

Polarization signatures of nano- and micro-plastics suspended in the water column simulated at the water surface and top-of-atmosphere levels

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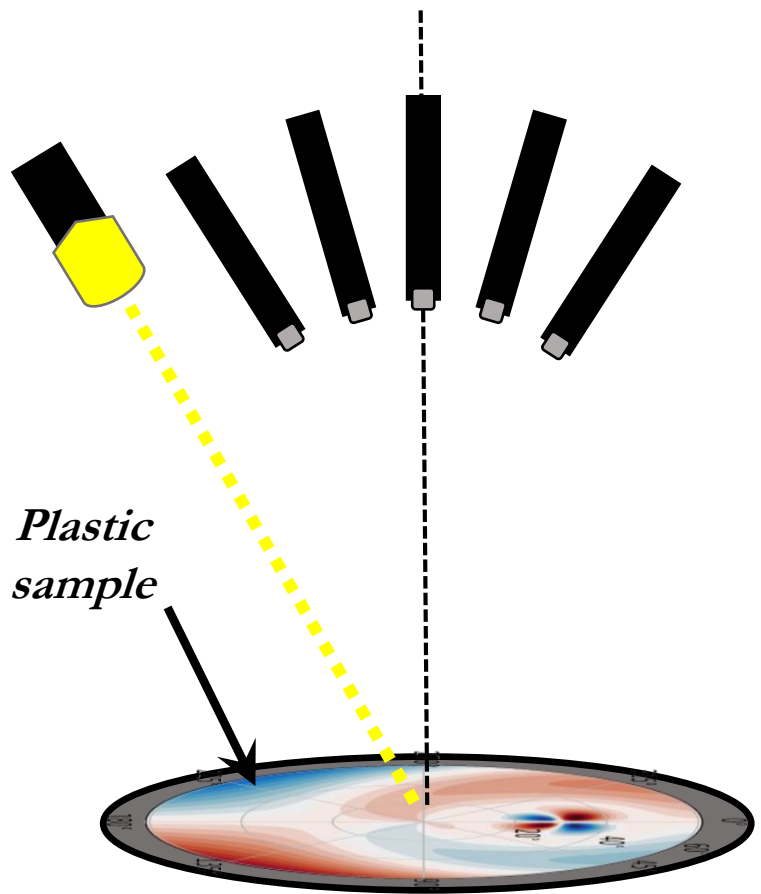


Paolo Corradi

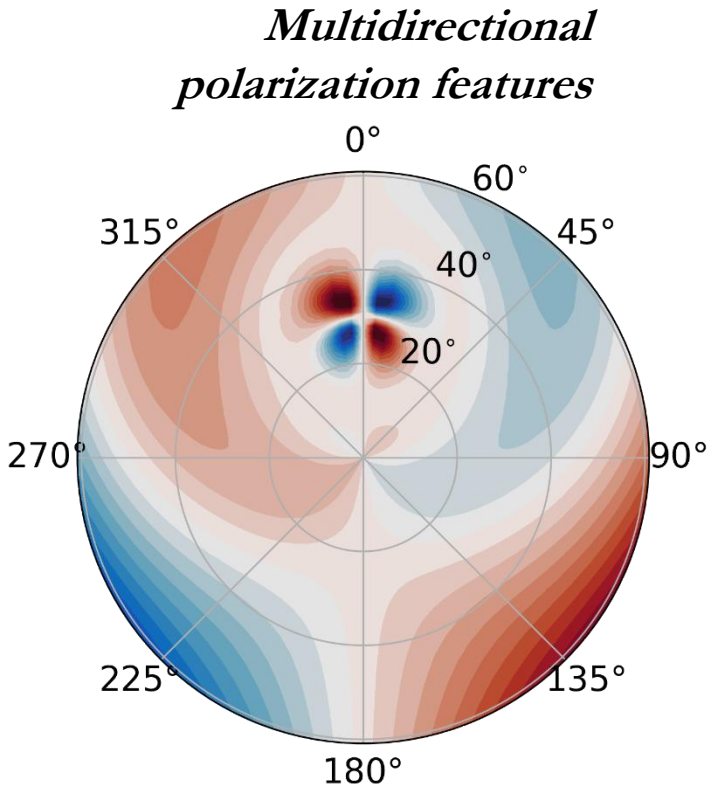




Ocean Plastics Polarization Properties OP³



Lab Experiment



Theoretical Modeling

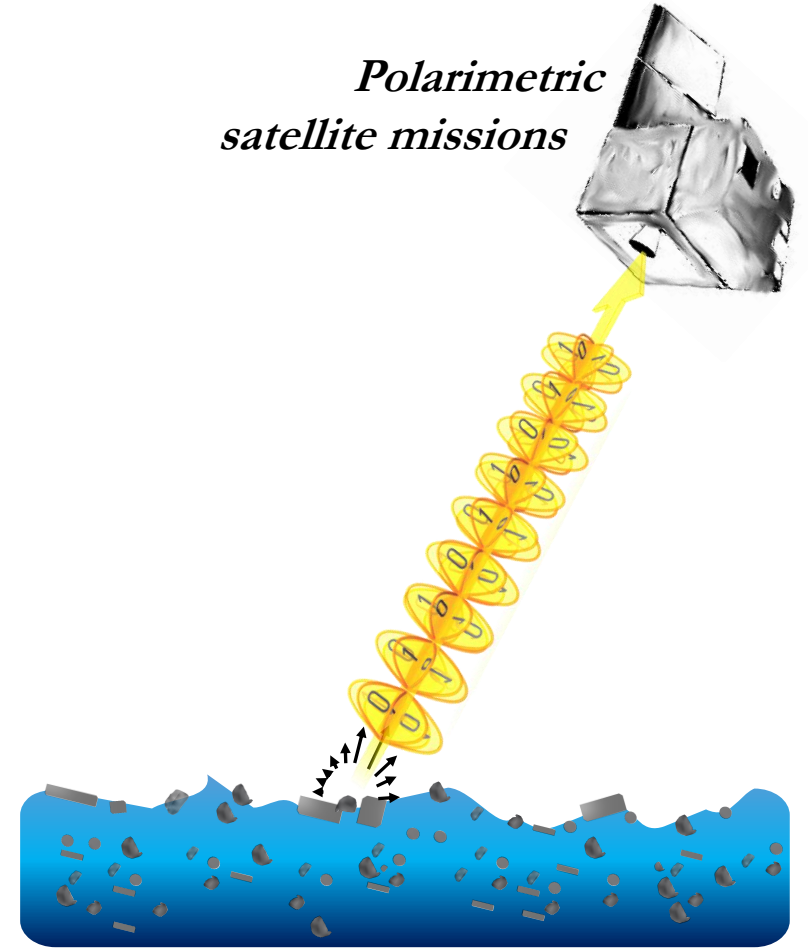
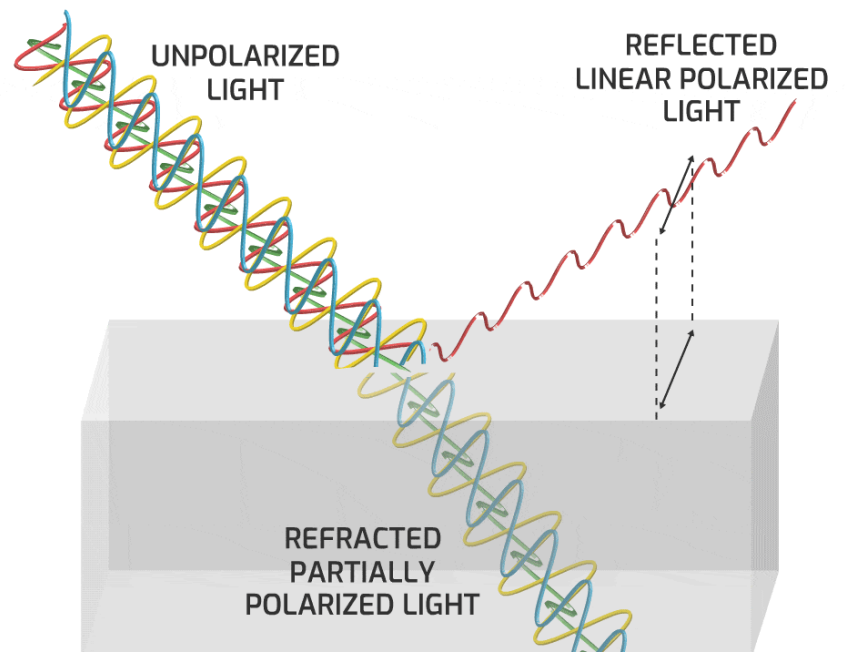
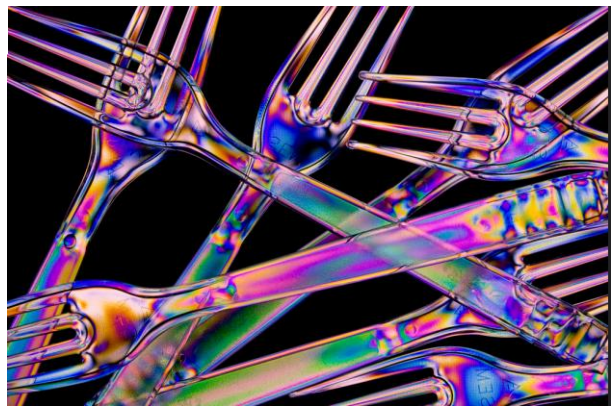
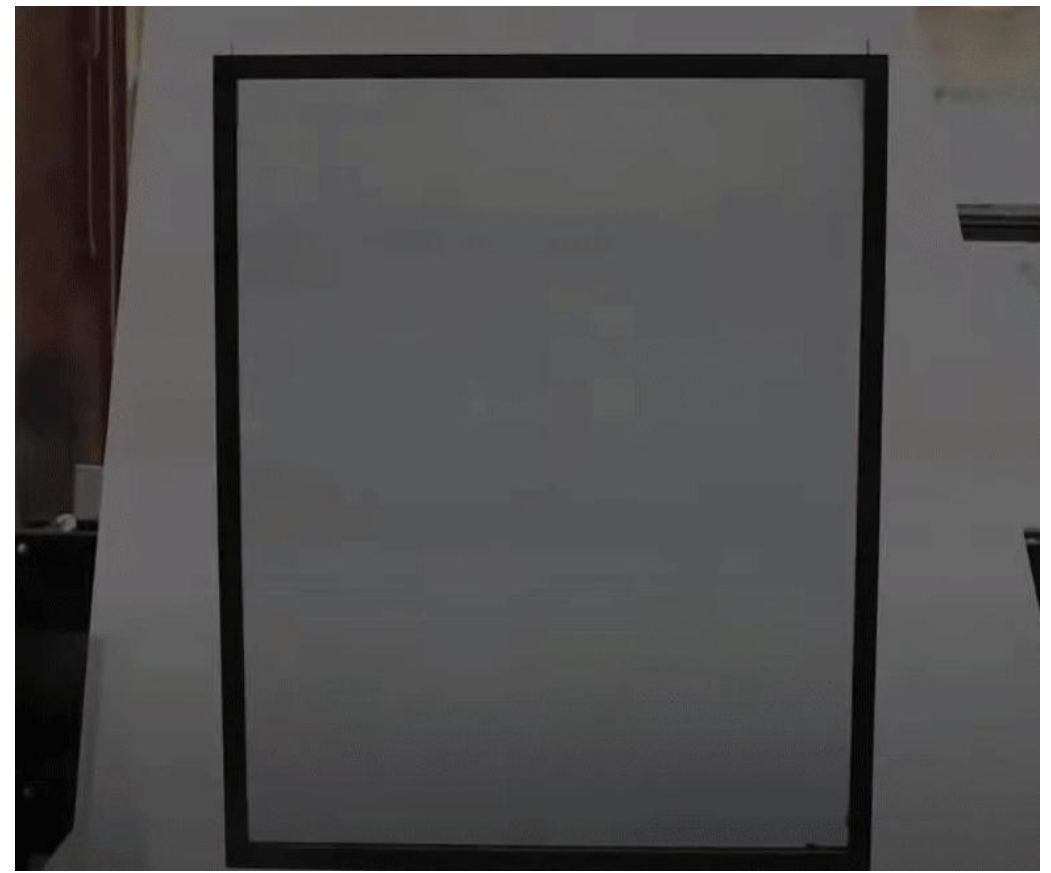


Image Interpretation

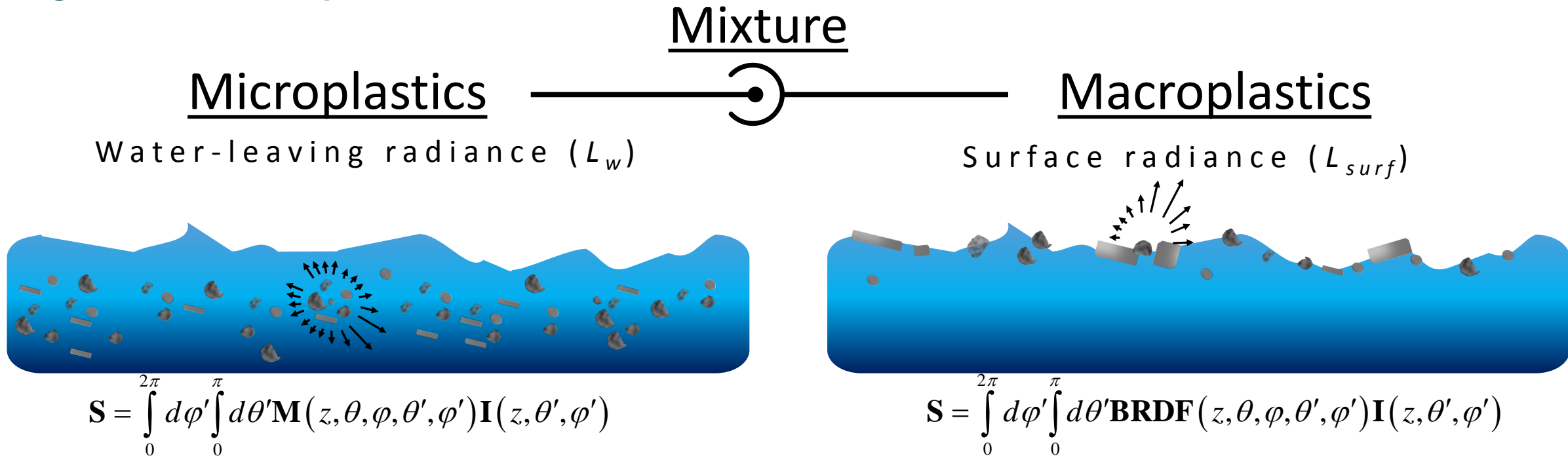
Why Polarization?



