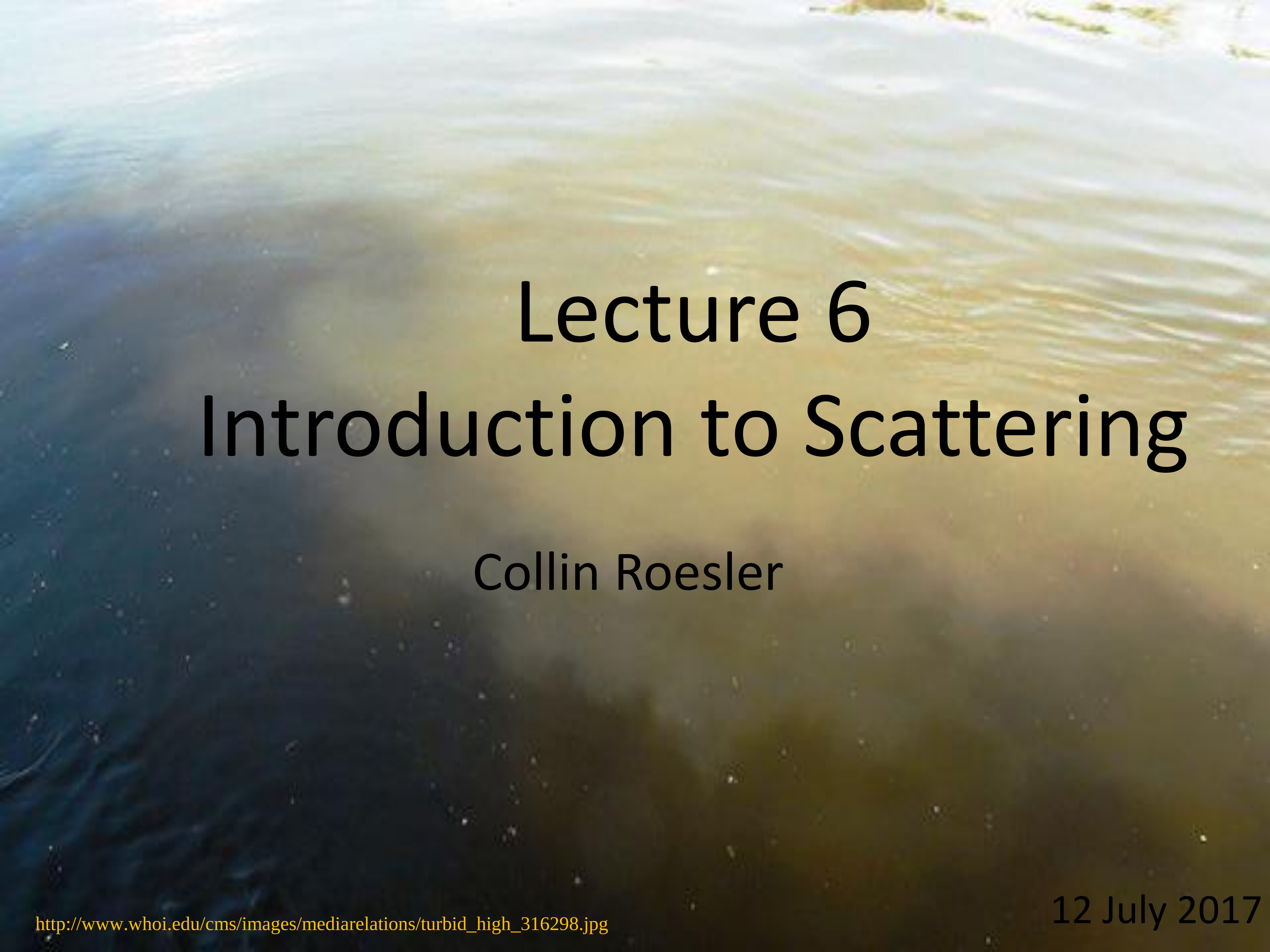


Lecture 6
Introduction to Scattering

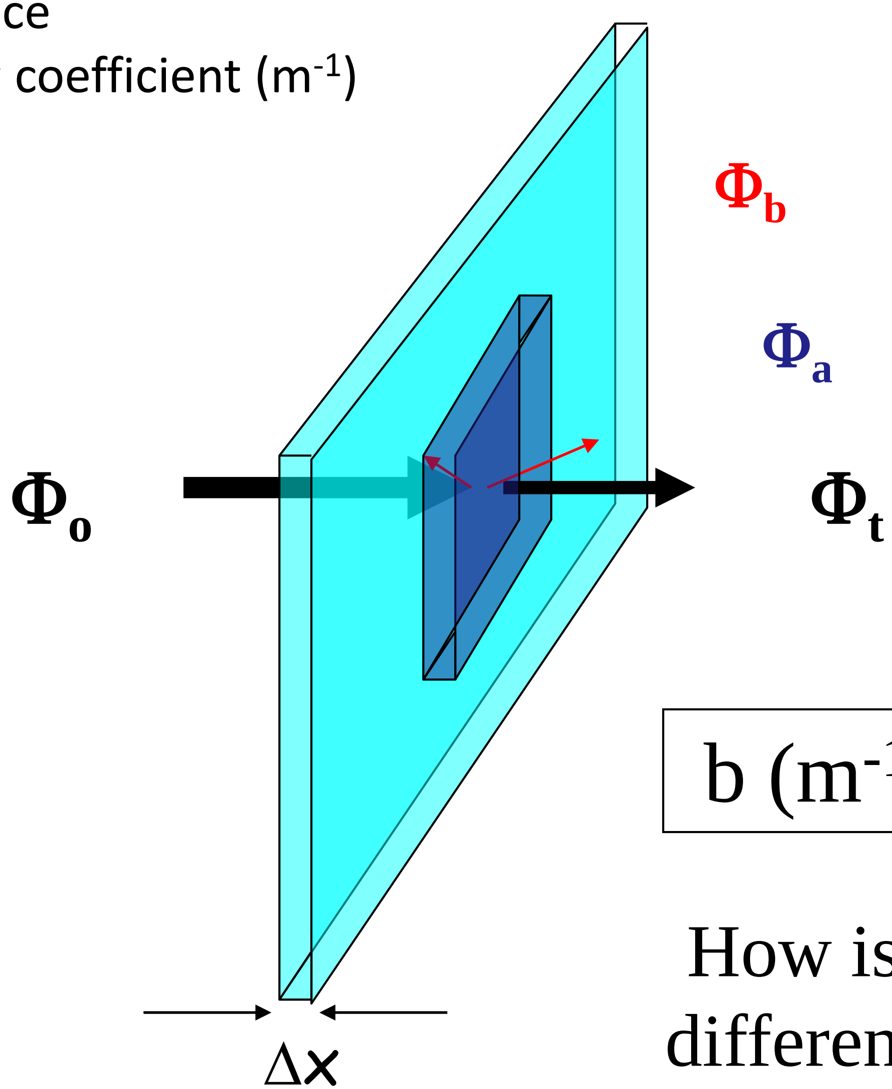
Collin Roesler

12 July 2017

http://www.whoi.edu/cms/images/mediarelations/turbid_high_316298.jpg

Scattering Theory

B = scatterance
b= scattering coefficient (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

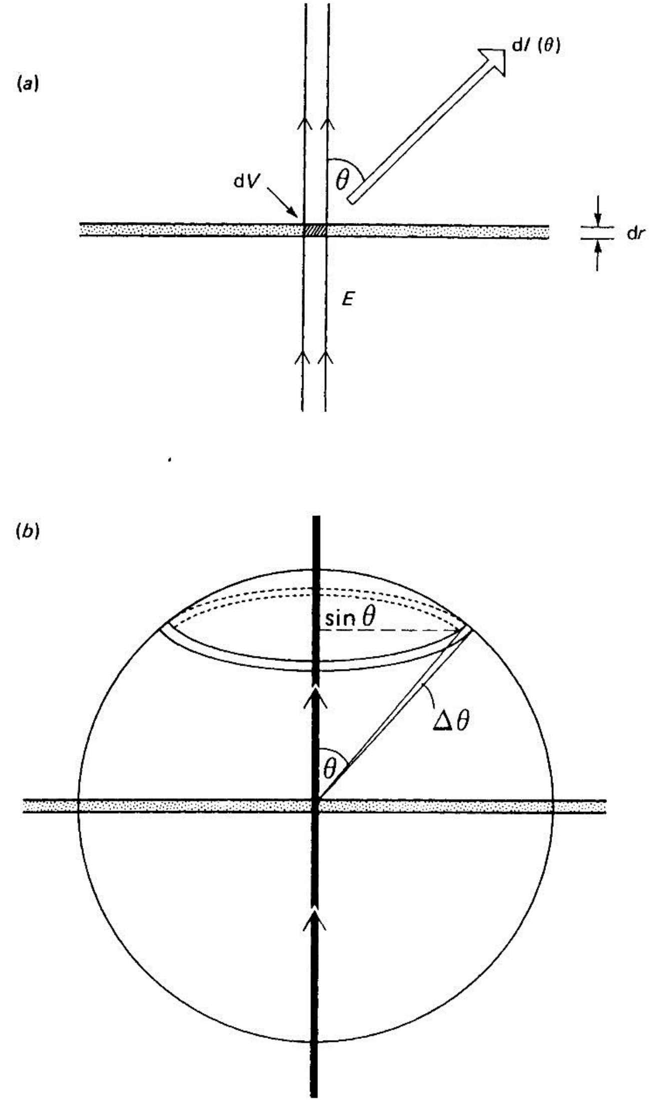


Fig. 1.5. The geometrical relations underlying the volume scattering function. (*a*) A parallel light beam of irradiance E and cross-sectional area $\mathrm{d}A$ passes through a thin layer of medium, thickness $\mathrm{d}r$. The illuminated element of volume is $\mathrm{d}V$. $\mathrm{d}I(\theta)$ is 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 $\sin\theta$ and width $\Delta\theta$, around the surface of the sphere. The area of the strip is $2\pi \sin\theta\Delta\theta$ which is equivalent to the solid angle (in steradians) corresponding to the angular interval $\Delta\theta$.

Volume Scattering Function (VSF)

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

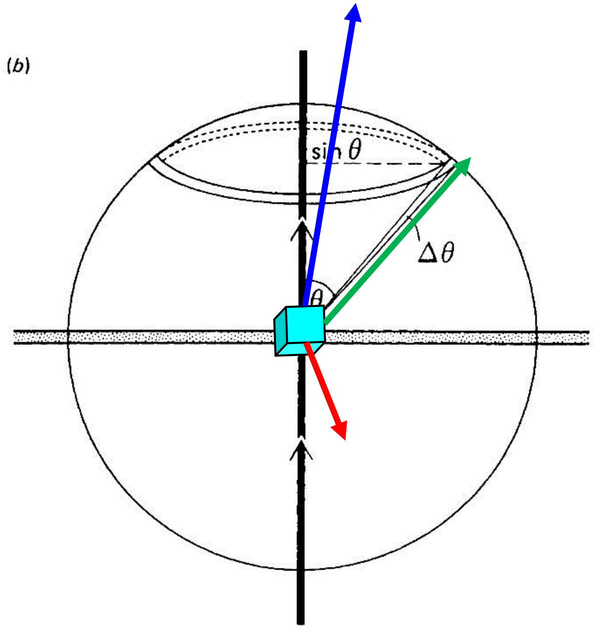
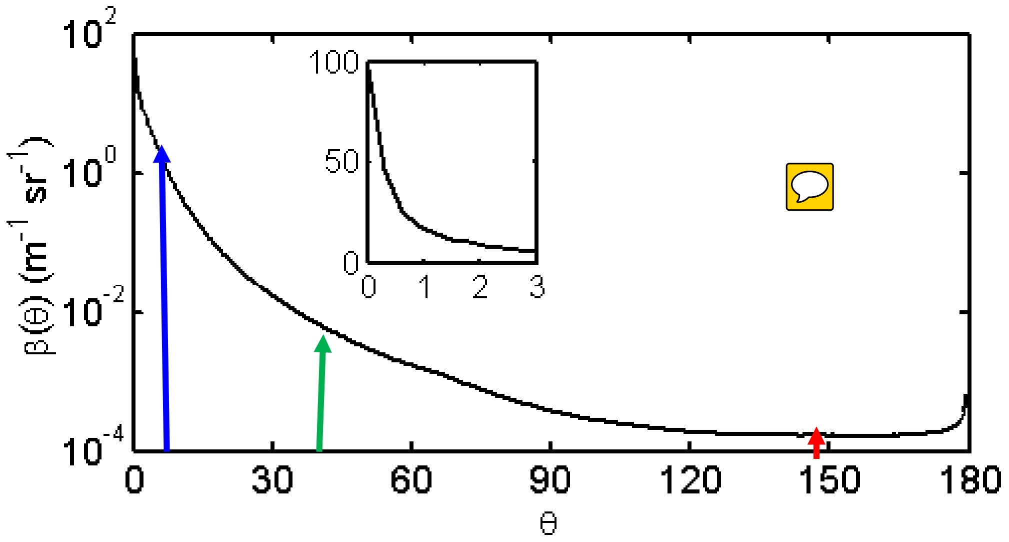


Fig. 1.5. The geometrical relations underlying the volume scattering function. (*a*) A parallel light beam of irradiance *E* and cross-sectional area d*A* passes through a thin layer of medium, thickness d*r*. The illuminated element of volume is d*V*. d*I*(*θ*) is the radiant intensity due to light 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 *θ* + Δ*θ* illuminates a circular strip, radius sin *θ* and width Δ*θ*, around the surface of the sphere. The area of the strip is 2*π* sin *θ*Δ*θ* which is equivalent to the solid angle (in steradians) corresponding to the angular interval Δ*θ*.



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

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

What is $d\Omega$?

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

Calculate Scattering, b, from the volume scattering function

this is what the open ocean looks like but not necessary other places

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

If there is azimuthal symmetry

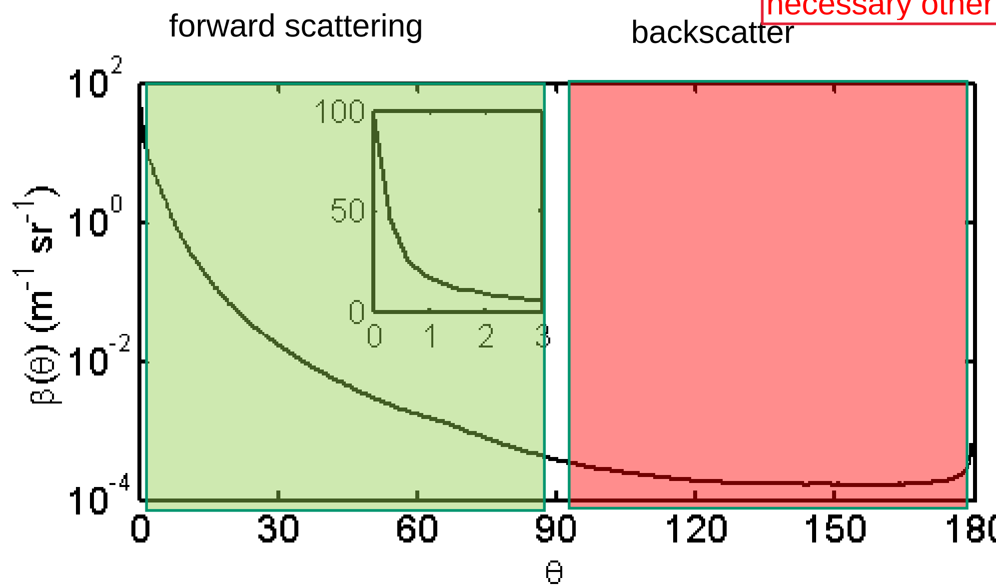
$$b = 2\pi \int_0^{\pi} \beta(\theta,\phi) \sin\theta\, \delta\theta$$

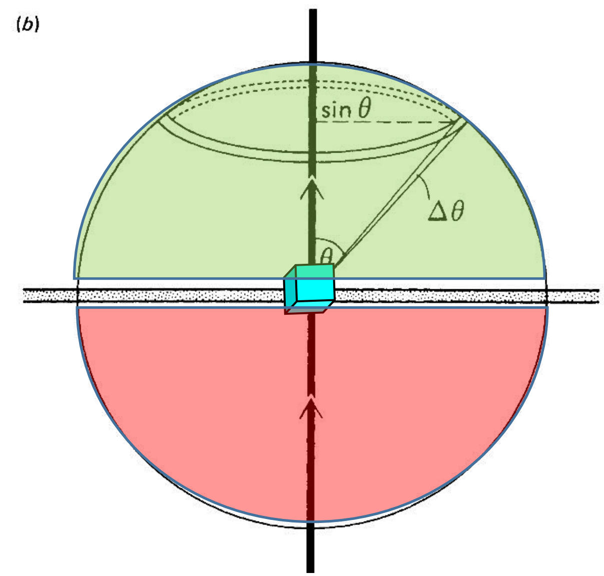
$$b_f = 2\pi \int_0^{\pi/2} \beta(\theta,\phi) \sin\theta\, \delta\theta$$

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

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

These are spectral!



