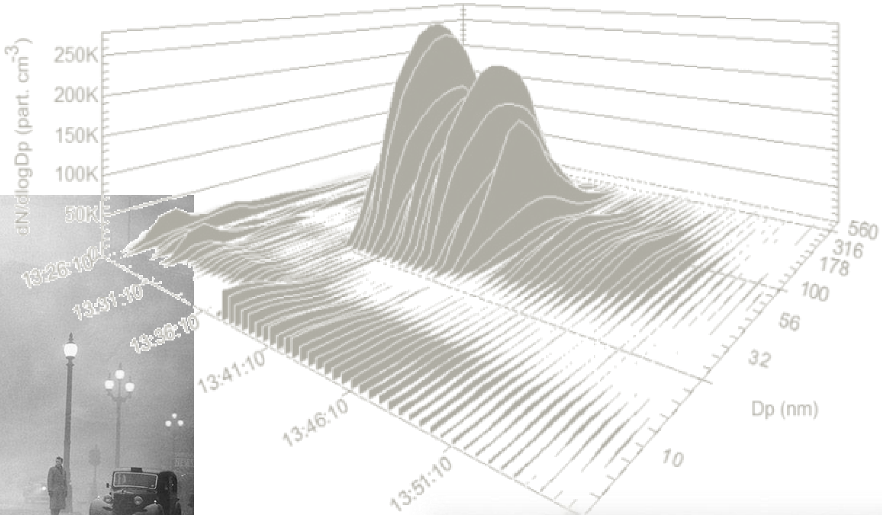
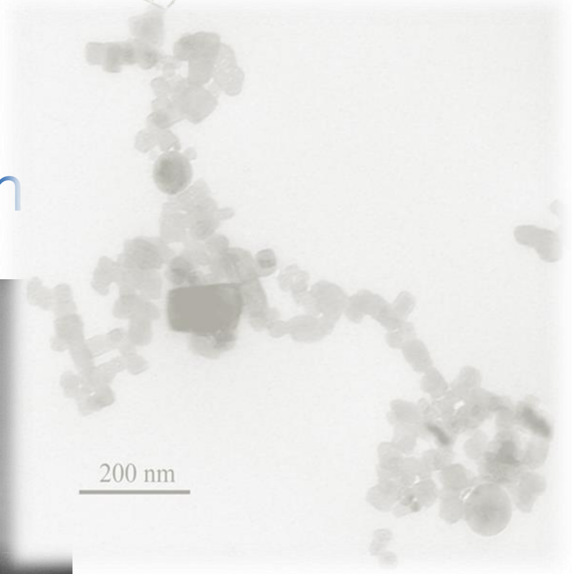
Environmental particles

Outlines

- Background information
- Particle thermodynamics
- Particle measurements
- Estimating exposures and emissions in indoor environmen
- Research at UNICAS



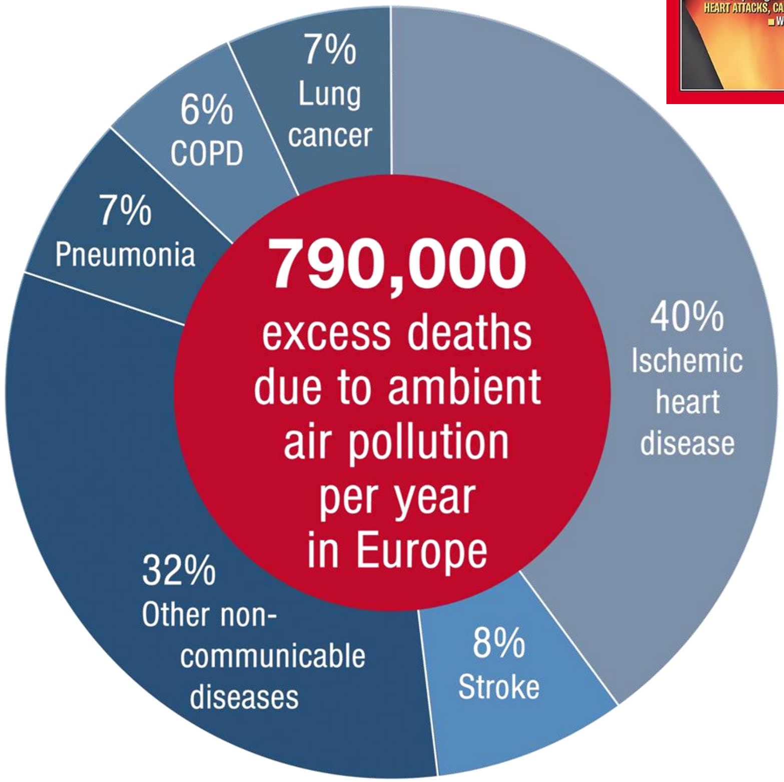


Background information

Why studying airborne particles

Effects on human health

- **Health effects.** Effect on morbidity and mortality in Europe and worldwide. Classified as carcinogenic compound Group 1 (PRESS RELEASE N°221 - Lyon/Geneva, 17 October 2013)
- **Environmental effects.** Airborne particles can also impact the environment. They contribute to air pollution, reducing visibility and contributing to phenomena such as smog. Certain particles, like black carbon, absorb sunlight and can accelerate the melting of ice and snow, thereby contributing to climate change.
- **Climate Change.** Particulate matter plays a complex role in the Earth's climate. Some particles, like sulfates, reflect sunlight and can cool the Earth, while others, like black carbon, absorb sunlight and contribute to warming.



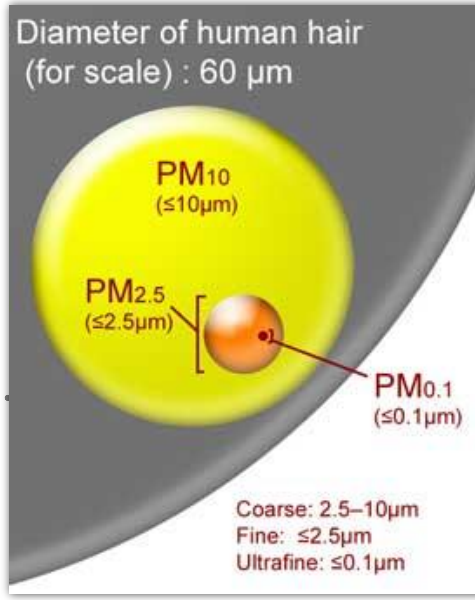
Definition and classification

Atmospheric Aerosol

is a metastable suspension of solid or liquid particles in a gas (e.g. air).

Classification by size

- PM_{10} mass fraction of particles with D_{eq} < 10 µm
- Coarse Particles ($PM_{2.5\text{-}10}$) mass fraction of particles with 2.5 µm < D_{eq} <
- Fine Particles ($PM_{2.5}$) mass fraction of particles with D_{eq} < 2.
- Ultrafine particles (UFPs) D_{eq} < 0.1 µm (100 nm)
- Nanoparticles D_{eq} < 0.050 µm (50 nm)

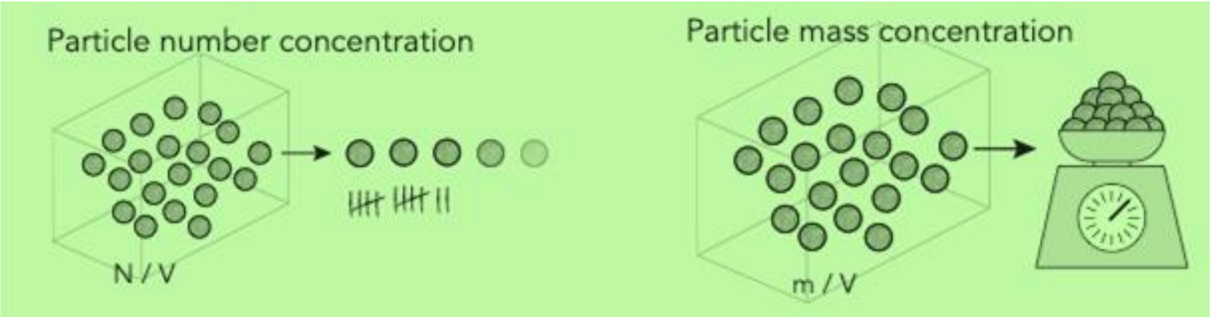


Origins and sources

- Combustion vs. mechanical generation
- Natural vs. anthropic; primary vs. secondary

Aerosol metrics and measurement approaches

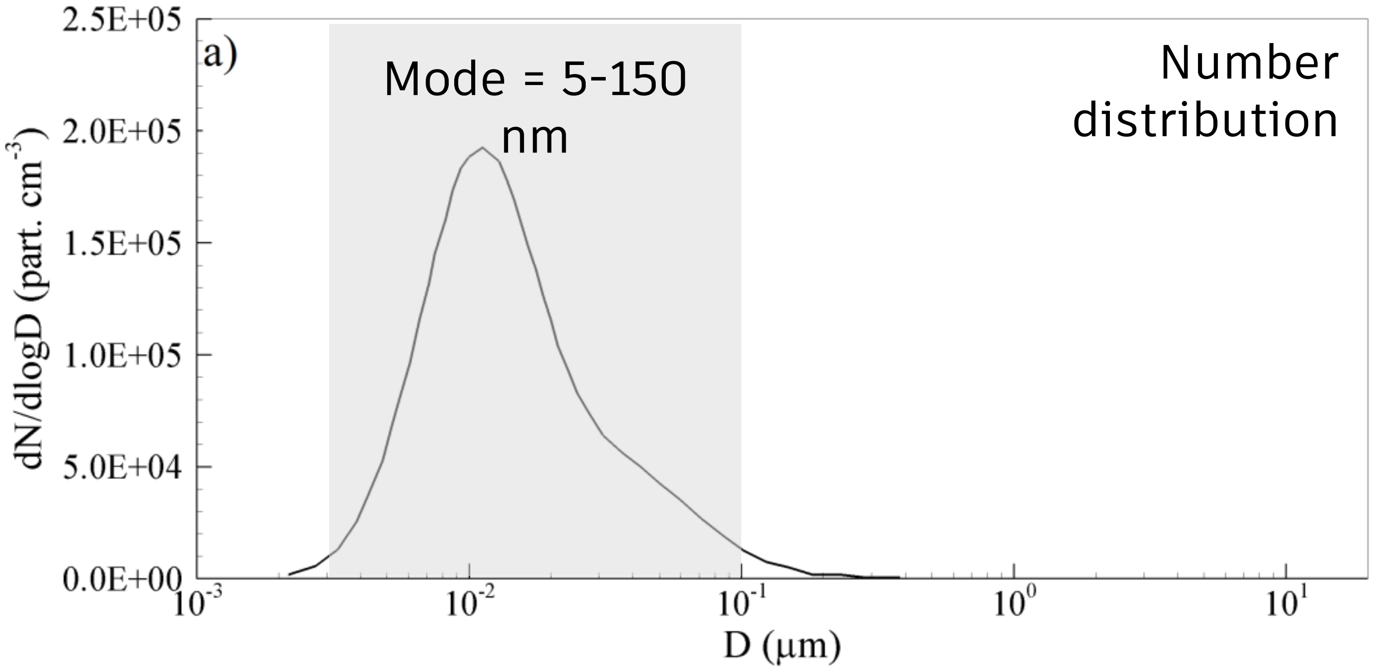
- Number, surface area vs. mass

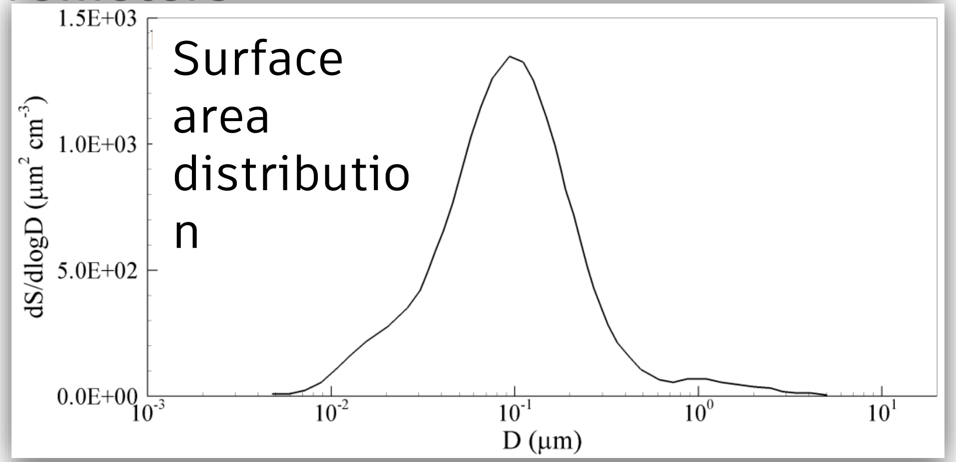


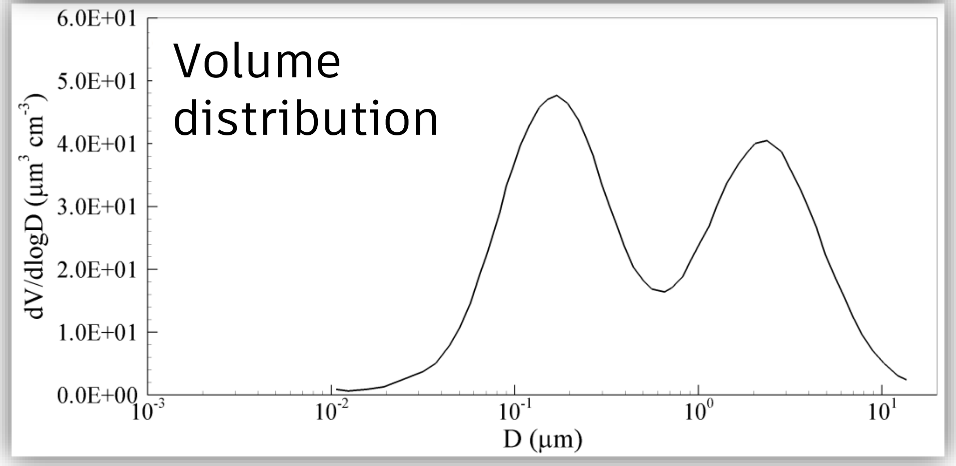
Definition and classification

Size distributions

- **size range** = few nanometers to tens or hundreds of micrometers
- **Modes** in different ranges (as a function of the metrics)

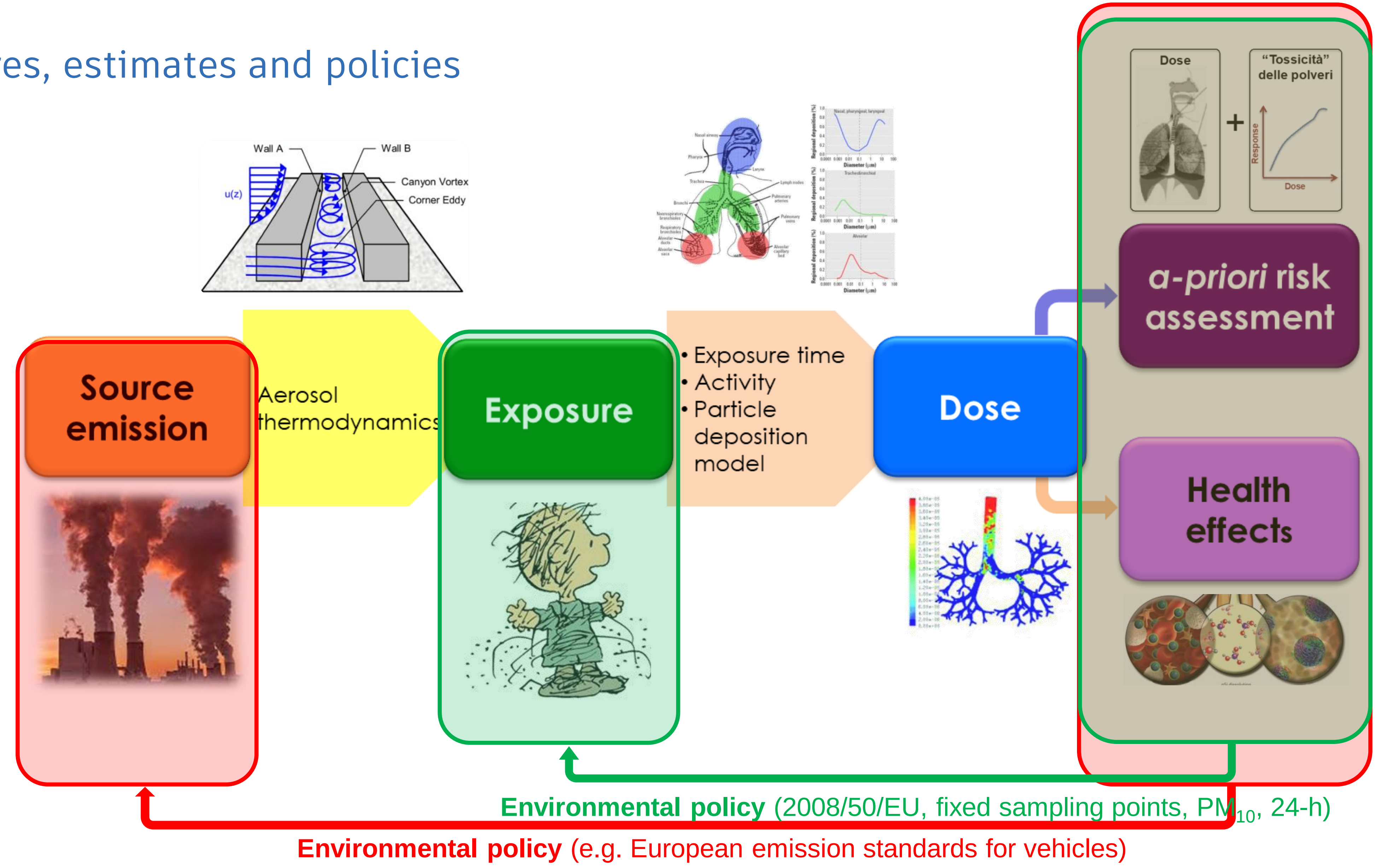






From emission to risk

Measures, estimates and policies



EUROPEAN
COMMISSION

Brussels, 26.10.2022
COM(2022) 542 final

2022/0347 (COD)

Proposal for a

DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

on ambient air quality and cleaner air for Europe

(recast)

l outdoor air quality

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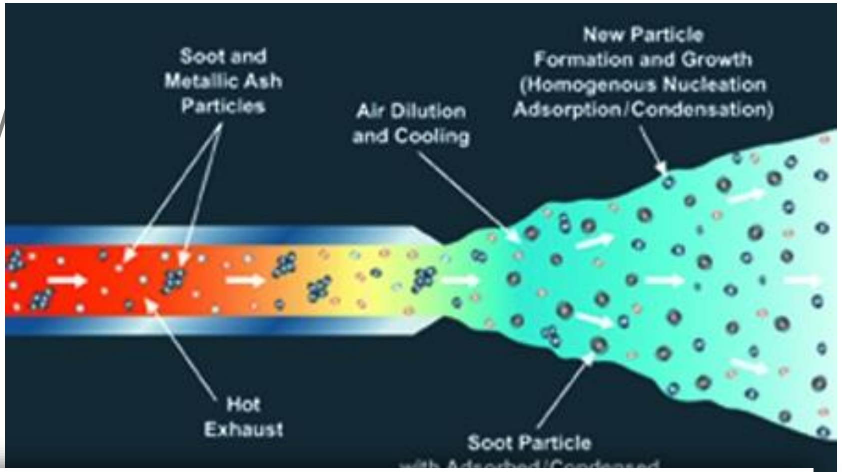
on;
nenomena;
on and mechanical generation



- 100-1000 part. cm
- 1000-5000 part. c
- 5000-20000 part.
- **<100000 part. cm**

- Sub-micrometric p
  - Residential heatin
  - vehicles;
  - *short-term* exposu
  - Metrological issue

D. Minimum number of sampling points for fixed measurements of ultrafine particles where high concentrations

Ultrafine particles shall be monitored at selected locations in addition to other air pollutants. Sampling points to monitor ultrafine particles shall coincide, where appropriate, with sampling points for particulate matter or nitrogen dioxide referred to in Point A, and be sited in accordance with Section 3 of Annex VII. For this purpose, at least 1 sampling point per 5 million inhabitants shall be established at a location where high UFP concentrations are likely to occur. Member States that have fewer than 5 million inhabitants shall establish at least 1 fixed sampling point at a location where high UFP concentrations are likely to occur.

WHO

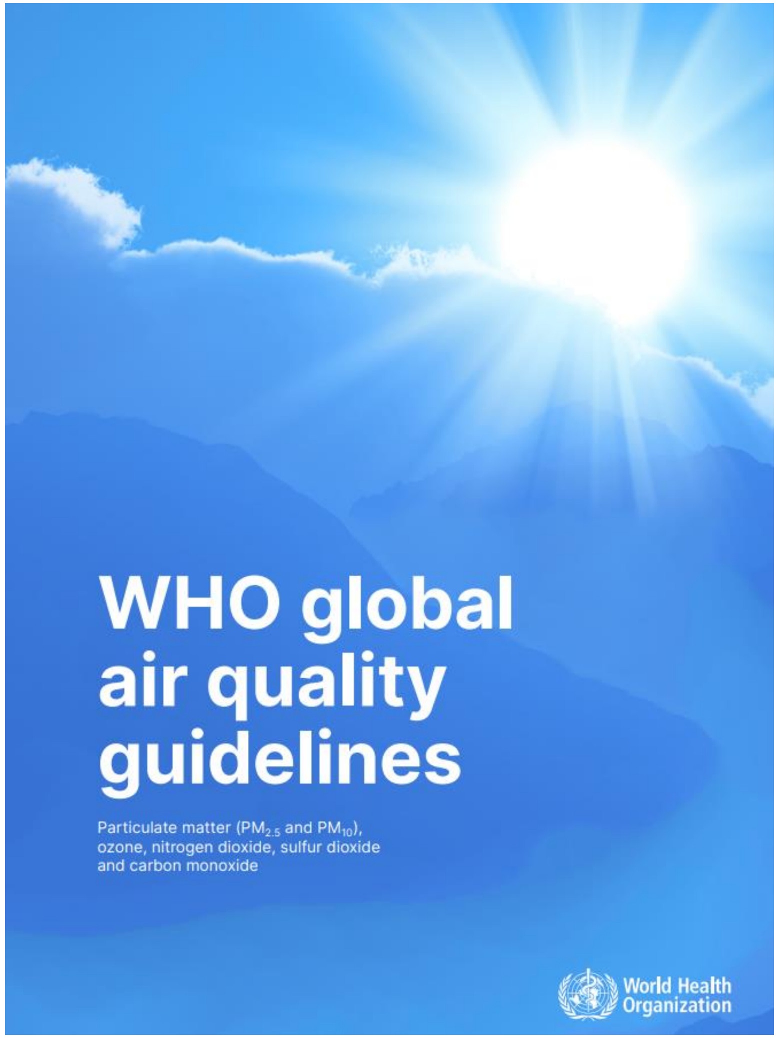


Table 0.1. Recommended AQG levels and interim targets

Pollutant	Averaging time	Interim target				AQG level
		1	2	3	4	
$PM_{2.5}$, µg/m³	Annual	35	25	15	10	5
	24-hour[a]	75	50	37.5	25	15
PM_{10}, µg/m³	Annual	70	50	30	20	15
	24-hour[a]	150	100	75	50	45
O_3, µg/m³	Peak season[b]	100	70	–	–	60
	8-hour[a]	160	120	–	–	100
NO_2, µg/m³	Annual	40	30	20	–	10
	24-hour[a]	120	50	–	–	25
SO_2, µg/m³	24-hour[a]	125	50	–	–	40
CO, mg/m³	24-hour[a]	7	–	–	–	4

[a] 99th percentile (i.e. 3–4 exceedance days per year).
[b] Average of daily maximum 8-hour mean O_3 concentration in the six consecutive months with the highest six-month running-average O_3 concentration.

WHO

Box 4.2. Good practice statement – UFP

The GDG decided to formulate the following four good practice statements on UFP to guide national and regional authorities and research towards measures to reduce ambient ultrafine particle concentrations.

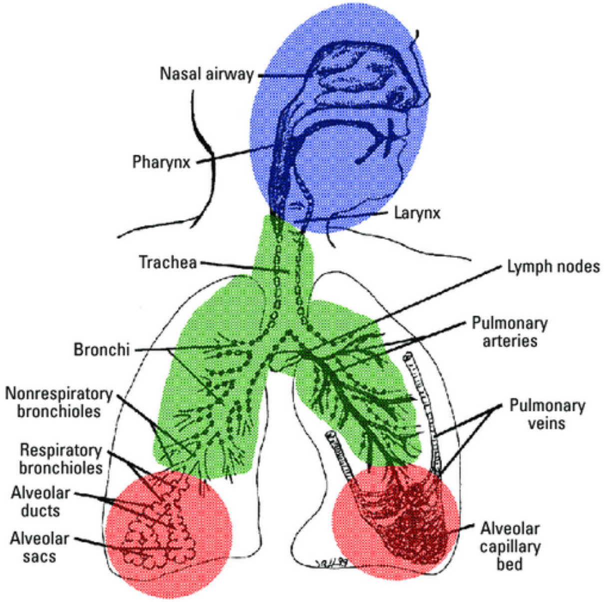
1. Quantify ambient UFP in terms of particle number concentration (PNC) for a size range with a lower limit of ≤ 10 nm and no restriction on the upper limit.
2. Expand the common air quality monitoring strategy by integration of UFP monitoring into existing air quality monitoring. Include size-segregated real-time PNC measurements at selected air monitoring stations in addition to, and simultaneously with, other airborne pollutants and characteristics of PM.
3. Distinguish between low and high PNC to guide decisions on the priorities of UFP source emission control. Low PNC can be considered < 1000 particles/cm3 (24-hour mean). High PNC can be considered > 10 000 particles/cm3 (24-hour mean) or 20 000 particles/cm3 (1-hour).
4. Utilize emerging science and technology to advance approaches to the assessment of exposure to UFP for application in epidemiological studies and UFP management.

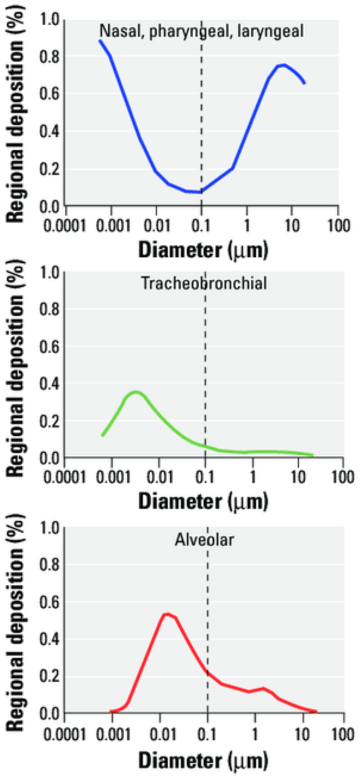
Health effects

Health effects, particle metrics

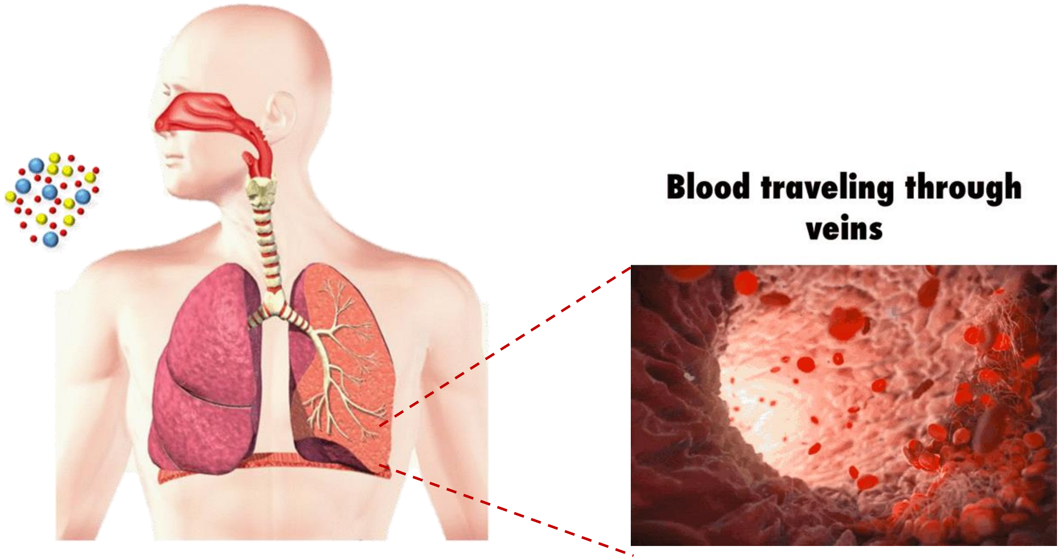
- Epidemiological studies recognized cardiovascular and respiratory issues related to the exposure to particle
- Which **size** or **property** is responsible? (PM_{10}, $PM_{2.5}$, Ultrafine, surface area, assumption rate, etc…)

Deposition in the lungs





Lungs as port of entry…

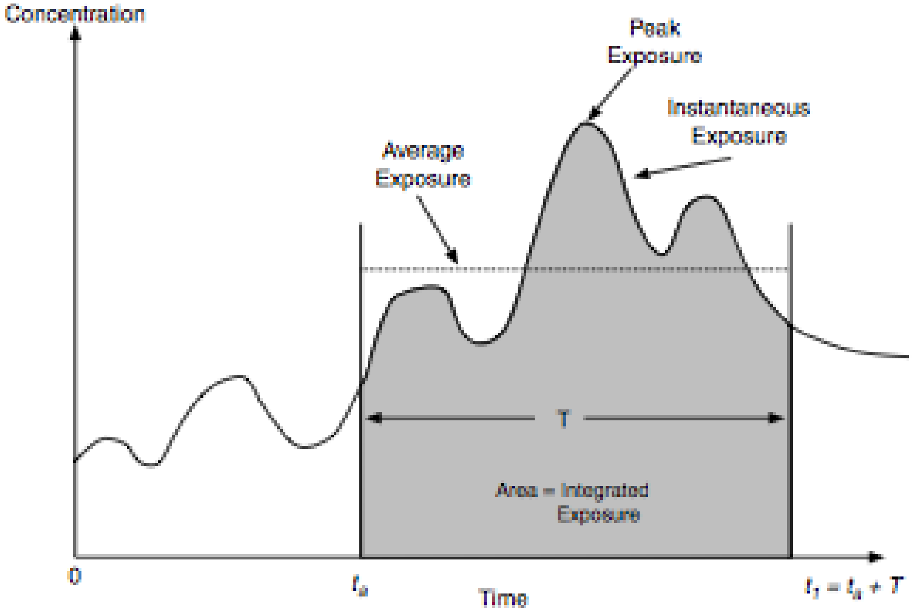


From exposure to dose

Take-home messages

- Huge number of small particles (sub-micrometric), very few large particles (super-micrometric);
- Exposure: personal measurements vs. fixed sampling points

Health effects are related to the dose: estimate of the dose?



$$DOSE_{Alv+TB} = \mathrm{IR} \cdot S_{Alv+TB} \cdot T \quad (\mathrm{mm}^2)$$

Inhalation rate

Lung-Deposited surface area concentration

Exposure time

From the dose to risk

Risk models

- e.g. Lung cancer risk model (Model by Sze-To et al. (2012))

Risk = Toxicity × Dose

c_f = 6.6×10^{-13} mg nm^{-2} (Sze-To *et al.*, 2012) equivalent toxicity of the particle surface area metric expressed as particle mass

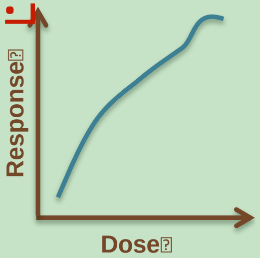
Daily **extra-doses** in LDSA and PM_{10}

$$ELCR_{extra} = \frac{1}{BW}\left(\sum_i^n SF_i \cdot \frac{m_i}{PM_{10}}\right) \cdot \left[c_f \cdot \delta_{Alv+TB} + \delta_{PM_{10}}\right] \cdot N_{day}$$

Body weight (70 kg)

Total exposure period (days per year)

SF: inhalation slope factor (lifetime cancer potency)
the percent increase in the risk of getting cancer associated with exposure to a unit concentration of a chemical every day for a lifetime, here assumed equal to 70 years



Chemical	SF (kg day mg^{-1})
BaP	3.9
As	15.1
Cd	6.3
Ni	0.91

mass concentration of the *i*-th pollutant present on the PM_{10}

$$SF_m = \sum_i^n SF_i \cdot \frac{m_i}{PM_{10}}$$

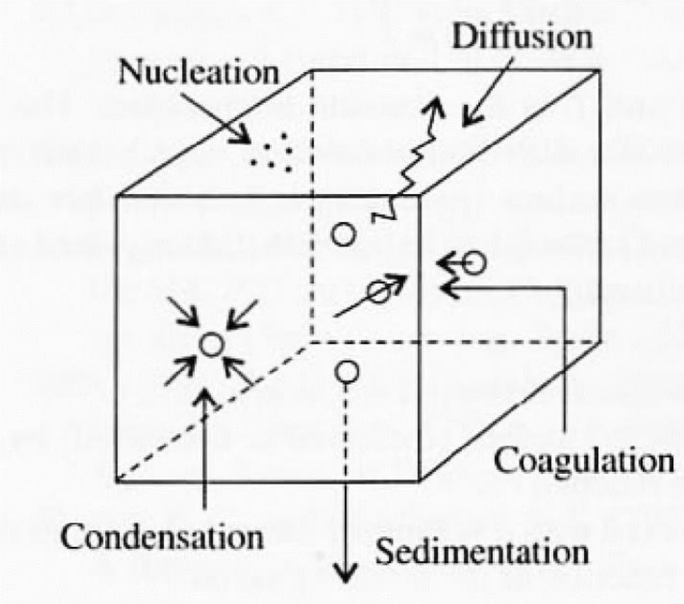
***SF* of the mixture** of the *n* carcinogenic pollutants on PM_{10}

Particle thermodynamics

Aerosol dynamics

General Dynamic Equation, GDE

- Aerosol is characterized by **dimensional**, **chemical** and **physical** variations: **metastable suspension**
- Thermodynamic and physical transformations of particle **formation**, **growth** and **removal**
- The general particle dynamics equation models the influence of chemical-physical phenomena on the aerosol distribution function.



$$\frac{\partial n_d}{\partial t} = -\nabla \cdot n_d \vec{v} + D\nabla^2 \cdot n_d - \nabla\left(\vec{c}\, n_d\right) + \left[\frac{\partial n_d}{\partial t}\right]_{gas-to-particle} - \left[\frac{\partial n_d}{\partial t}\right]_{coagulazione}$$

Particle transport

Diffusion (Fick’s laws)

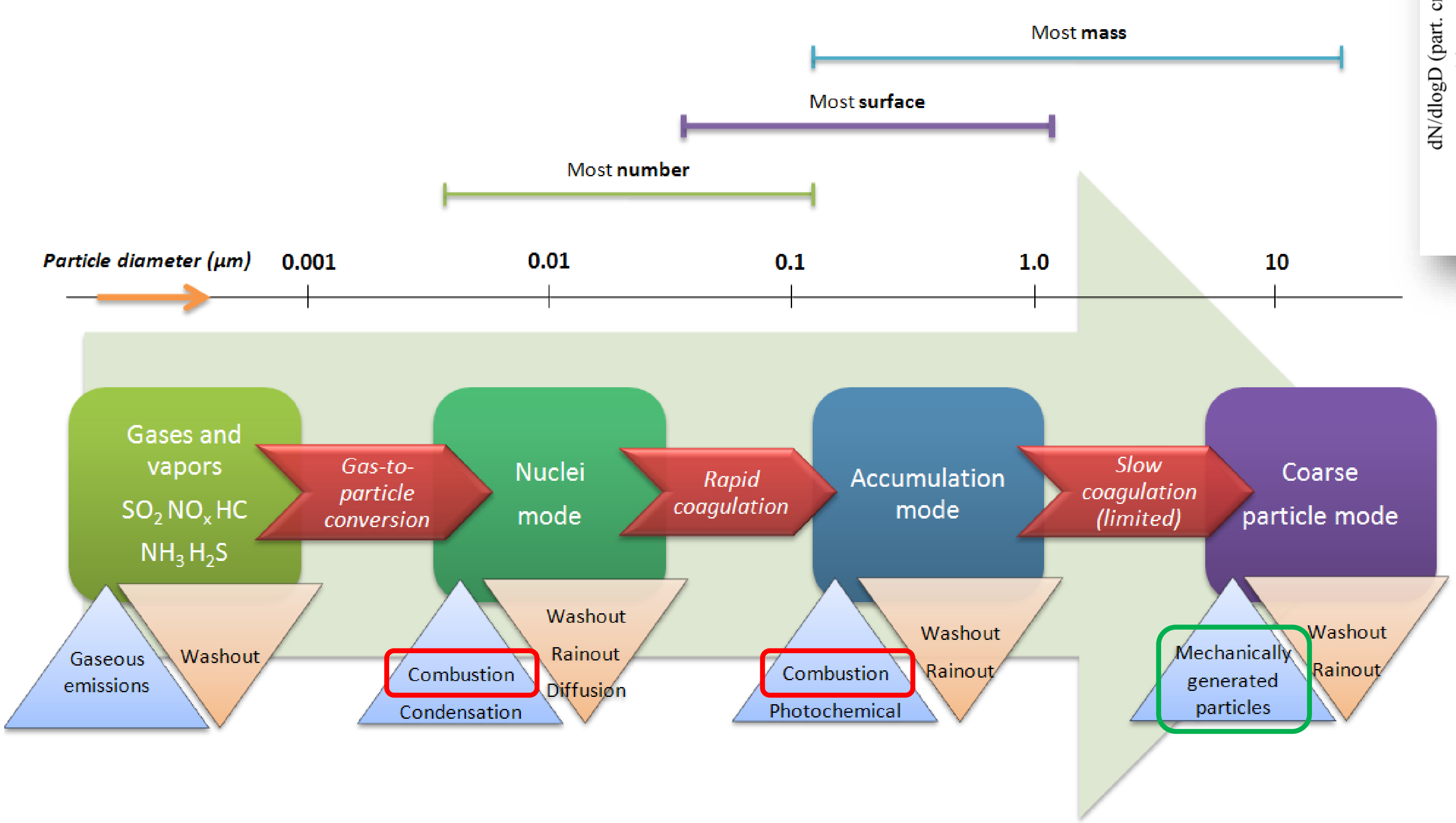
External forces

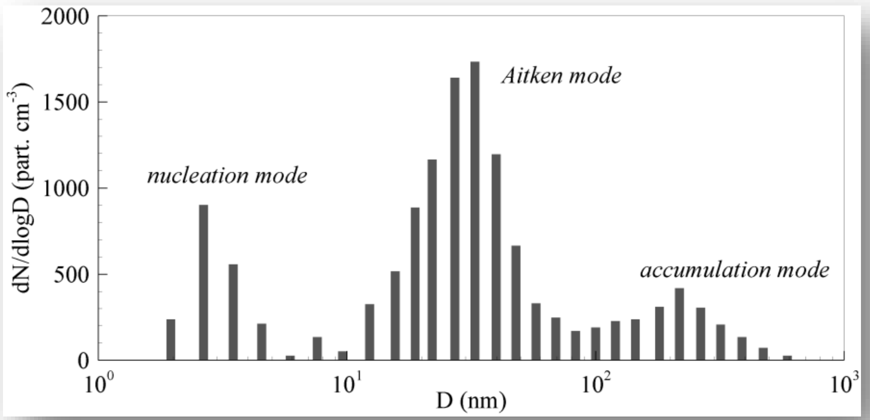
Nucleation (increases particle concentration)

Coagulation (reduces particle concentration)

Aerosol dynamics

Formation, growth and removal: particle size evolution





Formation: nucleation

gas-to-particle conversion (GPC) – ULTRAFINE PARTICLES - Nucleation

- formation of new nanoparticles from molecules in the gas phase
- on a molecular scale, nucleation is due to the random **formation of agglomerates** of molecules that constitute stable **clusters** once a critical size has been reached

- At the molecular scale, nucleation begins with the random and spontaneous aggregation of molecules.
- These molecules might be in a vapor or a solution, and under certain conditions, they start to come together due to intermolecular forces. Initially, these clusters are unstable and can easily disband, but if they reach a certain "critical size," they become stable and can continue to grow.
- The critical size is the point at which the cluster is energetically favorable to grow rather than shrink.

Formation: nucleation

The saturation ratio plays a crucial role in nucleation. The saturation ratio is defined as the ratio of the actual concentration of molecules (in vapor or solution) to the equilibrium concentration at which the phase transition (like condensation or crystallization) would naturally occur.

- If the saturation ratio is less than 1, the environment is undersaturated, meaning that molecules are more likely to remain in their dispersed state rather than aggregate. Under these conditions, nucleation is unlikely because the energy barrier for forming a stable nucleus is too high.
- If the saturation ratio is exactly 1, the system is in equilibrium, and while nucleation can occur, it will do so at a much slower rate because the energy barrier is still significant.
- When the saturation ratio is greater than 1, the environment is supersaturated. In this state, the energy barrier for nucleation decreases, making it easier for molecular clusters to reach the critical size and become stable. The higher the saturation ratio, the more likely it is that nucleation will occur, and the faster the process will proceed.

Saturation ratio (S)

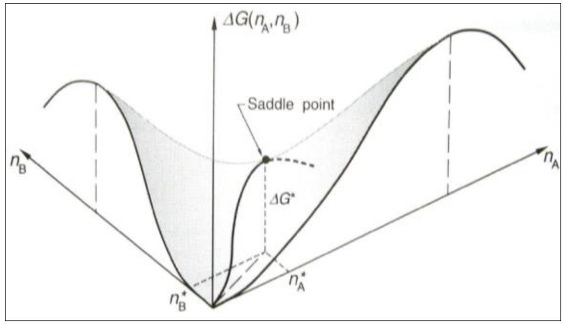
$$S = \frac{p_A}{p_A^s} = \frac{p_A}{p_A^s(T)}$$

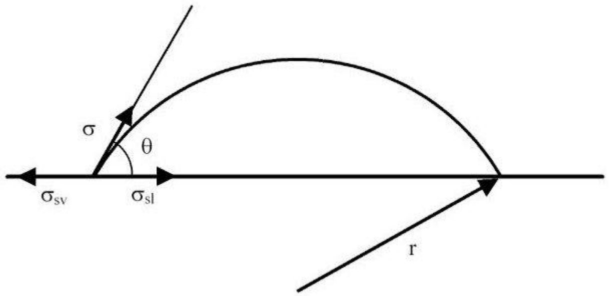
- ***S=1*** no stable condensed phase
- ***S>1*** *large clusters can be formed, some of them exceed a* ***critical size,*** *grow rapidly to form a stable condensed phase.*

Formation: nucleation

Homogeneous nucleation

- does only occur when the vapor phase of this species is supersaturated with respect to the condensed phase of this specie





Heterogeneous nucleation

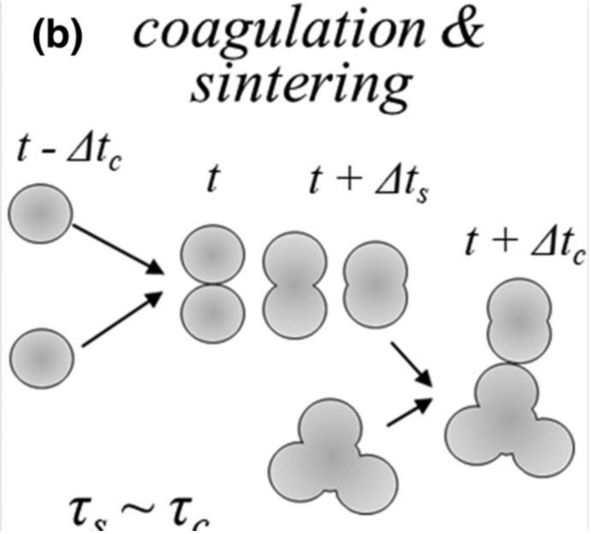
- the energy barrier for stable nucleus formation is reduced
- enables gas-to-particle conversion at even lower supersaturation
- Nucleation on an Insoluble Foreign Surface
- Ion-Induced Nucleation

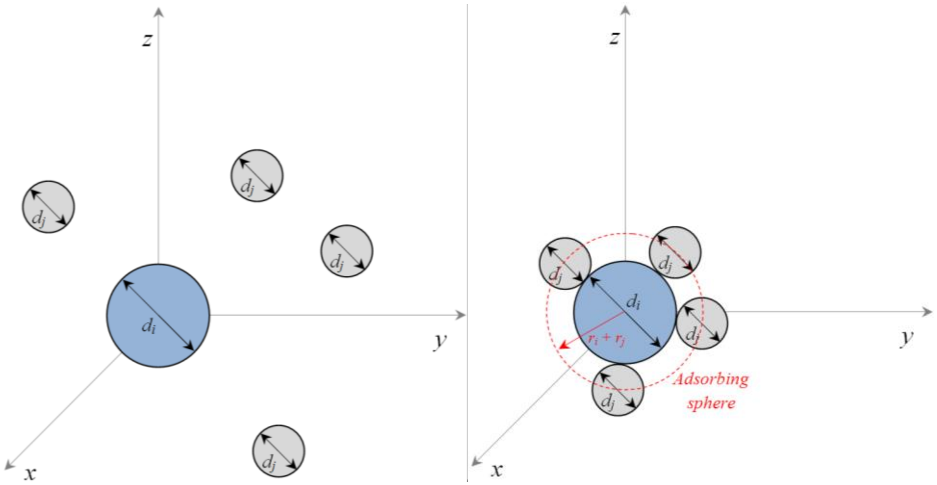
Homogeneous nucleation occurs uniformly throughout the volume of a pure substance, requiring higher levels of supersaturation or supercooling to overcome a higher energy barrier, as it lacks any surfaces or impurities to facilitate the process. In contrast, heterogeneous nucleation takes place at specific sites such as surfaces, container walls, or impurities, where the presence of these interfaces lowers the energy barrier, allowing nucleation to occur more easily and at lower levels of supersaturation or supercooling. As a result, homogeneous nucleation is less common and requires more extreme conditions, while heterogeneous nucleation is more prevalent in natural and industrial contexts.

