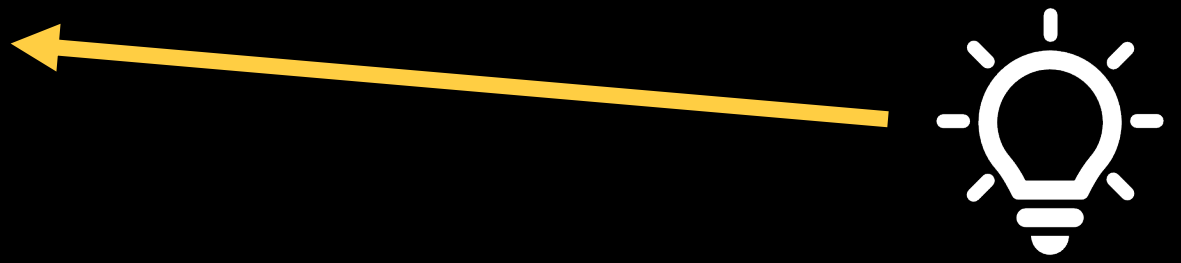
SIGGRAPH THINK BEYOND

2020 S2020.SIGGRAPH.ORG

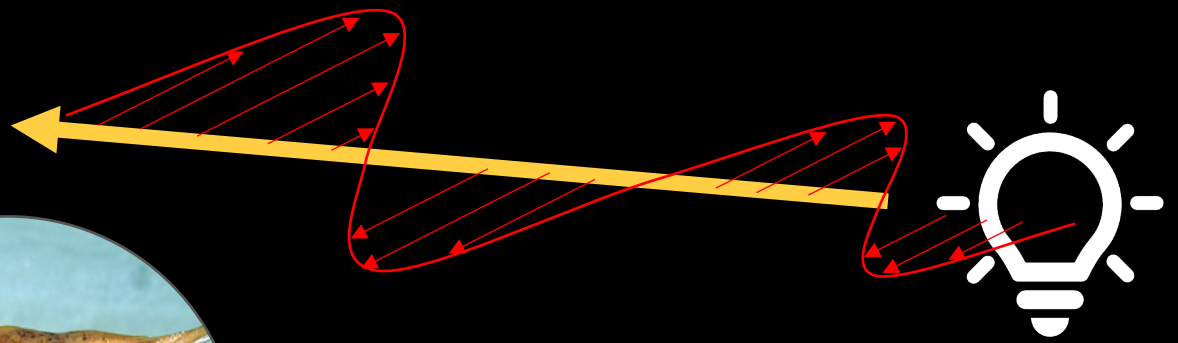
IMAGE-BASED ACQUISITION AND MODELING OF POLARIMETRIC REFLECTANCE

Seung-Hwan Baek, Tizian Zeltner, Hyun Jin Ku,
Inseung Hwang, Xin Tong, Wenzel Jakob, Min H. Kim

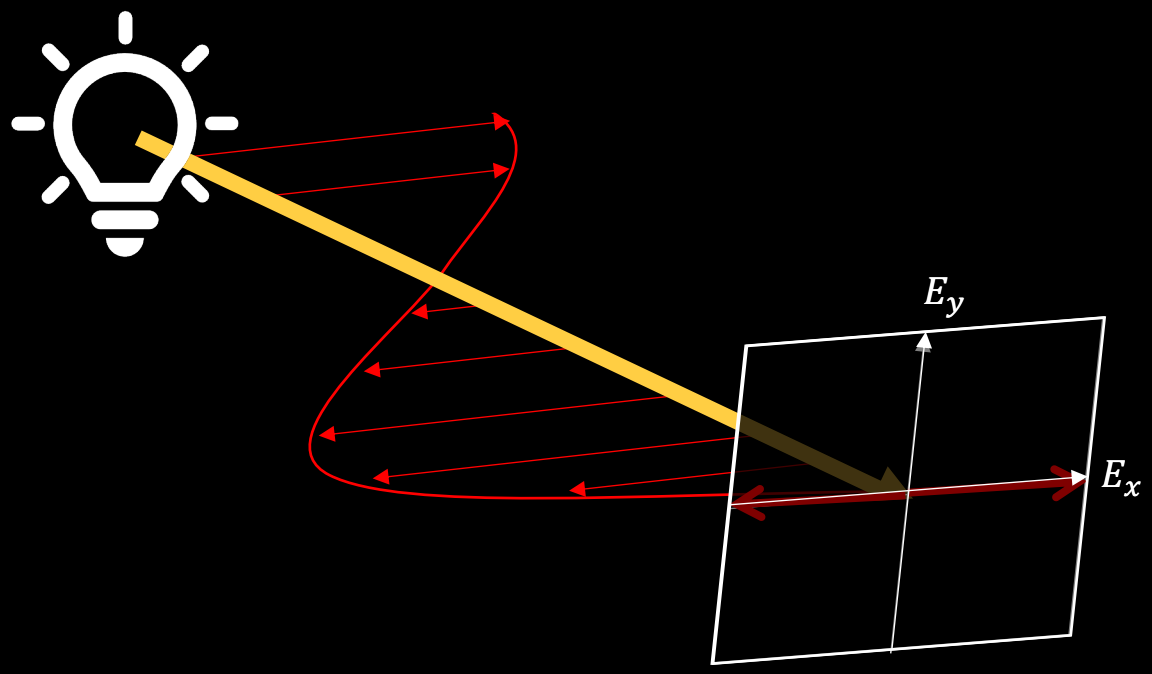
Human vision senses light

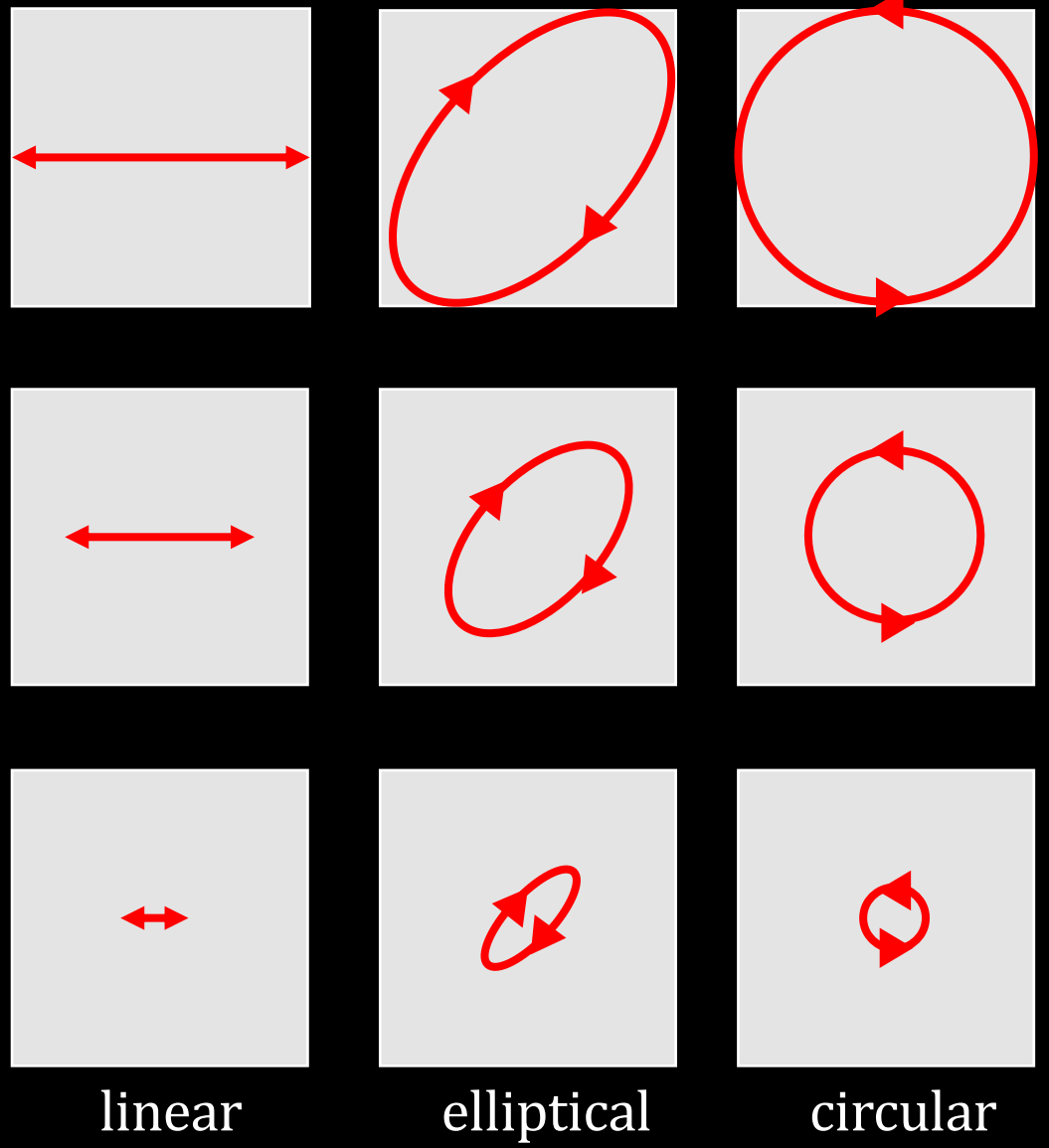


Light “wave”

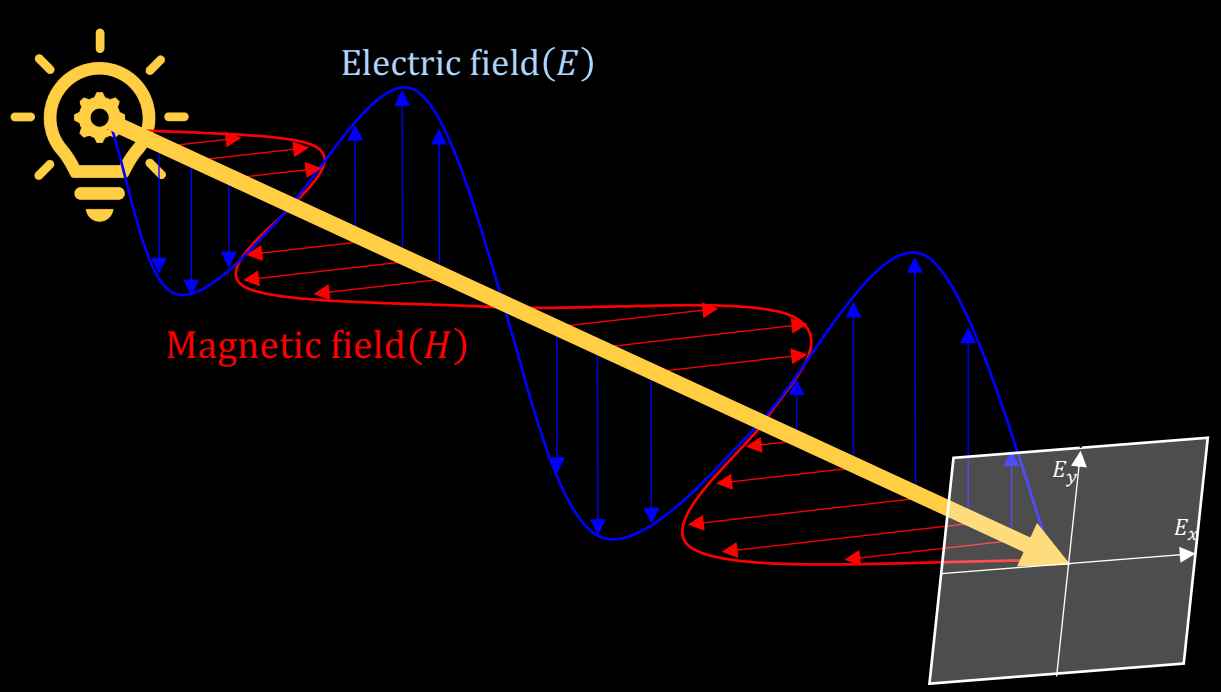


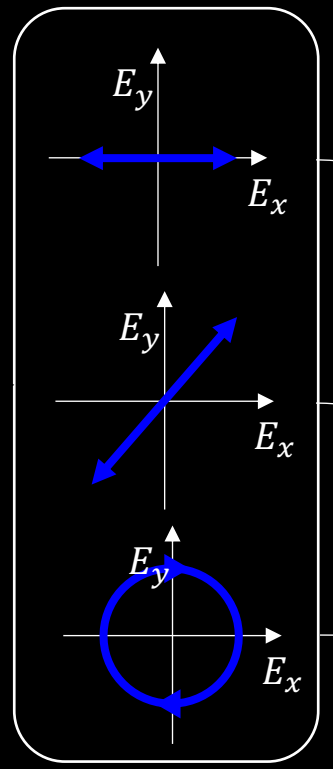
Polarization





Stokes Vector





Geometric orientation of
the E-field's oscillation

$$\begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix}$$

Overall Intensity

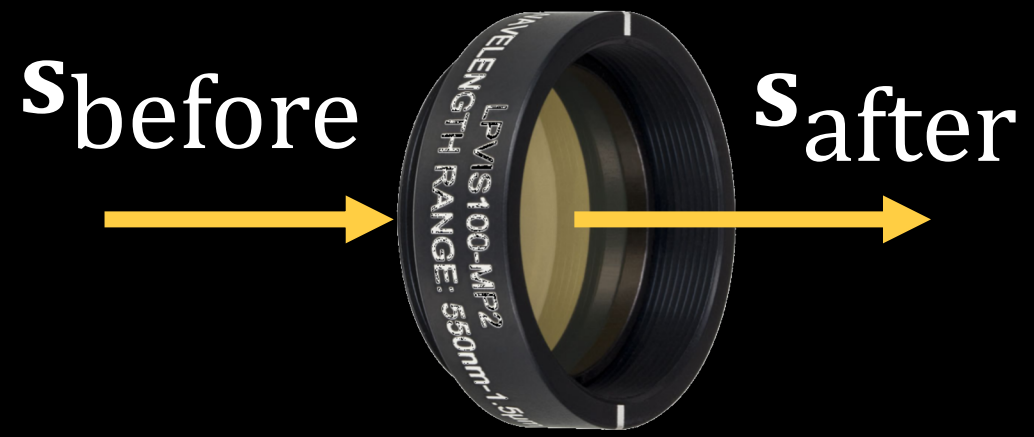
0 degree

45 degree

Circular

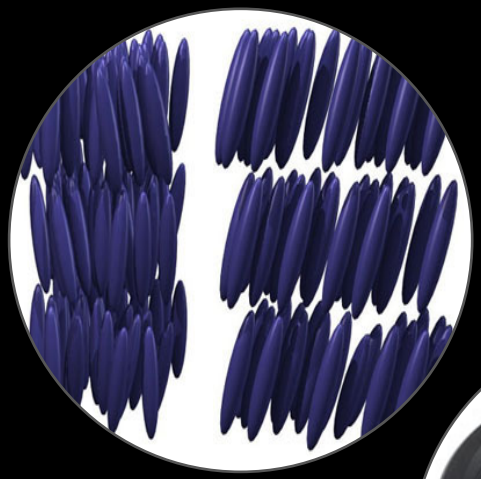
Mueller Matrix

$$\mathbf{M} = \begin{bmatrix} M_{00} & M_{01} & M_{02} & M_{03} \\ M_{10} & M_{11} & M_{12} & M_{13} \\ M_{20} & M_{21} & M_{22} & M_{23} \\ M_{30} & M_{31} & M_{32} & M_{33} \end{bmatrix}$$



