Ergonomics and Aerosol Technology
Ergonomi och Aerosolteknologi

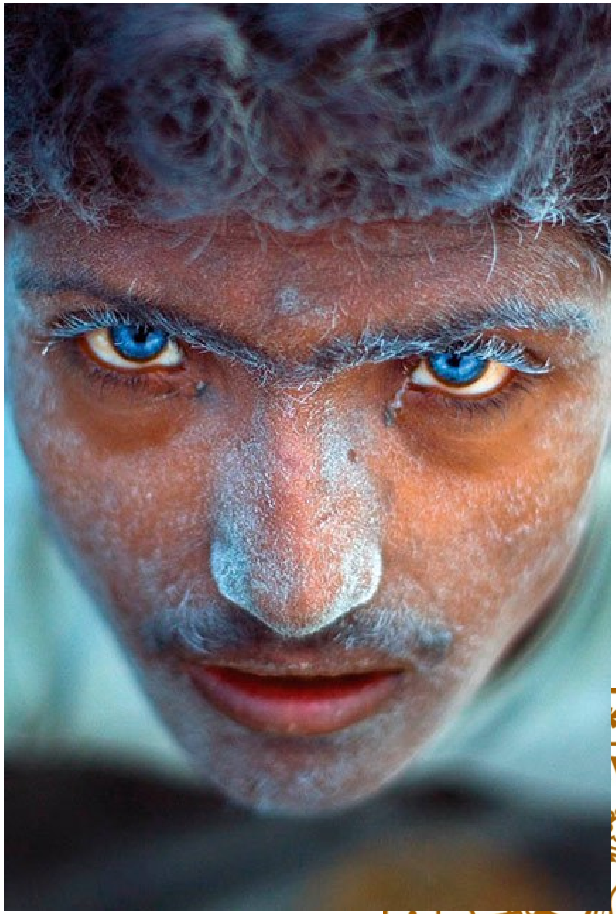
Aerosols

Airborne particles and health effects

Christina Isaxon
christina.isaxon@design.lth.se

Airborne solid or liquid particles in suspension in a gas

Dust

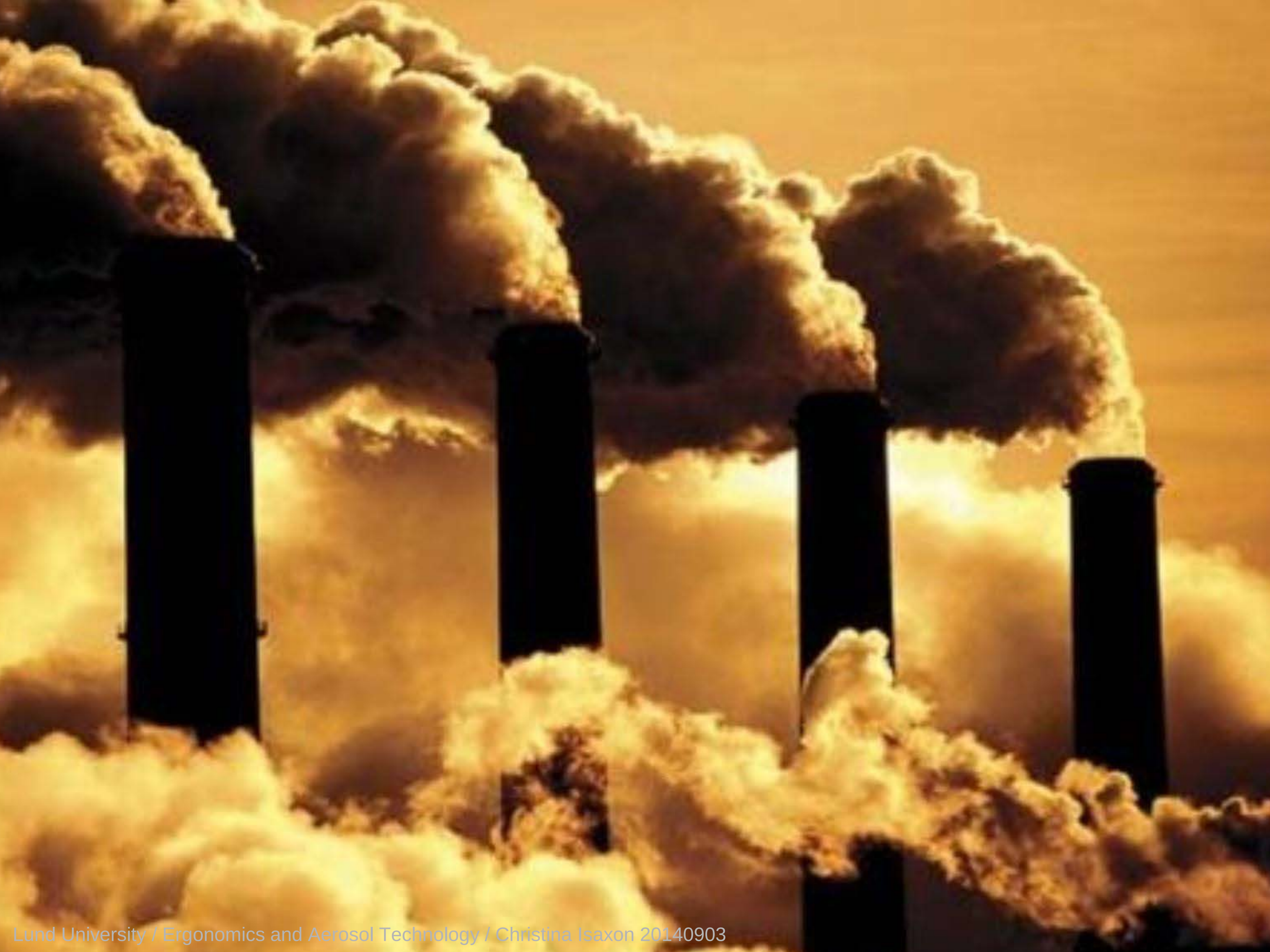


Luftföroreningar

Gaser och partiklar i luften som har en negativ påverkan på människa och miljö

Air pollution

Gases and air borne particles which have negative influence on people and environment



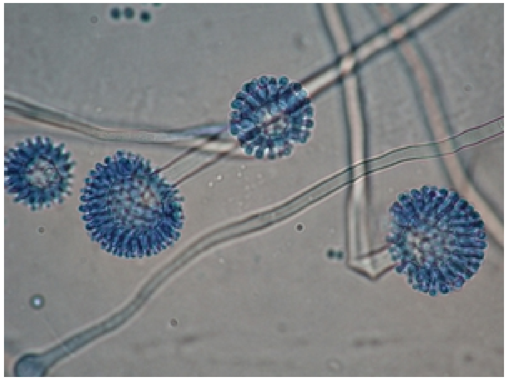
Fume

Smoke

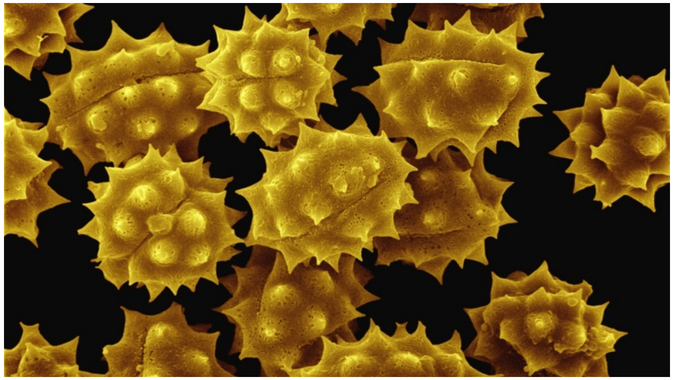
Mist

Smog

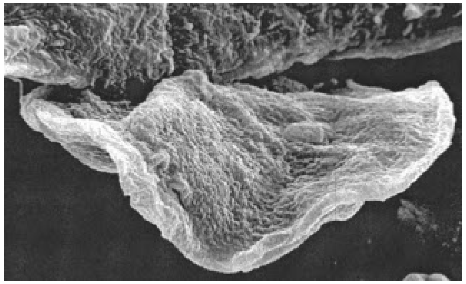
Fog



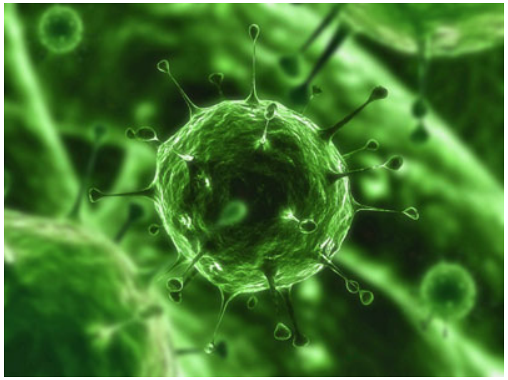
Spores



Pollen



Skin flakes



Virus

Bacteria

Sizes…

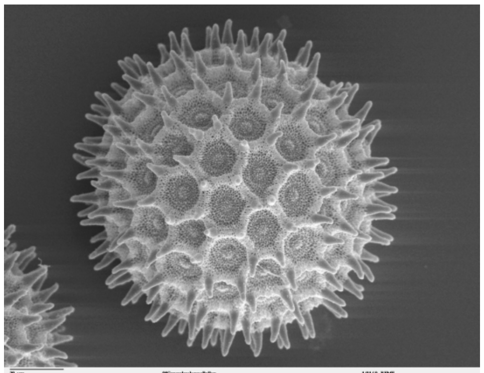
=air

Particles in suspension in a gas

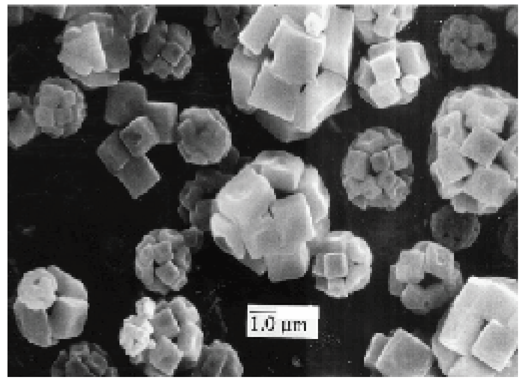
1 nm 100 µm

1 nm – 100 µm

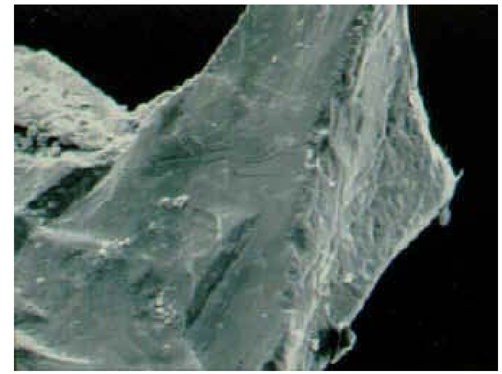
Speaking of diameters…



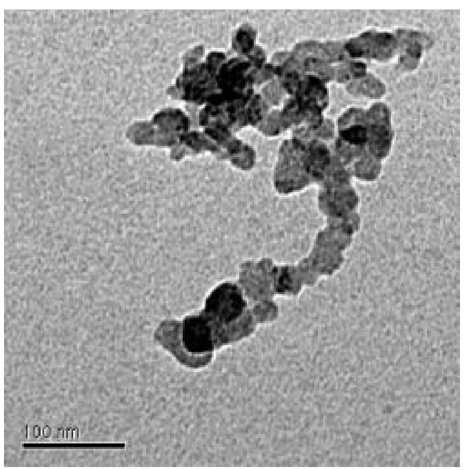
Pollen



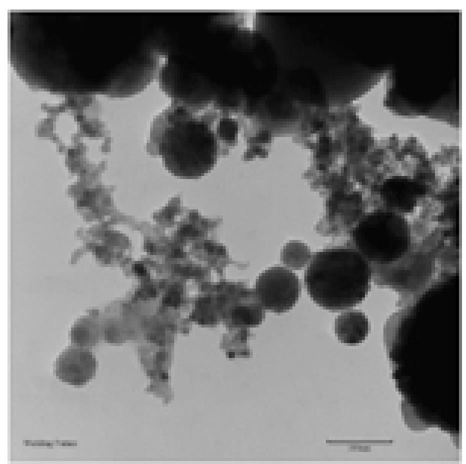
Havssalt



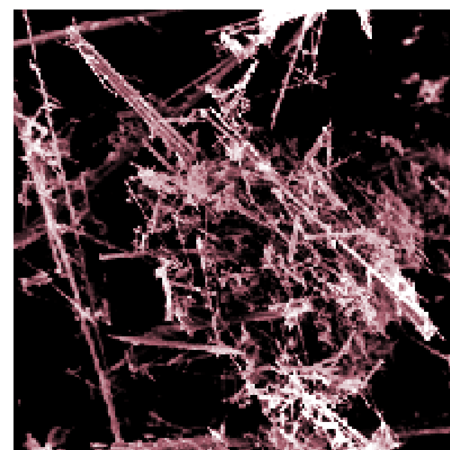
Jord



Dieselavgaser

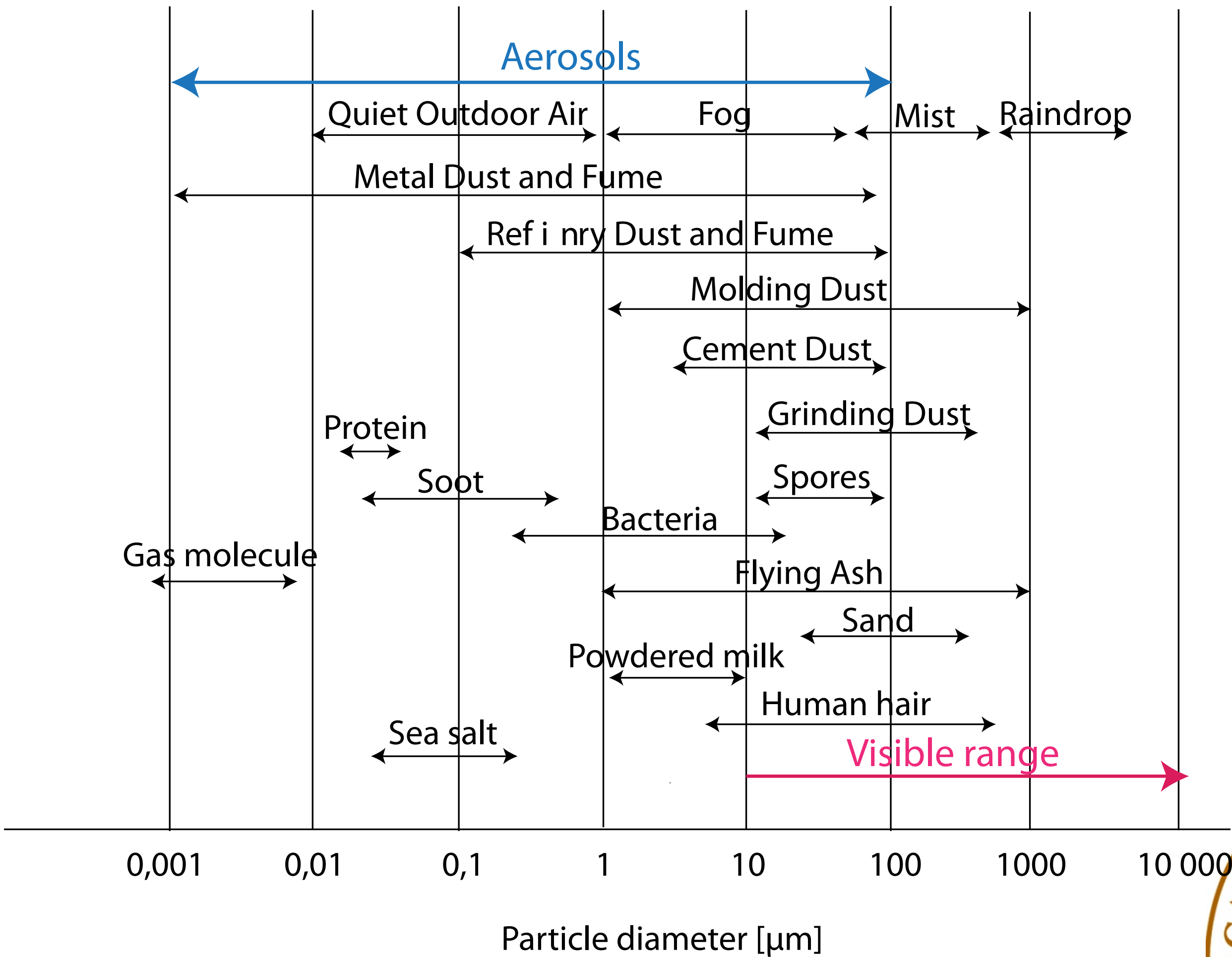


Svetsrök



Asbest

Size ranges



Aerosols
Quiet Outdoor Air
Fog
Mist
Raindrop
Metal Dust and Fume
Ref i nry Dust and Fume
Molding Dust
Cement Dust
Grinding Dust
Protein
Soot
Spores
Bacteria
Gas molecule
Flying Ash
Sand
Powdered milk
Human hair
Sea salt
Visible range
0,001
0,01
0,1
1
10
100
1000
10 000
Particle diameter [µm]

Depending on the particle source, there are two main categories of particles:

Natural

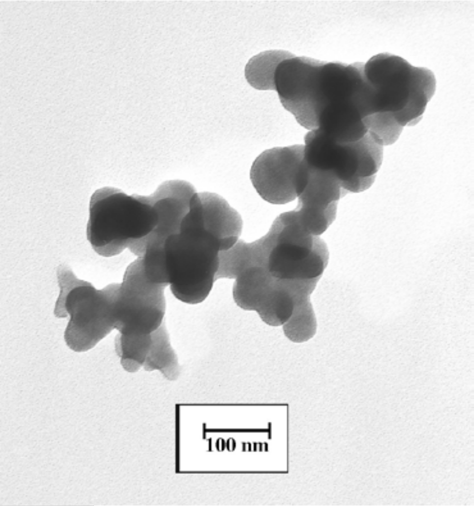
Antropogenic

Where can we find aerosols?