From <https://thinklucid.com/>



Posing the radiometric problem



Need to document angularly and spectrally:

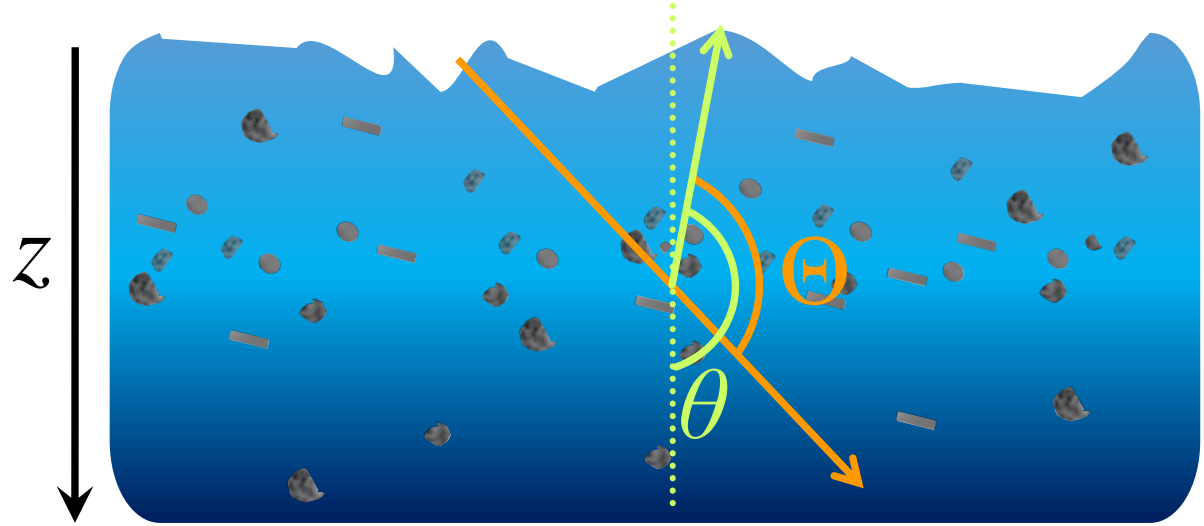
Scattering matrix **M**

Reflection matrix **BRDF**

→ Forward model → Remote sensing exploitation

Posing the radiometric problem

Radiative Transfer Equation* (RTE)



$$\cos \theta \frac{dI(z, \theta)}{dz} = -c(z)I(z, \theta) + \int_0^\pi VSF(z, \Theta)I(z, \Theta) \sin \Theta d\Theta$$

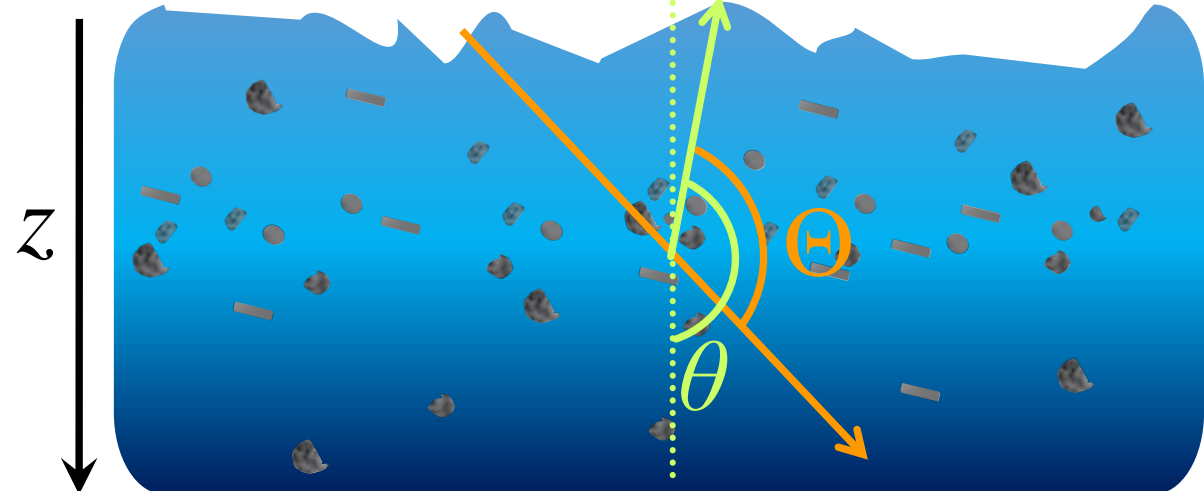
$$c = a + b$$

\uparrow \uparrow
 absorption + scattering $b = 2\pi \int_0^\pi VSF(\Theta) \sin \Theta d\Theta$

*simplified

Posing the radiometric problem

Vector Radiative Transfer Equation* (VRTE:
with polarization)



$$\cos \theta \frac{d\mathbf{I}(z, \theta)}{dz} = -c(z)\mathbf{I}(z, \theta) + \int_0^\pi \mathbf{M}(z, \Theta)\mathbf{I}(z, \Theta)\sin \Theta d\Theta$$

$$\cos \theta \frac{d\mathbf{I}(z, \theta)}{dz} = -c(z)\mathbf{I}(z, \theta) + \mathbf{S}$$

Source function to be documented

Stokes Vector

$$\mathbf{I} = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

Mueller Matrix

$$\mathbf{M} = \begin{pmatrix} m_{11} & \dots & m_{14} \\ \vdots & \ddots & \vdots \\ m_{41} & \dots & m_{44} \end{pmatrix}$$

*simplified

Ocean Plastics Polarization Properties **OP³**

FLIR camera



Degree of Linear Polarization

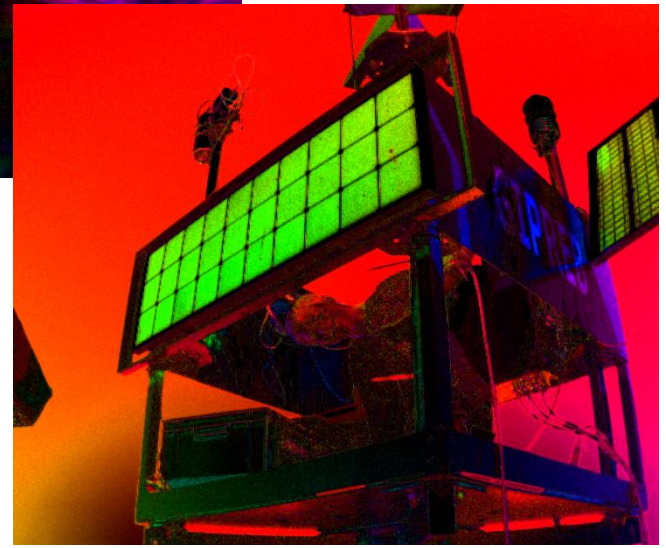
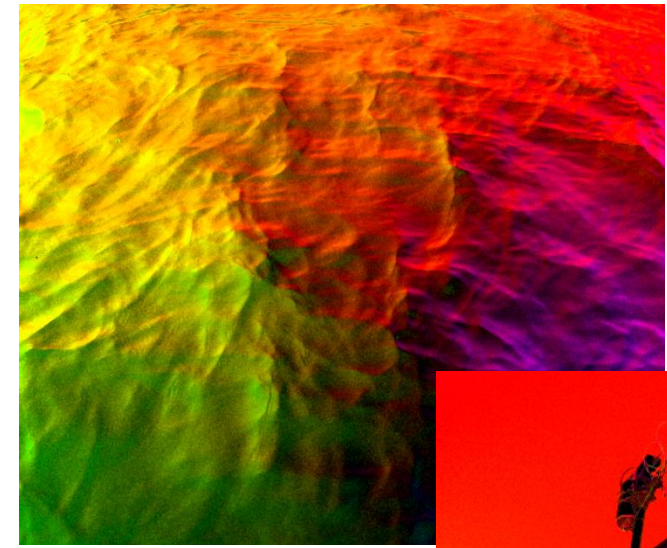
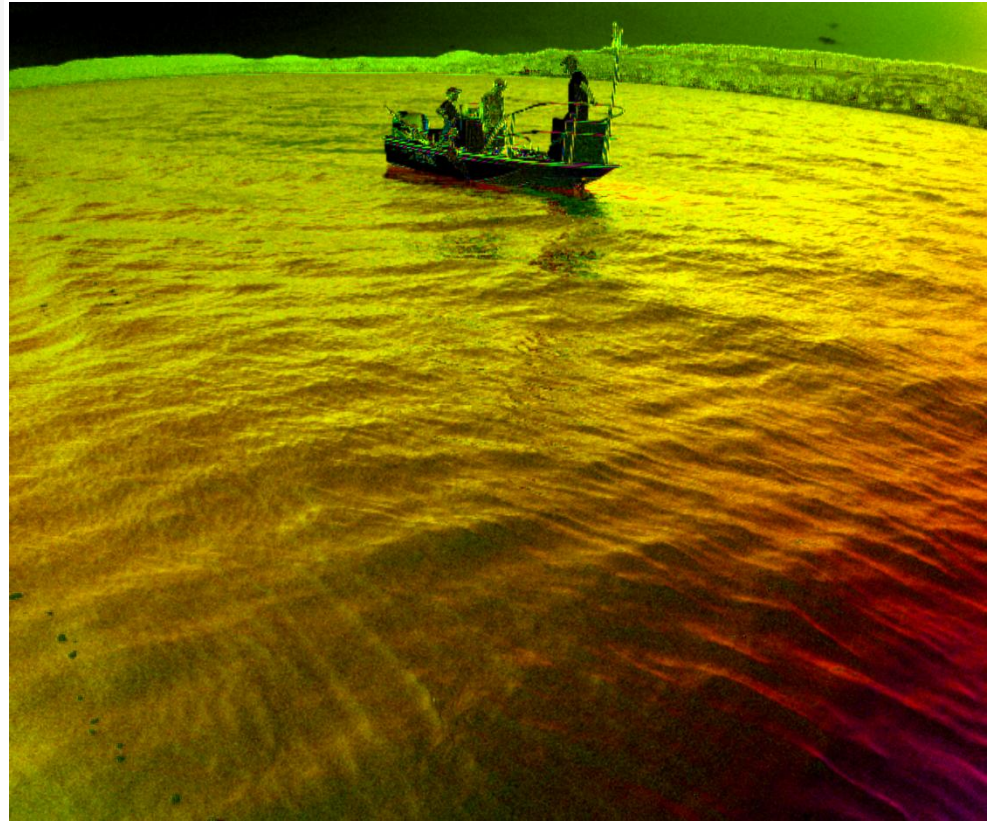
Brightness

$$DoLP = \frac{\sqrt{Q^2 + U^2}}{I}$$

Angle of Linear Polarization

Hue

$$AoLP = \frac{1}{2} \arctan\left(-\frac{U}{Q}\right)$$



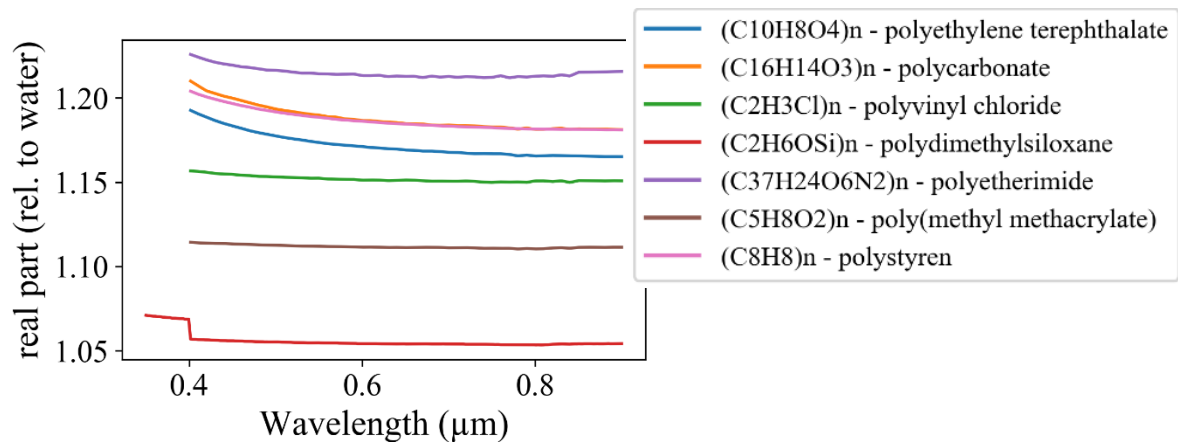
Field Campaign (PIs: Doxaran, Harmel, Gernez, Tormos)
Lake Berre (France), HYPERNETS station



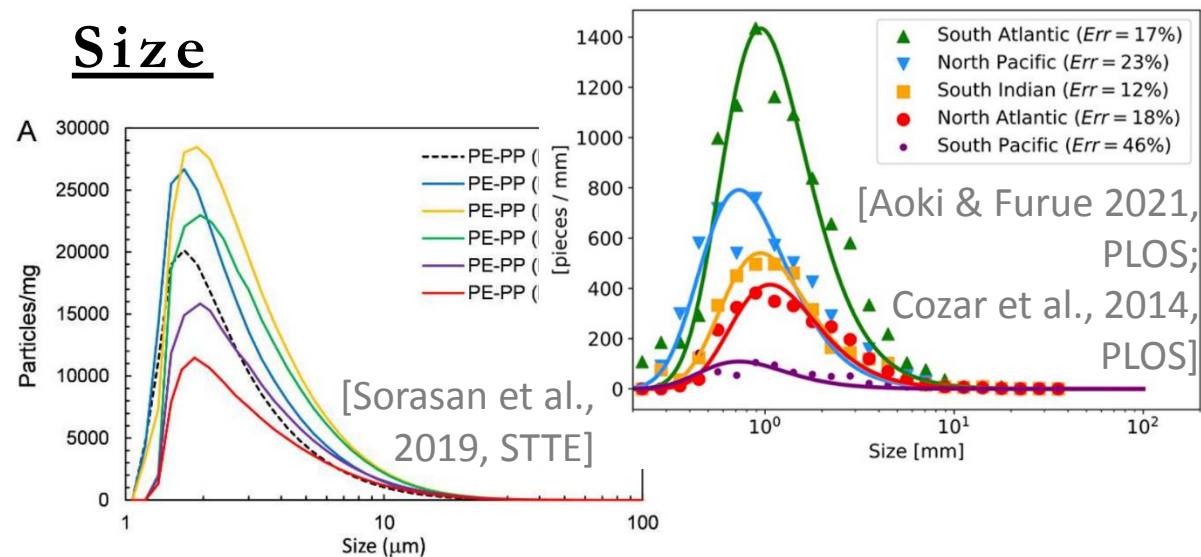
Ocean Plastics Polarization Properties OP^3

~plastic optical properties... What matters?

