UNIVERSITÀ DEGLI STUDI DI MILANO
DIPARTIMENTO DI FISICA

PhD First-Year Workshop

EXPERIMENTAL AND MODELLING APPROACHES TO INVESTIGATE OPTICAL PROPERTIES OF ATMOSPHERIC AEROSOL

Sara Valentini

Atmospheric aerosol and its interaction with radiation

Atmospheric aerosol (PM): collection of solid and liquid particles suspended in the atmosphere

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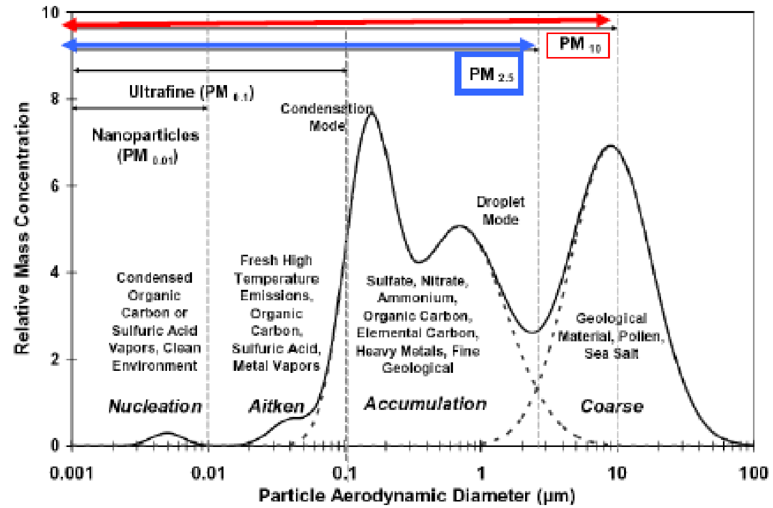
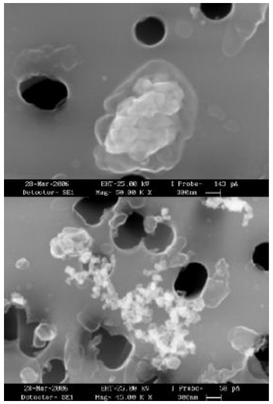
Atmospheric aerosol (PM): collection of solid and liquid particles suspended in the atmosphere

Particle composition, size, shape





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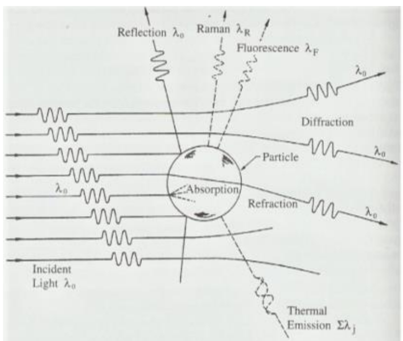
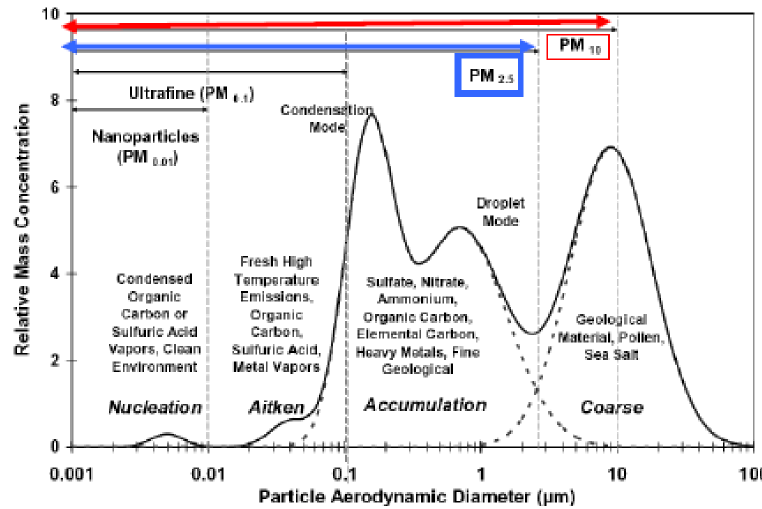
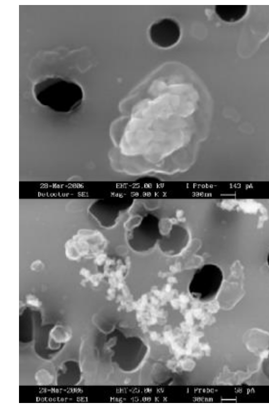
Interaction with solar and terrestrial radiation







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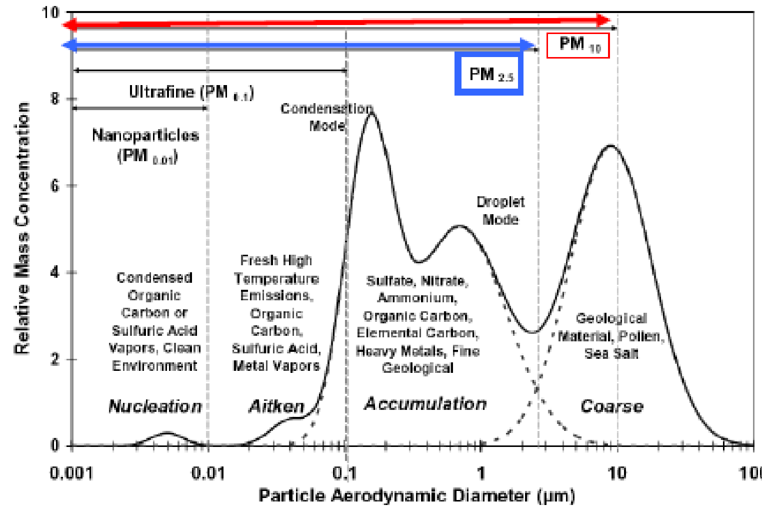

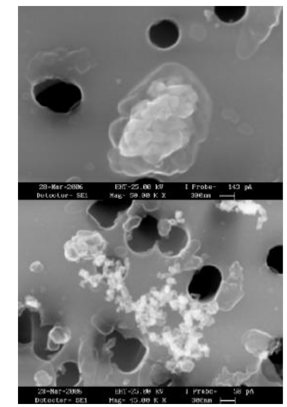

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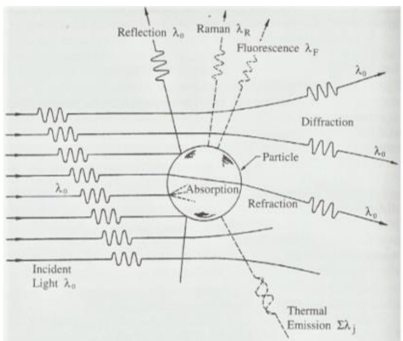
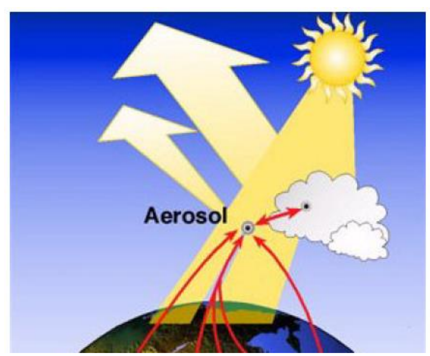


Effects at global and local scale (Earth radiative balance, visibility)



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Atmospheric aerosol: effects on Earth radiative balance

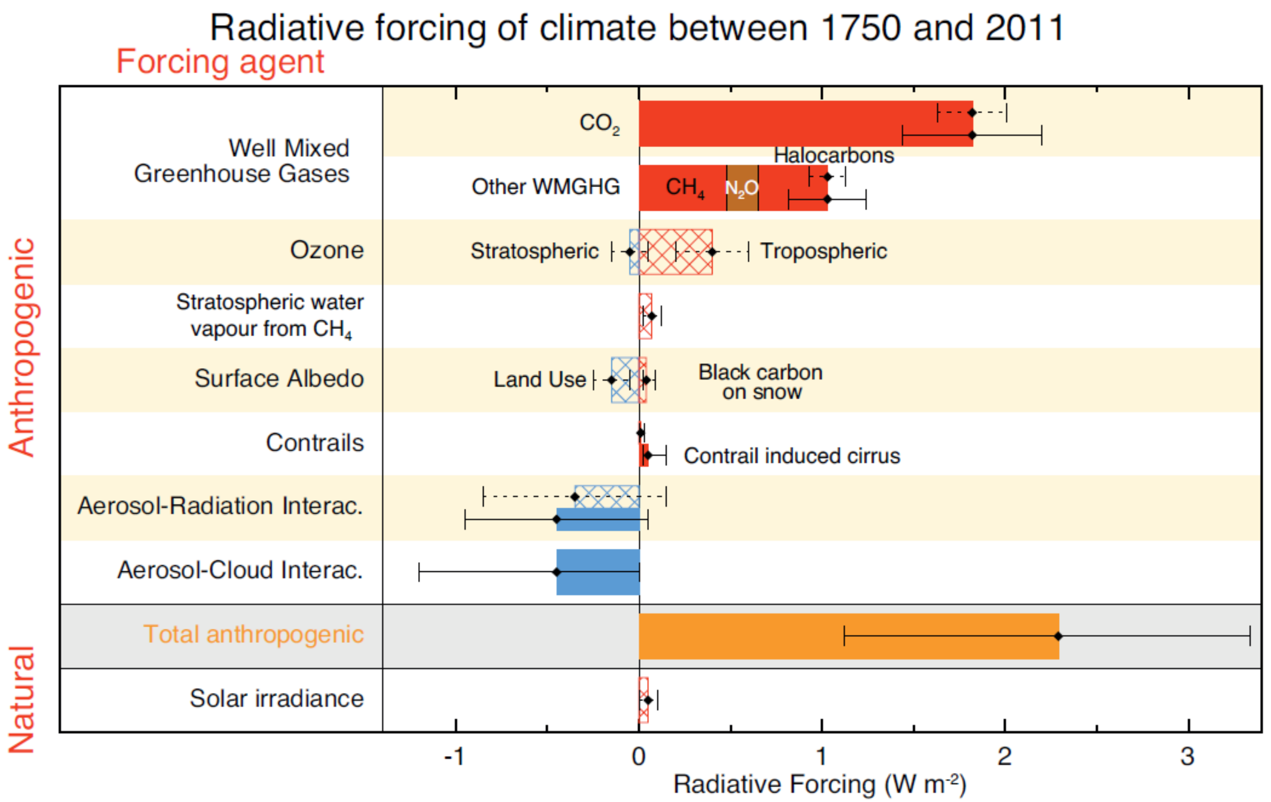

Figure 8.15 | Bar chart for RF (hatched) and ERF (solid) for the period 1750–2011, where the total ERF is derived from Figure 8.16. Uncertainties (5 to 95% confidence range) are given for RF (dotted lines) and ERF (solid lines).

IPCC, 2013

RF: net flux at tropopause

ERF: net flux at top of atmosphere

IPCC: Intergovernmental Panel on Climate Change

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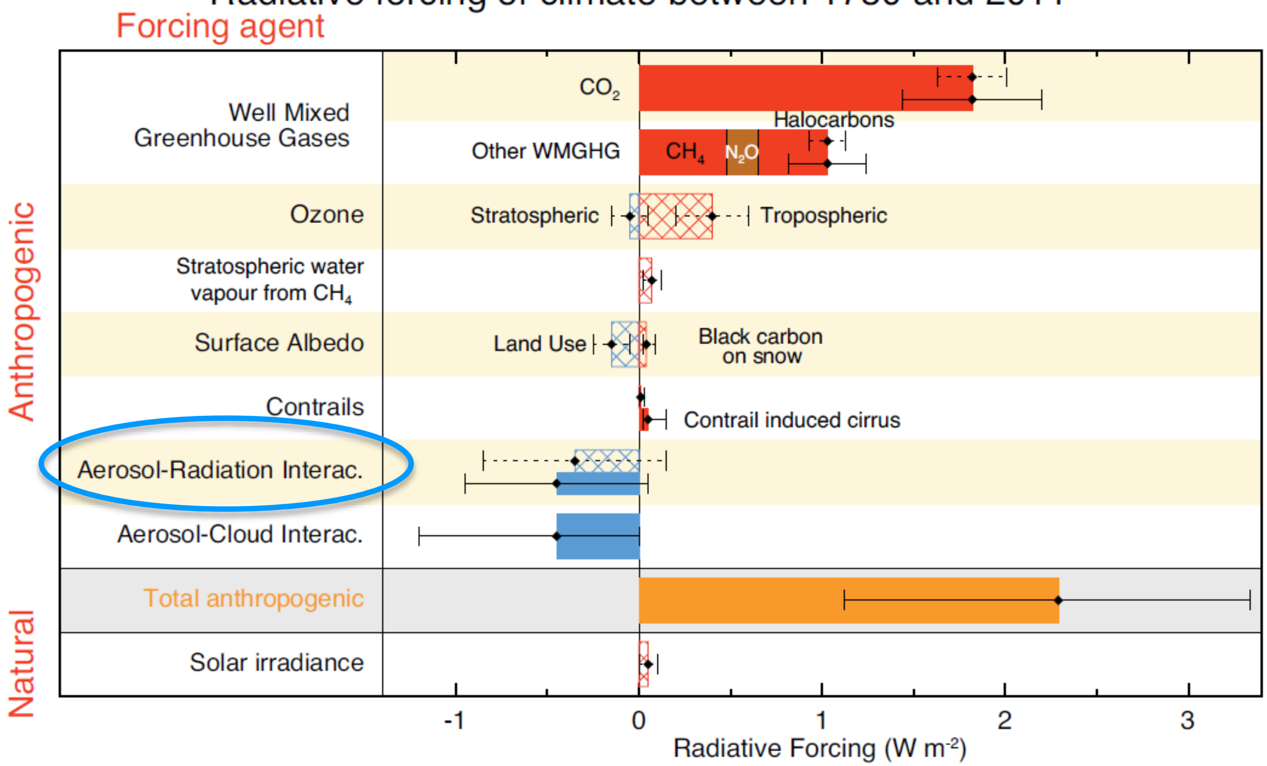
Atmospheric aerosol: effects on Earth radiative balance

Radiative forcing of climate between 1750 and 2011



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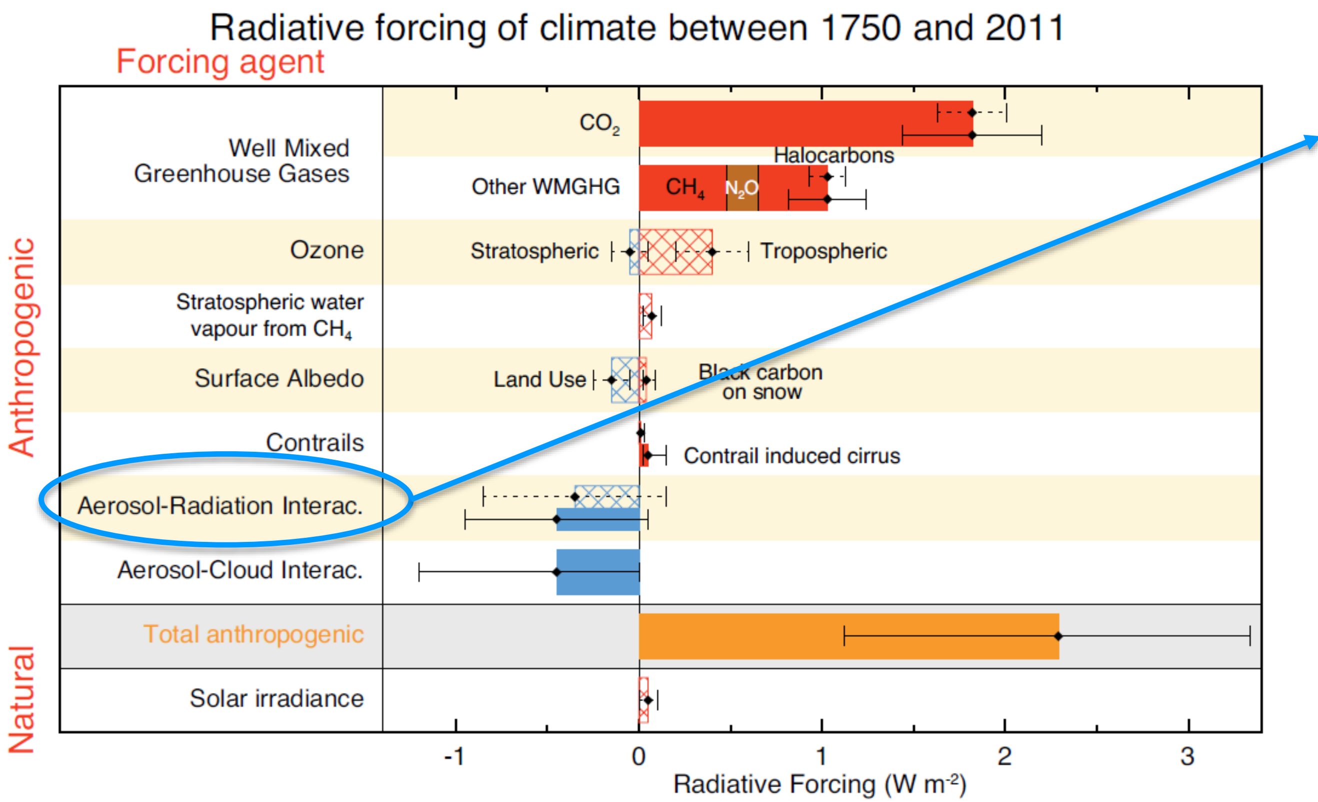

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IPCC, 2013

EXTINCTION

scattering + absorption

$$m(\lambda) = n(\lambda) - ik(\lambda)$$

complex refractive index

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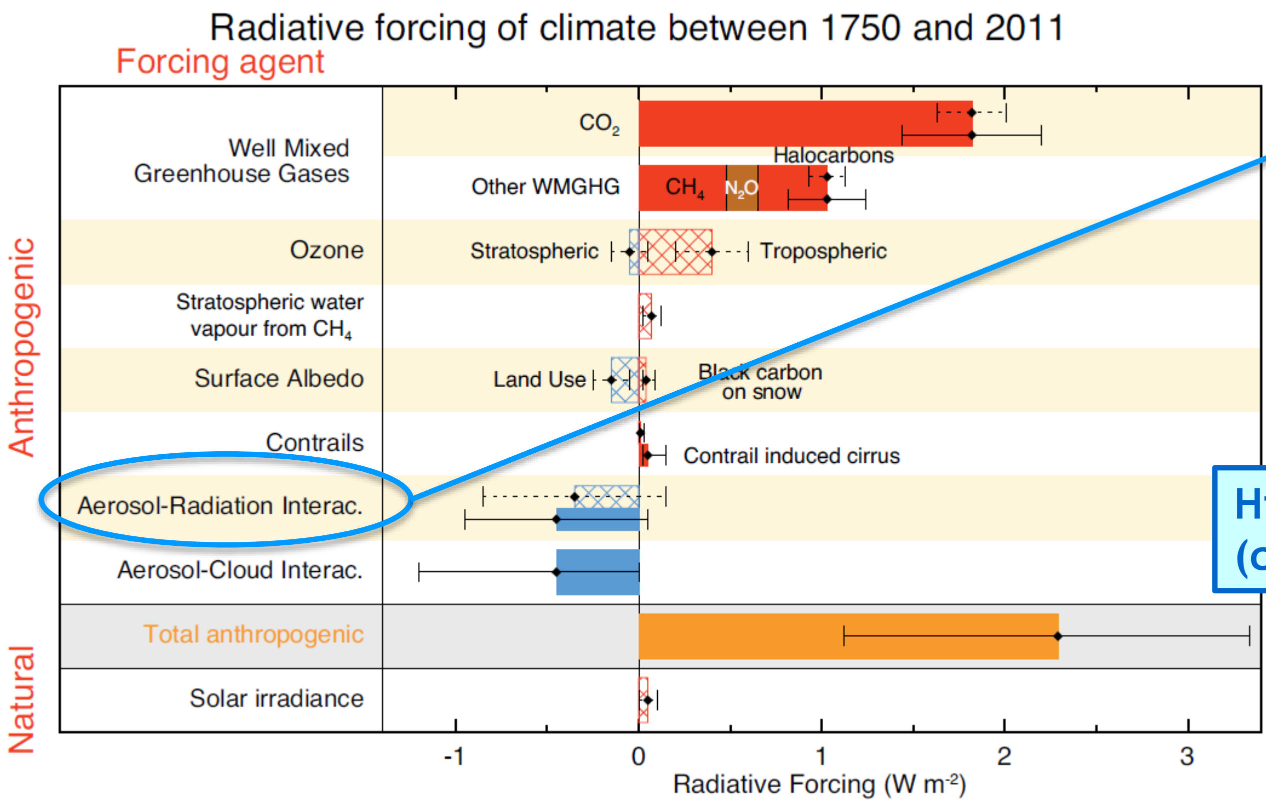
Atmospheric aerosol: effects on Earth radiative balance



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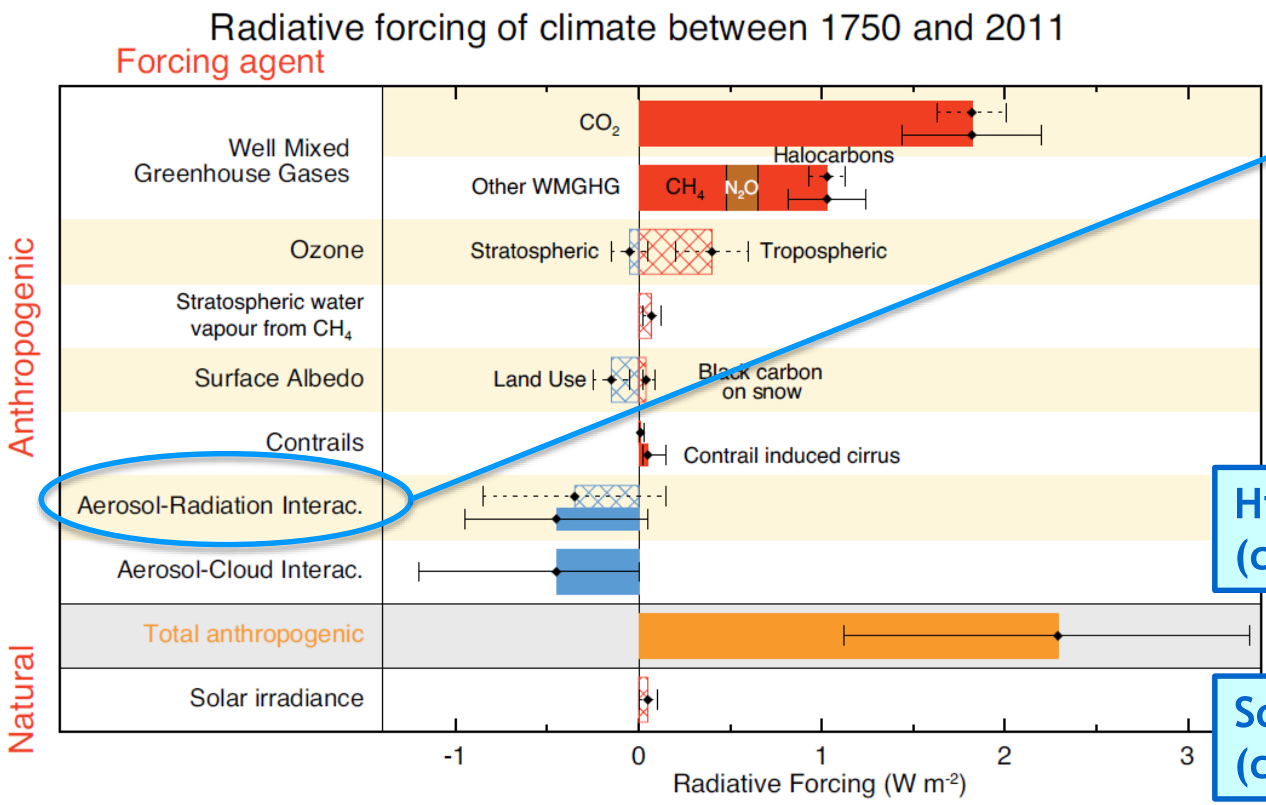

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EXTINCTION

scattering + absorption

$$m(\lambda) = n(\lambda) - ik(\lambda)$$

complex refractive index

High uncertainties (comparable to estimates)!