Soil particles
Ocean spray
Photochemically formed particles
Atmospheric clouds of water droplets or ice particles

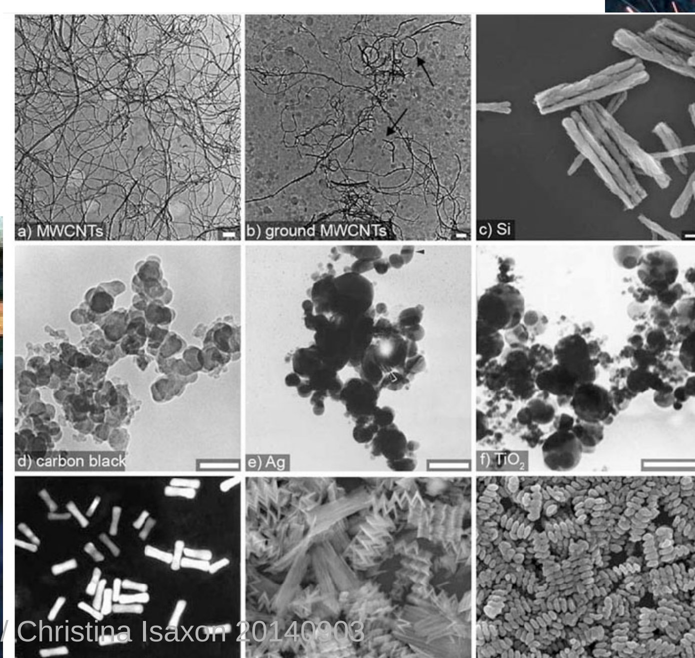
Where can we find aerosols?

Antropogenic sources



Where do we find aerosols?

Industry



Where can we find aerosols?

Indoors

How are particles formed?

Direct release (i.e. primary aerosols)

Breakdown of a material (e.g. erosion, grinding)

Resuspension (e.g. of dust , tyre-road)

Ocean spray

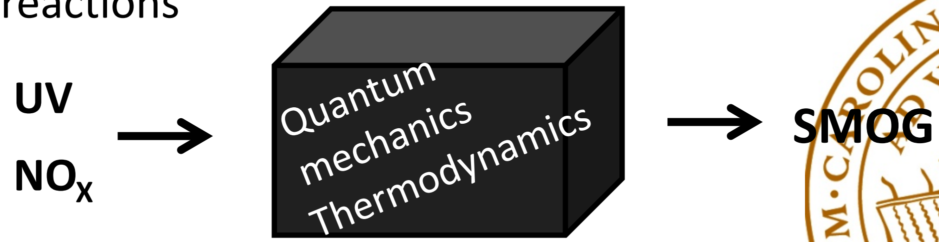
Forest fire, volcano erruption

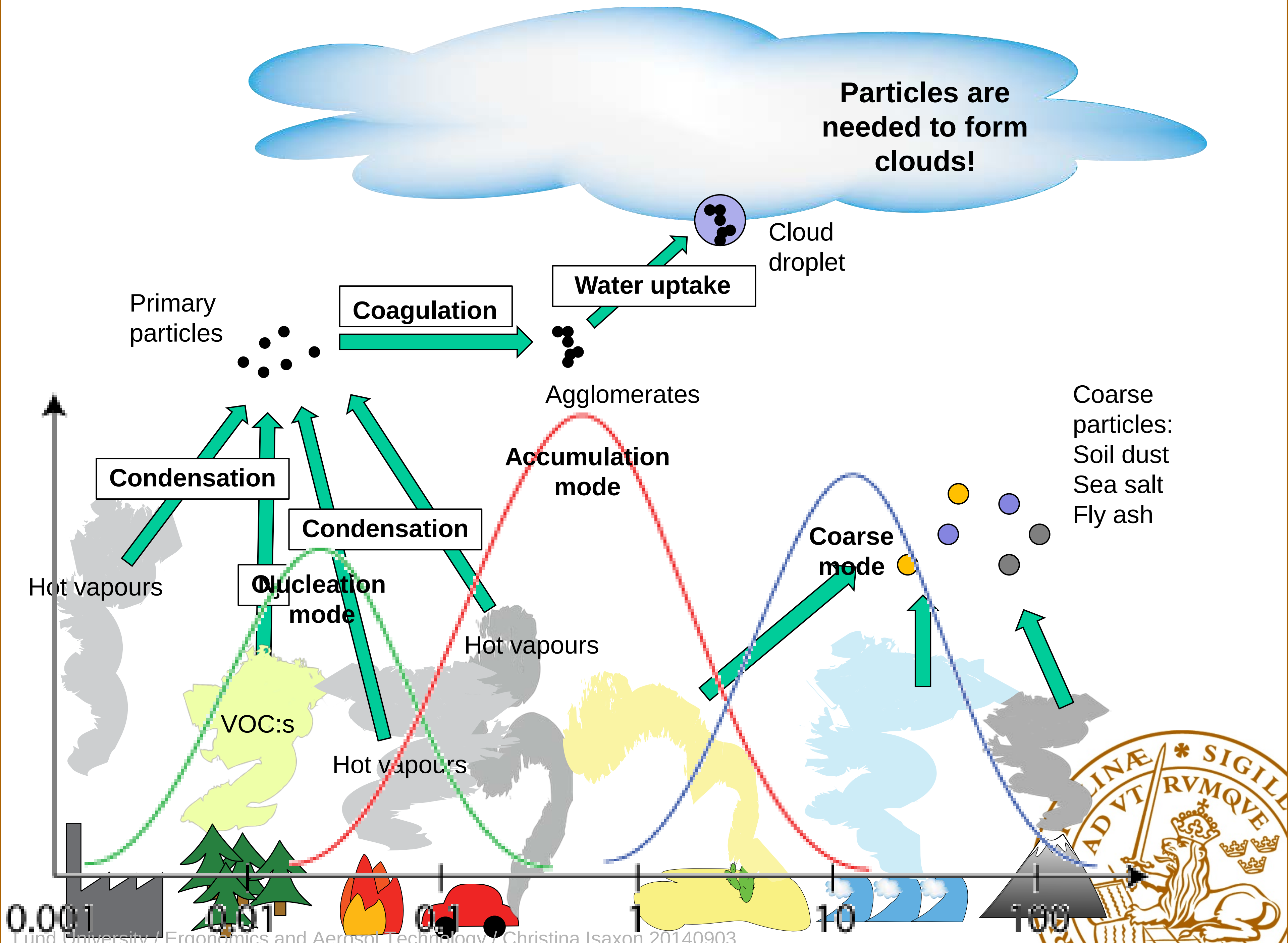
Biologic activitet

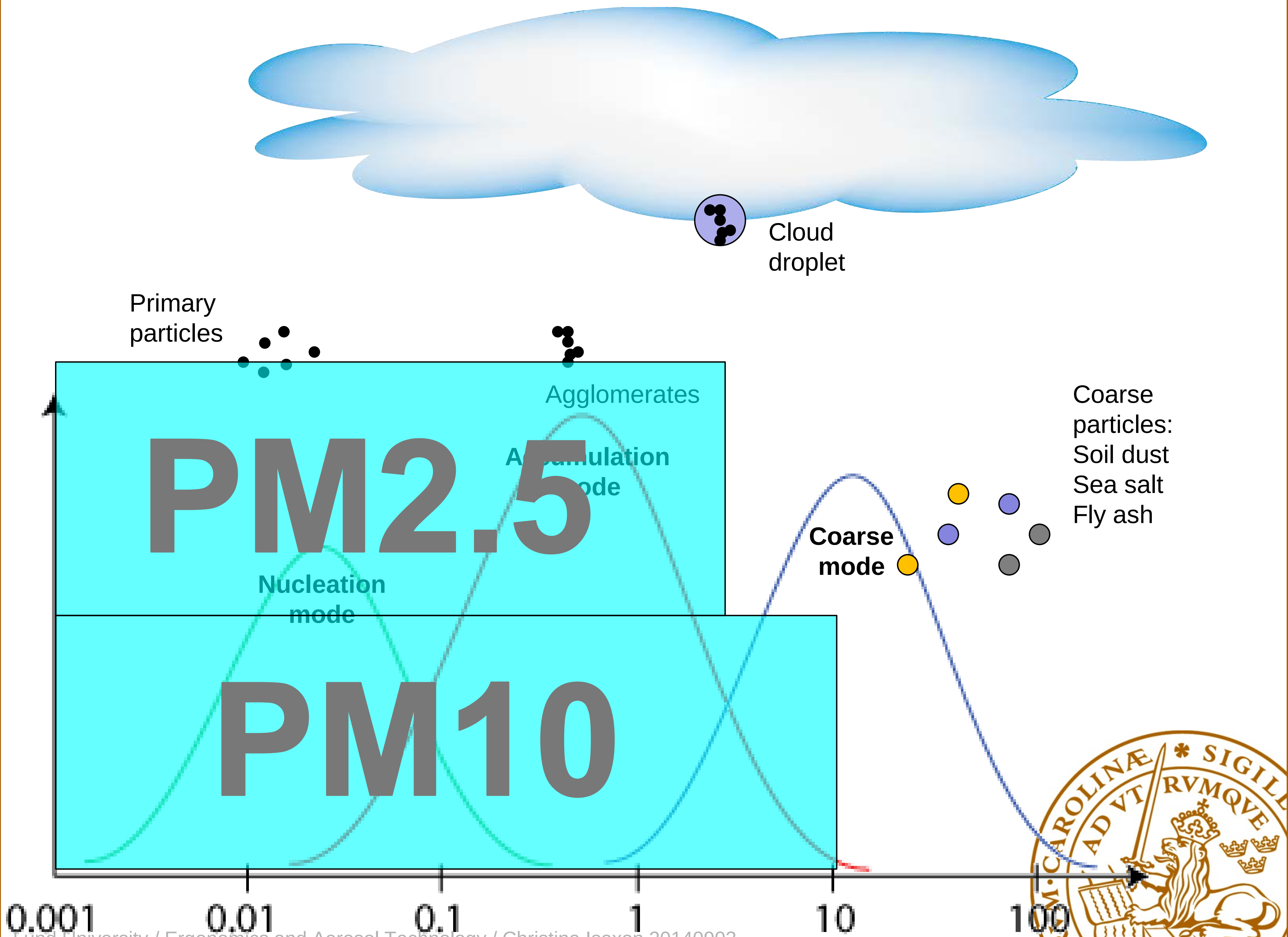
Combustion processes (organic compounds, soot and metals)

Particle formation in the atmosphere (i.e. secondary aerosols)

Ozon from outdoors reacting with VOCs
Complex, often fotochemical, reactions

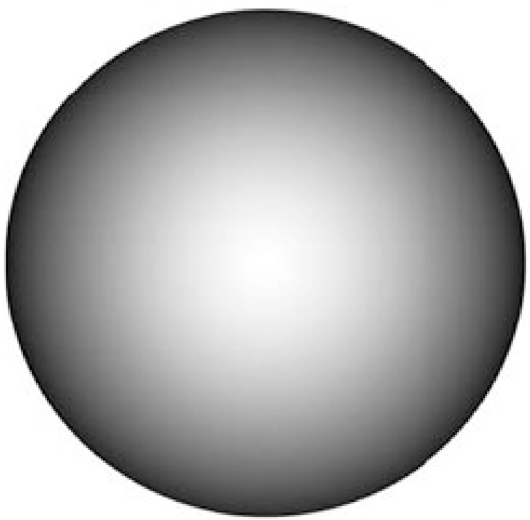



Particles are needed to form clouds!
Cloud droplet
Water uptake
Coagulation
Primary particles
Agglomerates
Condensation
Condensation
Nucleation mode
Accumulation mode
Coarse mode
Coarse particles:
Soil dust
Sea salt
Fly ash
Hot vapours
Hot vapours
Hot vapours
VOC:s
0.001
0.01
0.1
1
10
100

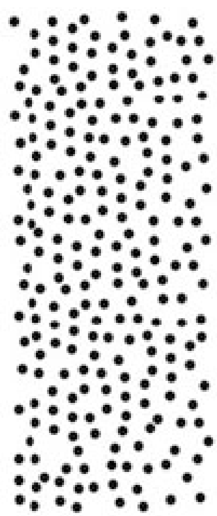

Cloud
droplet
Primary
particles
Agglomerates
Accumulation
mode
PM2.5
Nucleation
mode
Coarse
mode
Coarse
particles:
Soil dust
Sea salt
Fly ash
PM10
0.001
0.01
0.1
1
10
100

Numberconcentration - massconcentration

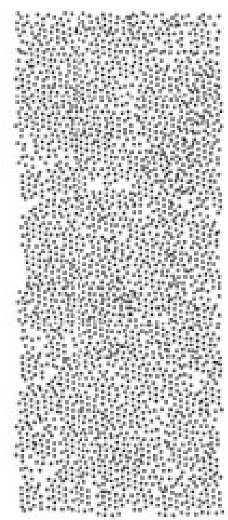
1 particle, diameter 60 µm
(like a human hair)

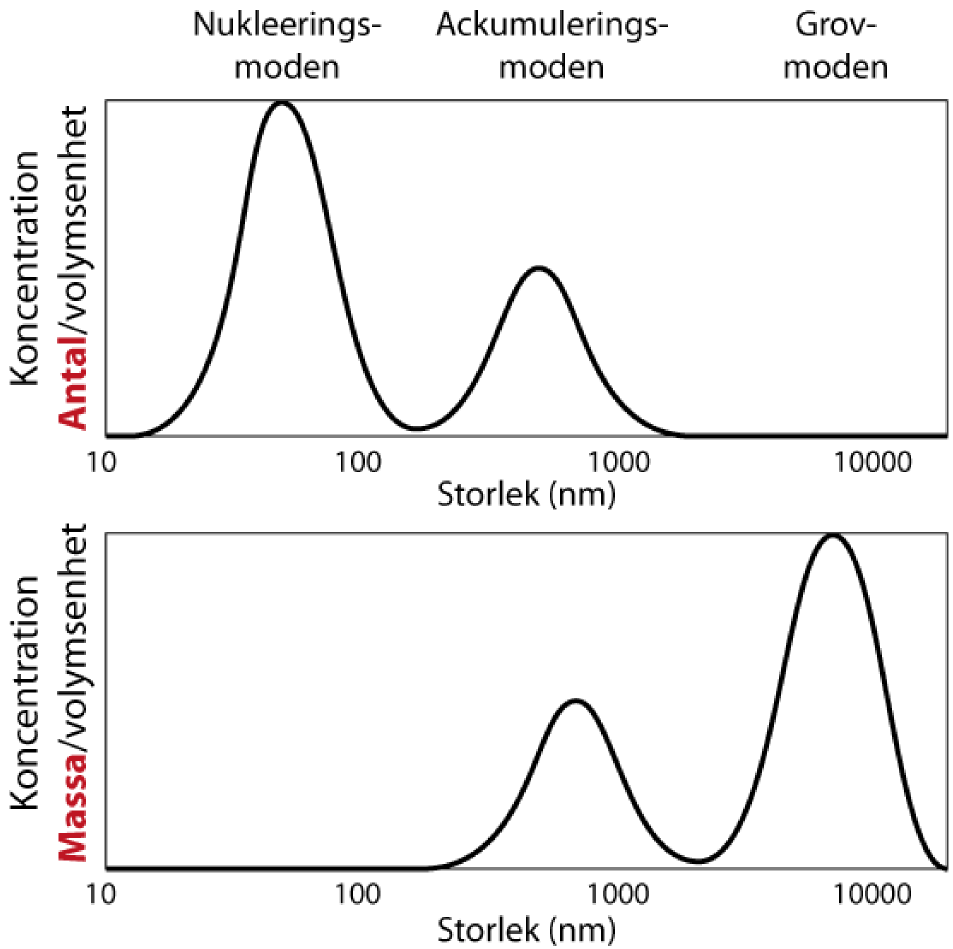


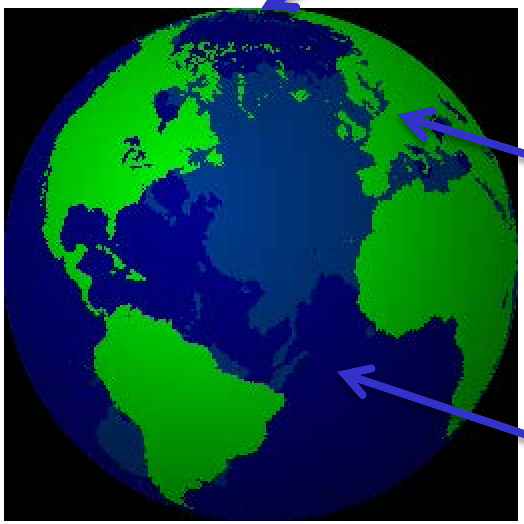
1 million particles
diameter 600 nm



1 billion particles
diameter 60 nm




Nukleerings-
moden
Ackumulerings-
moden
Grov-
moden
Koncentration
Antal/volymsenhet
10
100
1000
10000
Storlek (nm)
Koncentration
Massa/volymsenhet
10
100
1000
10000
Storlek (nm)



Arctic: 10-100 particles/cm³

0-1 µg/m³

Rural: 500-5000 particles/cm³ 5-100 µg/m³

Urban: 1000-100 000 particles/cm³ 10-100 µg/m³

Ocean: 100-1000 particles/cm³

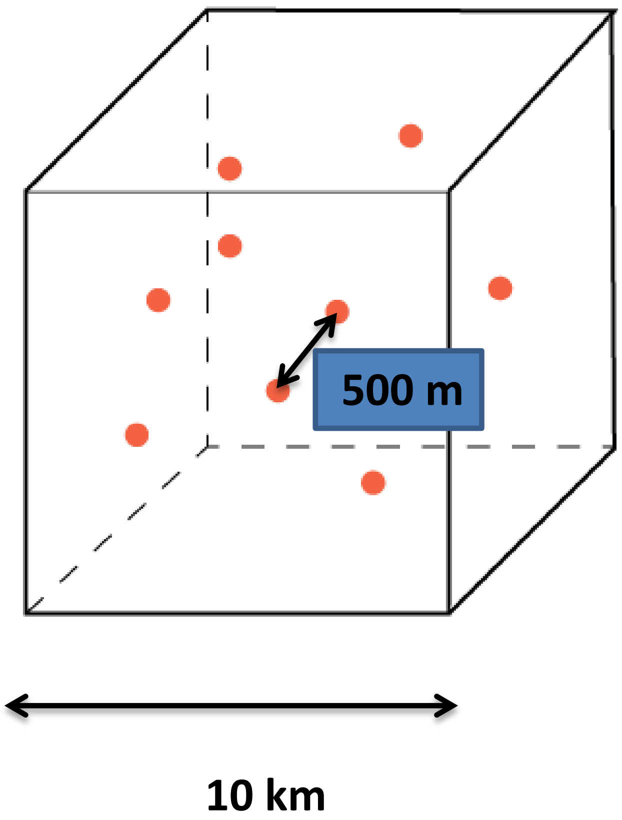
1-10 µg/m³

10 000 partiklar/cm^3

10-100 µg/m^3

Låt oss anta att alla partiklar är 1 µm.

