Lecture 5
Scattering

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http://marketingdeviant.com/wp-content/uploads/2008/01/underwater-light-beams.jpg

8 July 2015

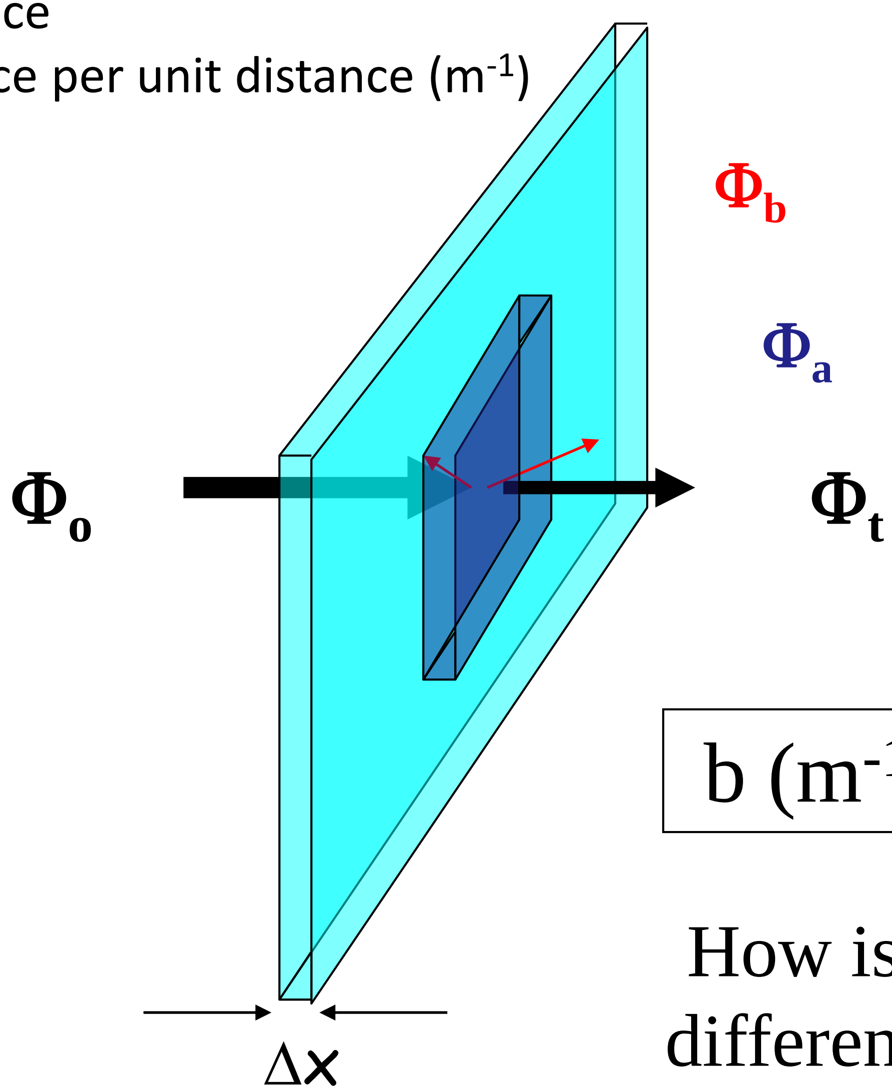
Scattering Theory

B = scatterance

b= scatterance per unit distance (m^{-1})

$B = \Phi_b / \Phi_o$

$b = B/\Delta x$



$$b\ (m^{-1}) = (-1/x)\ \ln(\Phi_t/\Phi_o)$$

How is this measurement difference from beam c, a?

Geometry of scattering

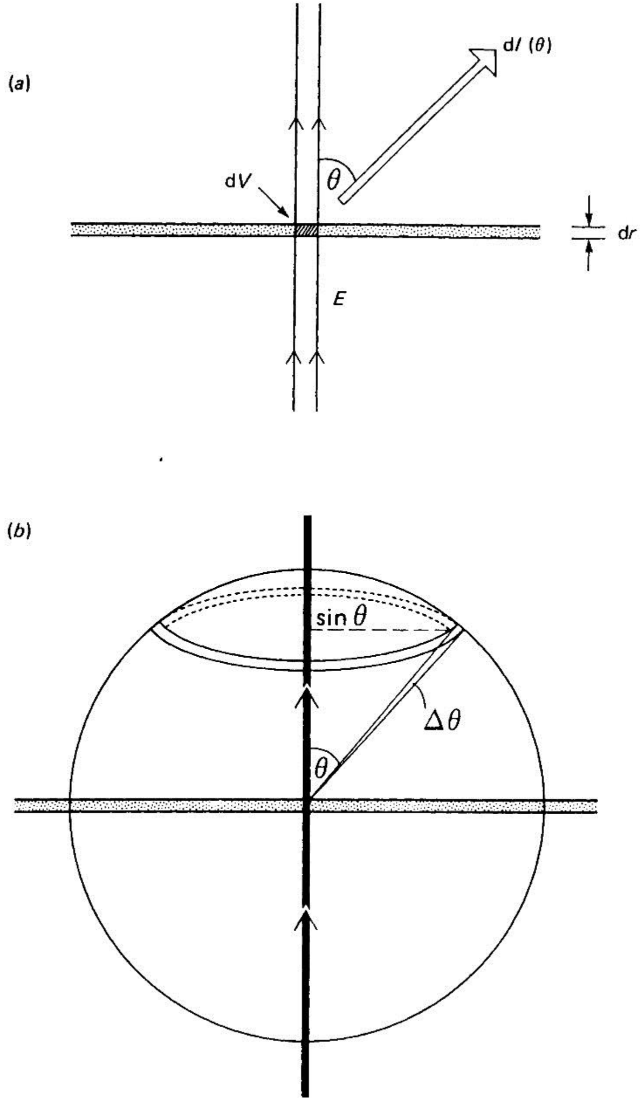
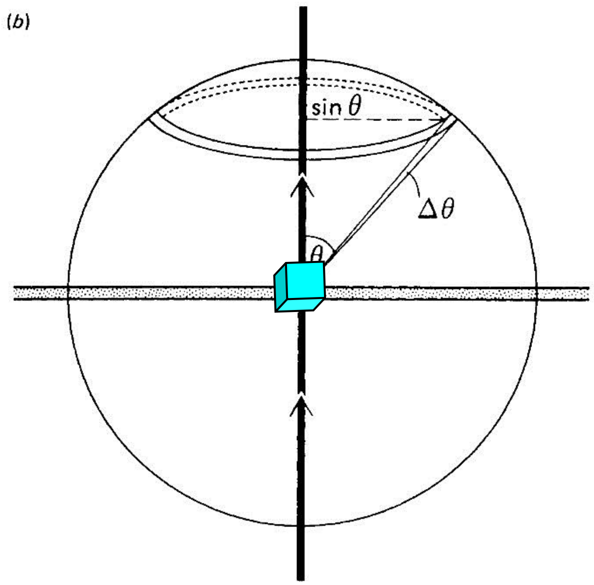


Fig. 1.5. The geometrical relations underlying the volume scattering function. (*a*) A parallel light beam of irradiance E and cross-sectional area dA passes through a thin layer of medium, thickness dr. The illuminated element of volume is dV. d$I(\theta)$ is the radiant intensity due to light scattered at angle θ. (*b*) The point at which the light beam passes through the thin layer of medium can be imagined as being at the centre of a sphere of unit radius. The light scattered between θ and $\theta + \Delta\theta$ illuminates a circular strip, radius sin θ and width $\Delta\theta$, around the surface of the sphere. The area of the strip is 2π sin $\theta\Delta\theta$ which is equivalent to the solid angle (in steradians) corresponding to the angular interval $\Delta\theta$.

Scattering has an angular dependence described by the volume scattering function (VSF)

$\beta(\theta, \phi)$ = power per unit steradian emanating from a volume illuminated by irradiance = $\dfrac{\delta\Phi}{\delta\Omega}\ \dfrac{1}{\delta V}\ \dfrac{1}{E}$



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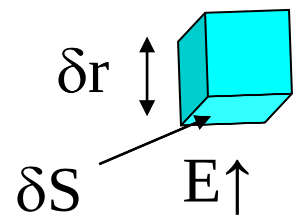
$E = \Phi/\delta S$ [μmol photon m^{-2} s^{-1}]

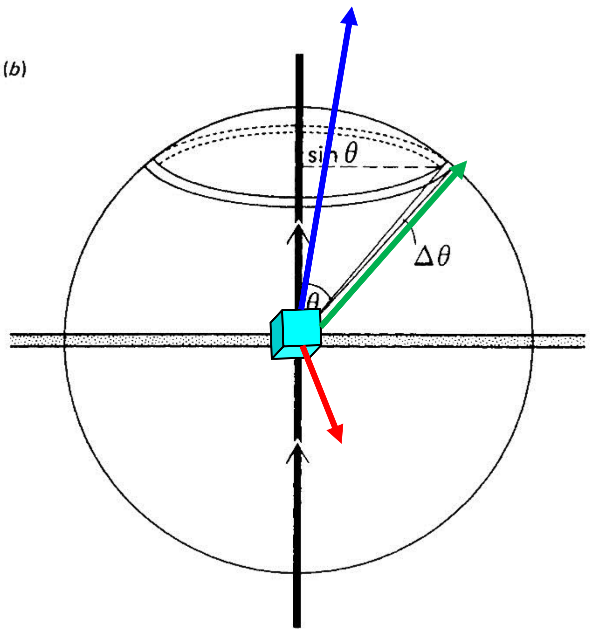
$\delta V = \delta S\ \delta r$



$$\beta(\theta,\phi) = \frac{\delta\Phi}{\delta\Omega}\ \frac{1}{\delta S\delta r}\ \frac{\delta S}{\Phi_o} = \frac{1}{\Phi_o}\ \frac{\delta\Phi}{\delta r\delta\Omega}$$

Volume Scattering Function (VSF)

$\beta(\theta, \phi)$ = power per unit <u>steradian</u> emanating from a volume illuminated by irradiance



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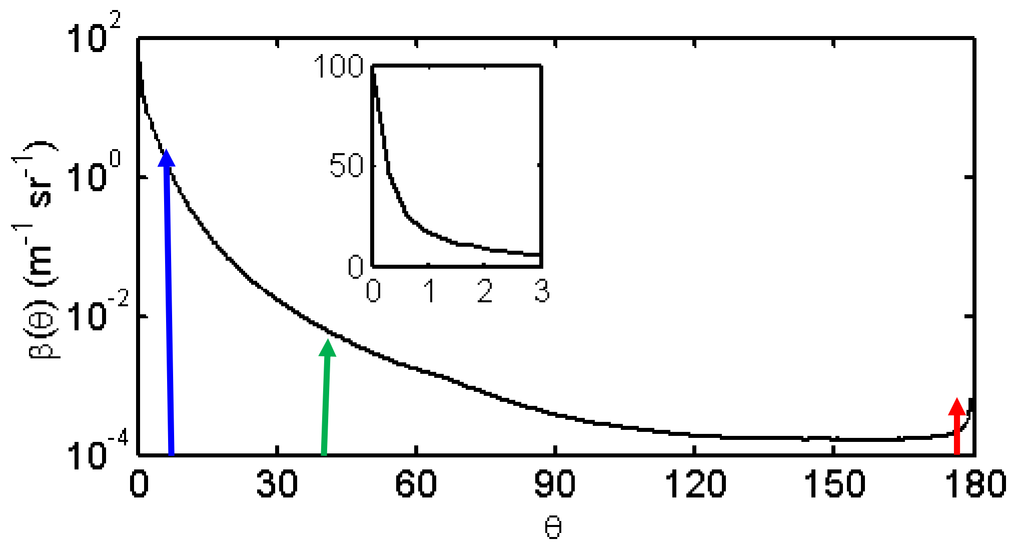


$$\beta(\theta,\phi) = \frac{1}{\Phi_o}\frac{\delta\Phi}{\delta r\delta\Omega}$$

$$b = \int_{4\pi} \beta(\theta,\phi)\, \delta\Omega$$

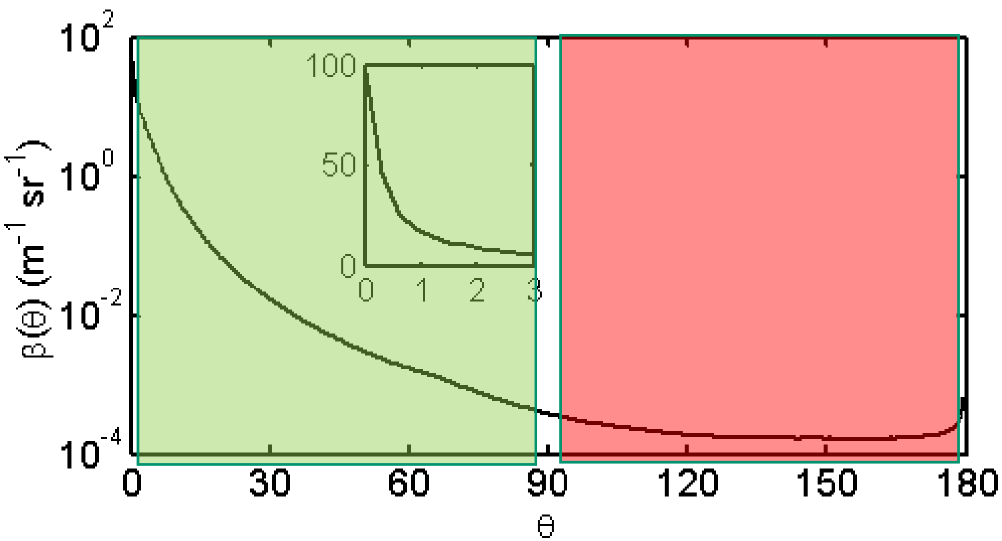
What is $\delta\Omega$?

$$b = \int_0^{2\pi}\int_0^{\pi} \beta(\theta,\phi) \sin\theta\, \delta\theta\, \delta\phi$$

Calculate Scattering, b, from the volume scattering function

If there is azimuthal symmetry

$$b = \int_{4\pi} \beta(\theta,\phi)\, \delta\Omega$$



$$b = 2\pi \int_0^{\pi} \beta(\theta,\phi) \sin\theta\, \delta\theta$$

$$b_f = 2\pi \int_0^{\pi/2} \beta(\theta,\phi) \sin\theta\, \delta\theta$$

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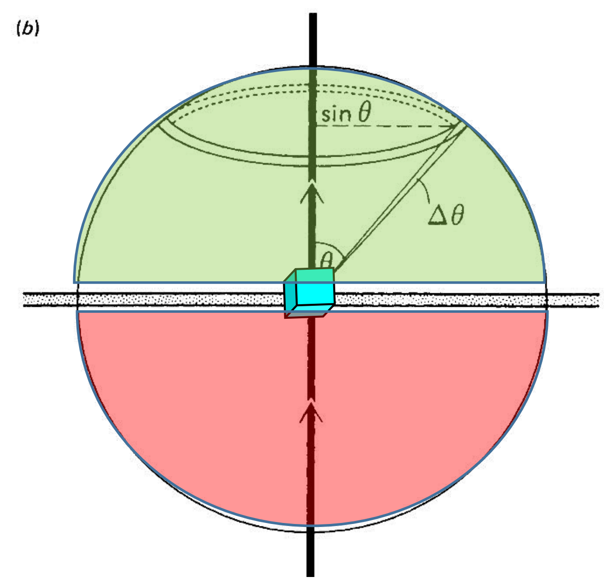


