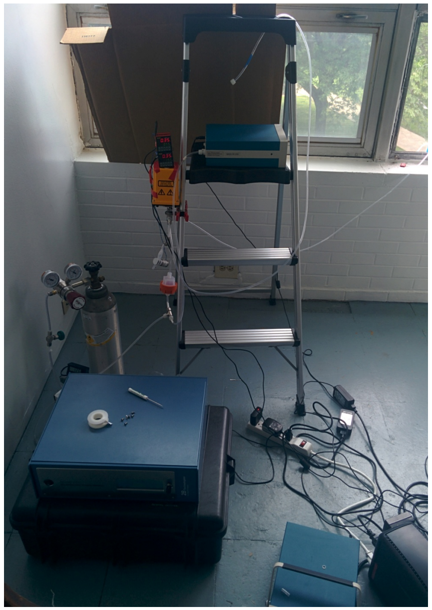
- P_{O3} = 0.89 ± 0.10
- AER = 0.93 ± 0.02 hr^{-1}
- **I/O O_3 = 0.22**

Factor of ~4.5

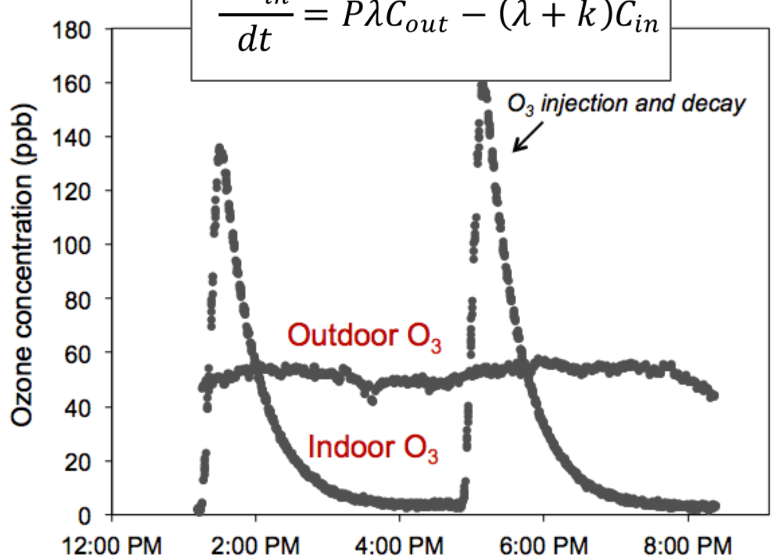
Most protective home, 2008

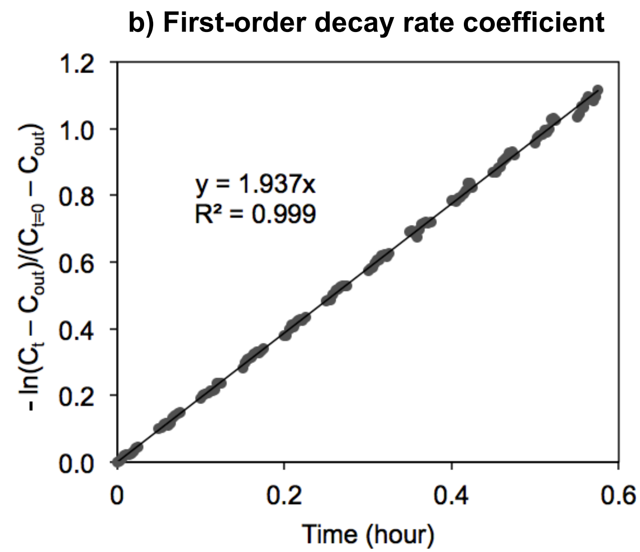
- P_{O3} = 0.62 ± 0.09
- AER = 0.24 ± 0.06 hr^{-1}
- **I/O O_3 = 0.05**

