Phytoplankton inherent optical properties

IOCCG SLS 2026

Pierre GERNEZ

Nantes Université

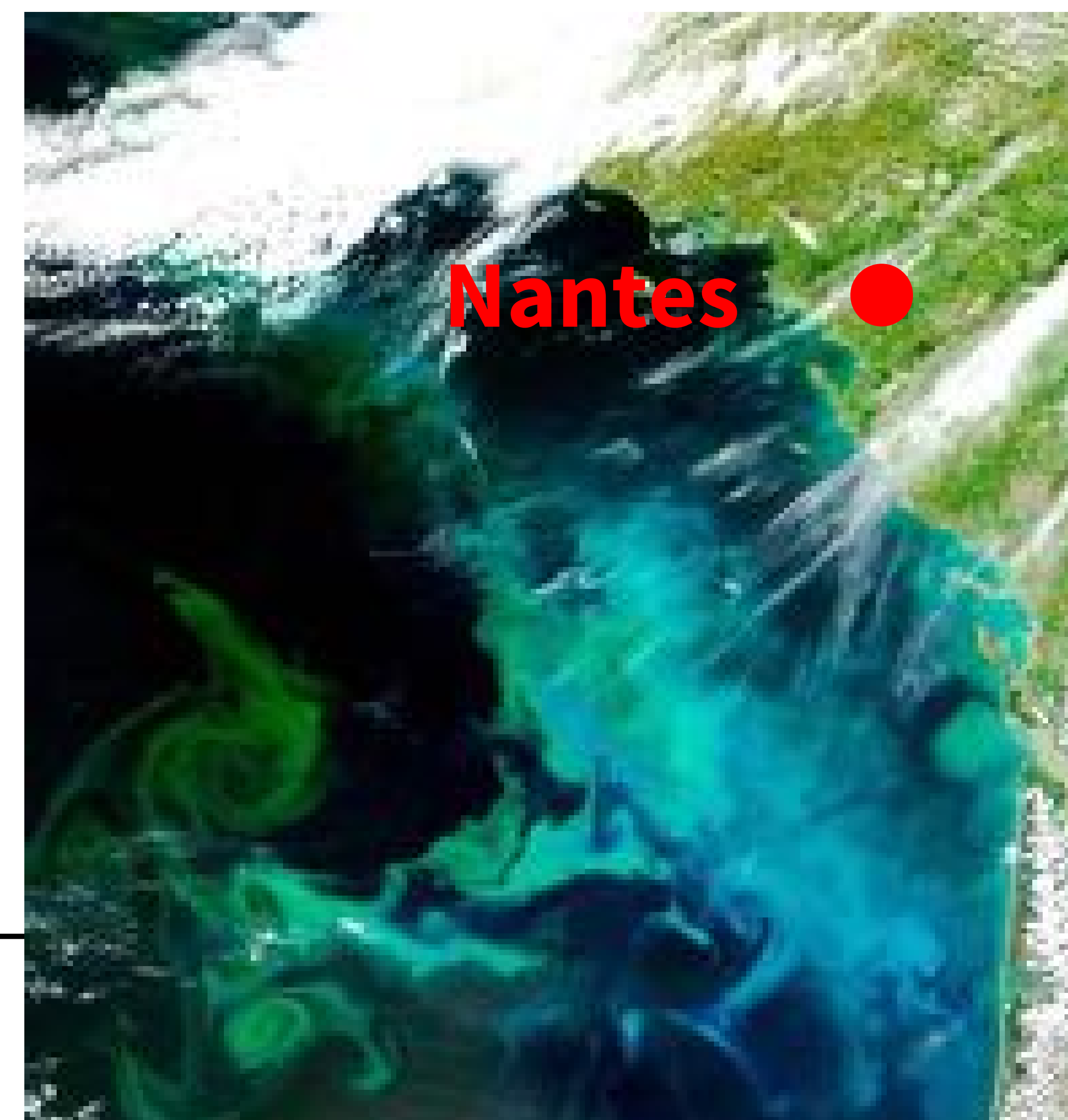
Welcome in Venice

Where I come from

Marine optics & ocean colour remote sensing

Ph. D student at Villefranche-sur-mer

Postdoc researcher at Scripps / UCSD

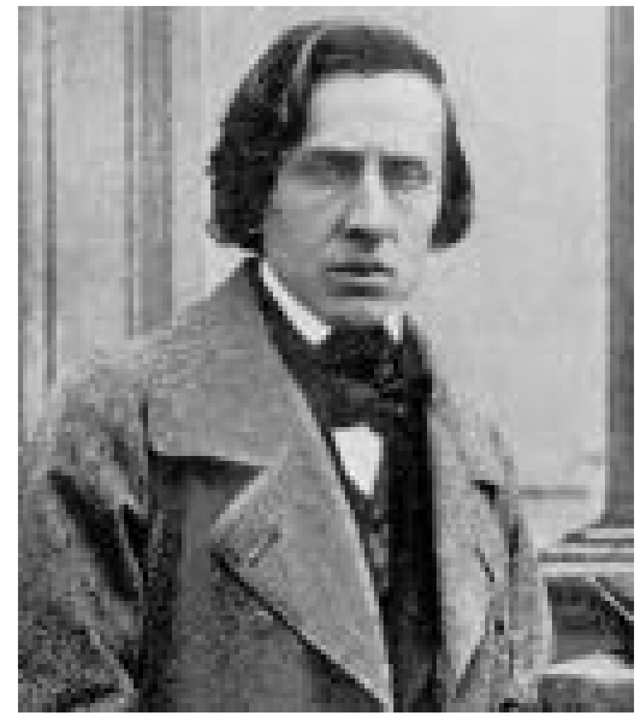


Marine ecology
(seagrass, phytoplankton, aquaculture)

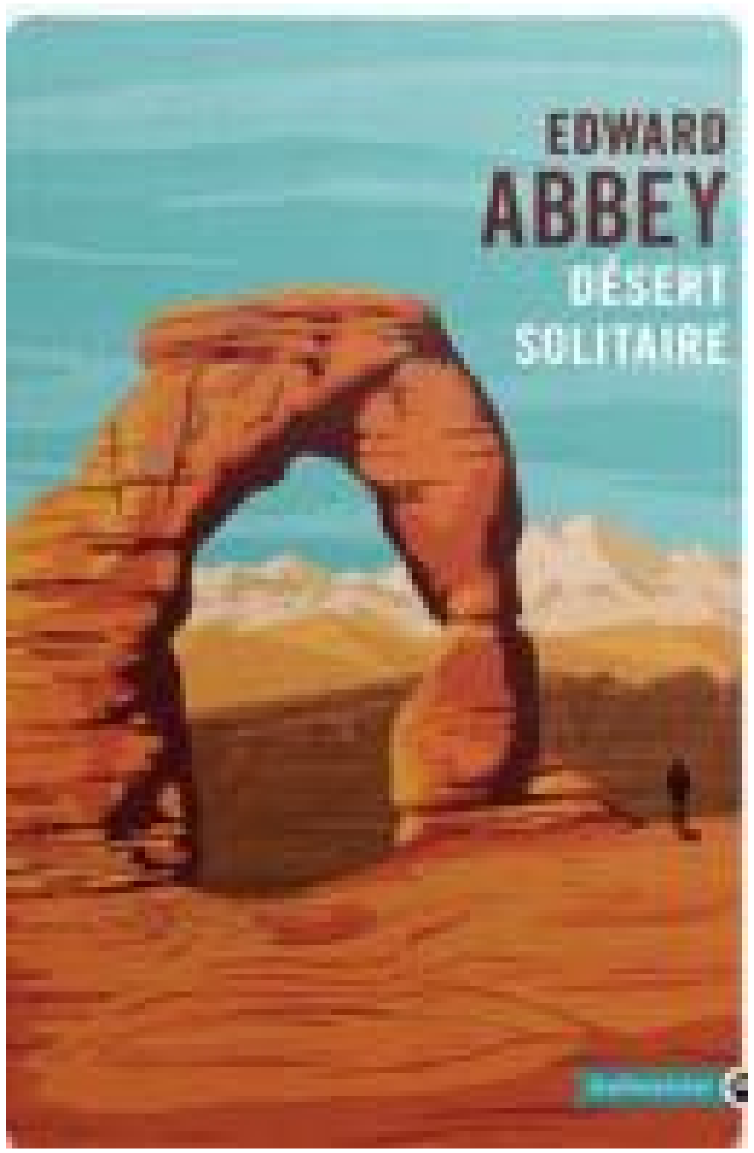
Lecturer at Nantes University (France)

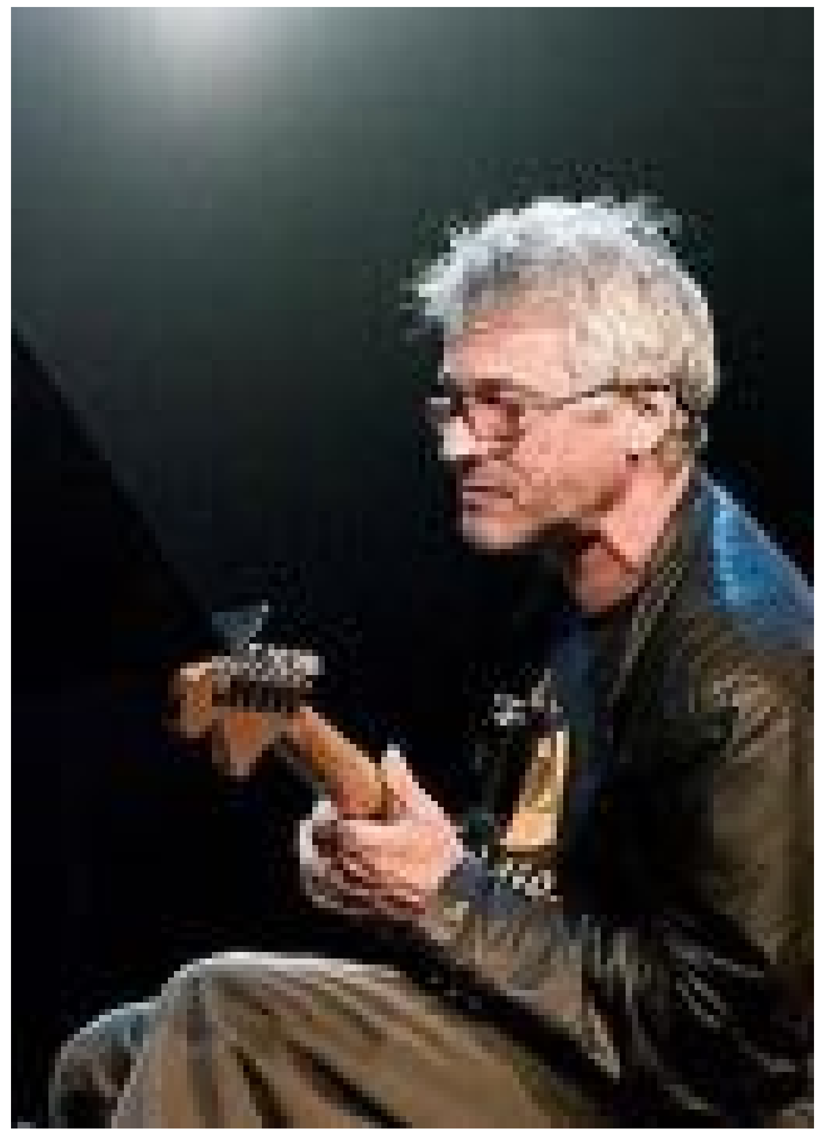
I love arts






and non-mainstream artists



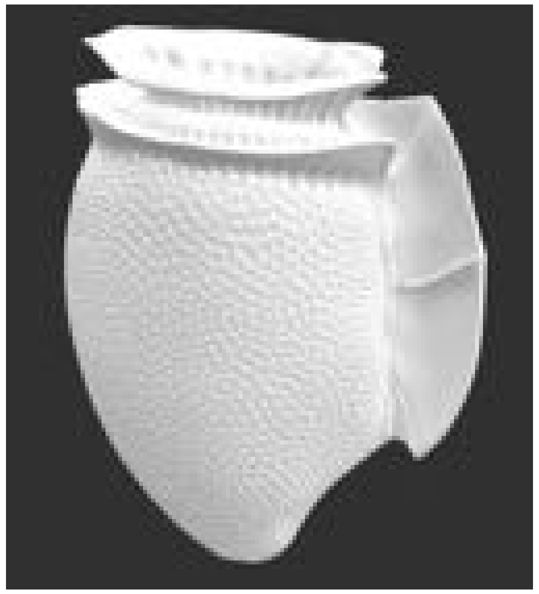


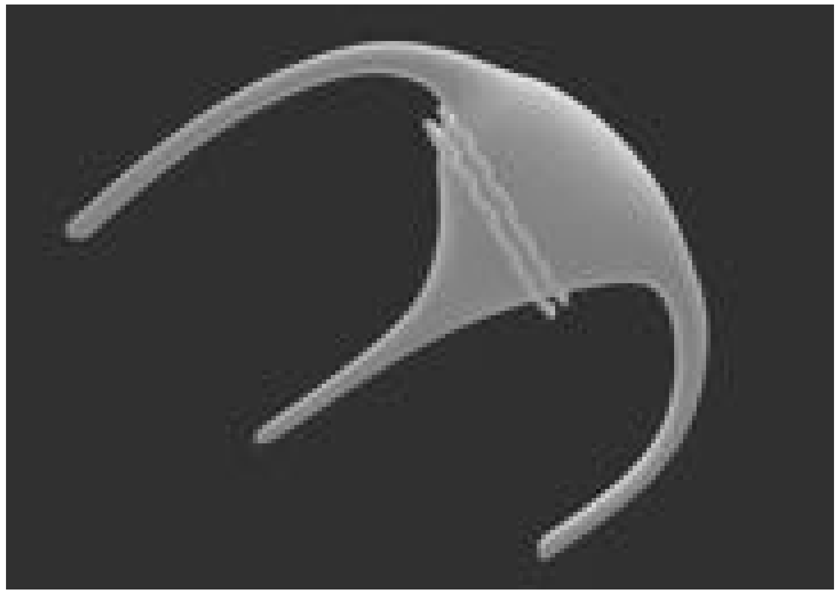
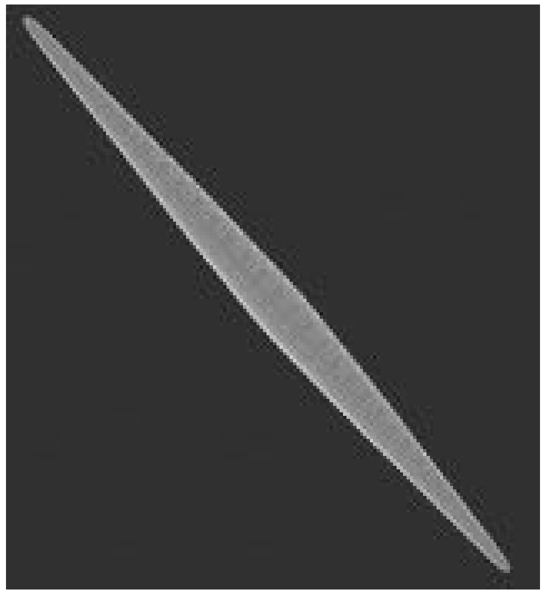
During this lecture, we'll see

A few things about phytoplankton biology & ecology

Phytoplankton optical properties
(in relationship with their biogeochemical properties)

some nice Japanese paintings

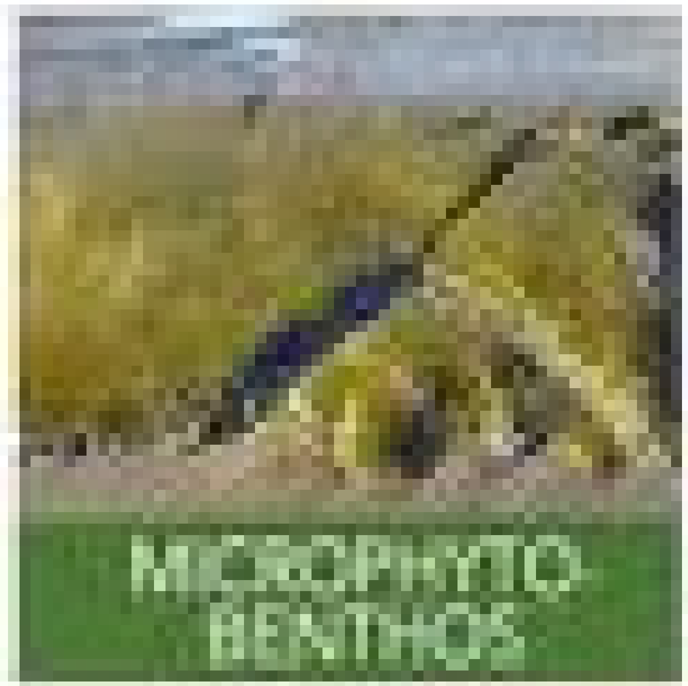


https://hab.whoi.edu/regions-resources/interactive-graphics-3d-models/

Microalgae

Benthic (= living on the substrate)



Pelagic (= living freely in the water column)

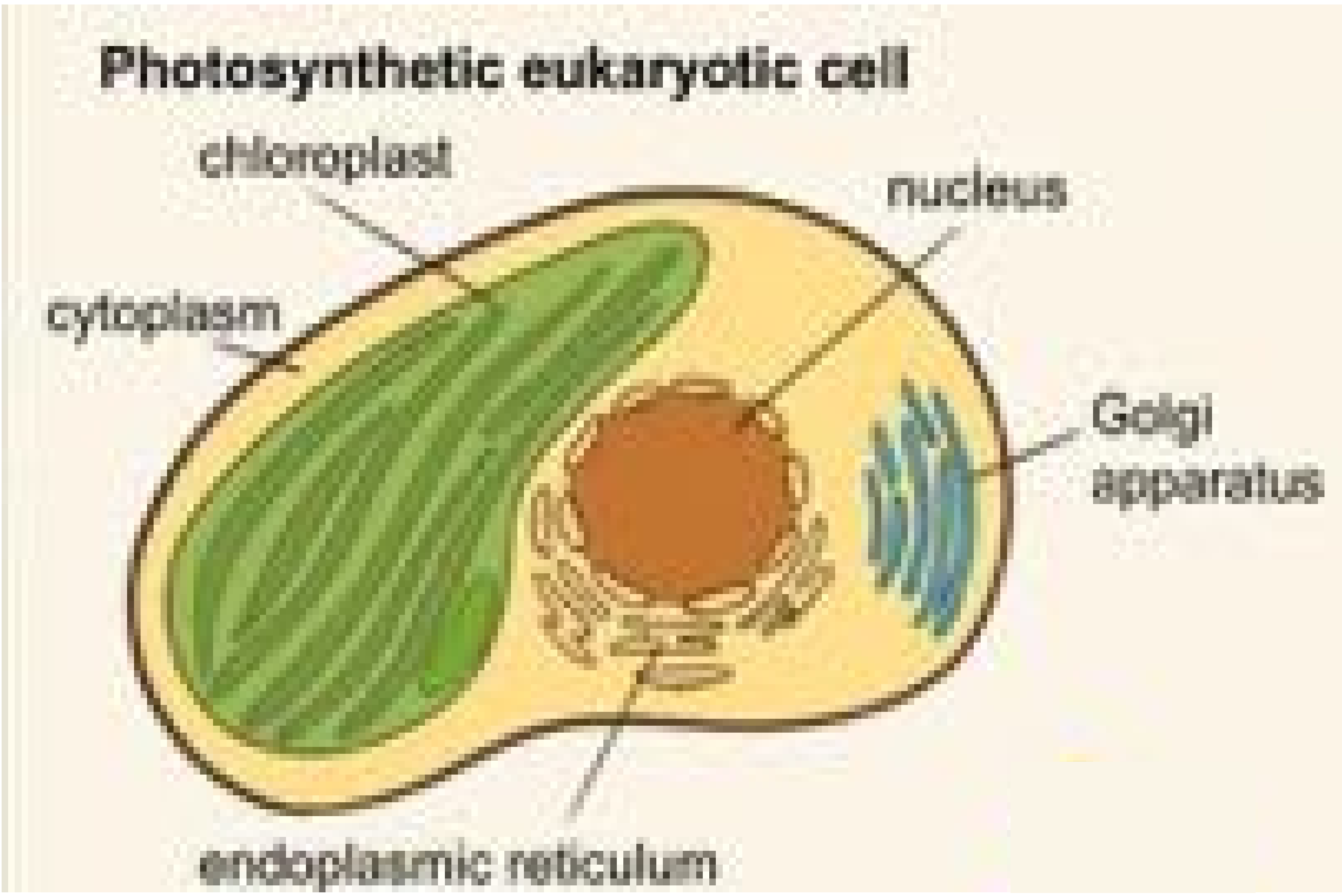
Phyto|plankton

from greek φυτόν / phyton :
"plant"

from greek πλαγκτός / planktós :
"to wander, to drift"
(Victor Hensen, 1887)

Phytoplankton : **photosynthetic microalgae living freely in the water column, that cannot swim against the current**

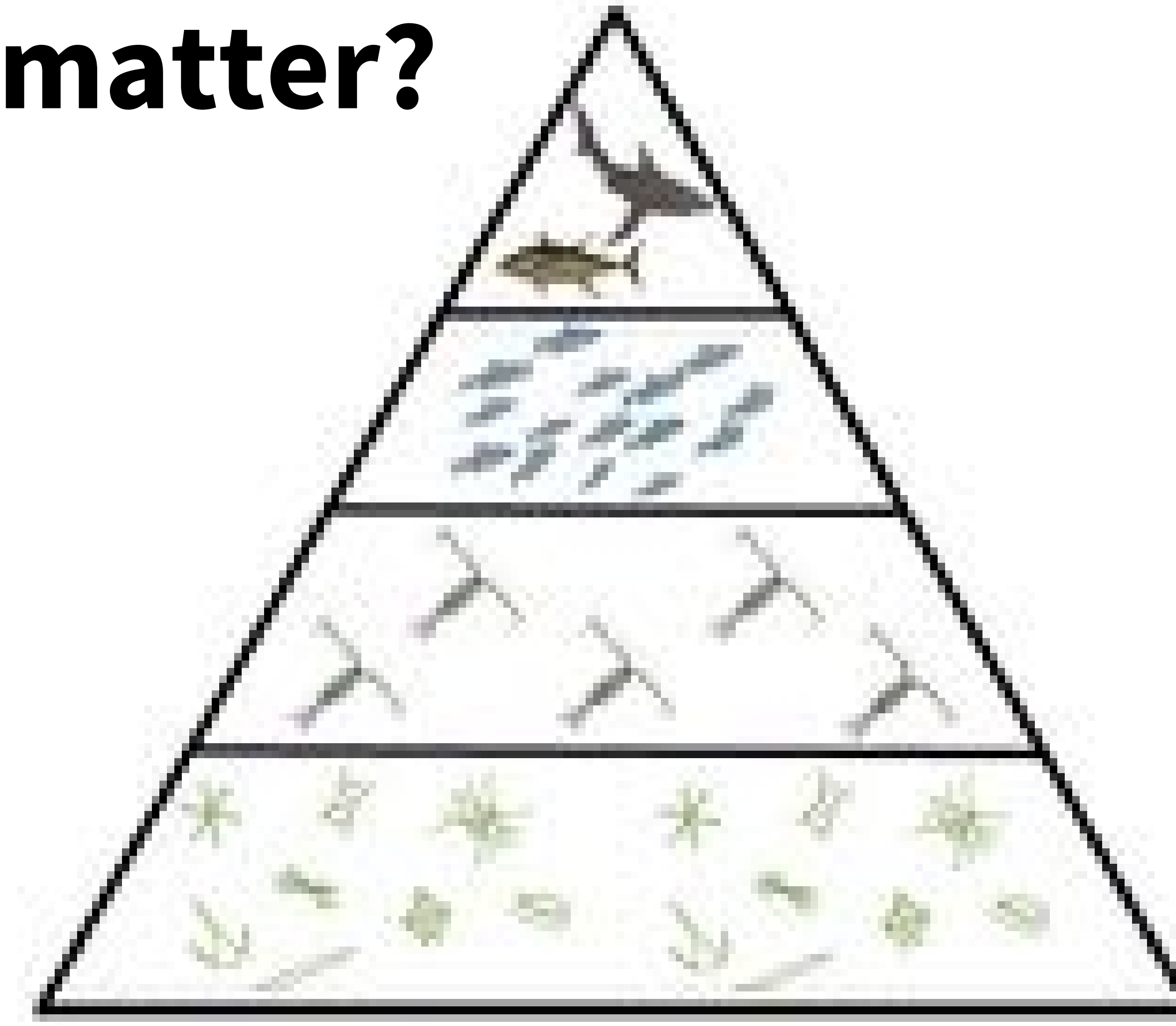
Unicellular microorganism



chloroplast: contains photosynthetic pigments such as chlorophylls and carotenoids, as well as non-photosynthetic pigments

Drawing from Zoé Besnard, Nantes Université

Why does phytoplankton matter?