Phase function: $\tilde{\beta}(\theta,\phi) = \beta(\theta,\phi)/b$

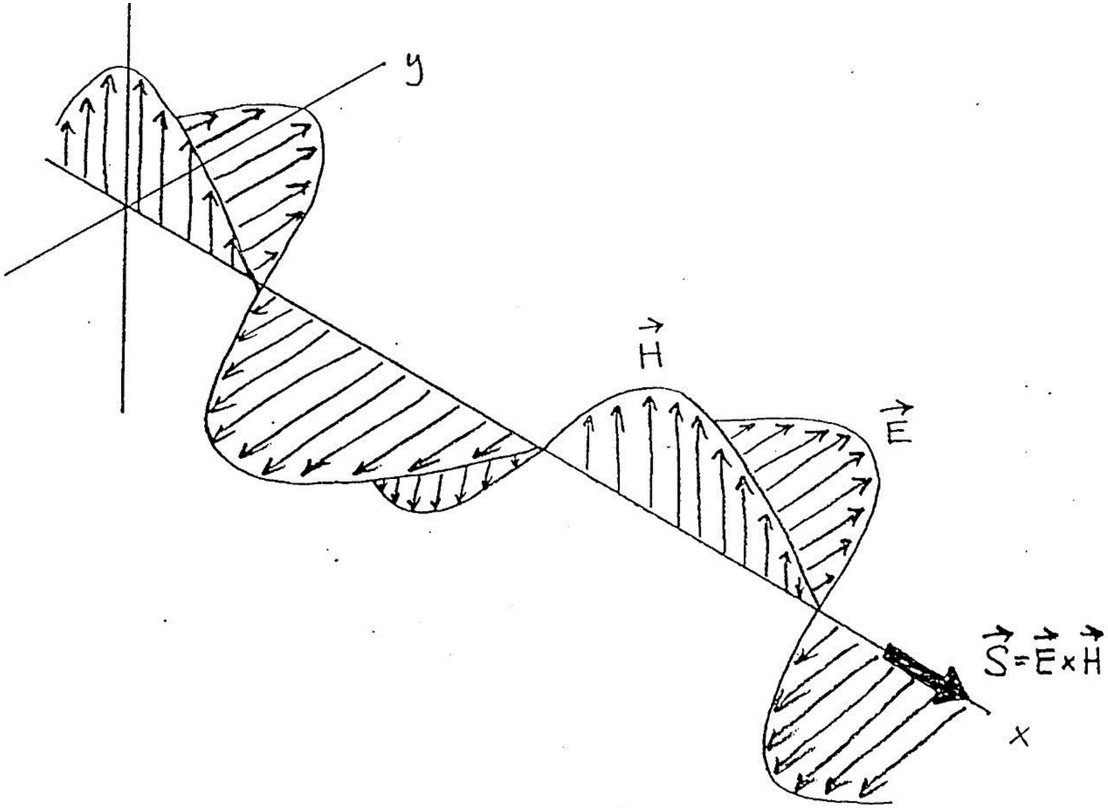
These are spectral!

Particle parameters that influence scattering

- Concentration
- Diameter : wavelength
- refractive index relative to surrounding medium
- absorption of radiation through particle
- Particle shape

Electromagnetic Radiation

- Oscillating magnetic and electric fields
- Perpendicular to direction of propagation
- Polarized



Interactions between EM radiation and particles

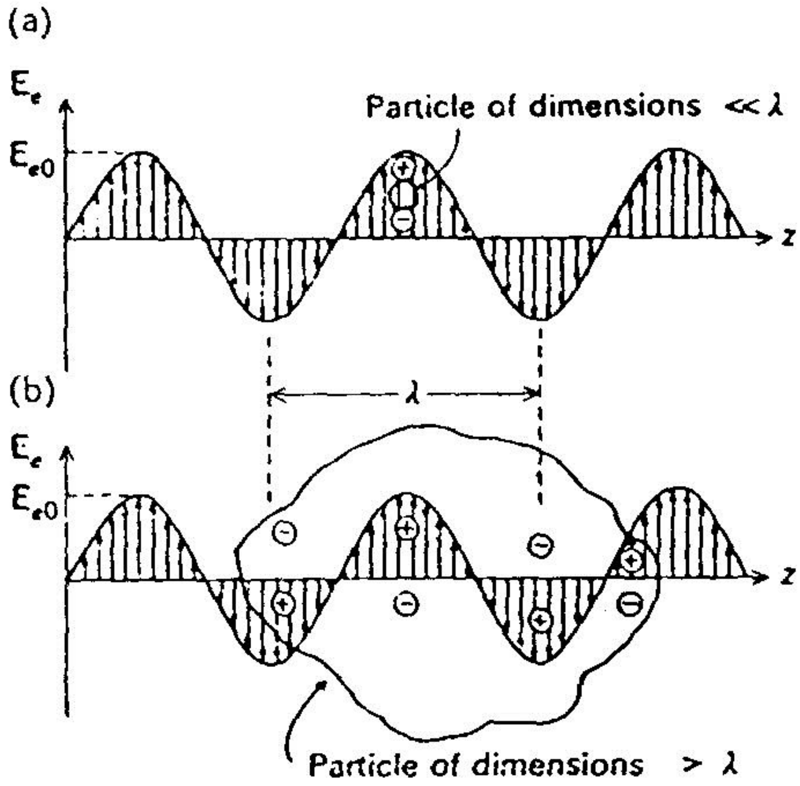
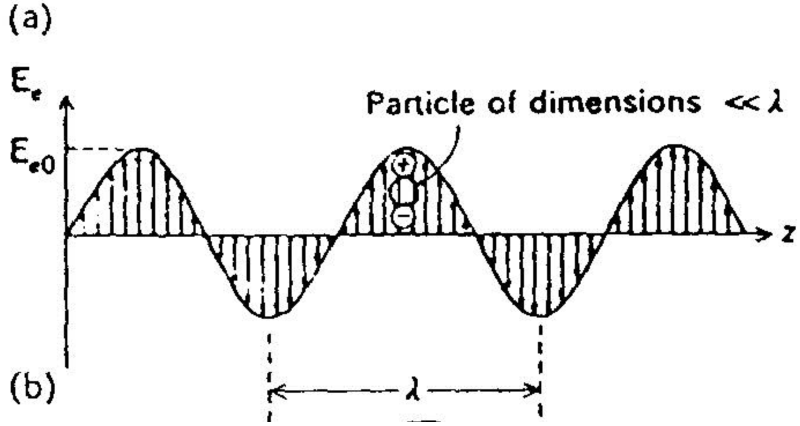


Fig. 4.3.2. Dimensions of scattering centres compared with the electrical field distribution of the electromagnetic wave.

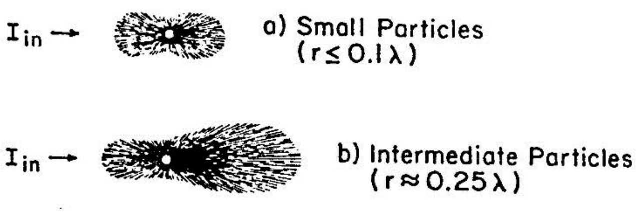
Small Particles: Rayleigh scatterers

- Propagating EM wave sets up oscillating dipole in particle



Small Particles: Rayleigh scatterers

- Propagating EM wave sets up oscillating dipole in particle
- Oscillating dipole induces EM radiation from particle (scattered radiation)



Small Particles: Rayleigh scatterers

- Angular distribution of radiation is called the volume scattering function (VSF or $\beta(\theta)$)
- Equal in forward and backward directions

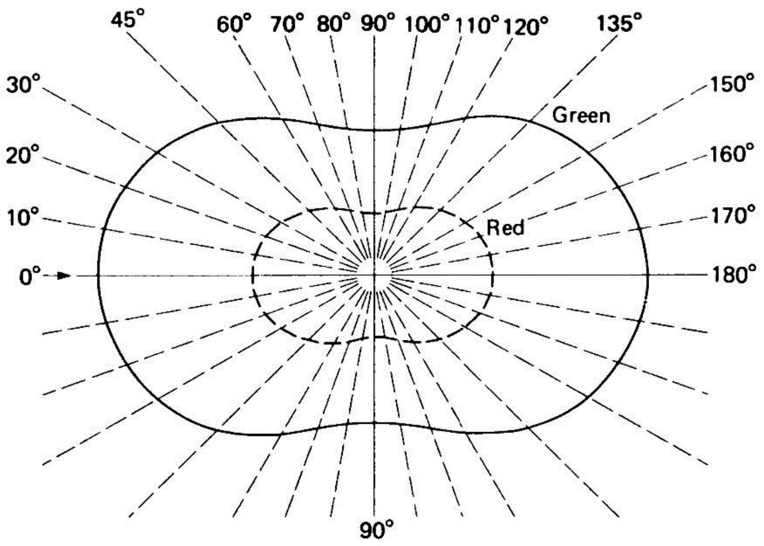


Fig. 2.2. Polar plot of intensity as a function of scattering angle for small particles ($r \simeq 0.025$ μm) for green ($\lambda \simeq 0.5$ μm) and red ($\lambda \simeq 0.7$ μm) light. (By permission, from *Solar radiation*, N. Robinson, Elsevier, Amsterdam, 1966.)

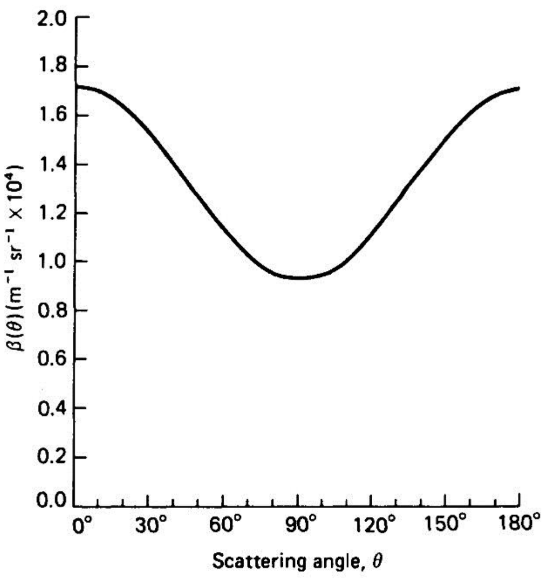
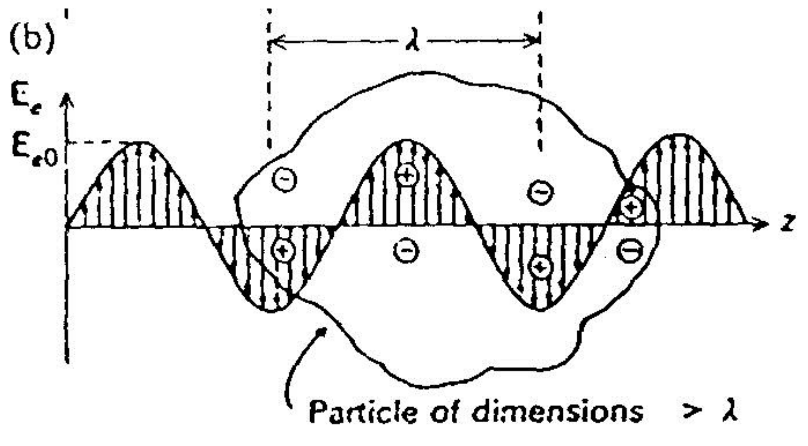


Fig. 4.8. Volume scattering function of pure water for light of wavelength 550 nm. The values are calculated on the basis of density fluctuation scattering, assuming that $\beta(90°) = 0.93 \times 10^{-4}$ m^{-1} sr^{-1} and that $\beta(\theta) = \beta(90°)(1 + 0.835 \cos^2 \theta)$ (following Morel, 1974).

Large particles: Mie scatterers



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EM radiation penetrates particle

Interaction of light with large particles (d>>λ)

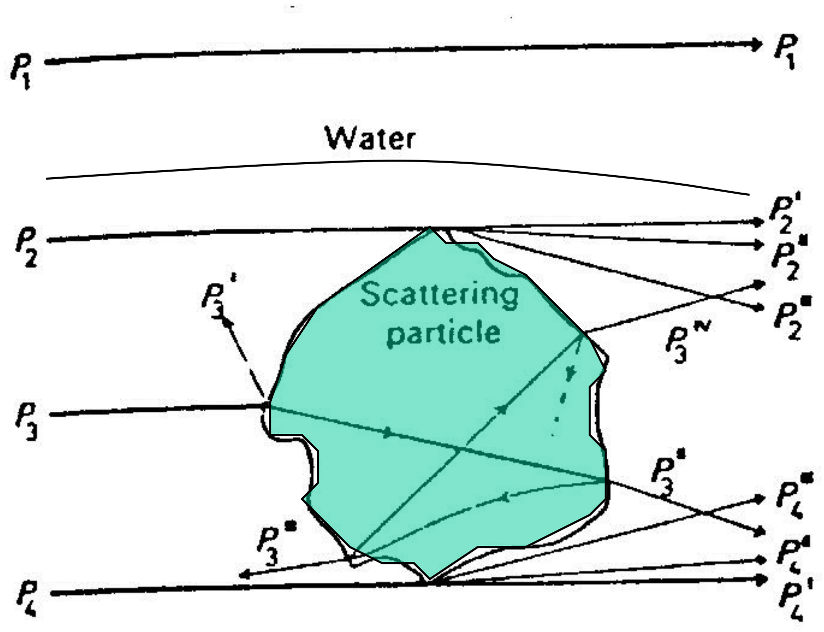
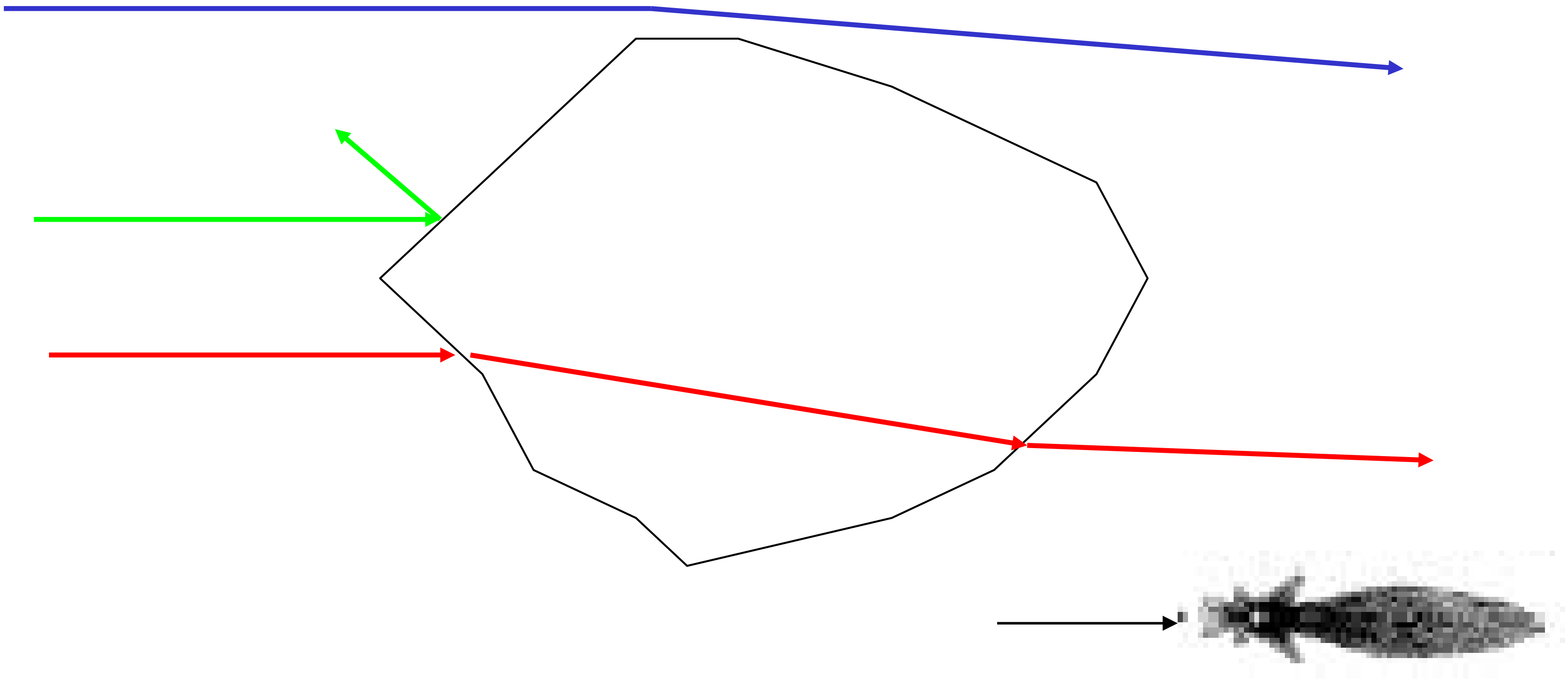


Fig. 4.3.1. A model of light scattering due to reflection, refraction and diffraction by large particles suspended in water. $P_1 - P_4$—incident rays; $P_2^{I} - P_2^{III}$, $P_4^{I} - P_4^{III}$—rays scattered owing to diffraction at the particle's edges; $P_3^{I} - P_3^{IV}$—rays scattered owing to refraction and reflection.