$$\mathbf{s}_{\text{after}} = \mathbf{M}\mathbf{s}_{\text{before}}$$

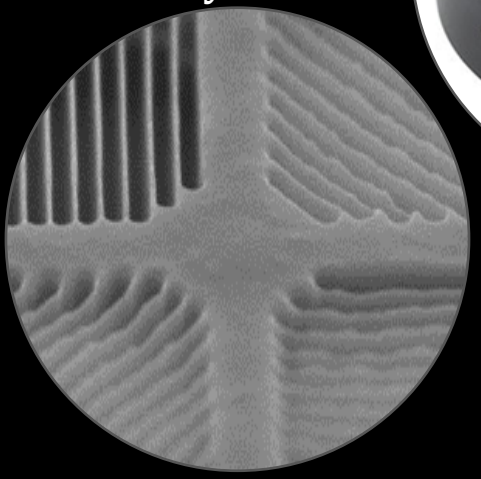
Polarization imaging



Liquid crystal

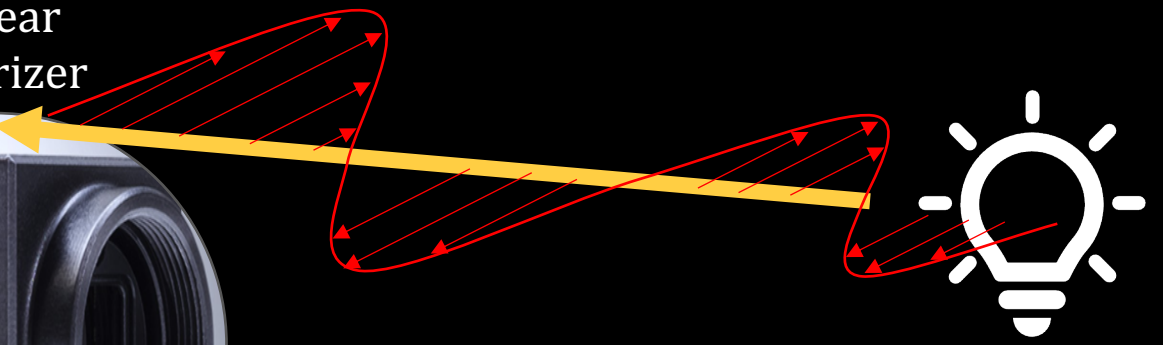
Linear polarizer

Quarter wave plate

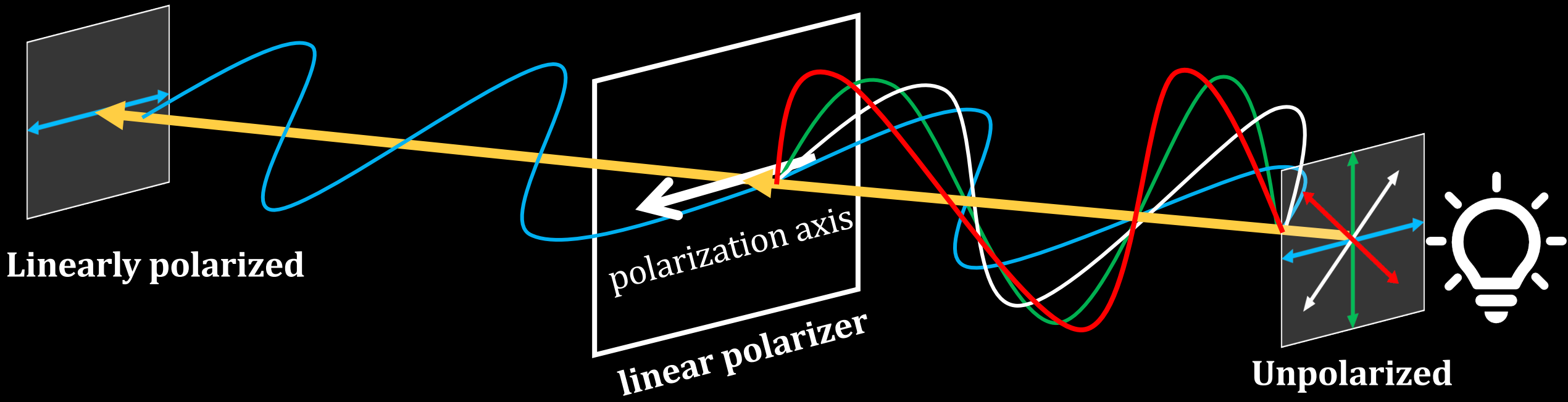


Polarization sensor

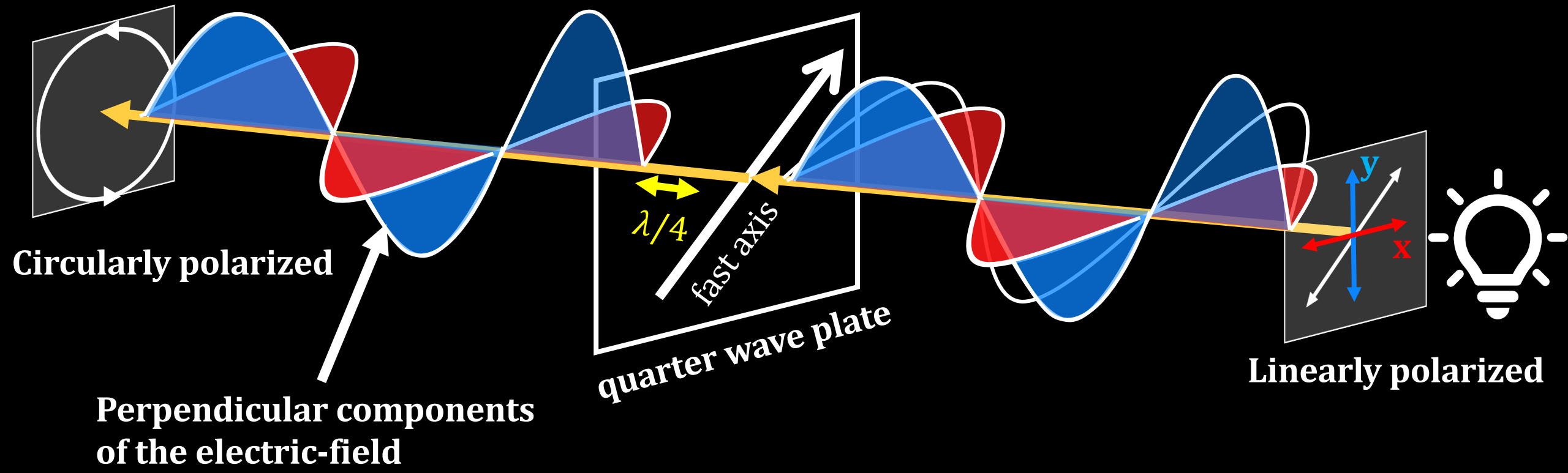
Polarization camera



Linear polarizer

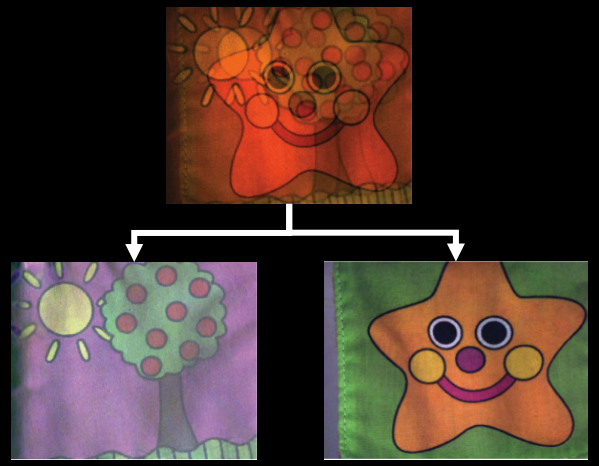


Quarter wave plate

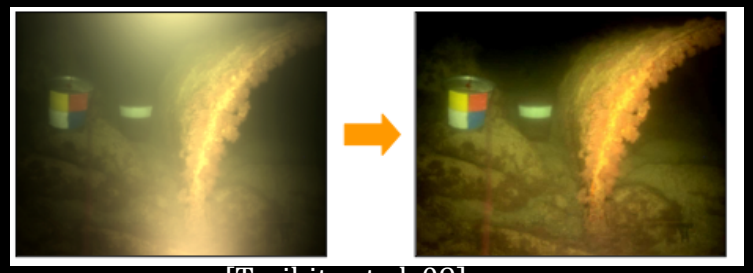


Polarization imaging for scene analysis

Reflection removal and descattering

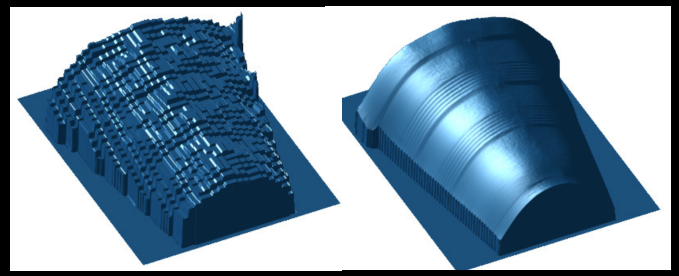


[Schechner et al. 99]



[Treibitz et al. 09]

Shape and appearance acquisition

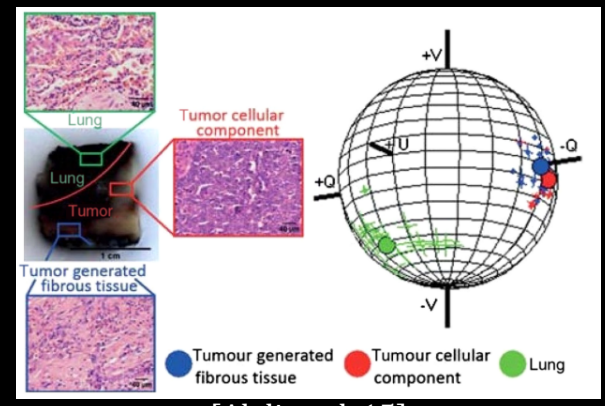


[Kadambi 15]

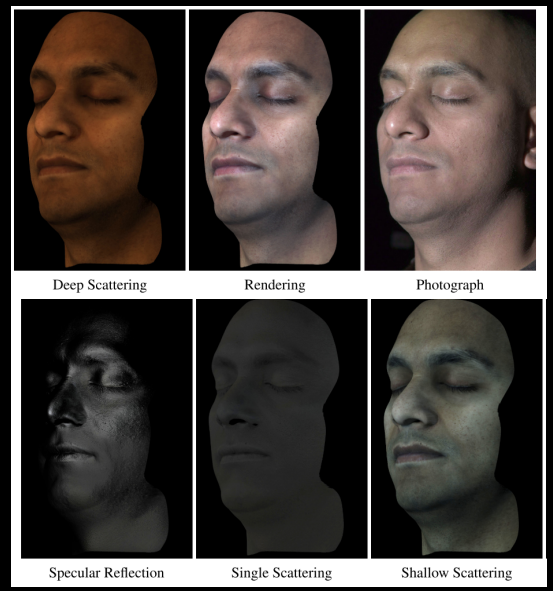
[Chen et al. 07]

[Baek et al. 18]

Segmentation

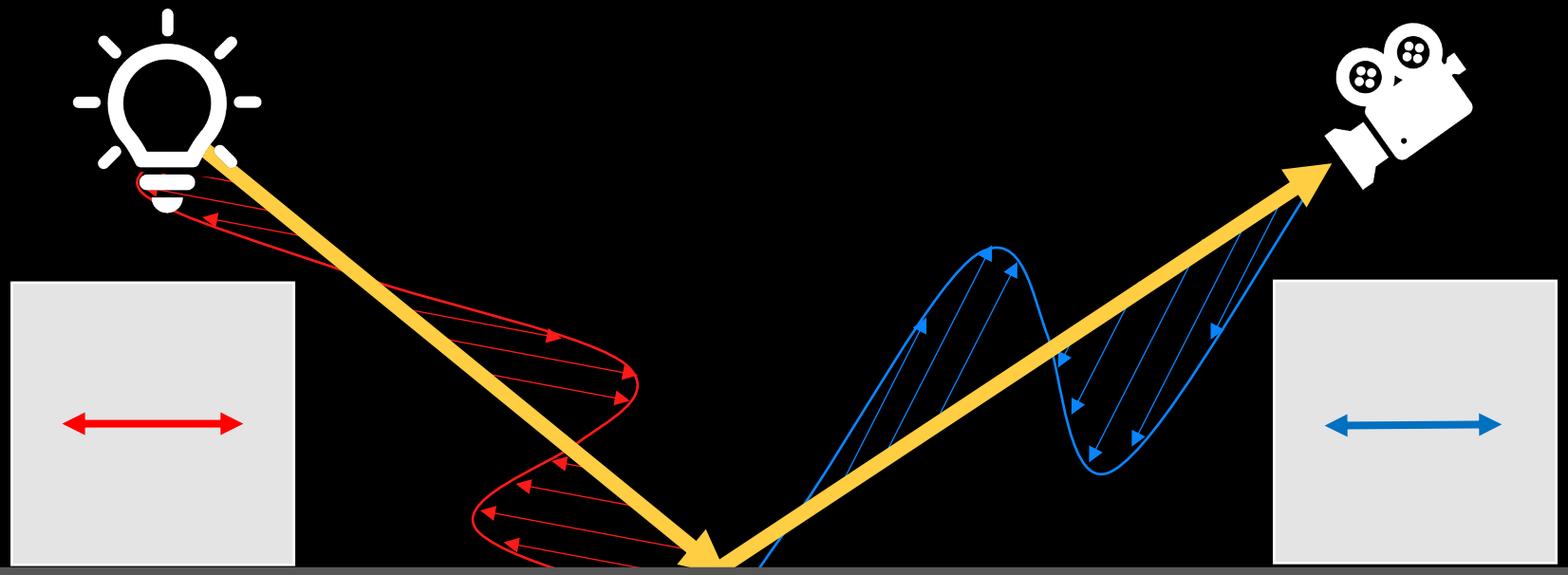


[Alali et al. 15]



