

Transmission of
Viruses in Droplets
and Aerosols

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VIRGINIA TECH*

26 MARCH 2020



Topics

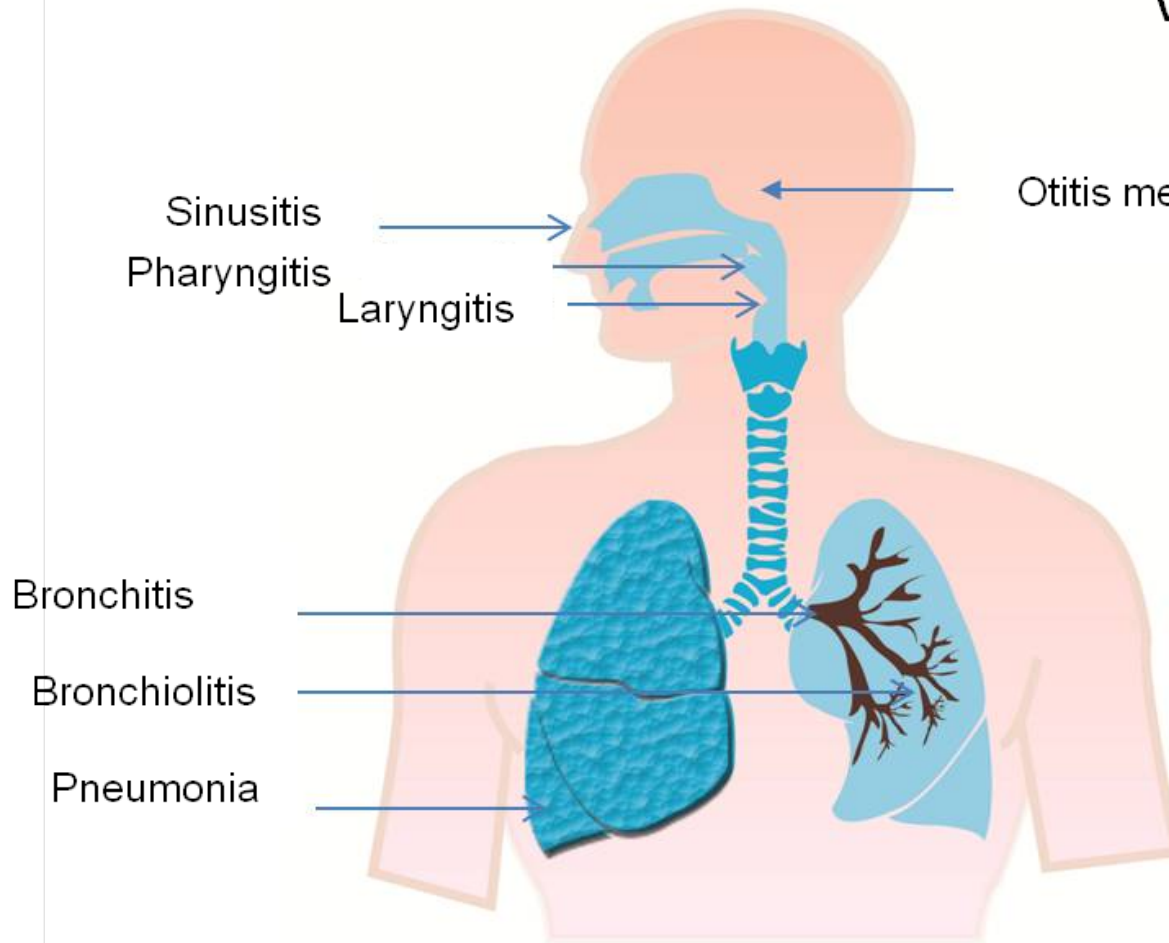
1. Respiratory viruses
2. Transmission modes
3. Size distributions and evaporation
4. Virus aerosol dynamics
5. Impact of temperature and humidity
6. Masks
7. SARS-CoV-2

Viruses that infect the upper respiratory tract

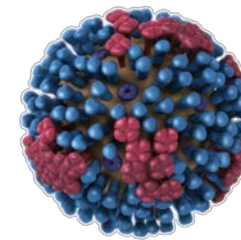
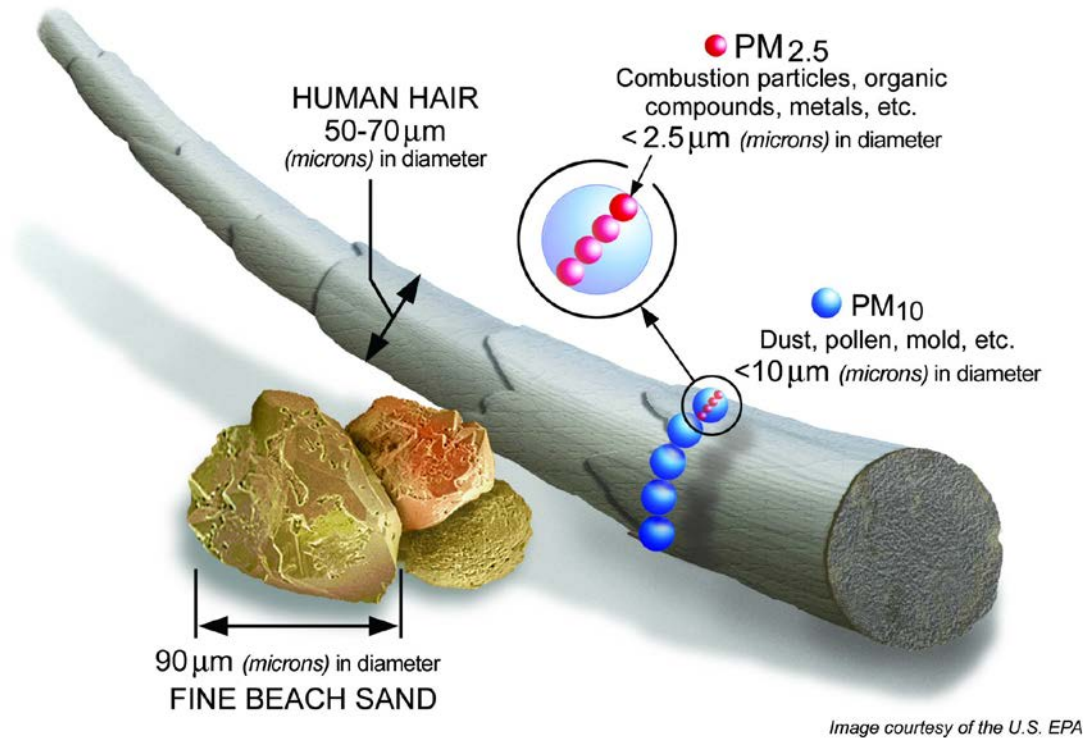
Rhinovirus
Coronavirus
Influenza virus
Parainfluenza virus
Respiratory Syncytial virus
Herpesvirus
Adenovirus
Bocavirus
Coxsackivirus

Viruses that infect the lower respiratory tract

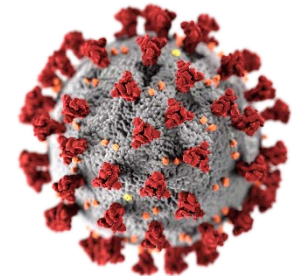
Influenza virus
Parainfluenza virus
Respiratory Syncytial virus
Adenovirus
Bocavirus
Metapneumovirus



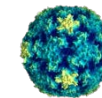
Virus Size



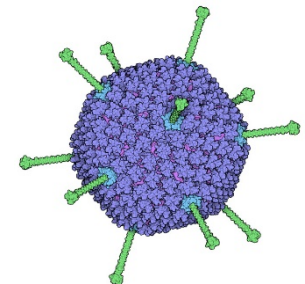
influenza
0.1 μm



SARS-CoV-2
0.12 μm



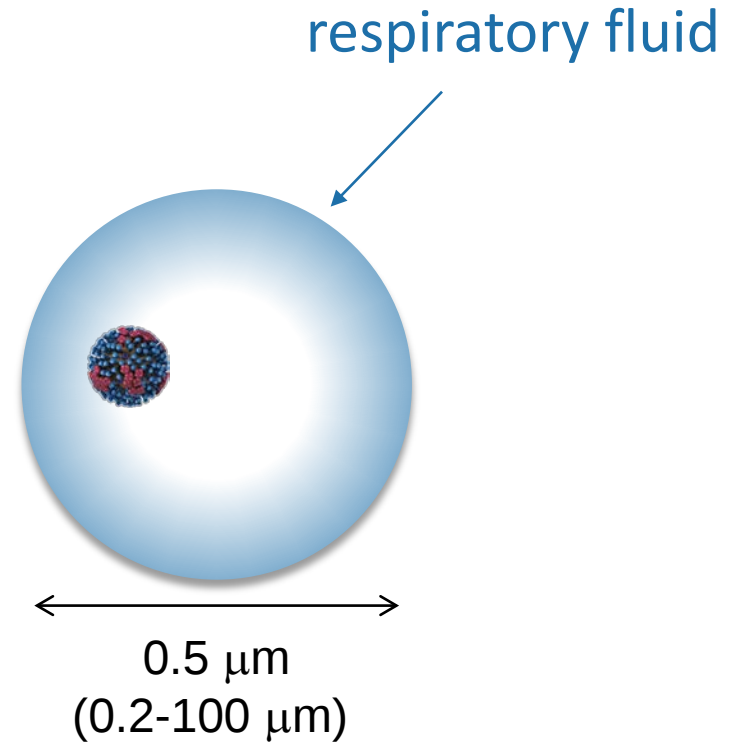
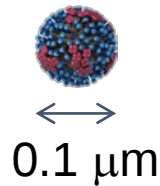
rhinovirus
0.03 μm



adenovirus
0.1 μm

Size Matters

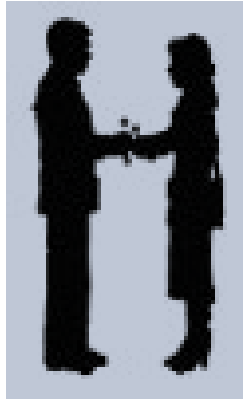
- Airborne virus is not naked!



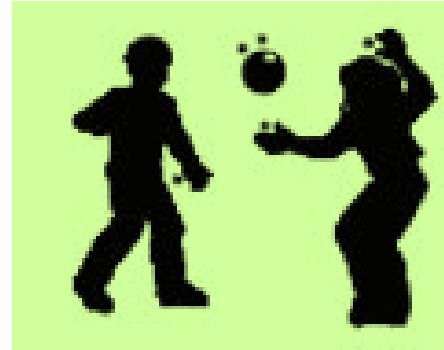
- Size determines
 - Lifetime in the atmosphere
 - Where it deposits in the respiratory system



Modes of Transmission

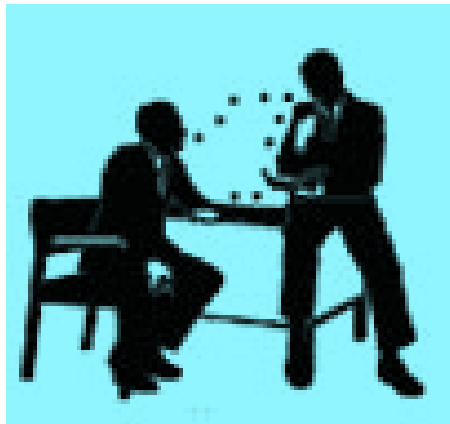


direct contact

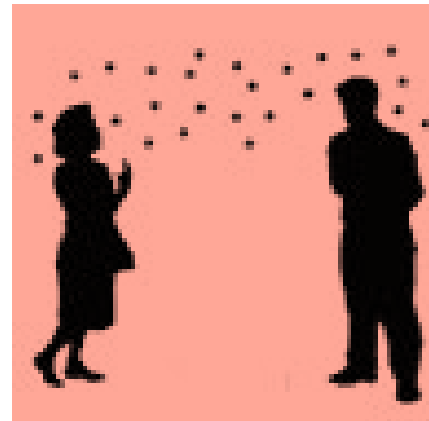


indirect contact

Defined as $>5 \mu\text{m}$
and happening at
close-range only
($<2 \text{ m}$)



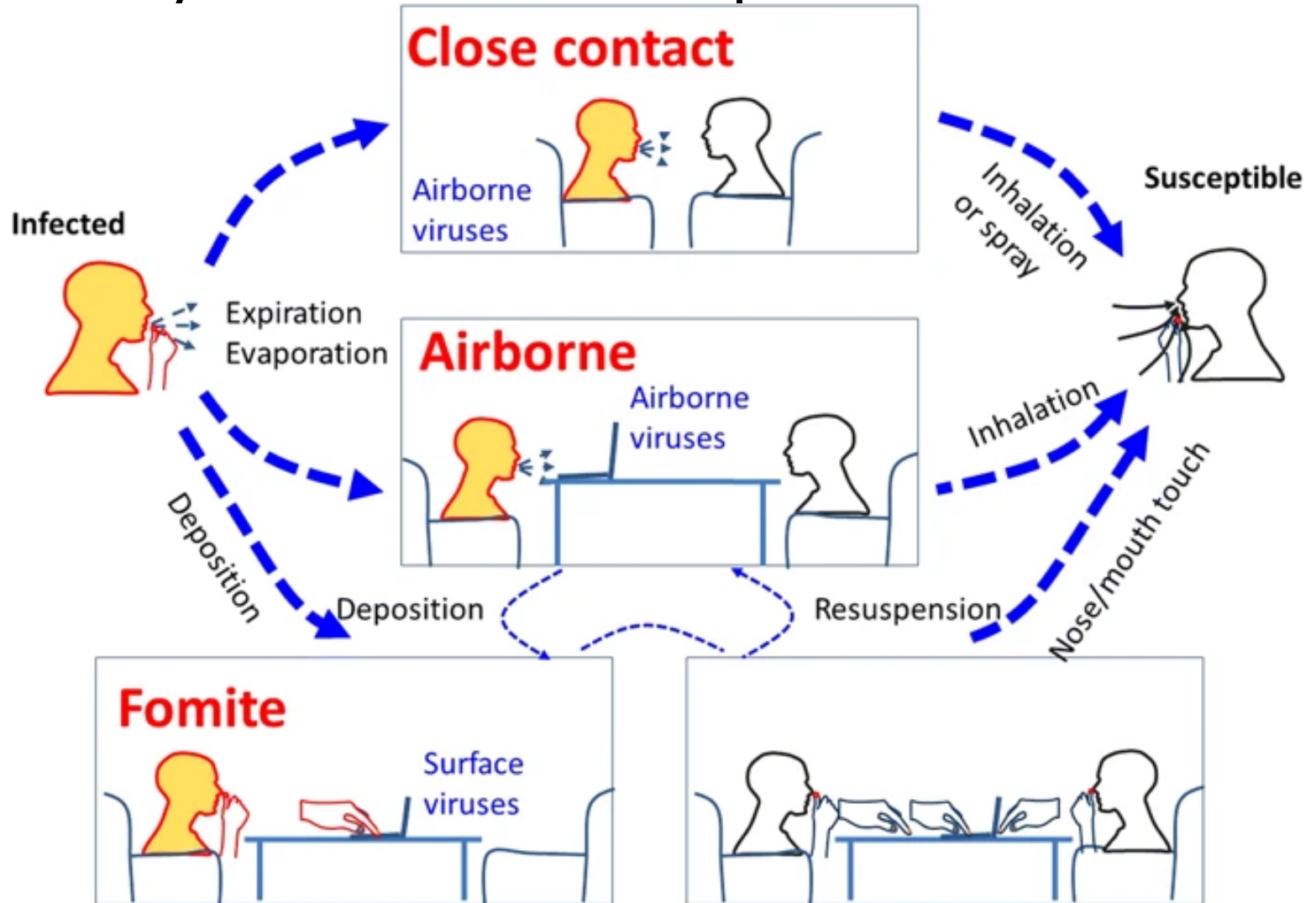
large droplets



Defined as $<5 \mu\text{m}$
and happening
mainly at long-
range ($>2 \text{ m}$)

