"If you dig deeply enough into anything, you find mathematics."

Thus, an applied mathematician is free to study anything…

Physical Applied Mathematics

- the application of mathematics to outstanding problems in the physical sciences

Faculty: John Bush , Ruben Rosales , Steven Johnson , Jorn Dunkel

My research

- involves the iteration between theory and experiment until consistent physical pictures and mathematical models emerge
- research centered in the Applied Math Laboratory

Fluid mechanics

- geophysical and environmental fluid mechanics
- interfacial flows: dominated by the influence of surface tension
- biocapillarity: the role of surface tension in biology
- ***hydrodynamic quantum analogs***

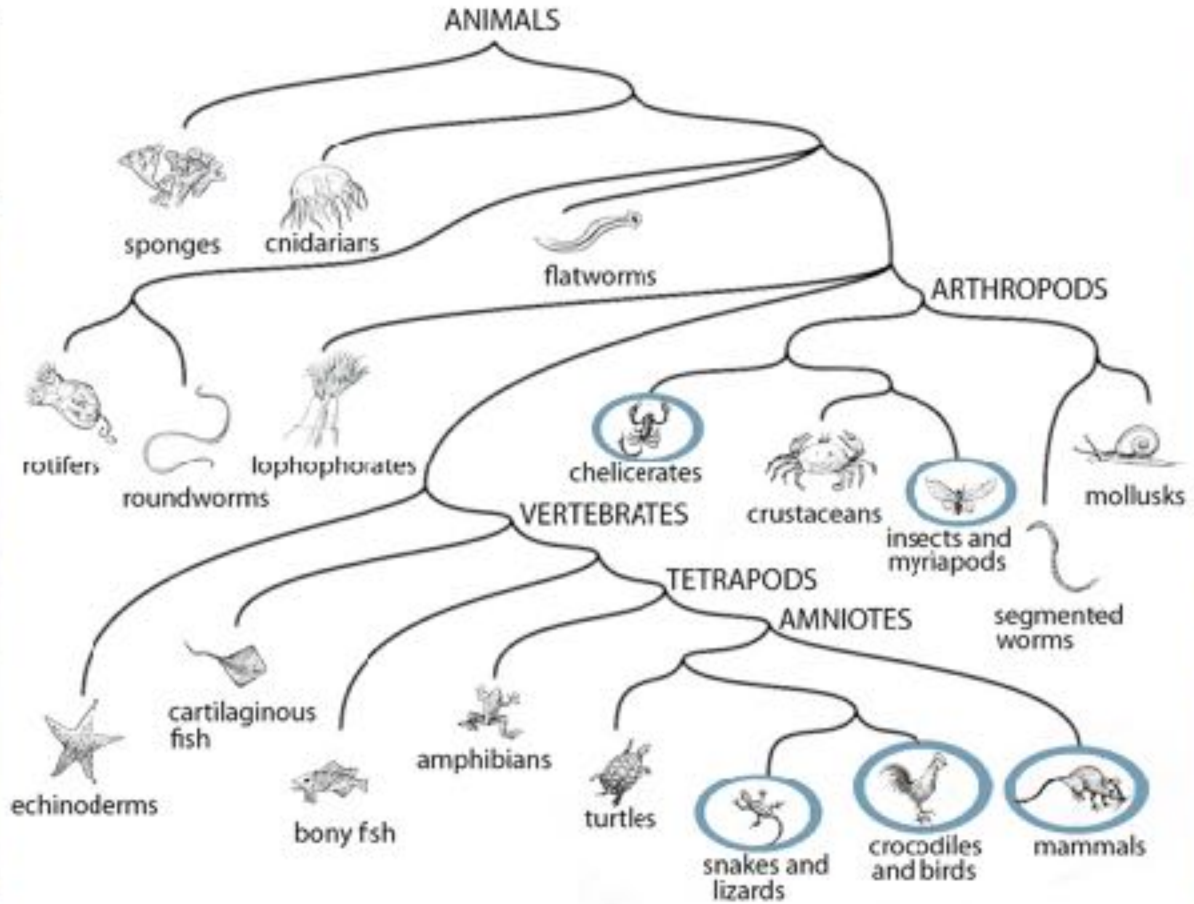
Interfacial flows

"I never before realized so strongly the splendour and beauty of the mere physical forms of Nature. A wonderful thing is the curious repetition of the same forms, of the same design almost, in the shape of the falling water. It gave me a sense of how completely what seems to us the wildest liberty of Nature is restrained by governing laws.

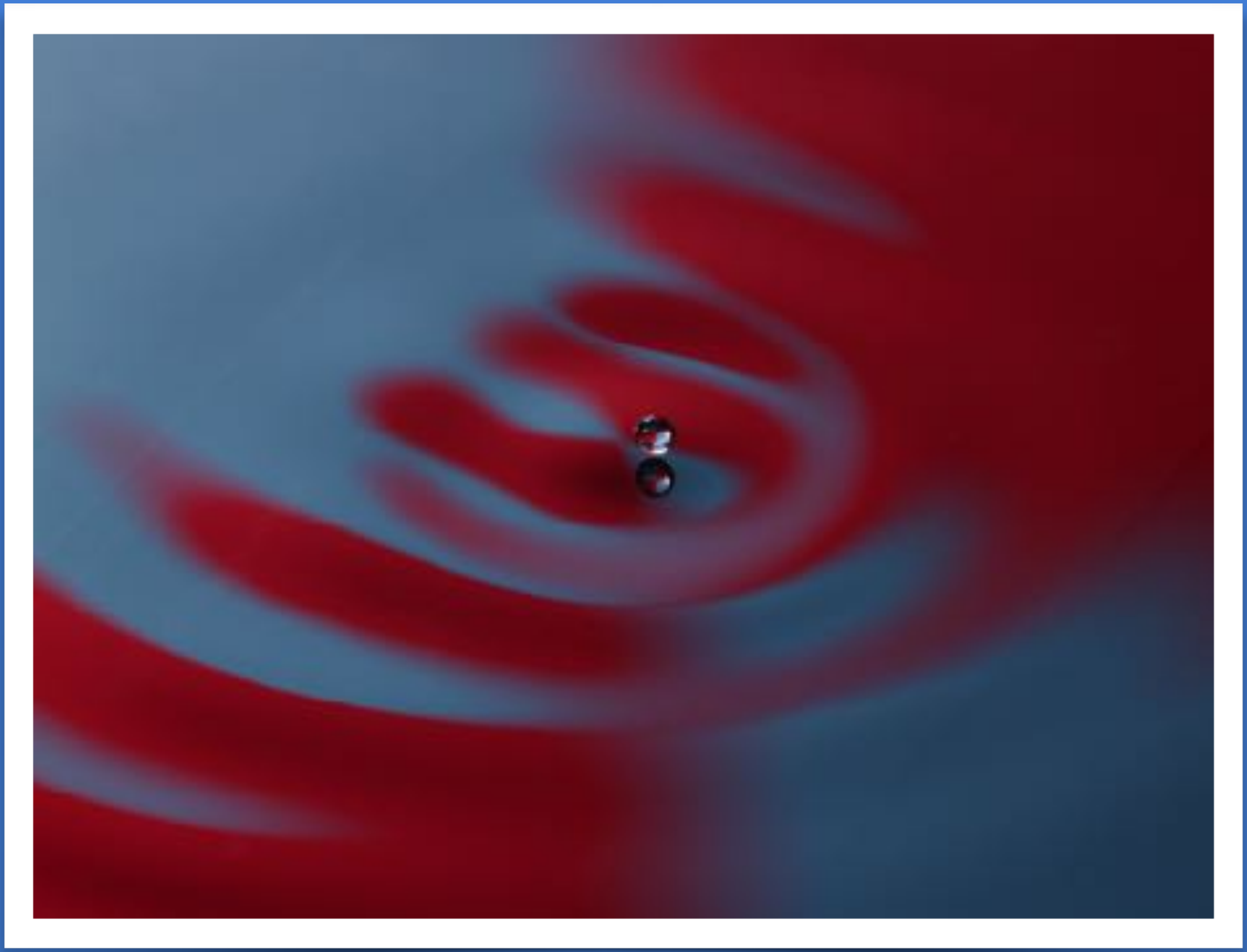
\- **Oscar Wilde**, on viewing Niagara Falls

Walking on water

- rationalized propulsion strategies



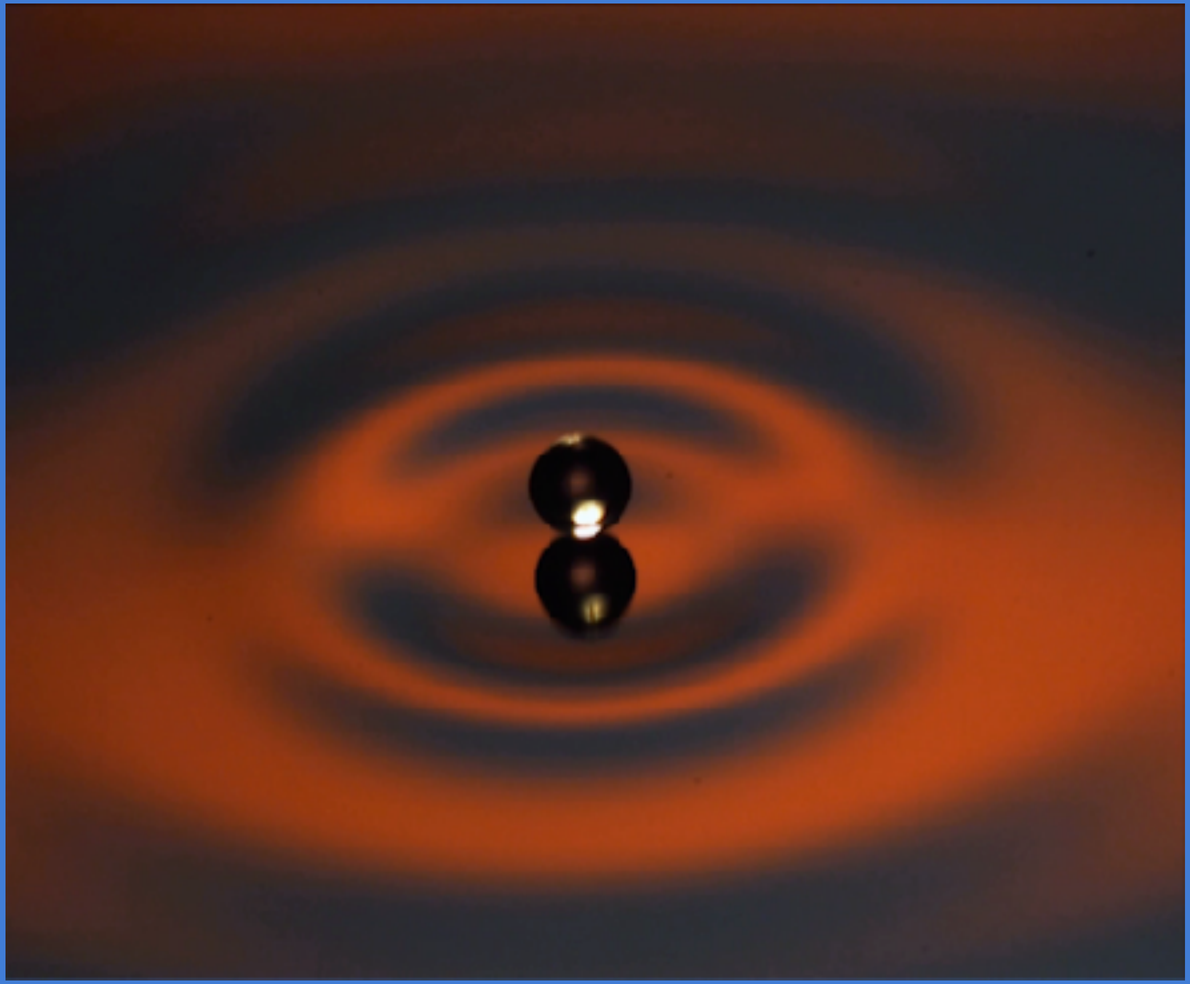
Hydrodynamic quantum analogs



- exploring the boundary between classical and quantum effects

Noncoalescence on a vibrated fluid bath

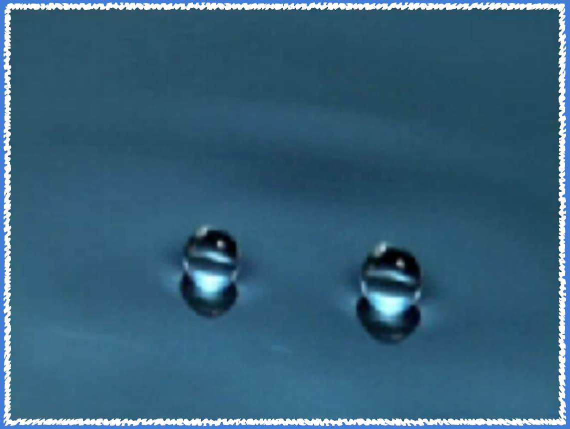
- coalescence avoided provided impact time is less than time required for air layer between drop and bath to drain to ~100 nm

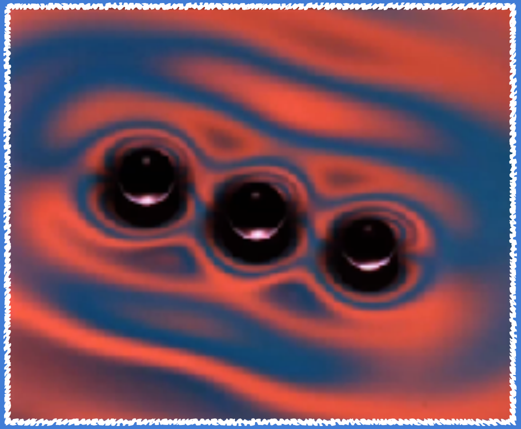


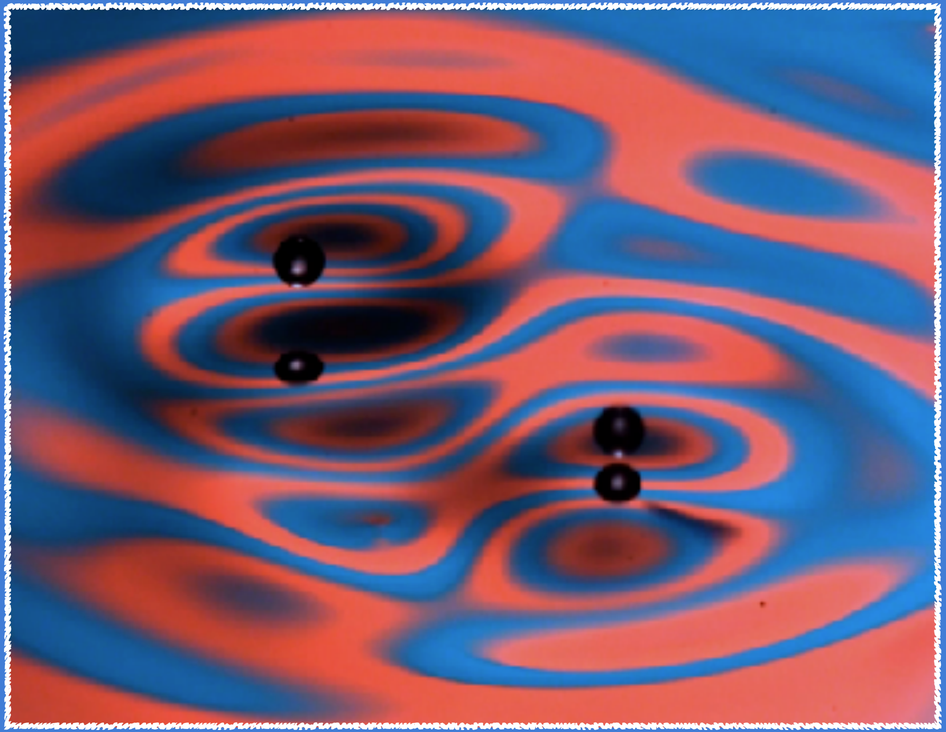
f ~ 50 Hz

50cS
Si oil

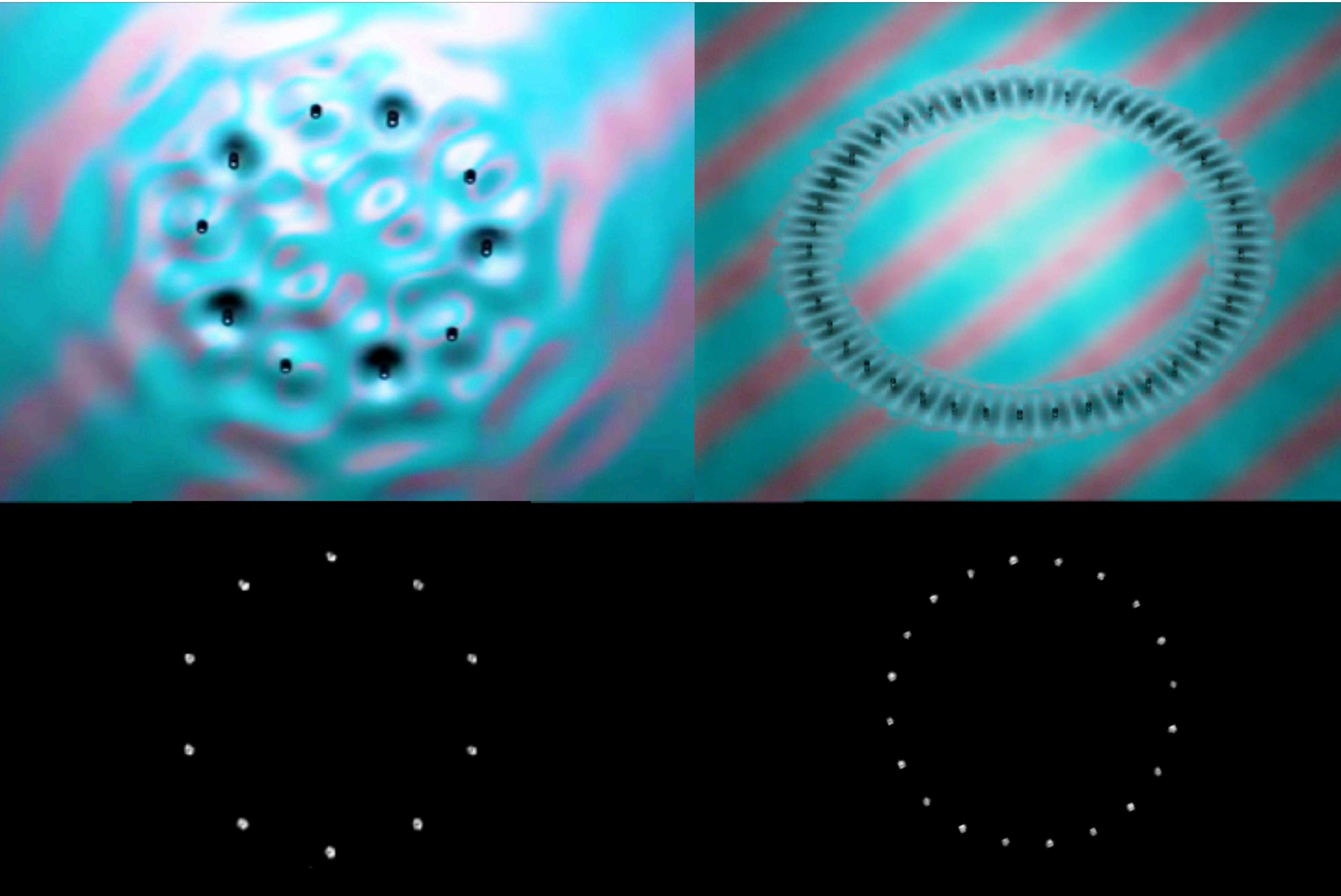
Static and dynamic bound states







Rings of bouncing droplets



Droplets walking on a vibrated fluid bath

- bouncing droplets interact with their own wave fields, walk
- spatially extended walkers consist of both droplet and guiding wave

- **a macroscopic realization of *wave-particle duality***

Wave-particle duality at the macroscopic scale

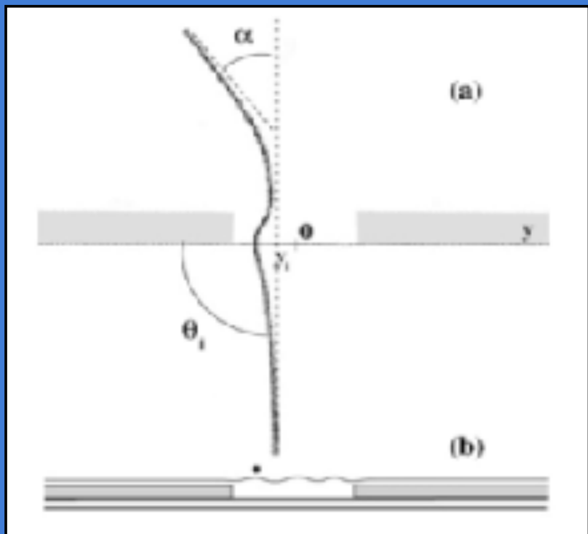
"Both matter and radiation possess a remarkable duality of character, as they sometimes exhibit the properties of waves, at other times those of particles.

Now it is obvious that a thing cannot be a form of wave motion and composed of particles at the same time - the two concepts are too different."

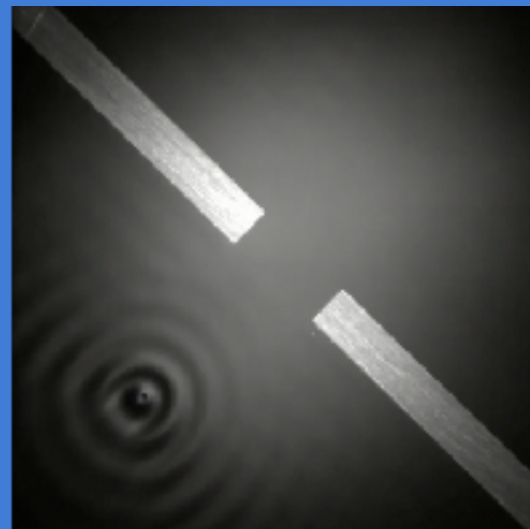
- Heisenberg, *On Quantum Mechanics (1930)*

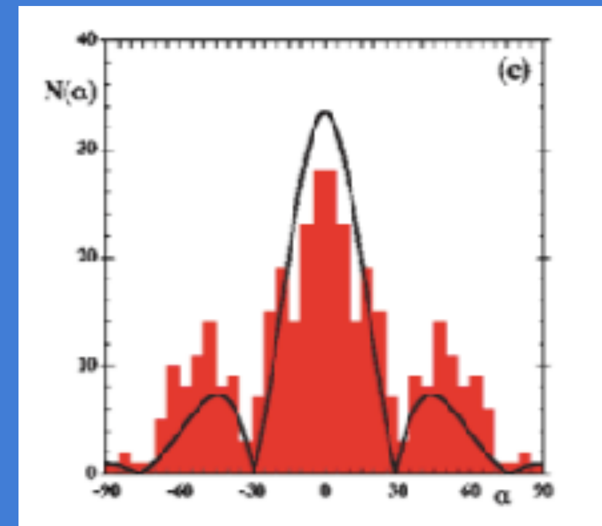
Single-walker diffraction and interference

Couder & Fort (2005)

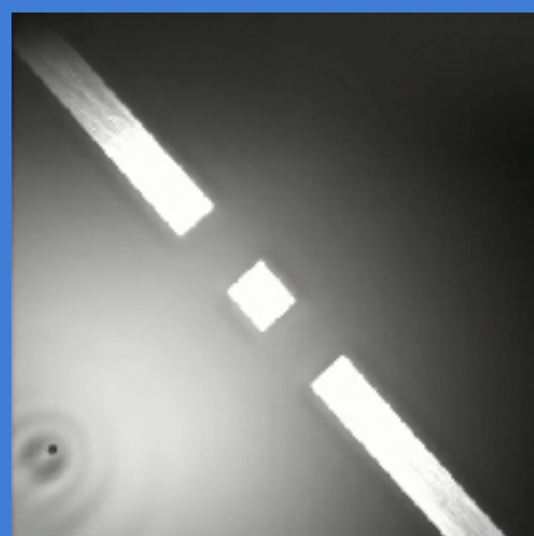


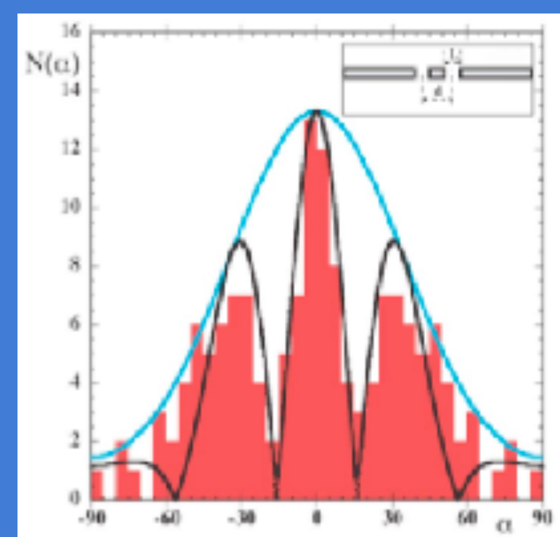
Single slit





Double slit

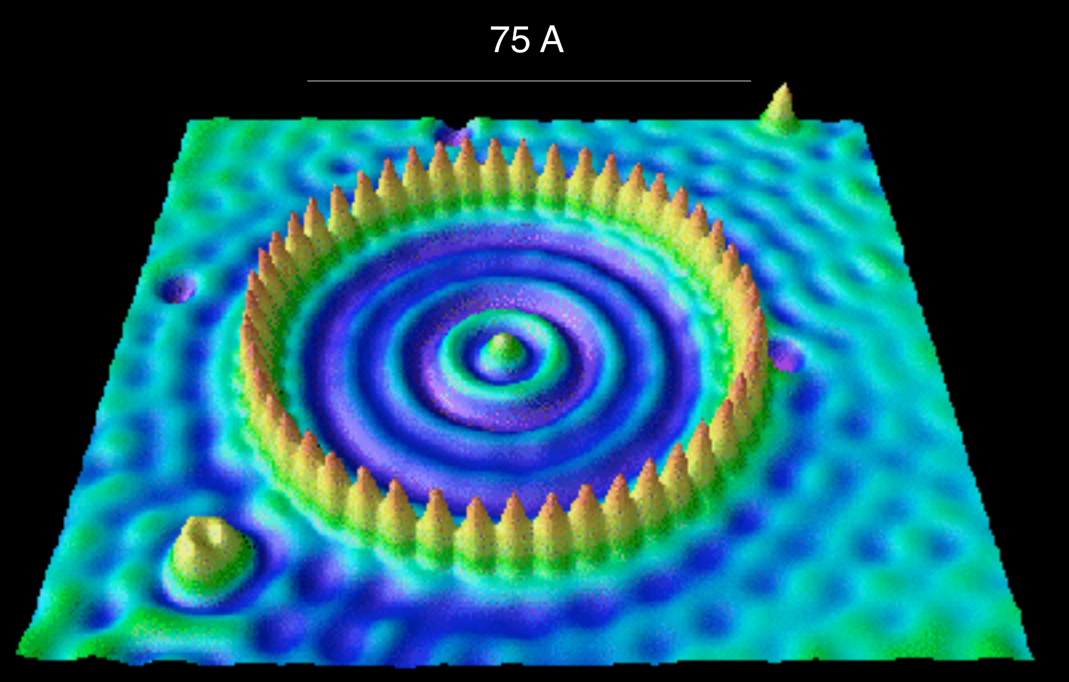




" A phenomenon which is impossible, absolutely impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the only mystery."