Låt oss sedan förstora dem till 1 m



1 m^3 “ren” luft vid jordytan väger ca 1 kg, alltså 1000000000 µg

EU:

What average	PM10 µg/m^3	PM2.5 µg/m^3
Yearly average	40	25 (from 2015)
Daily average, < 36 times/year	50	
urban background, 3 year average		20 (from 2015

WHO:

What average	PM10 µg/m^3	PM2.5 µg/m^3
Yearly average	20	10

Oro efter rekorddålig luft i Peking

Högsta halten föroreningar någonsin
(2:32 min)

Luftföroreningarna i Peking överstiger stort WHO:s gränsvärden. Foto: Alexander F. Yuan/Scanpix.

Peking har ännu en dag drabbats av smog och höga koncentrationer av hälsofarliga små partiklar i luften. Det även om läget i dag är något bättre än vad det varit de senaste dagarna. Och luftföroreningarna upprör Pekingborna.

Publicerat tisdag 15 januari 2013 kl 15:45

DELA

David Carlqvist, Peking
Ekot

I helgen uppmättes de högsta nivåerna någonsin av luftföroreningar i Peking. 30 gånger högre än världshälsoorganisationen WHO:s gränsvärden.

– Luften är riktigt dålig nu, och särskilt jobbigt är det för de som redan har andningssvårigheter, säger 31-åriga Yang Liang. Han är på väg till jobbet här i Peking och har en vit ansiktsmask på sig.

Smogen ligger fortfarande tung över staden. Skyskrapornas toppar kan knappt urskiljas i det gulgrå diset. Många personer bär, precis som Yang, en ansiktsmask över munnen och näsan för att försöka skydda sina lungor.

De senaste dagarnas rekorddåliga luft i Peking har gjort att försäljningen av sådana här ansiktsmasker, och av luftreningsapparater man kan ha hemma, har skjutit i höjden.

De minsta och hälsofarligaste partiklarna kallas för PM 2,5. De här partiklarna är så små att de kan ta sig in i blodkärlen i lungorna och orsaka hjärt- och kärlsjukdomar och cancer.

Enligt världshälsoorganisationen, WHO, så är det hälsofarligt om koncentrationen av de här partiklarna är högre än 25 mikrogram per kubikmeter luft.

I lördags, när luften var som sämst, uppmätte USA:s ambassad är i Peking koncentrationer på över 700 mikrogram per kubikmeter. Som jämförelse kan nämnas att årsmedelvärdet på vad som ibland kallas för Sveriges mest förorenade gata, Hornsgatan i Stockholm, aldrig har varit över 20 mikrogram per kubikmeter.

Pekingborna är oroliga, och upprörda. Mikrobloggarna på internet har varit fyllda av kritiska kommentarer. Men det har faktiskt även de statskontrollerade medierna varit.

Den dåliga luften går omöjligen att dölja, och istället för att sopa problemet under mattan, har medierna nu valt att belysa det.

Pressen på myndigheterna att lösa problemet är således stor, men frågan är hur.

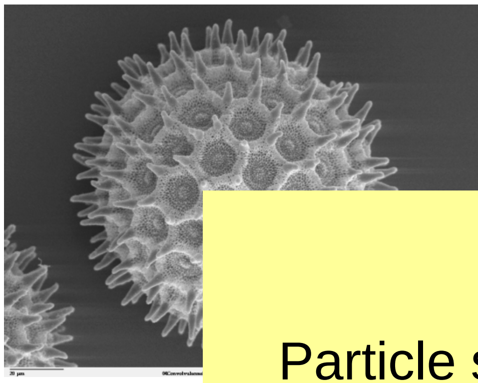
– Det är utsläppen från alla bilarna som orsakar smogen, säger Yang Liang. Och bilarna blir bara fler och fler i Kina, i takt med att landet blir rikare. Och fler blir även en ännu värre miljöbov, kolkraftverken. I snitt har det de senaste åren öppnats ett nytt kolkraftverk per vecka i Kina.

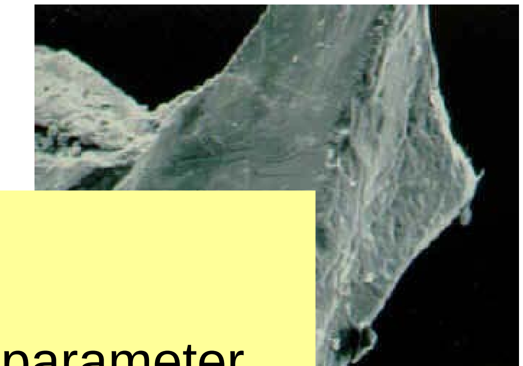
SKRIV UT

Nyckelord

I lördags, när luften var som sämst, uppmätte USA:s ambassad är i Peking koncentrationer på **över 700 mikrogram per kubikmeter**. Som jämförelse kan nämnas att årsmedelvärdet på vad som ibland kallas för Sveriges mest förorenade gata, Hornsgatan i Stockholm, aldrig har varit över 20 mikrogram per kubikmeter.

This thing about ”size”…

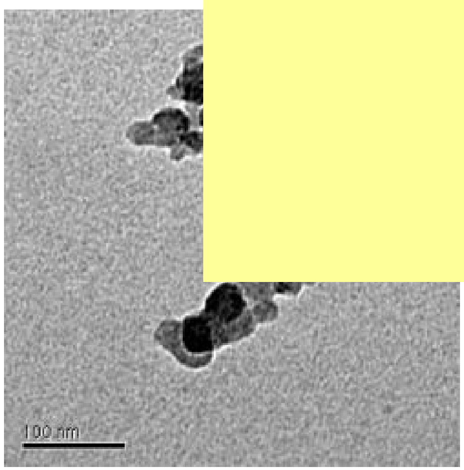




P

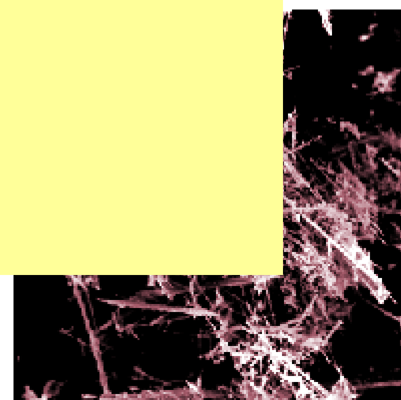
Particle size is the most important parameter for predicting the behavior of an aerosol.

Equivalent diameter



Diesel exhaust

Welding fume



Asbestos

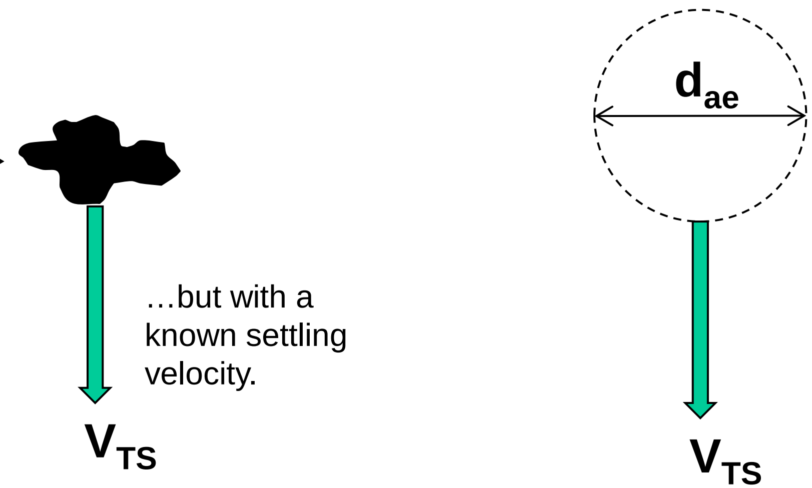
Equivalent diameters

The term refers to the diameter of a sphere that has the same value of a particular physical (measurable) property as that of the particle of interest.

The most common (but far from only) equivalent diameter is the **aerodynamic equivalent diameter, d_{ae}.**

Irregular particle with some shape and some density…

…but with a known settling velocity.



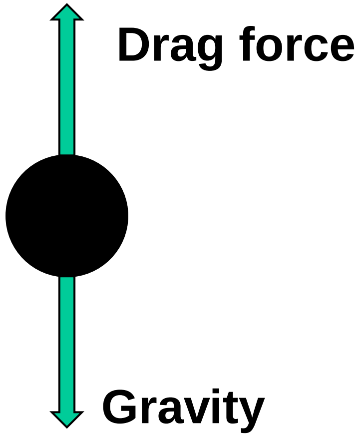
The diameter of a **spherical** particle, with **unit density** (1000 kg/m^3) and the **same settling velocity** as the irregular particle is the aerodynamic equivalent diameter.

The **aerodynamic equivalent diameter** governs how particles behave in an airflow – which is important!

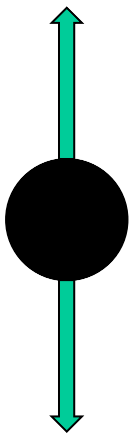
Settling velocity?

We are used to everything falling down due to gravity, but in the microscopic world…

When the drag force and the gravitational force are in balance, the particle has reached its terminal settling velocity, V_{TS}.



Let’s take a little detour before continuing with ”the bigger picture”…



Drag force

Gravity

The drag force is described by **Stoke’s law**:

Gas viscosity

Particle velocity

Particle diameter

$$F_d = \frac{3\pi\eta V d}{C_C}$$

Gravity is described by: $$mg = \frac{\pi}{6} d^3 \rho_p g$$

When the drag force and the gravitational force are in balance, the particle has reached its terminal settling velocity, **V_{TS}**.

$$F_d = mg$$

$$\Rightarrow$$

Terminal settling velocity:

$$V_{TS} = \frac{\rho_p d^2 g C_c}{18\eta}$$

?

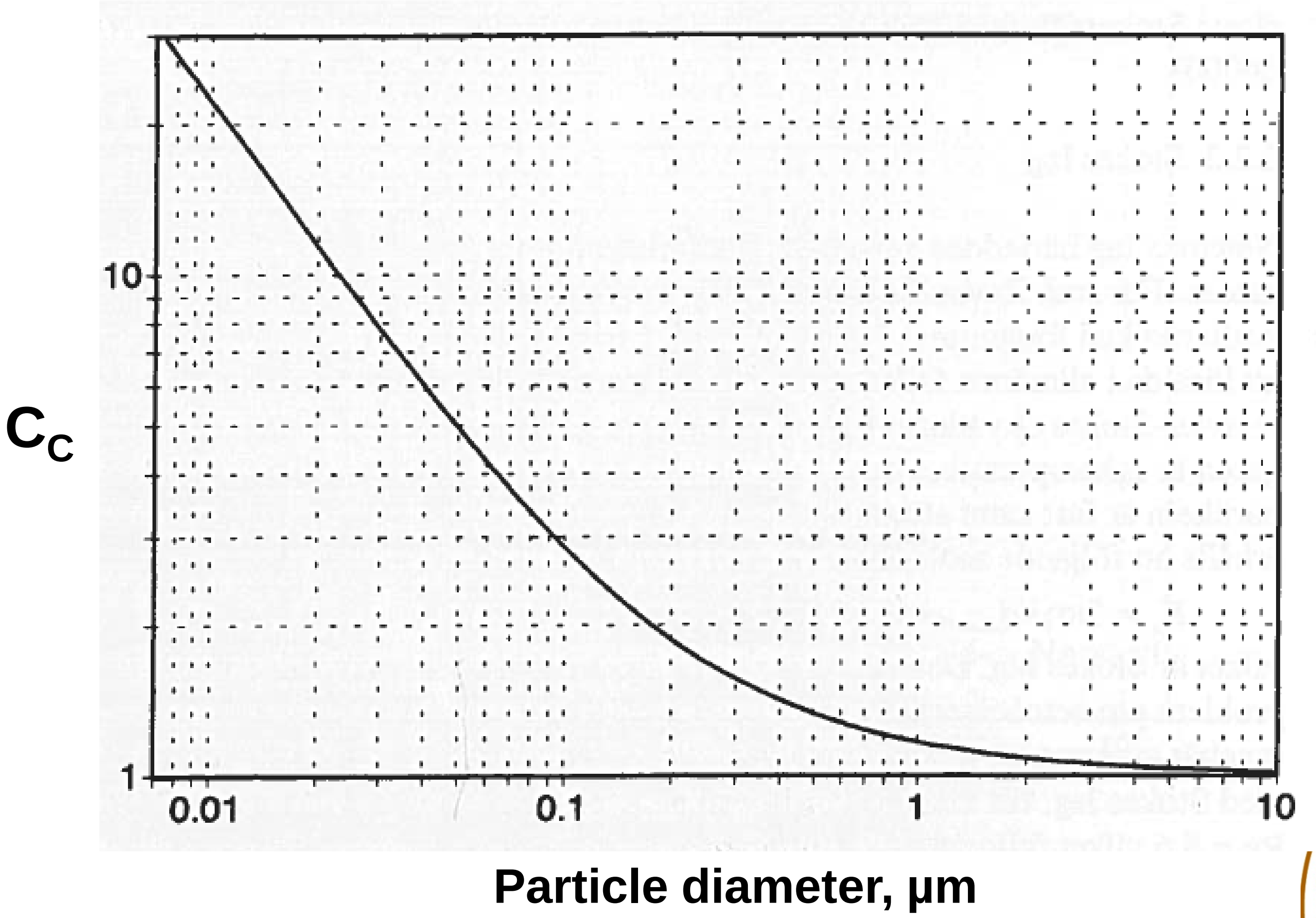
C_C, the Cunningham slip correction

- Particles less than 0.1 µm in diameter are affected by the motion of individual gas molecules (*free molecular regime)*
- Larger particles can be treated as being submersed in a continuous gaseous medium *(continuum regime)*
- Intermediate-sized particles (*transition* or *slip regime*) can be treated by adjustment of equations from the continuum regime.

$$F_d = \frac{3\pi\eta V d}{C_C}$$

- The derivation of Stokes Law, which is used to calculate the drag force on small particles, assumes a No-slip condition. C_c is used to account for noncontinuum effects when calculating the drag on small particles.

Cunningham factor vs particle diameter



Now, let's get back to what forces affect the motion of the particles!

- **Size matters…!**

What affects the particles?

Sedimentation

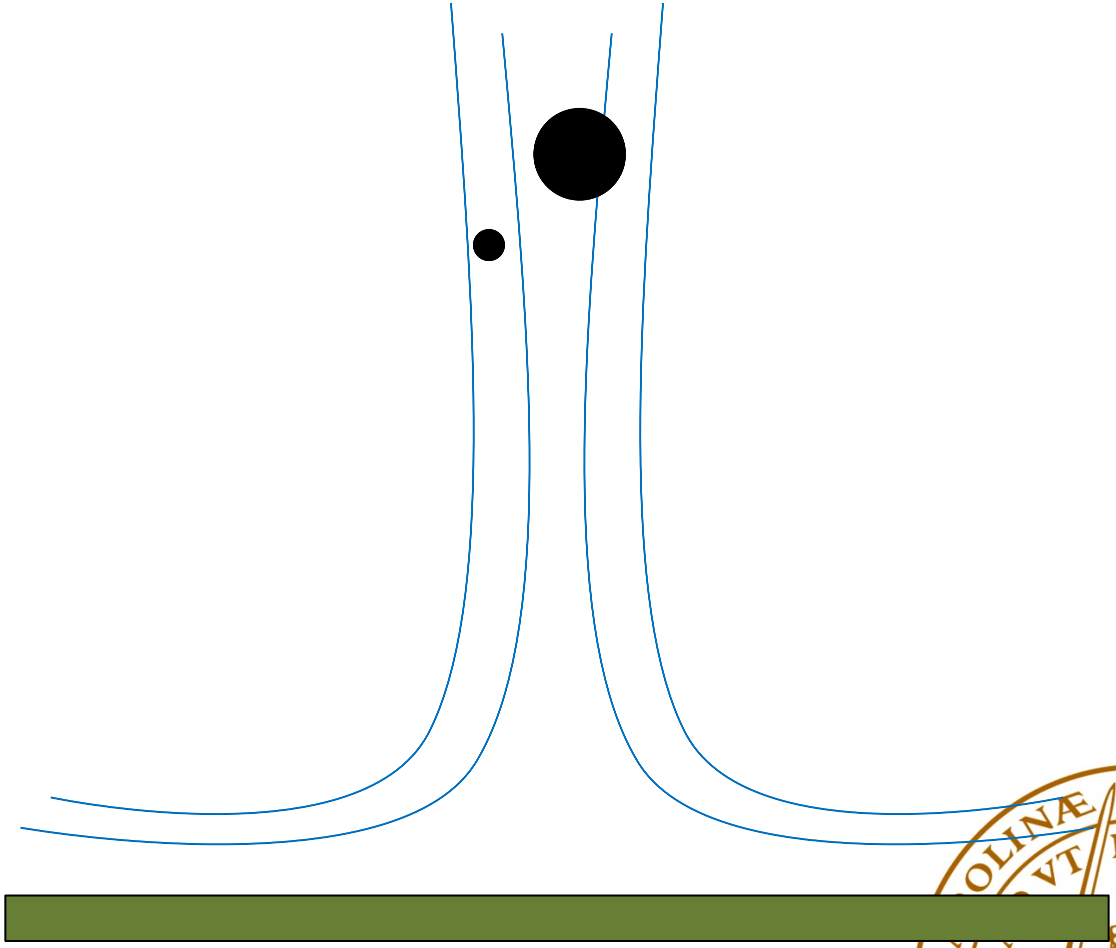
1 µm : 1 meter in 8 hours

100 µm : 1 meter in 3 seconds

What affects the particles?

