Building design and operational choices that impact indoor exposures to outdoor particulate matter inside residences

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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*

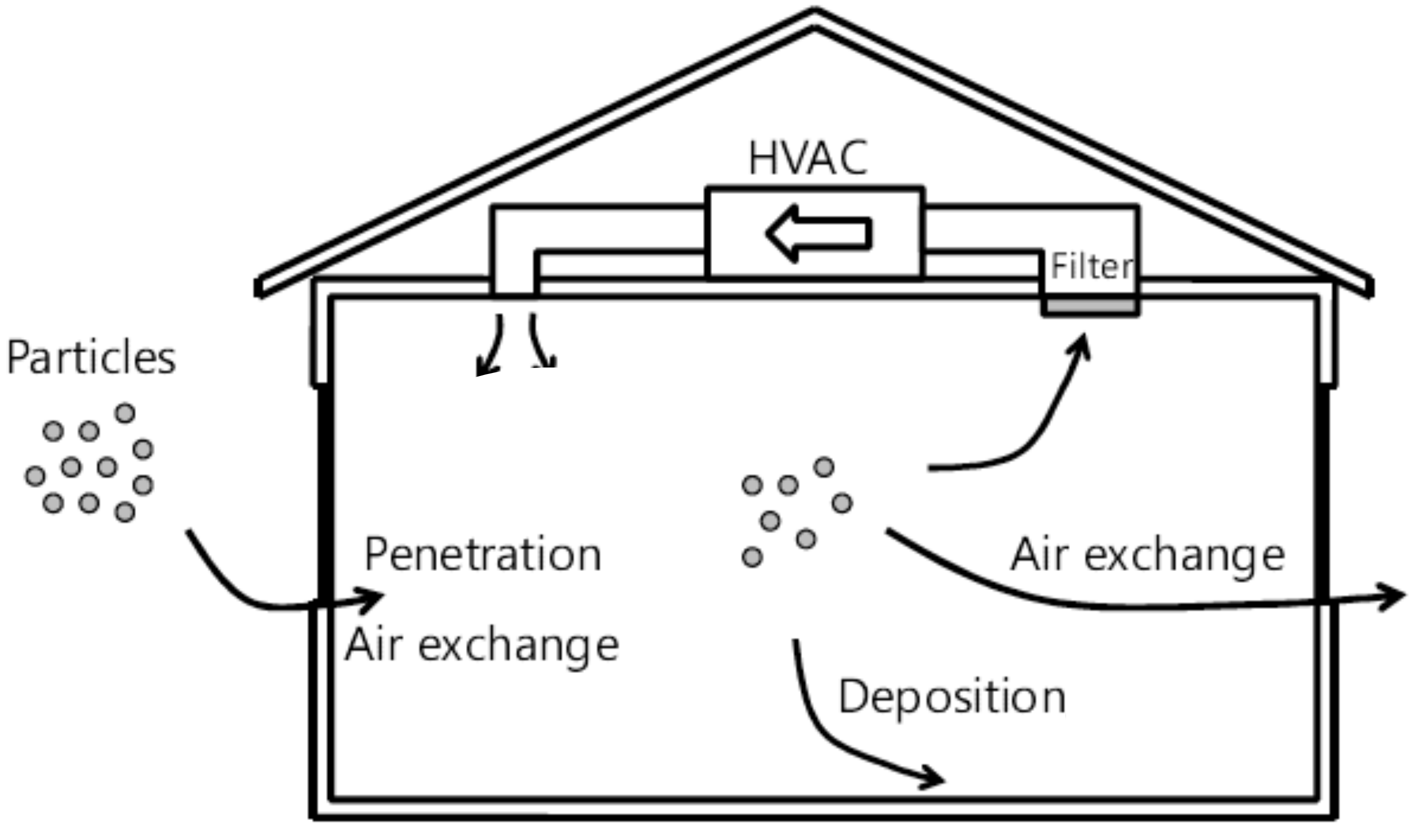
- Outdoor particles can infiltrate and persist in homes with varying efficiencies Chen and Zhao, **2011** *AE;* Williams et al., **2003** *AE;* Kearney et al., **2010** *AE*

- 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



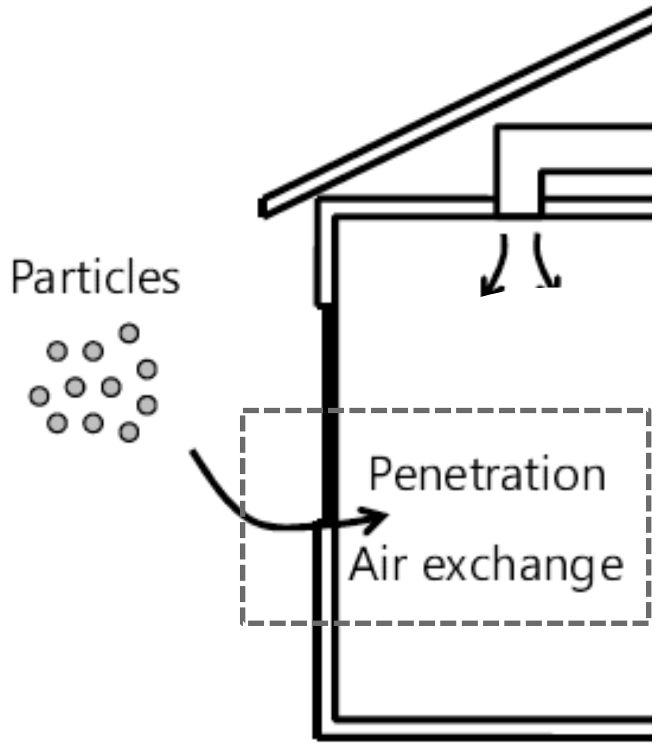
C_{in} = indoor concentration (#/m^3)
C_{out} = outdoor concentration (#/cm^3)
P = penetration factor (-)
λ = air exchange rate (1/hr)
k = surface deposition rate (1/hr)
f = fractional HVAC runtime (-)
η = filter removal efficiency (-)
Q = HVAC airflow rate (m^3/hr)
V = indoor air volume (m^3)

