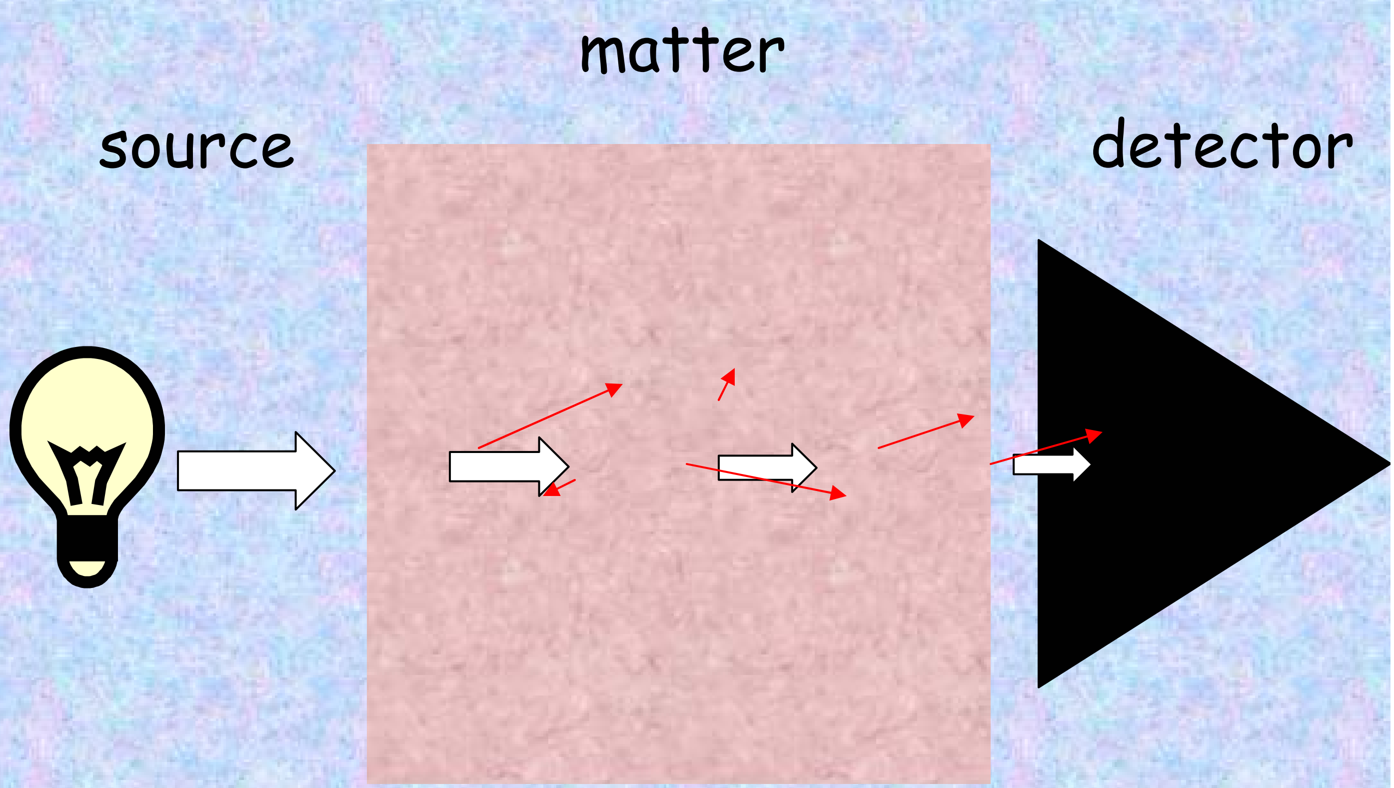
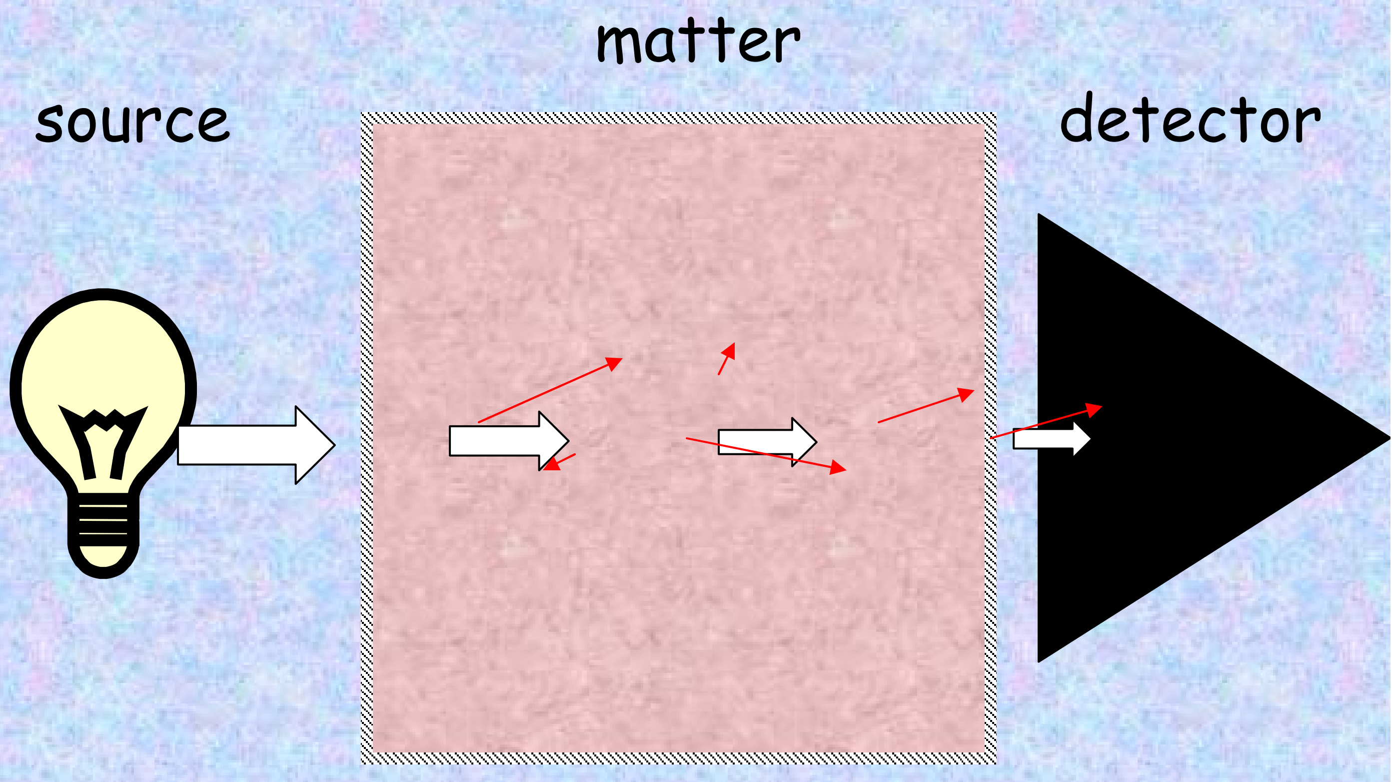
Inherent optical properties

Describing what happens to light as it goes through matter.

Properties of the matter → information on substances in the medium.



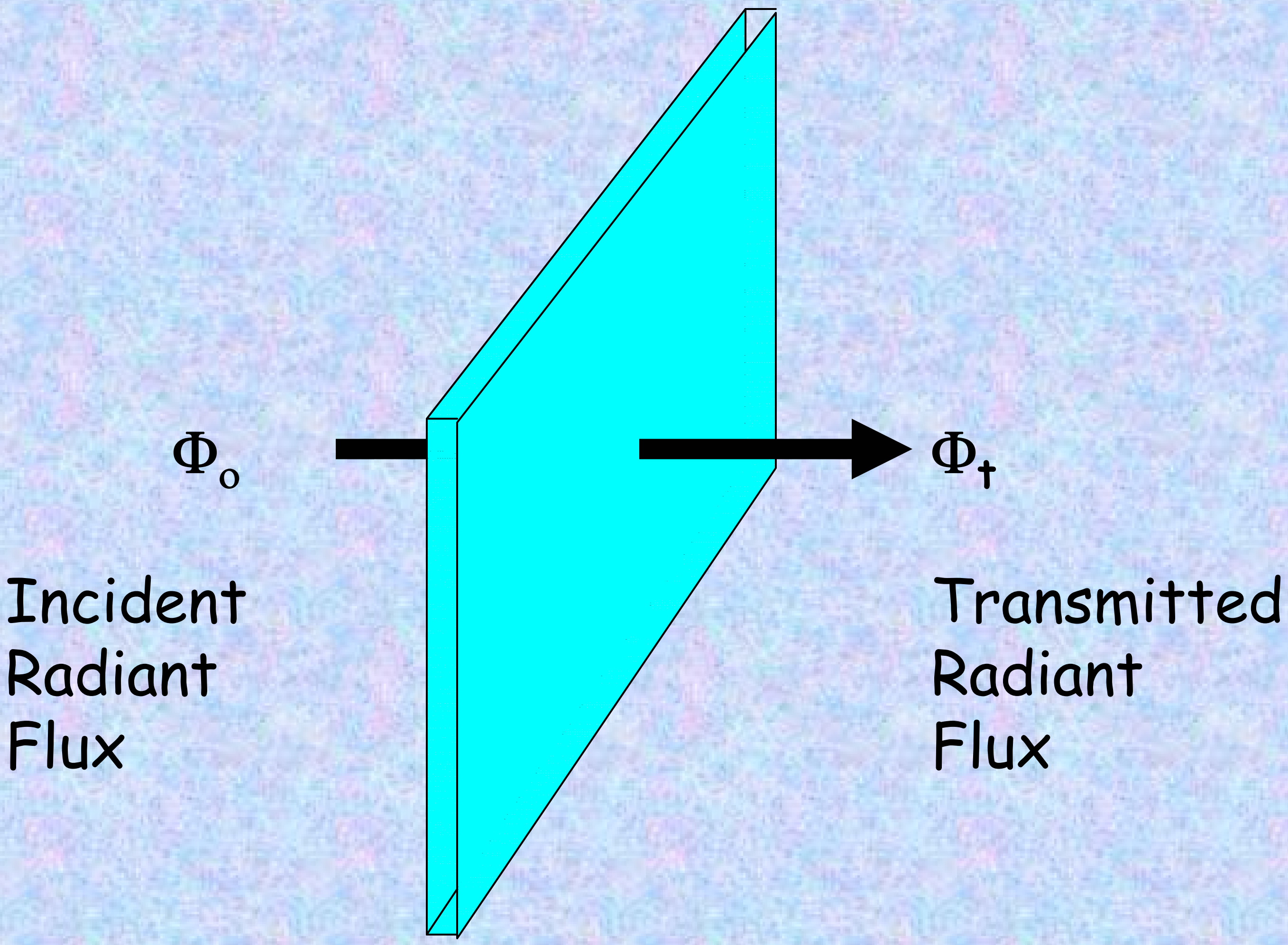
*Based, in parts, on lectures by Mobley & Roesler.



Issues:

- Source: $L(\theta,\phi,\lambda)$ leaving the source.
- Detector: acceptance angle and wavelength sensitivity.
- Interaction of light with boundaries.
- Interaction of light with Matter: Fate of photons (Absorption, scattering and fluorescence).