- Richard Feynman

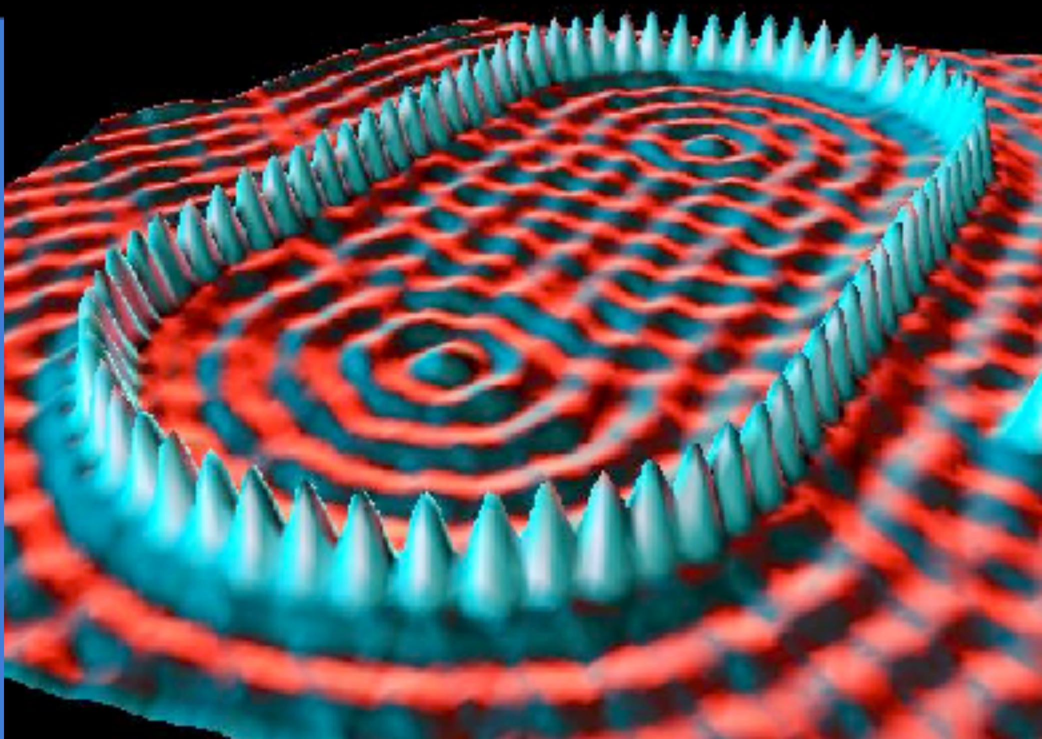
- **coherent, wave-like statistics emerge from chaotic pilot-wave dynamics**



The quantum corral

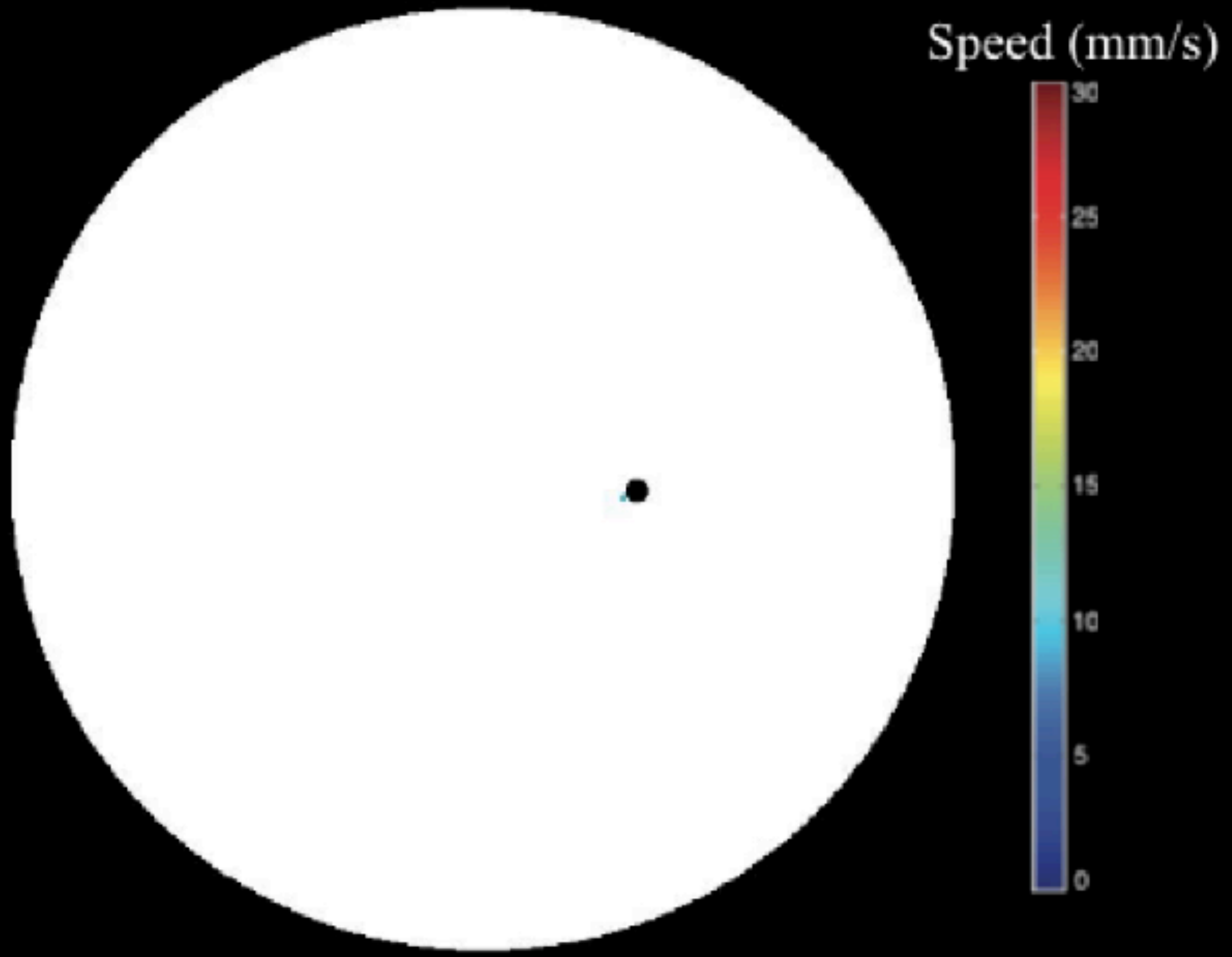
Crommie, Lutz & Eigler (1993)

Fiete & Heller (2003)

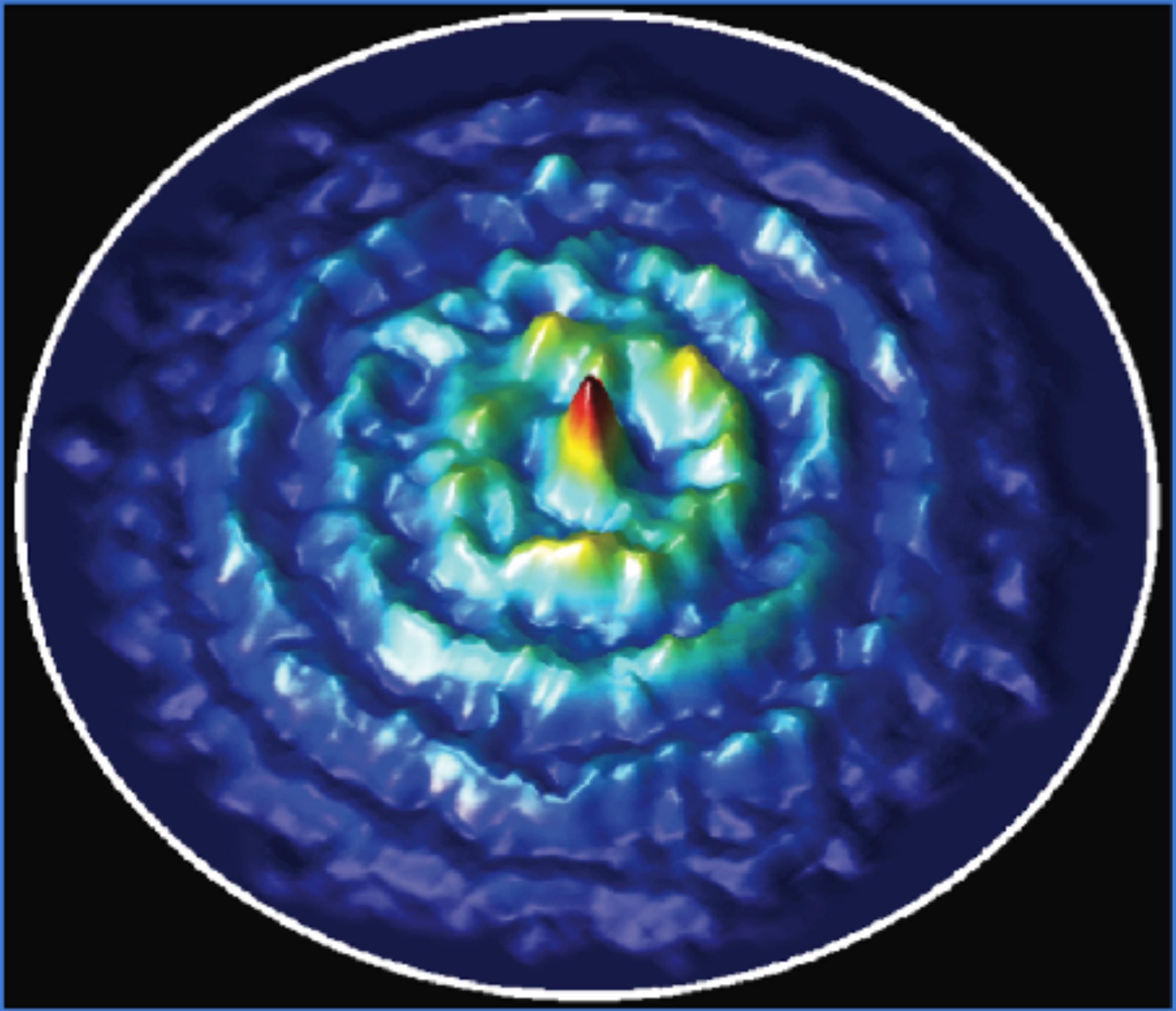


- de Broglie waves evident in the pdf of a sea of electrons trapped on a metal surface, excited by an SEM

Droplet walking in a circular corral

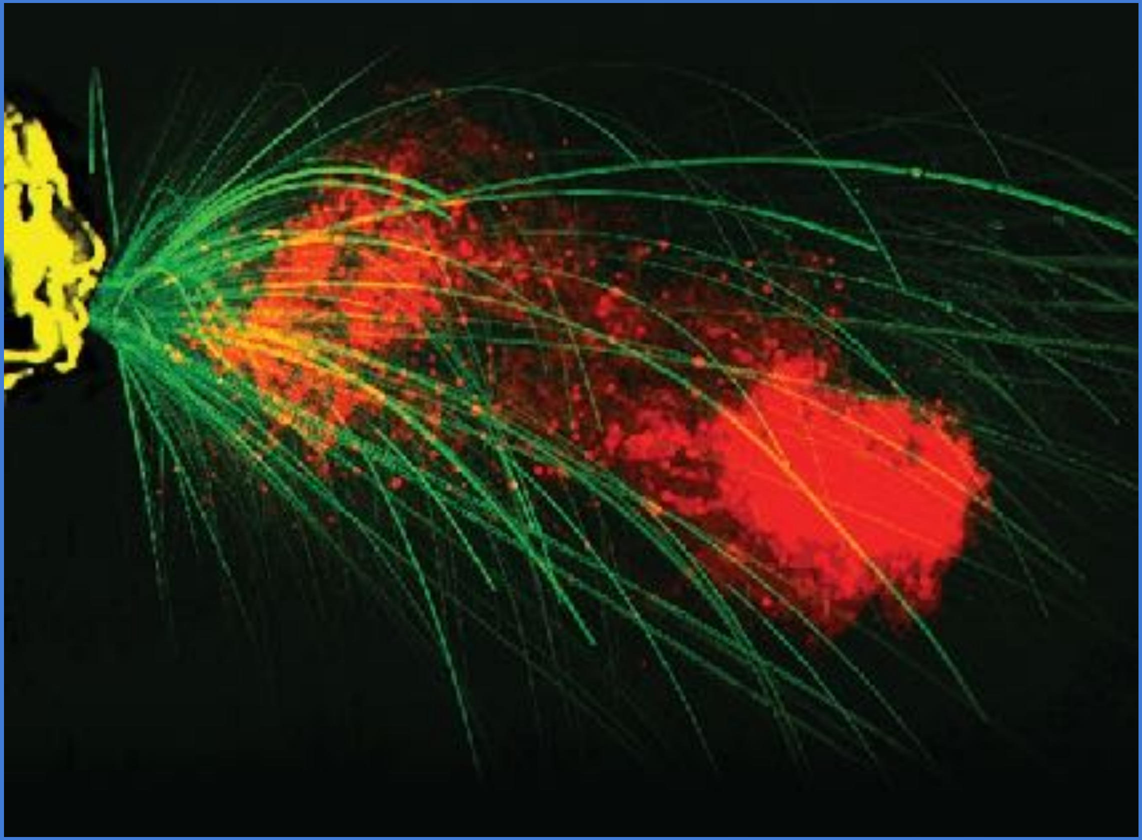


Probability density function



- coherent, wave-like statistics emerge from chaotic pilot-wave dynamics
- emergent statistics not inconsistent with the notion of particle trajectories

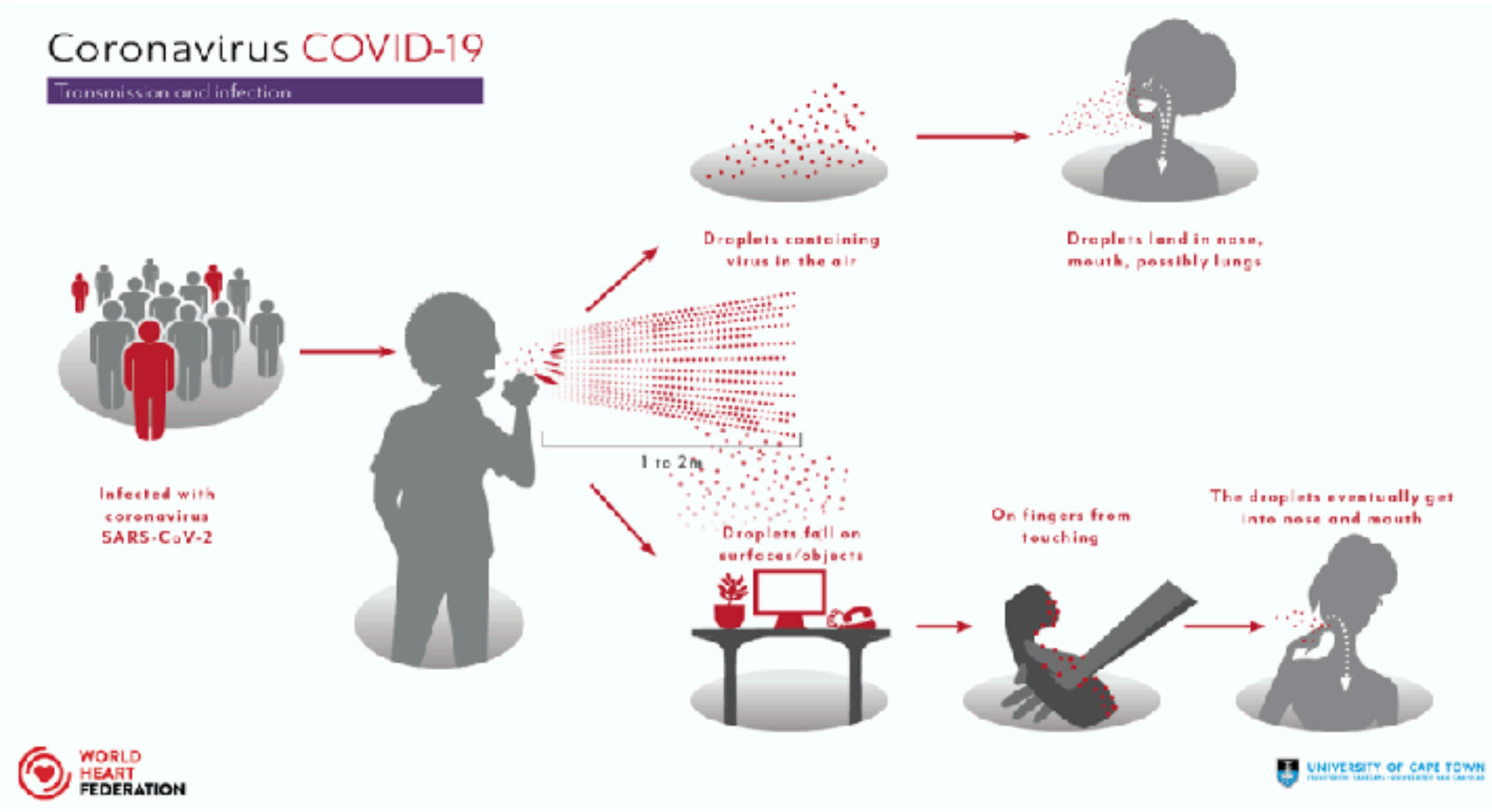
Beyond 6 feet:
Respiratory flows and airborne disease transmission



John W. M. Bush
Department of Mathematics, MIT

COVID-19 transmission

- via intake of pathogen-bearing respiratory drops expelled by an infected person



3 Modes of transmission of COVID-19

- all via intake of respiratory drops generated by liquid fracture

I. Contact transmission

- contact with droplets deposited on surfaces, `fomites', and transfered to recipient's respiratory mucosae

II. Large-drop (~1mm) transmission

- from mouth of an infected individual to eye, nose mouth of a susceptible individual
- eliminated entirely by masks
- minimized by adherence to the 6-Foot (2-Meter) Rule

III. Airborne transmission

- via small, micron-scale pathogen-bearing drops suspended by respiratory flows and/or circulation flows in indoor spaces

Talk outline

I. Why is the 6-Foot Rule insufficient? (with L. Bourouiba)

- the form of respiratory flows

II. How can we do better? (with M. Bazant)

- transmission dynamics in indoor spaces
- develop a safety guideline for airborne transmission

III. How can we implement this guideline?

(with M. Bazant, K. Khan, A. Cohen, Z. Gu, O. Kodio)

- carbon dioxide monitoring for COVID safety
- COVID Indoor Safety App

The 6-Foot Rule

WSJ | OPINION

By The Editorial Board Follow
Jan. 11, 2024 at 6:34 pm ET

OPINION REVIEW & OUTLOOK Follow

Anthony Fauci Fesses Up

It turns out the six-feet social-distancing rule had no scientific basis.

Anthony Fauci has never struggled to speak his mind. But now that he has left government, he is finally speaking at least some of the truth about government policies and Covid. For instance, the six-feet rule for social distancing "sort of just appeared" without a solid scientific basis. That's one of the admissions that Members of Congress say the former National Institutes of Health potentate made this week in two days of closed-door testimony to the House Select Subcommittee on the Coronavirus Pandemic.

