Estimating the Mortality Burden of Fine Particulate Matter Exposure Attributable to Indoor and Outdoor Microenvironments

Brent Stephens, Ph.D., Illinois Institute of Technology, Chicago, IL

Parham Azimi, Ph.D., Harvard T.H. Chan School of Public Health, Boston, MA

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Disclaimer

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Brent Stephens, Ph.D.

Associate Professor and Department Chair

Department of Civil, Architectural, and Environmental Engineering

ILLINOIS INSTITUTE OF TECHNOLOGY

Built Environment Research @ IIT

web www.built-envi.com
email brent@iit.edu
twitter @built_envi

Parham Azimi, Ph.D.

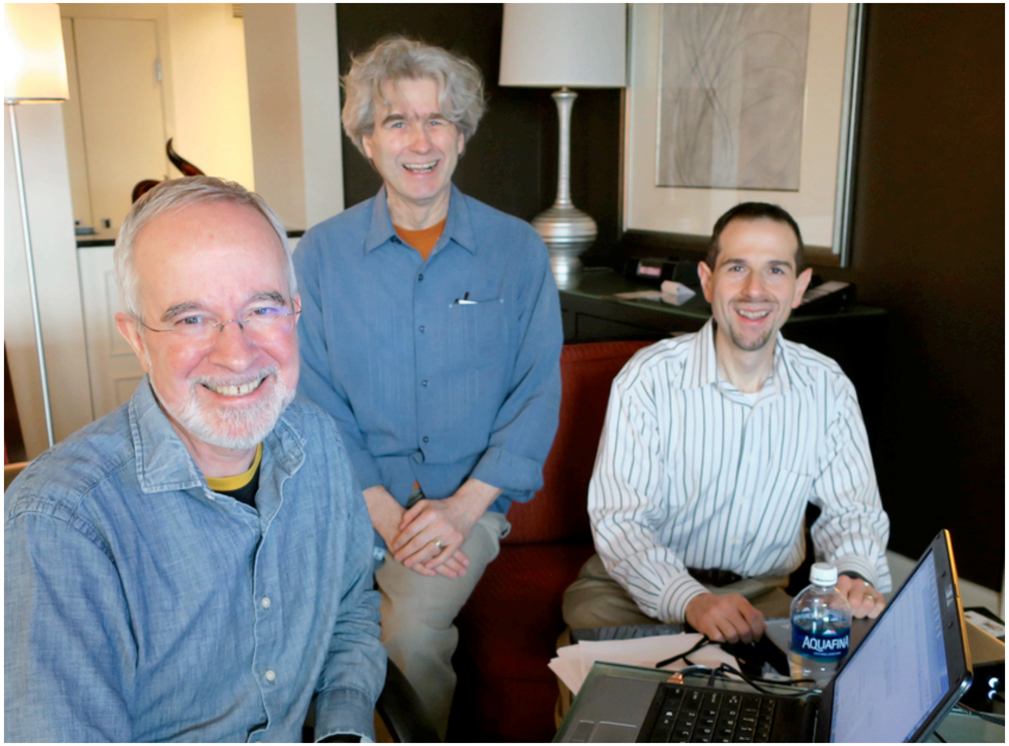
Postdoctoral Fellow, Healthy Buildings Program

Harvard T.H. Chan School of Public Health

HARVARD T.H. CHAN SCHOOL OF PUBLIC HEALTH

email pazimi@hsph.harvard.edu

Acknowledgements



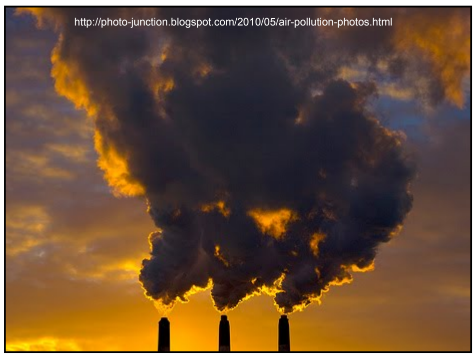
Left to right: Lew Harriman (Mason-Grant), Terry Brennan (Camroden), Vito Ilacqua (EPA)

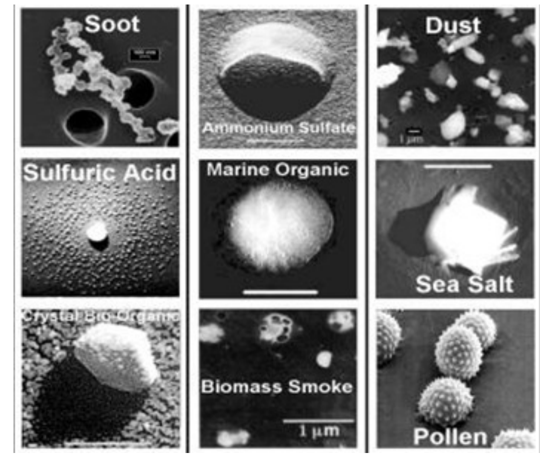
Laura Kolb (EPA)

PARTICULATE MATTER EXPOSURE AND HUMAN HEALTH

Particulate Matter (PM): Indoors and Outdoors

- Solid and liquid particles suspended in air
- Many indoor and outdoor sources
  - **Outdoors:** Traffic, industry, natural, atmospheric reactions





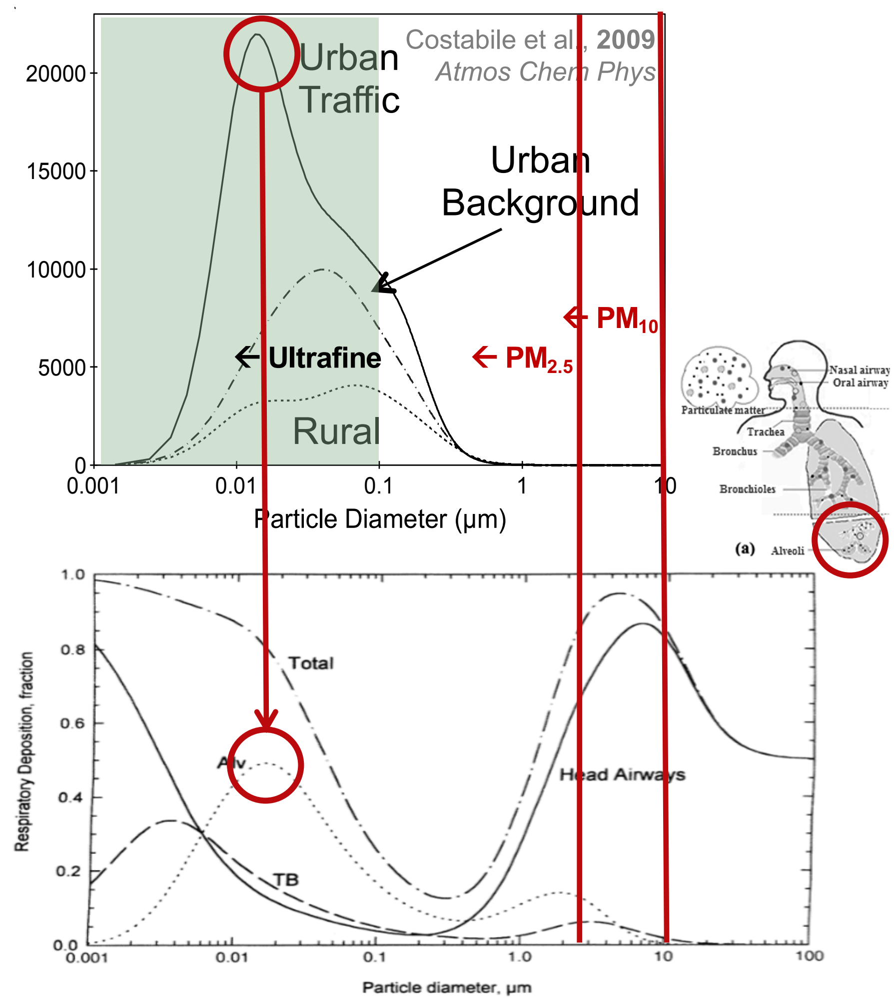
https://slideplayer.com/slide/8670425/

  - **Indoors:**
    - Appliances
    - Cleaning
    - Combustion
    - Chemical reactions
    - Resuspension
    - Others

http://nationalacademies.org/IndoorPM

Particulate Matter (PM): Indoors and Outdoors

- Wide range of sizes and constituents
  - <5 **nanometers** to >50 **micrometers**
  - Size governs deposition in the respiratory tract
  - Most particles of outdoor origin are smaller than 100 nm



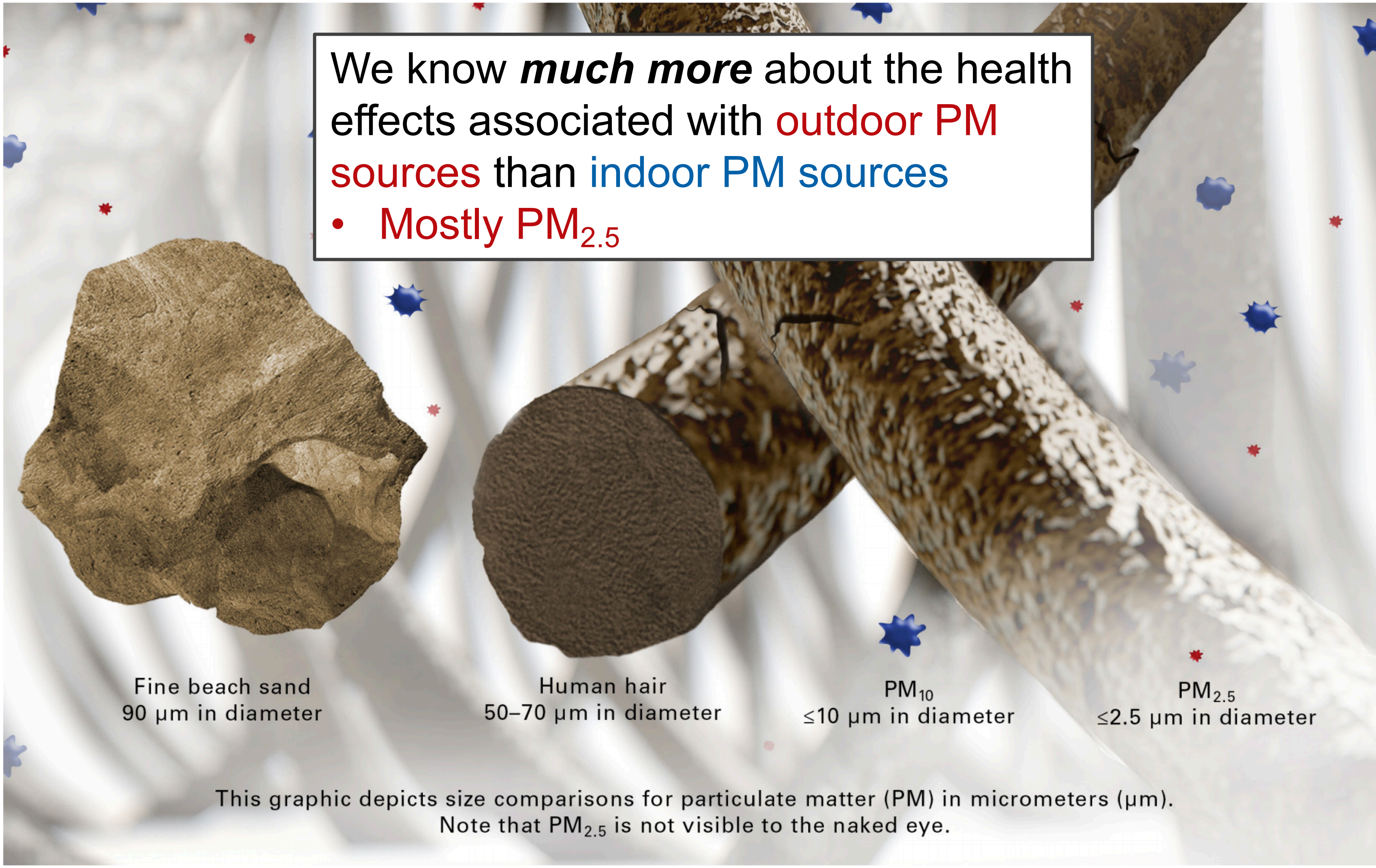
Hinds **1999** *Aerosol Technol*

- 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)

Particulate Matter (PM): Indoors and Outdoors

We know ***much more*** about the health effects associated with outdoor PM sources than indoor PM sources

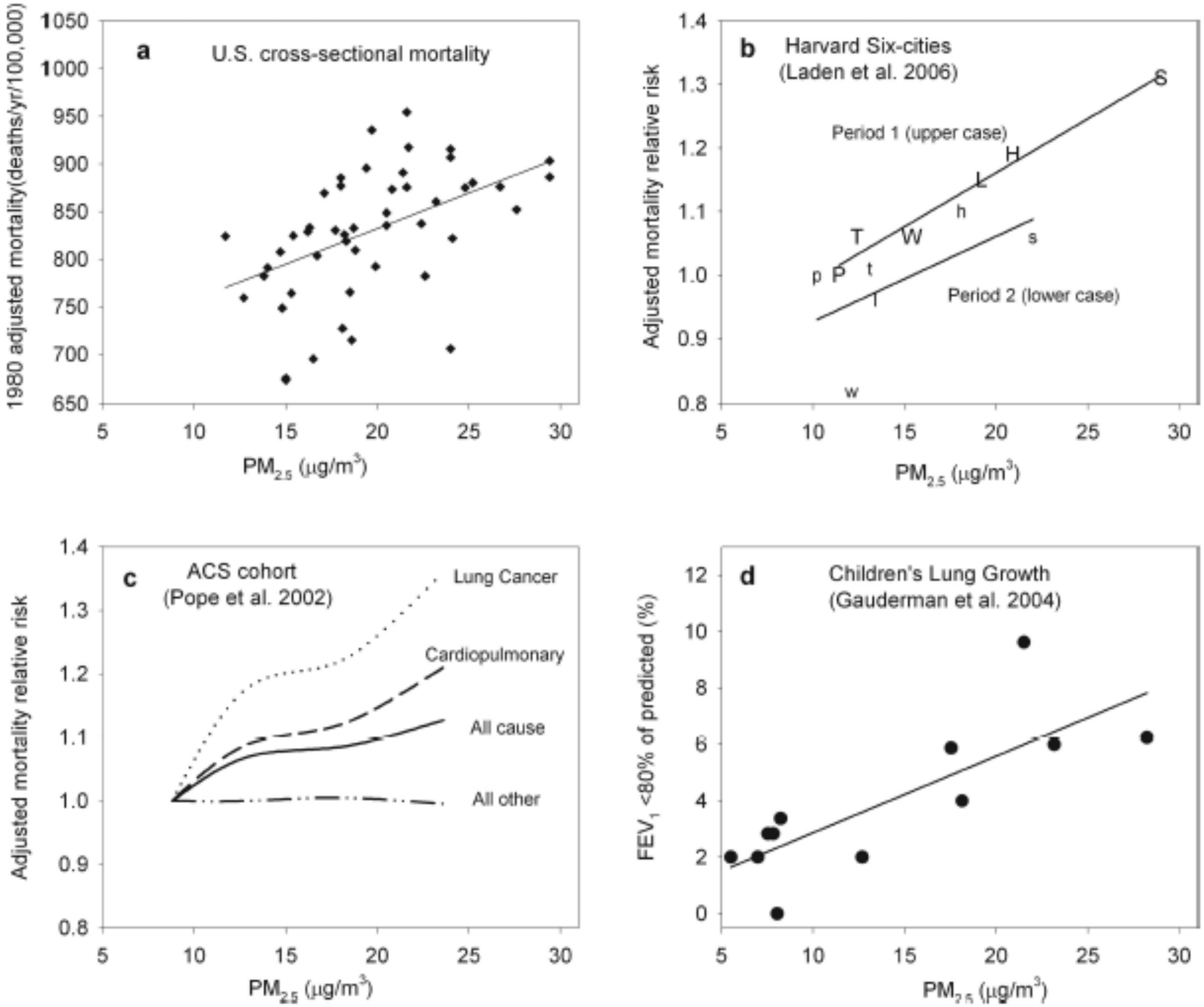
- Mostly $PM_{2.5}$



https://www.epa.gov/indoor-air-quality-iaq/air-cleaners-and-air-filters-home-printable

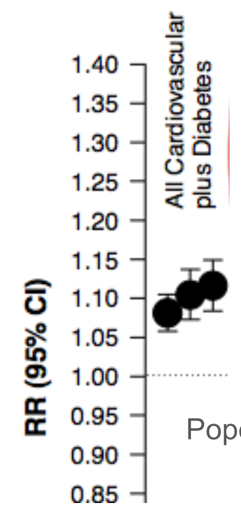
Outdoor PM and Mortality: Epidemiology

Associations with ambient fine particulate matter ($PM_{2.5}$)