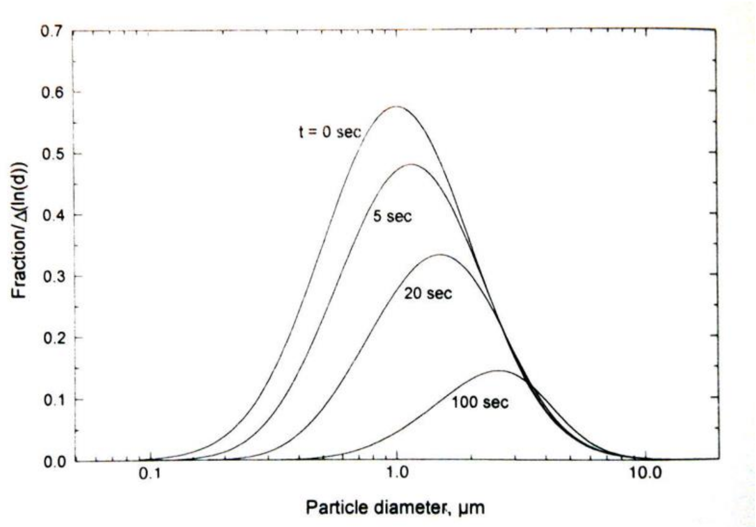
Growth: coagulation

Coagulation of UFPs

- The coagulation phenomenon is a growth process of particles characterized by the union of the particles themselves following their relative movement
- Consequent decrease in the number and surface area concentration (not mass)
- The collision, which causes coagulation phenomena, can be due to Brownian motions (thermal coagulation) or to external forces (gravitational, inertial, electrical, etc.; kinematic coagulation)



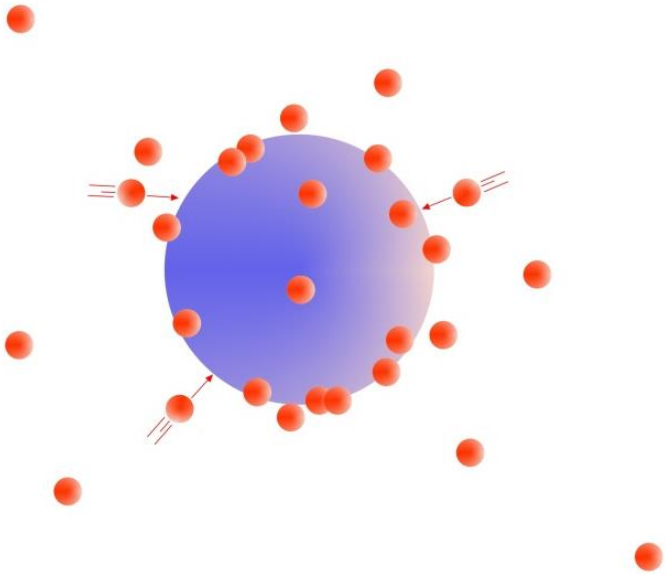


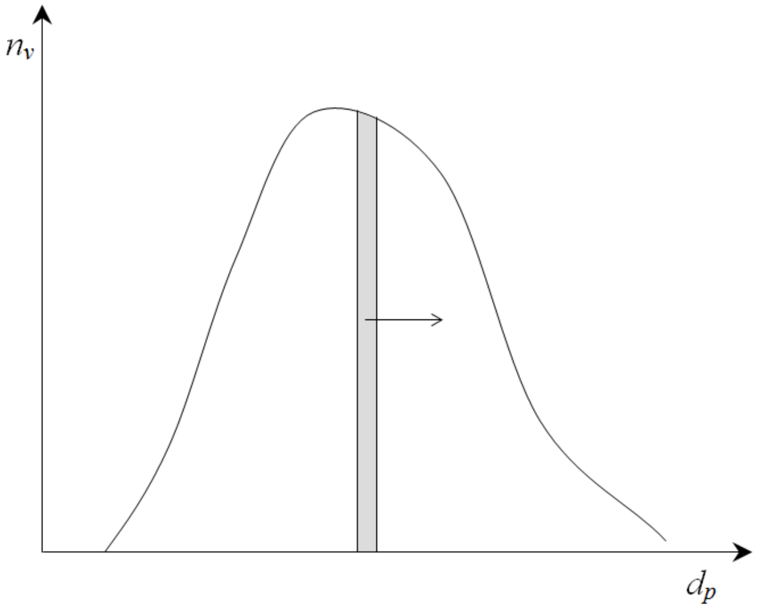


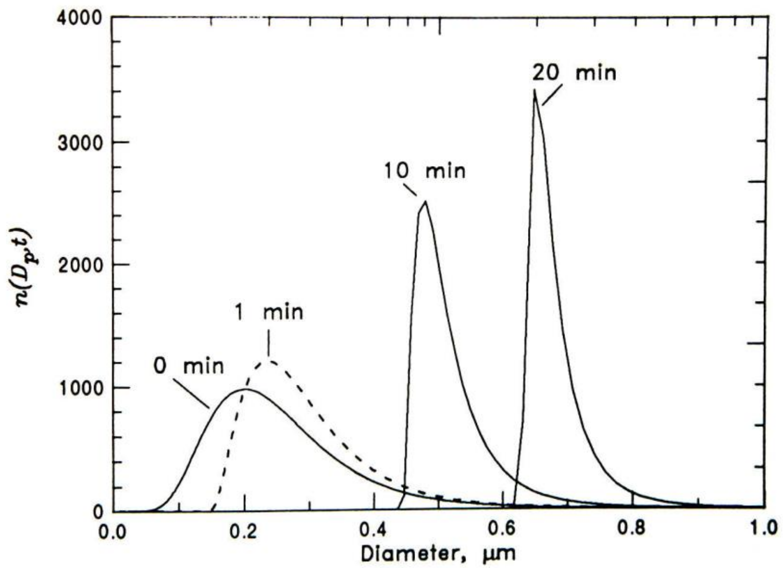
Growth: condensation

Condensation for sub-micron particles

- Condensation processes usually require a **supersaturated vapor** and a surface for the vapor to condense onto, e.g. existing aerosol particles
- For particles smaller than the gas mean free path (λ = 66 nm) the kinetic theory of gases gives us for the number of molecules colliding with particles per unit time and unit volume





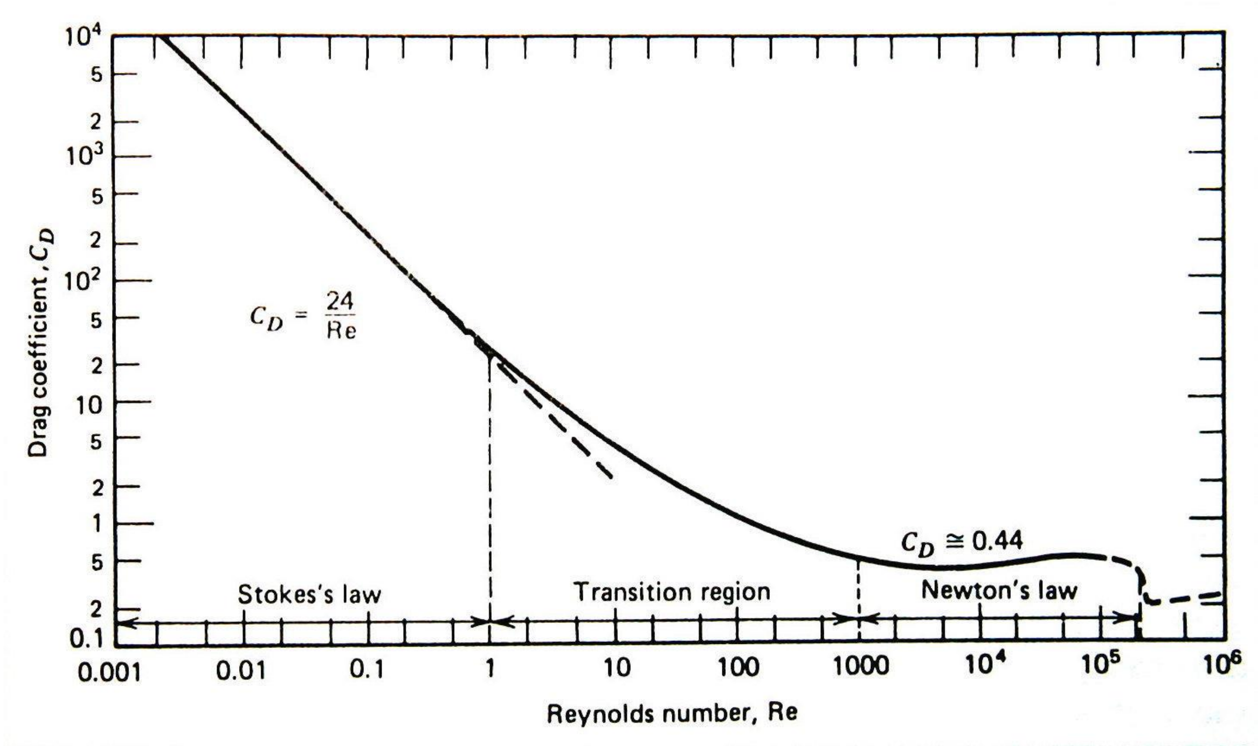


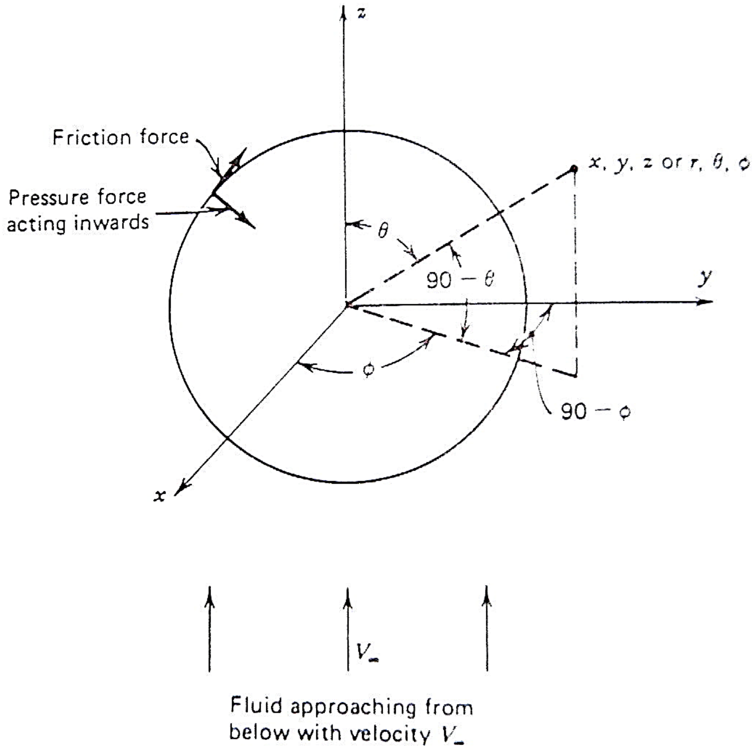
Dynamics: particle motion

Drag force

Stokes's law: describes the drag force on a spherical particle of diameter d_p that travels through a gas of viscosity η with velocity u_∞ (Re<<1)

$$F_d = 6\pi\eta u_\infty r_p = 3\pi\eta u_\infty d_p \qquad F_d = C_D \frac{1}{8}\rho_g \pi d_p^2 u_\infty$$





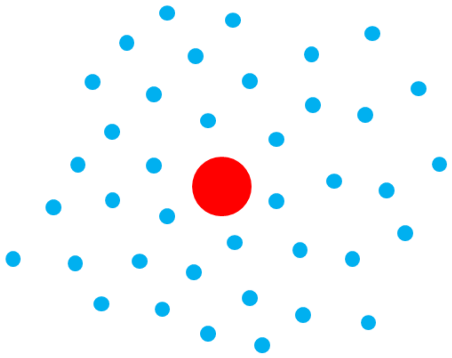
Dynamics: particle motion

Drag force

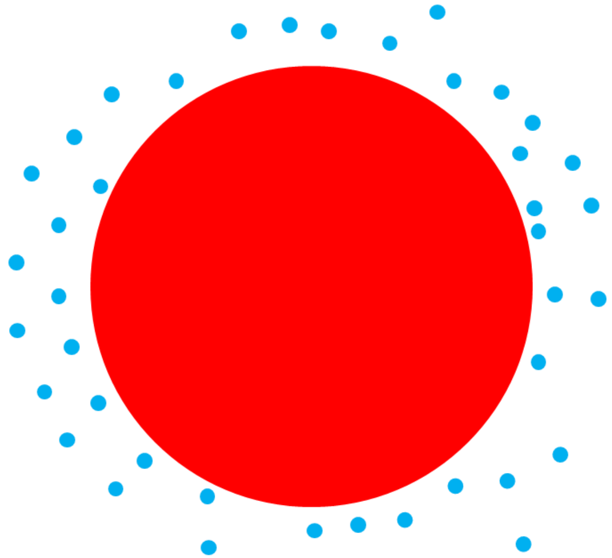
- One of the assumptions for the derivation of Stokes's law is that the relative velocity of the gas at the surface of the aerosol particle is zero (***no slip condition***). This assumption is valid for large particles where we can treat the surrounding air like a homogeneous fluid
- Particles smaller than about 1 μm in diameter, especially nanoparticles, **settle significantly faster than predicted by Stokes's law**. This is caused by the 'slip' at the surface of the particle when the particle size approaches the dimension of the mean free path. A correction factor to account for this effect was determined by Cunningham and is called Cunningham slip correction factor C_c.

$$F_d = \frac{3\pi\eta u_\infty d_p}{C_c}$$

d_p (μm)	C_c
0.001	216
0.005	43.6
0.01	4.95
0.1	2.85
0.5	1.32
1.0	1.16
5.0	1.03
10.0	1.01



Free-molecule regime
(slip condition)



Continuum regime
(no slip condition)

Dynamics: external forces

Newton's laws and conservation of momentum

- a body tends to preserve its state of inertia
- the rate of change of the momentum of a body is equal to the net force acting on the body

Settling fo

Drag force

Size (µm)	Settling velocity (m/s)	Relaxation time (s)
0.3	4.16E − 06	4.24E − 07
1	3.44E − 05	3.50E − 06
2.5	1.96E − 04	2.00E − 05
5	7.61E − 04	7.76E − 05
7.5	1.69E − 03	1.73E − 04
10	3.00E − 03	3.06E − 04
20	1.19E − 02	1.21E − 03

velocity

**settling velocity at the equilibrium between forces*

- *Relaxa* … nges in exte
- *stoppi* … when, starting from an initial speed due to the application of an external force, it reaches the equilibrium velocity

$$\tau = \frac{m_p C_c}{3\pi\eta\, d_p}$$

$$s_p = \frac{\rho_p\, d_p^2\, C_c v_0}{18\eta}$$

Dynamics: external forces

The Stokes number (St) is a dimensionless number used in fluid dynamics to characterize the behavior of particles suspended in a fluid flow. It is defined as the ratio of the particle's relaxation time to a characteristic time scale of the flow. The Stokes number is given by:

$$\mathrm{St} = \frac{\tau_p}{\tau_f}$$

Where:

- τ_p is the particle relaxation time, which represents the time it takes for a particle to adjust to changes in the fluid flow. It depends on the particle's size, density, and the viscosity of the fluid.
- τ_f is the characteristic time scale of the fluid flow, typically related to the flow's velocity and a characteristic length scale (such as the size of an obstacle or the distance over which the flow changes).

The Stokes number indicates how well particles can follow the flow of the fluid:

- **St ≪ 1**: Particles closely follow the fluid flow, as their relaxation time is much smaller than the flow time scale.
- **St ≫ 1**: Particles are less influenced by the fluid flow and tend to continue moving in their original direction rather than following the flow.

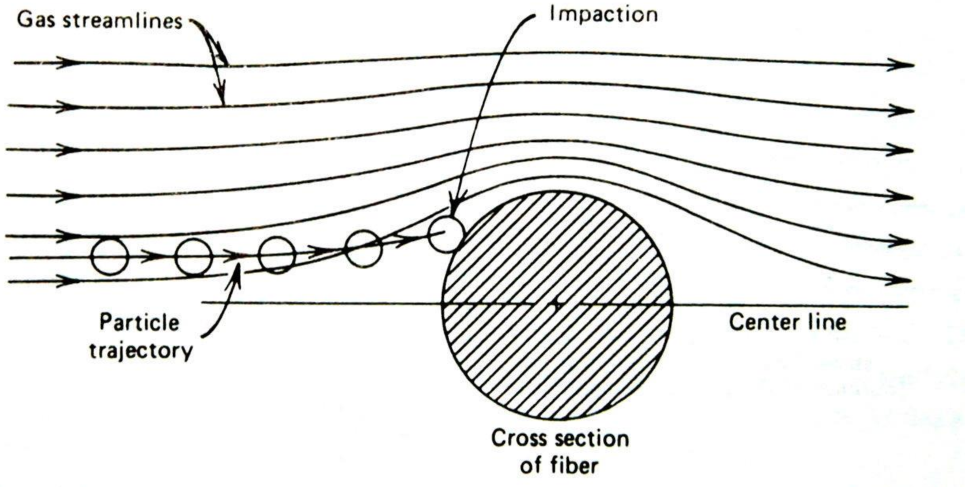
Dynamics: external forces

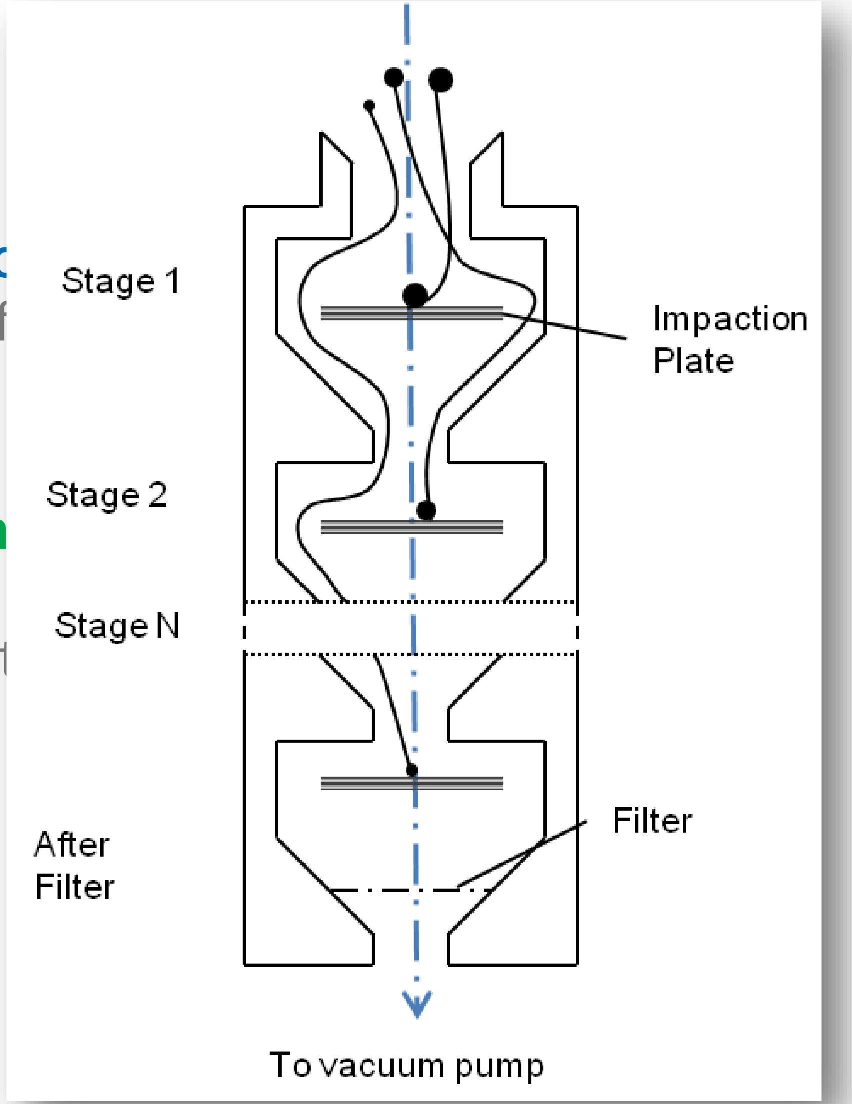
Stokes number and impaction

Stokes number gives direct information about the behavior of the obstacle.

- **Stk >> 1** The particle **will not be able to stop within a distanc obstacle**, which also will be the dimension of the change of consequence the particle will travel in a straight line and streamlines.
- **Stk << 1** The particle **will be able to stop within a distance m obstacle** and consequently much smaller than the dimension gas flow. Under t low t deviation only.

$$Stk = \frac{s_p}{L}$$





Dynamics: external forces

Electrical forces

Equilibrium between drag forces and electrical forces...

$$\vec{F}_i = q\vec{E}$$

$$m_p \frac{d\vec{v}}{dt} = \frac{3\pi\eta d_p}{C_c}\left(\vec{u} - \vec{v}\right) + q\vec{E}$$

Terminal velocity in an electric field

$$v_{te} = \frac{q E C_c}{3\pi\eta d_p}$$

electrical mobility Z_p gives the velocity of the particle in an external electrical field v_{te} of certain strength E

$$v_{te} = Z_p E$$

$$Z_p = \frac{q C_c}{3\pi\eta d_p}$$

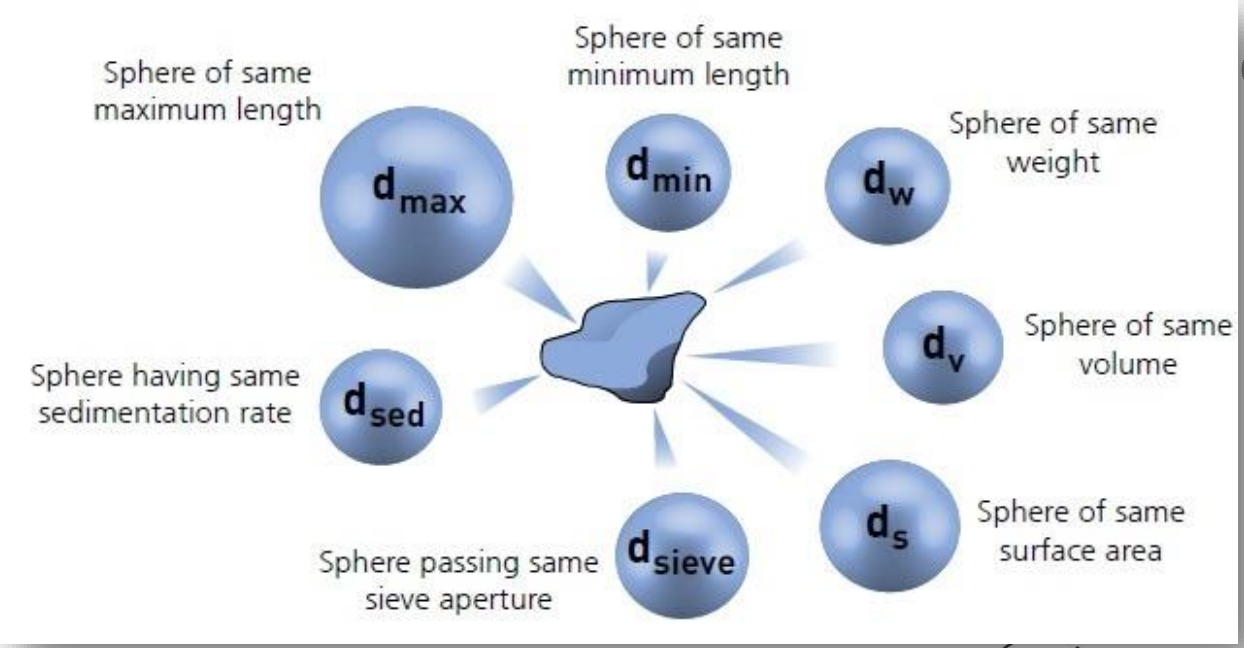
TABLE 15.2 Electrical Mobility of Electrons, Ions, and Aerosol Particles at Standard Conditions

Particle Diameter (μm)	Electrical Mobility ($m^2/V \cdot s$)[a] Singly Charged	Maximum Charge[b]
Electron	6.7×10^{-2}	
Negative air ion	1.6×10^{-4}	
Positive air ion	1.4×10^{-4}	
0.01	2.1×10^{-6}	7.3×10^{-4}
0.1	2.7×10^{-8}	9.3×10^{-4}
1.0	1.1×10^{-9}	(2.5×10^{-3})[c]
10	9.7×10^{-11}	(6.7×10^{-3})[c]
100	9.3×10^{-12}	(1.1×10^{-2})[c]

Dynamics: equivalent diameters

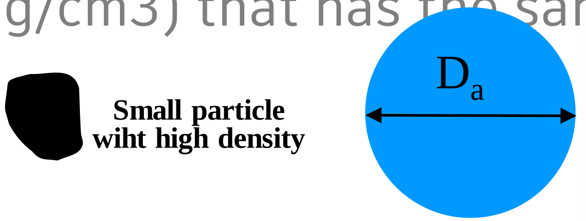
Equivalent diameters

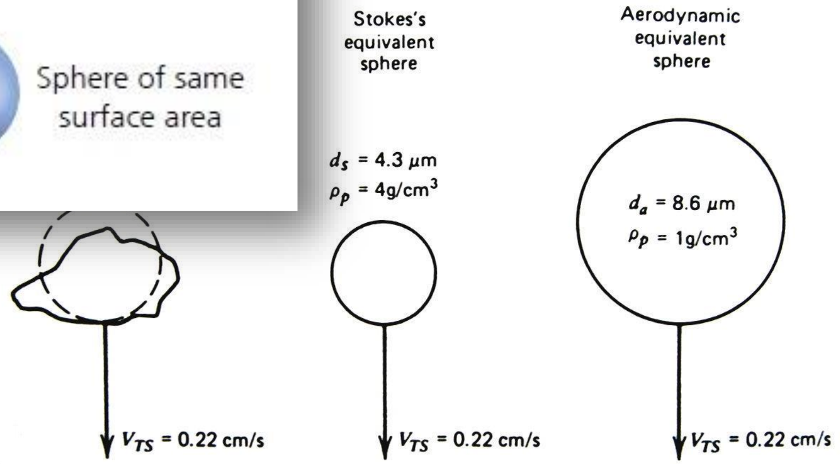
equivalent diameters are defined as those of **spherical particles that would behave the same as the measured particle** in a particular measurement setup. Since there are a large **variety of ways** to measure parti… e equivalent particle **diameters**.



Aerodynamic equivalent

diameter of a particle is … of unit density (ρ = 1 g/cm3) that has the sam…





Equivalent electrical mobility diameter

diameter of a particle of unit density that has the same electrical mobility (Z) as the particle under examination.

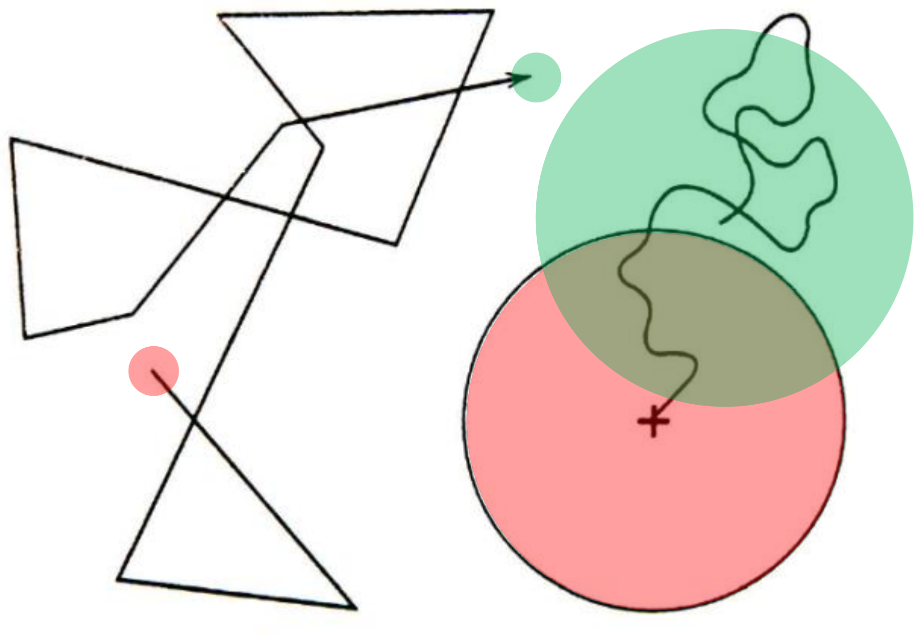
Dynamics: Diffusion

net flux or diffusion flux of particles is a result of the concentration gradient

Brownian Motion

- Particles suspended in surrounding air are continuously bombarded by gas molecules.
- In every collision inertia is transferred from the gas molecule to the aerosol particle, changing the direction of motion of the particle.
- This transfer of inertia together with the statistical distribution of the gas molecules colliding with the particles results in a ‘random walk’ of the particles (Brownian motion).

$$m_p \frac{d\vec{v}}{dt} = -\frac{3\pi\eta d_p}{C_c}\vec{v} + m_p \vec{a}$$



(a) (b)

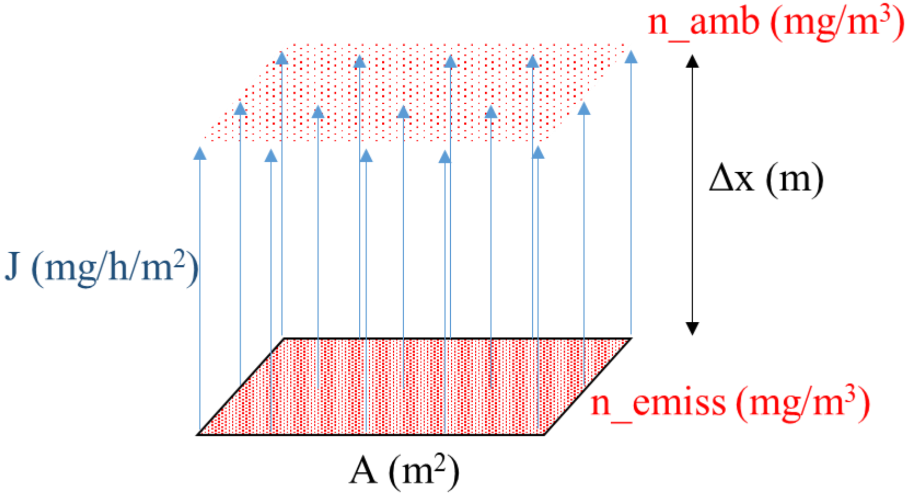
Figure 2.31: Projection of the path of (a) an air molecule and (b) of an aerosol particle of $d_p = 0.1$ µm undergoing Brownian motion. For the aerosol particle the path of motion of the center of the particle is shown. (from Hinds 1999)

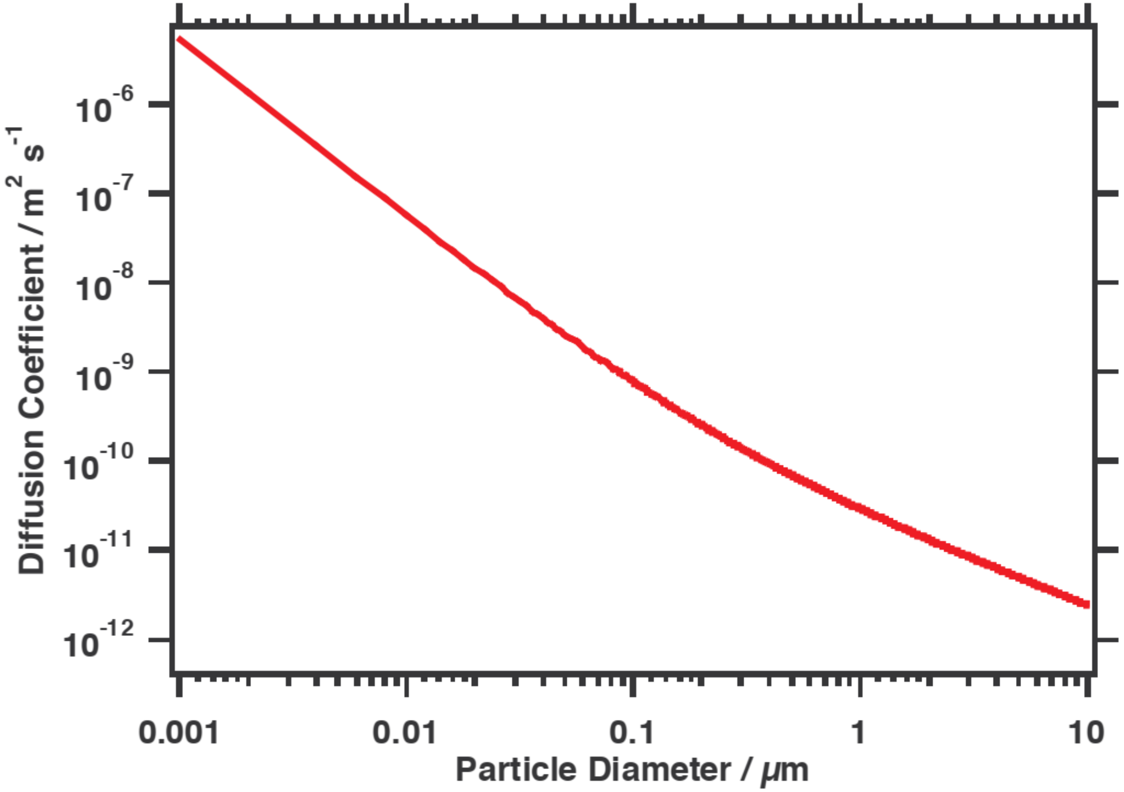
Dynamics: Diffusion

- net flux or diffusion flux of particles is a result of the concentration gradient
- Fick's laws
- Diffusion coefficient: the proportionality between flux and concentration gradient

$$D = \frac{kTC_c}{3\pi\eta d_p}$$

$$\frac{\partial n}{\partial t} = -\frac{\partial J_x}{\partial x} = D\frac{\partial^2 n}{\partial x^2}$$

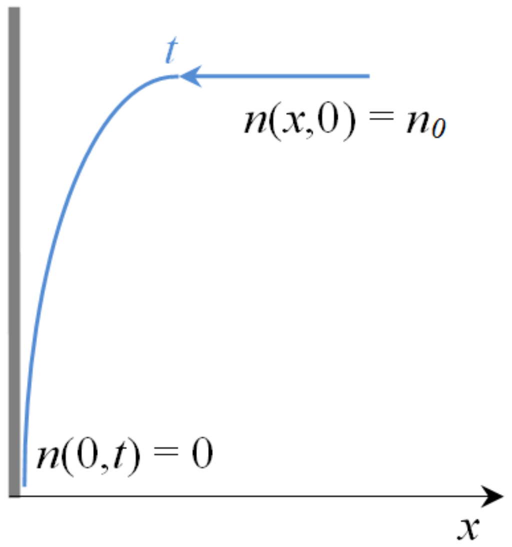




Dynamics: deposition

Deposition by diffusion

- Unlike gas molecules aerosol particles (especially small ones) **stick to surfaces** when they collide with them
- **Surfaces are sinks** for the particles and that the particle concentration at the surface is zero.
- So close to a surface the particle concentration will have a gradient that causes a continuous diffusion flux of particles onto the surface



Particle diameter, d_p (µm)	Deposition by diffusion (part. m^{-2})	Deposizione by gravitational settling (part. m^{-2})	Diffusion/gravitational settling ratio
0.001	2.6×10^{4}	0.68	3.4×10^{4}
0.01	2.6×10^{3}	6.9	380
0.1	300	88	3.4
1.0	59	3500	0.017
10	17	3.1×10^{5}	5.5×10^{-5}
100	5.5	2.5×10^{7}	2.2×10^{-7}

Dynamics: deposition

Deposition in ducts, transport losses

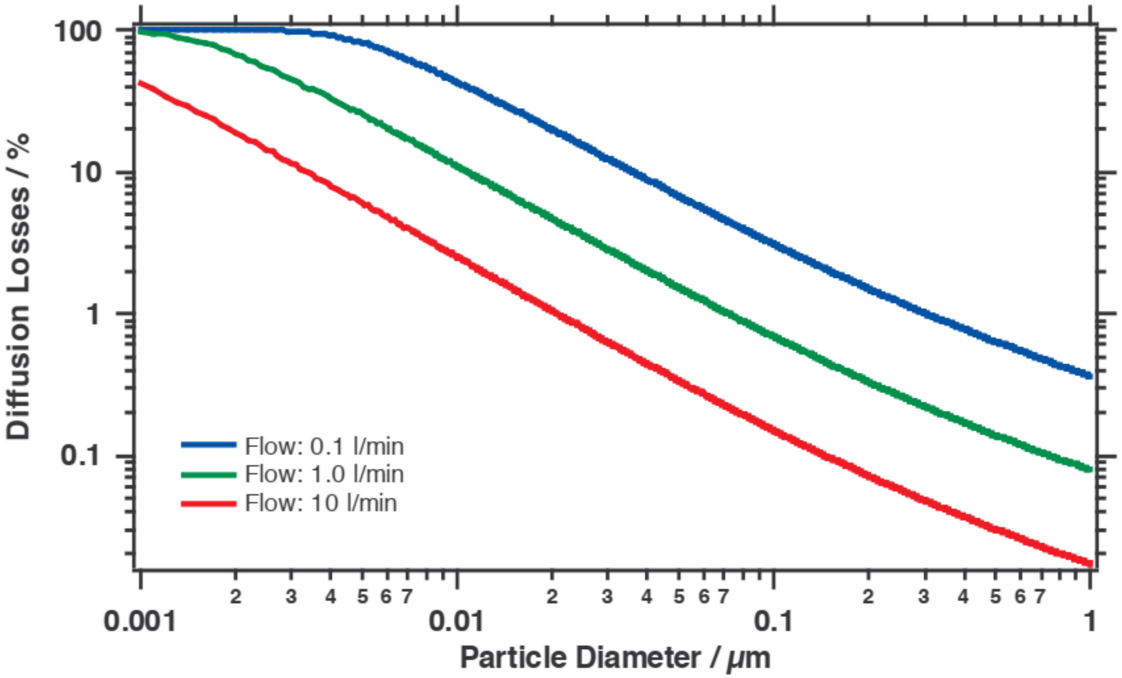
Penetration of particle in a ducts...

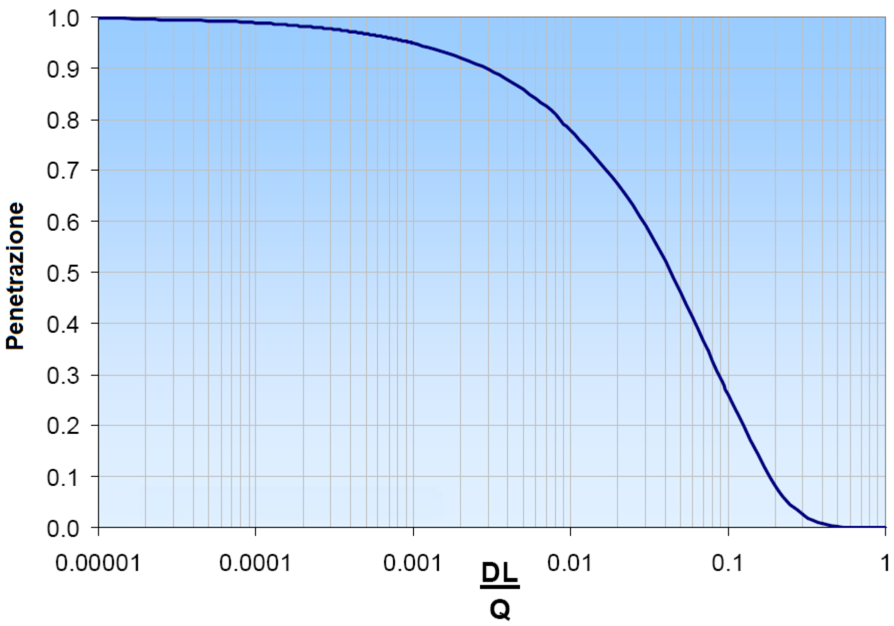
$$P = \frac{n_{out}}{n_{in}} \qquad \mu = \frac{4\,D\,L}{\pi\, d_t^3\, u_\infty} = \frac{D\,L}{Q}$$

$$P = 1 - 5.50\mu^{2/3} + 3.77\mu \qquad \text{per } \mu < 0.009$$

$$P = 0.819\exp(-11.5\mu) + 0.0975\exp(-70.1\mu) \qquad \text{per } \mu \geq 0.009$$

L lenght of the tube
u_∞ average velocity
Q flow rate

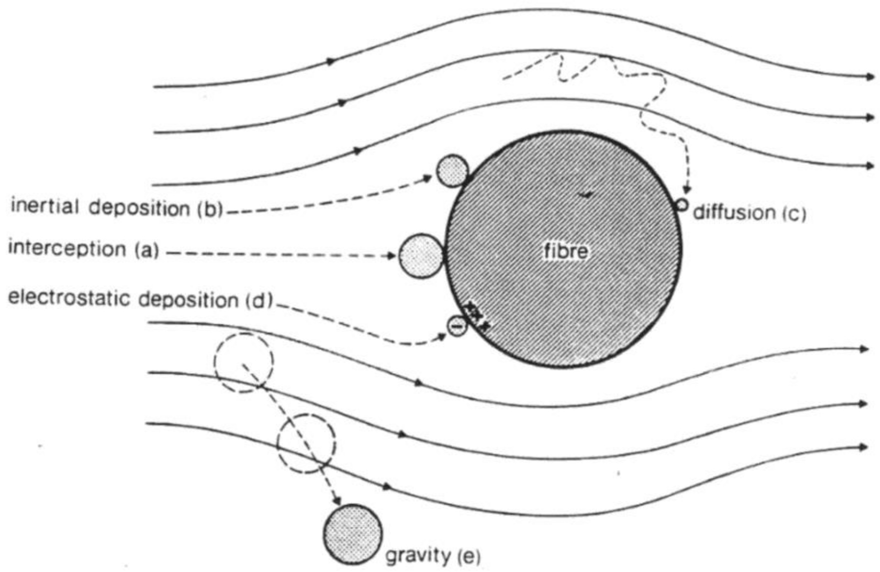


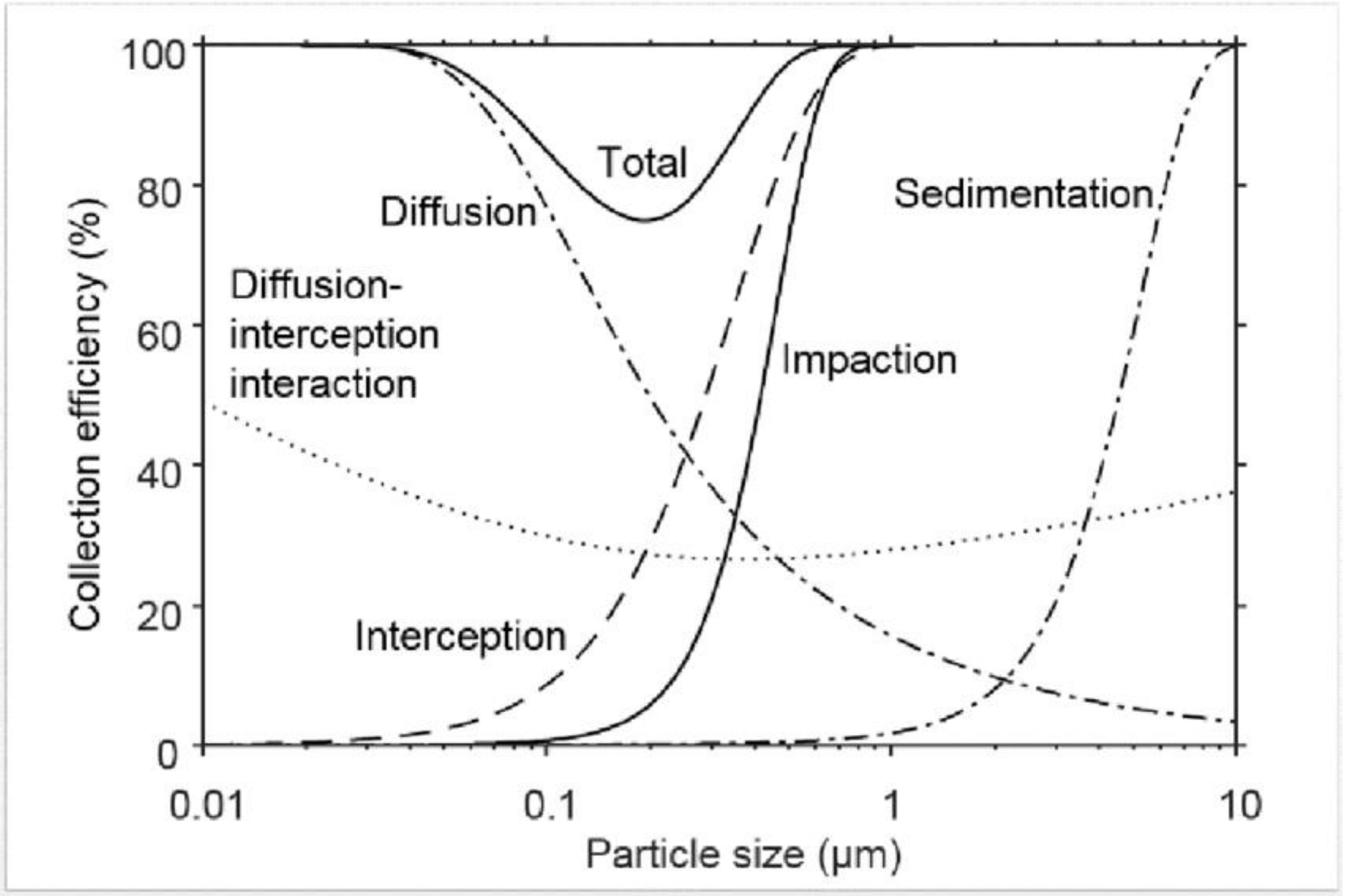


Dynamics: deposition

Particle removal and deposition:

- impaction (inertia)
- diffusion
- gravitational settling
- electrostatic forces
- thermophoresis
- interception





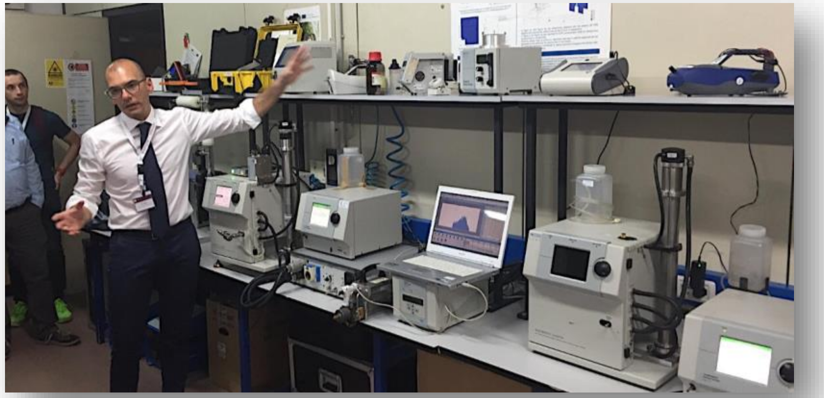
Particle measurements

Laboratory at UNICAS

- **PM samplings/measurements**
  - Gravimetric samplers & heads (PM_{10}, $PM_{2.5}$, PM_1)
  - 1 Nanoparticle Aerosol Sampler TSI 3089
- **Particle number concentration/distribution measurements**
  - 2 Scanning mobility particle sizer (SMPS) TSI 3936
  - 1 Aerodynamic Particle Sizer Spectrometer (APS) TSI 3321
  - 2 CPC TSI 3775 (buthanol) + 1 CPC TSI 3750
  - 1 Fast Mobility Particle sizer (FMPS) TSI 3091
  - 1 Nanoparticle Surface Aerosol Monitor TSI 3550
  - 1 Thermodiluter for submicrometer particles
  - 1 Diluter for APS
- **Generation/calibration**
  - 1 monodisperse aerosol generation system (TSI 3940)
  - 1 Aerosol electrometer TSI 3068B
  - 1 Super-micron aerosol disperser Palas
- **Portable instruments**
  - 4 Philips Nanotracer/Testo Discmini
  - 1 CPC TSI 3007
  - 1 Nanoscan SMPS TSI 3910
  - 1 Optical Particle Sizer 3330
  - 1 DustTrak photometer 8534
  - 1 Aethalometer AE51 BC monitor







Gravimetric measurement

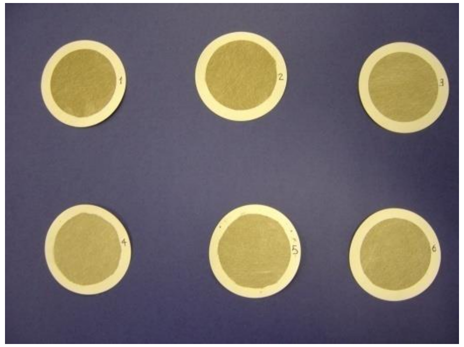
Measurement principle

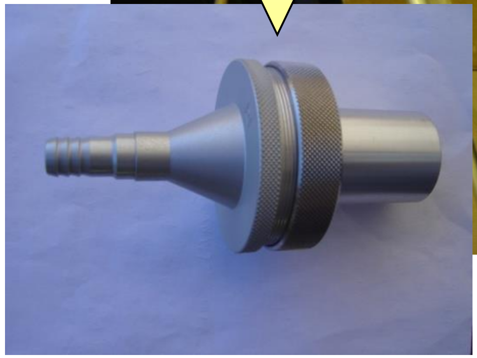
- Particulate matter is determined through **air filtration** resulting in the collection of particulate matter suspended in the air.
- The final concentration of particulate matter is obtained by determining the change in mass of the filter **divided by the volume** of normalized aspirated gas (0 °C and 101325 Pa).

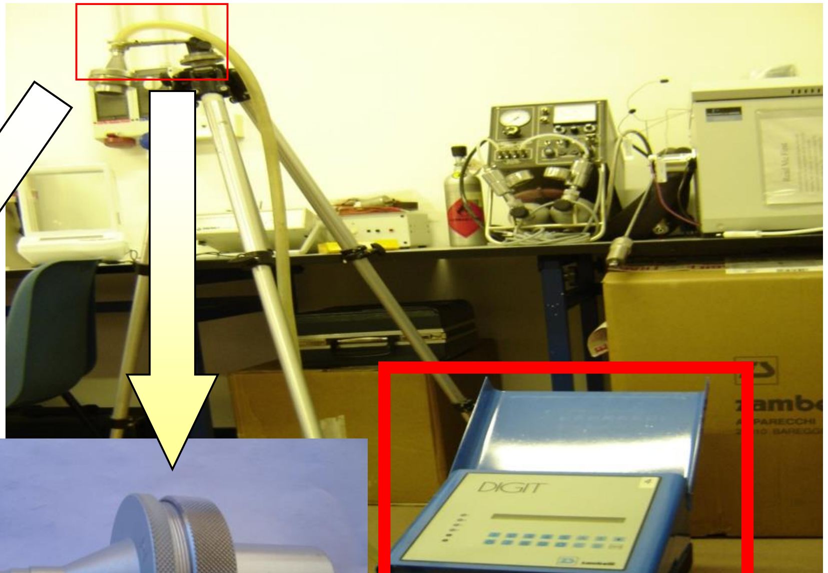
$$C = \frac{\Delta m}{V} = \frac{m_f - m_i}{V}$$

Experimental apparatus

- Analytical scale
- Constant flow volumetric sampler
- Filter holder
- Cellulose filter
- Connecting pipes



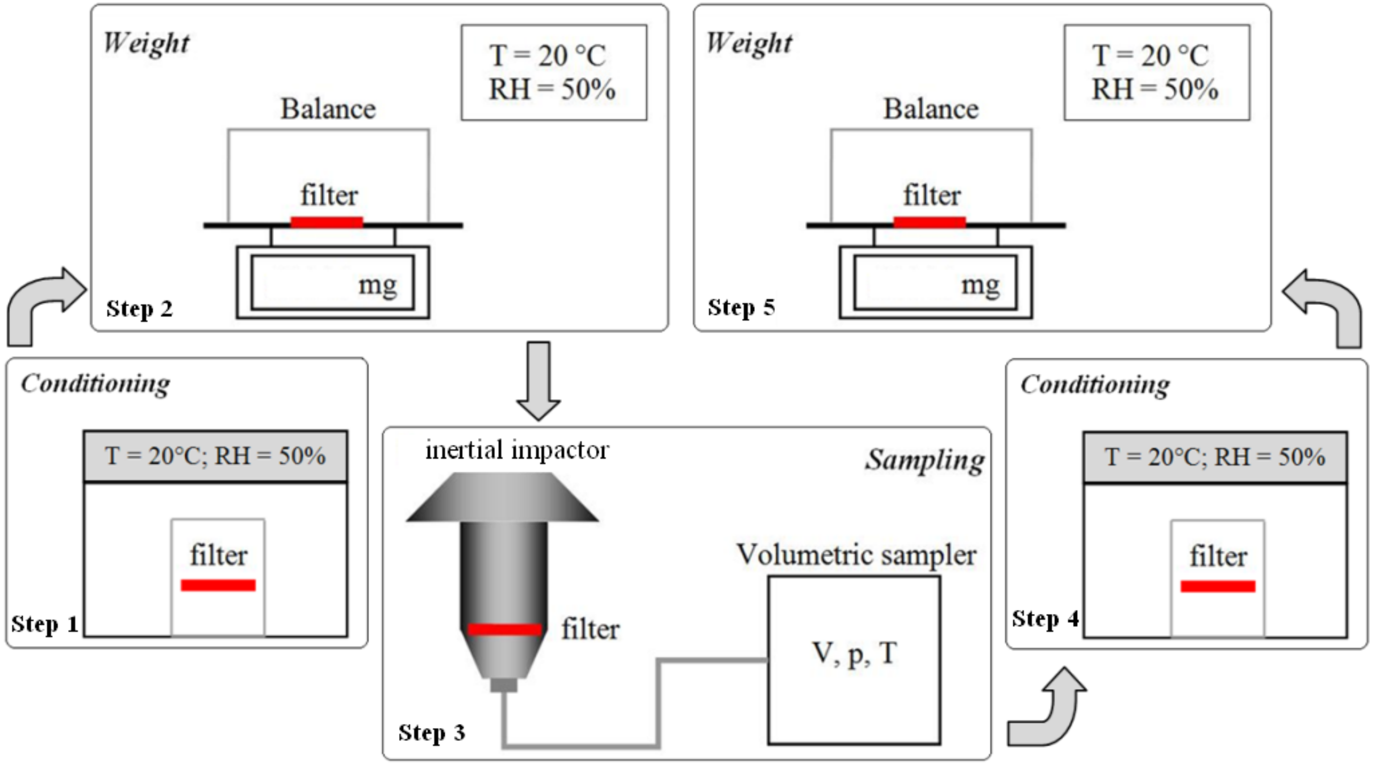


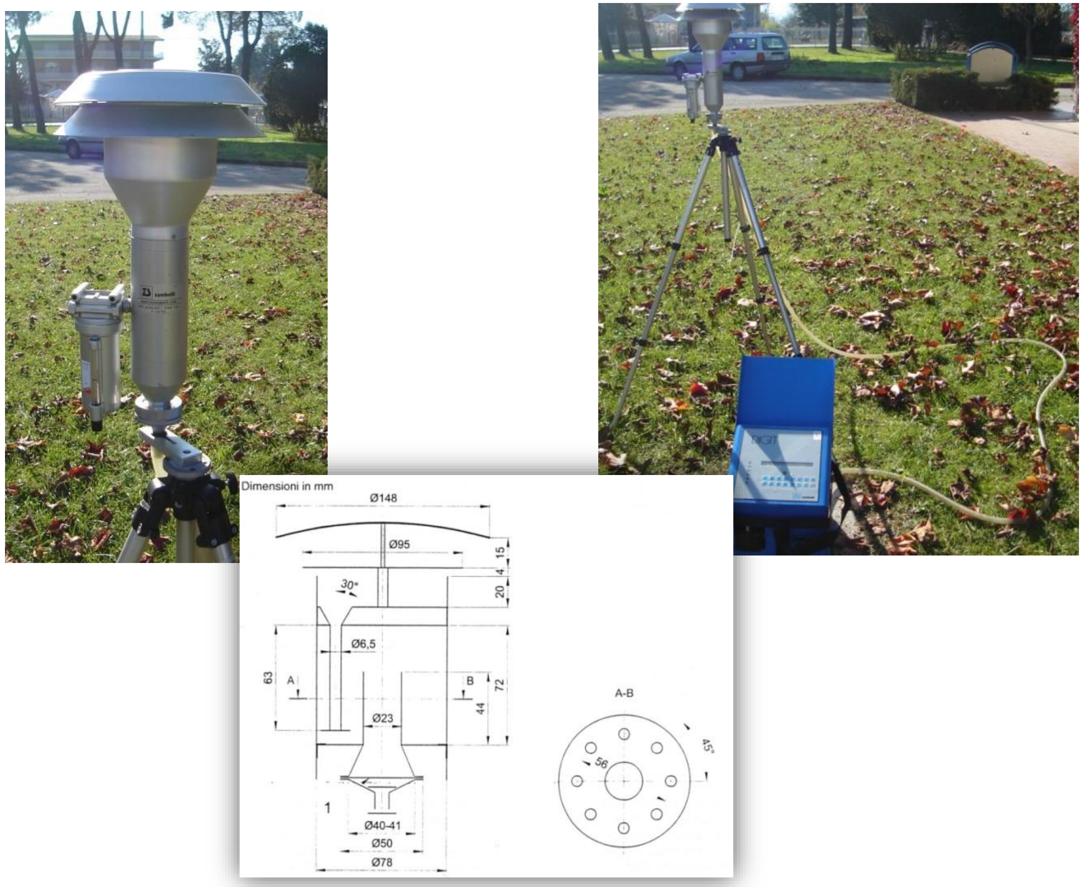


Gravimetric measurement

Outdoor PM measurement

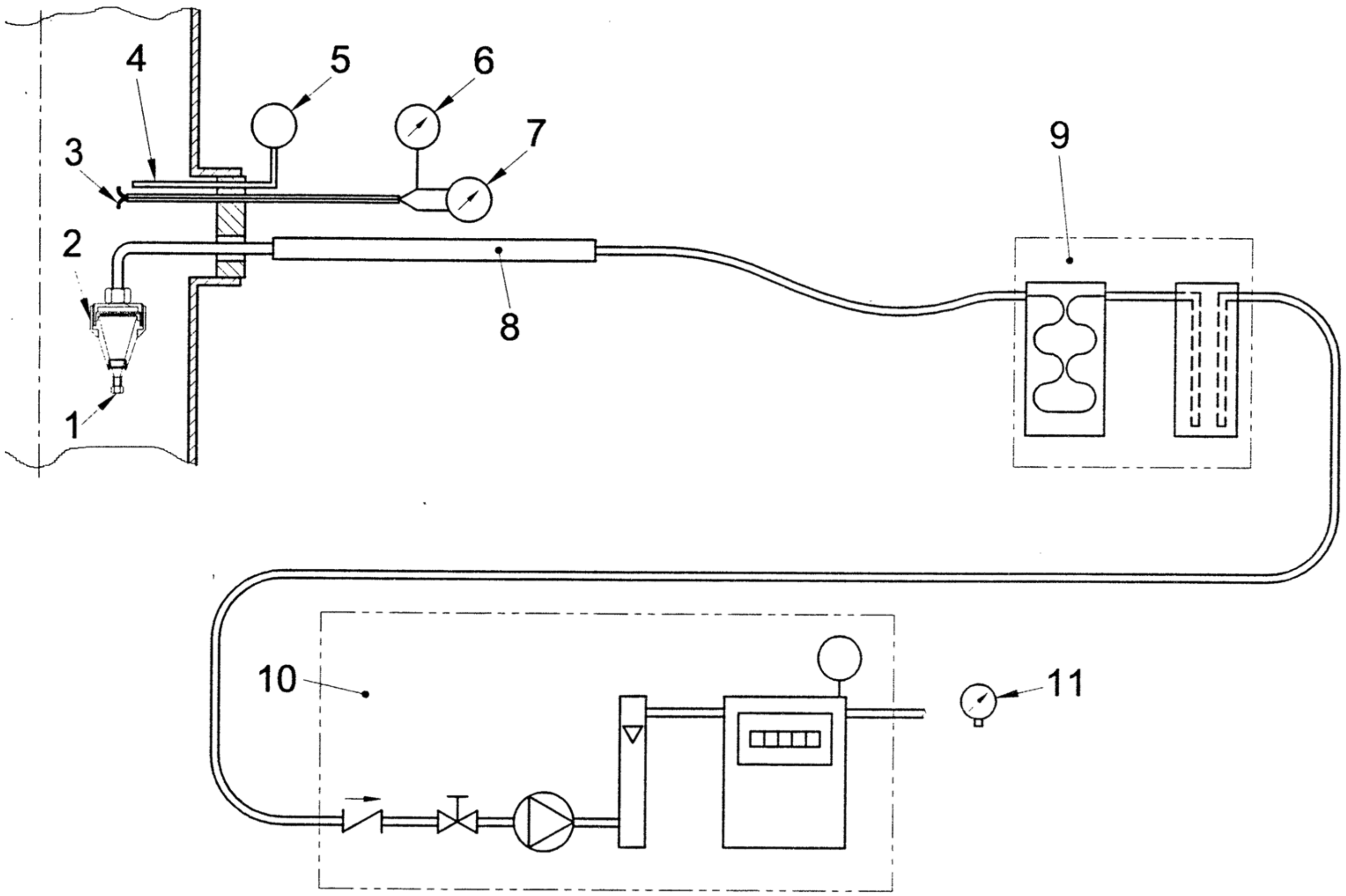
Sampling head (PM_1, $PM_{2.5}$ o PM_{10}) allows a "selection" by inertial impact.