Sedimentation

Impaction

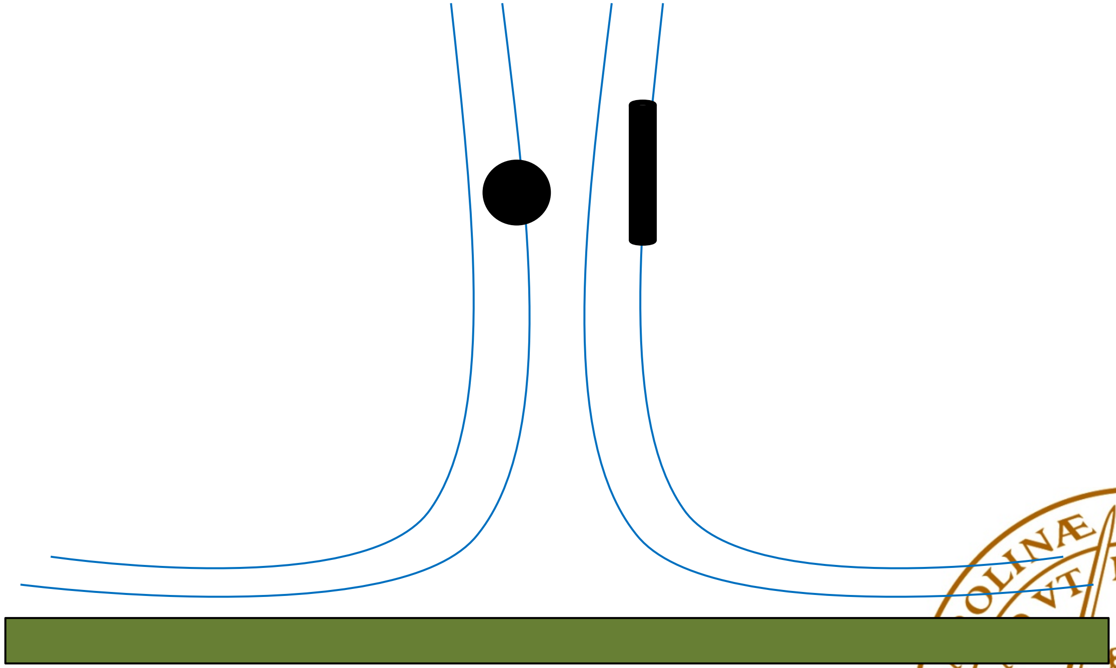


What affects the particles?

Sedimentation

Impaction

Interception



What affects the particles?

Sedimentation

Impaction

Interception

Diffusion < 100 nm

What affects the particles?

Sedimentation

Impaction

Interception

Diffusion

Termophoresis

What affects the particles?

Sedimentation

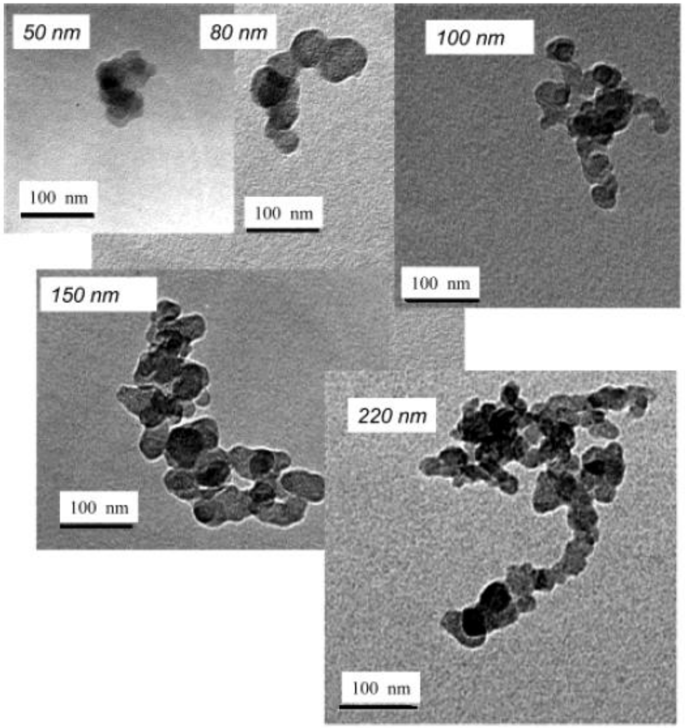
Impaktion

Interception

Diffusion

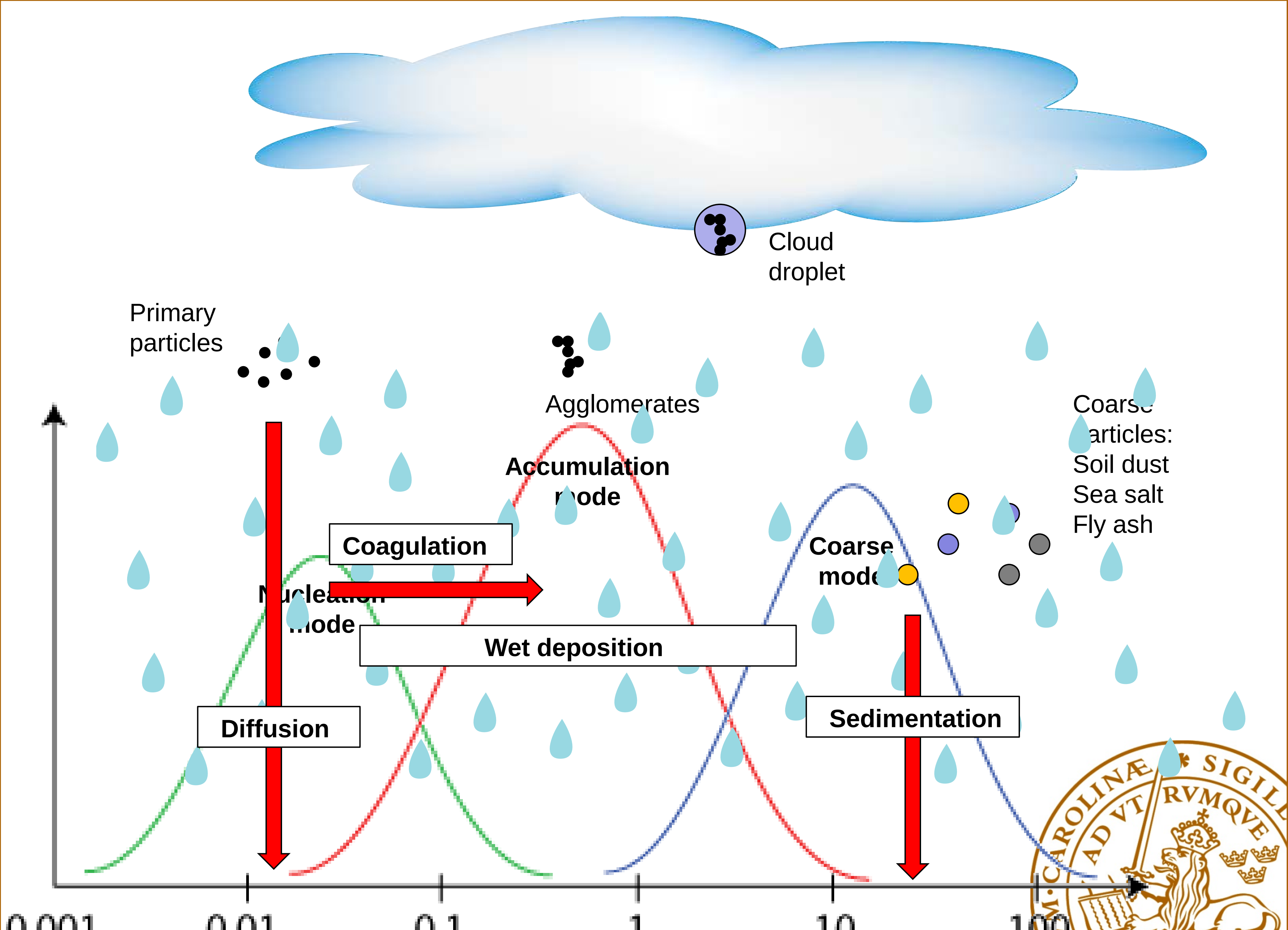
Termoforesis

Coagulation



Diffusion vs sedimentation

Particle size (µm)	Displacement during 1 second due to diffusion (m)	Settling during 1 second due to sedimentation (m)
0,01	0,00033	0,000000069
10	0,0000022	0,0031


Cloud
droplet
Primary
particles
Agglomerates
Accumulation
mode
Coagulation
Nucleation
mode
Wet deposition
Coarse
mode
Coarse
particles:
Soil dust
Sea salt
Fly ash
Diffusion
Sedimentation
0.001
0.01
0.1
1
10
100

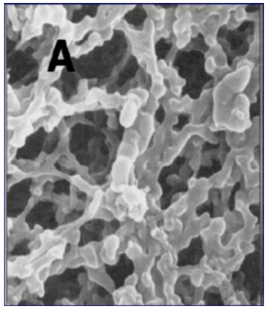
How are particles measured?

- Time resolved data or not?
- Mass concentration
- Number concentration
- Other property concentration (e.g. surface area)
- Chemical composition
- Shape

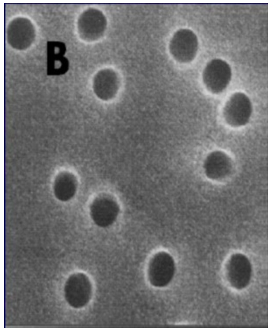
Mass concentration

- **Filter collection**
  - **Gives mass concentration but no size resolution**
  - **Can be used together with an impactor to give e.g. PM10 or PM2.5**
  - **Very common method due to simplicity (however…)**

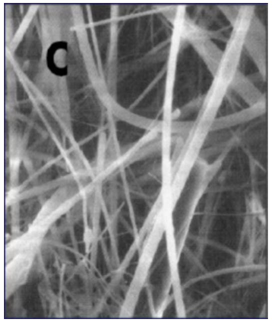
How are particles deposited on a filter?



Porous membrane filters

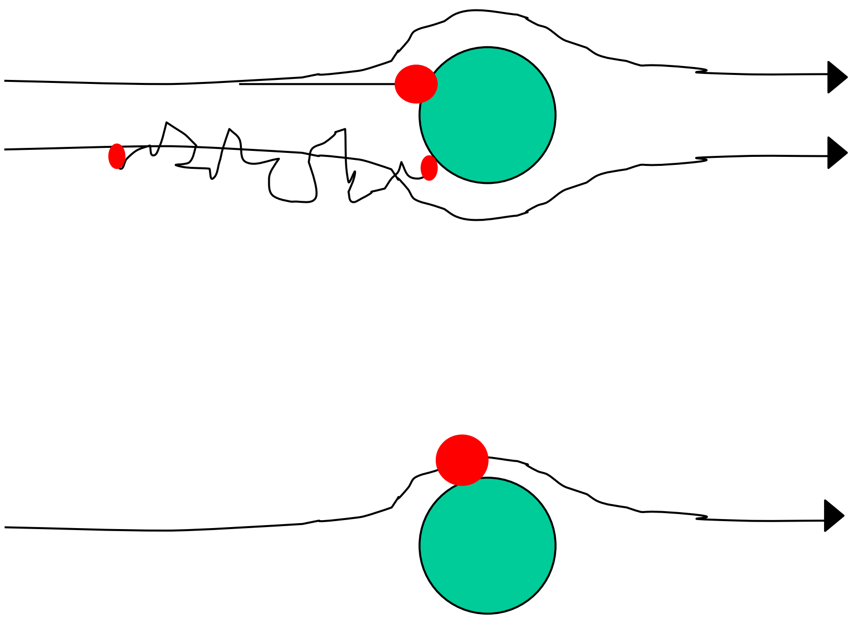


Straight-through pore filters



Fibrous filters

Main deposition mechanisms

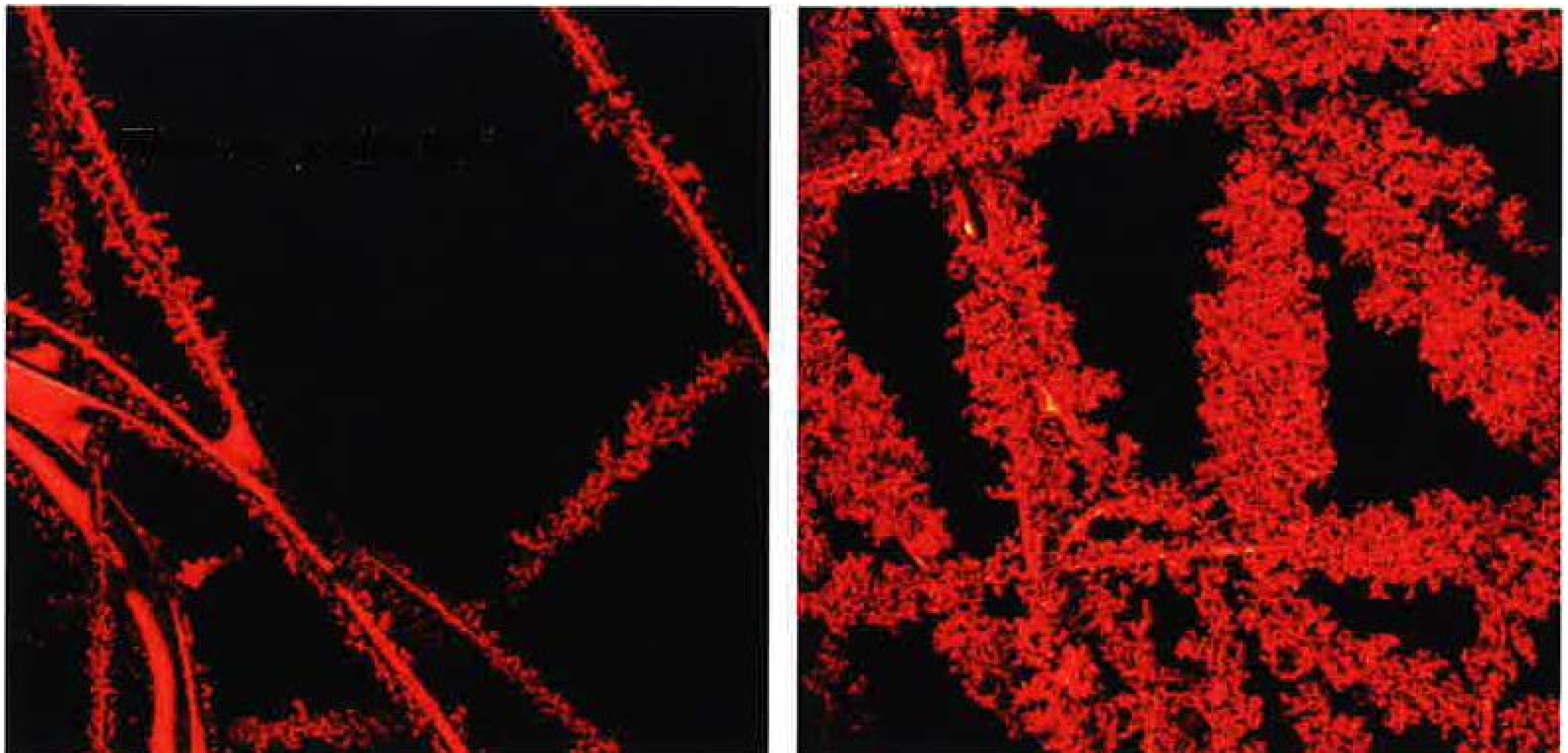


Impaction (due to inertia)

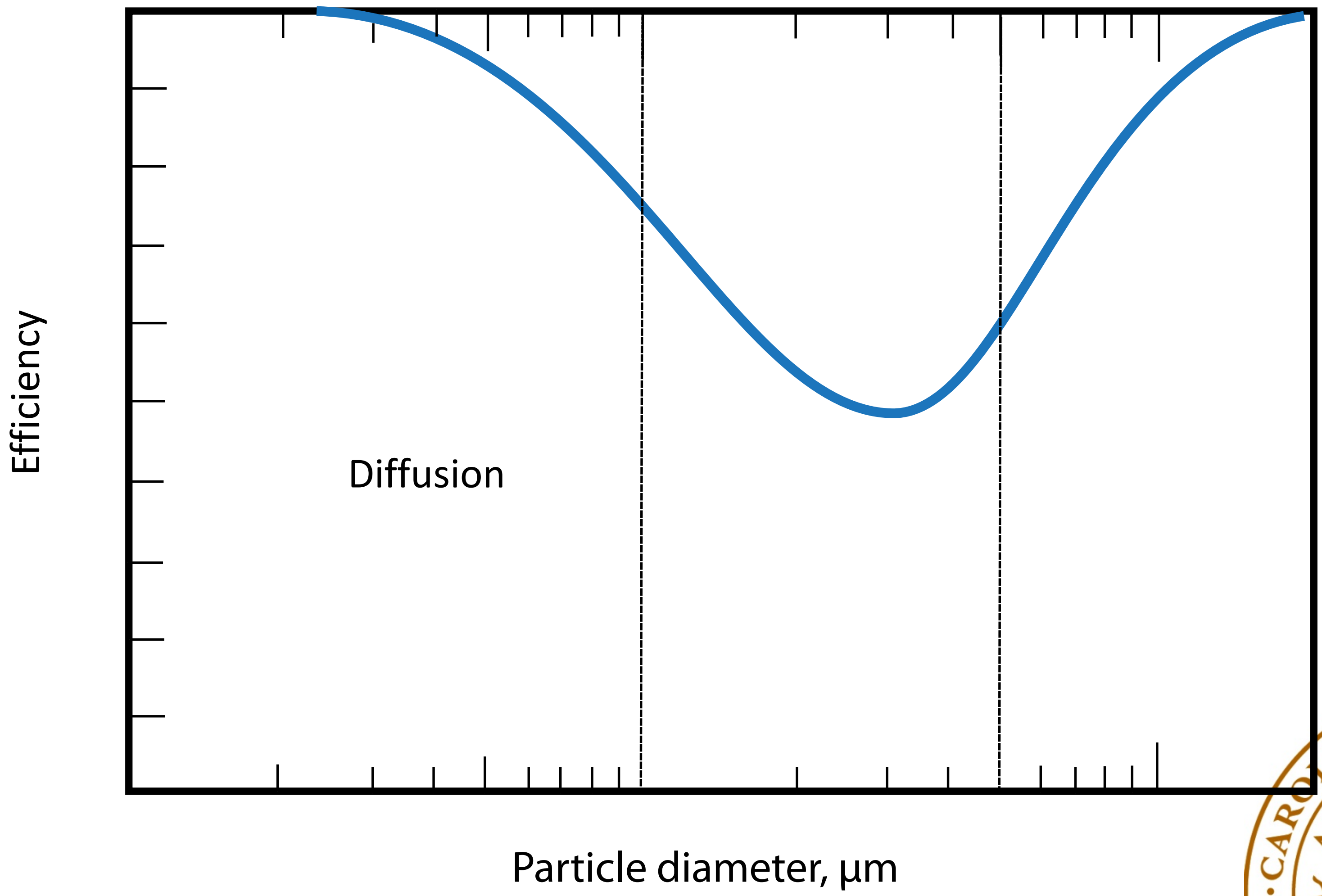
Diffusion

Interception

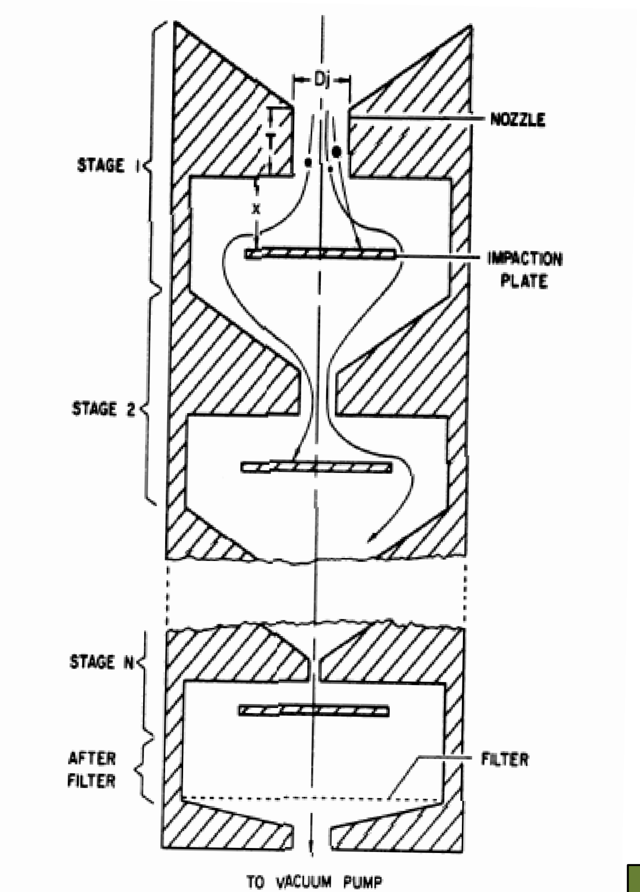
Particles are not “stuck in holes” between the fibers!



