Some simple physics of corona virus transmission

or

Corona virus: The unseen deadly soft matter that may be around us

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thanks to Daan Frenkel (U Cambridge) for ideas/discussion

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Outline

1. Our adversary: SARS-CoV-2
2. Modified version of models of Roland Netz & Matthew Evans, for virus transmission
3. Physics of masks
4. Conclusions

Disclaimer: Obviously I am just a computational physicist, don't rely on anything in this talk for medical advice, see NHS, a medical doctor, etc

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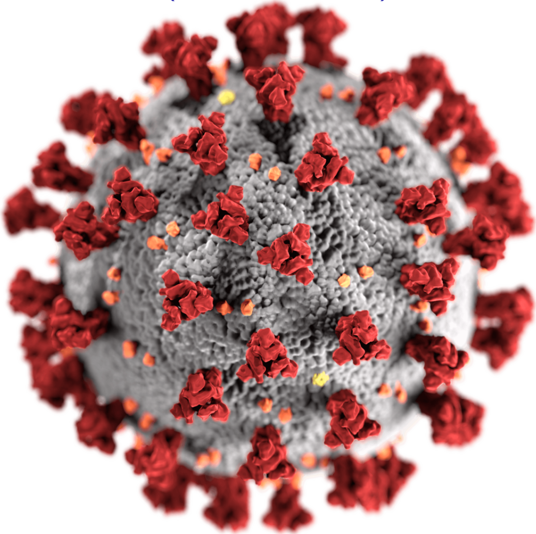
Our adversary: Severe Acute Respiratory Syndrome coronavirus 2 (SARS-CoV-2)

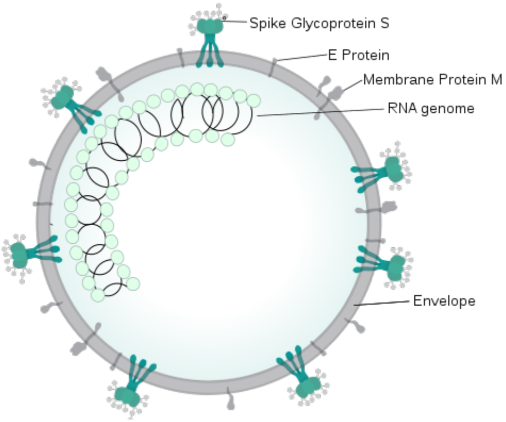


$\approx$ 100 nm across

it is a respiratory virus, i.e., infects mainly via our throat/nose

What are viruses?

Viruses = simplest of all life, just genes for replication inside a protein (and maybe fatty) coat



Other examples: flu, HIV, ebola, measles, SARS, polio, ...

What are our options to fight a virus?

1. DRUGS: Few or no drugs so no cure for many viral diseases. Why? Viruses have no metabolism outside of cells — so nothing to poison — antibiotics poison vital aspects of bacterial metabolism
2. VACCINES: Most effective: vaccination has completely eliminated the viral disease smallpox — one of the best achievements in history. But take time to develop.
3. STOP TRANSMISSION: No vaccine, no drugs that can cure, stopping transmission our only option

Why are we afraid?

1. Mortality rate highly variable but in elderly/those with pre-existing conditions, $\gtrsim 10$ %

2. Highly contagious. Some people can show **no** symptoms but be infectious: You or a friend/partner could be infected, infectious and not know not it. This makes it hard to stop/slow the spread.

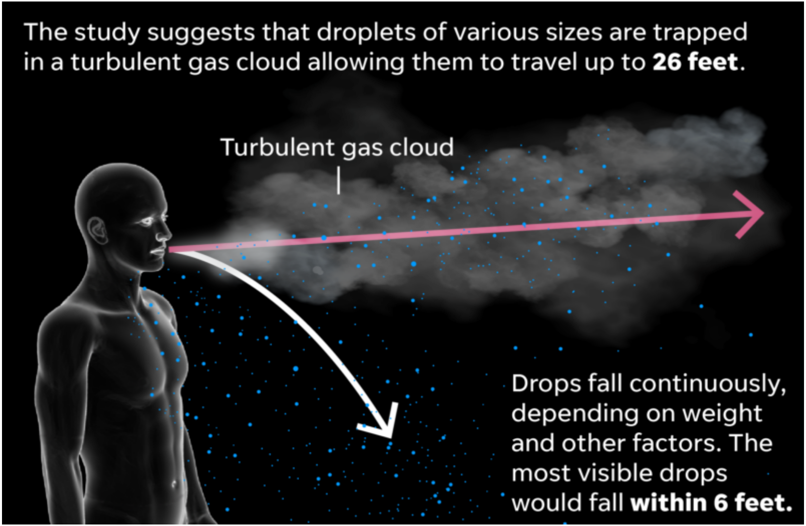
Simple model for SARS-CoV-2 transmission