Gravimetric measurement

Measurement at the stack of plants



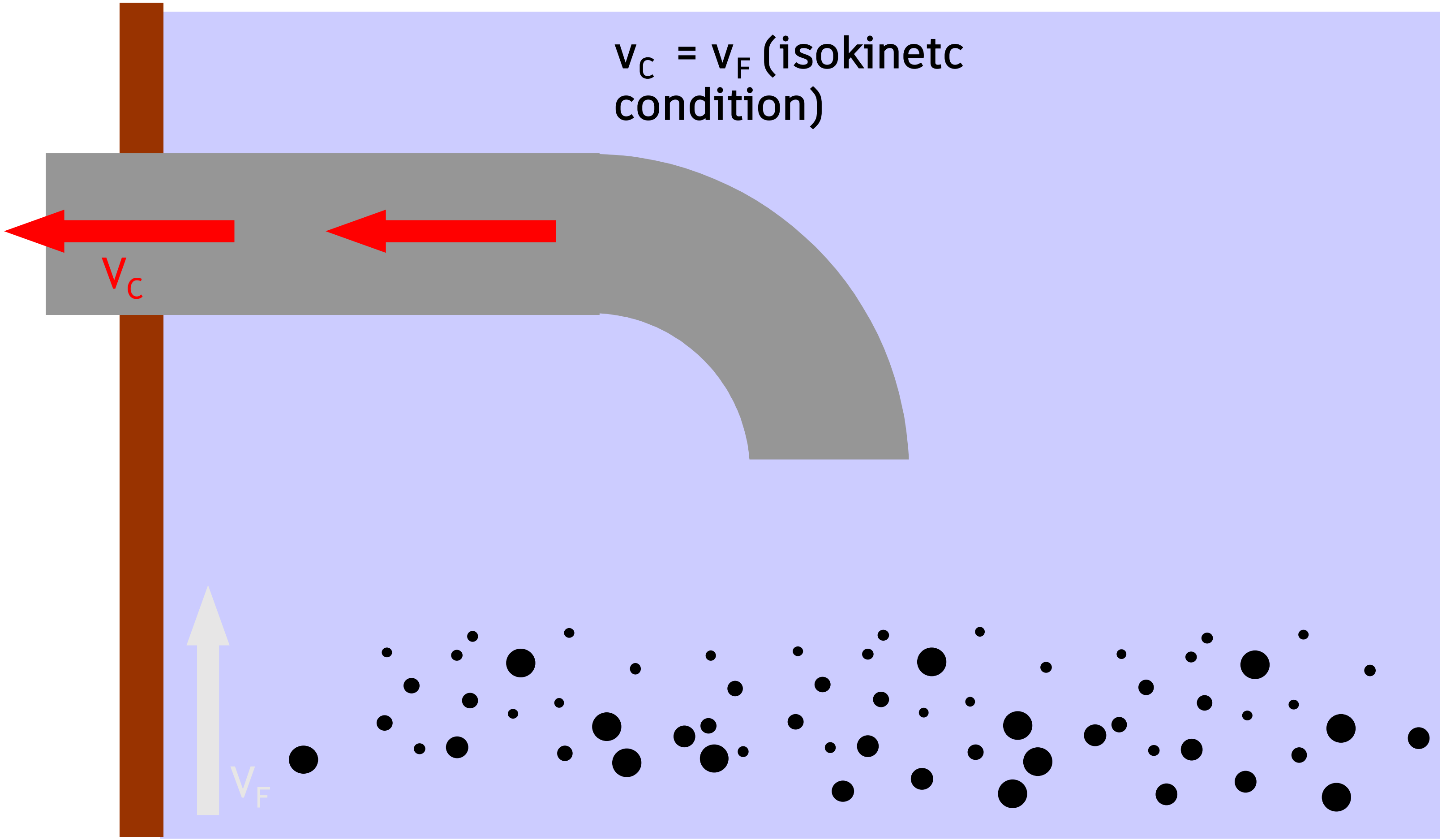
1. Inlet nozzle
2. Filter holder
3. Pitot tube
4. Temperature sensor
5. Temperature indicator
6. Static pressure measurement
7. Dynamic pressure measurement
8. Support
9. Cooling and gas collection system
10. Suction unit and gas measuring device
11. Manometer

Gravimetric measurement

Measurement at the stack of plants

Metrological issue: the **isokinetic sampling**

v_C = sampling velocity
v_F = exhaust velocity



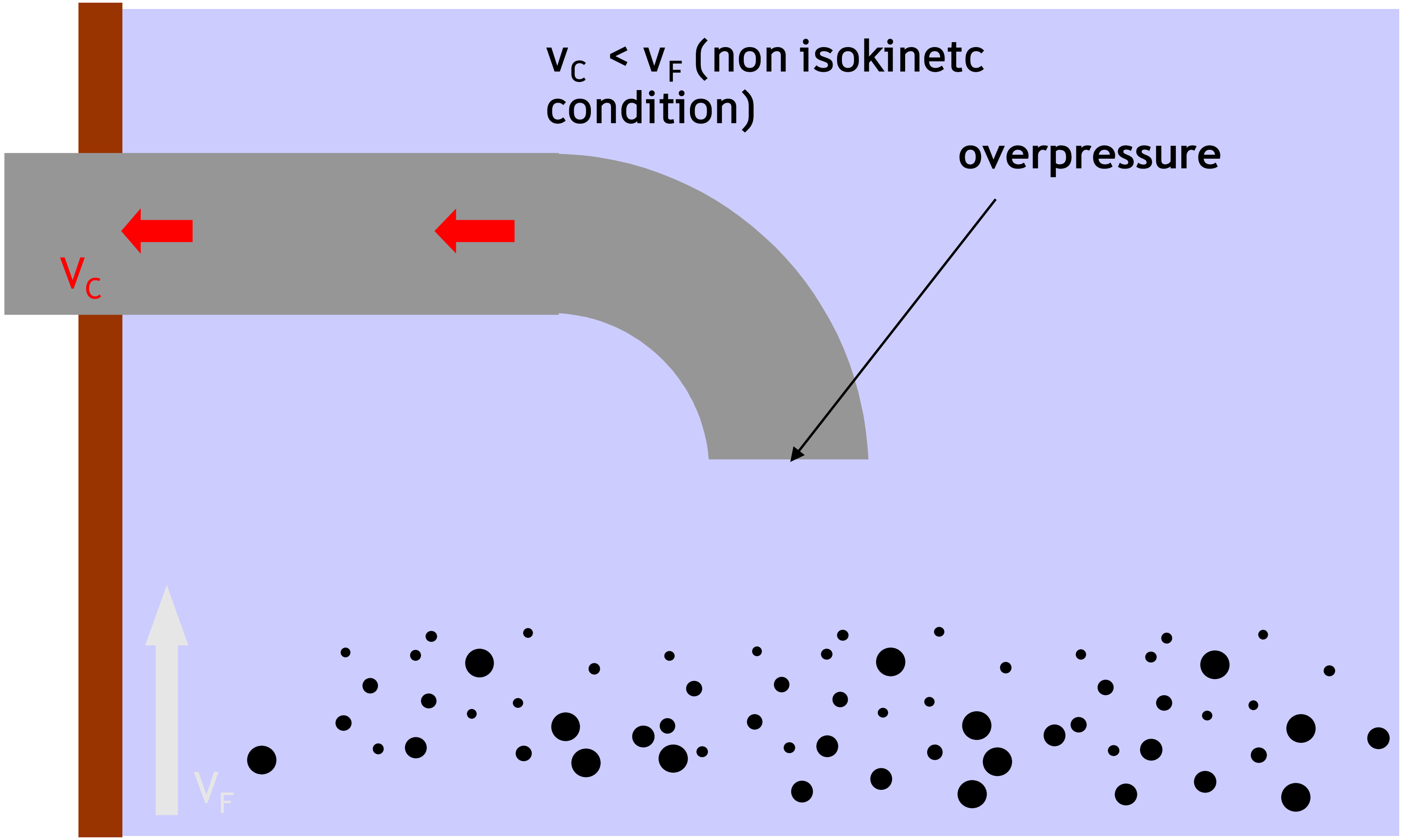
Luca Stabile (*l.stabile@unicas.it*)

Gravimetric measurement

Measurement at the stack of plants

Metrological issue: the **isokinetic sampling**

v_C = sampling velocity
v_F = exhaust velocity

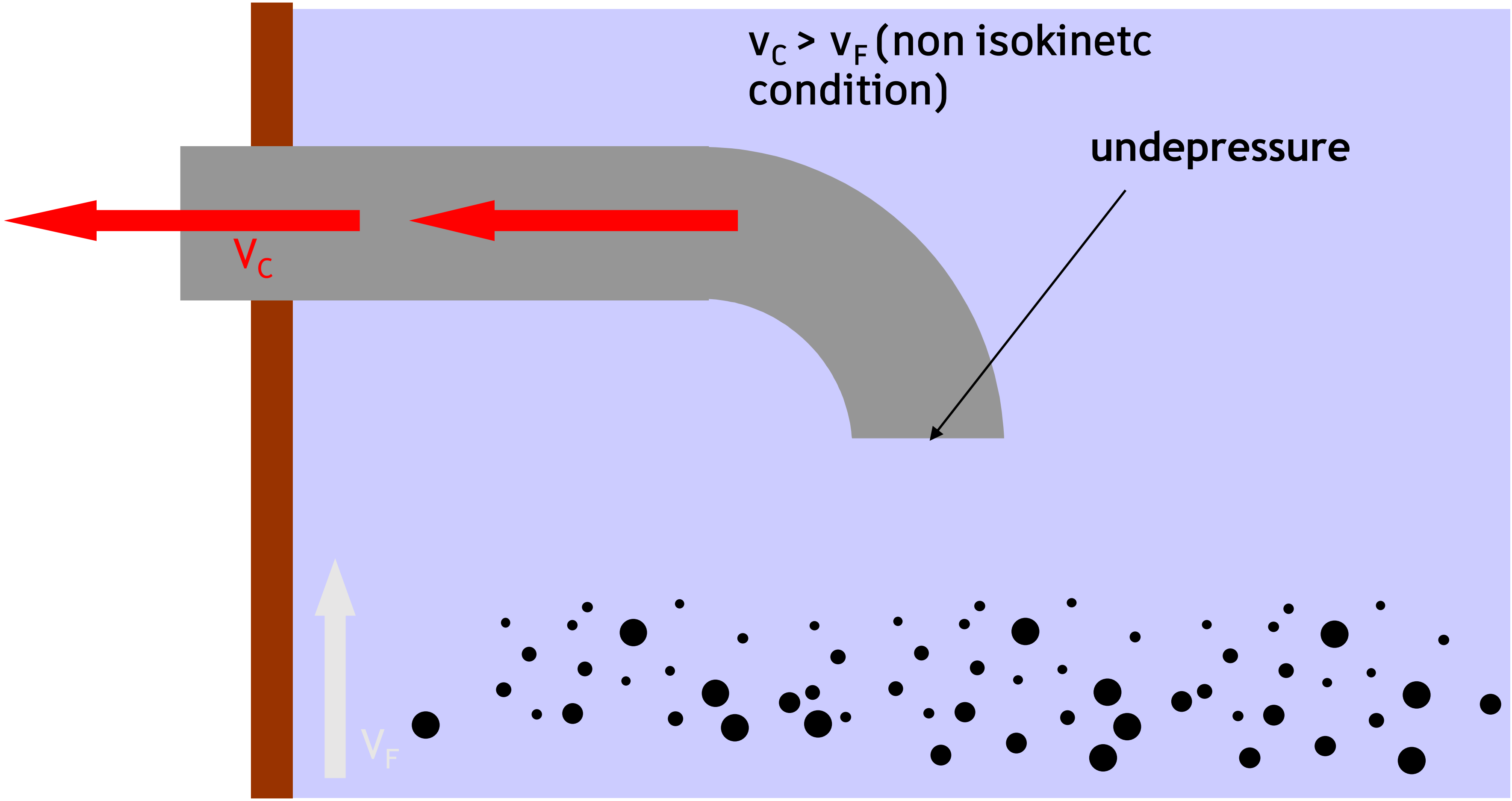


Gravimetric measurement

Measurement at the stack of plants

Metrological issue: the **isokinetic sampling**

v_C = sampling velocity
v_F = exhaust velocity



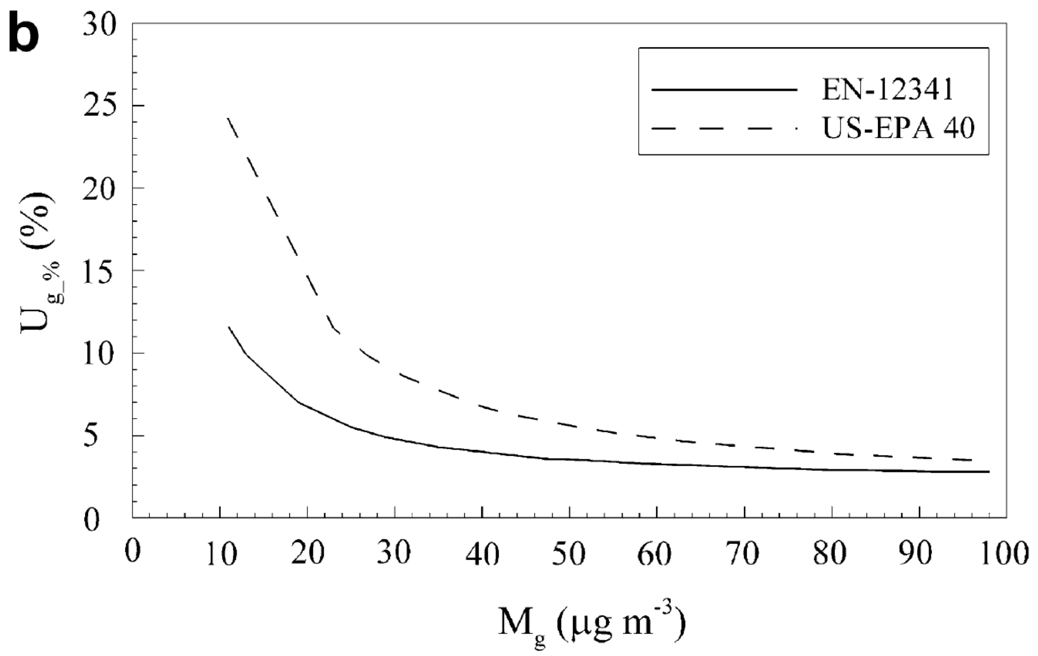
Gravimetric measurement

Uncertainty budget

- weighing procedure and wrong filter conditioning can generate high PM uncertainties!
- European standards guarantee lower uncertainties than US-EPA (flow rate effect!)

Uncertainty budget for $PM_{2.5}$ concentration in San Vittore del Lazio (Italy), May 28th, 2008.

Source of uncertainty	Value	Unit	Distribution	*k*	Standard uncertainty	Sensitivity coefficient	Absolute uncertainty contribution
Sampling	5.0	µg	Rectangular	$\sqrt{3}$	2.9	2.0E−02	5.8E−02
Mass							
1. Initial mass filter contribution					27.0	2.0E−02	5.4E−01
a. Conditioning	40.0	µg	Rectangular	$\sqrt{3}$	23.1		
b. Balance calibration and drift	4.09	µg	Normal	2	0.8		
c. Filter repeatability	13.9	µg	Normal	1	13.9		
2. Final mass filter contribution					23.9	2.0E−02	4.8E−01
a. Conditioning	40.0	µg	Rectangular	$\sqrt{3}$	23.1		
b. Balance calibration and drift	4.09	µg	Normal	2	0.8		
c. Filter repeatability	6.0	µg	Normal	1	6.0		
Volume							
a. Flow meter calibration and drift	5%		Normal	2	1.4	3.6E−01	5.1E−01
b. Pressure sensor	1%		Normal	2	509	2.0E−04	1.0E−01
c. Temperature sensor	1.0	°C	Normal	2	0.5	6.4E−02	3.2E−02
Combined uncertainty		$\mu g\ m^{-3}$					8.9E−01
Statistical cover factor *K*							2
Expanded uncertainty (U_g)		$\mu g\ m^{-3}$					1.79
PM concentration (M_g)		$\mu g\ m^{-3}$					20.3
Relative expanded uncertainty ($U_{g\_\%}$)							8.8%



Measuring ultrafine particles

Gravimetric method for UFPs?

- Reference method for PM (not for PN).
- representative only of the fraction of particles that have a significant contribution in terms of mass.

Particle counting

- The industrial need to individually select and count extremely small particles has made possible the development of optical detection techniques and the refinement of particle size classification methodologies
- The Aitken dust counters utilized heterogeneous nucleation to grow particles in order to be detected by the human eye
- The Aitken dust counters revolutionized aerosol science by allowing measurement of concentrations of particles over a broad size range!

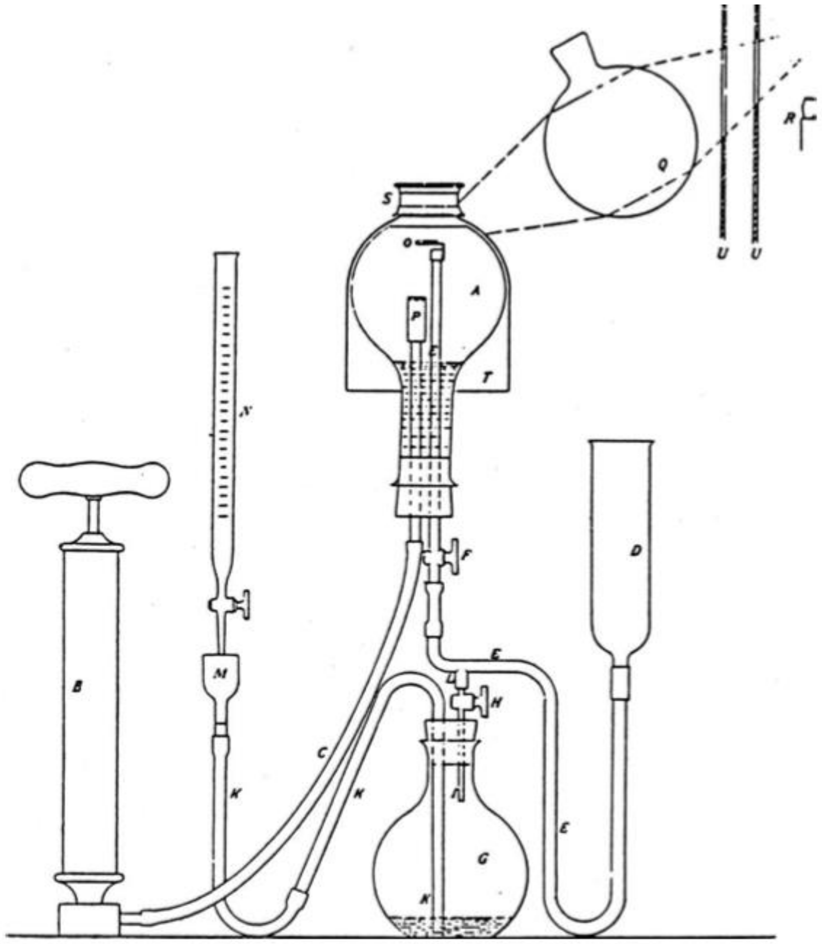


FIG. 1. Aitken's laboratory dust counter (1888): 500 cm^3 expansion flask (A) with a stage (O) for sedimented droplet counting with the aid of a magnifying glass (S). Sampling flask (G) and pump of 150-cm^3 capacity for saturated air expansion (B).

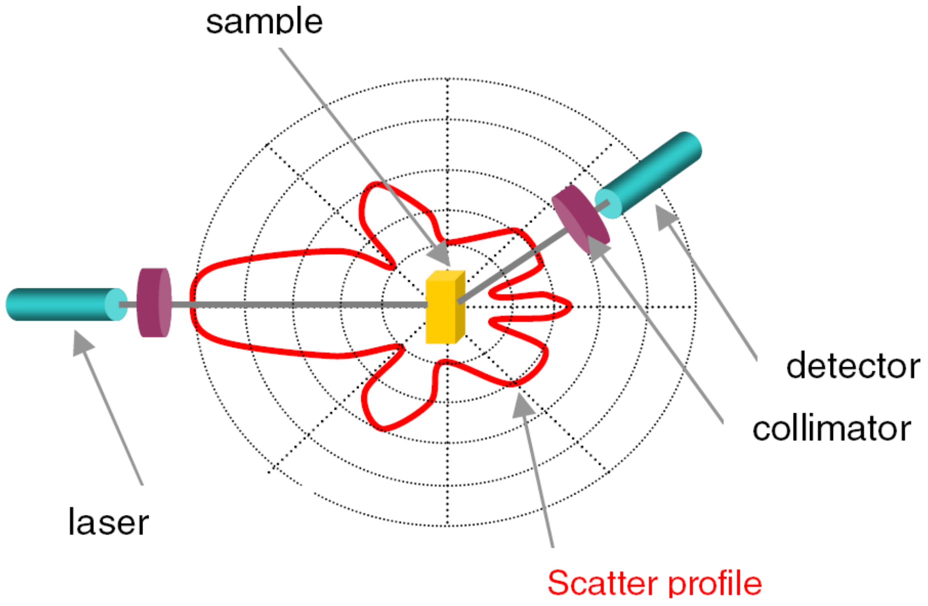
Measuring ultrafine particles

Particle counting or…?

Direct optical sizing techniques for ultrafine particles is problematic due to:

- weak optical diffraction signal of light characteristic of objects of dimensions much smaller than the wavelength of the light itself,
- non-direct proportionality of the optical properties to a particular property of the particle over the entire dimensional range of interest.

Moreover, classification techniques exploiting inertial and gravimetric methods can only be used at pressures much lower than atmospheric ones.



Thus…ultrafine particles need to be counted and classified by electrical techniques!

Measuring ultrafine particles

CPC 3775 (TSI Inc.) -

Condensation techn

An aer
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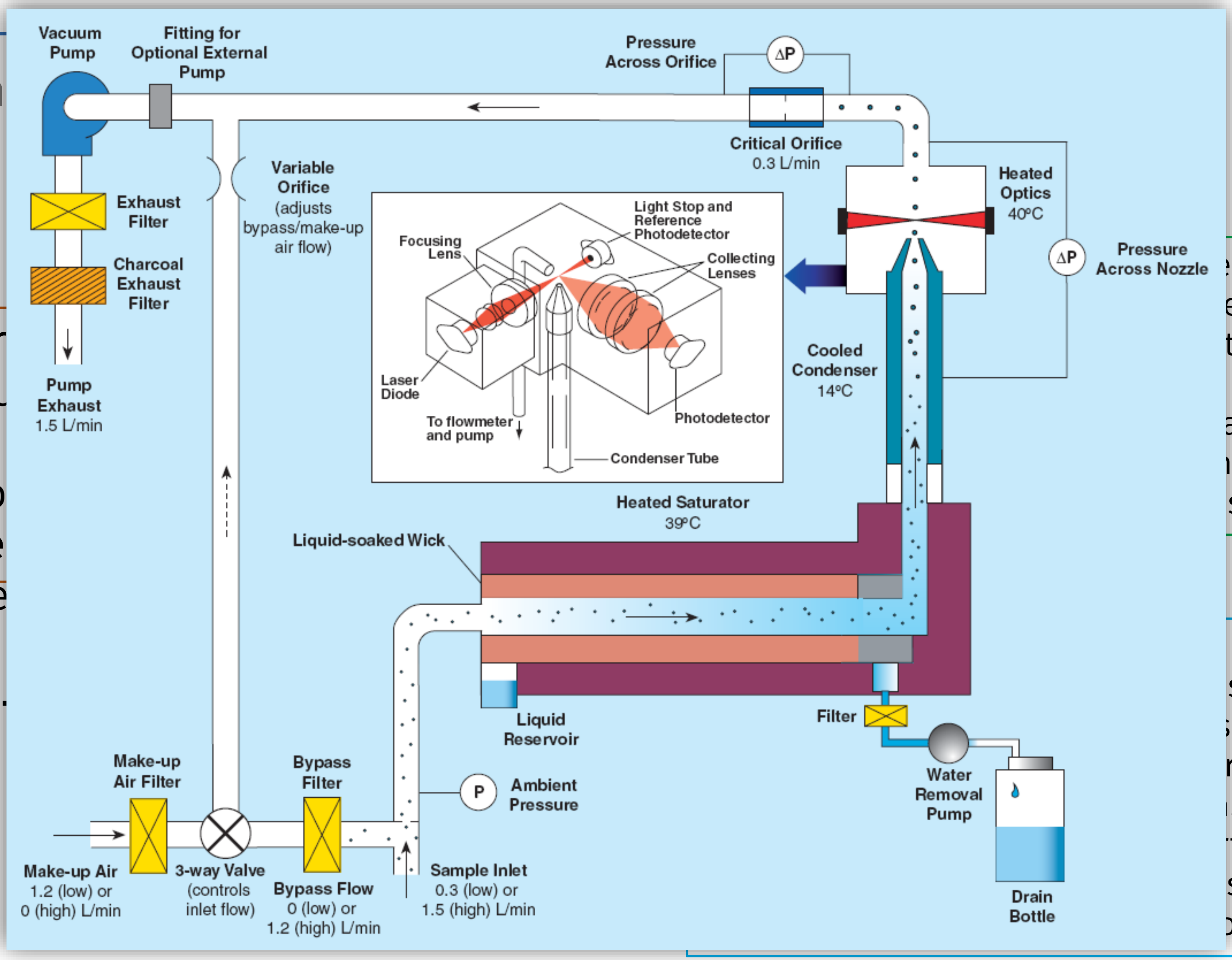
Aerosol sample



el 3775 CPC uses a
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light from particles.
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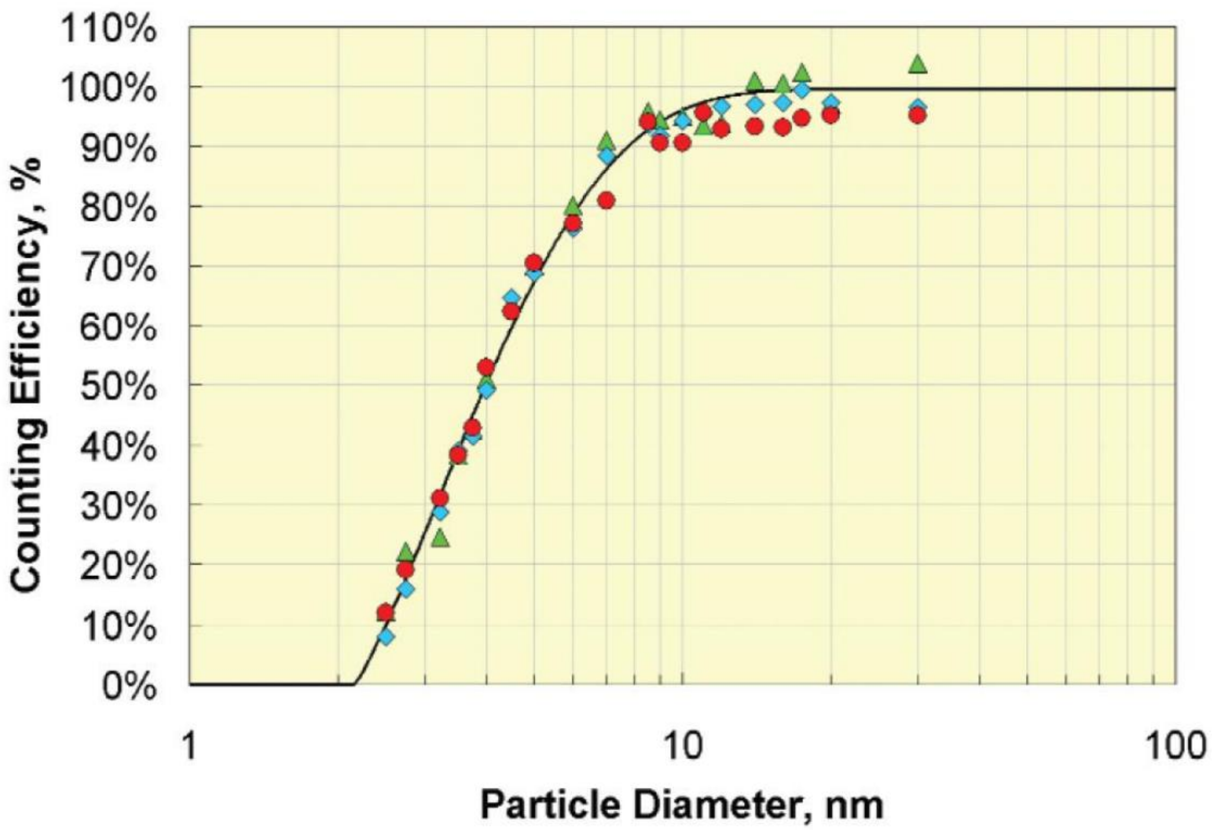
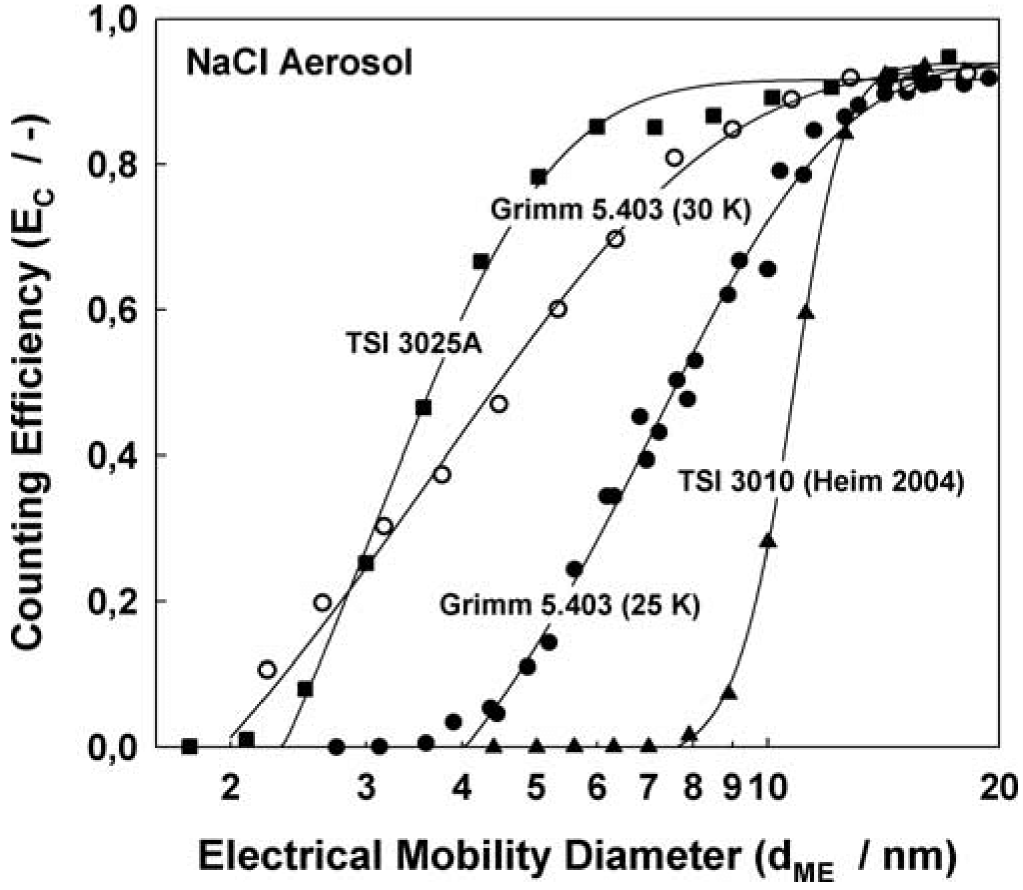
Measuring ultrafine particles

CPC 3775 (TSI Inc.) – Condensation Particle Counter

Counting efficiency

Cut-off diameter (Kelvin effect)





Measuring ultrafine particles

Scanning Mobility Particle Sizer - SMPS 3936 TSI

Classification and counting

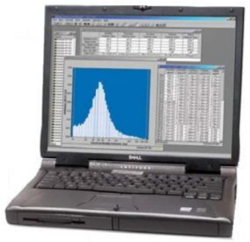
Measurement range: 0.01 – 1 µm

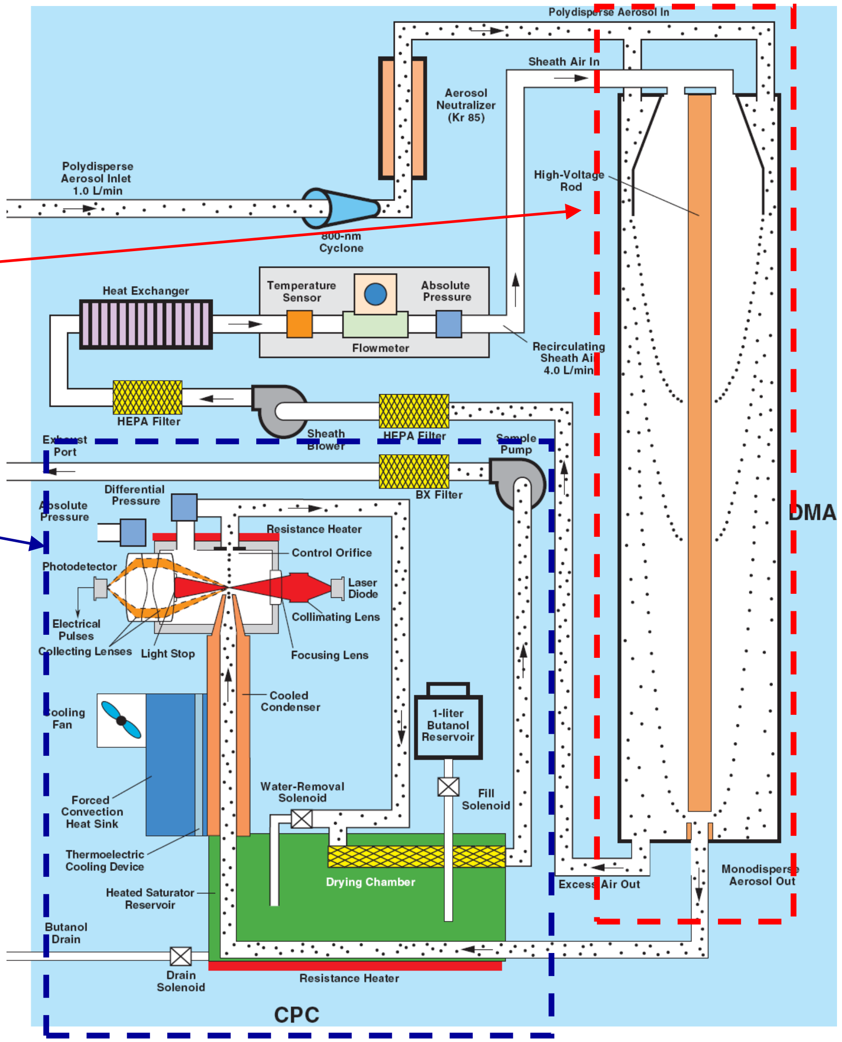
How it works

SMPS spectrometer uses electrical-mobility particle size classification (Electrostatic Classifier), combined with a Condensation Particle Counter (CPC).

Electrostatic Classifier
EC *3080 TSI*

Condensation Particle Counter
CPC *3775 TSI*





Measuring ultrafine particles

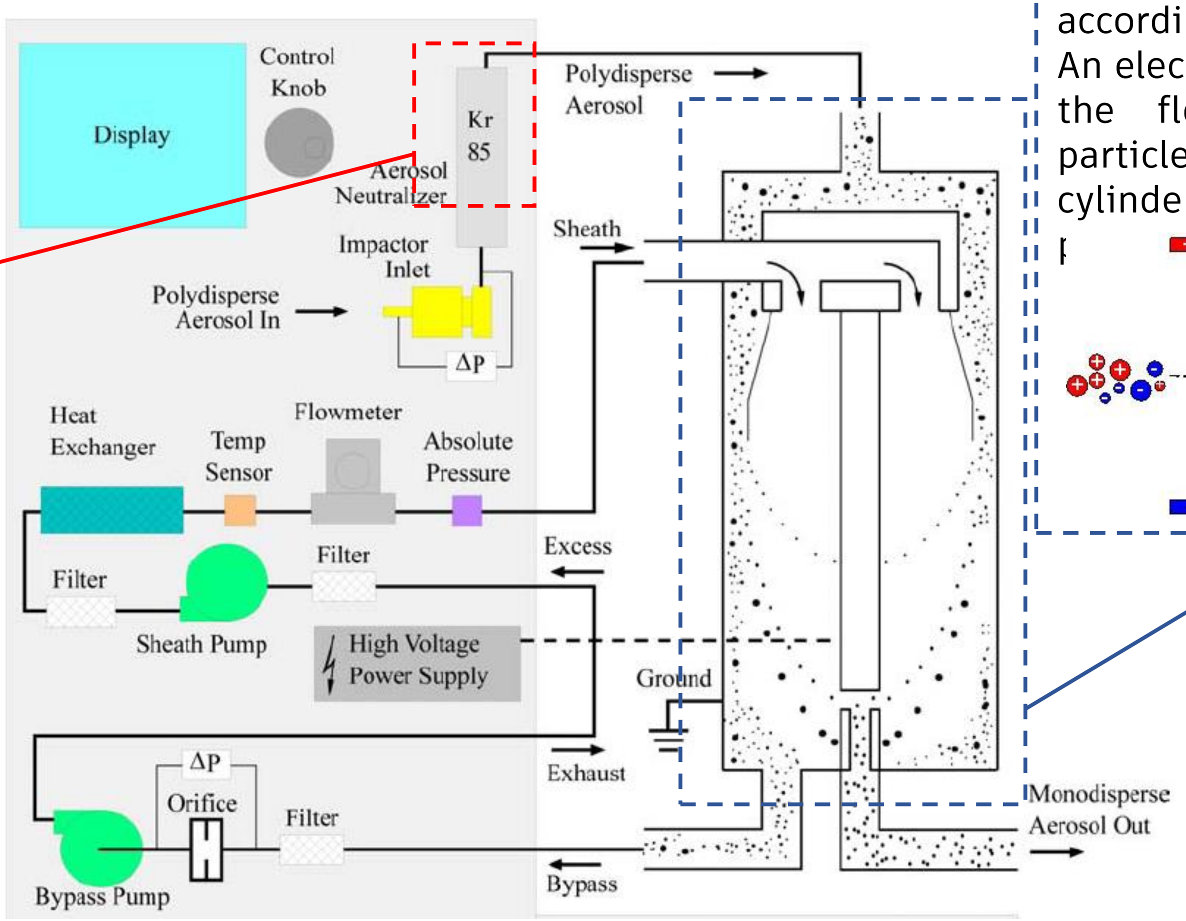
Electrostatic classifier

Classification according to particle electrical mobility

Aerosol Neutralizer 3077(TSI Inc.)

Polydisperse, sub micrometer aerosol passes through a radioactive bipolar charger, establishing a bipolar equilibrium charge level on the particles

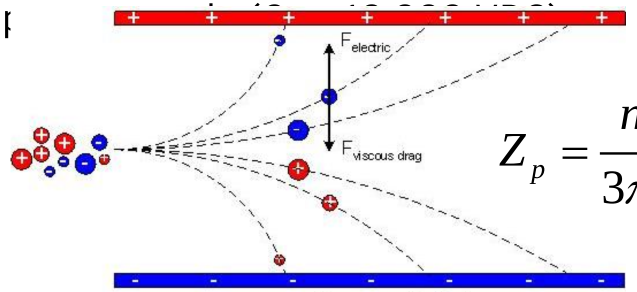
$$f(N)=\frac{e}{\sqrt{4\pi^2\varepsilon_0 D_p kT}}\exp\frac{-\left[N-\frac{2\pi\varepsilon_0 D_p kT}{e^2}\ln\left(\frac{Z_{i+}}{Z_{i-}}\right)\right]^2}{2\frac{2\pi\varepsilon_0 D_p kT}{e^2}}$$



DMA 3081 (TSI Inc.)

The particles then enter the differential mobility analyzer (DMA) and are separated according to their electrical mobility.

An electric field inside the DMA influences the flow trajectory of the charged particles. The DMA contains an inner cylinder that is connected to a negative

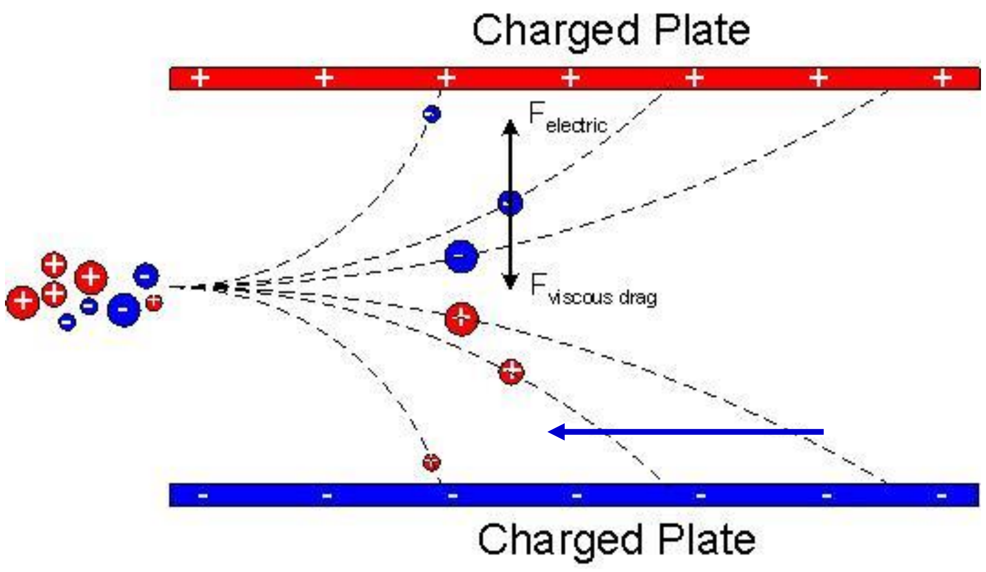


$$Z_p = \frac{n_p e C}{3\pi\mu D_p}$$

Measuring ultrafine particles

Electrostatic classifier

- **Smaller particles**, characterized by high electrical mobility, are attracted more quickly towards the electrode, while,
- **larger particles**, with lower electrical mobility, are influenced more by the forces of the flow field and are therefore able to complete a longer trajectory in the classification region.



$$Z_p = \frac{\text{Particle Velocity}}{\text{Electric Field Strength}} = \frac{v}{E} = \frac{n_p e C}{3\pi\mu D_p}$$

n_p = number of charges/particle
e = elementary unit of charge
μ = viscosity of gas
D_p = particle diameter
C = Cunningham slip correction

Measuring ultrafine particles

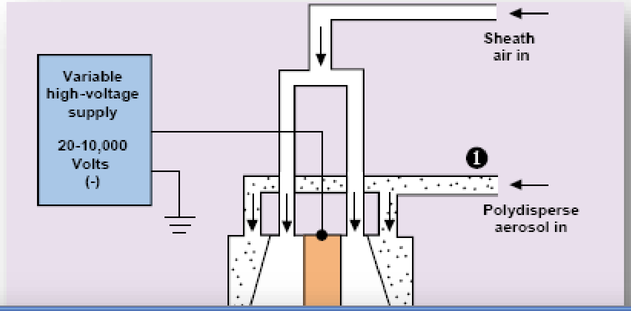
DMA 3081 (TSI Inc.) – Differential mobility analyzer

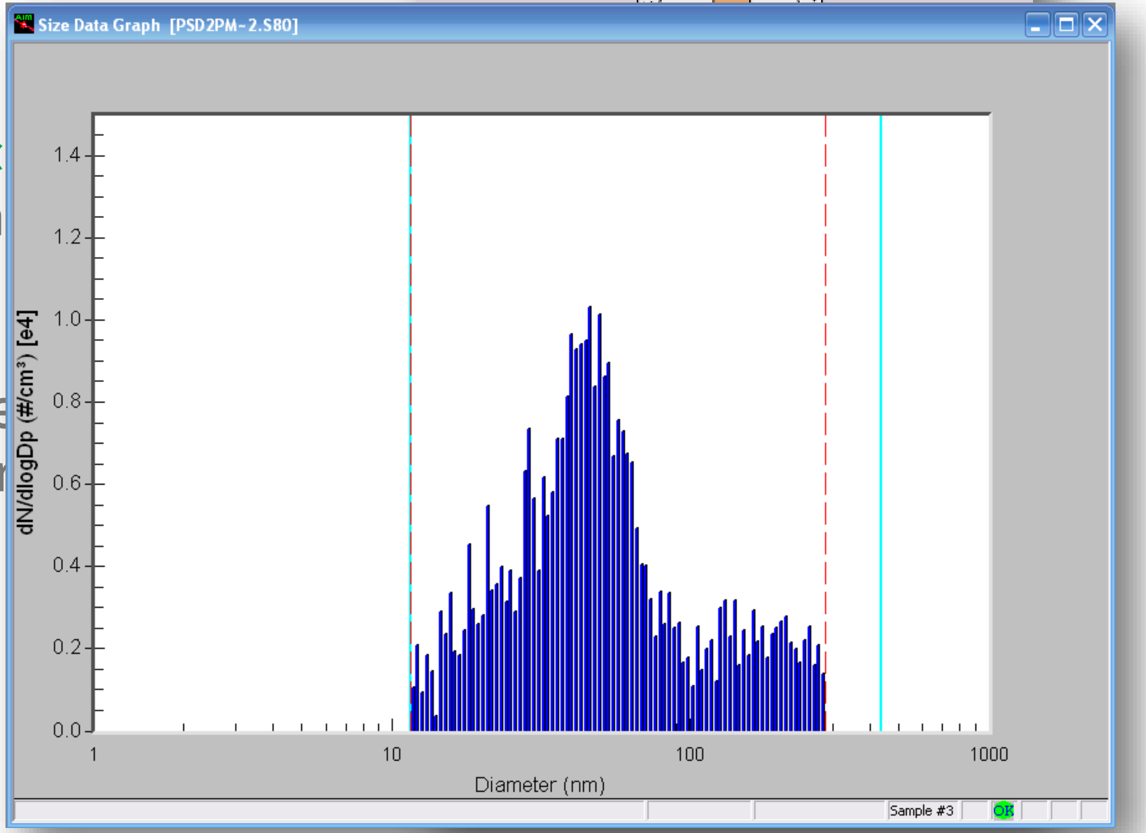
- The classification region is made up of two coaxial steel cylinder-electrodes: the center rod, connected to a power generator capable of providing voltages up to -10 kV

- Varying the center rod voltage varies the elec in the classification region (annular region which the particle moves.

- Only particles within a **narrow range of e** **mobility** have the correct trajectory to pass thr open slit near the DMA exit.

- …automatic scan of the entire size range!

