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Outdoor air and (non-combustion) appliances as sources of indoor particulate matter (PM)

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Indoor exposures to outdoor PM

WHAT WE KNOW

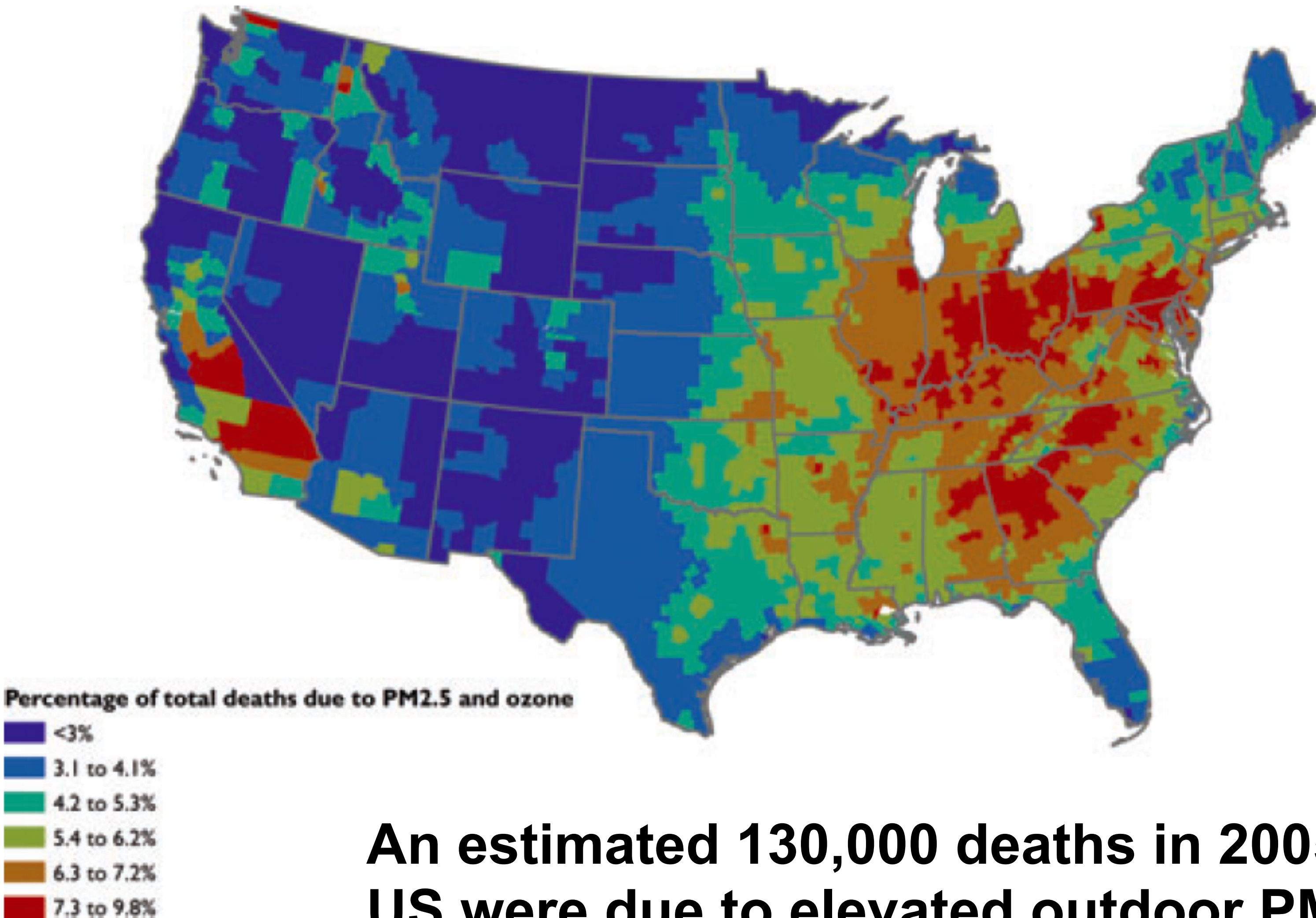
Outdoor PM and adverse health effects

- Documented health effects include:
  - Stroke
  - Heart disease
  - Lung cancer
  - Chronic and acute respiratory diseases (including asthma)
  - Lung function
  - Mortality

- Measures of PM (some causal, some suggestive):
  - PM_{10}
  - $PM_{2.5}$
  - Ultrafine particles (UFPs, less than 100 nm)
  - Various chemical components of PM

US EPA **2009** *Integrated Science Assessment for Particulate Matter* and many references therein

Outdoor $PM_{2.5}$ and mortality



An estimated 130,000 deaths in 2005 in the US were due to elevated outdoor $PM_{2.5}$

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

Indoor exposures to outdoor PM

- We spend most of our time indoors
  - Nearly 90% of the time, on average (~70% at home)

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

- Outdoor PM enters into buildings with varying efficiencies
  - Outdoor PM becomes indoor PM