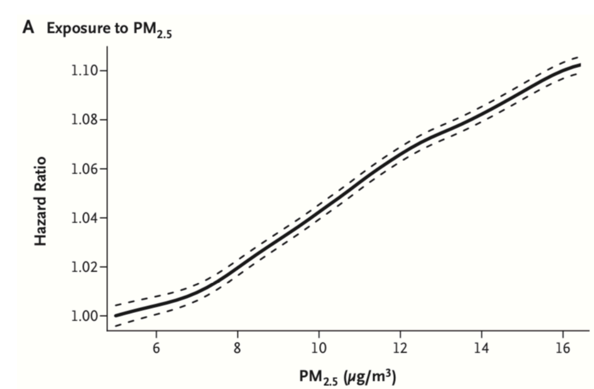


Pope and Dockery, **2006** *J Air Waste Manage Assoc*

PM in <u>outdoor</u> air



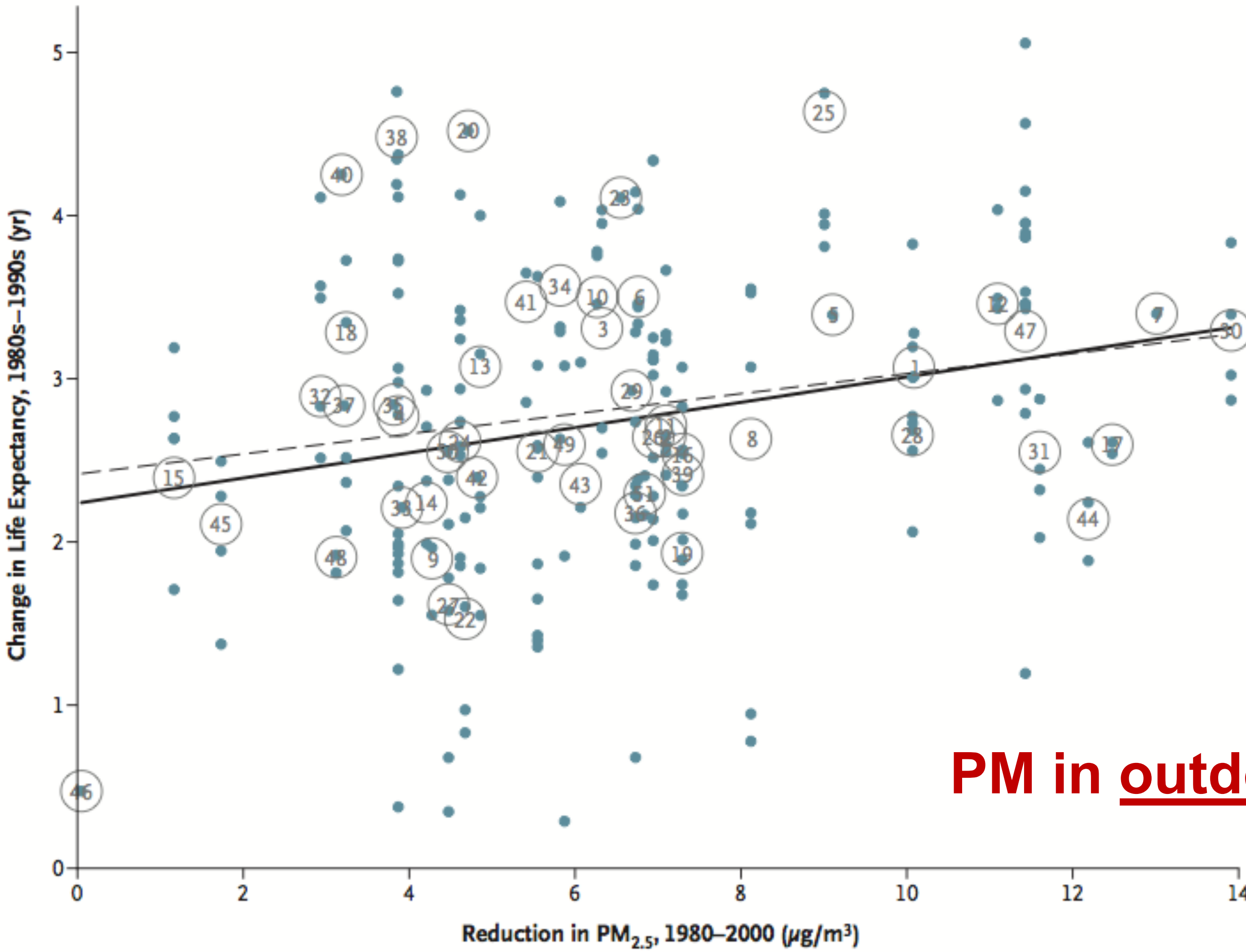
Pope et al., **2004** *Circulation*



Di et al., **2017** *NEJM*

Outdoor PM and Mortality: Epidemiology

Reduce outdoor $PM_{2.5}$ by 10 μg/m³ → increase life expectancy by 0.61 years



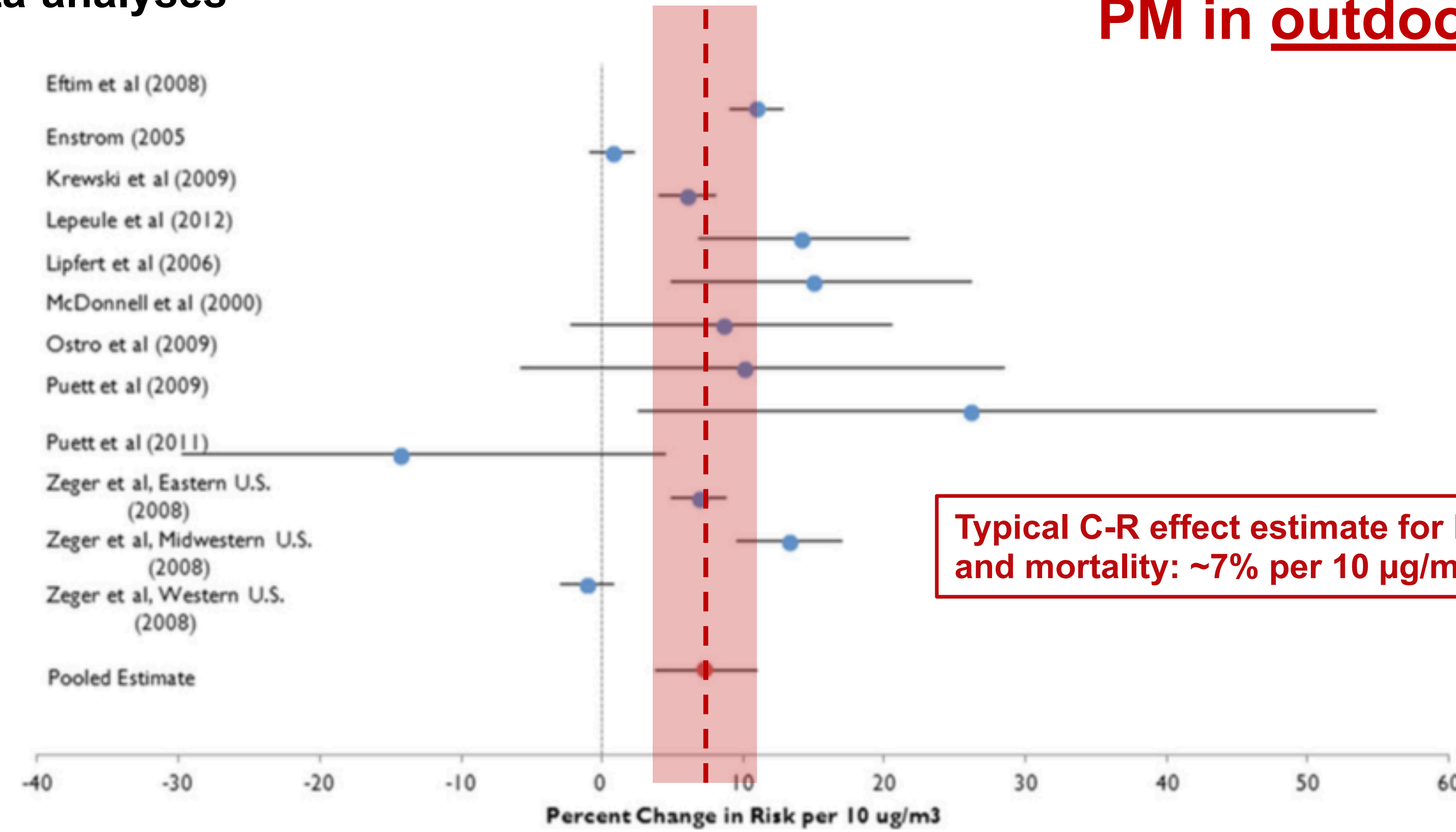
PM in <u>outdoor</u> air

Pope et al., **2009** *NEJM*

Outdoor PM and Mortality: Epidemiology

Meta-analyses

PM in <u>outdoor</u> air



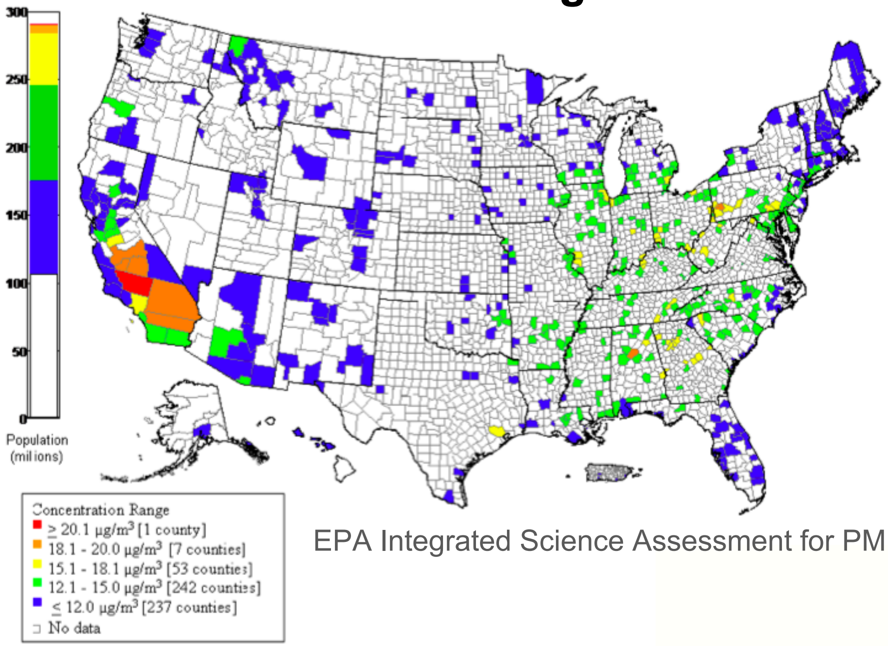
Typical C-R effect estimate for $PM_{2.5}$ and mortality: ~7% per 10 μg/m^3

Fig. 2. Pooled estimate of long-term all-cause mortality using the studies available to the experts in USEPA's 2006 elicitation and the newer studies.

Fann et al. **2016** *Risk Analysis*

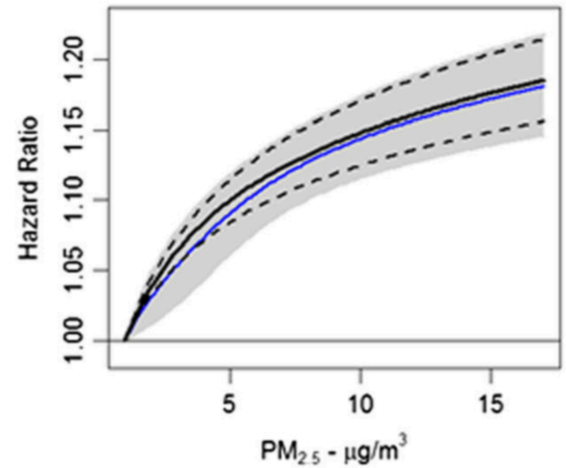
Outdoor PM and Mortality: Epidemiology → Models

Ambient monitoring sites



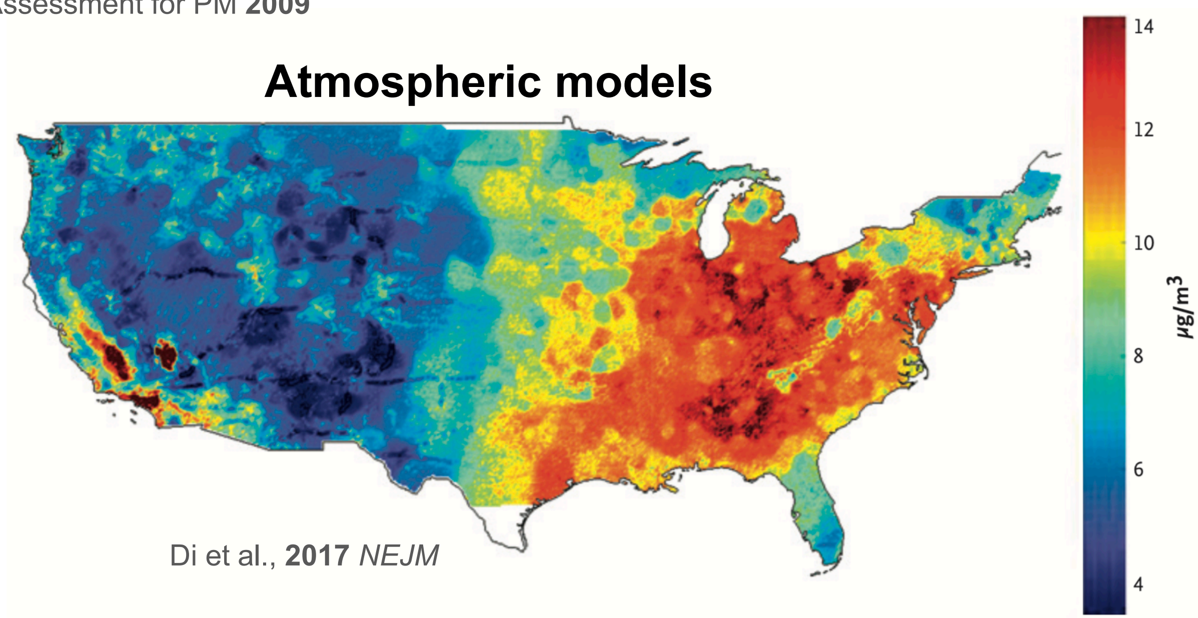
EPA Integrated Science Assessment for PM **2009**

Concentration-response (CR) functions



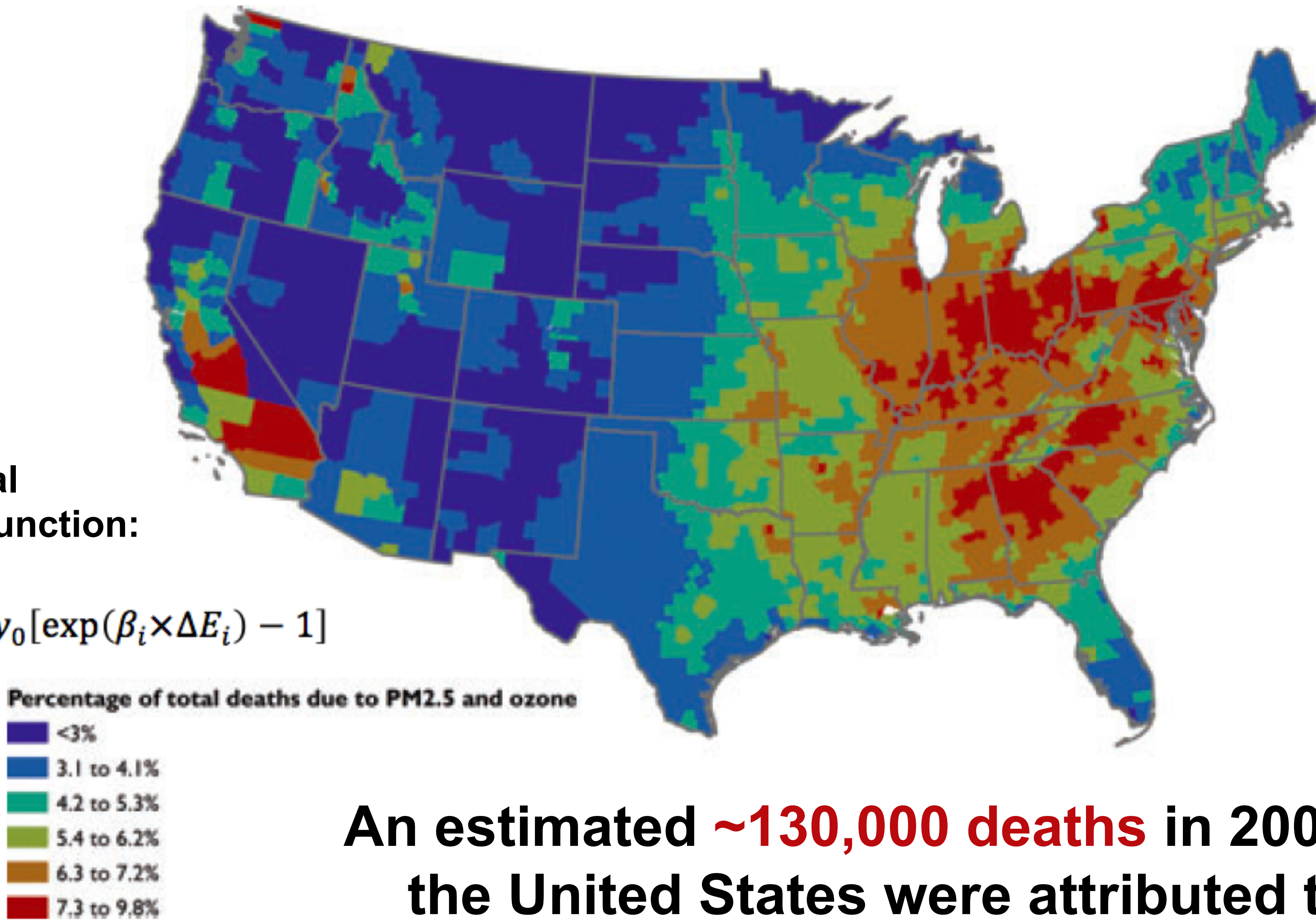
Nasari et al. **2016** *Air Qual Atmos Health*

Atmospheric models



Di et al., **2017** *NEJM*

Outdoor PM and Mortality: Epidemiology → Models



Typical C-R Function:

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

An estimated ~130,000 deaths in 2005 in the United States were attributed to outdoor $PM_{2.5}$

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

Outdoor PM and Mortality: Epidemiology → Models

- A variety of approaches have been used to estimate the mortality burden associated with exposure to ambient $PM_{2.5}$, both in the United States and globally.

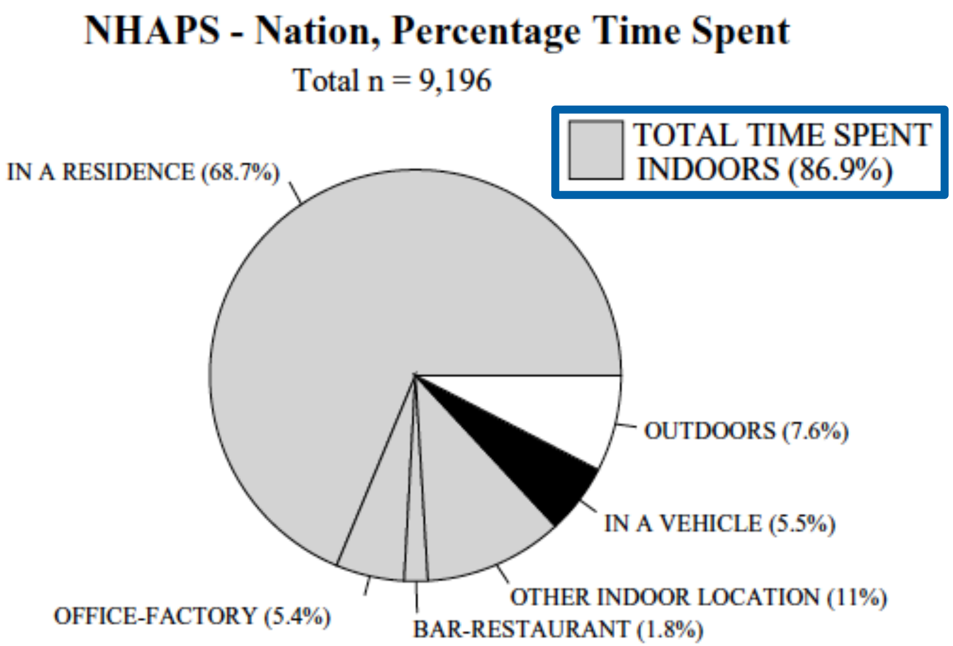
Reference	Function	U.S. Mortality Burden
Fann et al. **2012** *Risk Analysis*	Log-linear $\Delta y = y_o(e^{\beta \Delta x} - 1) Pop$	130k (51k–200k) in 2005 320k (180k–440k) in 2005
Fann et al. **2017** *Env Health Persp*	Log-linear $y_{ija} = m_{0ija} \times (e_{ij}^{\beta \cdot C} - 1) \times P_{ija}$	120k (83k–160k) in 2010 200k (43k–1.1M) in 2010
Cohen et al. **2017** *Lancet*	GBD IER $RR_{IER}(z) = 1 + \alpha \{1 - \exp[-\gamma (z - z_{cf})^{\delta}]\}$	88k (67k–115k) in 2015
Burnett et al. **2018** *PNAS*	GEMM $R(z) = \exp\{\theta \log(1 + z/\alpha)\omega(z)\}$.	121k–213k in 2015 (United States+Canada)
Tessum et al. **2019** *PNAS*	Modified GBD $HR(C) = \exp\left(\frac{\gamma * \ln(C+1)}{1 + \exp[-(C - \delta)/\lambda]}\right)$	131k (no CI) in 2015

GEMM, General Matrix-Matrix Multiplication; GBD, global burden of disease; IER, Institute for Energy Research.

