

# 2015 Summer Course on Optical Oceanography and Ocean Color Remote Sensing

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## The Volume Scattering Function and Models for Scattering

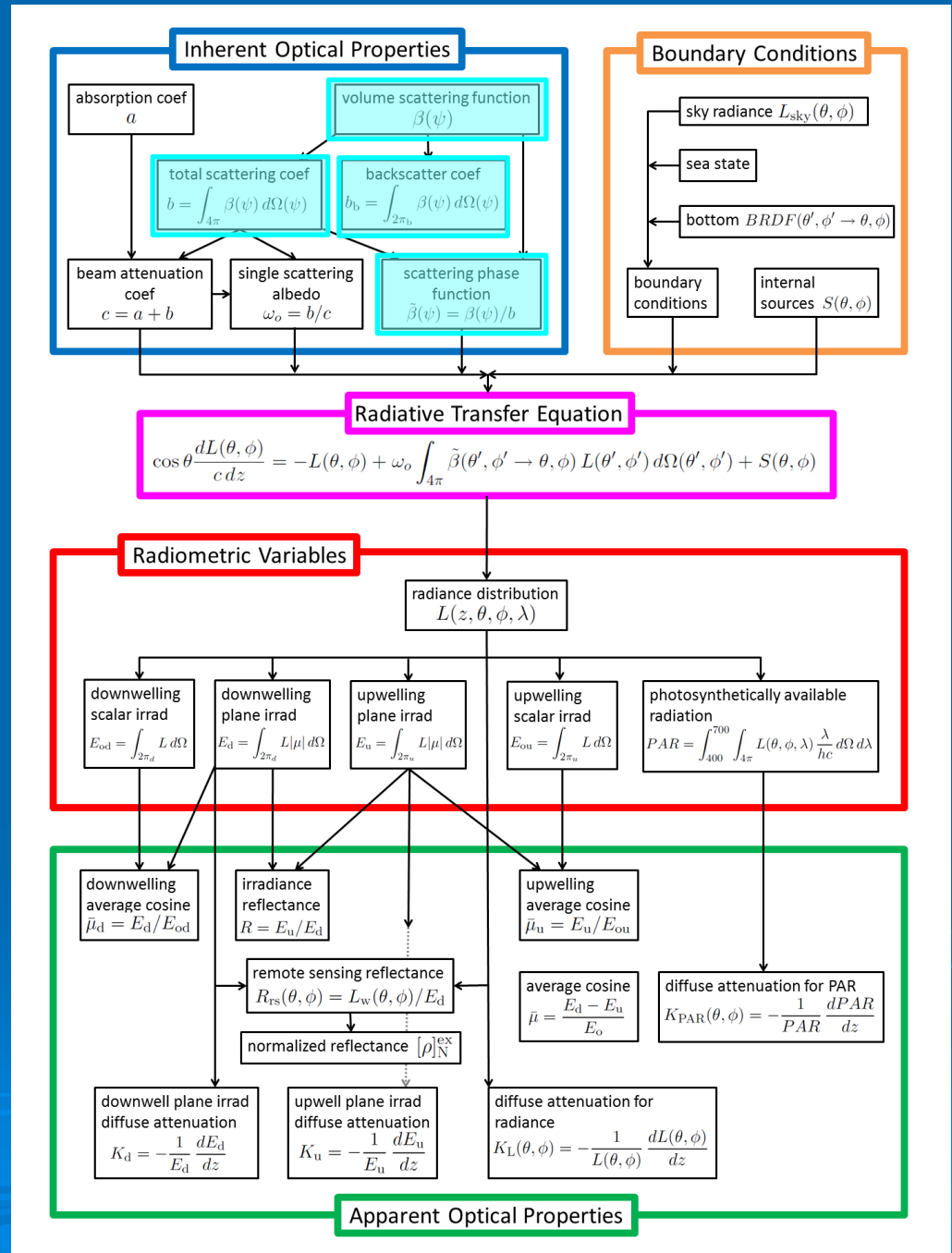
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University of Maine  
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# Inherent Optical Properties (IOPs)

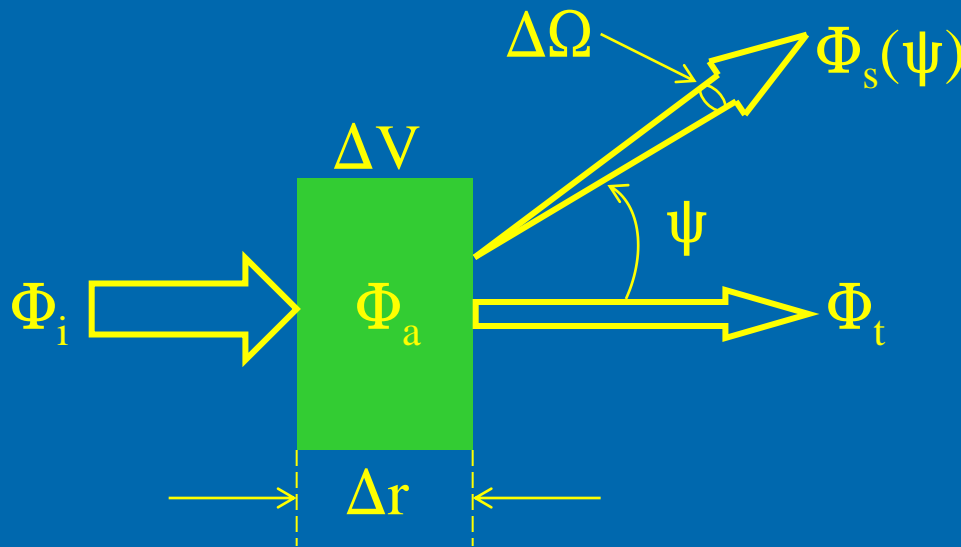
- depend on the concentration, size distribution, and compositions of the particulate and dissolved material in the water (and on the water itself)

- do NOT depend on the light field in the water (therefore, can measure in situ or on a water sample)

The two fundamental IOPs are the absorption coefficient and the volume scattering function—all others can be derived from these two



# The Volume Scattering Function (VSF)



it is assumed that  $\Delta r$  is small enough that only single scattering occurs in  $\Delta V$

$$\beta(\psi, \lambda) \equiv \text{Limit}_{\Delta r \rightarrow 0} \text{Limit}_{\Delta \Omega \rightarrow 0} \frac{\Phi_s(\psi, \lambda)}{\Phi_i(\lambda) \Delta r \Delta \Omega}$$

$$= \text{Limit}_{\Delta V \rightarrow 0} \frac{I_s(\psi, \lambda)}{E_i(\lambda) \Delta V} \quad [\text{m}^{-1} \text{sr}^{-1}]$$

The VSF tells you everything you need to know about how a volume of matter scatters light (ignoring polarization)

# Other Measures of Scattering (1)

The total scattering coefficient:

$$b(\lambda) = \int_{4\pi} \beta(\psi, \lambda) d\Omega = 2\pi \int_0^\pi \beta(\psi, \lambda) \sin\psi d\psi = c - a \quad [\text{m}^{-1}]$$

$b$  tells how much light is scattered, without regard for the direction of the scattering

The scattering phase function:

$$\tilde{\beta}(\psi, \lambda) \equiv \frac{\beta(\psi, \lambda)}{b(\lambda)} \quad [\text{sr}^{-1}]$$

angular dependence of the scattered light

strength and angular dependence of scattering

strength of scattering

The phase function gives the angular pattern of the scattered light, without regard for the magnitude of the scattering

## Other Measures of Scattering (2)

The backscatter coefficient:

$$b_b(\lambda) \equiv 2\pi \int_{\pi/2}^{\pi} \beta(\psi, \lambda) \sin \psi \, d\psi \quad [\text{m}^{-1}]$$

$b_b$  tells how much light is scattered through  $\psi = 90$  to  $180$  deg

The backscatter fraction:  $B = b_b / b$

$B$  gives the fraction of the total light scattered that is scattered through  $90$  to  $180$  deg

The albedo of single scattering:  $\omega_o = b / (a + b)$

$\omega_o$  gives the fraction of the light scattered (vs. absorbed) in any interaction with matter; also called *the probability of photon survival*

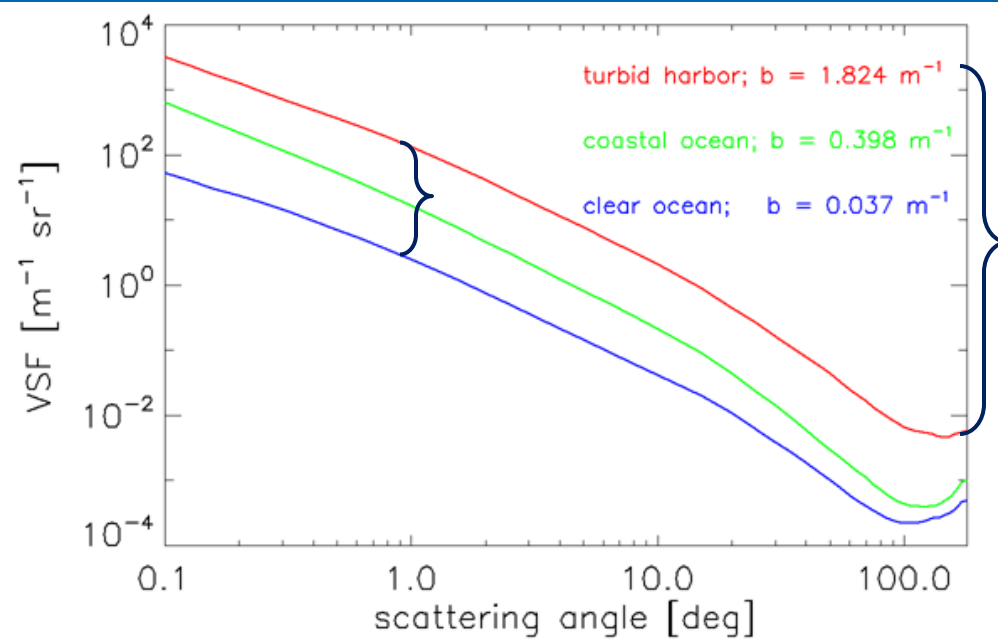
# Measurement of the VSF

A number of instruments have been developed over the years to measure the VSF. However, most of them are unique and not commercially available. Therefore, the VSF is seldom measured. This may change within the next decade, as new commercial instruments are developed.

