Analysis of hyperspectral data for identification of phytoplankton: from lab experiments to satellite remote sensing of super blooms

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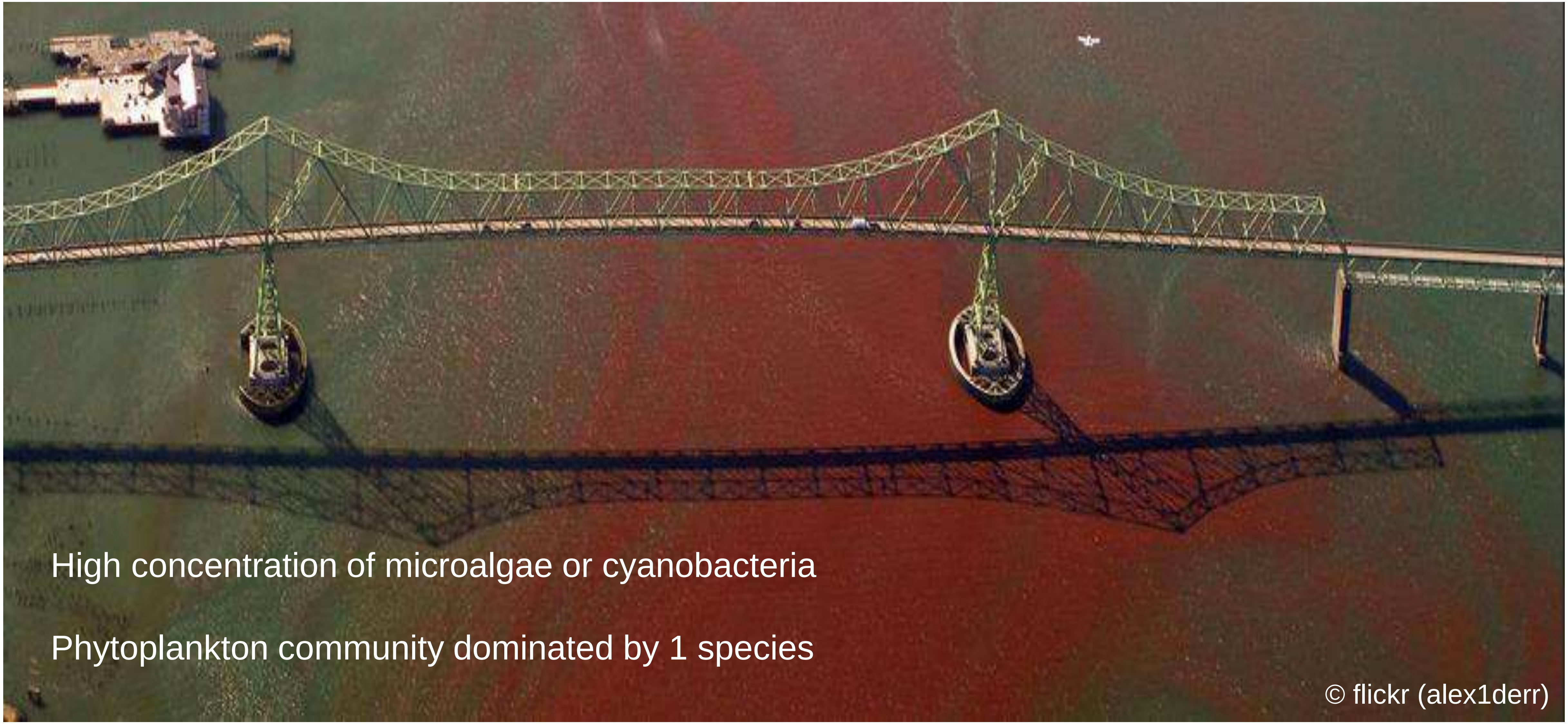
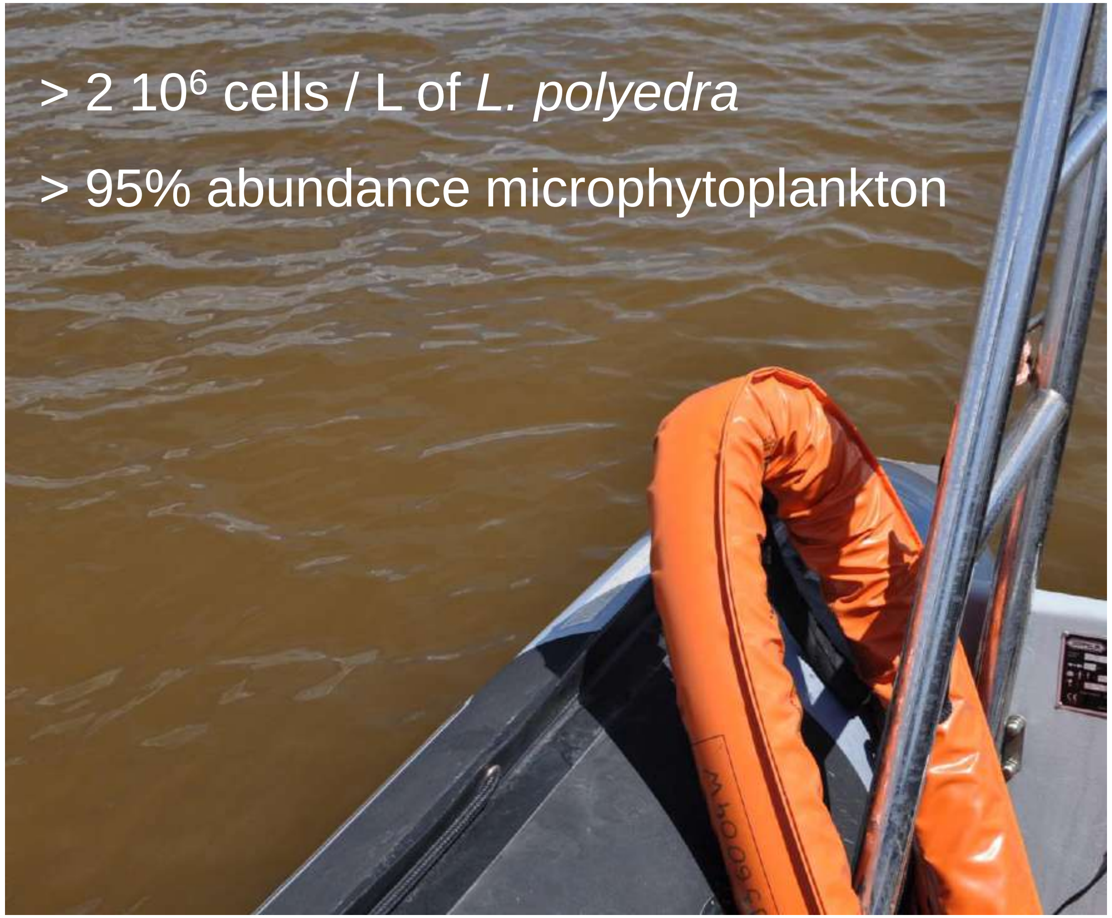
Harmful algal blooms

Proliferation of phytoplankton, harmful due to toxins and/or subsequent hypoxia

Red tide


High concentration of microalgae or cyanobacteria
Phytoplankton community dominated by 1 species
© flickr (alex1derr)

Simplified optical variability during red tide



Seawater optical variability dominated by phytoplankton

$$\boldsymbol{a(\lambda) \sim a_w(\lambda) + a_{phy}(\lambda)} + \cancel{a_{cdom}}(\lambda) + \cancel{a_{nap}}(\lambda)$$

Phytoplankton dominated by one bloom-forming species

$$\boldsymbol{a_{phy}(\lambda) \sim a_{phy,1}(\lambda)} + \cancel{a_{phy,2}}(\lambda) + \cancel{a_{phy,3}}(\lambda) + \cancel{a_{phy,4}}(\lambda) + \cancel{a_{phy,5}}(\lambda) + \ldots$$