Credits: University of Maryland
https://teachoceanscience.org/

Key component of oceanic life…

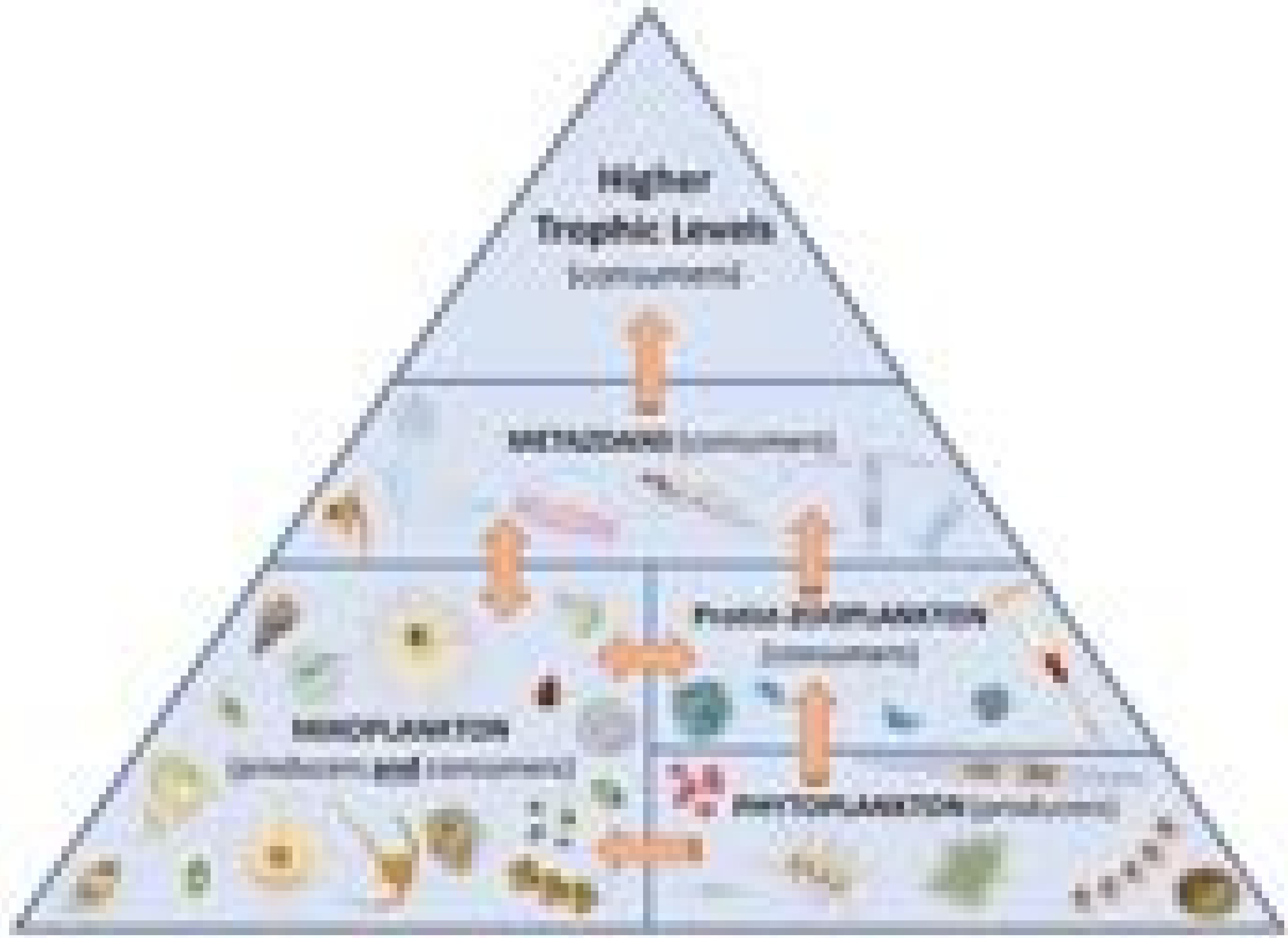
- Basis of most marine food webs
- Essential for aquaculture and fisheries

… and of global carbon/oxygen cycles

- 45% global primary production (not 45% of oxygen we breathe!!!)
- Produce O_2 and organic carbon using atm. and/or dissolved CO_2
- Carbon biological pump

(but it takes a looonng time…won't reduce current global warming!!!)

All phytoplankton are not pure autotrophs



Mitra, A., & Leles, S. G. (2023). A revised interpretation of marine primary productivity in the Indian Ocean: the role of mixoplankton. In *Dynamics of planktonic primary productivity in the Indian ocean* (pp. 101-128). Springer International Publishing.

Diversity

Main taxonomic classes

Eukaryotes
Bacillariophyceae
Chlorarachnea
Chlorophyceae
Chrysophyceae
Cryptophyceae
Dictyochophyceae
Dinophyceae
Euglenophyceae
Haptophyta
Mamiellophyceae
Rhodophyceae
Raphidophyceae

Prokaryotes
Cyanophyceae

Mandala with zoo- and phytoplankton

Credits: Christian Sardet, CNRS

How many species??

Eukaryotes
4,300 know species (from morphology)
13,800 operational taxonomic units (OTUs) sequenced (Tara Oceans)

Prokaryotes
> 2,700 cyanobacteria
(marine + freshwater)

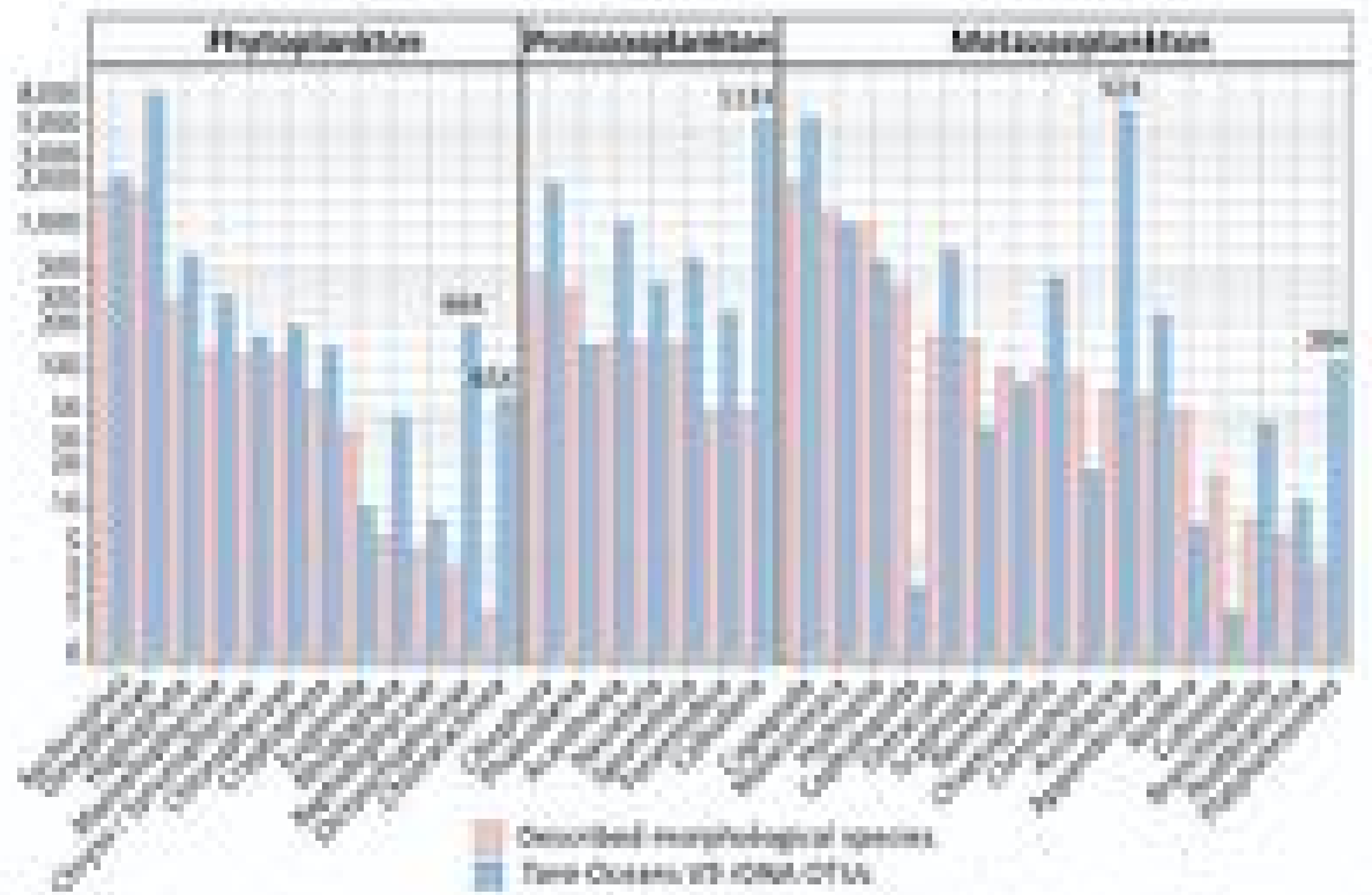


Fig. 2. Unknown and known components of eukaryotic plankton biodiversity.

De Vargas, C., et al. (2015). Eukaryotic plankton diversity in the sunlit ocean. Science, 348, 1261605.

Phytoplankton is a complex thing

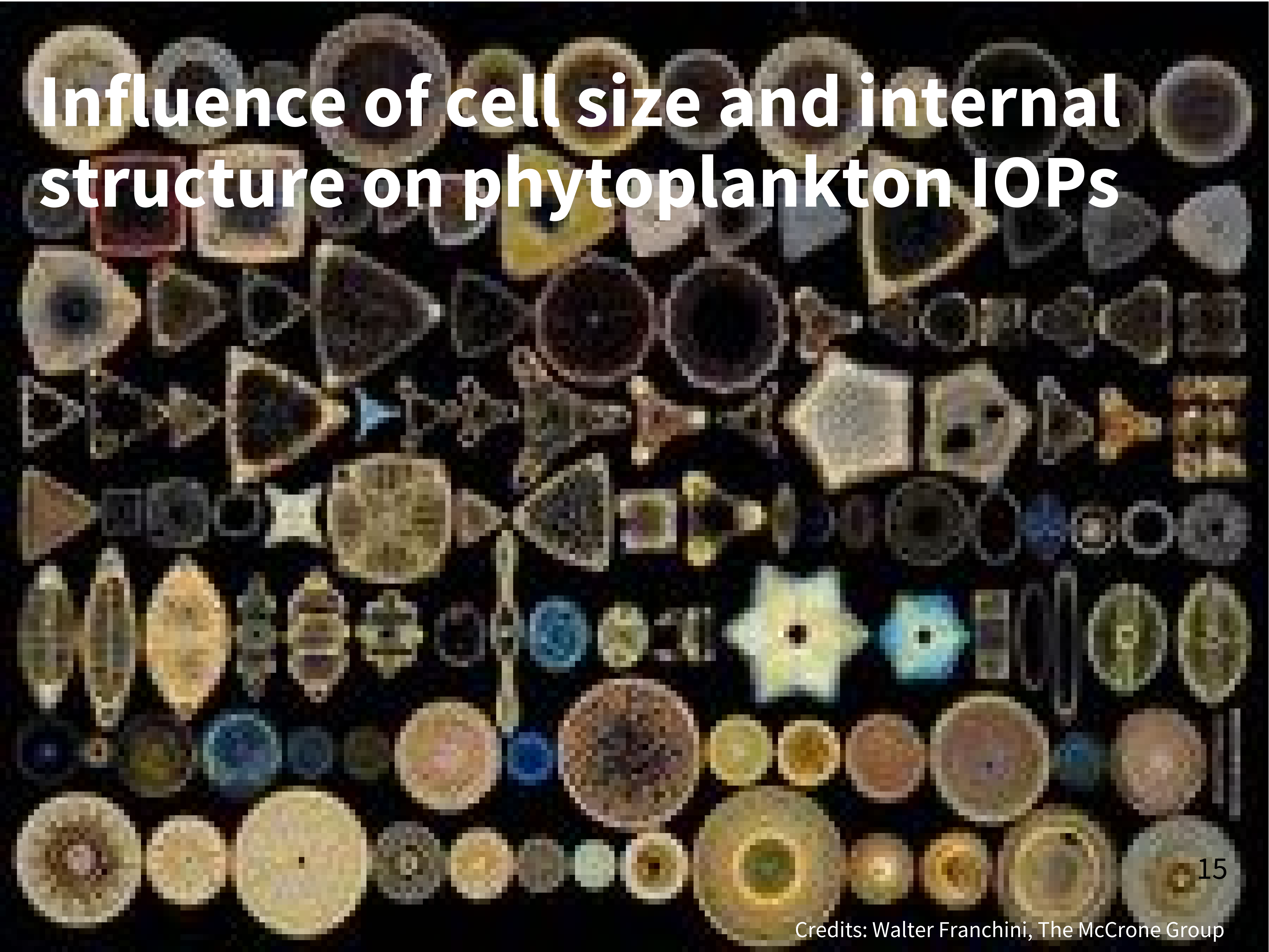
Huge taxonomic diversity
together with high degree of variability in size and shape

How to take this diversity into account in IOP models?

$$a(\lambda) = a_{\mathrm{w}}(\lambda) + a_{\mathrm{phy}}(\lambda) + a_{\mathrm{nap}}(\lambda) + a_{\mathrm{cdom}}(\lambda)$$

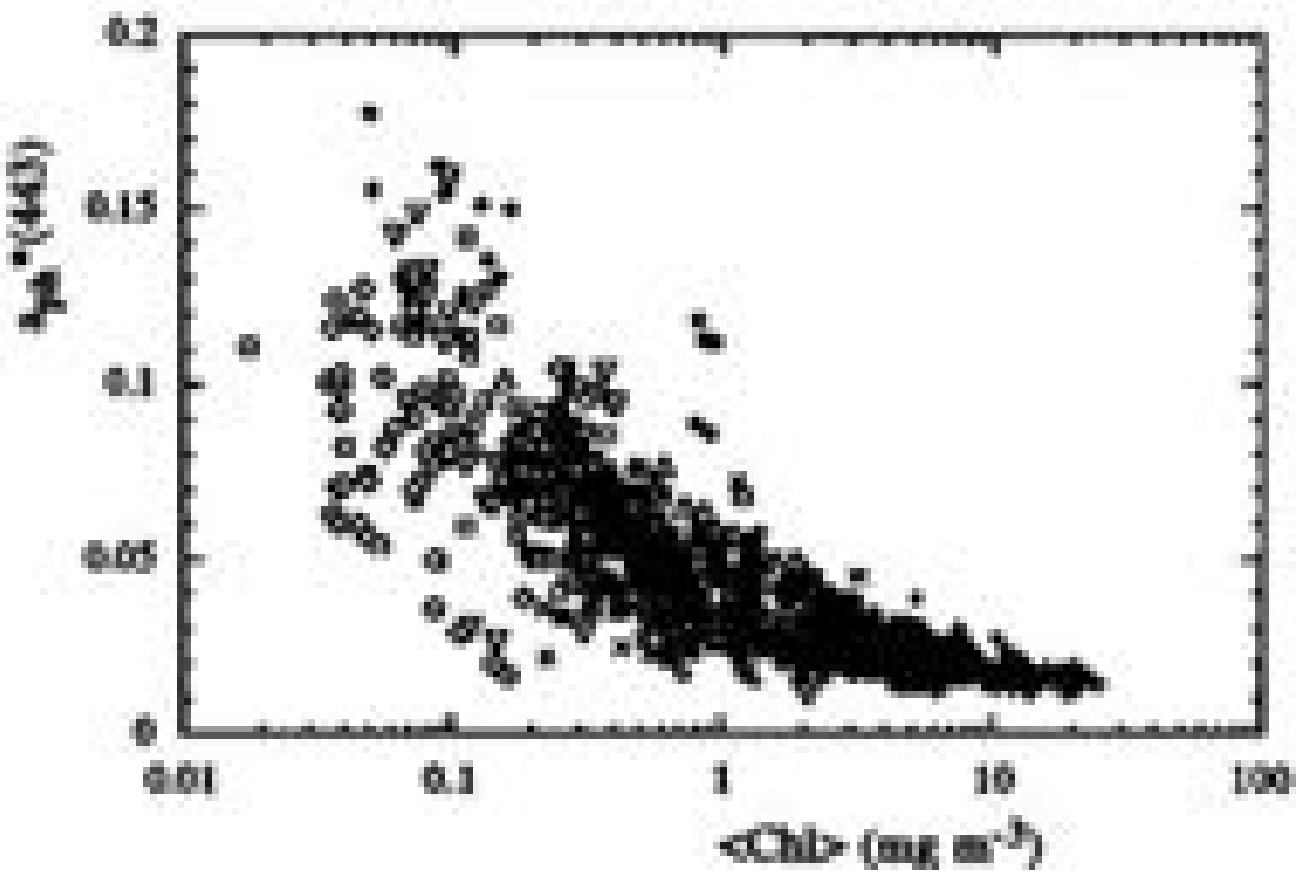
$$\boldsymbol{a_{\mathrm{phy}}(\lambda) = ??}$$

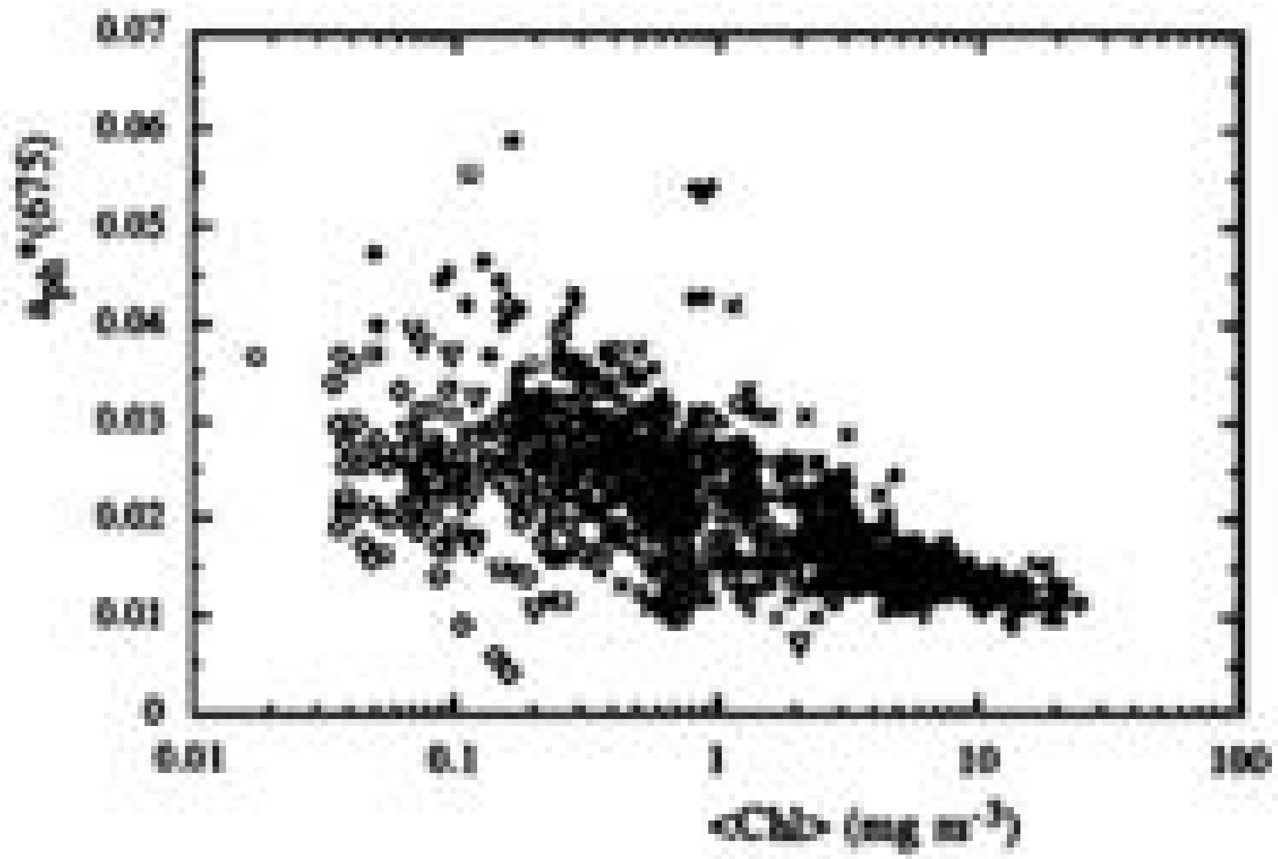
Influence of cell size and internal structure on phytoplankton IOPs