How does transmission occur from an infected person, to another person in the same room?

following Roland Netz, J Phys Chem 2020
&
Mathew Evans, arXiv 2005.10988 2020

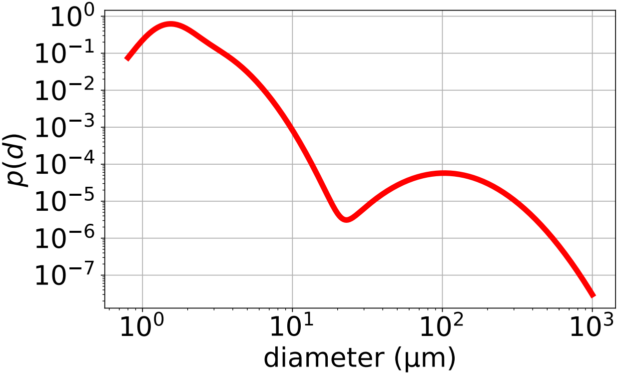
We breathe out droplets

We all breathe out droplets especially when we speak.



swartzlaw.com

We breathe out droplets with a very wide range of sizes



Johnson et al, J Aero Sci (2011)

Two peaks: Peak 1: most droplets a few μm. Peak 2: smaller in number peak near 100 μm

Note that one 100 μm droplet can contain 10^6 times as much virus as a μm one!

We breathe out droplets

Small droplets, a few μm: about 10^3/minute, total volume $10^5 \mu m^3$/minute

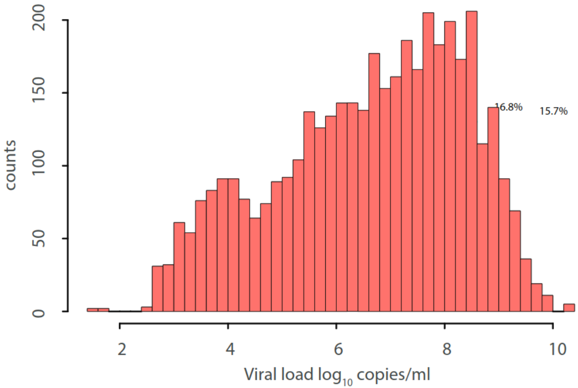
Big droplets, 100 μm: about 10/minute, total volume $10^8 \mu m^3$/minute

Although about 99% of the droplets we breath out are small, as bigger droplets have almost a million times the volume, bigger droplets have over 99% of the liquid volume we breathe out when speaking!

Johnson et al, J Aero Sci (2011) breathing 7.5 litres/minute

Are some infected people a billion times as infectious as others?

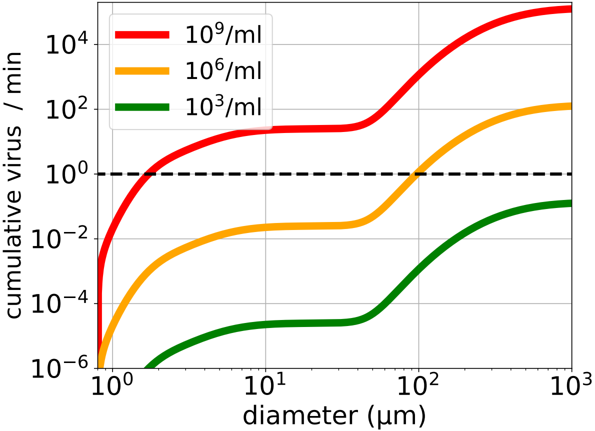
Concentration of virus (viral gene) in mucus (from swab) per ml



Jacot et al medRxiv 2020

Some infected people at some times during infection have much higher concentration of virus

