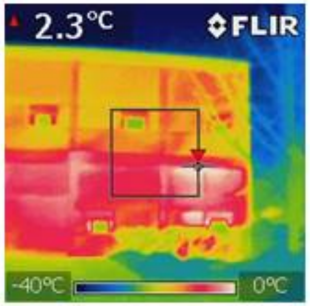

Energy and air quality in the built environment

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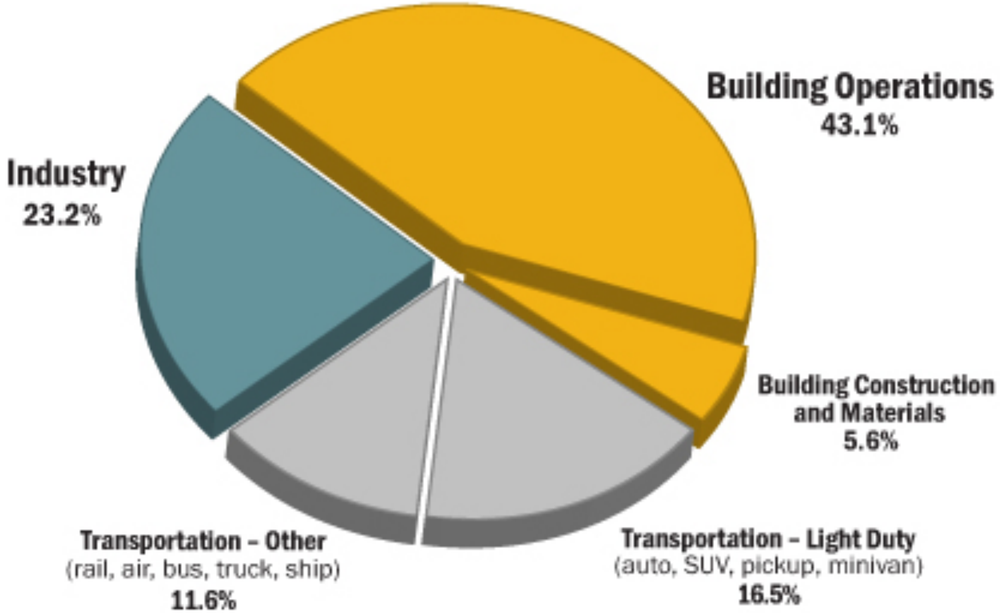
What do you think of when you hear "energy"?





What do I think of when I hear "energy"?

Buildings

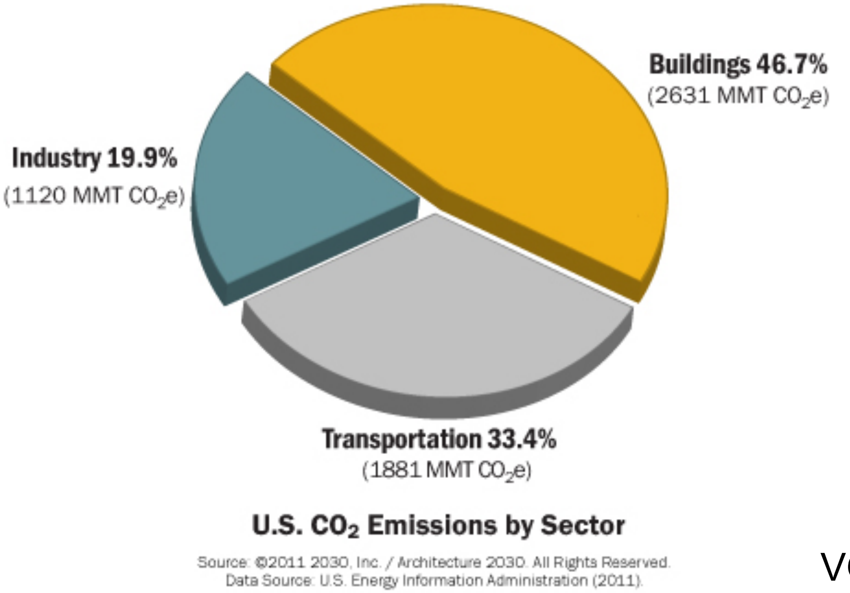


Buildings account for ~43-48% of total U.S. energy consumption

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

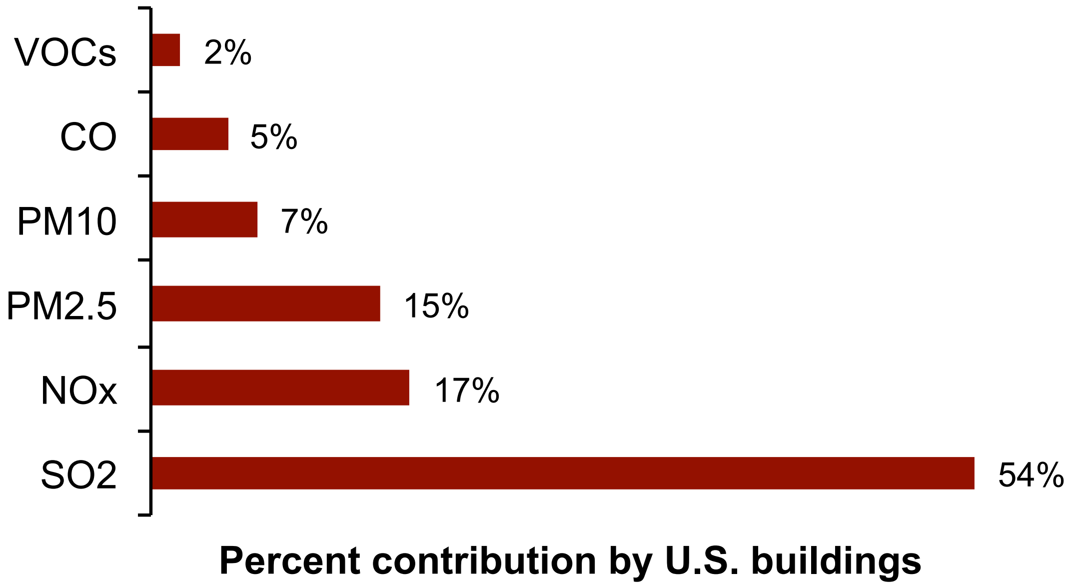
Contribution to GHGs



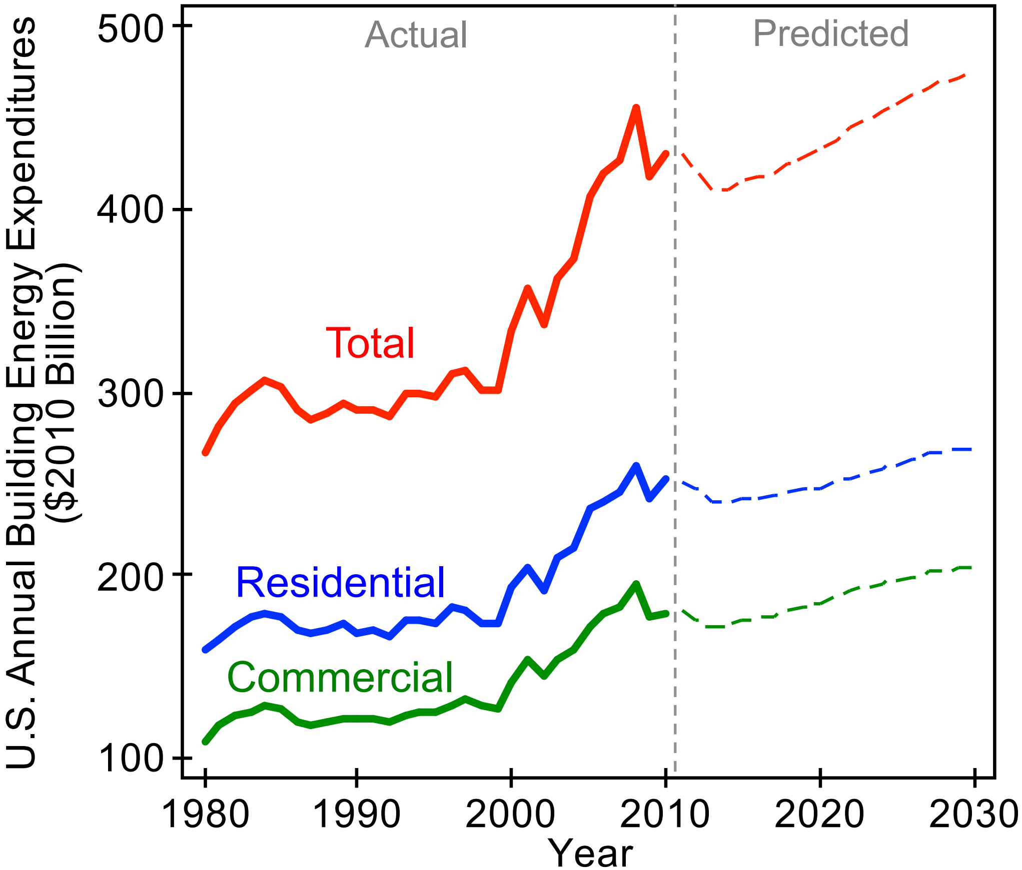
Major uses

- Heating
- Cooling
- Lighting
- Water heating

Contribution to outdoor air pollution

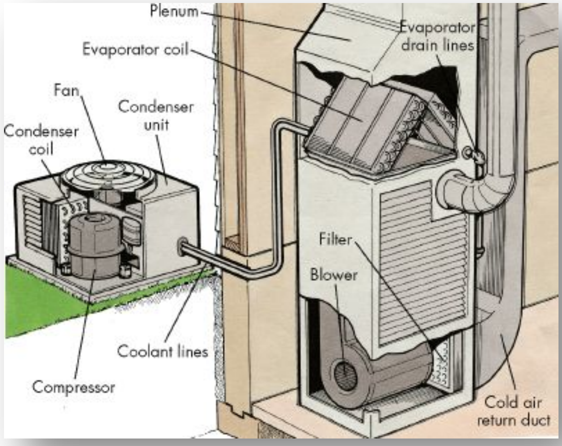


Building energy use costs *a lot* of money



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"?

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"?

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

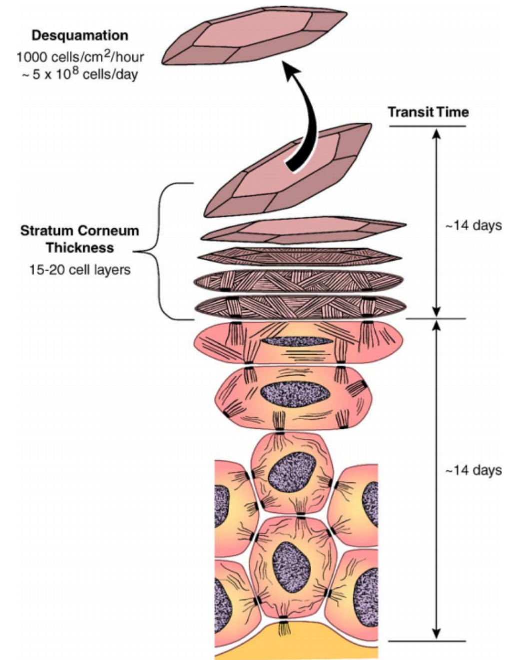
Zock et al., *Am. J. Respir. Crit. Care. Med.* **2007**, 176, 735-741

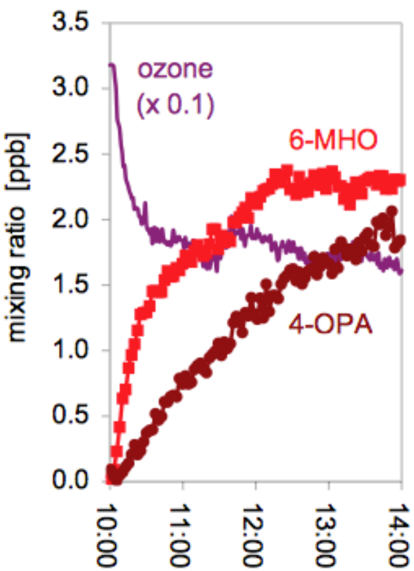
What do I think of when I hear "air pollution"?

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

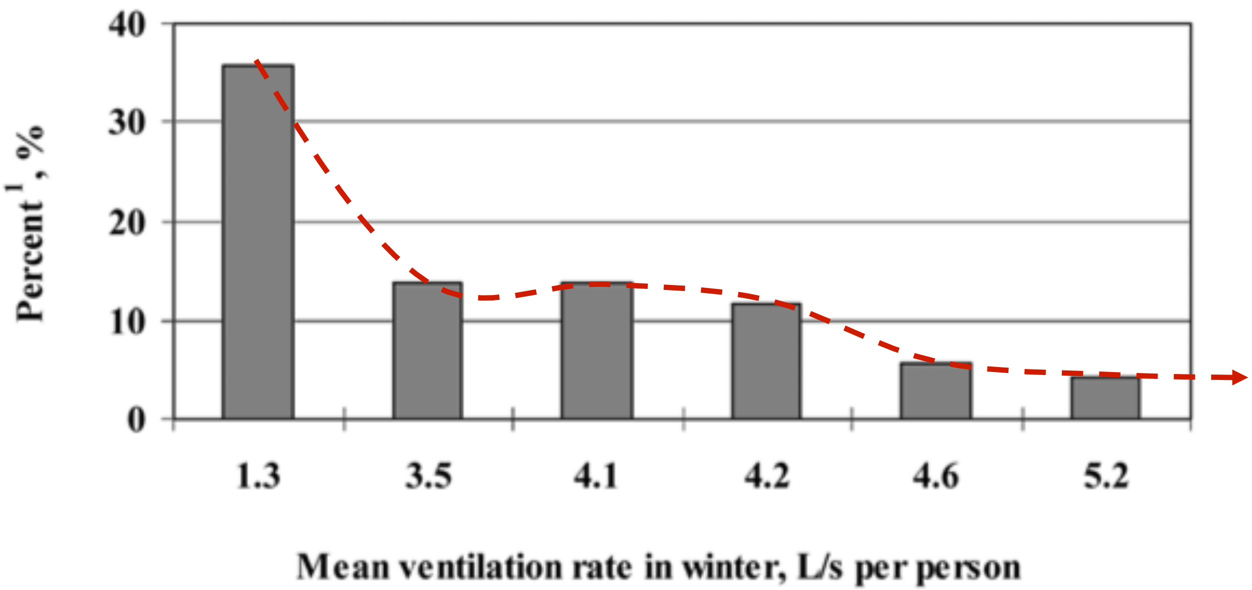
What do I think of when I hear “air pollution”?

Evidence of Airborne Transmission of the Severe Acute Respiratory Syndrome Virus

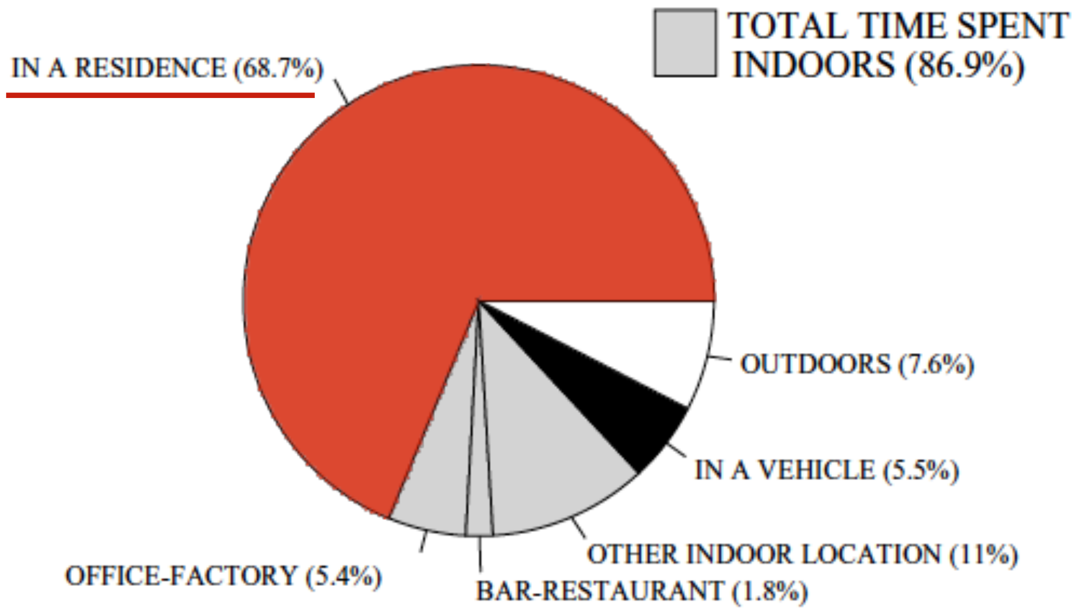
Yu et al., *New Engl. J. Med* **2004**, 350, 1731-1739

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

- Residential indoor air pollution is estimated to result in **5-14%** of the annual non-communicable, non-psychiatric **disease burden** in the U.S.
  - Excludes SHS and radon

Logue et al., *Environ. Health Perspect.* **2012**, 120, 216-222

- Cumulative lifetime **cancer risks** of **1-10** excess cases **per 10,000** people

Wallace et al., *Environ. Health Perspect.* **1991**, 95, 7-13
Sax et al., *Environ. Health Perspect.* **2006**, 114, 1558-1566
Hun et al., *Environ. Health Perspect.* **2009**, 117, 1925-1931

Buildings impact people, energy, and the environment

The design, construction, and operation of buildings greatly affect their contribution to energy use, greenhouse gas emissions, financial expenditures, human exposures to airborne pollutants, and human health

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

Research areas:

Indoor air quality

Building science measurements and methods

HVAC filtration and air cleaning

Human exposure assessment

Building energy efficiency and energy modeling

The Built Environment Research Group

advancing energy, environmental, and sustainability research within the built environment at Illinois Institute of Technology

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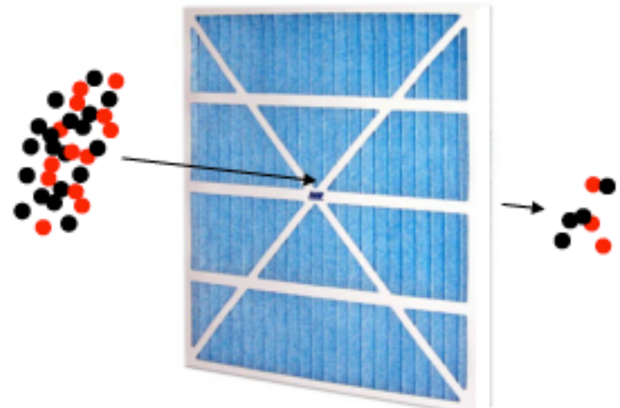
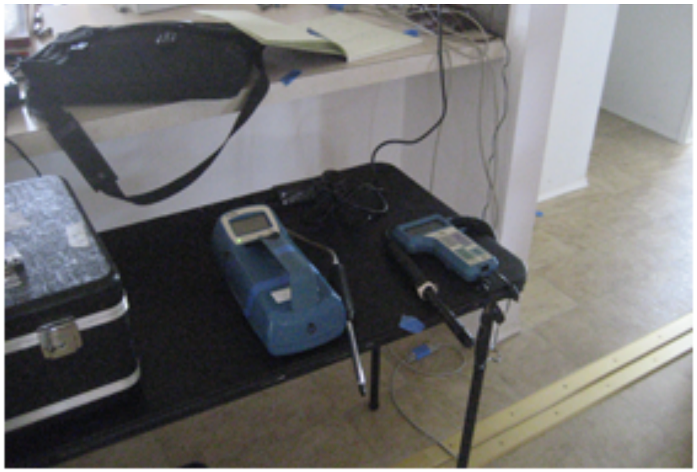
BS Candidate, ECE
Deion Debose
BS Candidate, CAEE
Jihad Zeid
BS Candidate, ChBE
Boyang “Bobo” Dong
BS Candidate, ECE
Rou Yi Yeap
BS Candidate, ChBE
Zack Zanzinger
BS Candidate, CAEE
Tommy Zakrzewski
Part-time PhD Candidate, CE