I. Why is the 6-Foot Rule insufficient?

- the form of respiratory flows

J. Fluid Mech. (2014), *vol.* 745, *pp.* 537–563.
doi:10.1017/jfm.2014.88

Violent expiratory events: on coughing and sneezing

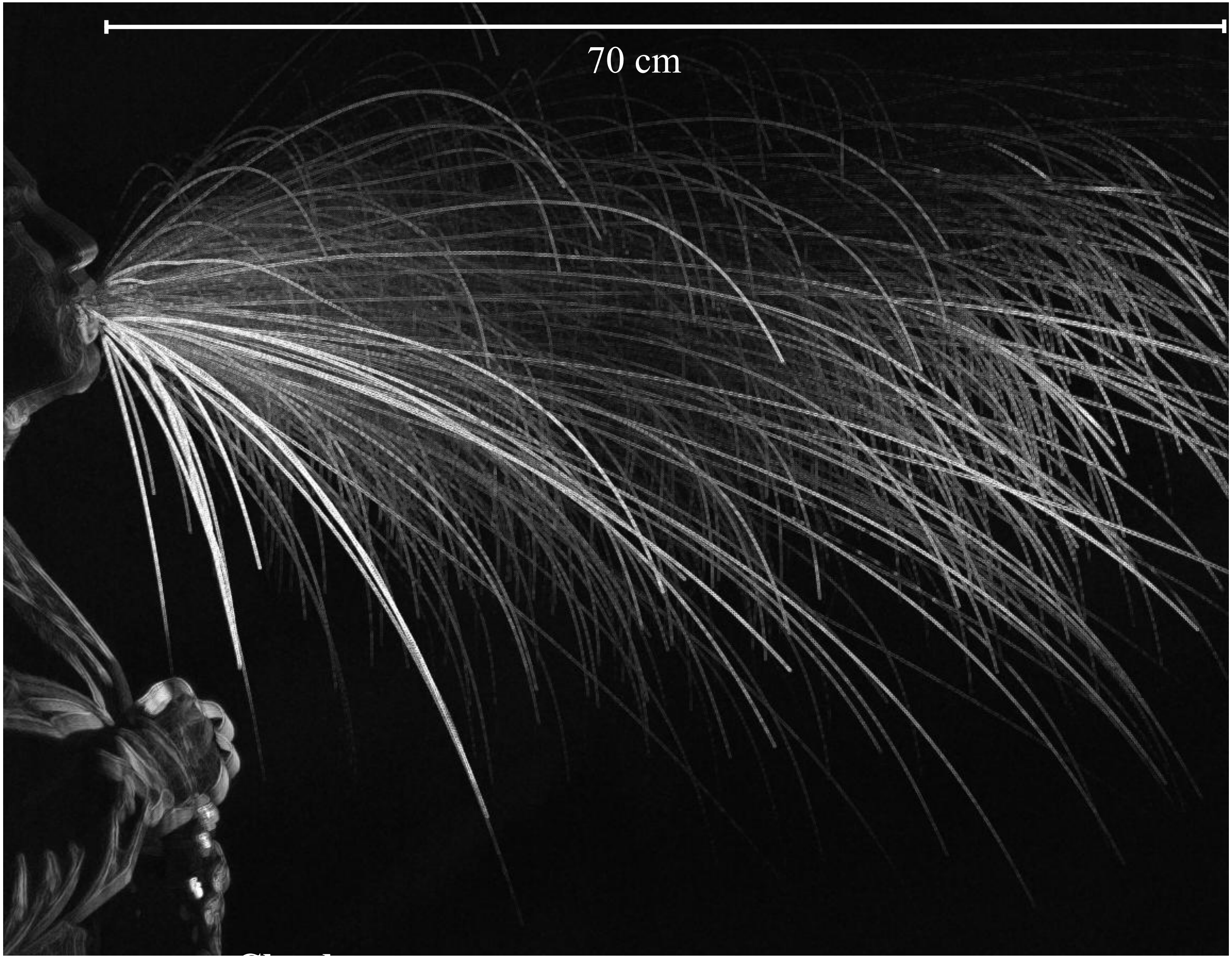
Lydia Bourouiba[1,2,†], Eline Dehandschoewercker[3] and John W. M. Bush[1]

[1]Department of Mathematics, Massachusetts Institute of Technology, Cambridge, MA 02130, USA

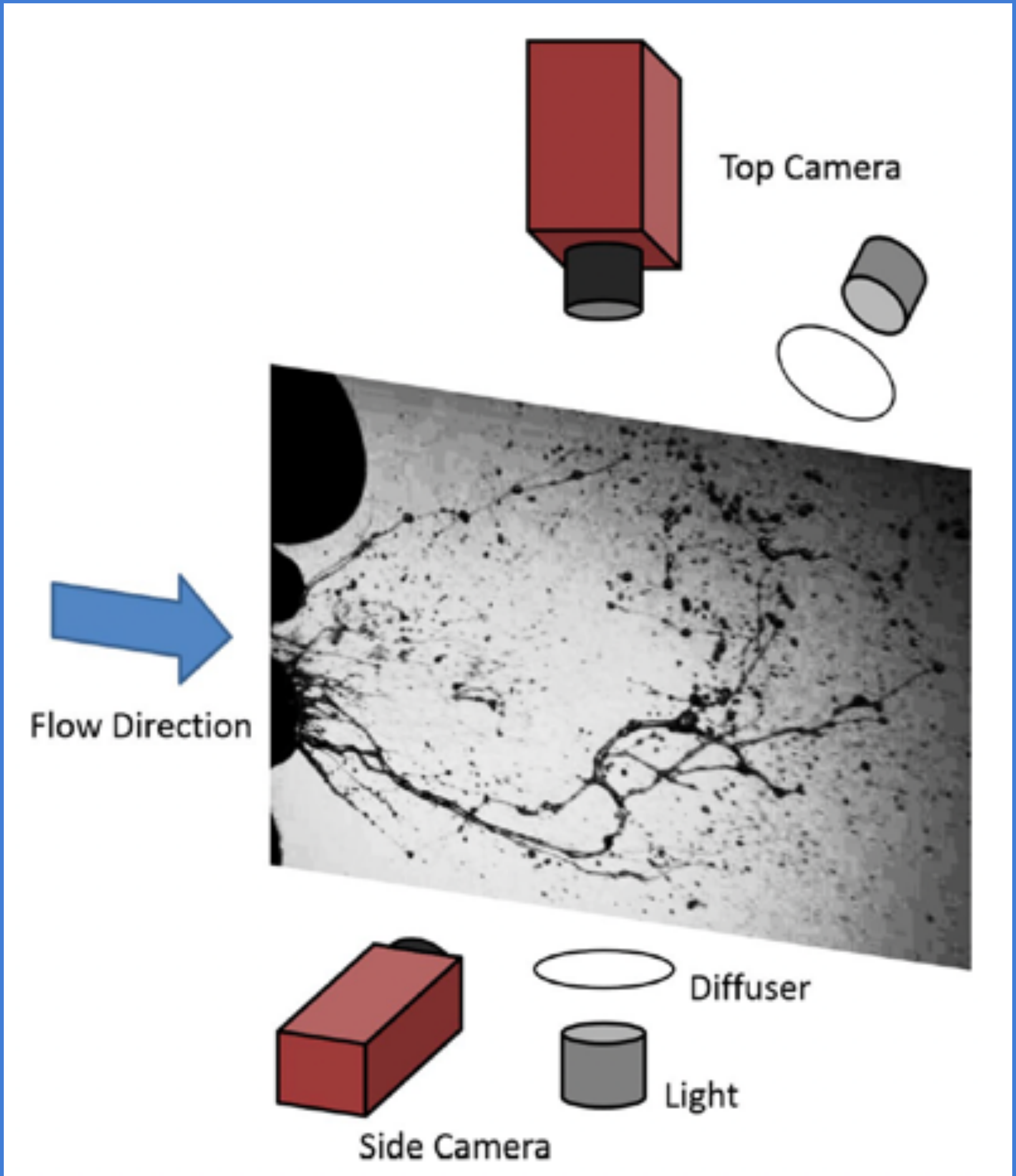
Doc Edgerton's ``The sneeze"

The cough

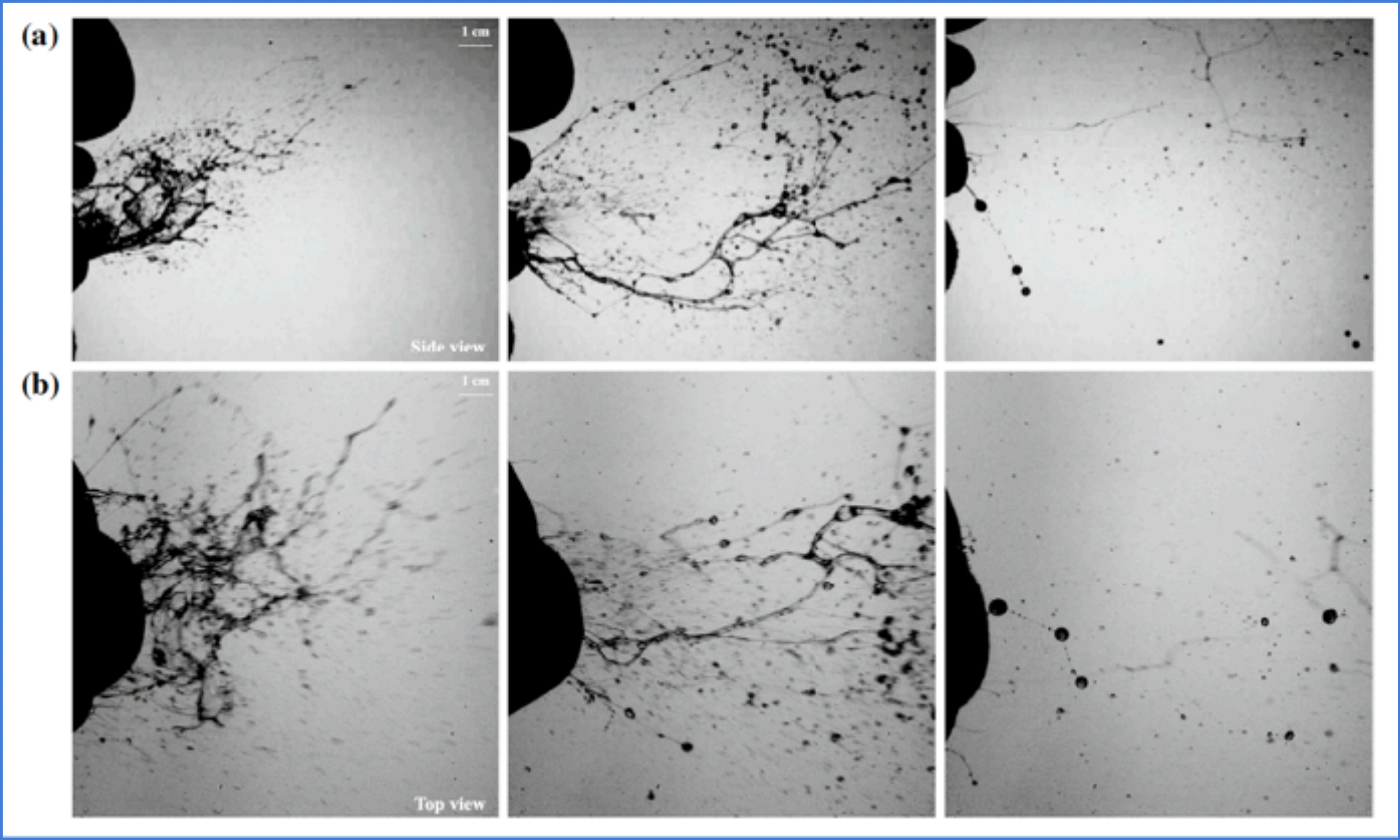
The cough and the 6ft-Rule



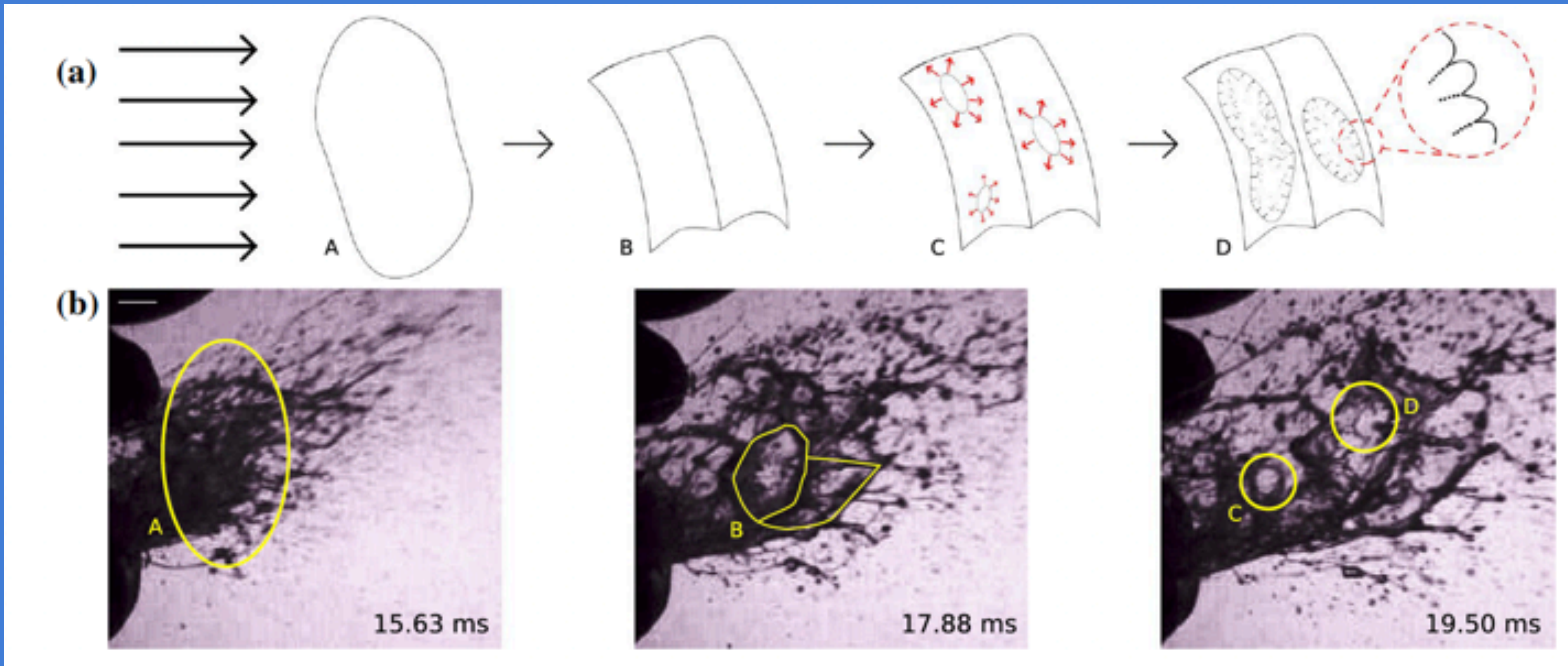
Visualization of sneeze ejecta



Visualization of sneeze ejecta

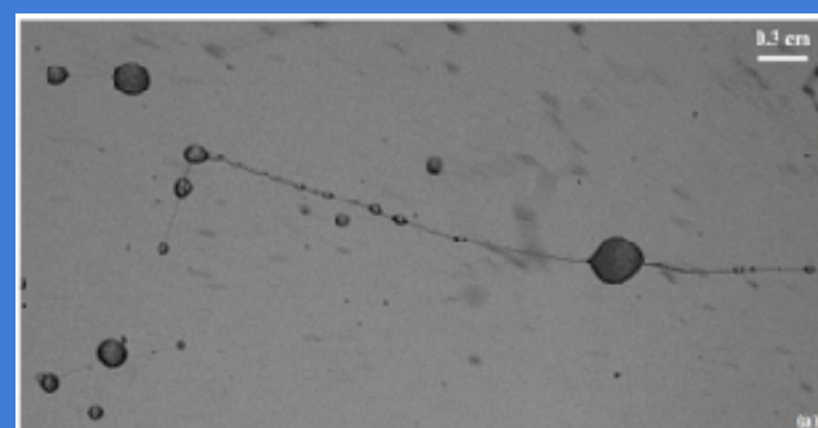


Visualization of sneeze ejecta

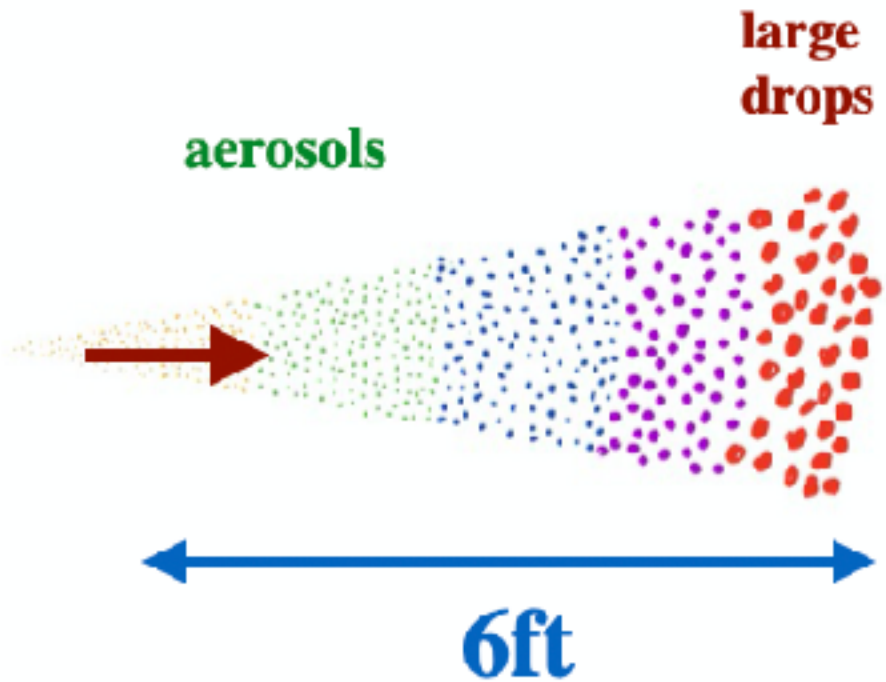


- liquid fracture inside respiratory tract and in air prescribe size distribution of pathogen-bearing droplets:

$$0.1\mu m < R < 2mm$$



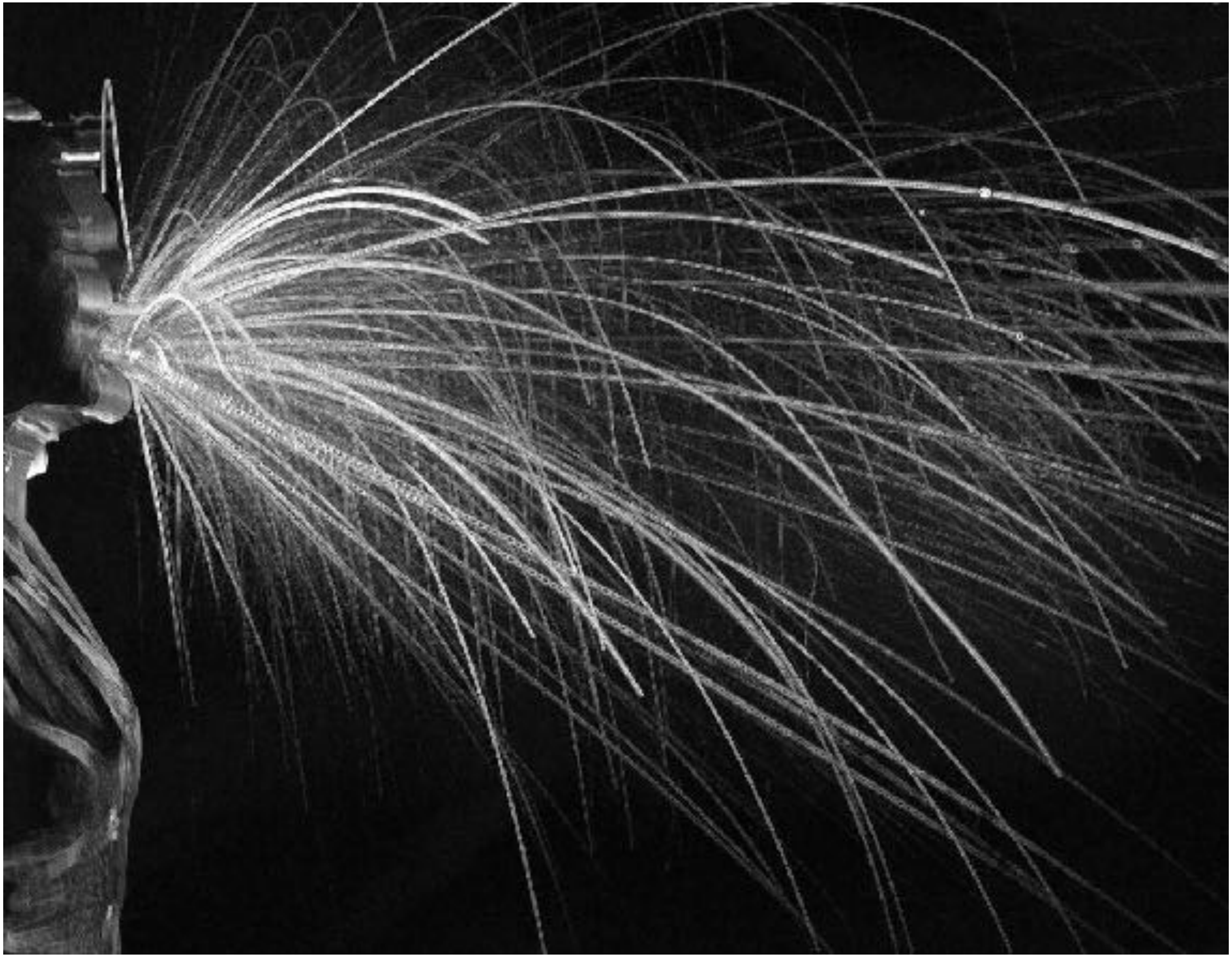
Suggested physical picture: the pathogen footprint



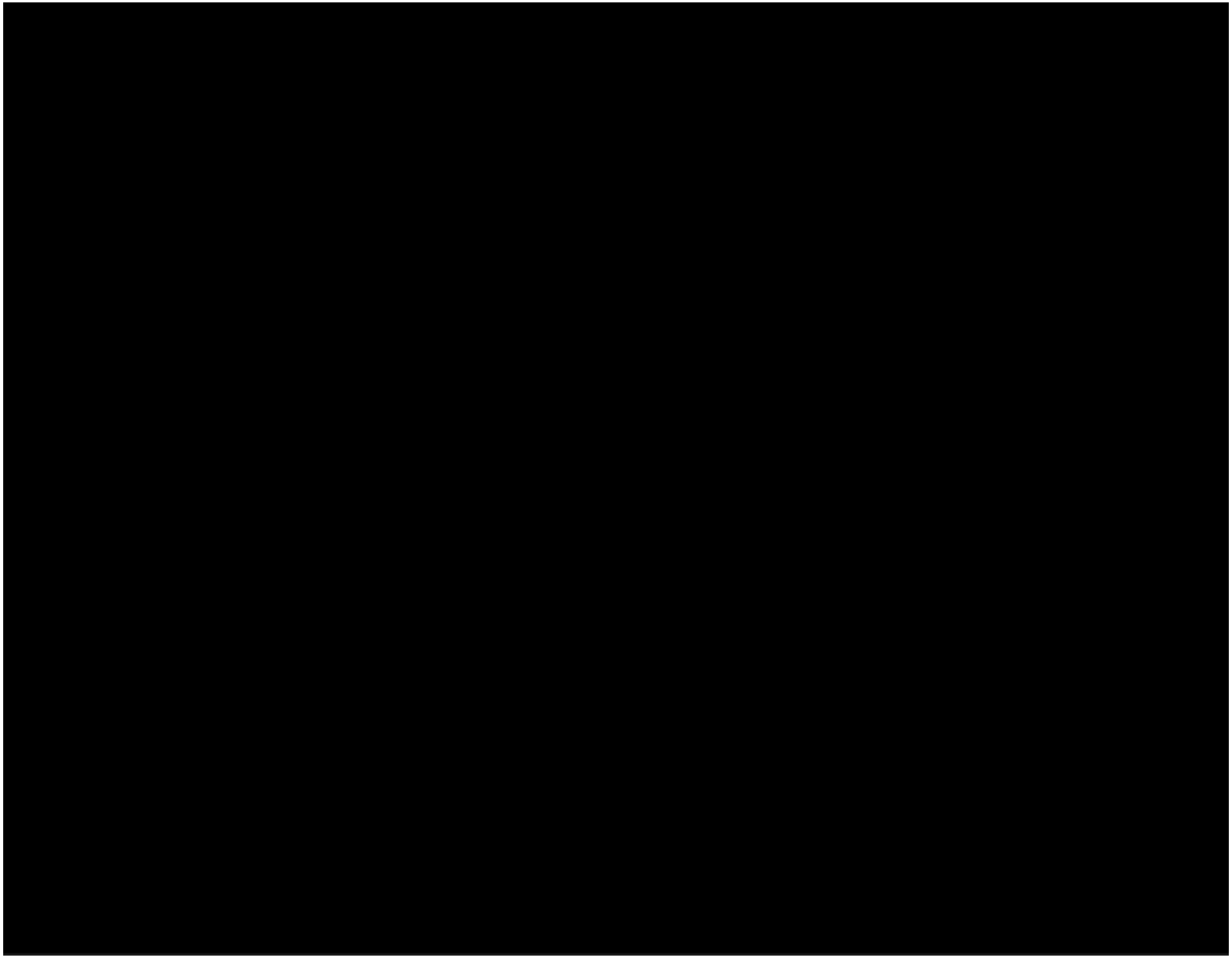
Wells (1950s)