Scattering vs absorption (cooling vs warming effects)

RF: net flux at tropopause

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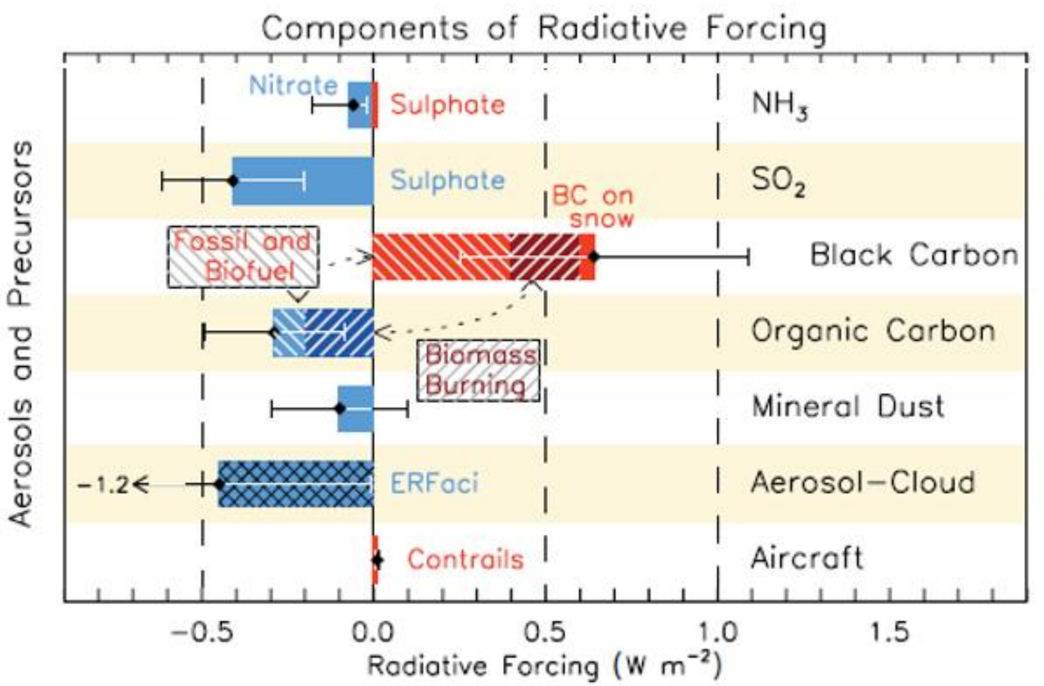
Atmospheric aerosol: effects on Earth radiative balance

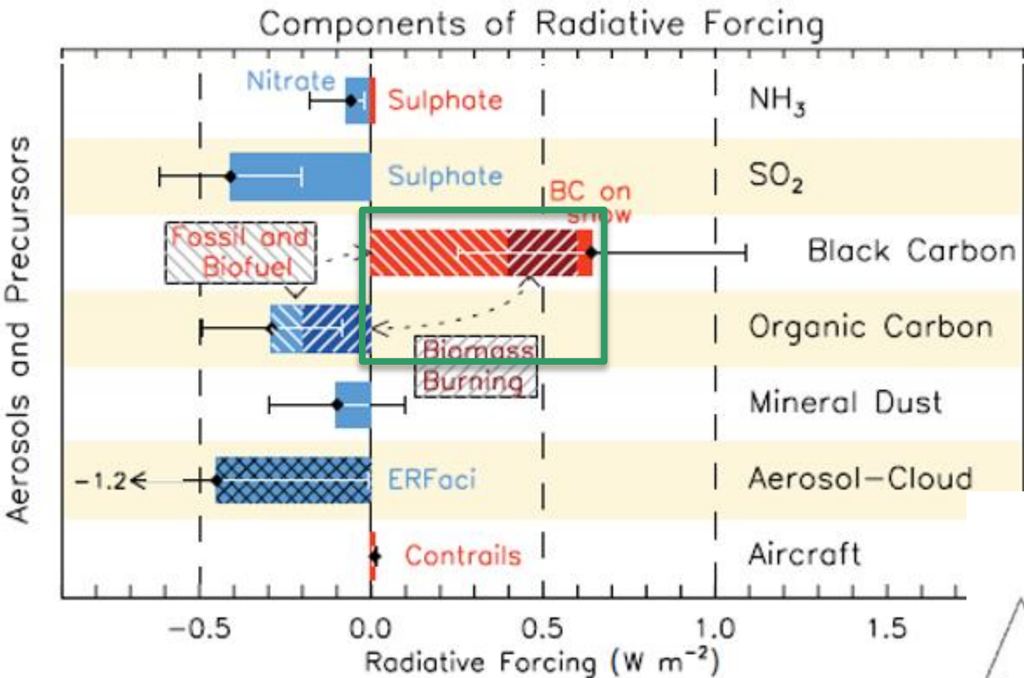


Adapted from IPCC, 2013

Atmospheric aerosol: effects on Earth radiative balance

Light absorption coefficient $b_{ap} \propto \lambda^{-\alpha}$

α: Ångström Absorption Exponent



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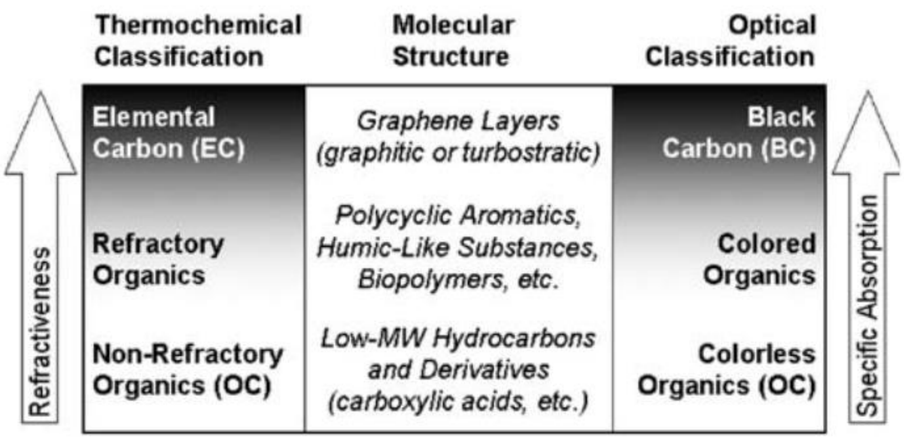
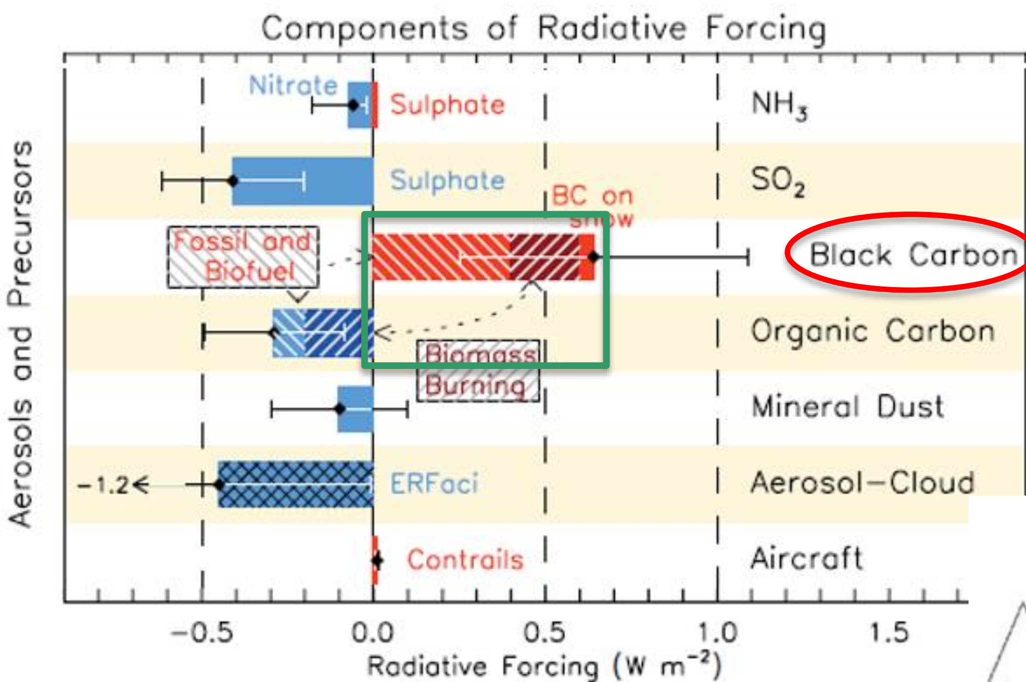


Fig. 1 Classification and molecular structure of carbonaceous aerosol components

Pöschl, 2005

Atmospheric aerosol: effects on Earth radiative balance



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Light absorption coefficient $b_{ap} \propto \lambda^{-\alpha}$

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Main light-absorbing species:

Black Carbon (BC)

- $k(\lambda) \approx const$
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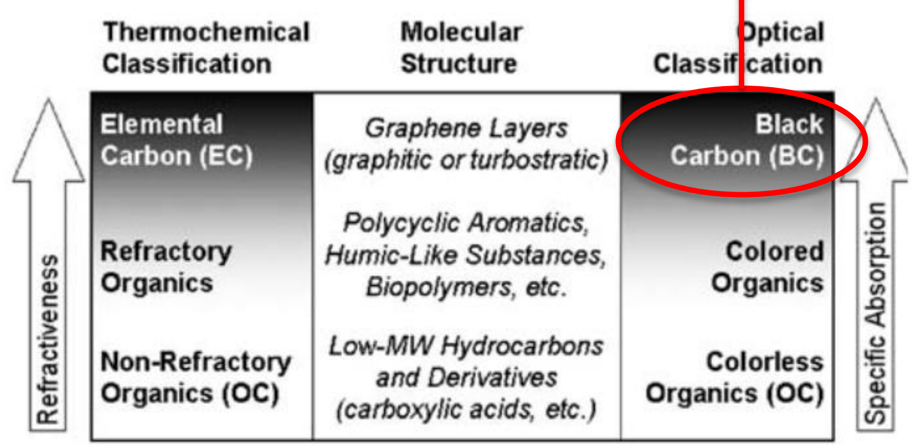

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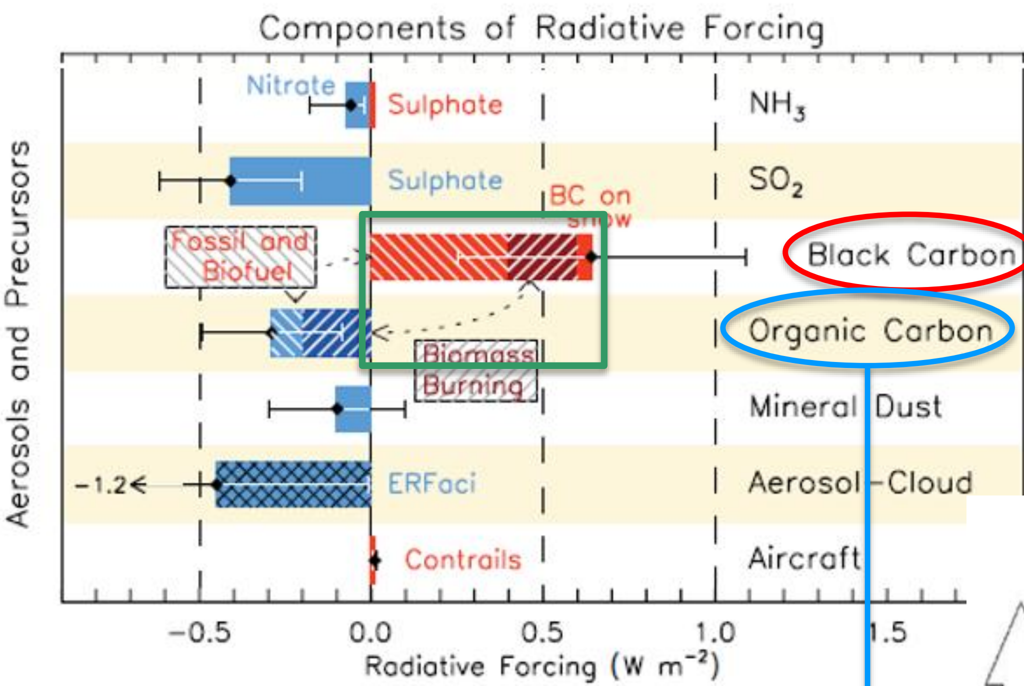

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Main light-absorbing species:

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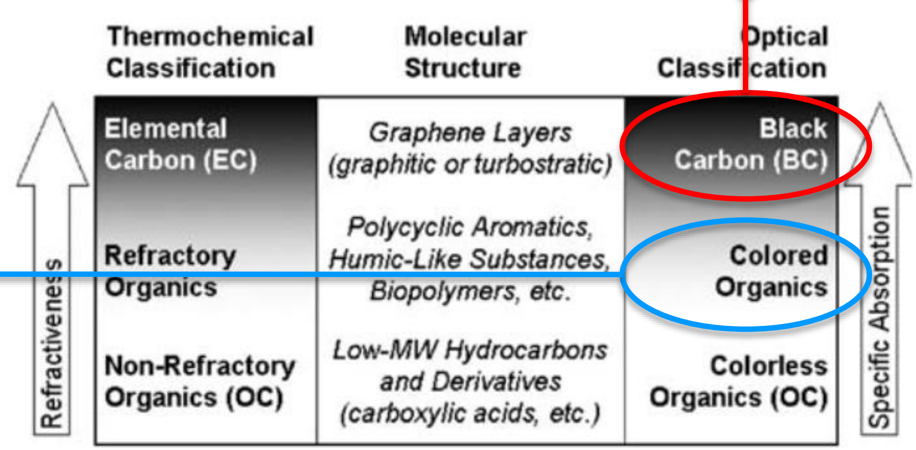
Other light-absorbing species:

Brown Carbon (BrC)

- $k(\lambda) \neq const$
- $\alpha > 1$
- Visible range: $b_{ap}(BrC) \ll b_{ap}(BC)$



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Aerosol mixing state: impact on aerosol optical properties

Particle mixing state influences aerosol optical properties (e.g. shell of non-absorbing material can enhance absorption by an absorbing core)

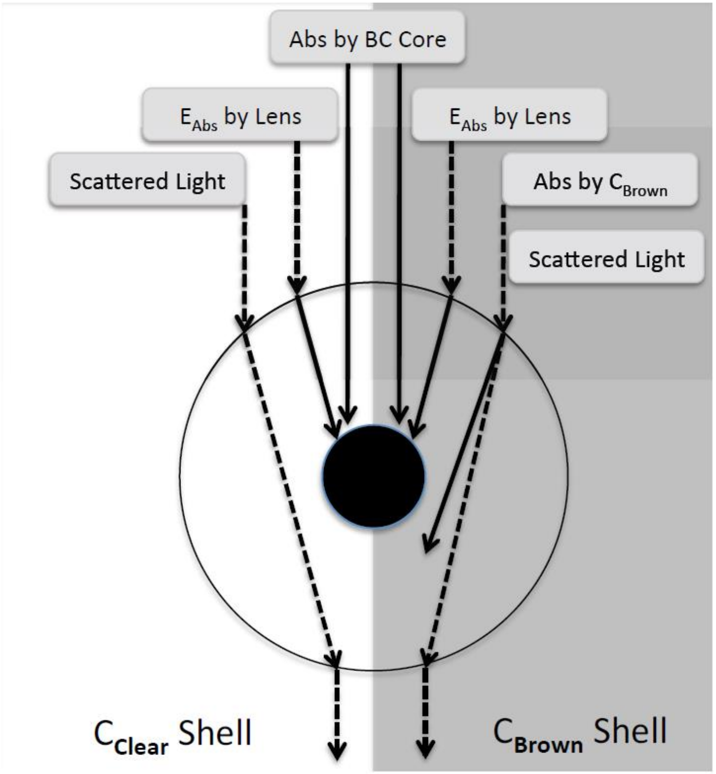
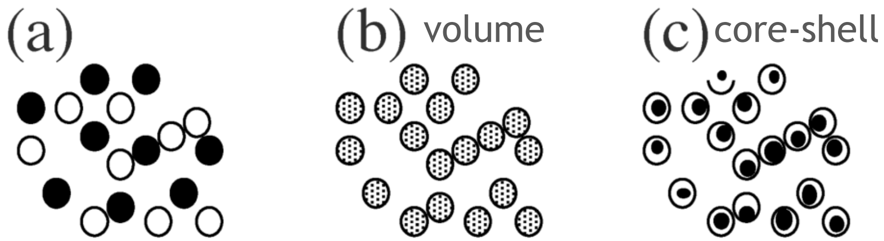


Fig. 1. Schematic of the effect of C_{Clear} and C_{Brown} shells on *BC* absorption.

