BERG summer meetings and presentations

Jun 9 - Brent - Zeineb's (former student) filter modeling
Jun 10 - Parham - Mapping outdoor particle size distributions to HVAC filtration efficiency for PM2.5 and ultrafine particles
Jun 11 - Torkan - Hot box measurement methods and results
Jun 12 - Hoaran/Jihad - Outdoor pollutant transport measurements
Jun 13 - Zack - OSBSS: In depth on 2-3 sensors/techniques (dual beam break; battery life extension; Builduino; etc.)
Jun 16 -
Jun 17 - Brent - Graphical display of information
Jun 18 - **White Sox game 12 pm** I have 10 tickets reserved!
Jun 19 - Akram - OSBSS: General overview of purpose, progress, example results, and path forward
Jun 23 - Brent - Technical writing
Jun 24 - Parham - Infectious risk modeling
Jun 25 - Rou Yi and Torkan - Energy and filter modeling
Jun 26 (or later depending on Dan's availability) - Dan and Parham - ASHRAE filter modeling project
Jun 27 -

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

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Indoor vs. outdoor air pollution

Air pollution is both an indoor and an outdoor issue

- Many indoor pollutant sources
- Outdoor pollutants also infiltrate and persist indoors

Thatcher et al. **2003** *AS&T*; Rim et al. **2010** *ES&T*; Chen and Zhao **2011** *AE*; Kearney et al **2011** *AE*

Much of our exposure to outdoor air pollution occurs indoors

Janssen et al., **2005** *OEM*; Meng et al., **2005** *JESEE*; Weschler, **2006** *EHP*; Wallace and Ott, **2011** *JESEE*

Indoor exposures are difficult to assess

- Time-consuming, invasive, and costly

Many connections are already made with outdoor pollutants

- There remains a need to **advance knowledge of indoor exposures**
  - Improve connections to health effects (reduce exposure error)
  - Inform how building design and operation impacts exposures

Baxter et al., **2010** *JESEE*; Meng et al., **2005** *ES&T*; Allen et al., **2012** *EHP*; MacNeill et al, **2013** *AE*

A few outdoor airborne pollutants are regulated

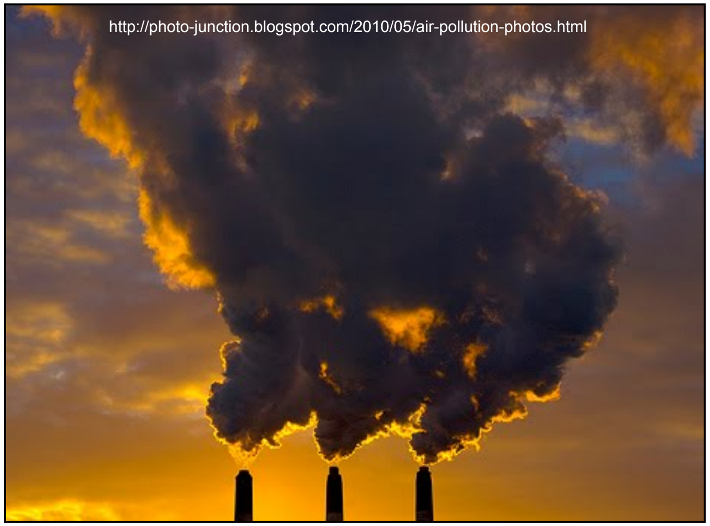
National Ambient Air Quality Standards (NAAQS)

- US EPA and the Clean Air Act (1970)
- Set limits for 6 "criteria" pollutants

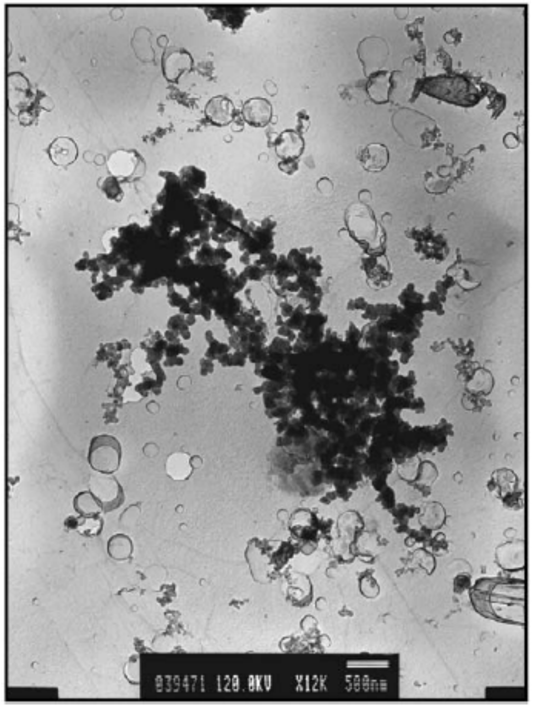
Pollutants Regulated Outdoors
Carbon monoxide (CO)
Lead (Pb)
Nitrogen dioxide (NO_2)
Ozone (O_3)
Particulate matter $PM_{2.5}$ and PM_{10} ←
Sulfur dioxide (SO_2)

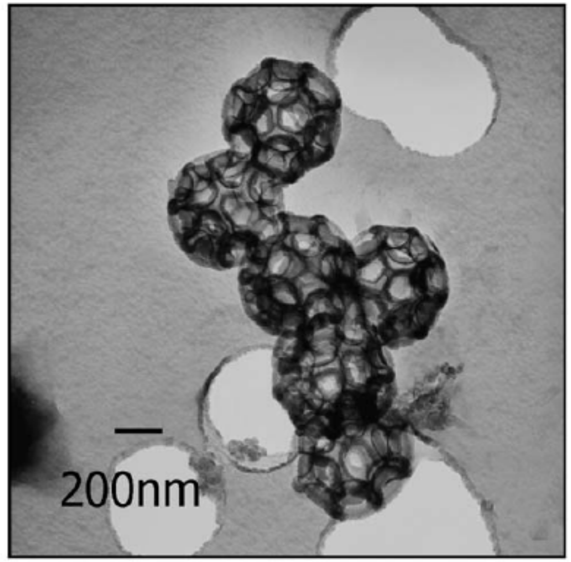
UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

