The particle size distribution and its optical proxies

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- What about a particle can we infer from its size?

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- What processes are affected by size?

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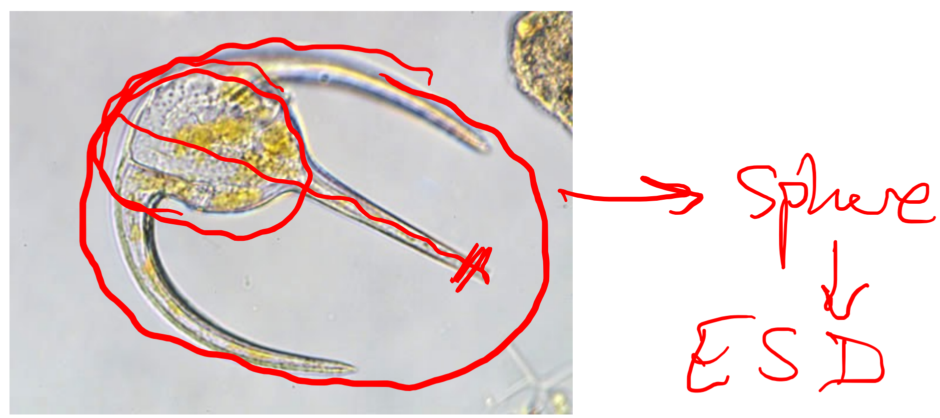
Questions:

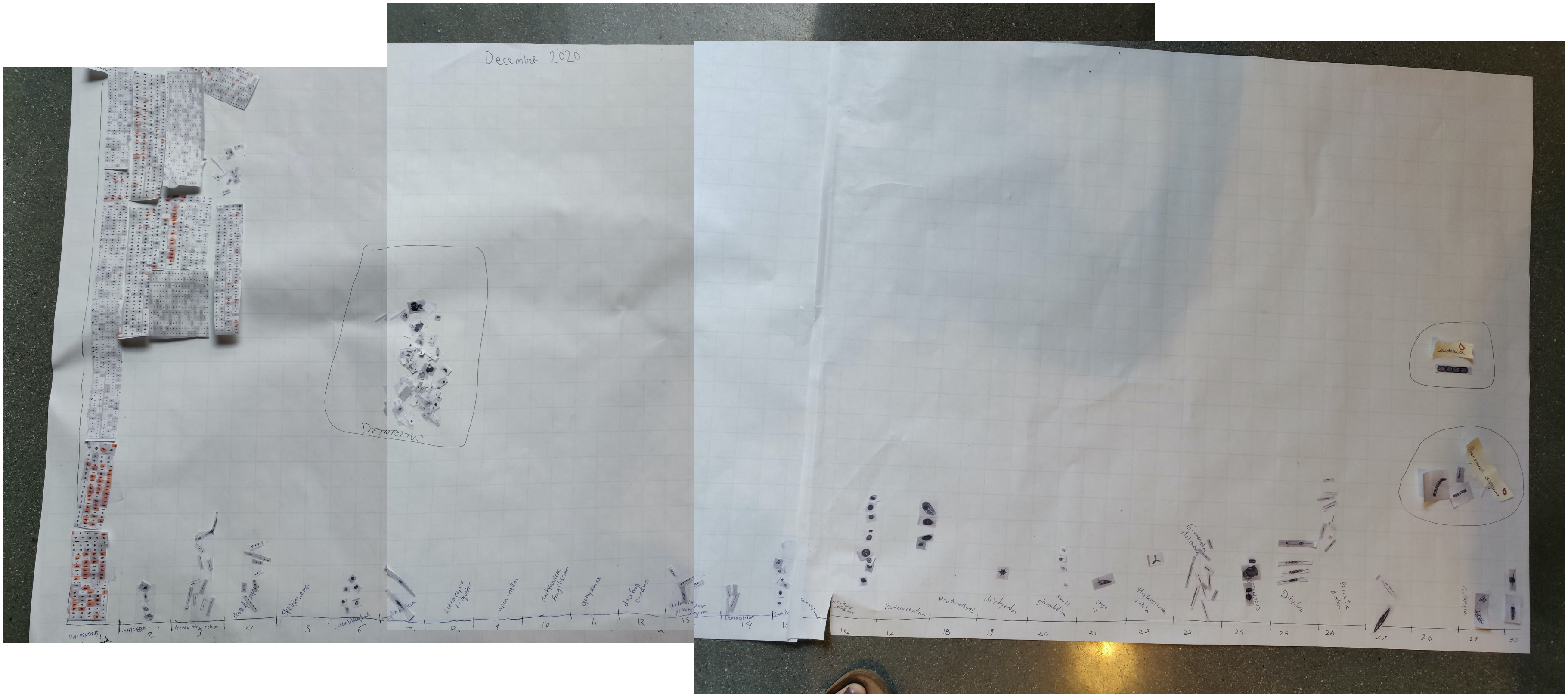
- What about a particle can we infer from its size?
- What processes are affected by size?
- What is the size of:

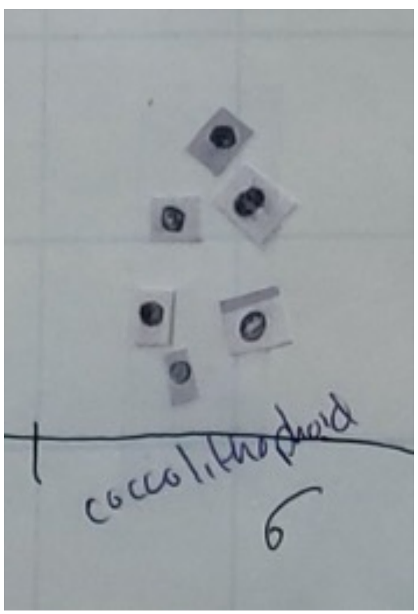


The calculus of size distribution

- How do we characterize the size of particles of varying shape?
- What aspects of size are different observations sensitive to?
- What are the units of the size distribution?
- How do we approximate discrete observations with a continuous distribution?
- How do we compare observations that have different size bins?
- What are the uncertainties in a size distribution?
- How do we convert back and forth between number size distribution and volume or mass?

Manual sorting of IFCB data: December 2020 data (excluding "detritus")





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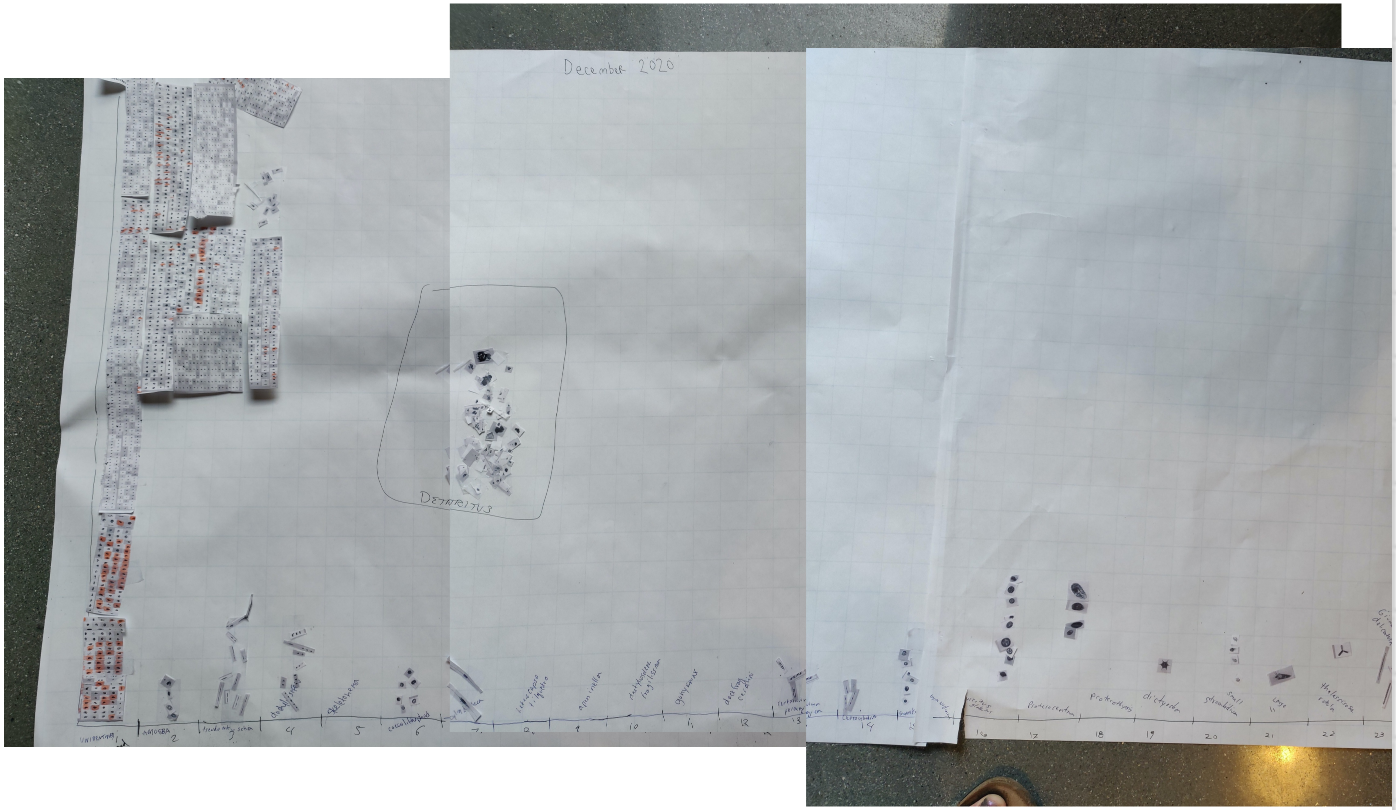

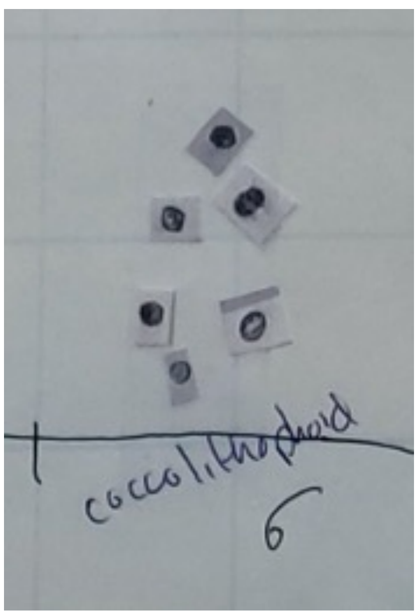

Category	*N*	*Size (um)*
1	1150	10
6	6	10
15	5	20
20	4	20
3	10	30
4	7	30
7	2	30
13	4	30
14	4	30
16	9	30
19	1	30
17	4	40
30	2	40
23	10	50
22	1	60
21	1	70
24	3	70
25	4	70
C. didymus	2	70
26	8	100
29	1	120
Lauderia	1	130
27	3	140

