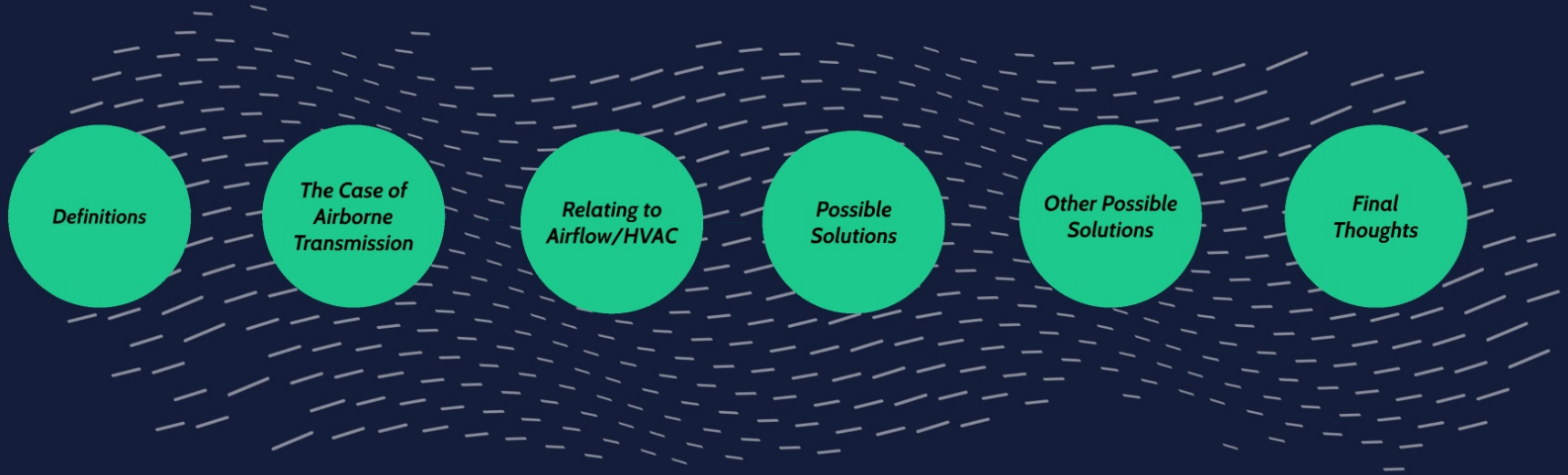
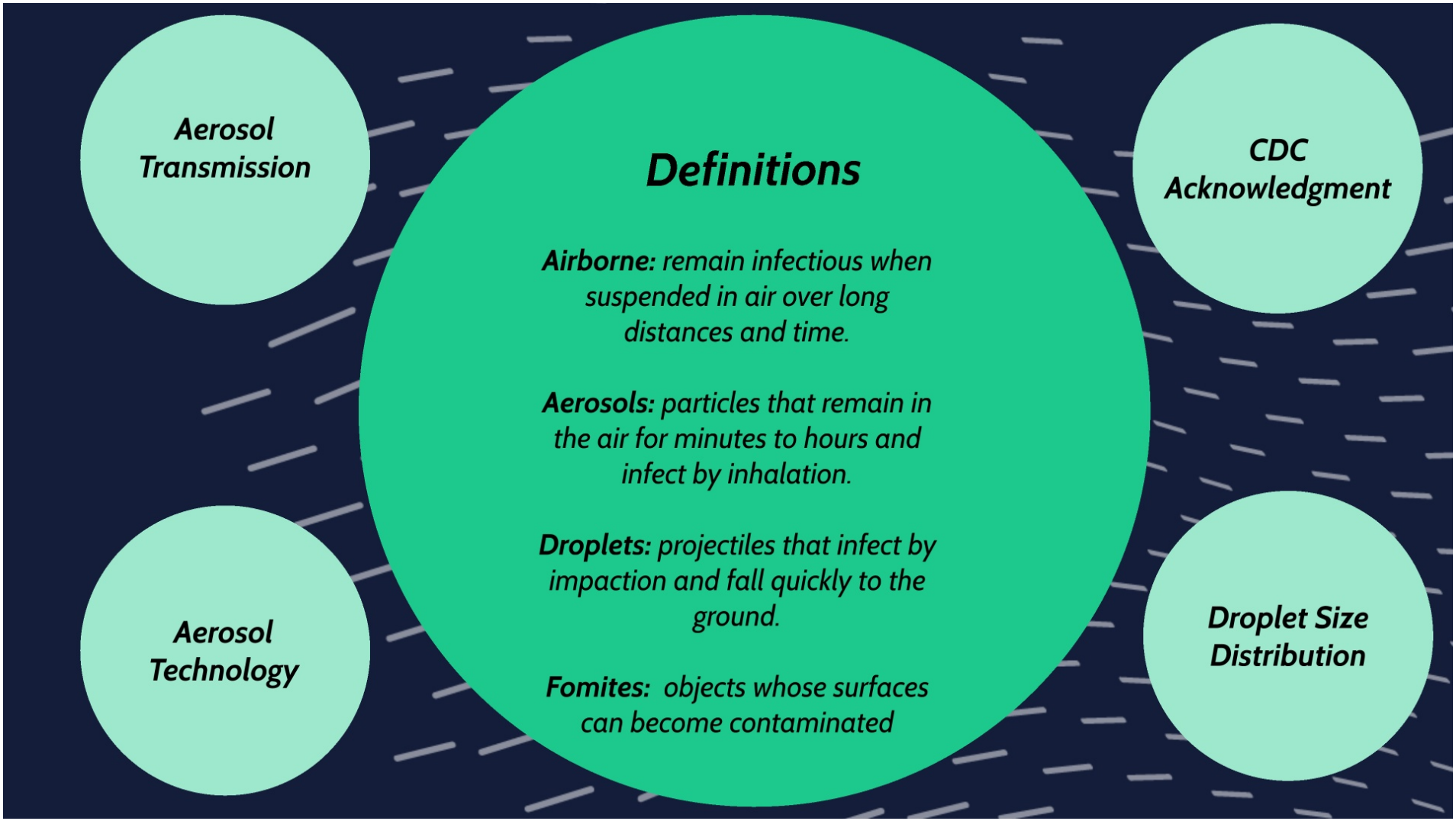
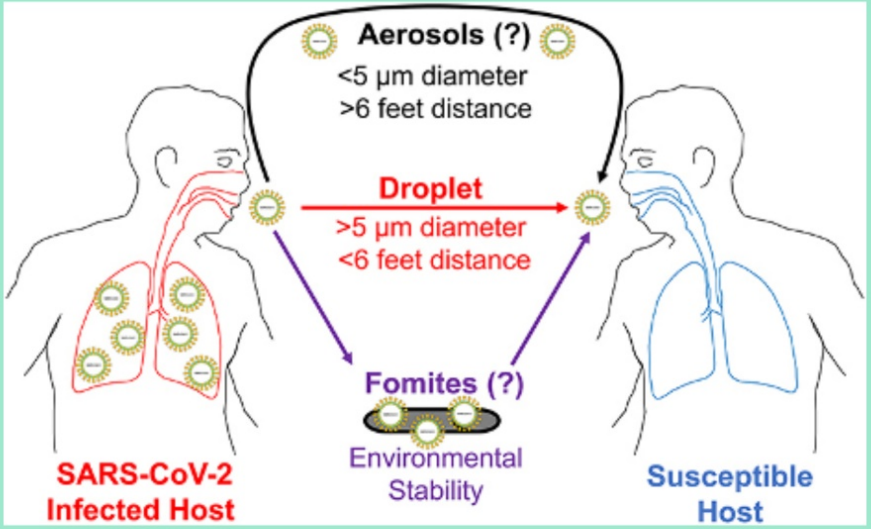
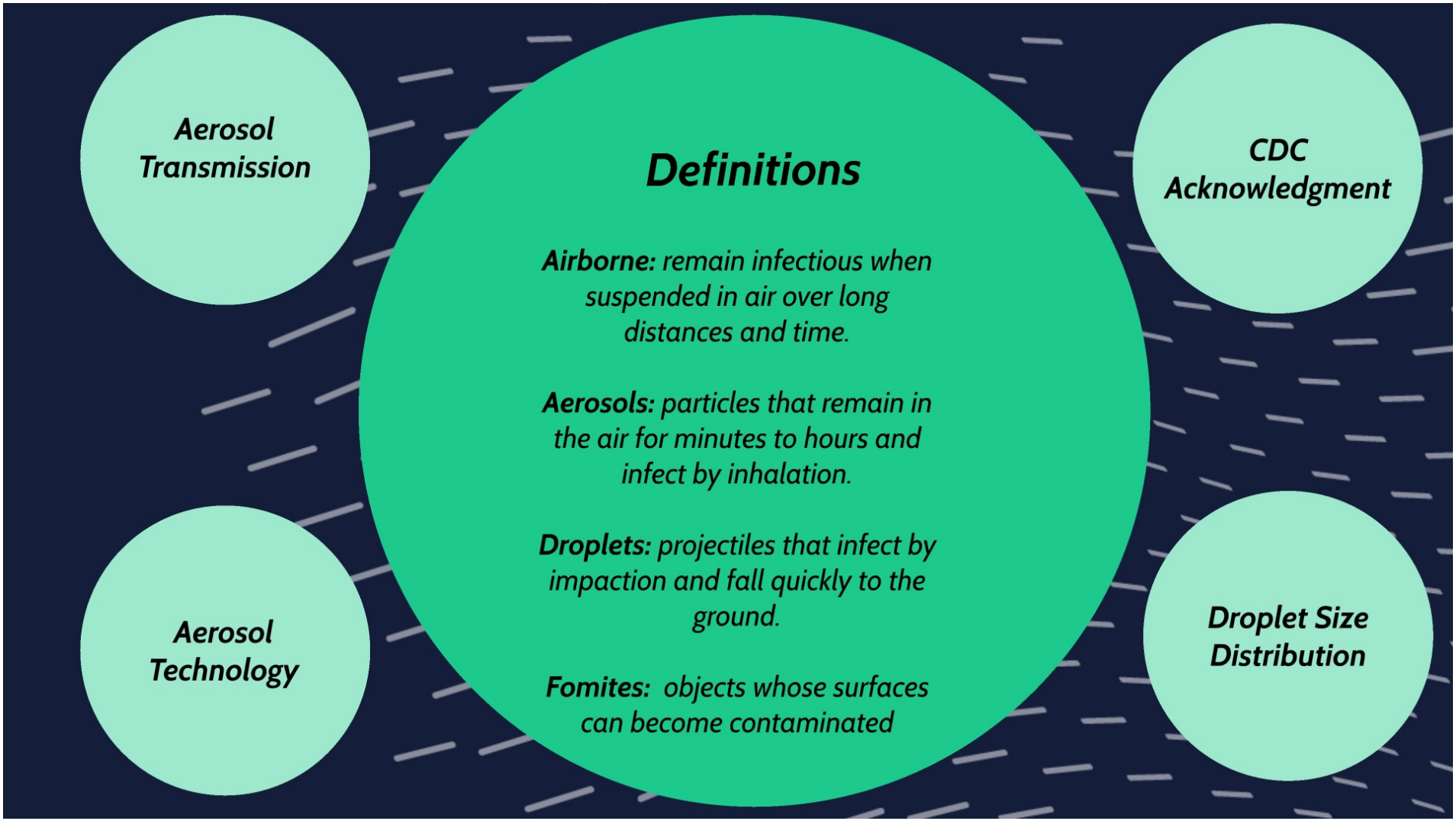
Aerosols, COVID-19 & HVAC




Aerosol Transmission
CDC Acknowledgment
Definitions
Airborne: remain infectious when suspended in air over long distances and time.
Aerosols: particles that remain in the air for minutes to hours and infect by inhalation.
Droplets: projectiles that infect by impaction and fall quickly to the ground.
Fomites: objects whose surfaces can become contaminated
Aerosol Technology
Droplet Size Distribution


Aerosols (?)
<5 μm diameter
>6 feet distance
Droplet
>5 μm diameter
<6 feet distance
Fomites (?)
Environmental
Stability
SARS-CoV-2
Infected Host
Susceptible
Host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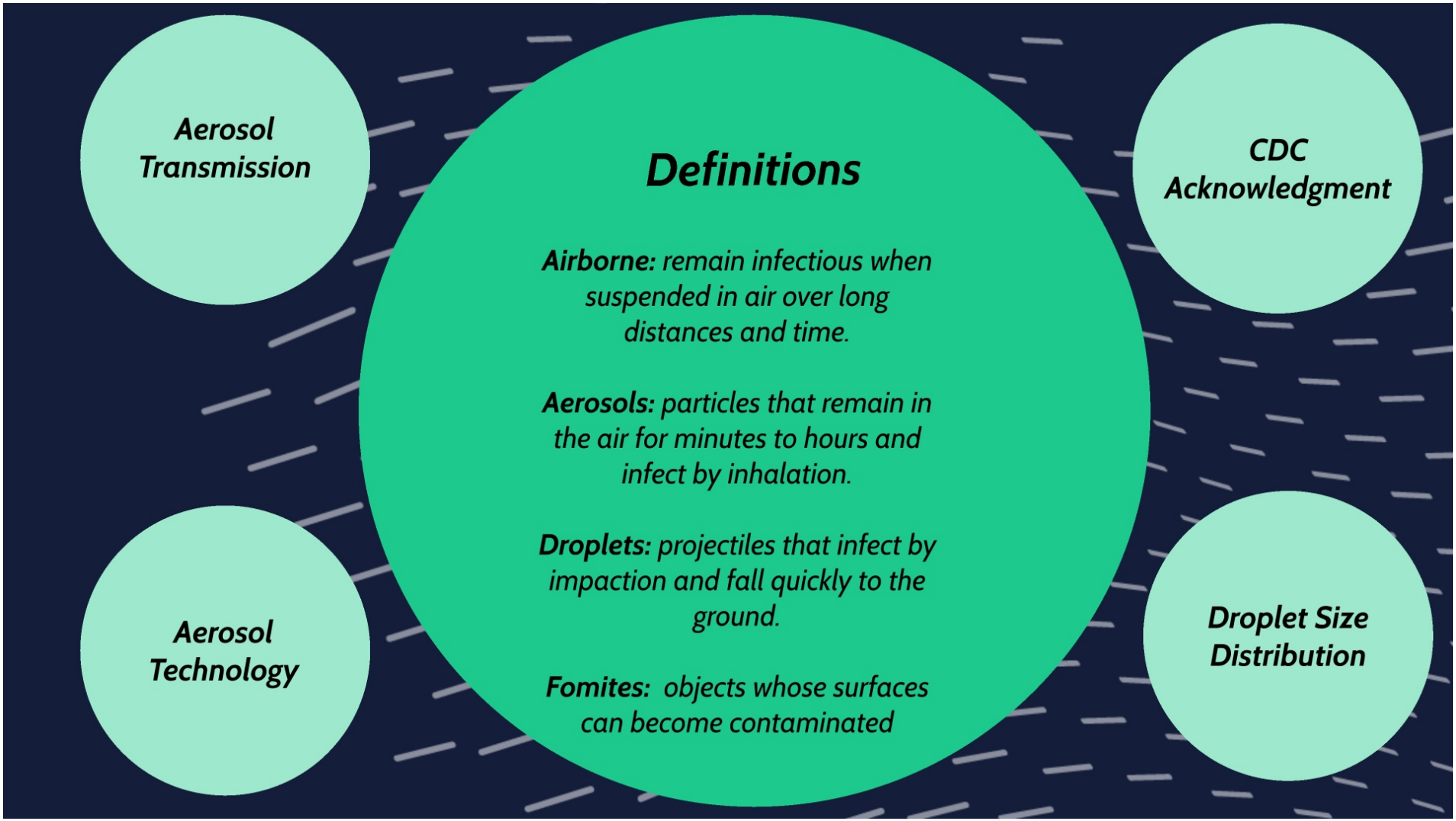
The term "aerosol" was coined 100 years ago (in 1920 - right after the 1918 flu) as the air analogy to hydrosol, a stable suspension of particles in a liquid. A key word in all of this is "suspended"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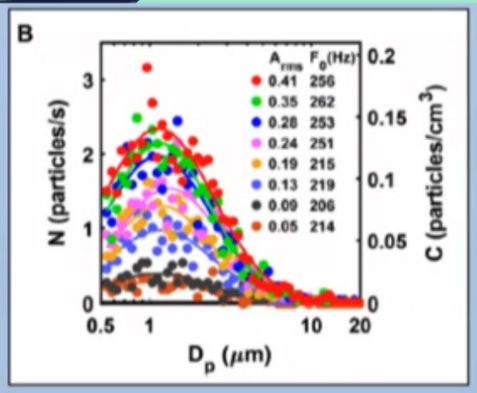
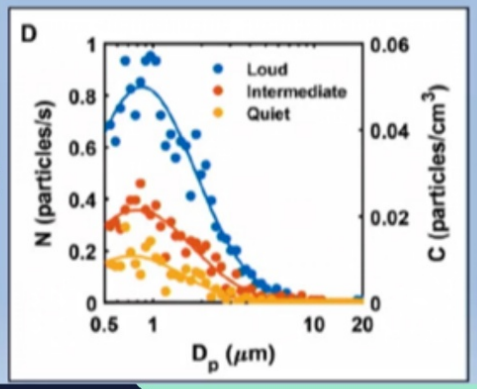
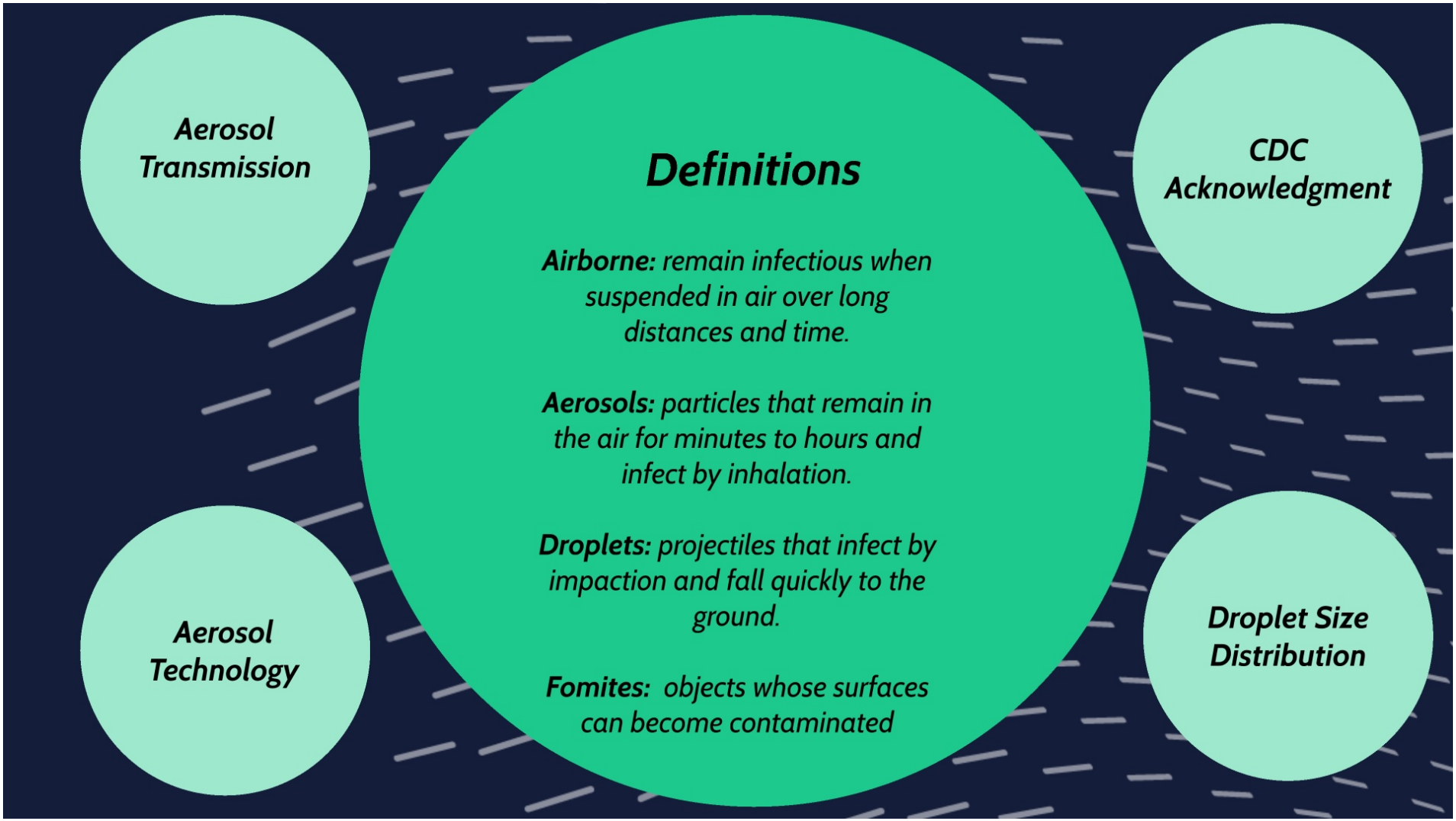


Droplet size distribution (mostly <10 μm diameter) when saying a single syllable (as in 'saw') at 8 different and increasing amplitudes (6 repeats at each).



Droplet size distribution (mostly <10 μm diameter) when reading the Rainbow passage at 3 different and increasing amplitudes – representative plot from a single individual.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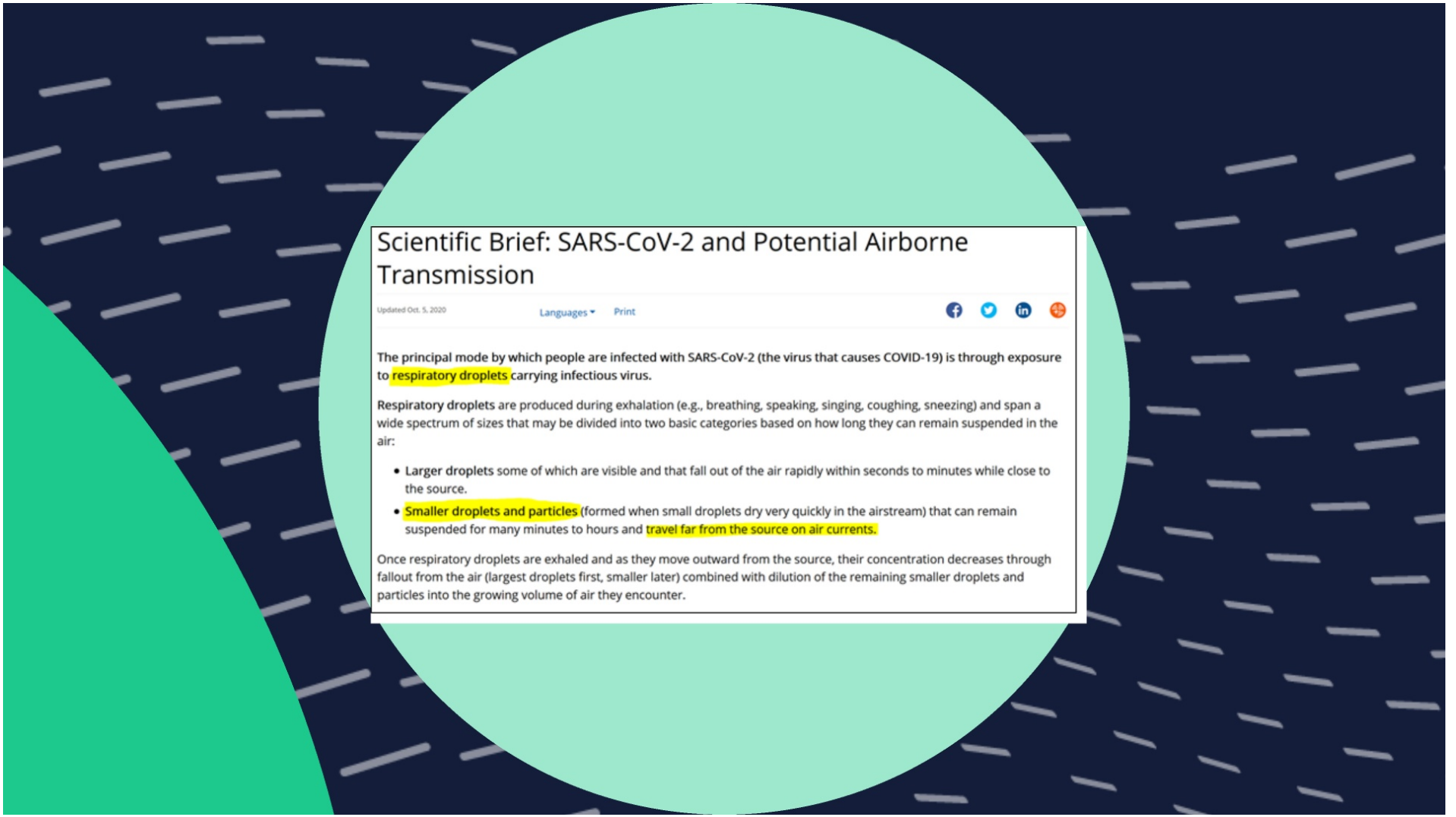
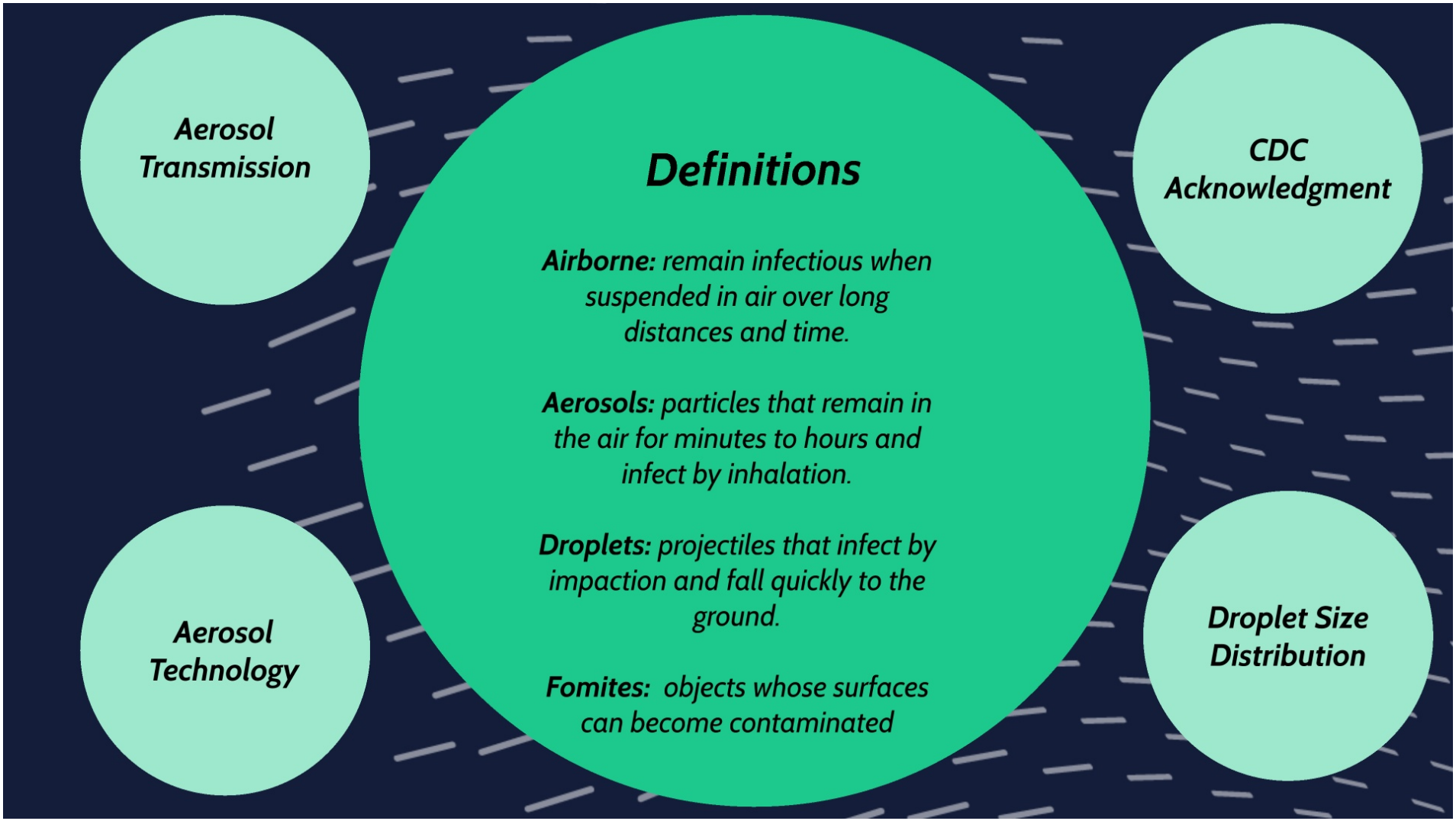

Scientific Brief: SARS-CoV-2 and Potential Airborne Transmission
Updated Oct. 5, 2020
Languages
Print
The principal mode by which people are infected with SARS-CoV-2 (the virus that causes COVID-19) is through exposure to respiratory droplets carrying infectious virus.
Respiratory droplets are produced during exhalation (e.g., breathing, speaking, singing, coughing, sneezing) and span a wide spectrum of sizes that may be divided into two basic categories based on how long they can remain suspended in the air:
Larger droplets some of which are visible and that fall out of the air rapidly within seconds to minutes while close to the source.
Smaller droplets and particles (formed when small droplets dry very quickly in the airstream) that can remain suspended for many minutes to hours and travel far from the source on air currents.
Once respiratory droplets are exhaled and as they move outward from the source, their concentration decreases through fallout from the air (largest droplets first, smaller later) combined with dilution of the remaining smaller droplets and particles into the growing volume of air they encounter.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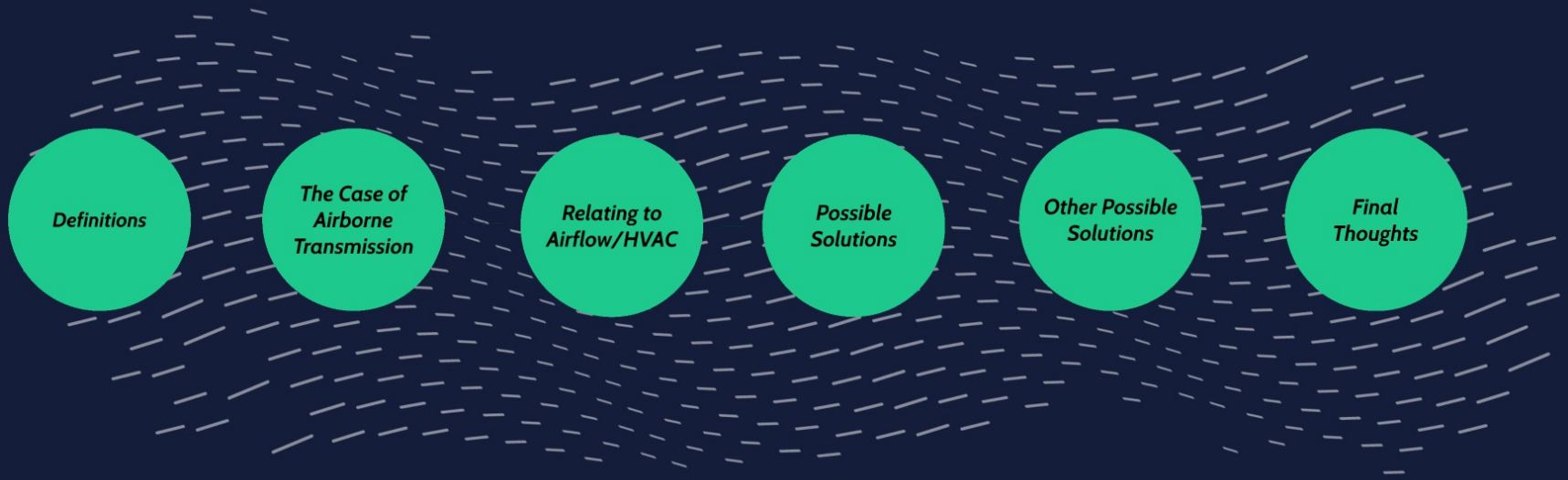
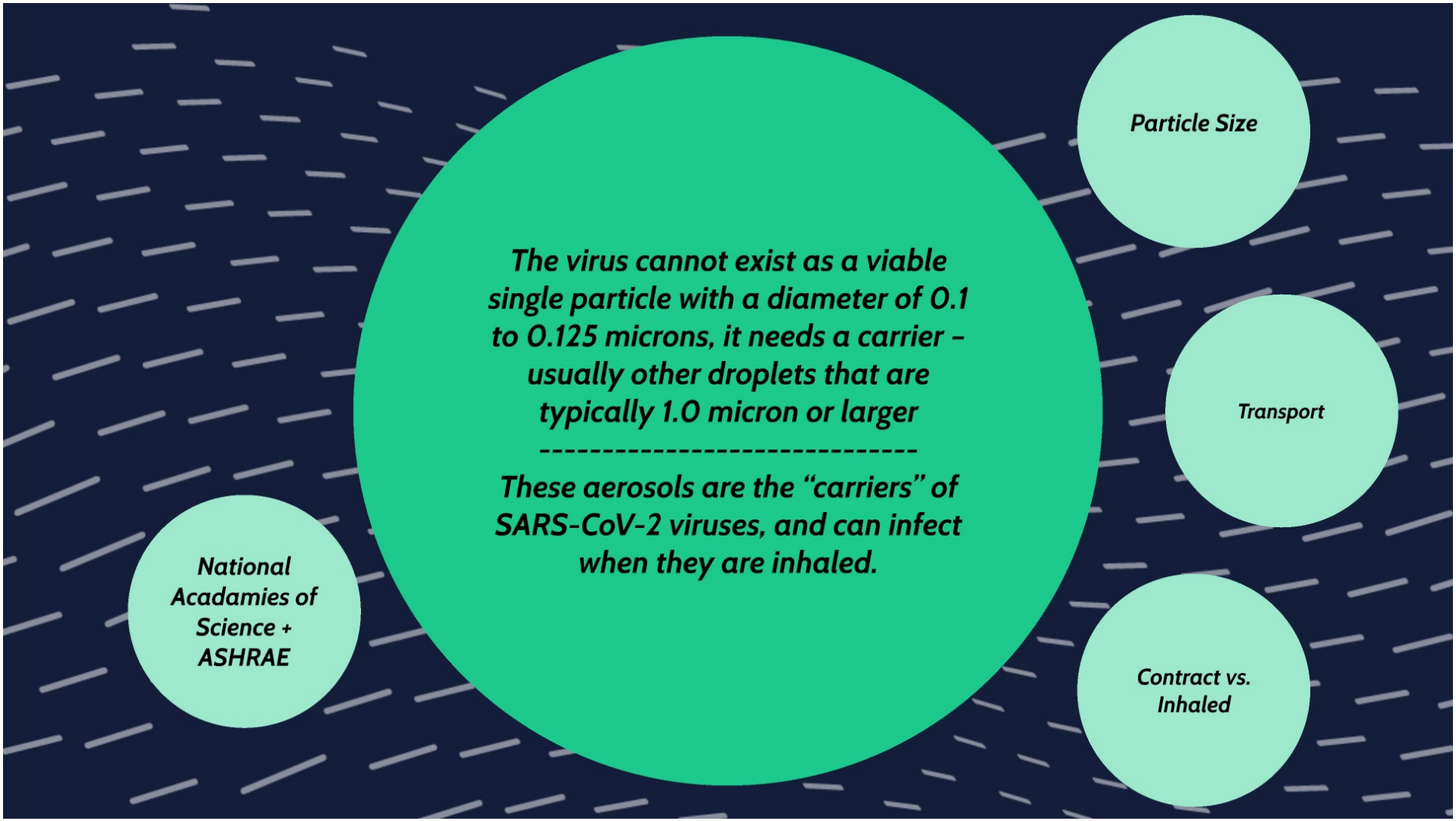
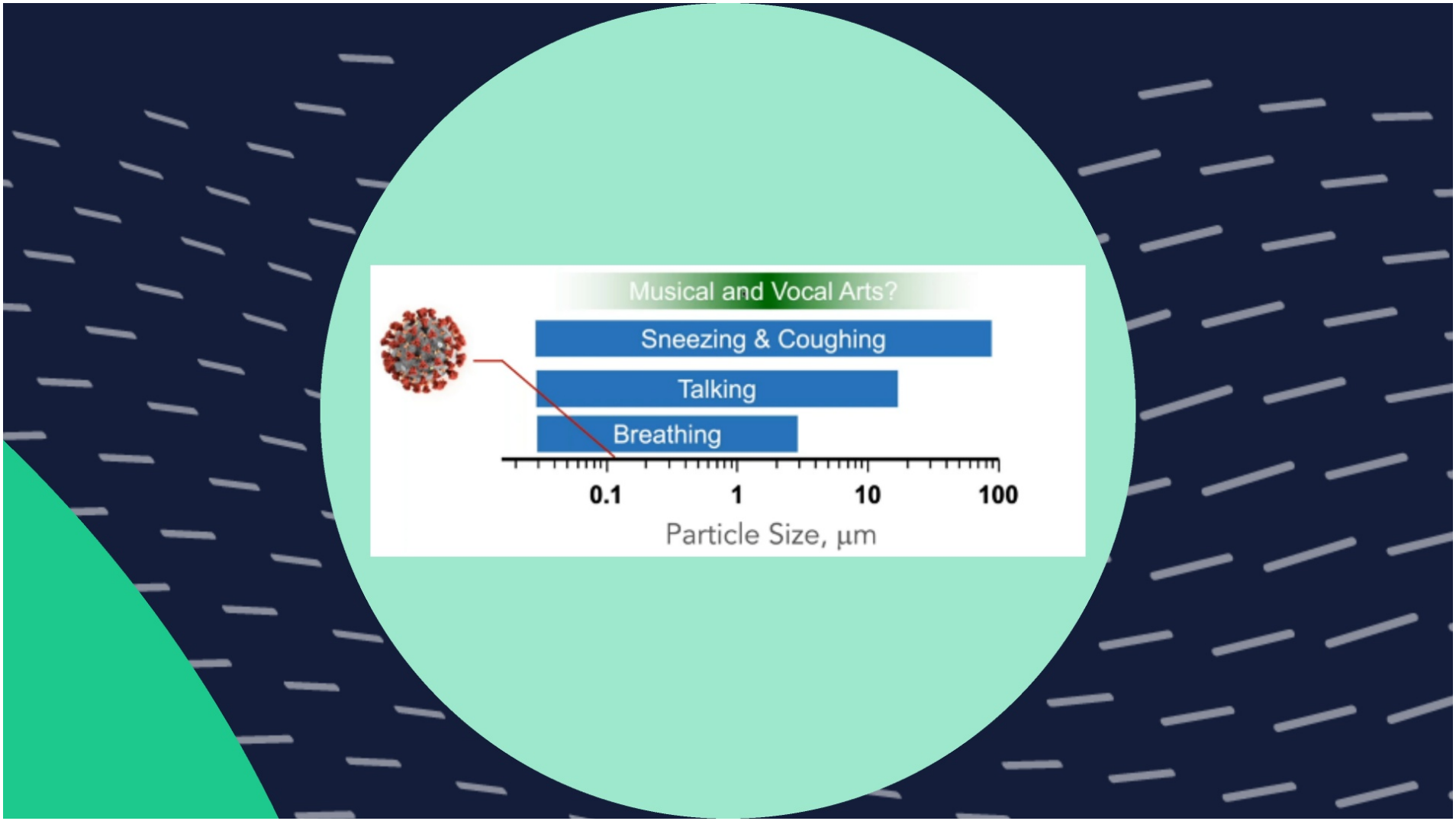
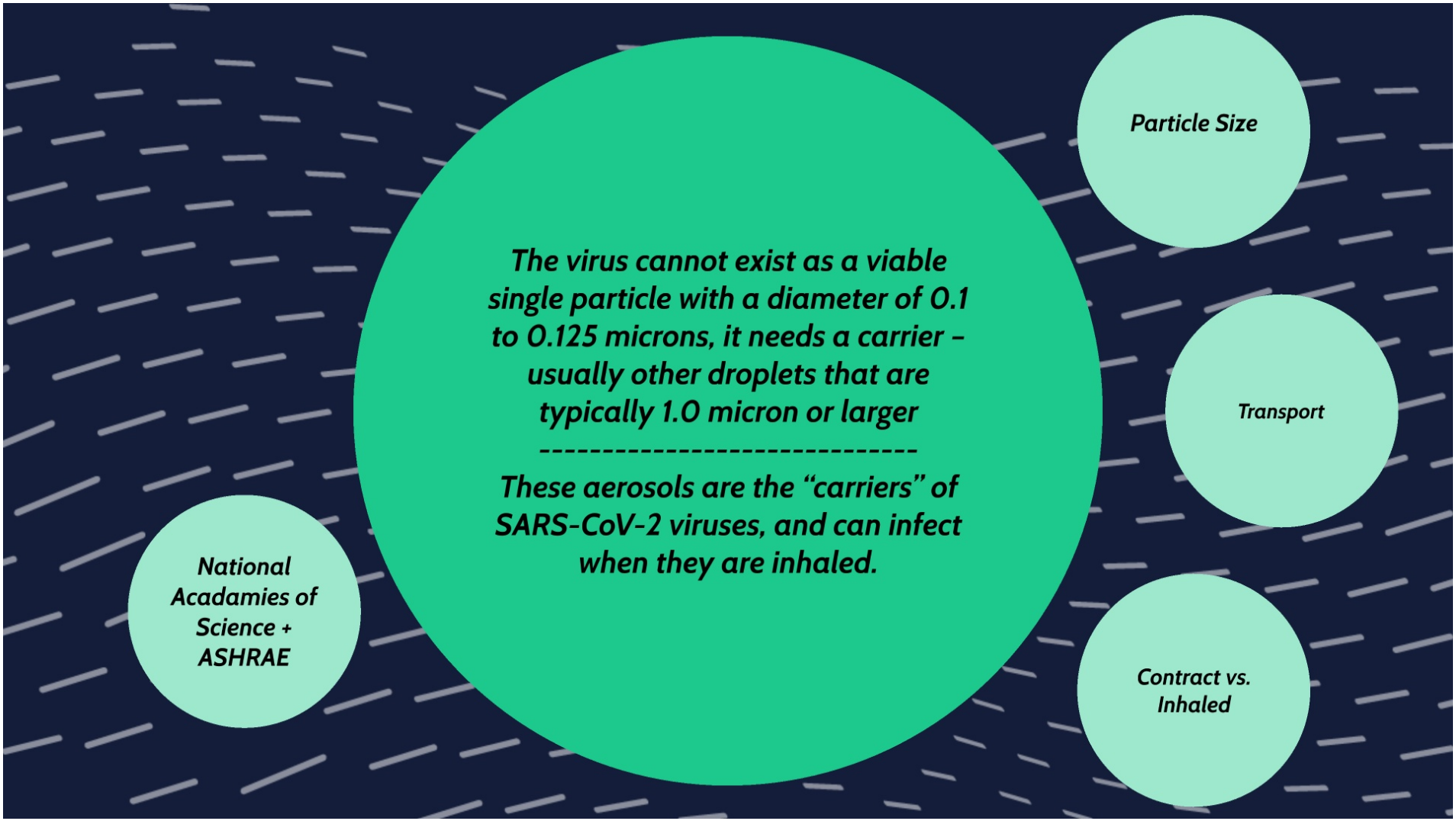