IOP Theory

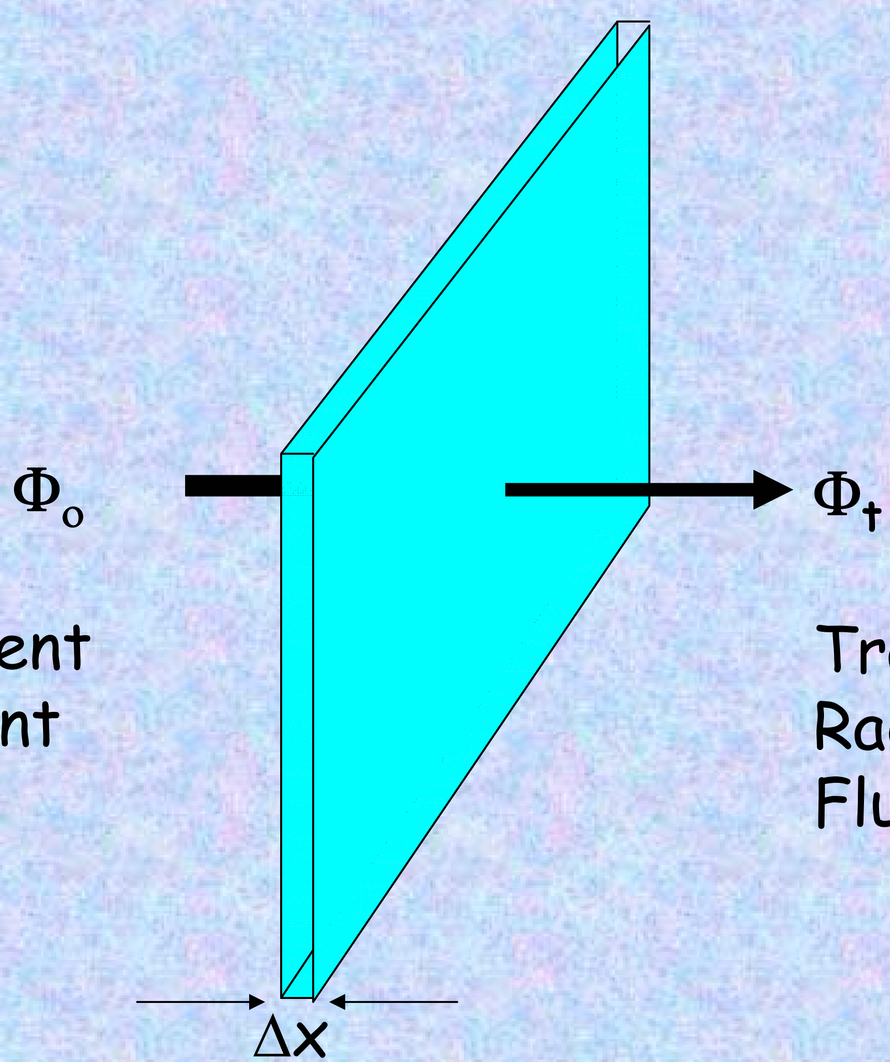


$\Phi_o = \Phi_t$ → No attenuation (extinction)

Radiant flux:

$\Phi = \mathbf{E}\ \Delta A$ **[W]**

IOP Theory



Incident Radiant Flux

Transmitted Radiant Flux

$\Phi_o < \Phi_t$ → attenuation

Transmission: Φ_t/Φ_o,
-- fraction of light getting to detector.

Beer-Lambert law:

$\ln(\Phi_t/\Phi_o)=\varepsilon$[conc.]$\Delta x$

$\rightarrow \Phi_t/\Phi_o=\exp(-c\Delta x)$, $c=\varepsilon$[conc.]

$$c = -\frac{1}{\Delta x}\ln\frac{\Phi_t}{\Phi_0}$$

c- beam-attenuation (extinction) coefficient. Units: m^{-1}

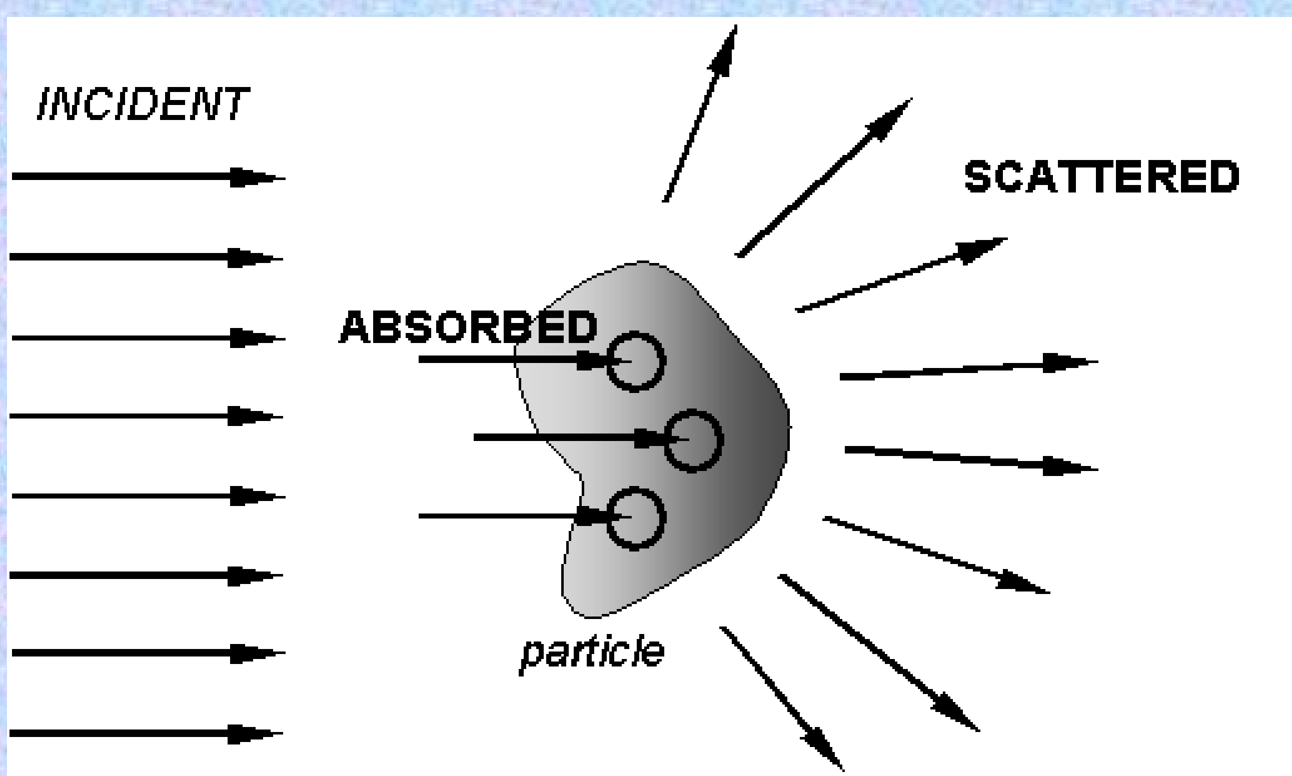
Can be derived from the statistics of interaction of photons with particles distributed with a constant concentration along the path (Poison statistics, Shifrin, 1988).

Two processes cause attenuation (loss of light):

a- absorption.

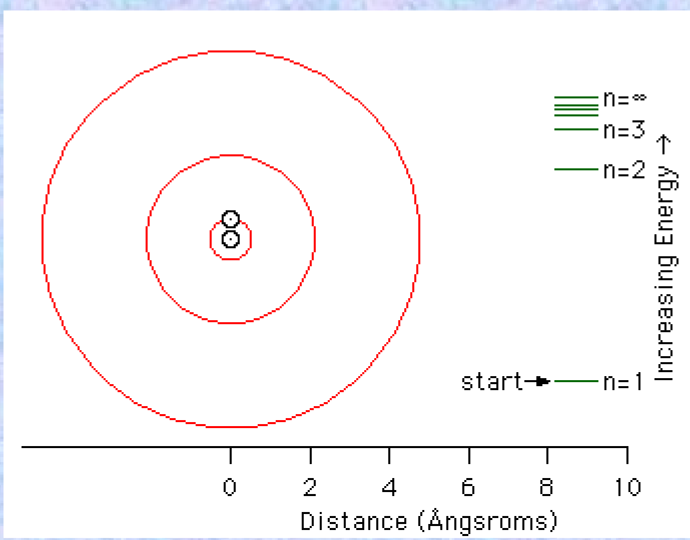
b- scattering (re-direction).

→ **c = *a* + b**



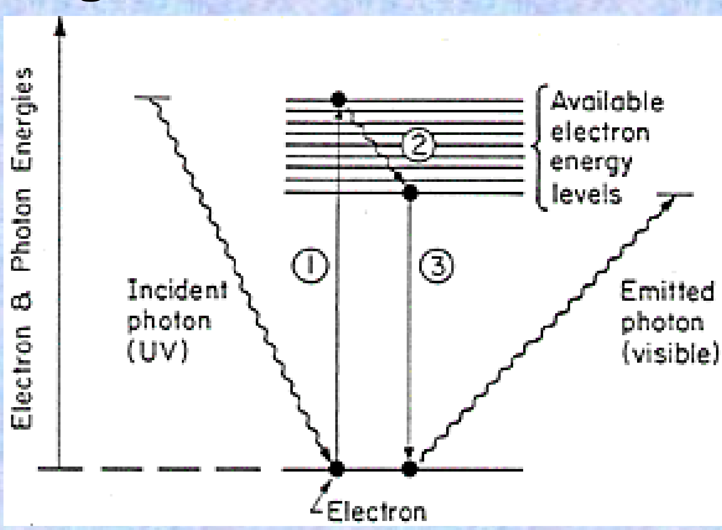
What is absorption:

Photons disappear due to interaction with matter.



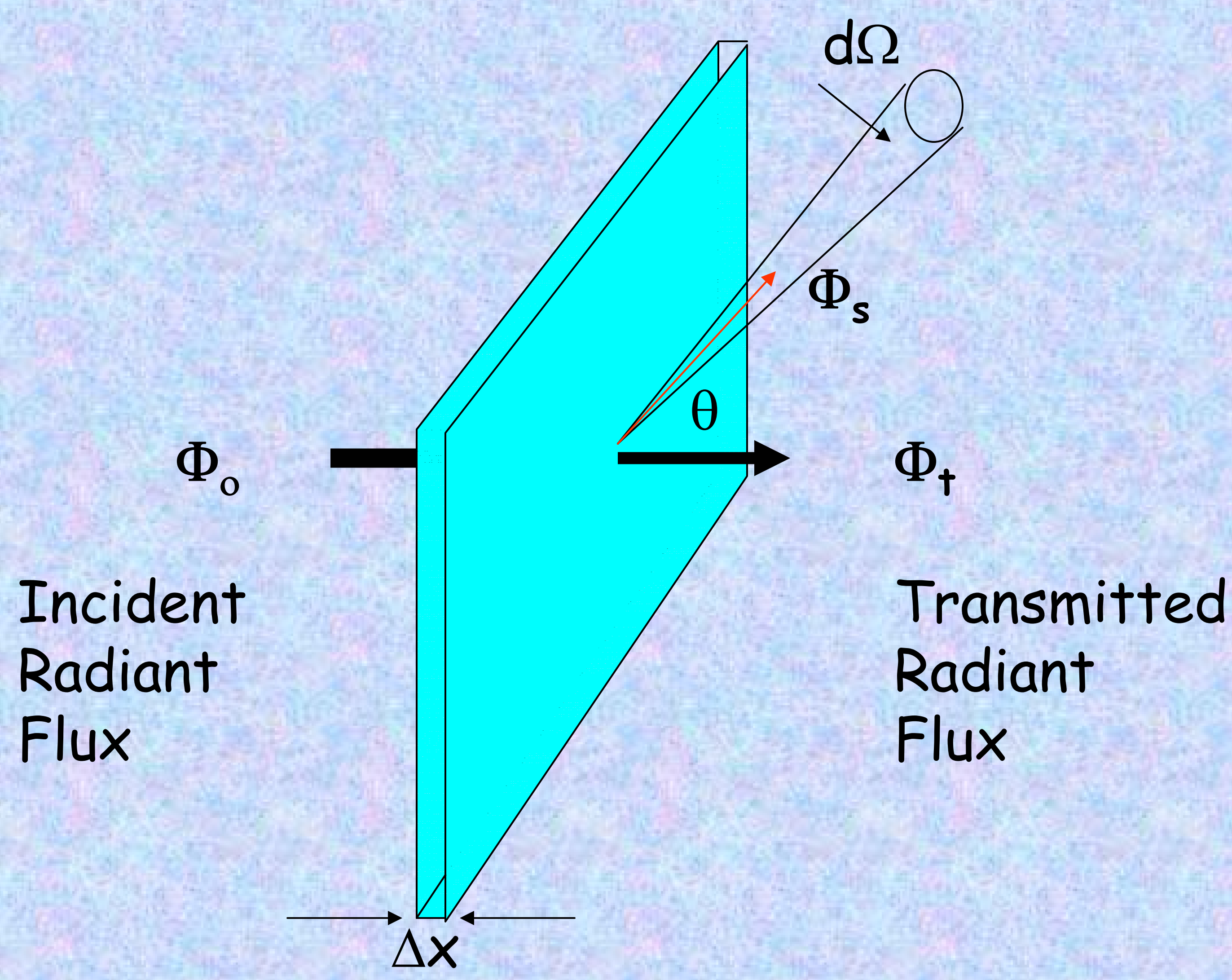
Feom: http://www.haverford.edu/chem/Scarrow/GenChem/quantum/BohrAtom.gif

Following absorption energy could be reemitted (or not) at the same or different wavelength (e.g. heat, fluorescence).



