

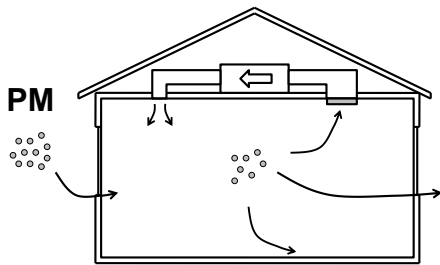
Outdoor-to-Indoor Transport Mechanisms and Particle Penetration for Fine Particulate Matter

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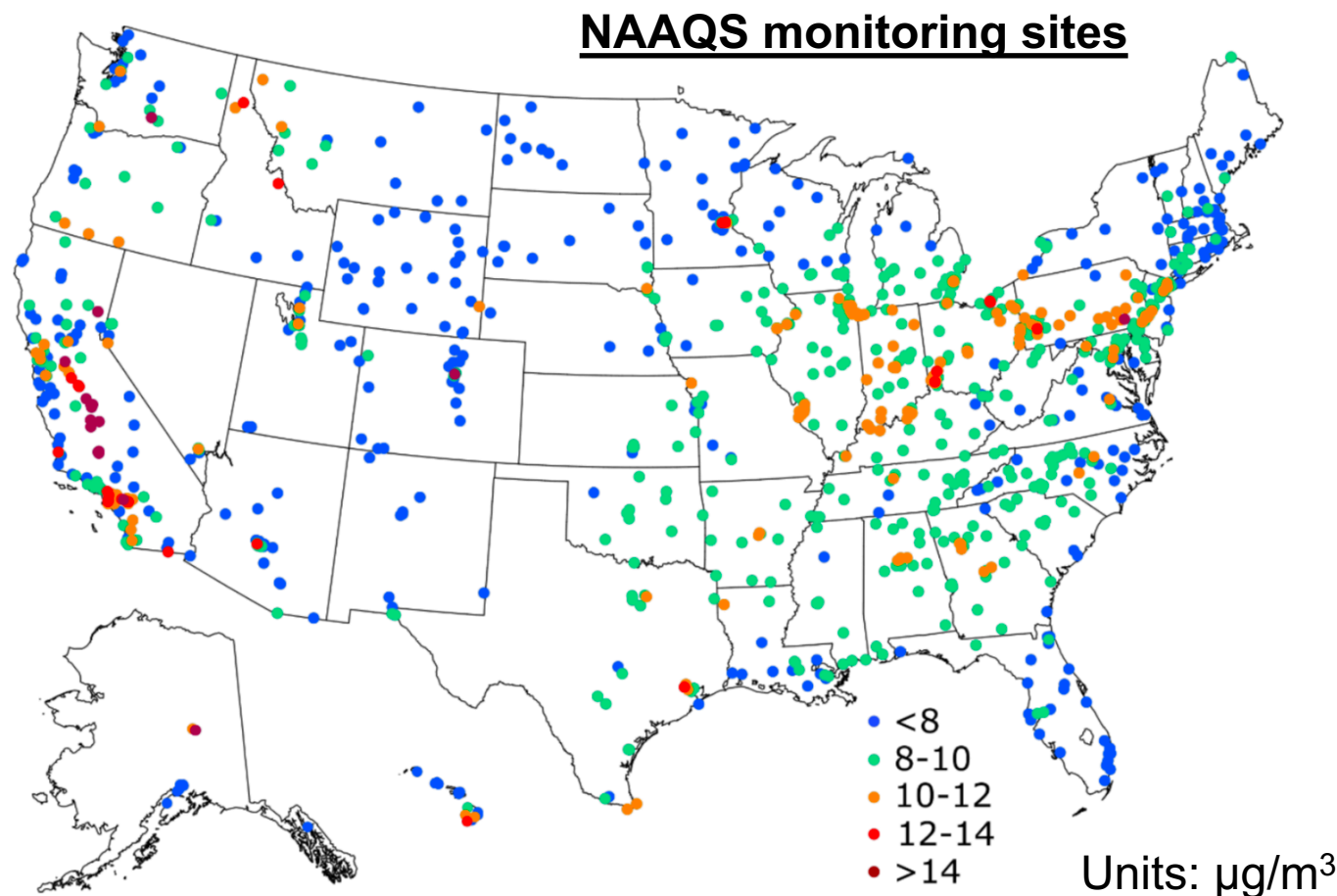
The Built Environment Research Group

advancing energy, environmental, and sustainability
research within the built environment
at Illinois Institute of Technology



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Outdoor PM_{2.5} monitoring stations in the U.S.



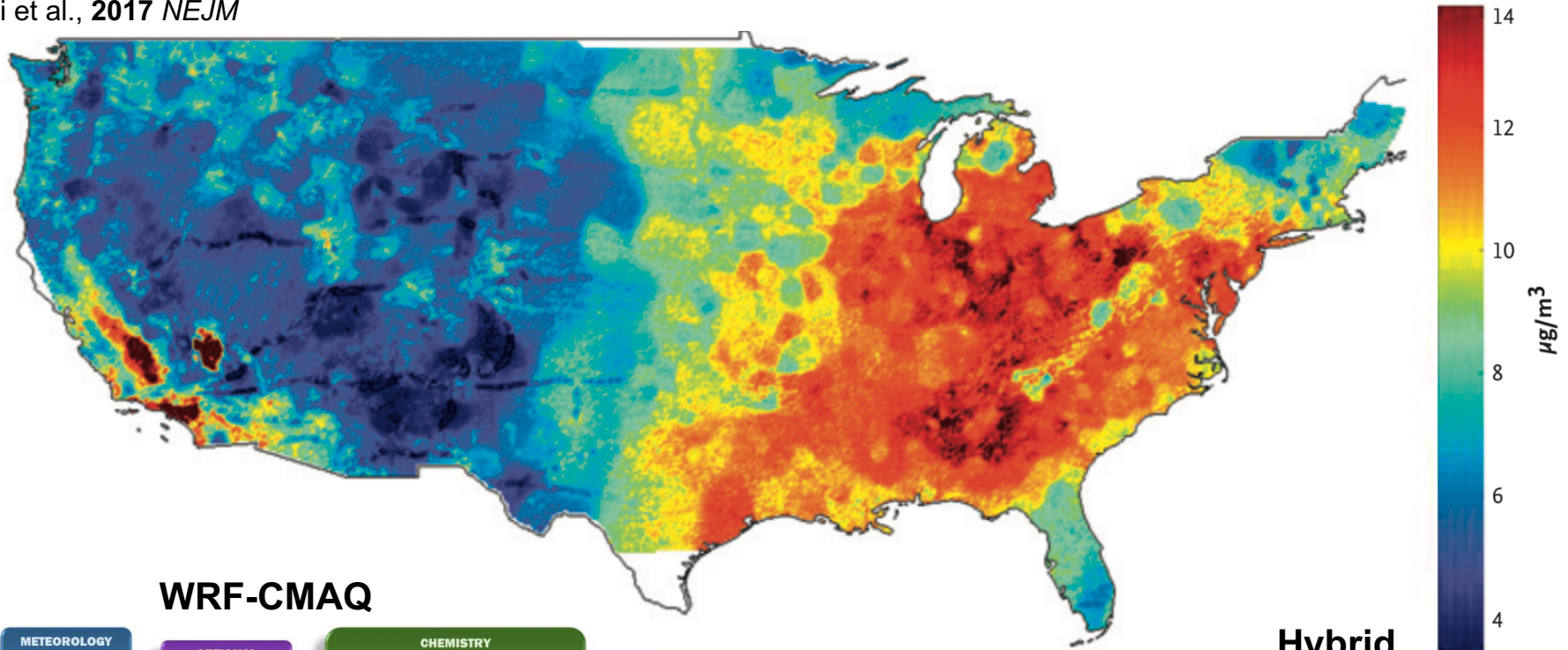
avg = average; PM_{2.5} = particulate matter with a nominal mean aerodynamic diameter less than or equal to 2.5 μm .

Source: U.S. EPA analysis of Air Quality System network data 2013–2015, prepared in 2016.

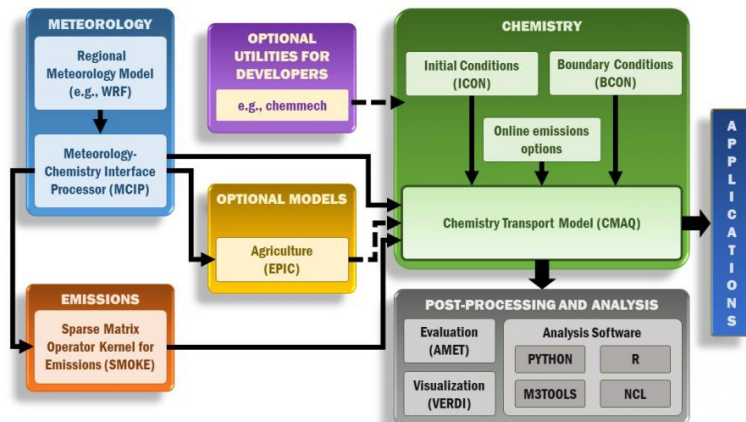
Figure 2-13 Three-year avg PM_{2.5} concentrations 2013–2015.