Credits: Walter Franchini, The McCrone Group

Modelling $a^*_{phy}(\lambda)$ from [Chl*a*]





$$a^*_{\mathrm{phy}}(\lambda) = \mathrm{A}(\lambda)\ [\mathrm{Chl}a]^{-\mathrm{B}(\lambda)}$$

Values coefficients A and B in Bricaud et al., (1995), Table 2

JOURNAL OF GEOPHYSICAL RESEARCH
Oceans
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Full Access

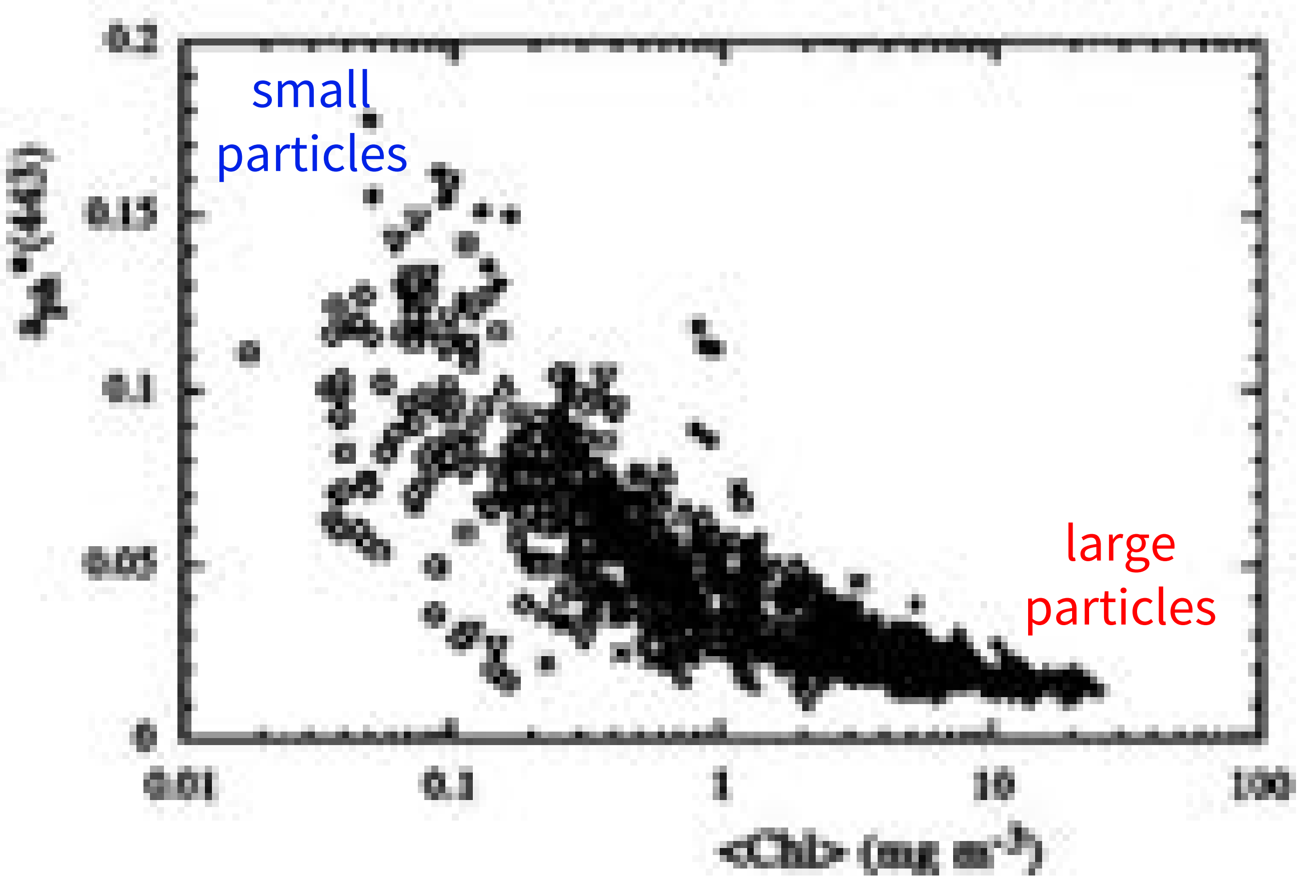
Variability in the chlorophyll-specific absorption coefficients of natural phytoplankton: Analysis and parameterization

Annick Bricaud, Marcel Babin, André Morel, Hervé Claustre

First published: 15 July 1995 | https://doi.org/10.1029/95JC00463 | VIEW METRICS

Bricaud, A., Babin, M., Morel, A., & Claustre, H. (1995). Variability in the chlorophyll-specific absorption coefficients of natural phytoplankton: Analysis and parameterization. Journal of Geophysical Research: Oceans, 100(C7), 13321-13332.

Modelling $a^*_{phy}(\lambda)$ from [Chl*a*]



1) Large degree of variability

2) Regions with low [Chl*a*] generally correspond to small phyto cells.
As a^*_{phy} increases at low [Chl*a*], small cells are expected to have high a^*_{phy}

Bricaud, A., Babin, M., Morel, A., & Claustre, H. (1995). Variability in the chlorophyll-specific absorption coefficients of natural phytoplankton: Analysis and parameterization. Journal of Geophysical Research: Oceans, 100(C7), 13321-13332.

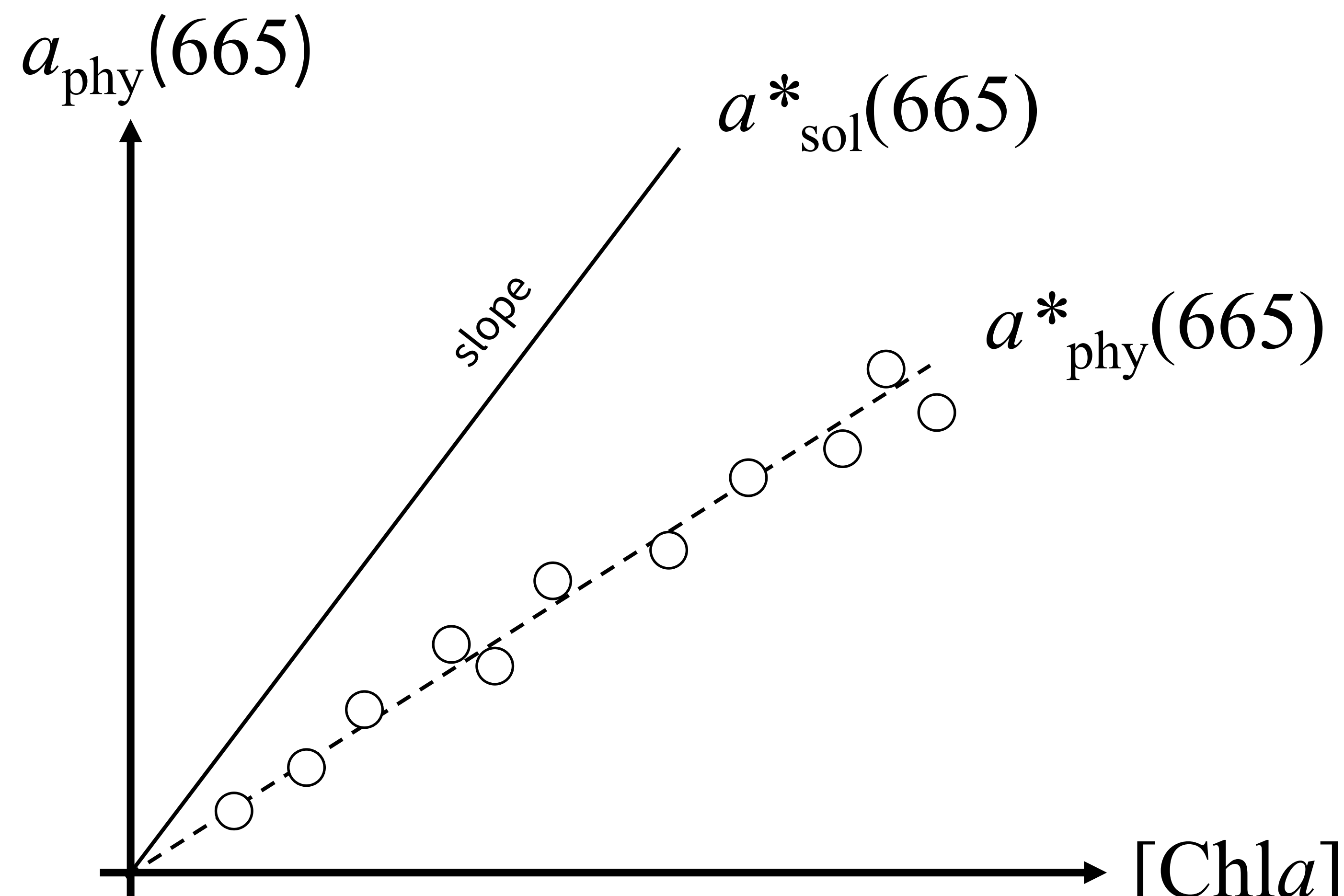
"Package effect"

Packaging (i.e. grouping) of pigments inside a phytoplankton cell reduces the total amount of light it can absorb compared to the ideal case where the same pigments would be homogeneously distributed inside the cell.

$$Q_a^*(\lambda) = \frac{a_{\text{phy}}^*(\lambda)}{a_{\text{sol}}^*(\lambda)}$$

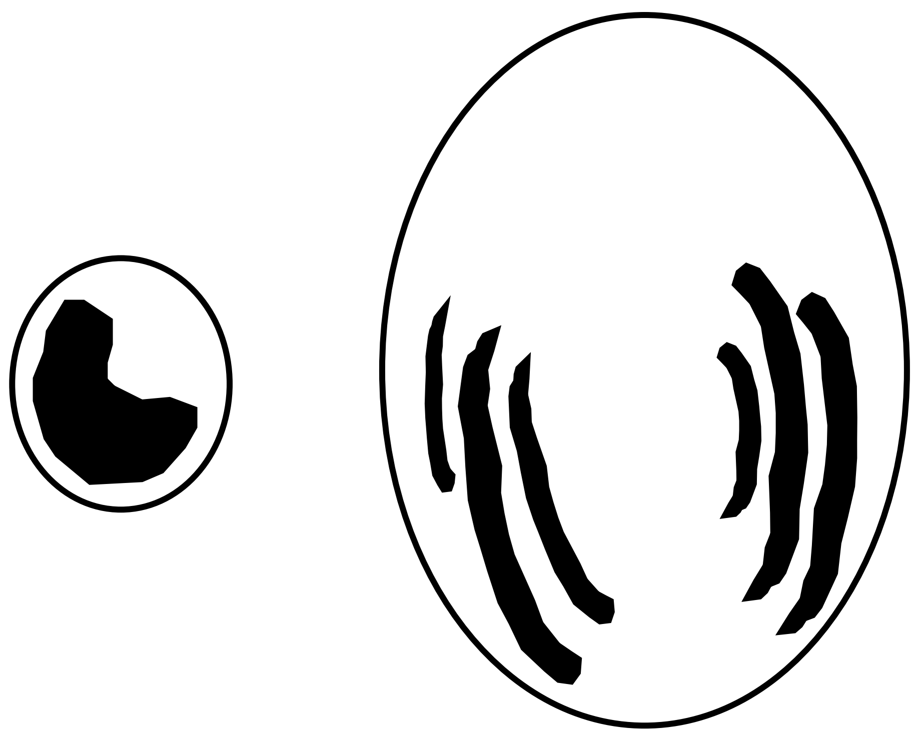
1: no package effect

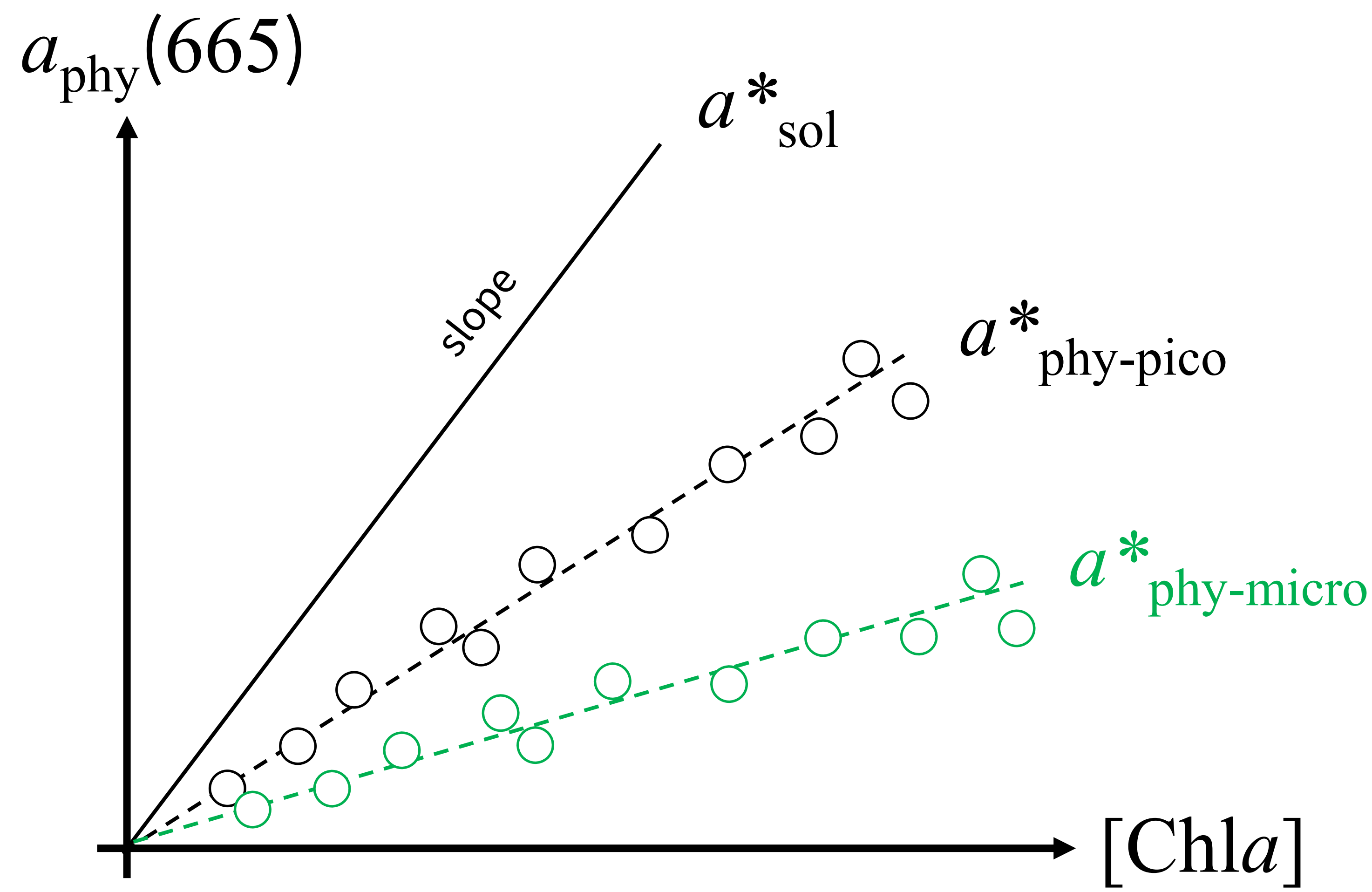
0: maxima package effect



Influence of cell size on a^*_{phy}

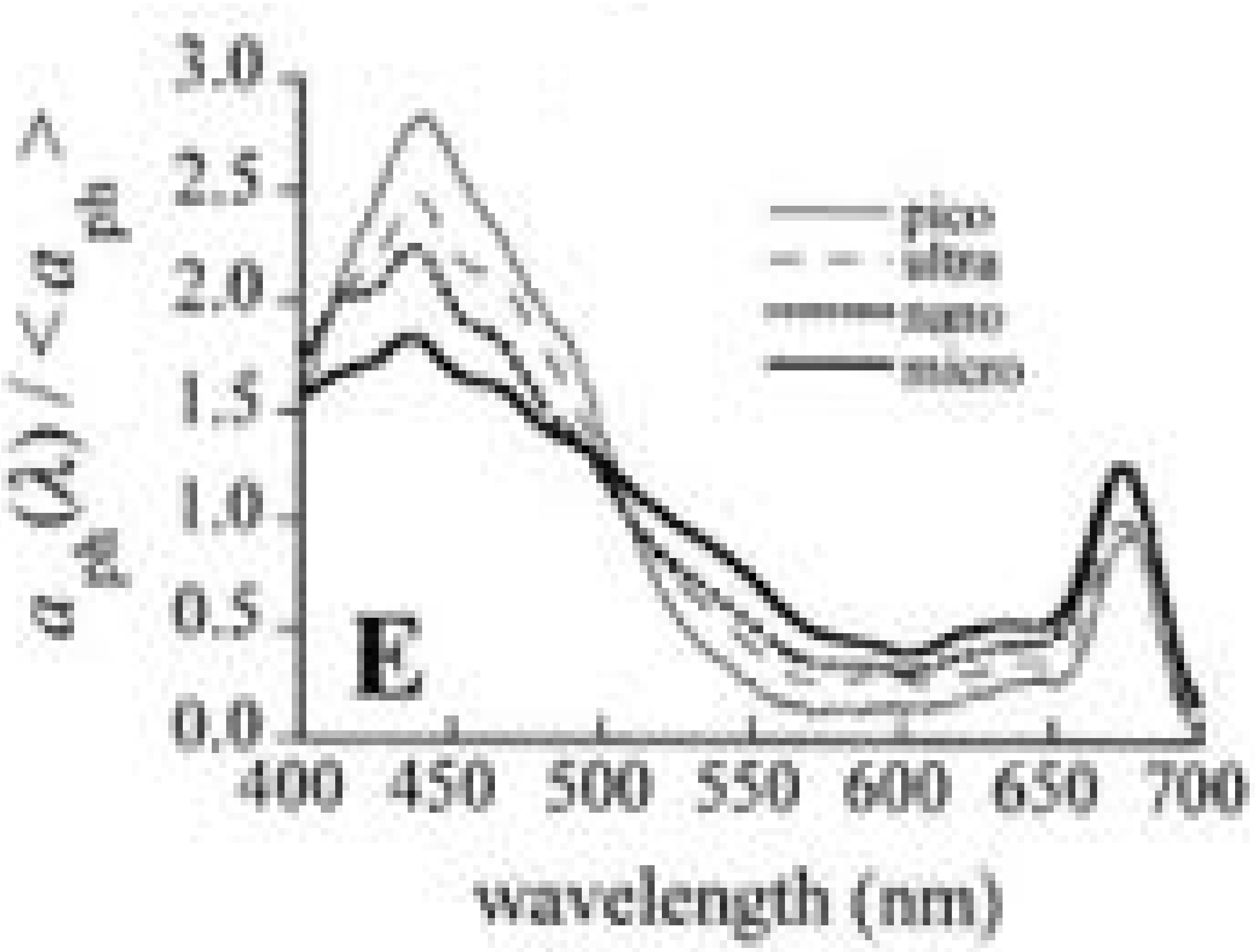
The larger the cell, the higher the package effect





Estimation of a "size parameter" from a^*_{phy}

Size parameter S_f defined as $a^*_{phy}(\lambda) = S_f\, a^*_{pico}(\lambda) + (1 - S_f)\, a^*_{micro}(\lambda)$



where a^*_{pico} and a^*_{micro} are "basis vectors" of the spectral shapes corresponding to the standardized absorption spectra for the smallest and largest cells (Ciotti et al., 2002)

LIMNOLOGY AND OCEANOGRAPHY

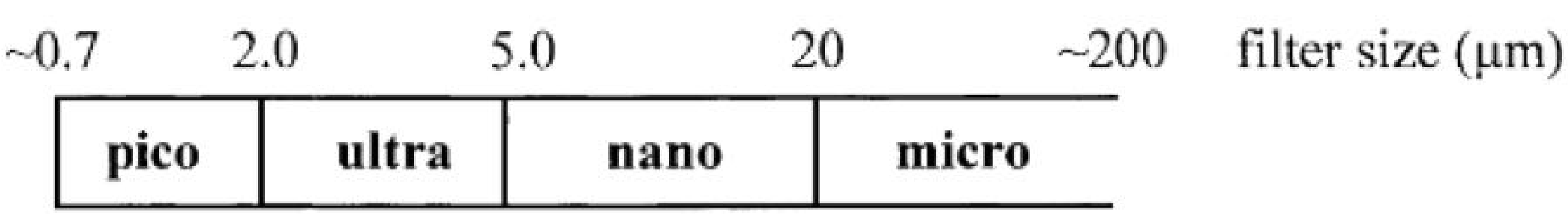
ASLO

Article | Full Access

Assessment of the relationships between dominant cell size in natural phytoplankton communities and the spectral shape of the absorption coefficient

