

# Energy and air quality in the built environment

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Civil, Architectural and Environmental Engineering



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research within the built environment  
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# What do you think of when you hear “energy”?

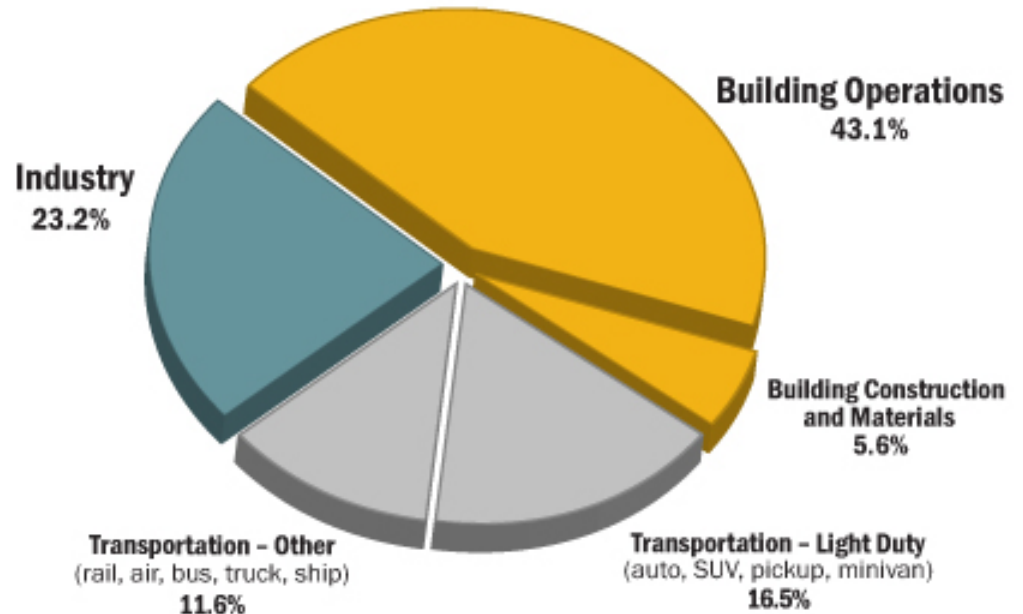




# What do I think of when I hear “energy”?



**Buildings**

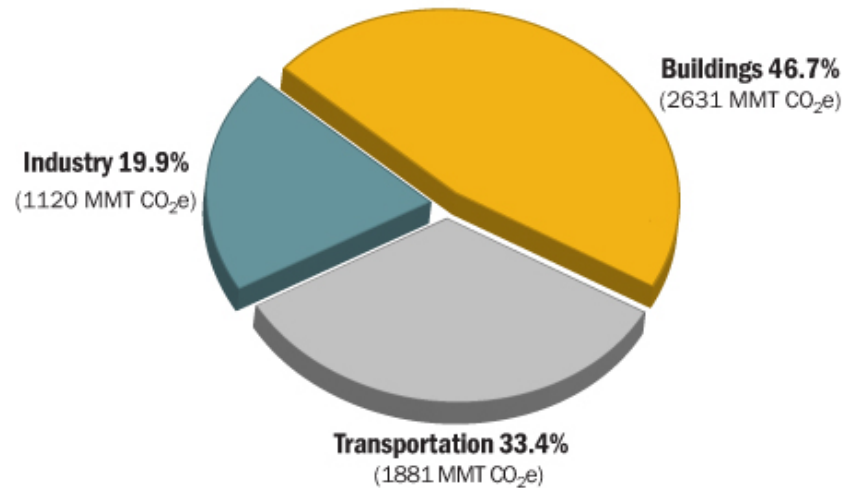


**Buildings account for ~43-48% of total U.S. energy consumption**

Buildings in the U.S. account for ~7% of the total amount of energy used in the **world**

# Buildings account for *a lot* of GHG and pollutant emissions

## Contribution to GHGs



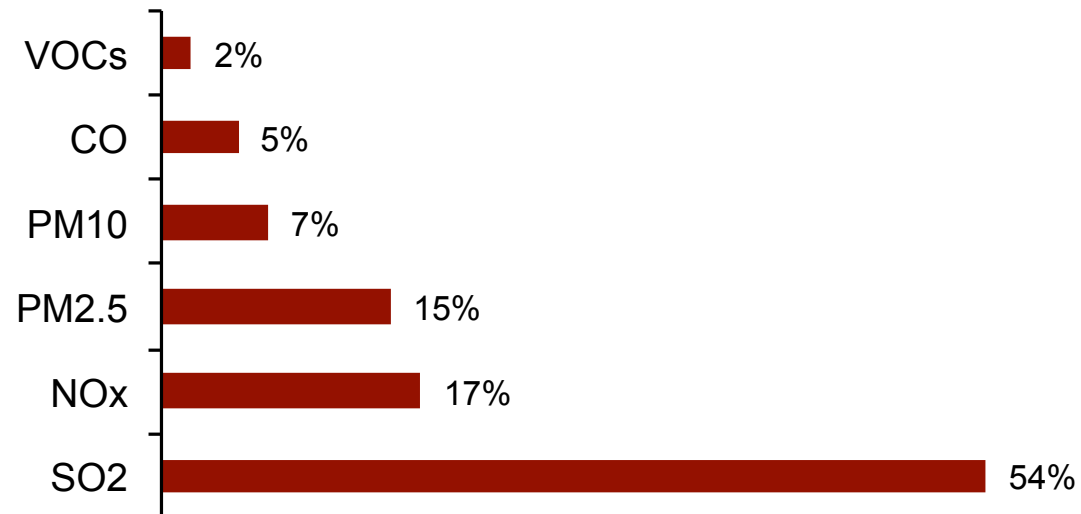
### U.S. CO<sub>2</sub> Emissions by Sector

Source: ©2011 2030, Inc. / Architecture 2030. All Rights Reserved.  
Data Source: U.S. Energy Information Administration (2011).

## Major uses

- Heating
- Cooling
- Lighting
- Water heating

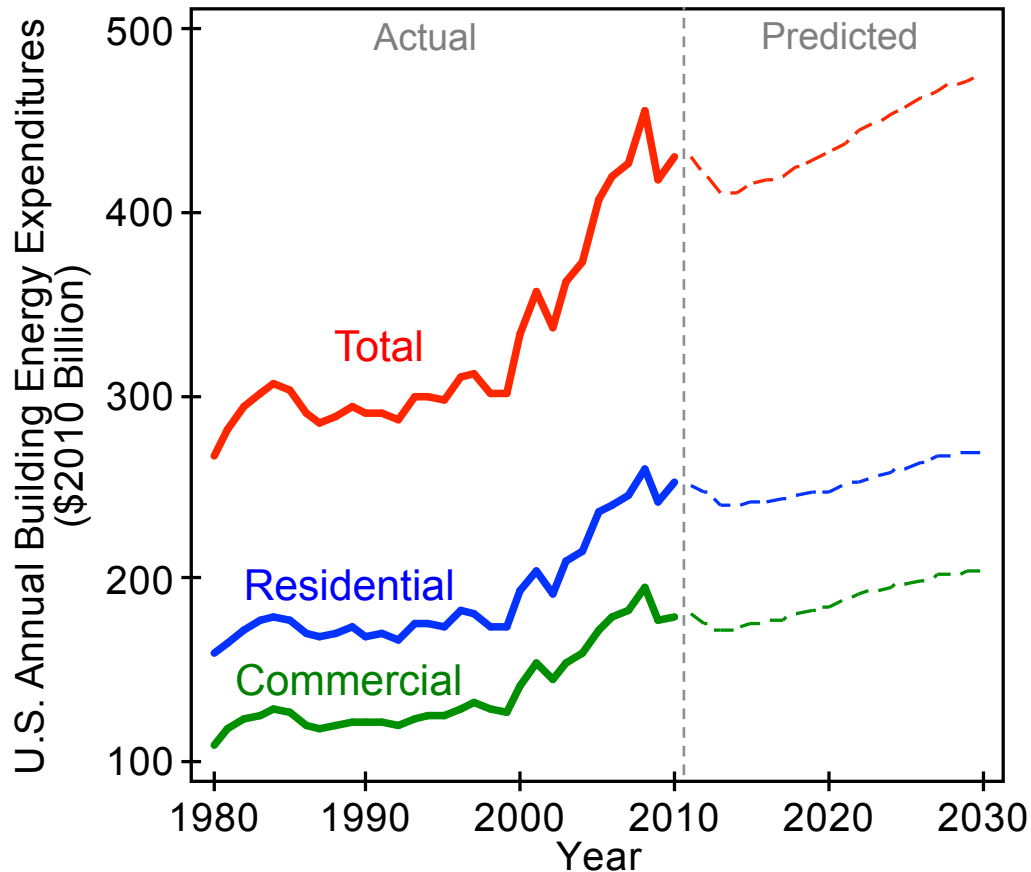
## Contribution to outdoor air pollution



Percent contribution by U.S. buildings

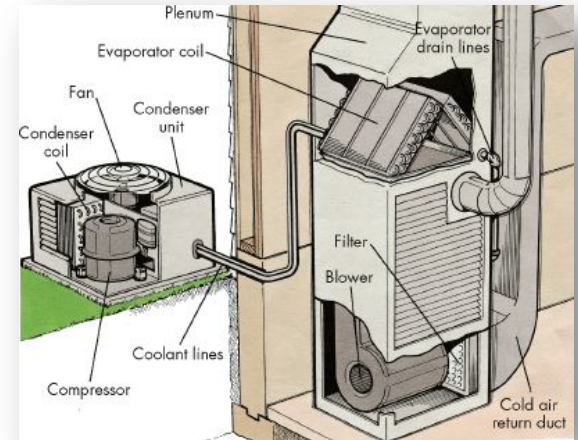


# Building energy use costs *a lot* of money



U.S. building energy expenditures totaled  
~\$430 billion in 2010

Approximately 3% of our GDP



Approximately 1/3 of  
building energy use is for  
space conditioning  
~1% of our GDP is spent on  
heating and cooling  
buildings

What do you think of when you hear “**air pollution**”?





# What do I think of when I hear “**air pollution**”?



## **Formaldehyde and Other Volatile Organic Chemical Emissions in Four FEMA Temporary Housing Units**

Maddalena et al., *Environ. Sci. Technol.* **2009**, 43, 5626-5632



## **Formaldehyde in the Indoor Environment**

Salthammer et al., *Chem. Rev.* **2010**, 110, 2536-2572

## **Emission Rates of Formaldehyde from Materials and Consumer Products Found in California Homes**

Kelly et al., *Environ. Sci. Technol.* **1999**, 33, 81-88

# What do I think of when I hear “**air pollution**”?

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## **Association between gas cooking and respiratory disease in children**

Melia et al., *British Medical Journal* **1977**, 2, 149-152

## **Indoor Air Pollution and Asthma**

Ostro et al., *Am. J. Respir. Crit. Care. Med.* **1994**, 149, 1400-1406

## **Respiratory Symptoms in Children and Indoor Exposure to Nitrogen Dioxide and Gas Stoves**

Garrett et al., *Am. J. Respir. Crit. Care. Med.* **1998**, 158, 891-895

## **Pollutant Exposures from Natural Gas Cooking Burners**

Logue et al., *Environ Health Perspect.* **2014**, 122, 43-50



## **Association of domestic exposure to volatile organic compounds with asthma in young children**

Rumchev et al., *Thorax* **2004**, 59, 746-751



# What do I think of when I hear “**air pollution**”?

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Cleaning products and air fresheners:  
exposure to primary and secondary air pollutants

Nazaroff and Weschler, *Atmos Environ.* **2004**, 38, 2841-2865

Frequent use of chemical household products is associated  
with persistent wheezing in pre-school age children

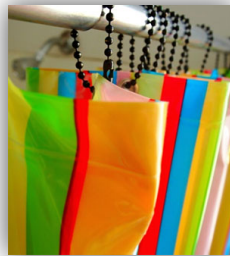
Sherriff et al., *Thorax* **2005**, 60, 45-49

## **The Use of Household Cleaning Sprays and Adult Asthma**

Zock et al., *Am. J. Respir. Crit. Care. Med.* **2007**, 176, 735-741

# What do I think of when I hear “**air pollution**”?

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## **The Association between Asthma and Allergic Symptoms in Children and Phthalates in House Dust: A Nested Case–Control Study**

Bornehag et al., *Environ. Health Perspect.* **2004**, 112, 1393-1397



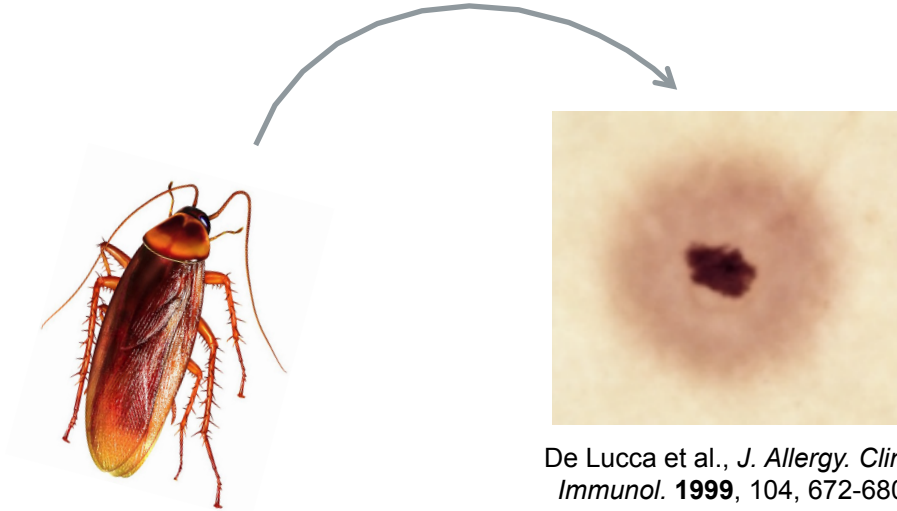
## **Intellectual Impairment in Children with Blood Lead Concentrations below 10 $\mu\text{g}$ per Deciliter**

Canfield et al., *New Engl. J. Med.* **2003**, 348, 1517-1526



# What do I think of when I hear “**air pollution**”?

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De Lucca et al., *J. Allergy. Clin. Immunol.* **1999**, 104, 672-680

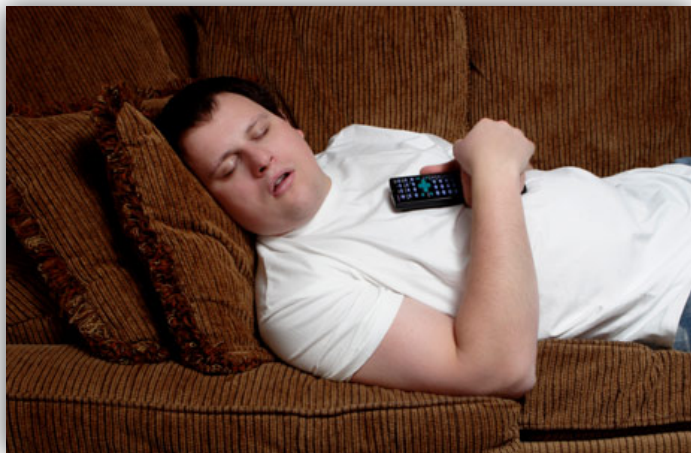
## THE ROLE OF COCKROACH ALLERGY AND EXPOSURE TO COCKROACH ALLERGEN IN CAUSING MORBIDITY AMONG INNER-CITY CHILDREN WITH ASTHMA

Rosenstreich et al., *New Engl. J. Med* **1997**, 336, 1356-1363

## Relationship of indoor allergen exposure to skin test sensitivity in inner-city children with asthma

Eggleston et al., *J. Allergy. Clin. Immunol.* **1998**, 102, 563-570

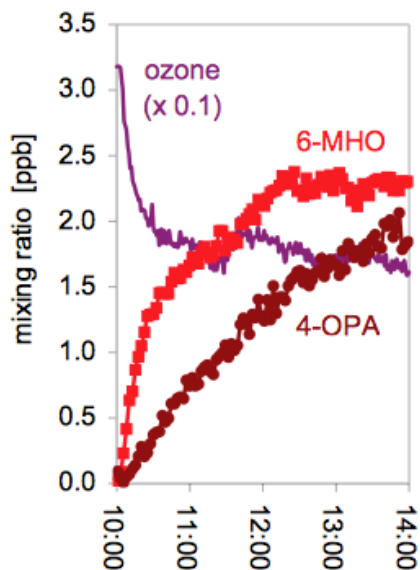
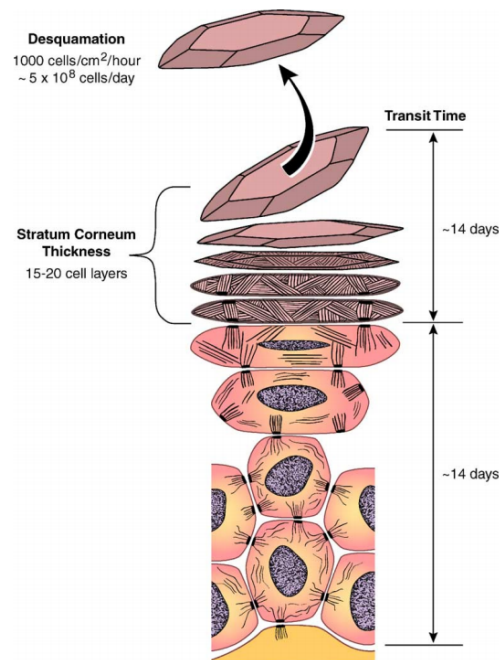
# What do I think of when I hear “**air pollution**”?



## Epidermal desquamation

Milstone, *J. Dermatol. Sci.* **2004**, 36, 131-140

We shed our entire outer layer of skin every 2-4 weeks



Reactions of ozone with human skin lipids:  
Sources of carbonyls, dicarbonyls,  
and hydroxycarbonyls in indoor air

Wisthaler and Weschler, *Proc Nat Acad Sci.* **2010**, 107, 6568-6575

# What do I think of when I hear “**air pollution**”?

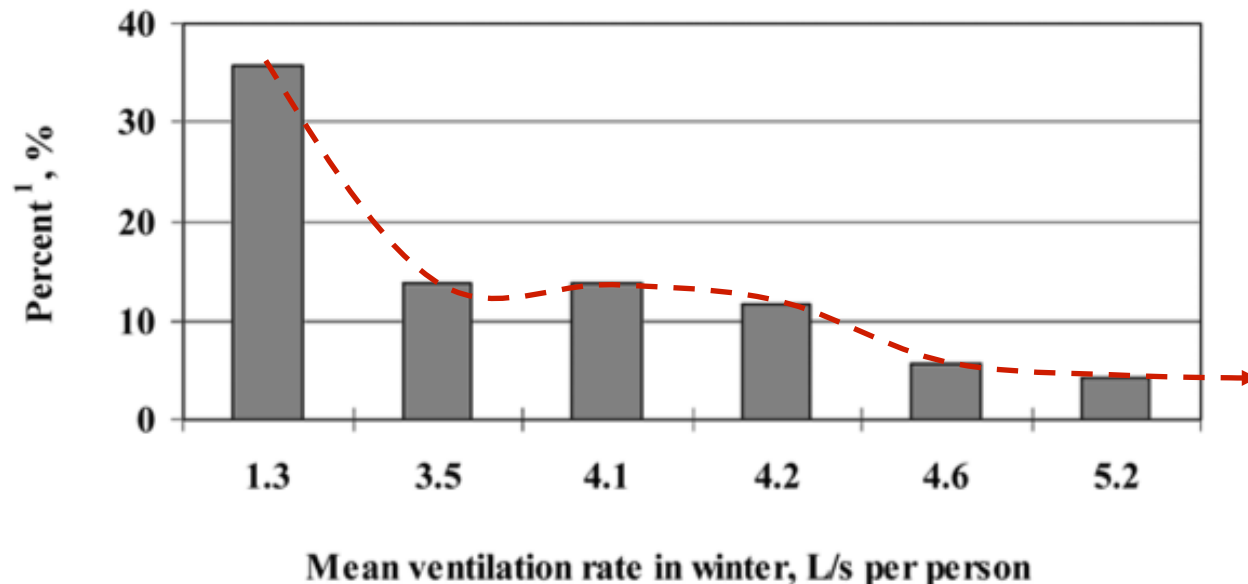


## Evidence of Airborne Transmission of the Severe Acute Respiratory Syndrome Virus

Yu et al., *New Engl. J. Med* **2004**, 350, 1731-1739

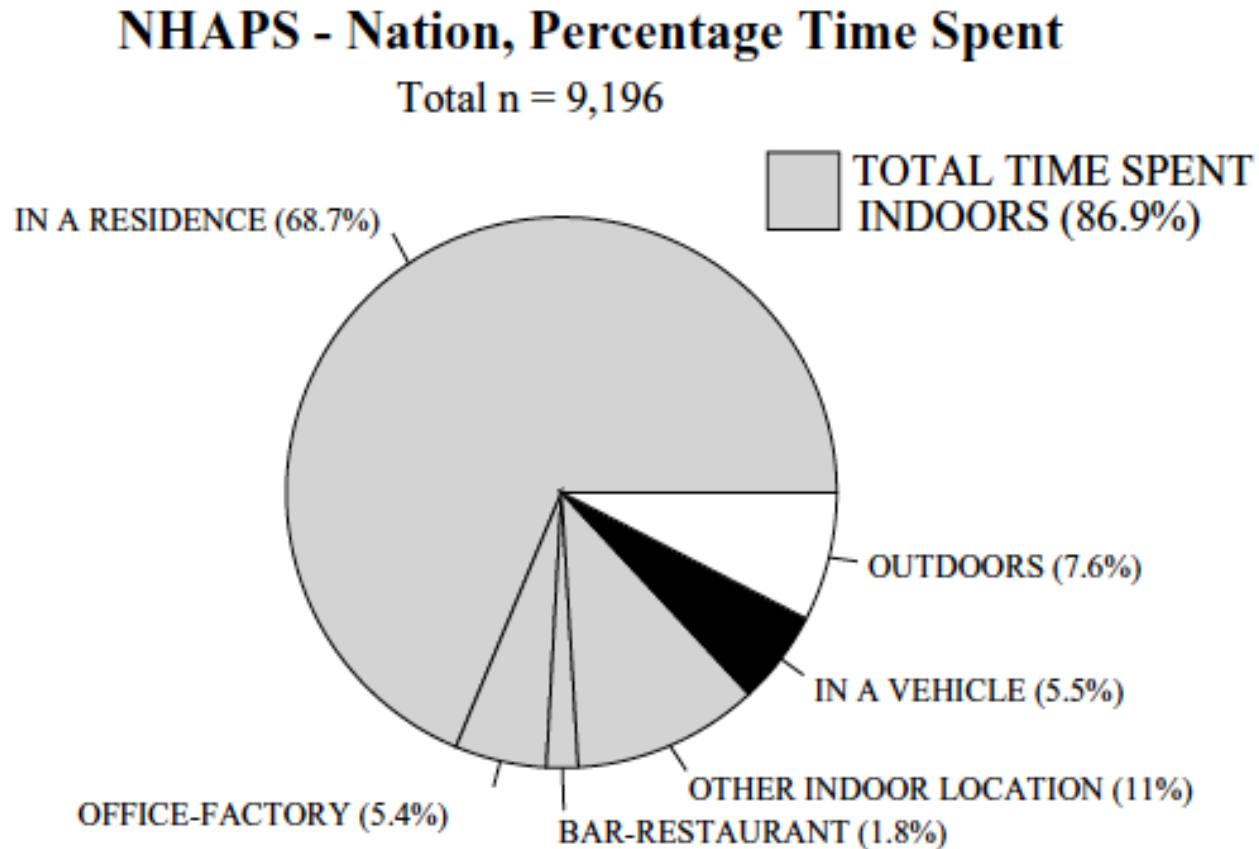
## In China, Students in Crowded Dormitories with a Low Ventilation Rate Have More Common Colds: Evidence for Airborne Transmission

Sun et al. **2011** *PLoS ONE* 6:e27140





# We spend *a lot* of our time in buildings



- Americans spend almost 90% of their time indoors
  - 75% at home or in an office

Klepeis et al., *J Exp. Anal. Environ. Epidem.* 2001, 11, 231-252

# Buildings impact people, energy, and the environment

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The design, construction, and operation of buildings, including their **heating, ventilation, and air-conditioning (HVAC) systems and building envelopes**, greatly affect their contribution to **energy** use, greenhouse gas **emissions**, financial **expenditures**, and human **exposures** to airborne pollutants in the indoor **environment**