Lack and Cappa, 2010

External mixing   Internal mixing



Bond and Bergstrom, 2006

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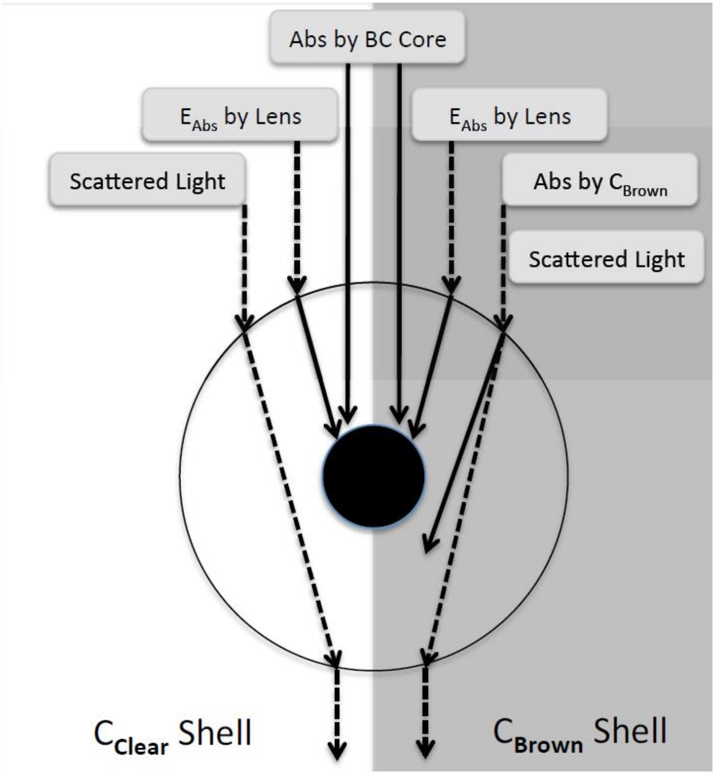

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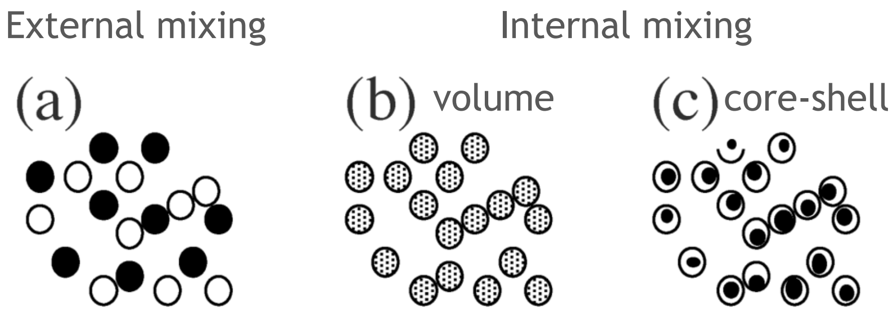

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- Problems in models representativeness: assumptions on particle shape and mixing state
- Need to measure atmospheric aerosol optical properties without sample pre-treatment

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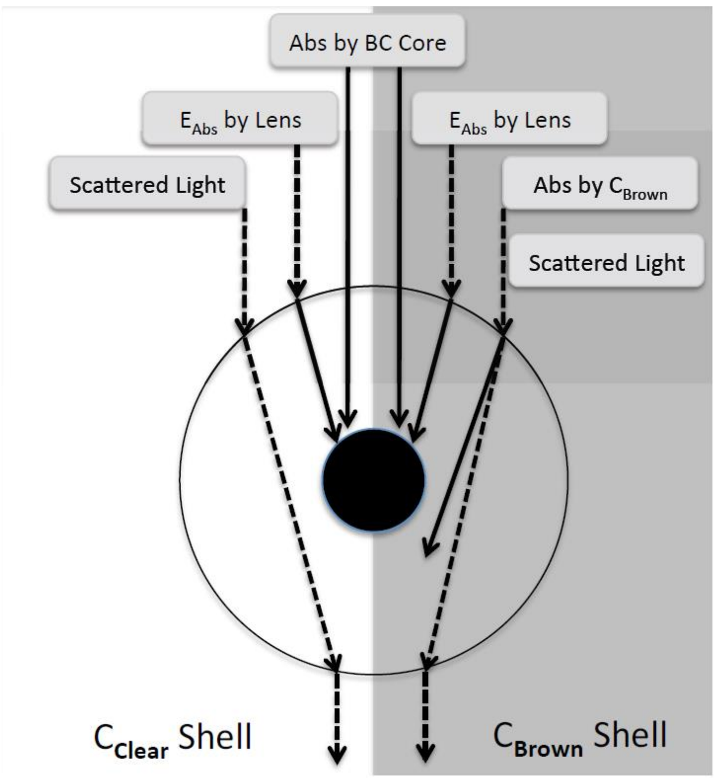

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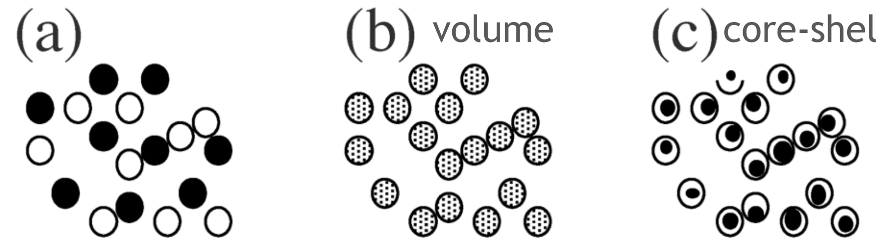

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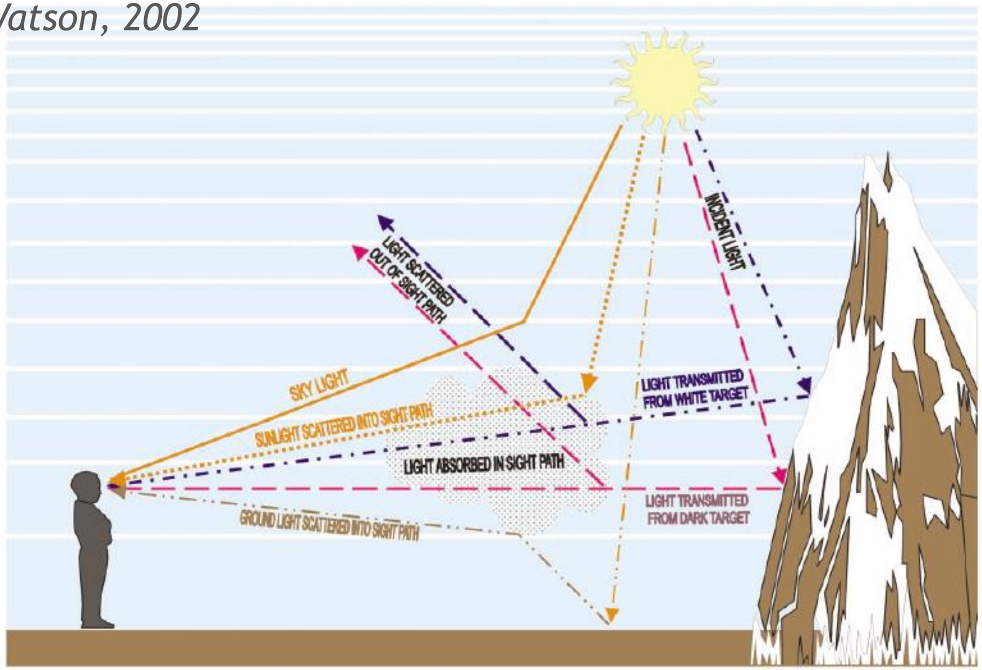
On-line measurements in air

Off-line filter-based measurements
(typically with pre-treatment, NOT in our research group)

Atmospheric aerosol: effects on visibility

Watson, 2002



Visibility: the greatest distance at which a black object of suitable dimensions can be seen and recognized when observed against the horizon sky [*WMO, 2008*]

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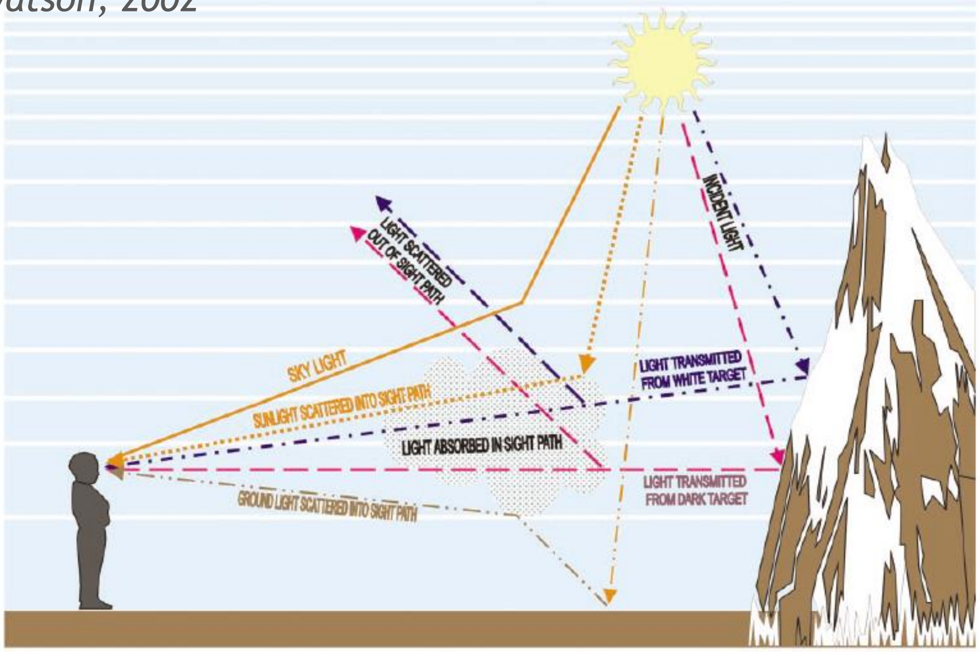

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LIGHT EXTINCTION

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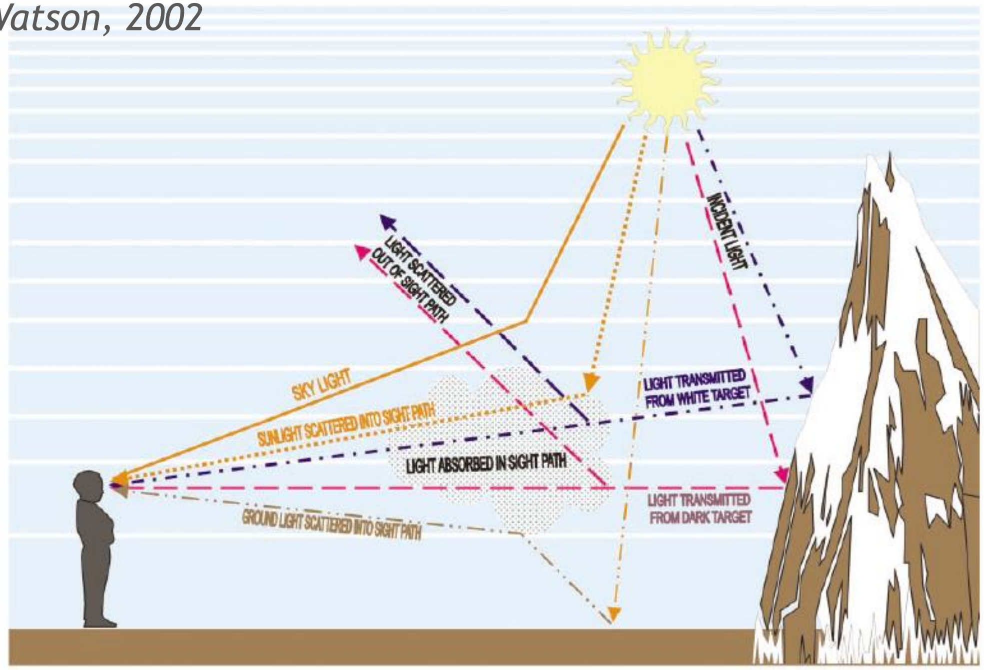

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Air quality related value

LIGHT EXTINCTION

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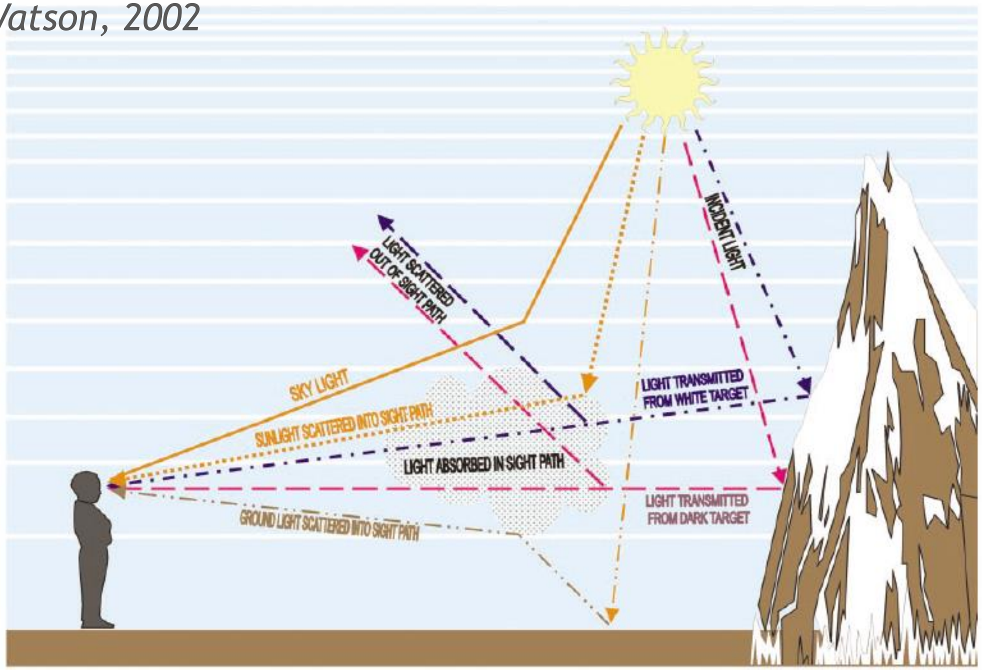

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Objective definition?

LIGHT EXTINCTION

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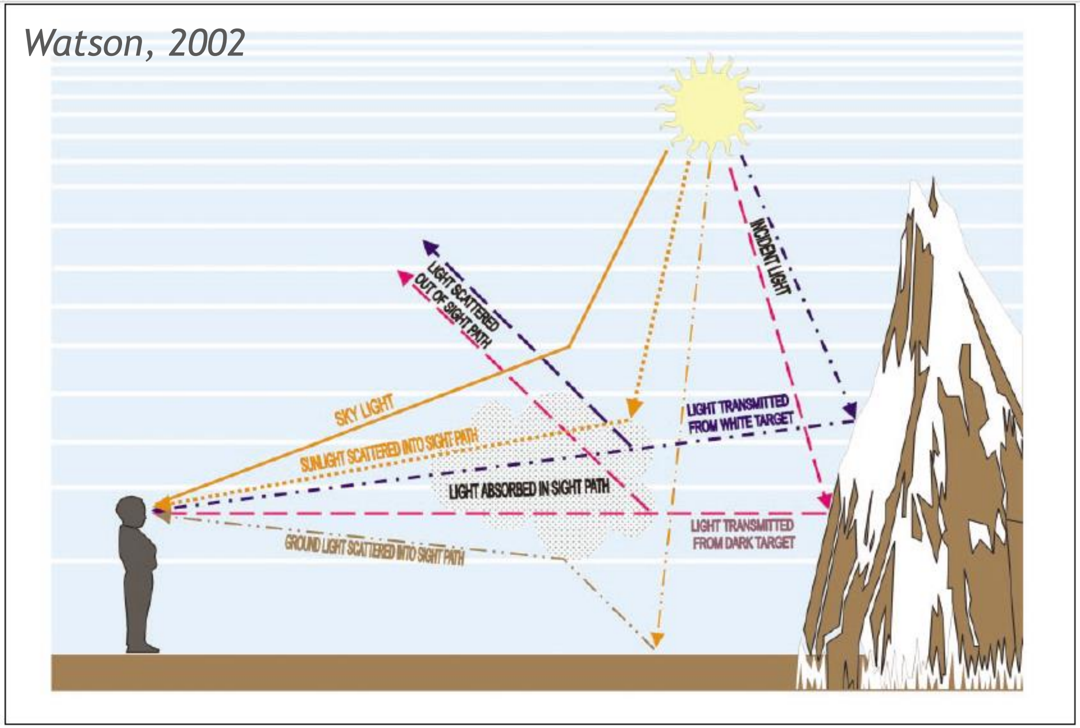

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Air quality related value

Objective definition?

Not routinely monitored

LIGHT EXTINCTION

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PhD research activity - 1^{st} Year

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  - Participation to the international collaborative project CARE (Carbonaceous Aerosol in Rome and Environs), for the determination of absorption and scattering coefficients of samples with high time resolution
  - Paper (Costabile et al., Atmosphere – submitted)

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- Tailoring of a model to reconstruct atmospheric light extinction (IMPROVE algorithm) to obtain valuable and site-specific visibility estimates
  - Poster presentation at Congresso del Dipartimento di Fisica
  - Poster presentation at European Aerosol Conference (EAC) 2017
  - Paper (Valentini et al., Atmospheric Environment – accepted)

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- Feasibility study on an experimental approach to retrieve the aerosol scattering coefficient of aerosol samples using the Polar Photometer developed by the Environmental Physics Research Group (currently used to obtain the aerosol absorption coefficient)

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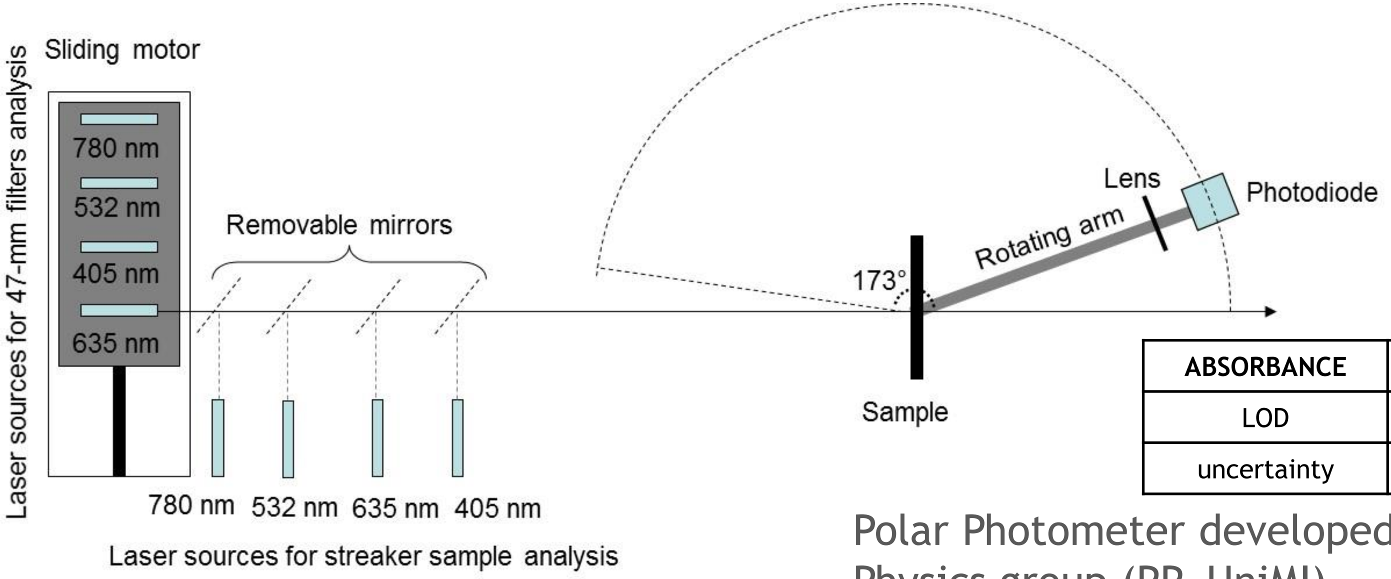
Filter-based measurements of atmospheric aerosol absorption: PP_UniMI

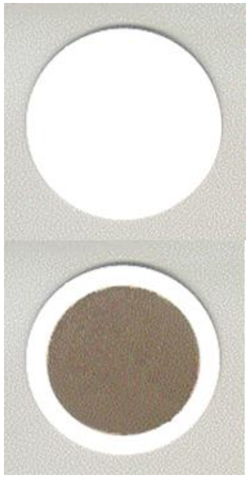


Multi-wavelength measurements of aerosol absorption coefficient

(b_{ap} - units: Mm^{-1})

ABSORBANCE	47-mm filters	Streaker samples
LOD	0.02-0.07	0.03-0.07
uncertainty	±0.01 (if ABS<0.1) – 10% (if ABS>0.1)	

Polar Photometer developed by the Environmental Physics group (PP_UniMI)



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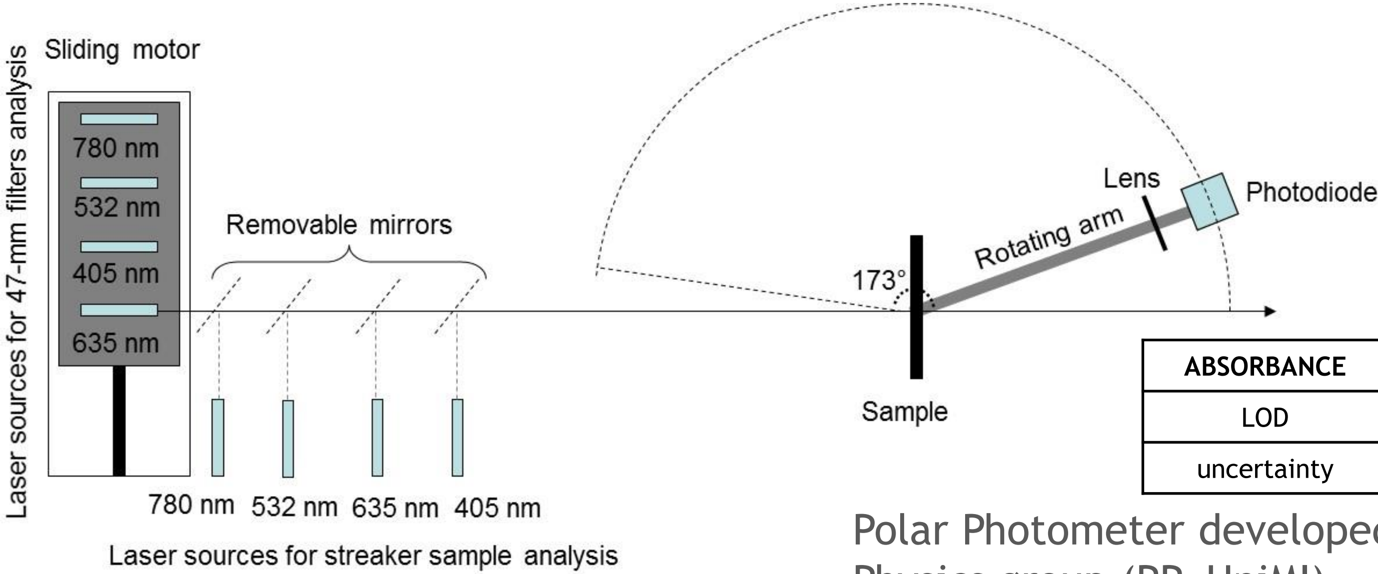

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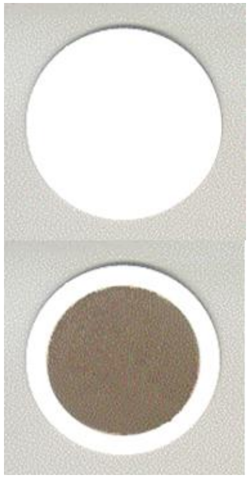

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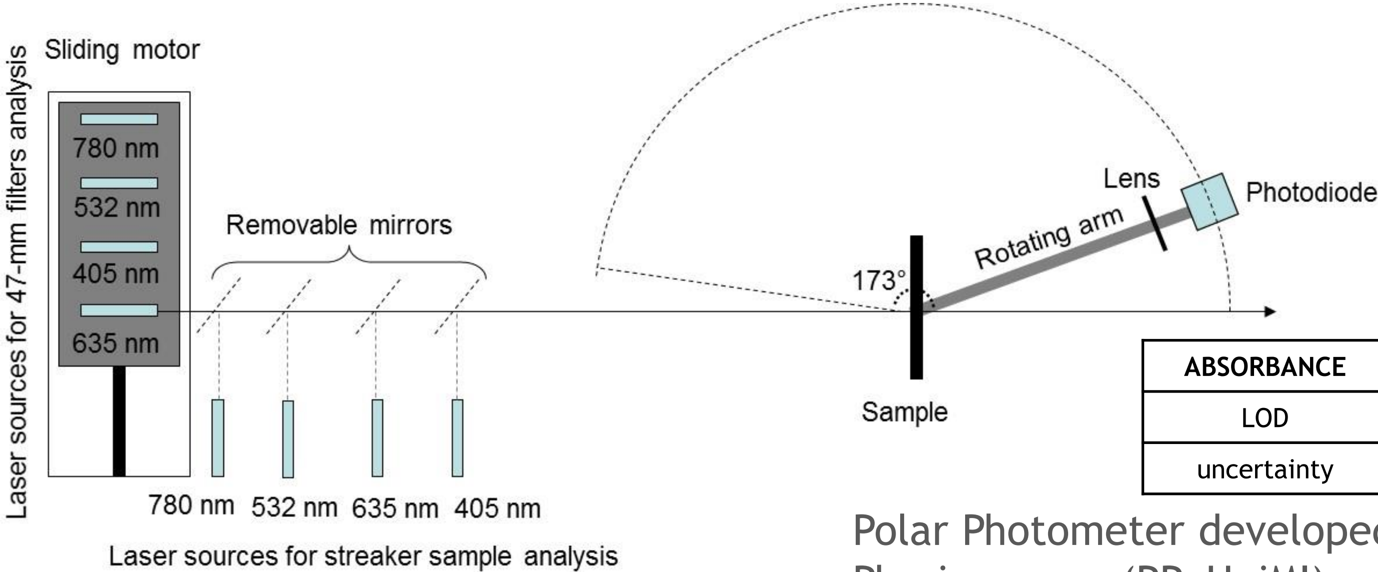