- aerodynamic effects neglected
- larger drops travel further than aerosols

The sneeze

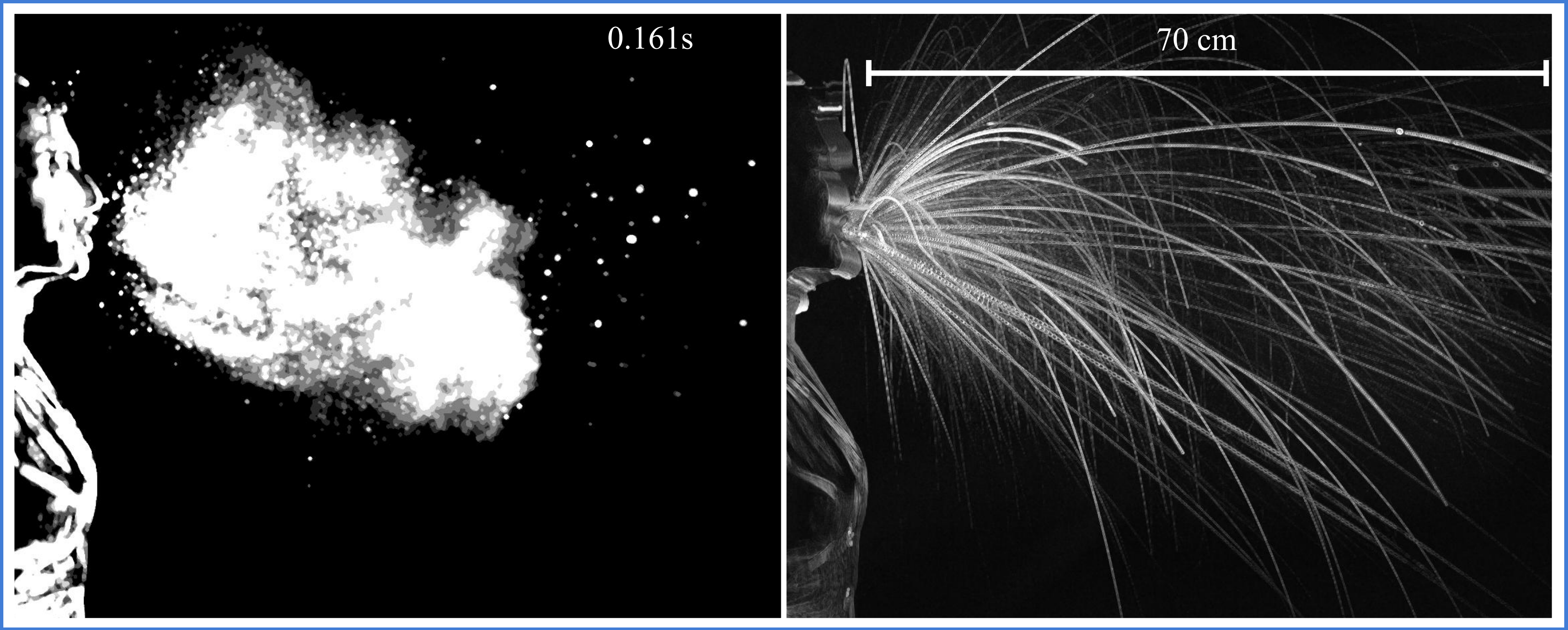


The sneeze



- exhaled smoke reveals coherent flow in gas phase

Coughs and sneezes



- liquid phase accompanied by gas phase comparable to a vortex ring
- gas phase critical in extending range of droplet-borne pathogen

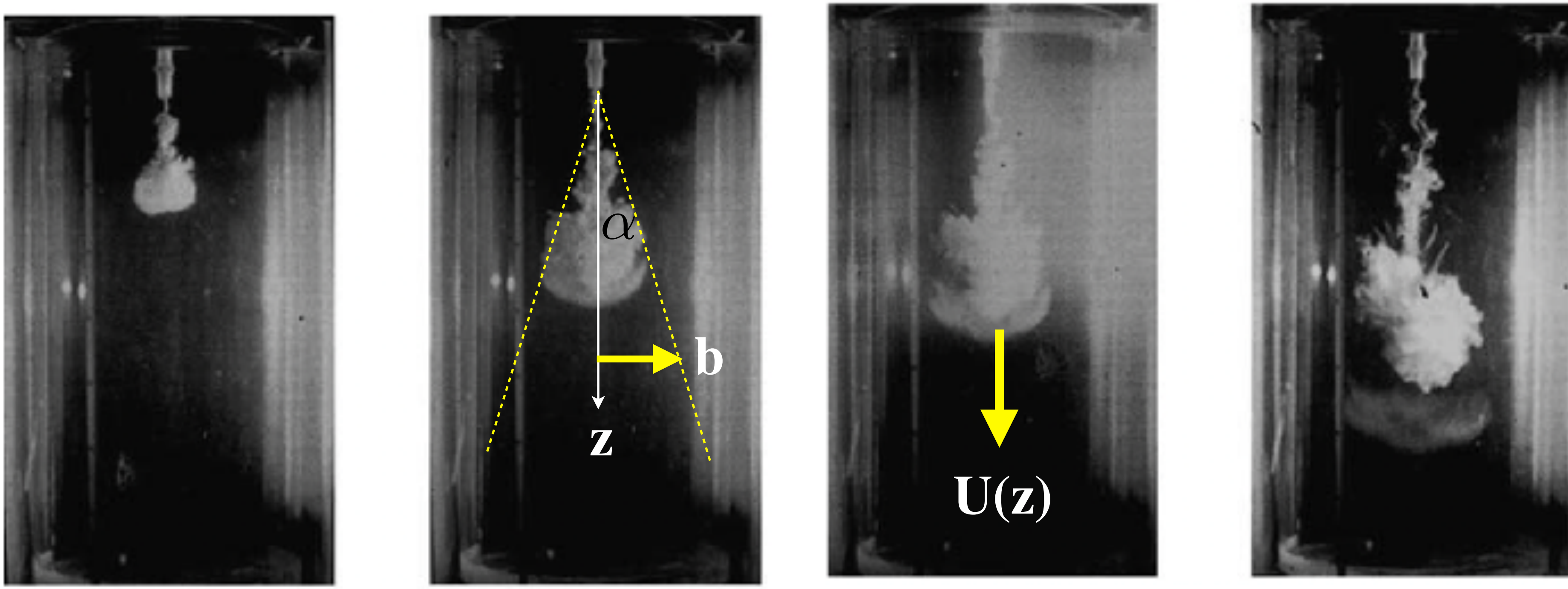
e.g. rationalizes how smaller drops fly further than large drops

Particle clouds (Bush *et al.*, JFM, 2003)

$$g' = g\frac{(\rho_0 - \rho)}{\rho_0}$$

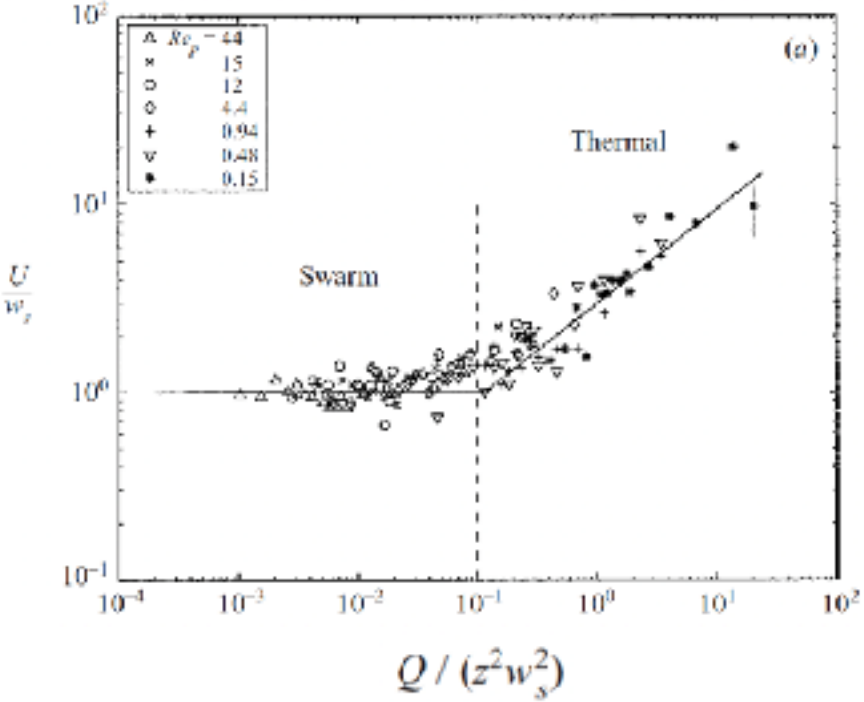
- release a volume of beads suspended in water

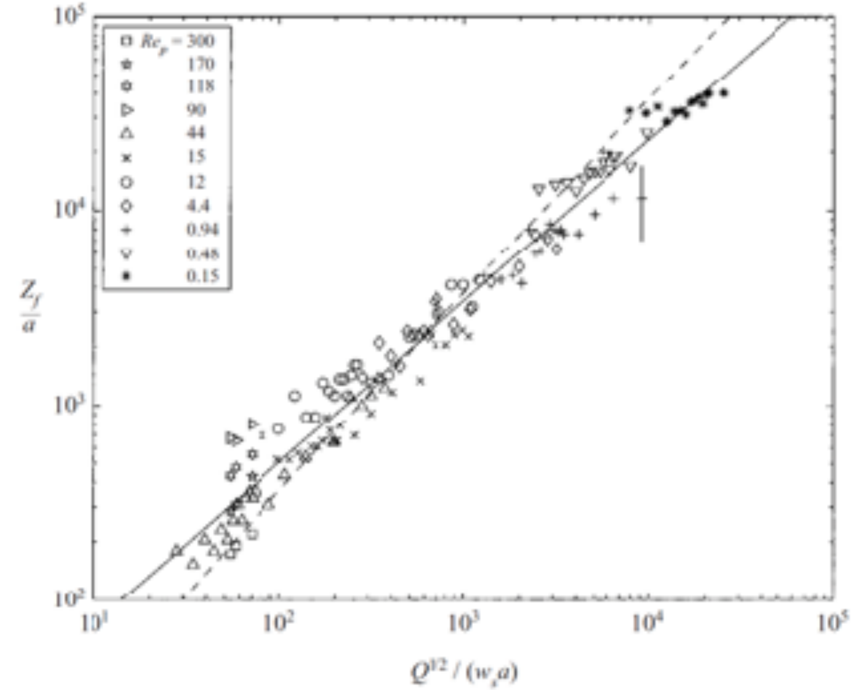
$$Q = g' V_0$$

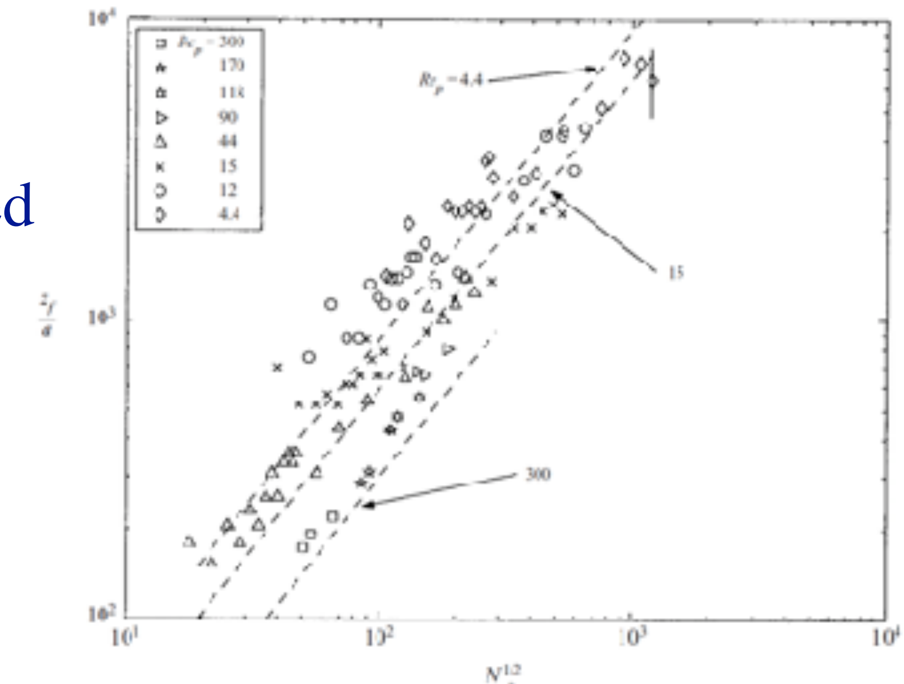


- release a volume of beads suspended in water
- negatively buoyant turbulent cloud grows by turbulent entrainment

Turbulent cloud scalings: $b = \alpha z, \quad U \sim Q^{1/2}/z, \quad g' \sim Q/z^3$







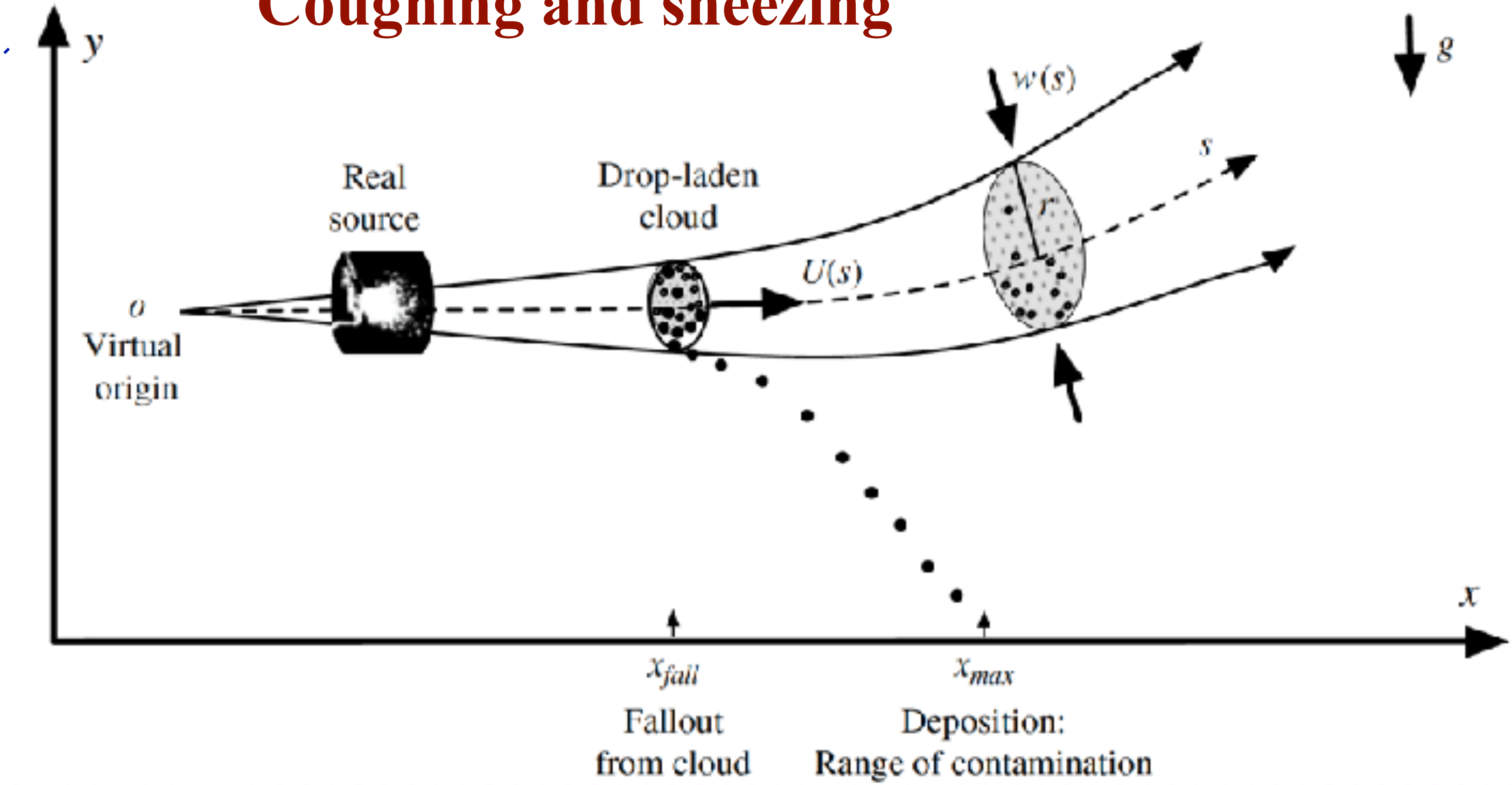
Fallout criterion

- cloud speed = particle settling speed

$$Z_f = C_3 \frac{Q^{1/2}}{w_s}$$

$$\rightarrow \quad Z_f = (9 \pm 2)\, a N_p^{1/2}$$

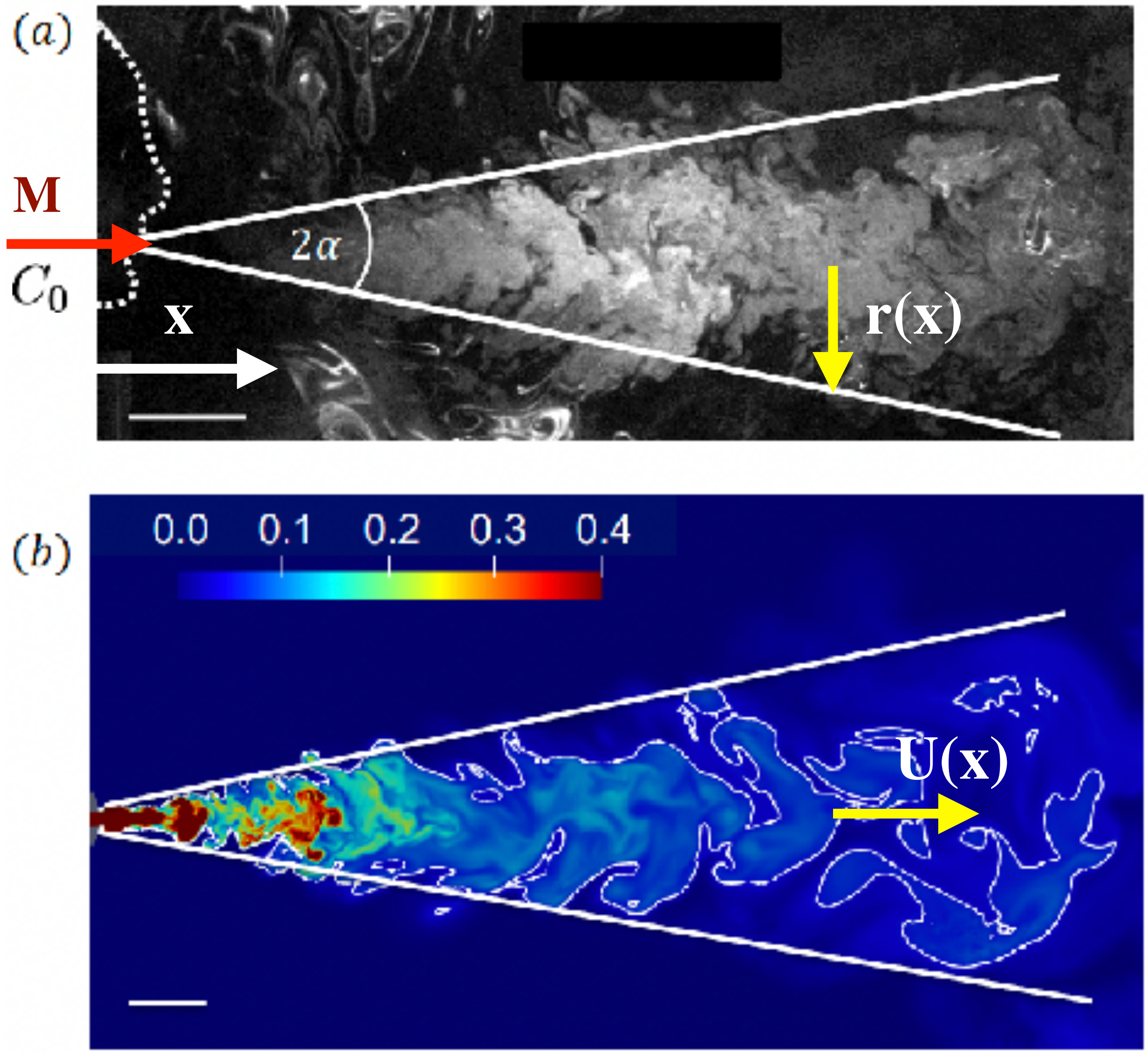
Coughing and sneezing



- droplets suspended in cloud until settling speed exceeds cloud speed
- smaller drops go further than larger drops
- smaller drops may be suspended indefinitely by ambient circulation

Breathing and speaking

Yang et al., PNAS (2020)



Jet scalings:

$$r = \alpha_t x$$

$$v(x) = \frac{M^{1/2}}{\alpha_t x \sqrt{\pi \rho_a}}$$

$$\frac{C_j(x)}{C_0} = \frac{A_m^{1/2}}{\alpha_t x}$$

where mouth area

$$A_m \approx 2cm^2$$

entrainment coefficient

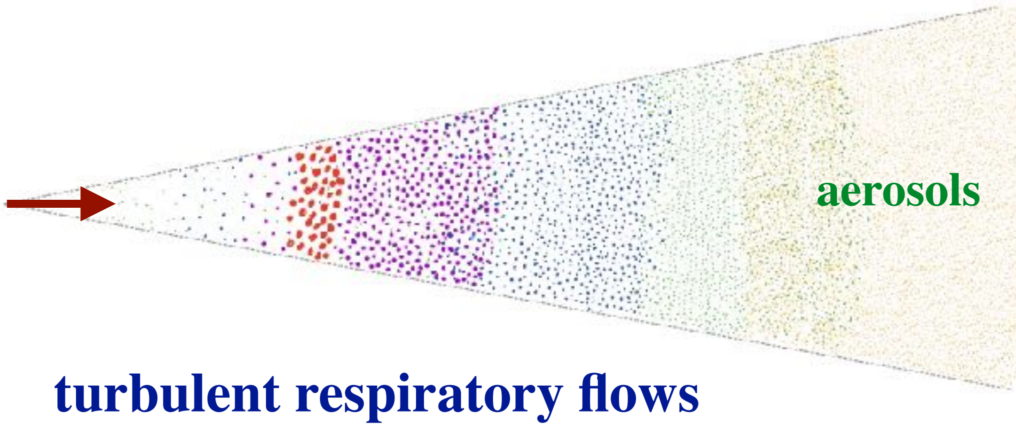
$$0.1 < \alpha_t < 0.15$$

- series of turbulent puffs - modeled as a continuous turbulent jet

The pathogen footprint

Wells (1950s)

Bourouiba & Bush (2014)



Environment International 139 (2020) 105730

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Airborne transmission of SARS-CoV-2: The world should face the reality

Lidia Morawska[a,*], Junji Cao[b]

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[b] Key Lab of Aerosol Chemistry & Physics (KLACP), Chinese Academy of Sciences, Beijing, China

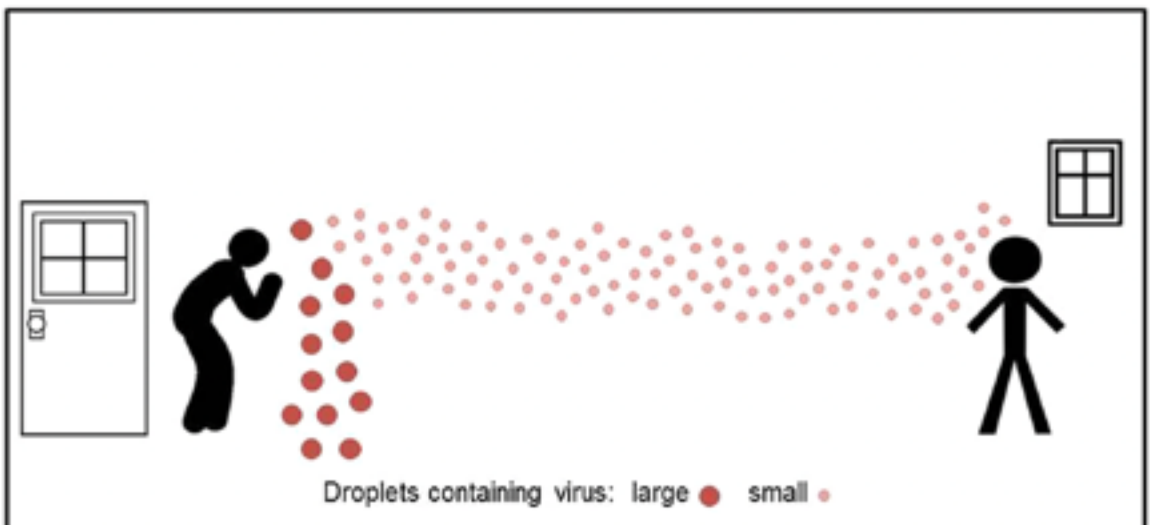


Fig. 1. Larger droplets with viral content deposit close to the emission point (droplet transmission), while smaller can travel meters or tens of meters long distances in the air indoors (aerosol transmission).