aerosols

Reality is More Complicated

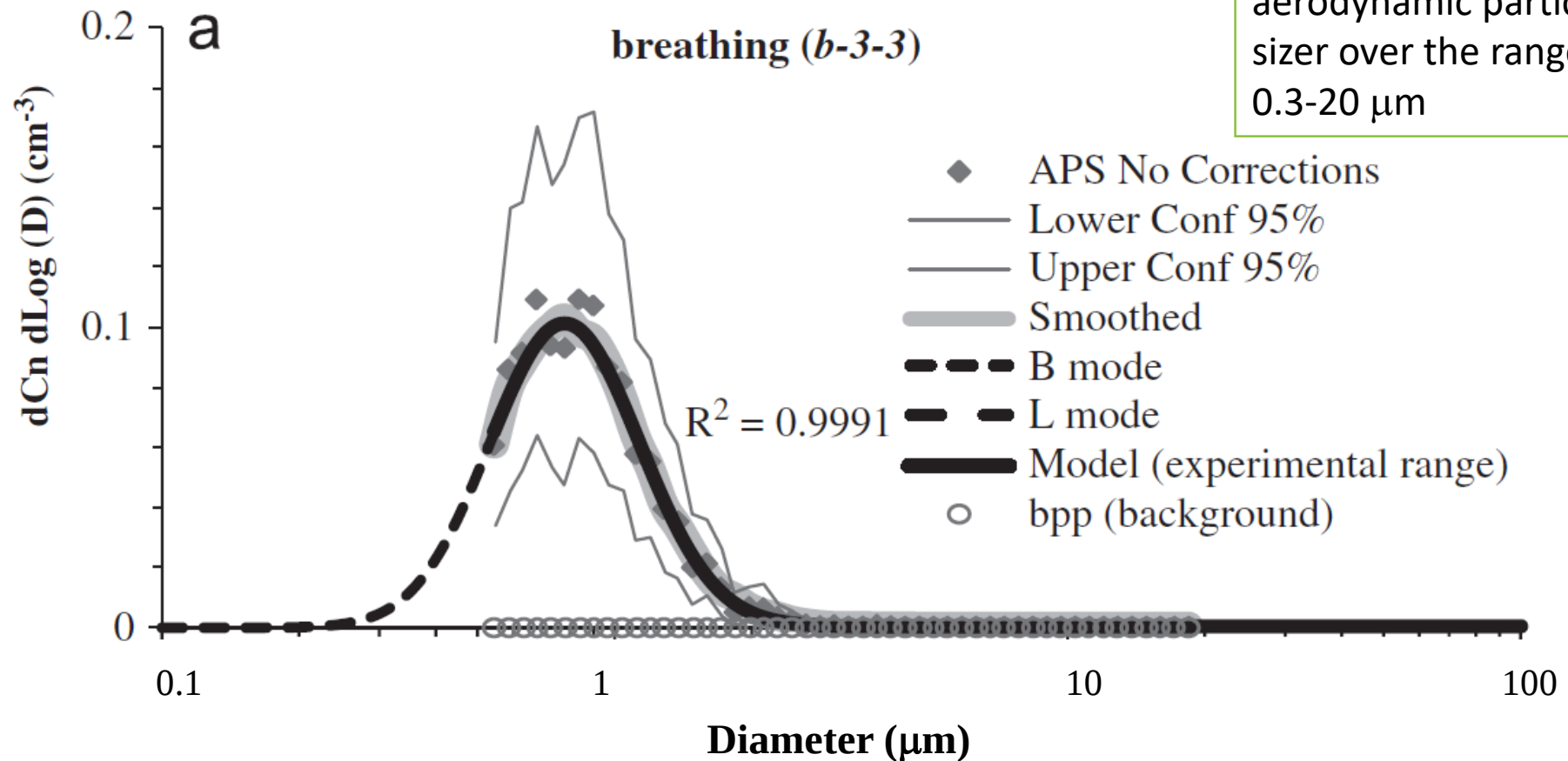


Droplets that are expelled into air can be inhaled, land on people's mucus membranes, or deposit onto surfaces, where someone can touch them or they can be resuspended into air.

What size are these droplets?

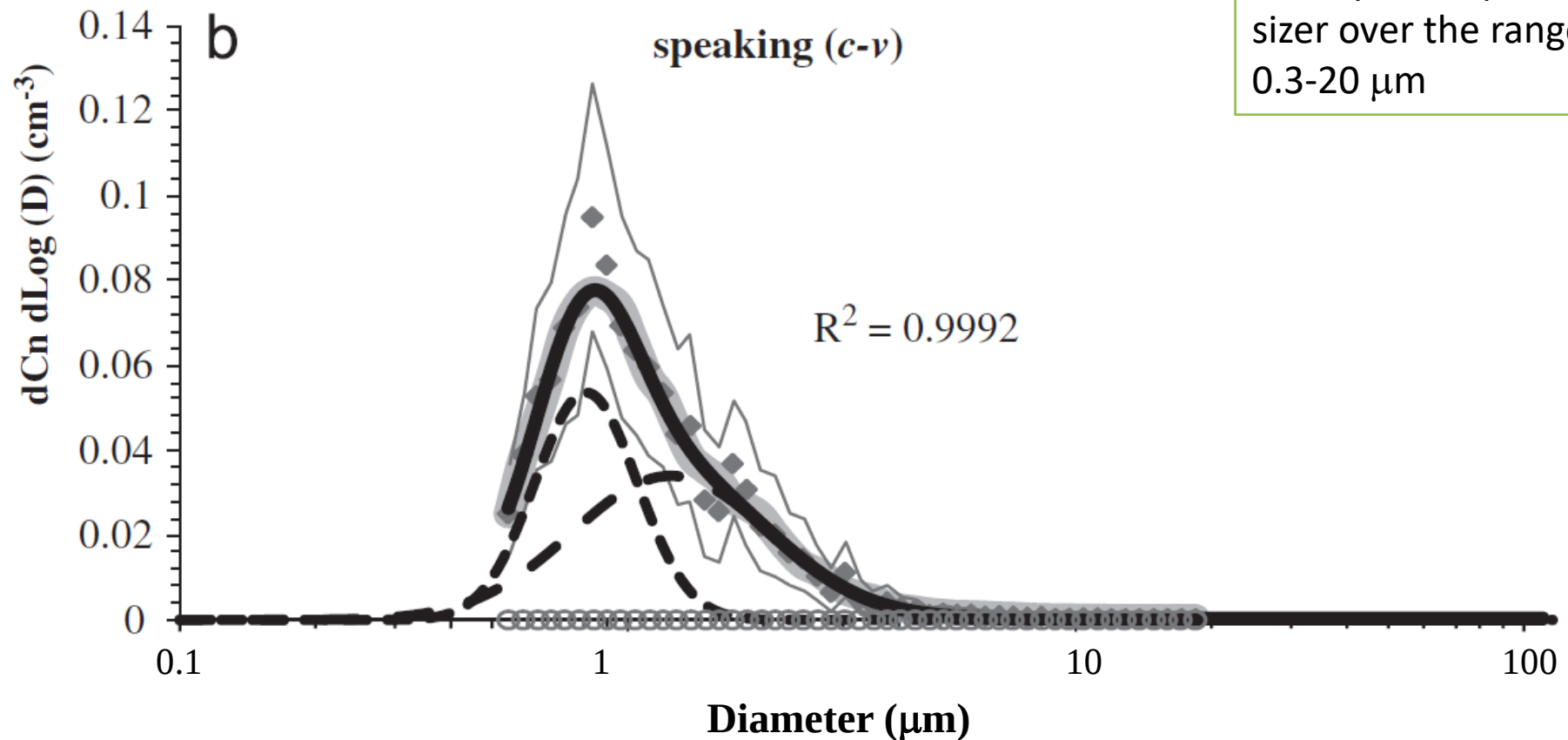
Size Distributions: Breathing

Measured by
aerodynamic particle
sizer over the range
0.3-20 μm



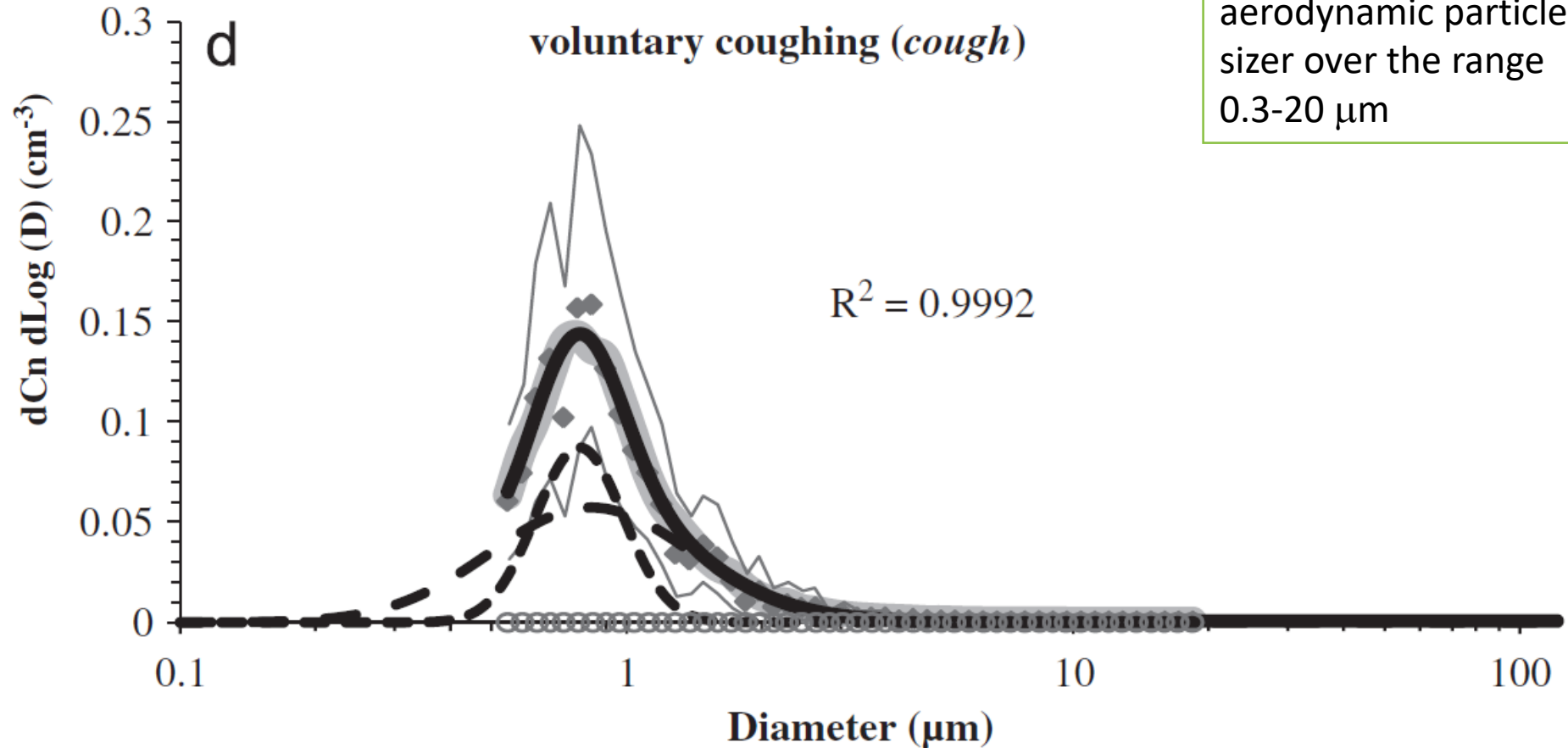
Size Distributions: Speaking

Measured by
aerodynamic particle
sizer over the range
0.3-20 μm



Size Distributions: Coughing

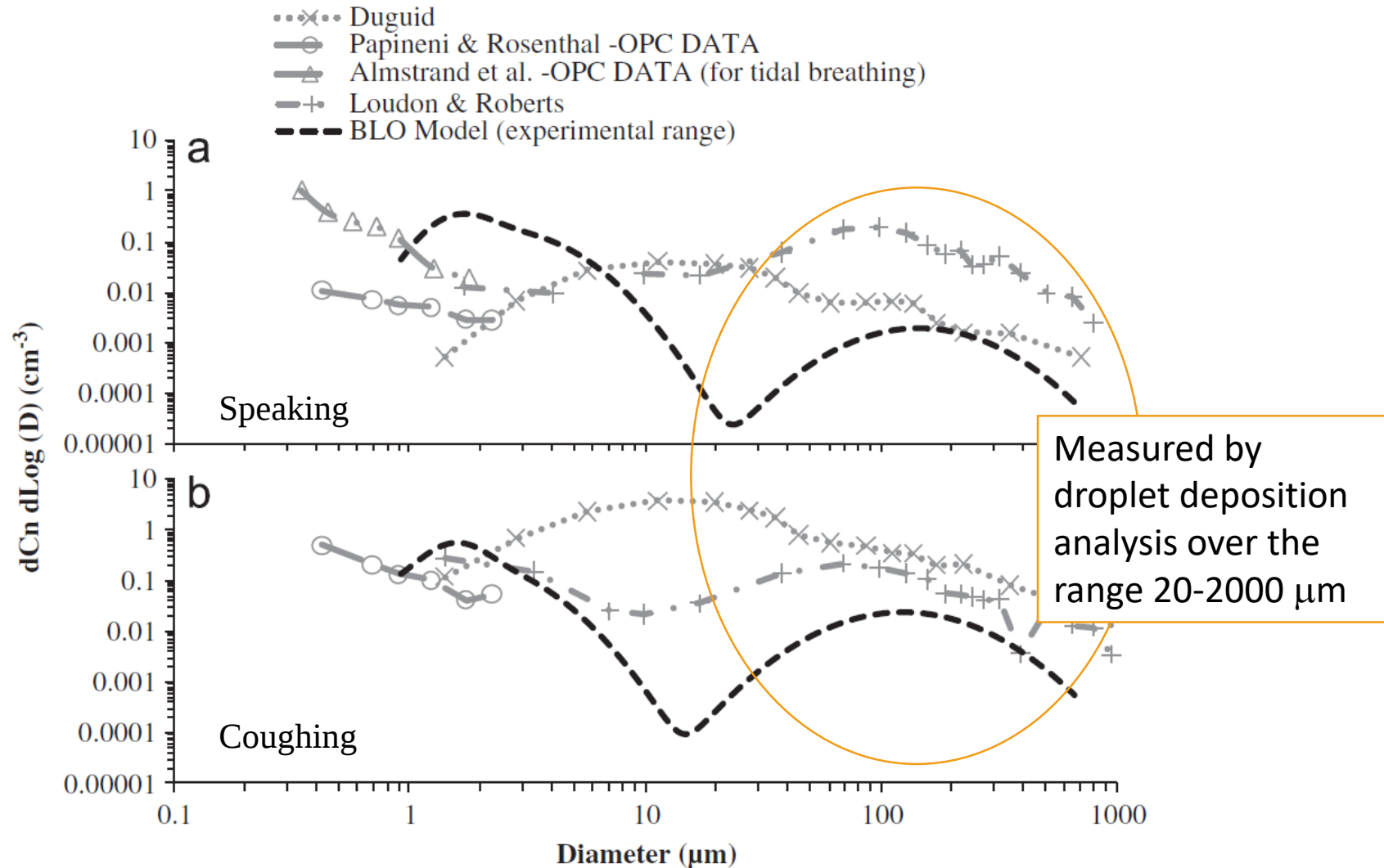
Measured by
aerodynamic particle
sizer over the range
0.3-20 μm





Corrected Size Distributions

Inferred number concentration in upper respiratory tract



Breathing, talking, and coughing release droplets that range from submicron to millimeter in size.