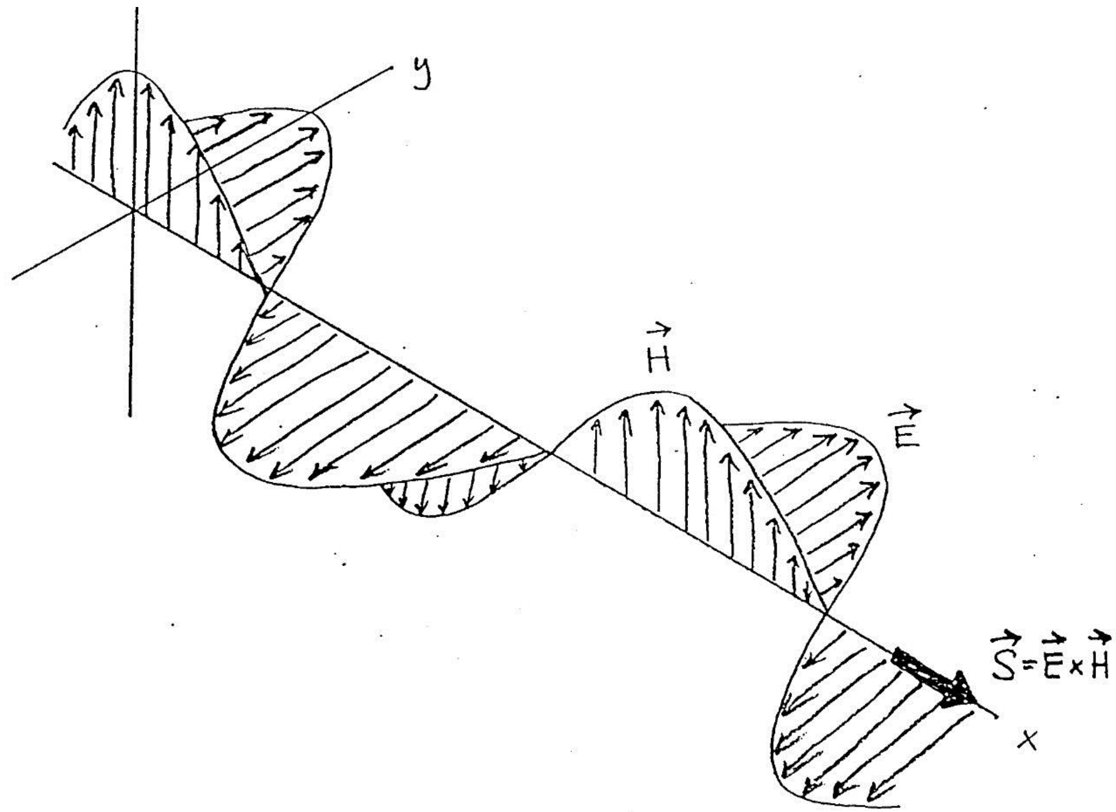


Particle parameters that influence scattering

- Concentration zero order source of variability
- Diameter : wavelength not absolute size, but size relative to the size of the wavelenth
- refractive index relative to surrounding medium
- absorption of radiation through particle
- Particle shape area we know the least about

Electromagnetic Radiation

- Oscillating magnetic and electric fields
- Perpendicular to direction of propagation
- May be polarized



Interactions between EM radiation and particles

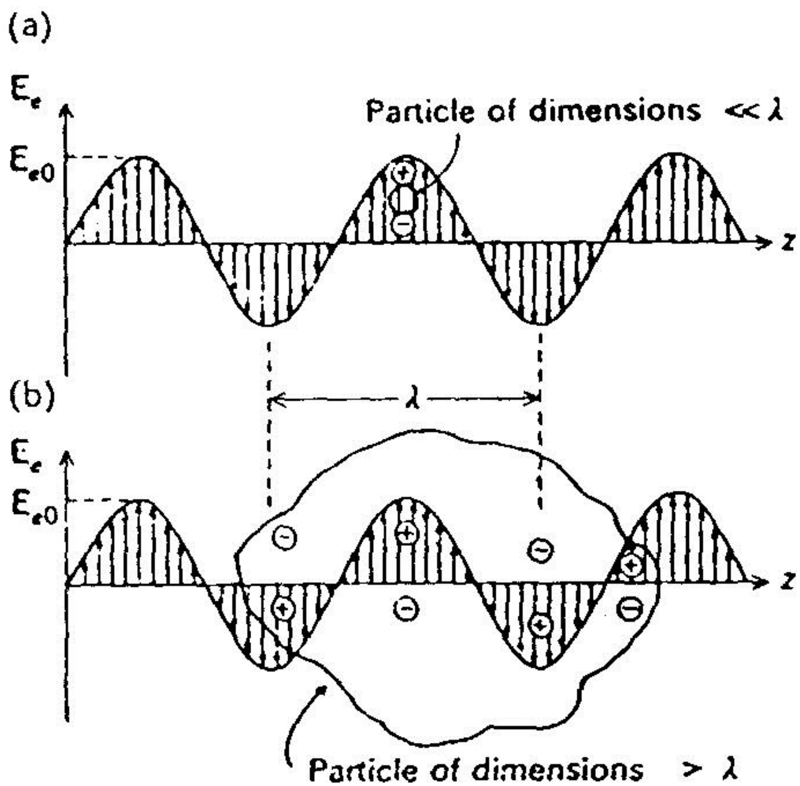
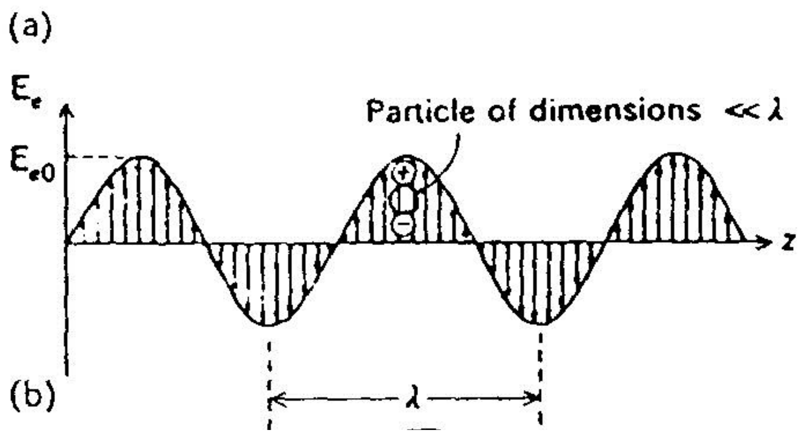


Fig. 4.3.2. Dimensions of scattering centres compared with the electrical field distribution of the electromagnetic wave.

Consider the relationship between particle size and EMR wavelength

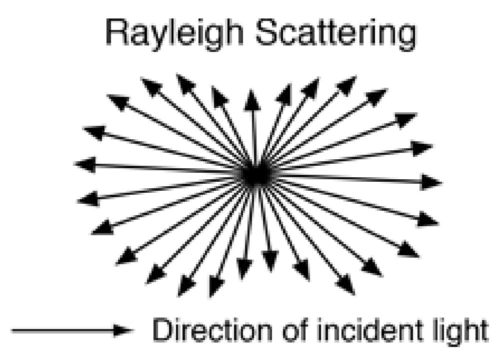
Interaction of light with small particles: Rayleigh scatterers

- d<<λ
- Energy from propagating EM wave sets up oscillating dipole in particle



Small Particles: Rayleigh scatterers

- $d << \lambda$
- 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

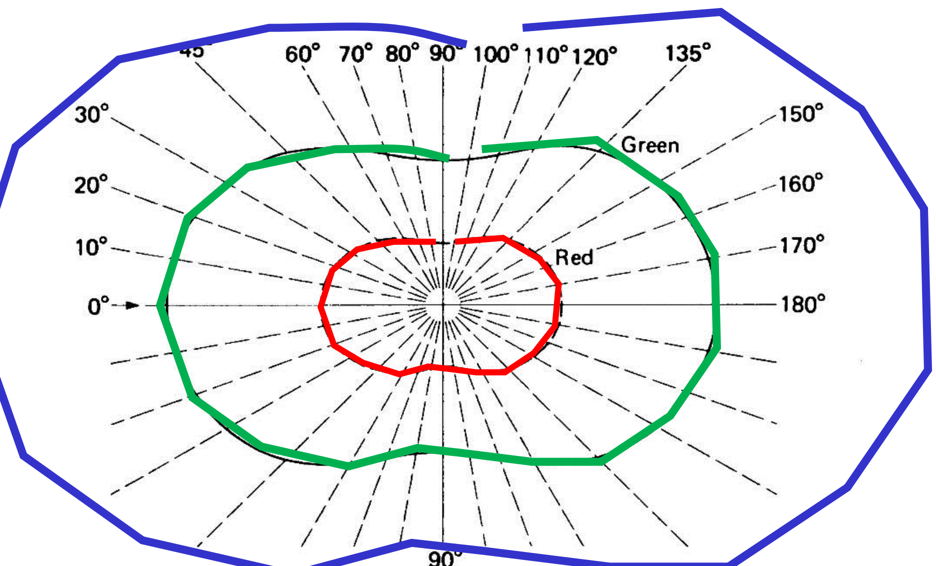
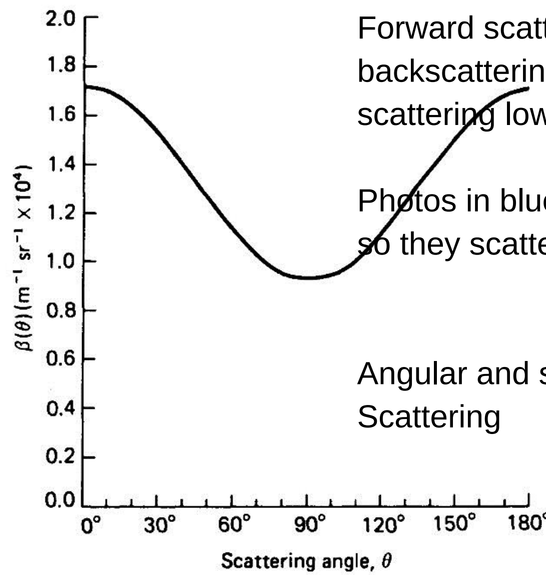


Fig. 2.2. Polar plot of intensity as a function of scattering angle for small particles ($r \simeq 0.025$ μm) for green ($\lambda \simeq 0.5$ μm) and red ($\lambda \simeq 0.7$ μm) light. (By permission, from *Solar radiation*, N. Robinson, Elsevier, Amsterdam, 1966.)



Forward scattering high, backscattering symmetrical, side scattering low (VSF)

Photos in blue have higher energy so they scatter more

Angular and spectral distribution of Scattering

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).

Interaction of light with large particles

particle size

- d>> λ
- EMR induces multiple dipole oscillations
- Some EMR penetrates particle

multiple processes
- can diffract,
absorb,

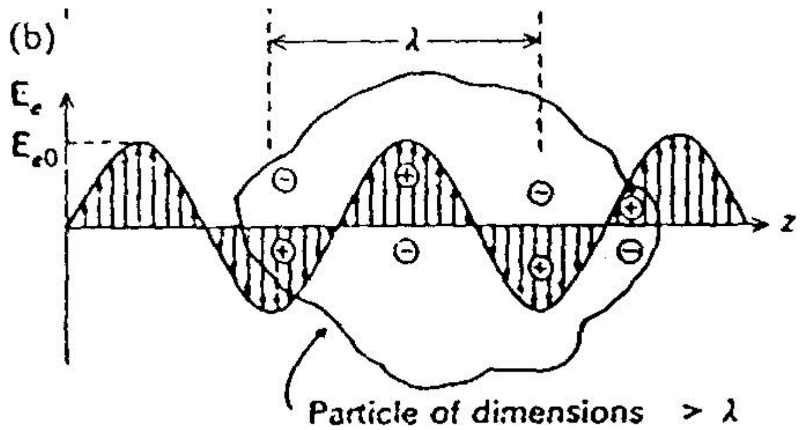
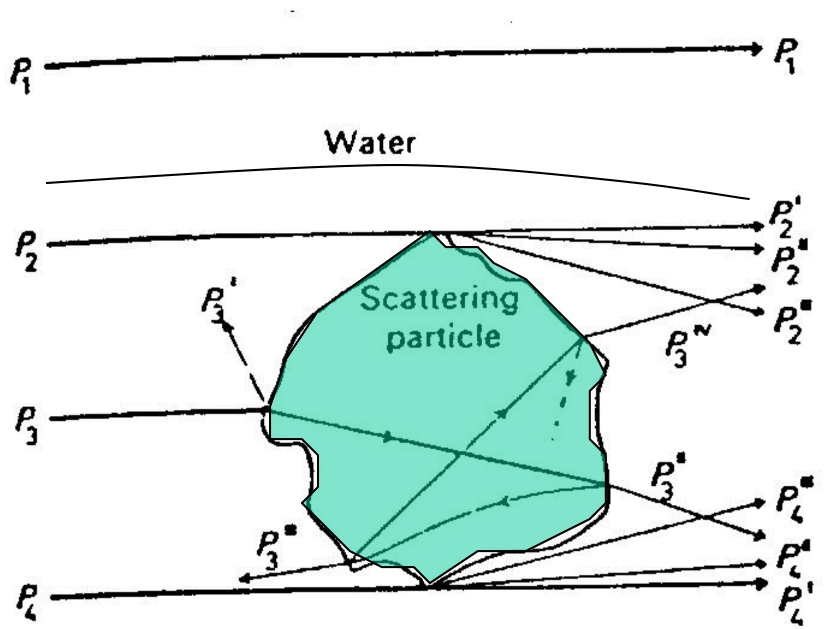


Fig. 4.3.2. Dimensions of scattering centres compared with the electrical field distribution of the electromagnetic wave.