Viruses per minute, in droplets, exhaled by speaking infected person



10s of viruses/minute in droplets $\lesssim 10\,\mu m$

100,000 viruses/minute in droplets $\sim 100\,\mu m$

Assumes swabs sample representative volume of mucus

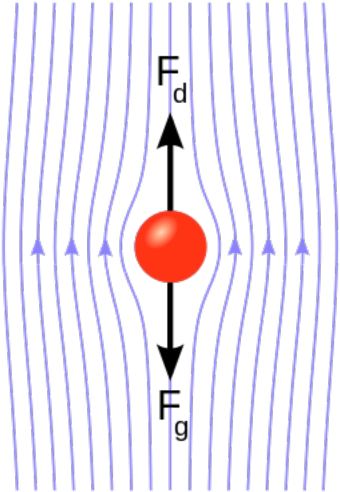
Big and small droplets

We breathe out droplets of all sizes from less than μm to a mm. But for simplicity consider the big and small ones separately.

NB medics often call small droplets aerosols.

Debate is raging as to relative importance of the big and small droplets in transmission!

Big droplets: Social distancing reduces the risk by using gravity to eliminate the big droplets



Wikimedia

Droplet diameter d falling in air feels two forces: gravity and drag. Falls to ground in

$$t_{FALL} \sim \frac{10^4}{d^2}\ \text{s} \quad d \ \text{in} \ \mu\text{m}$$

$d = 100\,\mu\text{m}$, $t_{FALL} \sim 1$ s. Droplets fall to ground within a metre or two — hence social distancing!

$d = 1\,\mu\text{m}$ sedimentation is negligible — these droplets spread throughout a room

Social distancing: most of the mucus volume is in the bigger droplets

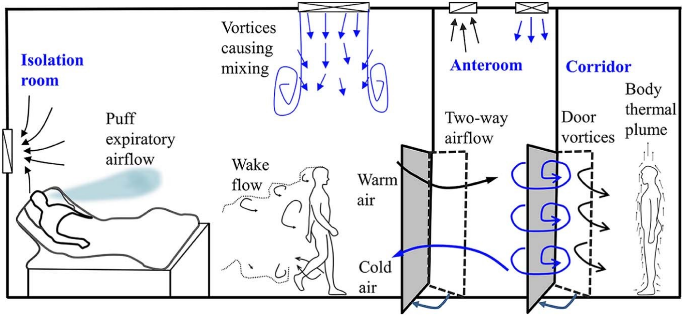
Bigger droplets should not go more than 1 or 2 m from the infected person, social distancing reduces risk from them!

But smaller droplets can move many metres!

Smaller droplets disperse on air currents, can move many metres

Droplets μm hardly fall at all, so persist in the air

All rooms have air currents in them that mix the air in them



Wei and Li, Am J Infection Control 2020

The air in rooms turns over

Building standards for rooms suggest air turnover should occur a few times an hour, then if someone breathes out tens of virus/minute, at steady state ~ 1000 viruses in room air.

10 virus/m^3 in room air, for 100 m^3 room (~ 6 m across)

Reality check: Nebraska hospital study finds 10^3virus/m^3
Santarpia et al, Sci Rep 10, 12732 (2020)

Sharing a room with an infected person

You breathe in ~ 7.5 litres/minute ~ 1 m^3/hour. So for 10 virus/m^3 in room air

you breathe in about 10 viruses per hour

Substantial uncertainty, 10^3/hour in Nebraska hospital room

Sharing a room with an infected person

We don't know dose that gives 50% probability of infection. But for flu, estimated as $\sim 10^3$ viruses (Nikitin et al, Adv Virology 2014).

$\sim$ 5%/hour probability of becoming infected

This estimate relies on a *lot* of assumptions!

Reality check: Using Nebraska data, in poorly ventilated cab, $\sim 10^5$virus/m^3, so infectious dose in minutes. Two taxi drivers infected by Diamond Princess passengers after 10 min trips

Respiratory virus transmission is complex, which is why no one understands it

To understand transmission you need to understand

1. Virology, how does virus, enter and leave cells, and reproduce inside them. How many copies of a virus are needed to infect us? How long does the virus last outside us?
2. Soft matter physics, how are (virus containing) droplets formed from the mucus, when we breathe, speak, cough, ... How do these droplets evaporate once they are airborne?
3. Fluid mechanics, how do the droplets move in air inside rooms? Outside?
4. Social science, do people social distance when you ask them? How does people's behaviour vary with age, job, education, ...
5. Epidemiology, how do we understand how an infectious disease spreads through a population?
6. ...

