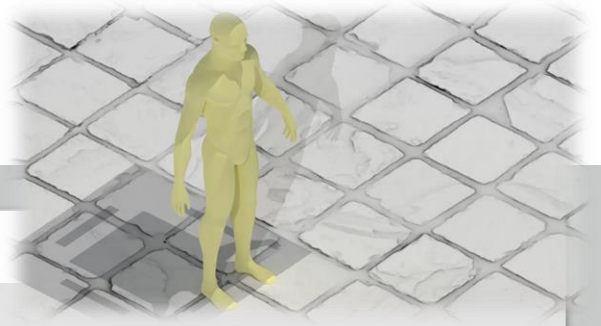
A STATISTICAL RISK ASSESSMENT OF VIRAL AIRBORNE RISK ASSESSMENT USING HIGH-FIDELITY SIMULATIONS

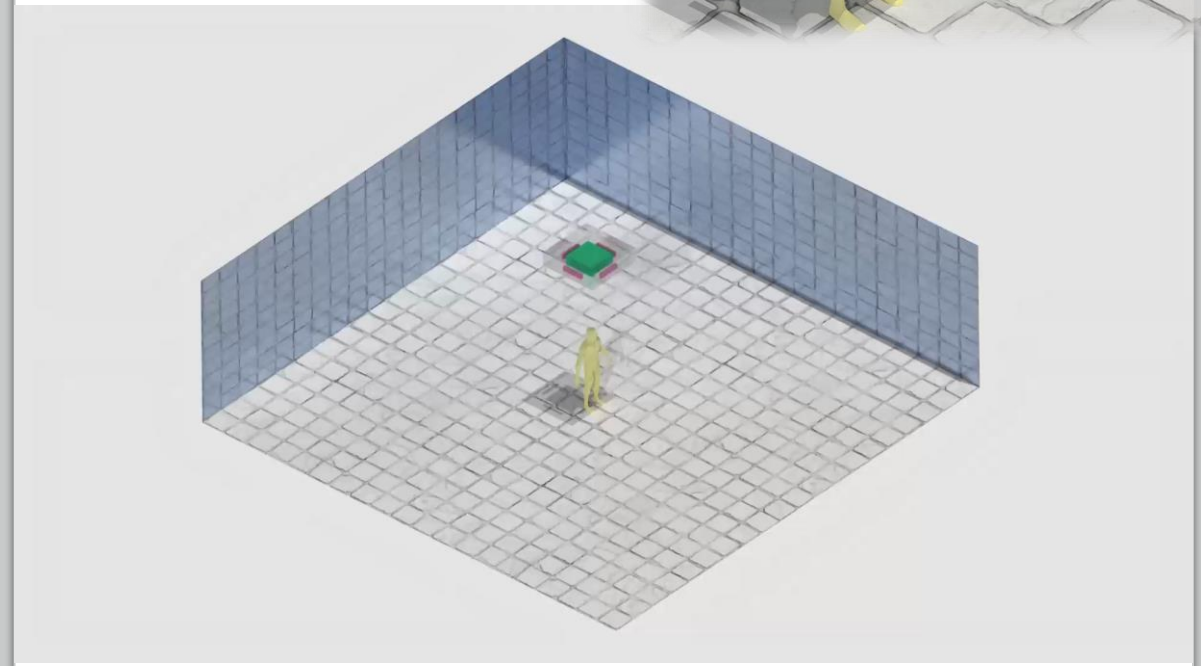
K.A. Krishnaprasad, J. Salinas, N. Zgheib, S. Balachandar
University of Florida, USA

Introduction

- Airborne viral contagion is a multidisciplinary problem
  - Immunology
  - Virology
  - Fluid Mechanics
- Most of our guidelines – research done in the 1950s

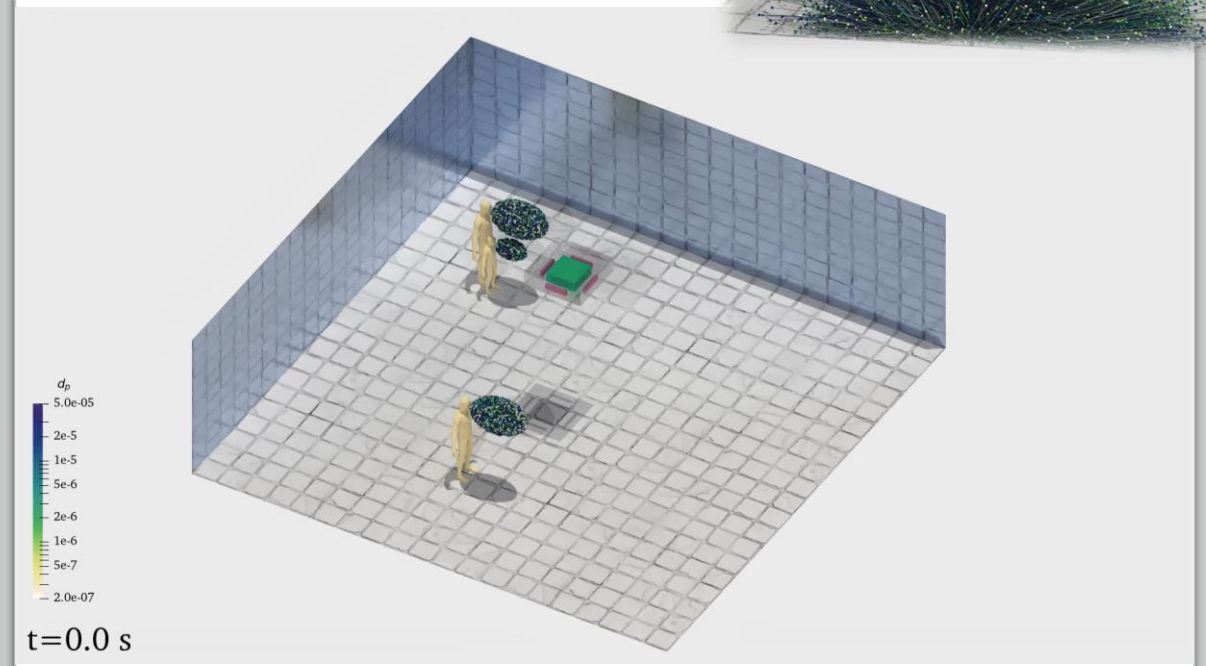
Ejection-Scale problem





K. Liu et al, Scientific Reports 11, 1 (2021).

Room-Scale problem



Well-Mixed Models

- Virus-laden particles mix over the entire room and can infect the receiver equally regardless of their location.