Large particle scattering



Diffraction bends around particle
Refraction bends in particle, refract and exit
Reflection

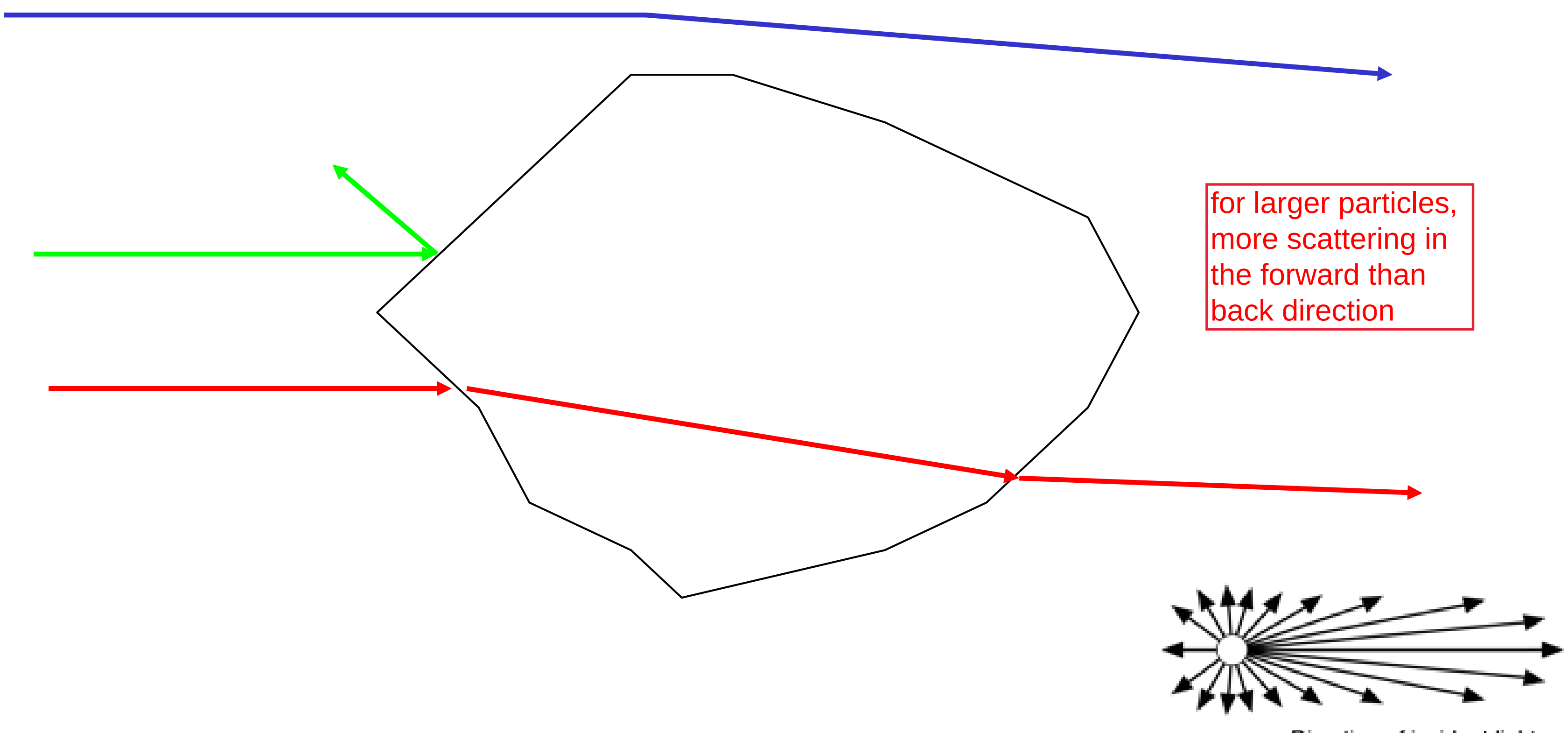
Fig. 4.3.1. A model of light scattering due to reflection, refraction and diffraction by large particles suspended in water. $P_1 - P_4$—incident rays; $P_2^{I} - P_2^{III}$, $P_4^{I} - P_4^{III}$—rays scattered owing to diffraction at the particle's edges; $P_3^{I} - P_3^{IV}$—rays scattered owing to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

Dera, Marine Physics

Large Particle Scattering

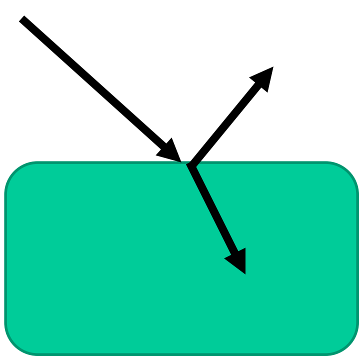
Three effects: refraction, reflection and diffraction

You can have more interaction between the waves because you have many dipoles oscillating. You can have constructive and destructive interference in large particles. You can have multiple paths of internal reflection in large particles

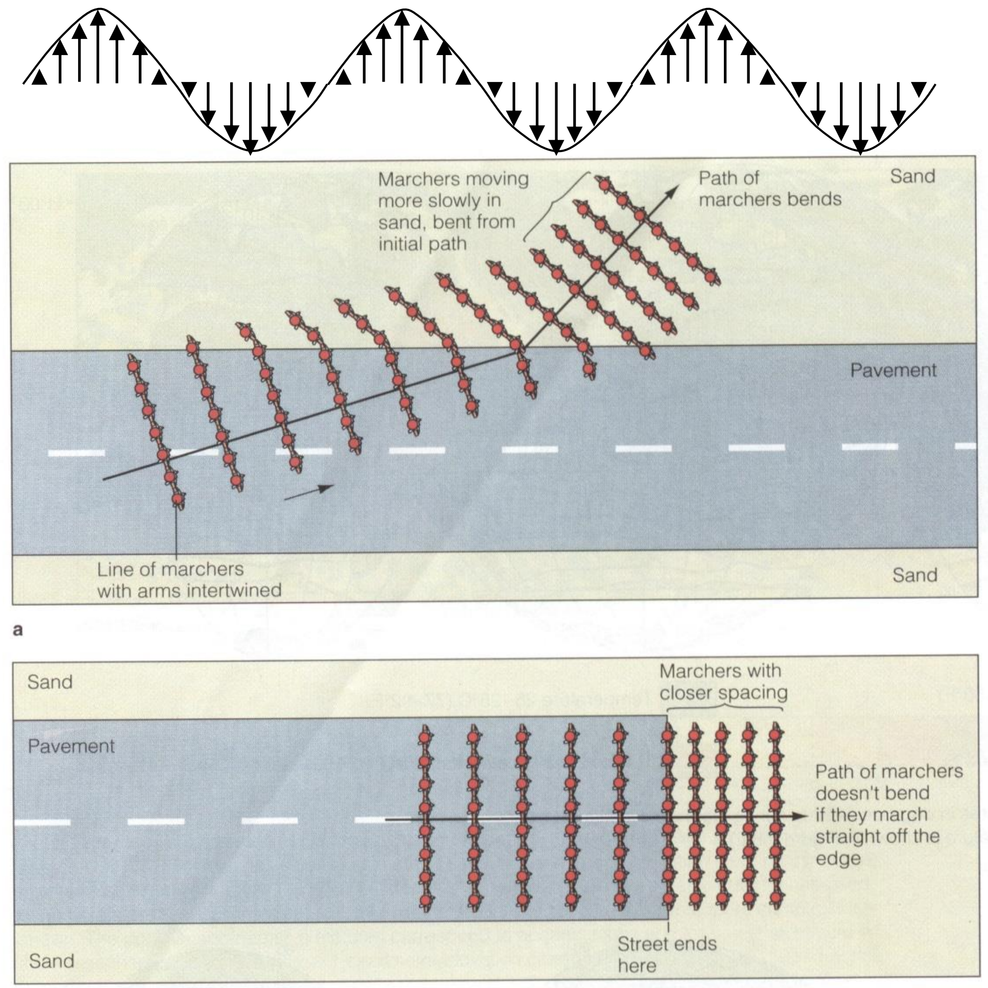


Fresnel's Law

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



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



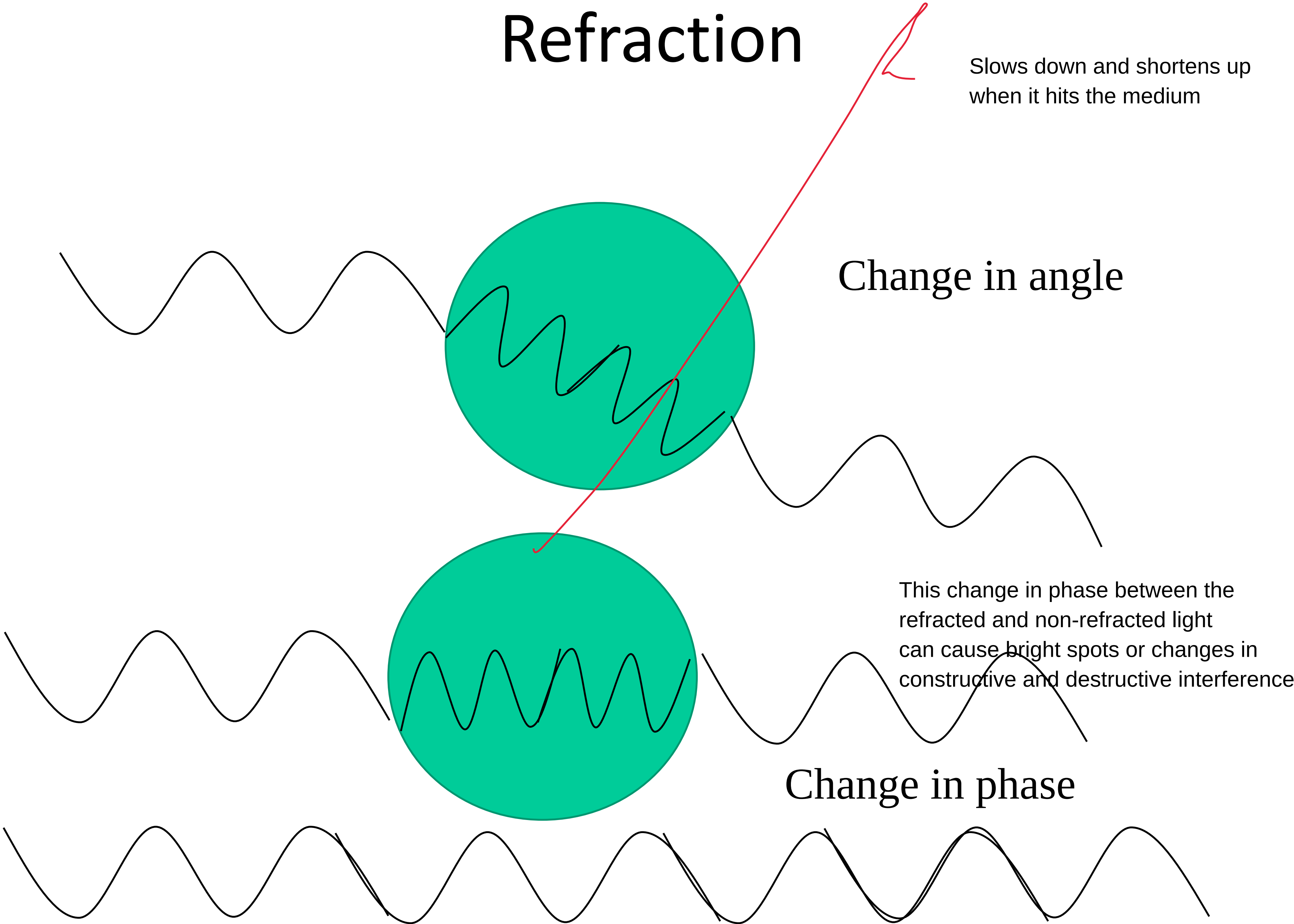
Refraction

speed in the water

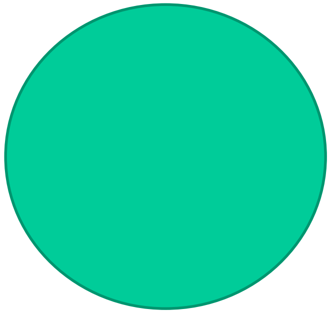
speed in the air

- As EMR crosses an interface (say from water to a particle) it will change celerity
- $$\lambda_{\text{medium}} = \lambda \frac{c_{\text{medium}}}{c} = \frac{\lambda}{n}$$
- If it slows down, the wavelength shortens up
- Thus it will bend (refract)
- Once it exits the particle, it will return to its original celerity and wavelength, but likely at a different angle and or phase than original

Refraction

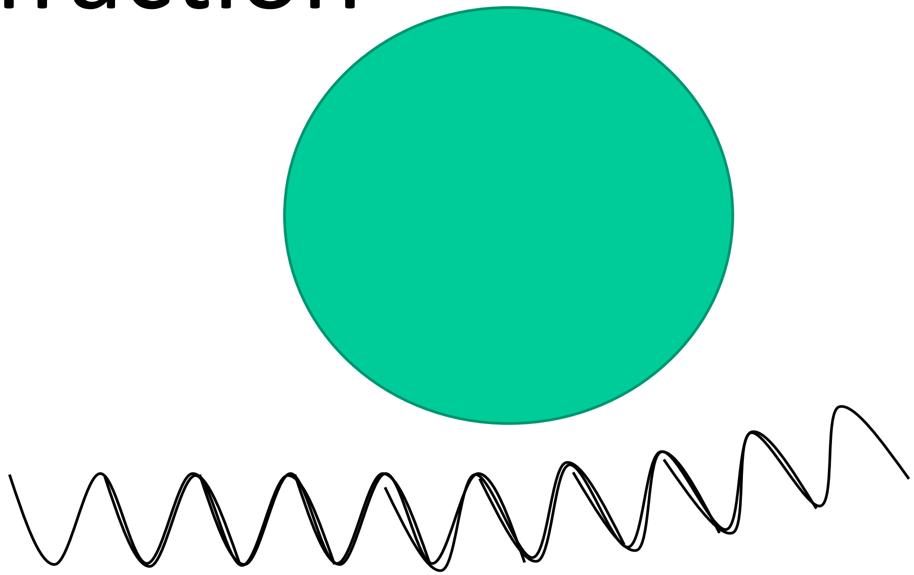

Slows down and shortens up when it hits the medium
Change in angle
This change in phase between the refracted and non-refracted light can cause bright spots or changes in constructive and destructive interference
Change in phase

Optical cross section



- Optical cross section for scattering?
- If every photon incident on the particle scatters → geometric cross section
- Optical/geometric cross section =1
- What about for absorbing particle?

Diffraction



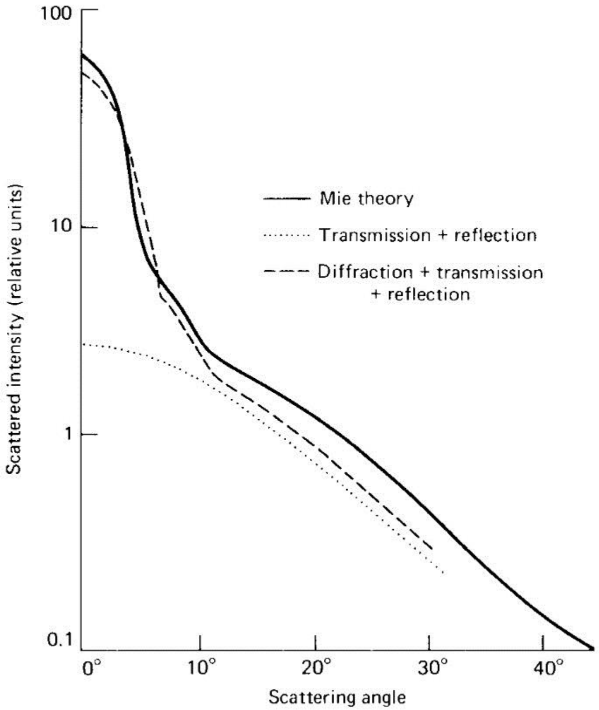
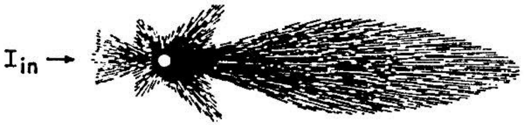
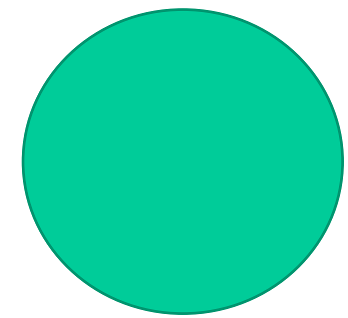


Fig. 4.1. Angular distribution of scattered intensity from transparent spheres calculated from Mie theory (Ashley & Cobb, 1958) or on the basis of transmission and reflection, or diffraction, transmission and reflection (Hodkinson & Greenleaves, 1963). The particles have a refractive index (relative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



Optical cross section

- Optical cross section for scattering if you include diffraction?
- Diffraction can occur 2 radii away
- Optical/geometric crossection = 2
- What about for absorbing particle?