My **Built Environment Research Group** at IIT is dedicated to investigating problems and solutions related to energy and air quality within the built environment

Read more online: <http://built-envi.com>

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*Advancing energy, environmental, and  
sustainability research within the built environment*

IIT Armour College  
of Engineering



ILLINOIS INSTITUTE OF TECHNOLOGY



# Highlights of some recent research topics

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1. Indoor exposures to outdoor pollutants
2. HVAC filters for reducing airborne infectious disease transmission indoors
3. Building science measurements in the Hospital Microbiome Project
4. Open source building science sensors (OSBSS)
5. Ultrafine particle emissions from desktop 3D printers

# **1. INDOOR EXPOSURES TO OUTDOOR AIR POLLUTION: PARTICULATE MATTER**

# Motivation: Health effects and outdoor PM

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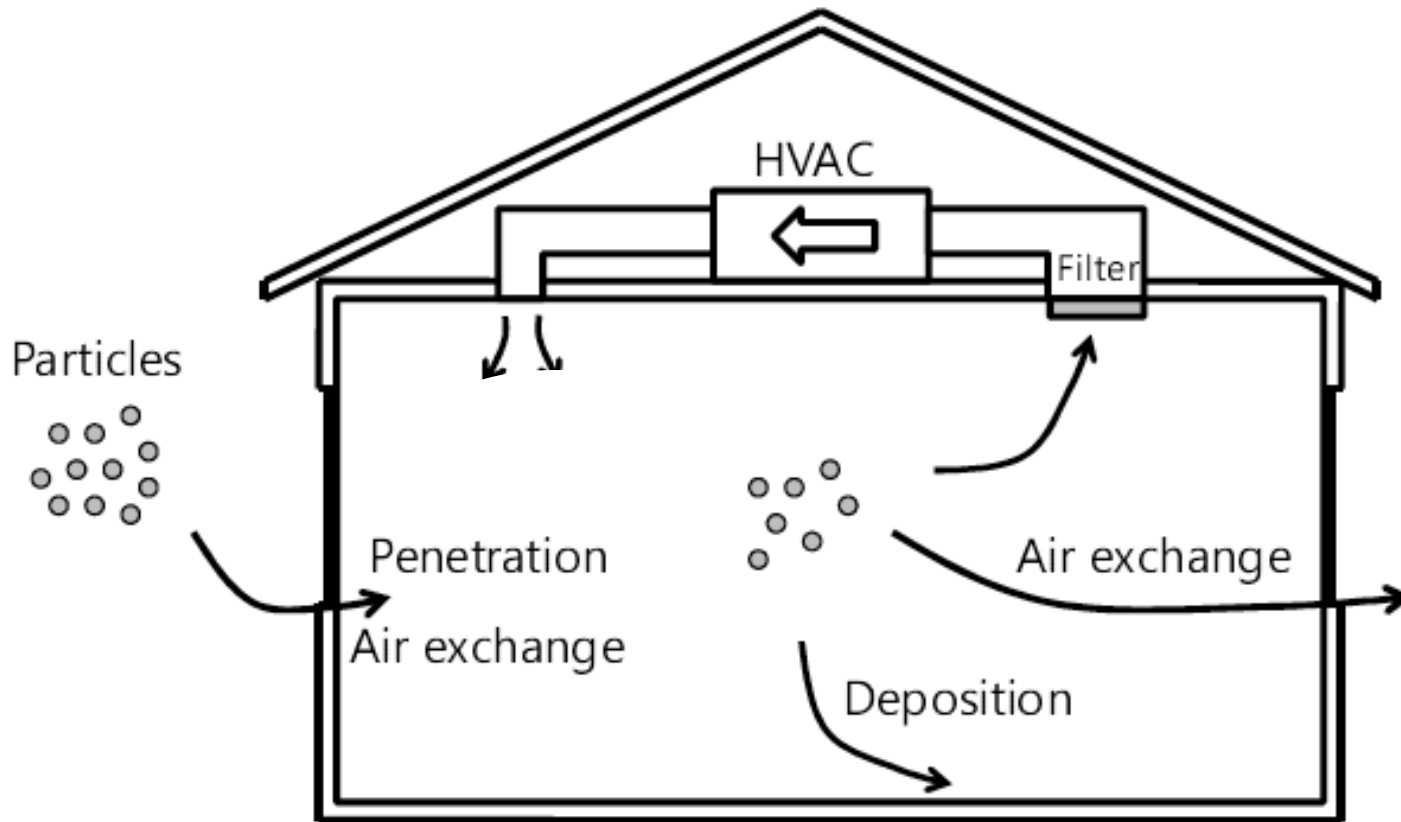
- Epidemiological studies show associations between elevated **outdoor** particulate matter (PM) and adverse health effects

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<sub>10</sub>, PM<sub>2.5</sub>, 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

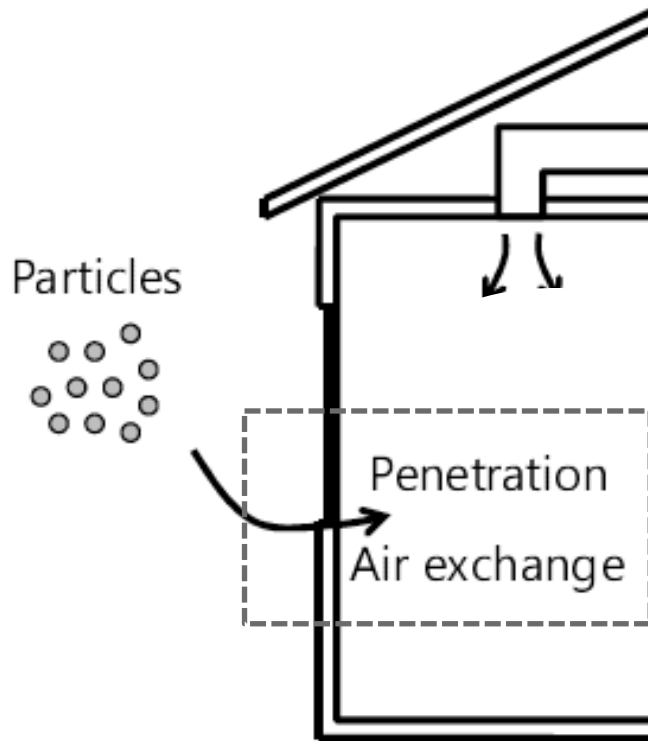


$C_{in}$  = indoor concentration (#/m<sup>3</sup>)  
 $C_{out}$  = outdoor concentration (#/cm<sup>3</sup>)  
 $P$  = penetration factor (-)  
 $\lambda$  = air exchange rate (1/hr)  
 $k$  = surface deposition rate (1/hr)  
 $f$  = fractional HVAC runtime (-)  
 $\eta$  = filter removal efficiency (-)  
 $Q$  = HVAC airflow rate (m<sup>3</sup>/hr)  
 $V$  = indoor air volume (m<sup>3</sup>)

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

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

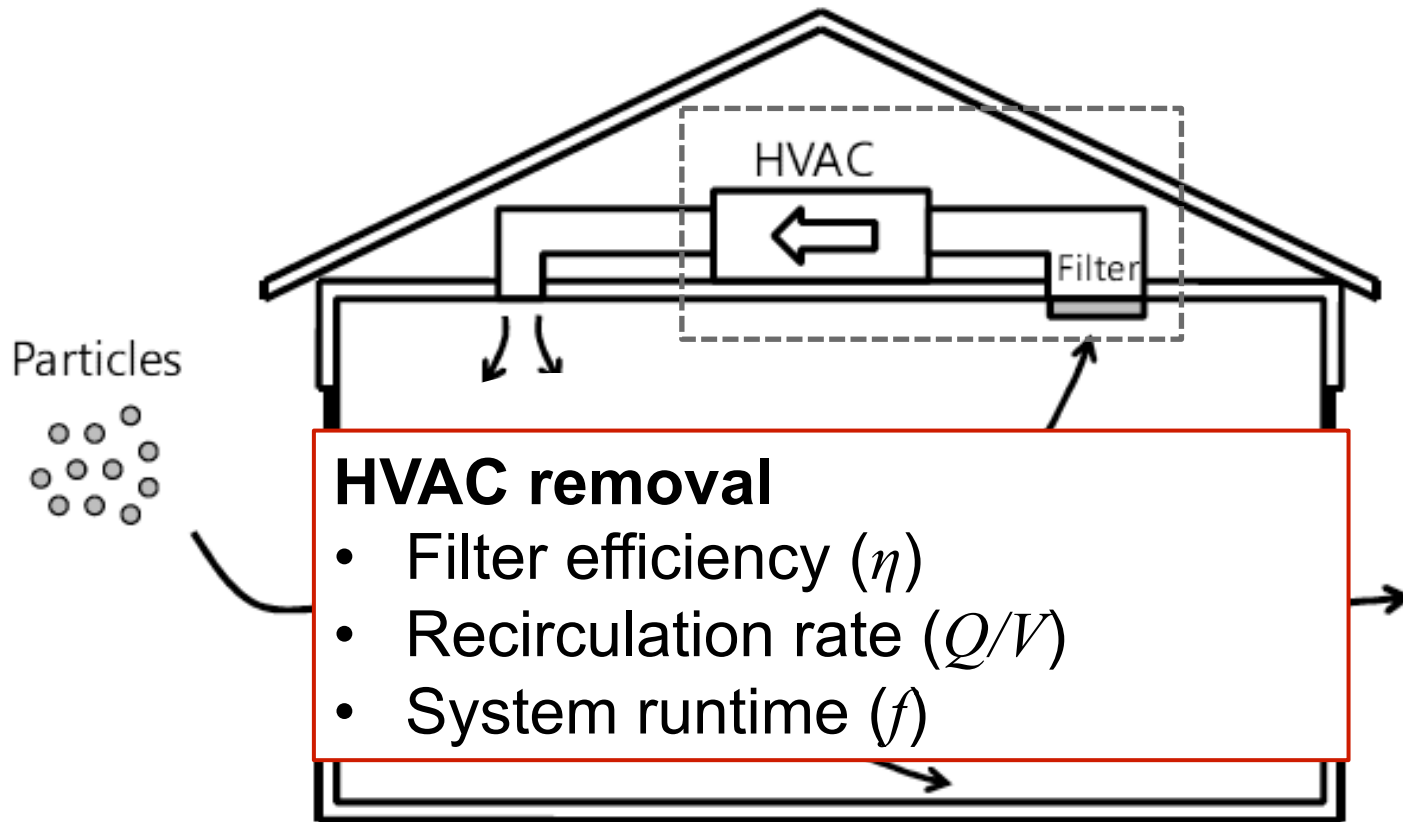
**If  $P = 0$ :**

The envelope offers complete protection

$C_{in}$  = indoor concentration (#/m<sup>3</sup>)  
 $C_{out}$  = outdoor concentration (#/cm<sup>3</sup>)  
 $P$  = penetration factor (-)  
 $\lambda$  = air exchange rate (1/hr)  
 $k$  = surface deposition rate (1/hr)  
 $f$  = fractional HVAC runtime (-)  
 $\eta$  = filter removal efficiency (-)  
 $Q$  = HVAC airflow rate (m<sup>3</sup>/hr)  
 $V$  = indoor air volume (m<sup>3</sup>)

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

# Mechanisms that impact indoor exposures to outdoor PM



## HVAC removal

- Filter efficiency ( $\eta$ )
- Recirculation rate ( $Q/V$ )
- System runtime ( $f$ )

$C_{in}$  = indoor concentration ( $\#/m^3$ )  
 $C_{out}$  = outdoor concentration ( $\#/cm^3$ )  
 $P$  = penetration factor (-)  
 $\lambda$  = air exchange rate (1/hr)  
 $k$  = surface deposition rate (1/hr)  
 $f$  = fractional HVAC runtime (-)  
 $\eta$  = 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



# Importance of source and removal mechanisms

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- **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<sub>2.5</sub> and PM<sub>10</sub> 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

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

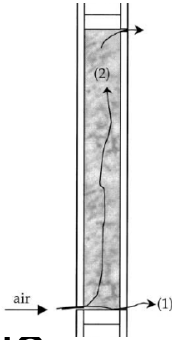
## Key parameters:

- Particle penetration factor,  $P$
  - Air exchange rate,  $\lambda$
  - 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?

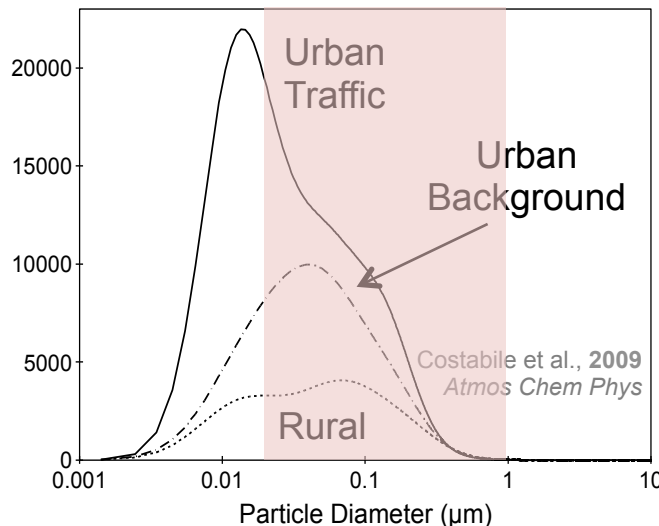
# Measuring particle infiltration

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

Liu and Nazaroff, 2001 *Atmos Environ*



Stephens and Siegel, 2012 *Indoor Air*



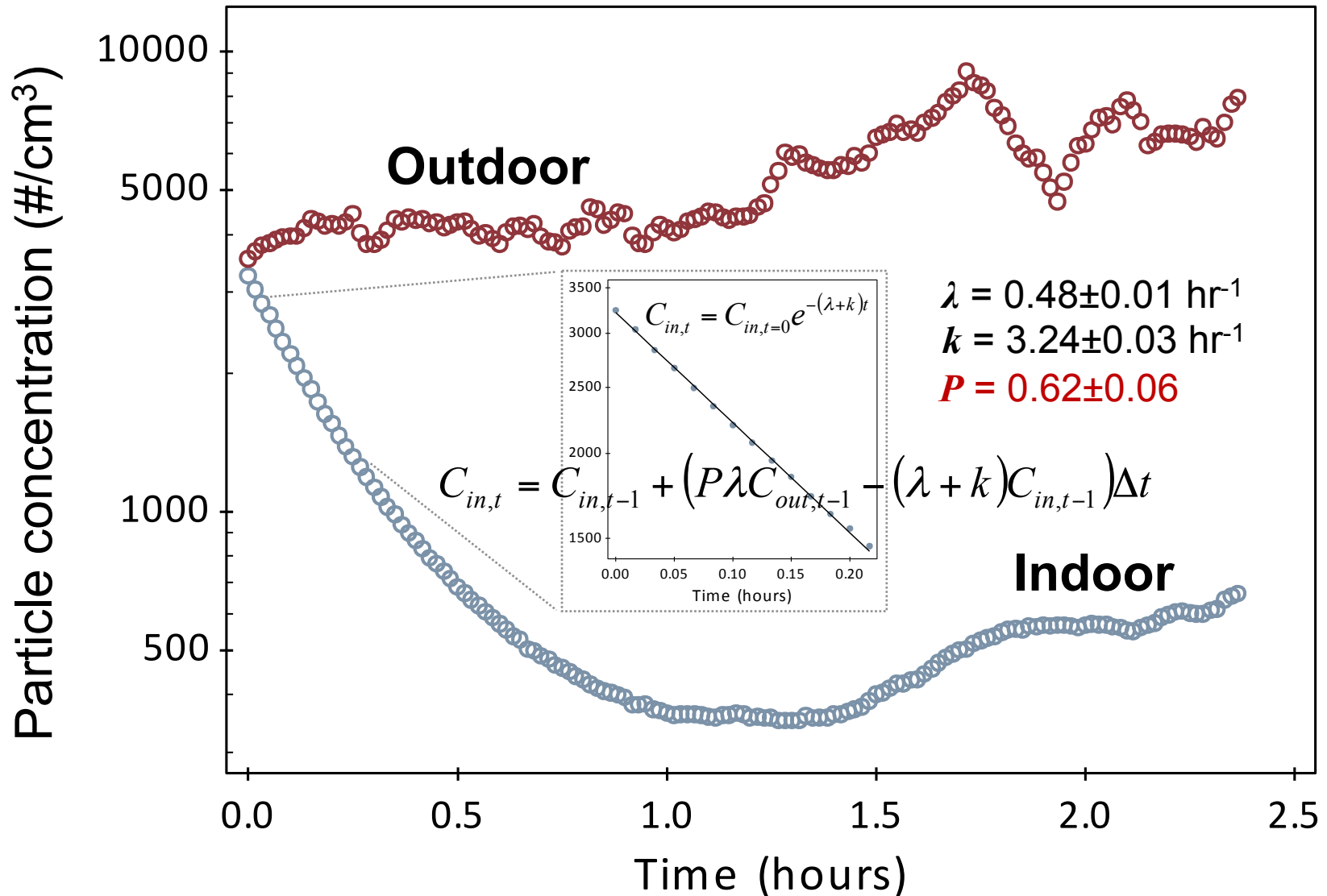
TSI P-Traks  
20 – 1000 nm



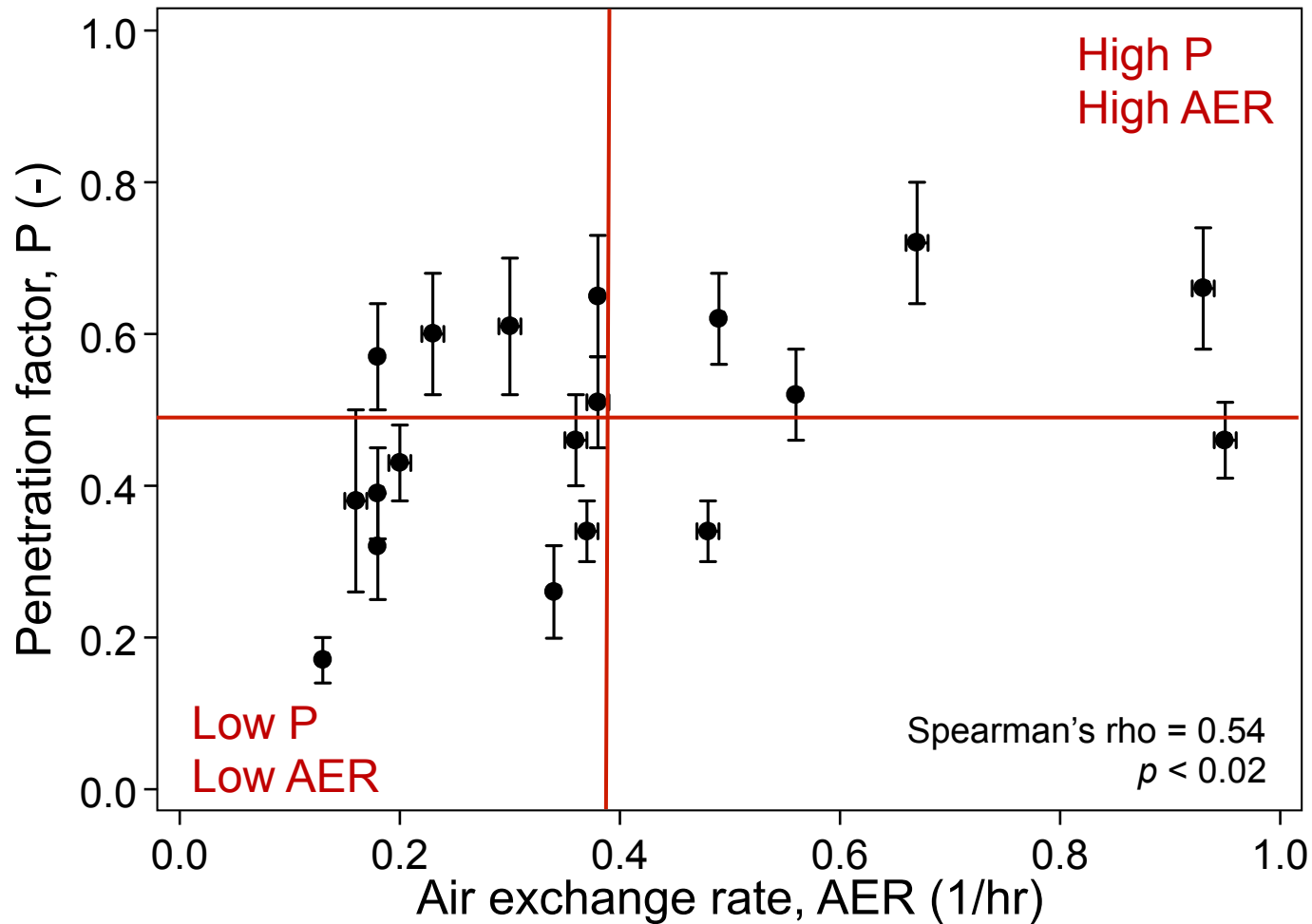
# PM infiltration: Test homes



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



# Particle infiltration results: P and AER



Penetration factors: Mean = 0.47

Range = 0.17 to 0.72

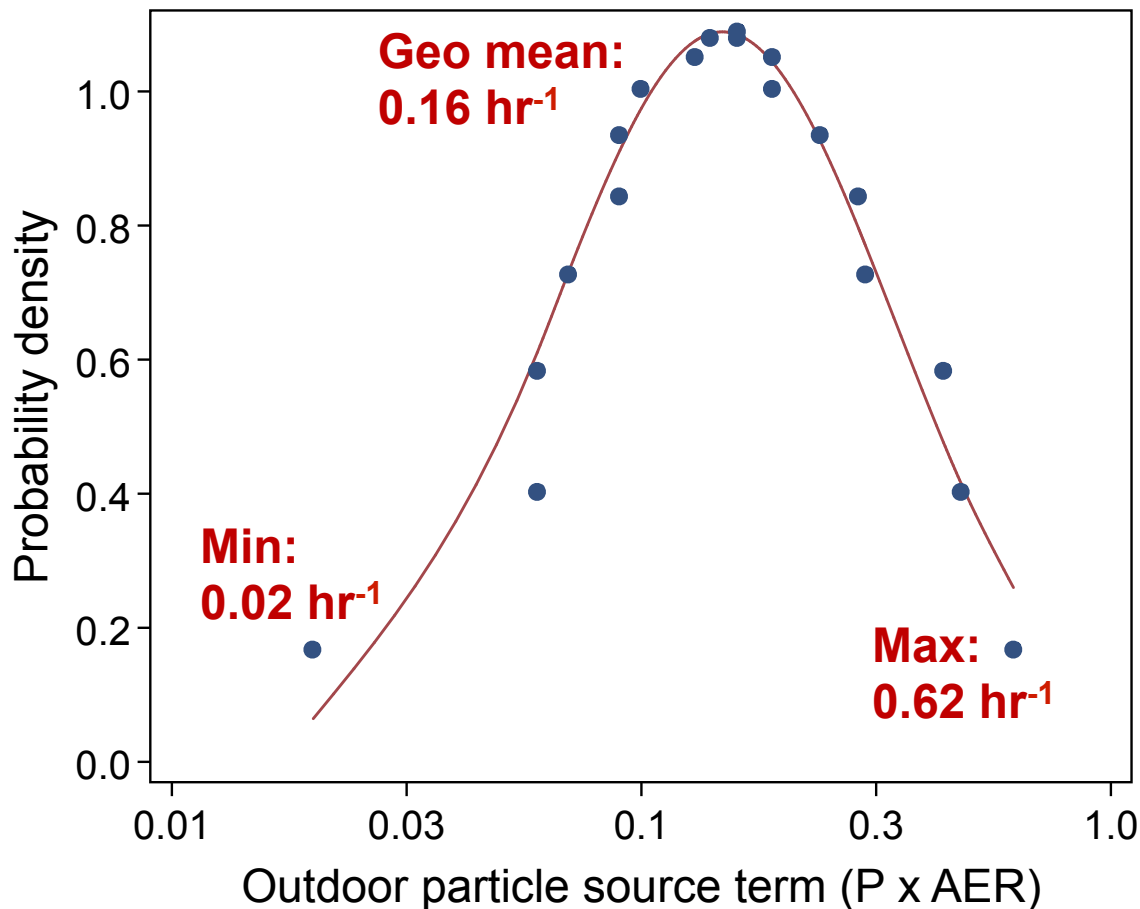
Air exchange rates: Mean = 0.39 hr<sup>-1</sup>