Particle Size
The virus cannot exist as a viable single particle with a diameter of 0.1 to 0.125 microns, it needs a carrier – usually other droplets that are typically 1.0 micron or larger
---
These aerosols are the "carriers" of SARS-CoV-2 viruses, and can infect when they are inhaled.
Transport
National Acadamies of Science + ASHRAE
Contract vs. Inhaled


Musical and Vocal Arts?
Sneezing & Coughing
Talking
Breathing
0.1
1
10
100
Particle Size, µm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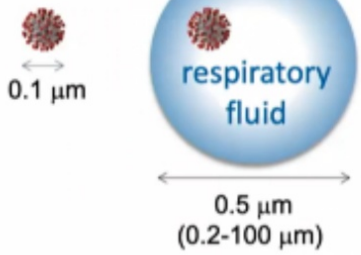
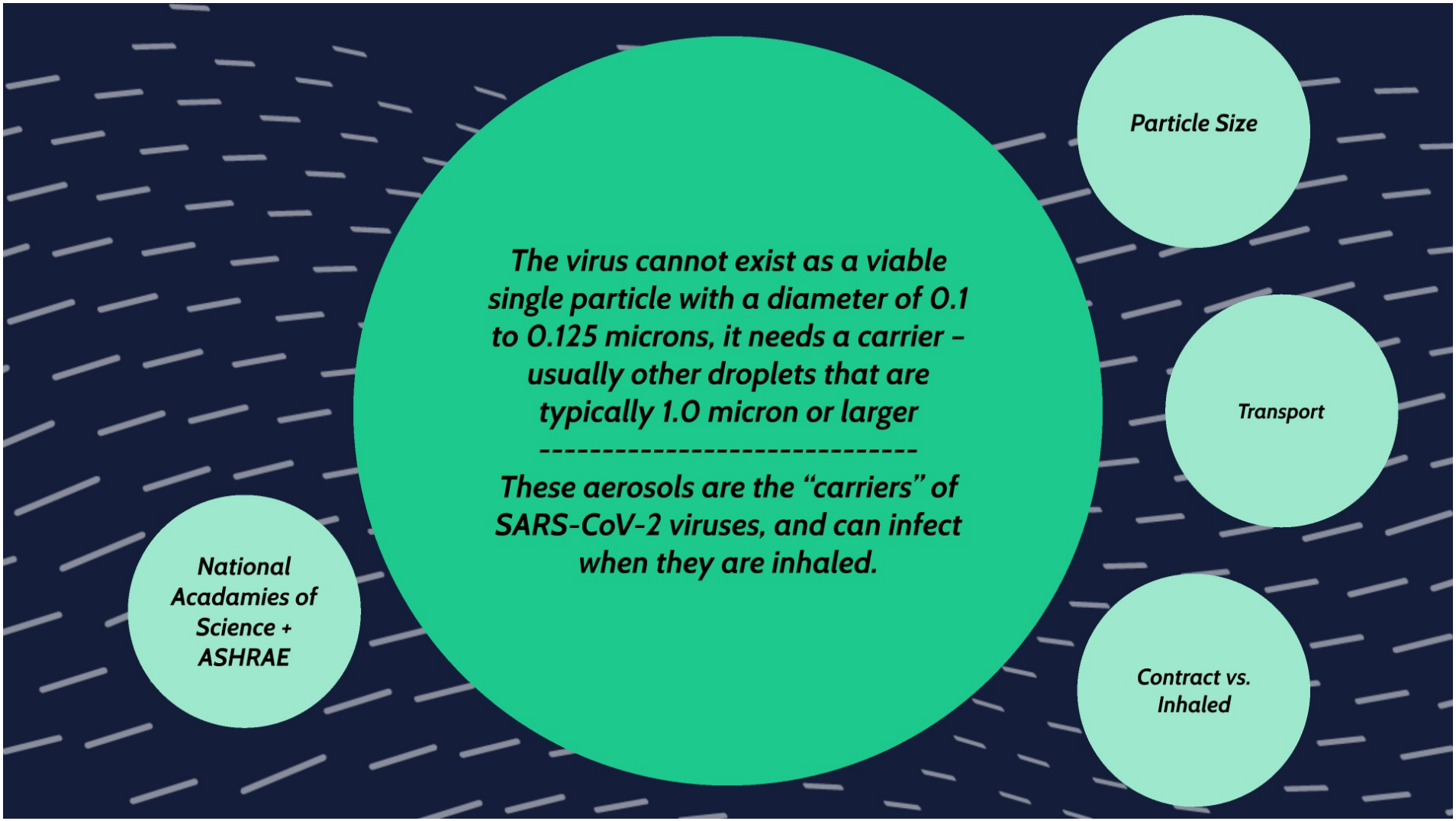
1. Airborne virus is not naked
2. Size of carrier droplet/aerosol defines transport



- How long it stays aloft
- How far it can travel
- How quickly it falls to surfaces
- Where it deposits in the respiratory system
- How efficiently it is removed by masks and filters
- Physics is the same for all viruses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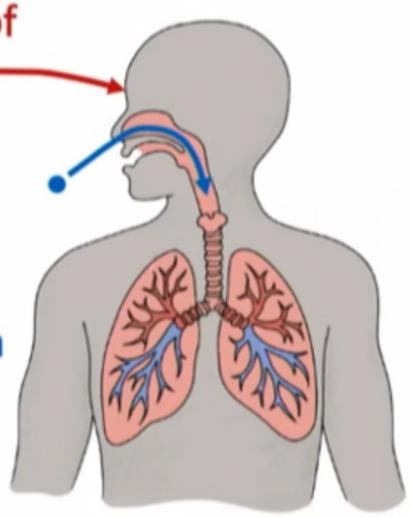
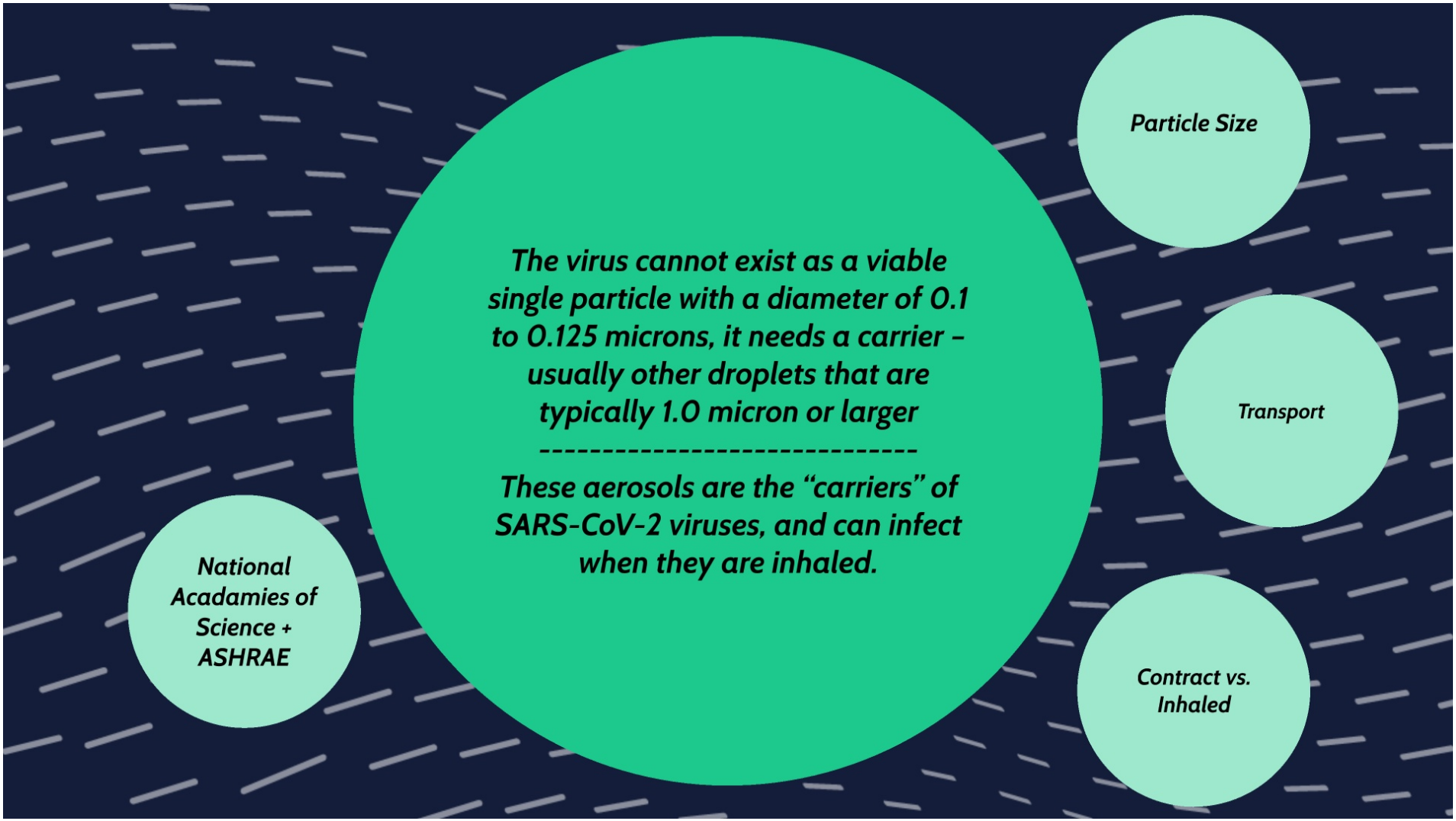
LARGE DROPLETS are sprayed onto the body, a form of contact transmission

AEROSOLS are inhaled into the respiratory system

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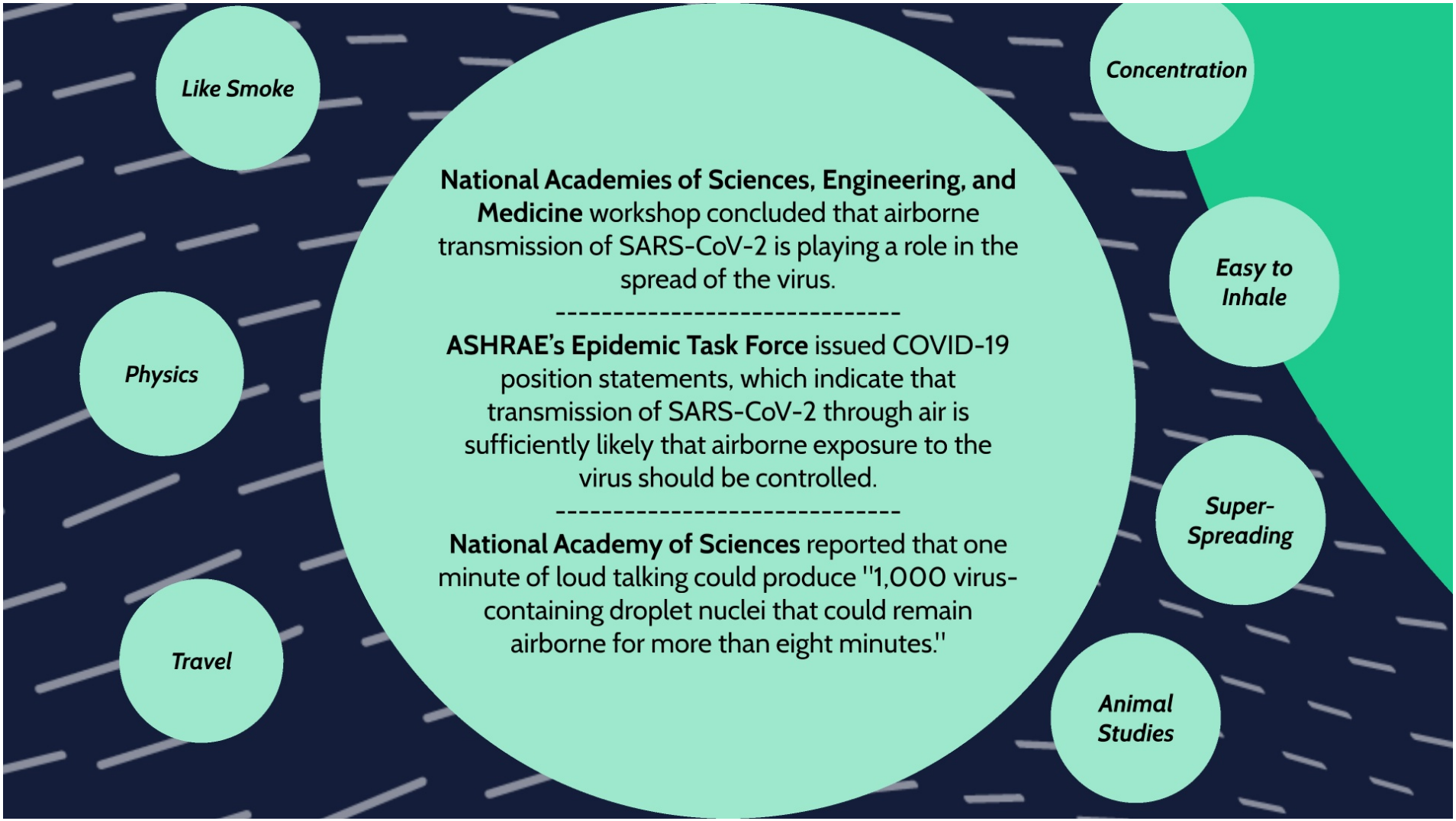
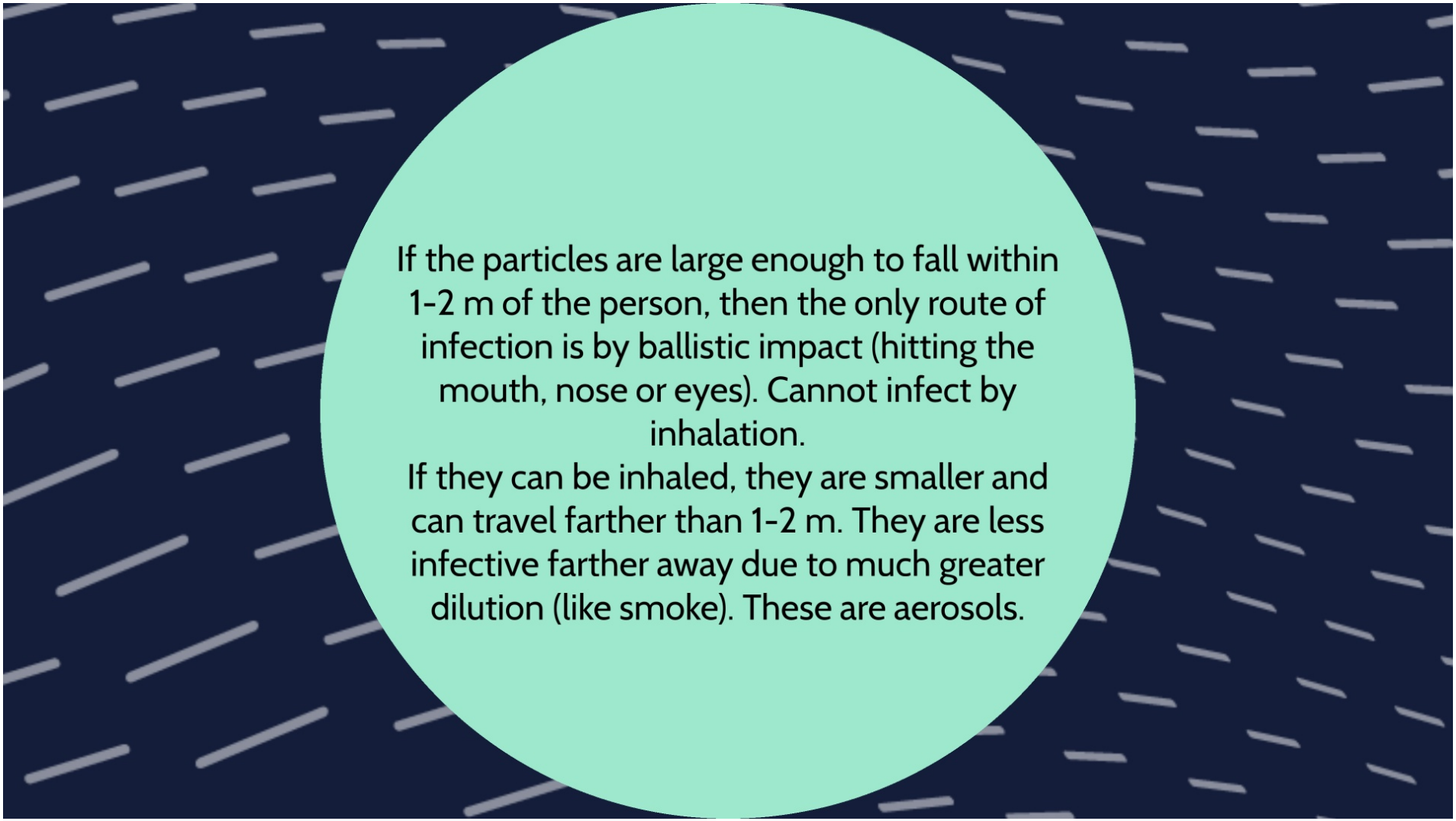
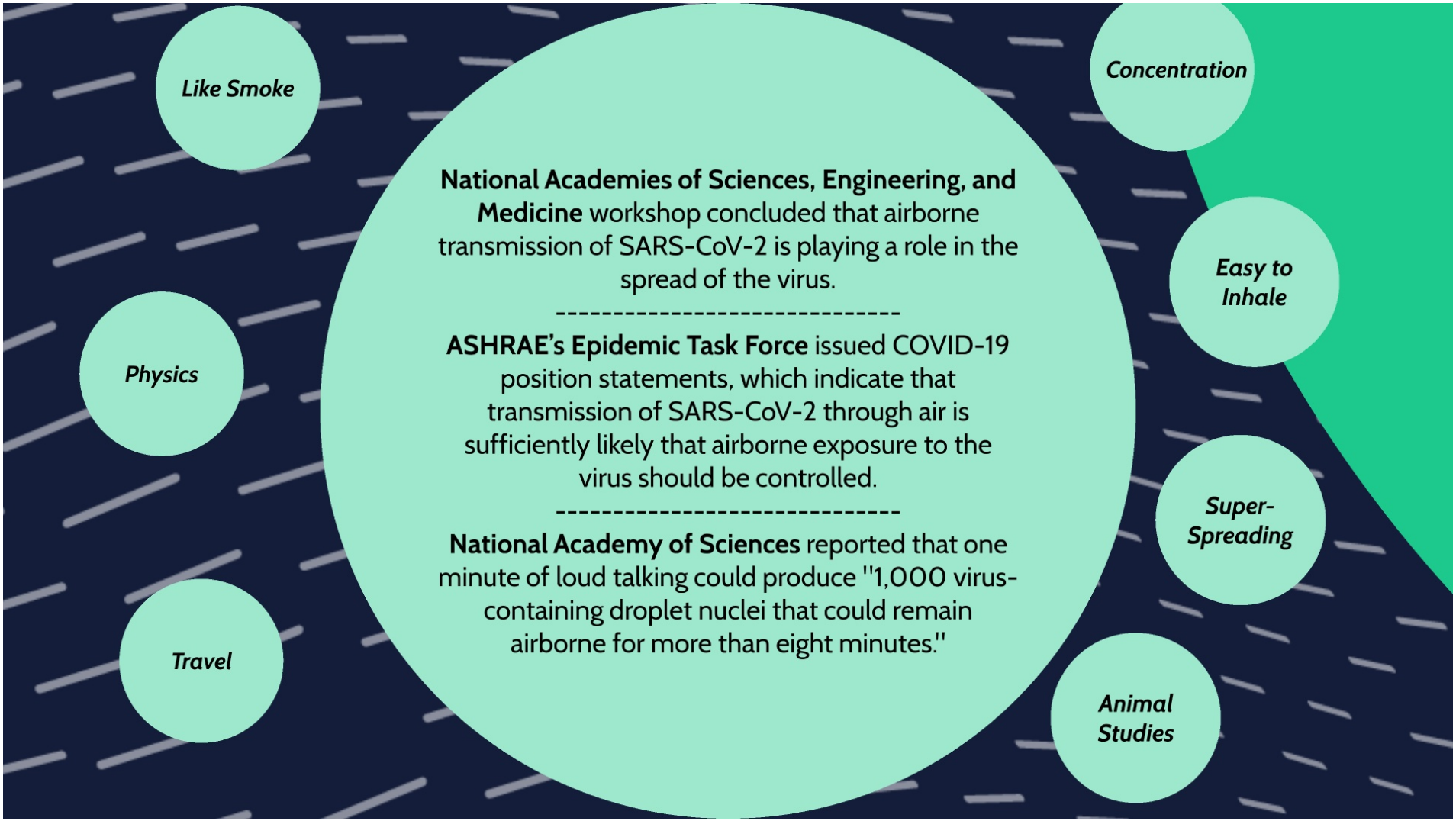

Like Smoke
Concentration
National Academies of Sciences, Engineering, and Medicine workshop concluded that airborne transmission of SARS-CoV-2 is playing a role in the spread of the virus.

ASHRAE's Epidemic Task Force issued COVID-19 position statements, which indicate that transmission of SARS-CoV-2 through air is sufficiently likely that airborne exposure to the virus should be controlled.

National Academy of Sciences reported that one minute of loud talking could produce "1,000 virus-containing droplet nuclei that could remain airborne for more than eight minutes."
Easy to Inhale
Physics
Super-Spreading
Travel
Animal Studies


If the particles are large enough to fall within 1-2 m of the person, then the only route of infection is by ballistic impact (hitting the mouth, nose or eyes). Cannot infect by inhalation.
If they can be inhaled, they are smaller and can travel farther than 1-2 m. They are less infective farther away due to much greater dilution (like smoke). These are aerosols.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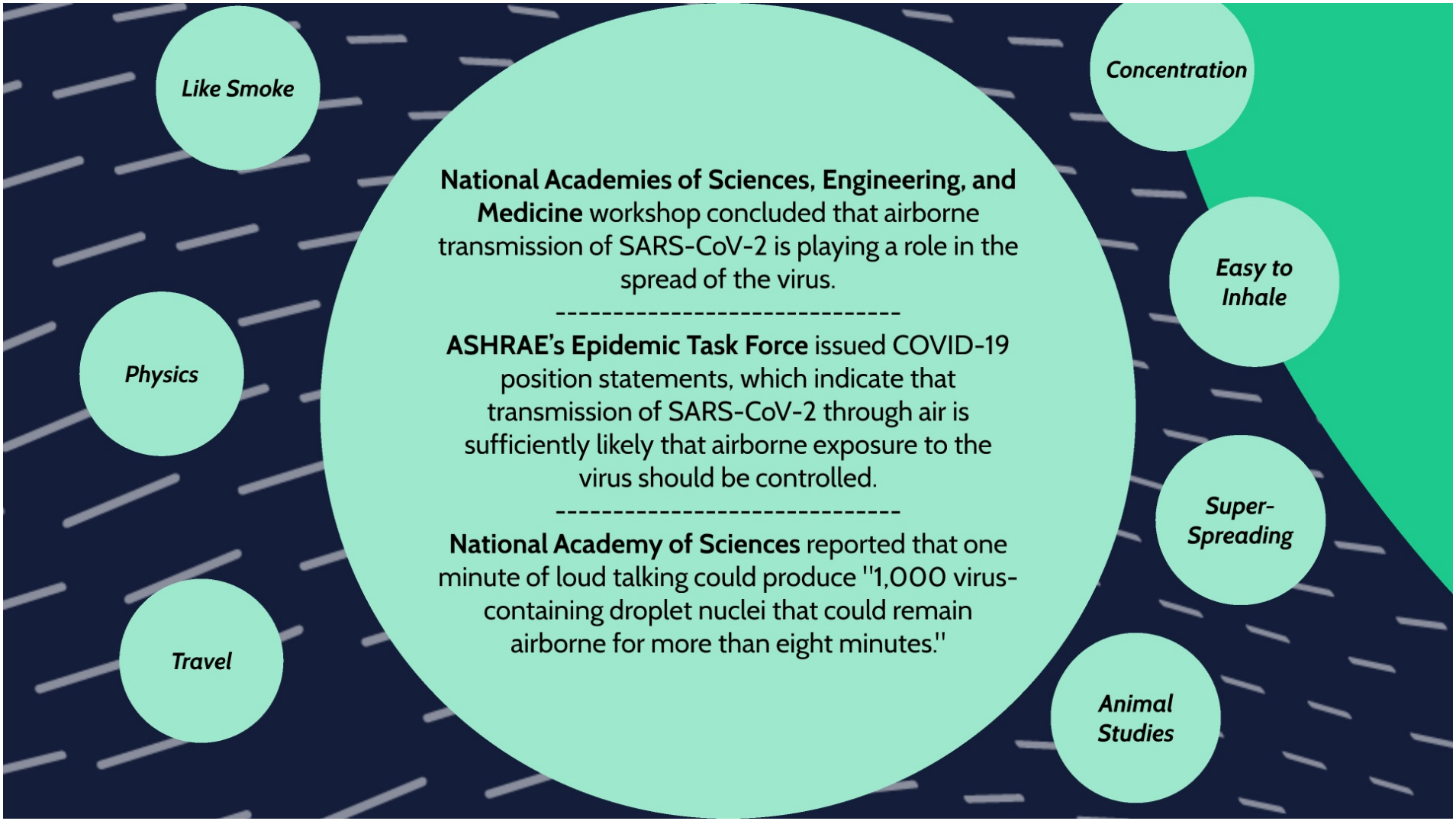
When talking, there are very few particles 300 um and larger (droplets), which are visible with the naked eye (a human hair is 80 um). And those very few particles have to hit very small targets: eyes, nostrils, mouth.

Aerosols stay in the air minutes to hours indoors, finely divided, many chances for inhalation.

Physics greatly favors aerosols and greatly disfavors droplets for infection under close proximity.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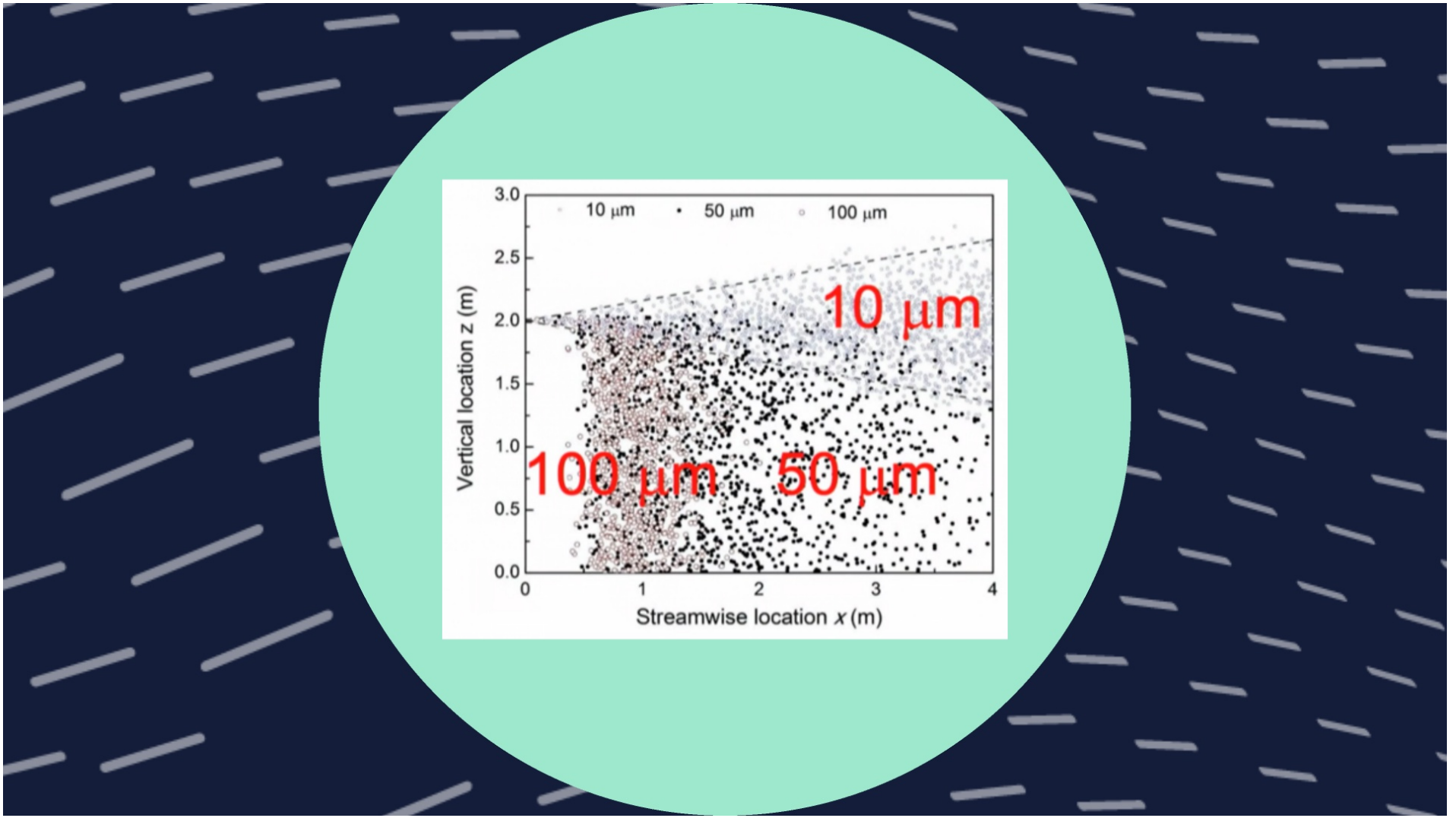
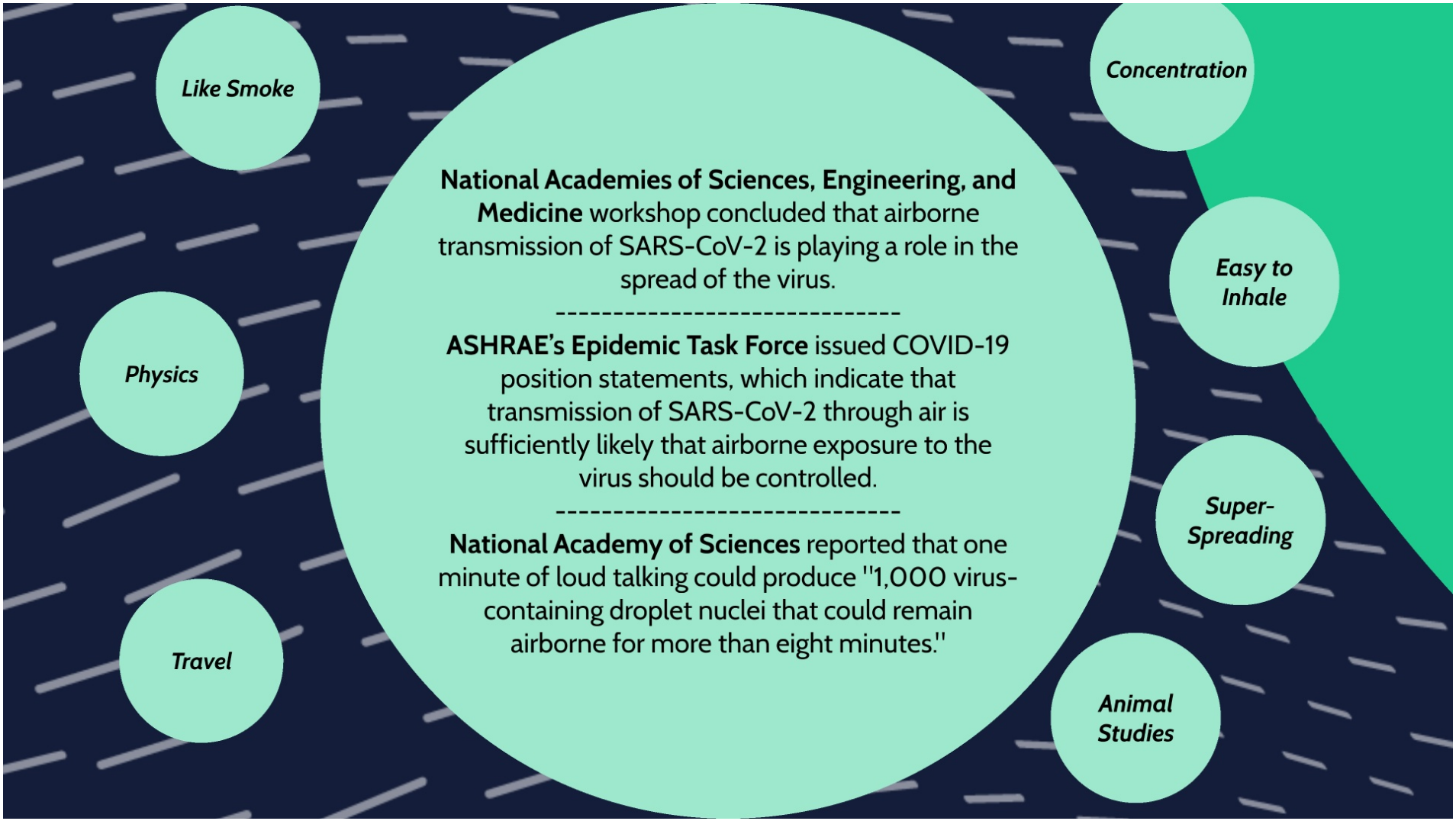

10 μm
50 μm
100 μm
Vertical location z (m)
Streamwise location x (m)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
10 μm
100 μm
50 μm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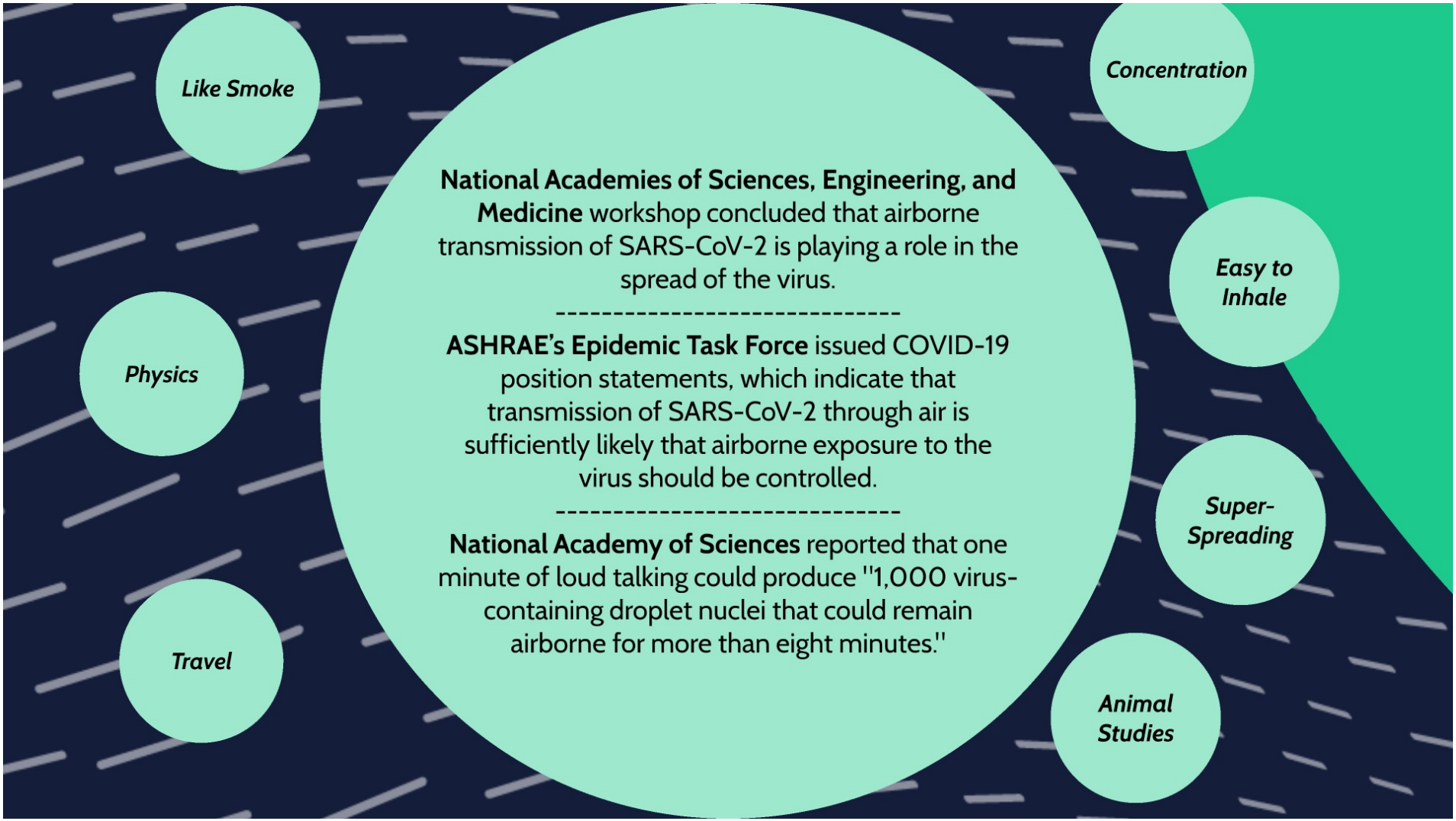
Larger Particles equate to less virus as they originate from the mouth. Smaller particles originate from deeper parts of the respiratory tract (location of the virus) and therefore contain higher virus concentration.