[Ghosh et al. 08]

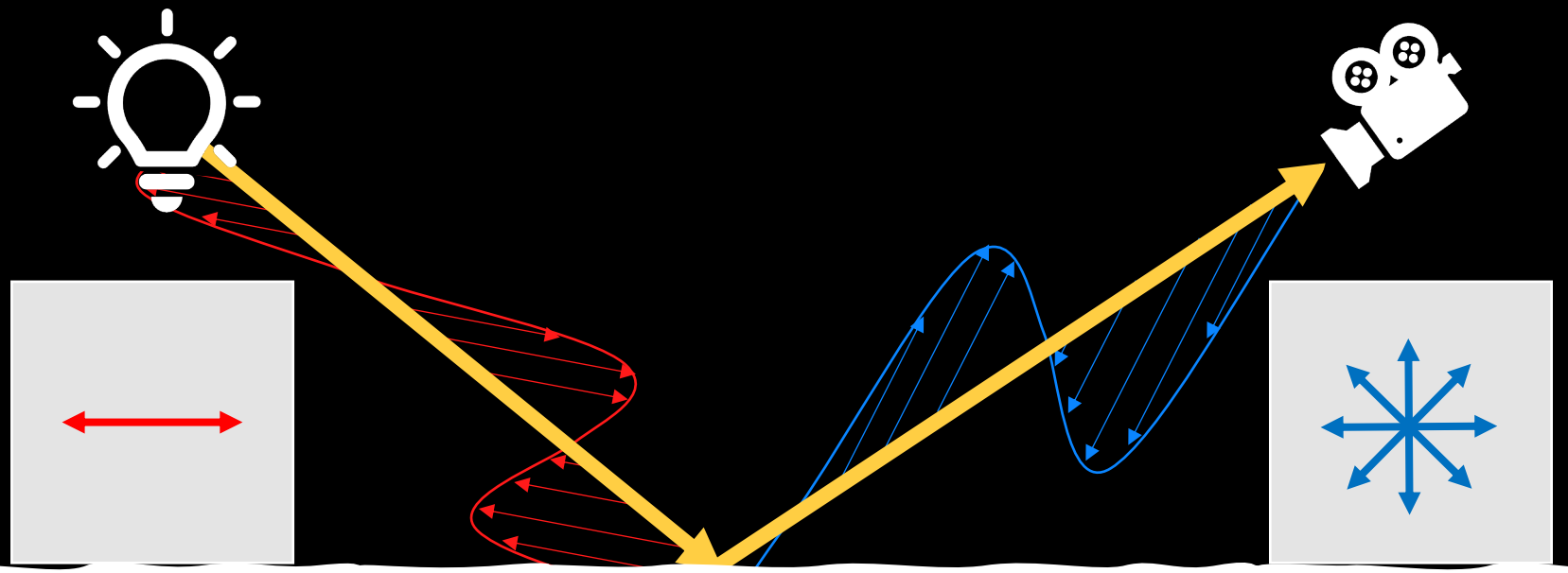
Polarization changes by reflection



Ideal mirror

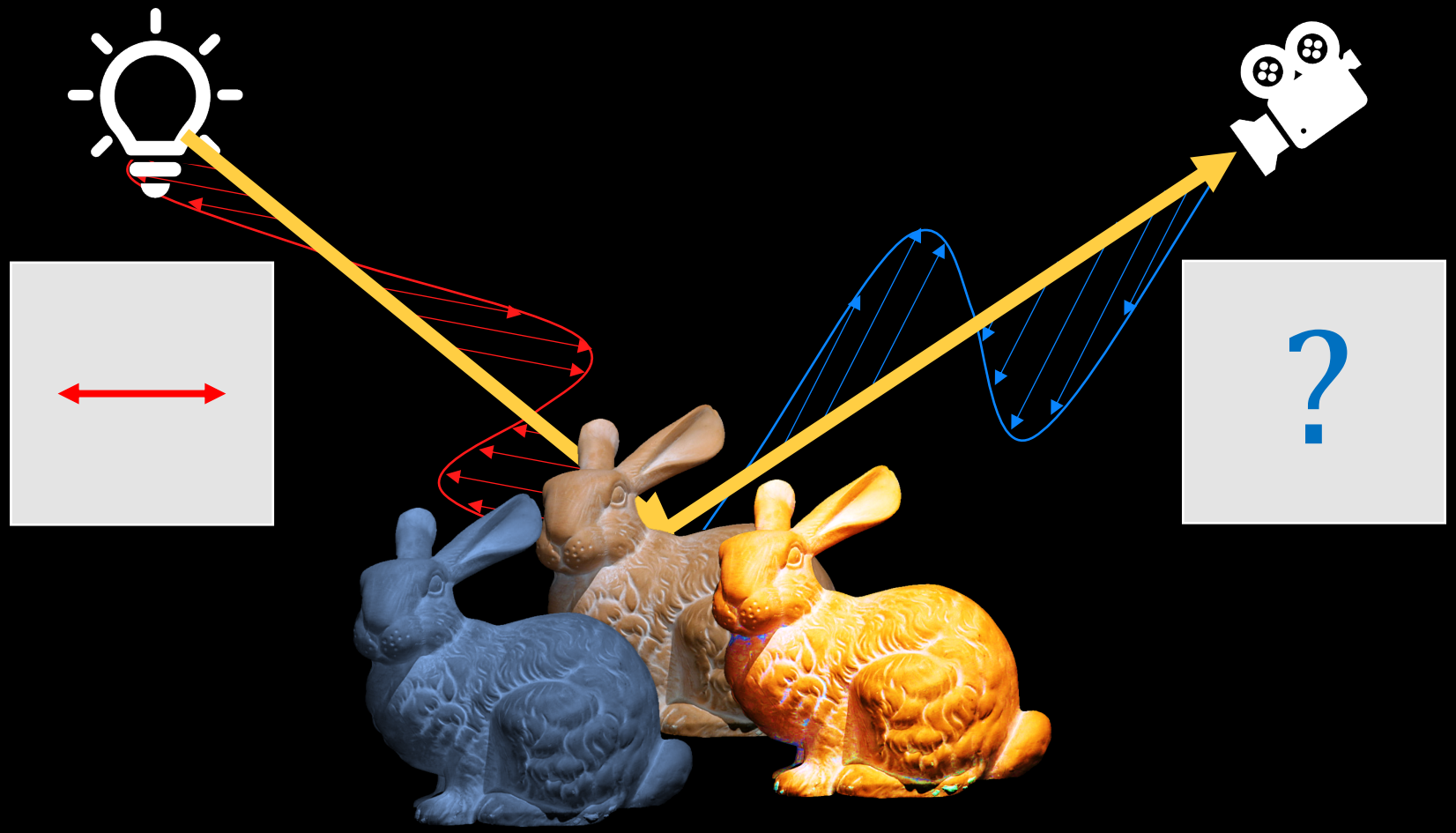
Fresnel reflection

Polarization changes by reflection



Ideal diffuse surface

Polarization changes by reflection

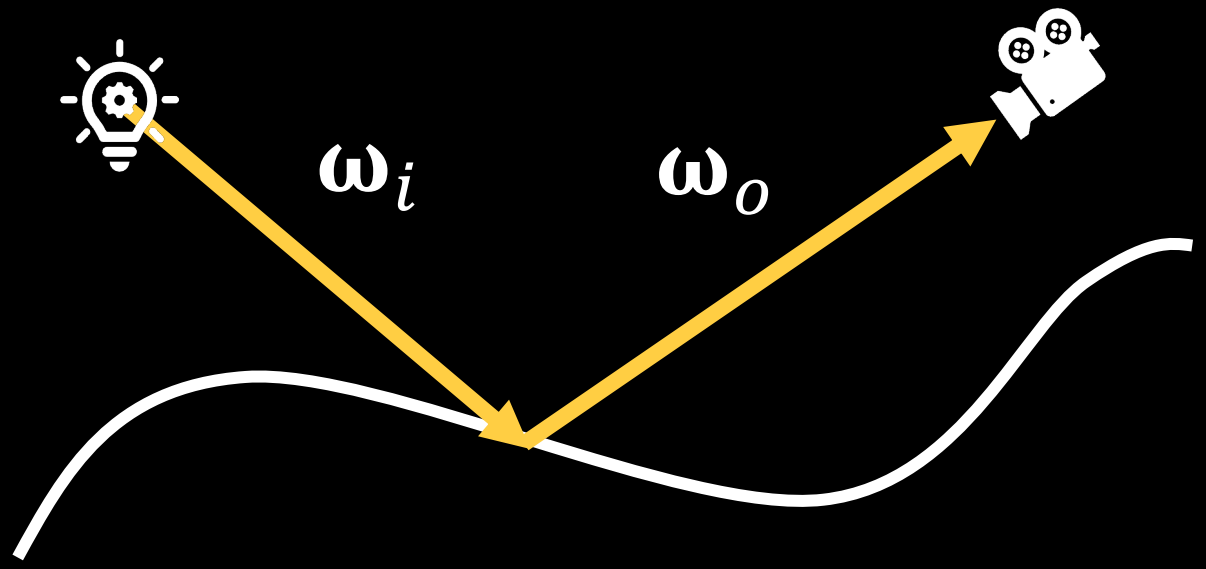


Real-world material

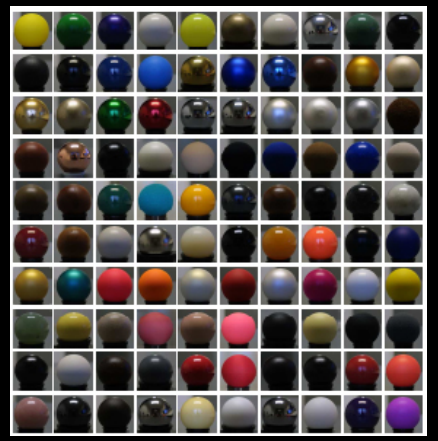
BRDF
- *Bidirectional Reflectance Distribution Function*

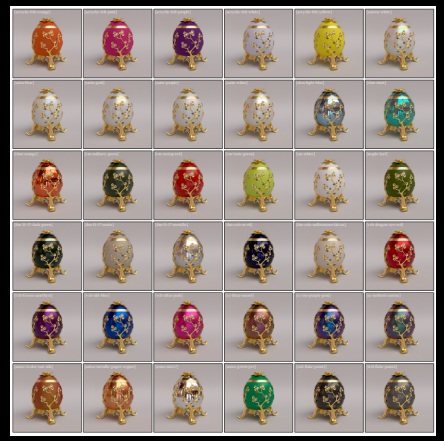
$$f(\lambda, \boldsymbol{\omega}_i, \boldsymbol{\omega}_o) \in \mathbb{R}^{1\times 1}$$

$\boldsymbol{\omega}_i$: incident light direction
$\boldsymbol{\omega}_o$: exitant light direction
λ: wavelength



Dataset


MERL

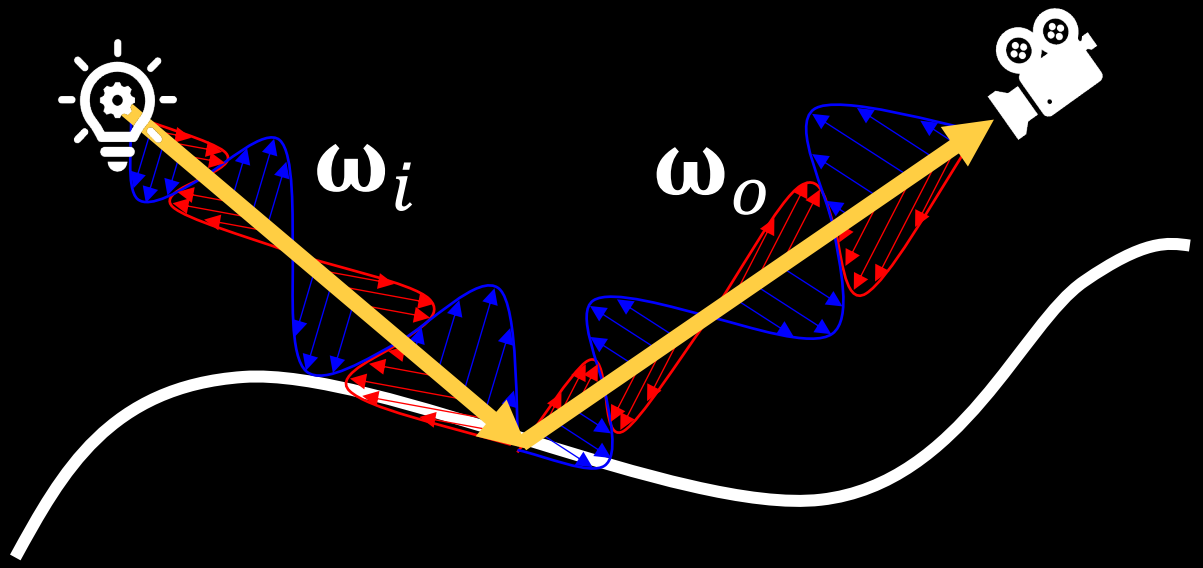

Dupuy and Jakob

- Understanding of BRDF
- Analytic modeling
- Forward/inverse rendering

pBRDF
- *Polarimetric BRDF*

$$\mathbf{M}(\lambda, \boldsymbol{\omega}_i, \boldsymbol{\omega}_o) \in \mathbb{R}^{4\times4}$$

$\boldsymbol{\omega}_i$: incident light direction
$\boldsymbol{\omega}_o$: exitant light direction
λ: wavelength



Dataset

[Riviere et al.], [Wellems et al.], [Boher et al.]

- Limited directional coverage
- Incomplete polarization change
- A few materials
- Not publicly available

- Understanding of pBRDF
- Analytic modeling
- Forward/inverse rendering

First comprehensive pBRDF dataset

- large directional coverage
- complete polarization change
- 25 real-world materials

Acquisition system - design goals

1. Direction

full coverage
for analysis and rendering

2. Polarization

complete change of polarization

3. Spectrum

narrow-spectral band

4. Capture time

reasonable amount of capture time

Solutions

Image-based acquisition
[Matusik et al. 03]

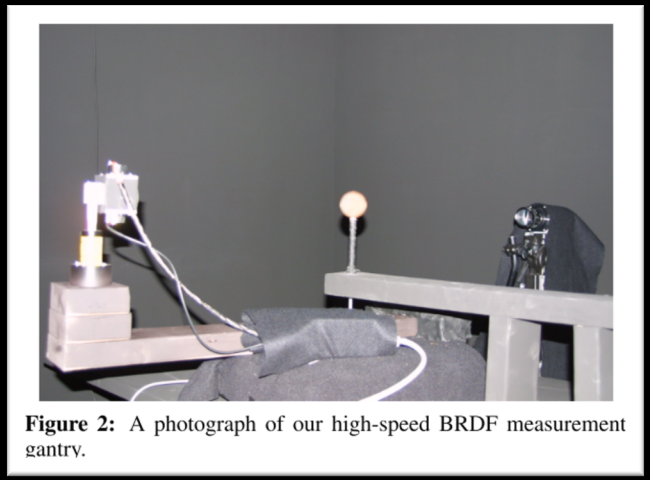


Figure 2: A photograph of our high-speed BRDF measurement gantry.