Range = 0.13 to 0.95 hr<sup>-1</sup>



# Outdoor particle source terms: $P \times AER$

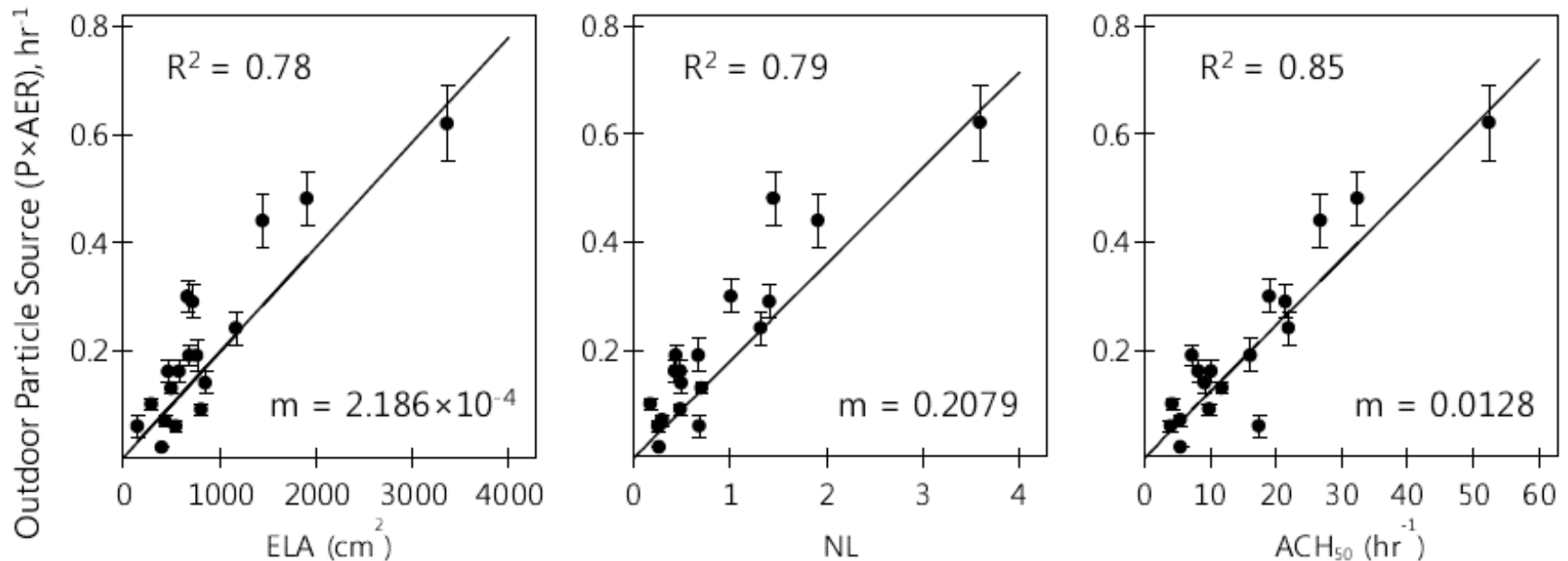
$$\frac{C_{in}}{C_{out}} = \frac{P \times AER}{AER + Loss}$$





# Outdoor particle sources and **envelope air tightness**

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



**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*

# 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



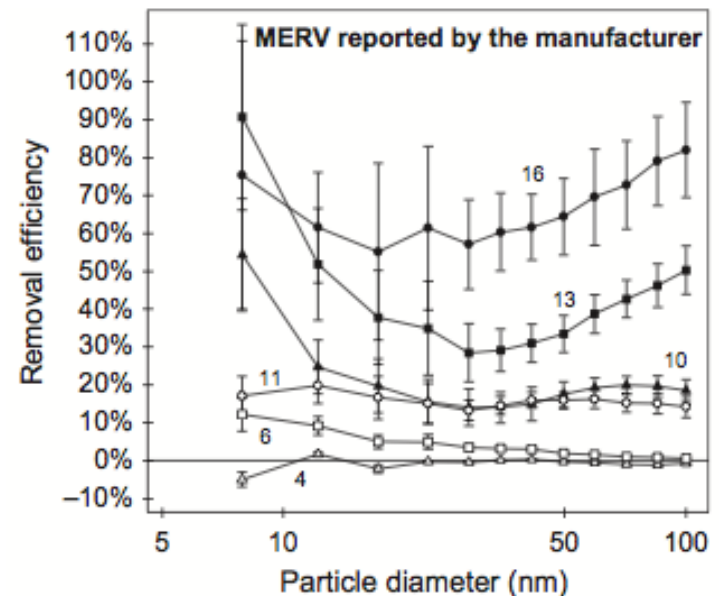
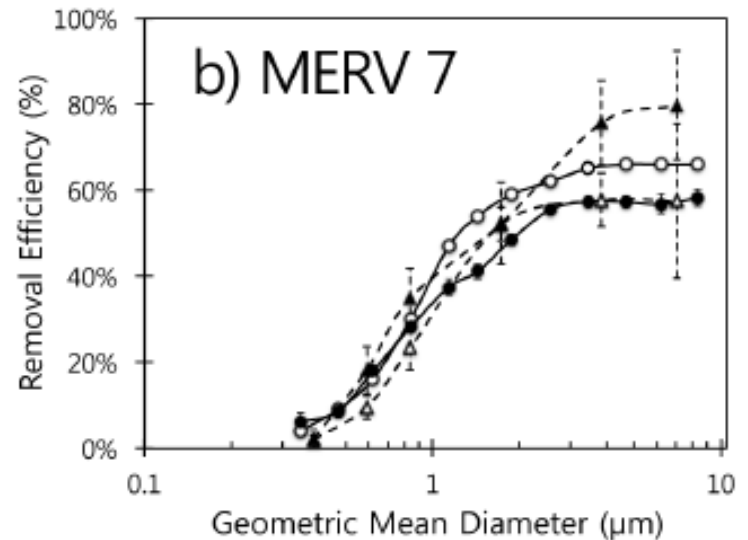
MERV 10



MERV 13



MERV 16

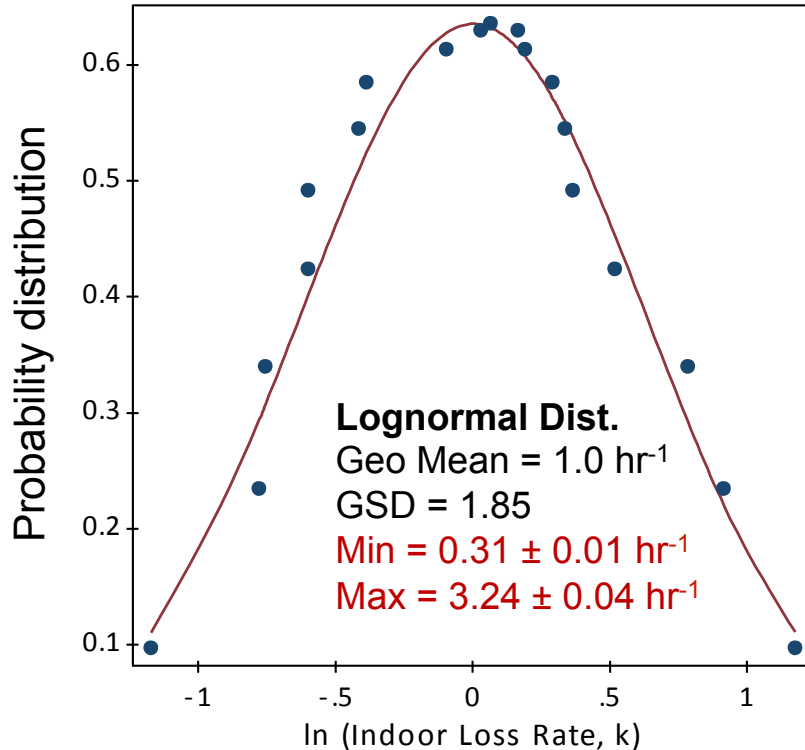


# Indoor particle removal rates

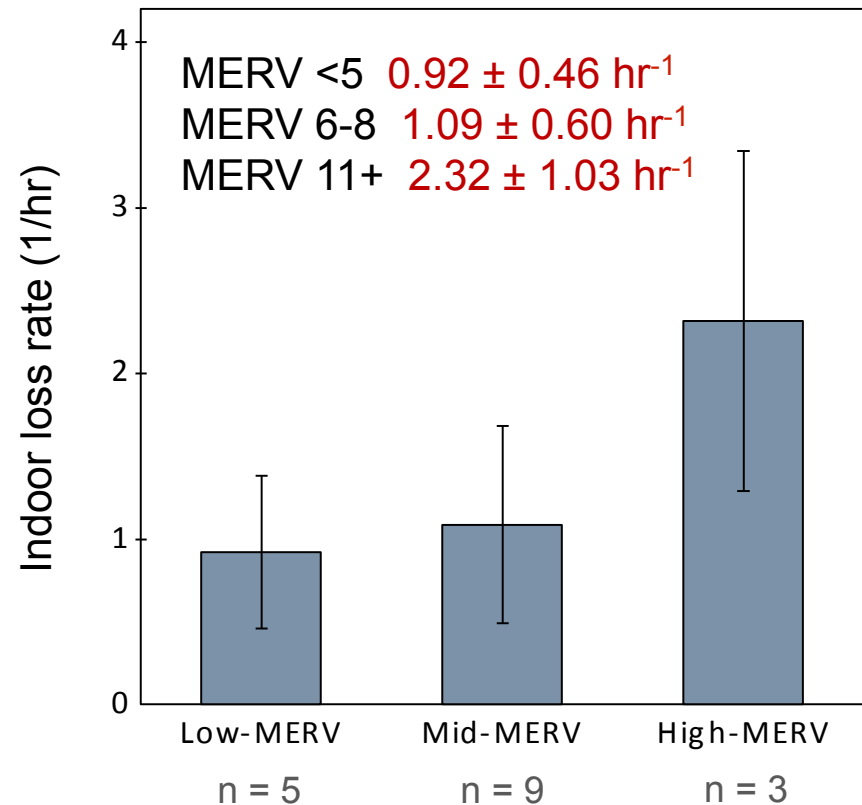
- Submicron particle loss with HVAC system operating 100%

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

where  $f = 1$

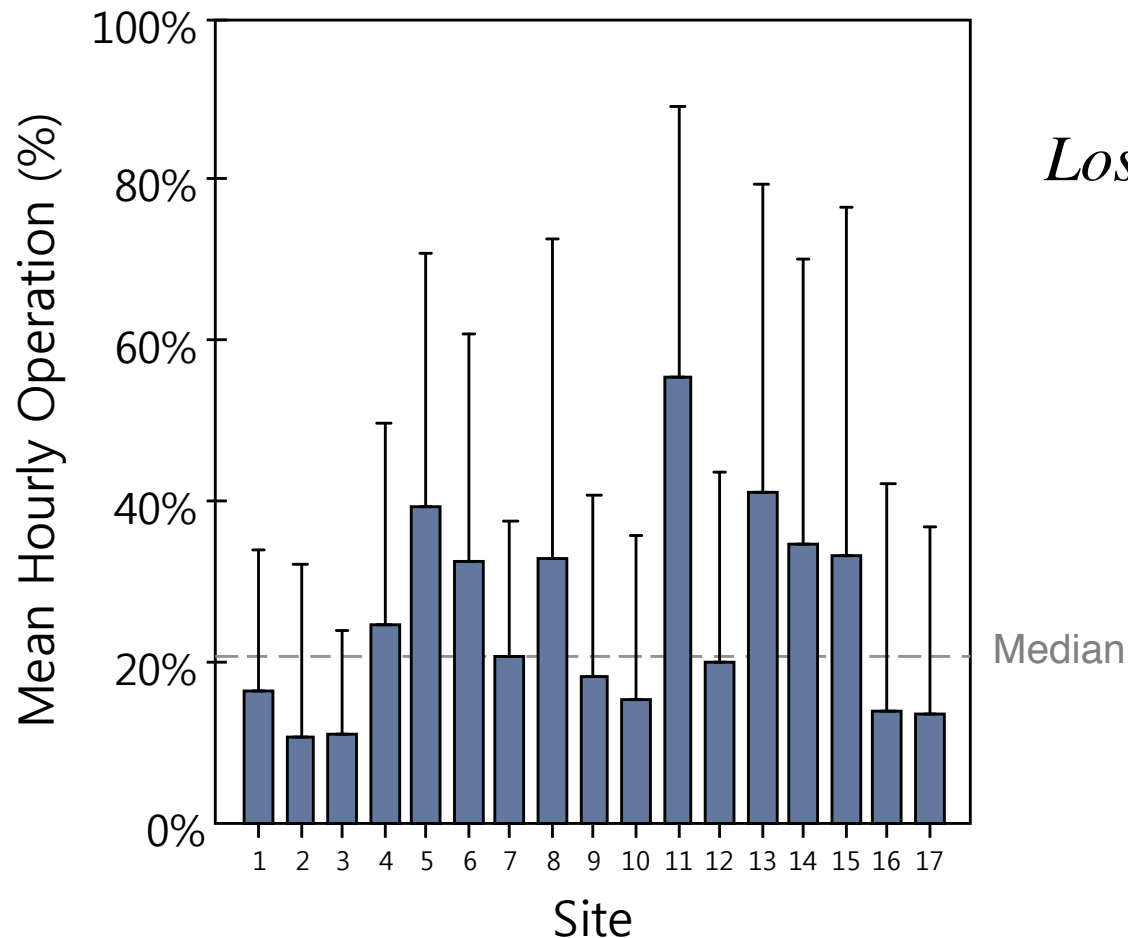


## Split by filter type



# 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)



$$Loss = k + \underbrace{f}_{\text{runtime}} \frac{\eta Q}{V}$$



# **VARIATIONS IN PM EXPOSURES**

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

# Implications for submicron PM exposure

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- Penetration factors ranged 0.17 to 0.72
- AER ranged  $0.13 \text{ hr}^{-1}$  to  $0.95 \text{ hr}^{-1}$
- Outdoor particle source terms ranged  $0.02 \text{ hr}^{-1}$  to  $0.62 \text{ hr}^{-1}$ 
  - Factor of **~30** difference from lowest to highest
  - Higher in older, leakier homes
- Indoor removal rates ranged  $0.31 \text{ hr}^{-1}$  to  $3.24 \text{ hr}^{-1}$ 
  - 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: 
$$F_{inf} = \frac{C_{in}}{C_{out}} = \frac{P \times AER}{AER + k + f \frac{\eta Q}{V}}$$

	Lower bound	Upper bound
Penetration factor, $P$	0.17	0.72
Air exchange rate, $AER$ (1/hr)	0.13	0.95
Outdoor source term, $P \times AER$ (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%
<b>I/O submicron PM ratio (<math>F_{inf}</math>)</b>	<b>0.01</b>	<b>0.70</b>

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
  - Knowledge of HVAC filter type
  - Building airtightness test results
  - I/O climate conditions

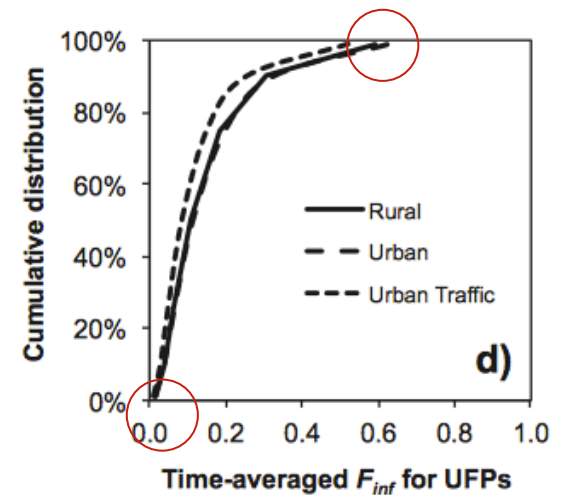
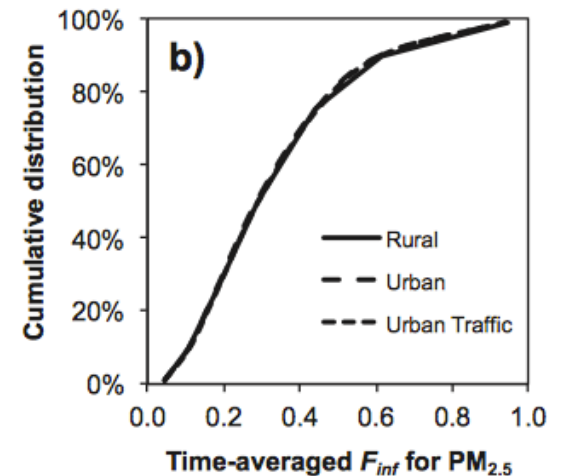
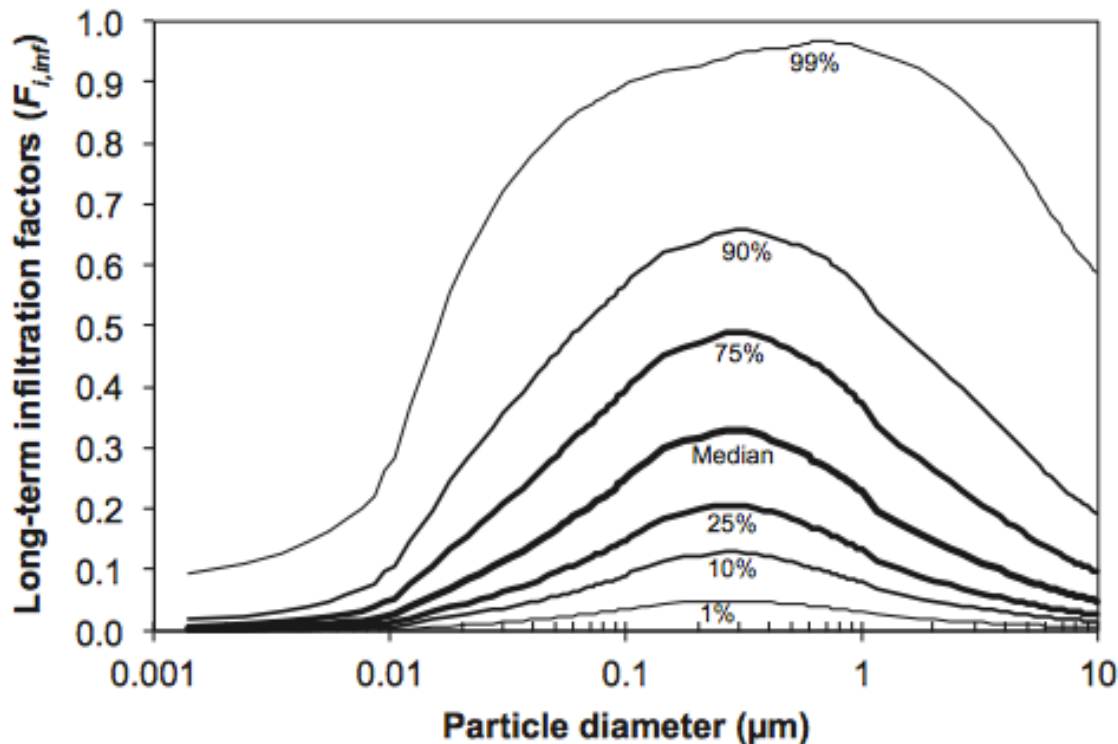
# Modeling size-resolved indoor PM of outdoor origin

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

Zeineb El Orch<sup>a</sup>, Brent Stephens<sup>a,\*</sup>, Michael S. Waring<sup>b</sup>

<sup>a</sup> Civil, Architectural and Environmental Engineering, Illinois Institute of Technology, Chicago, IL, USA

<sup>b</sup> Civil, Architectural and Environmental Engineering, Drexel University, Philadelphia, PA, USA



## **2. FILTRATION OF INFECTIOUS AEROSOLS**



# Motivation

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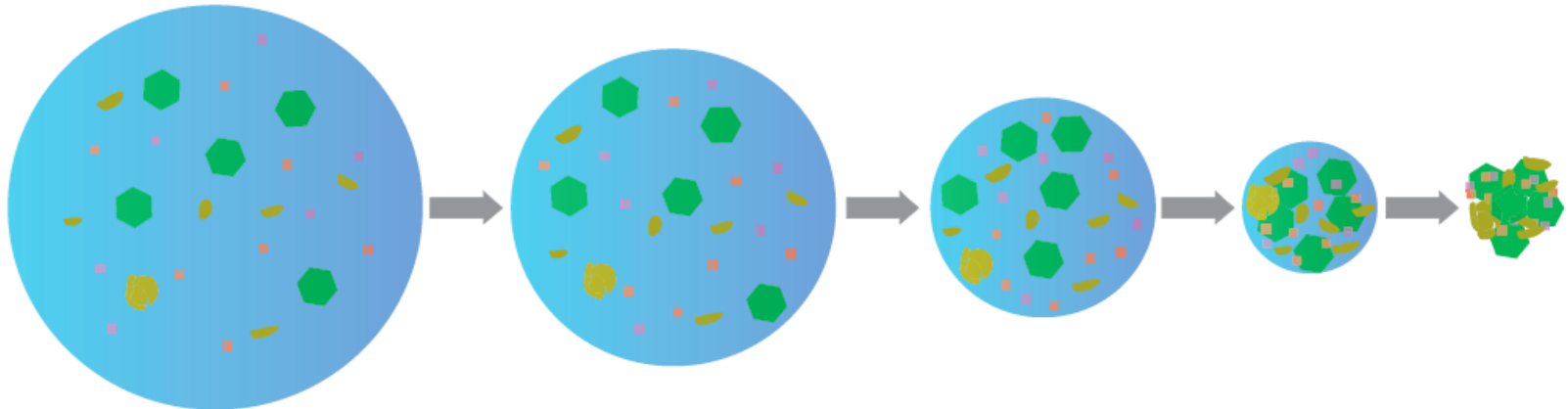
- Communicable respiratory illnesses have significant economic impacts in the U.S.
  - 43 common colds and 26 cases of influenza per 100 persons
  - Healthcare costs, absence from work, lost worker productivity
    - Total cost was ~\$70 billion in 2000 Fisk 2000 *Ann Review Energy Environ* 25:537-566
- Airborne transmission of respiratory pathogens is complex
  - Continuing debate about transmission modes
- Control of airborne infectious disease transmission
  - Studies suggest building characteristics, outdoor air ventilation rates, and lower occupant density can reduce respiratory illnesses 15-76%  
Langmuir et al. 1948 *Am J Hyg*; Brundage et al. 1988 *JAMA*;  
Drinkwater et al. 1996 *Am Geriatr Soc*; Fisk 2000; Li et al. 2007 *Indoor Air*
- Others: UVGI, facemasks, isolation ... HVAC filtration?

The diagram illustrates the transmission of influenza virus through shared spaces. On the left, a person is shown coughing, releasing droplets and aerosols. On the right, a person is shown holding a smartphone, which is labeled as a fomite. The diagram shows the virus particles (droplets and aerosols) traveling through the air between the two people. Labels include: Droplet, Influenza virus, Aerosol, Fomite, Shared spaces, and Distance.