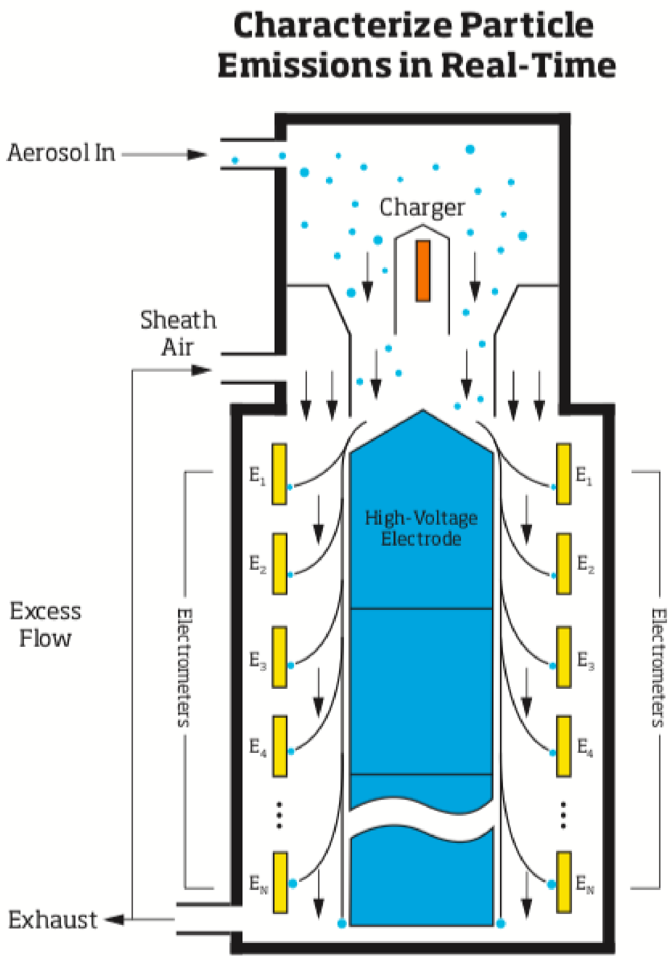


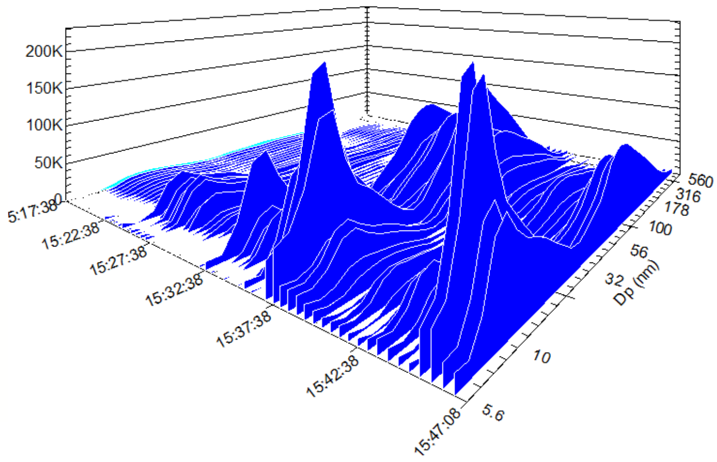


Measuring ultrafine particles

Fast Mobility Particle Sizer

- The FMPS™ spectrometer performs particle size classification based on differential electrical mobility classification (as with the SMPS™).
- The charged aerosol enters the analyzer column near on-axis and above the central rod.
- The particles are deflected radially outward and collected on electrically isolated electrodes that are located at the outer wall.
- The particle number concentration is determined by measurement of the electrical current collected on a series of electrodes.

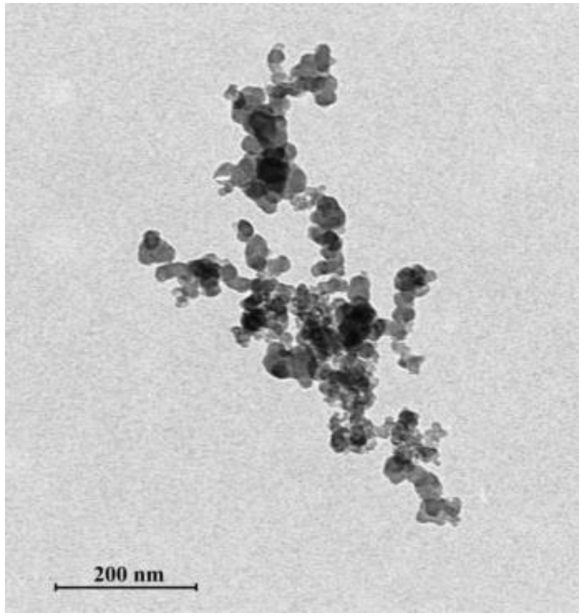




Measuring ultrafine particles

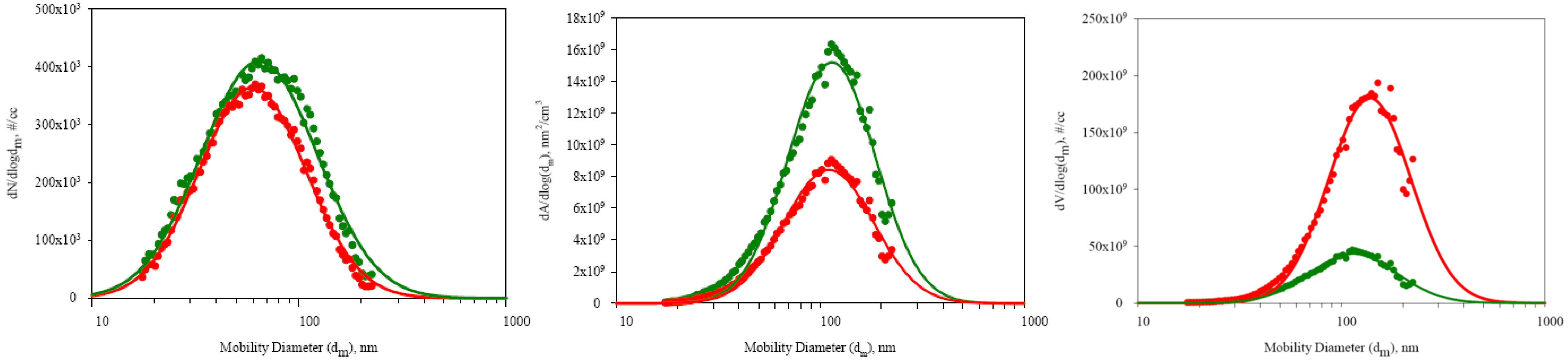
Measurement issues

Aggregates



Morphological analysis

- Idealized Aggregate theory (Lall and Friedlander, 2006)
- Fractal dimension < 2
- ag

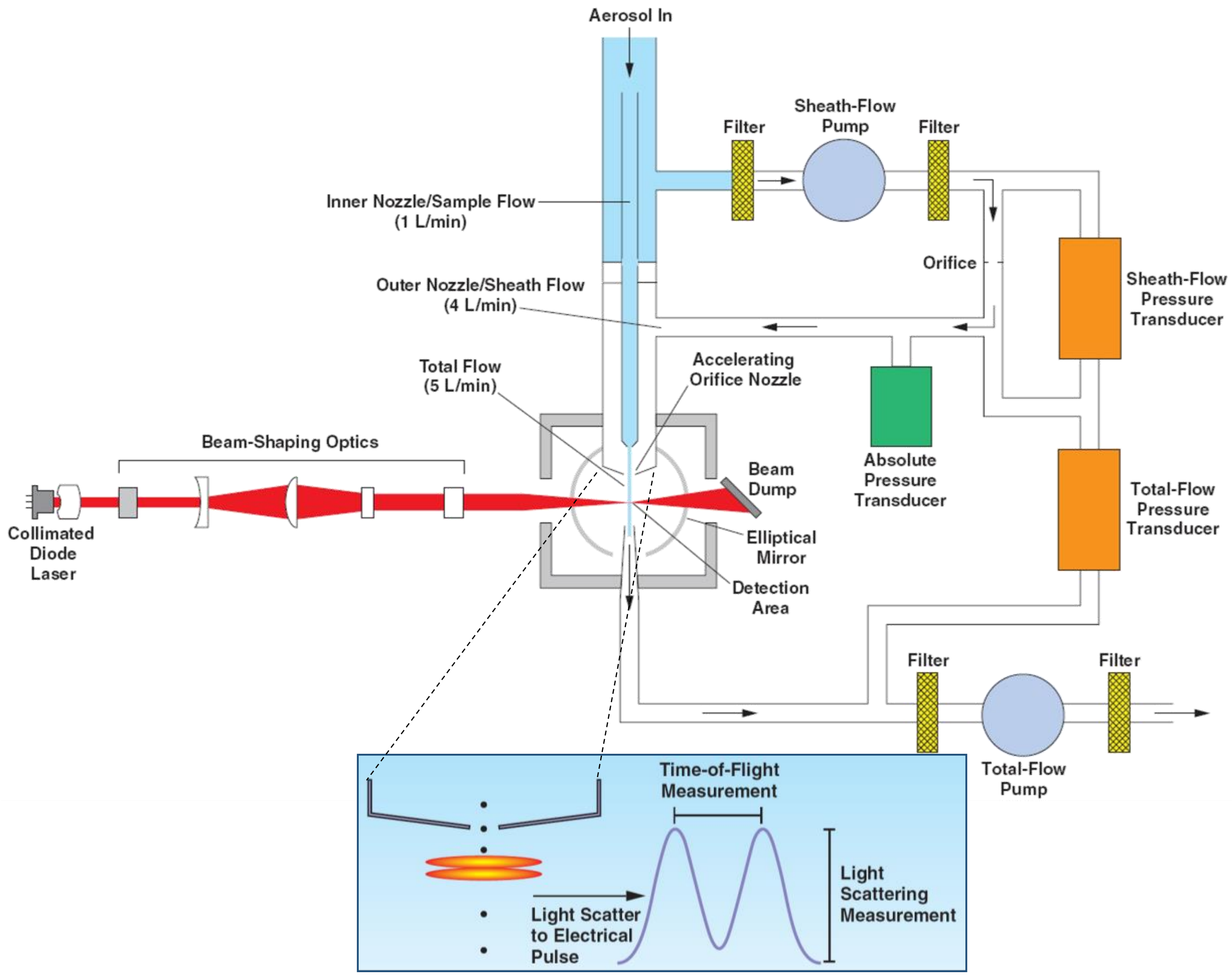


Measuring super-micrometric particles

Aerodynamic Particle Sizer - APS 3321 TSI

Measurement range: 0.5 – 20 µm
sizing and counting technique: *time-of-flight*

- The APS accelerates the aerosol sample flow through an accelerating orifice.
- The aerodynamic size of a particle determines its rate of acceleration, with larger particles accelerating more slowly due to increased inertia.
- As particles exit the nozzle, they cross through two partially overlapping laser beams in the detection area.
- Peak-to-peak time-of-flight is measured with 4 nanosecond resolution for aerodynamic sizing. The amplitude of the signal is logged for light-scattering intensity.



Measuring super-micrometric particles

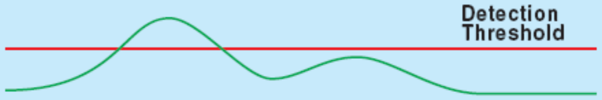
Aerodynamic Particle Sizer - APS 3321 TSI

Time-of-Flight Measurement Results

Every particle signal is processed in real time as one of four distinct events. The Model 3321 logs the occurrence of all events, but only Events 1 and 2 are included in size distribution results. Light-scattering intensity is recorded for Event 2 only.

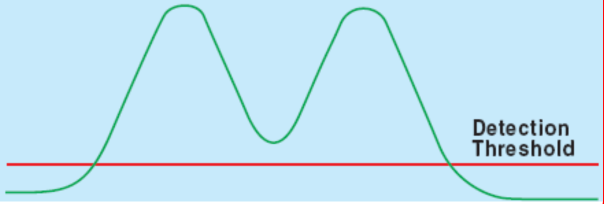
Event 1

This event occurs when the signal for a small particle cannot stay above the threshold and only one crest is detected. The measurement is aborted, and the time-of-flight of the particle is not recorded. However, the event is logged for concentration calculations and displayed in the <0.523-µm size channel in uncorrelated mode.



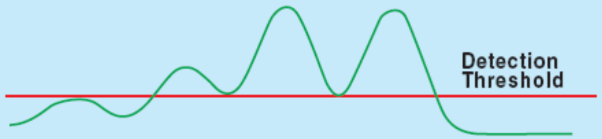
Event 2

This is a valid particle measurement. The signal stays above the threshold and two crests are detected. The time-of-flight between the two crests is recorded and the events are included in the concentration calculations.



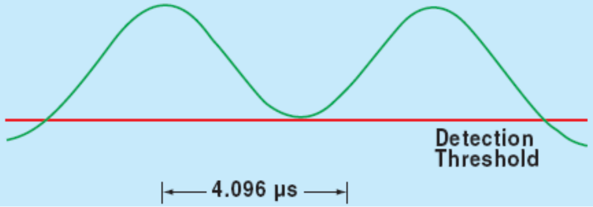
Event 3

This event is caused by coincidence. Although the signal stays above the threshold, three or more crests are detected. Events of this type are logged but not recorded for concentration or time-of-flight.



Event 4

This event is outside the maximum range of the timer. The signal remains above the threshold until it moves outside the timer range, and only one crest is detected. A type 4 event is normally caused by large or recirculating particles. Again, the event is logged, but no time-of-flight is recorded.



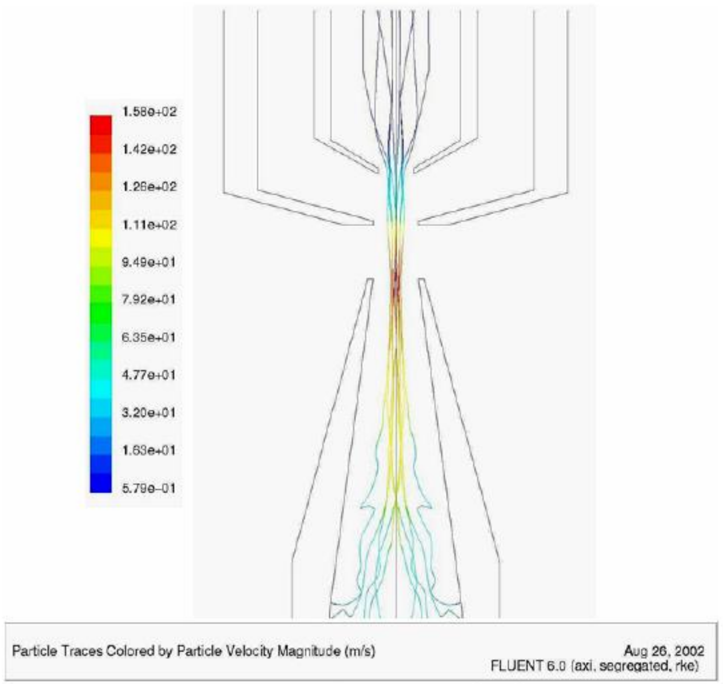
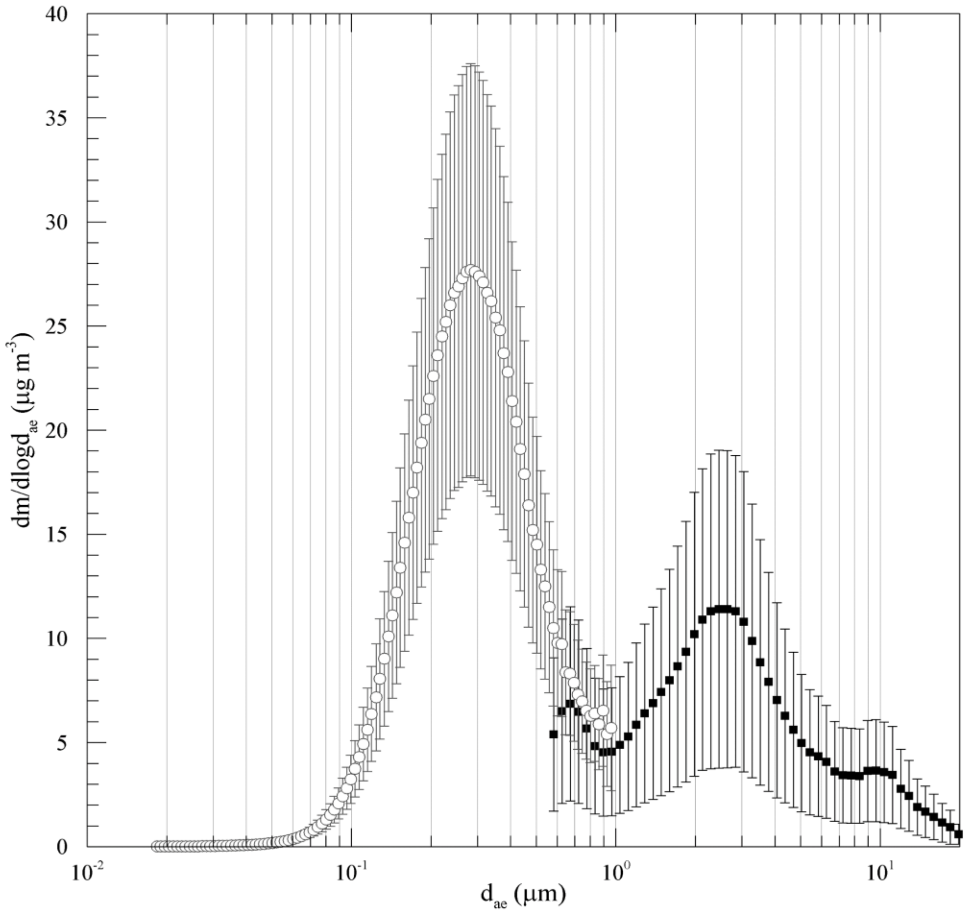


Figure 4: Flow recirculation is restricted in Model 3320 APS with a redesigned eduction nozzle[6] that is identical to the nozzle in Model 3321.

Measuring super-micrometric particles

SMPS-APS to measure PM



SMPS uncertainty contribution in the $PM_{2.5}$ measurement referred to the 5–10 September 2008 period

	Uncertainty value	Distribution	Uncertainty contribution $u_{m-SMPS,i}(x_i)$ (μg m^{-3})
Raw count (c')	$\pm 1/\sqrt{c'_i}$	Poisson	$1.09 \cdot 10^{-1}$
Sampling flow rate* (θ)	$\pm$0.015 L min^{-1}	Normal	$3.94 \cdot 10^{-1}$
Diffusion efficiency correction (η_{diff})	$\pm$10%		$1.26 \cdot 10^{-1}$
CPC efficiency correction (η_{CPC})	$\pm$8%	Rectangular	$1.01 \cdot 10^{-1}$
DMA efficiency correction (η_{DMA})	Included in volumetric diameter uncertainty		
Sampling time* (t)		Negligible	
Particle density* (ρ_p)	$\pm$0.5 g cm^{-3}	Rectangular	2.68
Volumetric diameter (d_{ve})	$\pm$0.95%	Rectangular	$2.46 \cdot 10^{-2}$
Flow ratio (ϕ)		Negligible	
Combined uncertainty (u_{M-SMPS})			2.72
Statistical cover factor k			2
Expanded uncertainty (U_{M-SMPS})			5.43
Total mass concentration (M_{SMPS})			15.8
Relative uncertainty			34.4%

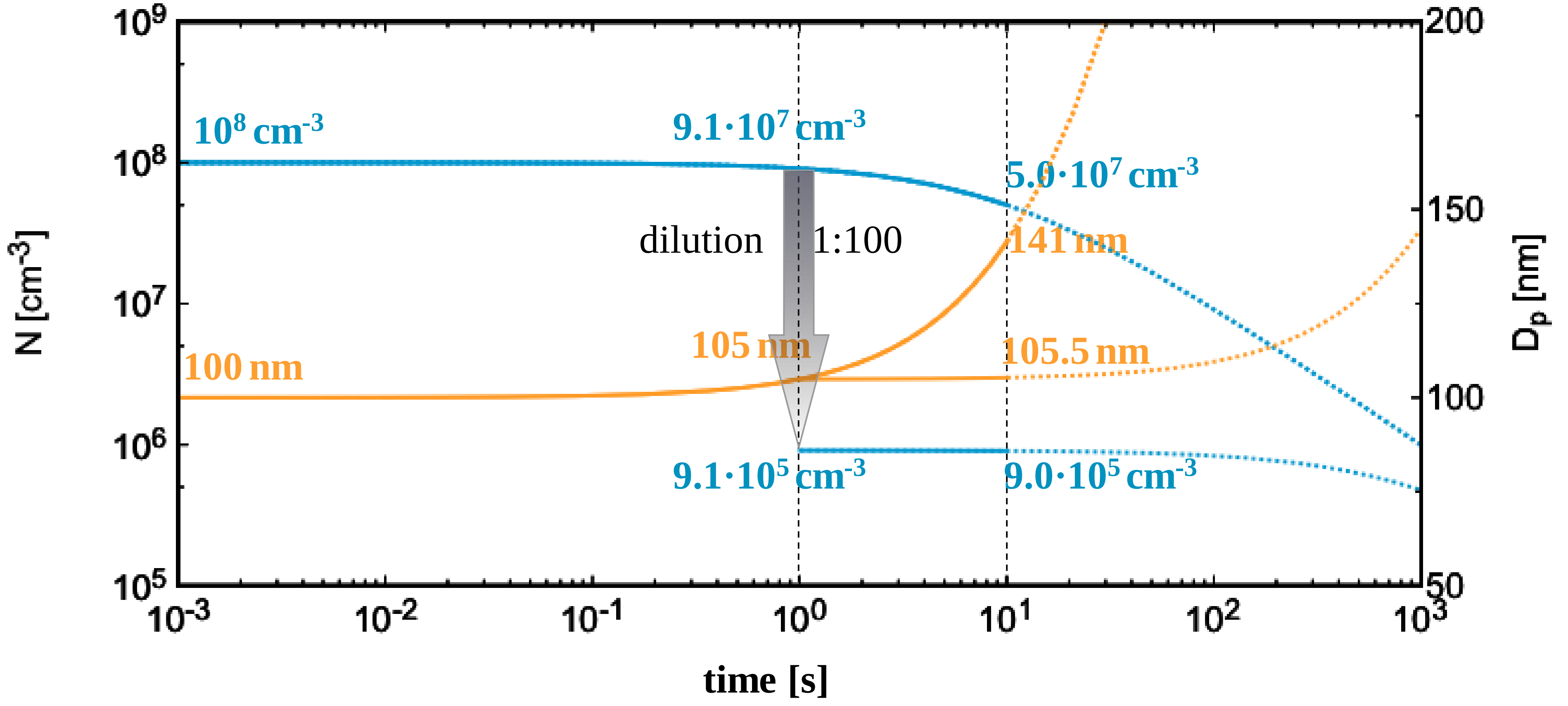
*Fully correlated contributions.

Measurement at the stack

Sampling issues

Measurement artifacts: coagulation, nucleation e condensation!

Thermo-dilution of the sampled aerosol flow



Measurement at the stack

Thermo-dilution system

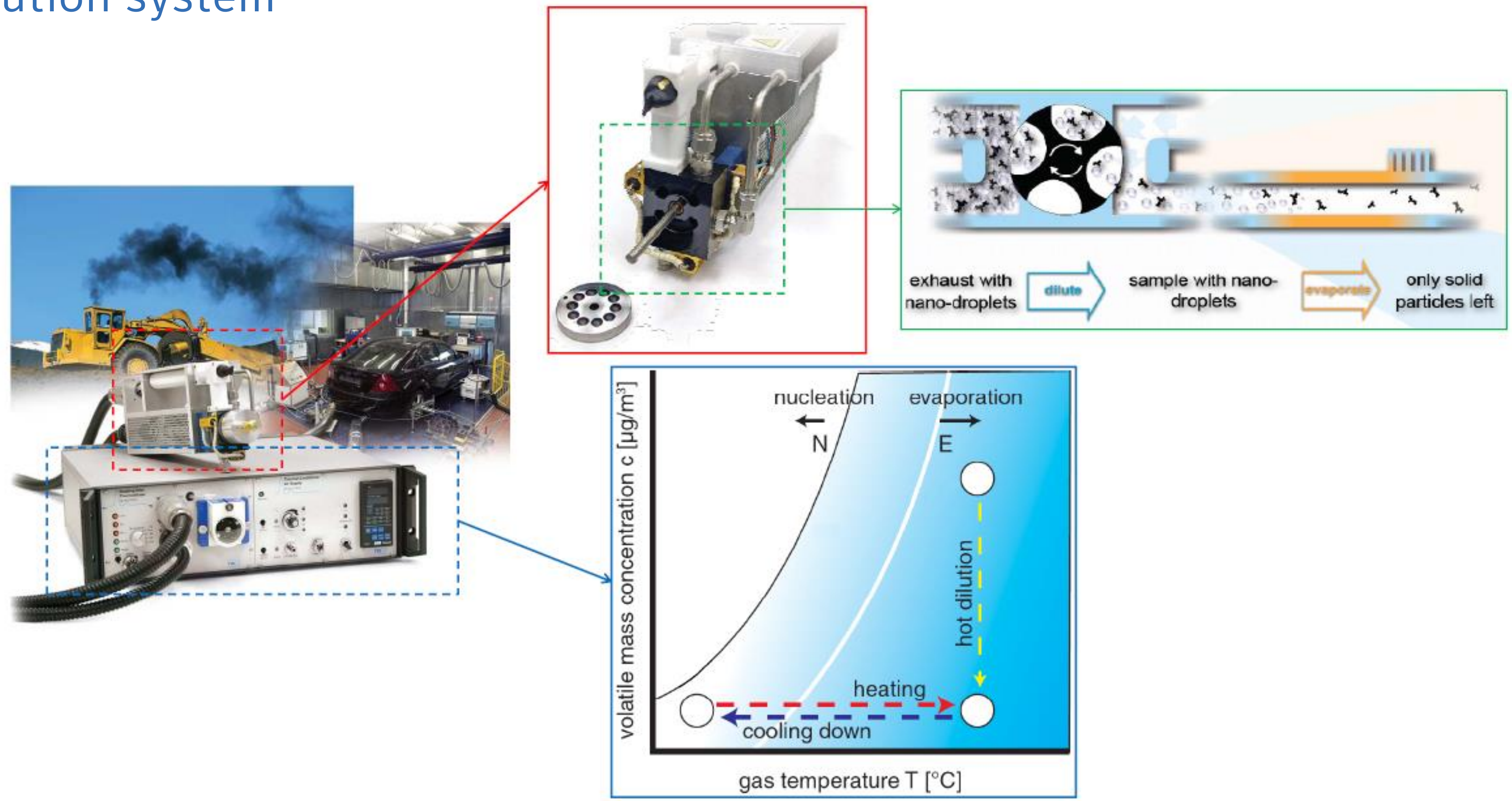
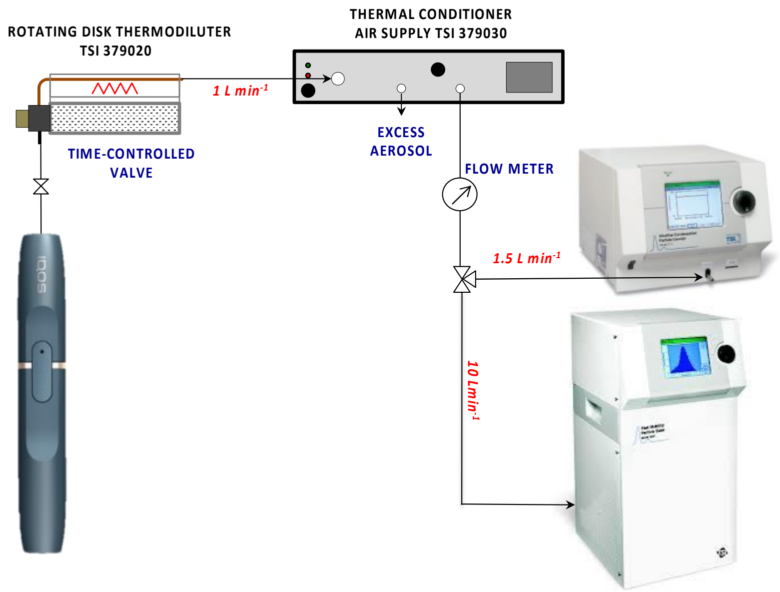
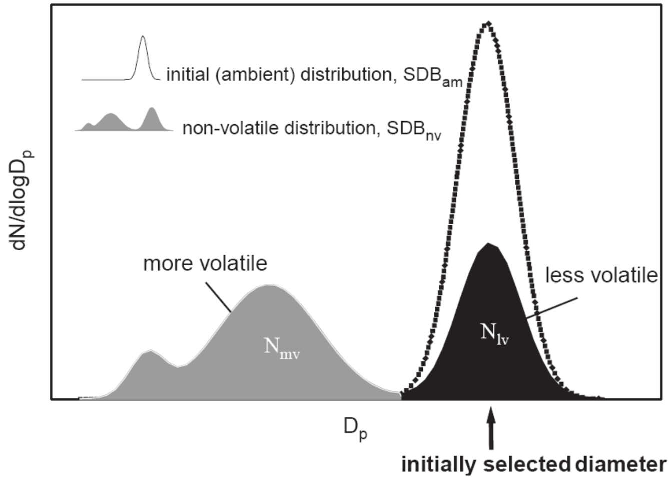


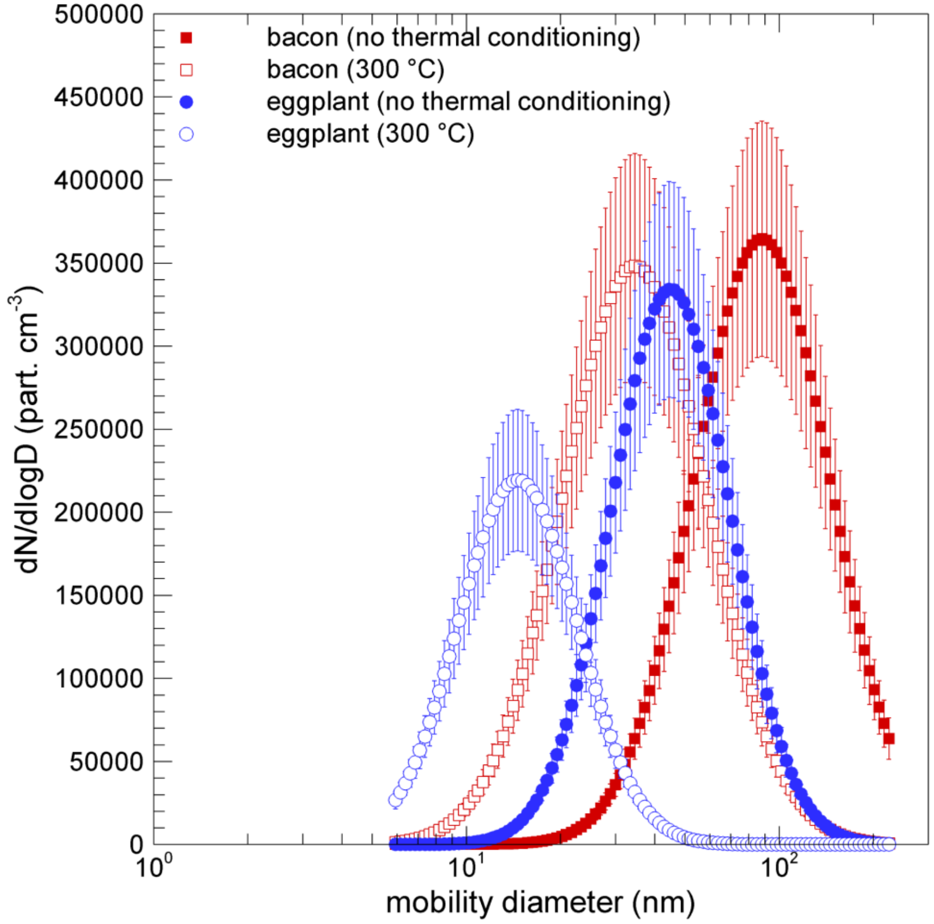
Figure 3 –*Exhaust Probe Rotating Disc and Thermal Conditioner (Matter Engineering).*

Volatility analysis

Removing volatile amount by thermodilution





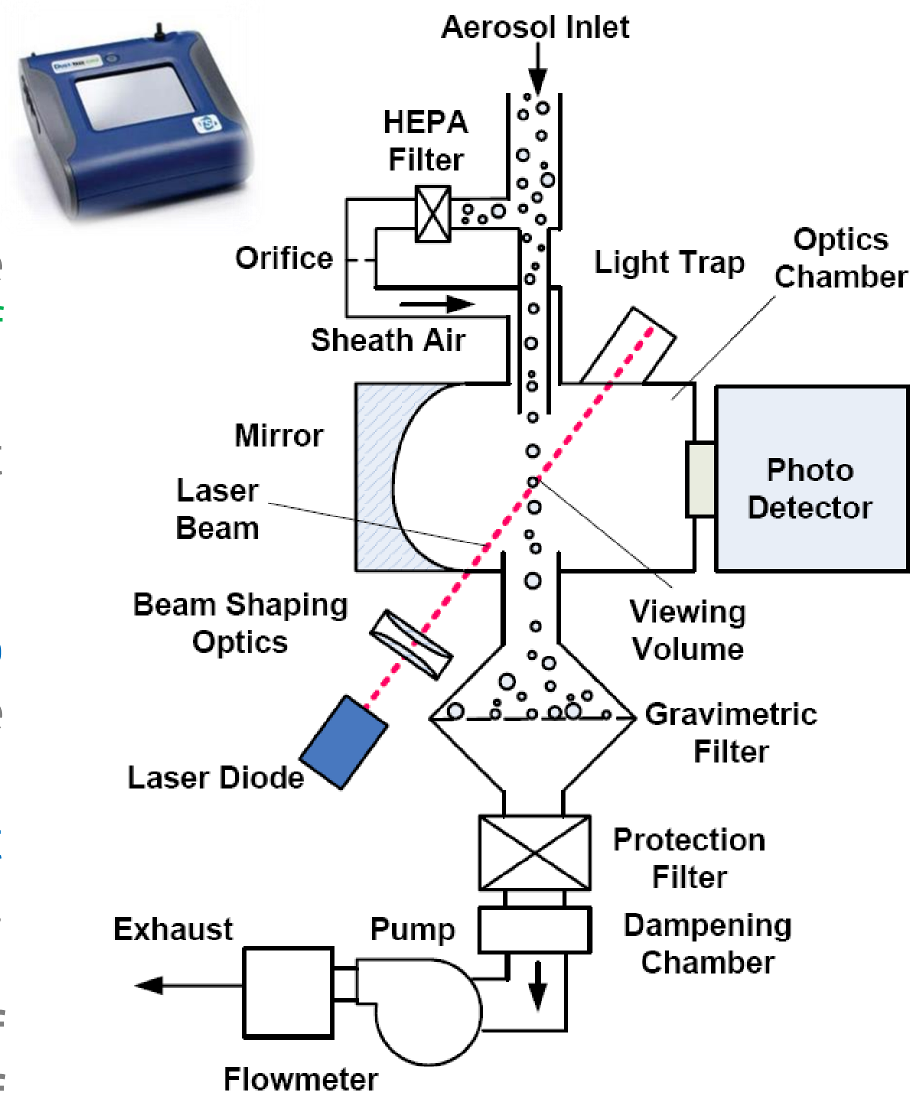


Portable instruments: photometer for PM

DustTrak photometer (TSI Inc.)

Measurement of PM fractions through **light scattering** technique.

- Sample flow passes through the inlet entering the sensing chamber; here, it is illuminated by a sheet of laser light (formed from a laser diode).
- A gold coated spherical mirror captures a significant fraction of the light scattered by the particles and focuses it on to a photo detector.
- The voltage across the photo detector is proportional to the mass concentration of the aerosol over a wide range of concentrations.
- The voltage is then multiplied by a calibration constant (determined from a known mass concentration, i.e. gravimetric measurement).
- **The scattered light depends on the size distribution of the aerosol, refractive index, shape factor and density of the aerosol!**

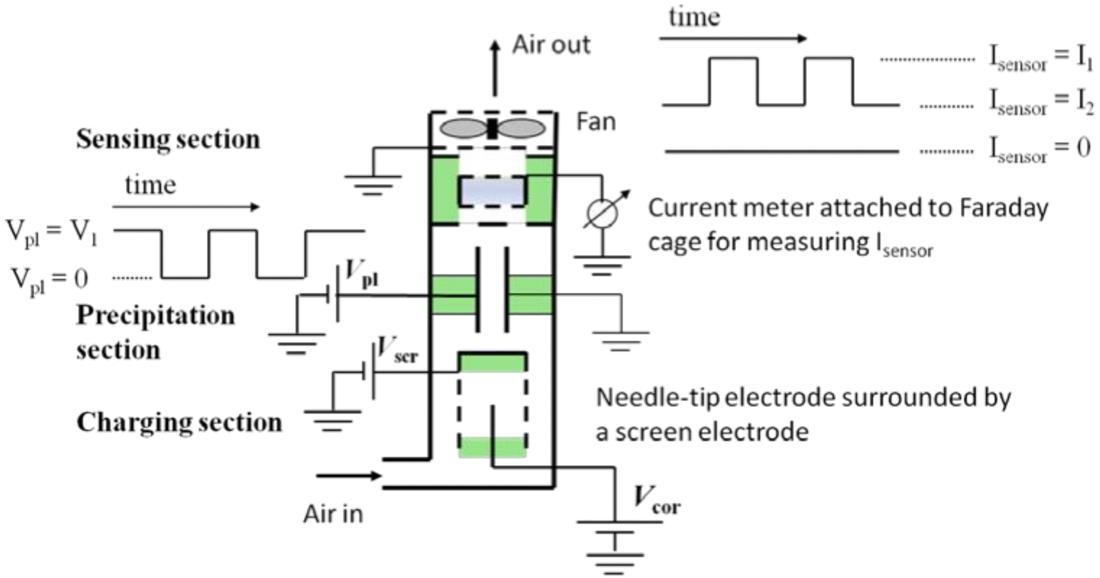


Portable instruments: counters for PN

Diffusion chargers

Measurement principle based on total electric charge of the particles collected.

- Particles are mixed with unipolar ions, which randomly collide with the particles by diffusion (hence the name) and transfer their charge to the particles.
- Excess ions are removed from the gas flow, the charged particles are subsequently captured in a particle filter, and a small current can be detected flowing from the filter.
- The diffusion charging process is material independent, and thus particles of different compositions cannot be distinguished.
- The average charge q acquired by a particle in this process depends solely on its diameter.
- Lung deposited surface area of the particles estimated (for a reference worker) – semiempirical relationships



Estimating exposures and emissions in indoor environments

Estimating the exposure in indoor environment

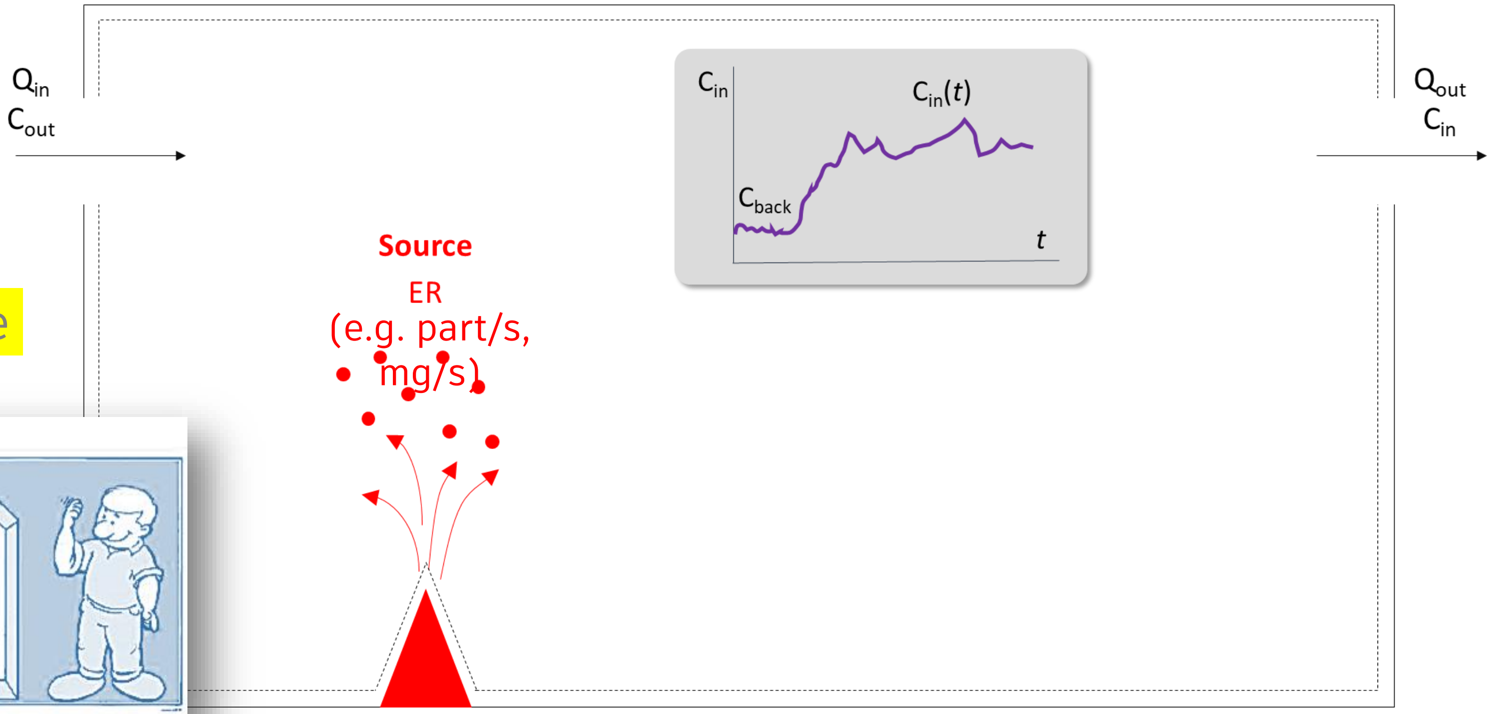
Well-mixed simplified approach

Mass balance

$$C_{out} \cdot Q_{in} \cdot P + ER = C_{in}(t) \cdot Q_{out} \cdot P + \frac{dN_{in}(t)}{dt}$$

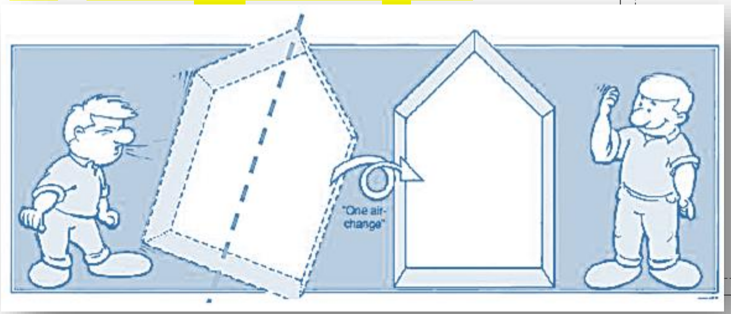
$$C_{in}(t) = C_{back} \cdot e^{-(AER \cdot P) \cdot t} + C_{out} \cdot \left(1 - e^{-(AER \cdot P) \cdot t}\right) + \frac{ER}{V \cdot (AER \cdot P)}\left(1 - e^{-(AER \cdot P) \cdot t}\right)$$

Particles entering from outdoor



Particles exiting outdoor

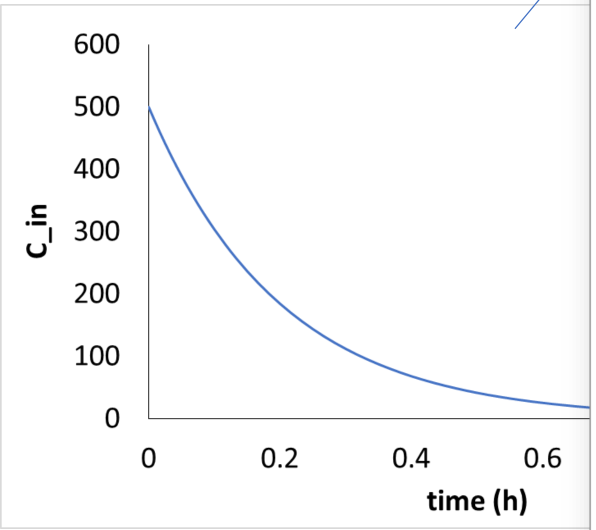
AER = air exchange rate (h^{-1}) = Q_{out}/V = Q_{in}/V

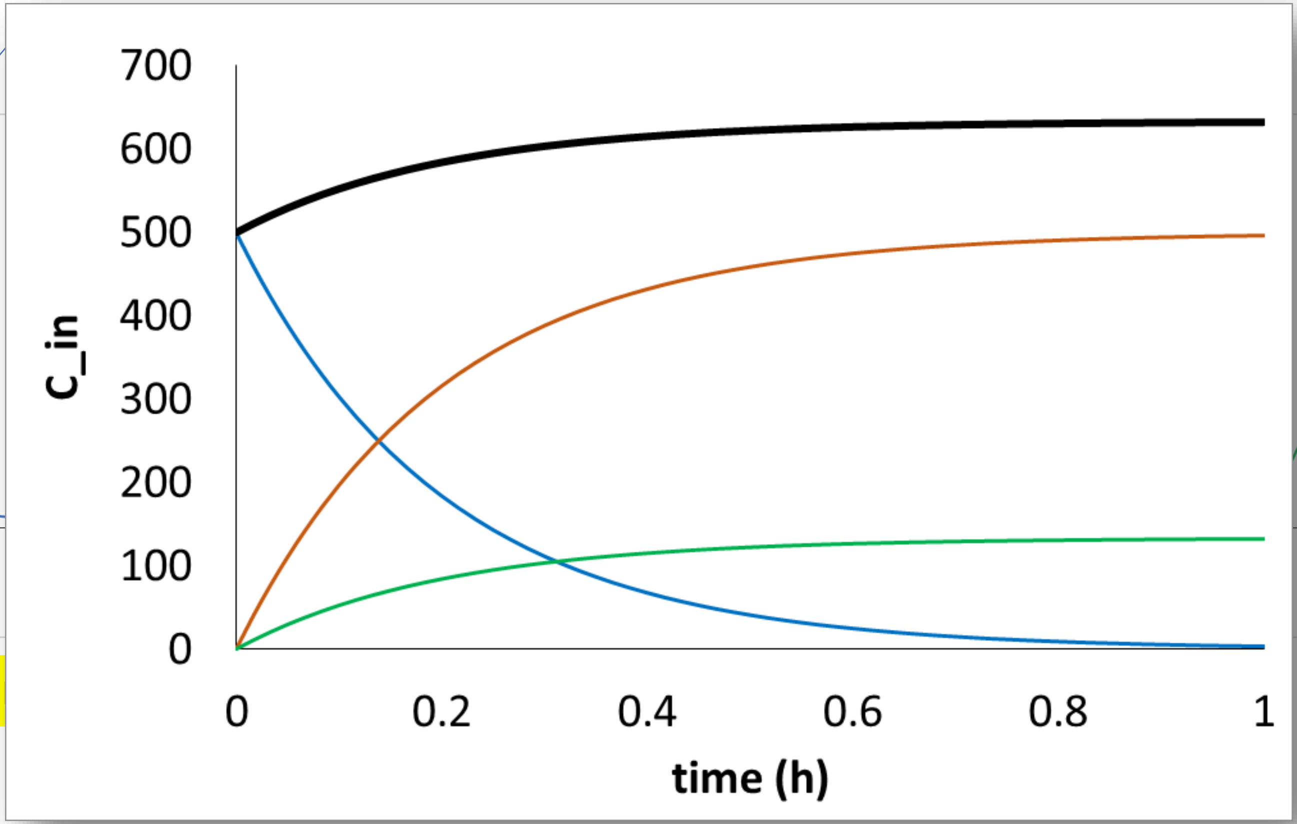


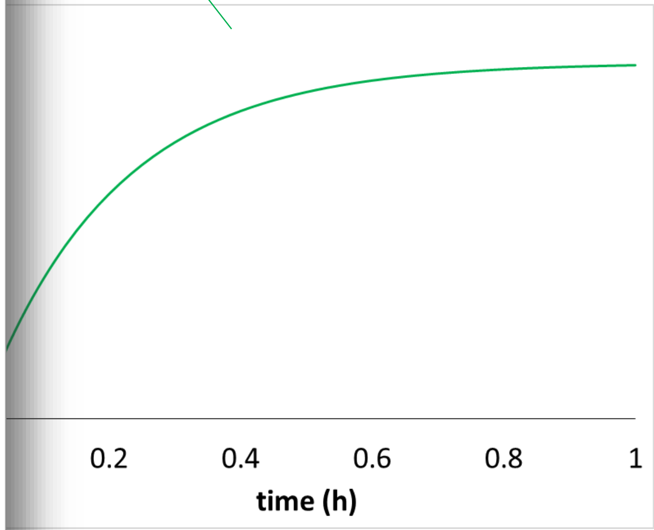
Estimating the exposure in indoor environment

Well-mixed simplified approach

$$C_{in}(t) = C_{back} \cdot e^{-(AER \cdot P) \cdot t} + C_{out} \cdot \left(1 - e^{-(AER \cdot P) \cdot t}\right) + \frac{ER}{V \cdot (AER \cdot P)} \left(1 - e^{-(AER \cdot P) \cdot t}\right)$$