Modeling & remote sensing fill regional PM_{2.5} gaps

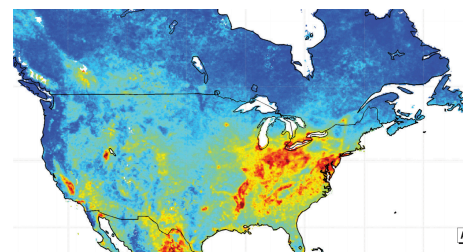
Di et al., 2017 NEJM



WRF-CMAQ

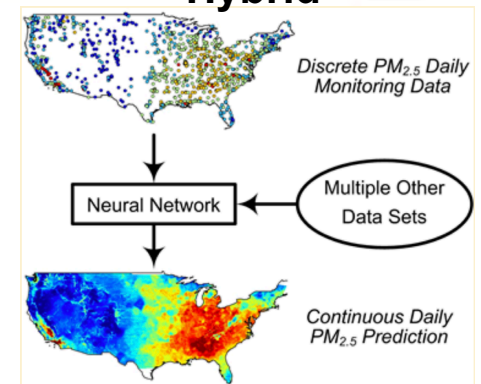


Satellite



Van Donkelaar et al., 2010 EHP

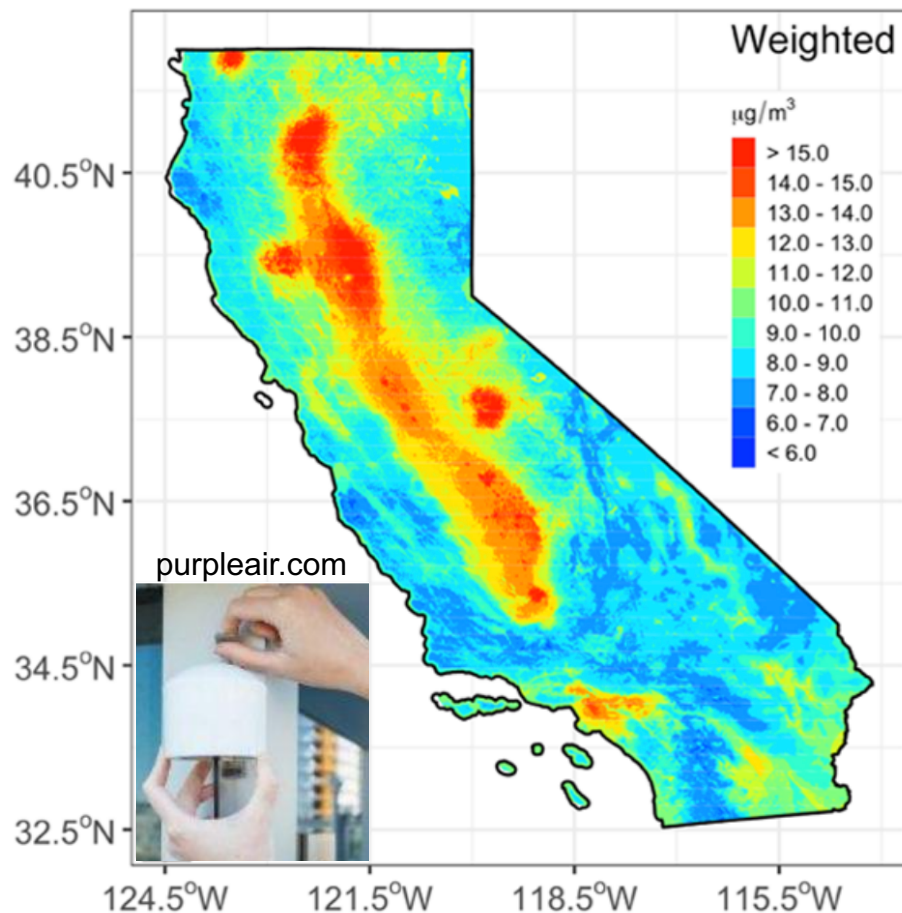
Hybrid



Di et al., 2016 Environ Sci Technol

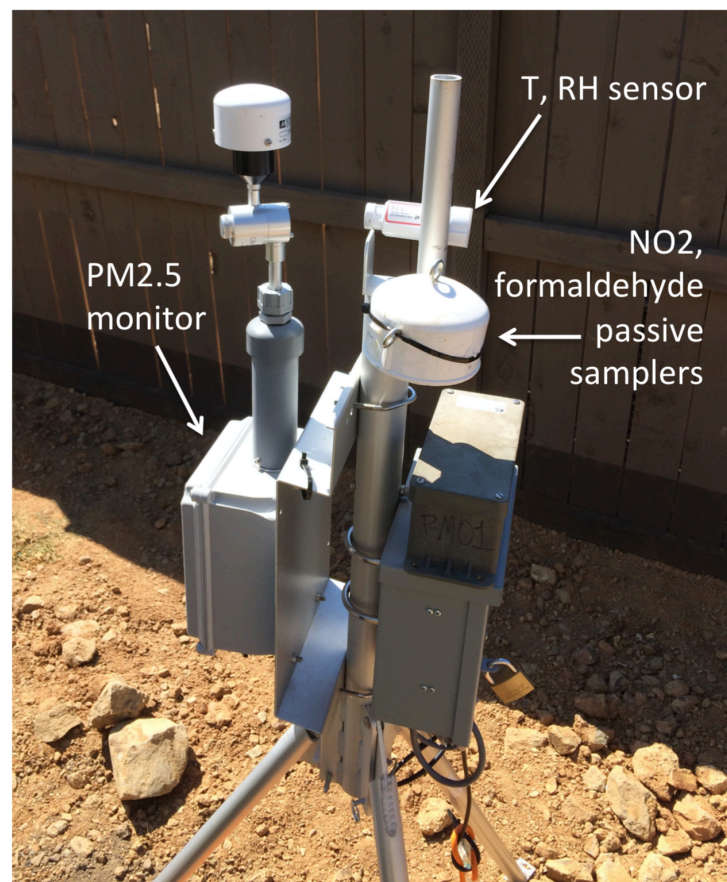
Modeling & local measurements fill local PM_{2.5} gaps

Low-cost sensors



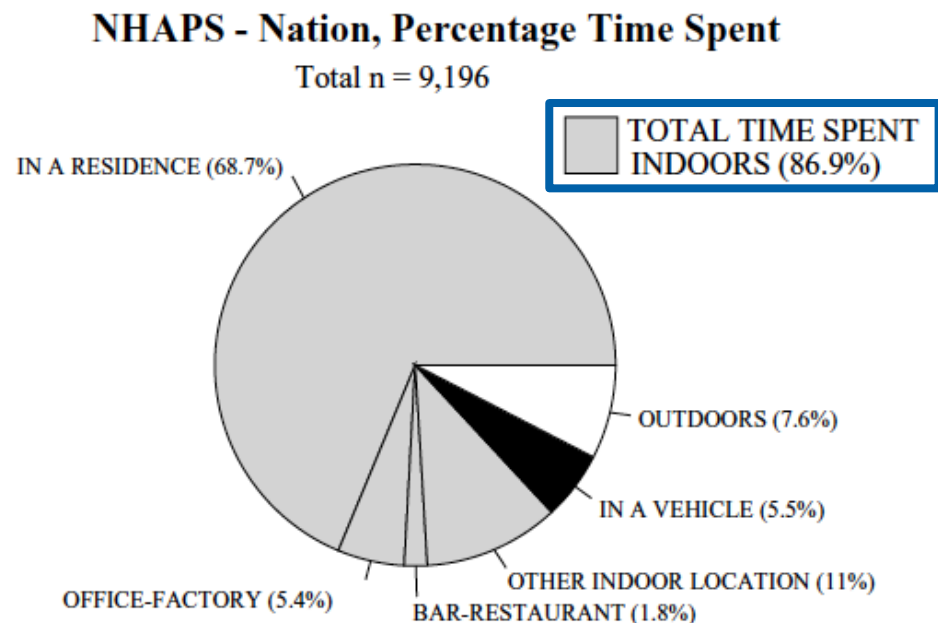
Bi et al., 2020 *Environ Sci Technol*

Looking Out My Back Door

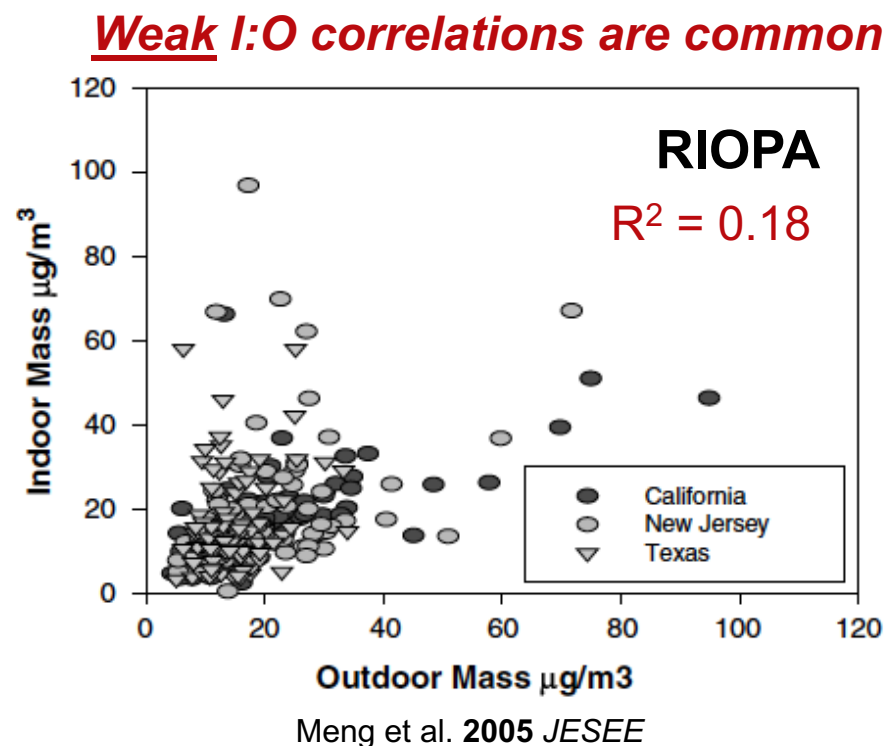


Chan et al., 2020 CEC-500-2020-023

Weak correlations between indoor and outdoor PM_{2.5}



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



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

We spend most of our time indoors!

Which leads to 'exposure misclassification'

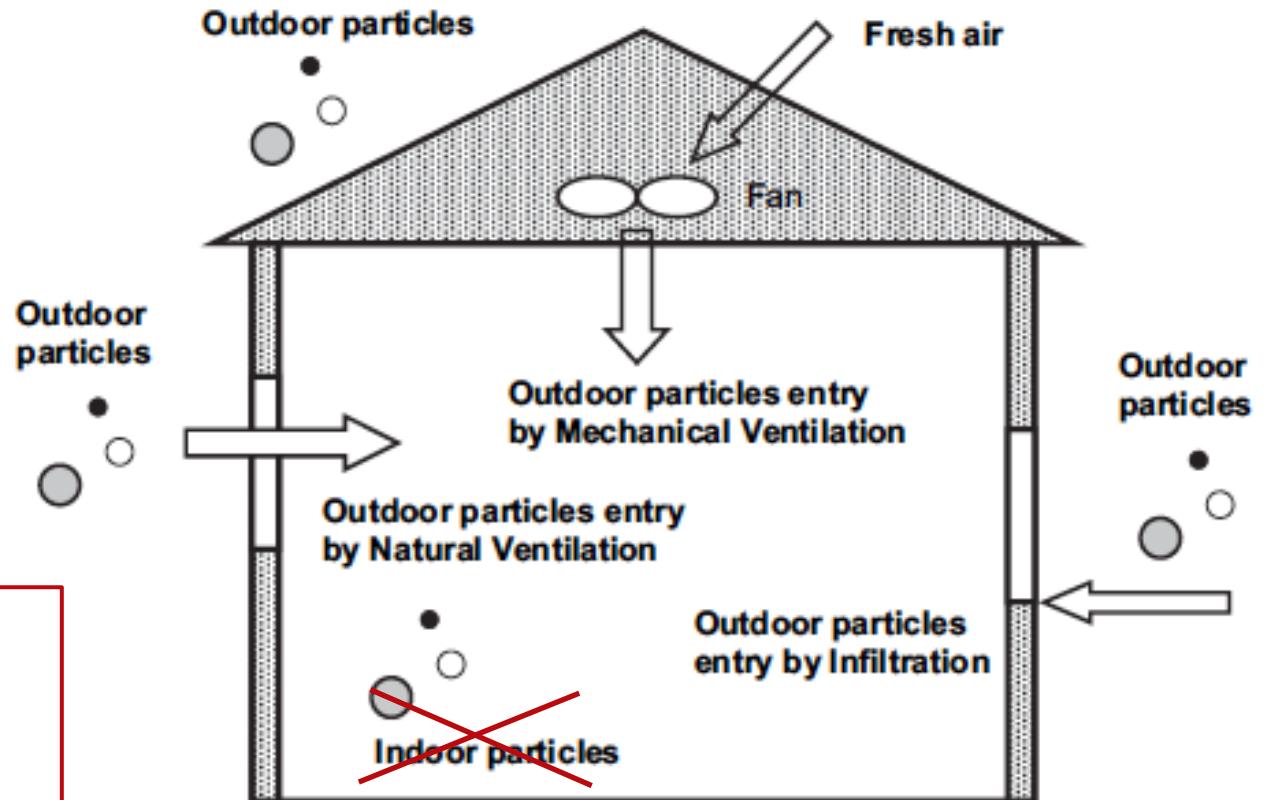
Indoor sources of outdoor PM and **key definitions**