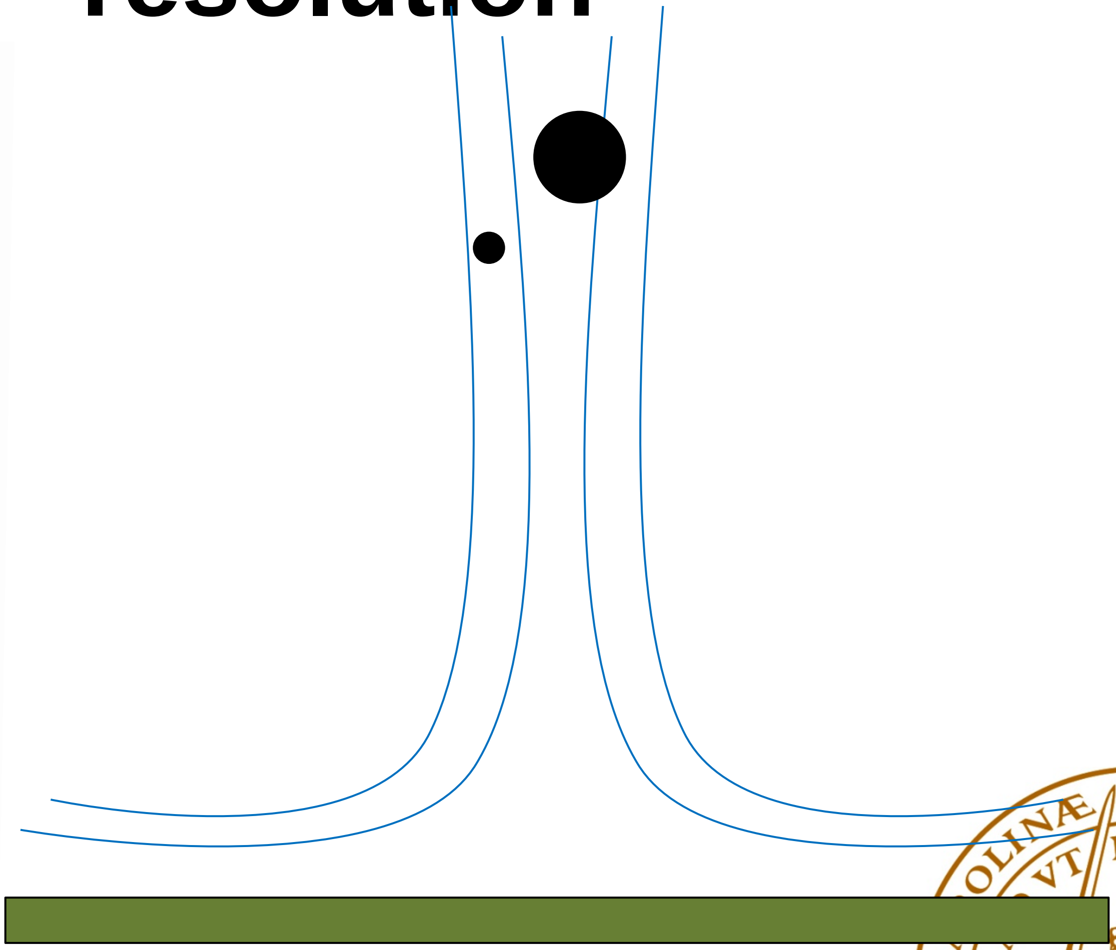
Filter deposition



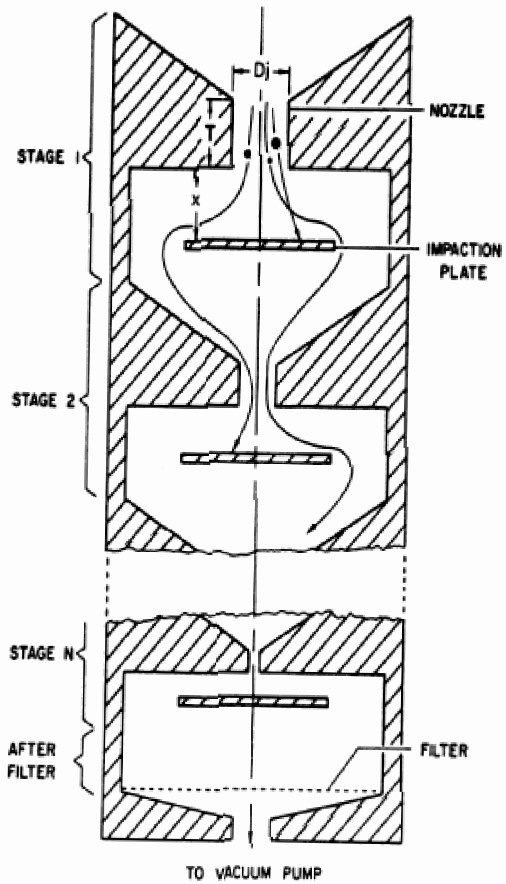
Impactor – adds size resolution



igure 11.
cascade impactor. Reproduced from Willeke and Baron 993).



Impactor – adds size resolution



igure 11.

cascade impactor. Reproduced from Willeke and Baron 993).

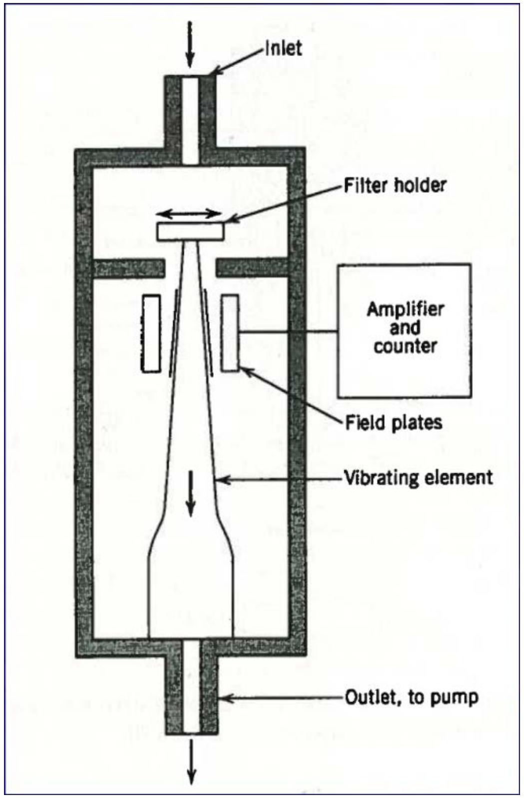
Particles get deposited on different stages due to their inertia

The impactor stages are arranged in order of decreasing cut-off size with the largest cut-off size first. This is achieved by decreasing the nozzle size at each stage, which increases the flow rate.

Because the aerosol flows in sequence through successive stages, the particles captured on the impaction plate of a given stage represent all particles smaller than the cut-off size of the previous stage and larger than the cut-off size of the given stage.

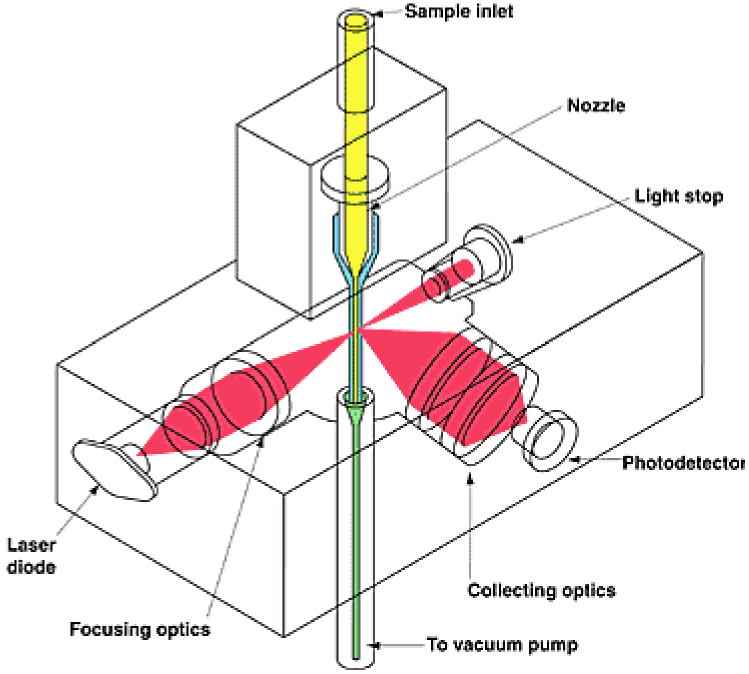
The impactor plates are weighed before and after collection

TEOM – time resolved mass concentration measurement



Portable, time resolved instruments

Photometer



Based on light scattering dependent on material and size

Robust, cheap instruments

Fast response to detect sudden changes (1s)

Can over- and underestimate the true mass concentrations, hence cannot be used as an absolute mass concentration measuring instrument

In the following example four aerosols all with a true concentration of 100 ug/m^3 were sampled with a photometer

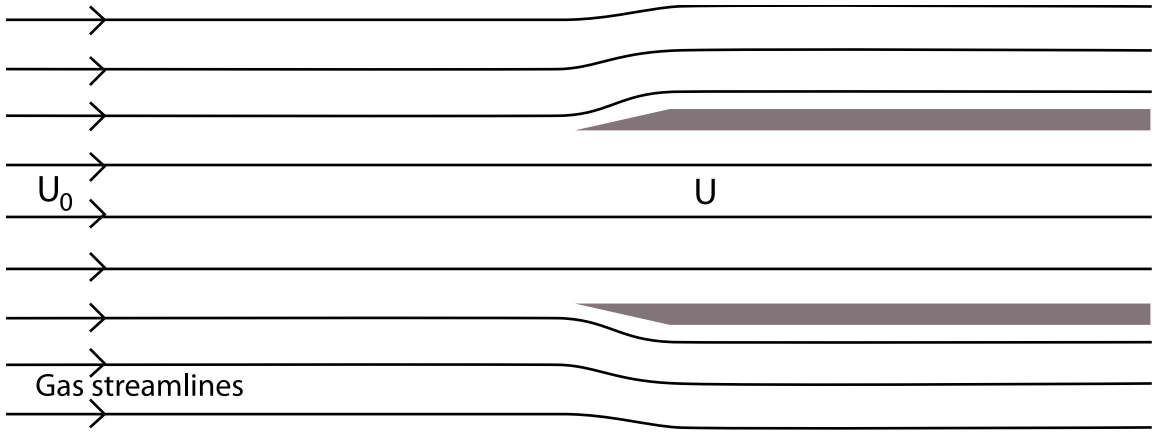
Aerosol	Mass conc. ug/m^3
DOS	100
Fly ash	22
Wood dust	55
Soil dust	175

Different optical properties and different particle densities cause the large differencies!

What can cause changes in aerosol characteristics during sampling?

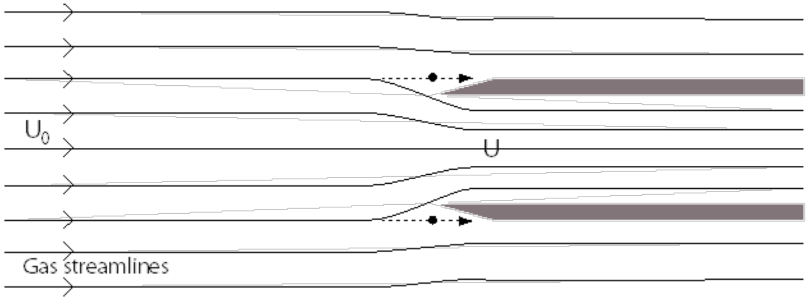
- Deposition during transport through the sampling line or during storage
- Agglomeration of particles during transport in sampling line
- Evaporation and/or condensation of aerosol material during transport in sampling line
- Re-entrainment of deposited aerosol material back to the sample flow
- High local deposition causing flow restrictions or plugging

Isokinetic sampling = The sampler should be a **thin walled** tube or probe, **aligned parellel to the gas streamlines** and the **gas velocity entering the probe should be equal to the free-stream velocity approaching the probe**.

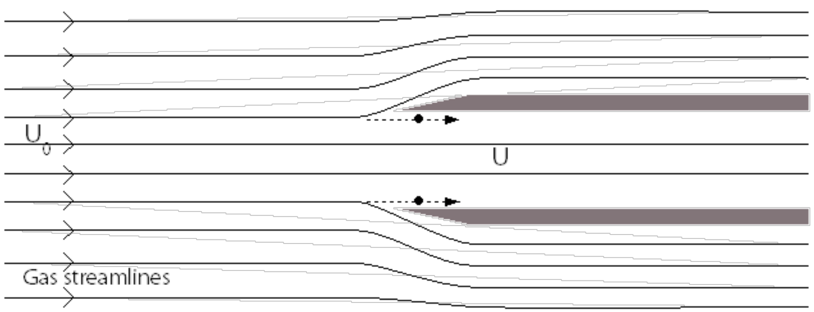


$\mathbf{U_0=U}$

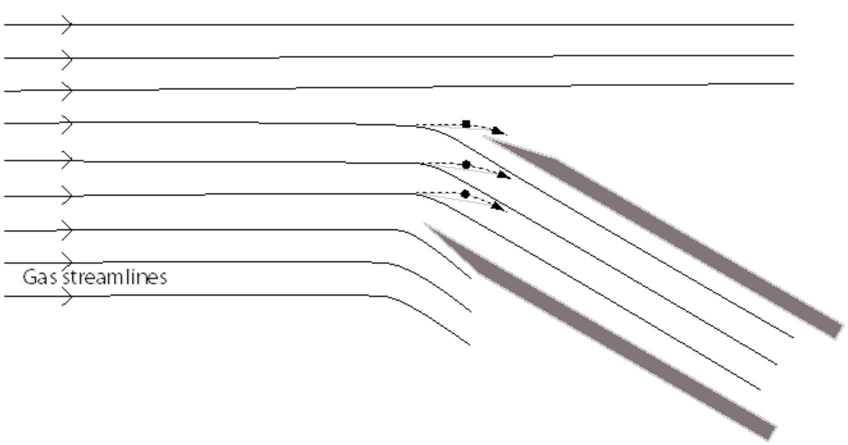
Anisokinetic sampling:



If $\mathbf{U_0}$**<U**, the sample will contain a deficiency of large particles, resulting in an underestimation of the concentration and a biased size distribution



If $\mathbf{U_0}$**>U**, the sample will contain an excess of large particles, resulting in an overestimation of the concentration and a biased size distribution



If the probe is misaligned, the sample will contain a deficiency of large particles, resulting in an underestimation of the concentration and a biased size distribution

Sampling from still air

- Isokinetic criteria of no value
- Orientation of sampling inlet important:
  - Facing upwards: concentration overestimation
  - Facing downwards: concentration underestimation
  - Horizontal: no bias due to particle settling
- Size and shape of inlet also important

Are the particles dangerous?

Stomach/ Skin / Lungs

1 m^2 — 2 m^2 — 100 m^2

Volume air/ breath: 0,5 l

Breathing frequency: 12 times/ min

Inhaled volume: 10 m^3 / dag

Assume 10 000 particles/cm^3...