From: http://acept.la.asu.edu/PiN/rdg/irnuv/d7.gif

Scattering:



Volume scattering function [$m^{-1}sr^{-1}$]:

$$\beta(\theta) \equiv \lim_{\Delta x \to 0} \lim_{\Delta\Omega \to 0} \frac{1}{\Delta x \Delta\Omega} \frac{\Phi_s}{\Phi_0}$$

Assumed isotropy (not ϕ dependent). OK for randomly oriented inhomogeneities.

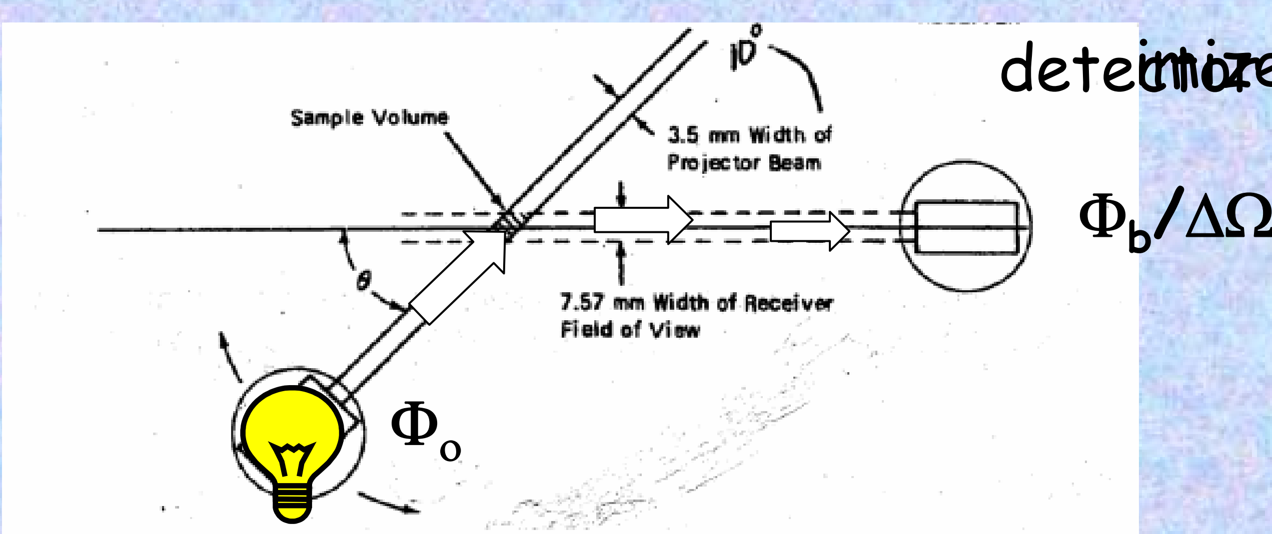
Scattering coefficient [m^{-1}]:

$$b \equiv \int \beta(\theta) d\Omega = 2\pi \int_0^{\pi} \beta(\theta) \sin\theta d\theta = c - a$$

Measurement realities:

1. A certain part of the near-forward scattered light is included in the transmitted light due to the finite area of the transmission detector.

2. It is very difficult to measure light scattered in the direction of the source ($\beta(\pi)$).



GASM = "General Angle Scattering Meter; developed by Petzold, et al., at Scripps Visibility Lab (figs from Petzold, SIO Ref. 72-78)

What is scattering:

Scattering refers to the redirection of energy of an 'infinite' 'plane-parallel' electro-magnetic wave due to interaction with matter. By interaction we mean that the wave travels at different speed at different location within the medium due to inhomogeneities within the medium. Such inhomogeneities may be caused by particles of different optical properties within the medium or 'fluctuations', regions within the medium that have slightly different concentrations of molecules.

The 'relative' index of refraction (n_r) of a particle relative to the medium in which it is embedded, is the ratio of the speeds of lights: $n_p = c_{medium}/c_p$.

For a *given* size and shape of particle, the more different the index of refraction is from 1 the more pronounce is the scattering.

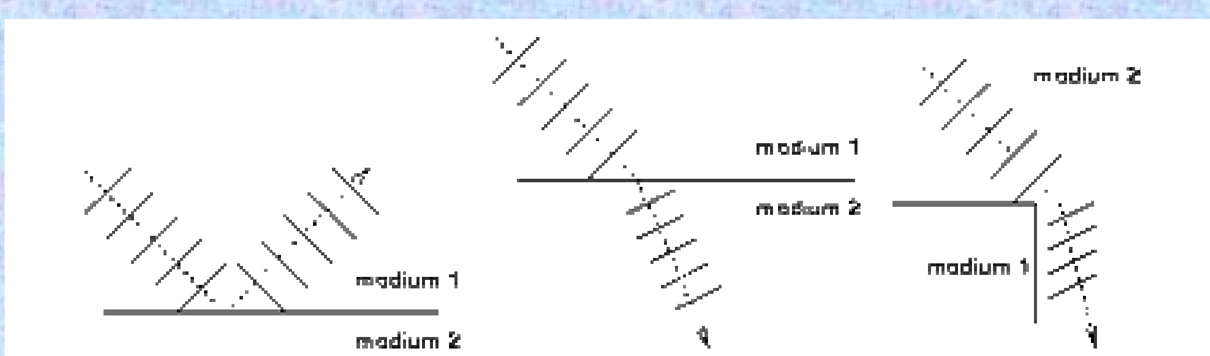
What is scattering:

Scattering is the sum of:

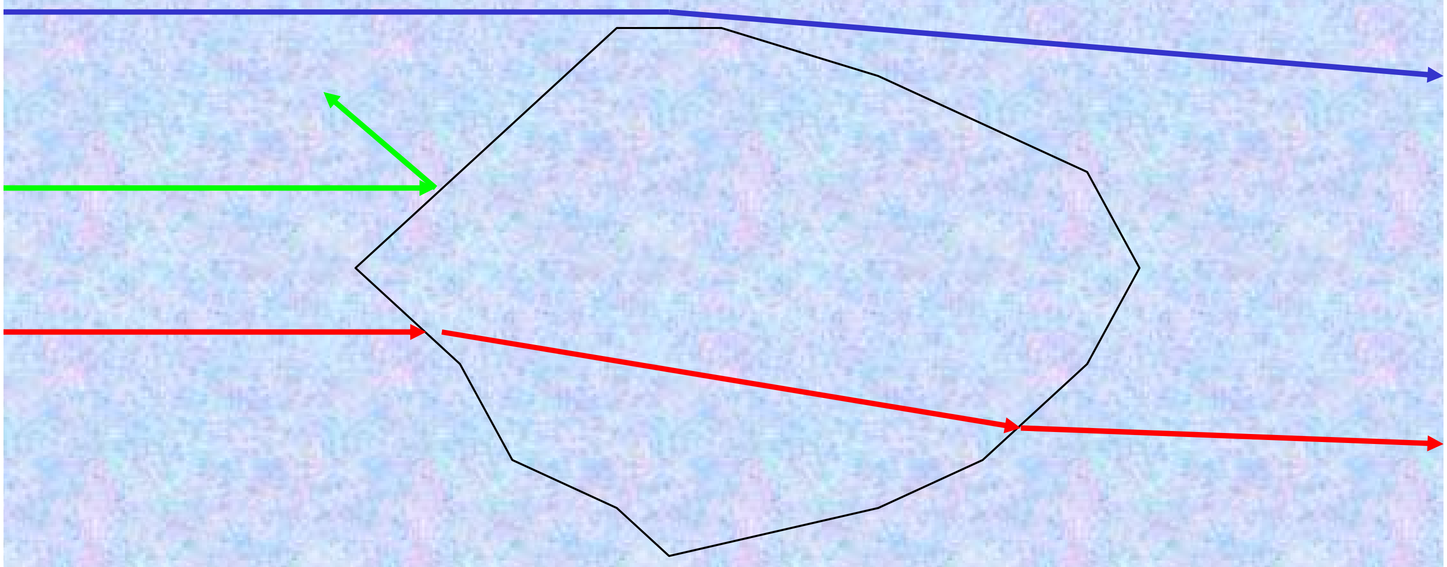
1. Reflection: at a boundary of a particle with different *n* than the medium in which it is embedded, a certain amount of radiation is reflected back.

2. Refraction: at a boundary of a particle with different *n* than the medium in which it is embedded, a certain amount of radiation penetrates into the particle, usually at a different angle than the angle of incidence (Snell).

3. Diffraction: the light propagating along the boundary of the particle responds to the boundary causing a change in direction.



From: http://www.cs.ucl.ac.uk/staff/S.Bhatti/D51-notes/img229.gif refraction, reflection and diffraction:



Large particles: scattering is dominated by diffraction, since light going through the particles is likely to be absorbed.
→ Geometric optics. Response is proportional to particle's cross-sectional area (sensitive to shape).

Small particles: scattering is dominated by refraction and reflection, Rayleigh scattering. Response is proportional to particle's volume (insensitive to shape).

In between (for sphere): Mie scattering. Analytical solutions exist for spheroids as well.

Dependence of IOP on properties of particles:

The output of Mie scattering codes for a particles with a given D/λ and n is:

Cross sections (C, [m^2]) or efficiency factors (Q, [ϕ]) for absorption, scattering and attenuation as well as the phase function (multiply by C to get angular scattering cross-section).

Example: the attenuation cross-section, C_{ext}, is the attenuation due to a single particle in a m^3 of medium:

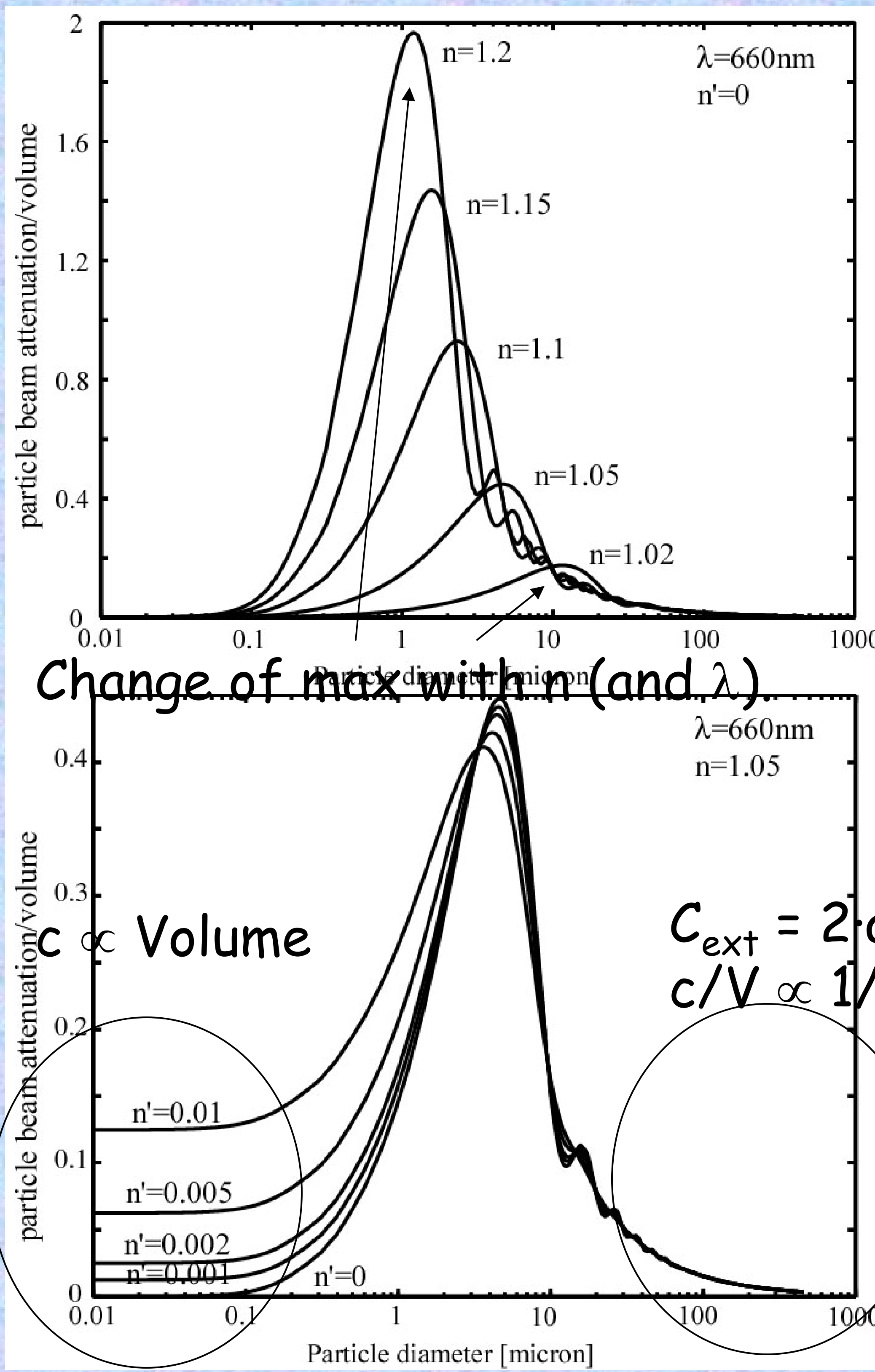
$c=C_{ext}\cdot 1=Q_{ext}\cdot \pi r^2\cdot 1$

Since the mass increase with size, it is instructive to study how the mass normalized optical properties vary as function of size and index of refraction.