- 40

# “Spreading”: Expulsion of droplets

- When a person coughs, sneezes, speaks or breaths:
  - Particles of liquid water, proteins, salts, and other matter are expelled
    - These are called **droplets**
    - These particles may contain smaller infectious organisms
  - Droplets rapidly deposit to surfaces and/or decrease in size as the surrounding liquid evaporates
    - **Droplet nuclei** remain after evaporation
    - Typically 40-50% smaller diameter ( $d_p$ ) than original droplets
      - Still contain infectious organisms

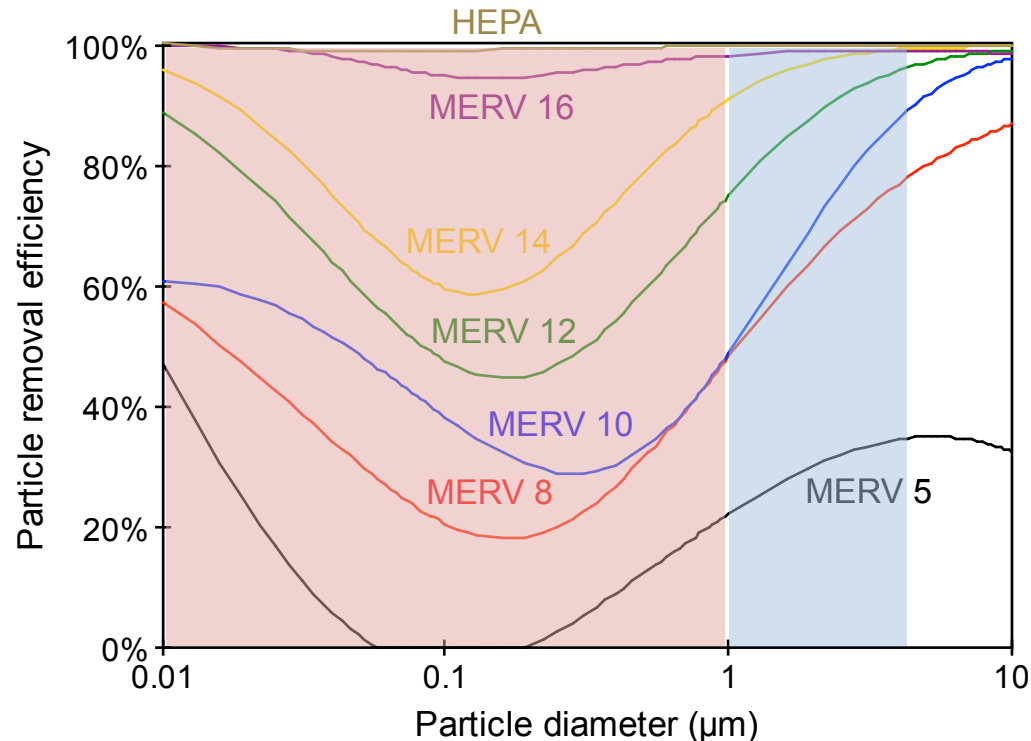


## Rapid evaporation of droplets, *Mythbusters*



# What particle sizes are actually emitted by humans?

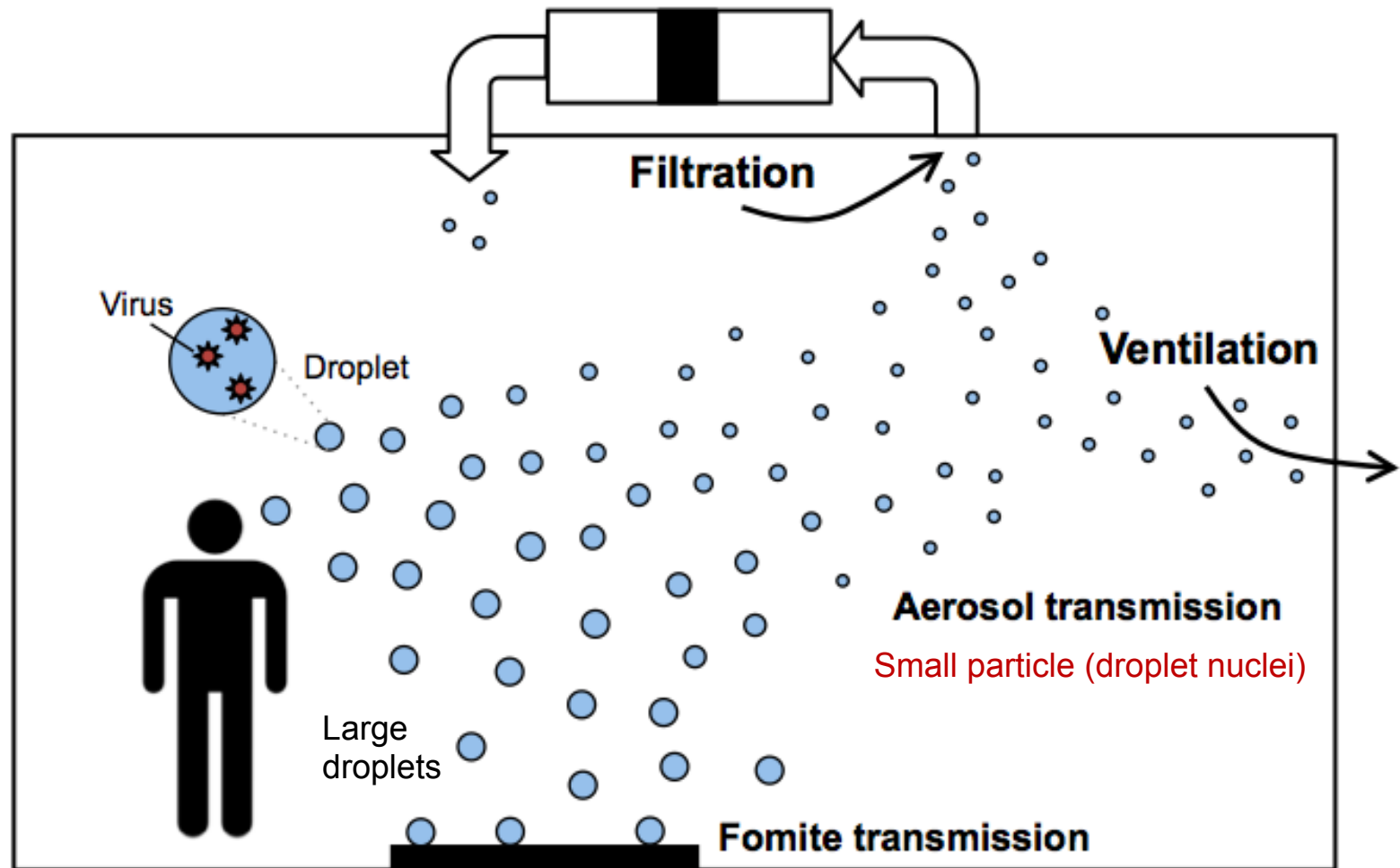
- When considering particle filtration of infectious aerosols
  - It is crucial to consider particle sizes of infectious aerosols



- Commonly believed that droplet nuclei average 1-3 μm
  - Recent studies show that 80-90% of particles expelled during human activities are actually **smaller than 1-2 μm**



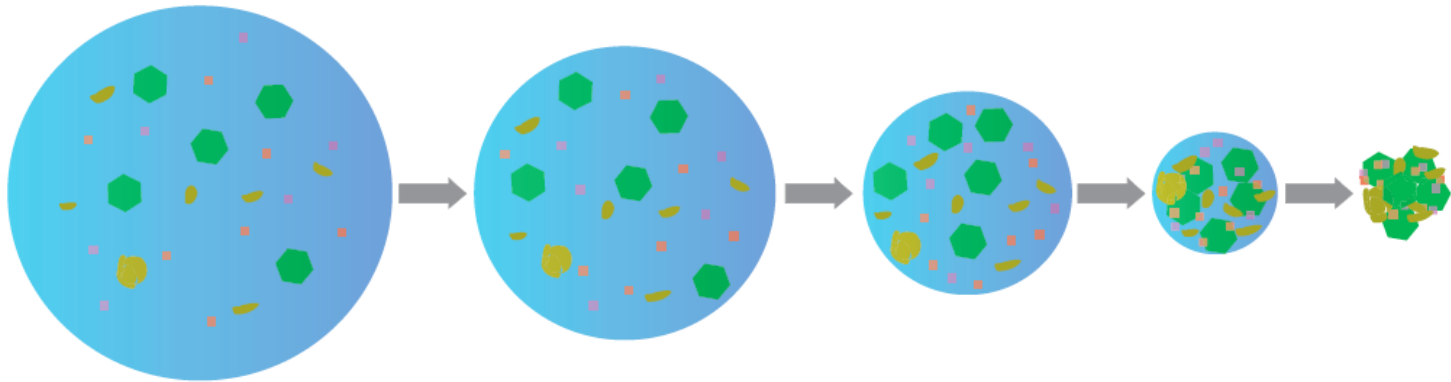
# Particle size is important for distribution and removal



# What about infectious organisms within particles?

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- Most particles emitted during human activities are smaller than **1-2  $\mu\text{m}$** 
  - But particle volume scales with  $d_p^3$
  - Does the amount of viral or bacterial material contained in droplet nuclei scale similarly?

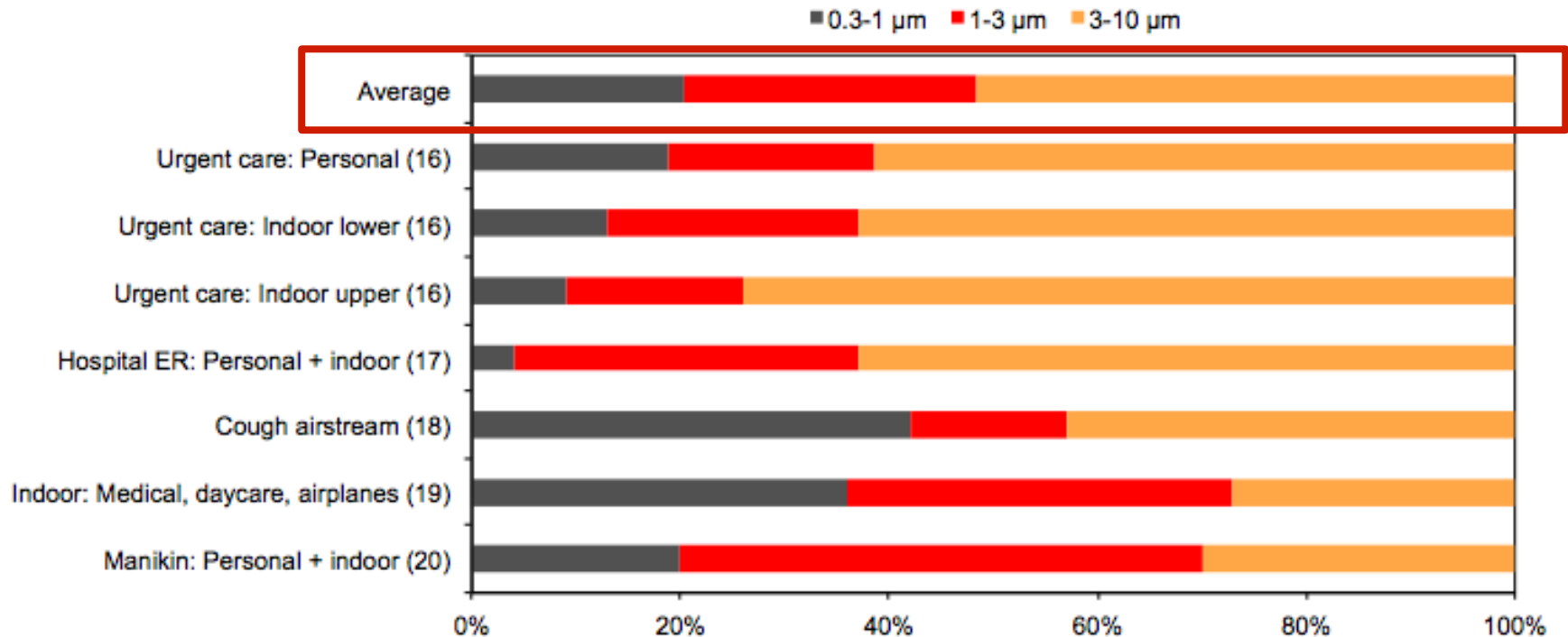


- Several recent studies have measured influenza virus content in size-fractionated indoor aerosols...

# Size-resolved influenza virus indoors: **Summary**

Recent measurements of influenza viruses in size-fractionated indoor aerosols:

- Healthcare centers, ER, cough airstreams, daycare, airplanes, manikins
- Adjusted to fit into Standard 52.2 size bins



**Average influenza size distribution:**

**20% <1  $\mu\text{m}$**

**29% 1-3  $\mu\text{m}$**

**51% >3  $\mu\text{m}$**

[16] Lindsley et al., **2010** *Clin Infect Dis* 50:693-698; [17] Blachere et al., **2009** *Clin Infect Dis* 48(4):438-40

[18] Lindsley et al., **2010** *PLoS ONE* 5:e15100; [19] Yang et al., **2011** *J R Soc Interface* 8:1176-1184;

[20] Noti et al. **2012** *Clin Infect Dis* 54(11):1569-77

# Methods of estimating infectious disease risks

## Wells-Riley model

$$P_{\text{infection}} = \frac{\text{cases}}{\text{susceptibles}} = 1 - e^{-\frac{Iqpt}{Q_{\text{oa}}}}$$

$P_{\text{infection}}$  = the probability of infection

cases = the number of infection cases

susceptibles = number of susceptible individuals

$I$  = number of infector individuals

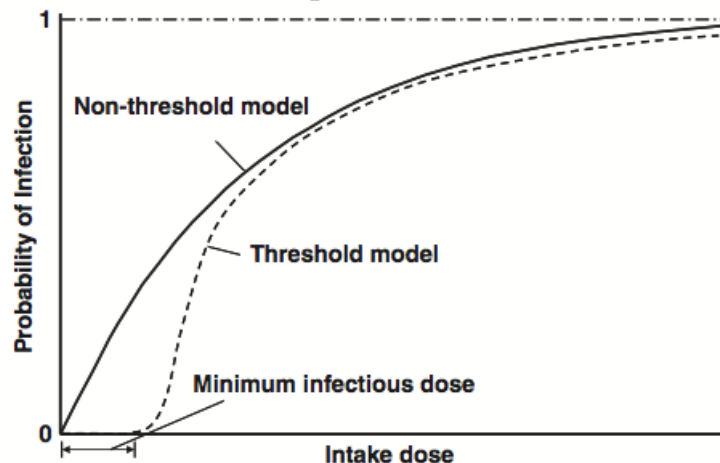
$p$  = pulmonary ventilation rate of a person ( $\text{m}^3/\text{hour}$ )

$q$  = quanta generation rate (1/hr)

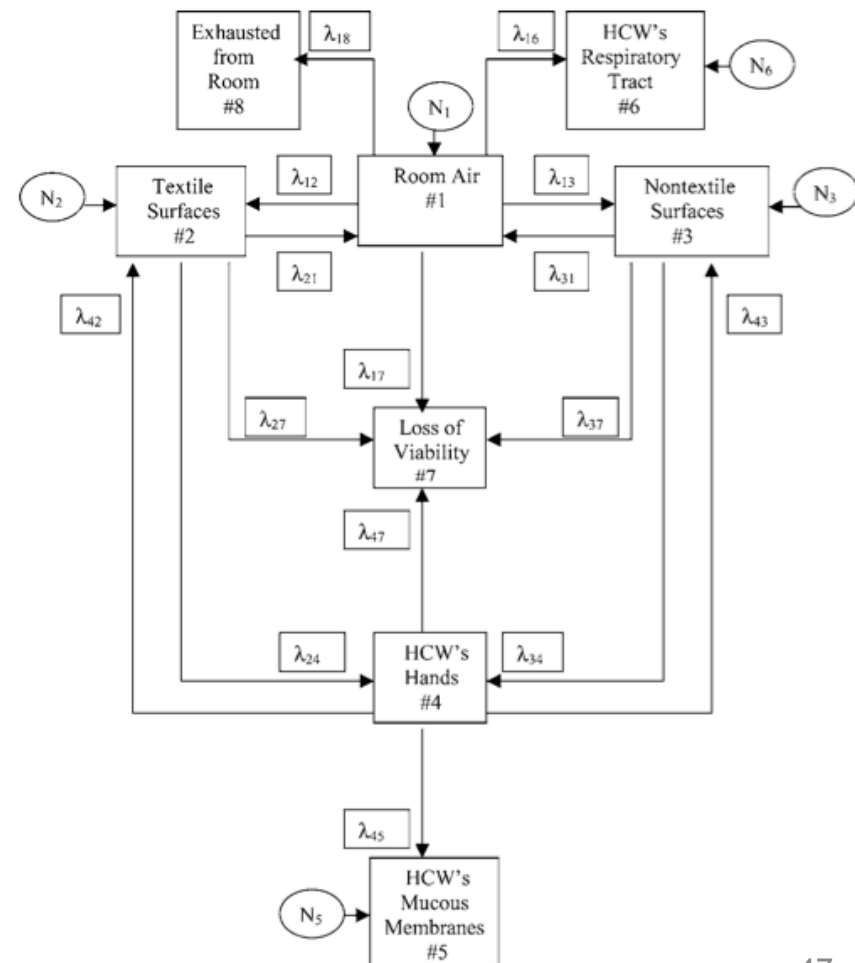
$t$  = exposure time (hr)

$Q_{\text{oa}}$  = room ventilation rate with clean air ( $\text{m}^3/\text{hour}$ )

## Dose-response models

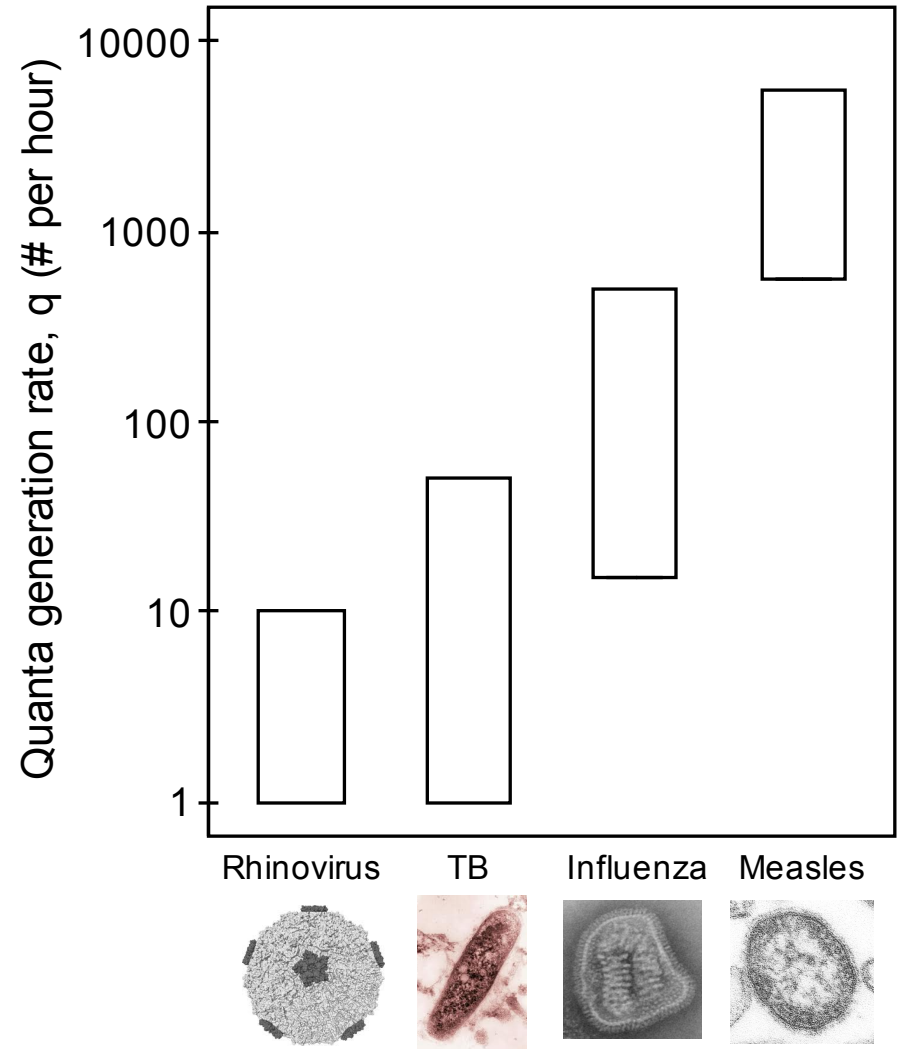


## Markov chain models



# Concept of quanta generation

- The unit *quantum of infection* is not an actual physical unit
- It is a hypothetical infectious dose
  - Back calculated from epidemiological studies
- Accounts for emissions, transport, inhalation, infectivity, and susceptibility all in one term



# Incorporating other loss terms into Wells-Riley model

$$P_{\text{infection}} = 1 - \exp \left[ - \frac{I q p t}{V} / \left( \lambda_{\text{ventilation}} + k_{\text{filtration}} + k_{\text{deposition}} \right) \right]$$

Loss by HVAC  
filtration (1/hr)

Loss by particle  
deposition (1/hr)

$$k_{\text{filtration}} = f_{\text{HVAC}} \frac{Q_{\text{filter}} \eta_{\text{filter}}}{V} = \lambda_{\text{recirculated}} \eta_{\text{filter}}$$

$f_{\text{HVAC}}$  = fractional HVAC operation time (-)

$Q_{\text{filter}}$  = airflow rate through filter (m<sup>3</sup>/hr)

$\eta_{\text{filter}}$  = particle removal efficiency of the filter (-)

$\lambda_{\text{recirculated}}$  = recirculation rate through the HVAC filter (1/hr)

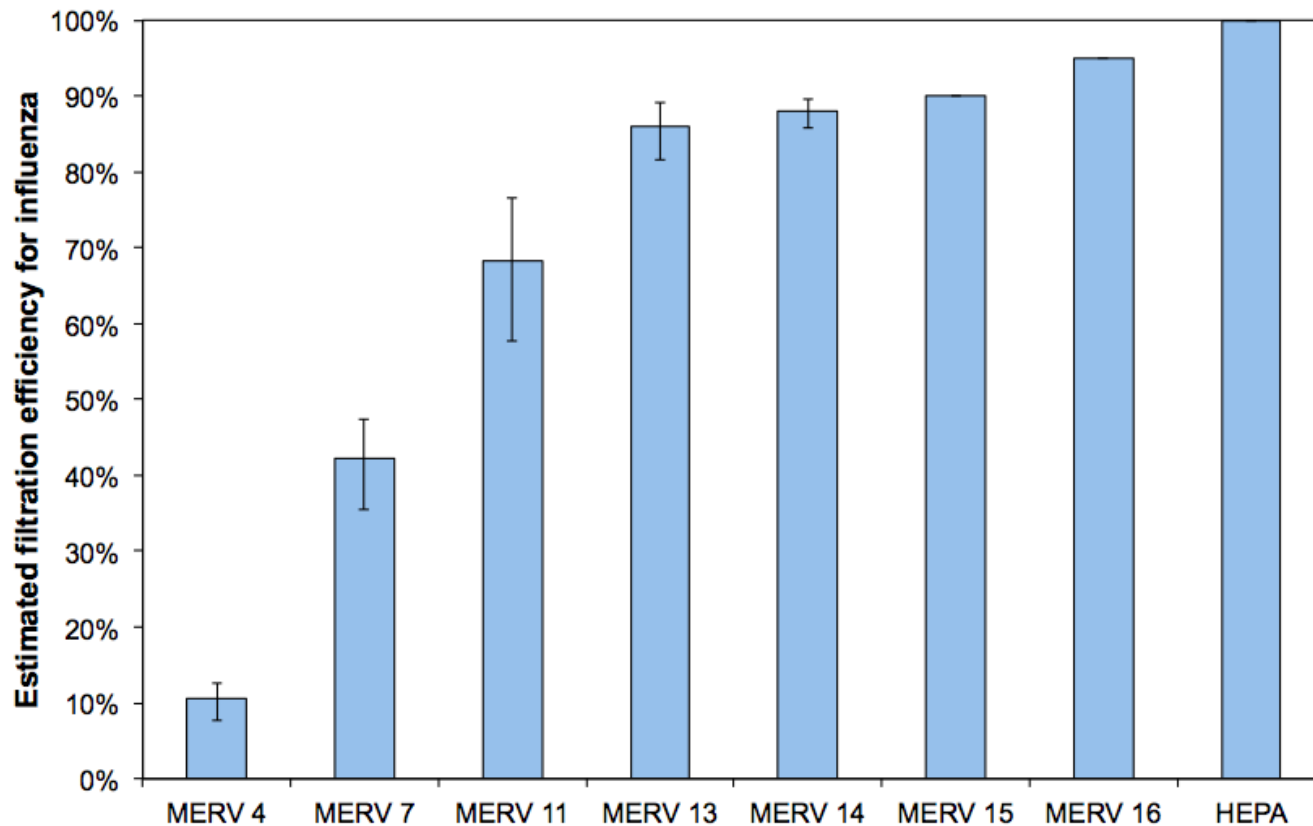
To connect Wells-Riley with filtration, we need to know several specific building characteristics as well as:

- Size-resolved quanta generation rates
- Removal efficiency of HVAC filters for infectious aerosols



# MERV and infectious aerosols: Removal efficiency

- Using previous data on influenza virus in size-resolved particle samples taken in real indoor environments, we can estimate the size-weighted average removal efficiency of a range of filters for infectious aerosols:

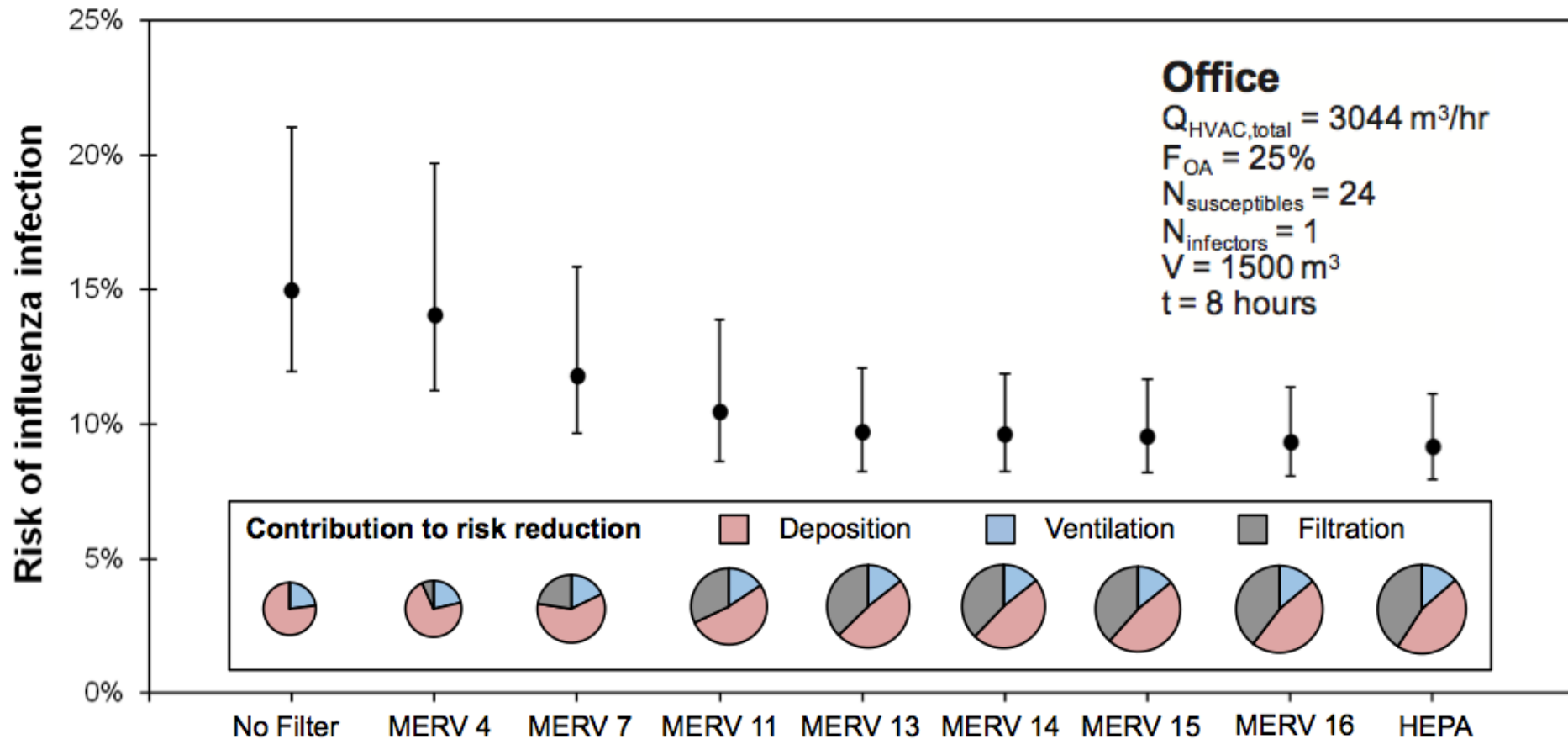


# Case study: Influenza in an office environment

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- Because the Wells-Riley model utilizes building volume, we must rely on case studies to explore possible impacts of filtration
  - Cannot generalize entirely because filtration effectiveness is a function of not only removal efficiency but recirculation rates through HVAC filters (flow vs. volume)
- We chose a hypothetical office environments with 1 infector:
  - 500 m<sup>2</sup>
  - 25 adult occupants
  - ASHRAE 62.1 minimum ventilation rates
  - 25% OA
  - 8 hours of occupancy
- Used mean quanta generation rate from previous studies
  - Influenza ( $q = 100/\text{hr}$ )

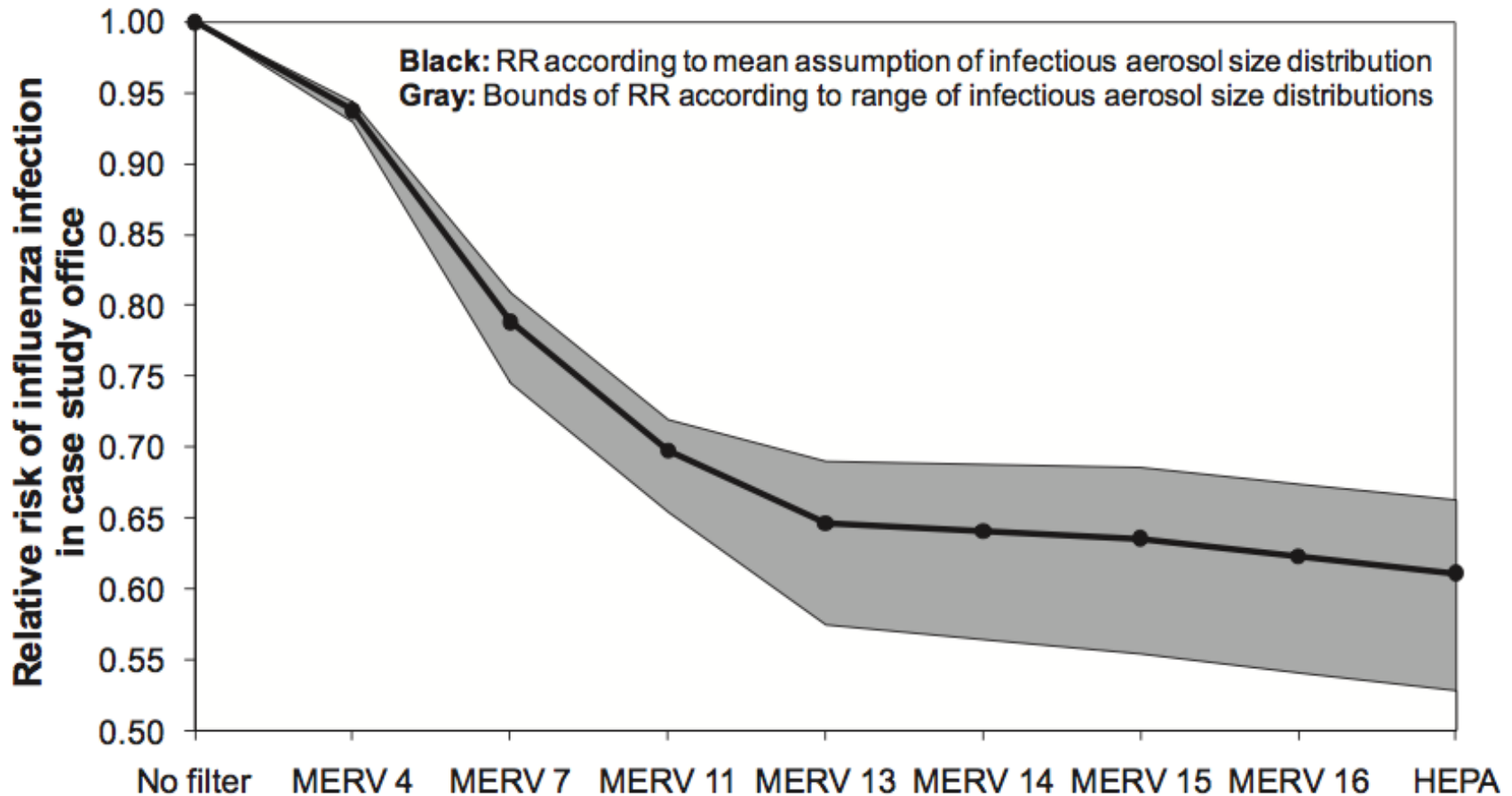
# Estimated risk of infection with HVAC filtration: Office



**From no filter to MERV 13 or greater:**  
**From 4 out of 24 occupants infected w/ flu to 2 out of 24**

# Generalizing results

- Using **relative risks** across all estimates of influenza aerosol size distributions and all HVAC filters allows us to identify trends and generalize results



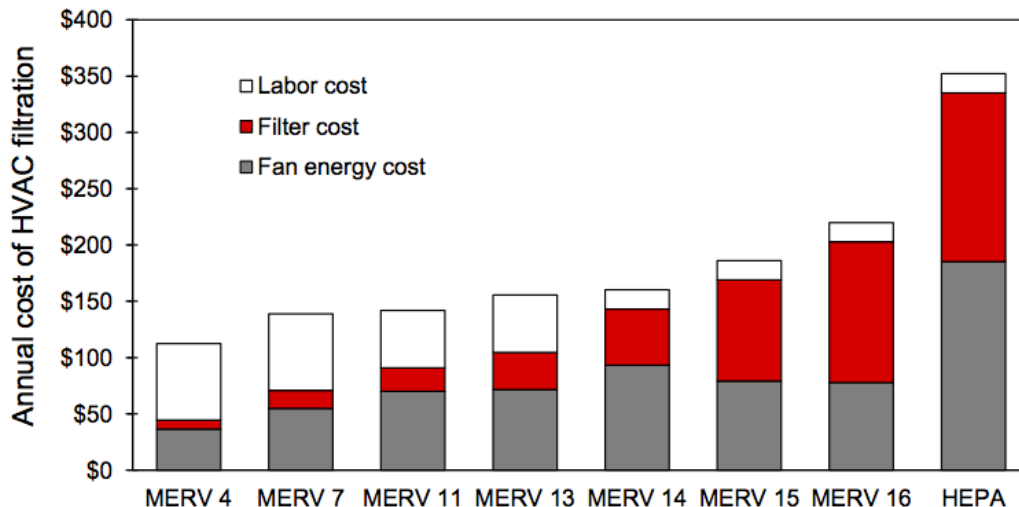
# Estimating costs of outdoor air vs. filtration

- Making assumptions about operational periods in each building type, costs of natural gas and electricity, and HVAC equipment efficiency we estimate the cost of conditioning each unit of outdoor air ventilation rate delivered in each of four cities:
  - Chicago, Charlotte, Houston, and Phoenix

$$E_{\text{heating}} = \lambda_{\text{ventilation}} V \rho_{\text{air}} C_{p,\text{air}} HDD \frac{1}{\eta_{\text{heating}}} \alpha$$

$$E_{\text{cooling}} = \lambda_{\text{ventilation}} V \rho_{\text{air}} C_{p,\text{air}} CDD \frac{1}{\eta_{\text{cooling}}} \beta$$

- We can also estimate the cost of filtration by combining filter costs, fan energy costs, and replacement costs (labor)

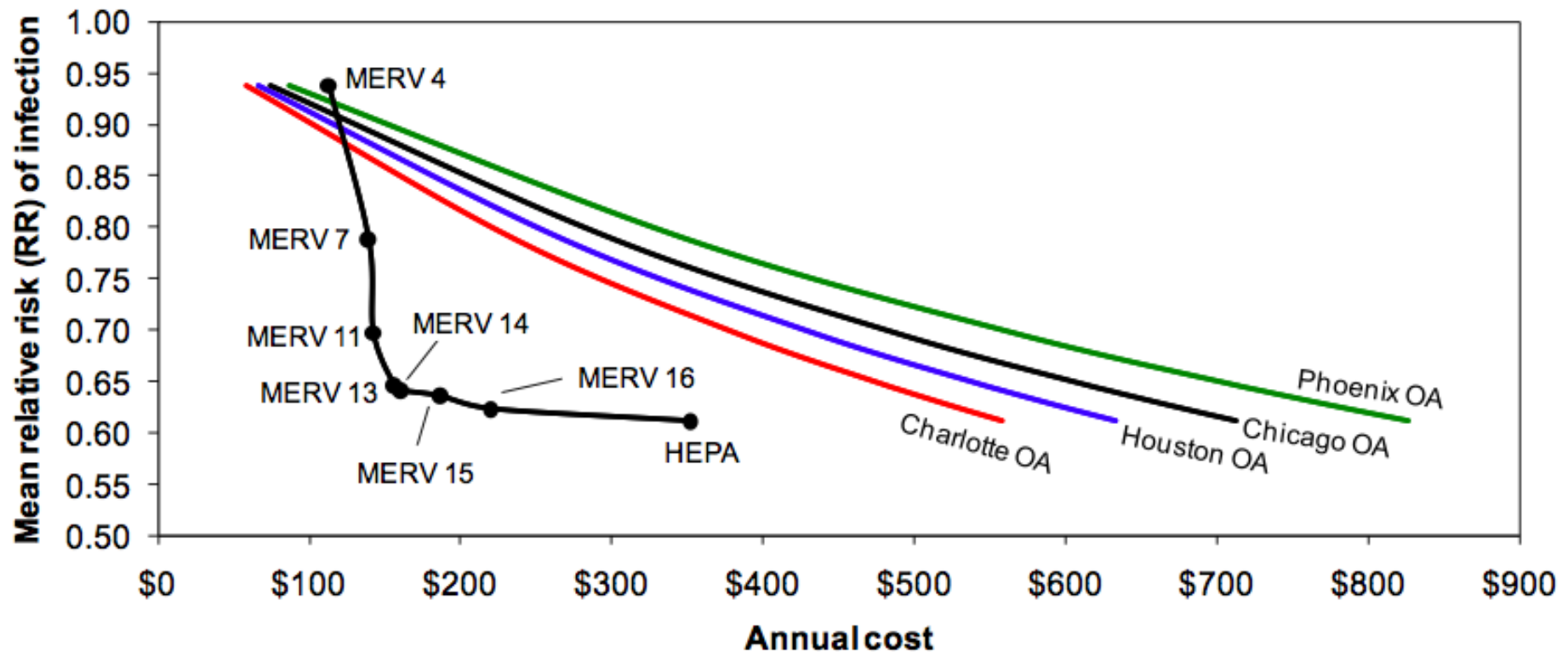


$$W_{\text{filtration}} = \frac{Q_{\text{recirculated}} \Delta P_{\text{avg}}}{\eta_{\text{fan}} \eta_{\text{motor}}}$$

$$C_{\text{filtration}} = W_{\text{filtration}} t_{\text{operating}} P_{\text{electric}}$$

Procedure similar to Bekö et al. **2008**  
*Building and Environment*

# Relative risk vs. estimated annual cost: Filtration vs. OA



**MERV 13-14 predicted to offer greatest risk reduction at lowest cost**



### **3. BUILDING SCIENCE MEASUREMENTS FOR THE HOSPITAL MICROBIOME PROJECT**

# The Hospital Microbiome Project (HMP)

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The Hospital Microbiome Project (HMP) is collecting microbial samples from surfaces, air, staff, and patients from the University of Chicago's new hospital pavilion in order to better understand the factors that influence bacterial population development in healthcare environments



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FOUNDATION



The HMP provides a unique opportunity to sample in a newly constructed hospital environment immediately prior to occupation and for nearly one year afterward

# Biological sampling

- Both culture (agar plates for antibiotic resistant bacteria) and culture-independent methods (16S rRNA, 18S rRNA, and fungal ITS on Illumina HiSeq, as well as qPCR on a subsection of samples) are being used to process over 12,000 microbial swab samples over the course of 1 year
  - 1 month prior to the hospital opening and 11 months after

## ***Patient and staff sampling***



*Floor, Bedrail, Cold water tap, Glove Box, and Air Filter\**

# Building science measurements in HMP

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- We also worked to characterize a number of building environmental and operational characteristics of the hospital during the yearlong HMP
  - Within 10 patient rooms
  - Within mechanical rooms serving each floor
- Our goal was to define a set of building science parameters that may have implications for biological findings
  - And that we could measure (within budget) robustly and accurately
- Many recent indoor microbial studies have not adequately characterized the indoor environments and operational parameters of buildings in which sampling takes place



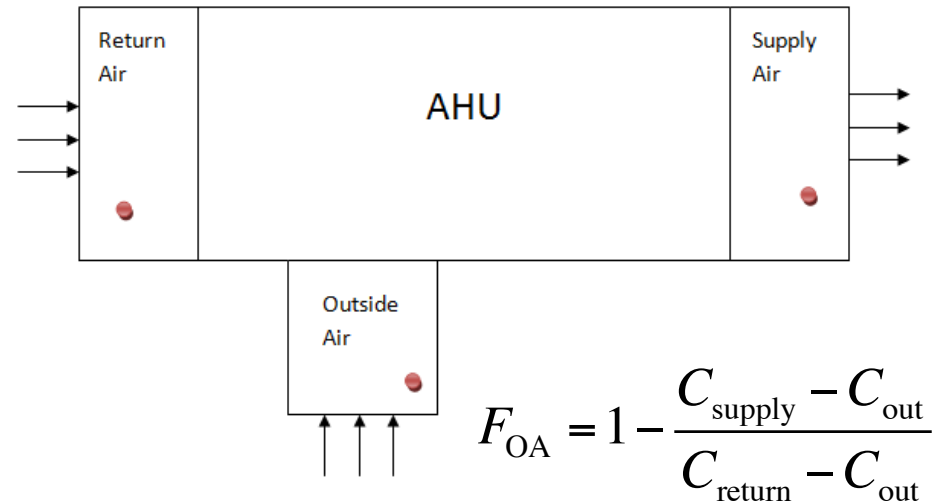


HVAC systems

Patient rooms  
5 rooms on 10<sup>th</sup> floor  
5 rooms on 9<sup>th</sup> floor

# Mechanical room measurements

- Outdoor air ventilation fraction (%OA) delivered to each floor
  - Each floor is served by a different HVAC system
  - CO<sub>2</sub> measurements in return, supply, and outdoor airstreams
  - Outdoor T and RH
    - 5-minute intervals







**AHU 6: 50,000 cfm**



**Outside Air**

**Supply Air**





CO<sub>2</sub> in OA

A close-up photograph of a green rectangular CO2 sensor mounted on a silver, insulated metal duct. A black cable is connected to the sensor. In the background, a black pipe with a yellow and black warning band is visible. The duct has some handwritten text in red and black ink, including "1-10/20" and "15-10/20".



CO<sub>2</sub> in SA

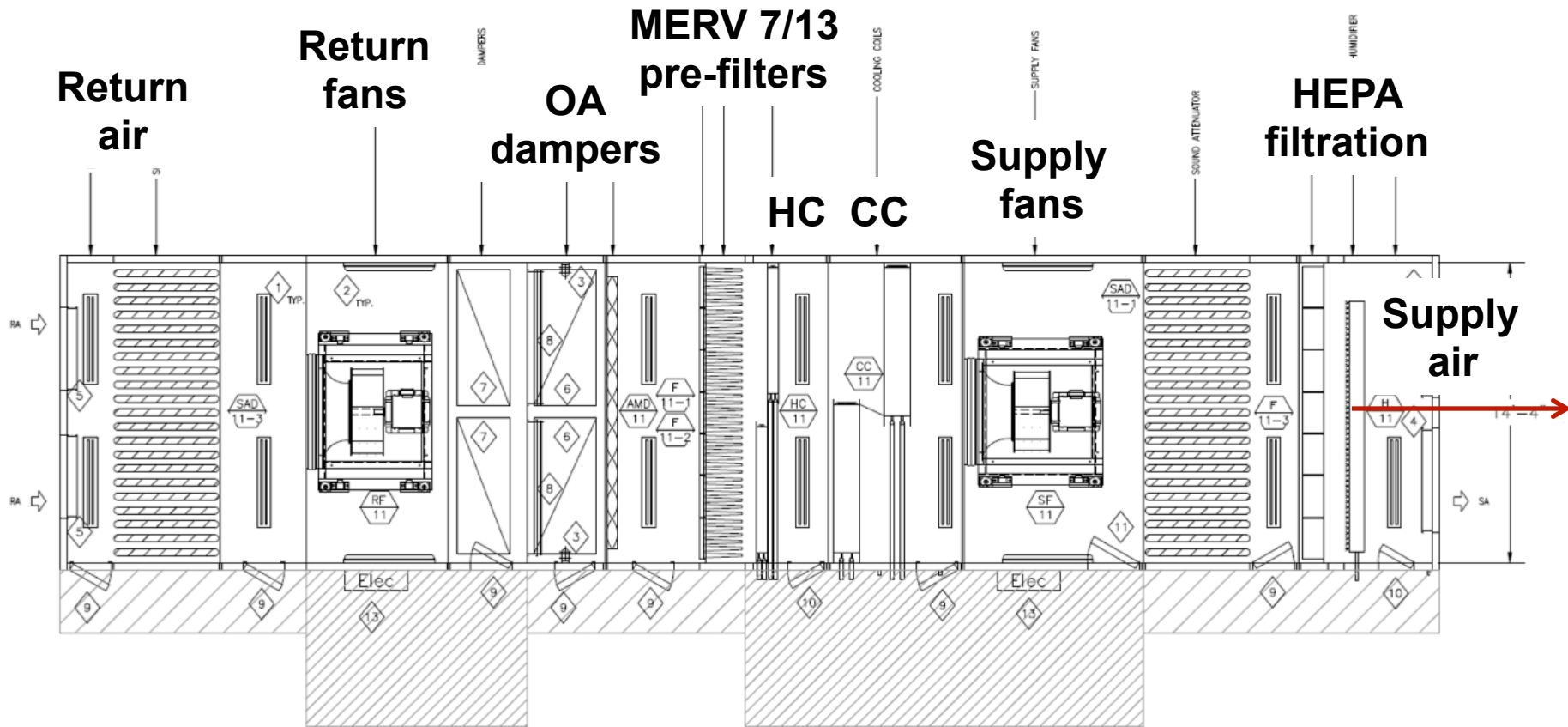
A close-up photograph of a green rectangular CO2 sensor mounted on a silver, insulated metal duct. The sensor is secured with red tape. A black cable is connected to the sensor. The duct is part of a larger system with other pipes and insulation visible.



CO<sub>2</sub> in RA

A photograph showing a person with long dark hair, wearing a dark jacket, sitting in a room and looking at a laptop. The room has silver, insulated metal walls and ceiling. A black cable is connected to a green rectangular CO2 sensor mounted on the wall. A black pipe with a yellow and black warning band is visible. The room is lit by fluorescent lights. A blue sign with white arrows and the letters "R" and "C" is visible on the right wall.