~ large scale open-air monospecific culture

High spatial resolution required

Sentinel-2/MSI (20 m)
Vilaine Bay, 21 June 2019

Too coarse spatial resolution

→ *bloom "diluted" with non-bloom pixels*

→ *optical fingerprint is not "pure"*

Sentinel-3/OLCI (300 m)
Vilaine Bay, 21 June 2019

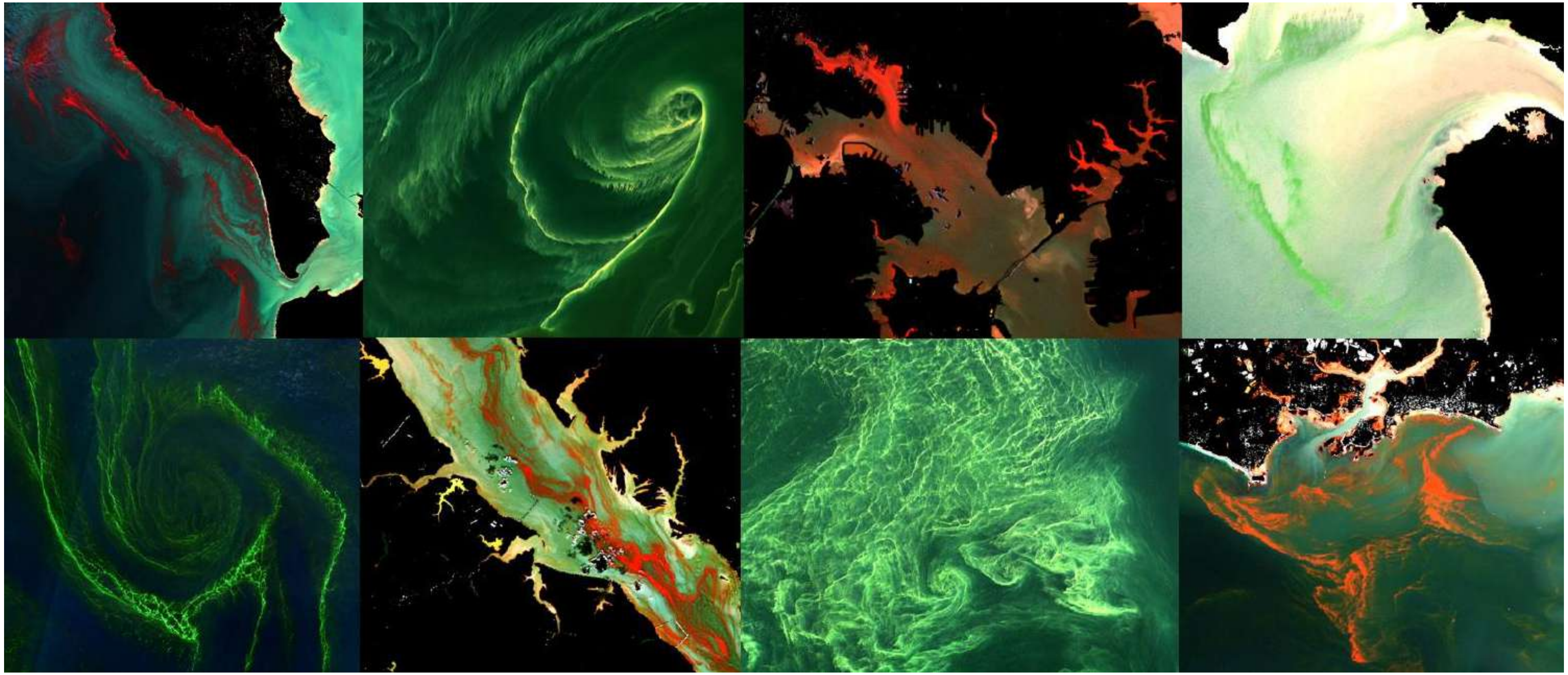
- ✓ Sentinel-2
- ✓ Landsat-8/9
- ✓ PRISMA
- ✓ EnMAP

- × Sentinel-3
- × MODIS
- × VIIRS
- × PACE

Identification of dominant species from space?

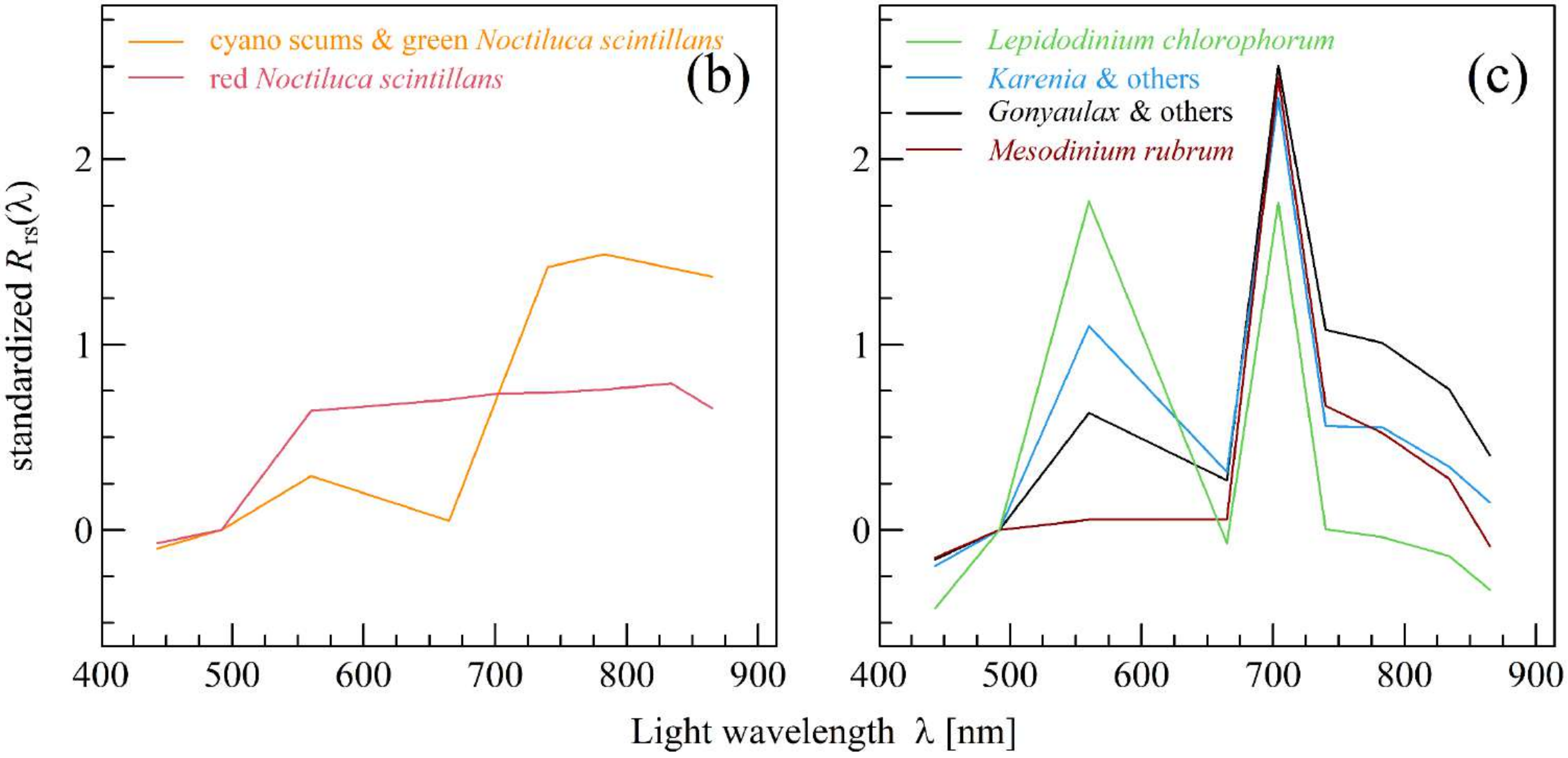
Inferring phytoplankton taxonomy is generally not possible or extremely challenging

Red tides are **exceptional cases** where it might be feasible



Examples of Sentinel-2 red tides (Gernez et al., 2023)

Optical Bloom Types with Sentinel-2



Gernez, P., Zoffoli, M. L., Lacour, T., Fariñas, T. H., Navarro, G., Caballero, I., & Harmel, T. (2023). The many shades of red tides: Sentinel-2 optical types of highly-concentrated harmful algal blooms. Remote Sensing of Environment, 287, 113486.

