Predictions and determinants of size-resolved particle infiltration factors in single-family homes in the U.S.

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Motivation: Health effects and outdoor PM

- Epidemiological studies show associations between elevated outdoor particulate matter (PM) and adverse health effects
  - PM_{10}, $PM_{2.5}$, and ultrafine particles (UFP, < 100 nm)

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*; Stölzel et al., **2007** *J Expo Sci Environ Epidem*; Andersen et al., **2010** *Eur Heart J;* Brook et al. **2010** *Circulation*; and many others

- But we spend most of our time indoors

  ~87% of the time on average (~69% at home)

Klepeis et al., **2001** *J Expo Anal Env Epi*

- Outdoor particles can infiltrate and persist in homes with varying efficiencies Chen and Zhao, **2011** *AE;* Williams et al., **2003** *AE;* Kearney et al., **2010** *AE*

Motivation: Exposure misclassification

- Much of our exposure to outdoor PM often occurs indoors
  - Often at home

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

- Failing to account for differences in indoor proportions of outdoor particles can result in large exposure misclassifications

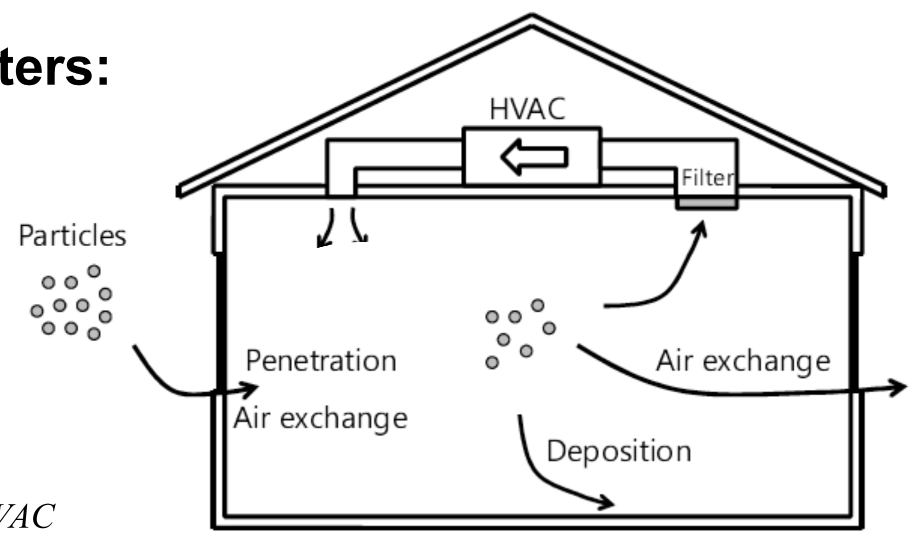
Baxter et al. **2010** *JESEE*; Meng et al. **2005** *ES&T*; Hodas et al. **2013** *JESEE*; Baxter et al. **2013** *Air Qual Atmos Health*

Goals of this work

- Develop and apply a Monte Carlo simulation tool to estimate the statistical distribution of long-term average size-resolved infiltration factors (F_{inf}) for particles 0.001-10 μm across the U.S. residential building stock
  - Allows for estimates of UFP and $PM_{2.5}$ as well

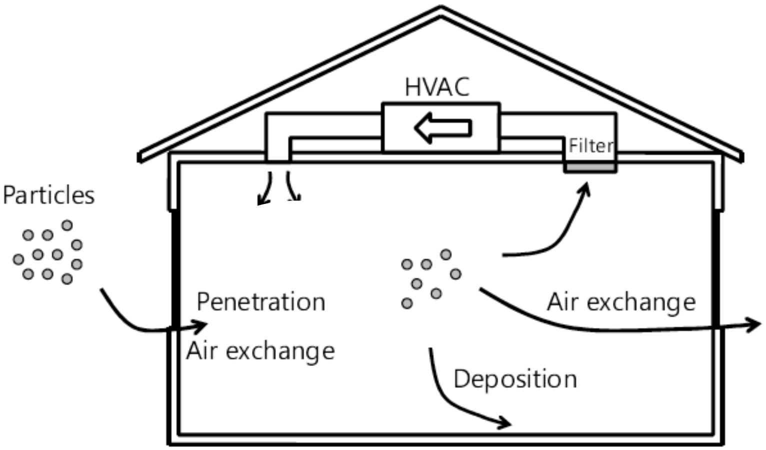
Explore influence of key parameters:

- Air exchange rate, λ
  - With and without windows open
- Particle penetration factor, P_i
  - With and without windows open
- Deposition rates, $k_{i,dep}$
- Removal by HVAC filter, $\eta_{HVAC}\lambda_{HVAC}$
  - And filter ownership
- HVAC system runtime, f_{HVAC}



$$F_{i,\text{inf}} = \frac{C_{i,\text{in}}}{C_{i,\text{out}}} = \frac{P_i \lambda}{\lambda + k_{i,\text{dep}} + \lambda_{\text{HVAC}} f_{\text{HVAC}} \eta_{i,\text{HVAC}}}$$

Methodology: Model framework



Long-term average size-resolved infiltration factor

$$F_{i,\mathrm{inf}} = \frac{C_{i,\mathrm{in}}}{C_{i,\mathrm{out}}} = \frac{P_i \lambda}{\lambda + k_{i,\mathrm{dep}} + \lambda_{\mathrm{HVAC}} f_{\mathrm{HVAC}} \eta_{i,\mathrm{HVAC}}}$$

Long-term average air exchange rates (AER, λ)

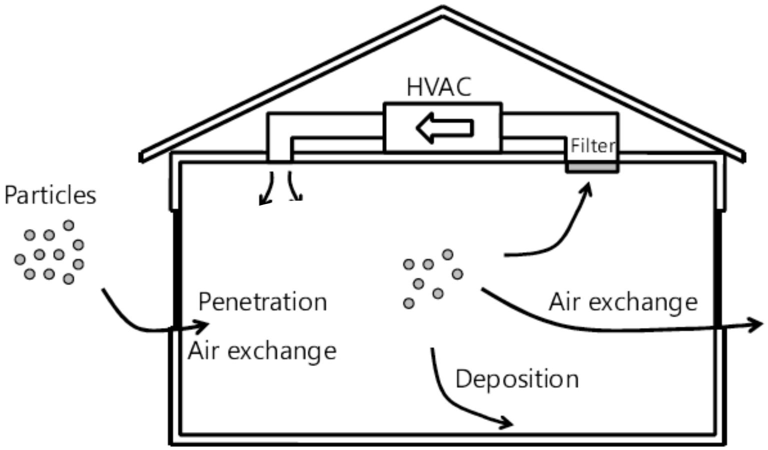
$$\lambda = \lambda_{\text{closed windows}}\left(1 - f_{\text{open windows}}\right) + \lambda_{\text{open windows}} f_{\text{open windows}}$$

$\lambda_{openwindows}$ = AER during periods of window opening (hr^{-1})

$f_{openwindows}$ = fraction of time of window opening (-)

$\lambda_{closedwindows}$ = AER during periods with closed windows (hr^{-1})

Methodology: Model framework



Long-term average size-resolved infiltration factor

$$F_{i,\text{inf}} = \frac{C_{i,\text{in}}}{C_{i,\text{out}}} = \frac{P_i \lambda}{\lambda + k_{i,\text{dep}} + \lambda_{\text{HVAC}} f_{\text{HVAC}} \eta_{i,\text{HVAC}}}$$

AERs with windows open

$$\lambda_{\text{openwindows}} = \lambda_{\text{closedwindows}} \left(\phi_{\text{openwindows,low}} m_{\text{openwindows,low}} + \phi_{\text{openwindows,high}} m_{\text{openwindows,high}} \right)$$