# HVAC systems





# Patient room measurements

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- Supply, return, and exhaust airflow rates (constant flow)
  - Measurements made during early stages of project
  - Estimates made using CO<sub>2</sub> mass balance throughout project
- Temperature + relative humidity + light intensity
  - Data loggers at 5-min intervals
    - Also at nurse stations
- Human occupancy
  - Beam break IR sensor at doorway (total breaks at 5 min intervals)
  - Patient room CO<sub>2</sub> concentrations (5 min intervals)
- Room pressurization (with respect to hallway)
  - Pressure transducers (5 min intervals)
- Air sampling via HVAC filter media
  - Periodic (weekly) → the only air sampling in the project



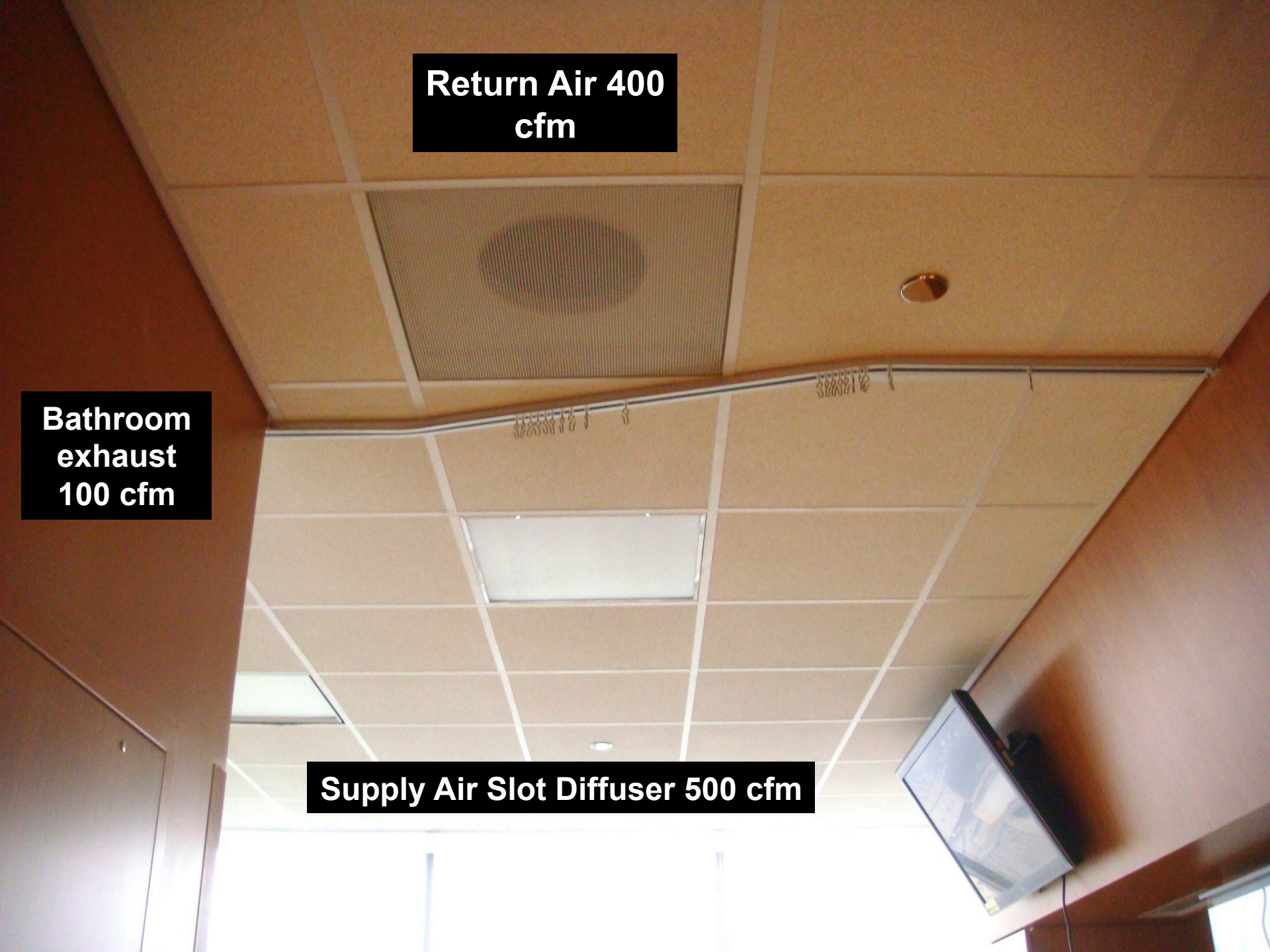
**Patient rooms**



**Return Air 400  
cfm**

**Bathroom  
exhaust  
100 cfm**

**Supply Air Slot Diffuser 500 cfm**





**Supply Air Slot Diffuser ~500 cfm  
w/ reheat coils**





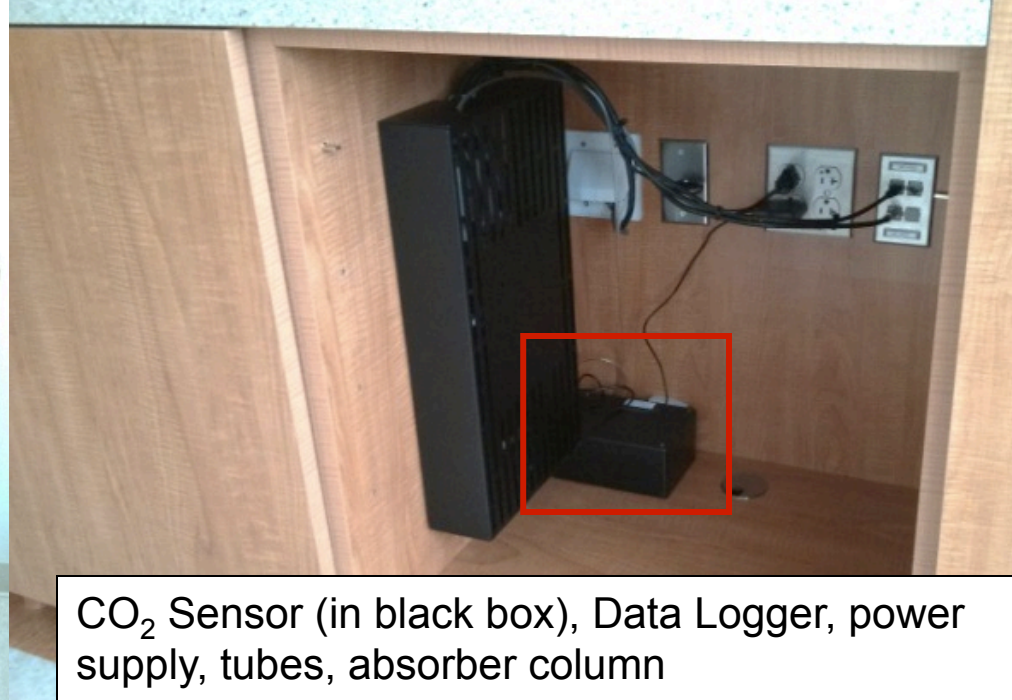


Data Logger (attached with adhesive) measuring temperature, relative humidity and light

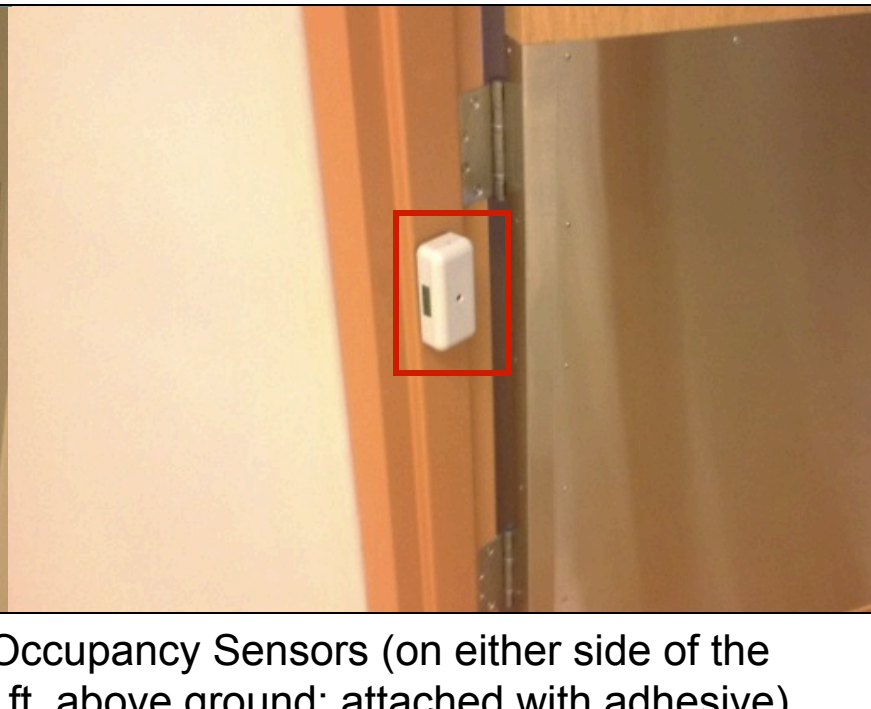


Differential Pressure Sensors (in black box with batteries, attached with adhesive), data logger, clear tube running to outer door frame





CO<sub>2</sub> Sensor (in black box), Data Logger, power supply, tubes, absorber column



Beam-break Occupancy Sensors (on either side of the door frame, 2 ft. above ground; attached with adhesive)

# Status update

---

- Weekly visits for data download and general maintenance
  - Just finished data collection on January 15<sup>th</sup>
- Still working to process data and QA/QC
  - Will end up with ~70 measures with about 100,000 data points each
  - Primary purpose is to provide measures for bio team to compare diversity and abundance to
    - Secondary purpose is simply to quantify some detailed operational characteristics of a new hospital

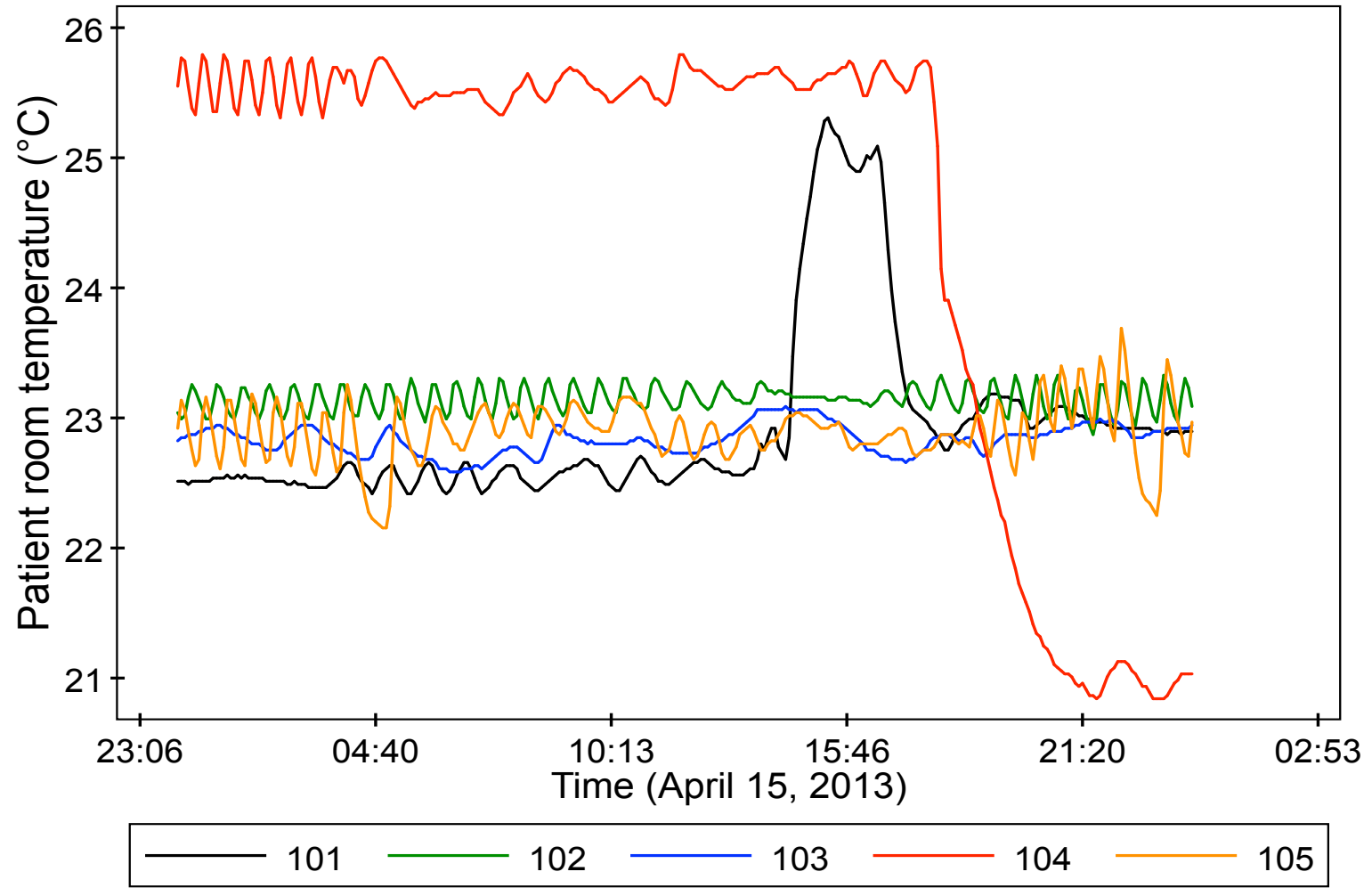


***HMP Building Science Project Team***

# **PRELIMINARY BUILDING SCIENCE DATA IN HMP**

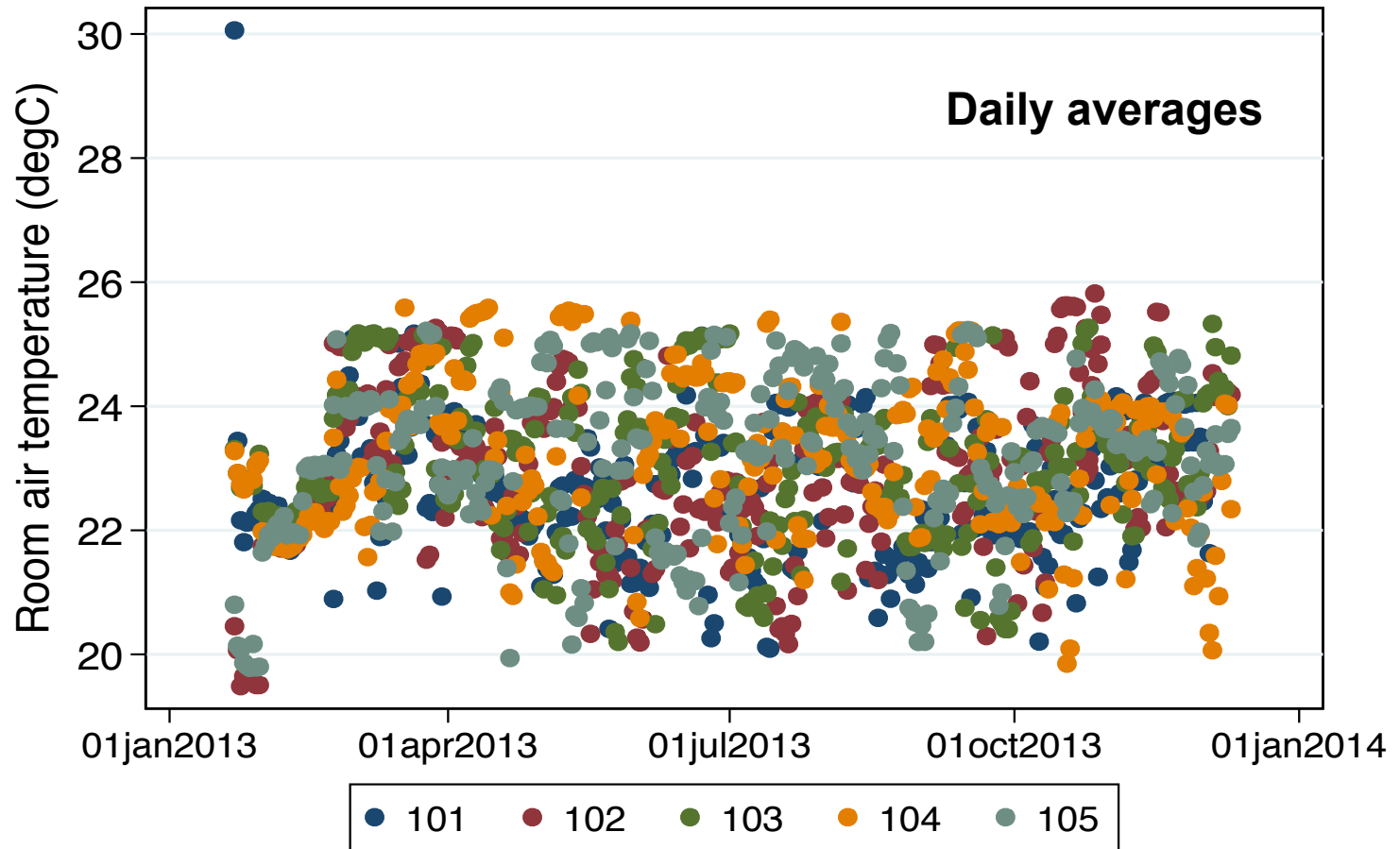


# Data snapshot: Patient room air temperatures



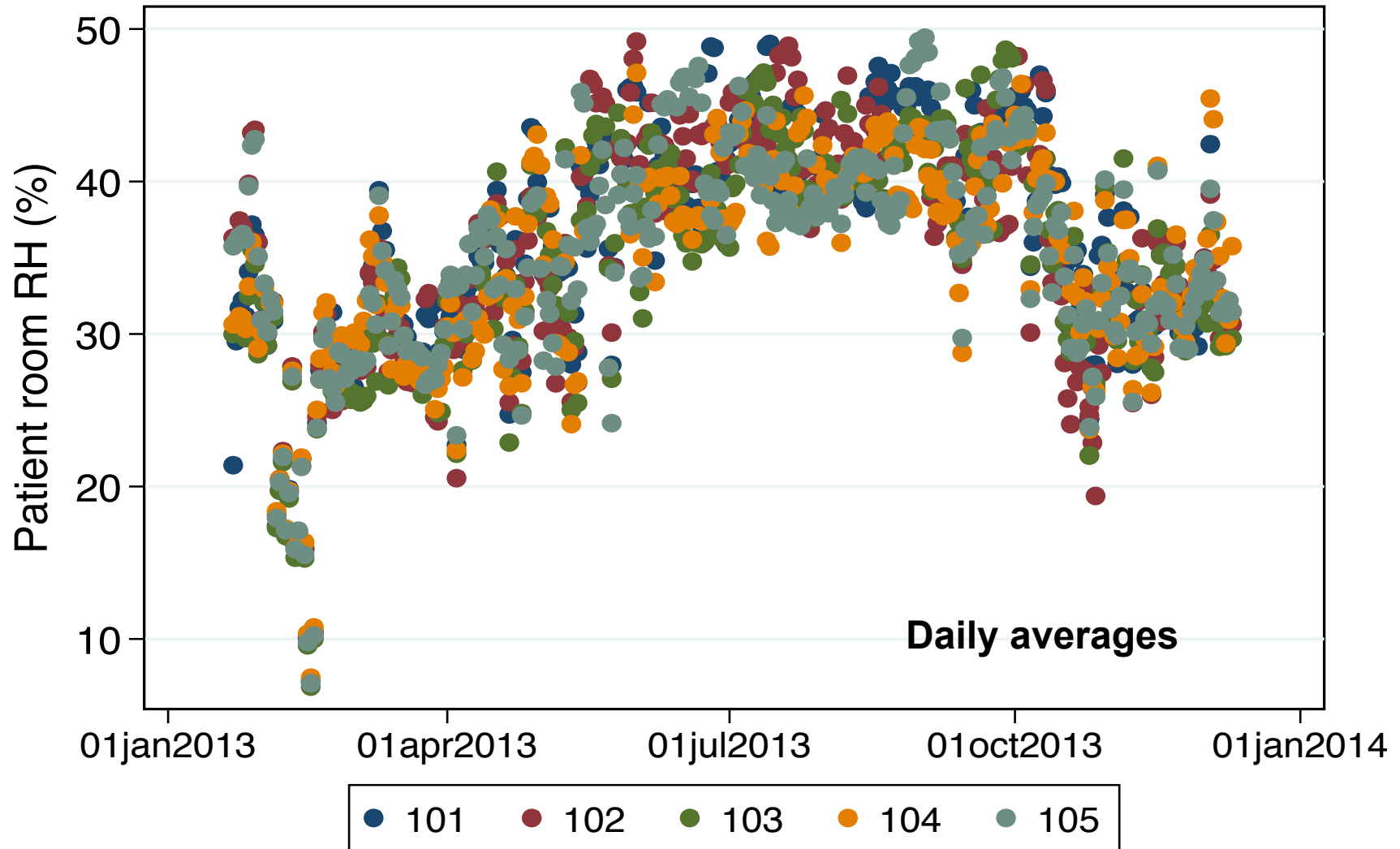
***Considerable variation in temperatures both between and within rooms***