Refractive index

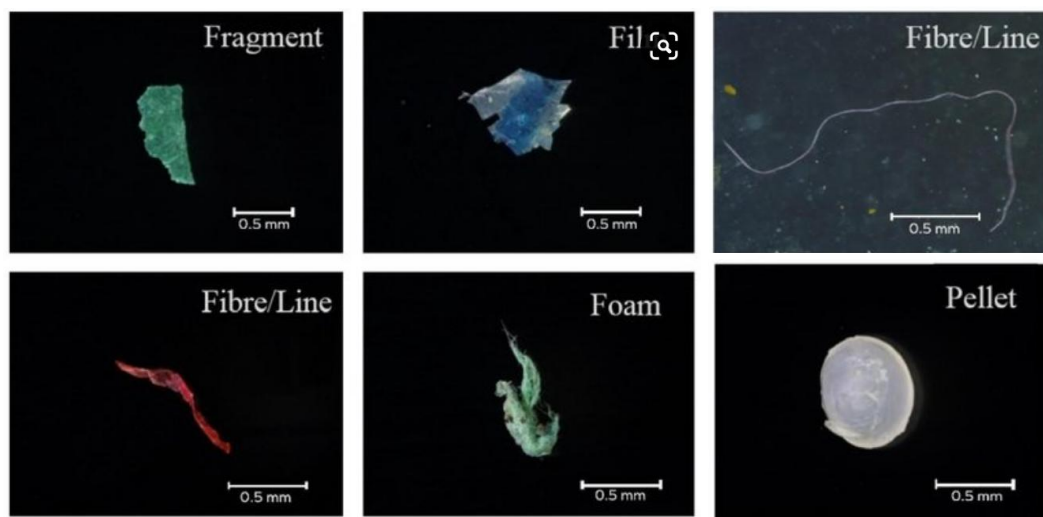


Size

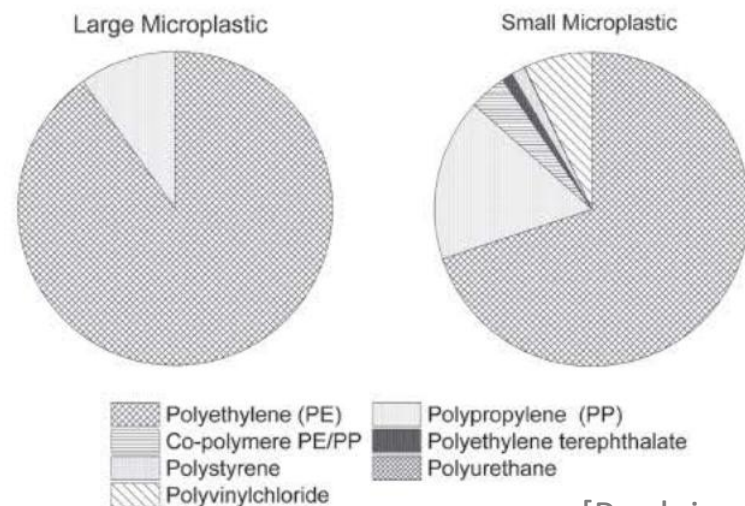


Shape

(from Robin et al., 2019, STTE)



Composition/mixture

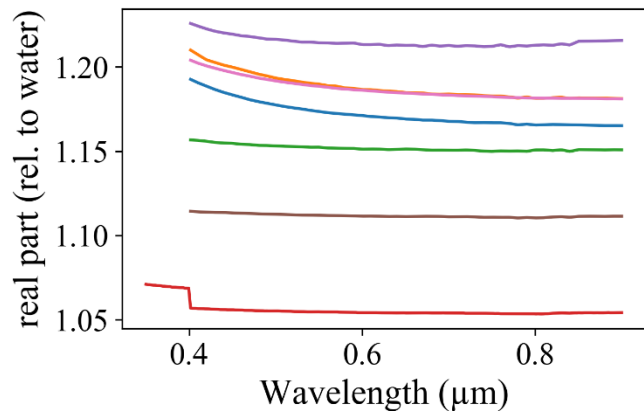


[Poulain et al., 2019, EST]

Ocean Plastics Polarization Properties **OP³**

~plastic optical properties... Assumptions

Refractive index



All the refractive indices
from 1.05 to 1.22
But imaginary part = 0
(i.e., no absorption)

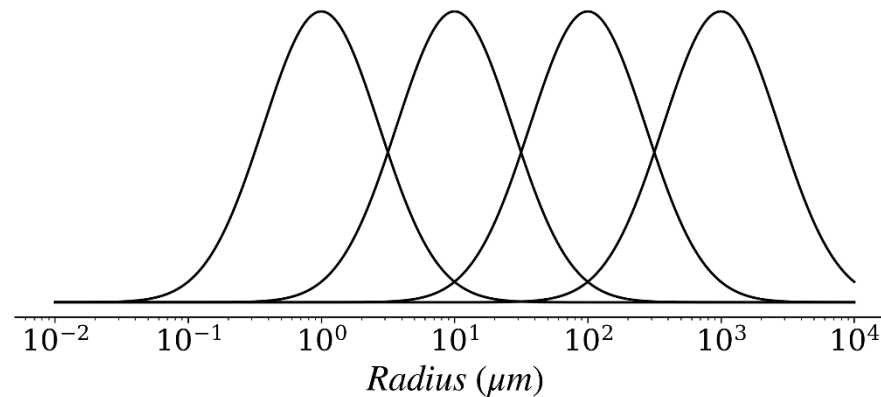
Shape

Homogeneous spheres



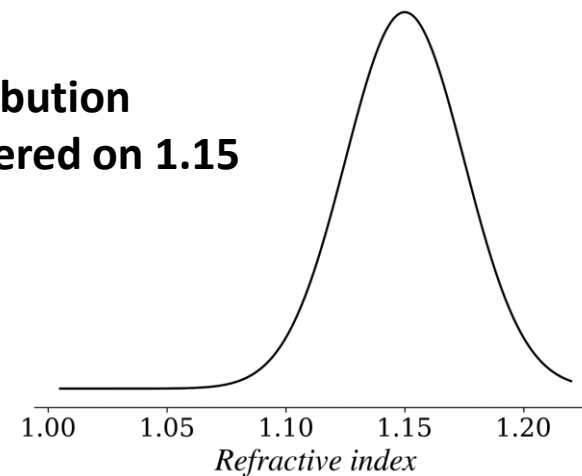
Size

Four lognormal distribution centered on :
1 μ m, 10 μ m, 100 μ m, 1mm

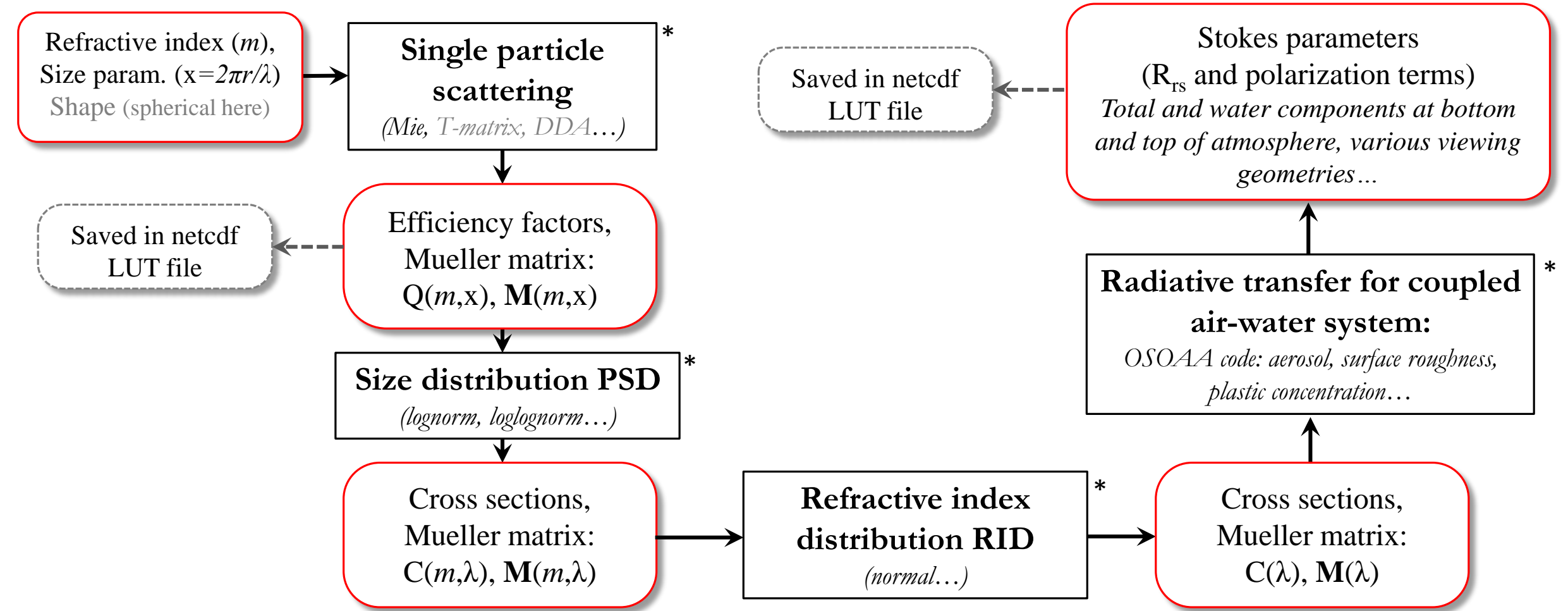


Composition / mixture

Via refractive index distribution
Normal distribution centered on 1.15



Ocean Plastics Polarization Properties **OP³**



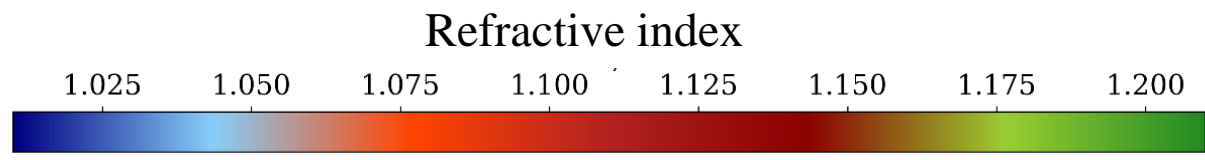
*All the computations were performed in *multiproc* mode (Number of CPU = 40)

Ocean Plastics Polarization Properties **OP³**



Refractive index:
 1.005:0.005:1.220,
 Size param.($x=2\pi r/\lambda$):
 0.1:40000

Single particle
 scattering



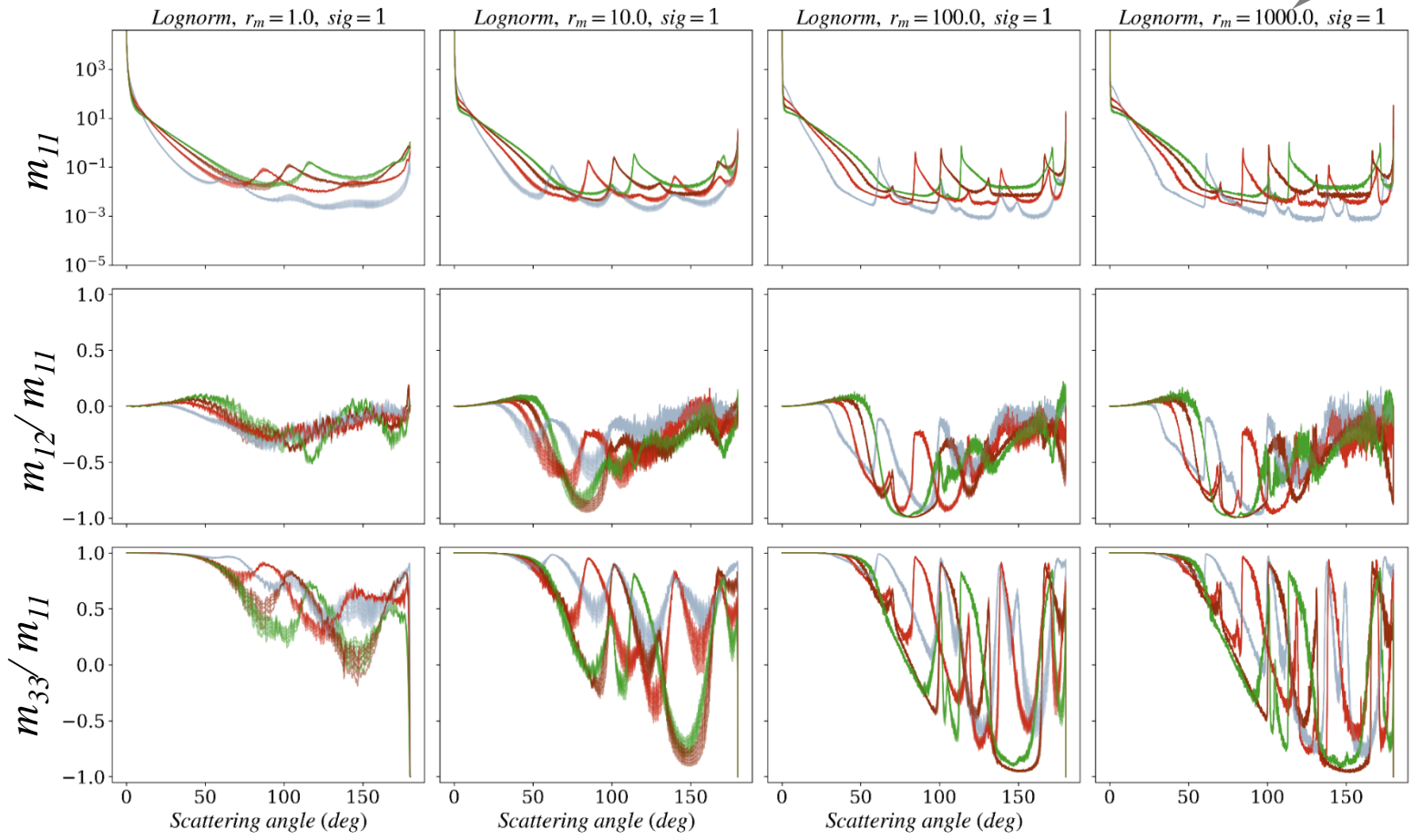
Increasing size from 1 μm to 1 mm (median radius)

Saved in netcdf
 LUT file

Mueller Matrix

$$\mathbf{M} = \begin{pmatrix} m_{11} & \dots & m_{14} \\ \vdots & \ddots & \vdots \\ m_{41} & \dots & m_{44} \end{pmatrix}$$

Useful terms: m_{11} , m_{12} , m_{33}

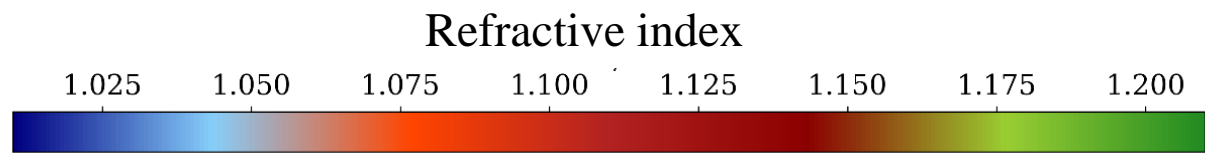


Ocean Plastics Polarization Properties **OP³**



Refractive index:
 1.005:0.005:1.220,
 Size param. ($x=2\pi r/\lambda$):
 0.1:40000