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

Rectangles/
cylinders

Circles/
spheres

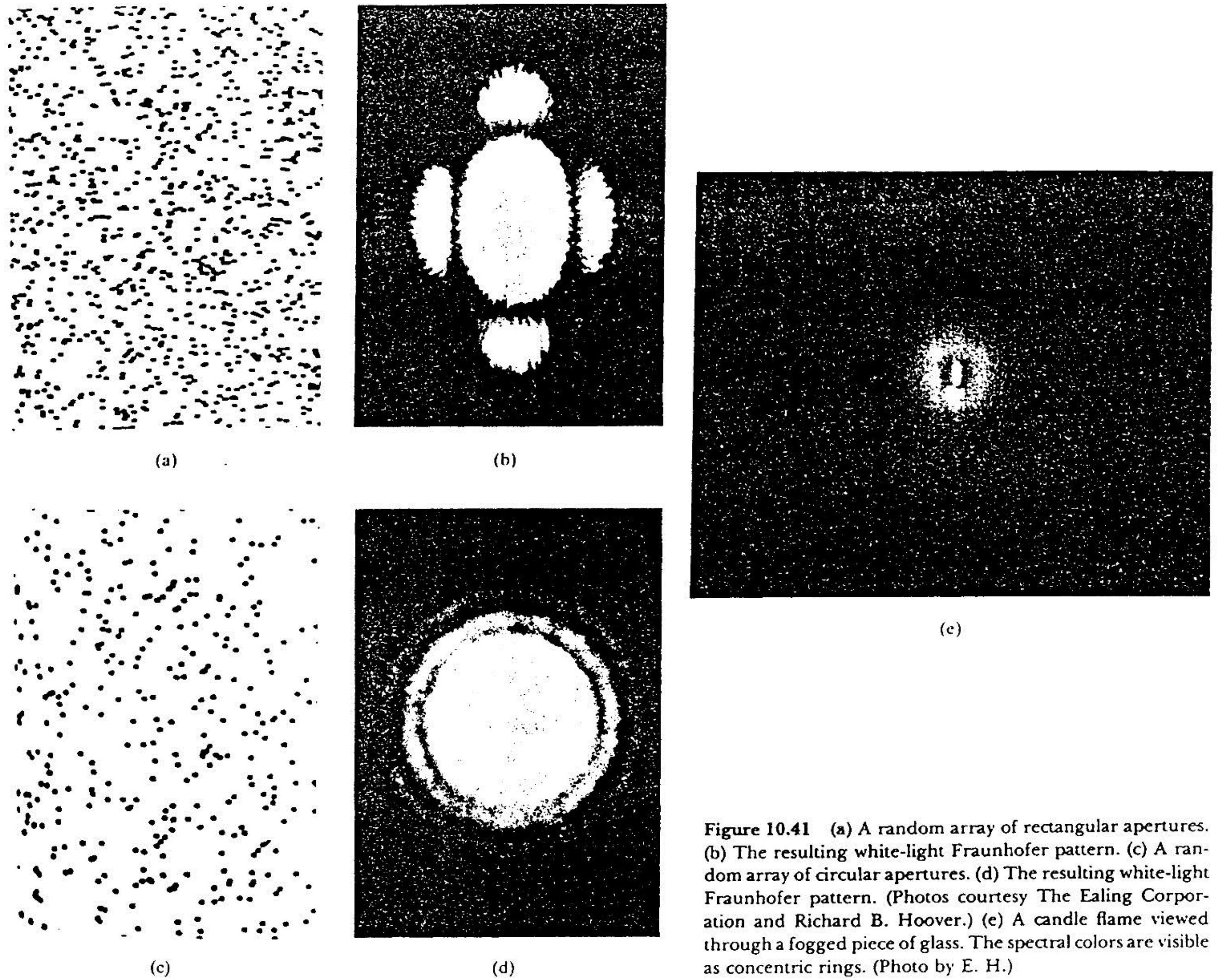
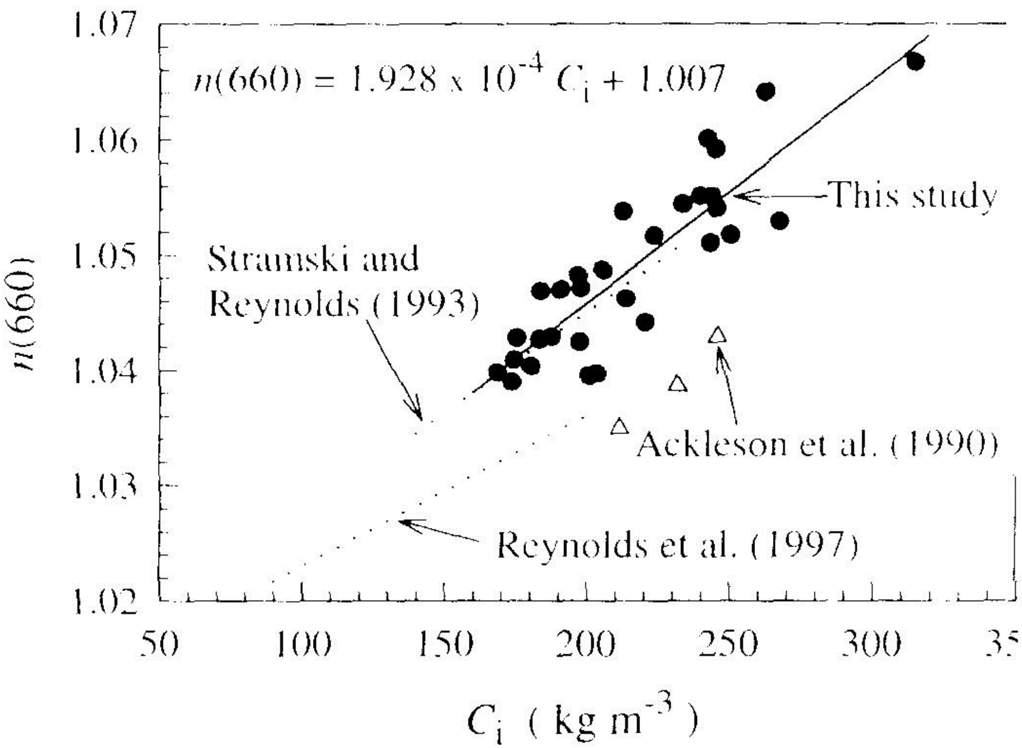


Figure 10.41 (a) A random array of rectangular apertures. (b) The resulting white-light Fraunhofer pattern. (c) A random array of circular apertures. (d) The resulting white-light Fraunhofer pattern. (Photos courtesy The Ealing Corporation and Richard B. Hoover.) (e) A candle flame viewed through a fogged 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.

carbon rich particles scatter light more effectively

What influences a particle's refractive index?

Phyto are weakly refractive (<1% backscattering)

sediment is highly refractive

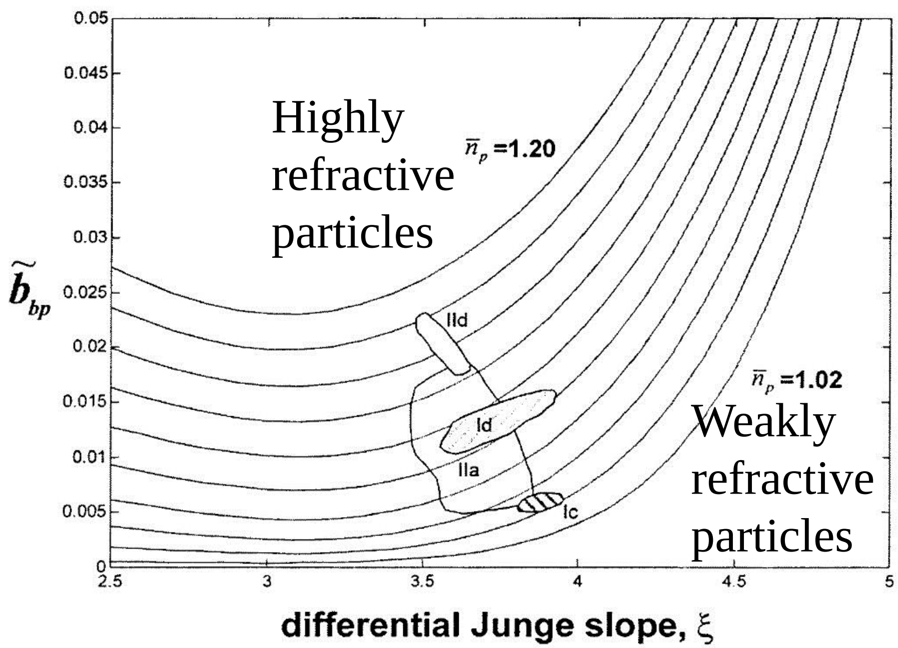


Figure 9. Estimated bulk refractive indices $\hat{n}_p(\tilde{b}_{bp}, \gamma)$ for four specific regions of the water column from the Gulf of California: (1) the case I stations below 100 m (Id), (2) the case I stations at the chlorophyll maximum (Ic), (3) the case II stations south of the sill (IIa), 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.

Mineral particles are highly refractive

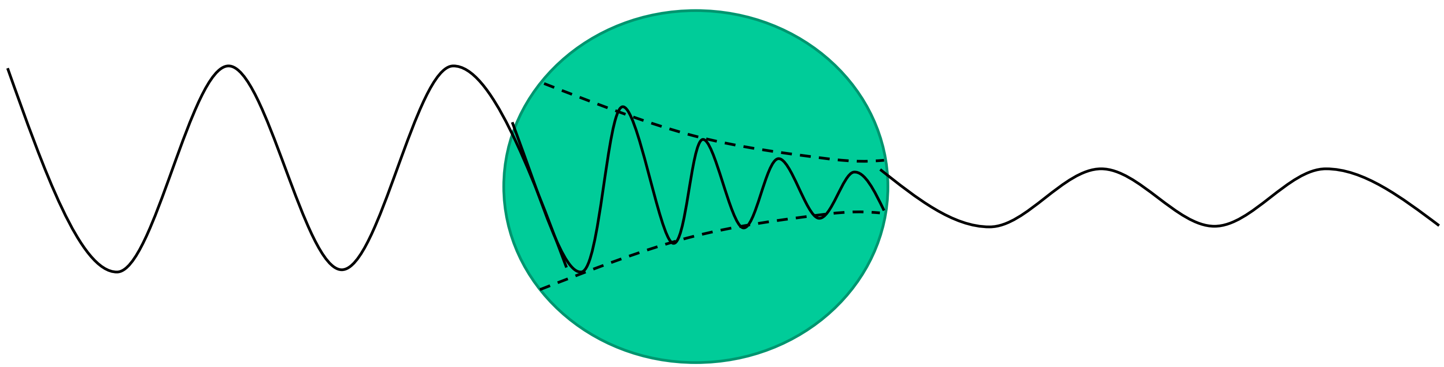
Chlorophyll maximum - weekly refractive

Middle section (detrital, somewhat refractive)

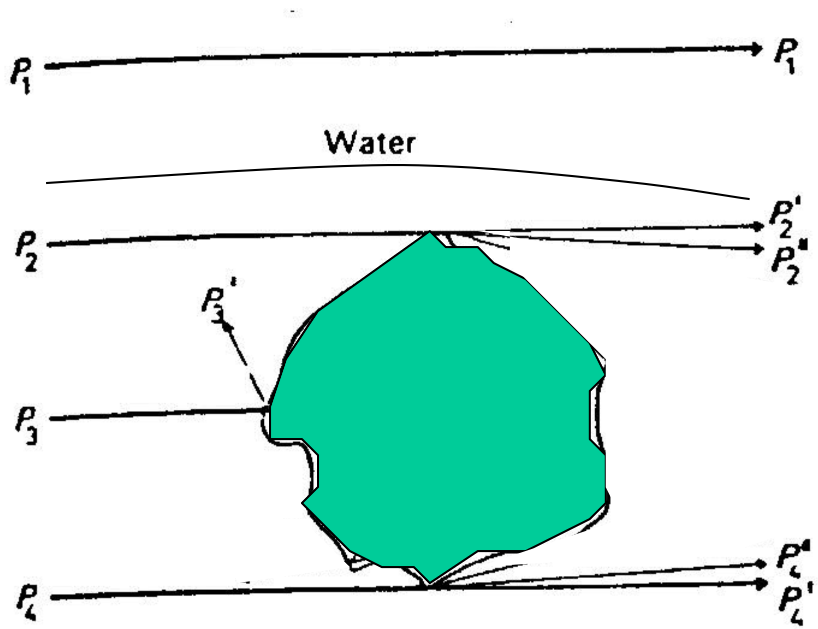
Effect of absorption

- 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

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.

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

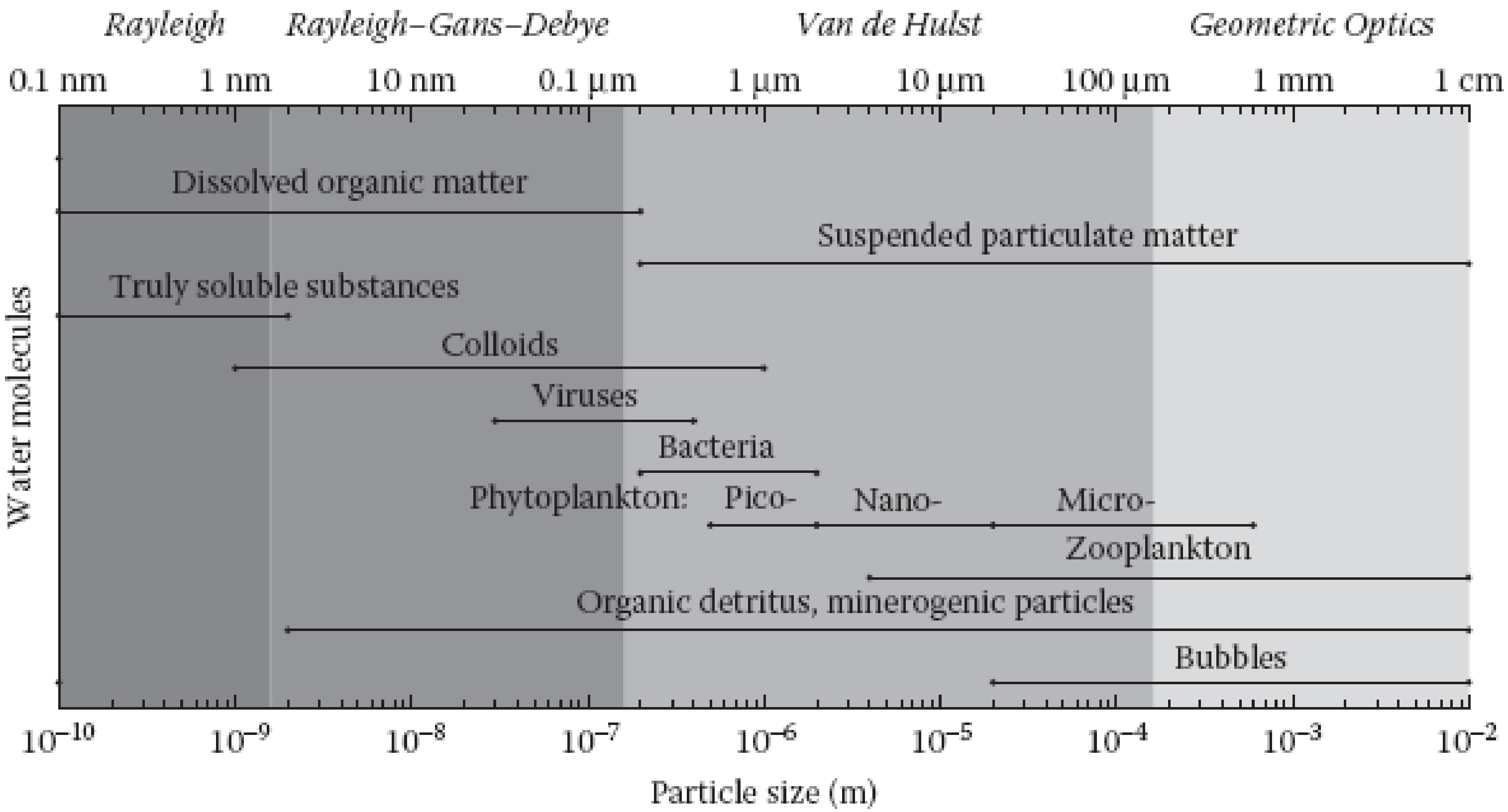
- Water molecules
- Dissolved matter
  - Inorganic salts
  - Organic matter (CDOM, colloids)

scattering by CDOM active area of research

- Particles
  - Organic
    - Cells and organisms (viruses, bacteria, phytoplankton, to…)
    - Detrital aggregates
  - Inorganic
    - Sediments
    - Minerals
    - Air bubbles

