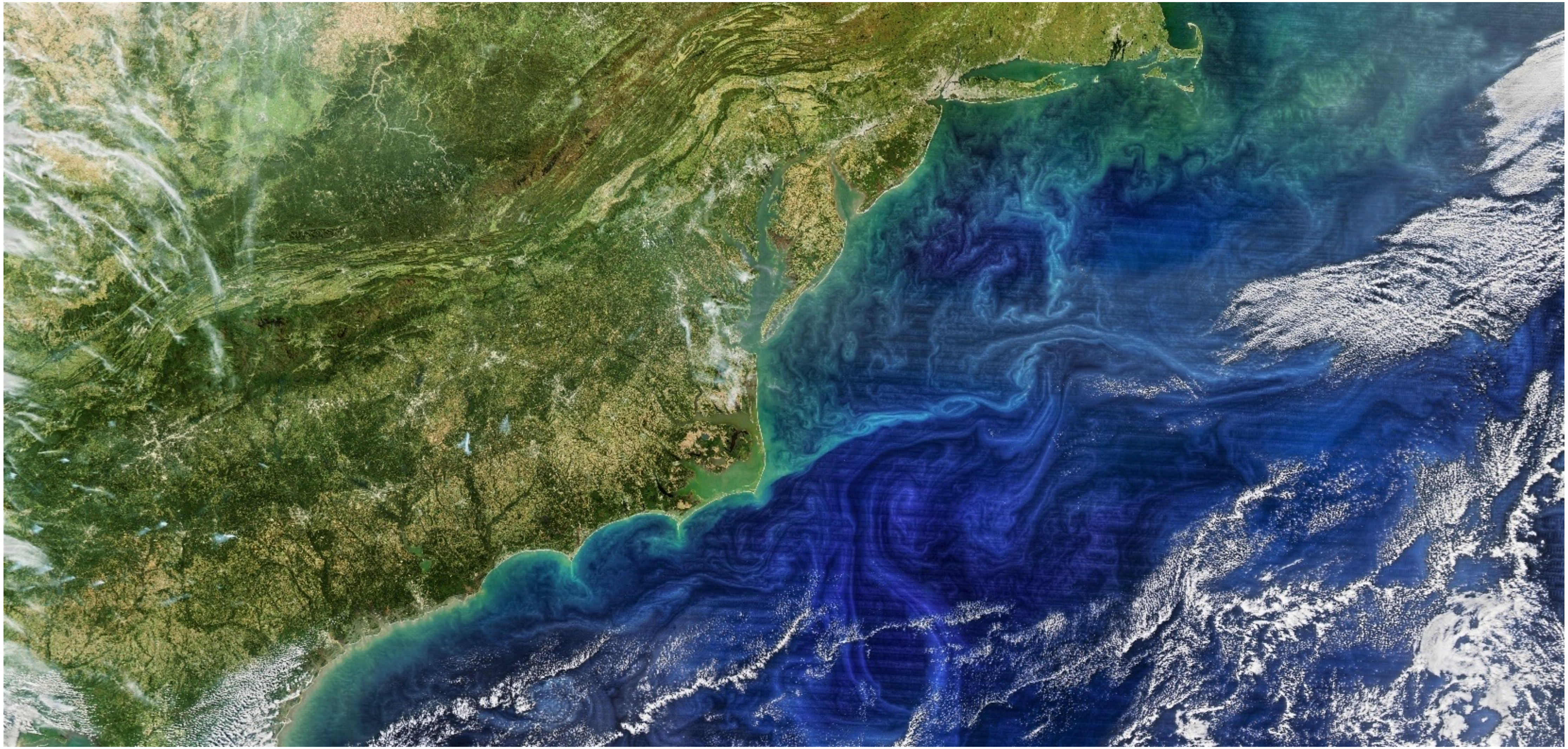
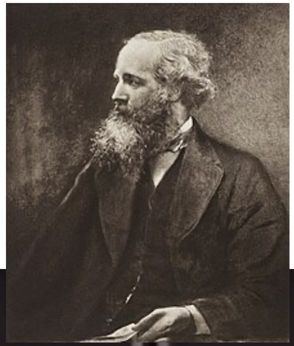
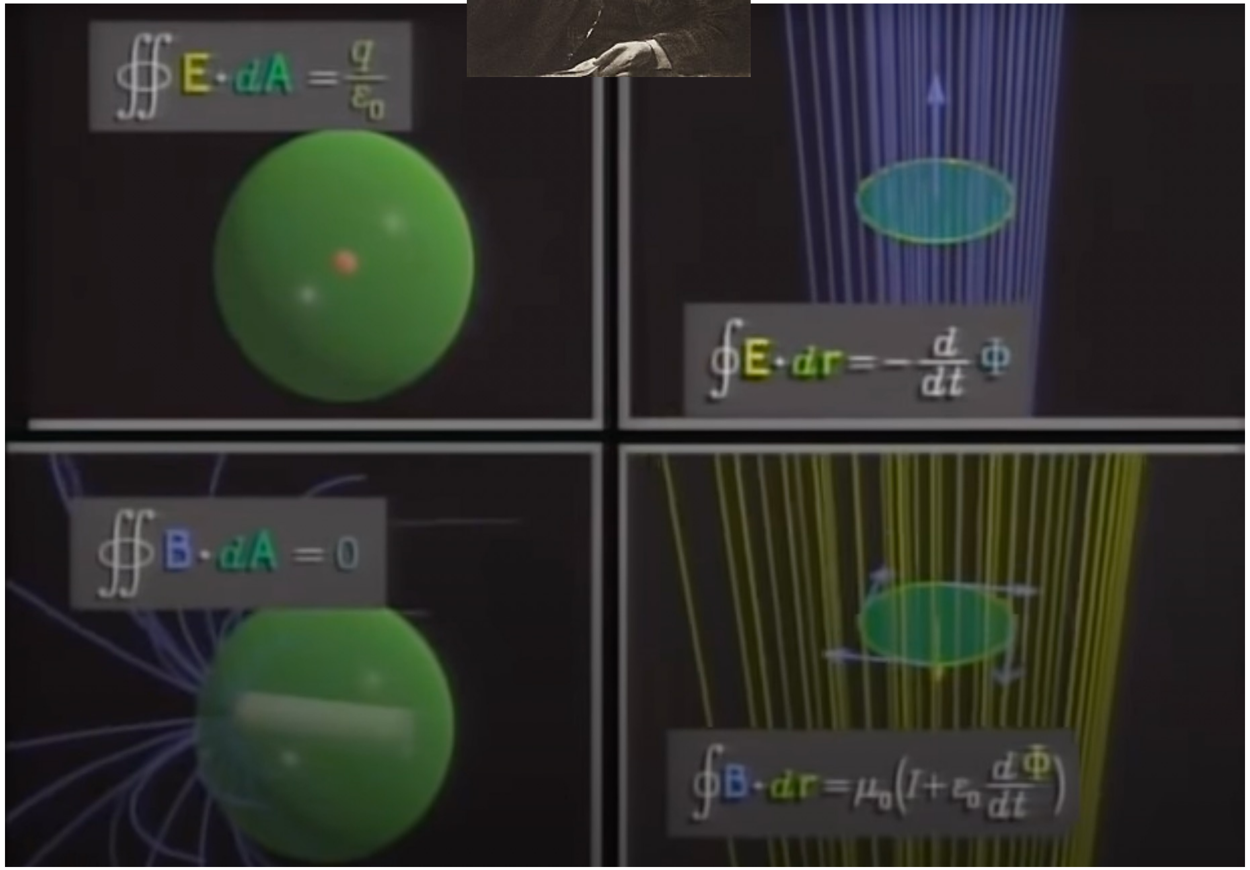
Polarization in Ocean Optics



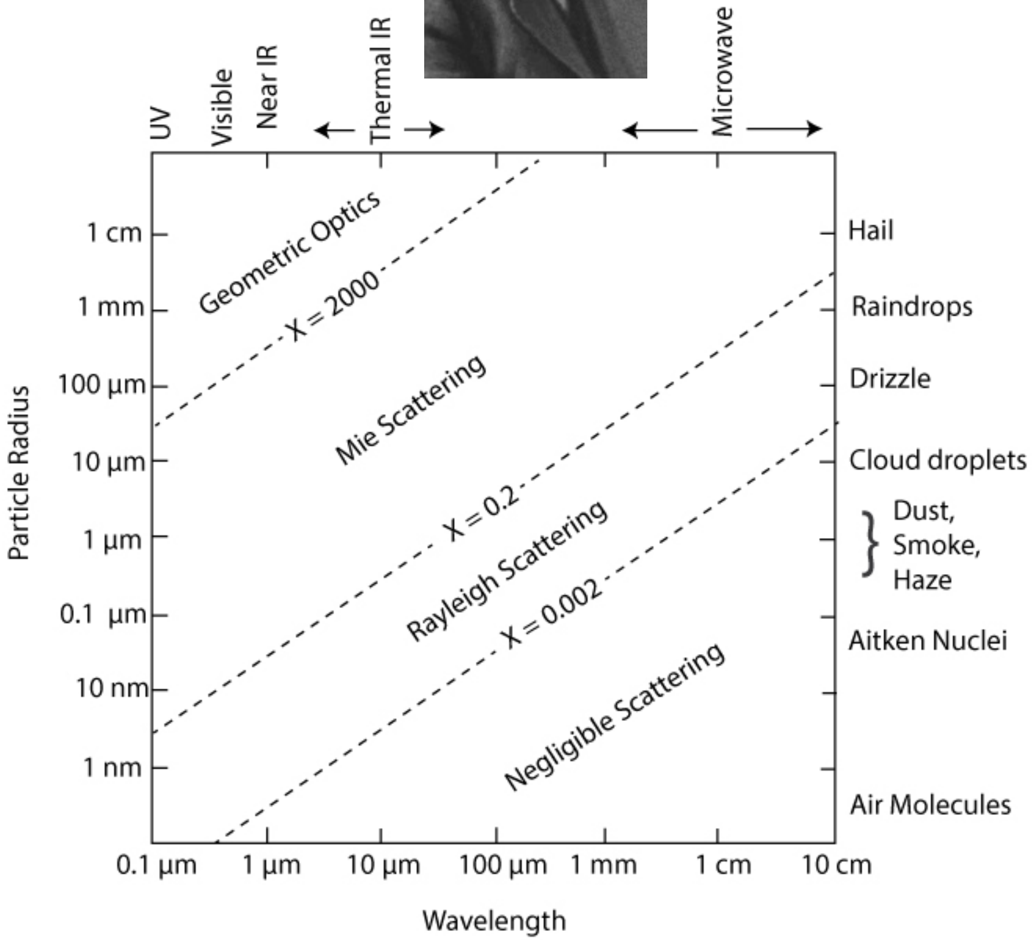
Patrick Gray
Zuckerman Postdoctoral Fellow
U of Maine / U of Haifa

Thanks James and Gustav!





Caltech *Mechanical Universe and Beyond*
Maxwell's Equations https://www.youtube.com/watch?v=SS4tcajTsW8

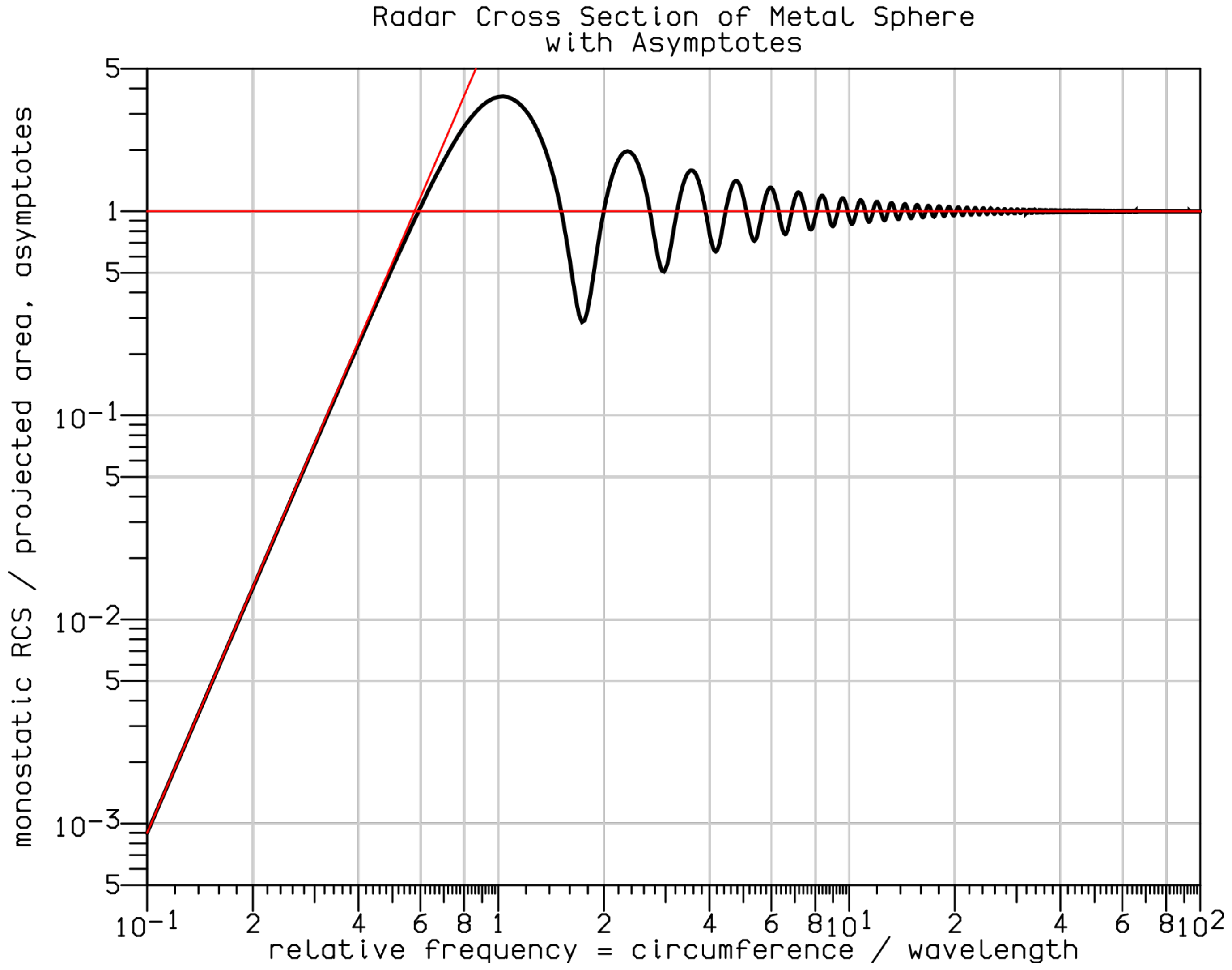


X = (pi*diam*n)/ lambda

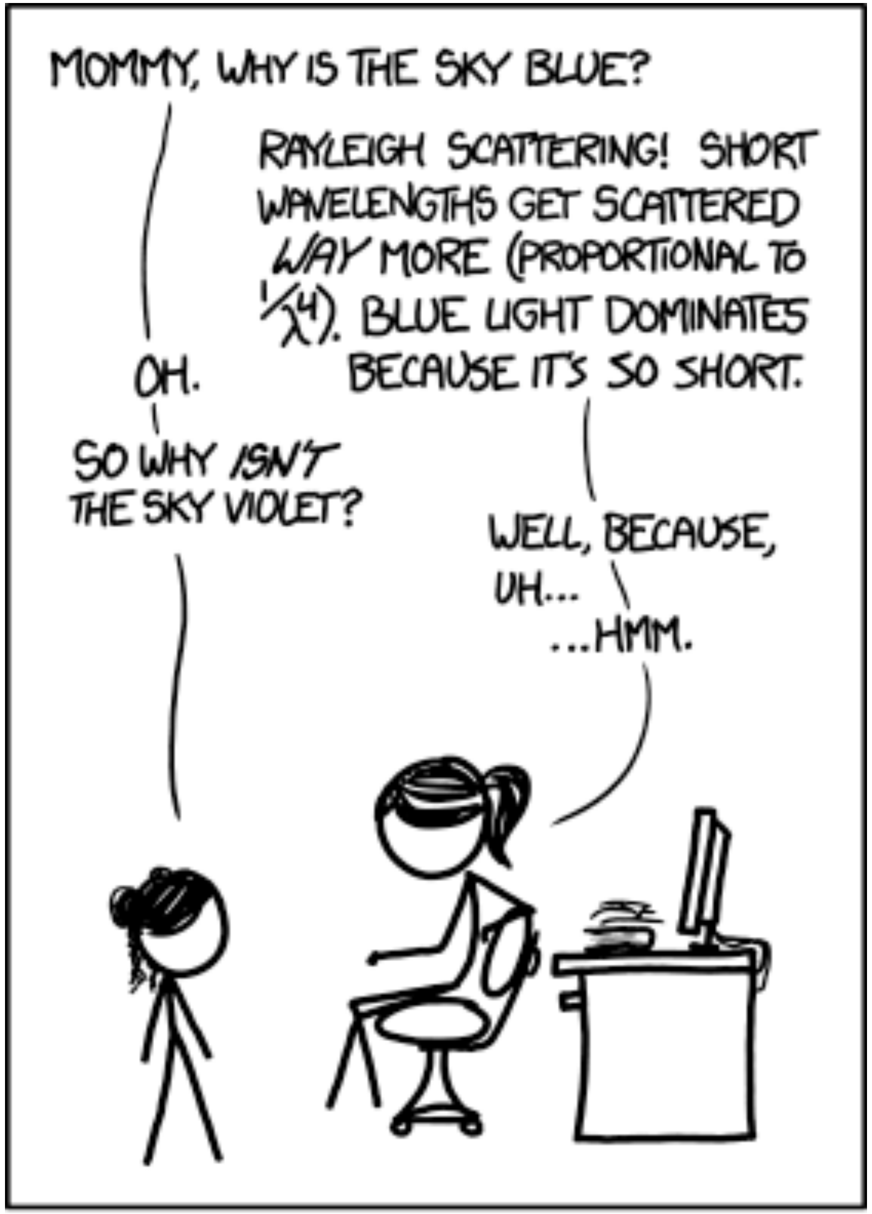
Scattering Brain Teasers

Why is the sky blue?

Why is the sky blue?

