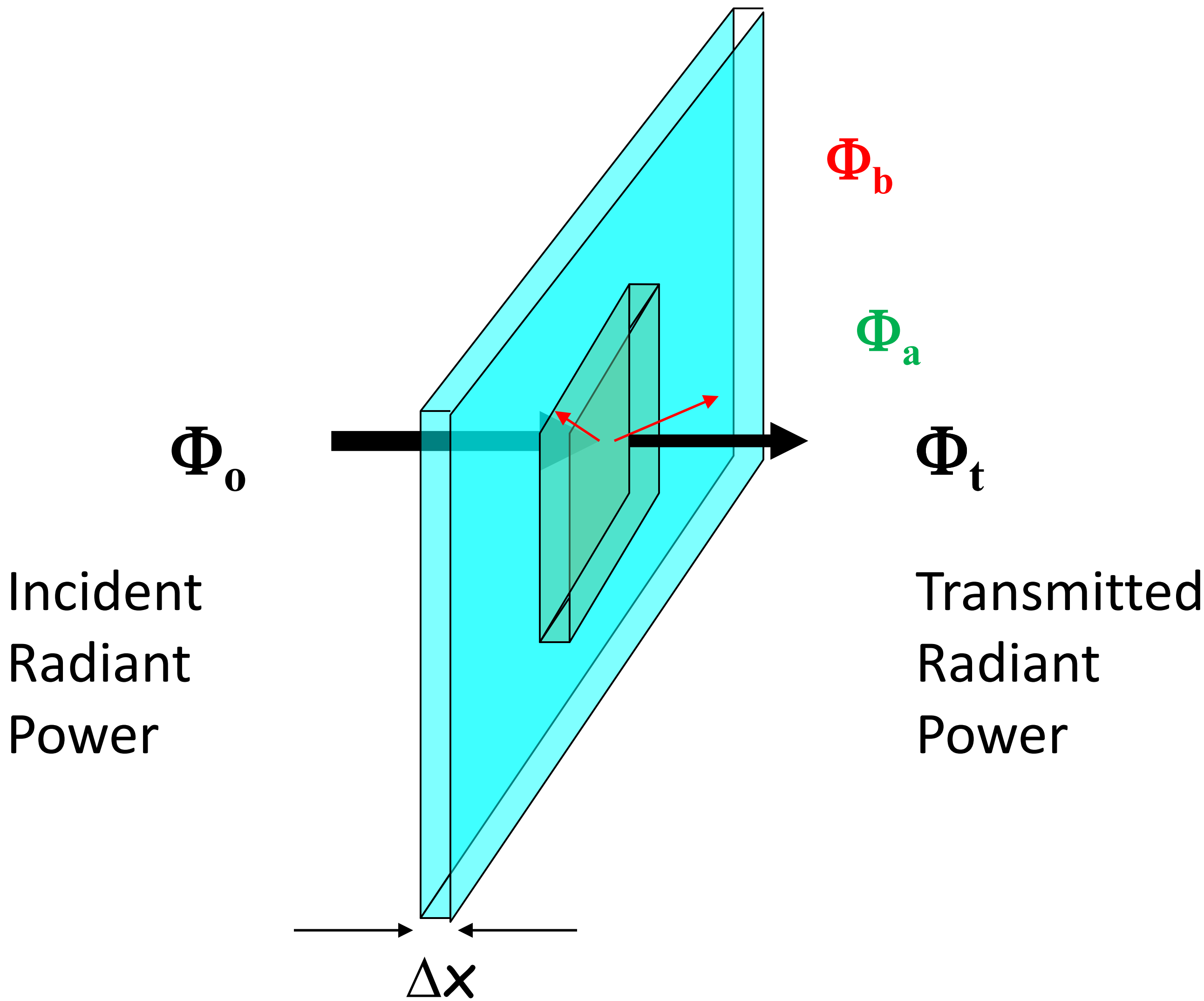
Lecture 6

Scattering Part 1-
theoretical basis of scattering, scattering by individual particles, bulk scattering measurements

Collin Roesler

21 July 2021

Review measurement *Theory*



Derivation of scattering coefficient

Scatterance

B = fraction of incident radiant power scattered

If no absorption

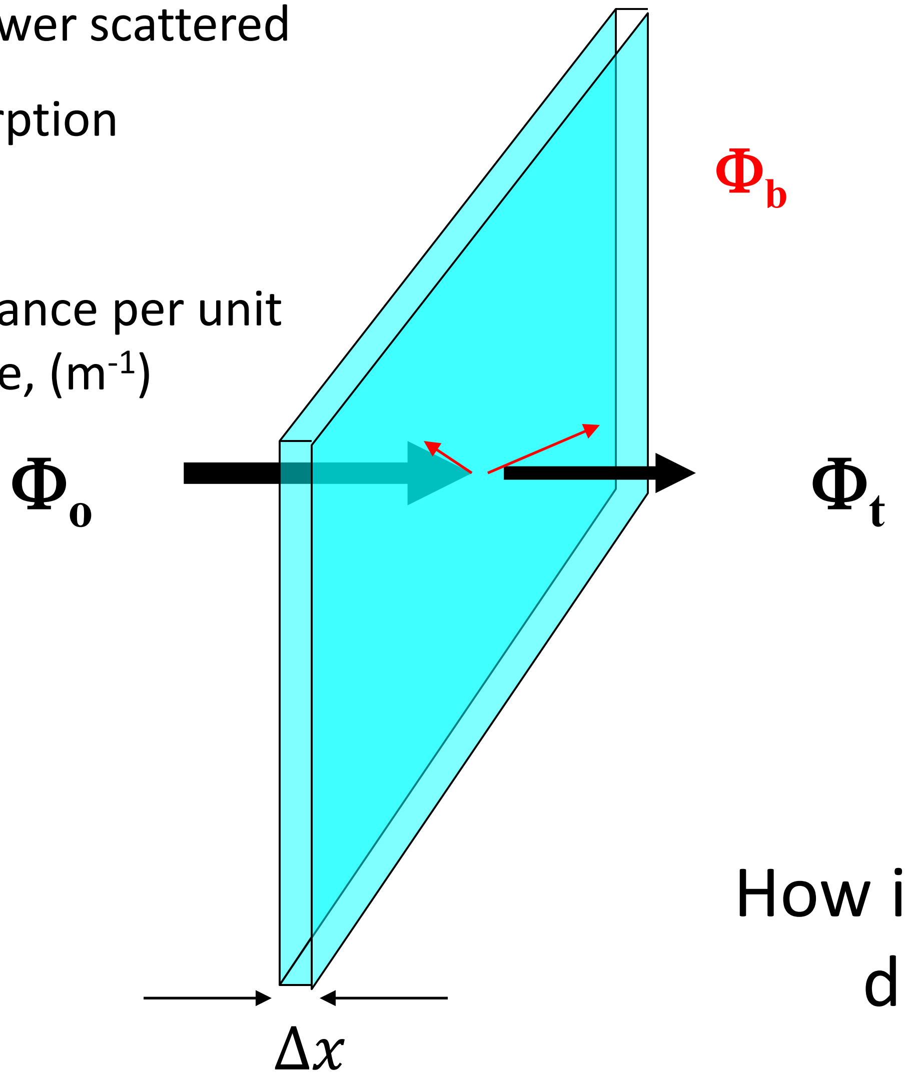
Scattering

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

$$\boldsymbol{B} = \frac{\Phi_b}{\Phi_o}$$

$$\boldsymbol{B} = \frac{\Phi_o - \Phi_t}{\Phi_o}$$

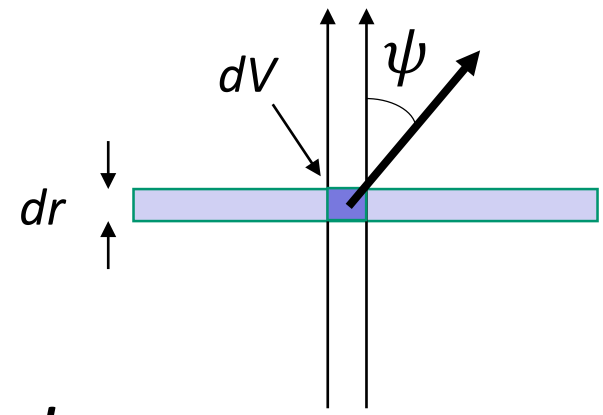
$$b(m^{-1}) = \frac{\boldsymbol{B}}{\Delta x}$$



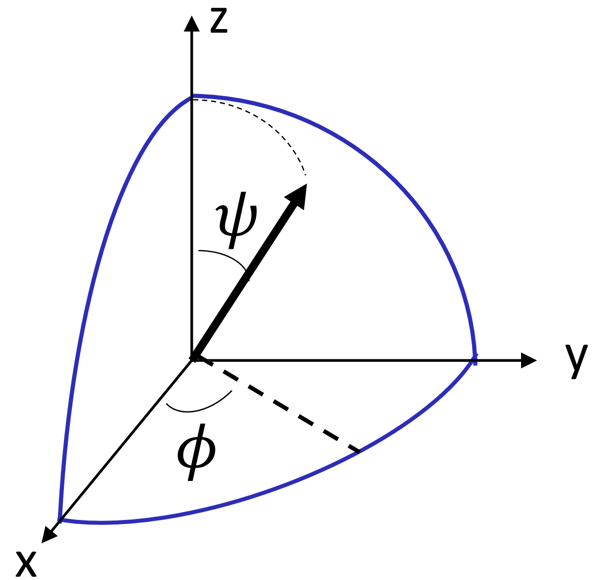
$$b(m^{-1}) = -\frac{1}{x}\ln\left(\frac{\Phi_t}{\Phi_o}\right)$$

How is this measurement different from a?