We do not have time to discuss particular VSF instruments, so I'll show only some example data.



# Variability in the VSF

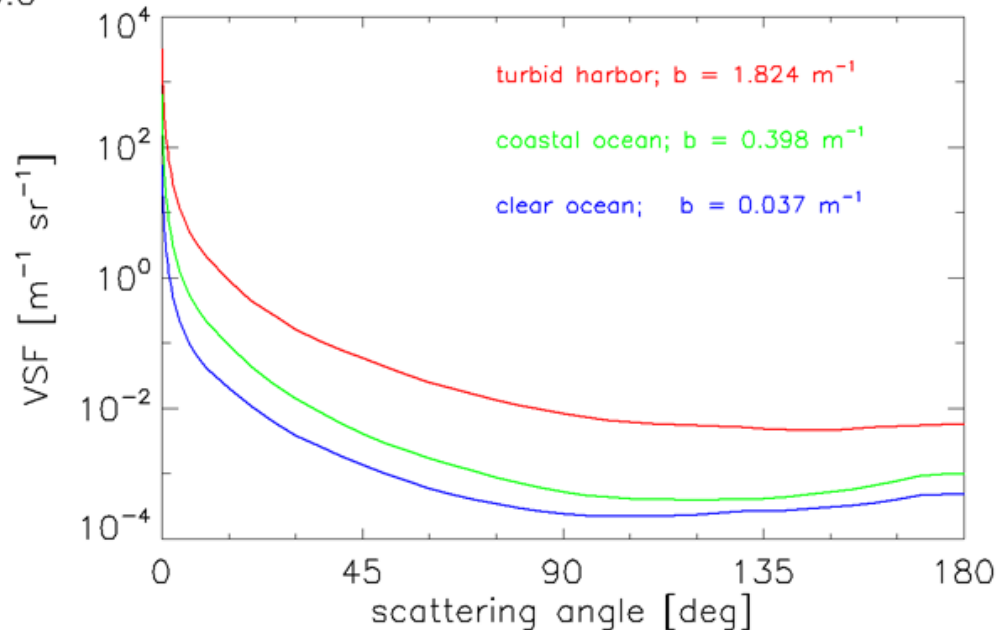


6 orders of magnitude variation between small and large scattering angles, for a given VSF

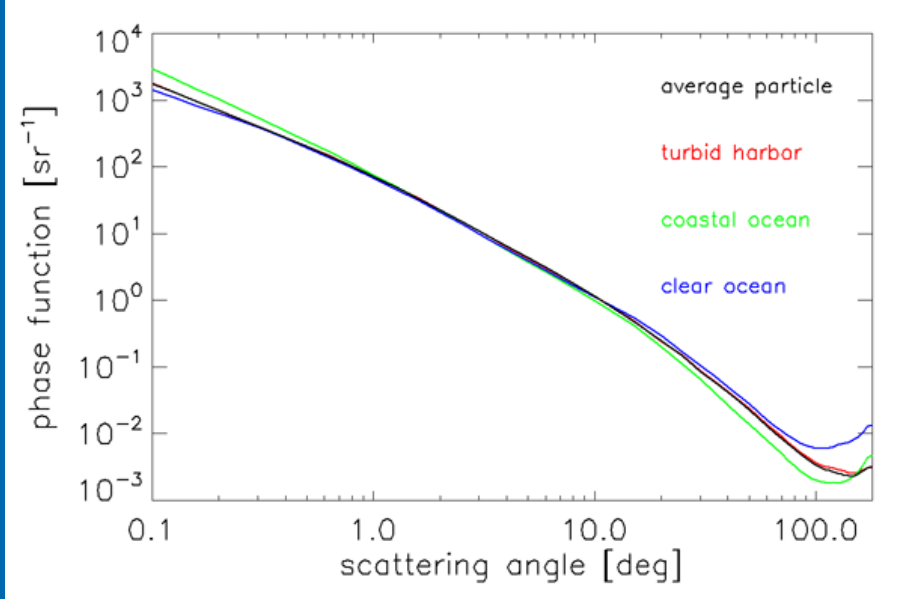
Petzold's data, see [www.oceanopticsbook.info/view/scattering/petzolds\\_measurements](http://www.oceanopticsbook.info/view/scattering/petzolds_measurements)

2 orders of magnitude variation between different water types

[www.oceanopticsbook.info/view/overview\\_of\\_optical\\_oceanography/visualizing\\_vsfs](http://www.oceanopticsbook.info/view/overview_of_optical_oceanography/visualizing_vsfs)



# An Idea



It would simplify optical oceanography if most of the variability in the VSF were contained in the scattering coefficient  $b$ , so that a common phase function could be used for all “particles.”

$$\tilde{\beta}(\psi, \lambda) \equiv \frac{\beta(\psi, \lambda)}{b(\lambda)}$$

maybe not too variable

highly variable

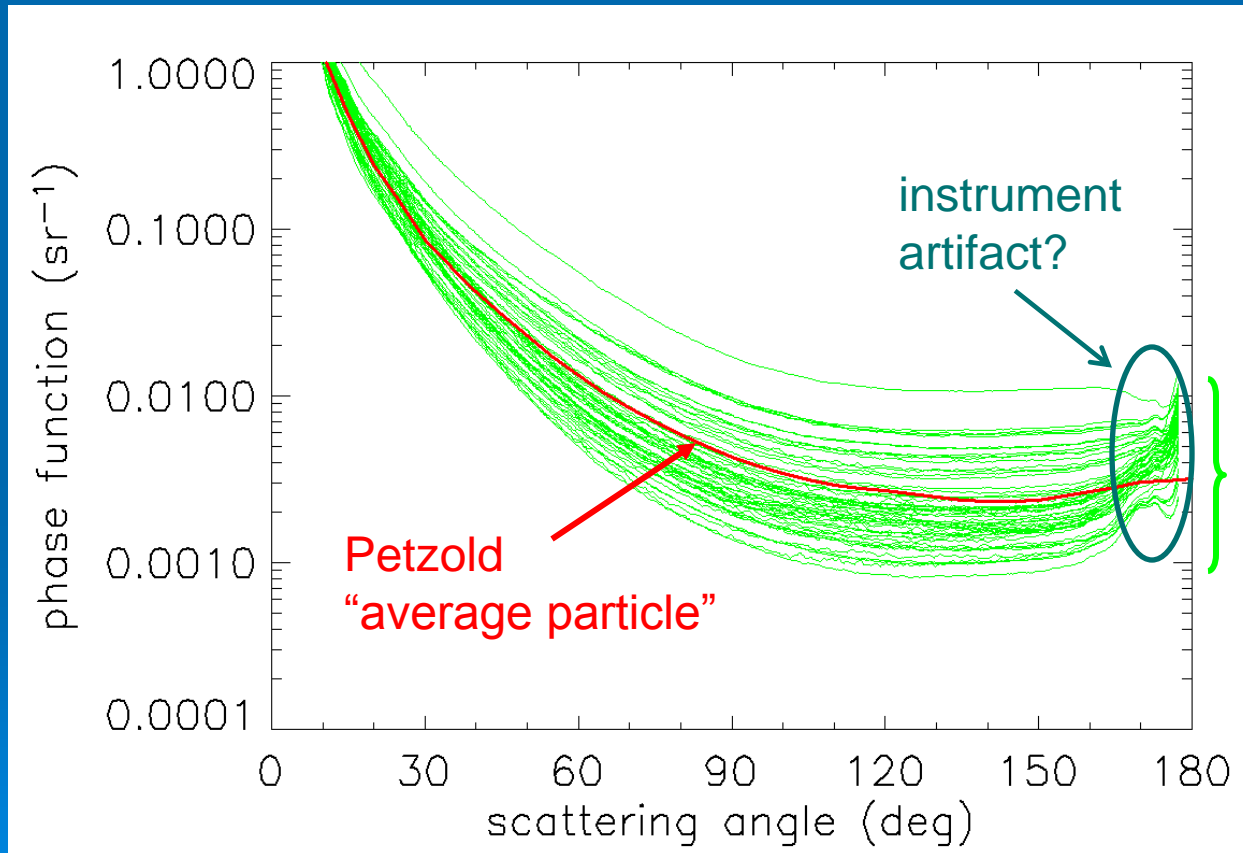
highly variable

Is this a good assumption?



# Variability in Phase Functions

62 phase functions measured in coastal New Jersey waters,  $\lambda = 530$  nm (VSM data courtesy of E. Boss, M. Lewis, et al.)



Note: Petzold may be fine on average, but way off in any particular instance.

# Variability in Phase Functions

When running HydroLight, you may have measurements of absorption and scattering from an ac-S, for example, but you rarely have measurements of the VSF or the scattering phase function. Therefore, you must guess what phase function to use.

Using the wrong phase function can mean that the HydroLight predictions are much different (factor of 2 to 10) than measured light variables. This is a very common problem in comparing HydroLight predictions with measurements (e.g., of remote-sensing reflectance).



# Warning

In the ocean, you can almost never neglect absorption compared to scattering, or scattering compared to absorption.

When measuring absorption, you always have to correct for scattering (e.g., the “scattering correction” for raw ac-9 or ac-S measurements).

When measuring scattering, you always have to correct for absorption.