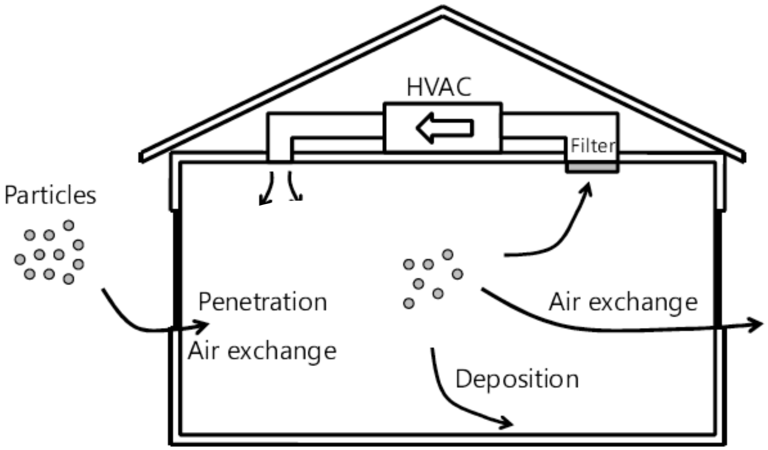
$\phi_{openwindows,low}$ = probability of low window opening (-)

$\phi_{openwindows,high}$ = probability of high window opening (-)

$m_{openwindows,low}$ = AER multiplier during low window opening (-)

$m_{openwindows,high}$ = AER multiplier during high window opening (-)

Methodology: Model framework



Long-term average size-resolved infiltration factor

$$F_{i,\text{inf}} = \frac{C_{i,\text{in}}}{C_{i,\text{out}}} = \frac{P_i \lambda}{\lambda + k_{i,\text{dep}} + \lambda_{\text{HVAC}} f_{\text{HVAC}} \eta_{i,\text{HVAC}}}$$

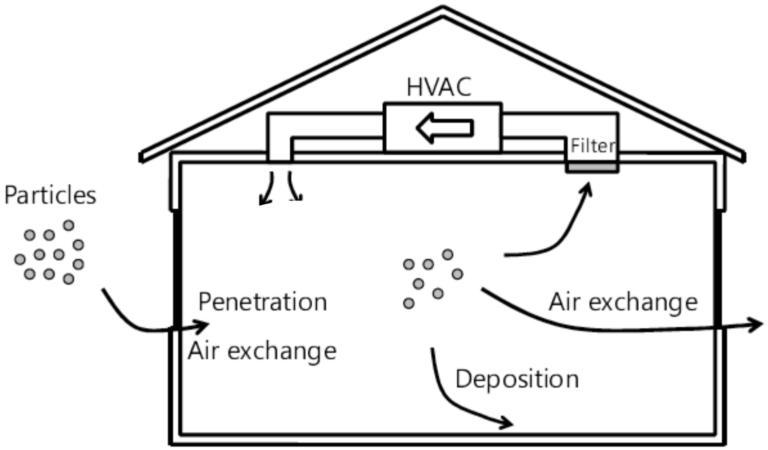
Fraction of time windows are open

$$f_{\text{openwindows}} = f_{\text{mild}} f_{\text{openwindows,mild}}$$

f_{mild} = fraction of mild weather (-)

$f_{openwindows,mild}$ = fraction of window opening during mild weather (-)

Methodology: Model framework



Long-term average size-resolved infiltration factor

$$F_{i,\mathrm{inf}} = \frac{C_{i,\mathrm{in}}}{C_{i,\mathrm{out}}} = \frac{P_i \lambda}{\lambda + k_{i,\mathrm{dep}} + \lambda_{\mathrm{HVAC}} f_{\mathrm{HVAC}} \eta_{i,\mathrm{HVAC}}}$$

Long-term average size-resolved envelope penetration factors

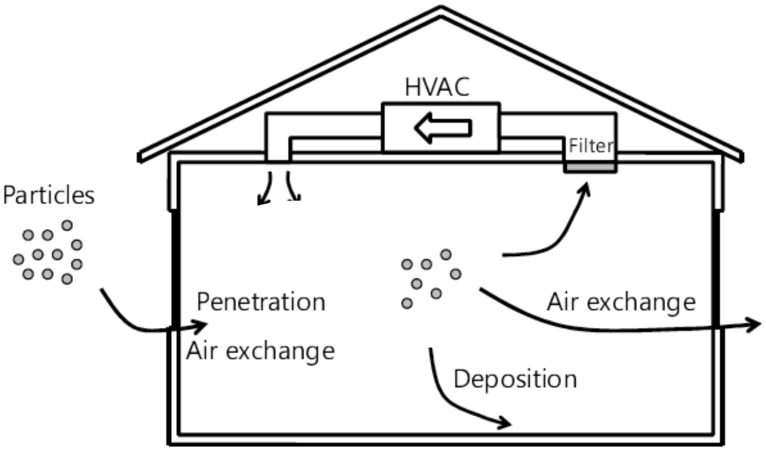
$$P_i = P_{i,\mathrm{closedwindows}} \left(1 - f_{\mathrm{openwindows}}\right) + P_{i,\mathrm{openwindows}} f_{\mathrm{openwindows}}$$

$P_{i,openwindows}$ = envelope penetration factor during periods of window opening (-)

$f_{openwindows}$ = fraction of time of window opening (-)

$P_{i,closedwindows}$ = envelope penetration factor during periods w/ closed windows (-)

Methodology: Model framework



Long-term average size-resolved infiltration factor

$$F_{i,\mathrm{inf}} = \frac{C_{i,\mathrm{in}}}{C_{i,\mathrm{out}}} = \frac{P_i \lambda}{\lambda + k_{i,\mathrm{dep}} + \lambda_{\mathrm{HVAC}} f_{\mathrm{HVAC}} \eta_{i,\mathrm{HVAC}}}$$

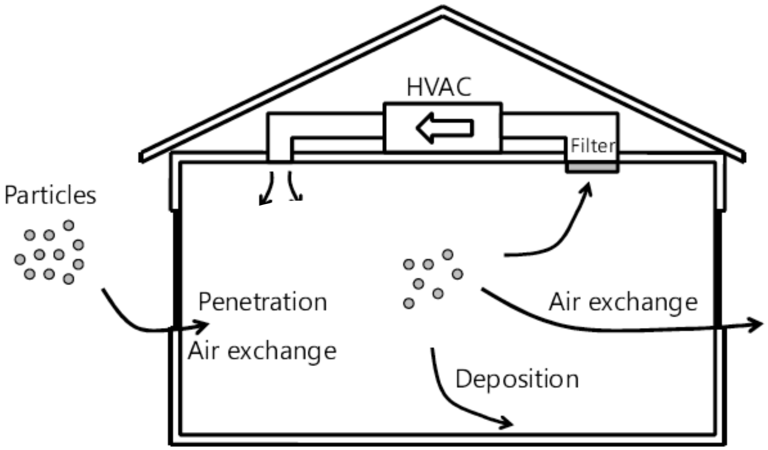
Envelope penetration factors with open windows

$$P_{i,\mathrm{openwindows}} = P_{i,\mathrm{openwindows,low}}\phi_{\mathrm{openwindows,low}} + P_{i,openwindows,high}\phi_{\mathrm{openwindows,high}}$$

$\phi_{openwindows,low}$ = probability of low window opening (-)

$\phi_{openwindows,high}$ = probability of high window opening (-)