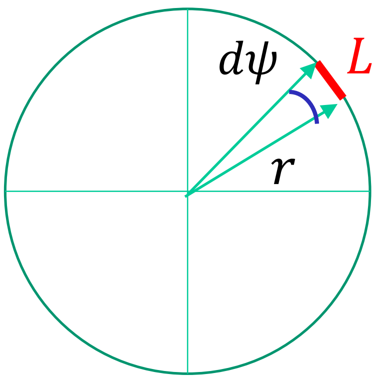
Scattering geometry

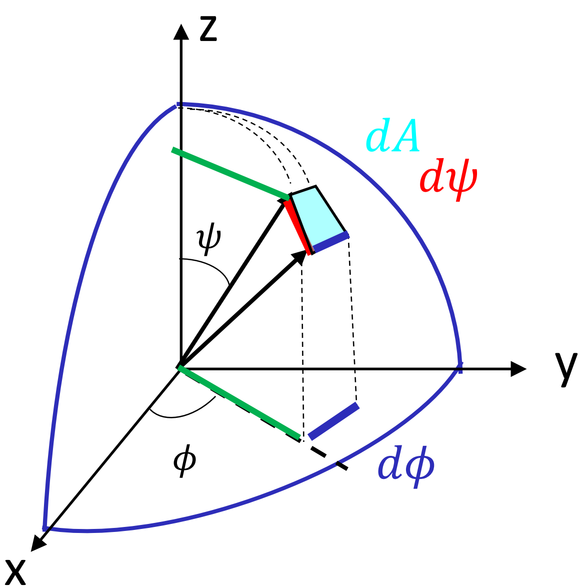


- Light passes through thin layer, *dr*
- Illuminating volume, dV
- Scattering at
  - polar angle ψ
  - azimuth angle ϕ



Solid angle

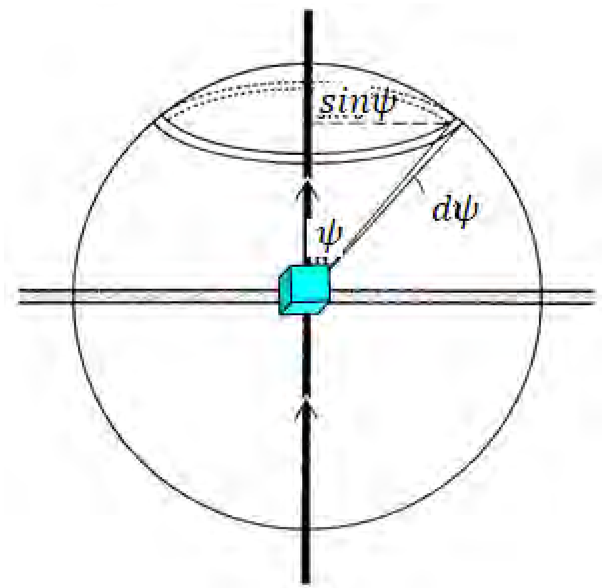




- **Circle**
  - Radius, r
  - Differential polar angle, $\mathrm{d}\psi$
  - Arc length $L = r\, d\psi$
- **Sphere**
  - Area on a sphere, dA
  - → $polar\ arc = r\ d\psi$
  - → $azimuthal\ arc = r\ sin\psi\ d\phi$
  - $dA = r^2 sin\psi d\psi d\phi$
  - $solid\ angle\ d\Omega \equiv \frac{dA}{r^2} = sin\psi\ d\psi\ d\phi$
  - Unit steradian

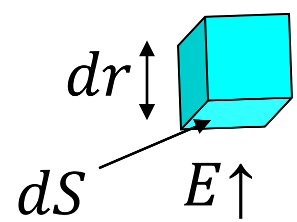
Scattering has an angular dependence described by the **V**olume **S**cattering **F**unction (VSF)

$\beta(\psi, \phi)$ = power (W) per unit steradian (sr^{-1}) emanating from a volume (m^3) illuminated by irradiance (Wm^{-2}) = $\frac{d\Phi}{d\Omega}\frac{1}{dV}\frac{1}{E}\,(m^{-1}sr^{-1})$



$$E = \frac{\Phi}{dS}(Wm^{-2})$$

$$dV = dS\,dr(m^3)$$

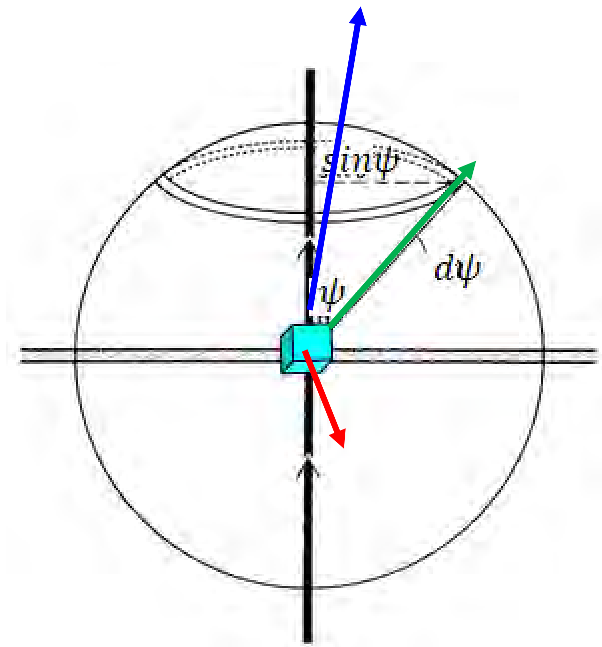


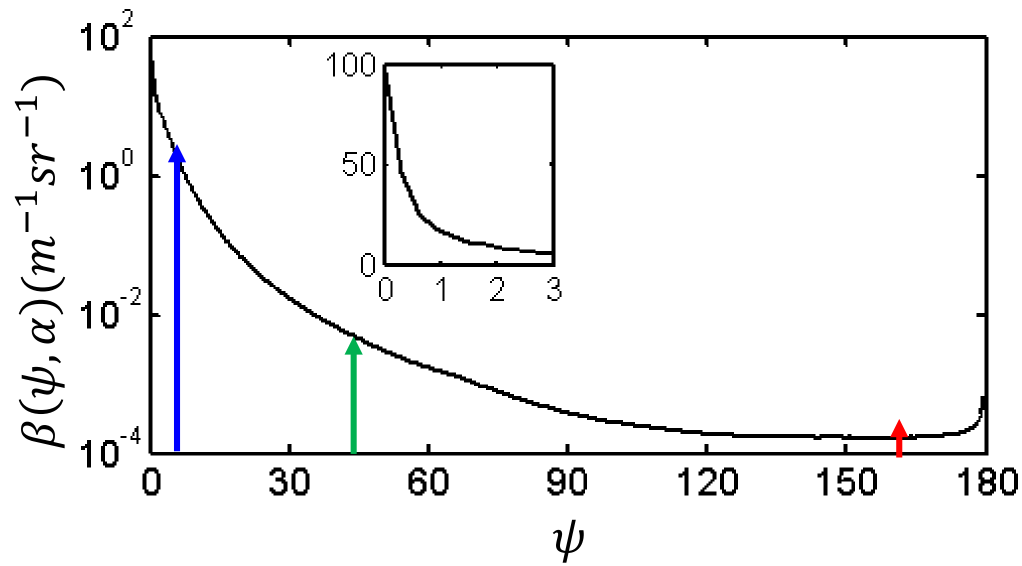
$$\beta(\psi, \alpha) = \frac{d\Phi}{d\Omega}\,\frac{1}{dS\,dr}\,\frac{dS}{\Phi}$$

$$= \frac{1}{\Phi}\frac{d\Phi}{dr\,d\Omega}$$

Volume Scattering Function (VSF)

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





$$\beta(\psi,\alpha) = \frac{1}{\Phi}\frac{d\Phi}{dr\,d\Omega}$$

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

What is $d\Omega$?

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

Calculate Scattering, b, from the volume scattering function

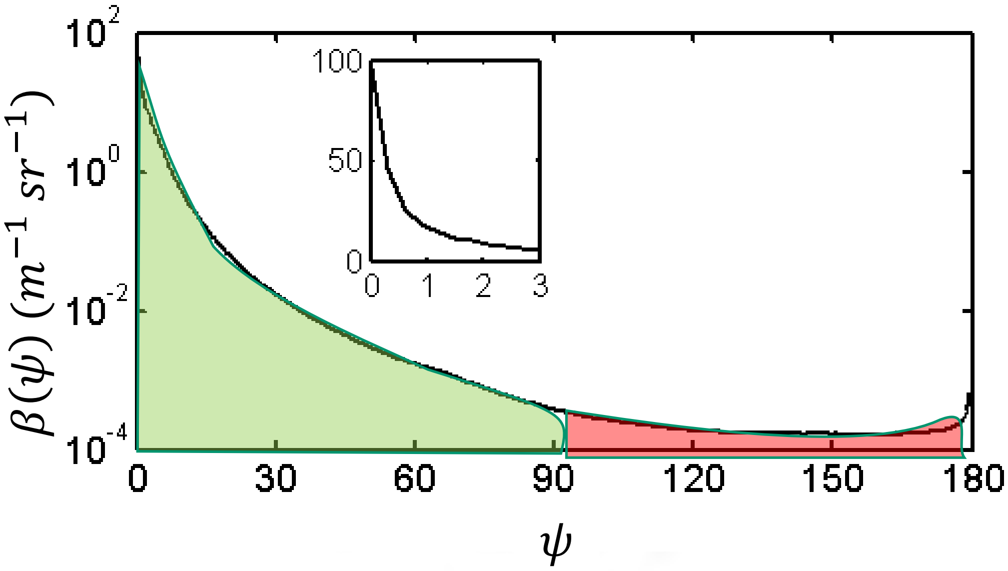
$$b = \int_0^{2\pi} \int_0^{\pi} \beta(\psi, \phi)\, sin\psi\, d\psi\, d\phi$$

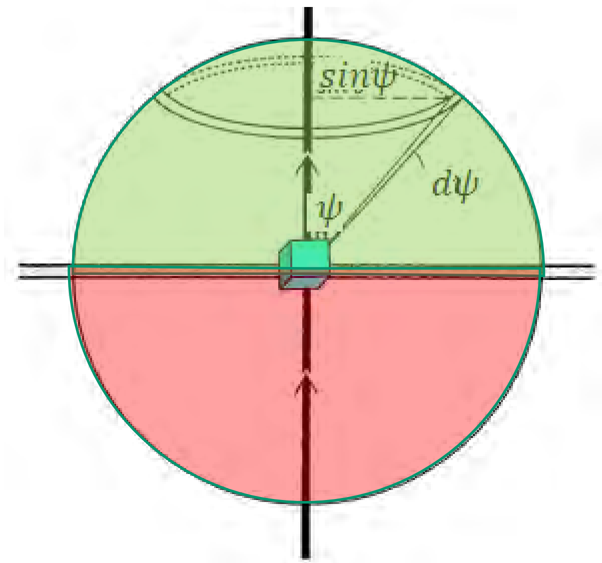
If there is azimuthal symmetry

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

$$b_f = 2\pi \int_0^{\frac{\pi}{2}} \beta(\psi)\, sin\psi\, d\psi$$

$$b_b = 2\pi \int_{\frac{\pi}{2}}^{\pi} \beta(\psi)\, sin\psi\, d\psi$$





$$Phase\ Function:\ \tilde{\beta}(\psi, \phi) = \frac{\beta(\psi, \phi)}{b} (sr^{-1})$$