Uncertainty

Counting error ~ $\sqrt{N}$

detection limit – small end (inst.)

large end (sample size)

Size bin choice, units

Regular increment

↓

log spacing

Category	N	Size (um)
1	1150	10
6	6	10
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3	10	30
4	7	30
7	2	30
13	4	30
14	4	30
16	9	30
19	1	30
17	4	40
30	2	40
23	10	50
22	1	60
21	1	70
24	3	70
25	4	70
C. didymus	2	70
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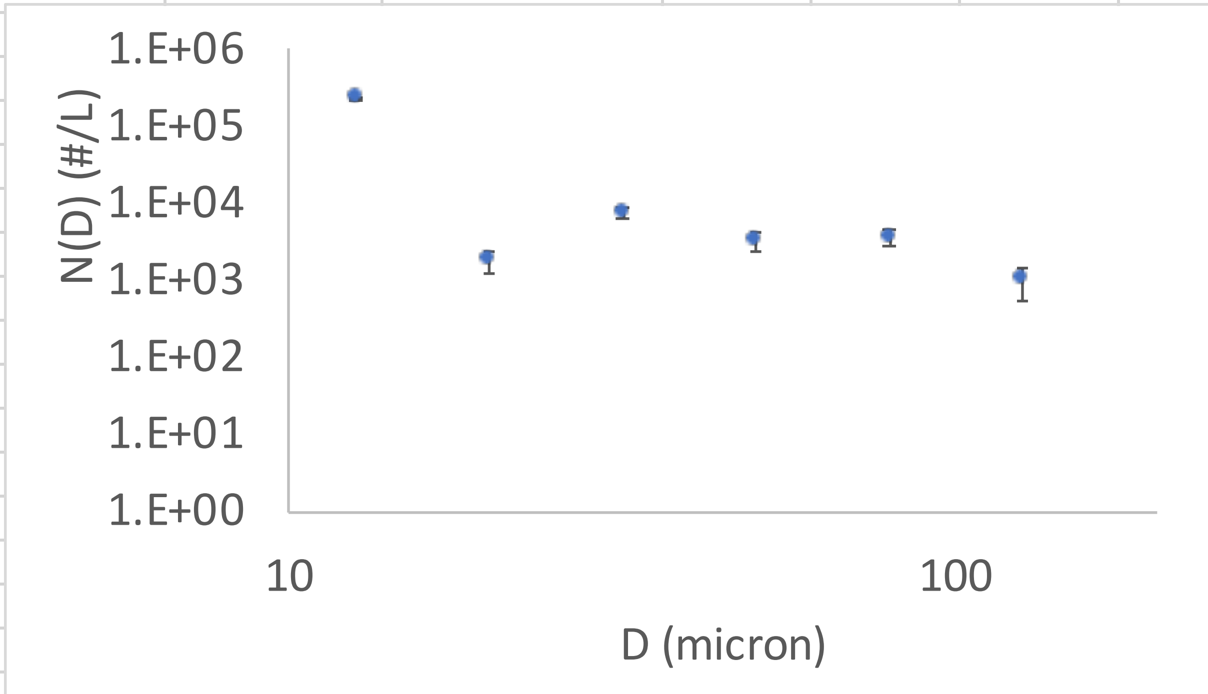
29	1	120
Lauderia	1	130
27	3	140

Geometric mean = $\sqrt{D_1 \cdot D_2}$

Category	N	Size (um)	N		Size bin edges	Size bin center	N (between edges)	Nerr	Rel. err	N(D) (#/L)	N(D)err (#/L)
1	1150	10	1150		10	13	1156	34	3%	231200	6800
6	6	10	6		16	20	9	3	33%	1800	600
15	5	20	5		25	32	37	6	16%	7400	1217
20	4	20	4		40	50	16	4	25%	3200	800
3	10	30	10		63	79	18	4	24%	3600	849
4	7	30	7		100	126	5	2	45%	1000	447
7	2	30	2		158						
13	4	30	4								
14	4	30	4								
16	9	30	9								
19	1	30	1								
17	4	40	4								
30	2	40	2								
23	10	50	10								
22	1	60	1								
21	1	70	1								
24	3	70	3								
25	4	70	4								
C. didymus	2	70	2								
26	8	100	8								
29	1	120	1								
Lauderia	1	130	1								
27	3	140	3								

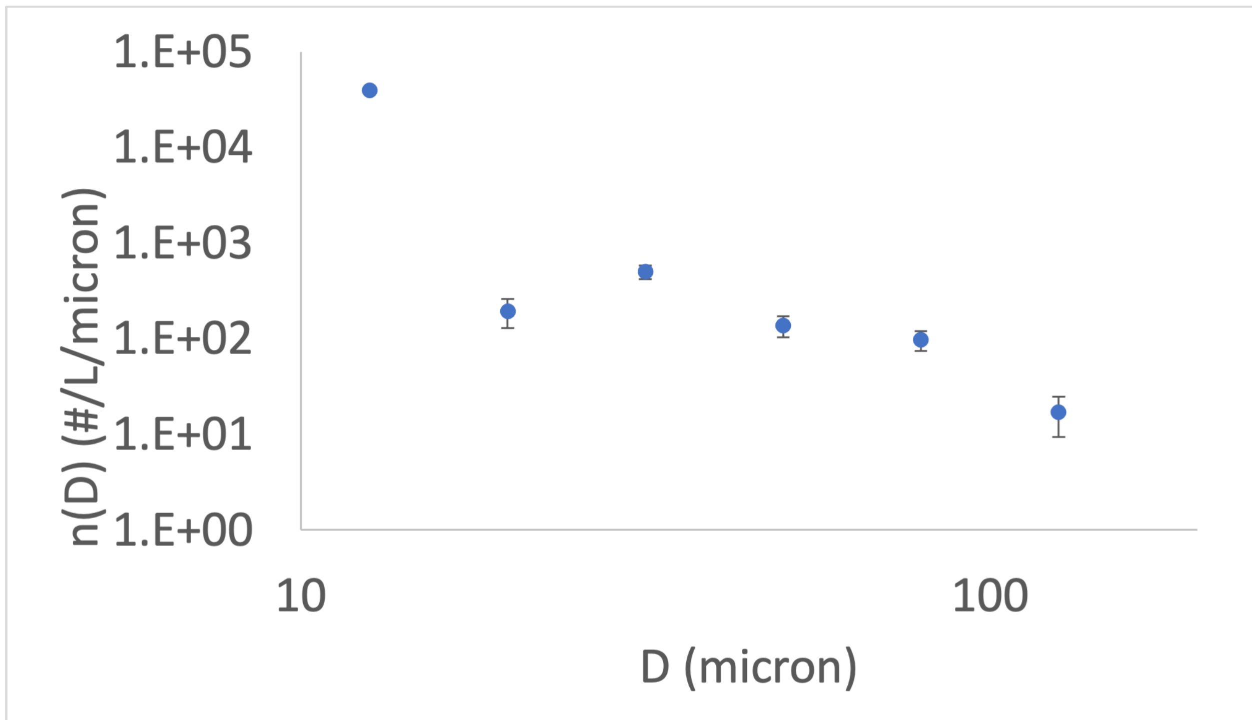


What if we want to compare these discrete data to another measurement? Or model a continuous distribution?

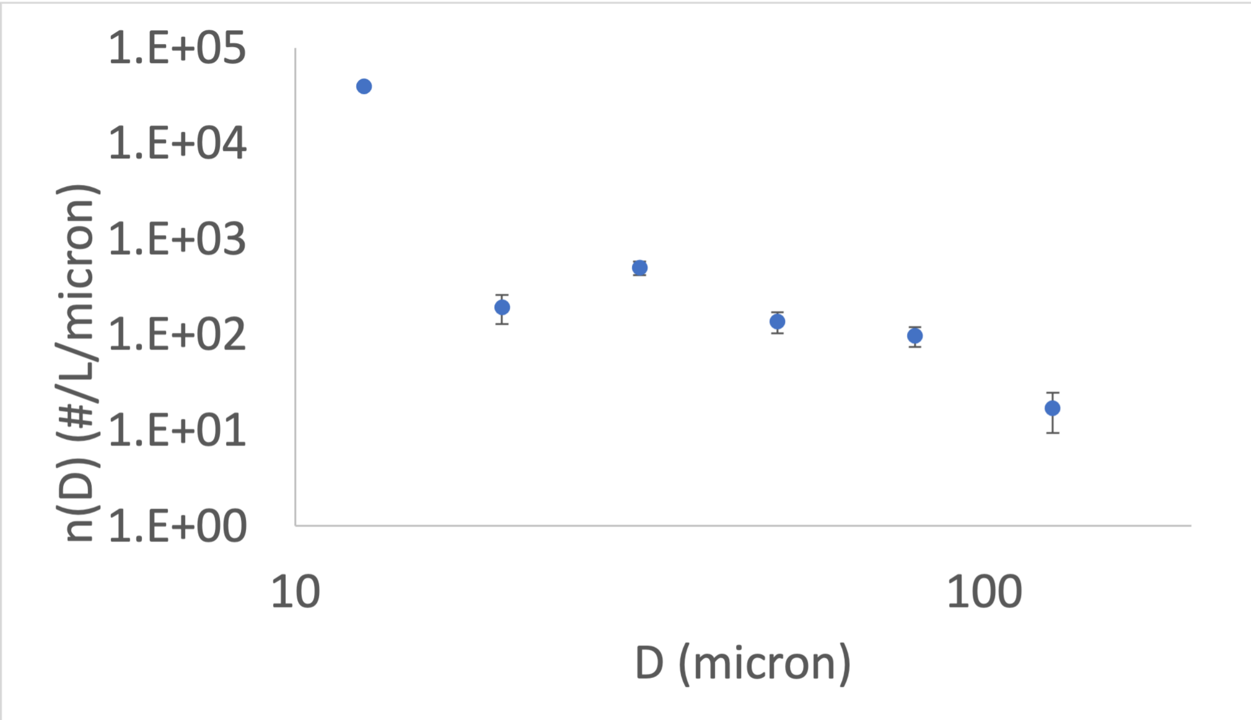
What if we want to compare these discrete data to another measurement? Or model a continuous distribution? --> differential number size distribution

$$\frac{N\,(\#/L)}{\Delta D\,(\mu m)} = n(D)\ [\#/L/\mu m]$$

differential number size distribution



How do we go from a differential number size distribution to a volume size distribution?