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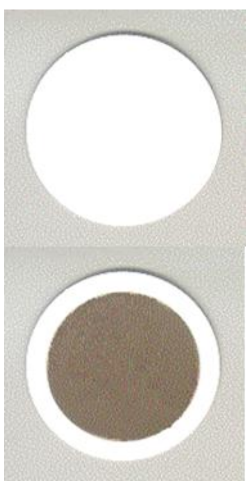

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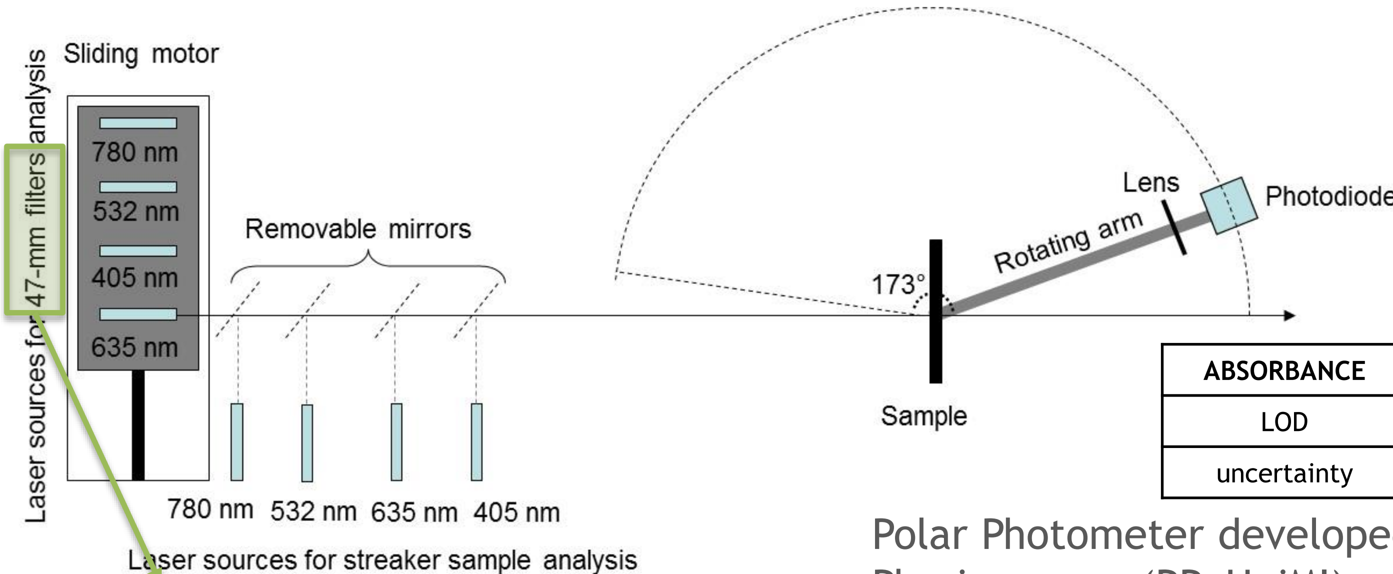
Filter-based measurements of atmospheric aerosol absorption: PP_UniMI



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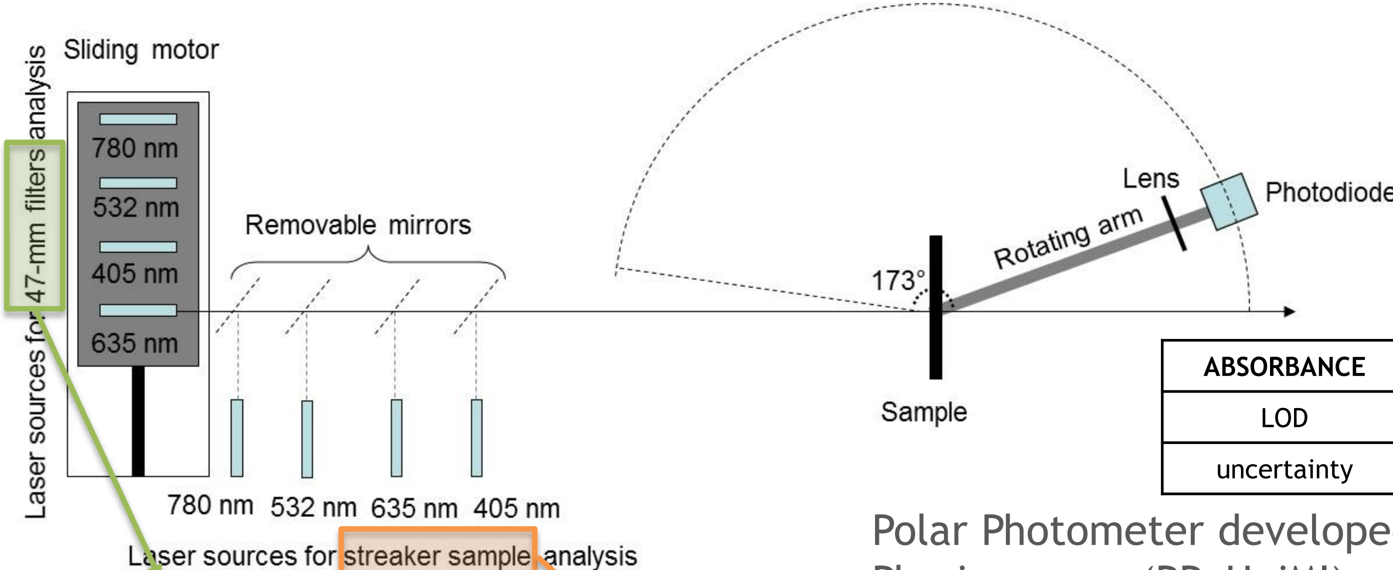

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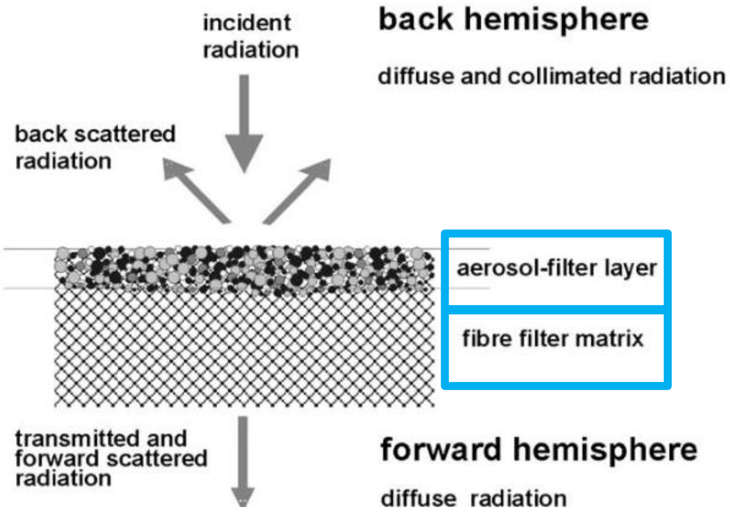
PP_UniMI: Two-layer radiative transfer model

Petzold and Schönlinner, 2004



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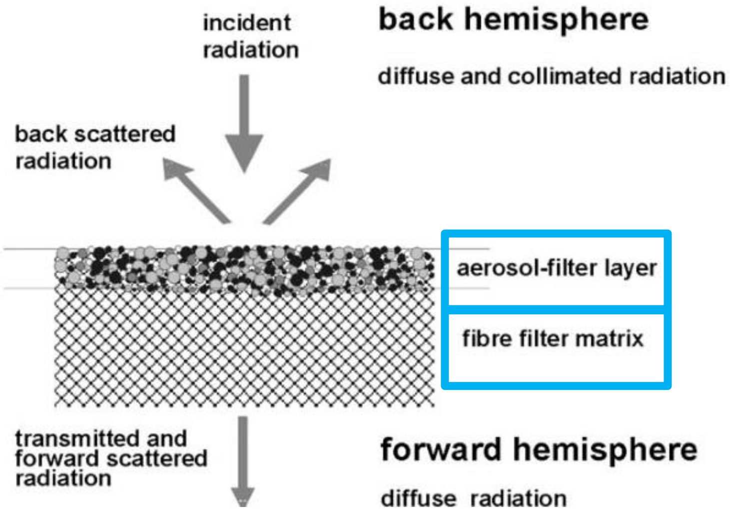

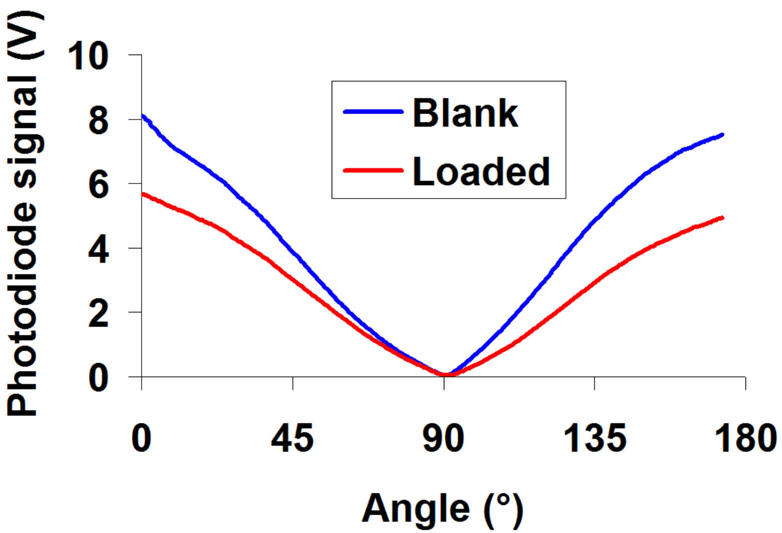

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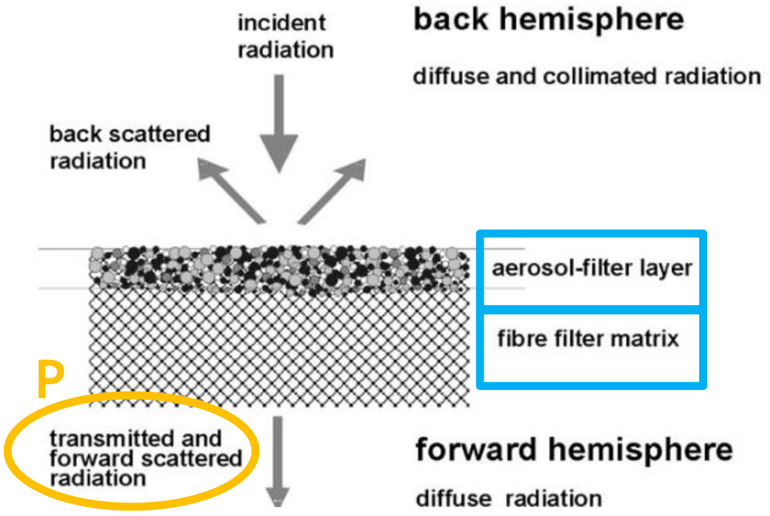

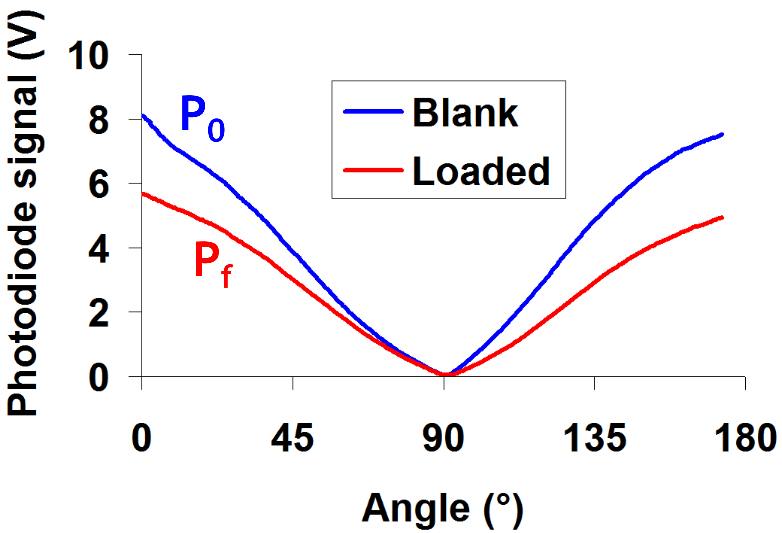

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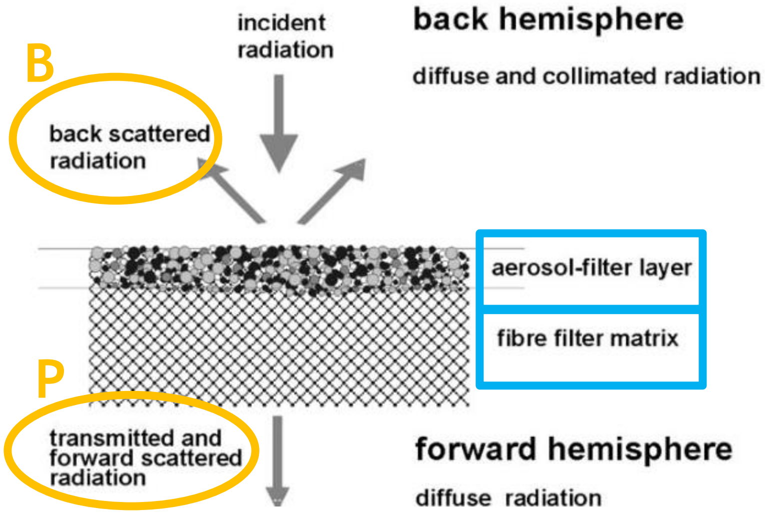

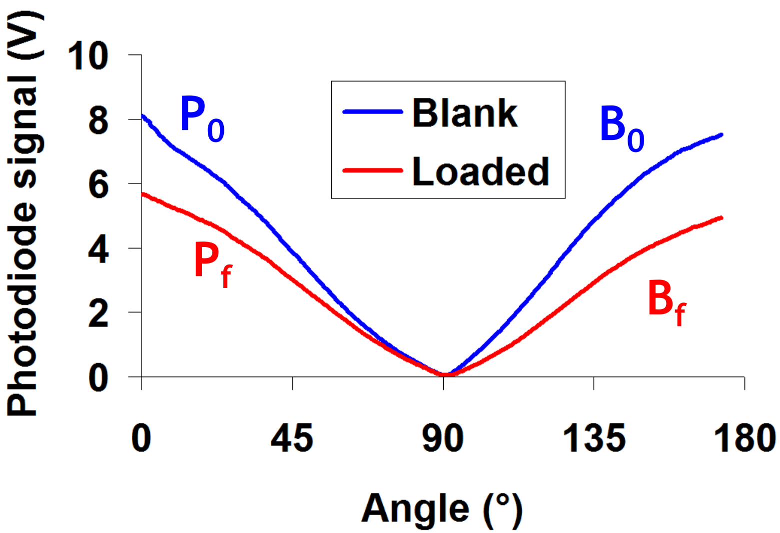

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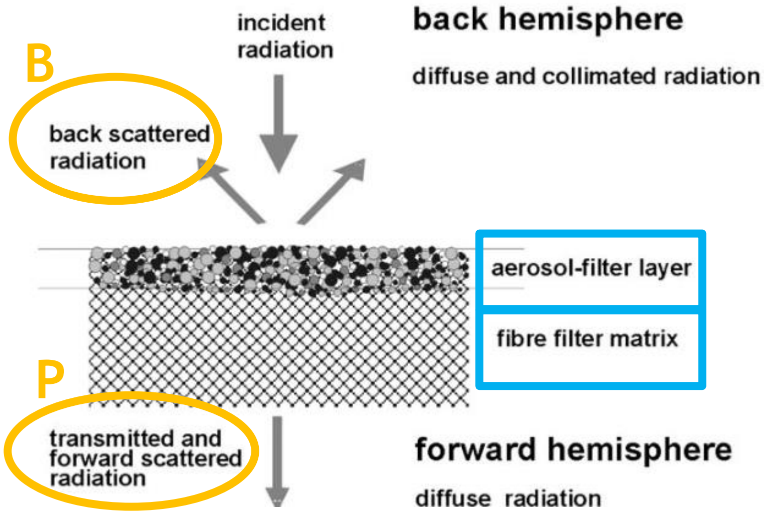

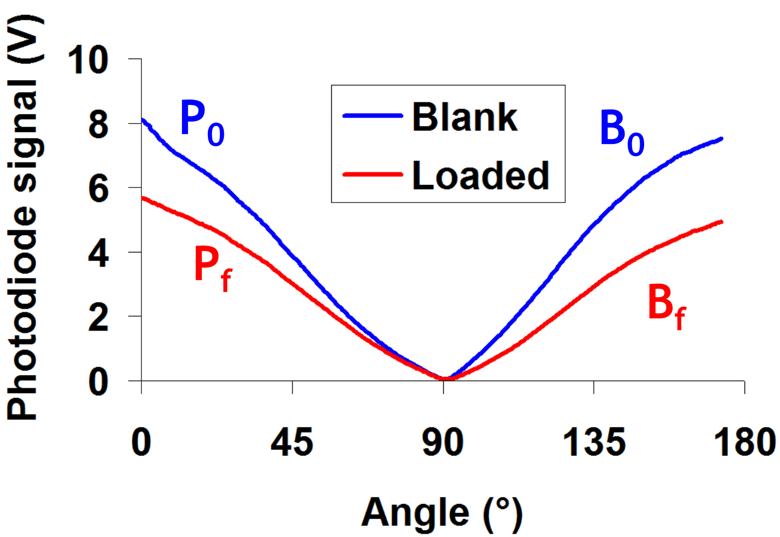

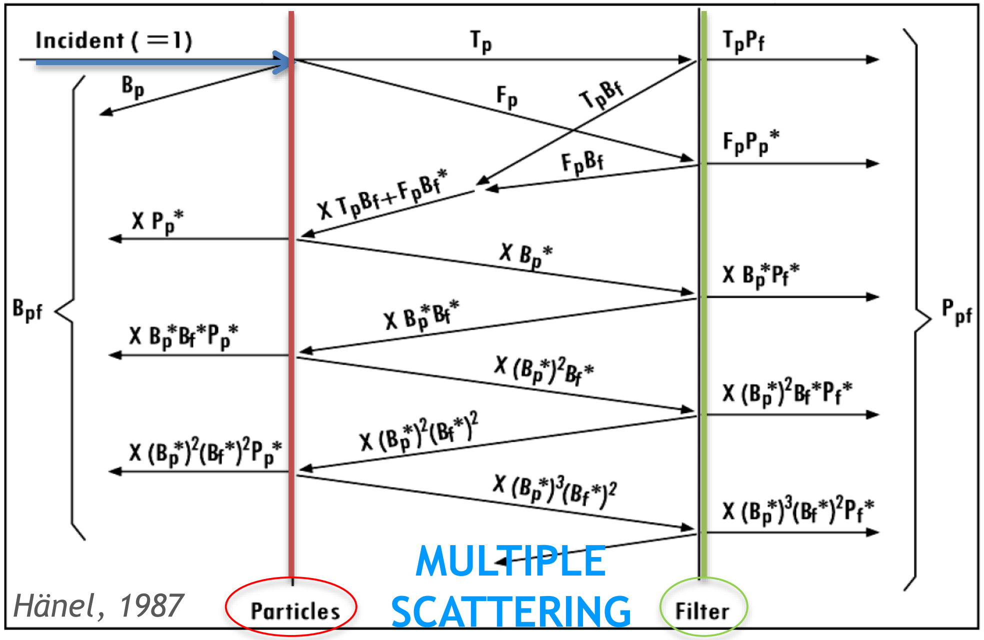

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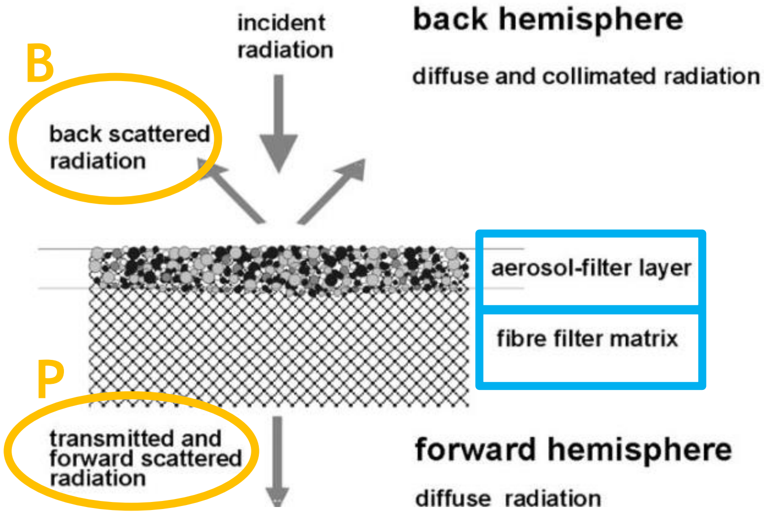