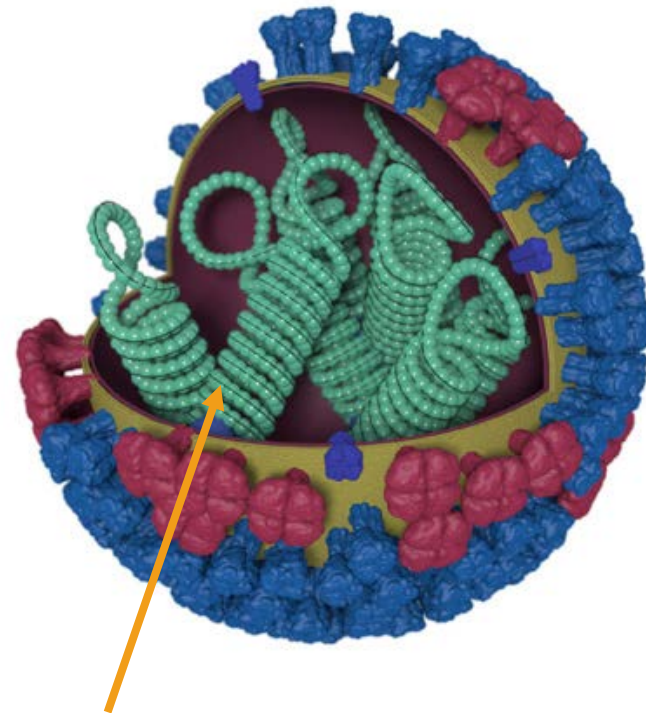
What size droplets carry viruses?

Virus Detection Methods

1. Total virus

- Number of genome copies (GC) determined by molecular techniques (quantitative polymerase chain reaction, qPCR)
- Reflects number of viruses with intact DNA or RNA
- Does NOT indicate whether virus is infectious or not

AN INFLUENZA VIRUS

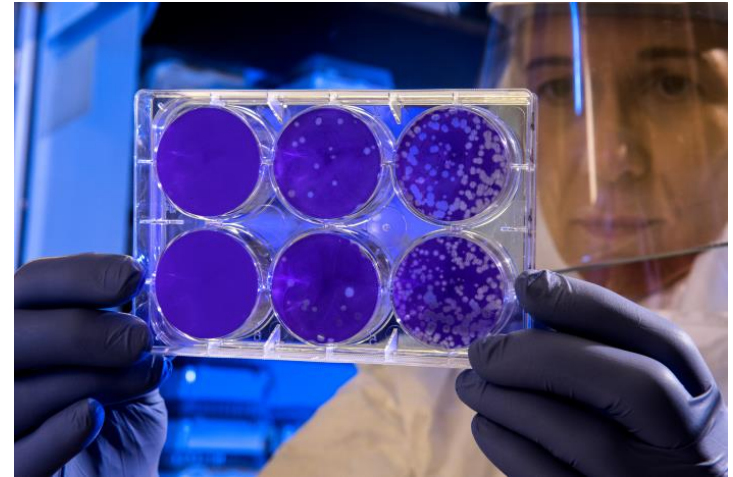


RNA is wrapped around
the ribonucleoprotein

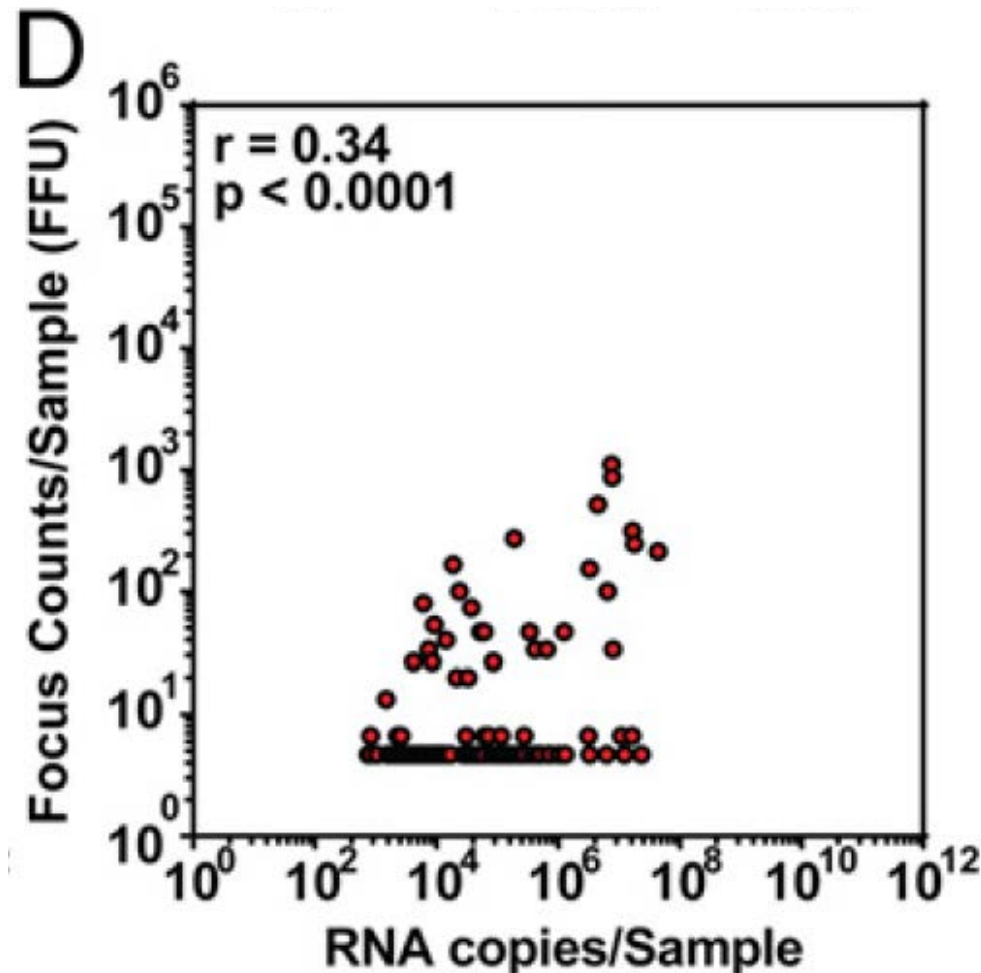
Virus Detection Methods

2. Infectious virus

- Number of viruses that are able to infect cells determined by culture (growing)
- PFU = plaque forming units, number of viruses capable of forming plaques on host cells, focus forming units (FFU) are related
- TCID₅₀ = median tissue culture infectious dose, concentration at which half of cells are infected after being exposed to the sample



Relationship Between the Two Methods for Flu Virus



There is a weak, but significant, correlation between virus RNA copies and infectious virus.

Amount of Flu Virus in Coarse vs. Fine Droplets (Particles) in Exhaled Breath

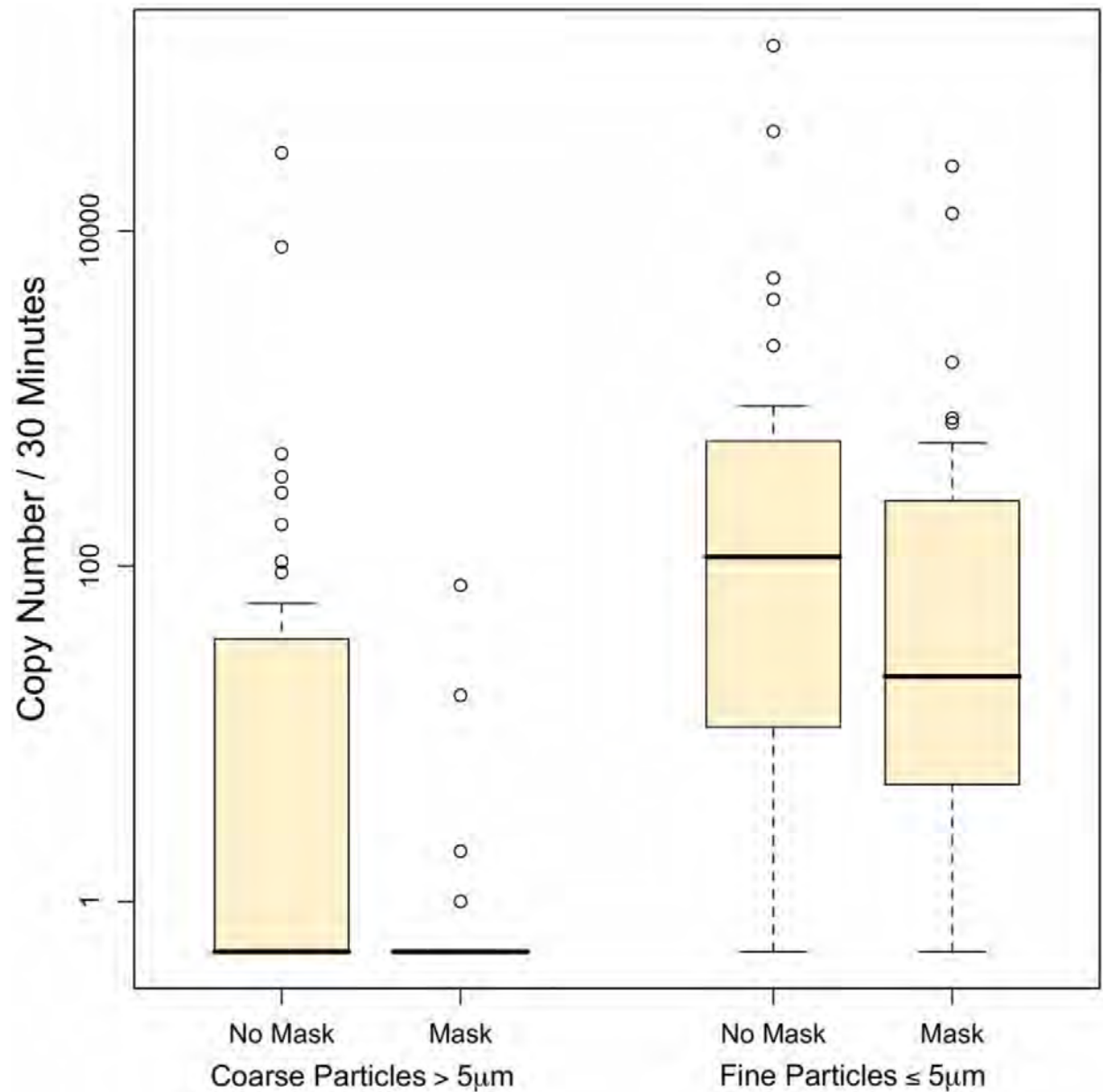
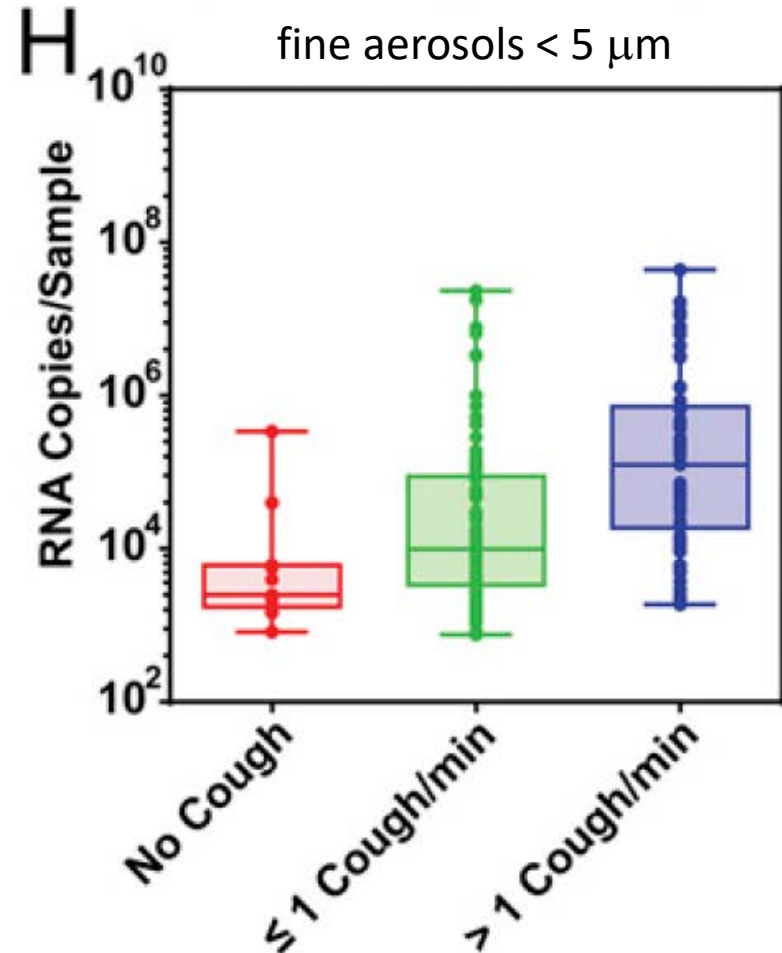
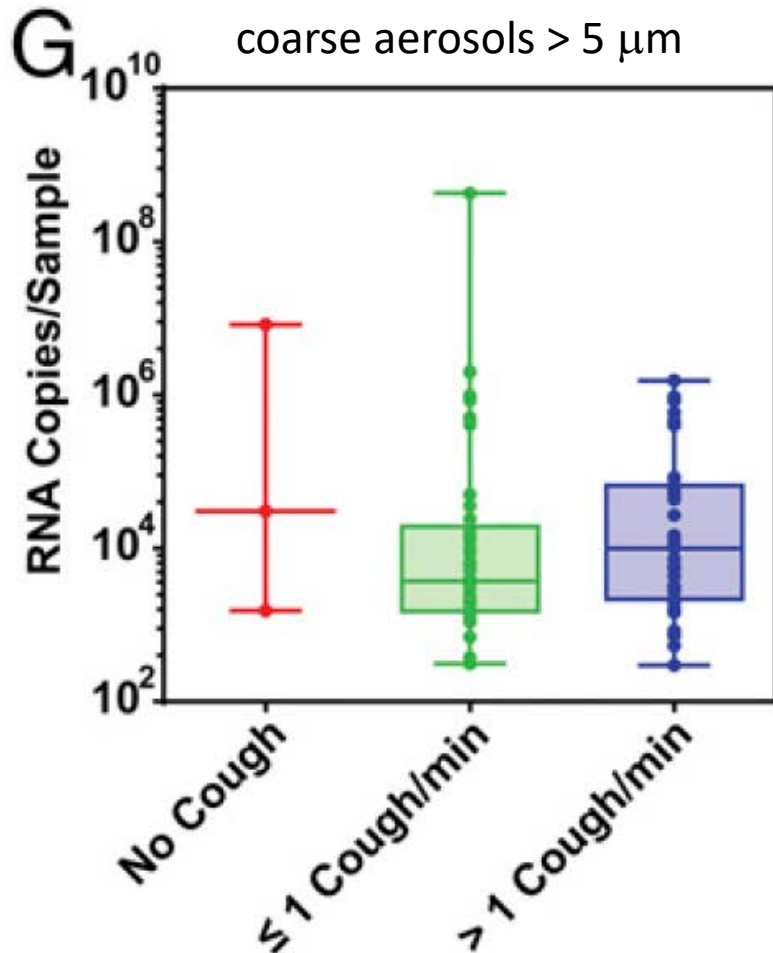