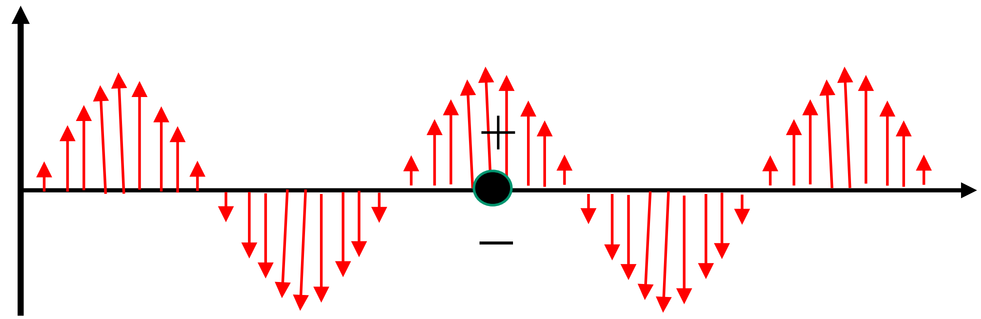
These are spectral!

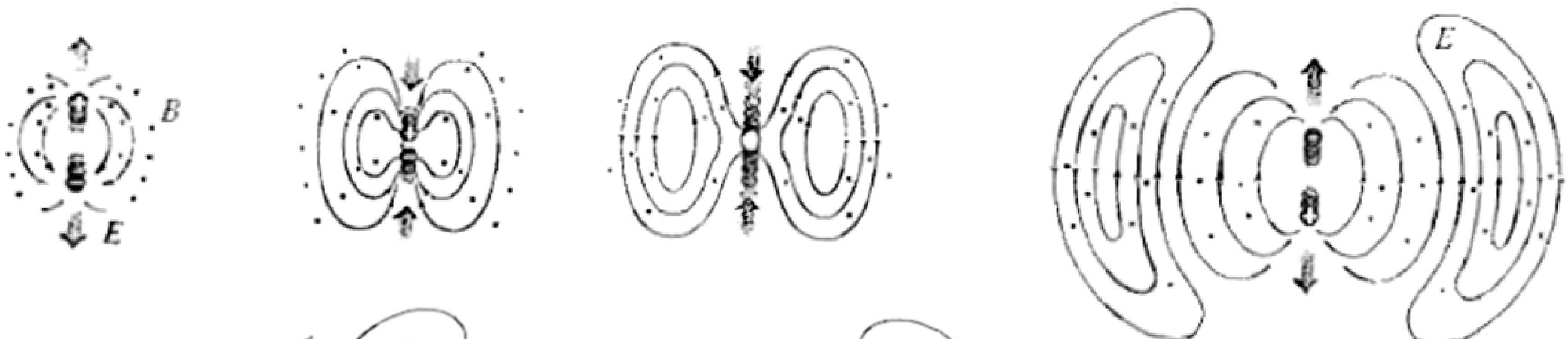
Particle parameters that influence scattering

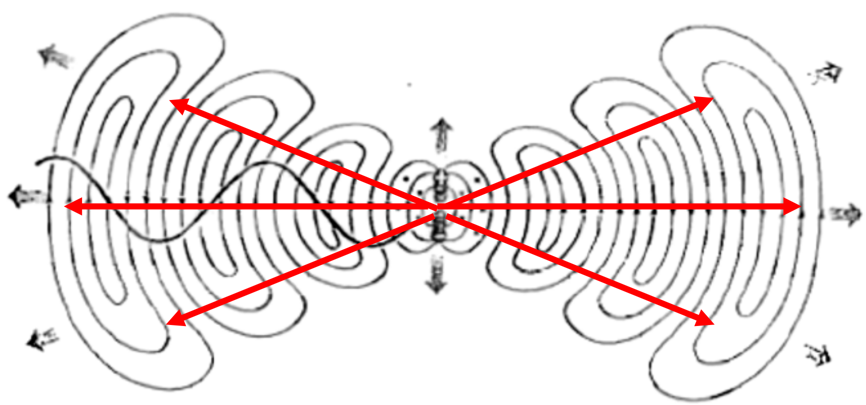
- size (Diameter : Wavelength)
- shape
- refractive index relative to surrounding medium
- absorption of radiation through particle

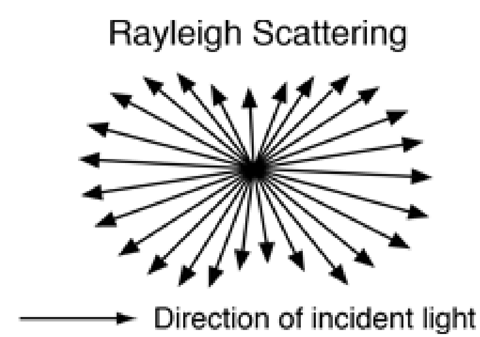
Small Particles: Rayleigh scatterers

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





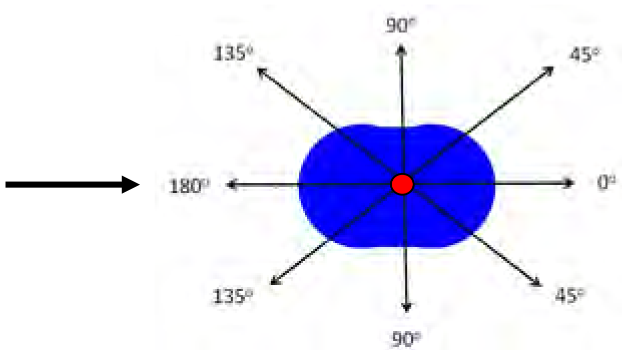


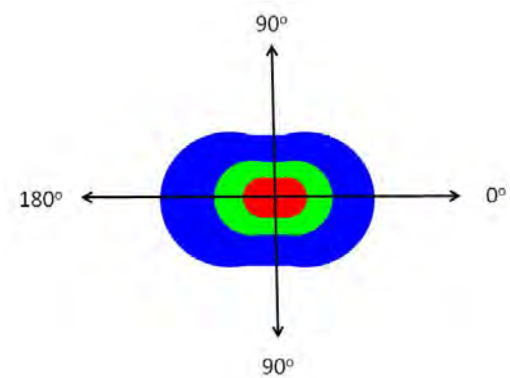


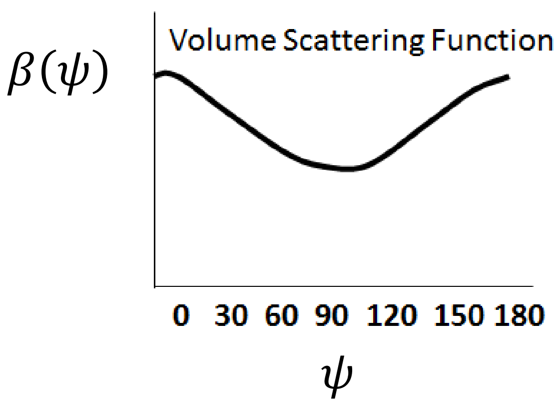
Credit D. Stramski

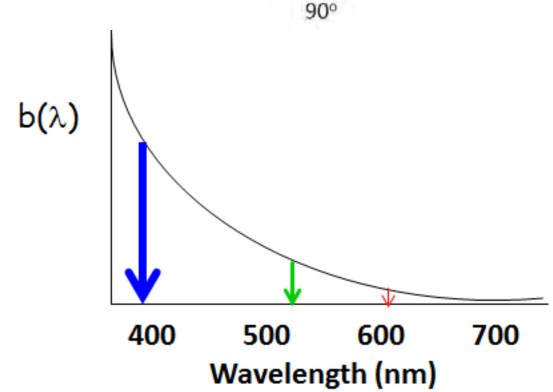
Scattering - Rayleigh

- Volume Scattering Function, $\beta(\psi)$ is almost equal in all directions
- The spectral dependence of scattering is proportional to λ^{-4} →shorter wavelengths preferentially scattered



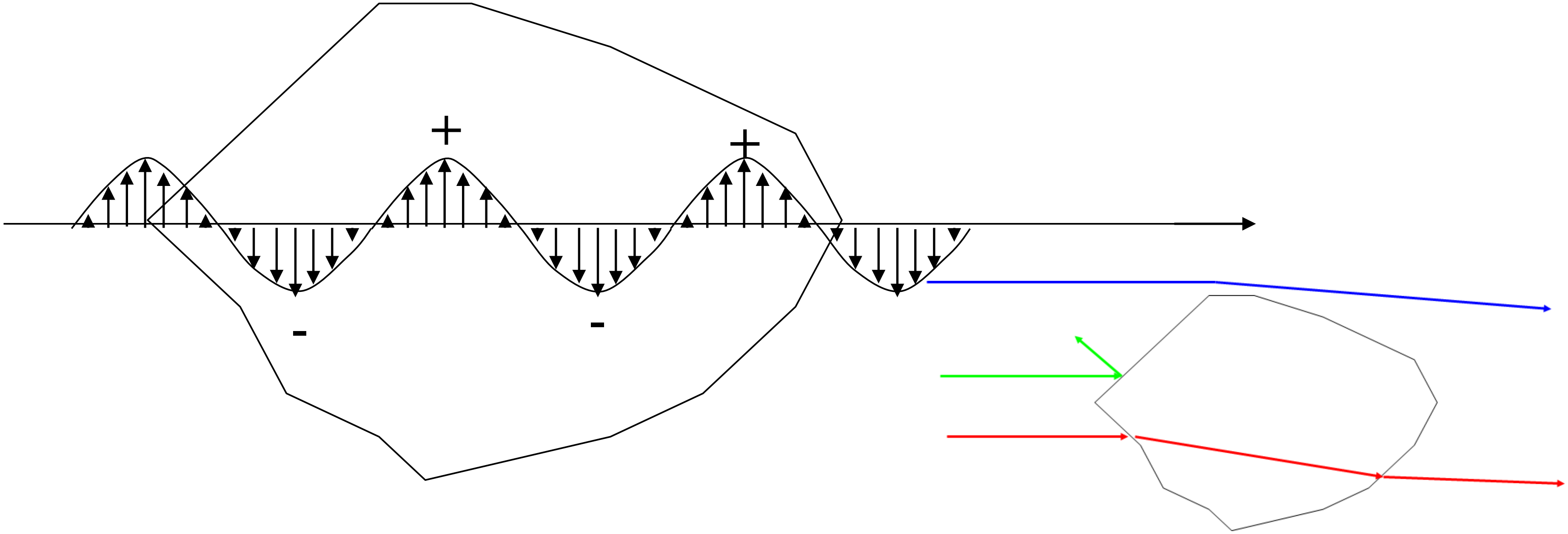






Scattering – Large particles

- Particle diameter >> wavelength of light
- Particle interacts with EMR as a geometric shape
- EMR wave oscillation *in* particle and *at* interfaces
- Scattering is predicted by Mie theory → *Mie scattering*
- Scattering is composed of refraction, reflection, diffraction