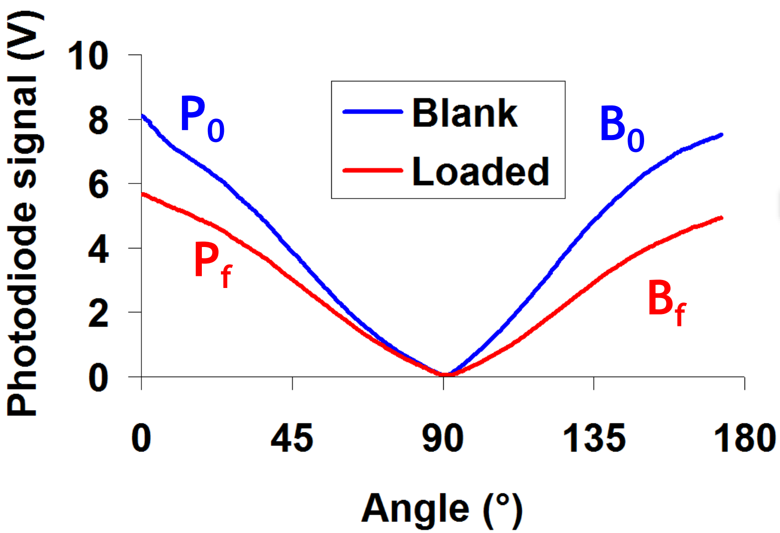

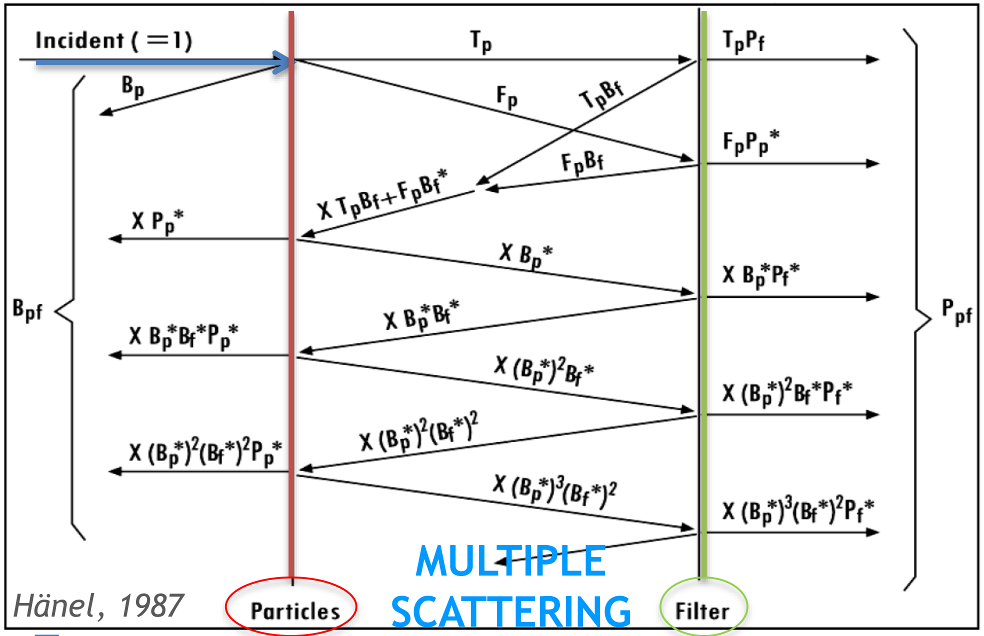

ω_p (single scattering albedo)

τ_p (optical depth)

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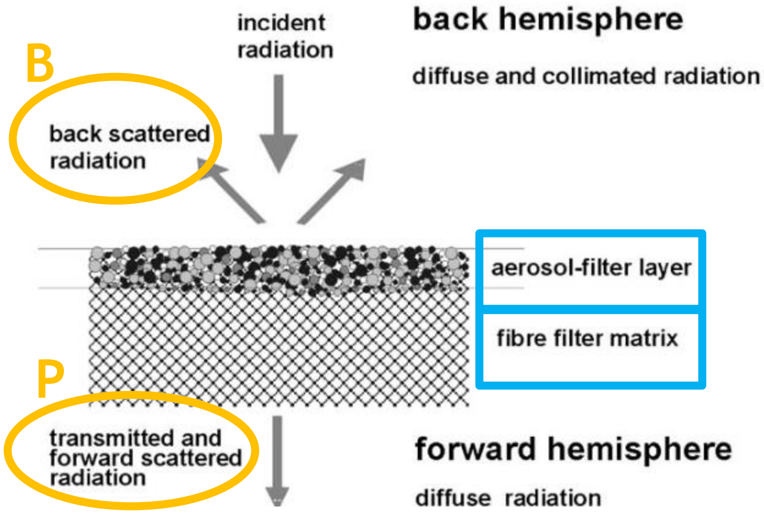

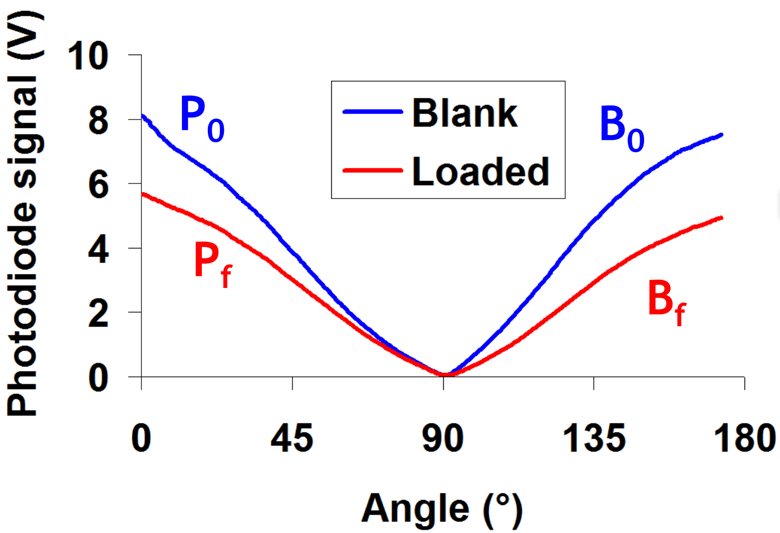

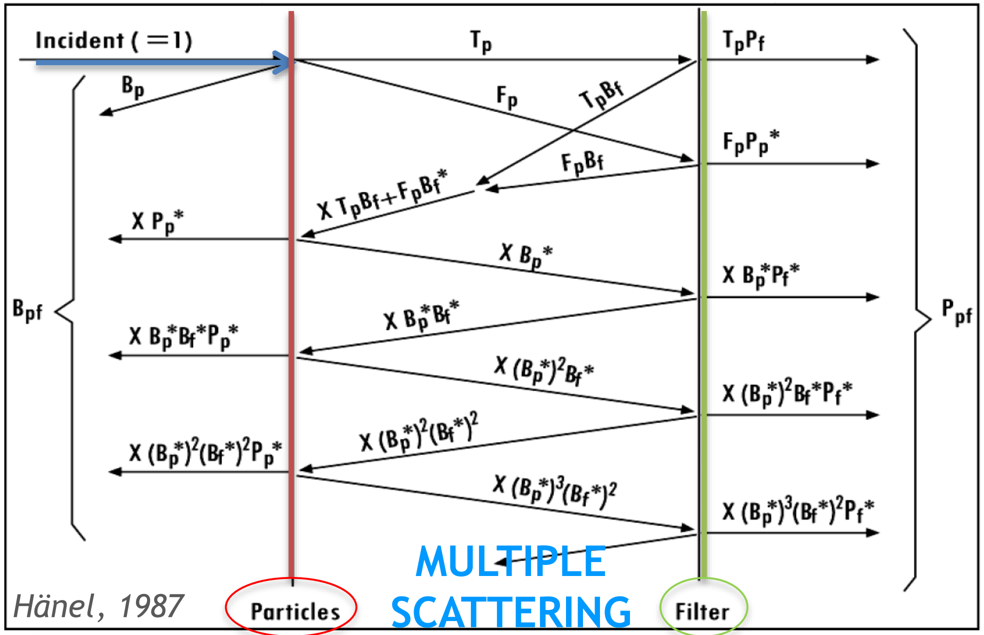

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$ABS = (1 - \omega_p)\tau_p$ (absorbance)

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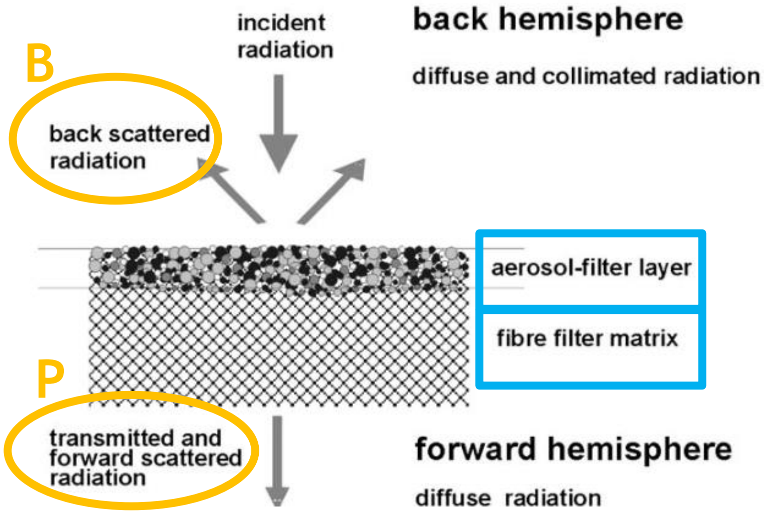

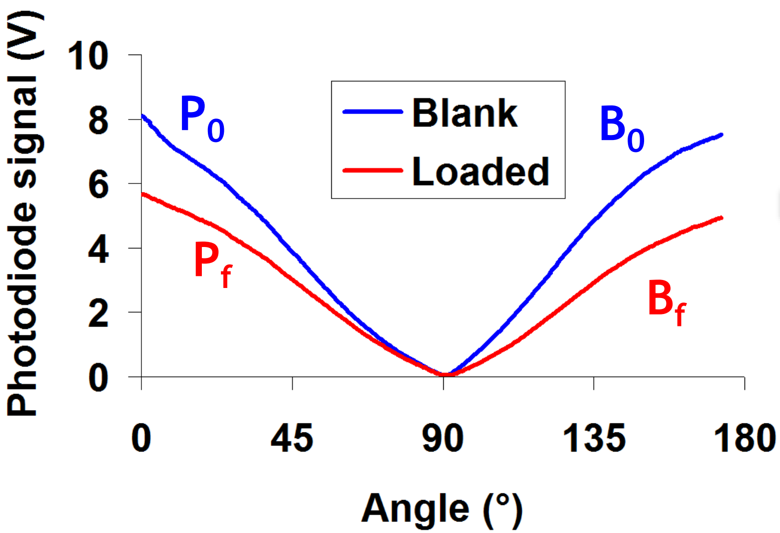

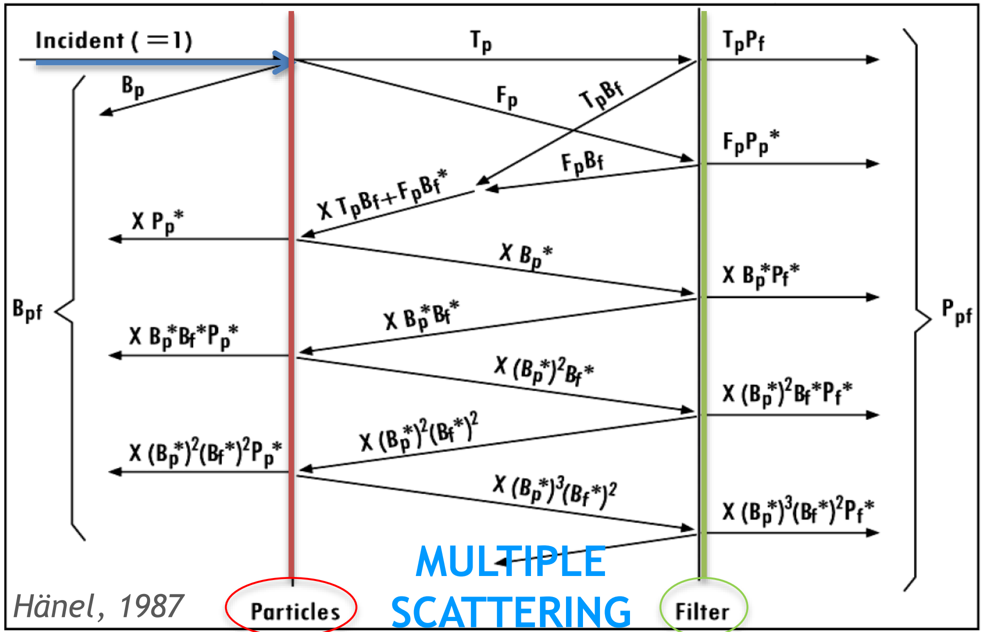

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A deposit area

V sampled volume

$b_{ap} = ABS \cdot A/V$

Carbonaceous Aerosol in Rome and Environs (CARE) project

Large collaborative project (13 national and international partners)

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Carbonaceous Aerosol in Rome and Environs (CARE) project

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MAJOR OBJECTIVES

Black Carbon
Brown Carbon

- size
- chemical composition
- optical properties
- toxicity

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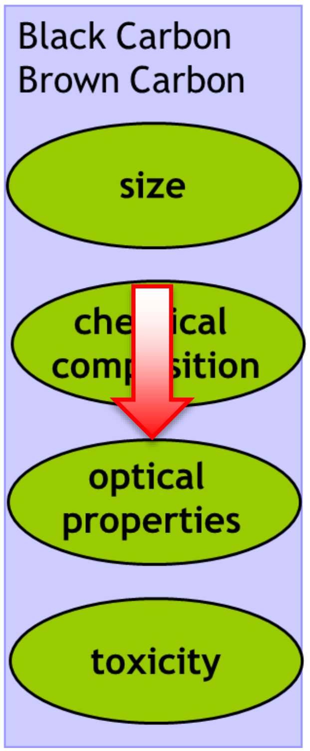

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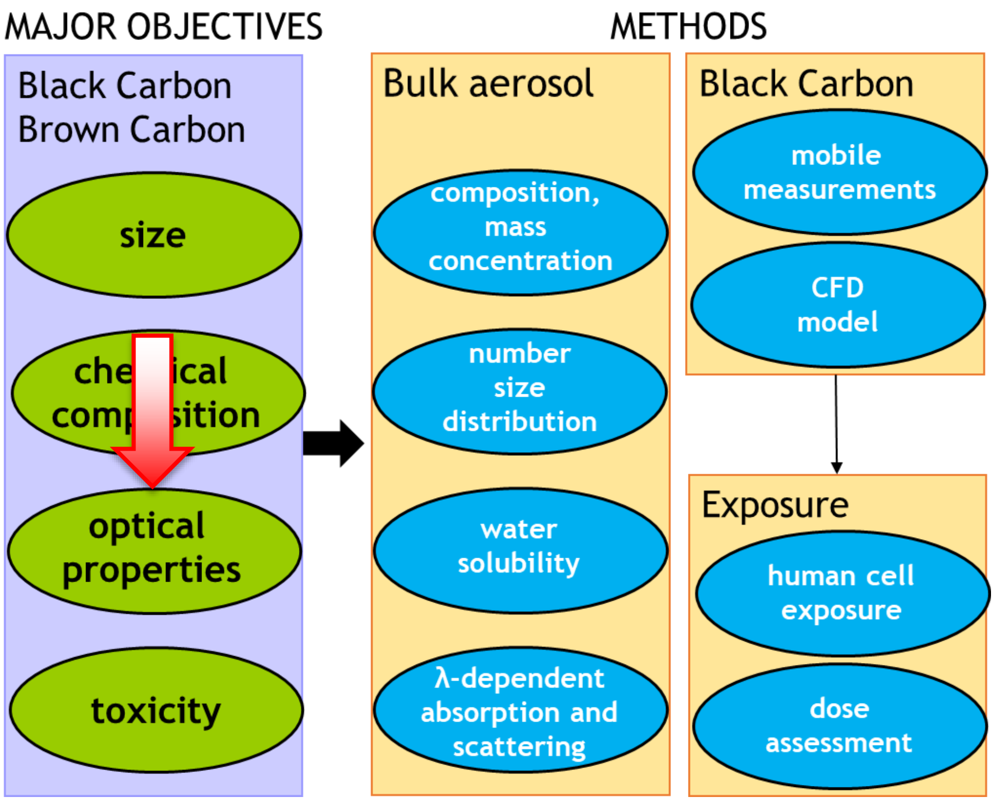

On-line and **off-line** analyses

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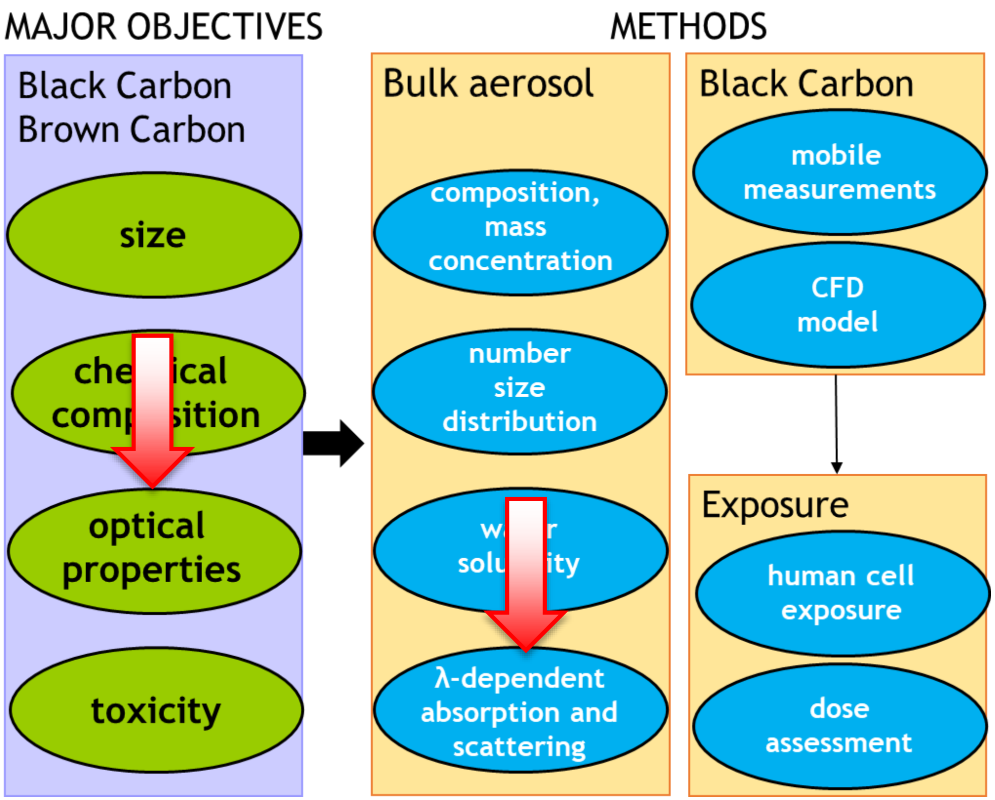

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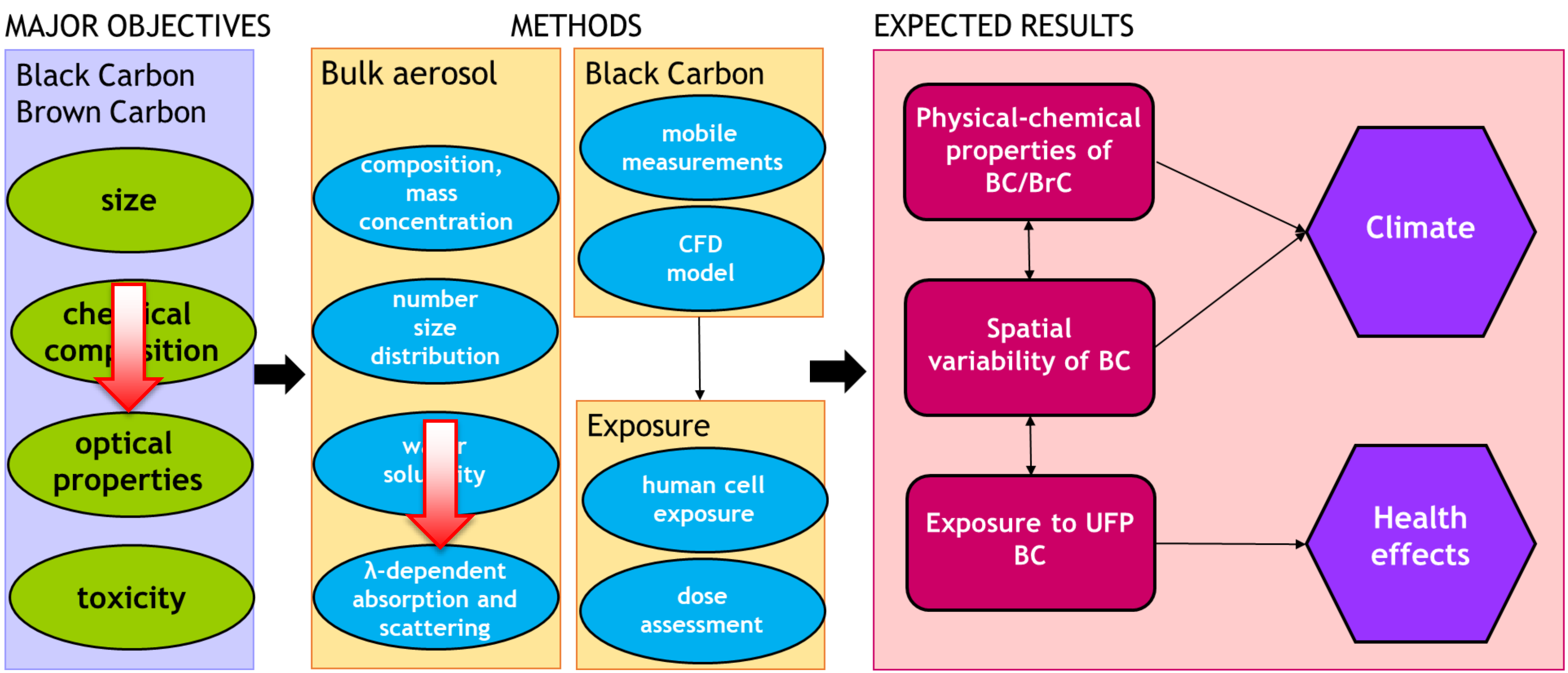