Methodology: Model framework



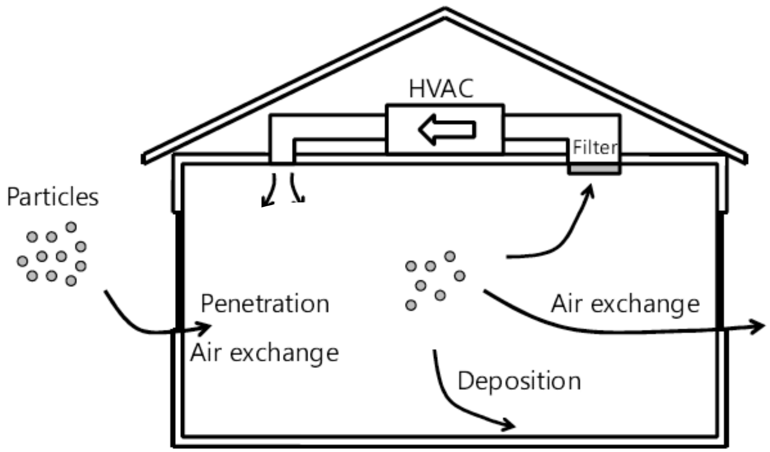
Long-term average size-resolved infiltration factor

$$F_{i,\mathrm{inf}} = \frac{C_{i,\mathrm{in}}}{C_{i,\mathrm{out}}} = \frac{P_i \lambda}{\lambda + k_{i,\mathrm{dep}} + \lambda_{\mathrm{HVAC}} f_{\mathrm{HVAC}} \eta_{i,\mathrm{HVAC}}}$$

Envelope penetration factors with open windows (scales with AER)

$$P_{i,\mathrm{openwindows,low}} = P_{i,\mathrm{closedwindows}} \frac{\lambda_{\mathrm{closedwindows}}}{\lambda_{\mathrm{openwindows,low}}} + (1) \frac{\lambda_{\mathrm{openwindows,low}} - \lambda_{\mathrm{closedwindows}}}{\lambda_{\mathrm{openwindows,low}}}$$

Methodology: Model framework



Long-term average size-resolved infiltration factor

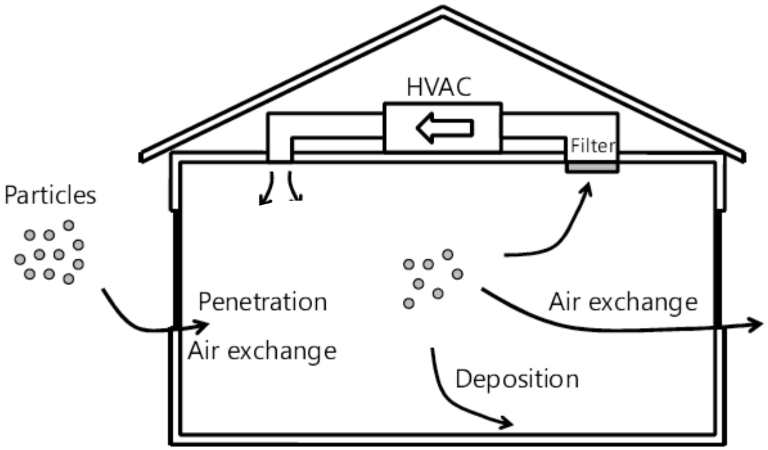
$$F_{i,\text{inf}} = \frac{C_{i,\text{in}}}{C_{i,\text{out}}} = \frac{P_i \lambda}{\lambda + k_{i,\text{dep}} + \lambda_{\text{HVAC}} f_{\text{HVAC}} \eta_{i,\text{HVAC}}}$$

Long-term average size-resolved particle deposition rates

$$k_{i,\text{dep}} = k_{i,\text{dep,closedwindows}} \left(1 - f_{\text{openwindows}}\right) + k_{i,\text{dep,openwindows}} f_{\text{openwindows}}$$

$$k_{i,\text{dep,openwindows}} = k_{i,\text{dep,openwindows,low}} \phi_{\text{openwindows,low}} + k_{i,\text{dep,openwindows,high}} \phi_{\text{openwindows,high}}$$

Methodology: Model framework



Long-term average
size-resolved infiltration factor

$$F_{i,\mathrm{inf}} = \frac{C_{i,\mathrm{in}}}{C_{i,\mathrm{out}}} = \frac{P_i \lambda}{\lambda + k_{i,\mathrm{dep}} + \lambda_{\mathrm{HVAC}} f_{\mathrm{HVAC}} \eta_{i,\mathrm{HVAC}}}$$

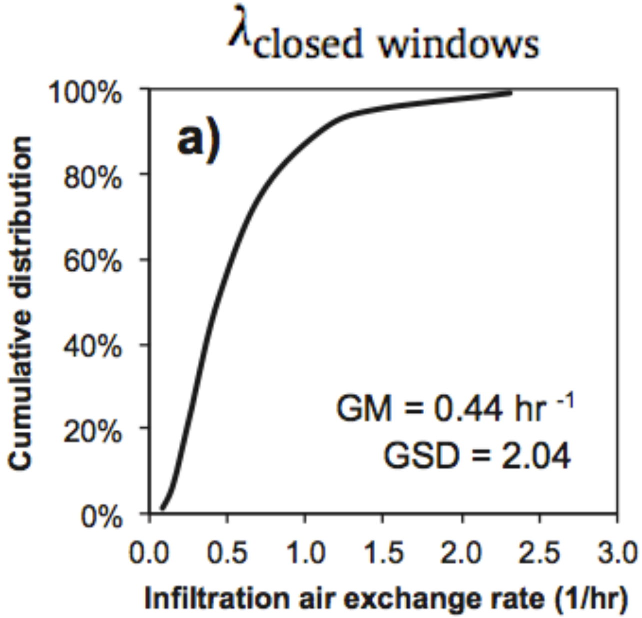
HVAC recirculation rates, fractional operation times, and filter efficiency

Culled directly from the literature

Methodology: Gathering input parameters

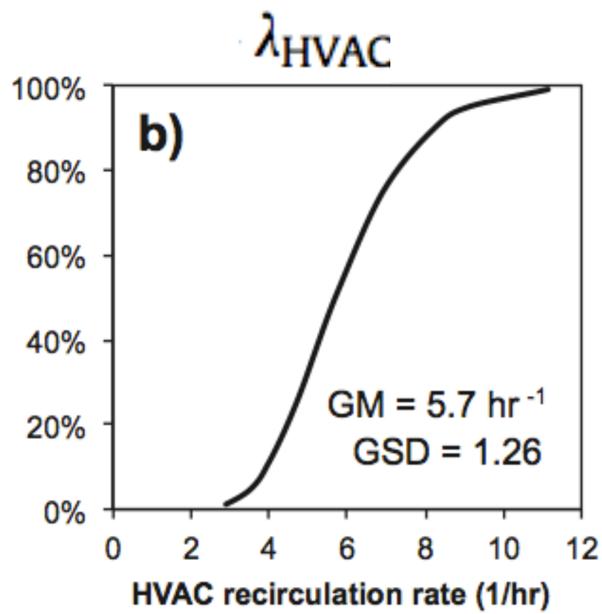
- Large literature review identified best estimates of distributions of input parameters across the US residential building stock