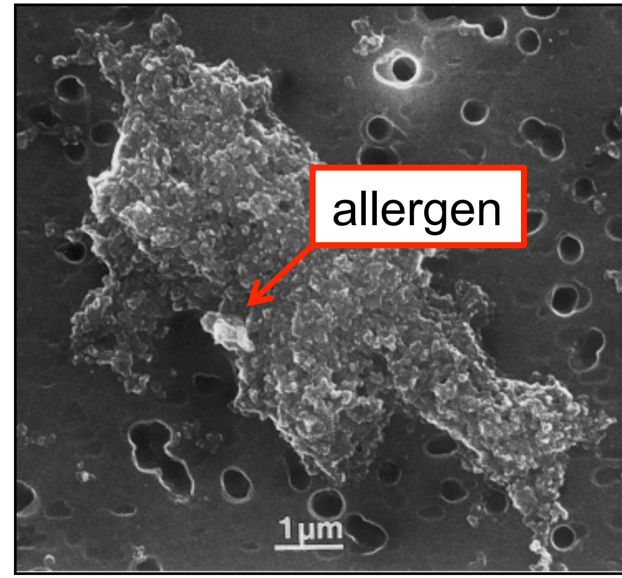
Outdoor particulate matter

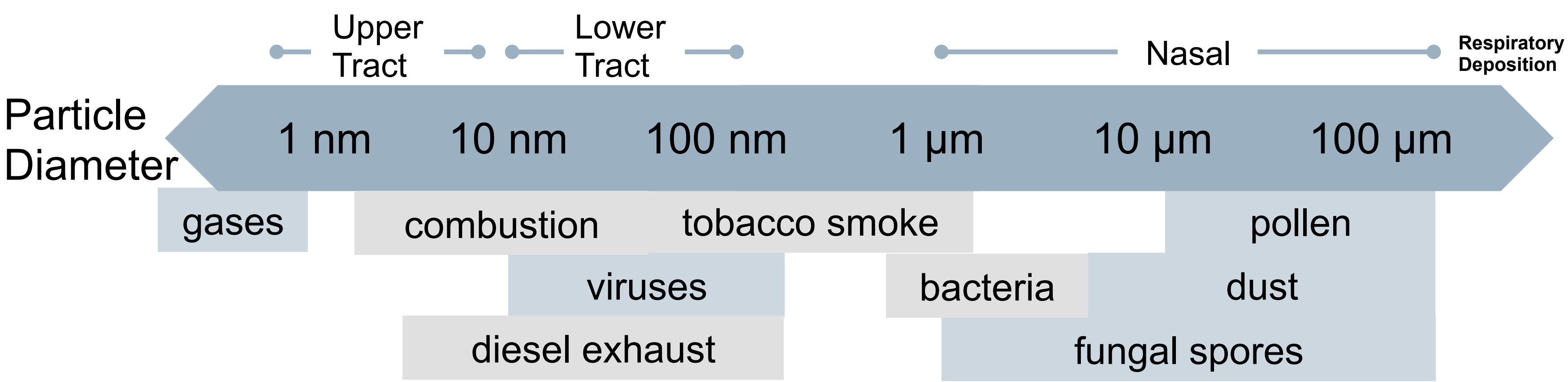


Particulate matter: Up close



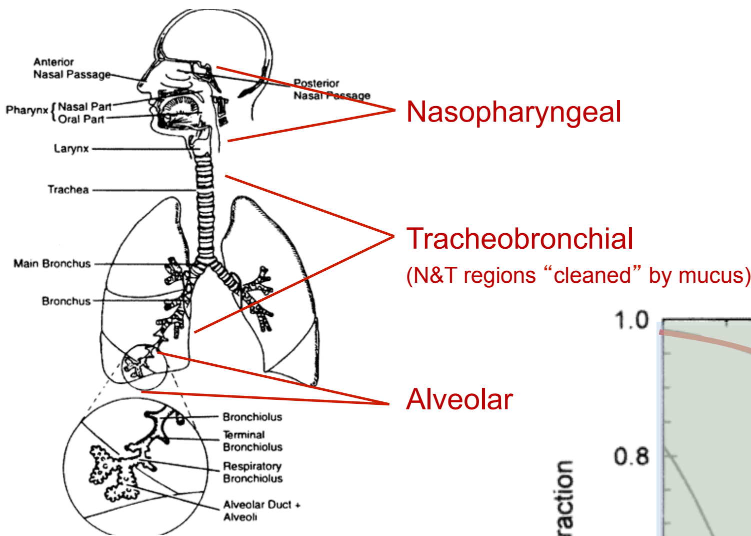


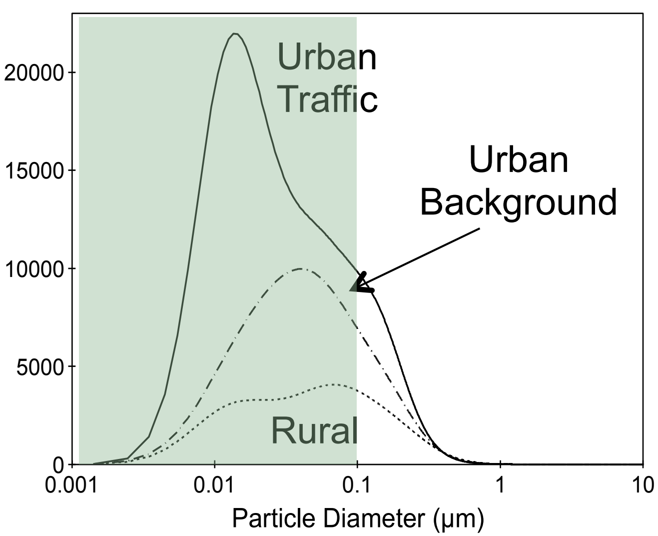




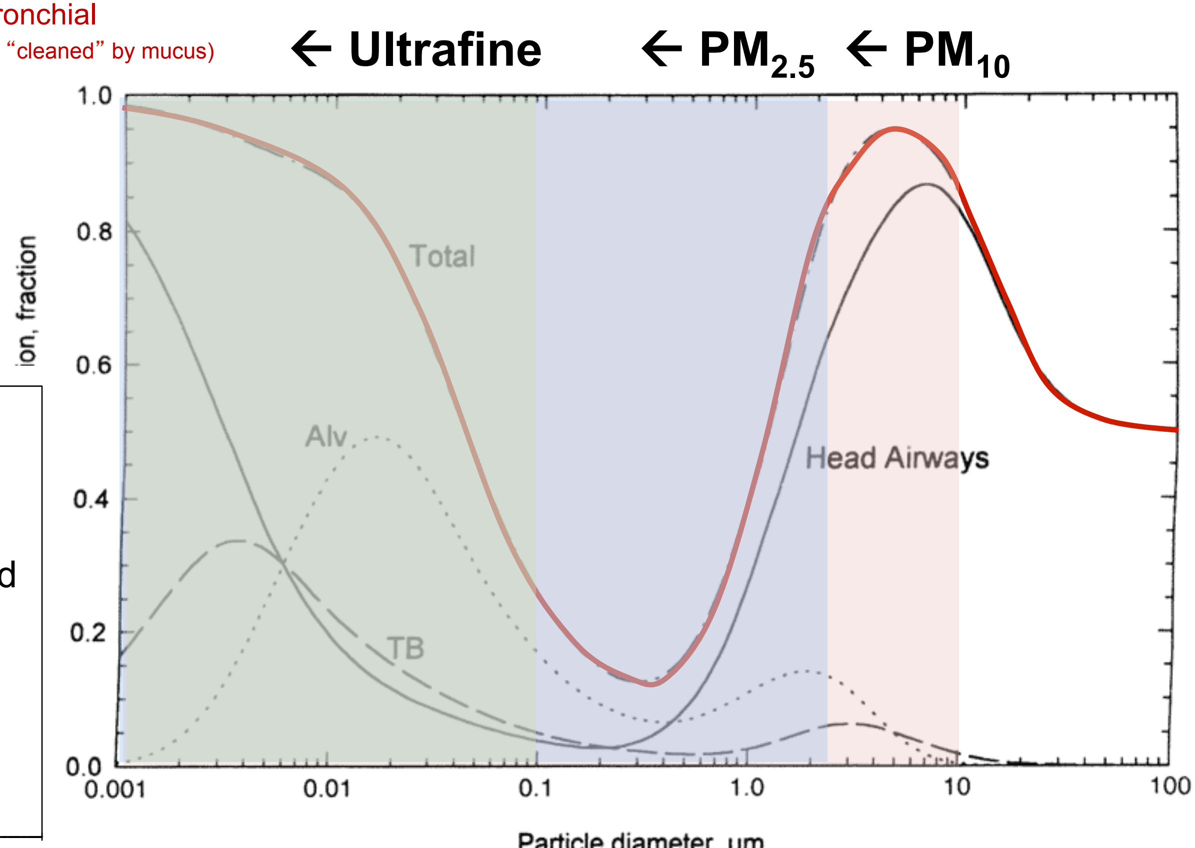
Casuccio et al., **2004** *Fuel Process. Technol.*; Ormstad, **2000** *Toxicol.;* Hinds, **1999** *Aerosol Technol.*

Particle deposition in the respiratory system





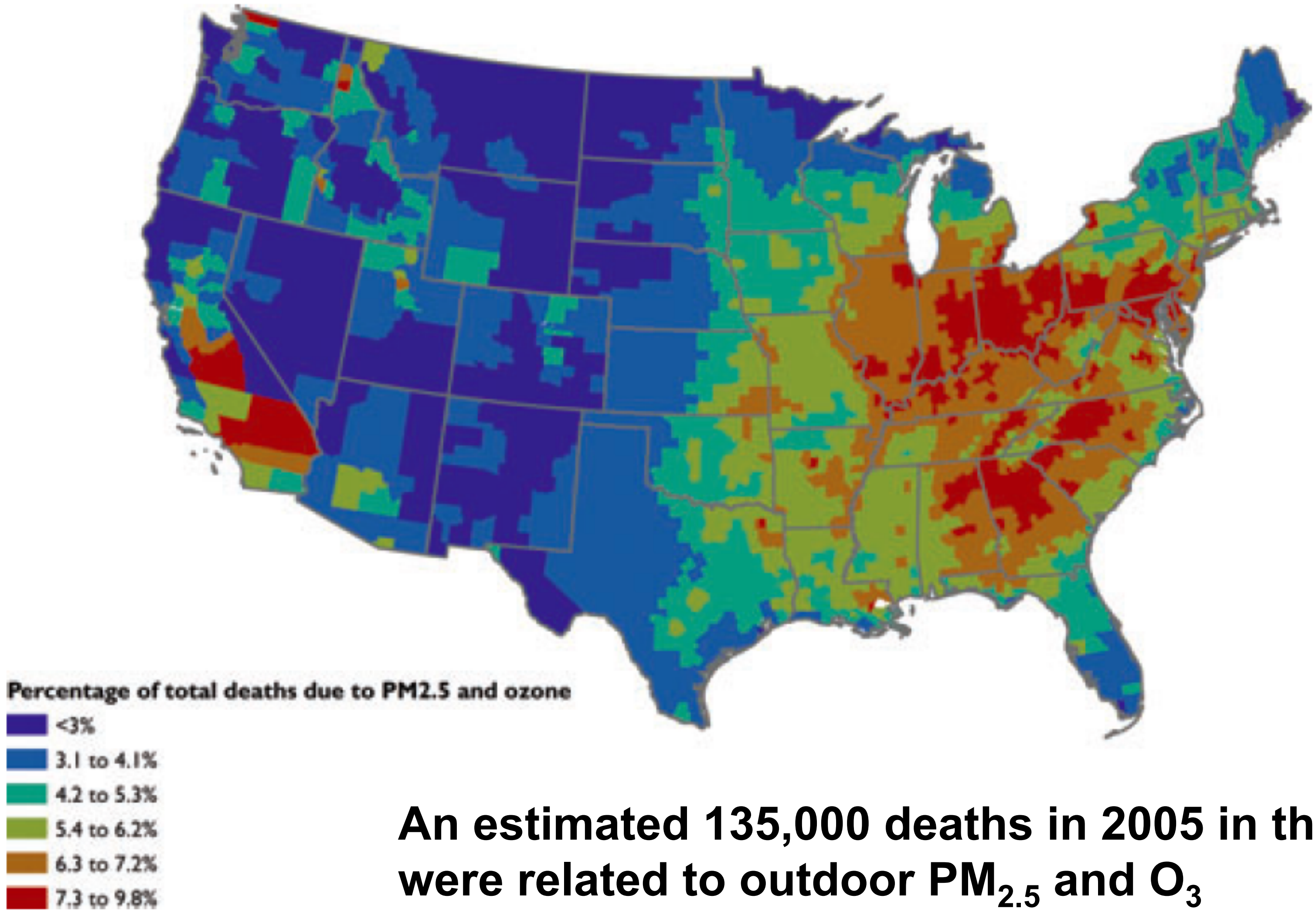
Costabile et al., **2009**
Atmos Chem Phys