Figure 1. Influenza virus copy number in aerosol particles exhaled by patients with and without wearing of an ear-loop surgical mask. Counts below the limit of detection are represented as 0.5 on the log scale.
doi:10.1371/journal.ppat.1003205.g001

Flu Virus in Droplets (Aerosols)

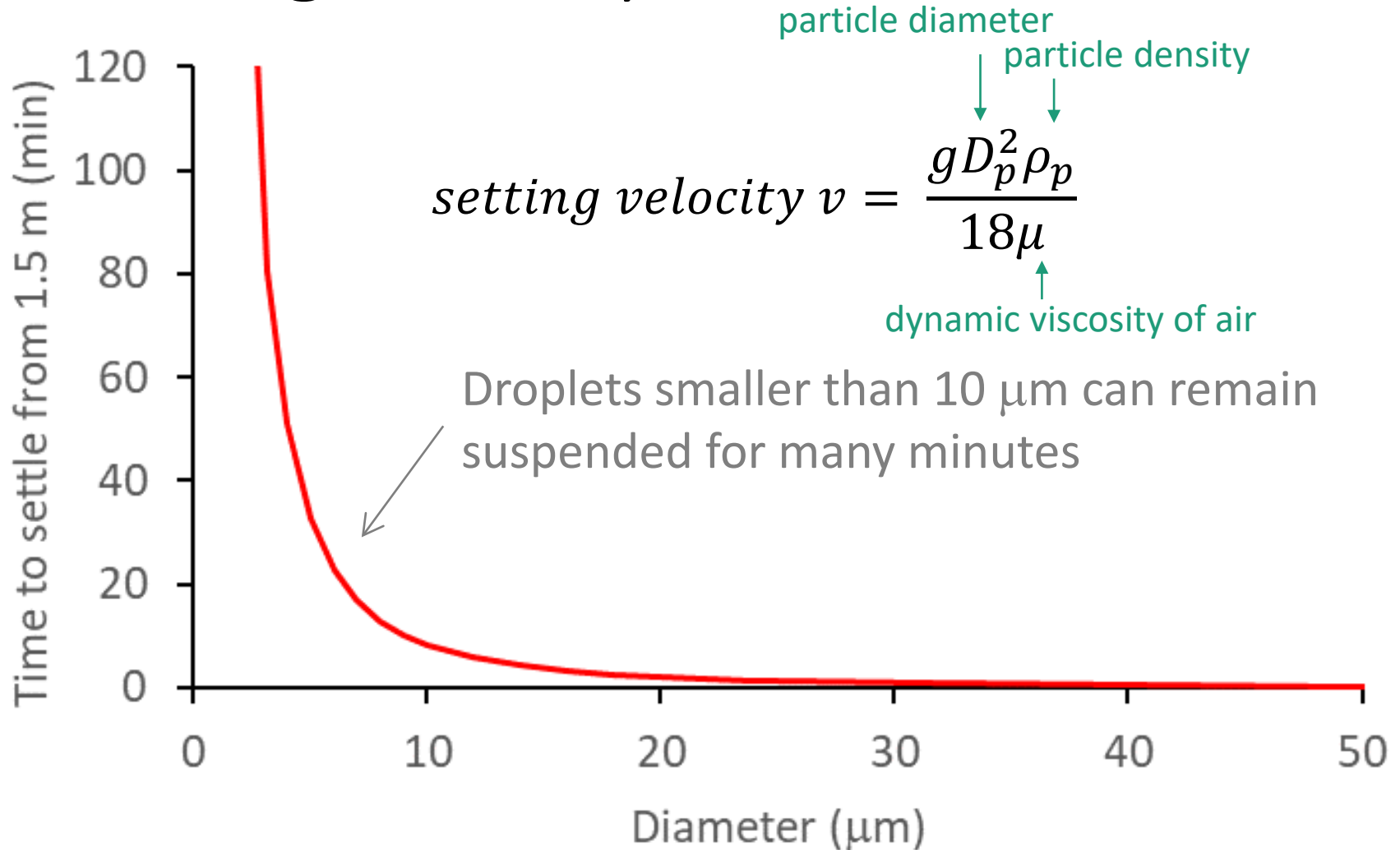


30-min sample
recite alphabet at 5, 15, 25 min

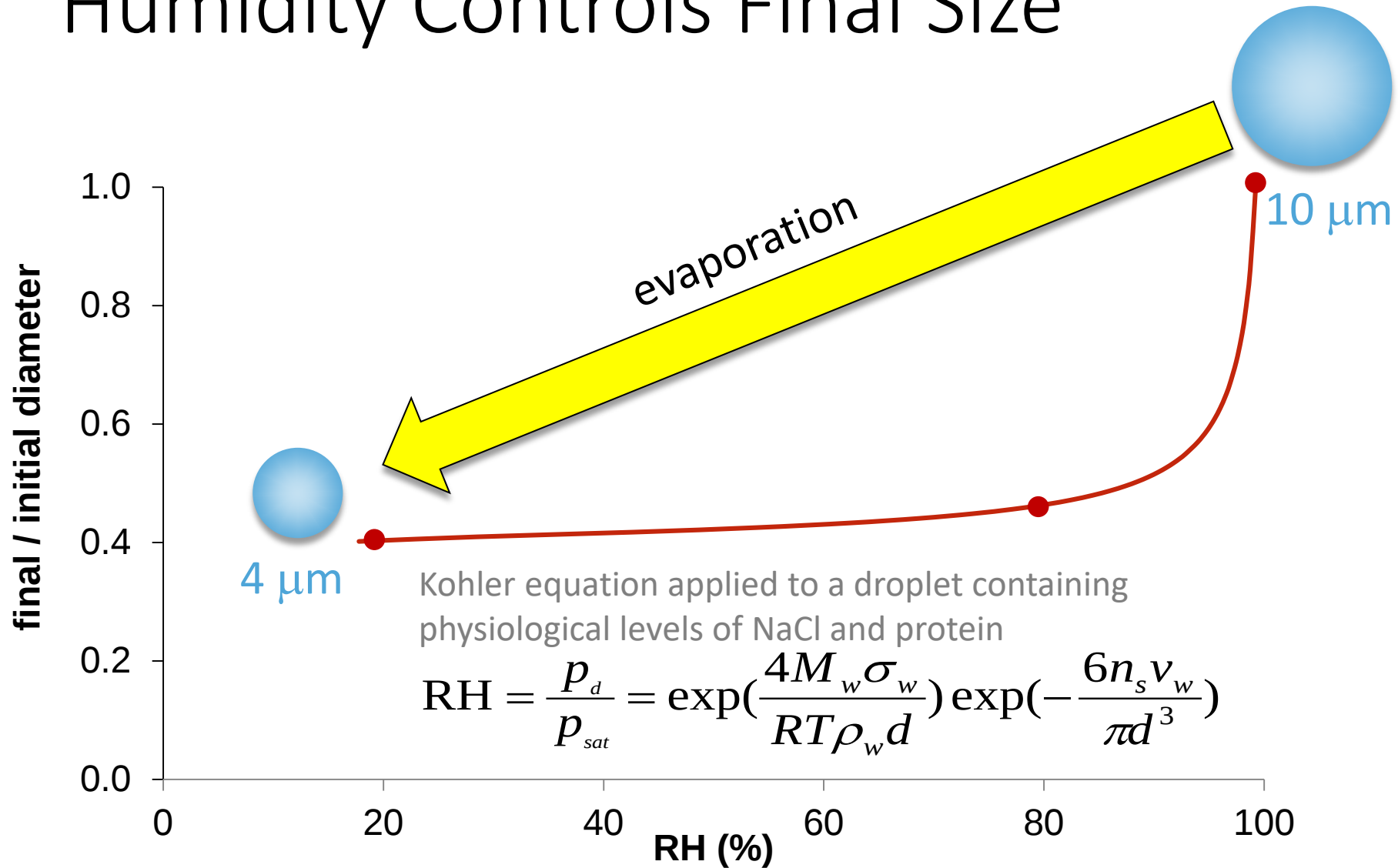
The majority of flu virus (RNA copies) is found in fine ($<5\ \mu\text{m}$), rather than coarse ($>5\ \mu\text{m}$), droplets/aerosols.

How do these droplets move around the indoor environment?

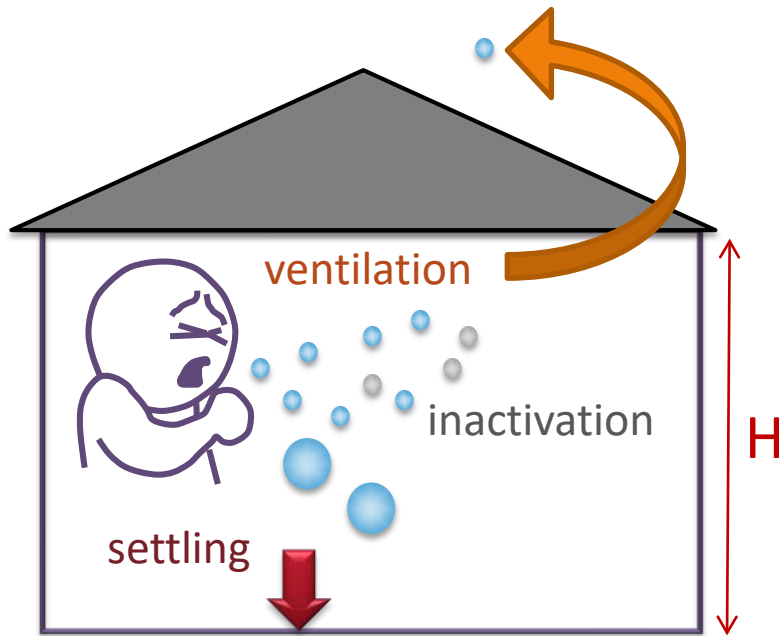
Settling Velocity and Time



Humidity Controls Final Size



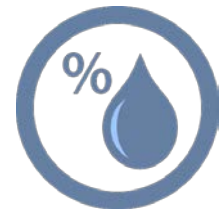
Virus Dynamics in Indoor Air



$$\frac{dC_d}{dt} = -\left(\frac{v}{H} + \lambda + k\right)C_d$$

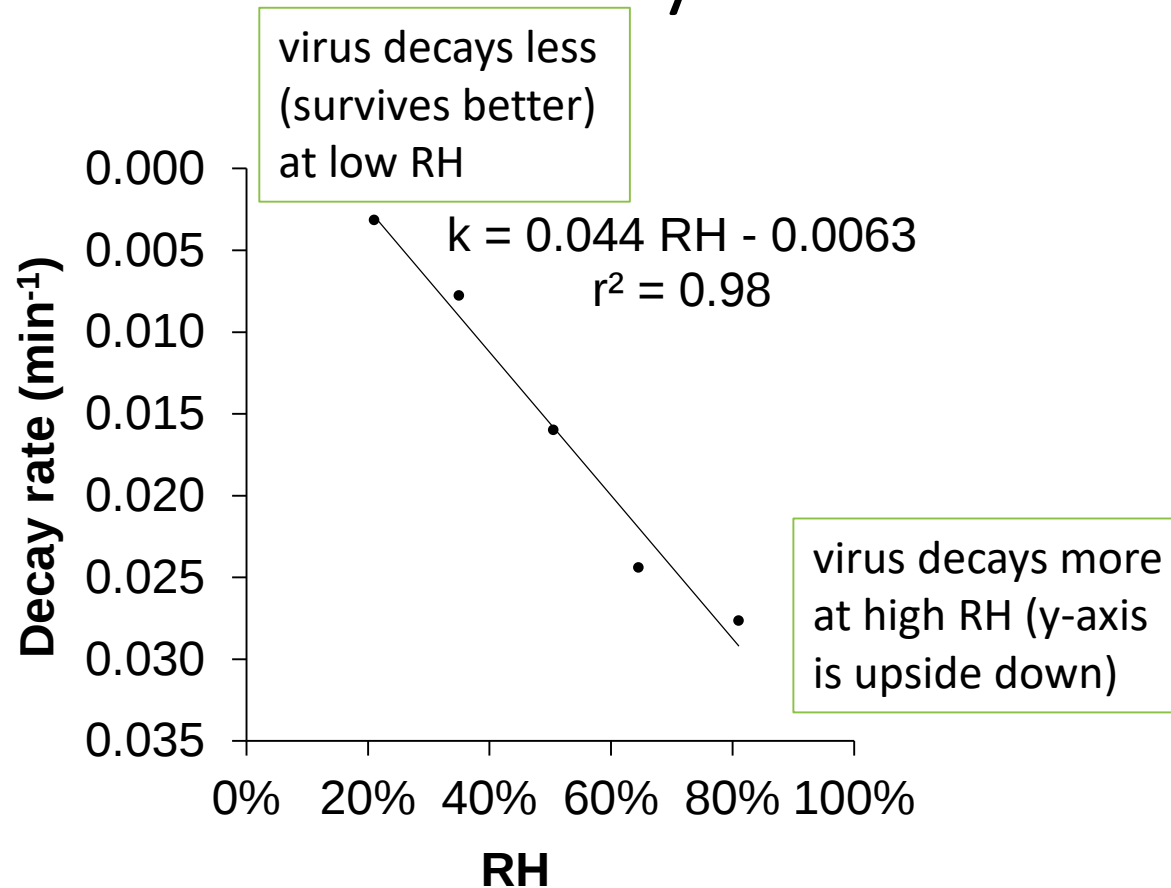
concentration of
infectious virus in
aerosols of diameter d

- Settling velocity v depends on diameter d
- Diameter depends on RH
- Inactivation rate k depends on RH