Infiltration AER



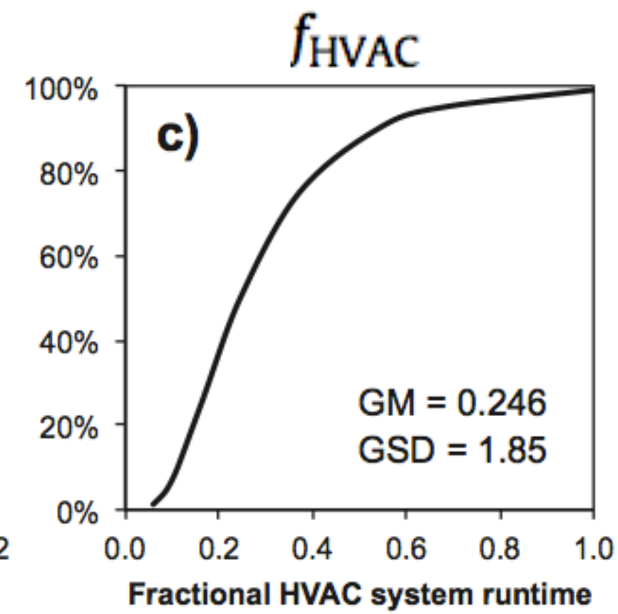
Persily et al. **2010** *Indoor Air*

Recirculation rate



Stephens et al. **2011** *Build Environ*

HVAC runtime



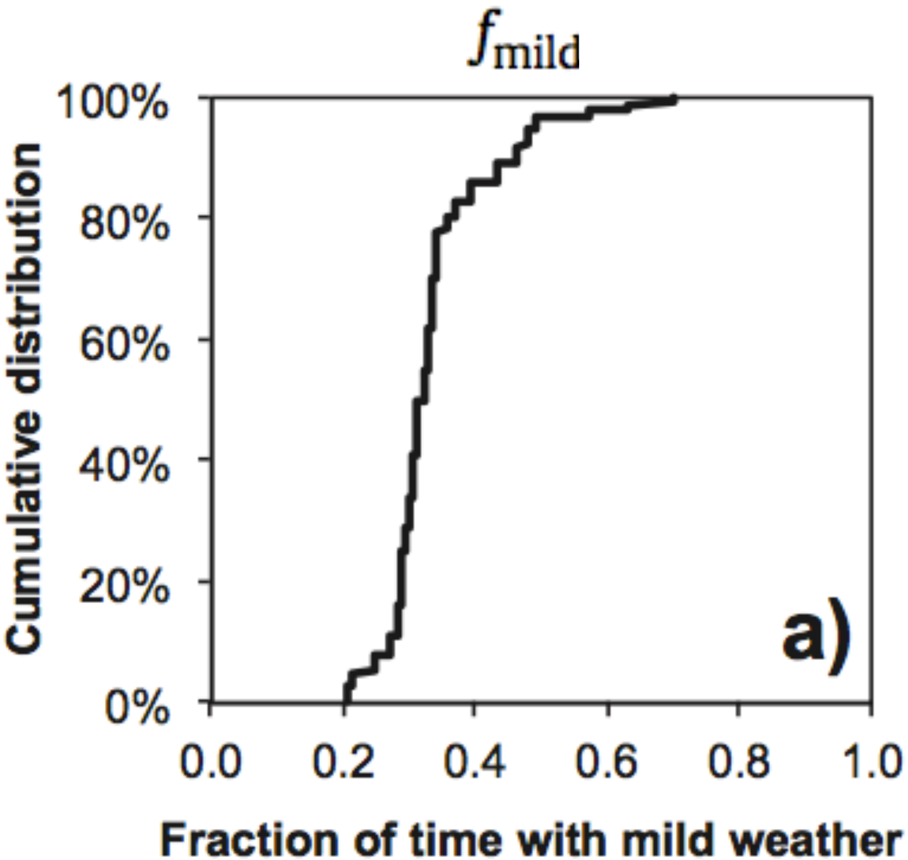
Thornburg et al. **2004** *Atmos Environ*
Stephens et al. **2011** *Build Environ*