$$C(r,t) = C_s(r)\left(1 - e^{-\lambda_c(r)t}\right)$$

$$C_s(r) = \frac{P(r)}{\lambda_c(r)V}$$

$$\lambda_c(r) = \lambda_a + \lambda_s(r) + \lambda_f(r) + \lambda_v(r)$$

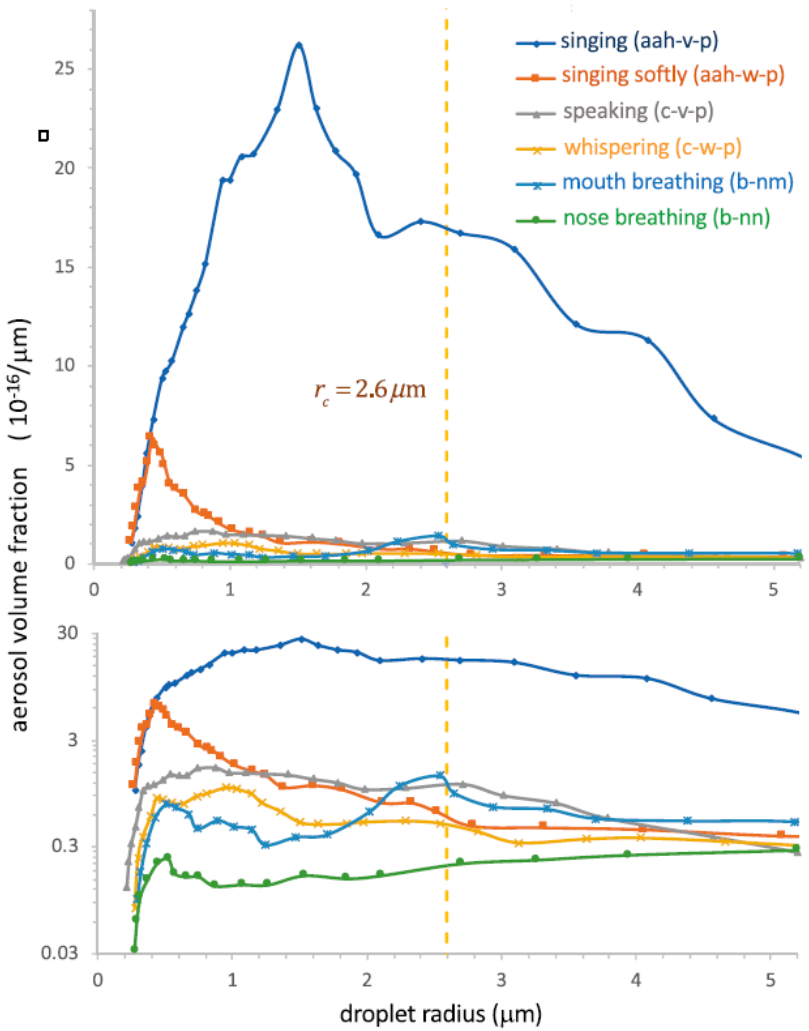
Filtration

Viral deactivation

Settling: $\lambda_s(r) = \frac{v_s(r)}{H}$

Ventilation: $\lambda_a(r) = \frac{ACH}{V_{room}}$

M. Z. Bazant and J. W. Bush, PNAS **118** (2021).



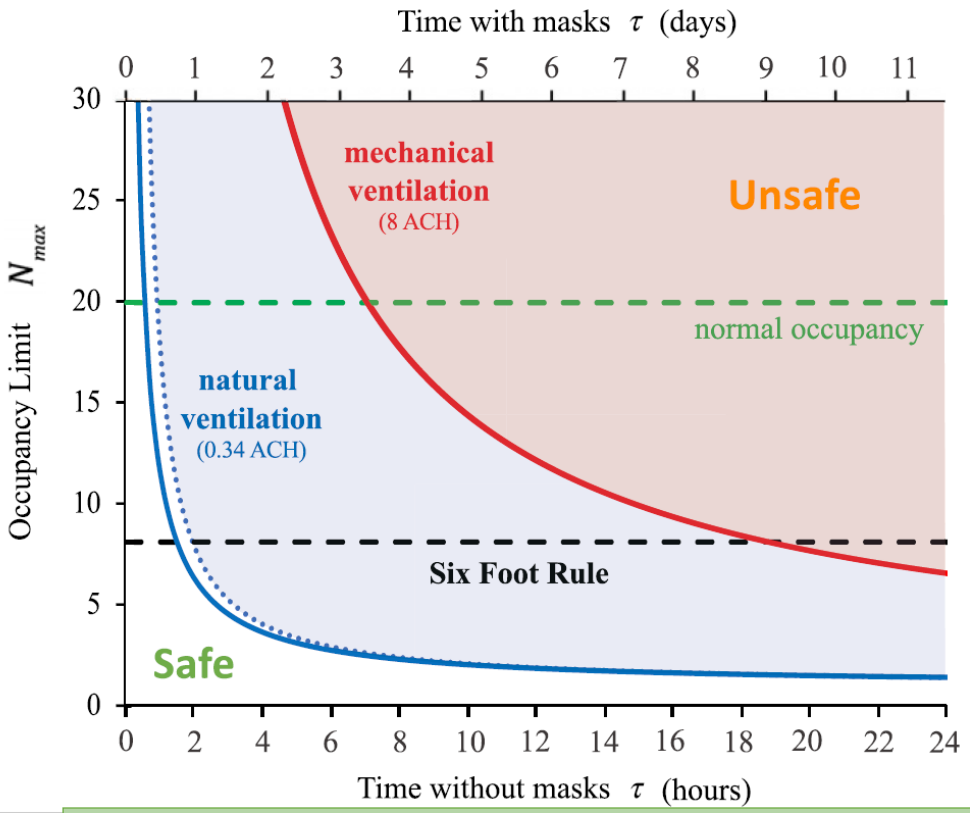
L. Morawska *et al.*, *J. Aerosol Sci.* **40**, 256–269 (2009).

Occupancy vs Cumulative Exposure Time

$$(N\tau)_{wm} = \frac{\epsilon}{Q_b^2 p_m^2 C_q s_r \overline{\hat{n}_{wm}}(\tau)}$$

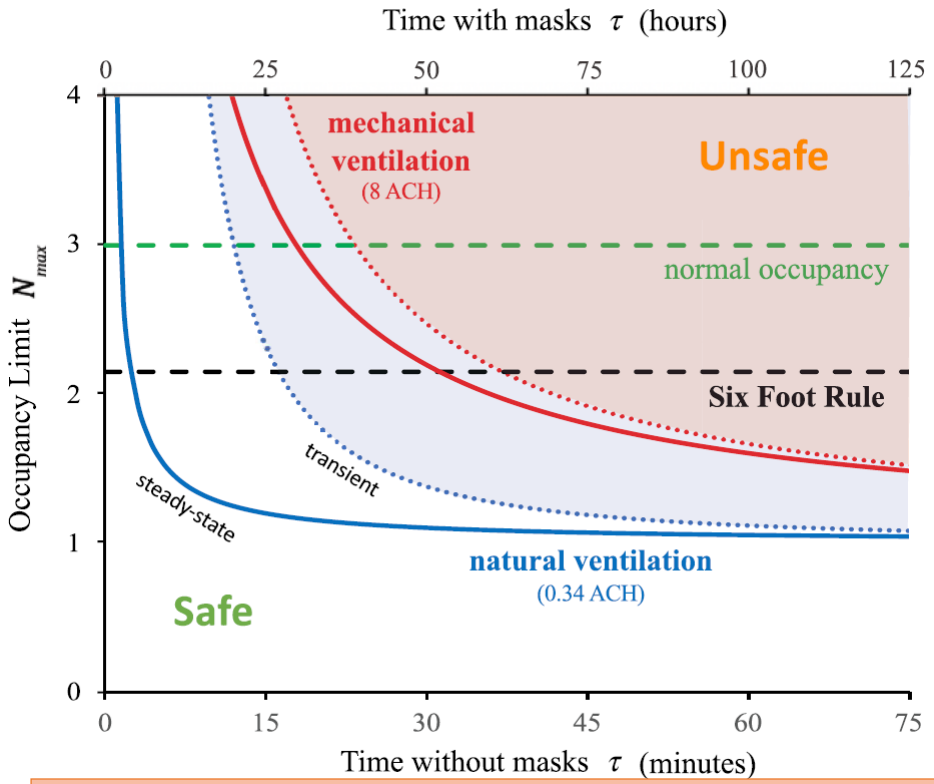
Q_b: Rate of quanta emission
p_m: Mask permeability
C_q: Rate of quanta emission

A Classroom



$A = 83.6\ m^2$, $V = 301\ m^3$. Low relative transmissibility ($s_r = 25\%$). Moderate risk tolerance ($\epsilon = 10\%$). Cloth masks ($p_m = 30\%$).