$c/V=Cext\cdot 1/\{0.75\pi r^2\}\equiv\alpha_v$

Dependence of IOP on properties of particles:

$c/V = C_{ext} \cdot 1/\{0.75\pi r^2\} \equiv \alpha_v$



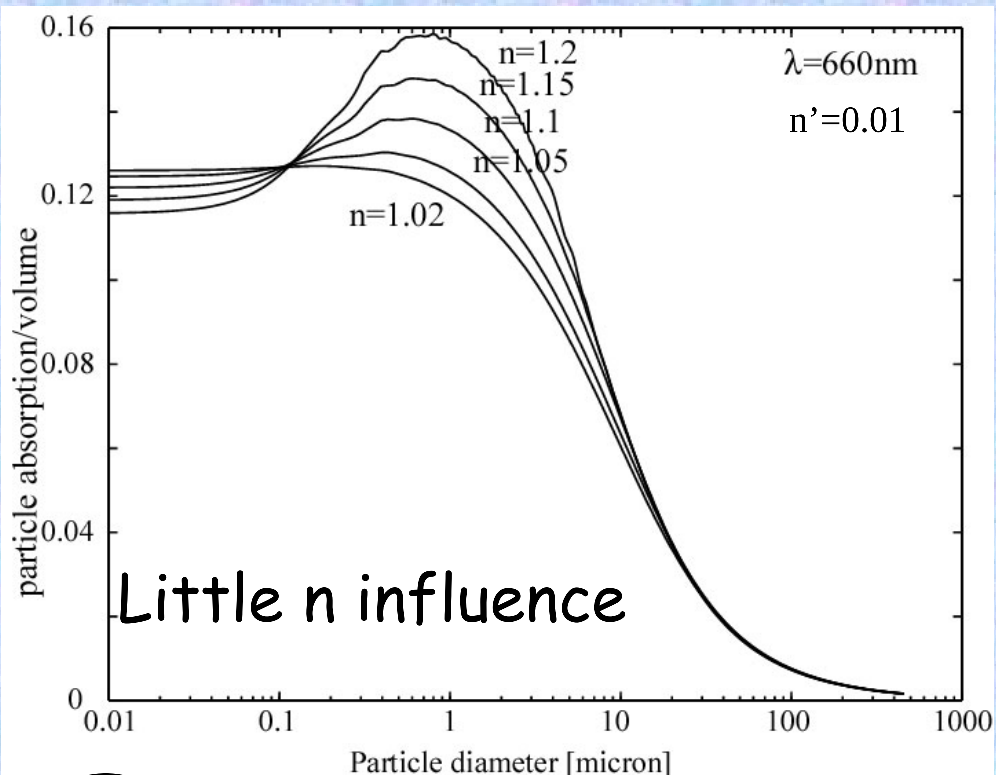
Change of max with n (and λ).

$c \propto$ Volume

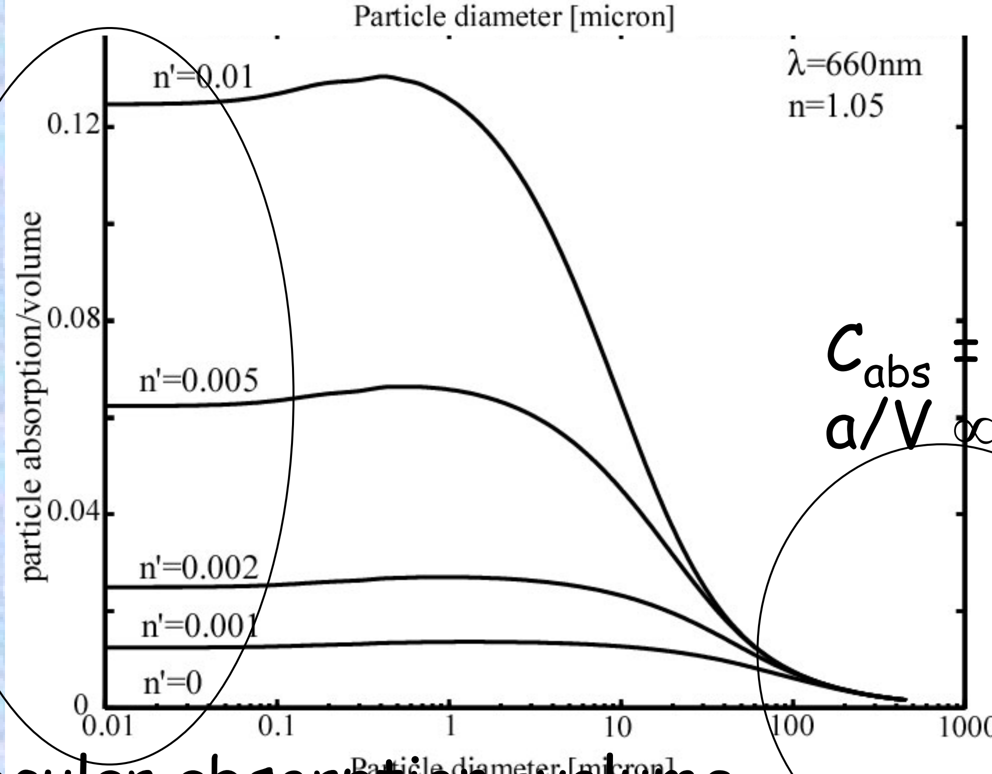
$C_{ext} = 2 \cdot$area→ $c/V \propto 1/D$

Dependence of IOP on properties of particles:

$a/V = C_{abs} \cdot 1/\{0.75\pi r^2\}$



Little n influence



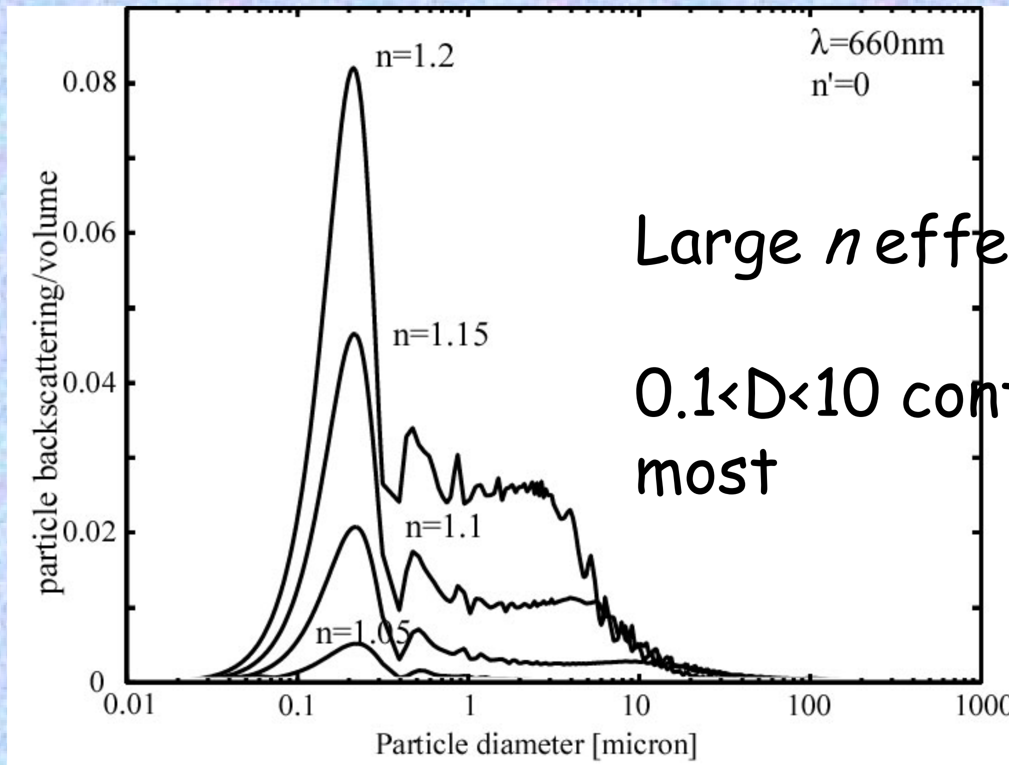
C_{abs} ∝ area→
$a/V \propto 1/D$

Molecular absorption∝volume.

'Packaging'

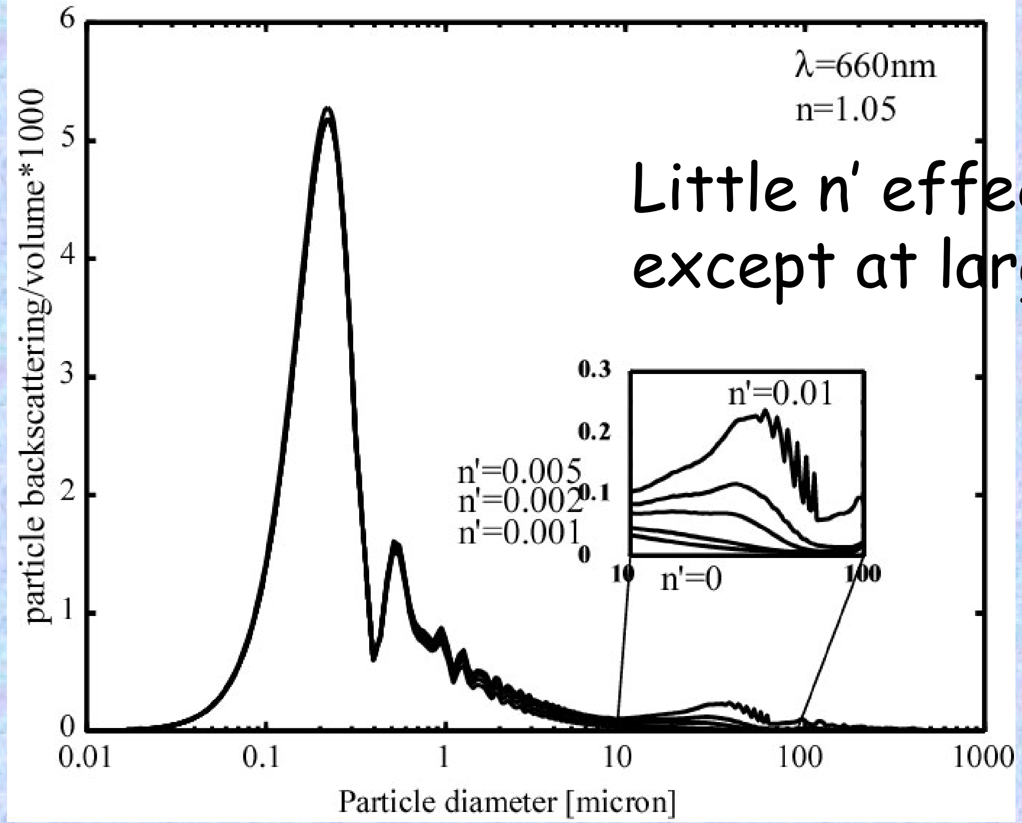
Dependence of IOP on properties of particles:

$b_b/V = C_{bb} \cdot 1/\{0.75\pi r^2\}$



Large *n* effect

0.1<D<10 contributes most



Little n′ effect except at large D

Lab example: general angle scattering

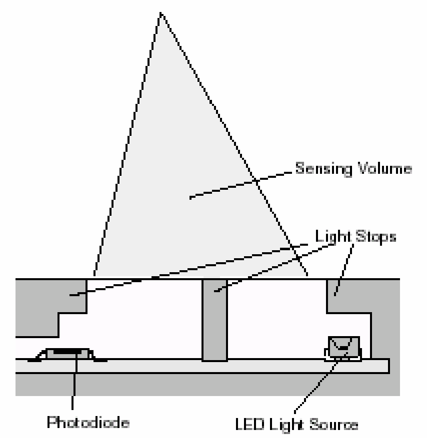
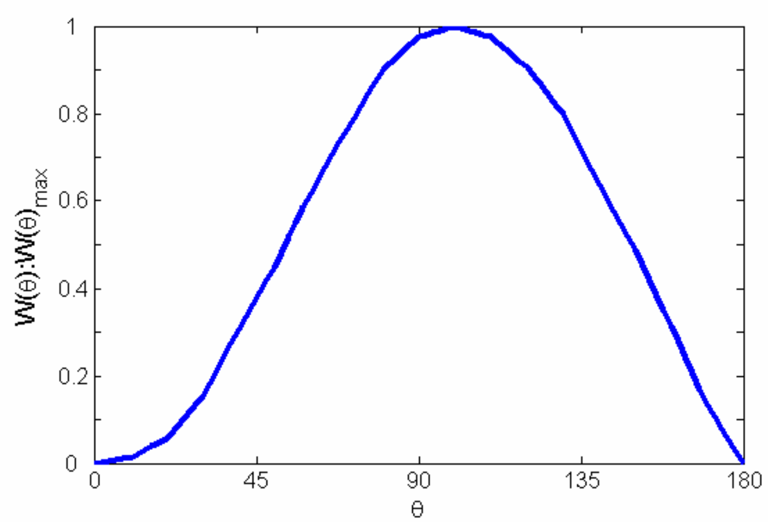
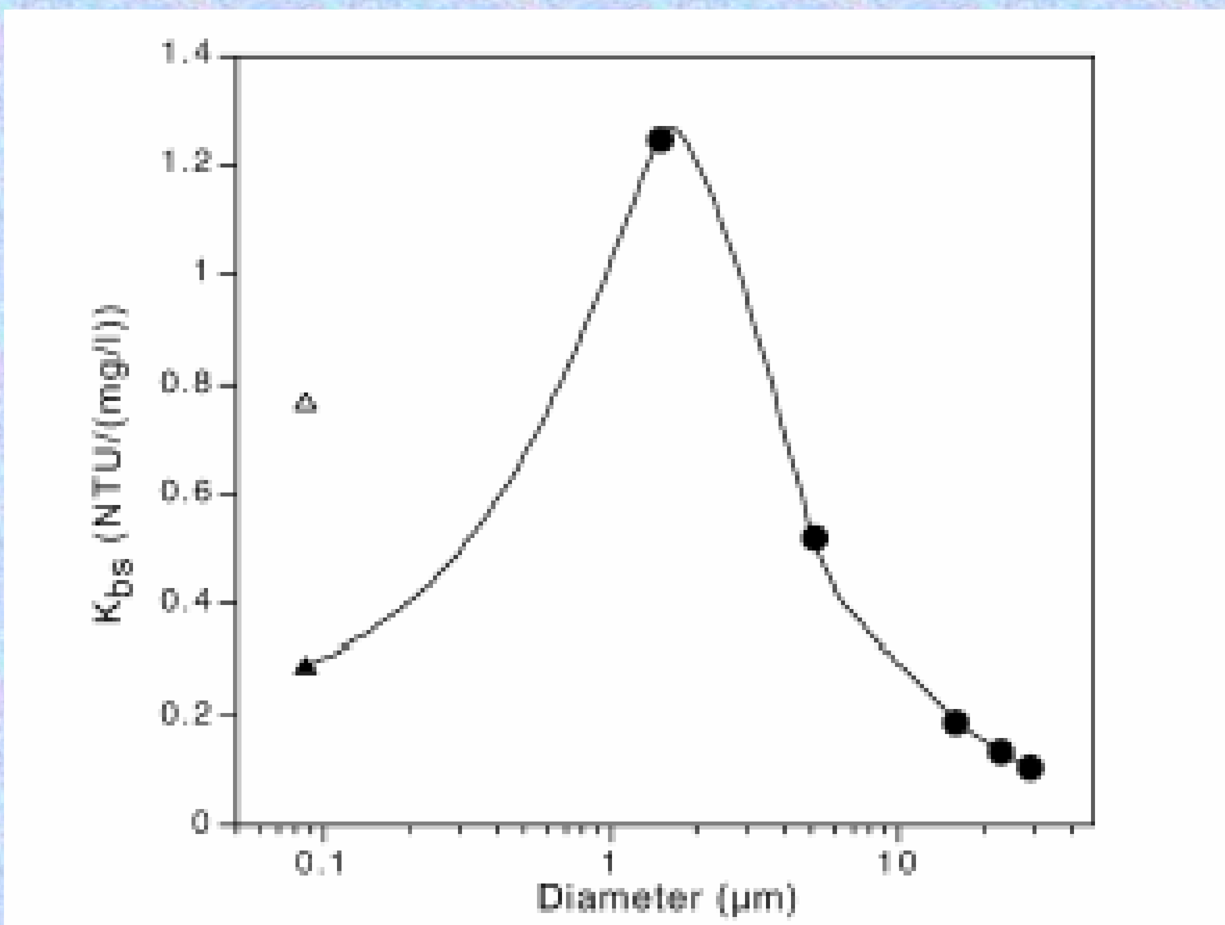


Figure 2. Diagram of Seapoint Turbidity Meter Optics

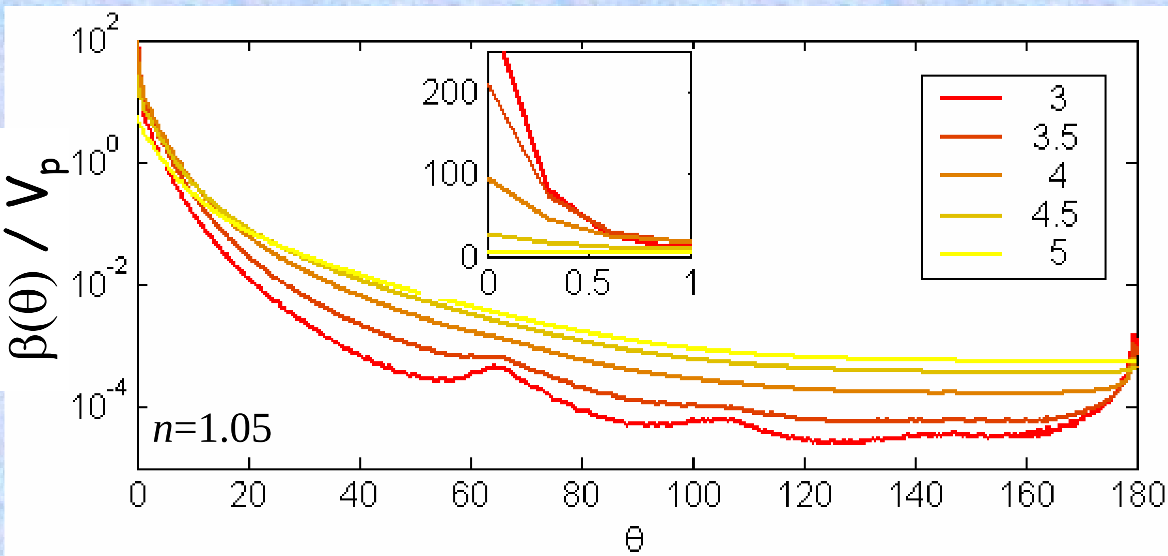


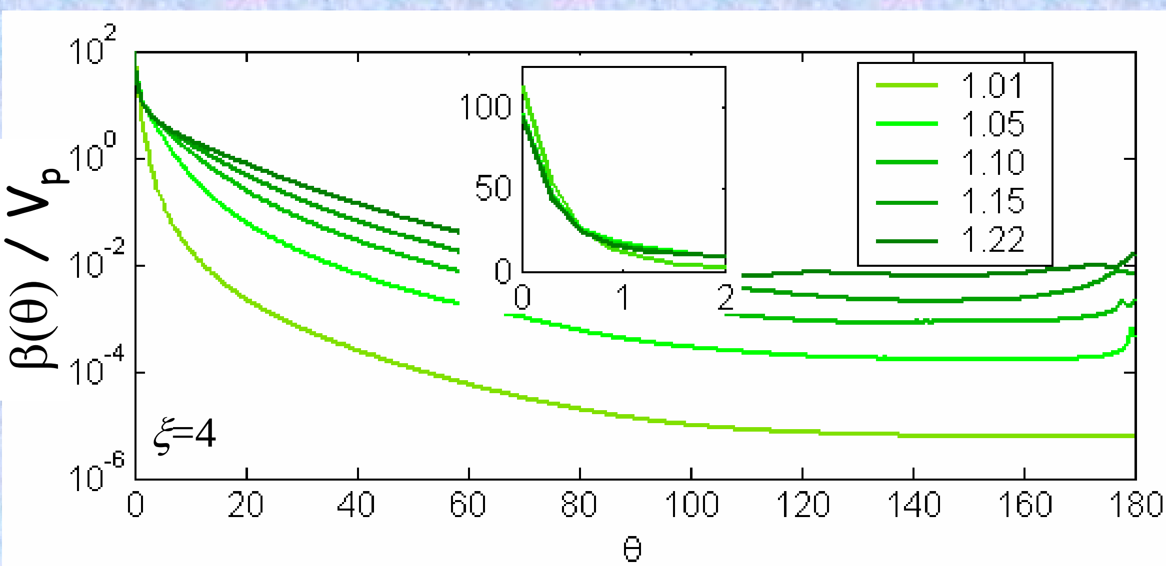
Response of the LSS/volume to size (Baker et al., 2001):



Dependence of IOP on properties of particles:

β/V:





Roesler and Boss, 2004

•Near forward scattering: Strong dependence on size, less on n.

•b_b/b: Strong dependence on n, less on size.

IOPs and scattering theory:

Provides a calibration to our sensors (LISST, b_b, flow-cytometers). For a *given* concentration of particles of a *given* size and *n* we expect a *given* signal.

Provides a check on our measurements (relationship between concentration, size distribution and likely optical property).

Examples: 1. what is the likely c(660) for a given concentration of phytoplankton ?

$r=20\mu m$
$[Conc.]=10^5/L= 10^8 m^{-3}$
$c_{ext} \sim 2\cdot Area= 2\cdot\pi\cdot(20)^2 10^{-12} m^2$
$\rightarrow c=c_{ext}\cdot[Conc] \sim 0.25m^{-1}$

2. Babin claims that $b^*_{555} \sim 0.5m^2/gr$. Is it sensible?

$c_{scat} \sim 1\cdot Area.$
$b^*_{555}=0.5=[conc.]*c_{scat}/ \{[conc.]*volume*density \}=0.75/\{r*density\}.$
For sediments, $density=2.5gr/cm^3 =2.5\cdot 10^6 gr/m^3$
$\rightarrow$ average $r \sim 0.6\mu m$, realistic yet somewhat small.

Transmission measurement reality:

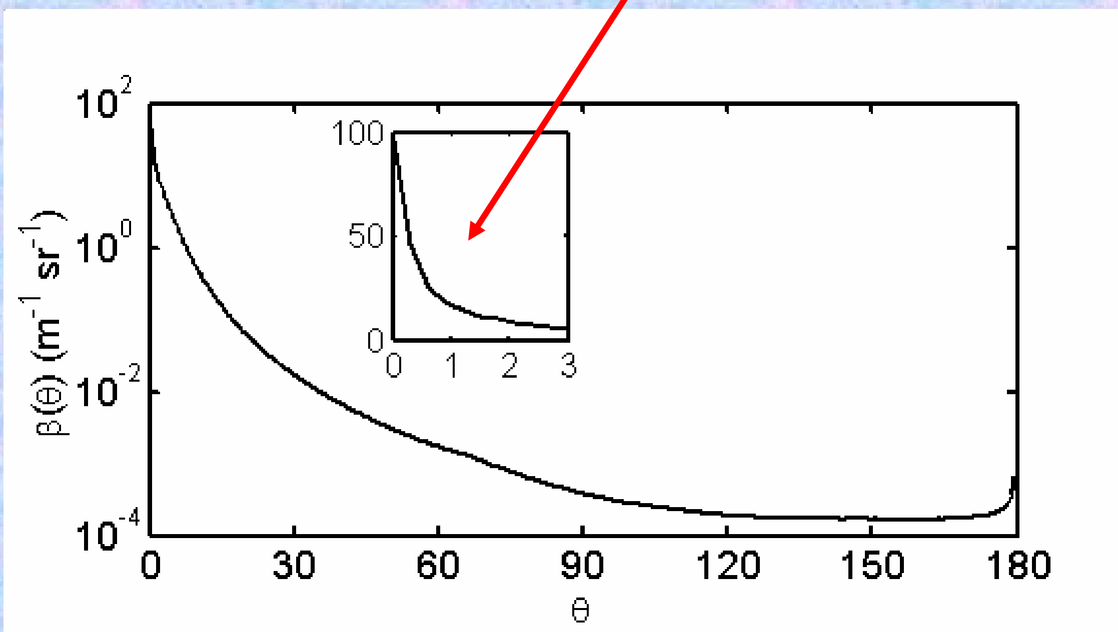
Table 1. Configuration specifications on beam attenuation meters

Instrument	beam source	beam width	acceptance angle (degrees)	pathlength (cm)
AlphaTracka	LED	15 mm	0.86	5
Sequioa LISST	solid state diode laser	6 mm	0.018, 0.036	5
WETLabs ac9	collimated incandescent bulb	10 mm	0.7	25
WETLabs cstar	LED	10mm	1.5, 1.9	25, 10

FOV	% b detected
0.018°	<1
0.7°	~ 5
0.86°	~ 7
1.5°	~14
1.9°	~18

Direct impact on accuracy of measured beam c

Huge dβ/dθ in near forward angles



Beer-Lambert law:

Φ_t/Φ_o=exp(-cΔx), c=ε[conc.]