Respiratory virus transmission is complex, which is why no one understands it

As transmission depends on such a diverse range of complex phenomena...

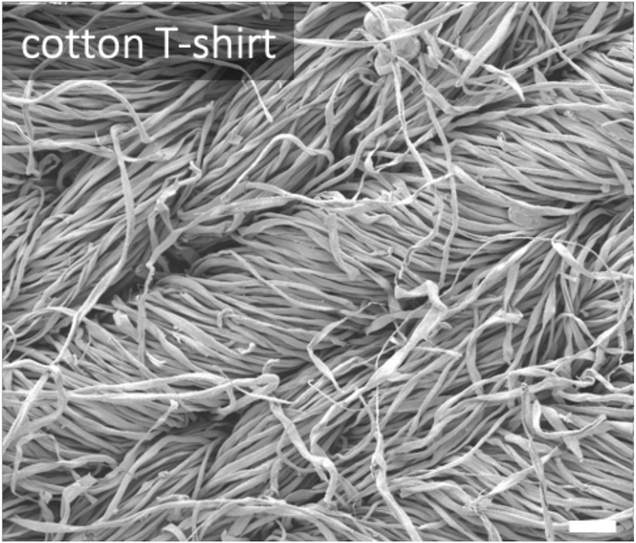
Nobody, not scientists, certainly not politicians, understands all of this

Serious research would cost hundreds of millions of pounds/dollar/euros, but this is cheap in comparison to trillions of economic damage

Masks

Efficacy of face coverings in reducing transmission of COVID-19: calculations based on models of droplet capture, Robinson et al, arXiv 2008.04995 (2020)

Cotton masks made from knitted or woven



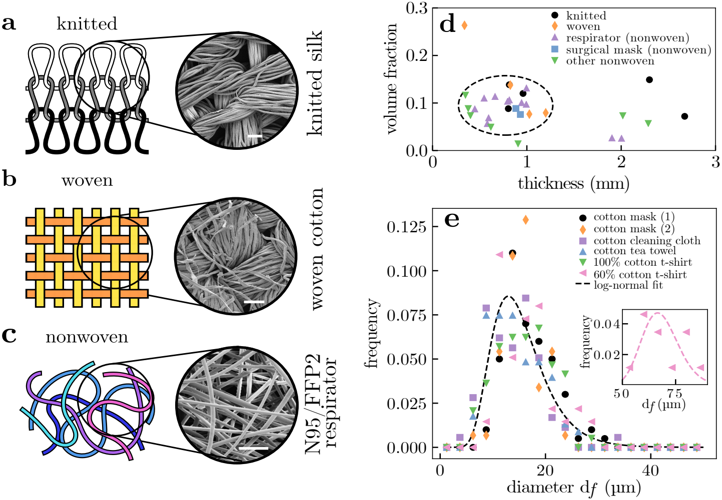
scalebar 100 μm note structure is basically hierarchical with smallest fibres $\sim$ 10 μm

Masks for professsional PPE (Personal Protective Equipment)

N95 - used by healthcare workers, regulated, to filter out 95% of even hard to filter 0.3 μm particles. Must have good fit!

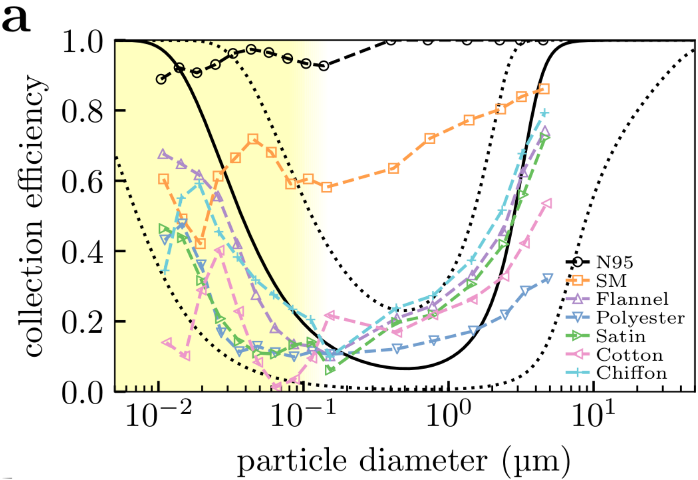
No valves!