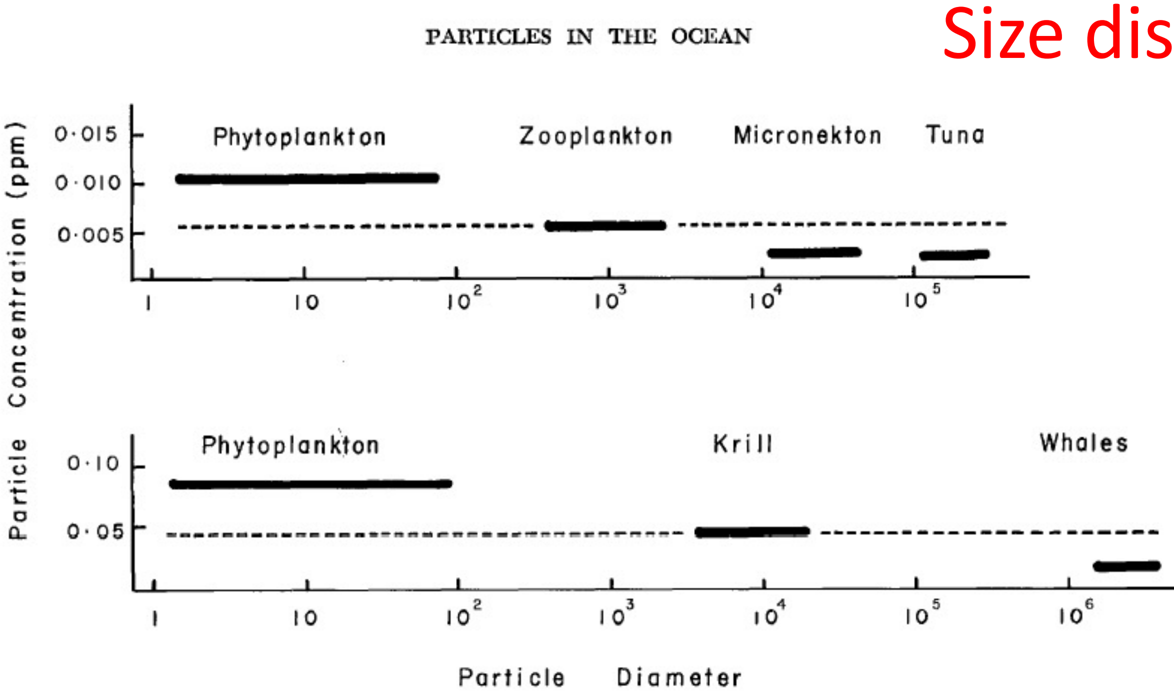
LISST

↓

$\frac{\mu L}{L}$ or ppm

$$\frac{\#\ \text{particles}}{L \cdot \mu m} \times \frac{V_{part}\ (\mu L)}{\text{particle}} \times \Delta D\ (\mu m) = \frac{\mu L}{L}$$

Size distributions in the ocean

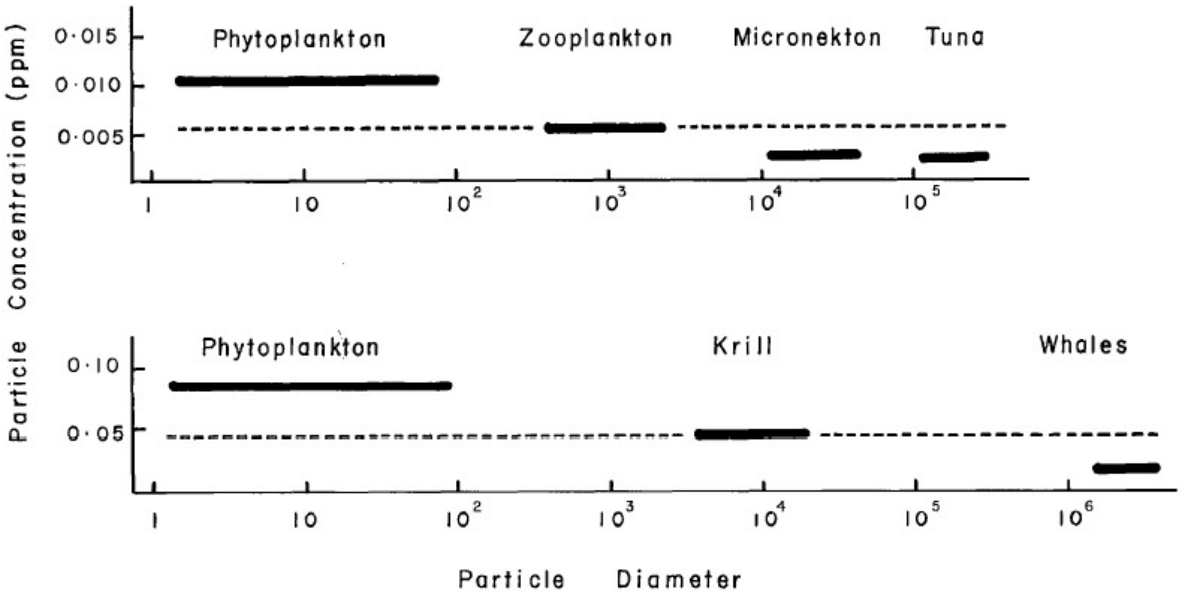


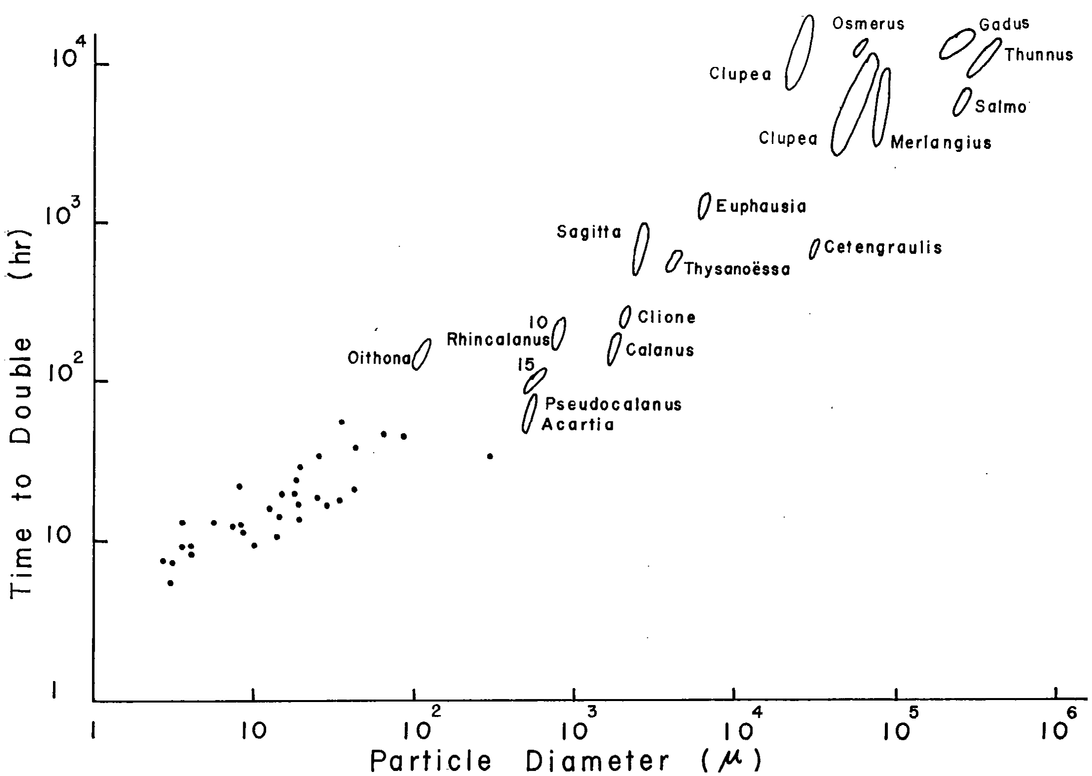
Sheldon et al., 1972:

- To first order, there are roughly equal amounts of material in particles of all sizes ranging logarithmically **“from 1 μ to about 10^6 μ, i.e. from bacteria to whales”**
- Consistent with $n(D) \sim D^{-4}$

Size distributions in the ocean

PARTICLES IN THE OCEAN





Sheldon et al., 1972:

- To first order, there are roughly equal amounts of material in particles of all sizes ranging logarithmically **"from 1 μ to about 10^6 μ, i.e. from bacteria to whales"**
- Consistent with $n(D) \sim D^{-4}$
- Has important ecological implications: growth rates must be inversely related to particle size, if this canonical value holds everywhere

A few common models used to approximate PSDs

Power-law size distribution:

$$f(D) = \begin{cases} 0, & \text{if } D < D_{min} \text{ or } D > D_{max}; \\ n_0 \left[\frac{D}{D_0} \right]^{-\xi}, & \text{if } D_{min} \le D \le D_{max} \end{cases} \quad [\# \, m^{-3} \mu m^{-1}],$$

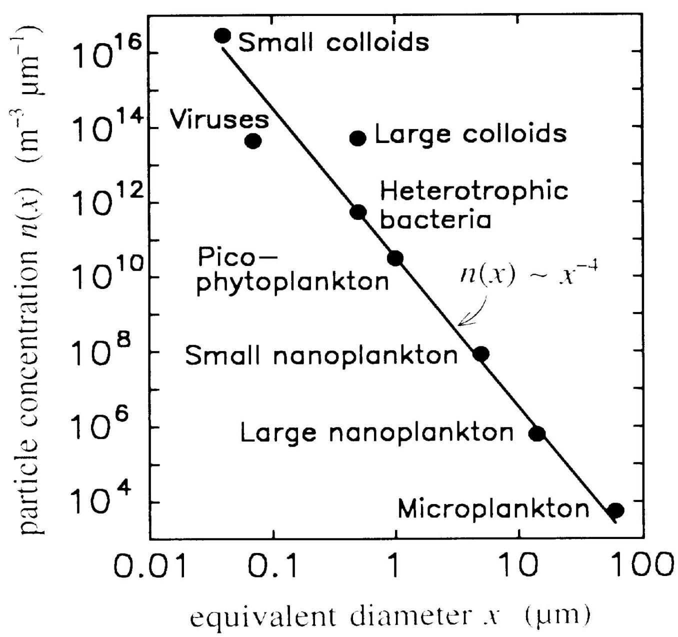


Fig. 3.2. Number size distribution typical of biological particles in the open ocean. [figure courtesy of D. Stramski]