# Data summary: Patient room air temperatures

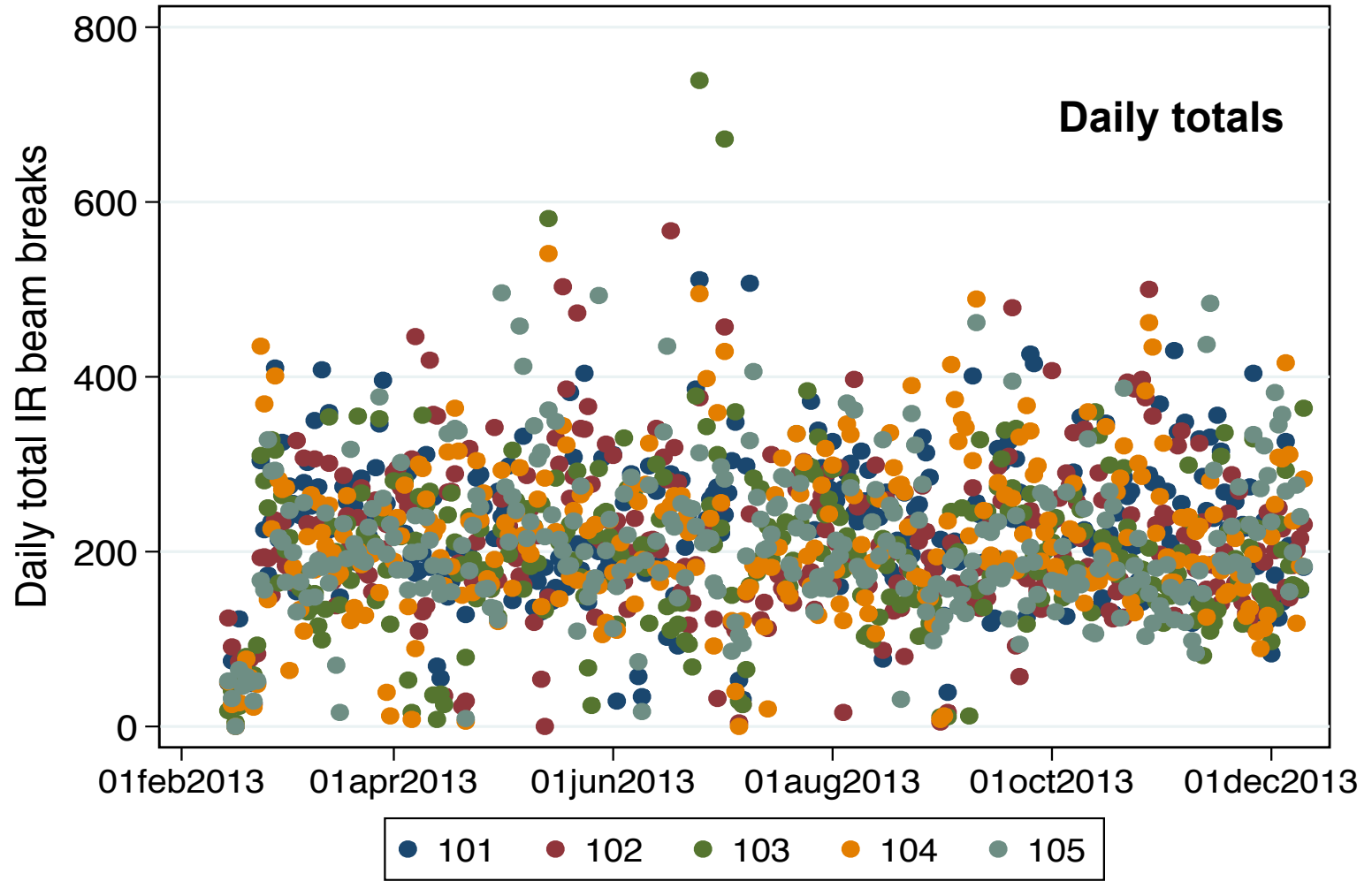


***Considerable variation in temperatures both between and within rooms***

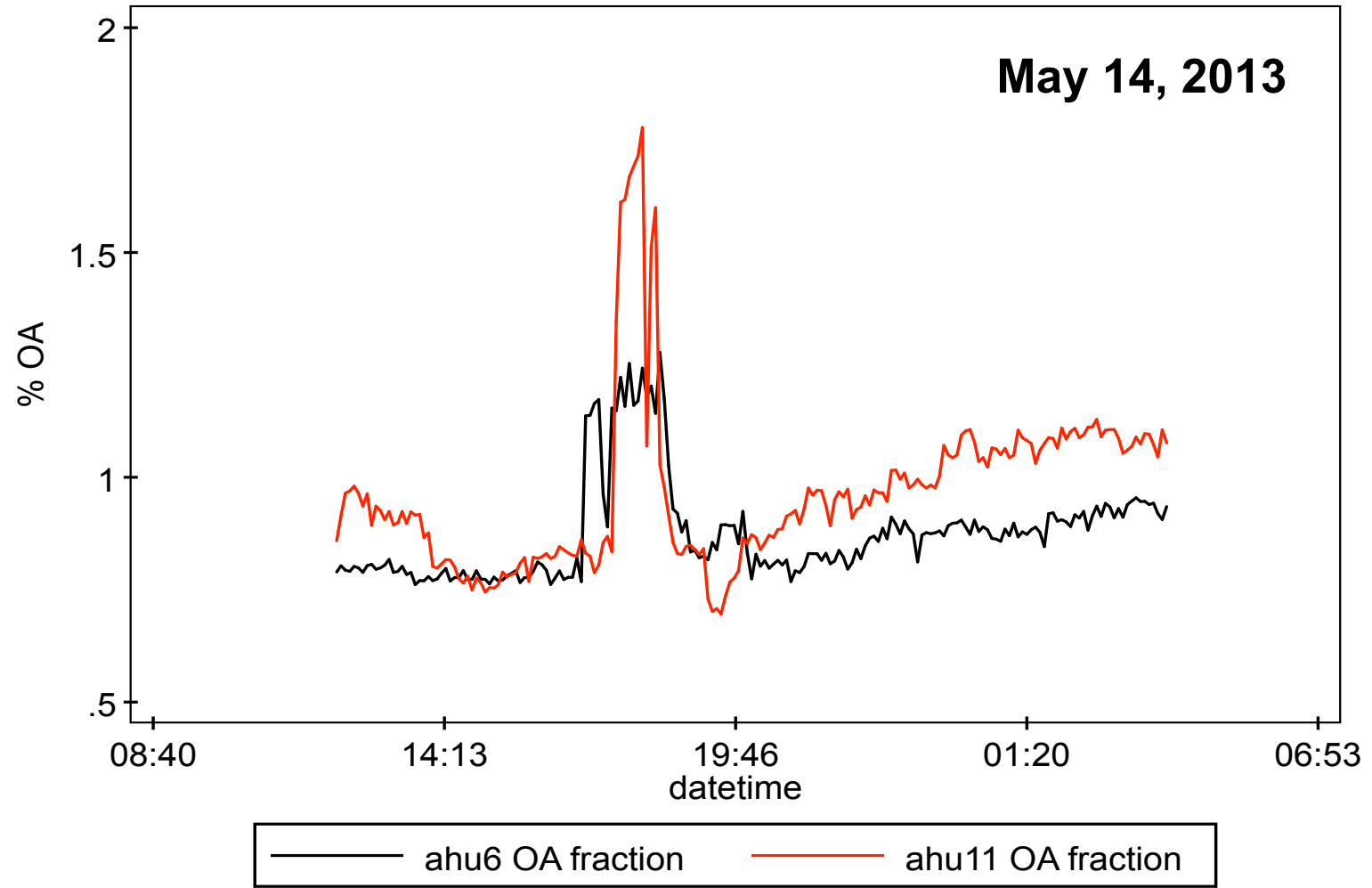
# Data summary: Patient room RH



# Data summary: Occupancy sensors

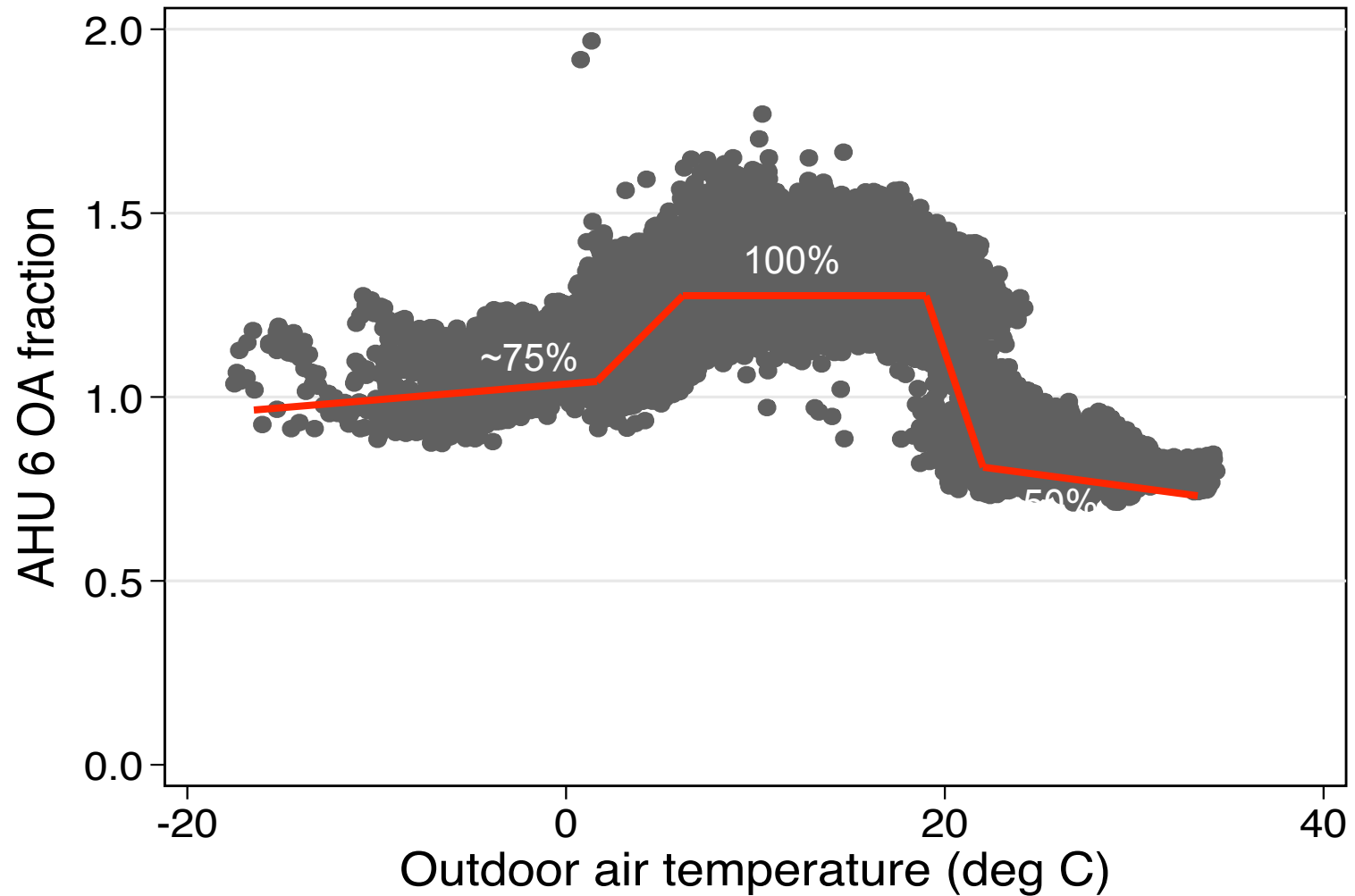


# Data snapshot: % outdoor air



*Issues with scaling due to low RA CO<sub>2</sub> concentrations*

# Calibrating OA measurements: %OA vs. outdoor T

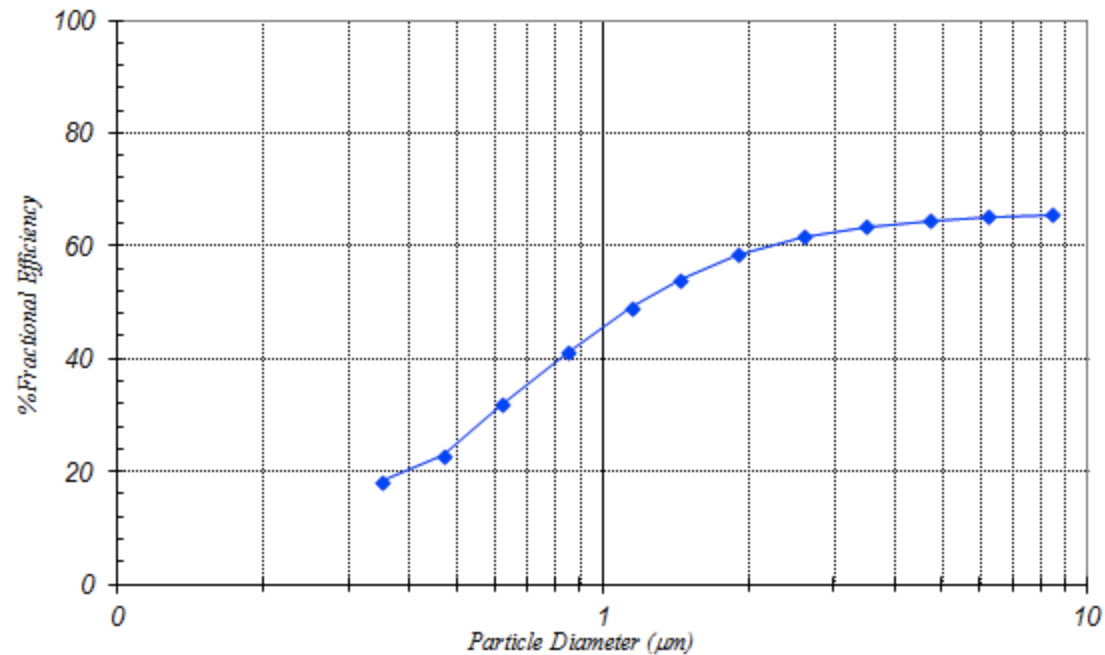




# HVAC filter bioaerosol ‘sampler’



- Sterilized and replaced weekly in all 10 patient rooms



\*Courtesy of Kevin Kinzer, 3M

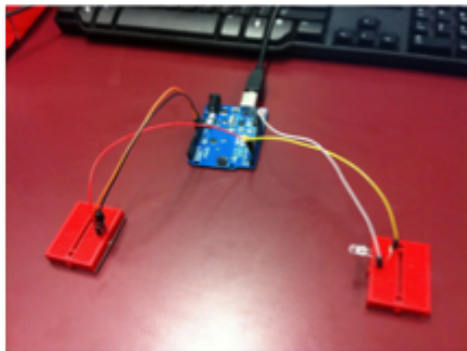
## **4. OPEN SOURCE BUILDING SCIENCE SENSORS**

# Open Source Building Science Sensors (OSBSS)

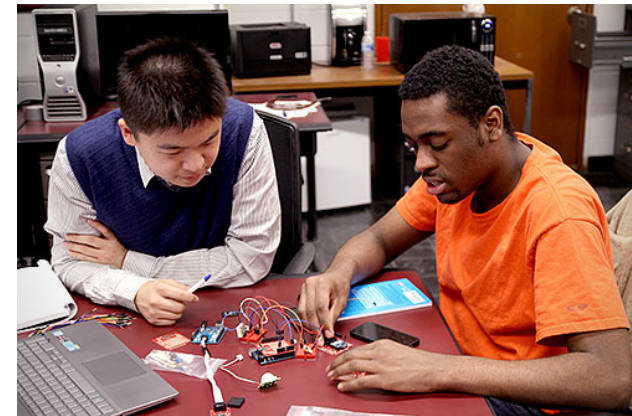


[Home](#) [Sensor Tutorials](#) [Blog](#) [Affiliations](#) [People](#)

*The Open Source Building Science Sensors (OSBSS) project demonstrates how to build inexpensive building environmental and operational sensors for long-term studies of the indoor environment using open source hardware and software.*



IR LED emitter & receiver - \$3



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Differential pressure



Proximity occupancy



Generic datalogger



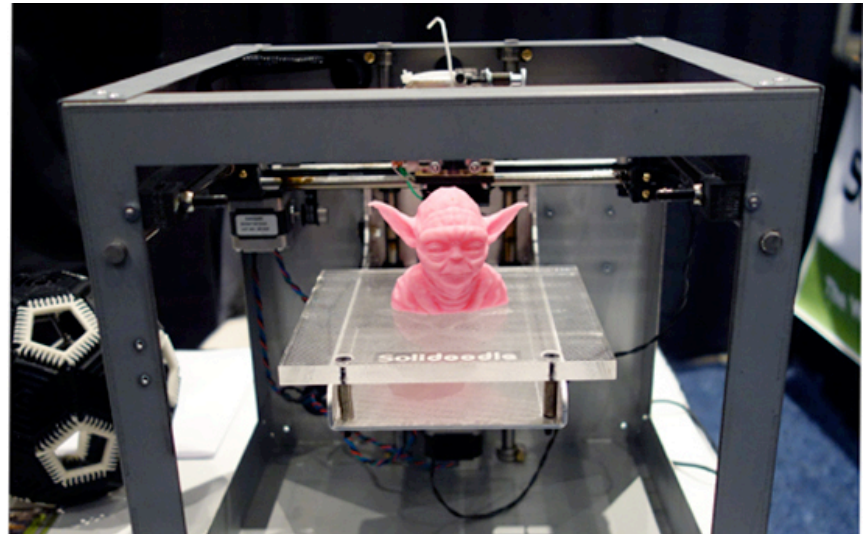
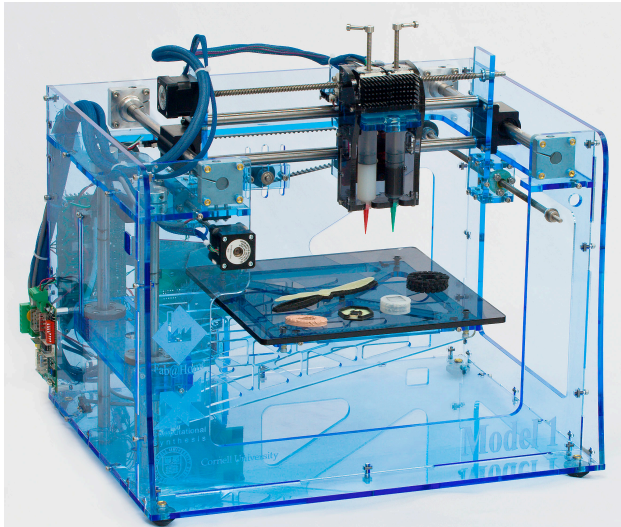
IR beam break occupancy

## **5. ULTRAFINE PARTICLE EMISSIONS FROM DESKTOP 3D PRINTERS**

# Desktop 3D printers: Cause for concern?

**3D printing** – or **additive manufacturing** – is a process of making a three-dimensional solid object from a digital model

- Widely used in rapid prototyping and custom fabrication
- Commercial applications include industrial design, architecture, engineering, fashion, dental industries, biotech, food, and many others



Recent advances have greatly reduced costs and made 3D printers widely available for less than **\$2,500** (or as little as **\$500**)



**For as little as \$500...**

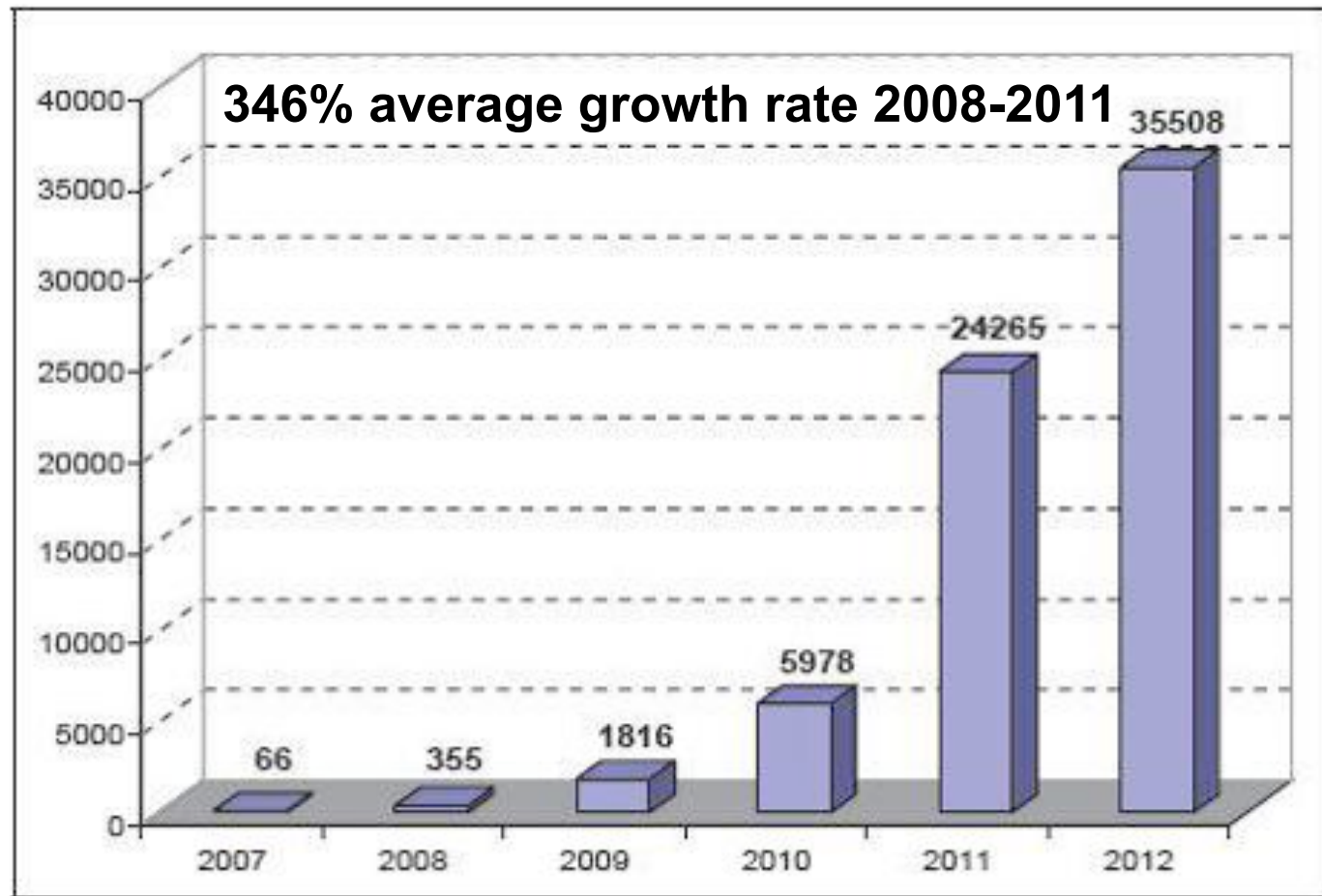
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**You can make all this ~~junk~~ interesting stuff!**



# Personal 3D printer sales are rising steadily



Source: Wohlers Associates, Inc.

Approximately **70,000** personal 3D printers in circulation in 2012

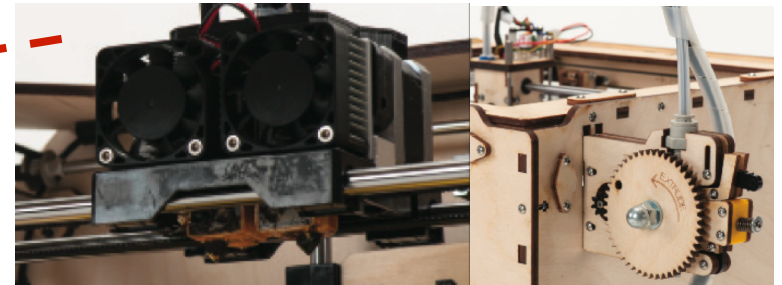
# Additive 3D printers: MPD/FDM

Most 3D printers use a technique called **molten polymer deposition (MPD)**, also known as **fused deposition modeling (FDM)**

Thermoplastic filament

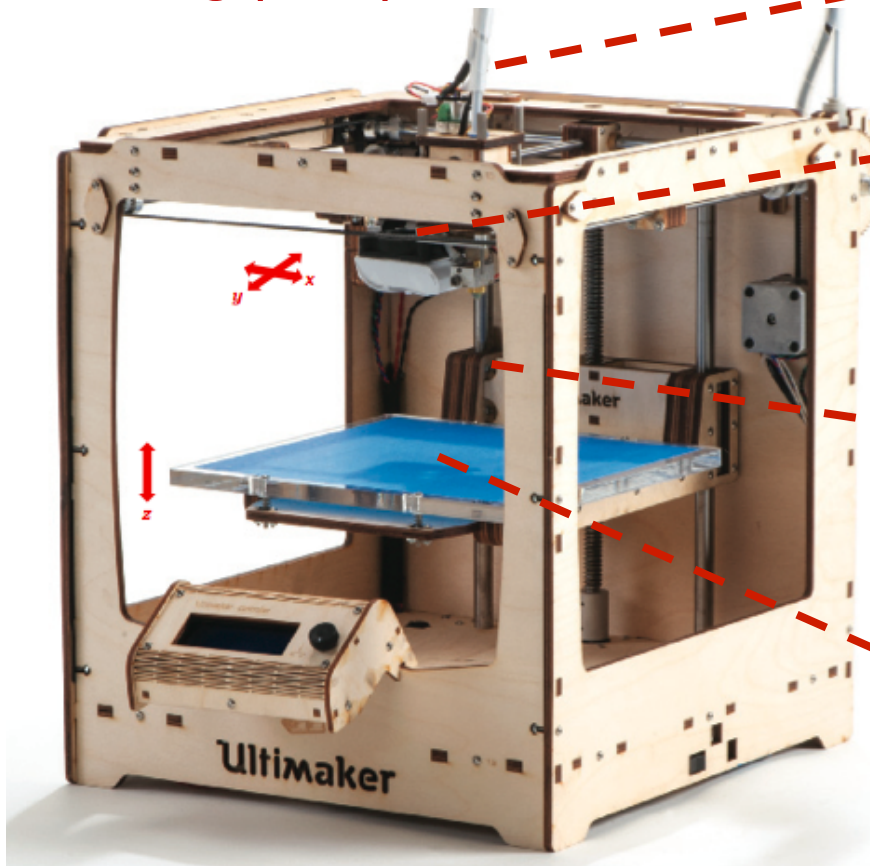
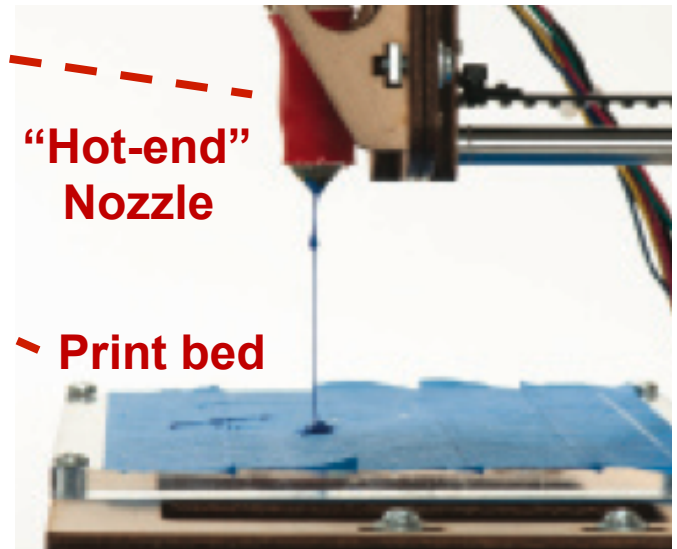