IOPs are additive:

$$a = \sum_i a_i, \beta = \sum_i \beta_i,$$

$$\Rightarrow b = \sum_i b_i, c = \sum_i c_i$$

For measurements it is important that we have a single-scattering environment (e.g. bΔx<1).

IOPs of aquatic materials.

Absorption:

- Water

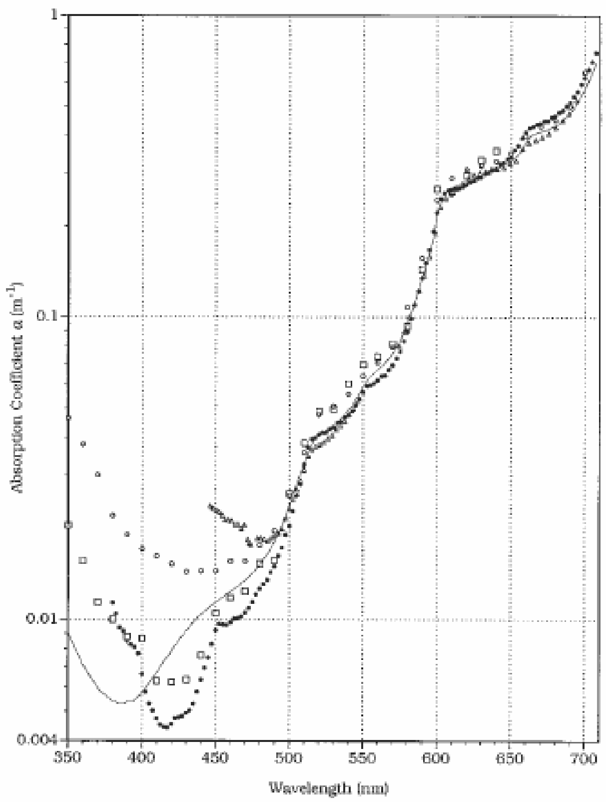


Fig. 10. Present results (●) for the absorption of pure water plotted with those from Buiteveld *et al.*[2] (smooth curve), Tam and Patel[4] (△), Smith and Baker[6] (○), and Sogandares and Fry[3] (□).

Pope and Fry, 1997

Salinity and Temp. effects:

Table 5. Slopes of Linear Regression of Dissolved Absorption Coefficients Measured in the Ocean versus Temperature[a]

Wavelength	Slope
412	0.0003
440	0.0002
488	0.0001
510	0.0004
555	0.0005
650	−0.0002
676	0.0001
715	0.0027

[a]The data used are those presented in Fig. 10, where the dissolved material absorption appears to be constant with depth. The up and down casts have been evaluated to ensure that the internal temperature compensation affected the measurement by less than 0.002 m^{-1}. Although this is a small number it still represents a possible slope error of 0.0004 $m^{-1}/°C$. It is also possible that there is some vertical variability in dissolved material concentration, which would affect the results most strongly at the shorter wavelengths.

Table 4. Slopes of the Absorption Coefficient versus Salinity Based on Linear Regression Analysis

Wavelength	Ψ_s Attenuation	Standard Deviation Attenuation
412	0.00012	0.00005
440	−0.00002	0.00002
488	−0.00002	0.00002
510	−0.00002	0.00003
532	−0.00003	0.00006
555	−0.00003	0.00003
650	0.00000	0.00003
676	−0.00002	0.00002
715	−0.00027	0.00006
750	0.00064	0.00003

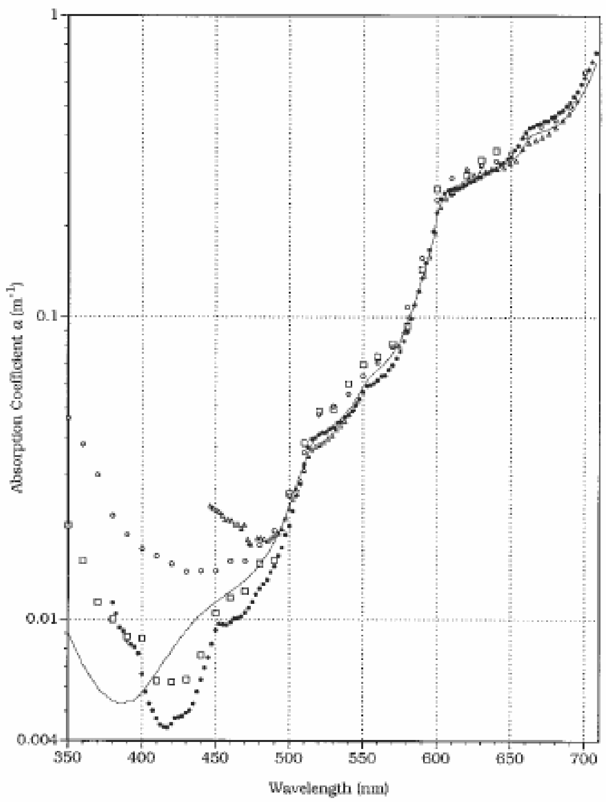
[a]A constant of 0.00005 has been added to each measured Ψ_S to correct for changes in the primary reflectance at the instrument windows that are due to changes in salinity.

Pegau et al., 1997

IOPs of aquatic materials.

Absorption:

- Water



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Pegau et al., 1997

IOPs of aquatic materials.

Absorption:

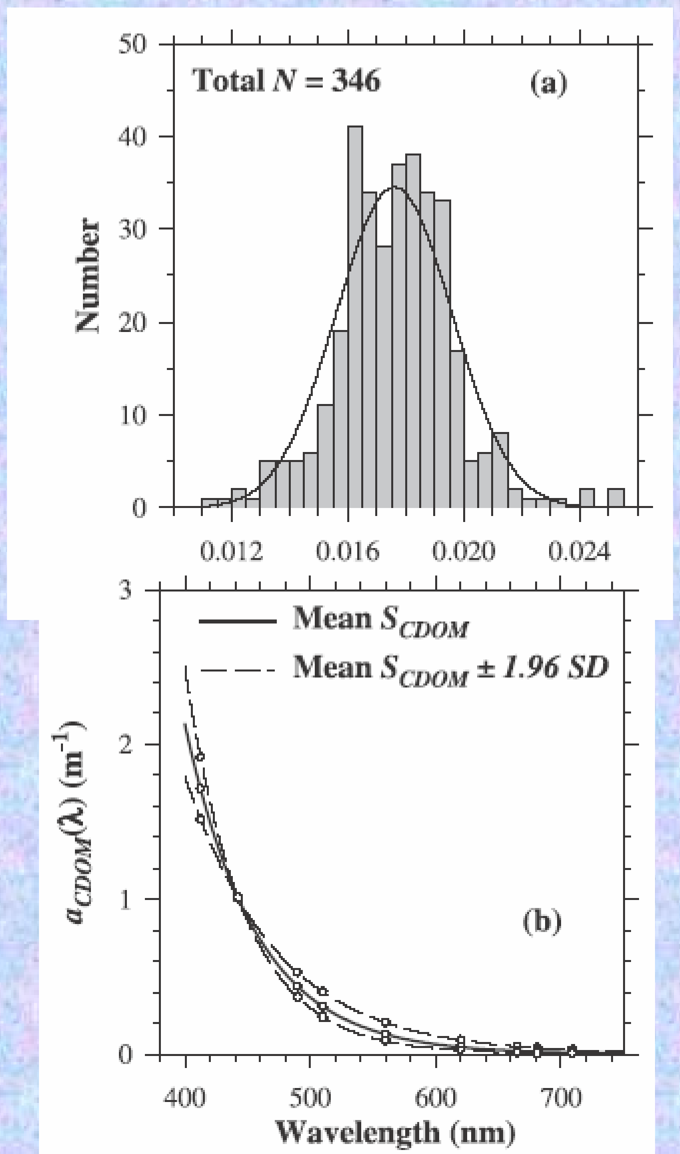
- CDOM

•Good fit by exponential

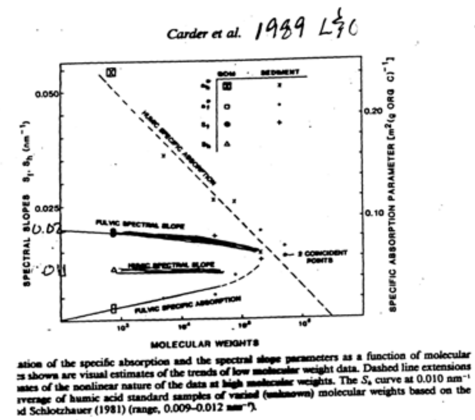
$$a_{CDOM}(\lambda) = a_{CDOM}(400)*\exp(-S_{CDOM}(\lambda-400))$$

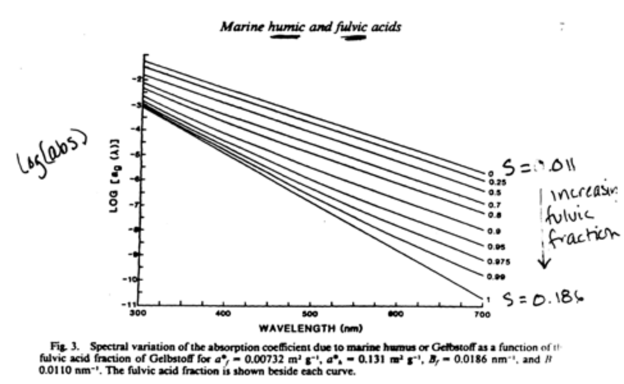
•Spectral shape changes with composition

S_{CdOM} = 0.011 to 0.022



Babin et al., 2003





Carder et al. 1989

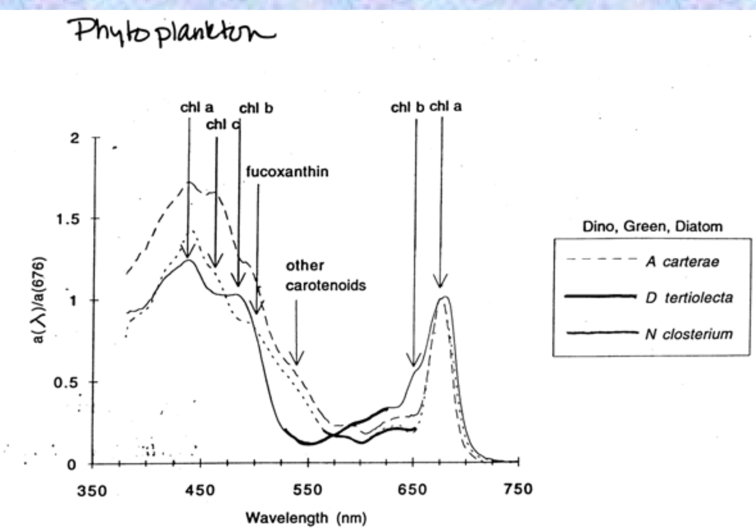
IOPs of aquatic materials.