This means that you need to measure both absorption and scattering simultaneously, and then (sometimes iteratively, sometimes with best guesses, e.g. about the shape of the phase function) correct one against the other. It's not a simple process.



# Scattering Depends Strongly on the Particle Size Distribution



Photo by Ensign John Gay, US Navy. The plane was traveling at 1,200 km/hr just 25 m above the sea surface. This photo won first prize in the science and technology division in the World Press Photo 2000 contest, which drew more than 42,000 entries worldwide.

# IOP Models for Scattering

First look at data and models for individual components

- water
- phytoplankton (algae)
- CDOM (negligible scattering)
- NAP
  - CPOM (detritus)
  - CPIM (minerals)

Then put the pieces together to get an IOP model for use in HydroLight



# The VSF and the Scattering Phase Function

$$\beta(\psi) = \sum_{i=1}^N \beta_i(\psi) \quad \text{VSFs are additive}$$

$$\tilde{\beta} = \sum (b_i/b) \tilde{\beta}_i \quad \text{phase functions must be weighted by the fraction of component scattering}$$

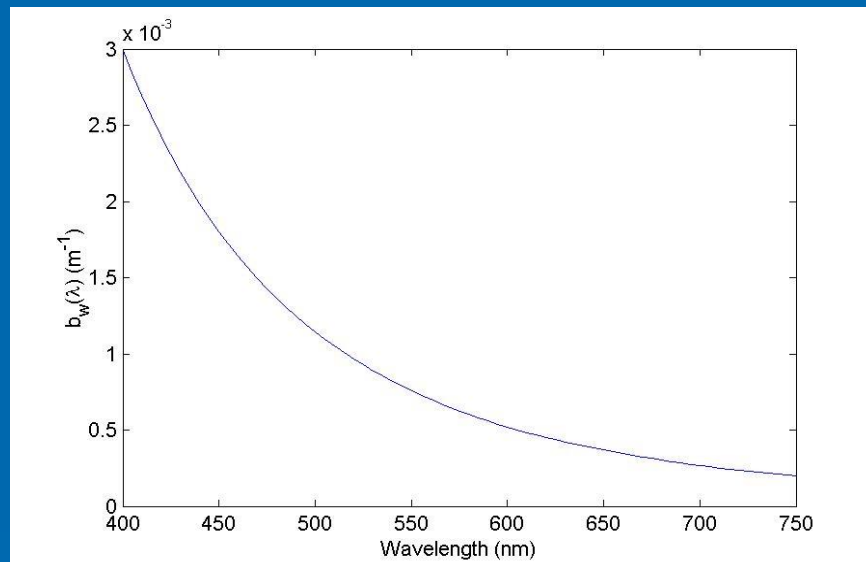
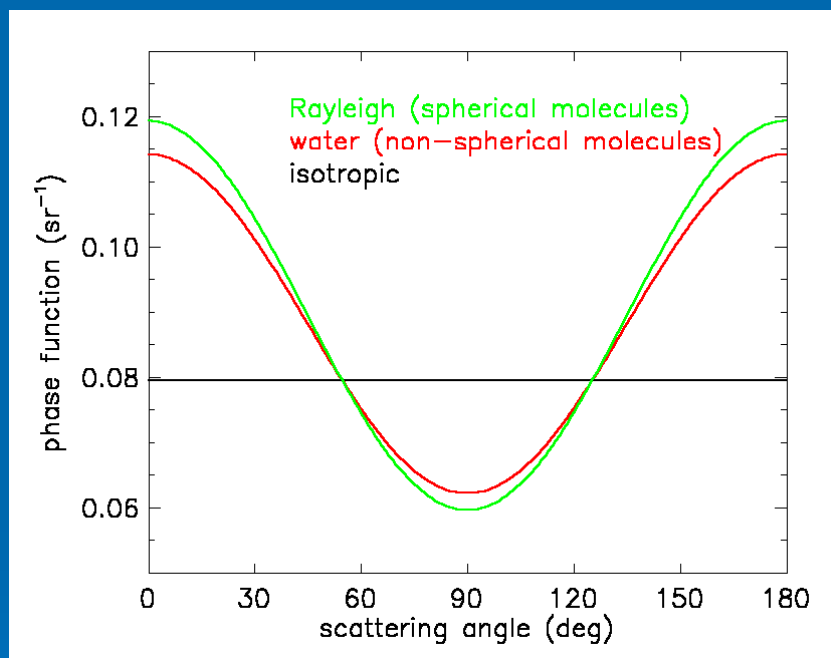
What components make sense for  $\beta$ ?

$$= b_w/b \tilde{\beta}_w + b_\phi/b \tilde{\beta}_\phi + b_{\text{CPOM}}/b \tilde{\beta}_{\text{CPOM}} + b_{\text{CPIM}}/b \tilde{\beta}_{\text{CPIM}}$$

$\tilde{\beta}_i$  is a phase function representative of the  $i^{\text{th}}$  component  
 $b_i/b$  = fraction of total scattering by particle type  $i$

# Scattering by Pure Sea Water

scattering by pure water is the only IOP that can be computed from fundamental physics; all others come from measurement



scattering spectrum

$$b_w(\lambda) = 0.003 (\lambda/400)^{-4.32}$$

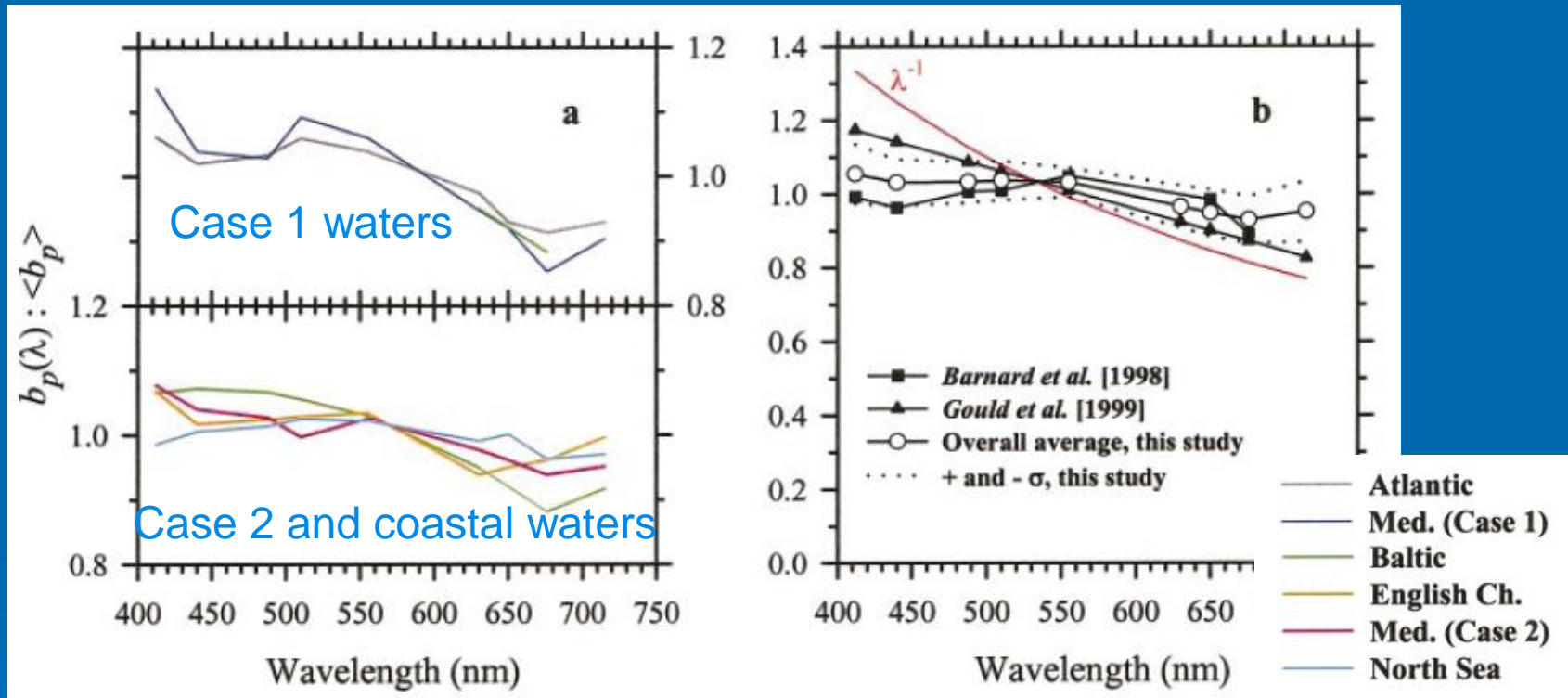
phase function

$$\tilde{\beta}_w(\lambda, \psi) = \tilde{\beta}_w(\lambda, 90^\circ) (1 + 0.835 \cos^2 \psi)$$

water volume scattering function

$$\beta_w(\lambda, \psi) = b_w(\lambda_0, 90^\circ) (\lambda/\lambda_0)^{-4.32} * (1 + 0.835 \cos^2 \psi)$$