Most particles of outdoor origin are smaller than 100 nm

Hinds, 1999 Ch. 11

Health effects: Outdoor air pollution and mortality



An estimated 135,000 deaths in 2005 in the US were related to outdoor $PM_{2.5}$ and O_3

As high as 10% of deaths in Los Angeles

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

Motivation: Health effects and outdoor PM

- Epidemiological studies show associations between elevated outdoor particulate matter (PM) and adverse health effects

  Pope et al., **2002** *J Am Med Assoc*; Peng et al., **2005** *Am J Epidem*; 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*; Ostro et al., **2010** *Environ Health Persp*

  – Effects ranging from respiratory symptoms to mortality

  – $PM_{10,}$ $PM_{2.5,}$ and ultrafine particles (UFP, < 100 nm)

    - Also specific constituents and seasonal differences

- 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*

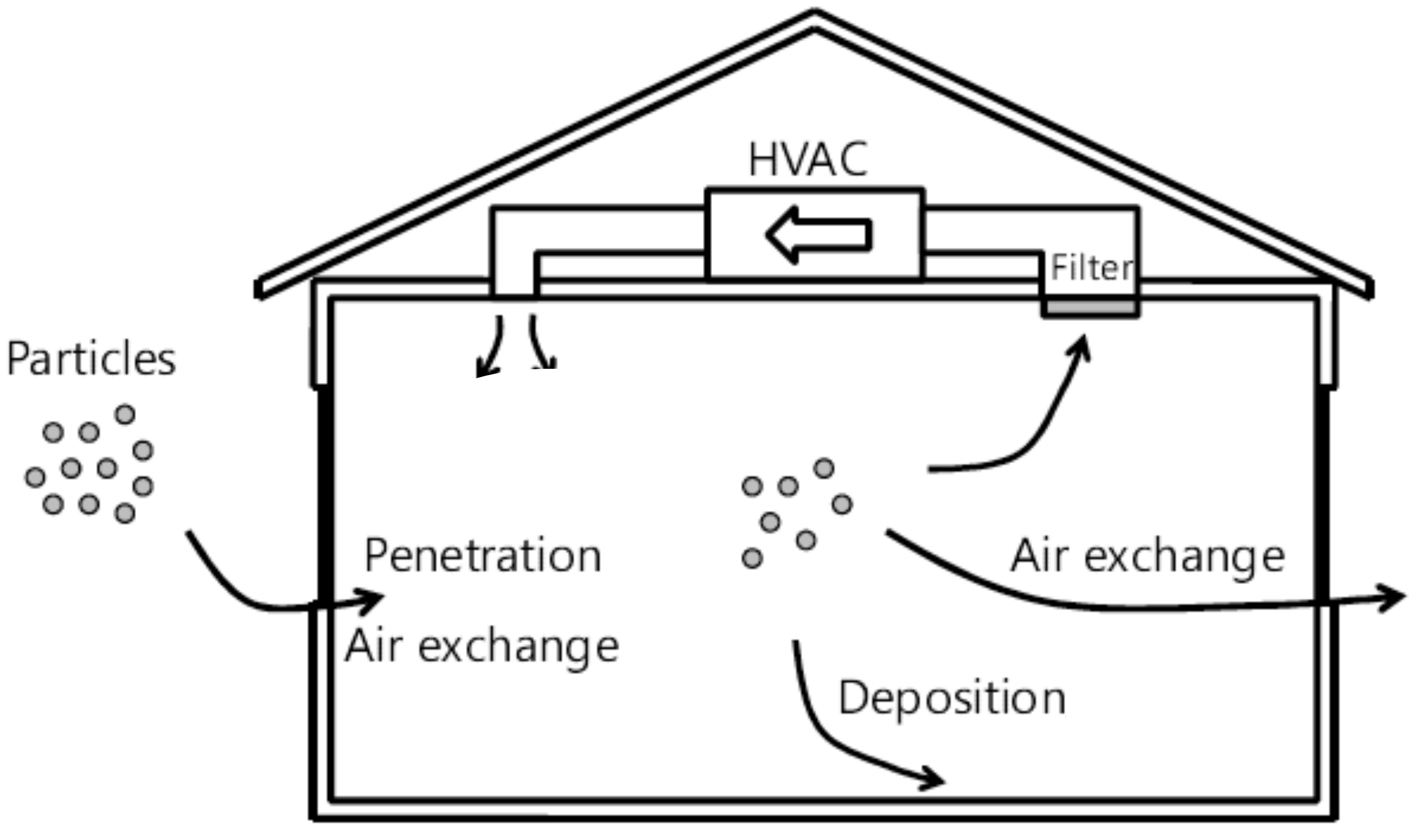
- Outdoor particles can infiltrate and persist in homes with varying efficiencies Chen and Zhao, **2011** *AE;* Williams et al., **2003** *AE;* Kearney et al., **2010** *AE*

- 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*

Mechanisms that impact indoor exposures to outdoor PM



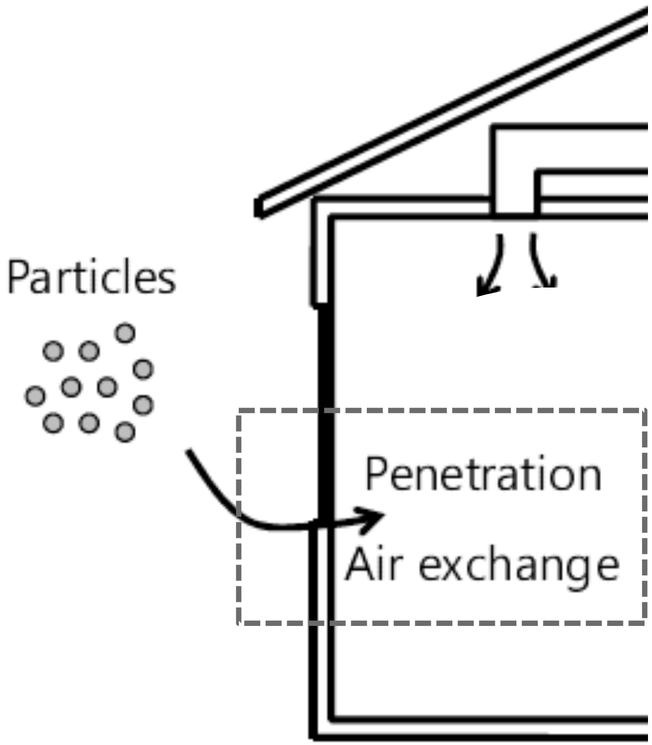
C_{in} = indoor concentration (#/m^3)
C_{out} = outdoor concentration (#/cm^3)
P = penetration factor (-)
λ = air exchange rate (1/hr)
k = surface deposition rate (1/hr)
f = fractional HVAC runtime (-)
η = filter removal efficiency (-)
Q = HVAC airflow rate (m^3/hr)
V = indoor air volume (m^3)

$$\frac{C_{in}}{C_{out}} = F_{\text{inf}} = \frac{P\lambda}{\lambda + k + f\frac{\eta Q}{V}}$$