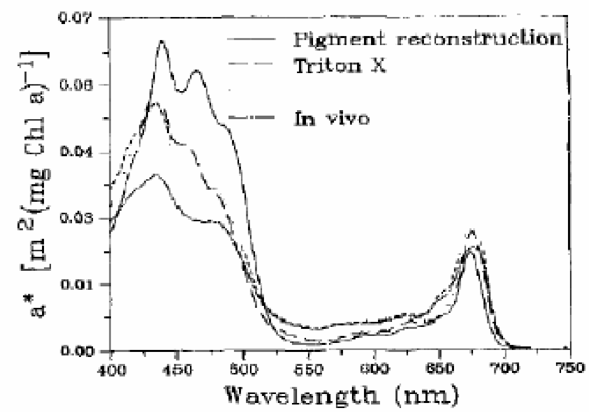
Absorption:

- Phytoplankton

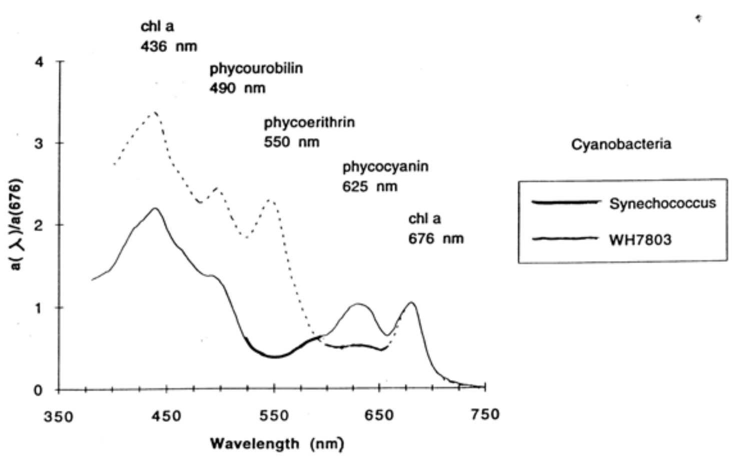
Species dependent

Size dependent



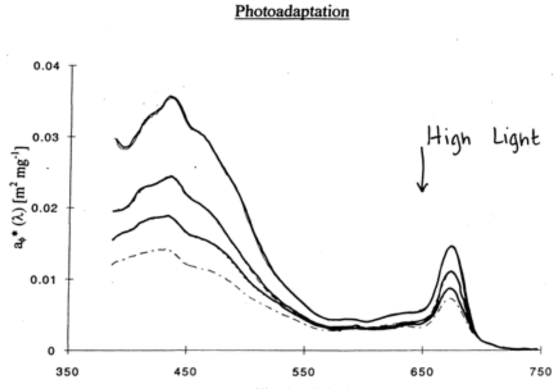


Sosik and Mitchell, 1991



Affected by growth conditions:

Photoadaptation



The efficiency of absorption per chlorophyll molecule

$$a_\phi^*(\lambda)\ [m^2\ mg^{-1}] = \frac{a_\phi(\lambda)\ [m^{-1}]}{chl\ [mg\ m^{-3}]}$$

IOPs of aquatic materials.

Absorption:

- Non-algal particles

Heterotrophic Ciliates and Flagellates, and Bacteria

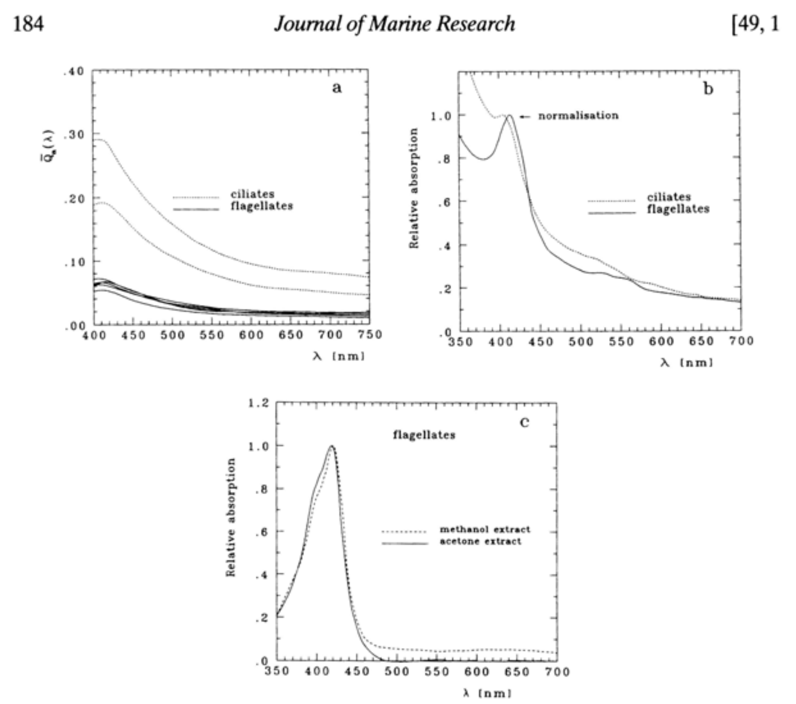


Figure 2. (a) Efficiency factor for absorption as function of wavelength for ciliates and flagellates. (b) Spectral absorption values, normalized by their maximum near 415 nm, when measurements are carried out with cells collected onto a GF/F; (c) absorption spectra (normalized as above) of acetonic and methanol extracts for flagellates only.

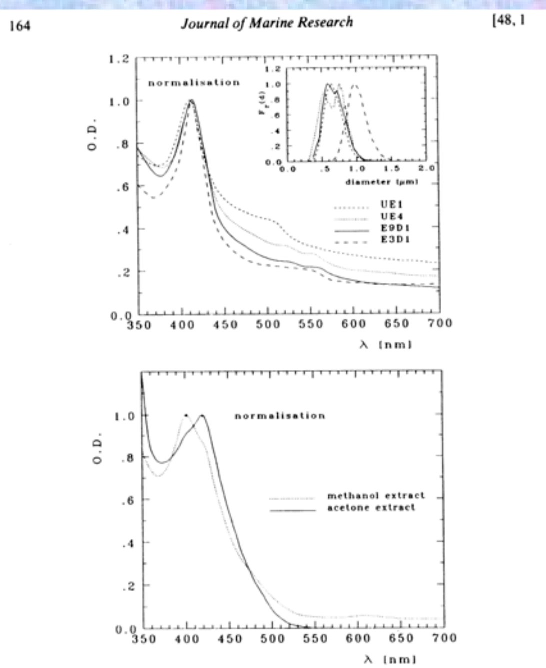
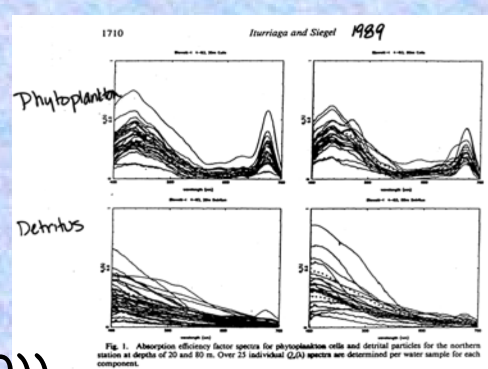


Figure 7. Spectral values of the optical density determined after having collected bacteria on a GF/F filter. The spectra are normalized with respect to their maximum at 412–415 nm (a). The corresponding size distribution functions for these four populations are shown in insert. Absorption spectra (normalized as above) of acetonic and methanol extracts (b).

Ahn and Morel, 1990, 1991



Detritus

$$a_{CPOM}(\lambda) = a_{CPOM}(400)*\exp(-S_{CPOM}(\lambda-400))$$

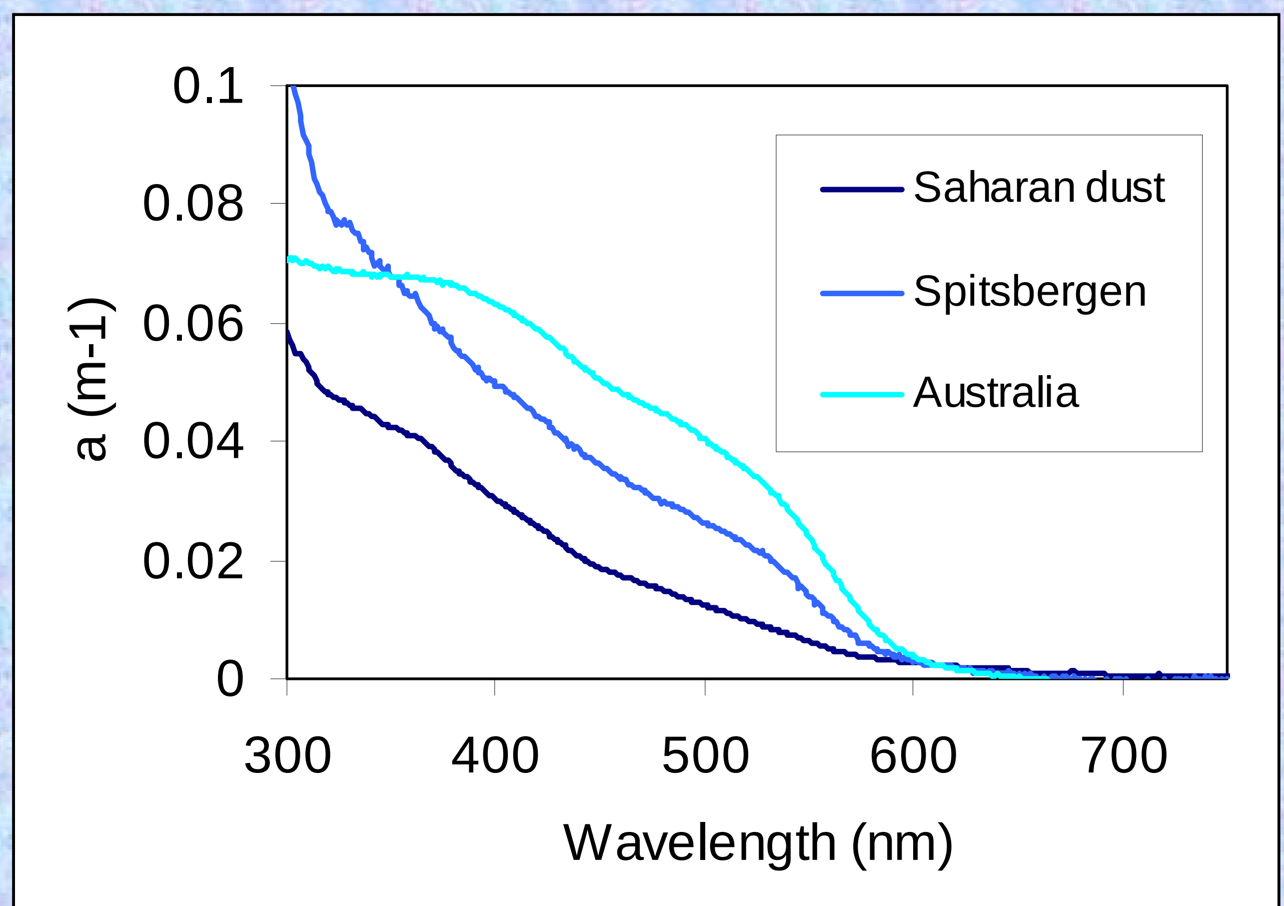
S_{CPOM} = 0.007 to 0.011

Iturriaga and Siegel 1989

IOPs of aquatic materials.