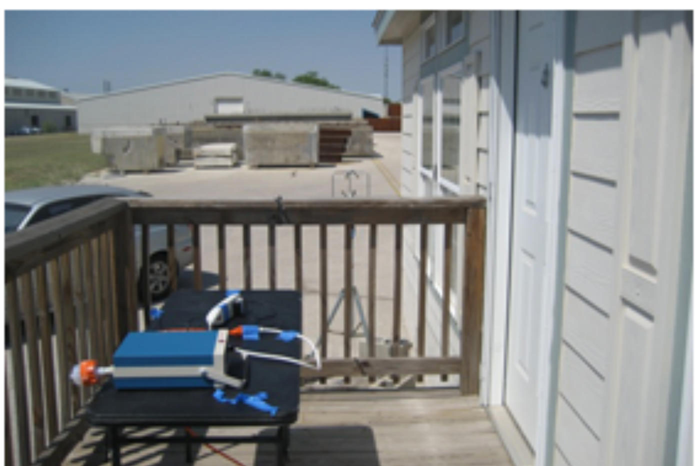
Highlights of some recent research projects

2) Filtration of indoor aerosols



1) Characterizing outdoor pollutant infiltration





3) Ultrafine particle emissions from 3D printers

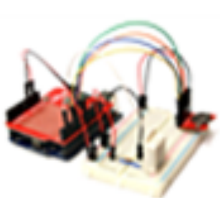
Highlights of some recent research projects

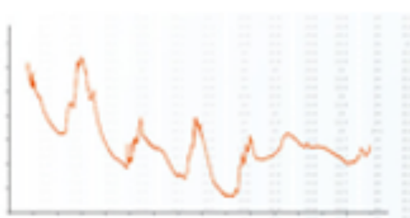
4) Building science measurements in the Hospital Microbiome Project

6) Optimizing Chicagoland housing retrofits for 50% energy savings

5) Open source building science sensors

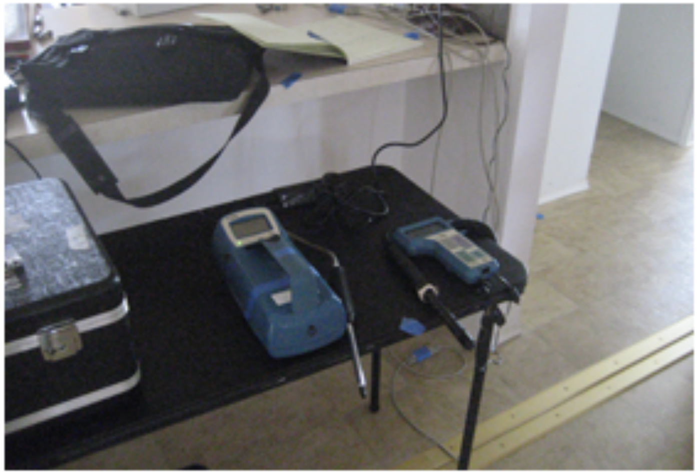
OSBSS

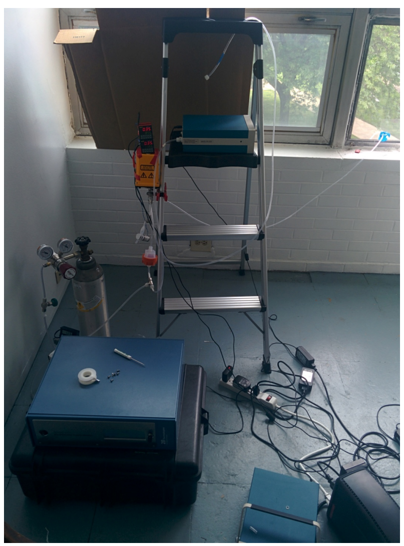




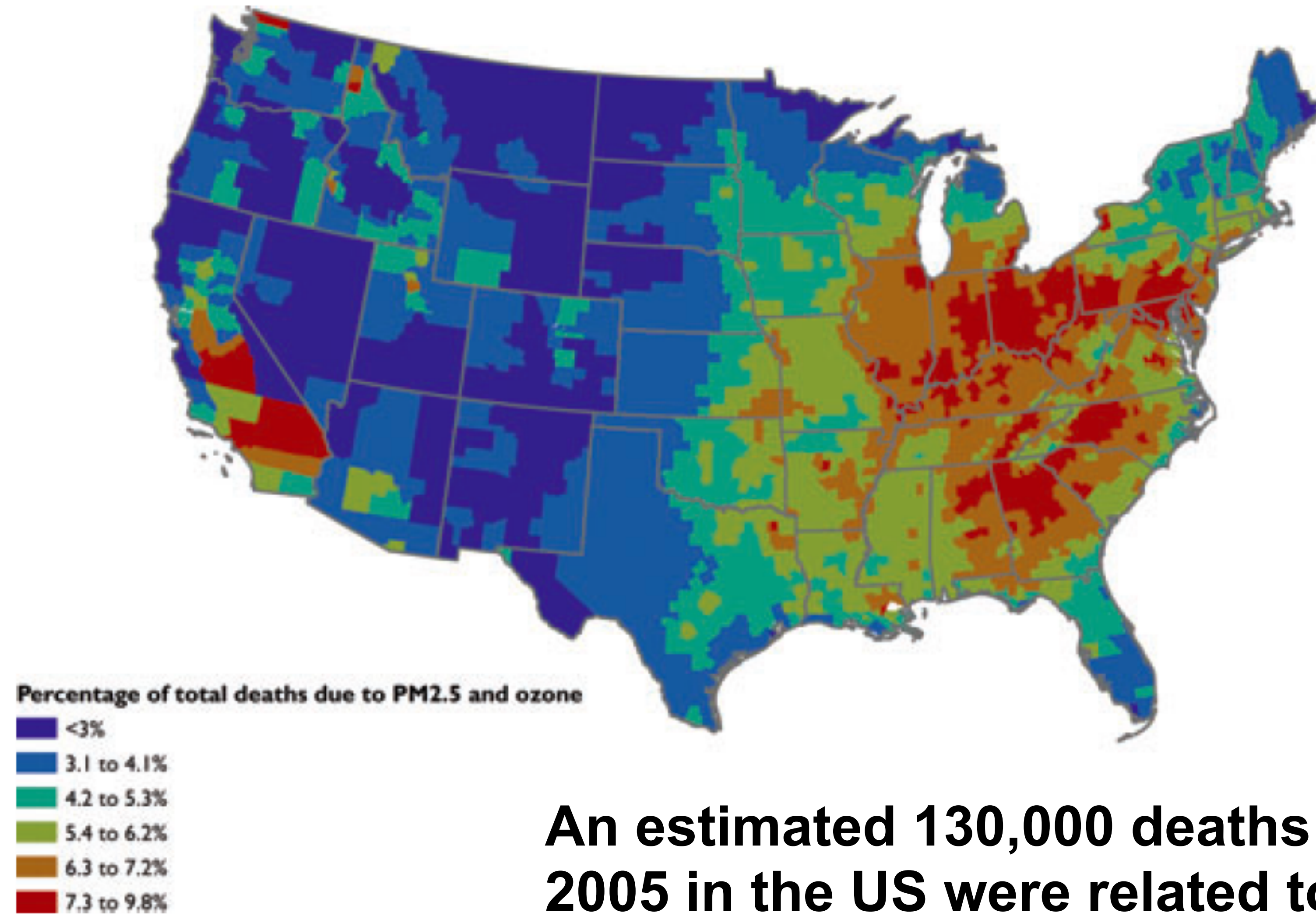
7) Indoor air and climate change

1) Characterizing outdoor pollutant infiltration





Motivation: Outdoor ozone and particulate matter



An estimated 130,000 deaths in 2005 in the US were related to outdoor $PM_{2.5}$ (and 4,700 w/ O_3)

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

Exposures to outdoor O_3 and PM

- Elevated outdoor concentrations → health effects

Particulate Matter (PM)	**Ozone (O_3)**
Respiratory symptoms, cardiovascular mortality, lung cancer	Hospital admissions, respiratory illness, short-term mortality
Pope et al., **2002** *J Am Med Assoc*; Pope and Dockery, **2006** *J Air Waste Manag Assoc*; Miller et al., **2007** *New Engl J Med*; Ostro et al., **2010** *Environ Health Persp*	Gent et al., **2003** *J Am Med Assoc*; Bell et al., **2004** *J Am Med Assoc*; Hubbell et al., **2005** *Environ Health Persp*; Jerrett et al., **2009** *New Engl J Med*

- Americans spend most of their time indoors (nearly 90%)

  ~70% at home Klepeis et al., **2001** *J Expo Anal Env Epi*

- Outdoor PM and O_3 infiltrate in buildings w/ varying efficiencies

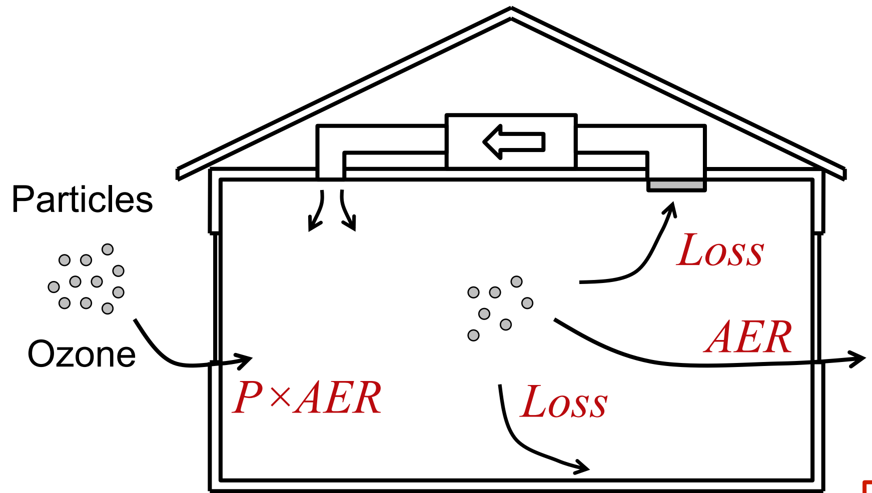
  PM: Chen and Zhao, **2011** *Atmos Environ*
  O_3: Avol et al., **1998** *Environ Sci Technol*; Weschler, **2000** *Indoor Air*

- Exposure to outdoor PM and O_3 (+ rxns) often occurs indoors

  PM: Meng et al., **2005** *J Exp Anal Environ Epidem*; Kearney et al., **2010** *Atmos Environ*
  O_3: Weschler, **2006** *Environ Health Persp*

- But we don't fully understand how and why infiltration varies
  - Lack of knowledge leads to "exposure misclassification"

Mechanisms that impact indoor exposures to outdoor pollutants



Penetration from outdoors

Indoor/Outdoor pollutant concentration

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

Removal by air exchange

Removal by deposition to or reaction with surfaces, homogenous reactions, and/or HVAC system

"Penetration Factor"

If *P* = 1:

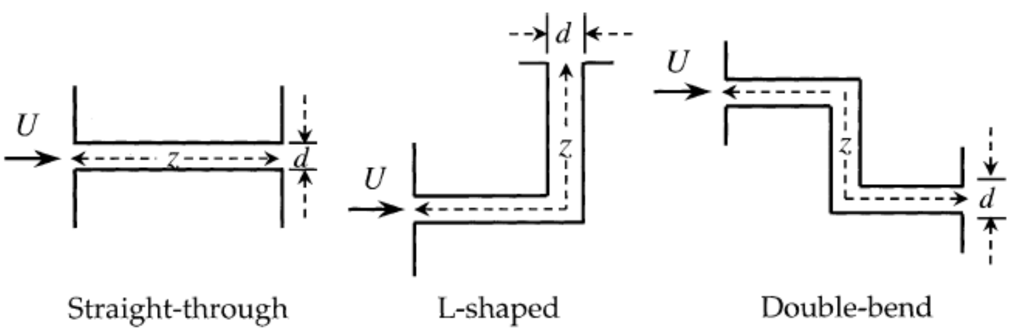
The envelope offers no protection

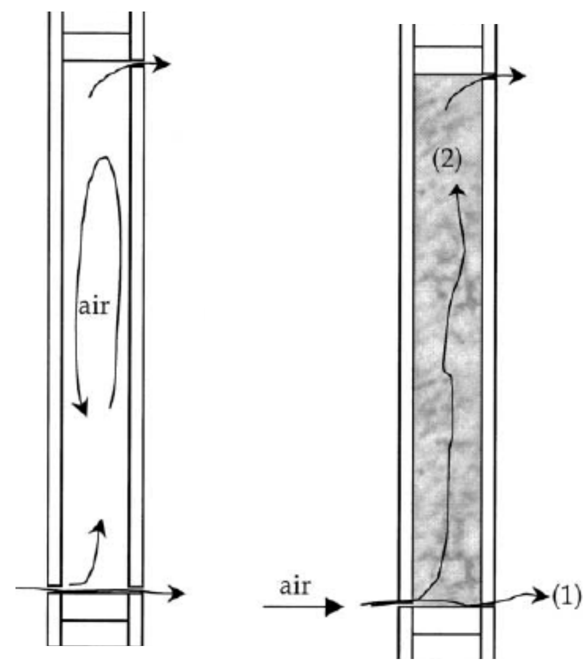
If *P* = 0:

The envelope offers complete protection

Envelope penetration factors

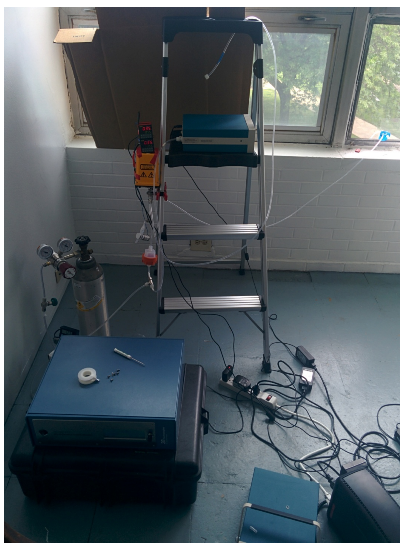
- O_3 and PM can infiltrate through leaks in building envelopes
  - Ozone can react with envelope materials
  - Particles can deposit on envelope materials
- No one has ever measured natural ozone penetration factors
  - Some modeling, some unrealistic measurements (by me)
- A few groups have measured PM penetration factors
  - Limited in number





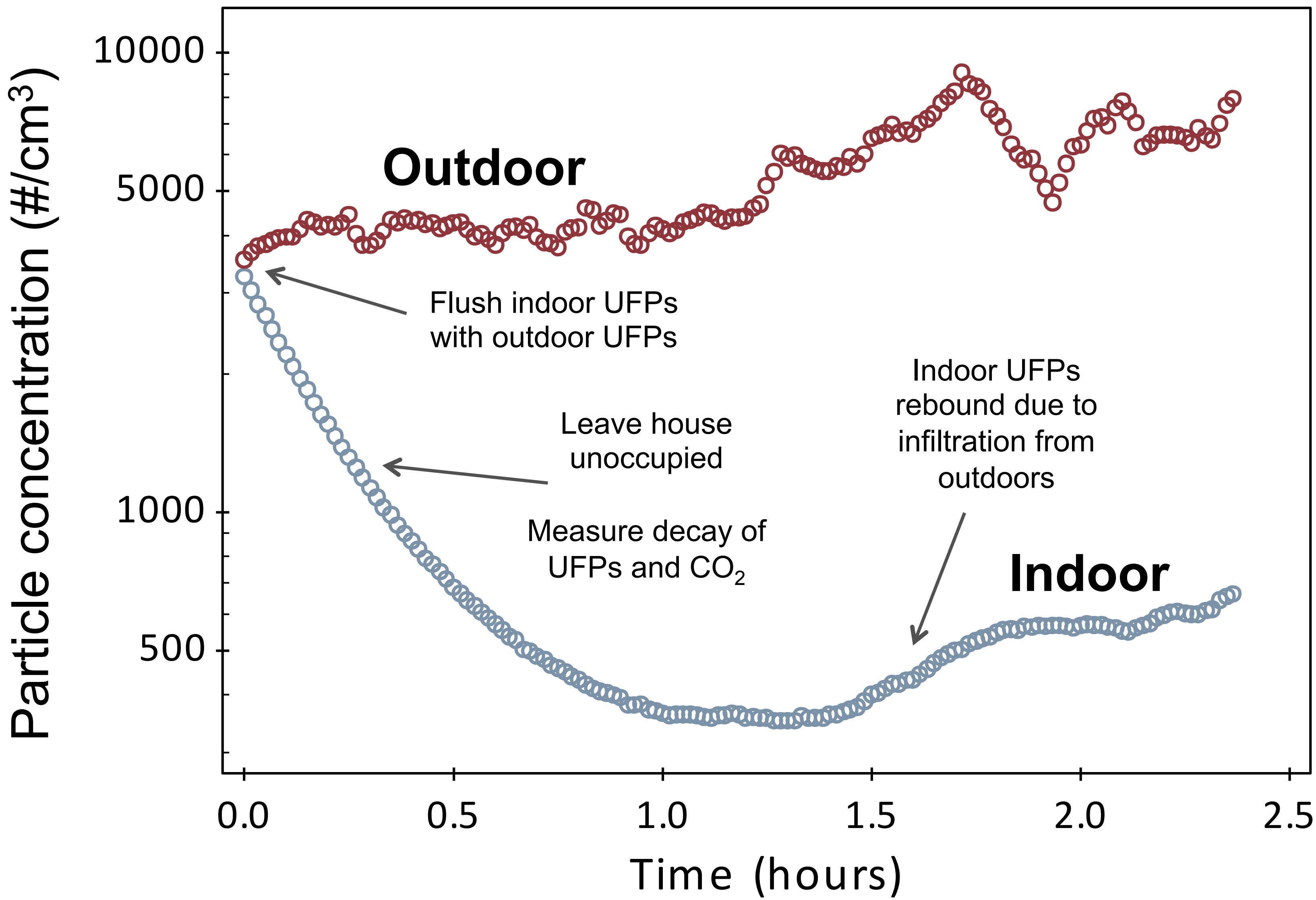
Measuring envelope penetration factors

We have been working on novel methods to rapidly measure envelope penetration factors in order to characterize the ability of building envelopes to prevent the transport of outdoor pollutants indoors