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

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

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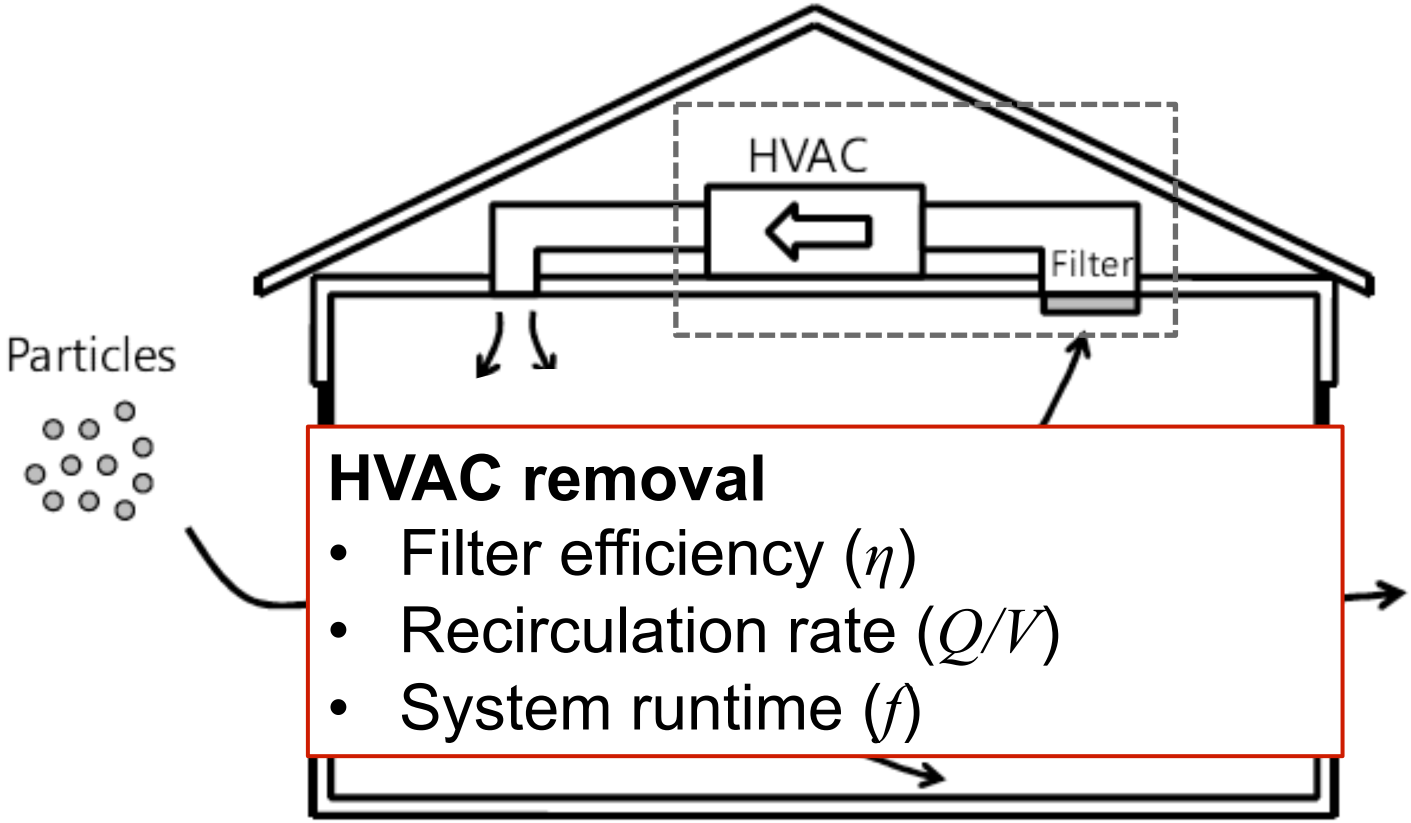
Penetration from outdoors

Mechanisms that impact indoor exposures to outdoor PM



HVAC removal

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

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

Filter removal
HVAC operation

Importance of source and removal mechanisms

- **Building envelope penetration**
  - Only recently has varying particle infiltration been implicated in observed health disparities with outdoor PM
    - Largely by varying AER, not penetration factor

Hodas et al., **2012** *J Expo Sci Environ Epidem*; Chen et al., **2012** *Epidemiology*

- **HVAC removal**
  - Prevalence of air-conditioning has been shown to be a modifier in $PM_{2.5}$ and PM_{10} mortality
    - Little information on filter removal efficiency and HVAC system runtime

Janssen et al., **2002** *Environ Health Persp*; Franklin et al., **2007** *J Expo Sci Environ Epidem*; Bell et al., **2009** *Epidemiology*

Goals of this work

- Further explore the impacts of building design and operation – including **building envelopes** and **HVAC filters** – on indoor PM of outdoor origin

  Key parameters:
  - Particle penetration factor, P
  - Air exchange rate, λ
  - Particle removal by HVAC filter, $\eta Q/V$
  - HVAC system runtime, f

- Using recently measured data from recent studies on residential (and some small commercial) buildings

- Can we also **predict** these impacts?