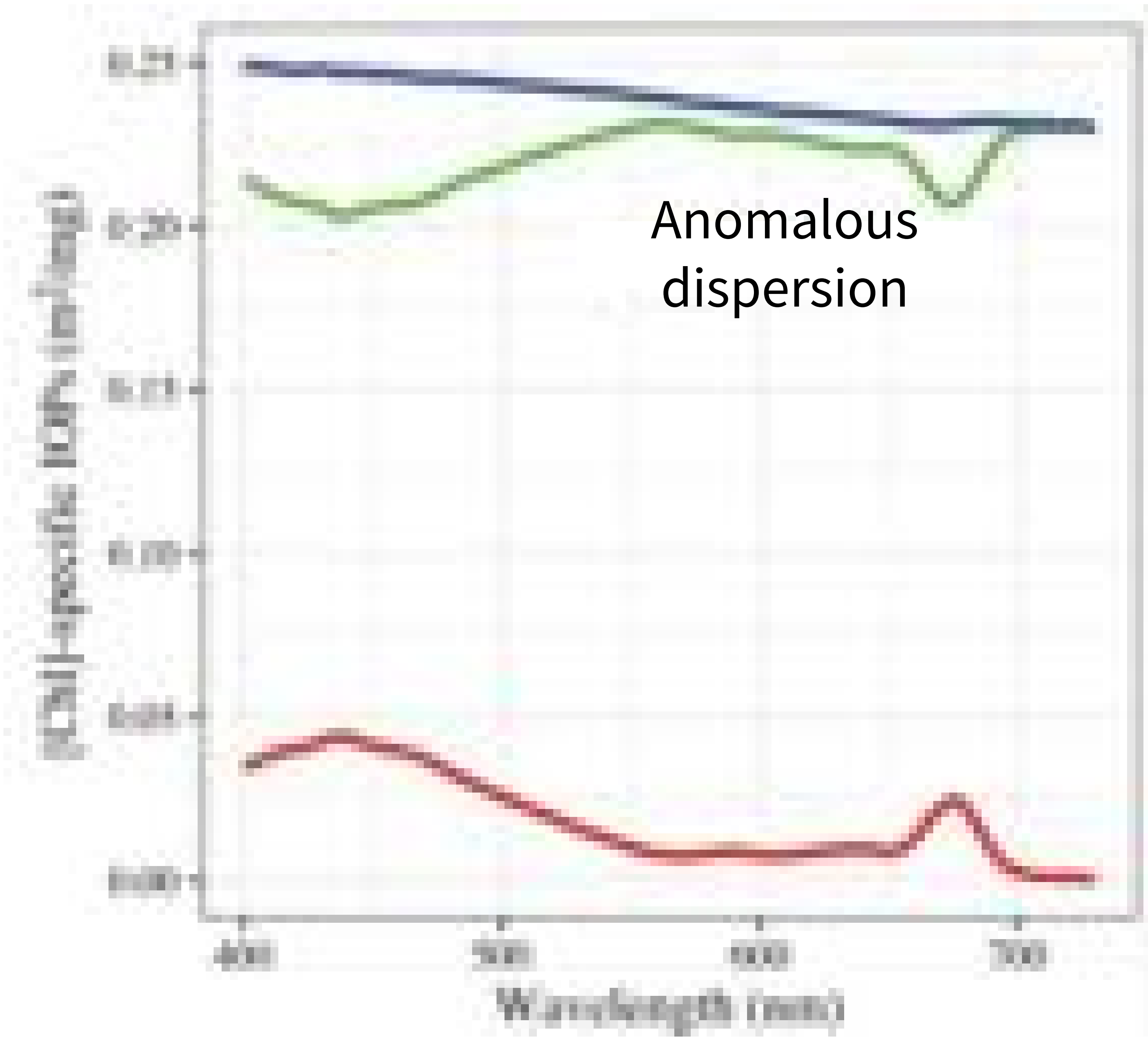
Aurea M. Ciotti, Marlon R. Lewis, John J. Cullen

First published: 27 March 2002 | https://doi.org/10.4319/lo.2002.47.2.0404 | VIEW METRICS



Ciotti, A. M., Lewis, M. R., & Cullen, J. J. (2002). Assessment of the relationships between dominant cell size in natural phytoplankton communities and the spectral shape of the absorption coefficient. Limnology and Oceanography, 47, 404-417.

[Chl*a*] specific IOPs



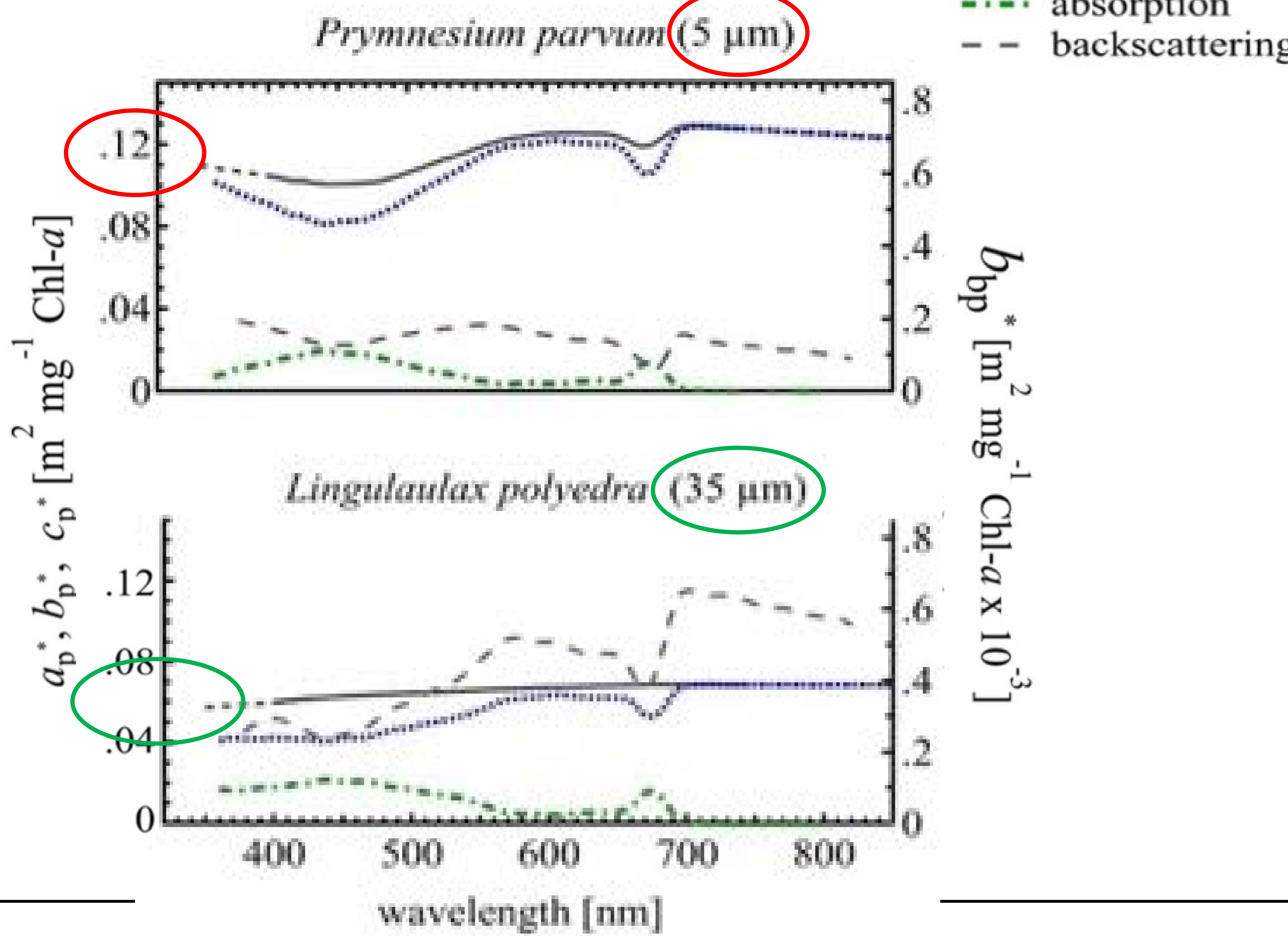
$c^*_{phy}(\lambda)$

$b^*_{phy}(\lambda)$

$a^*_{phy}(\lambda)$

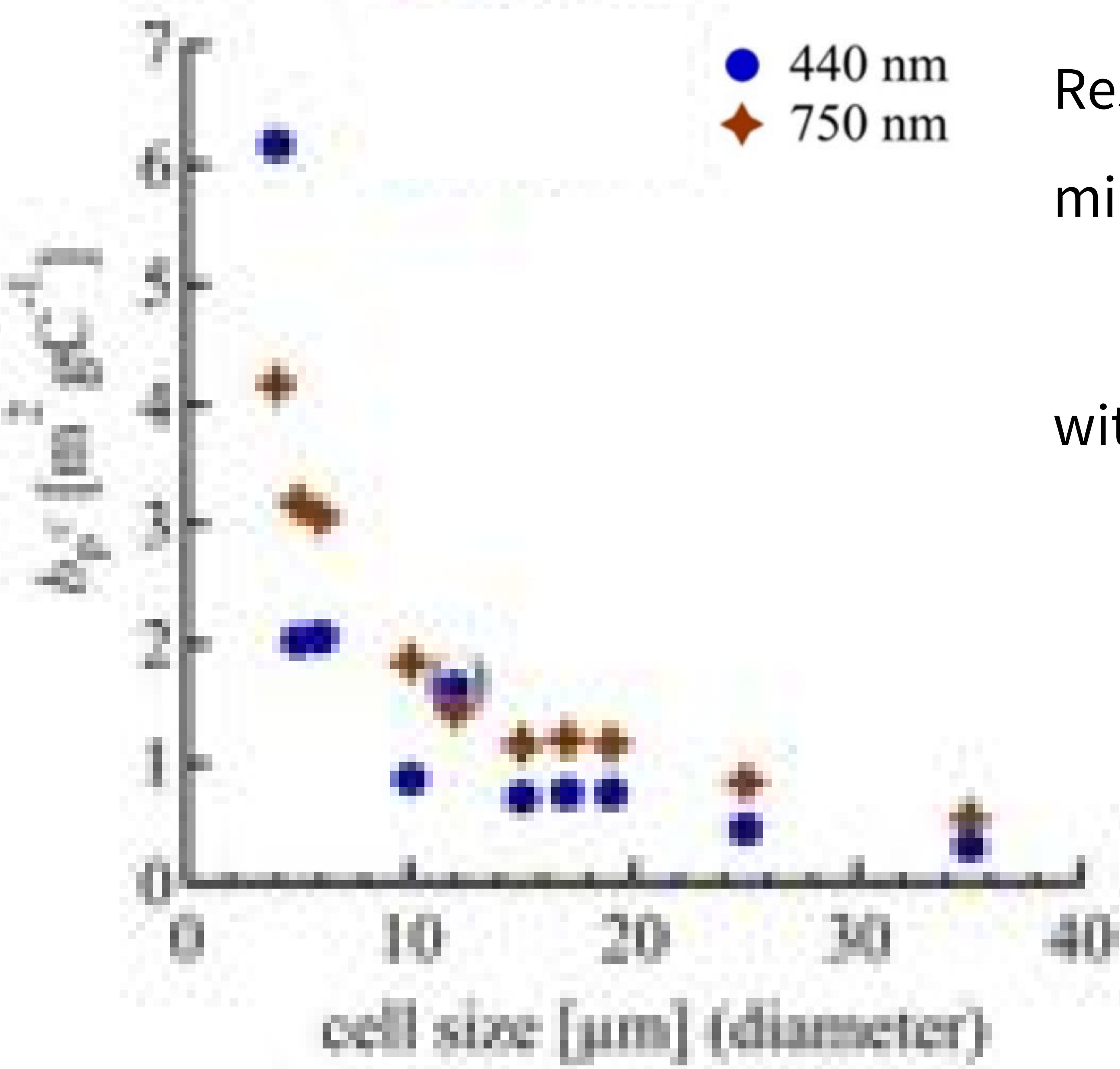
Bi, S., Hieronymi, M., & Röttgers, R. (2023). Bio-geo-optical modelling of natural waters. Frontiers in Marine Science, 10, 1196352.

Effect of cell size on c_p and b_p



Röttgers et al. (in prep.)

Effect of cell size on b_p



Results from lab measurements on monospecific microalgae cultures (Röttgers et al., in prep)

with b_p^c carbon-specific scattering coefficient

(i.e. b_p / [POC])

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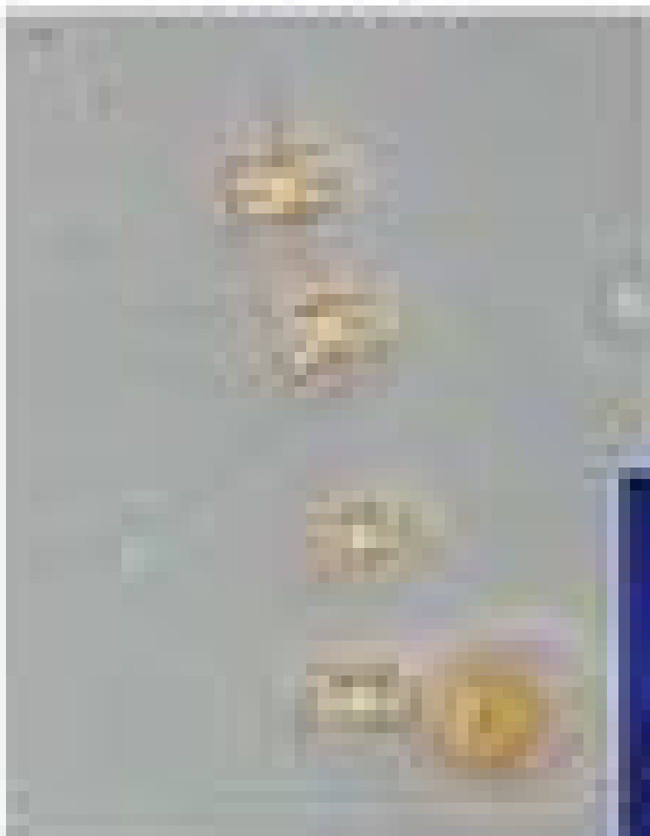
Röttgers et al. (in prep.)

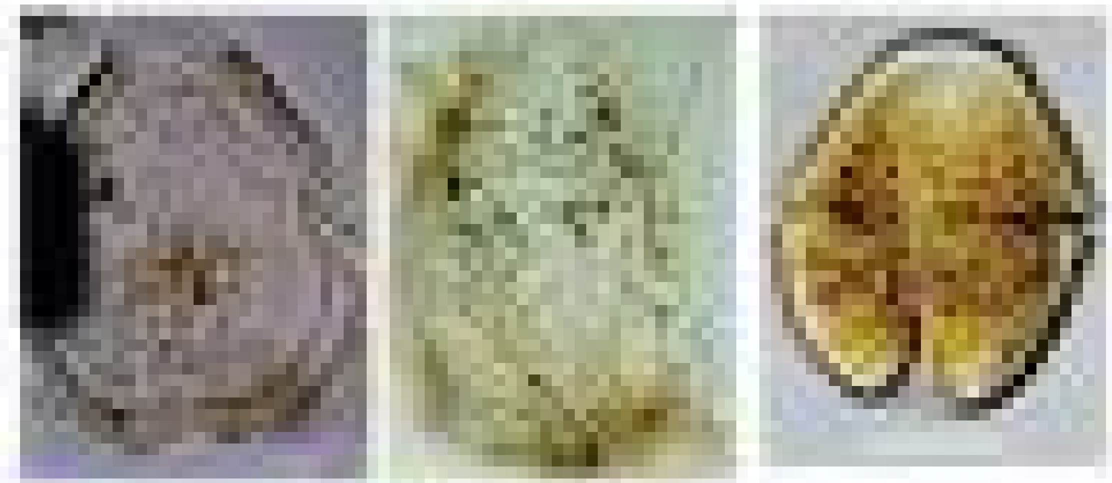
Testing the “Complex Particle” Hypothesis

Thalassiosira weissflogii

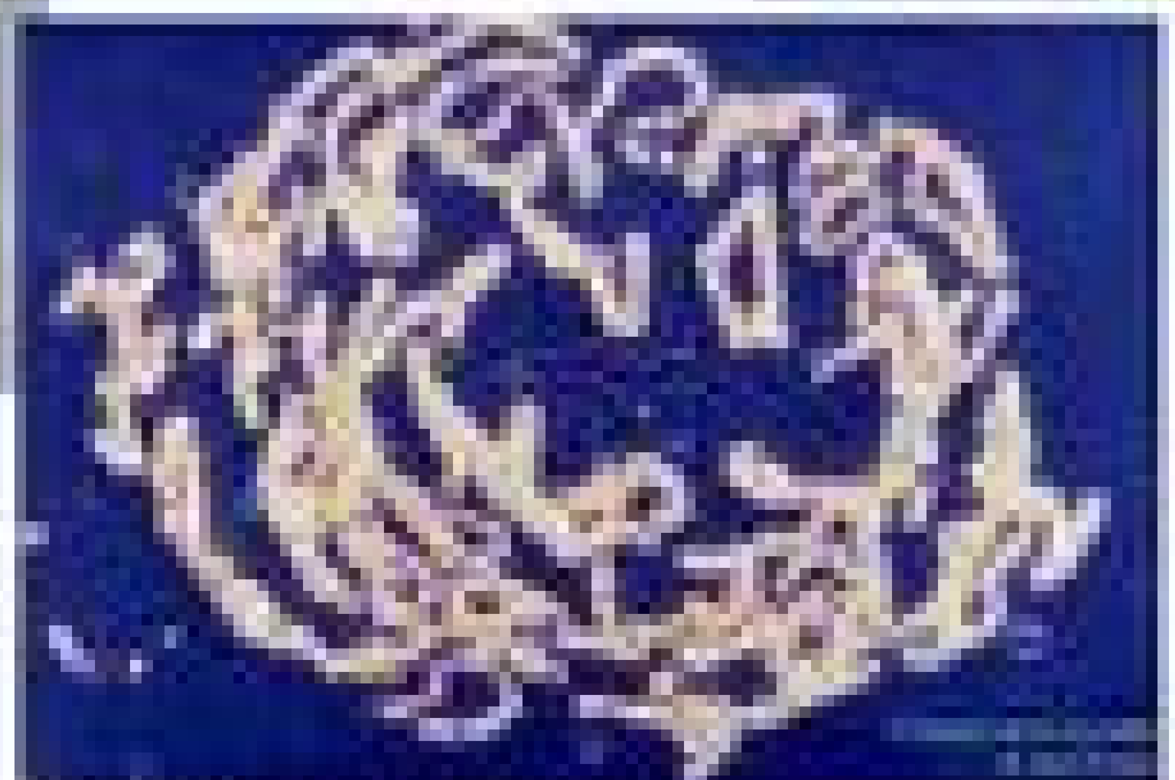


~25 µm diameter

Gyrodinium instriatum



~50 mm diameter

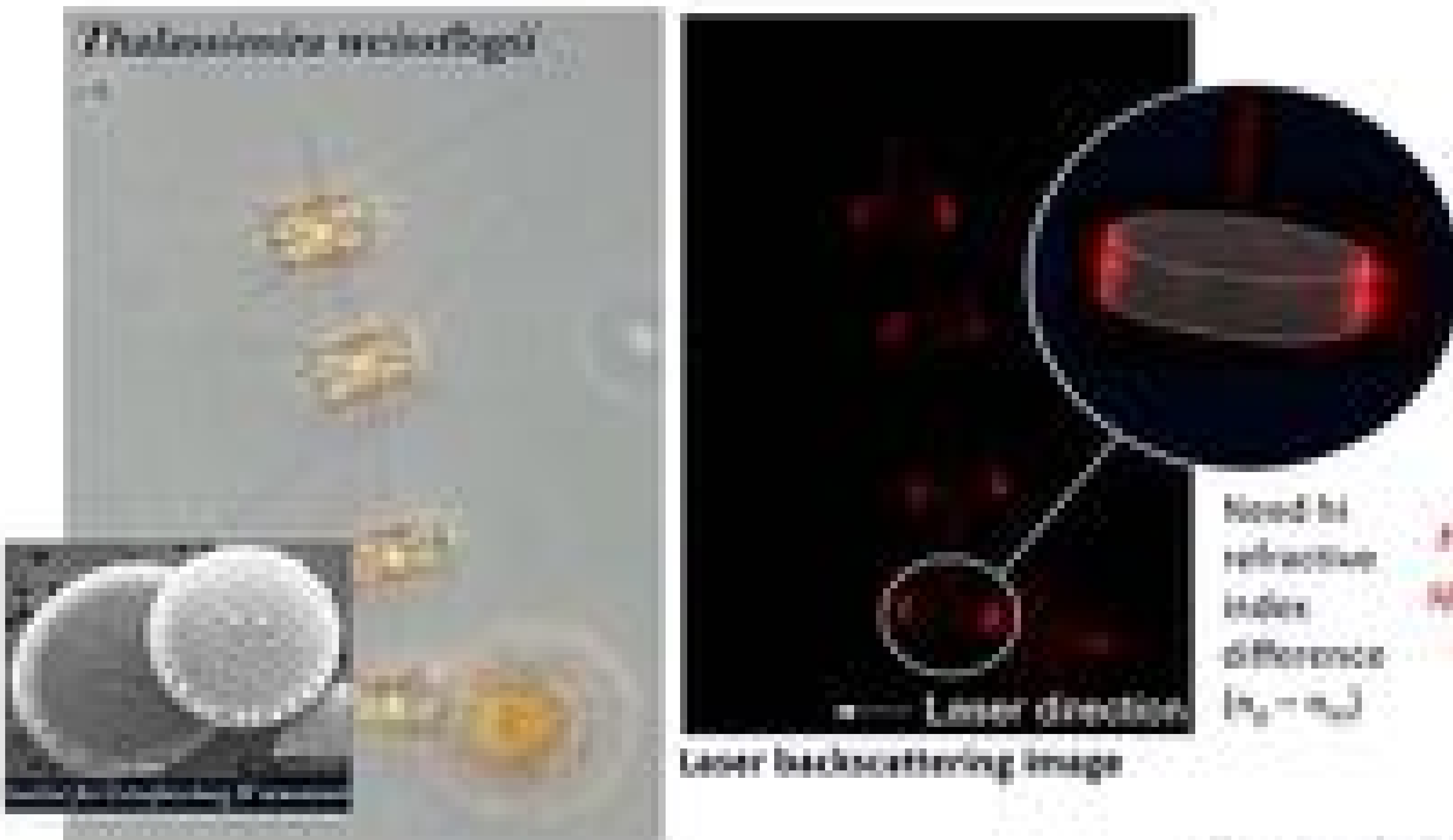


~10 µm cell diameter
Up to 1 mm colonies

Chaetoceros socialis

Slide from Mike Twardowski’s lecture

Imaging Particle Backscattering



Laser backscattering image

Need hi refractive index difference $(n_p - n_w)$

Homogeneous sphere model is problematic

Twardowski, Sullivan, McFarland

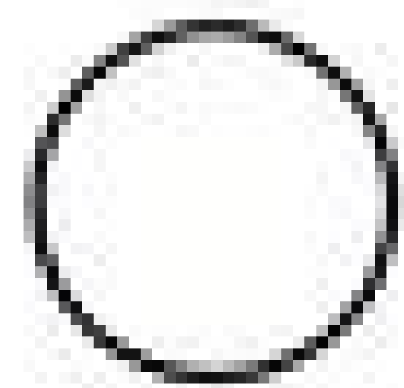
Slide from Mike Twardowski's lecture

Phytoplankton scattering: measurements and modeling

b_{bp}/b_p

	Measured	Mie theory	Coated Mie theory
Thalassiosira cells	**0.013**	0.006	0.013
Gyrodinium cells	**0.006**	0.003	0.007
C. socialis cells	**0.004**	0.0006	0.0237
C. socialis [1]cell Q_{bb} [2]colony Q_b	**0.004**	0.004	