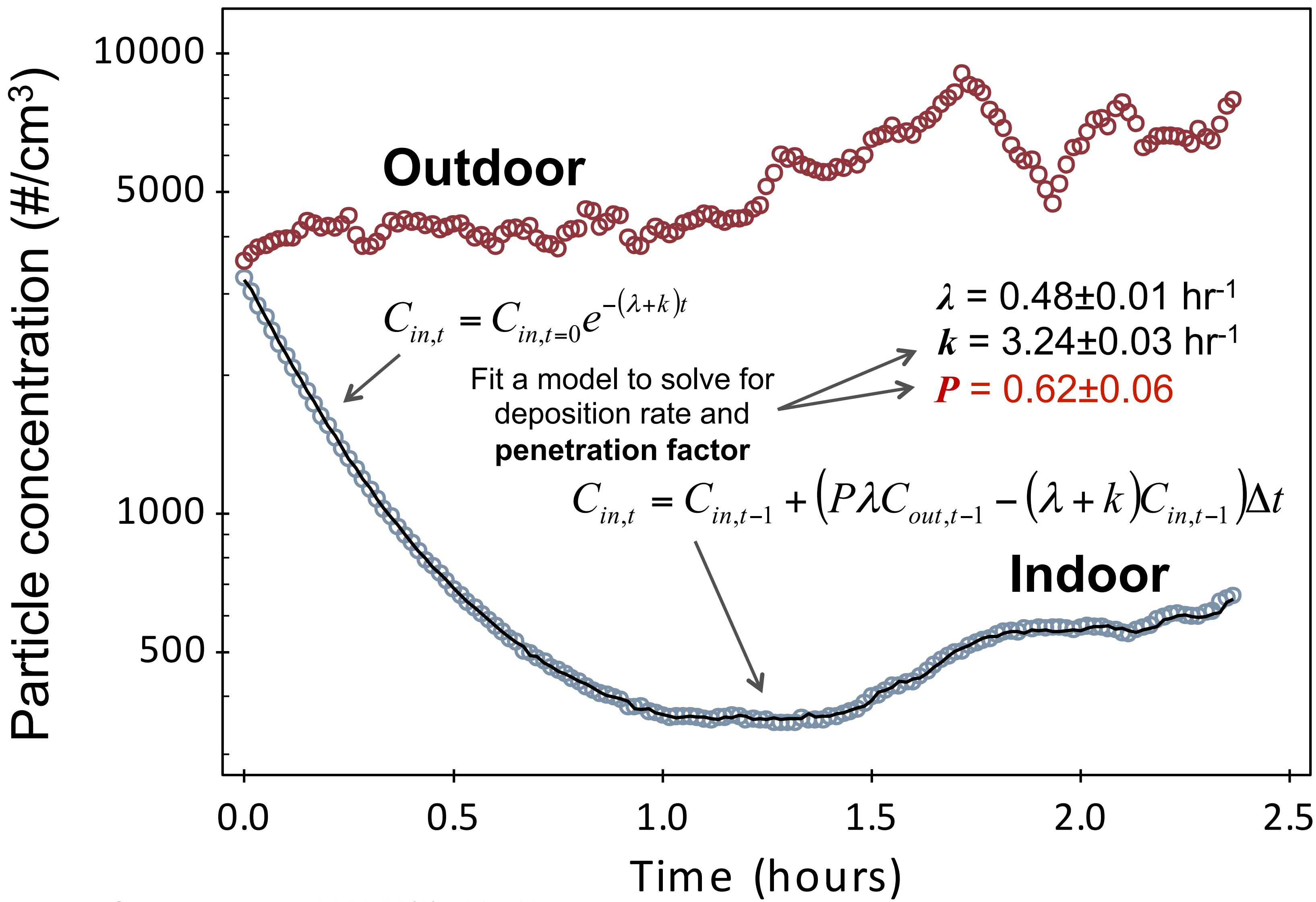
- Size-resolved PM 0.01-10 μm
- $PM_{2.5}$
- Ultrafine particles (UFPs < 100 nm)
- Black carbon
- O_3
- NO_x

Test method for ultrafine particle (UFP <100 nm) penetration



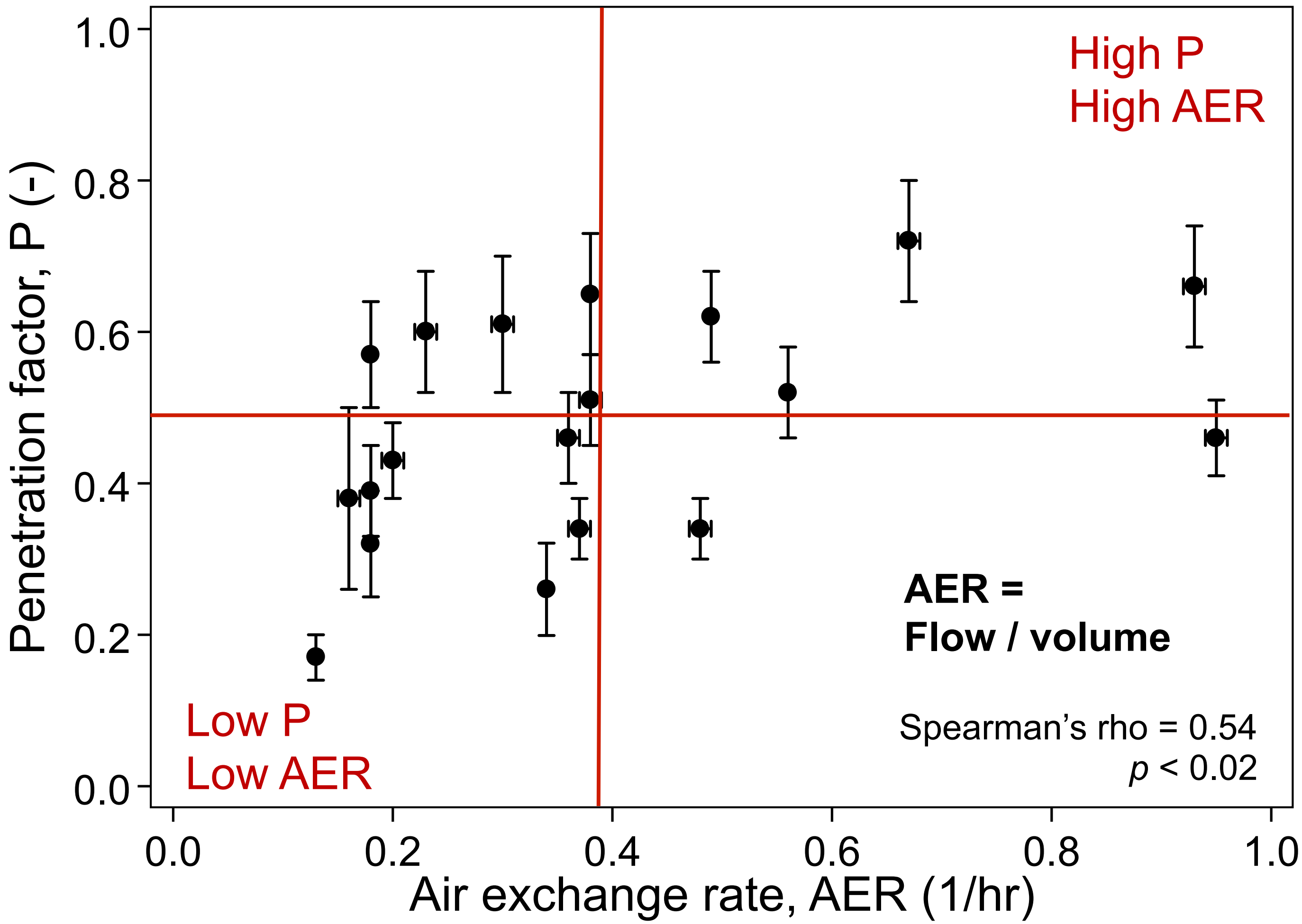
Stephens and Siegel, *Indoor Air* **2012** 22(6):501-512

Test method for ultrafine particle (UFP <100 nm) penetration



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

UFP penetration results: P vs. AER



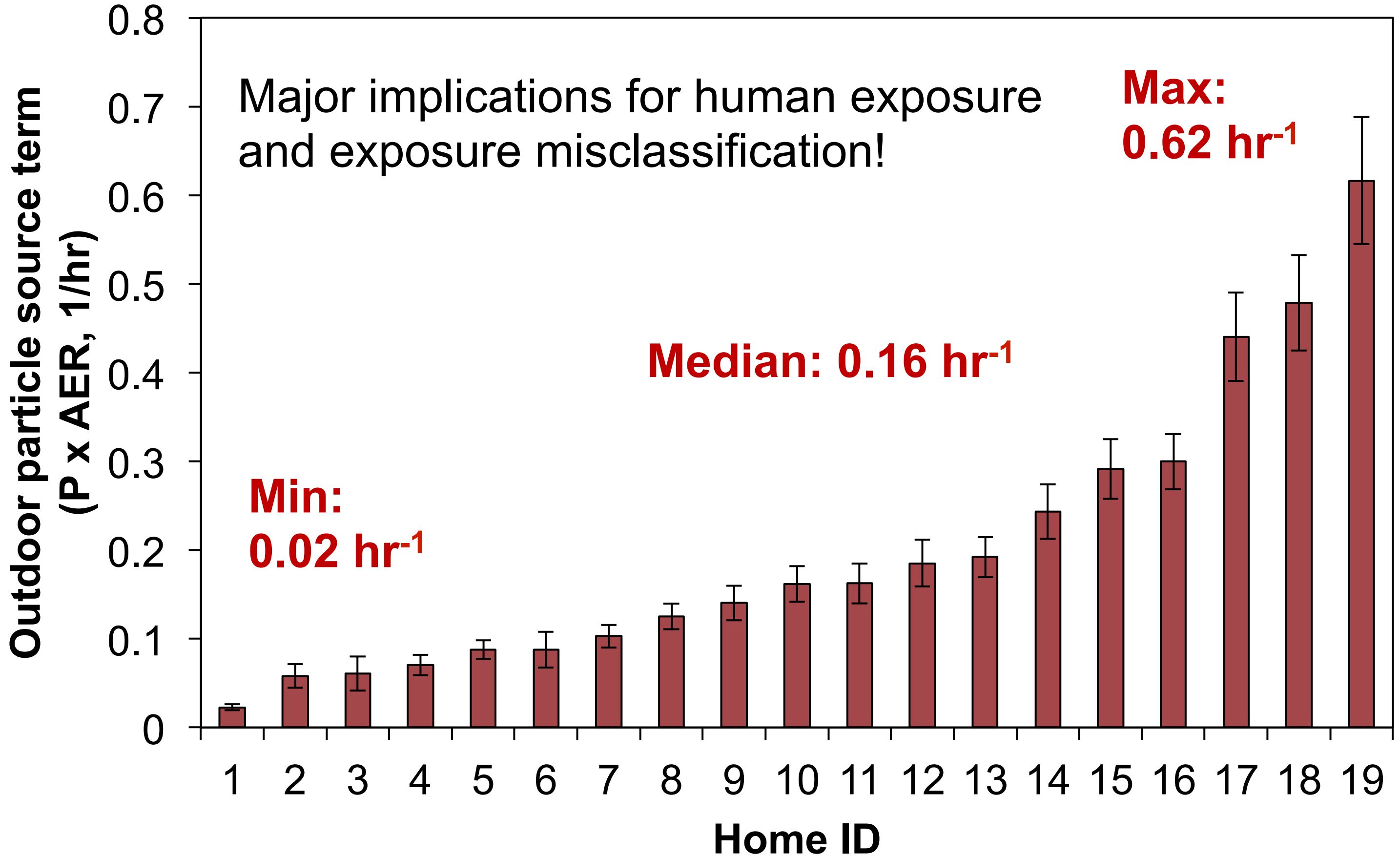
Penetration factors: Mean = 0.47 Range = 0.17 to 0.72

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

Stephens, *Science and Technology for the Built Environment* **2014** 21:3-13

Outdoor UFP source terms: Penetration × AER

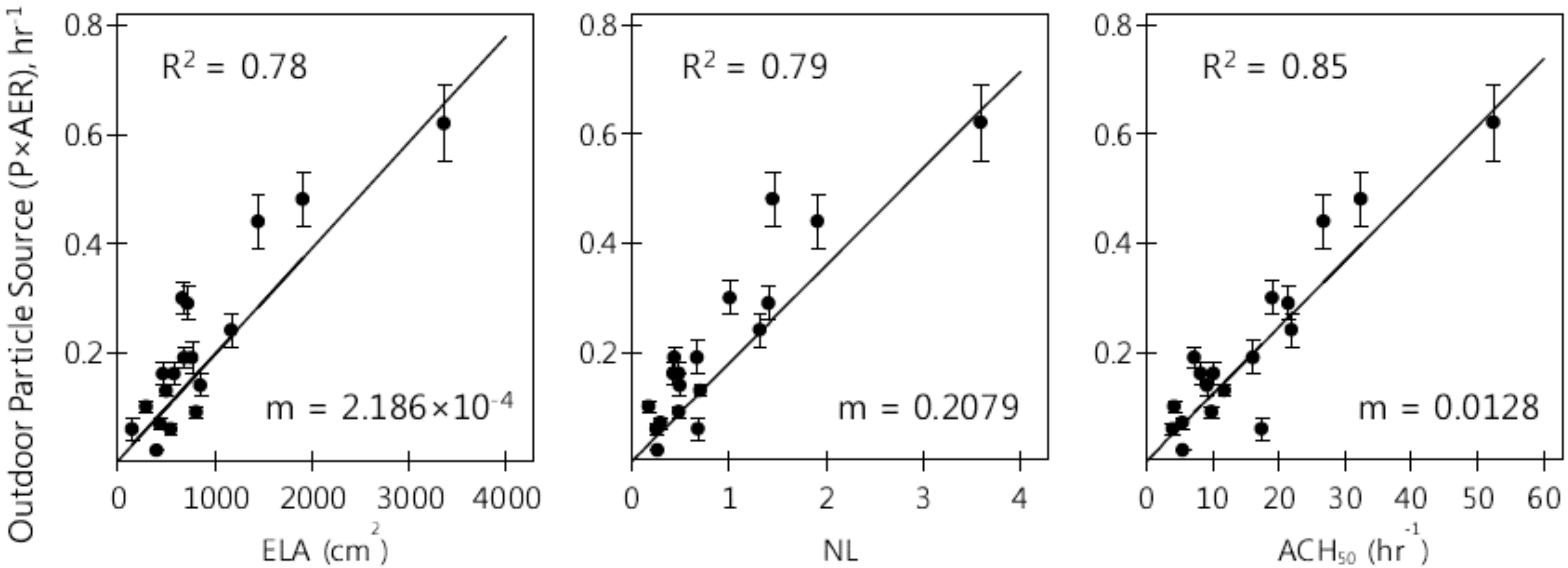
$$\frac{C_{in}}{C_{out}} = \frac{P \times AER}{AER + Loss}$$



Stephens, *Science and Technology for the Built Environment* **2014** 21:3-13

Outdoor UFP source terms and air leakage

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



Leakier homes had much higher outdoor particle source rates

- Leaky homes are also older – predictive ability?
- Potential socioeconomic implications: low-income homes are also leakier

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

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

Outdoor ozone (O_3) infiltration

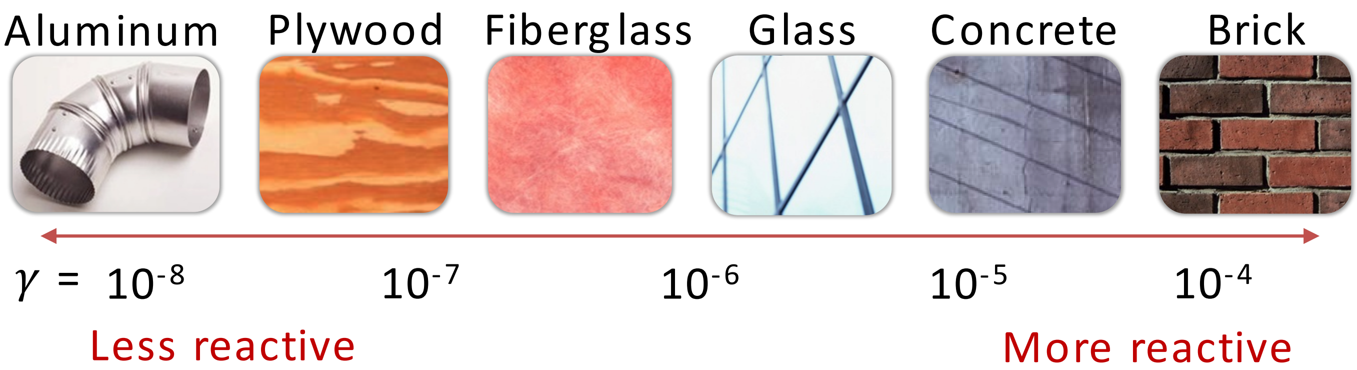
- Typically assumed that ozone penetration factor = 1

Weschler, **2000** *Indoor Air*; Weschler, **2006** *Environ Health Persp*

- But ozone reacts with common envelope materials:

O_3 Reaction Probability, γ

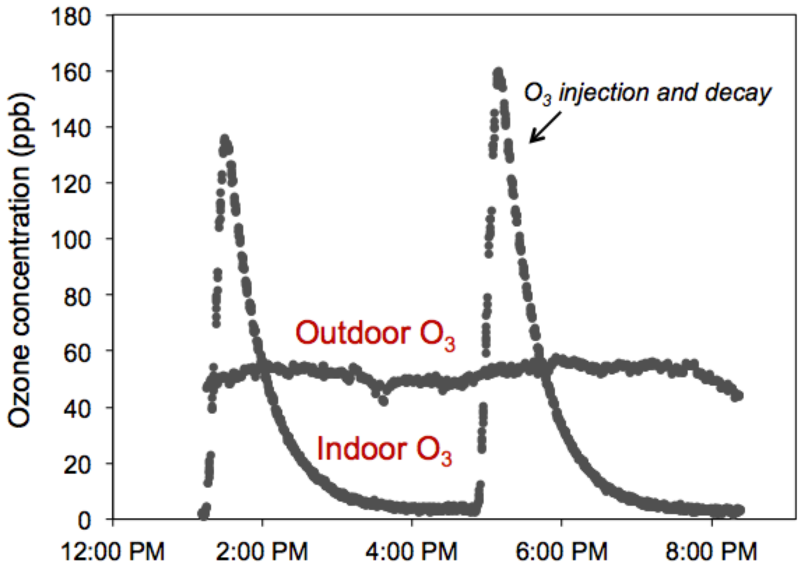
From Liu and Nazaroff (2001)



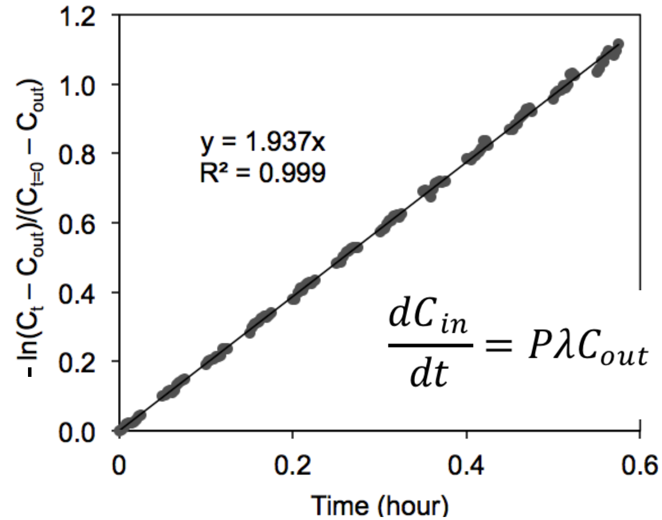
- Need a test method to solve for two unknown parameters with one equation
  - Ozone injection and decay with simultaneous air exchange measurements

Improved method for measuring O_3 penetration

a) Raw experimental data



b) First-order decay rate coefficient



$$\frac{dC_{in}}{dt} = P\lambda C_{out} - (\lambda + k)C_{in}$$

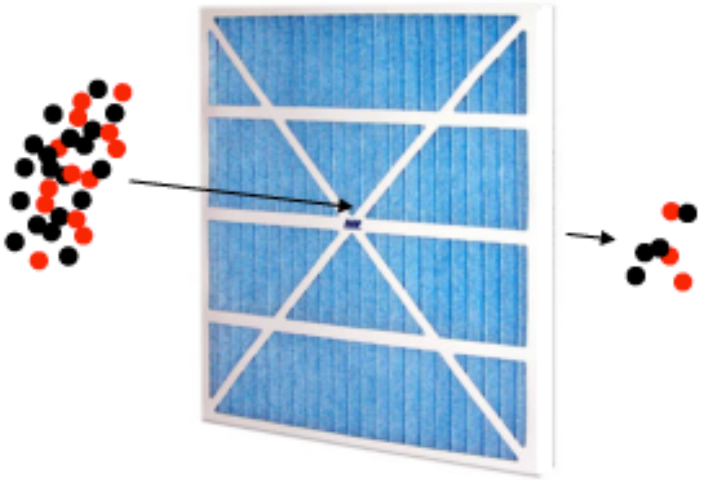
Approximately 45% of outdoor ozone reacted with the envelope during natural infiltration tests