# Wavelength Dependence of Scattering by Particles (Phytoplankton and NAP)



Babin et al. 2003, *Limnol. Oceanogr.* 48(2), 843-859



# Models for Scattering by Particles

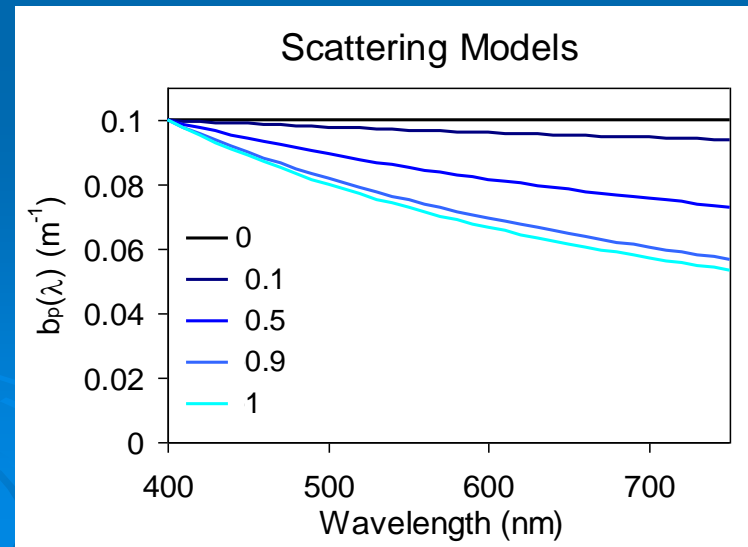
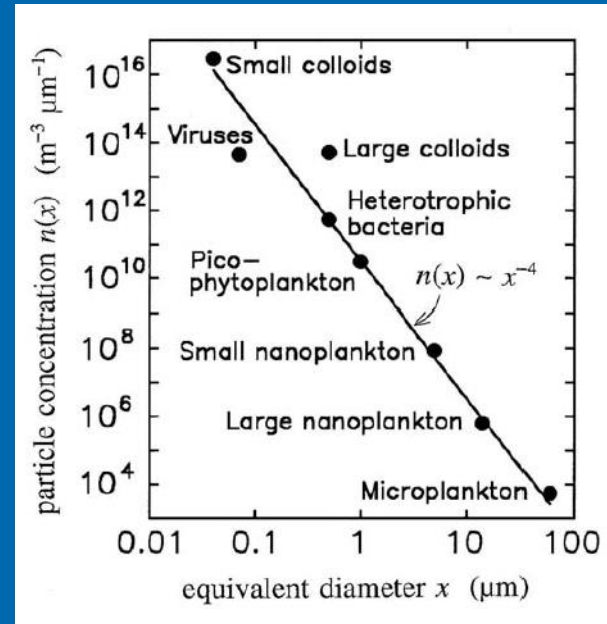
Historically, scattering was hard to measure, so scattering often was modeled using Mie theory (which is exact only for homogeneous spheres) and a Junge size distribution, which gives a power law:

$$b_p(\lambda) = b_p(\lambda_o) \left( \frac{\lambda}{\lambda_o} \right)^{-n}$$

$n = 0$  to  $1$ , depending on the size distribution (large particles have a small  $n$ , small particles have a large  $n$ )

$$b = c - a$$

What do we know about  $c$  and  $a$ ?



# Models for Scattering by Phytoplankton and NAP

A power law gives a better fit to beam attenuation than to scattering

$$c_p(\lambda) = c_p(\lambda_o) \left( \frac{\lambda}{\lambda_o} \right)^{-n}, \quad \text{Boss et al. 2001}$$

so get  $b$  from  $c - a$

$$b_{NAP}(\lambda) = c_{NAP}(\lambda_o) \left( \frac{\lambda}{\lambda_o} \right)^{-n} - a_{NAP}(\lambda)$$

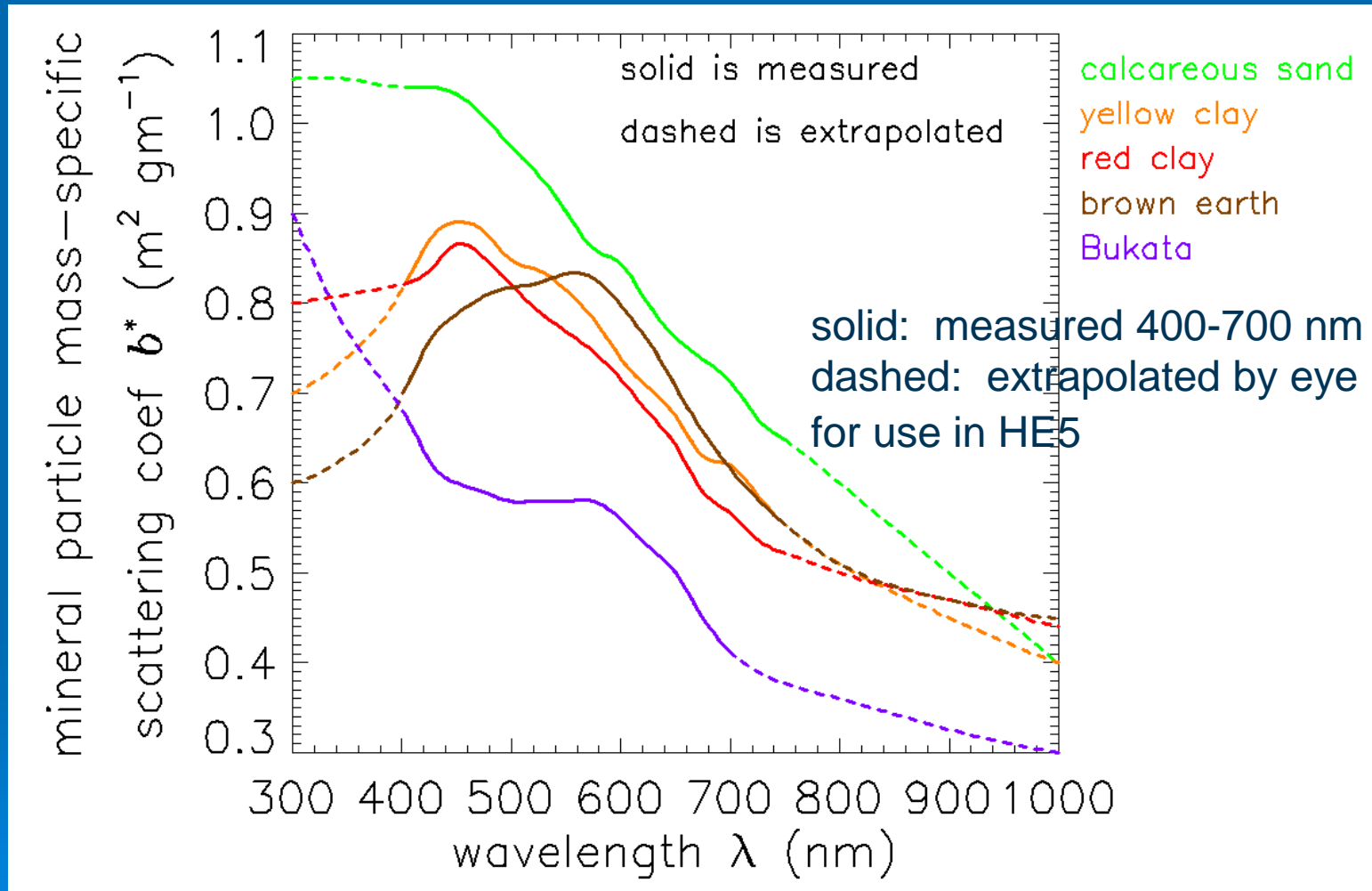
a smoothly  
varying function  
of wavelength

$$b_{\phi}(\lambda) = c_{\phi}(\lambda_o) \left( \frac{\lambda}{\lambda_o} \right)^{-n} - a_{\phi}(\lambda)$$

not so smoothly  
varying function

# Scattering by Minerals

(measured and extrapolated spectra used in HE5)



# Models for Backscattering by Phytoplankton and NAP

Mie theory shows that particle backscattering has same spectral shape as scattering (approximately true for nonspherical, inhomogeneous particles). Therefore the backscatter fraction  $B_p = b_{bp}/b_p$  is often assumed to be independent of wavelength.

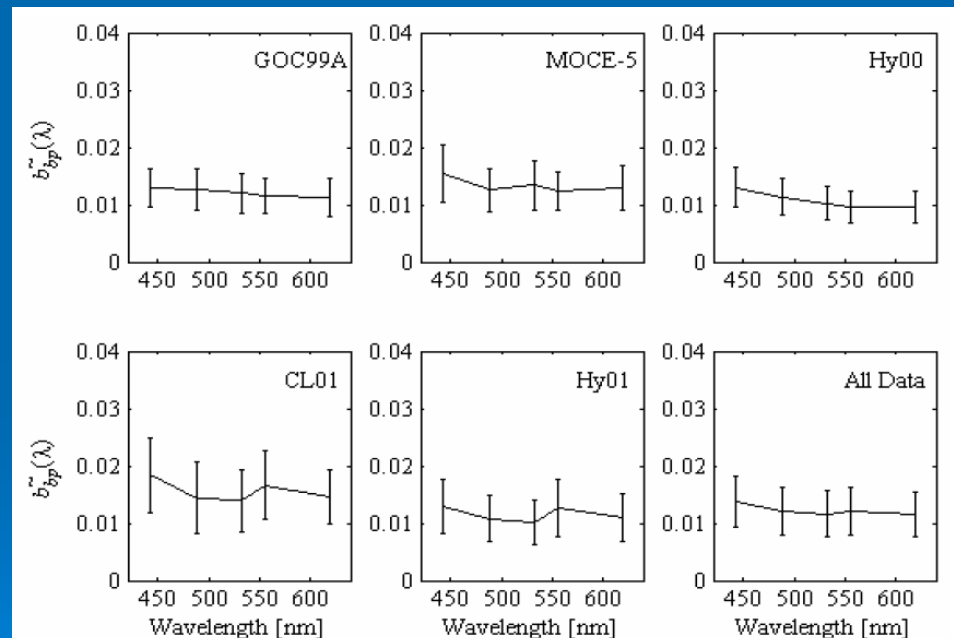


Fig. 3. Mean particulate backscattering ratio spectra for individual data sets, with one standard deviation shown for each data point. The spectra are as follows: GOC99A (top, left), MOCE-5 (top, middle), HyCODE 2000 (top, right), Crater Lake 2001 (bottom, left), HyCODE 2001 (bottom, middle), and the mean of all of the data sets (bottom, right).

