# Occupancy detection via environmental sensing

Paper synopsis

M. Jin; N. Bekiaris-Liberis; K. Weekly; C. J. Spanos; A. M. Bayen,
"Occupancy Detection via Environmental Sensing,"
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# Why occupancy detection matters?

- Buildings account for 40% total energy use
- Energy consumption in buildings is highly correlated to occupants
- Occupancy information can be used to:


**Monitor occupant specific energy use**

Individual energy use (Chen and Ahn, 2014)

Occupant classification: energy efficiency, entropy, intensity (Gulbinas et al., 2015)


**Improve occupant behavior modeling**

Social connectivity vs. energy saving study (Peschiera and Taylor, 2012)

Improve proposed/future occupancy models (Hong et al. 2016)


**Real time building automatic control**

Demand-controlled ventilation

Geo-fencing

Lighting control

# Occupancy detection can be classified by information granularity


| Sensors | Presence | Count | Activity | Identity | Track |
|---|---|---|---|---|---|
| $CO_2$ | ✓ | ✓ | ✗ | ✗ | ✗ |
| PIR | ✓ | ✗ | ✗ | ✗ | ✗ |
| Ultrasonic | ✓ | ✗ | ✗ | ✗ | ✗ |
| Power meter | ✓ | ✗ | ✓ | ✗ | ✗ |
| Camera | ✓ | ✓ | ✓ | ✓ | ✓ |
| Sound | ✓ | ✓ | ✓ | ✓ | ✓ |
| WiFi access | ✓ | ✓ | ✗ | ✓ | ✓ |
| Computer app. | ✓ | ✓ | ✓ | ✓ | ✗ |

*Privacy concerns*

(Labeodan et al., 2015)