The 2 types of airborne transmission

Short-range

- like direct smoke from smoker

Long-range

- like `2nd-hand smoke’

- inhalation of turbulent plumes
- mitigated by social distancing
- largely eliminated by mask use

- arises throughout well-mixed space
- not mitigated by social distancing
- reduced by mask use

Long-range airborne transmission

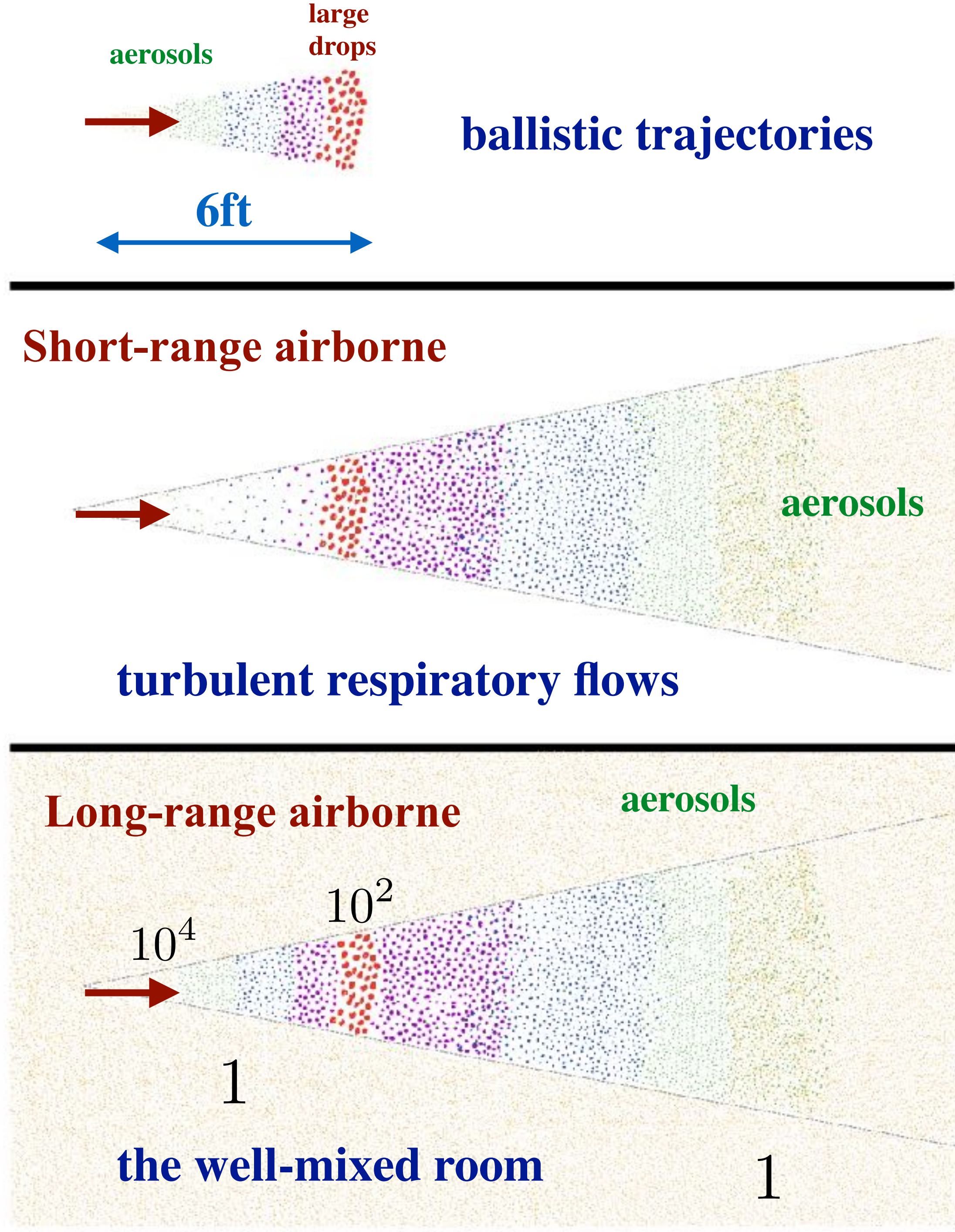
- occurs via inhalation of micron-scale, pathogen-bearing droplets suspended by air currents in indoor spaces
- airborne plagues in historic times were met with great trepidation, thought to be due to a `poisoned aether'
- implicated in the spread of many respiratory illnesses, including influenza, tuberculosis, measles, H1N1 and SARS-Cov-1
- CDC and WHO were slow to acknowledge that SARS-Cov-2 is airborne, perhaps because there were no clear guidelines indicating how to mitigate airborne spread
- theoretical models of risk assessment assume that airborne pathogen is mixed uniformly through indoor spaces
  — Wells (1953) , Riley et al. (1953), Stalianakis et al. (2010)

The pathogen footprint

Wells (1950s)

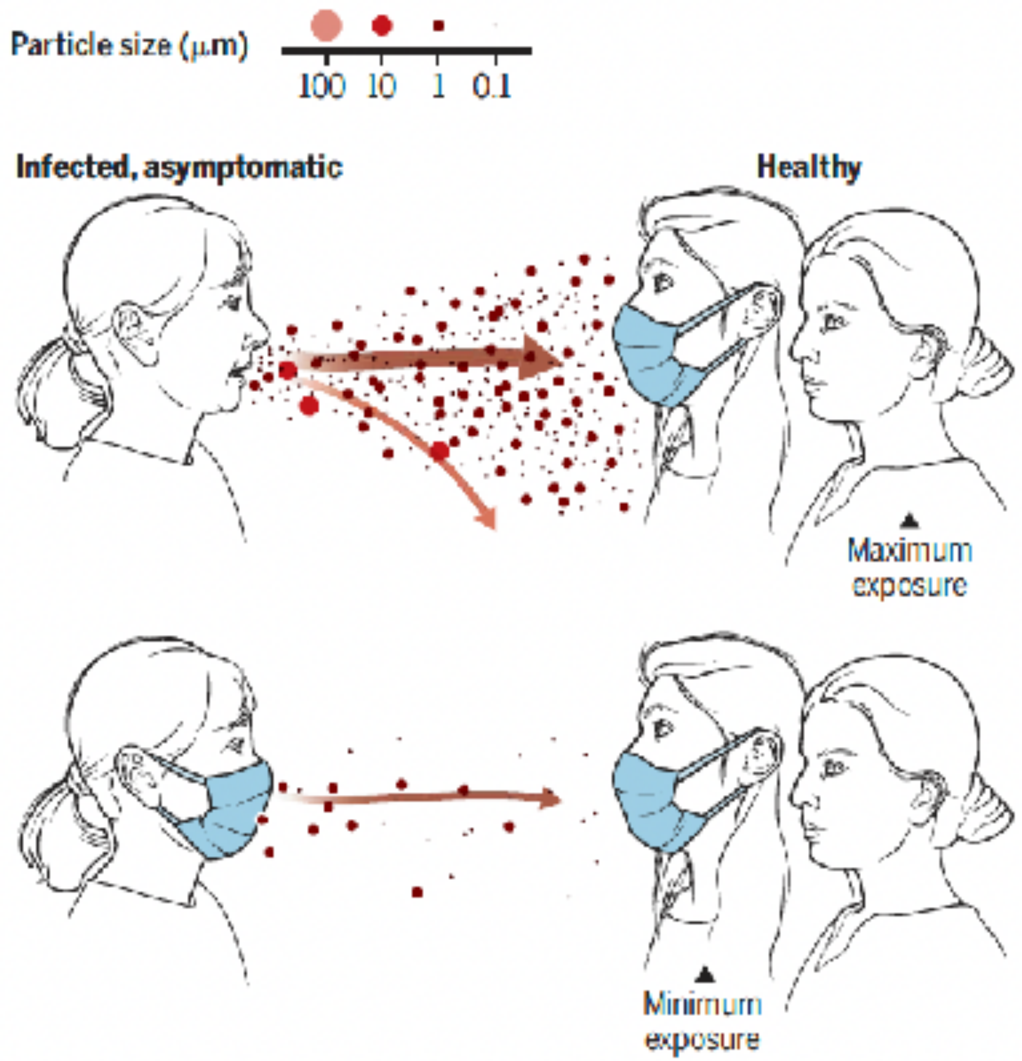
Bourouiba & Bush (2014)

Bazant & Bush (2021)



The effect of masks

Prather et al., Science (2020)

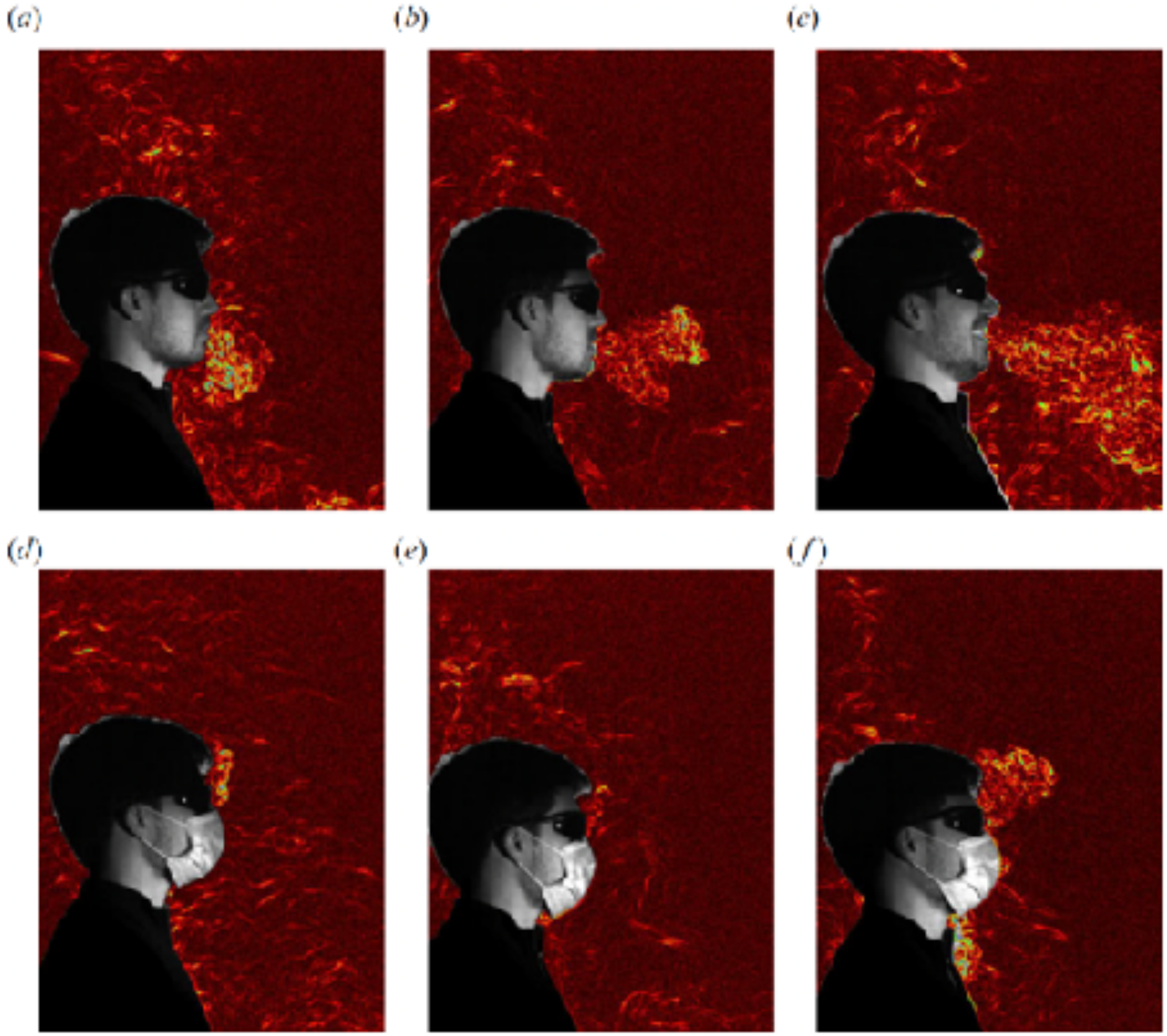


N95 Cloth

- filters outgoing and incoming pathogen, reducing by factor $p_m \sim 0.01 - 0.3$

The effect of masks

Bhagat et al., JFM (2020)



- effectively eliminates respiratory jets (and so short-range airborne transmission)

→ **when masks are worn, long-range transmission is dominant**

II. How can we do better?

- transmission dynamics in indoor spaces
- develop a safety guideline for airborne transmission

A guideline to limit indoor airborne transmission of COVID-19

Martin Z. Bazant[a,b,1] and John W. M. Bush[b]

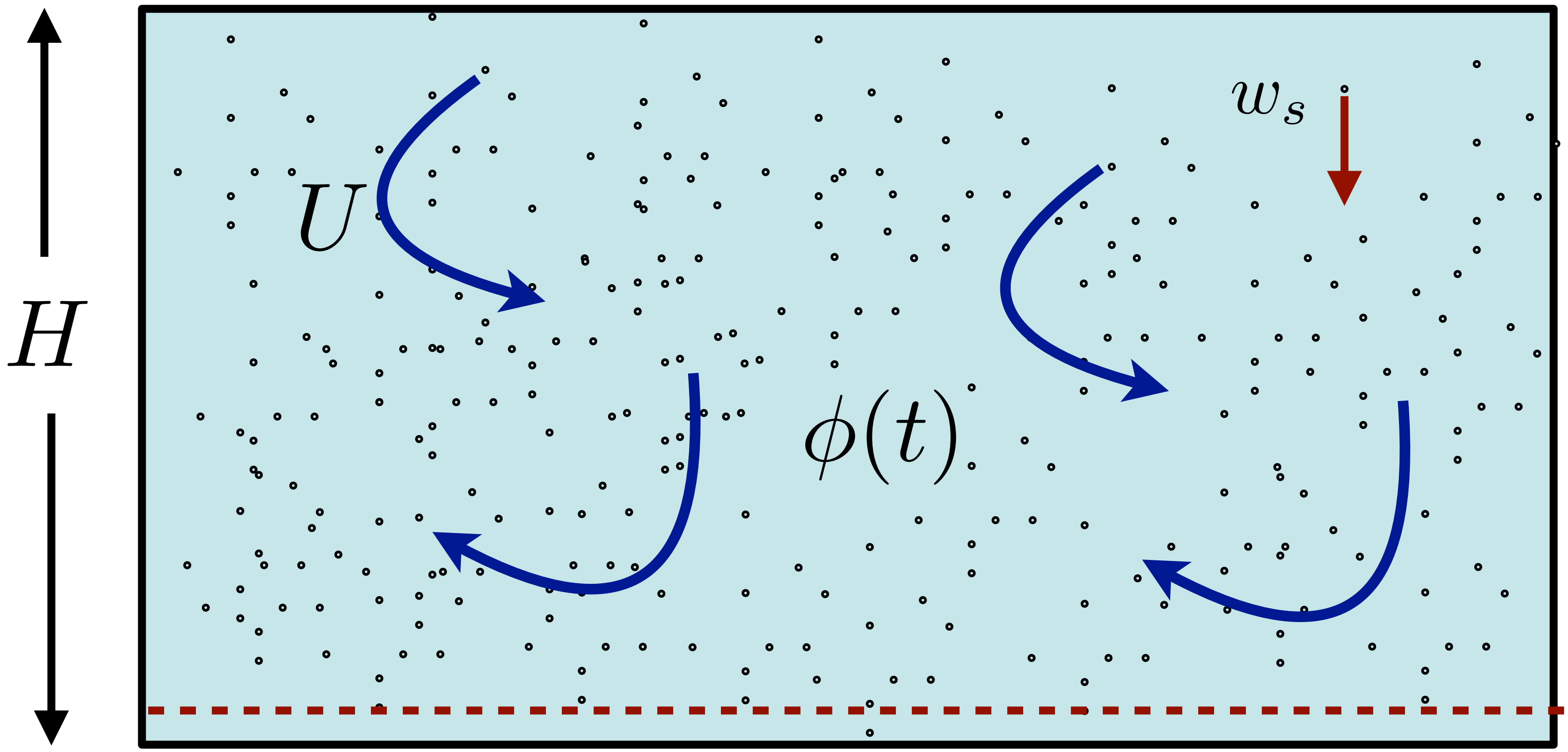
[a]Department of Chemical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139; and [b]Department of Mathematics, Massachusetts Institute of Technology, Cambridge, MA 02139

PNAS 2021 Vol. 118 No. 17 e2018995118

Preliminaries: Sedimentation in a well-mixed domain

— Pendelton & Middleton (1952), Martin & Nokes (1987)

- when sedimentation speed w_s < characteristic ambient speed U



Concentration of suspended sediment:

$$\phi(t) = \phi_0 \exp(-\frac{w_s}{H} t)$$

decays over sedimentation time $\frac{H}{w_s}$

Sedimentation of polydisperse respiratory drops

- Stokes settling speed (for r < 100 μm): $v_s(r) = 2\Delta\rho g r^2/(9\mu_a)$
- air circulation speed: $v_a = (Q + Q_r)/A$

EXCHANGE RECIRCULATION

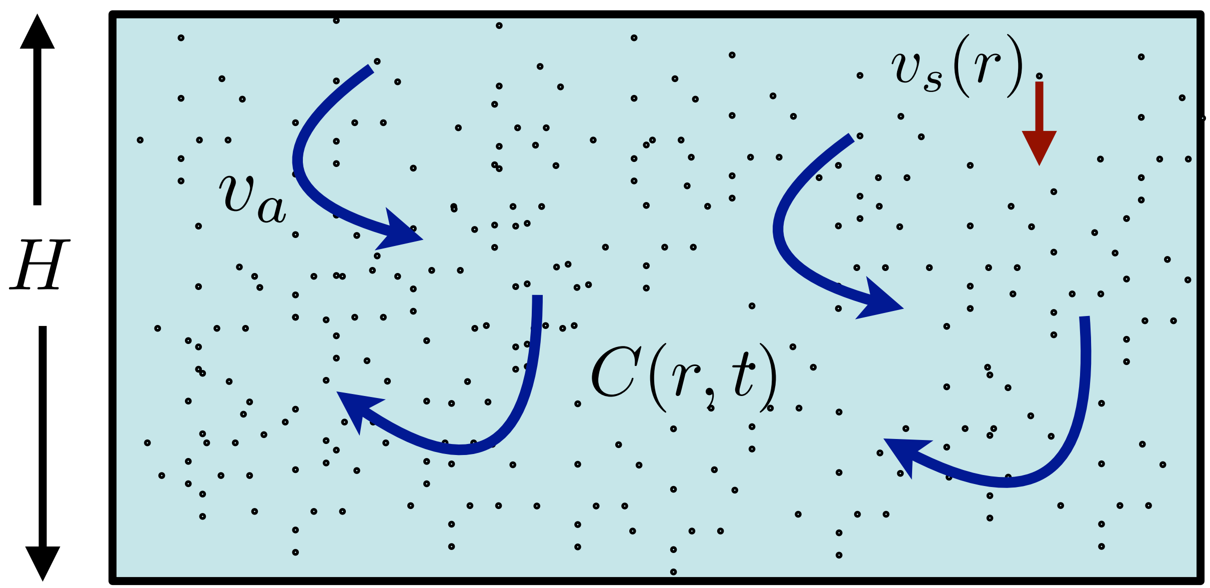
$V = HA$

$H/v_s = V/Q$ for

SETTLING TIME REMOVAL TIME

Critical drop size

$$r_c = \sqrt{\frac{9\lambda_a H \mu_a}{2g\Delta\rho}}$$



$\lambda_a = Q/V$

- drops with $r > r_c$ generally sediment out
- drops with $r < r_c$ are suspended until removal by air change

→ a dynamic sifting process survived by aerosol droplets

— for typical settings, $r_c \sim 2\mu m$

Evolution of concentration of polydisperse airborne pathogen

$$V\frac{dC}{dt} = IP - (Q + p_f Q_r + v_s A + \lambda_v V)\, C$$

RATE OF CHANGE | PRODUCTION BY EXHALATION | AIR EXCHANGE | LOSS VIA: FILTRATION | SEDIMENTATION | DEACTIVATION

$C(r,t)$	concentration suspended on drops of radius r
V, A	room volume and projected area
I	number of infected individuals in room
P	pathogen production rate per infected person
Q	air exchange rate
Q_r	air recirculation rate
p_f	probability of filtration via masks or filters
v_s	sedimentation speed
λ_v	deactivation rate

A single infected individual enters a room at t = 0.

Pathogen concentration

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

relaxes to equilibrium

$$C_s(r) = P(r)/(\lambda_c(r)V)$$

at a rate

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

$\lambda_a = Q/V$ air change rate

$\lambda_f(r) = p_f(r)Q_r/V$ filtration rate

$\lambda_s(r) = v_s(r)/H$ sedimentation rate

$\lambda_v(r)$ deactivation rate

Airborne transmission: due to inhalation of airborne pathogen

Transmission rate:

$$\beta_a(t) = Q_b s_r \int_0^\infty C(r,t) p_m(r) c_i(r) dr$$

- accounts for polydisperse pathogen-bearing droplet distribution
- $c_i(r)$ is the *a priori* unknown infectivity of the pathogen
- s_r accounts for relative susceptibility in different populations

Indoor reproductive number:

$$\mathcal{R}_{in}(\tau) = N_s \int_0^\tau \beta_a(t) dt$$

- the mean number of transmissions per infected individual,

  where $N_s = p_s(N-1)$ is the number of susceptibles

Indoor safety guideline:

$$\mathcal{R}_{in}(\tau) = N_s \int_0^\tau \beta_a(t) dt < \epsilon.$$

where $\epsilon < 1$ is a suitably chosen risk tolerance

Steady-state solution

- consider times $\tau > \lambda_a^{-1}$ (minutes to hours), for which equilibrium pathogen concentration obtains: $C(r,t) \rightarrow C_s(r)$

Constant transmission rate:

$$\frac{\overline{\beta}_a}{s_r} = \frac{Q_b^2 p_m^2}{V} \int_0^\infty \frac{n_q(r)}{\lambda_c(r)} dr = \frac{Q_b^2 p_m^2}{V} \frac{C_q}{\lambda_c(\overline{r})}$$

where the concentration of infection quanta per drop volume

$$n_q(r) = n_d(r) V_d(r) c_v(r) c_i(r)$$

PATHOGEN CONCENTRATION

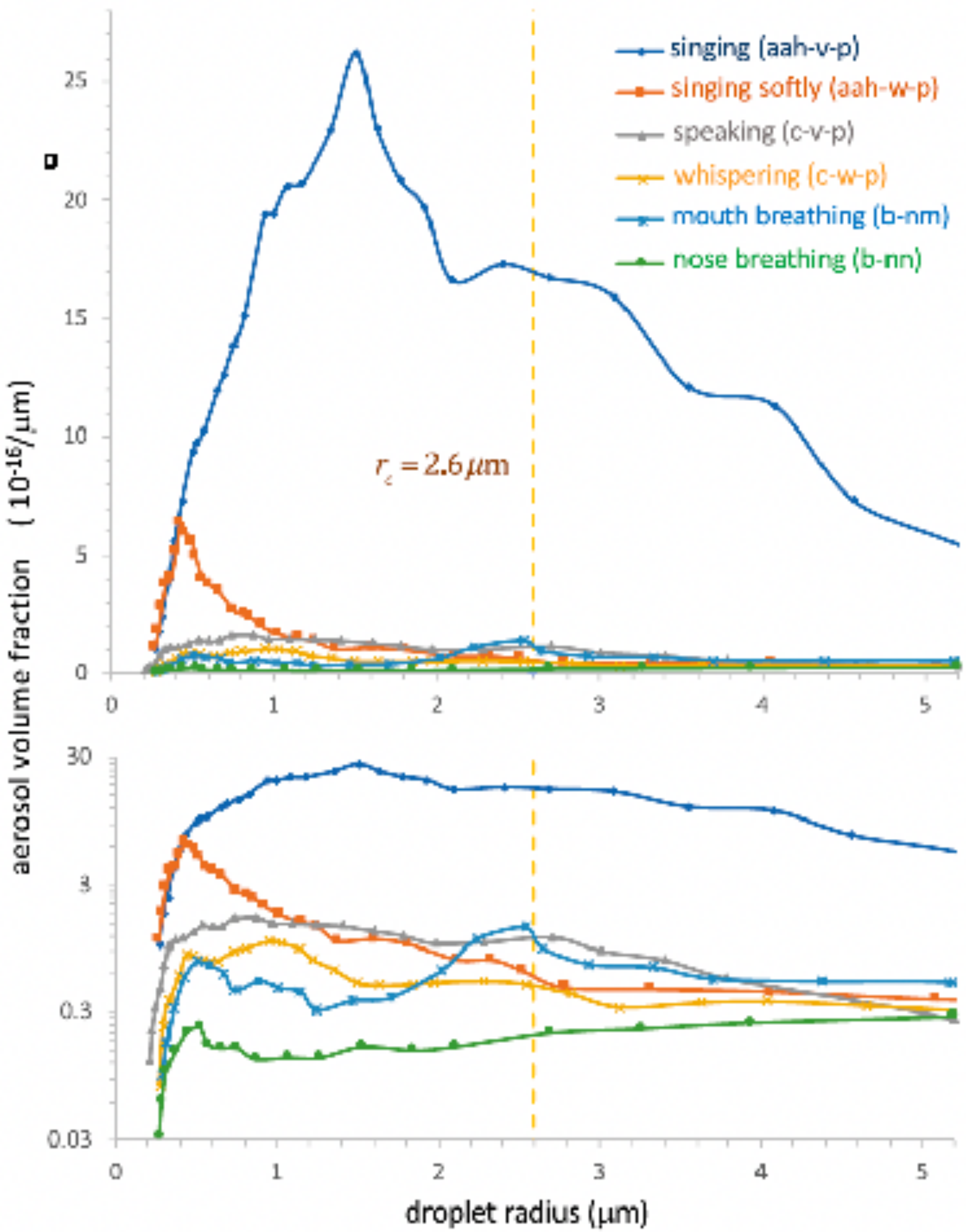
PATHOGEN INFECTIVITY

and the concentration of infection quanta, `infectiousness' of the air

$$C_q = \int_0^\infty n_q(r) dr.$$

as may be assessed in different settings given drop-size distributions

Model prediction for drop size distributions



- take input data from drop size distributions reported by Morowska et al. (1997)
- take room parameters corresponding to Skagit Choir superspreader
- allows for assessment of relative risk of various activities

Inferences of C_q, $\lambda_q = C_q Q_b$ for various activities

Activity	Experiment (74)	Q_b (m^3/h)	ϕ_1 (10^{16})	C_q (q/m^3)	λ_q (q/h)
breathing at rest	nose in, nose out (b-nn)	0.5	0.35	8.8	4.2
breathing heavily	nose in, mouth out (b-nm)	0.5	1.3	33	16
whispering	whispered counting (c-w-p)	0.75	1.5	37	28
speaking	voiced counting (c-v-p)	0.75	2.9	72	54
singing softly	whispered "aahs" (aah-w-p)	1.0	4.1	103	103
singing	voiced "aahs" (aah-v-p)	1.0	39	970 (53)	970

Table S2. Activity dependence of airborne transmission of COVID-19. Expiratory droplet size distributions for different activities are taken from the experiments reported by Morawska et al. (74), and reasonable estimates are made for the exhaled air volume per time Q_b from breathing (0.5 m^3/h), speaking (0.75 m^3/h) and singing (1.0 m^3/h). Our model is then used to predict the steady-state aerosol volume fraction, $\phi_1 = \int_0^{r_c} \phi_s(r)\,dr$, that results from exhalation of a single infectious individual in a setting corresponding to the Skagit Valley Choir room (Table S1), by integrating the distributions shown in Fig. 1 up to the critical radius $r_c = 2.5\mu$m. The concentration of COVID-19 infection quanta in the breath of an infected individual is assumed to be $C_q = 970$ q/m^3 for the singing case, as estimated for the Skagit Valley Chorale incident by Miller et al. (53), and values of C_q for other activities are calculated by rescaling with the appropriate ratio of aerosol volume fractions, ϕ_1. The quanta emission rate for each activity is then given by $\lambda_q = Q_b C_q$.