B Nursing home



$A = 22.3\ m^2$, $V = 53.5\ m^3$. High relative transmissibility ($s_r = 100\%$). Low risk tolerance ($\epsilon = 1\%$). Surgical masks ($p_m = 10\%$).

M. Z. Bazant and J. W. Bush, PNAS **118** (2021).

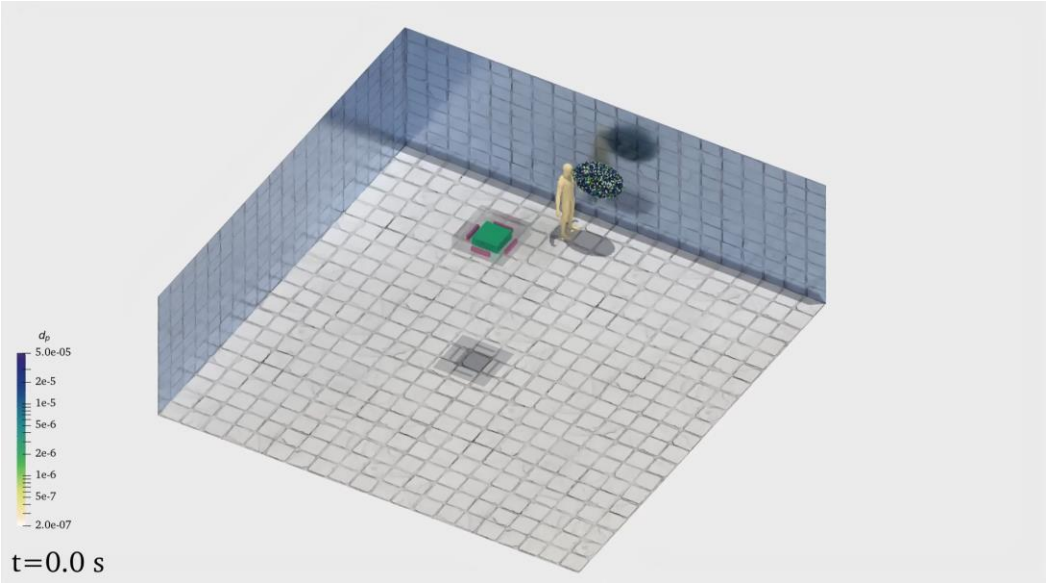
Objectives

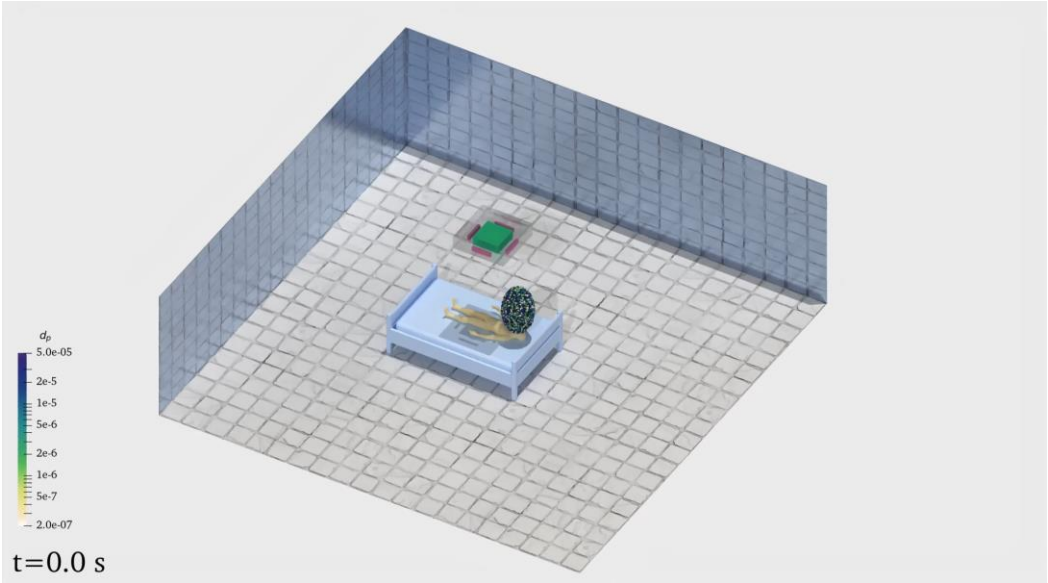
$$(N\tau)_{wm} = \frac{\epsilon}{Q_b^2 p_m^2 C_q s_r \overline{\hat{n}_{wm}}(\tau)}$$