- **Only ~55% enters indoors**

Lead: Haoran Zhao

Zhao and Stephens, under review in *Environ. Sci. Technol.*

2) Filtration of indoor aerosols



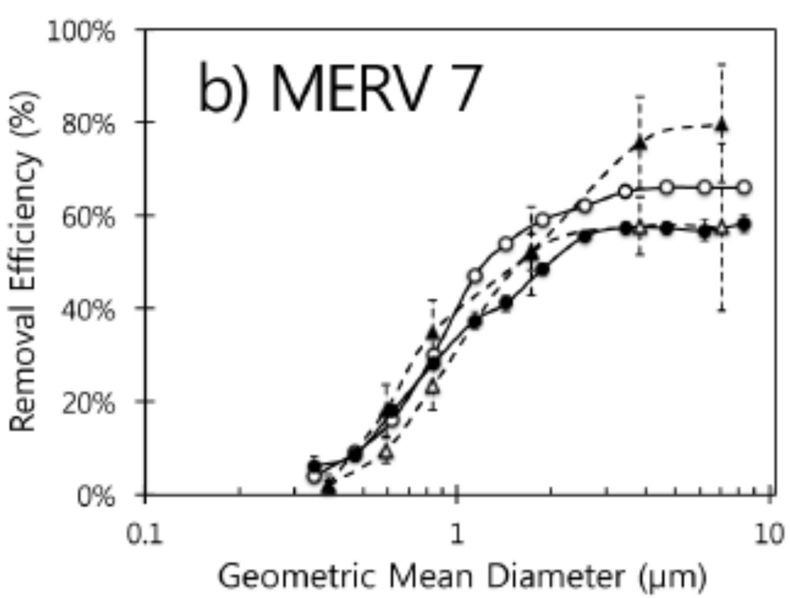
HVAC filter performance

ASHRAE Standard 52.2 → "MERV" rating

- Filter efficiency for 0.3 to 10 μm particles
- Higher MERV → higher removal efficiency for particle sizes tested

BUT:

- Vast majority of particles in indoor environments are less than 0.3 μm



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

1-inch depth

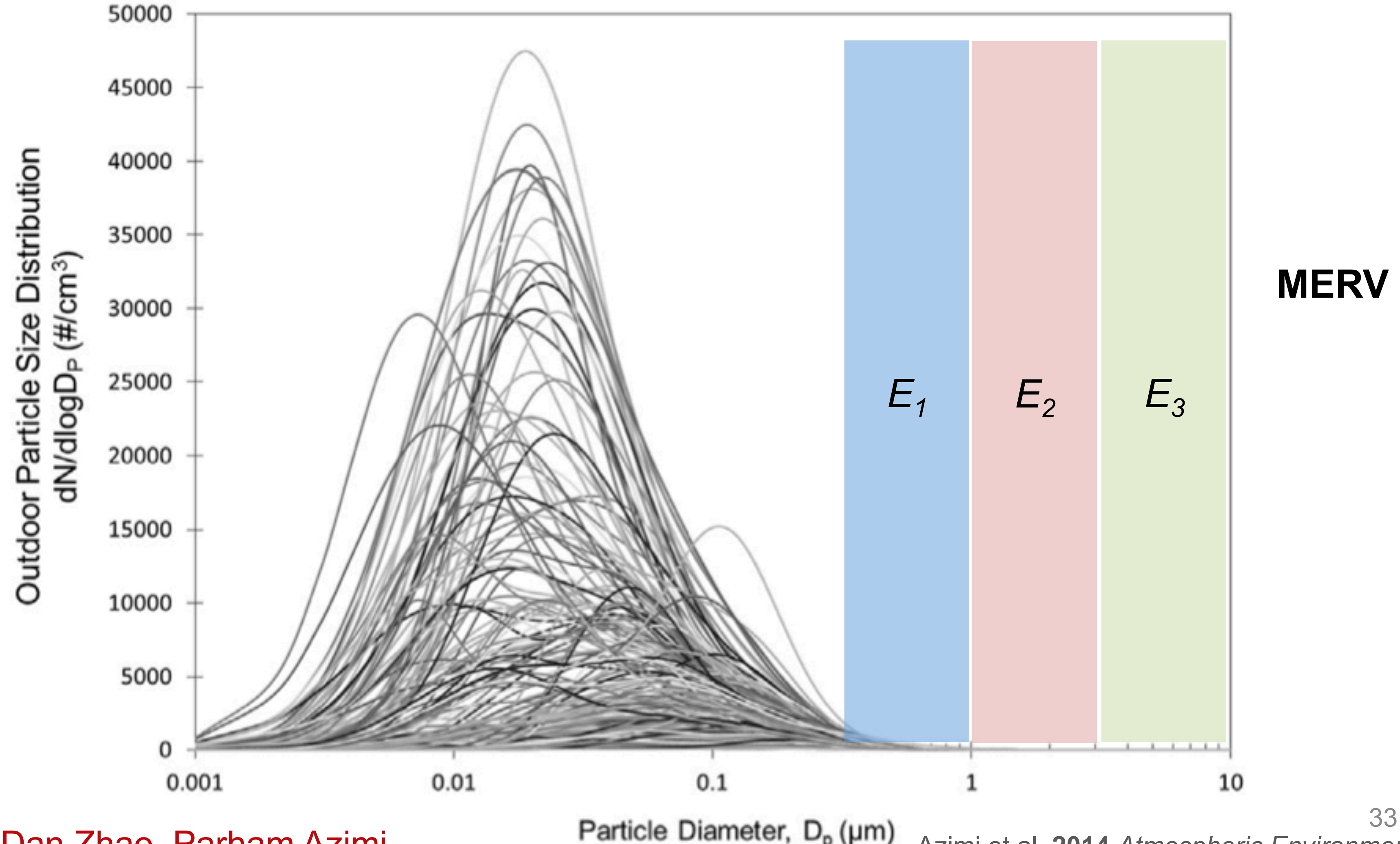
MERV 4 MERV 6 MERV 11

5-inch depth

MERV 10 MERV 13 MERV 16

HVAC filter efficiency for outdoor $PM_{2.5}$ and UFPs

We gathered 194 long-term average (1-year or more) outdoor particle size distributions from the literature from all over the world



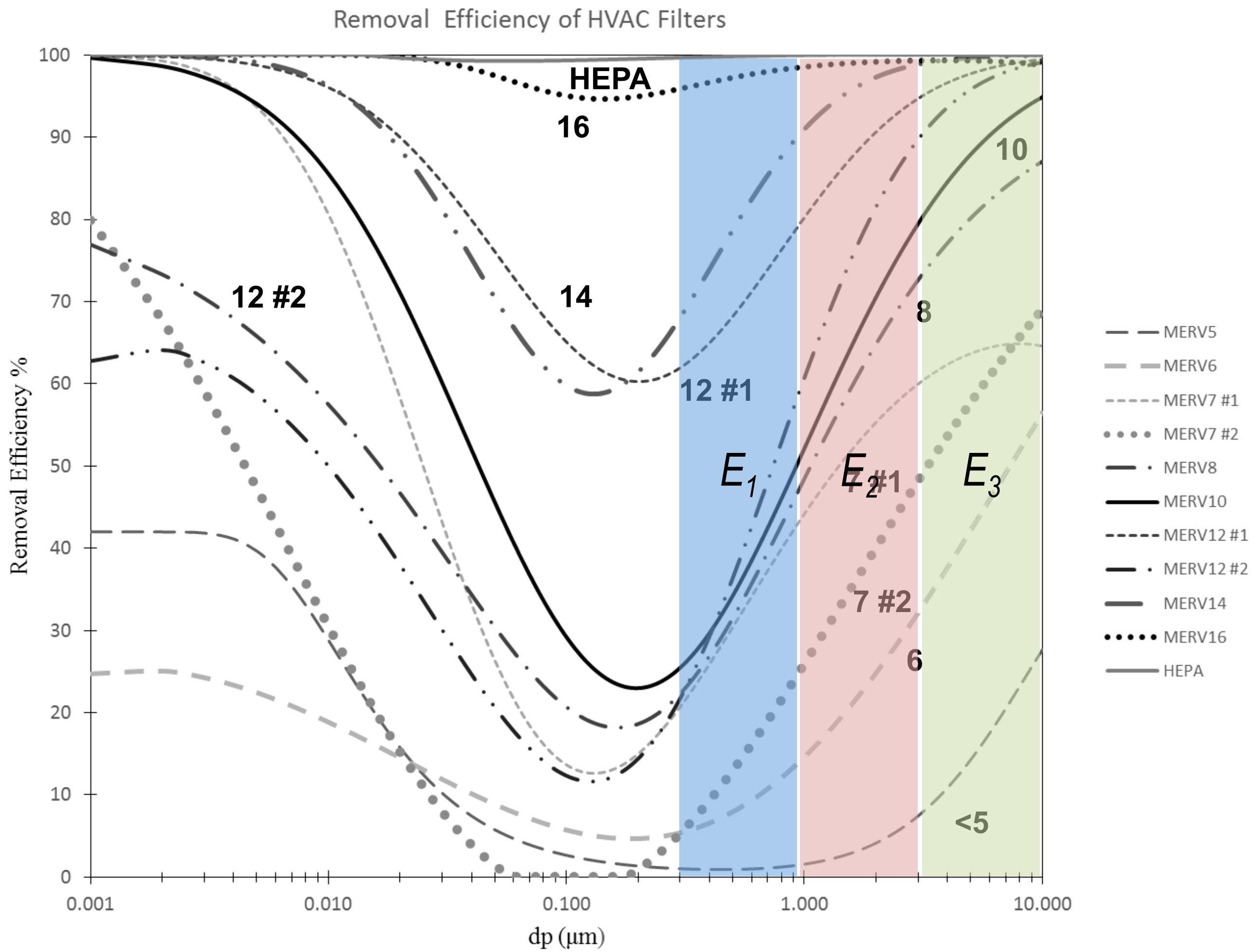
Leads: Dan Zhao, Parham Azimi

Azimi et al. **2014** *Atmospheric Environment*

HVAC **filter efficiency** for outdoor $PM_{2.5}$ and UFP

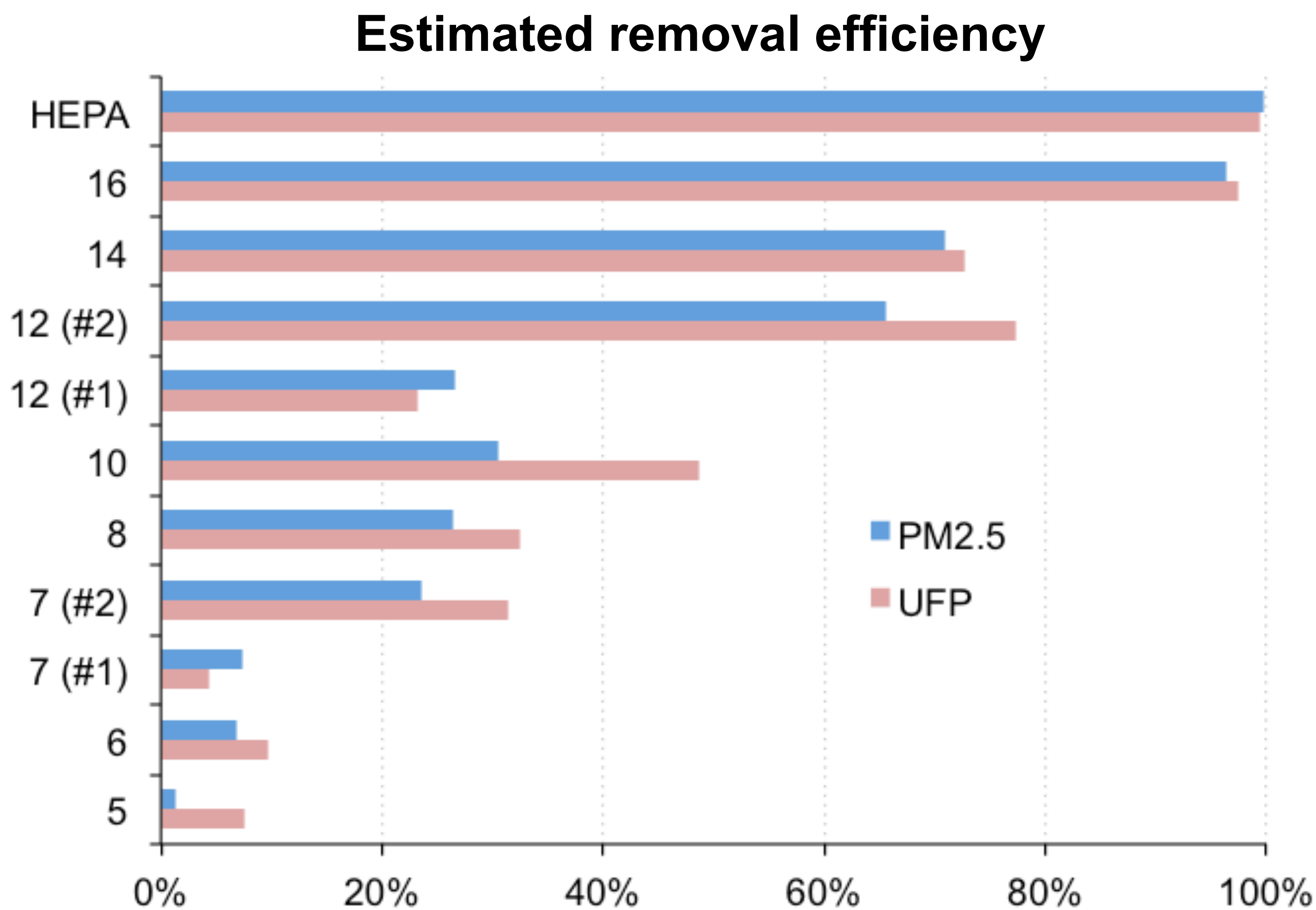
Filtration efficiency varies with **particle size**

- Impaction
- Interception
- Diffusion
- Settling



Hecker and Hofacre **2008** *EPA Report 600/R-08/013*

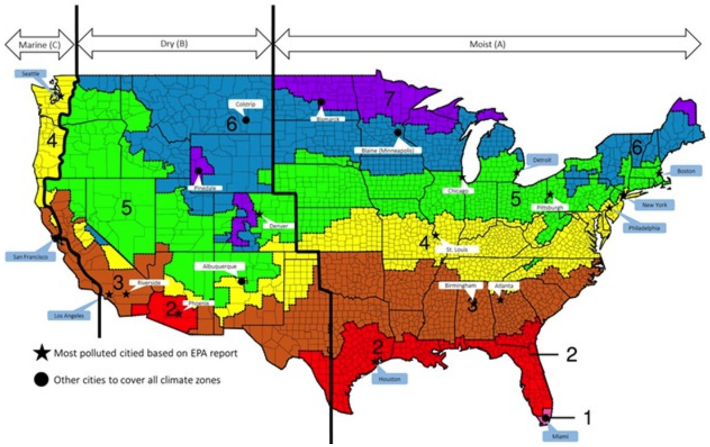
Mapping outdoor size distributions to filtration efficiency for outdoor origin $PM_{2.5}$ and UFPs



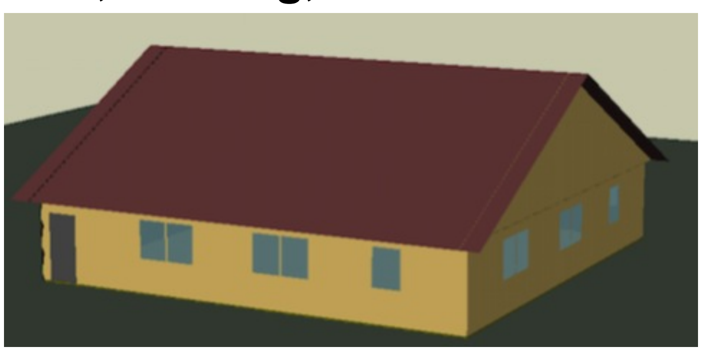
Azimi et al. **2014** *Atmospheric Environment*

ASHRAE RP-1691: Modeling the impact of HVAC filters on indoor particles of outdoor origin ($PM_{2.5}$ and UFPs)

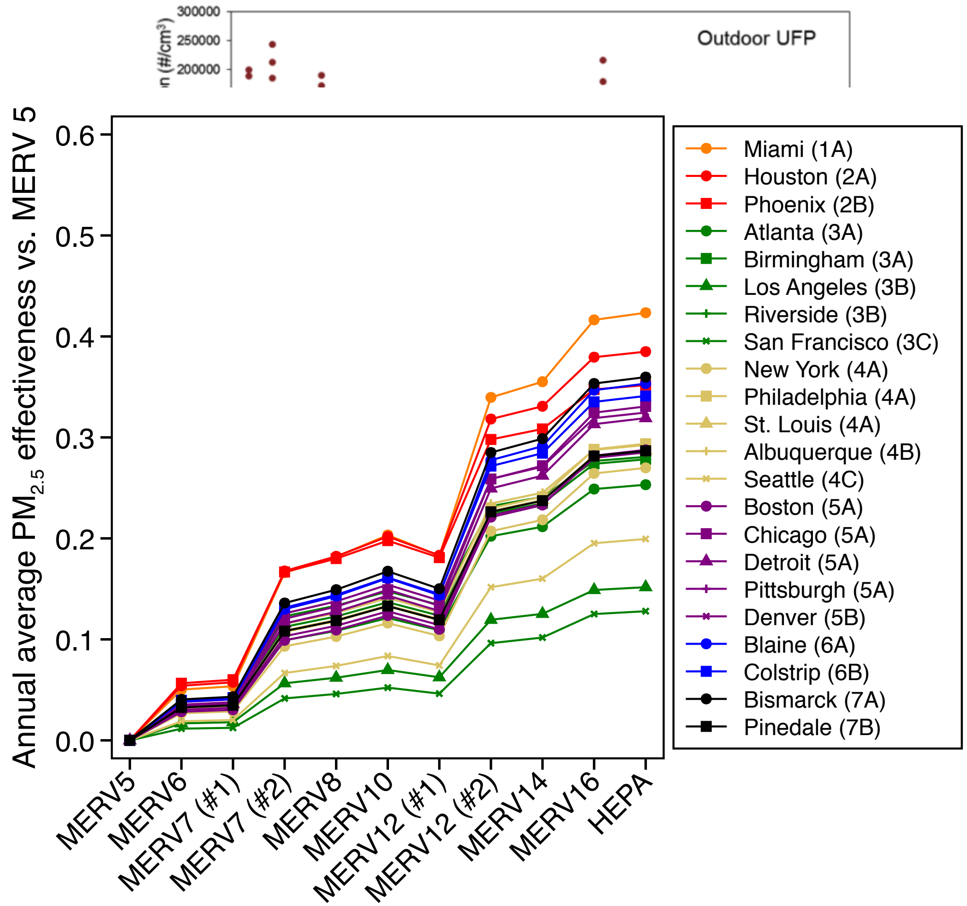
22 cities across the U.S.