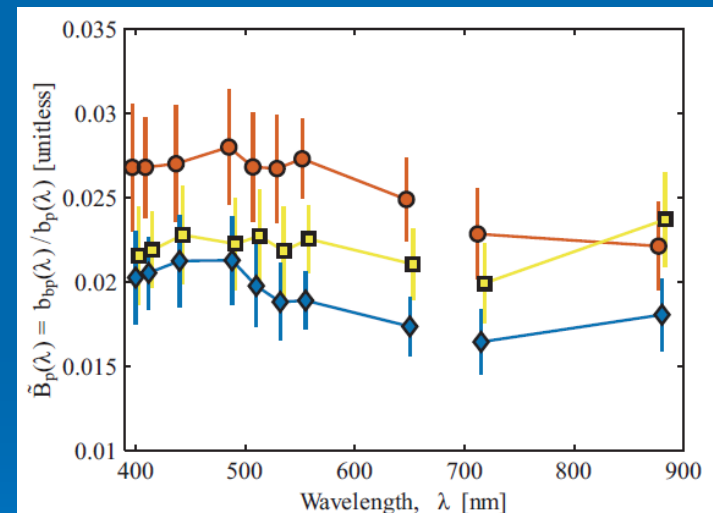


Fig. 13. Spectral backscattering ratio,  $\hat{B}_p(\lambda)$ , calculated using ac-9 and BB9 measurements for the three characteristic compositions described in Section 3B: (red circles) resuspension-dominated; (yellow squares) less energetic, low chlorophyll; (blue diamonds) less energetic with higher chlorophyll. Error bars represent uncertainty of  $\pm\sigma$  in both  $b_{bp}(\lambda)$  and  $b_p(\lambda)$  from the Monte Carlo model.

# Models for Backscattering by Phytoplankton and NAP

So we end up with...

$$b_{bp}(\lambda) = \frac{b_{bp}}{b_p} \left( c_p(\lambda_o) \left( \frac{\lambda}{\lambda_o} \right)^{-n} - a_p(\lambda) \right), \text{ Roesler and Boss 2003}$$

model or data for  $b_p(\lambda)$

model  $B_p = b_{bp}/b_p$  (often assume independent of  $\lambda$ ).

# Models for Backscattering by Phytoplankton and NAP

Various people have published simple models for  $B_p$  as a function of  $Chl$ , e.g.

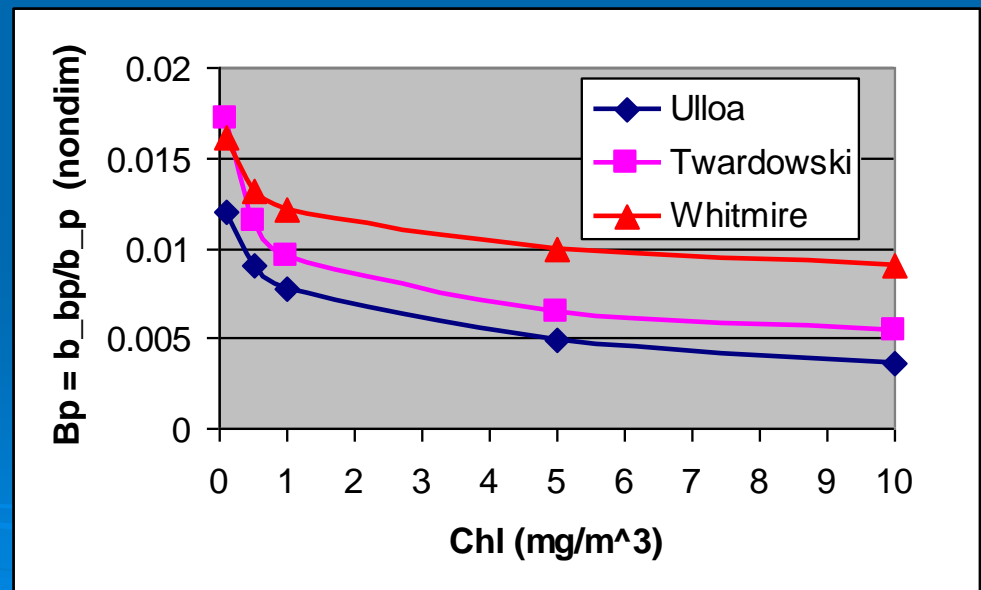
$$B_p = 0.01[0.78 - 0.42 \log_{10} Chl] \quad (\text{Ulloa, et al, 1994})$$

$$B_p = 0.0096 Chl^{-0.253} \quad (\text{Twardowski et al., JGR, 2001, Case 1 water})$$

$$B_p(555 \text{ nm}) = 0.0121 Chl^{-0.125} \quad (\text{Whitmire et al., Opt. Exp, 2007})$$

The predictions vary widely because

- \* the models are fits to different data sets
- \* scattering does not correlate well with  $Chl$



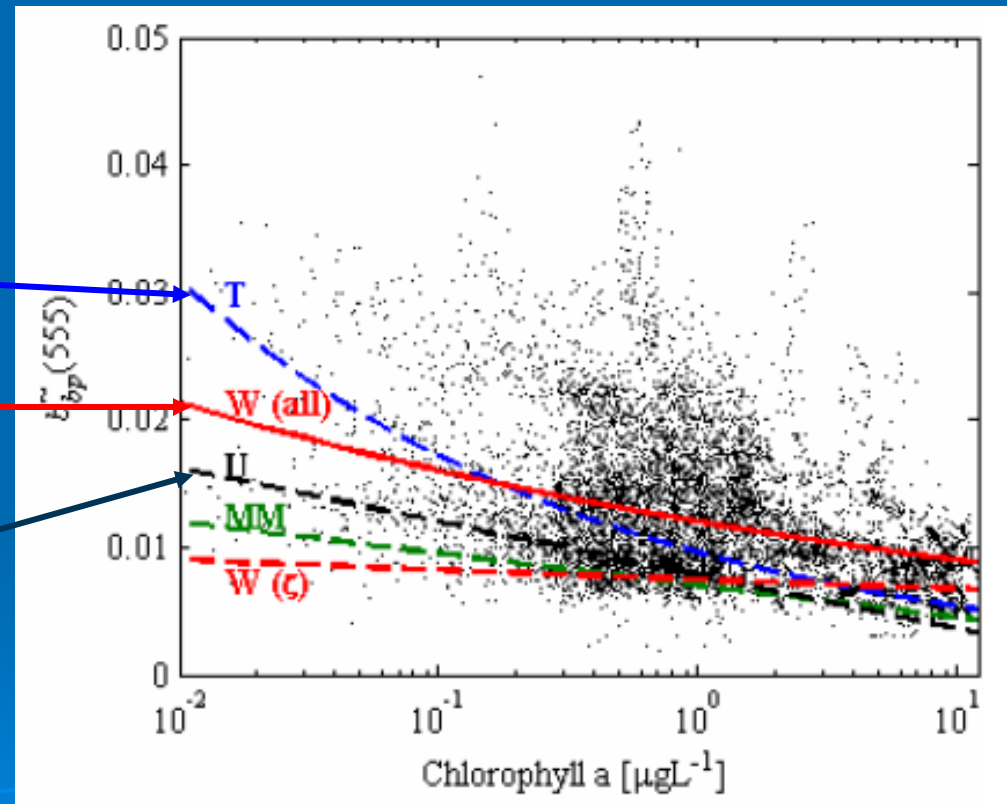
# Models for Backscattering by Phytoplankton and NAP

Although there are several “best fit” models for  $B_p$ , the variability in  $B_p$  vs  $Chl$  makes them almost useless, even in Case 1 waters.

$$B_p = 0.0096 Chl^{0.253}$$

$$B_p(555 \text{ nm}) = 0.0121 Chl^{0.125}$$

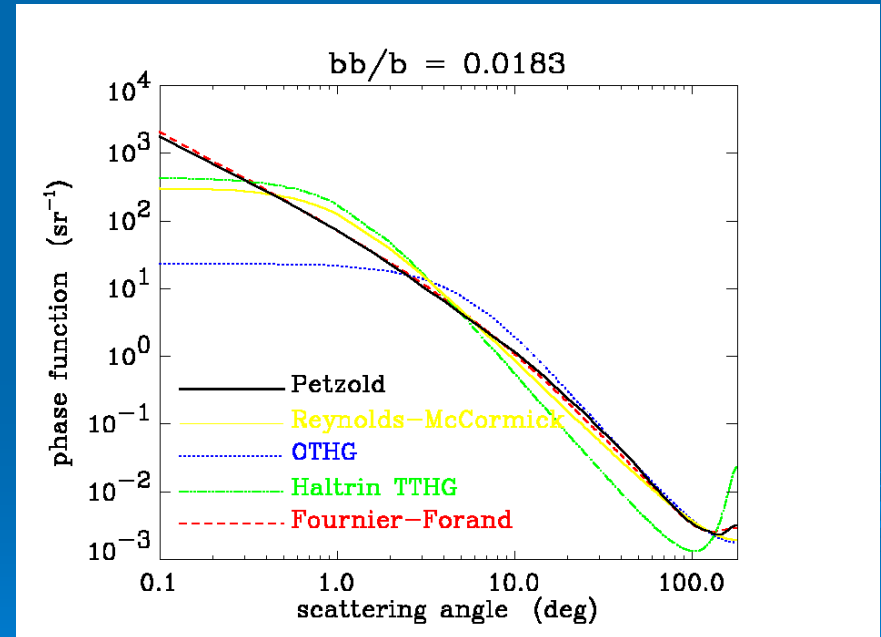
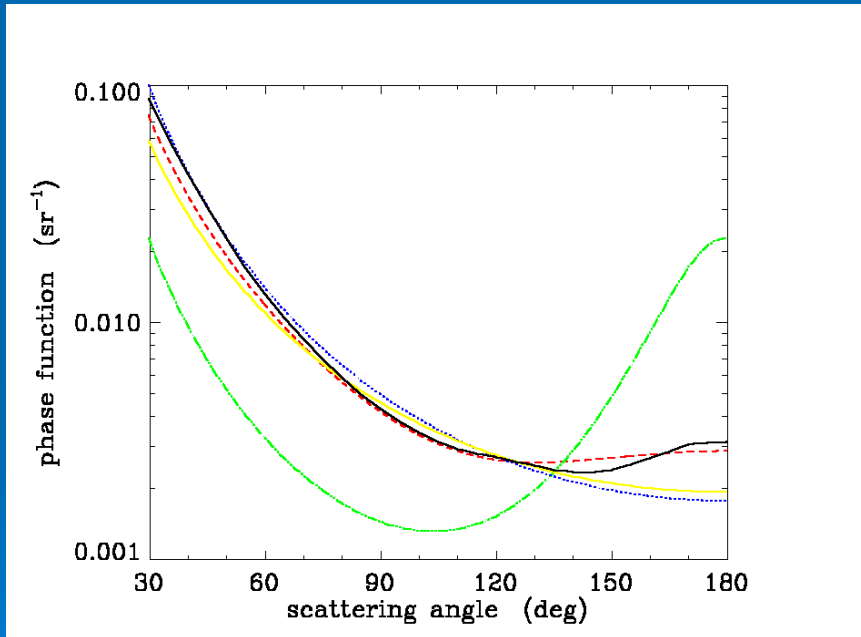
$$B_p = 0.01[0.78 - 0.42 \log_{10} Chl]$$