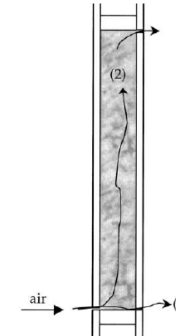
- Describe one case study on a **net zero energy capable home** with mechanical ventilation

RECENT PARTICLE INFILTRATION MEASUREMENTS

Measuring particle infiltration

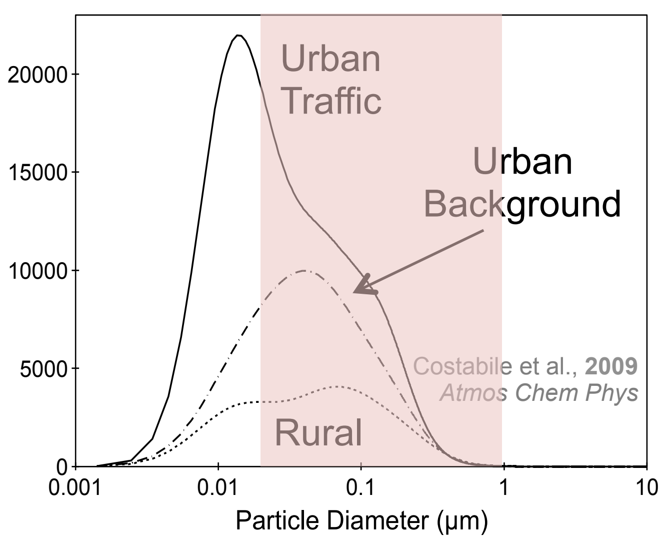
- Particles can penetrate through cracks in building envelopes
  - Theoretically a function of:
    - Crack geometry
    - Air speed through leaks

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



- Are building details and particle penetration factors correlated?
  - e.g., air leakage parameters or building age
  - Needed a test method for measuring *P* quickly
- Applied a particle penetration test method in 19 homes

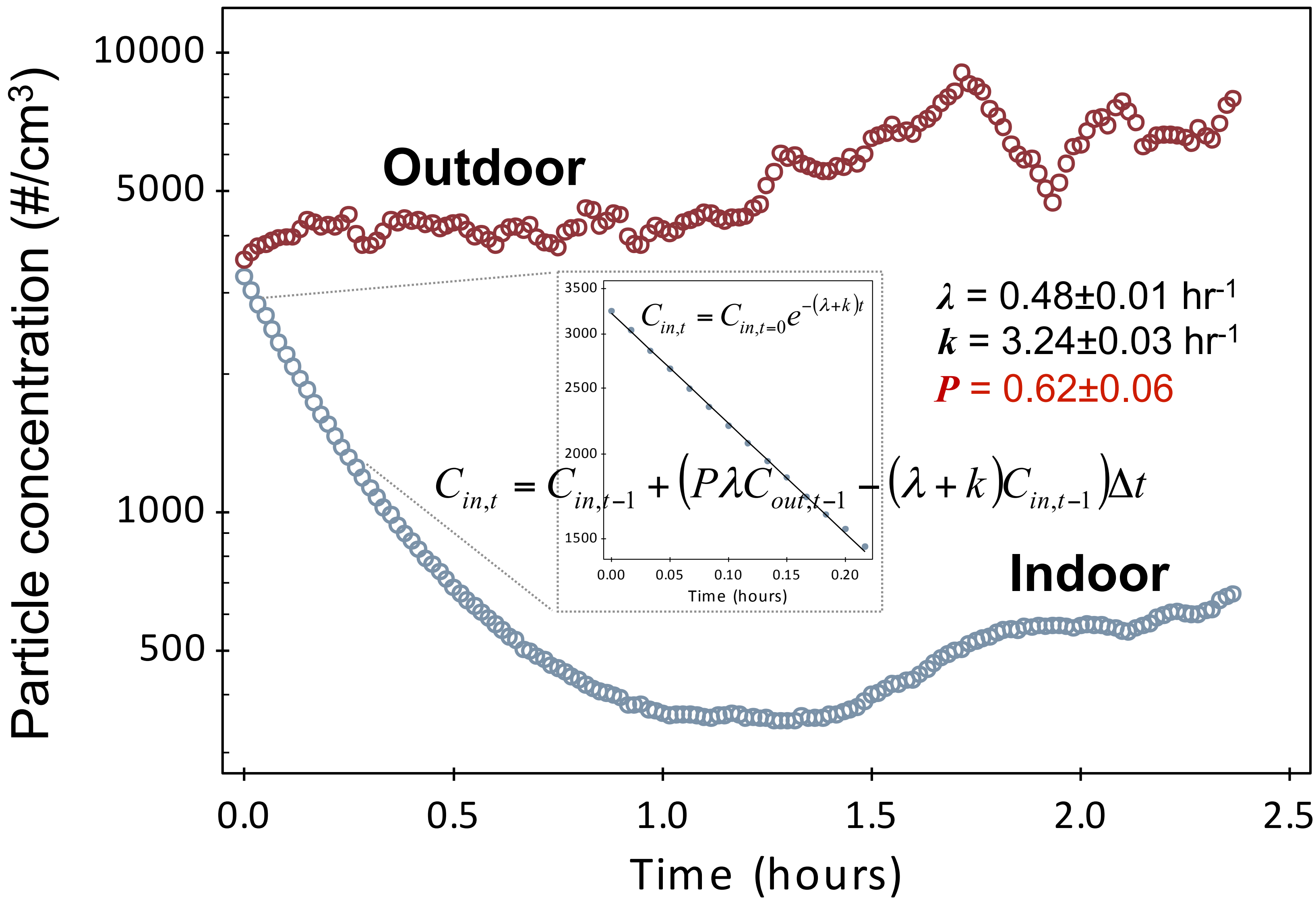
Stephens and Siegel, **2012** *Indoor Air*