Improved method for measuring O_3 penetration



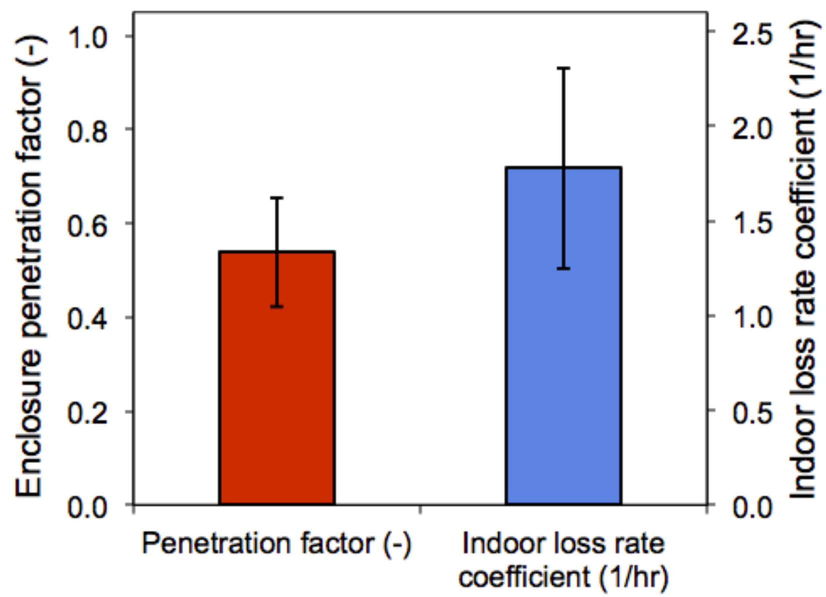
$$\frac{dC_{in}}{dt} = P\lambda C_{out} - (\lambda + k)C_{in}$$





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

- **Only ~55% enters indoors**

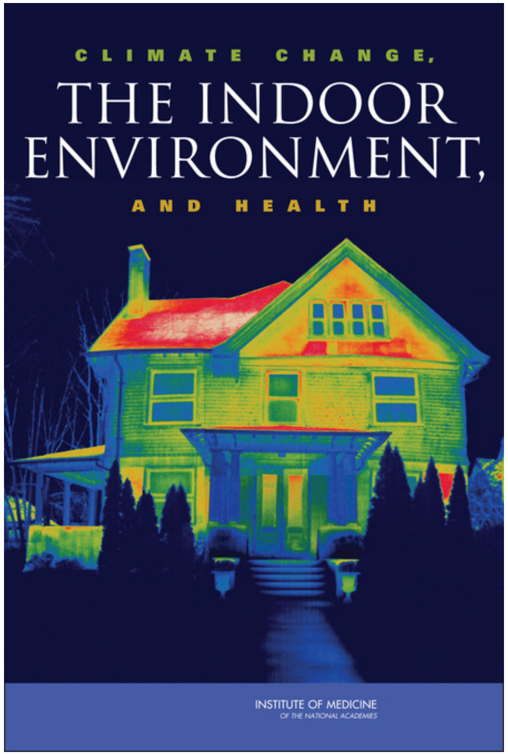


Zhao and Stephens, **2016** *Indoor Air*

CLIMATE CHANGE AND INDOOR AIR

Climate change, the indoor environment, and health

Climate change is expected to influence indoor environments and public health



IOM **2011**

US EPA asked the Institute of Medicine (IOM) of the National Academy of Sciences (NAS) to convene an expert committee to summarize the state of scientific understanding of the effects of climate change on indoor air and public health and to identify priorities for action

Spengler **2012** *Indoor Air* 22:89-95

Climate change, the indoor environment, and health

- Climate change is expected to influence indoor pollutant exposures in a number of **direct** and **indirect** ways

Nazaroff **2013** *Environ Res Lett* 8:015022

1) Changes in concentrations of outdoor pollutants → Changes in indoor **concentrations** of pollutants of **outdoor origin**

2) Buildings are operated differently (intentionally or unintentionally) → Changes in ventilation rates or HVAC operation alter indoor **concentrations** of pollutants of **both indoor and outdoor origin**

3) People alter their activities (e.g., time spent indoors or apply building retrofits to save energy) → Changes in indoor **exposures** to pollutants of **both indoor and outdoor origin**

EPA STAR: Impacts of climate change on indoor air

EPA STAR Project (2014-2017):

“Combining measurements and models to predict the impacts of climate change and weatherization on indoor air quality and chronic health effects in U.S. residences”

- What are the estimated impacts of (a) changing meteorological conditions in future climate scenarios and (b) widespread application of weatherization retrofits on indoor air quality and chronic health effects in residential buildings across the U.S.?

- **Modeling** concentrations, exposures, and health effects of indoor air in homes across U.S.
- **Field measurements** in 30 homes before and after retrofits
  - Envelope airtightness
  - *Outdoor pollutant penetration (PM, O_3, BC, NO_x)*

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