$$N\tau = \frac{1}{\gamma}(N\tau)_{wm}$$

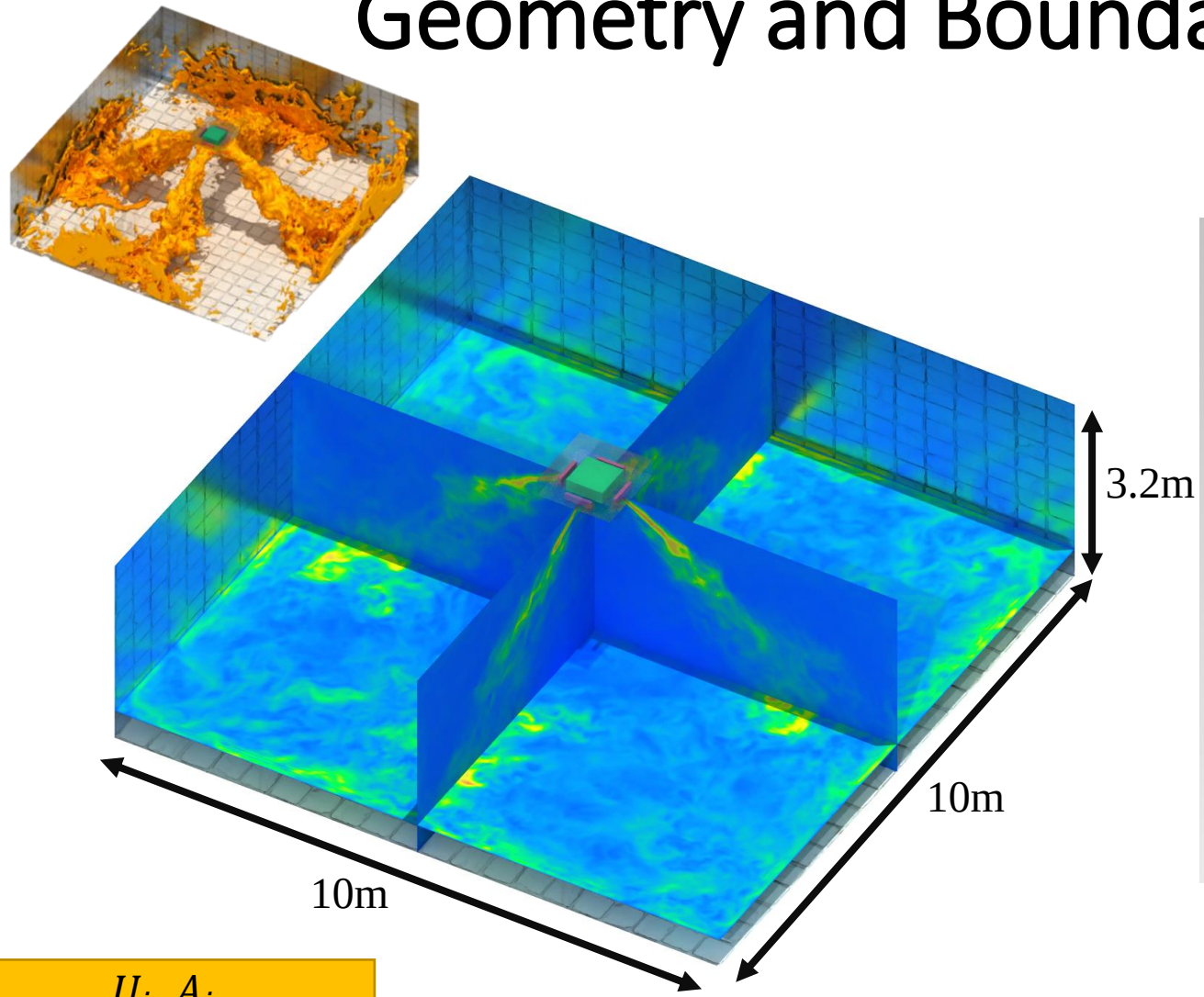
Correction Factor

1. To test the robustness of well-mixed model in predicting airborne viral contagion
2. To recommend modified fluid-mechanics based guidelines for occupancy and CET.

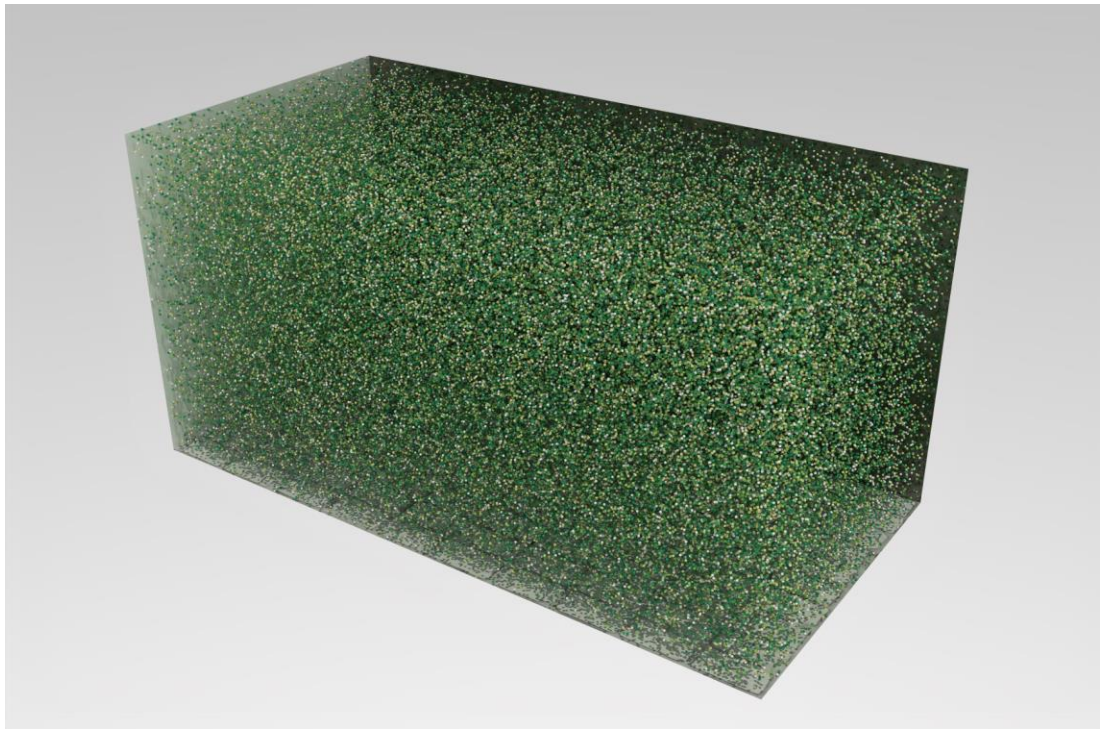




Geometry and Boundary Conditions



Statistical Overloading



$$ACH = \frac{U_{in}A_{in}}{V_{room}} (h^{-1})$$

Particle radii: 0.1, 0.5, 1, 2.5, 5, 7.5, 10, 12.5, 15, 20, 25 µm

2 million particles per radius

Governing Equations

Fluid Phase (Nek5000)

$$\nabla \cdot \tilde{\boldsymbol{u}} = 0$$

$$\frac{\partial \tilde{\boldsymbol{u}}}{\partial t} + \tilde{\boldsymbol{u}} \nabla \cdot \tilde{\boldsymbol{u}} = -\nabla p + (\nu + \nu_t) \nabla^2 \tilde{\boldsymbol{u}}$$

ν_t is obtained using dynamic Smagorinsky

$\tilde{\boldsymbol{u}}$ is the resolved velocity field

$\boldsymbol{u}'$is the perturbation velocity obtained using the Langevin model

Droplet Phase (Ppiclf)

$$\frac{d}{dt}\begin{bmatrix} \boldsymbol{X}_l \\ \boldsymbol{U}_l \end{bmatrix} = \begin{bmatrix} \boldsymbol{U}_l \\ \boldsymbol{F}_l / m_l \end{bmatrix}$$

$$\boldsymbol{F}_l = \boldsymbol{F}_{qs,l} + \boldsymbol{F}_{g,l}$$

$$\begin{aligned} \boldsymbol{F}_{qs,l} &= 6\pi \mu_f r_l [\boldsymbol{u}(\boldsymbol{X}_l) - \boldsymbol{U}_l] \Phi(\mathrm{Re}_l) \\ \boldsymbol{F}_{g,l} &= V_l (\rho_p - \rho_f) g \end{aligned}$$