A few common models used to approximate PSDs

Gamma:

$$n(r) = \begin{cases} 0 & r < 0 \\ Cr^{\mu}e^{-br} & r \geq 0;\ \mu > -1;\ b > 0, \end{cases}$$

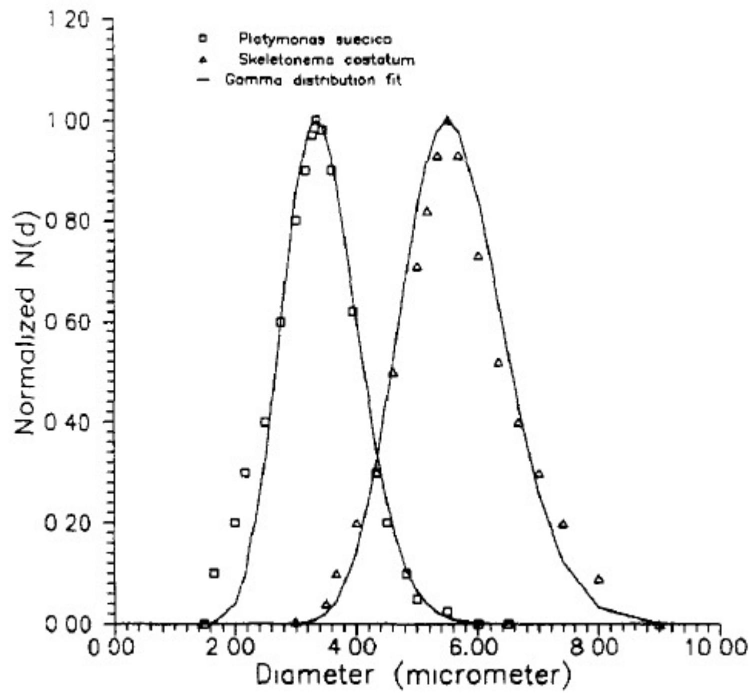


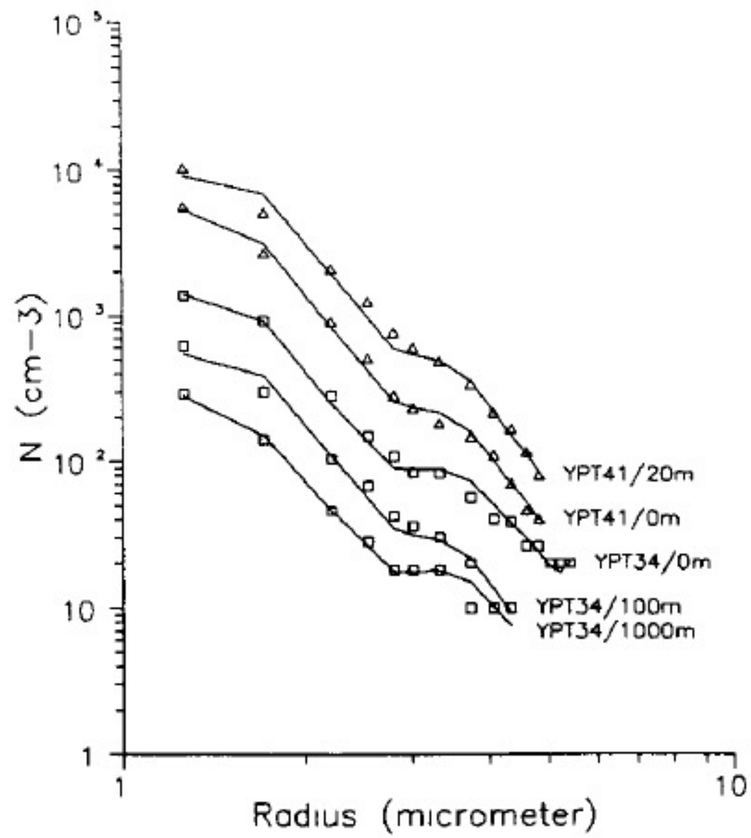
Fig 1 Normalized size distribution of phytoplankton species *Platymonas suecica* and *Skeletonema costatum* (Bricaud and Morel, 1986) and corresponding gamma distributions fit. Parameters of the respective distributions are $\mu = 20$, $b = 5.71$ and $\mu = 40$, $b = 7.279$

A few common models used to approximate PSDs

Risovic (1993):

$$f(D) = \begin{cases} 0, & \text{if } D < D_{\min} \text{ or } D > D_{\max}; \\ n_S \left[\dfrac{D}{D_0} \right]^{\mu_S} \exp(-\tau_S D^{\nu_S}) + n_L \left[\dfrac{D}{D_0} \right]^{\mu_L} \exp(-\tau_L D^{\nu_L}), & \text{if } D_{\min} \le D \le D_{\max} \end{cases} \quad [\# \, m^{-3} \mu n$$

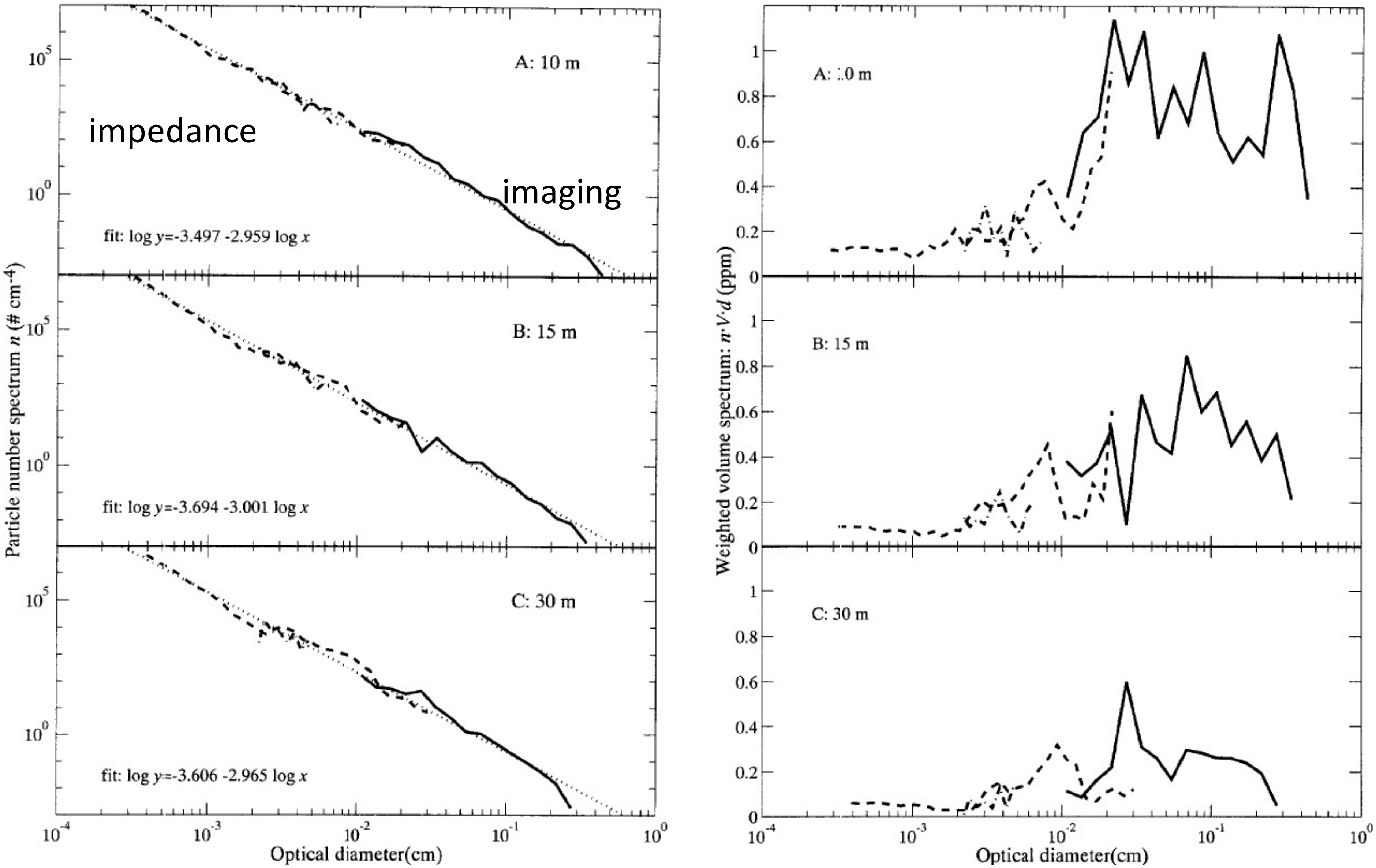
(28)



Example of size distribution

Number distribution

Volume distribution (accounting for packing)



Jackson et al., 1997

Different sizing methods are most ‘sensitive’ to different sizes.

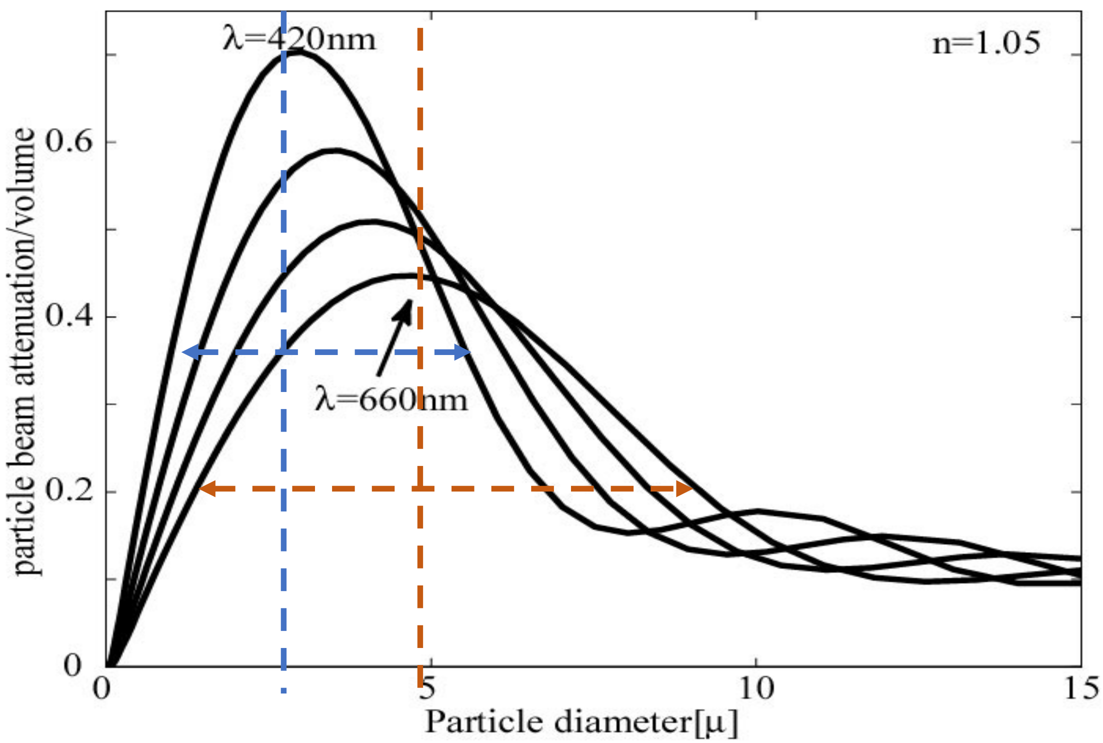
In general, a physical measurement associated with waves (sound, EM) will be most affected by ‘inhomogeneities’ in the environment which have sizes similar to the wavelength (resonance).