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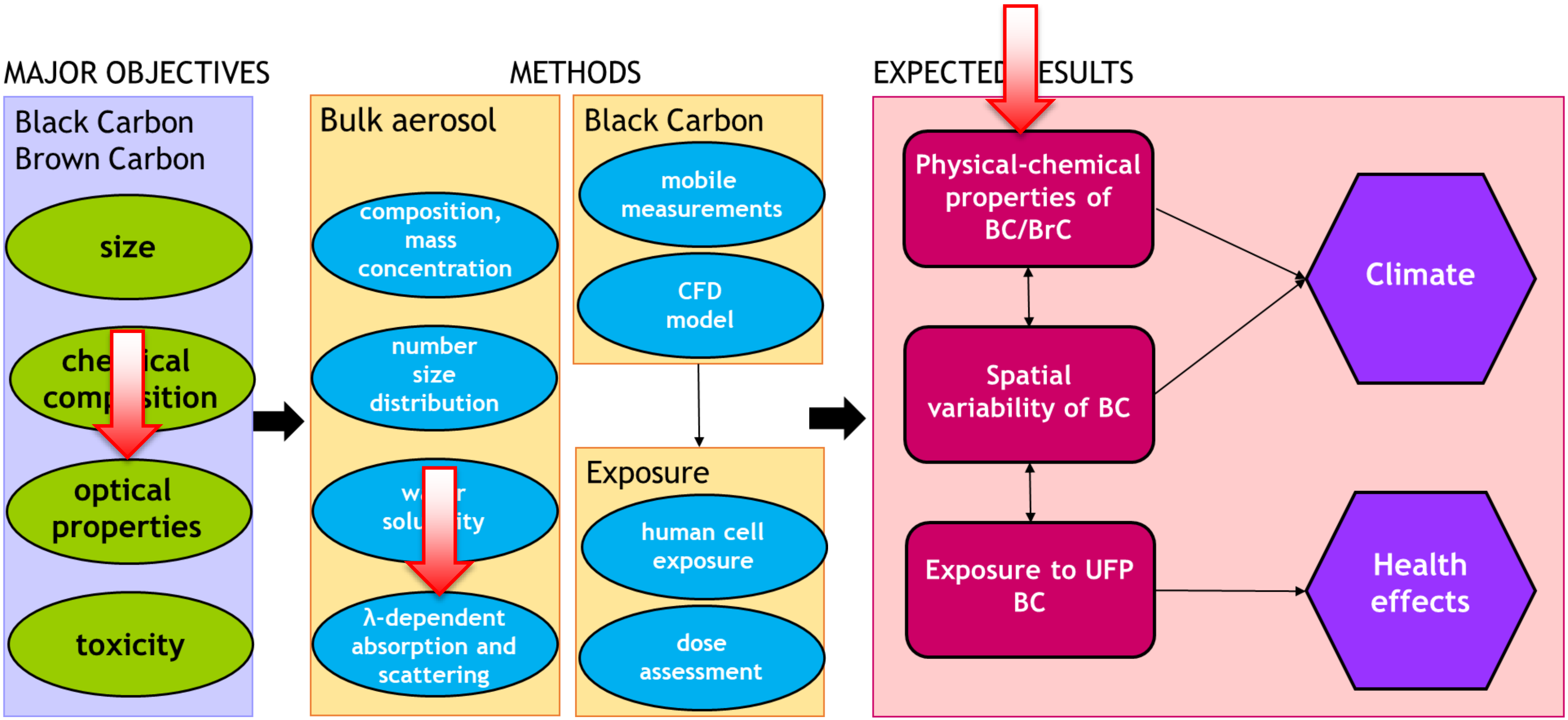

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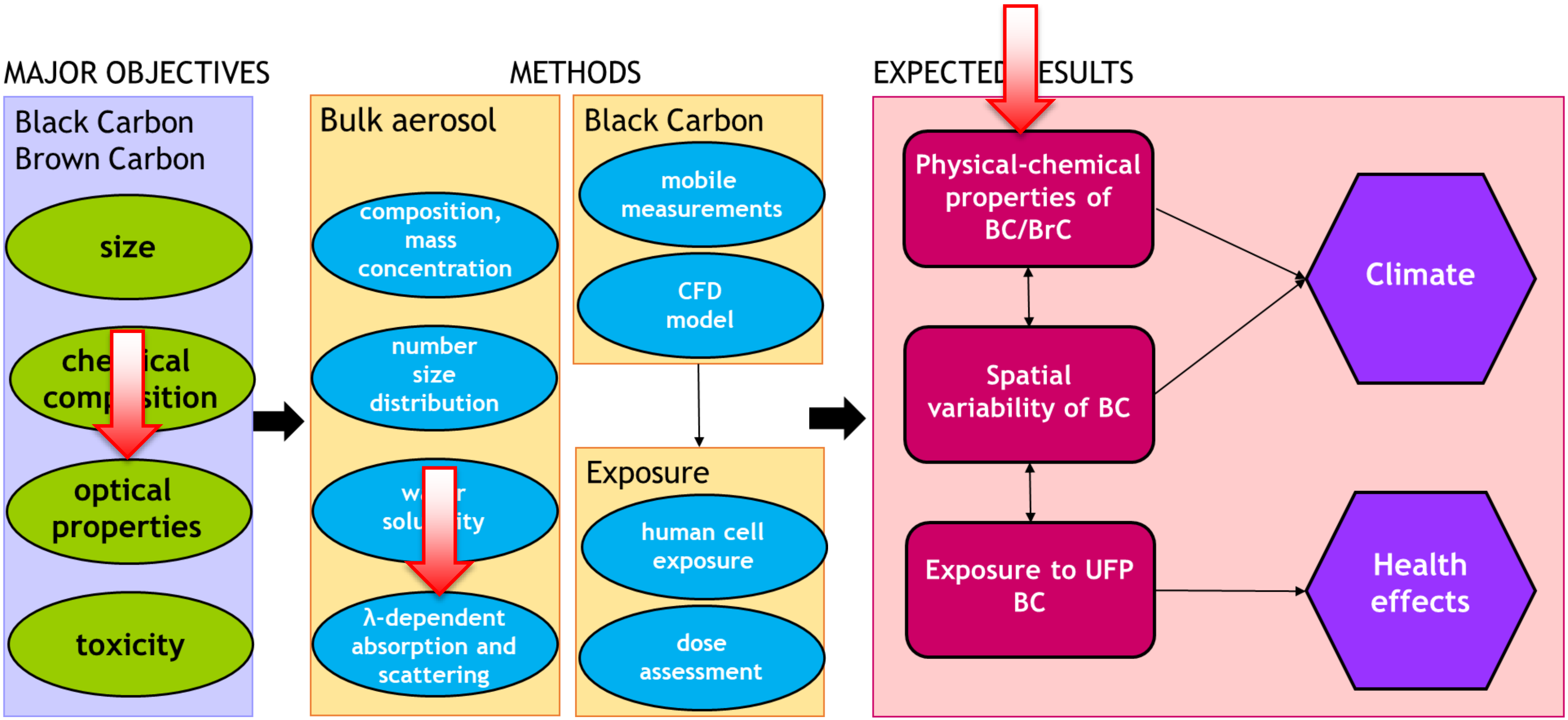

On-line and **off-line** analyses

Data analysis still in progress…

CARE project: contributions and results

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- Multi-wavelength measurements of aerosol absorption coefficient (b_{ap}) on daily and hourly $PM_{2.5}$ samples (performed with PP_UniMI)

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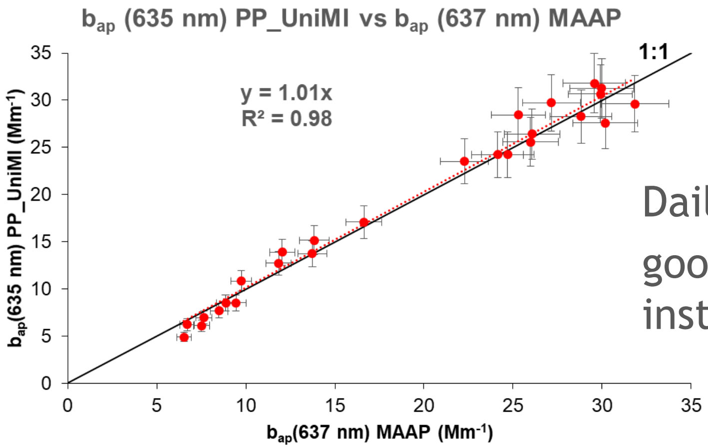

Daily samples:

good agreement with a reference instrument (MAAP – 1 λ)

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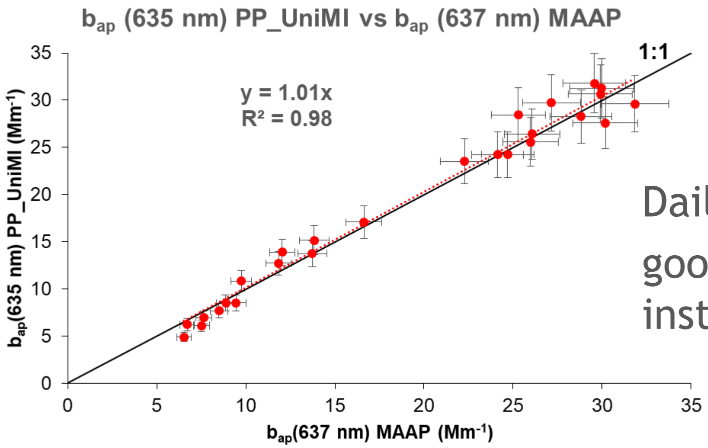

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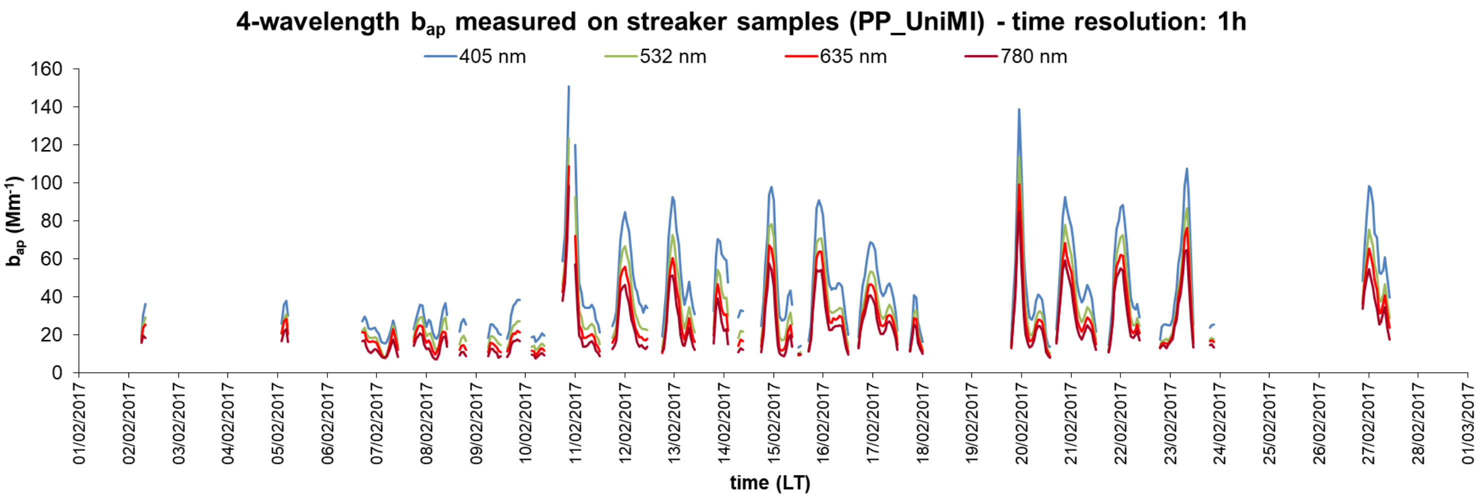
High-time resolution aerosol absorption properties



The IMPROVE algorithm

- U.S. IMPROVE algorithm: developed to reconstruct light extinction at remote and rural sites (U.S. national parks) -> visibility monitoring

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Need to tailor coefficients to make the algorithm site-specific!

Credits to M. Lazzarini, ARPA Lombardia

Tailored approach: site-specific reconstruction of light extinction at urban sites

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Main aerosol components:

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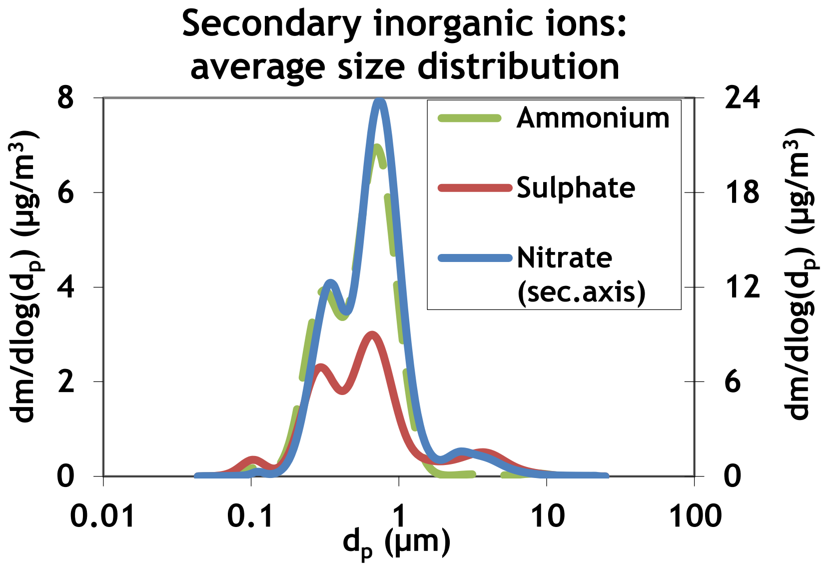

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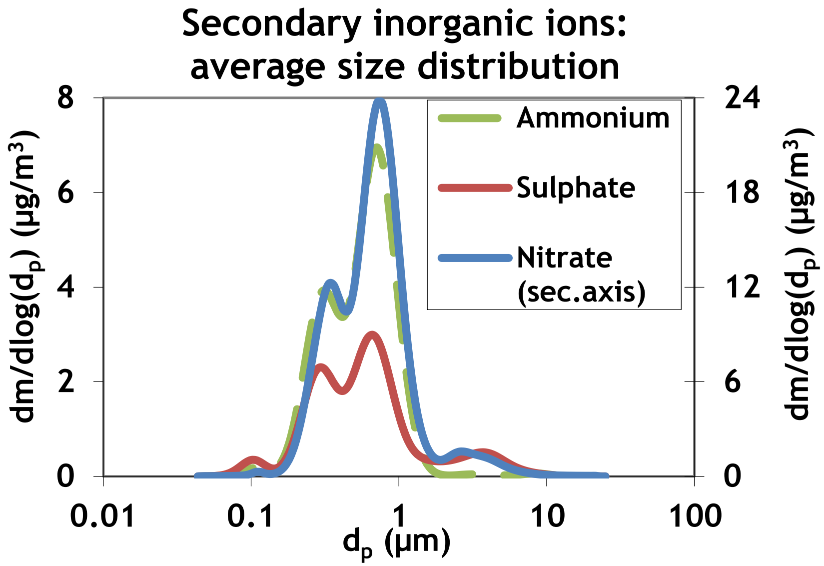

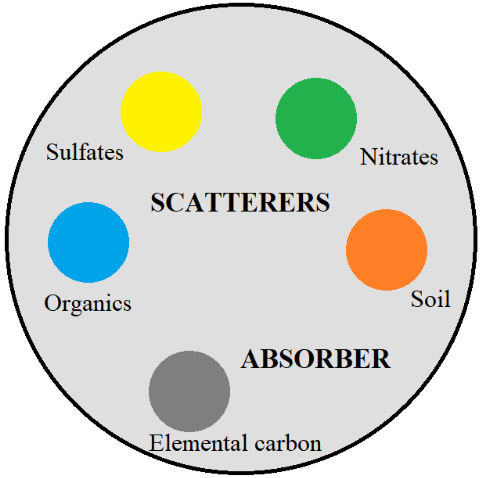

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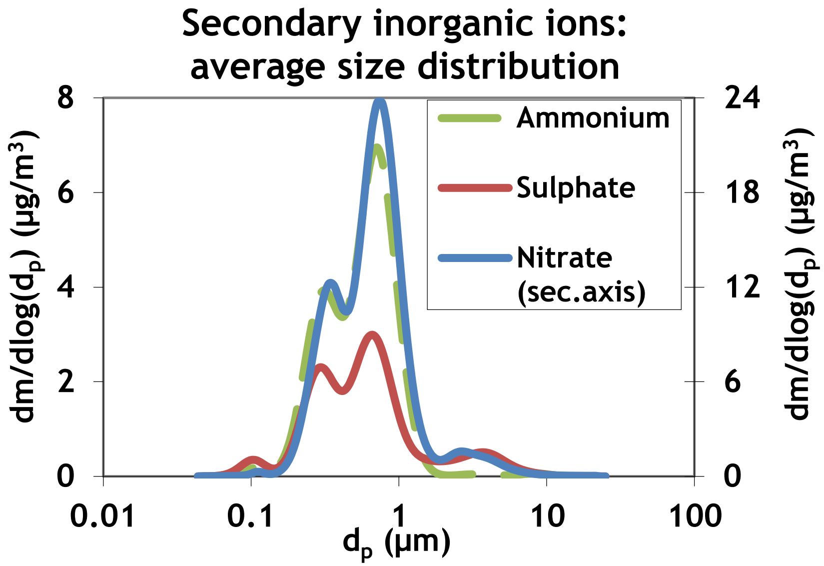

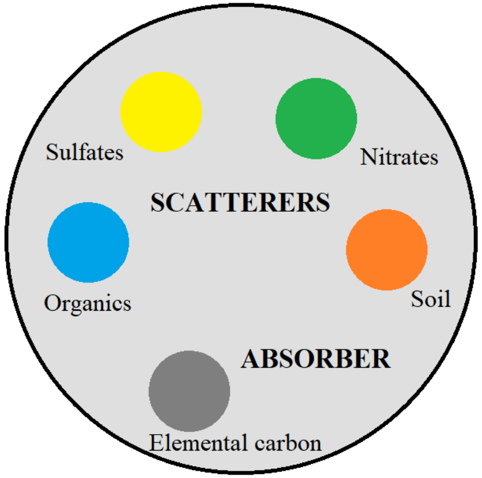

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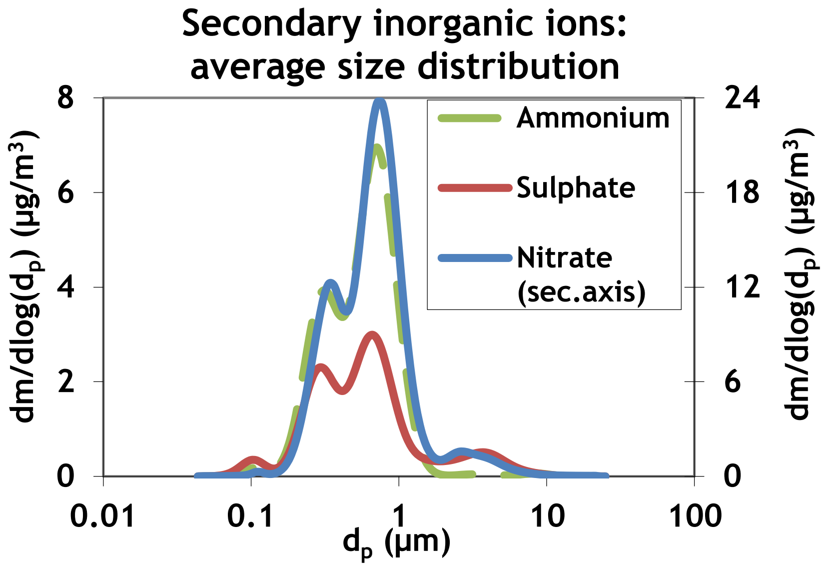

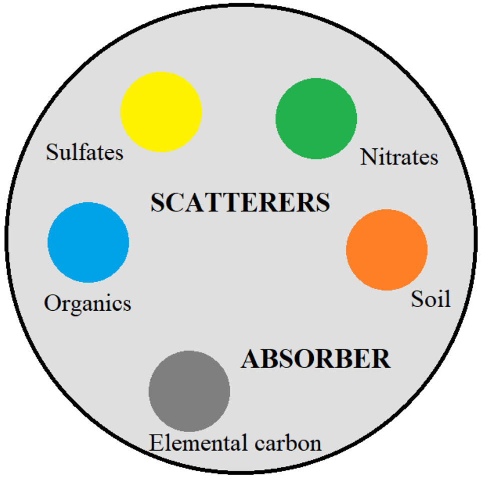

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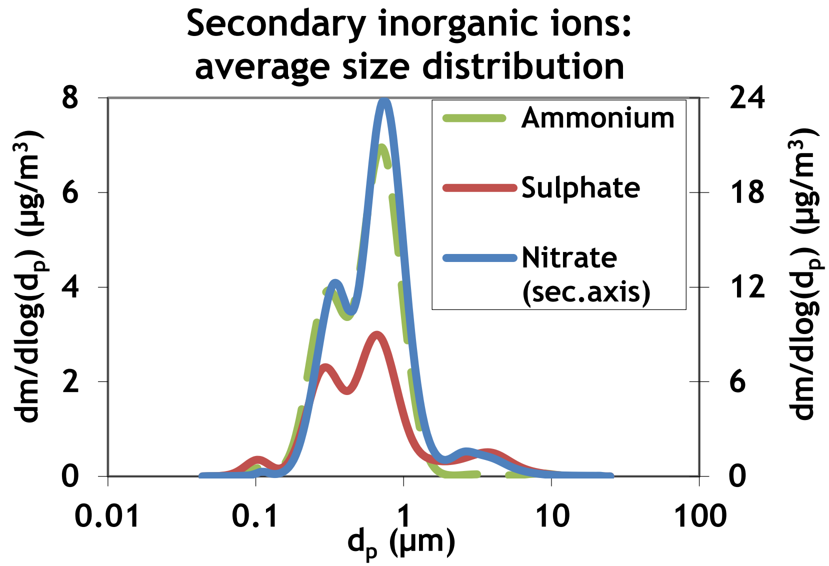