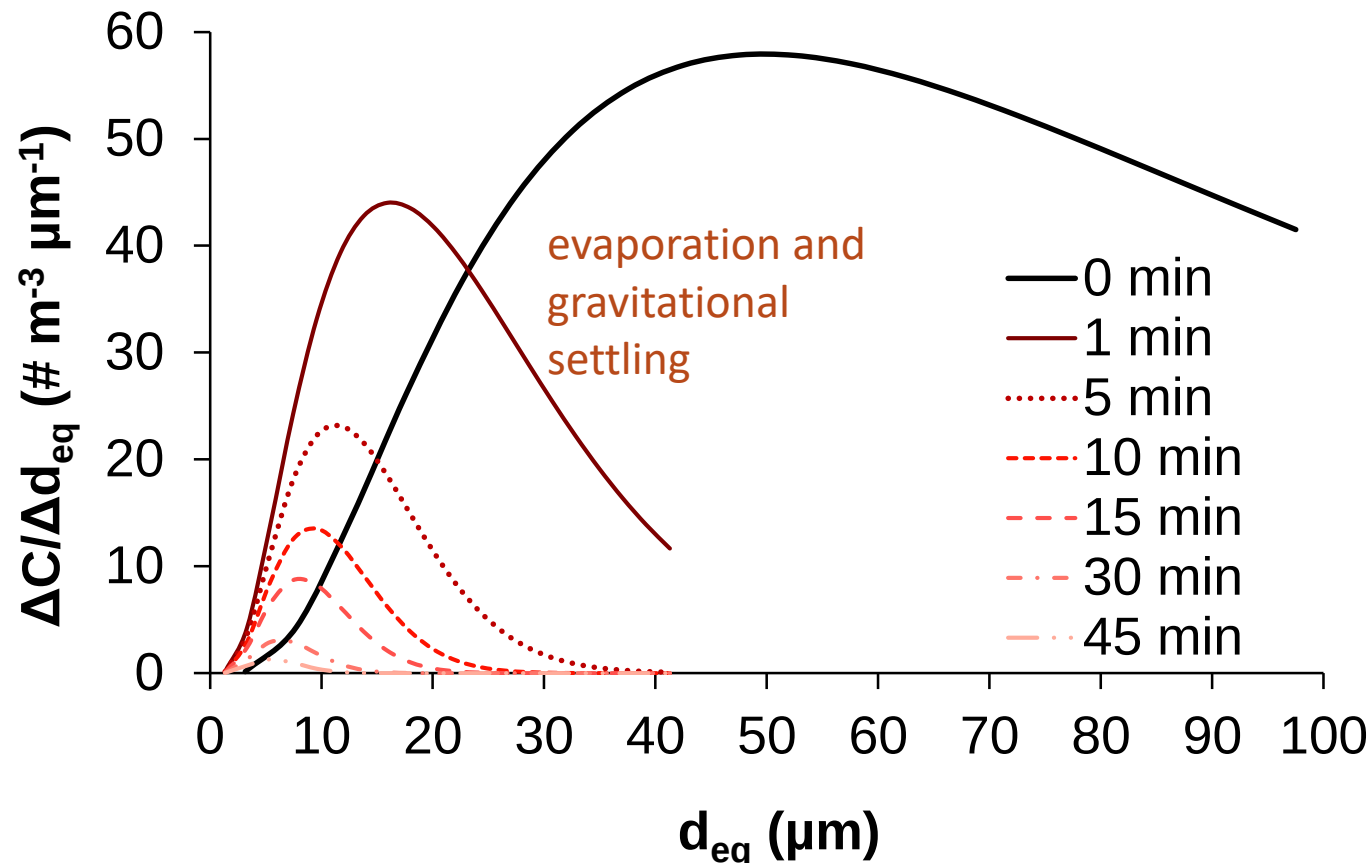
relative humidity (RH)

Virus Viability vs. RH



Virus-Aerosols From a Cough

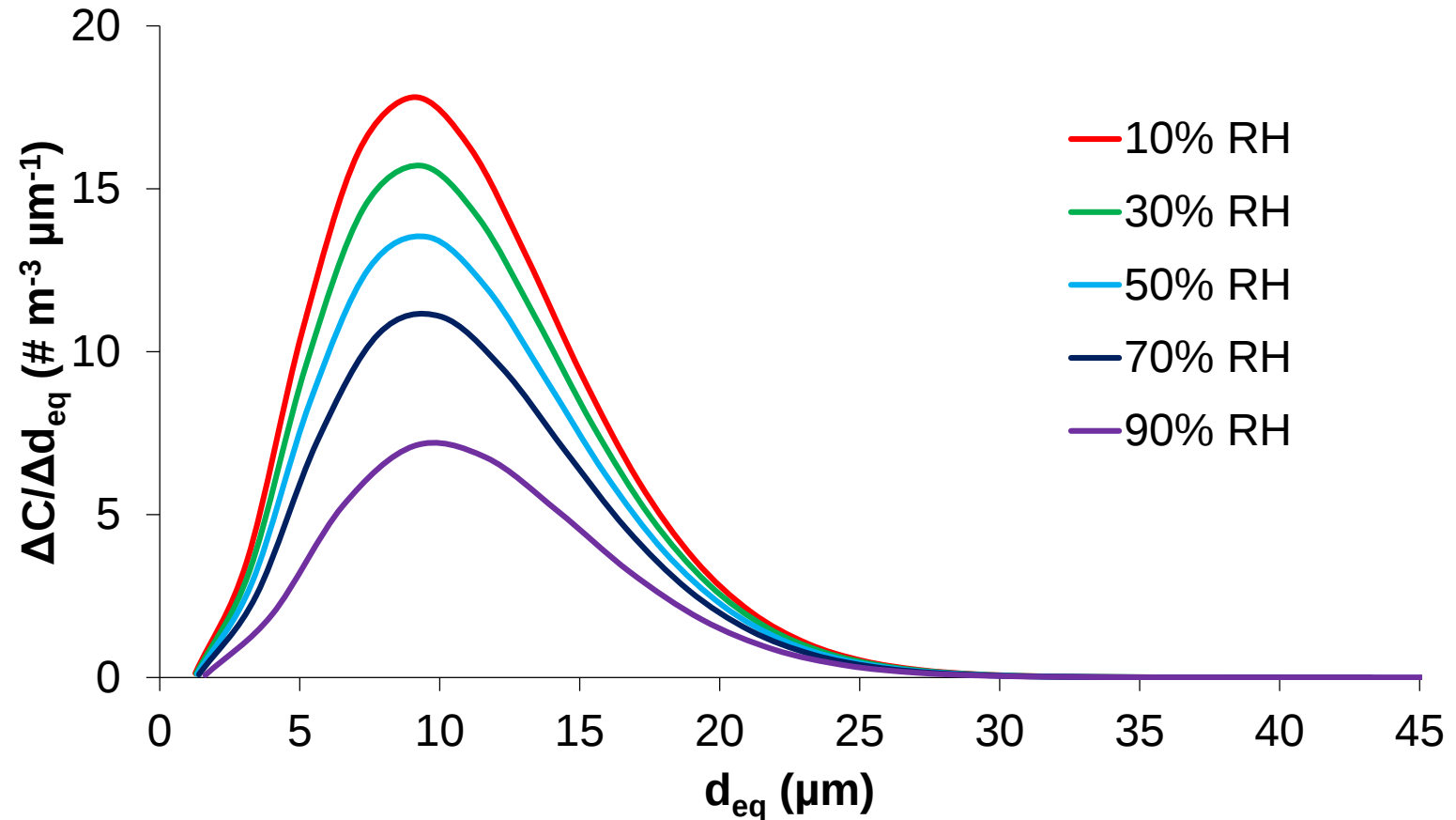
$\lambda = 1$ ACH at RH = 50%



There is a size shift due to loss of larger droplets by gravitational settling.

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Infectious Concentrations vs. RH

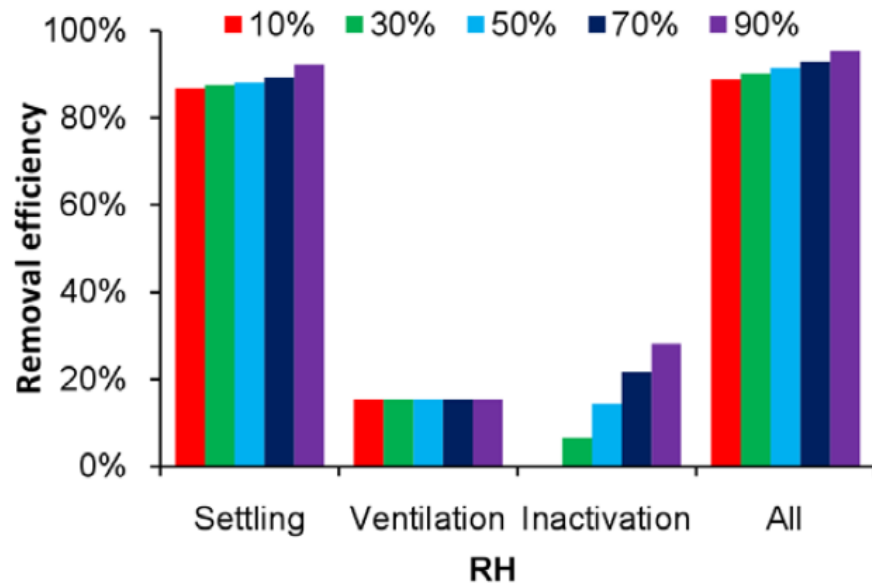


Concentrations are higher at lower RH mainly because lab-determined inactivation rate is lower.

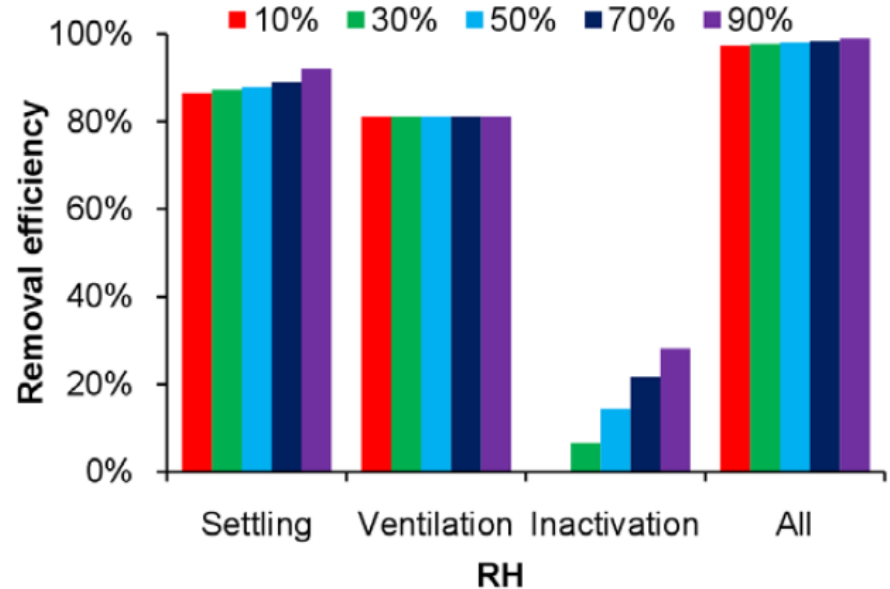
RH and Removal Mechanisms

- Settling: main removal mechanism, efficient for large but not small droplets
- Ventilation: effective for all sizes, important in public places
- Inactivation: effective for all sizes, important for small droplets