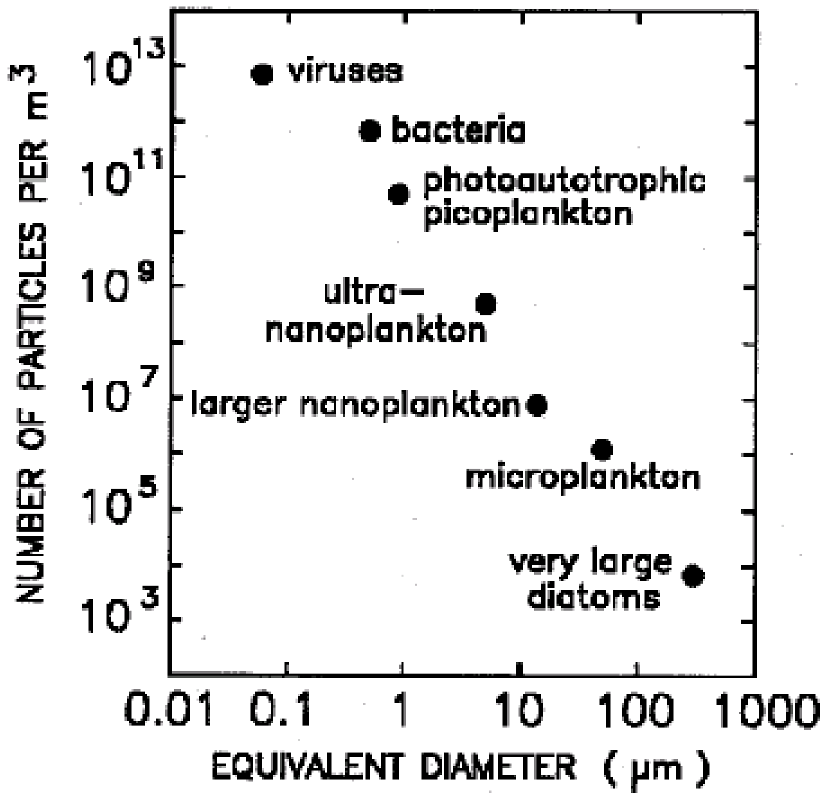
Size matters

Applicable scattering theory



Particle Size Range

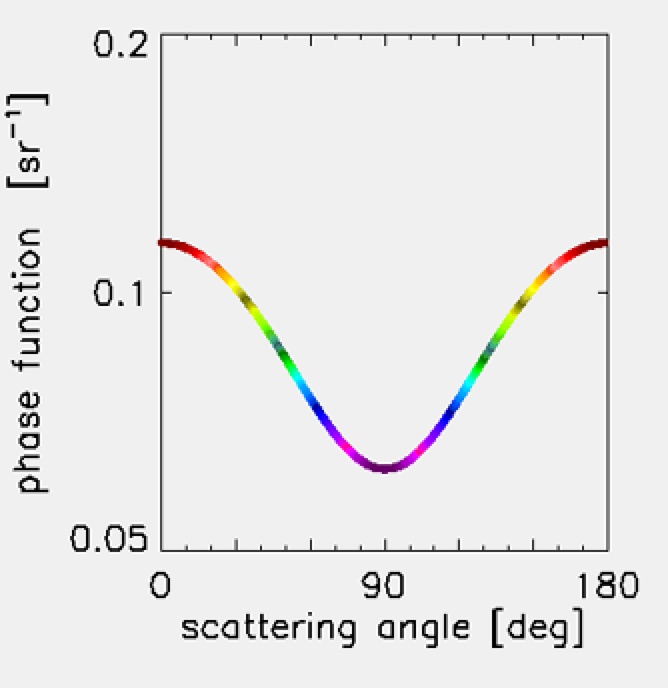
Particle size in the ocean

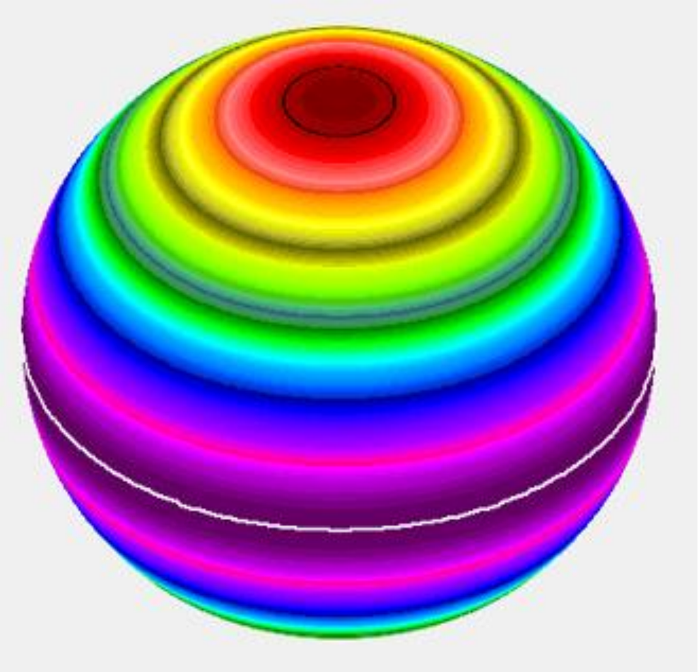


Stramski and Kiefer 1991

Scattering in the ocean: water molecules

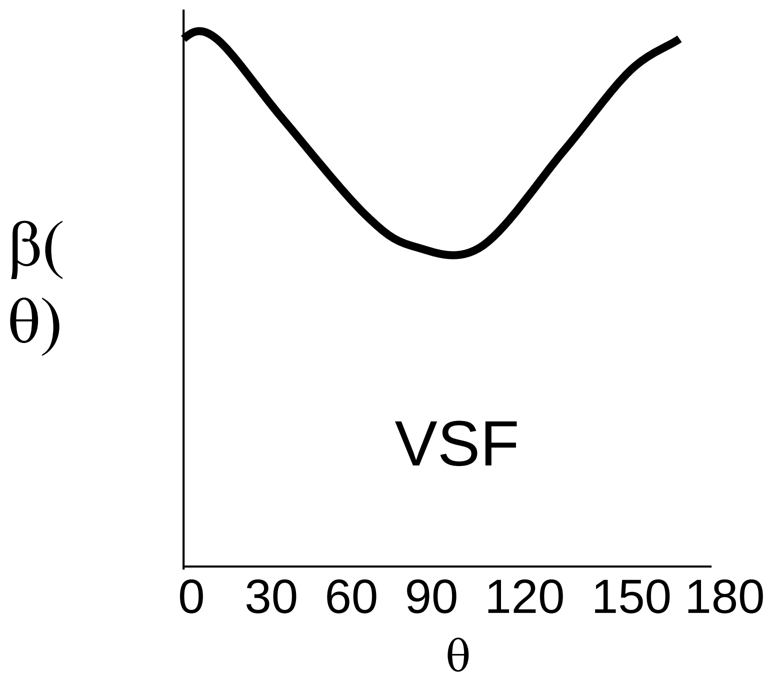
Rayleigh Scattering



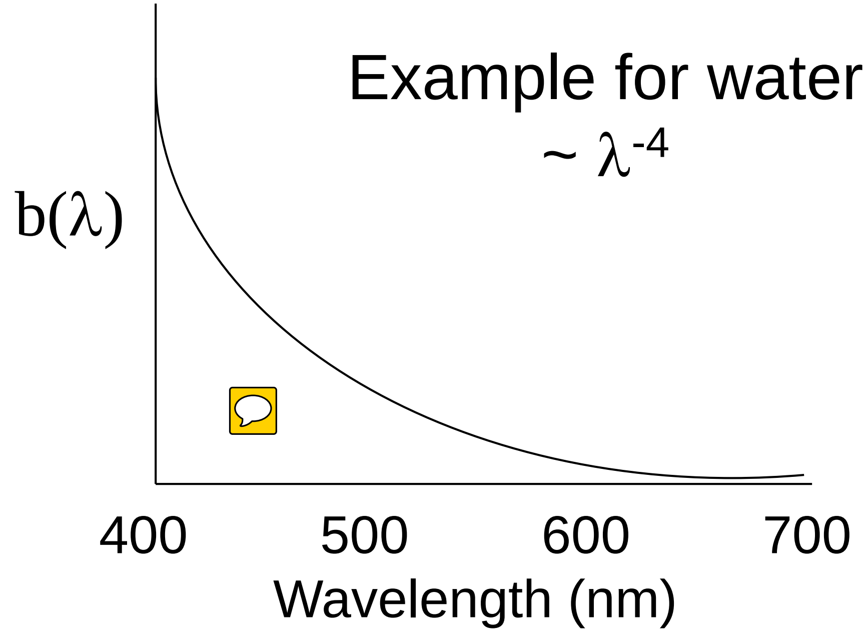


http://www.oceanopticsbook.info/view/overview_of_optical_oceanography/visualizing_vsfs

Small Particle Scattering follows Rayleigh Theory

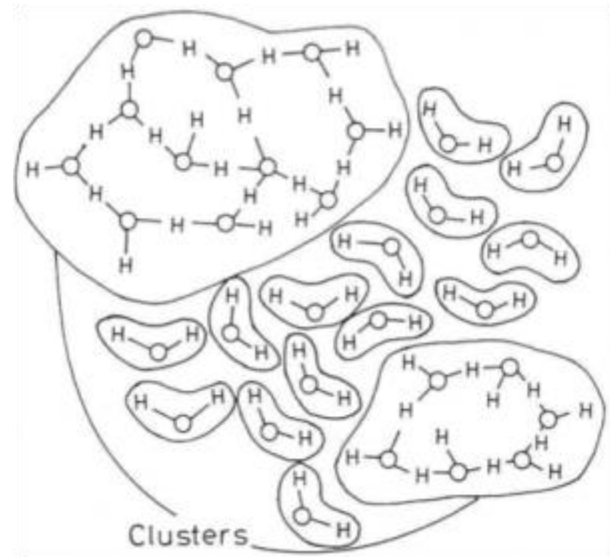


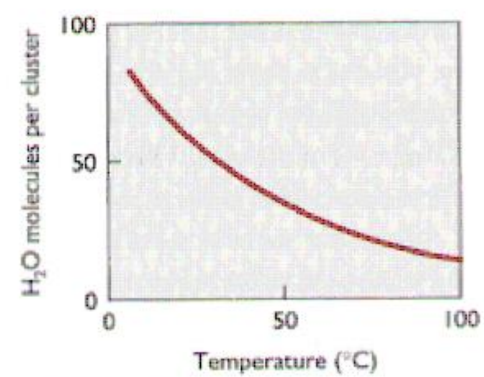
small particles - high scattering in blue and low in the red



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)



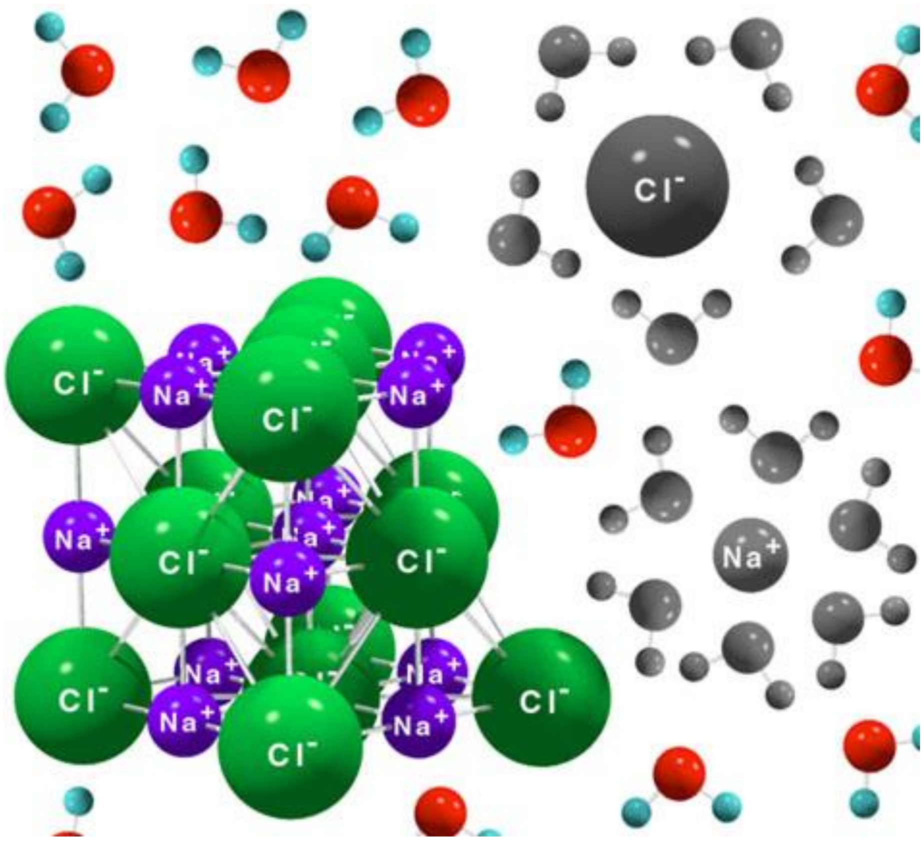


(e) SIZE OF WATER CLUSTERS

more salt = more scattering

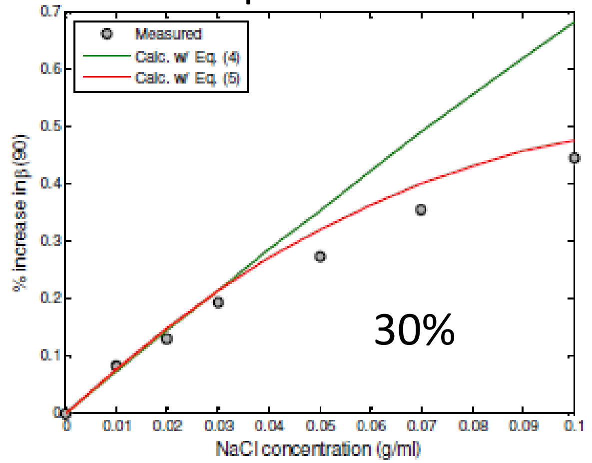
Scattering in the ocean: dissolved salts

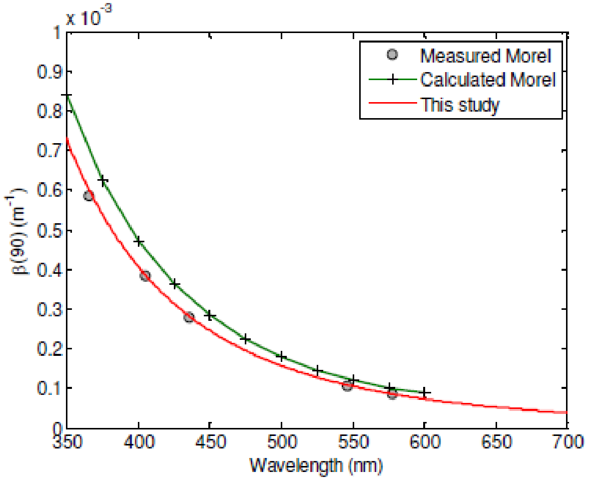
Increased b relative to pure water



Model of salt dissociation

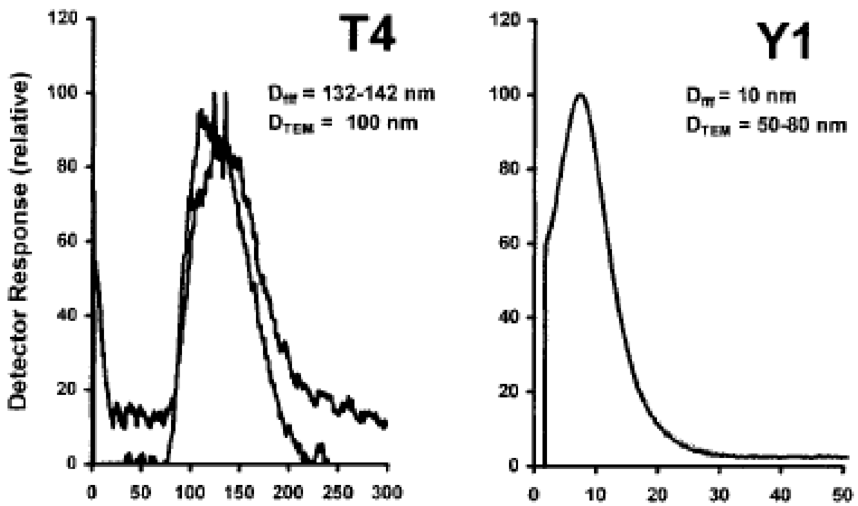
http://www.chemistry.wustl.edu/~edudev/LabTutorials/Water/PublicWaterSupply/PublicWaterSupply.html