- allows for analysis of a number of super-spreader events
- consideration of different physical settings (room parameters and activity) allows for estimation of airborne pathogen concentration (C_q) and rationale for transmission dynamics (observed β_a)

Transmission dynamics: the SEIR model

Susceptible [S], Exposed [E], Infected [I] and Recovered [R] populations:

$$\frac{dS}{dt} = -\beta SI, \quad \frac{dE}{dt} = \beta SI - \alpha E, \quad \frac{dI}{dt} = \alpha E - \gamma I, \quad \frac{dR}{dt} = \gamma I$$

where β is the infection rate, α the incubation rate, γ the recovery rate

Spreading events of duration $\tau \ll \gamma^{-1}$: neglect R

Solve for infection rate: $i_S(\tau) = (E(\tau) + I(\tau) - I_0)/S_0$

Case 1: Slow incubation

$(\tau \ll \beta, \alpha^{-1})$

$$i_S(\tau) = 1 - e^{-I_0 \int_0^\tau \beta(t)dt}$$

Case 2: Fast incubation

$(\tau \gg \beta, \alpha^{-1})$

$$i_S(\tau) = \left[1 - i_0^{-1}\left(e^{N \int_0^\tau \beta(t)dt} - 1\right)^{-1}\right]^{-1}$$

Superspreading events considered

- the Skagit Church Choir: 53 of 61 infected in a 2.5 hr practice

SLOW
INCUBATION

- the Ningbo Bus Tour: 23 of 61 infected in a 2-hour bus ride

- the Wuhan City outbreak during first lockdown
  — 80% occurred in the home setting

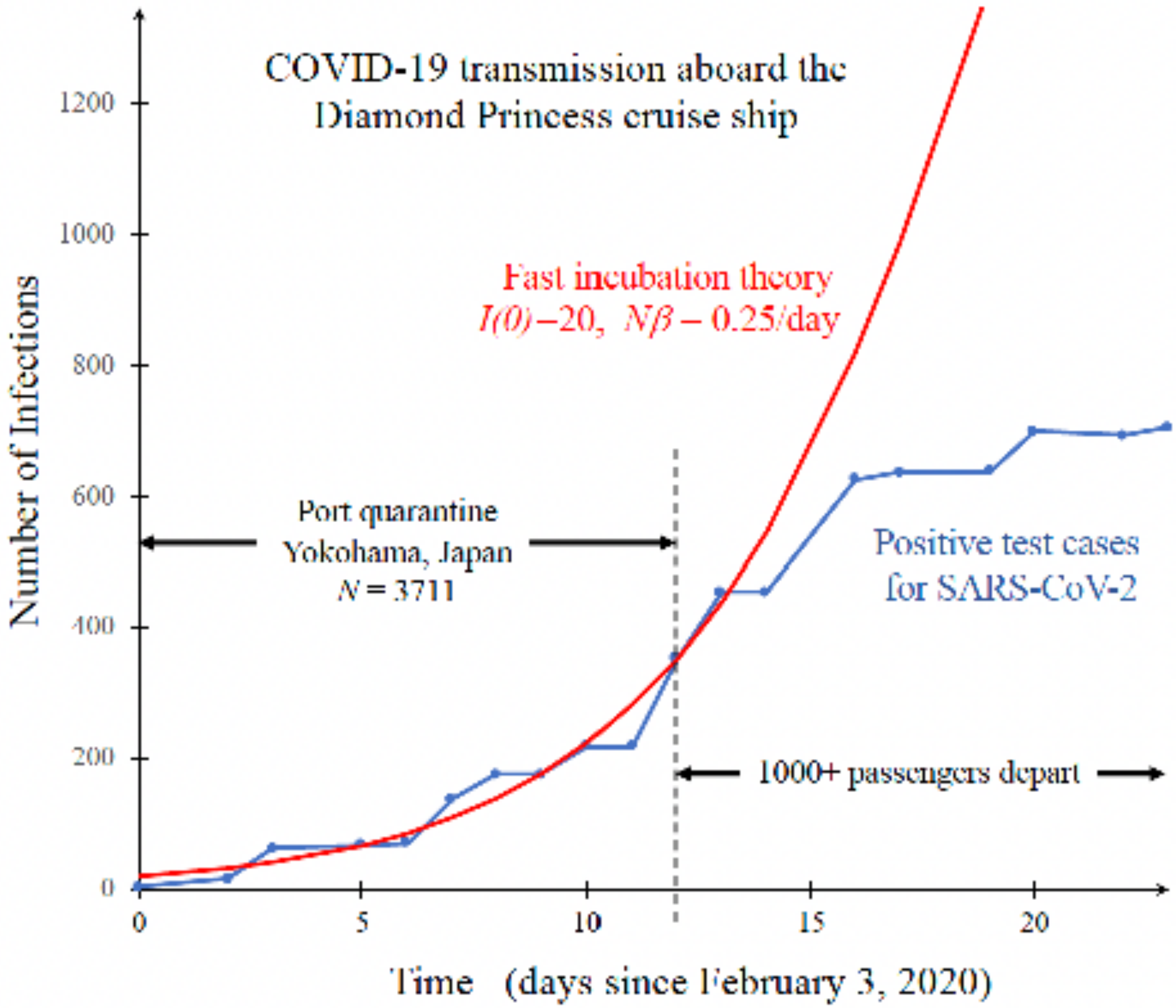
- the Diamond Princess during quarantine
  — 354 of 3711 people infected over 12 days

FAST
INCUBATION

	N	τ (h)	I_0	$I(\tau)$	λ_a (1/h)	A (m^2)	H (m)	Q_b (m^3/h)	C_q (q/m^3)	λ_q (q/h)
Skagit Church Choir	61	2.5	1	53	0.65	180	4.5	1.0	870	870
Ningbo Tour Bus	68	1.7	1	21	1.25	25	1.8	0.5	90	45
Diamond Princess	3711	288	20	354	8	139,000	2.1	0.5	30	15
Wuhan City Outbreak	3.03	132	1	1.63	0.34	90	2.4	0.5	29	14

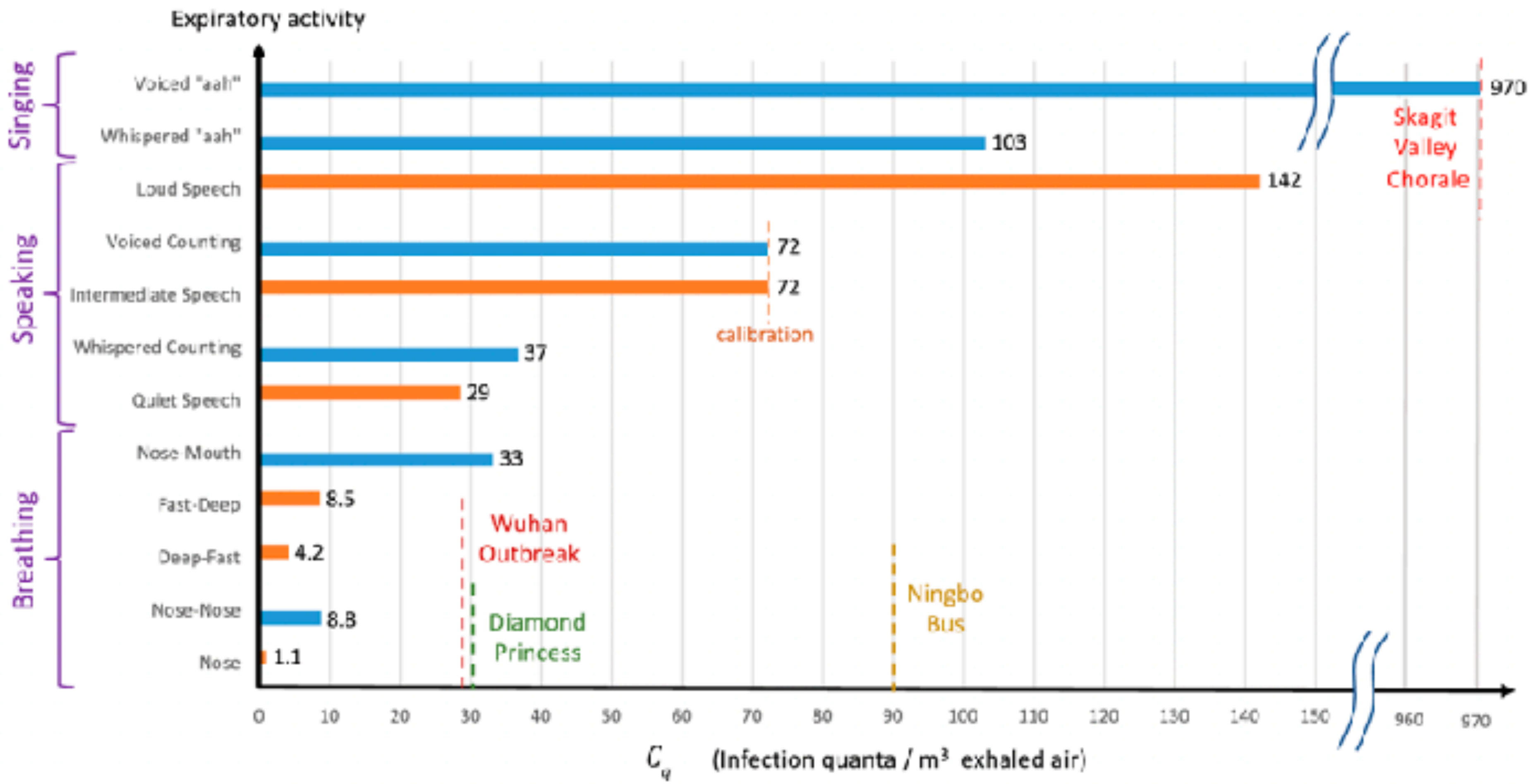
- comparison allows for consistency checks of inferred infectivity

Spreading during the Diamond Princess quarantine



- allows for inference of initial number infected and transmission rate, which indicates the concentration of infection quanta from breathing

Model prediction for infectivity of air , C_q



Self-consistent inference of infectivity of SARS-Cov2: $c_i \approx 0.1$

— ten times more infectious than SARS-Cov1

Indoor safety guideline: $\mathcal{R}_{in}(\tau) = N_s \int_0^\tau \beta_a(t) dt < \epsilon.$

- for a steady-state environment with one infected individual…

Bound on `cumulative exposure time':

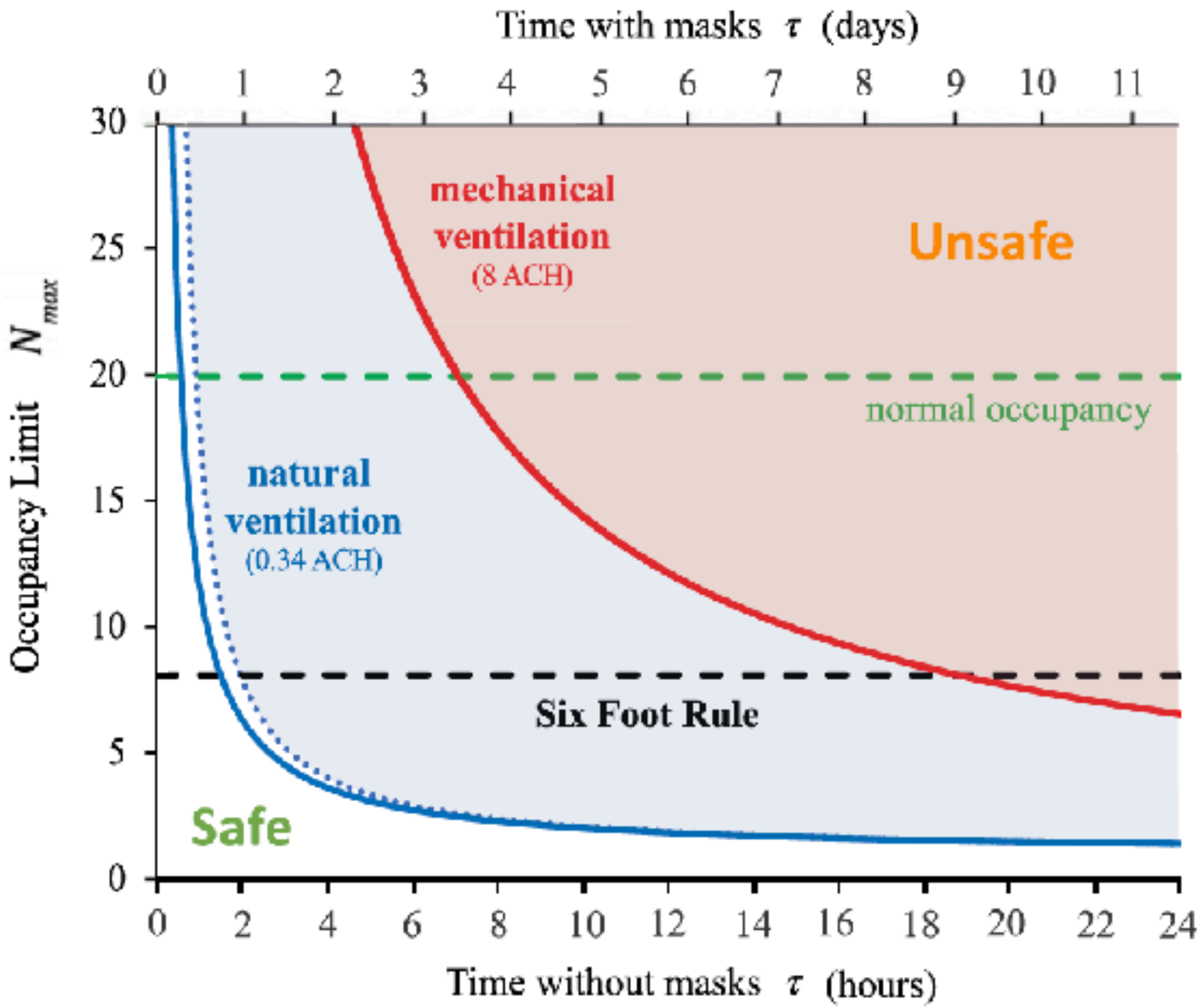
$$N\tau < \epsilon \frac{\lambda_a V}{Q_b^2 p_m^2 C_q s_r}$$

To minimize risk

- minimize time spent with large crowds
- avoid small, poorly ventilated spaces
- avoid areas where people are exerting themselves, e.g. singing or working out in a gym
- wear a mask, avoid places where people are maskless

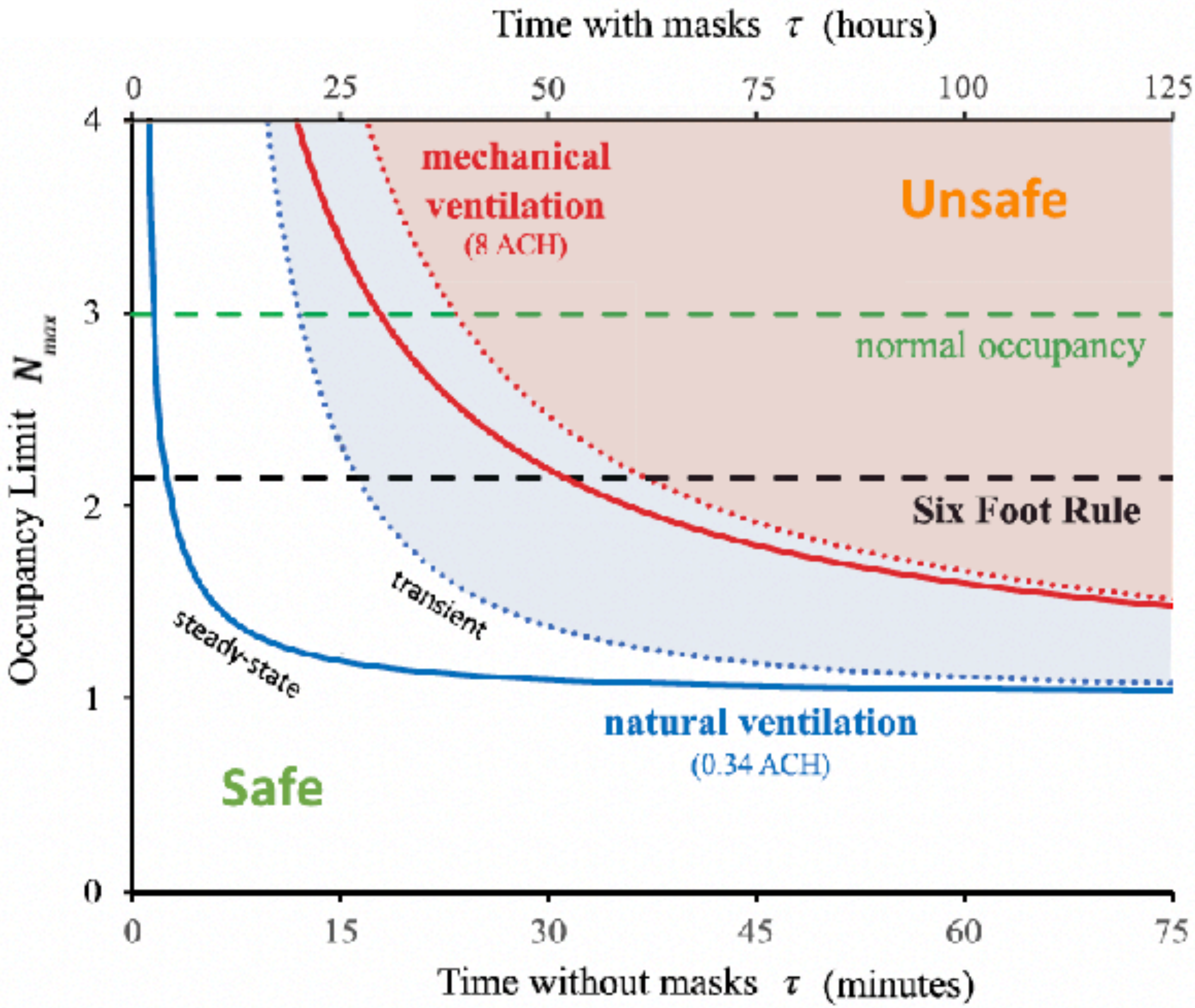
American classroom

$\epsilon = 0.1$



Room in a nursing home

$\epsilon = 0.01$



Relative risk coefficient

- for a given individual, one may eliminate (ϵ, s_r) from consideration

$$I_R = \frac{N \tau C_q Q_b^2 p_m^2}{\lambda_a V}$$

- allows for assessment of relative risk of various settings; *e.g.* an afternoon in a well-ventilated lab, or an hour in the gym

To minimize risk

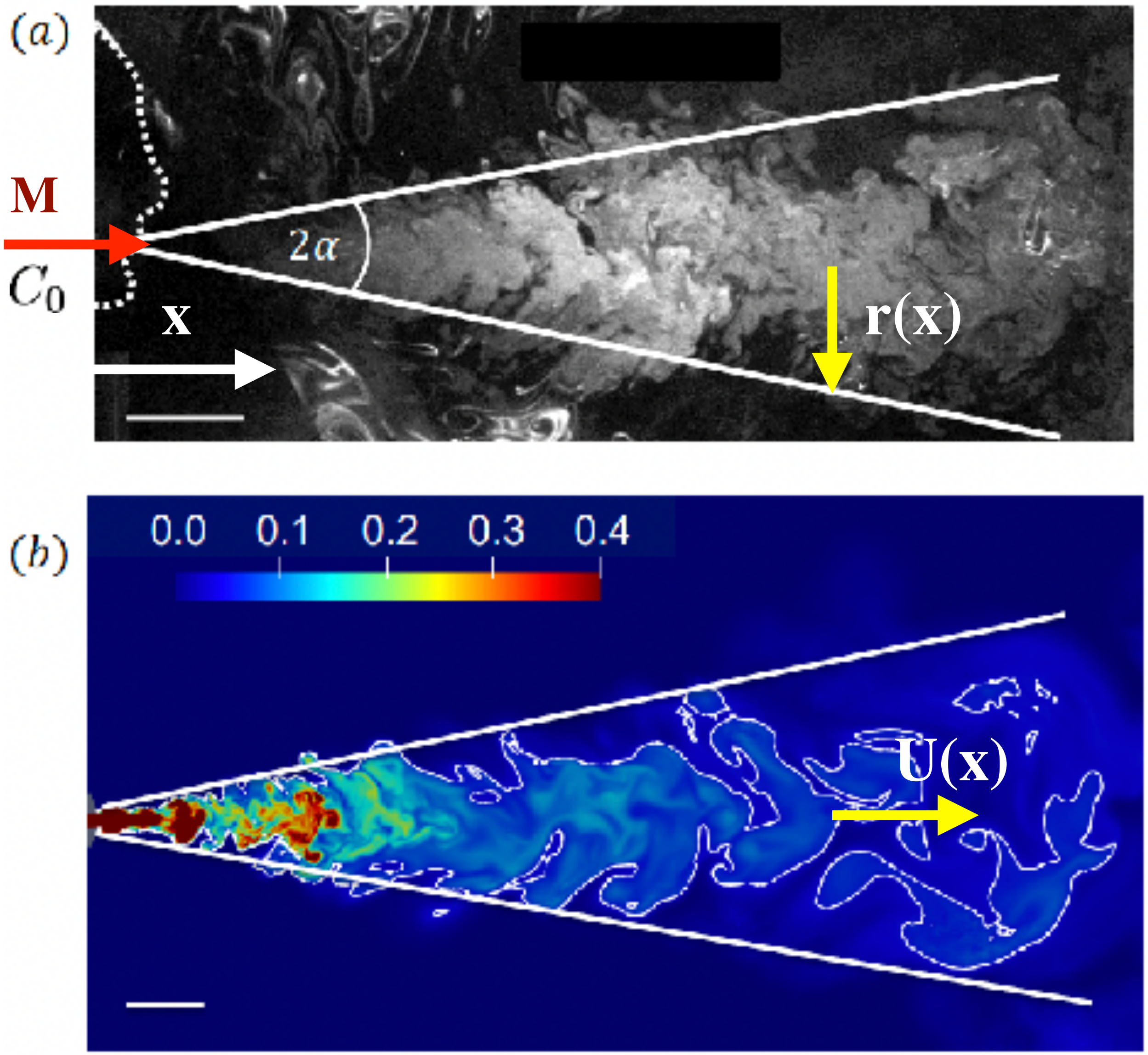
- avoid small, poorly ventilated spaces; wear a mask
- avoid areas where people are exerting themselves