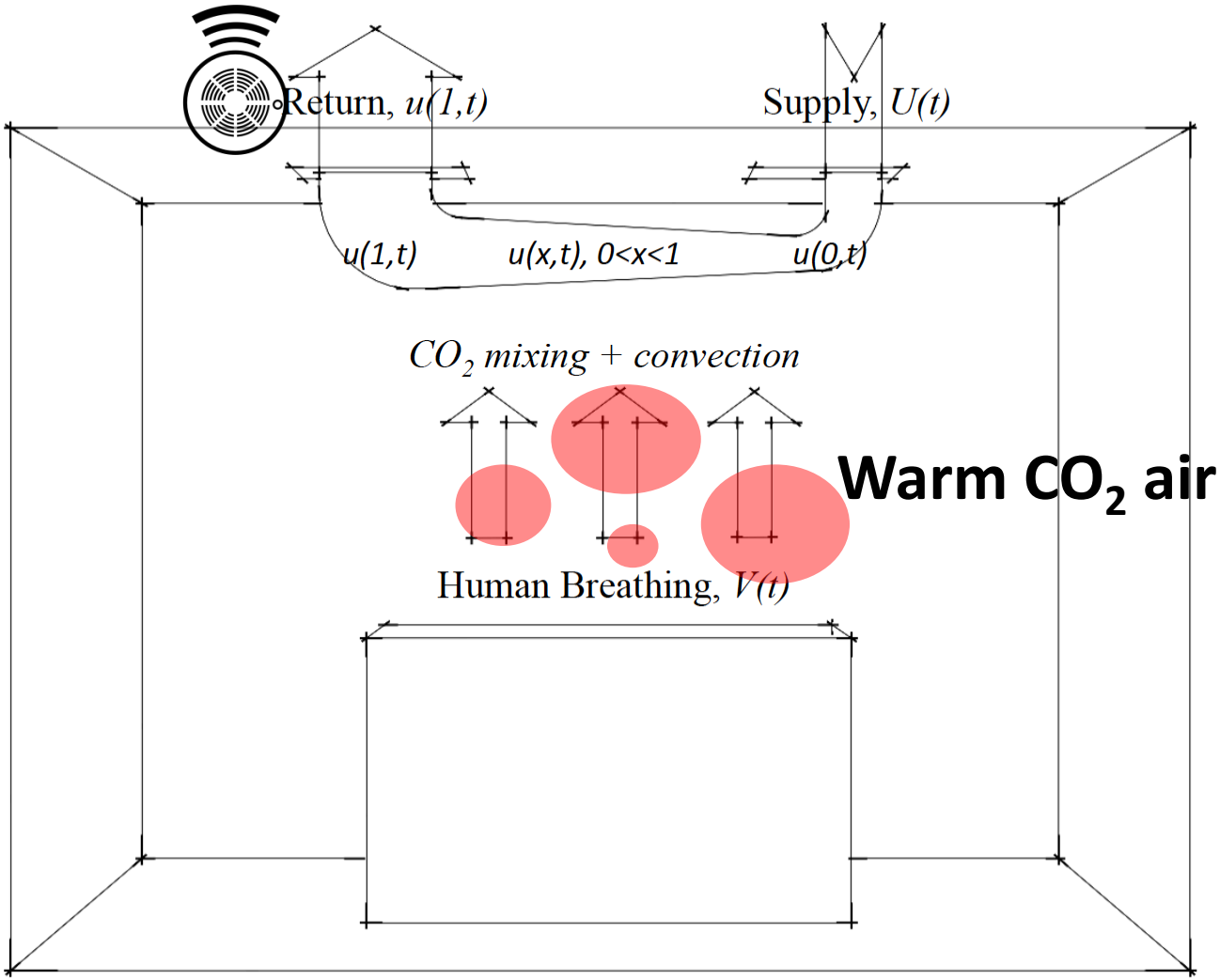
# Why (or not) $CO_2$ based detection

+ Humans naturally exhale $CO_2$ – occupancy proxy
+ $CO_2$ sensors can be integrated with climate sensors & HVAC systems
+ $CO_2$ provides info on indoor air quality, linked to productivity (Fisk, 2013)


*"The 'Sensing by Proxy' model is more accurate than previously used machine learning models, and could be used to improve the efficiency of Demand-Controlled Ventilation systems (DCV) currently in use."*