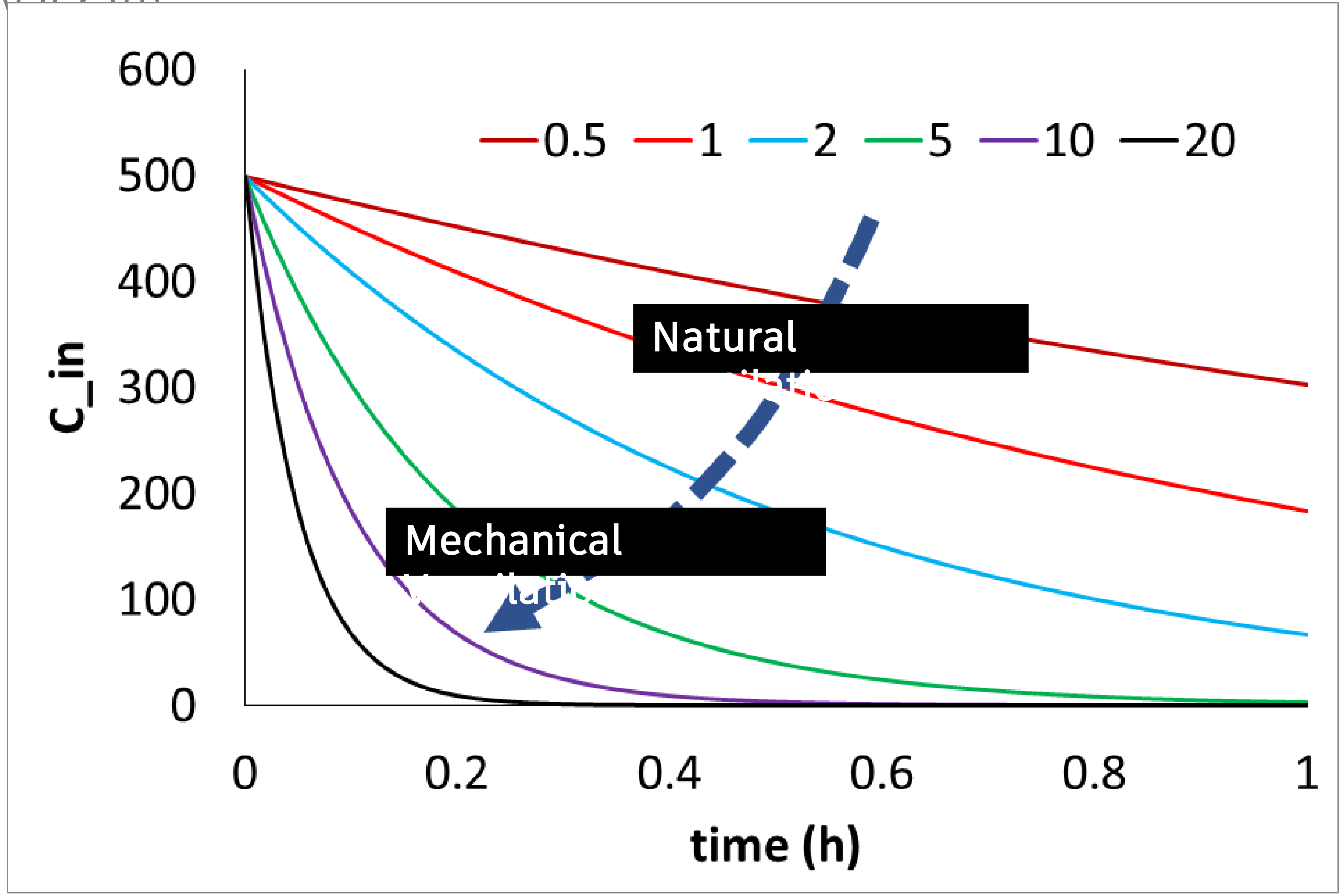


–(AER·P)·t = “removal

Estimating the exposure in indoor environment

Well-mixed simplified approach

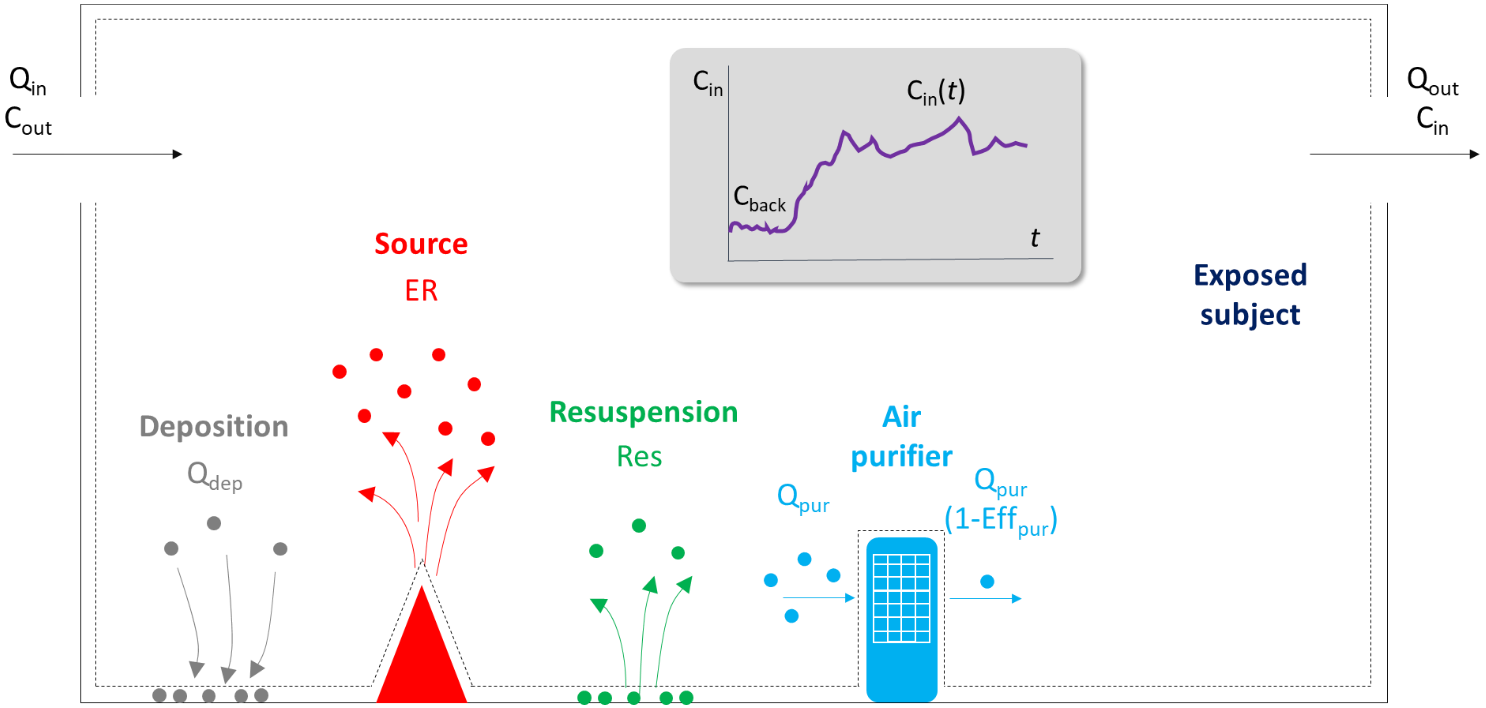
AER and removal rate



Estimating the exposure in indoor environment

Well-mixed simplified approach

- Deposition
- Resuspension
- Removal through air purifier
- …



ACH = air change rate (h^{-1}) = Q_{pur}/V

$$C_{in}(t) = C_{back} \cdot e^{-(AER \cdot P + k + ACH \cdot Eff_{pur}) \cdot t} + \frac{C_{out} \cdot AER \cdot P}{AER \cdot P + k + ACH \cdot Eff_{pur}}\left(1 - e^{-(AER \cdot P + k + ACH \cdot Eff_{pur}) \cdot t}\right) +$$

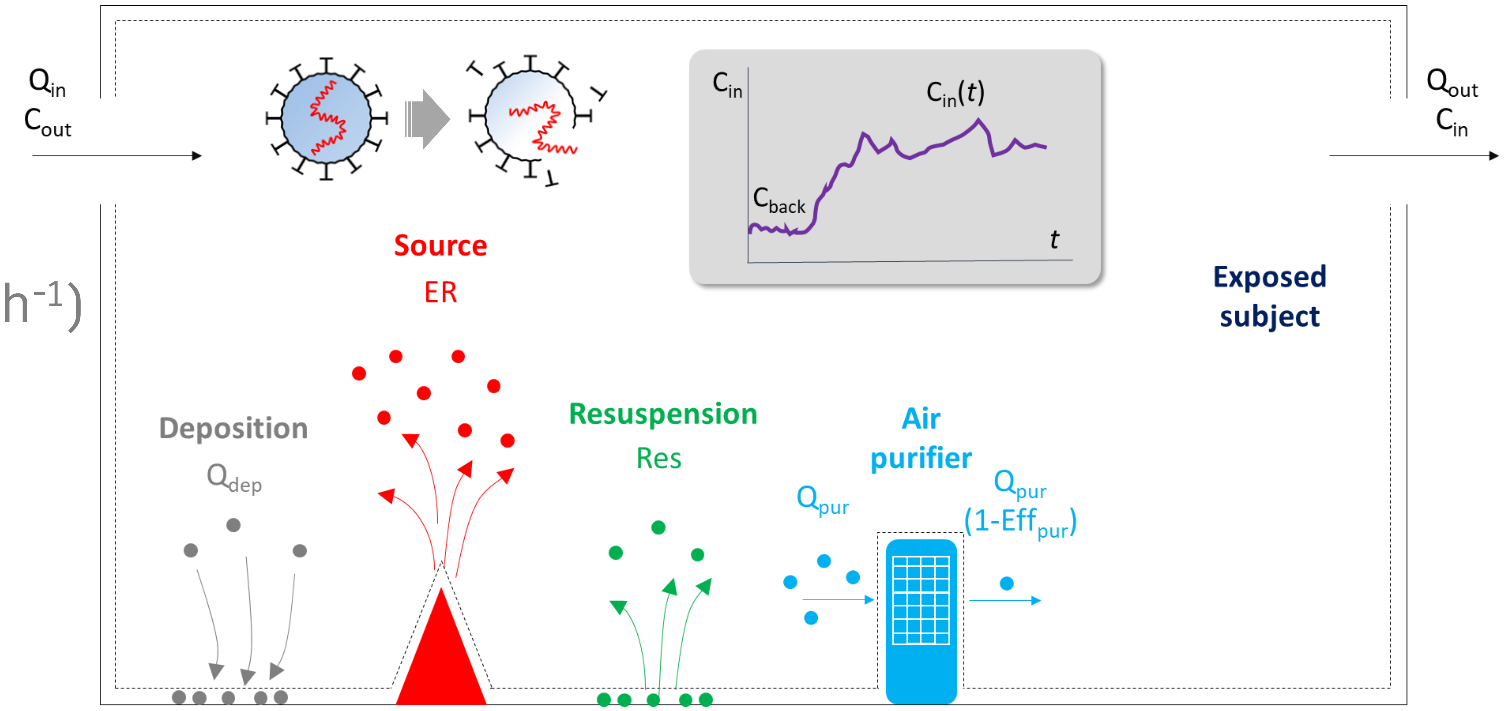
$$+ \frac{ER + Res}{V \cdot (AER \cdot P + k + ACH \cdot Eff_{pur})}\left(1 - e^{-(AER \cdot P + k + ACH \cdot Eff_{pur}) \cdot t}\right)$$

$-(AER \cdot P + k + ACH \cdot Eff_{pur}) \cdot t$ = “removal rate”

Estimating the exposure in indoor environment

Well-mixed simplified approach

- Deposition
- Resuspension
- Removal through air purifier
- Viral inactivation - for viruses, λ (h^{-1})



$$C_{in}(t) = C_{back} \cdot e^{-(AER \cdot P + k + ACH \cdot Eff_{pur} + \lambda) \cdot t} + \frac{C_{out} \cdot AER \cdot P}{AER \cdot P + k + ACH \cdot Eff_{pur} + \lambda}\left(1 - e^{-(AER \cdot P + k + ACH \cdot Eff_{pur} + \lambda) \cdot t}\right) +$$

$$+ \frac{ER + Res}{V \cdot (AER \cdot P + k + ACH \cdot Eff_{pur} + \lambda)}\left(1 - e^{-(AER \cdot P + k + ACH \cdot Eff_{pur} + \lambda) \cdot t}\right)$$

λ = viral inactivation rate (h^{-1})

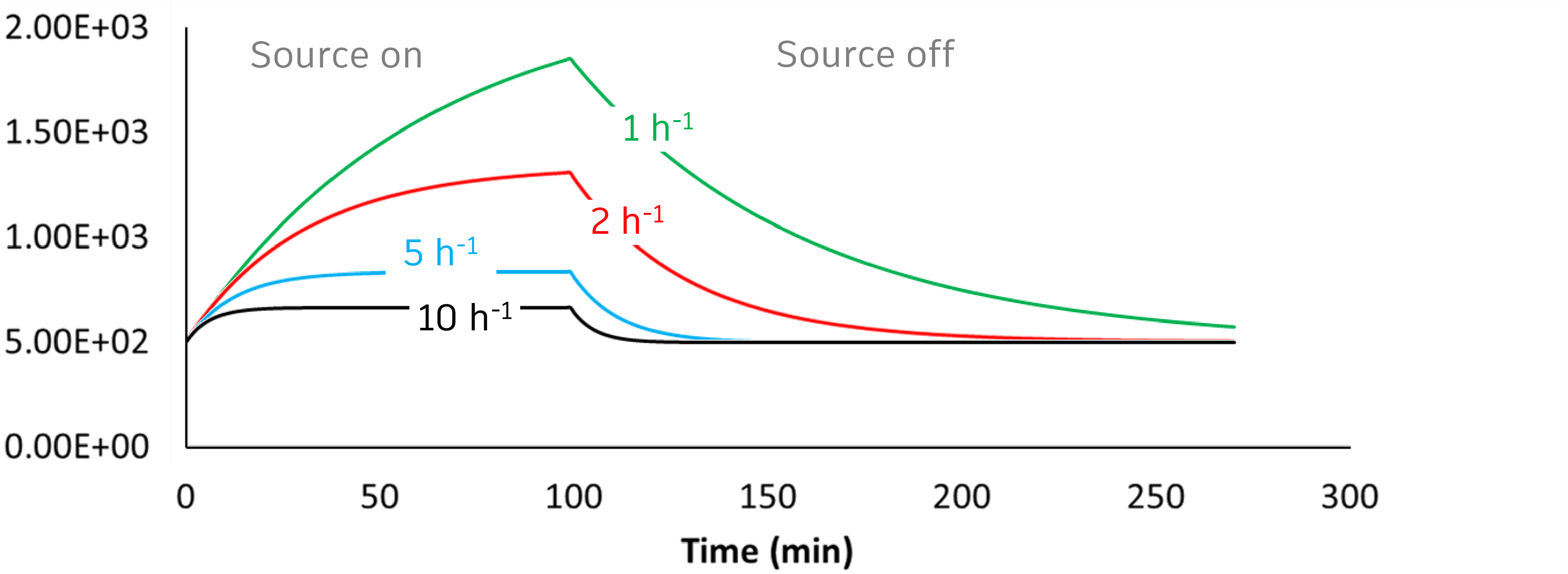
$-(AER \cdot P + k + ACH \cdot Eff_{pur} + \lambda) \cdot t$ = “removal rate”

Estimating the emission factor/emission rate

Quantifying the emission of indoor sources

Mass balance approach

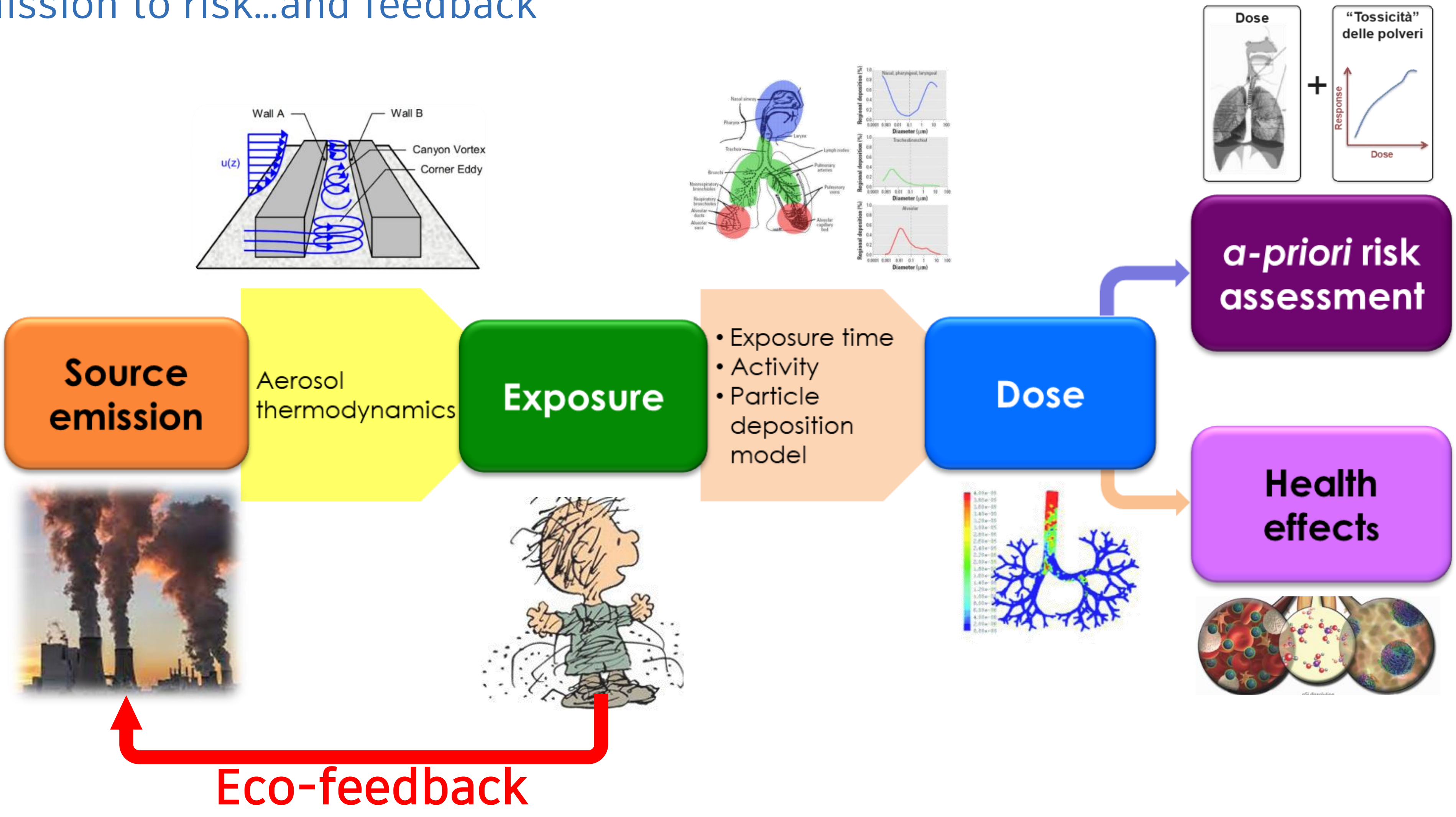
- Emission rate (emission per unit time)
- Emission factor (emission per unit mass, quantity…)



Research at UNICAS

Research studies

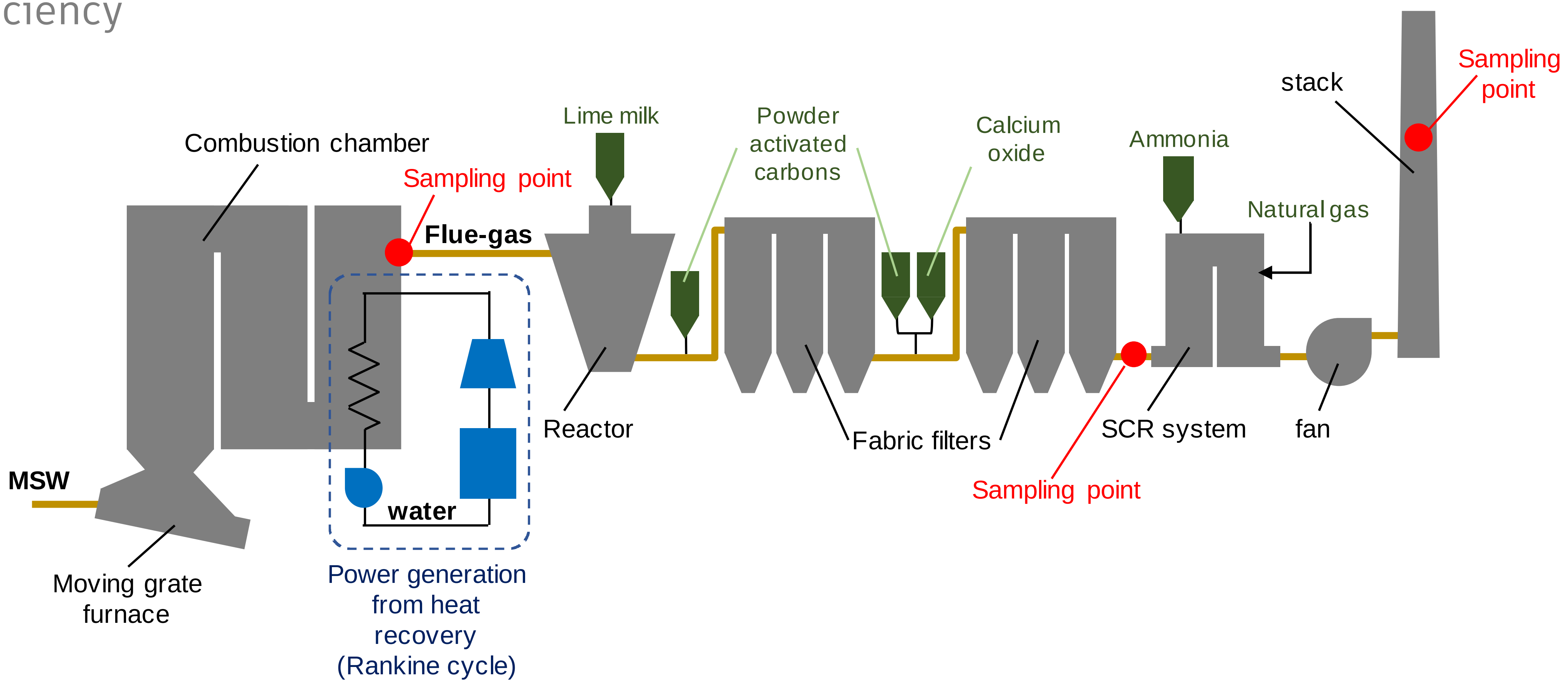
From emission to risk…and feedback



Outdoor sources

Incinerator plants

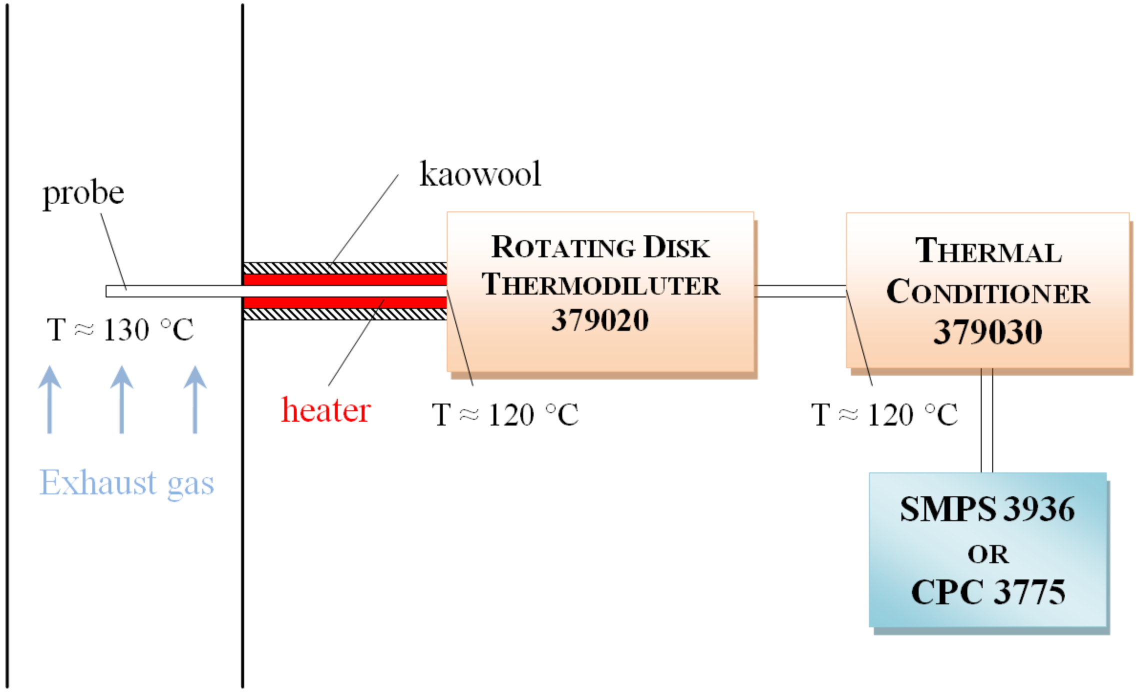
- At the stack
- Filter efficiency

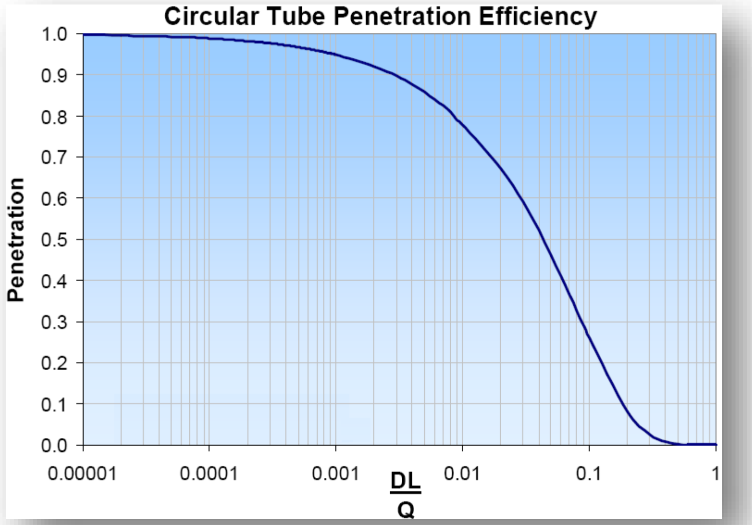


Outdoor sources

Incinerator plants

- Thermodilution
- Measurement artifacts



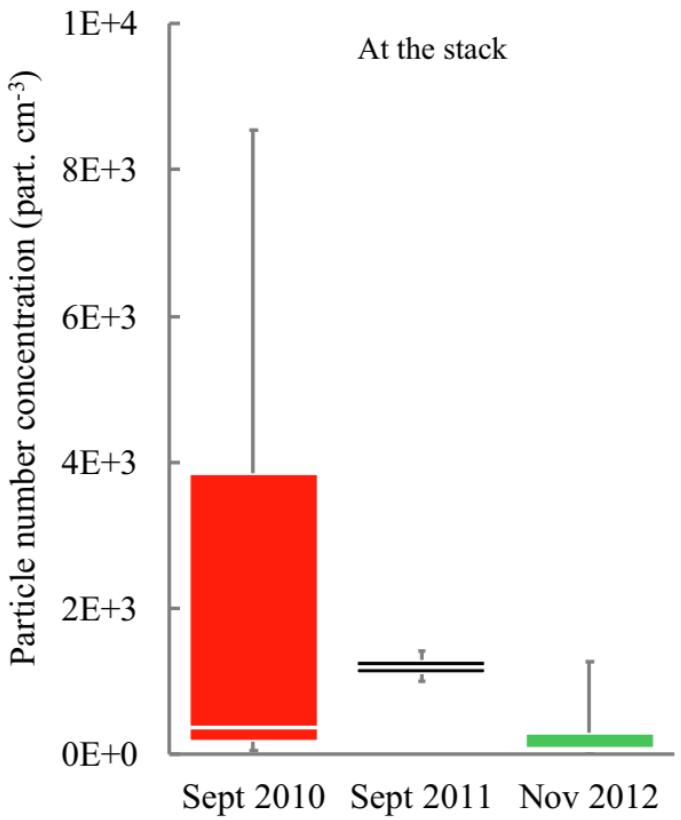


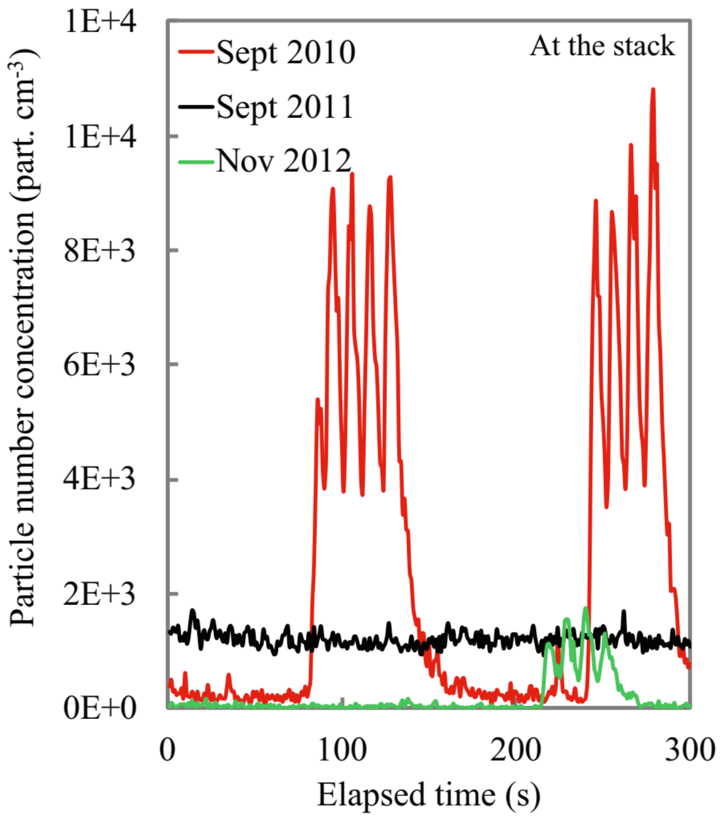
Luca Stabile (*l.stabile@unicas.it*)

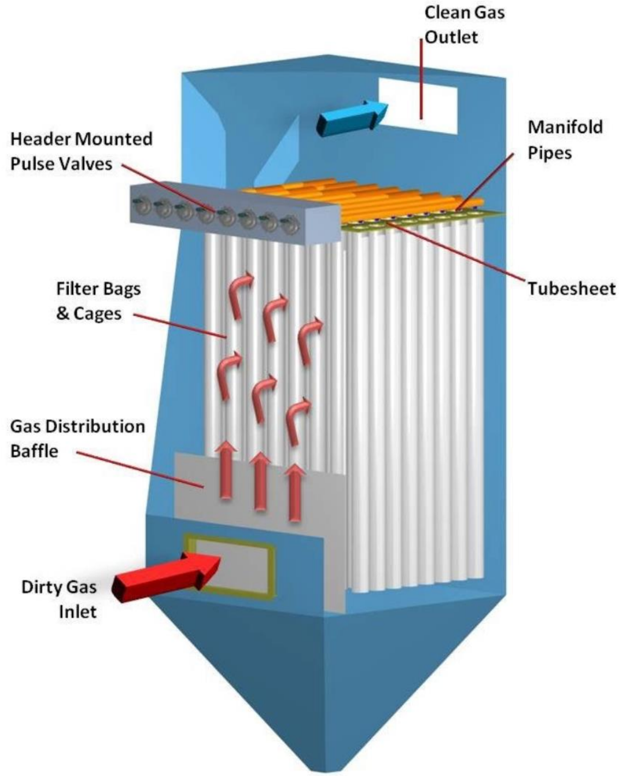
Outdoor sources

Incinerator plants

Results







Pulse jet bag filter

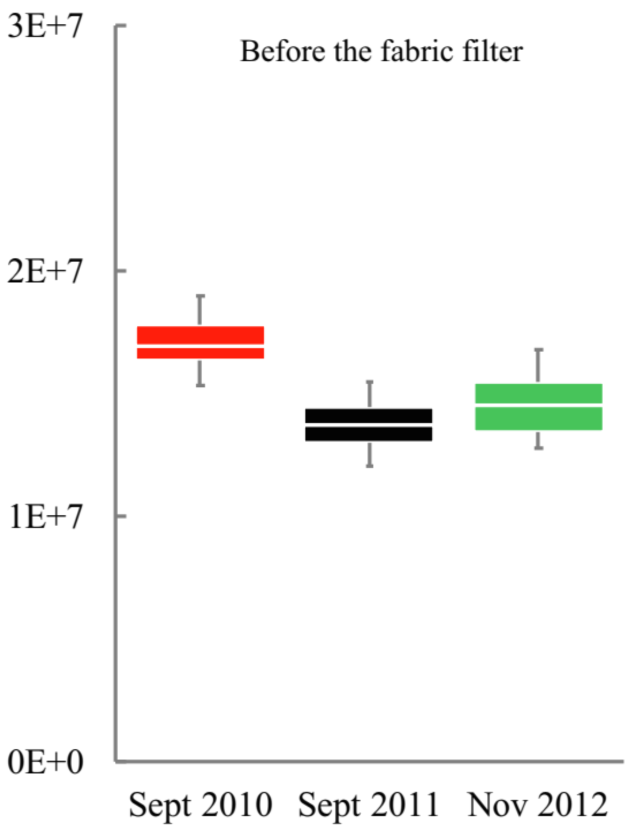
Plant equipped with Electrostatic filters: 3.0×10^{5} part. cm^{-3}.

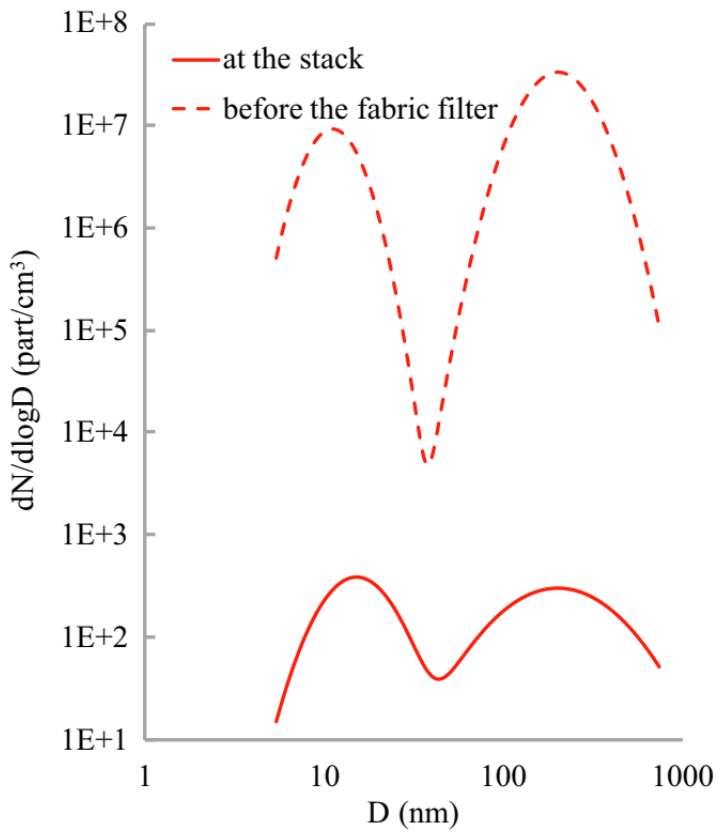
Outdoor sources

Incinerator plants

Results

- Fabric filter efficiency for UFPs > 99.99%;





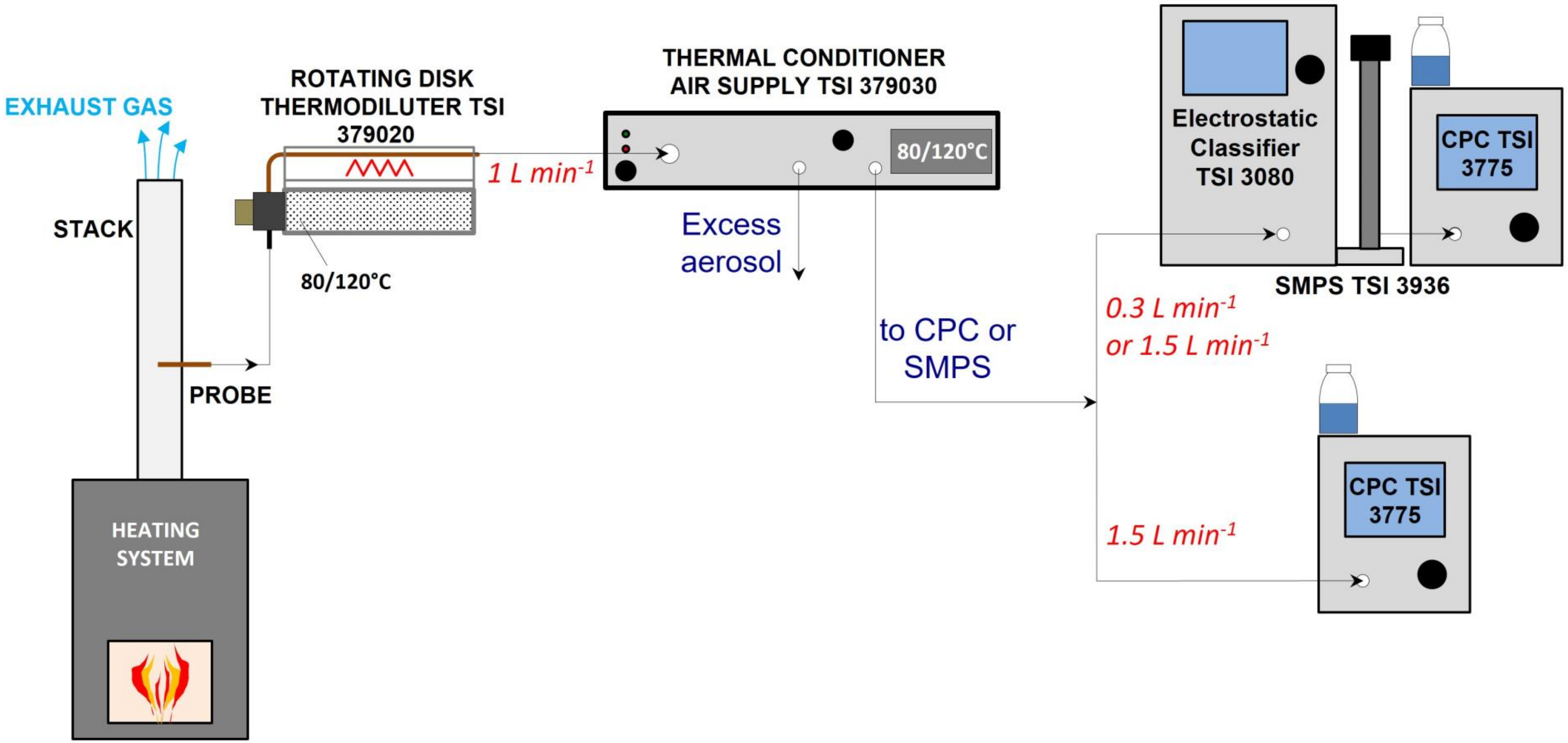
Outdoor sources

Thermal plants for residential heating

Boilers (LPG and methane)

Condensing Boilers (LPG and methane)

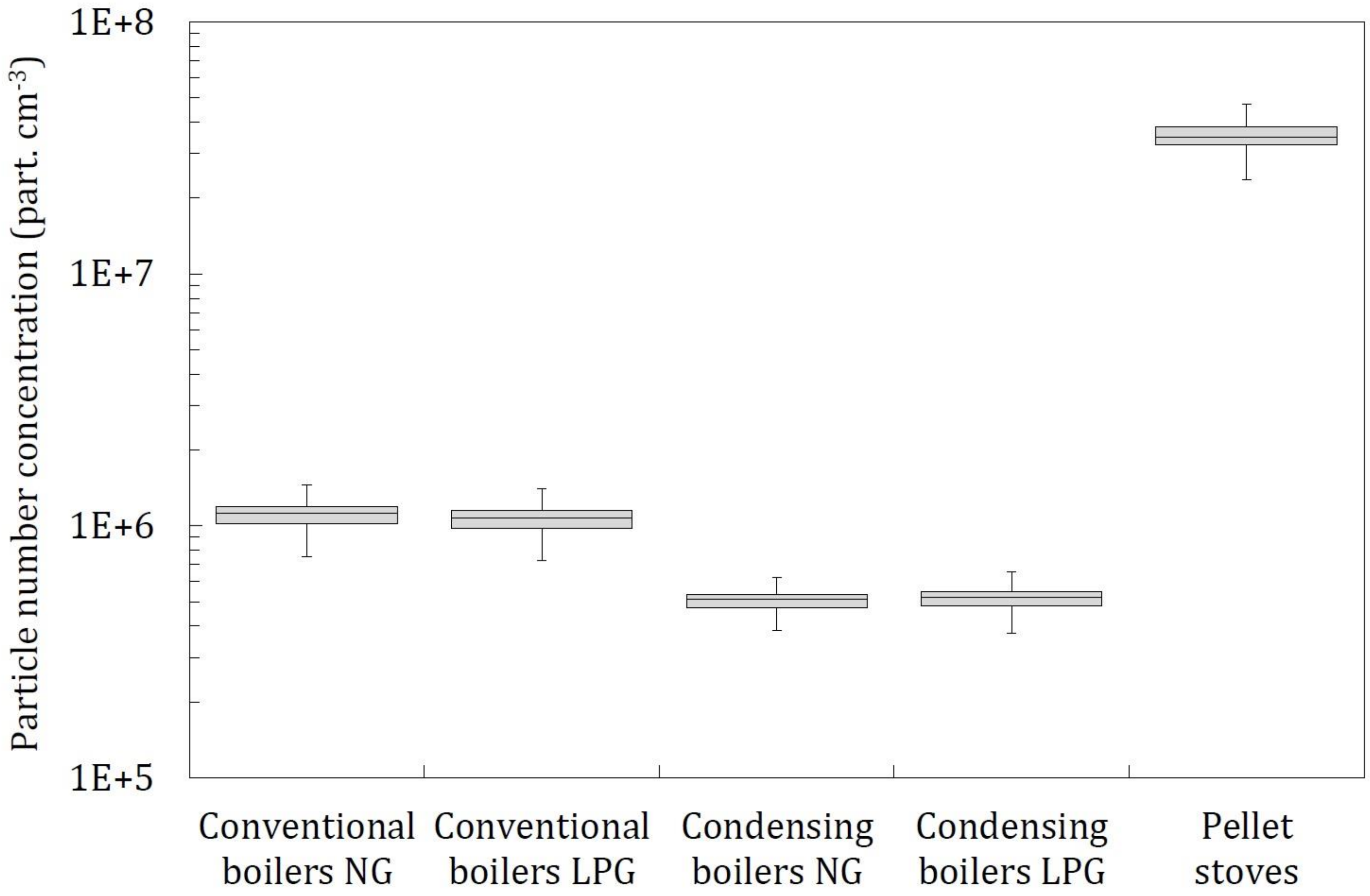
Pellet Stoves



Outdoor sources

Thermal plants for residential heating

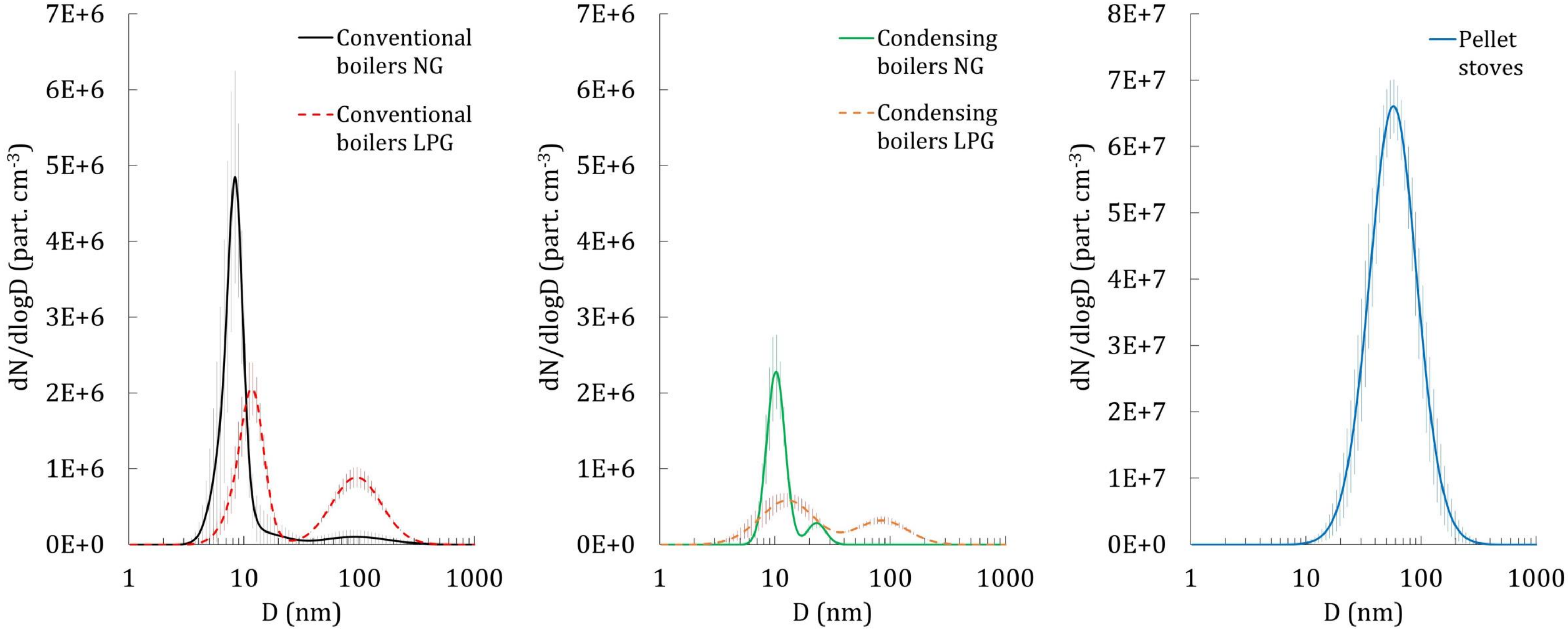
Concentrations



Outdoor sources

Thermal plants for residential heating

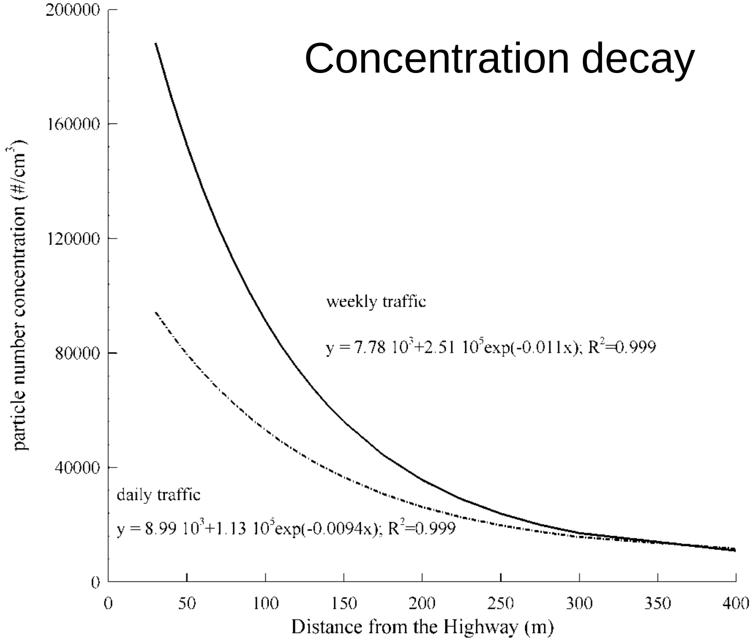
Distributions

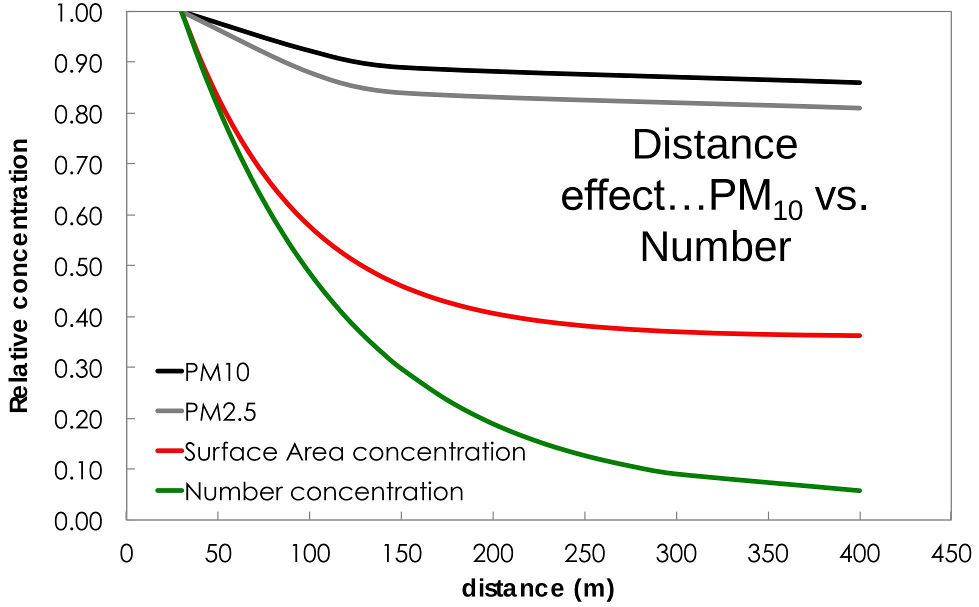


Aerosol Thermodynamics: particle dispersion

Highway

- Emission
- Dilution

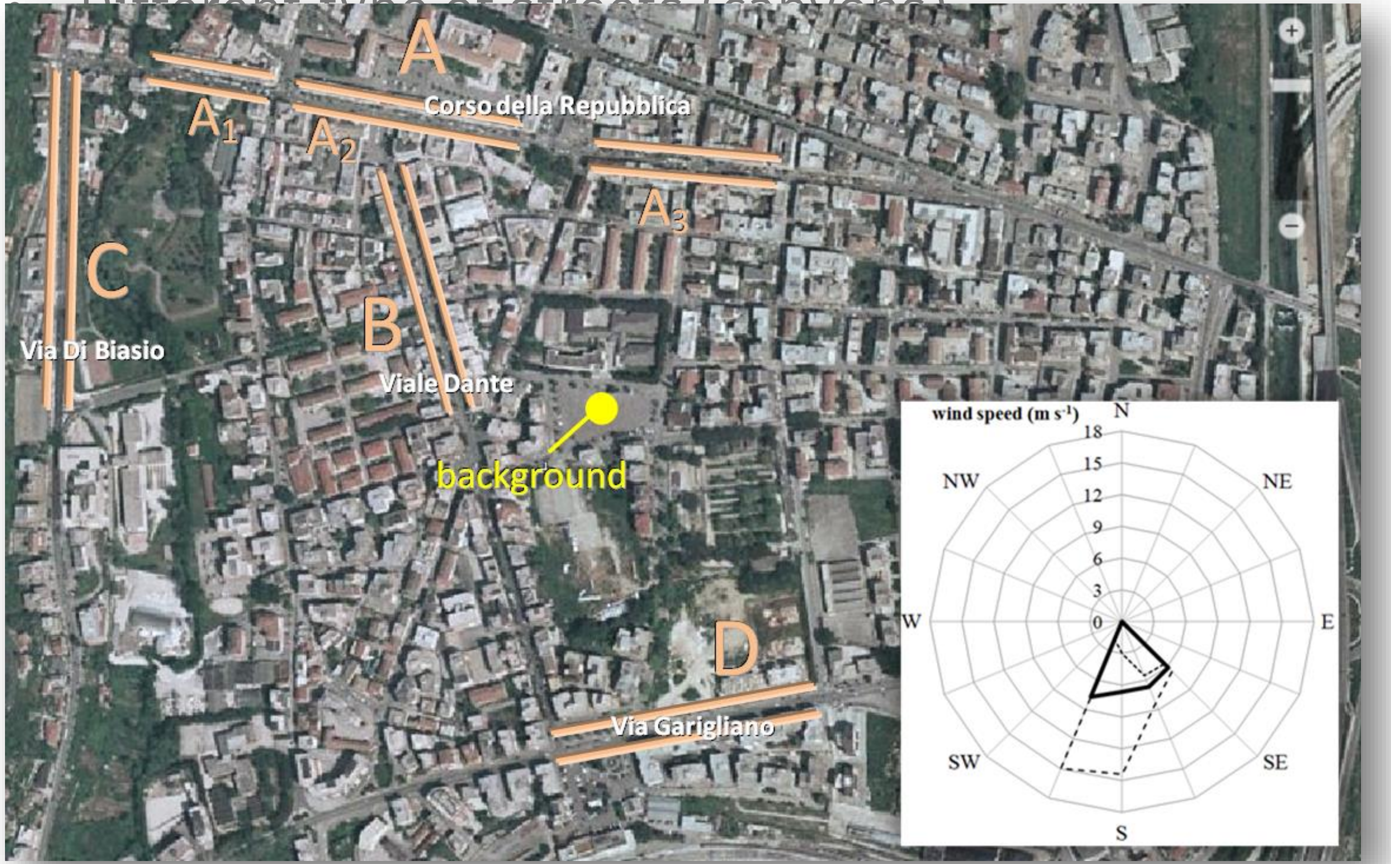




Aerosol Thermodynamics: particle dispersion

Urban areas

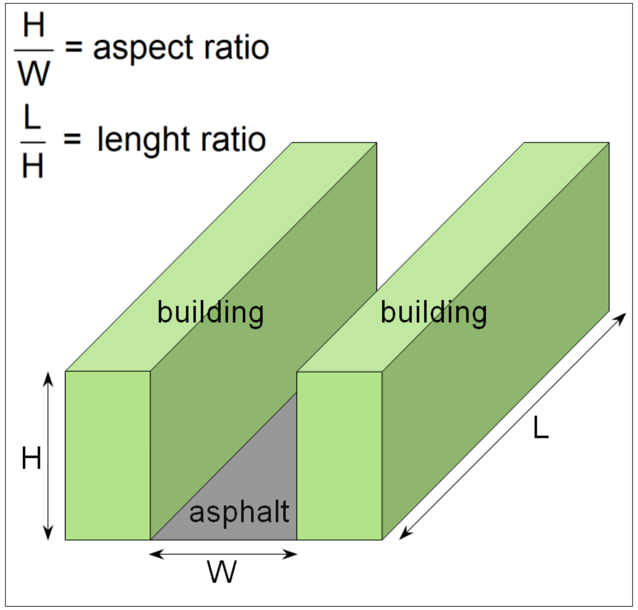
- Mobile platform to measure concentrations and distributions
- Different type of streets (canyons)