+

Spectroscopic ellipsometry
[Azzam et al. 78]

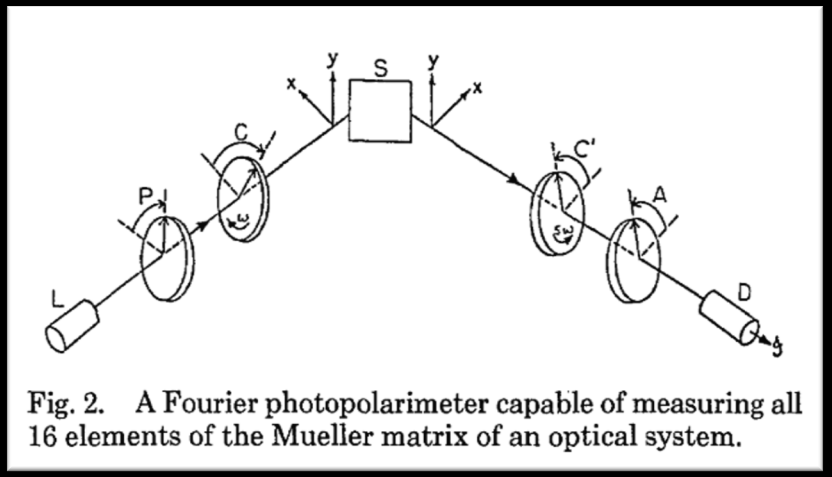
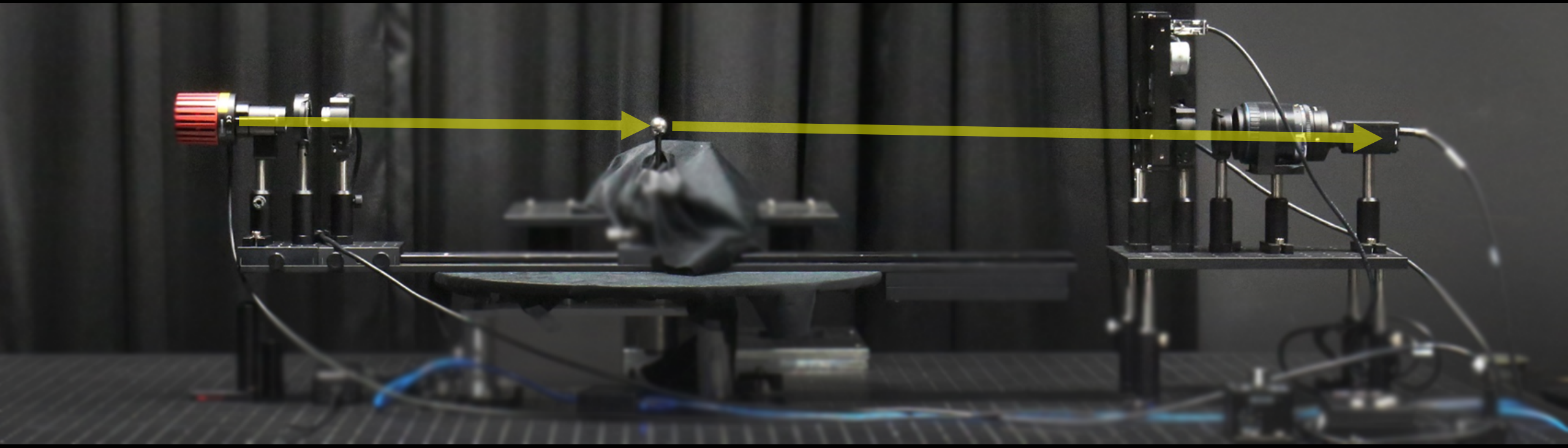


Fig. 2. A Fourier photopolarimeter capable of measuring all 16 elements of the Mueller matrix of an optical system.

