Analysis of Circular Polarization Scattering from Ellipsoidal Cell Nuclei and Its Application to Near-Infrared Cancer Diagnosis

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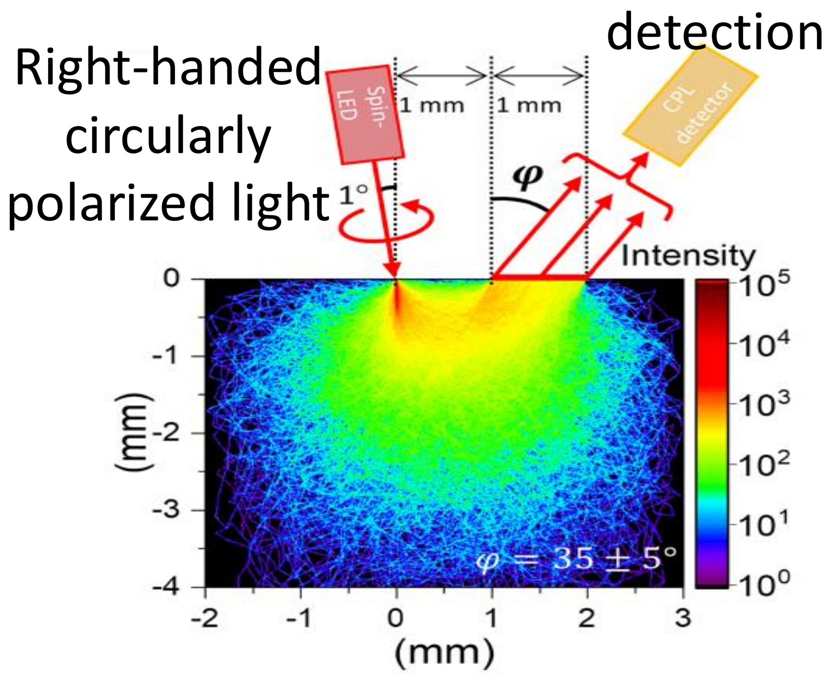
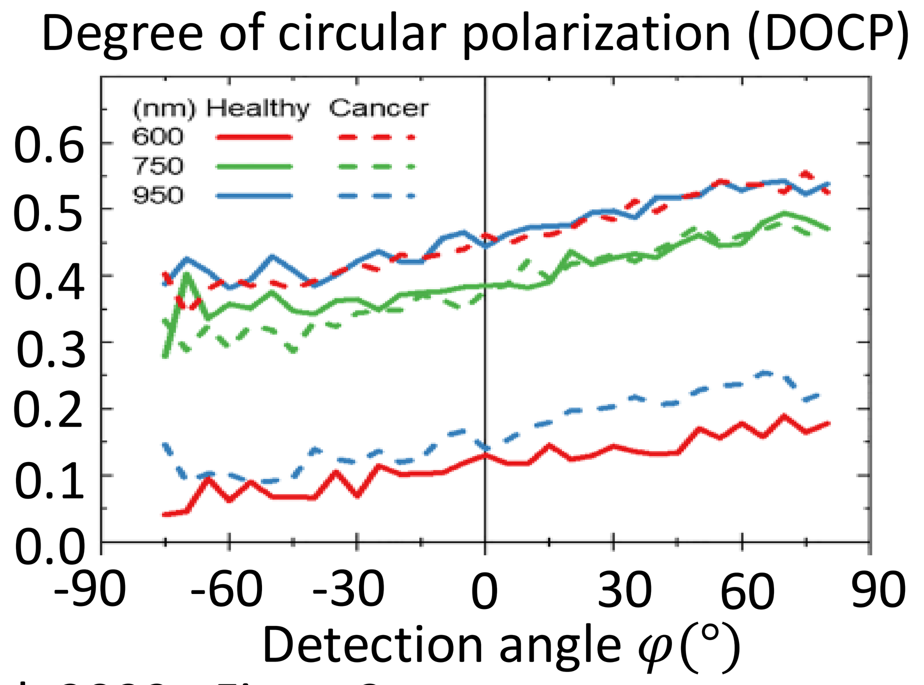
Introduction

- Near-infrared (NIR) light has low absorption and high safety in biological tissues, making it useful for diagnostics. **Circularly polarized light is particularly sensitive to the size and shape of scatterers**.
- Healthy cell nuclei (∼5.9 μm) enlarge to ∼ 11 μm in cancer, **and prior studies modeled them as spheres**, suggesting that circular polarization could be a potential indicator for gastric cancer diagnosis (Nishizawa et al. 2022).