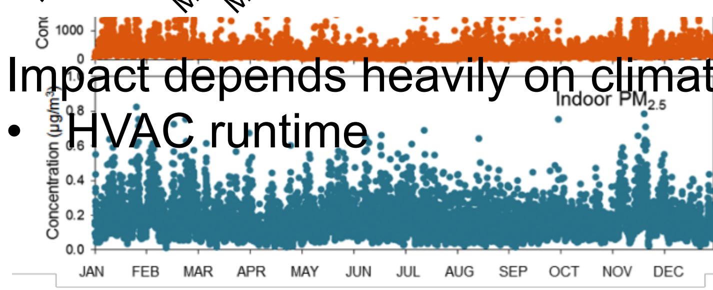


New, existing, and older homes



Combined BEopt + EnergyPlus (AER and HVAC runtime) with custom dynamic IAQ model (MATLAB) to predict impact of filters on indoor PM2.5 and UFPs of outdoor origin





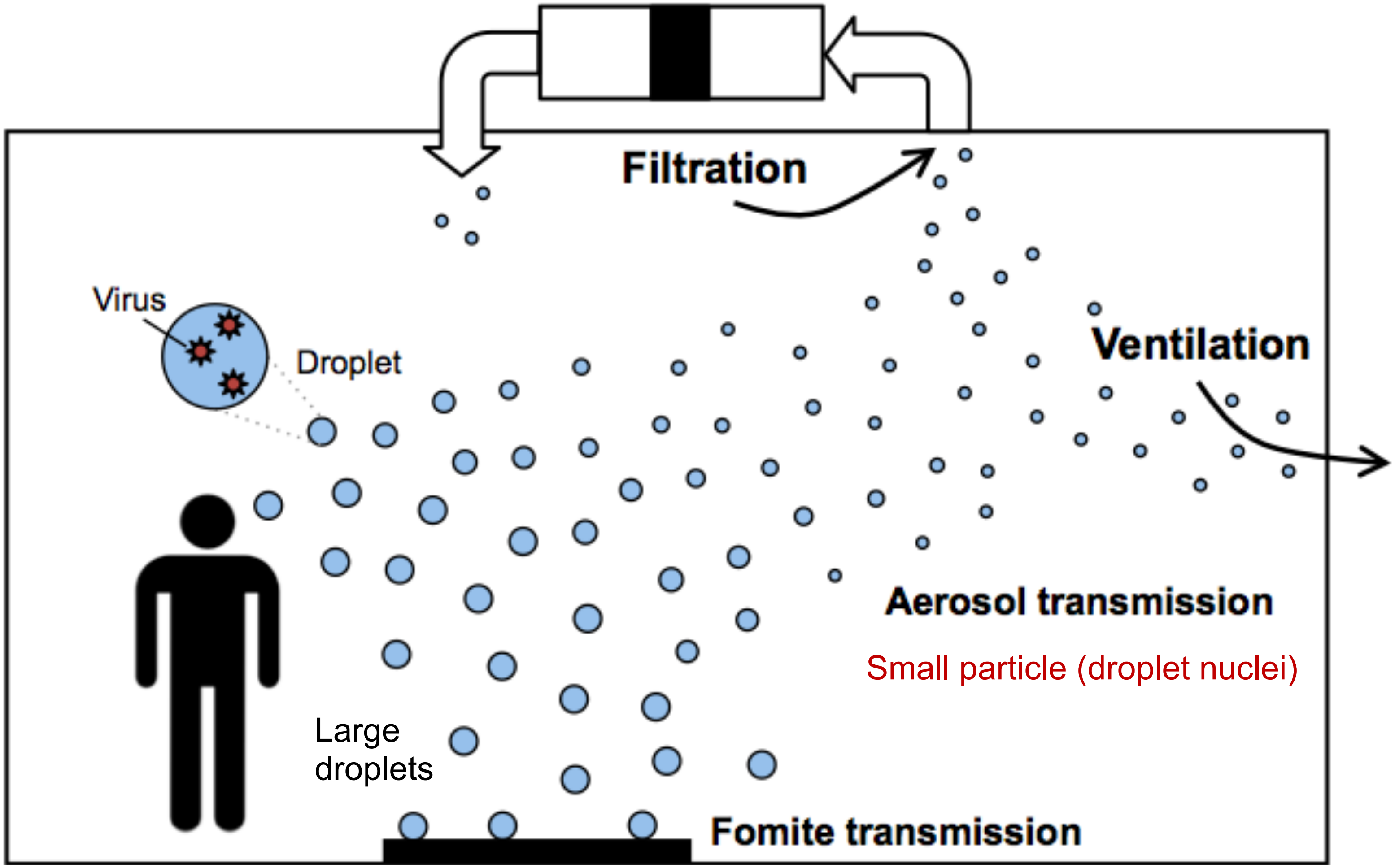
Impact depends heavily on climate

- HVAC runtime

Leads: Dan Zhao, Parham Azimi

Indoor aerosols: **Bioaerosols**
Rapid evaporation of droplets, *Mythbusters*

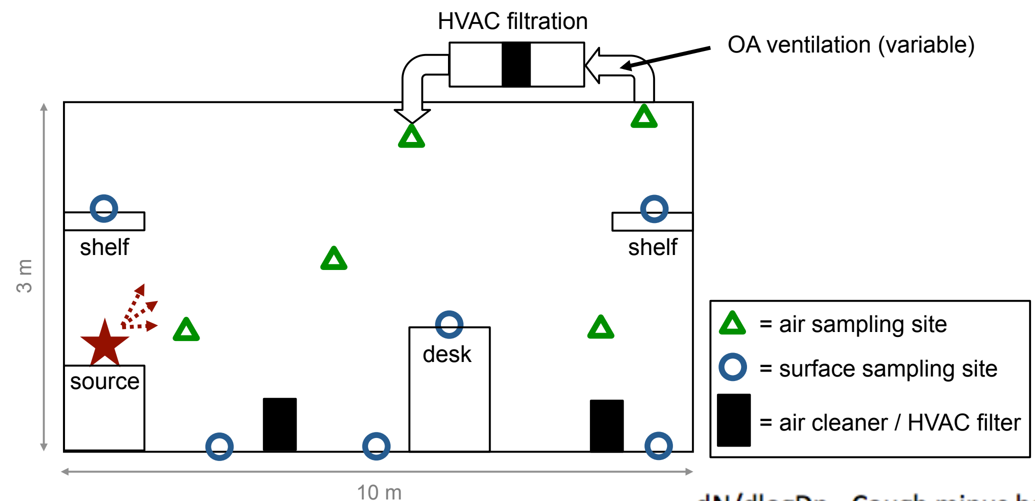
Particle size is important for distribution and removal



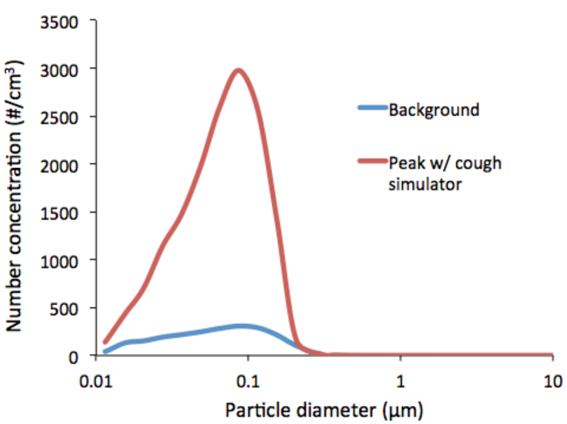
Bioaerosol transport and control: Experimental

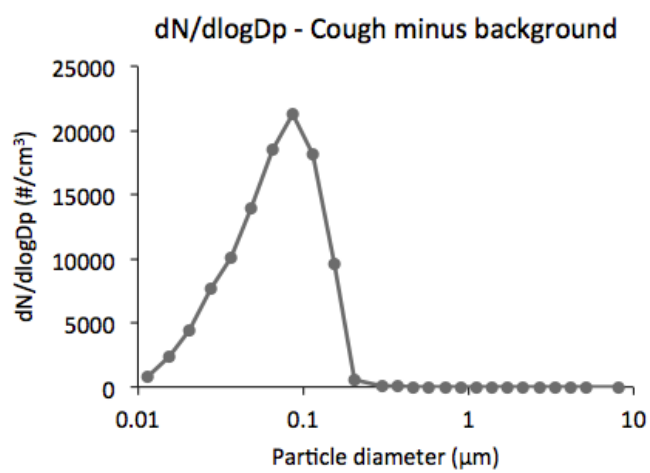
Development of an experimental system for assessing indoor bioaerosol transport and control

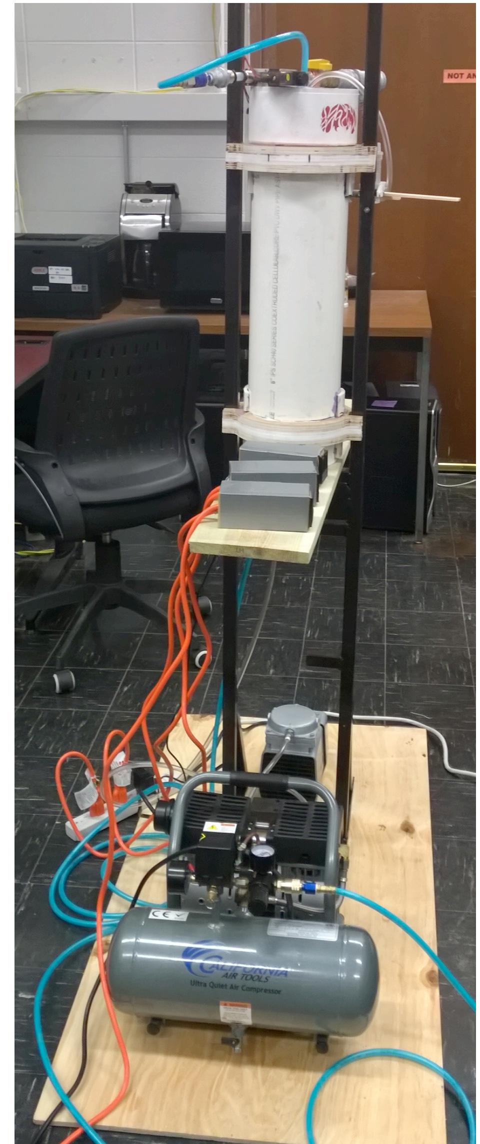
Sponsor: Sloan Foundation Postdoctoral Fellowship (Kunkel)



MERV 13

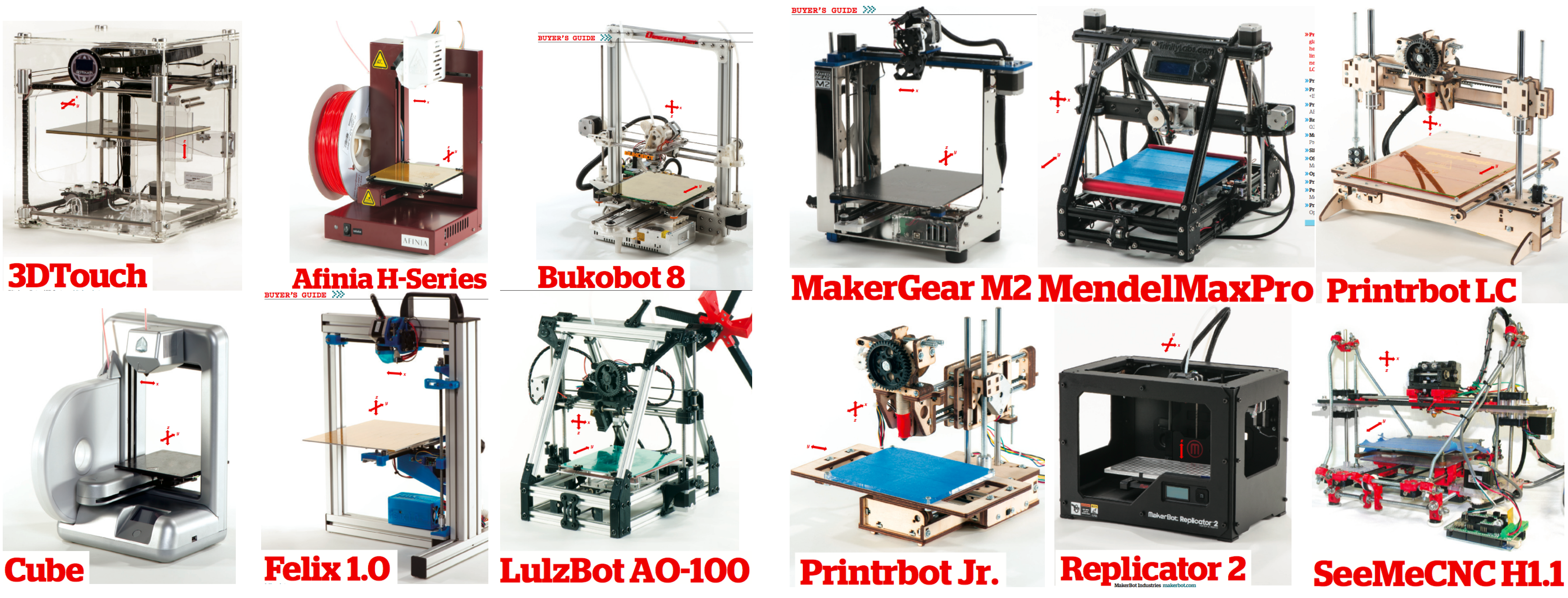






Leads: Stephanie Kunkel, Parham Azimi

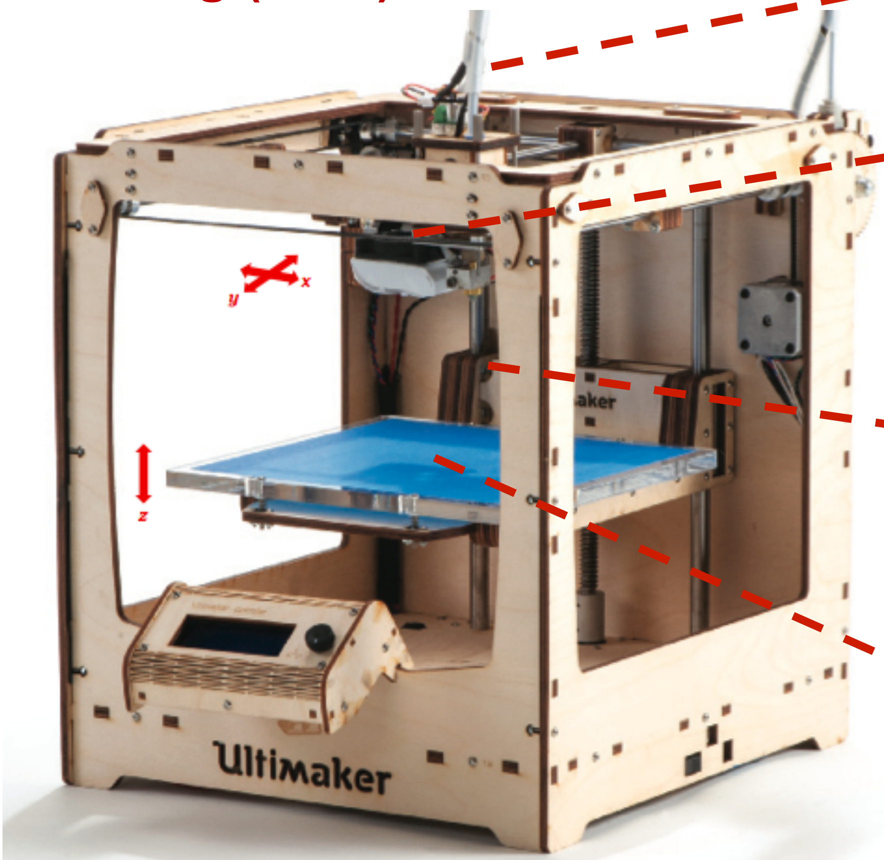
3) Ultrafine particle emissions from 3D printers



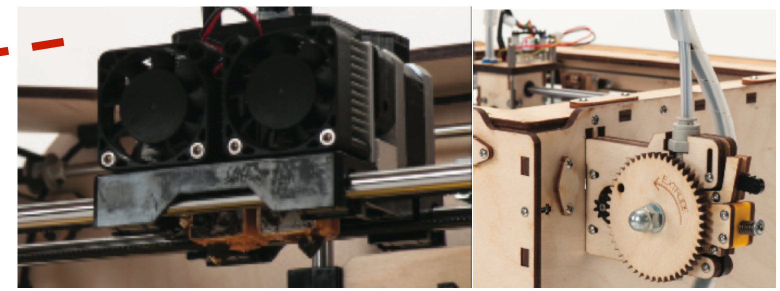
Additive 3D printers: MPD/FDM

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

Thermoplastic filament

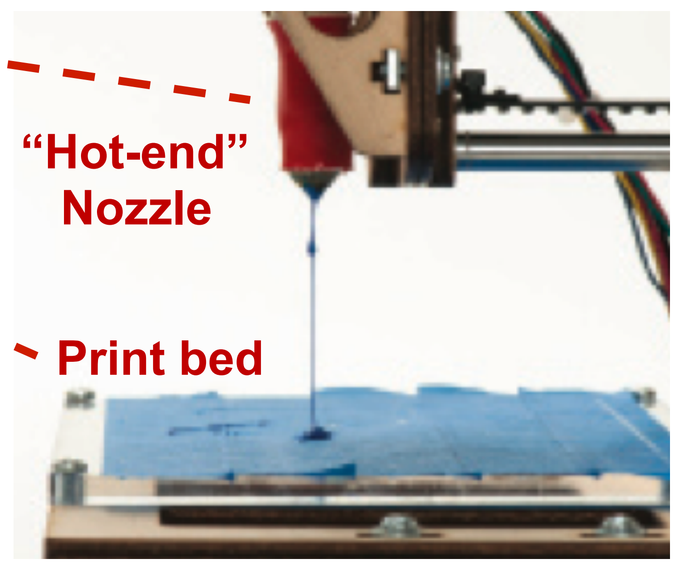


Extruder

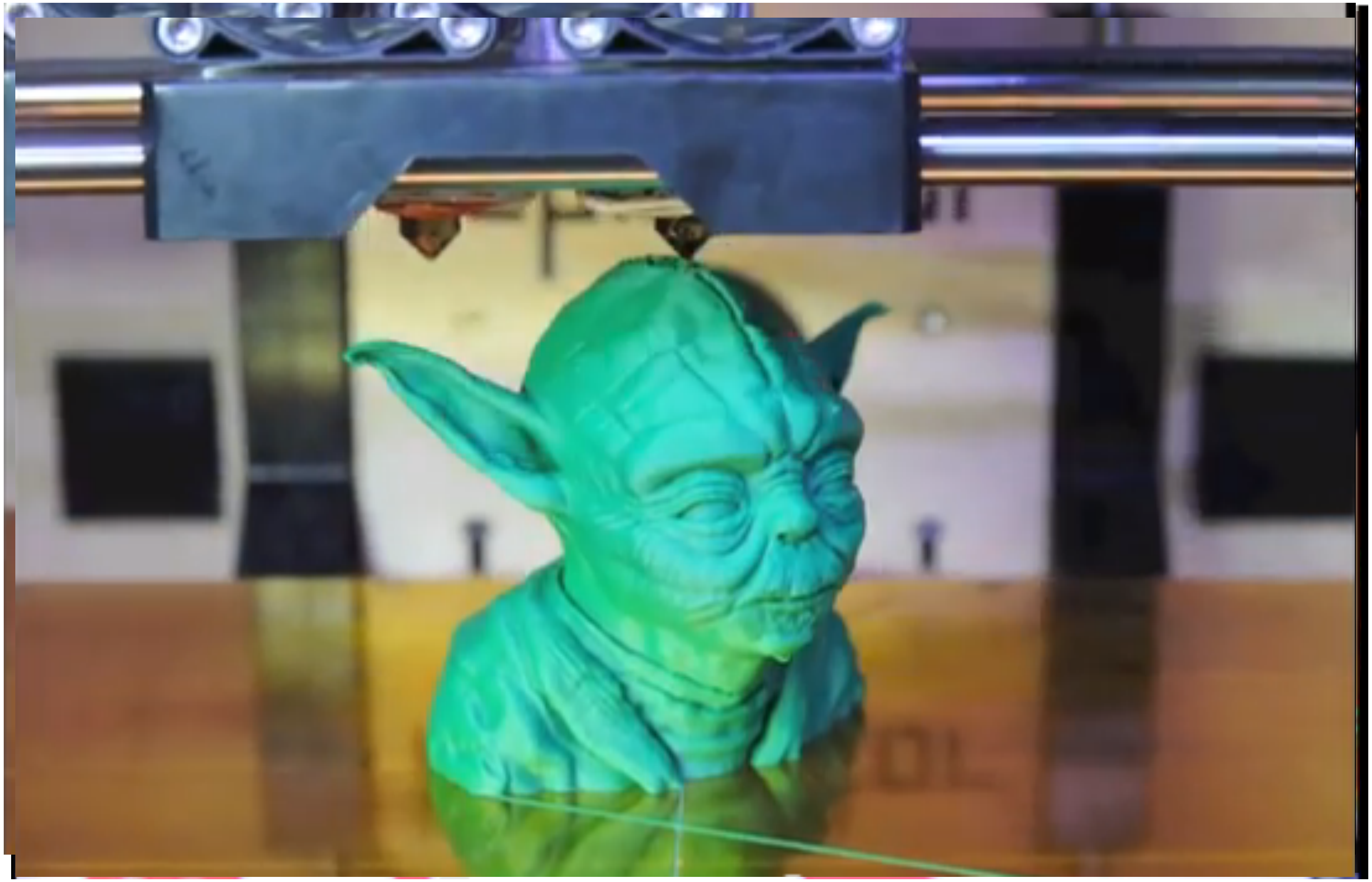


“Hot-end” Nozzle

Print bed



MPD/FDM 3D printer in action



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

Additive 3D printers: MPD/FDM

Thermoplastic filaments

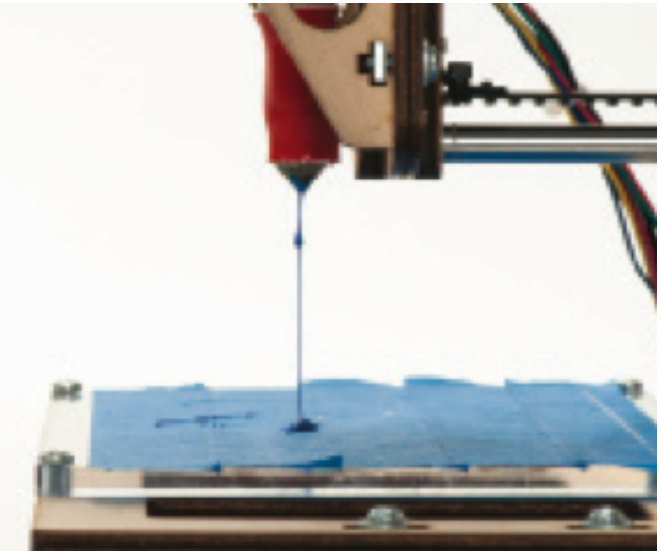
Acrylonitrile butadiene styrene (ABS)
Polylactic acid (PLA)
Polyvinyl alcohol (PVA)
Many others