AER multipliers:
2 when open 'low' amount
4 when open 'high' amount

Wallace et al. **2002** *JEAEE*; Marr et al. **2012** *HVAC&R Research*

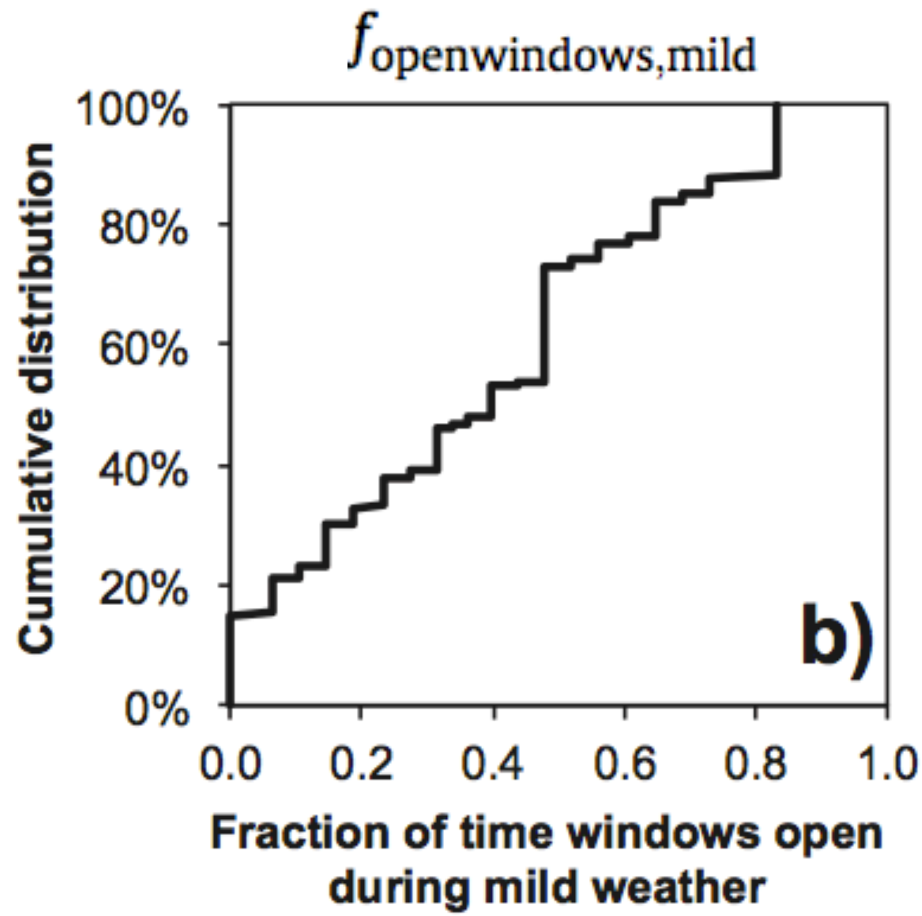
Methodology: Gathering input parameters

Fraction of mild weather



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

Fraction of window opening during mild weather



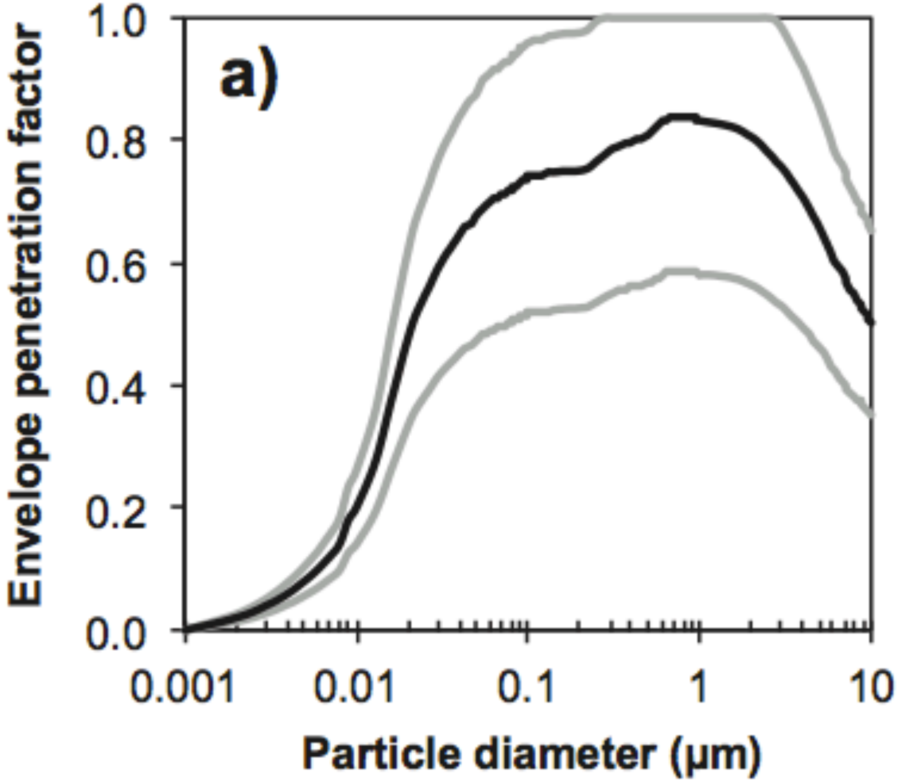
Price and Sherman **2006** *LBNL 59620*

80% open ‘low’ amount
20% open ‘high’ amount

Methodology: Gathering input parameters

Envelope penetration factor

$P_{i,\text{closedwindows}}$

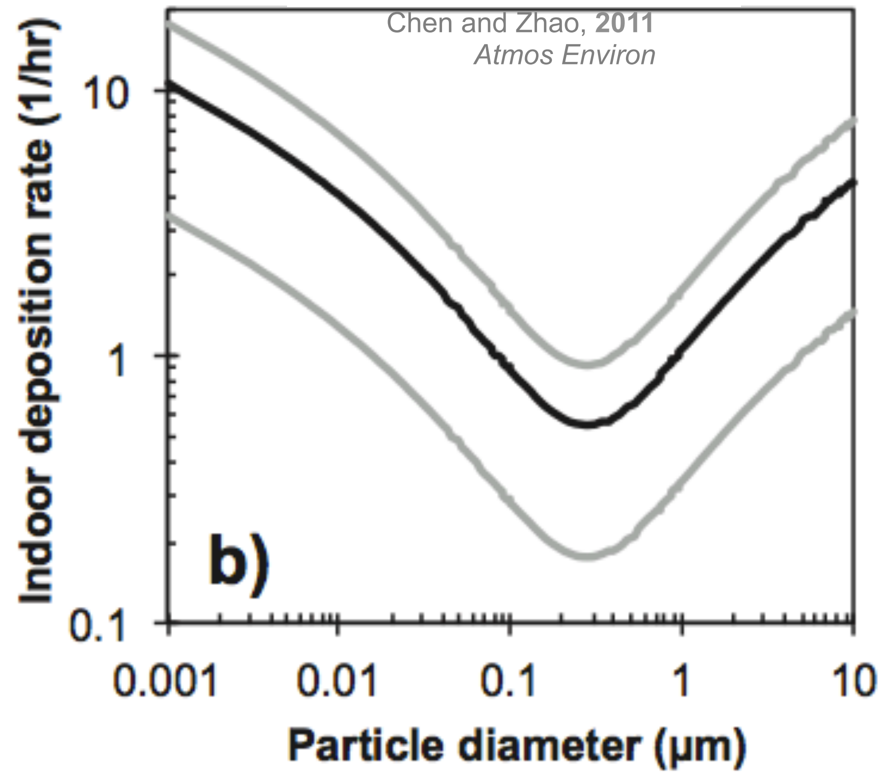


Chen and Zhao **2011** *Atmos Environ*
Rim et al. **2010** *Environ Sci Technol*
Stephens and Siegel **2012** *Indoor Air*
Williams et al. **2003** *Atmos Environ*

Deposition rate

$k_{i,\text{dep,closedwindows}}$

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



Adjusted from He et al. **2005** *Atmos Environ*

$k_{i,dep}$ **multipliers:**

1.2 when windows open 'low' amount

1.7 when windows open 'high' amount

He et al. **2005** & assumed to vary with AER multipliers

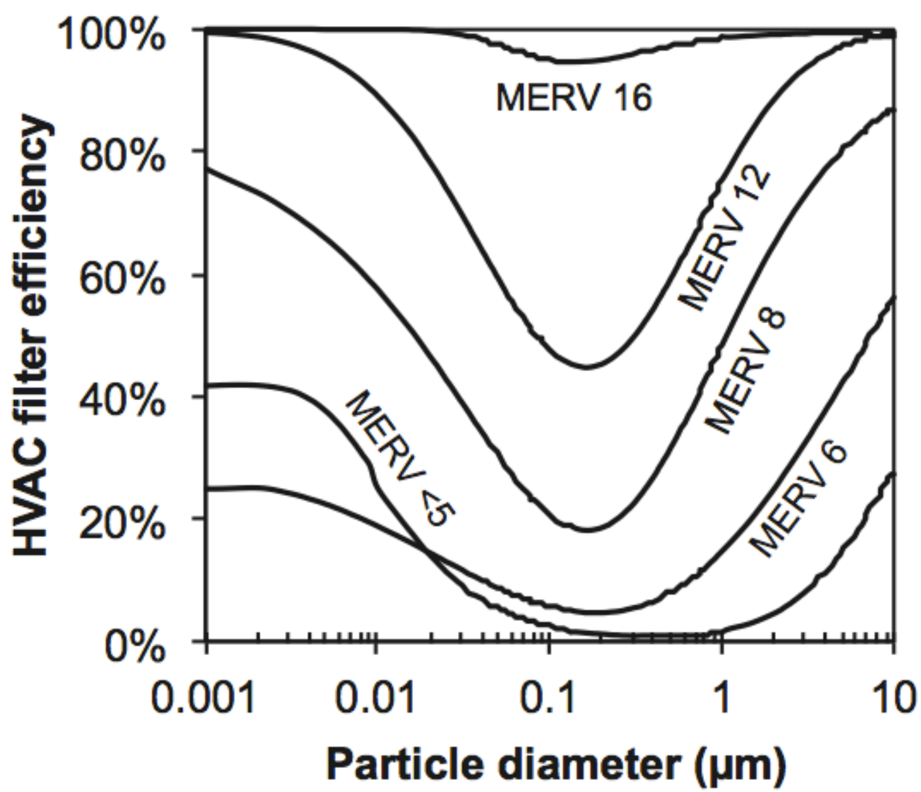
Methodology: Gathering input parameters

Estimate of HVAC filter ownership across the residential building stock (for homes with HVAC systems).

Filter type	% Ownership
MERV < 5	25%
MERV 6	30%
MERV 8	30%
MERV 12	10%
MERV 16	5%

Filter ownership

Stephens and Siegel **2012** *Indoor Air*
Offermann **2009** *CARB Report*
Anonymous filtration industry contacts