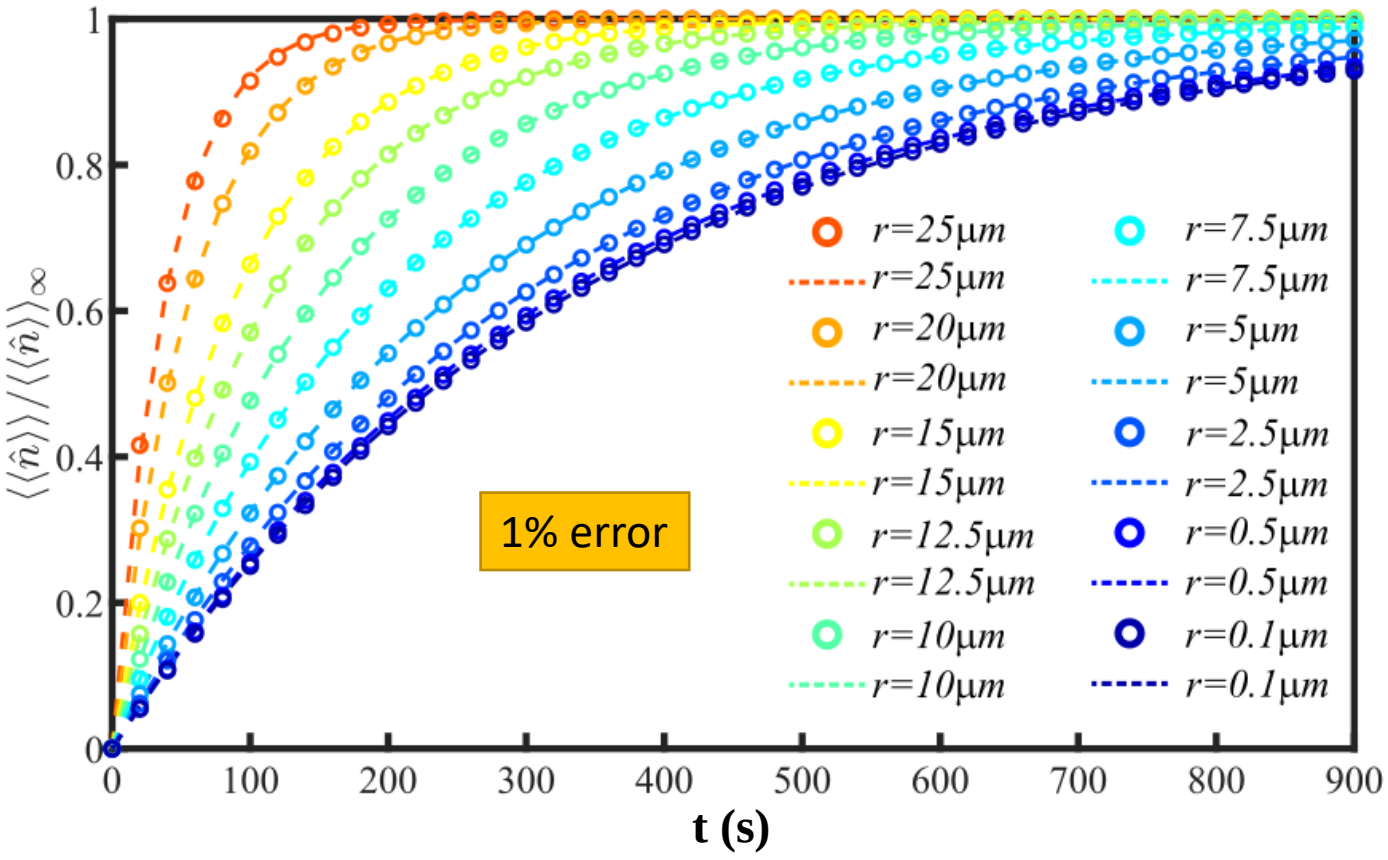
$$\boldsymbol{u}(\boldsymbol{X}_l) = \tilde{\boldsymbol{u}}(\boldsymbol{X}_l) + \boldsymbol{u}'(\boldsymbol{X}_l)$$

Langevin Model:

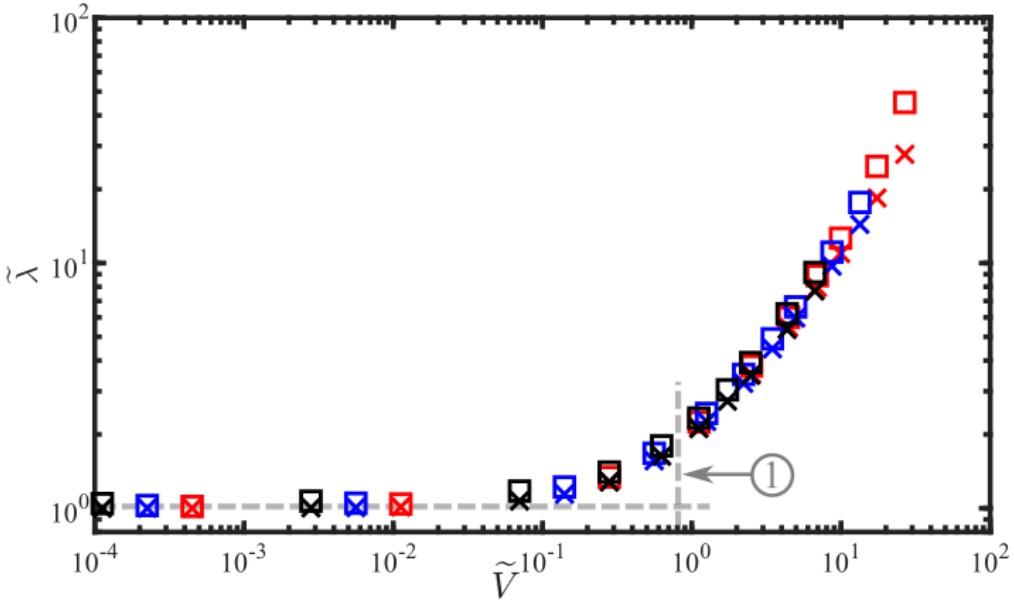
$$u'(X_l(t+\Delta t), t+\Delta t) = \left[1 - \left(\frac{1}{2} + \frac{3C_0}{4}\right)\left(\frac{C_s^2 |\tilde{S}|}{2C_Y}\right)\right] u'(X_l(t), t) + \sqrt{\frac{C_0}{3\tilde{\varepsilon}\Delta t}} f_w \xi$$