I/O ratio:

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

Infiltration factor:

$$F_{inf} = \frac{C_{in}}{C_{out}} \bigg|_{no\ indoor\ sources}$$



Chen and Zhao, 2011 *Atmos Environ*

$$C_{in} = C_{og} + C_{ig} = F_{INF} \cdot C_{out} + C_{ig}$$

og = outdoor generated
ig = indoor generated

See presentation from 2016 NAS Workshop on Indoor PM:

<http://built-envi.com/wp-content/uploads/stephens-IOM-presentation-feb-2016.pdf>

Underlying mechanisms that govern F_{inf}

Liu and Nazaroff 2001 *Atmos Environ*

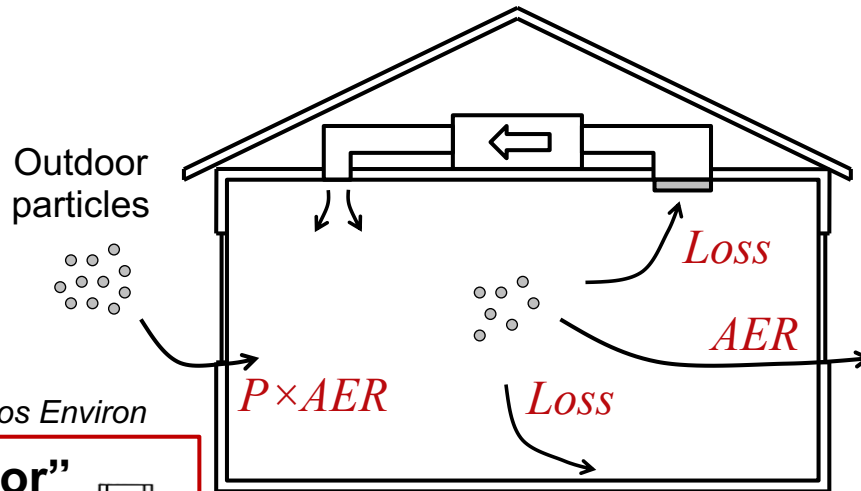
“Penetration Factor”

If $P = 1$:

The envelope offers no protection

If $P = 0$:

The envelope offers complete protection



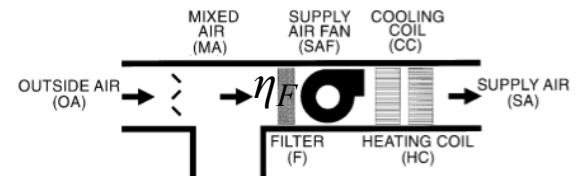
Penetration from outdoors

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

Removal by air exchange

In commercial buildings:

$$P = 1 - \eta_F$$



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

See presentation from 2016 NAS Workshop on Indoor PM:

<http://built-envi.com/wp-content/uploads/stephens-IOM-presentation-feb-2016.pdf>

INFILTRATION FACTORS

Methods to measure PM infiltration factors (F_{inf})

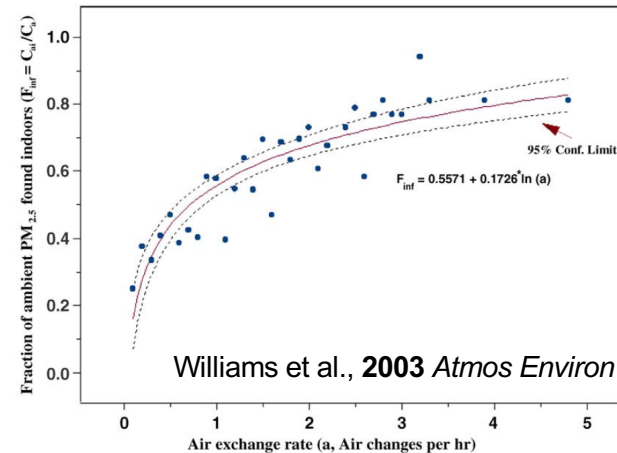
Chemical surrogate (e.g., sulfur/sulfate) of gravimetric PM samples

$$F_{inf} \propto \frac{S_{indoor}}{S_{outdoor}}$$

Sarnat et al. **2002** *Environ Sci Technol*

Wallace and Williams **2005** *Environ Sci Technol*

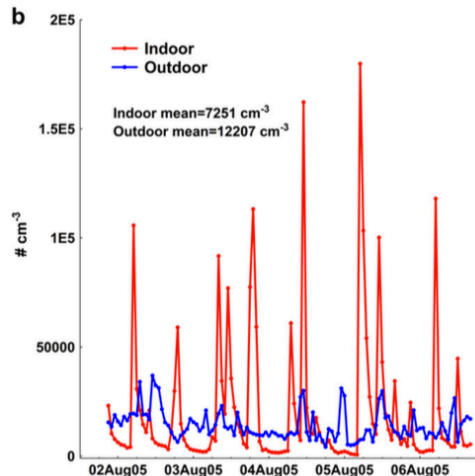
Tang et al. **2018** *JESEE*



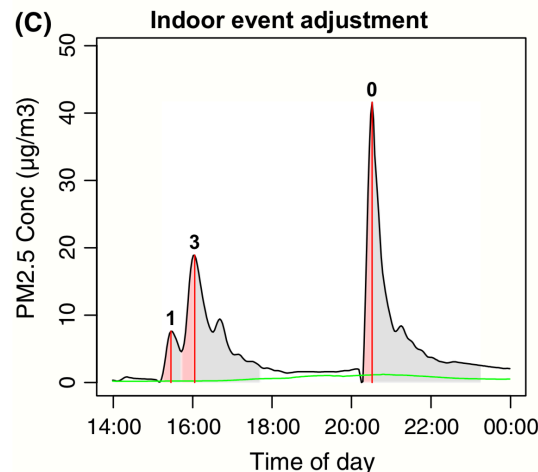
skcinc.com

Time-resolved monitoring and data processing

Peak-catching & elimination

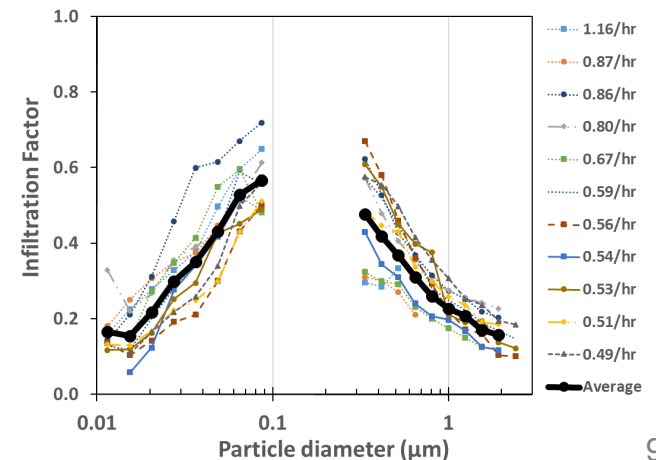


Kearney et al. **2011** *Atmos Environ*



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

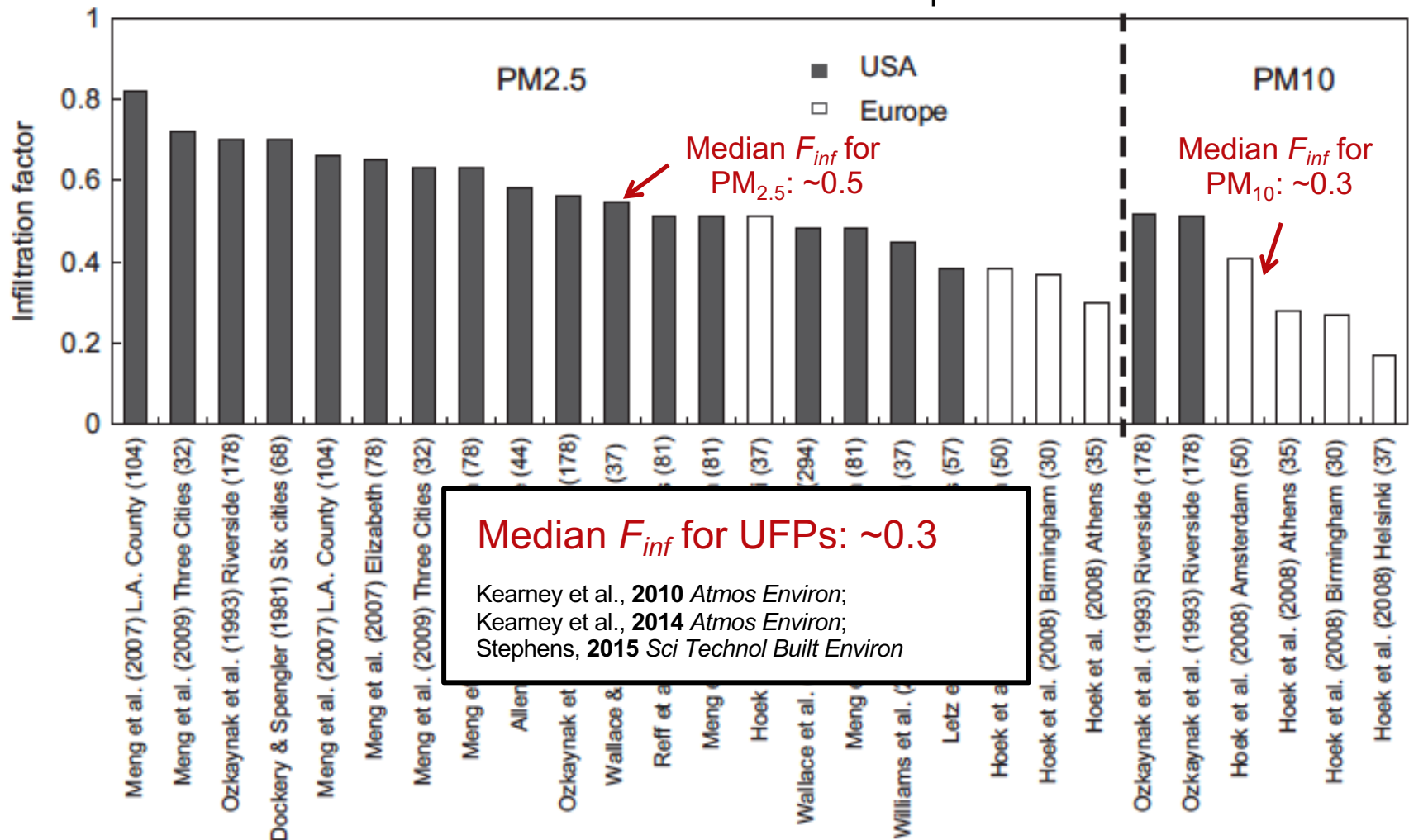
Unoccupied/no sources



Zhao and Stephens **2017** *Indoor Air*

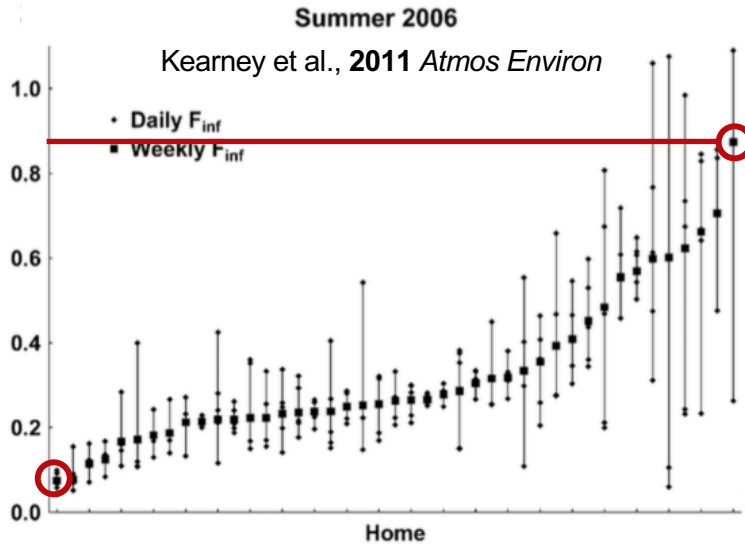
Large surveys of PM infiltration factors (F_{inf})