Scattering – Large particles

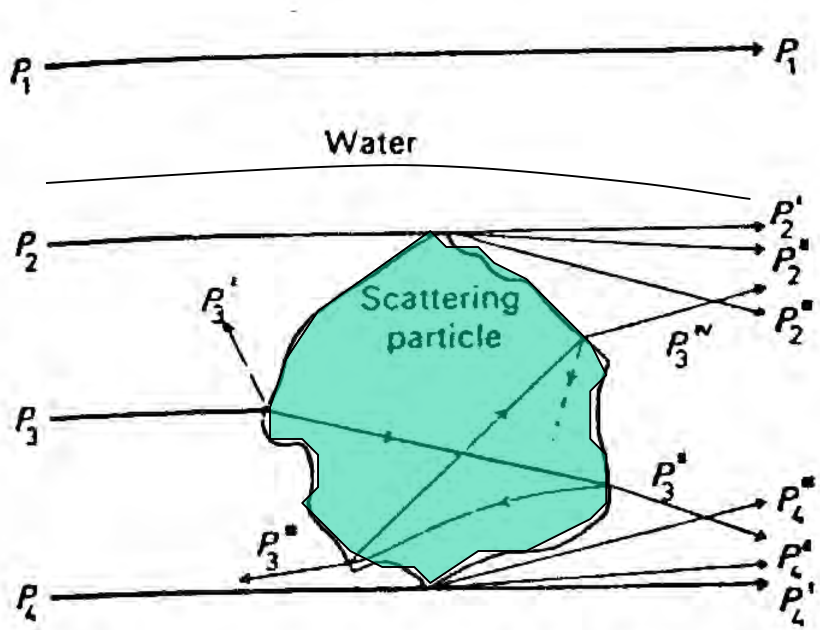


Fig. 4.3.1. A model of light scattering due to reflection, refraction and diffraction by large particles suspended in water. $P_1 - P_4$—incident rays; $P_2^{I} - P_2^{III}$, $P_4^{I} - P_4^{III}$—rays scattered owing to diffraction at the particle's edges; $P_3^{I} - P_3^{IV}$—rays scattered owing to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

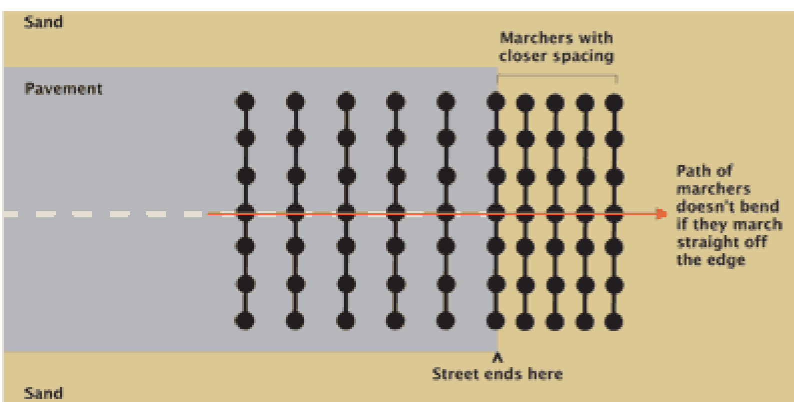
Dera, Marine Physics

Refractive Index

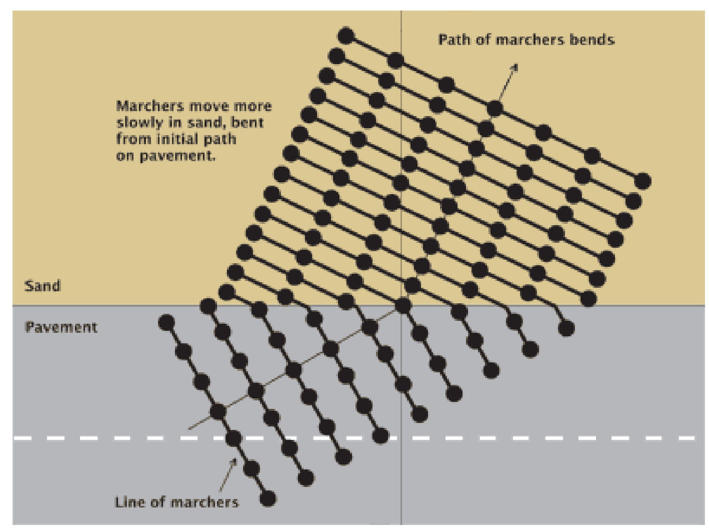
- Speed of EMR
  - in a vacuum (air), $c = 3*10^8$ m/s
  - Slows down in other media
- the **index of refraction**, ***n***
  - is a property of a medium
  - $n \equiv c/v$, where v is the speed of EMR in the medium
  - $n_{air} = 1$; $n_{water} = 1.33$, $n_{seawater} = 1.34$
- We typically parameterize refractive index of oceanic particles relative to the seawater medium, $m = n_p/n_{sw}$

Refraction

- As EMR enters a particle from seawater, it slows down (unless it is a bubble)
- The wavelength shortens
- Can change propagation angle if incidence angle not ⊥ to interface



http://www.dosits.org/images/dosits/marchers.nolabel.sm.gif



Reflection and Transmission

- Fresnel's Law quantifies reflection and transmission of EM radiation across an interface between two media with different refractive indices
  - $\Phi_{\text{Incident}} = \Phi_{\text{transmitted}} + \Phi_{\text{reflected}}$
  - Function of relative index of refraction, n, and incidence angle

Diffraction:
independent of index of refraction, bending of EMR around particle

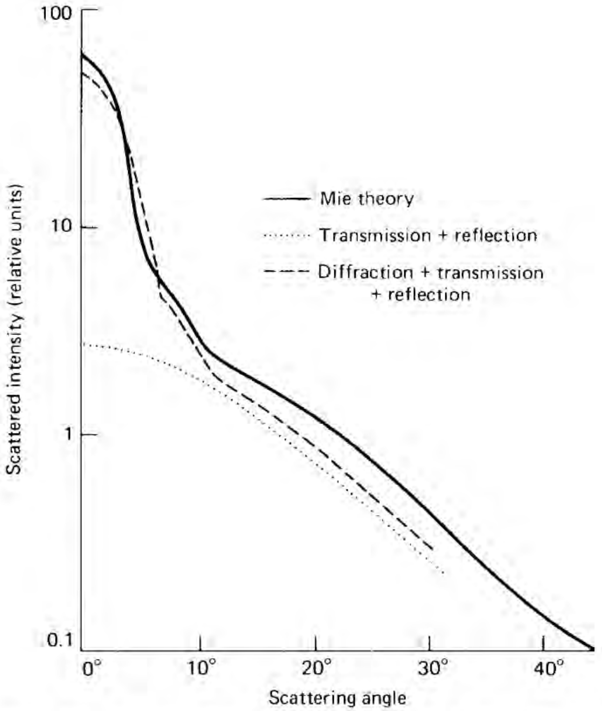
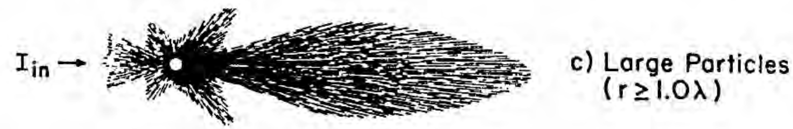
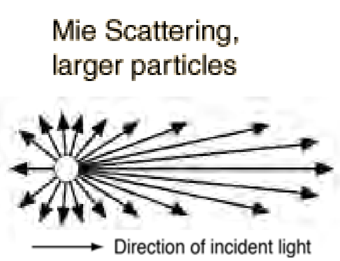


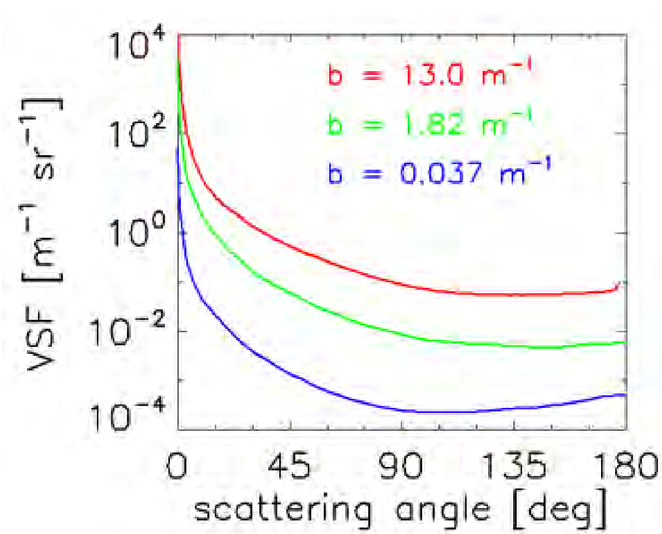
Fig. 4.1. Angular distribution of scattered intensity from transparent spheres calculated from Mie theory (Ashley & Cobb, 1958) or on the basis of transmission and reflection, or diffraction, transmission and reflection (Hodkinson & Greenleaves, 1963). The particles have a refractive index (relative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