Nishizawa et al. 2022 : Figure3

- However, **real cell nuclei exhibit irregular, non-spherical shapes**, meaning that simple spherical models may not fully capture their scattering behavior.

This study's topic

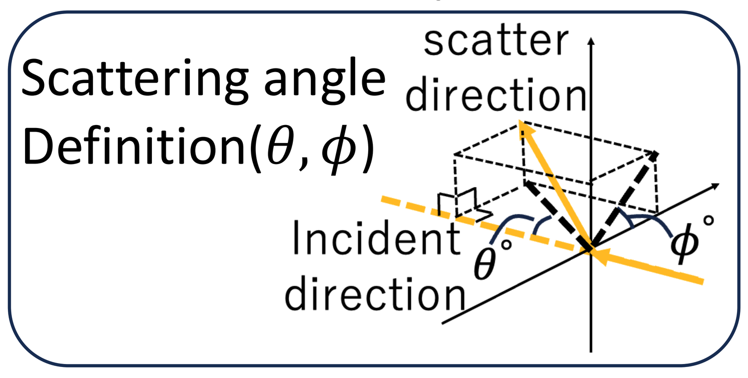
- ☐ Investigate the **single scattering by ellipsoidal nuclei**
- ☐ Perform **3D radiative transfer**

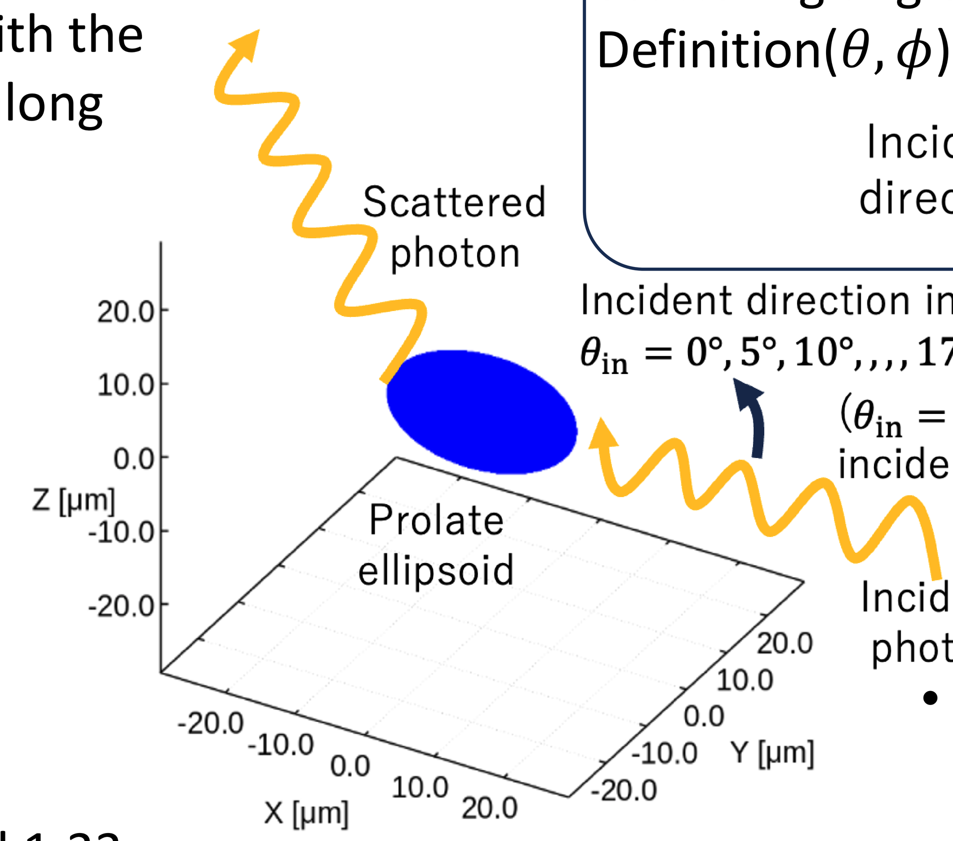
Single scattering by ellipsoidal nuclei

Methods

Using the **discrete dipole approximation**, we model **ellipsoidal nuclei as dipole arrays** to