Absorption:

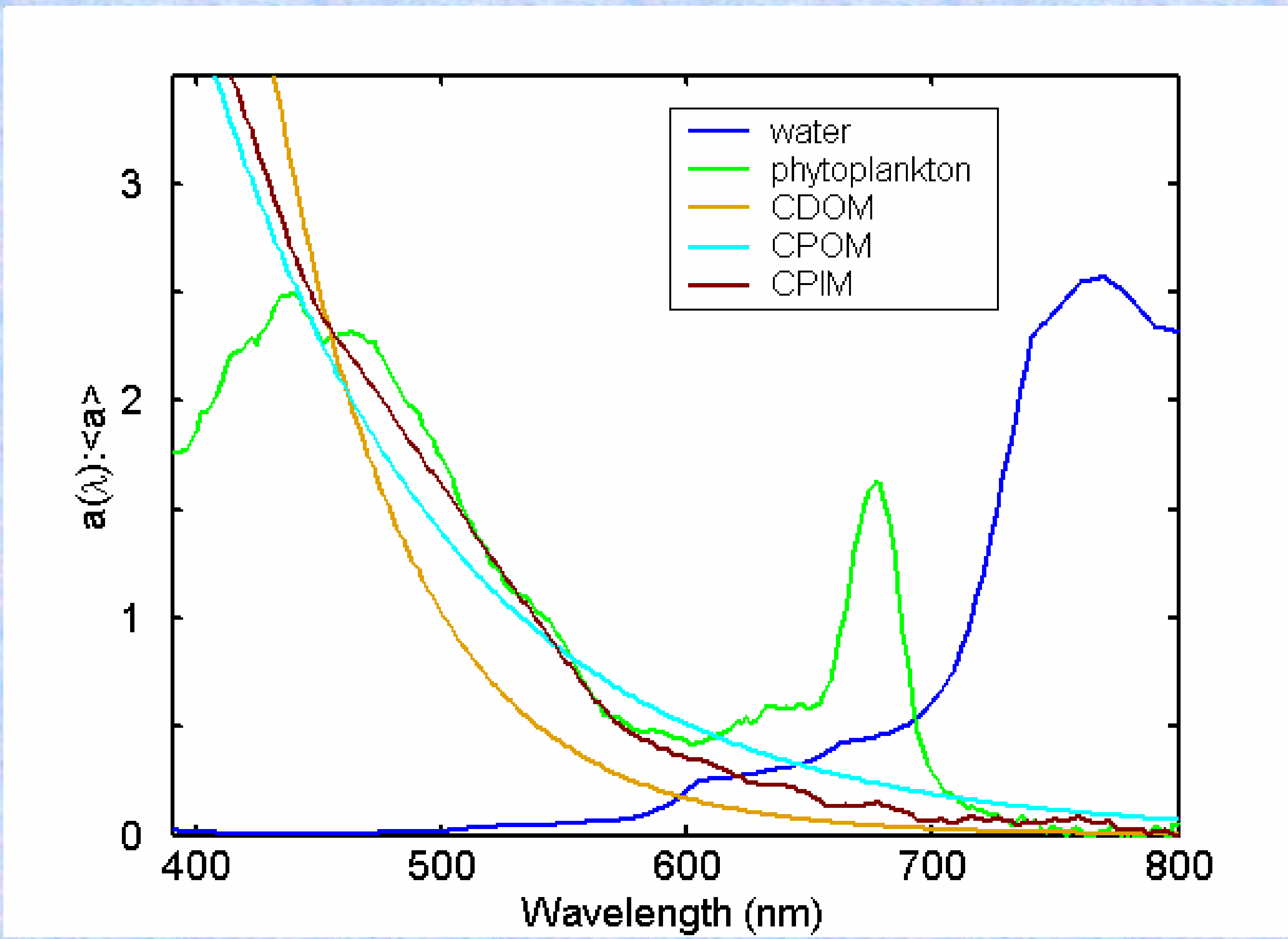
- Non-algal particles



Babin and Stramski 2002

IOPs of aquatic materials.

Absorption, summary:



IOPs of aquatic materials.
Scattering:

- Water

Scattering by density inhomogeneities

Water clusters

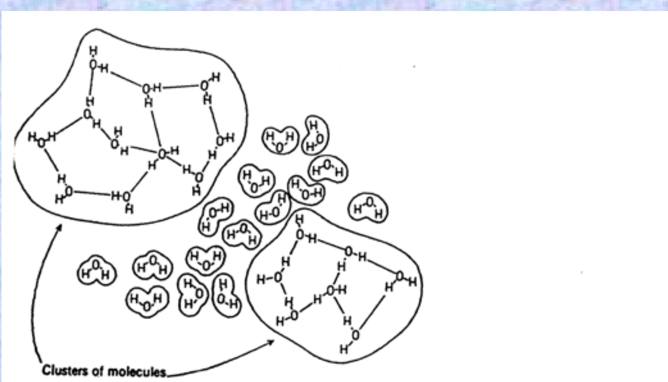


Fig. 2.2.4. The Frank–Wen cluster model of liquid water (adaptation taken from Nemethy an Scheraga, 1962, with permission of the American Institute of Physics; see also Horne, 1969)

... clusters of molecules are hydrogen-bonded,

Water clusters with salt

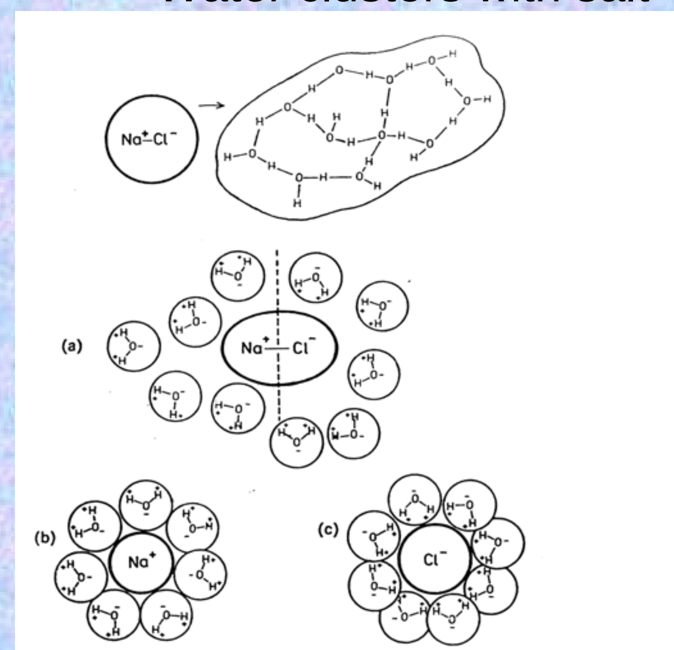
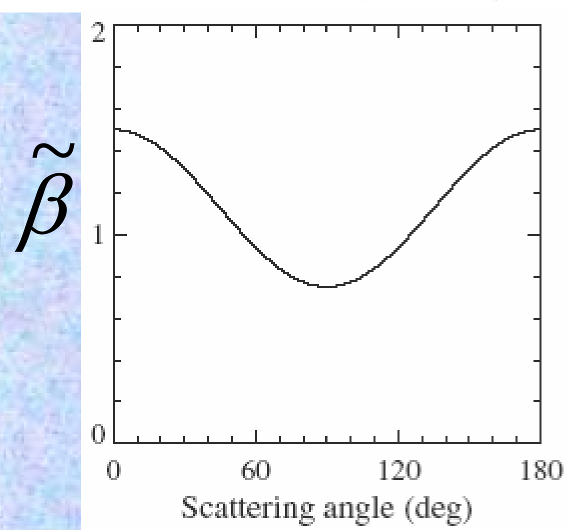


Fig. 2.3.1. The dissociation of a salt ion in water (a) and the formation of ion aggregates (b) and (c).

$b \propto \lambda^{-4.32}$

$b_b = 0.5b$

$b(s) = b(s=0)\{1 + 0.3 \cdot S/37\}$

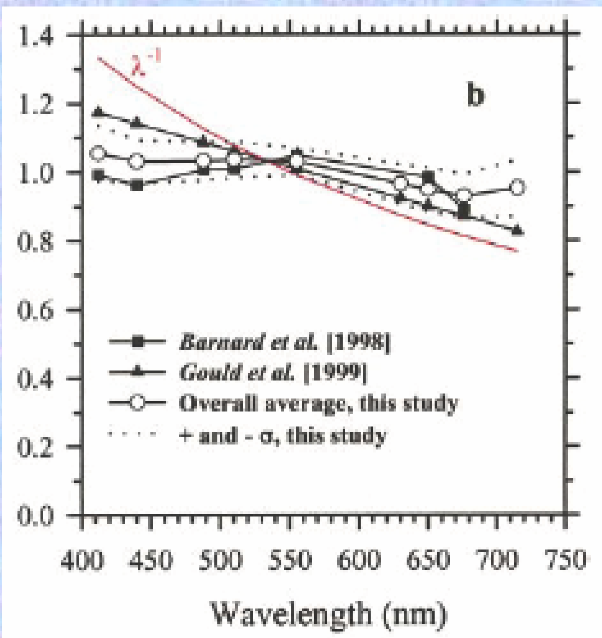


IOPs of aquatic materials.

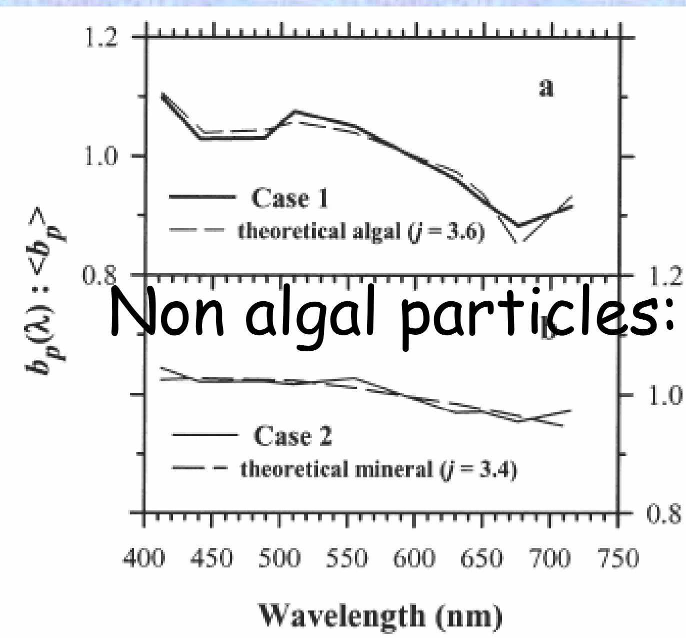
Scattering:

- Particles

Average spectral shape:



Phytoplankton:

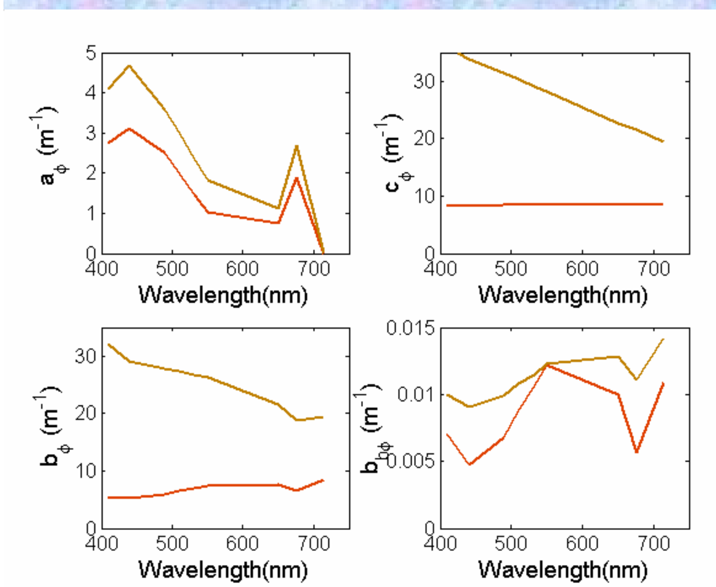


Non algal particles:

Fig. 11. The observed average spectra of the $b_p(\lambda) : \langle b_p \rangle$ ratio for (a) case 1 and (b) case 2 waters (*see also Fig. 3*). The calculated spectra for typical pure phytoplankton and pure mineral particles are also shown.

IOPs of aquatic materials.
Beam attenuation and HABs:

- Phyto. blooms



Roesler and Etheridge, 2002

Prorocentrum micans (27μm)

Photo M. Keller

- BBL:

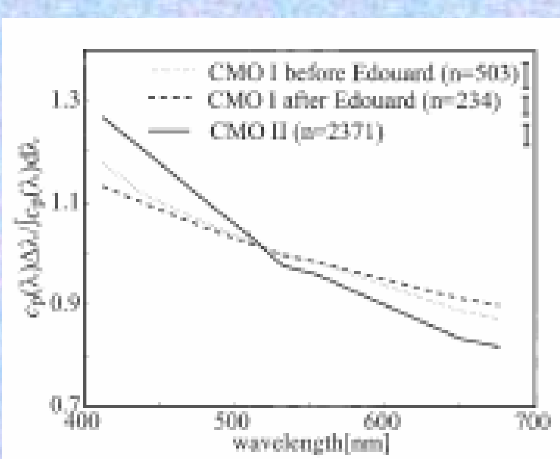


Figure 1. Medians of the area-normalized shape of the particle attenuation spectra $c_p(\lambda)$ (the average of normalized shape is 1). Bars on the right-hand side denote the mean deviation from the 16th to the 84th percentile. Numbers in parentheses denote the number of spectra used for the analysis.

Aureococcus anafragefferens (3μm)

Photo S. Etheridge

Boss et al., 2001