REHVA (the Federation of European Heating, Ventilation and Air Conditioning Associations) and **ASHRAE** have acknowledged the potential airborne hazard indoors and recommended ventilation control measures accordingly.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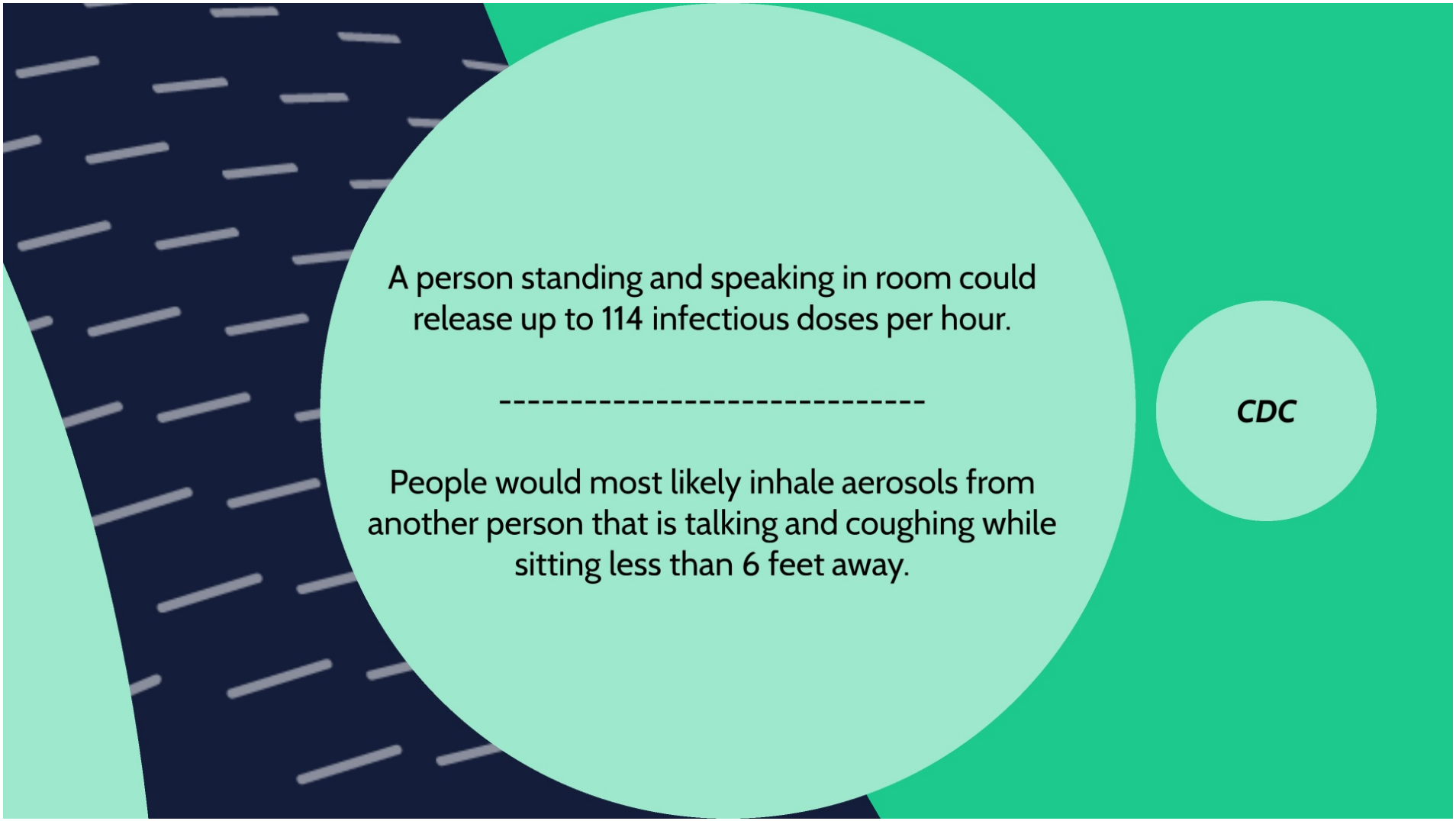
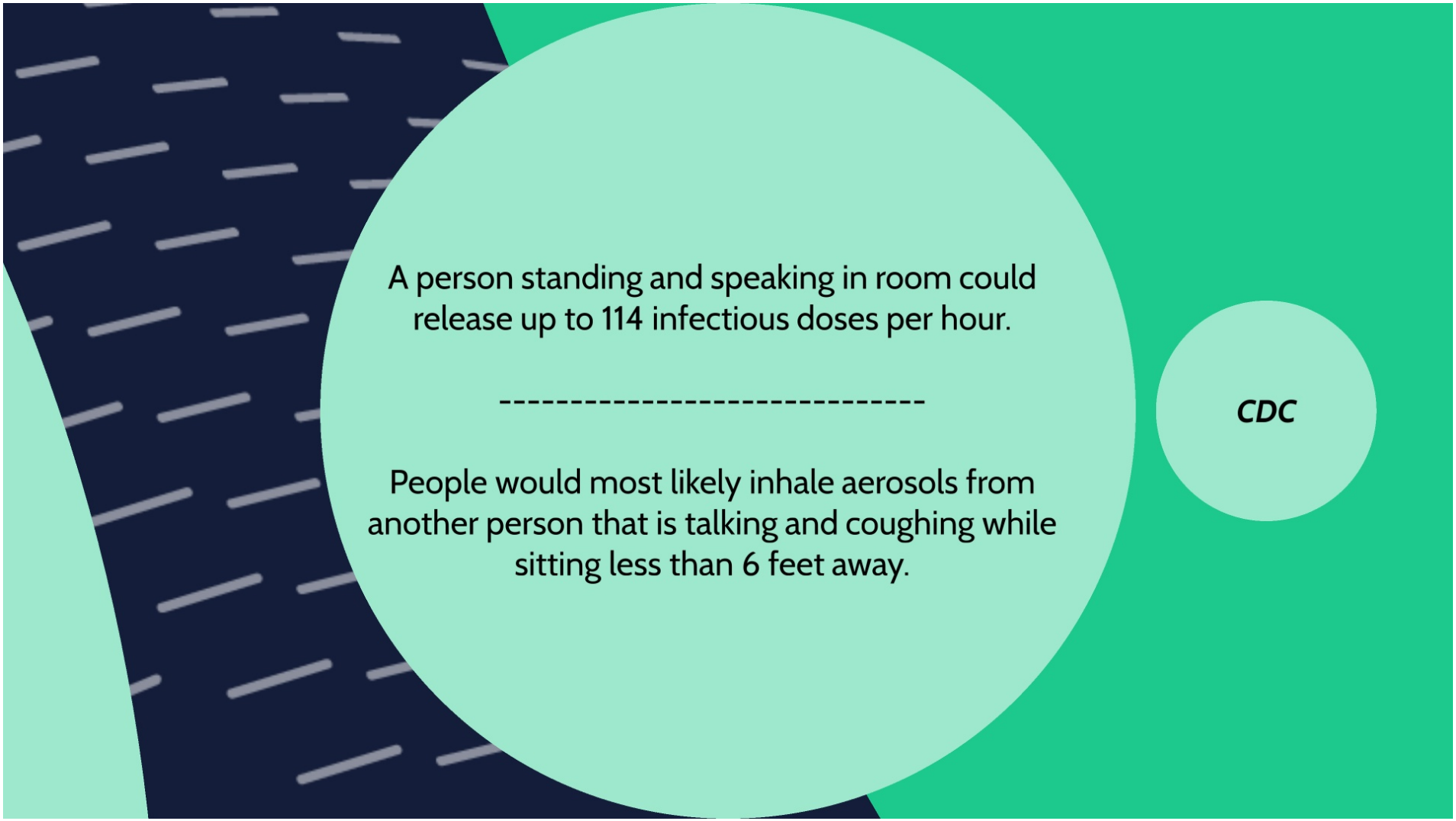

A person standing and speaking in room could release up to 114 infectious doses per hour.

People would most likely inhale aerosols from another person that is talking and coughing while sitting less than 6 feet away.
CDC

Airborne transmission of SARS-CoV-2 can occur under special circumstances

Pathogens that are mainly transmitted through close contact (i.e., contact transmission and droplet transmission) can sometimes also be spread via airborne transmission under special circumstances. There are several well-documented examples in which SARS-CoV-2 appears to have been transmitted over long distances or times. These transmission events appear uncommon and have typically involved the presence of an infectious person producing respiratory droplets for an extended time (>30 minutes to multiple hours) in an enclosed space. Enough virus was present in the space to cause infections in people who were more than 6 feet away or who passed through that space soon after the infectious person had left. Circumstances under which airborne transmission of SARS-CoV-2 appears to have occurred include:

- **Enclosed spaces** within which an infectious person either exposed susceptible people at the same time or to which susceptible people were exposed shortly after the infectious person had left the space.
- **Prolonged exposure to respiratory particles**, often generated with expiratory exertion (e.g., shouting, singing, exercising) that increased the concentration of suspended respiratory droplets in the air space.
- **Inadequate ventilation or air handling** that allowed a build-up of suspended small respiratory droplets and particles.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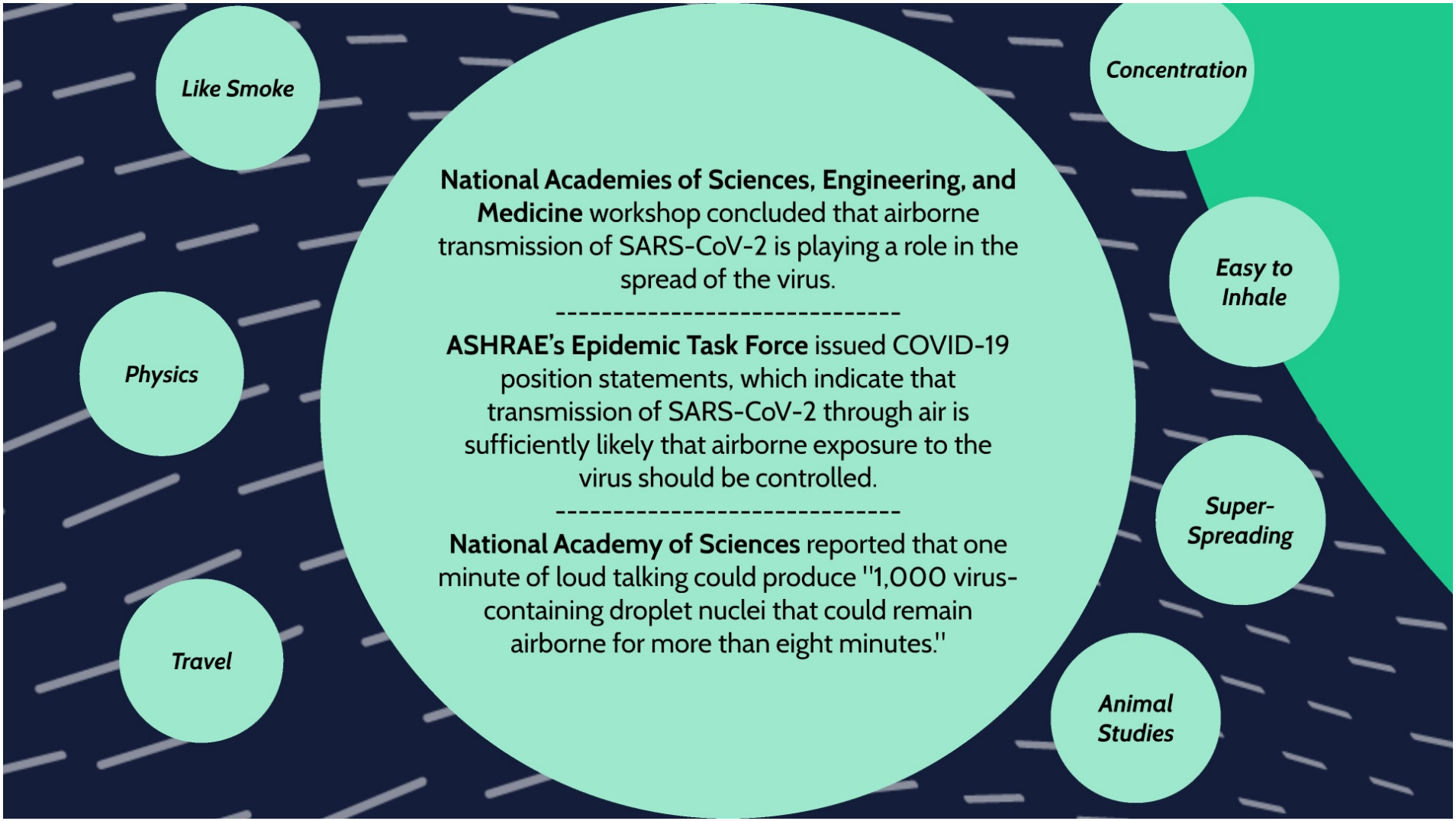
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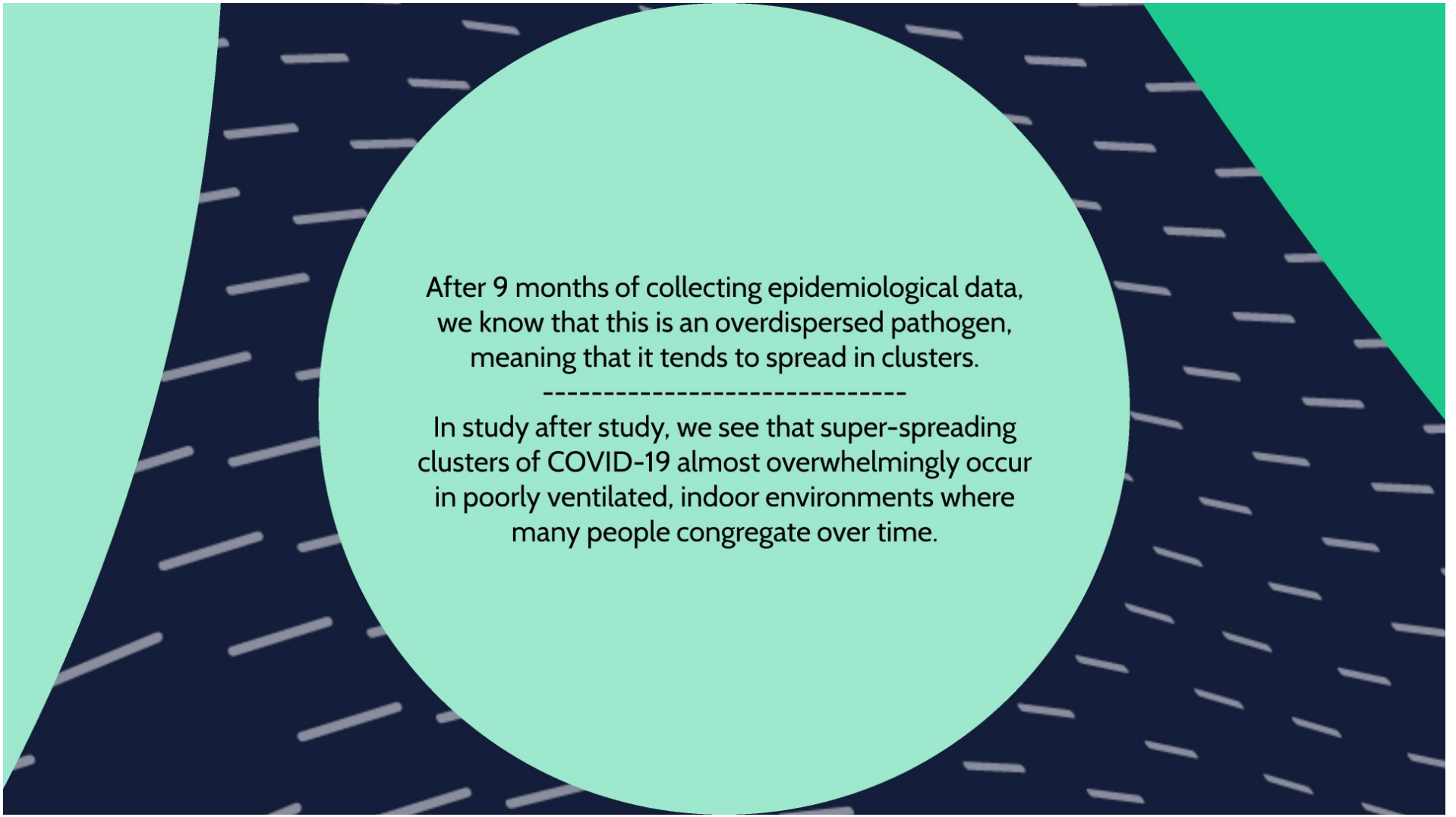
After 9 months of collecting epidemiological data, we know that this is an overdispersed pathogen, meaning that it tends to spread in clusters.

In study after study, we see that super-spreading clusters of COVID-19 almost overwhelmingly occur in poorly ventilated, indoor environments where many people congregate over time.

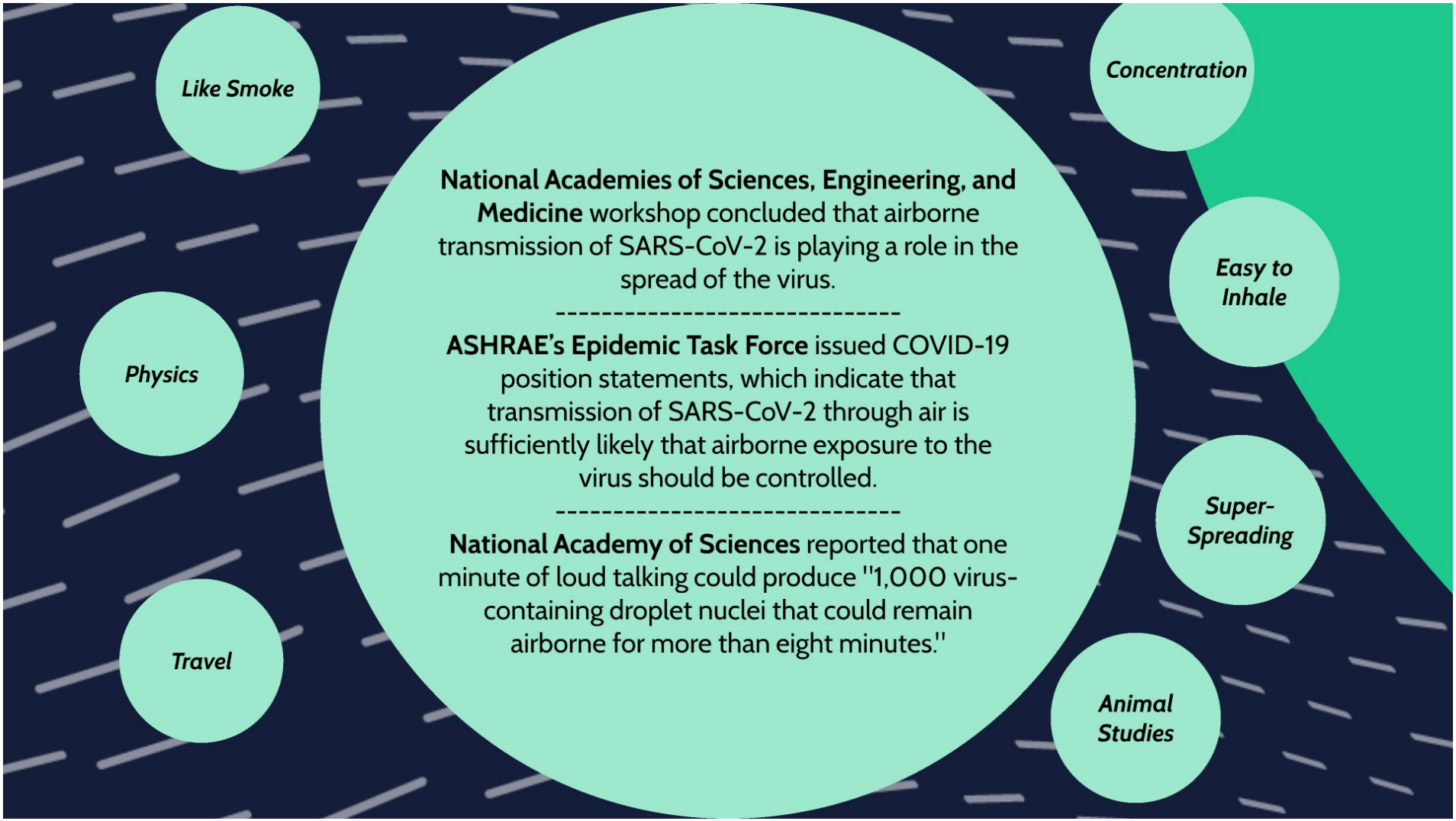
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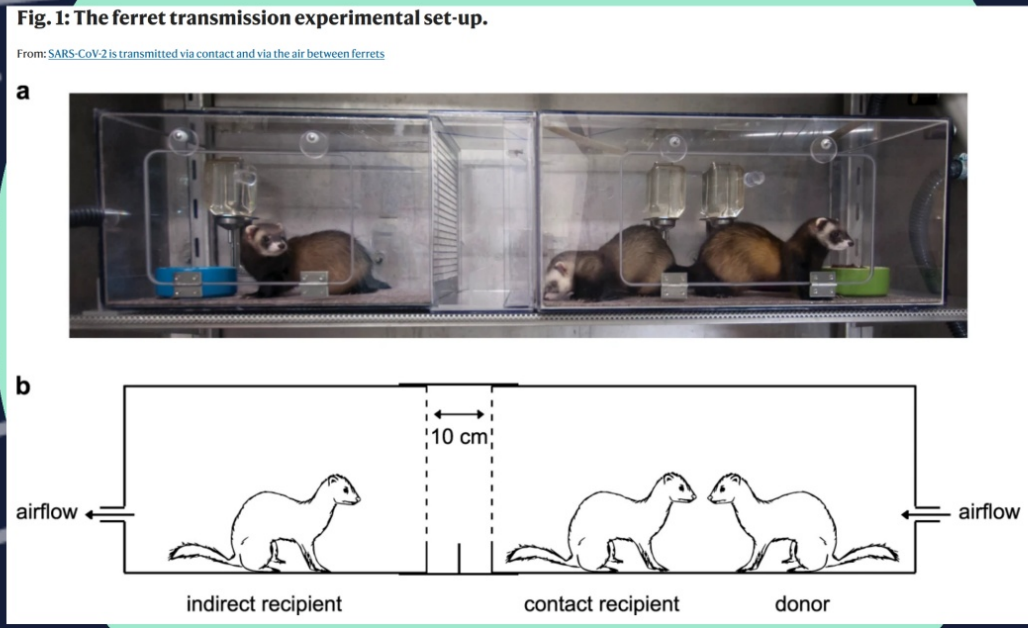
Fig. 1: The ferret transmission experimental set-up.

From: SARS-CoV-2 is transmitted via contact and via the air between ferrets

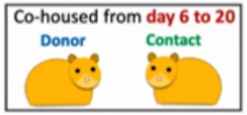


Hampster Study

Multi-route transmission of SARS-CoV-2 in golden hamsters

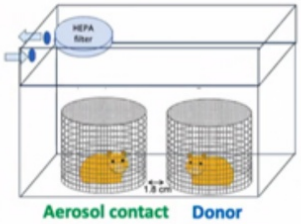
Direct contact transmission

- Dose of intra-nasal inoculation: 8×10^4 $TCID_{50}$
- Efficient transmission by direct contact (3/3).



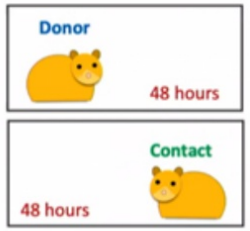
- No transmission by direct contact (0/3).
- Communicable period is short.

Aerosol transmission



- Contacts were exposed to donors for 8 hours on day 1 post-inoculation.
- Efficient aerosol transmission (3/3).

Fomite transmission



- Contacts were single-housed in donors' soiled cages for **48 hours**.
- Inefficient fomite transmission (1/3).

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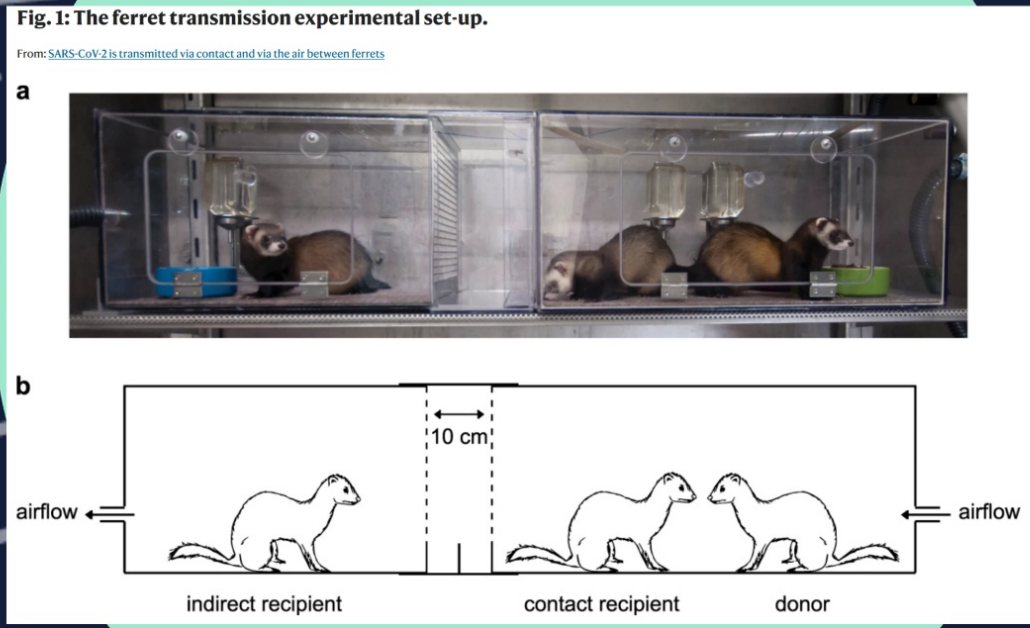

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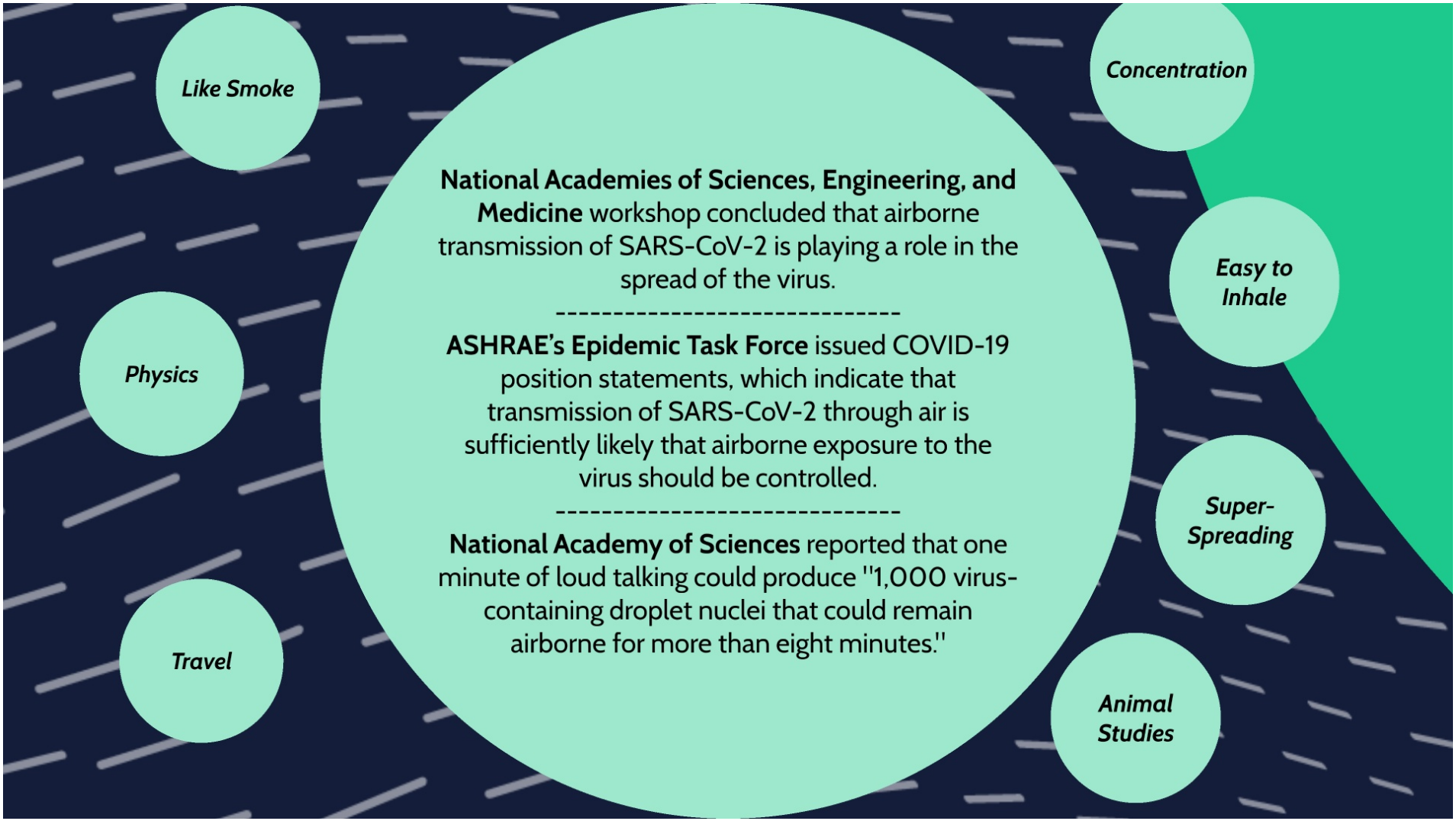
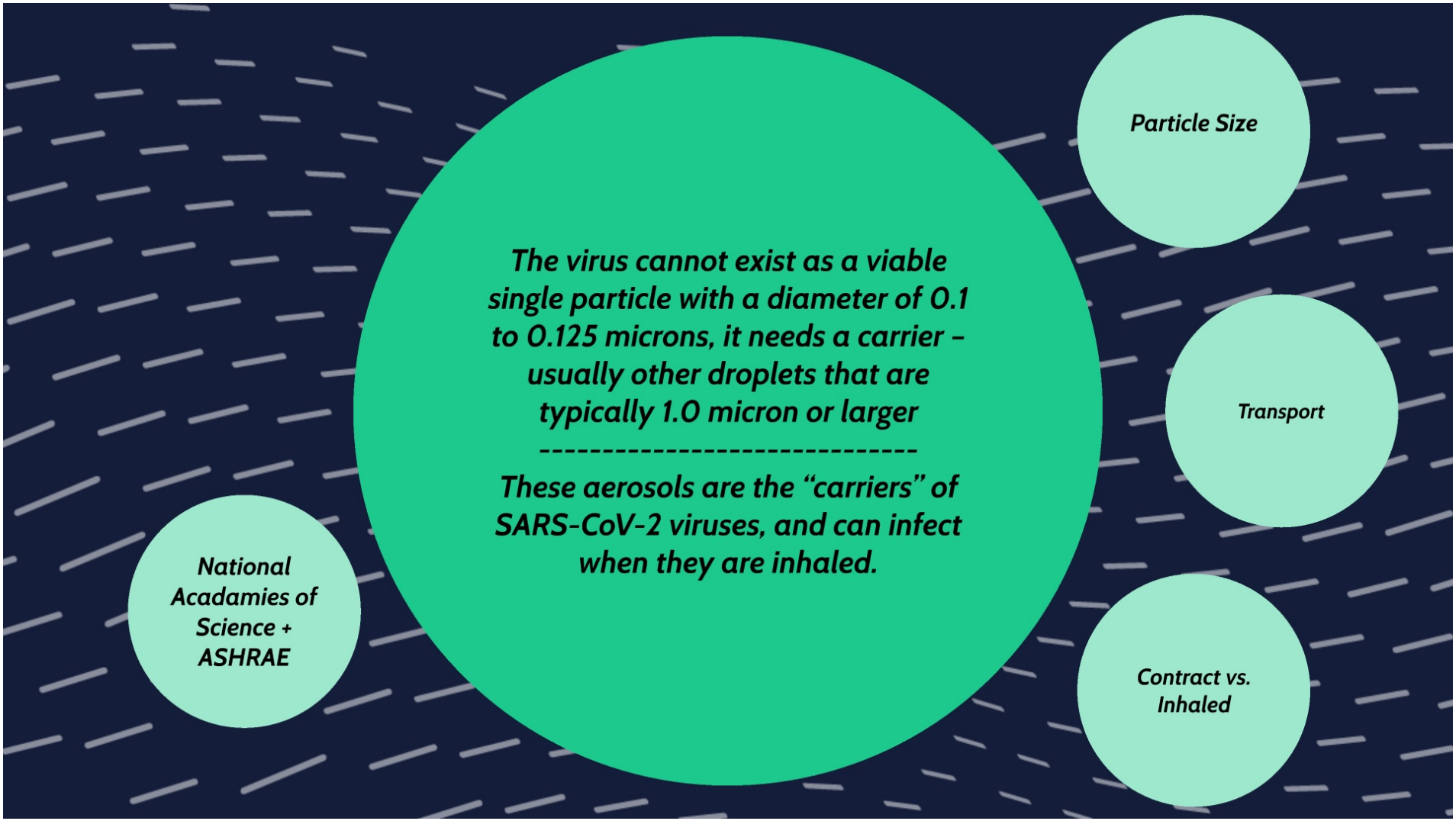
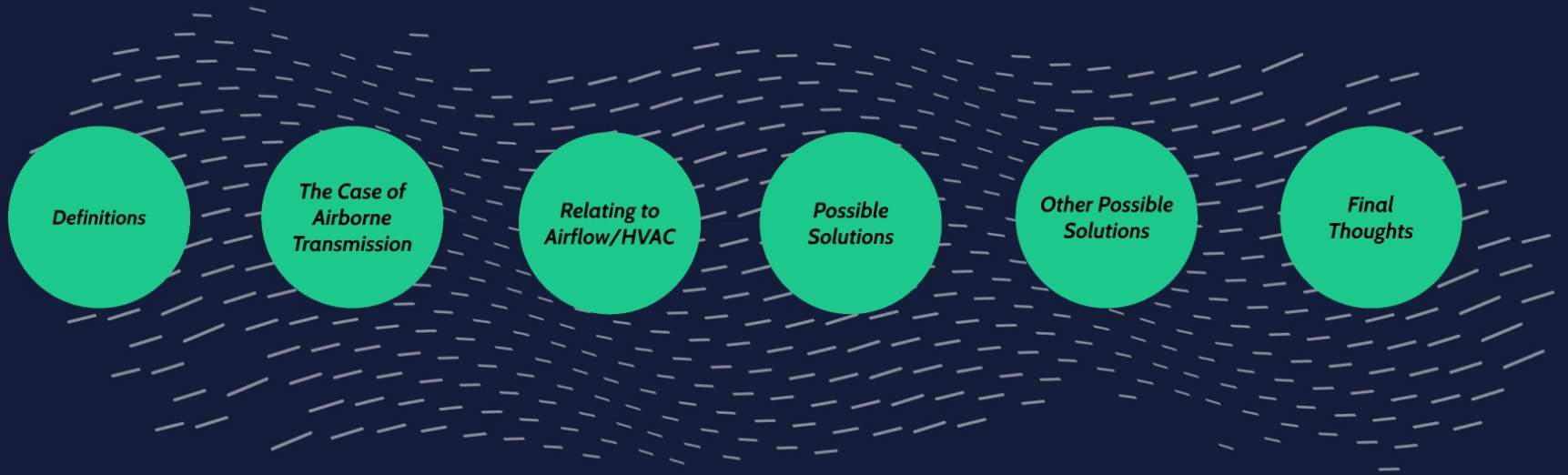

Like Smoke
Concentration
National Academies of Sciences, Engineering, and Medicine workshop concluded that airborne transmission of SARS-CoV-2 is playing a role in the spread of the virus.

ASHRAE's Epidemic Task Force issued COVID-19 position statements, which indicate that transmission of SARS-CoV-2 through air is sufficiently likely that airborne exposure to the virus should be controlled.