Filter efficiency

$\eta_{i,\mathrm{HVAC}}$

Hecker and Hofacre **2008** *EPA*
Waring and Siegel **2008** *Indoor Air*

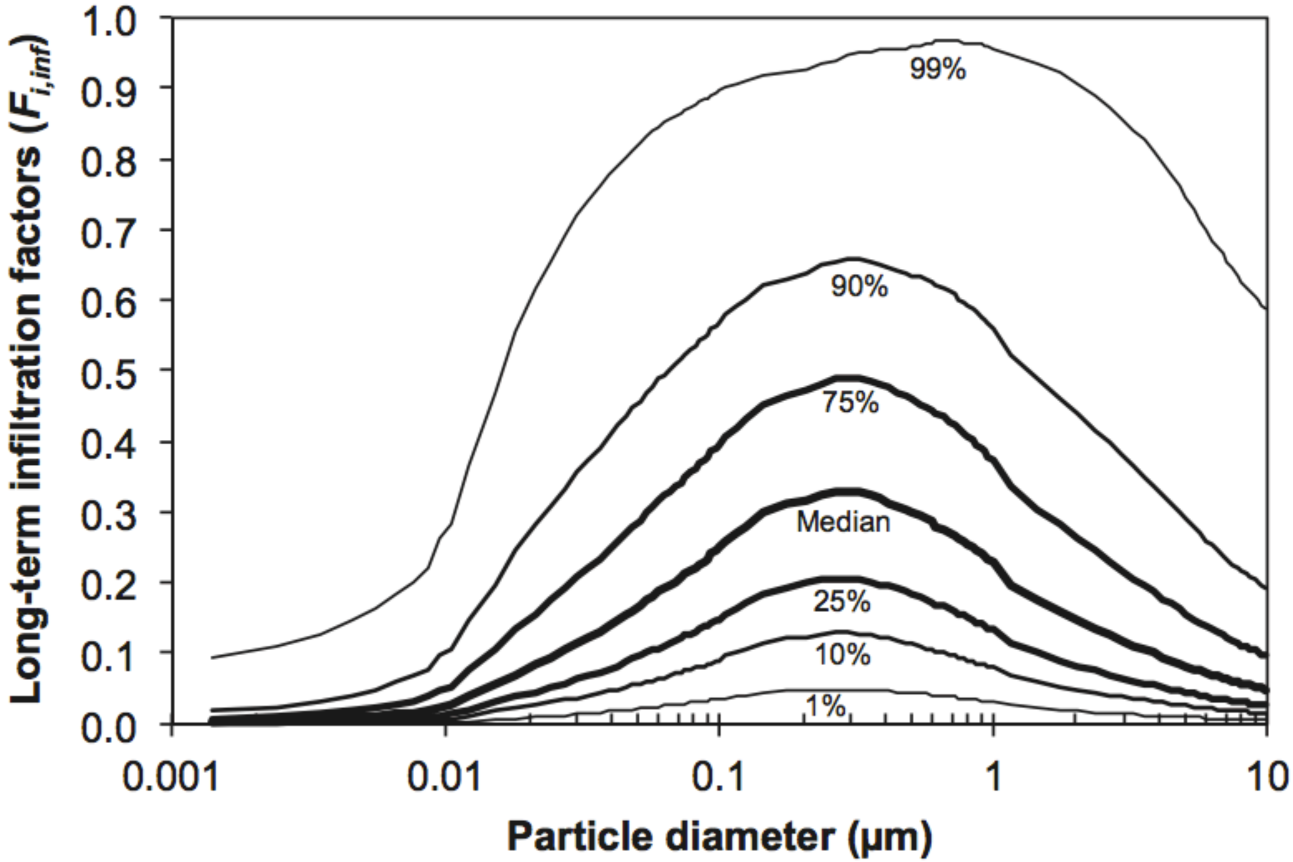
Methodology for simulations

- A Monte Carlo simulation was used to model long-term average infiltration factors for 100,000 homes across the U.S. residential building stock using these best available data for input parameters
- Long term parameters were calculated as a combination of infiltration parameters and open-window parameters
- Size-resolved simulations (0.001 to 10 μm)
- We assumed that our sample of homes was comprised of:
  - 65% of homes own HVAC systems HUD **2007**
    - Filters ranging from MERV <5 to MERV 16
  - 35% of homes without HVAC systems (no filtration) HUD **2007**

El Orch et al. **2014** *Building and Environment* 74:106–118

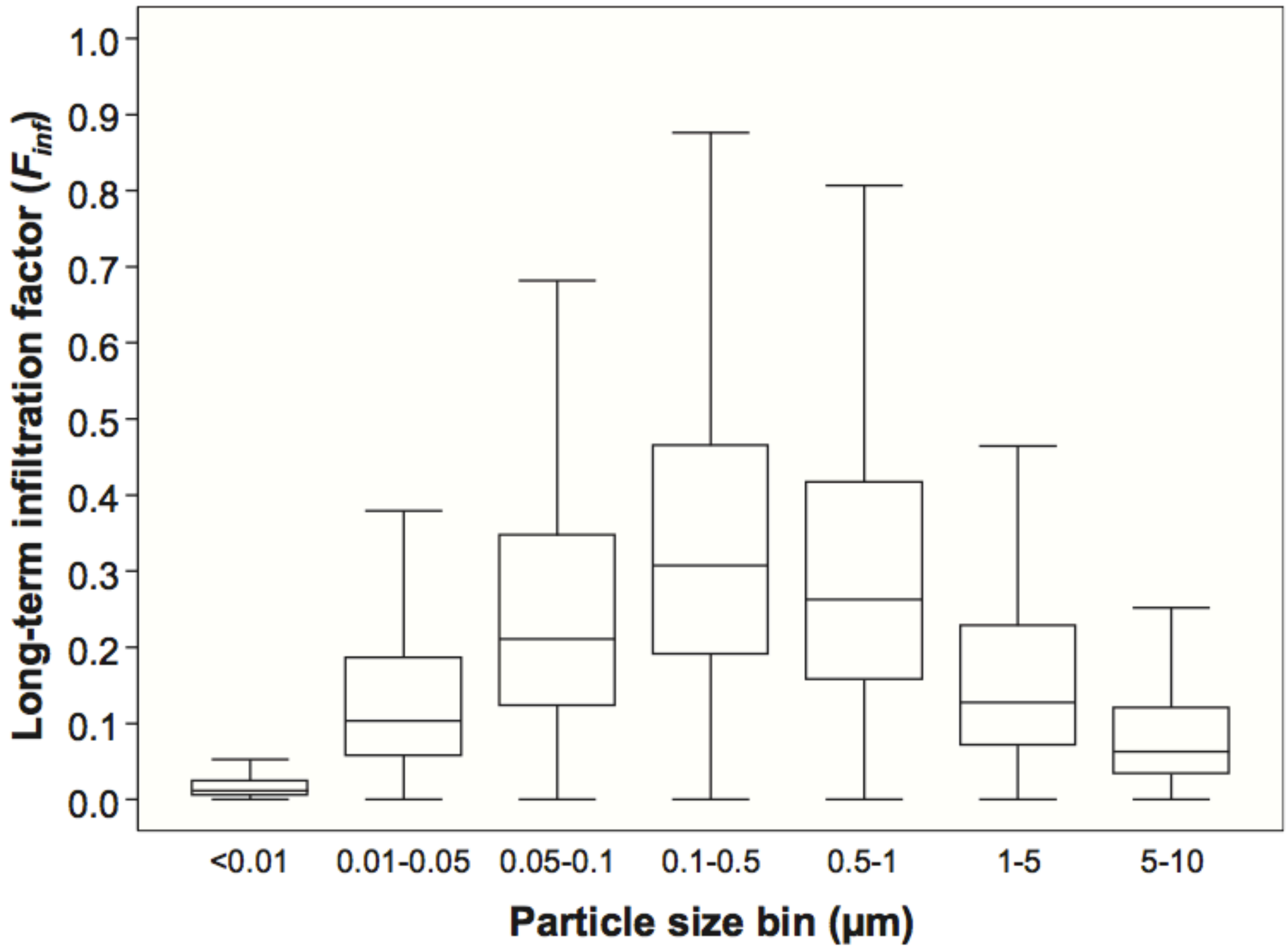
Results: Long-term average size-resolved F_{inf}

Infiltration factors were predicted to be 20-100 higher in the most protective homes (1st percentile) vs. the least protective ones (99th percentile)



El Orch et al. **2014** *Building and Environment* 74:106–118

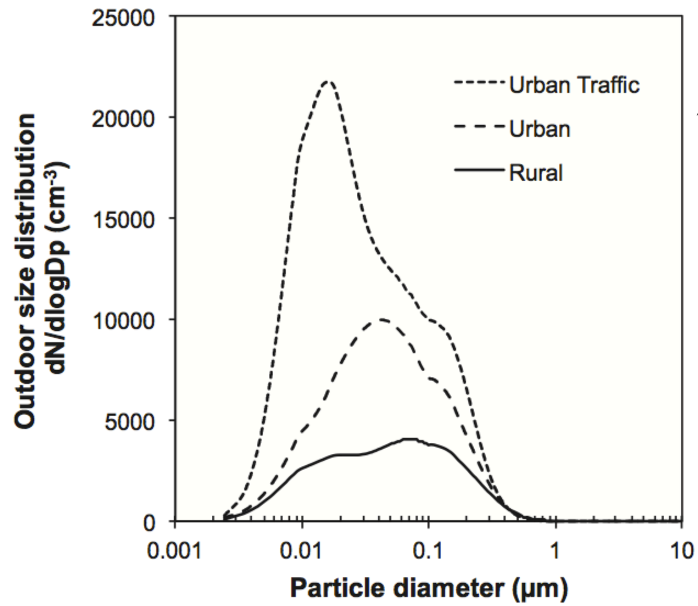
Results: Long-term average binned F_{inf}