TSI P-Traks
20 – 1000 nm

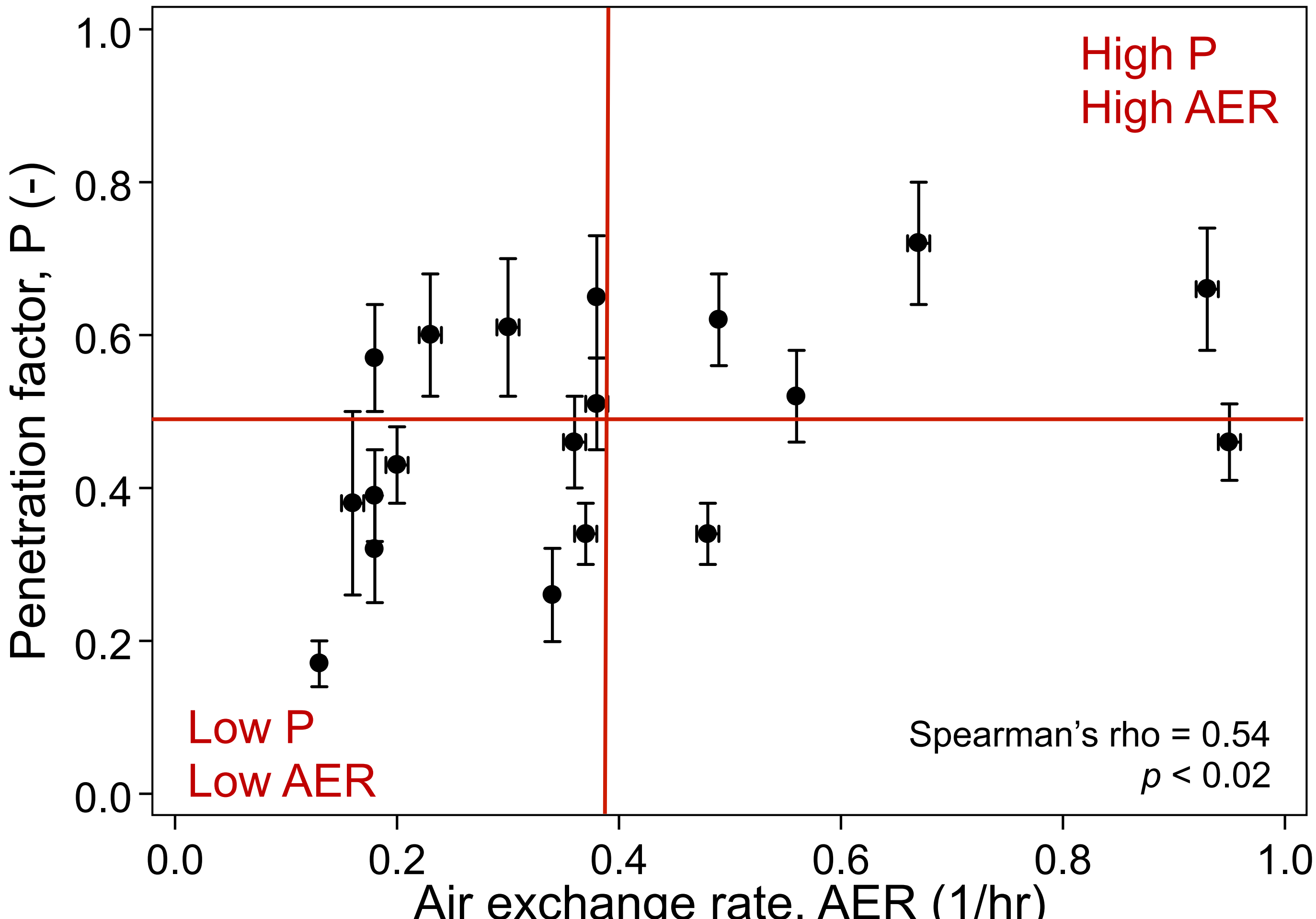
PM infiltration: Test homes

Test method: Submicron particle infiltration (20-1000 nm)



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

Particle infiltration results: P and AER



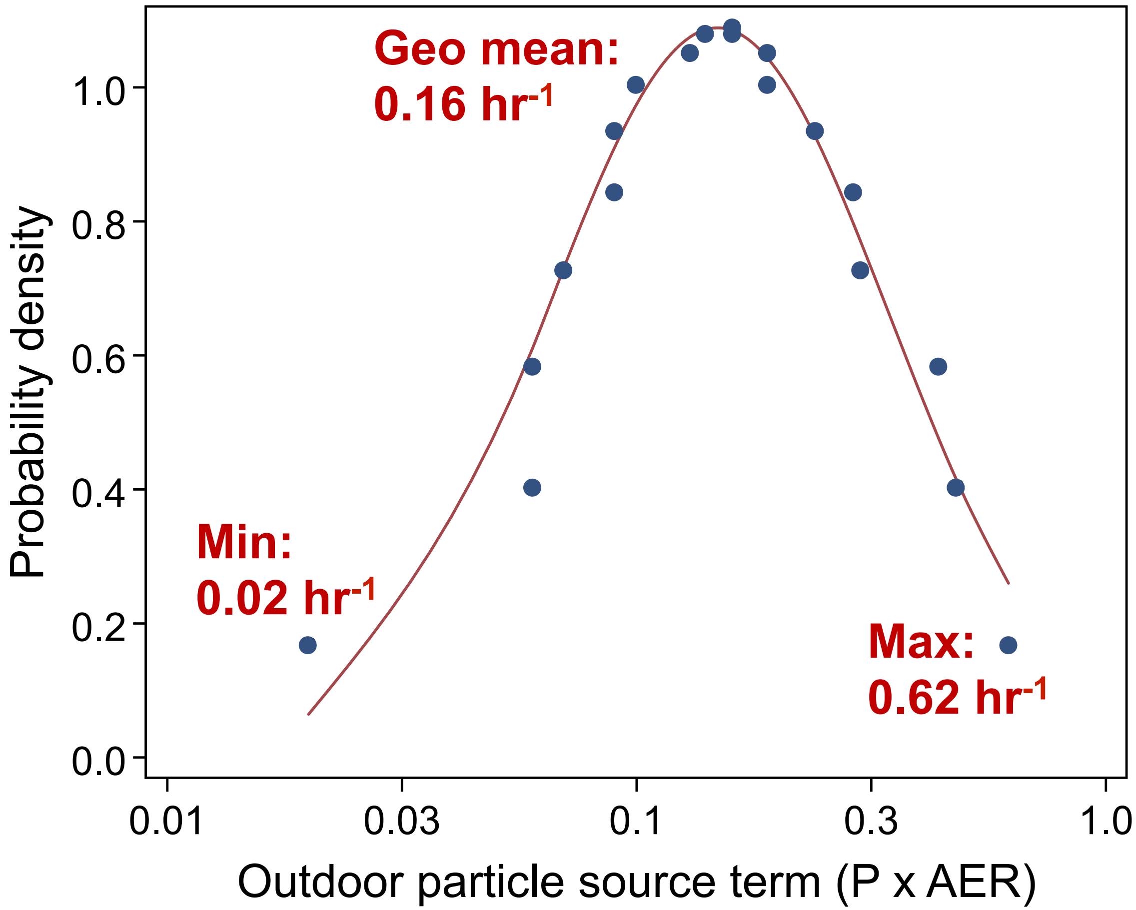
Penetration factors: Mean = 0.47 Range = 0.17 to 0.72