Where Are We Exposed to $PM_{2.5}$?

Nearly all outdoor air pollution epidemiology studies don't account for an important point…

We spend most of our time indoors!



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

Where Are We Exposed to $PM_{2.5}$?

Joseph Allen @j_g_allen · May 20

"So there is a big question here. If all these studies have found an association between outdoor air pollution and a decrease in life quality and life expectancy, but we're not outside, how does that relationship still hold?" -@marinavance #HomesForHealth

The Hidden Air Pollution in Our Hom

Outdoor air has been regulated for dec
domestic activities may be more dange

newyorker.com

2 16 26

Joseph Allen
@j_g_allen

Following

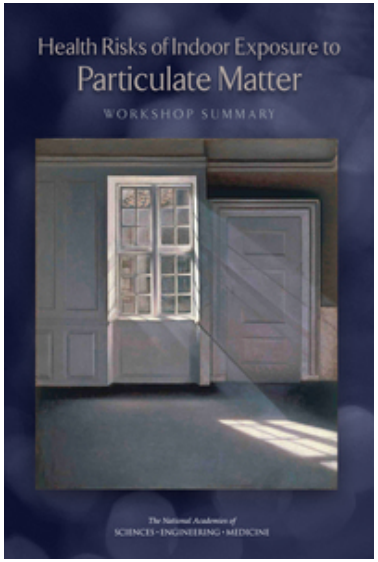
Exactly. This is the dirty secret of outdoor air pollution
(Or, more accurately, the dirty secret of outdoor air pollution epidemiology.)

> **Peter DeCarlo** @ProfPeteD
> Replying to @j_g_allen @marinavance
>
> Because in the absence of major sources (cooking/smoking) indoor fine PM levels are due to outdoor PM transported inside and, while indoor levels are lower in concentration, they are strongly correlated to outdoor PM levels.

11:15 AM - 20 May 2019

2 Likes

Where Are We Exposed to $PM_{2.5}$?



Health Risks of Indoor Exposure to

Particulate Matter

WORKSHOP SUMMARY

The National Academies of

SCIENCES · ENGINEERING · MEDICINE

said. Charles Weschler from Rutgers University said he would argue that since the bulk of exposure to outdoor PM particles occurs indoors, more is known about the risk of indoor exposure to outdoor PM than is known about the risk of outdoor exposure to outdoor PM or indoor exposure to PM of indoor origin. Kipen replied that he agreed with Weschler but that that fact is not actualized in regulation.

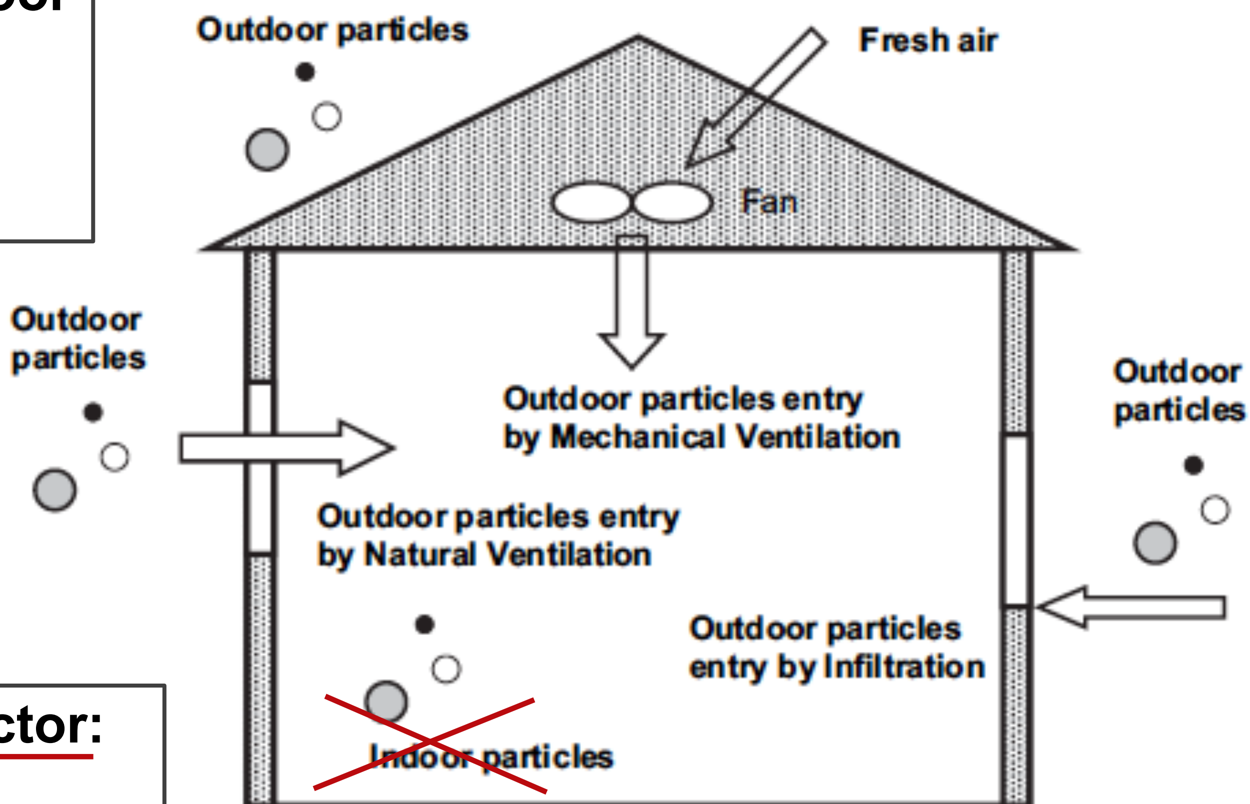
http://nationalacademies.org/IndoorPM

ATTRIBUTING $PM_{2.5}$ EXPOSURES: CONCEPTUAL FRAMEWORK

Indoor PM: Key Definitions

Indoor/Outdoor ratio:

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



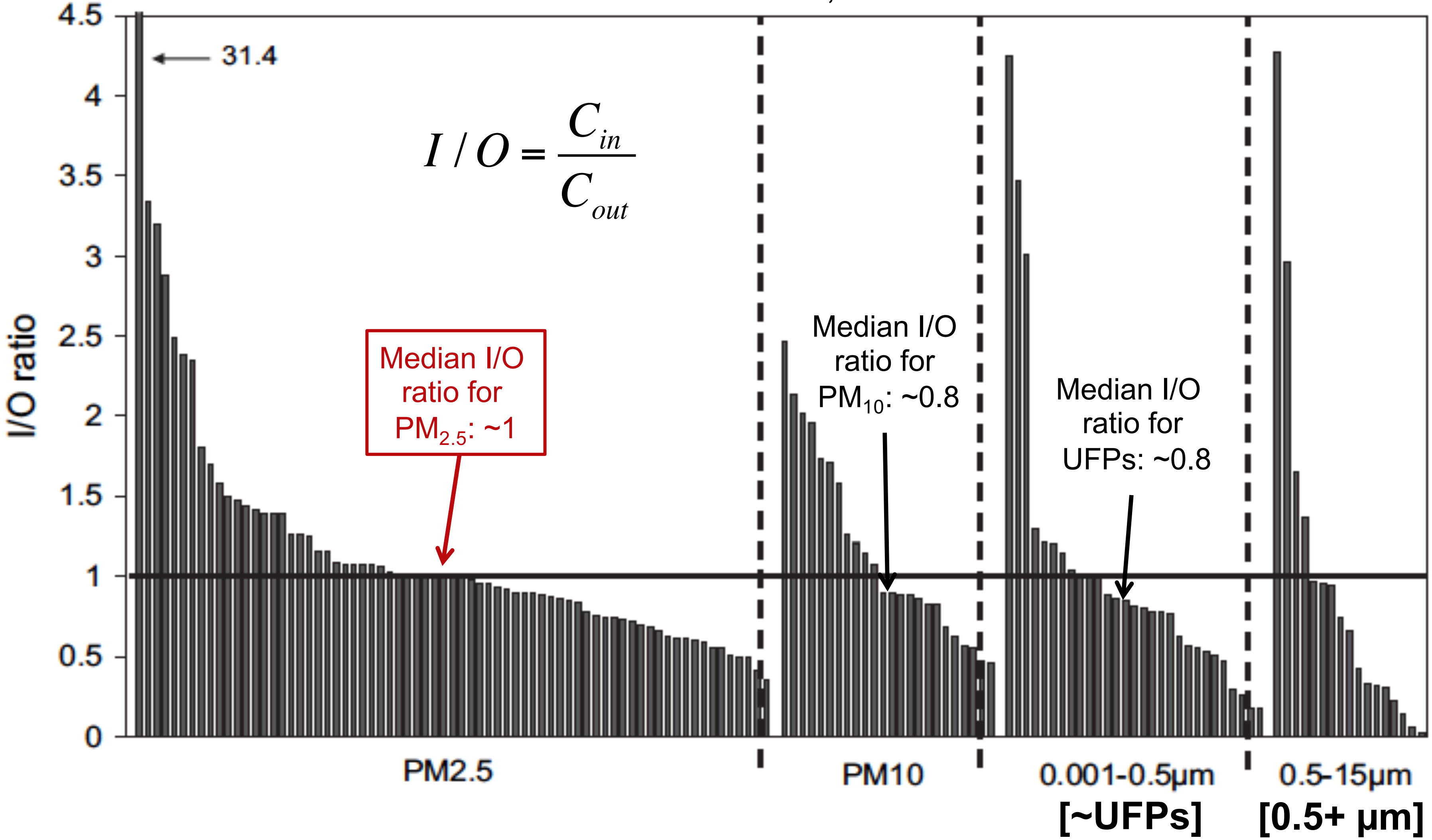
Chen and Zhao, **2011** *Atmos Environ*

Infiltration factor:

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

I/O PM Ratios: Indoor + Outdoor Sources

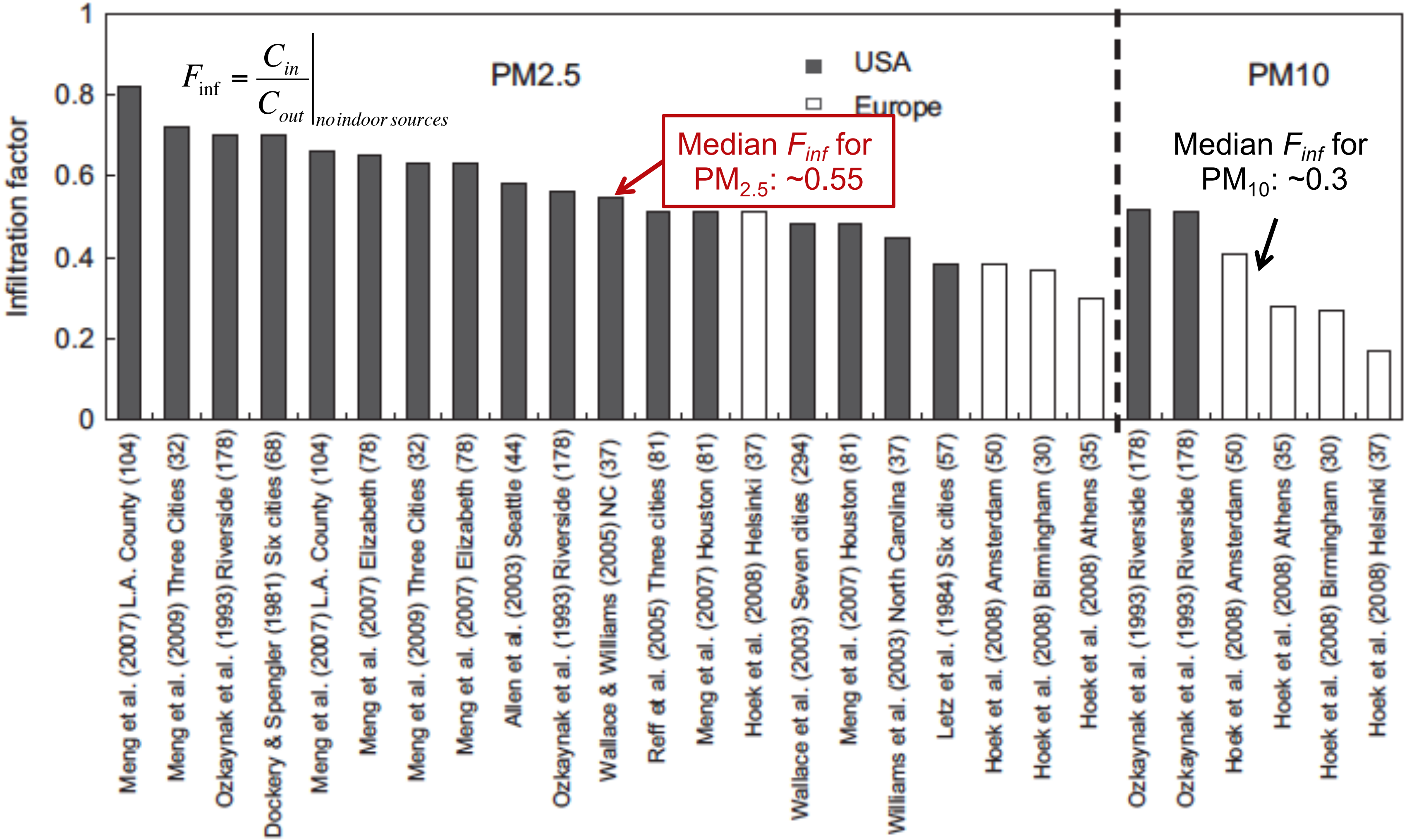
Means from 77 studies and over 4000 homes; includes indoor and outdoor sources



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

PM Infiltration Factors: Indoor PM of Outdoor Origin

Means from 21 samples from more than 20 homes (includes only outdoor PM infiltration)
Total number of homes: ~1000 in the United States and ~150 in Europe



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

Attributing $PM_{2.5}$ Exposures and Mortality Burden

- **Key issue:** Historical associations between ambient $PM_{2.5}$ concentrations and adverse health effects (e.g., mortality) have inherently (inadvertently?) accounted for exposures in all of the different environments in which people spend their time. **PLUS**, we are exposed to $PM_{2.5}$ from numerous indoor sources.

- **Our goal:** To develop and apply a framework for estimating the total U.S. mortality burden attributable to $PM_{2.5}$ exposure of both indoor and outdoor origin in the primary nonsmoking microenvironments in which people spend most of their time.

Attributing $PM_{2.5}$ Exposures and Mortality Burden

- **The framework** combines a typical **exposure-response function** with **adjusted mortality effect estimates** that account for underlying exposures to $PM_{2.5}$ of outdoor origin that likely occurred in the original epidemiology populations from which effect estimates are derived.

- We **demonstrate** the framework using **several scenarios** to estimate the potential magnitude and bounds of the U.S. mortality burden attributable to total $PM_{2.5}$ exposure (**both indoor and outdoor sources**) across all nonsmoking environments under a variety of assumptions.

Journal of Exposure Science & Environmental Epidemiology

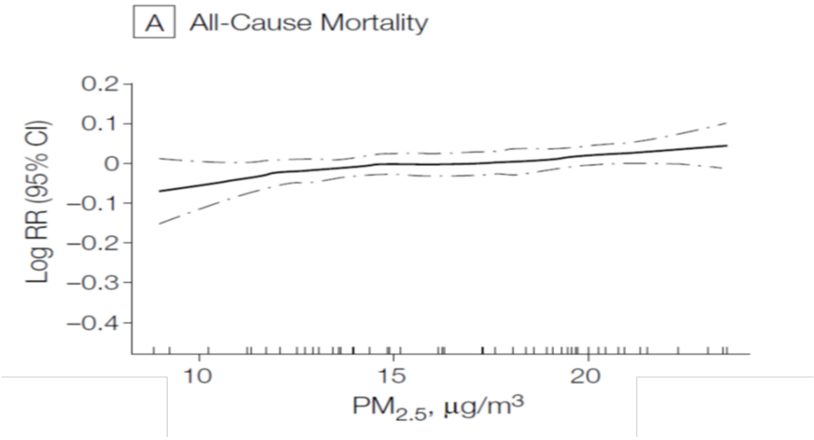
A framework for estimating the US mortality burden of fine particulate matter exposure attributable to indoor and outdoor microenvironments

Parham Azimi[1] · Brent Stephens[1]

https://www.nature.com/articles/s41370-018-0103-4

Received: 23 January 2018 / Revised: 25 September 2018 / Accepted: 12 November 2018

$PM_{2.5}$ Mortality Effect Estimates



For example, Pope et al. (2002) reported a **6%** increase in all-cause mortality *Relative Risk* (RR) with **10 μg/m^3** increase in outdoor $PM_{2.5}$ concentration

Pope et al. **2002** *JAMA*

Does the **average human's exposure concentration** to $PM_{2.5}$ of outdoor origin increase 10 μg/m^3 if the **outdoor $PM_{2.5}$** increases 10 μg/m^3?