Penetration from outdoors

Air exchange
Deposition
HVAC filter removal

Mechanisms that impact indoor exposures to outdoor PM



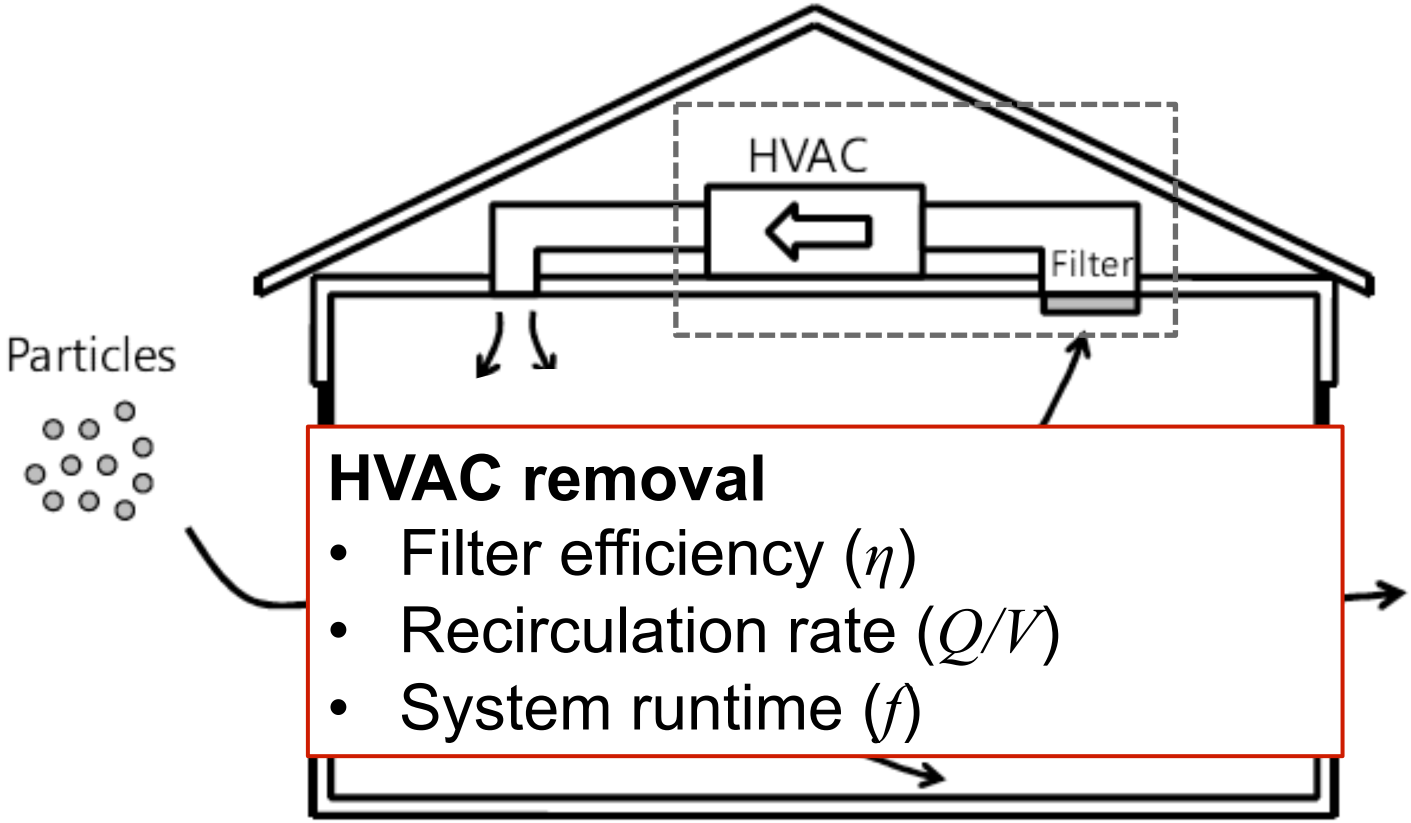
"Penetration Factor"
If *P* = 1:
The envelope offers no protection
If *P* = 0:
The envelope offers complete protection

C_{in} = indoor concentration (#/m^3)
C_{out} = outdoor concentration (#/cm^3)
P = penetration factor (-)
λ = air exchange rate (1/hr)
k = surface deposition rate (1/hr)
f = fractional HVAC runtime (-)
η = filter removal efficiency (-)
Q = HVAC airflow rate (m^3/hr)
V = indoor air volume (m^3)

$$\frac{C_{in}}{C_{out}} = F_{\text{inf}} = \frac{\boxed{P\lambda}}{\lambda + k + f\frac{\eta Q}{V}}$$

Penetration from outdoors

Mechanisms that impact indoor exposures to outdoor PM



HVAC removal

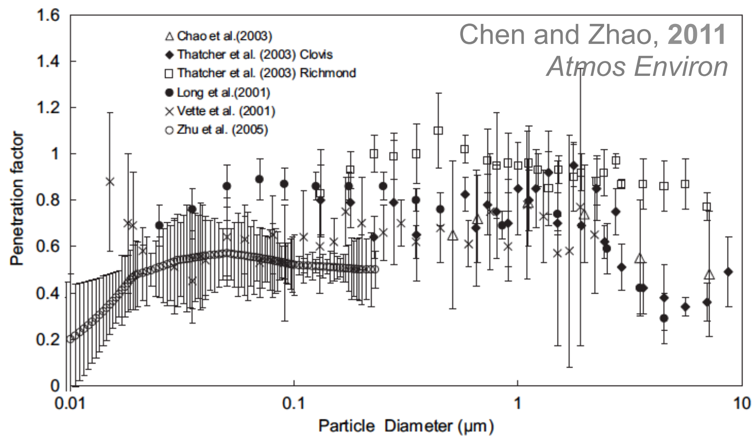
- Filter efficiency (η)
- Recirculation rate (Q/V)
- System runtime (f)

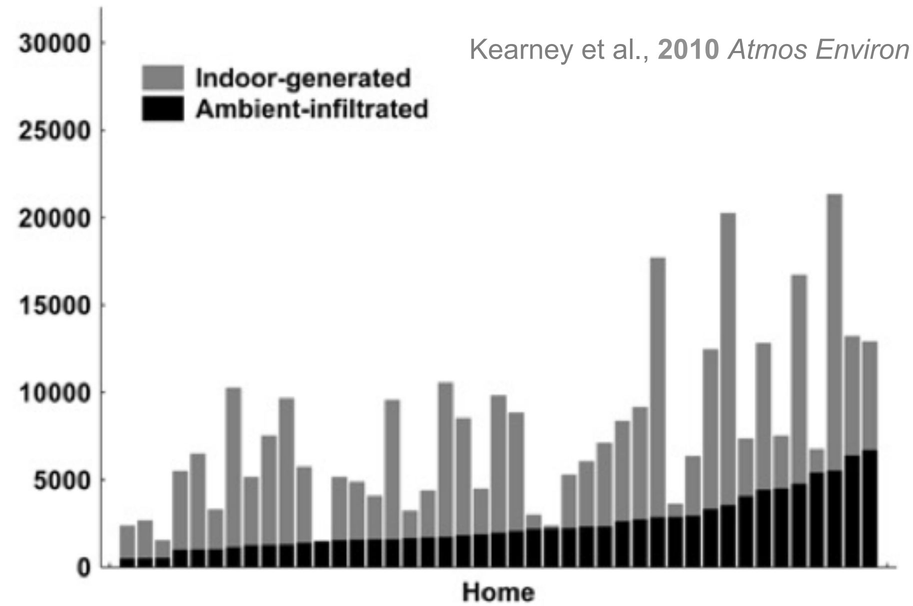
C_{in} = indoor concentration (#/m^3)
C_{out} = outdoor concentration (#/cm^3)
P = penetration factor (-)
λ = air exchange rate (1/hr)
k = surface deposition rate (1/hr)
f = fractional HVAC runtime (-)
η = filter removal efficiency (-)
Q = HVAC airflow rate (m^3/hr)
V = indoor air volume (m^3)

$$\frac{C_{in}}{C_{out}} = F_{\inf} = \frac{P\lambda}{\lambda + k + f\frac{\eta Q}{V}}$$

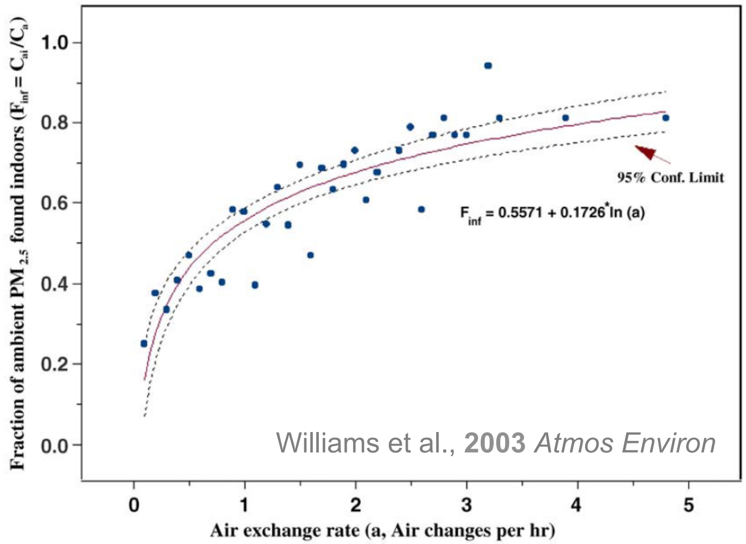
Filter removal
HVAC operation

Indoor proportion of outdoor particles





Outdoor particles infiltrate into and persist within buildings with varying efficiencies



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*

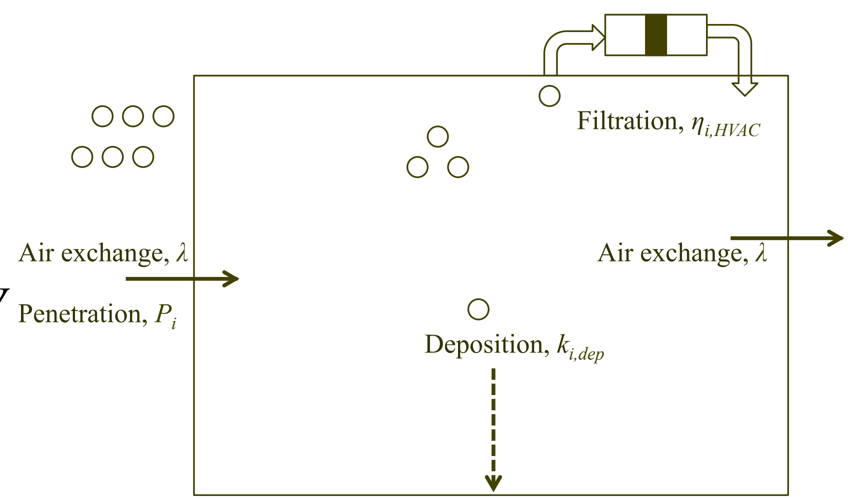
Goals of this work

- Estimate the statistical distribution of long-term average size-resolved infiltration factors for particles between 0.001 and 10 µm across the residential building stock
  - Allows for estimates of UFP and $PM_{2.5}$ as well

Key parameters:

- Air exchange rate, λ
  - With and without windows open
- Particle penetration factor, P
  - With and without windows open
- Deposition rates, k
- Particle removal by HVAC filter, $\eta Q/V$
  - And filter ownership
- HVAC system runtime, f