Dera, Marine Physics

Large Particle Scattering

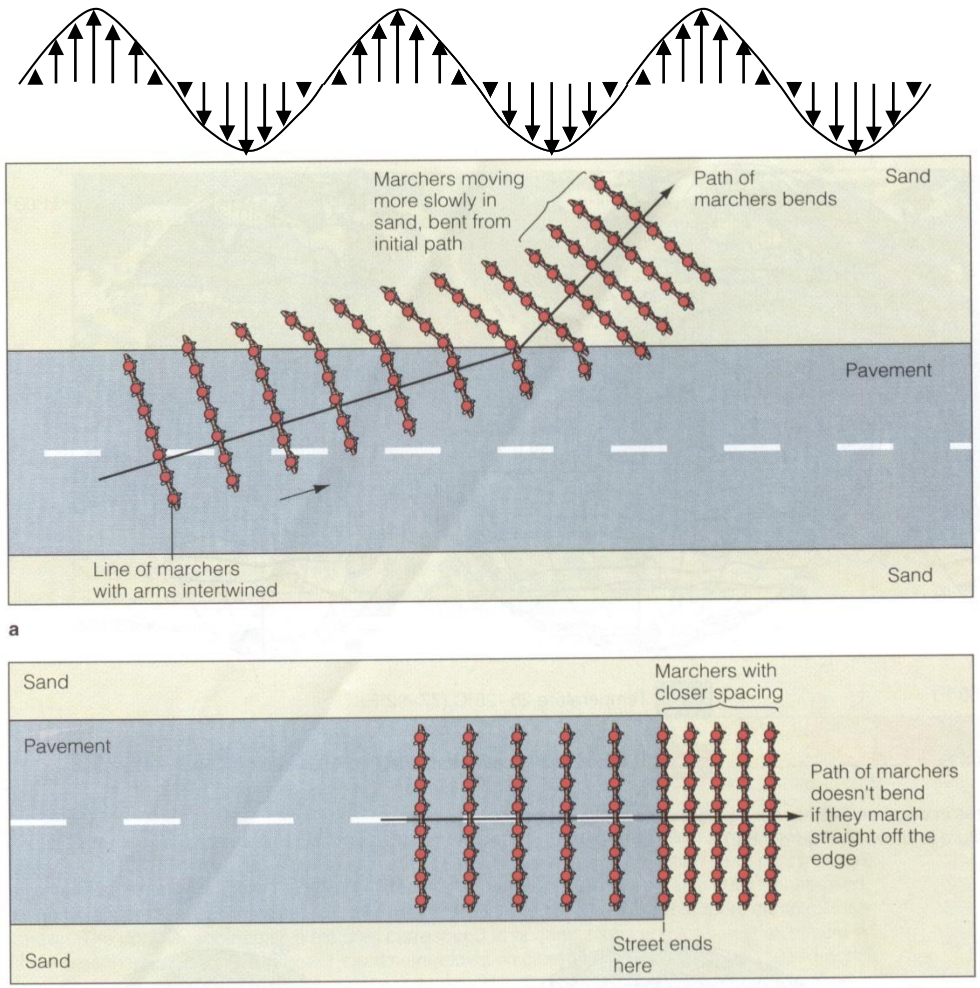
Three effects: refraction, reflection and diffraction



Fresnel's Law

- Quantifies reflection and transmission of EM radiation across an interface between two media with different refractive indices
  - $R_{Incident} = R_{transmitted} + R_{reflected}$
  - Fcn of relative indices of refraction and incidence angle

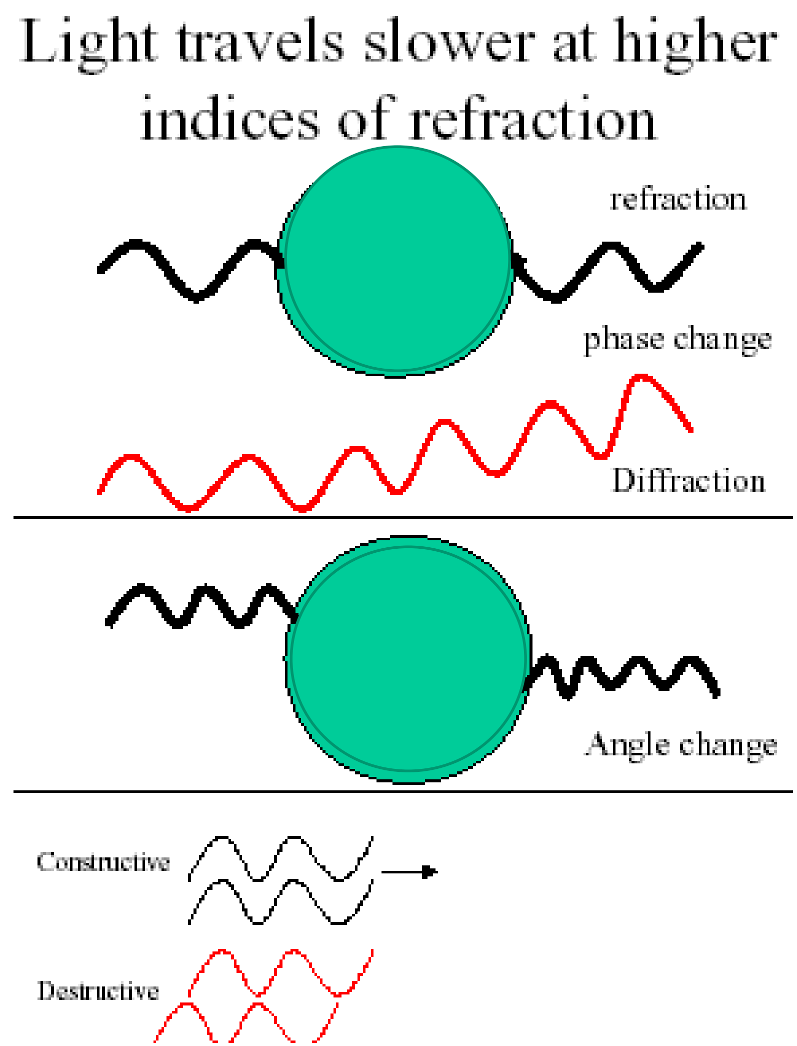
Snell's Law: refractive index impact on wave propagation, describes angle of transmission



Refraction

Changes the speed of propagation leading to directional changes and phase changes

$$\lambda_{\mathrm{medium}} = \lambda \frac{c_{\mathrm{medium}}}{c} = \frac{\lambda}{n}$$



Diffraction

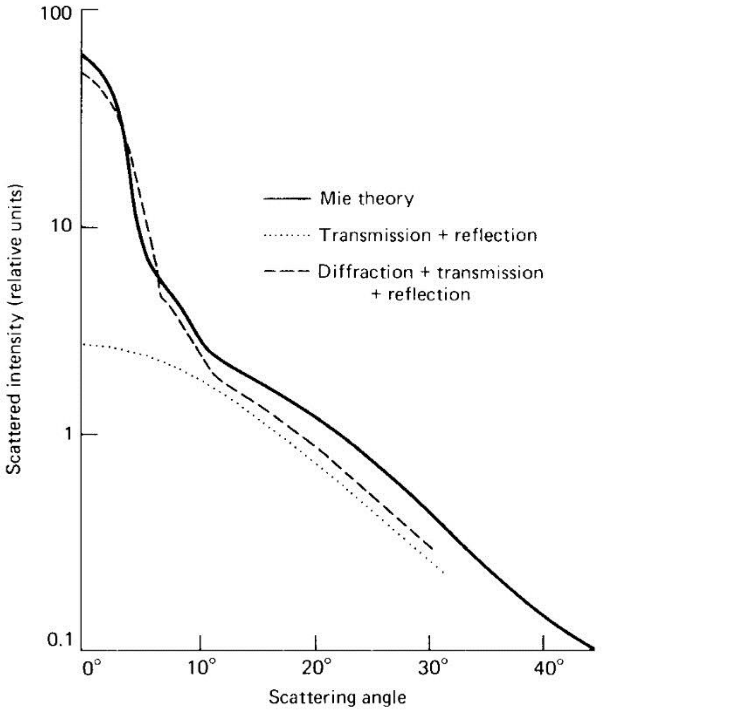
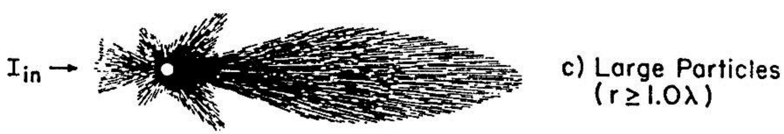


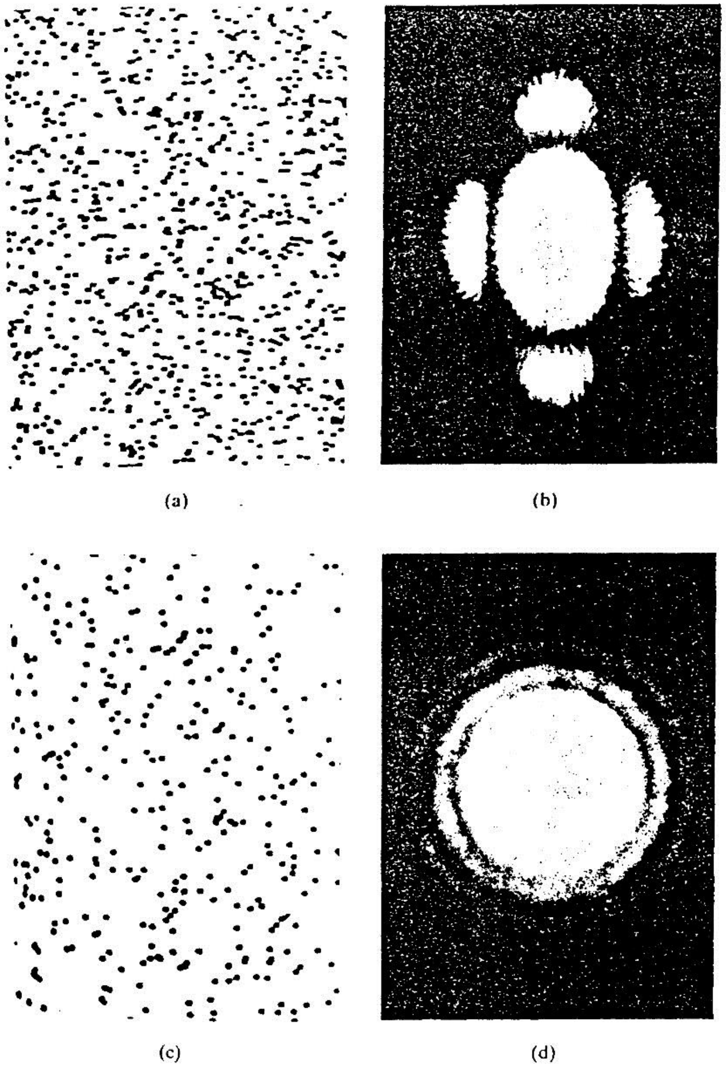
Fig. 4.1. Angular distribution of scattered intensity from transparent spheres calculated from Mie theory (Ashley & Cobb, 1958) or on the basis of transmission and reflection, or diffraction, transmission and reflection (Hodkinson & Greenleaves, 1963). The particles have a refractive index (relative to the surrounding medium) of 1.20, and have diameters 5–12 times the wavelength of the light. After Hodkinson & Greenleaves (1963).



Effect of non-sphericity on diffraction (forward scattering pattern)

Rectangles/ cylinders

Circles/ spheres



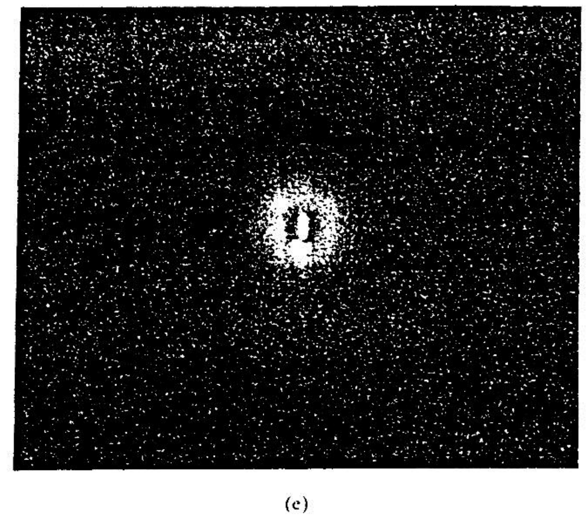
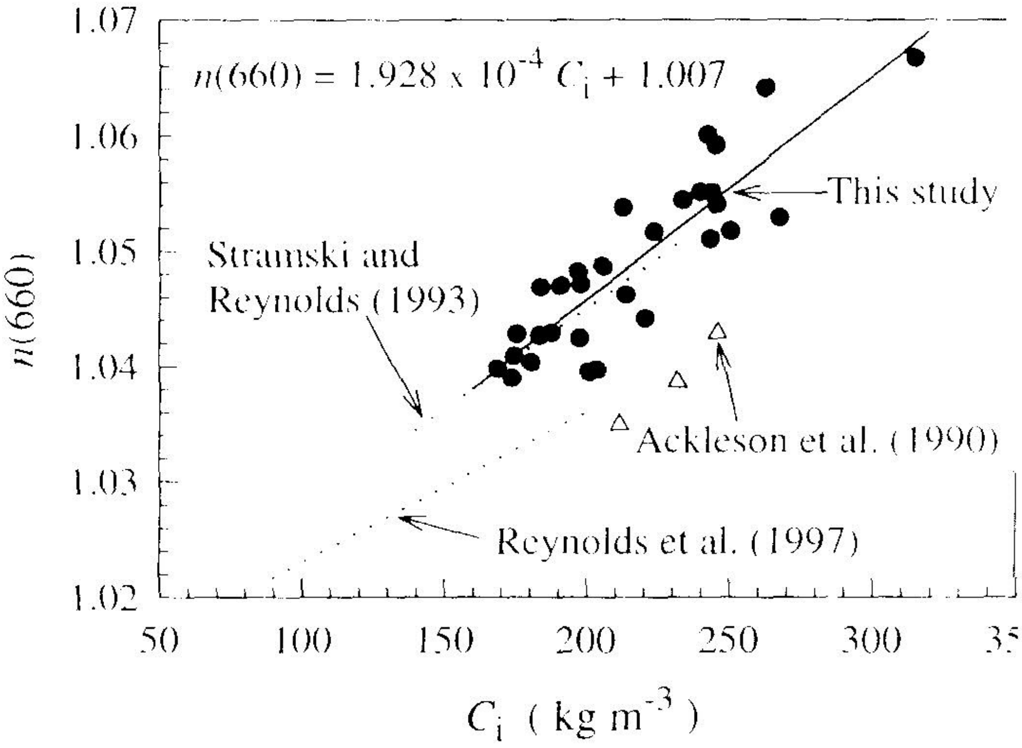


Figure 10.41 (a) A random array of rectangular apertures. (b) The resulting white-light Fraunhofer pattern. (c) A random array of circular apertures. (d) The resulting white-light Fraunhofer pattern. (Photos courtesy The Ealing Corporation and Richard B. Hoover.) (e) A candle flame viewed through a fogged piece of glass. The spectral colors are visible as concentric rings. (Photo by E. H.)