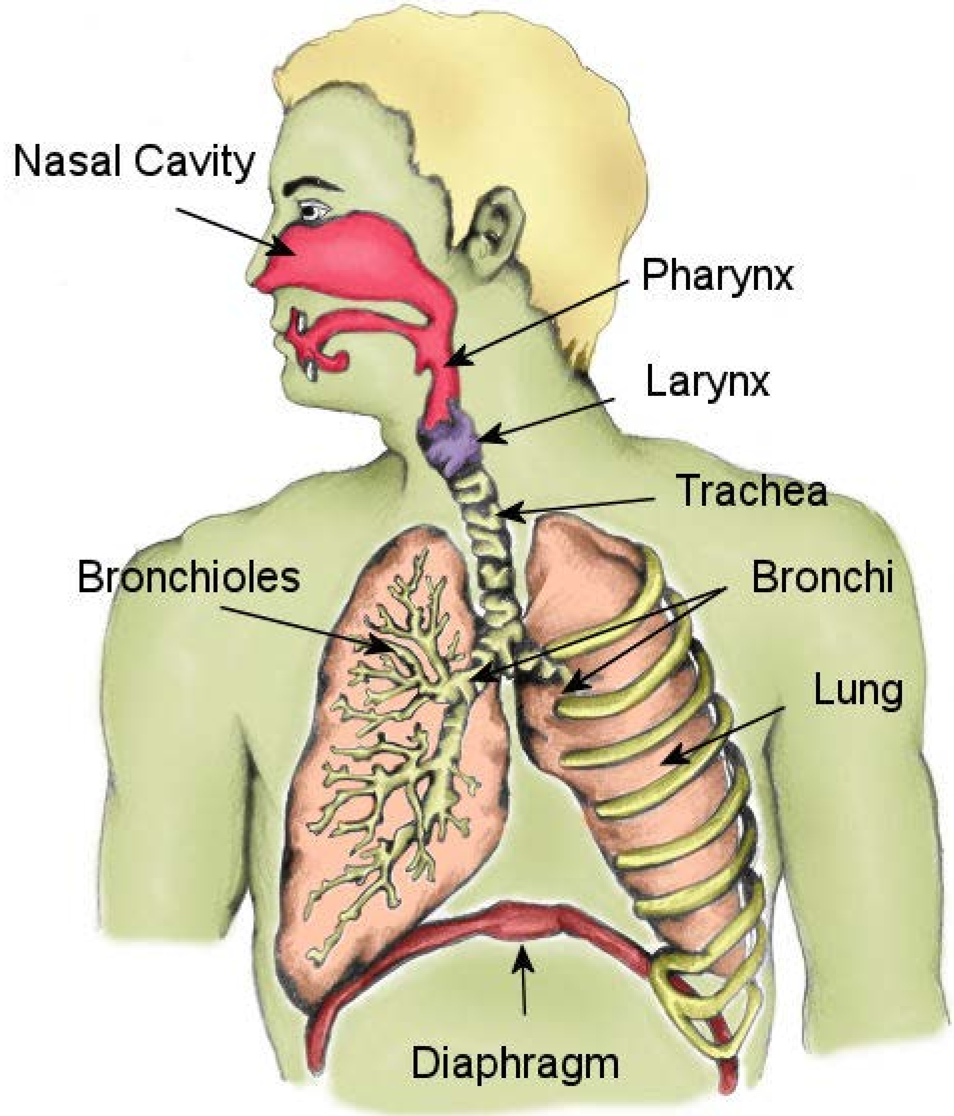
100 billion inhaled particles every day!

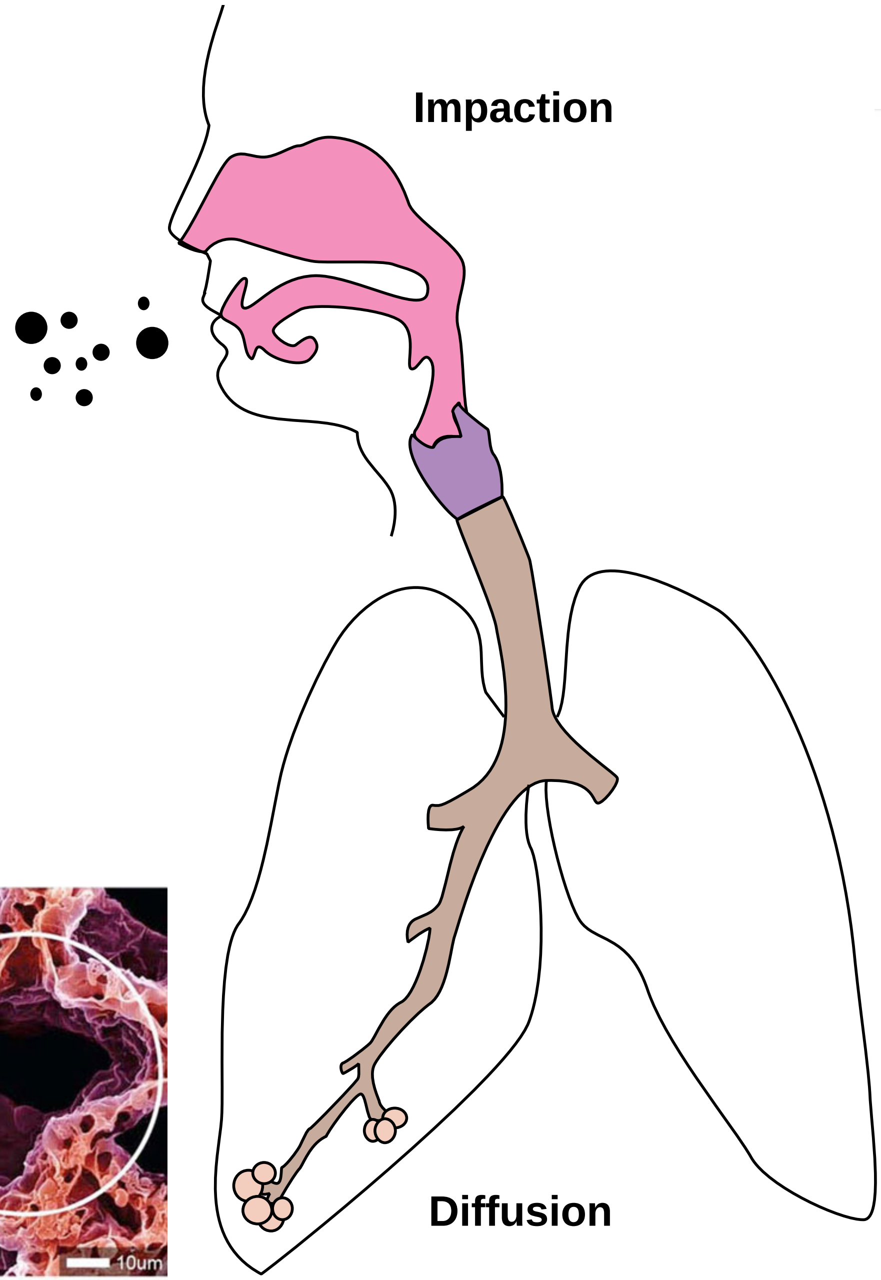
The respiratory system

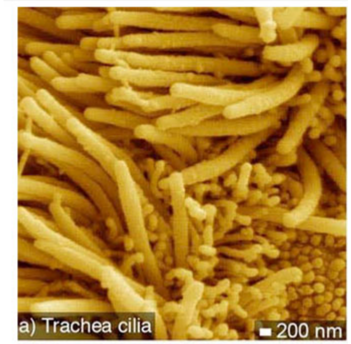
Upper airways

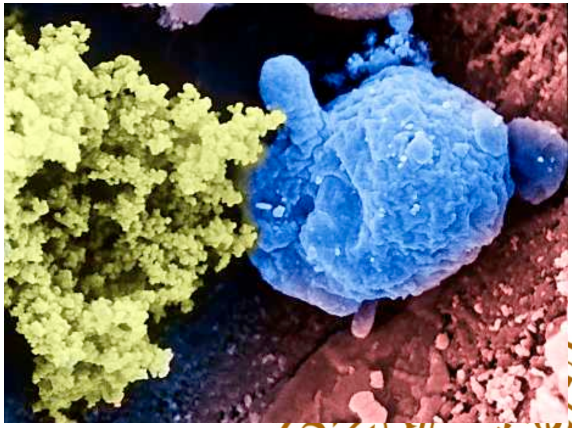
Tracheo-bronchial region

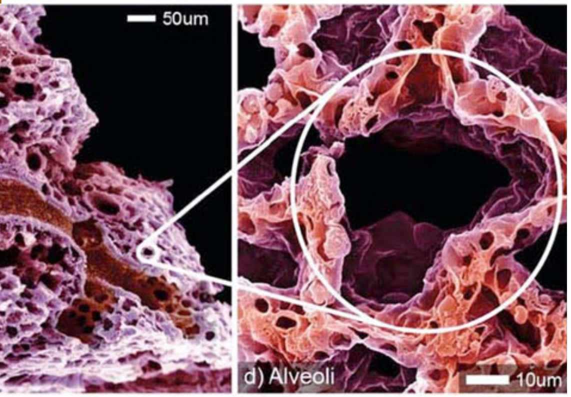
Alveolar region




Impaction
Diffusion


a) Trachea cilia
200 nm




50um
d) Alveoli
10um

Lung deposition

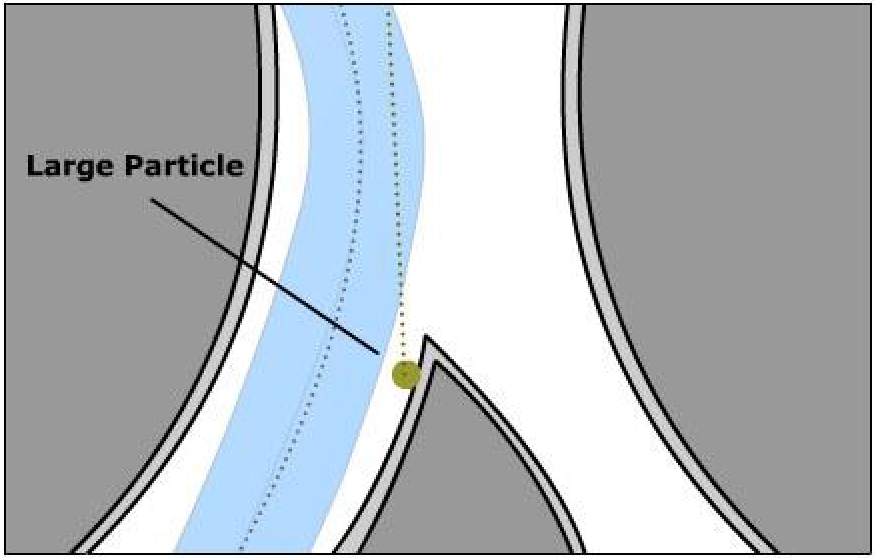
Deposition is determined by 4 main mechanisms:

- Impaction
- Sedimentation
- Diffusion
- Interception (Fibre)

Particles generally do not bounce

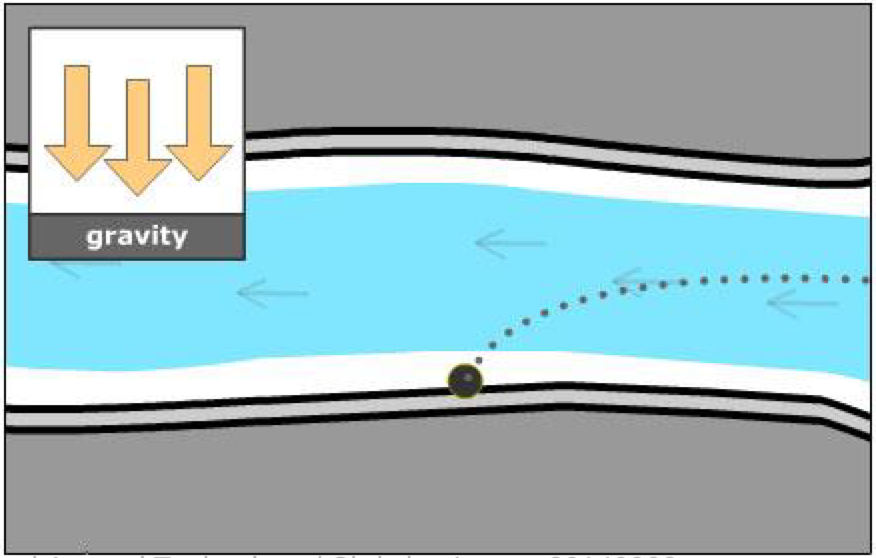
Impaction

- Stopping distance increases with particle size (proportional to d^2)
- Particles > 1µm
- Upper airways (high airflow)



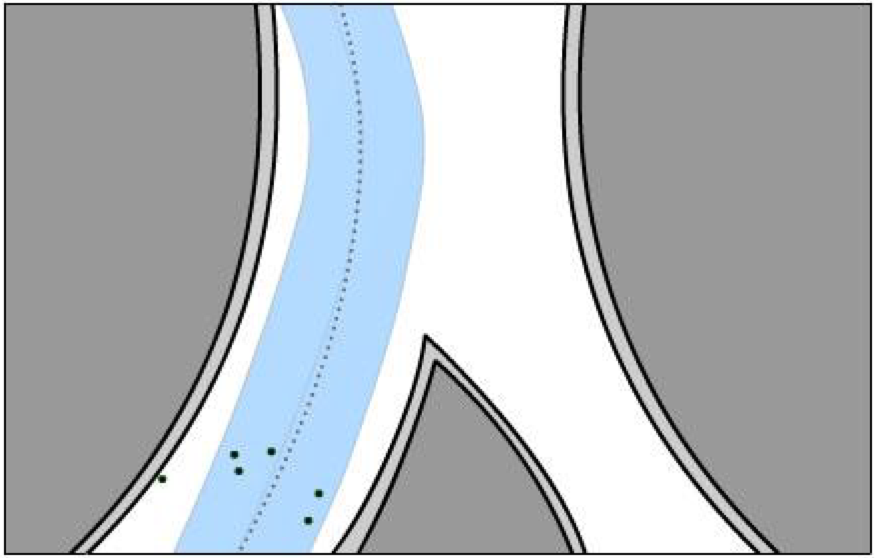
Sedimentation

- Sedimentation speed proportional to d^2
- Particles > 0.2 µm
- Most important in the smaller airways and alveoli, and horizontal airways (short distances, long residence time)



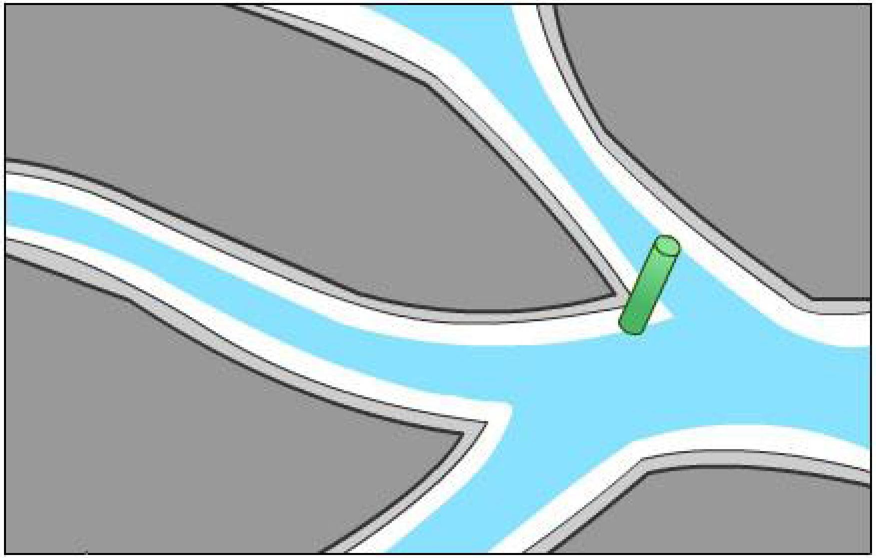
Diffusion

- Most important mechanism for particles < 0,5 µm
- Lower airways (short distances, long residence time).



Interception

- Shape (fibers)



ICRP Lung deposition model

$$IF = 1 - 0.5\left(1 - \frac{1}{1 + 0.00076 d_p{}^\wedge 2.8}\right)$$

$$DF_{HA} = IF\left(\frac{1}{1 + e^{6.84 + 1.183 ln d_p}} + \frac{1}{1 + e^{0.924 - 1.885 ln d_p}}\right)$$

$$DF_{TB} = \left(\frac{0.00352}{d_p}\right)\left[e^{-0.234\left(ln d_p + 3.4\right){}^\wedge 2} + 63.9 e^{-0.819\left(ln d_p - 1.61\right){}^\wedge 2}\right]$$

$$DF_{AL} = \left(\frac{0.0155}{d_p}\right)\left[e^{-0.416\left(ln d_p + 2.84\right){}^\wedge 2} + 19.11 e^{-0.482\left(ln d_p - 1.362\right){}^\wedge 2}\right]$$

$$DF = IF\left(0.0587 + \frac{0.911}{1 + e^{4.77 + 1.485 ln d_p}} + \frac{0.943}{1 + e^{0.508 - 2.58 ln d_p}}\right)$$

ICRP

$$IF = 1 - 0.5\left(1 - \frac{1}{1 + 0.00076d_p\text{^}2.8}\right)$$

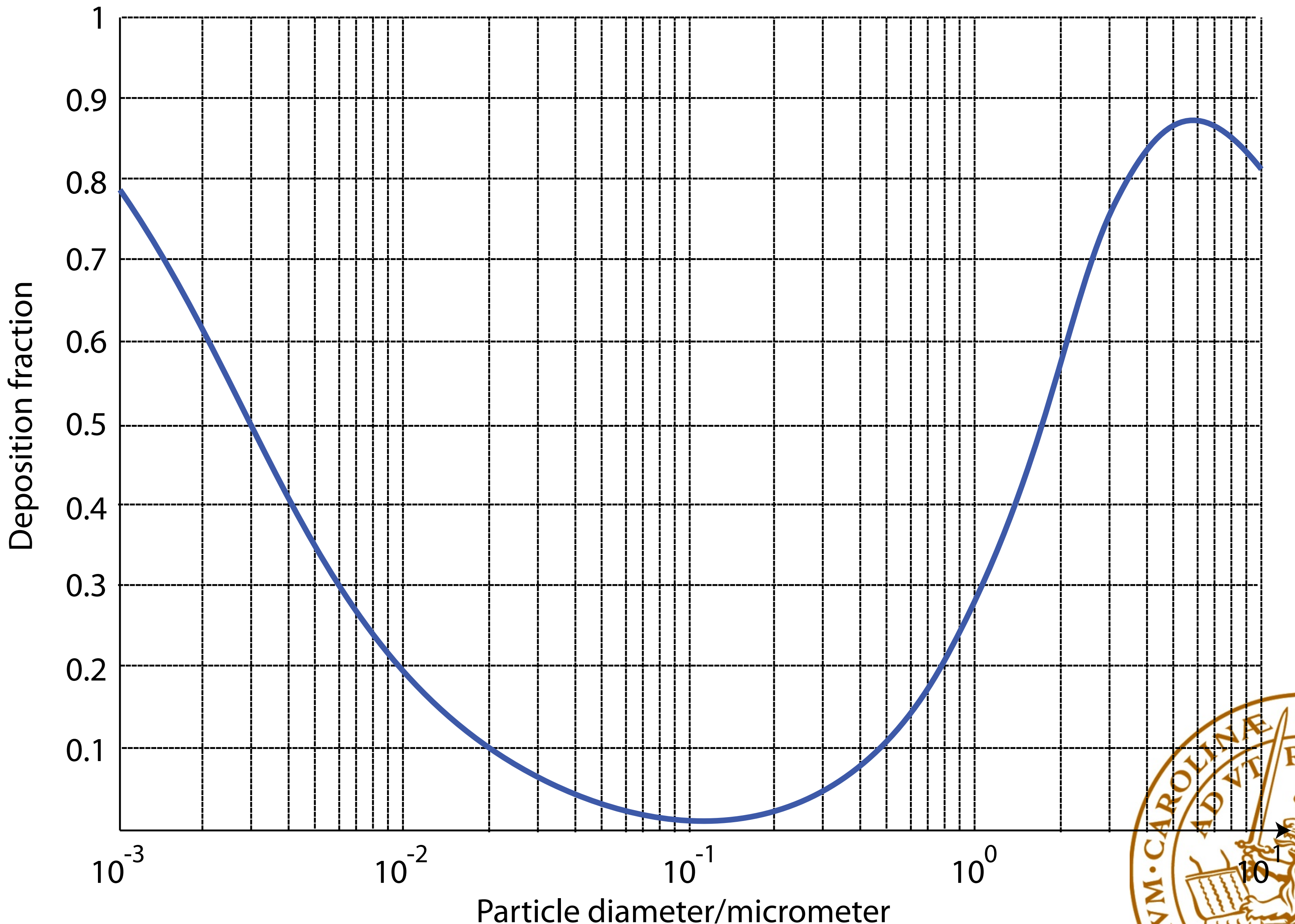
$$DF_{HA} = IF\left(\frac{1}{1 + e^{6.84+1.183lnd_p}} + \frac{1}{1 + e^{0.924-1.885lnd_p}}\right)$$

$$DF_{TB} = \left(\frac{0.00352}{d_p}\right)\left[e^{-0.234\left(lnd_p+3.4\right)\text{^}2} + 63.9e^{-0.819\left(lnd_p-1.61\right)\text{^}2}\right]$$