In addition, issues of resolution (e.g. pixel size of a camera) may limit the smallest resolvable size.

Hence, if we want to sense particles of a certain size we need to choose a tool that will be sensitive to that size range.

All methods have problems at both ends due to sensitivity to small particles and rarity of large particles.

C_{ext}/volume is sensitive to the wavelength of measurement:



The particle size where the maximum occurs, and the width of the peak, changes between blue to red wavelengths. *Spectral* c_p contains size information!

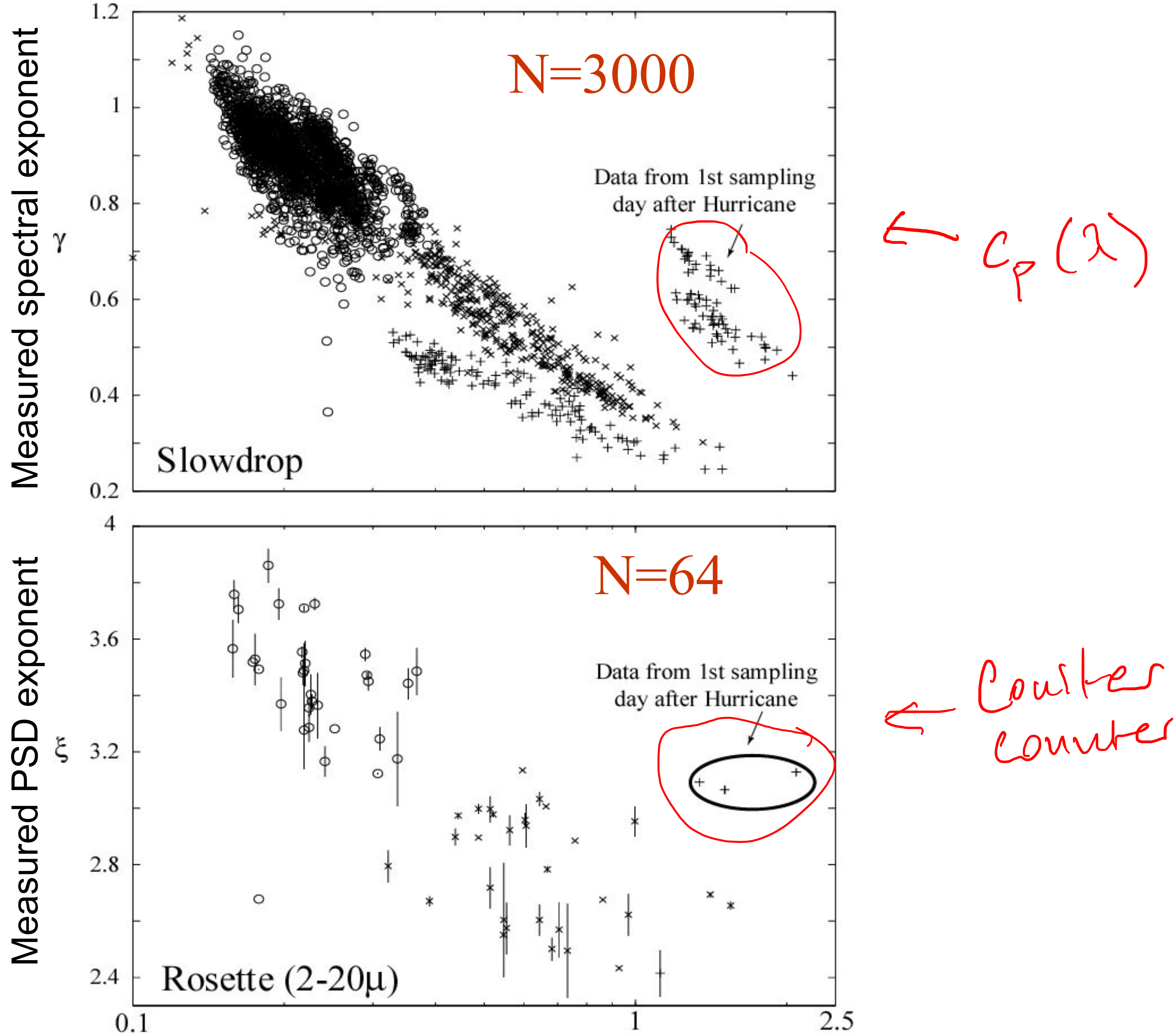
Beam-c and PSD relationship predicted from Mie theory:

Volz (1954): For non-absorbing particles of the same n and a power-law distribution from D_{min}=0 to D_{max}=∞,

$$N(D)=N_o(D/D_o)^{-\xi}$$

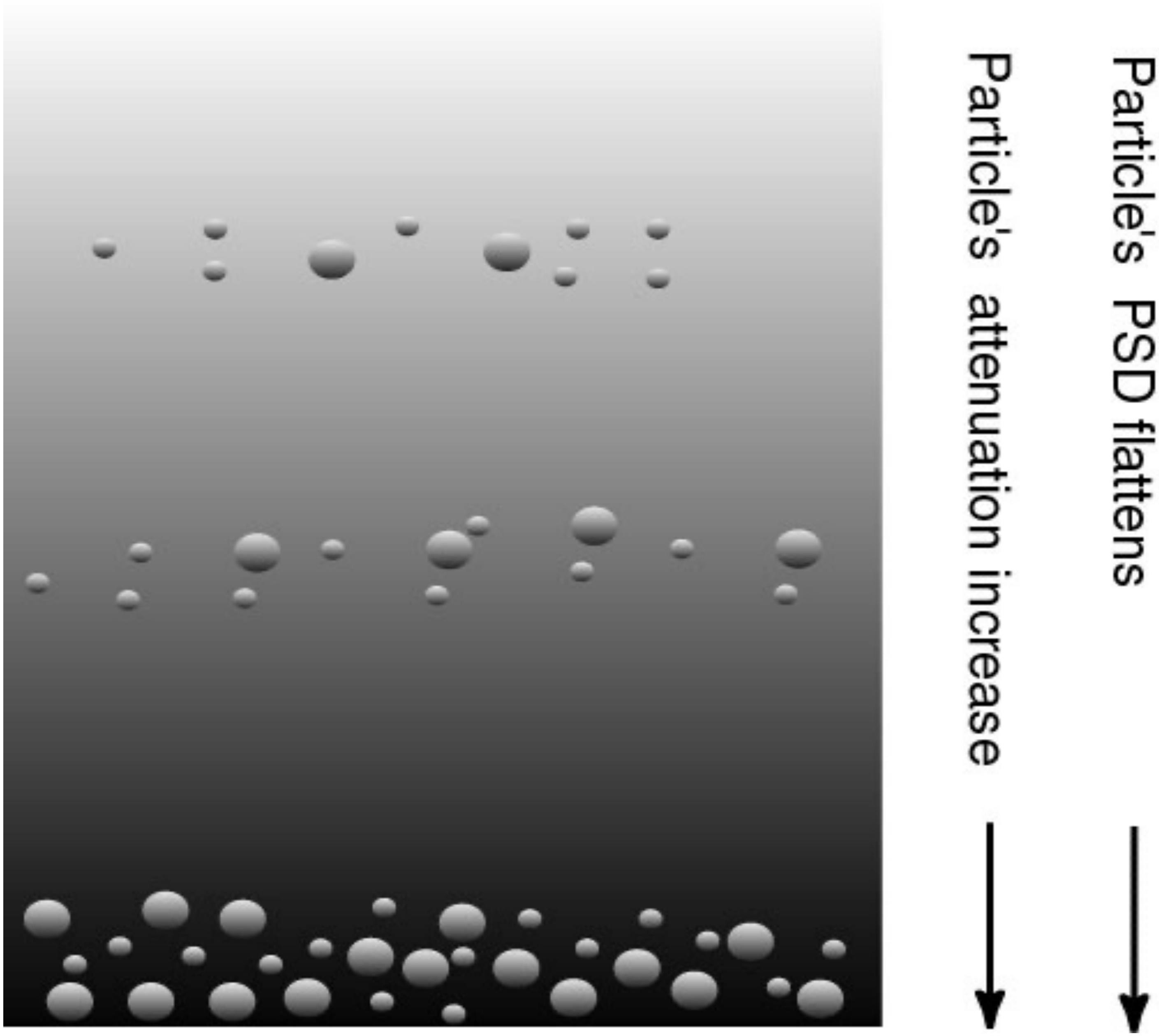
$$c_p(\lambda)=c_p(\lambda_0)\left(\frac{\lambda}{\lambda_0}\right)^{-\gamma}, \xi=\gamma+3$$

→ expect a relation between attenuation spectrum and PSD.