People are usually exposed to a fraction of outdoor $PM_{2.5}$, depending on their activity patterns (e.g. <10 μg/m^3)

We think we **SHOULD NOT** use the **Relative Risk (RR) results directly** from epidemiology studies for estimating all-cause mortality associated with **indoor exposures**

Modifying the Concentration-Response (C-R) Function

Typical C-R

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

Modified C-R

$$\Delta y_{PM2.5} = y_0\left[\exp\left(\sum_z\left(\beta_{PM2.5,z,modified} \times \sum_j\left(\Delta C_{PM2.5,z,j} \times t_j\right)\right)\right) - 1\right]Pop$$

- y_0 : Annual baseline prevalence of illness (per person per year)
- β : C-R endpoint effect estimate for $PM_{2.5}$ (per μg/m^3)
- ΔE : Change in exposure concentration (μg/m^3)
- ΔC_j : Long-term $PM_{2.5}$ concentrations in a particular microenvironment j with respect to an assumed reference value (μg/m^3)
- t_j : Average fraction of time spent in a particular microenvironment j
- z: Model parameters for either indoor or ambient generated particles

Modifying the Concentration-Response (C-R) Function

- **Expanding to include indoor and outdoor $PM_{2.5}$ sources:**

$$\Delta y_{PM2.5} = y_0 \left[\exp\left(\beta_{PM2.5,IG,modified} \times \sum_j (\Delta C_{PM2.5,IG,j} \times t_j) + \beta_{PM2.5,AG,modified} \times \sum_j (\Delta C_{PM2.5,AG,j} \times t_j) \right) - 1 \right] Pop$$

Key assumption—

We assume that $PM_{2.5}$ of both indoor and outdoor origin have similar toxicity (i.e., same $\beta_{PM2.5,modified}$)

This is a key assumption, with some precedent, but the framework also can handle other assumptions if warranted

There is limited evidence both for/against this assumption:

- Ambient origin PM may be more harmful than indoor-generated PM

  Ebelt et al. **2005** *Epidemiology*
  Koeing et al. **2005** *Environ Health Perspect*

- Indoor-generated PM is at least as toxic as outdoor PM, if not more

  Long et al. **2001** *Environ Health Perspect*
  Monn and Becker **1999** *Toxicol Appl Pharmacol*

Selecting a C-R Effect Estimate for $PM_{2.5}$ Mortality

$$\Delta y_{PM2.5} = y_0 \left[\exp\left(\sum_z \left(\underbrace{\beta_{PM2.5,z,modified}}_{1} \times \sum_j \left(\Delta C_{PM2.5,z,j} \times t_j \right) \right) \right) - 1 \right] Pop$$

***β:* C-R endpoint effect** estimates commonly range from 5.8% to 26% per 10 μg/m^3

Di et al. **2017**, *NEJM*; Jerrett et al. **2005**, *Epidemiology*; Pope et al. **2002**, *JAMA*; Roman et al. **2008**, *Environ Sci Technol*; and others

We assume an all-cause mortality relative risk (RR) for $PM_{2.5}$ of ambient origin from a **recent meta-analysis** of ambient $PM_{2.5}$ mortality effects:

7.3% per 10 μg/m^3 (95% CI: 3.7% to 11%)

Fann et al. **2016**, *Risk Analysis*

$$\beta_{PM2.5} = \ln(RR)/10$$

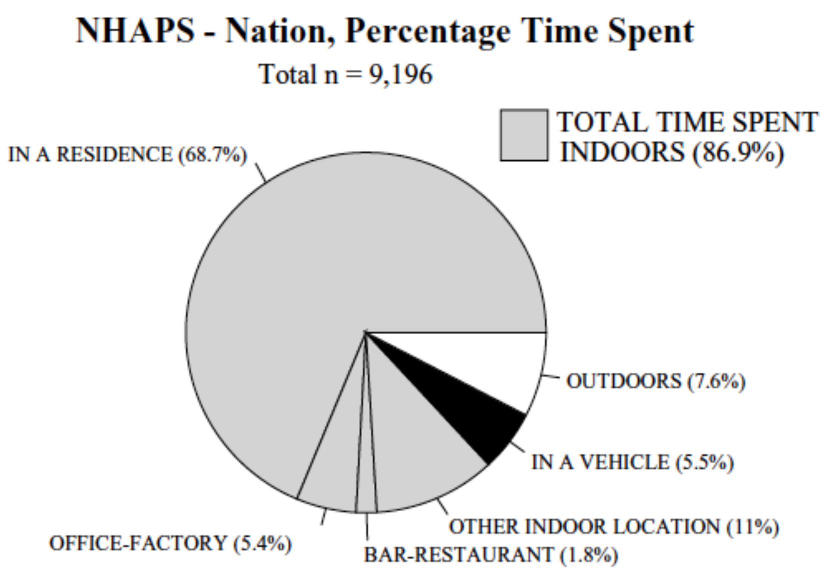
$\beta_{PM2.5,OutdoorOrigin}$: **0.0070** (95% CI: 0.0036 to 0.0104) per 1 μg/m^3

Modifying the C-R Effect Estimate to Account for Exposure

$$\beta_{PM2.5,modified} = \frac{\beta_{PM2.5}}{\Sigma F_j \times t_j}$$

$$\Sigma F_j \times t_j = (F \times t)_{outdoor} + (F \times t)_{residence} + (F \times t)_{vehicle} + (F \times t)_{other\ indoor}$$

- F_j : Average $PM_{2.5}$ infiltration in a particular microenvironment *j*
- t_j : Average fraction of time spent in a particular microenvironment *j*



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

Four main microenvironments—

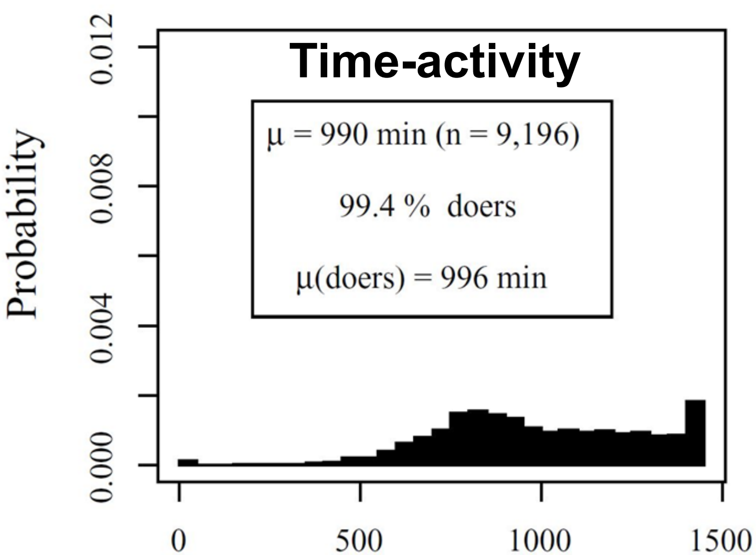
1. Inside residences
2. Inside other buildings
3. Inside vehicles
4. Outside

Modifying the C-R Effect Estimate to Account for Exposure

People in the United States spend their time in a variety of microenvironments with different $PM_{2.5}$ infiltration factors (F_j):

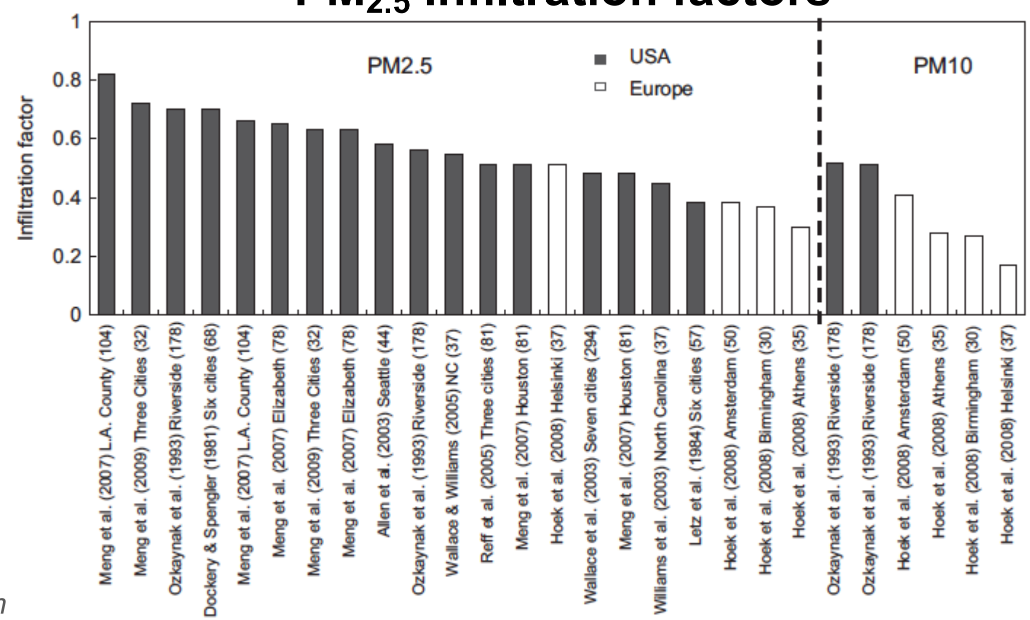
- Time spent, $t_{residence}$ = 68.7% in residences
- $F_{residence}$ = 0.59

Beta distributions were used to fit to the ranges of infiltration factors for each microenvironment.



Klepeis et al. **2001**, *J Exposure Analysis Environ Epidem*

$PM_{2.5}$ infiltration factors



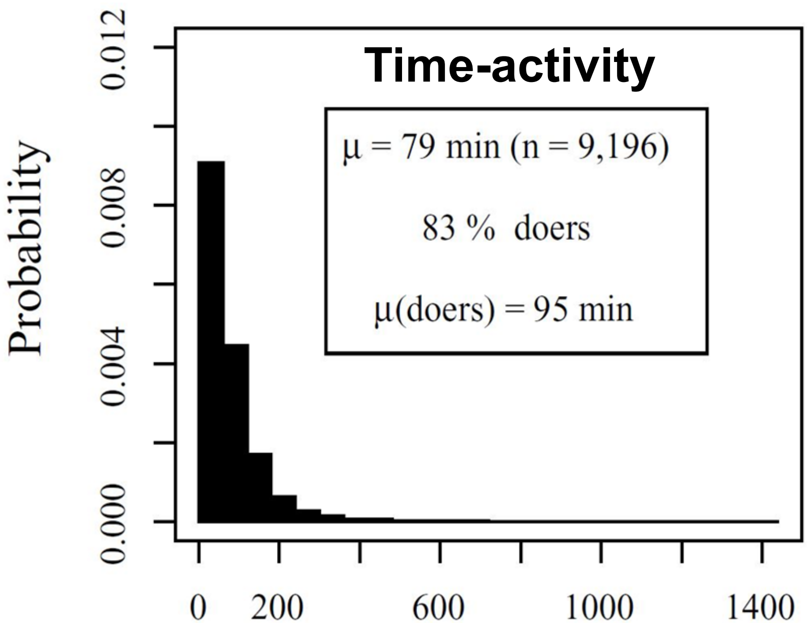
Chen and Zhao **2011**, *Atmospheric Environment*

Inside residences

Modifying the C-R Effect Estimate to Account for Exposure

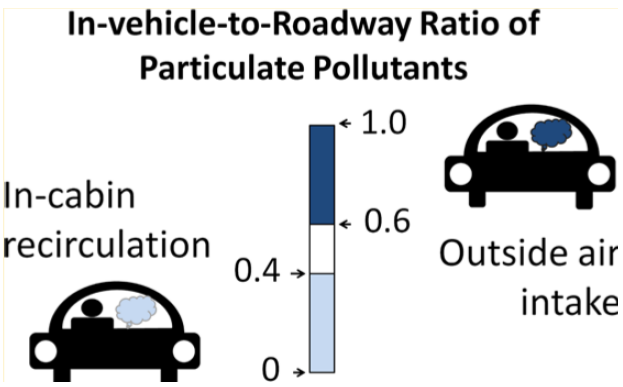
- Time spent, $t_{vehicle}$ = 5.5% in vehicles
- $F_{vehicle}$ = 0.43

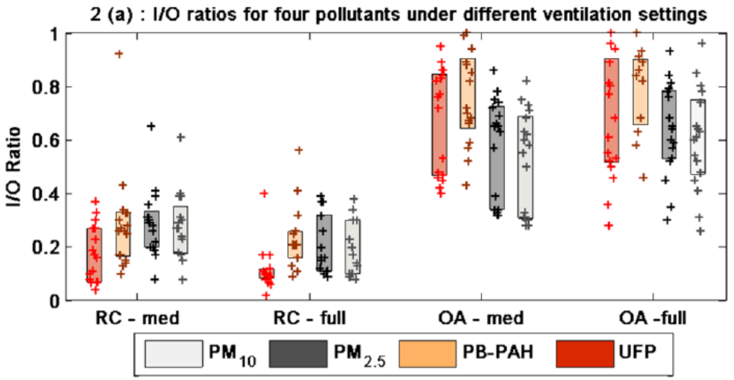
(assuming 0.25 with recirculated air and 0.61 with outdoor air ventilation)



Klepeis et al. **2001**, *J Exposure Analysis Environ Epidem*

$PM_{2.5}$ infiltration factors





Hudda and Fruin **2013**, *Environ Sci Technol*

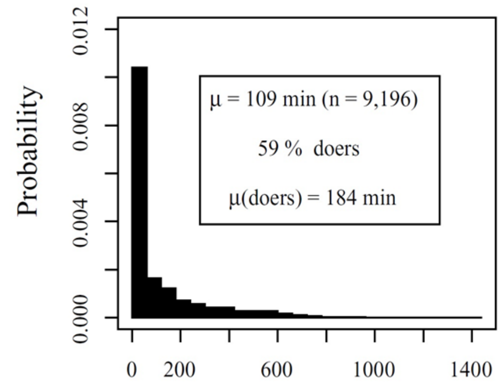
Inside vehicles

Modifying the C-R Effect Estimate to Account for Exposure

- Time spent, $t_{outdoor}$ = 7.6% outdoors
- $F_{outdoor}$ = 1

Outdoors

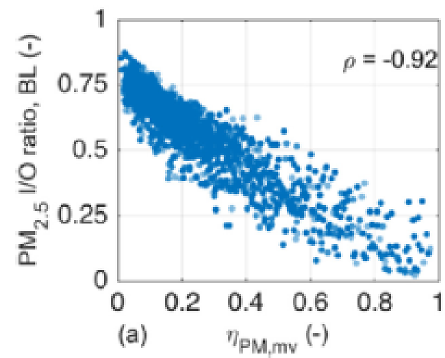
Klepeis et al. **2001**, *J Exposure Analysis Environ Epidem*



- Time spent, $t_{other\ indoor}$ = 18.2% in indoor locations other than residences (e.g., offices, factories, bars, schools, and restaurants)
- $F_{other\ indoor}$ = 0.49

Inside other buildings

Ben-David et al. **2017**, *Building and Environment*



$$\beta_{PM2.5,modified} = \frac{\beta_{PM2.5}}{\Sigma F_j \times t_j}$$

The mean value of $\Sigma F_i \times t_i$ was estimated to be ~0.60

$$\beta_{PM2.5,modified} = \mathbf{0.16}$$ per 10 μg/m³

Modifying the Concentration-Response (C-R) Function

$$\Delta y_{PM2.5} = y_0 \left[\exp\left(\sum_z \left(\beta_{PM2.5,z,modified} \times \sum_j \left(\underline{\Delta C_{PM2.5,z,j}} \times t_j \right) \right) \right) - 1 \right] Pop$$

2

- **Expanding to include <u>indoor</u> and <u>outdoor</u> $PM_{2.5}$ sources in the <u>four</u> <u>main</u> <u>microenvironments</u>:**

IG = Indoor-generated
AG = Ambient-generated

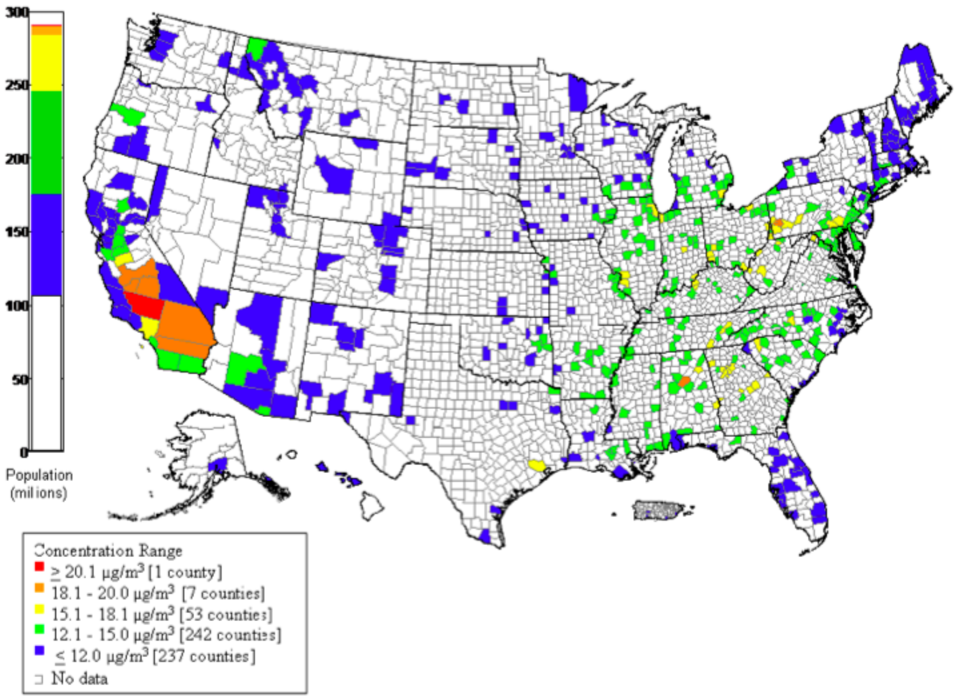
$$\sum_j (\Delta C_{PM2.5,IG,j} \times t_j) = \left(\Delta C_{PM2.5,IG,residences} \times t_{residences} \right) + \left(\Delta C_{PM2.5,IG,other\ indoor} \times t_{other\ indoor} \right)$$

$$\sum_j (\Delta C_{PM2.5,AG,j} \times t_j) = \left(\Delta C_{PM2.5,AG,residences} \times t_{residences} \right) + \left(\Delta C_{PM2.5,AG,other\ indoor} \times t_{other\ indoor} \right) + \left(\Delta C_{PM2.5,AG,vehicles} \times t_{vehicles} \right) + \left(\Delta C_{PM2.5,outdoor} \times t_{outdoor} \right)$$

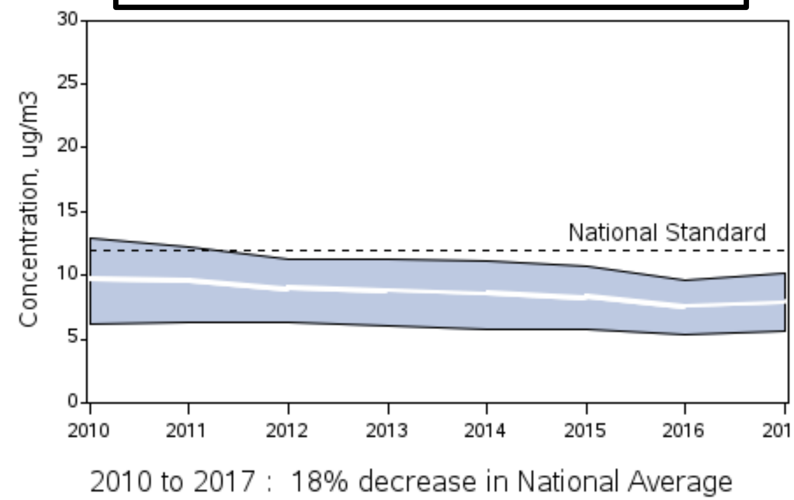
- We use various assumptions to gather distributions of microenvironmental $PM_{2.5}$ concentrations of indoor and outdoor origin.