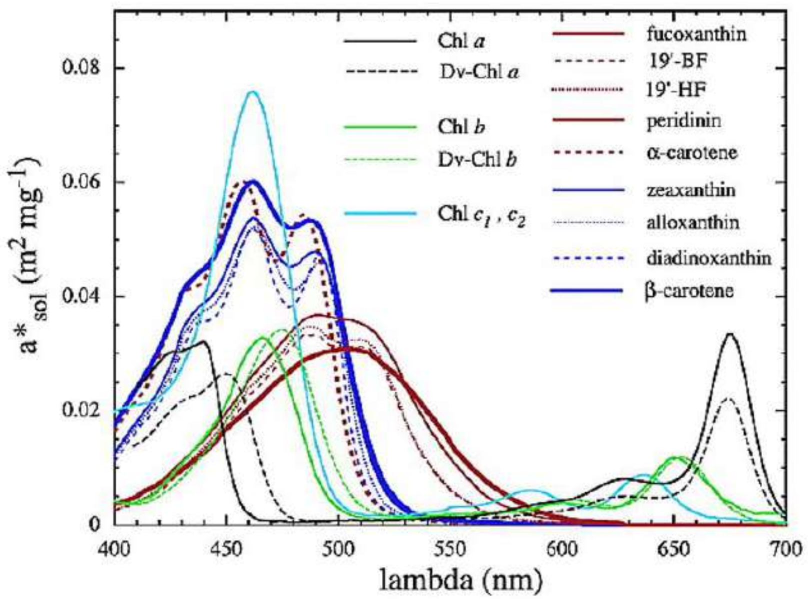
Importance of spectral resolution

Higher spectral res = higher ability to discriminate absorption bands of "marker pigments"

i.e. contrary to PRISMA, S2/MSI lacks spectral bands at :

620 nm to detect Phycocyanin (Cyanobacteria)

650 nm to detect Chlorophyll-b (Green algae)



Bricaud et al., (2004)

Several "marker pigments" are not optically discriminant

i.e. Zeaxanthin, Alloxanthin, β-carotene: very similar $a_{pig}(\lambda)$

Several "marker pigments" are not taxonomically discriminant

i.e. Fucoxanthin (diatoms) also present in pelagophytes,

raphidophytes and some dinoflagellates (such as *Karenia* sp.)

Objectives and approaches

Previous works were empirical and/or limited in terms of spectral resolution and taxonomic diversity.

Optical properties of bloom-forming microalgae and cyanobacteria species still poorly documented.

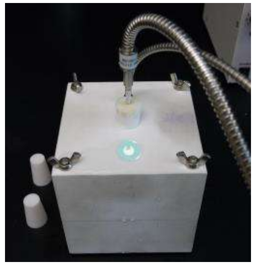
269 known harmful species

Optical properties?

Can we identify it from space?

We performed a **detailed characterization of the inherent optical properties** of HABs species, in order to develop an improved understanding of their optical variability and assess the degree of taxonomic resolution amenable from hyperspectral satellite remote sensing during a red tide

Hyperspectral absorption of bloom-forming species



PSICAM: Point-Source Integrating Cavity Absorption Meter

Monospecific algal cultures

Compiling **Xi et al., (2015)**, *Lomas et al., (2024)* **+ new data**

Particulate absorption coef. $a_p(\lambda)$ measured using *filter pads* or **cells suspension (PSICAM)**

164 hyperspectral $a_p(\lambda)$ spectra

8 taxonomic classes

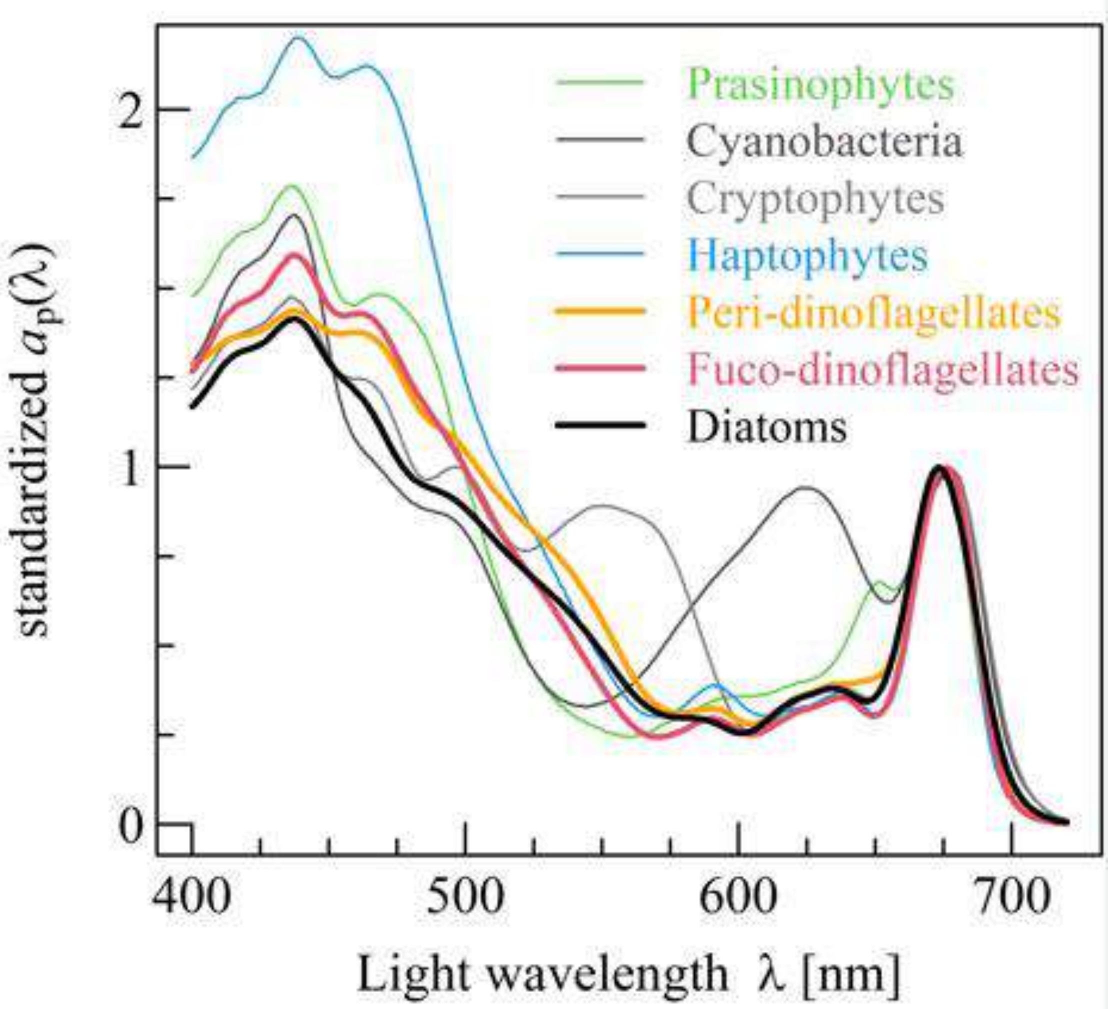
60 HAB species

Processing of $a_p(\lambda)$ spectra

9-nm moving average, 2nd derivative, classification using Similarity Index & HCA

Absorption diversity: 7 clusters at class level

Class-averaged absorption of 7 optical clusters



Prasinophytes

Cyanobacteria

Cryptophytes

Easy due to unique pigments and absorption signature

Haptophytes

Peridinin-bearing dinoflagellates

Fucoxanthin-bearing dinoflagellates

Diatoms and/or raphidophytes

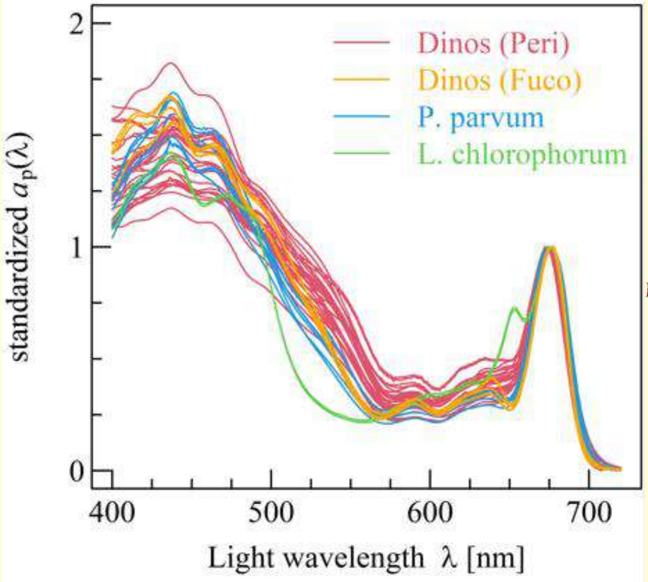
more challenging (next slide)