A $\lambda = 1$ ACH



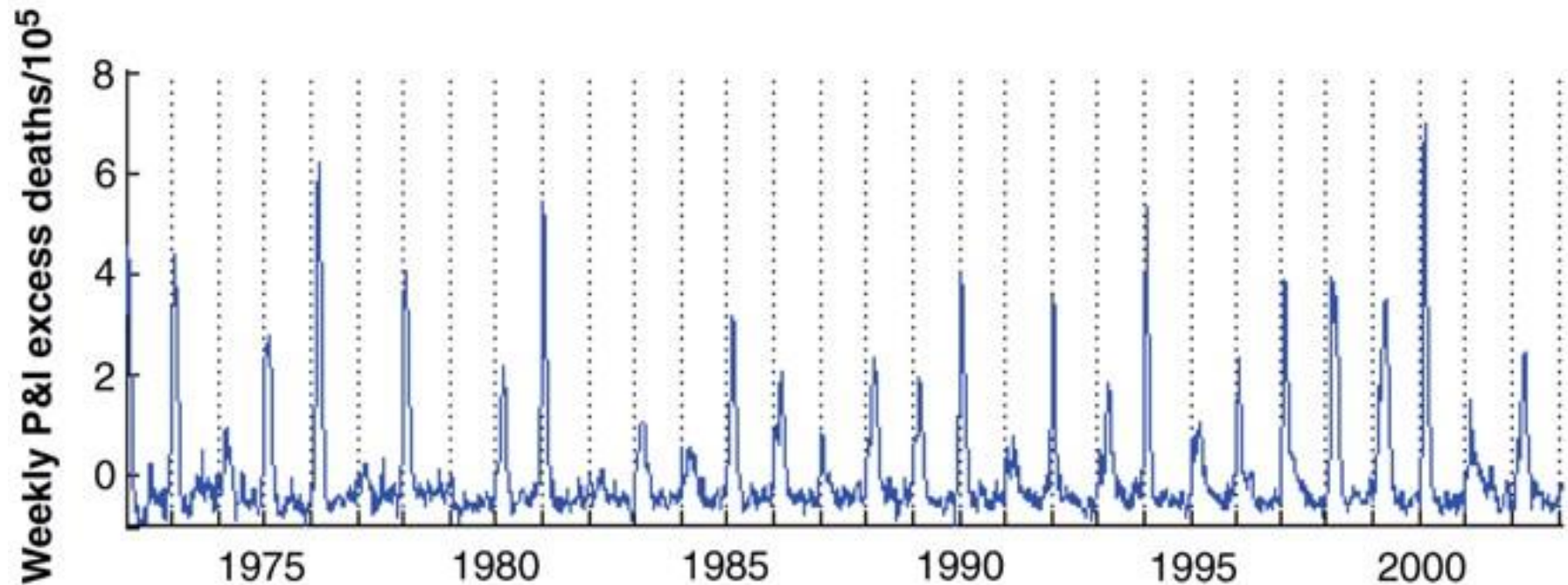
B $\lambda = 10$ ACH

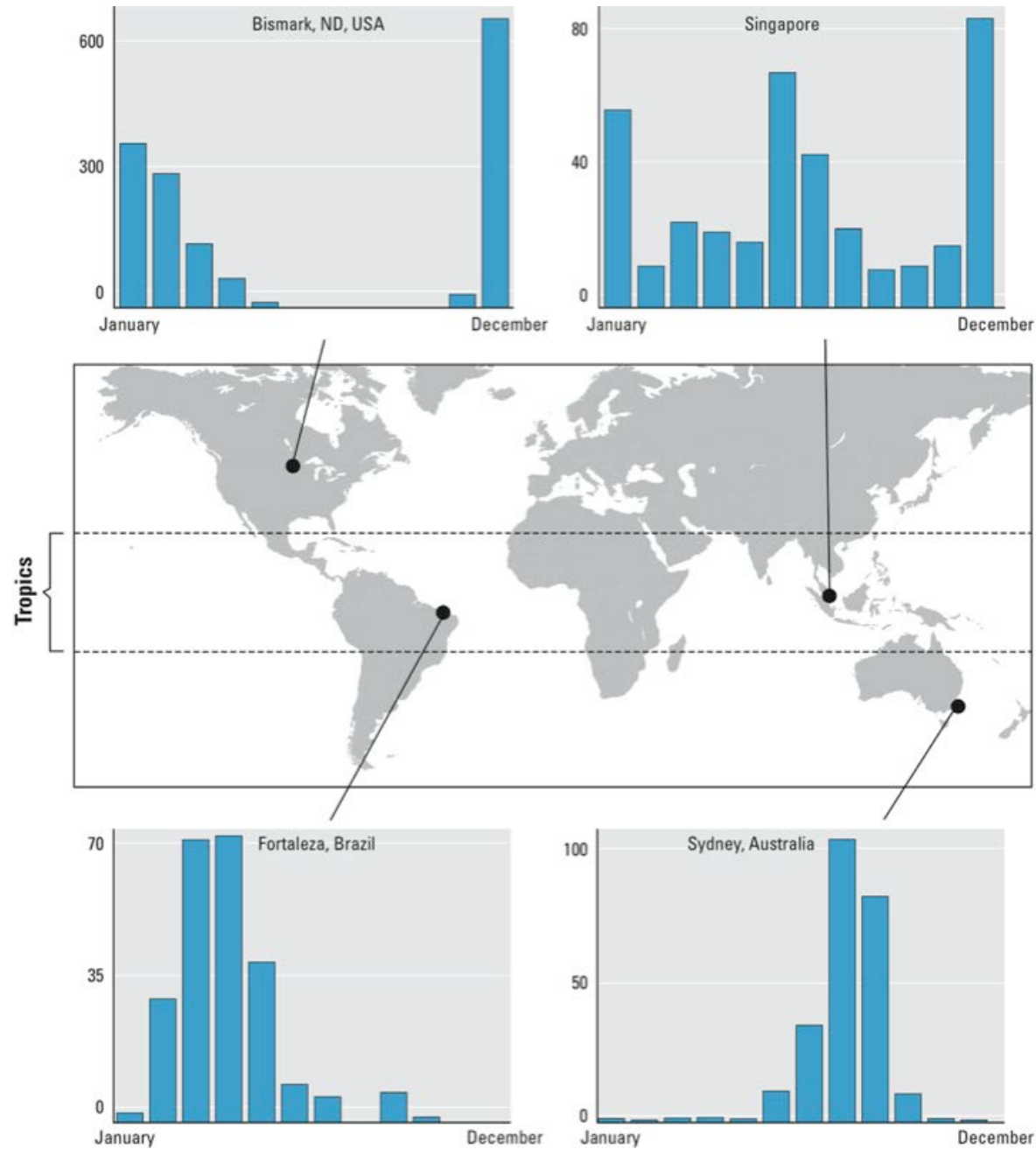


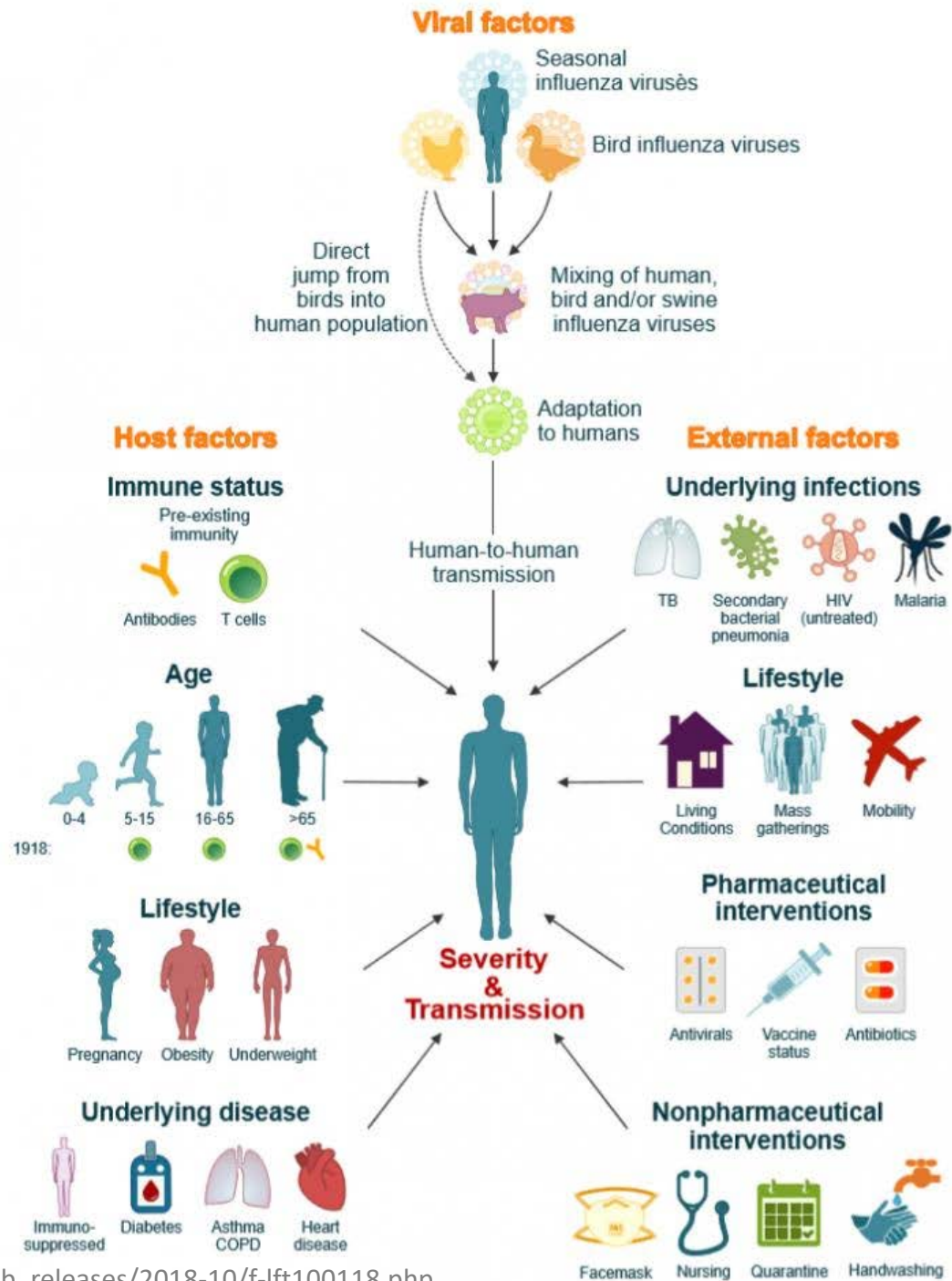
Viruses can be removed from indoor air by settling, ventilation, and inactivation; some of these processes depend on humidity.

How do temperature and humidity affect transmission?

Seasonality of the Flu







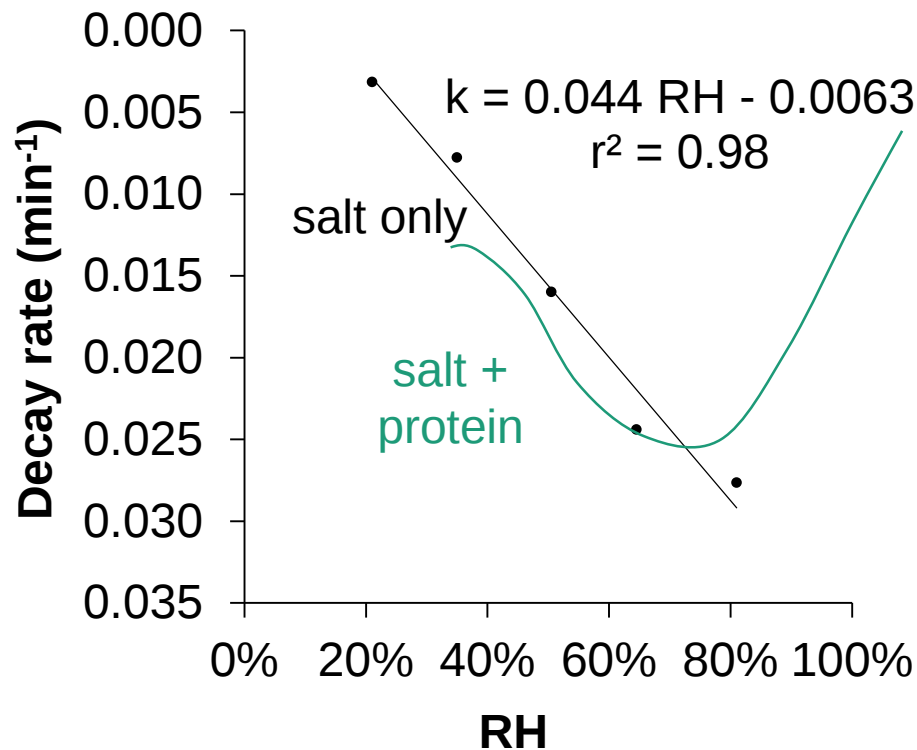
Virus Viability

- Temperature (T): In general, viruses survive better at lower T.
- Relative humidity (RH): Many, but not all, viruses in aerosols and droplets survive best at low RH (<40%). Some survive well at very high RH (>95%).
- Indoor T and RH are key because most transmission probably occurs indoors.



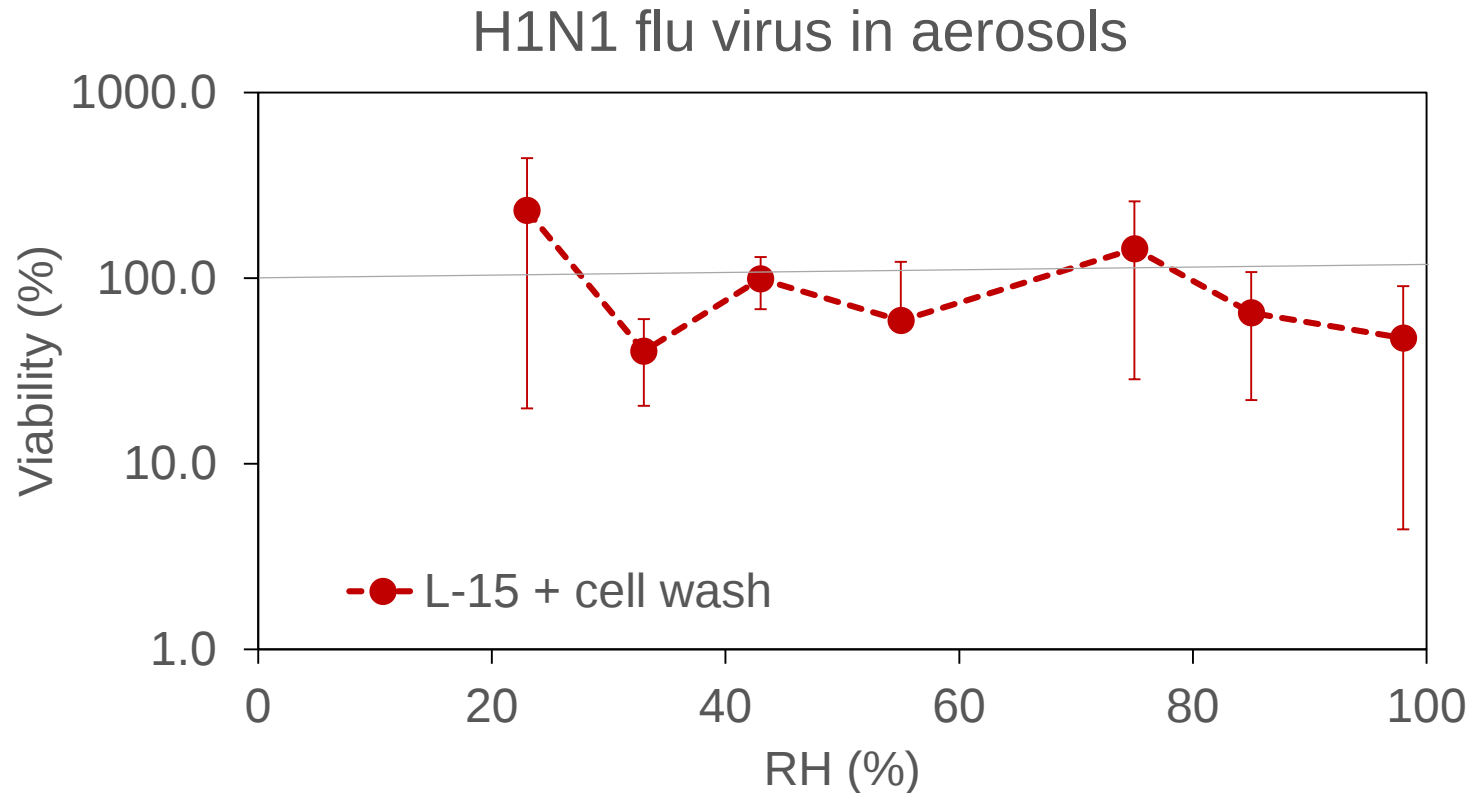


Virus Viability vs. RH



Conflicting results in the literature

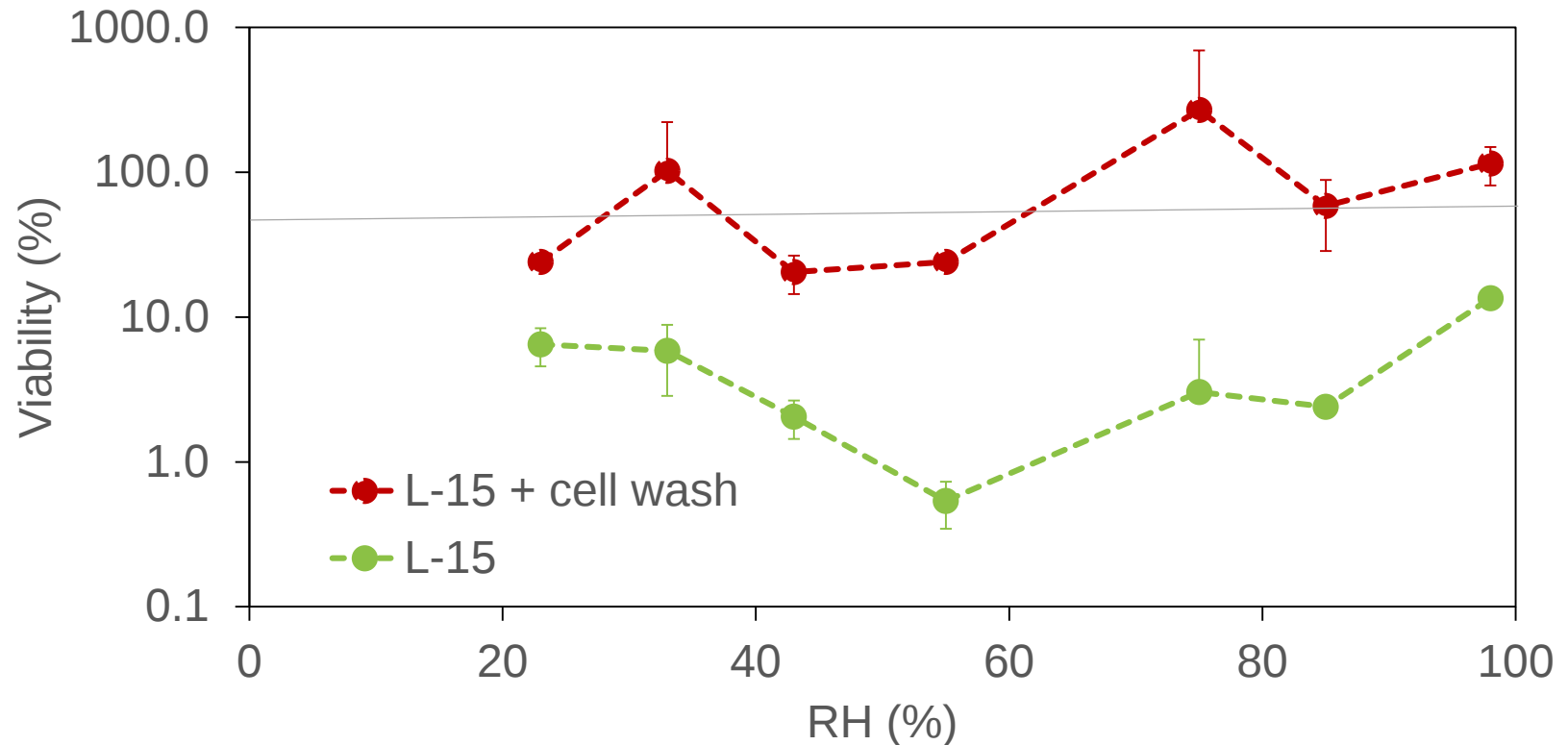
Flu Remains Viable at All RH



Virus in L-15 medium + human bronchial epithelial cell wash maintains high viability across all RHs tested.