<u>Outdoor</u> $PM_{2.5}$ Concentrations

National and regional annual average outdoor $PM_{2.5}$ concentrations with lognormal distributions were taken from the EPA's nationwide monitoring network data for the year **2012**



For 2012:
Average: 9.1 µg/m³
10th percentile: 6.6 µg/m³
90th percentile: 11.2 µg/m³



https://www.epa.gov/air-trends/particulate-matter-pm25-trends

Estimating the Indoor $PM_{2.5}$ Concentration of Indoor Origin in Residences

Scenario 1: Nationwide estimate based on prior **field studies** for **residences**

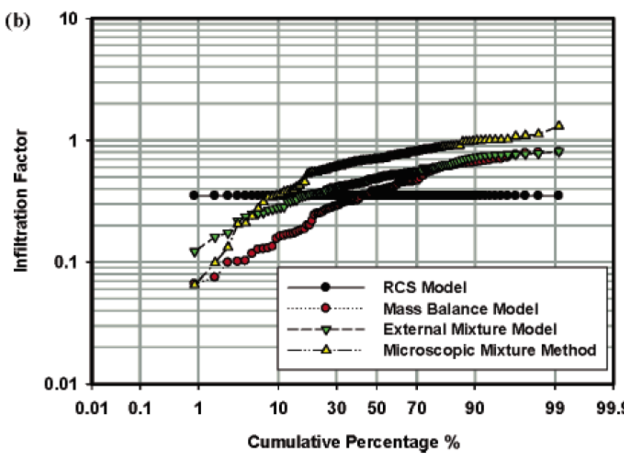
We considered two of the largest field studies of indoor and outdoor $PM_{2.5}$ sources:

- RIOPA (212 non-smoking residences in three U.S. cities)
- MESA Air (more than 200 homes in seven U.S. cities)

Three combinations were considered:

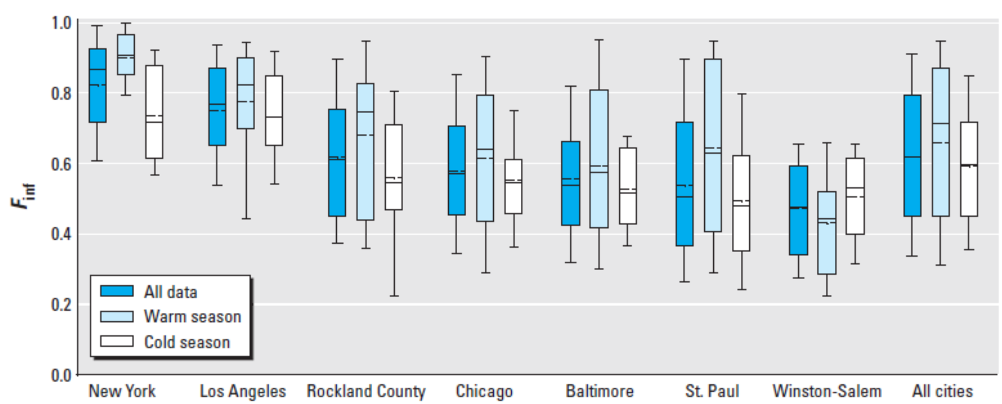
- RIOPA only (Mean indoor $PM_{2.5}$ of indoor origin – C_{in_in}: 9.5 µg/m^3)
- MESA Air only (Mean C_{in_in} : 2.8 µg/m^3)
- RIOPA-MESA 50-50% (Mean C_{in_in}: 6.1 µg/m^3) ← **Our primary scenario**

RIOPA (three U.S. cities)



Meng et al. **2005**, *Environmental Science and Technology*

MESA Air (seven U.S. cities)

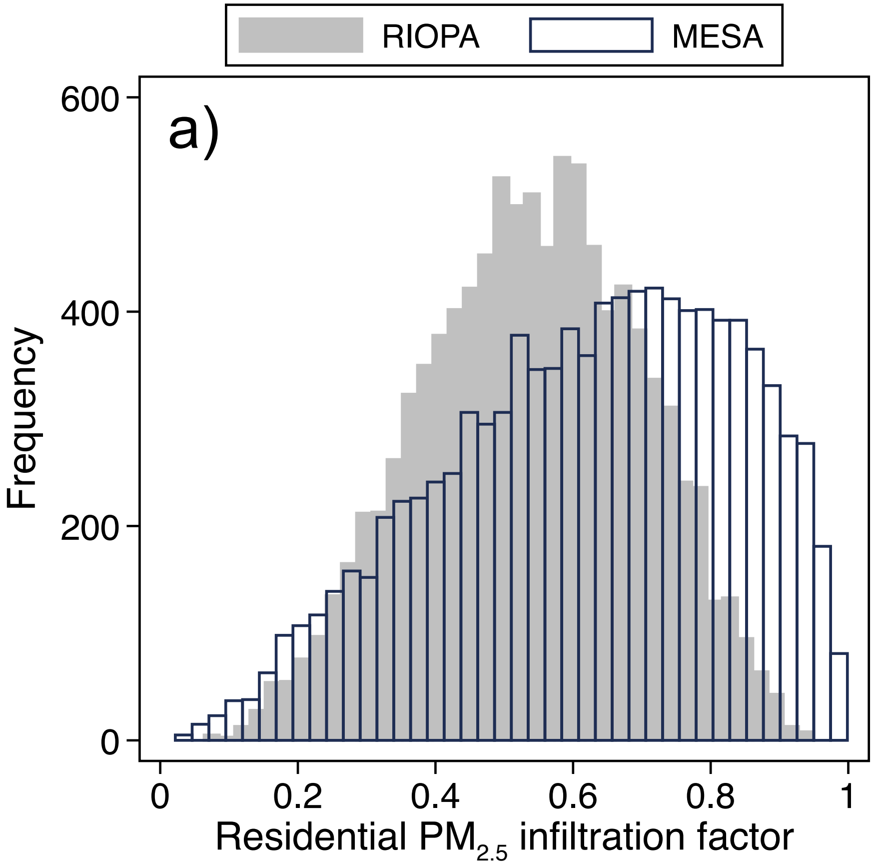


Allen et al. **2012**, *Environmental Health Perspectives*

RIOPA, Relationship of Indoor Outdoor and Personal Air; MESA, Multi-Ethnic Study of Atherosclerosis.

Estimating the Indoor $PM_{2.5}$ Concentration of Outdoor Origin in <u>Residences</u>

- **Indoor $PM_{2.5}$ of ambient origin inside residences—**



RIOPA
Mean $F_{residence,RIOPA}$ = 0.54

Meng et al. **2005**, *Environmental Science and Technology*

MESA AIR
Mean $F_{residence,MESA}$ = 0.60

Allen et al. **2012**, *Environmental Health Perspectives*

Estimating the Indoor $PM_{2.5}$ Concentration of Both Indoor and Outdoor Origin in <u>Residences</u>

Scenario 2: Nationwide estimate based on **regional model outputs**

We used a **nationally representative set** of combined residential energy and indoor air quality (**REIAQ**) models for nonsmoking U.S. residences

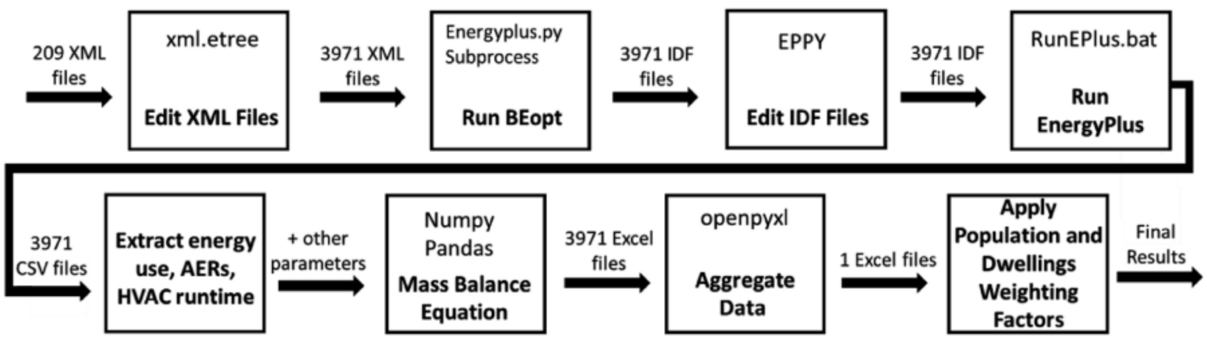
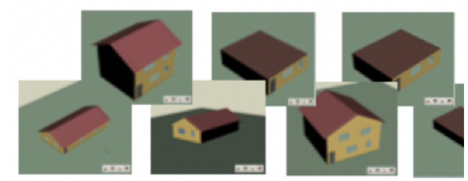
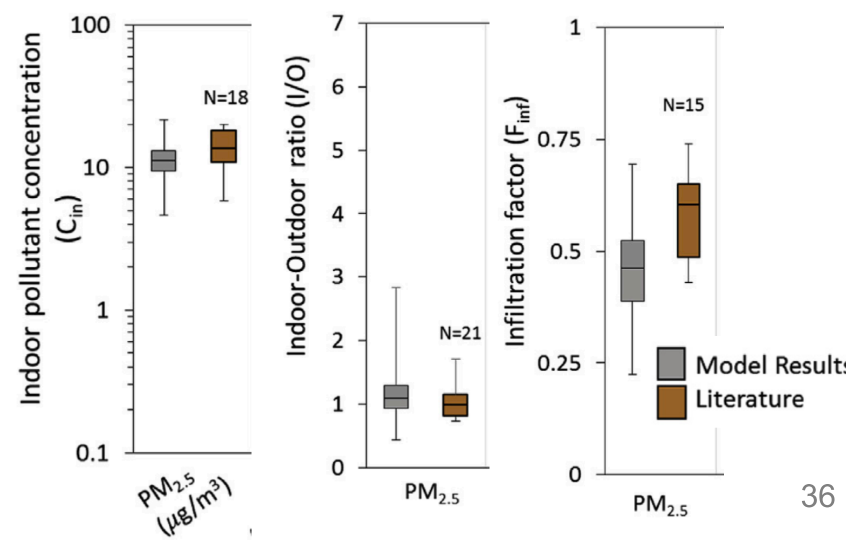


Fig. 2. Model workflow in Python.



REIAQ modeled the hourly concentrations of $PM_{2.5}$ in 2012:

- A total of 3971 individual home models in 19 U.S. cities
- Representative of ~80% of the U.S. housing stock
- Population weighted average indoor $PM_{2.5}$ of indoor origin: 5.9 μg/m³



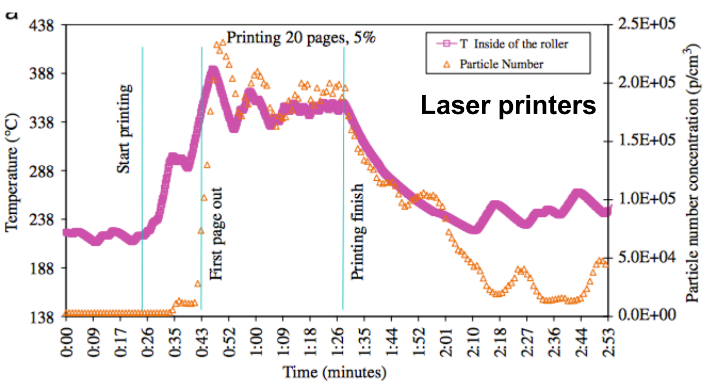
Fazli and Stephens **2018** *Building and Environment*

Estimating the Indoor $PM_{2.5}$ Concentration of Indoor Origin in Other Microenvironments

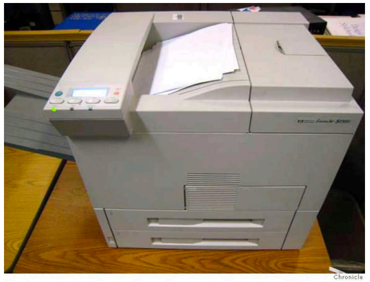
For **nonresidential buildings** in both scenarios:

We used a **lognormal distribution** for indoor $PM_{2.5}$ of indoor origin with a mean ± SD of 4.18 ± 4.98 μg/m³ based on a study in office buildings in Finland.

Hänninen et al. **2005**, *Indoor Air*



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



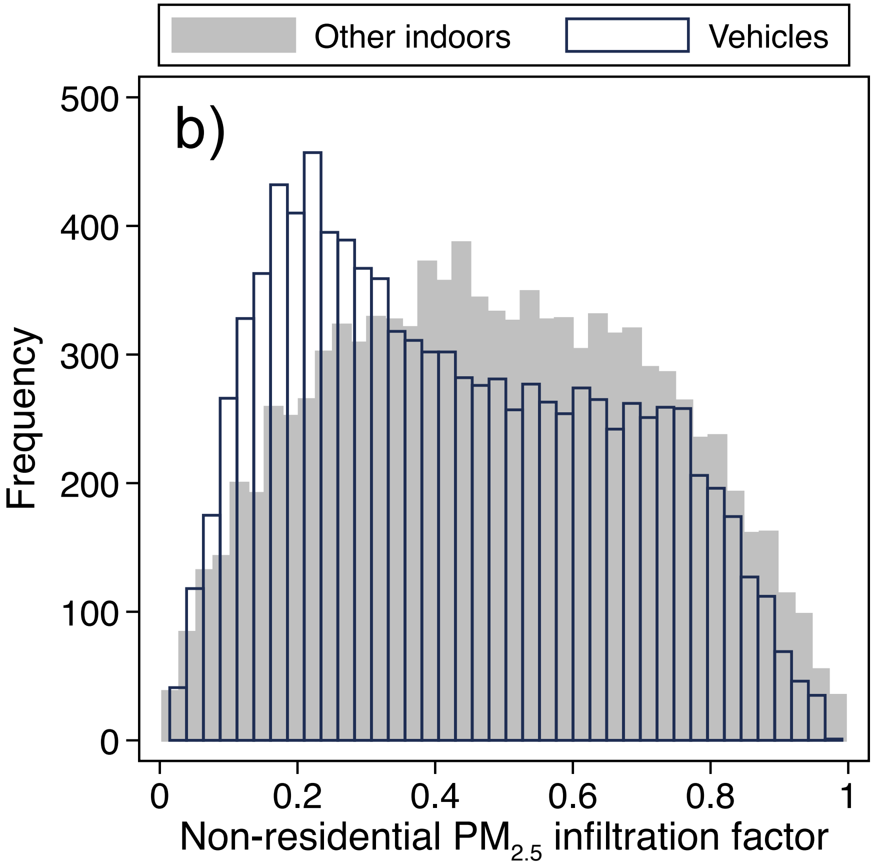
https://www.sfgate.com/health/article/Big-health-risk-seen-in-some-laser-printers-2526921.php

For **vehicles** in both scenarios:

We assumed that there are no sources of $PM_{2.5}$ inside vehicles (nonsmoking).

Estimating the Indoor $PM_{2.5}$ Concentration of Outdoor Origin in Other Microenvironments

- **$PM_{2.5}$ of ambient origin inside other microenvironments:**



Other indoors
Mean $F_{other\ indoor}$ = 0.49

Ben-David et al. **2017**, *Building and Environment*

Vehicles
Mean $F_{vehicle}$ = 0.43

Hudda and Fruin **2013**, *Environ Sci Technol*

Threshold Microenvironmental $PM_{2.5}$ Concentrations

We assumed a threshold $PM_{2.5}$ concentration of 0 μg/m^3 in each microenvironment.

Roman et al. **2008**, *Environmental Science and Technology*; Crouse et al. **2012**, *Environmental Health Perspectives*; Pinault et al **2016**, *Environmental Health*

Reference	$PM_{2.5}$ threshold	U.S. Mortality Burden
Fann et al. **2012** *Risk Analysis*	~1 μg/m^3 (natural BG)	130k (51k–200k) in 2005 320k (180k–440k) in 2005
Fann et al. **2017** *Env Health Persp*	0 μg/m^3	120k (83k–160k) in 2010 200k (43k–1.1M) in 2010
Cohen et al. **2017** *Lancet*	2.4-5.9 μg/m^3	88k (67k–115k) in 2015
Burnett et al. **2018** *PNAS*	2.4 μg/m^3	121k–213k in 2015 (United States+Canada)
Tessum et al. **2019** *PNAS*	5 or 8 μg/m^3	131k (no CI) in 2015

Applying Model Parameters to the Modified C-R Function

$$\Delta y_{PM2.5} = y_0 \left[\exp\left(\sum_z \left(\beta_{PM2.5,z,modified} \times \sum_j \left(\Delta C_{PM2.5,z,j} \times t_j \right) \right) \right) - 1 \right] Pop$$

4 3

y_0: Annual baseline mortality rate (per person per year)

Pop: Population over 35 years old in 2012 (persons)

Census Division	Residential $C_{in,in}$ Mean (SD)	Residential F_{inf} Mean (SD)	C_{out} in 2012 (10^{th} – 90^{th})	y_0 in 2012 (per 100,000)	Over-35 Pop in 2012
New England	5.78 (2.14)	0.50 (0.08)	9.22 (7.25–11.2)	1429.5	8,209,960
Middle Atlantic	5.84 (2.01)	0.50 (0.08)	9.22 (7.25–11.2)	1475.6	22,655,120
East North Central	5.66 (1.91)	0.46 (0.09)	9.98 (8.74–11.43)	1576.8	25,115,038
West North Central	5.69 (1.86)	0.45 (0.09)	9.40 (7.74–11.16)	1566.0	10,965,126
South Atlantic	6.47 (2.07)	0.40 (0.08)	8.86 (6.90–10.66)	1481.7	33,363,675
East South Central	6.81 (1.94)	0.40 (0.08)	9.82 (8.34–11.37)	1759.6	9,999,343
West South Central	4.80 (1.54)	0.46 (0.09)	9.61 (8.01–11.14)	1449.3	18,513,908
Mountain	5.38 (1.82)	0.49 (0.09)	7.95 (6.03–10.25)	1332.1	11,481,569
Pacific	6.30 (2.03)	0.46 (0.08)	9.06 (6.01–12.88)	1241.2	26,212,977
Nationwide	6.19 (10.06)	0.58 (0.19)	9.1 (6.6–11.2)	1463.1	166,516,716

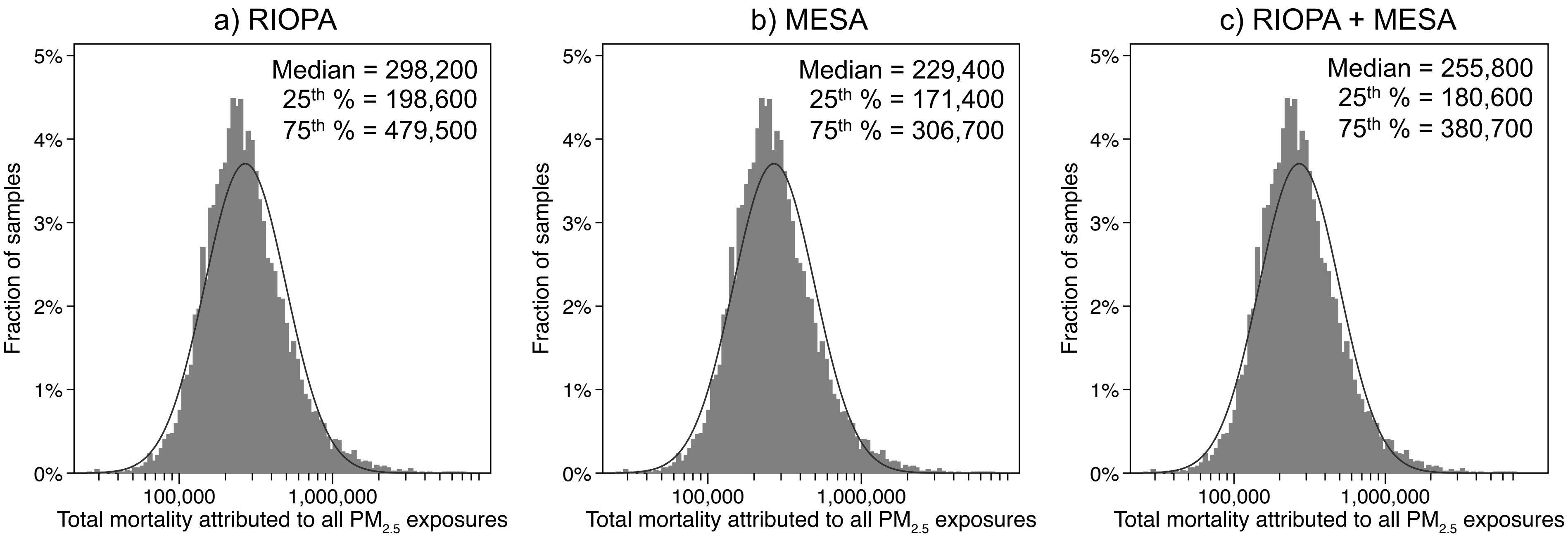
Scenario 1: Estimates of Total $PM_{2.5}$ Mortality Burden

We used Monte Carlo simulations with 10,000 iterations to sample from distributions of each model input parameter.