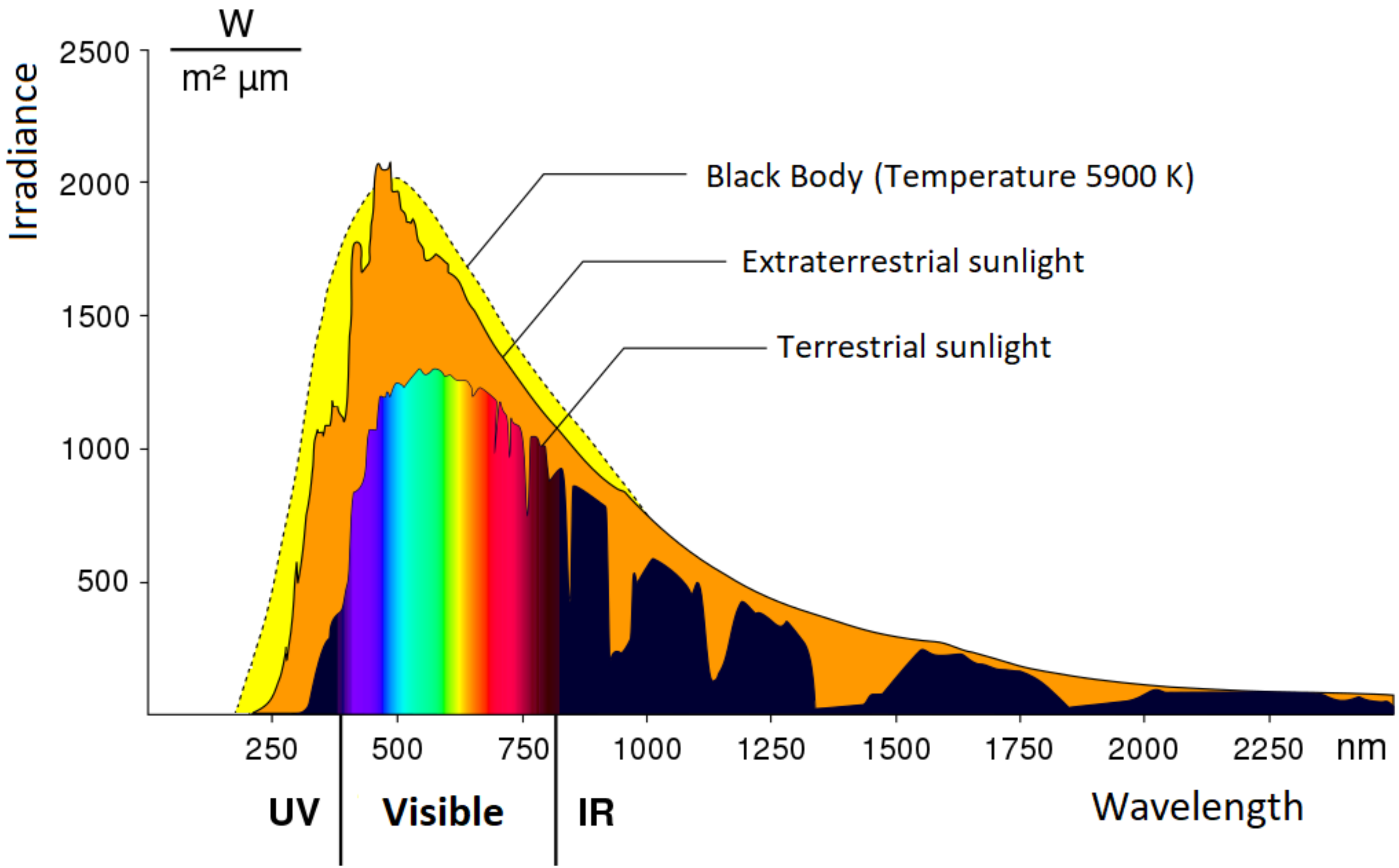


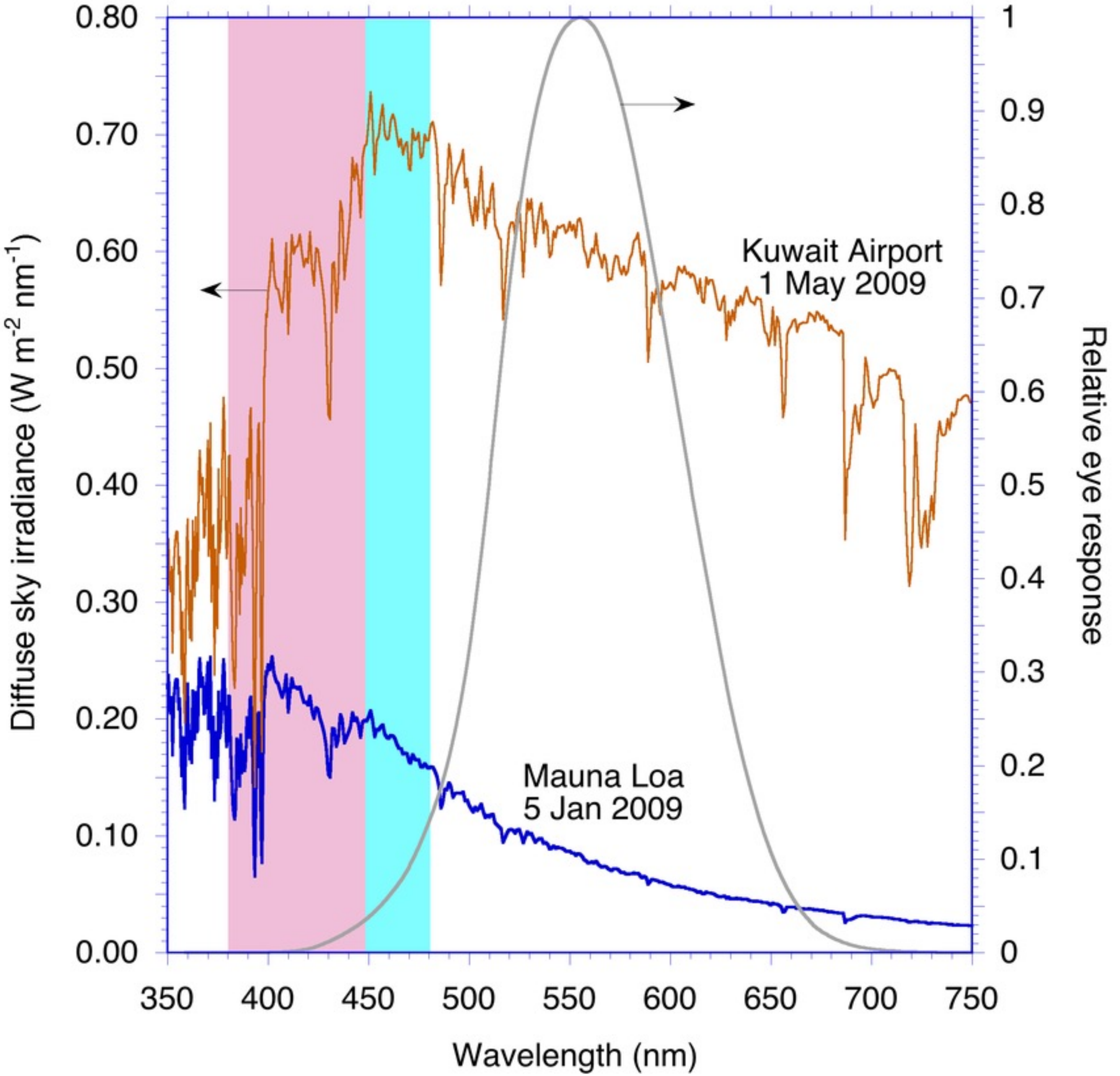
Why isn't the sky violet?



MY HOBBY: TEACHING TRICKY QUESTIONS TO THE CHILDREN OF MY SCIENTIST FRIENDS.

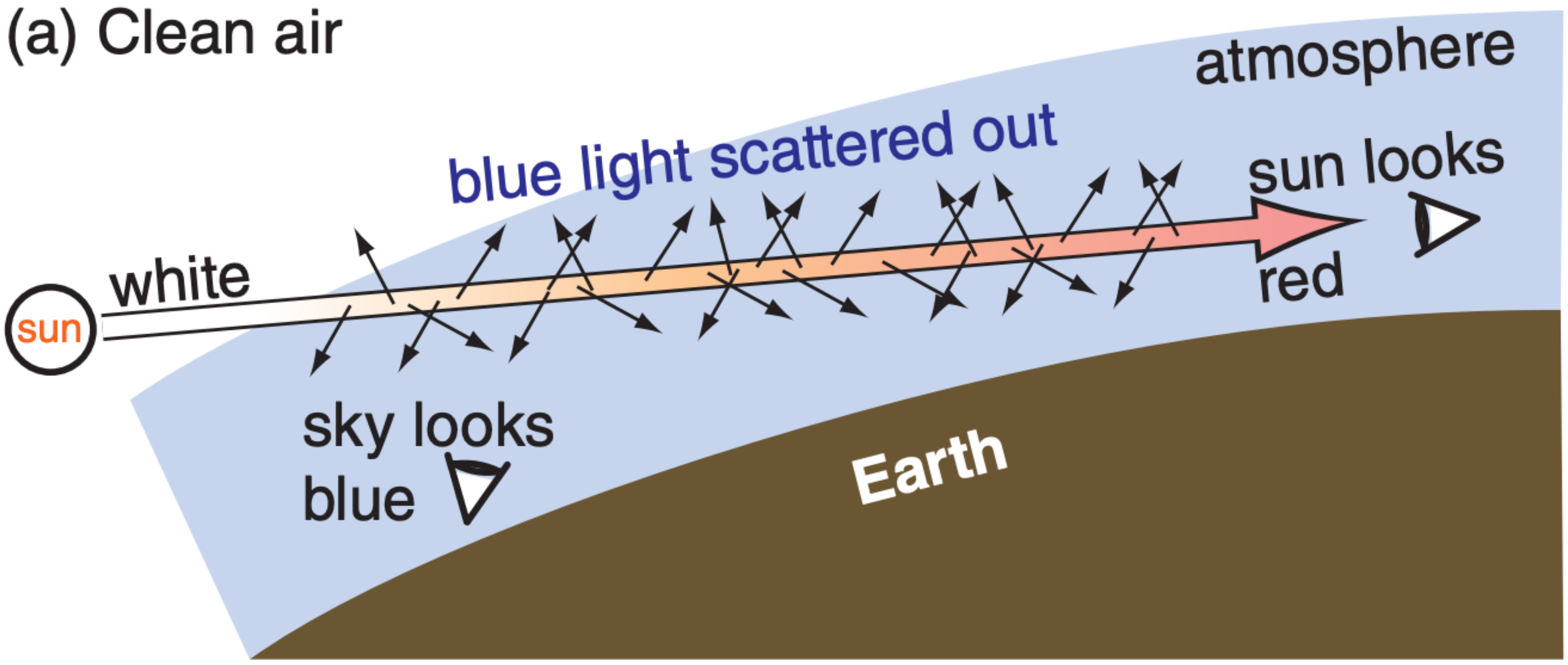
Why isn't the sky violet?

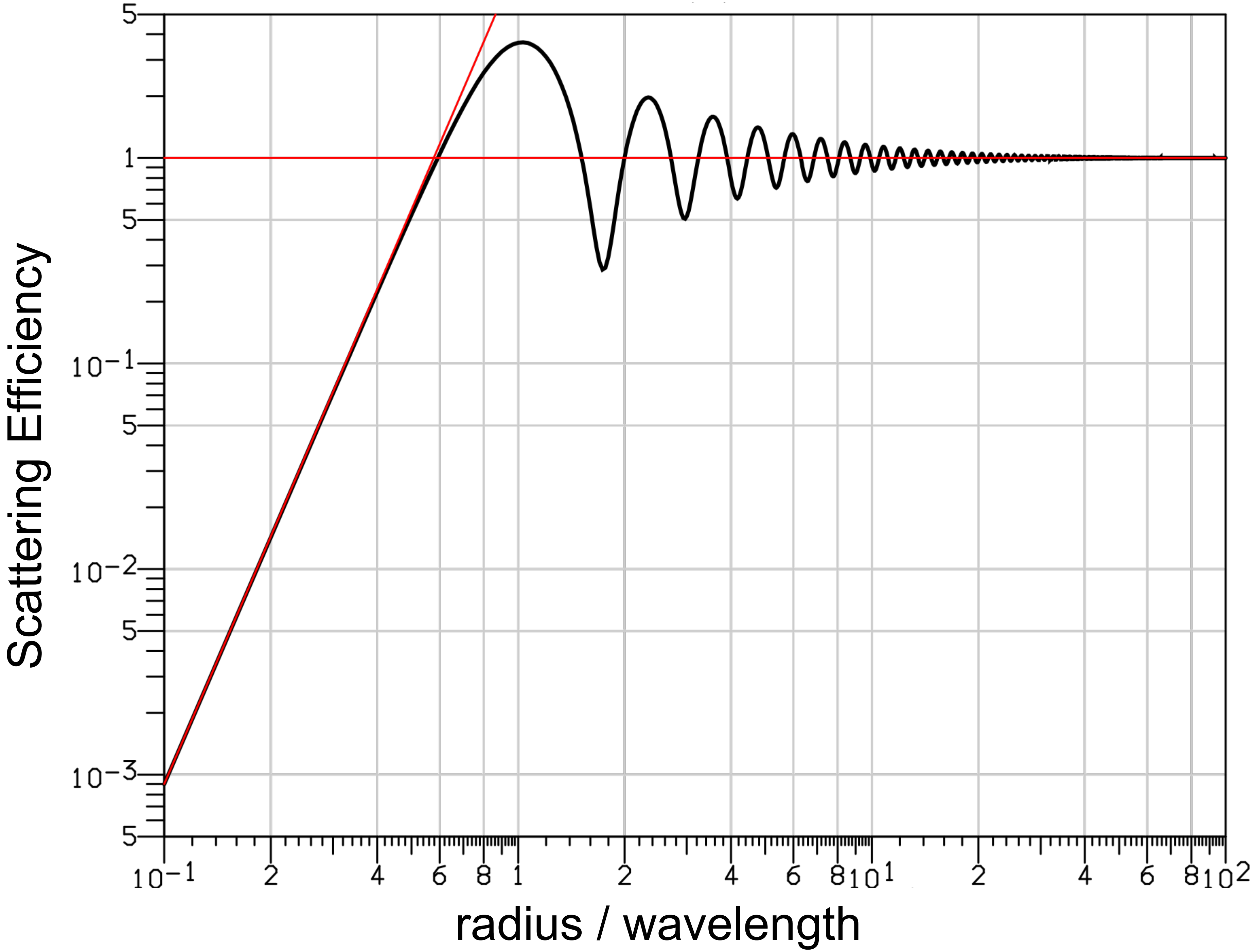



0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Diffuse sky irradiance (W m-2 nm-1)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Relative eye response
Kuwait Airport
1 May 2009
Mauna Loa
5 Jan 2009
350
400
450
500
550
600
650
700
750
Wavelength (nm)

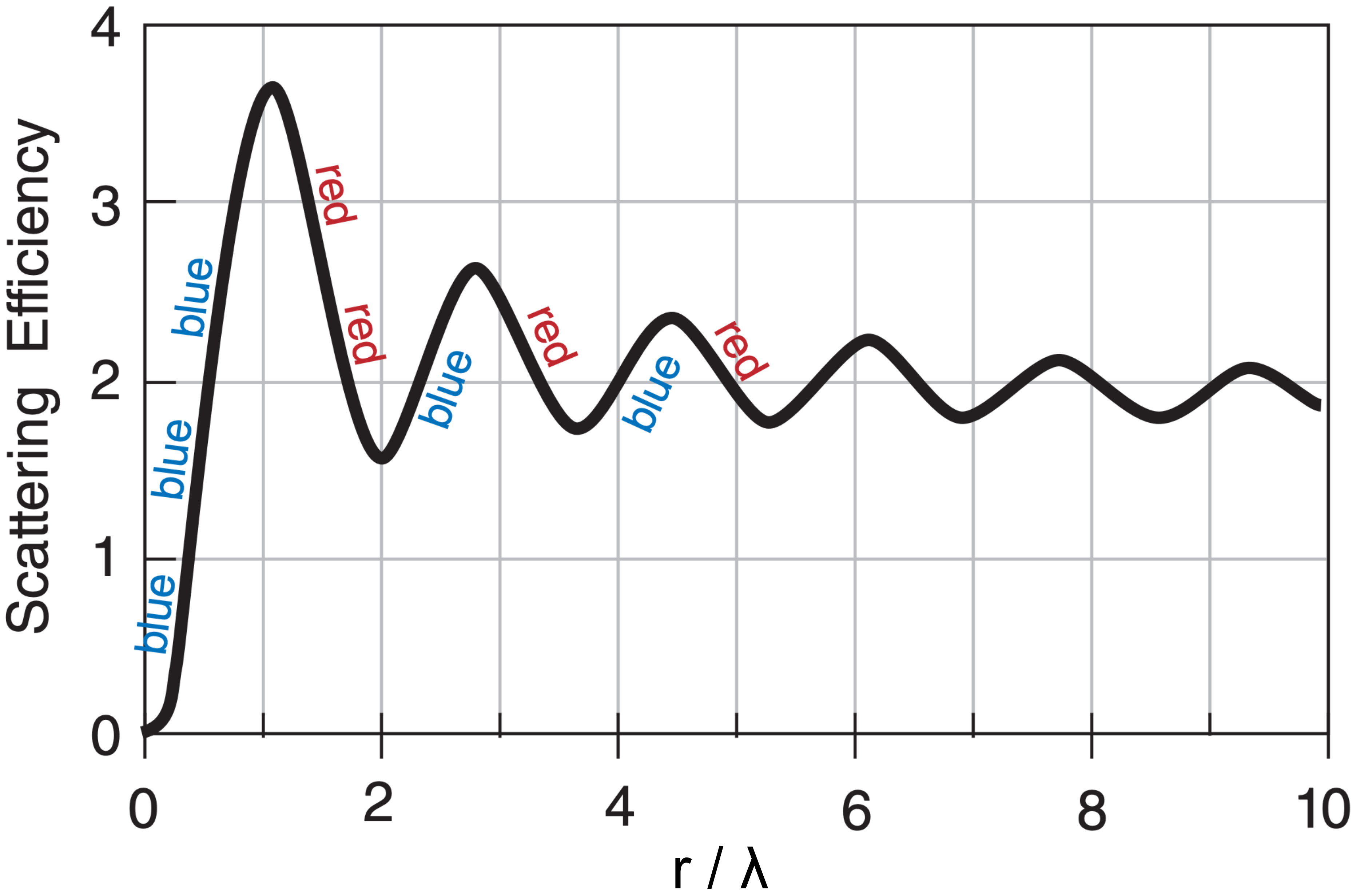
So why are sunsets red?

So why are sunsets red?