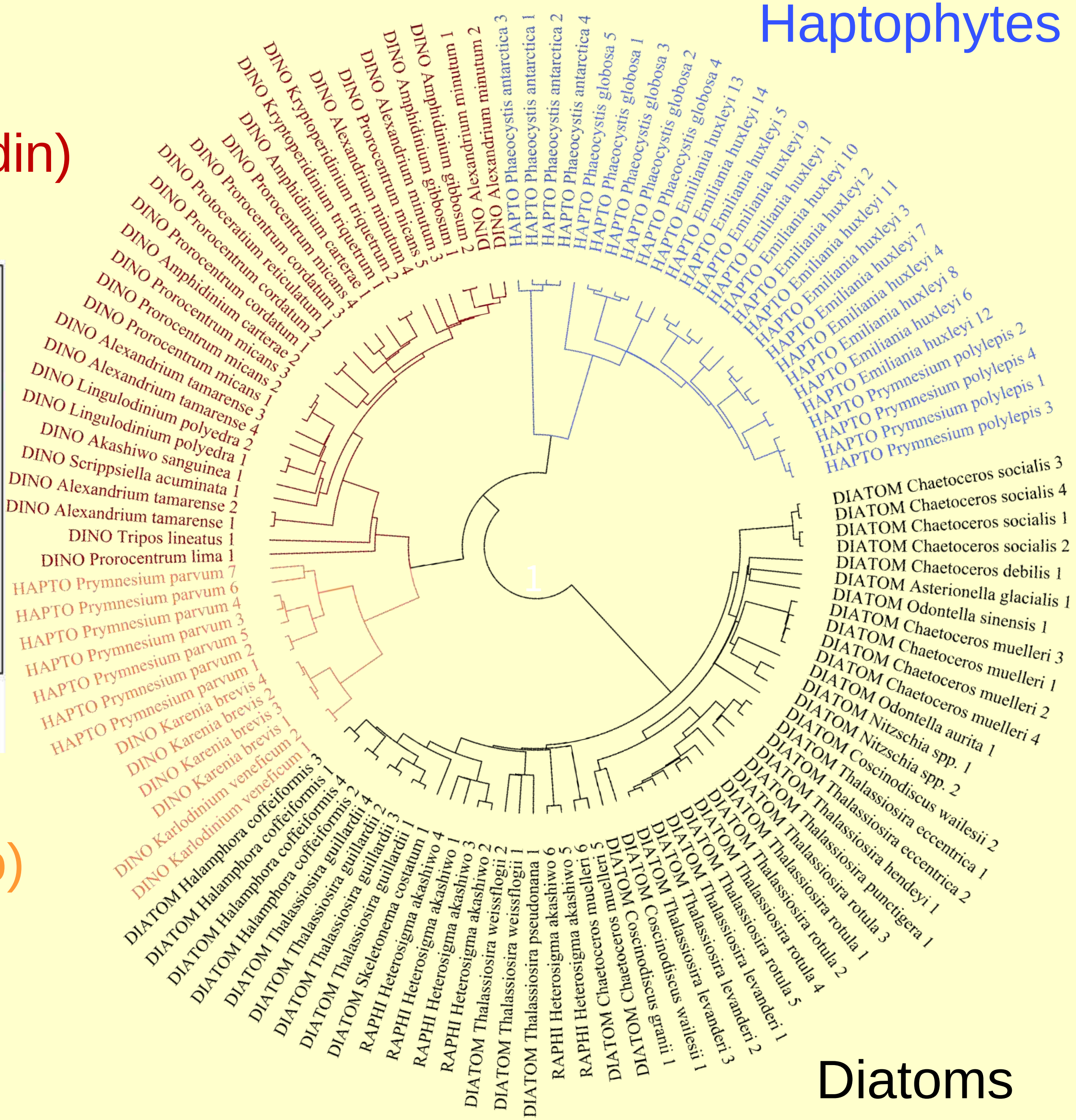
Dinoflagellates (Peridin)

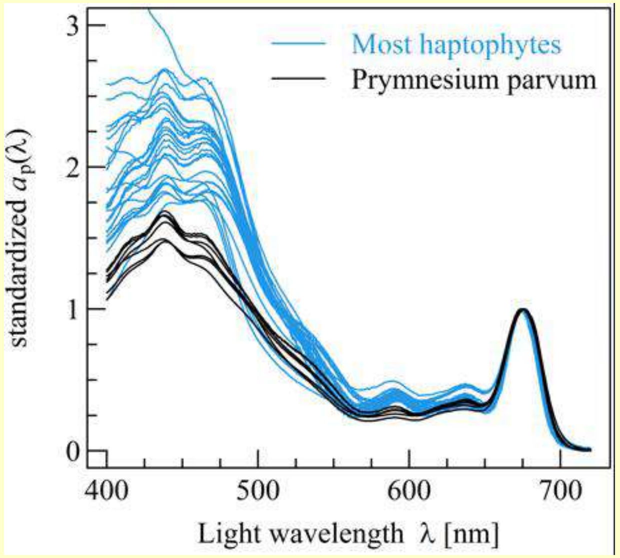
Dinoflagellates (Fuco)

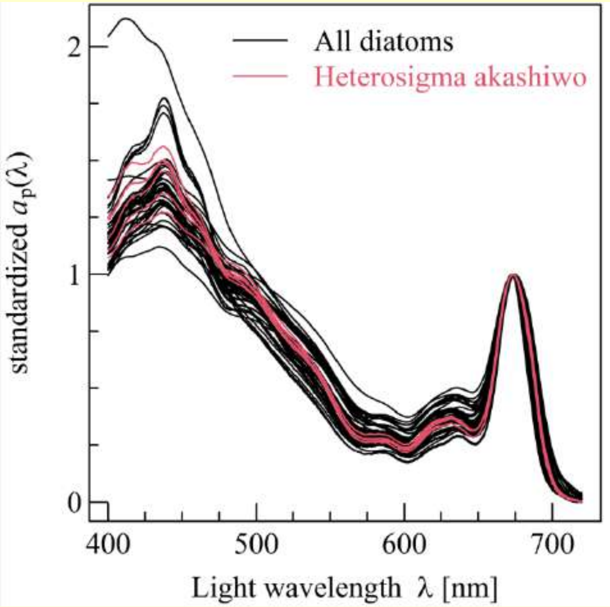
Haptophytes

Diatoms



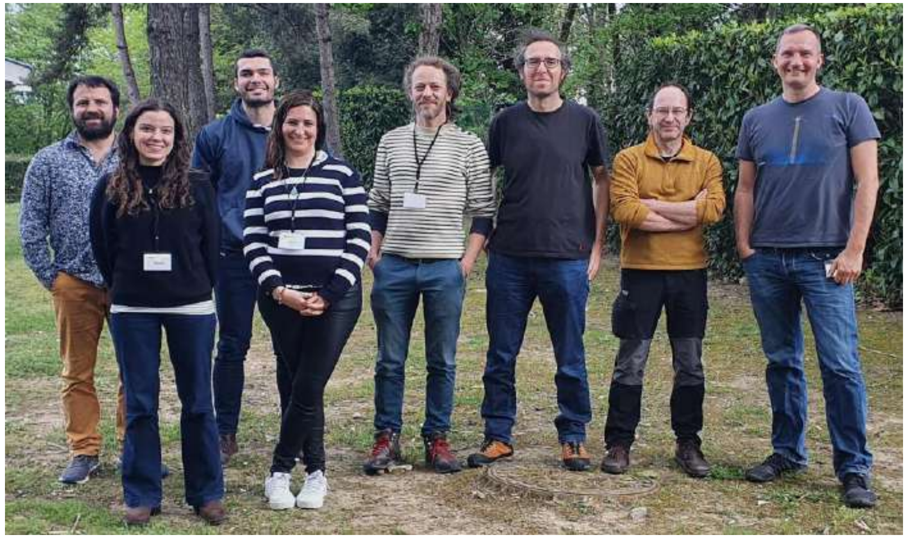






Scattering coef. of phytoplankton cultures

HABLAB: full characterization of phytoplankton scattering using advanced instruments



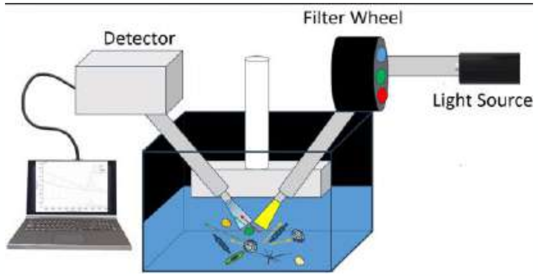
Attenuation $c_p(\lambda)$ and scattering $b_p(\lambda)$ coefficients (ac-s)

Angular scattering at 515 nm $\beta_p(\theta)$

Hyperspectral backscattering coefficient $b_{bp}(\lambda)$

LISST-VSF: directional scattering at 515 nm (phase function + polarization terms)