Each iteration is representative of one estimate of **total $PM_{2.5}$ mortality burden** associated with particles of both indoor and outdoor origin in all microenvironments.

The curve fits are approximately lognormal.

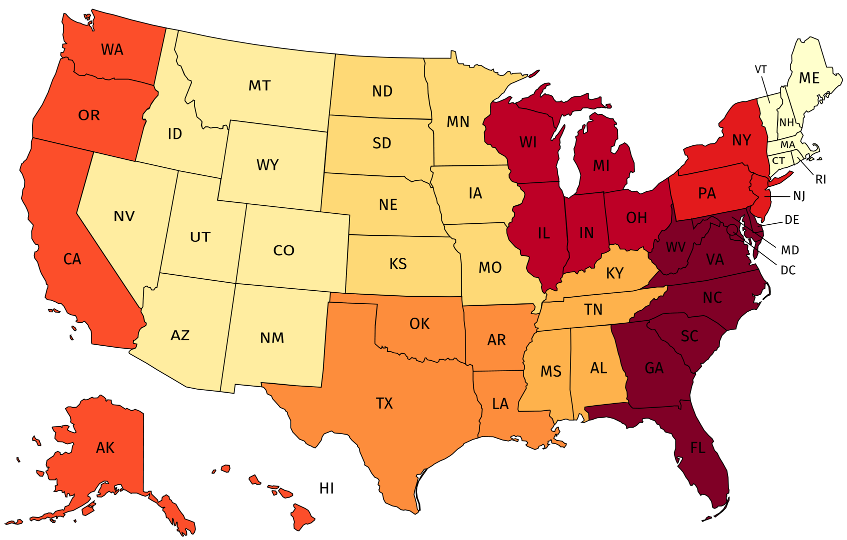
Scenario 1: Total $PM_{2.5}$ mortality (indoor + outdoor sources)



Scenario 2: Regional Mortality

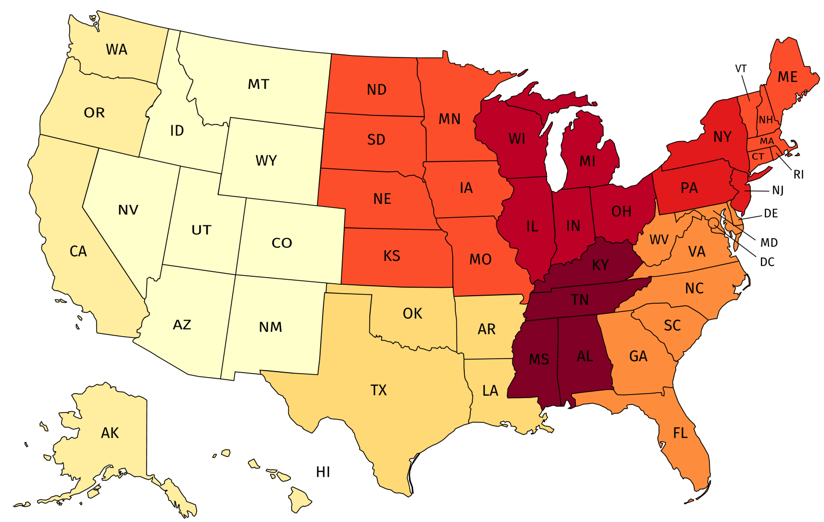
Without taking into account the differential time activity patterns or potentially differential toxicity—

Total mortality rate in U.S. census divisions



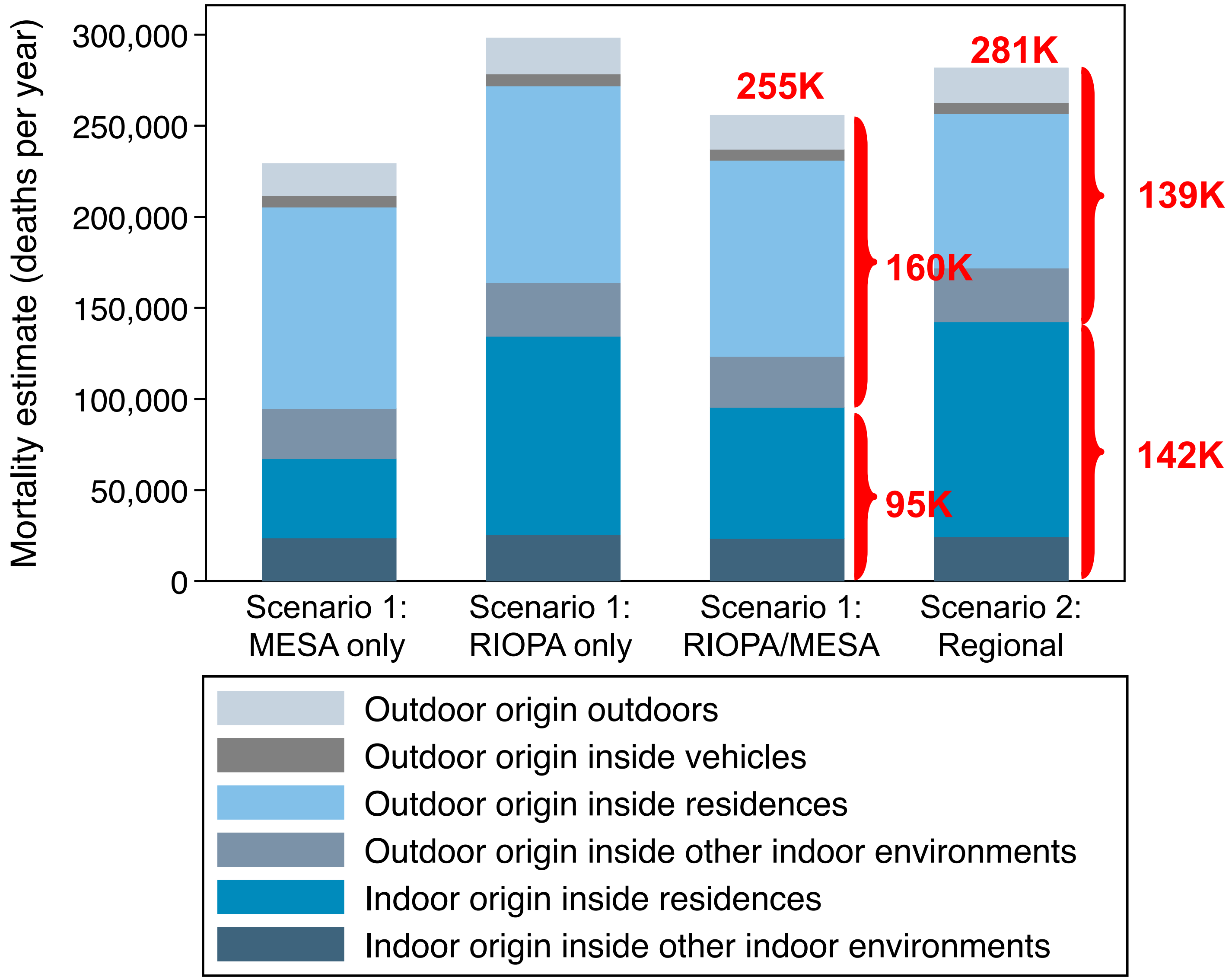
- South Atlantic (56,200)
- East North Central (47,100)
- Middle Atlantic (39,600)
- Pacific (38,500)
- West South Central (29,300)
- East South Central (21,600)
- West North Central (19,700)
- Mountain (16,000)
- New England (13,900)

Mortality rate per 100,000 population in U.S. census divisions



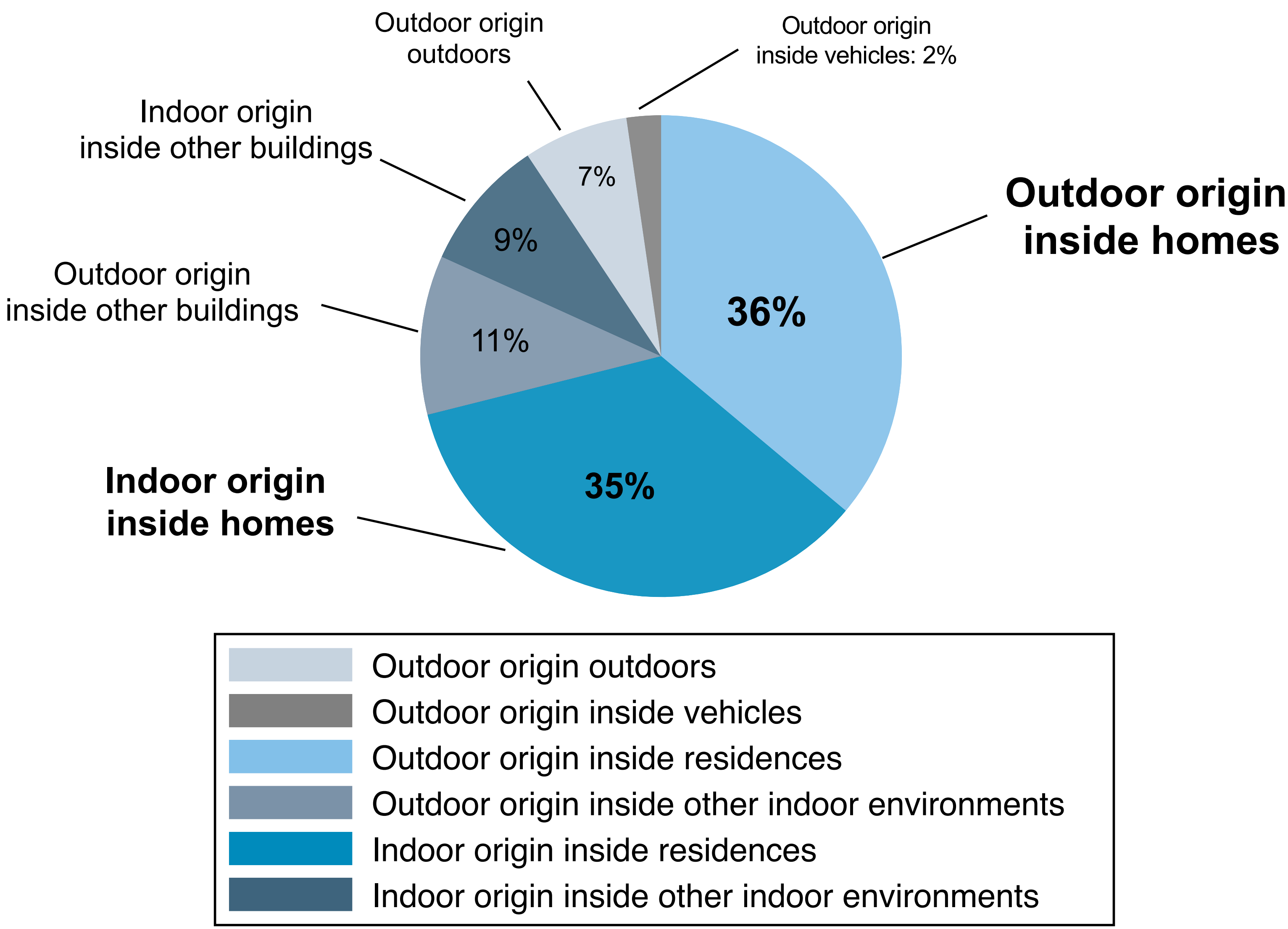
- East South Central (116)
- East North Central (101)
- Middle Atlantic (96)
- New England, West North Central (95)
- South Atlantic (92)
- West South Central (78)
- Pacific (76)
- Mountain (71)

Best Estimates of the Annual Number of Deaths in the United States in Scenarios 1 and 2



Average Microenvironmental $PM_{2.5}$ Exposure Attribution

Average across all scenarios



Getting the Ambient Attribution Right…

Our best estimates of the mortality burden attributable to outdoor $PM_{2.5}$ sources ranged: **139k–160k**

Comparisons to other recent literature:

Reference	Function	U.S. Mortality Burden
Fann et al. **2012** *Risk Analysis*	Log-linear $\Delta y = y_o(e^{\beta\,\Delta x} - 1)\,Pop$	130k (51k–200k) in 2005 320k (180k–440k) in 2005
Fann et al. **2017** *Env Health Persp*	Log-linear $y_{ija} = m_{0ija} \times (e_{ij}^{\beta \cdot C} - 1) \times P_{ija}$	120k (83k–160k) in 2010 200k (43k–1.1M) in 2010
Cohen et al. **2017** *Lancet*	GBD IER $RR_{IER}(z) = 1 + \alpha\,\{1 - \exp[-\gamma\,(z - z_{cf})^{\delta}]\}$	88k (67k–115k) in 2015
Burnett et al. **2018** *PNAS*	GEMM $R(z) = \exp\{\theta \log(1 + z/\alpha)\omega(z)\}$.	121k-213k in 2015 (United States+Canada)
Tessum et al. **2019** *PNAS*	Modified GBD $HR(C) = \exp\left(\frac{\gamma * \ln(C+1)}{1 + \exp[-(C - \delta)/\lambda]}\right)$	131k (no CI) in 2015

Limitations

- Assumes causality and quantifiable relationship between $PM_{2.5}$ and mortality
- Assumes no threshold concentration
- Did not consider other forms of exposure-response functions
- Did not consider double-counting of the health effects of indoor $PM_{2.5}$ sources in prior epidemiology studies
- Did not consider variability in $PM_{2.5}$ toxicity based on chemical constituents of indoor or outdoor sources
- Did not consider any changes in toxicity that may occur due to size-resolved particle dynamics upon ambient transport indoors
- Assumed equal toxicity for indoor and outdoor $PM_{2.5}$ sources:

$$\beta_{PM2.5,in} = \beta_{PM2.5,out} = \beta_{PM2.5,modified}$$

Ongoing Research Needs

- Nationally representative studies of indoor and ambient $PM_{2.5}$ sources in various microenvironments
- Differential toxicity studies
  - Does ambient PM toxicity change as it infiltrates indoors?
  - Are indoor PM sources equally toxic? Less so? More so? It depends?
- Incorporation of different exposure-response model forms and model parameters
- Translation to other PM metrics (e.g., PM_1 or UFPs) and/or other health end points (e.g., short-term effects)

Estimating the Mortality Burden of Fine Particulate Matter Exposure Attributable to Indoor and Outdoor Microenvironments

Brent Stephens, Ph.D.

Associate Professor and Department Chair

Department of Civil, Architectural, and Environmental Engineering

ILLINOIS INSTITUTE OF TECHNOLOGY

Built Environment Research @ IIT

web www.built-envi.com
email brent@iit.edu
twitter @built_envi

Parham Azimi, Ph.D.

Postdoctoral Fellow, Healthy Buildings Program

Harvard T.H. Chan School of Public Health

HARVARD T.H. CHAN SCHOOL OF PUBLIC HEALTH

email pazimi@hsph.harvard.edu

Question and Answers

Please use the “Chat” feature on the side of your screen to submit questions to our speakers.

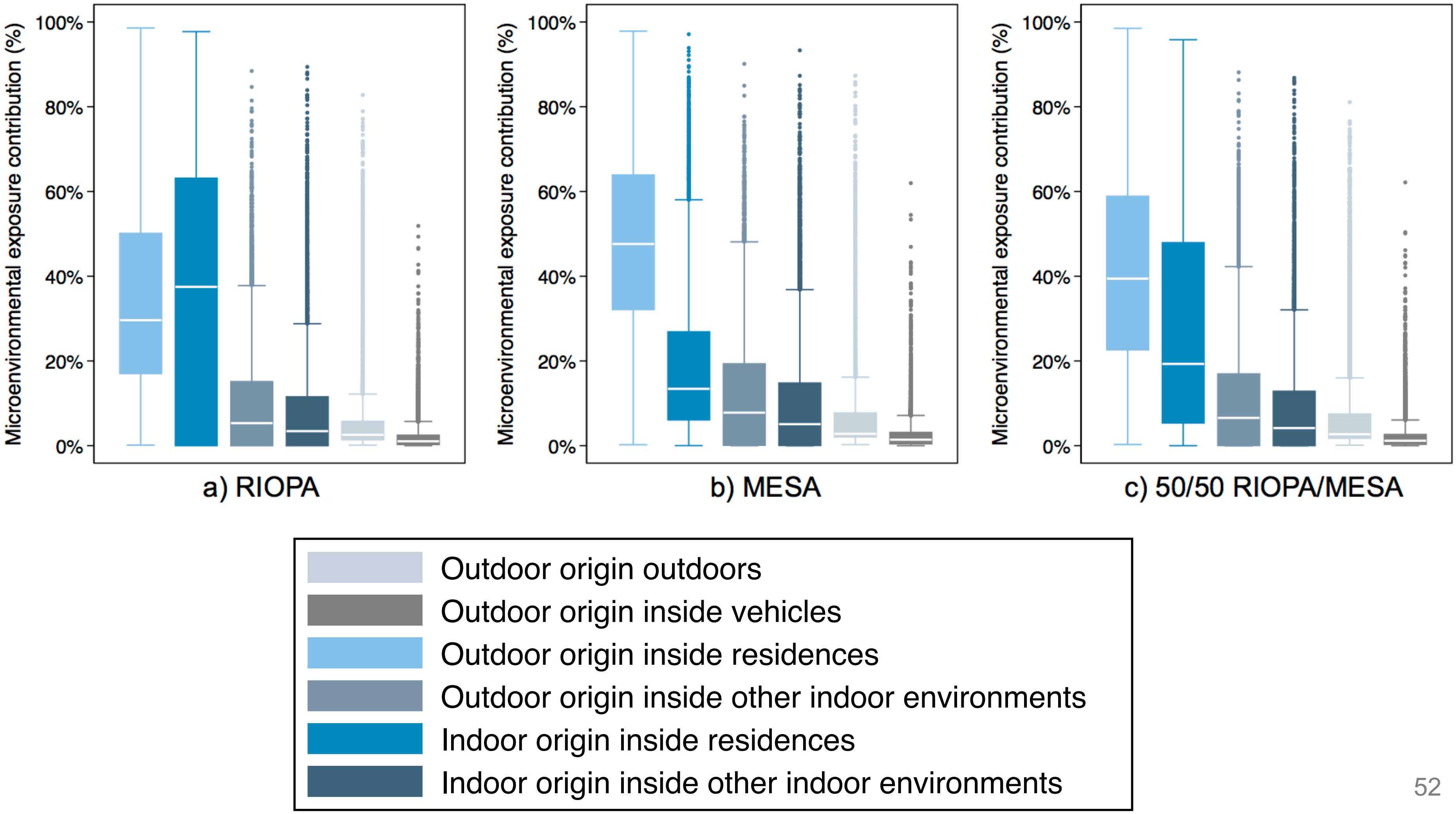
Thank you for participating in today's webinar, which is part of the EPA Indoor Environments Division's IAQ Science Webinar Series.