compute **first-principles light – matter interactions** and predict angular dependence of circular scattering.

- Prolate ellipsoids with the major axis aligned along the x-direction
- Axial size ratios of 1:2, 1:3, and 1:4
- All models scaled to have the same volume as an 11μm-diameter sphere
- The particle and matrix refractive indices are 1.59 and 1.33





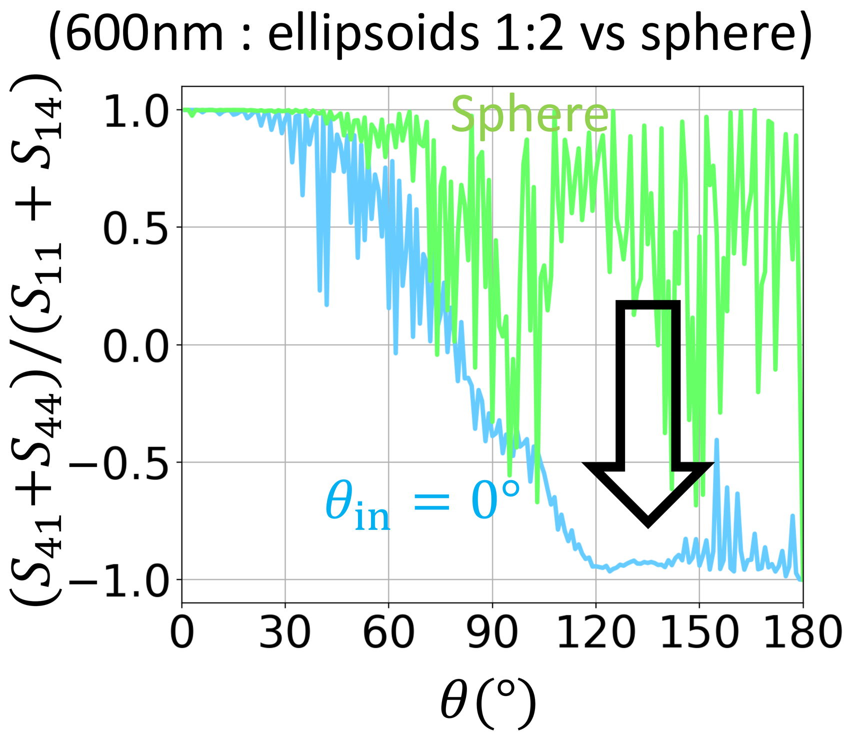
Incident direction in XY plane
$\theta_{in} = 0°, 5°, 10°, , , , 170°, 175°$
($\theta_{in} = 0°$ corresponds to incidence from the +X)