Mie theory is a model for scattering by particles making the first order assumption they are homogeneous spheres

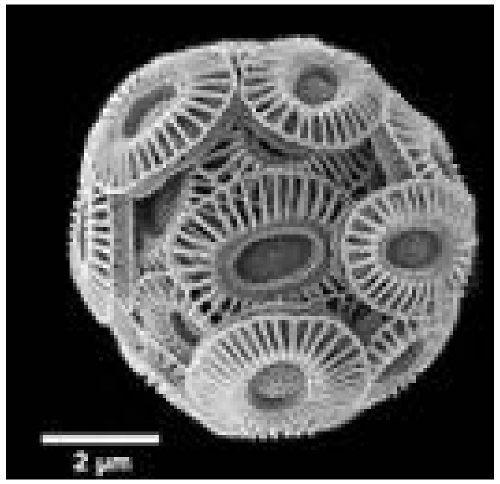


Twardowski, Sullivan, McFarland

Slide from Mike Twardowski's lecture

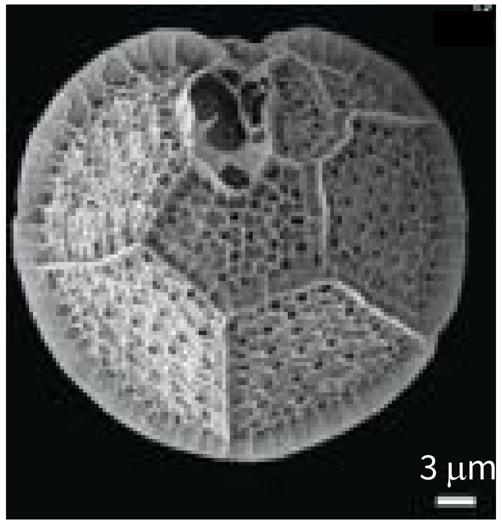
Influence of cell wall structure on b_{bp} / b_p

A



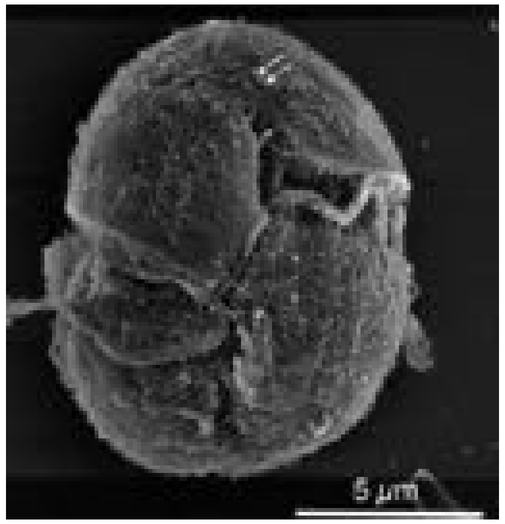
***G. huxleyi* (4 µm)**
(new name of *E. huxleyi*)
Cell wall made of calcite (coccoliths)

B

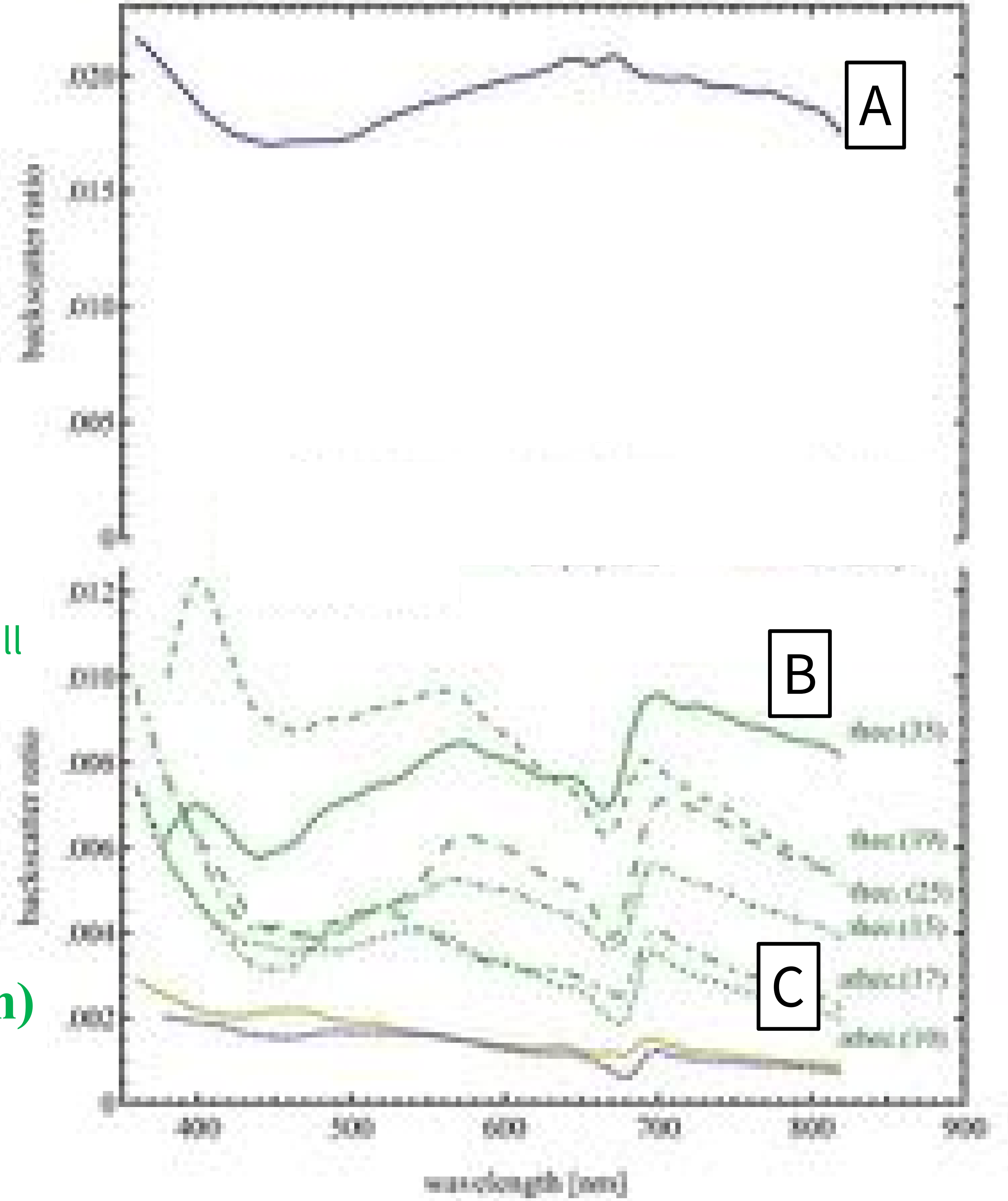


***L. Polyedra* (35 µm)**
Thick, rigid cellulose cell wall (theca), highly structured

C



***K. Veneficum* (10 µm)**
athecate



Röttgers et al. (in prep.)

Issues with cultures…

Growing microalgae is a lot of work: you need to work with biologists

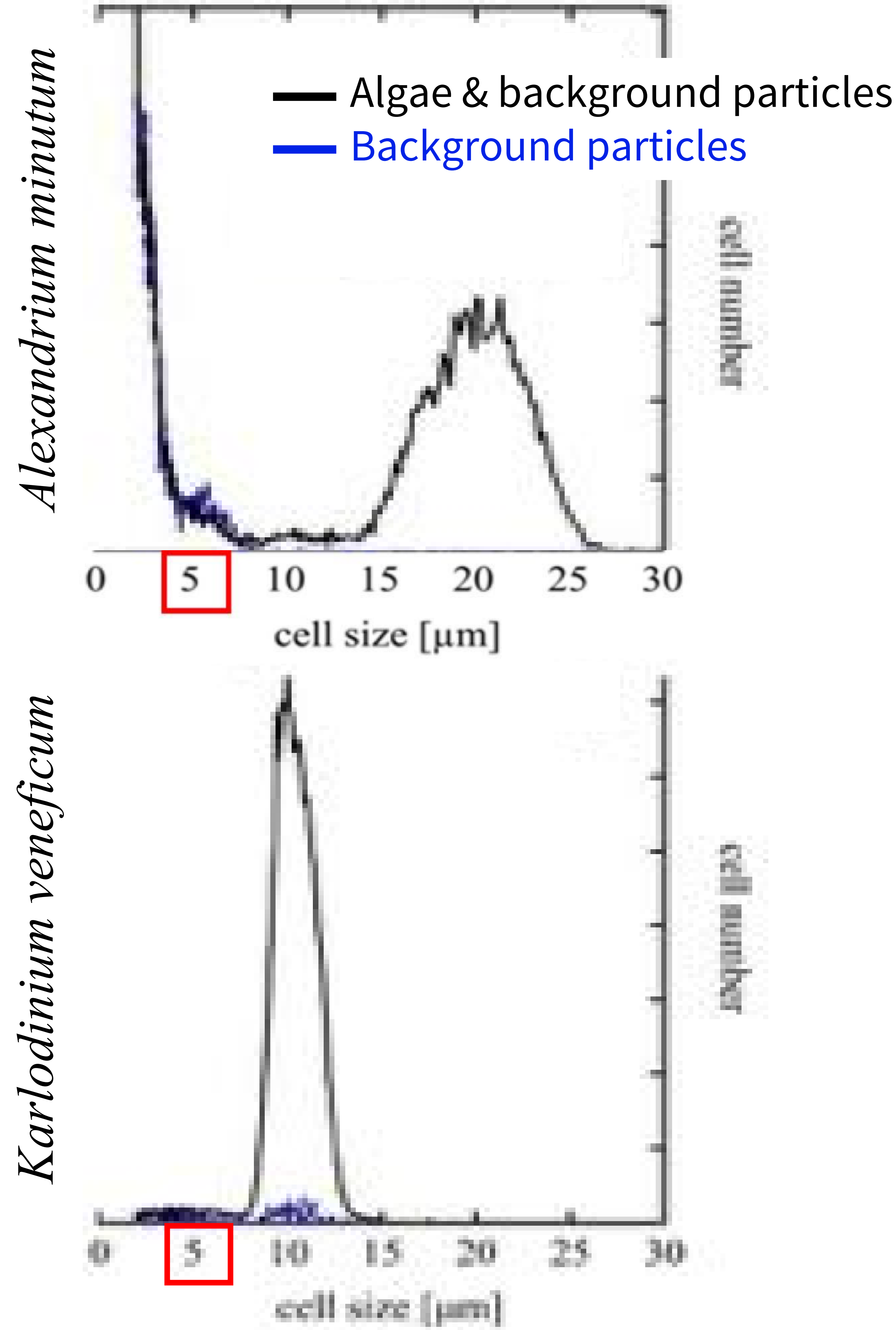
Thomas Lacour, Ifremer

Background particles

Separating algae from small background particles

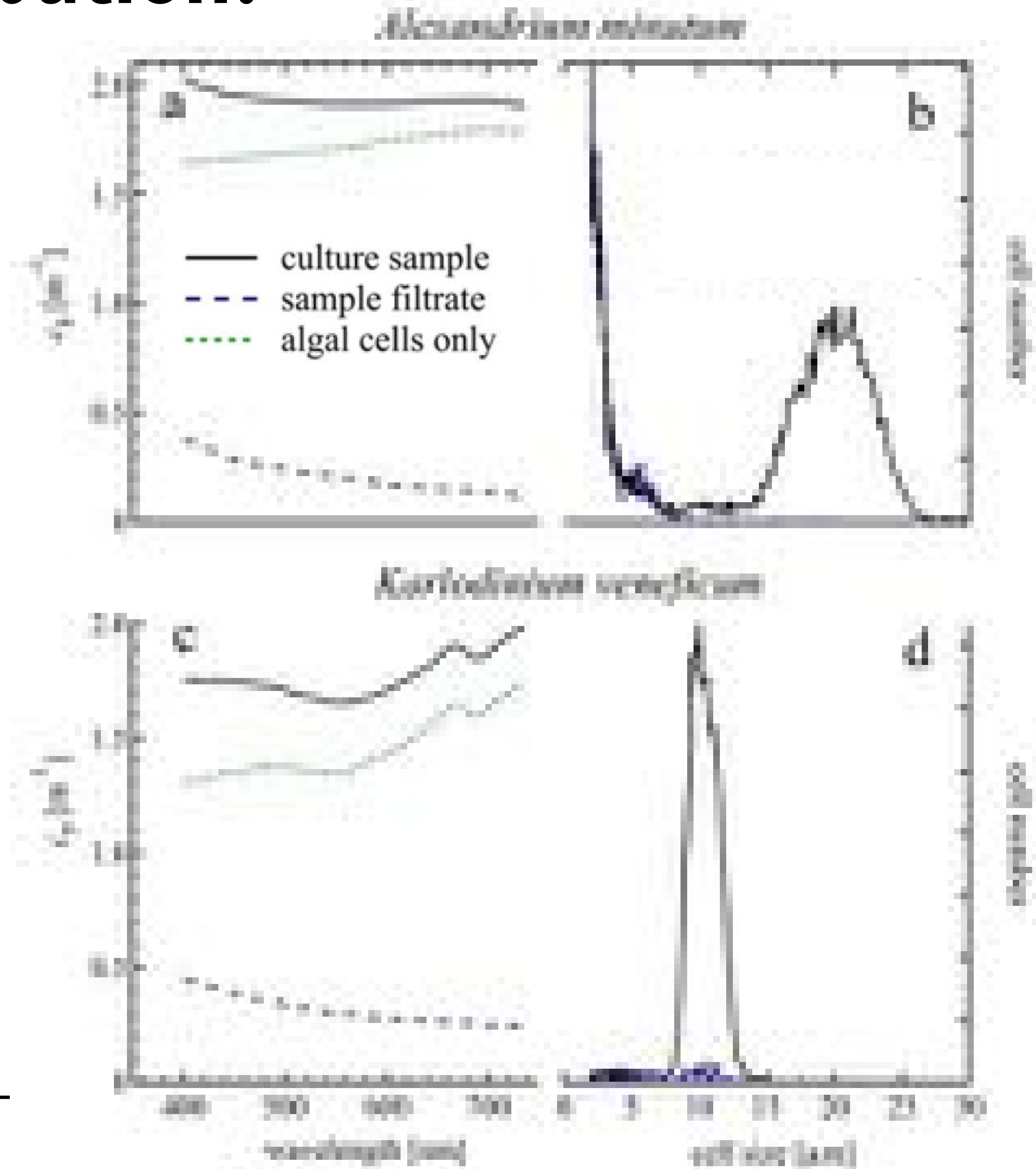
Size fractionation using filter with pore size < cell size
(here 5 μm)

Challenging and fastidious:
- filters can get clogged
- some cells can squeeze in
- not feasible for small microalgae



Röttgers et al. (in prep.)

Significant contribution!



Amplitude

- attenuation (~ 35%)
- scattering (~ 45%)
- backscattering (~ 50%)

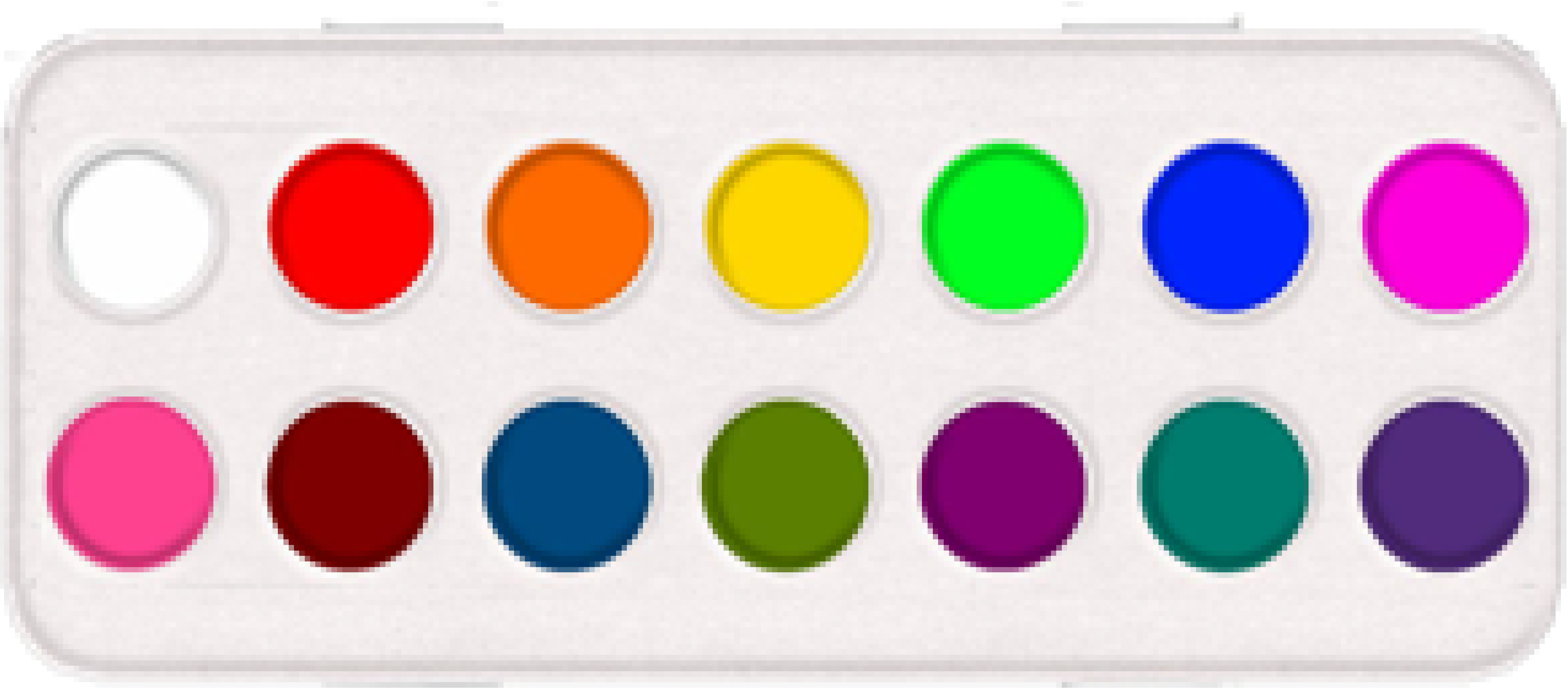
Spectral shape

Measuring IOPs require many instruments

Lomas, M. W., Neeley, A. R., Vandermeulen, R., Mannino, A., Thomas, C., Novak, M. G., & Freeman, S. A. (2024). Phytoplankton optical fingerprint libraries for development of phytoplankton ocean color satellite products. Scientific Data, 11, 168.

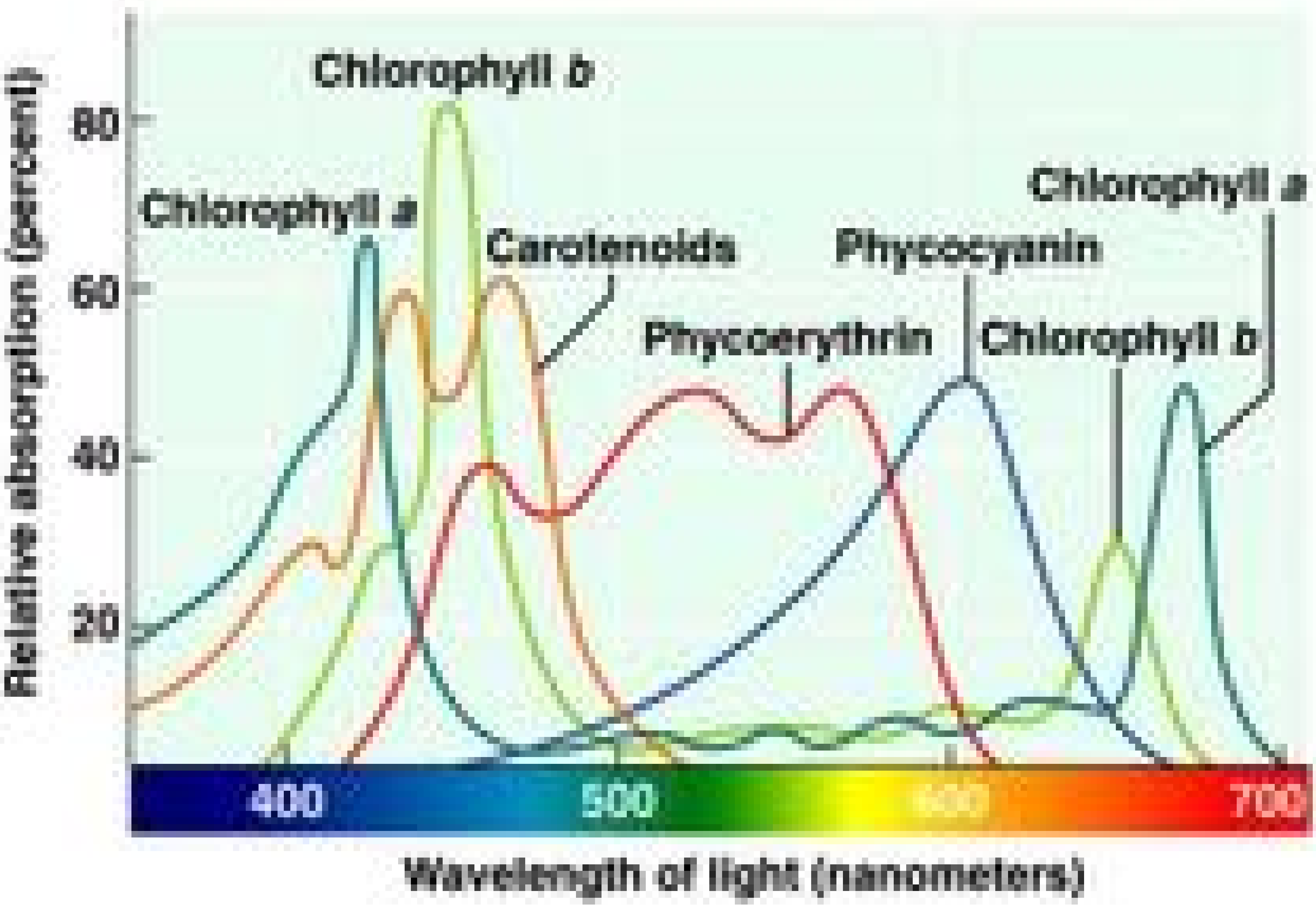
Importance of team work!