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

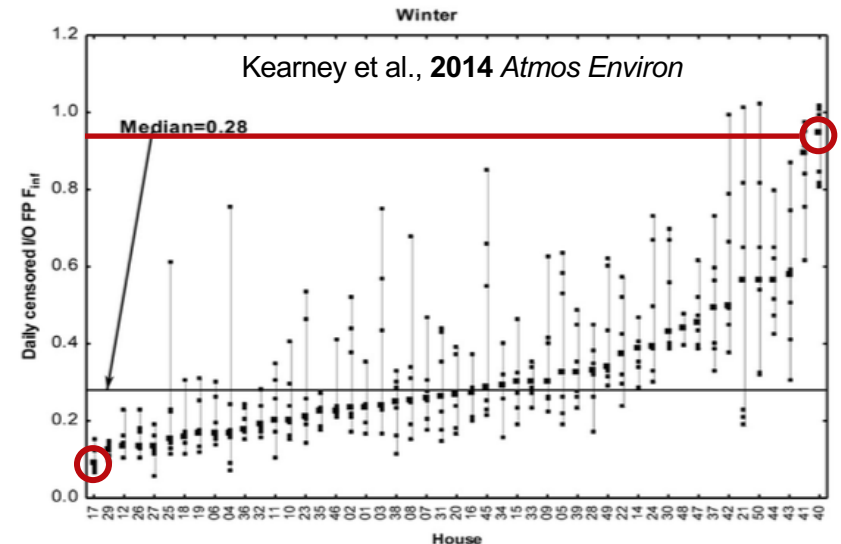


Between-home variability in infiltration factors (F_{inf})

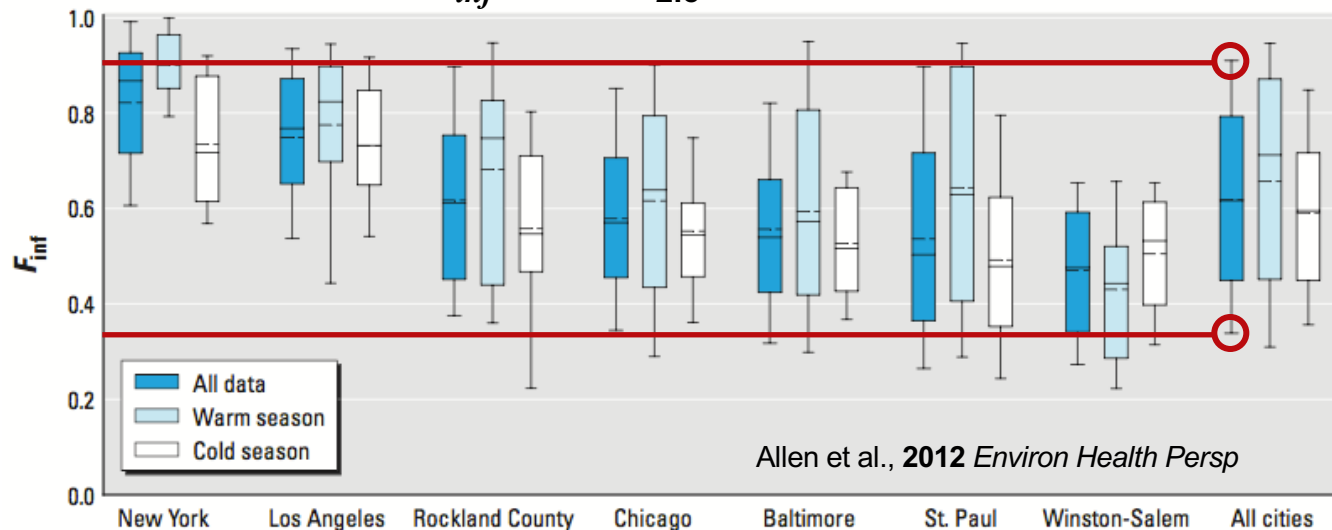
F_{inf} for UFPs in Windsor, ON



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



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

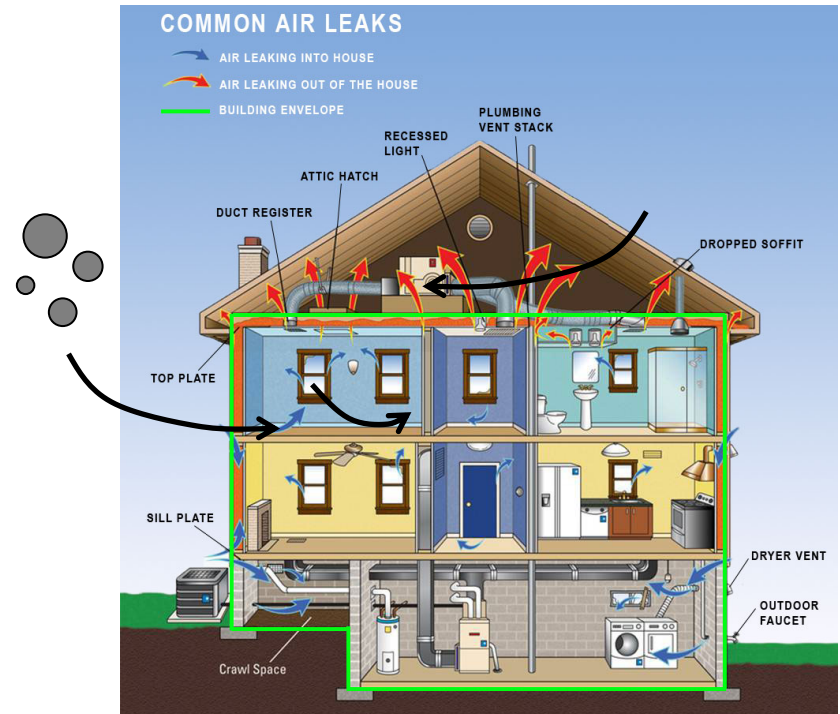


Allen et al., 2012 *Environ Health Persp*

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

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 change rate (ACR/ACH)
 - Meteorological driving forces (e.g., I/O temperatures, wind speed/direction)
 - Building envelope characteristics (e.g., airtightness)
- HVAC system runtime and filtration efficiency



PENETRATION FACTORS

Methods to indirectly measure penetration factors (P)

- Accuracy challenges w/ integrated gravimetric PM_{2.5} samples
 - Usually estimated via regression analysis across homes

Table 3. Parameter estimation by NLIN regression.

Table 3. Parameter estimation by NLIN regression.					Meng et al. 2005 JESEE	
State	<i>N</i>	Boundary condition ^a	<i>P</i>	95% CI of <i>P</i>	<i>k</i> (h ⁻¹)	95% CI of <i>k</i> (h ⁻¹)
Overall	268	Y	0.91	(0.71, 1.12)	0.79	(0.18, 1.41)
		N	0.91	(0.71, 1.12)	0.79	(0.18, 1.41)
California	112	Y	1.00	(1.00, 1.00)	0.90	(0.53, 1.28)
		N	1.04	(0.75, 1.33)	0.98	(0.28, 1.69)
New Jersey	80	Y	0.73	(0.42, 1.05)	0.46	(−0.44, 1.36)
		N	0.73	(0.42, 1.05)	0.46	(−0.44, 1.36)
Texas	76	Y	1.00	(1.00, 1.00)	0.99	(−1.38, 3.35)
		N	1.35	(0.46, 2.23)	1.18	(−1.57, 3.92)

^ameans parameters are estimated with boundary condition $P \in [0,1]$; N means no boundary conditions for parameter estimation.

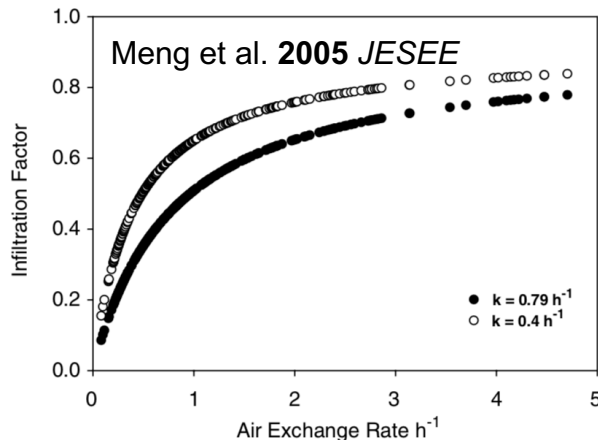


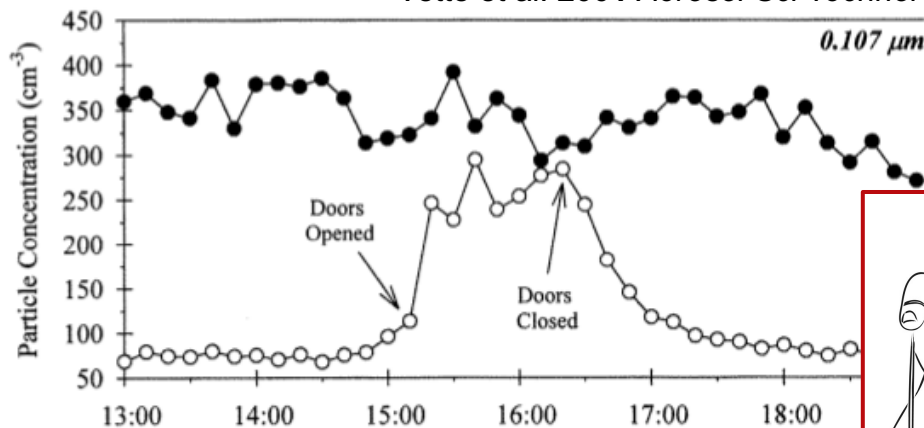
Table 7

Calculating P 's and k 's for PM_{2.5} using mixed model slopes

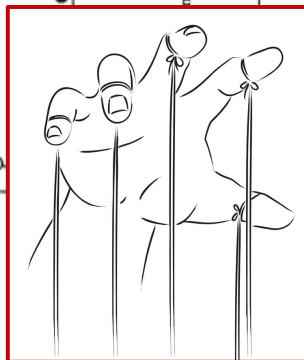
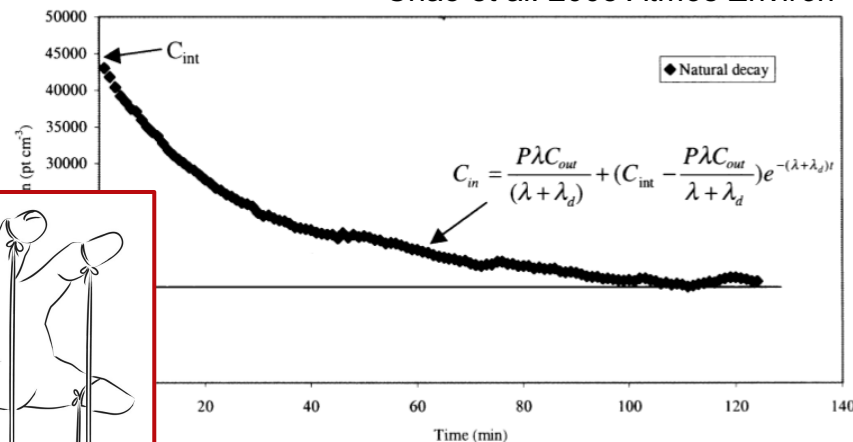
Variable	Min	Max	Mean	Std	PTEAM ^a	Seattle ^b
AER (h ⁻¹)	0.14	4.84	0.72	0.63	0.97	0.59
P	0.11	1.00	0.72	0.21	1.00	0.97
k (h ⁻¹)	0.10	0.80	0.42	0.19	0.39	0.15
F_{inf}	0.05	0.94	0.45	0.21	0.71	0.78