- wavelength 600nm, 950nm

Results

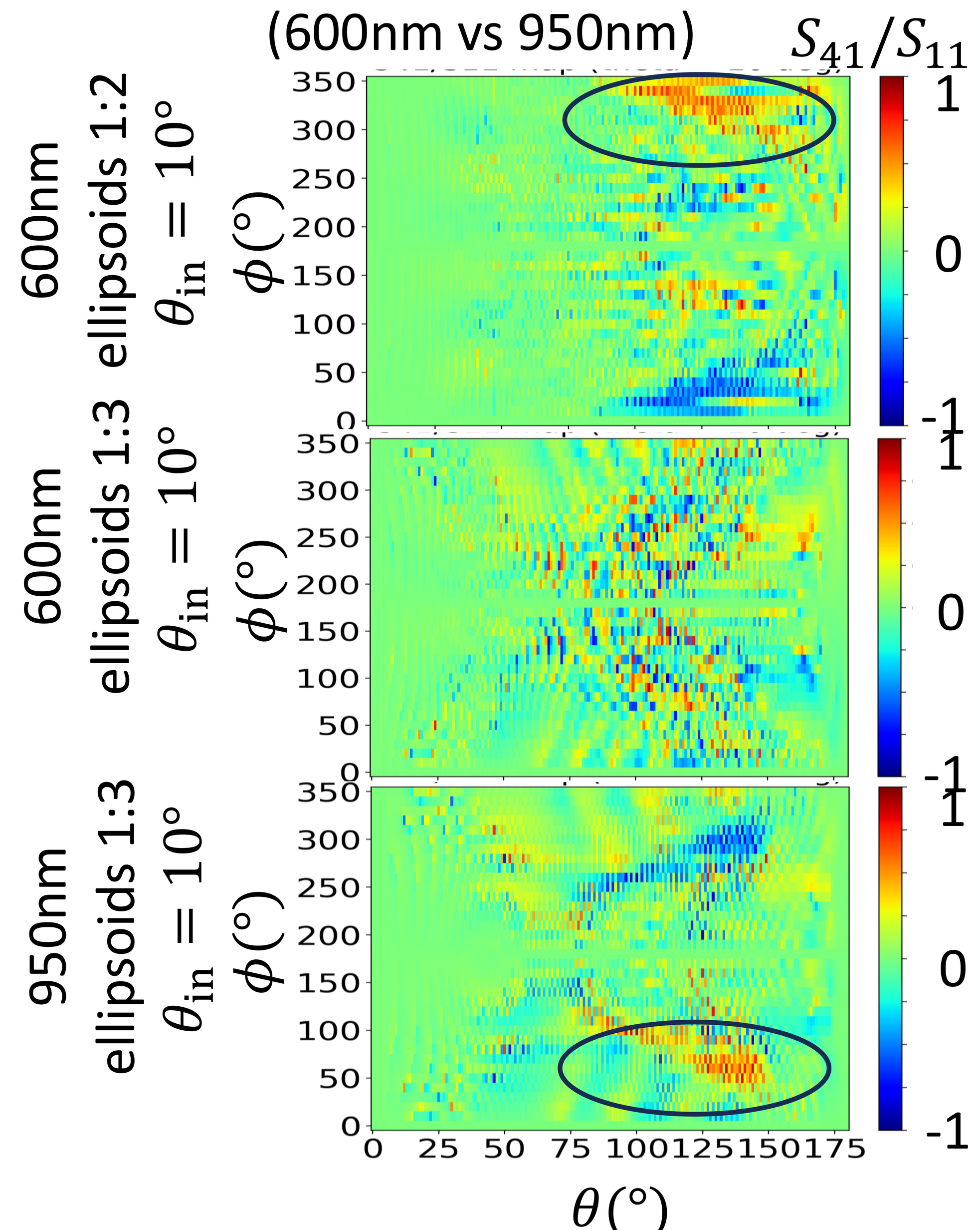
The Mueller matrix S_{ij} transforms the incident Stokes parameters (I_i, Q_i, U_i, V_i) into the scattered ones (I_s, Q_s, U_s, V_s).

ϕ-averaged DOCP for (I_i, Q_i, U_i, V_i)=(1,0,0,1), (600nm : ellipsoids 1:2 vs sphere)