Today's presentation will be available online at **www.epa.gov/iaq**

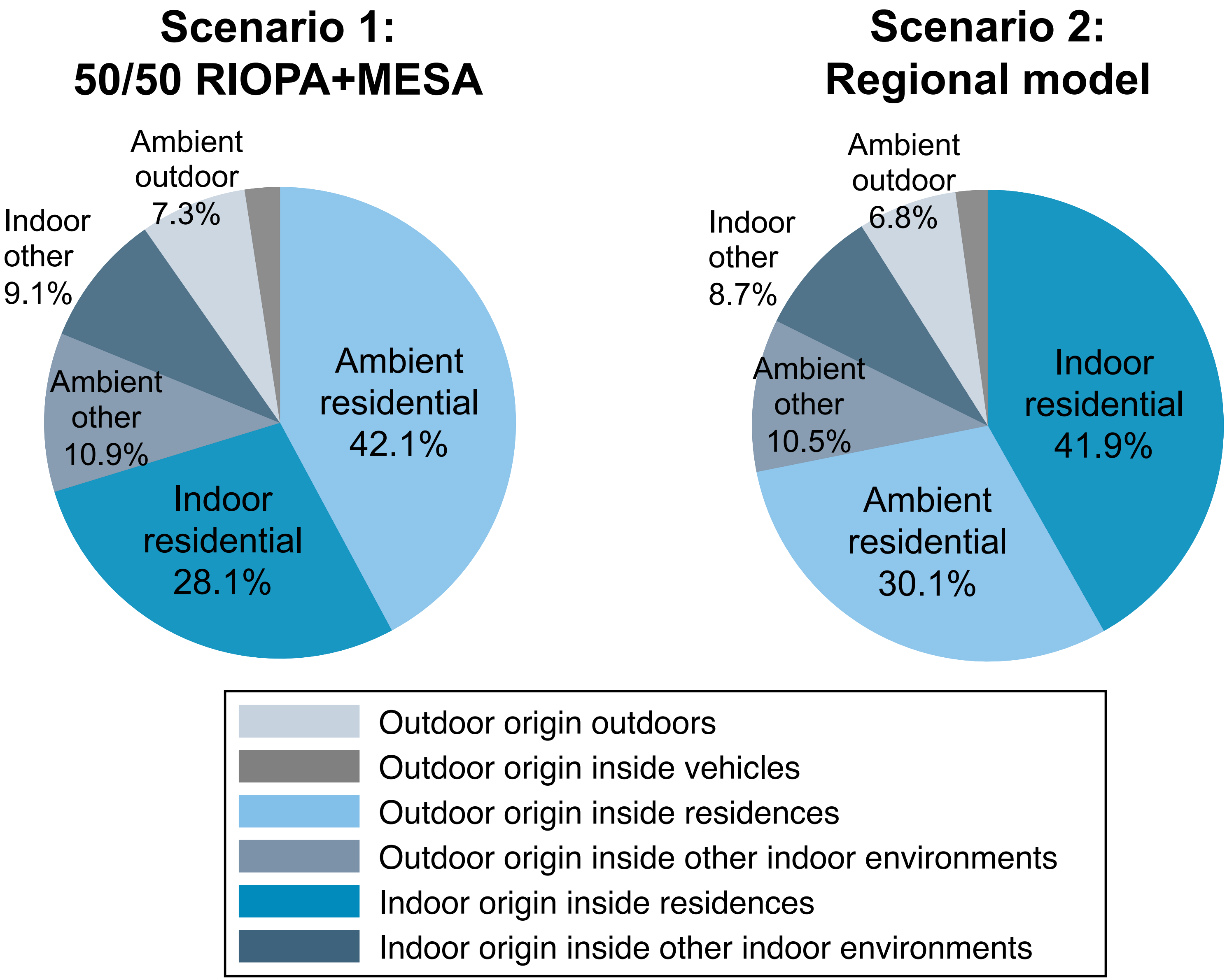
Please monitor your inbox for announcements of future IAQ Science Webinar Series presentations throughout the year.

Bonus slides

Scenario 1: Microenvironmental $PM_{2.5}$ Exposure Attribution



Average Microenvironmental $PM_{2.5}$ Exposure Attribution



Indoor PM and Health (Epidemiology)

Health benefits of particle filtration

Fisk **2013** *Indoor Air*

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

PM in <u>indoor</u> air

Air cleaners typically reduce indoor PM concentrations by ~50%

- Usually $PM_{2.5}$
- Sometimes PM_{10} or total number counts (TNC) (e.g. <1 μm)

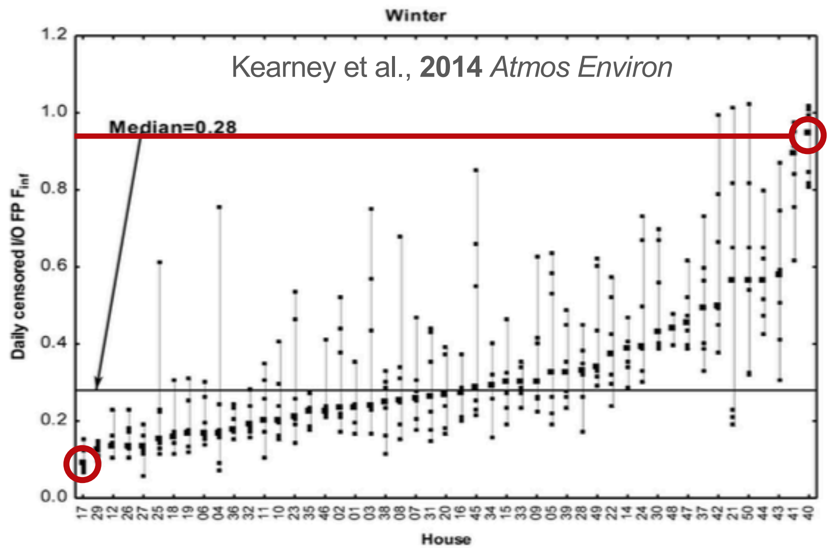
Documented health improvements with (mostly portable) air cleaners include:

- Modest improvements in lung function in asthmatics
- Fewer asthma-related doctor visits
- Modest improvements in markers of cardiovascular/pulmonary function
- *Very few studies on central filtration*

New EPA Guidance on air cleaners in the home:
https://www.epa.gov/indoor-air-quality-iaq/air-cleaners-and-air-filters-home

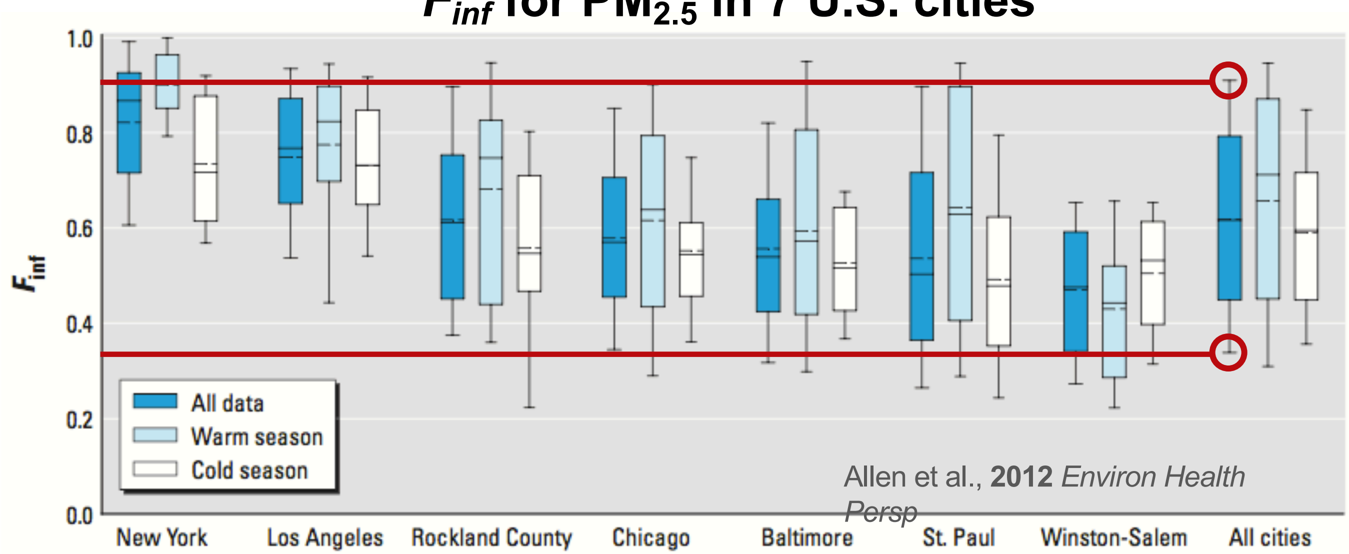
Variability in Residential $PM_{2.5}$ and UFP Infiltration Factors

F_{inf} for $PM_{2.5}$ in Edmonton, Alberta, Canada



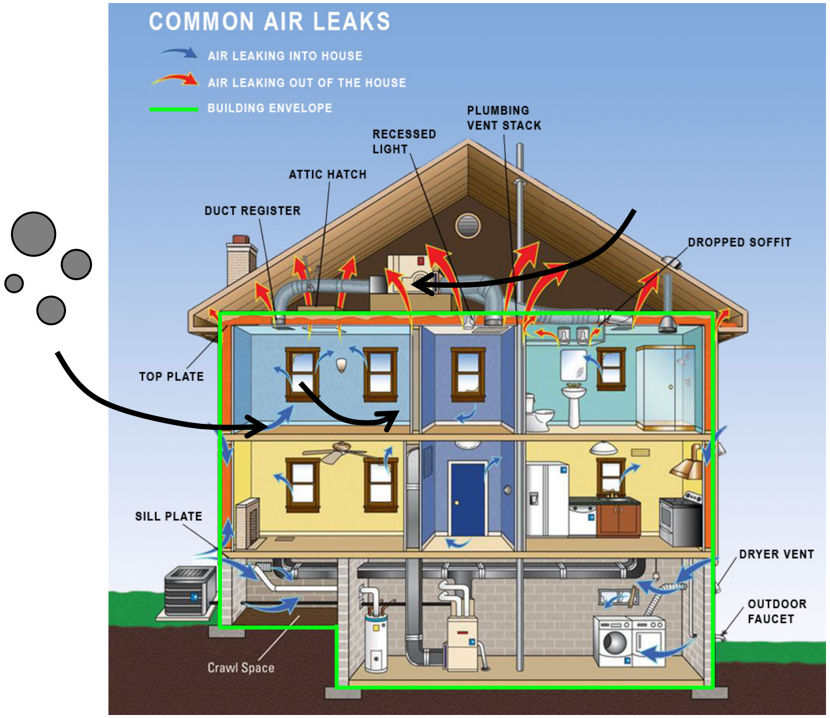
Between-home variations for $PM_{2.5}$:
$0.1 < F_{inf} < 1$

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



Key Drivers of Variability in Infiltration Factors

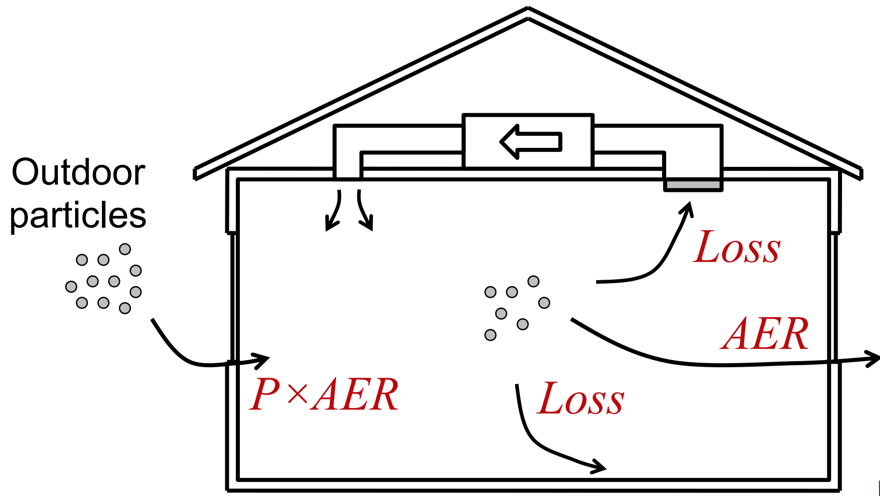
- Pollutant characteristics
  - Sizes/classes/components of PM
- Source of ventilation air
  - Infiltration (envelope leaks)
  - Mechanical ventilation
  - Natural ventilation (open windows)
- Human behaviors
  - Window opening frequencies
  - Portable air cleaners



- 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)
- 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*

Underlying Mechanisms That Govern F_{inf}



Penetration from outdoors

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

Removal by air exchange

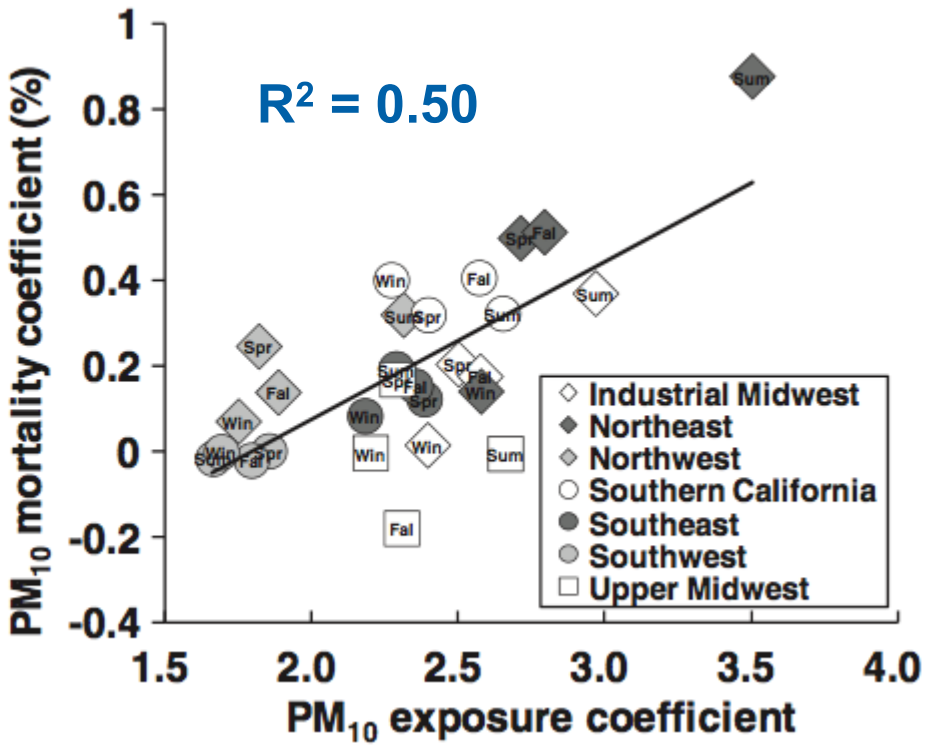
Removal by deposition to surfaces, phase changes, or control by filters or air cleaners

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

How Does Variability in F_{inf} Contribute to Effect Estimates?

Accounting for variations in AERs and window opening:

PM_{10} and long-term mortality (U.S.)



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

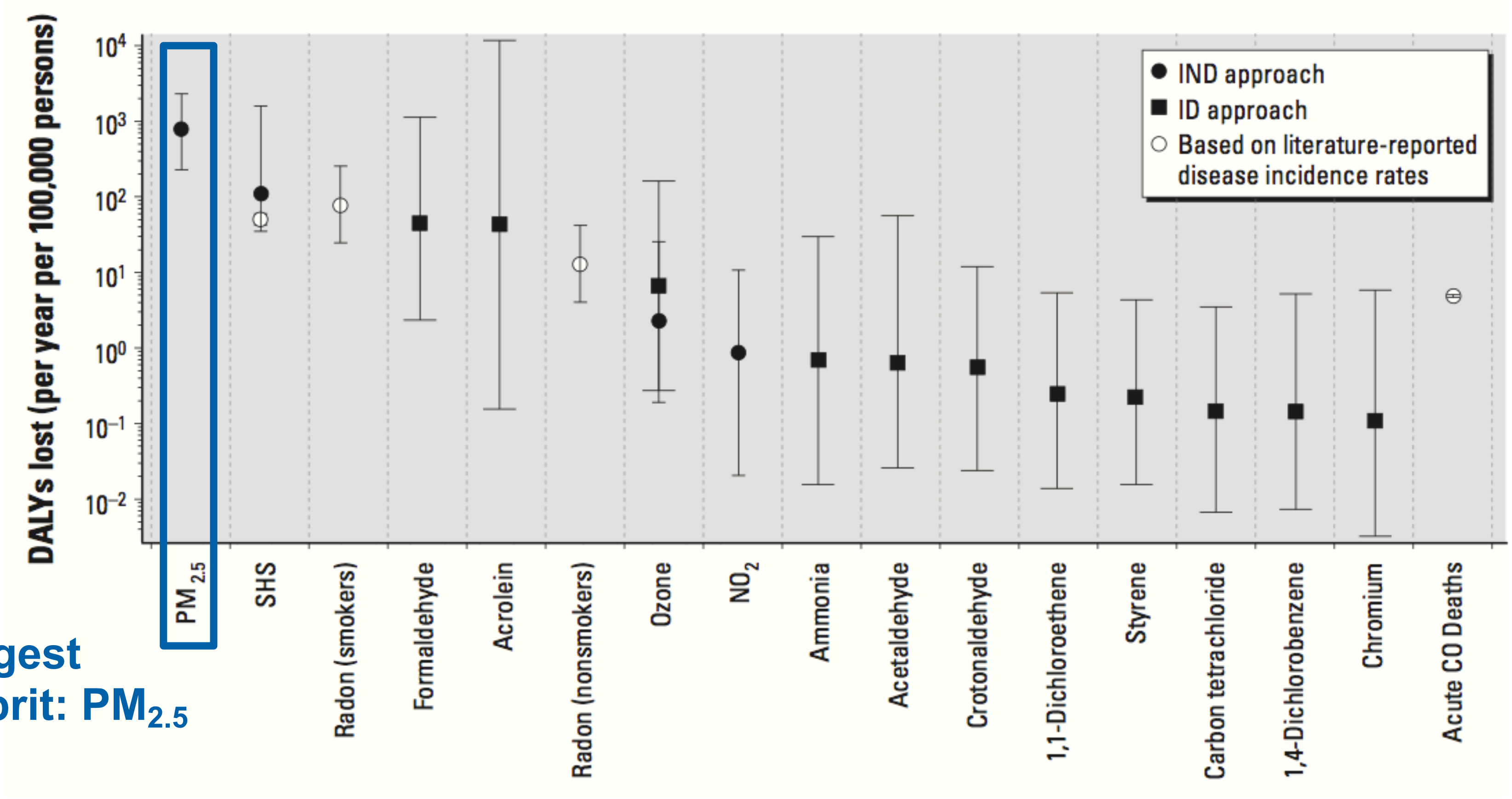
Key point:
If you can account for the underlying differences in indoor exposures to outdoor pollutants in epidemiology studies, you can explain a lot of the variability in their results.