Single particle
 scattering



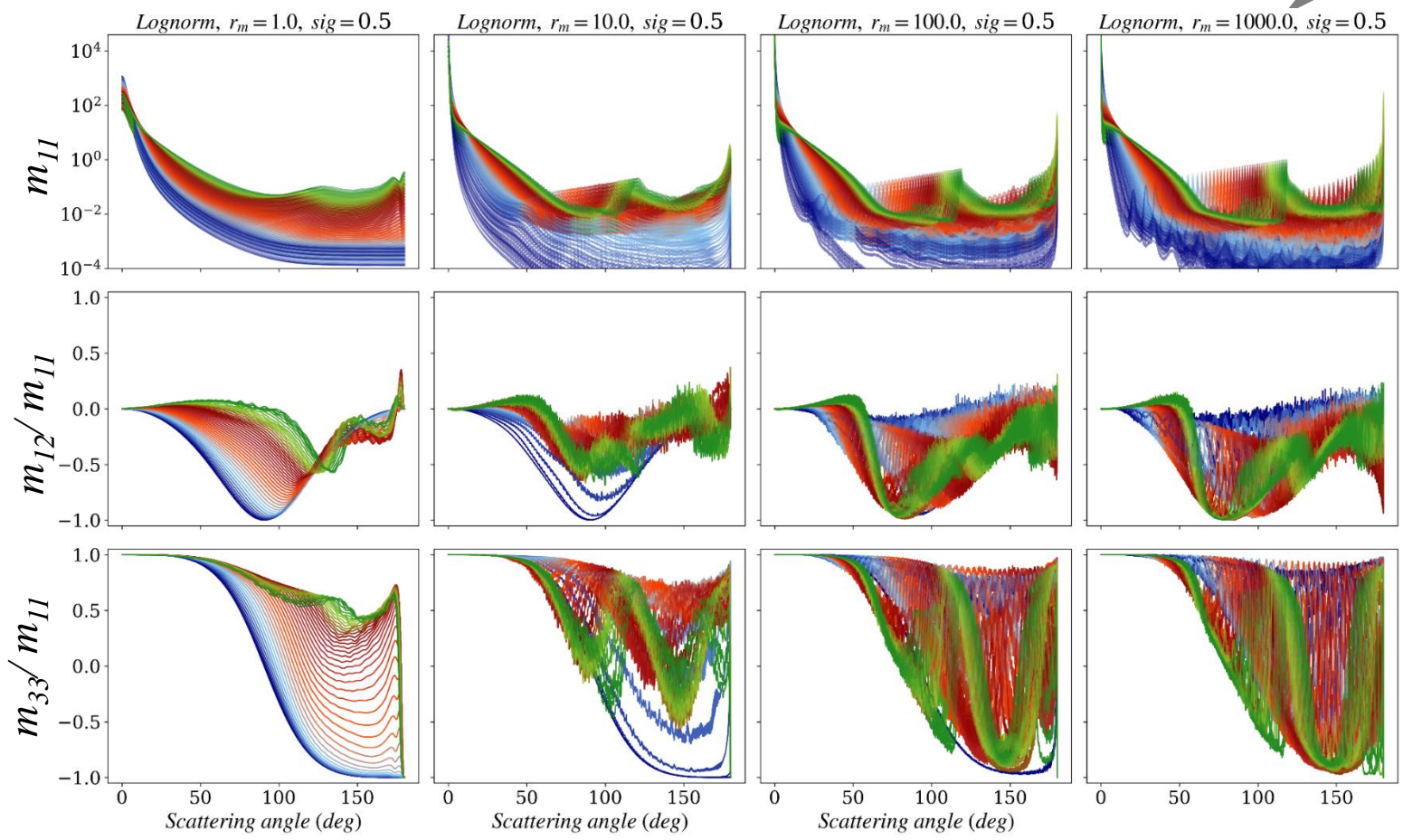
Increasing size from 1 μm to 1 mm (median radius)

Saved in netcdf
 LUT file

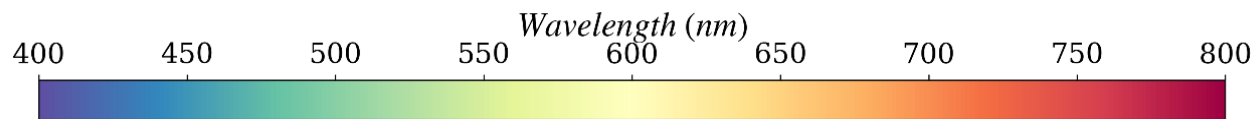
Mueller Matrix

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Useful terms: m_{11} , m_{12} , m_{33}



Ocean Plastics Polarization Properties OP^3

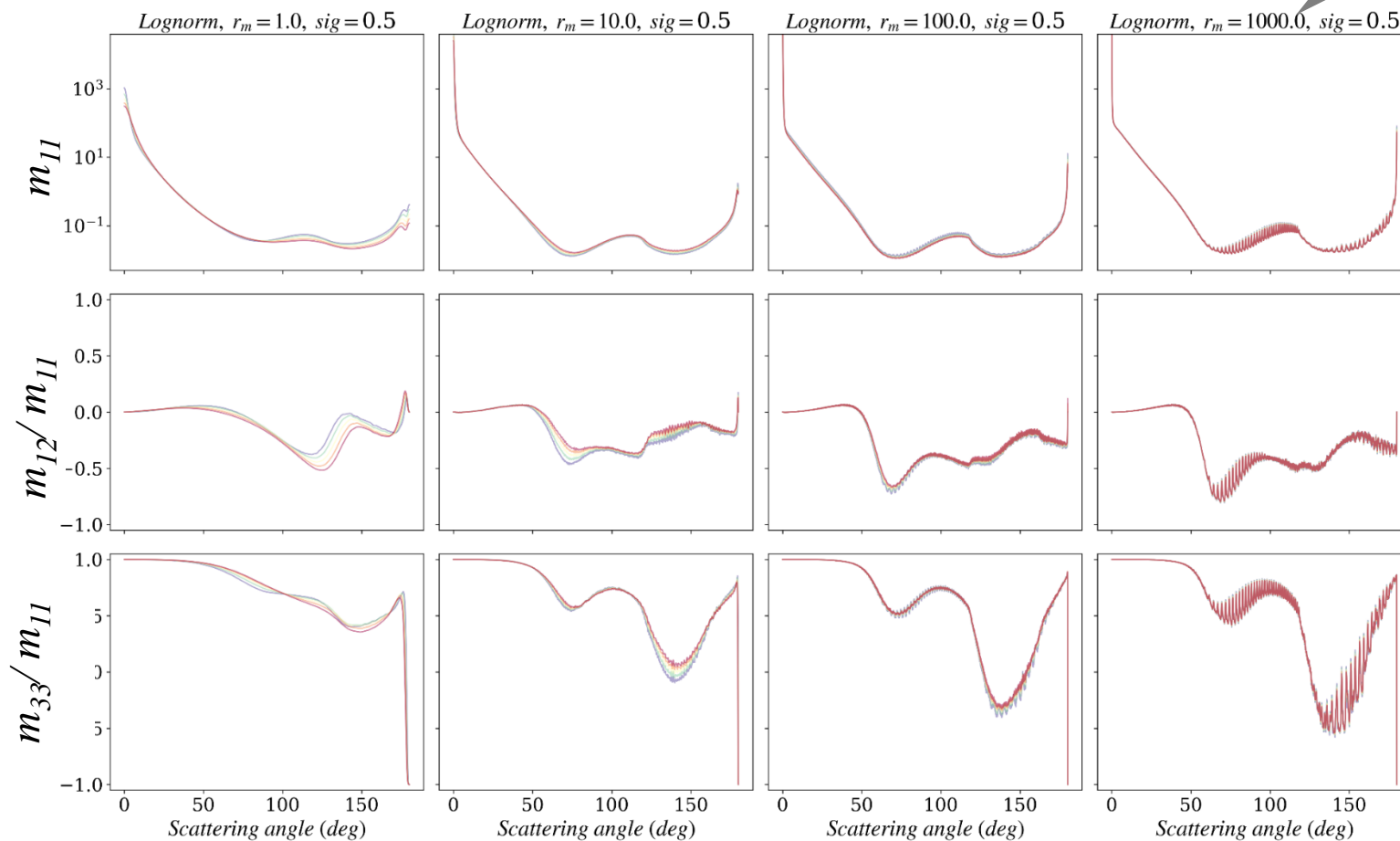
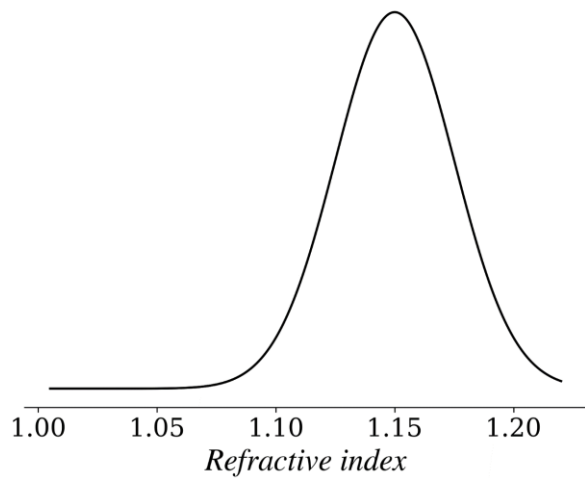


Refractive index:
 $1.005:0.005:1.220$,
 Size param. ($x=2\pi r/\lambda$):
 $0.1:40000$

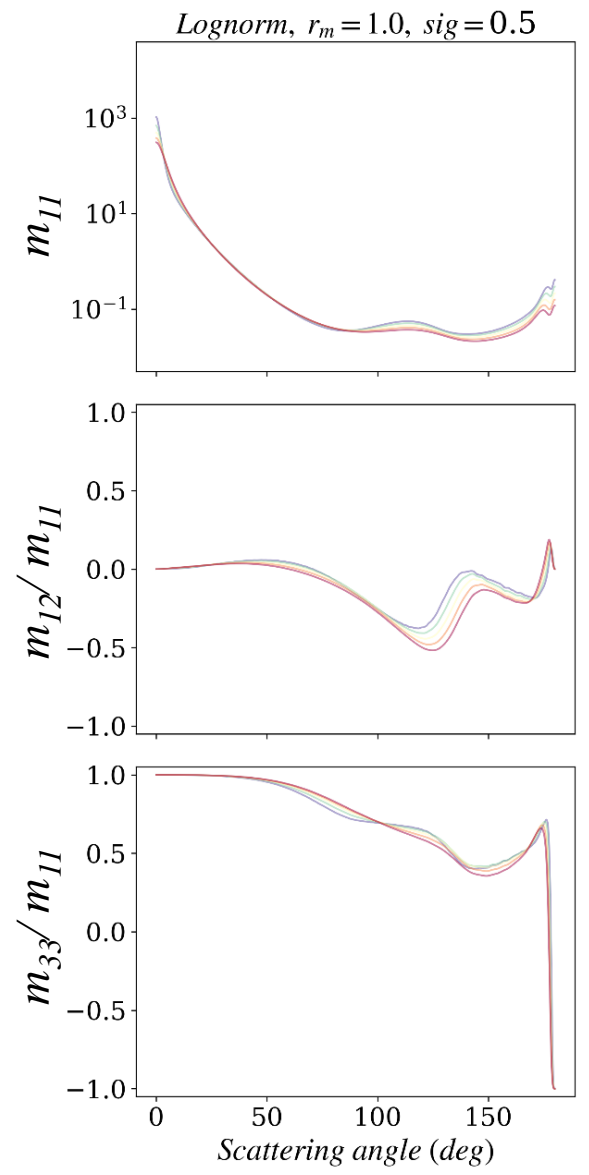
Single particle
 scattering

Increasing size from $1\mu\text{m}$ to 1mm (median radius)

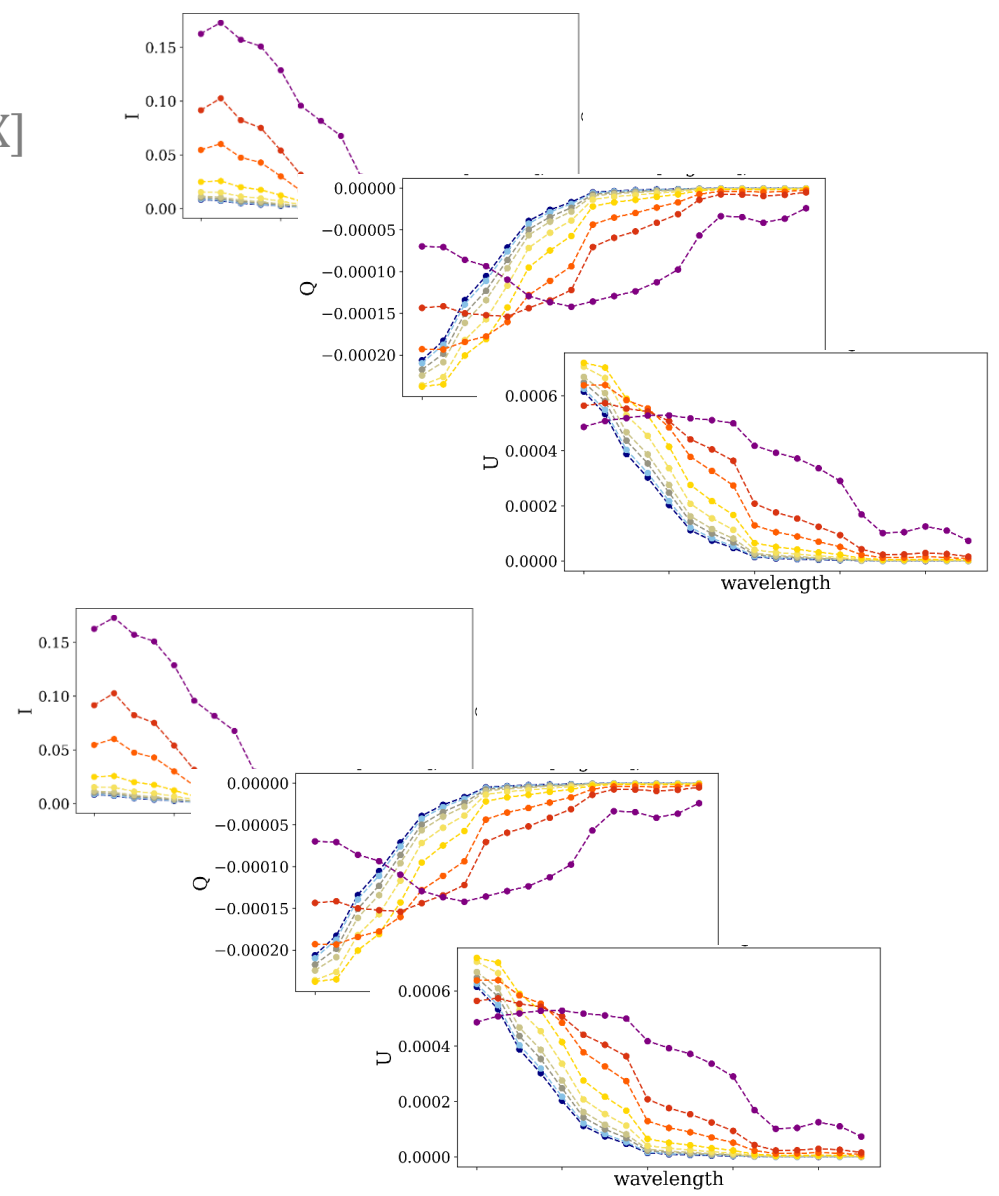
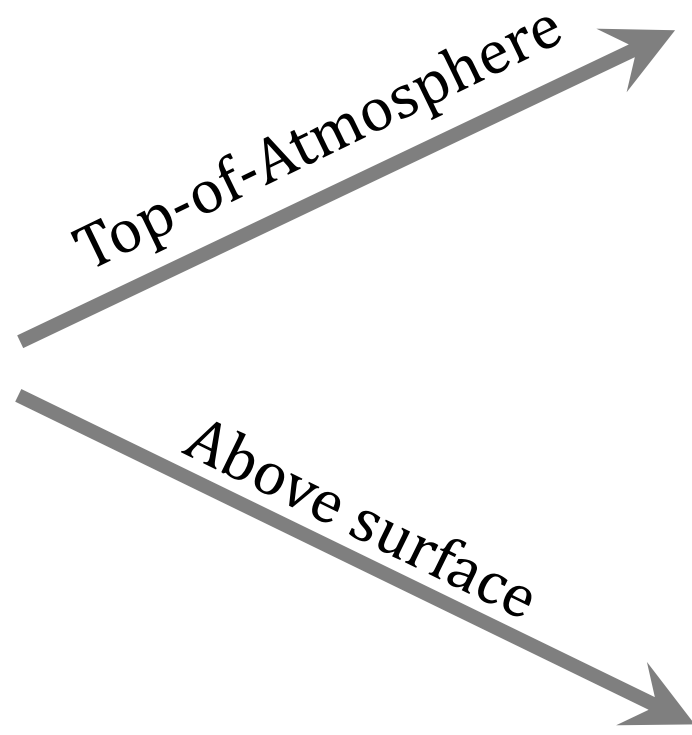
Refractive index
 distribution RID
 (normal...)