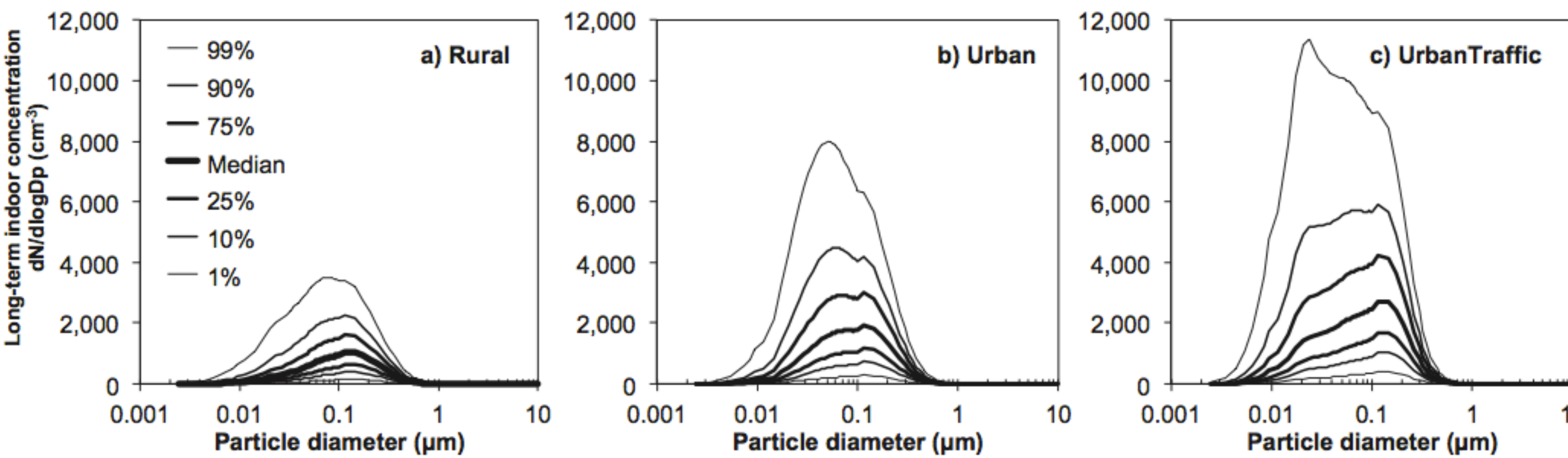
UFP estimates generally in line with measurements in Kearney et al. 2011 *Atmos Environ*: 0.03-0.9, median of 0.19-0.27, and others

El Orch et al. **2014** *Building and Environment* 74:106–118

Results: Mapping to outdoor size distributions



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

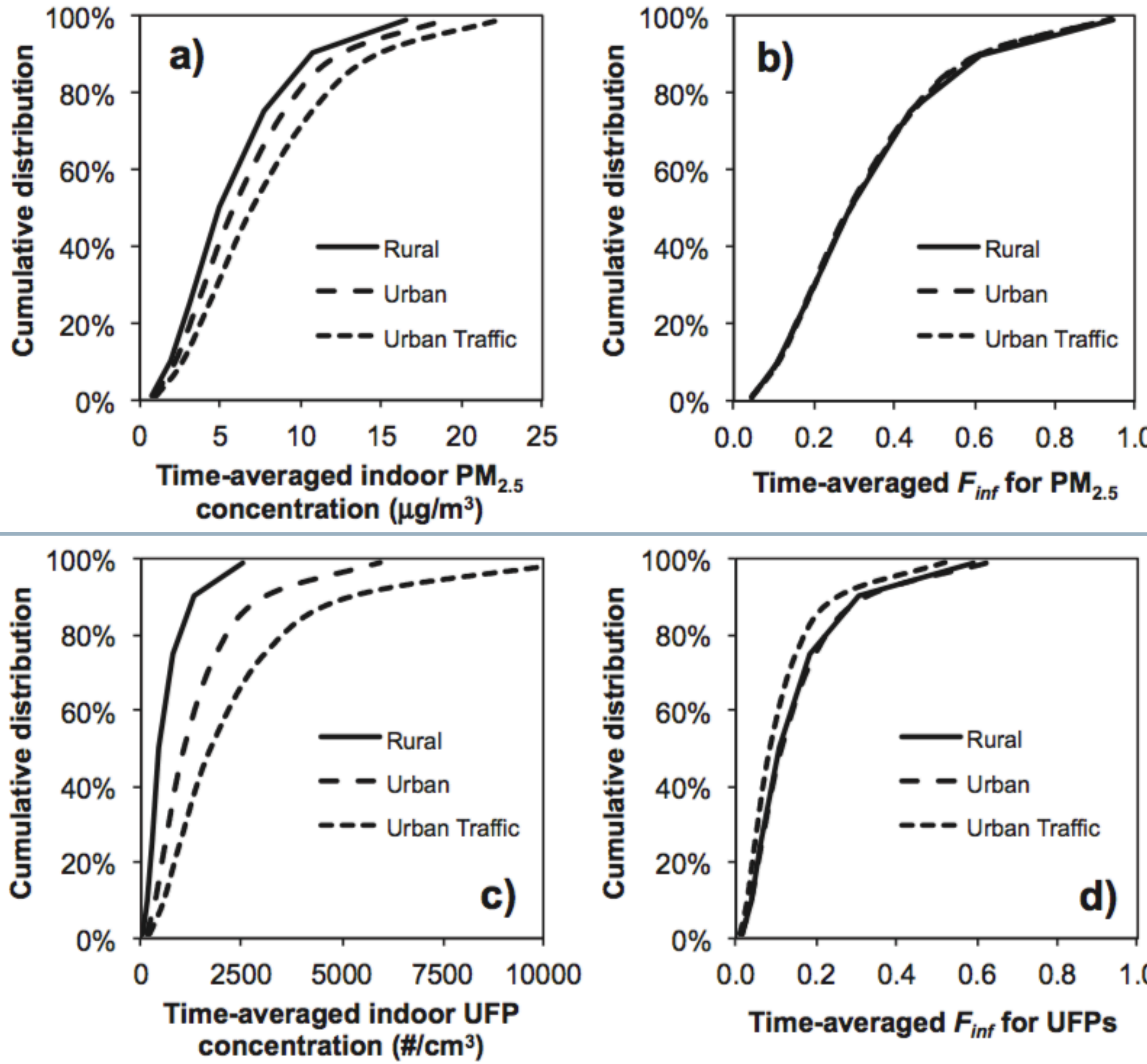


El Orch et al. **2014** *Building and Environment* 74:106–118

Results: Predicting CDFs of UFPs and $PM_{2.5}$

$PM_{2.5}$

UFPs (< 100 nm)