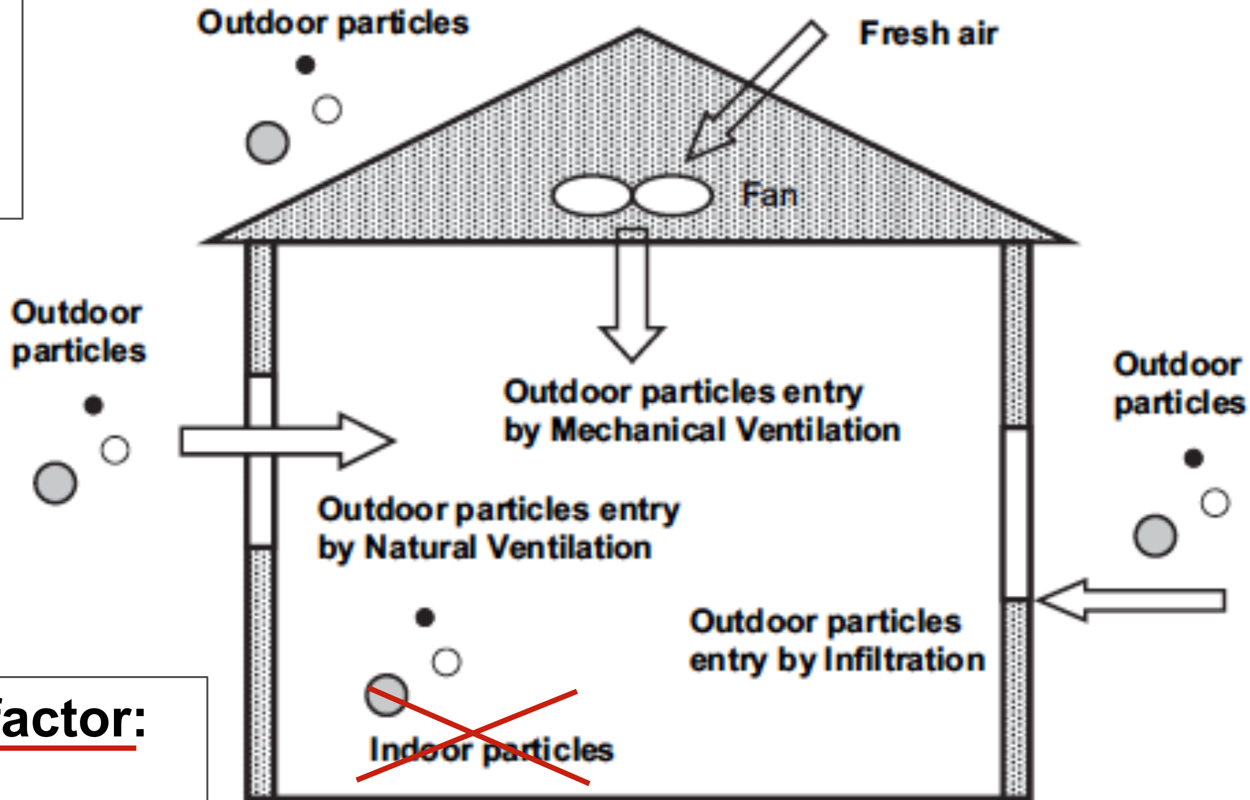
- Human exposure to outdoor PM often occurs indoors
  - And often at home

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*; MacNeill et al. **2014** *Indoor Air*

Indoor sources of outdoor PM and key definitions

I/O ratio:

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

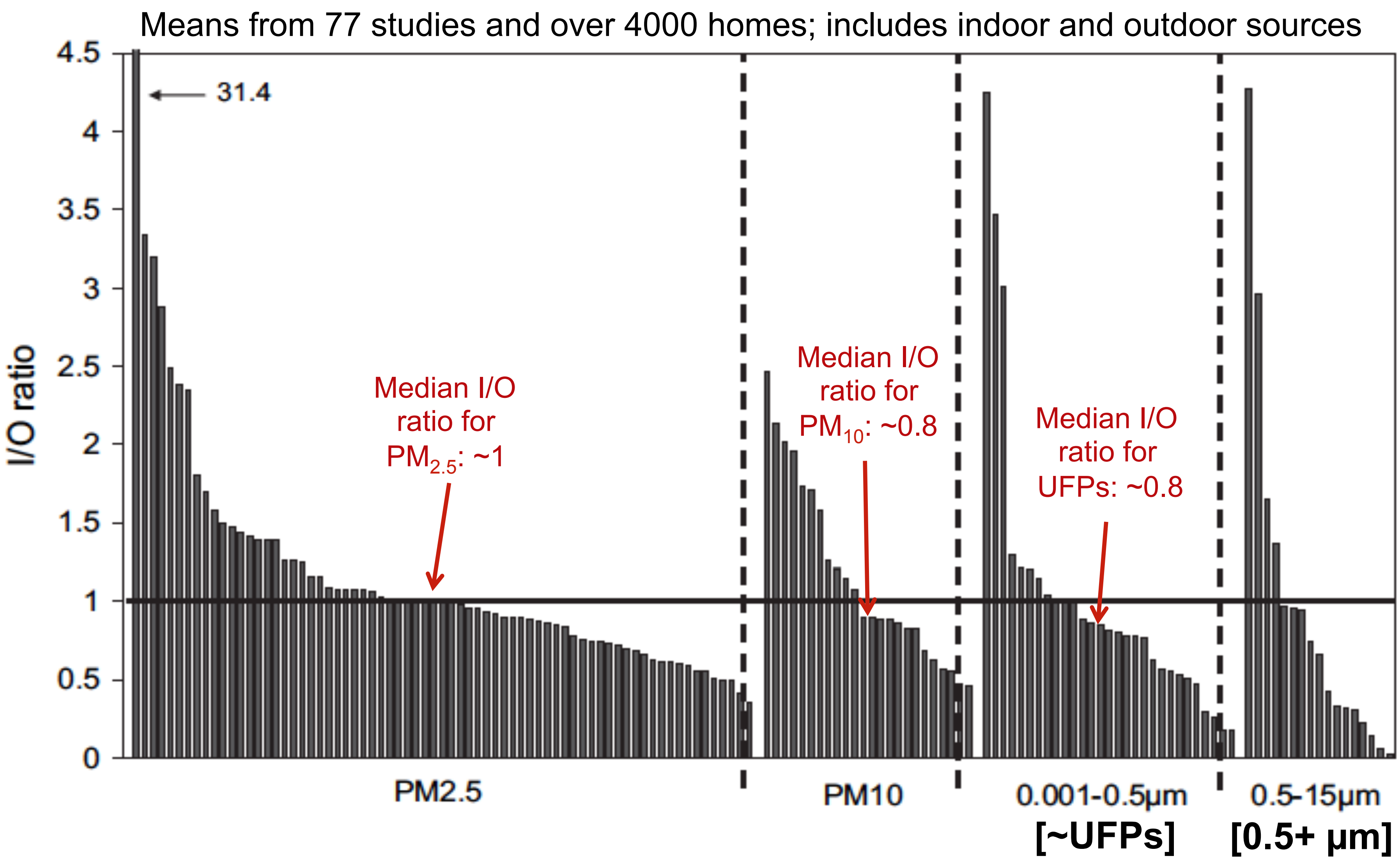


Chen and Zhao, **2011** *Atmos Environ*

Infiltration factor:

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

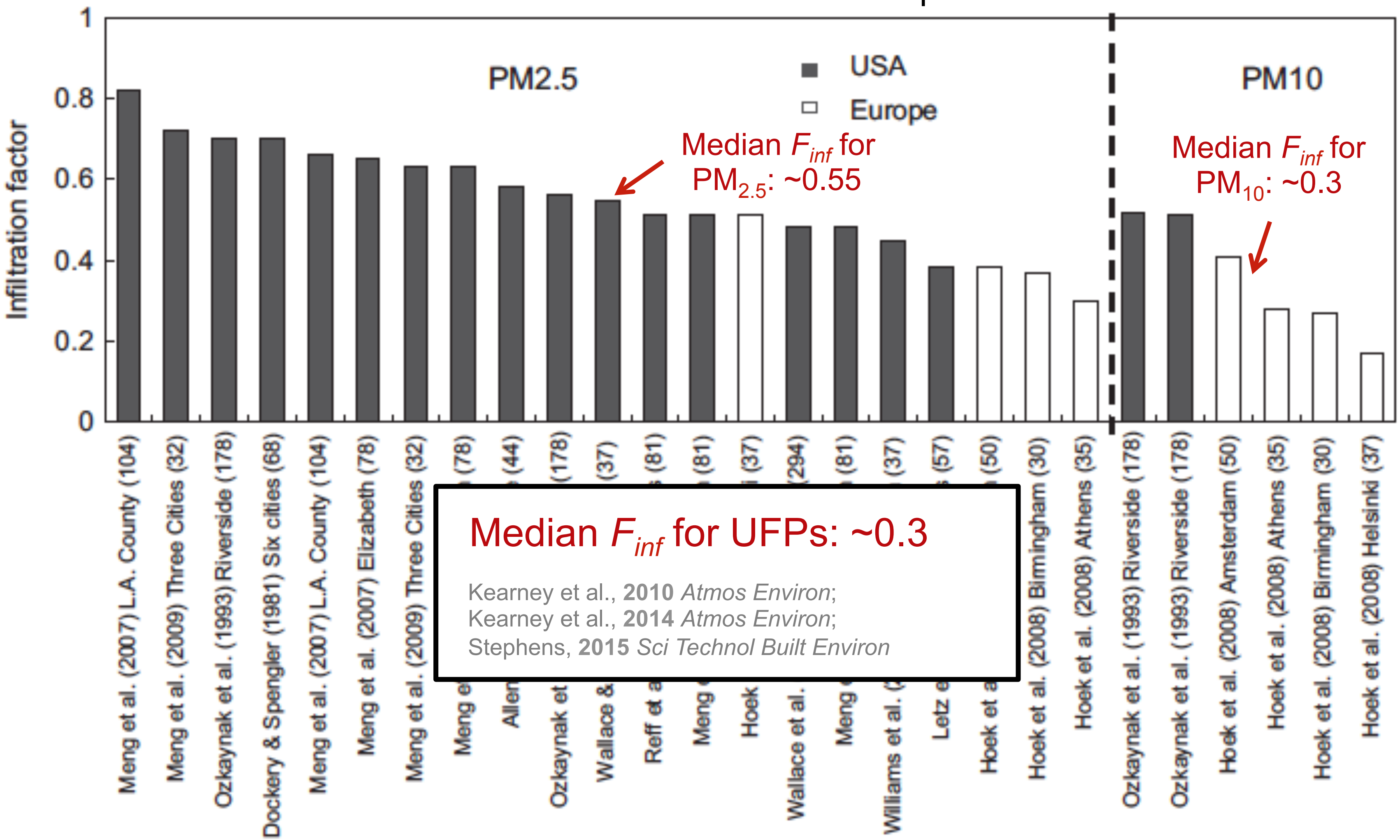
I/O PM ratios: Indoor + outdoor sources



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

Infiltration factors: Outdoor PM sources only

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



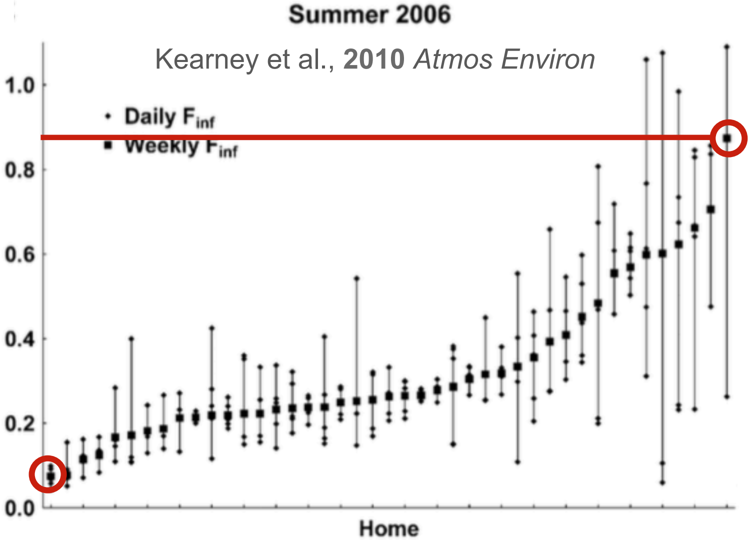
Median F_{inf} for UFPs: ~0.3

Kearney et al., **2010** *Atmos Environ*;
Kearney et al., **2014** *Atmos Environ*;
Stephens, **2015** *Sci Technol Built Environ*