Phytoplankton pigments



Some different phytoplankton pigments

"Everything that lives strives for color" - Goethe (1840)



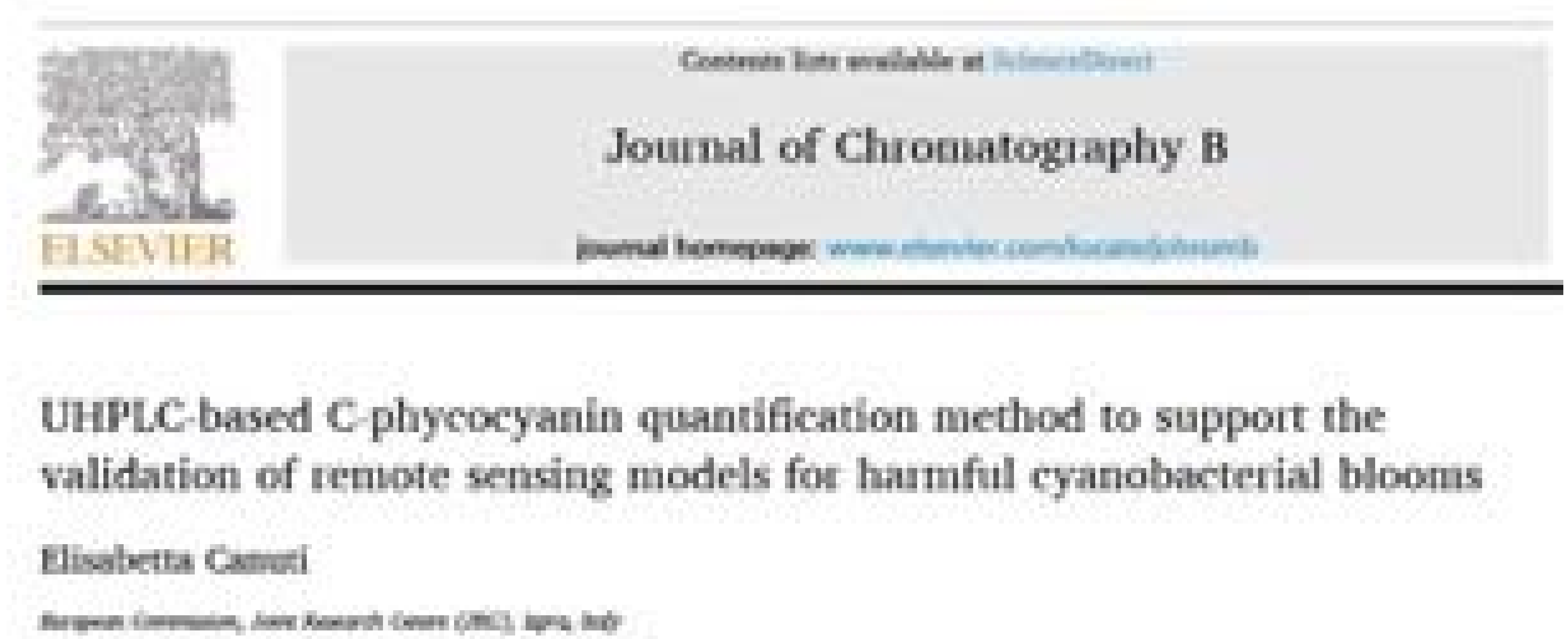
Slide from Mike Twardowski's lecture

Measuring pigments

High-performance liquid chromatography (HPLC)
see text book from Roy et al., 2011

Commonly used to **quantify phytoplankton's lipophilic pigments (Chl, Fuco, Peri, etc.)**

Water-soluble pigments such as **phycocyanin or phycoerythrin are more tricky**
see Canuti (2025)


Contents lists available at ScienceDirect

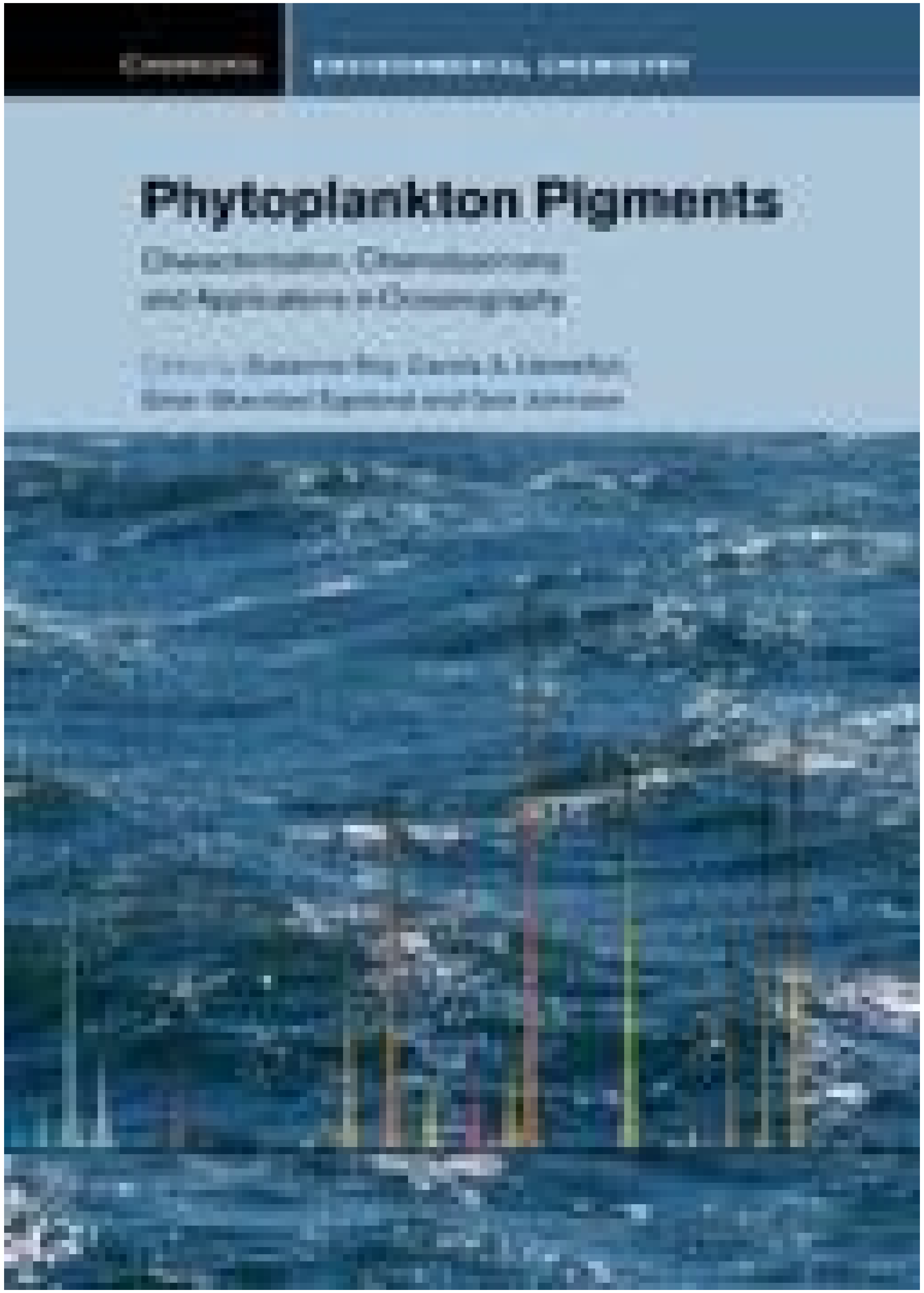
Journal of Chromatography B

ELSEVIER

UHPLC-based C-phycocyanin quantification method to support the validation of remote sensing models for harmful cyanobacterial blooms

Elisabetta Canuti

Canuti, E. (2025). UHPLC-based C-phycocyanin quantification method to support the validation of remote sensing models for harmful cyanobacterial blooms. Journal of Chromatography B, 124759.



Chapter 1: Jeffrey SW, Wright SW, Zapata M. **Microalgal classes and their signature pigments.**

In: Roy S, Llewellyn CA, Egeland ES, Johnsen G, eds. *Phytoplankton Pigments: Characterization, Chemotaxonomy and Applications in Oceanography*. Cambridge Environmental Chemistry Series. Cambridge University Press; 2011:3-77.

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Pigments as biochemical fingerprints

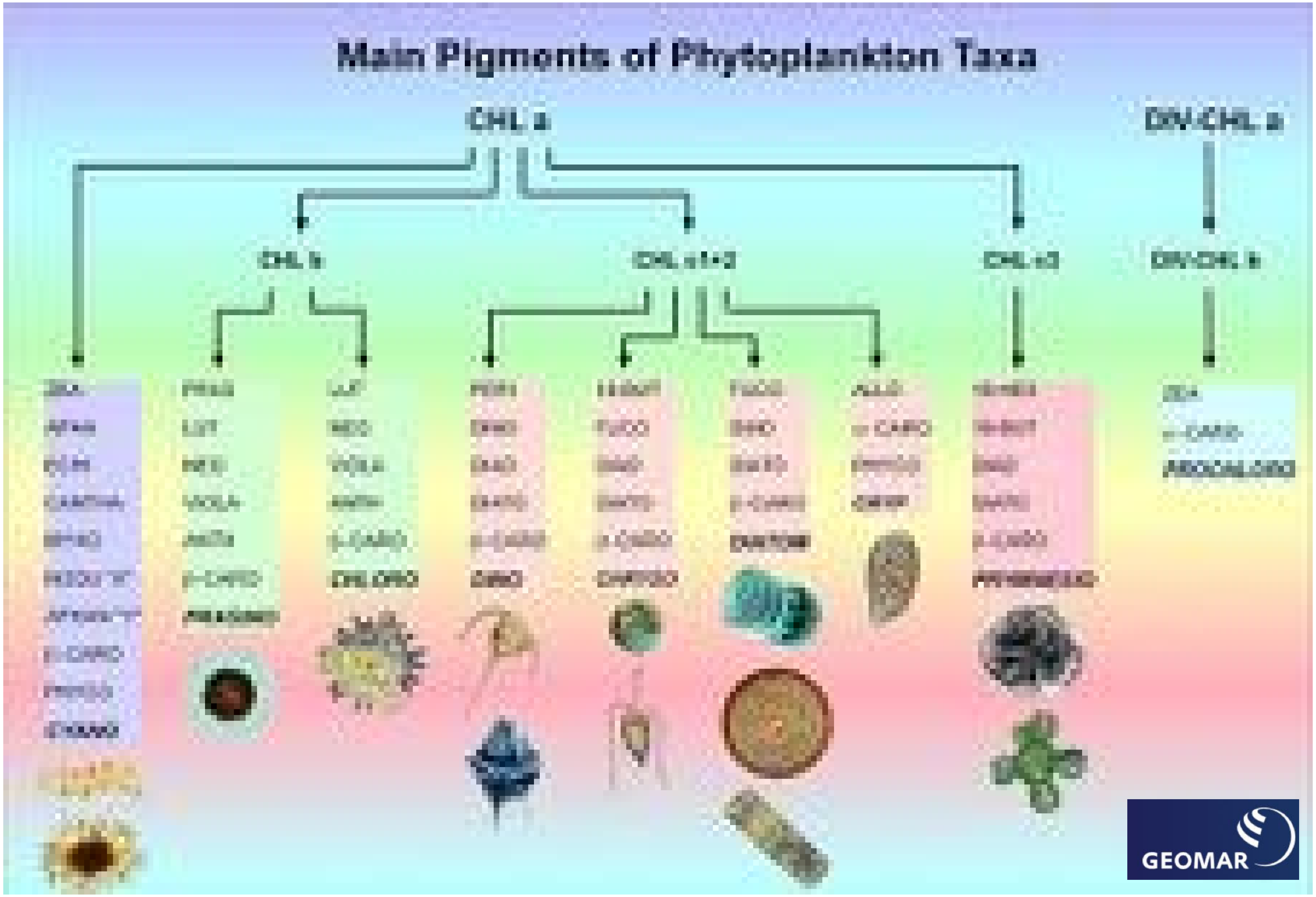
“Phytoplankton pigments serve as biochemical fingerprints that reveal the composition, physiological state and succession of microscopic algae in aquatic ecosystems.

Through the quantification of chlorophylls, carotenoids and accessory pigments, researchers can infer taxonomic groups, estimate biomass and track responses to environmental drivers such as nutrient availability, light regimes and temperature anomalies.

Pigment-based chemotaxonomy, often implemented with high-performance liquid chromatography coupled to statistical deconvolution algorithms, enables rapid, objective classification of complex communities across temporal and spatial scales.”

https://www.nature.com/nature-index/topics/l4/phytoplankton-pigment-analysis-and-community-dynamics

Chemotaxonomy of phytoplankton pigments



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https://www.geomar.de/en/research/fb2/fb2-bi/infrastructure/hplc-analyses

Mismatches between taxo- and chemodiversity

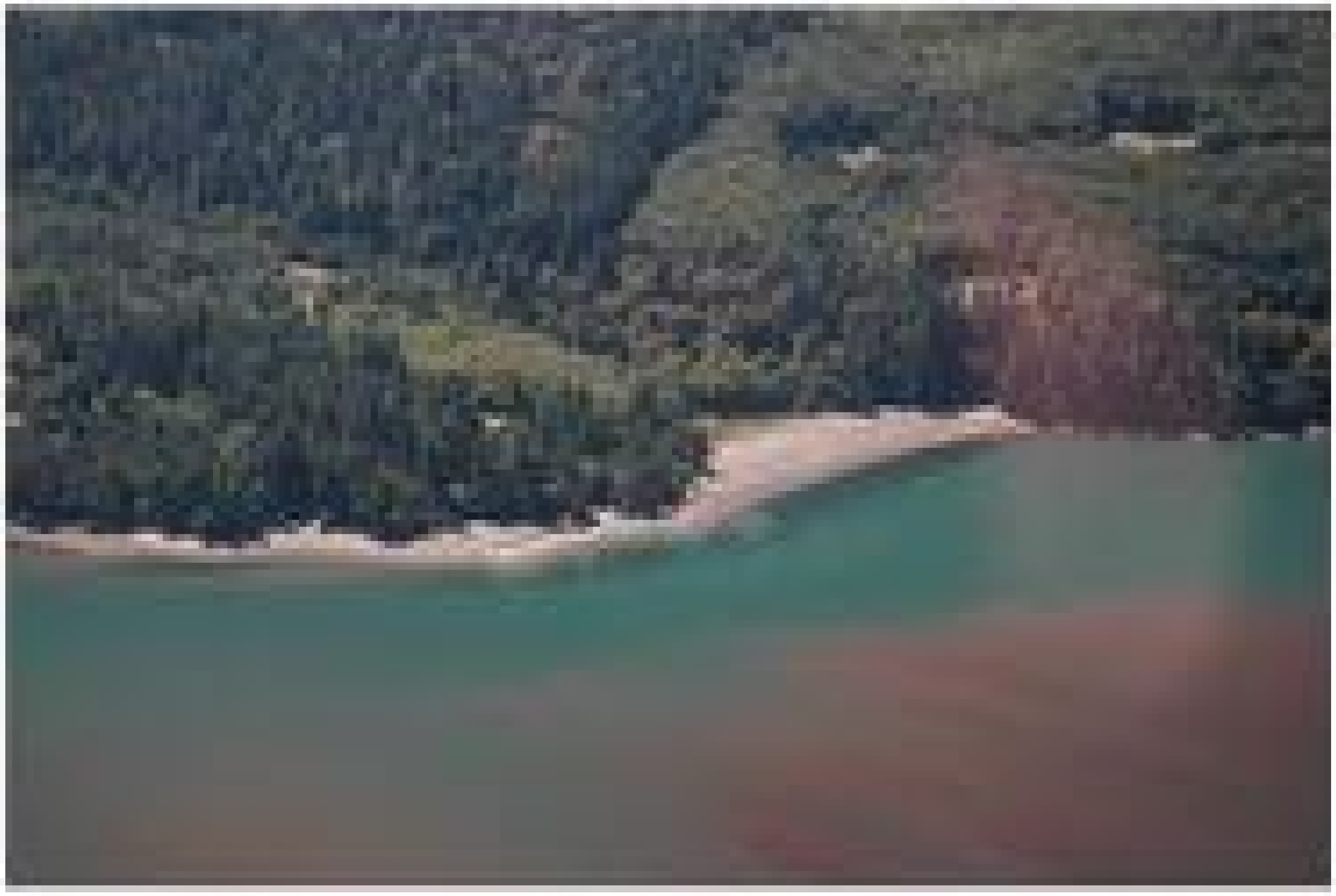
Fucoxanthin is not limited to diatoms, it is also present in:

All chrysophytes

All raphydophytes,
in particular *Heterosigma akashiwo*

Some dinoflagellates such as
Karenia sp.
Karlodinium veneficum

At least one haptophyte species
Prymnesium parvum



Pigment-based chloroplast types in dinoflagellates

Manuel Zapata[1,†], Santiago Fraga[2], Francisco Rodríguez[2,*], José L. Garrido[1]

Vol. 465: 33–52, 2012
doi: 10.3354/meps09879

MARINE ECOLOGY PROGRESS SERIES
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Published September 28

Table 6. Distribution (●) of pigment-based chloroplast types across Dinophyta (class Dinophyceae)

Representative species	Chloroplast type 1	2	3	4	5	6
Dinophysiales						
Dinophysis acuminata	–	–	–	–	●	–
Gonyaulacales						
Alexandrium minutum	●	–	–	–	–	–
Gymnodiniales						
Gymnodinium catenatum	●	–	–	–	–	–
Karenia mikimotoi	–	●	–	–	–	–
Karlodinium veneficum	–	–	–	–	–	–
Takayama cf. *helix*	–	–	●	–	–	–
Lepidodinium chlorophorum	–	–	–	–	–	●
Peridiniales						
Heterocapsa sp.	●	–	–	–	–	–
Durinskia baltica	–	–	–	–	–	–
Galeidinium rugatum[a]	–	–	–	–	–	–
Kryptoperidinium foliaceum	–	–	–	●	–	–
Prorocentrales						
Prorocentrum lima	●	–	–	–	–	–
Thoracosphaerales						
Thoracosphaera heimii	●	–	–	–	–	–

[a]From Tamura et al. (2005)

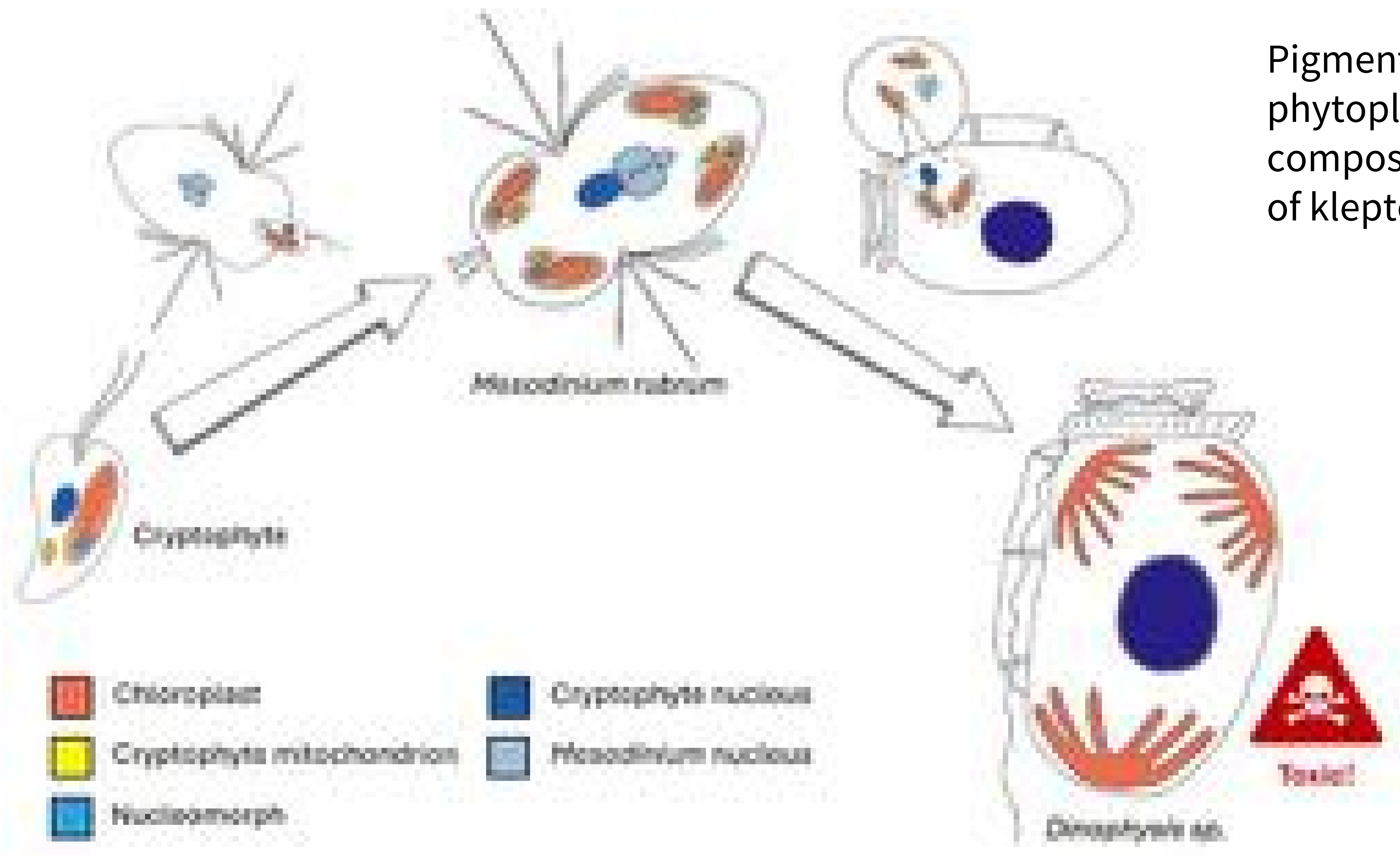
Up to 6 pigment types!