Hot-end nozzle

0.2-0.8 mm diameter hole
~215-250°C for ABS
~160-220°C for PLA
~190°C for PVA

Print bed

~110°C for ABS
<40°C for PLA



Our ad-hoc experiment

- 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

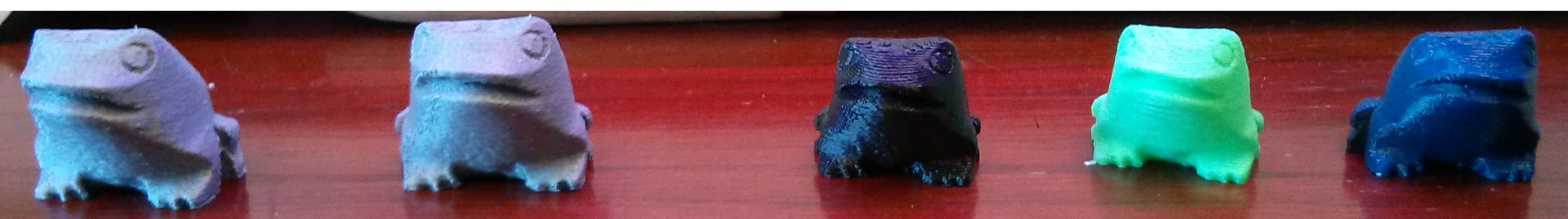
- Two types of filaments at different operational conditions
  - 2 PLA @ 200°C nozzle and 18°C bed temperatures
  - 3 ABS @ 220°C nozzle and 118° bed temperatures

- Operating in a closed 45 m^3 (1600 ft^3) office environment
  - Floor area ~19 m^2 (200 ft^2)

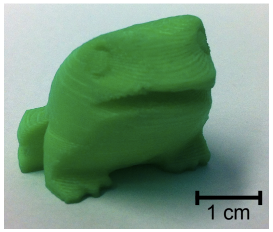
- Ultrafine particle concentrations measured w/ TSI NanoScan SMPS

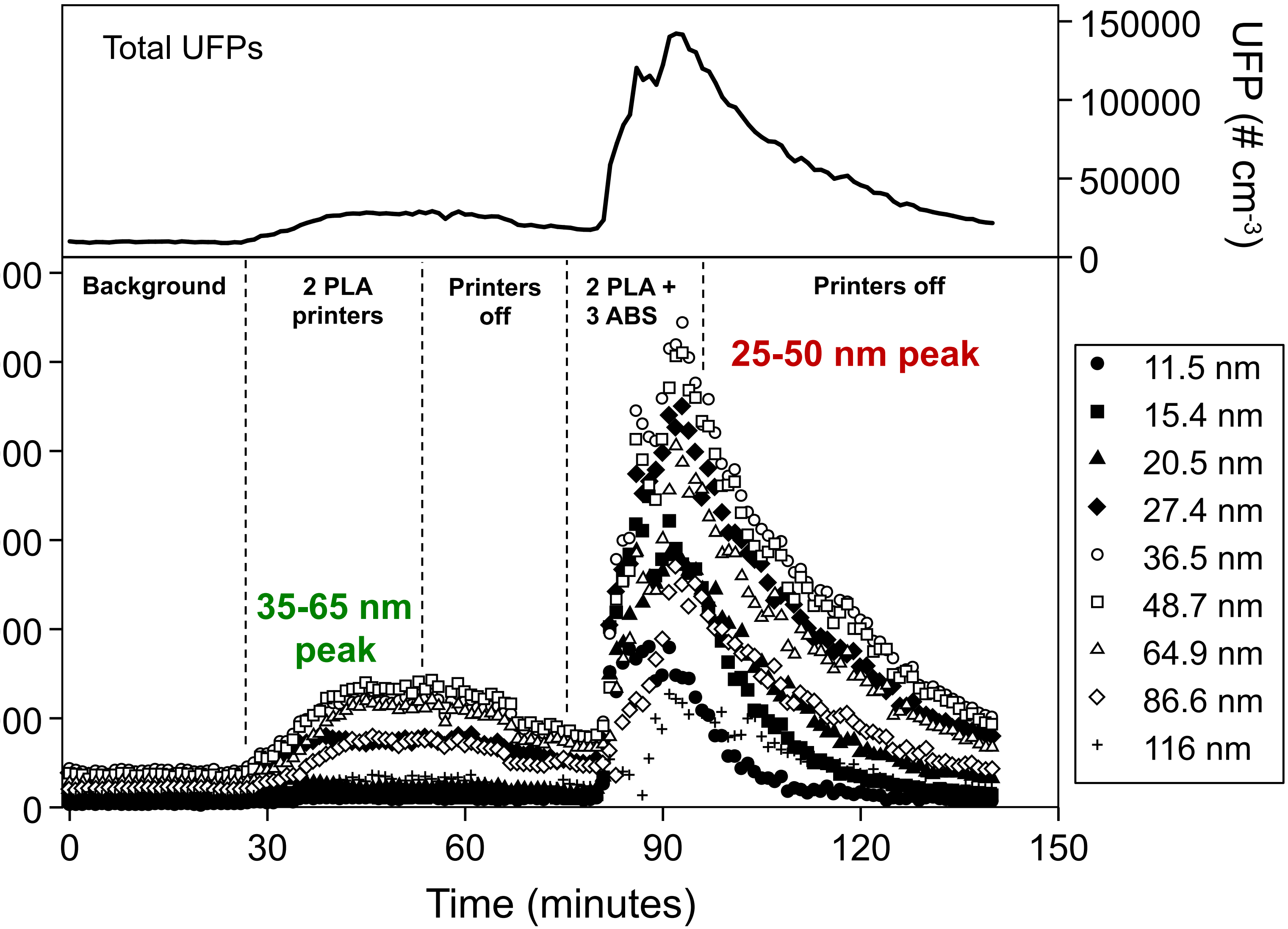
Tritscher et al. **2013** *J Physics* 429

Lead: Parham Azimi



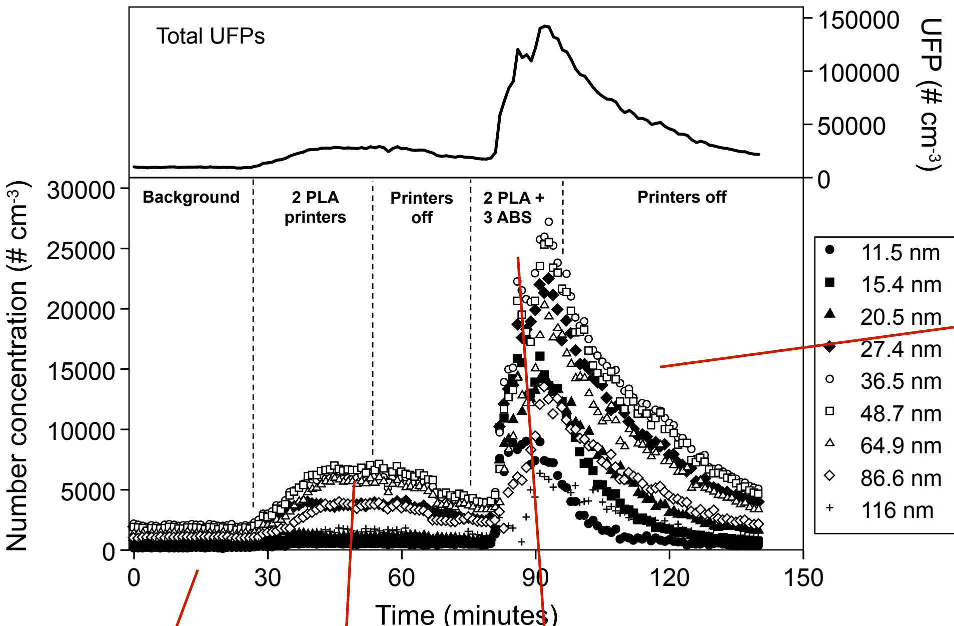
Measured ultrafine particle concentrations





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

Estimating emission rates



Emission rates are independent of the test space

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

$C_{i,in,ss,bg}$

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

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

Units

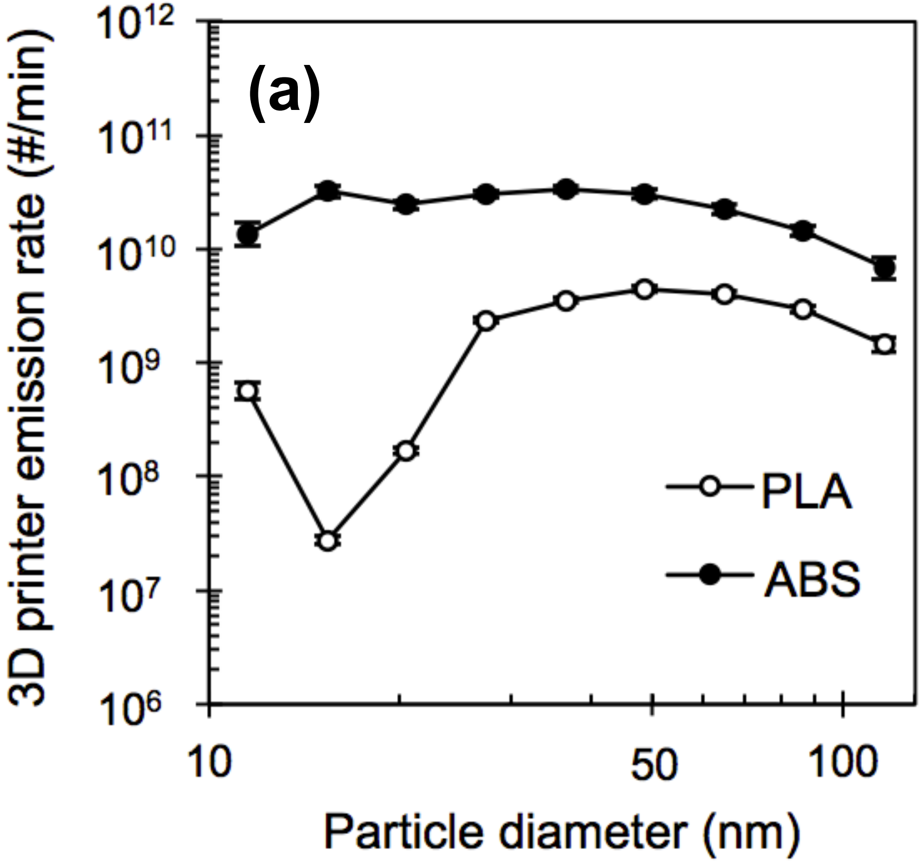
C_i [#/cm^3]

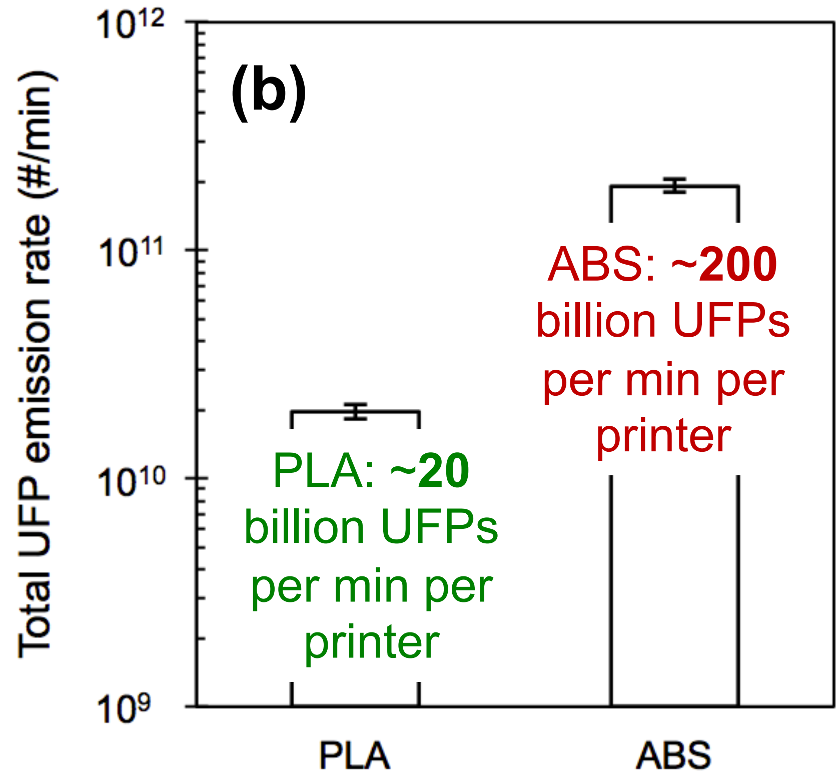
E_i [#/min]

L_i [1/min]

V [cm^3]

Size-resolved and total UFP emission rates





Total UFP emission rates:
~1.9×10^{11} #/min from ABS printer
~2.0×10^{10} #/min from PLA printer

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

News coverage: Tell your own story

FOX NEWS .com Fair & Balanced

Are 3D printers harmful to your health?

BETA D NEWS

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

FAST COMPANY

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

Public and scientific interest

Atmospheric Environment

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The most downloaded articles from ScienceDirect in the last 90 days.

1. Ultrafine particle emissions from desktop 3D printers

November 2013

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

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....

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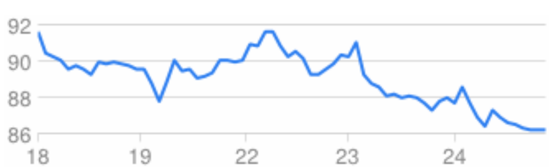
Accessed October 7, 2014

Stratasys, Ltd.

NASDAQ: SSYS - Jul 24 3:02pm ET

86.40 -1.29 (-1.47%)



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

1d 5d 1m 6m 1y 5y max

Google Finance - Yahoo Finance - MSN Money Disclaimer

Moving forward: Research needs

1. Characterize **emissions**
   – More printers, more filaments, both particles (UFPs) and gas-phase compounds (VOCs, SVOCs), chemical constituents

2. Characterize **exposures** in realistic environments
   – Homes, offices, schools, etc.

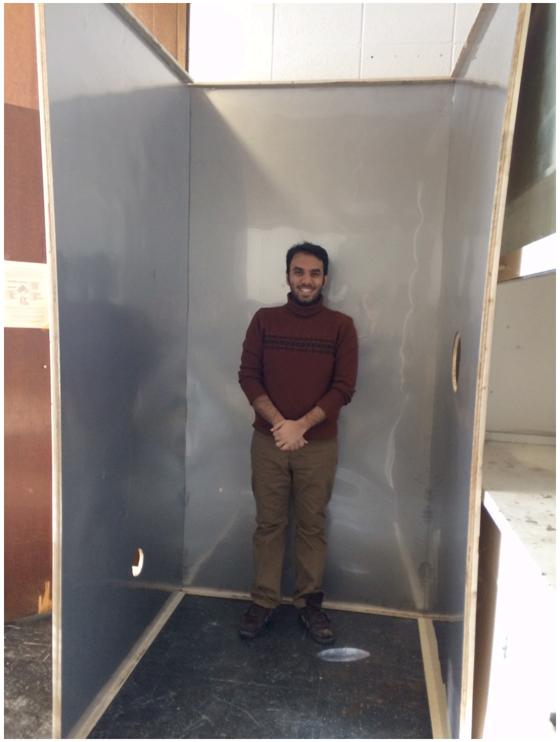
3. Inhalation **toxicology** and **health** outcomes
   – Using cell lines, mouse models, or human subjects

4. Investigate **control strategies**
   – Exhaust ventilation, gas and particle filtration, enclosures

Moving forward: New project

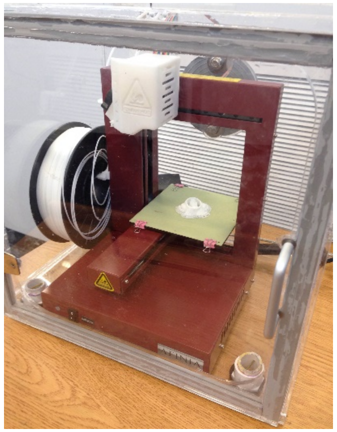
We were recently awarded research funding through CDC/NIOSH:

- NIOSH R03: *Evaluating and controlling airborne emissions from desktop 3D printers*



3 phases over 2 years:

1. Chamber testing to characterize emissions of particles and VOCs from 5 of the most popular desktop 3D printers
2. Measurements (and models) of realistic exposures in real occupational environments
3. Development and evaluation of custom gas and particle filtration devices and enclosures