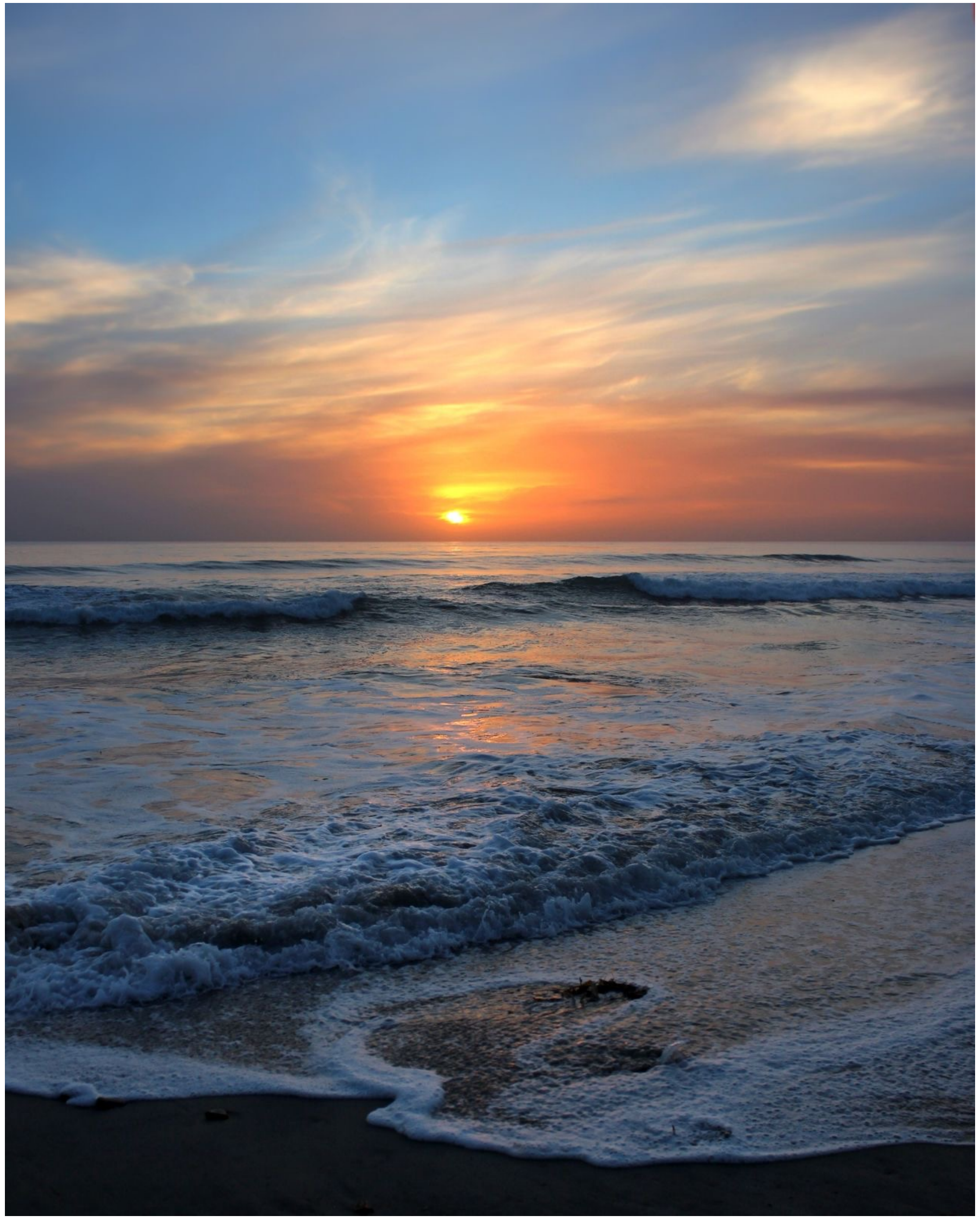


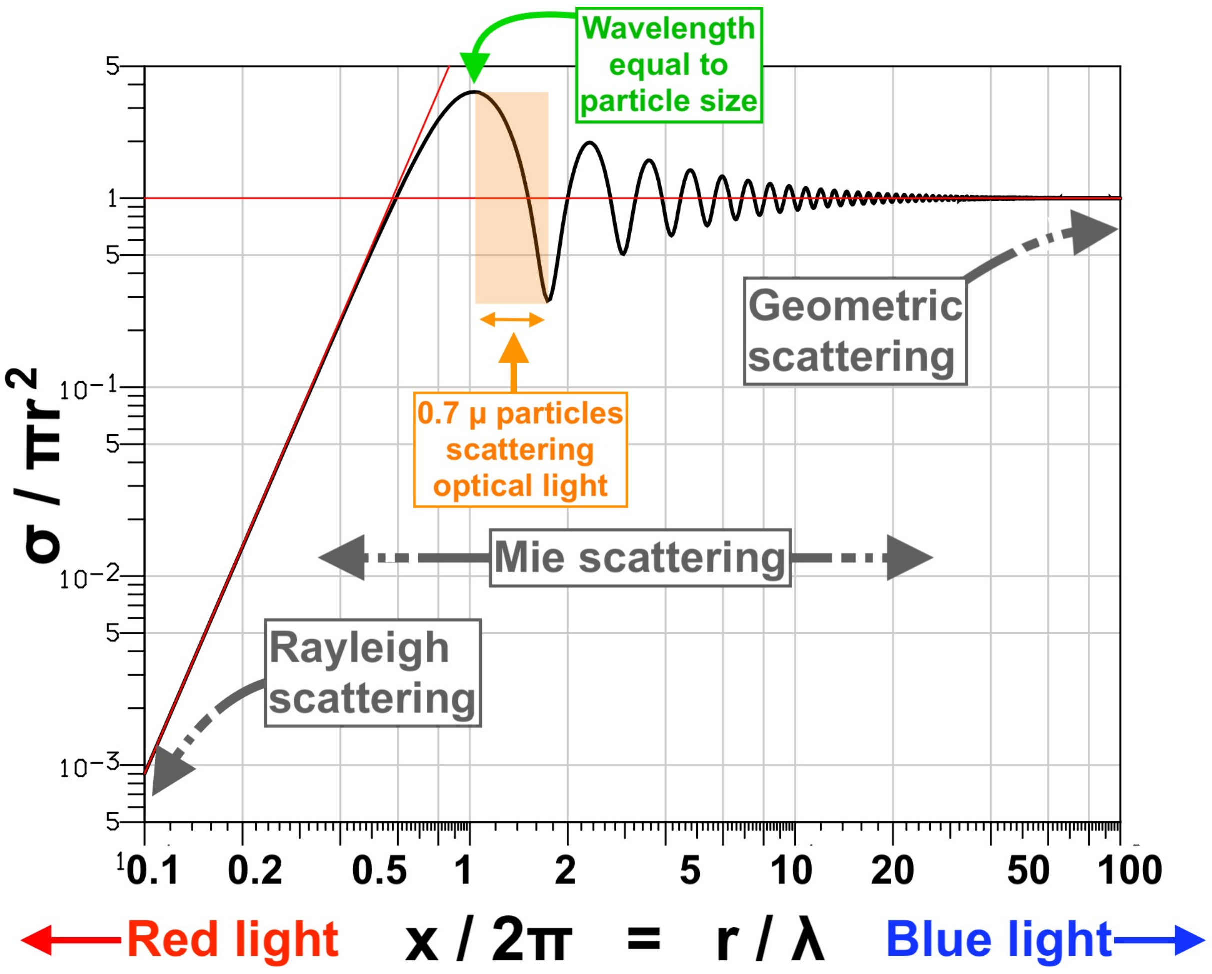


Scattering Efficiency
radius / wavelength
5
1
5
10−1
5
10−2
5
10−3
5
10−1
2
4
6
8
1
2
4
6
8
10¹
2
4
6
8
10²



Scattering Efficiency
r / λ
0
1
2
3
4
0
2
4
6
8
10
blue
blue
blue
red
red
blue
red
blue
red




Wavelength equal to particle size
0.7 μ particles scattering optical light
Geometric scattering
Mie scattering
Rayleigh scattering
σ / πr²
0.1
0.2
0.5
1
2
5
10
20
50
100
Red light
x / 2π = r / λ
Blue light

How can we get a red sky with particles $r << \lambda$?

Intuition check

How can we get a red sky with particles r << λ?

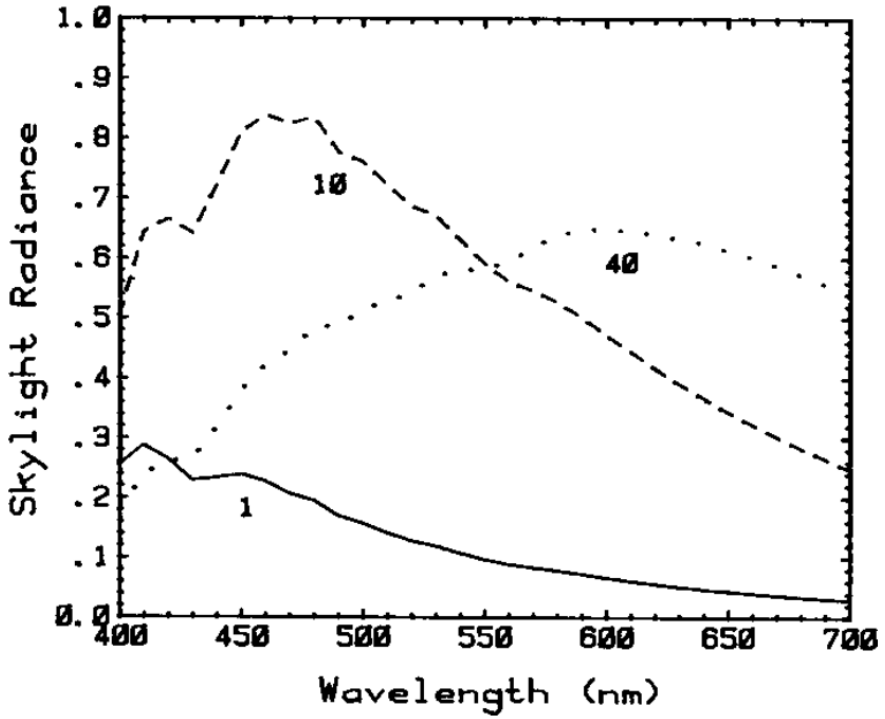
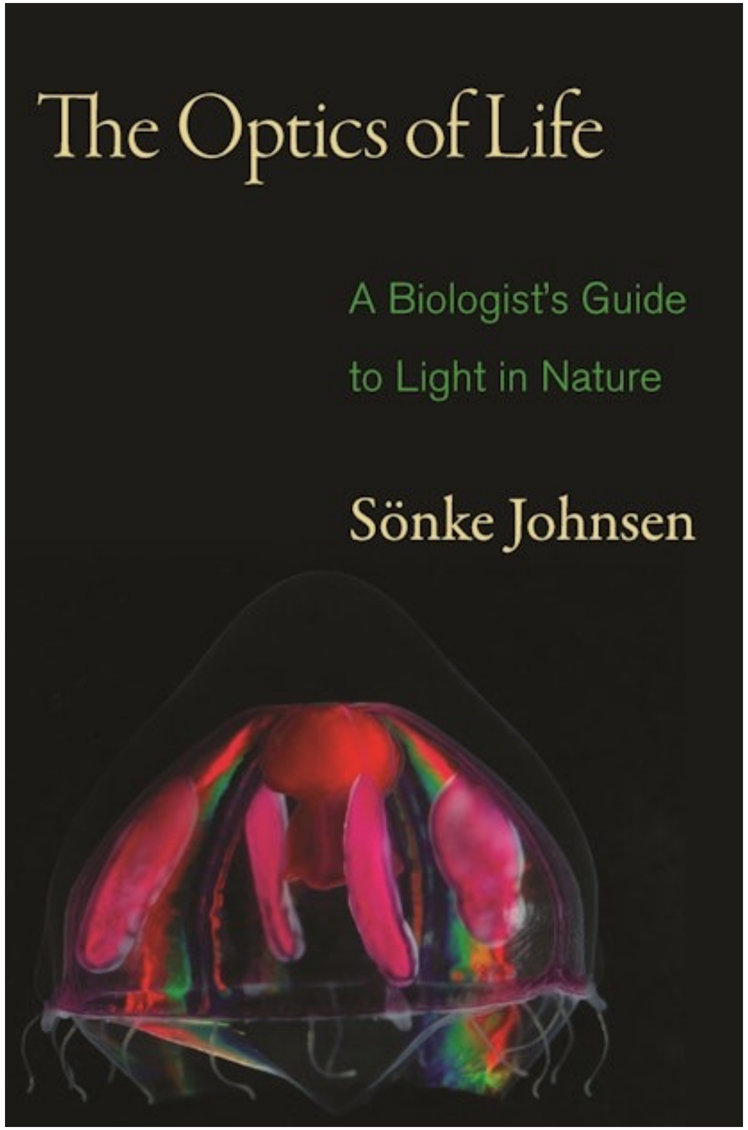


Fig. 5 Spectrum of overhead skylight for the present molecular atmosphere (solid curve), as well as for hypothetical atmospheres 10 (dashes) and 40 (dots) times thicker

On to polarization of light

"As with radiometry, polarization can be a confusing topic. Unfortunately, unlike radiometry, its complexity is not primarily due to confusing units."

-Johnsen



Why else do we care?

- Size, shape, and refractive index can influence polarization
  - Maybe we can gain new insight!

Fundamentals

- What is a dielectric?
- Polarizability?
- What is permittivity?

Resonance

- Natural frequency of an object
  - Swings
  - Tides
  - Bathtub
  - Guitar strings
  - Dipoles!
- Much of what we see from Mie is actually the impact of resonances between the dipole (swing) and wavelength of light (push)

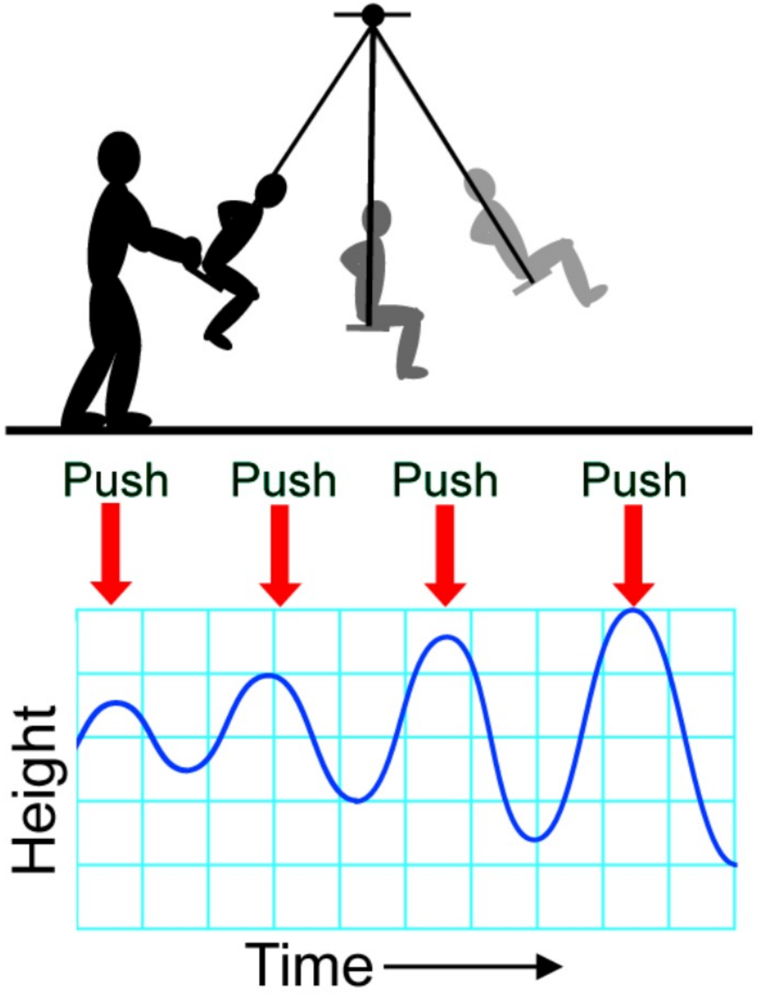
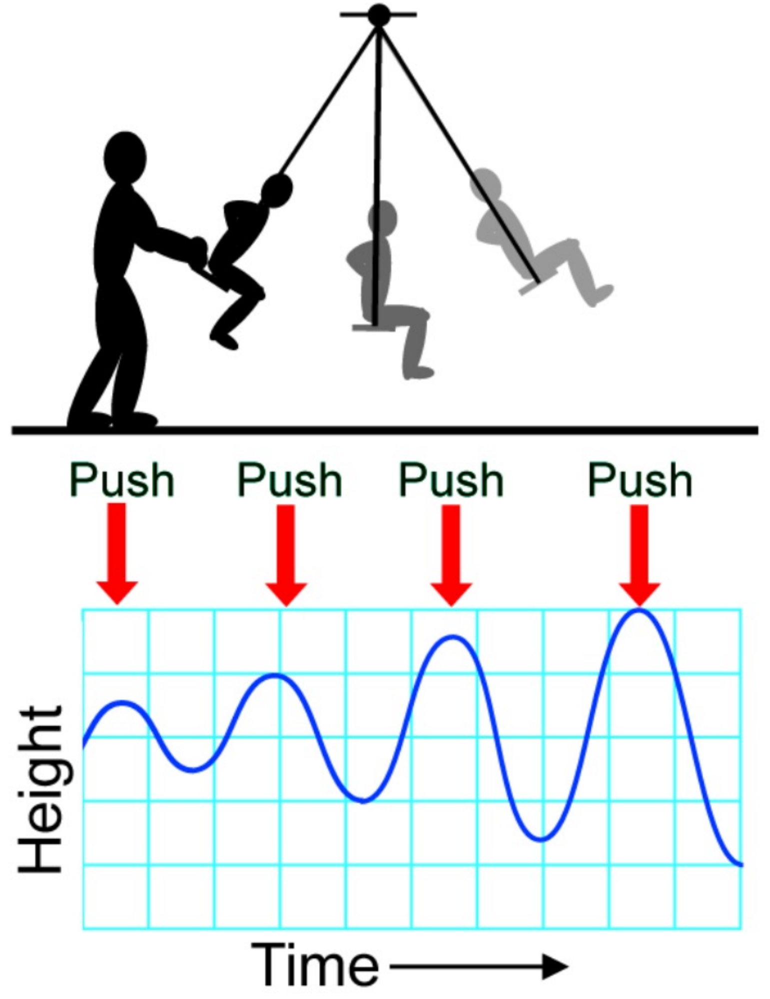
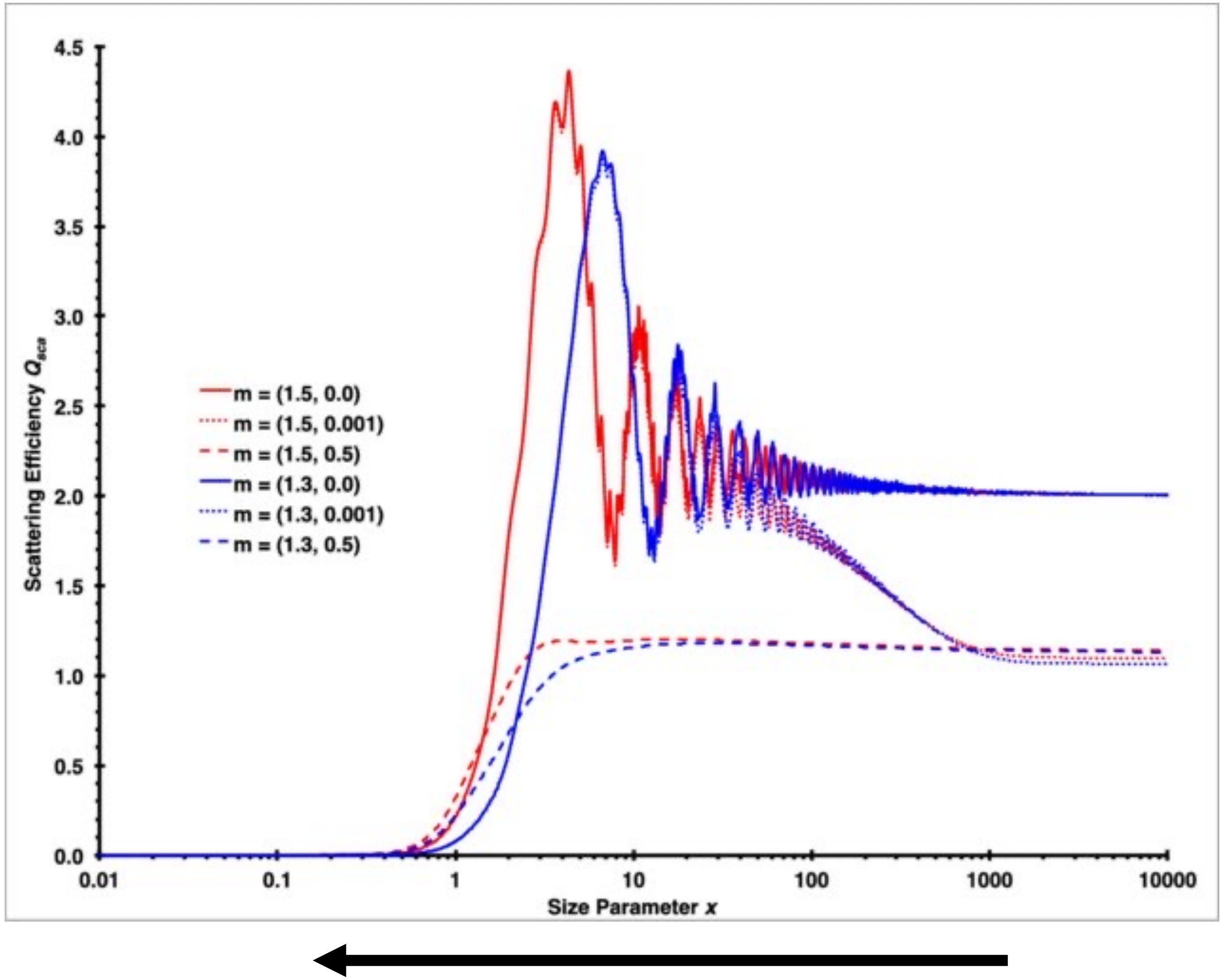


Figure 19.16: *Each push of a swing at the right time increases the amplitude (height) of the swing. Each push is a periodic force.*





Harmonic input (EM wave) getting faster

Permittivity determines the refractive index

- The applied electric field tends to align the polar molecules, but random thermal motions tend to randomize the directions.
- It takes time for the molecules to rotate into alignment, so if the applied field is not constant, P depends on the frequency of the applied field.
  - This is the origin of the frequency wavelength dependence of the index of refraction!

Permittivity determines the refractive index

Dipole structure → polarizability → permittivity → refractive index

ref index + → dipole resonances → interaction w/ → scattering efficiency
size/lambda + light field
Morphology

Fundamentally refractive index is about how electrons interact with the EM wave

Permittivity determines the refractive index

Dipole structure → polarizability → permittivity → refractive index

???