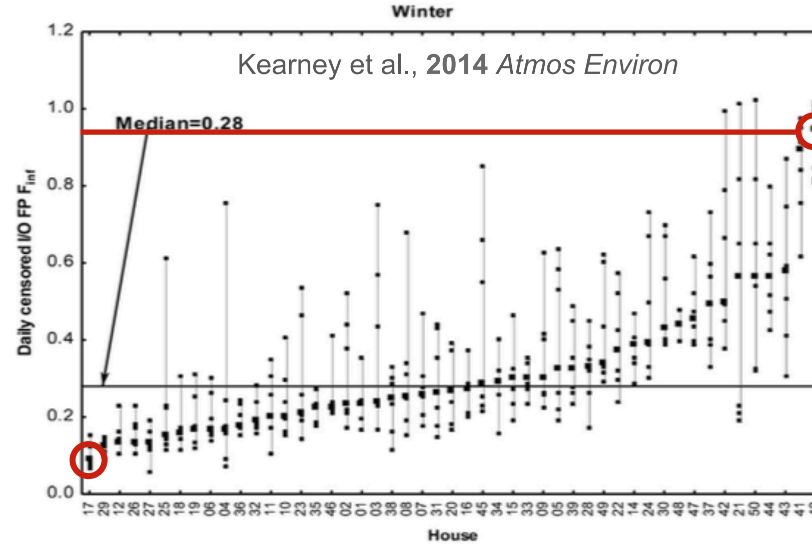
Chen and Zhao, **2011** *Atmos Environ*

Variability in infiltration factors

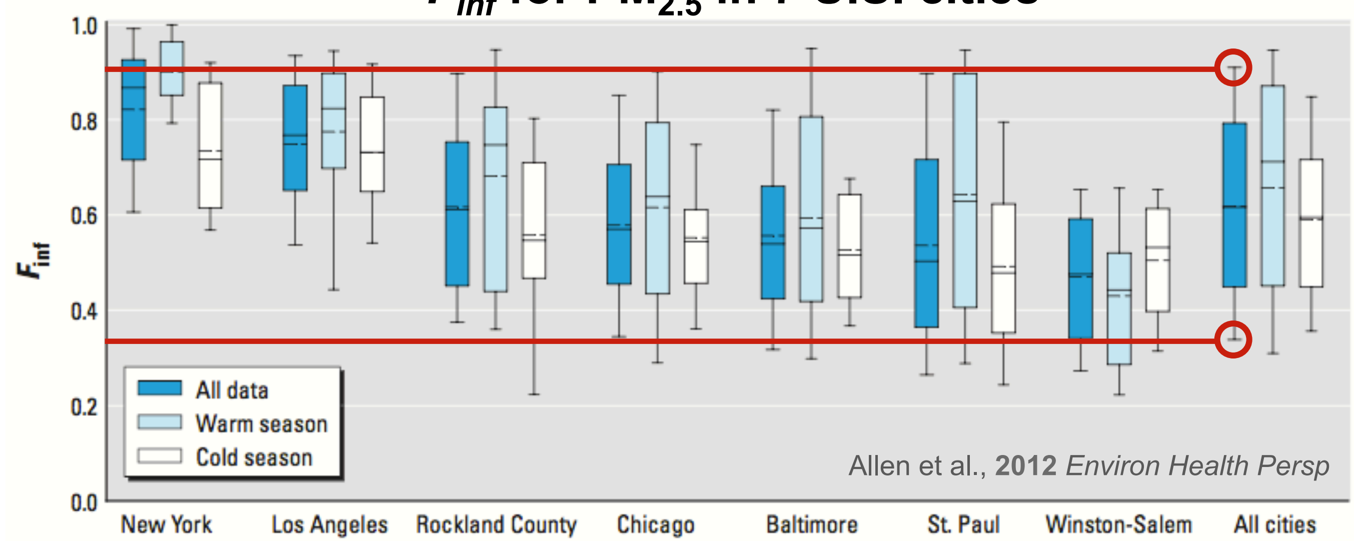
F_{inf} for UFPs in Windsor, ON



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



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



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

Key drivers of variability in infiltration factors

- Source of ventilation air
  - Infiltration (leaks)
  - Mechanical ventilation
  - Natural ventilation
- Human behaviors (e.g., window opening frequencies)
- Magnitude of the air exchange rate (AER)
  - Meteorological conditions
- Sizes/classes/components of PM
- Building characteristics (e.g., airtightness)
- HVAC system design and operation

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*

Indoor exposures to outdoor PM

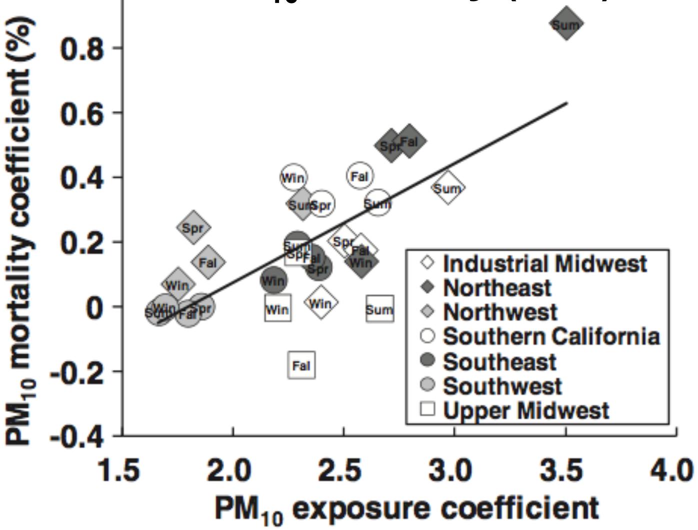
WHAT WE DO NOT KNOW

Or what do we know *less* about?

How does variability in F_{inf} contribute to effect estimates?

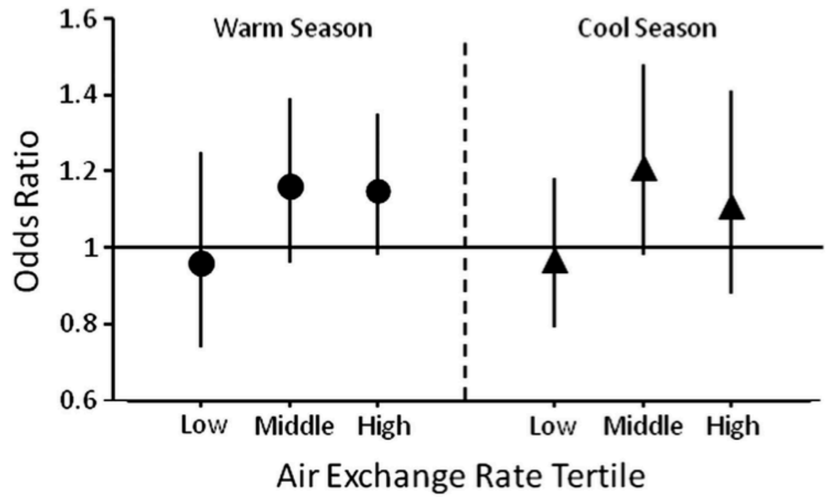
Accounting for variations in AERs and window opening

PM_{10} mortality (U.S.)