Leads: Parham Azimi, Dan Zhao

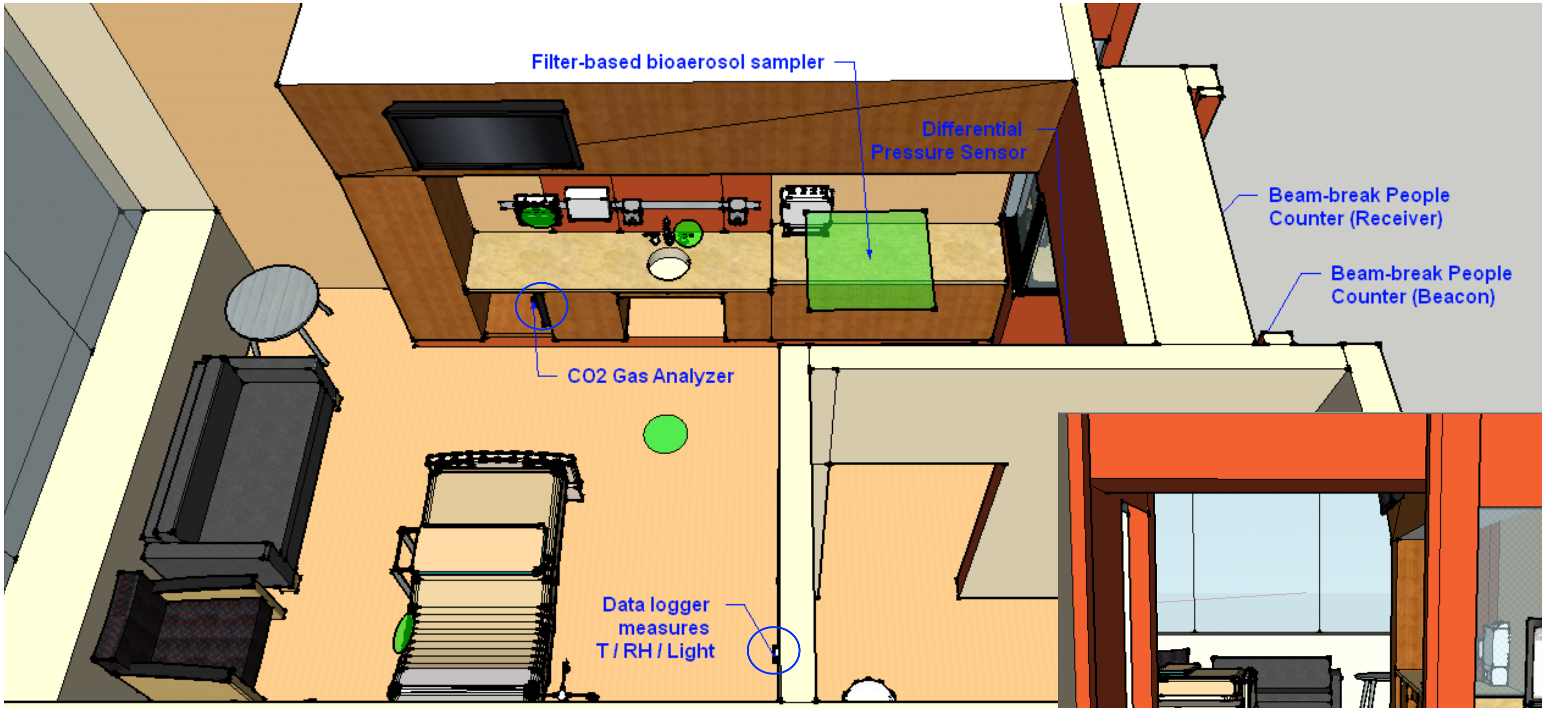
Hospital Microbiome

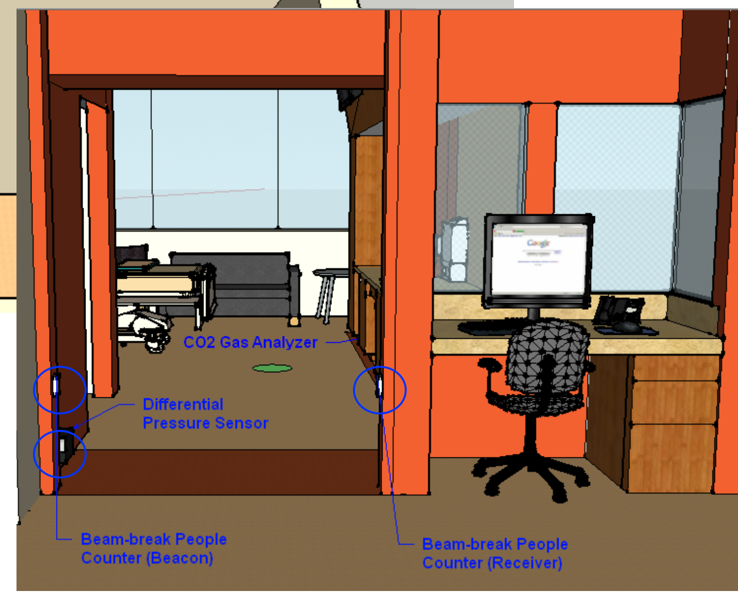
4) Building science measurements in the Hospital Microbiome Project

http://hospitalmicrobiome.com/

Hospital Microbiome

Bio sampling + building science measurements





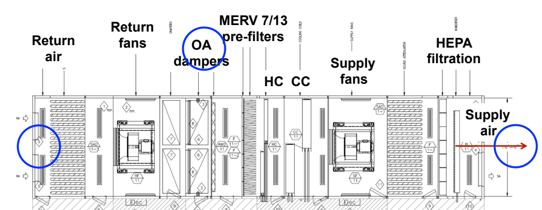
Biological sampling sites   Building science equipment sites

Bio sampling summary

- ~10,000 swabs in rooms, nurse stations, and patients/ staff
- 16S/18S/ITS sequencing (ongoing)

Building science data summary

- 80+ variables measured continuously every 5 minutes
- 100,000+ data points per variable → 8 million+ data points
- over 8500+ hours of active data collection per variable



+ OA fractions in HVAC

Images courtesy of Tiffanie Ramos

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_2 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)

Mechanical room: Air handling units

Building science data summary

How do ______________ vary ____________ ?

① Air temperature
② Relative humidity
③ Absolute humidity
④ Illumination levels
⑤ Human occupancy
⑥ Pressurization
⑦ Ventilation rates (OA fractions)

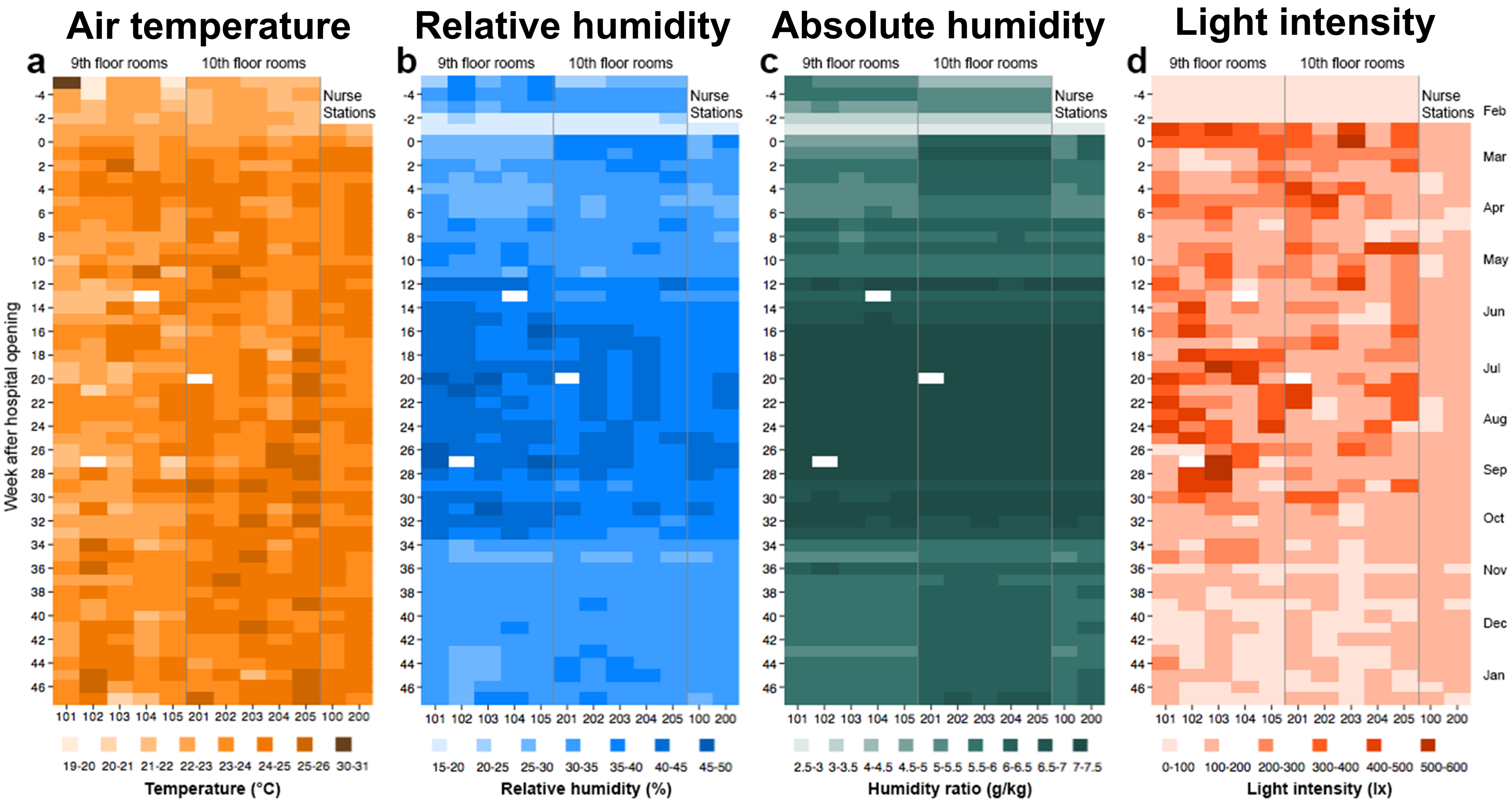
① Within rooms
② Between rooms
③ Between floors
④ Between night and day

And what are the potential implications for microbiology?

Lead: Tiffanie Ramos

Hospital Microbiome

Weekly average environmental conditions



- Air temperatures ranged 19-27℃
- No correlation between rooms
- Controlled by occupants

- RH ranged 5-60%
- Strong correlation between rooms
- Governed by HVAC

- Humidity ratio even stronger than RH
- Strong seasonal signals

- Illuminance typically 10-200 lx
- Weak correlations between rooms

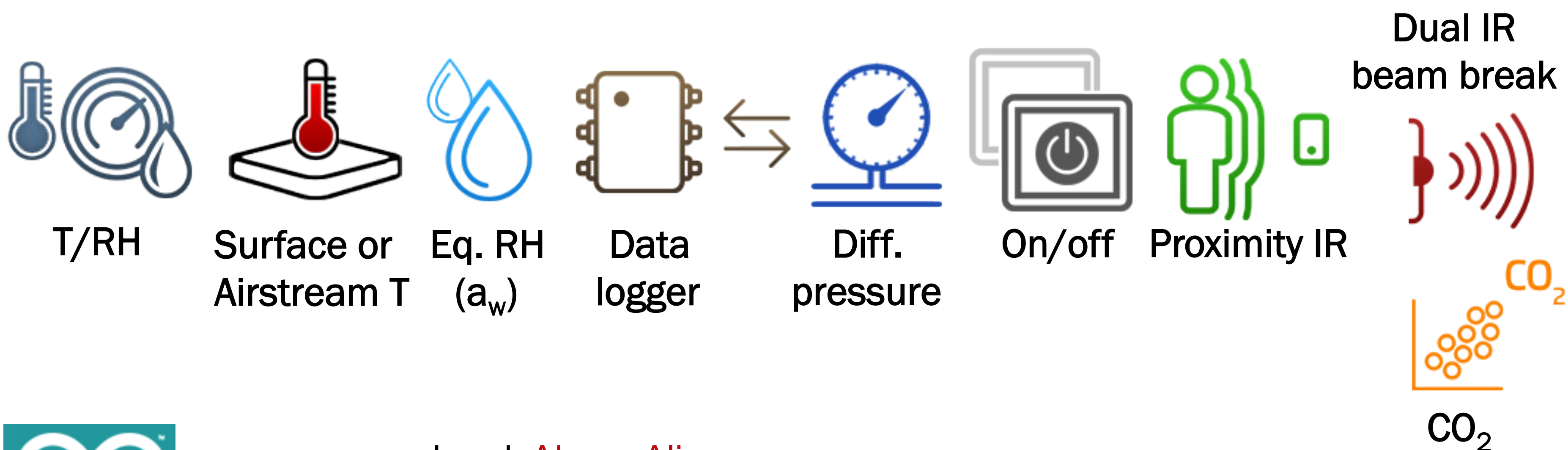
Ramos et al. **2015** accepted in *PLoS ONE*

5) Open source building science sensors

OPEN SOURCE
BUILDING SCIENCE SENSORS

OPEN SOURCE BUILDING SCIENCE SENSORS

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



ARDUINO

Lead: Akram Ali

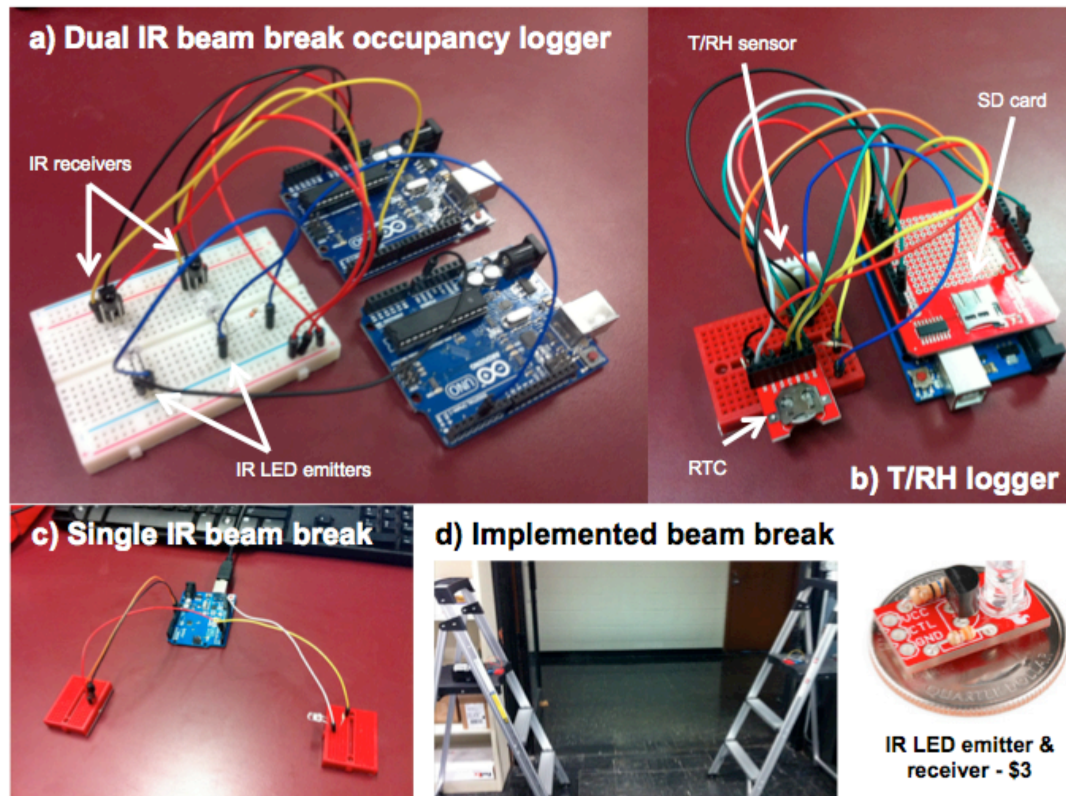
Support: Torkan Fazli, Joseph Chee Poh Huan, Bobo Dong, Deion Debose, Zack Zanzinger

http://www.osbss.com

Development process: Stage 1 (Concept)

- Begin with breadboard (solder-less) concept development on **Arduino Uno** controllers with off-the-shelf sensors
  - Allows for testing basic functionality, accuracy, and developing code

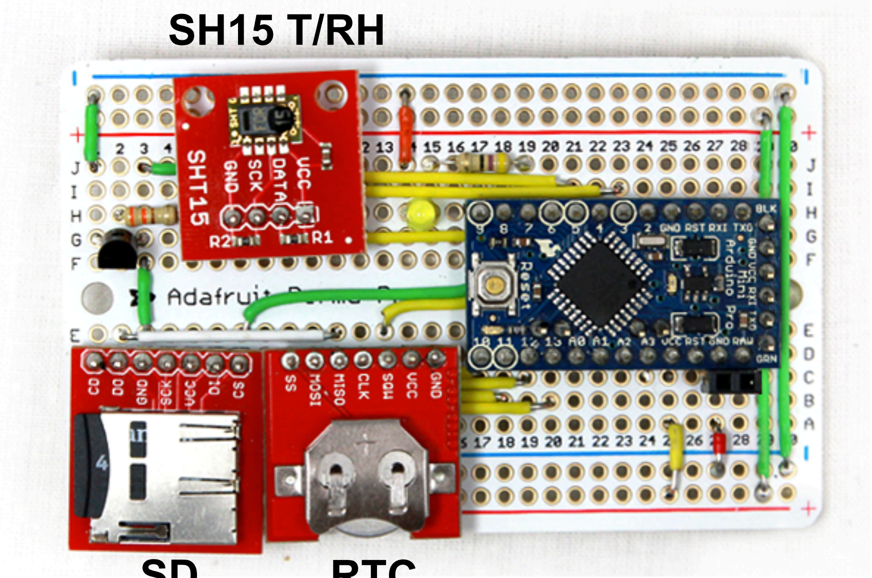
- Issues at this stage:
  - High power draw
  - Real time clock (RTC)
  - Data storage
  - Durability
  - Aesthetics



Lead: Akram Ali

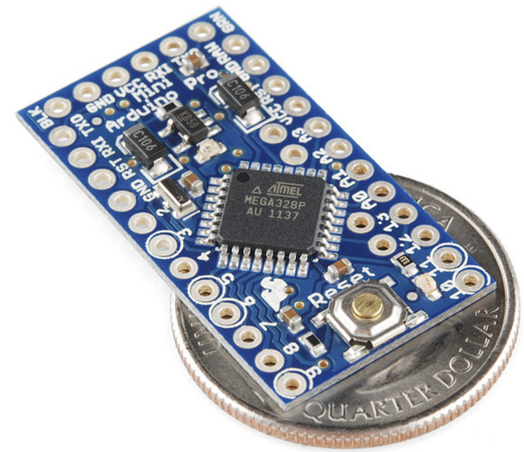
Development process: Stage 2 (Prototype)

- Select most promising sensor(s)
- Move from Arduino Uno to **Arduino Pro Mini**
  (or knock-off versions for $3)
  - Large reductions in power draw with custom libraries
  - Use of sleep mode functions
- Upgrade to solder-able breadboard
  - Improves durability
- Upgrade to custom enclosures
  - Improves aesthetics
- Provides base low-power logger



Development process: Stage 2 (Prototype)

Why the Arduino Pro Mini 328?