Whitmire et al., Opt. Exp, 2007

# Analytic Models for Phase Functions

There are many analytic phase function models. Most of these were developed for non-oceanographic studies (atmospheric optics, astronomy, etc.). Although the shapes are roughly like ocean phase functions, there are usually large differences at very small and/or large scattering angles.



Petzold is measured. The others are analytic models. Only the Fournier-Forand phase function does a good job of matching Petzold over all scattering angles.



# The Fournier-Forand Phase Function

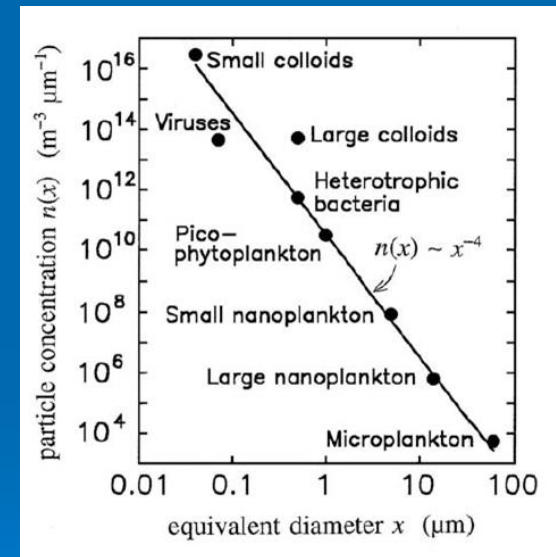
Derived from Mie theory

- homogeneous spheres with real refractive index,  $n$
- hyperbolic (Junge) size distribution with slope,  $-\mu$
- integrate over particles sizes from 0 to infinity

$$\begin{aligned}\tilde{\beta}_{\text{FF}}(\psi) = & \frac{1}{4\pi(1-\delta)^2\delta^\nu} \left[ \nu(1-\delta) - (1-\delta^\nu) \right. \\ & \left. + [\delta(1-\delta^\nu) - \nu(1-\delta)] \sin^{-2}\left(\frac{\psi}{2}\right) \right] \\ & + \frac{1-\delta_{180}^\nu}{16\pi(\delta_{180}-1)\delta_{180}^\nu} (3\cos^2\psi - 1),\end{aligned}$$

where

$$\nu = \frac{3-\mu}{2}, \quad \delta = \frac{4}{3(n-1)^2} \sin^2\left(\frac{\psi}{2}\right).$$



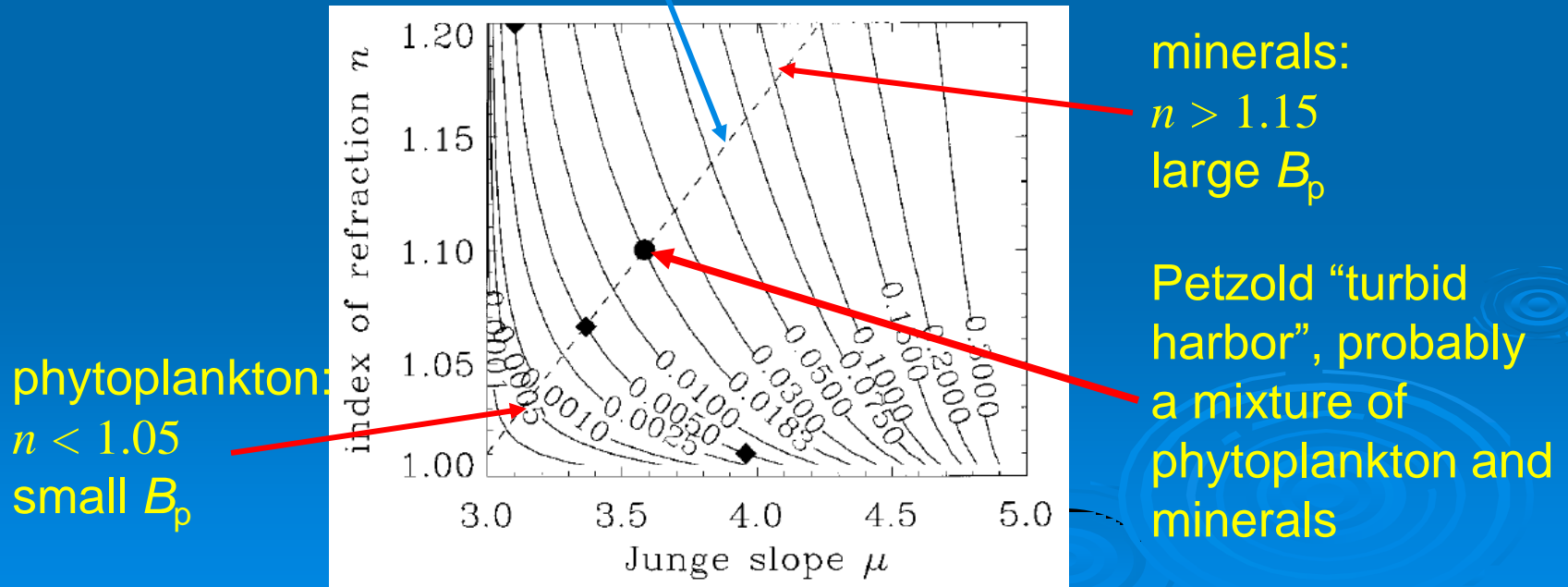
from Mobley et al., 2002

# The Fournier-Forand Phase Function

$n$  and  $\mu$  can be related to the backscatter fraction  $B_p$

$$B_p = 1 - \frac{1 - \delta_{90}^{\nu+1} - 0.5(1 - \delta_{90}^{\nu})}{(1 - \delta_{90})\delta_{90}^{\nu}}$$

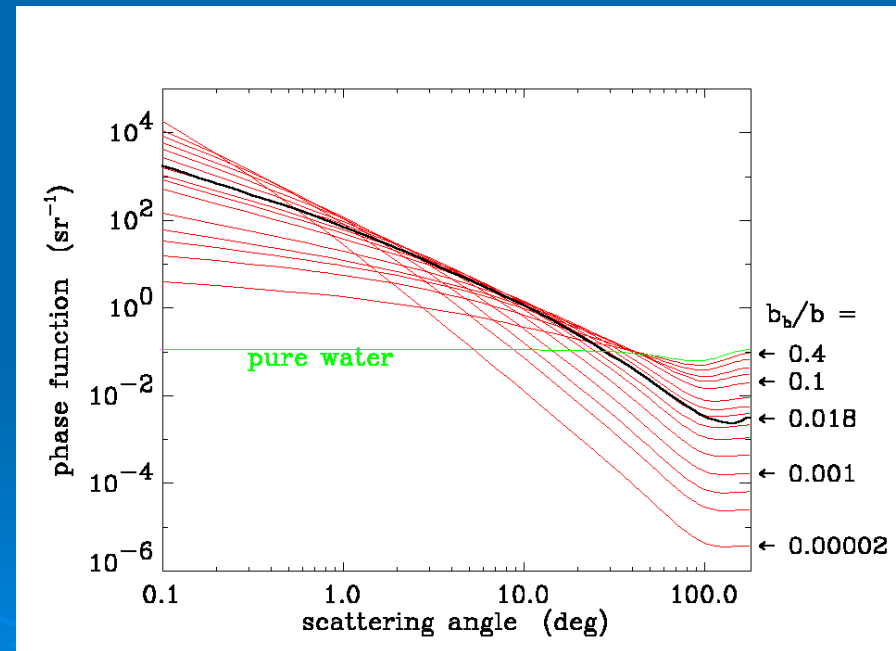
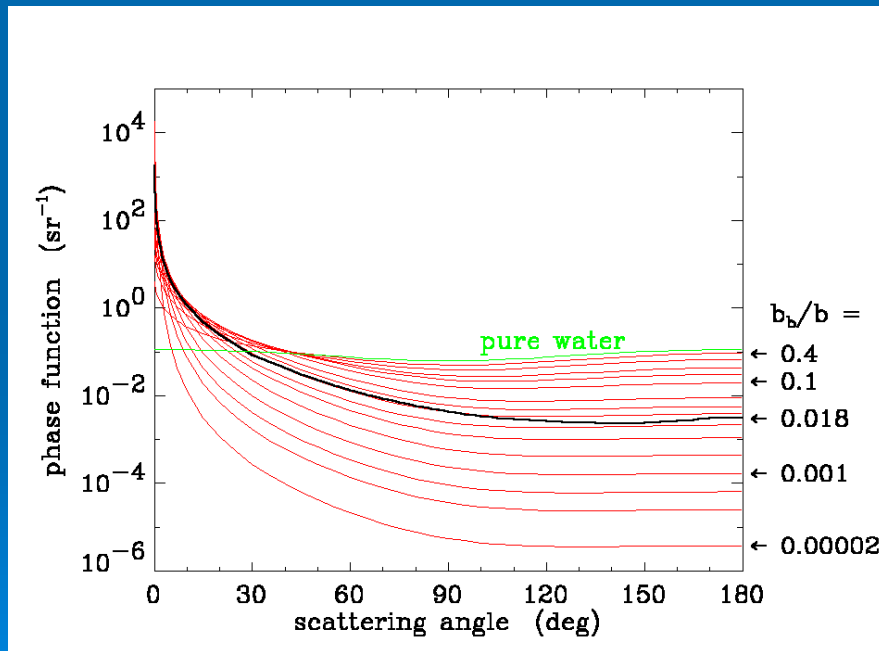
When selecting a F-F pf by the backscatter fraction, H uses values along the dotted line