Type 1: PERI
Types 2, 3, 4: FUCO
Type 5: ALLO (and PE)
Type 6: Chl-*b*

"Caution must be observed when only peridinin is used for tracking photosynthetic dinoflagellates in field samples"

There are some weird kleptoplastidic phyto

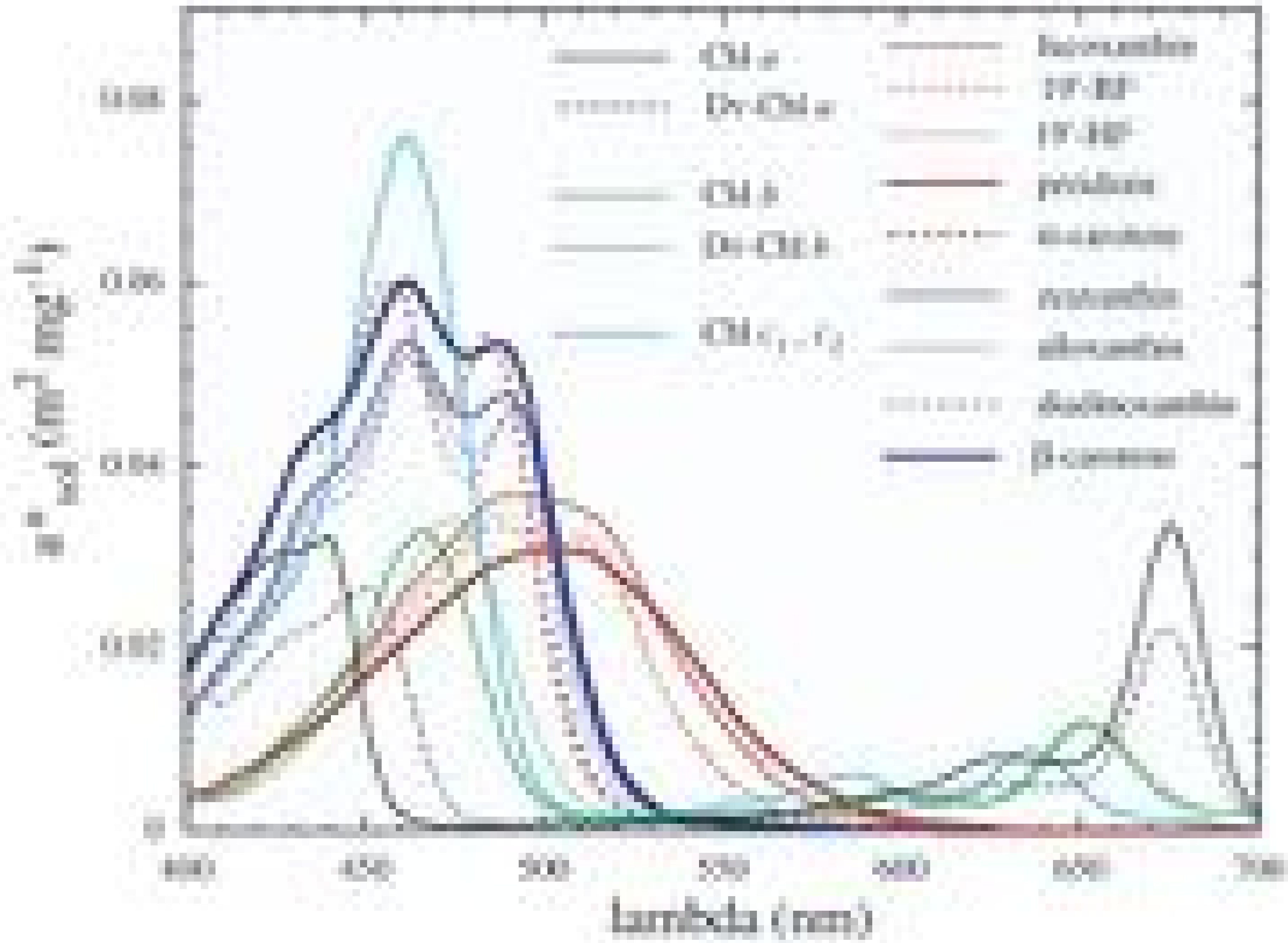
The ciliate *M. rubrum* and dinoflagellate *Dinophysis* have cryptophyte pigments



Pigment-based estimations of phytoplankton community composition biased in the case of kleptoplastidic species

Drawing from Victor Pochic, Nantes Université

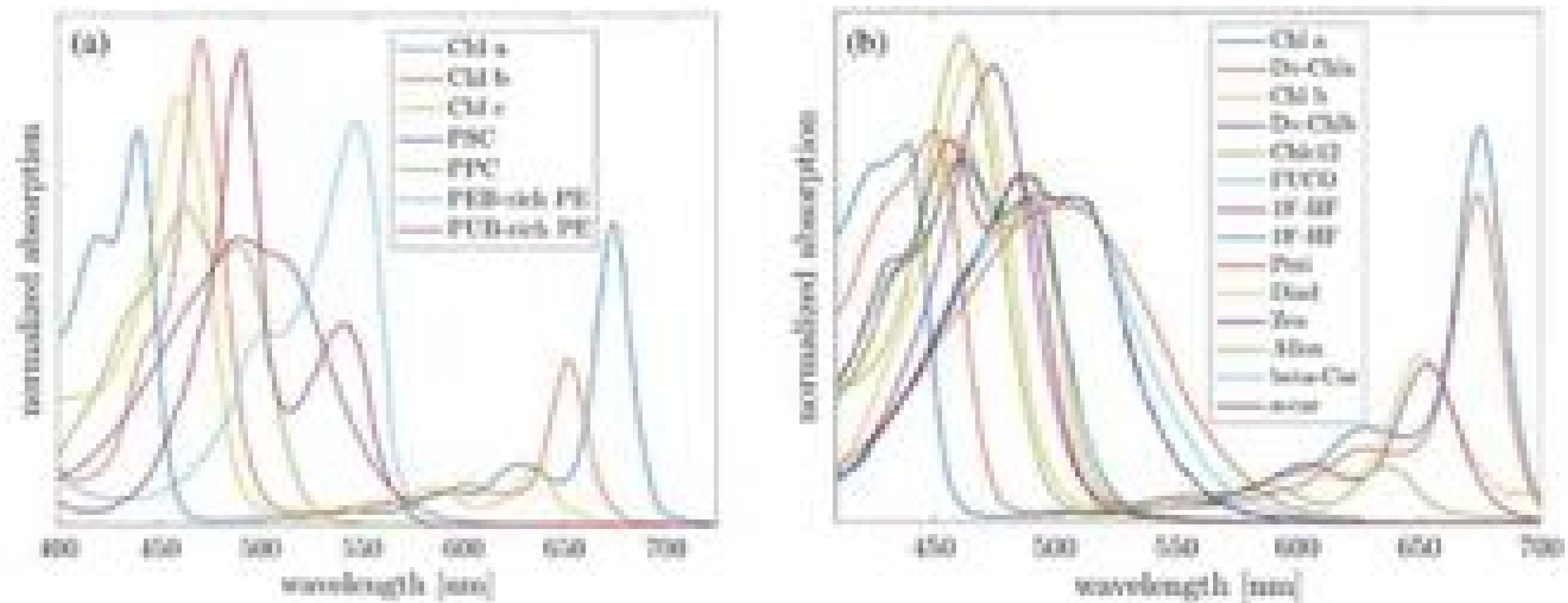
Pigment absorption spectra



Absorption of pure phytoplankton pigments
extracted in solvent (w/o phycobiliproteins)

Bricaud, A., Claustre, H., Ras, J., & Oubelkheir, K. (2004). Natural variability of phytoplanktonic absorption in oceanic waters: Influence of the size structure of algal populations. Journal of Geophysical Research: Oceans, 109

Pigment absorption spectra



Cael et al. (2020). Standardized pigment absorption spectra
using data from (a) Bidigare et al. (1990) and (b) Bricaud et al. (2004)

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Cael, B. B., Chase, A., & Boss, E. (2020). Information content of absorption spectra and implications for ocean color inversion. Applied Optics, 59, 3971-3984.

Bidigare et al. (1990) SPIE proceedings

Phytoplankton absorption spectra ($a_{ph}(\lambda)$) were reconstructed from knowledge of the in vivo weight-specific absorption coefficients of the major pigment types ($a_i^*(\lambda)$, $m^2 \cdot mg^{-1}$) and their volume-based concentrations (C_i, $mg\ m^{-3}$)[4]:

$$\boxed{a_{ph}(\lambda) = \sum a_i^*(\lambda)\, C_i} \quad (1)$$

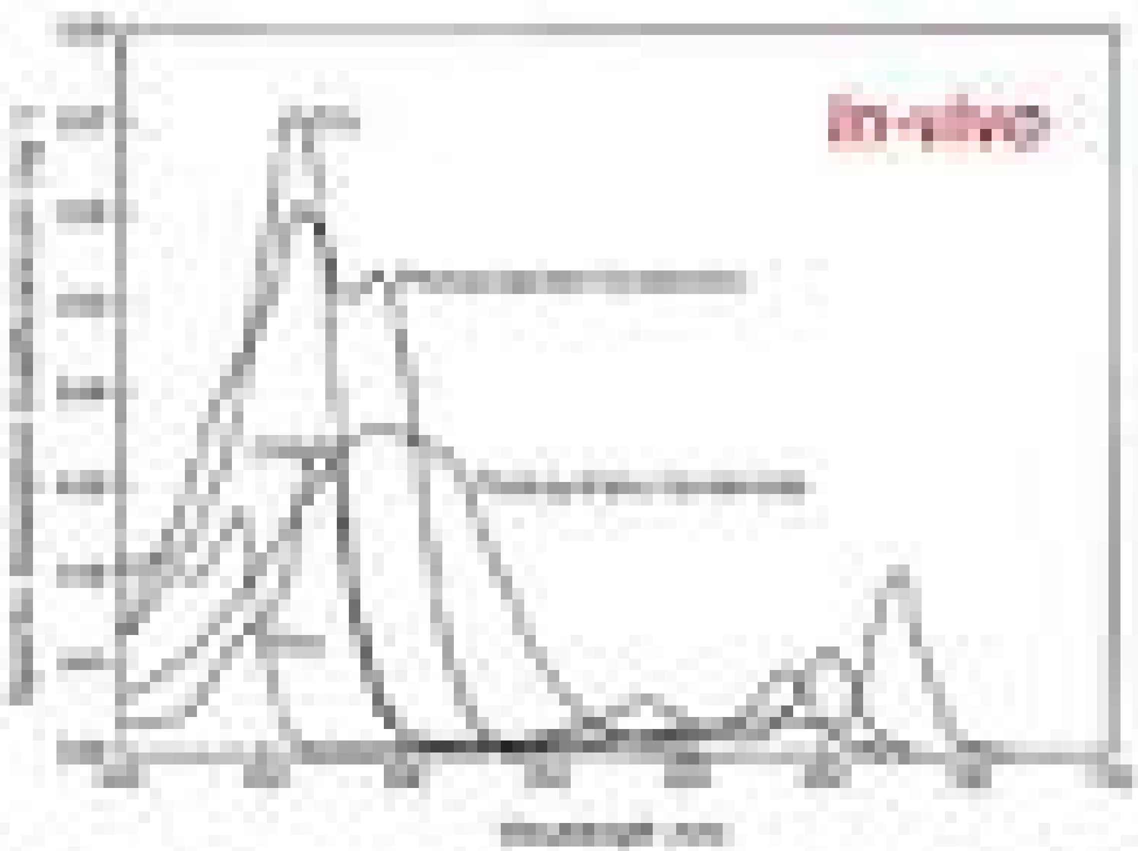


Fig. 1. Weight-specific absorption coefficients ($a_i^*(\lambda)$, $m^2\ mg^{-1}$) derived for the major pigment types found in marine phytoplankton.

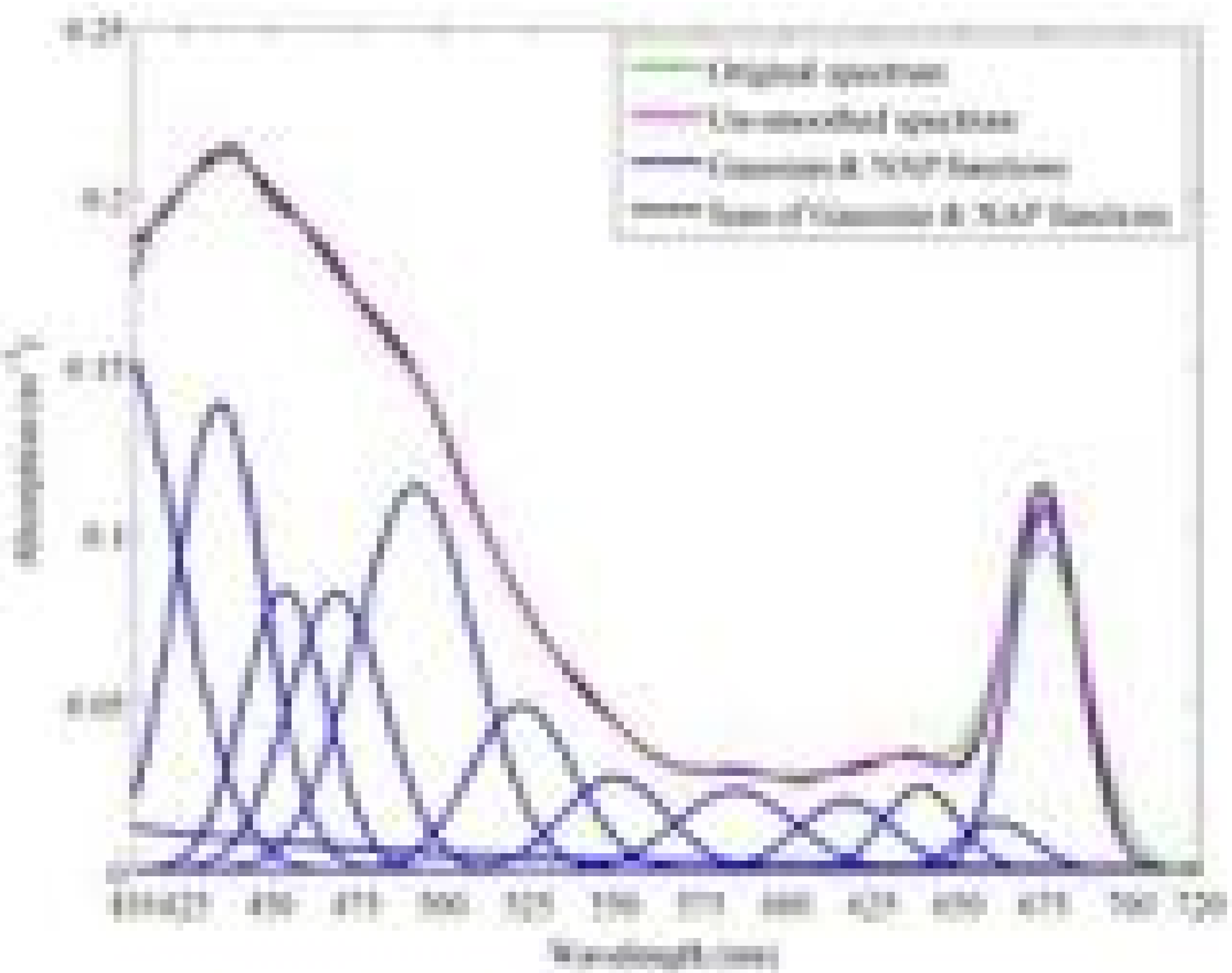
a^*_{ph} - specific absorption for phytoplankton ($m^2\ mg^{-1}$)

Pigment packaging complicates application…

Slide from Mike Twardowski's lecture

Decomposition of phytoplankton absorption

$$a_{\mathrm{phy}}(\lambda) = \sum_{i}^{n} [\mathrm{pigment_i}]\, a_{\mathrm{pigment_i}}(\lambda)$$



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Chase, A., Boss, E., Zaneveld, R., Bricaud, A., Claustre, H., Ras, J., ... & Westberry, T. K. (2013). Decomposition of in situ particulate absorption spectra. *Methods in Oceanography*, *7*, 110-124.

Measuring the absorption coefficient

IOCCG

IOCCG Protocol Series

Ocean Optics & Biogeochemistry Protocols for Satellite Ocean Colour Sensor Validation

Volume 1: Inherent Optical Property Measurements and Protocols: Absorption Coefficient (v1.0)

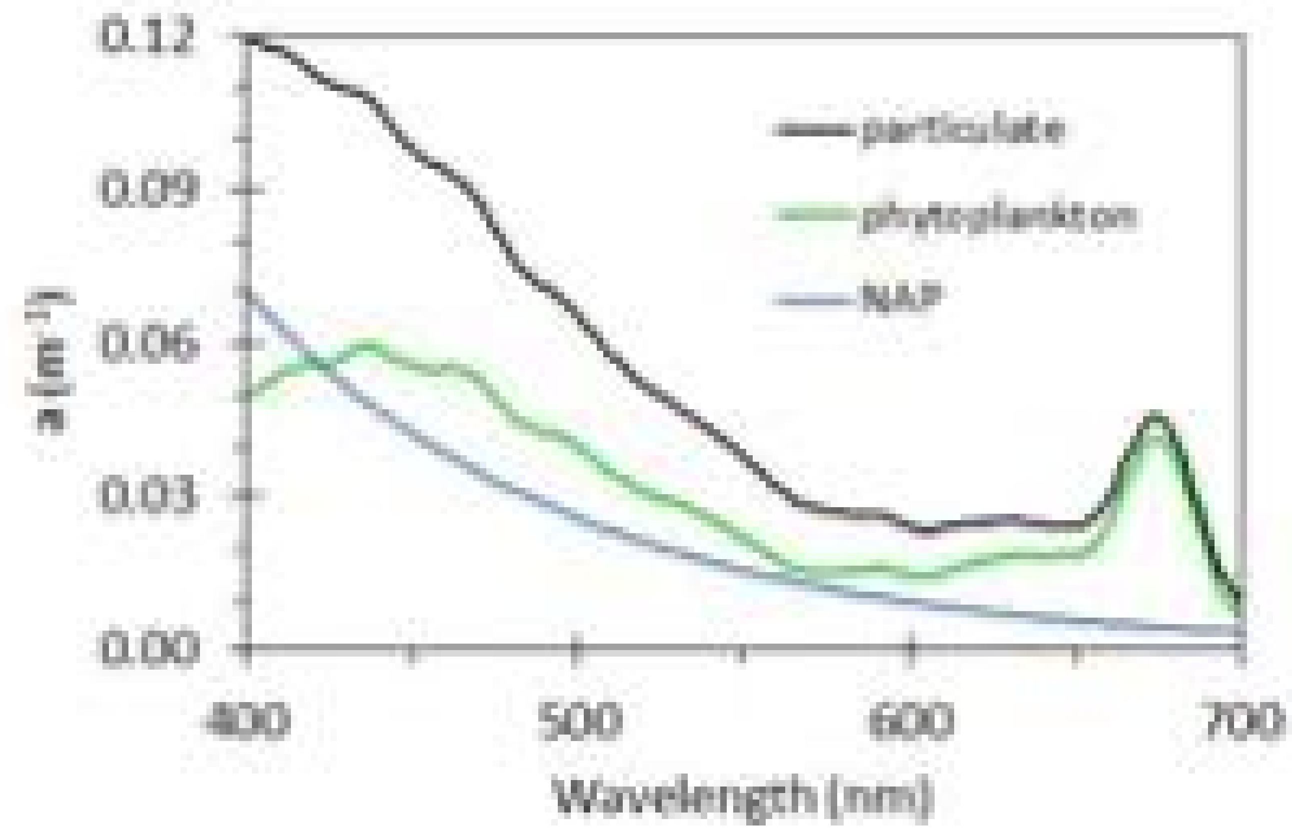
Editors
Aimee R. Neeley and Antonio Mannino

Authors
Emmanuel Boss, Eurico J. D'Sa, Scott Freeman, Ed Fry, James L. Mueller, Scott Pegau, Rick A. Reynolds, Collin Roesler, Rüdiger Röttgers, Dariusz Stramski, Michael Twardowski and J. Ronald V. Zaneveld

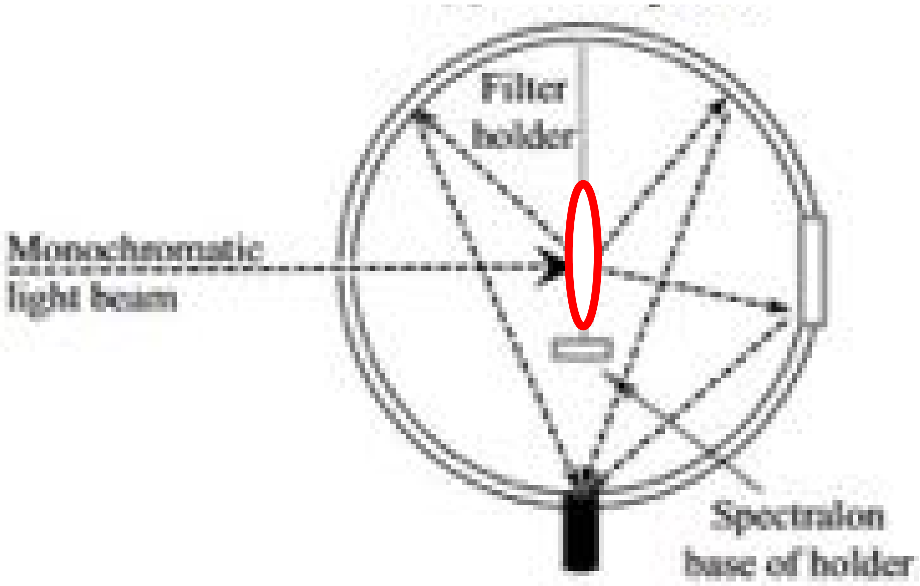
International Ocean Colour Coordinating Group (IOCCG) in collaboration with National Aeronautics and Space Administration (NASA)

Measuring $a_p(\lambda)$ and $a_{phy}(\lambda)$ using filter pad

1. Filter seawater onto GF/F filter
2. Measure $a_p(\lambda)$ on filter
3. Extract pigments and measure $a_{nap}(\lambda)$
4. Compute $a_{phy}(\lambda) = a_p(\lambda) - a_{nap}(\lambda)$



GF/F filter inside sphere



Chapter 5: Spectrophotometric Measurements of Particulate Absorption Using Filter Pads

Collin Roesler[1], Dariusz Stramski[2], Eurico J. D'Sa[3], Rüdiger Röttgers[4], and Rick A. Reynolds[2]

See also Röttgers & Gehnke (2012) and Stramski et al., (2015)

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Stramski, D., Reynolds, R. A., Kaczmarek, S., Uitz, J., & Zheng, G. (2015). Correction of pathlength amplification in the filter-pad technique for measurements of particulate absorption coefficient in the visible spectral region. Applied Optics, 54, 6763-6782.