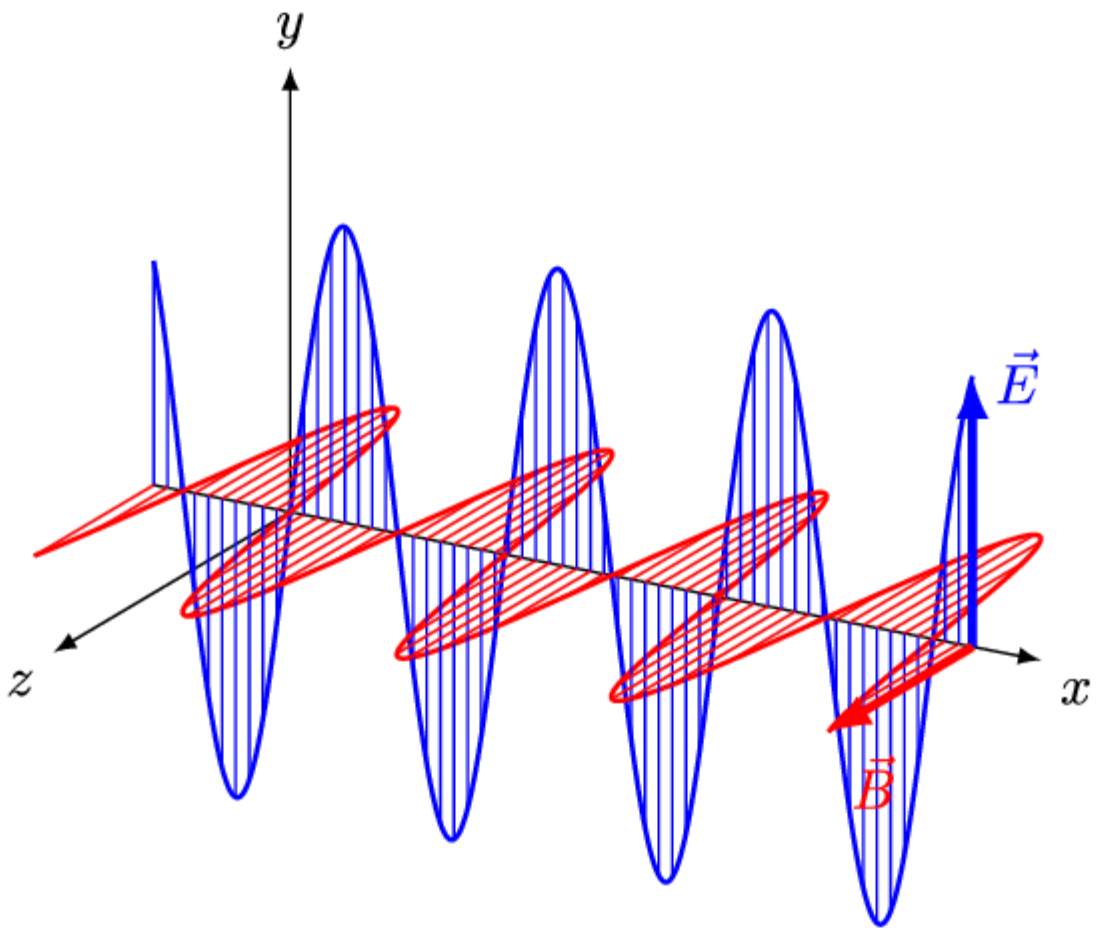
ref index + → dipole resonances → interaction w/ → scattering efficiency
size/lambda + light field
Morphology

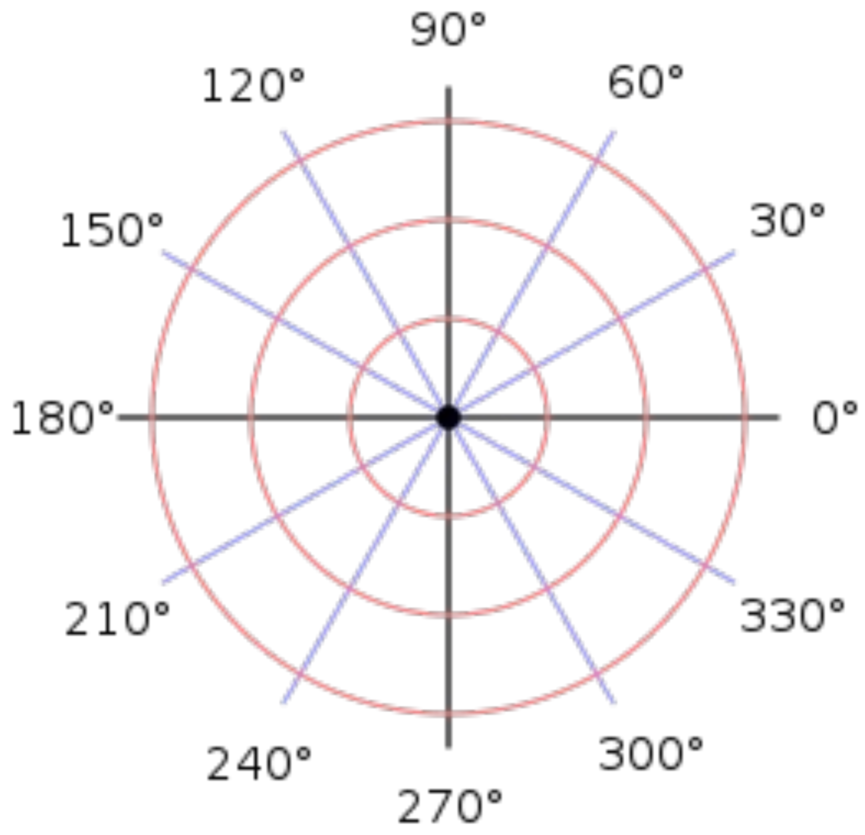
Fundamentally refractive index is about how electrons interact with the EM wave

To first order:

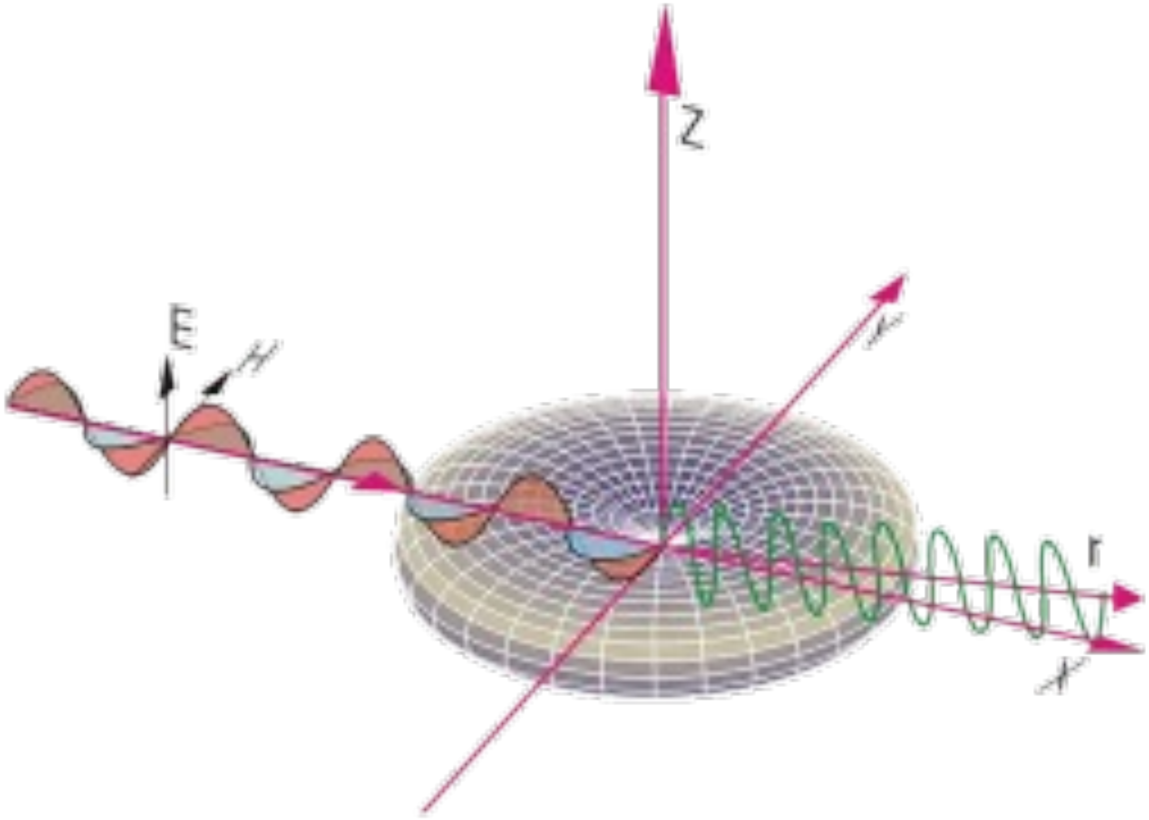
- EM waves make dipoles oscillate (wiggle)
  - direction they wiggle and radiate depends on polarization
- high refractive index → more mineral
- low refractive index → more organic

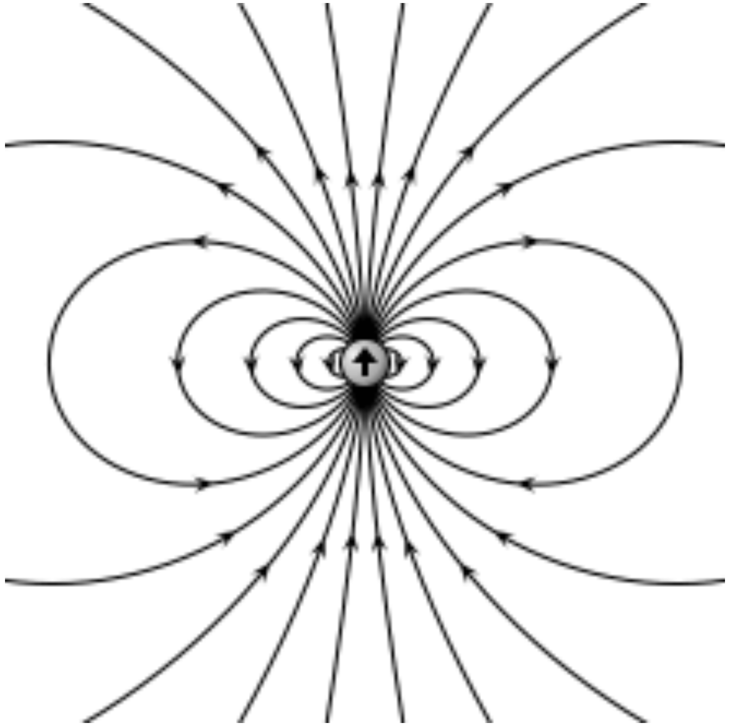
So what even is polarization?





So why is scattered light often polarized?





Polarized scattering: https://www.youtube.com/watch?v=QrOOwT2JWqo

Let’s make some polarized rope

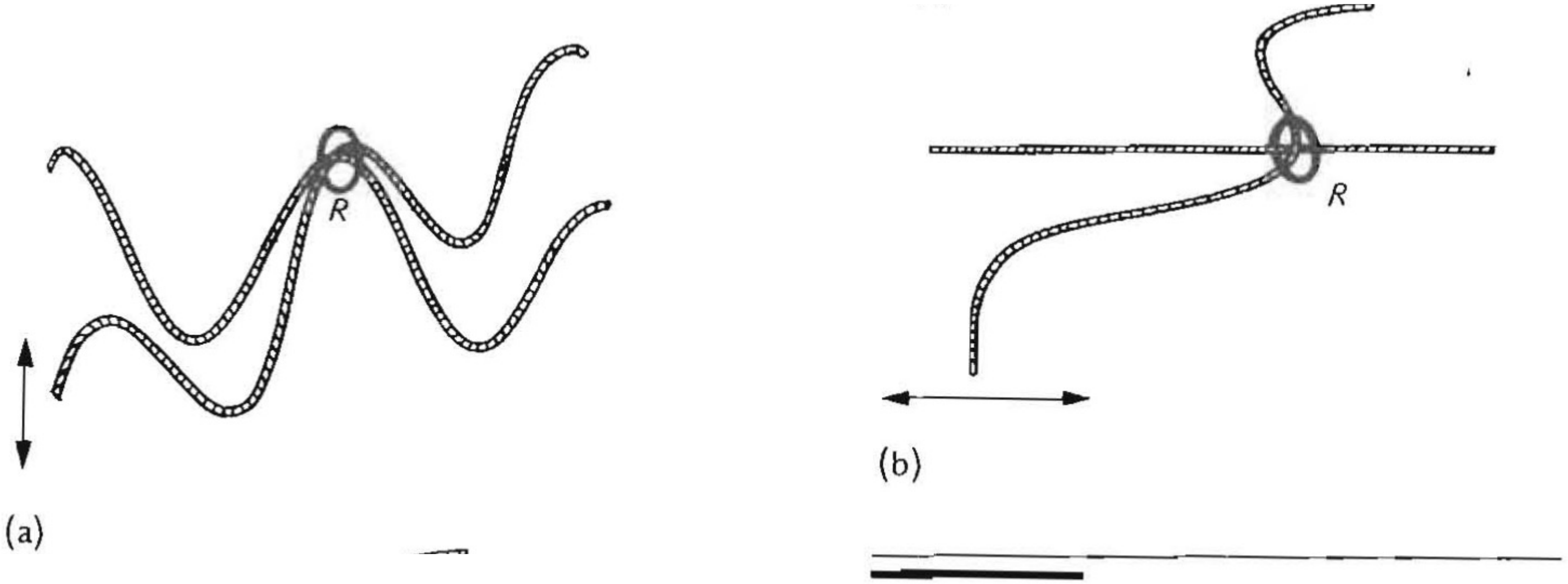
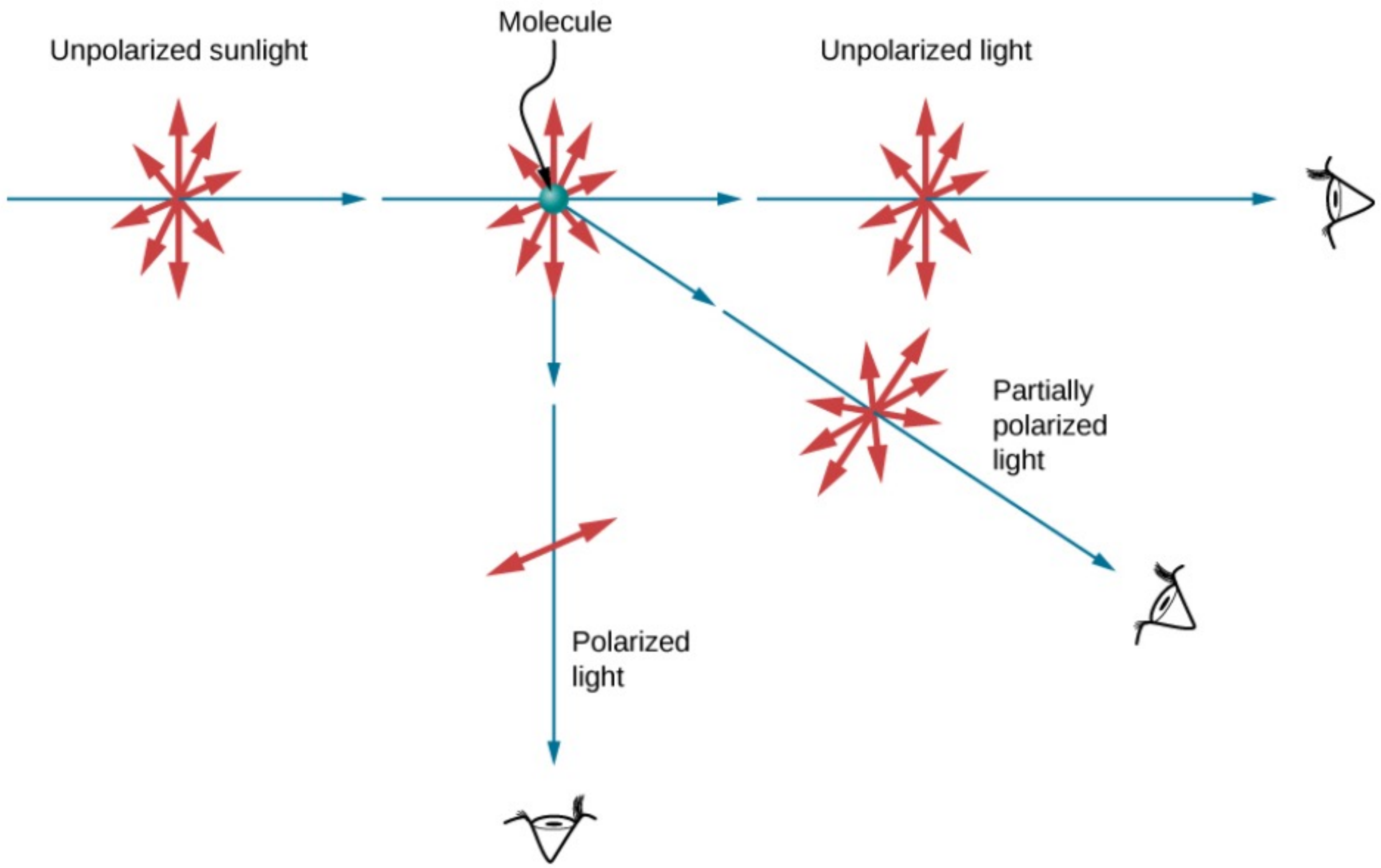
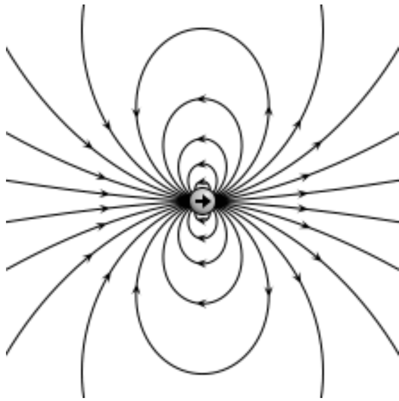


FIGURE 13.3


Molecule
Unpolarized sunlight
Unpolarized light
Partially
polarized
light
Polarized
light



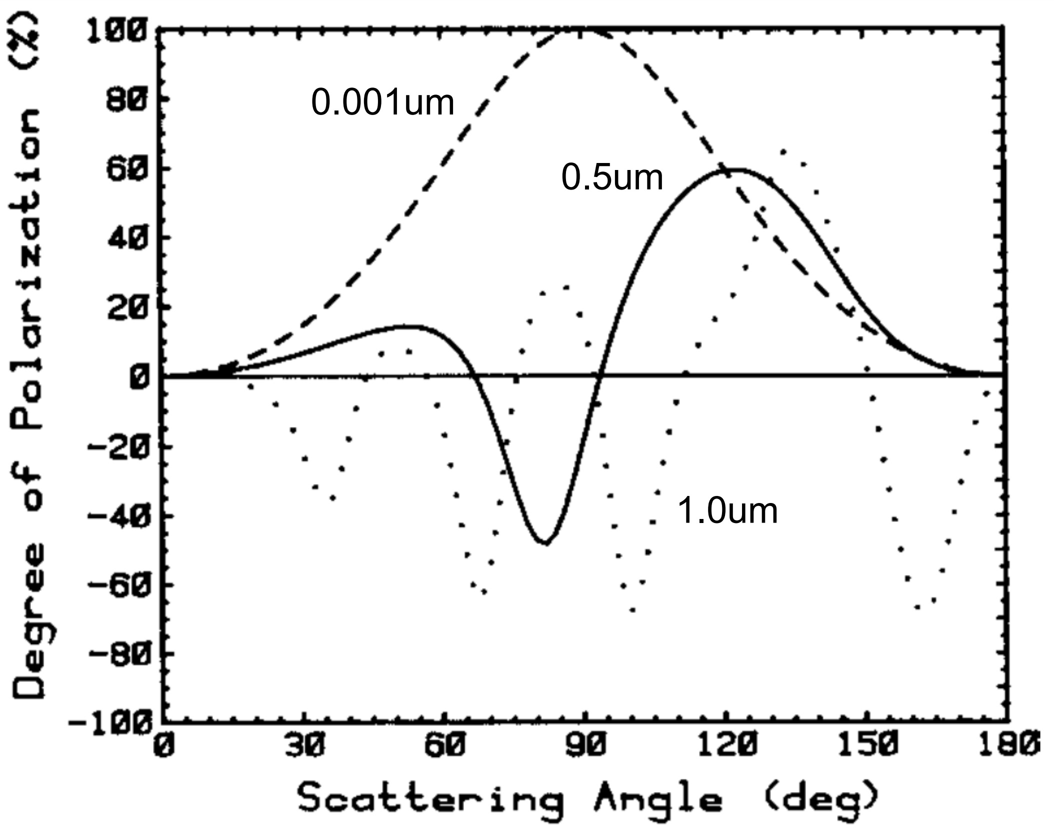
Multiple scattering impacts?

When r << λ isn't true?