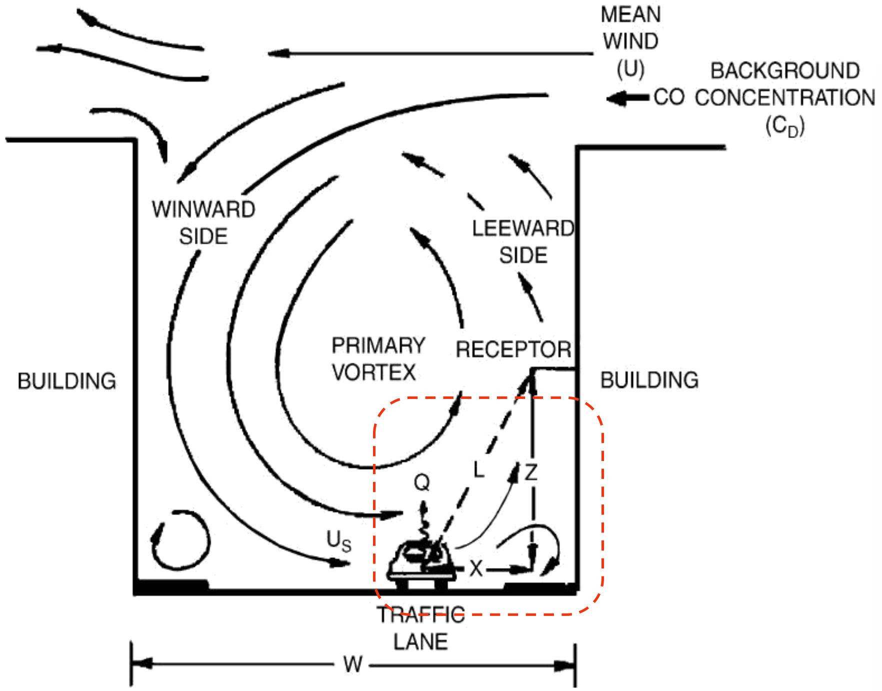


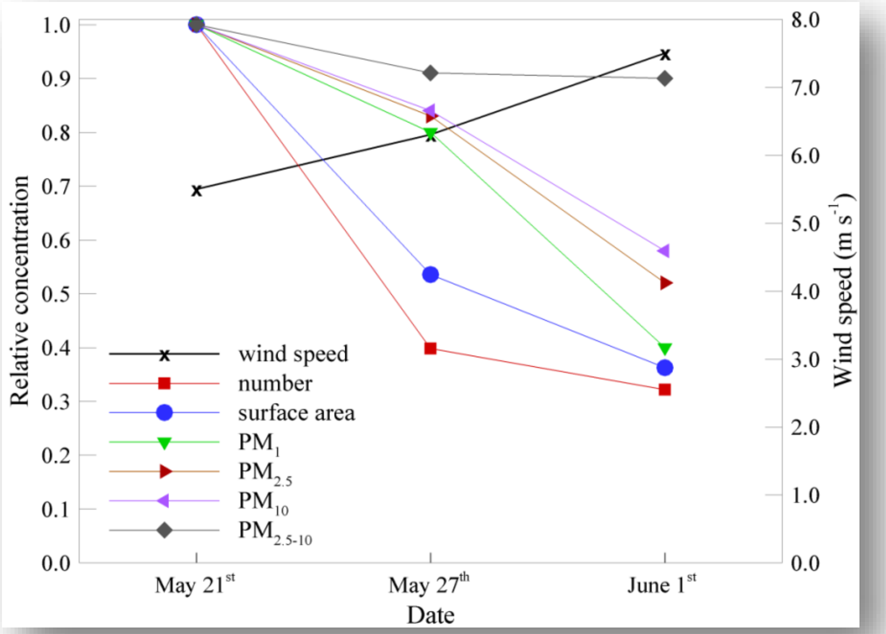
Aerosol Thermodynamics: particle dispersion

Urban areas

- Street canyon







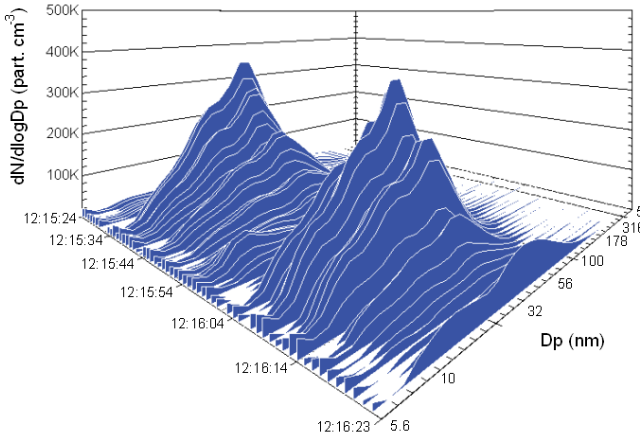
Aerosol Thermodynamics: particle dispersion

Urban areas

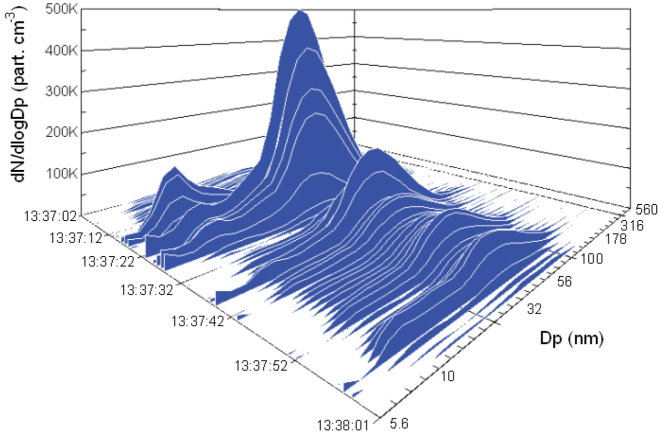
- canyon effect
- Proximity effect
- Concentration gradient of UFPs

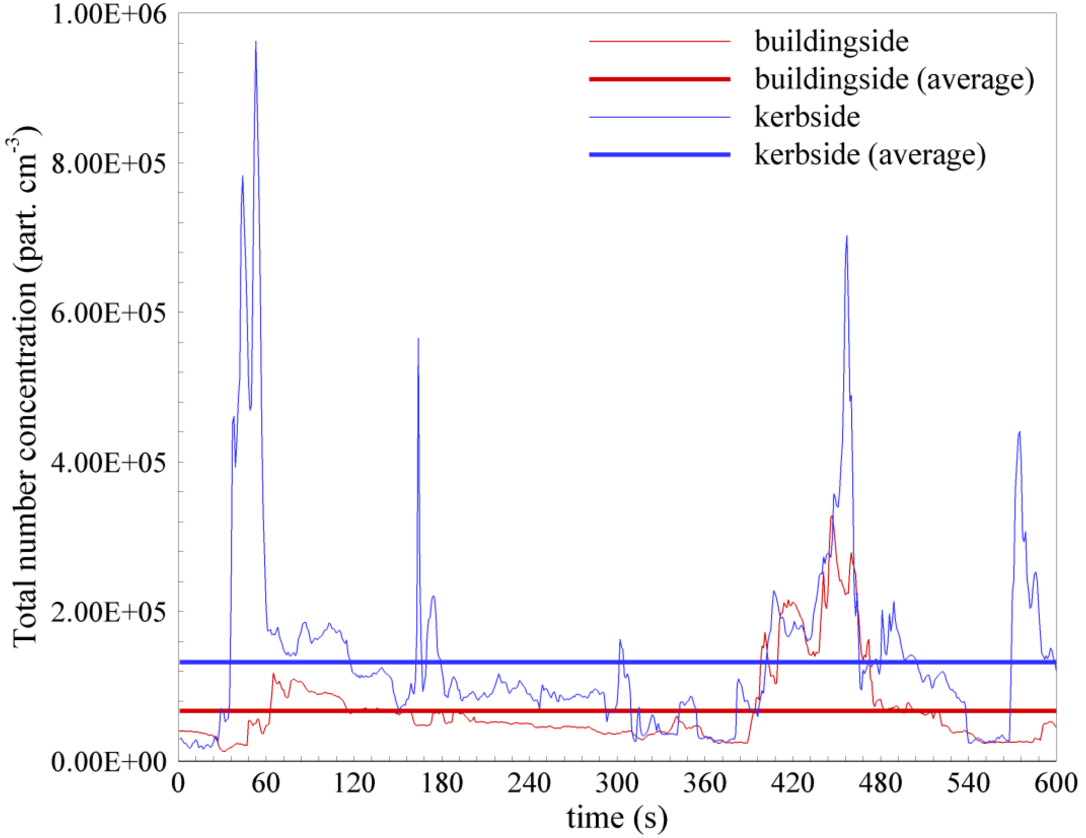
Dilution phenomena: street *vs.* avenue canyon.

Street canyon (street A)



Avenue canyon (street D)

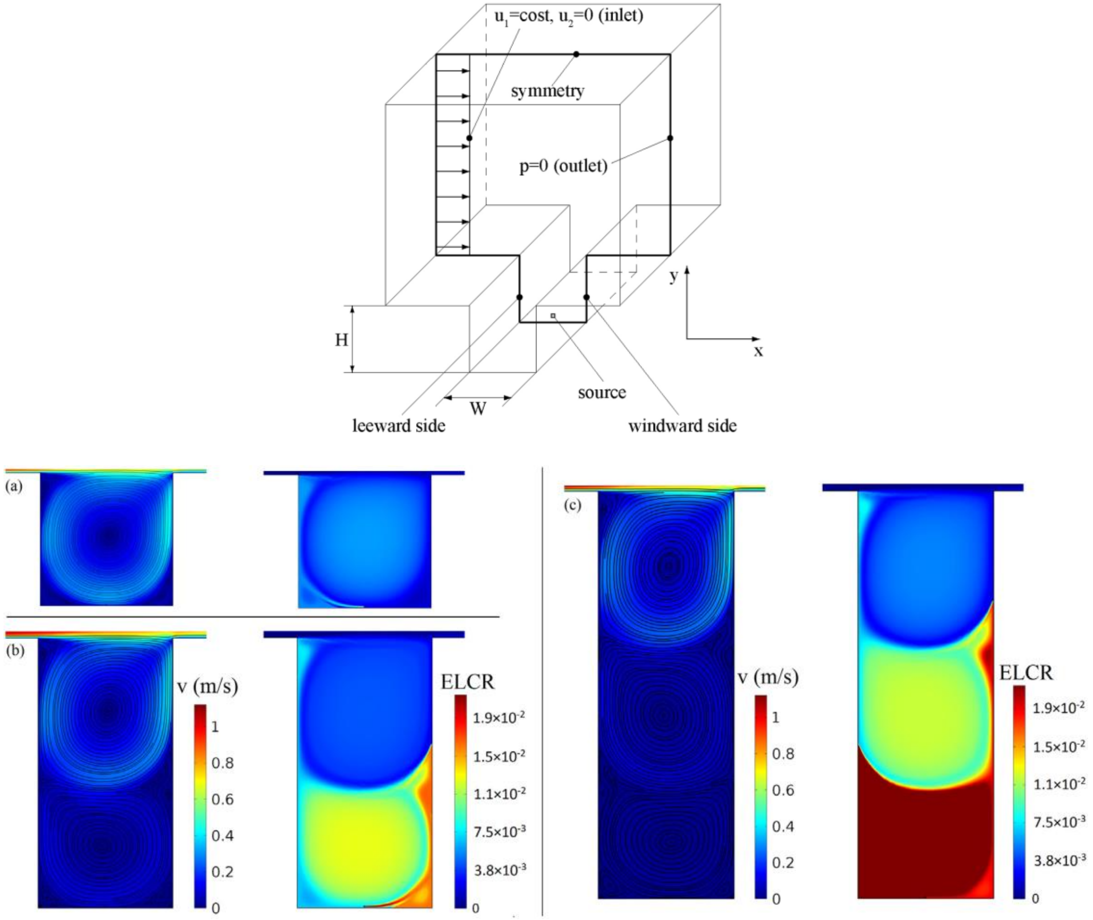


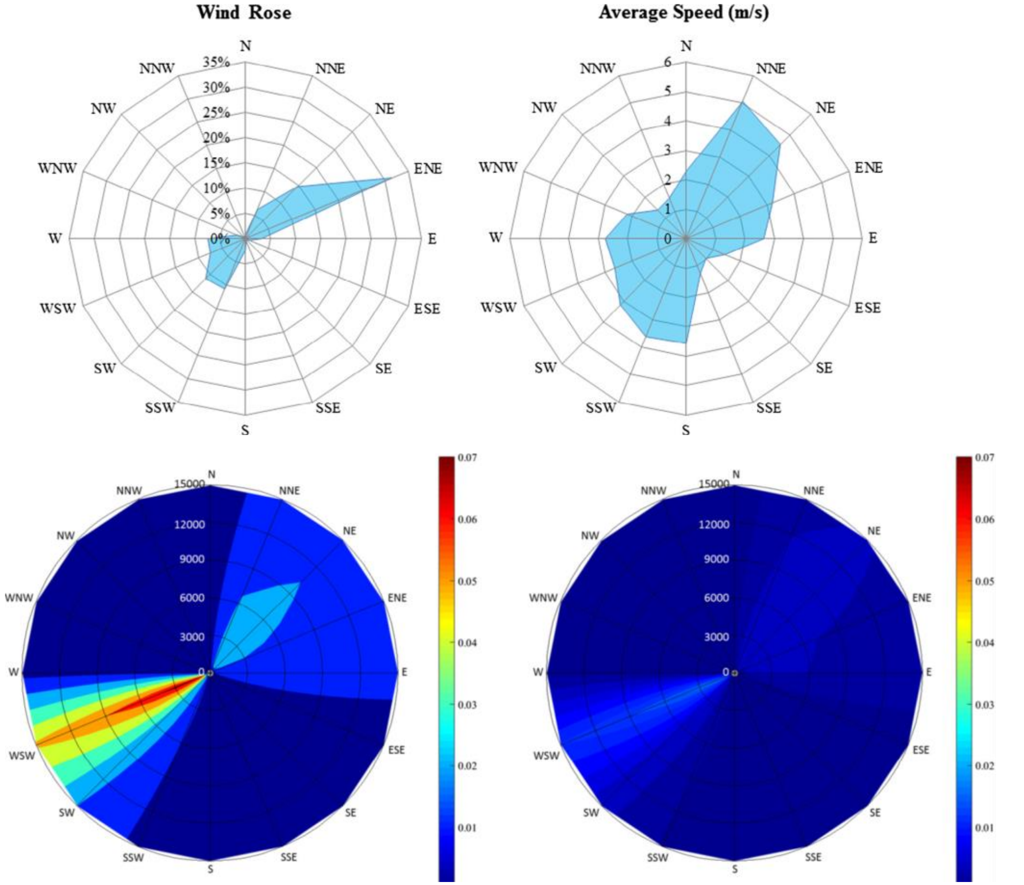


Aerosol Thermodynamics: particle dispersion

CFD studies

CFD analysis of particle dispersion in street-canyons…and industrial areas

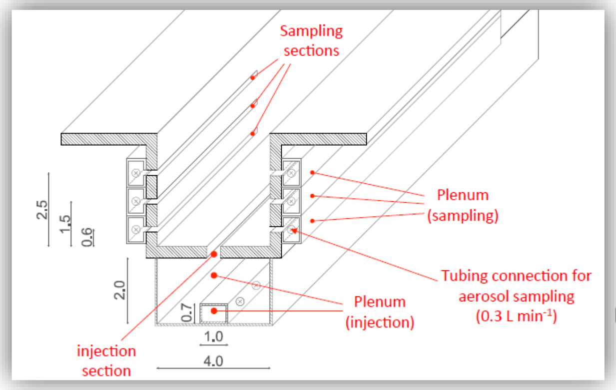


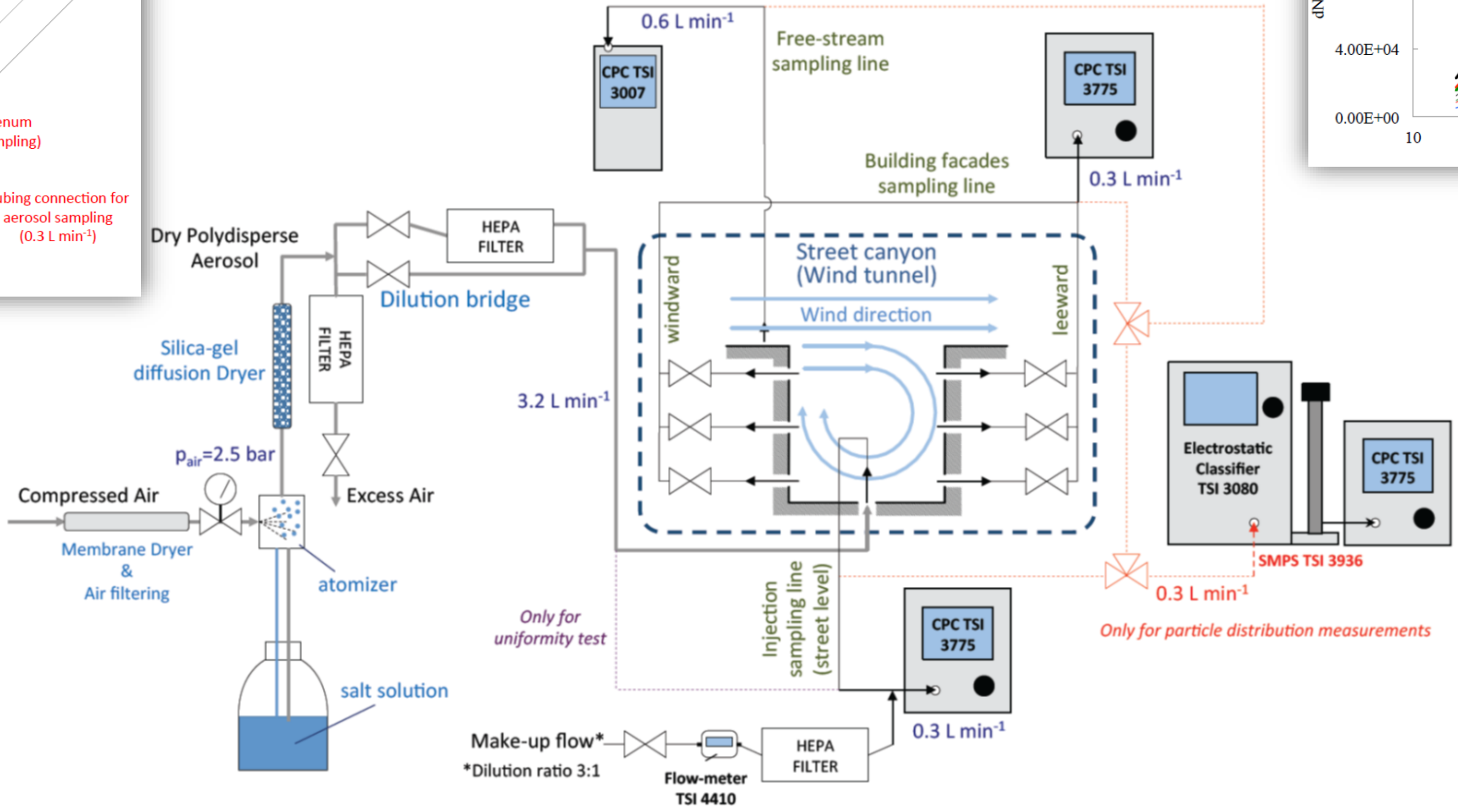


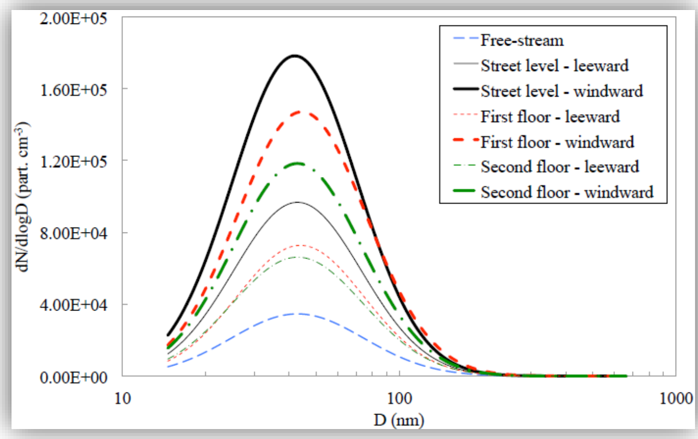
Aerosol Thermodynamics: particle dispersion

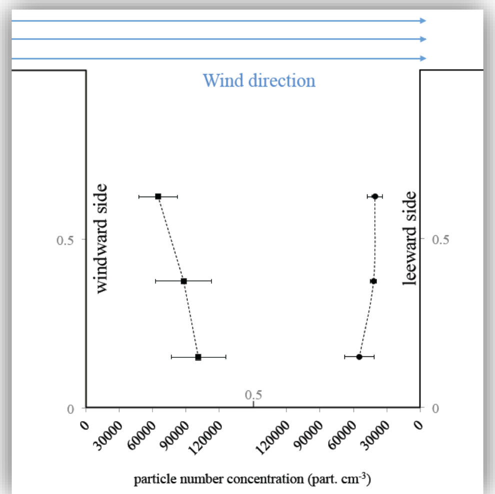
Validation of CFD models

- Wind tunnel & particle concentration measurements









Indoor sources

Cooking activities

Concentrations and distribution

Different cooking activities

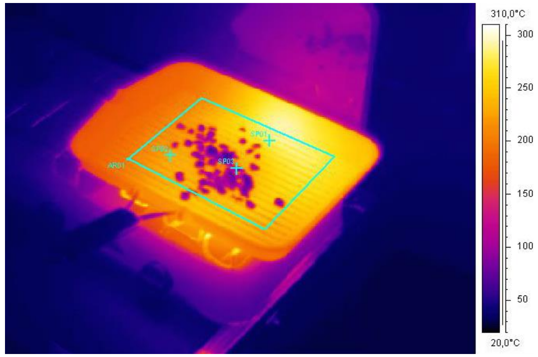
Different types of food

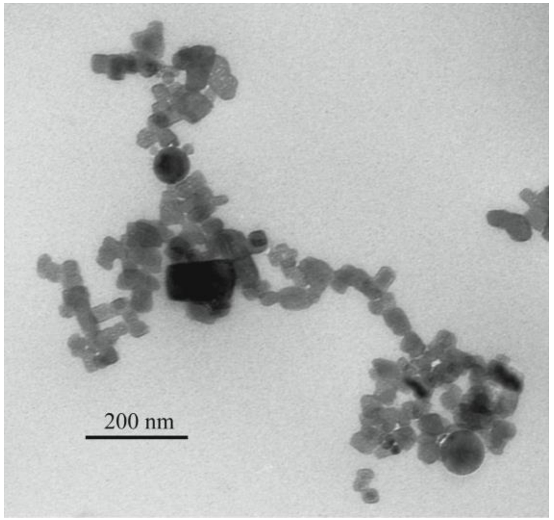
Emission rate

Volatility analysis

Summary of the emission factors for generated using a gas stove at maximum power for the frying of 50 g of chips: emission factor (EF), peak value (PV) and mode diameter (MD) for number (*N*), surface area (*S*) and mass (*M*).

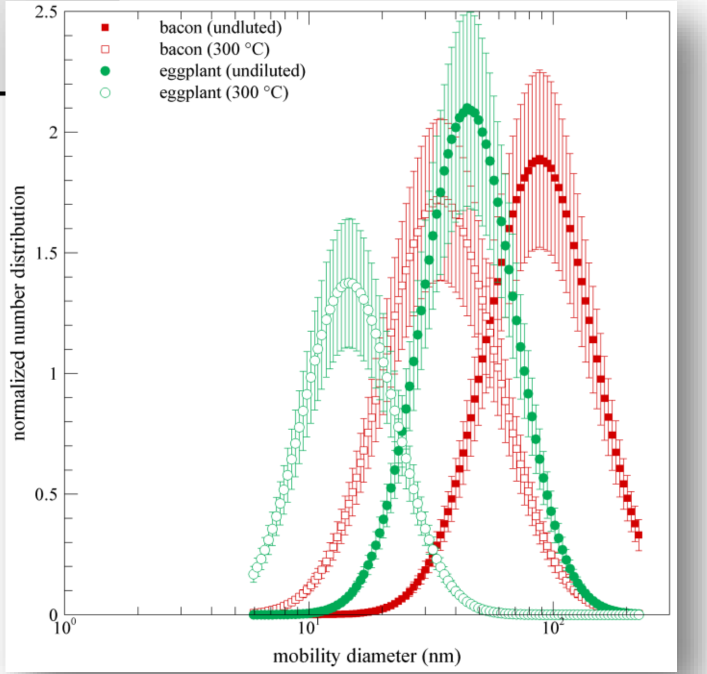
	Olive oil	Peanut oil	Sunflower oil (specific for frying)
NEF (part. min^{-1})	1.8×10^{12}	2.3×10^{12}	1.1×10^{12}
SEF (μm^2 min^{-1})	2.5×10^5	1.6×10^5	1.2×10^5
MEF (μg min^{-1})	2.8×10^3	1.8×10^3	1.2×10^3
NPV (part. cm^{-3})	1.2×10^5	1.2×10^5	1.1×10^5
SPV (nm^2 cm^{-3})	1.1×10^{10}	6.8×10^9	6.0×10^9
MPV (μg m^{-3})	118	68	60
NMD (nm)	61.5	49.6	49.6
Geometric standard deviation (nm)	1.91	1.82	1.80





Summary of the size distribution of aerosols generated using a gas stove at maximum power when grilling cheese, wurstel (pork meat), bacon and eggplants (vegetable). Emission factor (EF), peak value (PV) and mode diameter (MD) for number (*N*), surface area (*S*) and mass (*M*).

	Cheese	Wurstel	Bacon	Eggplants
NEF (part. min^{-1})	3.4×10^{12}	3.1×10^{12}	2.8×10^{12}	2.6×10^{12}
SEF (μm^2 min^{-1})	1.6×10^5	1.8×10^5	2.3×10^5	4.8×10^4
MEF (μg min^{-1})	9.5×10^3	1.0×10^4	1.2×10^4	5.2×10^2
NPV (part. cm^{-3})	1.1×10^5	1.3×10^5	1.0×10^5	1.2×10^5
SPV (nm^2 cm^{-3})	4.6×10^9	5.8×10^9	9.8×10^9	2.8×10^9
MPV (μg m^{-3})	283	352	389	78
NMD (nm)	41	43	49	29



Indoor sources

Other indoor sources

Incenses/candles

Printers

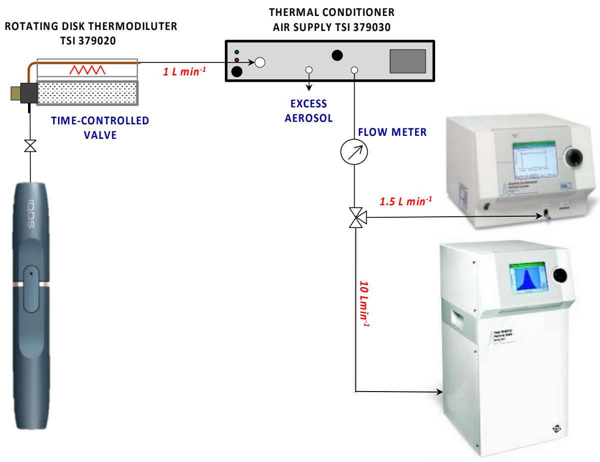
3D printers

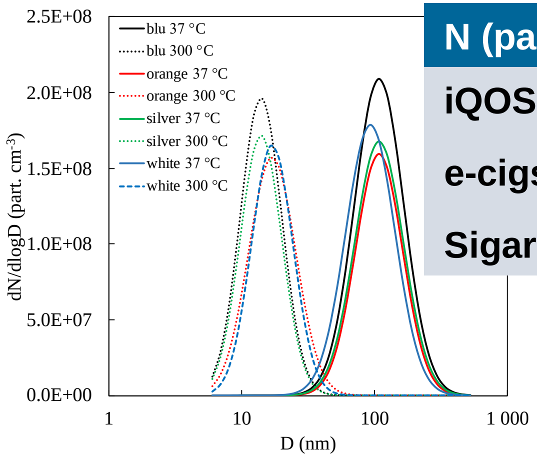
Cigarettes & Co.

Incense, candle

Source	N (part h^{-1}) Average
I1	7.74×10^{14}
I2	4.54×10^{14}
I3	1.08×10^{15}
C1	4.85×10^{13}
C2	4.07×10^{13}
M1	4.57×10^{14}
M2	2.92×10^{14}

cigarette, e-cigs, iQOS cigs





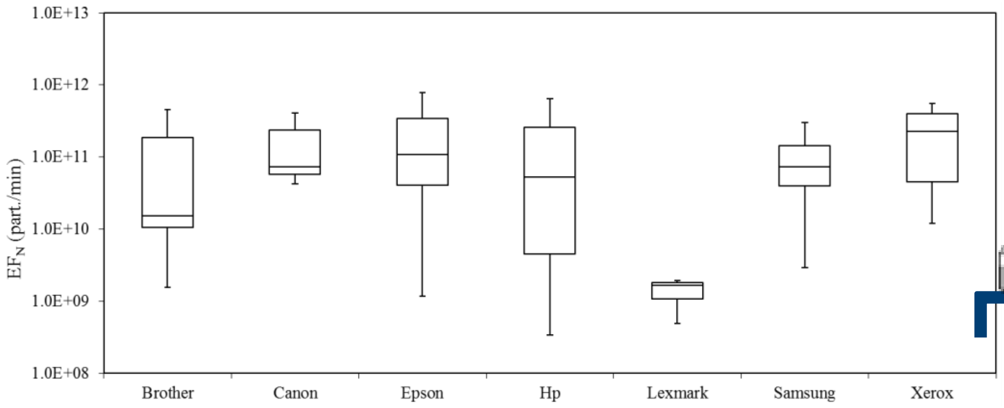
N (part. cm^{-3})

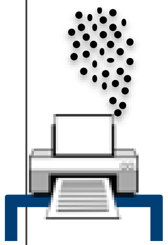
iQOS <1×10^8

e-cigs = 10^8 - 10^9

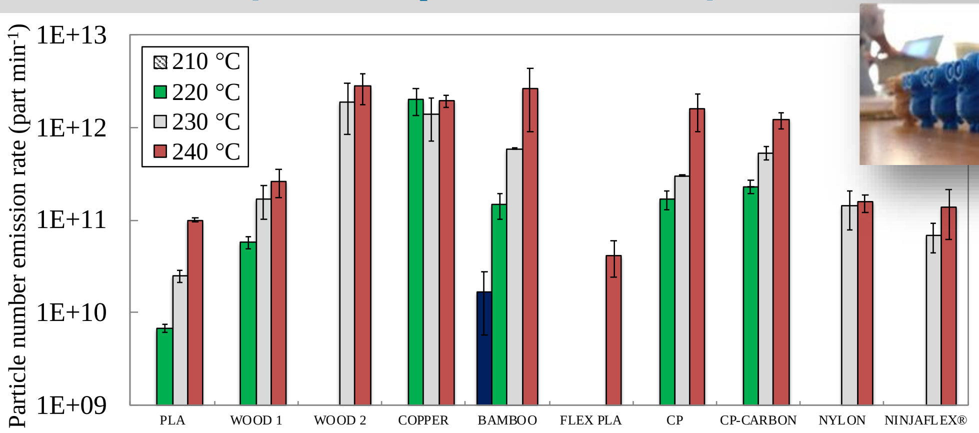
Sigarette <10^9

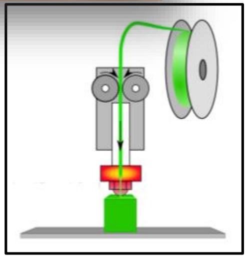
printers





3D printers (material, temperature effect)





Indoor sources

Size-resolved chemical analysis of freshly emitted particles

Incenses
candles
Mosquito coils
Cooking activities

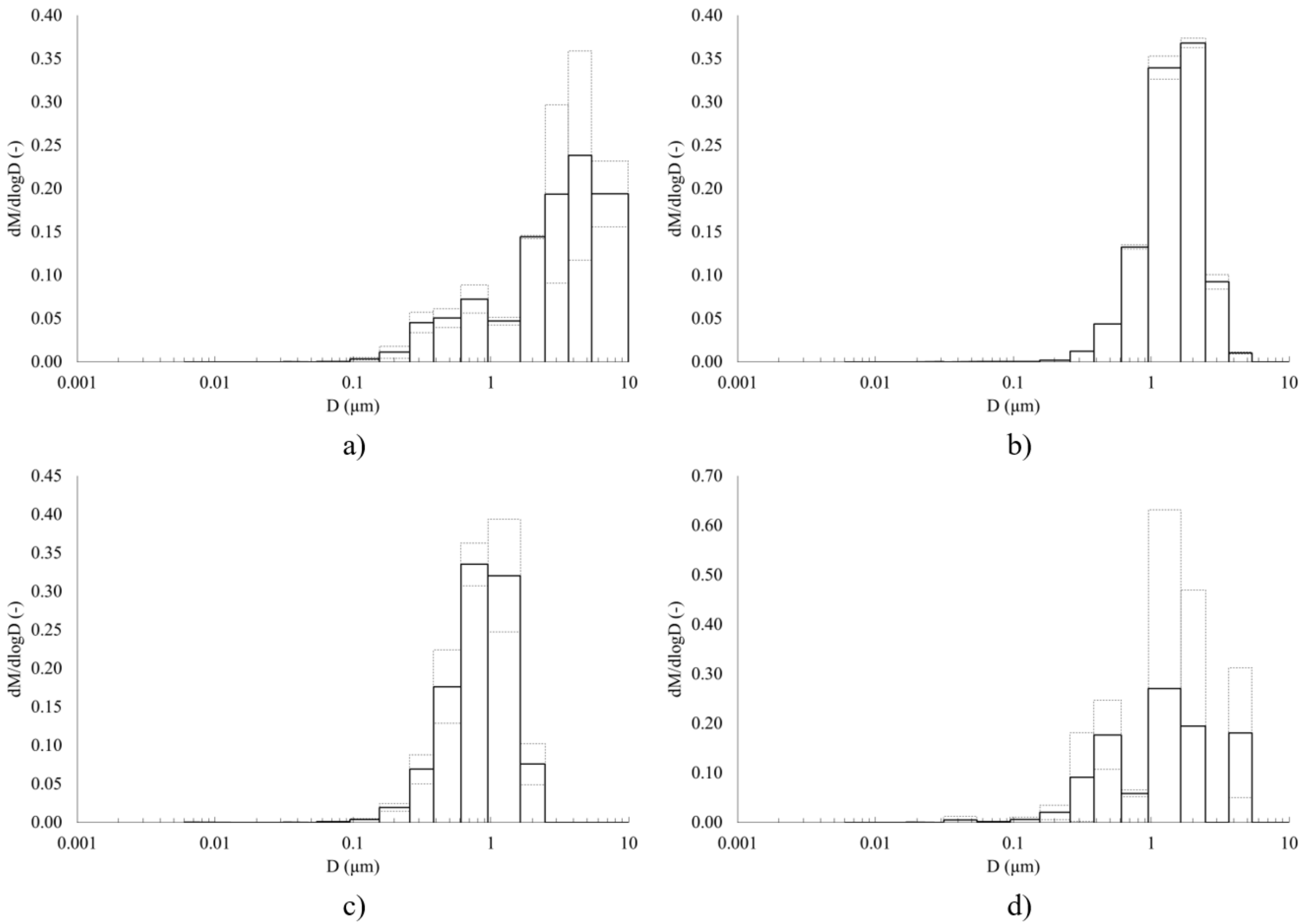


Figure 1 – Particle mass distributions, normalized to the total concentration, measured during combustion of candles (a), incenses (b), mosquito coils (c), and grilling bacon (d) through the ELPI+™: solid lines represent average distributions, dashed lines represent standard deviations of the measured distributions.

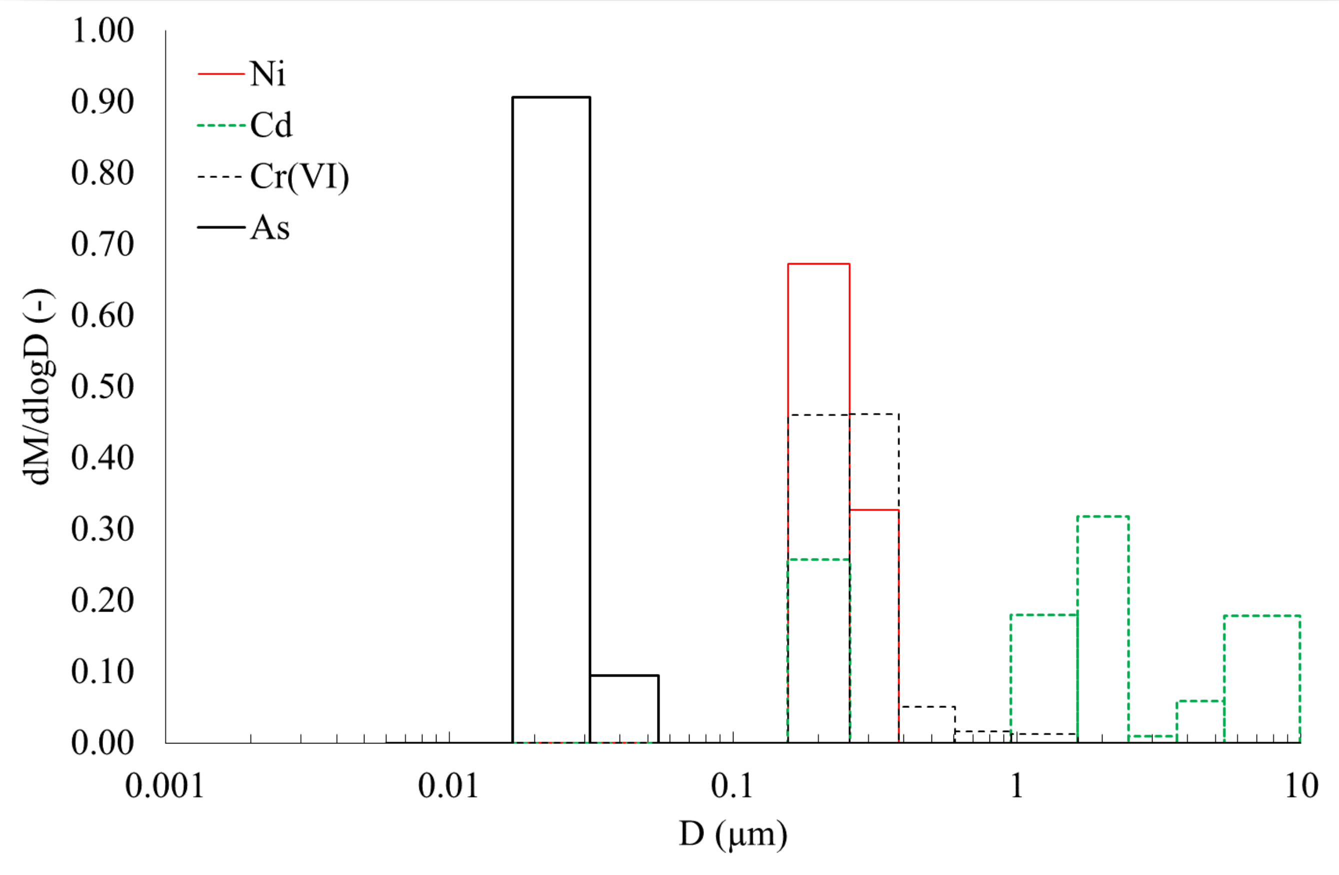
Indoor sources

Size-resolved chemical analysis of freshly emitted particles

Incenses
candles
Mosquito coils
Cooking activities

Table 5 – Mass fra… …e indoor sources
under investigation. …ic compounds are

Source		… n	Mn
Candles		$\times 10^{-5}$	4.96×10^{-7}
Incenses		$\times 10^{-5}$	
Mosquito coils	2. …	$\times 10^{-5}$	

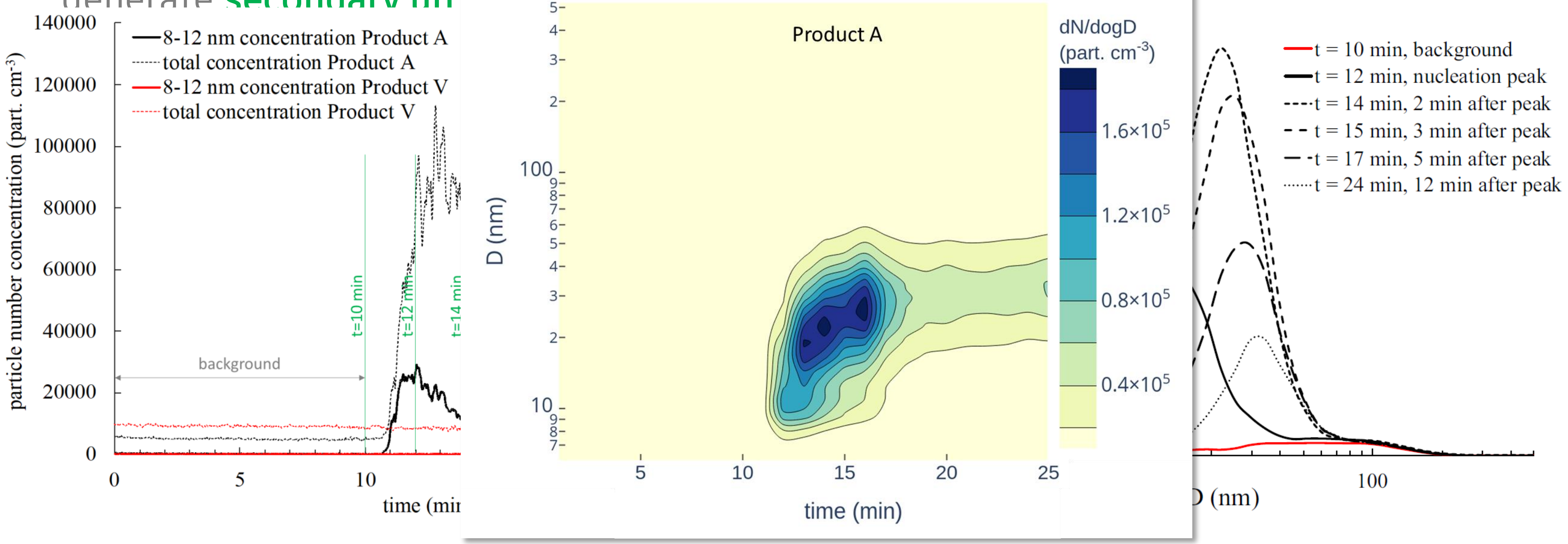


Indoor sources

Other sources (no combustion): nucleation

Cleaning products

- Chemical reactions induced by ozone and volatile organic compounds (VOCs) produce multi-oxygenated compounds (e.g. dicarbonyls, peroxides) that, after condensations, generate **secondary ult**



Outdoor exposure

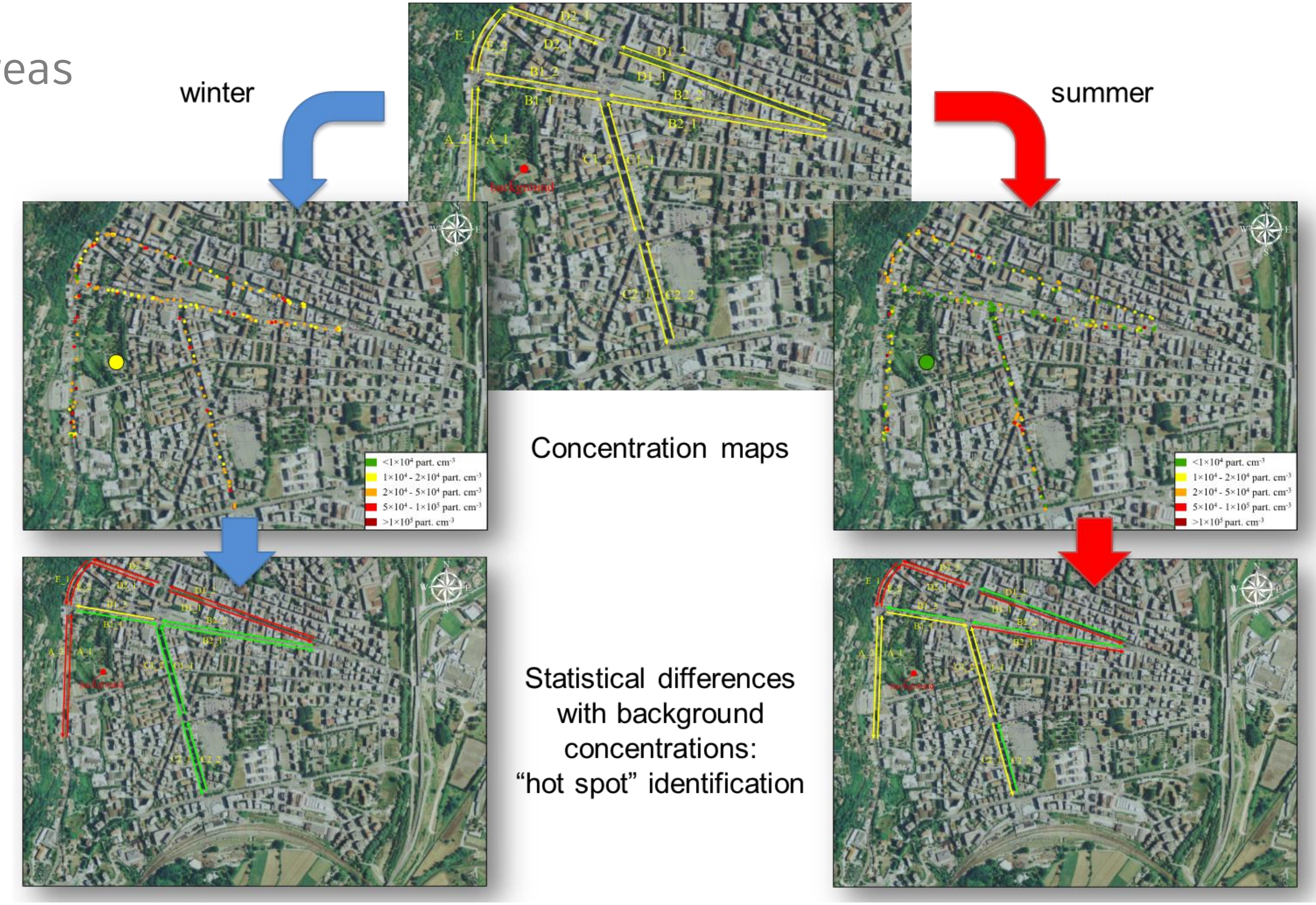
Urban areas

Concentration gradients in urban areas

Table 5

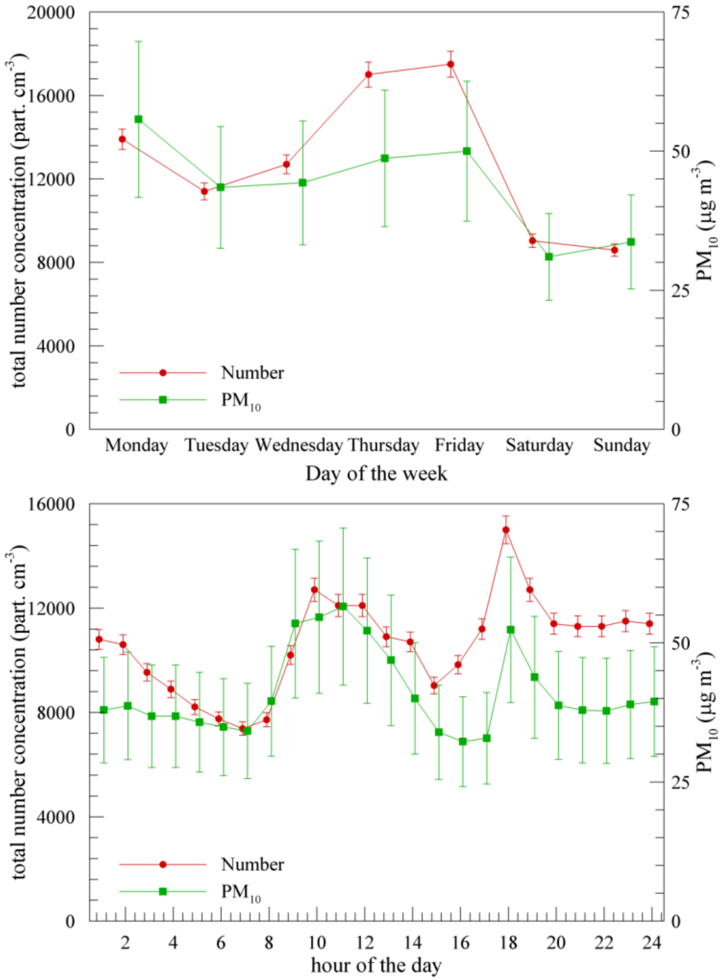
Number of road links' sides (over 16 investigated) having concentrations statistically larger than the simultaneous background levels in terms of particle number (N), alveolar-deposited surface area (S), and PM_{10}.