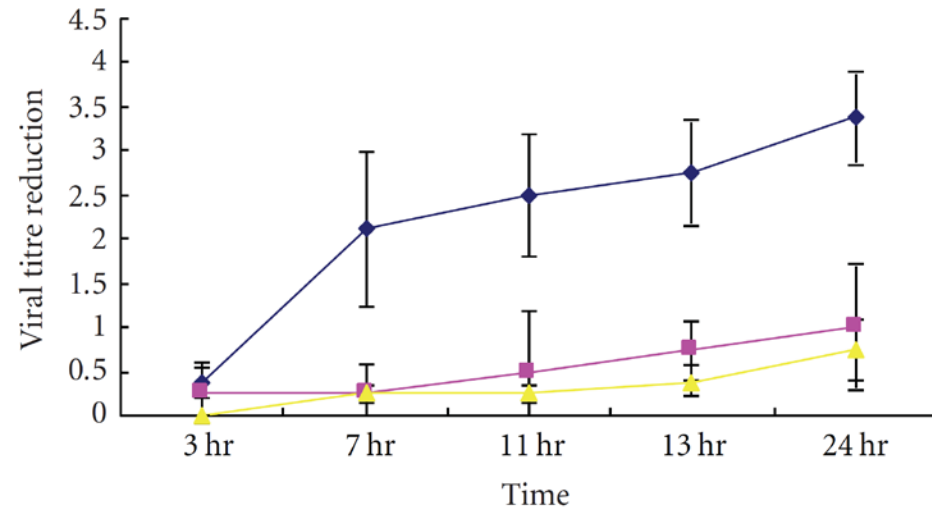
Respiratory Secretions Protect

H1N1 flu virus in droplets

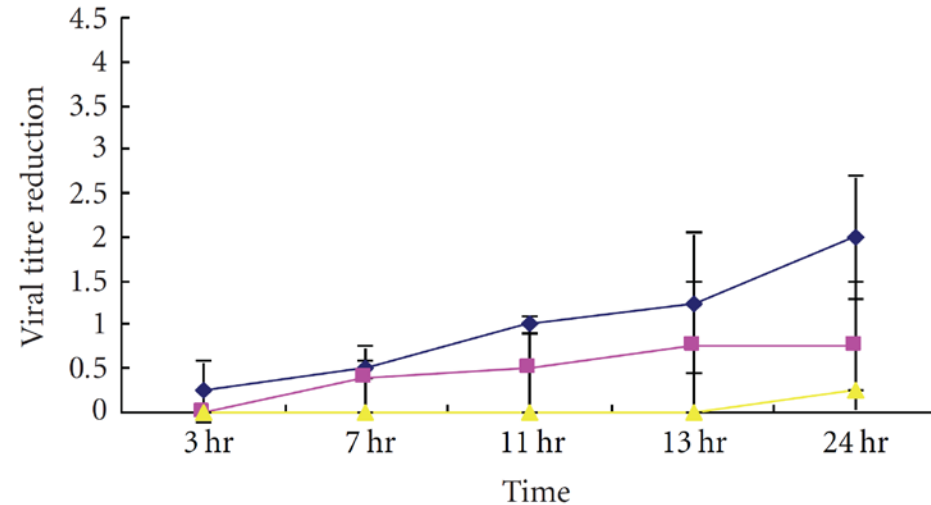


Viability is lower without human bronchial epithelial cell wash. Also for bacteriophage $\Phi 6$.

SARS-CoV-1 in Droplets



(a)



(b)

FIGURE 2: Infectivity of SARS Coronavirus ($10^5/10 \mu\text{L}$) to different temperatures at (a) >95% relative humidity, (b) >80–89%.

Dried SARS-CoV-1 on plastic decayed faster at higher temperature and faster at >95% RH than at 80-89% RH. In another study, it decayed much more quickly at 56 and 60 °C than at 4 °C.

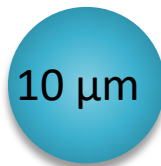
How Might RH Affect Transmission?

Low RH

Medium RH

Very high RH

Physics

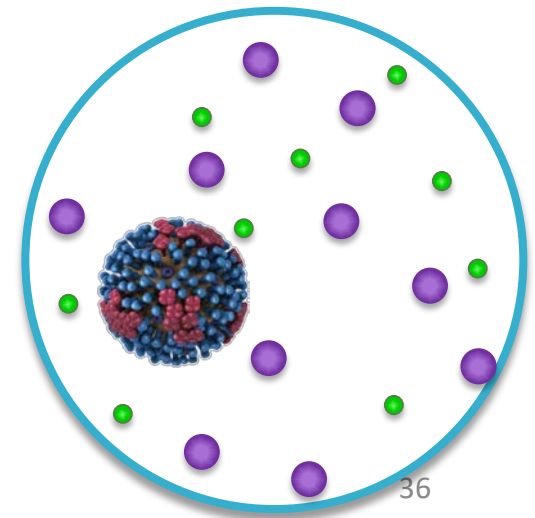
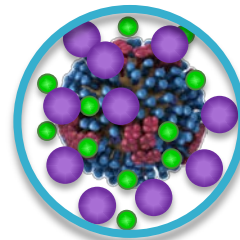
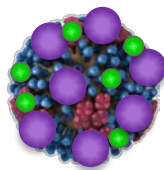


settles in
8 min



settles in
1 min

Chemistry



Viruses in air and on surfaces survive better at lower temperatures. Survival varies with humidity and liquid composition.

How do masks work?

Types of Masks



surgical mask

intended to keep the wearer from spraying droplets onto others



respirator

intended to reduce the wearer's exposure to inhaled particles

Three Key Factors Required for a Respirator to be Effective



Correct*



Incorrect

- ① The respirator must be put on correctly and worn during the exposure.
- ② The respirator must fit snugly against the user's face to ensure that there are no gaps between the user's skin and respirator seal.



- ③ The respirator filter must capture more than 95% of the particles from the air that passes through it.

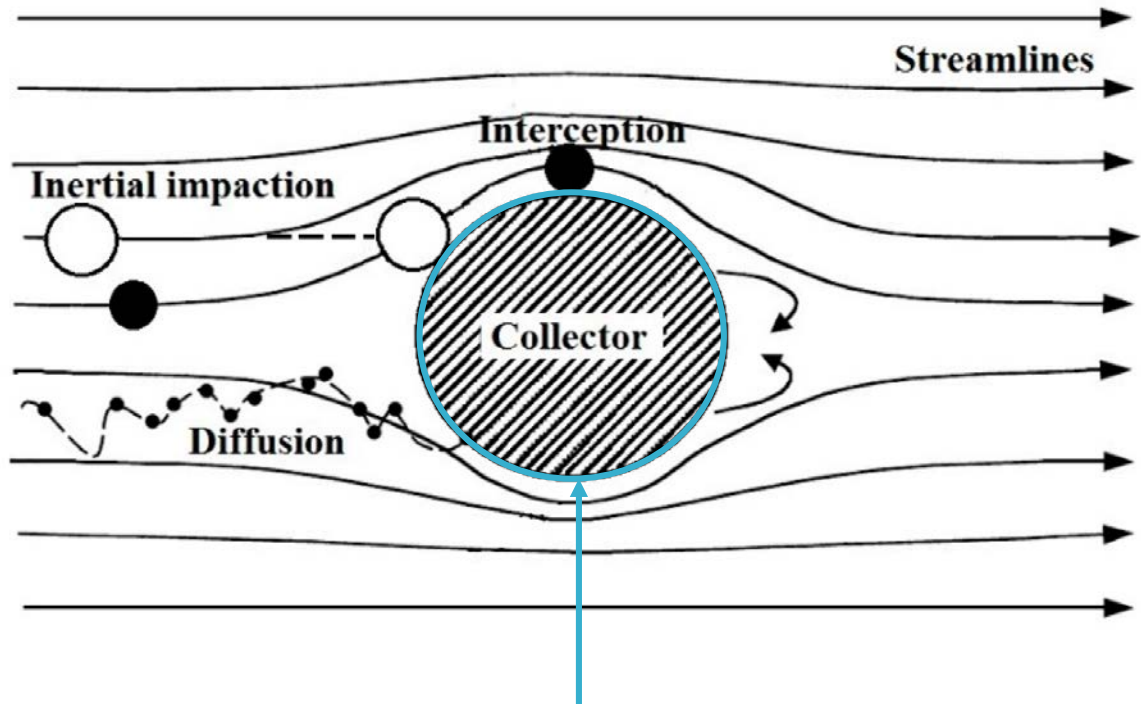


*If your respirator has a metal bar or a molded nose cushion, it should rest over the nose and not the chin area.



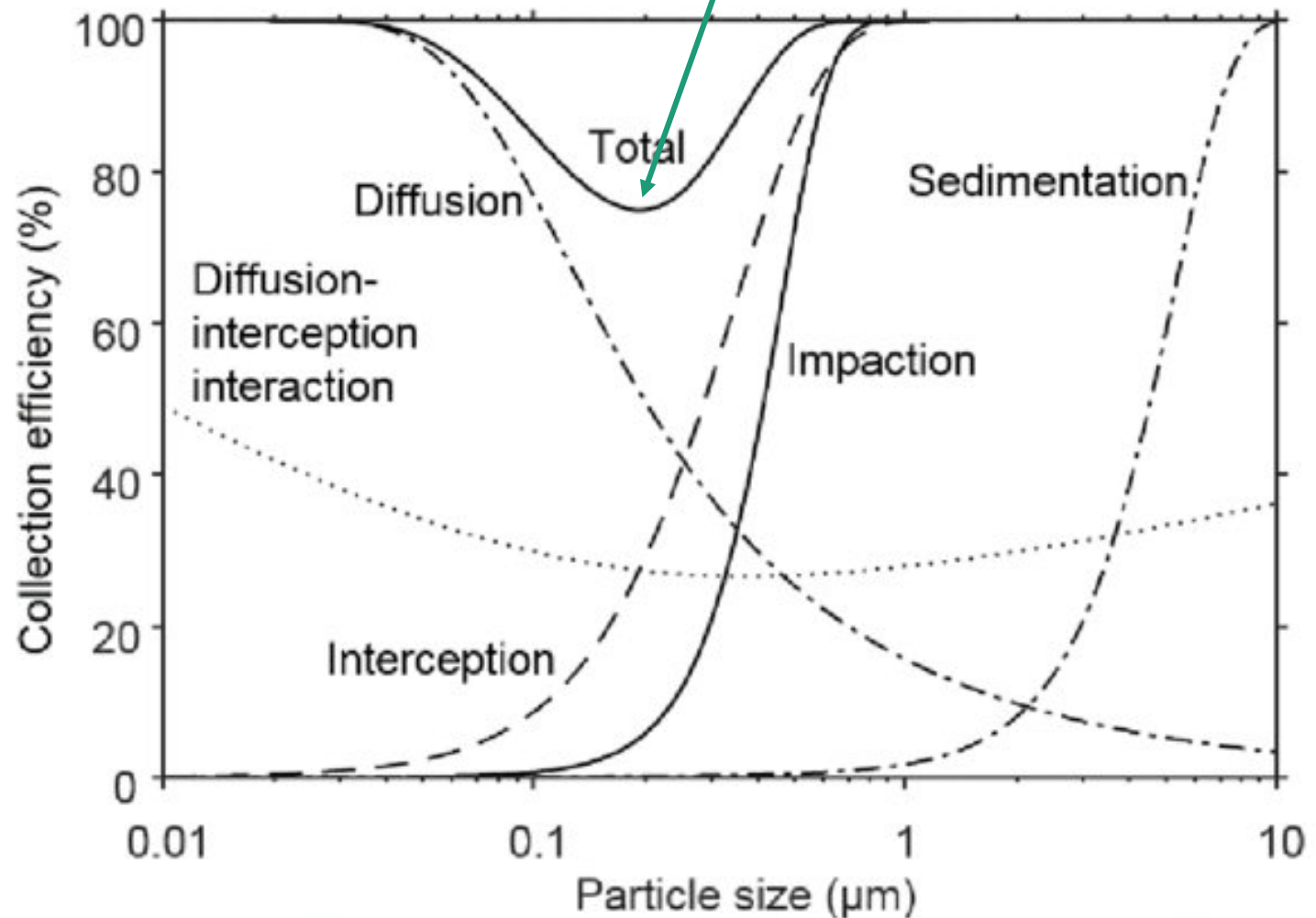
Filtration Mechanisms

- Impaction
- Interception
- Diffusion
- Not sieving!



“collector” = single fiber in a filter

Filter Efficiency



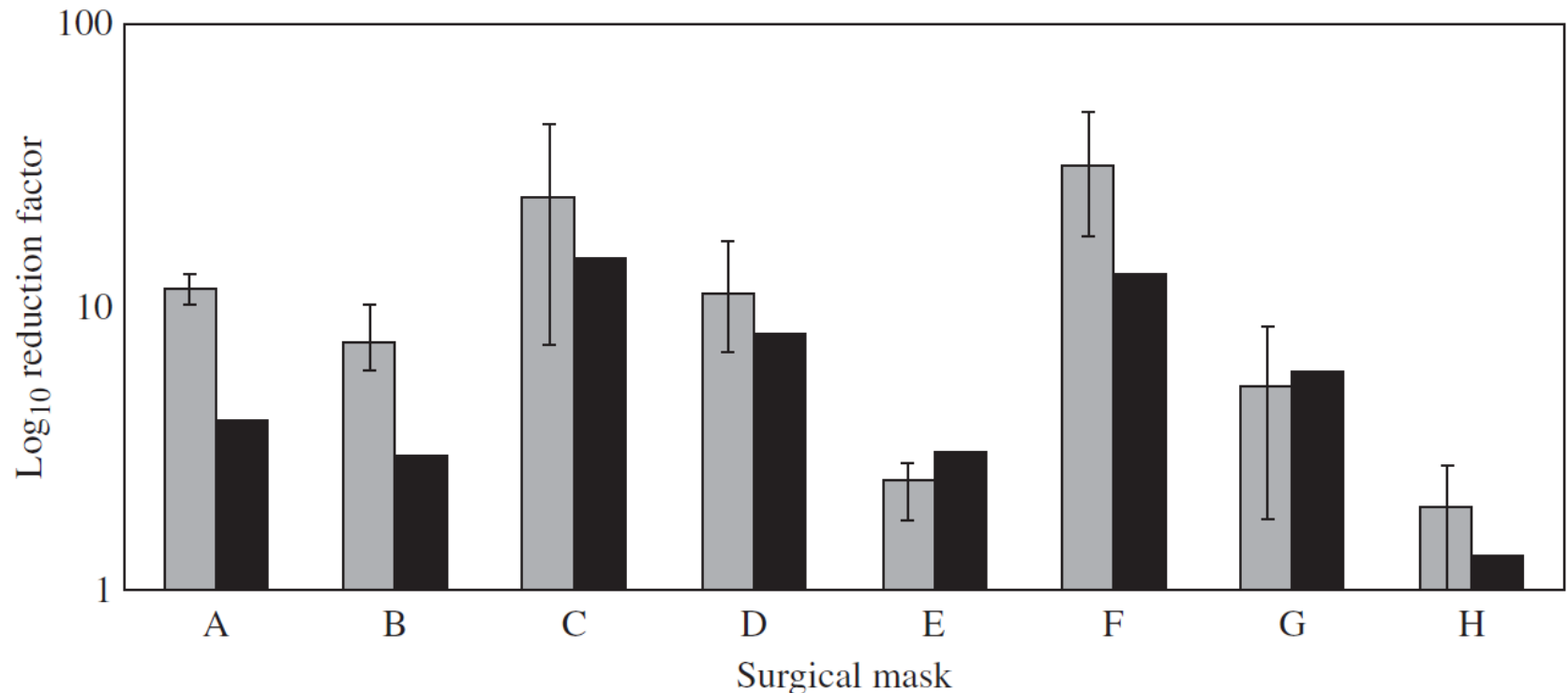
N95

- Blocks at least 95% of particles of diameter $0.3\ \mu\text{m}$
- Removal efficiency is even better for particles $>0.3\ \mu\text{m}$ and particles $<0.3\ \mu\text{m}$
- Capture efficiency depends on the size and density of the particle and should be the same whether the particle contains a virus or not



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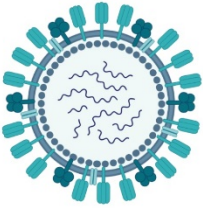
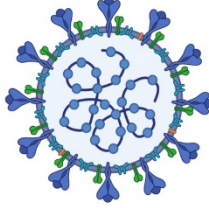
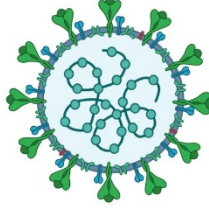
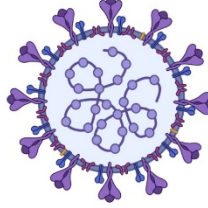
Surgical Masks and Flu Virus



Different types of surgical masks reduced the amount of infectious flu virus measured behind the mask on a manikin by an average of a factor of 6 (range 1.1-55).