Room Averaged Statistics

Concentration is double averaged over all source and sink locations



1% error



$$\tilde{\lambda} = \frac{3600}{ACH}\lambda$$

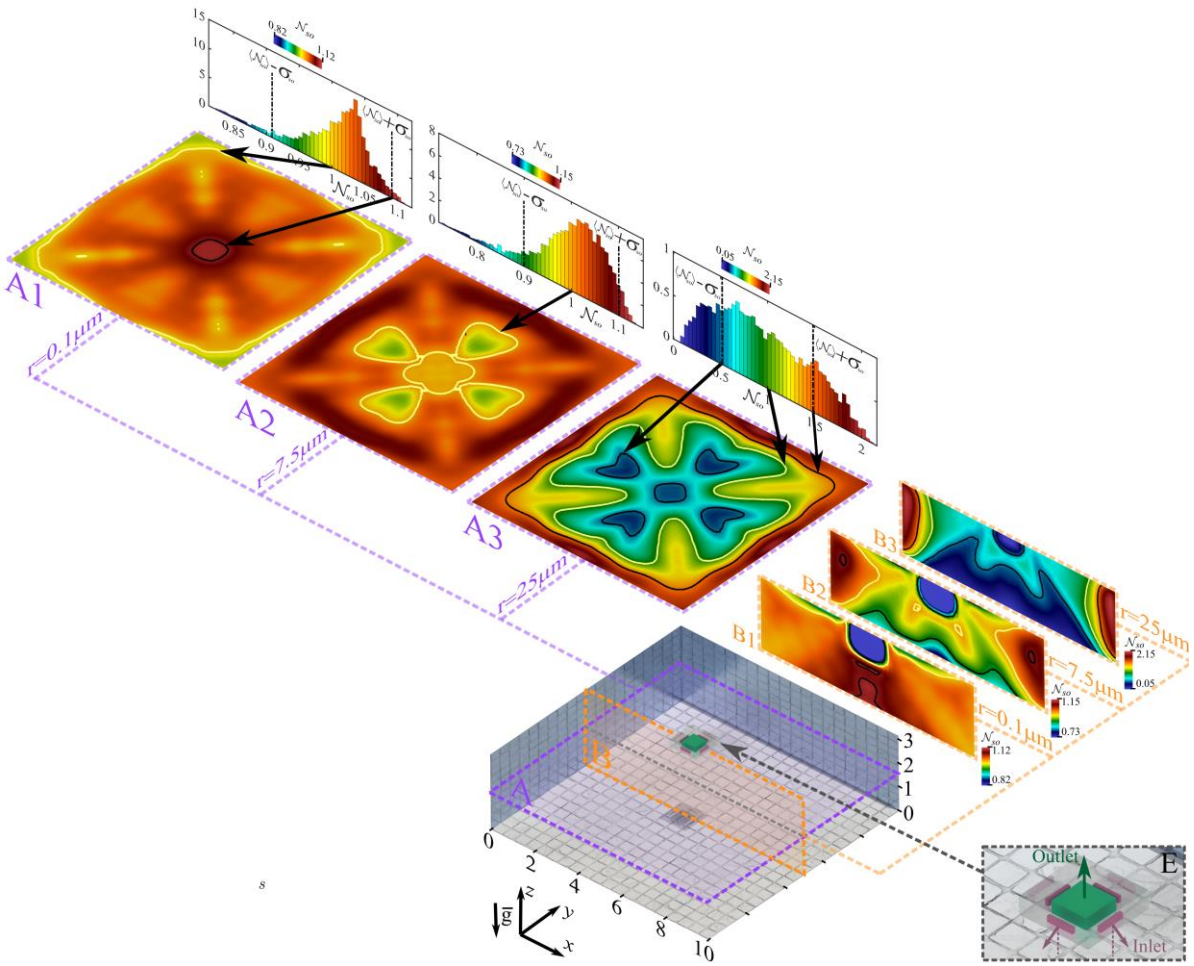
$$\tilde{V}_s = \left(\frac{3600}{ACH}\right)\left(\frac{V_s}{H}\right)$$

Concentration is normalized by the steady state value of concentration

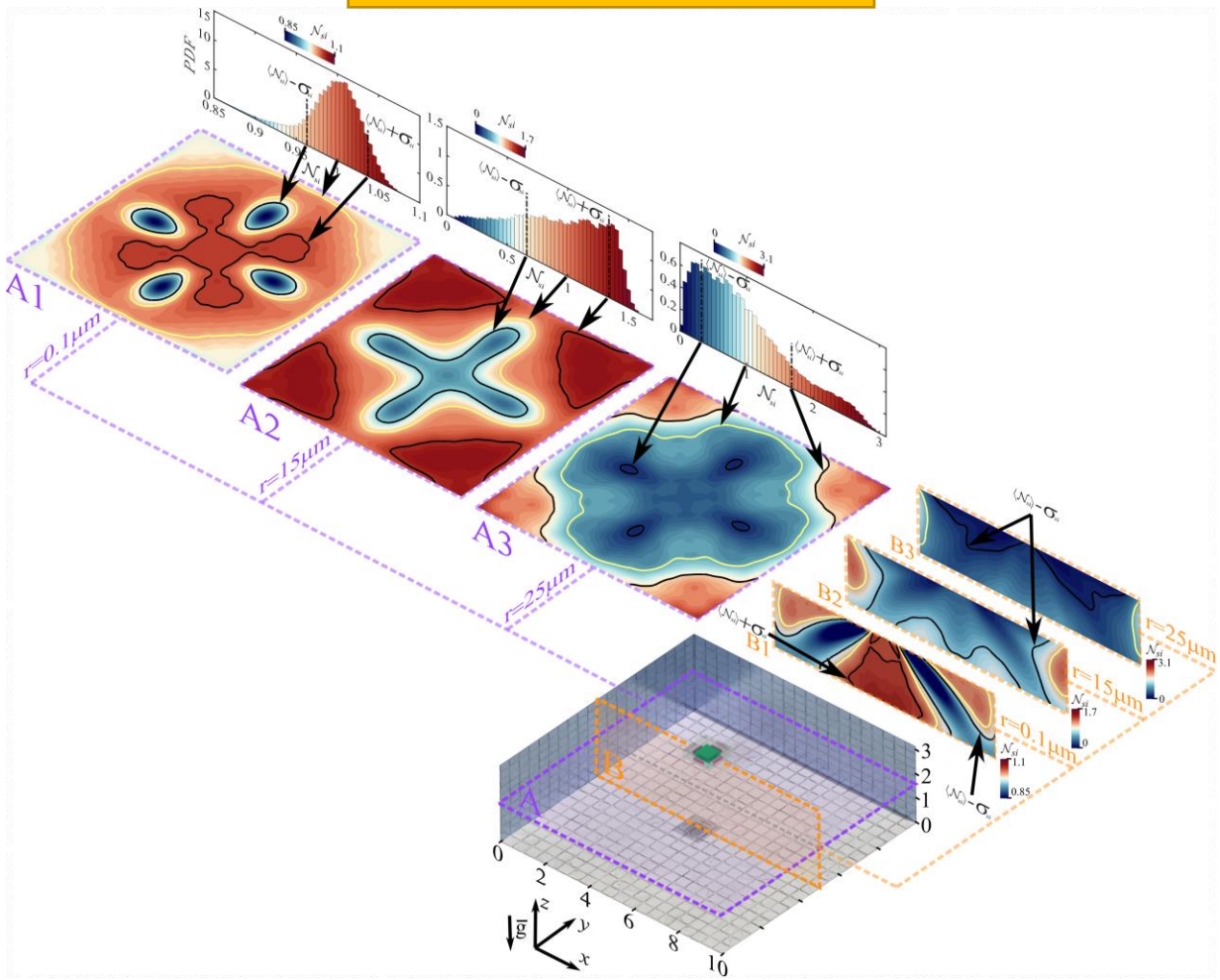
$$r_c = \sqrt{\frac{9(ACH)H\mu_a}{7200g\Delta\rho}}$$

Well-mixed theory remarkably accurate even for $r > r_c$

Sink Averaged: From the source perspective



Source Averaged: From the sink perspective



$$\mathcal{N}_{so}(x_{so},r) = \frac{\langle \hat{n} \rangle_{si,\infty}(x_{so},r)}{\langle \langle \hat{n} \rangle \rangle_{\infty}(r)}$$

Normalized with the room average concentration

$$\mathcal{N}_{si}(x_{si},r) = \frac{\langle \hat{n} \rangle_{so,\infty}(x_{si},r)}{\langle \langle \hat{n} \rangle \rangle_{\infty}(r)}$$