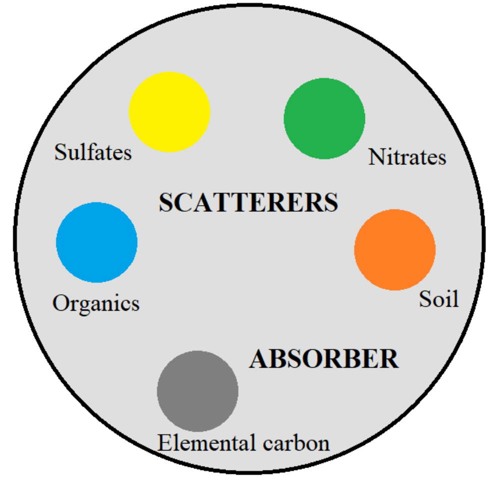

Meteorological parameters (T, P, RH)

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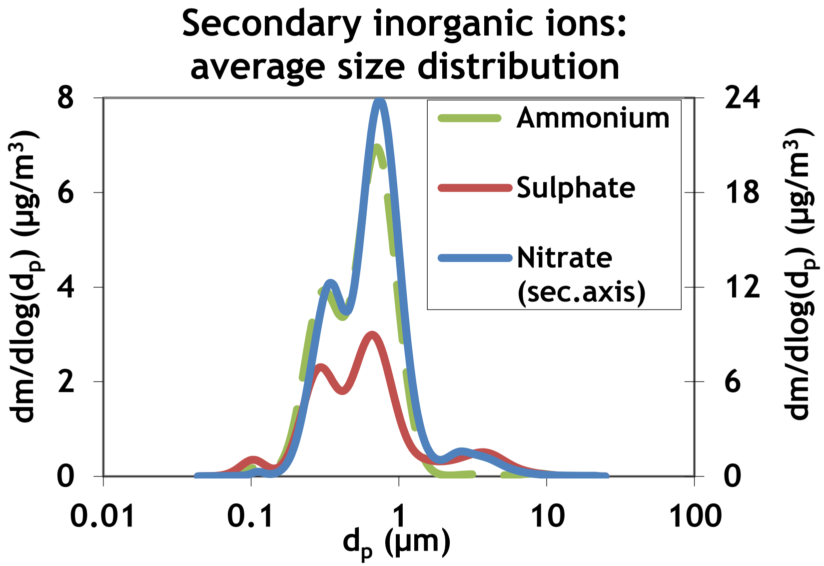

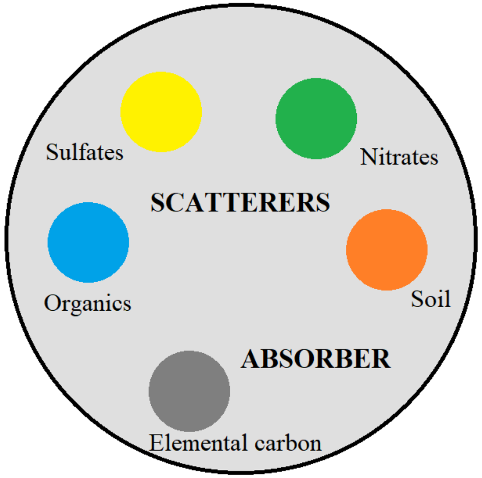

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RAYLEIGH SCATTERING RS
Tailored WATER GROWTH FUNCTIONS $f(RH)_i$

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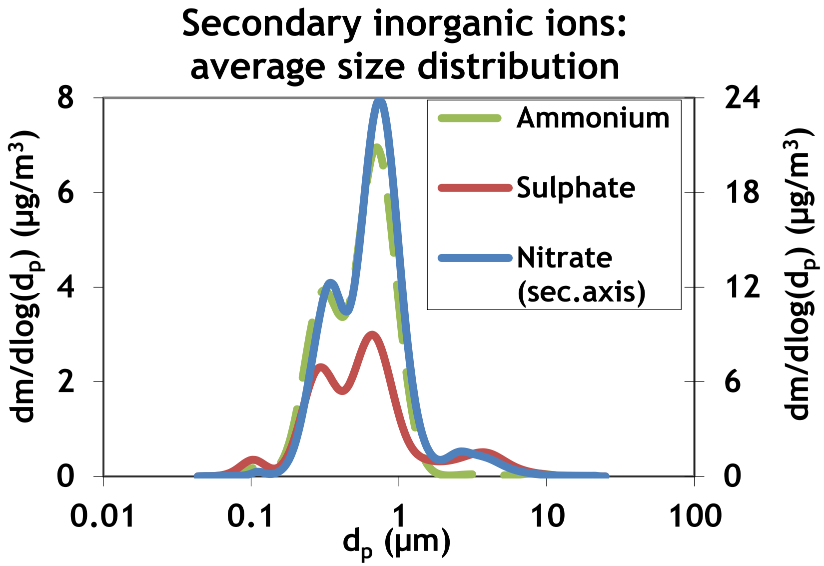

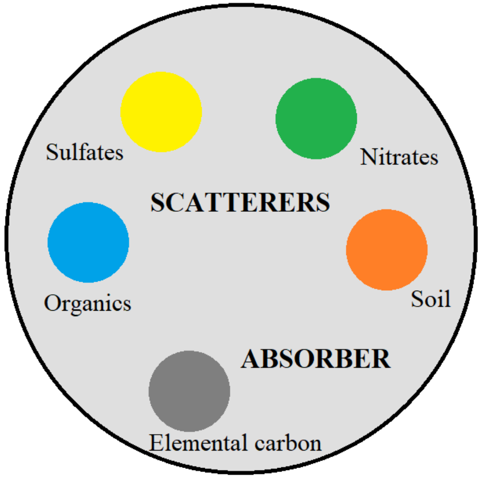

Meteorological parameters (T, P, RH)

Tailored DRY MASS EXTINCTION EFFICIENCIES c_i of main aerosol components	CONCENTRATIONS of main aerosol components and NO_2 PM LIGHT ABSORPTION COEFFICIENT b_{ap}	RAYLEIGH SCATTERING RS Tailored WATER GROWTH FUNCTIONS $f(RH)_i$

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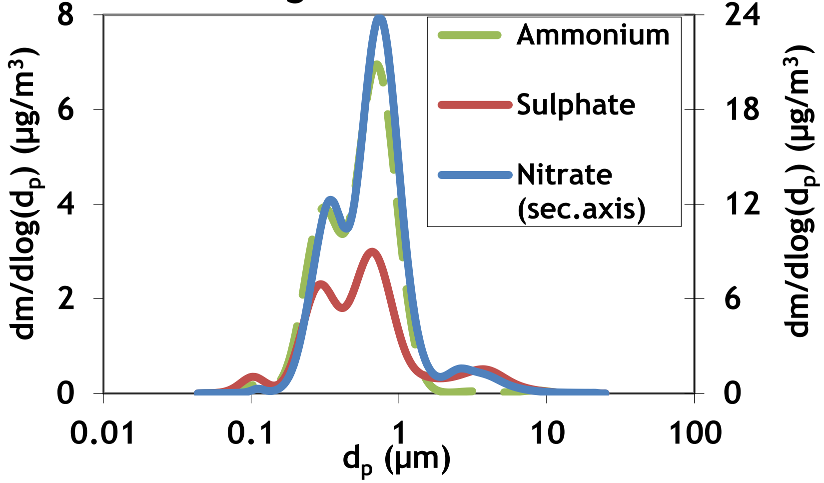
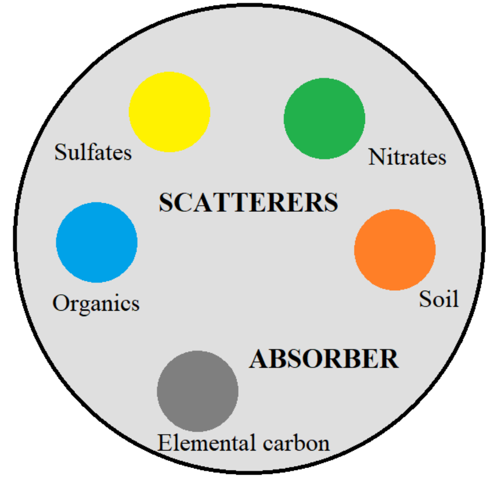
Secondary inorganic ions: average size distribution





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Light extinction coefficient @ 550 nm

$$b_{ext}(RH) = c_1 f(RH)_1 [AMSUL] + c_2 f(RH)_2 [AMNIT] + c_3 f(RH)_3 [OM] + c_4 [FS] + 0.60[CM] + RS + b_{ap} + 0.33[NO_2(ppb)]$$

AMSUL= ammonium sulphate; AMNIT: ammonium nitrate; OM: organic matter; FS: fine soil; CM: coarse mass [$PM_{10-2.5}$]

Tailored approach: results and outlooks

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Tailored approach: results and outlooks

Tailored dry mass extinction efficiencies

Component	c_i (m^2/g)
AMSUL	4.44
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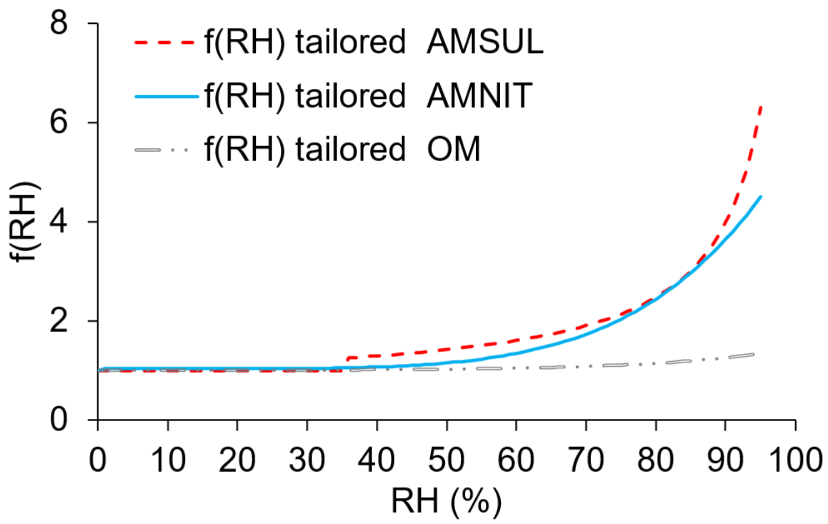

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Reconstructed b_{ext}

↓

Visual range $VR = -\ln 0.02 / b_{ext}$

(Koschmieder equation)

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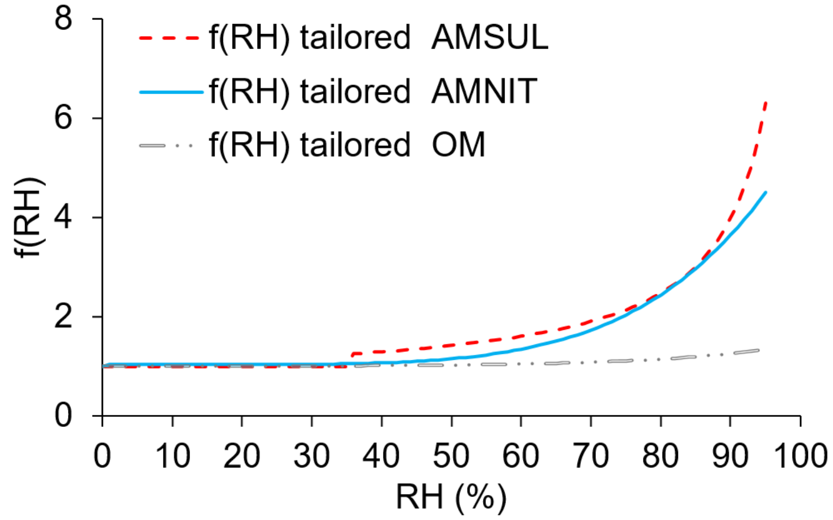

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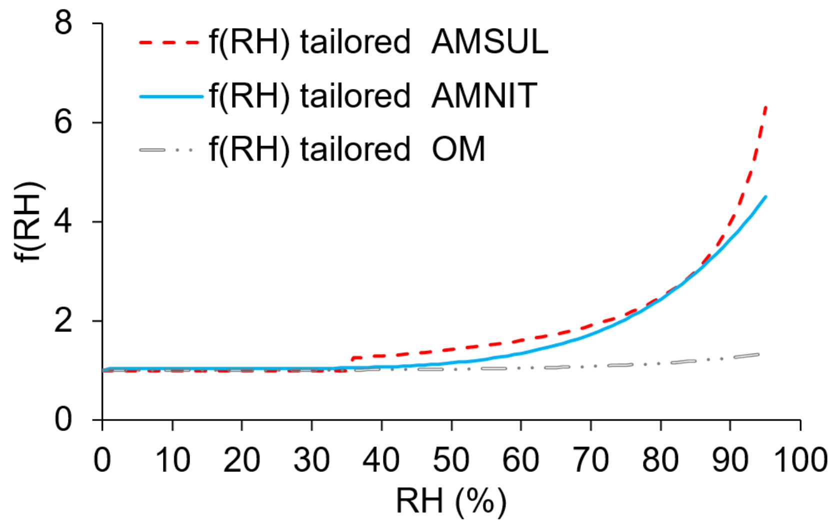

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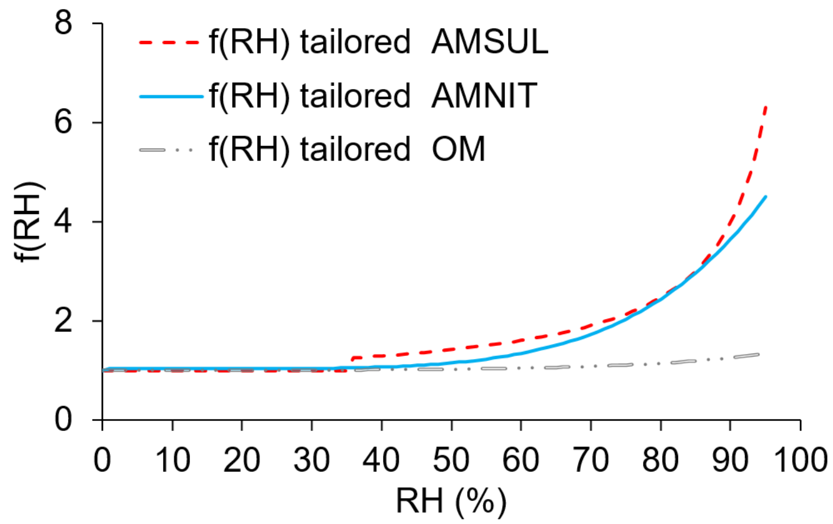

Outlooks:

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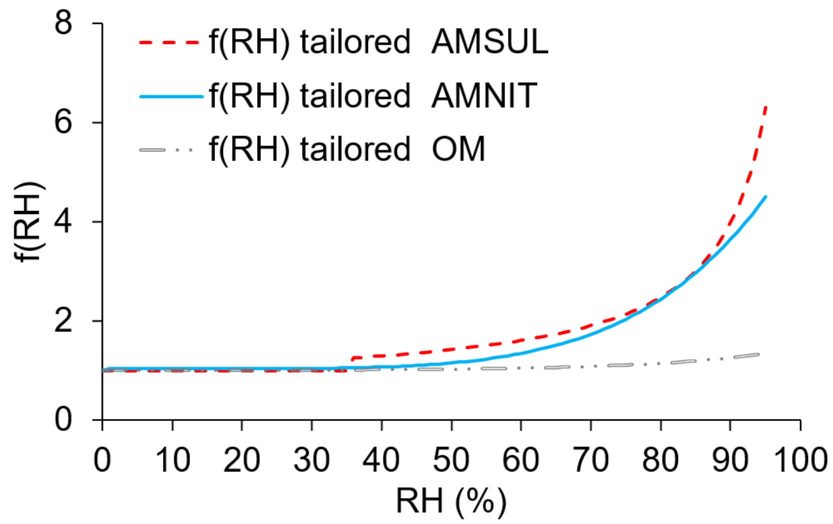

Outlooks:

- Model check and improvement by comparison with parallel direct measurements of b_{ext} or visual range
- Implement the use of the algorithm in standard monitoring networks, in order to obtain visual range as an additional parameter

Future work

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- Planned activities:

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  - Multi-wavelength determination of b_{ap} in samples collected in an area heavily impacted by anthropogenic sources (Terni), to be coupled with a detailed chemical characterization (collaboration with Università la Sapienza - Rome): outdoor and indoor (first time!) samples

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  - Optical analysis of aerosol samples collected in the frame of the Aerosol, Clouds and TRace gases InfraStructure (ACTRIS)-2 – Mt. Cimone Field Campaign (European intercomparison project)

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    - Investigation of important aerosol optical parameters (e.g. asymmetry factor)
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  - Development of a methodology to obtain aerosol scattering coefficients with PP_UniMI for samples collected on suitable filter media

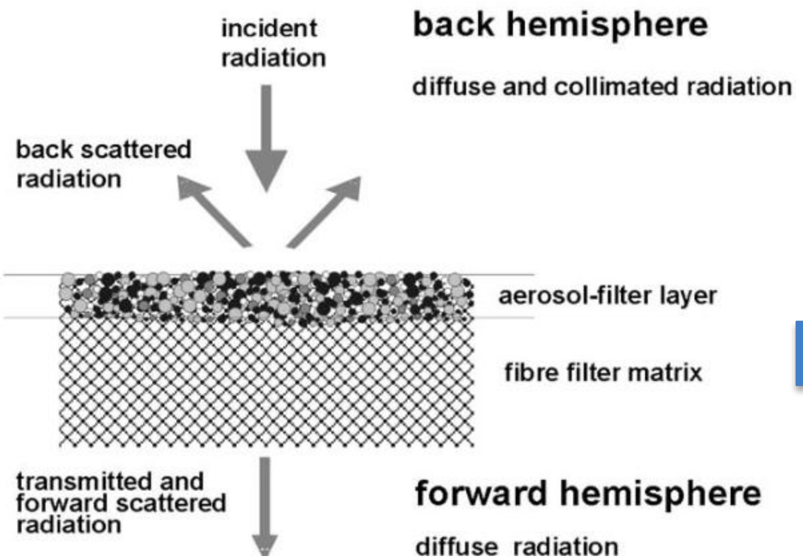
Thank you for your attention!