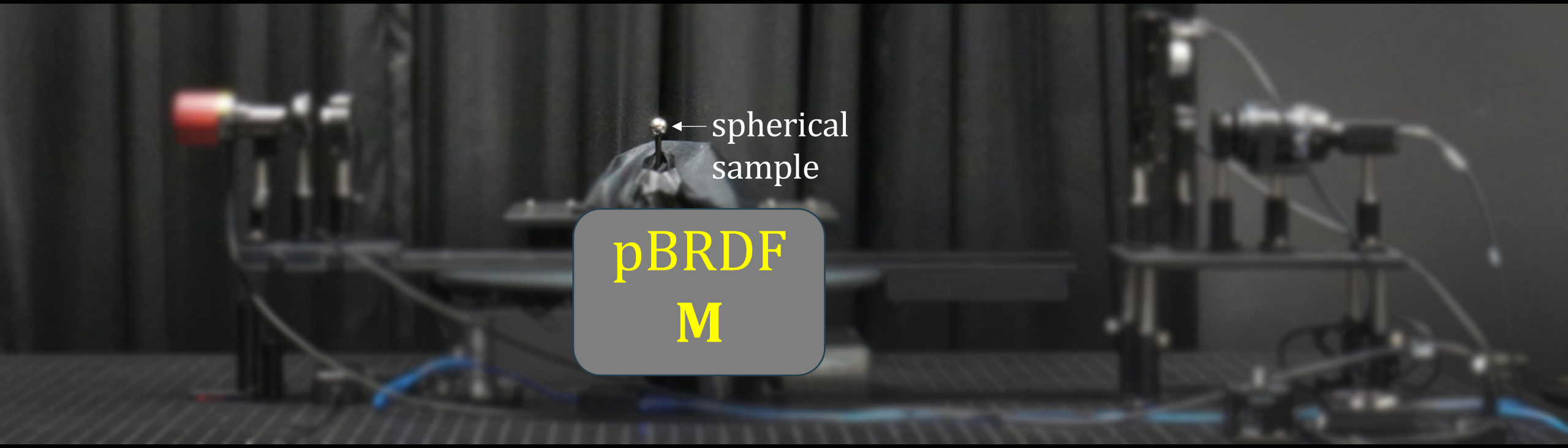
Capture time

3 days per material

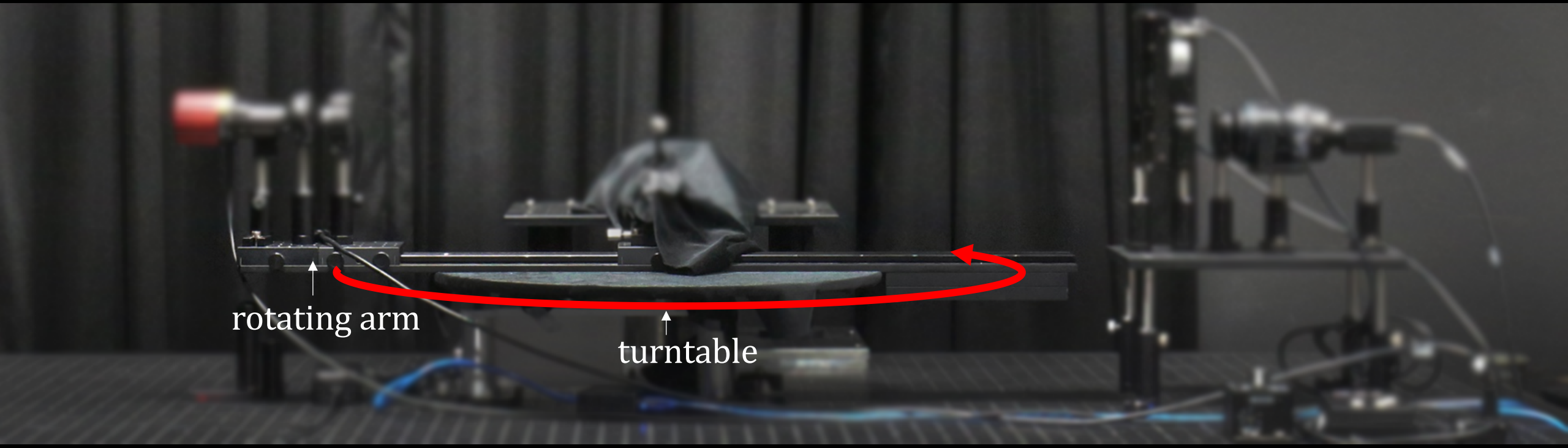
Our acquisition system



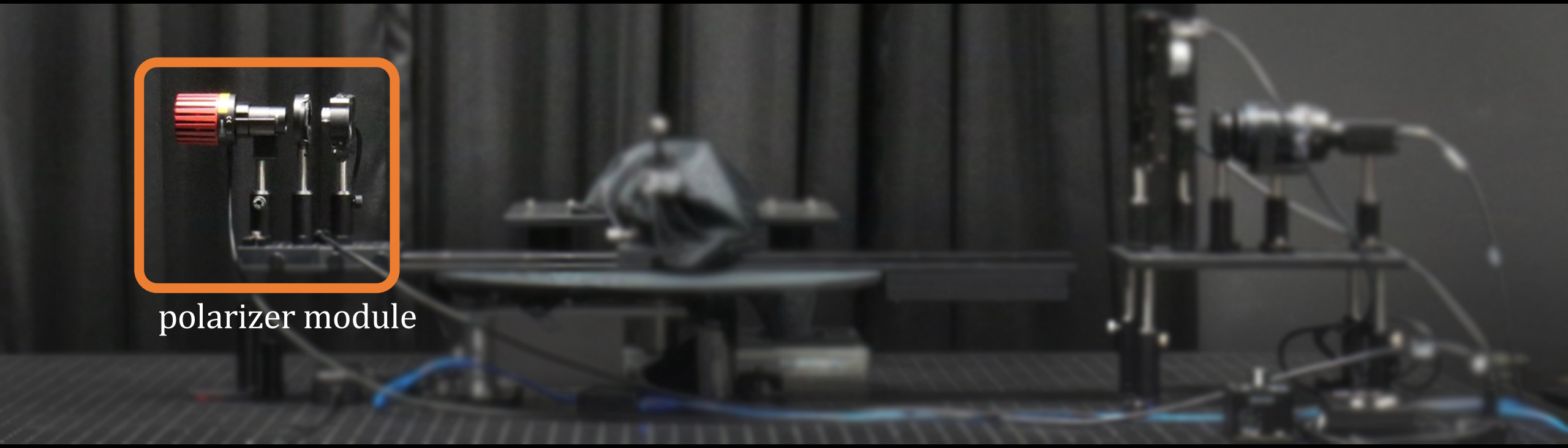
Homogeneous spherical sample



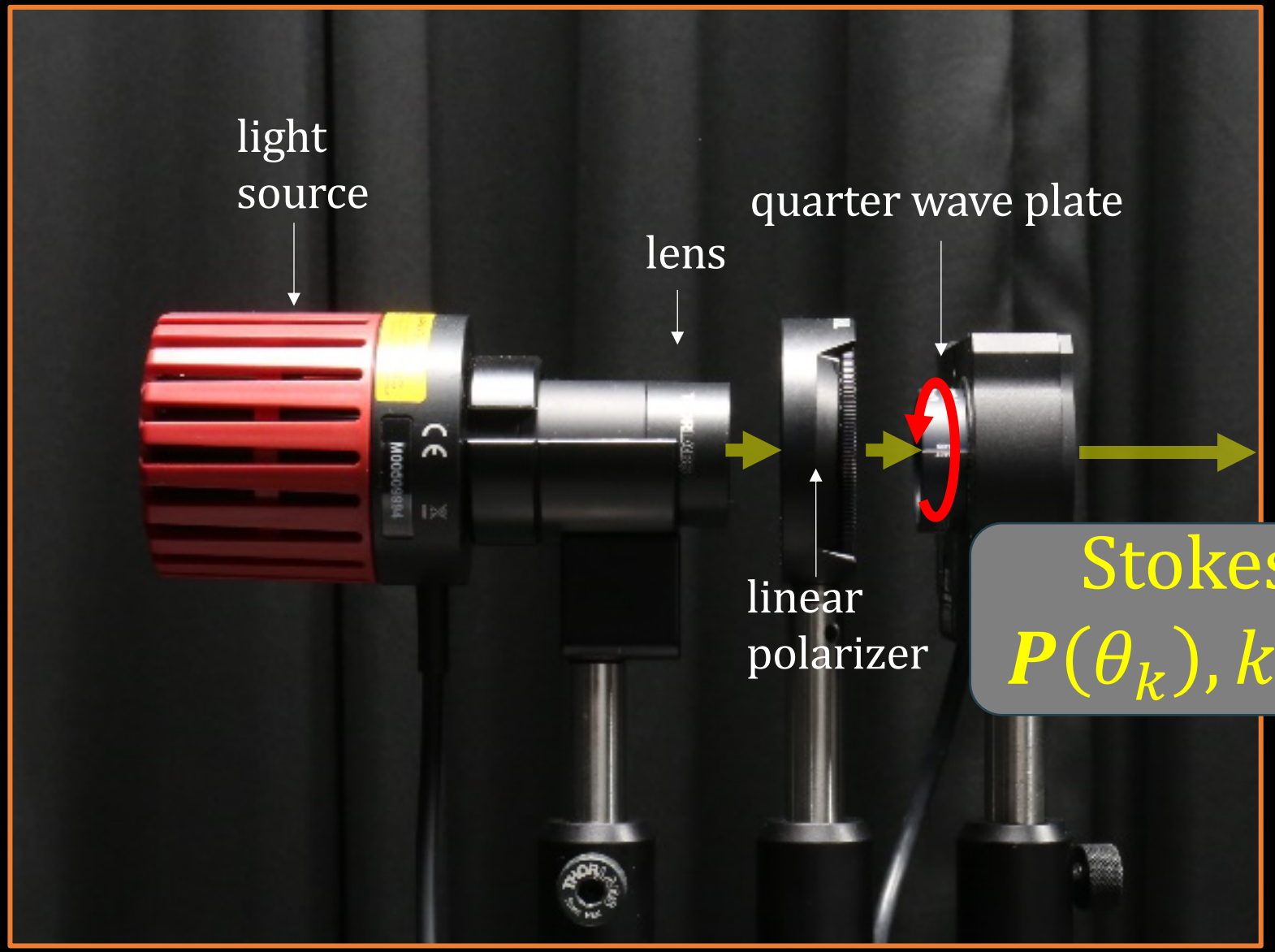
Turntable



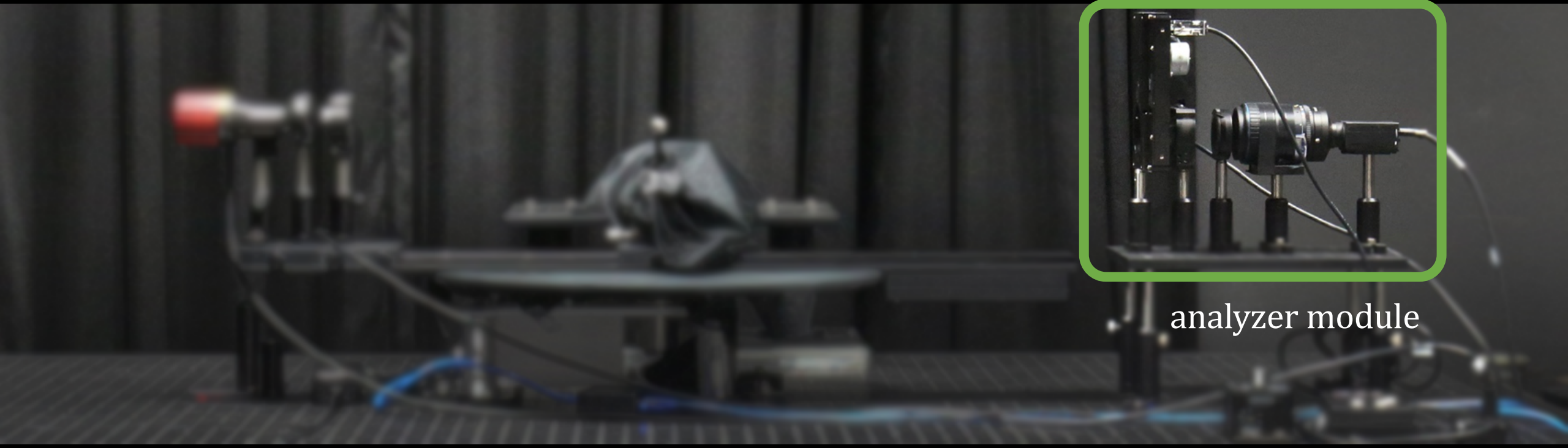
Polarizer module



Polarizer module

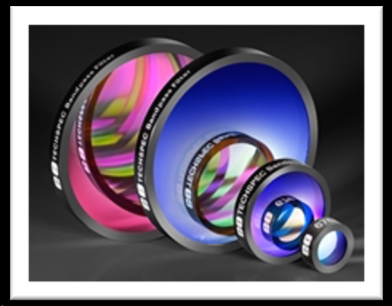


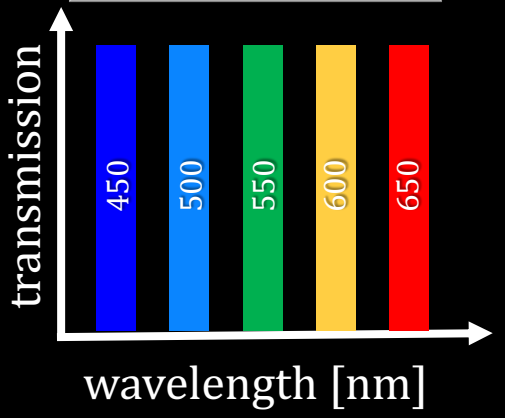
Analyzer module

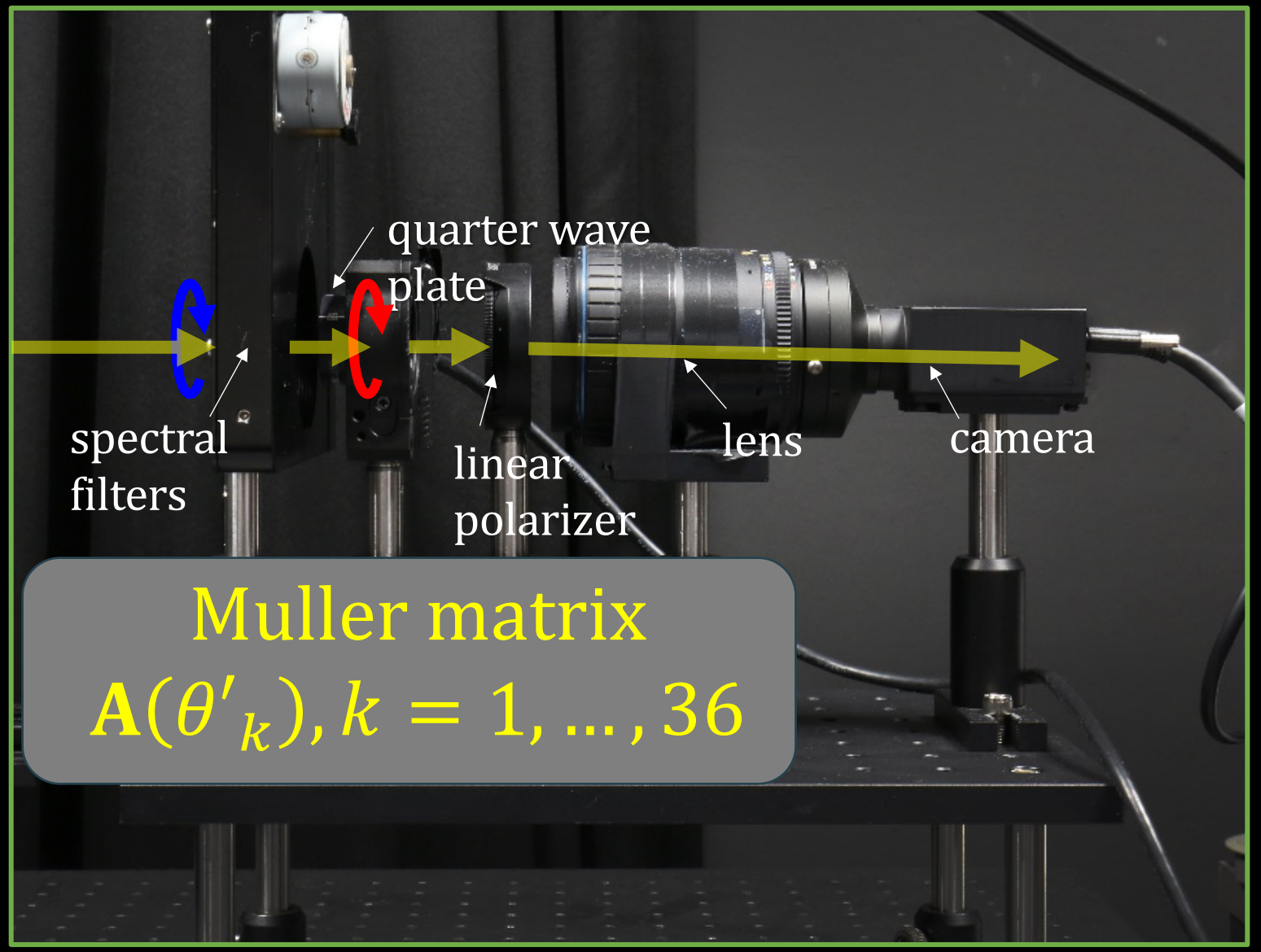


analyzer module

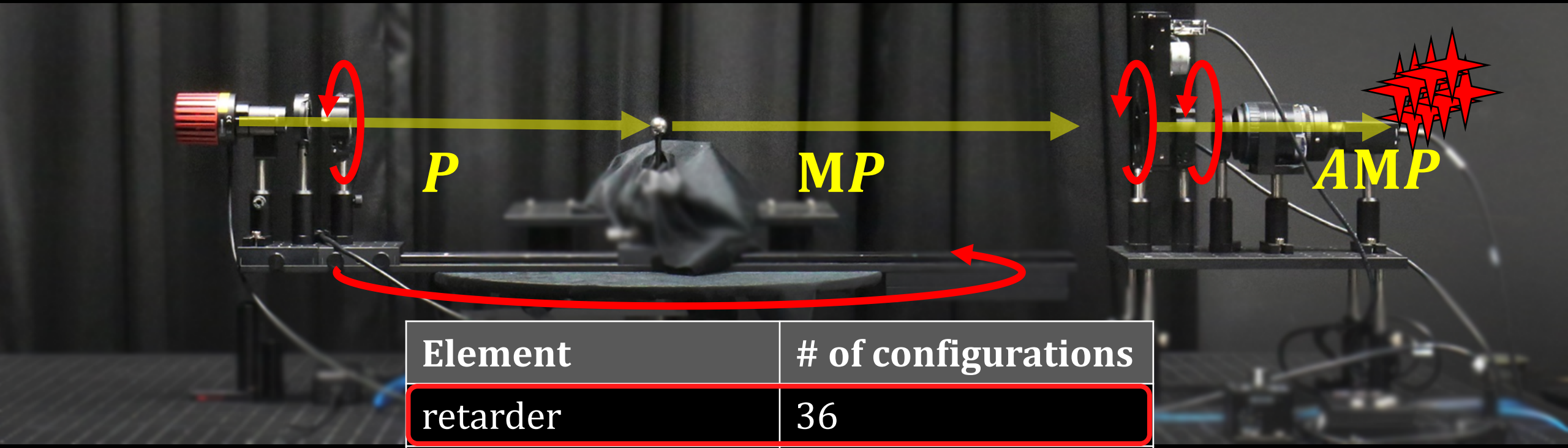
Analyzer module







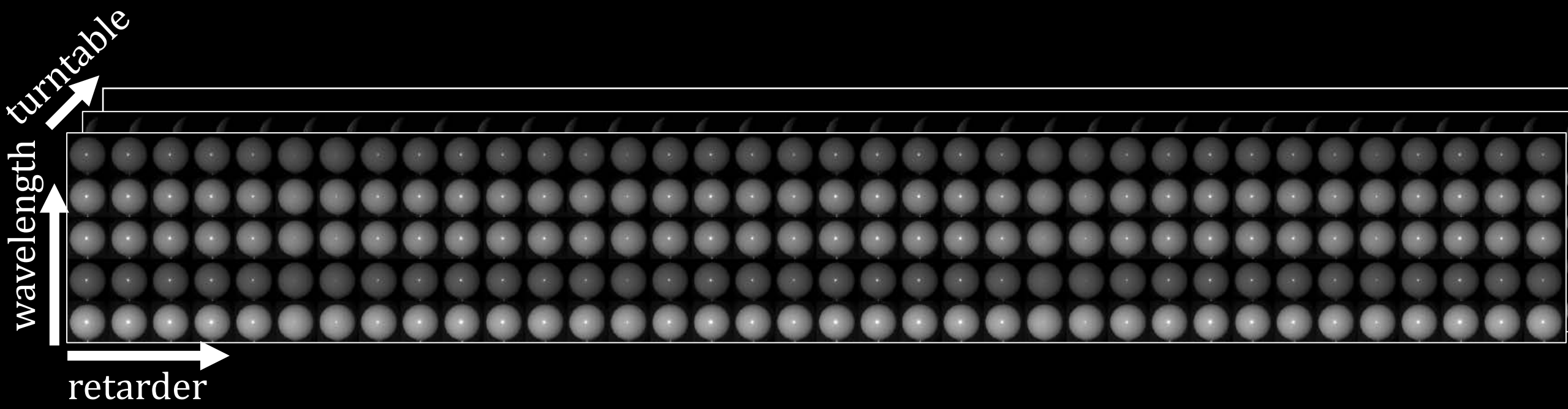
Multiple configurations



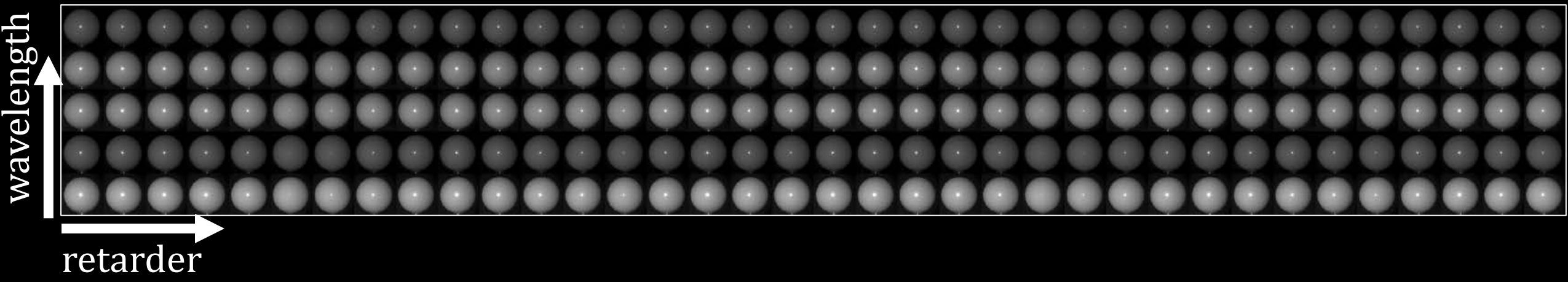
Element	# of configurations
retarder	36
turntable	147
spectral filter	5
exposure	8