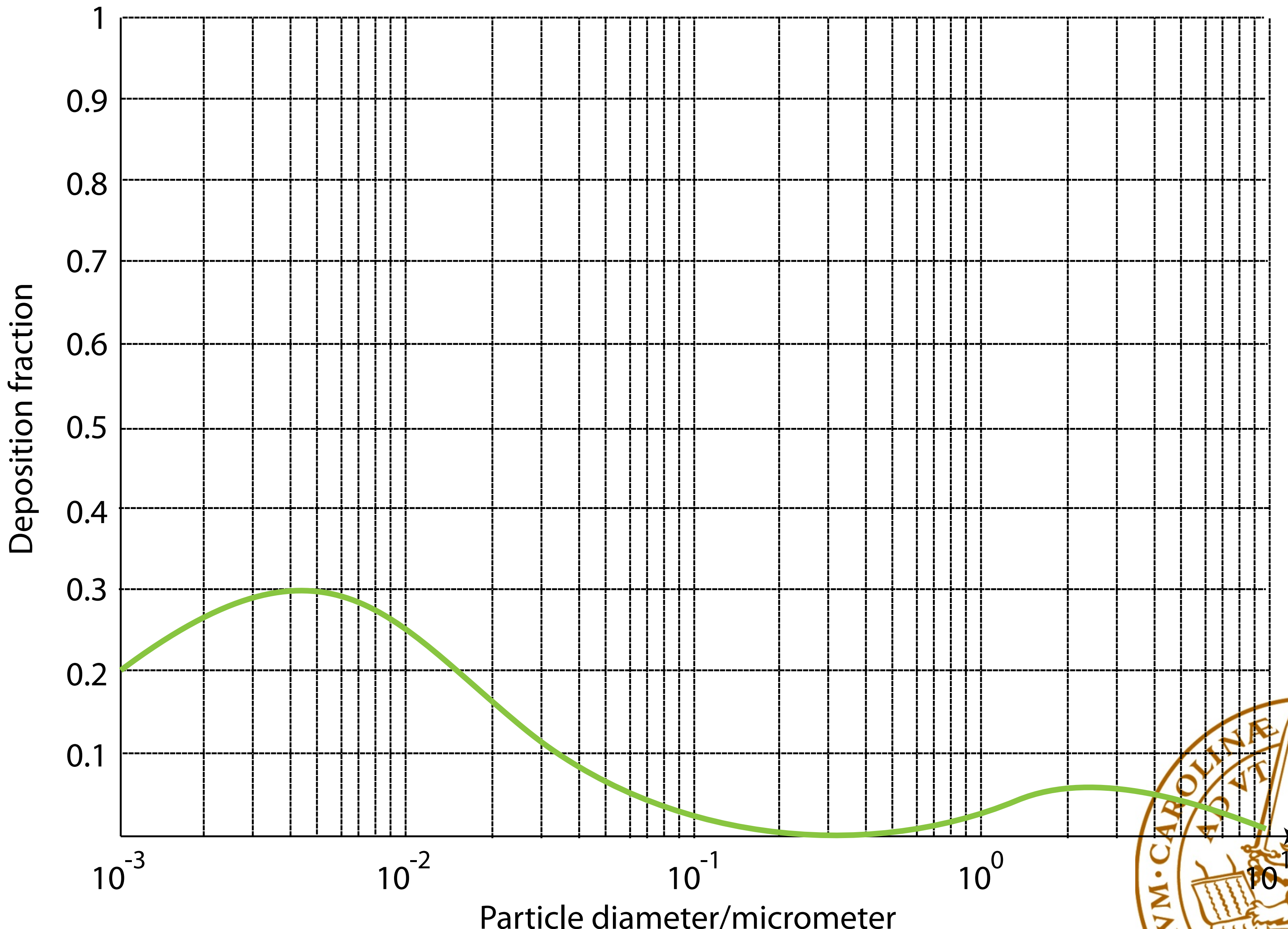
$$DF_{AL} = \left(\frac{0.0155}{d_p}\right)\left[e^{-0.416\left(lnd_p+2.84\right)\text{^}2} + 19.11e^{-0.482\left(lnd_p-1.362\right)\text{^}2}\right]$$

$$DF = IF\left(0.0587 + \frac{0.911}{1 + e^{4.77+1.485lnd_p}} + \frac{0.943}{1 + e^{0.508-2.58lnd_p}}\right)$$

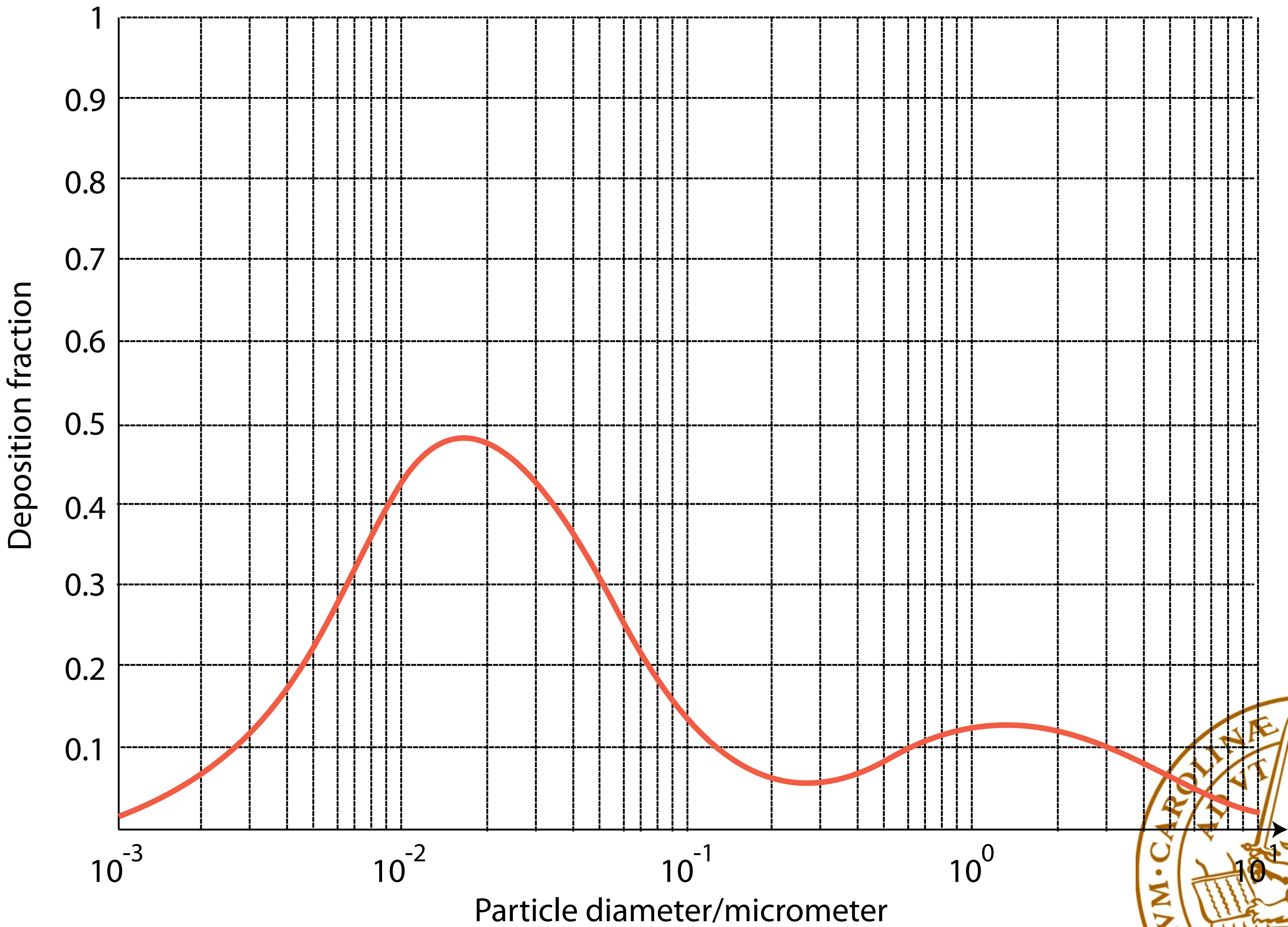
Head airways



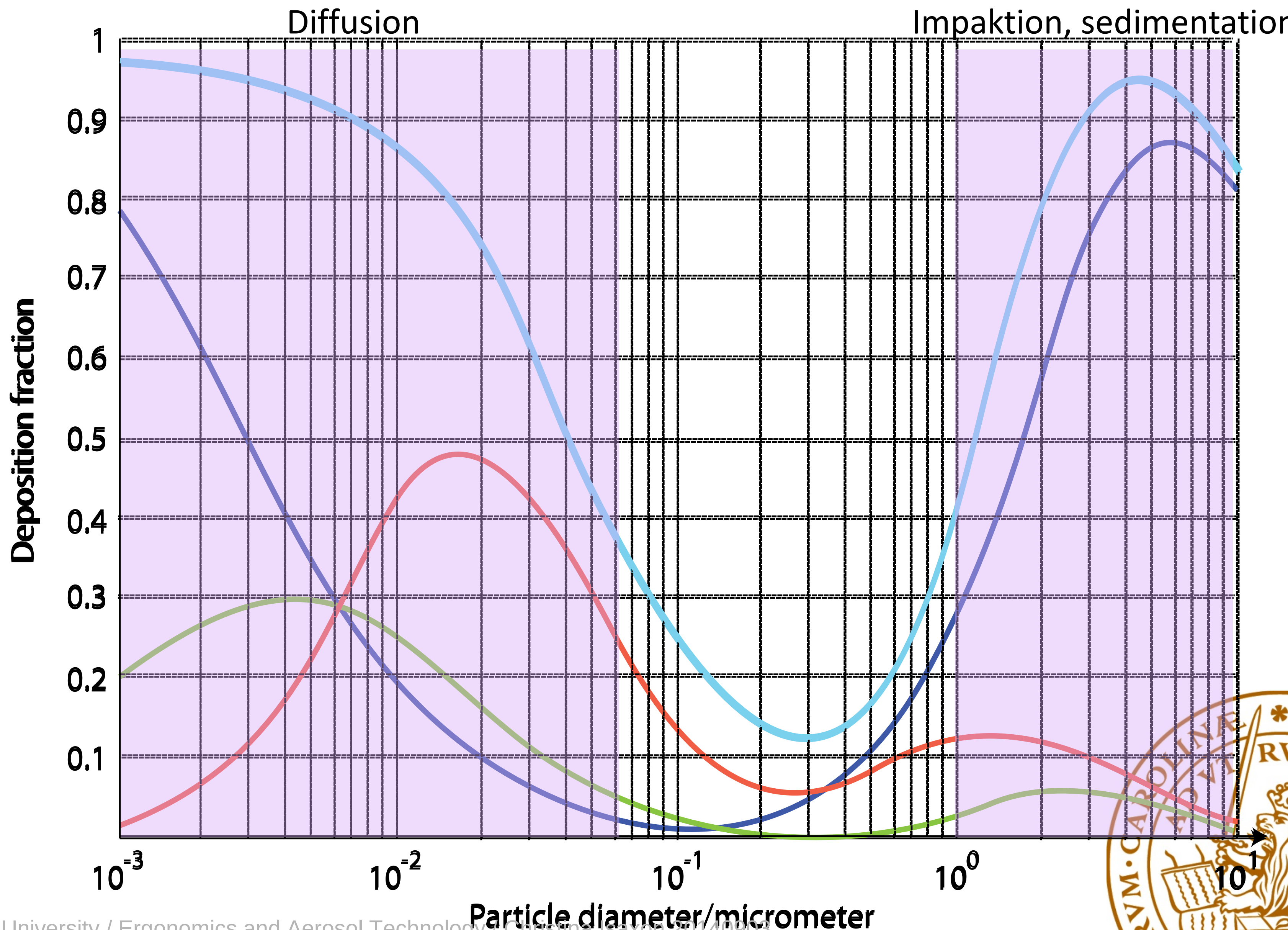
Tracheo-bronchial region



Alveolar region



Total deposition



Particle health effects

Lungs and respiratory tract

Discomfort, cough
Asthma
Chronic obstructive pulmonary disease (COPD)
Respiratory infections (elderly and children)
Cancer

Systemic effects (heart and blood)

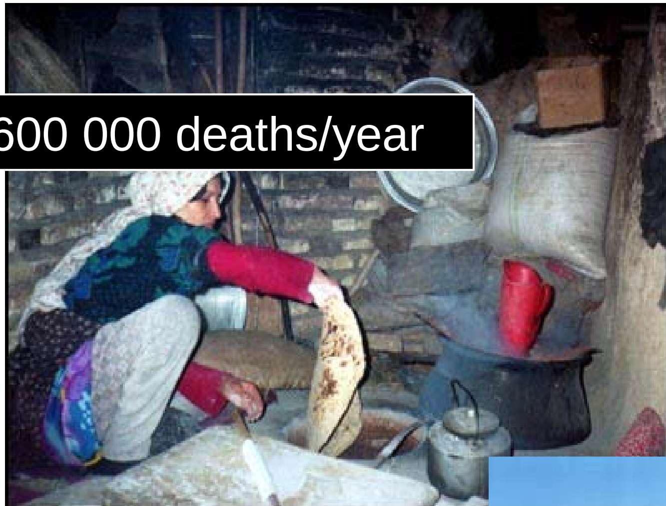
Cardiovascular problems
Heart attac
Stroke

Reproduction

Deaths of new-born in infection of the respiratory passage
Reduced birth weight
Effects on cevelopment of children’s lungs

Aerosols affect the Health

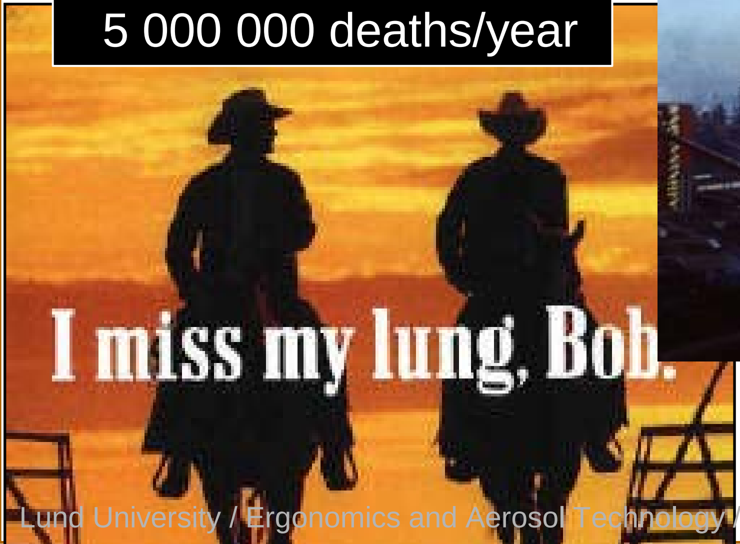
1 600 000 deaths/year



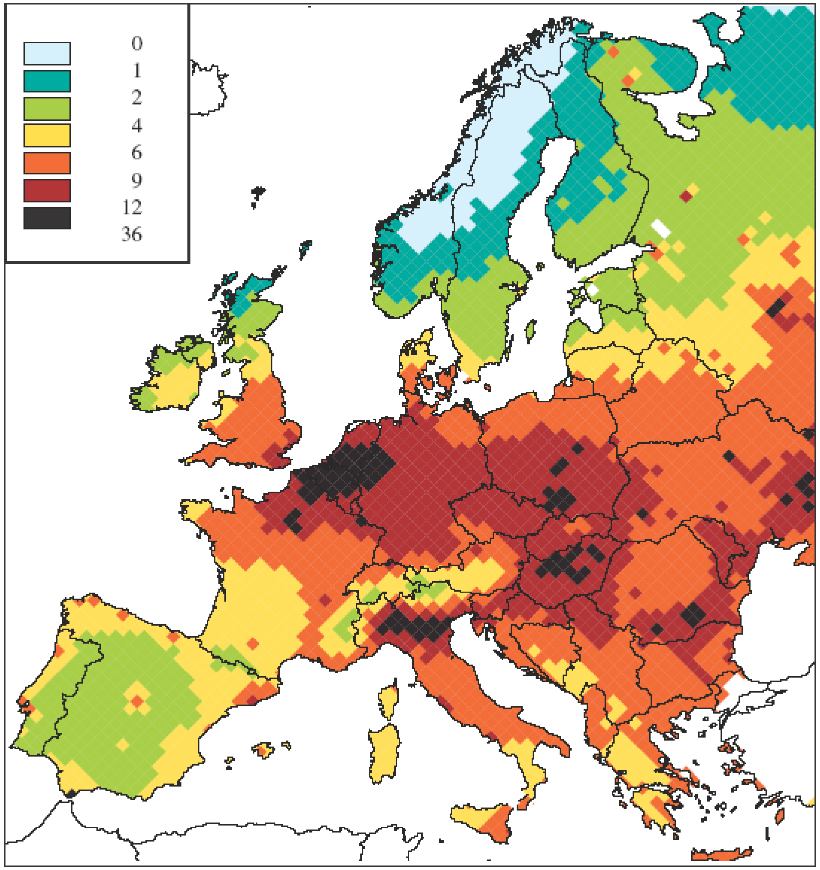
The London smog 1952

800 000 deaths/year

5 000 000 deaths/year

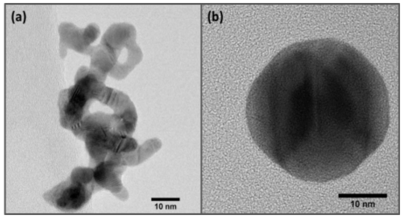


Loss in statistical life expectancy (months) that can be attributed to antropogenic contributions to PM 2.5



What makes the particles dangerous?