SEQUOIA



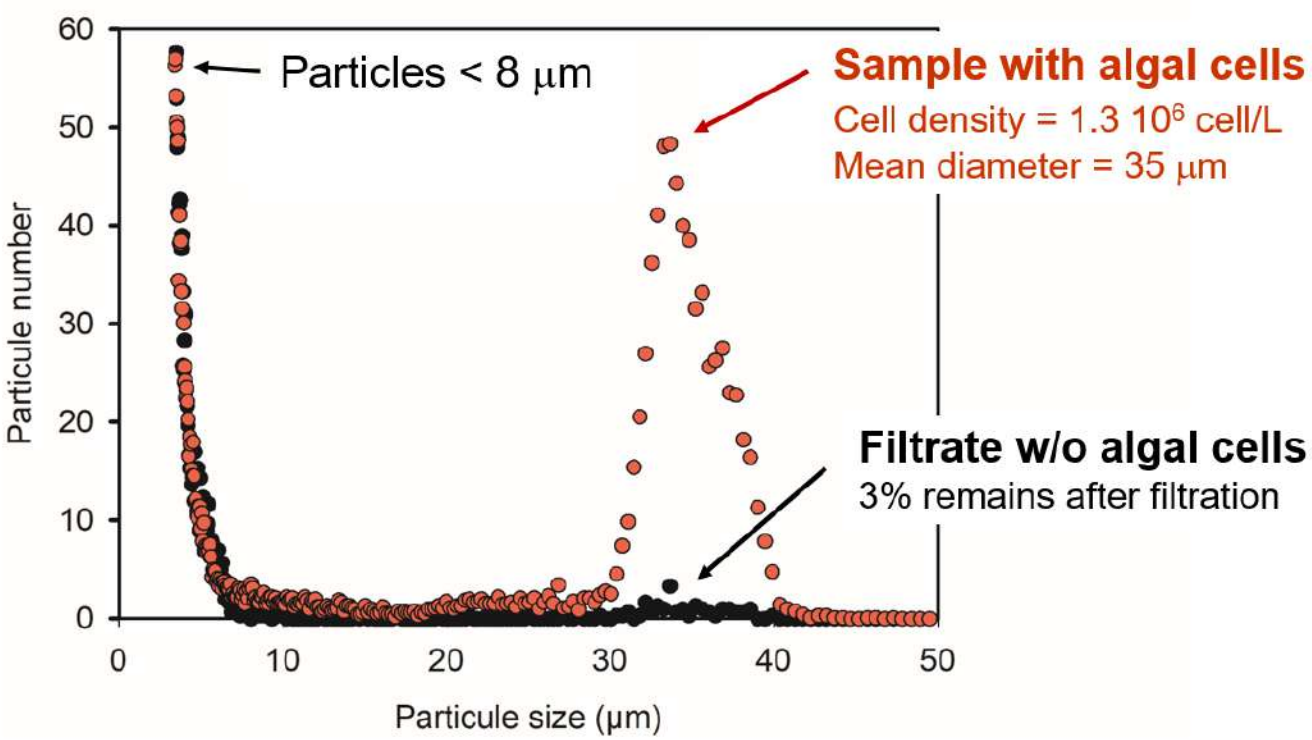
Hyfi-bb: hyperspectral backscattering through mono-directional VSF measurement (*Novak et. al, 2024*)

https://doi.org/10.1364/OE.529061

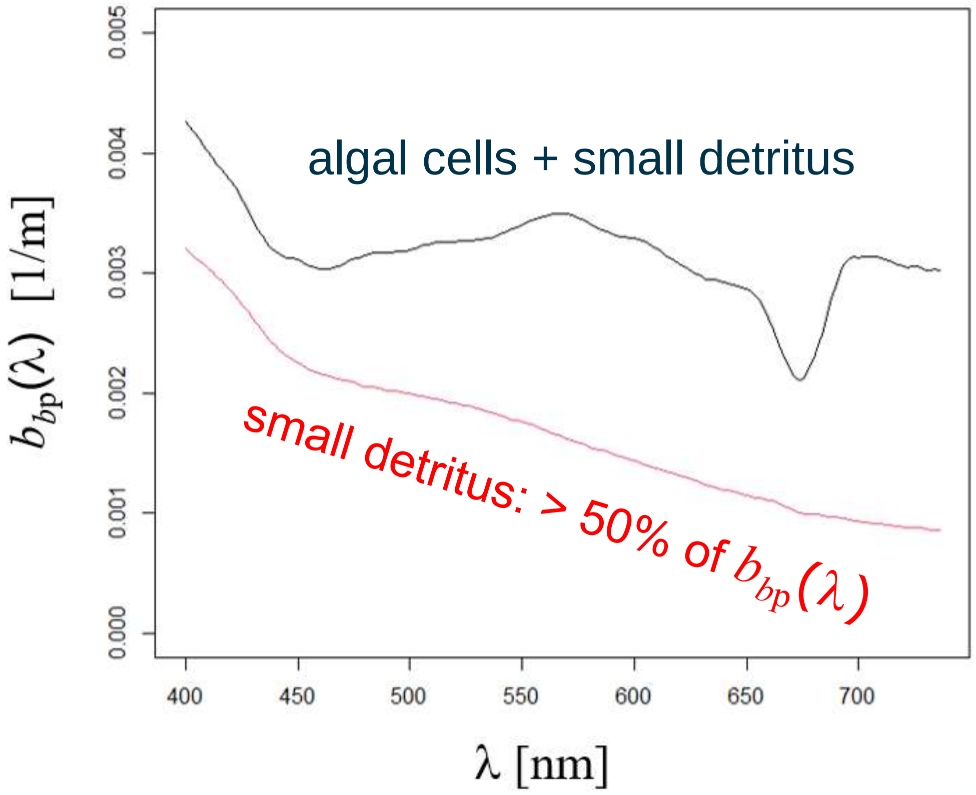
Removing detrital particles

Removing small detritus using nucleopore filters

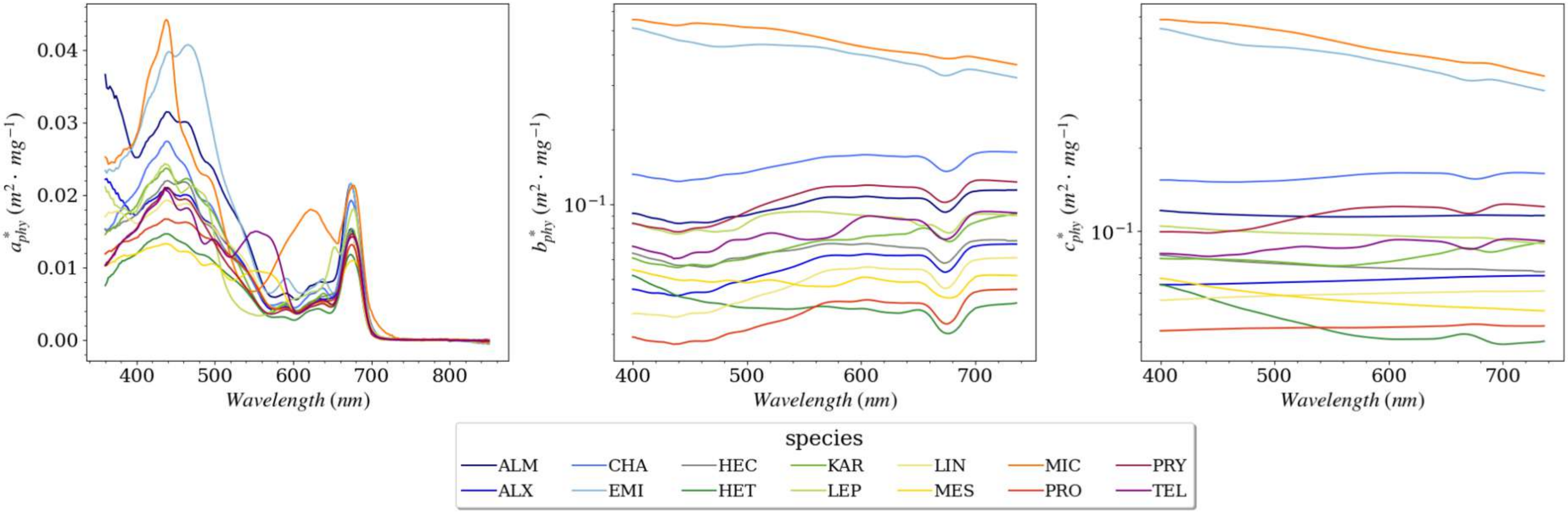
Required to measure microalgae scattering without bias