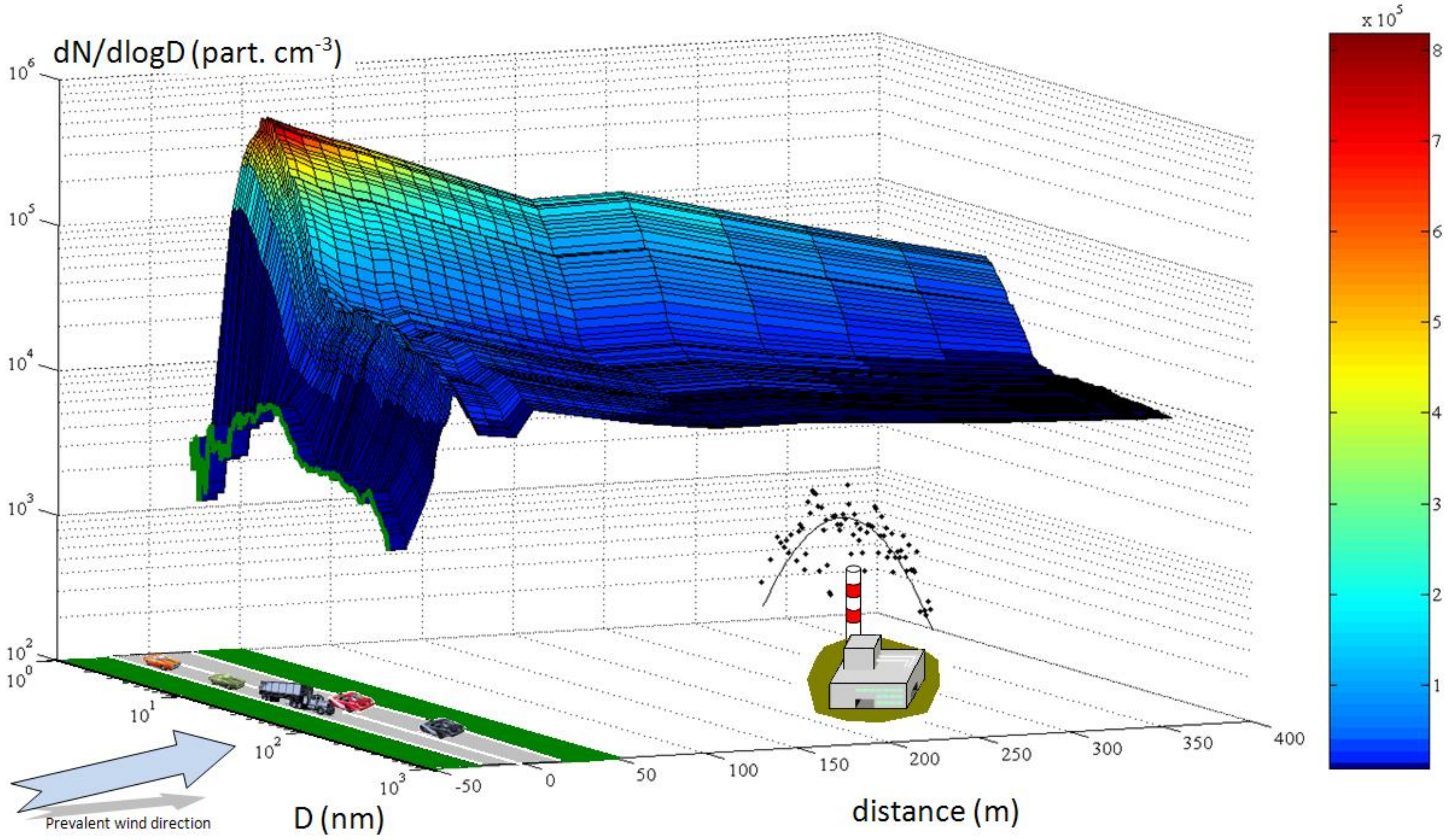
Date	Run	N	S	PM_{10}
27-Jan	1	9 of 16	11 of 16	–
	2	8 of 16	4 of 16	–
	3	3 of 16	5 of 16	–
	4	4 of 16	5 of 16	–
19-Feb	1	8 of 16	4 of 16	2 of 16
	2	2 of 16	3 of 16	2 of 16
Median Heating season		8 of 16	3 of 16	2 of 16
5-May	1	7 of 16	10 of 16	6 of 16
14-May	1	9 of 16	6 of 16	5 of 16
24-Jun	1	7 of 16	8 of 16	–
25-Jun	1	2 of 16	13 of 16	–
	2	8 of 16	12 of 16	–
29-Jun	1	9 of 16	8 of 16	–
Median Non-heating season		6 of 16	10 of 16	5 of 16



Outdoor exposure

Incinerators vs. streets/roads



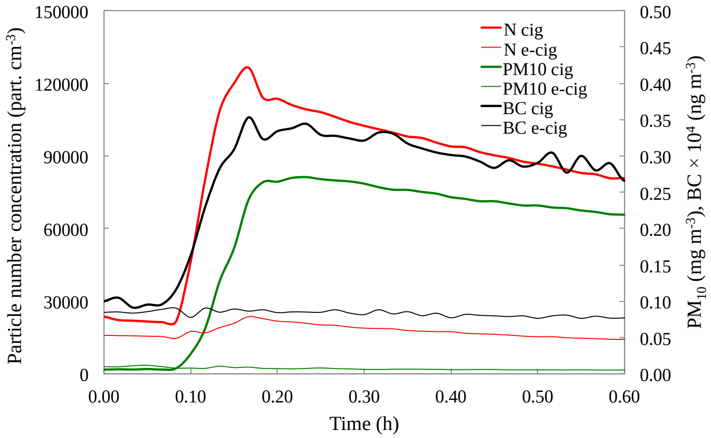


Indoor exposure

Exposure due to indoor sources

- Homes (cooking, biomasses, cigarette
- Workplace
- Industries (welding, etc.)
- Operating rooms
- …

Second-hand smoking



Operating rooms

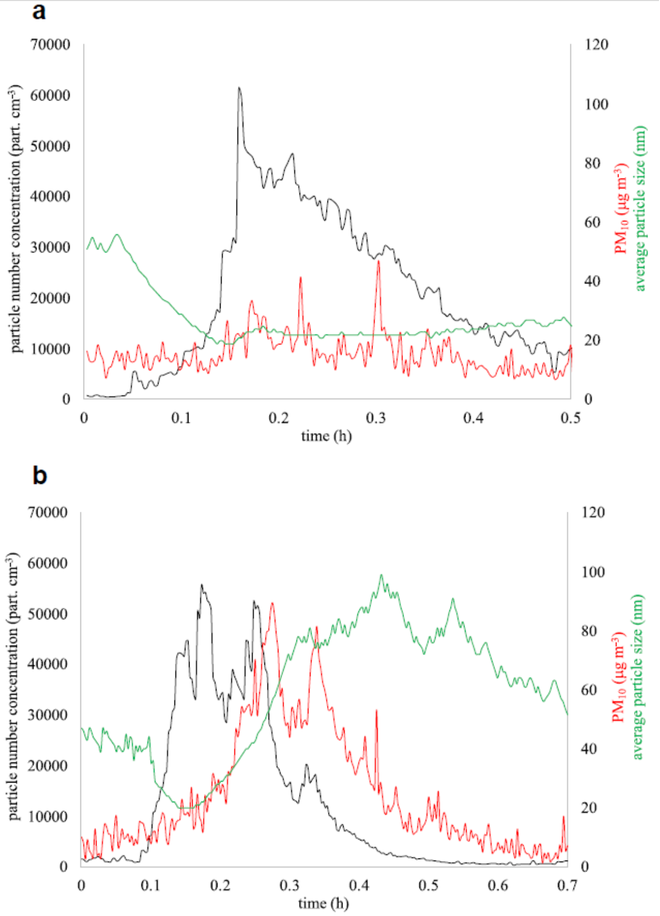
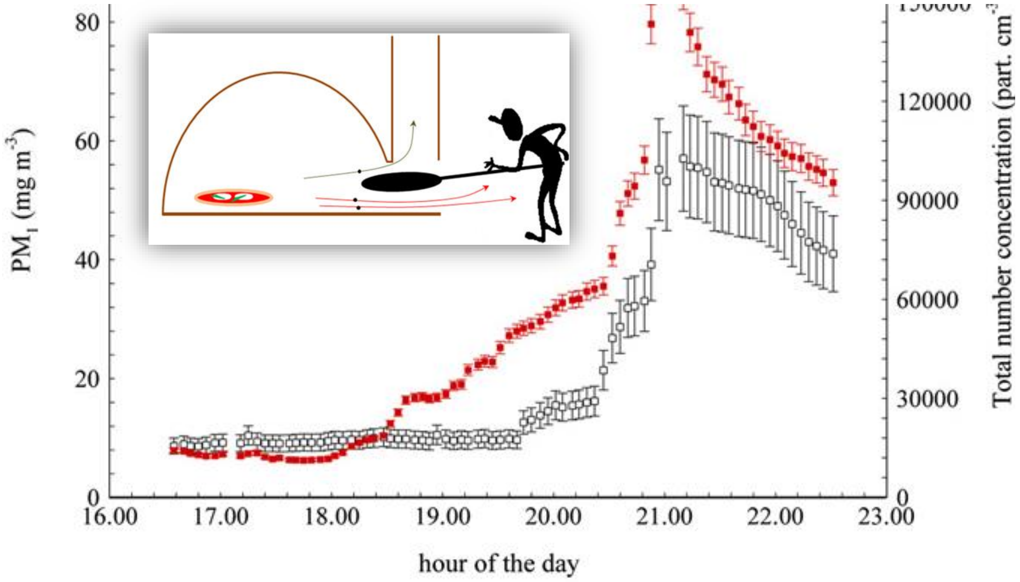
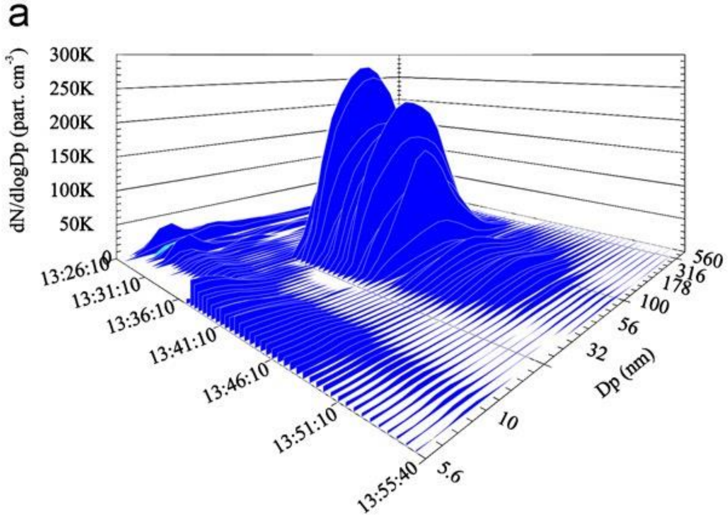


Fig. 1. Particle number concentration, PM_{10}, and average particle size as a function of time measured during a cesarean section operation (CSO 14) and an orthopedic surgery (OS 10).

Pizzerias/restaurants



Welding sites



Indoor exposure

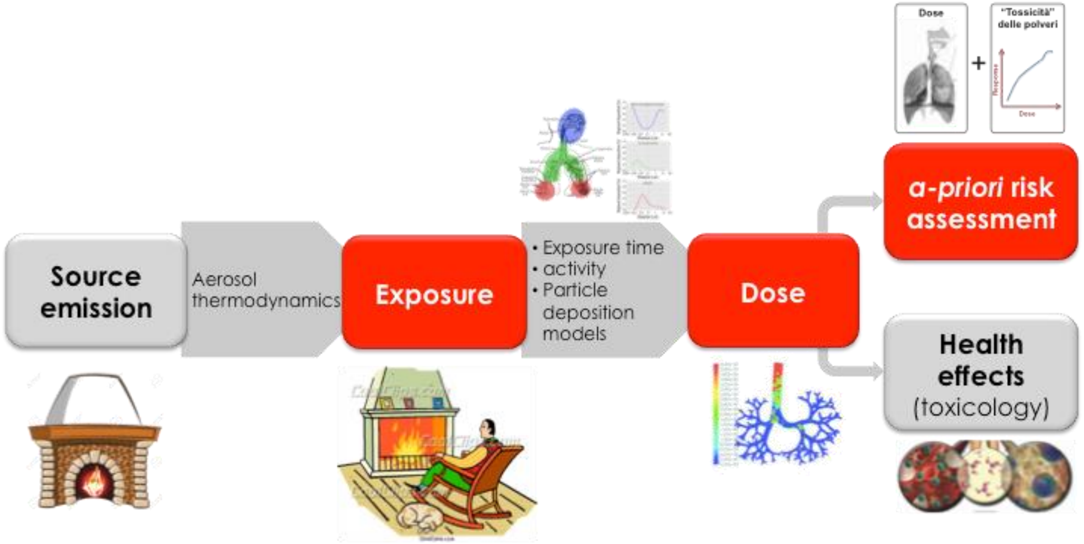
Emission of residential heating systems

State-of-art & Open questions

- Biomass-burning emission in outdoors
- Indoors?
- Ultrafine Particles?
- Exposure assessment?
- Dose?
- Risk?

Aim of the research

- Indoor exposure
  - Open and closed fireplaces, pellet stoves
  - N, S, PM_{10}
  - Carcinogenic compounds
- Dose and risk estimate



Indoor exposure

Emission of residential heating systems

Methodology

Measurment of the exposure in 30 houses (10 per each heating system)

- Apparatus - hand-held monitors:
- diffusion charging counter (particle number & lung-deposited surface area)
- laser photometer (PM_{10}).
- Procedure:
  - 30-60 min of background concentrations (no other sources),
  - 2-4 h of measurement during the combustion phenomena (no other sources).

Carcinogenic compound on PM10

Quantification of di As, Cd, Ni, BaP (Group 1 IARC)

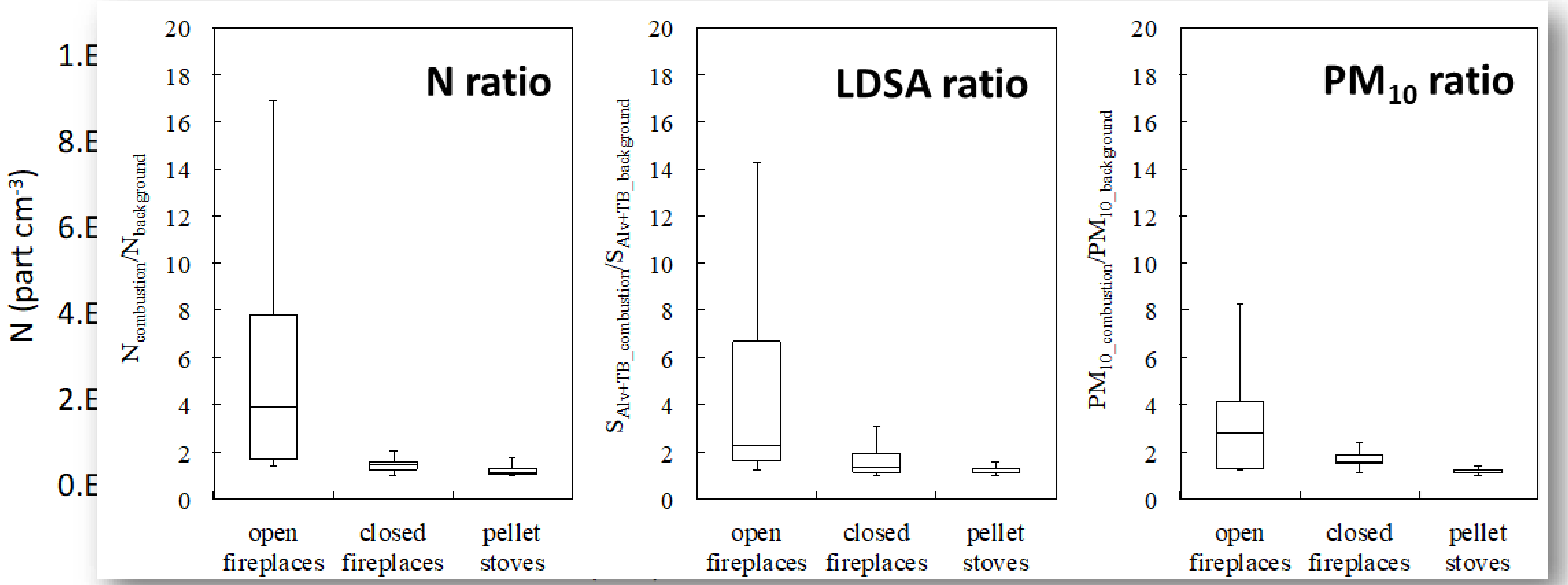
- Gravimetric sampling (PM_{10}) emitted by wood and pellet
- GC/MS for BaP
- INAA technique for heavy metals.

Indoor exposure

Emission of residential heating systems

Results

Concentrations and «over-exposure»

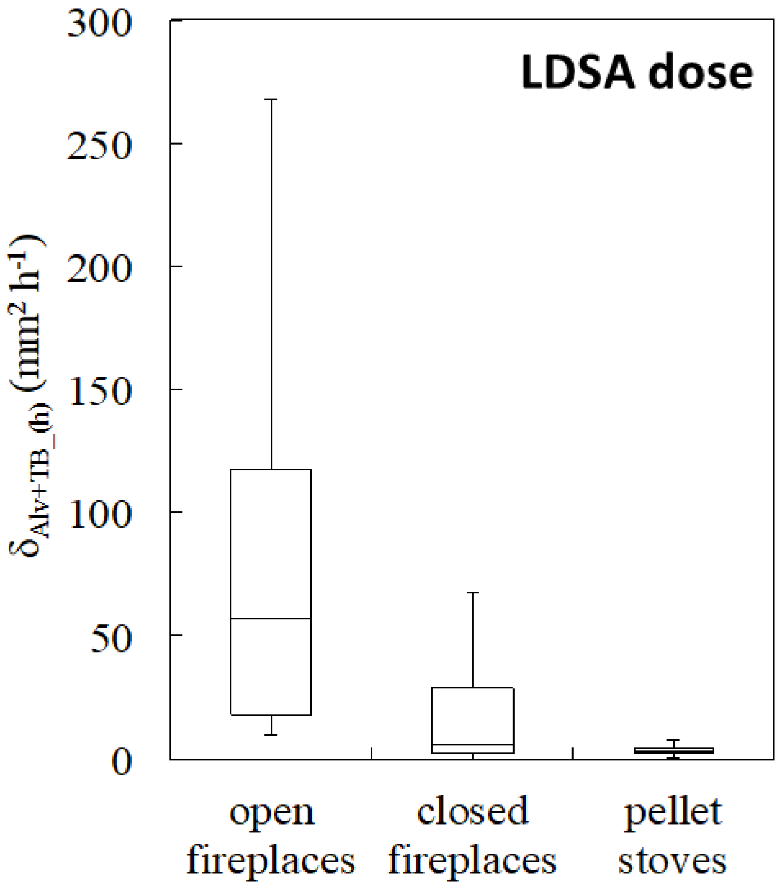


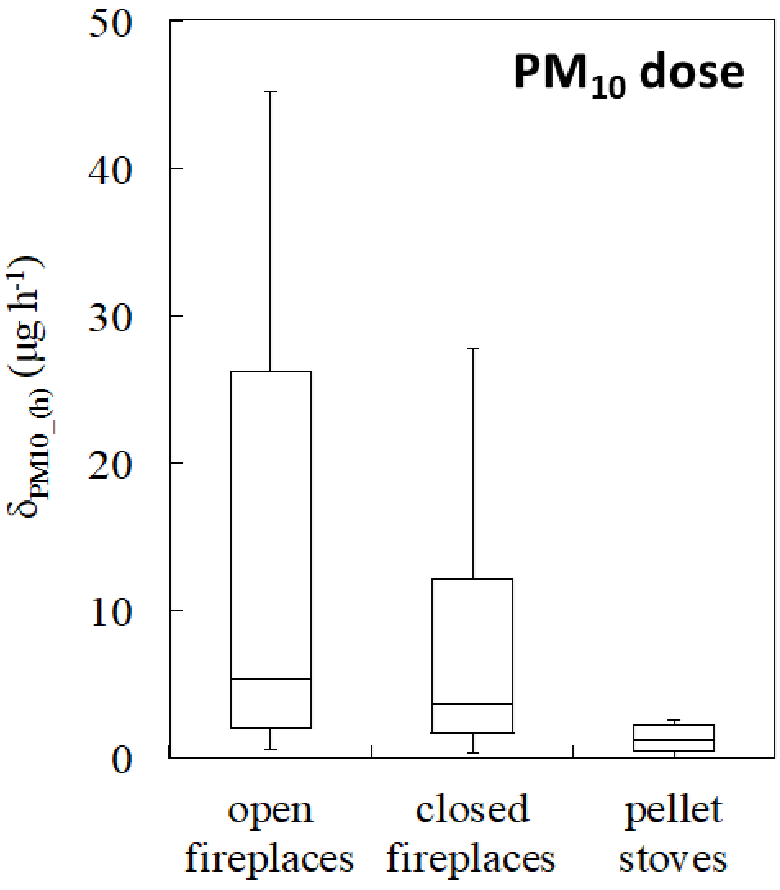
Indoor exposure

Emission of residential heating systems

Results

Extra-doses





Indoor exposure

Emission of residential heating systems

Results

Toxicity and risk

$$SF_m = \sum_i^n SF_i \cdot \frac{m_i}{PM_{10}}$$

	Wood	Pellet
m_{BaP}/PM_{10}	$6.2 \pm 0.7 \times 10^{-5}$	$4.0 \pm 0.3 \times 10^{-6}$
m_{As}/PM_{10}	< LOD	$9.0 \pm 1.8 \times 10^{-5}$
m_{Cd}/PM_{10}	$2.4 \pm 0.5 \times 10^{-4}$	$4.3 \pm 0.9 \times 10^{-4}$
m_{Ni}/PM_{10}	$7.2 \pm 1.4 \times 10^{-3}$	$1.2 \pm 0.2 \times 10^{-2}$
SF_m	**$6.9 \pm 1.3 \times 10^{-3}$**	**$1.3 \pm 0.2 \times 10^{-2}$**
Contribution to the SF_m	BaP=4%, As<1%, Cd=2%, **Ni=94%**	BaP<1%, As=11%, Cd=2%, **Ni=87%**

	Open fireplaces	Closed fireplaces	Pellet stove
Lifetime $ELCR_{extra}$	**9.0×10^{-3}**	**1.1×10^{-3}**	**1.4×10^{-3}**
LDSA contribution	99.97%	99.93%	99.93%
PM_{10} contribution	0.03%	0.07%	0.07%

…comparison

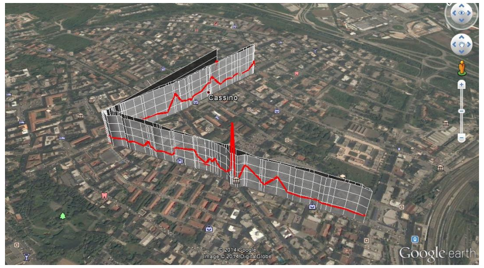
Exposure scenario	Risk
Italian not smoking pop.	$\approx 2 \times 10^{-2}$
Smokers	$\approx 1\text{-}5 \times 10^{-1}$
Italian students (5 yrs)	$\approx 2 \times 10^{-4}$
Downwind of incinerator	$\approx 7 \times 10^{-7}$

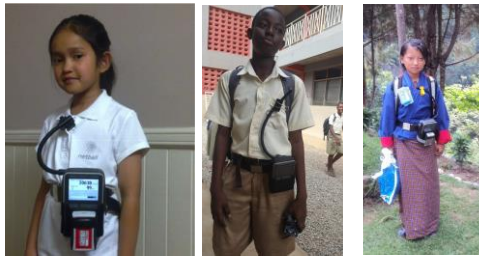
Maximum tolerable risk EPA-WHO = **1×10^{-5}** (1 new case per 100000 people)

Indoor vs. outdoor exposure

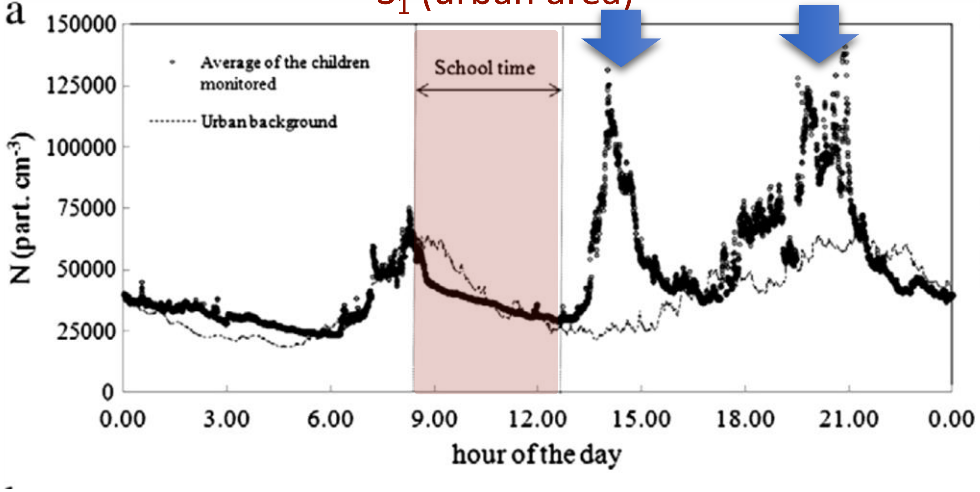
Measurement at “personal” scale

- Portable counters (Italia, Ghana, Bhutan, Australia, Brasile, Egitto, Inghilterra, Svezia, Spagna, etc.)
- Children – schools
- Adults

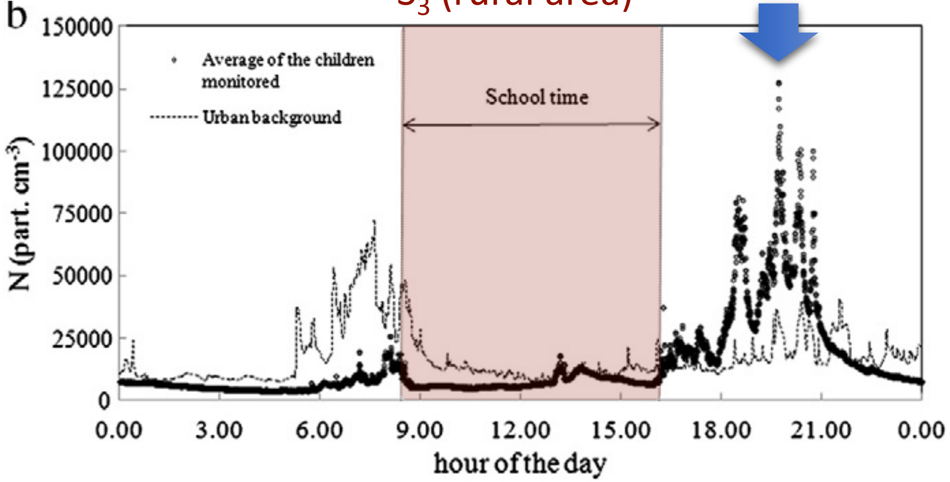




S$_1$ (urban area)



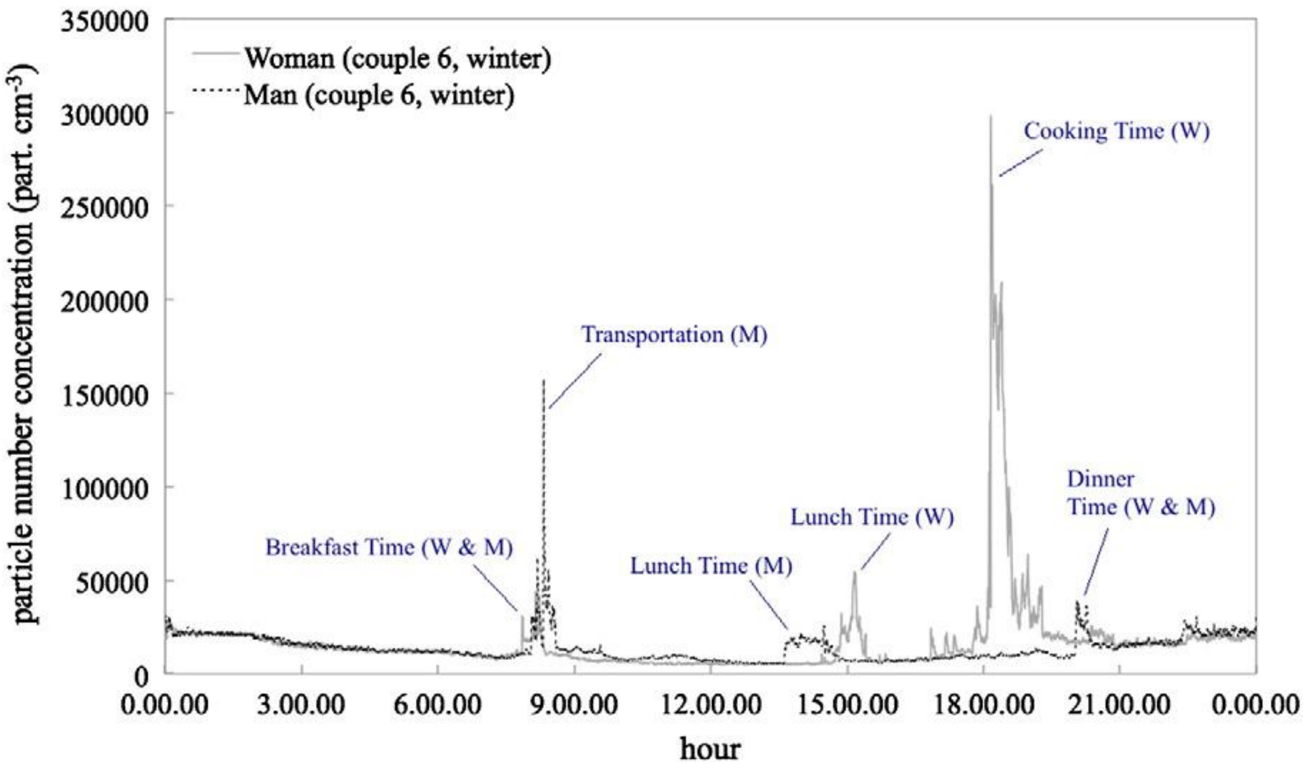
S$_3$ (rural area)



Indoor vs. outdoor exposure

Measurement at “personal” scale

- Lifestyle effect
- Average exposure or housewives 30-40% higher than workers
- Cooking contribution to the exposure



Indoor vs. outdoor exposure

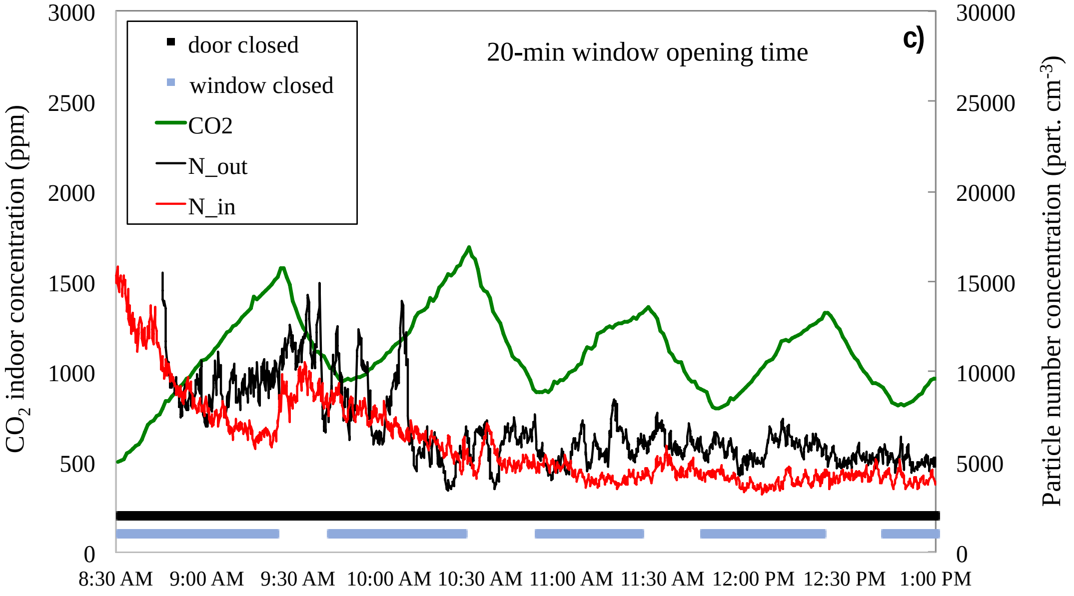
Exposure in schools: emission vs. ventilation

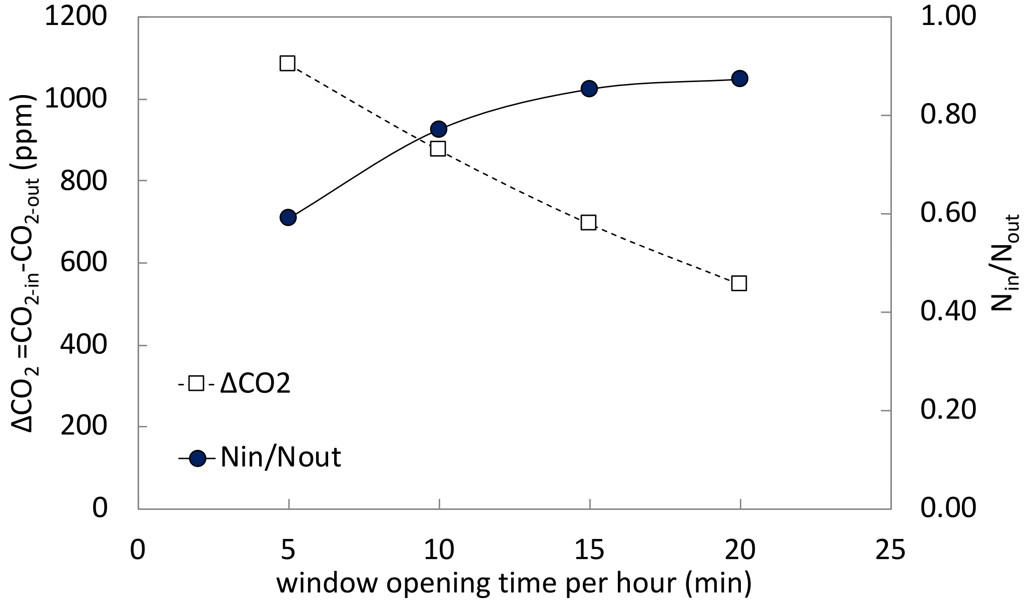
- Measurements of PM_{10}, Number concentrations, CO_2
- Naturally-ventilated classrooms (pre-retrofit)

Diffusion Charger Particle Counter

DustTrak photometer 8534: PM_{10}

Non-dispersive infrared analyzer: CO_2, T & RH





Indoor vs. outdoor exposure

Exposure in schools: emission vs. ventilation

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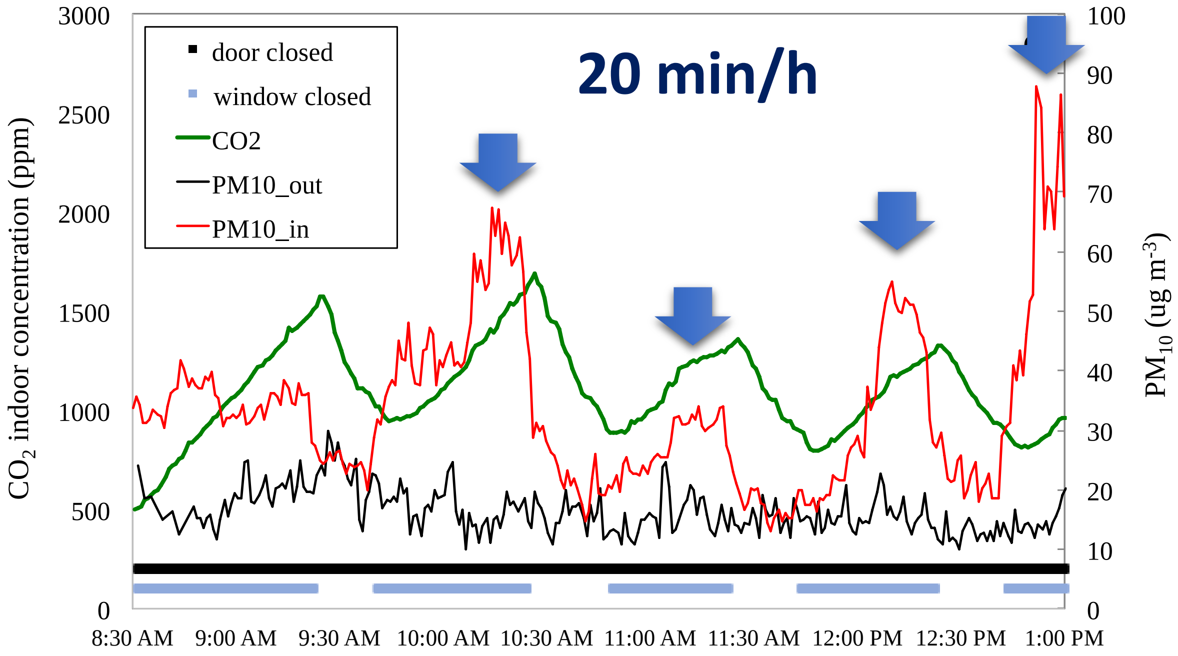
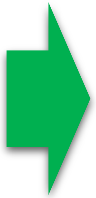
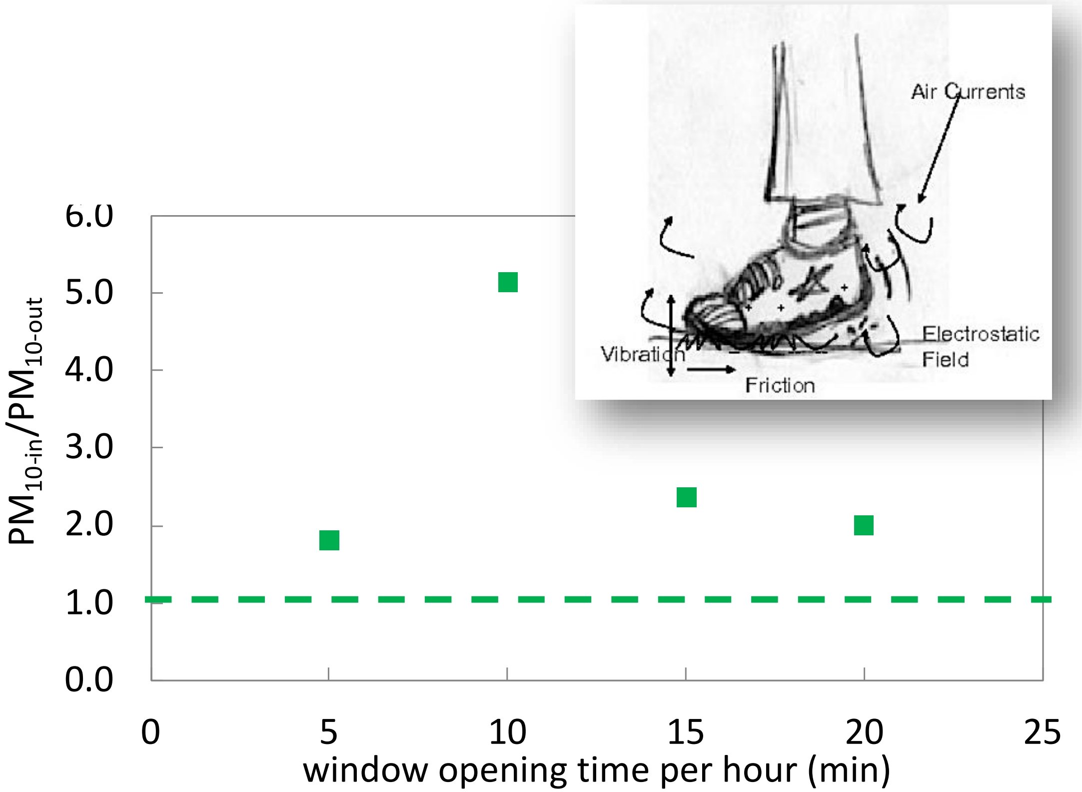






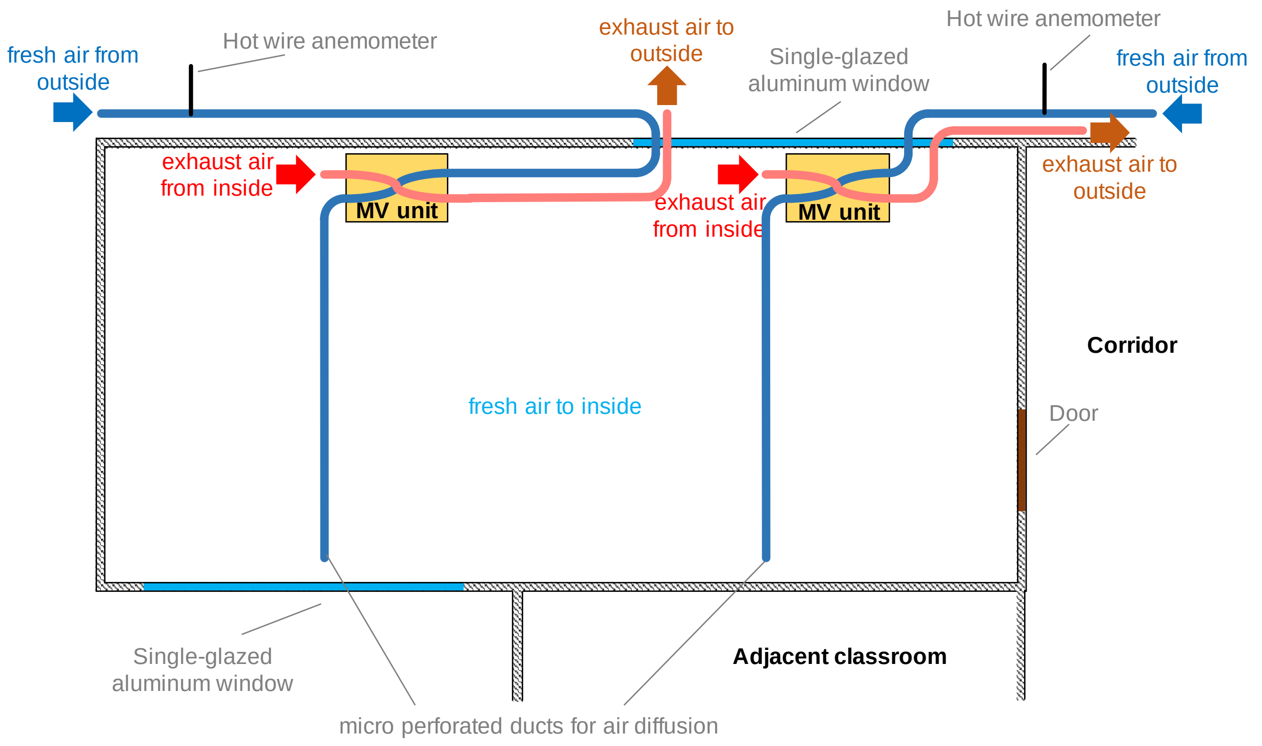
Manual airing reduces CO_2 (and indoor-generated gaseous pollutants) but increases sub-micrometric particles (effect on PM_{10} negligible)

Luca Stabile (*l.stabile@unicas.it*)

Indoor vs. outdoor exposure

Exposure in schools: emission vs. ventilation

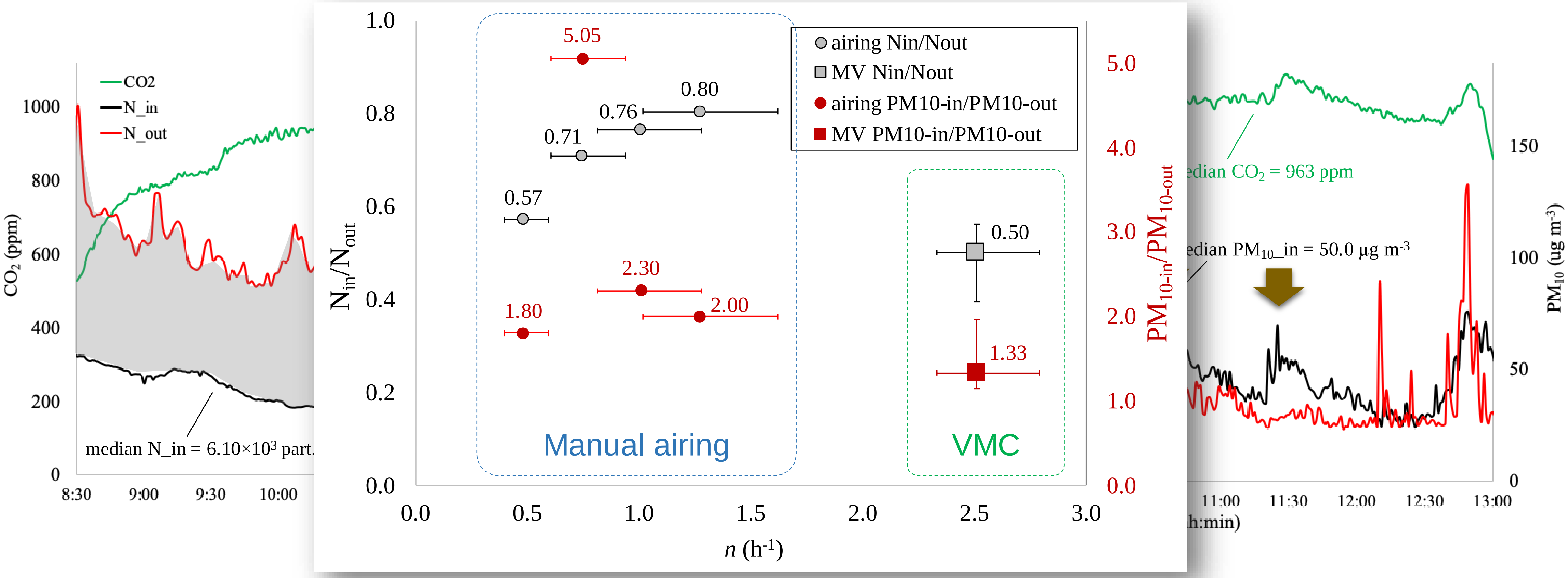
- Measurements of PM_{10}, Number concentrations, CO_2
- Mechanical ventilated classrooms (post-retrofit)



Indoor vs. outdoor exposure

Exposure in schools: emission vs. ventilation

- Measurements of PM_{10}, Number concentrations, CO_2
- Mechanical ventilated classrooms (post-retrofit)

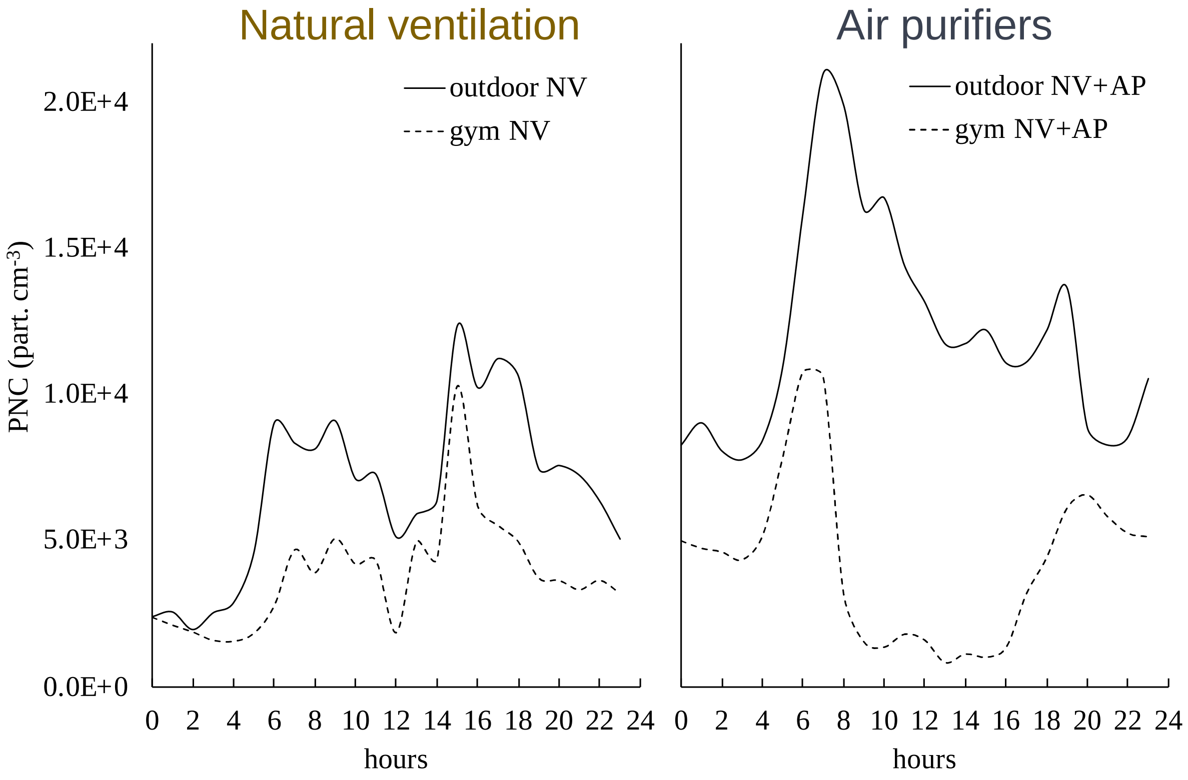


Indoor vs. outdoor exposure

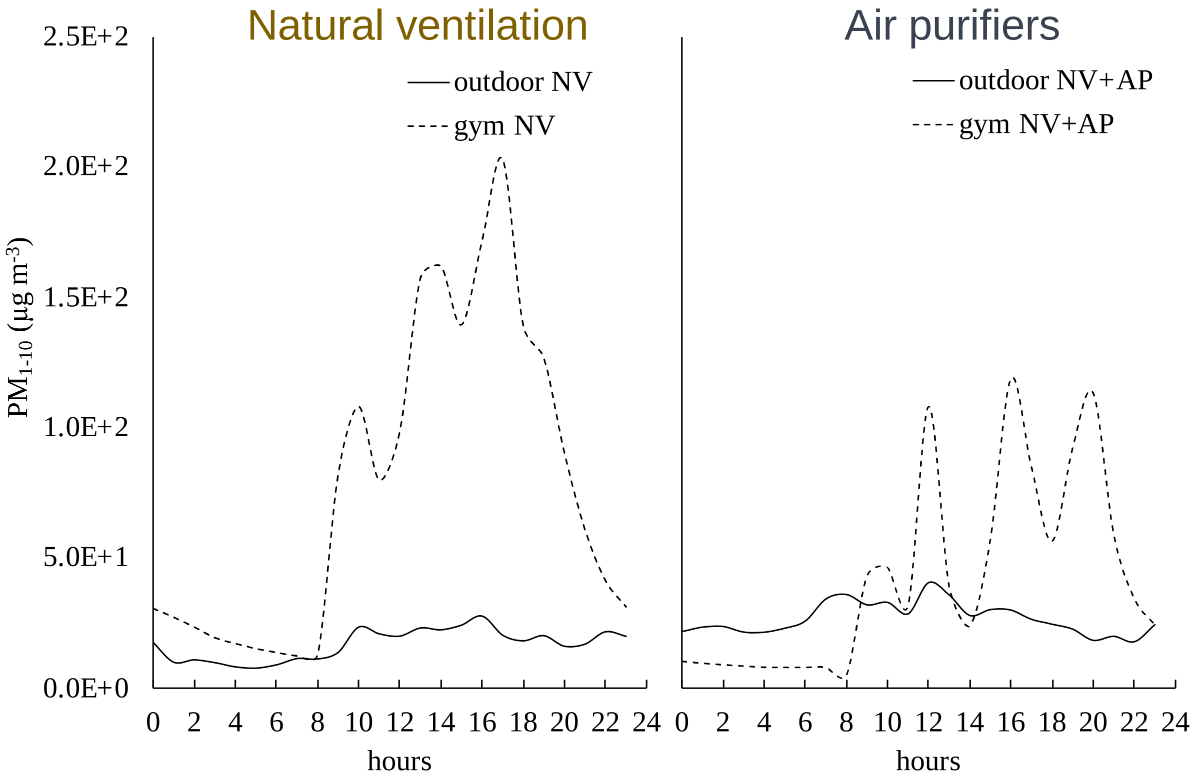
Exposure in schools: air purifiers

School gyms in Barcelona

Particle number concentrations

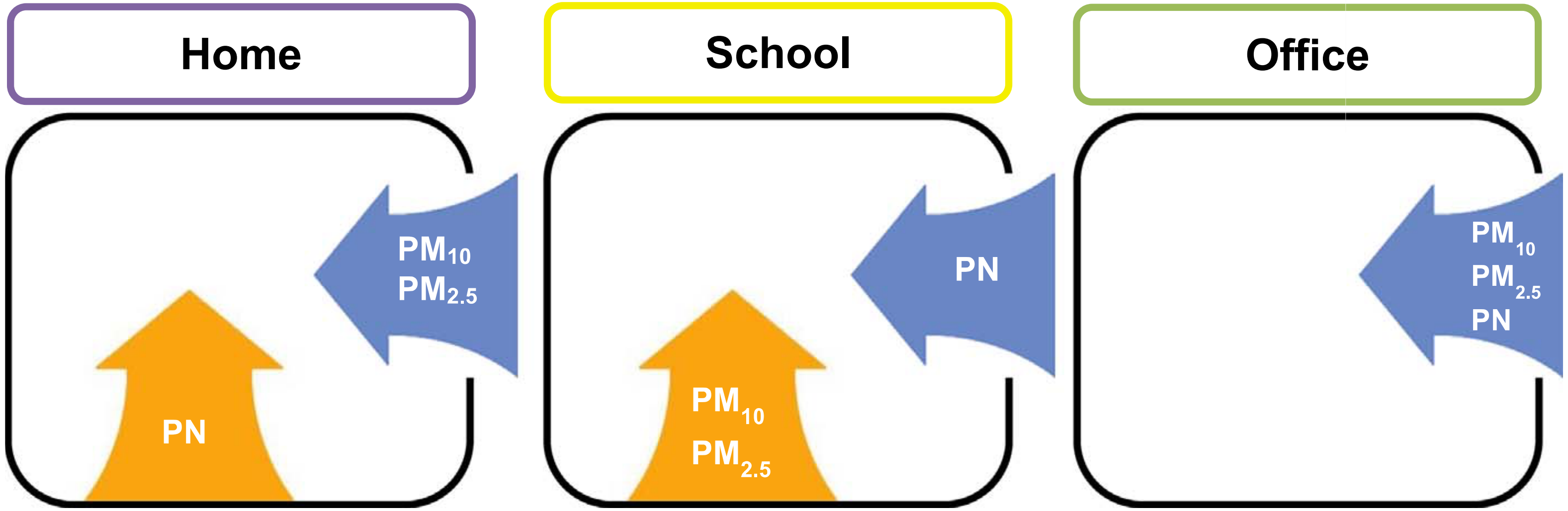


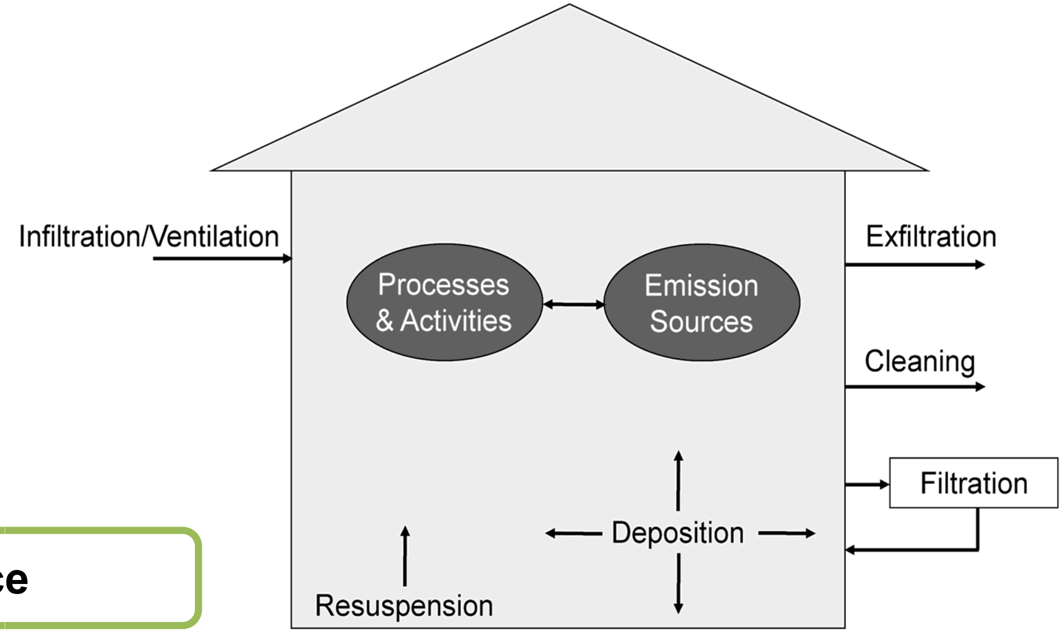
PM_{10}



Indoor vs. outdoor exposure

Type of buildings





Dose

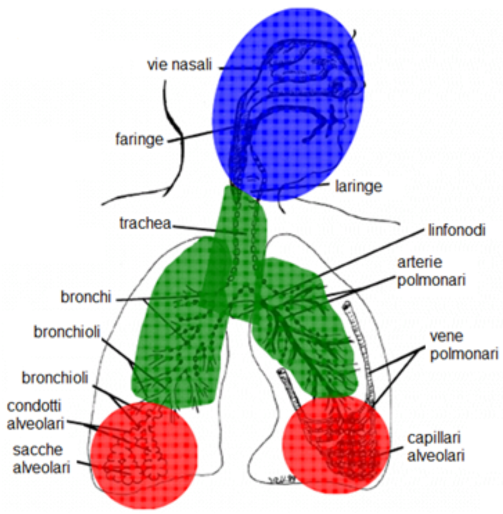
Dose estimate from personal monitoring

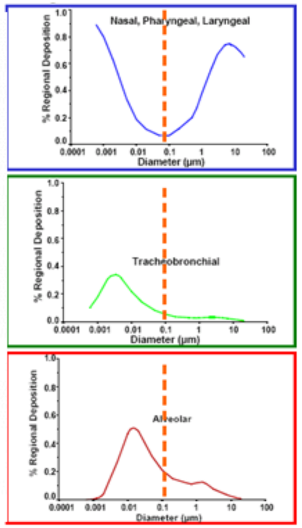
$$DOSE_{Alv+TB} = \mathrm{IR} \cdot S_{Alv+TB} \cdot T \quad (\mathrm{mm}^2)$$