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

$PM_{2.5}$ and acute myocardial infarction (NJ)



Hodas et al., **2013** *J Exp Sci Environ Epidem*

$PM_{2.5}$ and ER visits (ATL)

	Low AER (< 0.227 hr^{-1})	Moderate AER (0.228 – 0.308 hr^{-1})	High AER (> 0.309 hr^{-1})
High $PM_{2.5}$ (> 19.2 $\mu g/m^3$)	1.056 (1.019 – 1.095)	1.018 (0.977 – 1.060)	1.021 (0.981 – 1.063)
Moderate $PM_{2.5}$ (13.4 – 19.1 $\mu g/m^3$)	1.031 (0.995 – 1.068)	1.040 (1.003 – 1.079)	1.043 (1.005 – 1.083)
Low $PM_{2.5}$ (< 13.3 $\mu g/m^3$)	1.000 (NA)	1.022 (0.986 – 1.059)	1.044 (1.009 – 1.081)

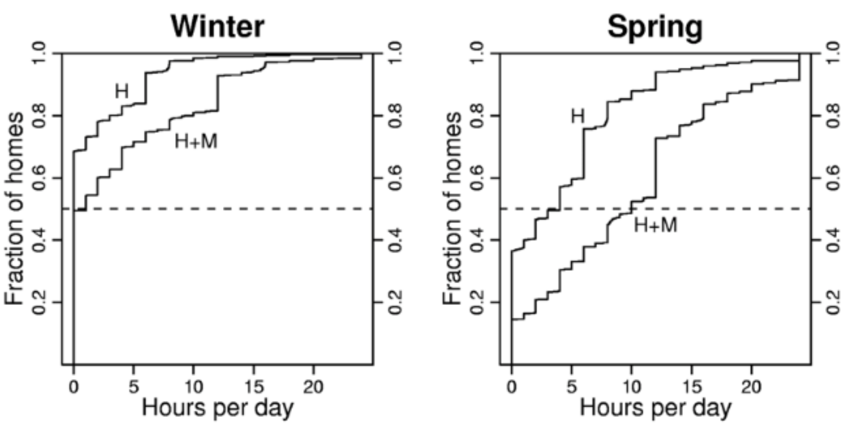
Sarnat et al., **2013** *J Exp Sci Environ Epidem*

Window opening frequencies and impact on AER

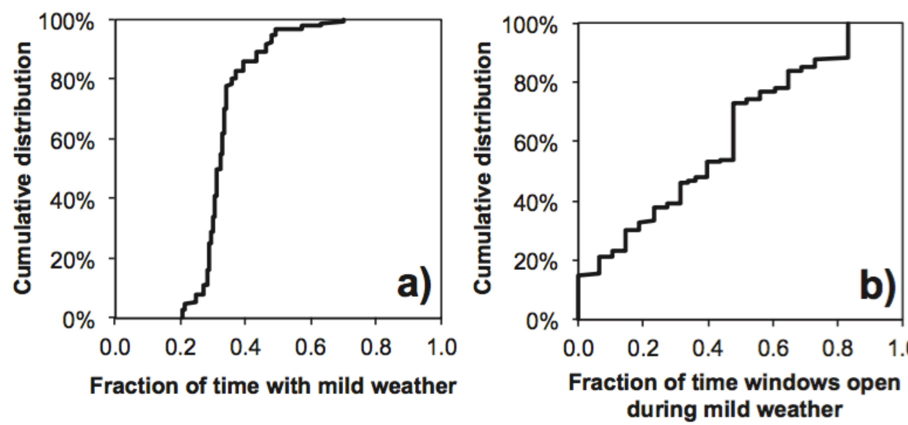
Determining the frequency of open windows in residences: a pilot study in Durham, North Carolina during varying temperature conditions

Category	Classification	Number of surveyed residences	Percentage of total surveyed residences	Percent of surveyed residences with one or more open windows or doors		
				Visit A	Visit B	Weighted average
Housing type	Detached one story	521	47.4	30.5	31.1	30.8
	Detached multistory	351	31.9	26.8	27.1	27.0
	Detached split level	83	7.5	22.9	32.5	27.7

Johnson and Long, **2005** *J Expo Anal Environ Epidem*



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



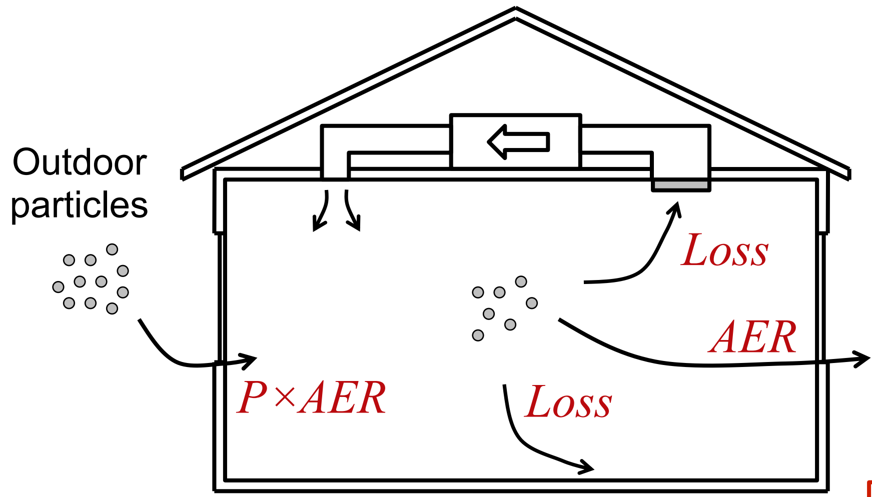
El Orch et al., **2014** *Build Environ*

Limited data on **air exchange rate multipliers** with open windows:

- Typically ~2-4 times higher, depending on area of openings, I/O ΔT

Marr et al., **2012** *HVAC&R Research*; Wallace et al., **2002** *J Expo Anal Environ Epidem*; Johnson et al., **2004** *J Expo Anal Environ Epidem*; Chen et al., **2012** *Epidemiology*

Underlying mechanisms that govern F_{inf}



Penetration from outdoors

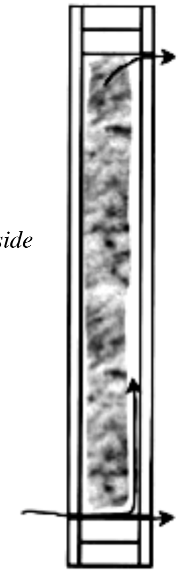
$$F_{inf} = \frac{P \times AER}{AER + Loss}$$

Removal by air exchange

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

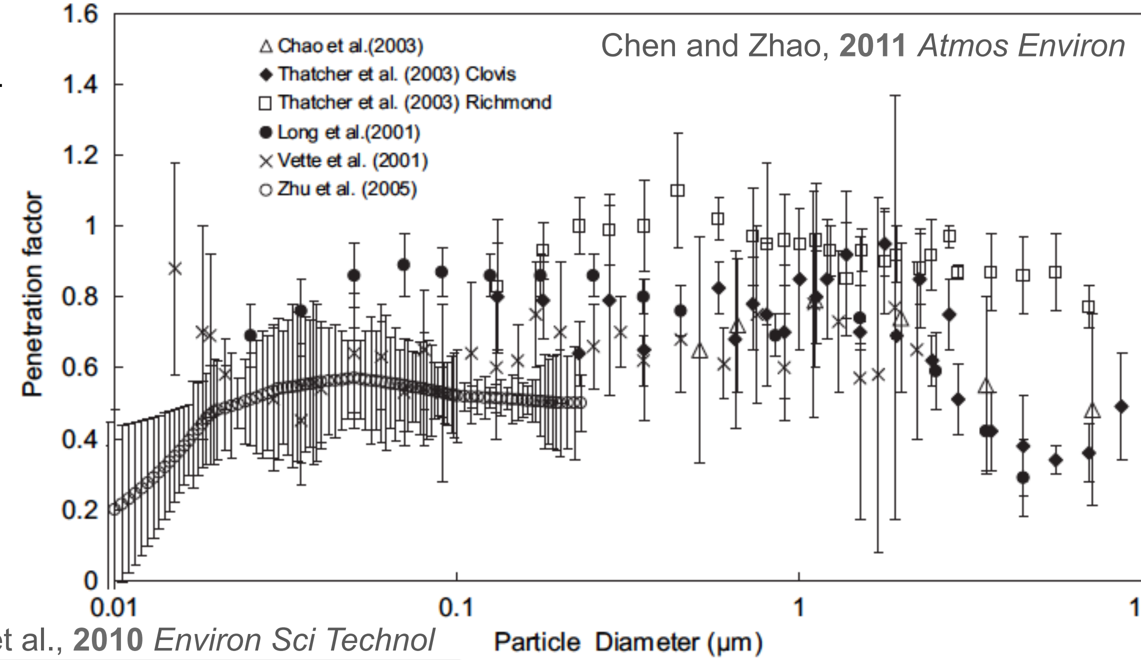
"Penetration Factor"
If *P* = 1:
The envelope offers no protection
If *P* = 0:
The envelope offers complete protection

Envelope penetration factors



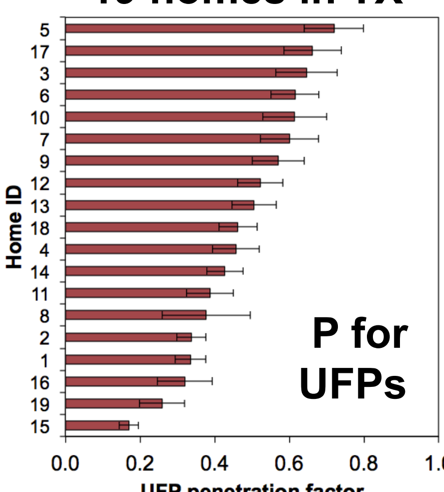
$$P_{envelope} = \frac{C_{inside}}{C_{outside}}$$

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



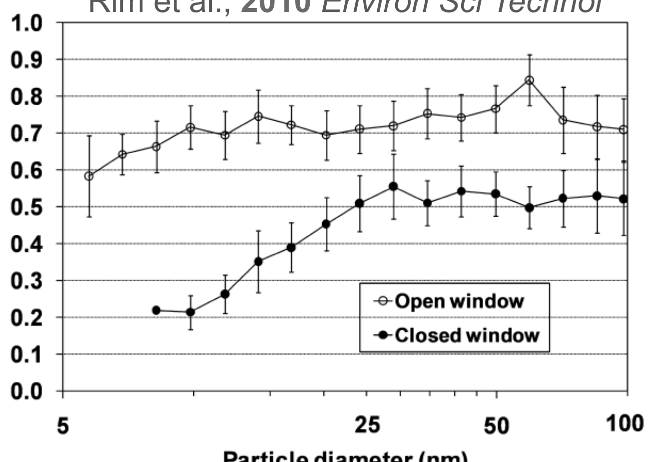
Chen and Zhao, **2011** *Atmos Environ*

19 homes in TX



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

Rim et al., **2010** *Environ Sci Technol*



# of homes with penetration factors measured:
Size-resolved PM: < 20 homes
UFPs: ~30-50 homes
$PM_{2.5}$: *estimated* in 100s of homes
- But seldom (never?) *measured*

Other unknowns (or less knowns)

- Associations between F_{inf} (or P) and building characteristics
  - Some evidence of associations w/ AC usage, year of construction, and envelope airtightness
  - How do they change after building retrofits?