Extruder



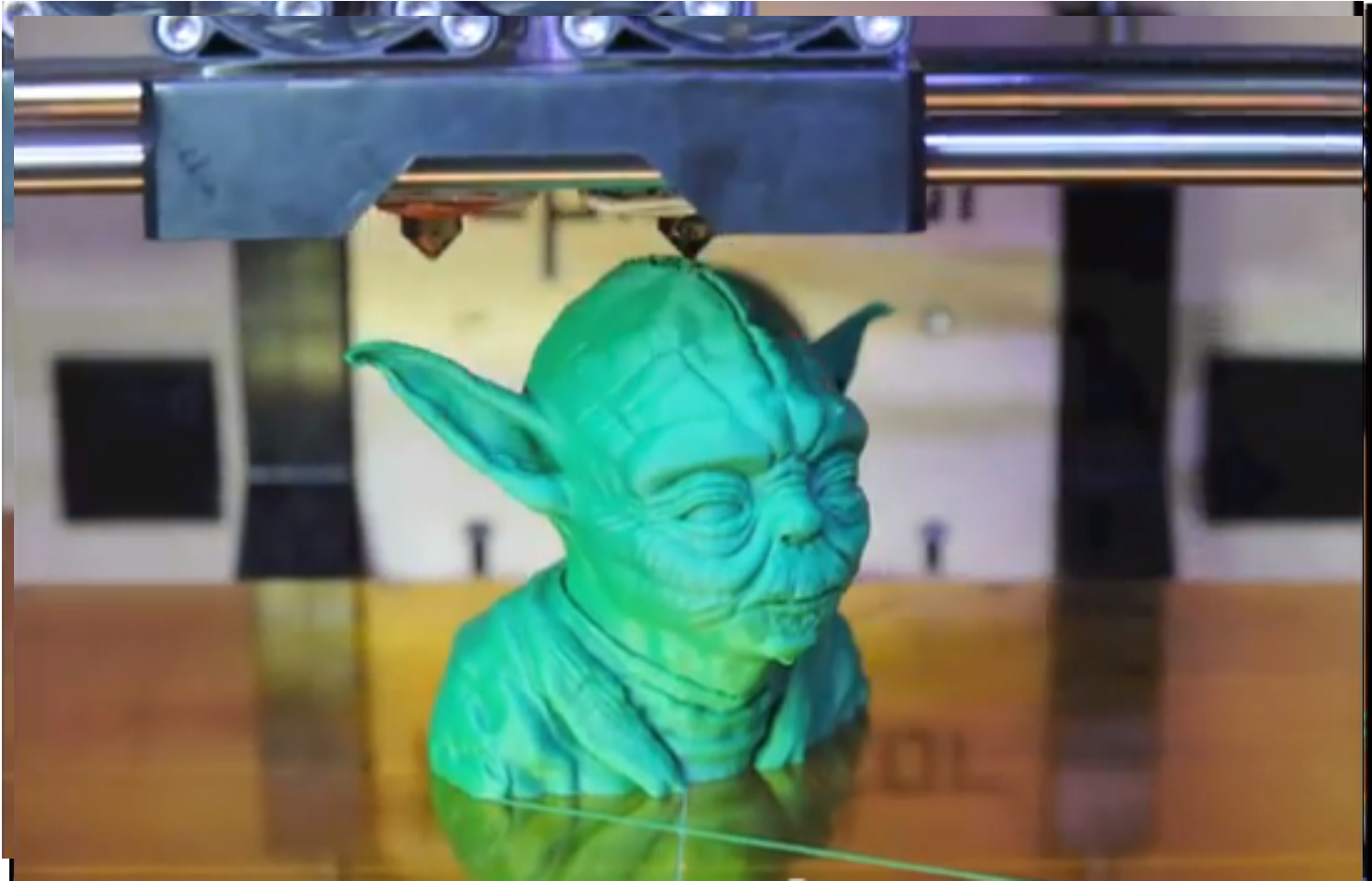
"Hot-end"  
Nozzle

Print bed



# MPD/FDM 3D printer in action

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Yoda head @ 0.1 mm layer height | [http://www.youtube.com/watch?v=8\\_vloWVgf0o](http://www.youtube.com/watch?v=8_vloWVgf0o)

# Additive 3D printers: MPD/FDM

## Thermoplastic filaments

Acrylonitrile butadiene styrene (ABS)

Polylactic acid (PLA)

Polyvinyl alcohol (PVA)

Many others

## Hot-end nozzle

0.2-0.8 mm diameter hole

~160-220°C for PLA

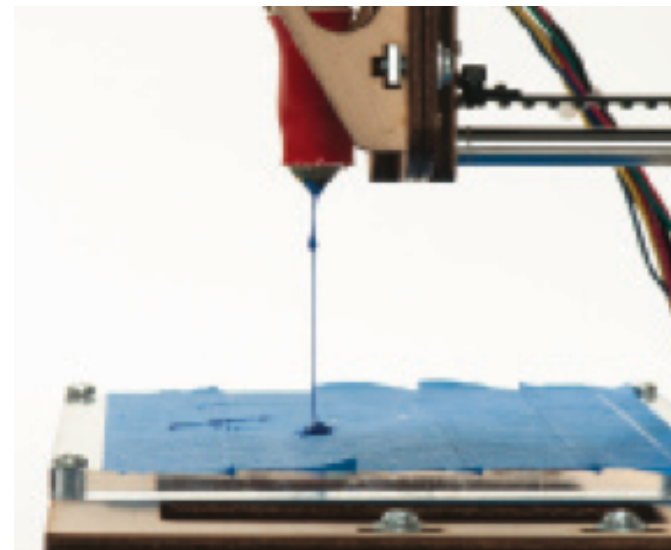
~190°C for PVA

~215-250°C for ABS

## Print bed

<40°C for PLA

~110°C for ABS





# Thermoplastic extrusion/deposition: Cause for concern?

---

- Previous work on large scale industrial thermoplastic processing showed that both gases and particles are emitted during operation

Rutkowski and Levin **1986** *Fire and Materials* 10:93-105; Contos et al. **1995** *J Air Waste Manag Assoc* 45:686-694; Unwin et al. **2013** *Ann Occ Hygiene* 57(3):399-406

- Exposure to decomposition products from ABS thermal processing has been shown to have toxic effects in rats and mice

Zitting and Savolainen **1980** *Archives of Toxicology* 46:295-304; Schaper et al. **1994** *Am Indust Hyg Assoc J* 55:924-934

- Exposure to fumes from thermal decomposition of other plastics (e.g. PTFE) has been shown to be acutely toxic to mammals

Oberdörster et al. **2005** *Environ Health Persp* 113:823-839

- Ultrafine particles appear to be more toxic than gases

Oberdörster et al. **1995** *Inhal Toxicol* 7:111-124;  
Johnston et al. **2000** *Toxicol Applied Pharmacol* 168:208-215

# Our ad-hoc experiment

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- Five 3D printers were tested
  - All 5 were the same popular commercial variety
  - All unenclosed designs



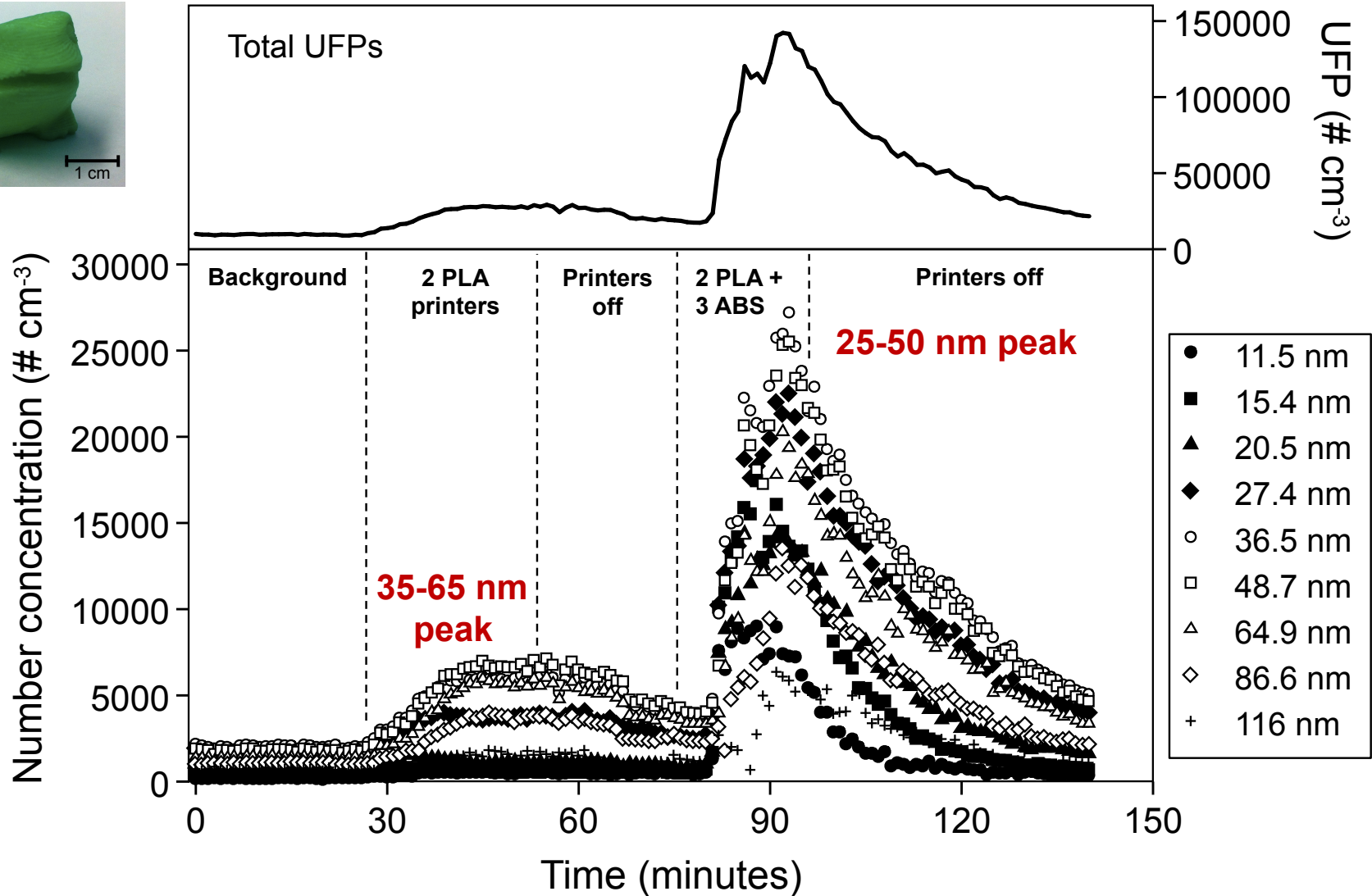
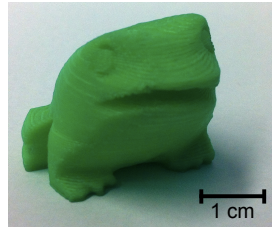
Stephens et al. **2013** *Atmos Environ* 79:334-339

- Two types of filaments at different operational conditions
  - 2 PLA @ 200°C nozzle T and 18°C bed T
  - 3 ABS @ 220°C nozzle T and 118° bed T
- Operating in a closed 45 m<sup>3</sup> office environment
- Ultrafine particle concentrations measured w/ TSI NanoScan SMPS

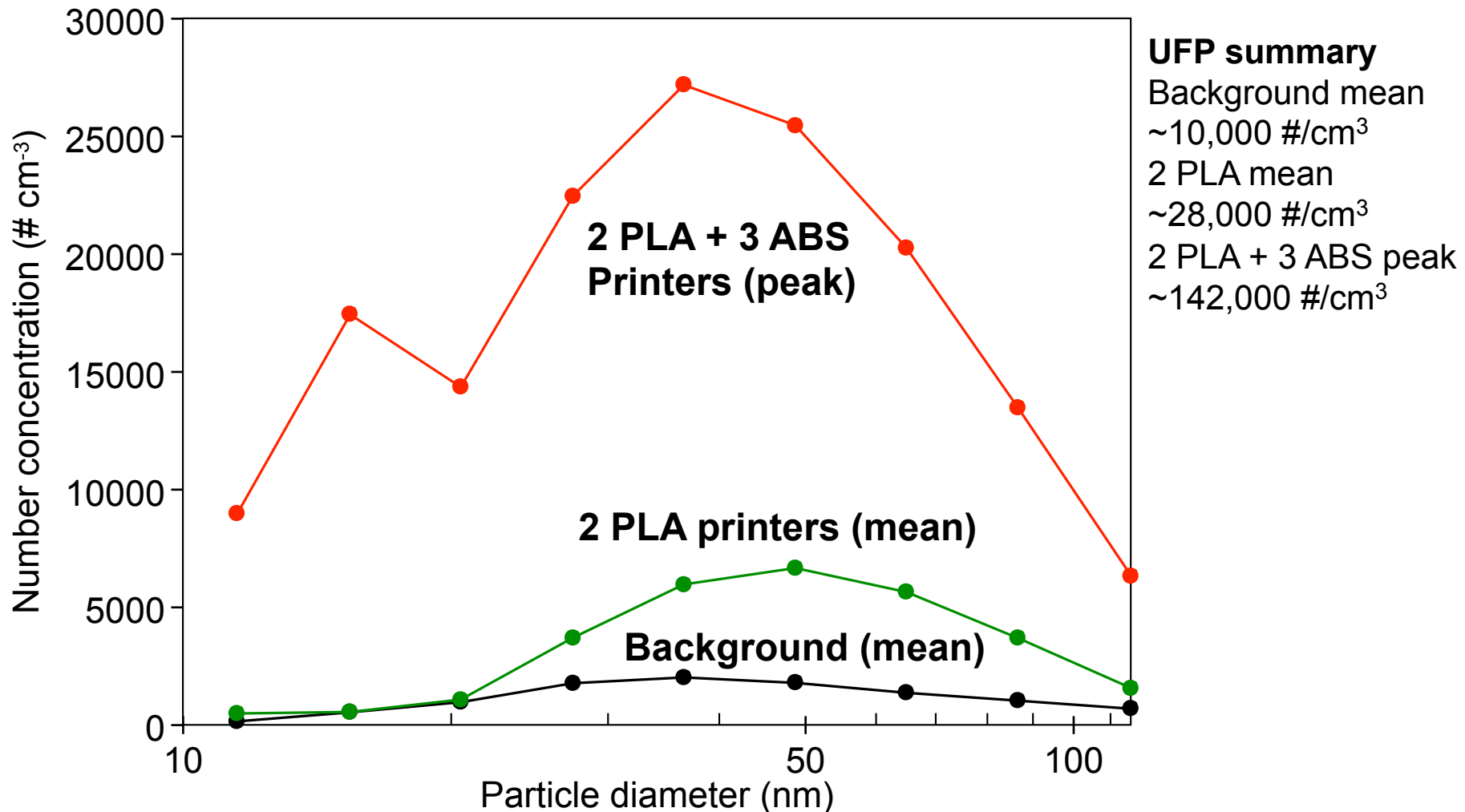
Tritscher et al. **2013** *J Physics* 429



# Measured ultrafine particle concentrations

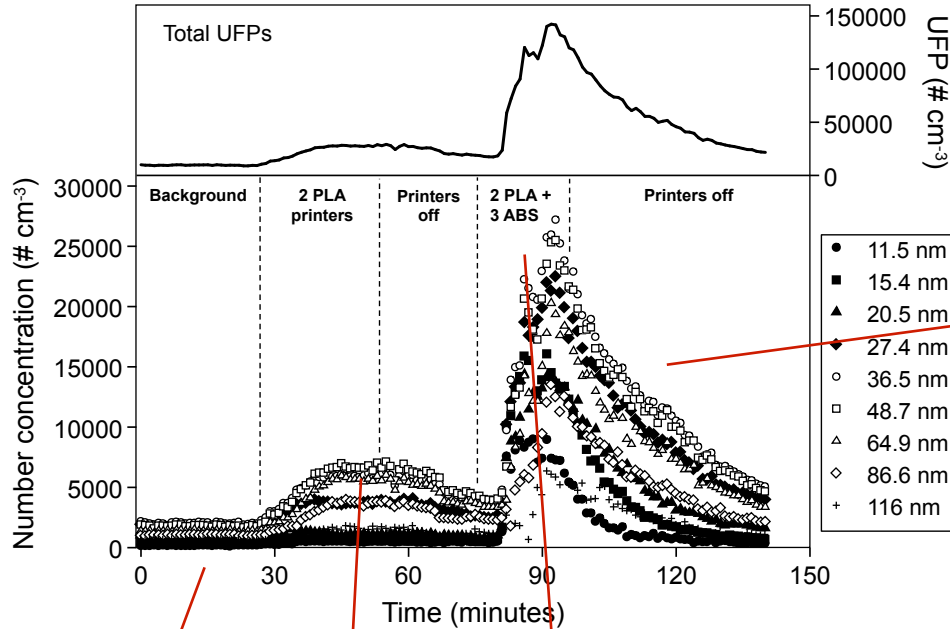


# Mean and peak UFP size distributions





# Estimating emission rates

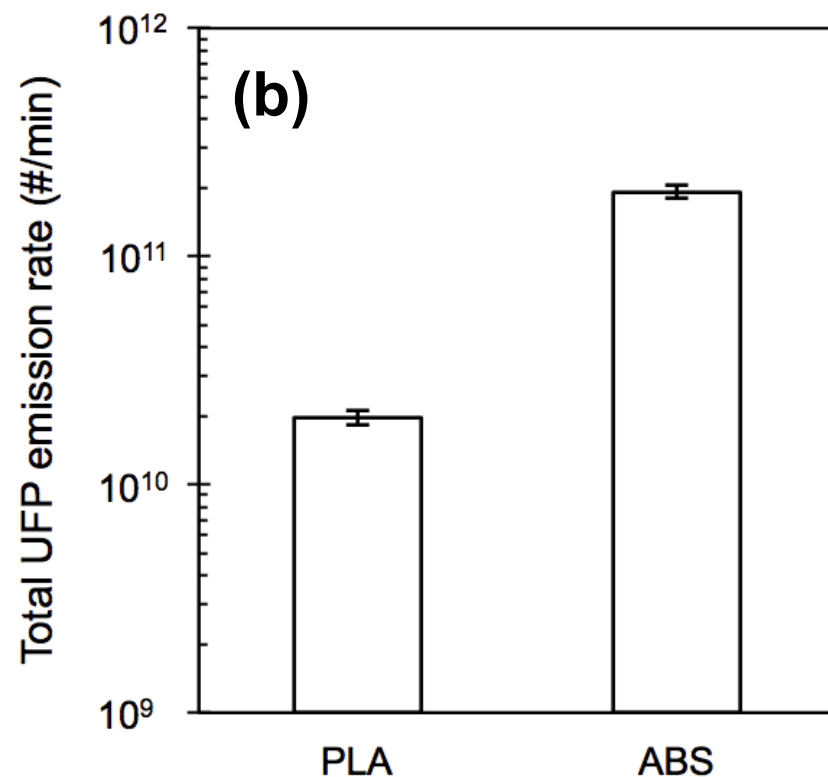
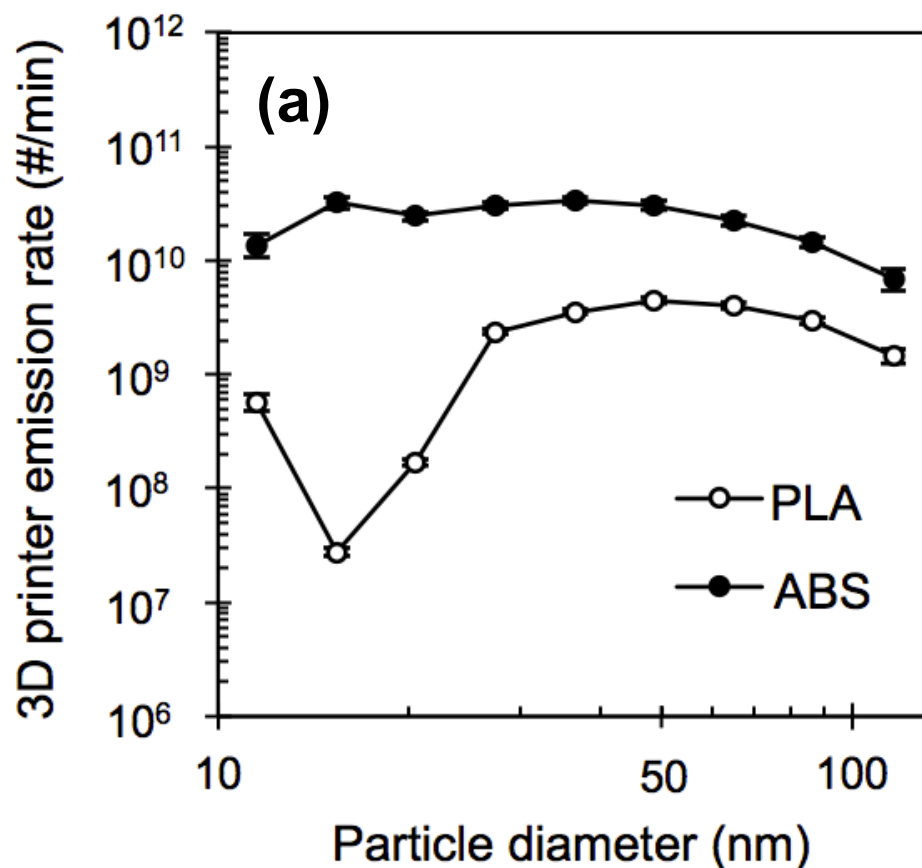


$$\ln \left( \frac{C_{i,in}(t) - C_{i,in,ss,bg}}{C_{i,in}(t=0) - C_{i,in,ss,bg}} \right) = -L_i t$$

$$C_{i,in,ss,2PLA} = C_{i,in,ss,bg} + \frac{2(E_{i,PLA} / V)}{L_i}$$

$$C_{i,in}(t) = C_{i,in,t=0} e^{-L_i t} + \left[ C_{i,in,ss,bg} + \frac{2(E_{i,PLA} / V) + 3(E_{i,ABS} / V)}{L_i} \right] (1 - e^{-L_i t})$$

# Size-resolved and total UFP emission rates



**Total UFP emission rates:**

$\sim 1.9 \times 10^{11}$  #/min from ABS printer

$\sim 2.0 \times 10^{10}$  #/min from PLA printer

# Comparison of emission rates to other indoor emitters

---

UFP emitting device	Size range	Emission rate (#/min)	Reference
Flat iron with steam	20-1000 nm	$6.0 \times 10^9$	Afshari et al. (2005)
Electric frying pan	10-400 nm	$1.1-2.7 \times 10^{10}$	Buonnano et al. (2009)
PLA	10-100 nm	$\sim 2.0 \times 10^{10}$	<i>This study</i>
Vacuum cleaner	20-1000 nm	$3.5 \times 10^{10}$	Afshari et al. (2005)
Scented candles	20-1000 nm	$8.8 \times 10^{10}$	Afshari et al. (2005)
Gas stove	20-1000 nm	$1.3 \times 10^{11}$	Afshari et al. (2005)
ABS	10-100 nm	$\sim 1.9 \times 10^{11}$	<i>This study</i>
Cigarette	20-1000 nm	$3.8 \times 10^{11}$	Afshari et al. (2005)
Electric stove	20-1000 nm	$6.8 \times 10^{11}$	Afshari et al. (2005)
Frying meat	20-1000 nm	$8.3 \times 10^{11}$	Afshari et al. (2005)
Radiator	20-1000 nm	$8.9 \times 10^{11}$	Afshari et al. (2005)
Laser printers	6-3000 nm	$4.3 \times 10^9$ to $3.3 \times 10^{12}$	He et al. (2010)
Cooking on a gas stove	10-400 nm	$1.1-3.4 \times 10^{12}$	Buonnano et al. (2009)

# News coverage: Tell your own story

---



Are 3D printers harmful to your health?



GEAR AND GADGETS

**3-D Printers Might Be Hazardous To Your Health**

JUL 25, 2013 03:34 PM ET // BY JESSE EMSPAK

**Airborne particles from 3D printers could be as harmful to your health as cigarette smoke**

**Mail**Online

**The Telegraph** 3D printers could cause strokes, researchers warn

**FASTCOMPANY**

**Will A 3-D Printer Destroy Your Lungs?**

**Is There Long-Term Health Risks to 3-D Printing? One Study Says 'Yes'**

**StreetInsider.com**  
*if you're not inside...you're outside*



# More good (and bad) press...



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### 1. Ultrafine particle emissions from desktop 3D printers

November 2013

Brent Stephens | Parham Azimi | Zeineb El Orch | Tiffanie Ramos

**Abstract:** The development of low-cost desktop versions of three-dimensional (3D) printers has made these devices widely accessible for rapid prototyping and small-scale manufacturing in home and office settings. Many desktop 3D printers rely on heated thermoplastic extrusion and deposition, which is a process that has been shown to have significant aerosol emissions in industrial environments. However, we are not aware of any data on particle emissions from commercially available desktop 3D printers. Therefore, we report on measurements of size-resolved and total ultrafine particle (UFP) concentrations resulting from the operation of two types of commercially available desktop 3D printers inside a commercial office space. We also estimate size-resolved (11.5 nm–116 nm) and total UFP (<100 nm) emission rates and compare them to emission rates from other desktop devices and indoor activities. Emission rates of total UFPs were large, ranging from polylactic acid (PLA) feedstock to  $1.9 \times 10^{11}$  #/h. For ABS, a temperature sensitive acrylonitrile butadiene styrene (ABS) currently sold as standalone devices without any safety warnings, we suggest caution should be used when operating these devices. Additionally, these results suggest that more comprehensive studies should fundamentally evaluate particle emissions from a wider range of desktop 3D printers.

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86.40 -1.29 (-1.47%)



1d

5d

1m

6m

1y

5y

max

Open	88.60
High	89.47
Low	85.95
Volume	289,346
Avg Vol	742,000
Mkt Cap	3.39B

# Potential for 3D printed 3D printer filtration systems

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# Moving forward...

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We continue to conduct research at the intersection of energy and air quality in the built environment

## New projects:

- OSBSS, Nov 2013 – April 2015
- Sloan Foundation MoBE Post-doc, Stevie Kunkel, Biology, 2014 – 2016
  - Control/filtration of airborne microorganisms (experimental)
- ASHRAE 1691-TRP Modeling impact of HVAC filters on indoor PM in homes, starting later this year

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