Masks are air filters on the your face



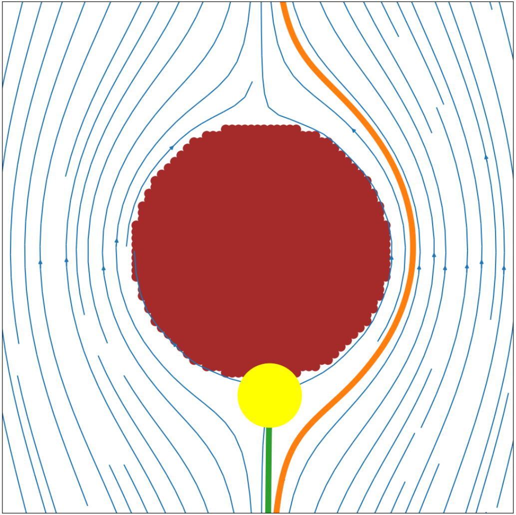
fabrics around 1 mm thick, and about 15 % fibres and so 85 % air.
Made of fibres tens of μm thick.

Filtration efficiency: model predictions and data



efficiency high for large and small droplets, low for droplets between 0.1 μm to 1 μm

Their inertia makes it easy to filter large droplets



Orange trajectory, drag force dominates inertia, so droplet follows air streamlines (blue) and moves around fibre (red) so is not filtered

Green trajectory, too much inertia to follow streamlines, collides with fibre and is filtered out

Their inertia makes it easy to filter large droplets

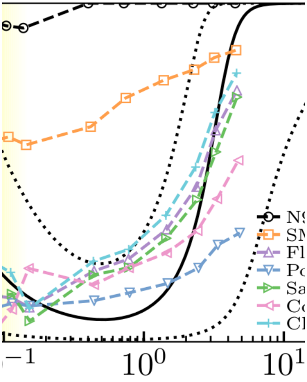
The effect of inertia on a droplet's trajectory in air is measured by the dimensionless

$$\text{Stokes number} = \text{St} = \frac{\text{inertia}}{\text{viscous drag}}$$

St$\ll 1$ and the drag force from air dominates and droplets faithfully follow the air flow and so flow with the air through the mask

St$\gg 1$ and inertia dominates and the droplet cannot follow the air flow, and it crashes into fibres and is filtered out

Their inertia makes it easy to filter large droplets



diameter d

Here Stokes number is

$$\mathrm{St} = 10^{-1}\frac{d^2}{d_f} \qquad d \;\;\&\;\; d_f \;\; \text{in} \;\; \mu\text{m}$$

For typical fibres $d_f = 10\,\mu\text{m}$, St$= 1$, for $d = 10\,\mu\text{m}$

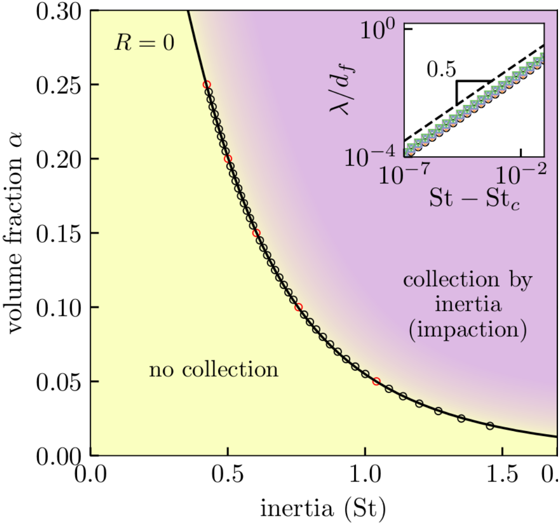
Droplets $\gtrsim 10\,\mu\text{m}$ have too much inertia to follow air so filtered out

Conclusion

1. We have no vaccine, we have no cures, we need to stop transmission
2. Transmission is complex and so poorly understood, we need a lot more data!
3. Reasonable to argue that:
   3.1 (Probably) Most virus is in large (tens of μm+) droplets that are both well filtered by simple masks and should be less of a problem 1 or 2 m away
   3.2 But some asymptomatic carriers breathing out virus in droplets small enough to carry across a room.