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



Methodology

- A Monte Carlo simulation was used to model infiltration factors on 100,000 homes across the U.S. residential building stock using 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 (filters ranging from MERV <5 to MERV 16)
  - 35% of homes without HVAC systems (no filtration)

El Orch et al. **2014** *Building and Environ*

Methodology: Model framework (*AER*)

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

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

$\lambda_{openwindows}$ = 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 (*AER*)

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

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

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

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

$\phi_{openwindows,low}$ = 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 (*P*)

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

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

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

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

Methodology: Model framework (*k*)

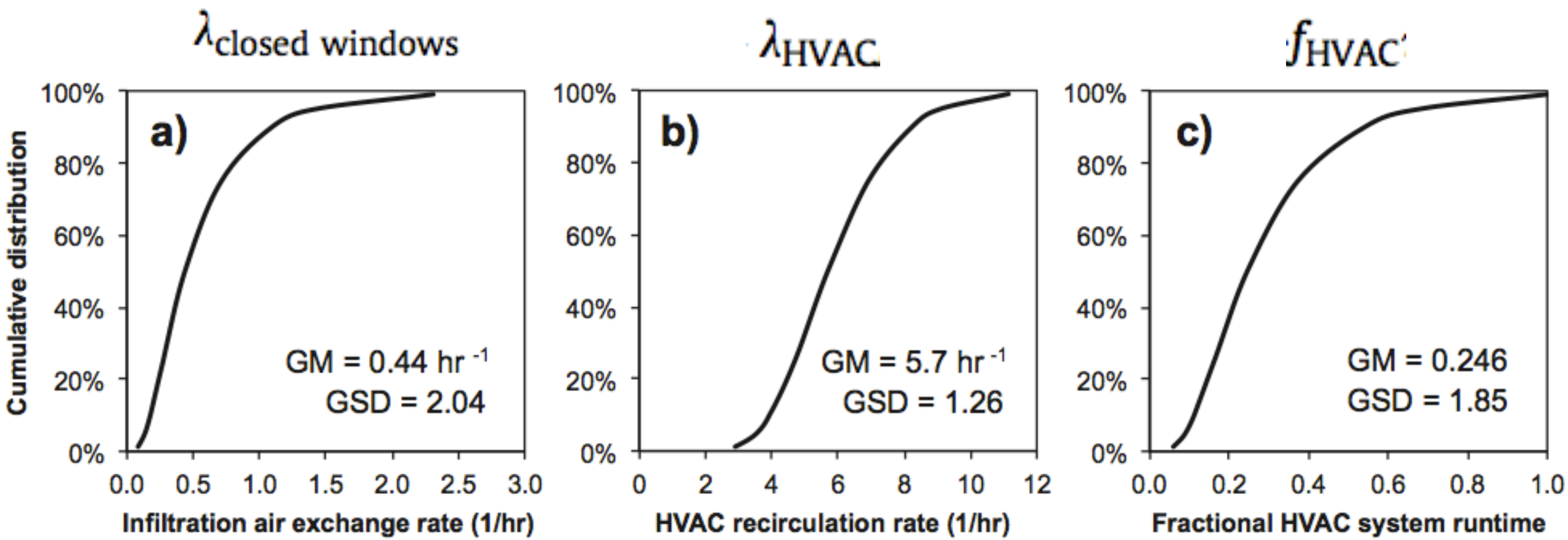
$$F_{i,\mathrm{inf}} = \frac{C_{i,\mathrm{in}}}{C_{i,\mathrm{out}}} = \frac{P_i \lambda}{\lambda + k_{i,\mathrm{dep}} + \lambda_{\mathrm{HVAC}} f_{\mathrm{HVAC}} \eta_{i,\mathrm{HVAC}}}$$

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

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

Methodology: Gathering input parameters

- Performed large literature review to find best estimates of distributions of these parameters across the US residential building stock

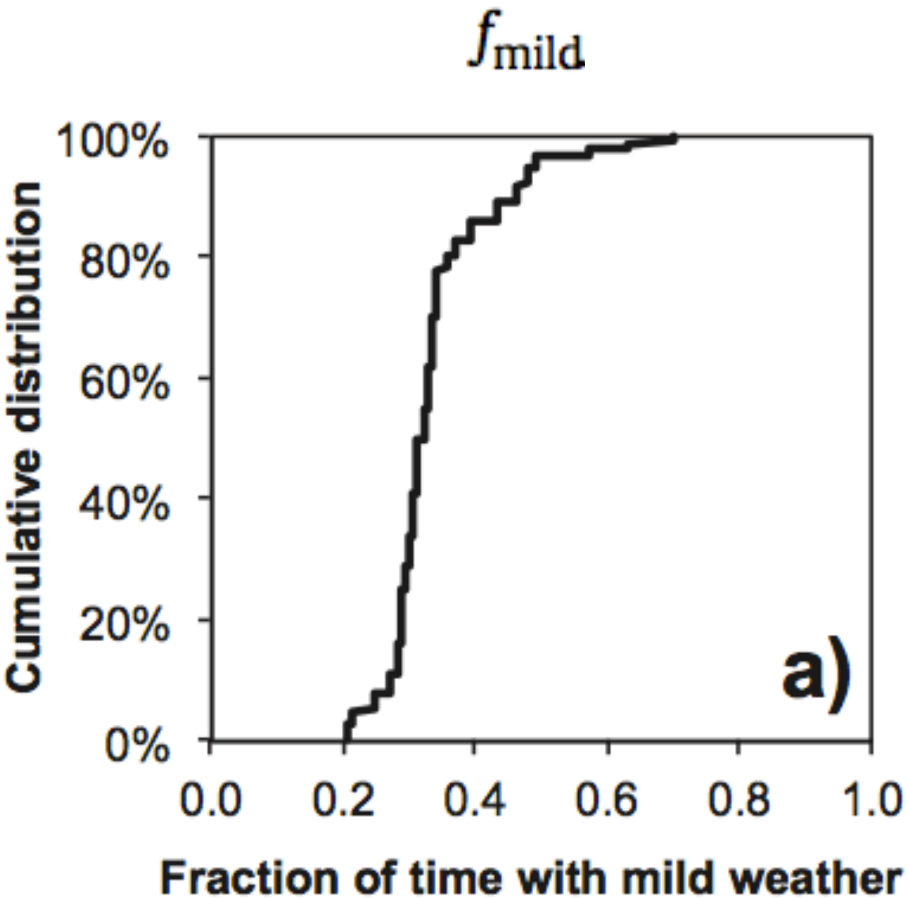


Persily et al. **2010** *Indoor Air*

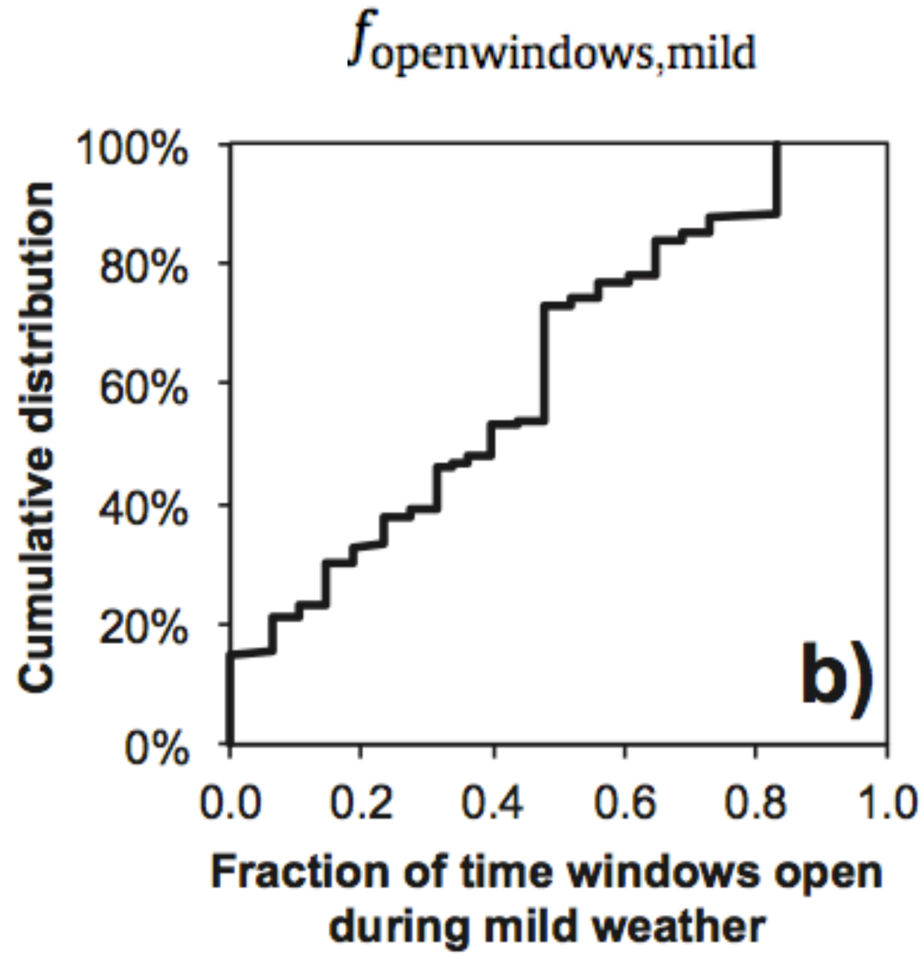
Stephens et al. **2011** *Build Environ*