Boss et al., 2001

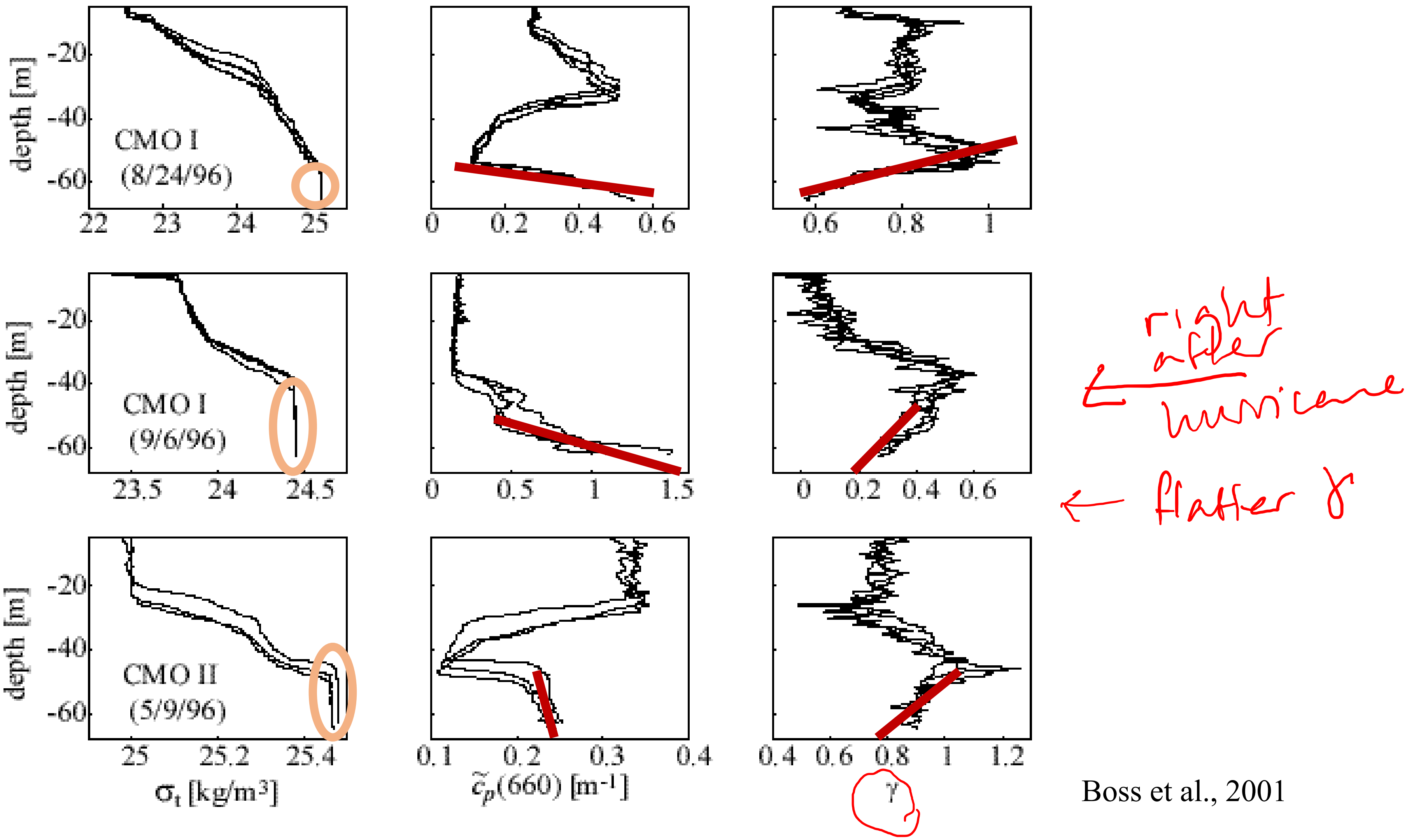
Example: particle distribution in the bottom boundary layer



Expect:
particle concentration and PSD to change with depth

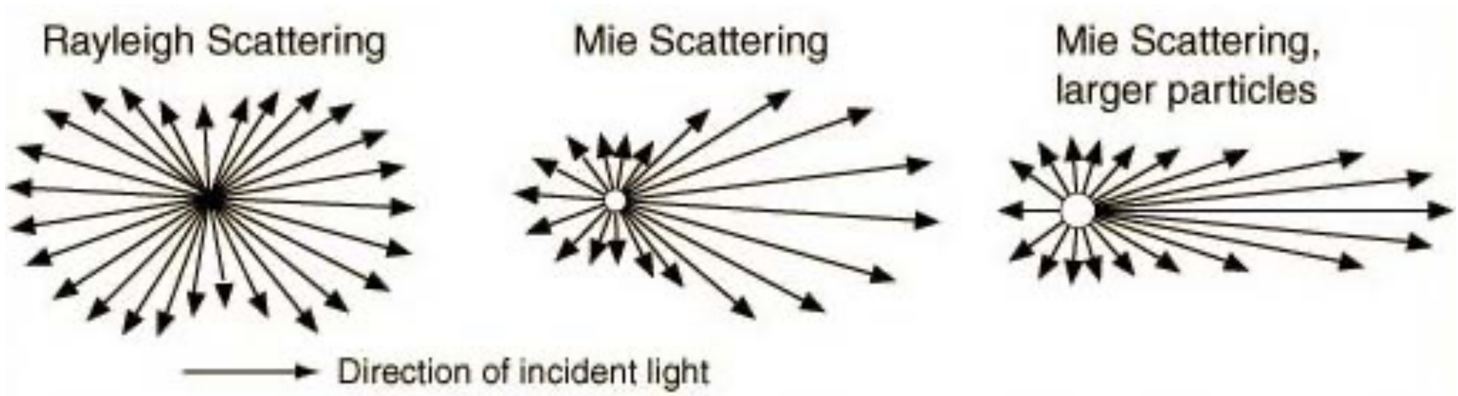
Why?
Settling is size dependent

Observations: bottom boundary layer

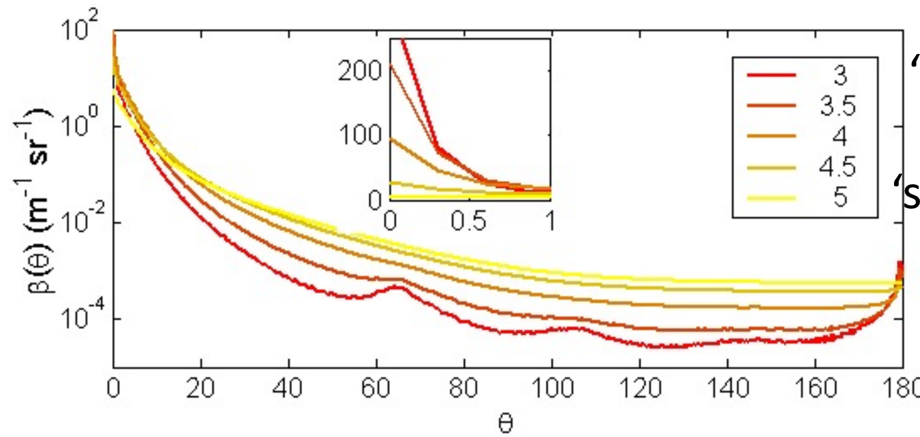


Boss et al., 2001

Angular dependence of scattering on size



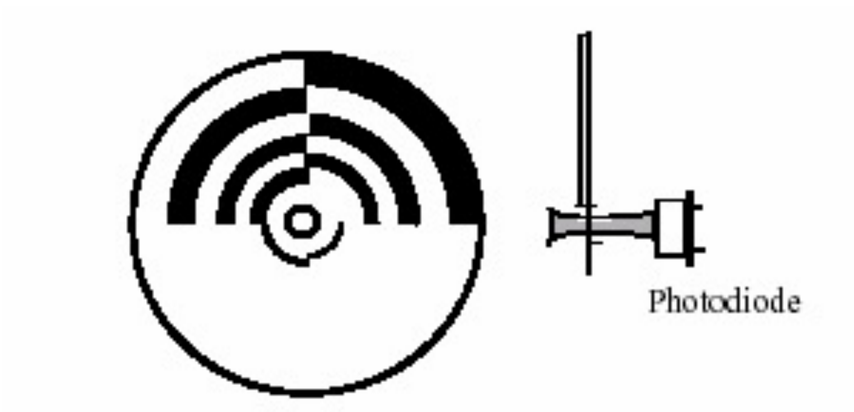
•Near forward scattering: Strong dependence on size, less on n.

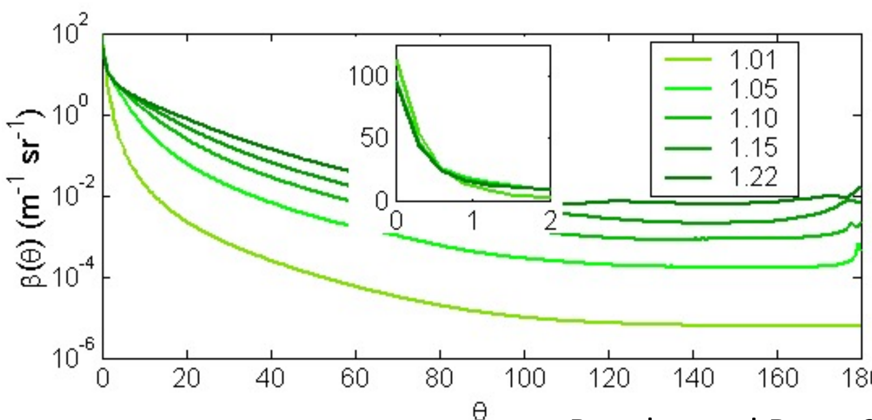


'large'

'small'

LISST detector:



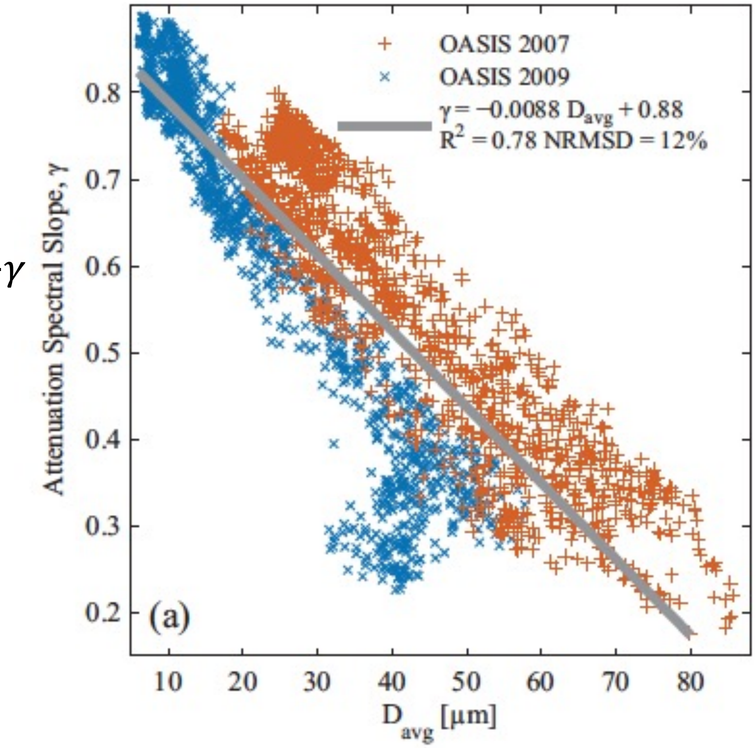


Roesler and Boss, 2008

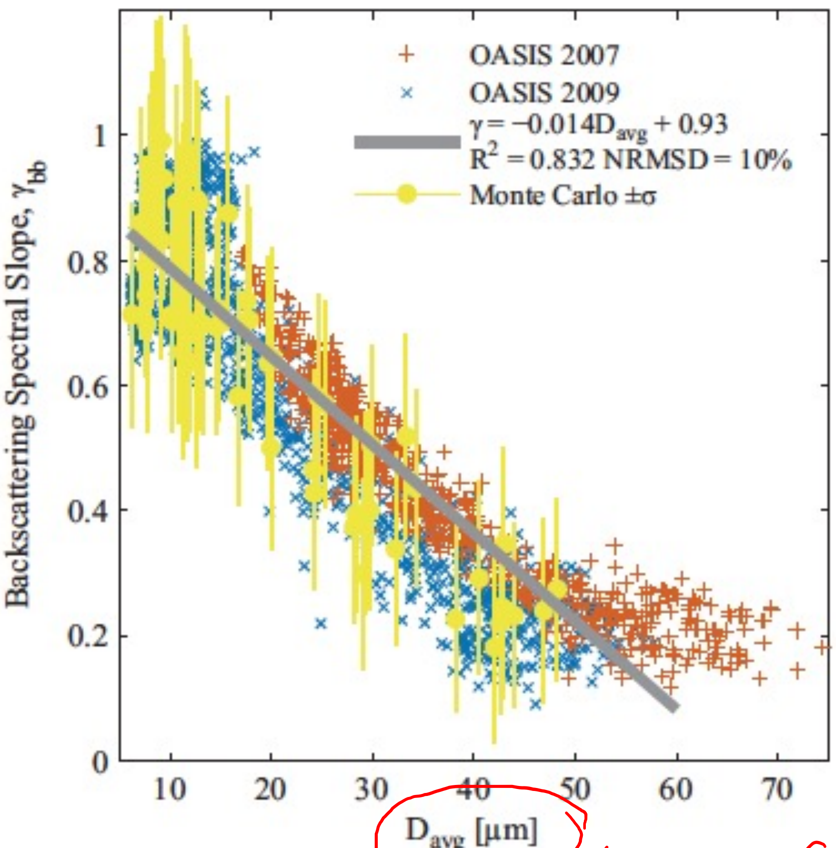
Closure: LISST vs. IOP spectral slopes

Field data from shelf bottom boundary layer (MVCO)

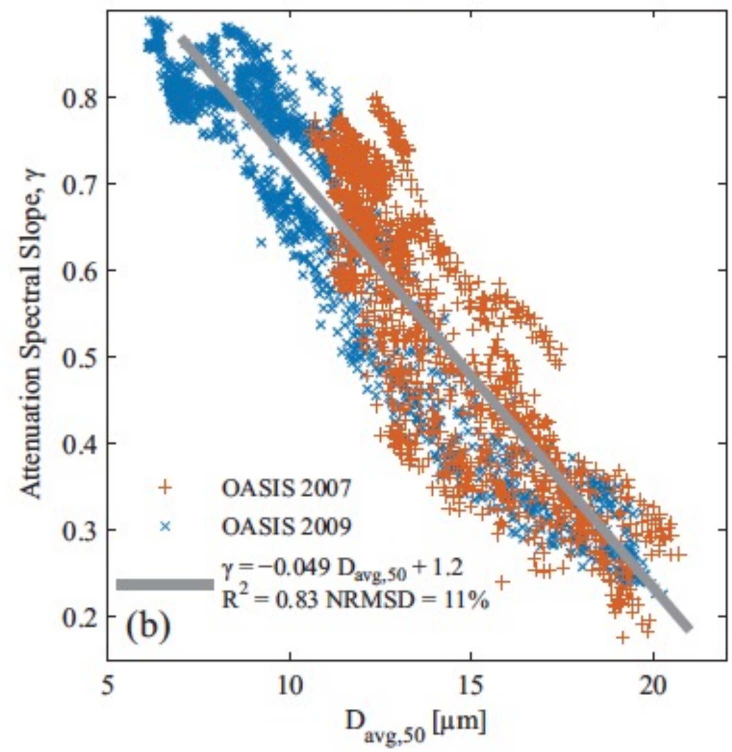
$$c_p(\lambda) = c_p(\lambda_0)\left(\frac{\lambda}{\lambda_0}\right)^{-\gamma}$$



$$b_{bp}(\lambda) = b_{bp}(\lambda_0)\left(\frac{\lambda}{\lambda_0}\right)^{-\gamma_{bb}}$$



LISST



Slade and Boss, 2015

Is $b_{bp}(\lambda) = b_{bp}(\lambda_0)\left(\frac{\lambda}{\lambda_0}\right)^{-\gamma_{bb}}$ a reasonable model for particles in the surface ocean?

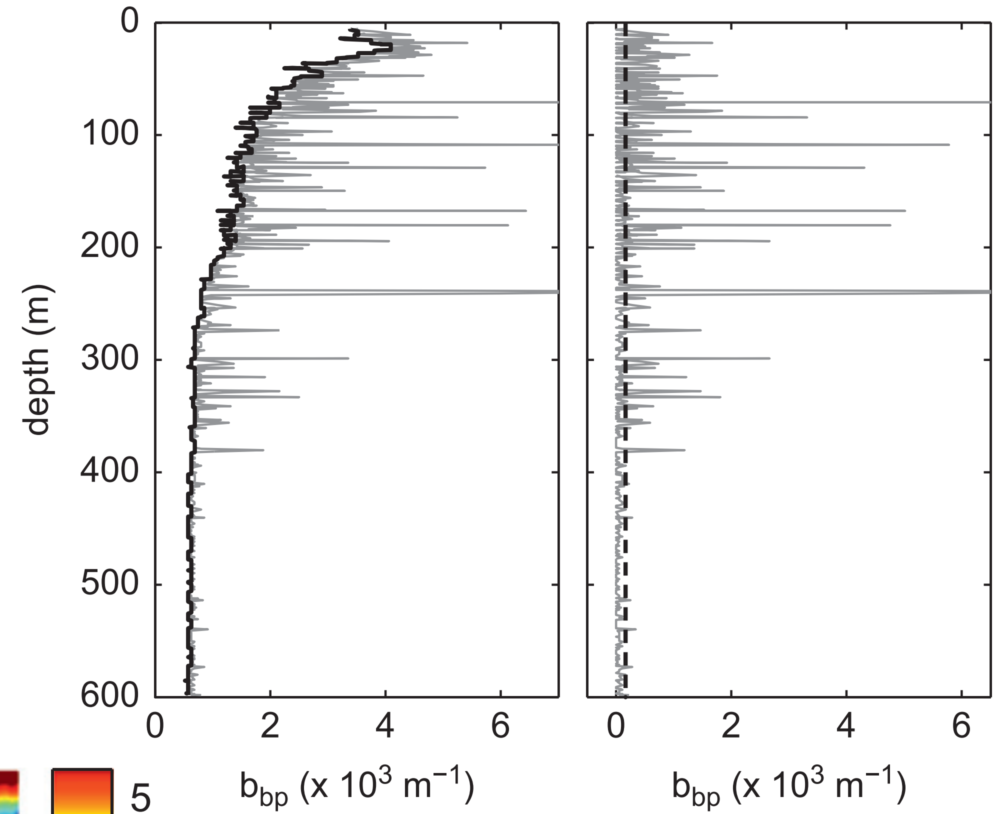
This model serves as the default model in most inversion algorithms.

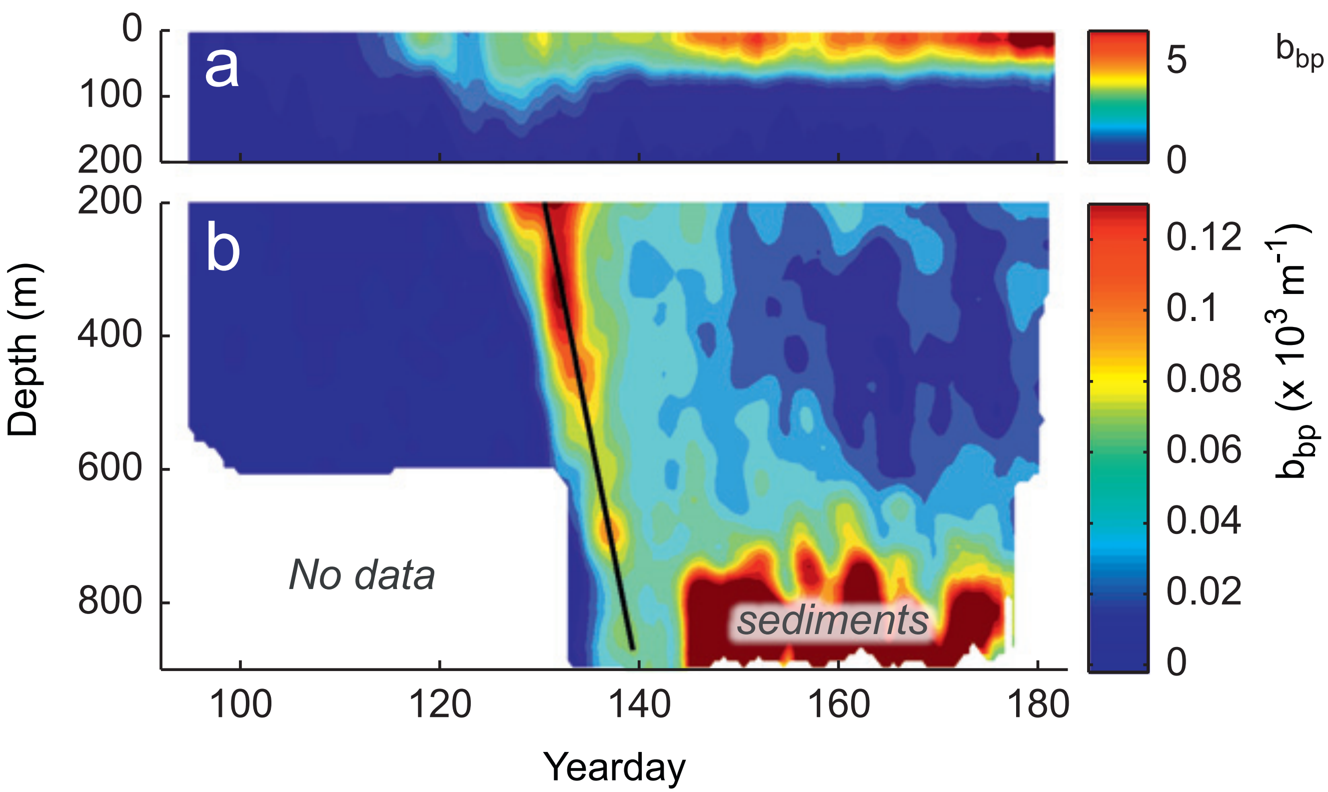
It is the basis of many PFT inversion models.