Basis for design of LISST

What influences a particle's refractive index?



- Variations in particle composition:

  Stramski et al. 2002.

What influences a particle's refractive index?

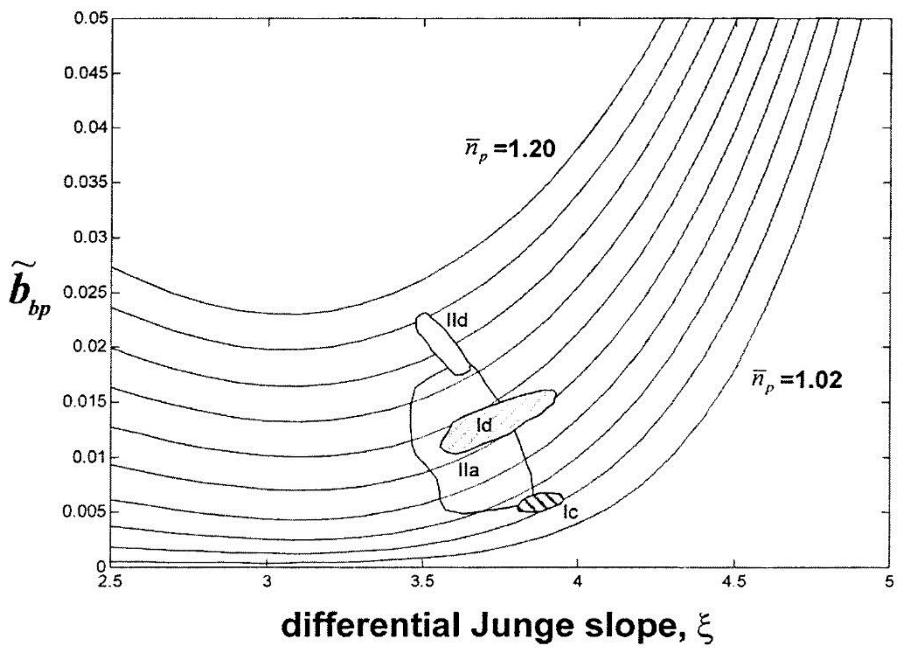


Figure 9. Estimated bulk refractive indices $\hat{n}_p(\tilde{b}_{bp}, \gamma)$ for four specific regions of the water column from the Gulf of California: (1) the case I stations below 100 m (Id), (2) the case I stations at the chlorophyll maximum (Ic), (3) the case II stations south of the sill (IIa), and (4) the bottom water at the case II stations north of the sill (IId). All data were meter-averaged except the Id group, where data were averaged to 5 m.

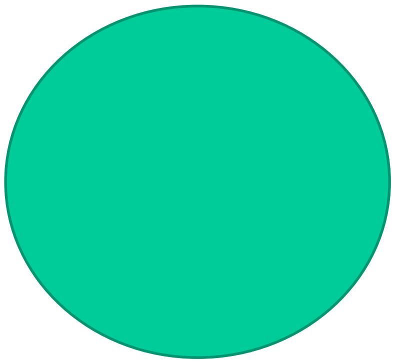
Variations in bulk composition:

Twardowski et al. 2001.

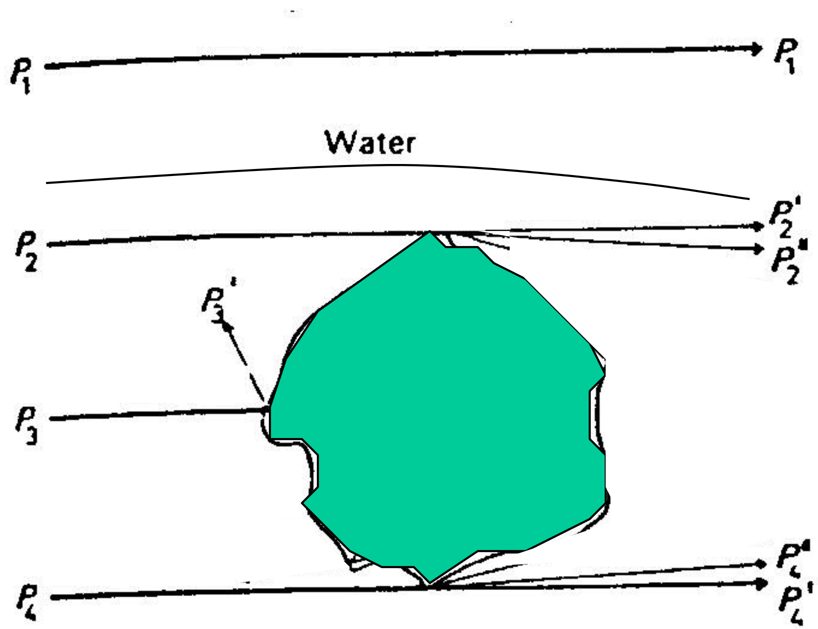
Effect of absorption

- Parameterized by n', the imaginary refractive index relative to surrounding medium
- Describes attenuation of EM radiation as it passes through particle
- Reduces scattered radiation

Draw absorption



Effect of Absorption in the extreme



Only diffraction

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What are the constituent properties that we need to consider

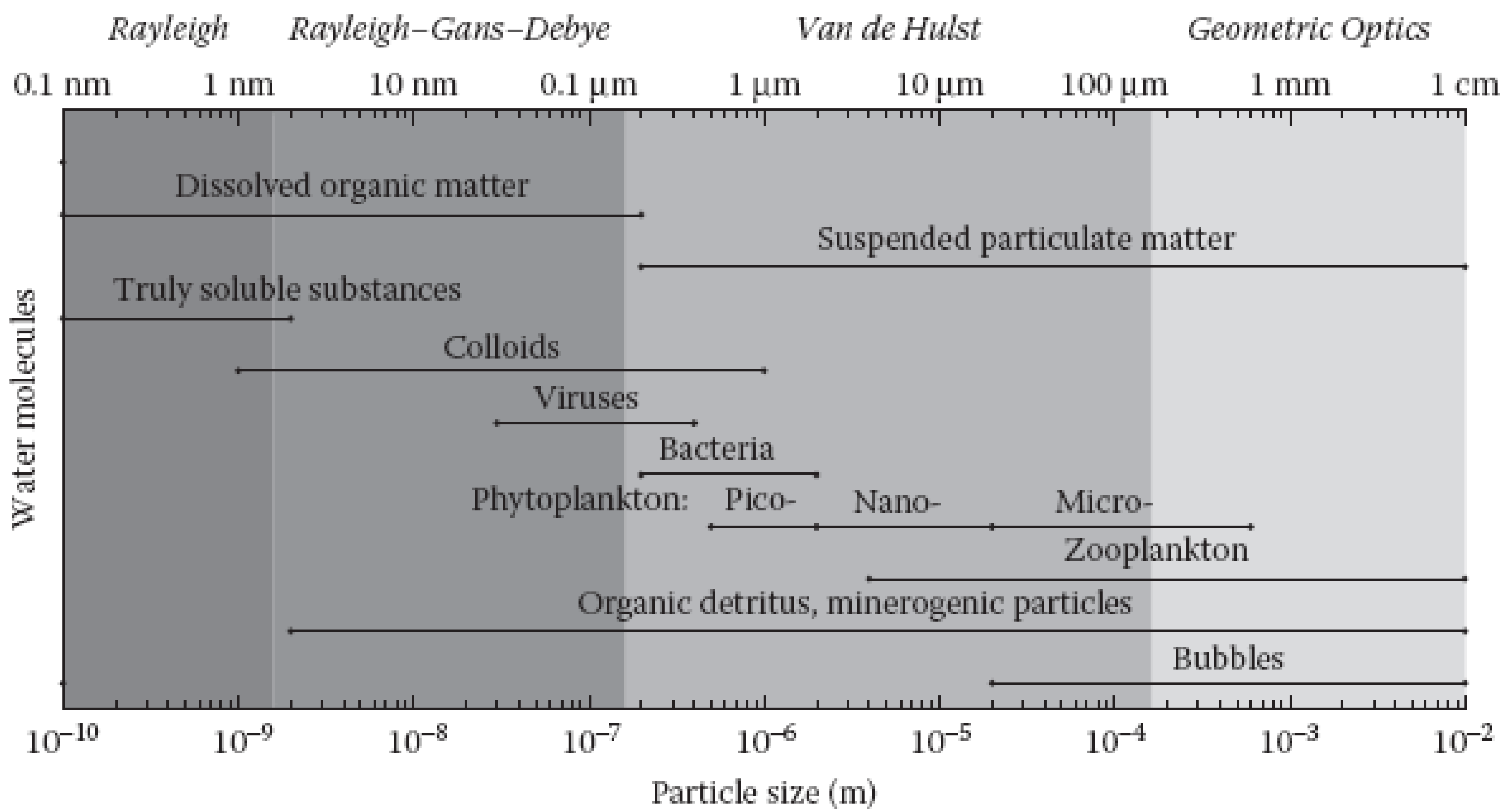
- Particle size
- Particle composition
  - Index of refraction (real part)
  - Index of refraction (imaginary part)
- Particle shape
- Internal structures

What are the particles in the ocean that are responsible for light scattering

- Water molecules
- Dissolved matter
  - Inorganic salts
  - Organic matter (CDOM, colloids)
- Particles
  - Organic
    - Cells and organisms (viruses, bacteria, phytoplankton, to…)
    - Detrital aggregates
  - Inorganic
    - Sediments
    - Minerals
    - Air bubbles