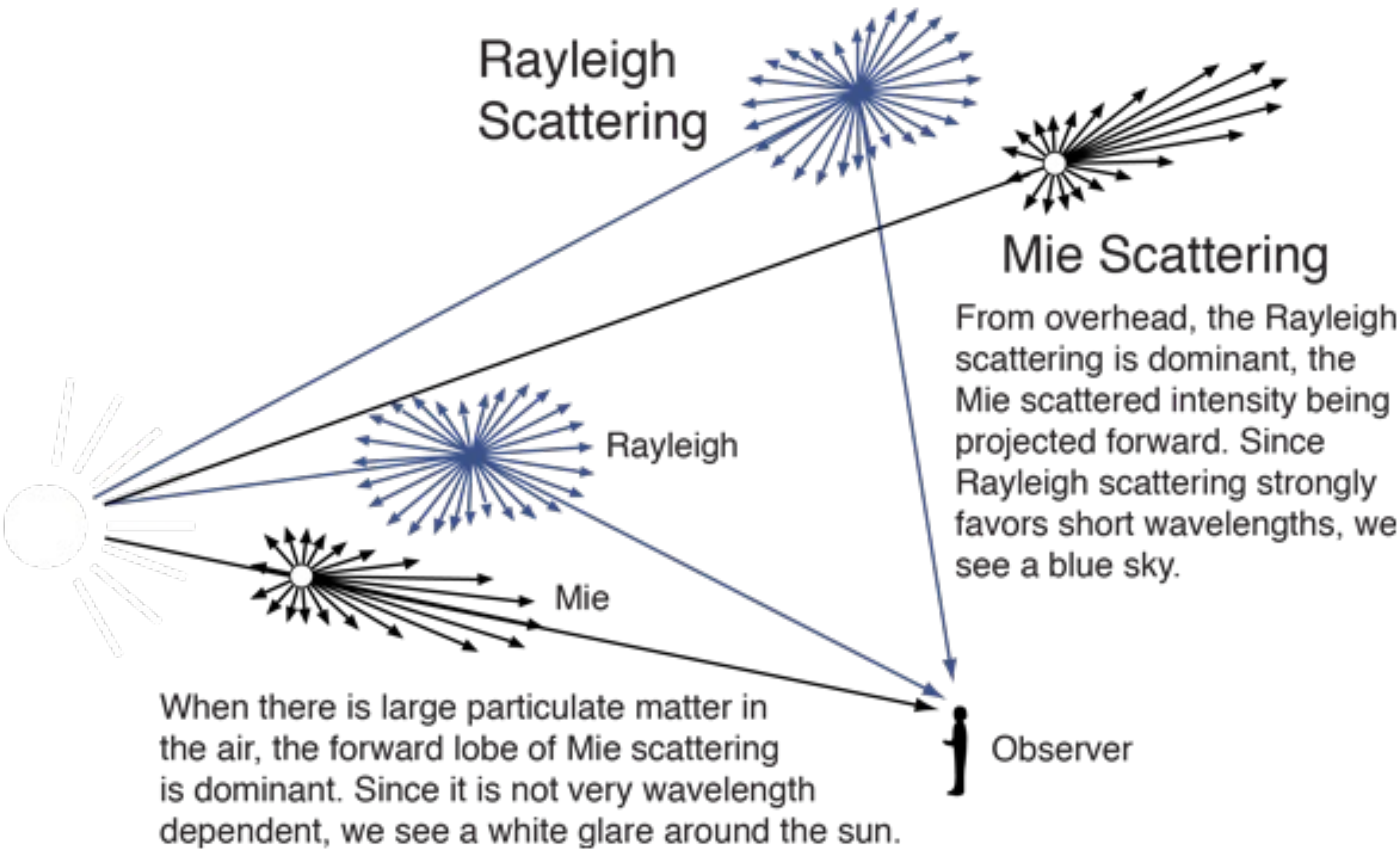
"**All the simple rules about polarization upon scattering are broken when we turn from molecules and small particles to particles comparable to the wavelength.**

… the degree of polarization of light scattered by small particles is a simple function of scattering angle. But simplicity gives way to complexity as particles grow"

-Bohren, *Atmospheric Optics*



λ = .55um


Rayleigh Scattering
Mie Scattering
From overhead, the Rayleigh scattering is dominant, the Mie scattered intensity being projected forward. Since Rayleigh scattering strongly favors short wavelengths, we see a blue sky.
Rayleigh
Mie
Observer
When there is large particulate matter in the air, the forward lobe of Mie scattering is dominant. Since it is not very wavelength dependent, we see a white glare around the sun.

So what is in the size range to polarize predictably?

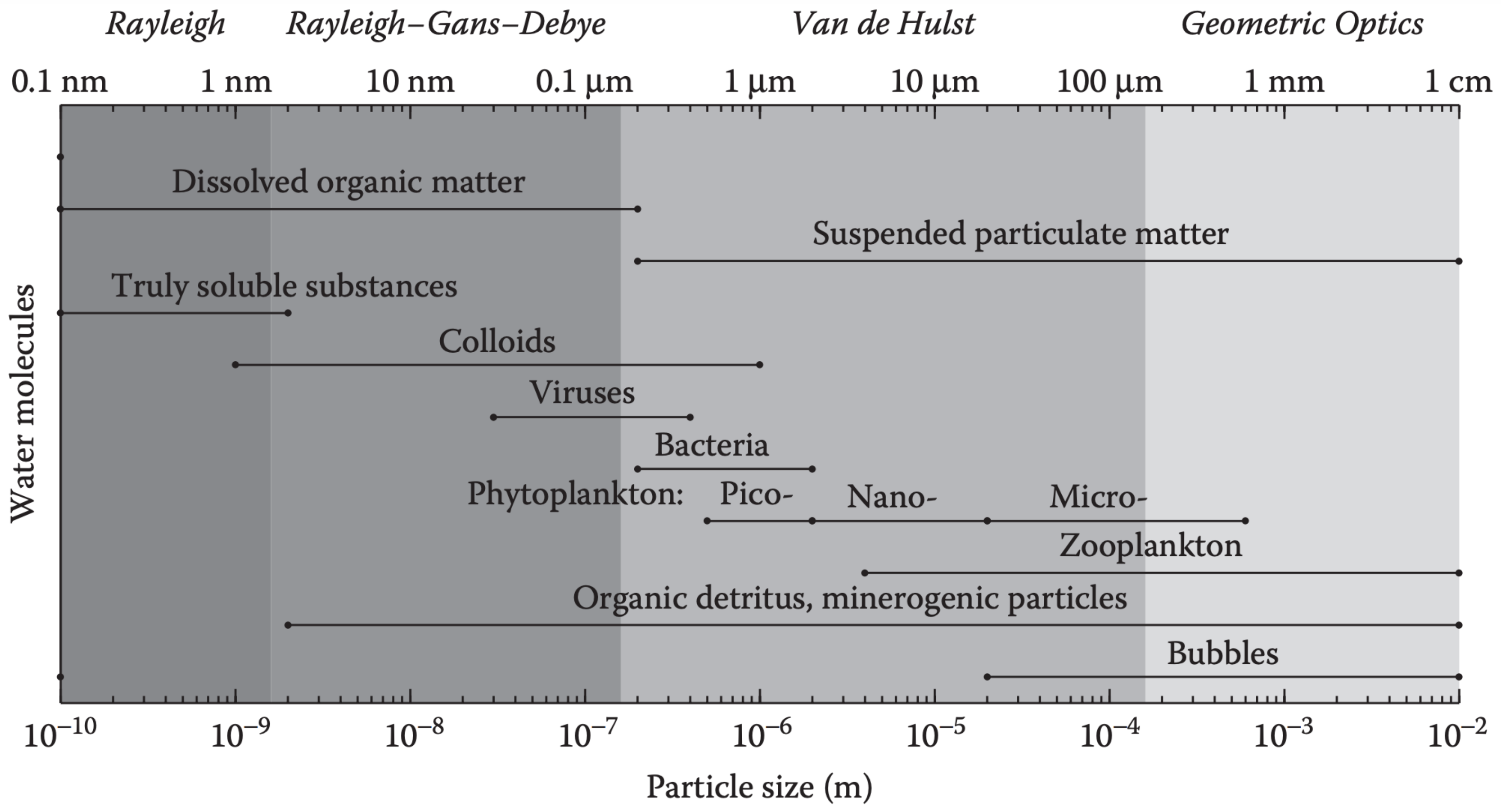
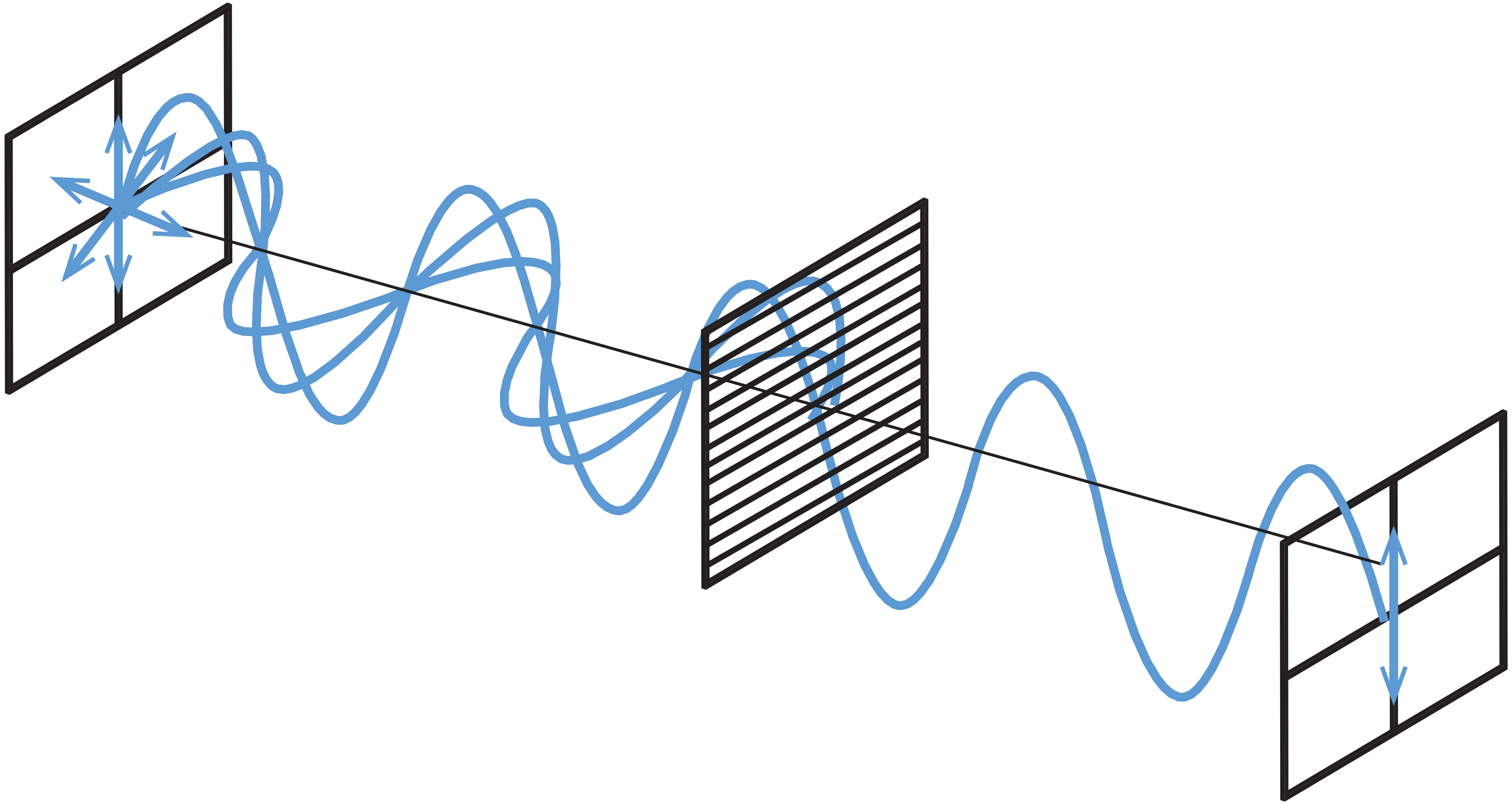


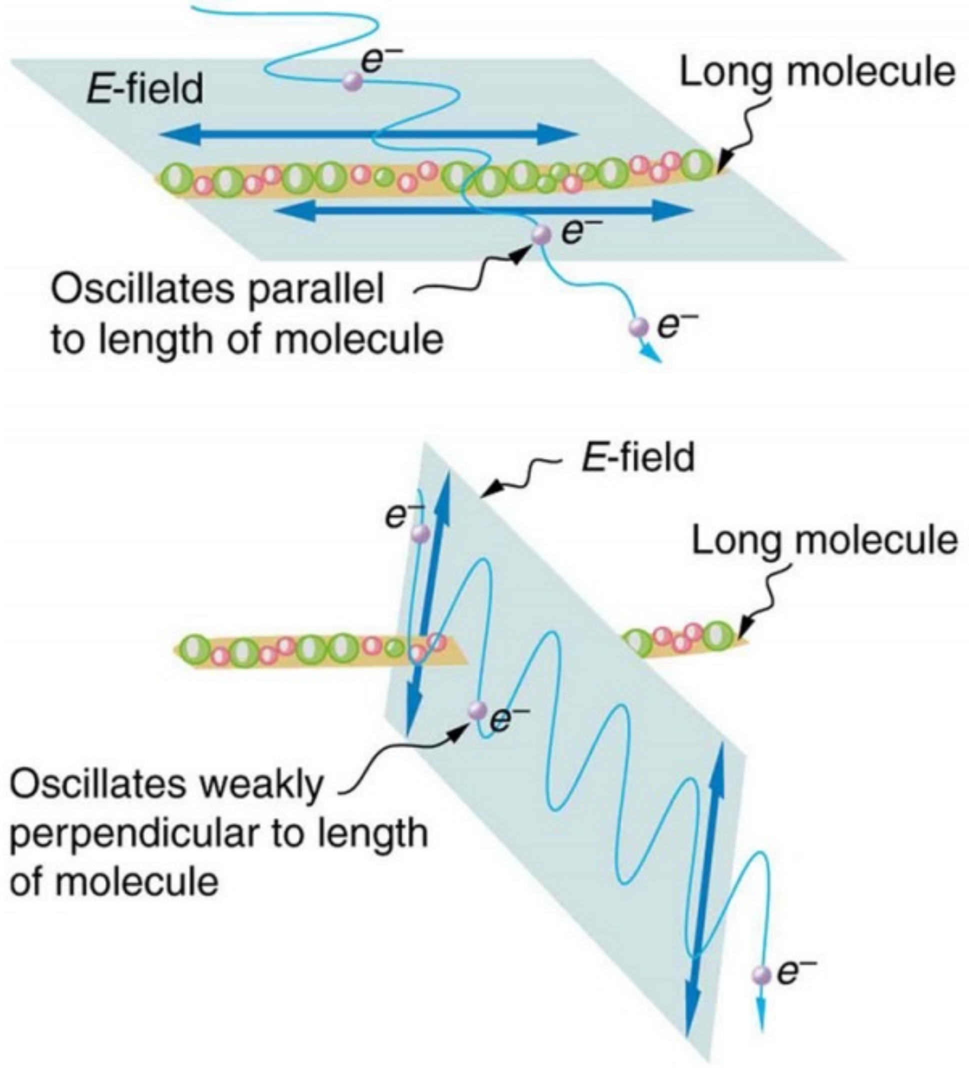
Figure 2 Representative sizes of different constituents in sea-water, after Stramski et al (2004). Optical regions referred to in the text are denoted at the top axis (shading represents approximate boundaries between these regions). These boundaries vary with refractive index for a given particle size.

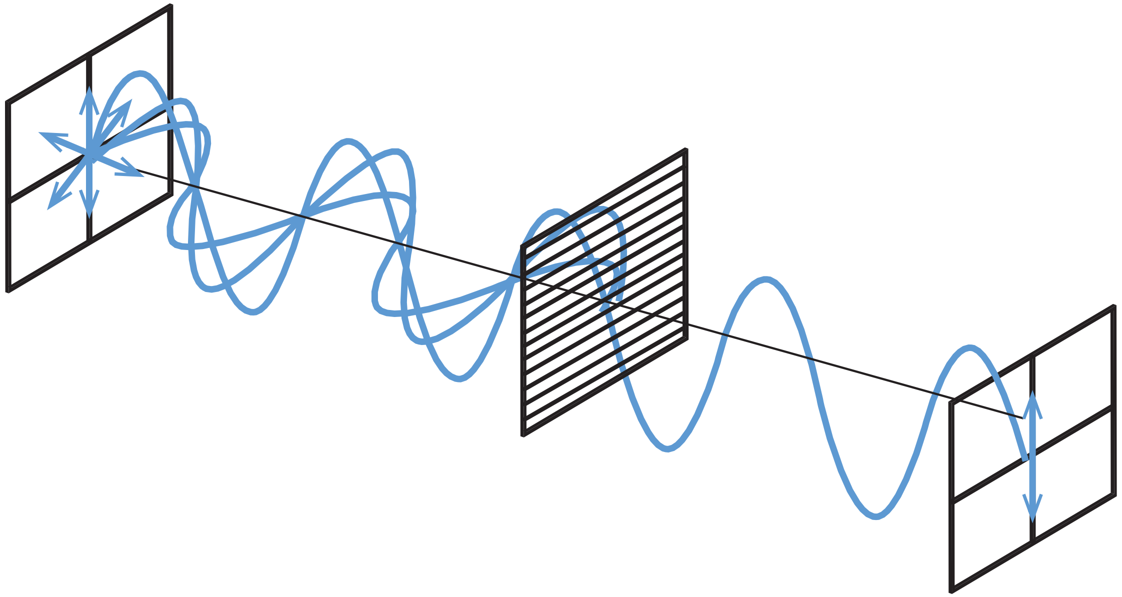
Clavano et al

Can absorption create polarized light?

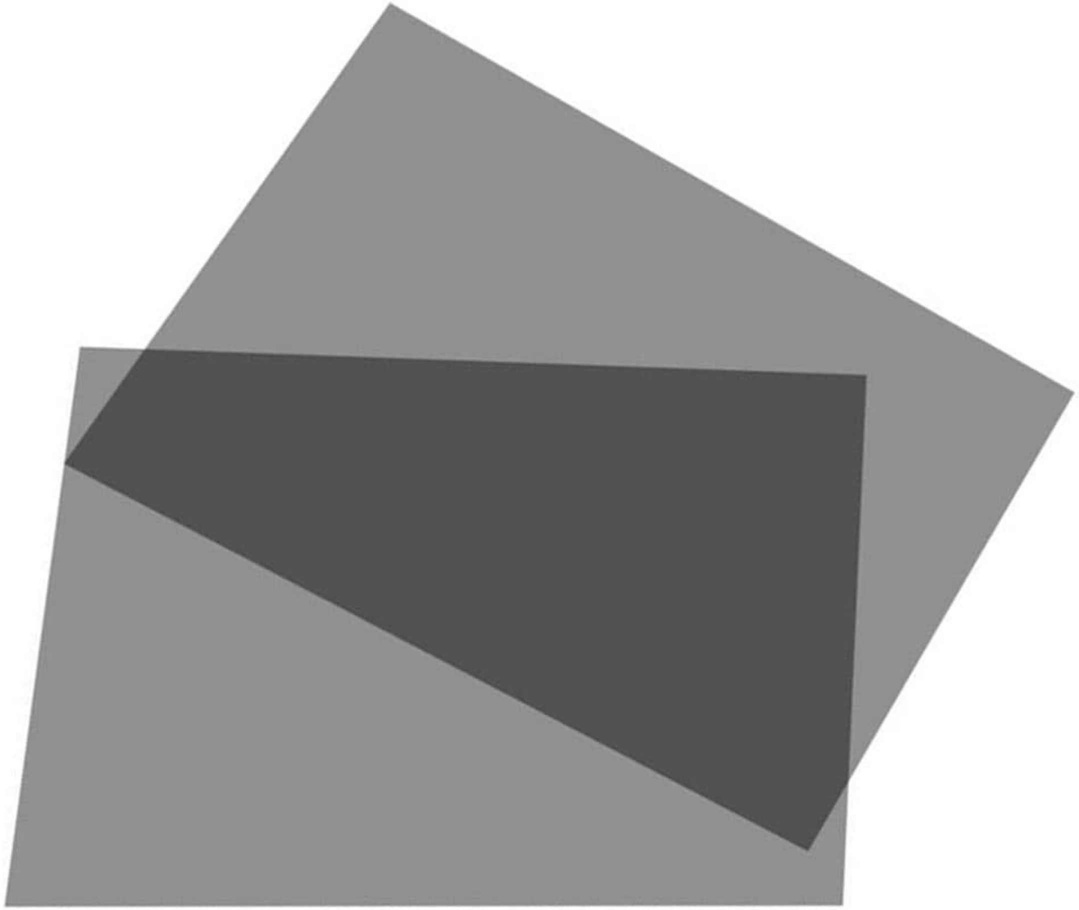


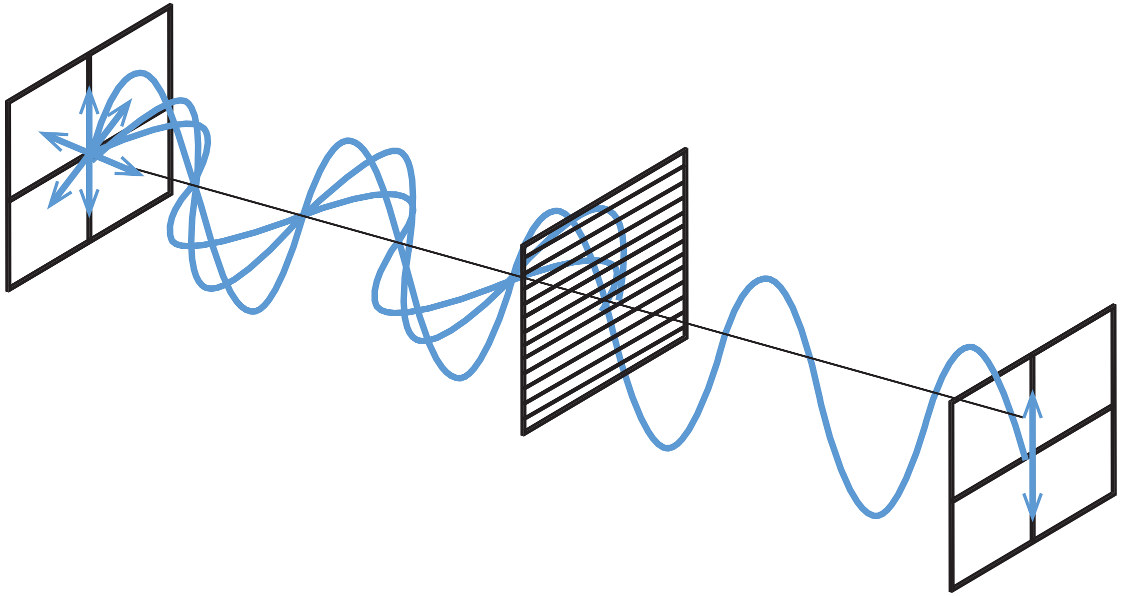
Can absorption create polarized light?