*-- CO2Meter.com*

# “Sensing by proxy” is based on a physical model




**Warm $CO_2$ air “bubble”**

# ODE-PDE model captures the dynamics of $CO_2$ concentration

Models $CO_2$ convection in space

**Partial Differential Equation (PDE)**

$$u_t(x,t) = -bu_x(x,t) + b_X X(t)$$

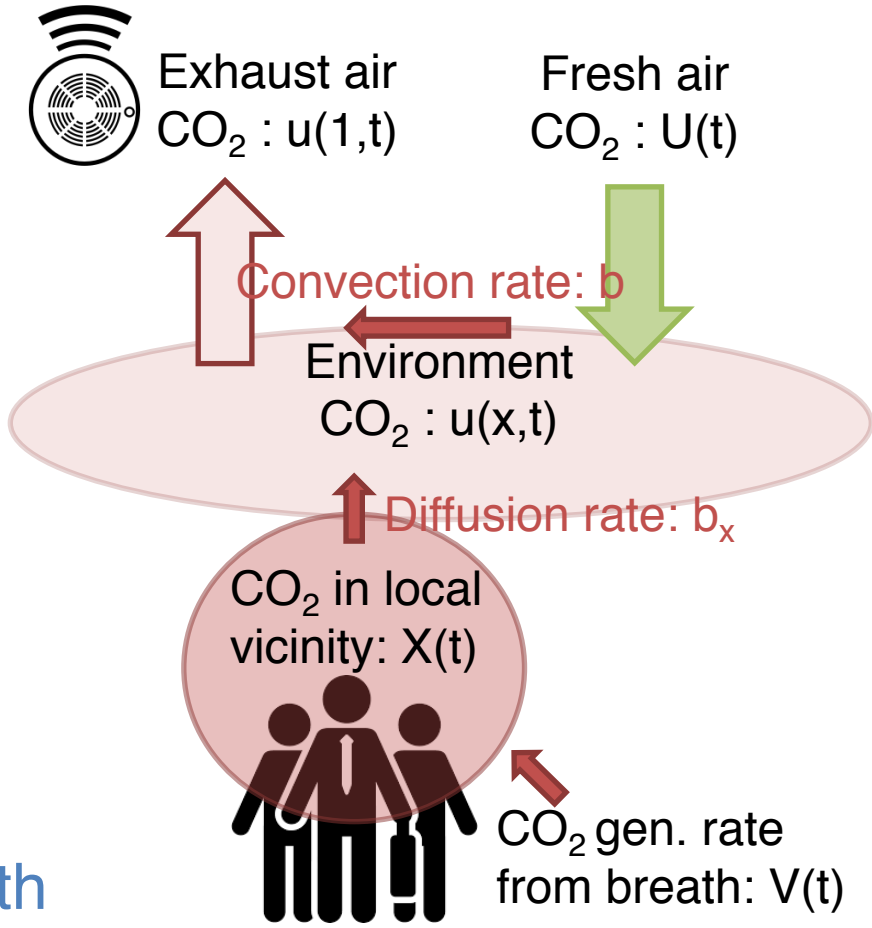
$$u(0,t) = U(t)$$

**Ordinary Differential Equation (ODE)**

$$\dot{X}(t) = -aX(t) + V(t)$$

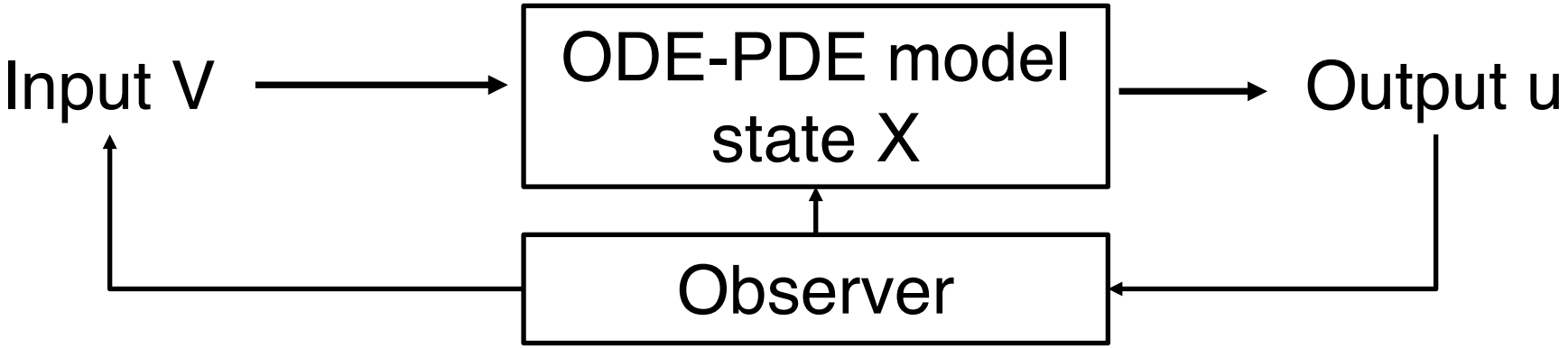
$$\dot{V}(t) = 0$$

Models $CO_2$ production from breath on local vicinity concentration



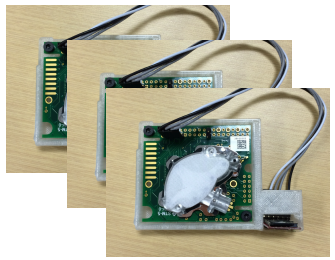
# Occupancy detection becomes an "observer" problem

→ *Given output, estimate input V(t) and state X(t)*




**$CO_2$ production**

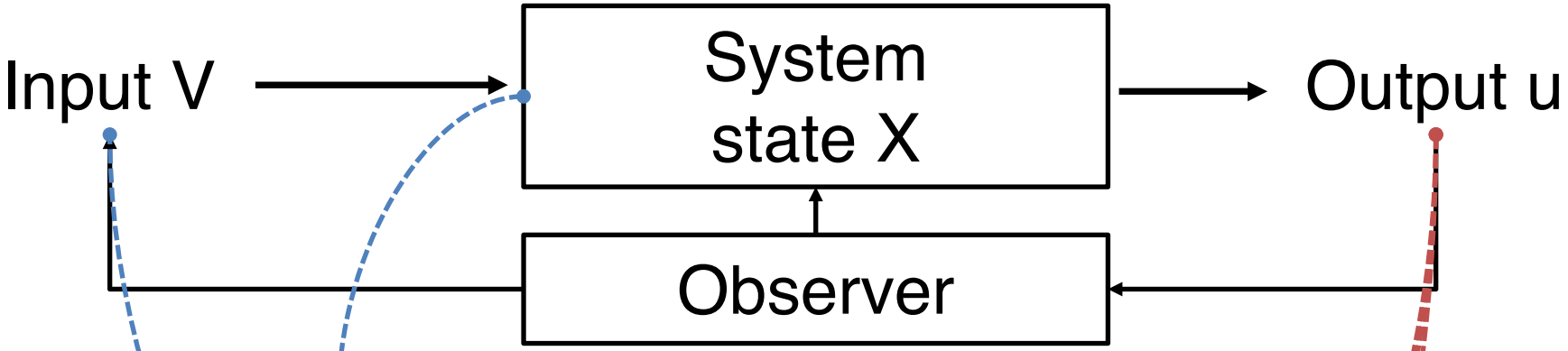

**Observations**



**Occupancy detection**

# Occupancy detection becomes an "observer design" problem

→ *Given output, estimate input V(t) and state X(t)*




**Observer for the ODE-PDE System**

$$\hat{u}_t(x,t) = -b\hat{u}_x(x,t) + b_X\hat{X}(t) + r(x)(u(1,t) - \hat{u}(1,t))$$