However, it has not been validated…

IOP fluctuations = proxy for particle size? (Briggs et al., 2011)

Filter to separate "spikes" from "baseline





Spikes

IOP fluctuation size proxy (Briggs et al., 2013)

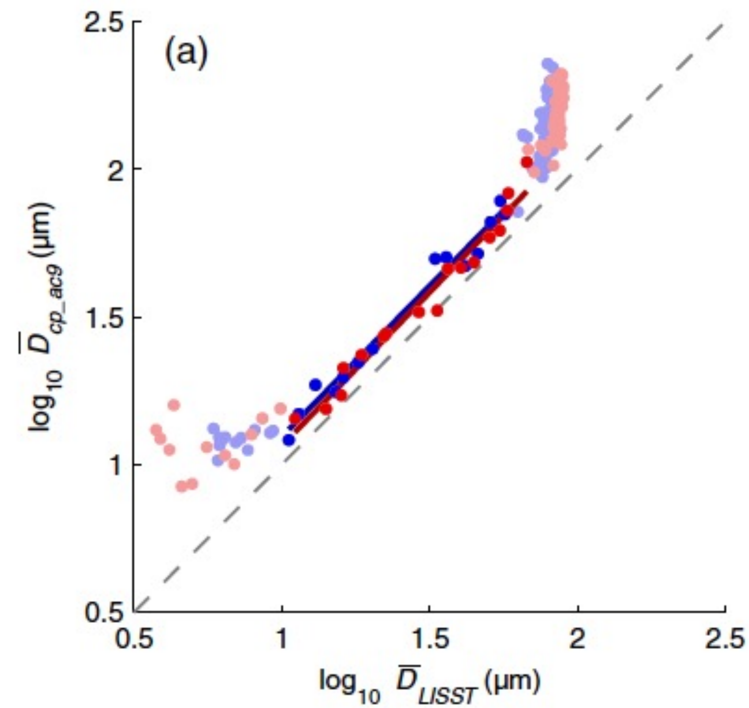
Closure: LISST vs. fluctuations during lab aggregation experiments

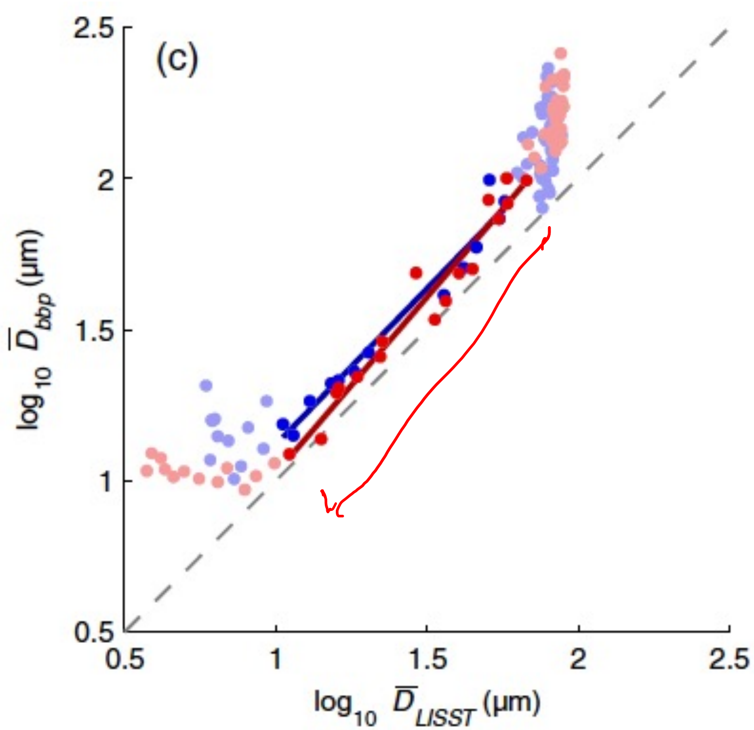
V: Sample volume

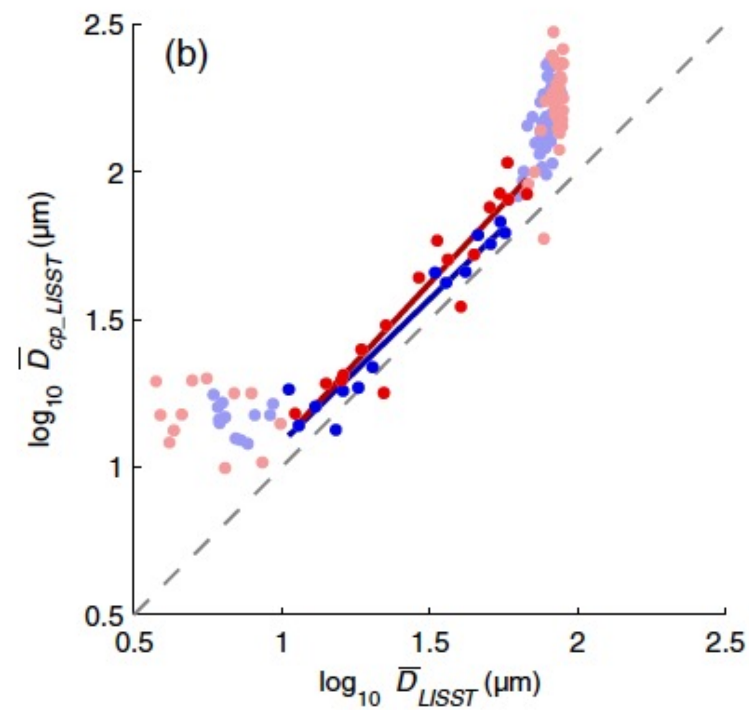
$$\bar{A}_{cp} = \frac{\mathrm{Var}[c_p(t)]}{E[c_p(t)]} \frac{V}{Q_c} \frac{1}{\alpha(\tau)}$$

$$\bar{D} = 2\sqrt{\bar{A}\pi^{-1}}$$

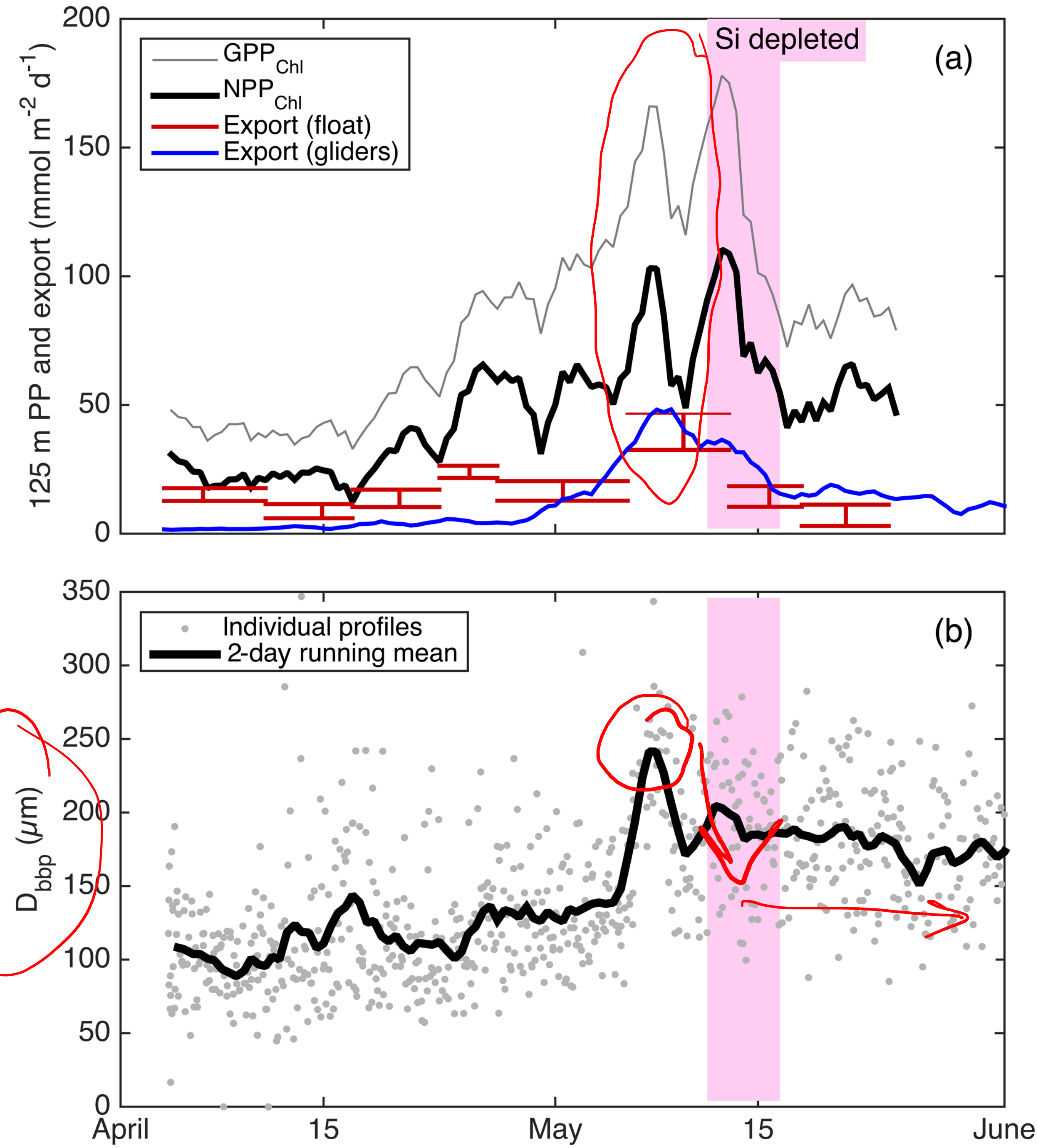
α: ratio of residence time to sample integration time







IOP fluctuation size proxy applied to NAB'08 measurements (Briggs et al 2018)



Summary

- Size matters, but it needs to be defined. Given that it varies over orders of magnitude using the diameter of an equivalent sphere may be a reasonable first-order approximation.
- All data looks great on a log-log plot.
- Simple calculus but details are important.
- Optical techniques are useful to constrain size.