Coulter counter measurements



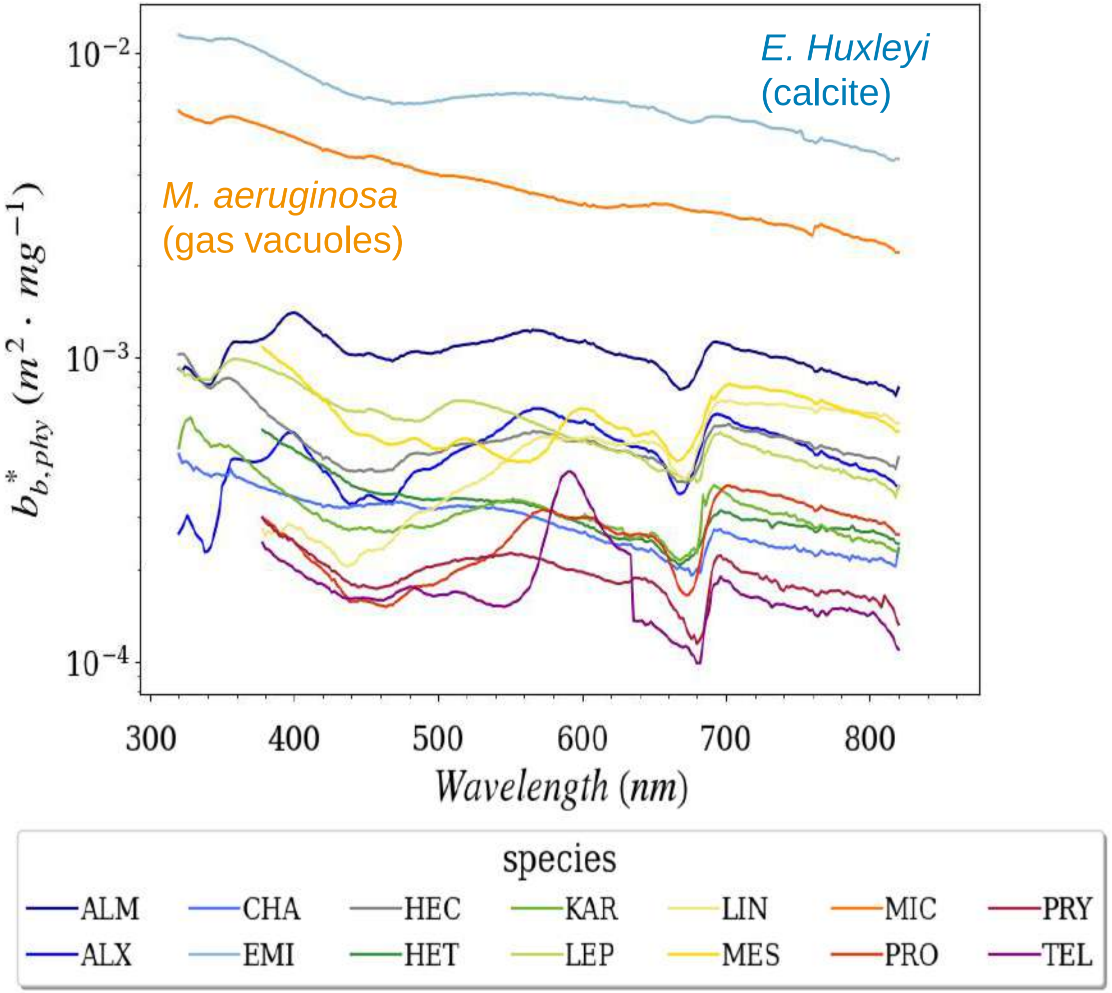
HABLAB results



ALM & ALX = *Alexandrium minutum*, CHA = *Chaetoceros muelleri*, HEC = *Heterocapsa triquetra*, KAR = *Karlodinium veneficum*, LIN = *Lingulaulax polyedra*, MIC = *Microcystis aeruginosa*, PRY = *Prymnesium parvum*, EMI = *Emiliania huxleyi*, HET = *Heterosigma akashiwo*, LEP = *Lepidodinium chlorophorum*, MES = *Mesodinium rubrum*, PRO = *Prorocentrum micans*, TEL = *Teleaulax amphioxeia*

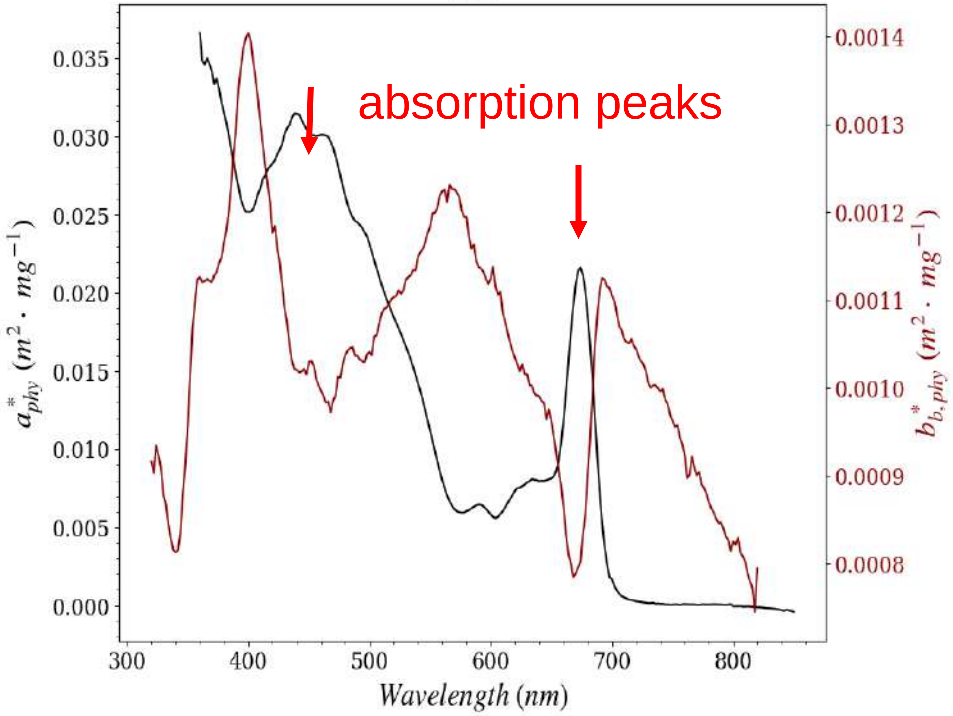
Phytoplankton backscattering coefficient

2 orders of magnitude !