Air exchange rates: Mean = 0.39 hr^{-1} Range = 0.13 to 0.95 hr^{-1}

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

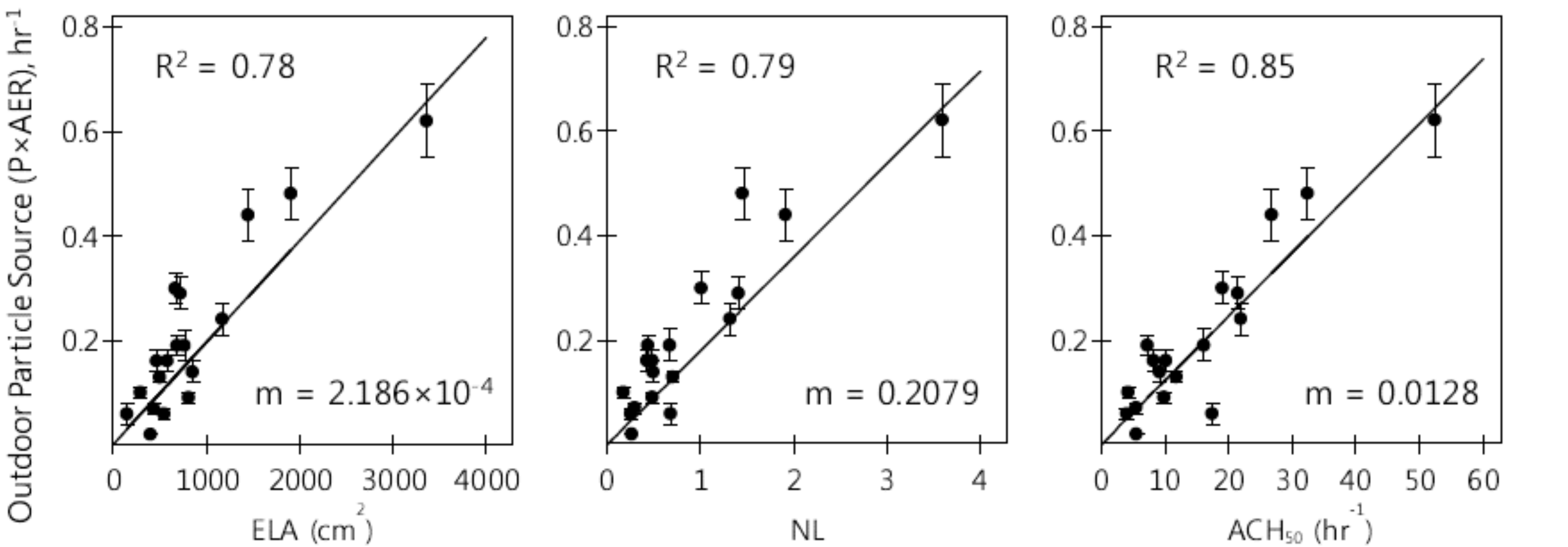
Outdoor particle source terms: P×AER

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



Outdoor particle sources and envelope air tightness

$$\frac{C_{in}}{C_{out}} = \frac{P \times AER}{AER + Loss}$$ vs. blower door test results