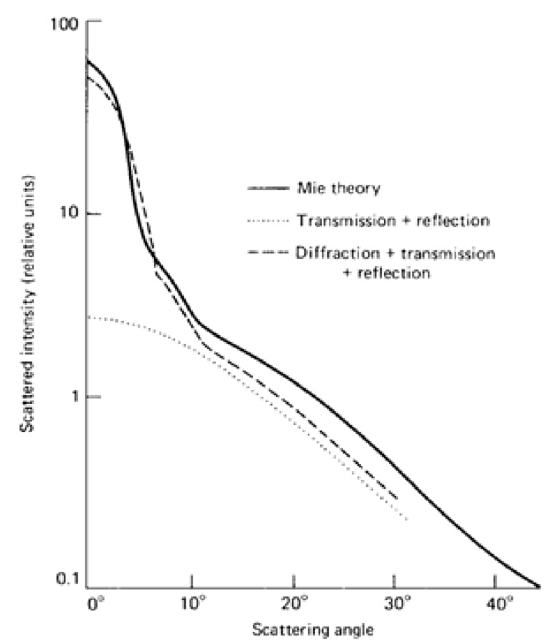


Scattering – Large particles

- Proportional to particle cross-sectional area (although not equal to it because of diffraction)
- Angular dependence of large particle scattering is primarily in the forward direction (because of diffraction)

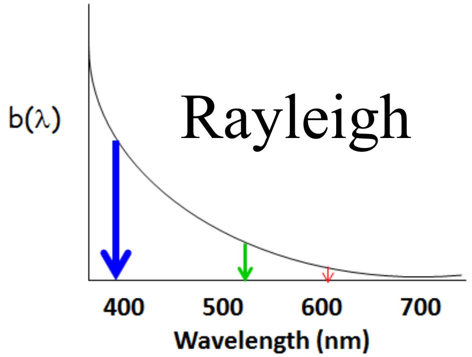


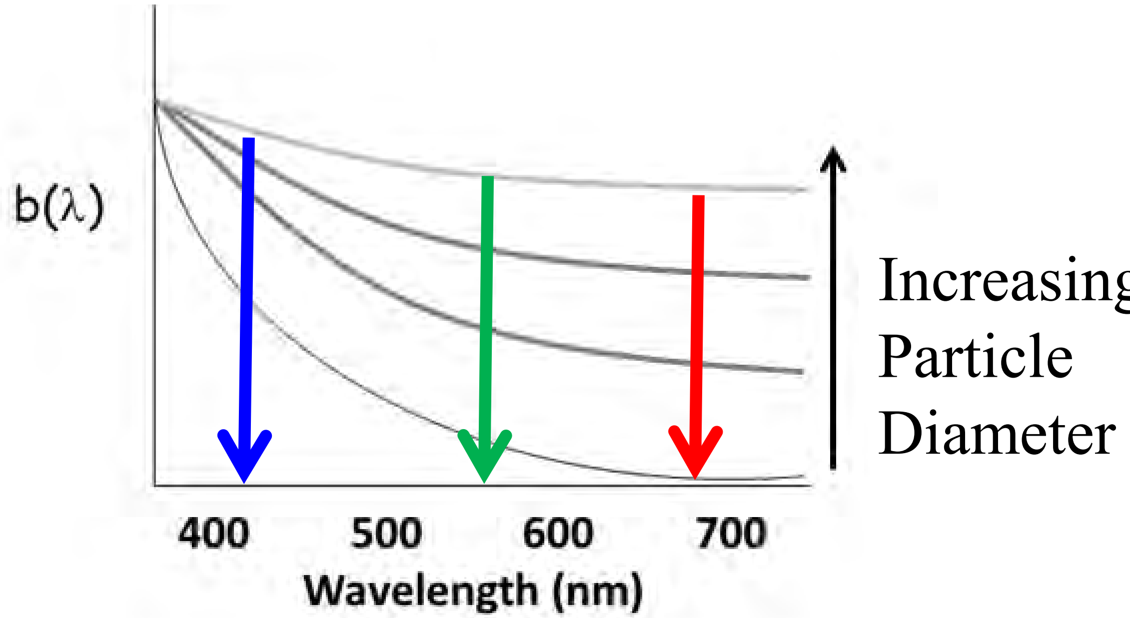




Scattering – Large particles

- Spectral dependence of scattering is very weak
- Paths through particle weakly depend on wavelength





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

Effect of Absorption in the extreme

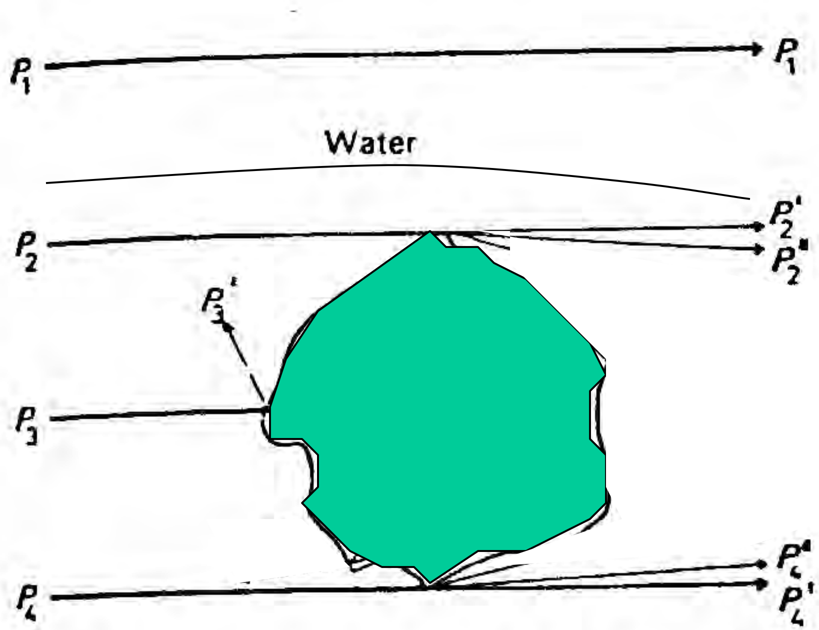


Fig. 4.3.1. A model of light scattering due to reflection, refraction and diffraction by large particles suspended in water. $P_1 - P_4$—incident rays; $P_2^{I} - P_2^{III}$, $P_4^{I} - P_4^{III}$—rays scattered owing to diffraction at the particle's edges; $P_3^{I} - P_3^{IV}$—rays scattered owing to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

Only diffraction

What are the constituent properties that we need to consider

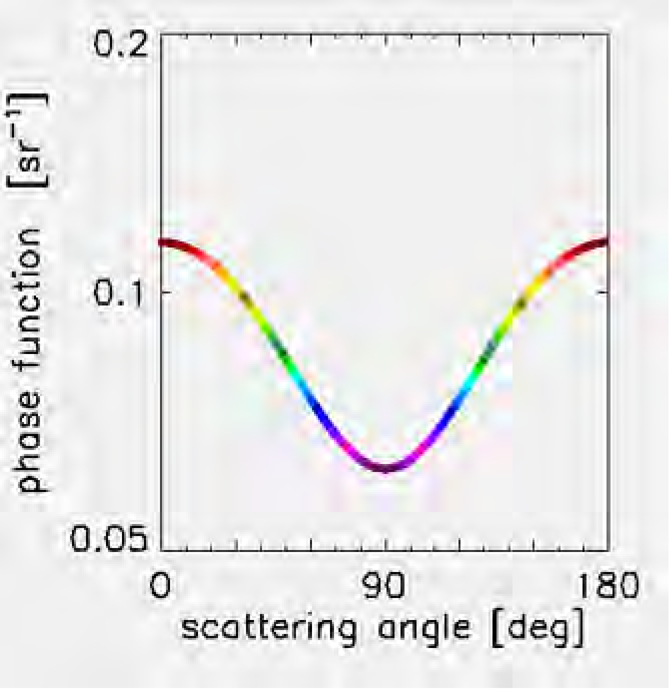
- Particle size
- Particle composition
  - Index of refraction (real part)
  - Index of refraction (imaginary part)
- Particle shape
- Internal structures

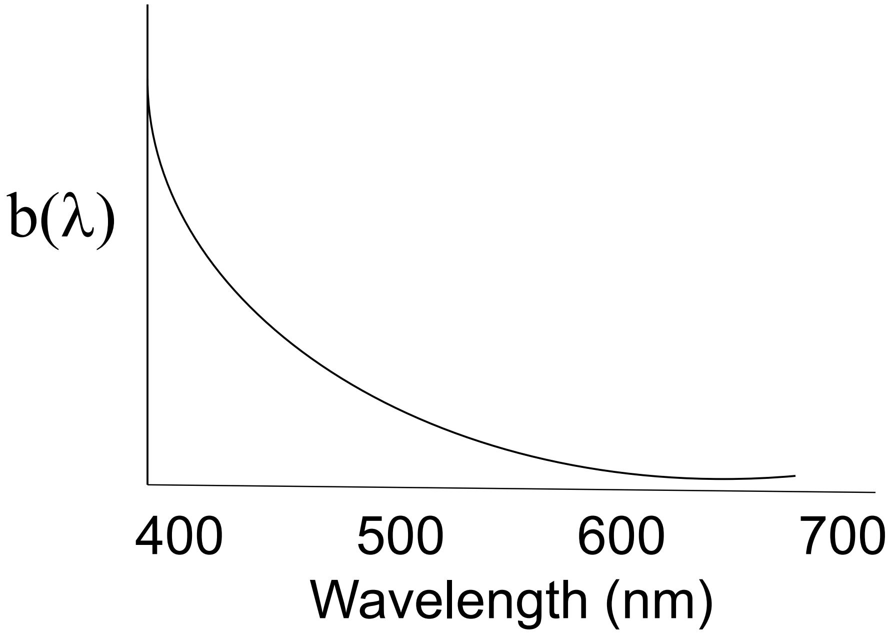
What are the particles in the ocean that are responsible for light scattering