Allen et al., **2012** *EHP*; MacNeill et al., **2012** *Atmos Environ*; Stephens and Siegel **2012** *Indoor Air*

- Chemical transformations
  - e.g. evaporative losses

Hodas et al., **2014** *Aerosol Sci Technol*

- High spatial- and temporal-resolution data for:
  - Outdoor particle size distributions
  - Outdoor size-resolved aerosol composition

Summary of outdoor → indoor PM transport research needs

- We need more integration between epidemiologists and exposure scientists
  - Address exposure misclassification
  - Improve health effect estimates

- We need more data on window opening frequencies and their impact on air exchange rates

- We need more field measurements of size-resolved, UFP, and $PM_{2.5}$ penetration factors
  - And explorations of associations with building characteristics

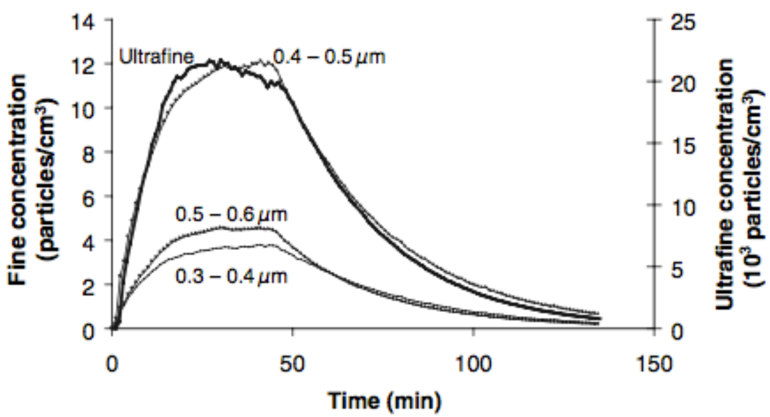
INDOOR PM SOURCES

Specifically: Non-combustion appliances

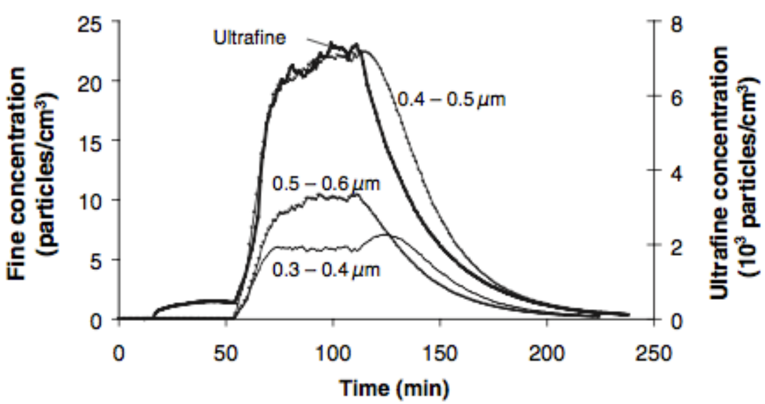
Non-combustion appliances as indoor PM sources

- Several (non-combustion) appliances emit PM indoors
  - Mostly in the UFP size range