Methods to directly measure penetration factors (P)

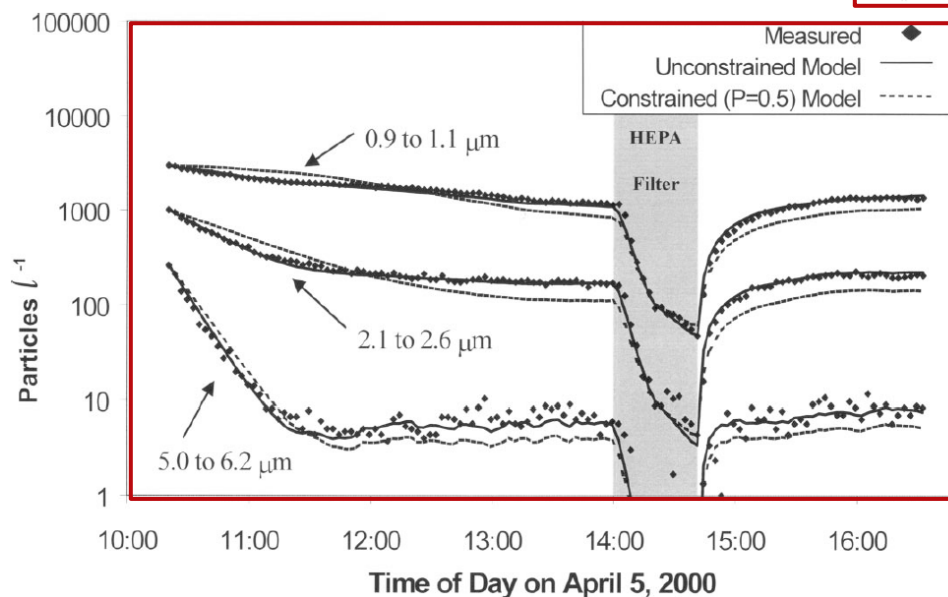
Vette et al. 2001 *Aerosol Sci Technol*



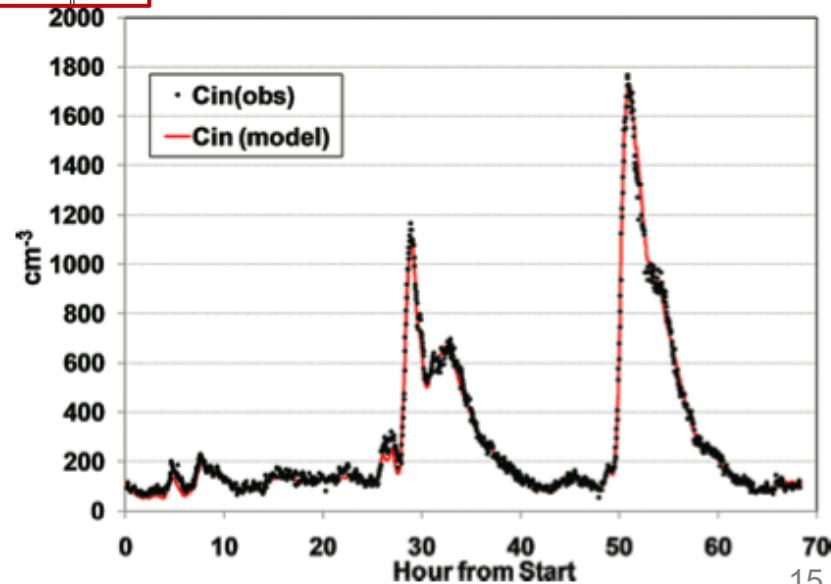
Chao et al. 2003 *Atmos Environ*



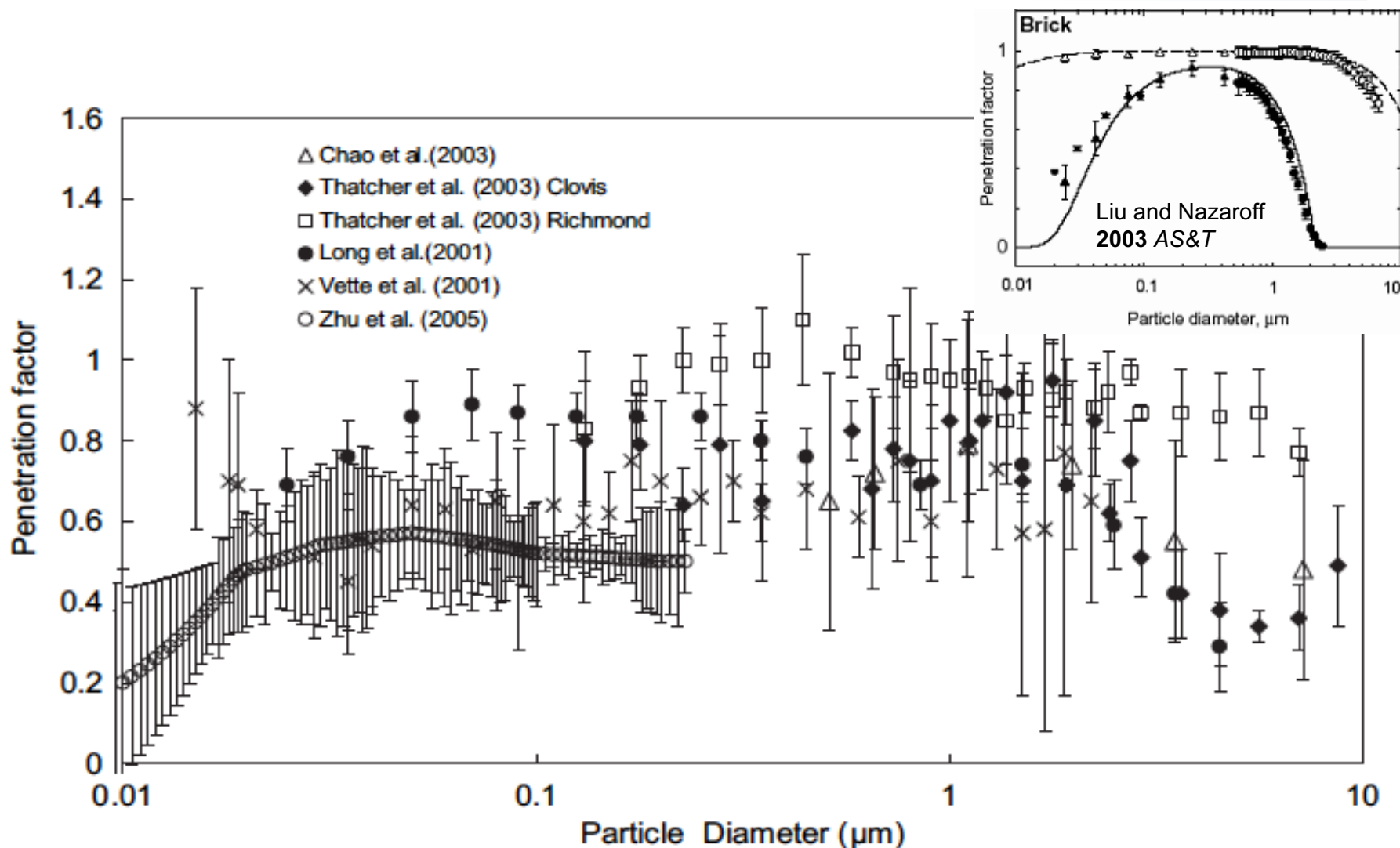
Thatcher et al. 2003 *Aerosol Sci Technol*



Rim et al. 2010 *Environ Sci Technol*



Summary of size-resolved penetration factors (P)

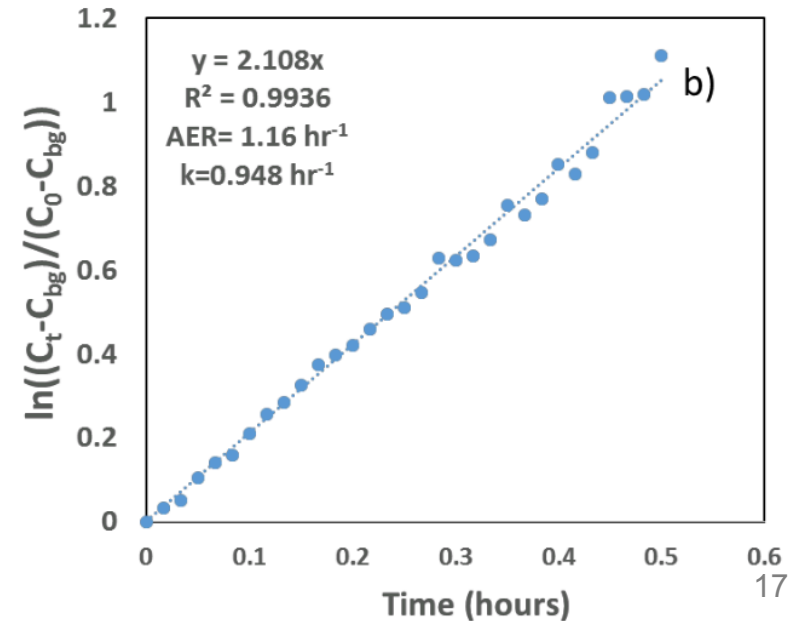
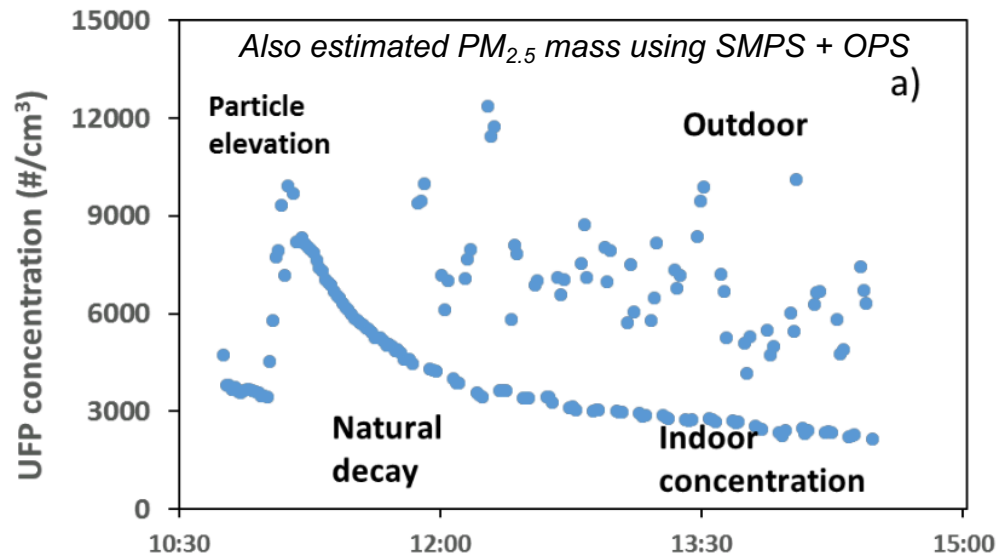