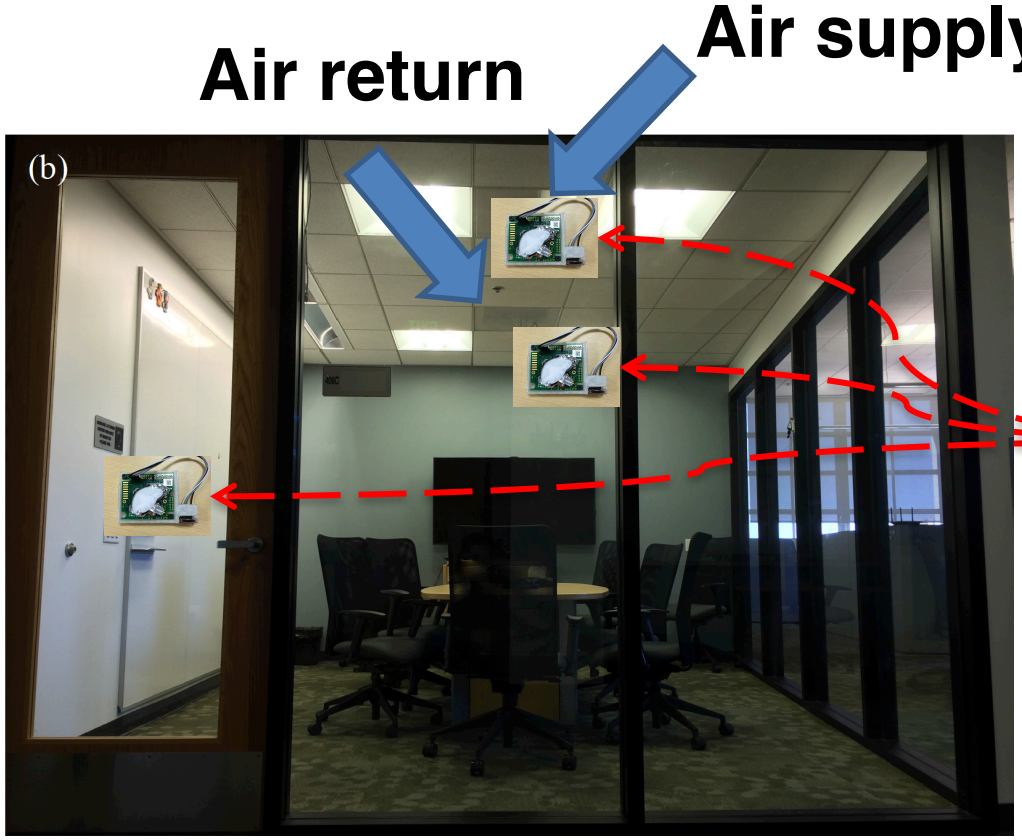
$$\hat{u}(0,t) = U(t)$$

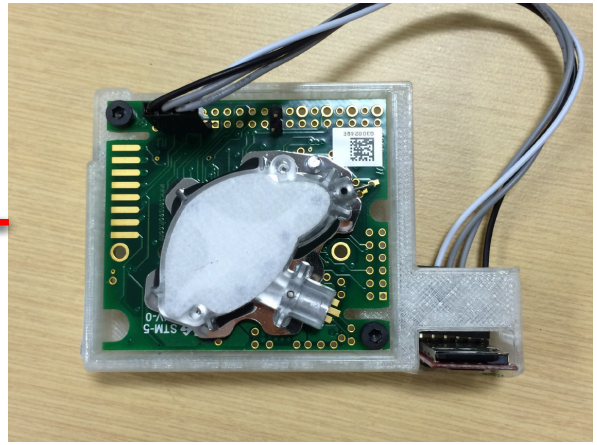
$$\dot{\hat{X}}(t) = -a\hat{X}(t) + \hat{V}(t) + L_1(u(1,t) - \hat{u}(1,t))$$