We know enough to be sure that there's no simple answer

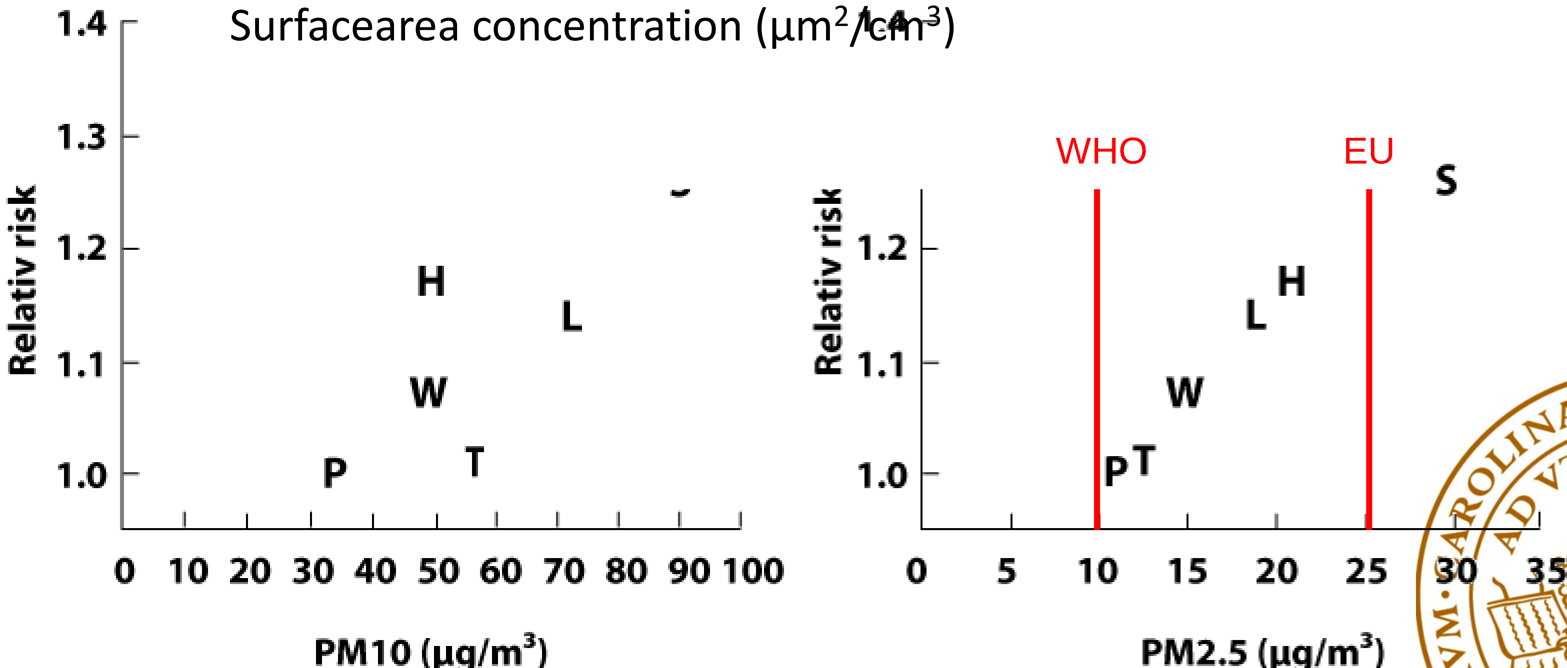


1. Concentration

Mass concentration ($\mu g/m^3$) - traditionally PM10

Number concentration ($\#/cm^3$) – makes the smallest particles "visible"

Surfacearea concentration ($\mu m^2/cm^3$)

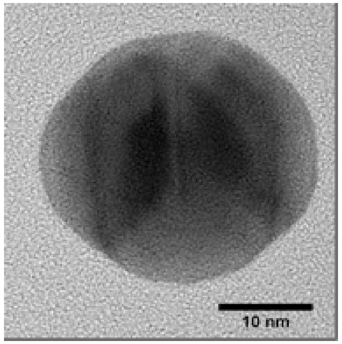


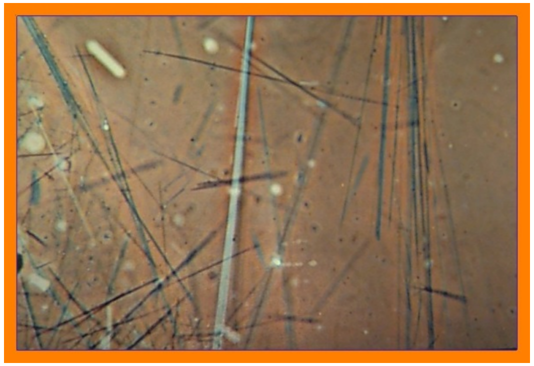
What makes the particles dangerous?

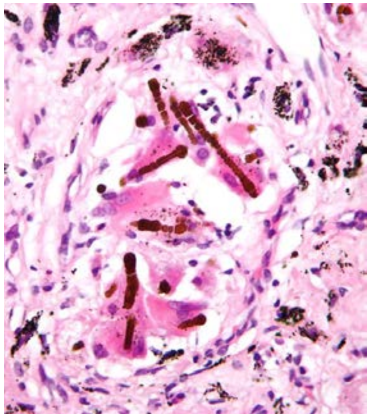
2. Physical properties

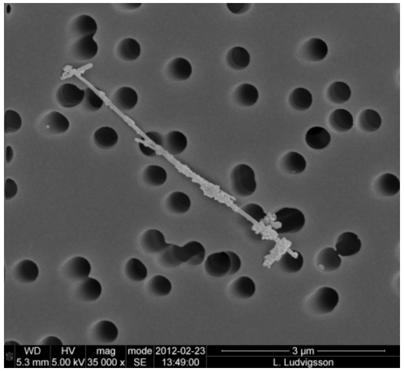
Shape

Size



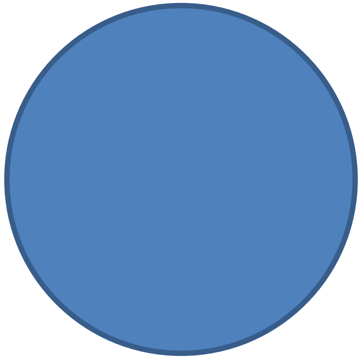


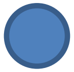




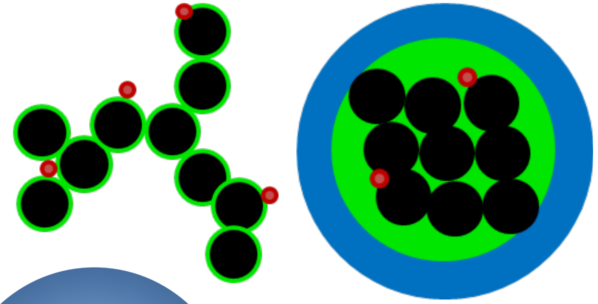
30 nm particle 5 % of its atoms on the surface

3 nm particle 50 % of its atoms are on the surface





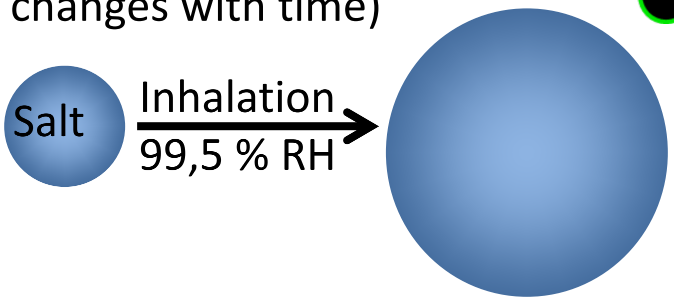
What makes the particles dangerous?



3. **Chemical properties**

Composition (often changes with time)

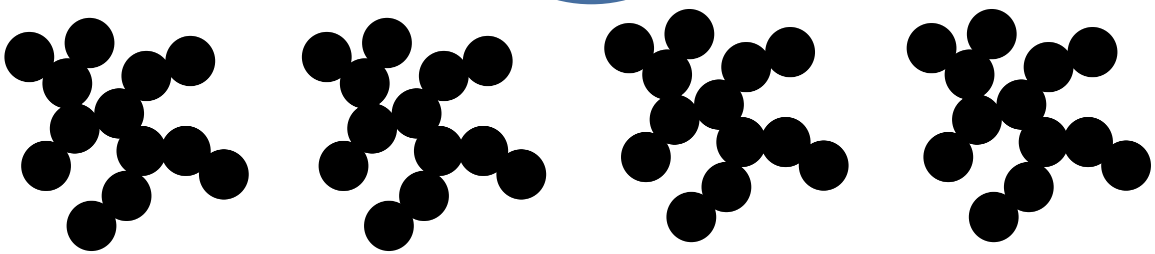
Hygroscopicity

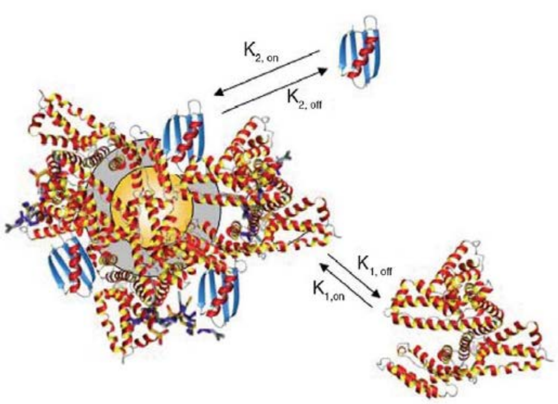


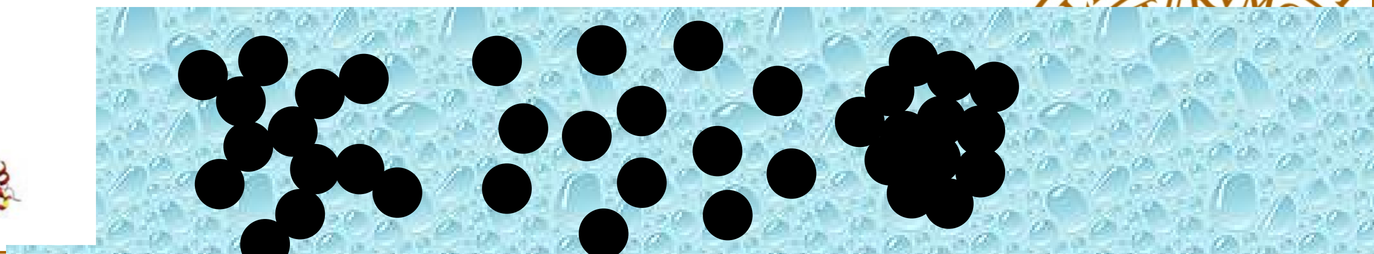
Solubility

Protein corona

Radioactivity







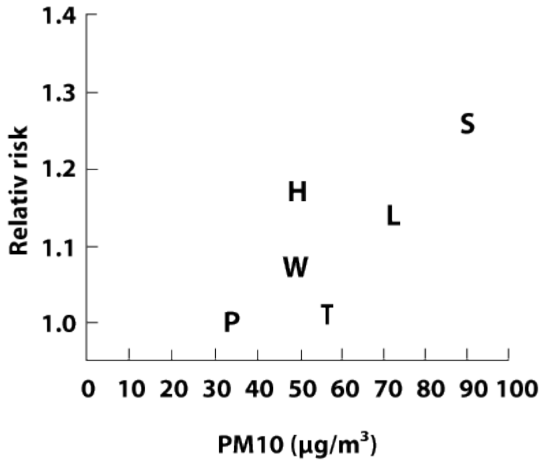
How to study health effects of particles?

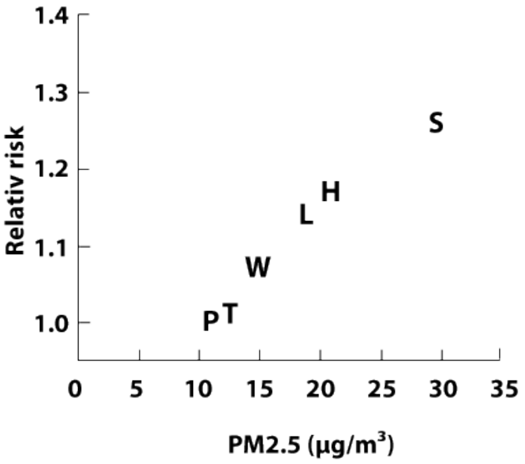
- Epidemiology

Time series of a populations

Cross section studies

Long term studies of selected sub population





How to study health effects of particles?

- Toxicology
  - Animal exposure
  - Human exposure

Severe provocation

Moderate provocation

  - In-vitro studies

Liquid

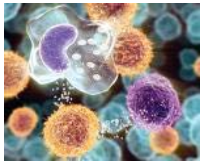
Air-liquid interface

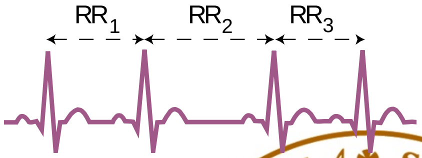
Animal exposure

- High doses can be used
- NOEL and LOEL
- Representative?
- Results have to be “translated” to the human system

Human exposure

Investigation of biomarkers and heart rate variability





Study design

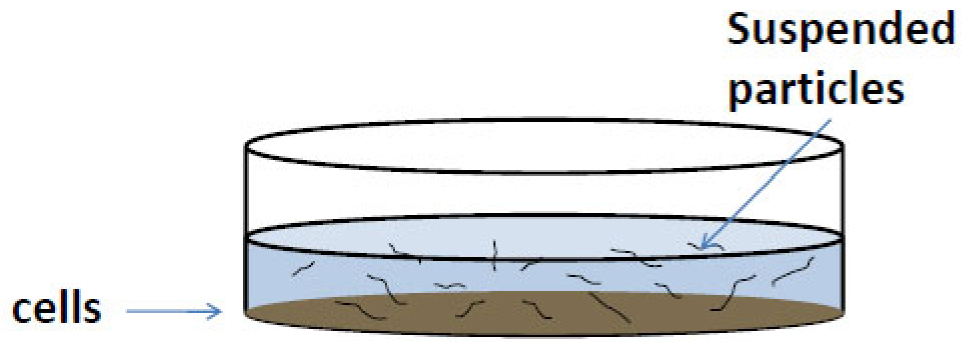
Healthy test subjects, three hours exposure
Particles and clean air according to a double blind protocol

Medical examination
Medical and work history
Blood and urine samples
Exhaled breath condensate, nasal lavage
Spirometry och acustic rhinometry
Lung deposition measurements
Eye- and airway symptoms
PEF-measurements
ECG

In vitro studies

Traditional liquid cell exposure

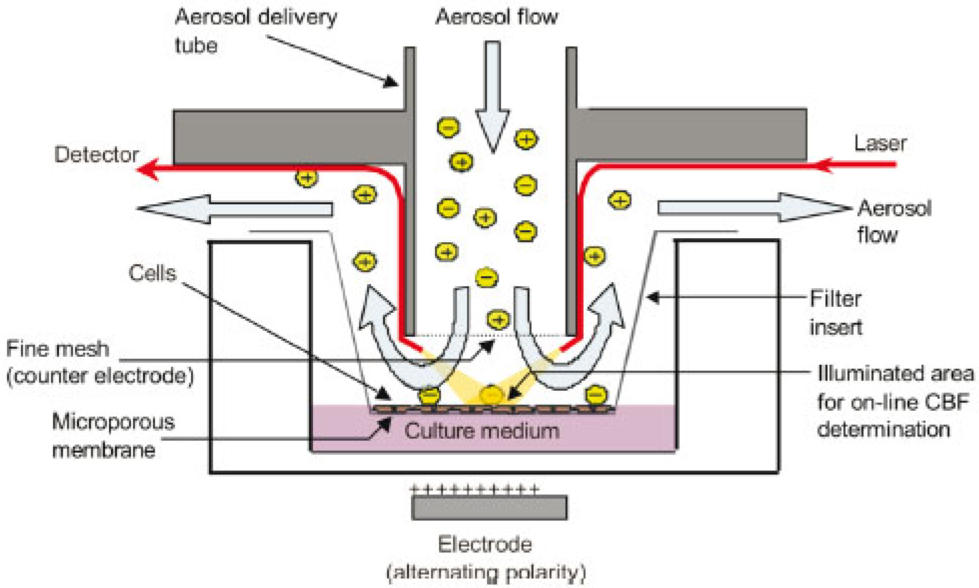
Dose: mg/ml



What dose are cells exposed to –
dependent on diffusion, sedimentation
(size dependent)
- Physical shape of particles in liquid?
- How test “real” aerosols?

In vitro studies

Air-Liquid Interface (ALI)



Conclusions (1)

- Air pollution = Aerosols (but not necessarily the other way around)
- Particles are everywhere (what does “clean air” mean?), and have always been. However, human activities increase the number of (small) particles
- Huge variety of sizes and shapes (and chemical composition)
- Formation processes
- PM / number concentration (and which of these are most important from a health perspective?)
- Aerodynamic diameter important (but is not the same as actual particle size)
- **Sedimentation, impaction, interception, diffusion, thermophoresis, coagulation** (and other phenomena) size dependent and important for predicting particle behavior in lung and in measurement instruments

Conclusions (2)

- Commonly used techniques for measuring mass concentration
- Things to keep in mind when setting up a measurement
- Lung deposition – size and shape dependent – smaller particles can reach the alveoli
- Cilia hairs and macrophages
- Health effects of particles and what causes them?
- Health effects of air pollution are studied by epidemiology and toxicology