High spectral variability due to anomalous dispersion

Alexandrium minutum



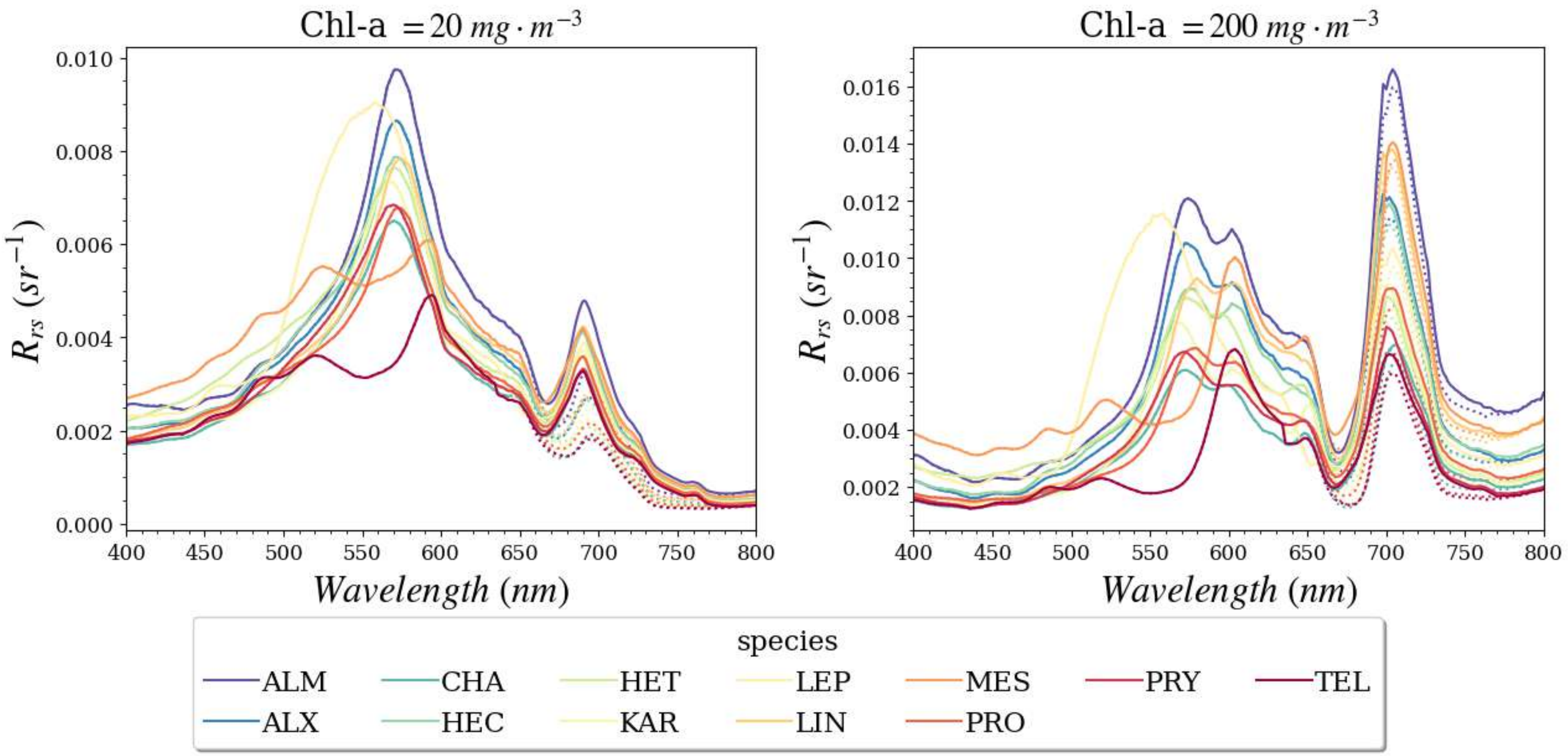
Radiative transfer simulations

RT model from Harmel et al., (in prep.)

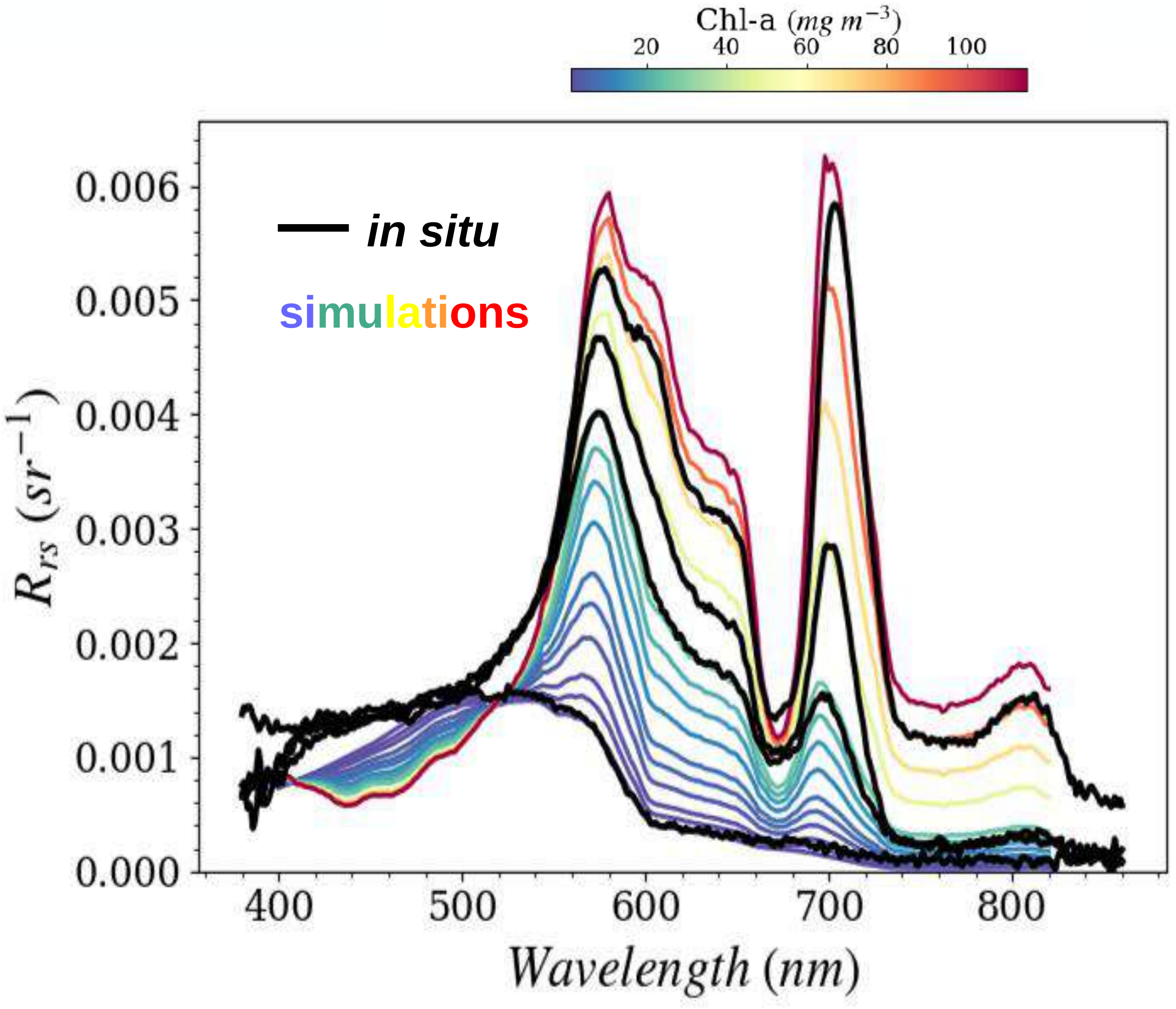
$$R_{rs}(\lambda,\theta_s,\theta_v,\Delta\phi) = f\left(\frac{b_b(\lambda)}{a(\lambda)},\theta_s,\theta_v,\Delta\phi\right)$$