Captured data

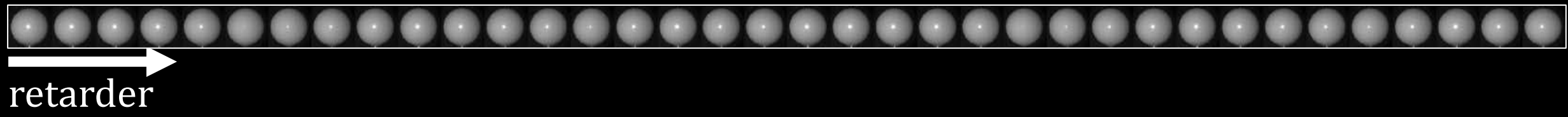
Captured data to Mueller matrix



For each turntable angle



For each turntable angle, wavelength



retarder

For each turntable angle, wavelength, pixel

Captured data to Mueller matrix

For each turntable angle, wavelength, pixel

captured

$f(\theta_k)$

* known
* unknown

Captured data to Mueller matrix

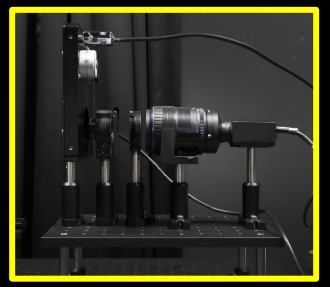
For each turntable angle, wavelength, pixel

captured

$f(\theta_k)$

analyzing optics

$\boldsymbol{A}(\boldsymbol{\theta'}_k)$



* known
* unknown

Captured data to Mueller matrix

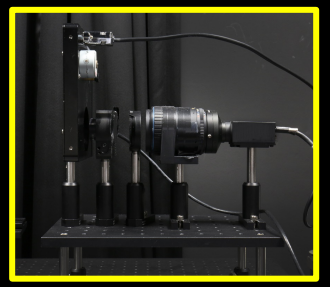
For each turntable angle, wavelength, pixel

captured

$f(\theta_k)$

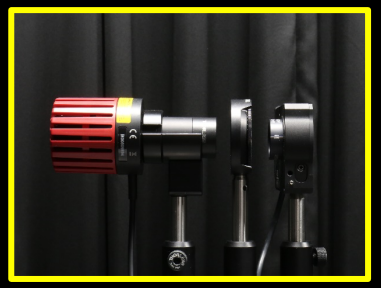
analyzing optics

$\boldsymbol{A}(\boldsymbol{\theta'}_k)$



polarizing optics

$\boldsymbol{P}(\boldsymbol{\theta}_k)$



* known

* unknown

Captured data to Mueller matrix

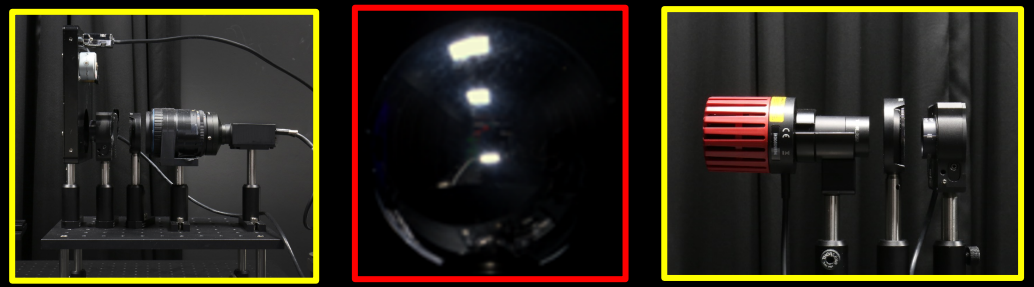
For each turntable angle, wavelength, pixel

captured

$$f(\theta_k)$$

analyzing optics pBRDF polarizing optics

$$\boldsymbol{A}(\boldsymbol{\theta'}_k)\,\mathbf{M}\,\boldsymbol{P}(\boldsymbol{\theta}_k)$$



* known
* unknown

Captured data to Mueller matrix

For each turntable angle, wavelength, pixel

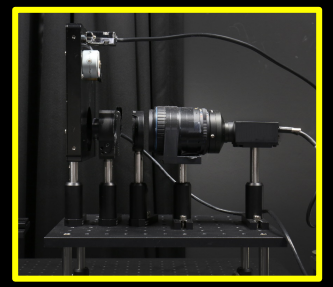
$$\text{minimize}_{\mathbf{M}} \sum_{k=1}^{36} \{ f(\theta_k) - [\boldsymbol{A}(\boldsymbol{\theta'}_k)\,\mathbf{M}\,\boldsymbol{P}(\boldsymbol{\theta}_k)]_{\mathbf{0}} \}^2$$

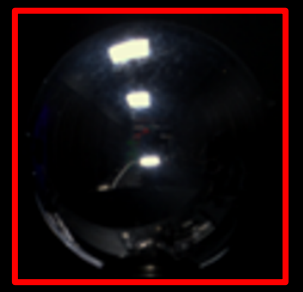
captured

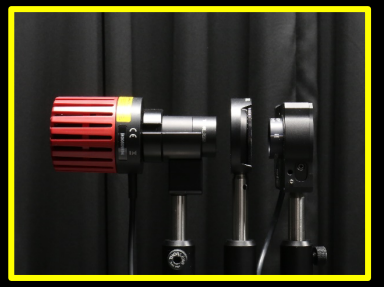
analyzing optics

pBRDF

polarizing optics



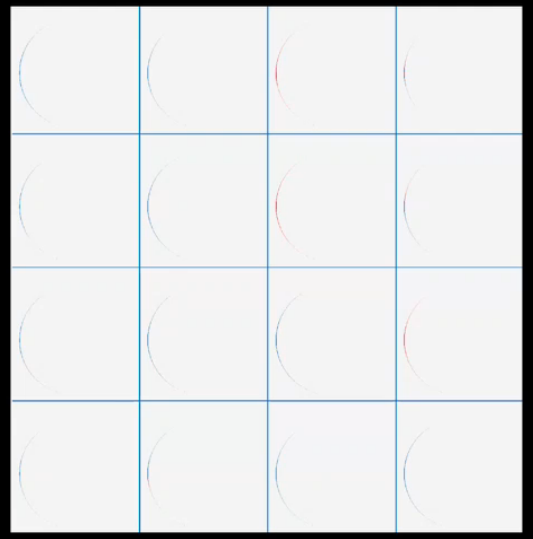




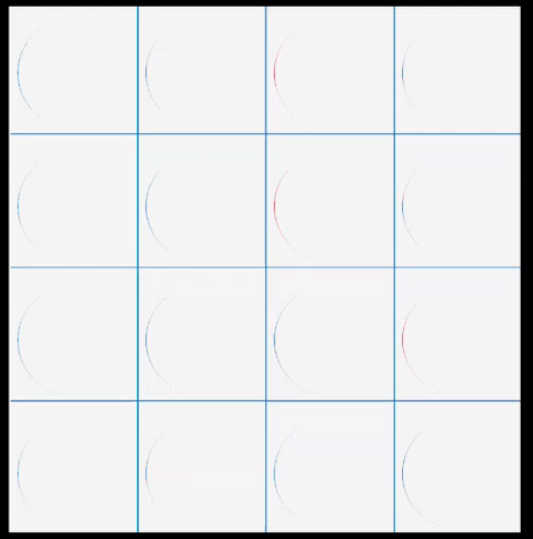
* known
* unknown

Reconstructed per-pixel pBRDF

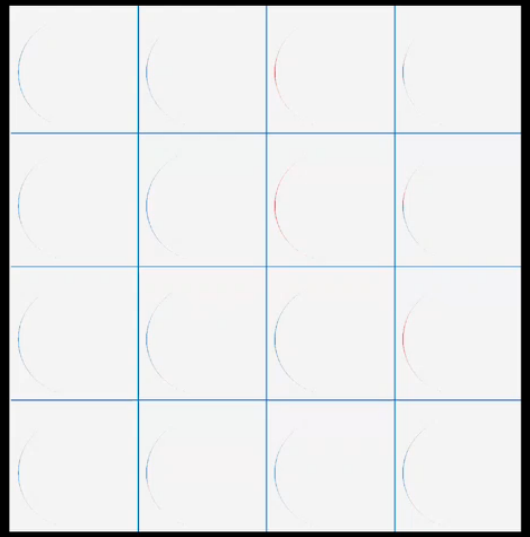
Reconstructed per-pixel pBRDF: gold



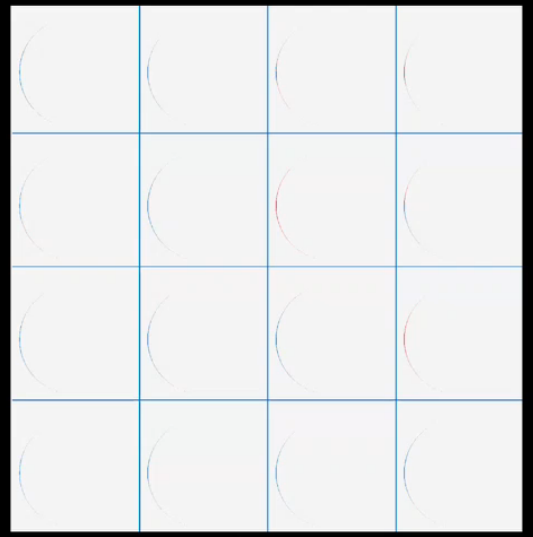
450nm



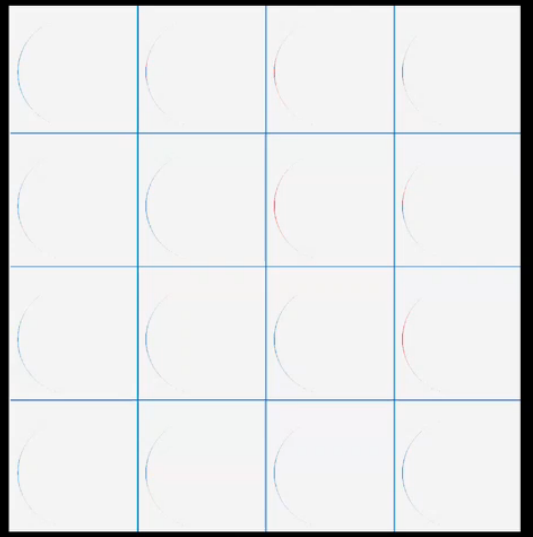
500nm



550nm



600nm



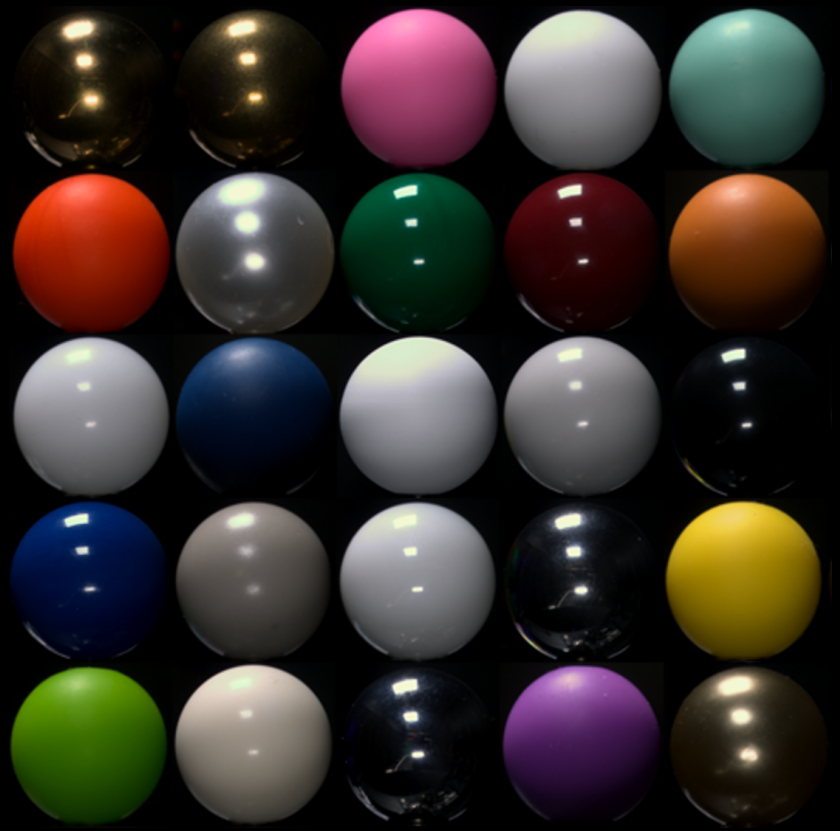
650nm

pBRDF dataset

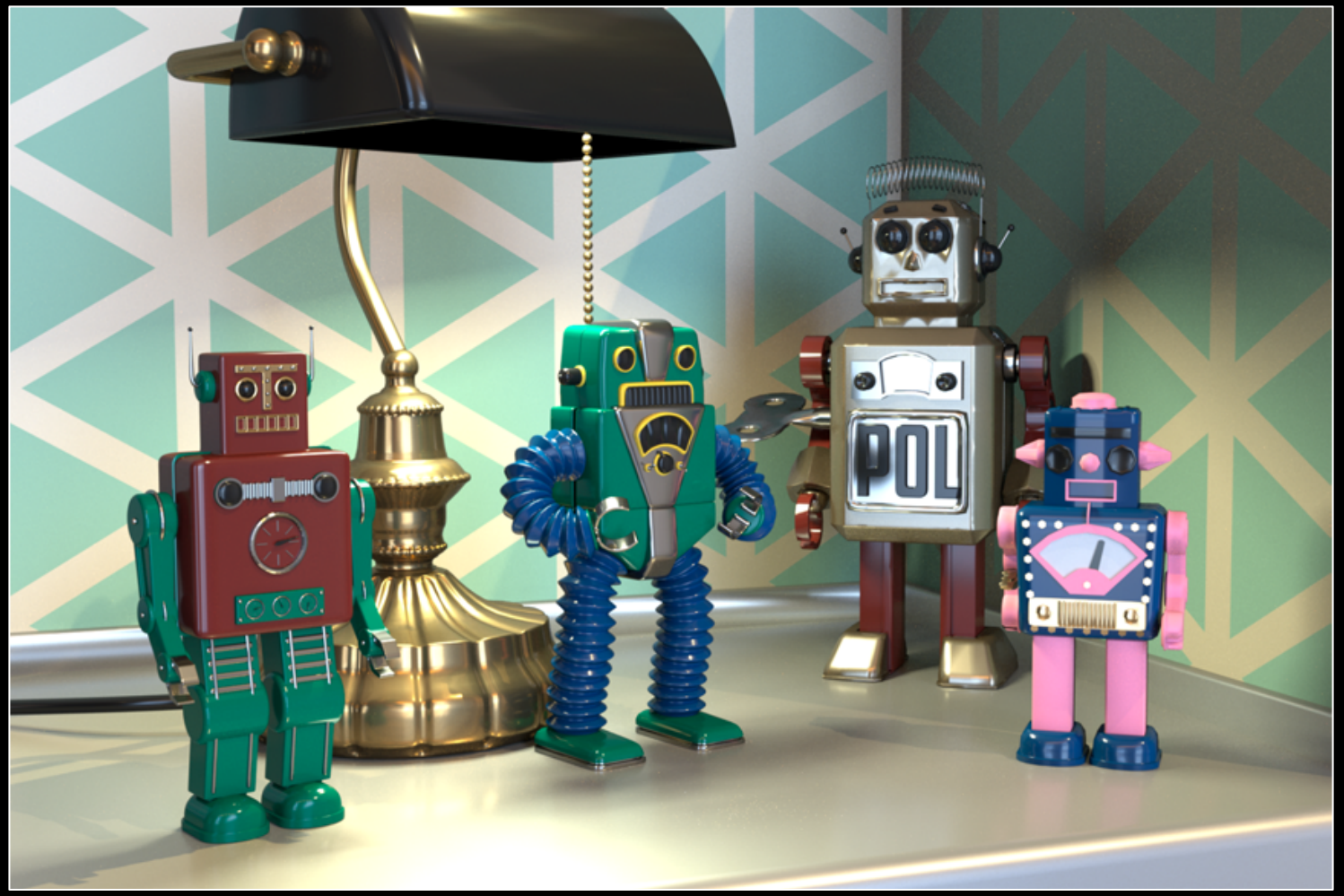
$$\mathbf{M}(\lambda, \theta_h, \theta_d, \phi_d)$$