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

Methodology: Gathering input parameters

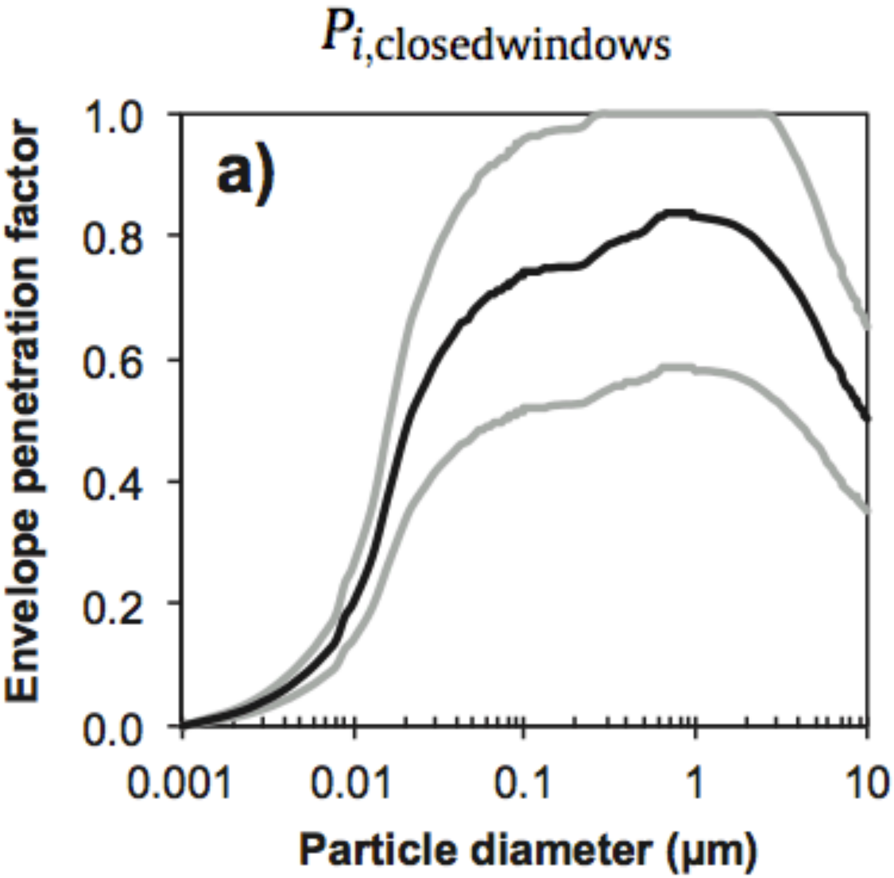


Chen et al et al. **2012** *Epidemiology*

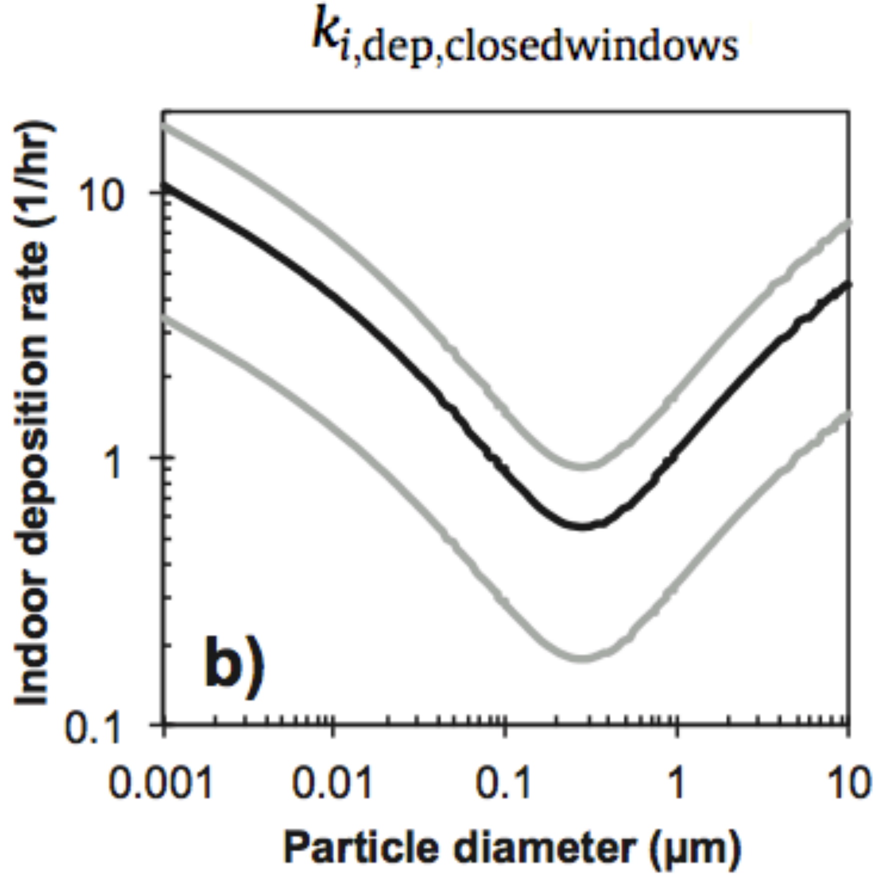


Price and Sherman **2006** *LBNL 59620*

Methodology: Gathering input parameters



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



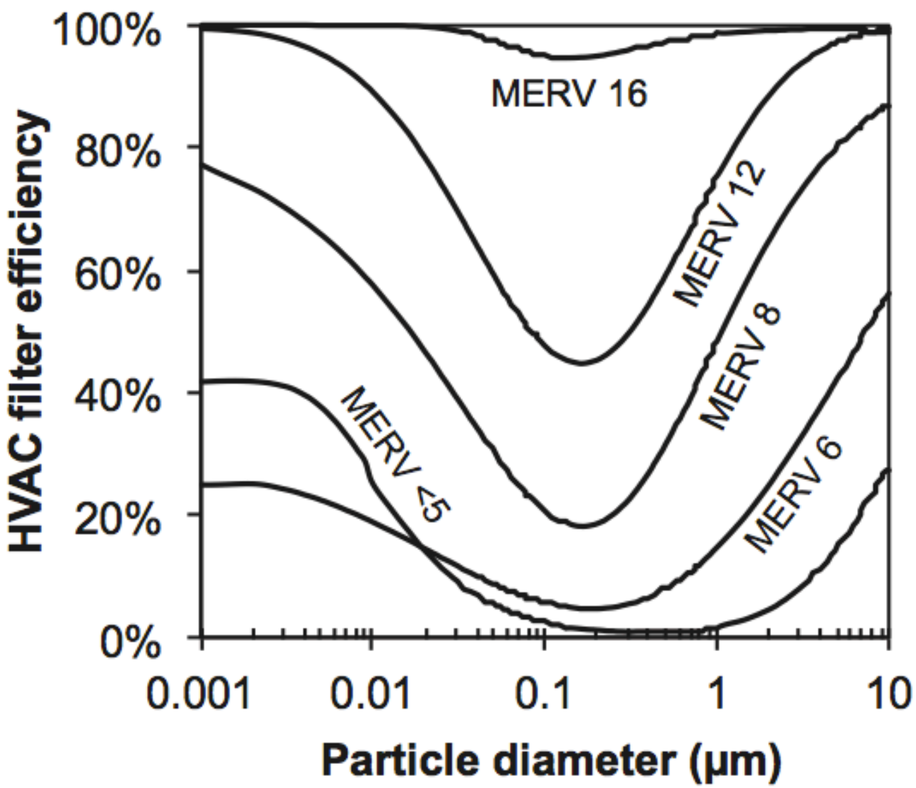
Adjusted from He et al **2005** *Atmos Environ*