$$\dot{\hat{V}}(t) = -L_2(u(1,t) - \hat{u}(1,t))$$

***Convergence guaranteed by Theorem 1***

# Experiment setup and $CO_2$ sensor

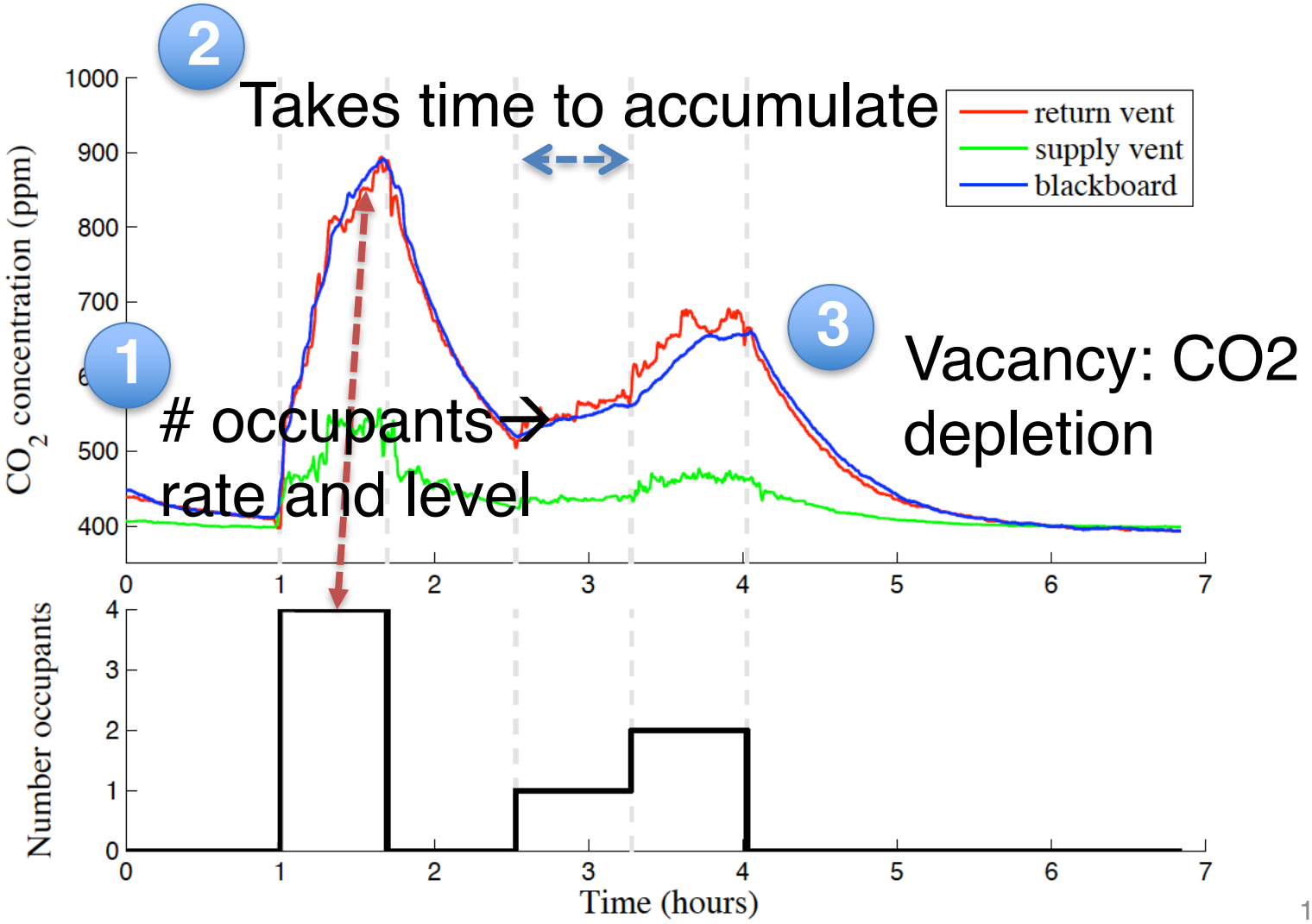


- 44 $m^3$ conference room
- Completely interior in the building

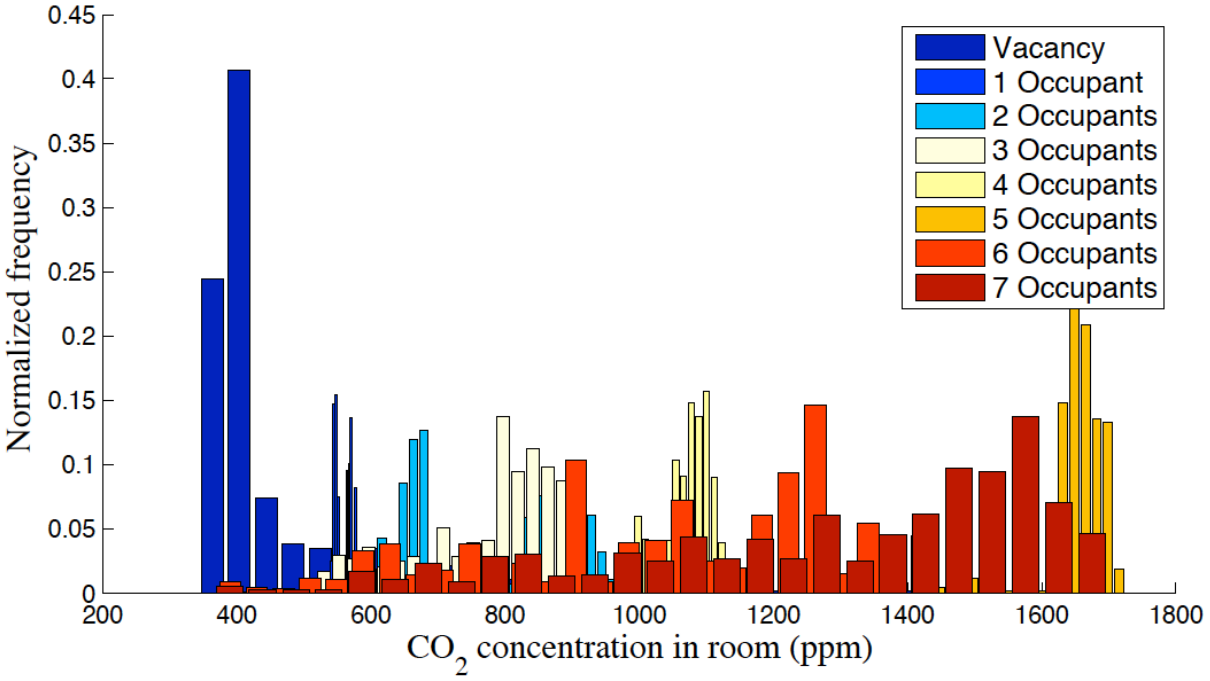
- K-30 Sensor Module
- Baselined via the Automatic Baseline Correction