Wavelength

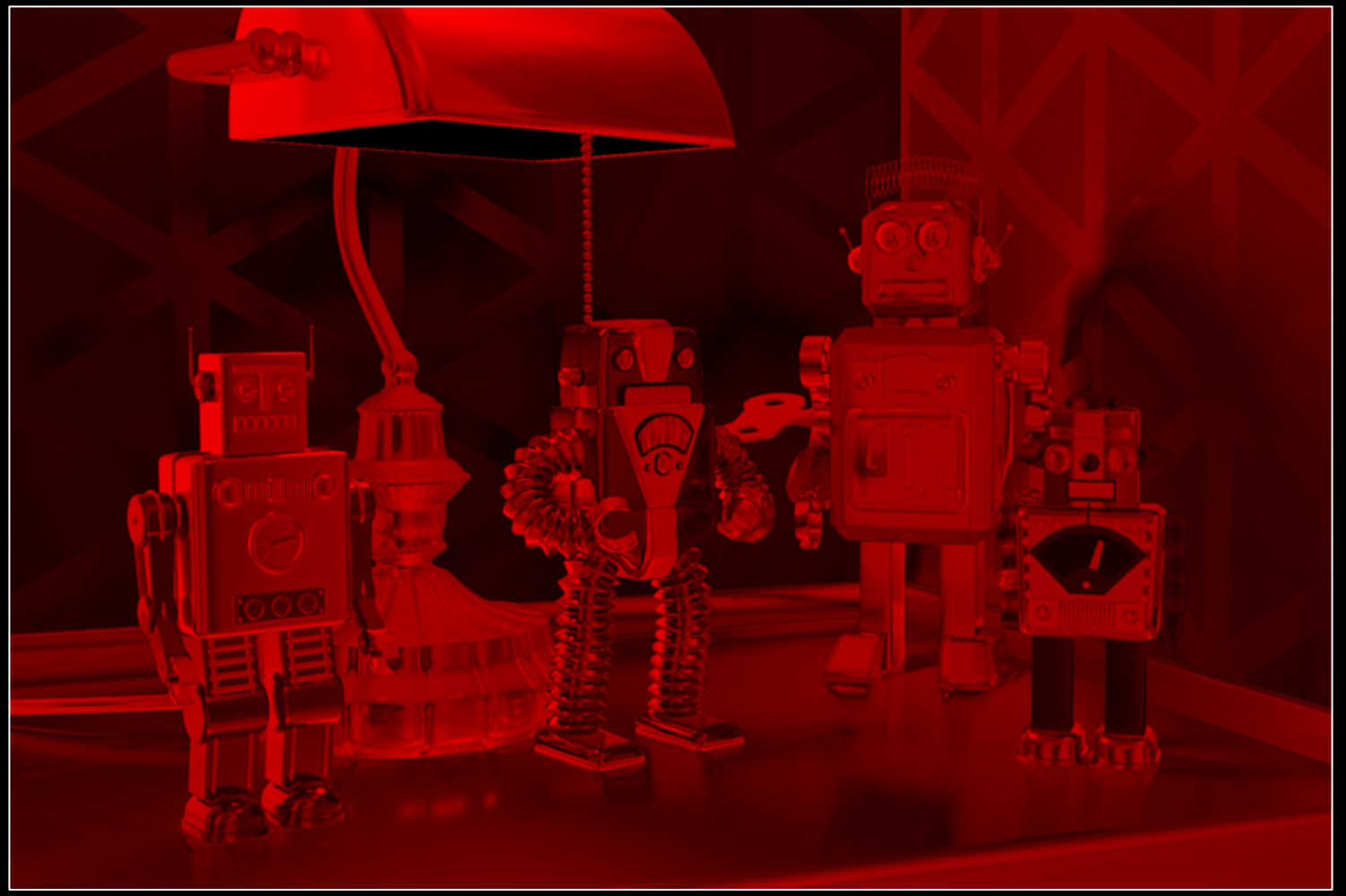
Rusinkiewicz angles



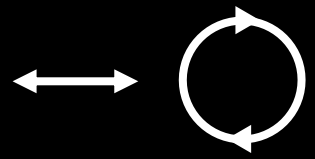
Intensity rendering

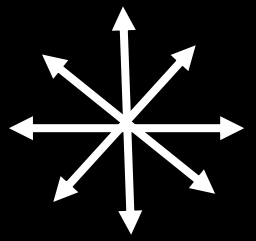


Degree of polarization (DoP)



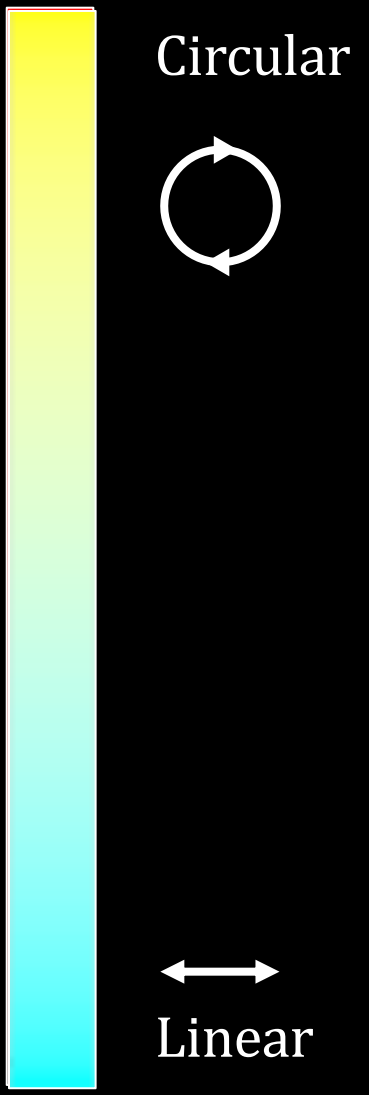
Fully polarized



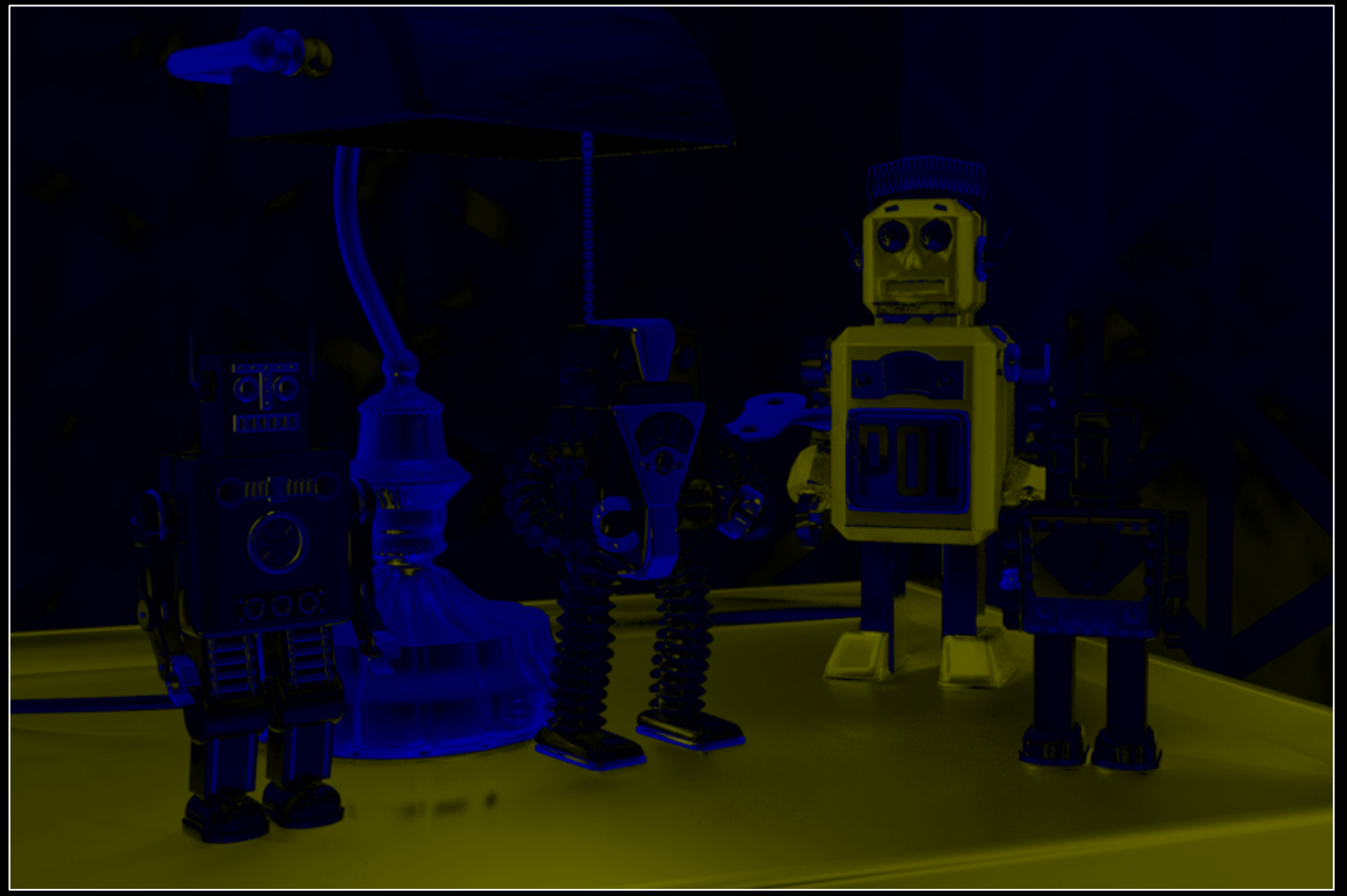


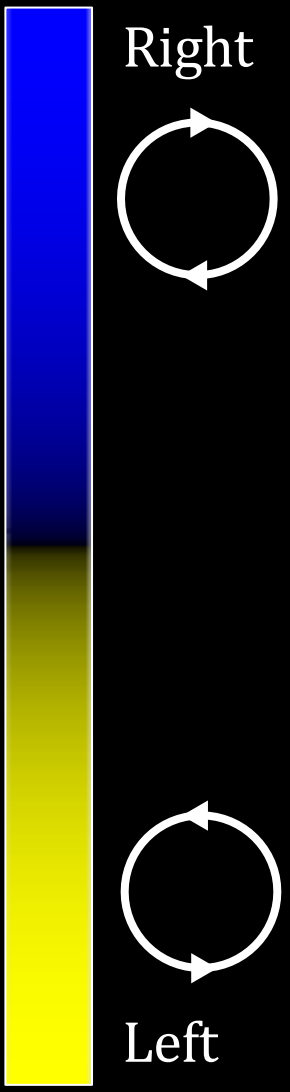
Unpolarized

Type of polarization (ToP)



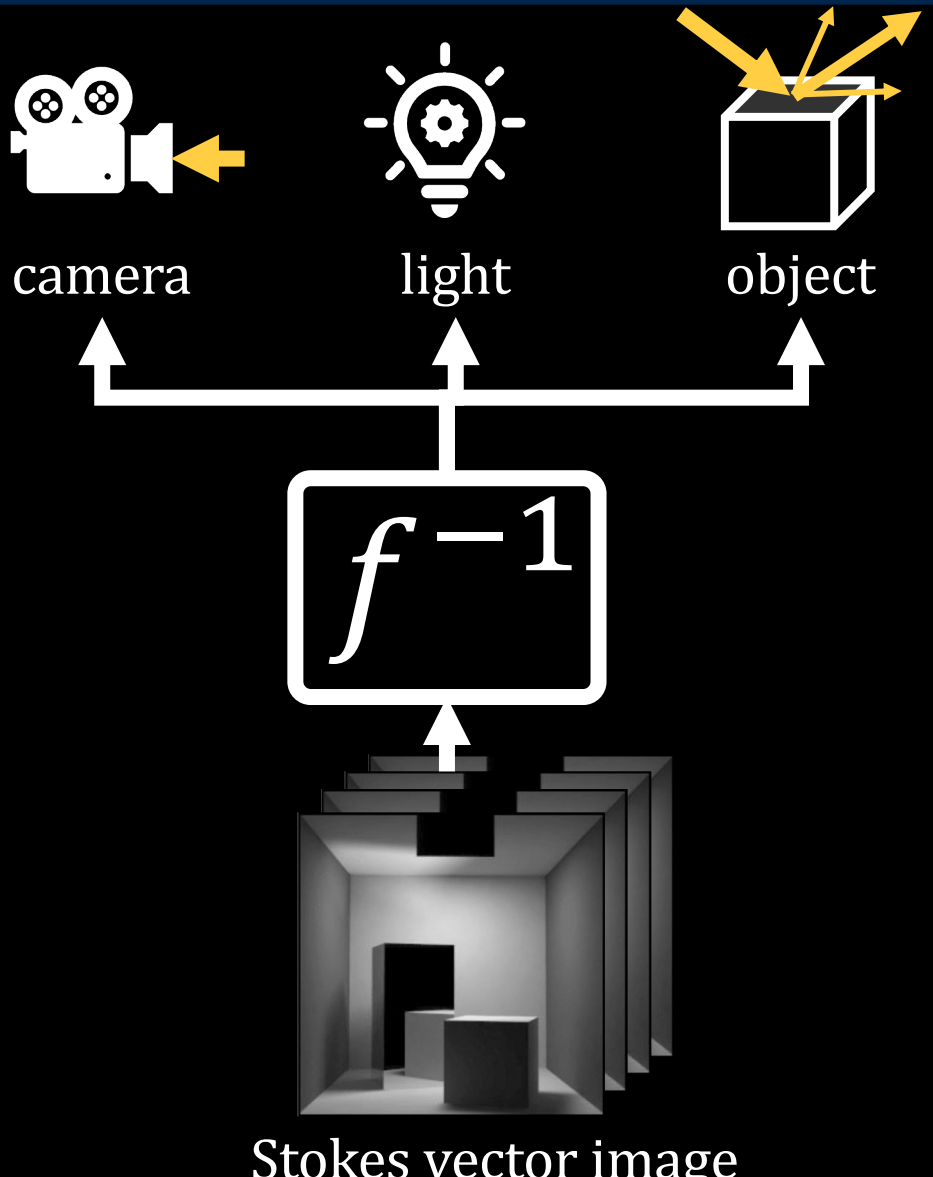
Chirality of polarization (CoP)