Leakier homes had much higher outdoor particle source rates

Older homes also had much higher outdoor particle source rates

- Potential socioeconomic implications: low-income homes are older/leakier

Chan et al., **2005** *Atmos Environ*

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

RECENT MEASUREMENTS OF HVAC FILTRATION

HVAC filter removal: Efficiency is not the whole story

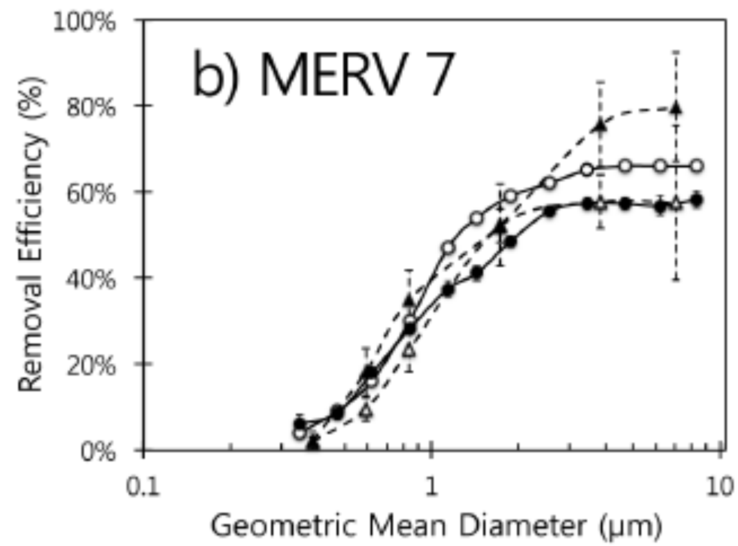
$$Loss = k + f\frac{\eta Q}{V}$$

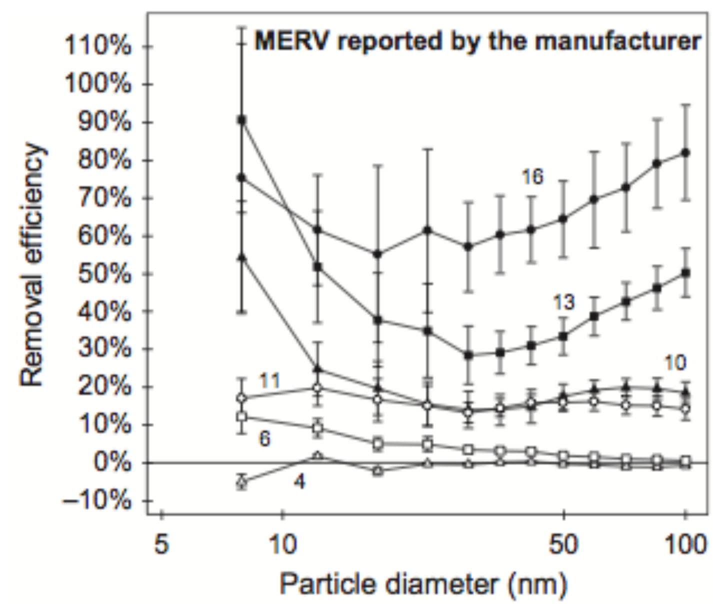
1-inch depth

MERV 4 MERV 6 MERV 11

5-inch depth

MERV 10 MERV 13 MERV 16





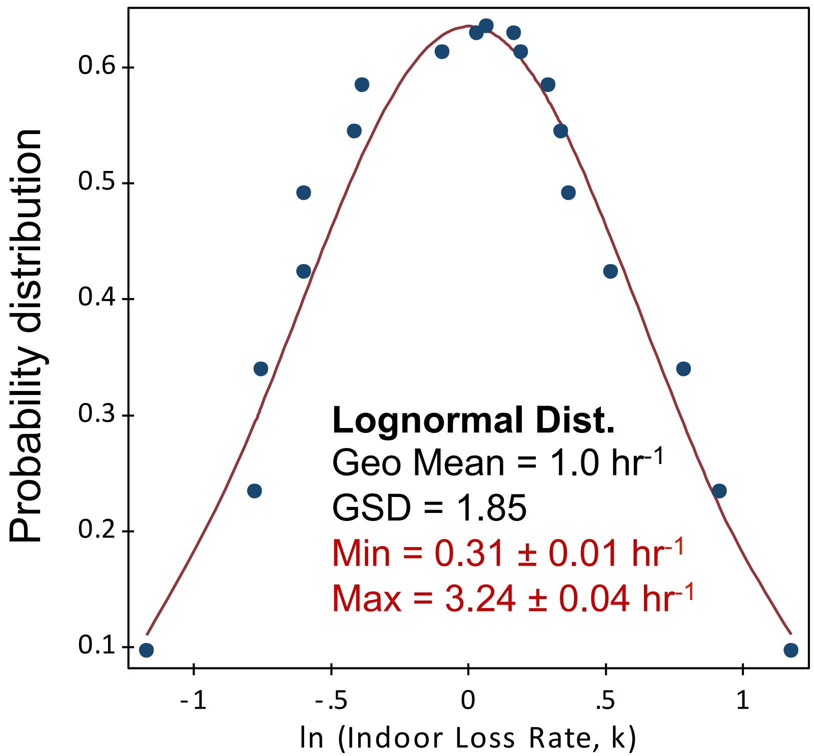
Stephens and Siegel, *Aerosol Sci. Technol.* **2012** 46(5), 504-513
Stephens and Siegel, *Indoor Air* **2013**

Indoor particle removal rates

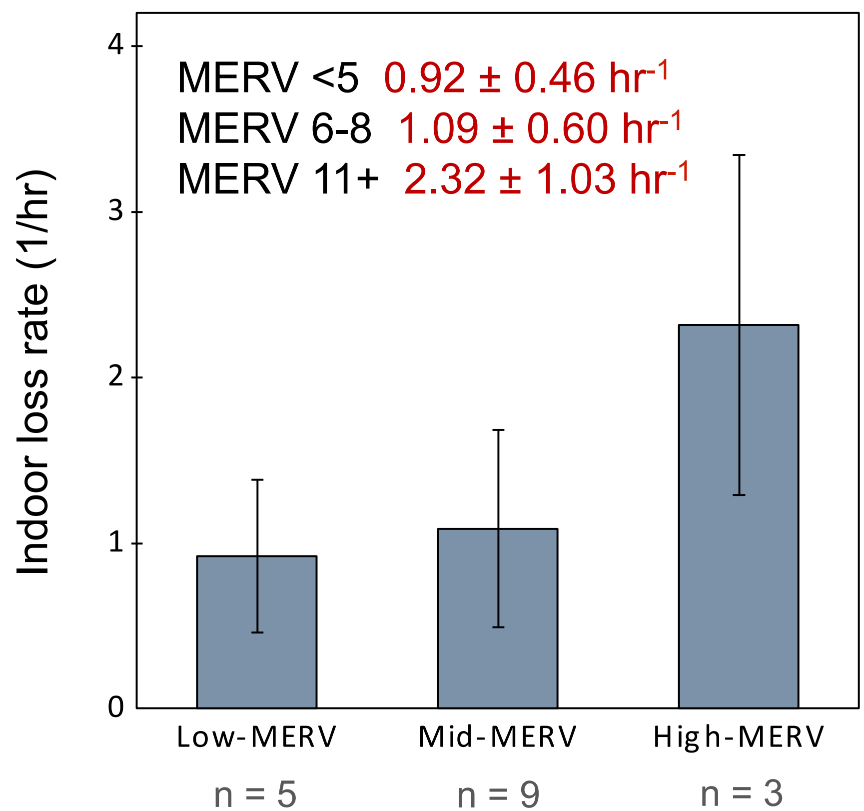
- Submicron particle loss with HVAC system operating 100%