Publications and presentations

- Bernardoni, V., Elser, M., Valli, G., Valentini, S., Bigi, A., Fermo, P., Piazzalunga, A., and Vecchi, R.; *Size-segregated aerosol in a hot-spot pollution urban area: Chemical composition and three-way source apportionment*; **Environmental Pollution** 231 (2017), 601-611
- Valentini S., Bernardoni V., Massabò D., Prati P., Valli G. and Vecchi R.; *Tailored coefficients in the algorithm to assess reconstructed light extinction at urban sites: A comparison with the IMPROVE revised approach*; **Atmospheric Environment** (accepted)
- Vecchi R., Bernardoni V., Fermo P., Piazzalunga A., Valentini S., and Valli G.; *Assessment of light extinction at a European polluted urban area during wintertime: Impact of PM1 composition and sources*; **Environmental Pollution** (under second review)
- Costabile F., et al.; *First results of the "Carbonaceous aerosol in Rome and Environs (CARE)" experiment: beyond current standards for PM10*; **Atmosphere** (submitted)
- Valentini S., Bernardoni V., Massabò D., Prati P., Valli G. and Vecchi R.; *Tailoring coefficients in IMPROVE algorithm to assess site-specific chemical light extinction*; poster presentation at **Congresso del Dipartimento di Fisica 2017**
- Forello A.C., Bernardoni V., Calzolai G., Chiari M., Lucarelli F., Massabò D., Nava S., Prati P., Valentini S., Valli G., Vecchi R.; *High-time resolved atmospheric aerosol characterization for source apportionment studies*; poster presentation at **Congresso del Dipartimento di Fisica 2017**
- Valentini S., Bernardoni V., Massabò D., Prati P., Valli G. and Vecchi R.; *Light extinction estimates using the IMPROVE algorithm: The relevance of site-specific coefficients*; poster presentation at **European Aerosol Conference EAC 2017**
- Bernardoni V., Forello A.C., Mariani F., Paroli B., Potenza M.A.C., Pullia A., Riccobono F., Sanvito T., Valentini S., Valli G., Vecchi R.; *Innovative instrumentation for the study of atmospheric aerosol optical properties*; Proceedings in Physics – **Congresso del Dipartimento di Fisica**, Springer (submitted)

Radiative transfer model: 2-layer scheme

Petzold and Schönlinner, 2004



Membrane filters

(e.g. PTFE, polycarbonate)

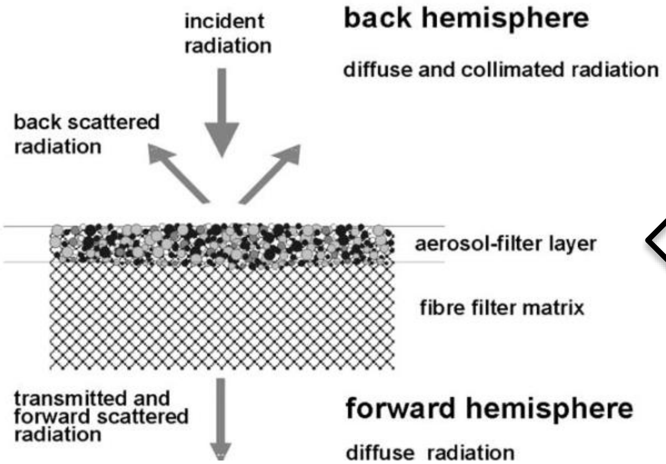
- Layer 1: aerosol
- Layer 2: filter

Fiber filters

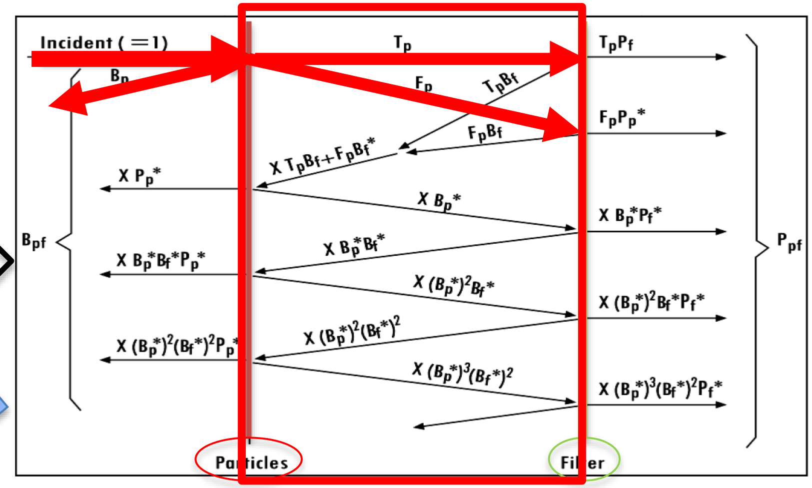
(e.g. quartz-fiber filters)

- Layer 1: aerosol+filter
- Layer 2: filter

Radiative transfer model: Adding method



RADIATIVE PROCESSES



$T + F + B + A = 1$ energy conservation

T transmittance

F fraction of forward scattered radiation

B fraction of backward scattered radiation

A absorbance

$P = T + F$ fraction of radiation passing into the forward hemisphere

Sum of relevant contributions:

- Part of incoming radiation scattered backwards from the filter towards the particles:

$$\beta_f^* = \frac{T_p B_f + F_p B_f^*}{1 - B_p^* B_f^*}$$

- Part of incoming radiation scattered from the particles towards the filter:

$$\sigma_p^* = F_p + B_p^* \beta_f^*$$

- Strength of radiation passage of the loaded filter:

$$P_{pf} = P_f T_p + P_f^* \sigma_p^*$$

- Strength of backward scattering of the loaded filter :

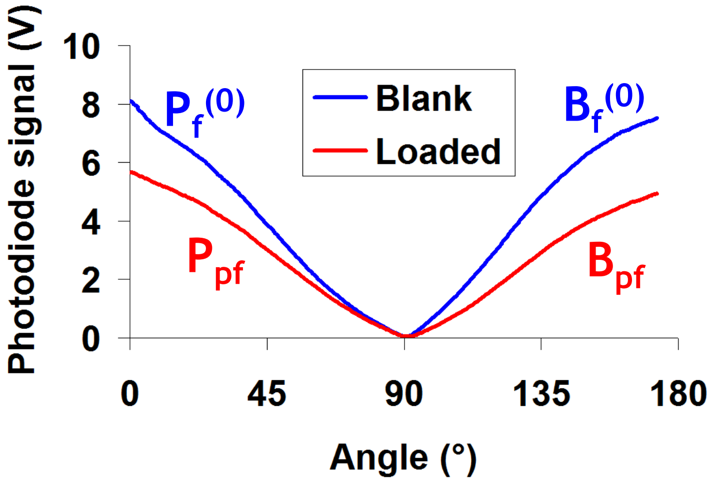
$$B_{pf} = B_p + P_p^* \beta_f^*$$

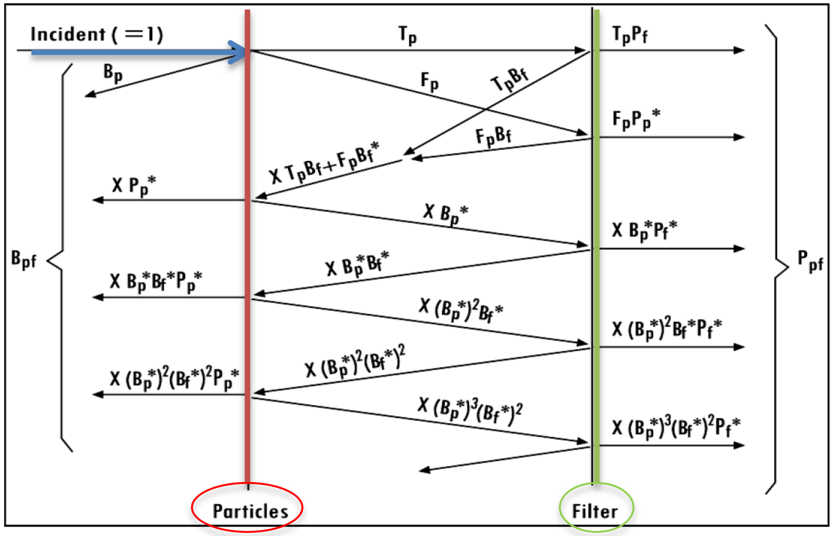
$$\frac{P_{pf}}{P_f^{(0)}} = \frac{T_p + F_p}{1 - B_p^* B_f}$$

$$\frac{B_{pf}}{B_f^{(0)}} = P_p^* \frac{T_p + F_p}{1 - B_p^* B_f} + \frac{B_p}{B_f}$$

Budget equations

Radiative transfer model: Adding method





ADDING METHOD: relates measurements of fractions of radiation in both hemispheres for blank and loaded filter to transmission/scattering properties of the two layers (aerosol and filter) separately

Scheme of radiative processes in a loaded filter [*Hänel, 1987*]

$$\frac{P_{pf}}{P_f^{(0)}} = \frac{T_p + F_p}{1 - B_p^* B_f}$$

$$\frac{B_{pf}}{B_f^{(0)}} = P_p^* \frac{T_p + F_p}{1 - B_p^* B_f} + \frac{B_p}{B_f}$$

5 unknowns

- T_p= transmittance of the particle layer
- F_p= fraction of parallel incident light scattered in the forward hemisphere by the particle layer
- B_p= fraction of parallel incident light scattered in the backward hemisphere by the particle layer
- P_p^*= fraction of light scattered by the filter and re-scattered by the particle layer towards the forward hemisphere
- B_p^*= fraction of light scattered by the filter and re-scattered by the particle layer towards the backwards hemisphere

Radiative transfer model: Two-stream approximation

F_p
P_p^*
B_p
B_p^*

Two stream approximation models
[*Coakley and Chýlek, 1975*]

ω_p (single scattering albedo)
τ_p (optical depth)

$$\omega_p = \frac{b_{sca}}{b_{ext}} \qquad \tau_p = -\ln T_p$$

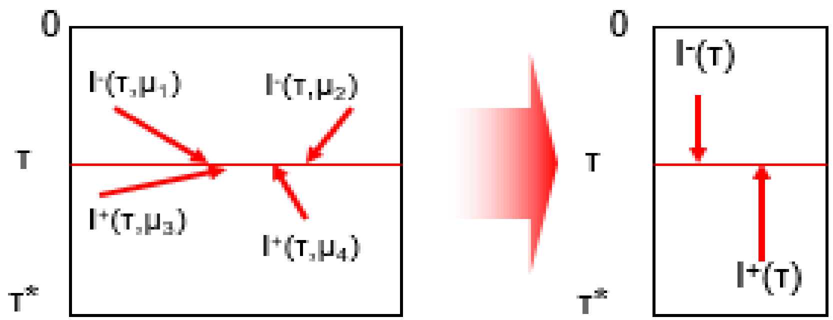
$$\mu \frac{dI^{(0)}(\tau,\mu)}{d\tau} = I^{(0)}(\tau,\mu) - \frac{1}{2}\int_{-1}^{1} d\mu' p^{(0)}(\mu,\mu') I^{(0)}(\tau,\mu')$$

$(\mu = \cos\vartheta)$

Radiative transfer equation for a plane-parallel scattering and absorbing atmosphere

It can be decomposed in:
$I^+(\tau,\mu) = I(\tau,\mu)$ e $I^-(\tau,\mu) = I(\tau,-\mu)$ for $0 \leq \mu \leq 1$

The two-stream approximation states that:
$I^+(\tau,\mu) = I^+(\tau)$ e $I^-(\tau,\mu) = I^-(\tau)$ (introduction of «effective» intensities, hemisphere-dependent)



Boundary conditions for an external source (parallel beam):

$$I^-(\tau = 0) = I_0$$
$$I^+(\tau = \tau^*) = 0$$

Boundary conditions for an internal source (diffuse radiation):

$$I^-(\tau = 0) = 0$$
$$I^+(\tau = \tau^*) = 0$$

Radiative transfer model: Two-stream approximation

F_p
P_p^*
B_p
B_p^*

Two stream approximation models
[*Coakley and Chýlek, 1975*]

ω_p (single scattering albedo)
τ_p (optical depth)

$$\omega_p = \frac{b_{sca}}{b_{ext}} \qquad \tau_p = -\ln T_p$$

For diffuse radiation terms:

$$B_p^* = \frac{b\left(1 - T_p^{2\sqrt{B}}\right)}{\sqrt{B} + a + \left(\sqrt{B} - a\right)T_p^{2\sqrt{B}}}$$

$$P_p^* = \frac{1}{2\sqrt{B}}\left[\left(\sqrt{B} - a + B_p^* b\right)T_p^{-\sqrt{B}} + \left(\sqrt{B} + a - B_p^* b\right)T_p^{\sqrt{B}}\right]$$

$$a = 2\left[1 - \omega_p\left(1 - \beta_p^*\right)\right],\ b = 2\omega_p\beta_p^*,\ B = a^2 - b^2$$

For parallel incident radiation terms:

$$B_p = \frac{c - \frac{p_1}{1+\sqrt{B}} - \left(c - \frac{p_1}{1-\sqrt{B}}\right)T_p^{2\sqrt{B}} - \frac{2p_1\sqrt{B}}{1-B}T_p^{1+\sqrt{B}}}{\sqrt{B} + a + \left(\sqrt{B} - a\right)T_p^{2\sqrt{B}}}$$

$$F_p = \frac{1}{2\sqrt{B}}\left[\left(d + B_p b + \frac{p_2}{1+\sqrt{B}}\right)T_p^{-\sqrt{B}} - \left(d + B_p b + \frac{p_2}{1-\sqrt{B}}\right)T_p^{\sqrt{B}}\right] + \frac{p_2}{1-B}T_p$$

$$c = \omega_p\beta_p,\ d = \omega_p\left(1 - \beta_p\right),\ p_1 = c - ac - bd,\ p_2 = -ad - bc - d$$

Where β_p and β_p^* are ratios of backscattered radiation to collimated and diffuse radiation, respectively, and are related to the asymmetry parameter g (assumption: $g = 0.75$ for atmospheric particles).

$$\beta_p = \frac{1}{2}\left[1 - g - \frac{4}{25}\left(1 - \frac{|1-2g|}{8} - \frac{7}{8}(1-2g)^2\right)\right]$$

$$\beta_p^* = \frac{1}{2}\left[1 - \frac{g}{4}\left(3 + g^{3+2g^3}\right)\right]$$

Intensity scattered at angle θ

$$g = \frac{1}{2}\frac{\int_0^\pi \cos\theta\, F(\theta)\sin\theta\, d\theta}{\int_0^\pi F(\theta)\sin\theta\, d\theta} = \frac{1}{2}\int_0^\pi \cos\theta\, P(\theta)\sin\theta\, d\theta$$

Phase function

Radiative transfer model: b_{ap} calculation

Given the assumption on g (thus β_p and β_p^* known), only 2 unknown quantities remain in the expression obtained by the adding method: $\boldsymbol{\omega_p}$ and the transmittance of particle layer $\boldsymbol{T_p}$

Budget equations

$$\begin{cases} \dfrac{P_{pf}}{P_f^{(0)}} = \dfrac{T_p + F_p}{1 - B_p^* B_f} \\ \dfrac{B_{pf}}{B_f^{(0)}} = P_p^* \dfrac{T_p + F_p}{1 - B_p^* B_f} + \dfrac{B_p}{B_f} \end{cases}$$

$$B_p^* = \frac{b\left(1 - T_p^{2\sqrt{B}}\right)}{\sqrt{B} + a + (\sqrt{B} - a) T_p^{2\sqrt{B}}}$$

$$P_p^* = \frac{1}{2\sqrt{B}}\left[\left(\sqrt{B} - a + B_p^* b\right) T_p^{-\sqrt{B}} + \left(\sqrt{B} + a - B_p^* b\right) T_p^{\sqrt{B}}\right]$$

$$a = 2\left[1 - \omega_p (1 - \beta_p^*)\right],\ b = 2\omega_p \beta_p^*,\ B = a^2 - b^2$$

$$B_p = \frac{c - \dfrac{p_1}{1+\sqrt{B}} - \left(c - \dfrac{p_1}{1-\sqrt{B}}\right) T_p^{2\sqrt{B}} - \dfrac{2p_1\sqrt{B}}{1-B} T_p^{1+\sqrt{B}}}{\sqrt{B} + a + (\sqrt{B} - a) T_p^{2\sqrt{B}}}$$

$$F_p = \frac{1}{2\sqrt{B}}\left[\left(d + B_p b + \frac{p_2}{1+\sqrt{B}}\right) T_p^{-\sqrt{B}} - \left(d + B_p b + \frac{p_2}{1-\sqrt{B}}\right) T_p^{\sqrt{B}}\right] + \frac{p_2}{1-B} T_p$$

$$c = \omega_p \beta_p,\ d = \omega_p (1 - \beta_p),\ p_1 = c - ac - bd,\ p_2 = -ad - bc - d$$

Solution of budget equations with an iterative method
Remember: $\tau_p = -\ln T_p$

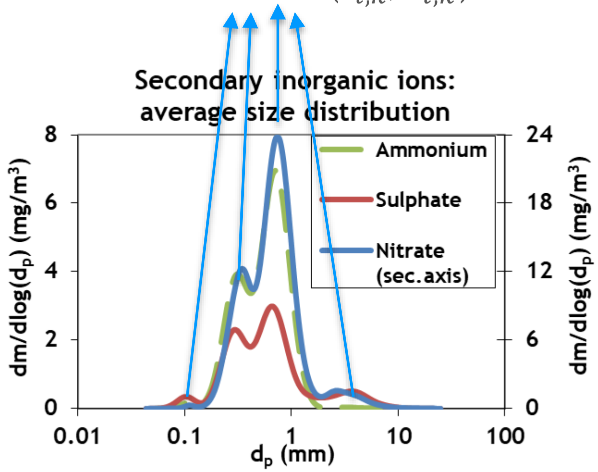
$$ABS = (1 - \omega_p)\, \tau_p$$ **ABSORBANCE**

Taking into account the deposit area A **and the sampled volume** V

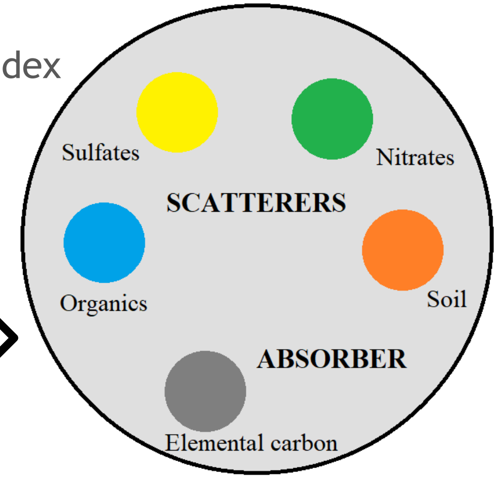
$$\boldsymbol{b_{ap}} = ABS \frac{A}{V}$$ **ABSORPTION COEFFICIENT**

Modelling approaches for the evaluation of b_{ext}

MODES $(r_{i,k}, \sigma_{i,k})$



Complex refractive index



i-th component, k-th mode

Discrete Dipole Approximation → ADDA code

General method to compute absorption and scattering of electromagnetic waves by particles of known geometry and composition

→ particle ideally divided into small cubical subvolumes («dipoles») of dielectric material

→ solution of a linear system for dipoles polarizations considering the interactions of dipoles among each other and with the incident field

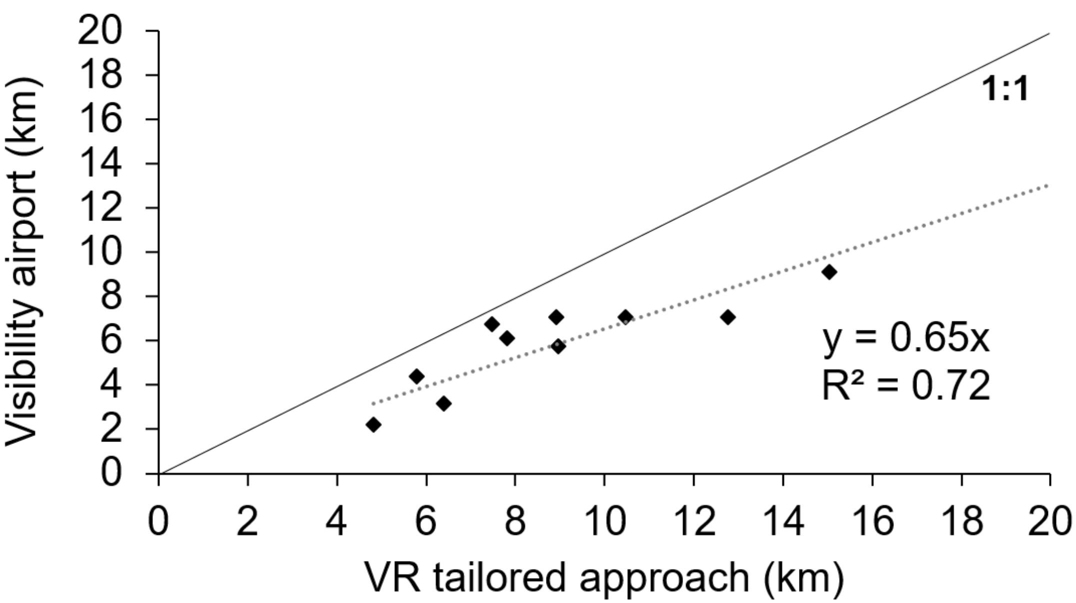
Single-particle extinction efficiency $Q_{ext,i,k}$

ρ_i
$r_{i,k}$
$\sigma_{i,k}$
$M_{i,k}$

Extinction coefficient b_{ext}

Modelling approaches for the evaluation of b_{ext}: visibility estimates

Example:
Application of the tailored approach to reconstruct light extinction for 1-week period (Milan, 2015)



Reconstructed b_{ext}

↓

Visual range $VR = -\ln \mathbf{0.02} / b_{ext}$

(Koschmieder equation)

Comparison of estimated visual range (VR) with visibility measured at Linate airport

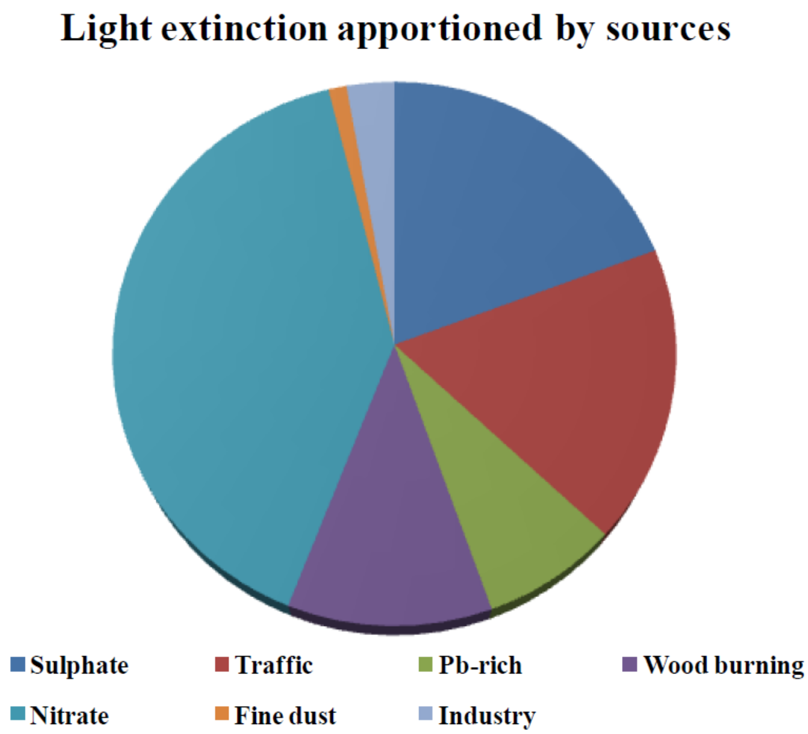
Good agreement, BUT slope < 1! (non-idealities in measurements performed at airports)

- Possible reduction of the Koschmieder constant ($-\ln \mathbf{0.02} = 3.912$) (already observed…)
- Need to compare the model results with directly measured b_{ext} or VR

Modelling approaches for the evaluation of b_{ext}: visibility estimates

Example:
Application of the tailored approach to reconstruct light extinction at an urban site

b_{ext} (in Mm^{-1})	Total	Amm. Sulphate	Amm. Nitrate	OM	b_{ap}	Fine Soil	Coarse Mass	Rayleigh Scattering	NO_2	Visual Range (km)
mean	**287.2**	24.1	108.9	77.1	28.2	0.8	21.1	12.0	14.9	18.8
std. dev.	**158.1**	20.0	88.1	44.9	15.2	0.5	11.6	0.2	4.4	13.2
min	**45.0**	1.6	1.4	12.4	5.5	0.3	1.9	11.5	4.9	4.3
max	**919.9**	111.5	510.9	214.4	75.1	4.8	64.8	12.5	26.1	86.9
average percentage		**8.5%**	**34.1%**	**27.0%**	**10.5%**	**0.4%**	**7.3%**	**5.7%**	**6.4%**	



Range of VR during this period:
4.3-86.9 km
Similar to values reported by literature studies:
10 km: polluted atmosphere
80-100 km: clear air

Possibility of tackling visibility impairment acting directly on PM source emissions

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