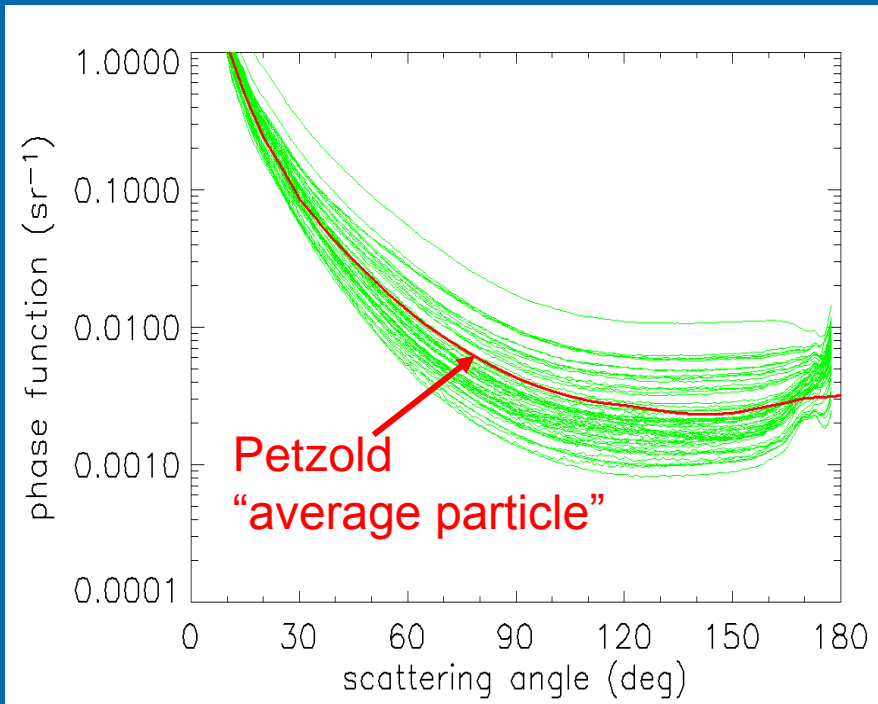
Mobley et al., 2002

# The Fournier-Forand Phase Function

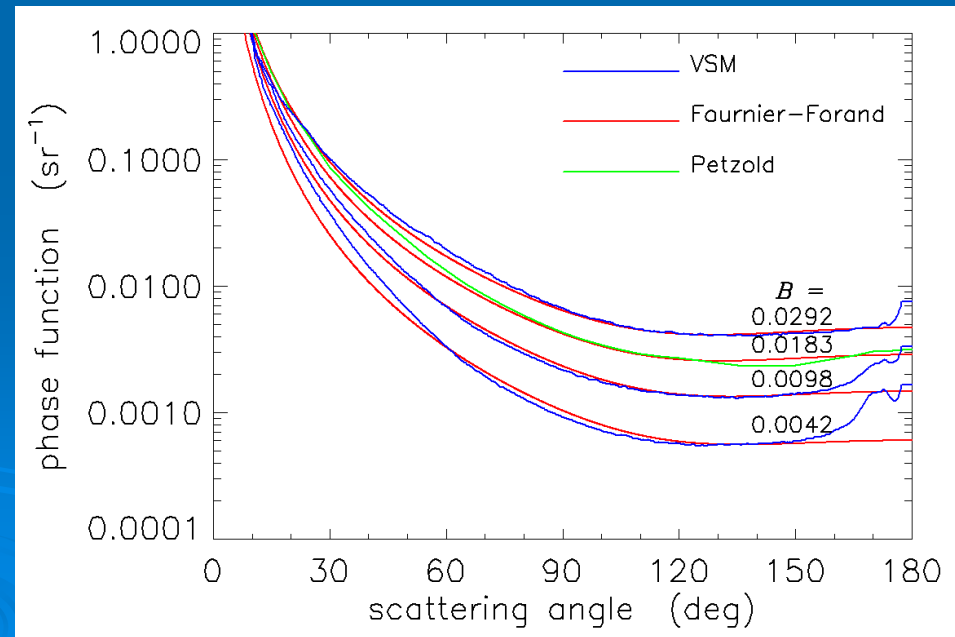
The HydroLight database has a large number of Fournier-Forand phase functions for various backscatter fractions  $b_b/b$ . These are interpolated to get the F-F pf for any value of  $b_b/b$ , to model any particular component.



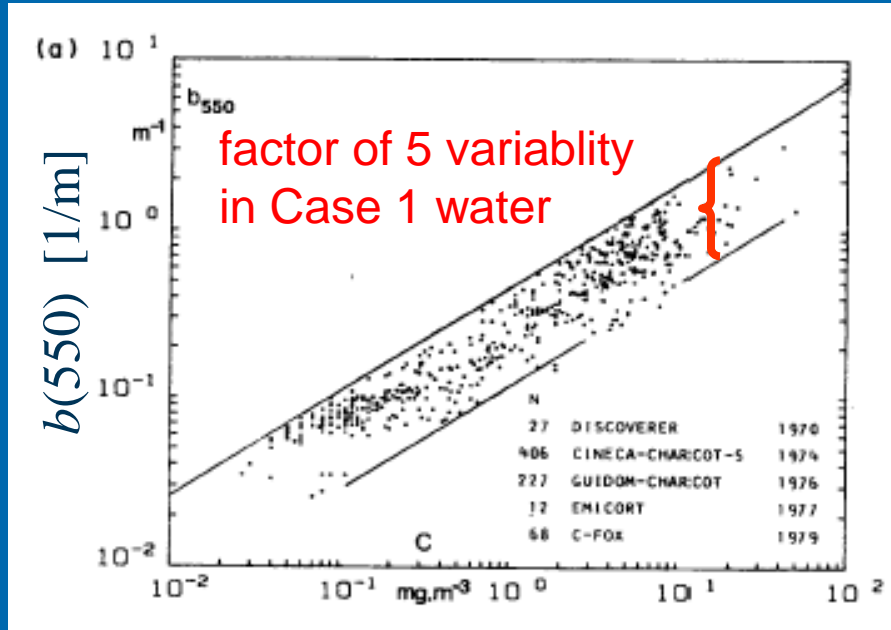
# The Fournier-Forand Phase Function



The FF phase function does an adequate job (at least for many purposes) of fitting most measured phase functions

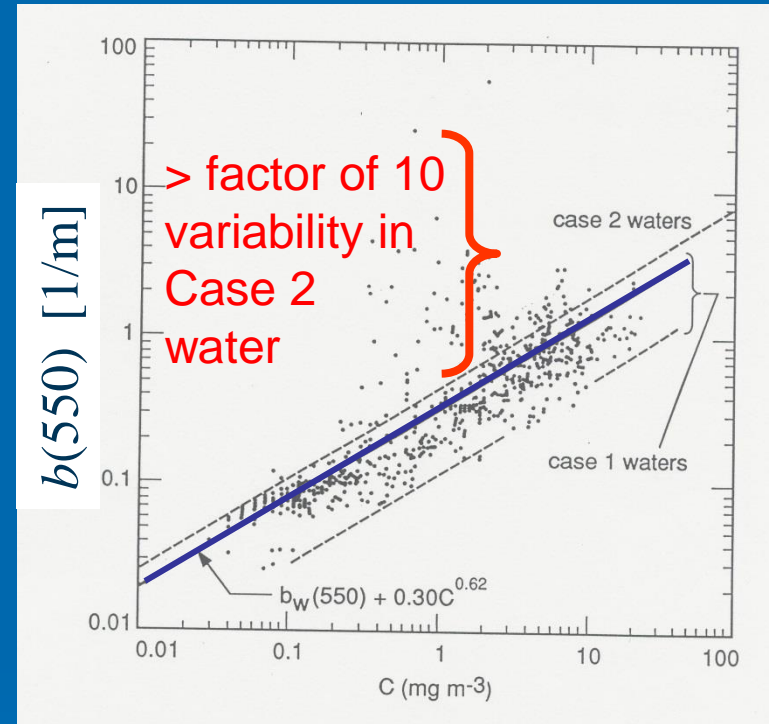


# Example: Scattering as a Function of *Chl*



*Chl* [mg m<sup>-3</sup>]

Morel 1987, DSR



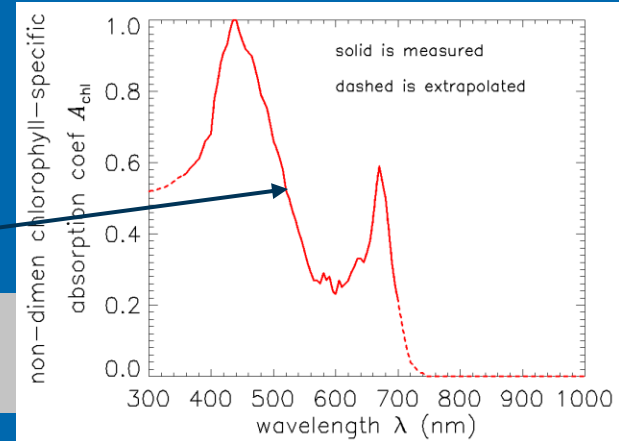
*Chl* [mg m<sup>-3</sup>]

The “classic” Case 1 model for scattering (Gordon and Morel, 1983) just fits a straight line through these data:  $b(550) = 0.30Chl^{0.62}$ . This may be good *on average*, but can be very inaccurate for a particular water body! Scattering does not correlate well with *Chl*, even in Case 1 water. Why?