Thanks to Virginia, Miryea, Malin, Louie, Katrin and Rhiannon for the invite

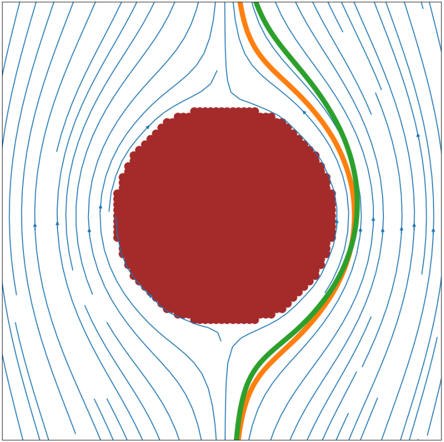
In the particle diameter/fibre diameter = 0 limit there is a dynamical phase transition



Curve is line of phase transitions, below it no droplets collide with fibres, at it droplets start to collide with fibres

Discovered by Araujo et al, Phys Rev Lett 2006

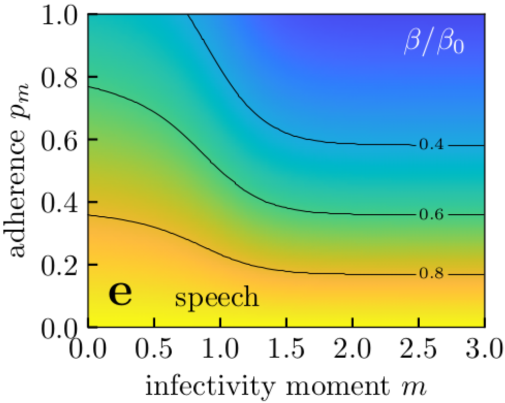
Why a dynamical phase transition?



Orange trajectory, low St, Green trajectory, large St.

Note that at low St, droplets tend to collide at side of the fibre, here increasing inertia actually causes the droplet to swing our further out further, so here little bit of inertia actually reduces filtration!

Estimated reduction in virus transmission due to mask wearing



assumes leakage around side of mask, 50% on breathing out, 25% on breathing in

$\alpha = 0.1$, 3 mm thick

droplets about 1/3 diameter on breathing in (dried out in air) as on breathing out

assumes both infected person and potential victim wear masks with probability p_m

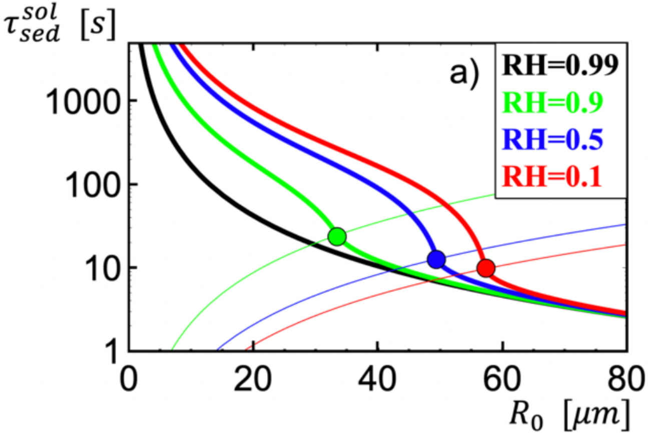
Small droplets evaporate very fast

Assuming limited by diffusion of water molecules in air away from evaporating droplet, time to evaporate from initial diameter d_0

$$t_{EVAP} \sim \frac{d_0^2}{v_W c_{SAT} D_{WA}} \sim 10^{-3} d_0^2 \text{ s} \qquad d_0 \text{ in } \mu\text{m}$$

v_W volume of water molecule, c_{SAT} concentration of water in air at saturation, D_{WA} diffusion constant of water in air

Droplets fall under gravity, and evaporate



$1/\mathrm{s}$ $\quad d \lesssim 10\,\mu\mathrm{m}$ $\qquad\qquad$ $10^3/\mathrm{s}$ $\quad d \gtrsim 10\,\mu\mathrm{m}$

Netz, J Phys Chem 2020