- 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

Scattering in the ocean: water molecules

Rayleigh Scattering



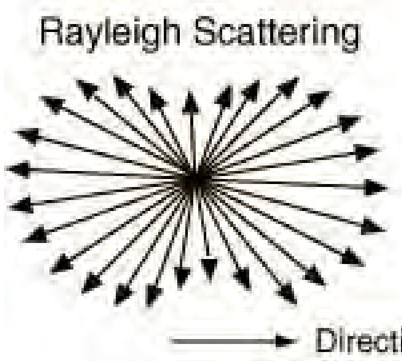


http://www.oceanopticsbook.info/view/overview_of_optical_oceanography/visualizing_vsfs

From Emmanuel Boss

Scattering by CDOM:

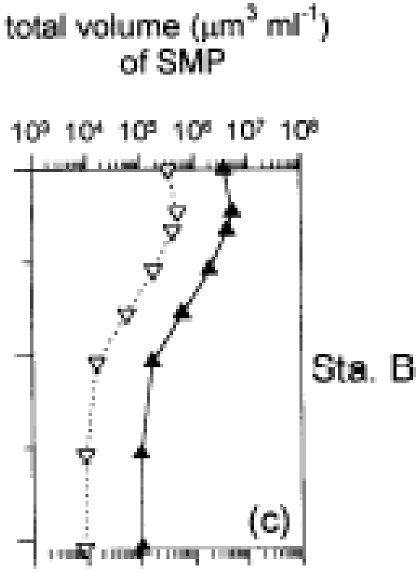
Scattering by molecules whose $D \ll \lambda$. Rayleigh scattering:

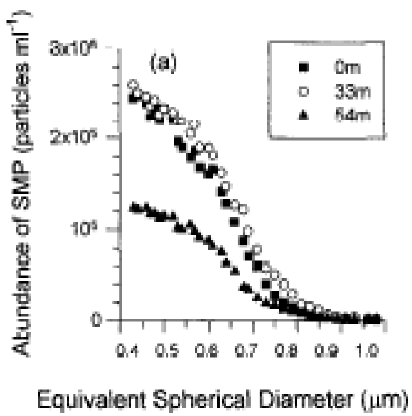


$$b(\lambda) \propto \lambda^{-4} \quad \beta(\theta) \propto \left(1 + \cos^2(\theta)\right)$$

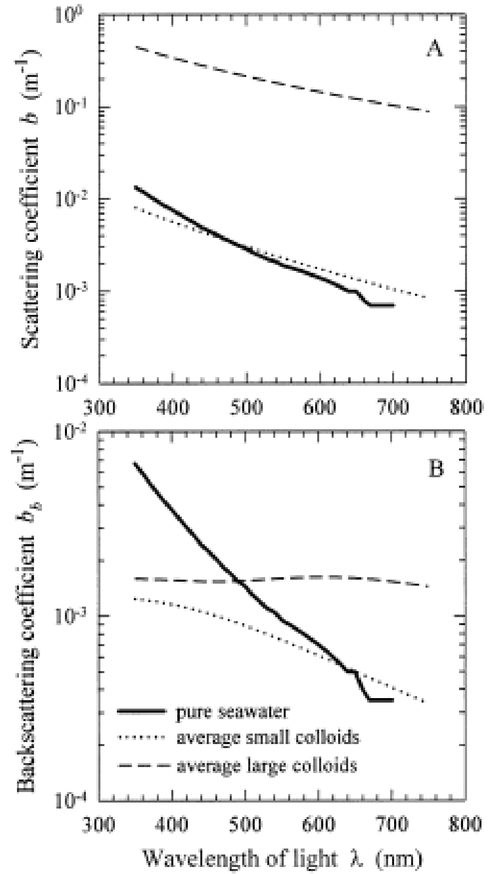
"No evidence in the literature that scattering is significant (the only place *I* have ever found significant dissolved scattering ($c_g > a_g$) was in pore water)."

Scattering in the ocean: submicron particles (~colloids)



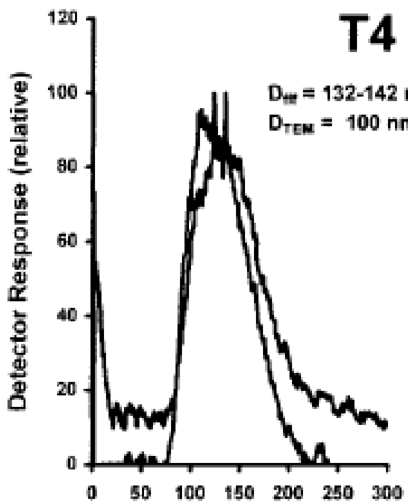


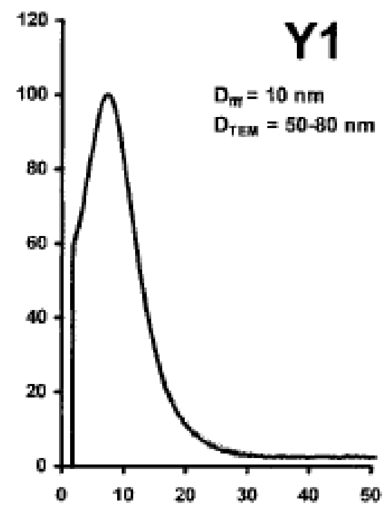
Yamasaki et al 1998

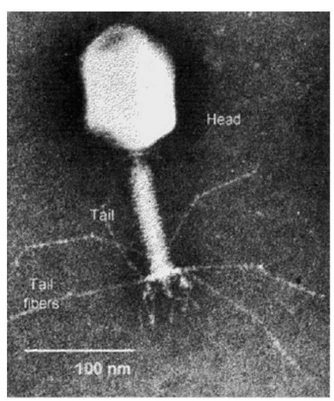


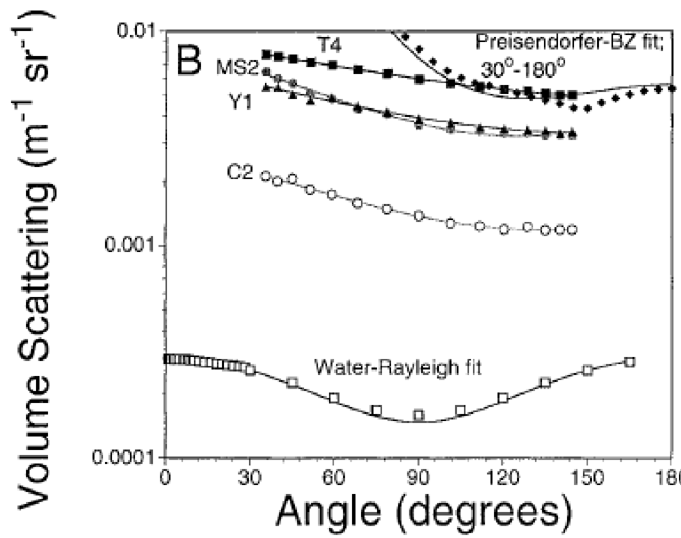
Stramski and Wozniak 2005

Scattering in the ocean: marine viruses



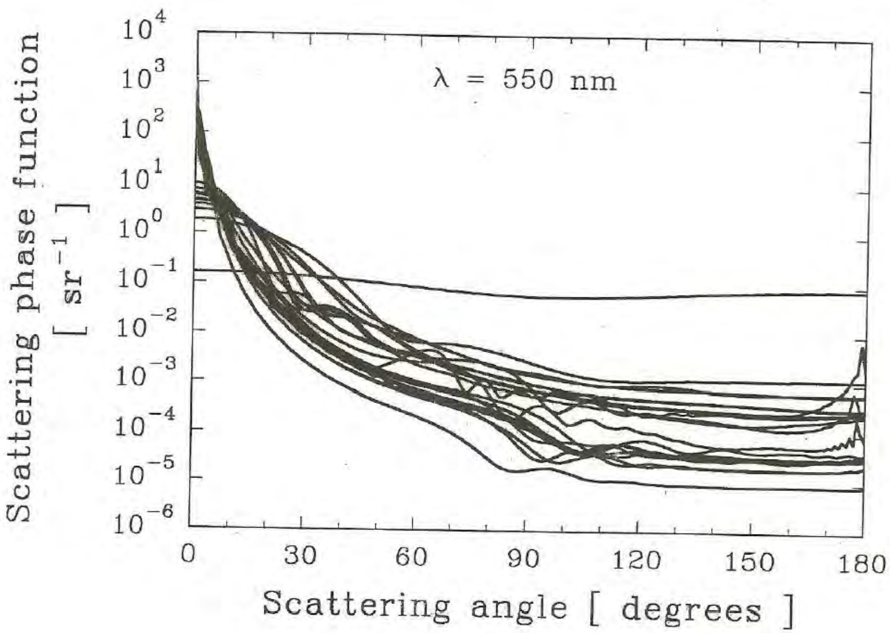


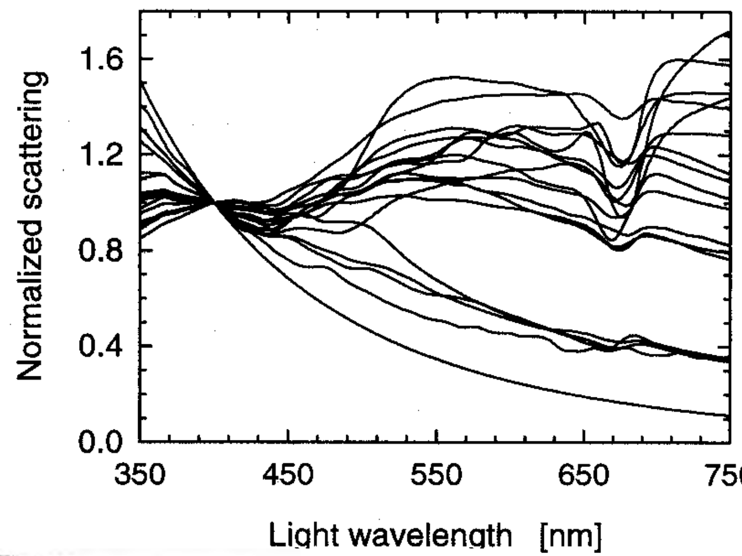




Balch et al. 1999

Scattering in the ocean: phytoplankton (modeled)