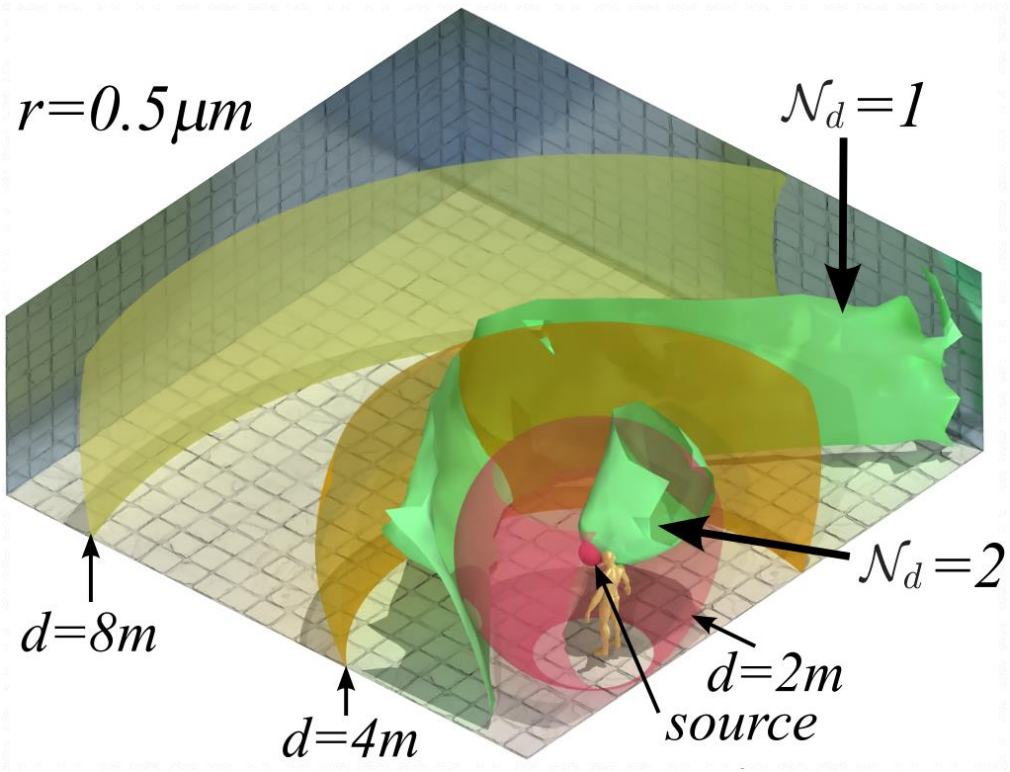
Source to Sink

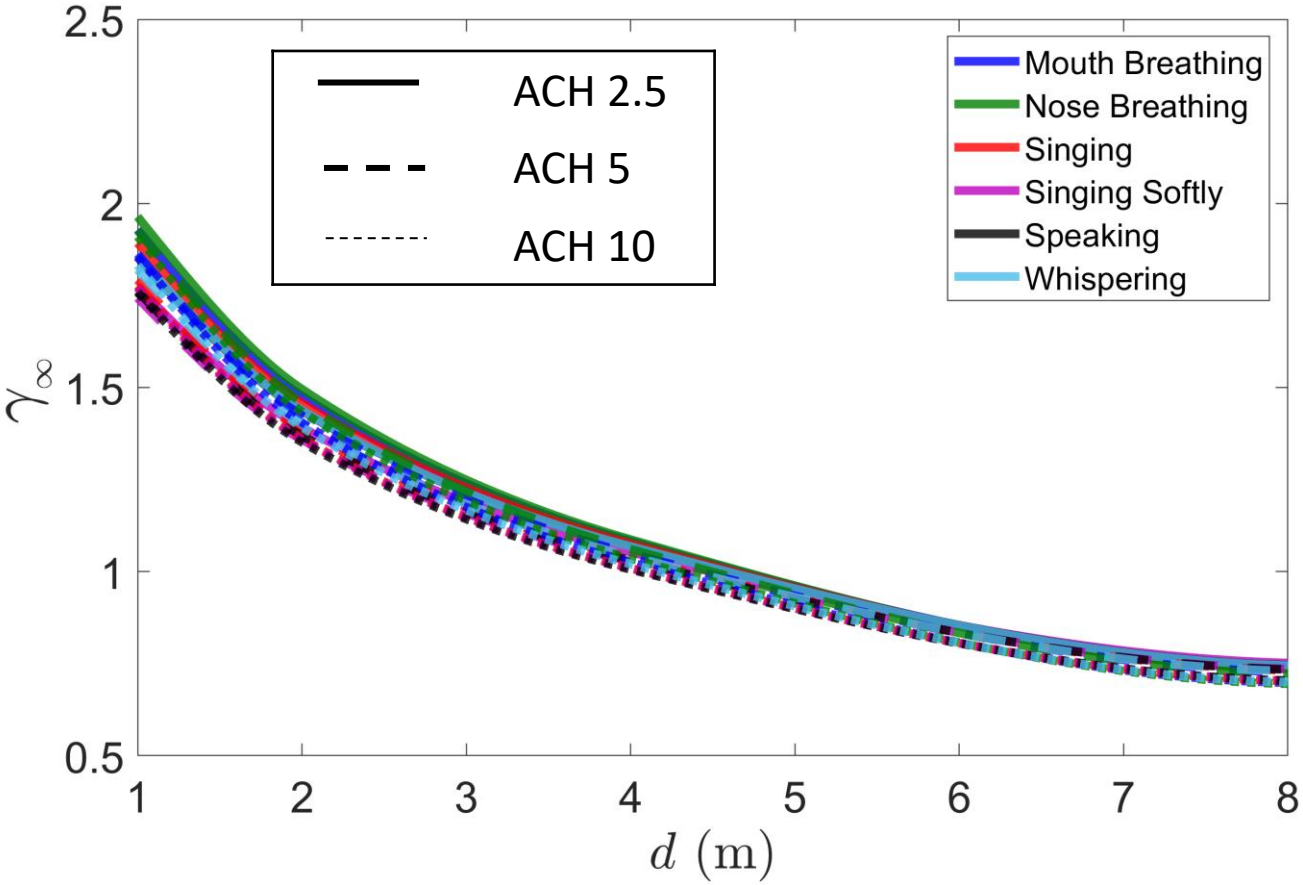
$$N\tau = \frac{1}{\gamma}(N\tau)_{wm}$$

Correction Factor

$$N\tau = \frac{\epsilon}{Q_b^2 p_m^2 C_q s_r \overline{\langle \hat{n} \rangle_d}(\tau)}$$