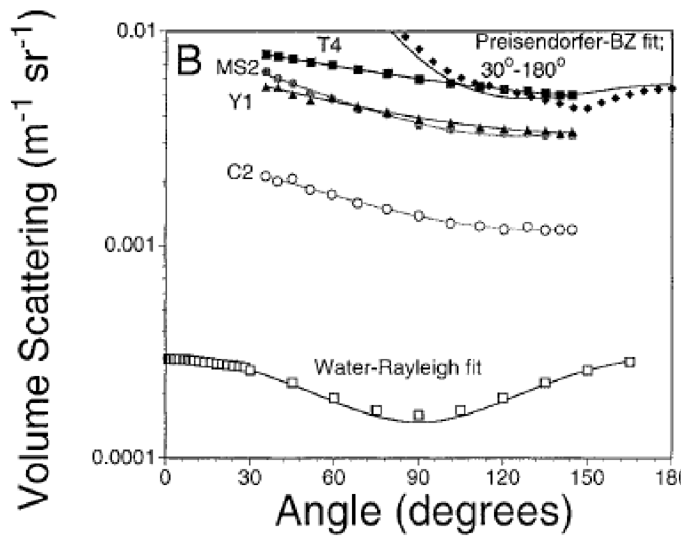


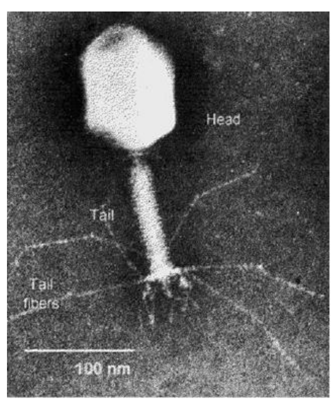


Zhang et al 2009 OptExp

Scattering in the ocean: marine viruses

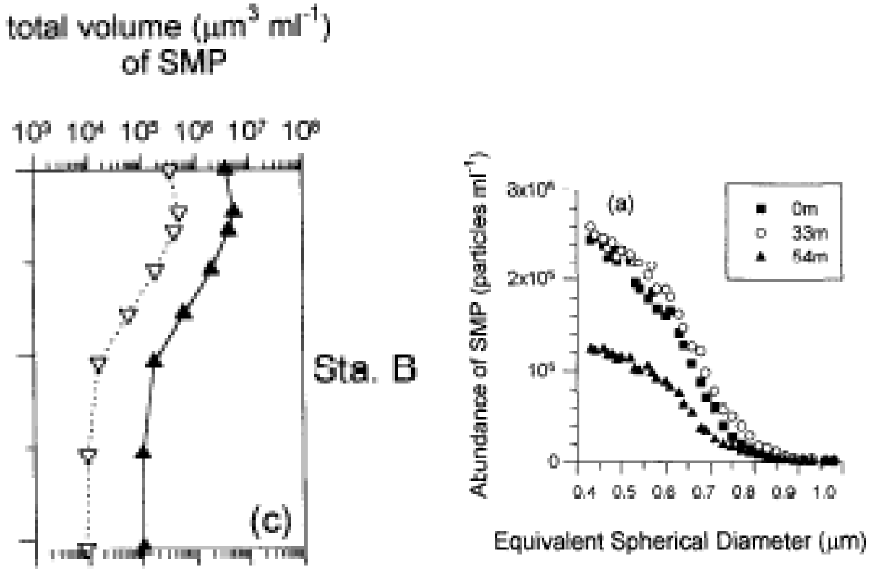




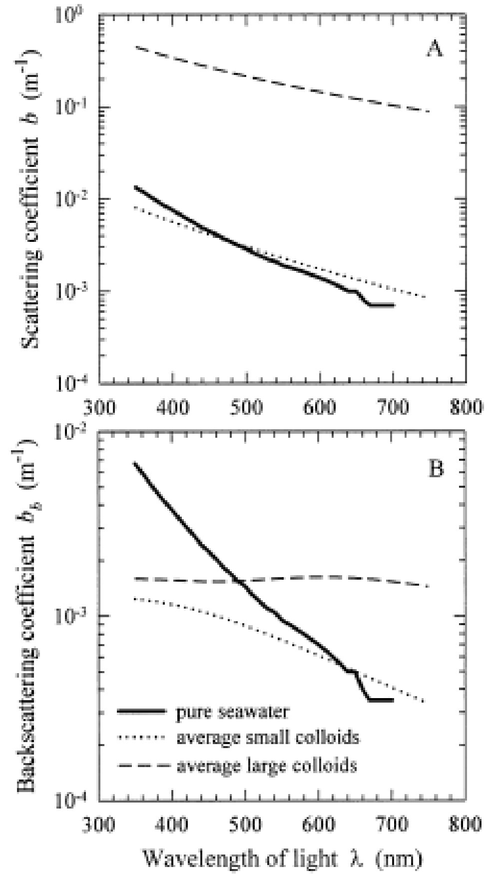


Balch et al. 1999

Scattering in the ocean: submicron particles (~colloids)



Yamasaki et al 1998

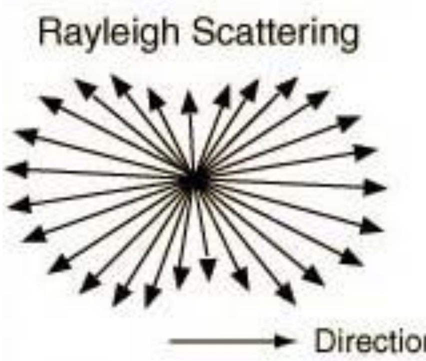


Stramski and Wozniak 2005

From Emmanuel Boss

Scattering by CDOM:

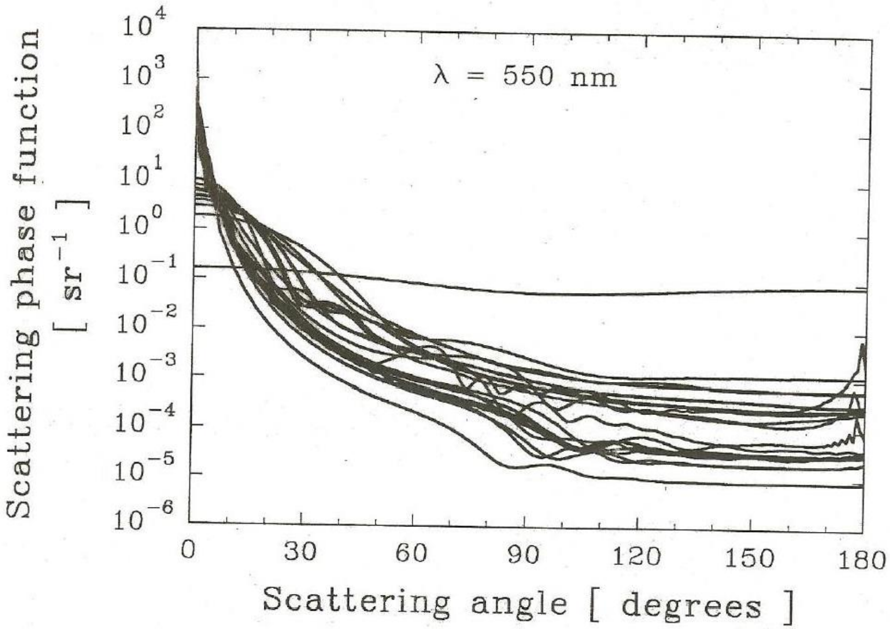
Scattering by molecules whose $D \ll \lambda$. Rayleigh scattering:

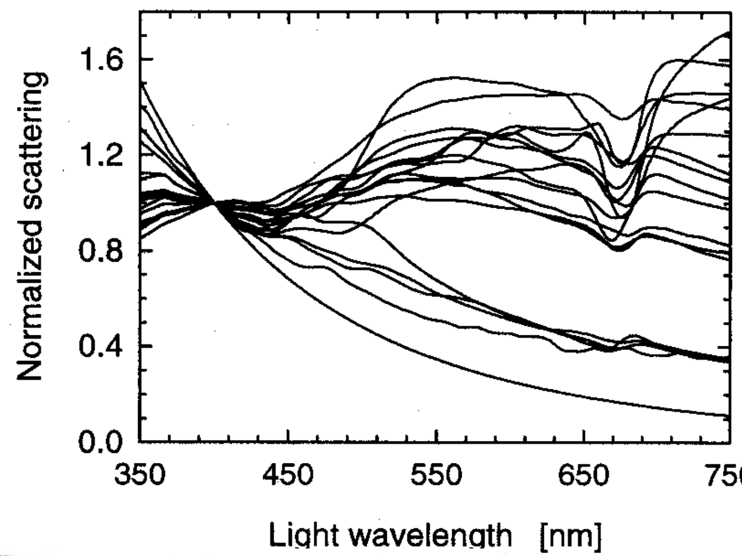


$$b(\lambda) \propto \lambda^{-4} \quad \beta(\theta) \propto \left(1 + \cos^2(\theta)\right)$$

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





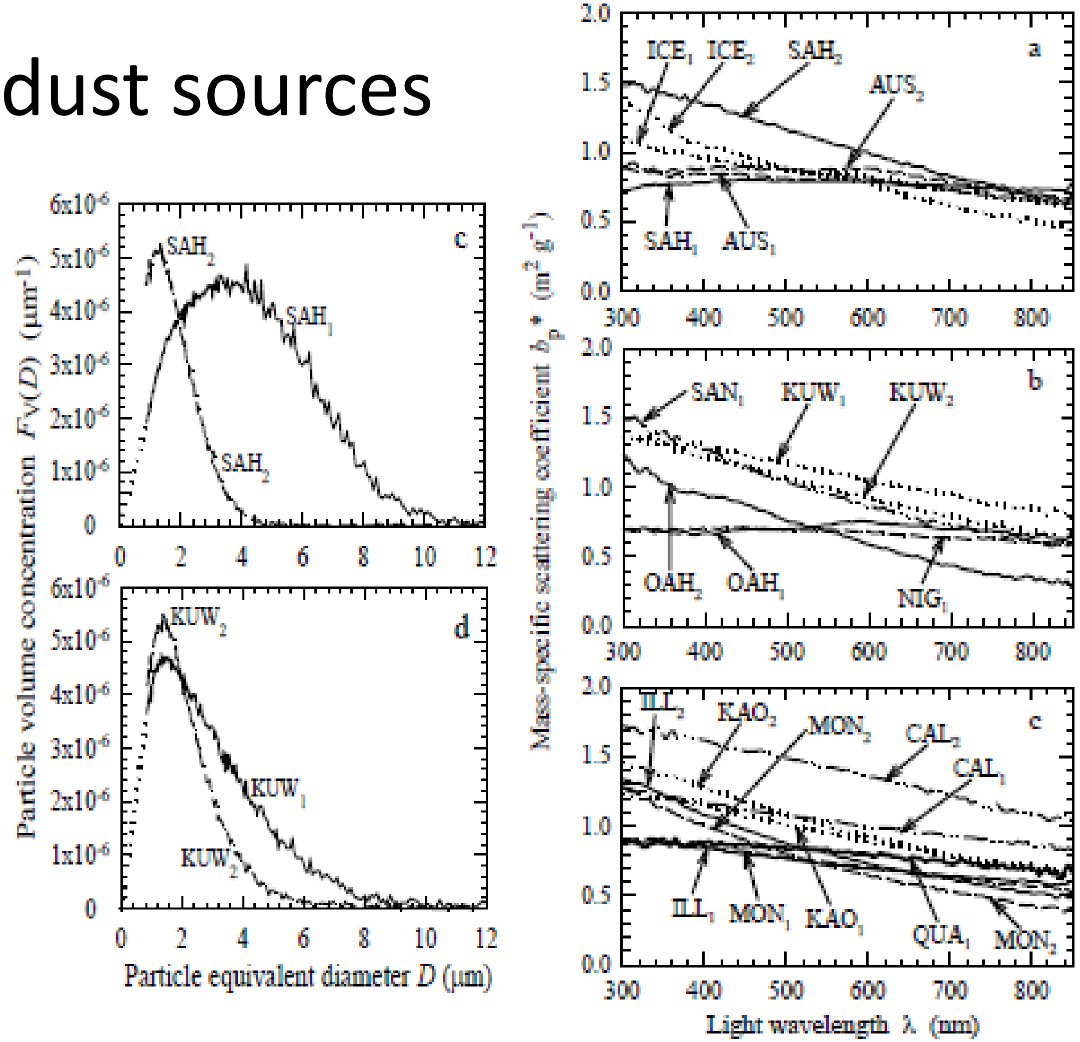
Viruses
Heterotrophic bacteria
Prochlorococcus (2 strains)
Synechococcus (Cyanophyceae, 5 strains)
Anacystis marina (Cyanophyceae)
Pavlova pinguis (Haptophyceae)
Thalassiosira pseudonana (Bacillariophyceae)
Pavlova lutheri (Haptophyceae)
Isochrysis galbana (Haptophyceae)
Emiliania hyxleyi (Haptophyceae)
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

large particles don't have a spectral dependence

Scattering in the ocean: inorganic minerals

- Terrestrial dust sources



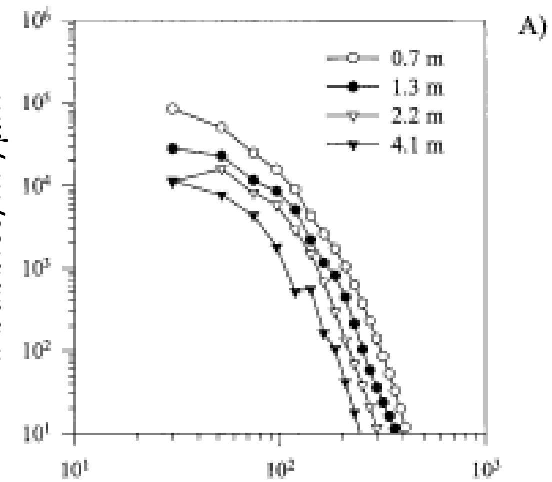
Stramski et al. 2007

Scattering in the ocean: air bubbles

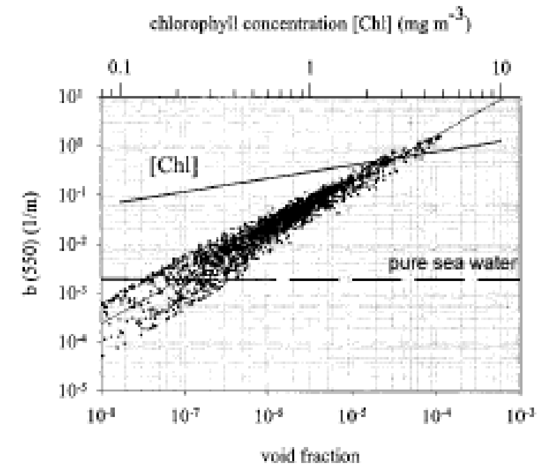
Terrill et al. 2001

- Acoustics
  - Size
  - distribution
- Modeled b

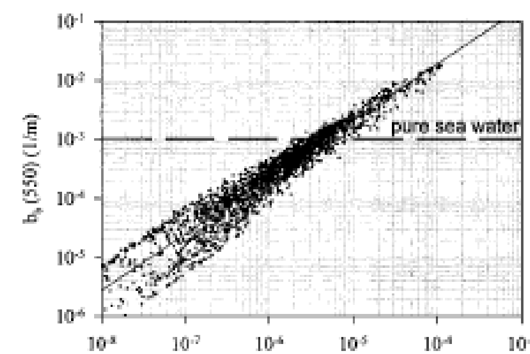
bubbles/m³/µm



Radius (µm)