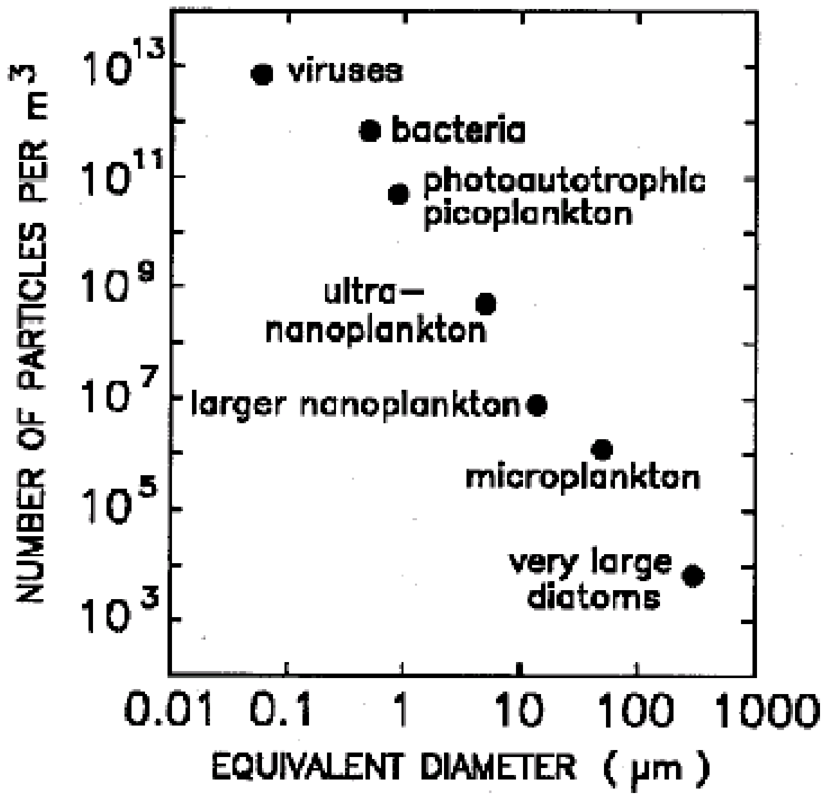
Size matters

Applicable scattering theory



Particle Size Range

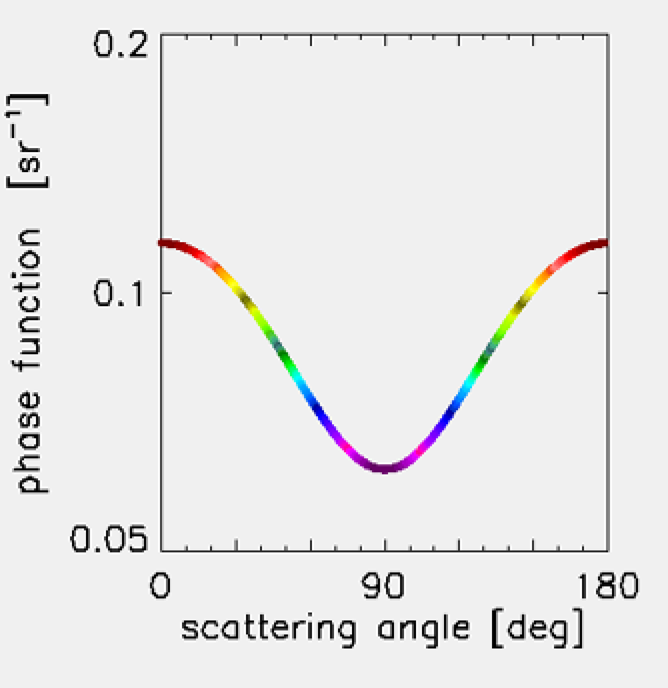
Particle size in the ocean

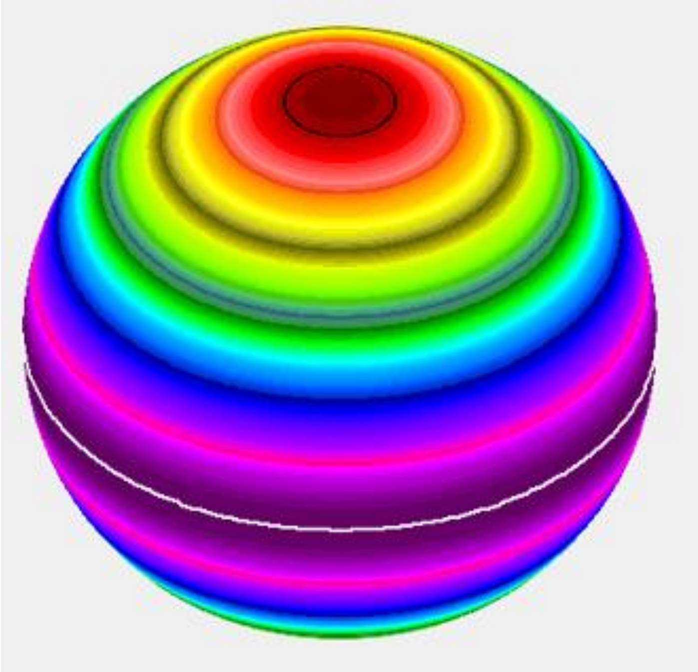


Stramski and Kiefer 1991

Scattering in the ocean: water molecules

Rayleigh Scattering

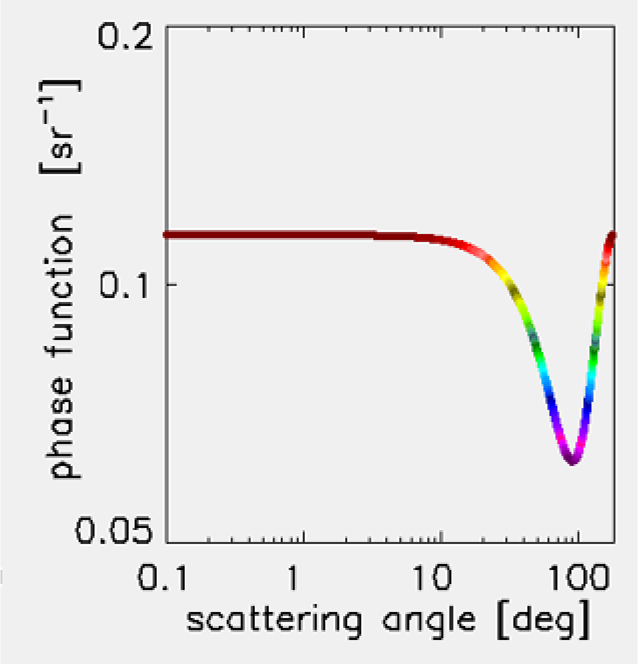


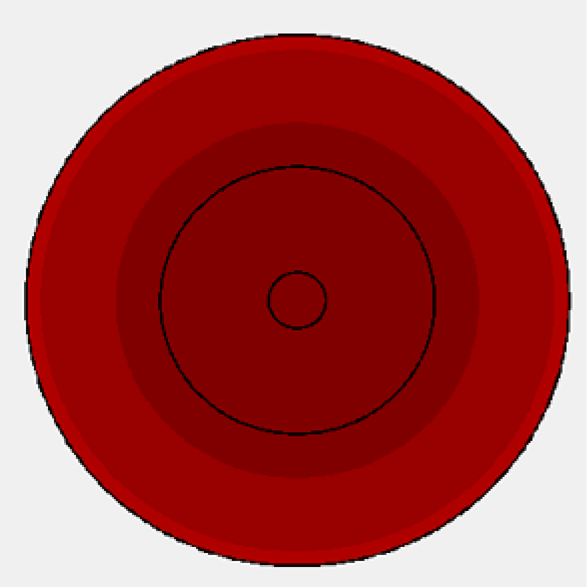


http://www.oceanopticsbook.info/view/overview_of_optical_oceanography/visualizing_vsfs

Scattering in the ocean: water molecules

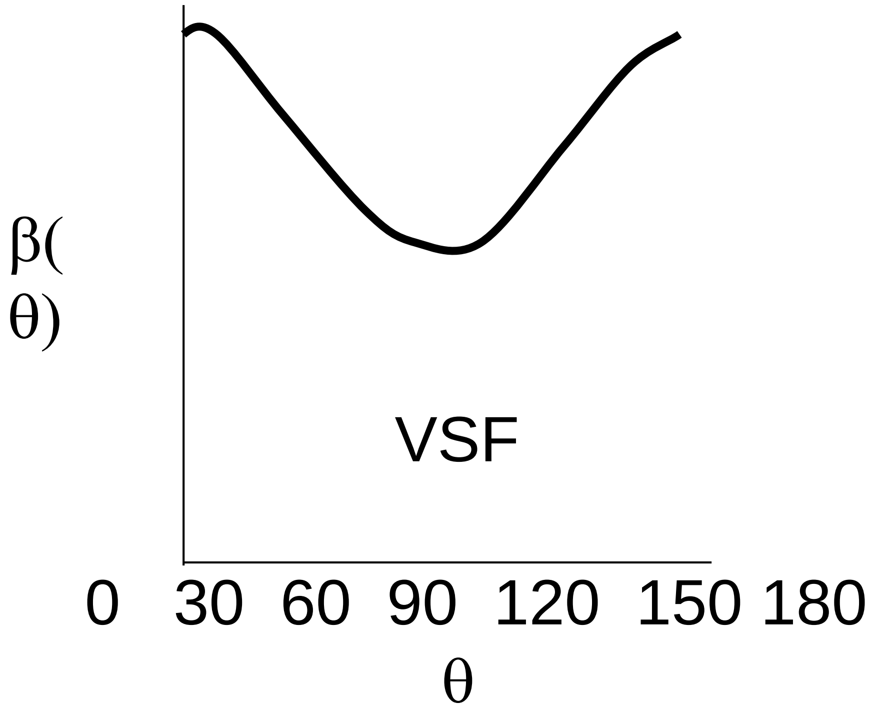
Rayleigh Scattering

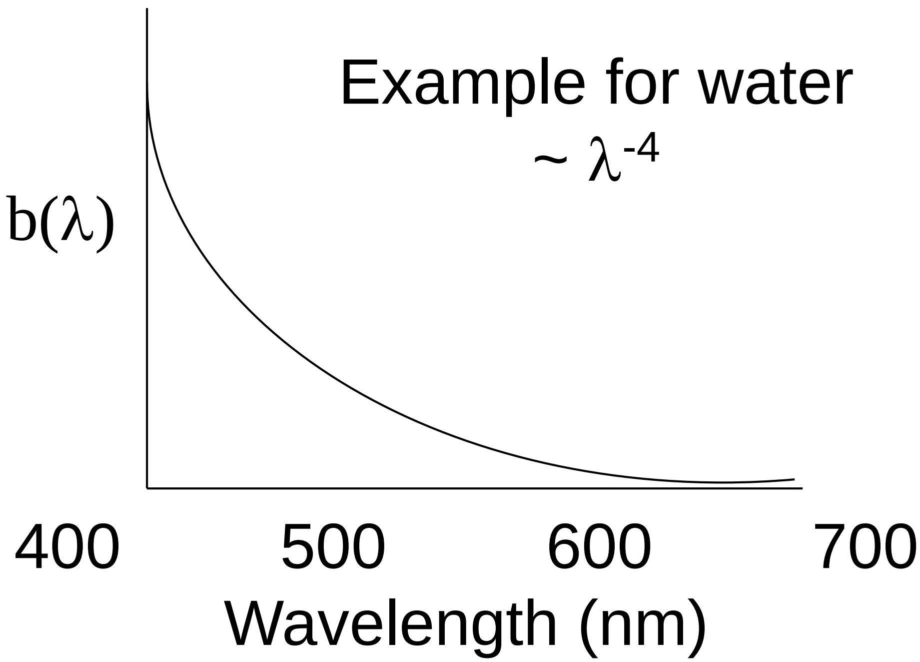




http://www.oceanopticsbook.info/view/overview_of_optical_oceanography/visualizing_vsfs

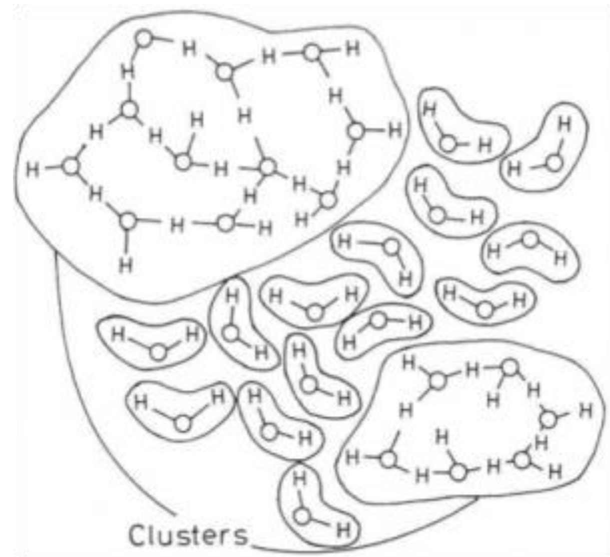
Small Particle Scattering follows Rayleigh Theory

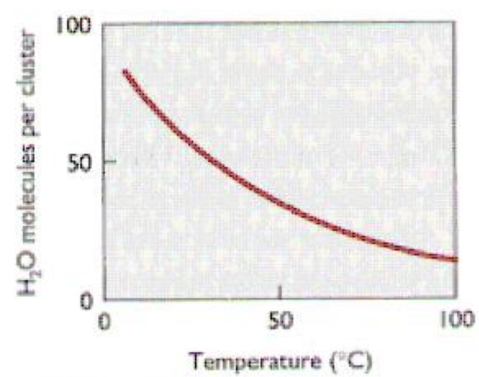




Scattering in the ocean: water

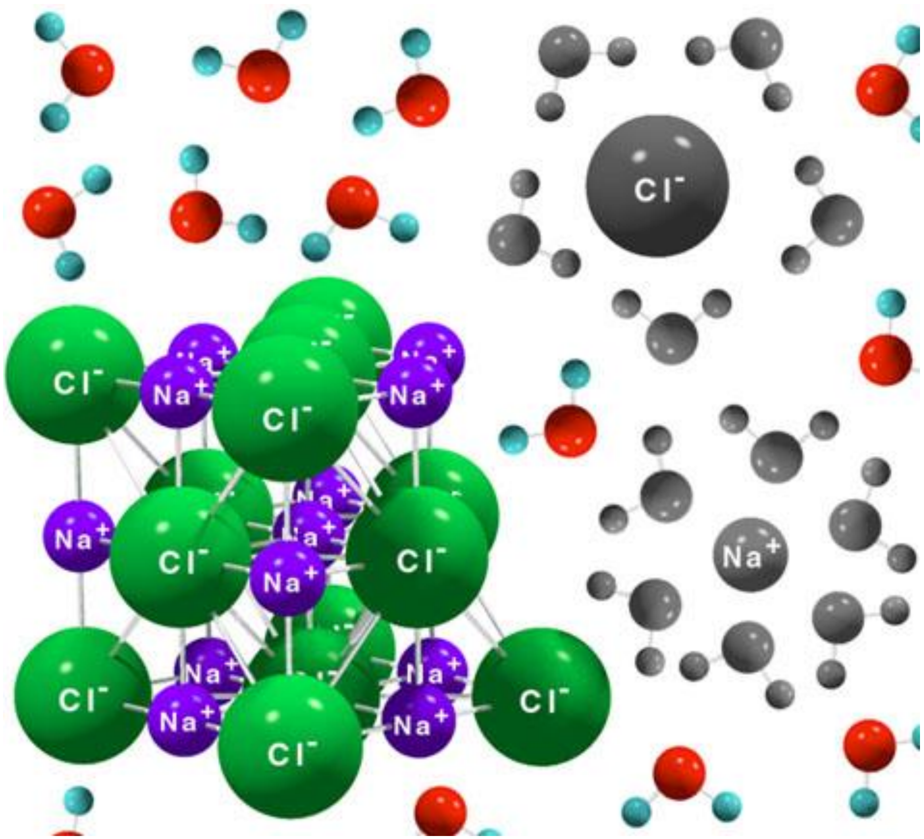
- Clusters formed from hydrogen bonds between the polar water molecule (Frank-Wen flickering cluster model)
- A function of temperature (kinetic energy)





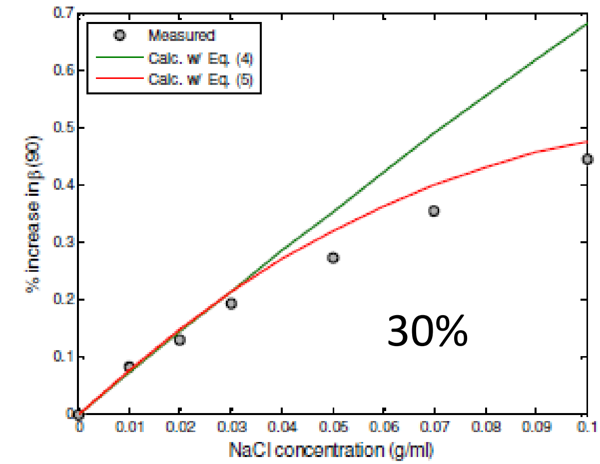
(e) SIZE OF WATER CLUSTERS

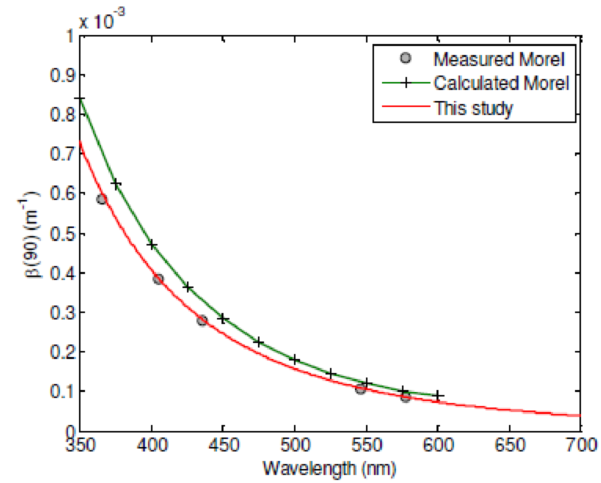
Scattering in the ocean: dissolved salts



Model of salt dissociation

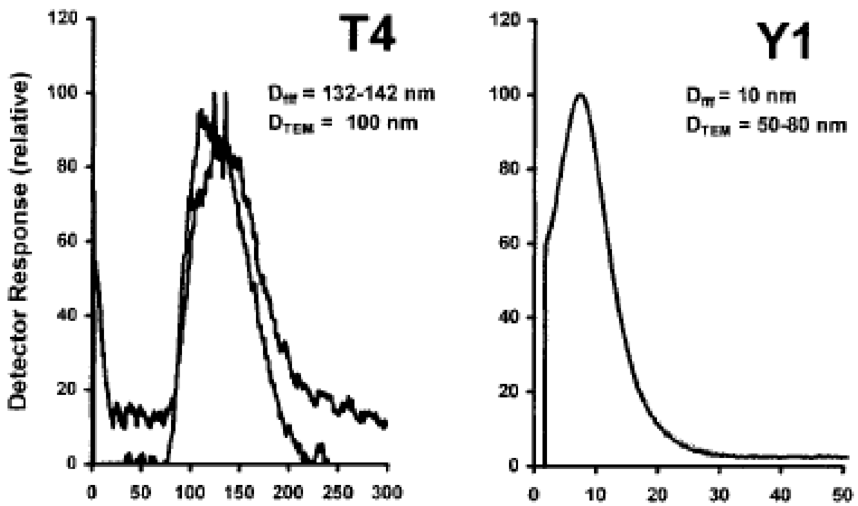
http://www.chemistry.wustl.edu/~edudev/LabTutorials/Water/PublicWaterSupply/PublicWaterSupply.html