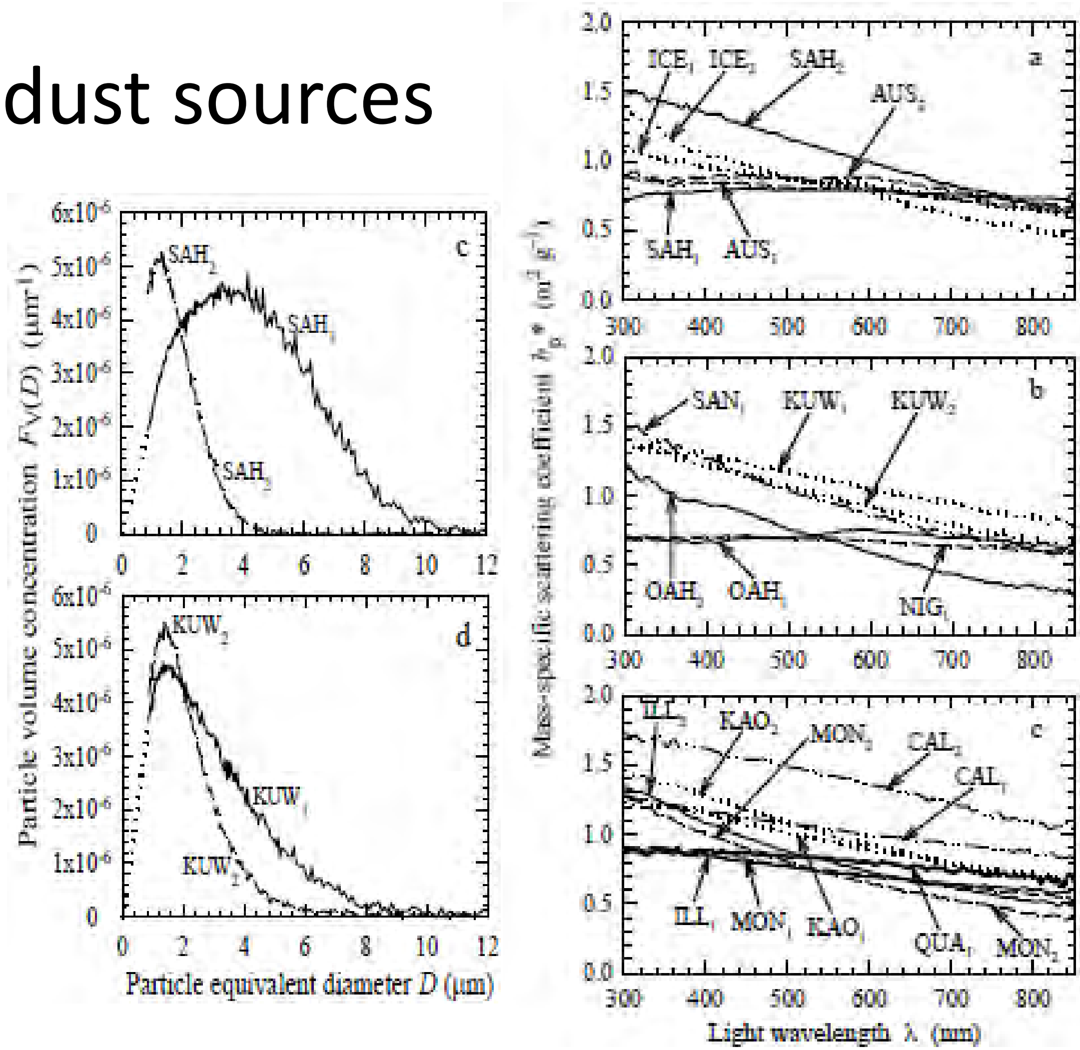


Viruses
Heterotrophic bacteria
Prochlorococcus (2 strains)
Synechococcus (Cyanophyceae, 5 strains)
Anacystis marina (Cyanophyceae)
Pavlova pinguis (Haptophyceae)
Thalassiosira pseudonana (Bacillariophyceae)
Pavlova lutheri (Haptophyceae)
Isochrysis galbana (Haptophyceae)
Emiliania hyxleyi (Haptophyceae)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