$$Loss = k + f\frac{\eta Q}{V}$$

where f = 1



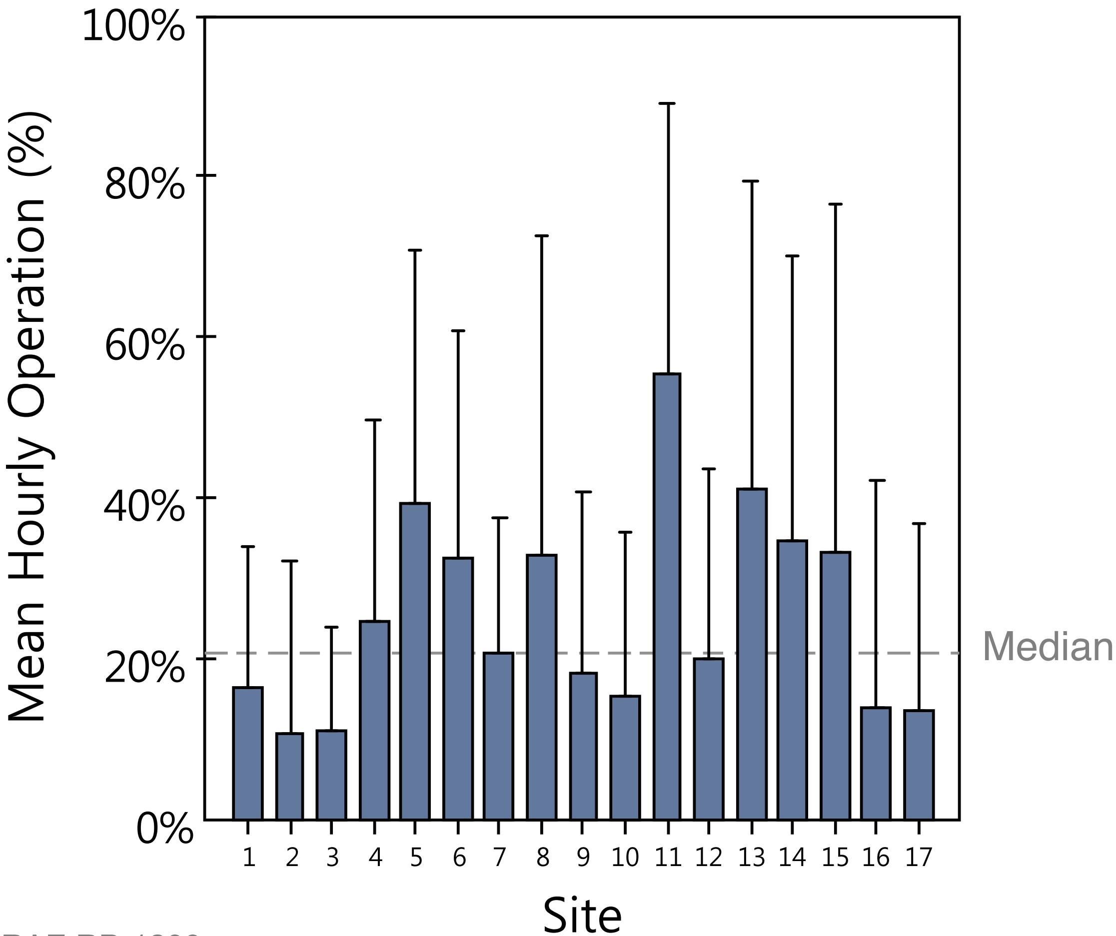
Split by filter type



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

HVAC system runtimes in other homes and small offices

- Mean HVAC runtimes in TX ranged 10.7% to 55.3%
  - Median $f \approx 21\%$ (influenced by climate and thermostat settings)



Stephens et al., **2010** ASHRAE RP-1299
Stephens et al., **2011** *Building and Environment* 46(10):1972-1983

VARIATIONS IN EXPOSURES

Across observed range of envelope penetration, filter efficiency, and runtimes

Implications for submicron PM exposure

- Penetration factors ranged 0.17 to 0.72
- AER ranged 0.13 hr^{-1} to 0.95 hr^{-1}
- Outdoor particle source terms ranged 0.02 hr^{-1} to 0.62 hr^{-1}
  - Factor of **~30** difference from lowest to highest
  - Higher in older, leakier homes

- Indoor removal rates ranged 0.31 hr^{-1} to 3.24 hr^{-1}
  - Factor of **~10** difference from least efficient to most efficient filter
  - Varied with rated filter efficiency (particularly for high-efficiency)

- HVAC fractional operation ranged 10.7% to 55.3%
  - Factor of **~5** difference
  - Varied with thermostat settings, occupancy, and outdoor climate

Implications for submicron PM exposure

- Combined effects: $F_{\text{inf}} = \frac{C_{in}}{C_{out}} = \frac{P \times AER}{AER + k + f\frac{\eta Q}{V}}$