National Academy of Sciences reported that one minute of loud talking could produce "1,000 virus-containing droplet nuclei that could remain airborne for more than eight minutes."
Easy to Inhale
Physics
Super-Spreading
Travel
Animal Studies


The virus cannot exist as a viable single particle with a diameter of 0.1 to 0.125 microns, it needs a carrier – usually other droplets that are typically 1.0 micron or larger
---
These aerosols are the "carriers" of SARS-CoV-2 viruses, and can infect when they are inhaled.
Particle Size
Transport
Contract vs. Inhaled
National Acadamies of Science + ASHRAE

Aerosols, COVID-19 & HVAC



Ventilation

Governing Bodies Positions

Outbreaks

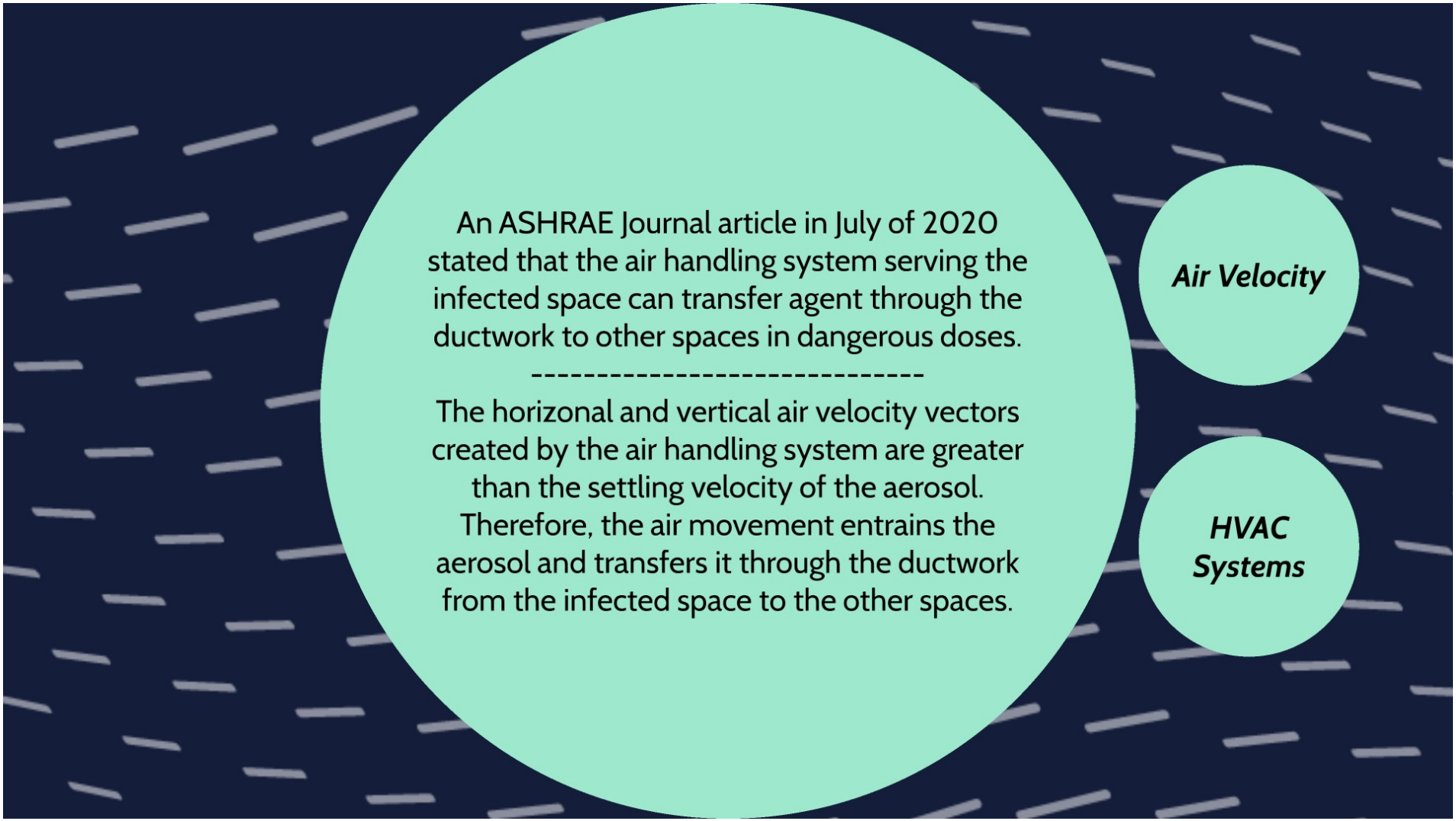
Where Should Our Focus Be?

Indoor Air Flow

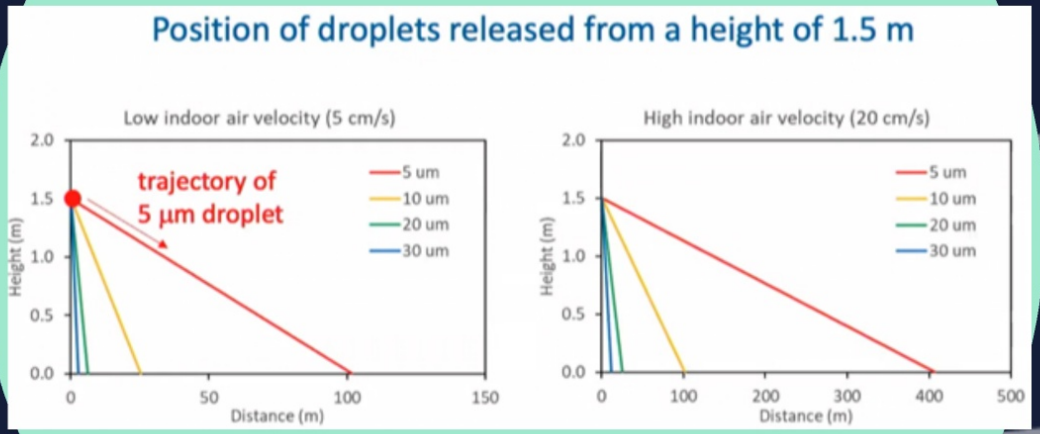
How Aerosols Behave Indoors

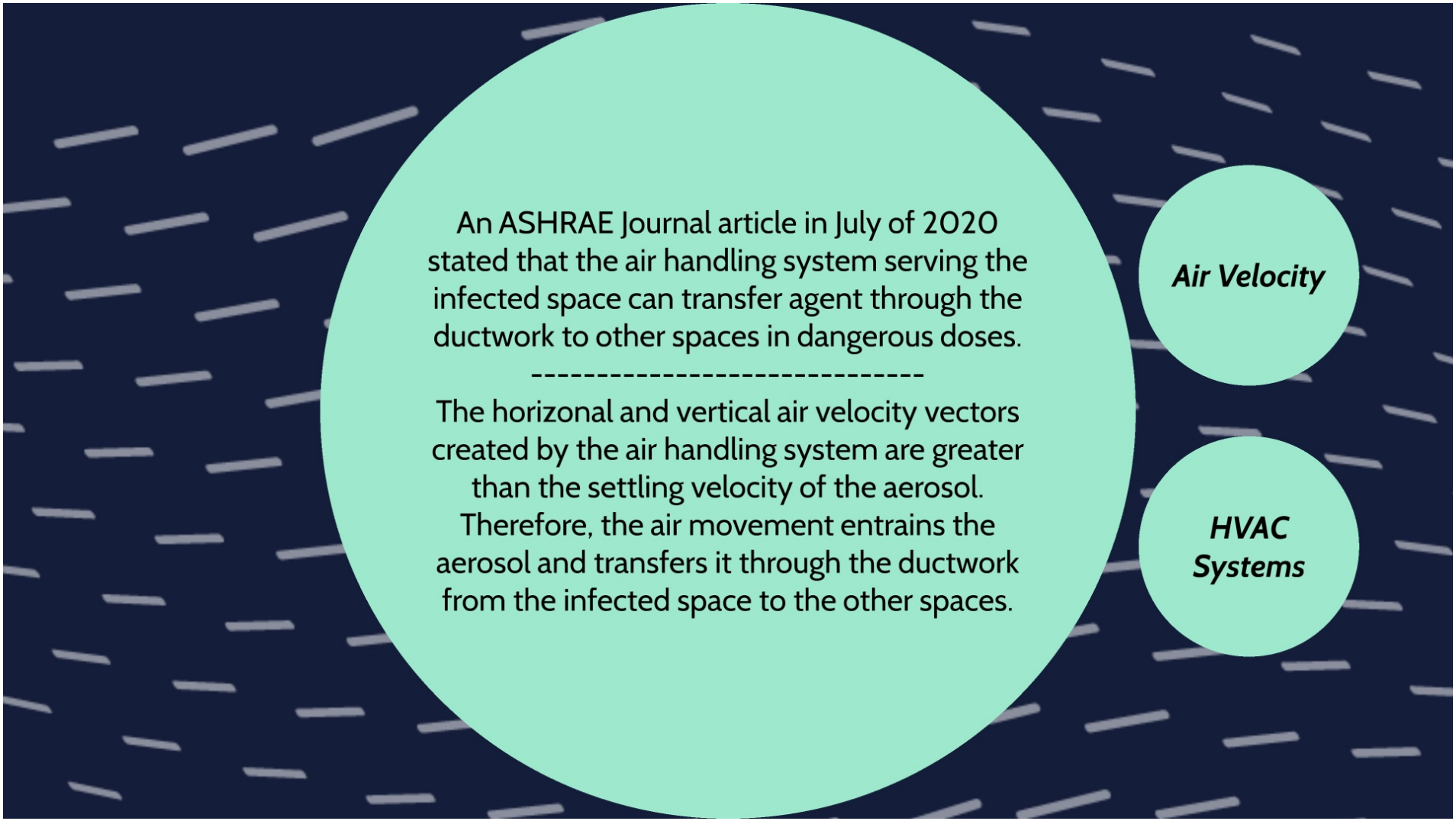
A 1988 study found that the cigarettes smoke particle size of six different brands all had an average diameter of 0.1 microns. As we know, COVID-19 has a diameter of 0.1 to 0.125 microns, and just like cigarette smoke, it usually travels with a carrier.


ASHRAE
Journal
Both the World Health Organization and U.S. Centers for Disease Control and Prevention say that poor ventilation increases the risk of transmitting the coronavirus.


An ASHRAE Journal article in July of 2020 stated that the air handling system serving the infected space can transfer agent through the ductwork to other spaces in dangerous doses.

The horizonal and vertical air velocity vectors created by the air handling system are greater than the settling velocity of the aerosol. Therefore, the air movement entrains the aerosol and transfers it through the ductwork from the infected space to the other spaces.
Air Velocity
HVAC Systems


Position of droplets released from a height of 1.5 m
Low indoor air velocity (5 cm/s)
trajectory of
5 µm droplet
5 um
10 um
20 um
30 um
Height (m)
2.0
1.5
1.0
0.5
0.0
0
50
100
150
Distance (m)
High indoor air velocity (20 cm/s)
5 um
10 um
20 um
30 um
Height (m)
2.0
1.5
1.0
0.5
0.0
0
100
200
300
400
500
Distance (m)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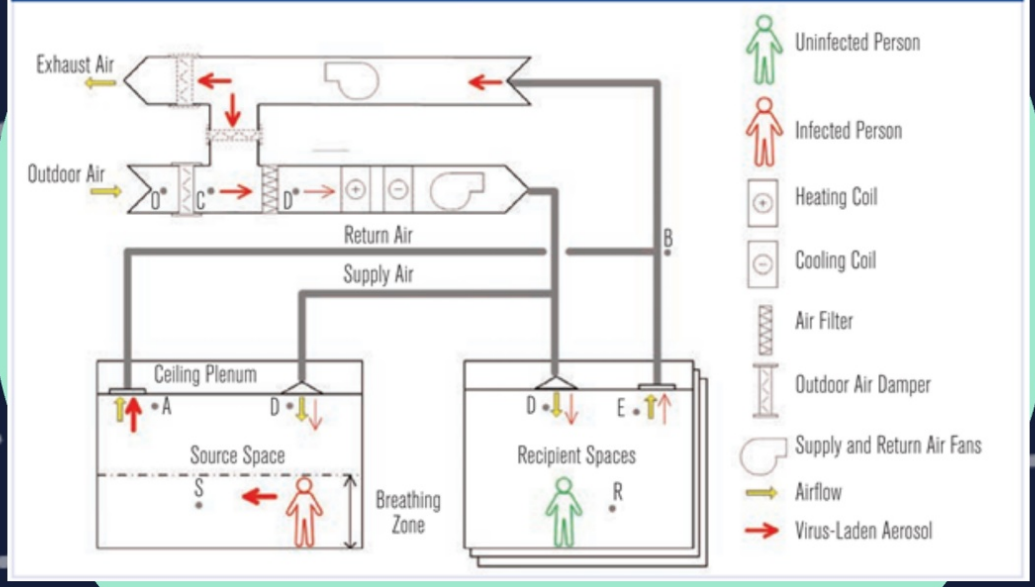
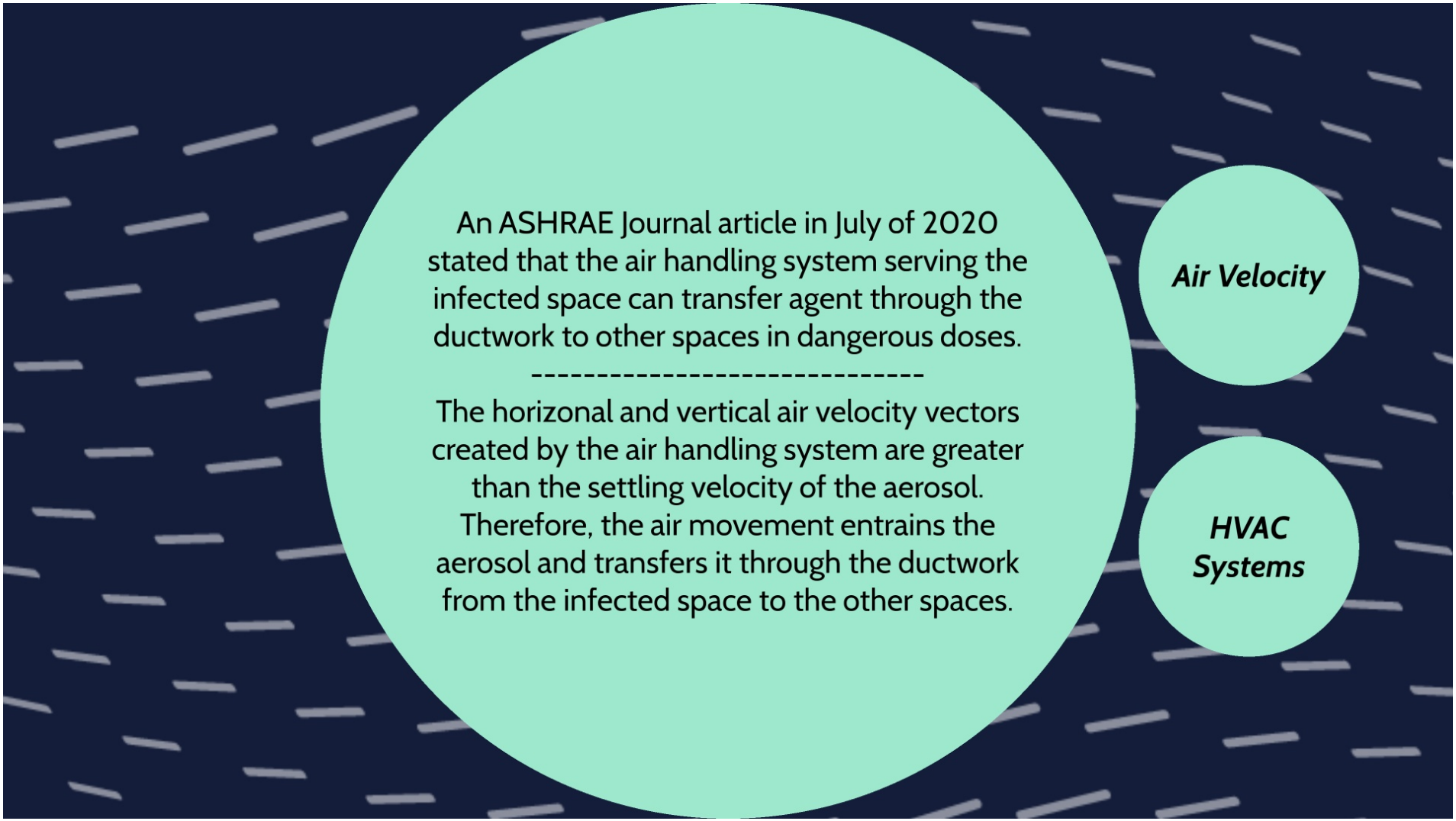
Air Velocity
HVAC Systems

FIGURE 2 Diagram of the virus-laden aerosol travel through air-handling system.

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Outbreaks

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Indoor Air Flow


OLD FORESTER
F-100


F-100
OLD FORESTER
BOTTLED BOURBON

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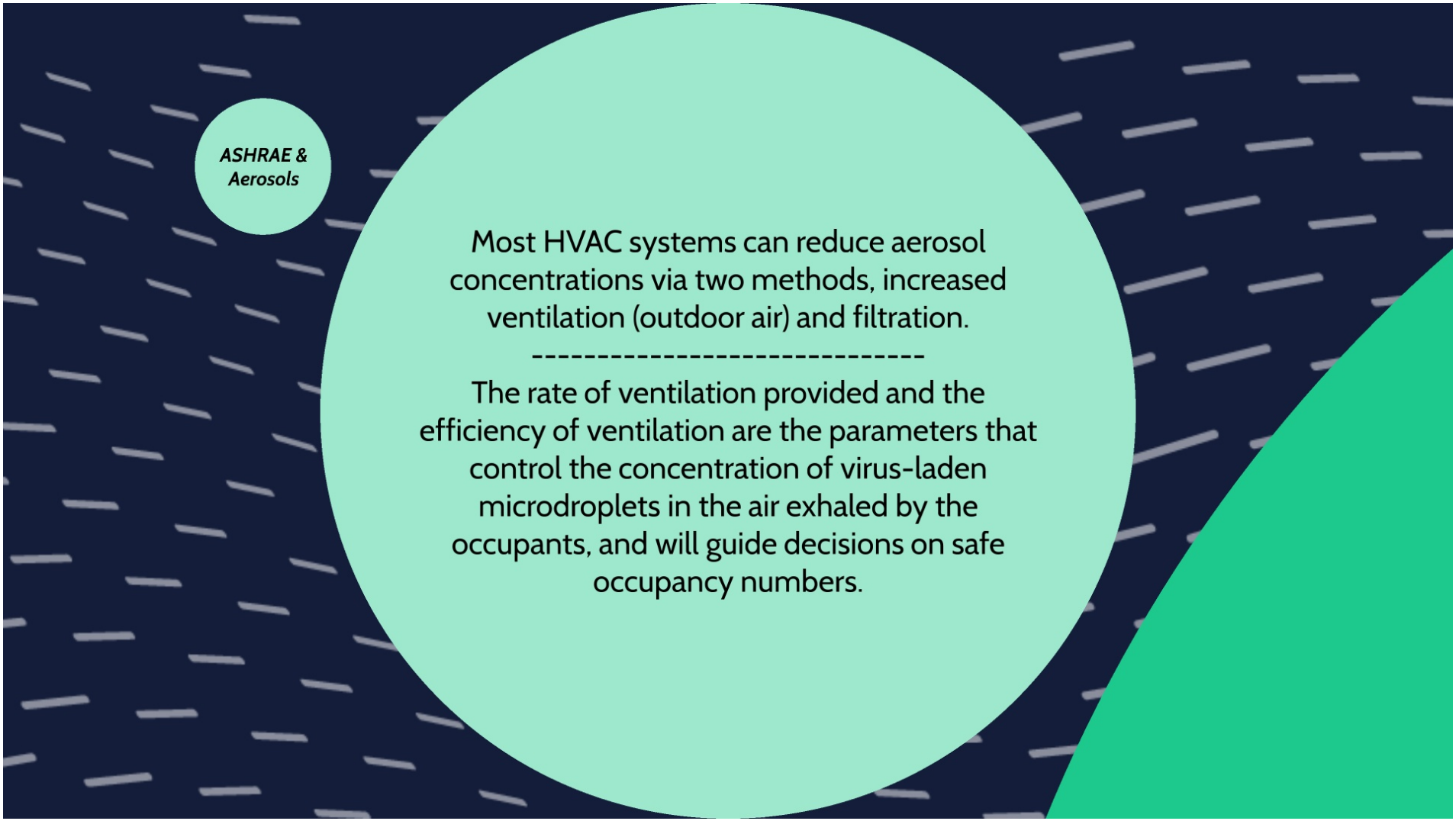
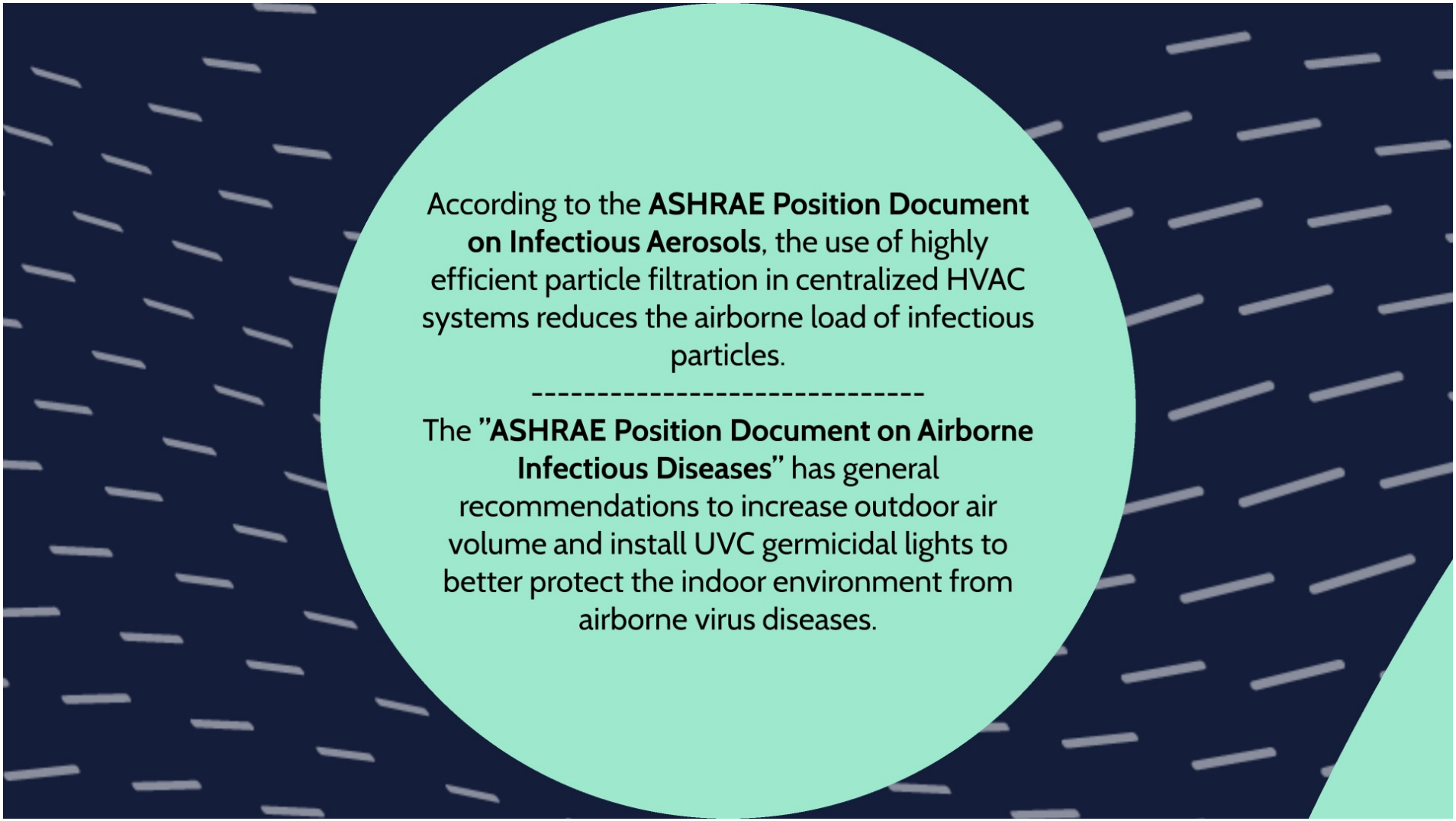
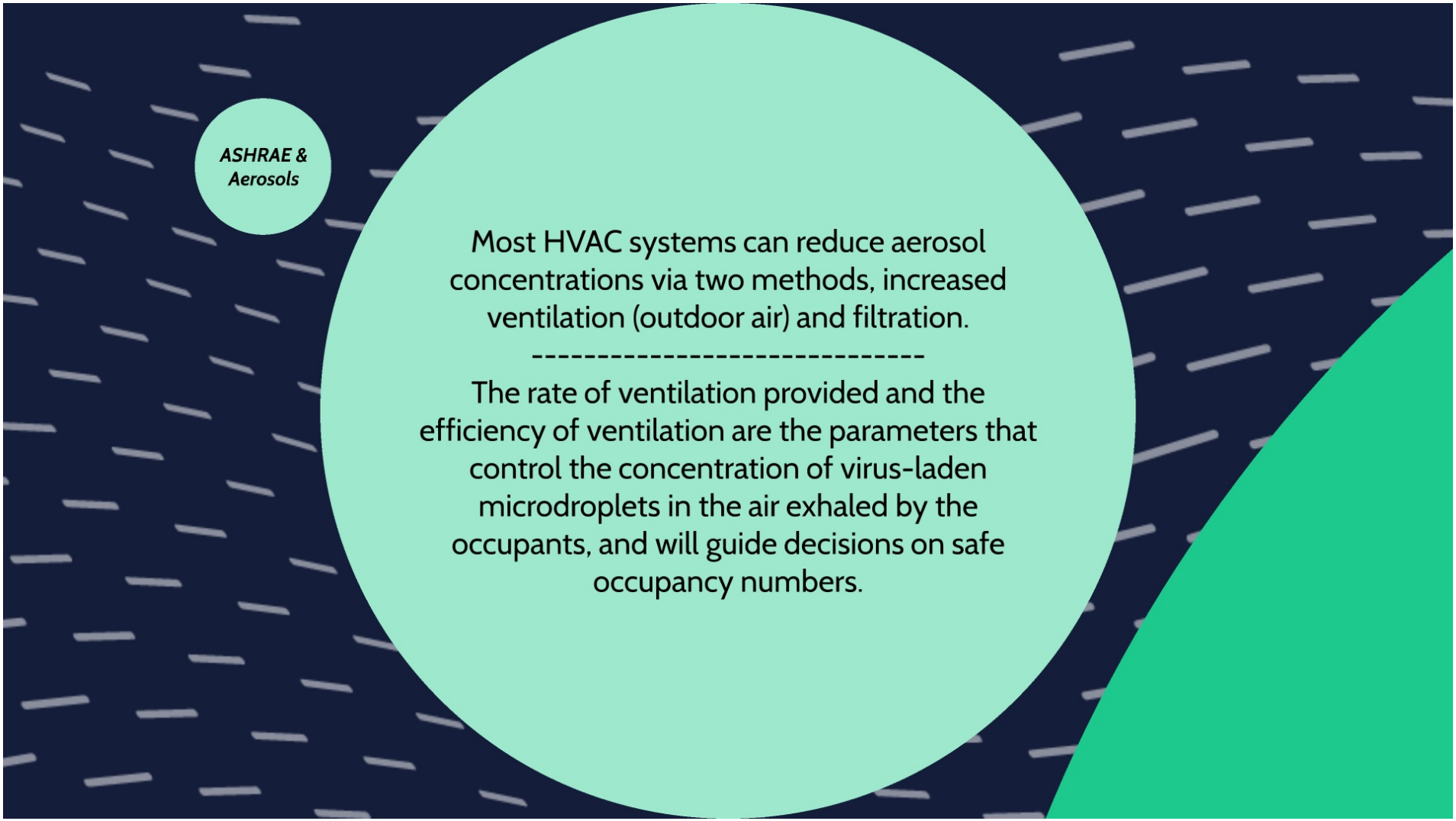

ASHRAE &
Aerosols
Most HVAC systems can reduce aerosol concentrations via two methods, increased ventilation (outdoor air) and filtration.

The rate of ventilation provided and the efficiency of ventilation are the parameters that control the concentration of virus-laden microdroplets in the air exhaled by the occupants, and will guide decisions on safe occupancy numbers.


According to the **ASHRAE Position Document on Infectious Aerosols**, the use of highly efficient particle filtration in centralized HVAC systems reduces the airborne load of infectious particles.

The **"ASHRAE Position Document on Airborne Infectious Diseases"** has general recommendations to increase outdoor air volume and install UVC germicidal lights to better protect the indoor environment from airborne virus diseases.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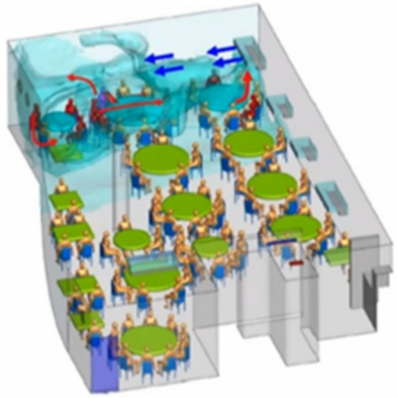
Aerosol Concentration

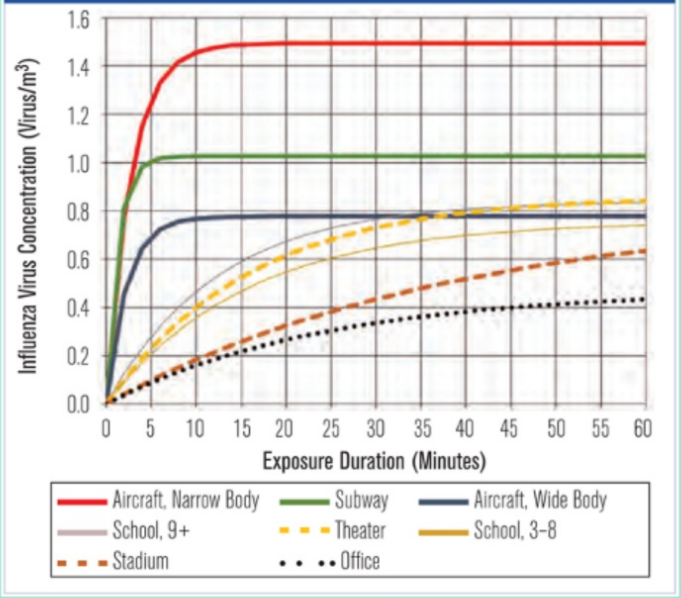
Likely Transmission in Restaurant, Guangzhou, China



- Internal air circulated by fan coil AC units
- Tracer gas tracked in restaurant as a surrogate for exhaled droplets
- Index patient (purple) transmitted 5 others (red) at adjacent tables but not to other patrons or staff in the room
- Authors speculate fine droplets were distributed by air currents from AC unit

Li Y, et al. *MedRxIV preprint* https://doi.org/10.1101/2020.04.16.20067728

FIGURE 2 Infectious aerosol concentration versus time predictions in the air in the eight settings for a group of 20 persons with one ill person within the group and assuming uniform mixing for the group. It shows how infectious aerosol concentration reaches its equilibrium concentration more quickly the higher the occupancy density, which in turn makes for a potentially higher viral inhalation dose.[14]



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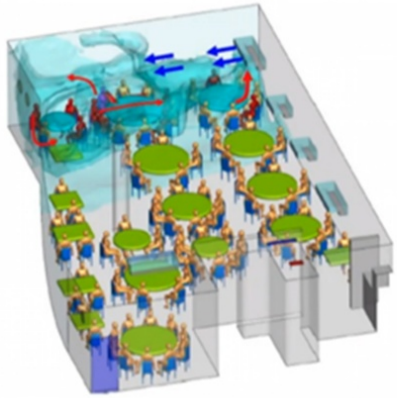

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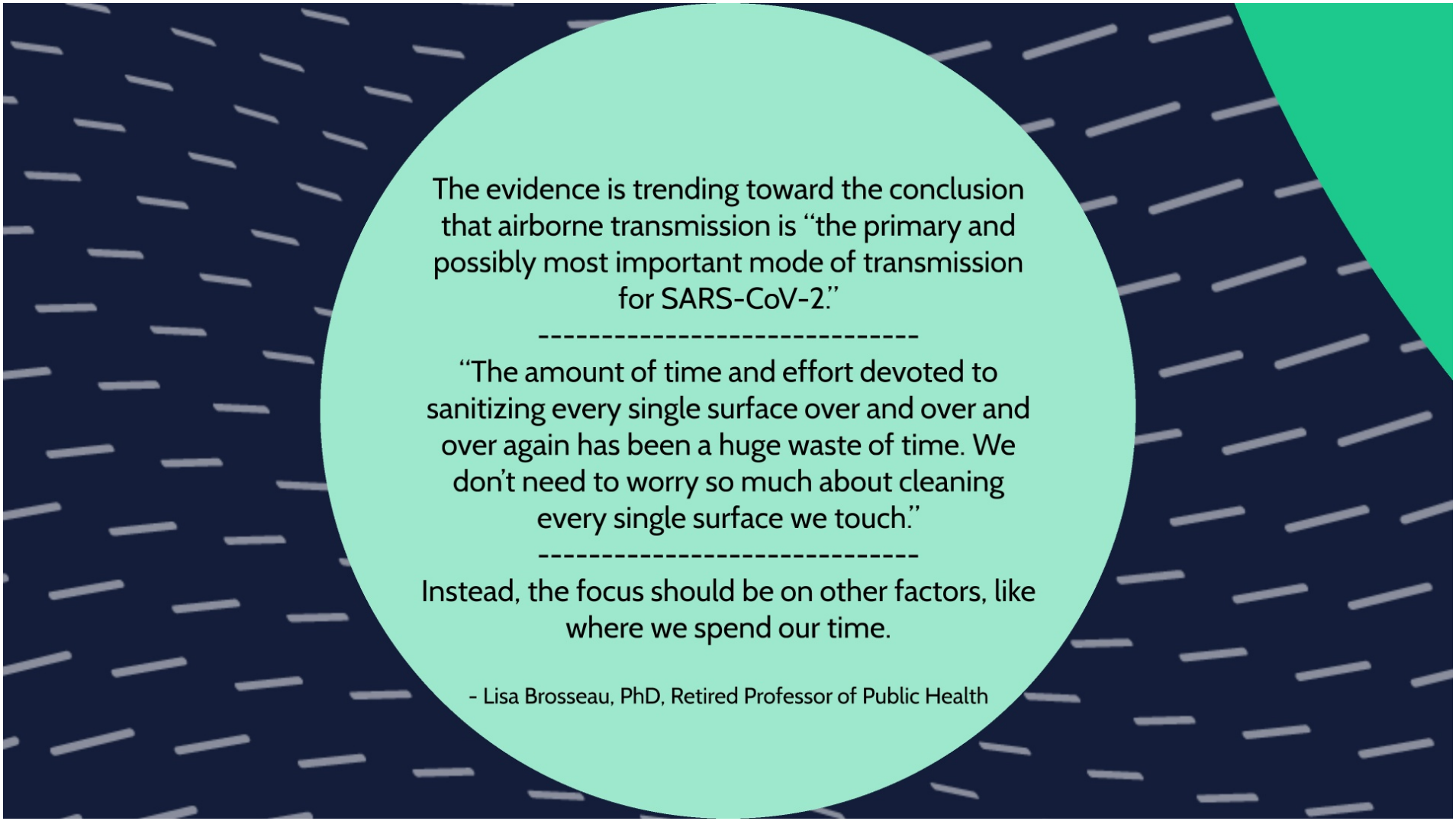
The evidence is trending toward the conclusion that airborne transmission is "the primary and possibly most important mode of transmission for SARS-CoV-2."

"The amount of time and effort devoted to sanitizing every single surface over and over and over again has been a huge waste of time. We don't need to worry so much about cleaning every single surface we touch."