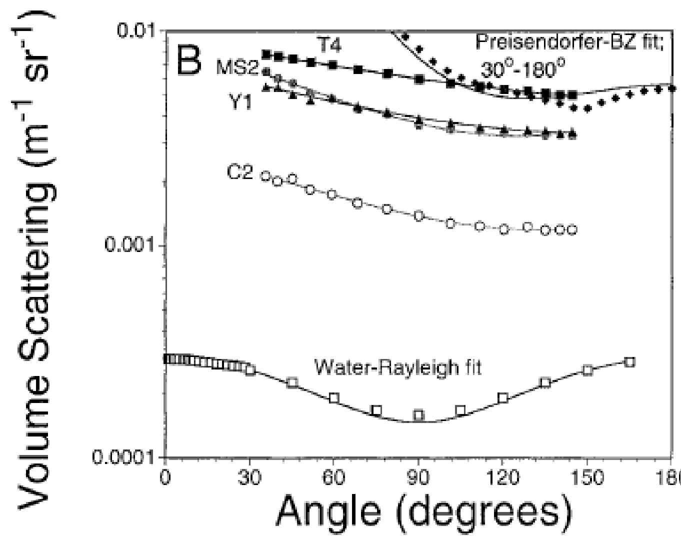


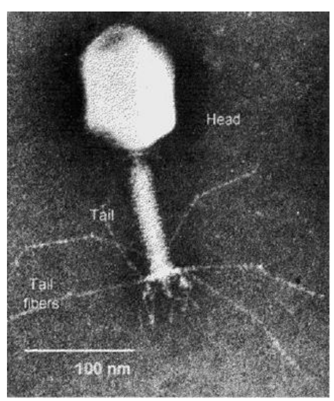


Zhang et al 2009 OptExp

Scattering in the ocean: marine viruses

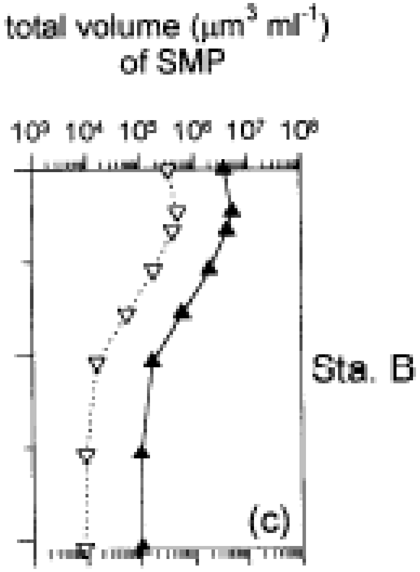


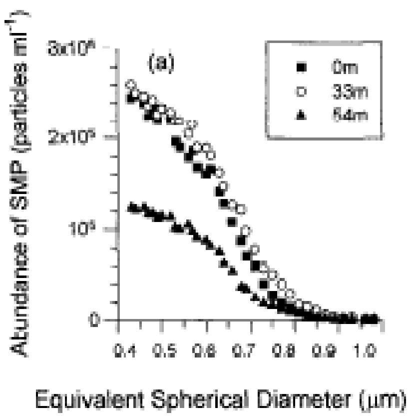




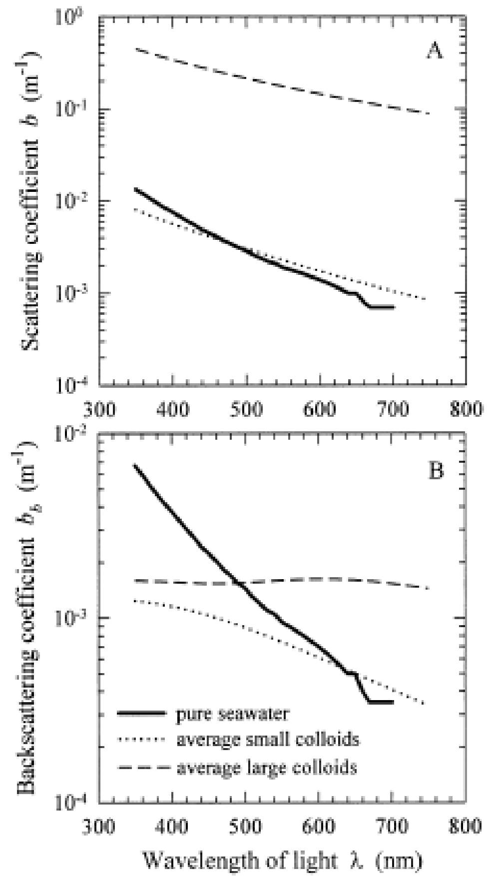
Balch et al. 1999

Scattering in the ocean: submicron particles (~colloids)





Yamasaki et al 1998

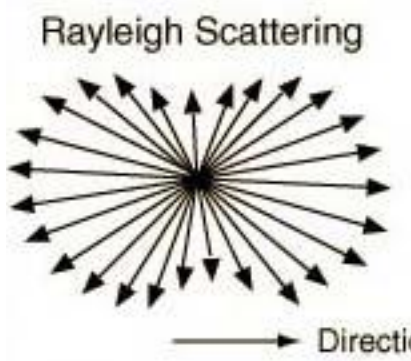


Stramski and Wozniak 2005

Scattering by CDOM:

From Emmanuel Boss

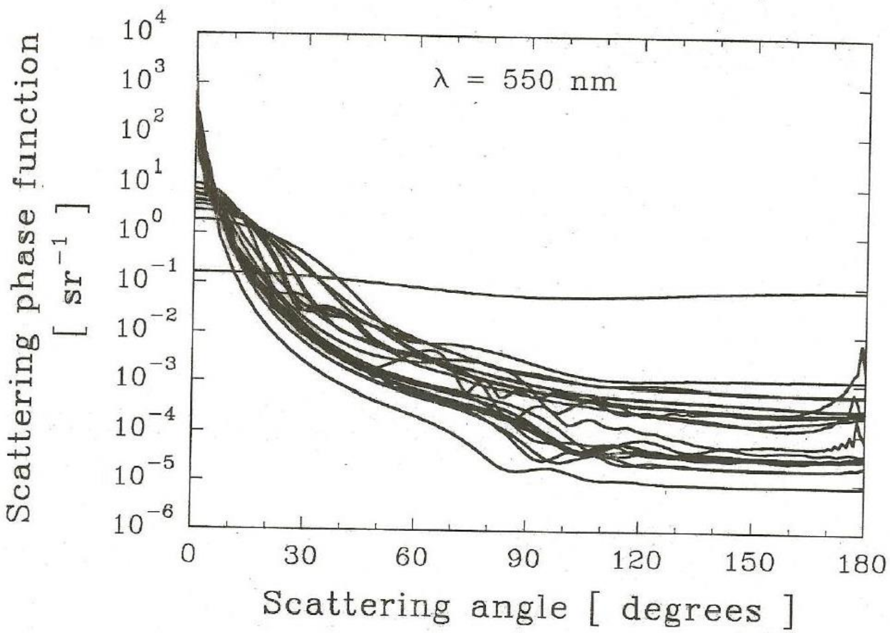
Scattering by molecules whose $D \ll \lambda$. Rayleigh scattering:

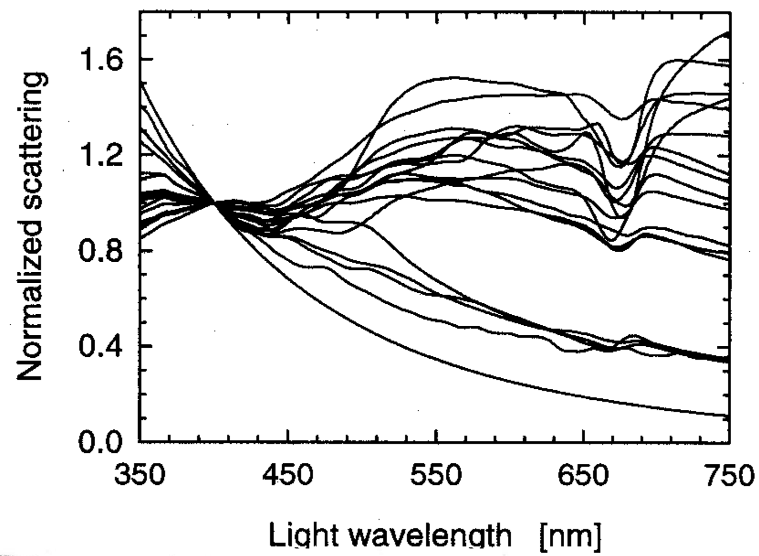


$$b(\lambda) \propto \lambda^{-4} \quad \beta(\theta) \propto \left(1 + \cos^2(\theta)\right)$$

No evidence in the literature that scattering is significant (the only place *I* have ever found significant dissolved scattering ($c_g > a_g$) was in pore water).

Scattering in the ocean: phytoplankton



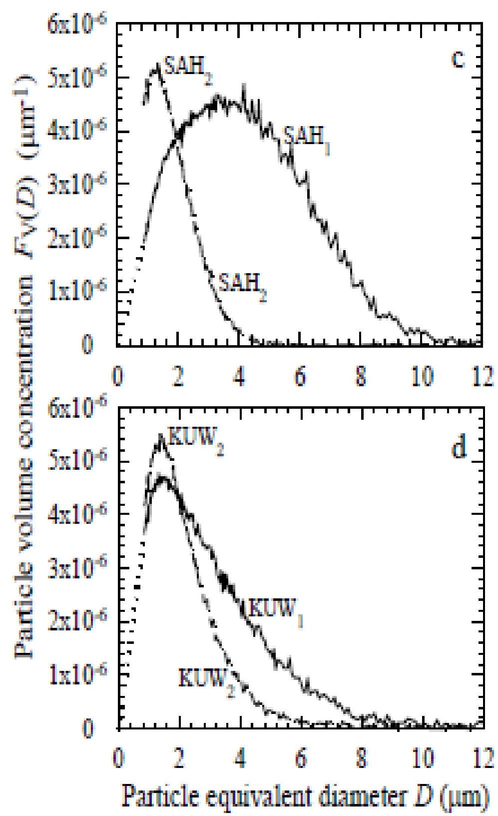


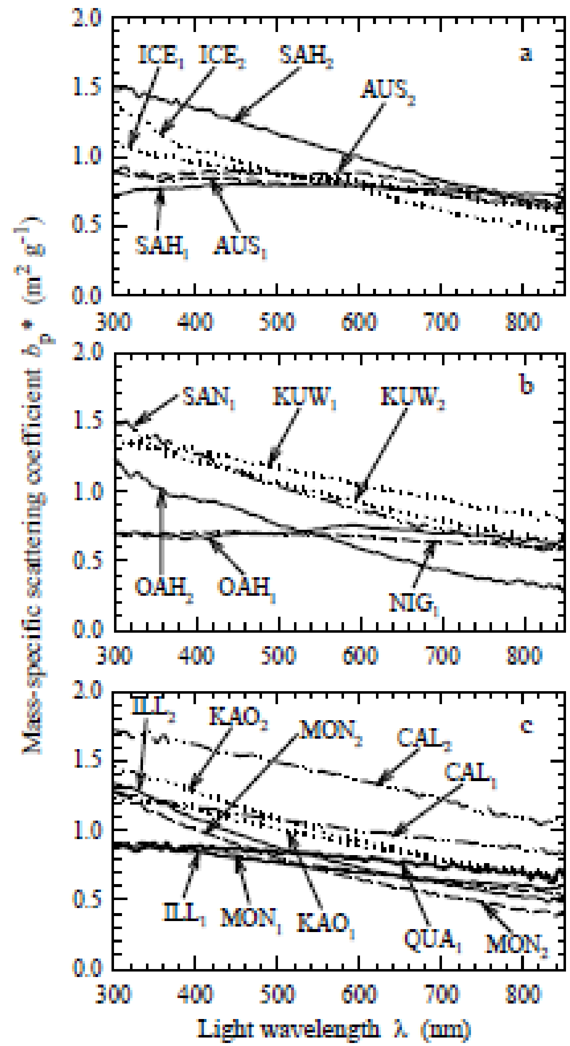
Viruses
Heterotrophic bacteria
Prochlorococcus (2 strains)
Synechococcus (Cyanophyceae, 5 strains)
Anacystis marina (Cyanophyceae)
Pavlova pinguis (Haptophyceae)
Thalassiosira pseudonana (Bacillariophyceae)
Pavlova lutheri (Haptophyceae)
Isochrysis galbana (Haptophyceae)
Emiliania hyxleyi (Haptophyceae)
Porphyridium cruentum (Rhodophyceae)
Chroomonas fragarioides (Cryptophyceae)
Prymnesium parvum (Haptophyceae)
Dunaliella bioculata (Chlorophyceae)
Dunaliella tertiolecta (Chlorophyceae)
Chaetoceros curvisetum (Bacillariophyceae)
Hymenomonas elongata (Haptophyceae)
Prorocentrum micans (Dinophyceae)

Stramski et al. 2001

Scattering in the ocean: inorganic minerals

- Terrestrial dust sources



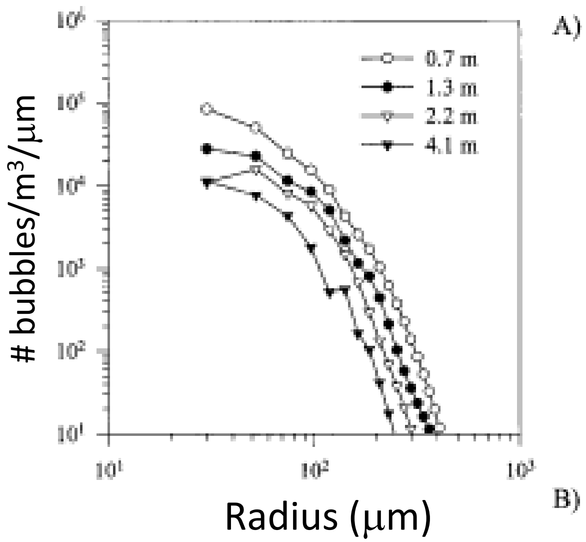


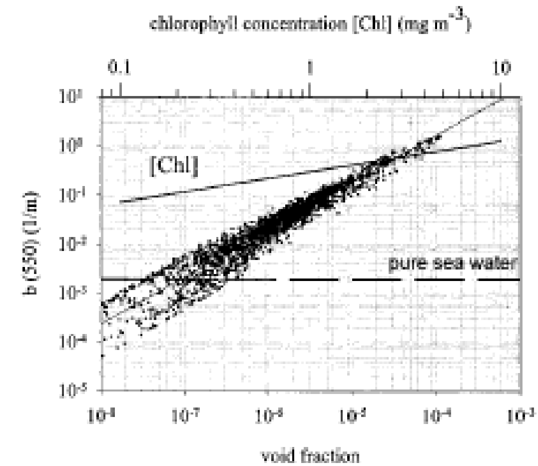
Stramski et al. 2007

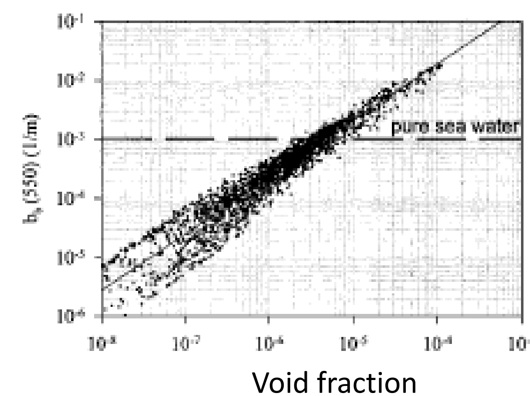
Scattering in the ocean: air bubbles

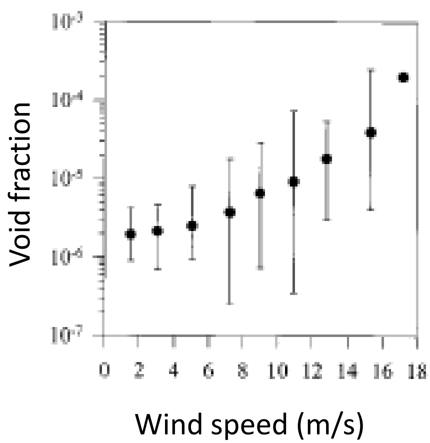
- Acoustics
  - Size
  - distribution
- Modeled b