	Lower bound	Upper bound
Penetration factor, *P*	0.17	0.72
Air exchange rate, *AER* (1/hr)	0.13	0.95
Outdoor source term, *P×AER* (1/hr)	0.02	0.62
Indoor loss rate, $k + \eta Q/V$ (1/hr)	3.24	0.31
Fractional HVAC operation, *f*	55.3%	10.7%
I/O submicron PM ratio (F_{inf})	**0.01**	**0.70**

Factor of **~70** difference in indoor proportion of outdoor particles between:
- A new airtight home with a very good filter and high HVAC operation, and
- A leaky old home with a poor filter and low HVAC operation

- Some potential for predictive ability using:
  - Age of home
  - Building airtightness test results
  - Knowledge of HVAC filter type
  - I/O climate conditions

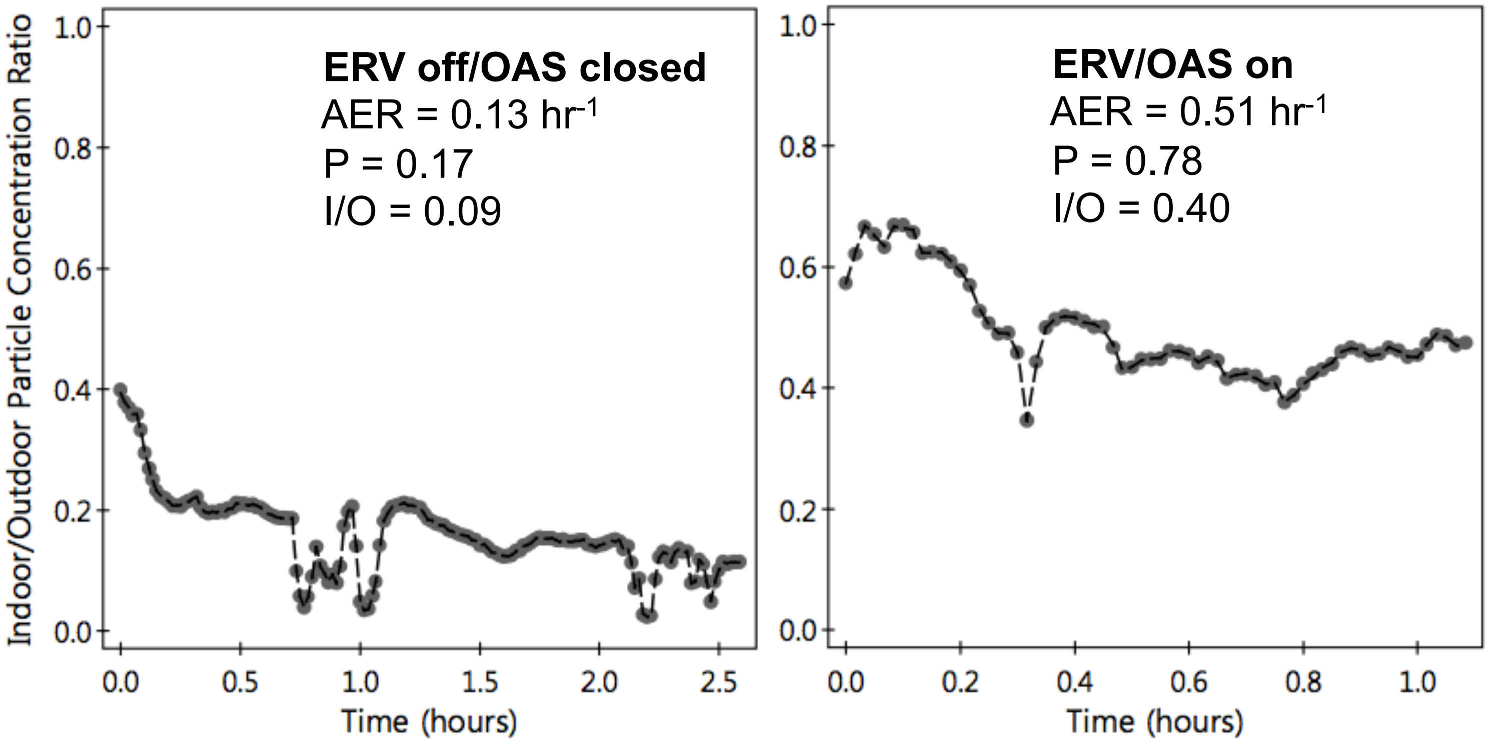
A CAUTIONARY TALE

In a new net-zero energy capable home (built 2011)

Impacts of high-efficiency HVAC systems

- One of the test homes (Site 15) had a dedicated mechanical ventilation system
- Outdoor air supply duct ran through an energy recovery ventilator (ERV) and was installed directly into the HVAC return plenum
- Previous results were only for natural infiltration, when the system was unplugged and capped
  - Relying on envelope leakage alone for ventilation air
- We repeated the test a second time with the ERV/OAS unit operating…

Impacts of mechanical ventilation



- This home was responsible for both the **lowest** and the **highest** envelope penetration factors!
  - Depending on whether or not the ERV was operating
- Problem: The ERV/OAS was ducted to directly ***downstream*** of the HVAC filter

Conclusions

- Outdoor particulate matter (PM) infiltration and persistence can vary greatly between homes
  - Generally lower in newer, tighter homes than in older, leakier homes
    - We also may be able to predict PM infiltration
  - Other design, construction, and operational parameters can further widen this gap between homes
    - HVAC filtration selection and system runtime, among others

- In very low-energy homes, envelopes are probably tight enough to nearly prevent infiltration of outdoor PM
  - Turns focus to indoor-generated pollutants
  - Effects can be *completely reversed* by poor construction!

Acknowledgments

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Questions/Comments

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