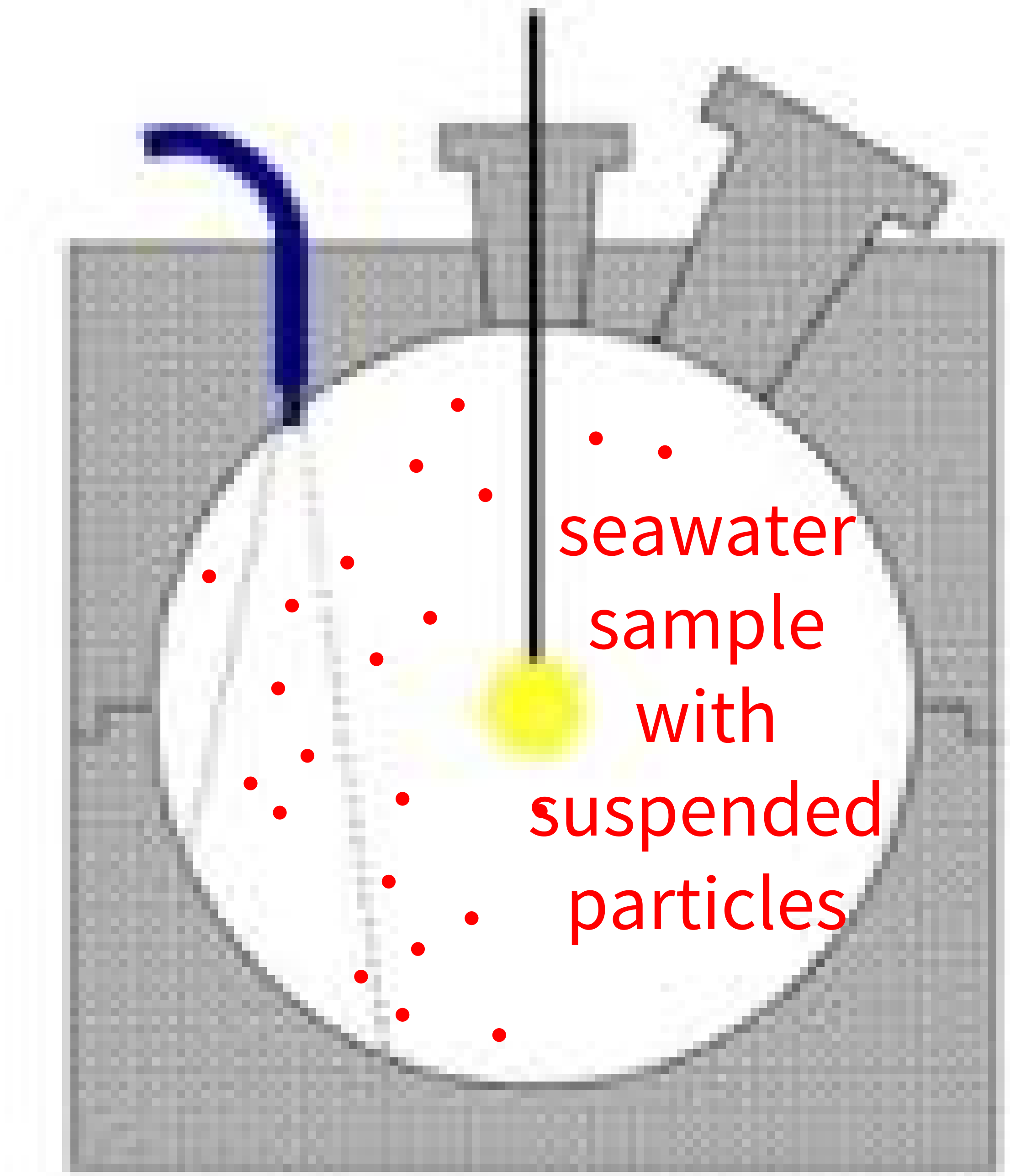
Röttgers, R., & Gehnke, S. (2012). Measurement of light absorption by aquatic particles: improvement of the quantitative filter technique by use of an integrating sphere approach. Applied Optics, 51, 1336-1351.

Measuring $a_p(\lambda)$ using a PSICAM

1. Fill in sphere with seawater sample
2. Measure $a_p(\lambda)$

Chapter 4: Point-Source Integrating Cavity Absorption Meters

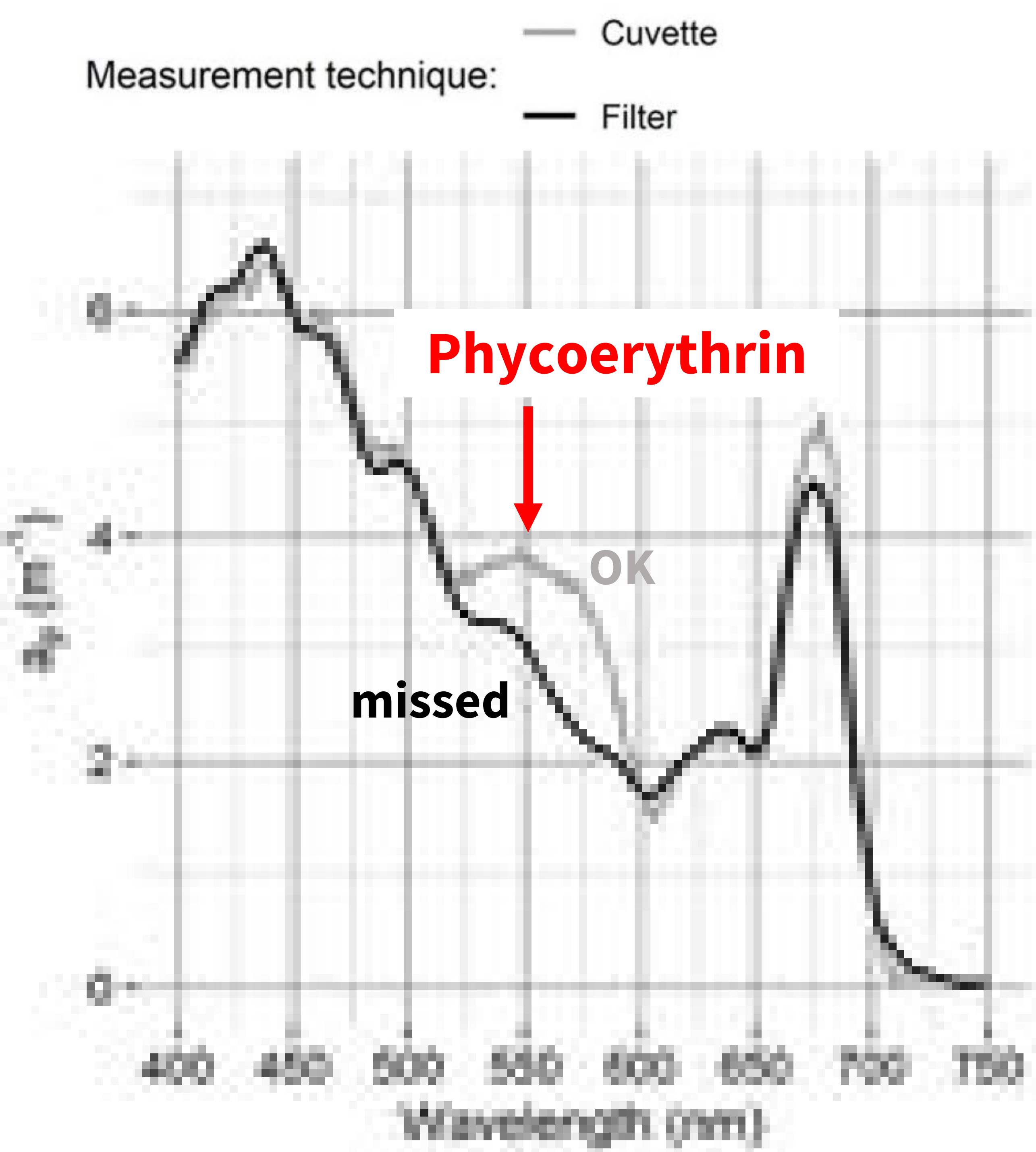
Rüdiger Röttgers



See also Röttgers et al., (2007)

Röttgers, R., Häse, C., & Doerffer, R. (2007). Determination of the particulate absorption of microalgae using a point-source integrating-cavity absorption meter: verification with a photometric technique, improvements for pigment bleaching, and correction for chlorophyll fluorescence. Limnology and Oceanography: Methods, 5, 1-12.

Phytoplankton absorption: hydro-soluble pigments



Phycobiliproteins (PE, PC) are soluble into water

They pass through the GF/F during filtration

Filter-pad $a_p(\lambda)$ measurements could be incomplete

Better to use a cuvette or a PSICAM

The "pink side" of the filter

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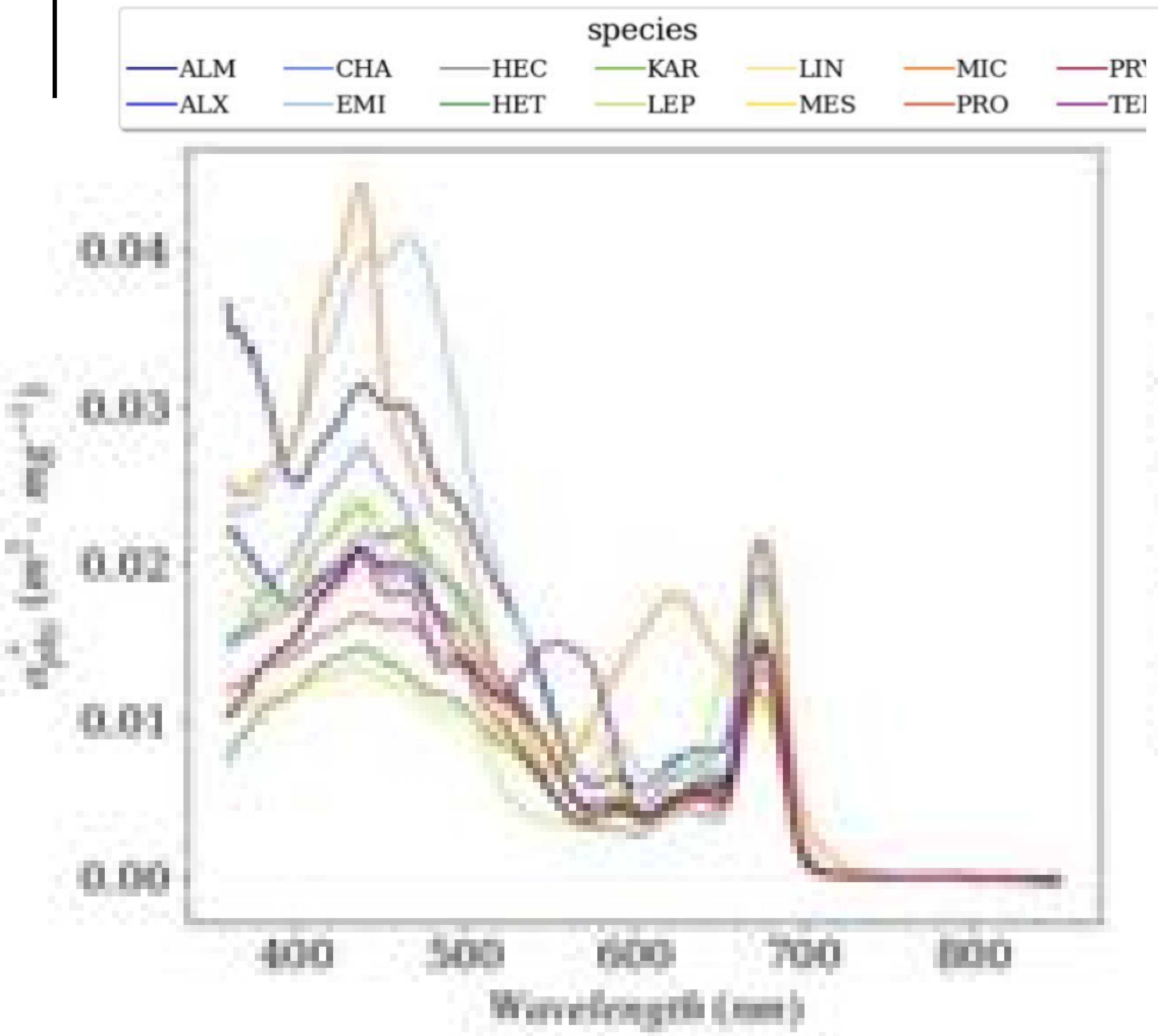
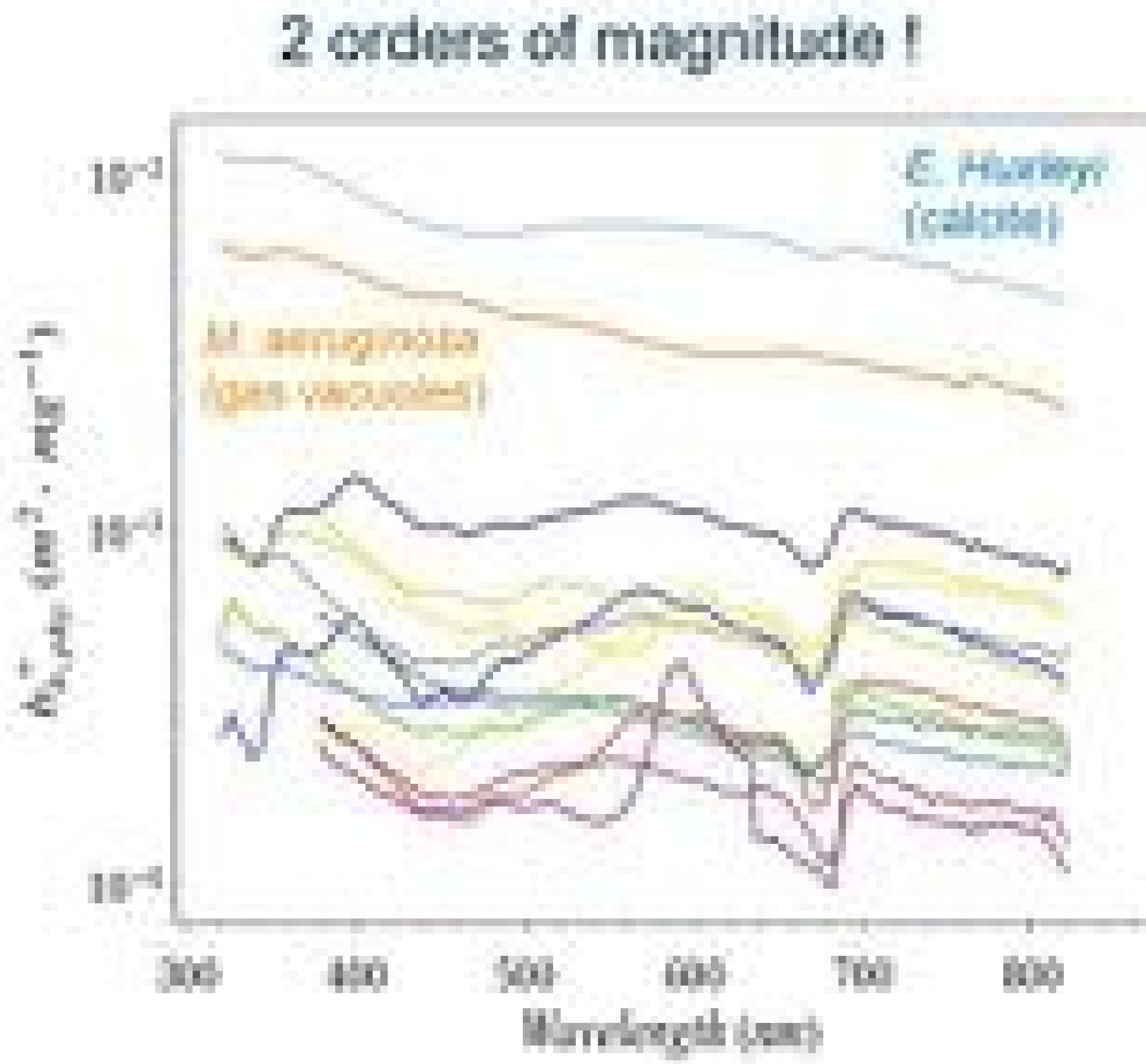
Pochic, V., Gernez, P., Zoffoli, M. L., Séchet, V., Carpentier, L., & Lacour, T. (2024). Photoacclimation in the kleptoplastidic ciliate *Mesodinium rubrum* and its cryptophyte prey *Teleaulax amphioxeia*: phenotypic variability and implications for red tide remote sensing. Journal of plankton research, 46, 100-116.

Summary: large $a_{phy}(\lambda)$ and $b_{bphy}(\lambda)$ diversity



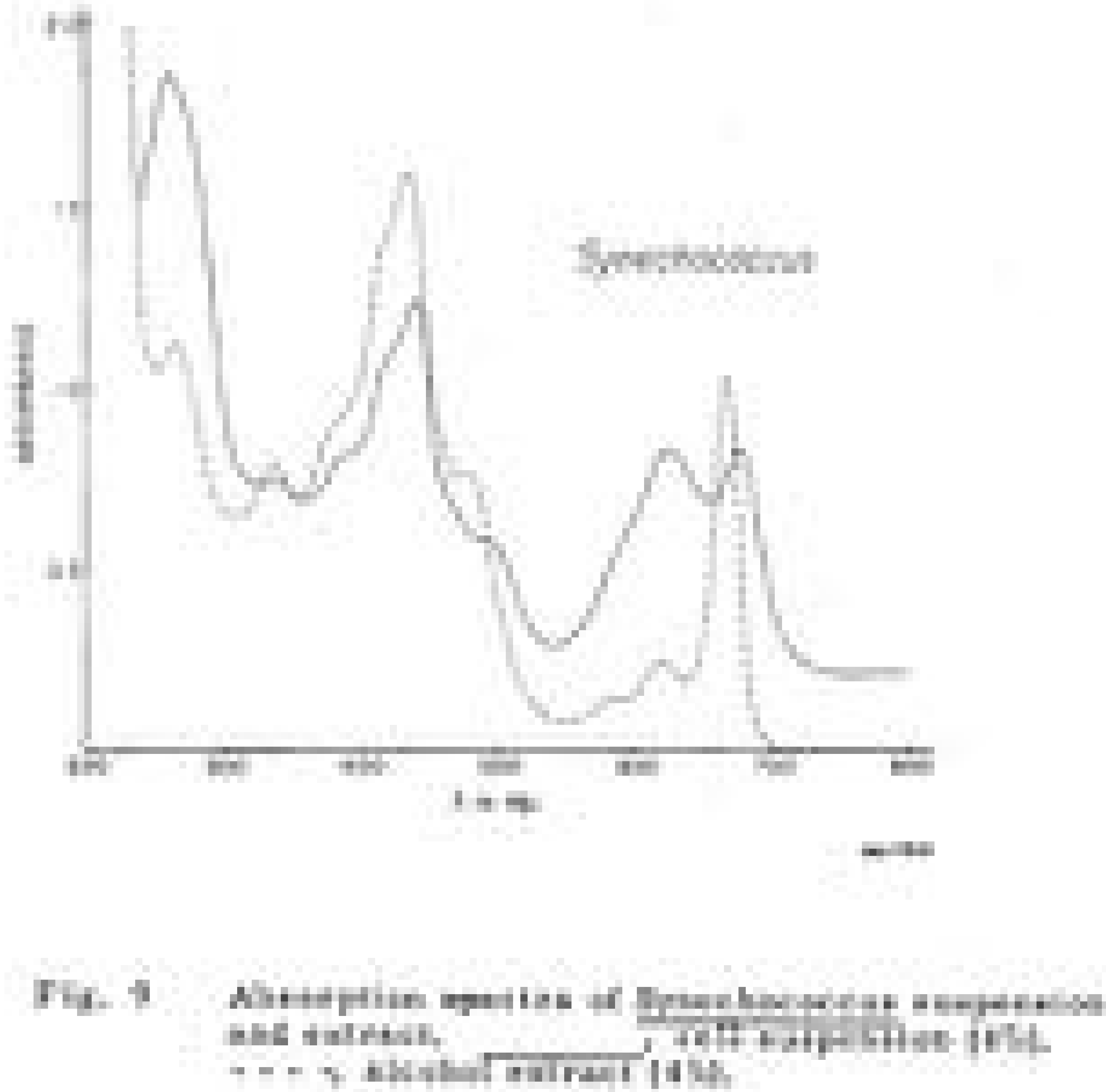


Generic IOP models limited when phytoplankton is abundant.

Alternative approaches required: we'll talk about it on Friday!

Pioneer work during the 1950s – 1960s

A photograph of Prof. Kazuo Shibata (1917–1983) from Ogawa (2025).



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Shibata, K., Benson, A. A., & Calvin, M. (1954). The absorption spectra of suspensions of living micro-organisms. Biochimica et Biophysica Acta, 15, 461-470.

Kazuo Shibata (1917–1983) was born as a son of Seiho Takeuchi, one of the greatest painters of Japanese arts

Takeuchi Seiho - Moonlight Venice (1905)
British Museum

Takeuchi Seiho - A Fine Day During the Rainy Season (1934)
Adachi Museum of Art (Japan)

Thank you for your attention!

Bibliographic references

All references listed in separate document.

Must read

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