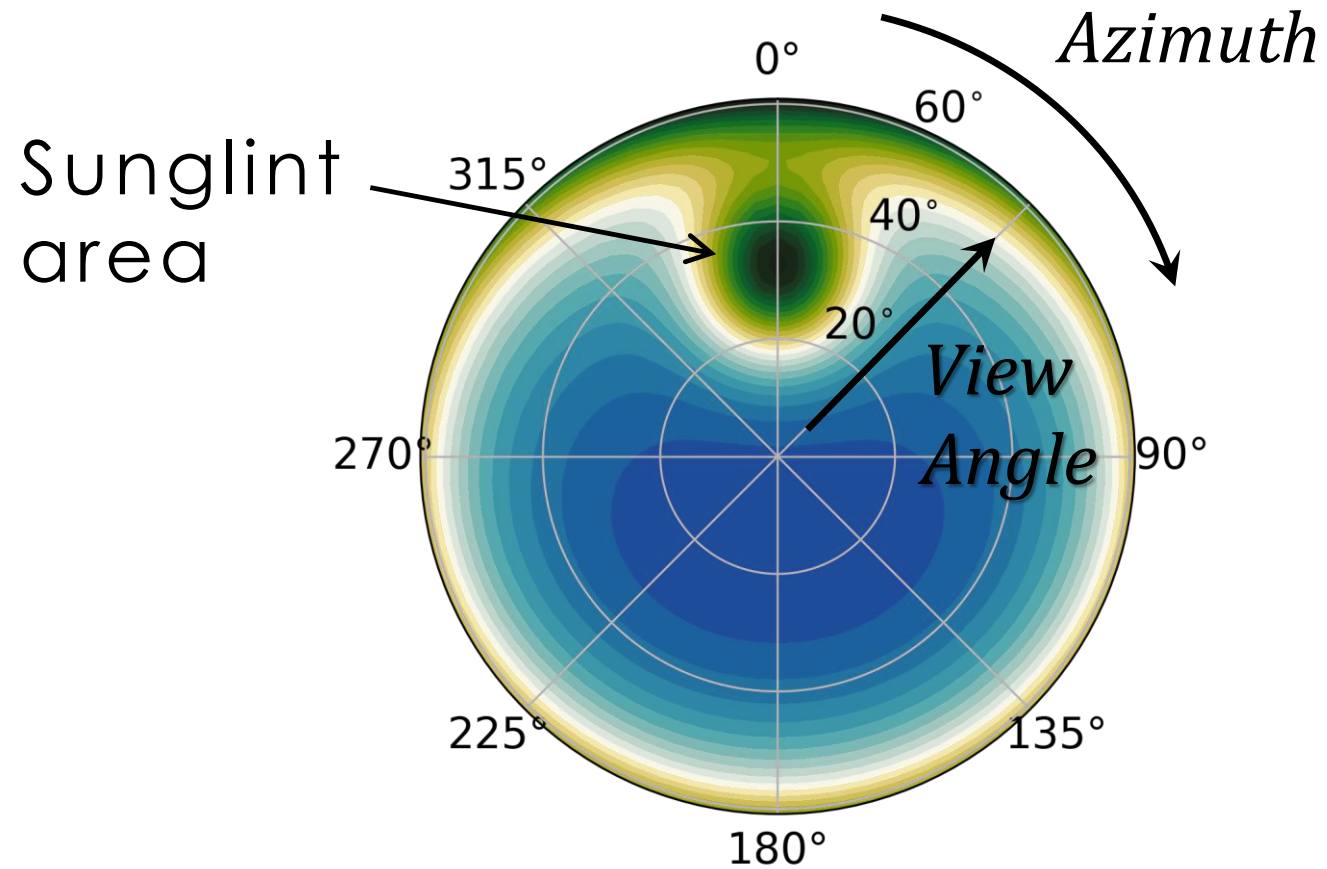
Ocean Plastics Polarization Properties **OP³**



OSOAA radiative transfer
[Chami et al, 2015, OPEX]



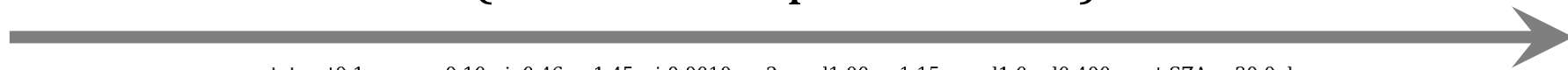
Radiative transfer simulation (directional)



Ocean Plastics Polarization Properties **OP³**

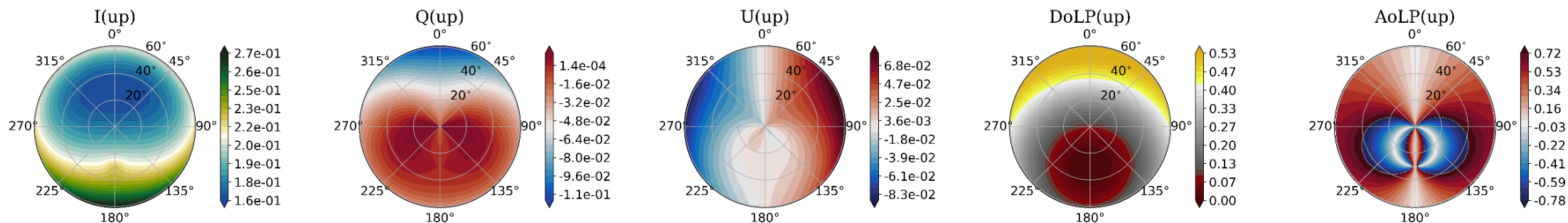
Total Stokes vector (radiance I + polarization) + DoLP + AoLP

Level

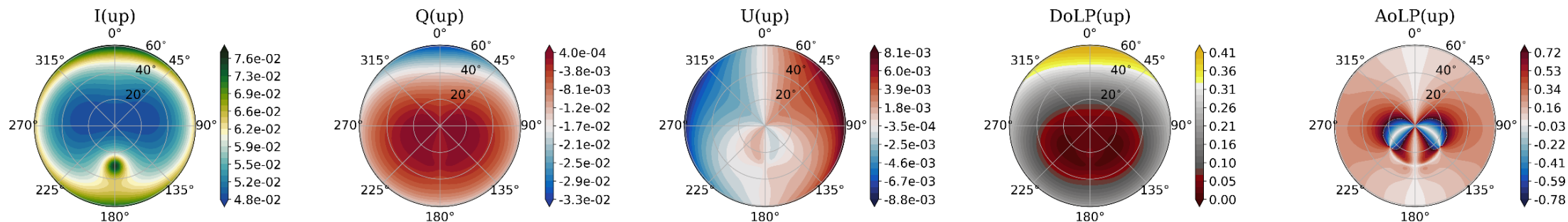


osoaa_tot_aot0.1_aero_rg0.10_sig0.46_nr1.45_ni-0.0010_ws2_sed1.00_nr1.15_rmed1.0_wl0.400.nc at SZA = 30.0 deg

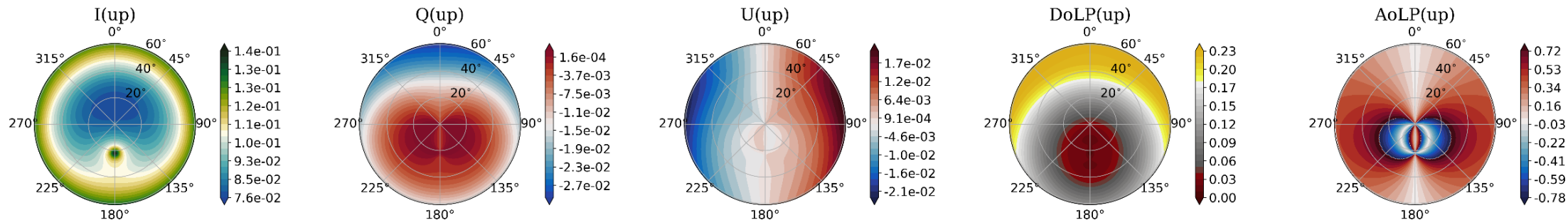
TOA



BOA
Above
surface



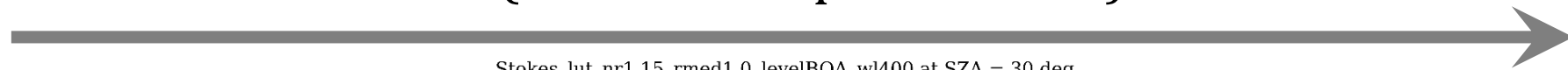
BOA
Below
surface



Ocean Plastics Polarization Properties **OP³**

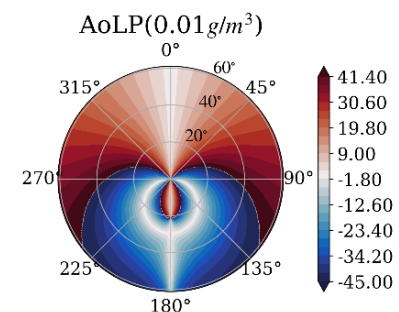
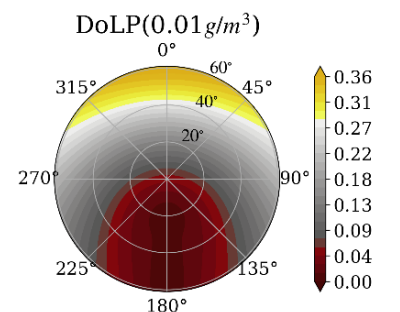
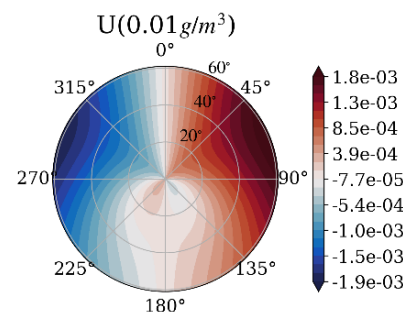
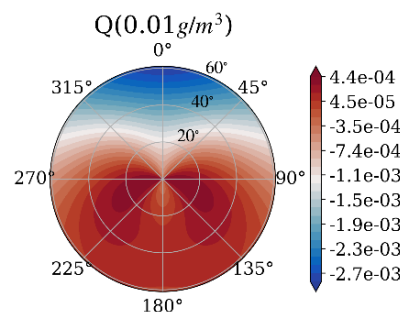
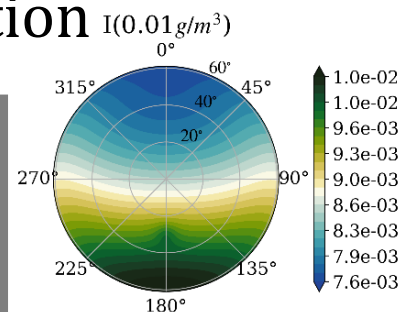
Water Stokes vector (radiance I + polarization) + DoLP + AoLP

Plastic items
concentration

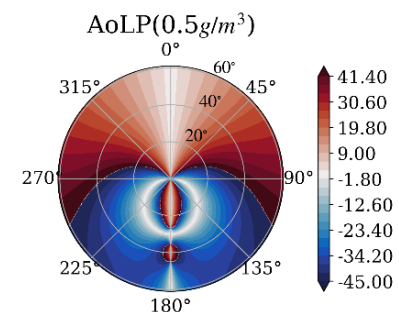
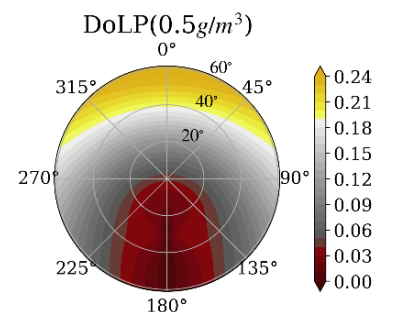
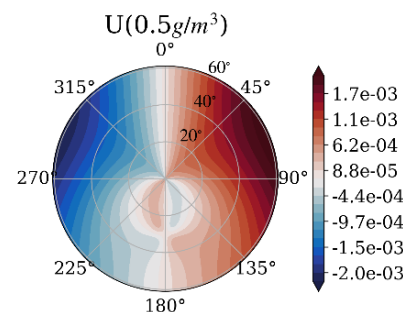
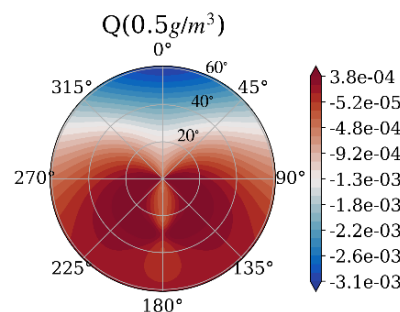
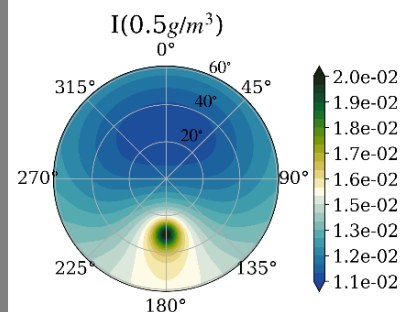


Stokes_lut_nr1.15_rmed1.0_levelBOA_wl400 at SZA = 30 deg

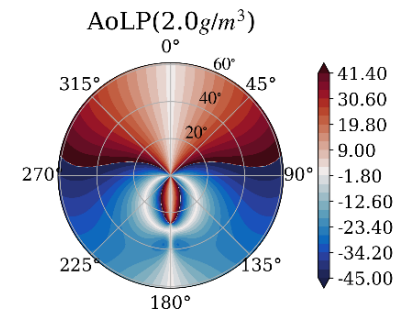
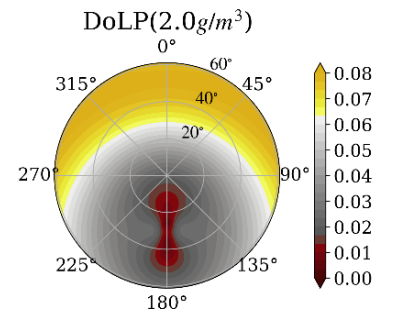
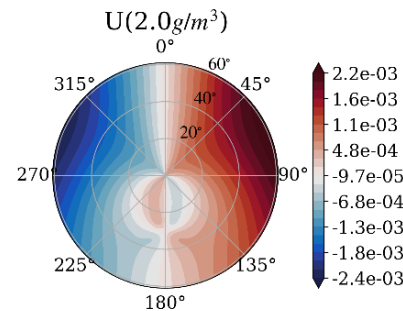
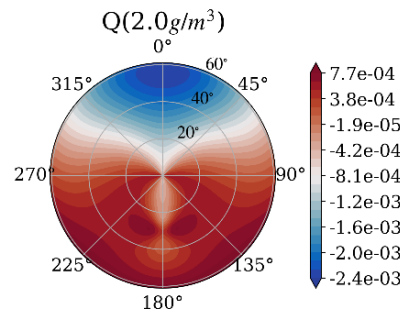
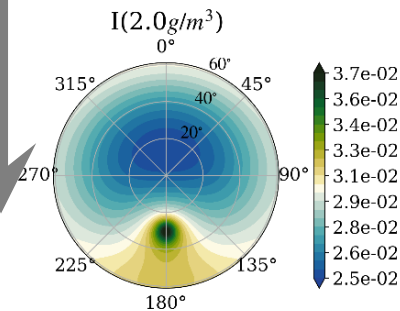
0.01 g/m³