But: limited direct measurements of $\text{PM}_{2.5}$ penetration factors

Direct measurements of penetration factors (P)

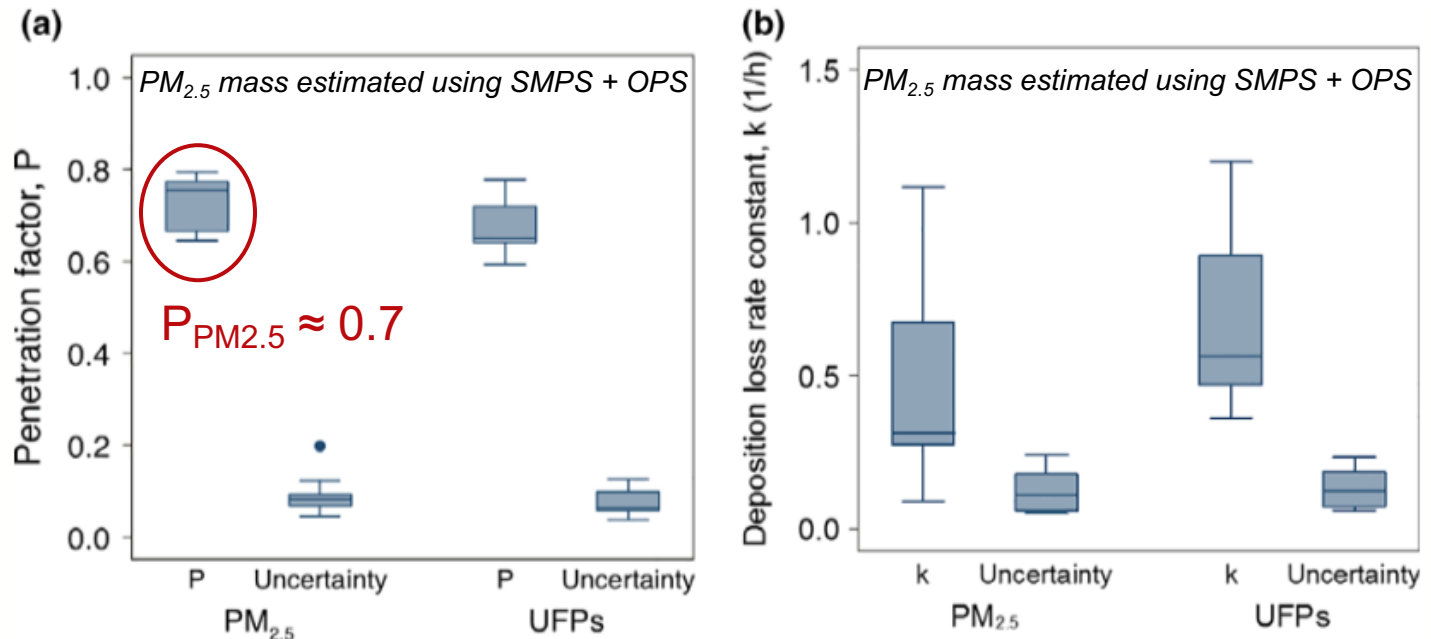
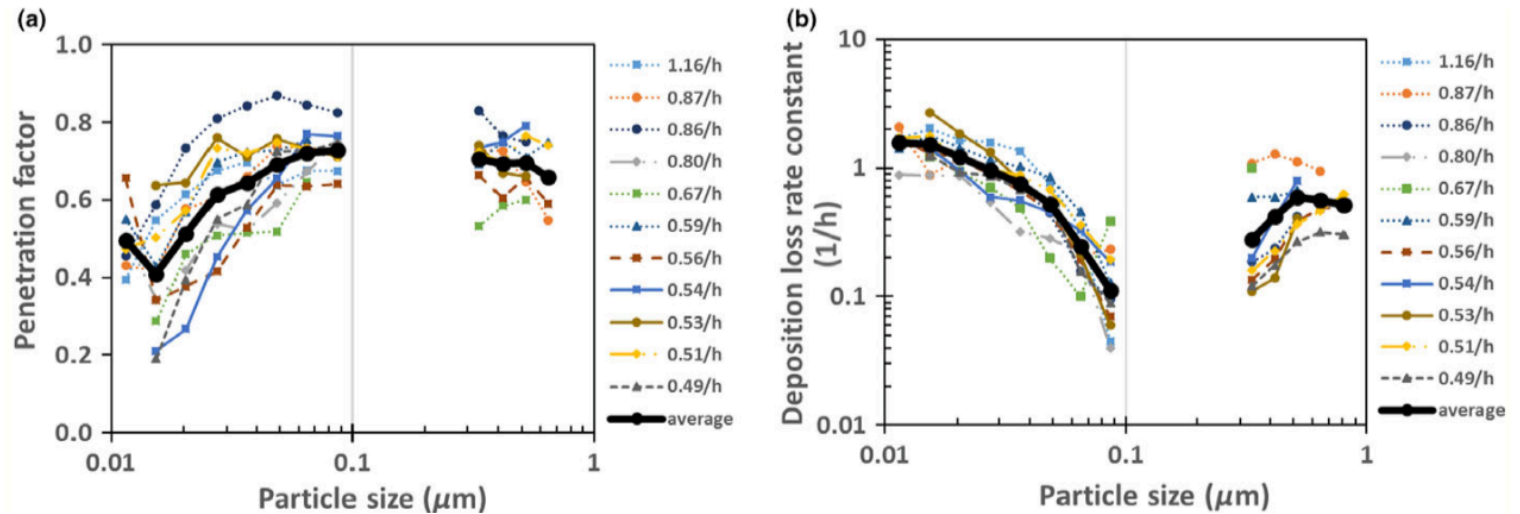


Funding: U.S. EPA (No. 83575001) & ASHRAE NIA



PM_{2.5} penetration factors (P) from size-resolved data

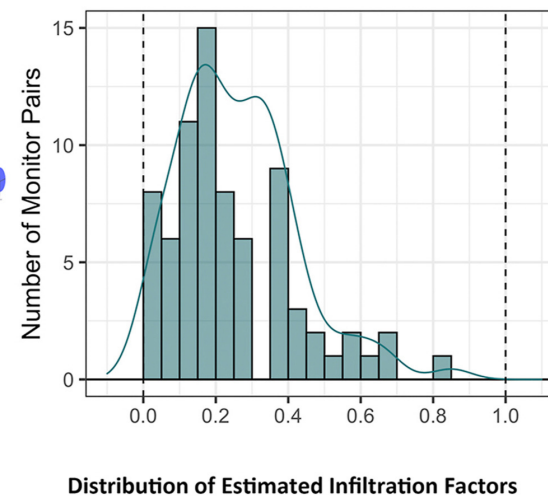
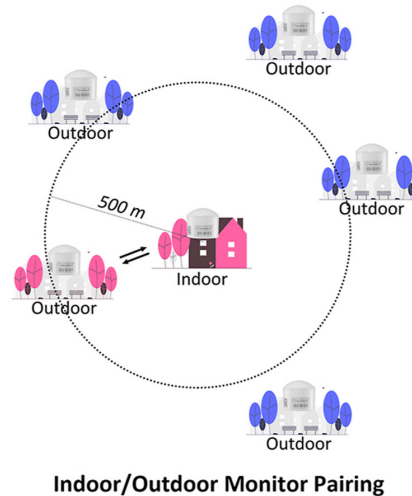
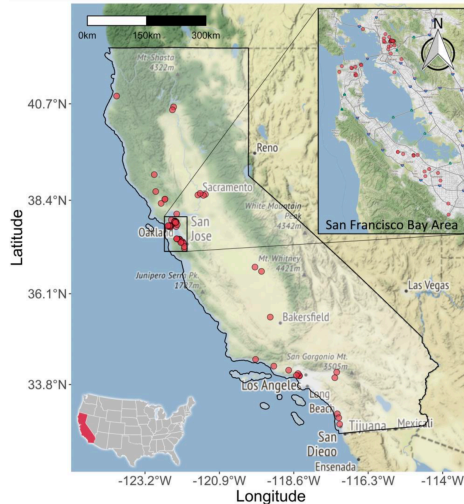
A single apartment unit:



NEW DIRECTIONS

New directions in assessing F_{inf} and P for PM_{2.5}

Estimating F_{inf} with low-cost sensor networks



Bi et al. 2021 *Environmental Pollution*



Modeling F_{inf} with building characteristics and other predictors

Table 5. Comparison of the current study and previous approaches to modeling infiltration and indoor PM_{2.5} concentrations.

	<i>Current study</i>	<i>Allen et al.³⁷</i>	<i>Baster et al.²⁷</i>	<i>Wallace and Williams⁶</i>
Study area	102 homes Boston	353 homes 7 cities across US	39 homes Boston	37 homes North Carolina
Infiltration proxy	Sulfur	Sulfur	GIS and housing characters	Sulfur
Model technique	Mixed-effects model	Multivariable regression	Bayesian model	Multivariable regression
Predictive power infiltration proxy	CV $R^2 = 89.3\%$	CV $R^2 = 30\text{--}60\%$	—	—
Predictive power on PM _{2.5}	CV $R^2 = 79.1\%$	—	CV $R^2 = 0.37$	$R^2 = 0.74$

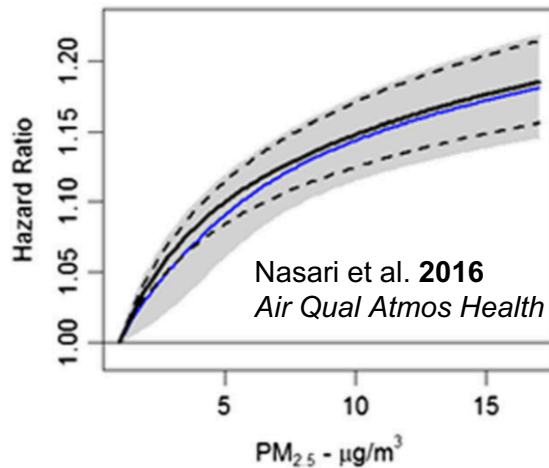
Abbreviation: CV, cross-validation.