# Experiment with occupants while measuring indoor $CO_2$



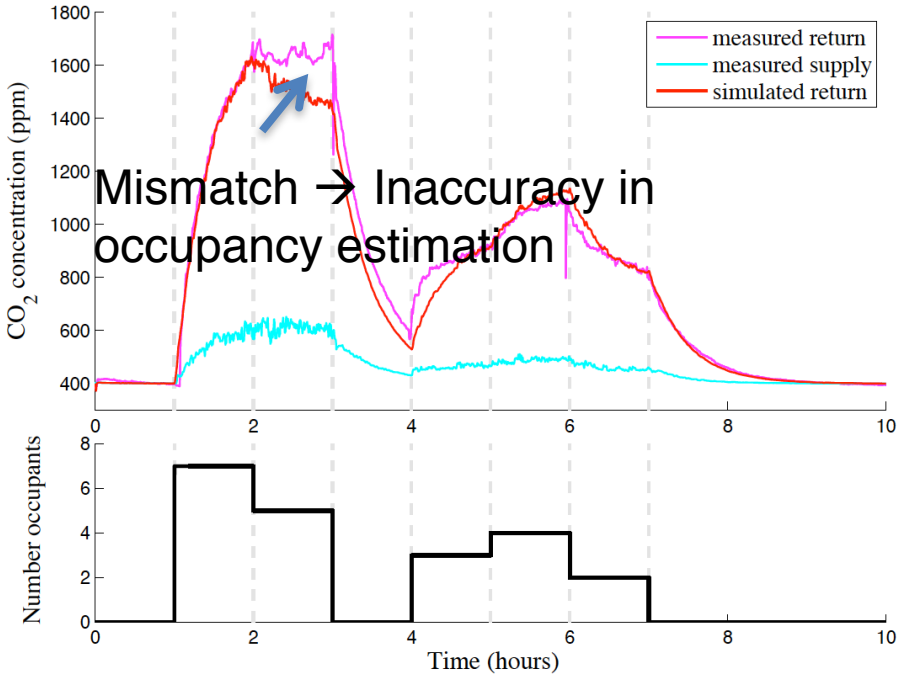
# $CO_2$ instant concentration is a poor indication of occupancy

$CO_2$ distributions for different occupancy level

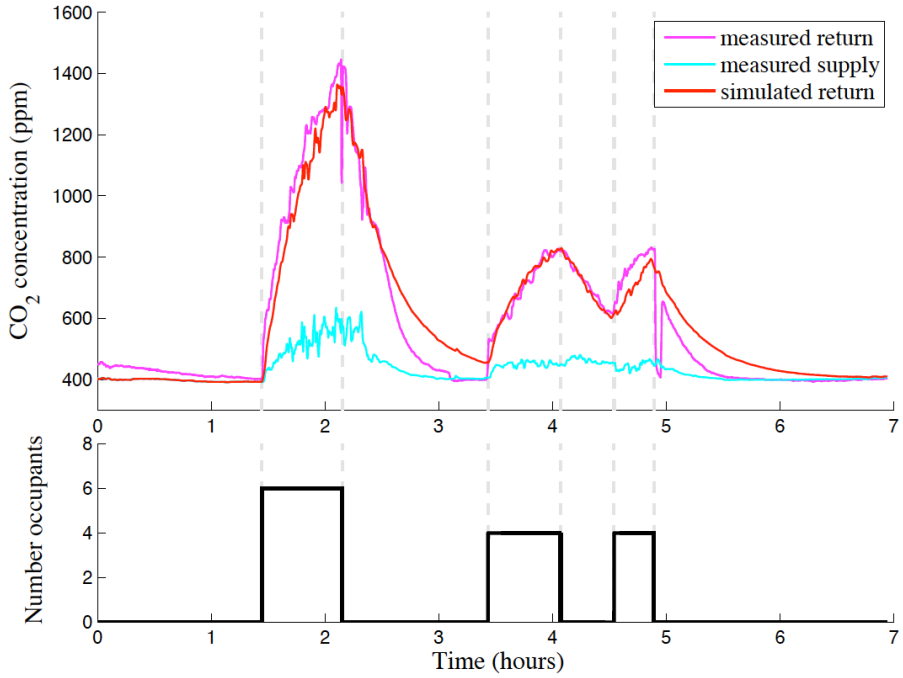



- Different occupancy levels can correspond to similar $CO_2$ concentration, due to slow accumulation/depletion