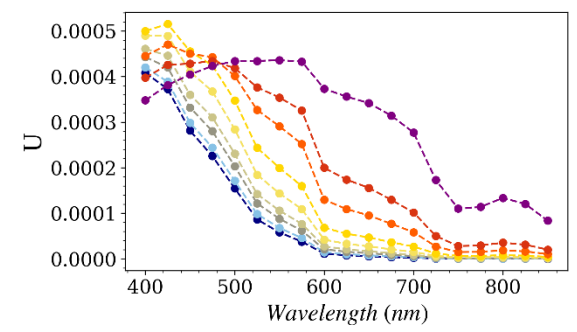
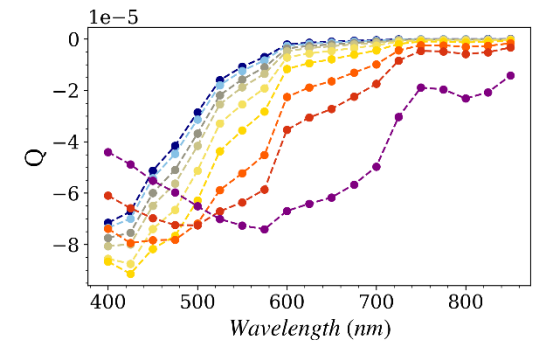
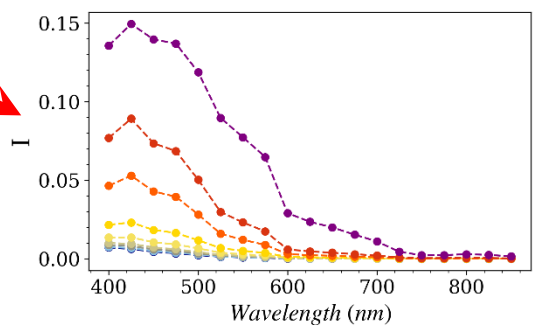
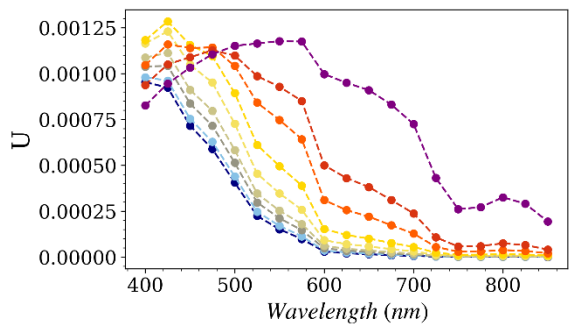
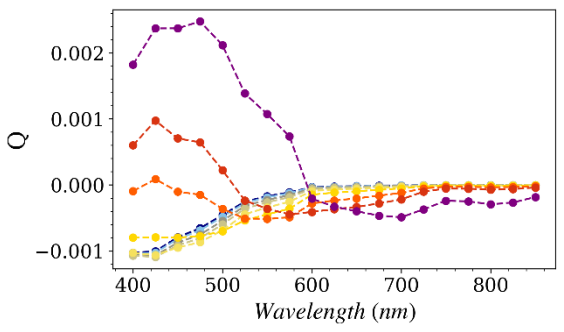
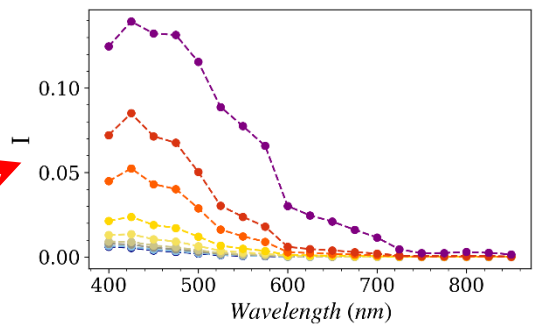
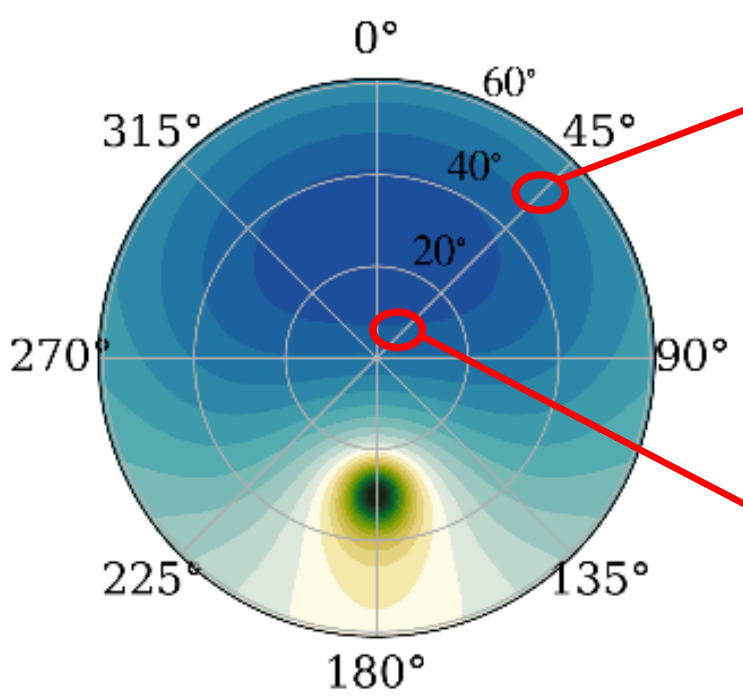
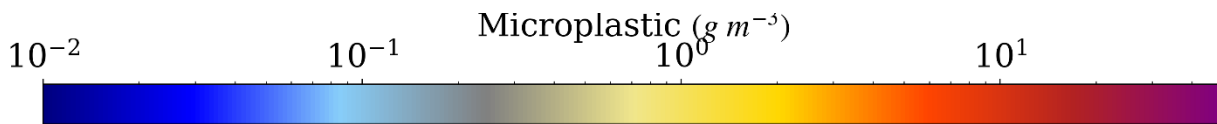
0.5 g/m³



2 g/m³



Ocean Plastics Polarization Properties **OP³**



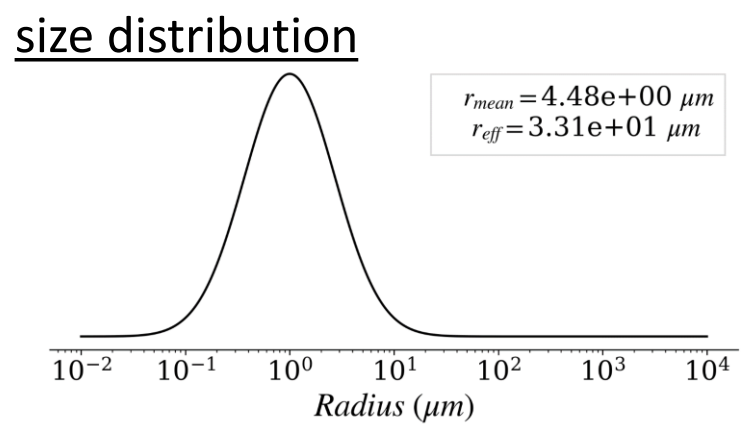
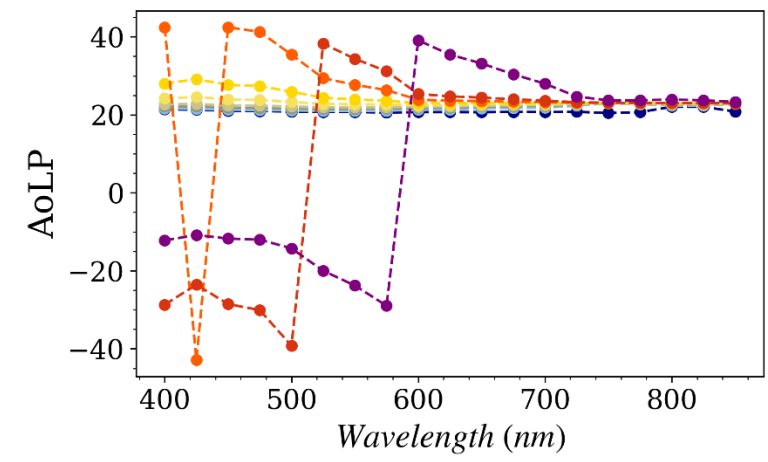
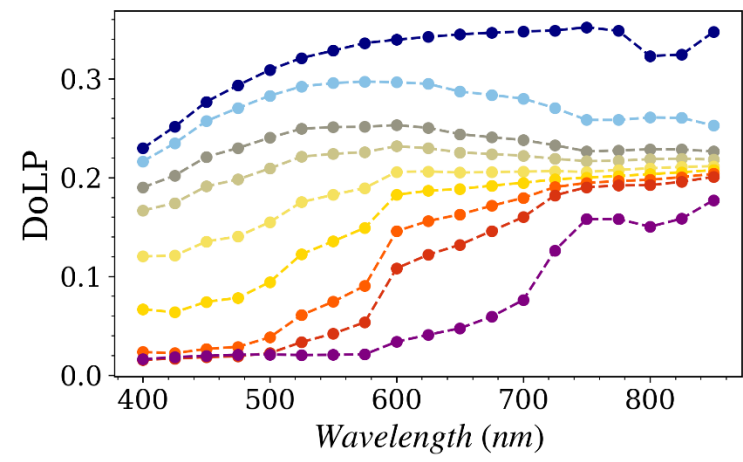
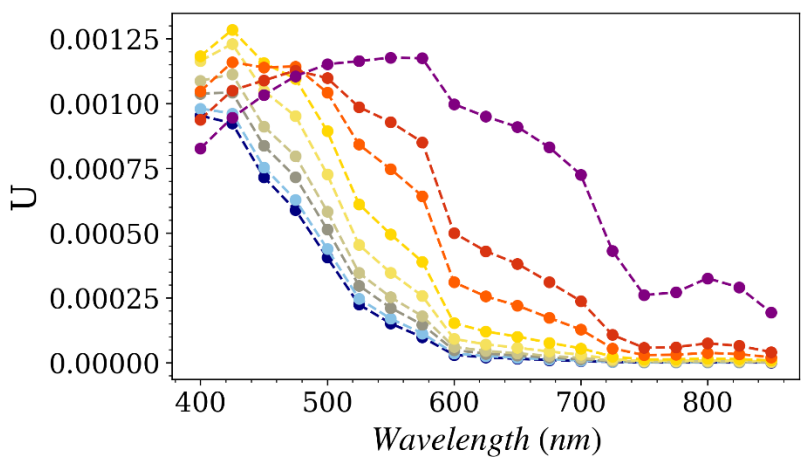
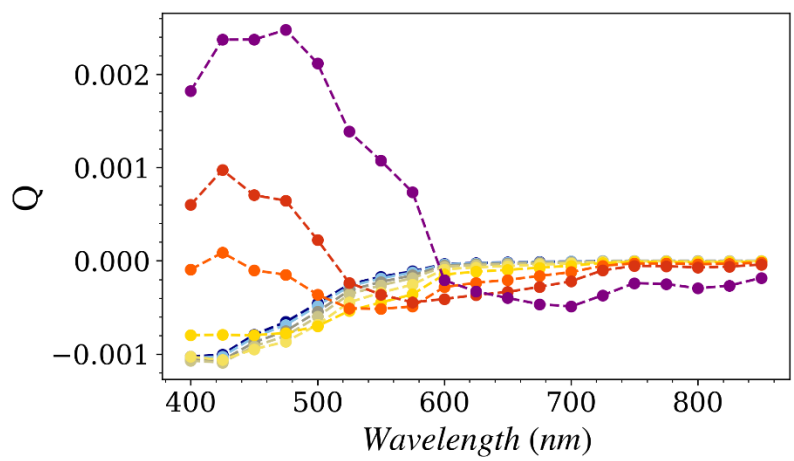
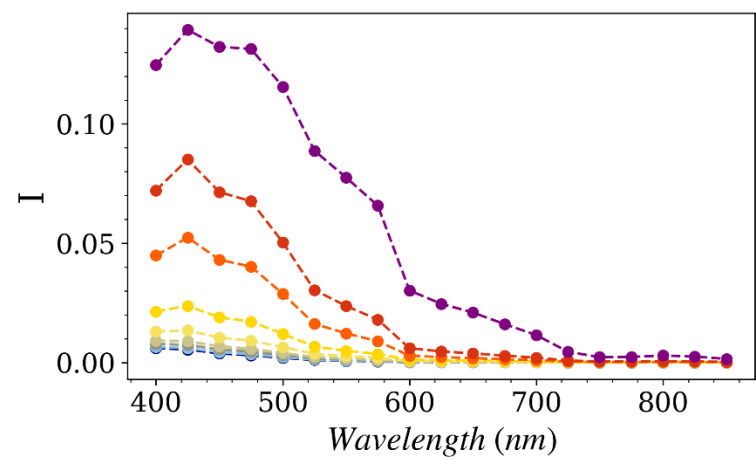


Ocean Plastics Polarization Properties **OP³**

Impact of size distribution: very small, $\sim 10^{-3}$ mm

DoLP: Degree of Linear Polarization
AoLP: Angle of Linear Polarization
I: reflectance
Q, U: 2nd and 3rd Stokes parameters

Stokes_lut_nr1.15_rmed1.0_sza30_vza50.42_azi45_level1
Microplastic ($g\ m^{-3}$)





Ocean Plastics Polarization Properties **OP³**

Impact of size distribution: small, $\sim 10^{-2}$ mm

DoLP: Degree of Linear Polarization
AoLP: Angle of Linear Polarization
I: reflectance
Q, U: 2nd and 3rd Stokes parameters