Measuring Polarization





Brewster’s Angle

VSF

V, H linear polarization

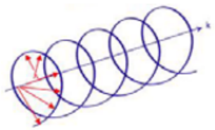
particle orientation

$$\begin{pmatrix} I_s \\ Q_s \\ U_s \\ V_s \end{pmatrix} = \frac{1}{k^2 r^2} \begin{pmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{pmatrix} \begin{pmatrix} I_i \\ Q_i \\ U_i \\ V_i \end{pmatrix}$$

total intensity

$\oplus$

$\otimes$



Stokes vector describing intensity and polarization of incident beam

SCATTERED BEAM

particle nonsphericity

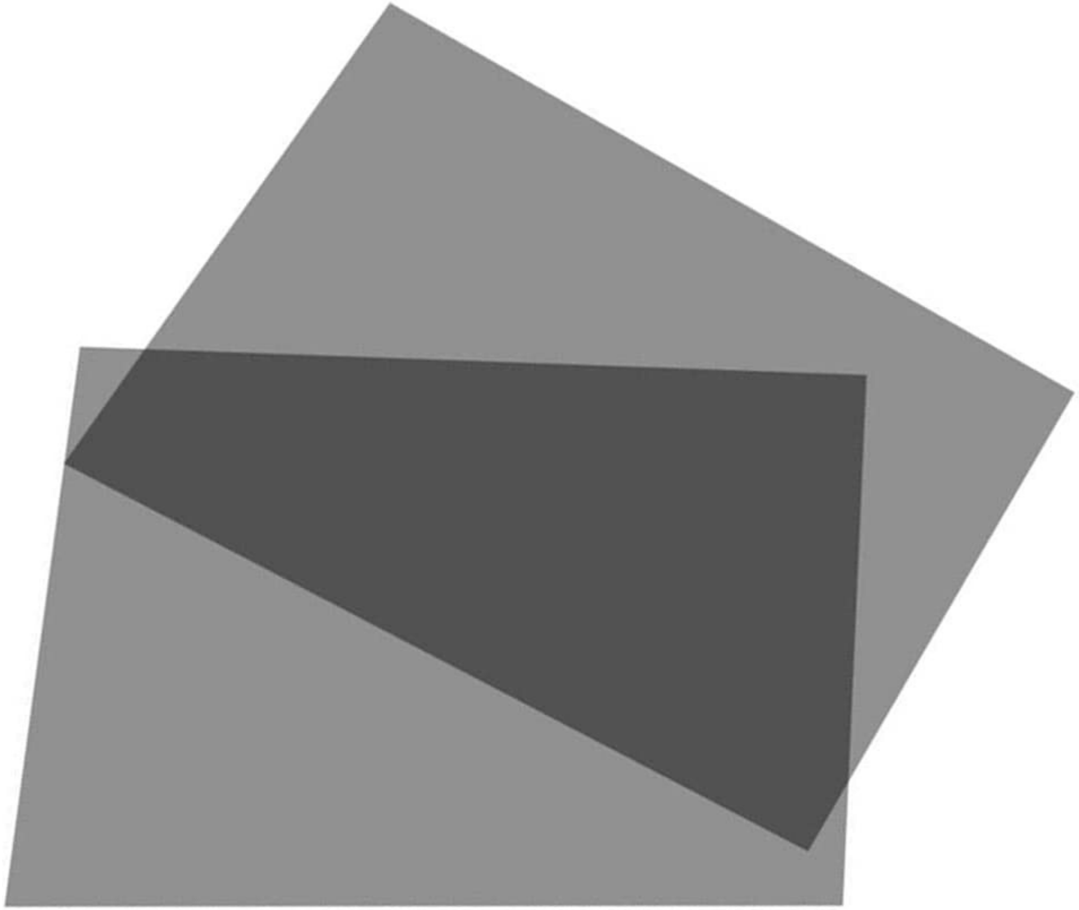
INCIDENT BEAM
(θ, λ)

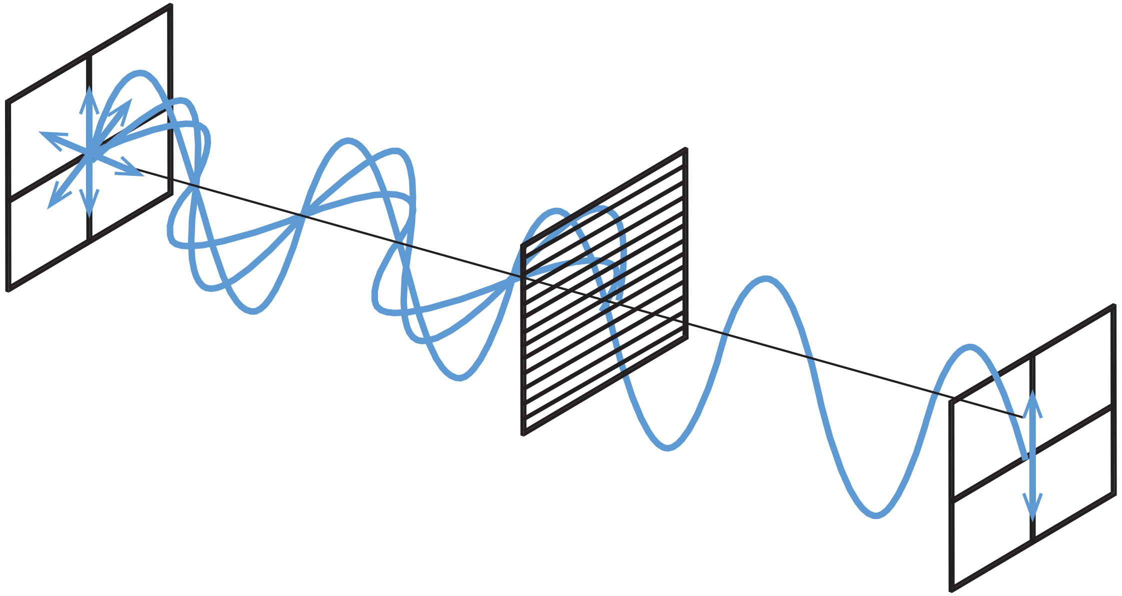
Mueller matrix (for a "scattering event")

Every element has wavelength and angular dependencies

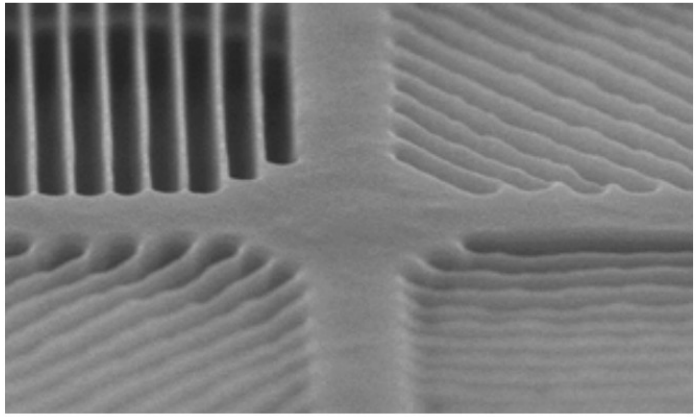
Twardowski IOCCG 2021

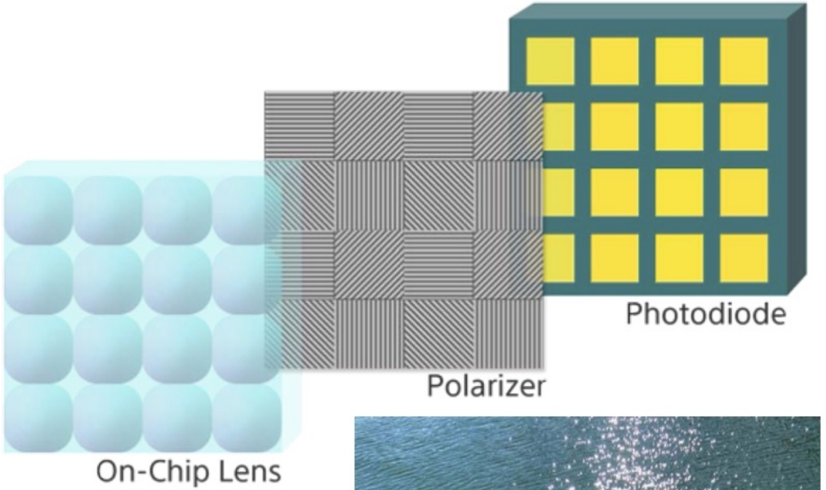
Measuring Polarization



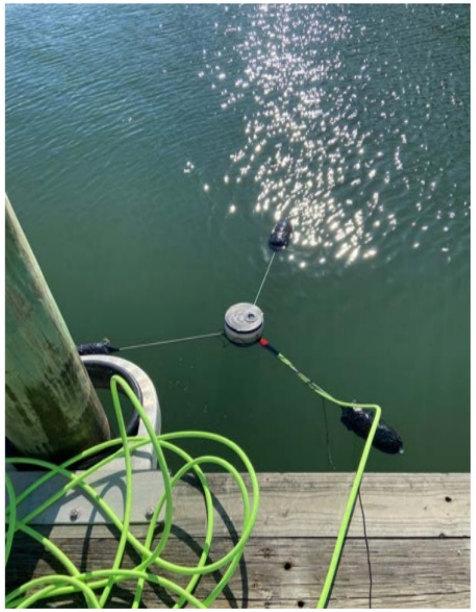


Measuring Polarization

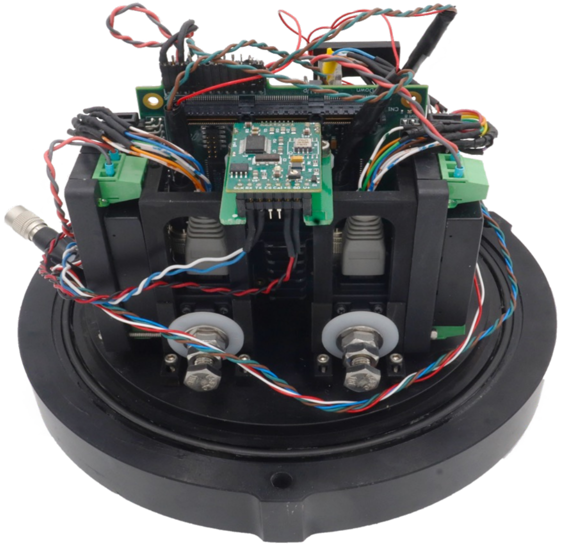
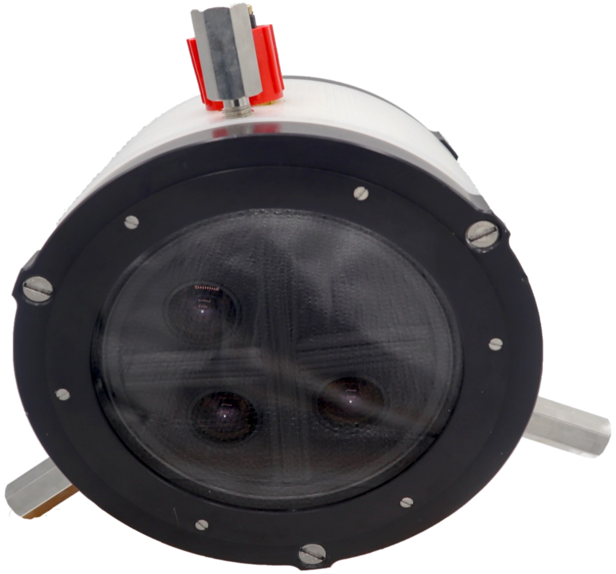


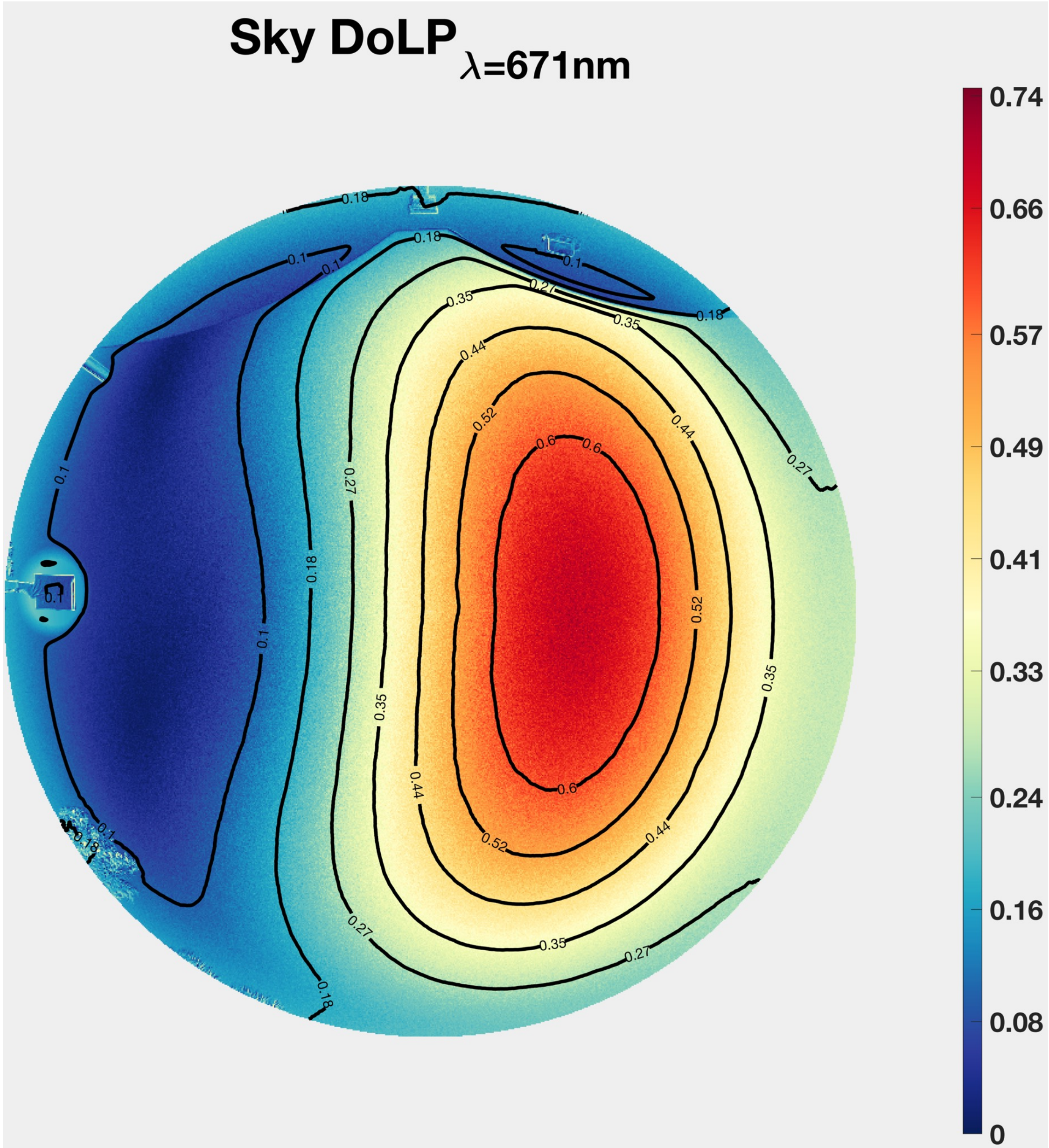


Polarsens image sensor (images from Sony web page)