Instead, the focus should be on other factors, like where we spend our time.
- Lisa Brosseau, PhD, Retired Professor of Public Health

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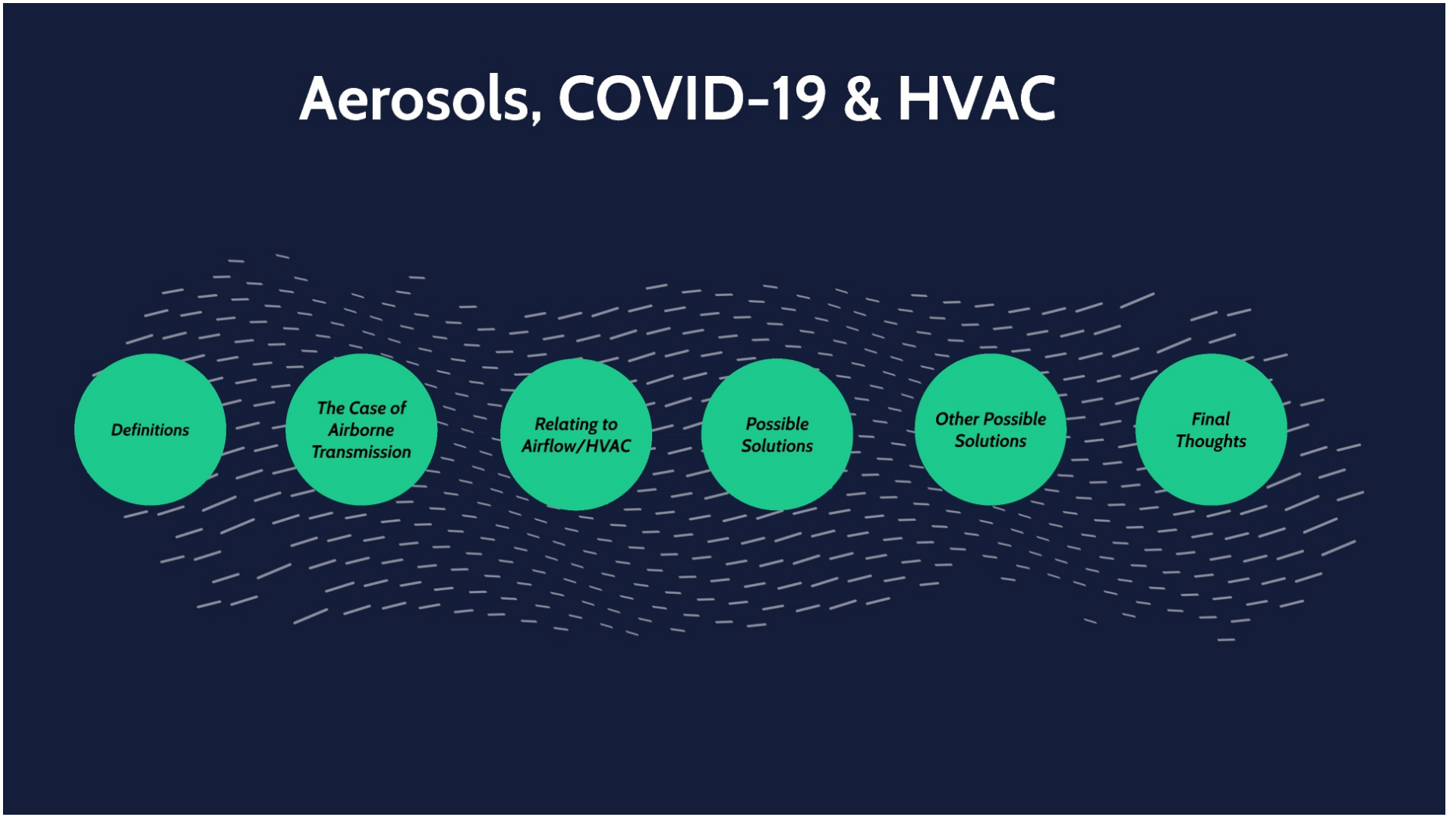
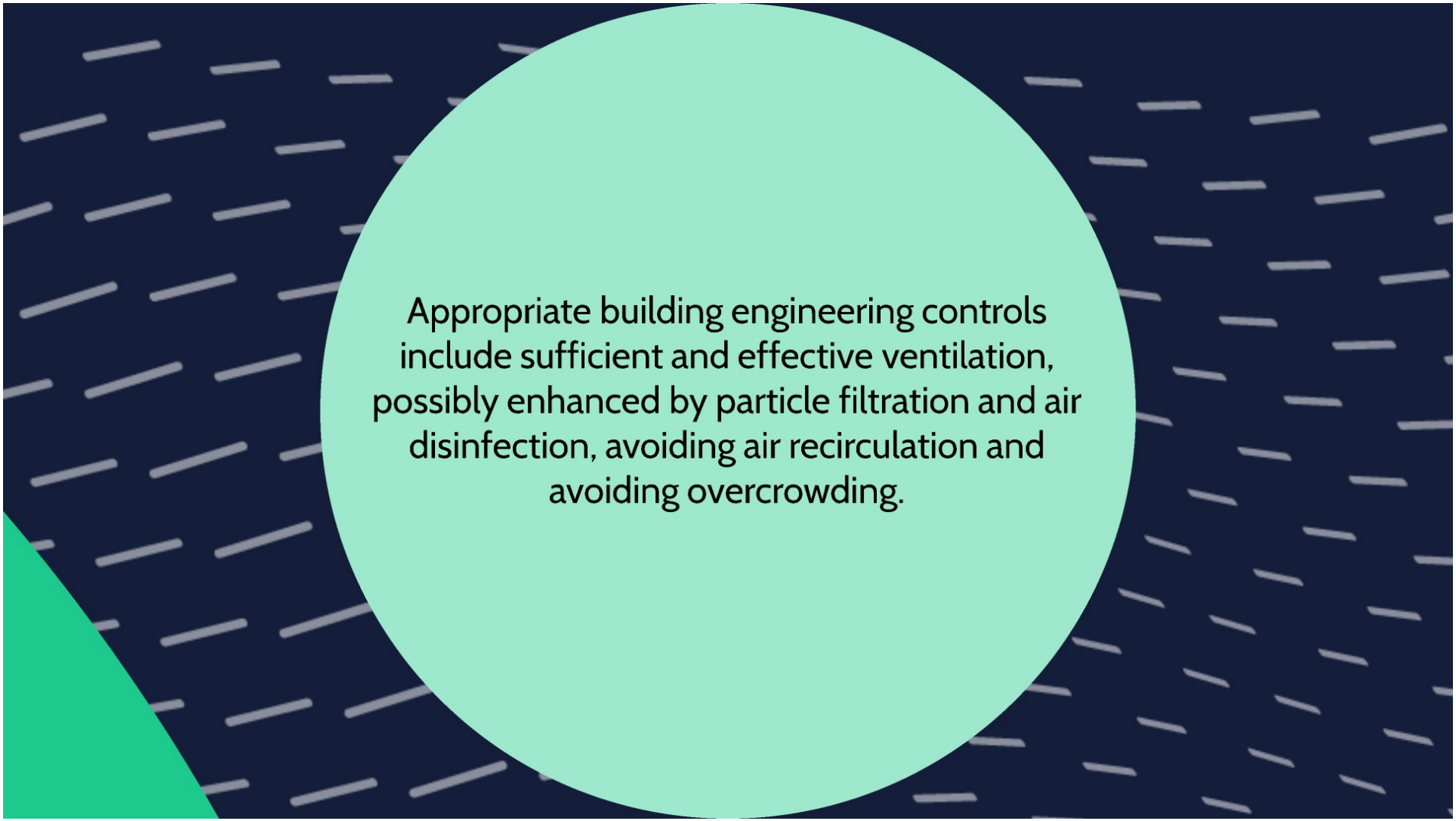

Aerosols, COVID-19 & HVAC
Definitions
The Case of Airborne Transmission
Relating to Airflow/HVAC
Possible Solutions
Other Possible Solutions
Final Thoughts


Air Changes
Avoid Recirculation
Partitions & Baffles
Ventilation Modes
Once the virus escapes into the air inside a building, you have two options: bring in **fresh air** from outside or **remove the virus** from the air inside the building.
As long as an infected individual is in an indoor space, virus-laden aerosol particles will accumulate to higher concentrations in that space until (in a well-mixed space) an approximate steady-state concentration occurs.
Engineering Controls
Ventilation Rates
Lines of Defense
Humidity


Appropriate building engineering controls include sufficient and effective ventilation, possibly enhanced by particle filtration and air disinfection, avoiding air recirculation and avoiding overcrowding.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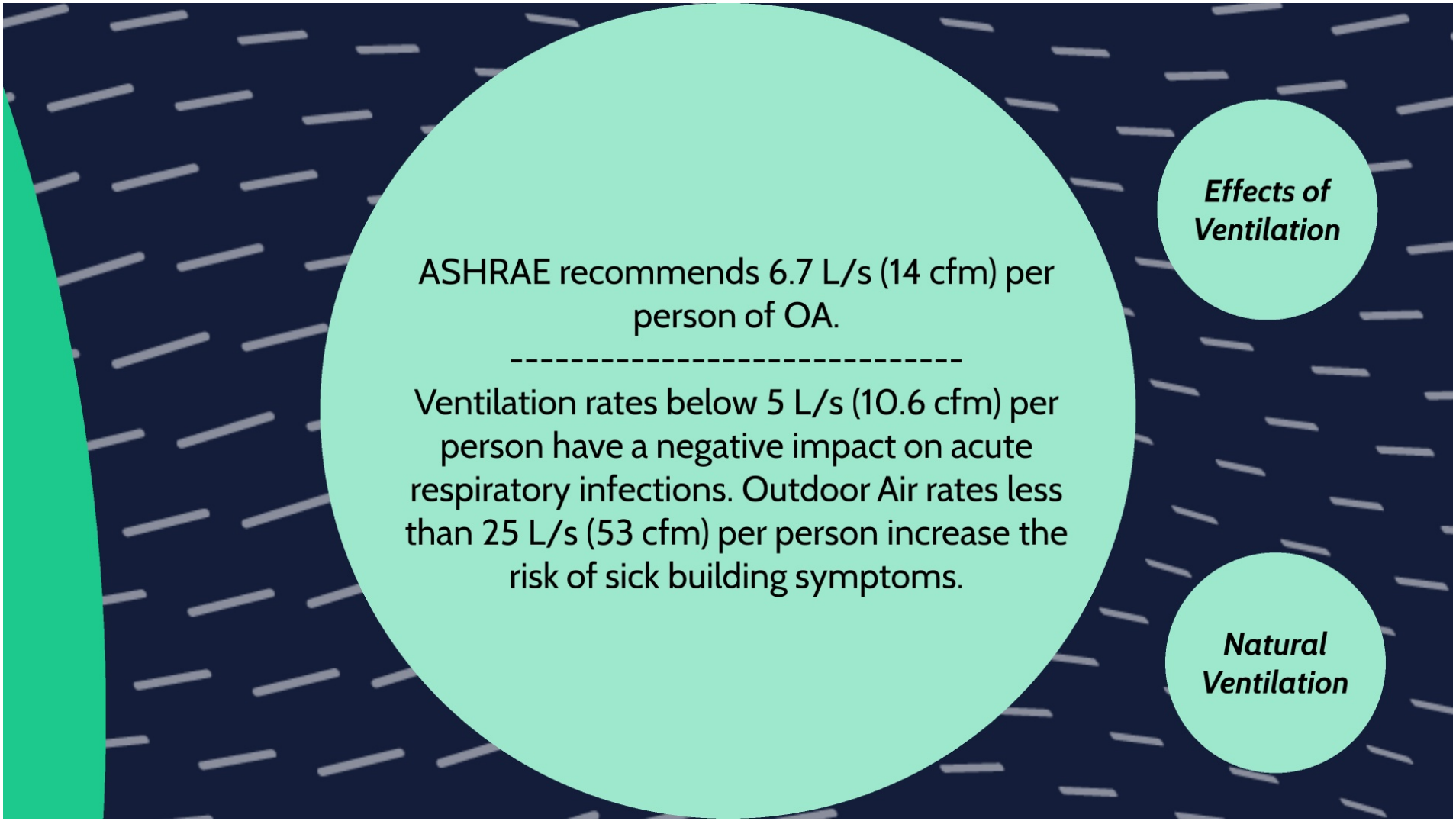
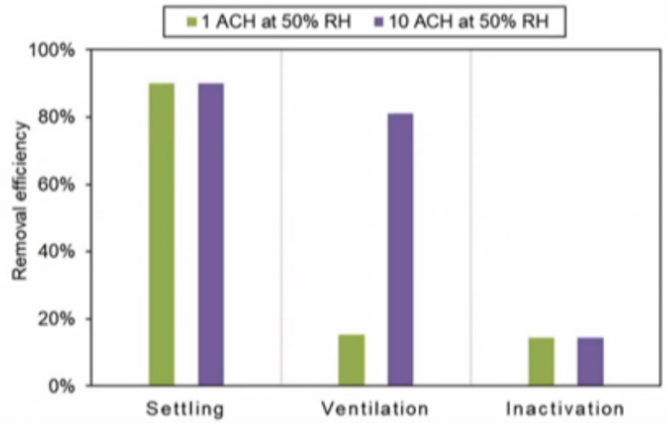
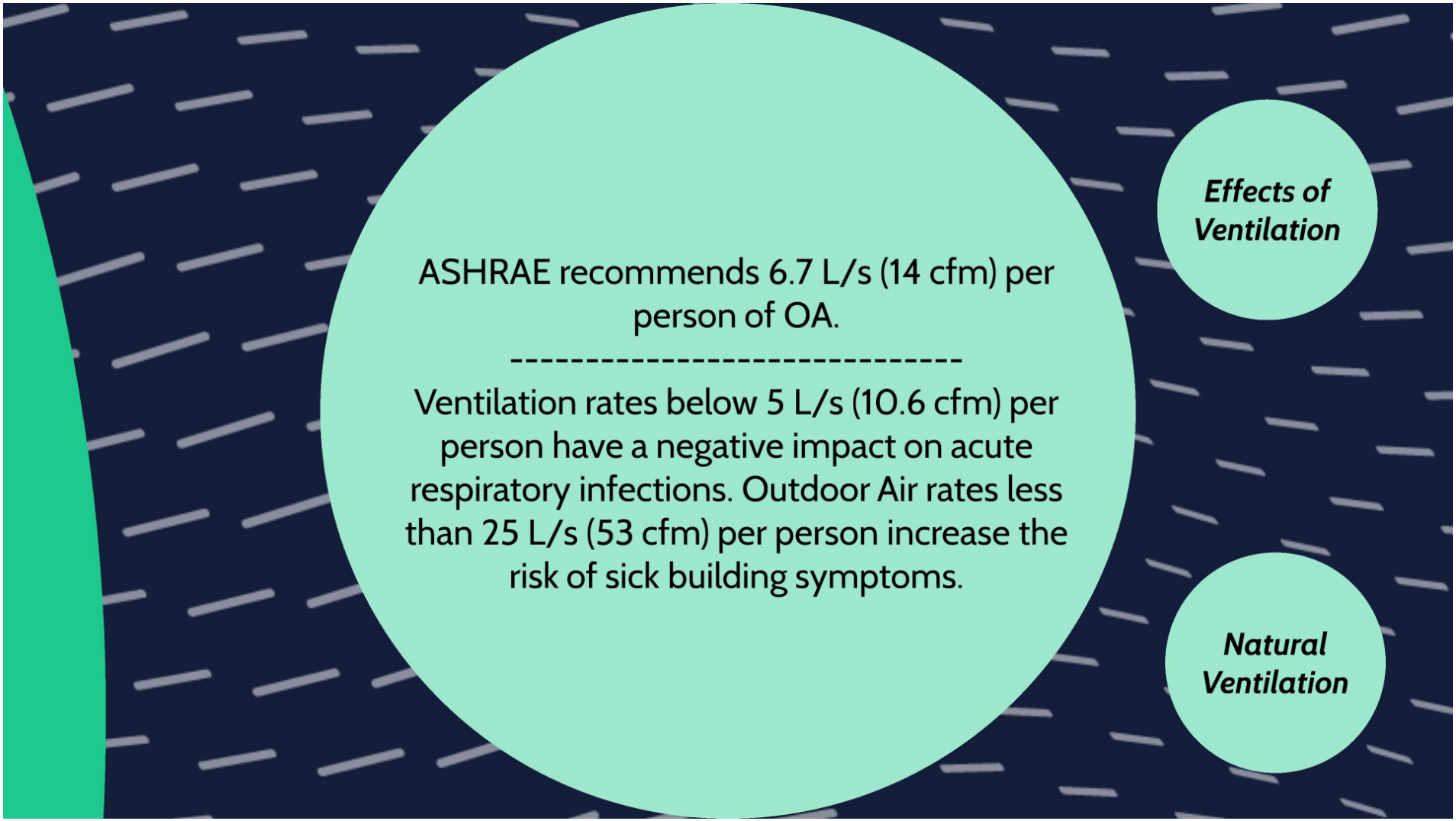

ASHRAE recommends 6.7 L/s (14 cfm) per person of OA.

Ventilation rates below 5 L/s (10.6 cfm) per person have a negative impact on acute respiratory infections. Outdoor Air rates less than 25 L/s (53 cfm) per person increase the risk of sick building symptoms.
Effects of Ventilation
Natural Ventilation

- Settling: main removal mechanism, efficient for large but not small droplets
- Ventilation: effective for all sizes, important in public buildings
- Inactivation: depends on the virus, may depend on humidity

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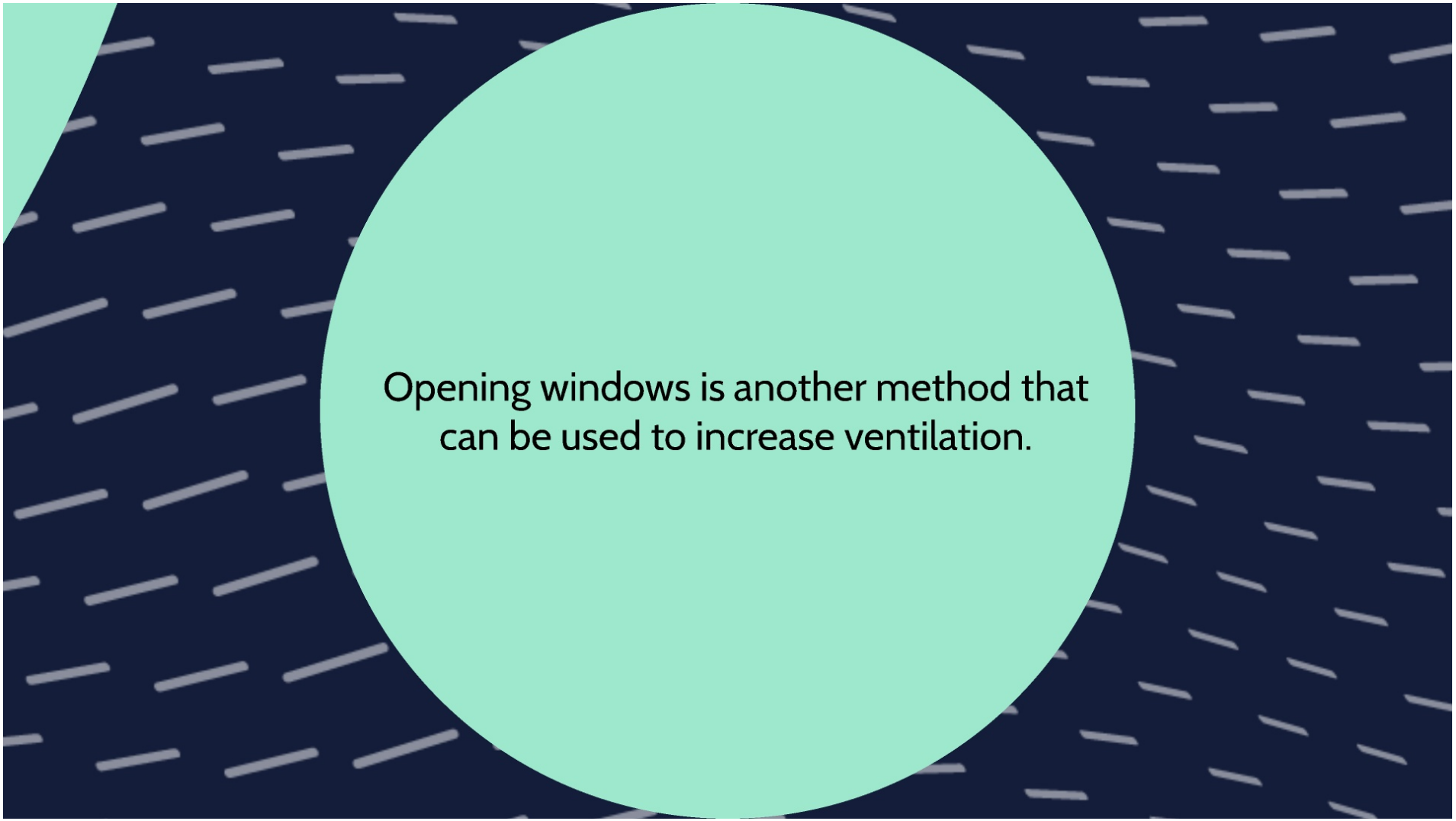
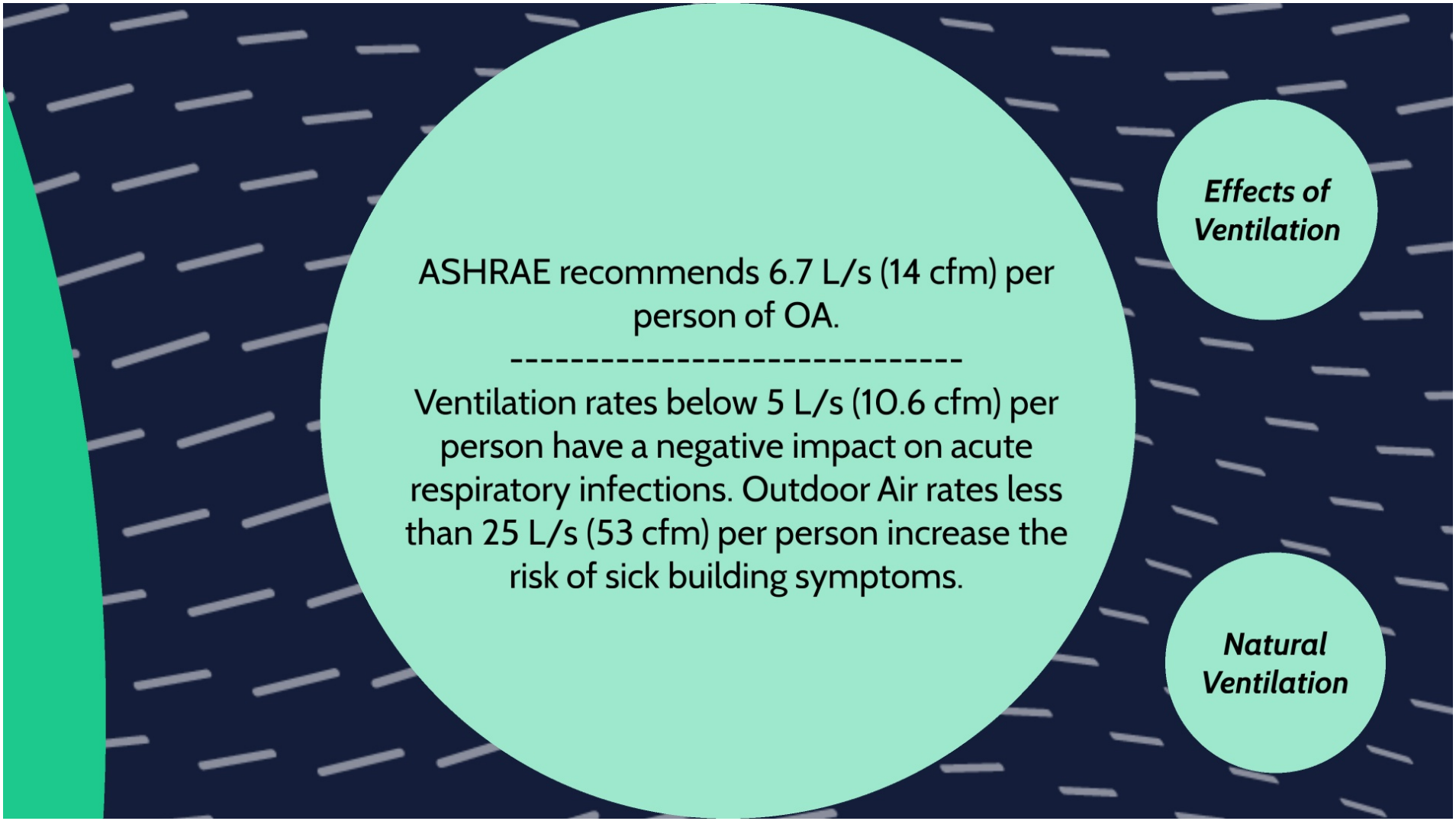

Opening windows is another method that
can be used to increase ventilation.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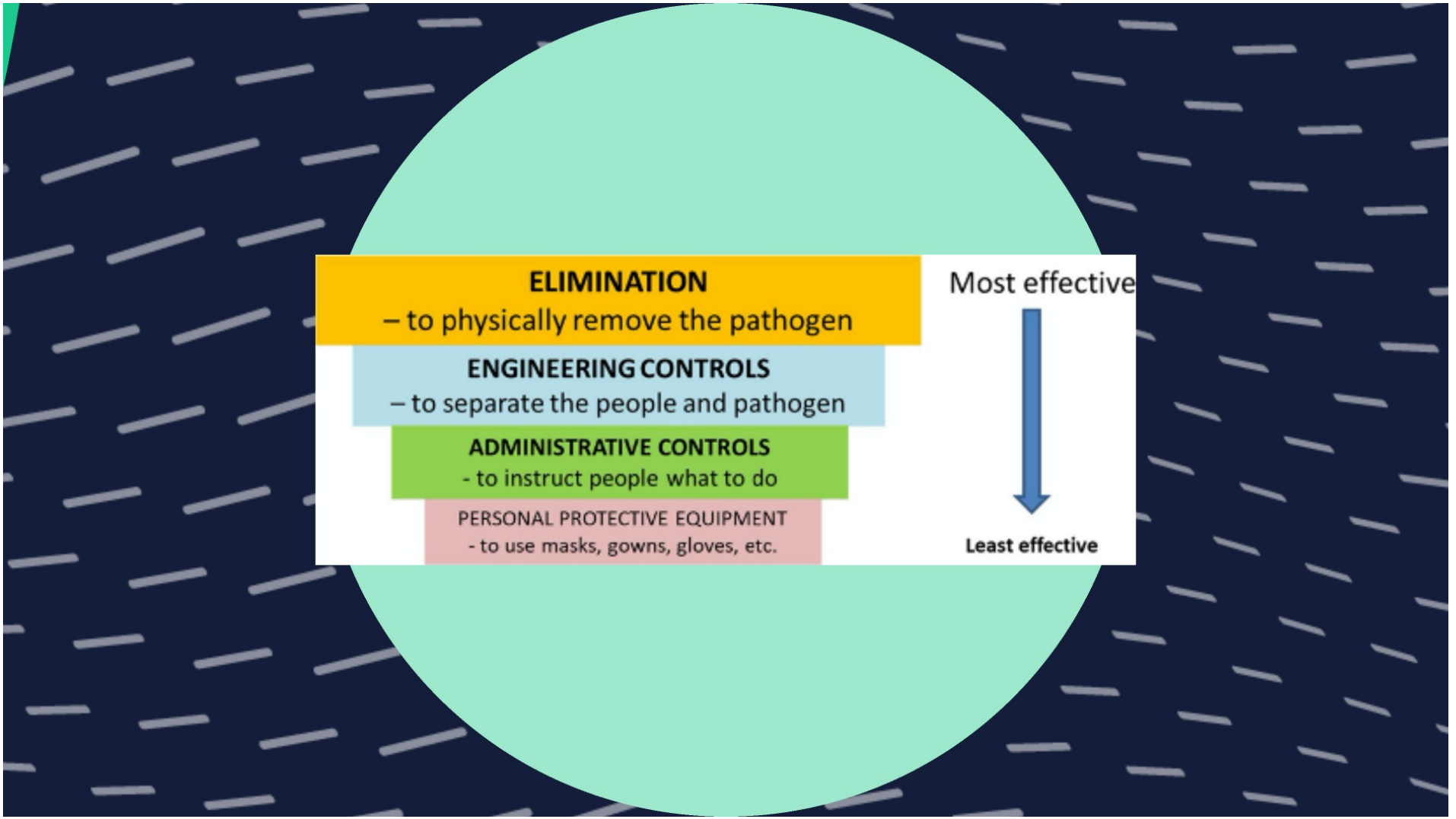
Humidity


ELIMINATION
– to physically remove the pathogen
ENGINEERING CONTROLS
– to separate the people and pathogen
ADMINISTRATIVE CONTROLS
- to instruct people what to do
PERSONAL PROTECTIVE EQUIPMENT
- to use masks, gowns, gloves, etc.
Most effective
Least effective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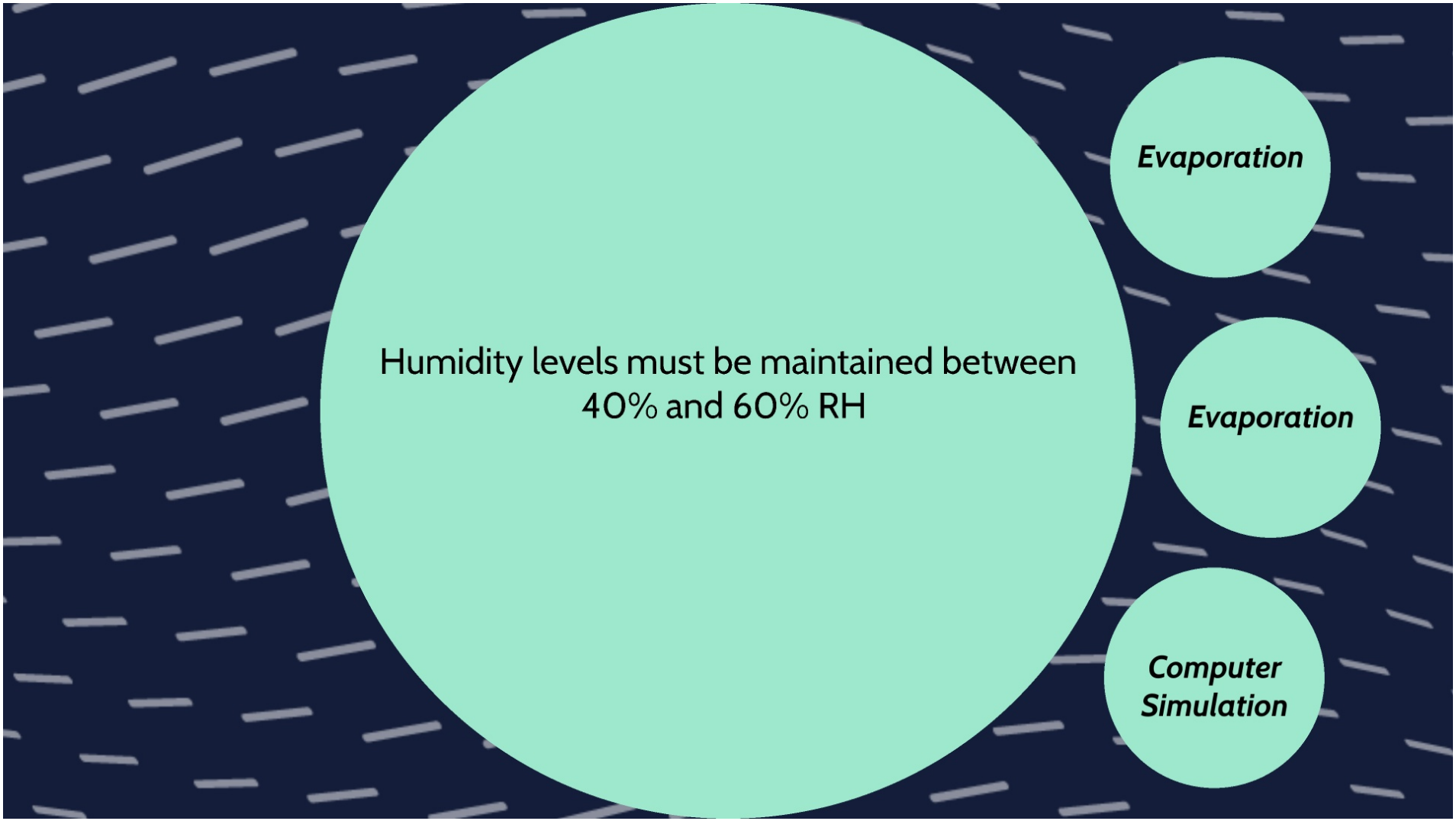
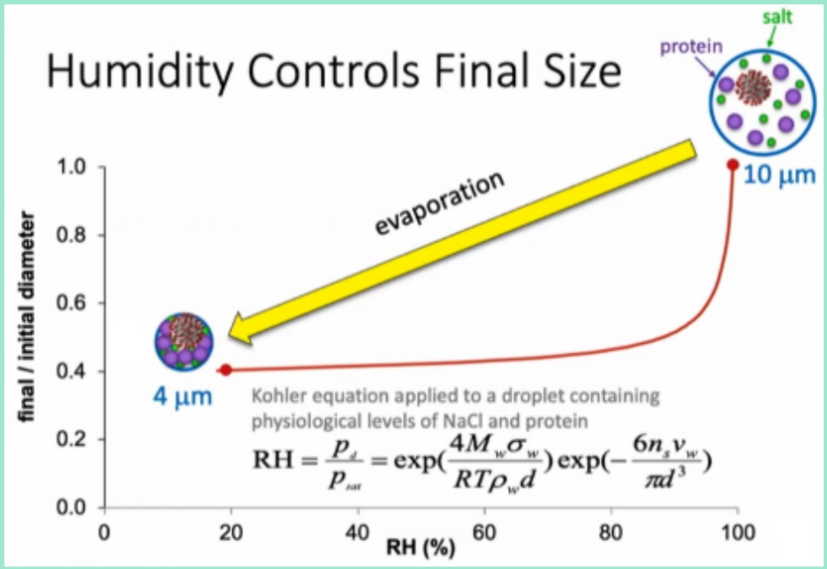
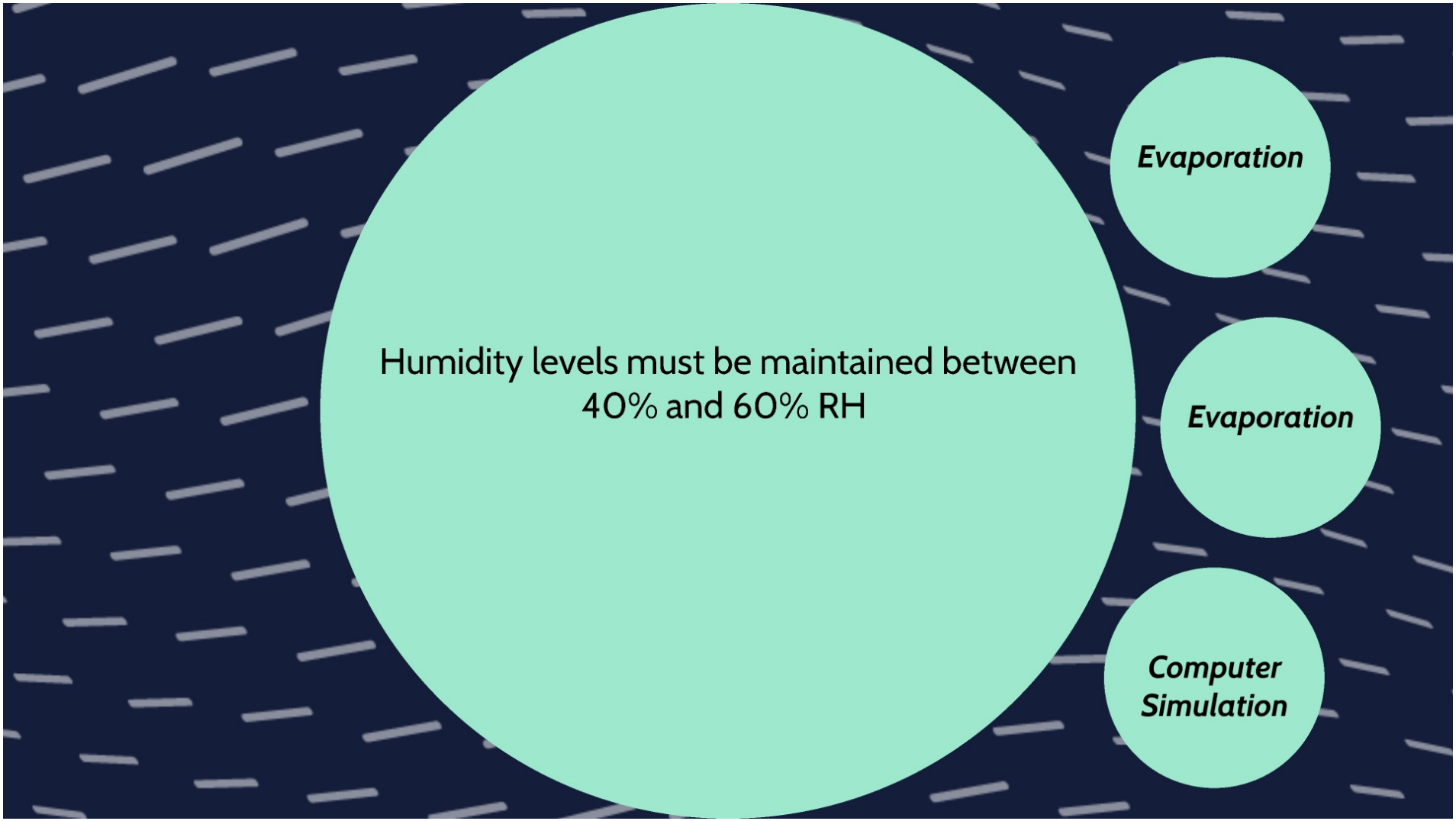

Humidity levels must be maintained between 40% and 60% RH
Evaporation
Evaporation
Computer Simulation