Terrill et al. 2001

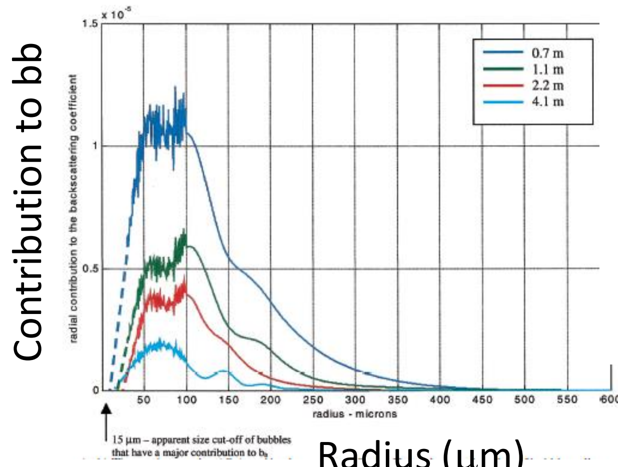




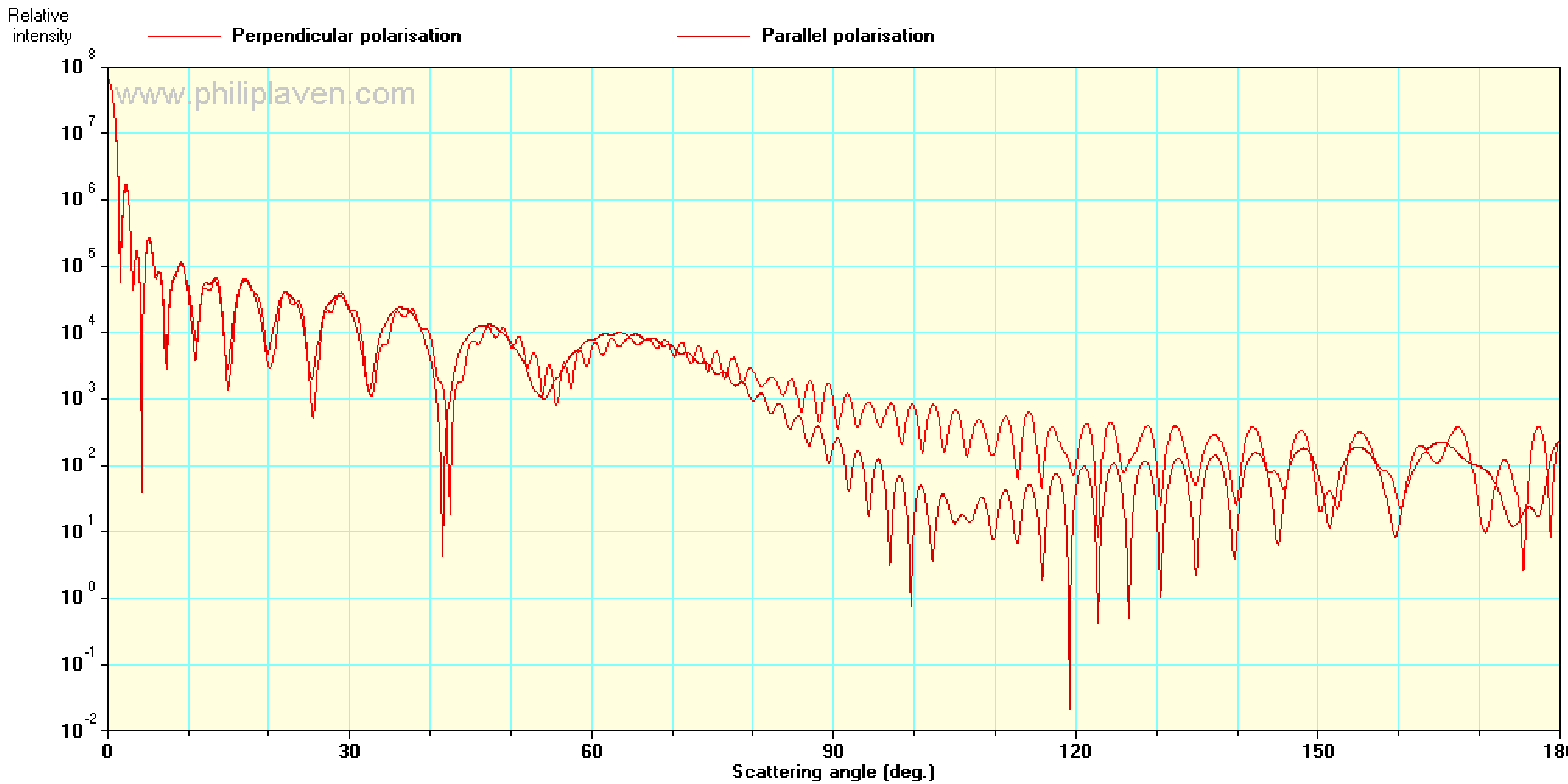




Terrill et al. 1998



Scattering in the ocean: air bubbles

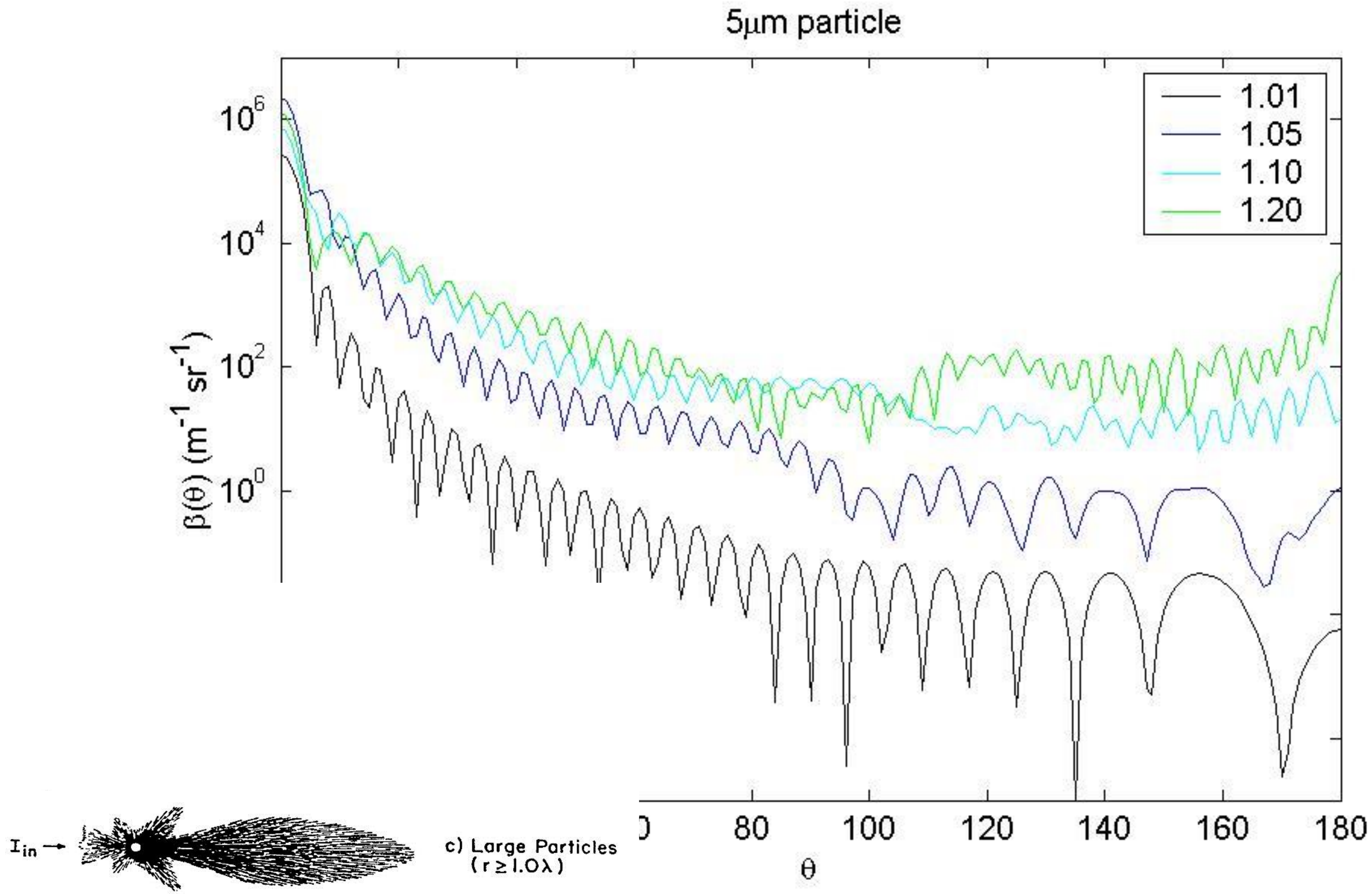


http://www.philiplaven.com/p8h1.html

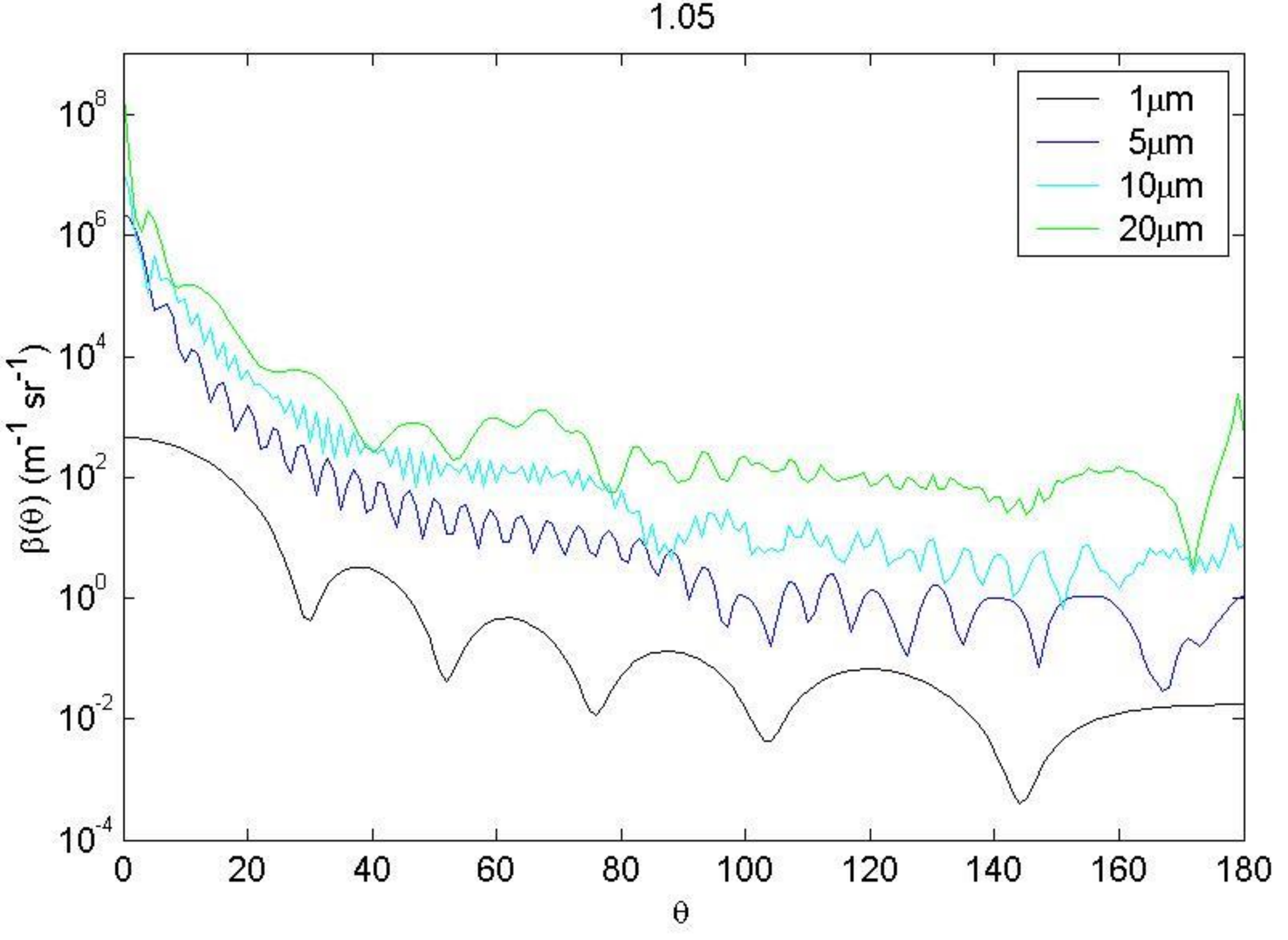
Mie Theory describes the interaction between EM and particles

- Homogeneous spheres
- Size index $\rho \sim d / \lambda$
- Real refractive index relative to surrounding medium ($n = m_p/m_w$)
  - Slows wave propagation
- Imaginary refractive index relative to surrounding medium ($n' = m_p'/m_w'$)
  - Attenuation of wave propagation