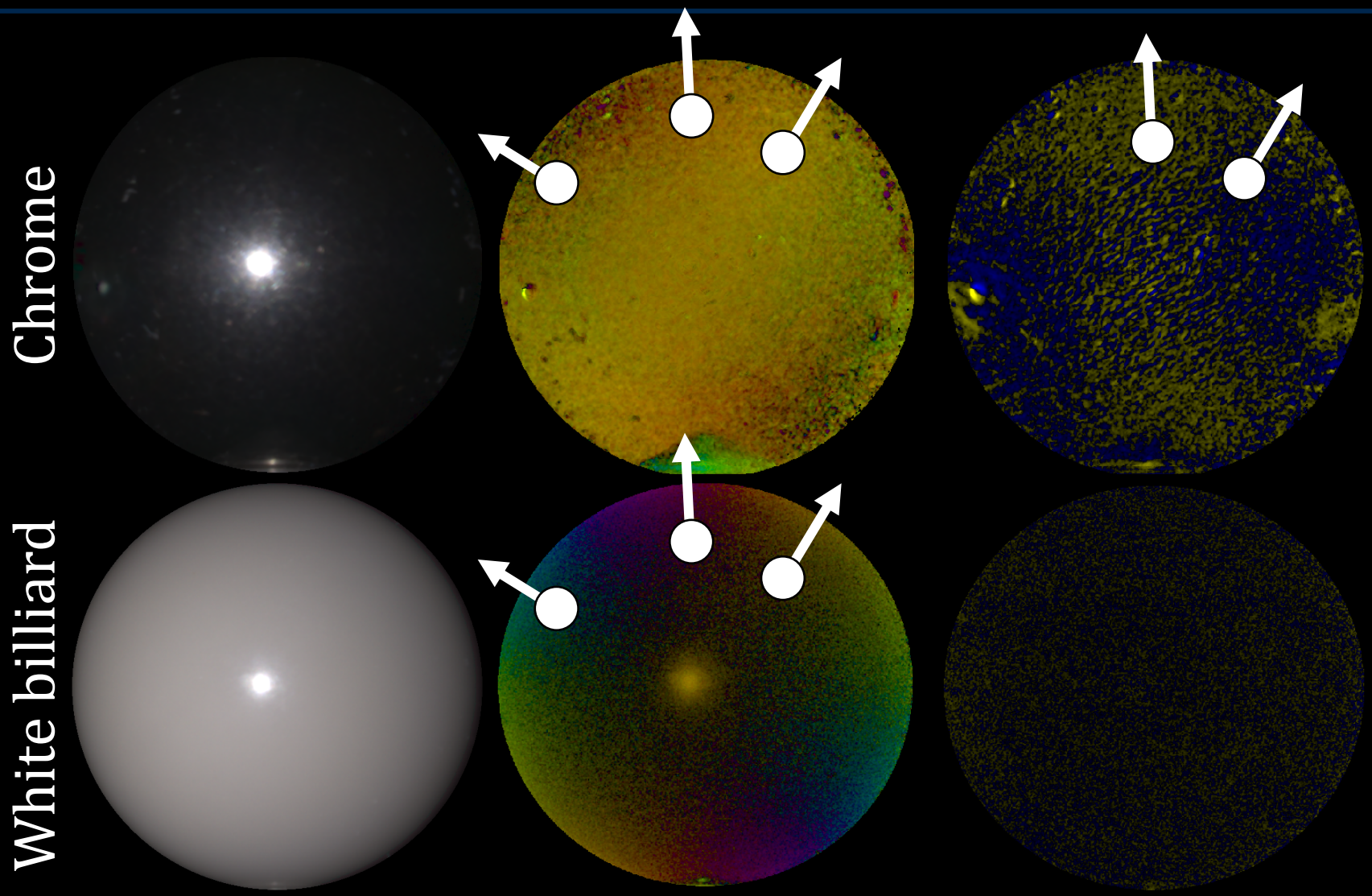
Angle of linear polarization (AoLP)

Polarimetric inverse rendering



- Surface normals
- Roughness
- Dielectric/metallic
- Color

Surface normal vs. polarization

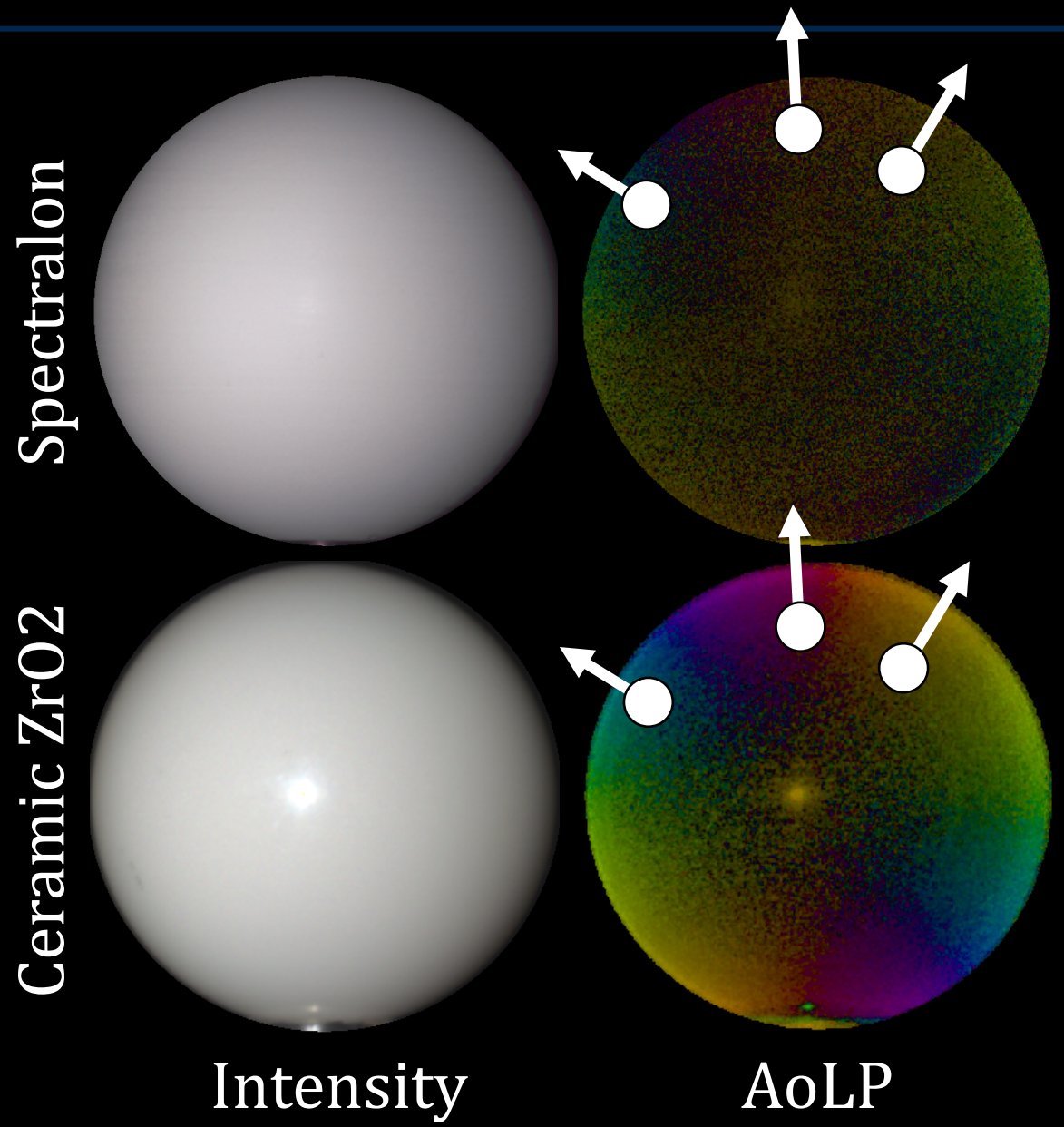


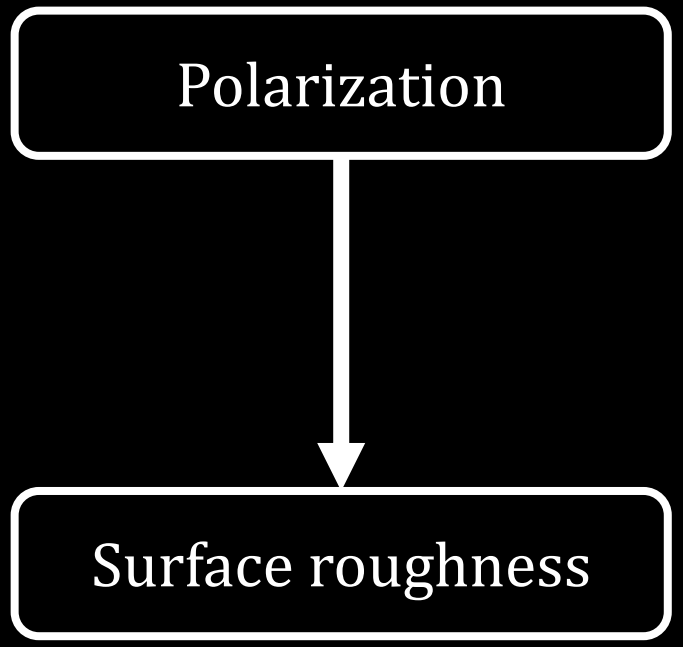
Circular polarization

↓

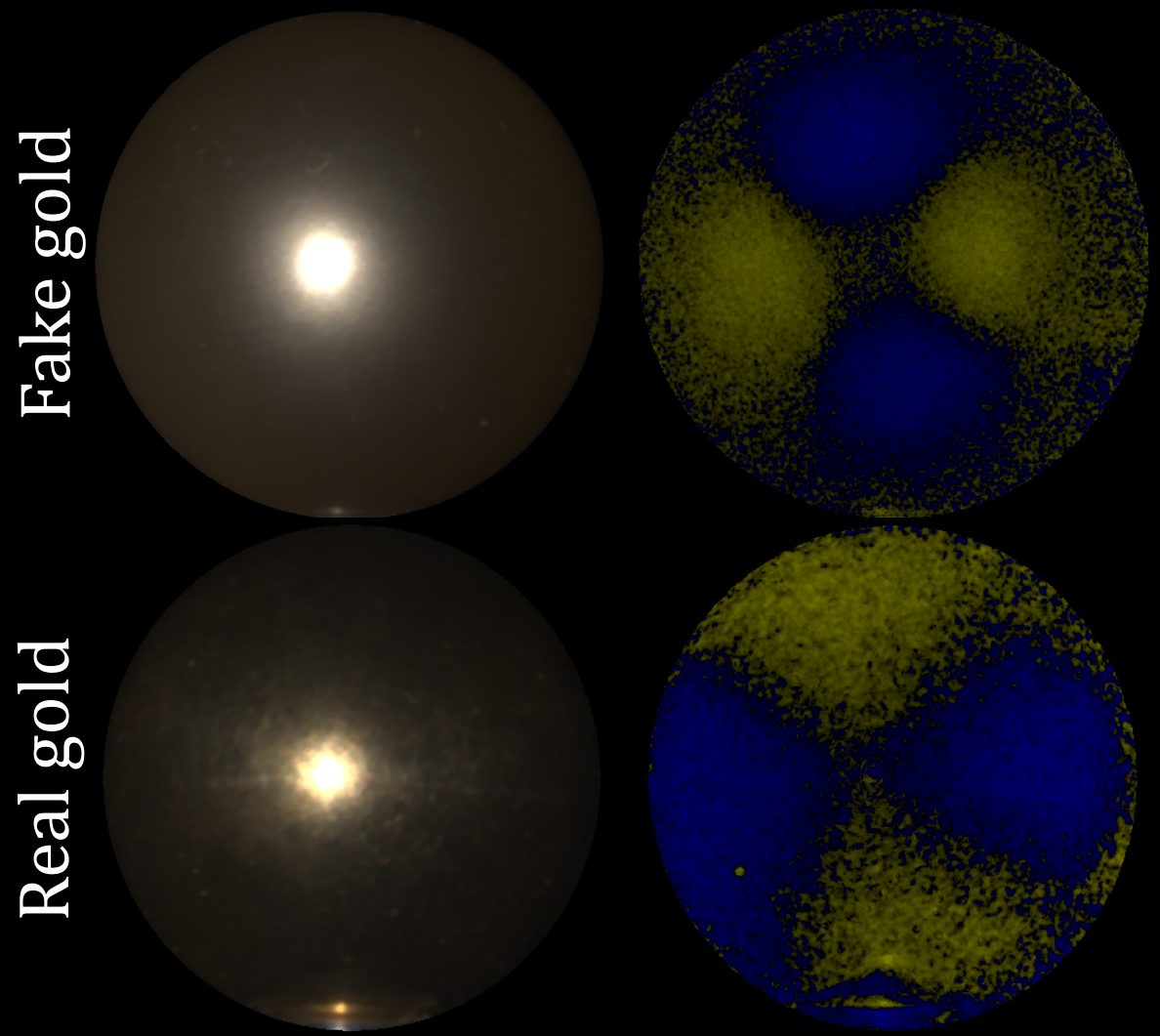
Surface normals of metallic material

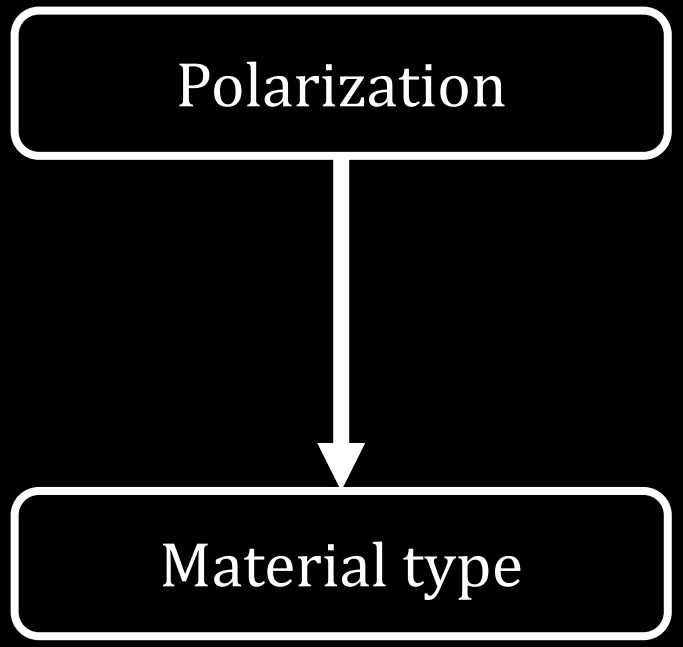
Roughness vs. polarization





Dielectric/metallic vs. polarization





Conclusions

Contributions

- practical pBRDF acquisition system
- pBRDF dataset
- polarimetric forward and inverse rendering

Dataset and code

- http://vclab.kaist.ac.kr/siggraph2020
- http://rgl.epfl.ch/publications/Baek2020Image
- https://www.mitsuba-renderer.org