Humidity Controls Final Size
salt
protein
10 µm
evaporation
4 µm
final / initial diameter
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
RH (%)
Kohler equation applied to a droplet containing physiological levels of NaCl and protein
$RH = \frac{p_d}{p_{sat}} = \exp(\frac{4M_w\sigma_w}{RT\rho_w d})\exp(-\frac{6n_g v_w}{\pi d^3})$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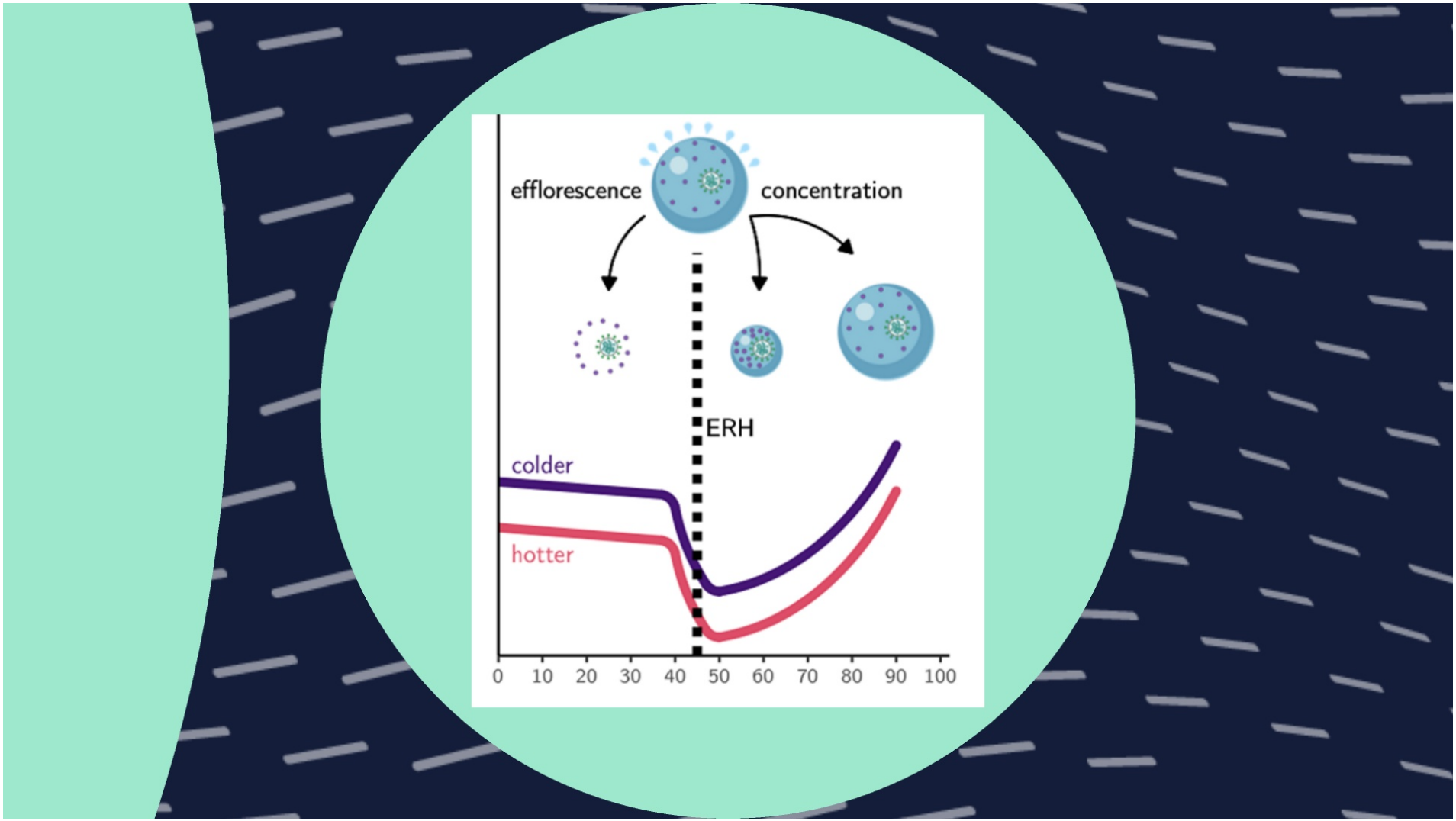
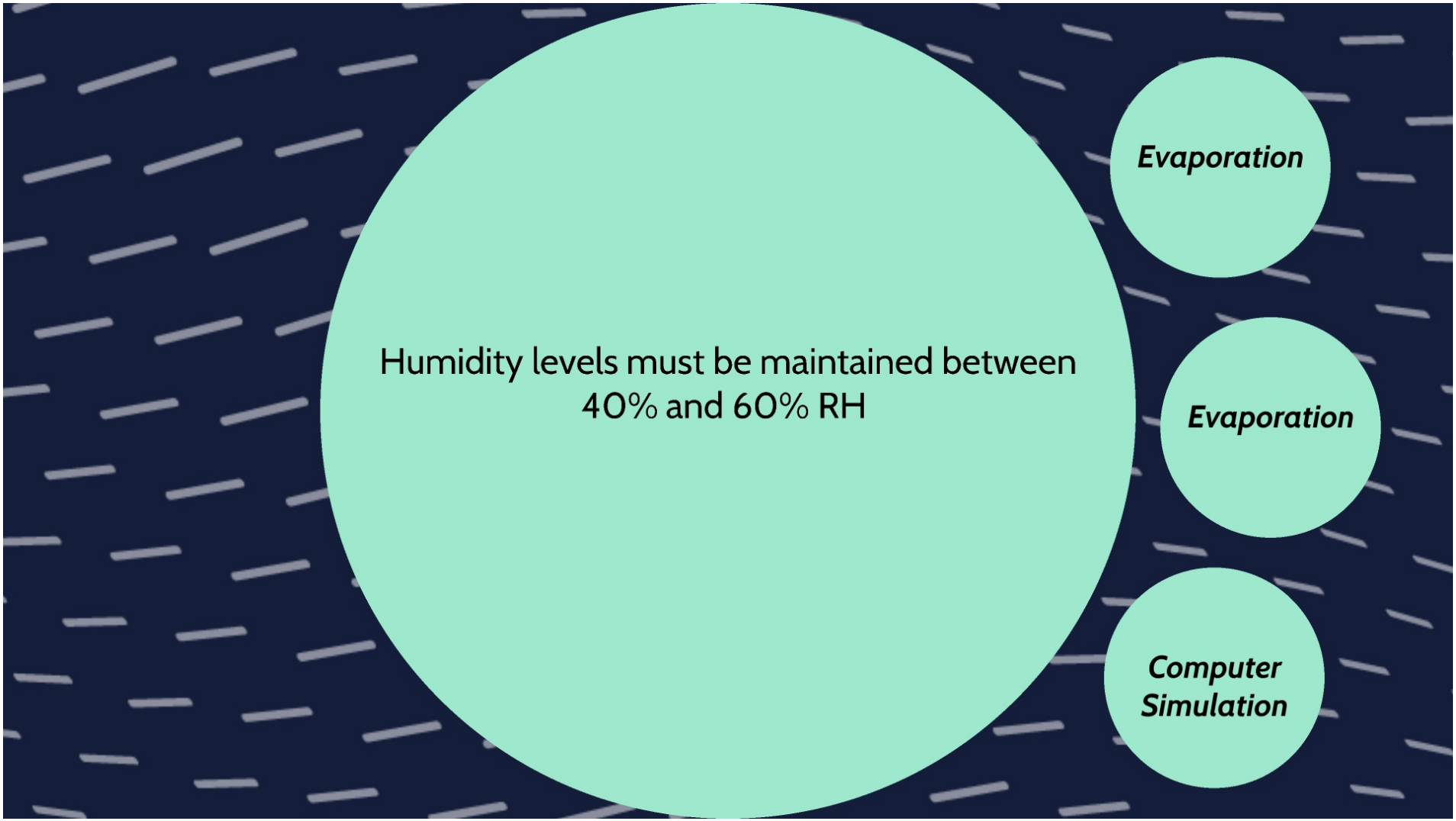

efflorescence
concentration
ERH
colder
hotter
0
10
20
30
40
50
60
70
80
90
100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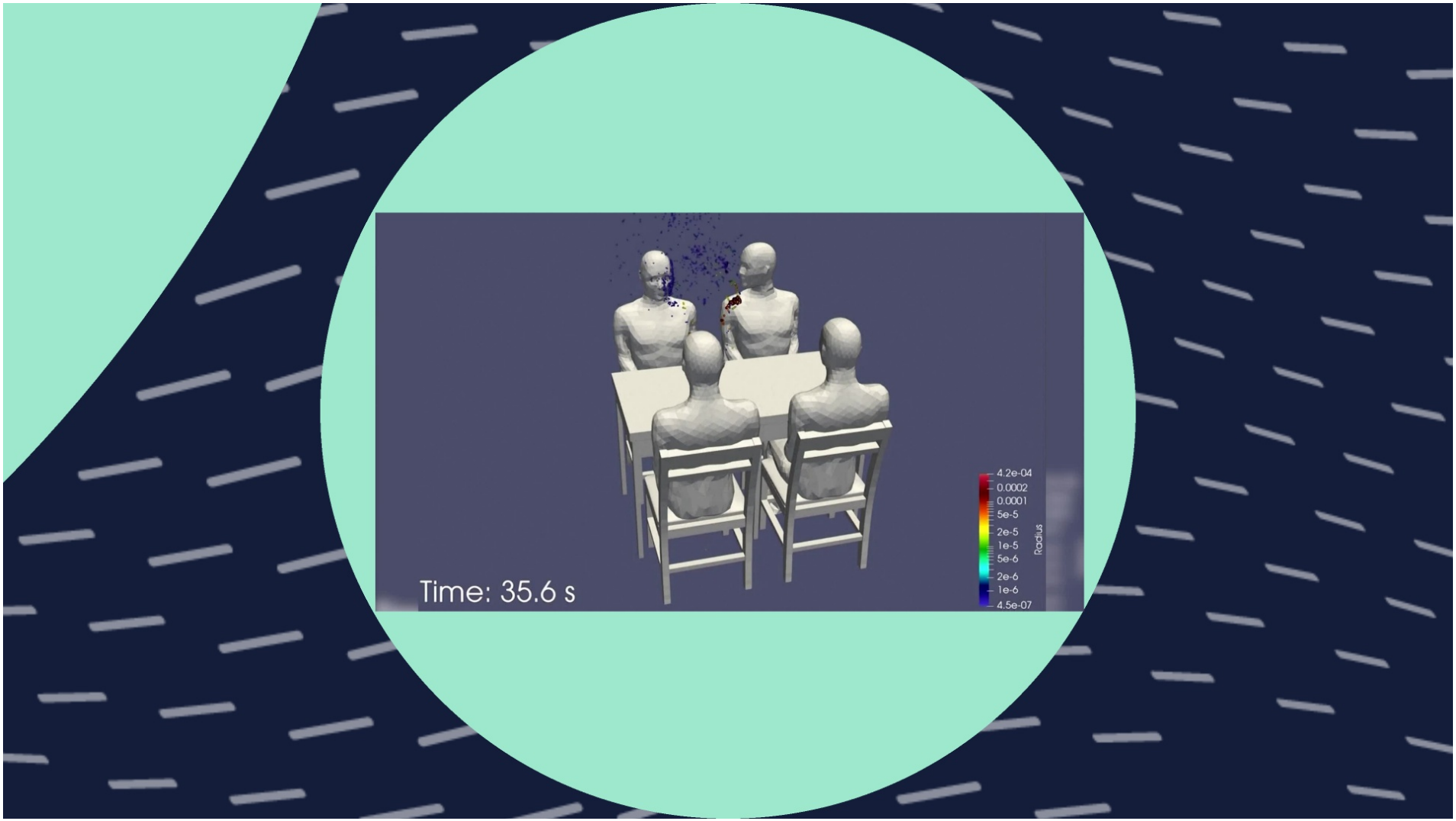
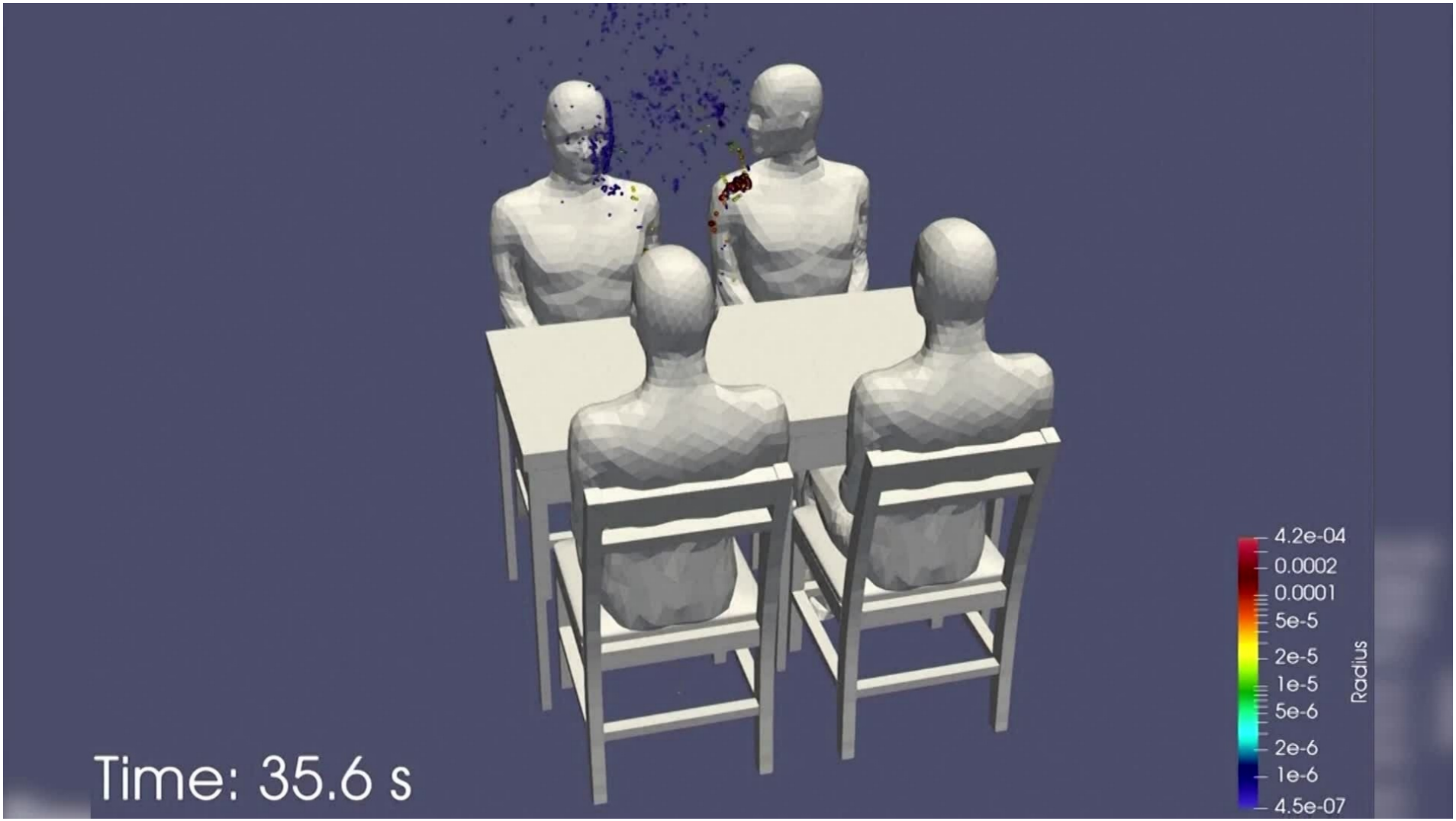

Time: 35.6 s
4.2e-04
0.0002
0.0001
5e-5
2e-5
1e-5
5e-6
2e-6
1e-6
4.5e-07
Radius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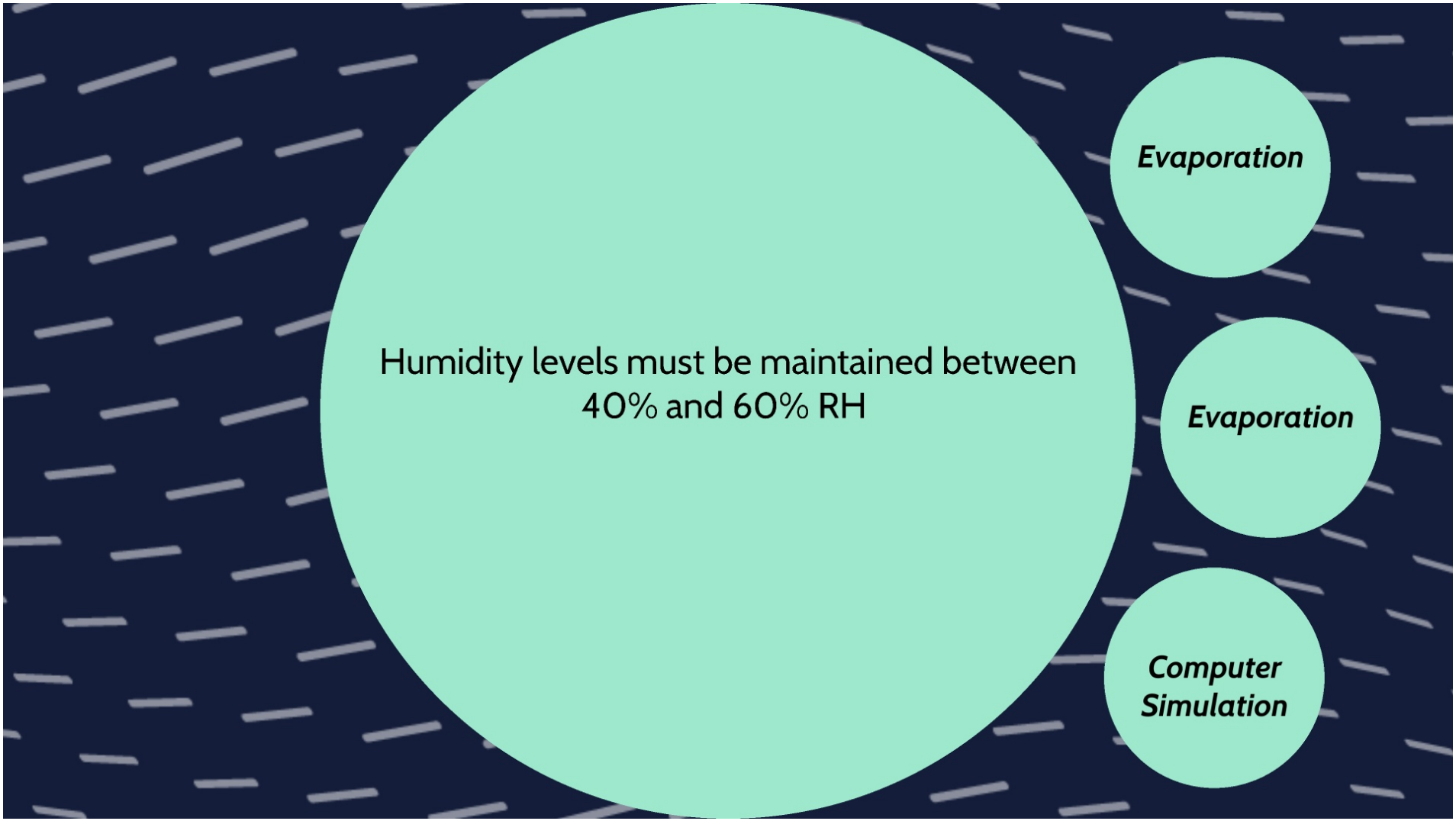
Radius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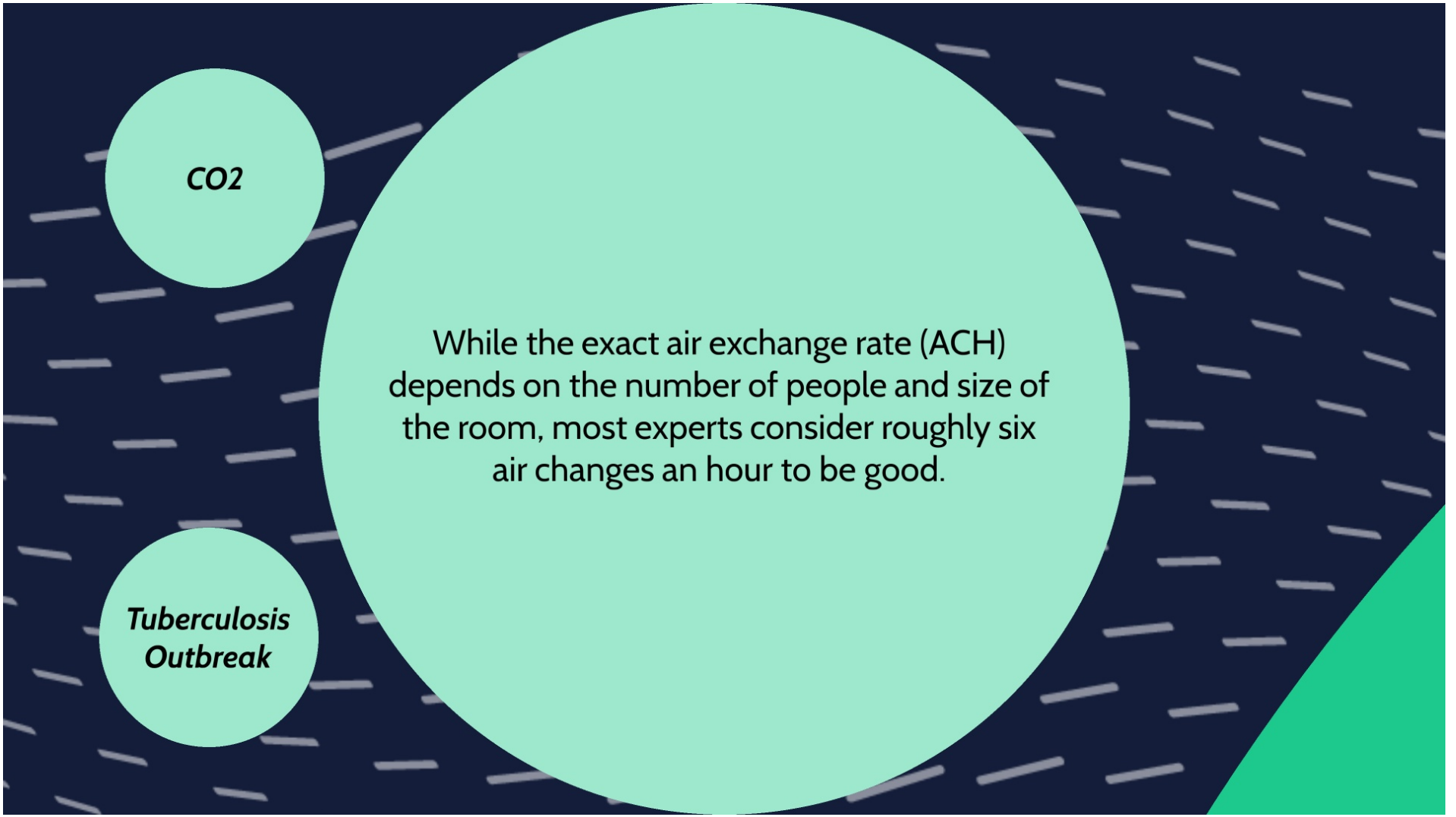
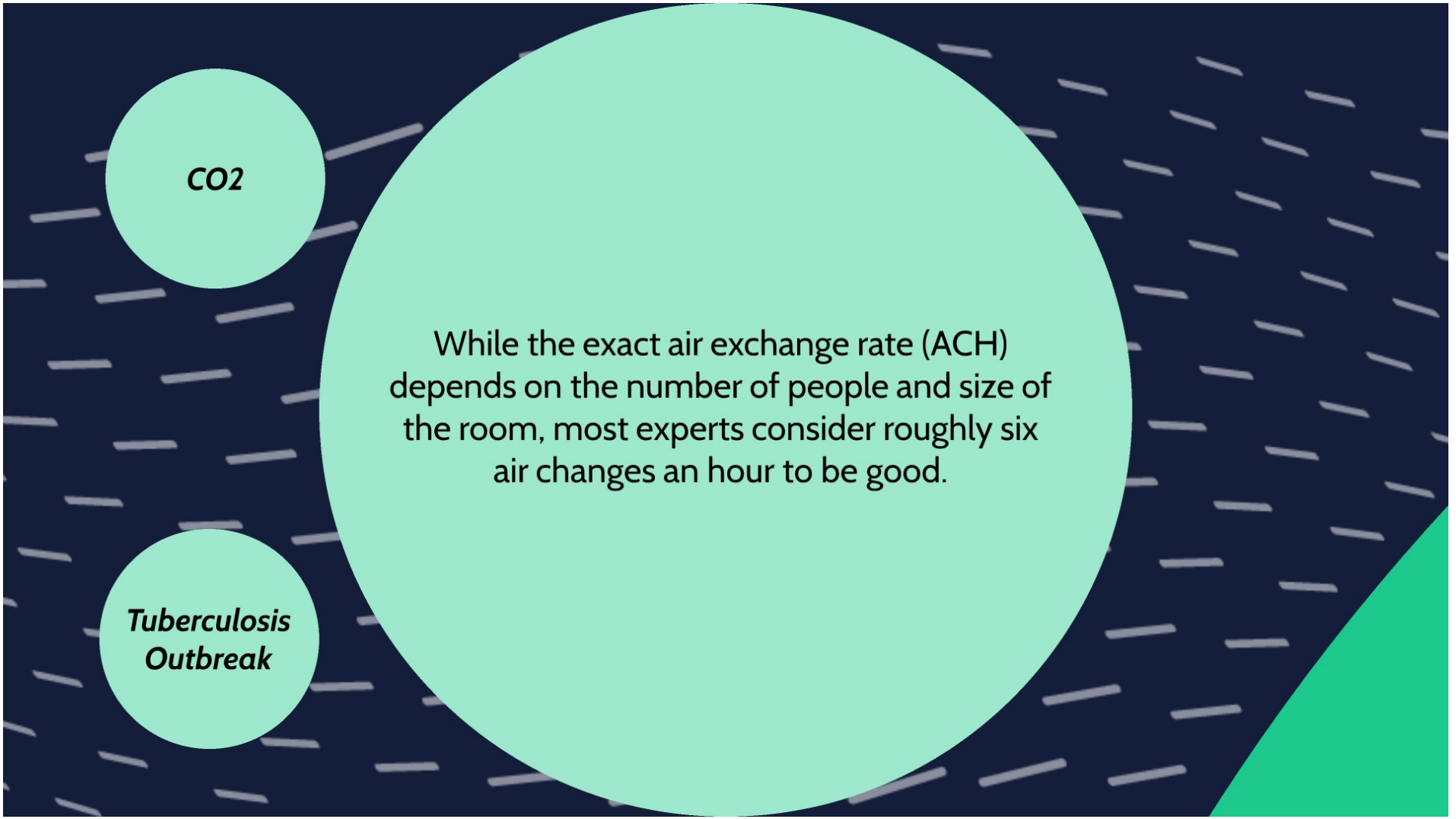
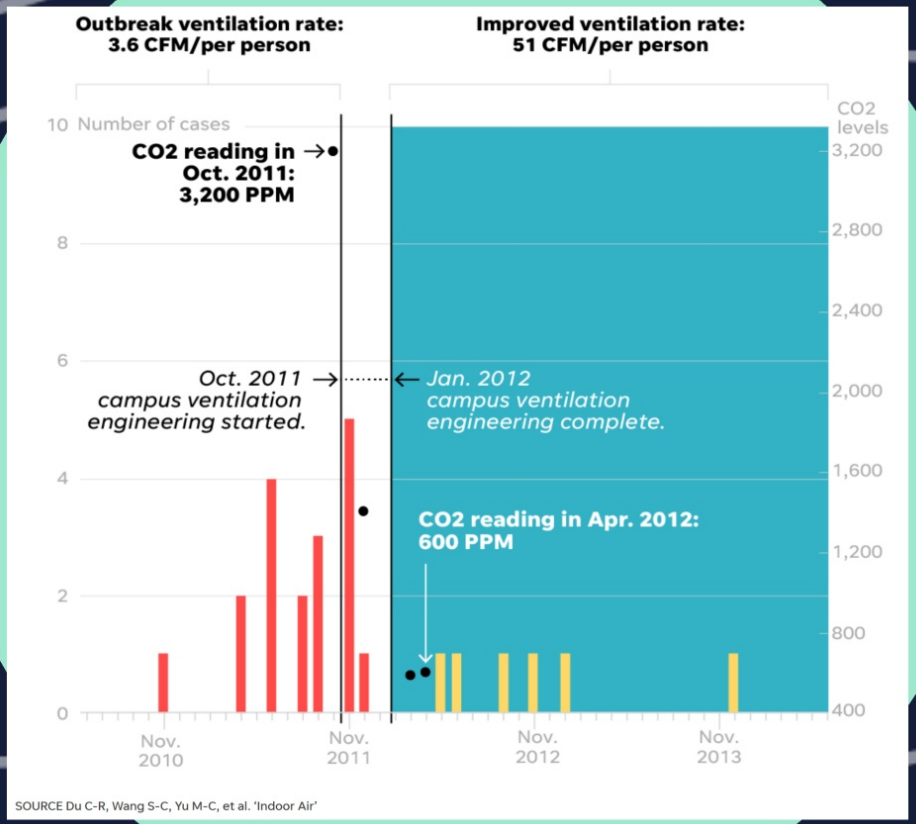
Engineering Controls
Ventilation Rates
Lines of Defense
Humidity

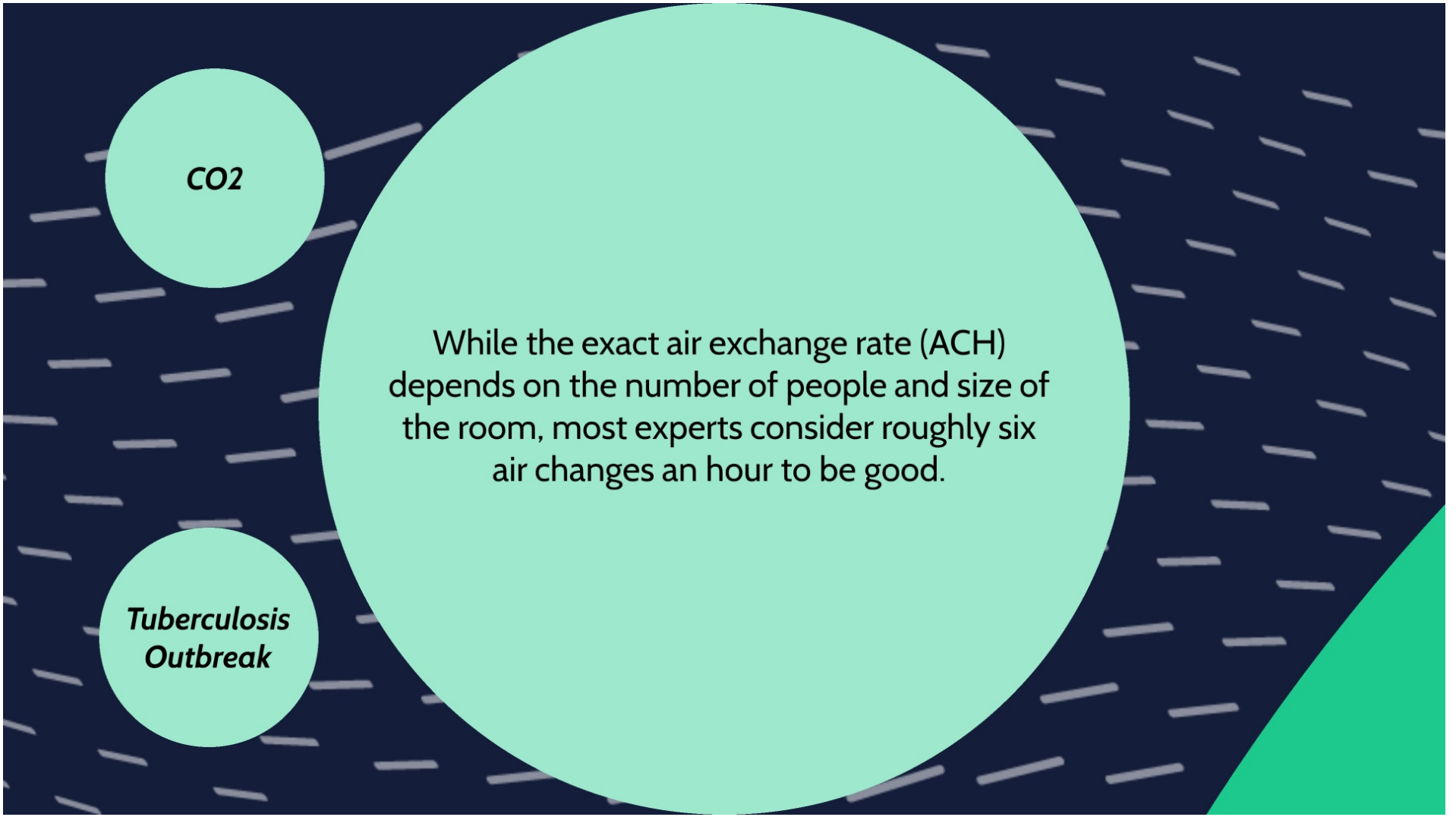

CO2
While the exact air exchange rate (ACH) depends on the number of people and size of the room, most experts consider roughly six air changes an hour to be good.
Tuberculosis Outbreak

So how do you know if the room you're in has enough air changes? Aside from measuring the supply air coming into the space, you can use CO2 as a proxy.

A well ventilated room will have around 800 ppm of CO2. Any higher than that and it is a sign the room might need more ventilation.


CO2
While the exact air exchange rate (ACH) depends on the number of people and size of the room, most experts consider roughly six air changes an hour to be good.
Tuberculosis Outbreak


Outbreak ventilation rate:
3.6 CFM/per person
Improved ventilation rate:
51 CFM/per person
10 Number of cases
CO2 levels
CO2 reading in Oct. 2011: 3,200 PPM
3,200
2,800
2,400
2,000
1,600
1,200
800
400
8
6
4
2
0
Oct. 2011 campus ventilation engineering started.
Jan. 2012 campus ventilation engineering complete.
CO2 reading in Apr. 2012: 600 PPM
Nov. 2010
Nov. 2011
Nov. 2012
Nov. 2013
SOURCE Du C-R, Wang S-C, Yu M-C, et al. 'Indoor Air'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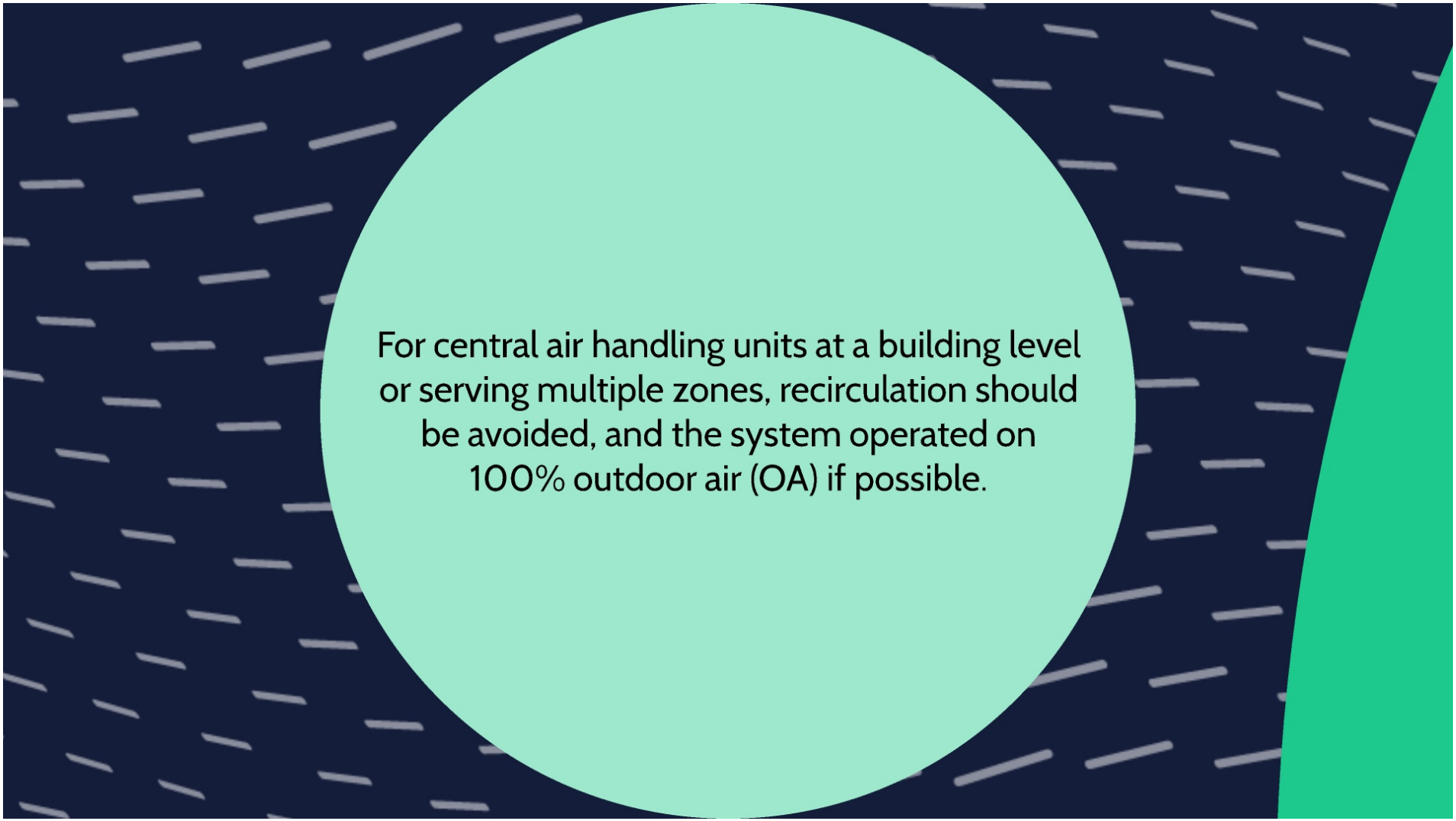
Air Changes
Avoid Recirculation
Partitions & Baffles
Ventilation Modes
Once the virus escapes into the air inside a building, you have two options: bring in **fresh air** from outside or **remove the virus** from the air inside the building.
As long as an infected individual is in an indoor space, virus-laden aerosol particles will accumulate to higher concentrations in that space until (in a well-mixed space) an approximate steady-state concentration occurs.
Engineering Controls
Ventilation Rates
Lines of Defense
Humidity


For central air handling units at a building level or serving multiple zones, recirculation should be avoided, and the system operated on 100% outdoor air (OA) if possible.


Air Changes
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2018 study - "Effects of Internal Partitions on Flow Field and Air Contaminant Distribution under Different Ventilation Modes"

For layouts using baffles to separate different zones, the baffles will significantly affect the indoor airflow distribution. It is suggested that the baffles' locations should be carefully designed in order to avoid blocking the airflow.