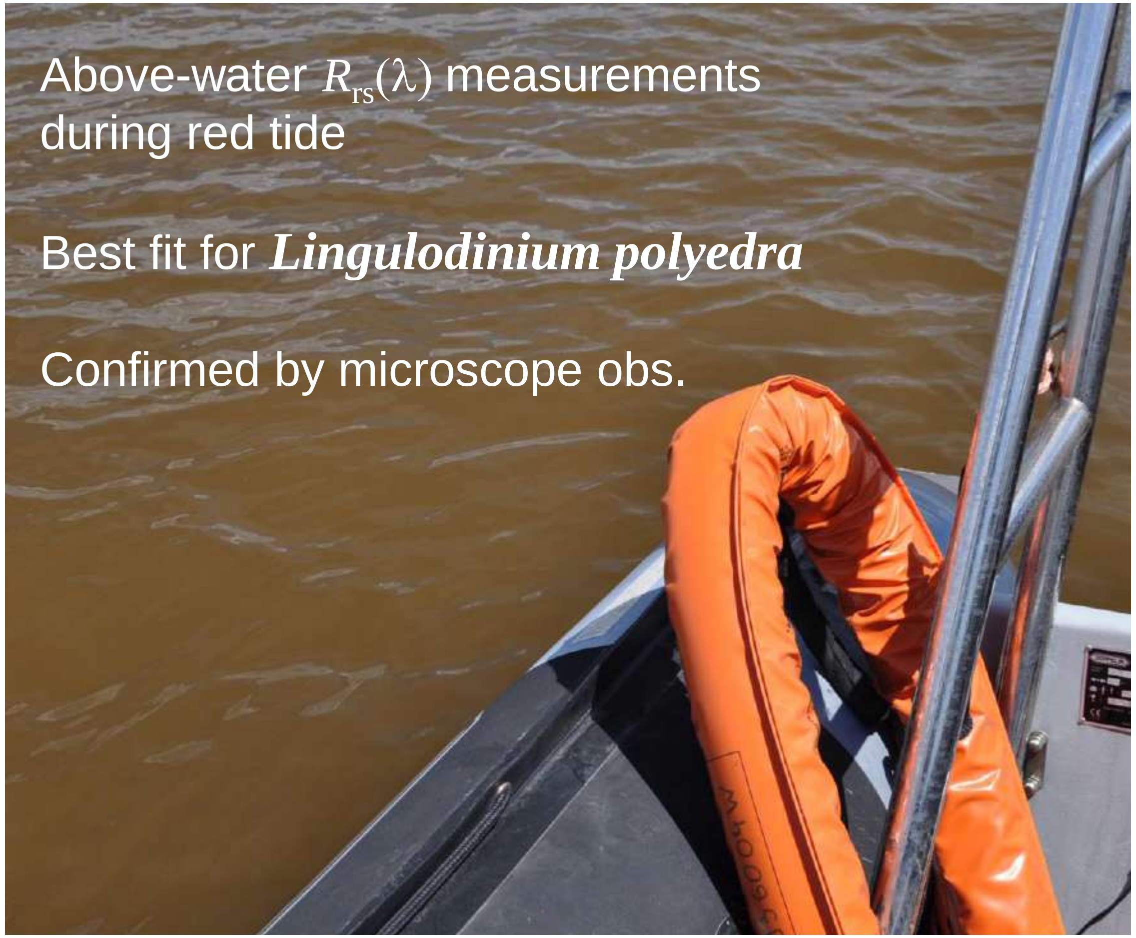
IOP model parameterized using lab data

$$\begin{cases} a(\lambda) = a_w(\lambda) + a_{cdom}(\lambda) + [\text{Chl-a}]\, \mathbf{a^*_{phy}(\lambda)} + a_{others}(\lambda) \\ b_b(\lambda) = b_{b,w}(\lambda) + [\text{Chl-a}]\, \mathbf{b^*_{b,phy}(\lambda)} + b_{b,others}(\lambda) \end{cases}$$



Applications to HAB monitoring: *in situ* $R_{rs}(\lambda)$





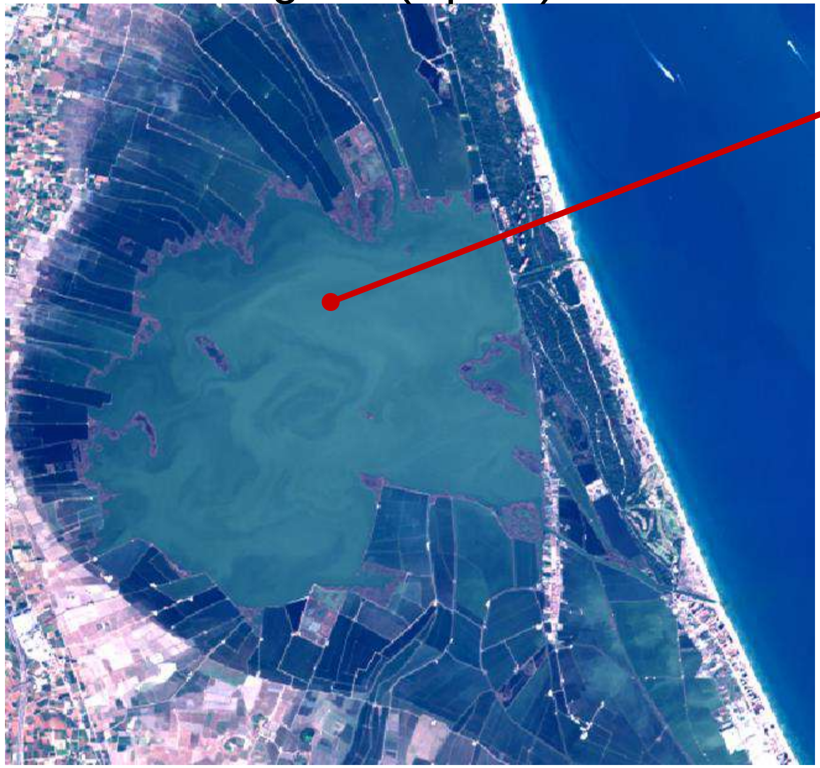
Above-water $R_{rs}(\lambda)$ measurements during red tide

Best fit for ***Lingulodinium polyedra***

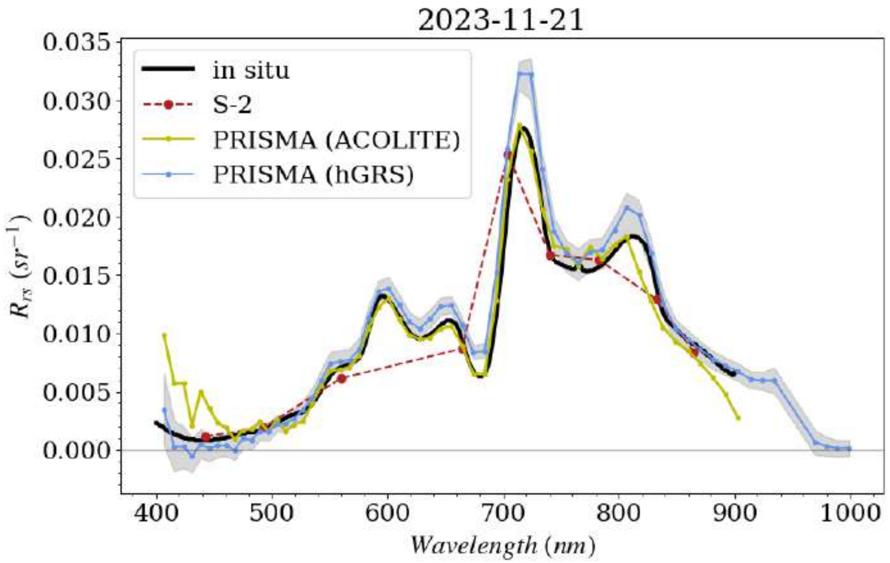
Confirmed by microscope obs.

Application to PRISMA

Albufera lagoon (Spain)



Bloom dominated by tiny reddish bacteria (likely *Raphidiopsis* or *Leptolyngbya*)

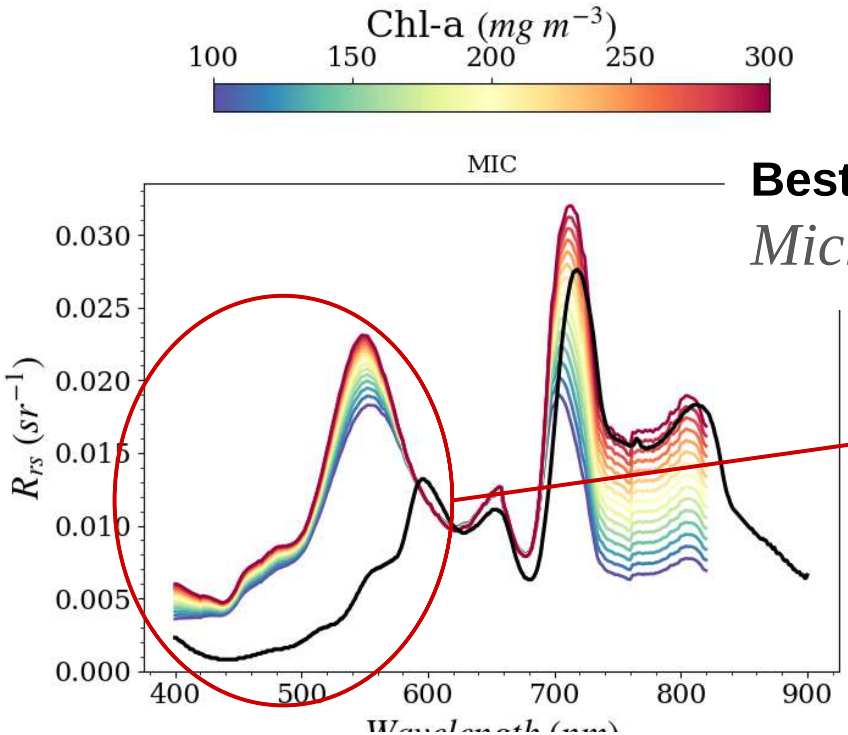


In situ data from
Antonio Ruiz Verdú et al.

Chl-*a*: 230.0 µg/l

CDOM (a_400): 2.78 m^{-1}

SPM : 28.57 mg/L



Best fit with cyanobacteria
Microcystis aeruginosa

discrepancies in blue-green

Need to expand IOPs dataset with more cyanobacteria species

Conclusions

Detailed characterization of phytoplankton IOPs for bloom-forming species

Laboratory measurements of volume scattering function, absorption and backscattering coefficients

Lab data used to feed forward & inverse RT model

Preliminary application to HAB monitoring using in situ and PRISMA

Next steps

Expand IOP database to include more cyanobacteria (currently just 1 species)

How many Optical Bloom Types could be identified using hyperspectral satellites?

Apply approach to HAB monitoring and phytoplankton bloom studies

Thank you !

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