Lifestyle risk assessment

- integrate I_R over the course of a day

Heightened risk: respiratory jets

Yang et al., PNAS (2020)



Jet scalings:

$$r = \alpha_t x$$

$$v(x) = \frac{M^{1/2}}{\alpha_t x \sqrt{\pi \rho_a}}$$

$$\frac{C_j(x)}{C_0} = \frac{A_m^{1/2}}{\alpha_t x}$$

where mouth area

$$A_m \approx 2cm^2$$

entrainment coefficient

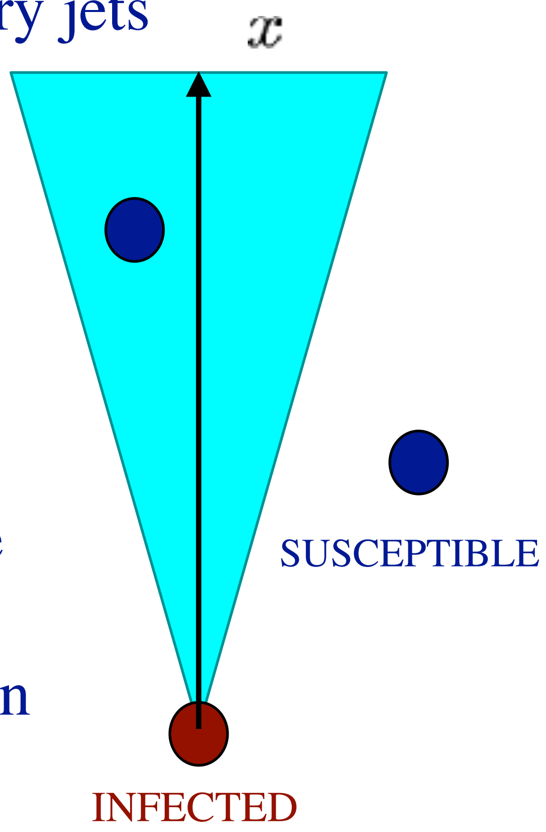
$$0.1 < \alpha_t < 0.15$$

- series of turbulent puffs - modeled as a continuous turbulent jet

Beyond the well-mixed room

- heightened risk associated with short-range airborne transmission
- consider risk of inhaling pathogen from respiratory jets

$$\mathcal{R}_{in}(\tau)\left[1+\frac{p_j A_m^{1/2}}{N_s f_d \alpha_t x}\right]<\epsilon.$$



where p_j is the probability of being in a jet
A_m is the mouth area
N_s is the number of susceptible people
α_t is the entrainment coefficient
x is the distance to the infected person
f_d is the room's dilution factor

- risk from respiratory jets clearly geometry dependent, may dominate
- this risk effectively eliminated with mask use

Rules of thumb

- if concentration of airborne pathogen in exhaled air is 1000 …
- it is diluted within the turbulent respiratory jet to 30 at 2m
- a background level of 1 endangers everyone in an indoor setting
- direct ingestion of a lung-full of infected air poses the same risk as an hour spent *anywhere* in a shared indoor, well-mixed setting with an infected individual

Informs contact tracing

- indicates limitations of `15min within 6ft' definition widely applied
- *all* occupants of a well-mixed room should be considered as contacts

III. How can we implement this new safety guideline?

- carbon dioxide monitoring for COVID safety
- COVID Indoor Safety App

Flow (2021), 1:0 1–18
doi:10.1017/flo.2021.1

FLOW CAMBRIDGE UNIVERSITY PRESS

RESEARCH ARTICLE

Monitoring carbon dioxide to quantify the risk of indoor airborne transmission of COVID-19

Martin Z. Bazant[1,2*], Ousmane Kodio[2], Alexander E. Cohen[1], Kasim Khan, Zongyu Gu[1] and John W. M. Bush[2] [1]

Recast safety guideline in terms of carbon dioxide concentration

— Rudnick & Milton (2003), Peng & Jimenez (2021)

Concentration of carbon dioxide $C_2(t)$ evolves as a passive scalar:

$$V\frac{\mathrm{d}C_2}{\mathrm{d}t} = P_2(t) - Q_a(t)C_2$$

where $P_2(t) = N(t)Q_b(t)C_{2,b}$ is the exhaled production rate,

CO_2 removed exclusively by air exchange at a rate $\lambda_a = Q_a(t)/V$

Excess CO_2 evolution: $\langle C_2 \rangle \approx \frac{\langle P_2 \rangle}{Q_a} - \left(\frac{1 - \mathrm{e}^{-\lambda_a \tau}}{\lambda_a \tau}\right)\frac{P_2(\tau)}{Q_a}$

Relaxes to steady state: $\boxed{C_{2,s} = \frac{P_2}{Q} = \frac{Q_b C_{2,b} N}{\lambda_a V}}$ for $\tau \gg \lambda_a^{-1}$

Recast safety guideline in terms of carbon dioxide concentration

$$\langle C_2\rangle\tau = \int_0^\tau C_2\,dt < \frac{\epsilon\, C_{2,b}}{\lambda_q s_r \overline{p}_m^2}\cdot\frac{\overline{\lambda}_c}{\lambda_a}\cdot\frac{N}{N_t}$$ ★

where $\lambda_q = Q_b C_q$ is the infection quanta emission rate

Evolving susceptibility of population

N people with probability of being infected, immune or susceptible:

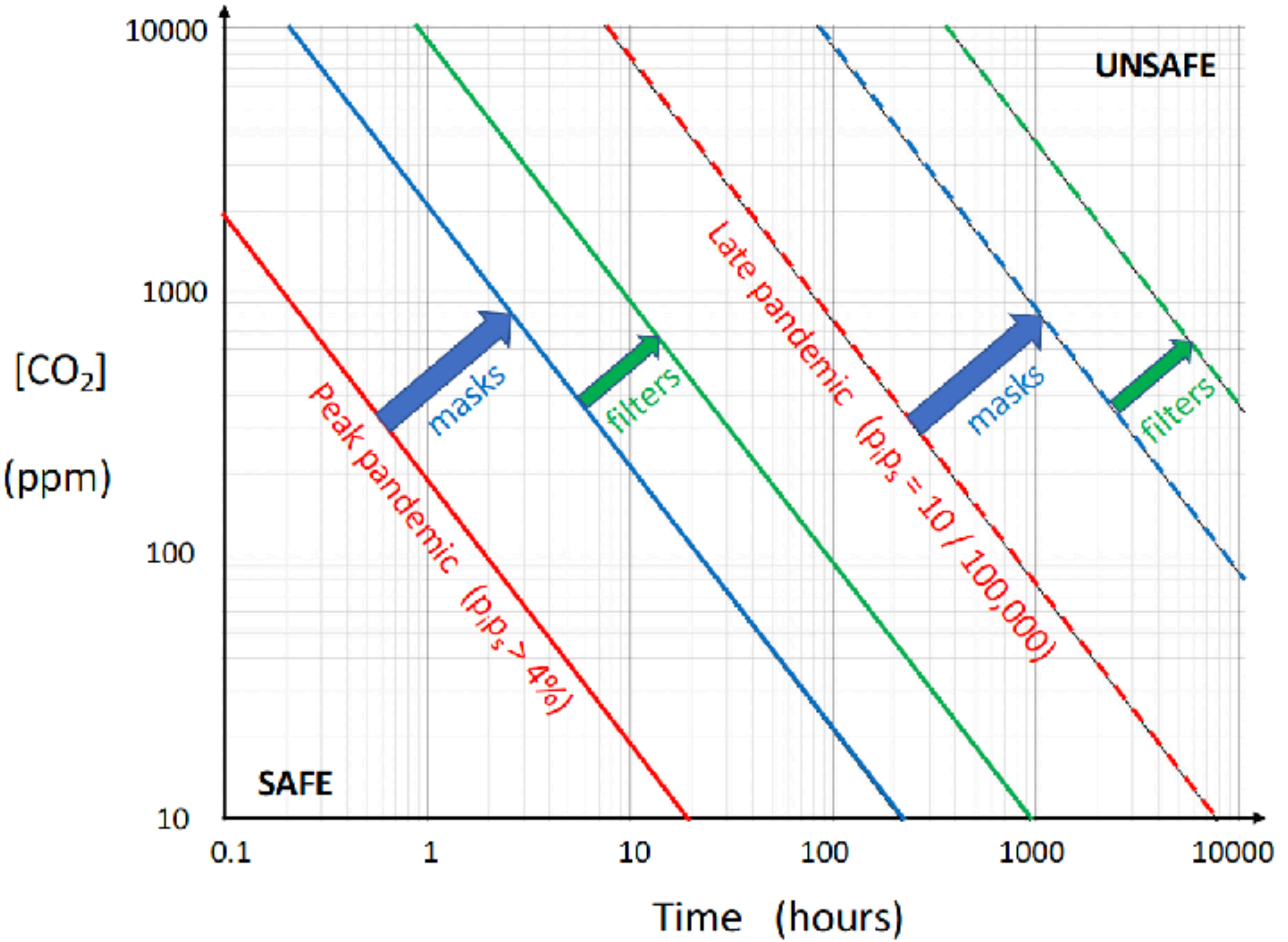
$$p_i,\; p_{im}\;,\; p_s = 1 - p_i - p_{im}$$

Expected number of infected-susceptible pairs: $N_t = N(N-1)p_i p_s$

Early pandemic: $N/N_t \approx 1$

Late pandemic: $p_i \to 0\;,\; p_{im} \to 1\;,\; N/N_t \to \infty$

★ supplanted by CO_2 safety

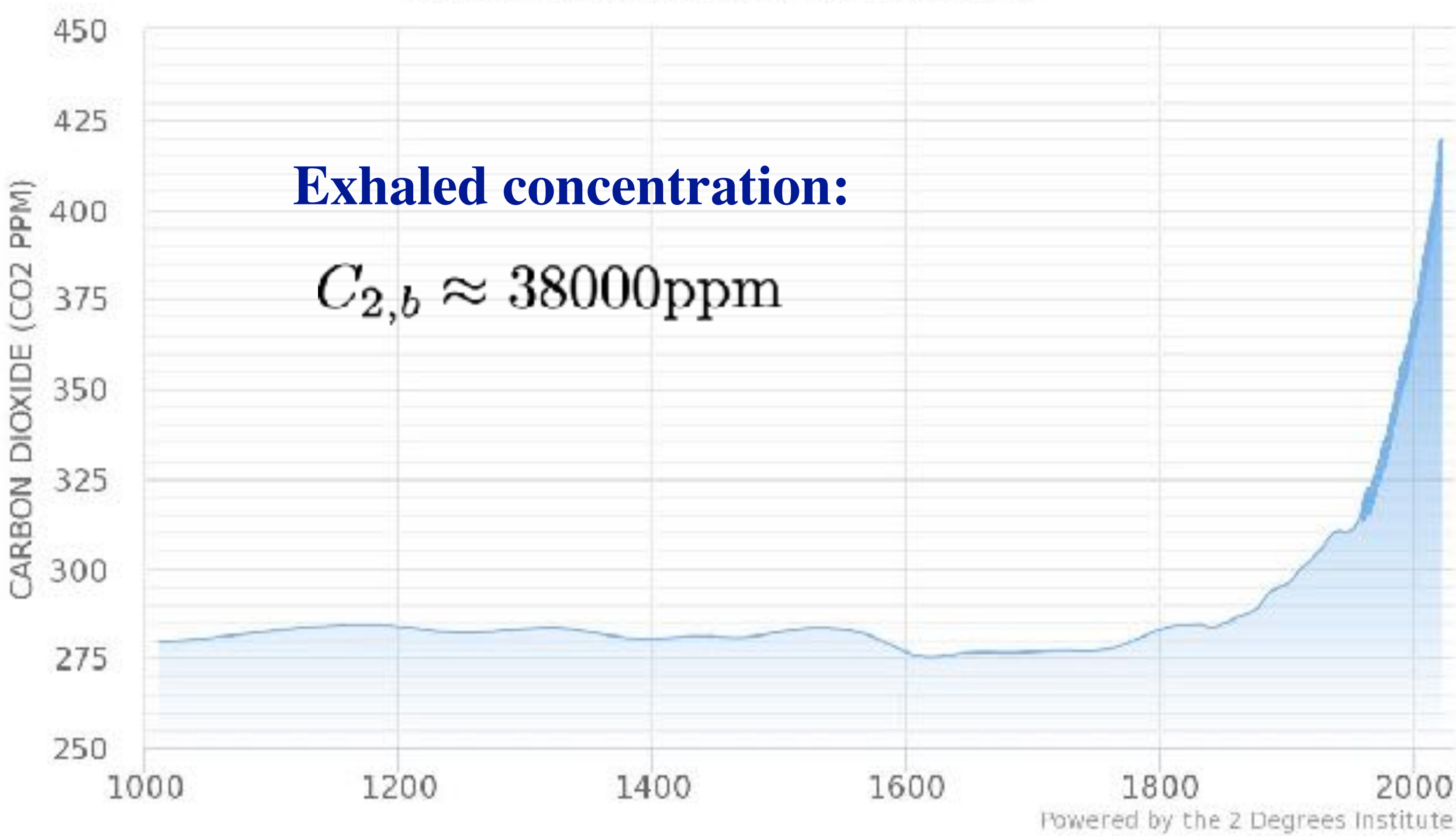


10000
1000
100
10
[CO2]
(ppm)
0.1
1
10
100
1000
10000
Time (hours)
UNSAFE
SAFE
Peak pandemic (pipS > 4%)
Late pandemic (pipS = 10 / 100,000)
masks
filters
masks
filters

Carbon dioxide levels on Planet Earth

Exhaled concentration:

$$C_{2,b} \approx 38000\text{ppm}$$



https://www.co2levels.org/

- human occupancy indoors may create levels well above 1000ppm
- drowsiness, decreased decision-making reported at > 1000ppm

Measuring carbon dioxide

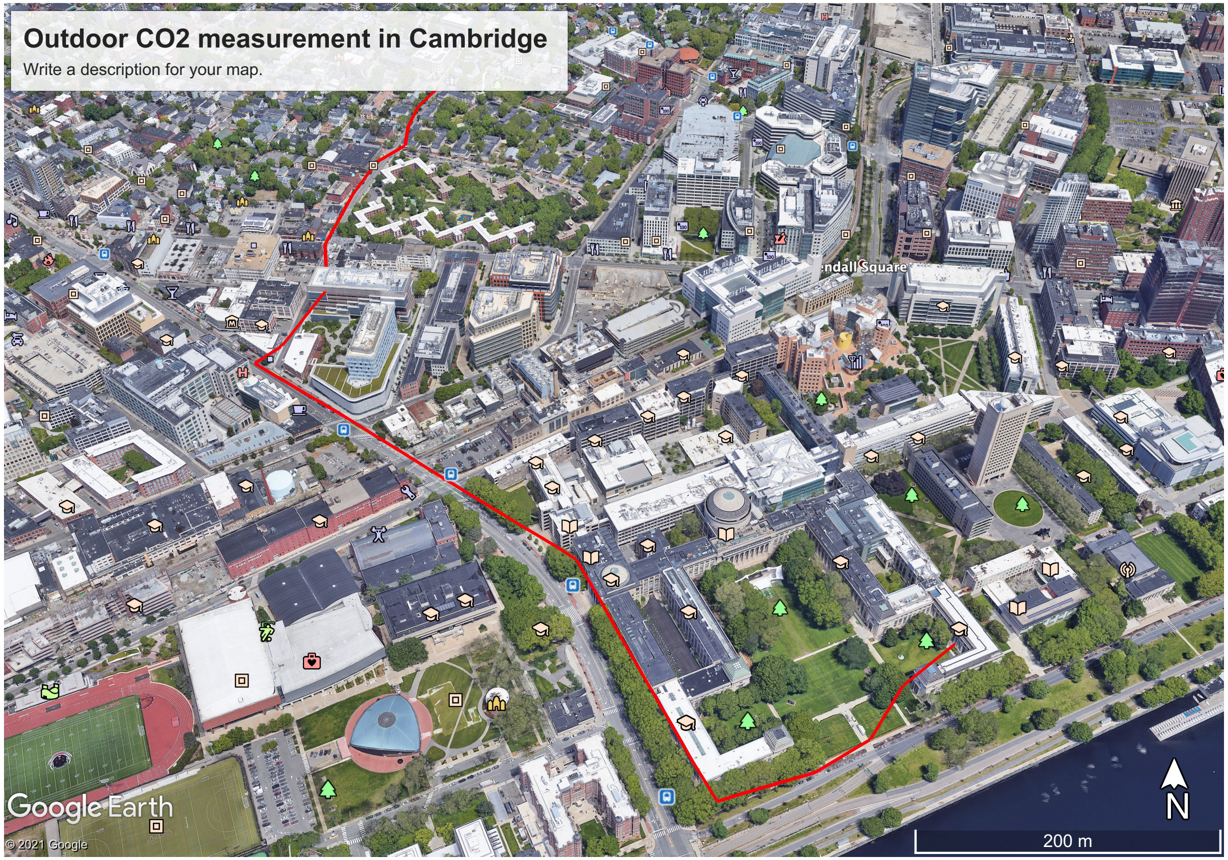
$168

$249

$151

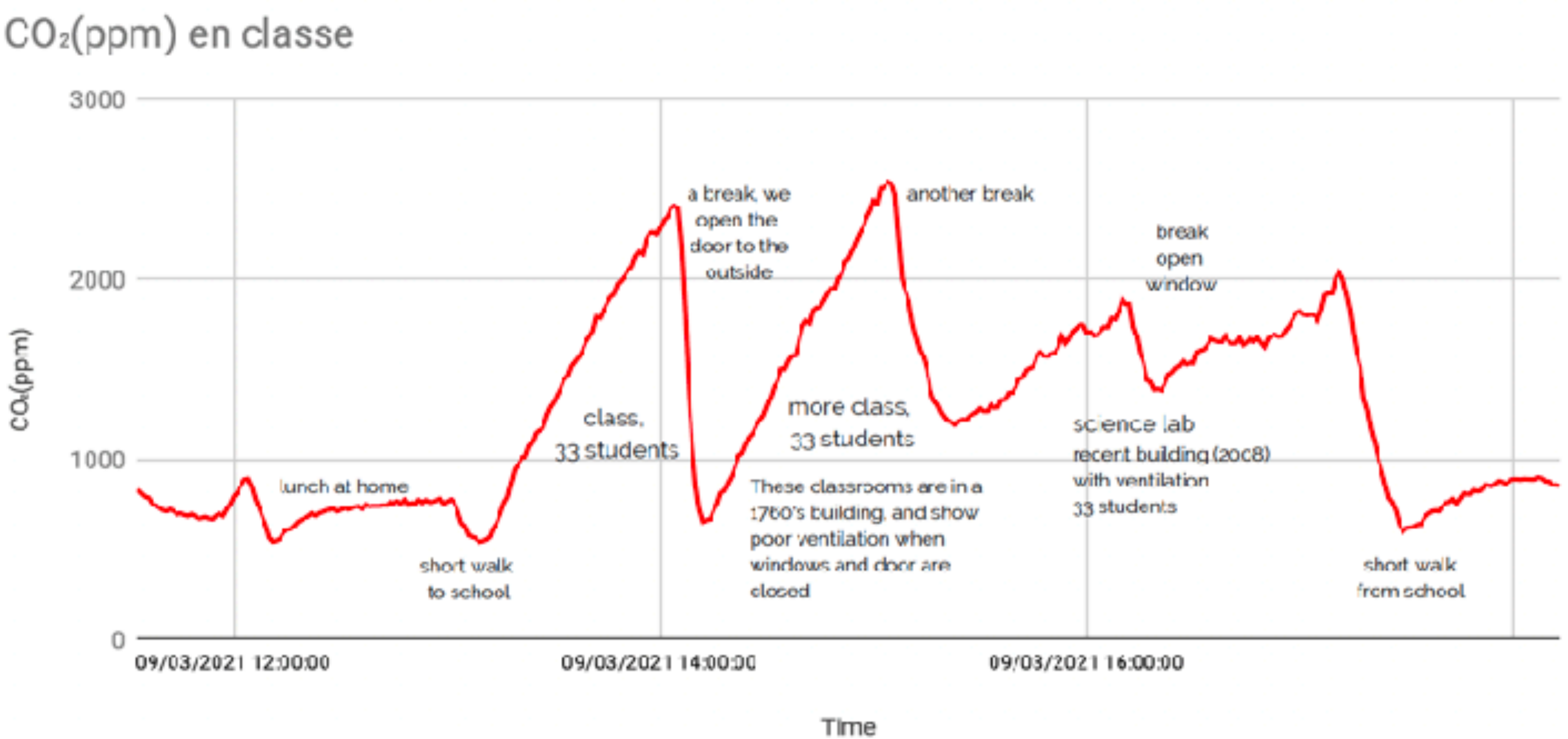
- various inexpensive, readily accessible, easy-to-use options
- widely used to assess indoor air quality in workplace, classroom

Outdoor carbon dioxide measurements at MIT

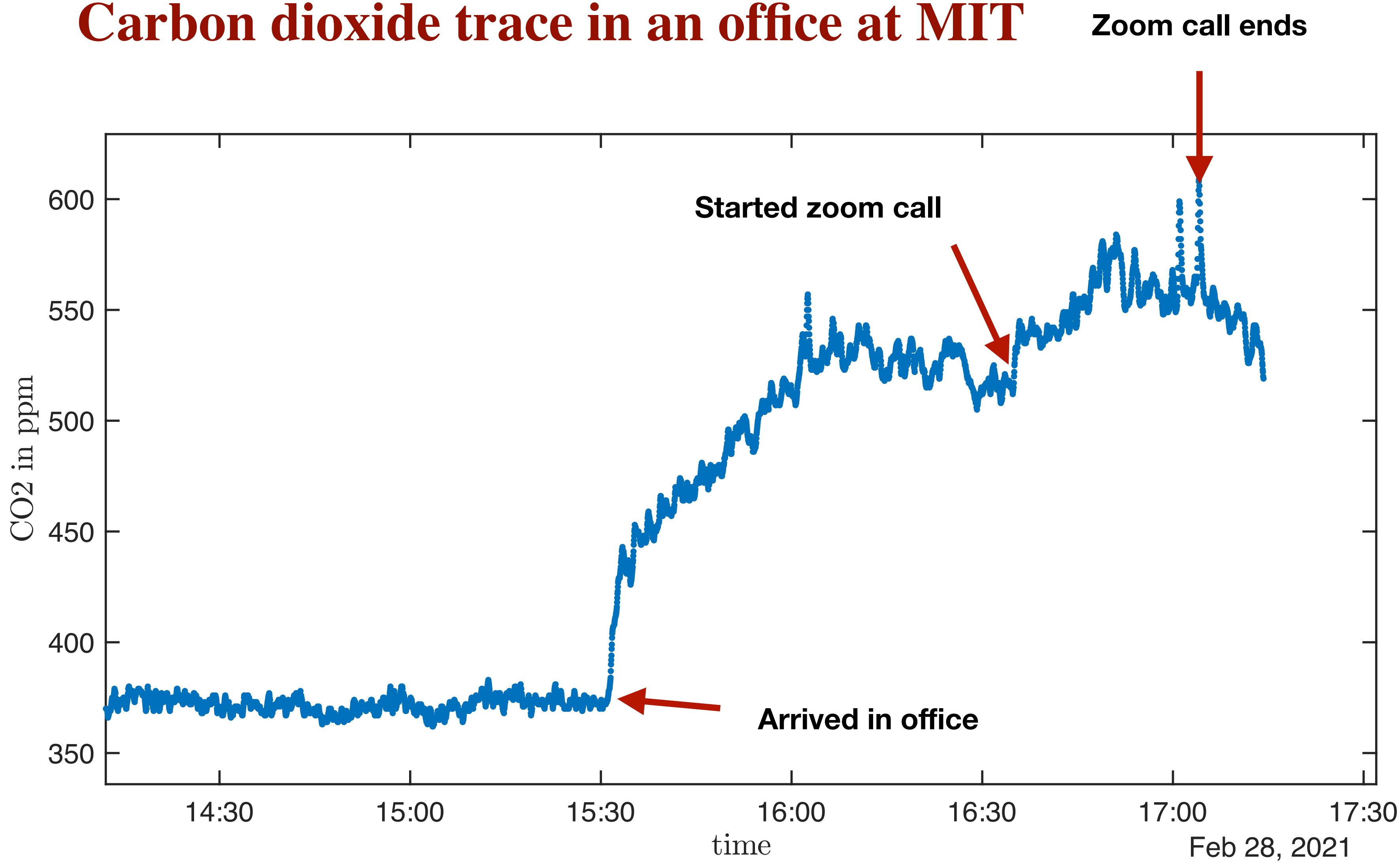


	CO_2(ppm)	Temperature(C)	Humidity(%)	Pressure(hPa)
count	13.000000	13.000000	13.000000	13.0
mean	444.846154	16.338462	15.307692	1024.0
std	8.464102	0.450071	2.897833	0.0
min	431.000000	15.400000	11.000000	1024.0