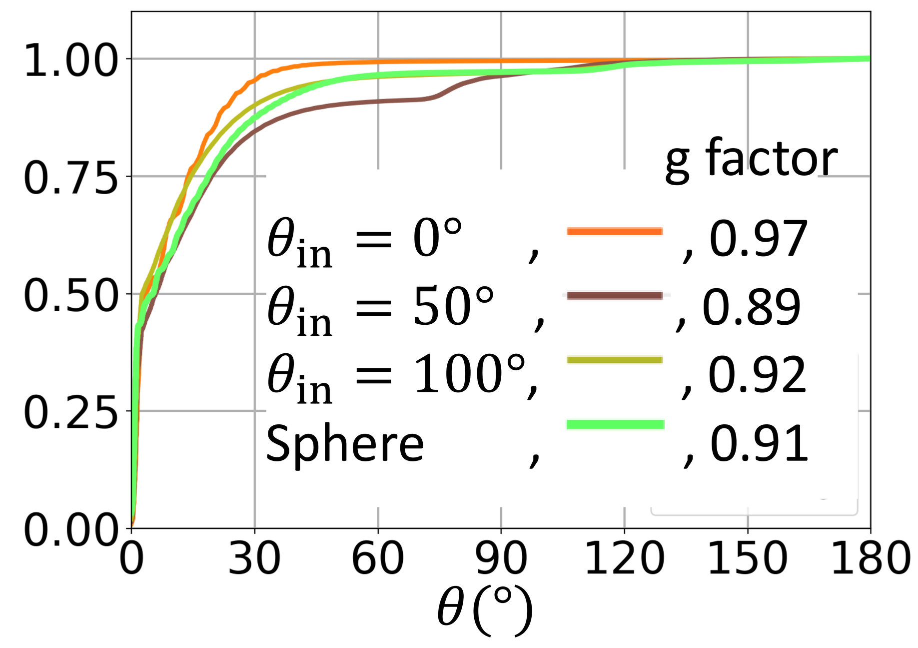
Incidence closer to the major axis shows a stronger **DOCP reversal in backward scattering than a sphere.**

DOCP for (I_i, Q_i, U_i, V_i)=(1,0,0,0), (600nm vs 950nm)



For incidence slightly off the major axis, **At 600 nm, larger axial size ratios produce right/left DOCP** at close angles, whereas at **950 nm the DOCP keeps a clear right-handed region** even for large axial ratios.

Cumulative distribution function averaged ϕ,(600nm : ellipsoids 1:2 vs sphere)



- Stronger forward scattering ($\theta_{in} = 0°$) than a sphere.
- Around $\theta_{in} = 90°$, the pattern is similar to a sphere.
- Around $\theta_{in} = 50°$, scattering is more side-scattering than a sphere.

3D radiative transfer

Methods

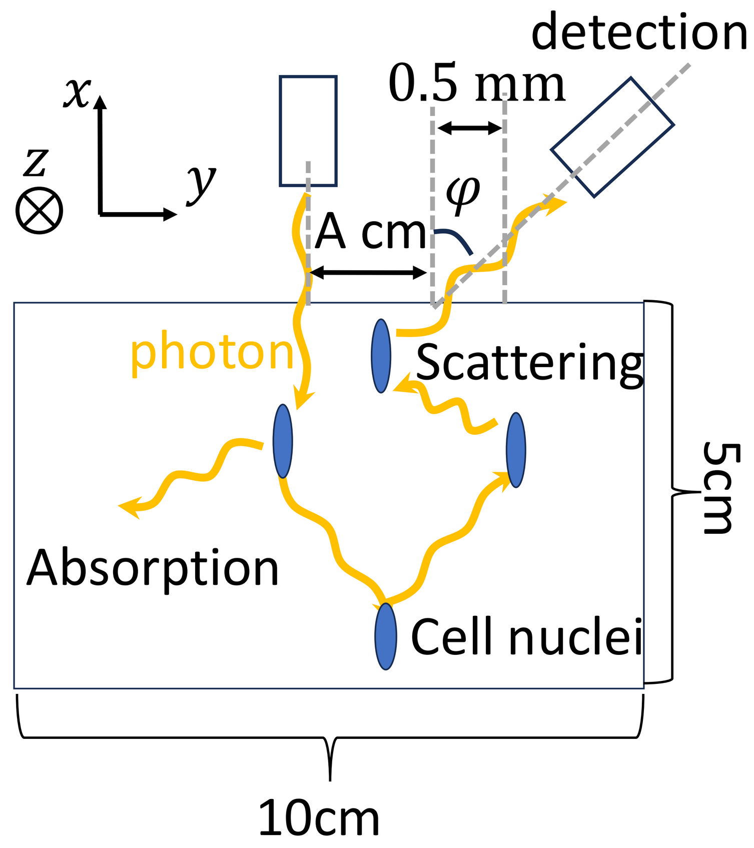
We perform 3D radiative transfer **using the single scattering results.**