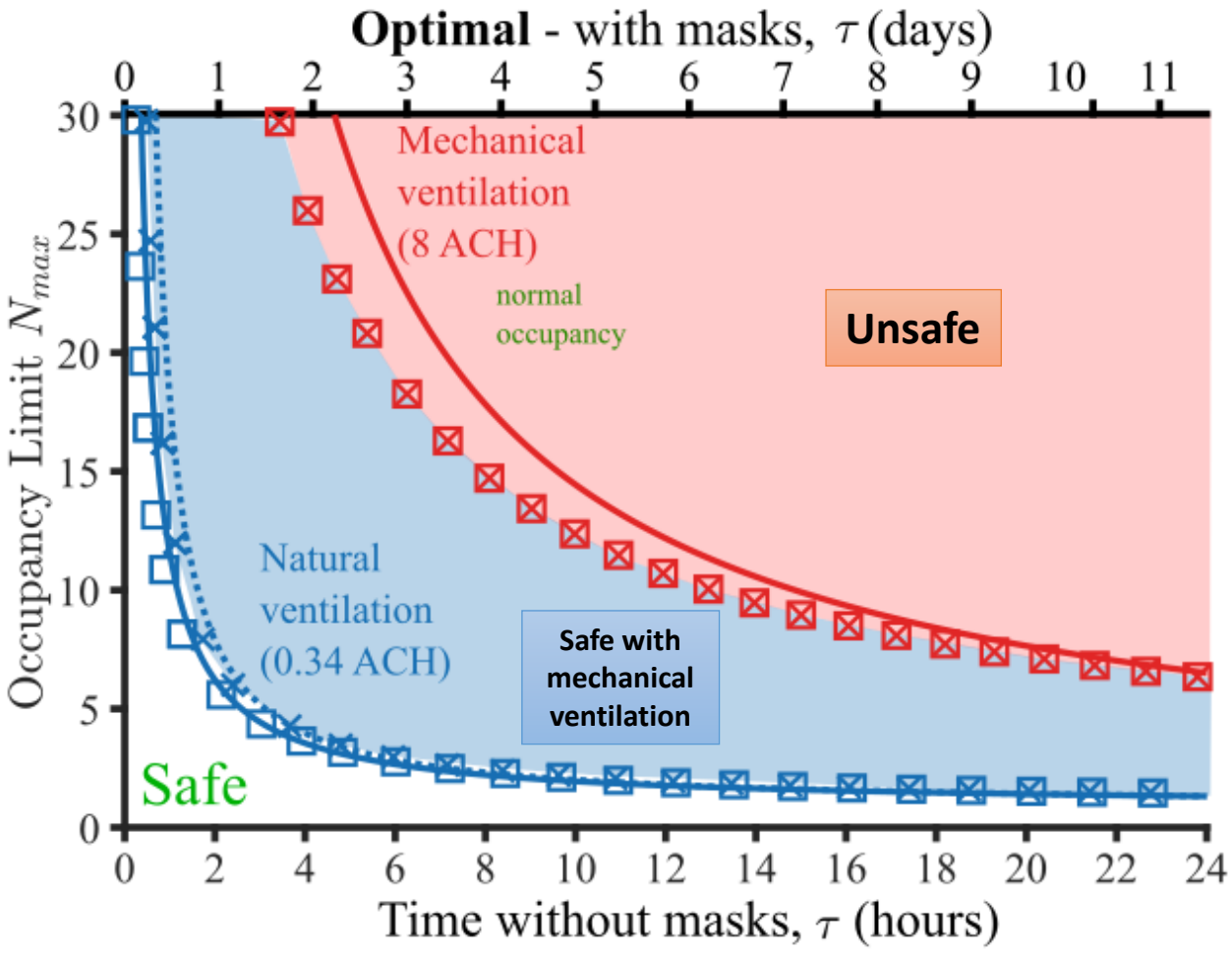
$$\overline{\langle \hat{n} \rangle_d}(\tau) = \frac{\int_0^{r_c} \langle \hat{n} \rangle_d(\tau, r) V(r) Q_b n_{so}(r) dr}{\int_0^{r_c} V(r) Q_b n_{so}(r) dr}$$



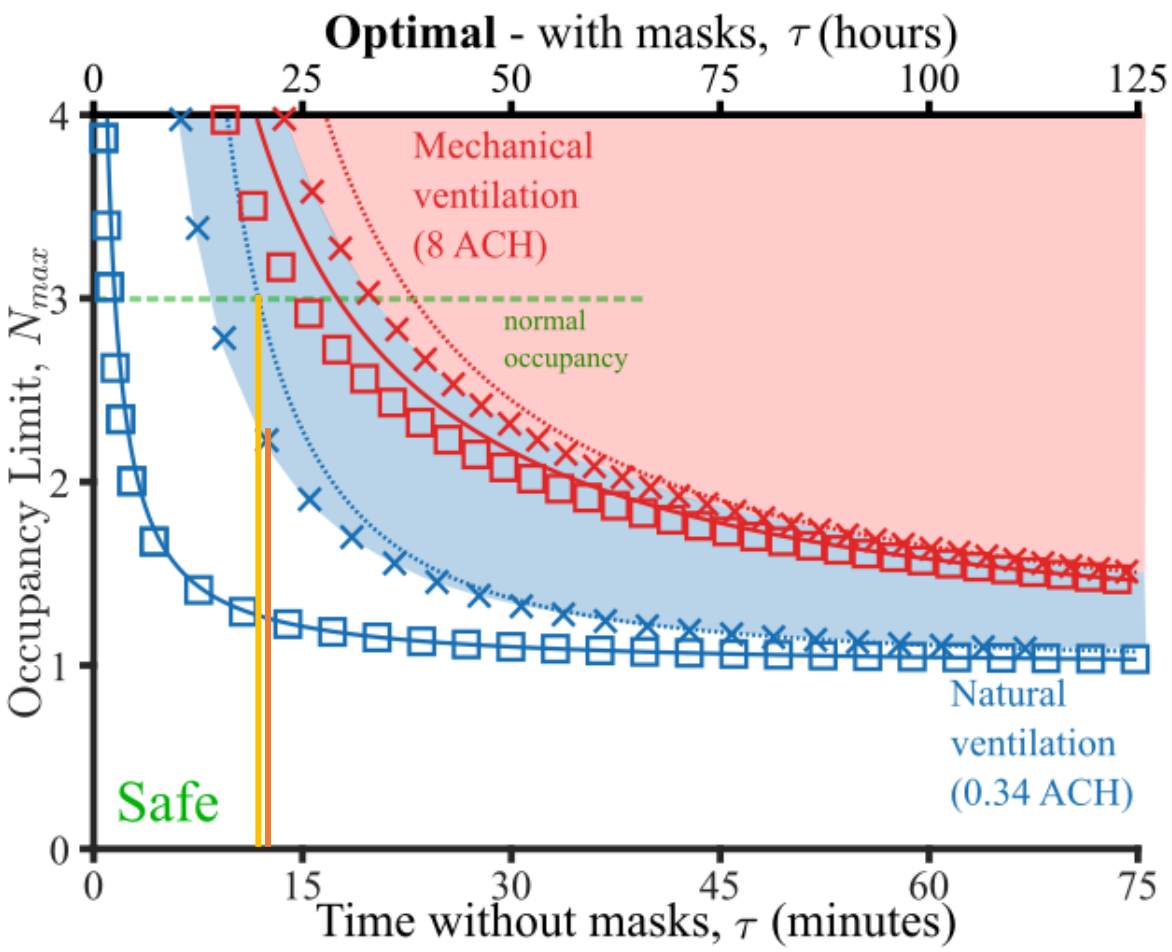


Corrected Guidelines

Classroom



Nursing Home



Conclusions

The well mixed assumption is extremely good at predicting the concentration at room level.

Well mixed theory fails for the larger diameters from a source and sink perspective.

Theory can be overly restrictive for the larger separation distances (d > 5m) and too lenient for shorter separation distances (d < 4m).

References

M. Z. Bazant and J. W. Bush, A guideline to limit indoor airborne transmission of covid-19, Proceedings of the National Academy of Sciences 118 (2021).

L. Morawska, Droplet fate in indoor environments, or can we prevent the spread of infection?, Indoor Air 16, 335 (2006).

K. Liu, M. Allahyari, J. S. Salinas, N. Zgheib, and S. Balachandar, Peering inside a cough or sneeze to explain enhanced airborne transmission under dry weather, Scientific Reports 11, 1 (2021).

K. Liu, M. Allahyari, J. Salinas, N. Zgheib, and S. Balachandar, (2021). Investigation of theoretical scaling laws using large eddy simulations for airborne spreading of viral contagion from sneezing and coughing. *Physics of Fluids*, *33*(6), 063318.