# The “Classic” Case 1 IOP Model in HE5

Pick the pure water spectrum (usually Pope and Fry data). Then particle absorption and scattering are given by

$$a_p(z, \lambda) = 0.06 a_c^{*/'}(\lambda) Chl(z)^{0.65}$$



$$a_{CDOM}(z, \lambda) = 0.2 [a_w(440) + a_p(z, 440)] \exp[-0.014 (\lambda - 440)]$$

$$b_p(z, \lambda) = 0.30 Chl(z)^{0.62} \left( \frac{550}{\lambda} \right)$$

The user then picks a particle phase function, e.g. a Fournier-Forand pf with a given backscatter fraction  $B_p$ . For guidance, can use one of the simple  $B_p$  models, but may be very inaccurate.

# The “New” Case 1 IOP Model in HE5

Based on papers by Bricaud et al. (1998) for absorption and Morel et al. (2002) for scattering. For details, see [www.oceanopticsbook.info/view/optical\\_constituents\\_of\\_the\\_ocean/\\_level\\_2/a\\_new\\_iop\\_model\\_for\\_case\\_1\\_water](http://www.oceanopticsbook.info/view/optical_constituents_of_the_ocean/_level_2/a_new_iop_model_for_case_1_water)

All IOPs are determined by the *Chl* value.

$$a_p(z, \lambda) = A_p(\lambda) \text{Chl}(z)^{E_p(\lambda)}$$

$a_p^*$  shape helps describe pigment packaging.  $A_p(\lambda)$  and  $E_p(\lambda)$  are tabulated.

$$b_p(z, \lambda) = 0.416 \text{Chl}(z)^{0.766} \left( \frac{\lambda}{550} \right)^v$$

$\lambda$  dependence of  $b_p$  now depends on *Chl*

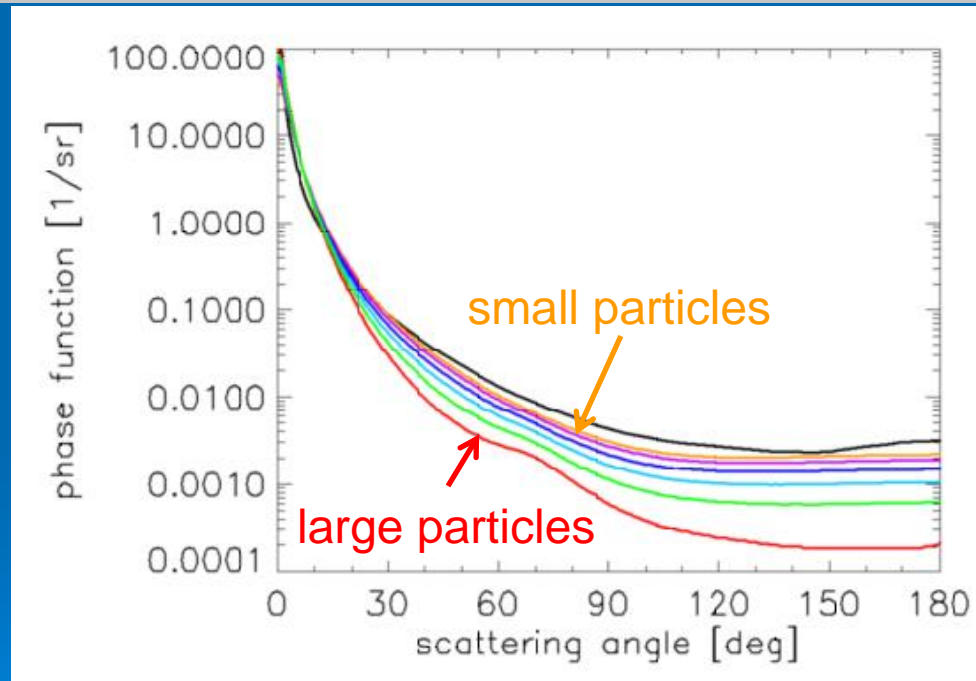
$$v = 0.5 \left[ \log_{10} \text{Chl}(z) - 0.3 \right] \quad \text{for } 0.02 \leq \text{Chl} < 2$$
$$= 0 \quad \text{for } \text{Chl} \geq 2$$

# The “New” Case 1 IOP Model in HE5

The particle phase function is now determined by the  $Chl$  value:

$$\tilde{\beta}_p(\psi, Chl) = \alpha_s(Chl) \tilde{\beta}_{small}(\psi) + (1 - \alpha_s) \tilde{\beta}_{large}(\psi)$$

$$\alpha_s = 0.855 \left[ 0.5 - 0.25 \log_{10} Chl \right]$$



Phase functions for small (orange) and large (red) particles as given by Morel et al. (2002). Phase functions for  $Chl = 0.01$  (purple),  $0.1$  (blue),  $1.0$  (teal), and  $10.0$  (green), and the Petzold average particle phase function (black) are shown.



# Never Forget ...

All IOPs are extremely variable, even for a particular component like phytoplankton or mineral particles. There is no “phytoplankton absorption spectrum,” and it’s even worse for scattering.

Every phytoplankton species, and every nutrient condition and light adaptation condition for a given species, has different absorption and scattering spectra. The same is true for minerals, CDOM, etc.

This variability makes it extremely hard to model IOPs, and extremely hard to know what IOPs to use as input to HydroLight, unless you measured them (which is impossible to do for every situation).

Models are always approximate. They can be good on average, but terrible in any specific case.

When HydroLight gives the “wrong answer,” it is almost always because the input IOPs do not correspond to the IOPs of the water body being simulated. Garbage in, garbage out.

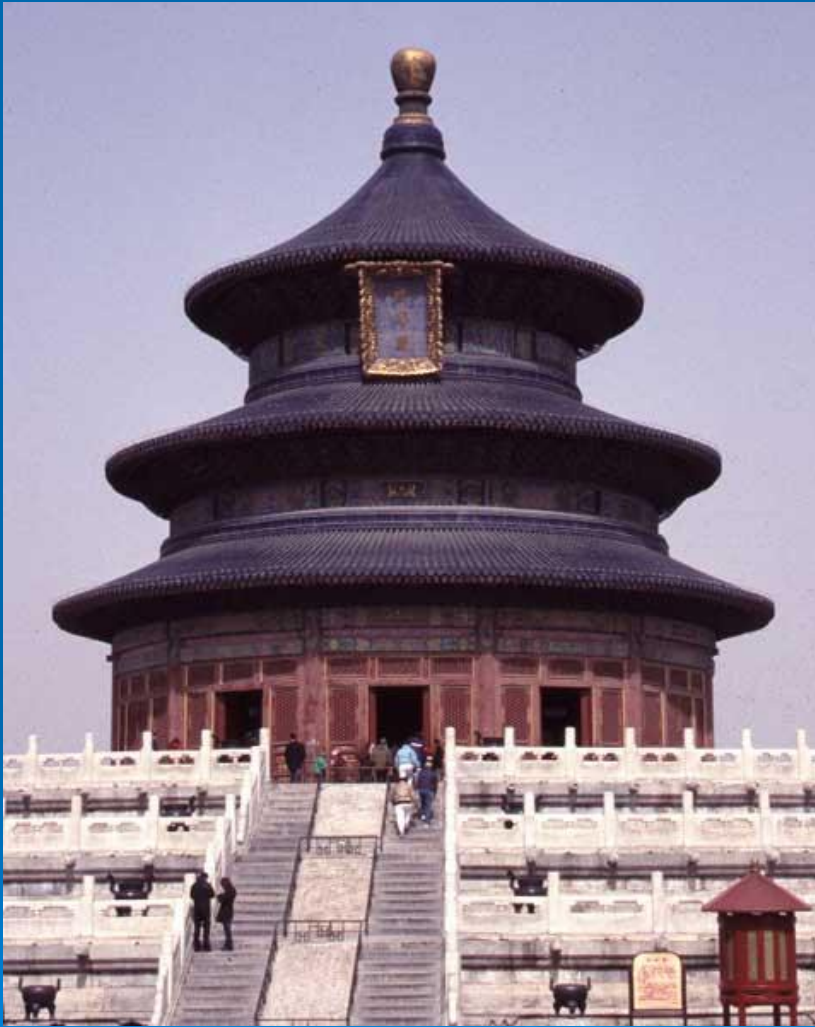
# Never Forget ...

When using any model for IOPs, think about:

- What data were used to develop the model?
- Global relationships are not appropriate regionally
- Regional models are not valid elsewhere (e.g., a model based on North Atlantic data can't be applied to the south Pacific)
- Models based on near-surface data cannot be applied at depth
- Models based on open-ocean data cannot be applied to coastal waters
- Was the model developed to use satellite-retrieved Chl to recover IOPs?
- Where was the division between Case I and II in the underlying data?

When using any model, always think “maybe good for average or typical values, but maybe terrible for my water body.”

# There are No Perfect IOP Models, but There is a Perfect Building



The Hall of Prayer for Good Harvests at the Temple of Heaven, Beijing. Photo by Curt Mobley.