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%

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



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

Results

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

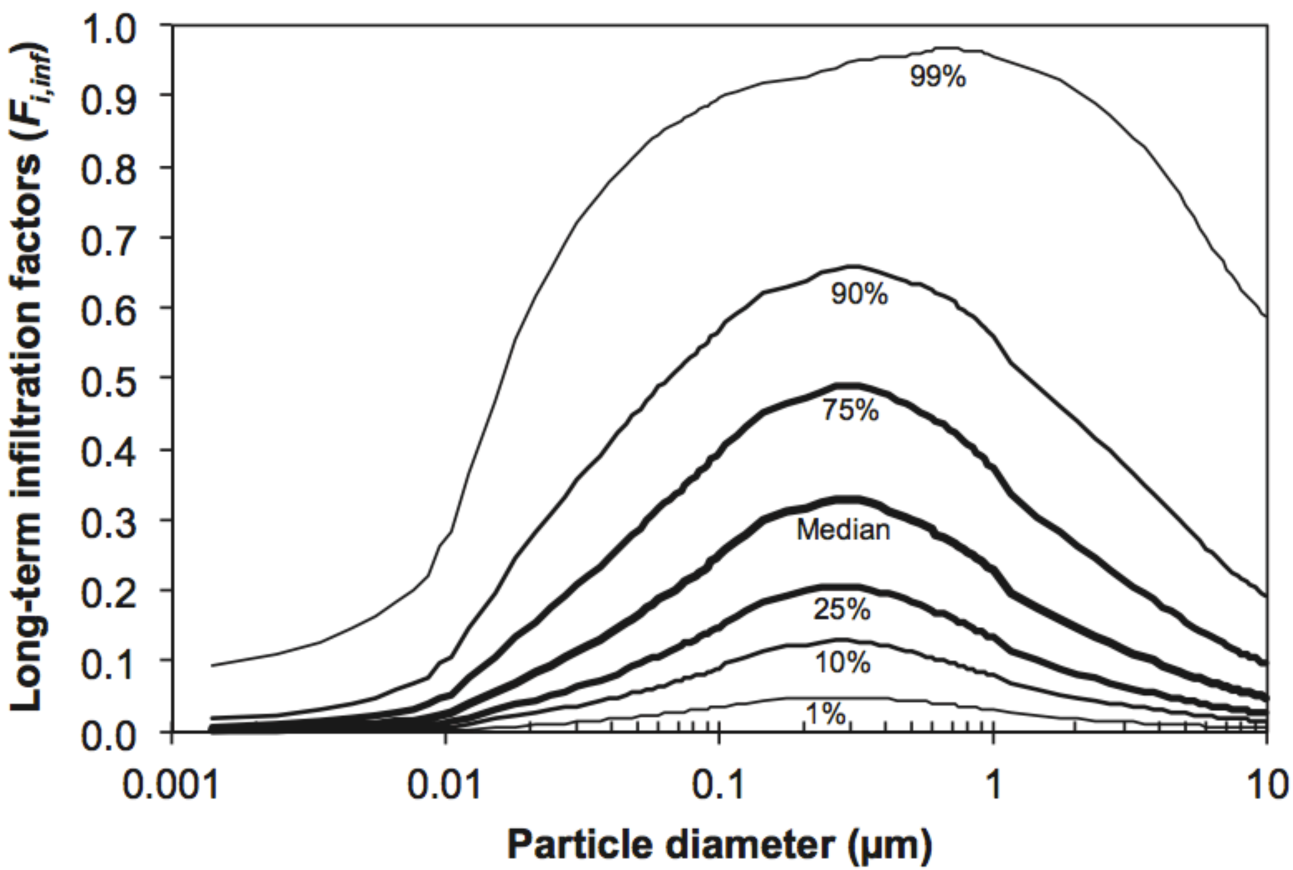
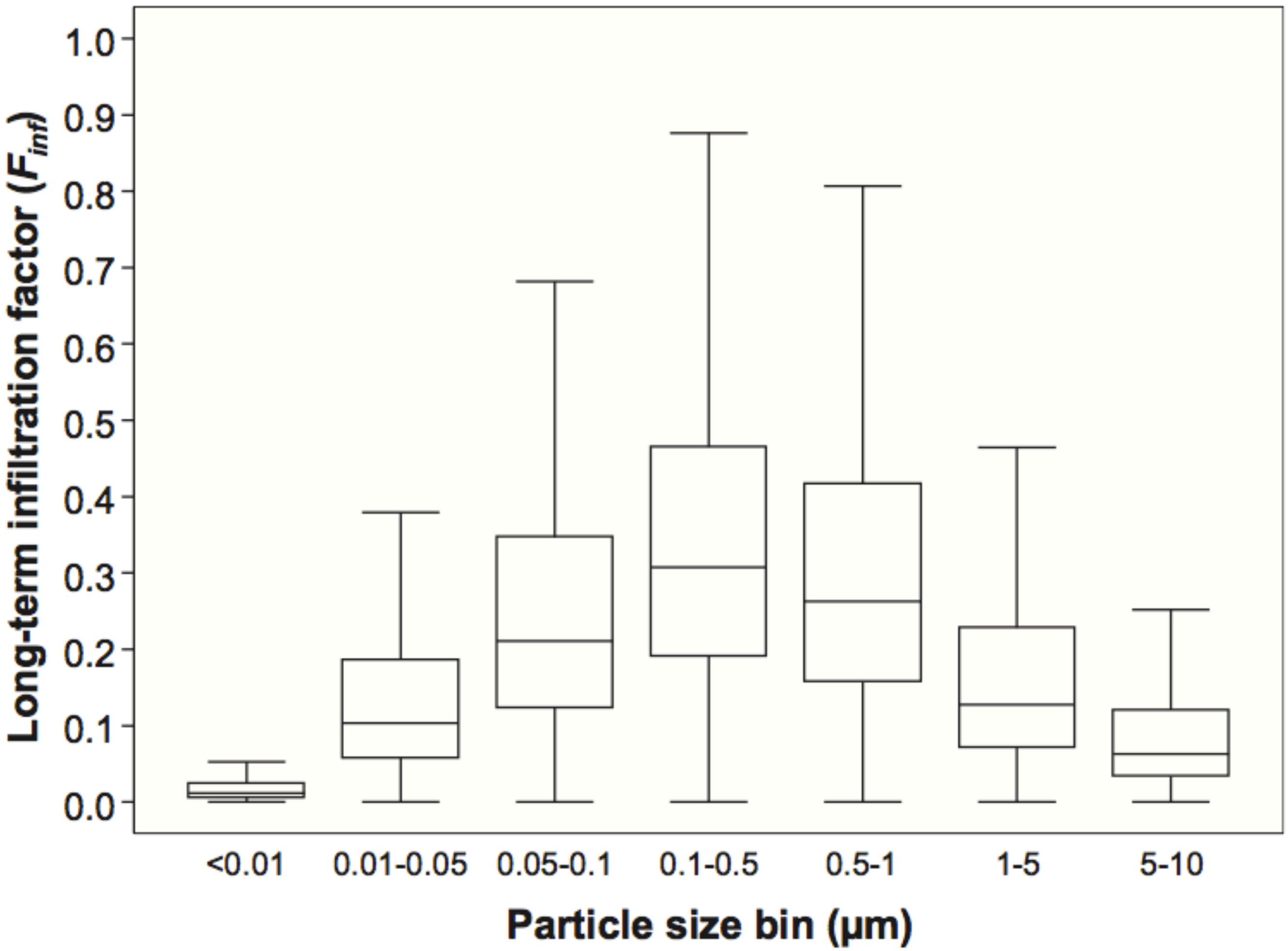


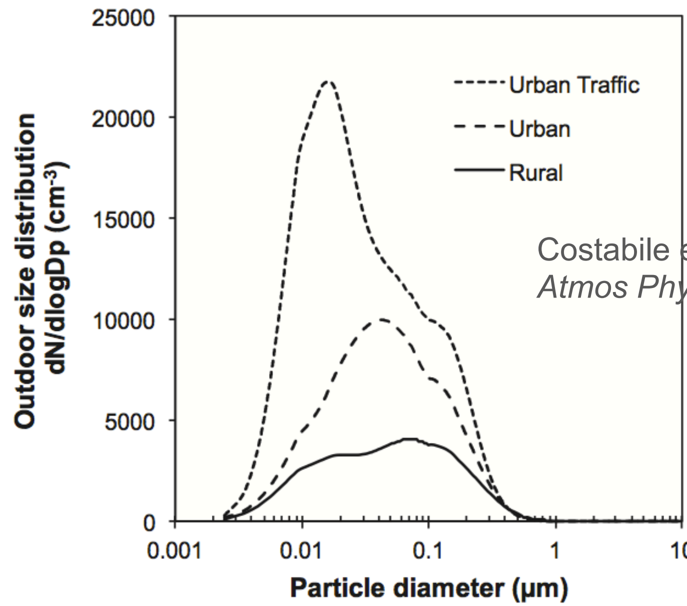
Fig. 5. Estimate of the distribution of time-averaged size-resolved infiltration factors ($F_{i,\text{inf}}$) across the U.S. single-family residential building stock resulting from the 100,000 simulations.

Results

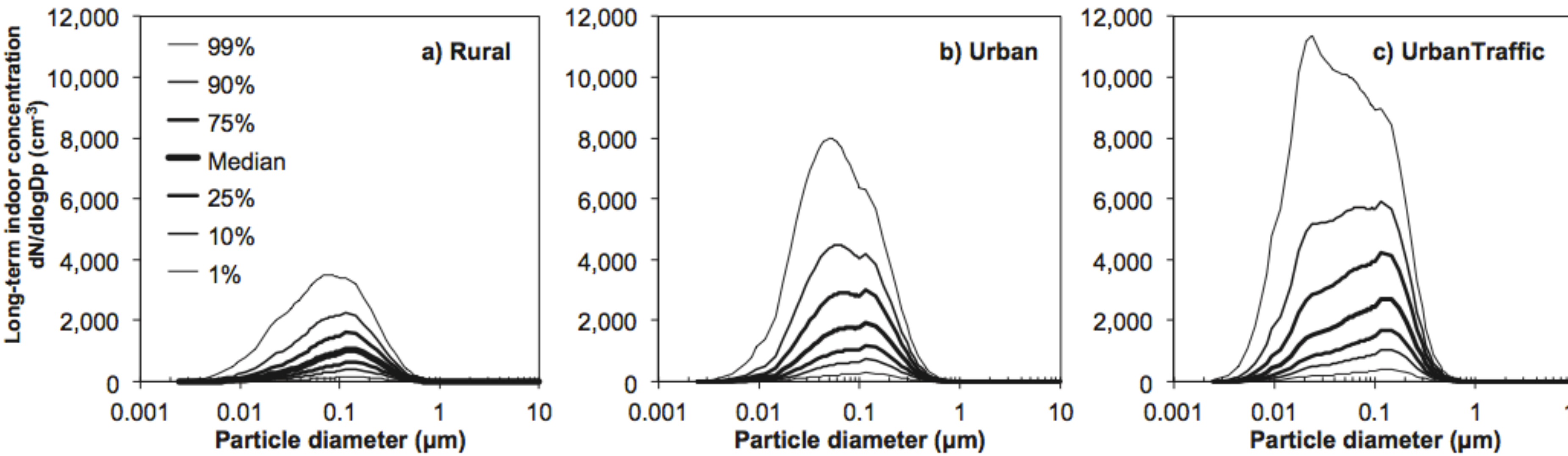


UFP estimates in line with measurements in Kearney et al (2011) *Atmos Environ*: 0.03-0.9, median of 0.19-0.27