VSF of 5 μm particle as a function of refractive index

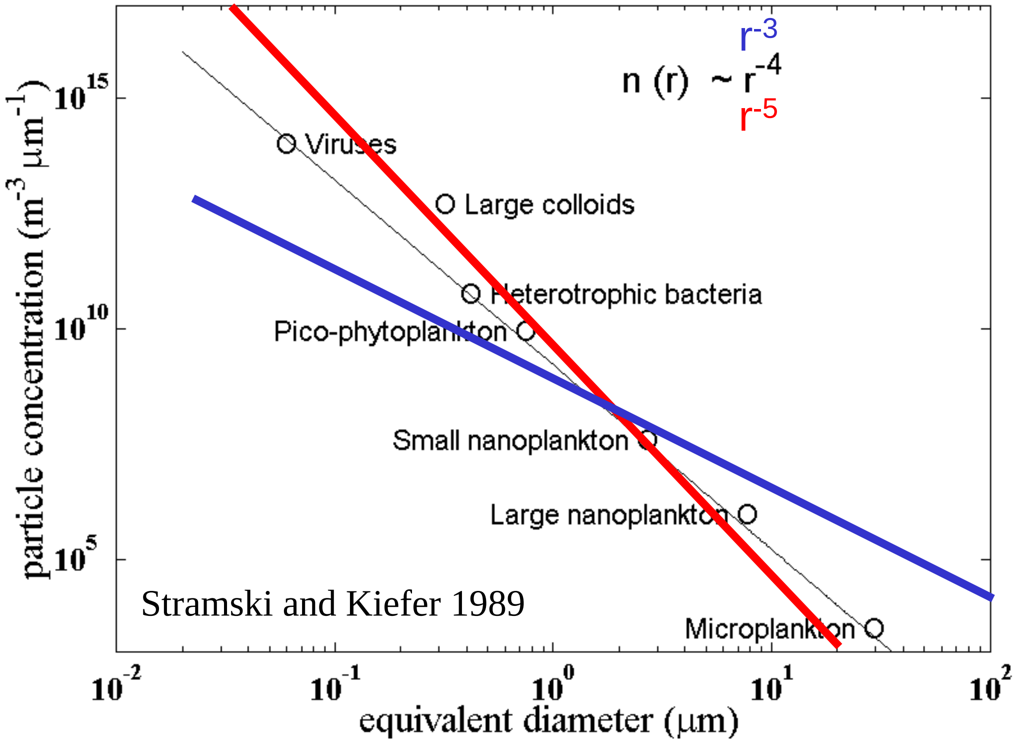


VSF of particles with refractive index 1.05

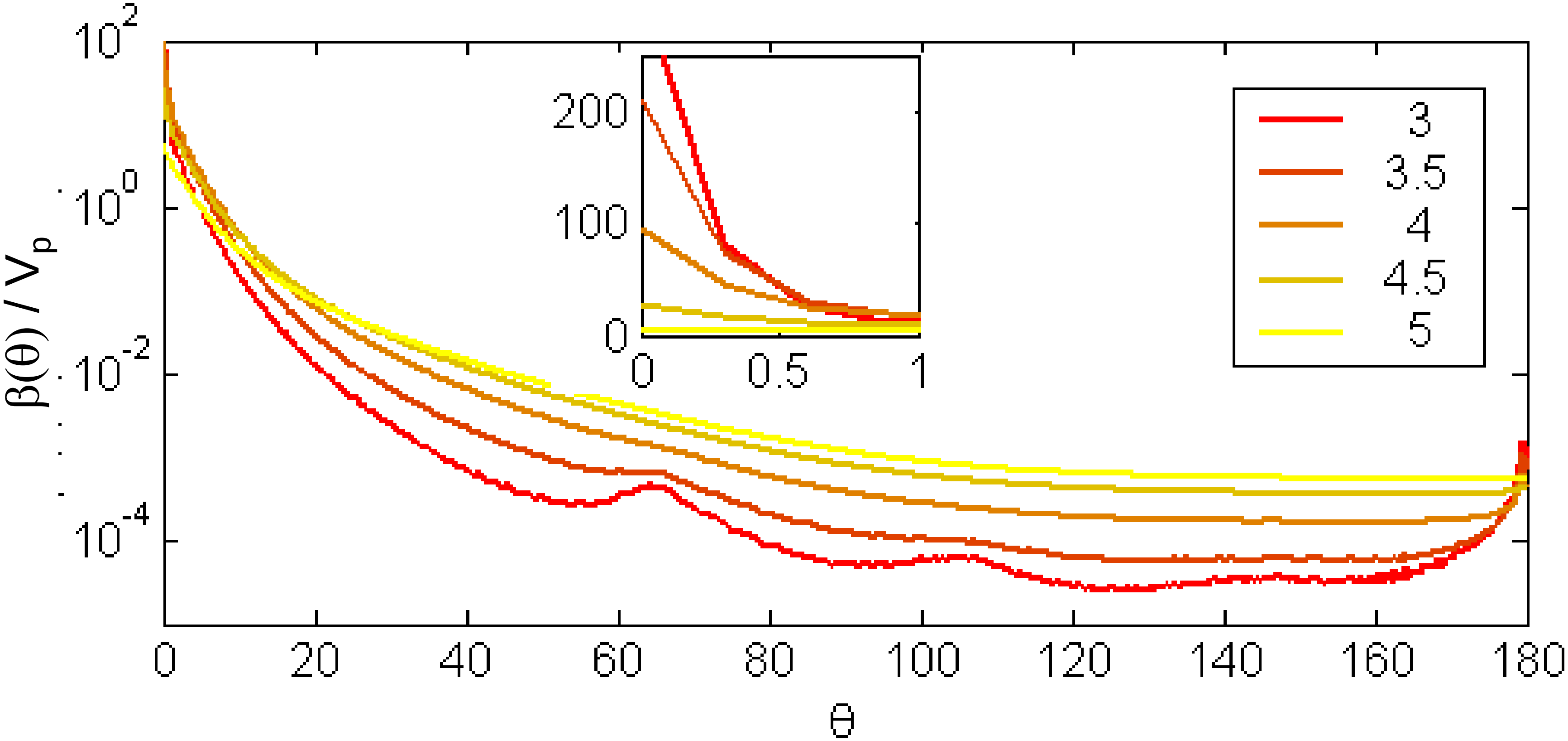


$\beta(\theta)$ response to particle size distribution

First let's talk about particle size distributions

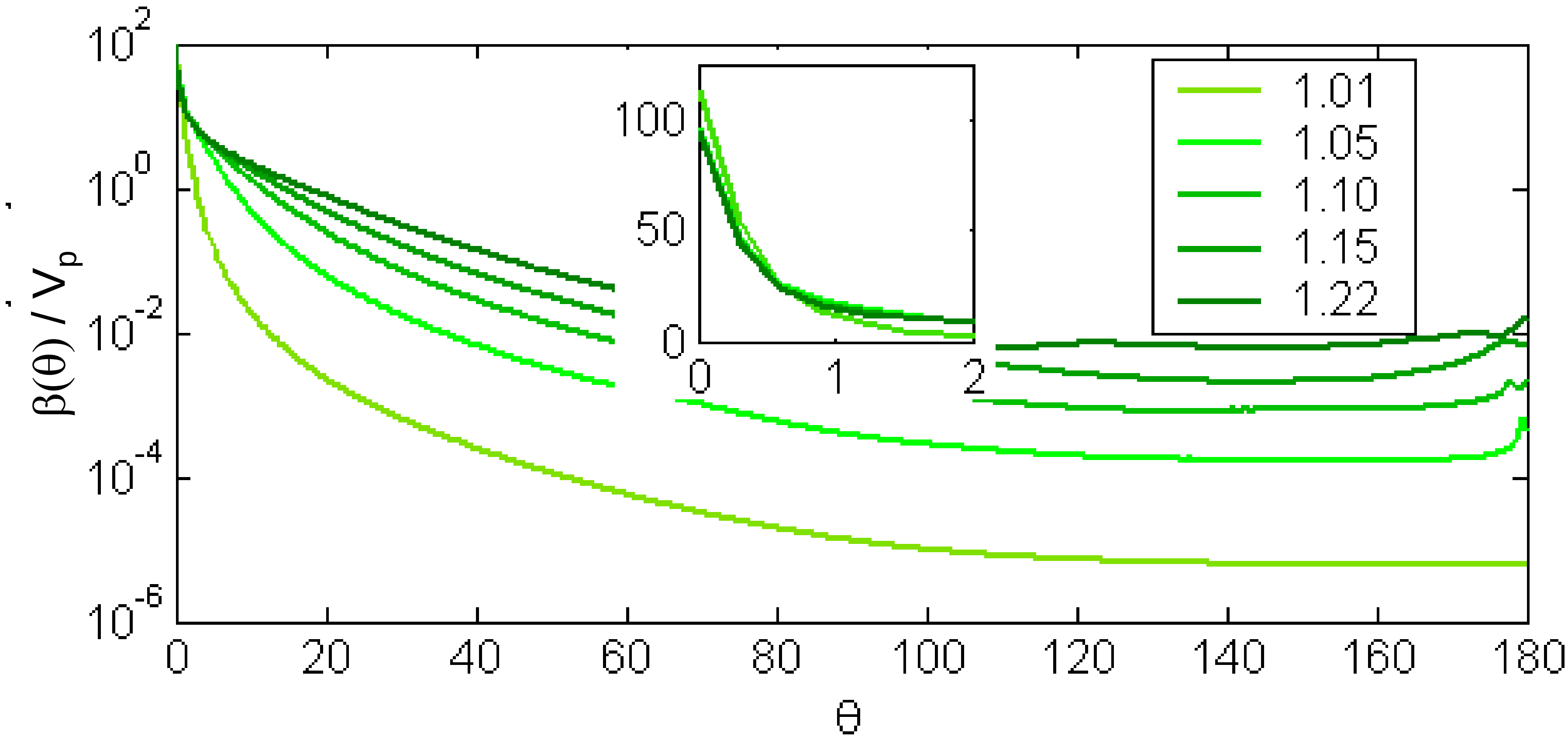


β(θ) and response to particle size distribution



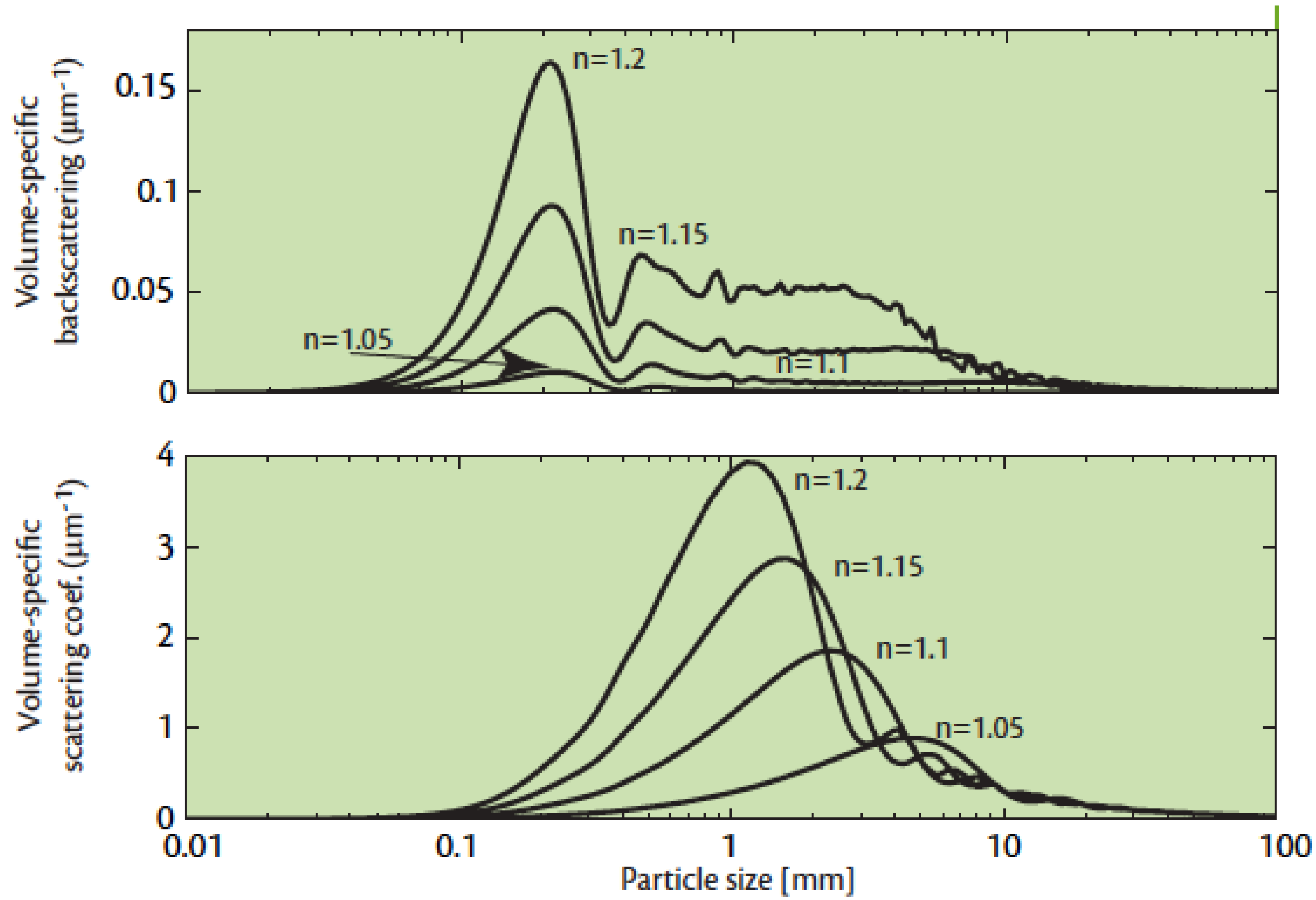
Roesler and Boss, 2008

$\beta(\theta)$ response to index of refraction



Roesler and Boss, 2008

Scattering in the ocean: which particles contribute



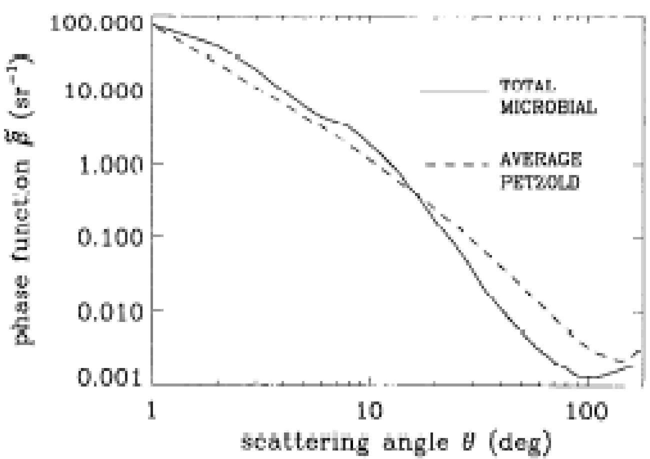
Boss et al., 2004, TOS

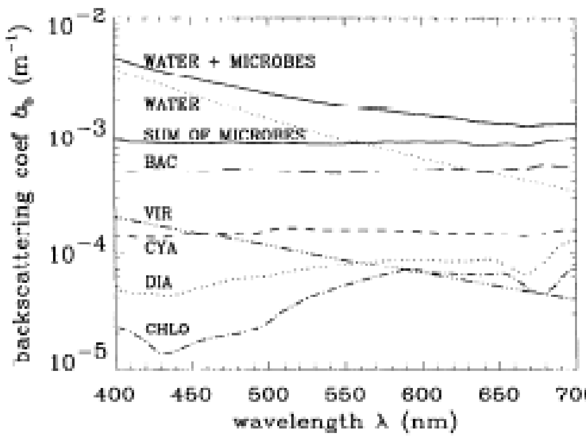
Consider what information scattering can provide and what do you want to measure

- b
- b_f
- b_b
- $\beta(\theta)$

Scattering closure

- Reductionist view (Stramski and Mobley 1997; Mobley and Stramski 1997)
  - Particle-specific volume scattering
  - Particle concentration





Importance of scattering in the ocean

- Competing forces of absorption and scattering on the downward propagation of light in the ocean

Importance of scattering in the ocean

- Competing forces of absorption and scattering on the downward propagation of light in the ocean
- Backscattering and the upward propagation of light from the ocean

Normalized water-leaving radiance in the Mediterranean Sea (Sept 2003)

412 nm

490 nm