Vacuum cleaner full bag

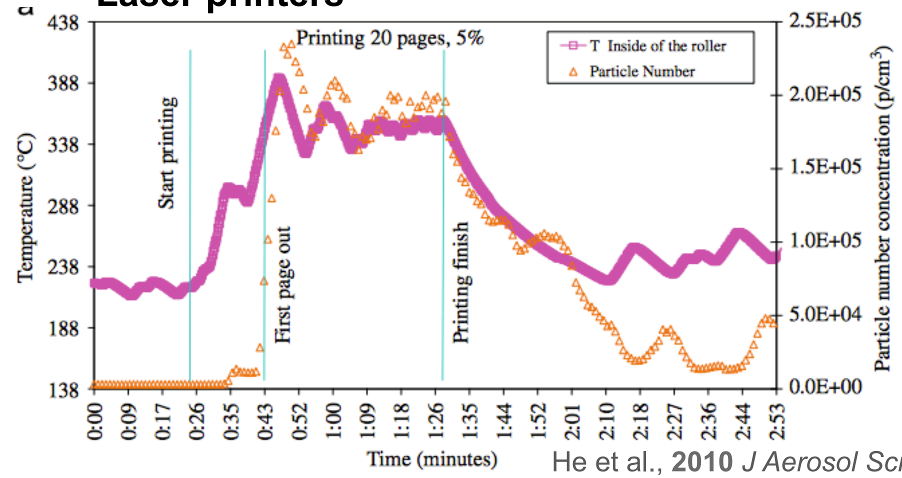


Ironing with steam



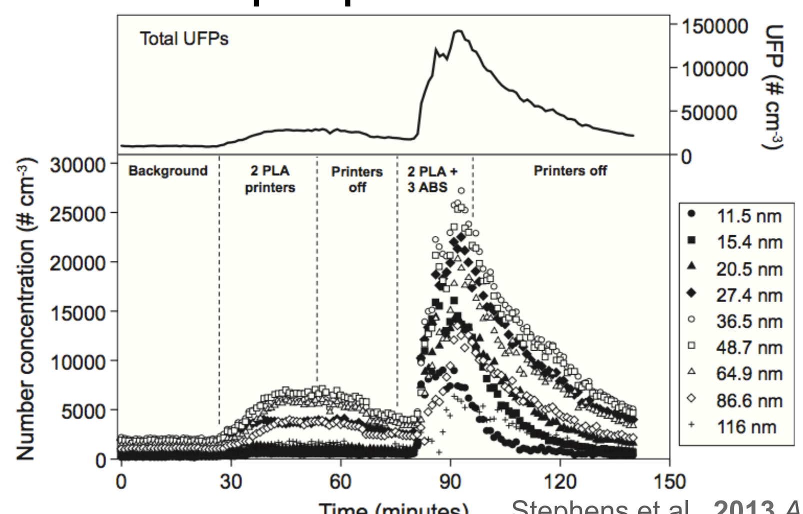
Afshari et al., **2005** *Indoor Air*

Laser printers



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

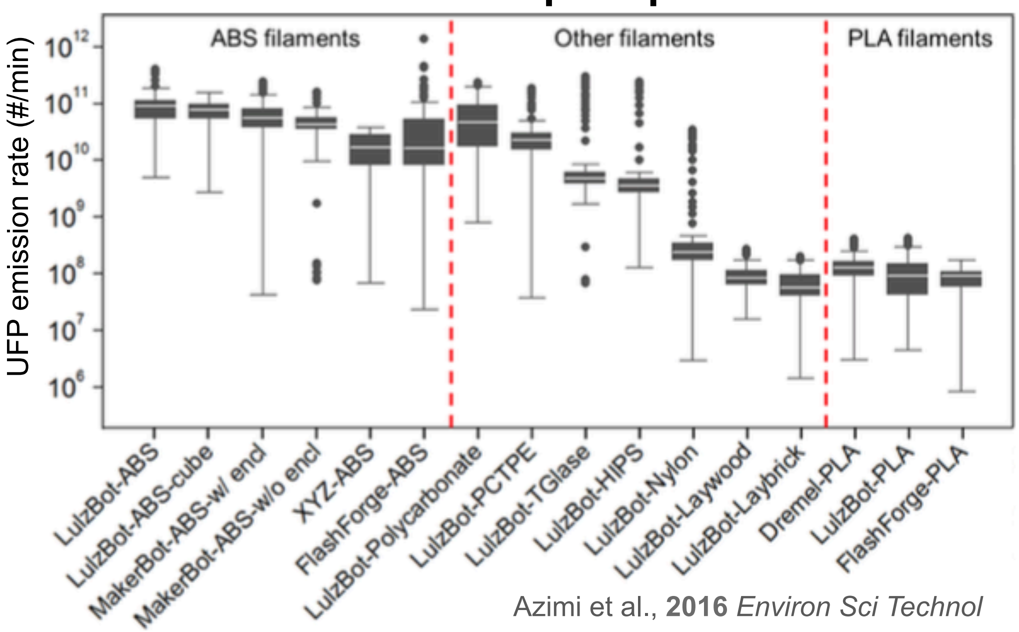
Desktop 3D printers

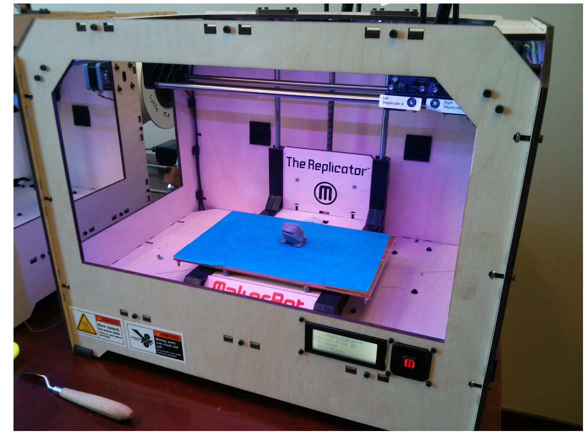


Stephens et al., **2013** *Atmos Environ*

Non-combustion appliances as indoor PM sources

More desktop 3D printers

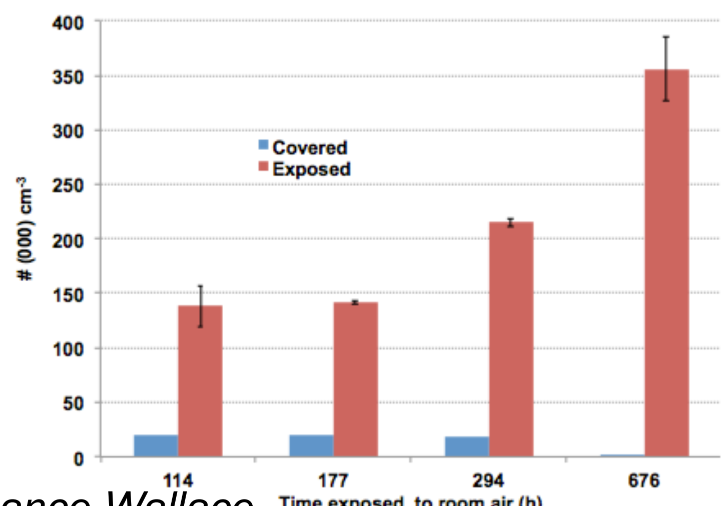




Azimi et al., **2016** *Environ Sci Technol*

Heated surfaces

Wallace **2015** *ISES Conference*



Procedure:
Wash, expose to indoor air, burn until UFP reaches zero

Proposed mechanisms:
1. Deposition of material on surface
2. Desorption of SVOCs on the heated surface
3. Followed by nucleation and particle growth in cooler air

Wallace et al., **2015** *Indoor Air*

Heated surfaces figures by Lance Wallace

Typical indoor UFP emission rates

UFP emitting device	Size range	Emission rate (#/min)	Reference
Flat iron with steam	20-1000 nm	6.0×10^{9}	Afshari et al. (2005)
Electric frying pan	10-400 nm	$1.1\text{-}2.7\times10^{10}$	Buonnano et al. (2009)
3D printer w/ PLA	10-100 nm	$\sim2.0\times10^{10}$	Stephens et al. (2013)
Vacuum cleaner	20-1000 nm	3.5×10^{10}	Afshari et al. (2005)
Scented candles	20-1000 nm	8.8×10^{10}	Afshari et al. (2005)
Gas stove	20-1000 nm	1.3×10^{11}	Afshari et al. (2005)
3D printer w/ ABS	10-100 nm	$\sim1.9\times10^{11}$	Stephens et al. (2013)
Cigarette	20-1000 nm	3.8×10^{11}	Afshari et al. (2005)
Electric stove	20-1000 nm	6.8×10^{11}	Afshari et al. (2005)
Frying meat	20-1000 nm	8.3×10^{11}	Afshari et al. (2005)
Radiator	20-1000 nm	8.9×10^{11}	Afshari et al. (2005)
Desktop 3D printers	10-100 nm	$\sim10^{8}$ to $\sim10^{12}$	Azimi et al. (2016)
Laser printers	6-3000 nm	4.3×10^{9} to 3.3×10^{12}	He et al. (2010)
Cooking on a gas stove	10-400 nm	$1.1\text{-}3.4\times10^{12}$	Buonnano et al. (2009)

Items in red are **non-combustion sources**
Items in black are combustion-related

Summary of (non-combustion) appliance emissions

- We continue to find new indoor sources of PM
  - Mostly UFPs
- We need to continue to gather emission rate data for these and other sources
  - Including size-resolved emission rate data
- We need to continue to explore source control and exposure mitigation strategies