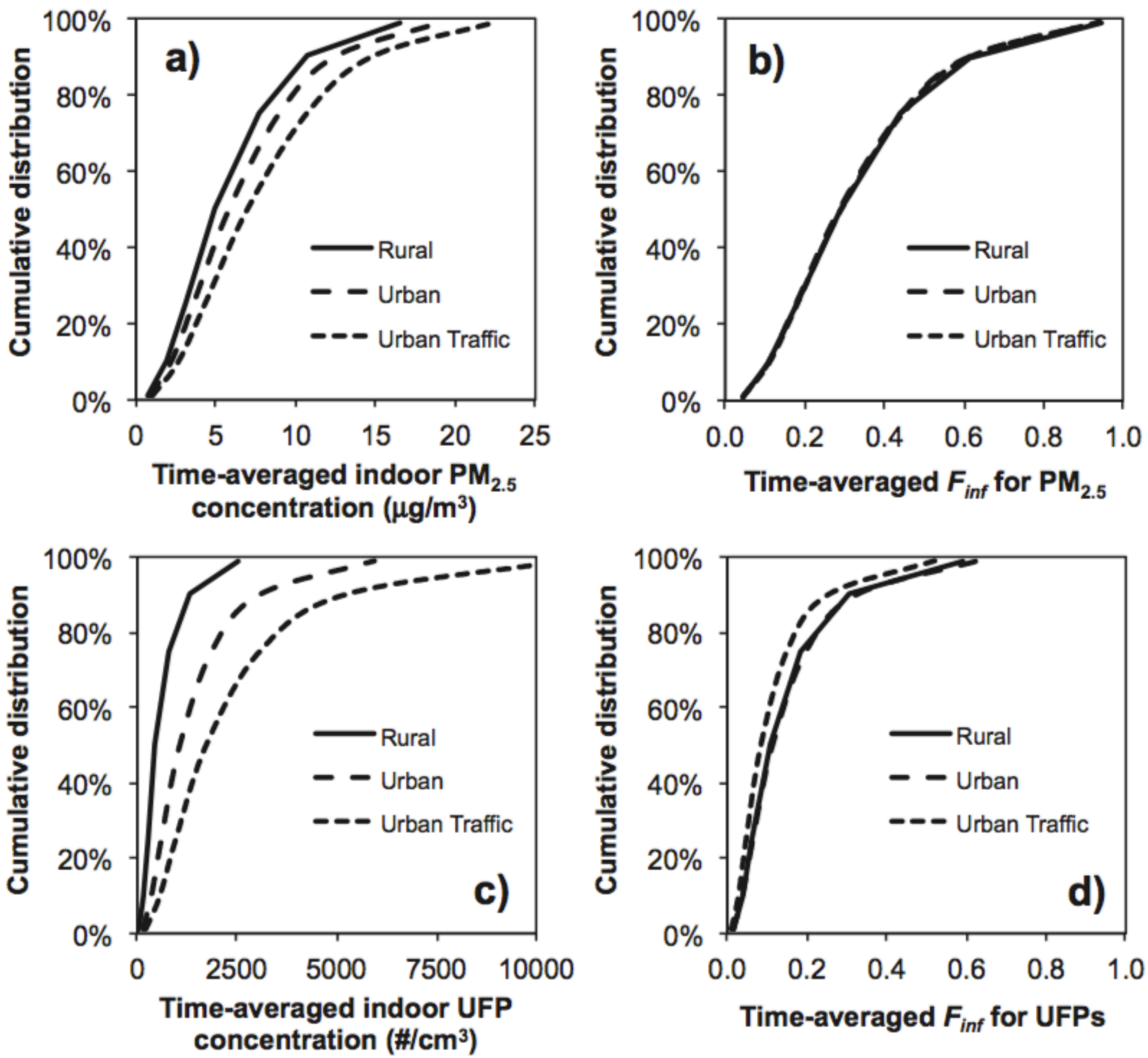
Results: Mapping to outdoor size distributions



Costabile et al **2009**
Atmos Phys Chem

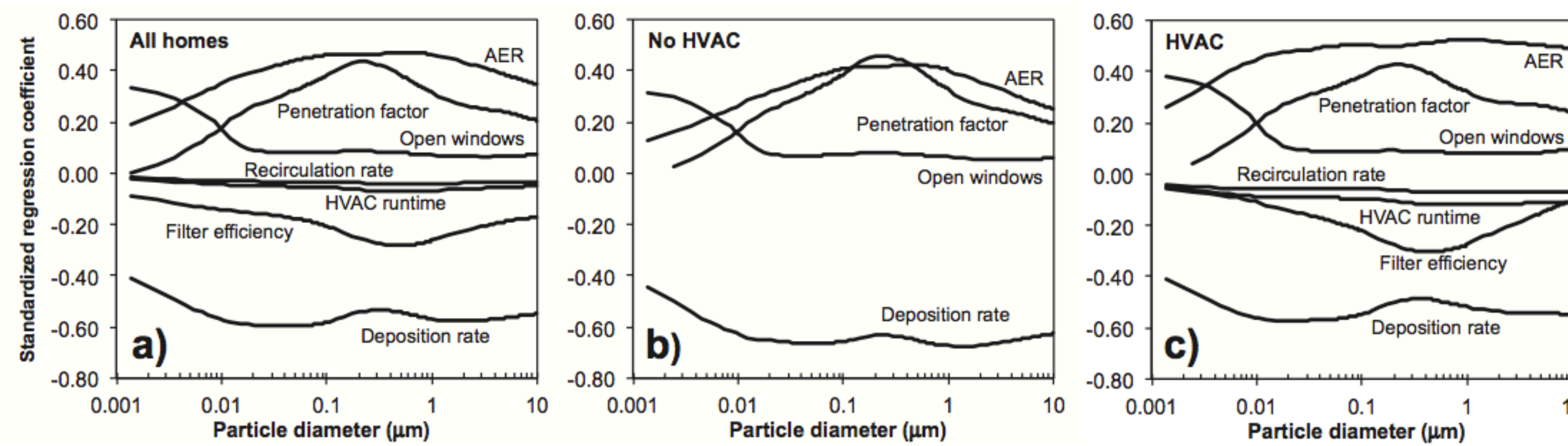


Results: Predicting CDFs of UFPs and $PM_{2.5}$



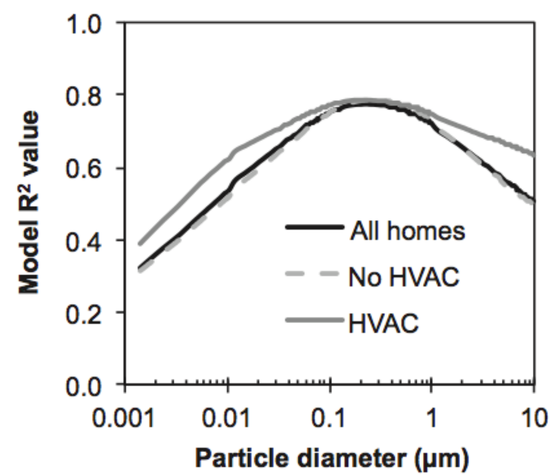
Results: Multiple regression for influential factors

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



Mean ± standard deviation of the standardized multiple linear regression coefficients for each input variable for (i) all homes, (ii) only those homes without HVAC systems, and (iii) only those homes with HVAC systems.

Input parameter	Mean ± s.d. standardized regression coefficients (SRCs) across all particle sizes		
	All homes	No HVAC	HVAC
Closed-window deposition rate, $k_{i,\mathrm{dep,closedwindows}}$	−0.56 ± 0.03	−0.65 ± 0.03	−0.53 ± 0.03
Closed-window air exchange rate, $\lambda_{\mathrm{closedwindows}}$	0.42 ± 0.06	0.35 ± 0.07	0.49 ± 0.04
Closed-window penetration factor, $P_{i,\mathrm{closedwindows}}$	0.30 ± 0.09	0.30 ± 0.10	0.31 ± 0.08
HVAC filter efficiency, $\eta_{i,\mathrm{HVAC}}$	−0.21 ± 0.05	Omitted	−0.20 ± 0.07
Fraction of time windows are open, $f_{\mathrm{openwindows}}$	0.09 ± 0.05	0.08 ± 0.05	0.11 ± 0.06
HVAC system runtime, f_{HVAC}	−0.06 ± 0.01	Omitted	−0.10 ± 0.01
Recirculation rate, λ_{HVAC}	−0.04 ± 0.00	Omitted	−0.06 ± 0.01



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

Acknowledgements

- Co-authors Zeineb El Orch (IIT) and Michael Waring (Drexel University)

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journal homepage: www.elsevier.com/locate/buildenv

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

CrossMark

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[b] Civil, Architectural and Environmental Engineering, Drexel University, Philadelphia, PA, USA

Next steps: PM infiltration measurements in Chicago