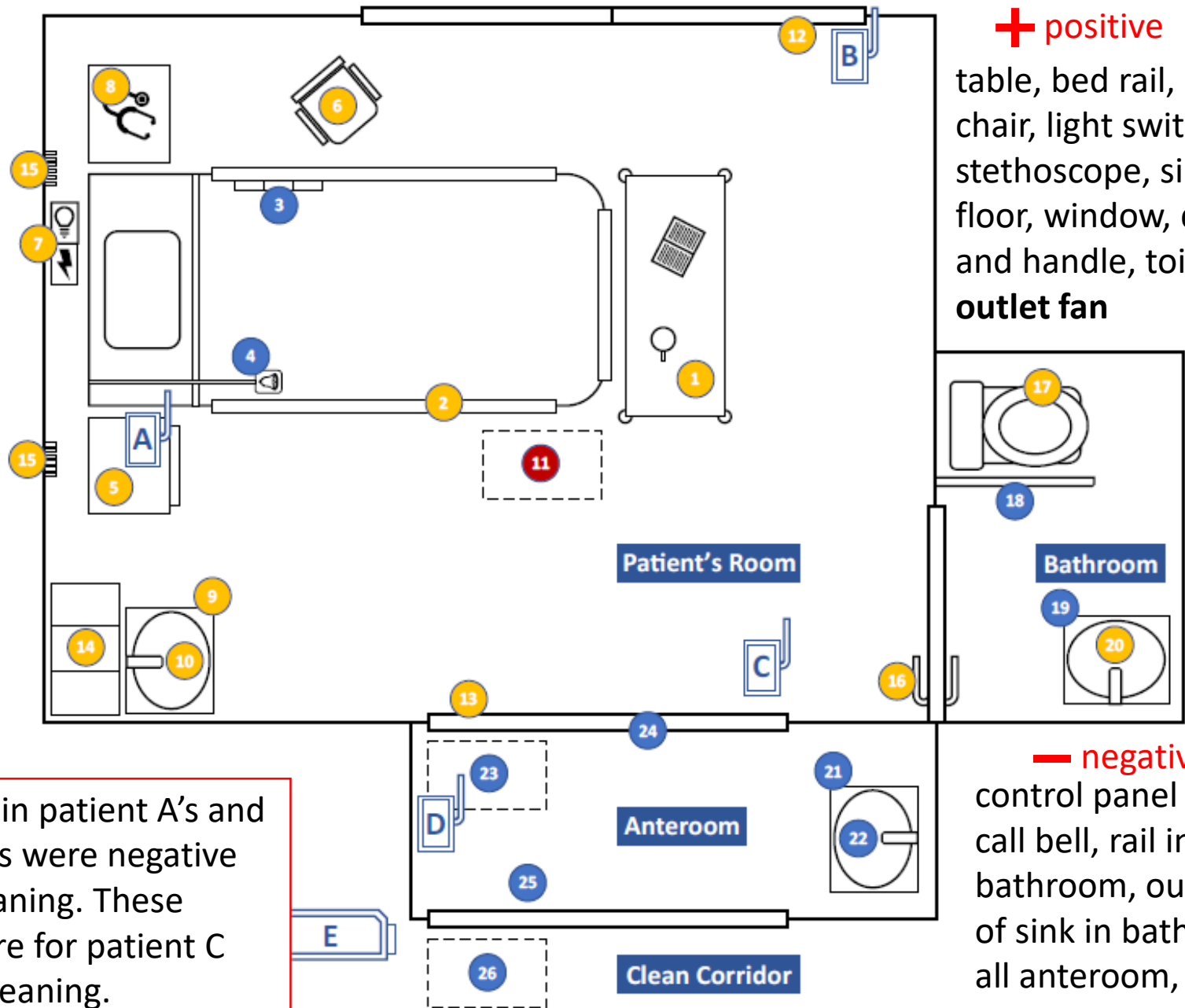
What do we know about SARS-CoV-2 in droplets/aerosols?

Epidemiological Comparison of Respiratory Viral Infections

Disease	Flu	COVID-19	SARS	MERS
Disease Causing Pathogen	 Influenza virus	 SARS-CoV-2	 SARS-CoV	 MERS-CoV
R_0 Basic Reproductive Number	1.3	2.0 - 2.5 *	3	0.3 - 0.8
CFR Case Fatality Rate	0.05 - 0.1%	~3.4% *	9.6 - 11%	34.4%
Incubation Time	1 - 4 days	4 - 14 days *	2 - 7 days	6 days
Hospitalization Rate	2%	~19% *	Most cases	Most cases
Community Attack Rate	10 - 20%	30 - 40% *	10 - 60%	4 - 13%
Annual Infected (global)	~ 1 billion	N/A (ongoing)	8098 (in 2003)	420
Annual Infected (US)	10 - 45 million	N/A (ongoing)	8 (in 2003)	2 (in 2014)
Annual Deaths (US)	10,000 - 61,000	N/A (ongoing)	None (since 2003)	None (since 2014)

* COVID-19 data as of March 2020.

Created in **BioRender.com** 



Samples in patient A's and B's rooms were negative after cleaning. These results are for patient C before cleaning.

SARS-CoV-2 Size Distributions

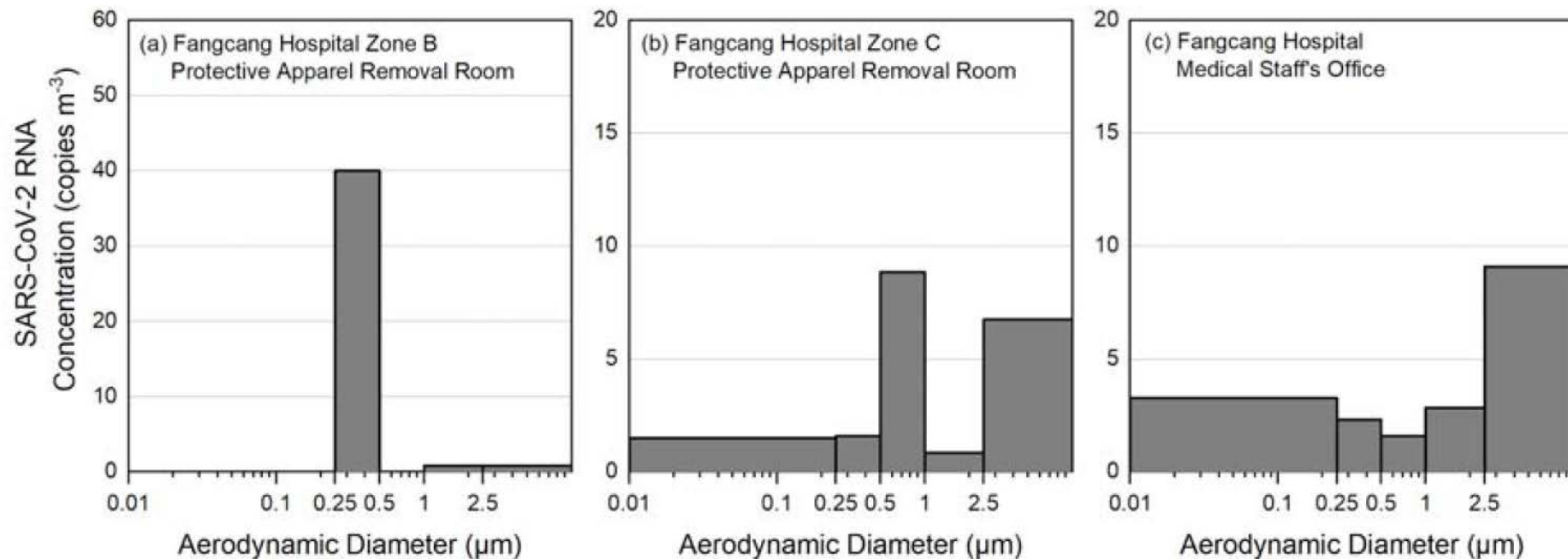
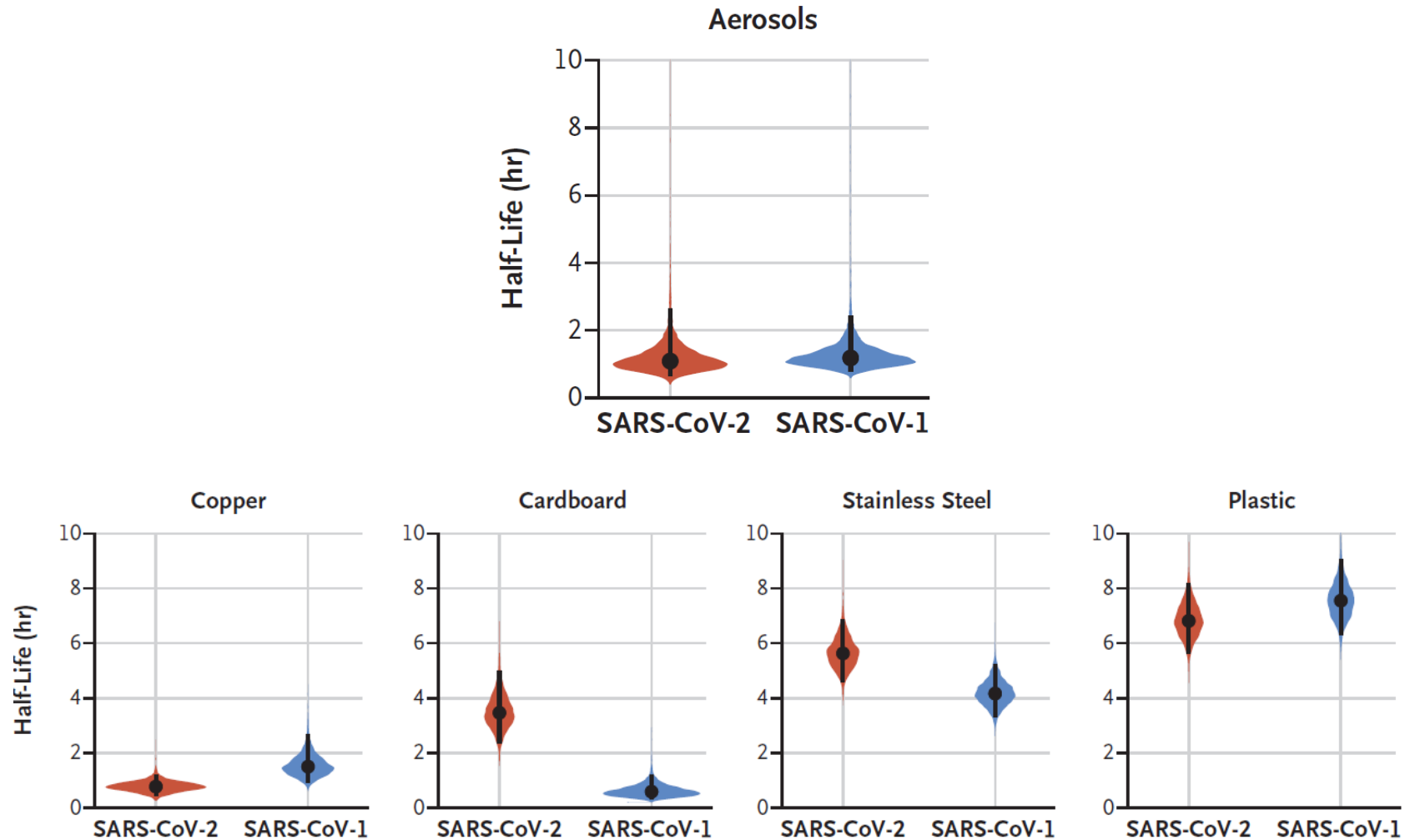


Figure 1 Concentration of airborne SARS-CoV-2 RNA in different aerosol size bins

SARS-CoV-2 Survival in Aerosols

C Half-Life of Viable Virus

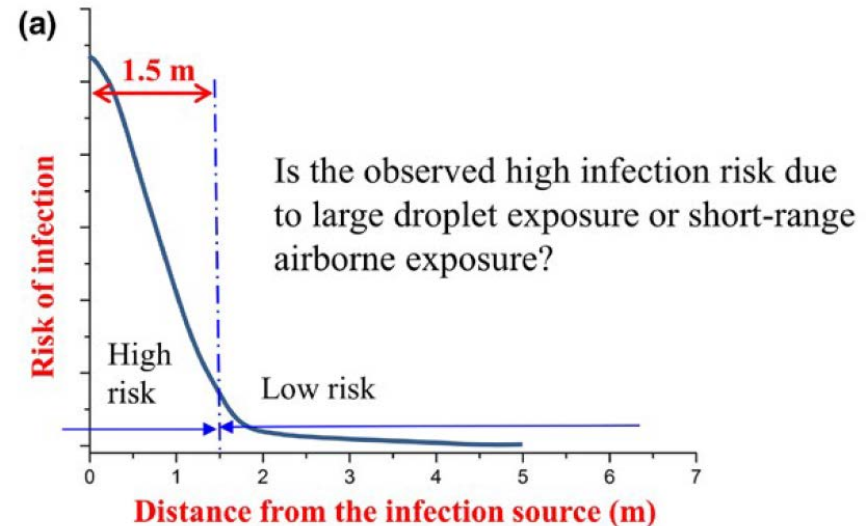


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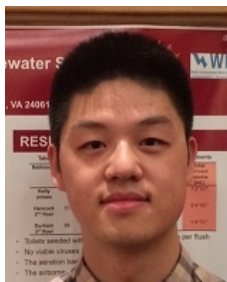
Major Unknowns

- Which transmission route is dominant: direct contact, indirect contact with contaminated objects (fomites), inhalation of aerosols, deposition of droplets?
- How are viruses inactivated in air and on surfaces?
- How much virus is released in what size aerosols at different stages of infection?
- How well does SARS-CoV-2 survive in aerosols under real-world conditions?



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Haoran Wei
Wan Yang



Center for the Environmental
Implications of NanoTechnology

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