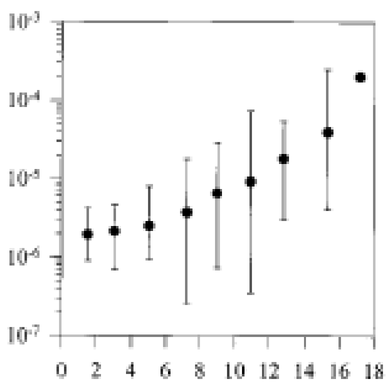


B)



Void fraction

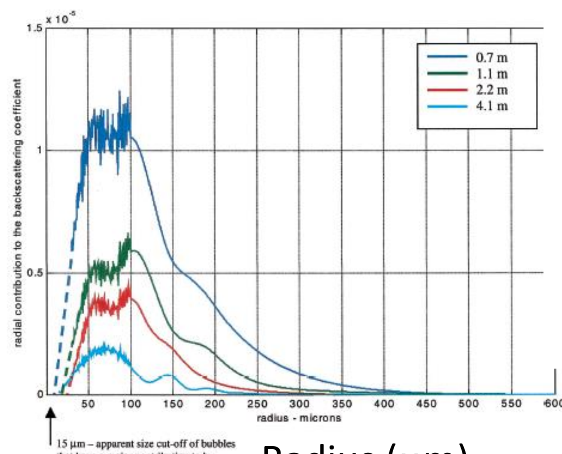
Void fraction



Wind speed (m/s)

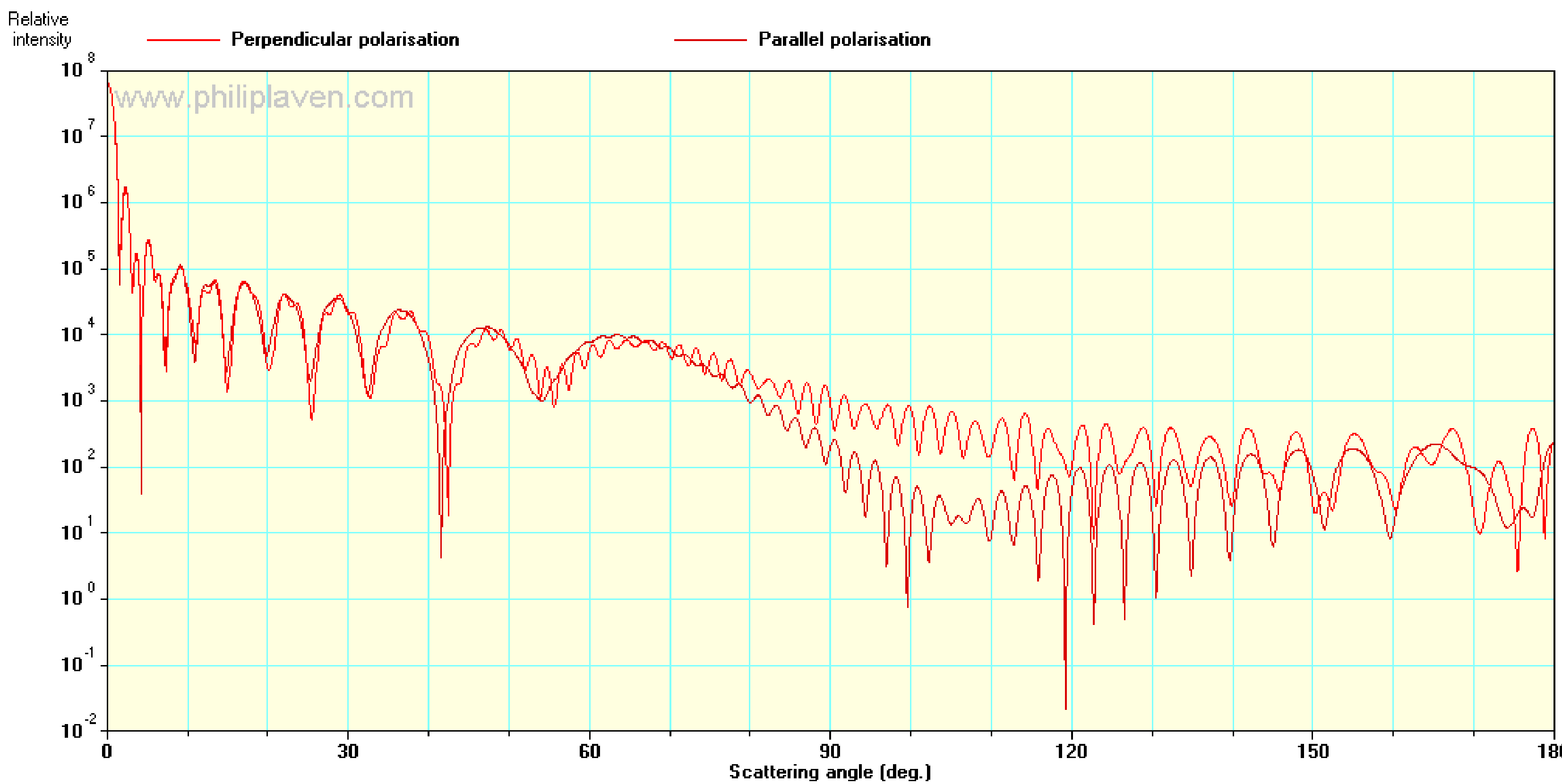
Terrill et al. 1998

Contribution to bb



Radius (µm)

Scattering in the ocean: air bubbles

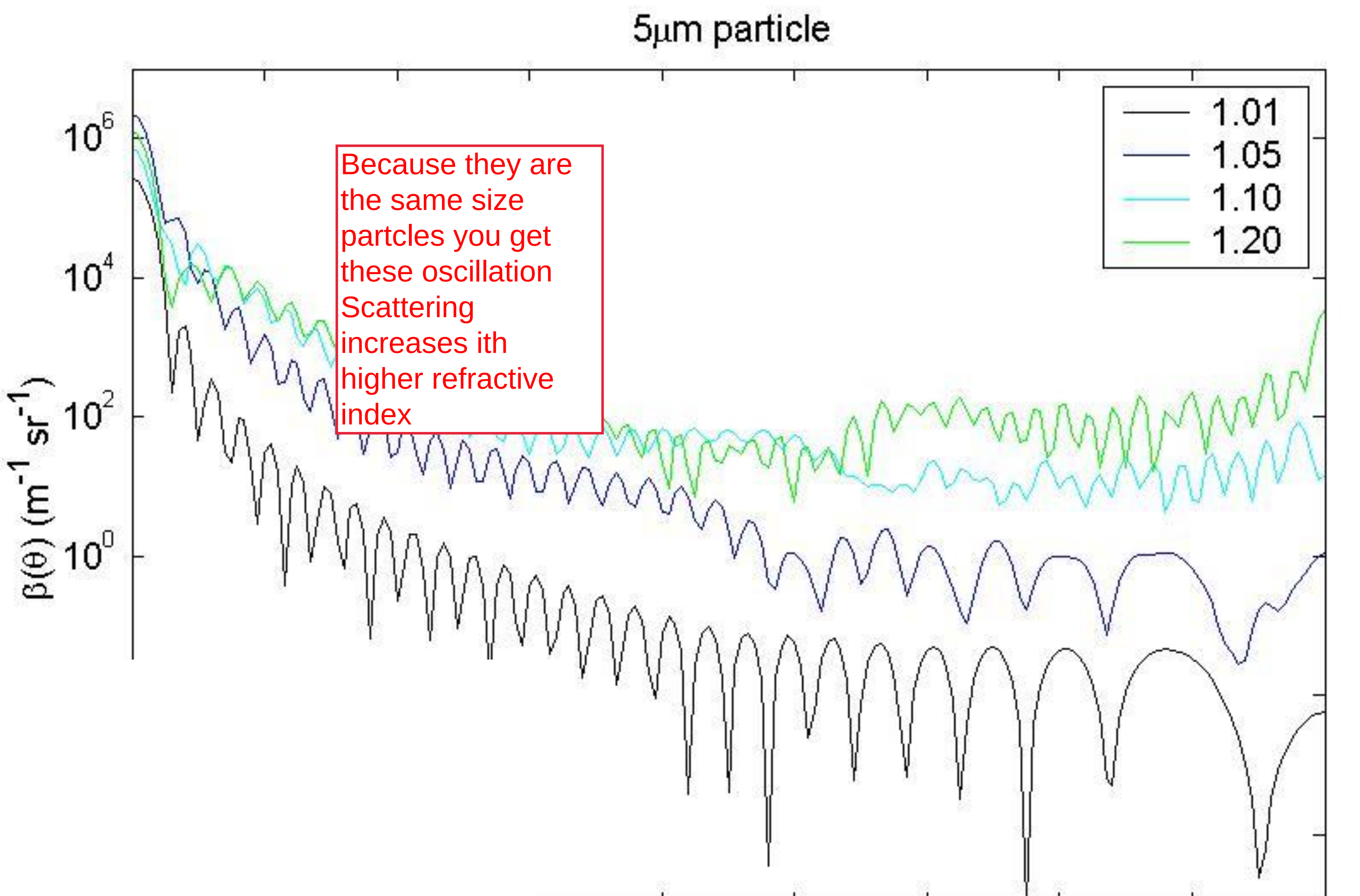


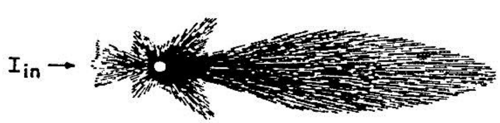
http://www.philiplaven.com/p8h1.html

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

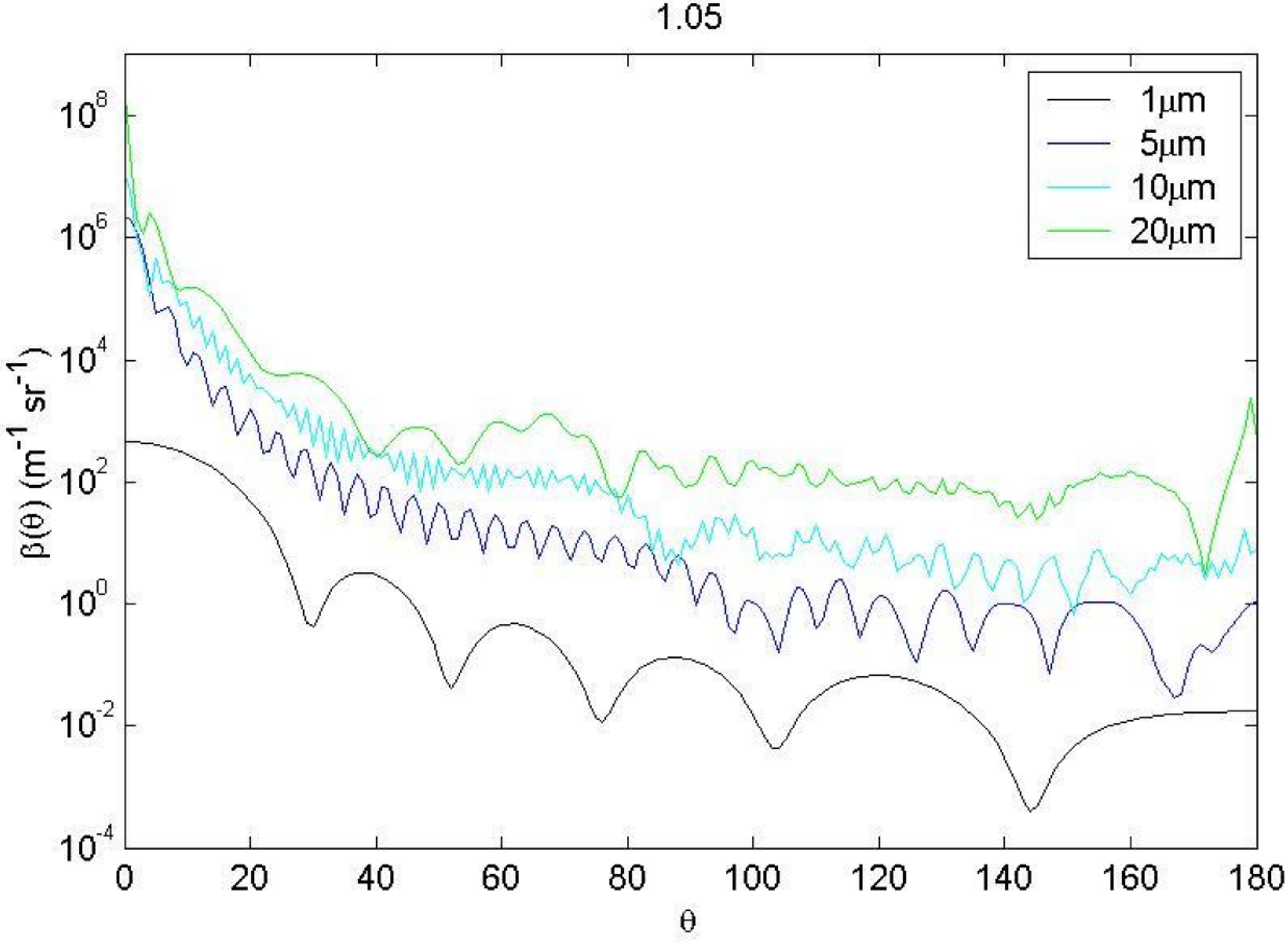
VSF of 5 μm particle as a function of refractive index





c) Large Particles ($r \geq 1.0\lambda$)

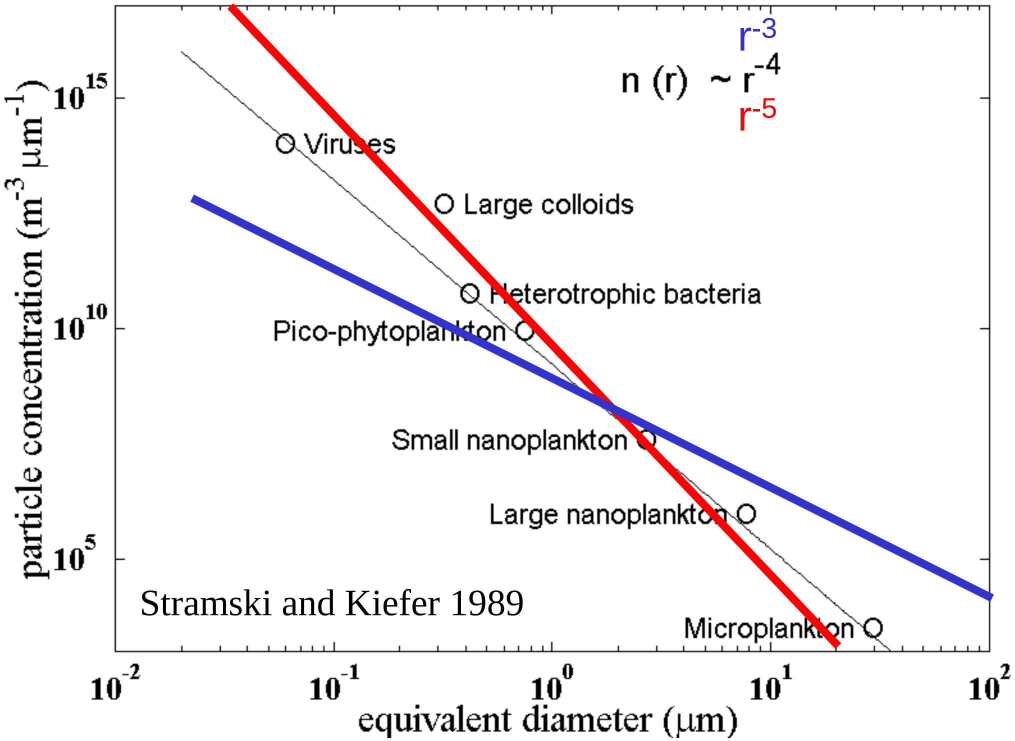
VSF of particles with refractive index 1.05



