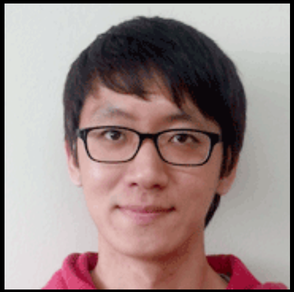
Birefractive Stereo Imaging for Single-Shot Depth Acquisition



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Diego Gutierrez[*]

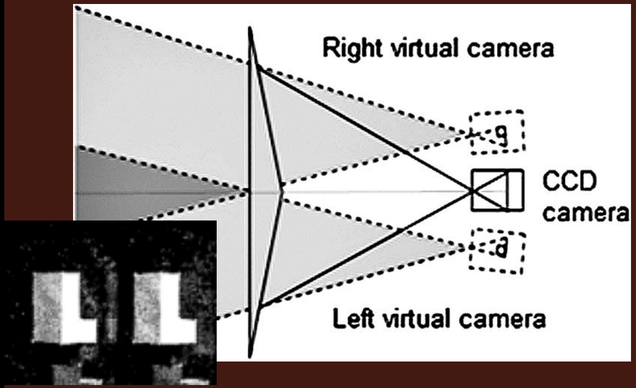
Min H. Kim[†]

KAIST[†]   Universidad de Zaragoza, I3A[*]

Birefractive Stereo Imaging

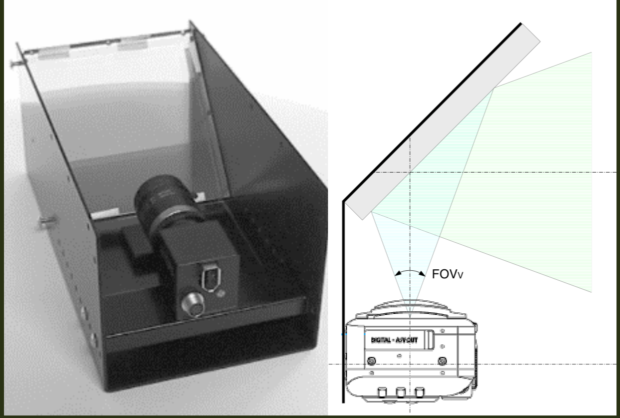
Depth from Refraction or Reflection

Bi-prism stereo
[Lee & Kweon 2000, Cui et al. 2014]



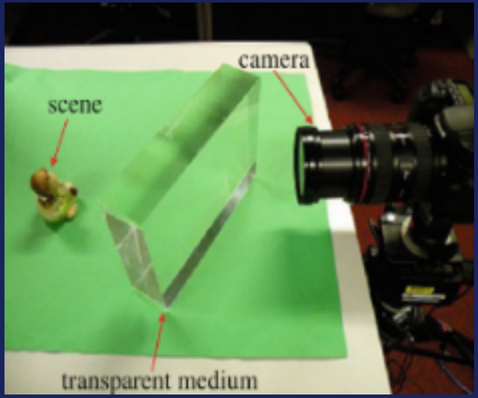
- Chromatic aberration
- Reduced sensor resolution

Reflective stereo
[Shimizu and Okutomi 2006]



- Large form factor
- View direction change

Refractive stereo
[Chen et al. 2012]