New directions in assessing F_{inf} and P for $PM_{2.5}$

Integrating F_{inf} in exposure assessment & environmental epidemiology

Funding: U.S. EPA (via SCG)

Modified concentration-response (C-R) functions



Typical C-R

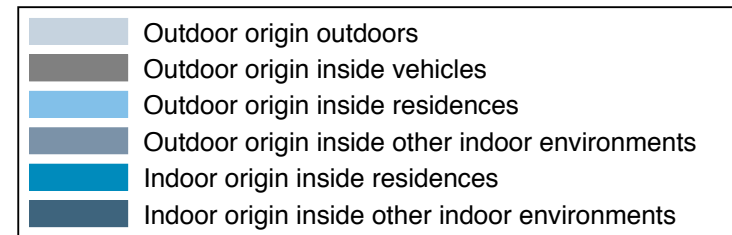
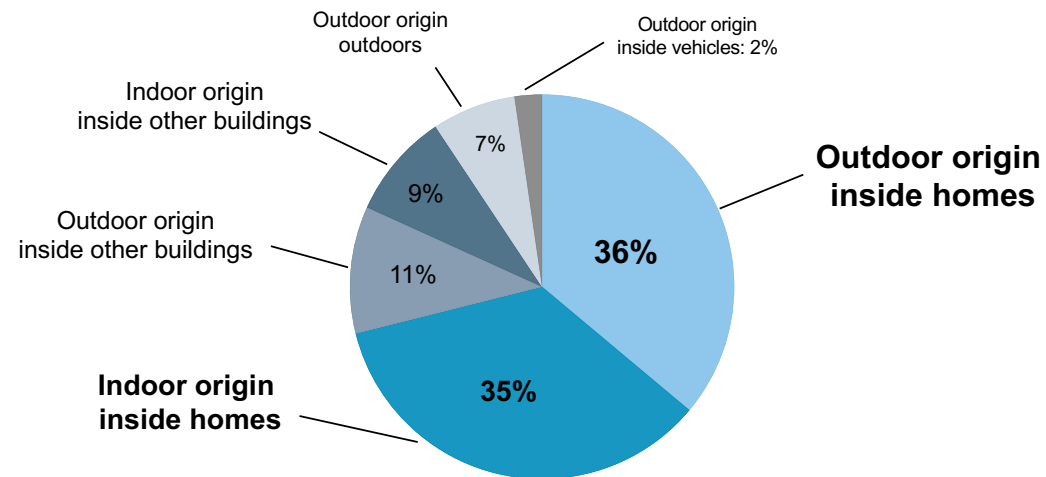
$$\Delta y_i = y_0 [\exp(\beta_i \times \Delta E_i) - 1] Pop$$

Modified C-R

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

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

Microenvironmental $PM_{2.5}$ exposure contributions



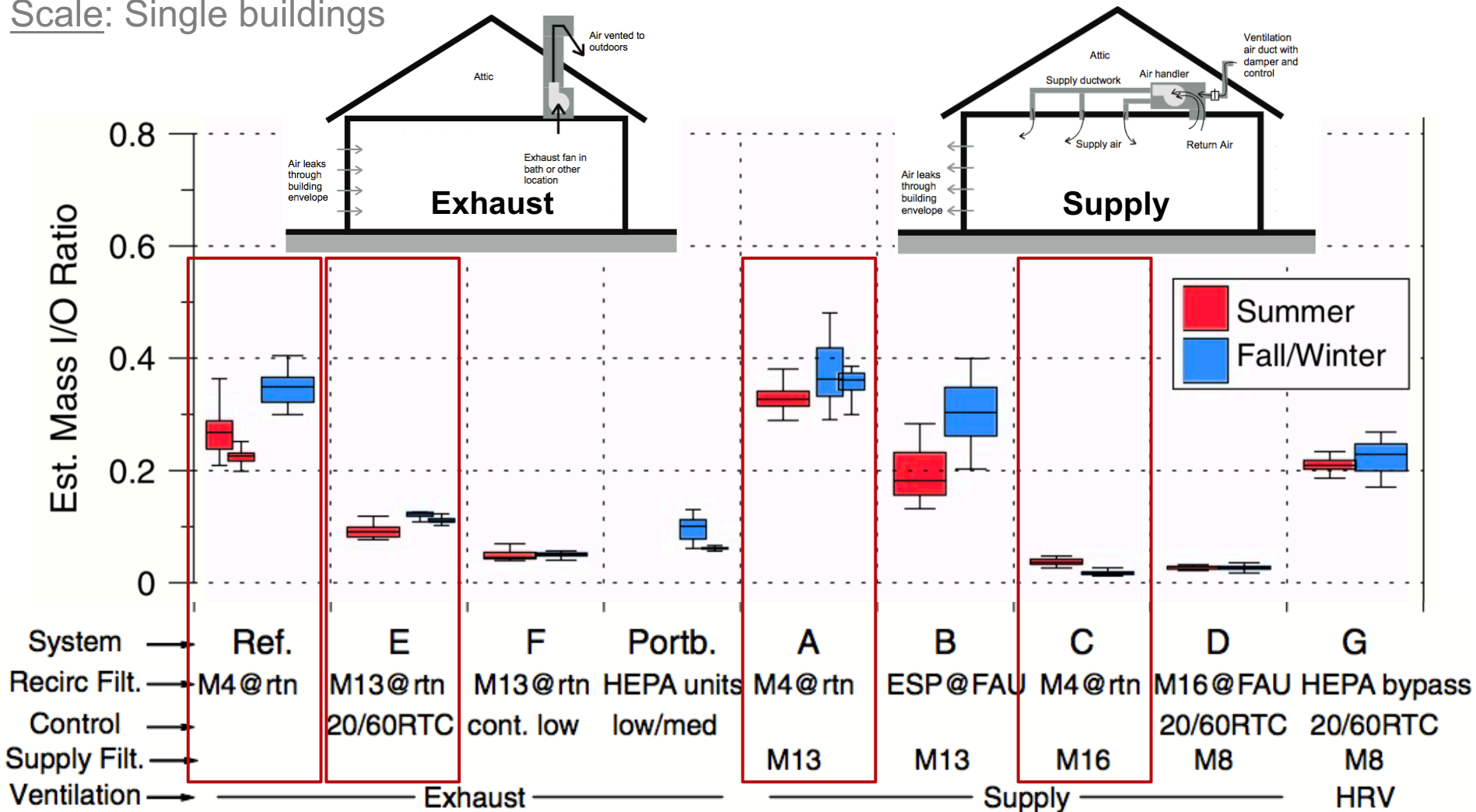
Azimi and Stephens 2020 JESEE

Scale: Building stock 21

New directions in assessing F_{inf} and P for PM_{2.5}

Exploring the impacts of mechanical ventilation and filtration on F_{inf}

Scale: Single buildings



Unoccupied test house

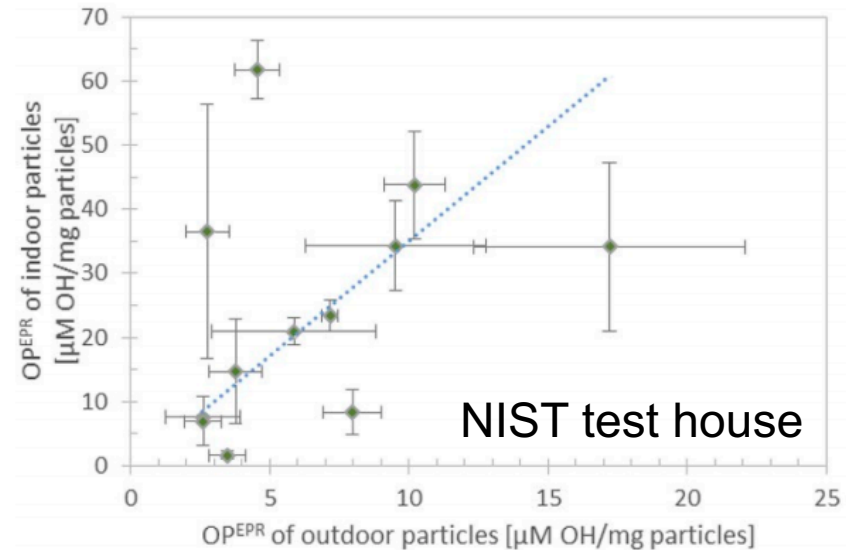
New directions in assessing F_{inf} and P for PM_{2.5}

Health-relevant metrics (e.g., oxidative potential) of indoor-infiltrated PM_{2.5}

Oxidative potential (OP) of indoor PM in an unoccupied test house:

- Generate reactive oxygen species (ROS)
- EPR spectroscopy
- Mass-normalized OP^{EPR} higher indoors than outdoors

Khurshid et al. **2019** *Building and Environment*

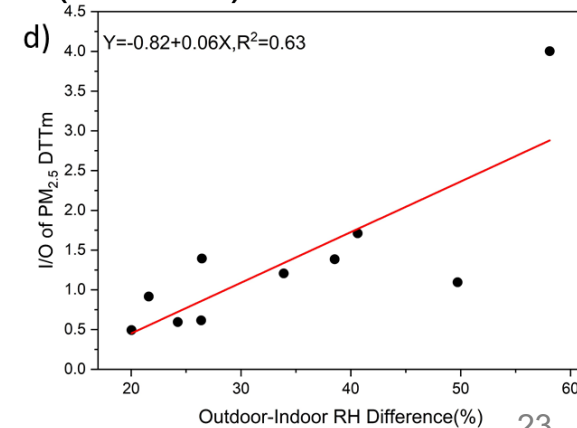
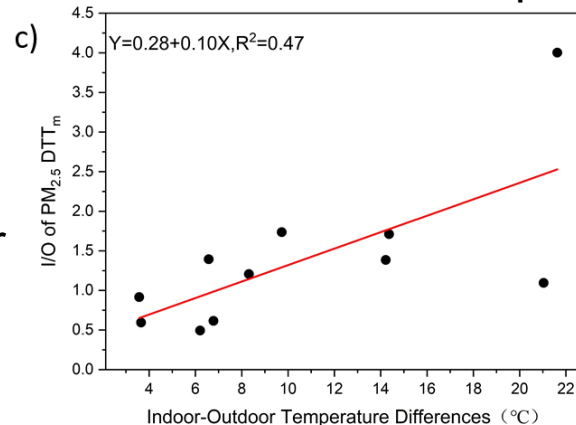


Oxidative potential of indoor PM of outdoor origin in an unoccupied apartment unit:

- Dithiothreitol (DTT) assay
- Mass-normalized DTT higher indoors than outdoors

Zeng et al. **2021** *under review*

IIT apartment (*studioE*)



Scale: Single buildings

Funding: ASHRAE NIA

Ongoing research needs

- Integrate indoor exposure attributions to ambient PM epidemiology investigations

- Address exposure misclassification
- Improve accuracy of health effect estimates

Chen et al. **2012** *Epidemiology*
Hodas et al. **2013** *JESEE*
Sarnat et al. **2013** *JESEE*

- Differential toxicity of PM of indoor/outdoor origin

Ebelt et al. **2005** *Epidemiology*; Koenig et al. **2005** *EHP*; Long et al. **2001** *EHP*; Monn and Becker **1999** *Tox Appl Pharm*

- Direct measurements of F_{inf} possible, but expensive at scale

- Typically limited to samples of convenience
- Potential to leverage advances in low-cost sensors

- Direct measurements of P remain very limited

- Increase sample sizes, incorporate PM chemical composition
- Standardize approaches, explore influencing factors