- Can use either 3.3V or 5V DC
- 8 MHz (3.3V) or 16 MHz (5V) processor
- Small footprint (0.7x1.3”)
- 8 analog pins
- 14 digital I/Os
- 32 kB flash memory (2 kB used by bootloader)

Original Apple Macintosh
Released: Jan 24, 1984
Intro price: $2,495
Clock speed: 7.8 MHz
Memory: 128 kB RAM

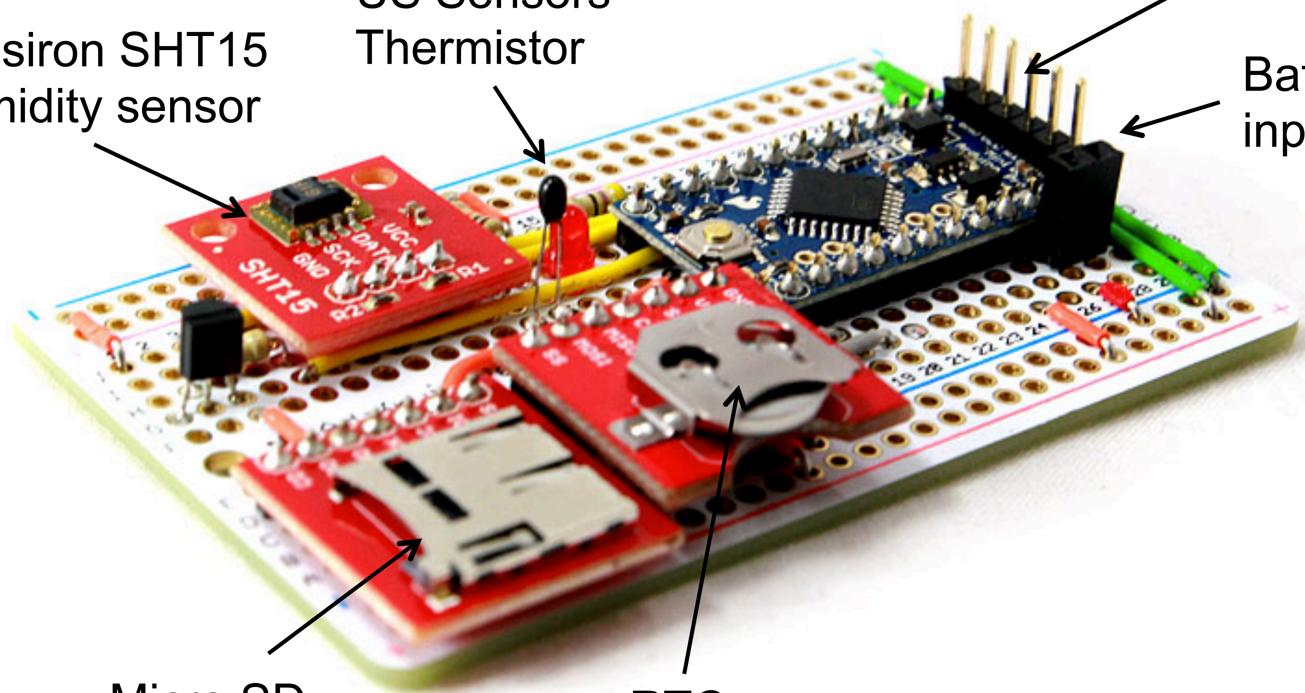
Pro Mini power draw:
From ~20 mA resting (Uno)
To ~0.2 mA resting (Mini + code)
From ~4 days to ~400 days on AA

Development process: Stage 3 (Tutorials)

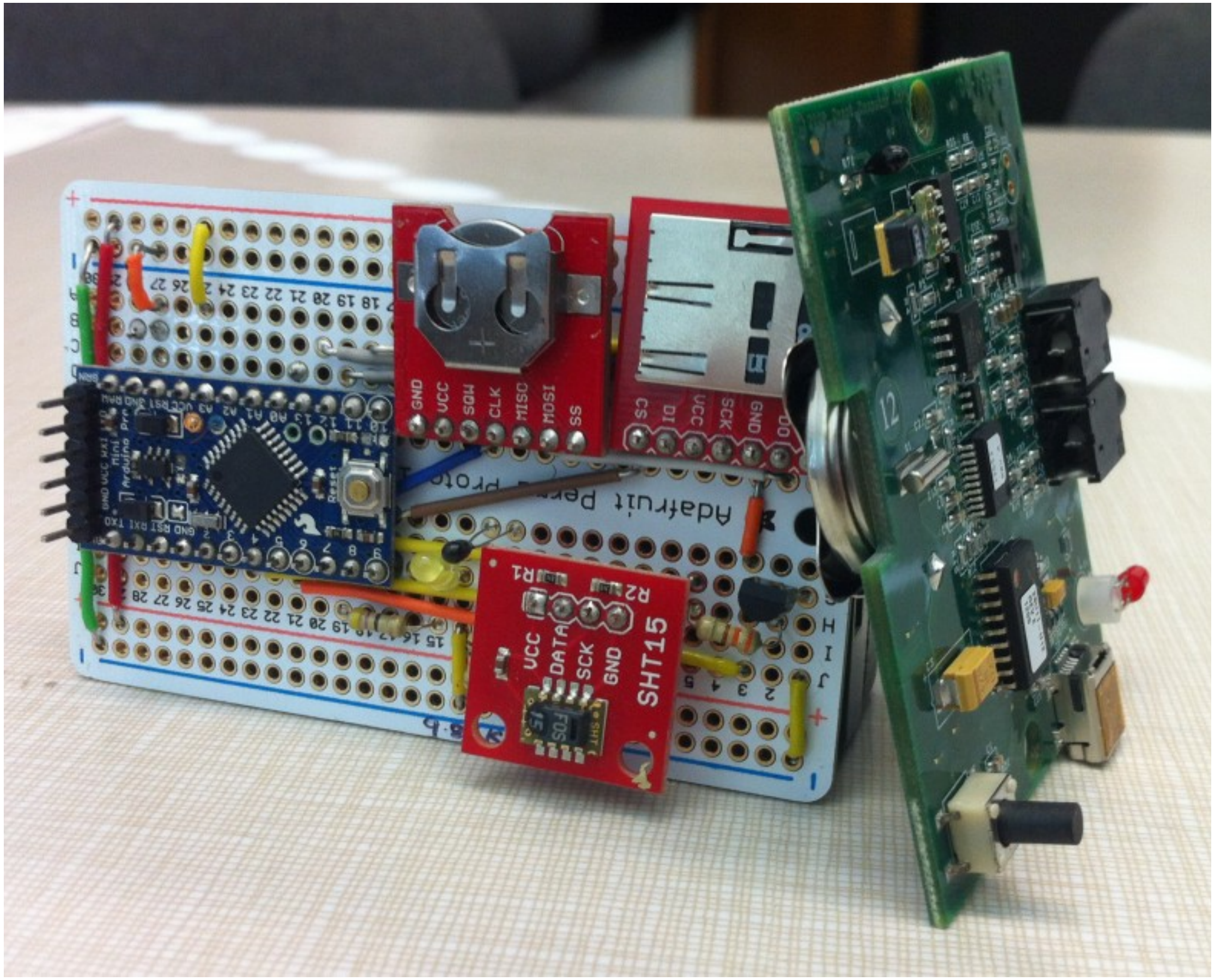
Total hardware cost: ~$95 USD

Temperature and RH

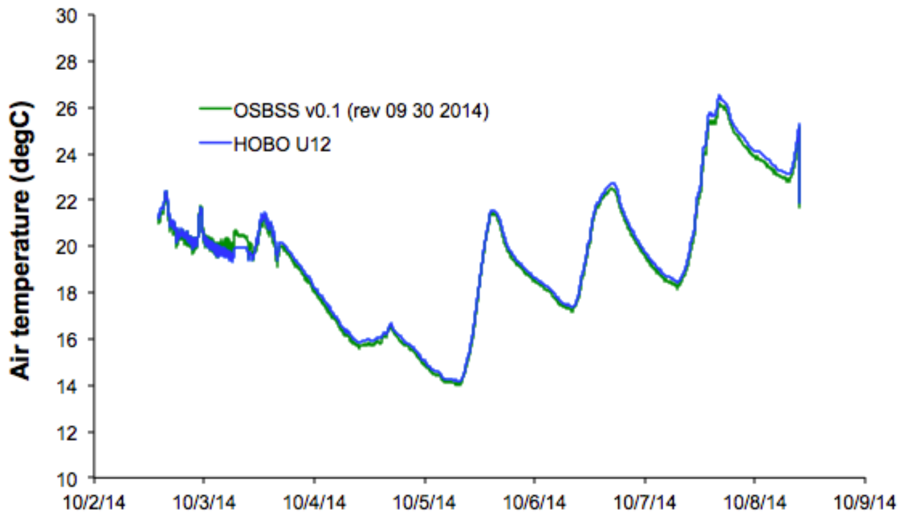
- Provided the base for our core long-term battery powered data logger
- Currently the only full tutorial online

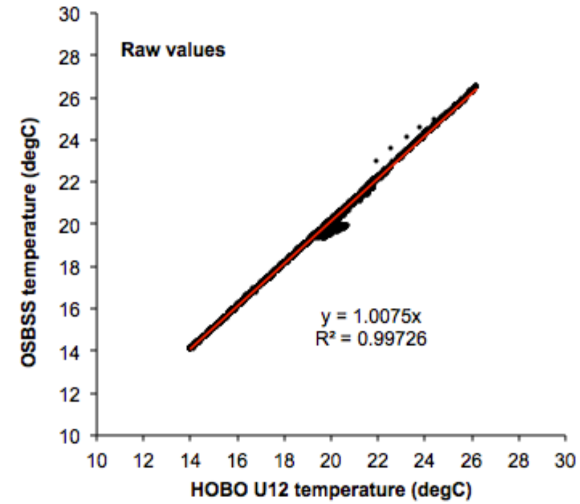


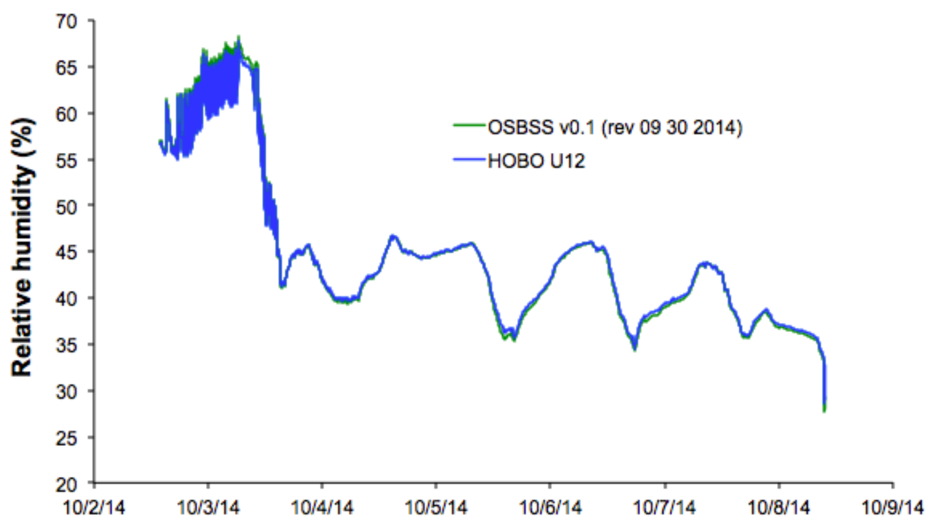
T/RH verification: OSBSS vs. HOBO

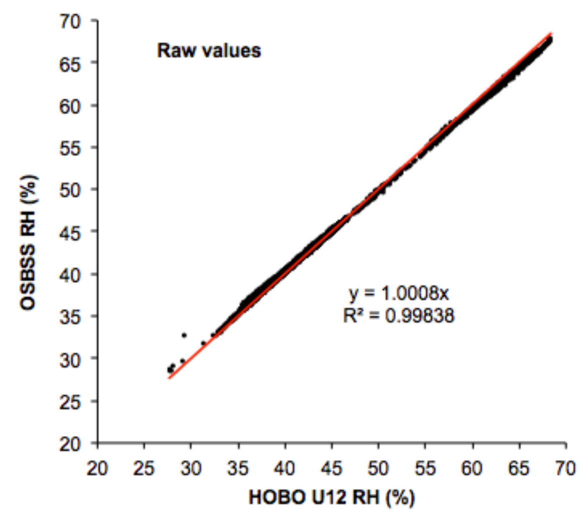


T/RH verification: OSBSS vs. HOBO









6) Optimizing Chicagoland housing retrofits for 50% energy savings

Retrofitting older Chicago homes

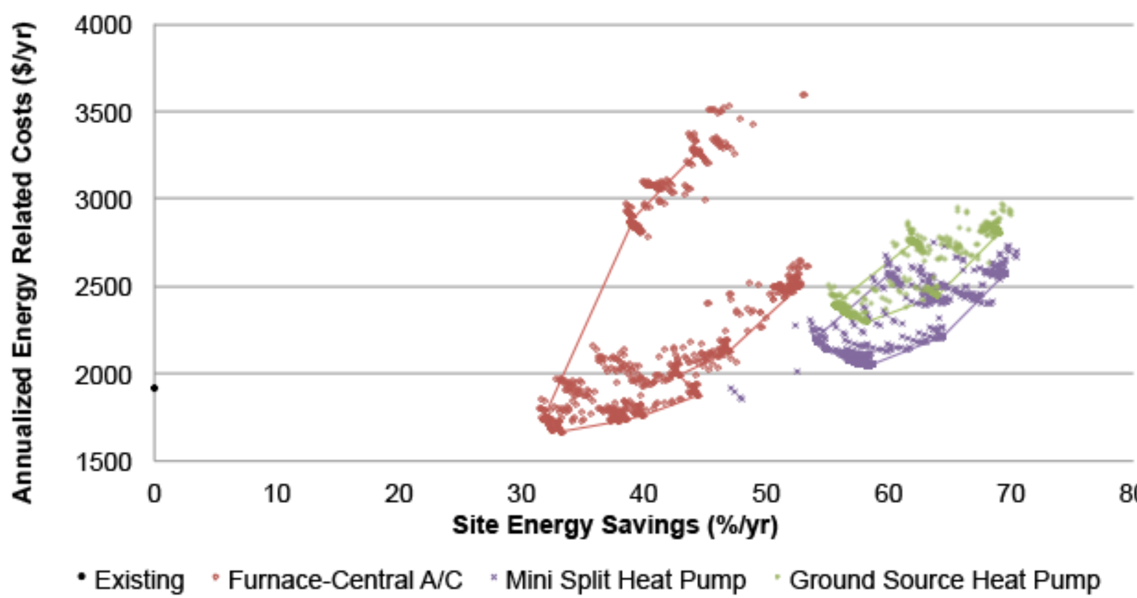
- Over 900,000 single-family homes in Chicagoland were built before 1978
  - Often poorly insulated, poor air sealing, and low efficiency heating and cooling equipment



Lead: Honnie Leinartas

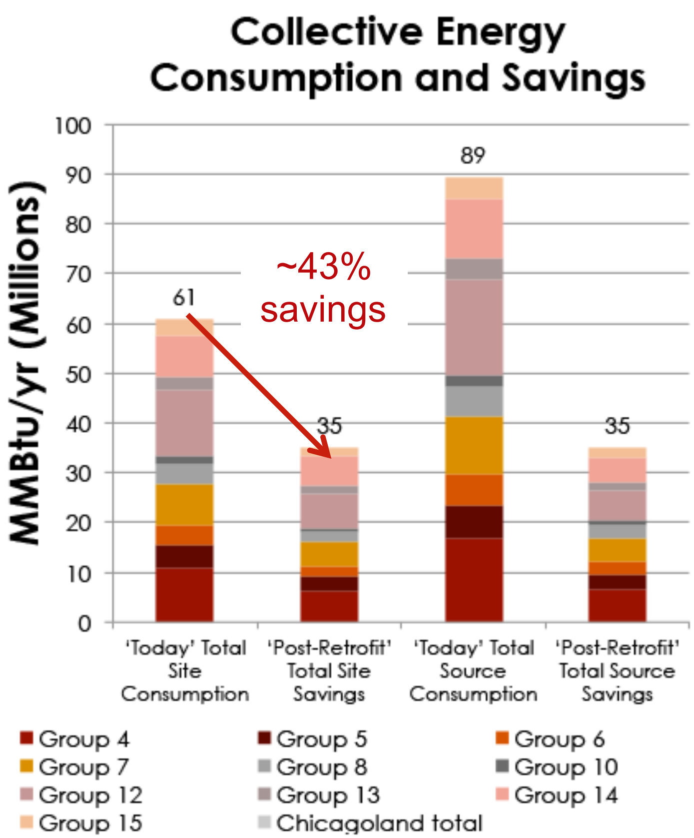
Retrofitting older Chicago homes

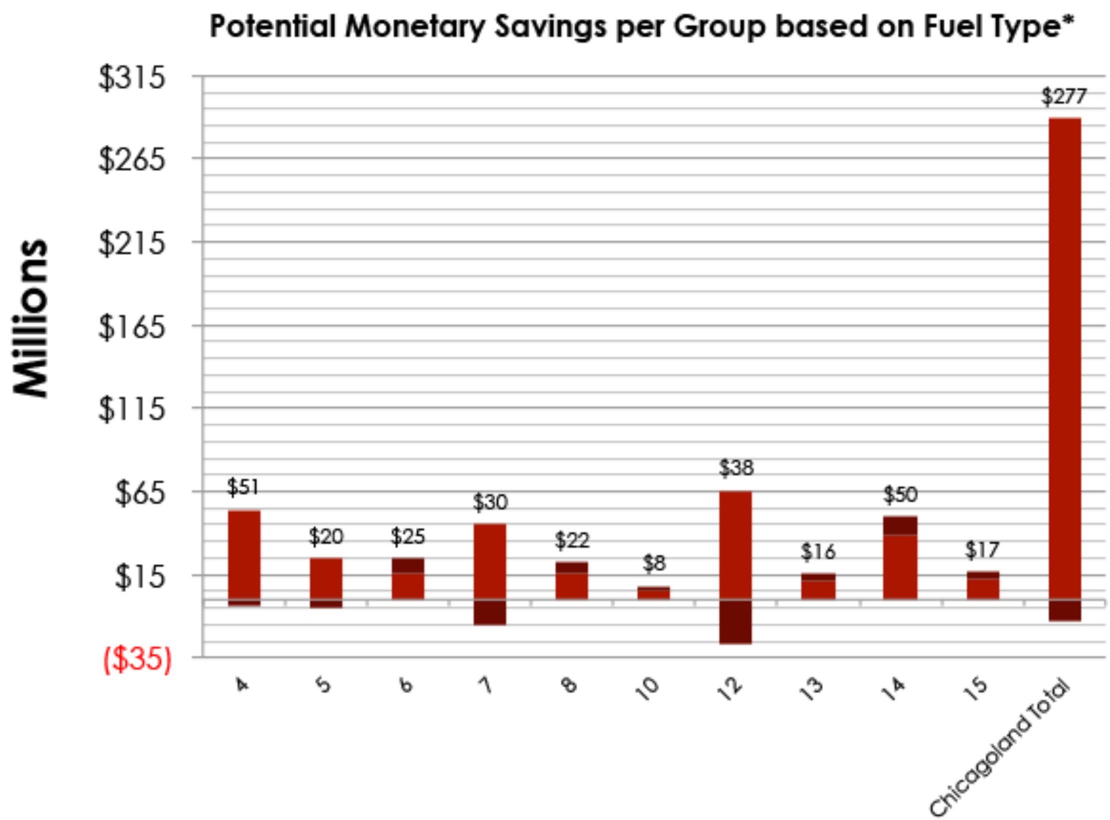
- We demonstrated the utility of whole building energy simulation and optimization software (BEopt + EnergyPlus) to construct a "tool box" of prescriptive deep energy retrofits that can be applied to large portions of the housing stock
  - Envelope retrofits, then HVAC retrofits
  - Sequential search optimization methods on Amazon EC2



Retrofitting older Chicago homes

- If we applied these retrofits across the Chicago building stock:





Estimated ~$280 million USD in annual energy savings!

7) Indoor air and climate change

EPA STAR: Impacts of climate change on indoor air

"Combining measurements and models to predict the impacts of climate change and weatherization on indoor air quality and chronic health effects in U.S. residences"

- Climate change is expected to impact the concentrations of airborne pollutants inside buildings in both direct and indirect ways

IOM 2011; Spengler *Indoor Air* **2012** 22: 89–95; Nazaroff *Environ Res Lett* **2013** 8: 015022

Direct:
- Changes in outdoor pollutants
- Changes in meteorological conditions that drive building performance and indoor concentrations
  - Air exchange rates
  - HVAC operation (and filtration)
  - Window opening behaviors

Indirect:
- Widespread policy responses
  - Weatherization of older buildings
  - Energy efficient new construction
  - Tighter buildings; altered HVAC runtimes

New EPA STAR Project (3 years):
- Modeling concentrations, exposures, and health effects of indoor air in homes across U.S.
- Field measurements in 30 homes before and after retrofits
  - Outdoor pollutant penetration
  - Envelope airtightness

Moving forward…

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

Many thanks to all of the homeowners, occupants, and business owners that let us inside their buildings

Funding sources, people, and projects:

- **I/O pollutants:** University of Texas at Austin Continuing Fellowship, NSF IGERT Award DGE #0549428, ASHRAE Grant-In-Aid & RP-1299, Thrust 2000 Endowed Graduate Fellowship (all UT-Austin), Jeff Siegel, Zeineb El Orch, Will Ollison, API, EPA
- **Filtration:** National Air Filtration Association (NAFA) Foundation, Al Veeck, Parham Azimi, ASHRAE
- **HMP:** Alfred P. Sloan Foundation, Jack Gilbert, Jeff Siegel, Tiffanie Ramos, Parham Azimi, Laurit Dide
- **OSBSS:** Alfred P. Sloan Foundation, Paula Olsiewski, ACE PURE, Akram Ali, Deion Debose, Boyang “Bobo” Dong, Torkan Fazli, Joseph Huan, Zack Zanzinger, OSBSS Advisory Board
- **3D printers:** Armour College of Engineering, Bobby Zylstra, Julie Steele (3D Printer Experience), Mike Moceri, Parham Azimi, Zeineb El Orch, Tiffanie Ramos, Sara Glade, NIOSH/CDC
- **Retrofits:** Honnie Leinartas
- **IA+CC:** EPA, Elevate Energy

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