- Right-handed circularly polarized light is incident
- wavelength : 600nm, 950nm

- Basic equation

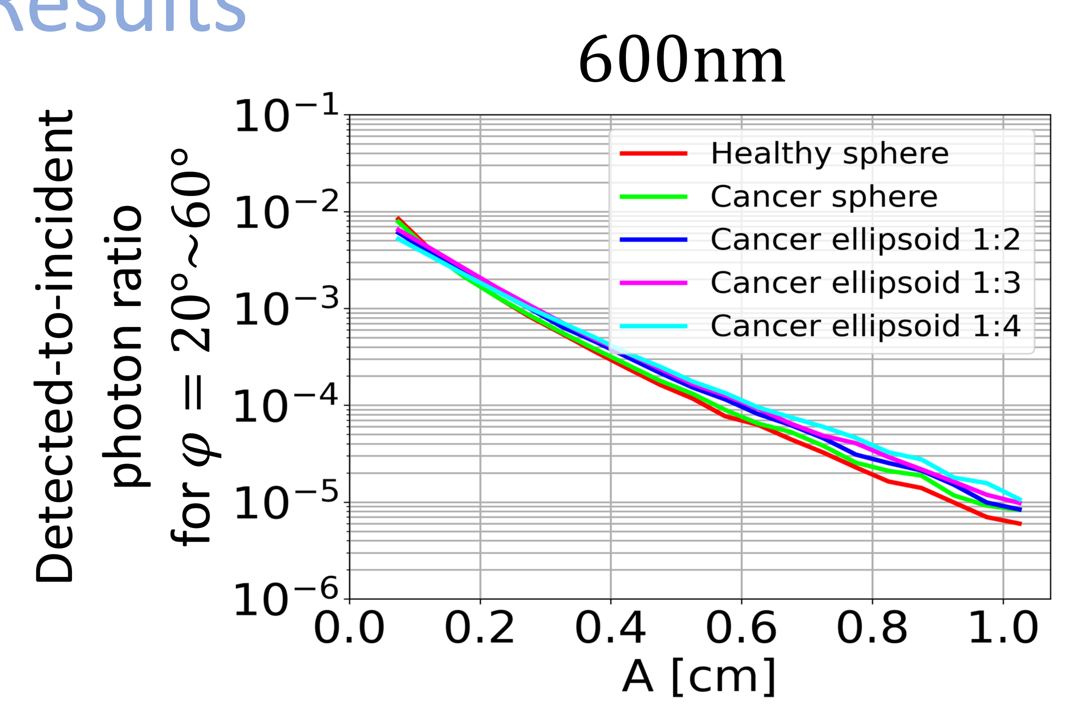
$$\frac{dI_\nu}{ds} = -(\nu_a + \nu_s)I_\nu + \nu_s \int I_\nu(\Omega')P(\Omega', \Omega)d\Omega$$