β(θ) response to particle size distribution

First let's talk about particle size distributions

Slope of line steeper with smaller particles

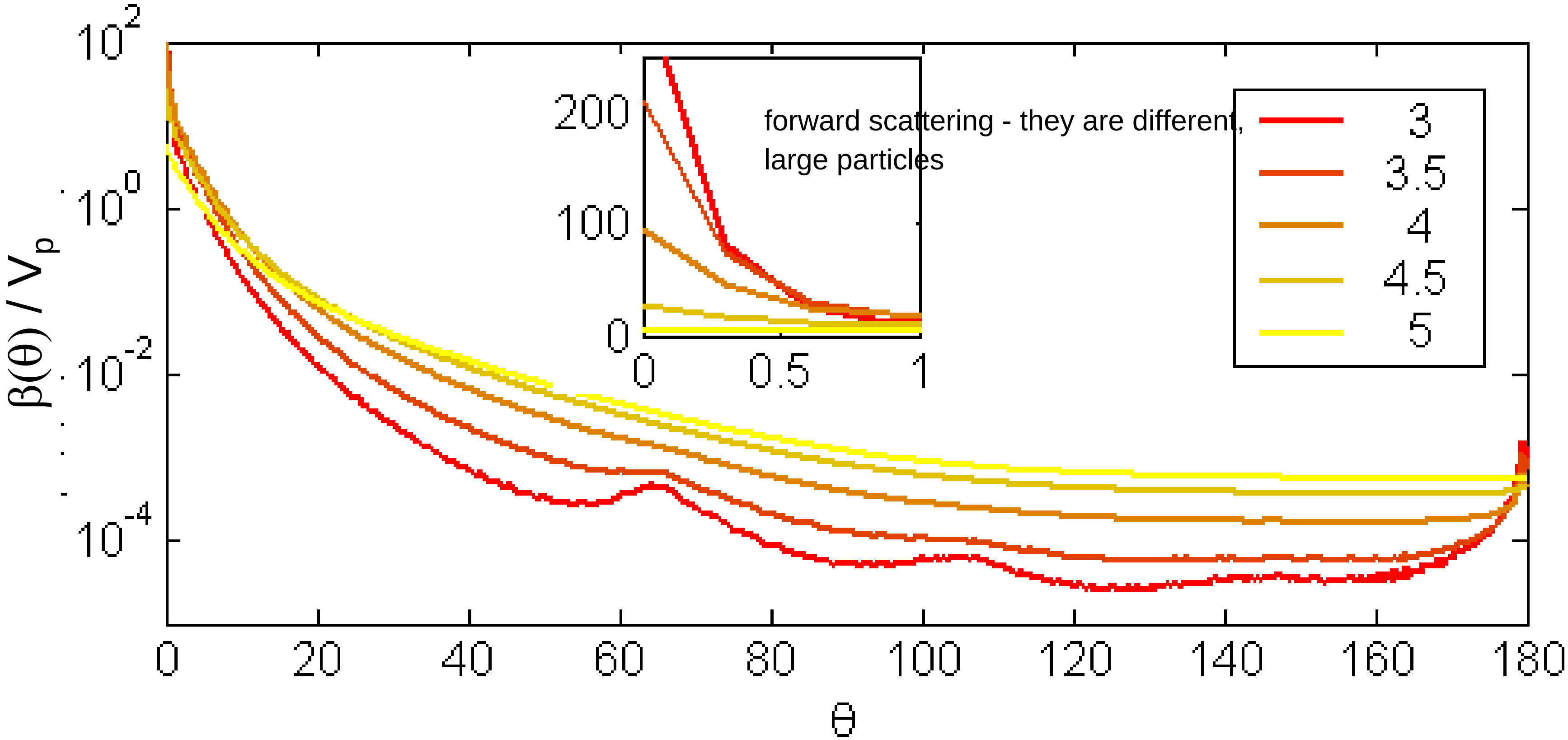


$\beta(\theta)$ and response to particle size distribution

Yellow dominated by small particles, red is dominated by large particles

Steeper VSF

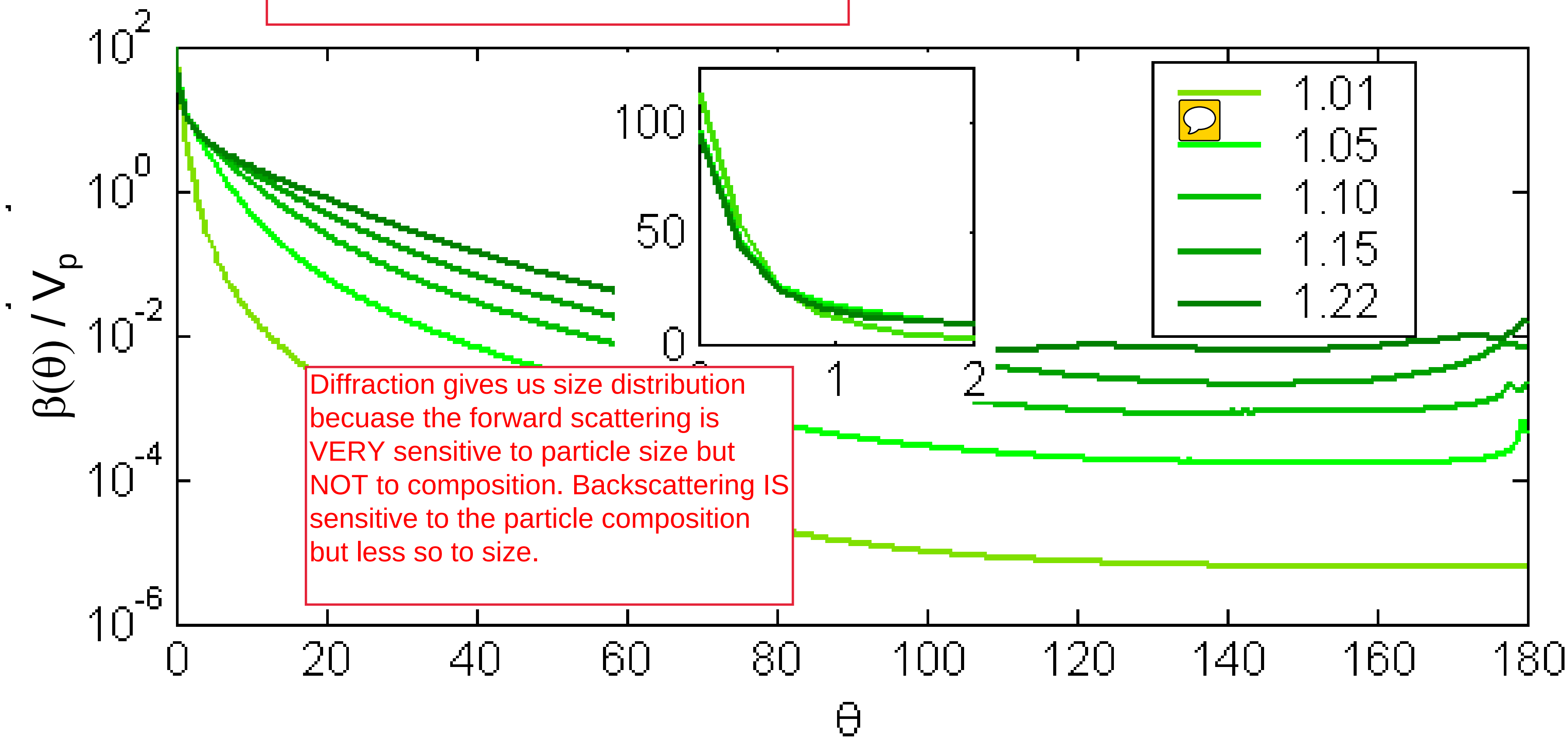
Relatively more forward scattering by larger particles



Roesler and Boss, 2008

β(θ) response to index of refraction

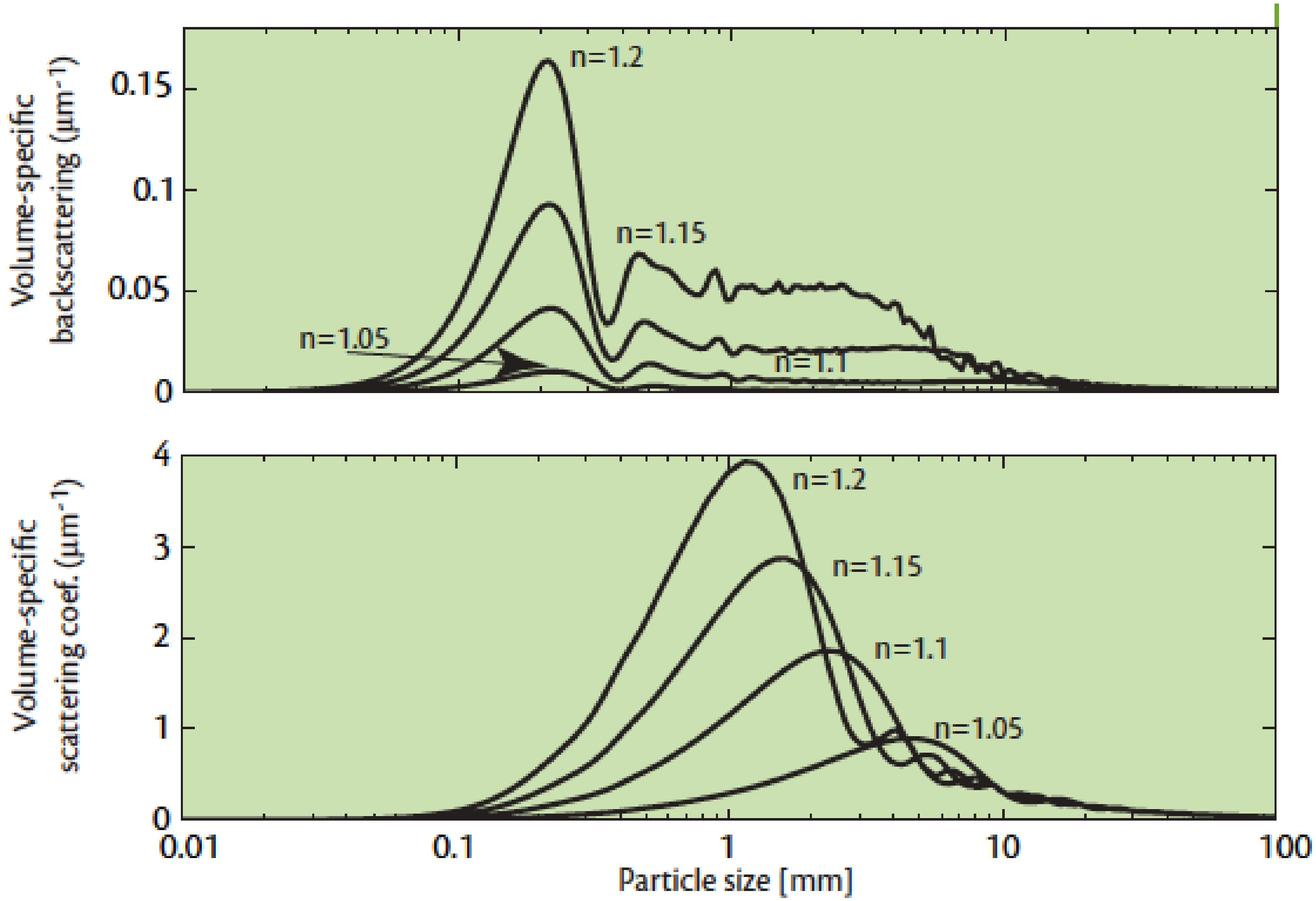
difraction dominates forward scattering and
insensitive to particle size
but IS sensitive to particle composition



Diffraction gives us size distribution
becuase the forward scattering is
VERY sensitive to particle size but
NOT to composition. Backscattering IS
sensitive to the particle composition
but less so to size.

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 forward scattering
- b_b backscattering
- $\beta(\theta)$ VSF -can derive everything else from it

IT is not microbubbles

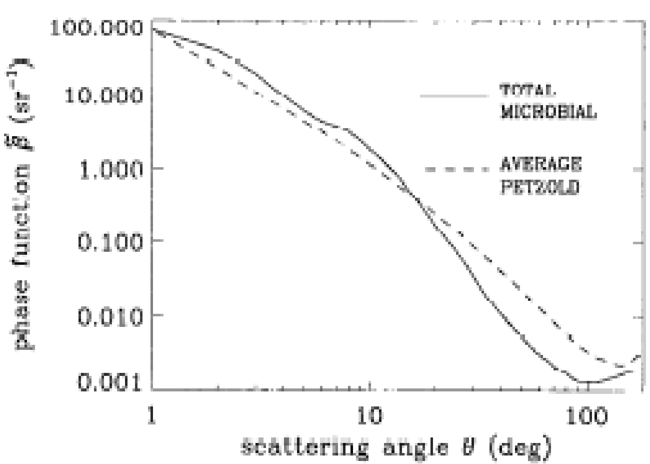
Scattering closure

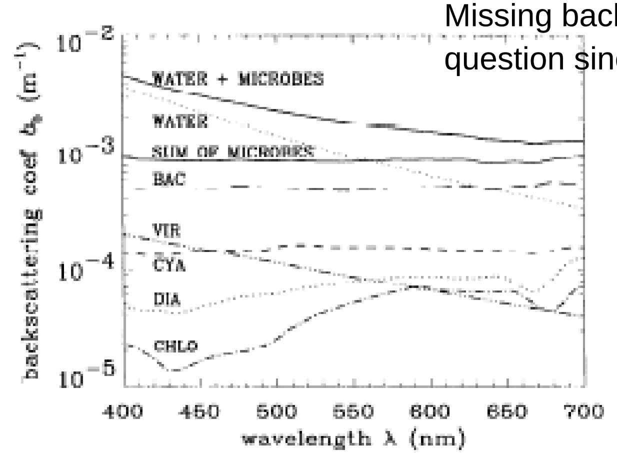
Why do we observe higher backscatter? This paper shows that we observe much higher backscatter than if we add up all the stuff in the ocean. IF we add it up ,we get a lower backscatter. We can't explain this!

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

bubbles and foam.
phytoplankton internal structure and shape

New work suggests small particles are why
Missing backscattering! open question since 1991





Importance of scattering in the ocean

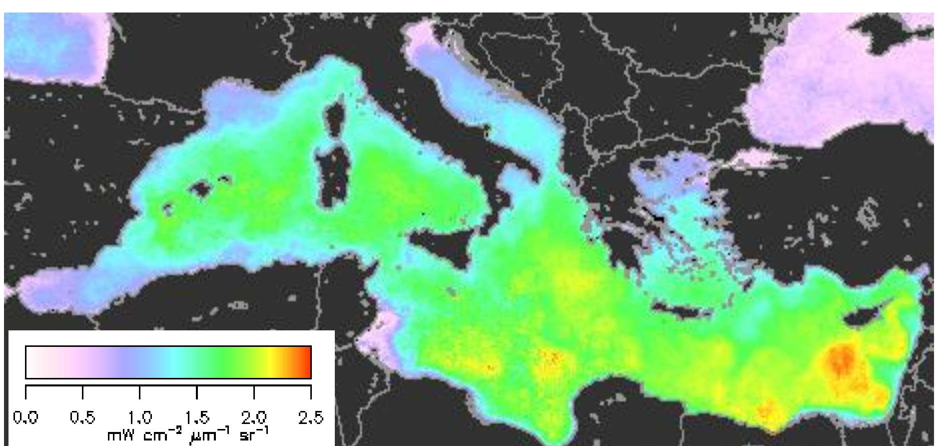
- Competing forces of absorption and scattering on the downward propagation of light in the ocean

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