Stokes_lut_nr1.15_rmed10.0_sza30_vza50.42_azi45_level0

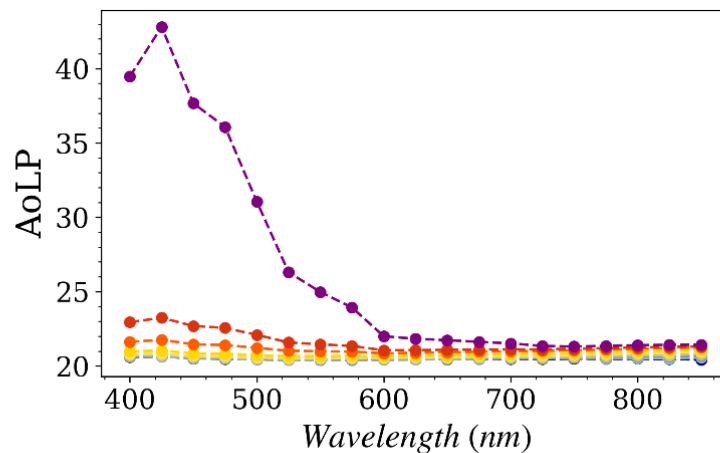
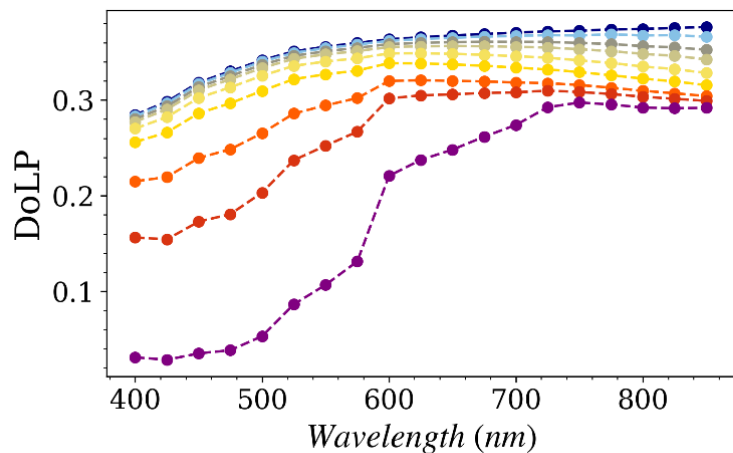
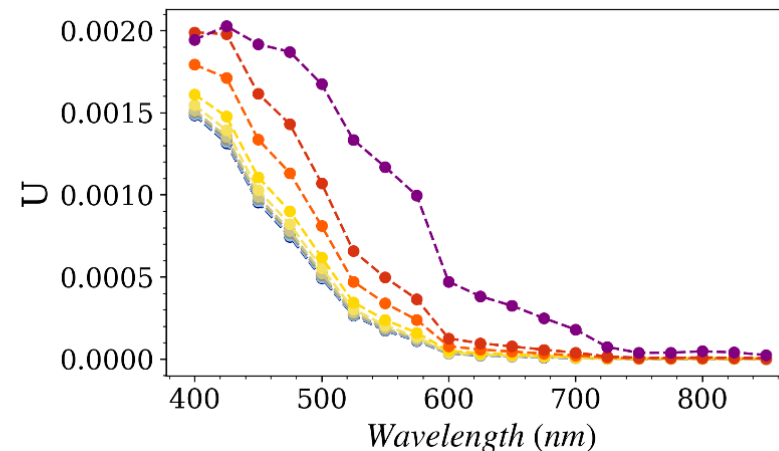
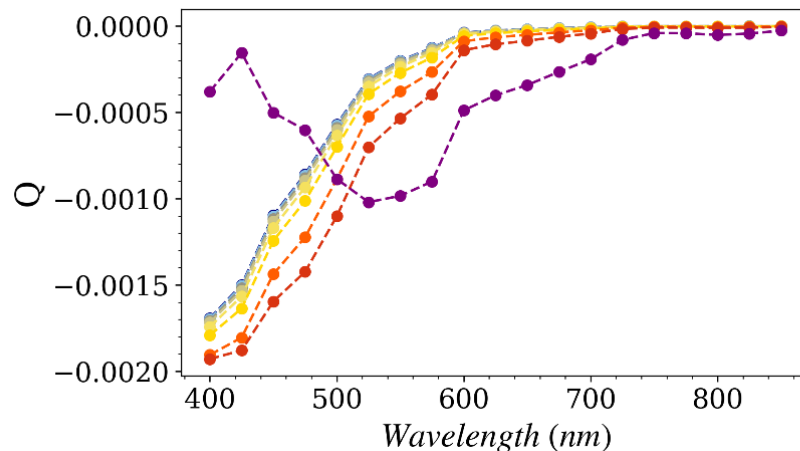
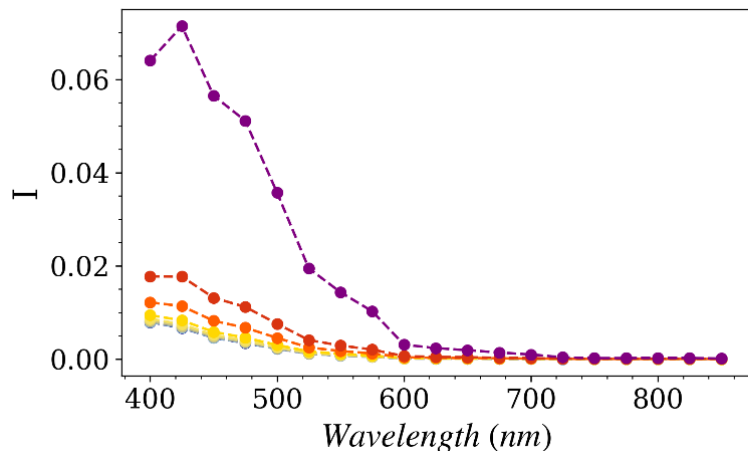
Microplastic ($g\ m^{-3}$)

10^{-2}

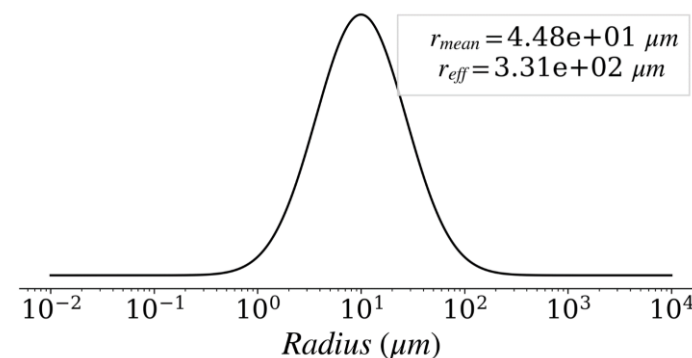
10^{-1}

10^0

10^1



size distribution

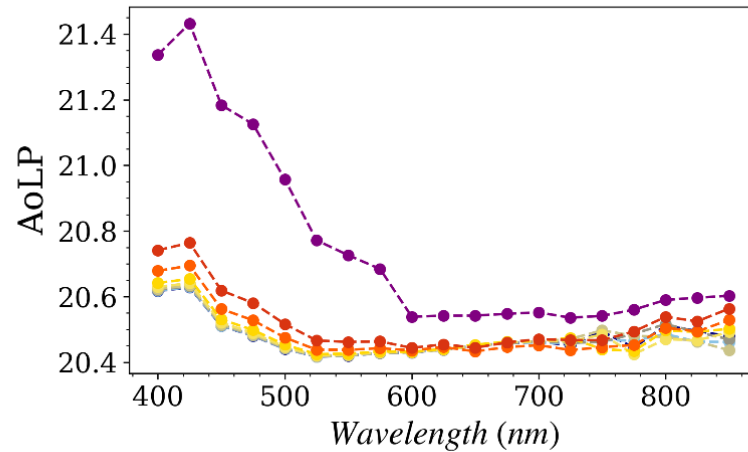
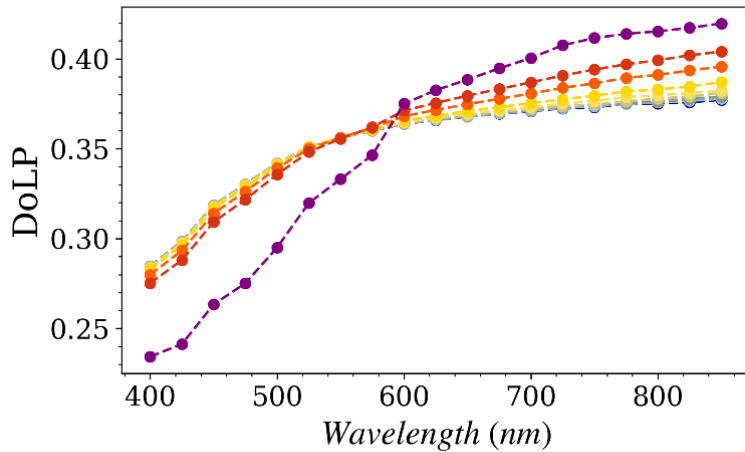
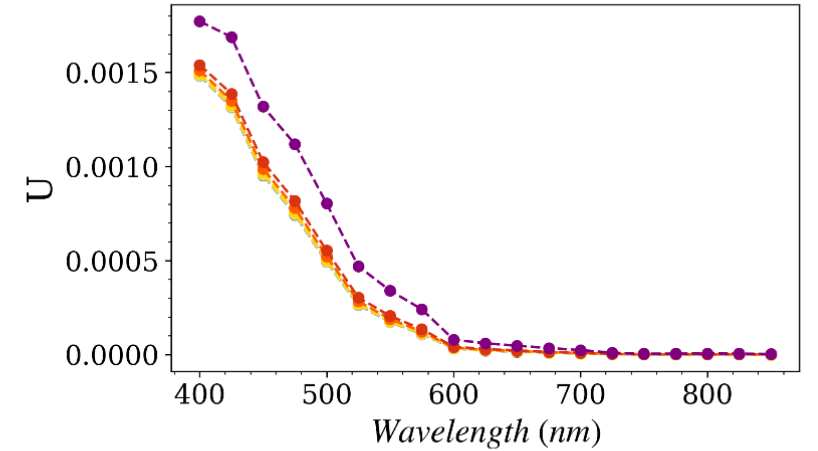
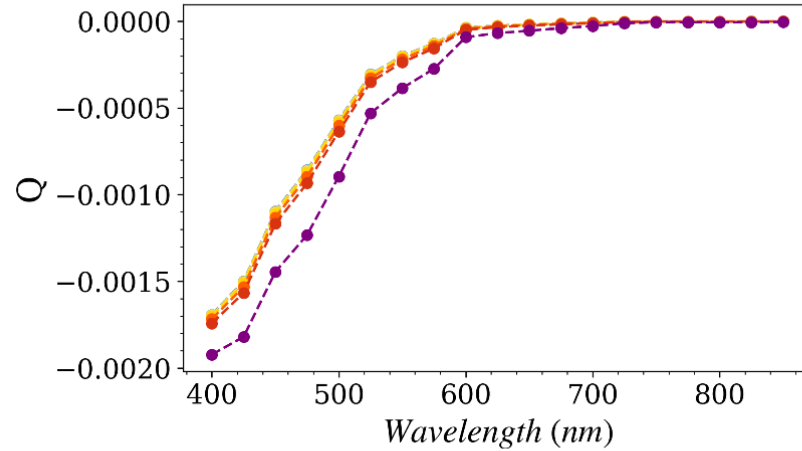
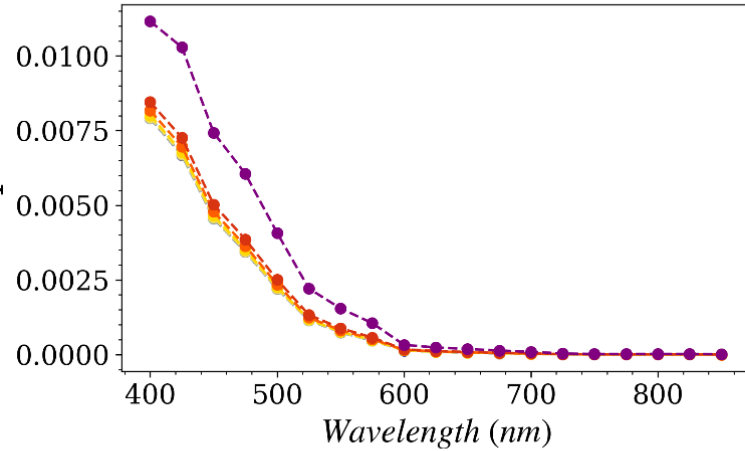
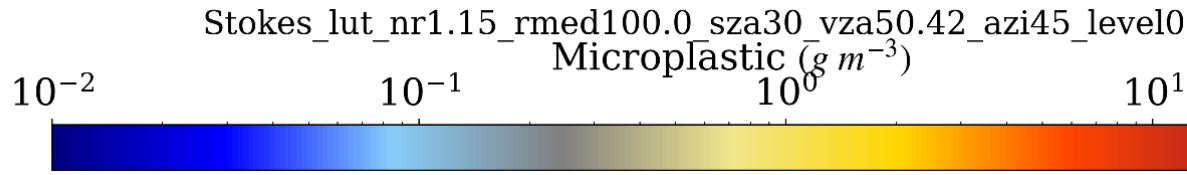




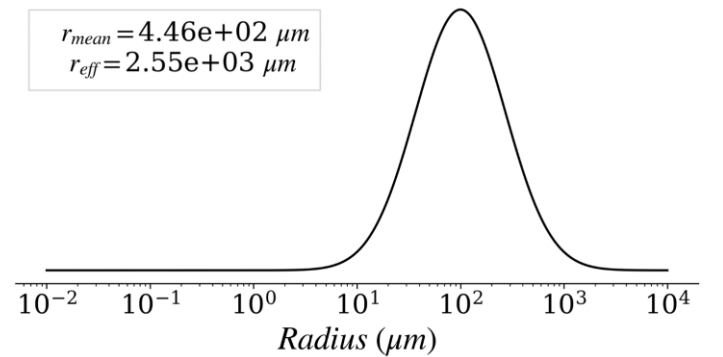
Ocean Plastics Polarization Properties OP^3

Impact of size distribution: medium, ~ 0.1 mm

DoLP: Degree of Linear Polarization
AoLP: Angle of Linear Polarization
I: reflectance
Q, U: 2nd and 3rd Stokes parameters