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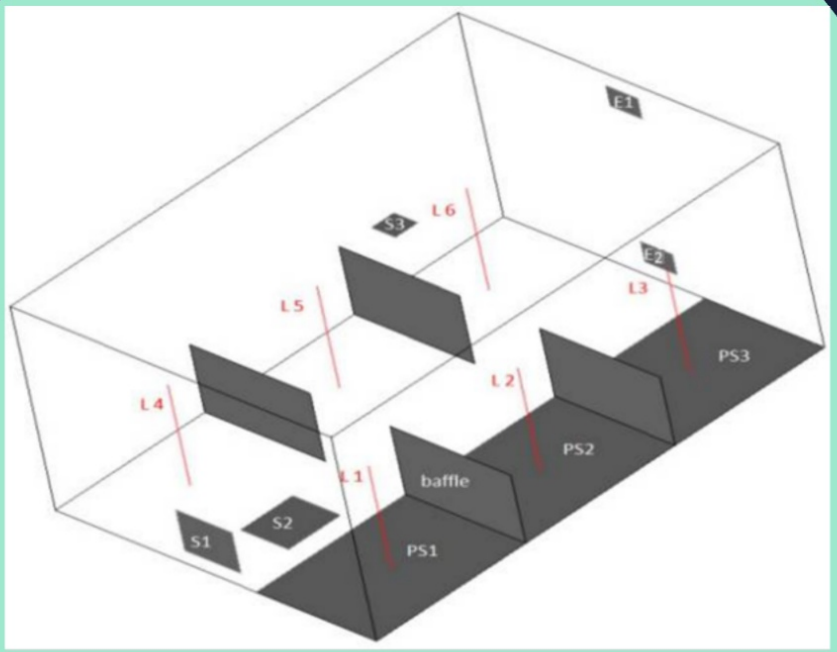
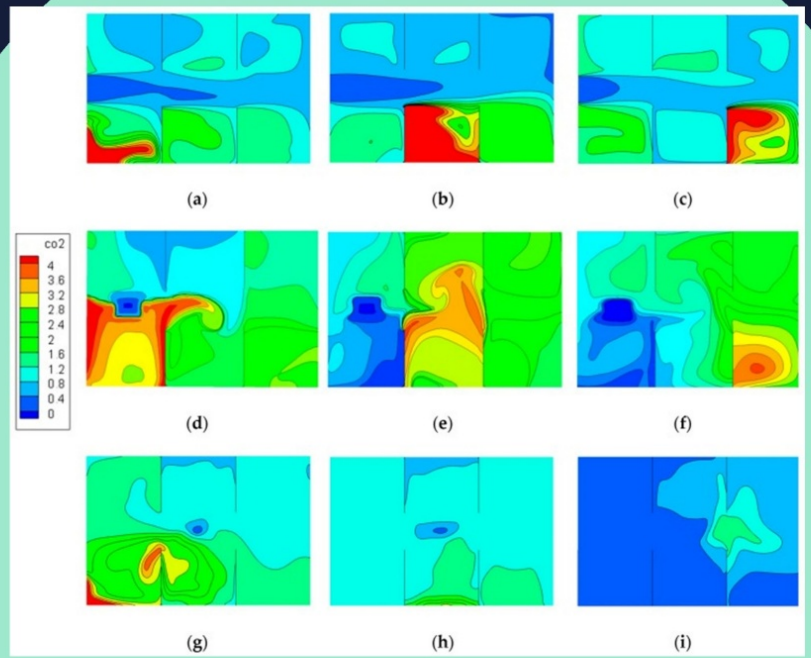
Results

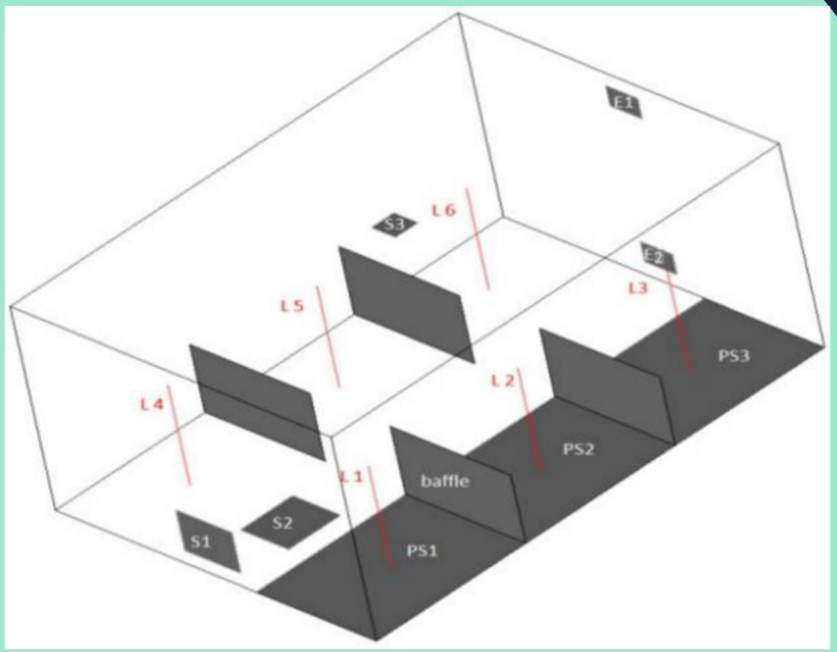


Supply and Exhaust Locations



The top-supply, down-return ventilation mode (g, h, i) shows better performance in removing pollutants

Results



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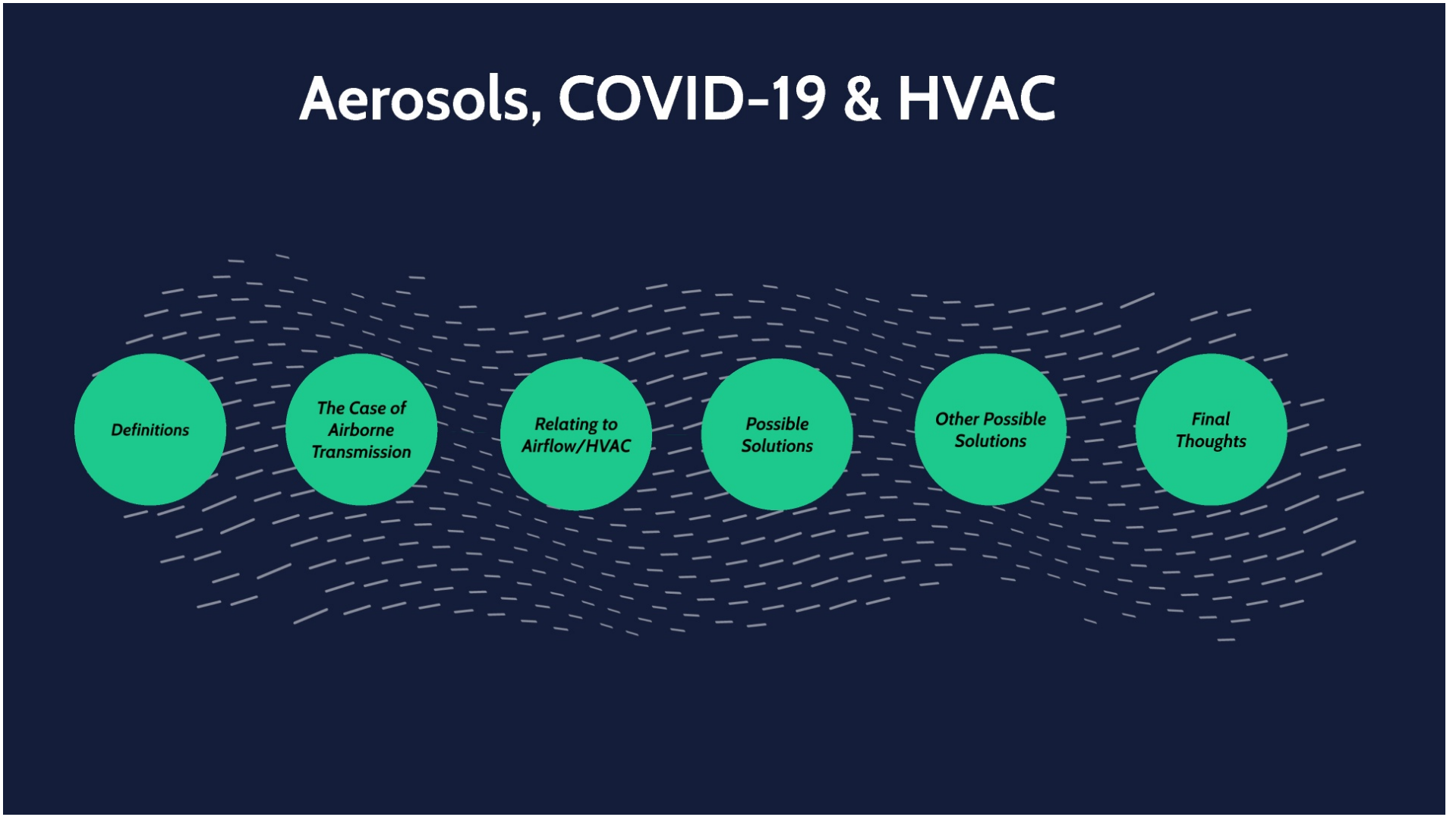
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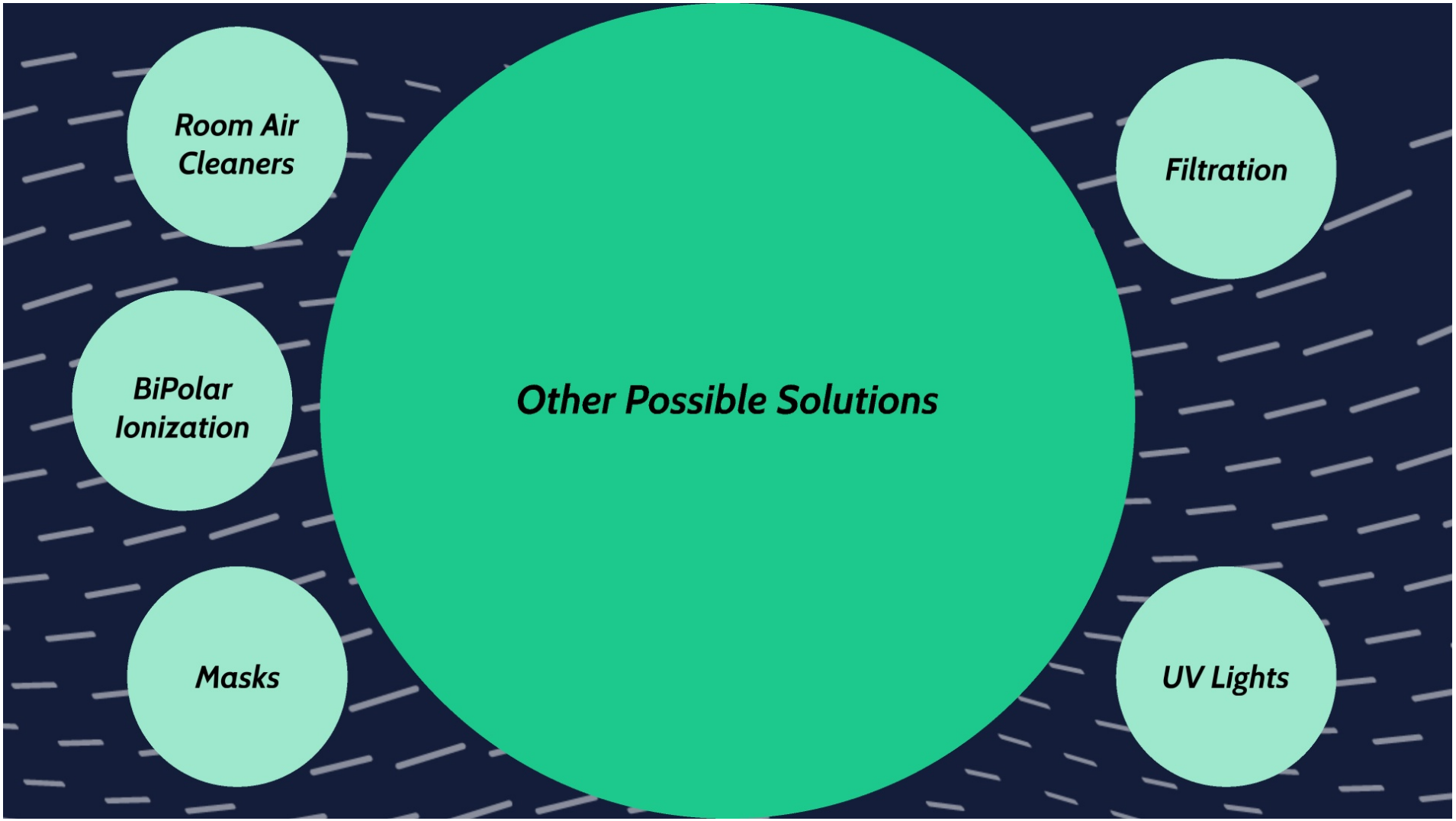
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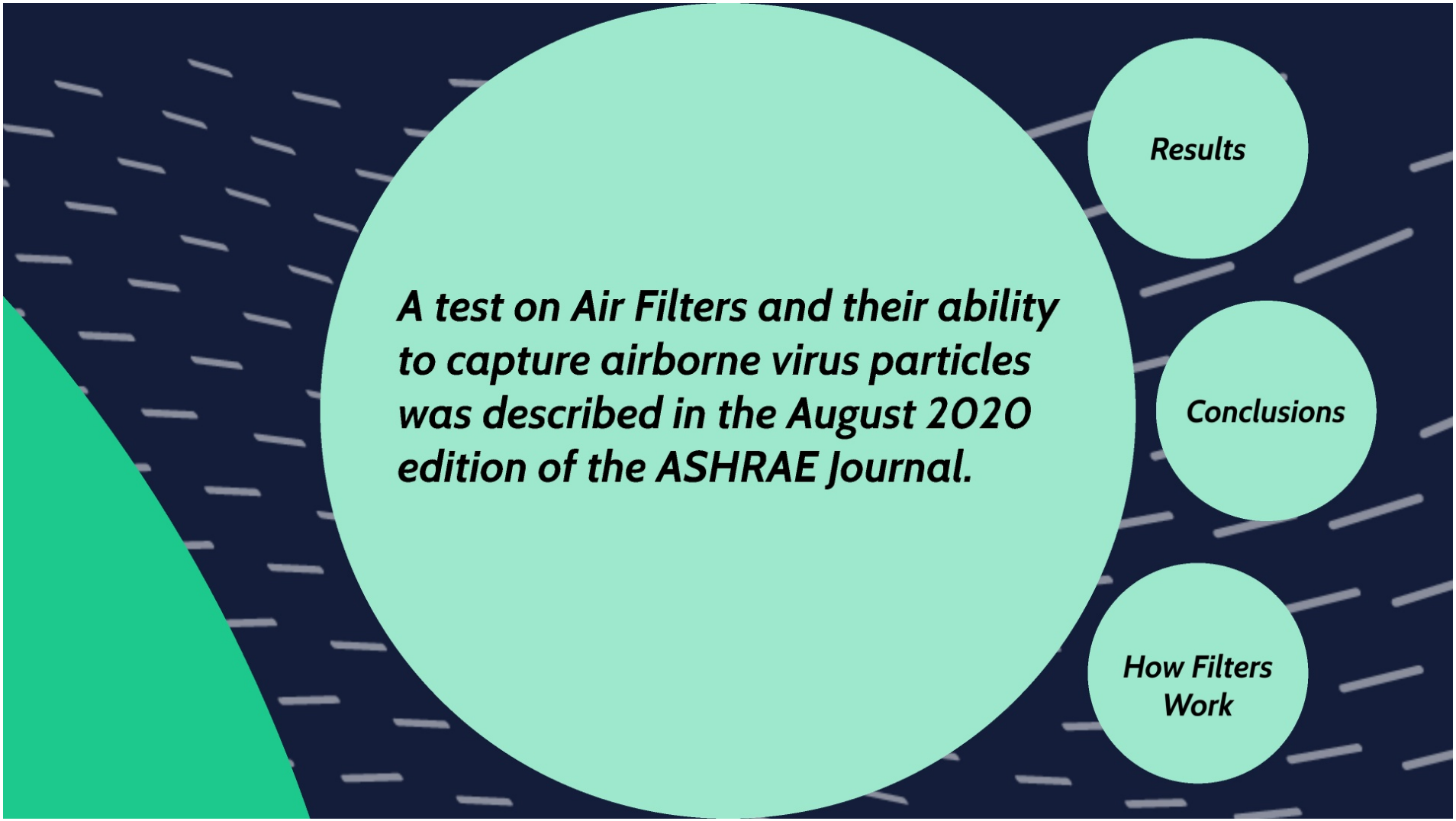
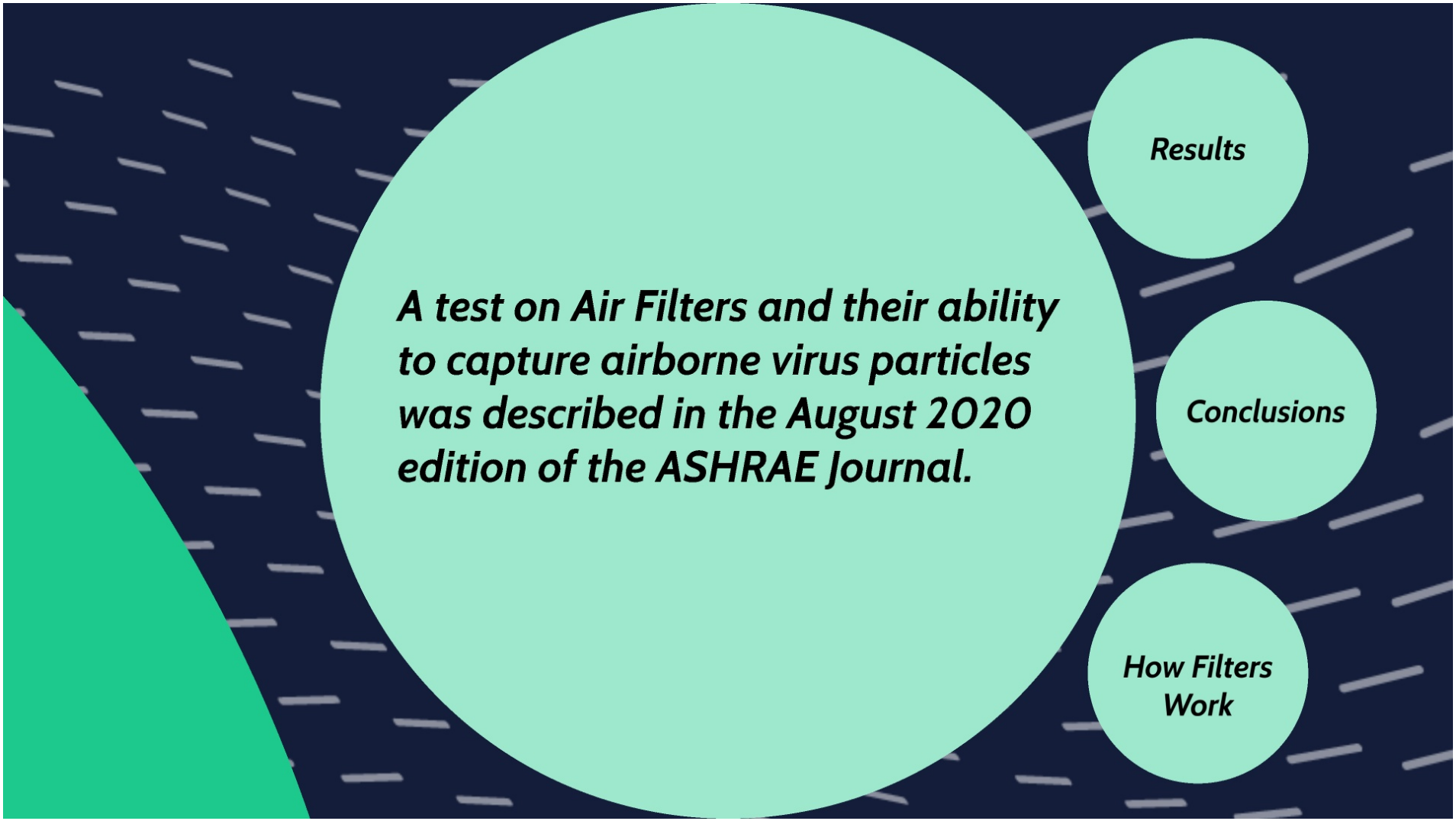

A test on Air Filters and their ability to capture airborne virus particles was described in the August 2020 edition of the ASHRAE Journal.
Results
Conclusions
How Filters Work

TABLE 4 Descriptive statistics of viral filtration efficiency data.

FILTER	N	MEAN	STD DEV	COEF VAR	MEDIAN	MINIMUM	MAXIMUM
MERV 5	6	32%	10.5%	32.8	36%	12%	40%
MERV 12	6	78%	8.8%	11.3	77%	70%	93%
MERV 13	6	89%	8.2%	9.3	91%	79%	98%
MERV 14	6	97%	1.4%	1.5	96%	95%	99%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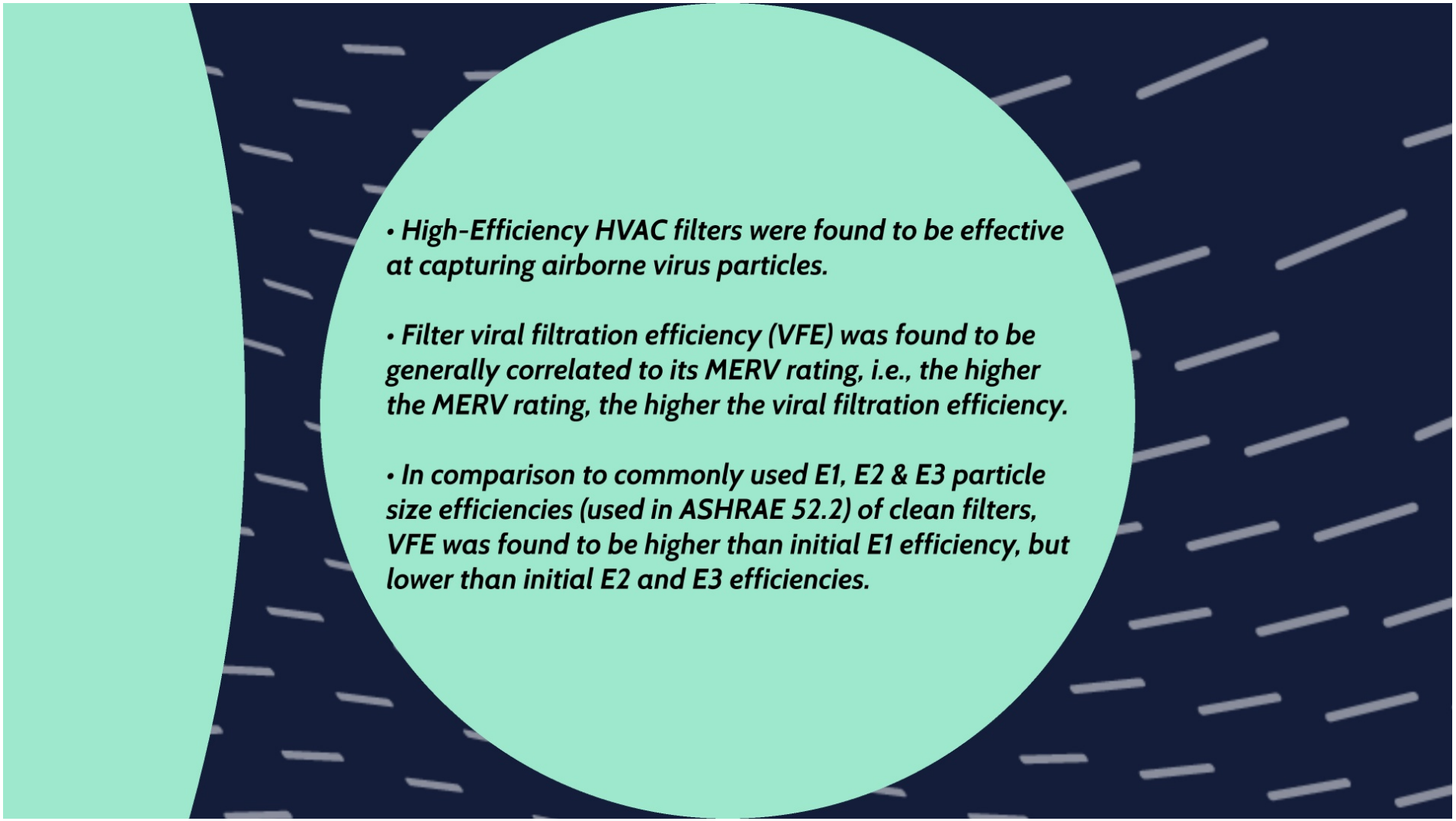
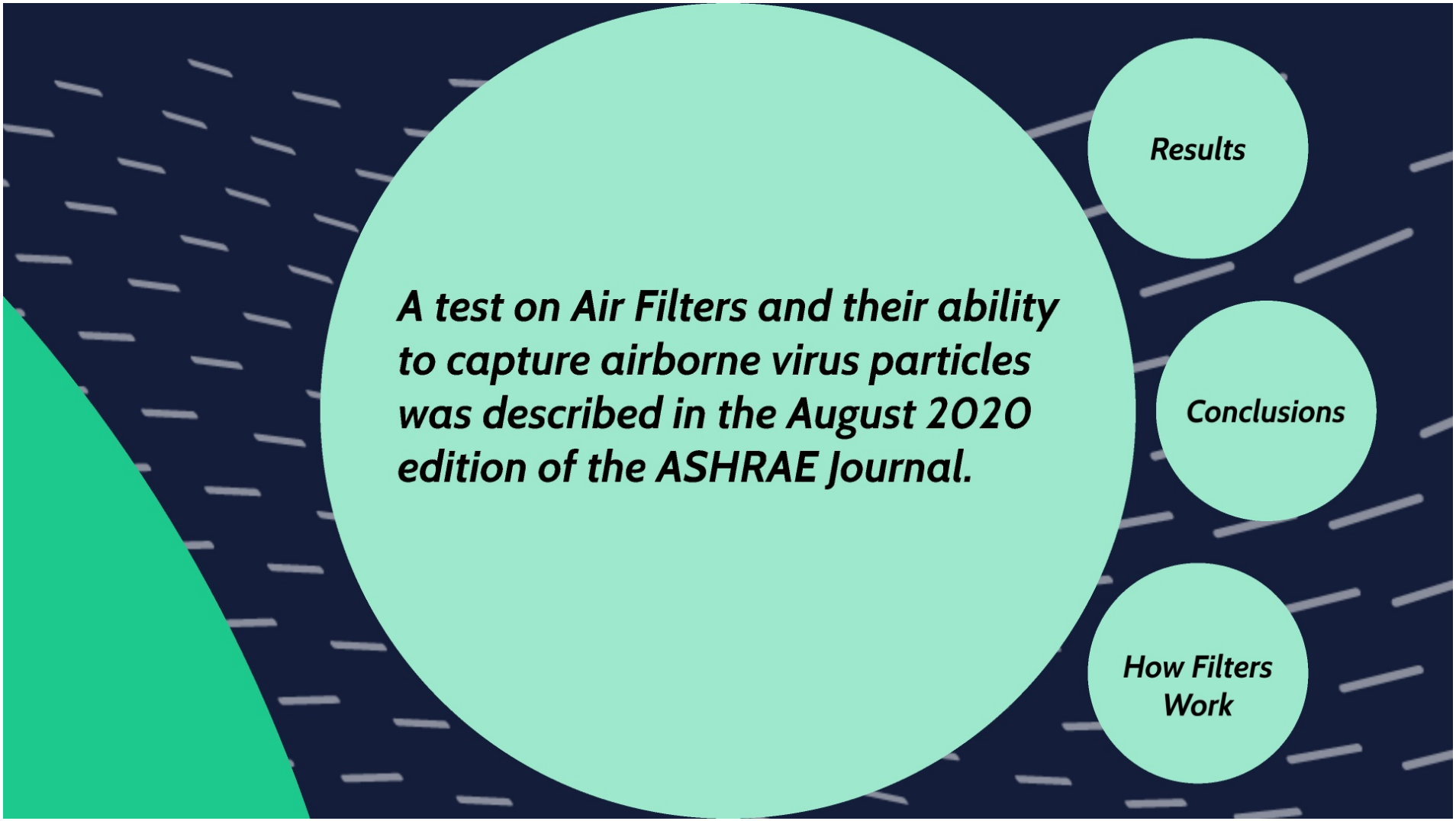

• High-Efficiency HVAC filters were found to be effective at capturing airborne virus particles.
• Filter viral filtration efficiency (VFE) was found to be generally correlated to its MERV rating, i.e., the higher the MERV rating, the higher the viral filtration efficiency.
• In comparison to commonly used E1, E2 & E3 particle size efficiencies (used in ASHRAE 52.2) of clean filters, VFE was found to be higher than initial E1 efficiency, but lower than initial E2 and E3 efficiencies.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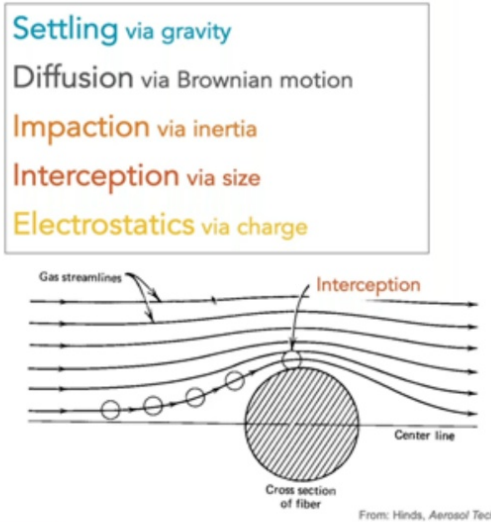
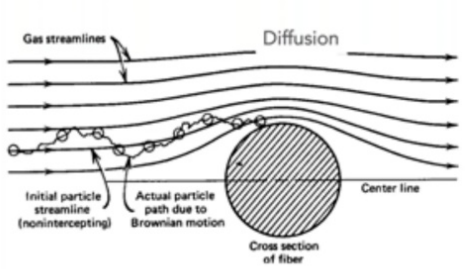
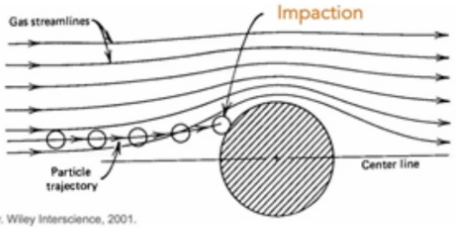
Aerosol Filtration is a combination of many capture mechanisms

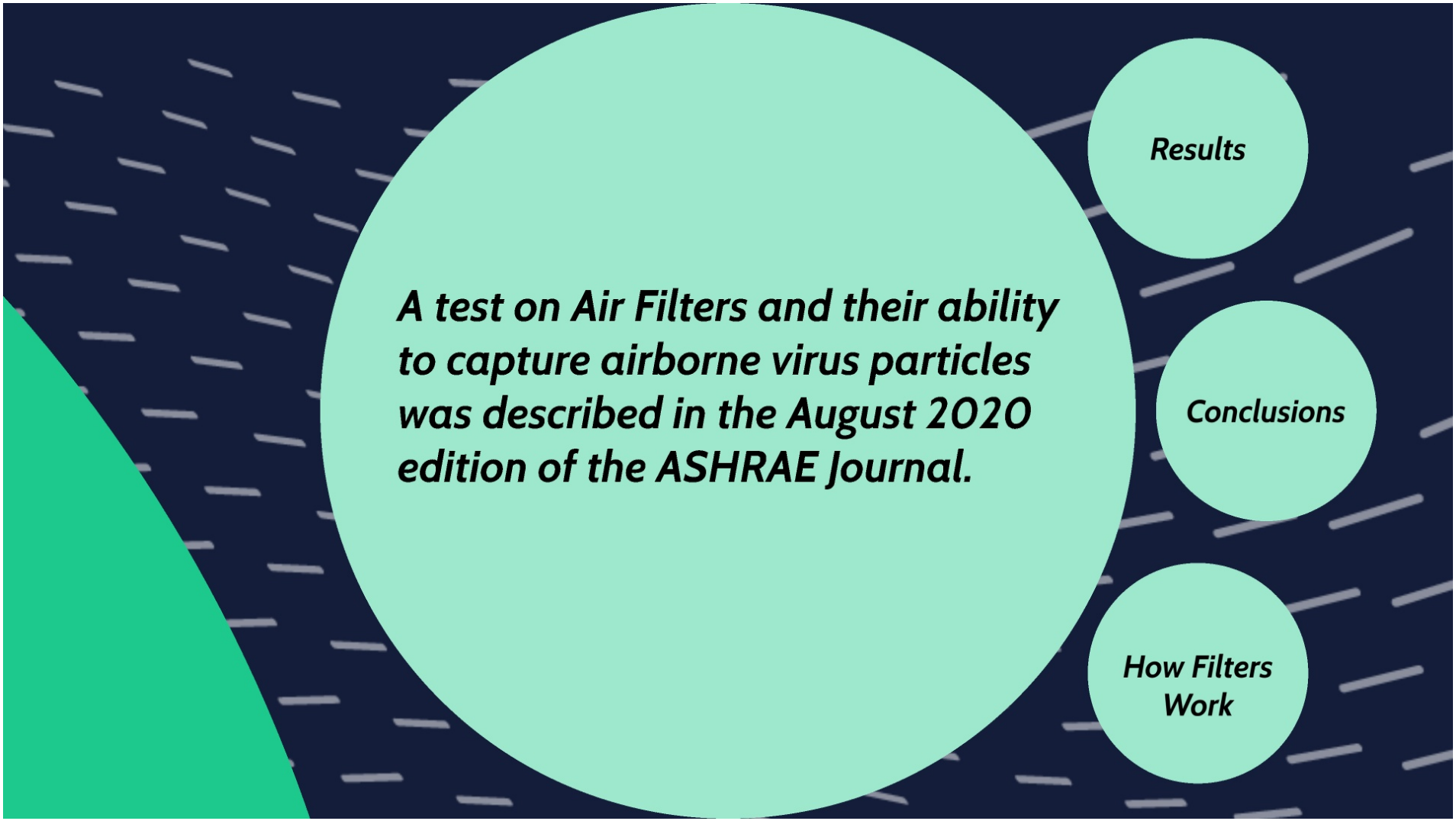
- Settling via gravity
- Diffusion via Brownian motion
- Impaction via inertia
- Interception via size
- Electrostatics via charge







From: Hinds, *Aerosol Technology*. Wiley Interscience, 2001.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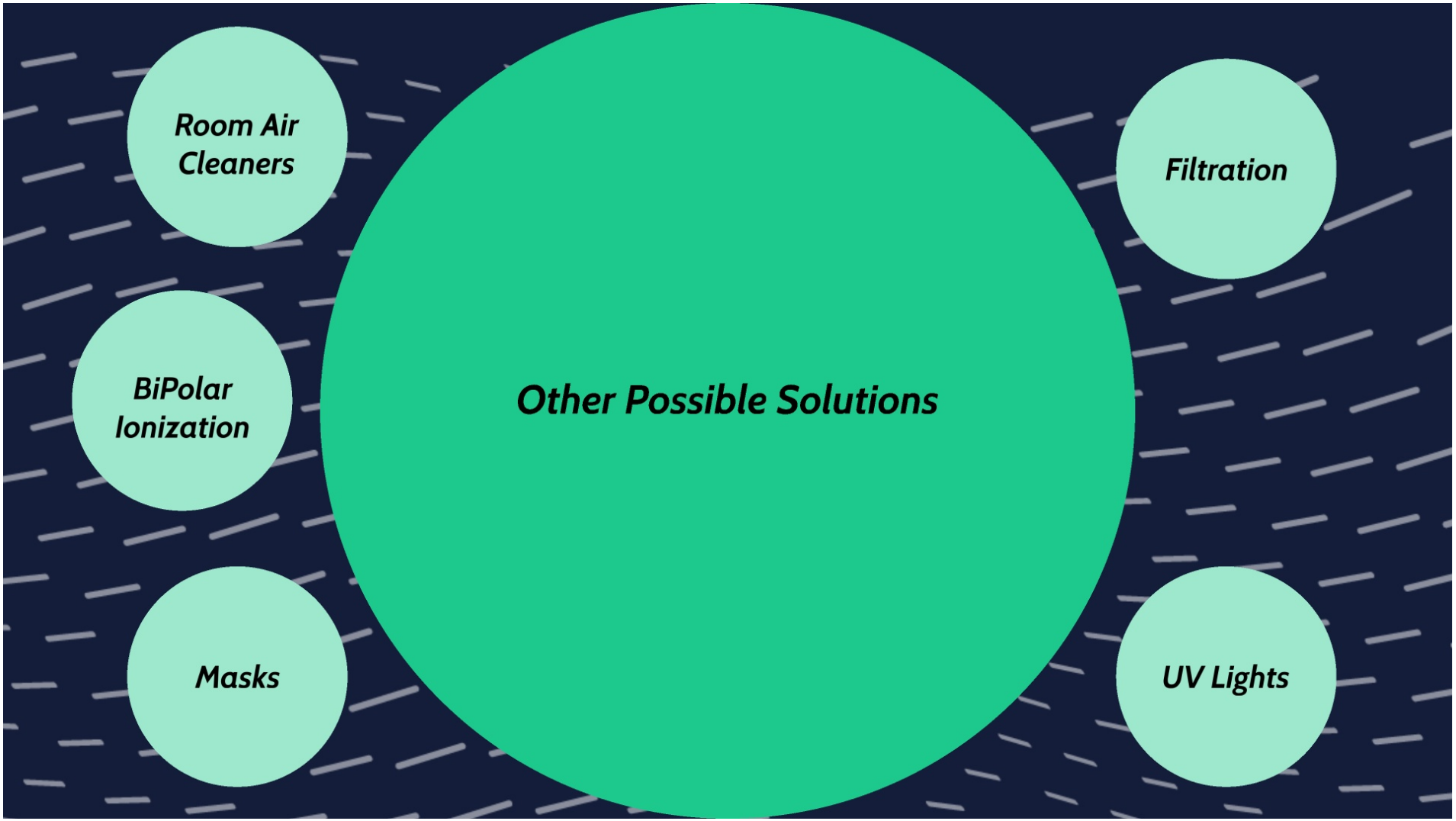
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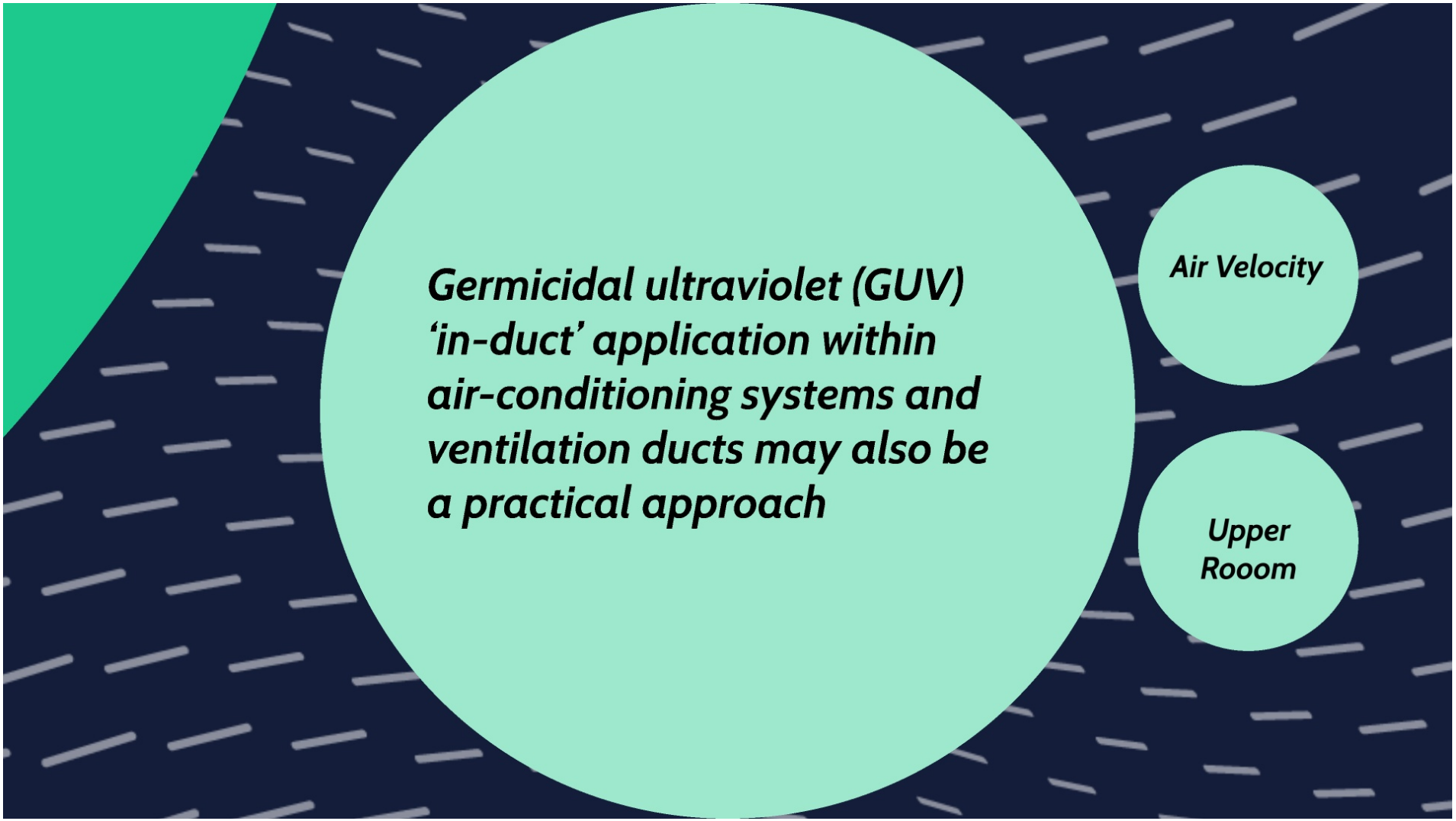
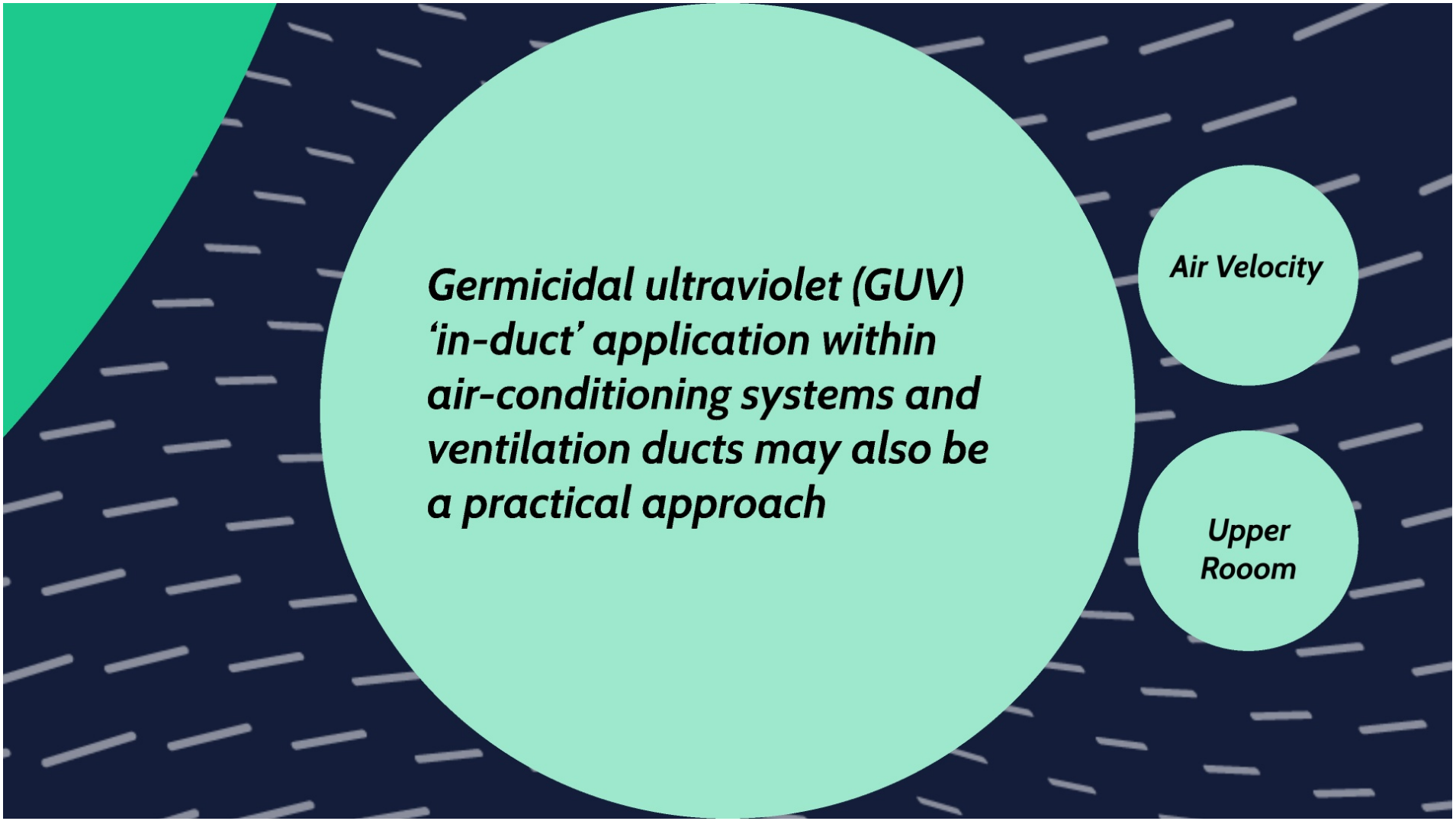