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

Indoor PM and Health (Models)

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

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



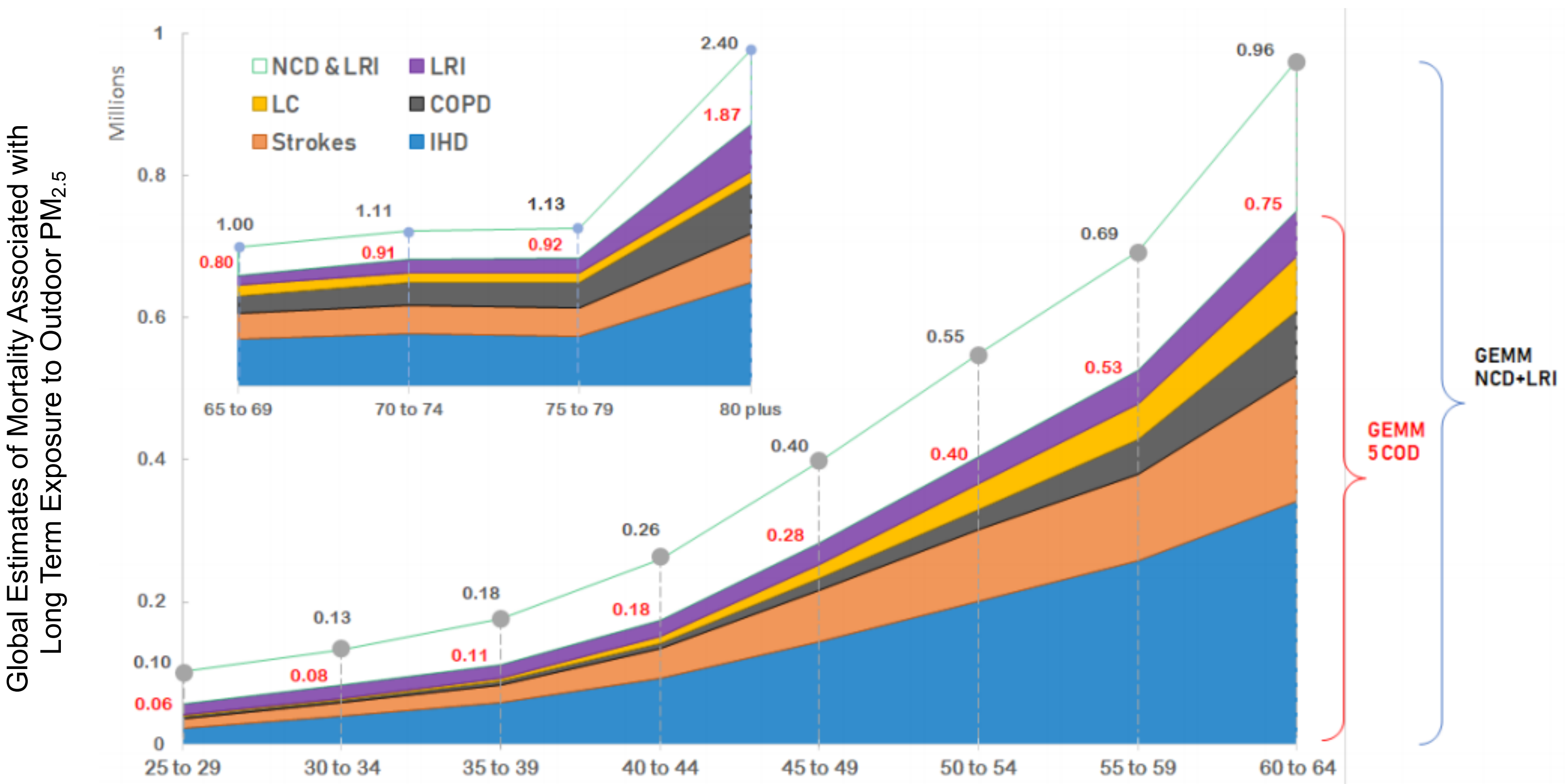
Biggest culprit: $PM_{2.5}$

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

Integrated Exposure-Response (IER) Model

Global Burden of Disease (GBD) study's integrated exposure-response (IER) methodology estimates the mortalities associated with $PM_{2.5}$ exposures for multiple causes of death in various age groups.

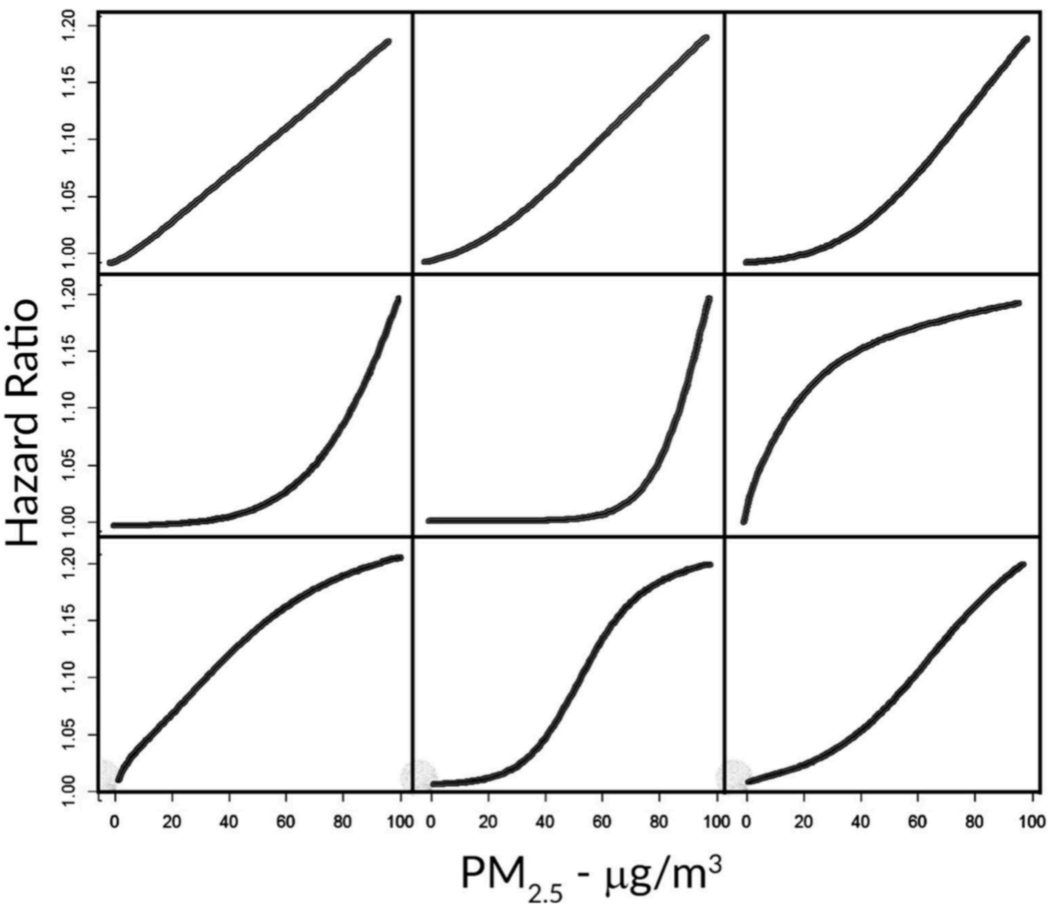
Apte et al. **2015**, *Environmental Science and Technology*; Cohen et al. **2017**, *The Lancet;* Fann et al. **2016**, *Risk Analysis*; Burnett et al. 2018, *National Acad Sciences*

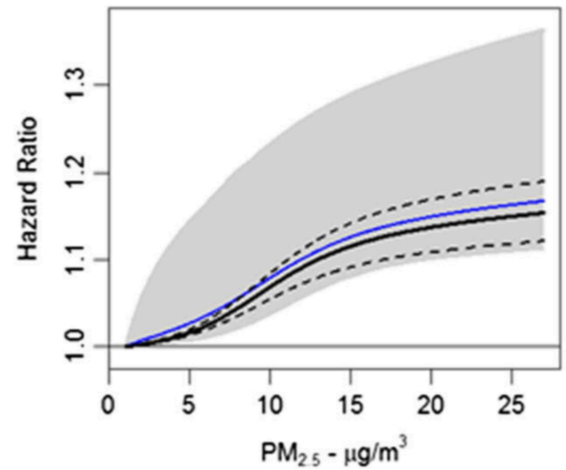


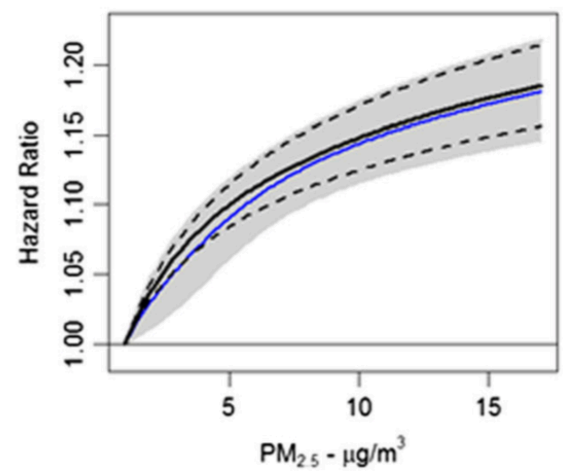
Burnett et al. 2018, *National Acad Sciences*

Shape of the C-R Curve

$$h(t|x,z) = h_o(t)\exp\left\{\gamma' x + \beta^* \omega(z|\mu,\tau)^* f(z)\right\}$$







Nasari et al. **2016** *Air Qual Atmos Health*

Potential for Double-Counting

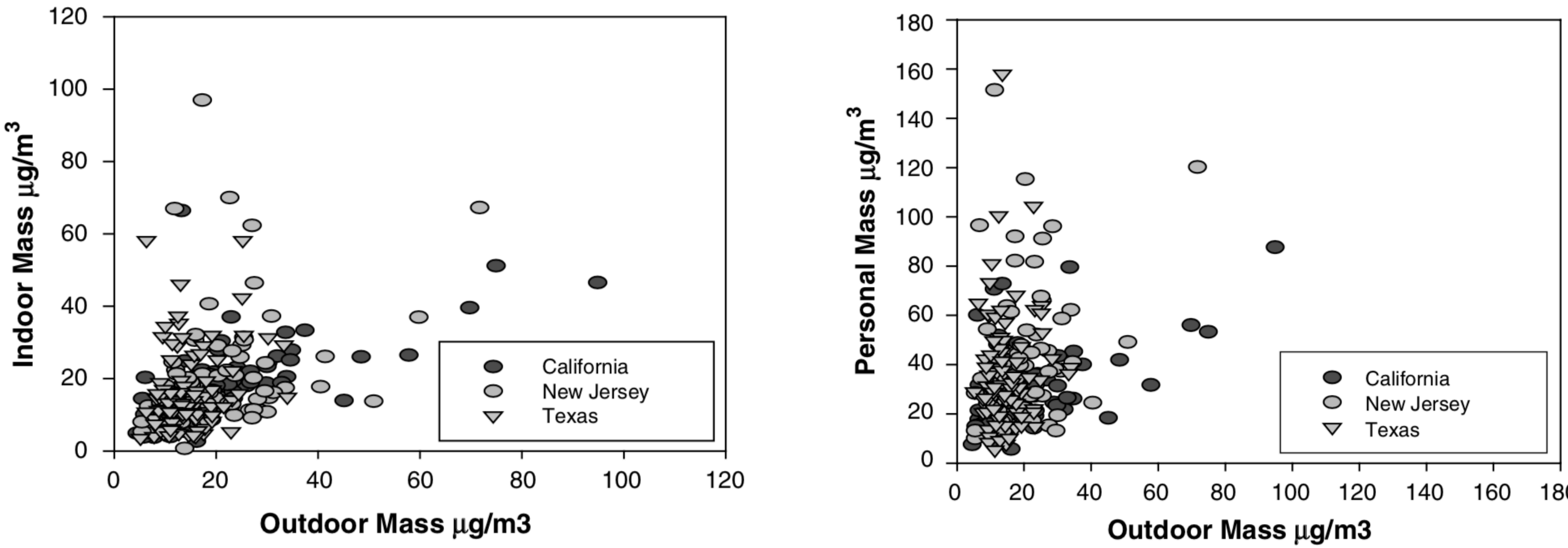


Table 2. Coefficients of determination (R^2) for $PM_{2.5}$ concentrations.

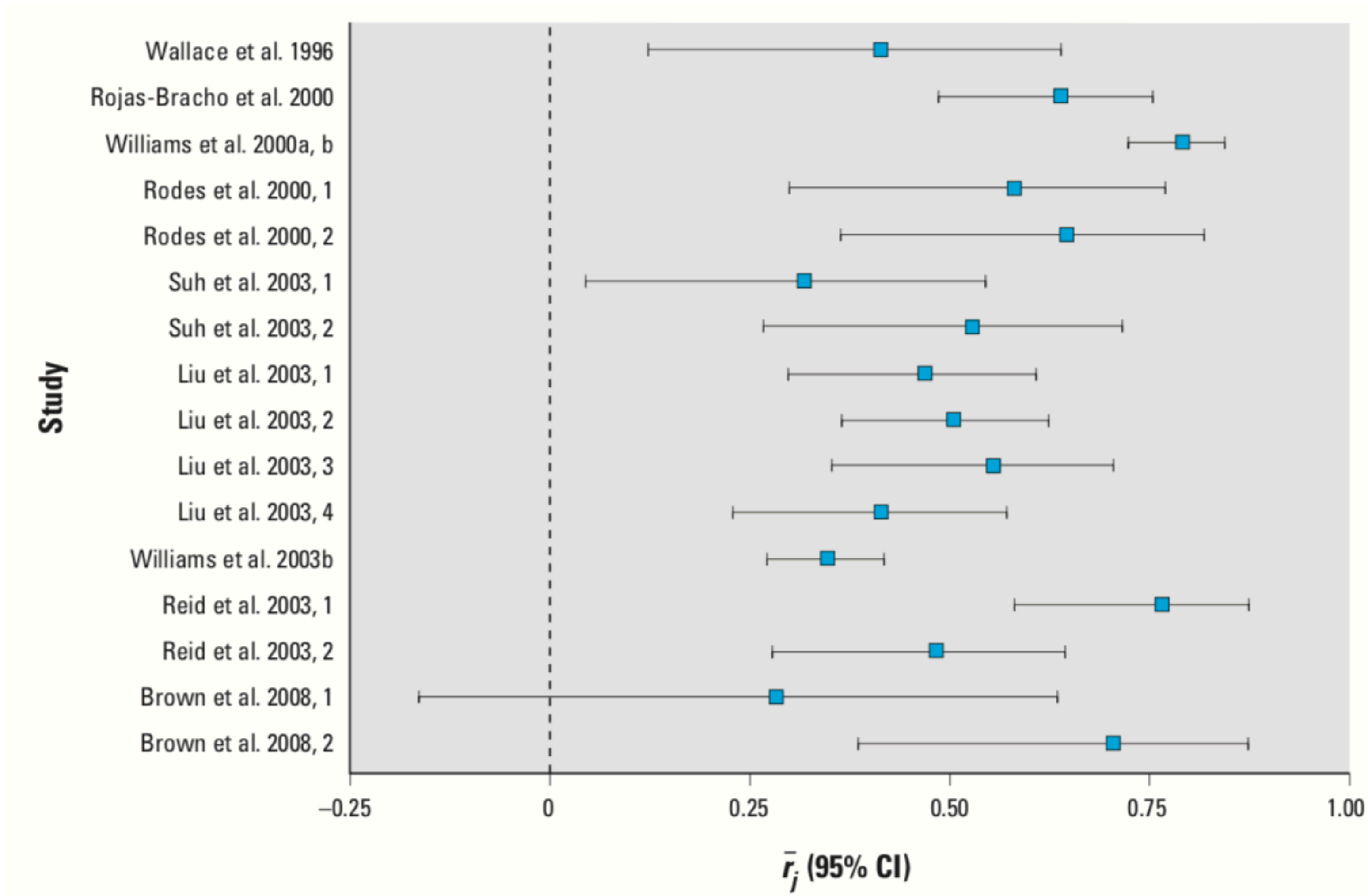
State	Group	Indoor vs. outdoor	Personal vs. indoor	Personal vs. outdoor
Overall study	All homes	0.18	0.20	0.05
	I/O <1 homes	0.71	0.15	0.10
California	All homes	0.44	0.27	0.21
	I/O <1 homes	0.80	0.40	0.33
New Jersey	All homes	0.12	0.19	0.05
	I/O <1 homes	0.66	0.16	0.09
Texas	All homes	0.06	0.13	0.007
	I/O <1 homes	0.43	0.03	0.02

I/O indicates R^2 for homes where indoor/outdoor $PM_{2.5}$ ratio is less than 1.

Meng et al. **2005** *J Exposure Analysis Environ Epidemiology*

Potential for Double-Counting

Figure 1. Forest plot for 16 estimates of $\bar{r}_j$ (95% CIs) from nine studies of the within-participant residential outdoor-personal $PM_{2.5}$ correlation.



Avery et al. **2010** *Environmental Health Perspectives*

Indoor/Outdoor PM: Differential Toxicity

Ambient origin PM may be more harmful than indoor-generated PM.

- Ebelt et al. (2005) *Epidemiology*
  - 16 COPD patients; measures of cardiopulmonary health
  - Lung function, blood pressure, ectopic heartbeats associated with ambient origin $PM_{2.5}$ but not indoor origin $PM_{2.5}$ exposures
- Koenig et al. (2005) *Environmental Health Perspectives*
  - 19 children with asthma; measures of lung function
  - Slightly stronger associations with outdoor $PM_{2.5}$ than indoor $PM_{2.5}$ exposures

Indoor-generated PM is at least as toxic as outdoor PM, if not more.

- Long et al. (2001) *Environmental Health Perspectives*
  - In vitro toxicity of 14 I/O paired $PM_{2.5}$ samples in rat alveolar macrophages
  - Similar tumor necrosis factor for indoor and outdoor samples; indoor more bioactive
- Monn and Becker (1999) *Toxicology and Applied Pharmacology*
  - $PM_{2.5}$ samples from EPA lab exposed to human monocytes
  - Similar cell toxicity with both indoor and outdoor samples