size distribution





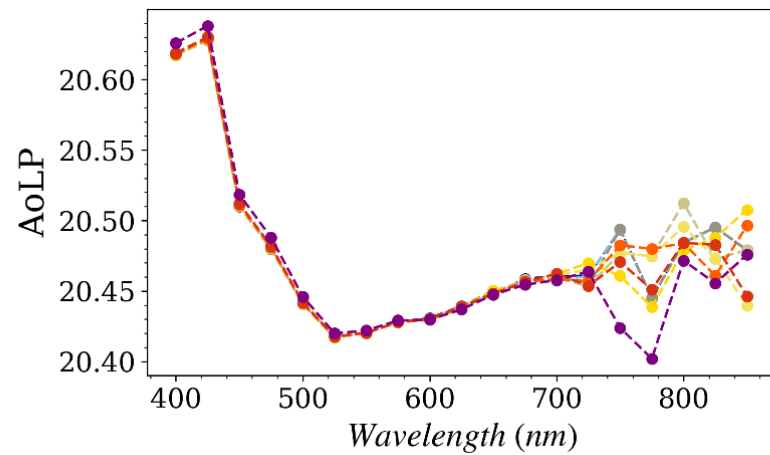
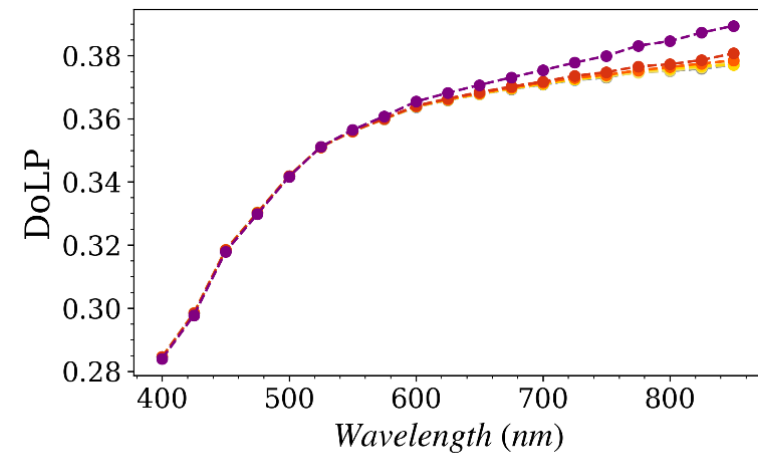
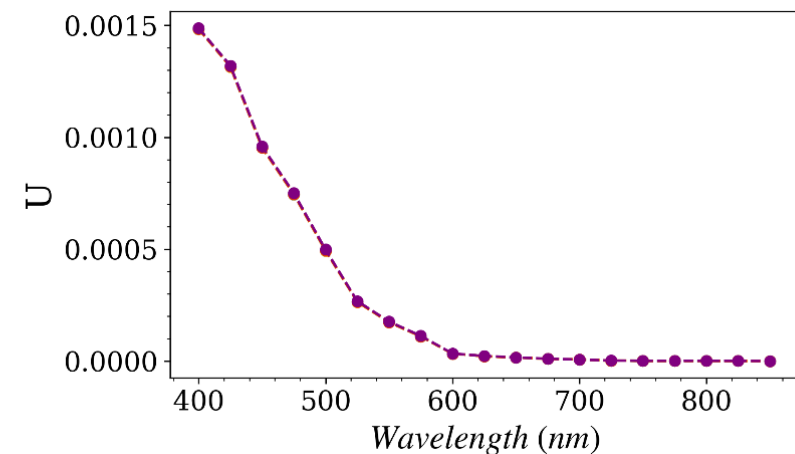
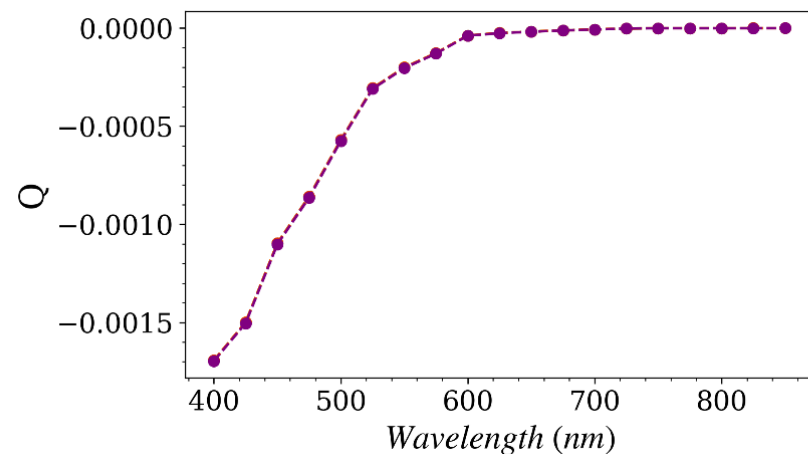
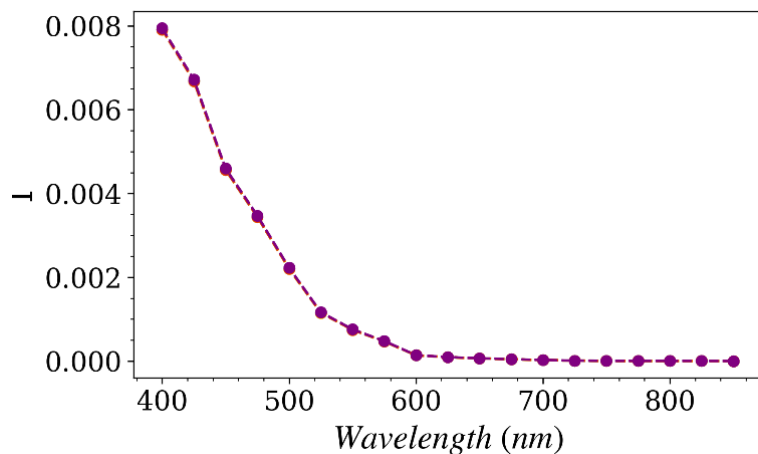
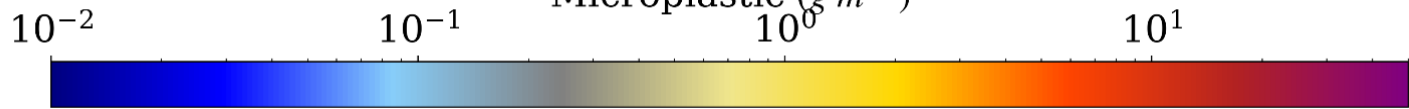
Ocean Plastics Polarization Properties **OP³**

Impact of size distribution: large, ~1 mm

DoLP: Degree of Linear Polarization
AoLP: Angle of Linear Polarization
I: reflectance
Q, U: 2nd and 3rd Stokes parameters

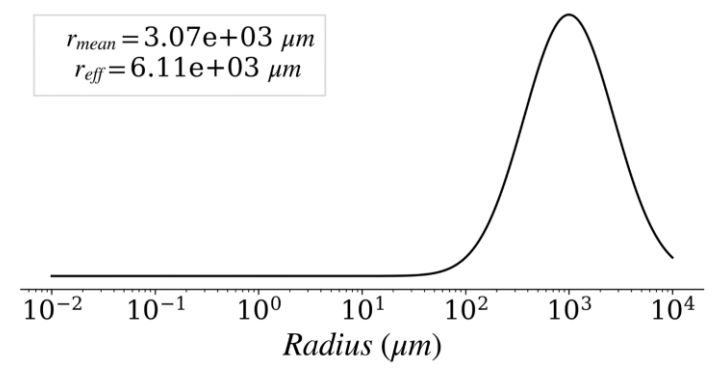
Stokes_lut_nr1.15_rmed1000.0_sza30_vza50.42_azi45_level0

Microplastic ($g\ m^{-3}$)



size distribution

$r_{mean} = 3.07e+03\ \mu m$
 $r_{eff} = 6.11e+03\ \mu m$

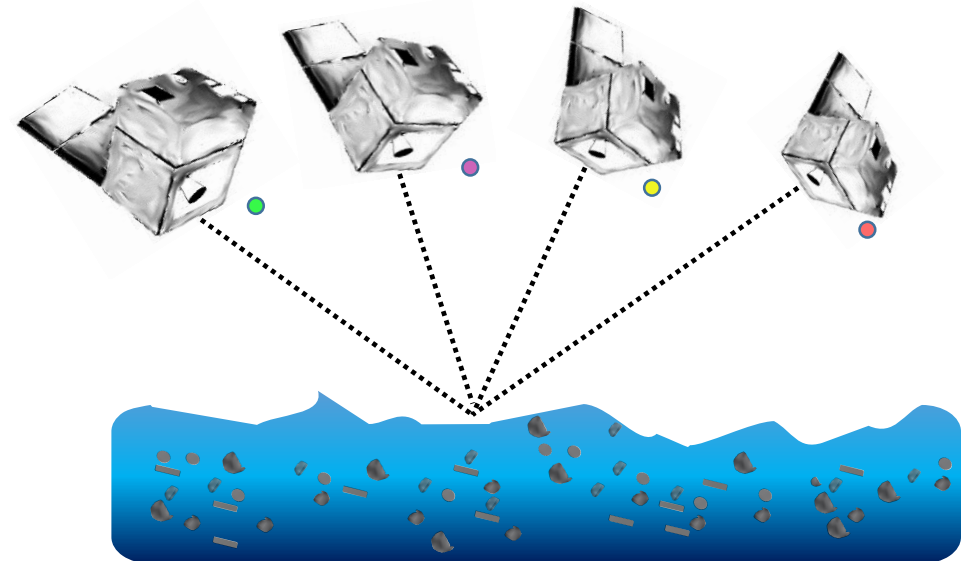
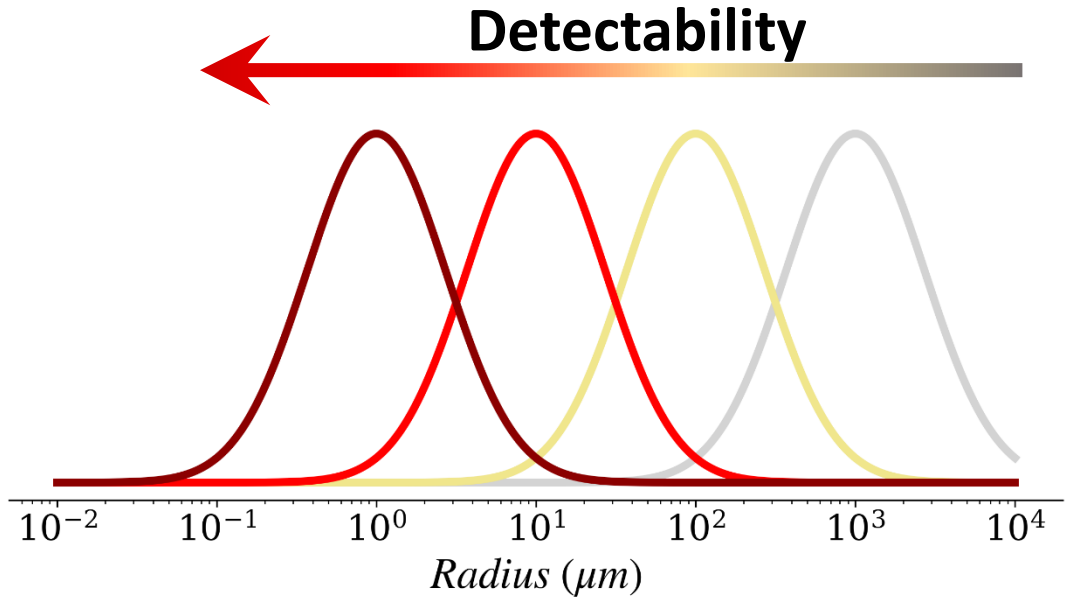
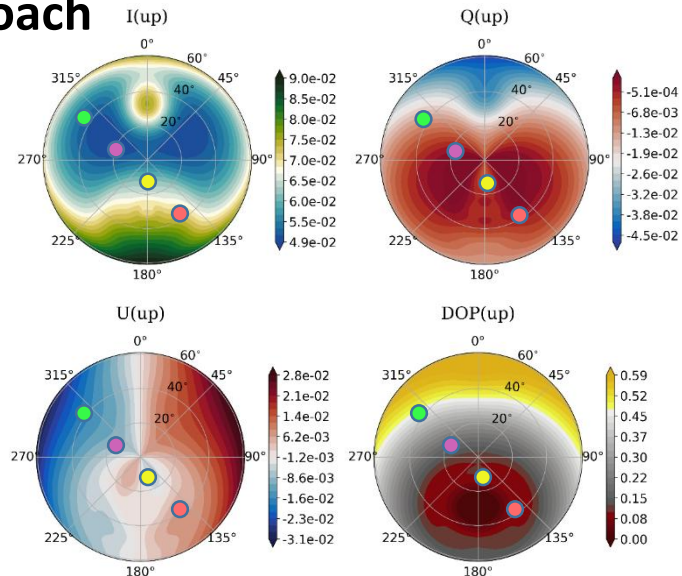


Conclusions

- **Detectability demonstrated** for micrometric up to hundreds of μm depending on concentration
- limited for larger microplastic items ($>1\text{mm}$)
- **Retrieval algorithms should be based on a multi-directional approach**

→ Exploitation of the CNES POLDER missions archive (~14 directions, 3 polar. Bands, >10years of data)

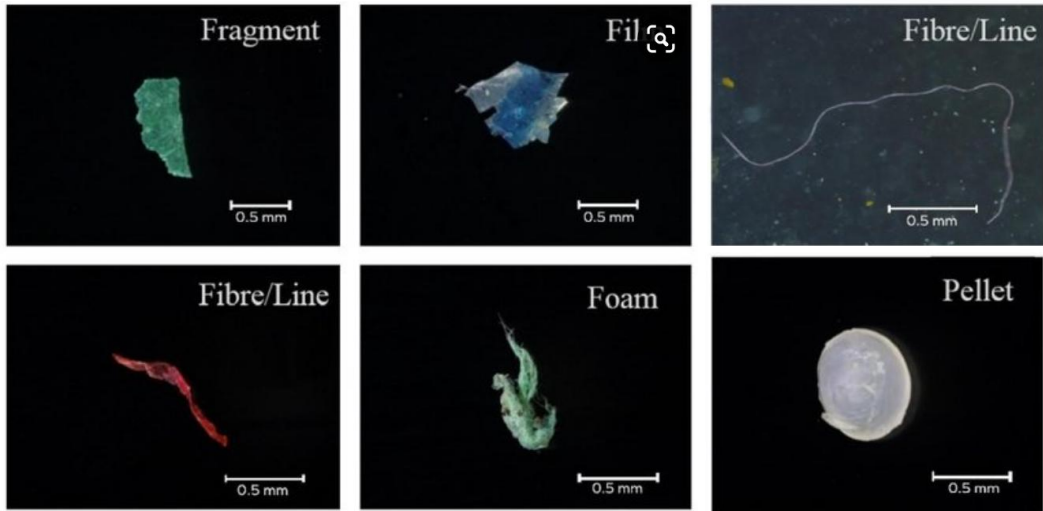
→ Waiting for PACE (NASA) and 3MI (EumetSat/ESA)



Ocean Plastics Polarization Properties OP^3

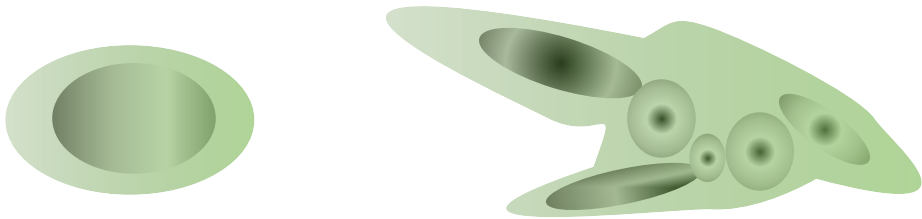
Outlooks: going beyond the sphere

Need to consider several shape types:

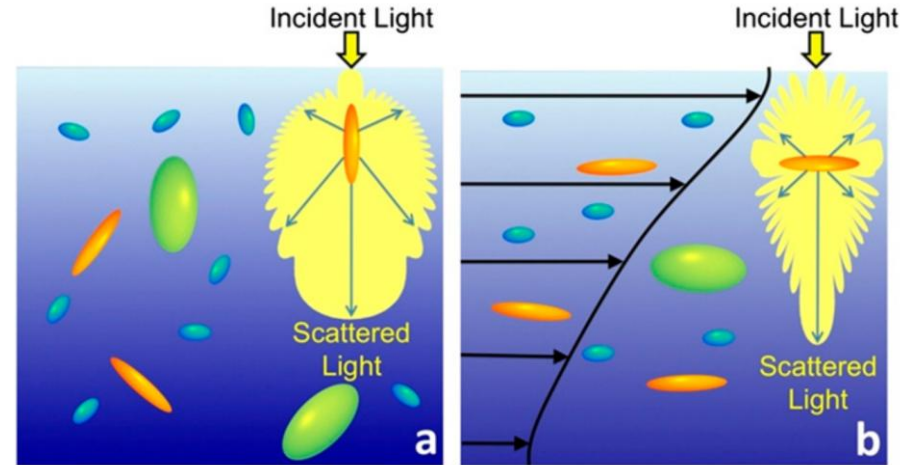


(from Robin et al., 2019, STTE)

Need to consider aggregates with biological coating/matrix:



Need to consider orientation and vertical profile



[Marcos et al., 2011, PNAS]

Need to consider several water types (Chl-a, CDOM, sediment)



Ocean Plastics Polarization Properties OP^3

Outlooks: critical need of actual data

Several sensors and prototypes

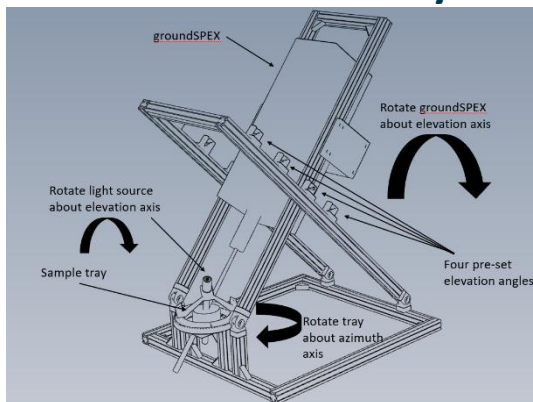
Specim-IQ camera



FLIR camera



GroundSpex Laboratory from Leiden University



Mantis: an all-sky visible-to-near-infrared hyper-angular spectropolarimeter

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LARRY PEZZANITI⁴



Mission of opportunity...
Please join!



Thank you!

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