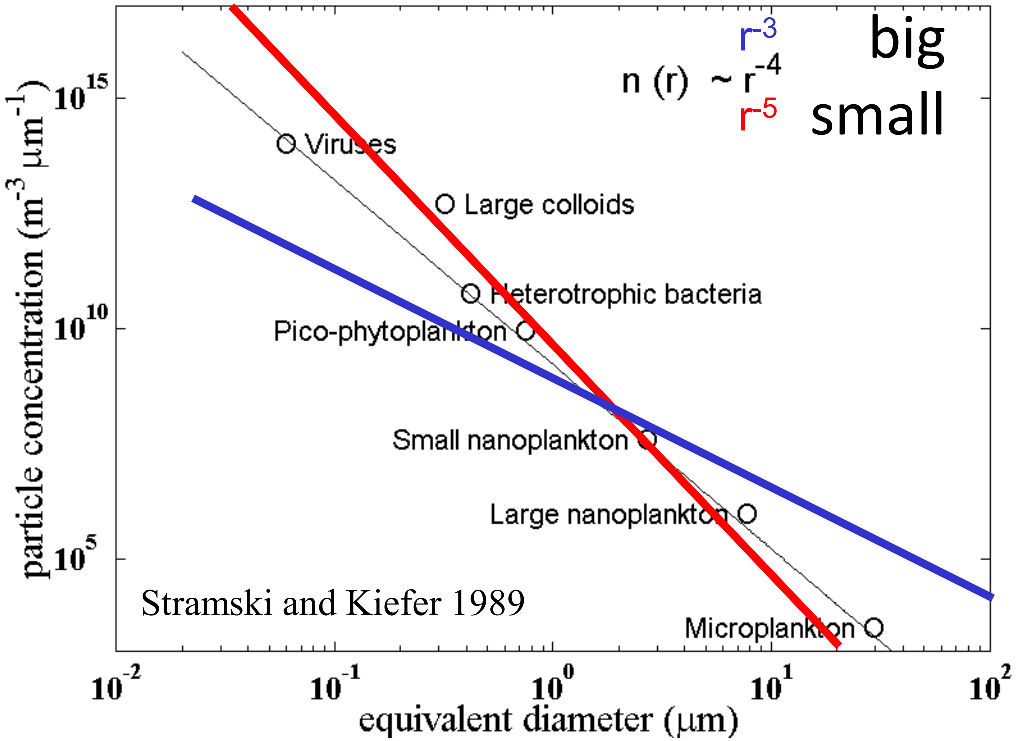
- Terrestrial dust sources



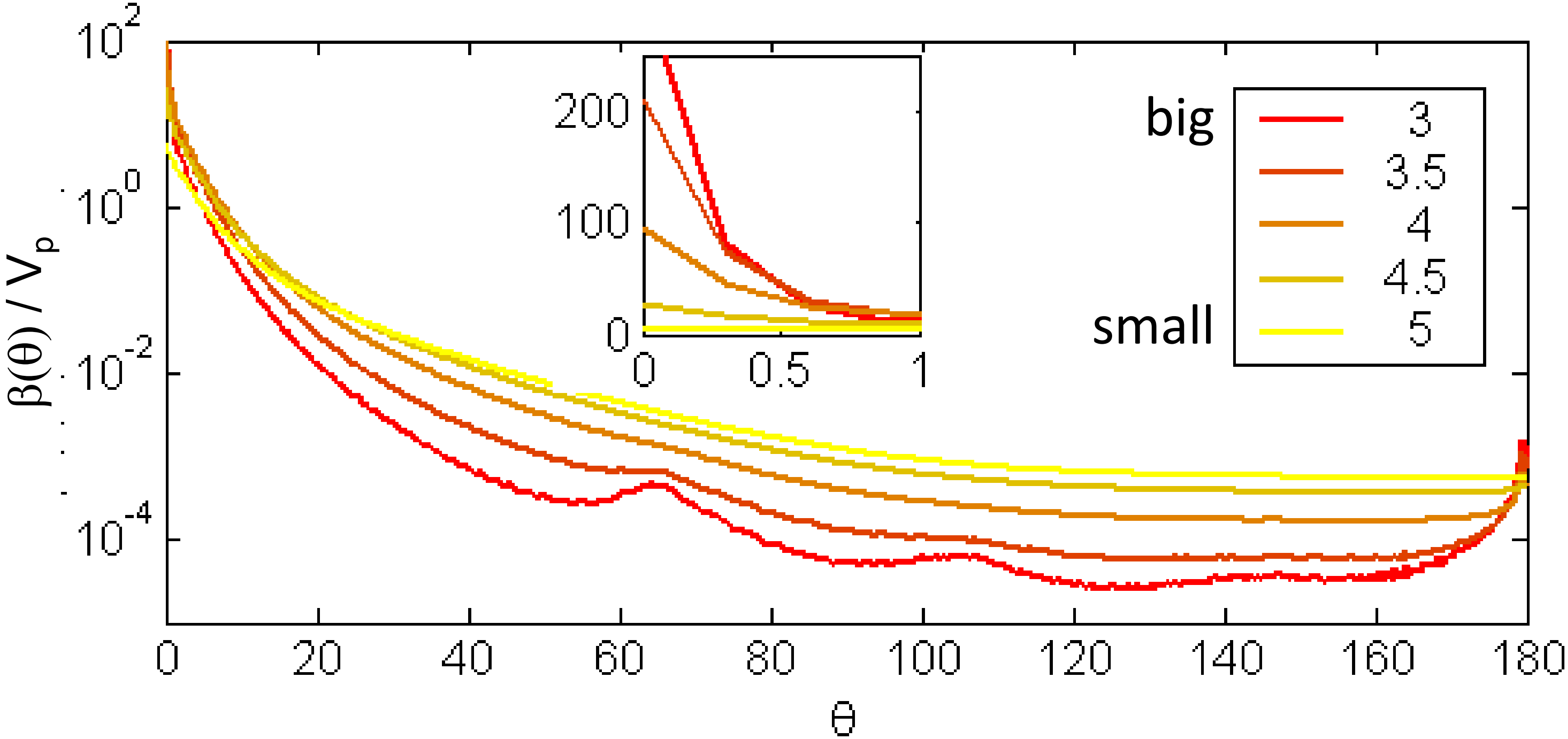
Stramski et al. 2007

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

Back to oceanic particle size distributions represented by size slope

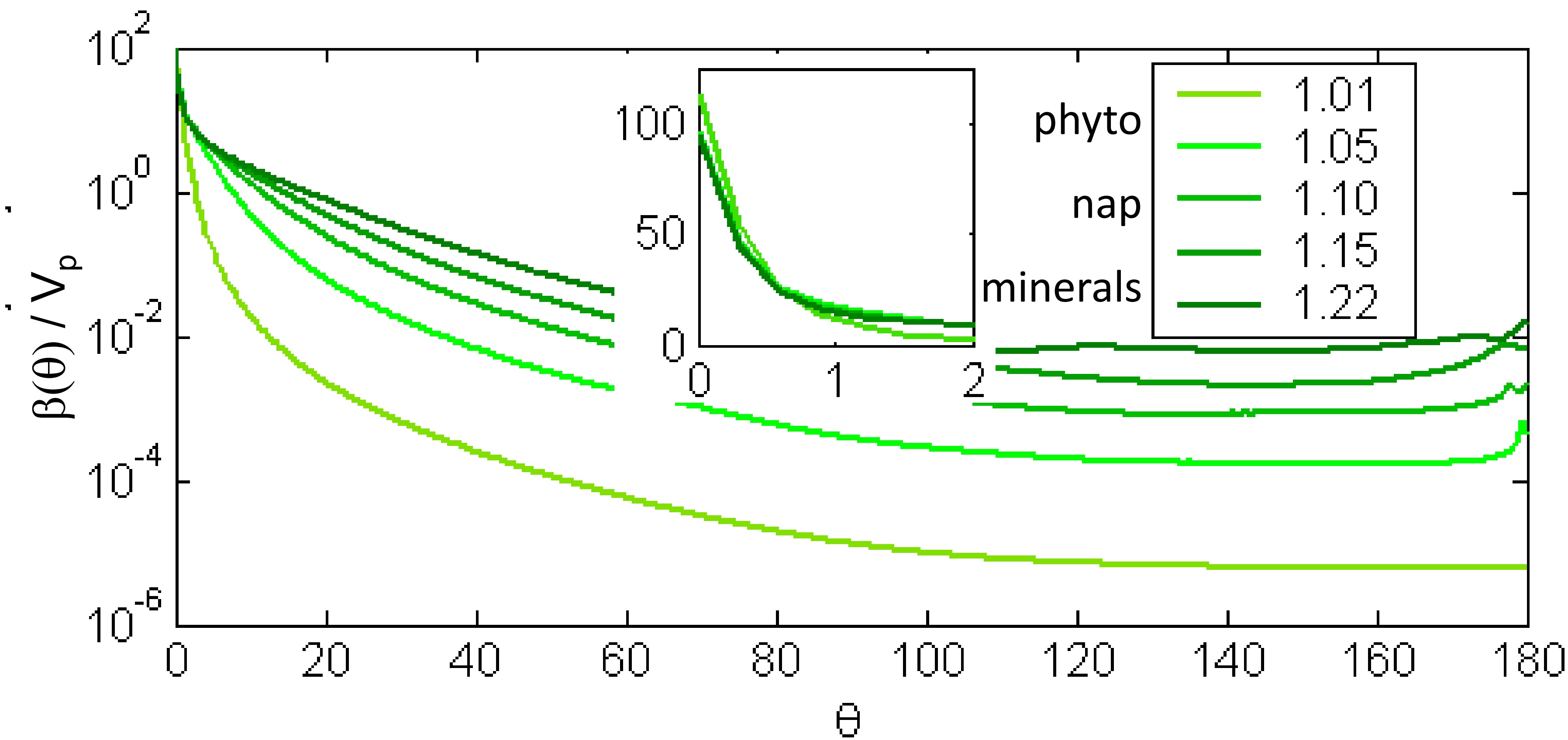


β(θ) as a function of particle size distribution (size slope), holding refractive index constant



Roesler and Boss, 2008

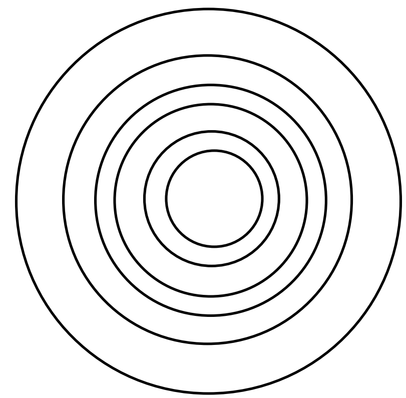
β(θ) as a function of index of refraction, holding size spectrum constant

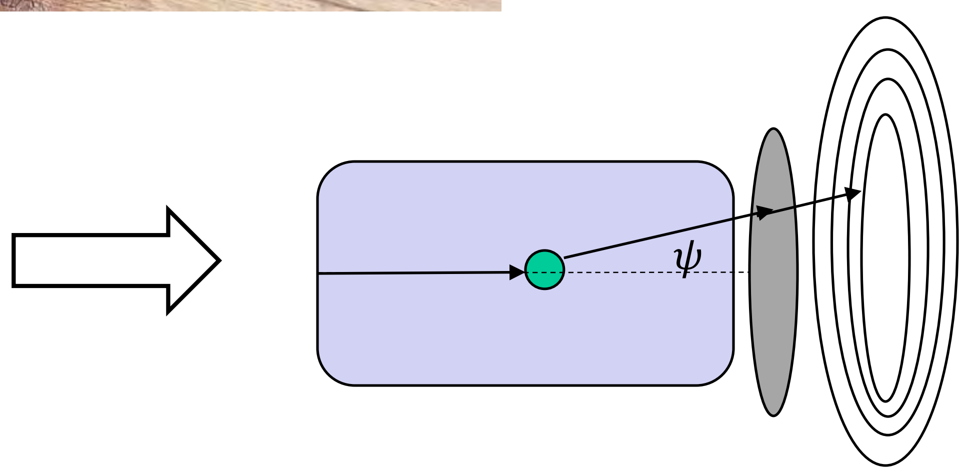


Roesler and Boss, 2008

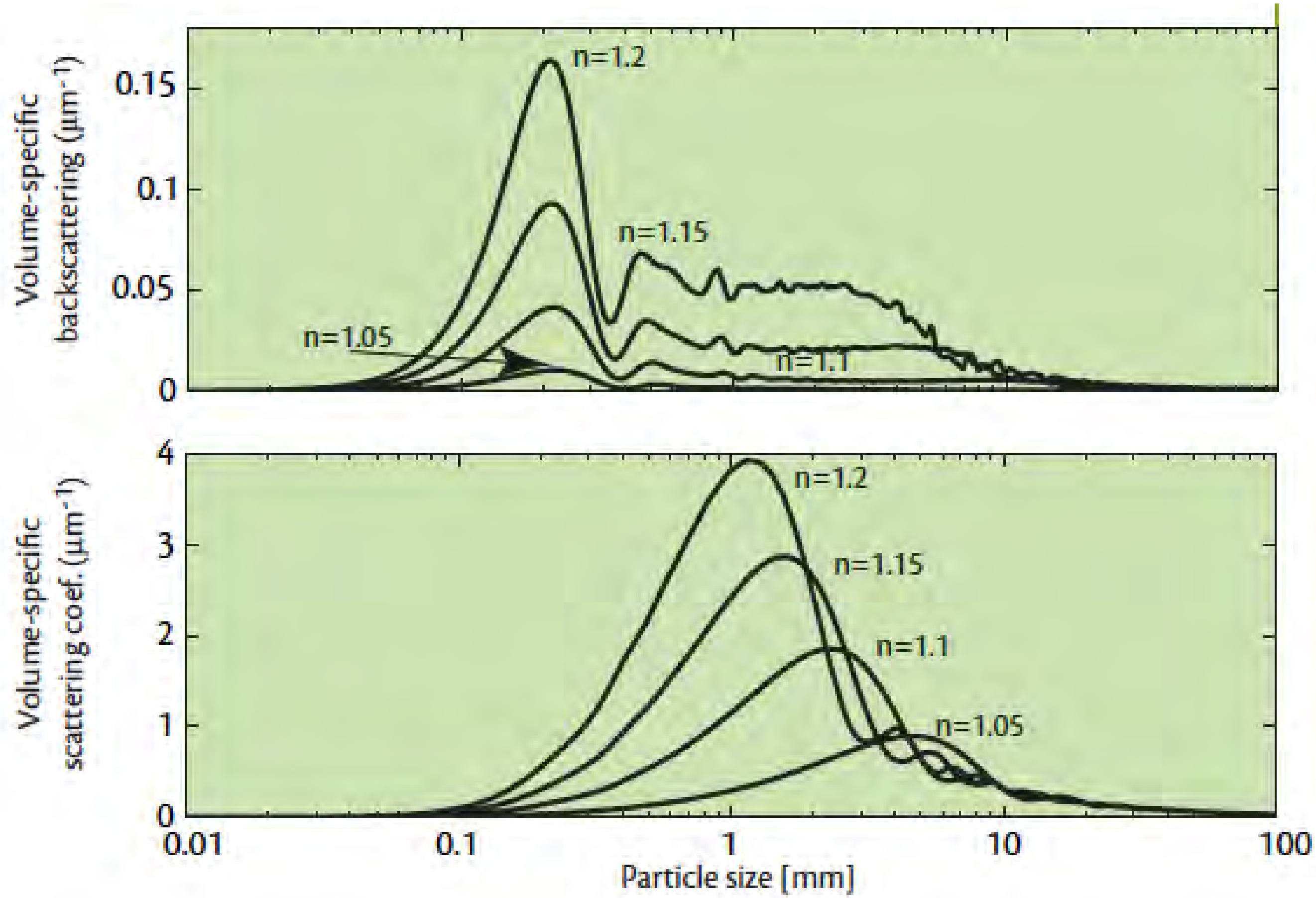
Basis for design of LISST

32 concentric ring detectors





Scattering in the ocean: which particles contribute to backscattering and scattering



Boss et al., 2004, TOS

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

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

- Concentration
- Size
- Shape
- Composition

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