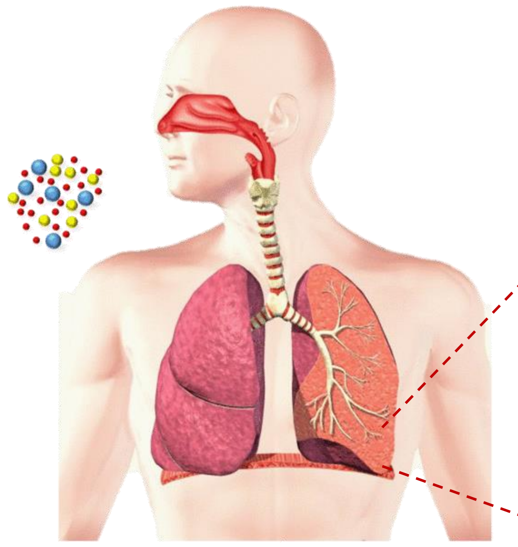
Inhalation rate

Lung-deposited surface area concentration

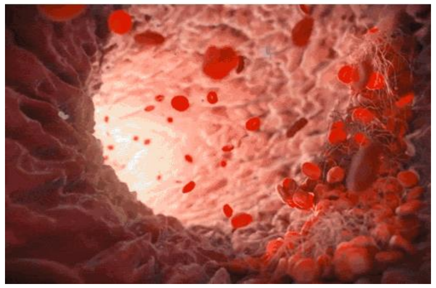
Exposure time







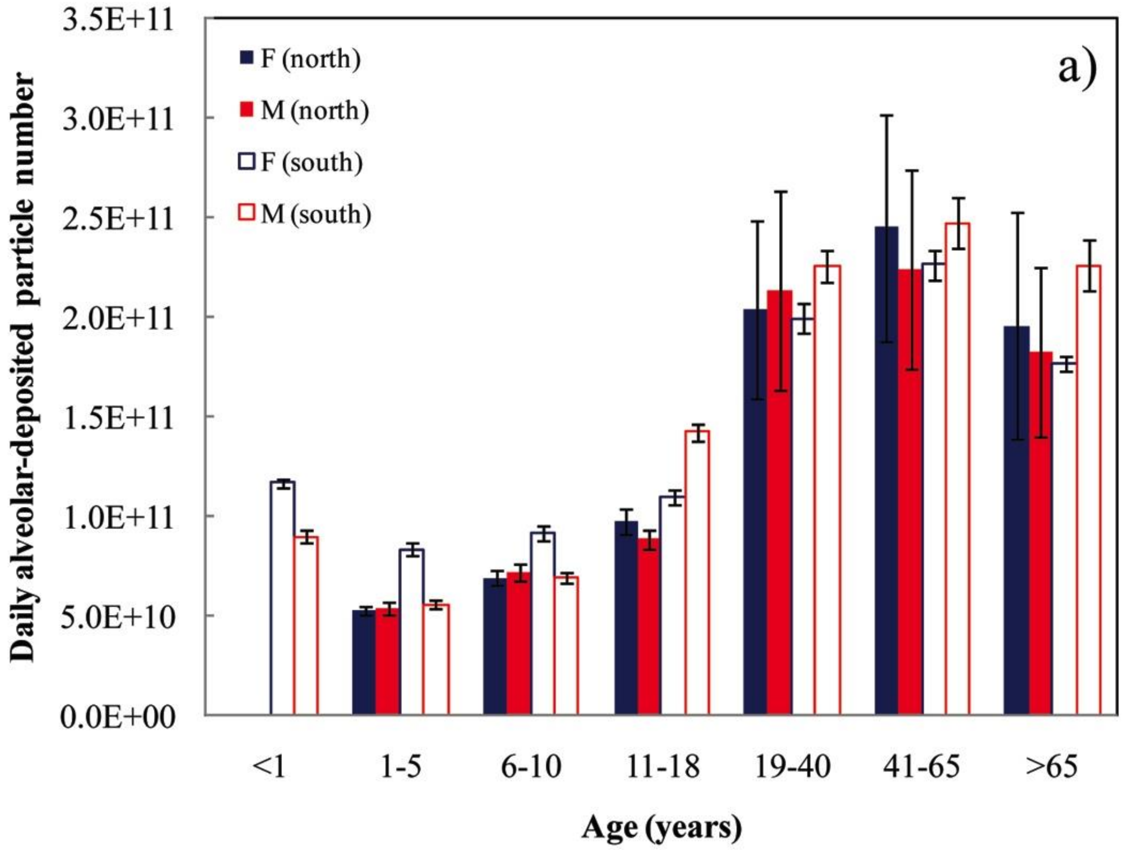
Blood traveling through veins

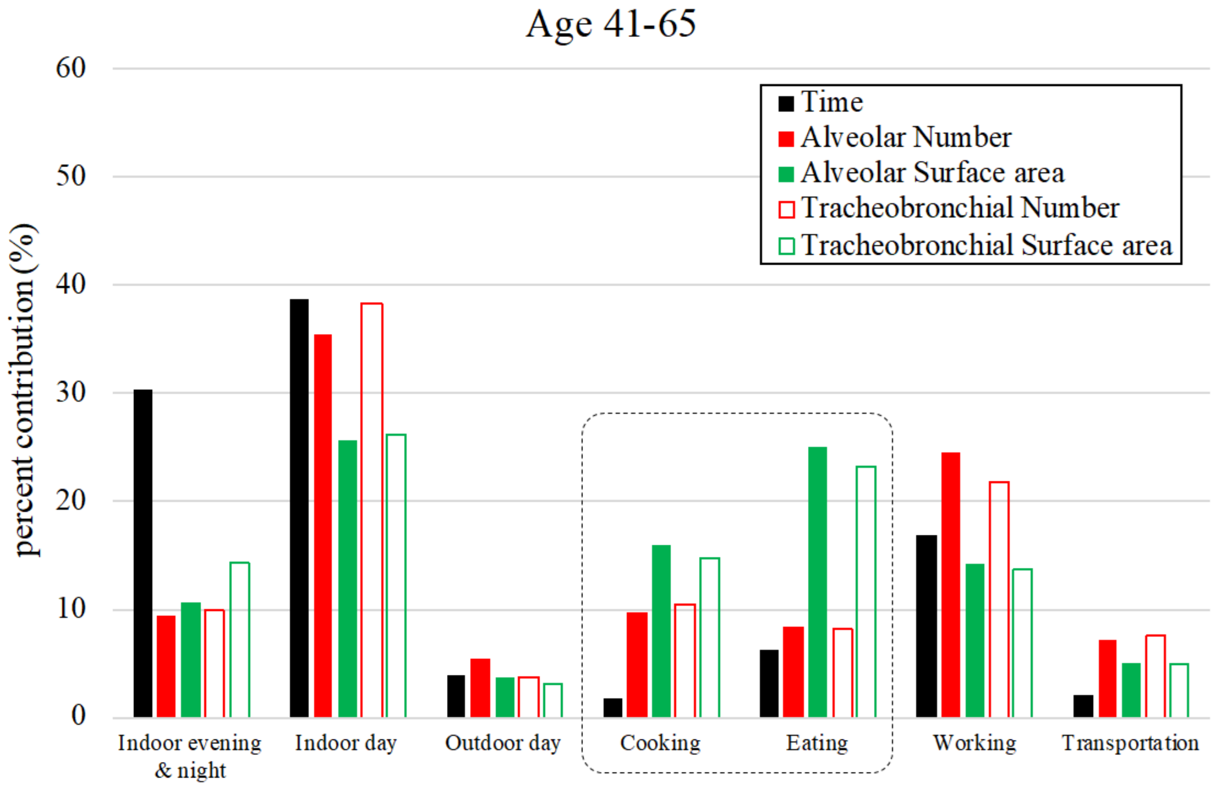


Dose

Dose estimate from personal monitoring

Age and activity effects

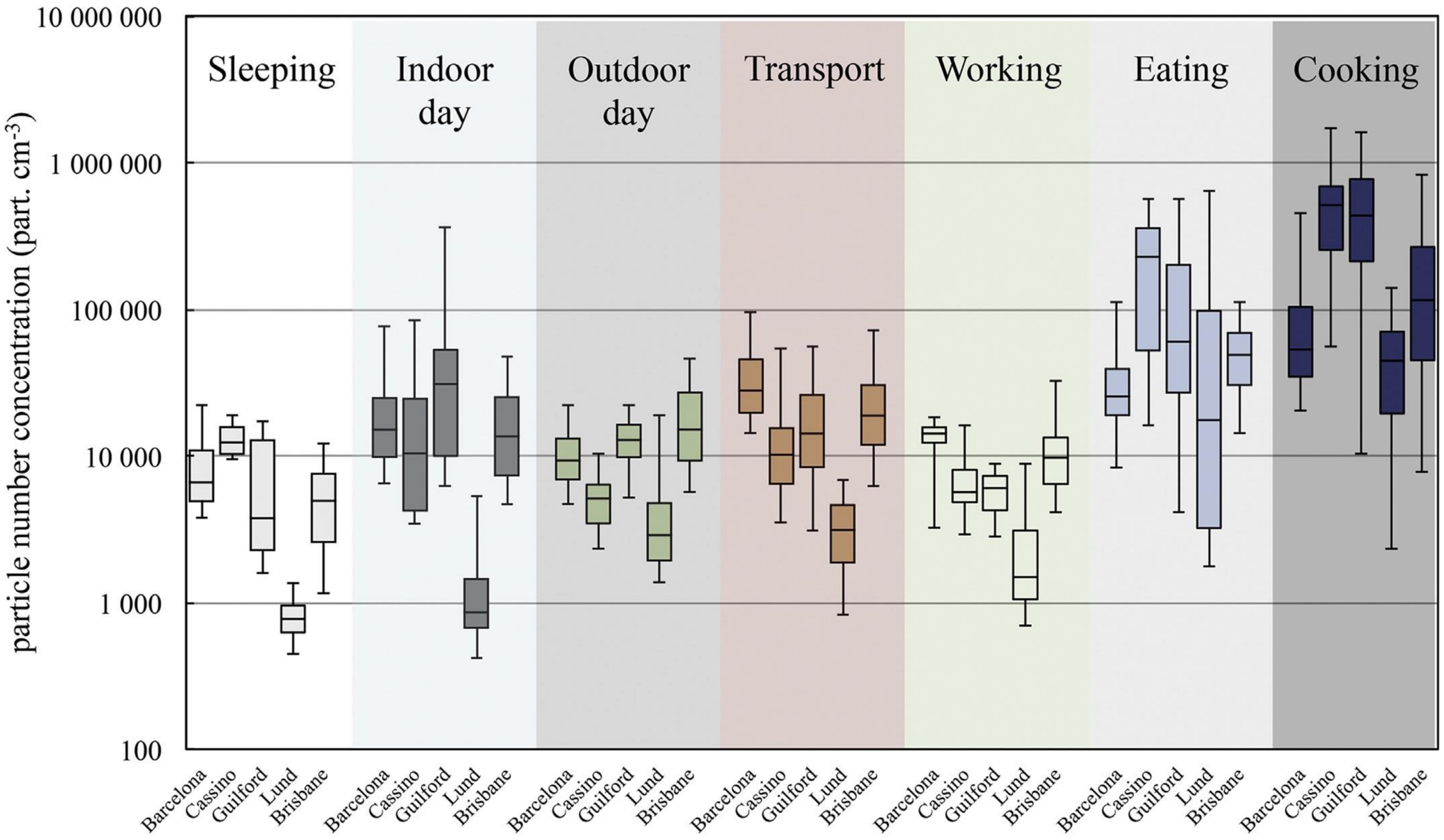




Dose

Dose estimate from personal monitoring

Different populations and lifestyles: western countries



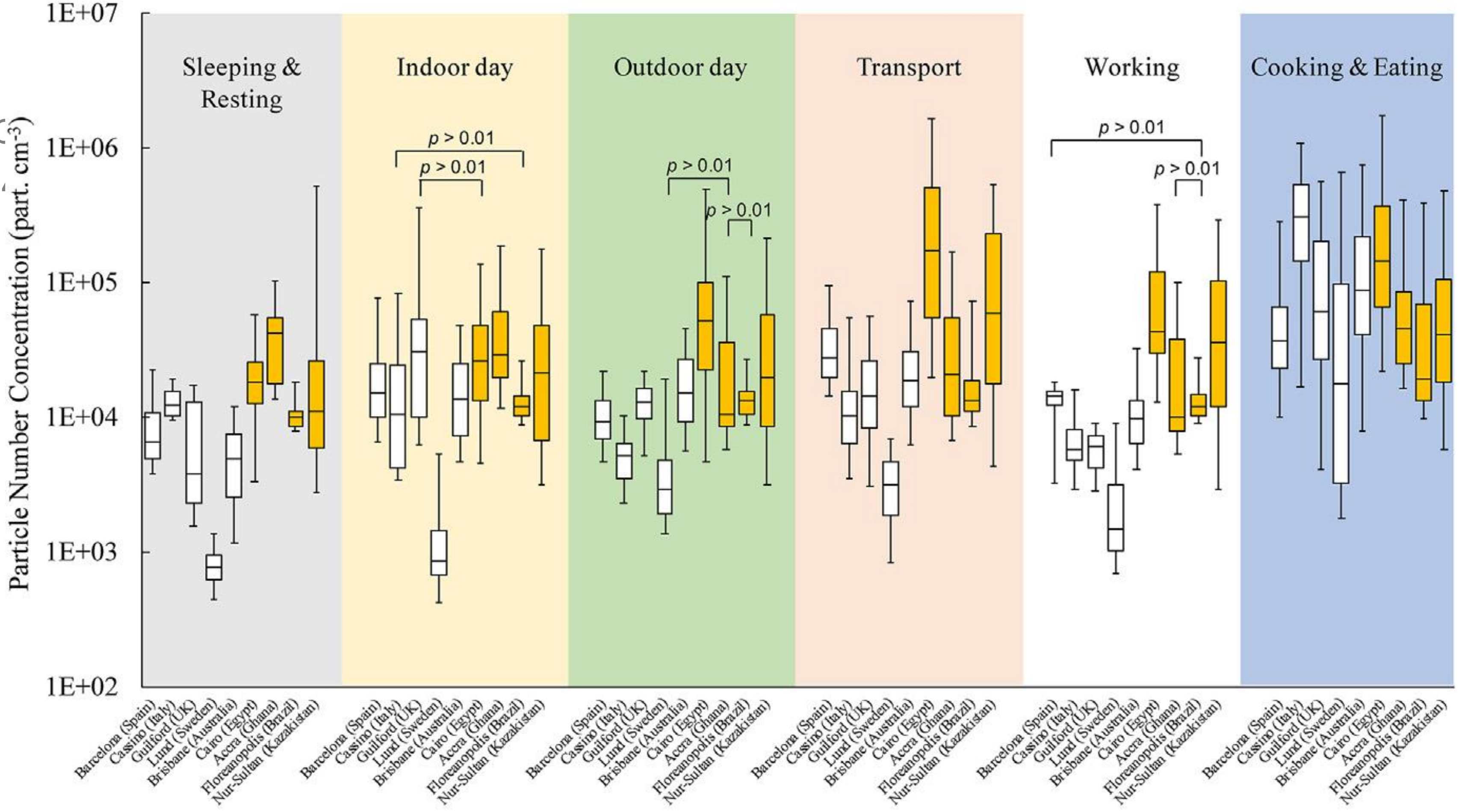
City	Daily Dose (mm^2)
Cassino (Italy)	1114-1873
London (UK)	1083-1521
Barcelona (Spain)	606-763
Brisbane (Aus)	570-782
Lund (Sweden)	52-123

Dose

Dose estimate from personal monitoring

Different populations and lifestyles: western countries…and other countries (e.g. low-income countries)

- Worse outdoor air quality
- Worse air quality while sleep
- Cooking & Eating (just 8%-1



Total doses:

- 1300 mm^2 for Egyptians
- 1100 mm^2 for Ghanaians
- 750 mm^2 for Kazakhstanis
- 450 mm^2 for Brazilians

Risk

Lung cancer risk estimate (applying models)

excess lifetime cancer risk (ELCR)

Risk = Toxicity × Dose

c_f = 6.6×10^{-13} mg nm^{-2} (Sze-To *et al.*, 2012) equivalent toxicity of the particle surface area metric expressed as particle mass

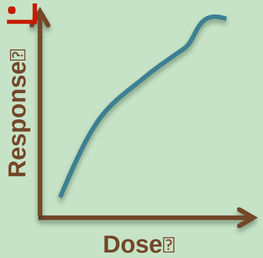
Daily **extra-doses** in LDSA and PM_{10}

$$ELCR_{extra} = \frac{1}{BW}\left(\sum_i^n SF_i \cdot \frac{m_i}{PM_{10}}\right) \cdot \left[c_f \cdot \delta_{Alv+TB} + \delta_{PM_{10}}\right] \cdot N_{day}$$

Body weight (70 kg)

Total exposure period (days per year)

SF: inhalation slope factor (lifetime cancer potency)
the percent increase in the risk of getting cancer associated with exposure to a unit concentration of a chemical every day for a lifetime, here assumed equal to 70 years



Chemical	SF (kg day mg^{-1})
BaP	3.9
As	15.1
Cd	6.3
Ni	0.91

mass concentration of the *i*-th pollutant present on the PM_{10}

$$SF_m = \sum_i^n SF_i \cdot \frac{m_i}{PM_{10}}$$

***SF* of the mixture** of the *n* carcinogenic pollutants on PM_{10}

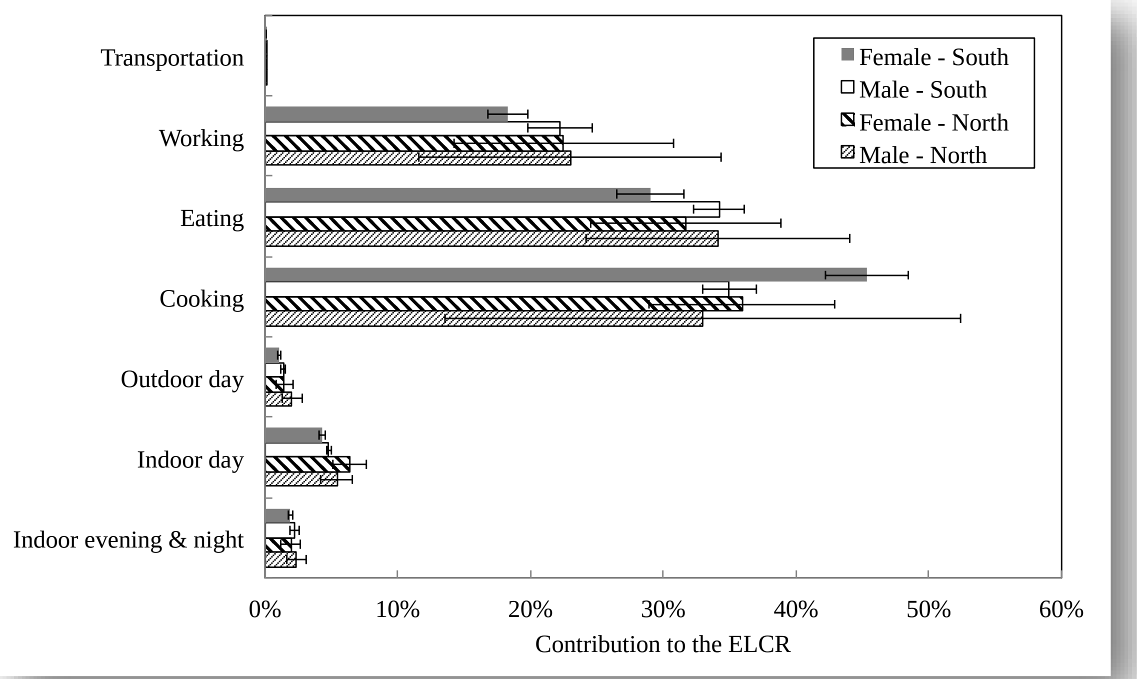
Risk

Lung cancer risk estimate (applying models)

Italian population

WHO guideline: ELCR < 1×10^{-5} (one new case for 100 000 people)

Exposure	ELCR
Avarage Italian population	1.9×10^{-2}
Avarage Italian population with **air quality**	1.5×10^{-2}
Avarage Italian population with **quality**	1.3×10^{-4}
Smokers	$>1\times10^{-1}$
Vapers	1×10^{-4}

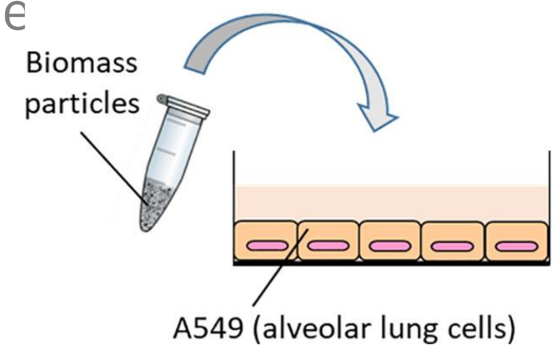


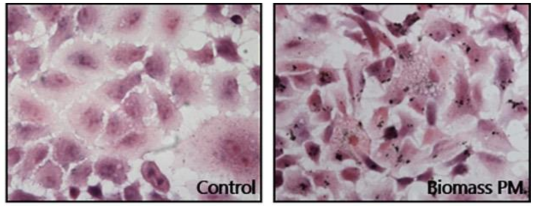
Health effects

Toxicity (In vitro) analysis of PM_{10} emitted by combustion

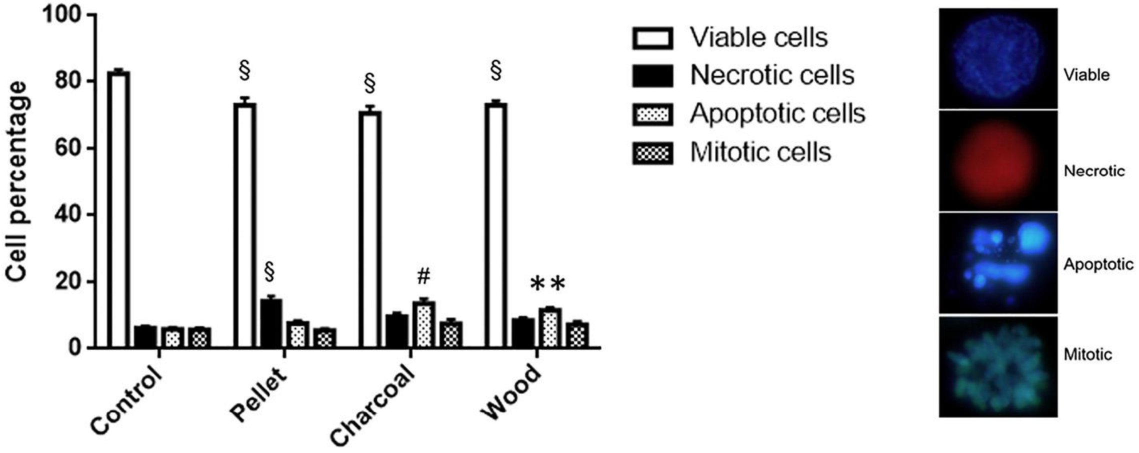
Different biomass sources (pellet, wood, charcoal)

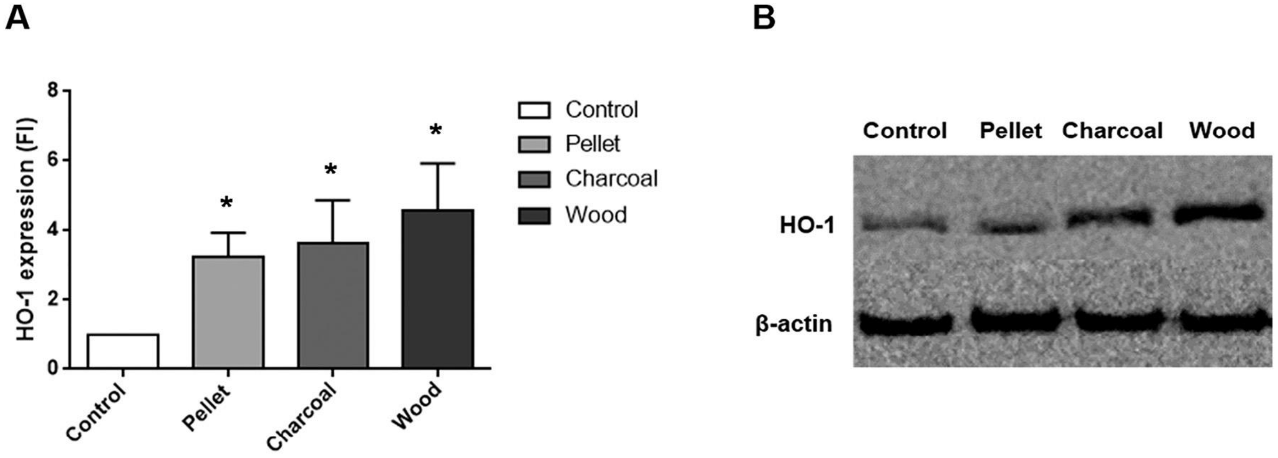
- Heavy metals is crucial in inducing acute effects related to cytoxicity and genotoxicity
- PAHs are responsible for the induction of the xenobiotic metabolizing systems and the oxidative stress ce





- Cytotoxicity
- Genotoxicity
- Cell cycle alterations



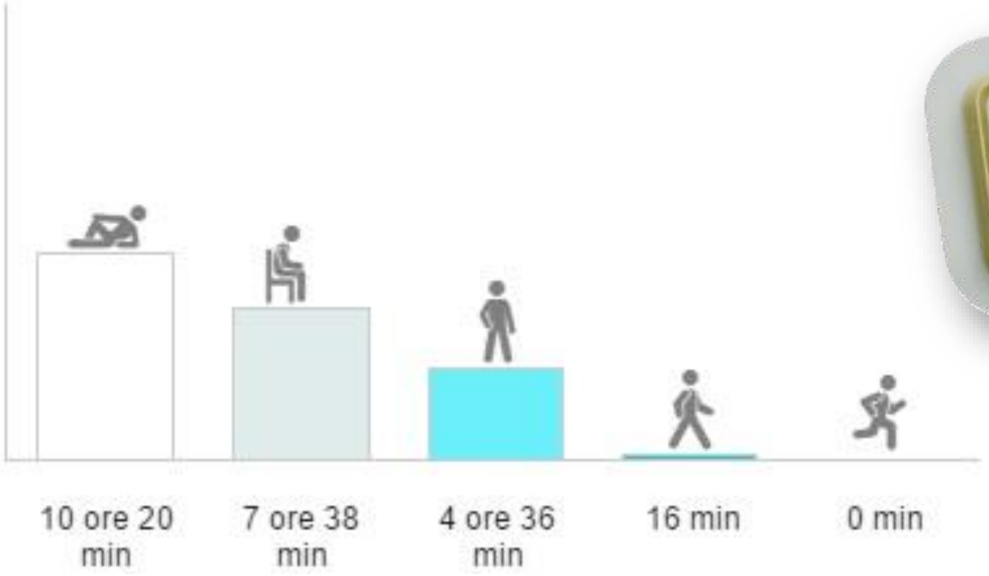


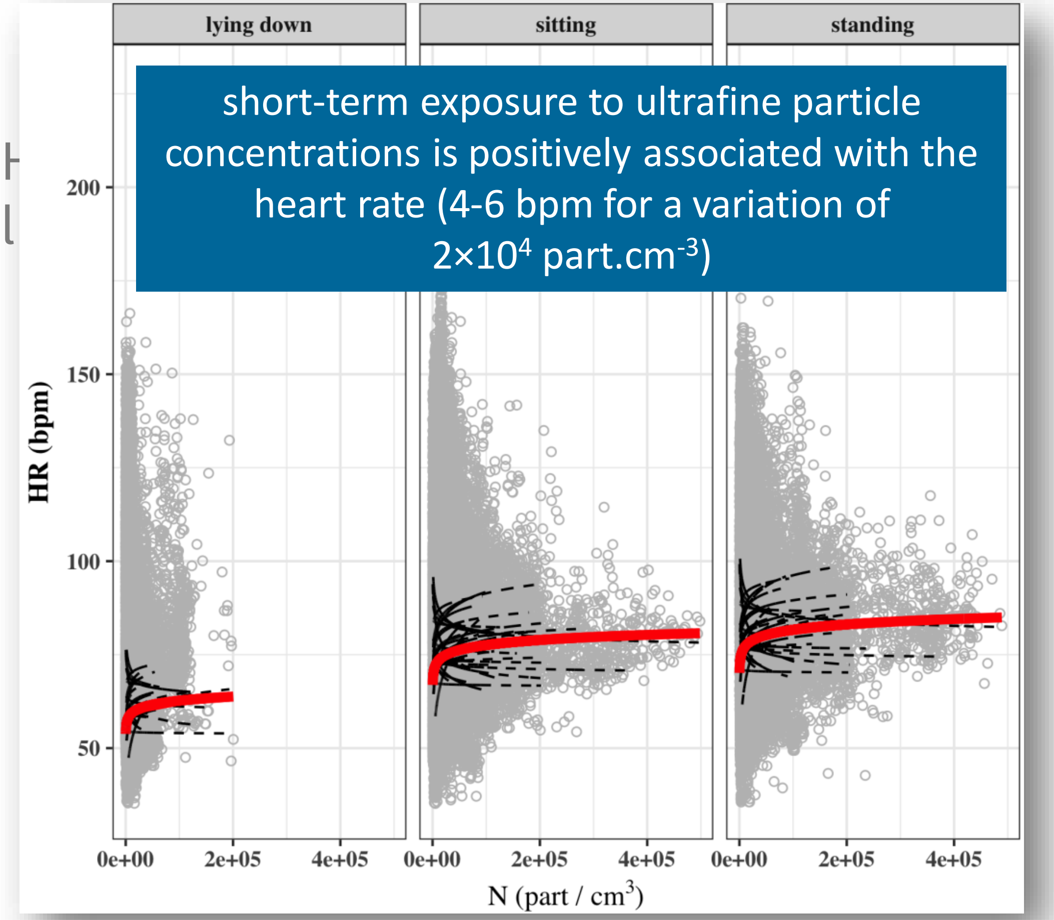
Health effects

Cardiovascular effects

Exposure to UFPs and heart rate

- 50 volunteers
- Measurement of exposure to UFPs
- Measurement of heart rate and activities (wearable H
- statistical linear mixed model to fit the experimental



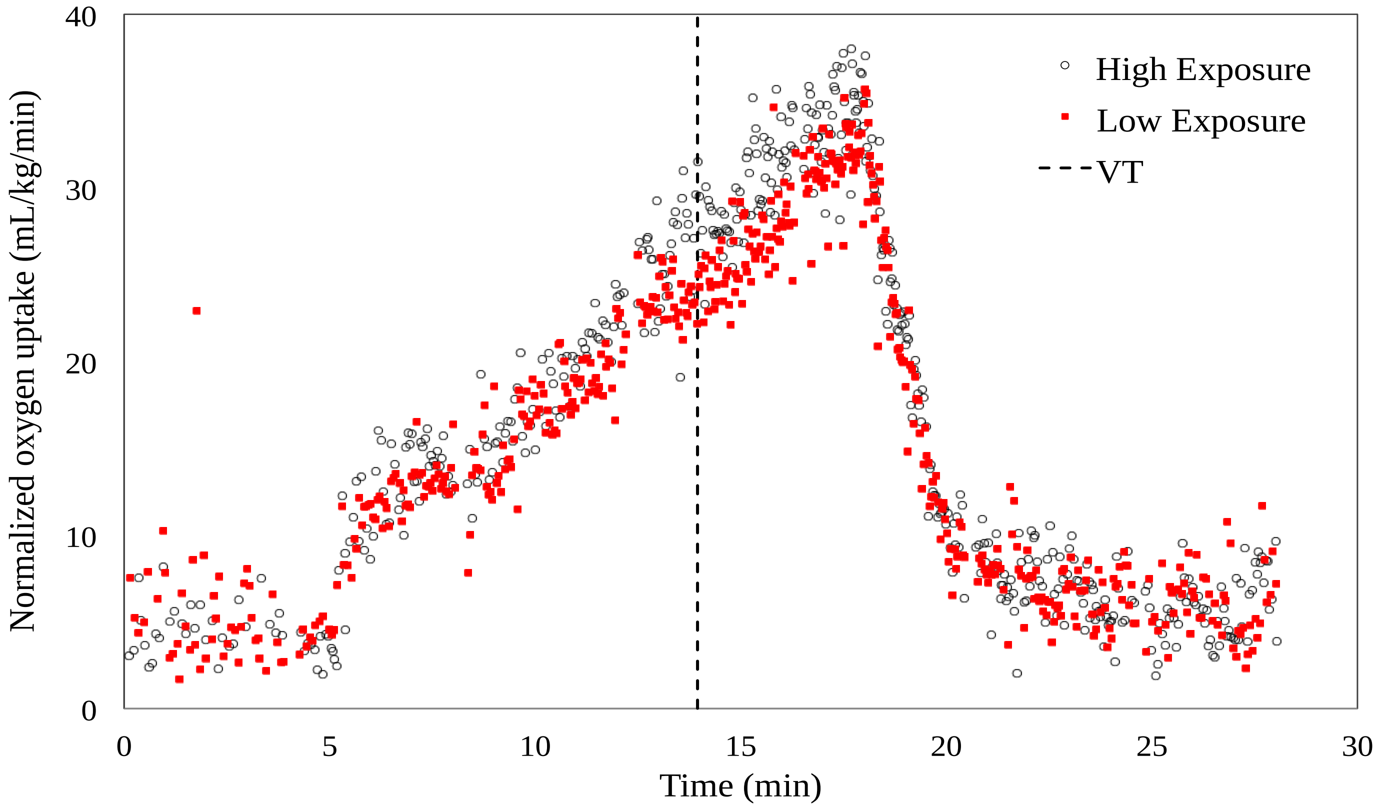


short-term exposure to ultrafine particle concentrations is positively associated with the heart rate (4-6 bpm for a variation of 2×10^4 part.cm^{-3})

Health effects

Performances of athletes

Effect of the exposure to airborne particles on the physical performances achieved by athletes

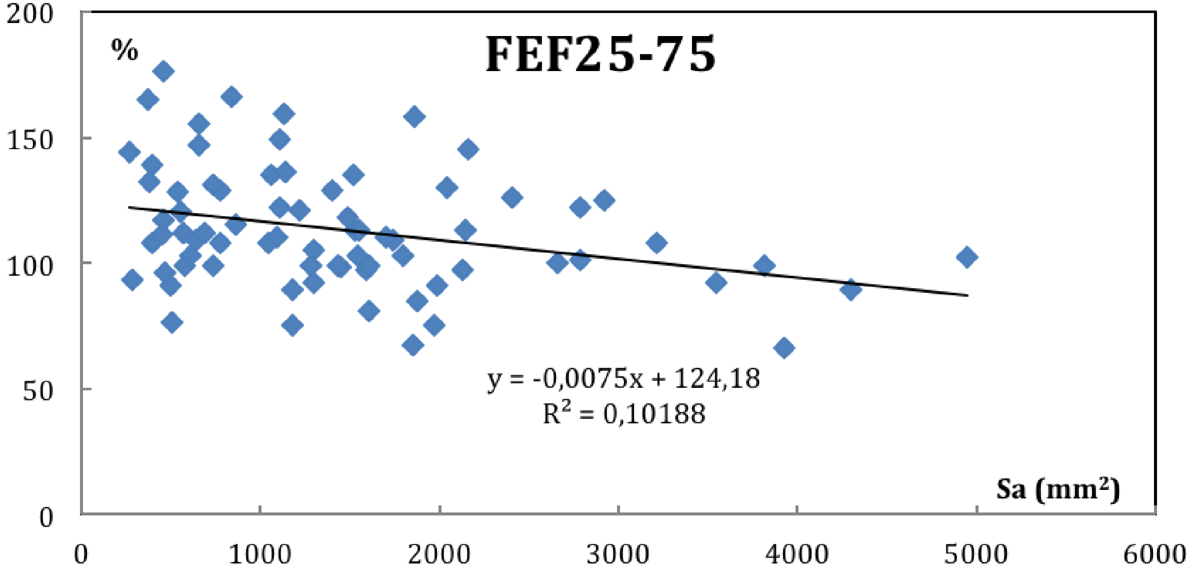


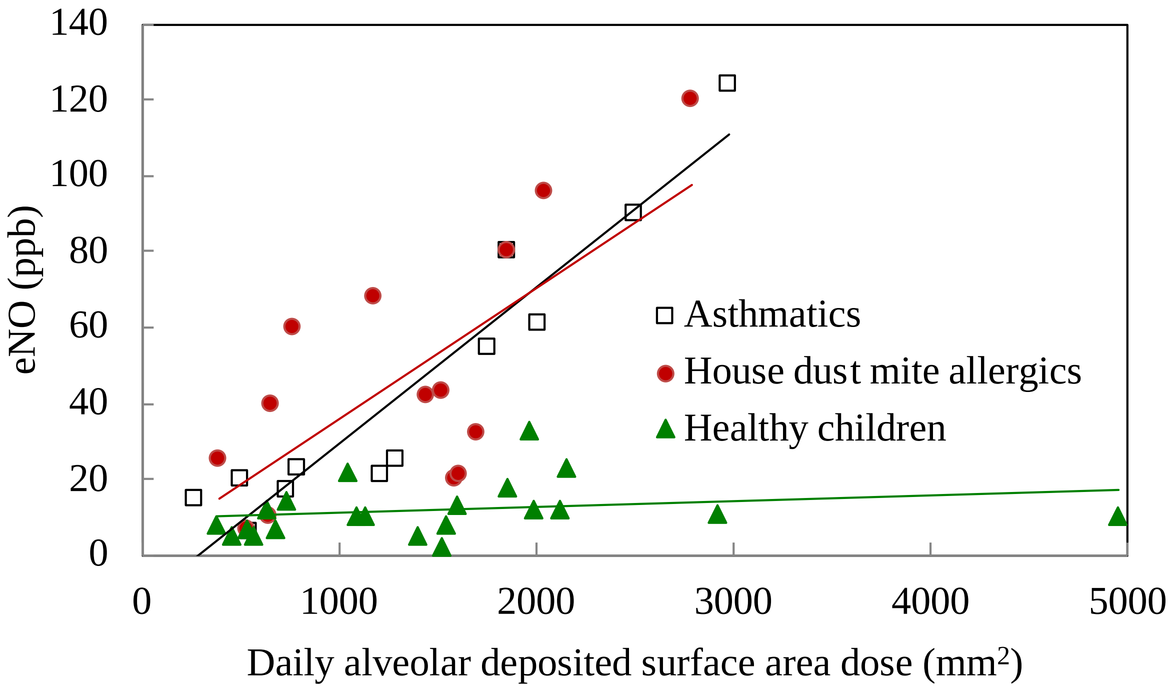
Reduction of the mechanical efficiency (oxygen uptake, peak heart rate and required metabolic power)

Health effects

Lung function & airways inflammation (Children)

- spirometry: an increase in daily alveolar deposited surface area dose was related to **FEV_1 and FEF_{25-75}**, respectively (i.e. *small airway obstruction*)
- eNO test : **eNO** increase with particle doses in allergic and asthmatic children





Feedback

Effectiveness of eco-feedback in improving the indoor air quality in residential buildings: mitigation of the exposure to different airborne particle metrics

State-of-art

- Occupants' behavior has a significant influence on Indoor Air Quality (IAQ) and vice-versa. Acting on behavioral change could improve the IAQ and reduce the exposure to airborne particles in indoor environments.

- A suitable approach to provoke a behavioral change is implementing "eco-feedback" strategies able to bridge the gap between the lack of awareness and the understanding how their behaviors affect the environment.

- Scientific questions on IAQ awareness to be addressed:
    - are the occupants aware of their exposure to airborne particles in their homes?
    - is it possible to make them aware through trustworthy information?
    - and, in case, are they able to mitigate their exposure to indoor-generated airborne particles?
    - how their mitigation strategies affect the different airborne particle metrics?

Feedback

Effectiveness of eco-feedback in improving the indoor air quality in residential buildings: mitigation of the exposure to di… s

Aims:

- Investigation of the IAQ awa… uestionnaire surveys;
- Application of an eco-feed… th a **trustworthy information campaign** and an **experime**… n the short-term the possible behavioral changes of the … in reducing airborne particle concentrations, while source…

Methodology:

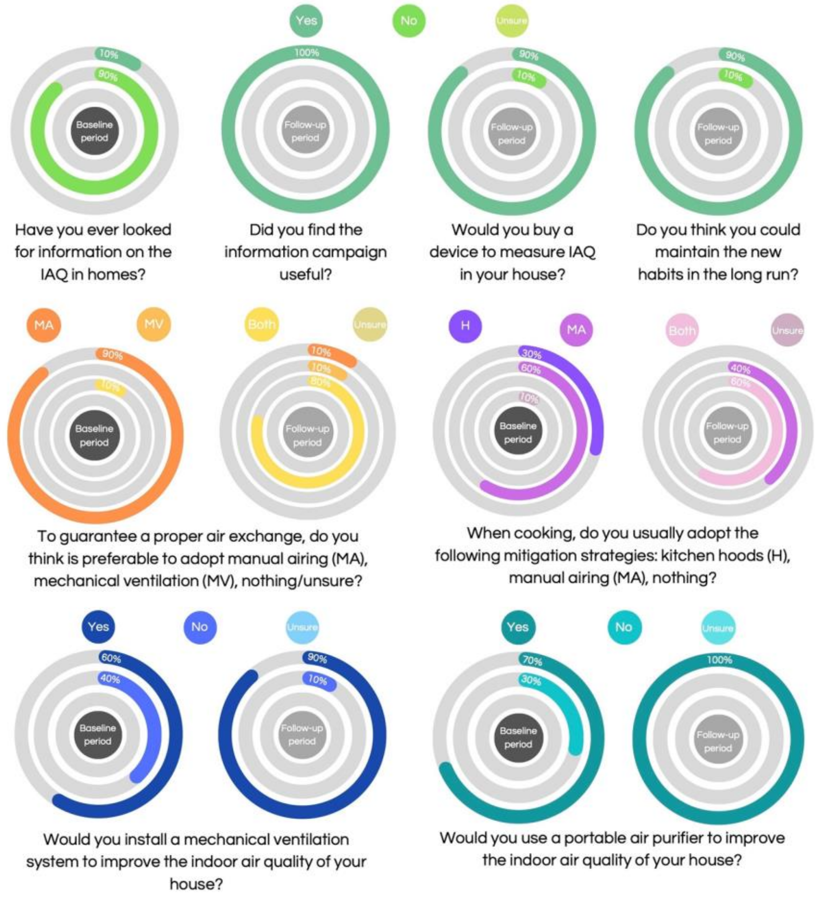
Scheme of the methodology adopted to e… an information campaign and an experimental

Feedback

Effectiveness of eco-feedback in improving the indoor air quality in residential buildings: mitigation of the exposure to different airborne particle metric

Results:

- the investigated population **is not properly aware** of the IAQ in their homes and of their exposure to airborne particles; indeed, they perceive the indoor air quality mostly affected by the outdoor rather than possible indoor sources;
- the **misperception of the IAQ also affects occupants' habits and intentions**: they do not routinely use mitigation strategies while indoor sources are in operation, and, in case, their use is mainly governed by other reasons than air quality (i.e. reducing smells and relative humidity)



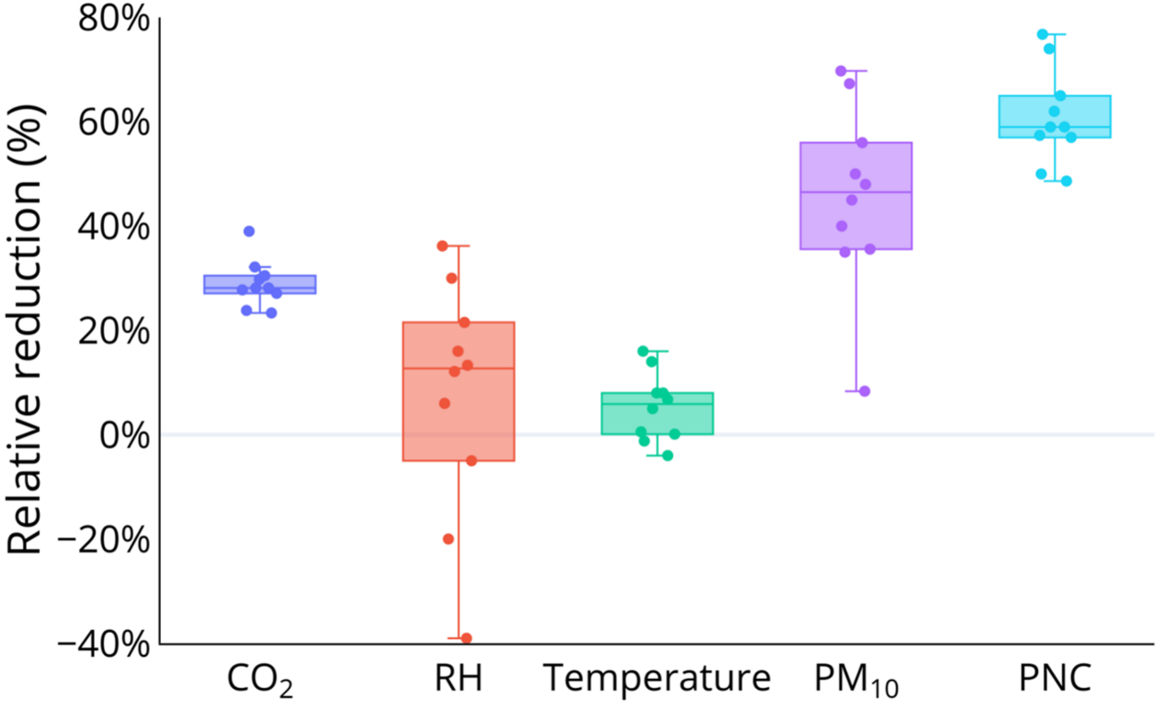
Change in perceptions, habits, and intentions of the IAQ of the ten families involved in the eco-feedback strategy

Feedback

Effectiveness of eco-feedback in improving the indoor air quality in residential buildings: mitigation of the exposure to different airborne particle metrics

Results:

- the **eco-feedback strategy adopted resulted successful** both in terms of promoting behavioral changes of the occupants and reducing the concentration levels while airborne particle emitting sources (i.e. cooking) were in operation;
- the **exposure to airborne particle metrics while cooking** events measured during the experimental campaign carried out after the information campaign (follow-up period) **resulted lower** than the baseline exposure; relative reductions of 47% and 59% were obtained for PM_{10} and PNC, respectively;



Relative reductions amongst median values measured during cooking activities performed within baseline and follow-up periods in the 10 homes as resulting from the quantitative analysis.

Thanks for your attention

Giorgio Buonanno

Department of Civil and Mechanical Engineering,

University of Cassino and Southern Lazio, Cassino (FR), Ita

Dipartimento di Ingegneria
Civile e Meccanica
UNIVERSITÀ DI CASSINO E DEL LAZIO MERIDIONALE