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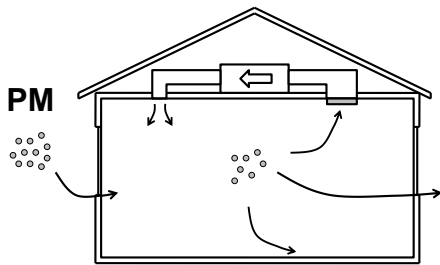
Outdoor-to-Indoor Transport Mechanisms and Particle Penetration for Fine Particulate Matter

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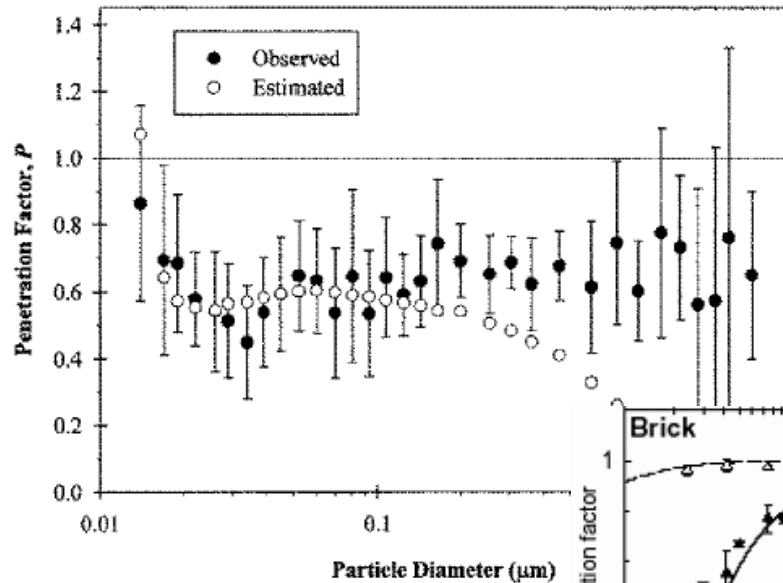


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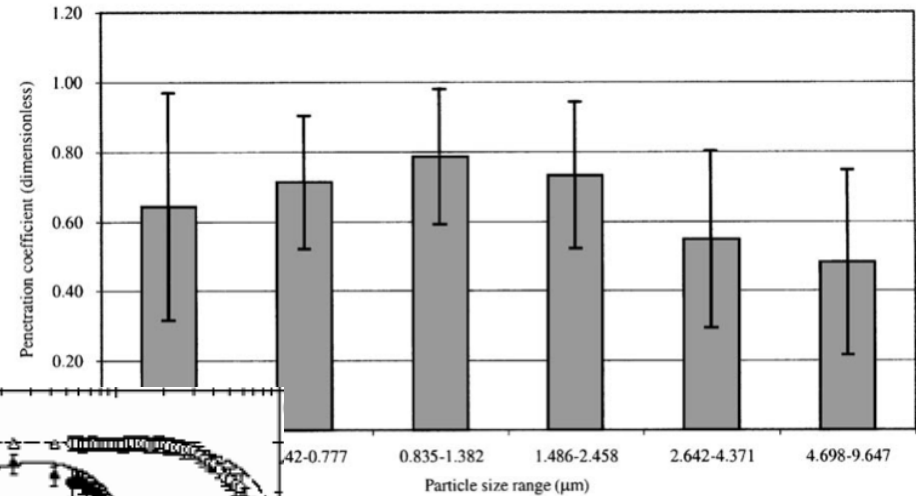
Bonus slides

Direct measurements of penetration factors (P)

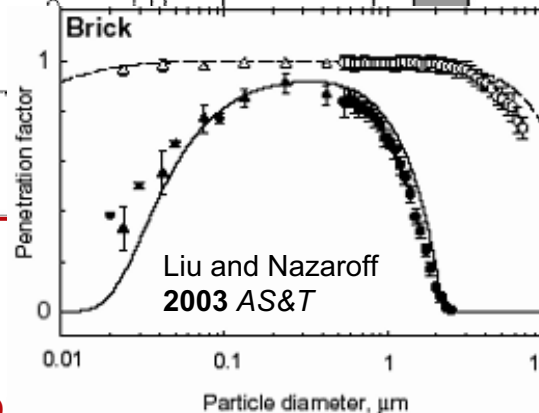
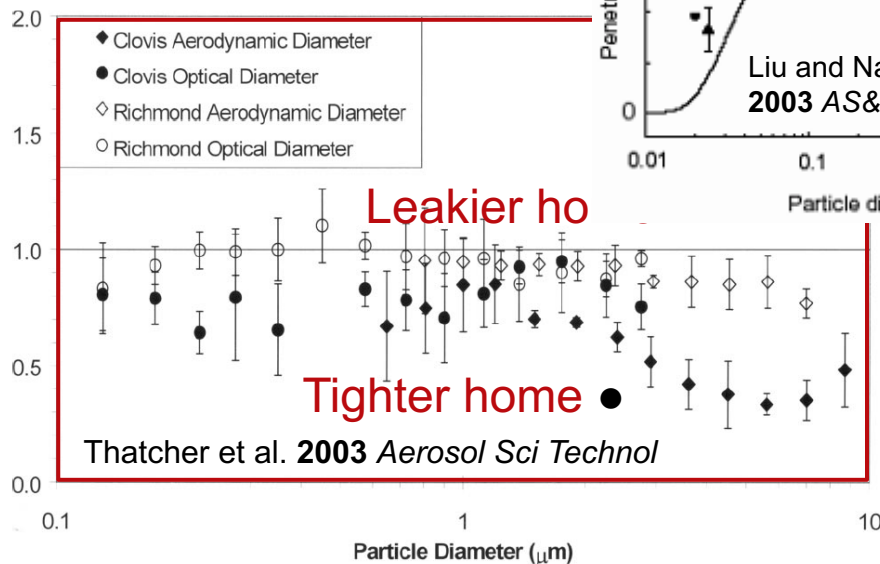
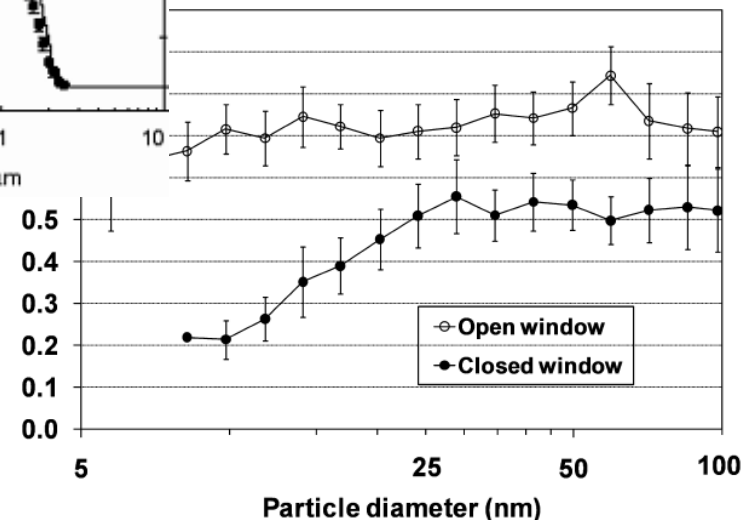
Vette et al. 2001 *Aerosol Sci Technol*



Chao et al. 2003 *Atmos Environ*



Rim et al. 2010 *Environ Sci Technol*



New directions in assessing F_{inf} and P for PM_{2.5}

Exploring the impacts of mechanical ventilation and filtration on F_{inf}

HUD HHTS: Impacts of ventilation system retrofits on IAQ and adult asthma outcomes (2016-2020)



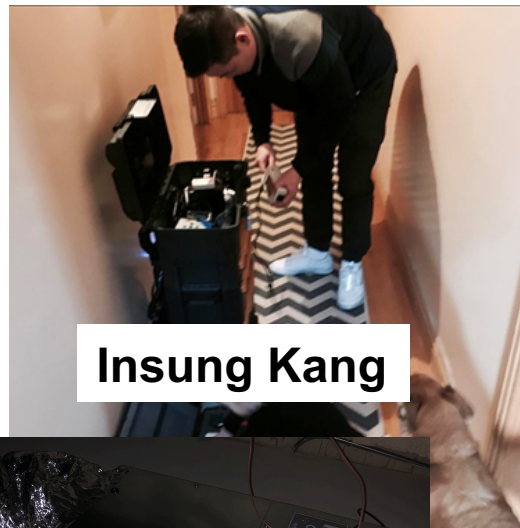
ELEVATE ENERGY
Smarter energy use for all



CHICAGO BUNGLOW ASSOCIATION



Parham Azimi



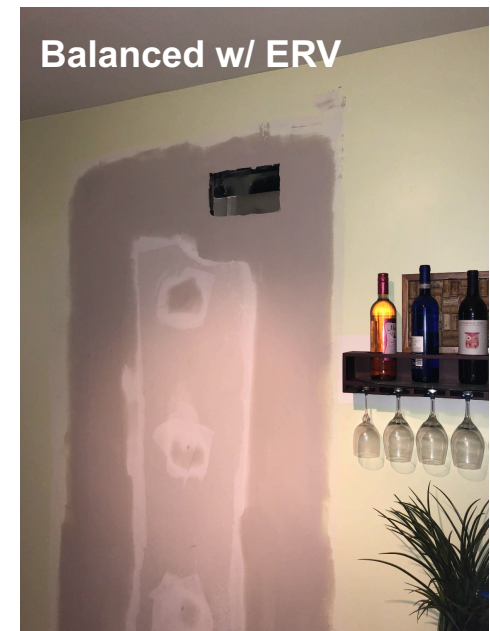
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Supply only



Exhaust only

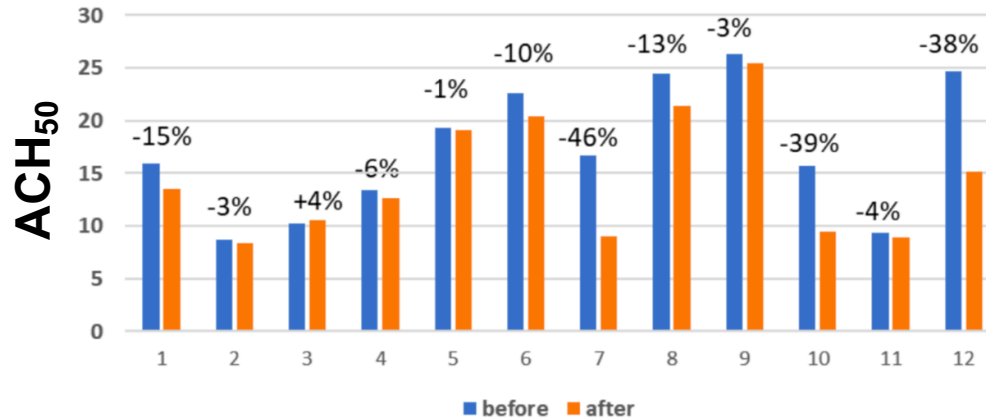


Balanced w/ ERV

New directions in assessing F_{inf} and P for PM_{2.5}

Assessing the impacts of energy efficiency retrofits on F_{inf} and P

Scale:
Single buildings



Homes in Chicago

Envelope air-sealing

- Mean ACH₅₀ reduction of ~16%