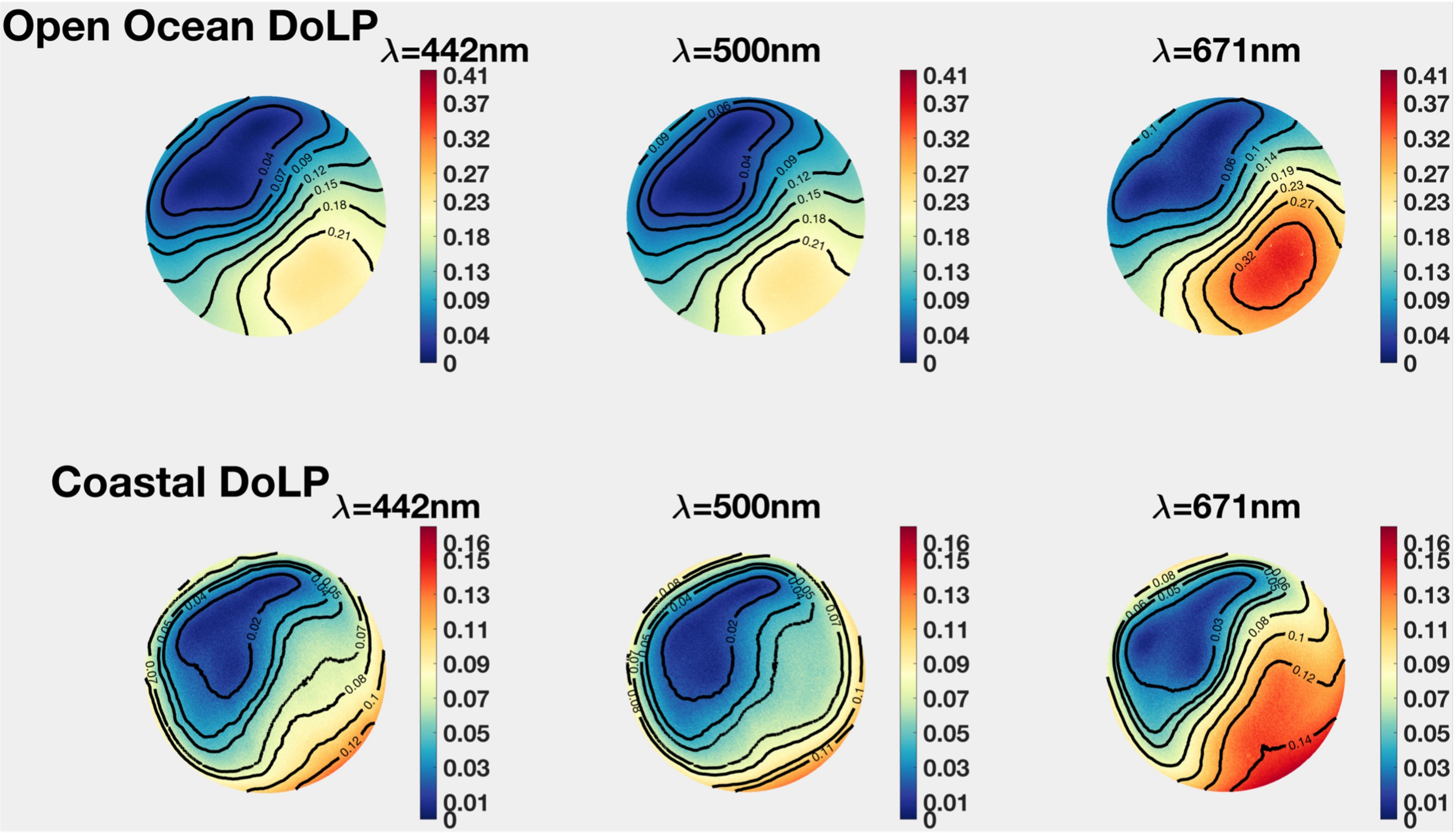


From Voss OO21


FLIR



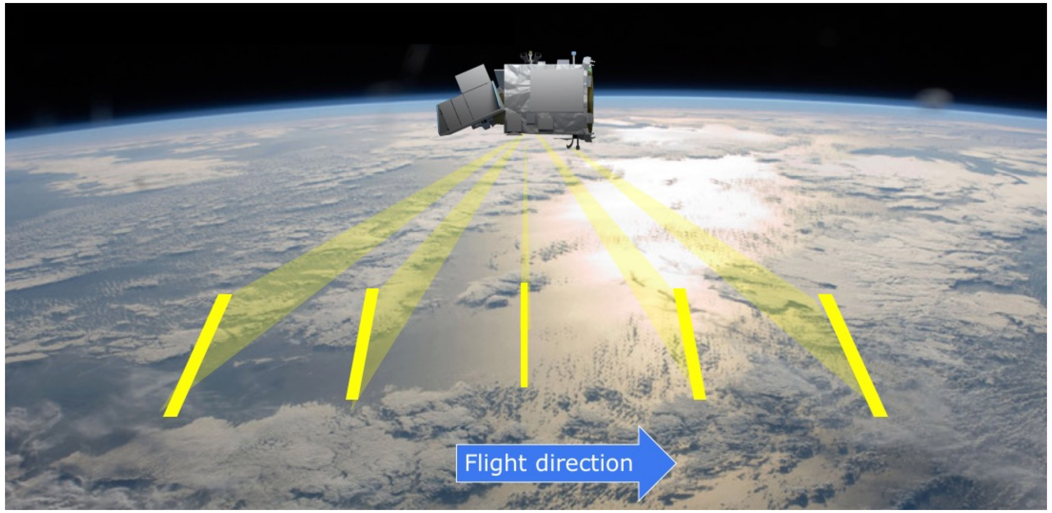



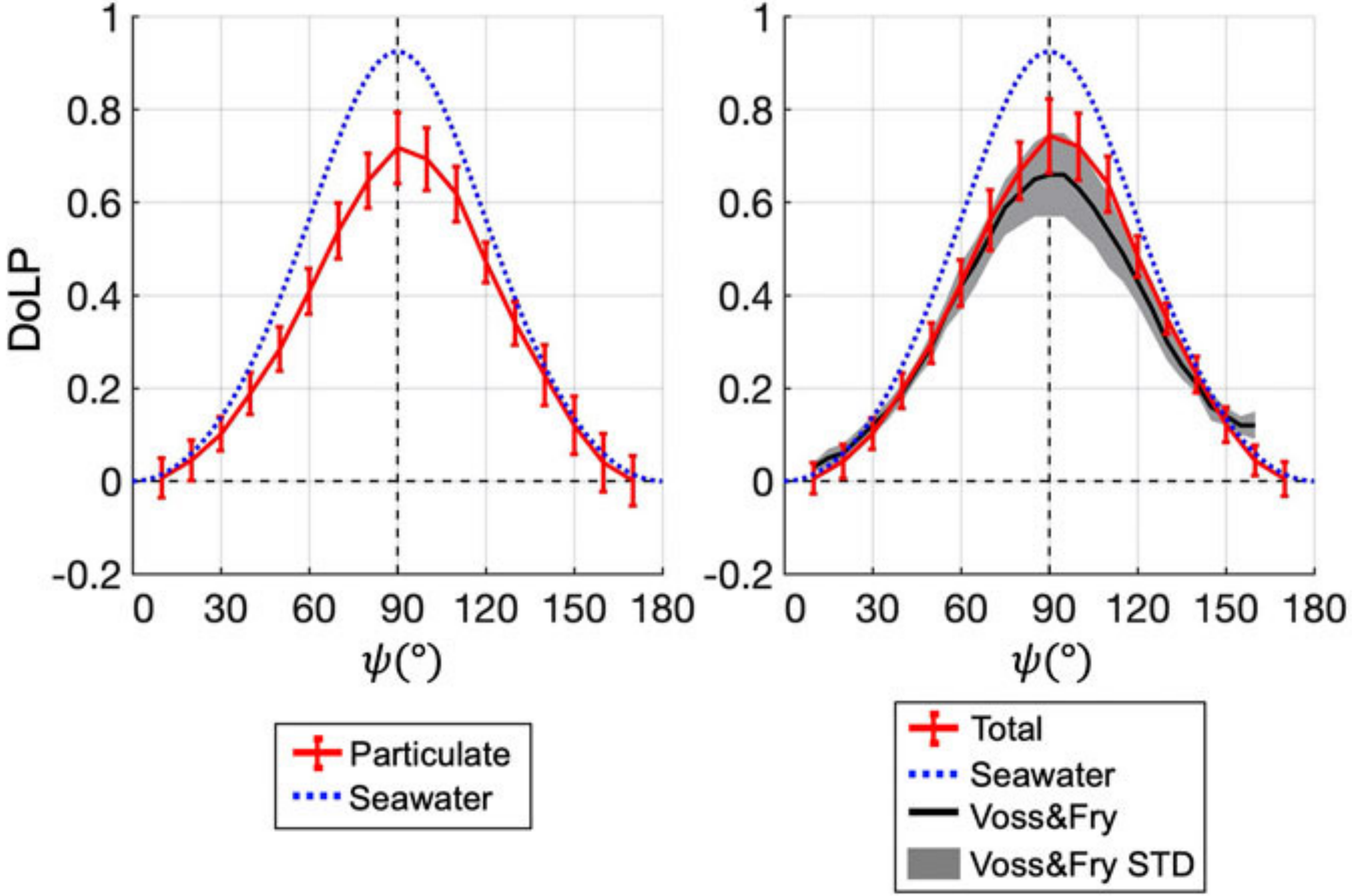
From Riley Blocker



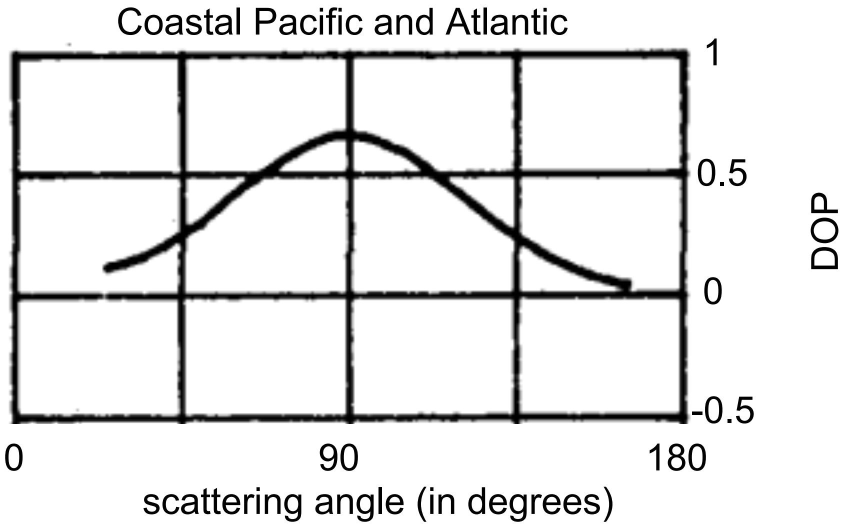
From Riley Blocker

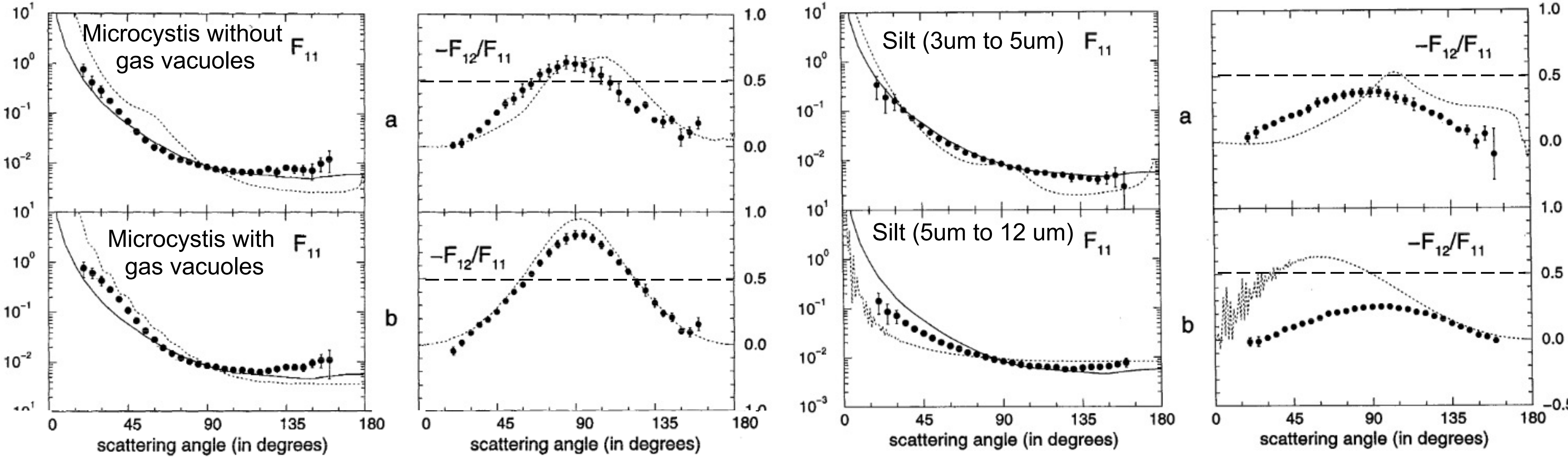
PACE Polarimeters



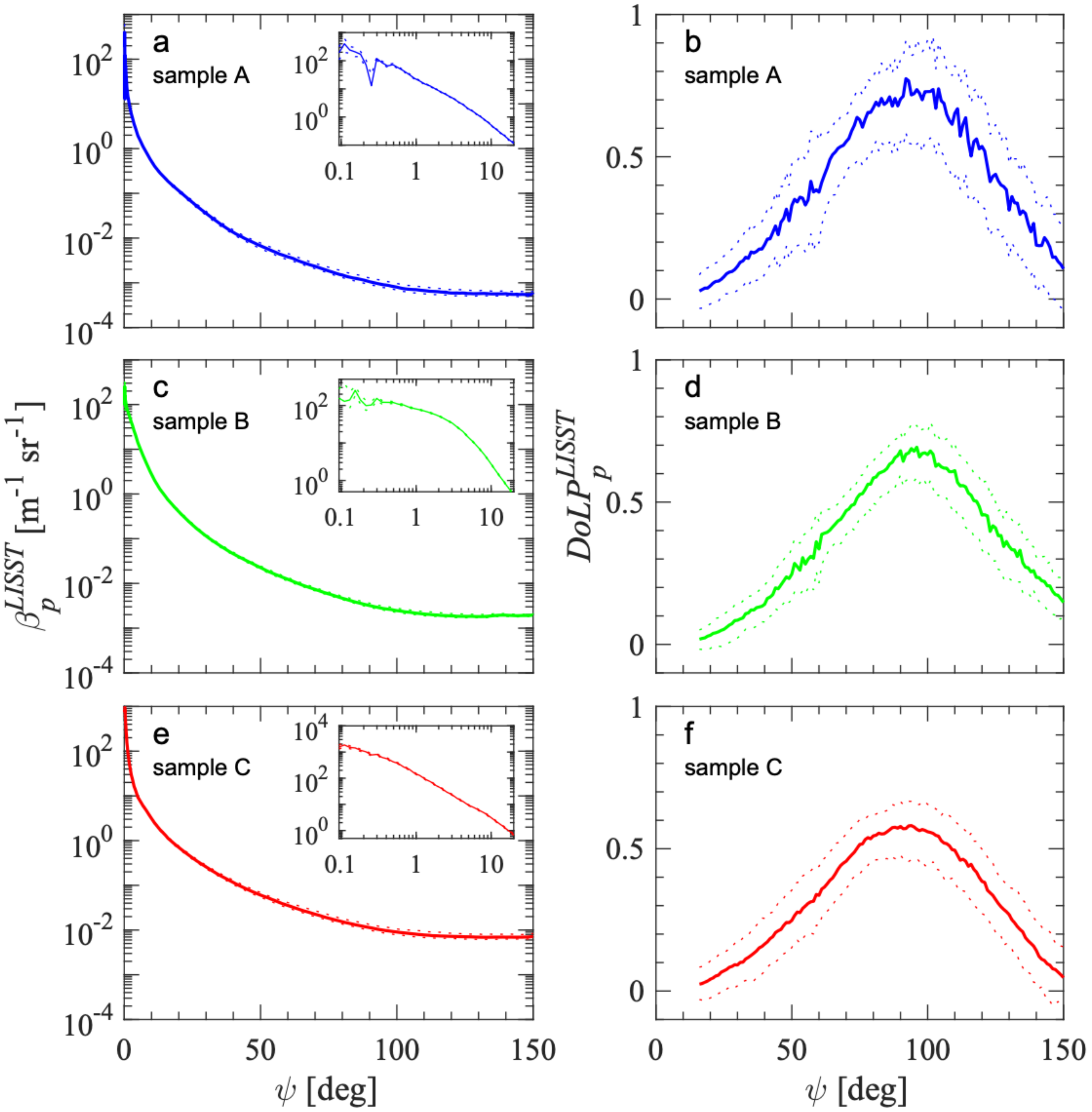


Zhai and Twardowski 2021





Voss and Fry and Volten et al



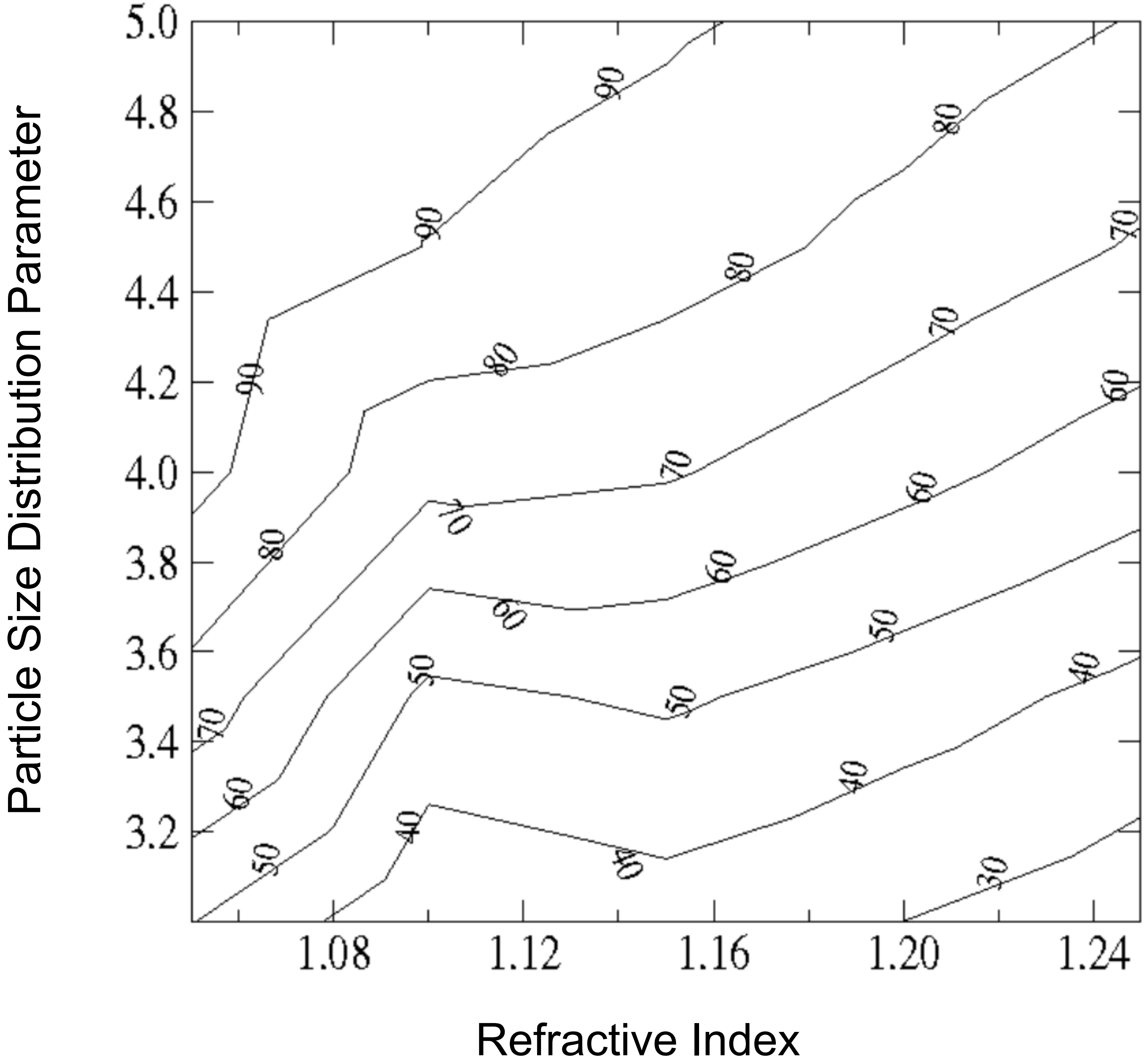
Offshore San Diego

Scripps Pier

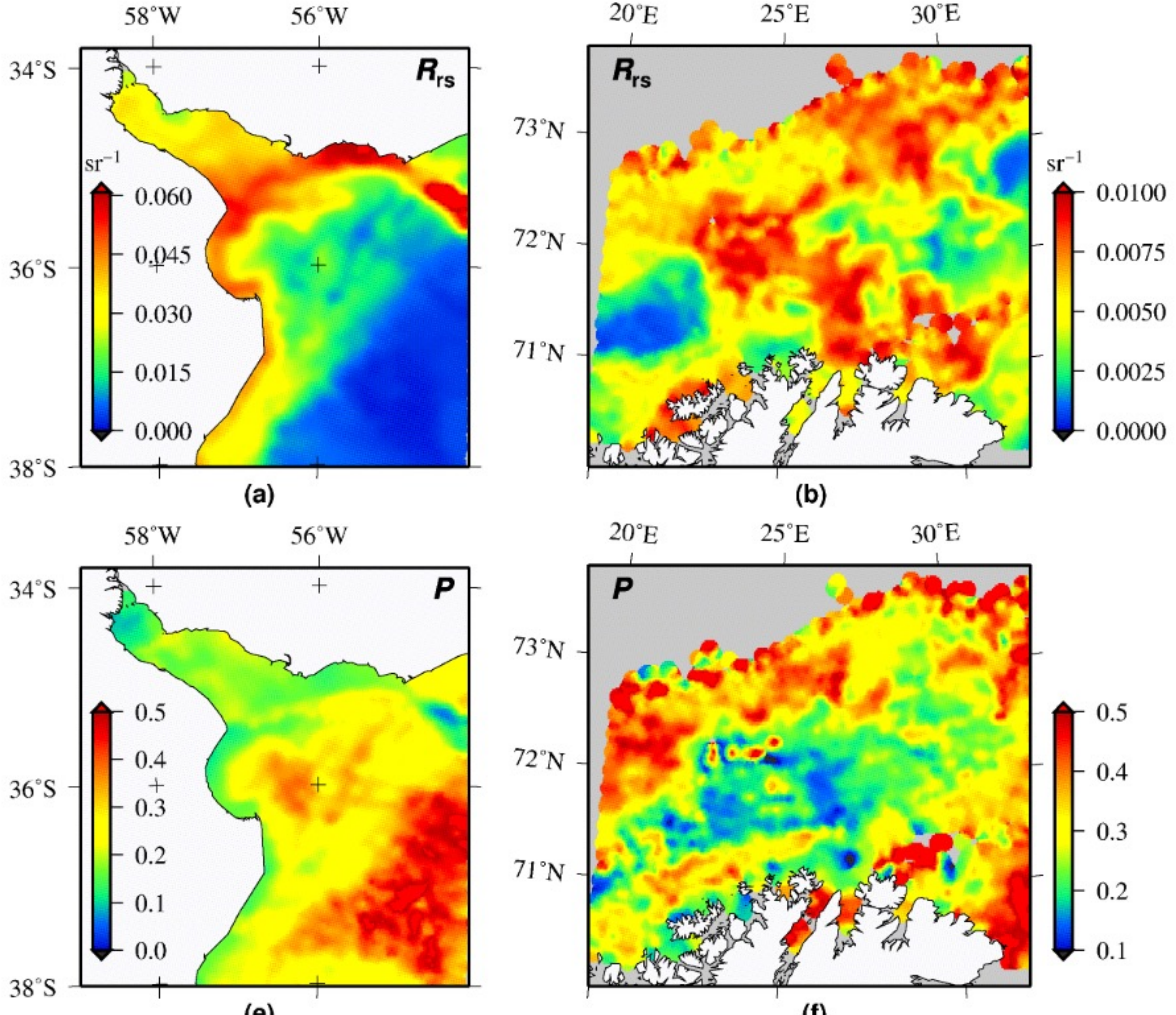
San Diego River Estuary

Koestner et al 2018

Degree of Polarization at 90°



Loisel et al 2008

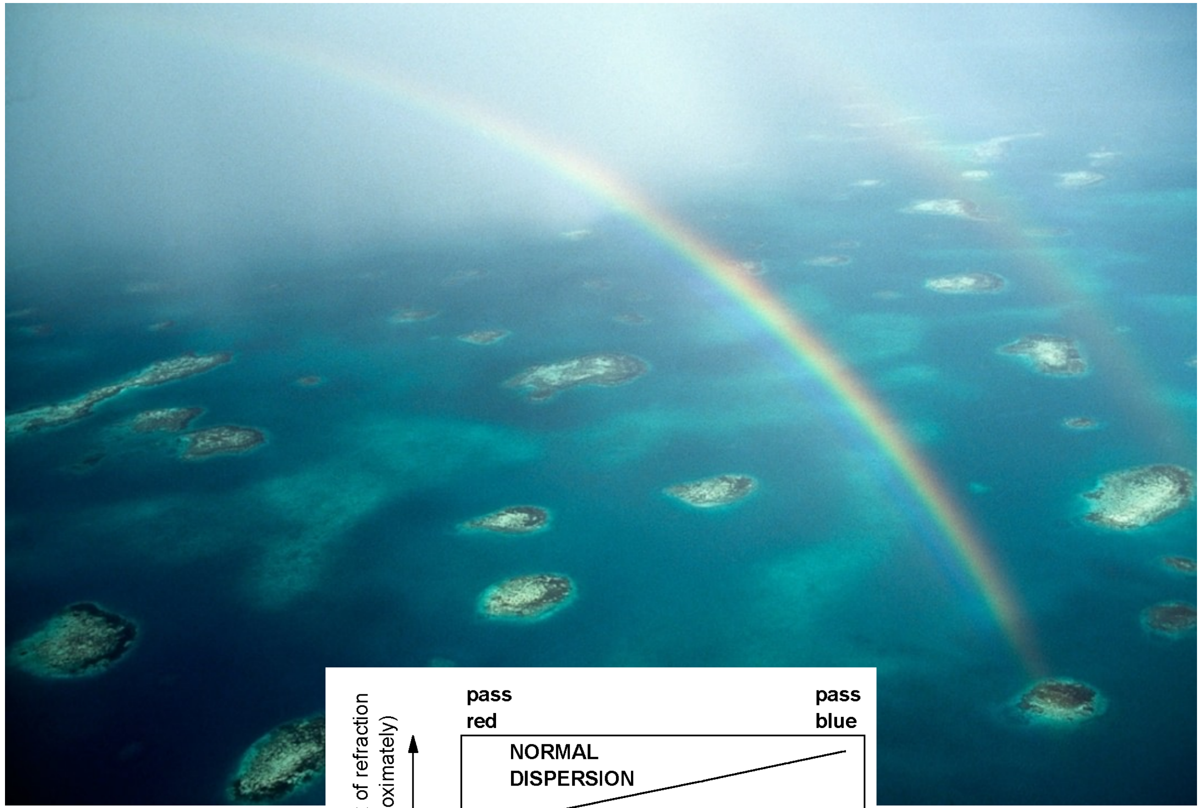


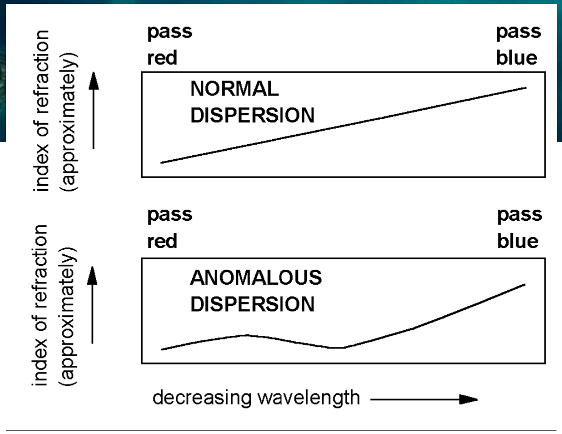
Loisel et al 2008

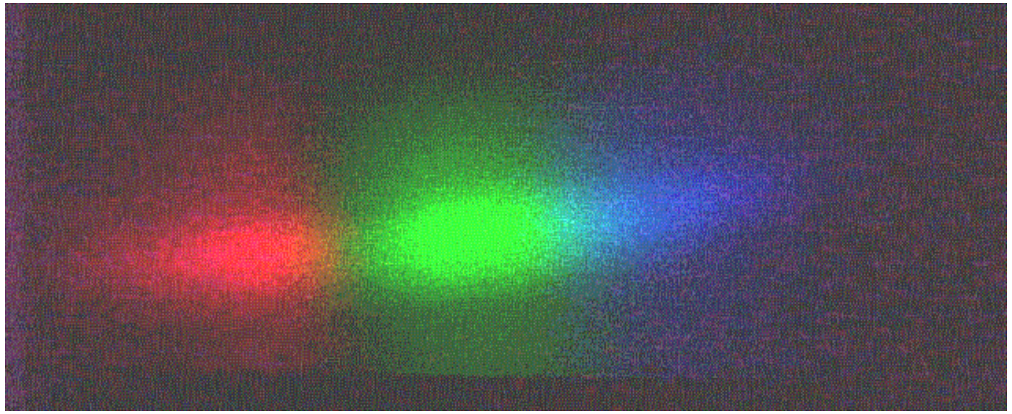
Intuition Test

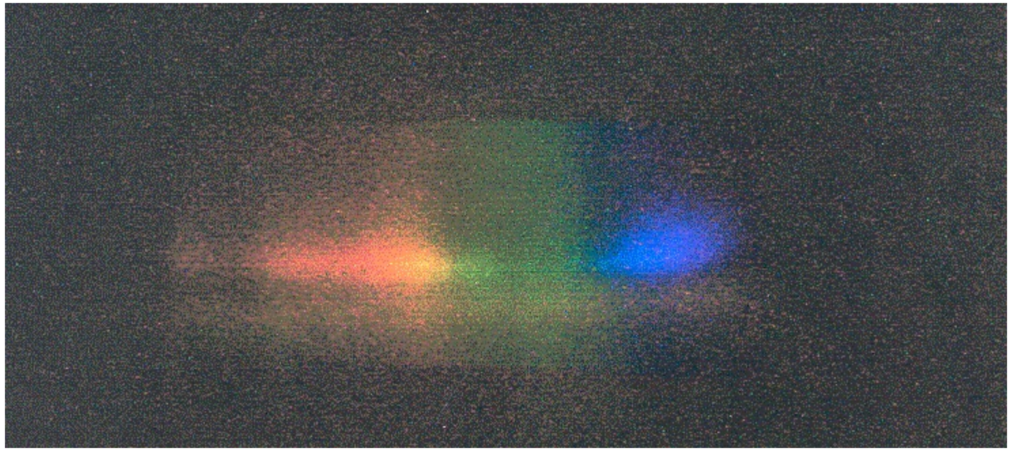
- Is light from the sun polarized?
- Is light from the sky polarized
- Is light from the ocean polarized?

Dispersion and Birefringence



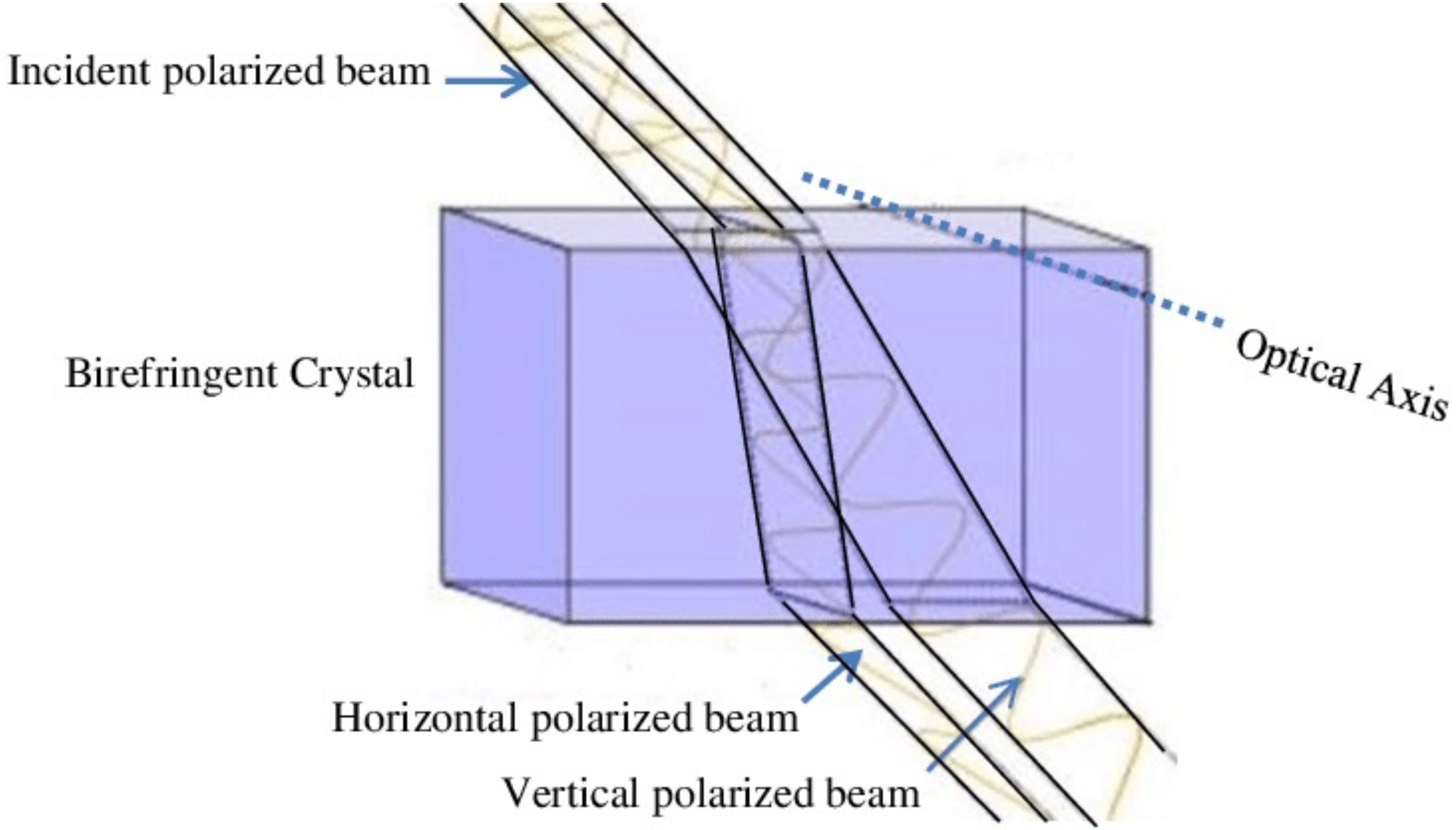






Nat Geo

Dispersion and Birefringence

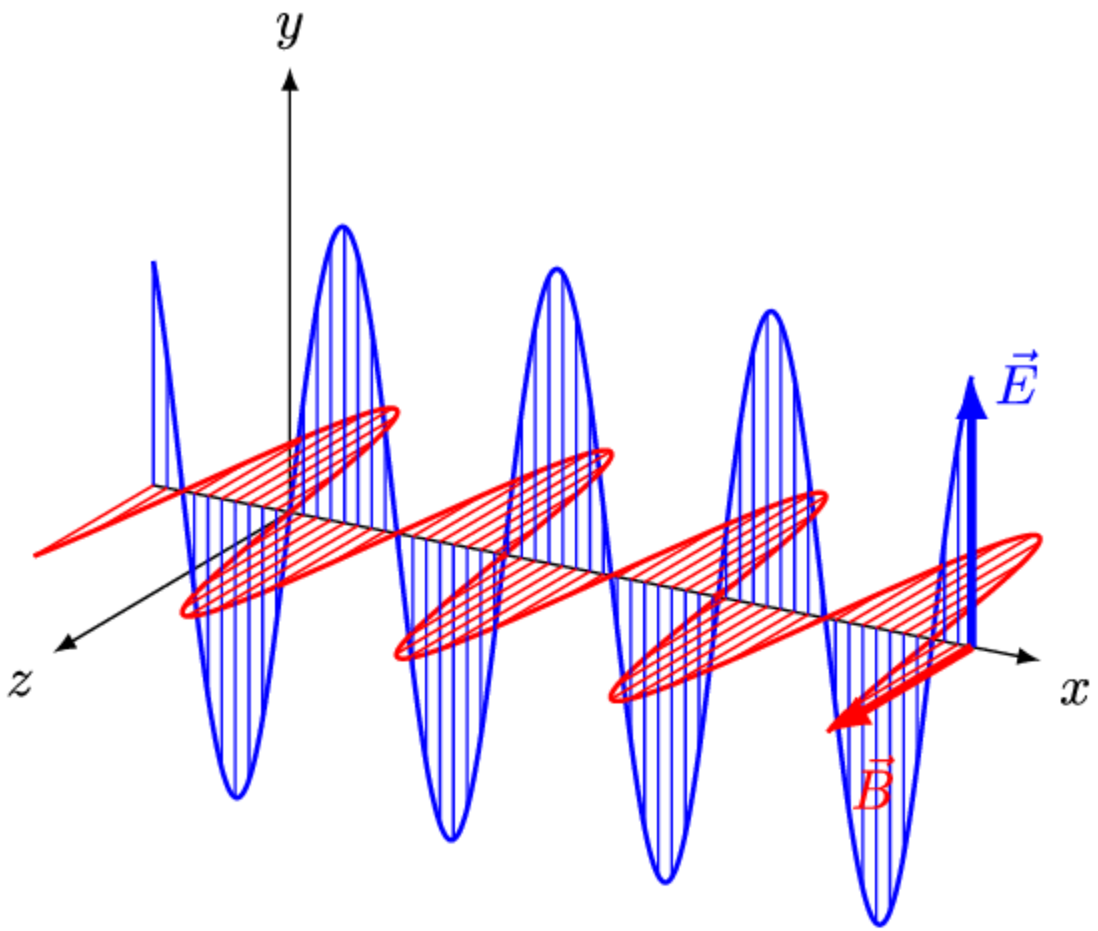


Johnsen 2011

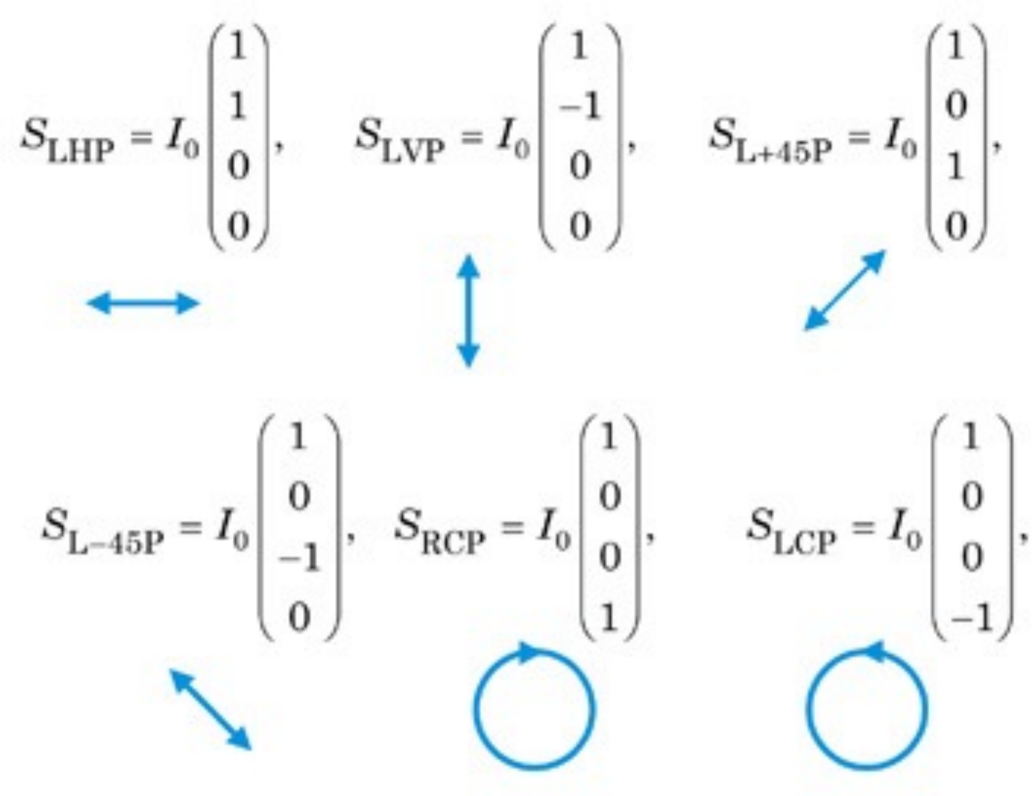