Germicidal ultraviolet (GUV) 'in-duct' application within air-conditioning systems and ventilation ducts may also be a practical approach
Air Velocity
Upper Rooom

At 2.2 m/s (433 fpm), the in-duct UV worked very well.
At 5.1 m/s (1004 fpm) there was no reduction.
Exposure time is critical.
Improvement in the UV light being installed in the mixed air duct versus the supply air duct.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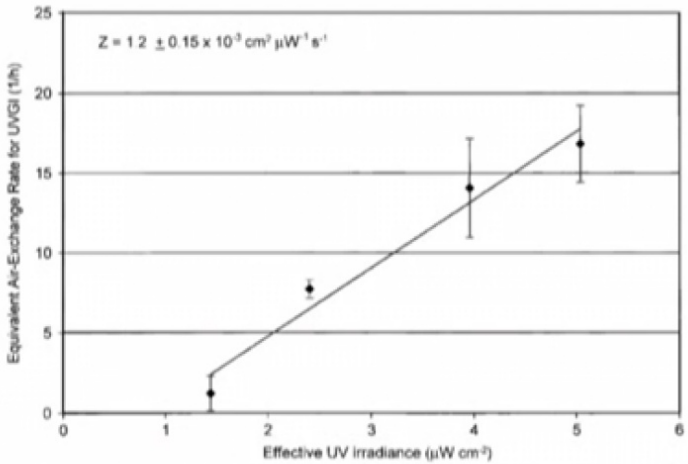
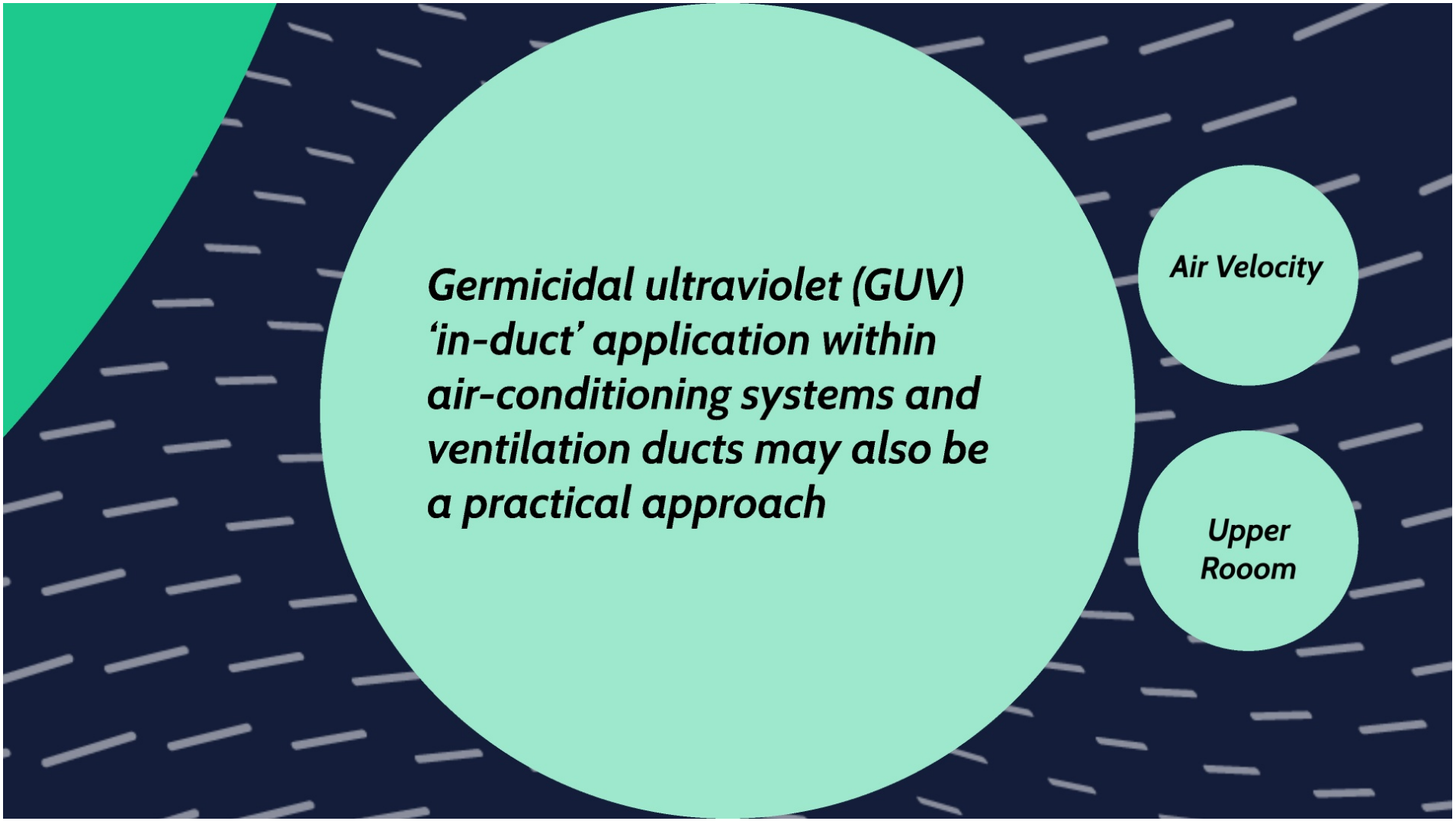


Fig. 7. UVGI inactivation rate as a function of effective UVGI spherical irradiance for *M. parafortuitum*. Effective UVGI spherical irradiance is the irradiance measured by actinometry in the upper-room zone only normalized to the fraction of room volume irradiated by UV (0.3/2.5 m).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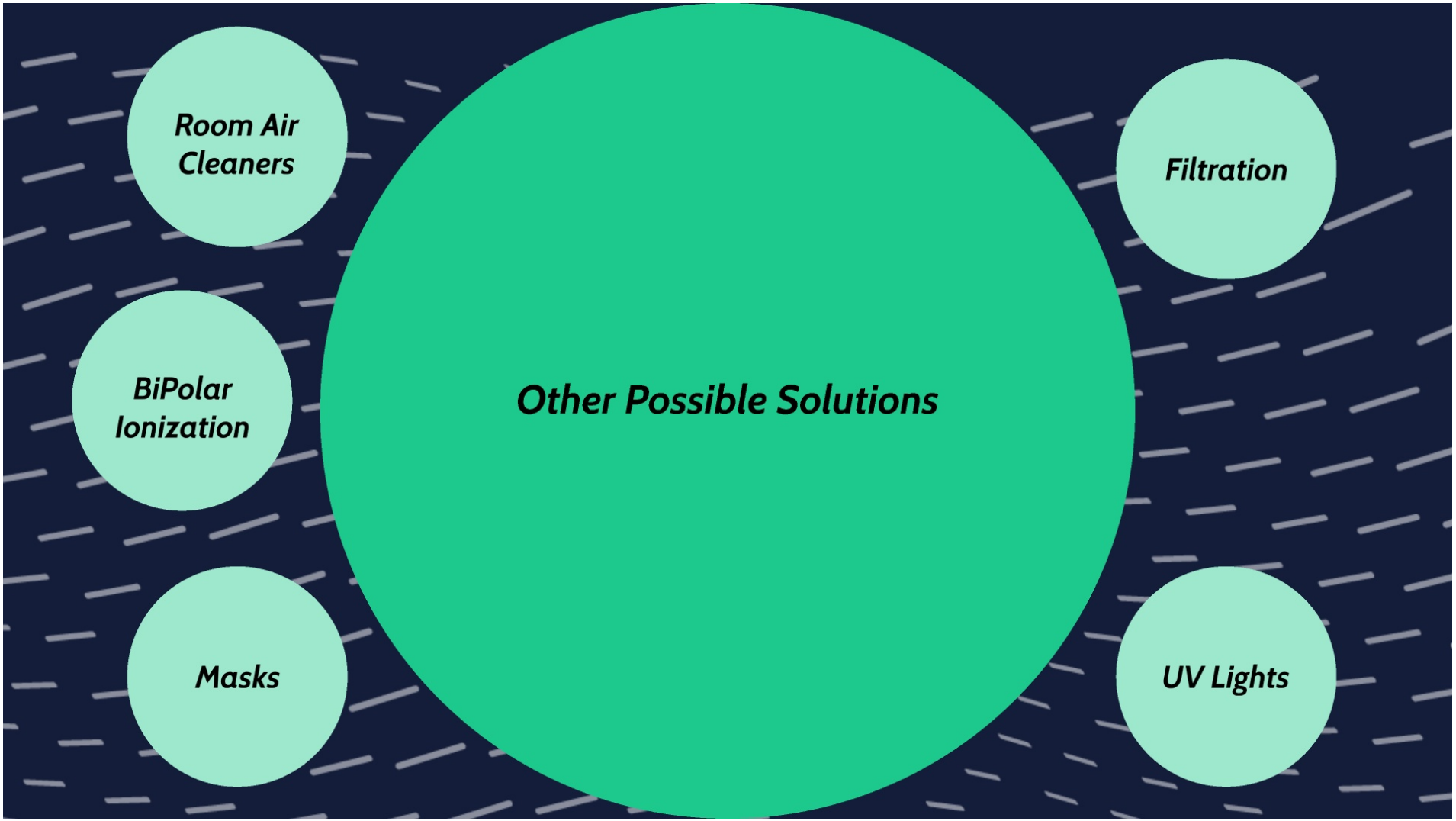
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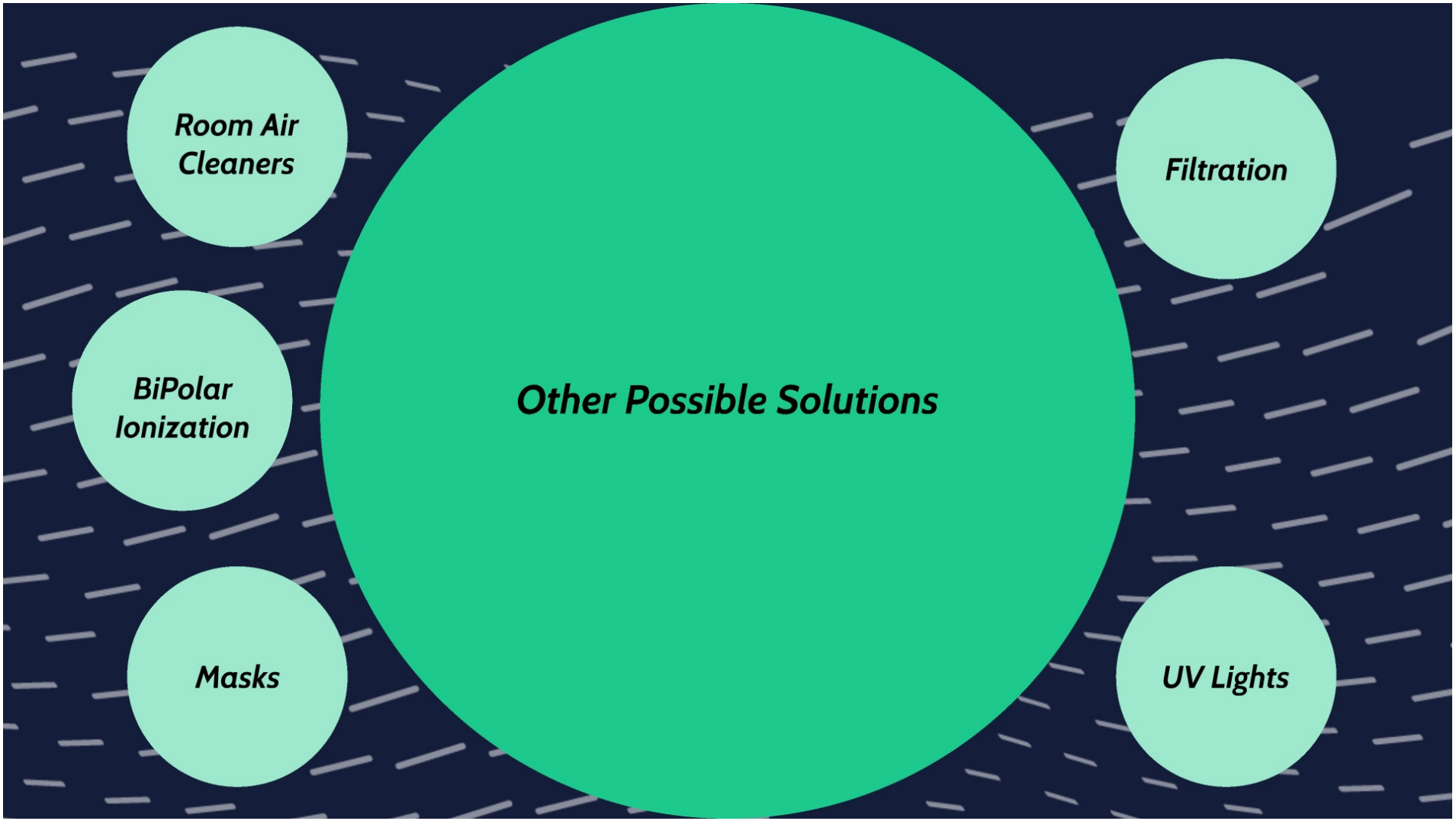
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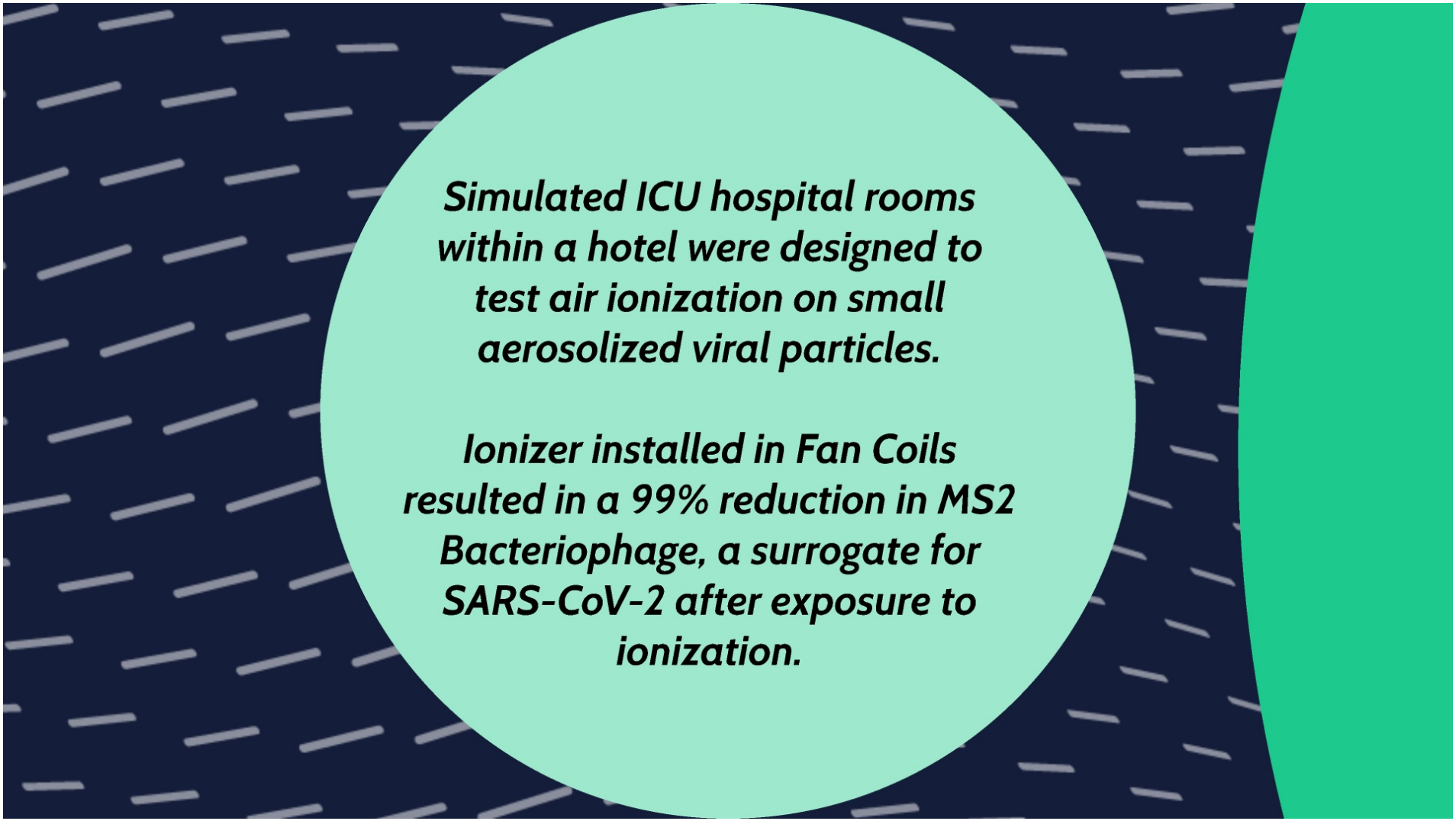
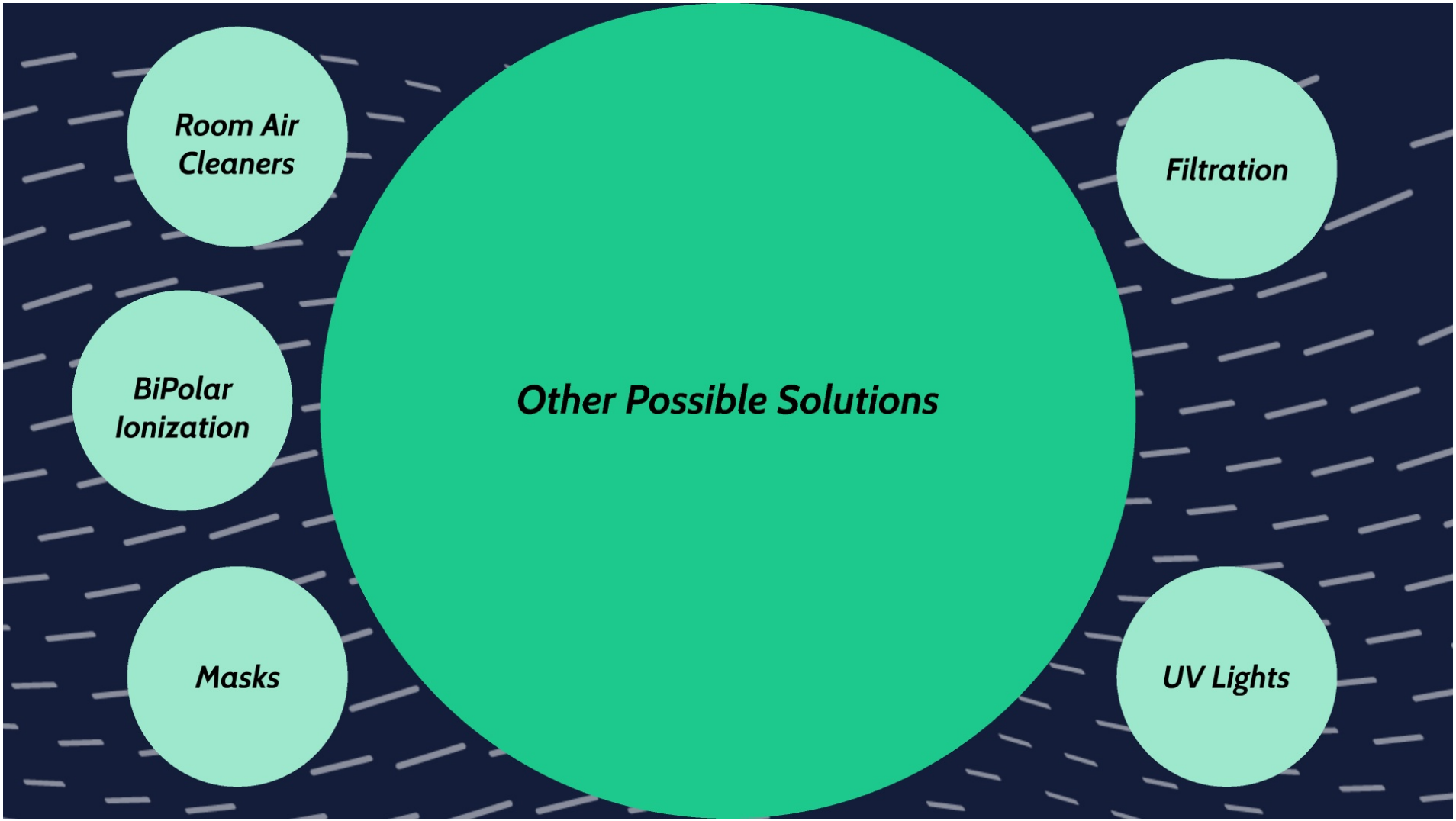

Simulated ICU hospital rooms within a hotel were designed to test air ionization on small aerosolized viral particles.
Ionizer installed in Fan Coils resulted in a 99% reduction in MS2 Bacteriophage, a surrogate for SARS-CoV-2 after exposure to ionization.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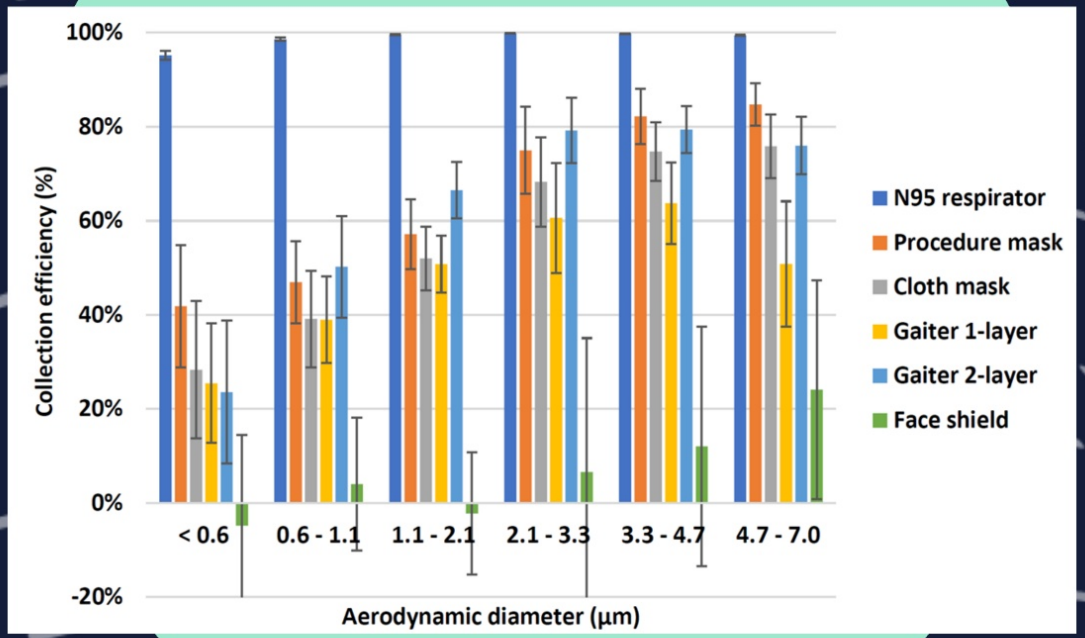
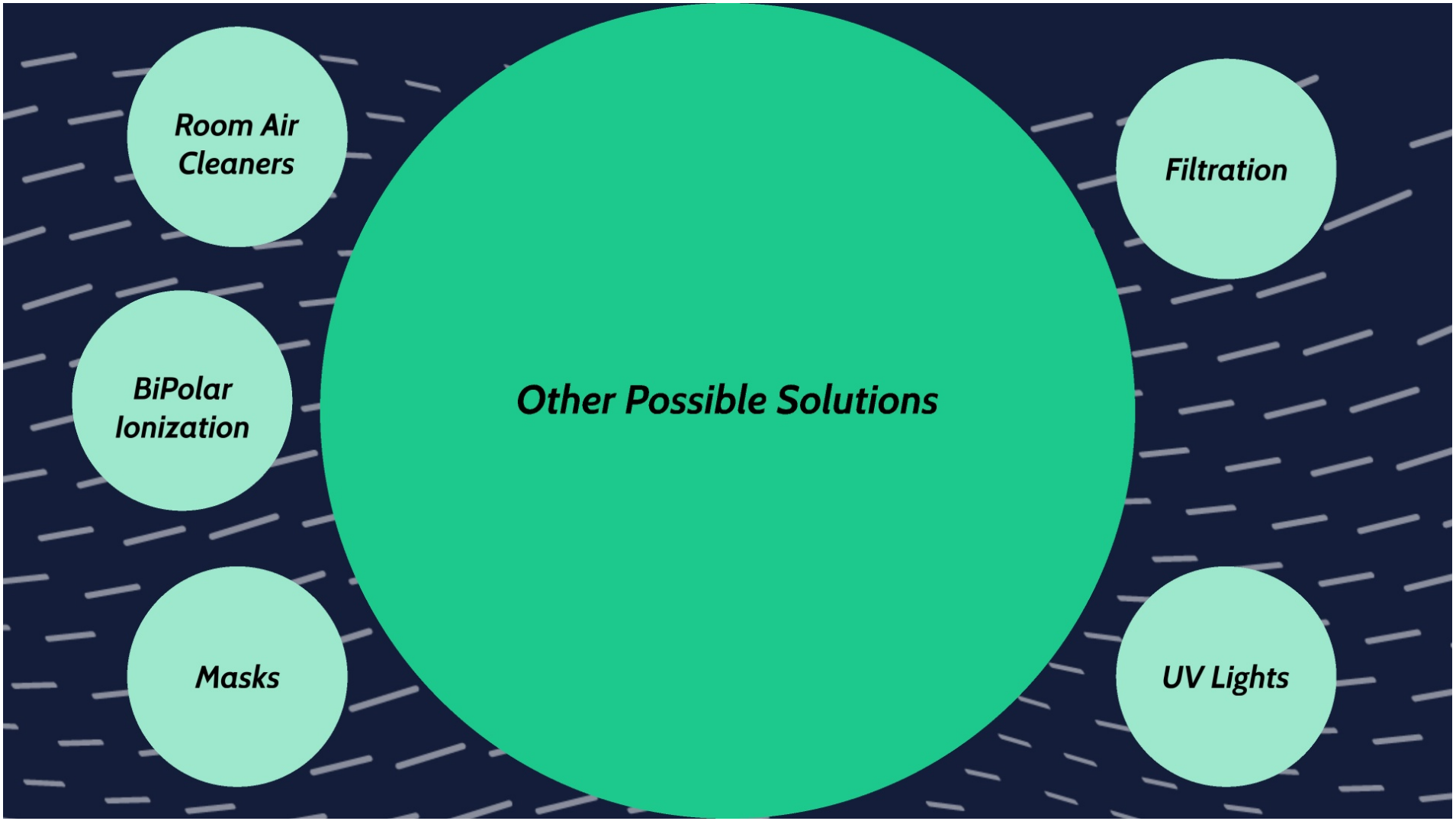

100%
80%
60%
40%
20%
0%
-20%
Collection efficiency (%)
< 0.6
0.6 - 1.1
1.1 - 2.1
2.1 - 3.3
3.3 - 4.7
4.7 - 7.0
Aerodynamic diameter (µm)
N95 respirator
Procedure mask
Cloth mask
Gaiter 1-layer
Gaiter 2-layer
Face shield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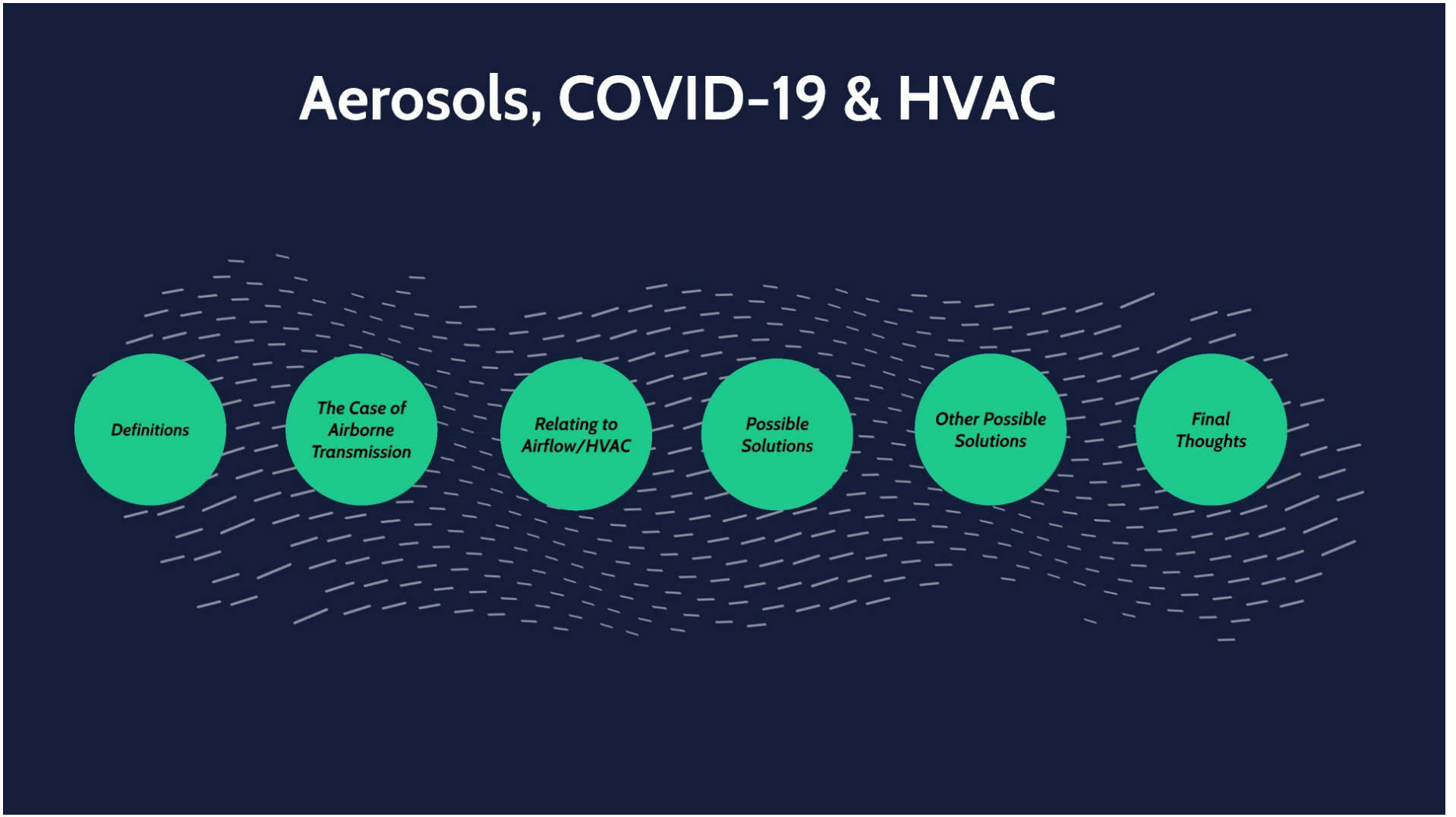
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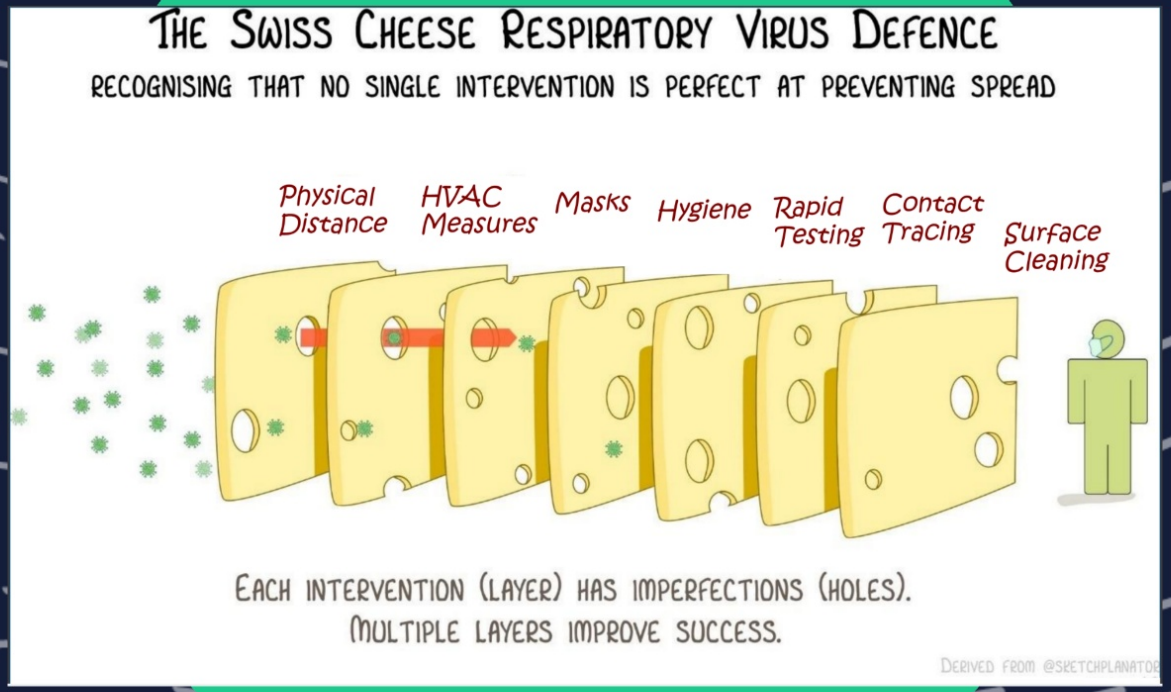
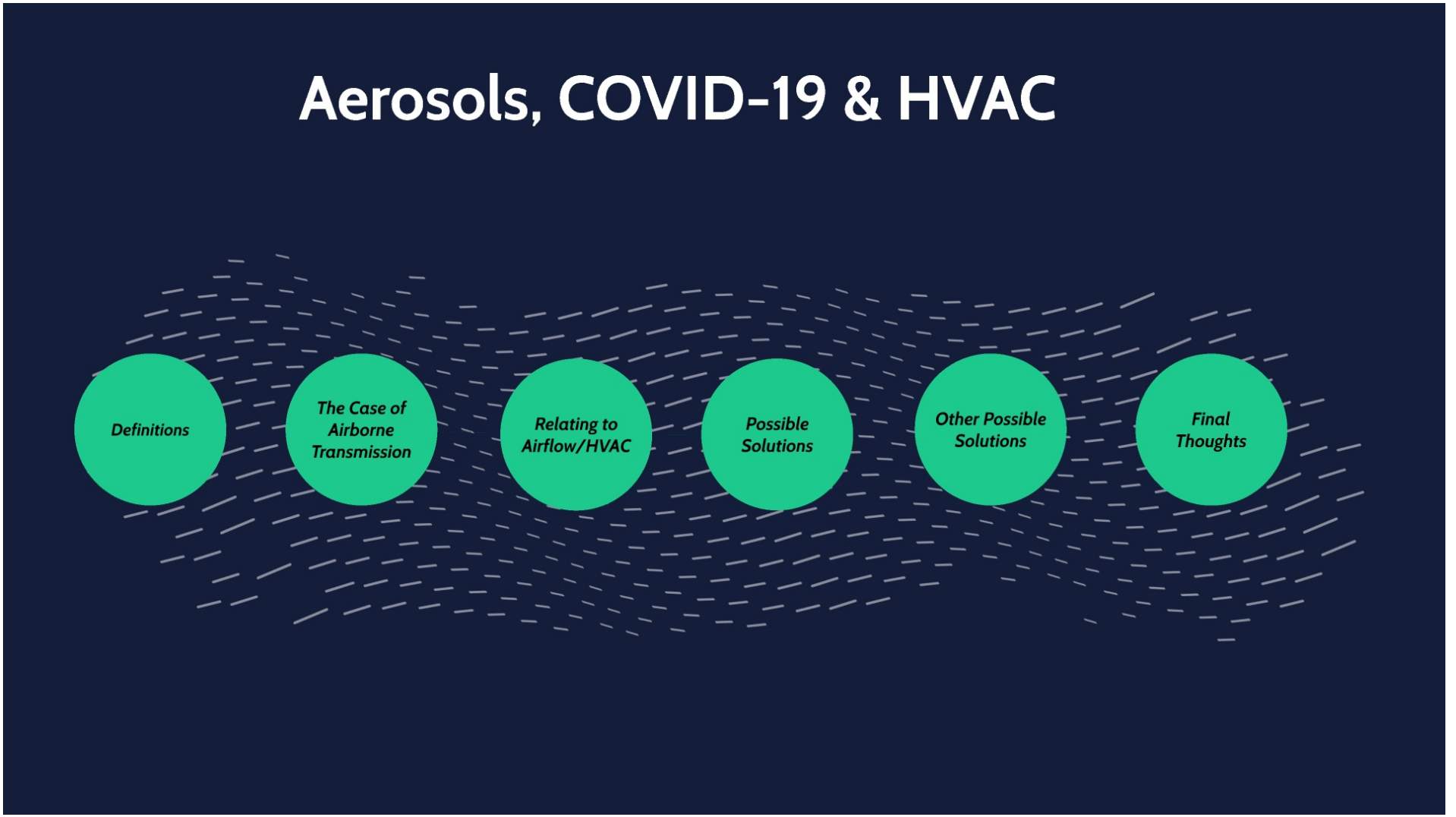

THE SWISS CHEESE RESPIRATORY VIRUS DEFENCE
RECOGNISING THAT NO SINGLE INTERVENTION IS PERFECT AT PREVENTING SPREAD
Physical Distance
HVAC Measures
Masks
Hygiene
Rapid Testing
Contact Tracing
Surface Cleaning
EACH INTERVENTION (LAYER) HAS IMPERFECTIONS (HOLES).
MULTIPLE LAYERS IMPROVE SUCCESS.
DERIVED FROM @SKETCHPLANATOR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