El Orch et al. **2014** *Building and Environment* 74:106–118

Results: Multiple regression for influential factors

Largest influences

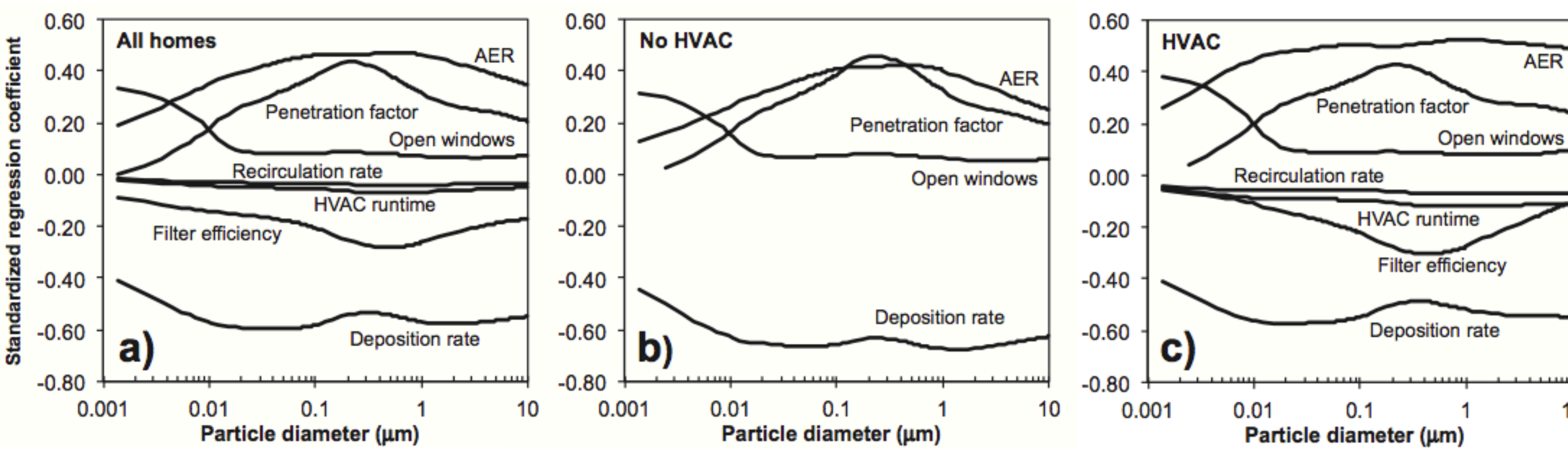
(1) Closed-window deposition rates
(2) Closed-window AER
(3) Closed-window penetration factor
(4) HVAC filter efficiency

MLR

$$F_{i,\mathrm{inf}} = \beta_0 + \beta_1 \lambda_{\mathrm{closedwindows}} + \beta_2 f_{\mathrm{openwindows}} + \beta_3 f_{\mathrm{HVAC}} + \beta_4 \lambda_{\mathrm{HVAC}} + \beta_5 \eta_{i,\mathrm{HVAC}} + \beta_6 k_{i,\mathrm{dep,closedwindows}} + \beta_7 P_{i,\mathrm{closedwindows}}$$

Model R^2 values ranged 0.35 to 0.79 depending on particle size

Standardized regression coefficients (size-resolved)



El Orch et al. **2014** *Building and Environment* 74:106–118

Limitations and future research

- Need more accurate measurements of the important predictors in a larger number and variety of buildings
  - Deposition rates, air exchange rates, and size-resolved penetration factors
- Need more accurate distributions of HVAC system runtimes, filter efficiencies, filter ownership, and window opening behaviors
- Need more information about U.S. outdoor particle size distributions
  - Although size distribution may not have a large impact on UFPs/$PM_{2.5}$
- Need to incorporate indoor sources into the Monte Carlo model
- Can also use this approach to model inhalation exposures with different individuals with different human activity patterns
- Need more information on correlation between input parameters in order to incorporate and improve this model
  - e.g. P and AER

Next steps: PM infiltration measurements in Chicago

Question/comments

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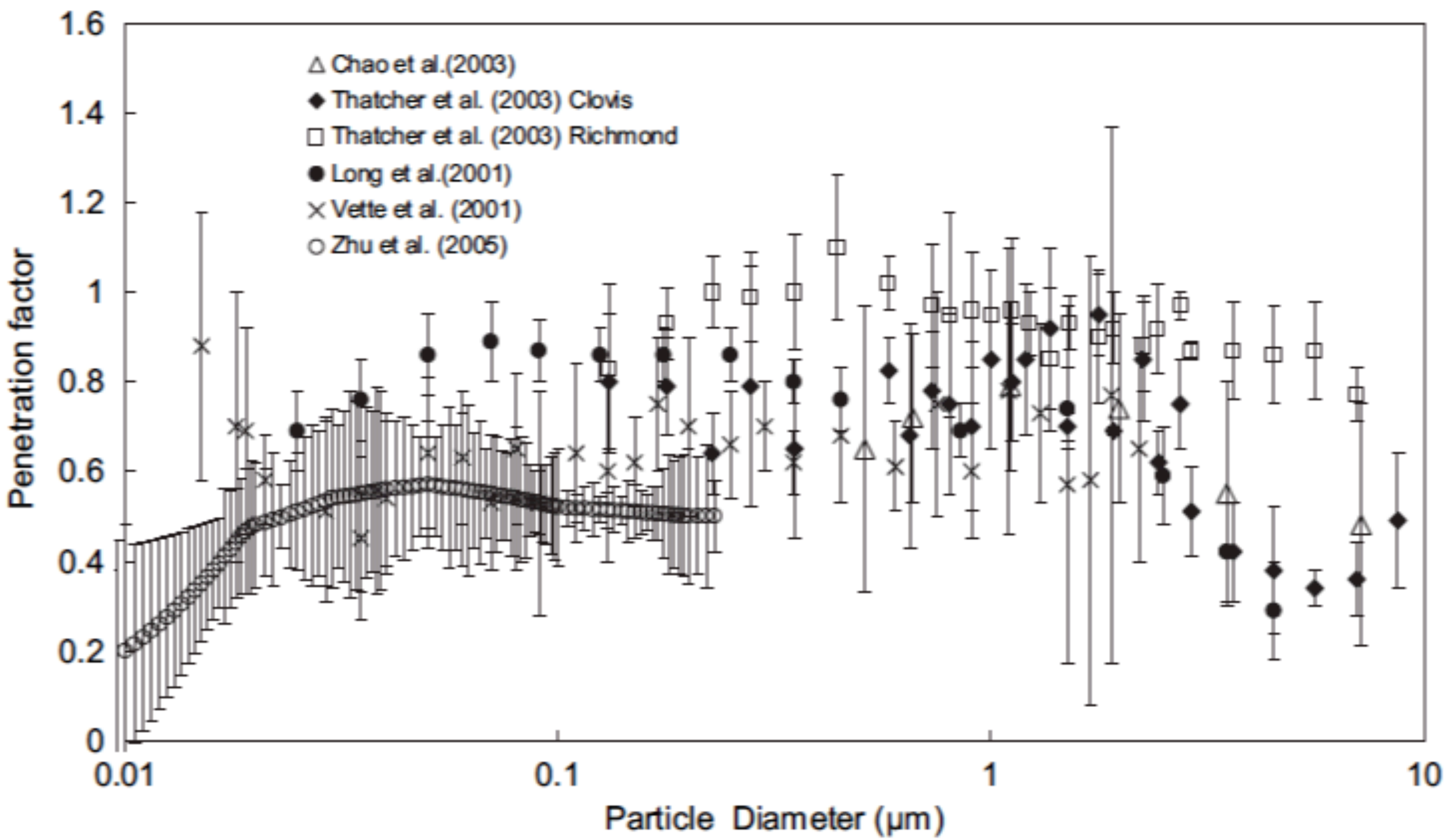
Chao et al.(2003)
Thatcher et al. (2003) Clovis
Thatcher et al. (2003) Richmond
Long et al.(2001)
Vette et al. (2001)
Zhu et al. (2005)
Penetration factor
Particle Diameter (μm)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.01
0.1
1
10