Reading List

- Papers
  - Volten et al., l&o, 1998 Laboratory measurements of angular distributions of light scattered by phytoplankton and silt
- Books
  - Optics of Life, Johnsen – very reader friendly and fun
  - Absorption and Scattering, Bohren &Huffman – comprehensive
  - Fundamentals of Atmospheric Radiation, Clothiaux & Bohren 2006
  - Oceanic Optics, Mobley – excellent and highly relevant
  - QED, Feynman – very fun

Stokes vectors to describe light polarization

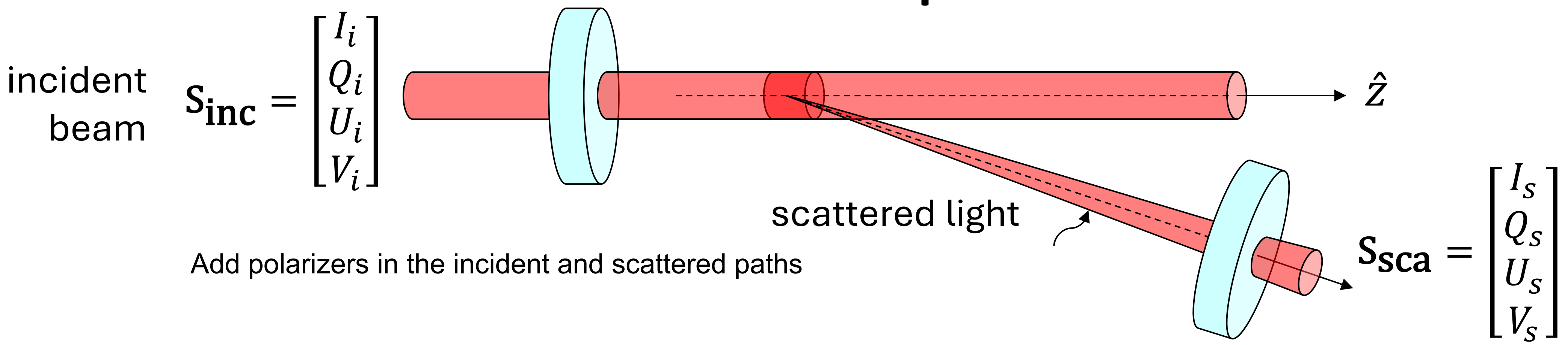


Polarization is defined in terms of the direction of the plane wave E-field



SPIE Field Guide to Polarization

Mueller matrix describes polarized scattering



Add polarizers in the incident and scattered paths

$$\begin{bmatrix} I_s \\ Q_s \\ U_s \\ V_s \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} & 0 & 0 \\ M_{21} & M_{22} & 0 & 0 \\ 0 & 0 & M_{33} & M_{34} \\ 0 & 0 & M_{43} & M_{44} \end{bmatrix} \begin{bmatrix} I_i \\ Q_i \\ U_i \\ V_i \end{bmatrix}$$

Simplified Mueller matrix for randomly oriented particles with symmetry

$$M_{11}(\psi) = \beta_p(\psi)$$

$$DoLP = \frac{M_{12}(\psi)}{M_{11}(\psi)}$$