# Sensing by proxy captures the indoor $CO_2$ dynamics




Mismatch → Inaccuracy in occupancy estimation




**Occupancy** → **PDE-ODE Model** → **Return vent $CO_2$**

Given occupancy, we can have accurate prediction of exhaust air $CO_2$ concentration

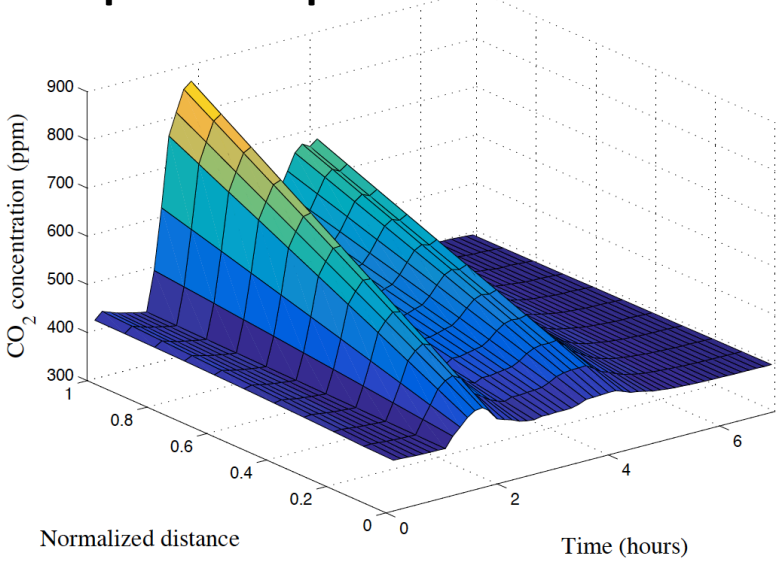
# The parameters are based on physics (room, ventilation rate, etc.)


**Fresh air equil.**: 400ppm

**Human breathe**: 0.183ppm/sec

| Param. | Physical meaning | Value | Unit |
|---|---|---|---|
| 1/a | Effect rate | 16.67 | sec |
| b | Convection rate | 2.5 | m/sec |
| $b_x$ | Diffusion rate | 1.5 | 1/sec |