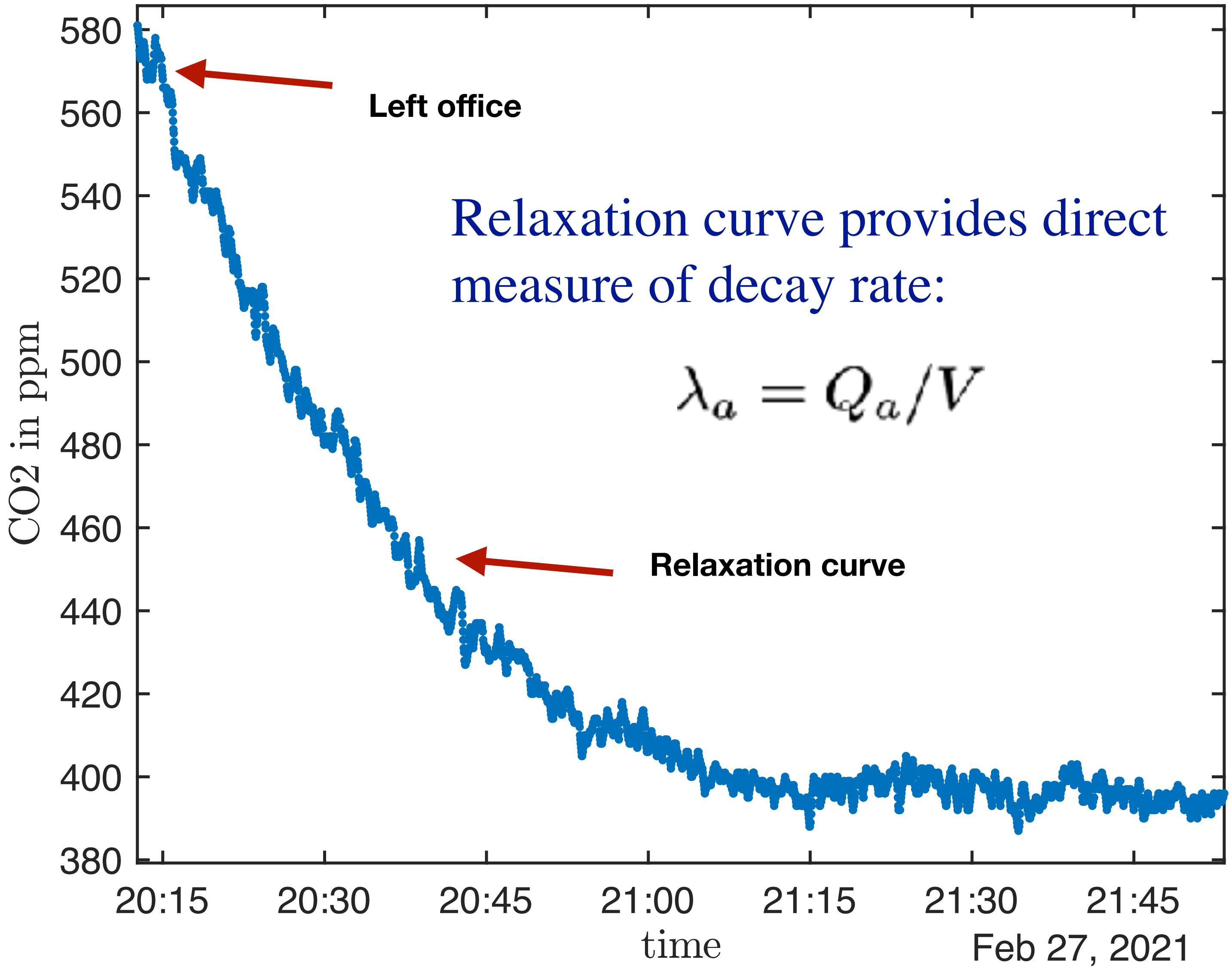
A daily trace of carbon dioxide concentration



Carbon dioxide trace in an office at MIT



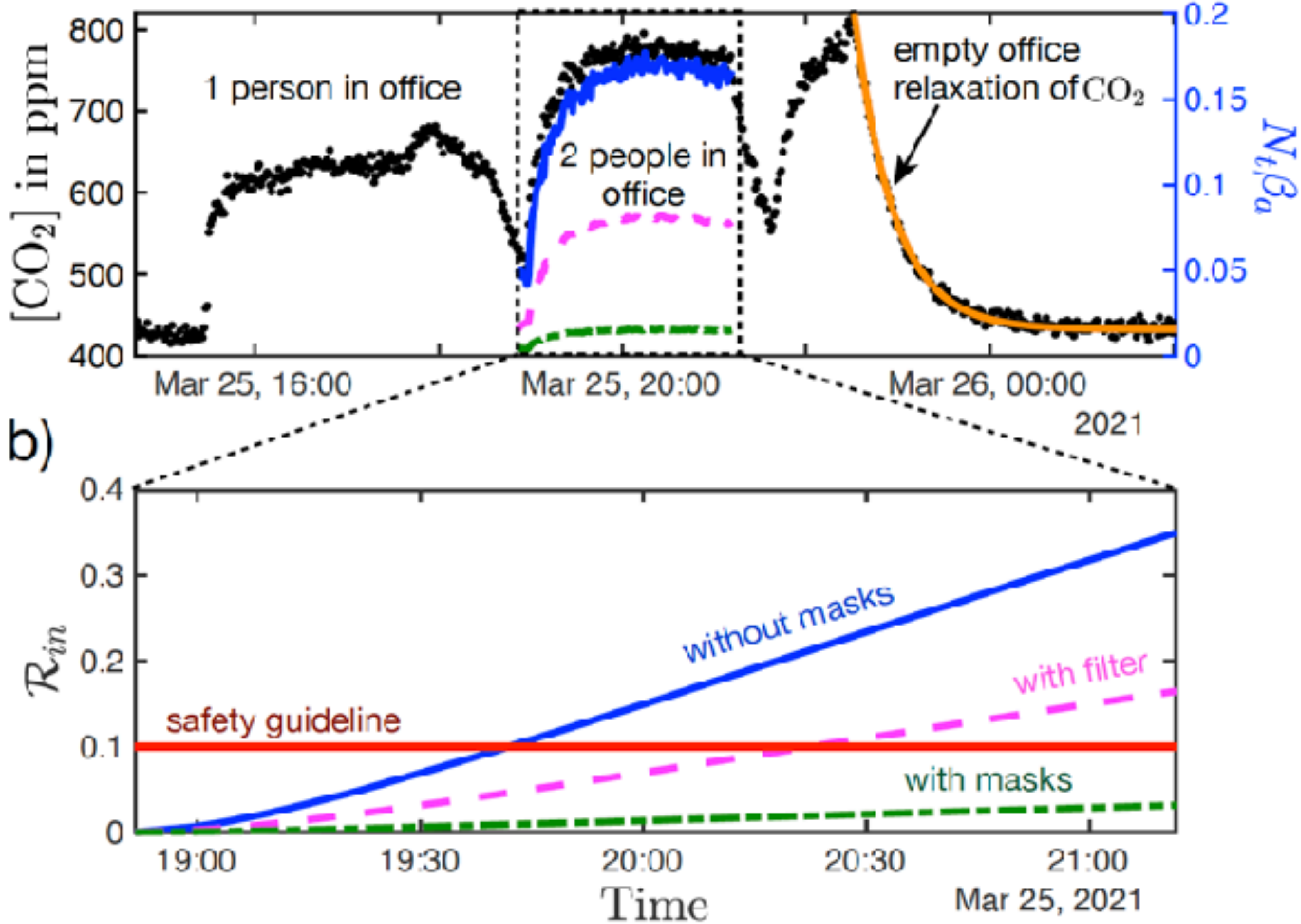
Carbon dioxide trace in an office



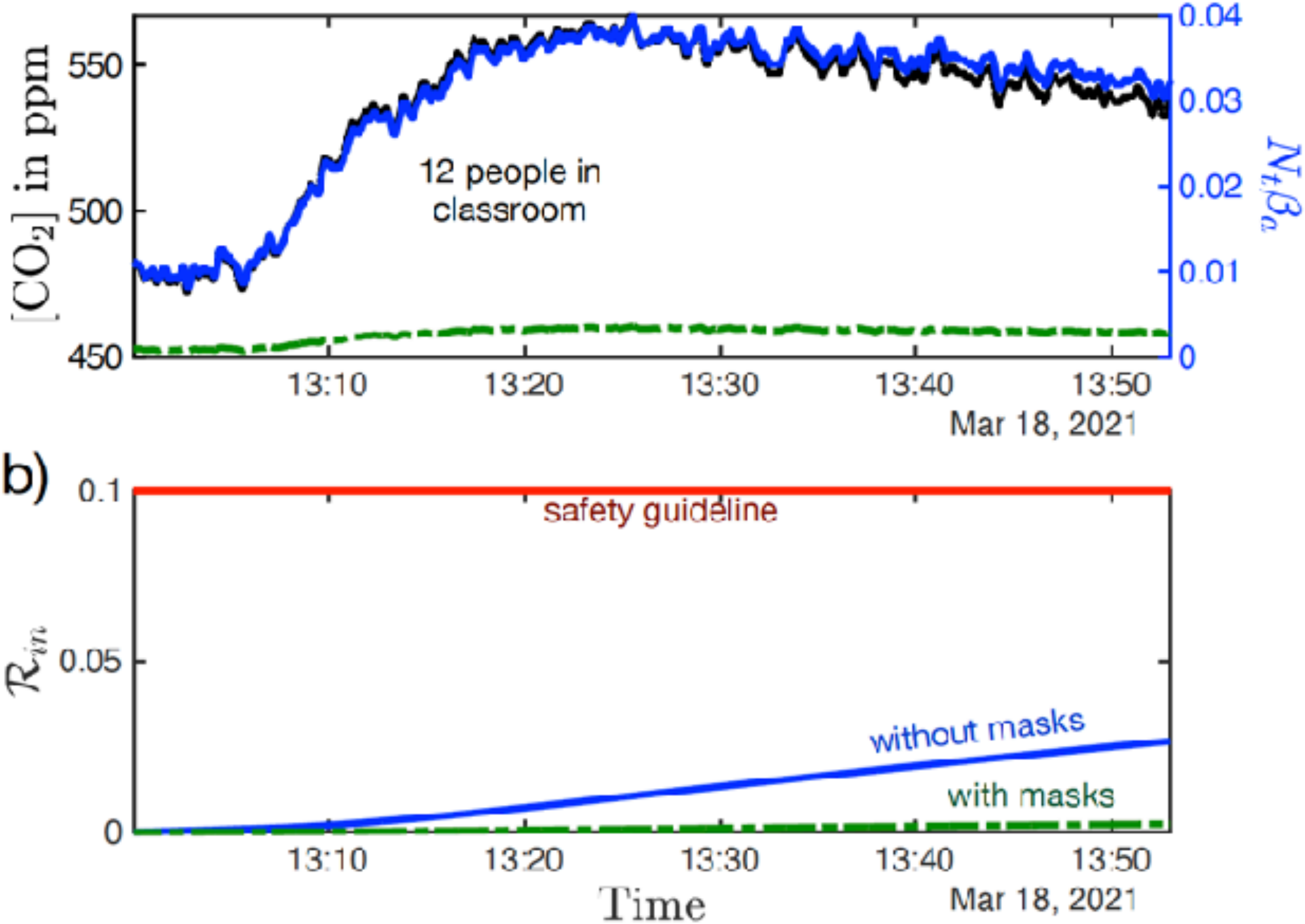
Relaxation curve provides direct measure of decay rate:

$$\lambda_a = Q_a / V$$

Carbon dioxide trace in an office with 2 people



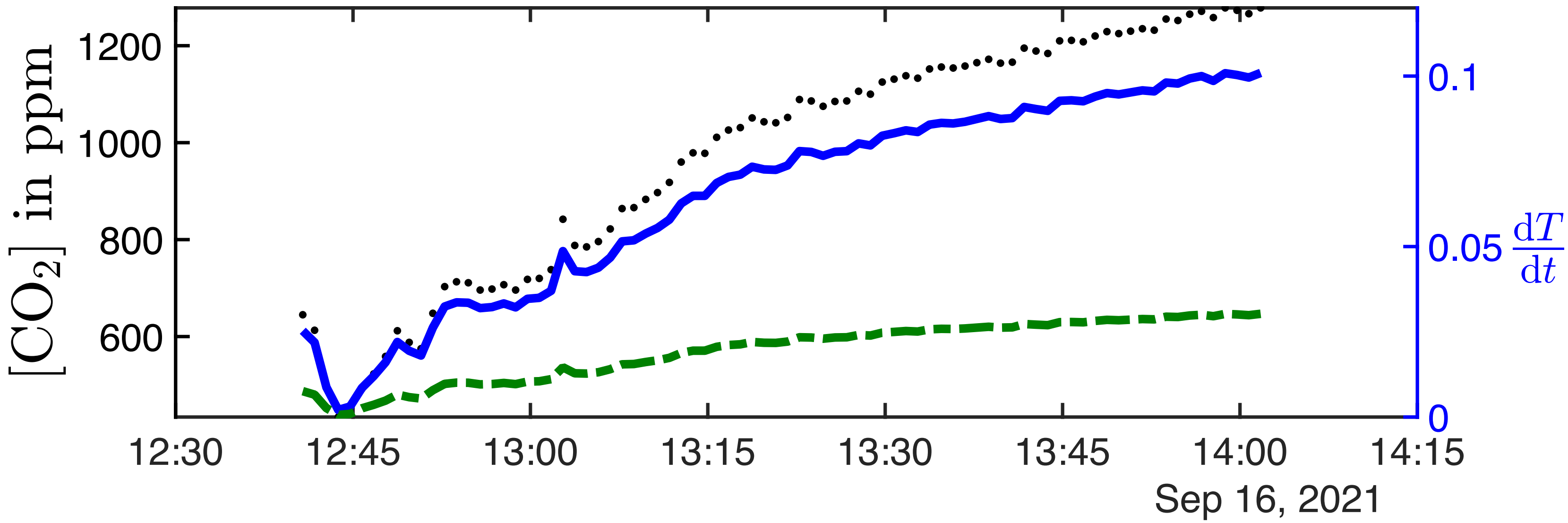
Carbon dioxide trace in a small classroom

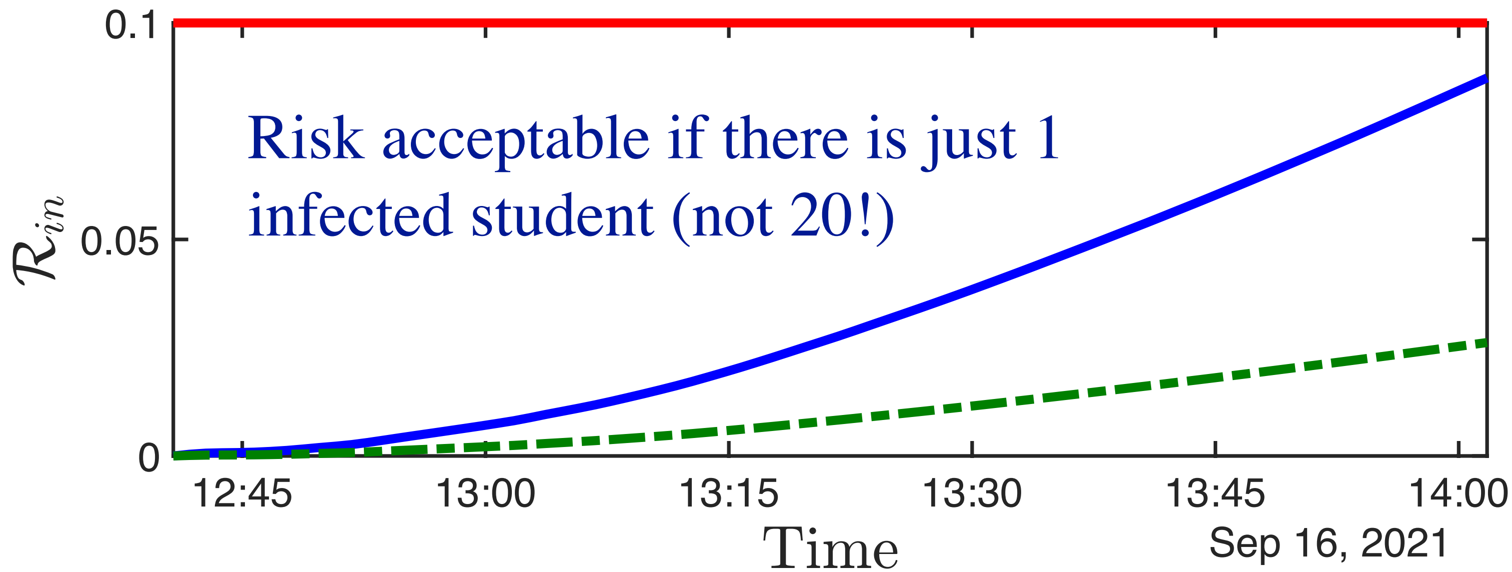


The large classroom where I caught COVID

26-100

300 people

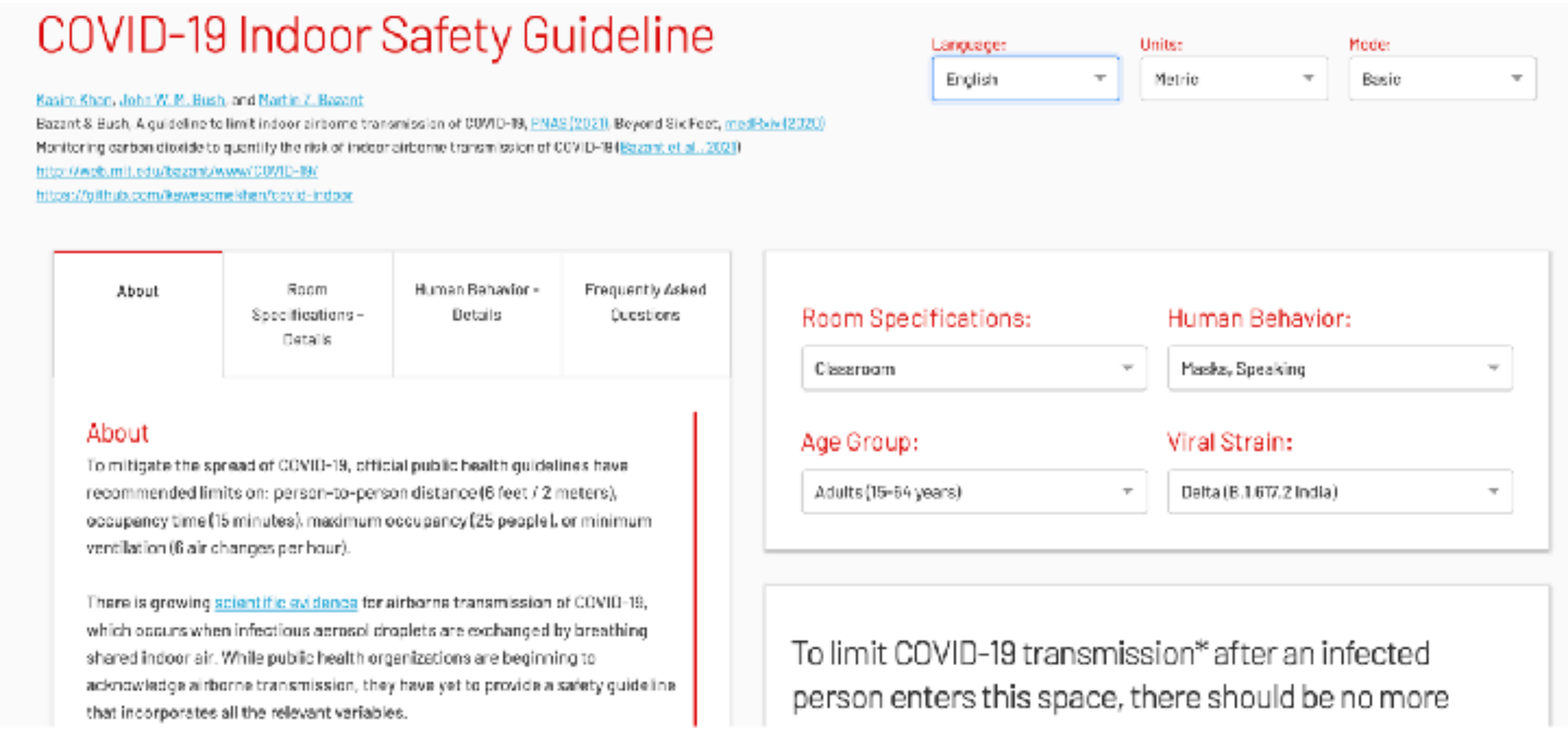




On-line app: developed with Kasim Khan, Martin Bazant

— allows for assessment of COVID risk in any indoor setting

— translated into 15 languages; over 1 million users



Conclusions

- gas-phase respiratory flows (jets, puffs) play a critical role in extending the range of pathogen-bearing droplets
- ambient room circulation may suspend aerosols indefinitely
- inferences from best reported super-spreader events implicate airborne transmission as the dominant mode
- relative importance of short- and long-range airborne transmission must be assessed in a case-by-case basis
- inference of infectivity of SARS-Cov2 suggests it is 10 times higher than that of its precursor, SARS-Cov1
- social-distancing guidelines should be augmented by bounds on time spent in indoor spaces
- using CO_2 as a proxy for airborne pathogen concentration allows for real-time assessment of COVID risk in indoor settings

MEDICAL MISINFORMATION WARNING

YouTube doesn't allow content that spreads medical misinformation that contradicts local health authorities or the WHO about COVID-19 on:

- Prevention
- Transmission
- Social distancing guidelines

Note: YouTube's policies on COVID-19 are subject to change in response to changes to global or local health authorities' guidance.

Scientists “Spreading Medical Misinformation”

The coronavirus pandemic and aerosols: Does COVID-19 transmit via expiratory particles?

Aerosol Sci Tech, 4/3/2020

Sima Asadi, Nicole Bouvier, Anthony S. Wexler & William D. Ristenpart

Airborne transmission of SARS-CoV-2: The world should face the reality

Environment International, 4/10/2020

Lidia Morawska[a,*], Junji Cao[b]

239 Experts With One Big Claim: The Coronavirus Is Airborne

The W.H.O. has resisted mounting evidence that viral particles floating indoors are infectious, some scientists say. The agency maintains the research is still inconclusive.

New York Times, 7/12/020

CDC reverses itself and says guidelines it posted on coronavirus airborne transmission were wrong

Agency removes statement, claiming website error *Washington Post, 9/21/2020*

Can “local health authorities” *themselves* unwittingly spread medical misinformation?

Coronavirus can be transmitted through the air, CDC confirms *Washington Post, 10/5/2020*

The virus is an airborne threat, the C.D.C. acknowledges. *New York Times, 5/7/2021*

EDITORIAL | ONLINE FIRST

COVID-19 transmission—up in the air

The Lancet Respiratory Medicine

Published: October 29, 2020 · DOI: https://doi.org/10.1016/S2213-2600(20)30514-2

“Public health guidance now needs to advise people how to navigate risk in indoor settings”...


WSJ | OPINION
LOCKDOWNS DIDN'T STOP COVID
May 9, 2021
The INDEPENDENT
CLOTH MASKS ARE USELESS IN FIGHT AGAINST OMICRON, EXPERT WARNS
December 22, 2021
CNBC
MIT RESEARCHERS SAY TIME SPENT INDOORS INCREASES RISK OF COVID AT 6 FEET OR 60 FEET IN NEW STUDY CHALLENGING SOCIAL DISTANCING POLICIES
April 23, 2021
FOX NEWS channel
DRACONIAN COVID RESTRICTIONS RUINED LIVES
THE NEXT REVOLUTION w/ STEVE HILTON
JESSE WATTERS PRIMETIME
STARTING TOMORROW 7PM ET

Thanks for your attention!

For more information, please see my webpage…

``Do not use the fire that God gave you to burn incense.”

— Edmond Rostand