Absorption coefficient, scattering coefficient, intensity, phase function

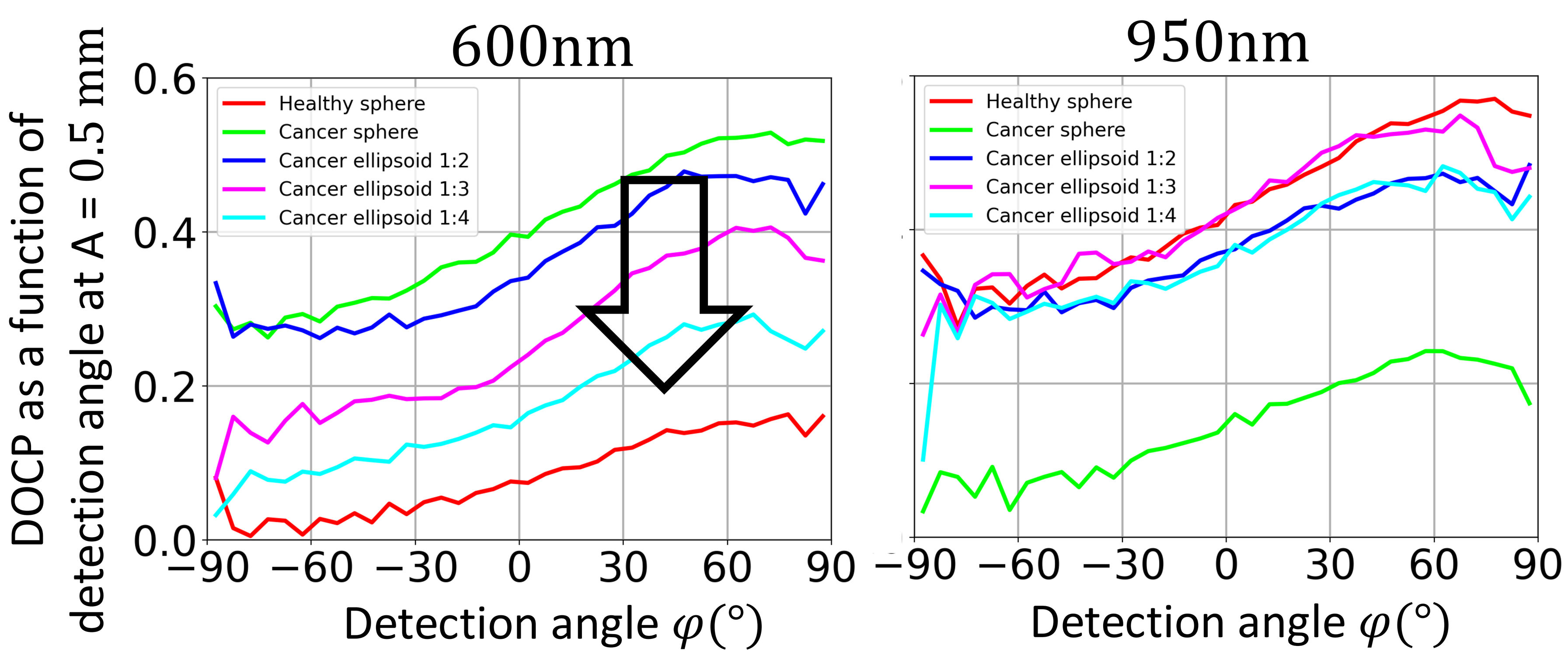


- Coefficient(Nishizawa et al. 2022)
  - ✓ 600nm : $\nu_a = 0.60\text{cm}^{-1}, \nu_s = 143\text{cm}^{-1}$
  - ✓ 950nm : $\nu_a = 0.35\text{cm}^{-1}, \nu_s = 76\text{cm}^{-1}$
- The particle and matrix refractive indices are 1.59 and 1.33
- Models:
  - ✓Healthy : 5.9 μm sphere
  - ✓Cancer: 11μm sphere and x-aligned ellipsoids (1:2, 1:3, 1:4)
- For all models, 10^7 photons are injected, assuming nuclei are uniformly distributed.

Results



The number of detected photons is similar across all models at each distance and wavelength.



As the ellipsoidal aspect ratio increases, the DOCP gradually decreases.

Even when the aspect ratio changes, the DOCP becomes comparable to that of healthy cells.

At 600 nm, the DOCP differences among axial size ratios remain distinguishable, suggesting potential shape discrimination after tissue propagation.

Conclusions

- We analyzed single scattering from ellipsoidal nuclei and used 3D radiative transfer to assess how circular polarization propagates through tissue.
- At 600 nm, DOCP is shape-sensitive, enabling discrimination of axial size ratios
- Even after 3D radiative transfer, detectable polarization survives, supporting its diagnostic potential even for prolate ellipsoids.