**Spatial temporal simulation**

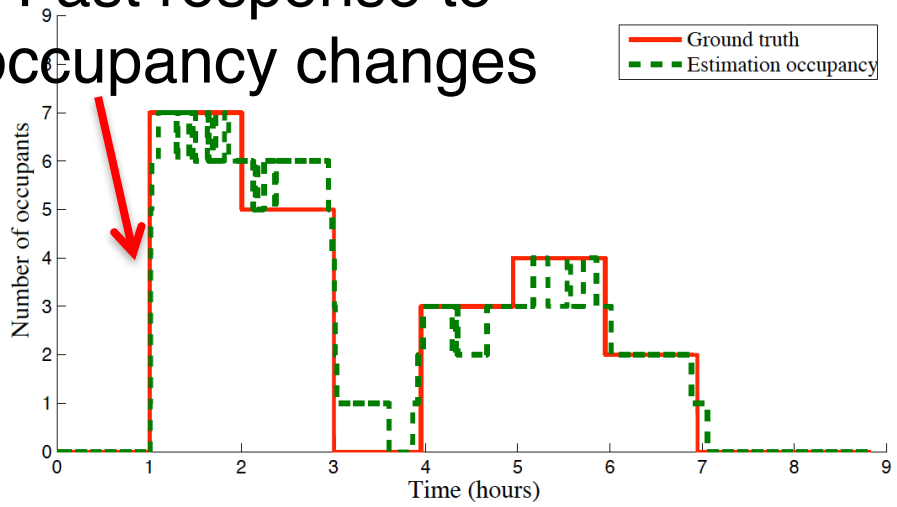



PDE-ODE can reproduce the spatio-temporal distribution of $CO_2$ concentration

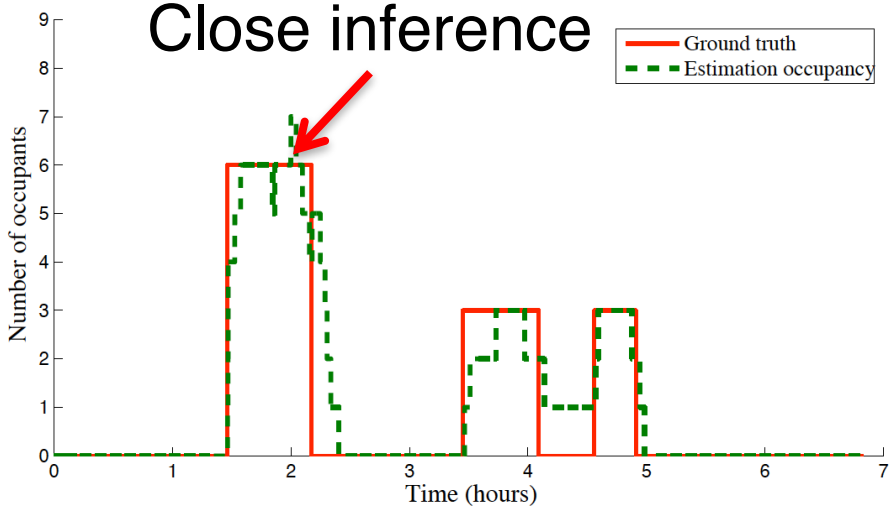
# SbP has fast response rate and high real-time accuracy


- Inference based on the dynamics of PDE-ODE Model
- Robust to non-uniformity (physique, positions), doors

Fast response to occupancy changes




Close inference



# SbP is more reliable than ML-based methods

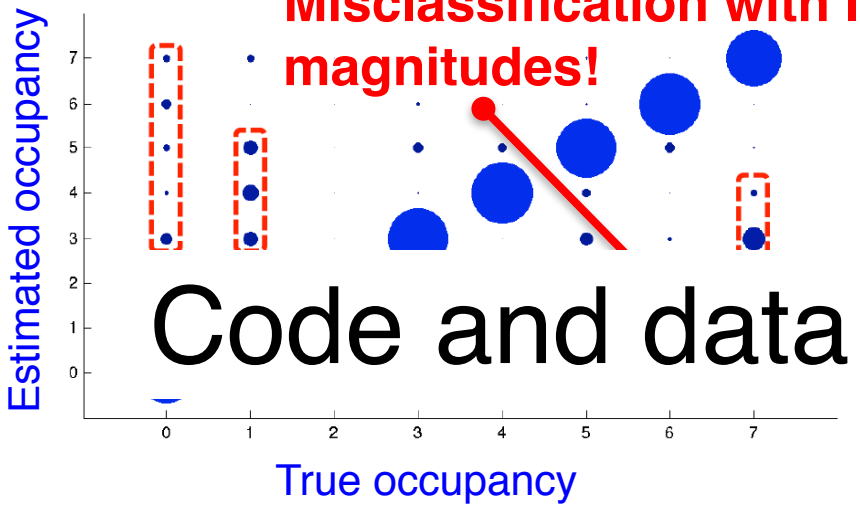
| | Naïve Bayes | Bayes Net | Logistic Regress. | Multi-Layer Perceptron | RBF Network | SMO | Ada-Boost | Sensing by Proxy |
|---|---|---|---|---|---|---|---|---|
| **RMSE** | 1.356 | 1.21 | 1.47 | 1.23 | 1.33 | 1.61 | 2.39 | 0.63 |

***Lower RMSE!***

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(TrueOcc(i) - EstOcc(i)\right)^2}$$

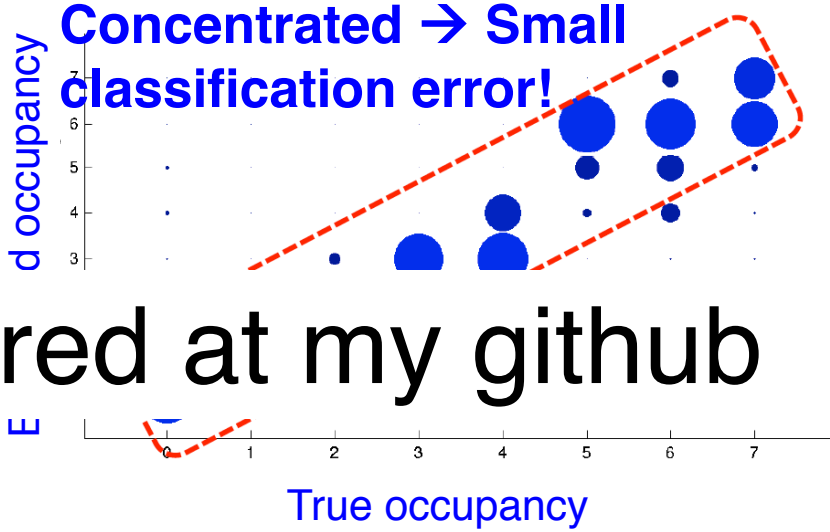
**Bayes Net**

**Misclassification with large magnitudes!**




**Sensing by Proxy**

**Concentrated → Small classification error!**




Code and data shared at my github