- At least two shots

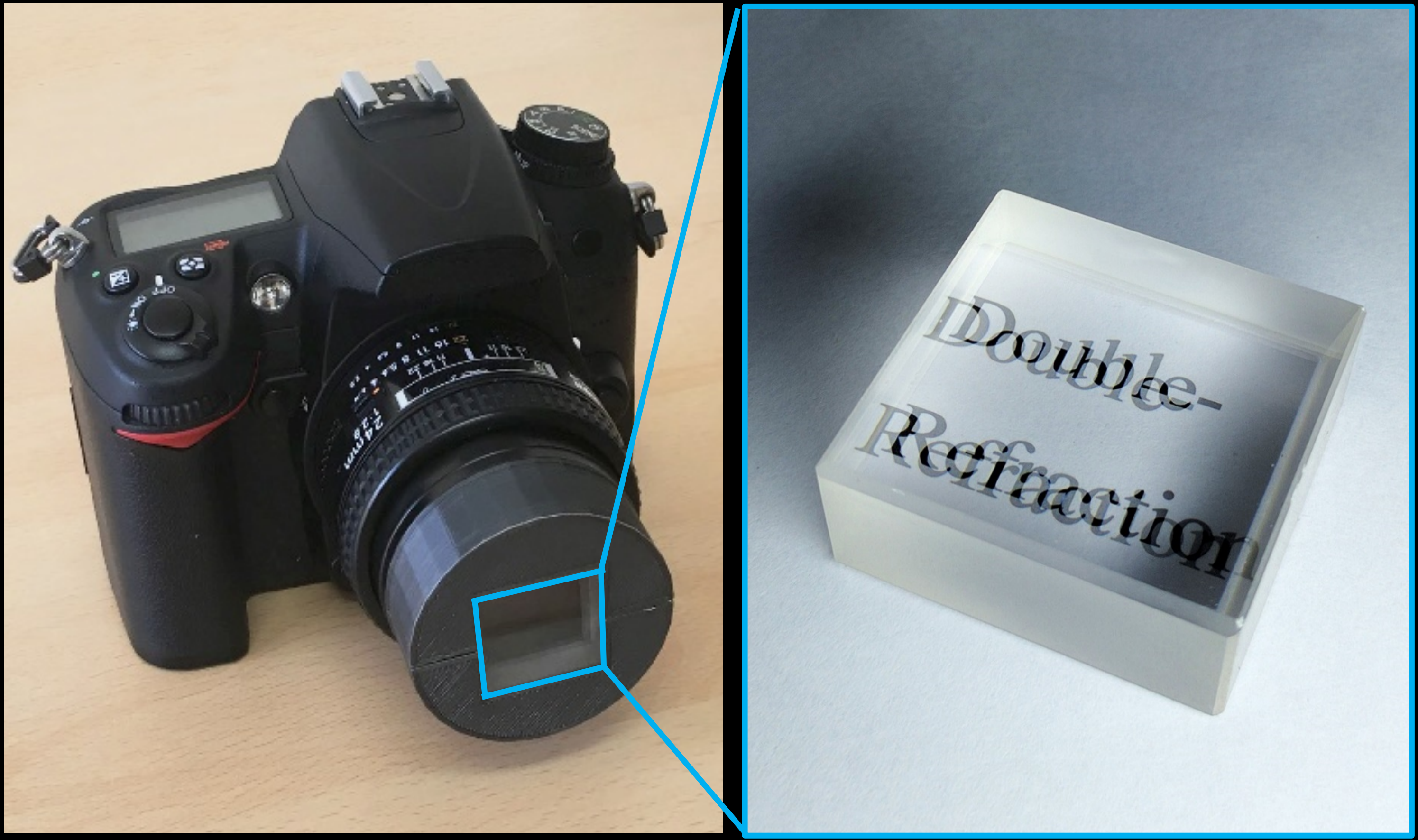
Birefractive stereo

+ No chromatic aberration
+ Full sensor resolution

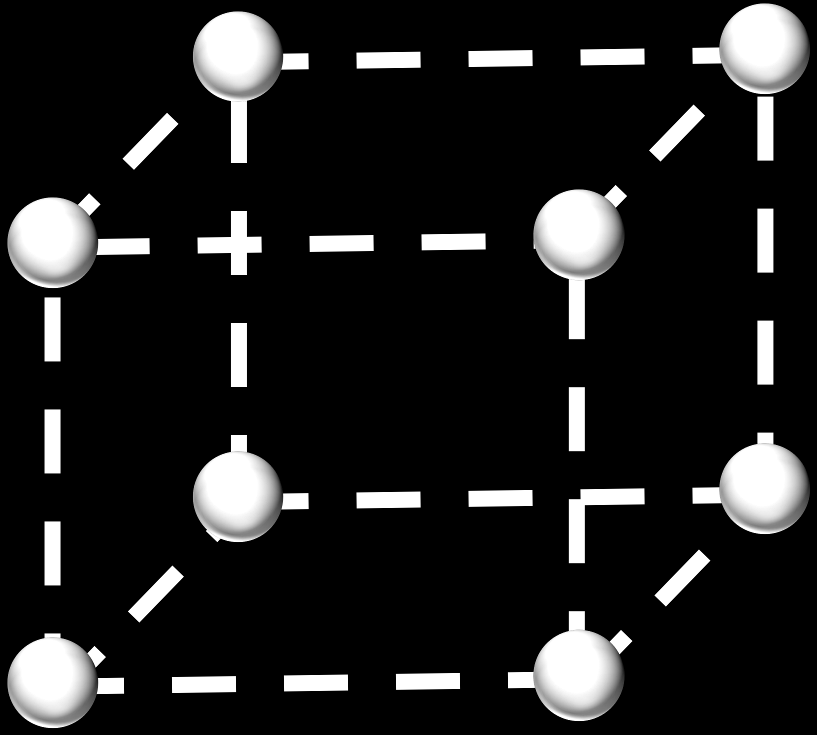
+ Compact
+ Consistent view direction

+Single shot

Birefringent Crystal

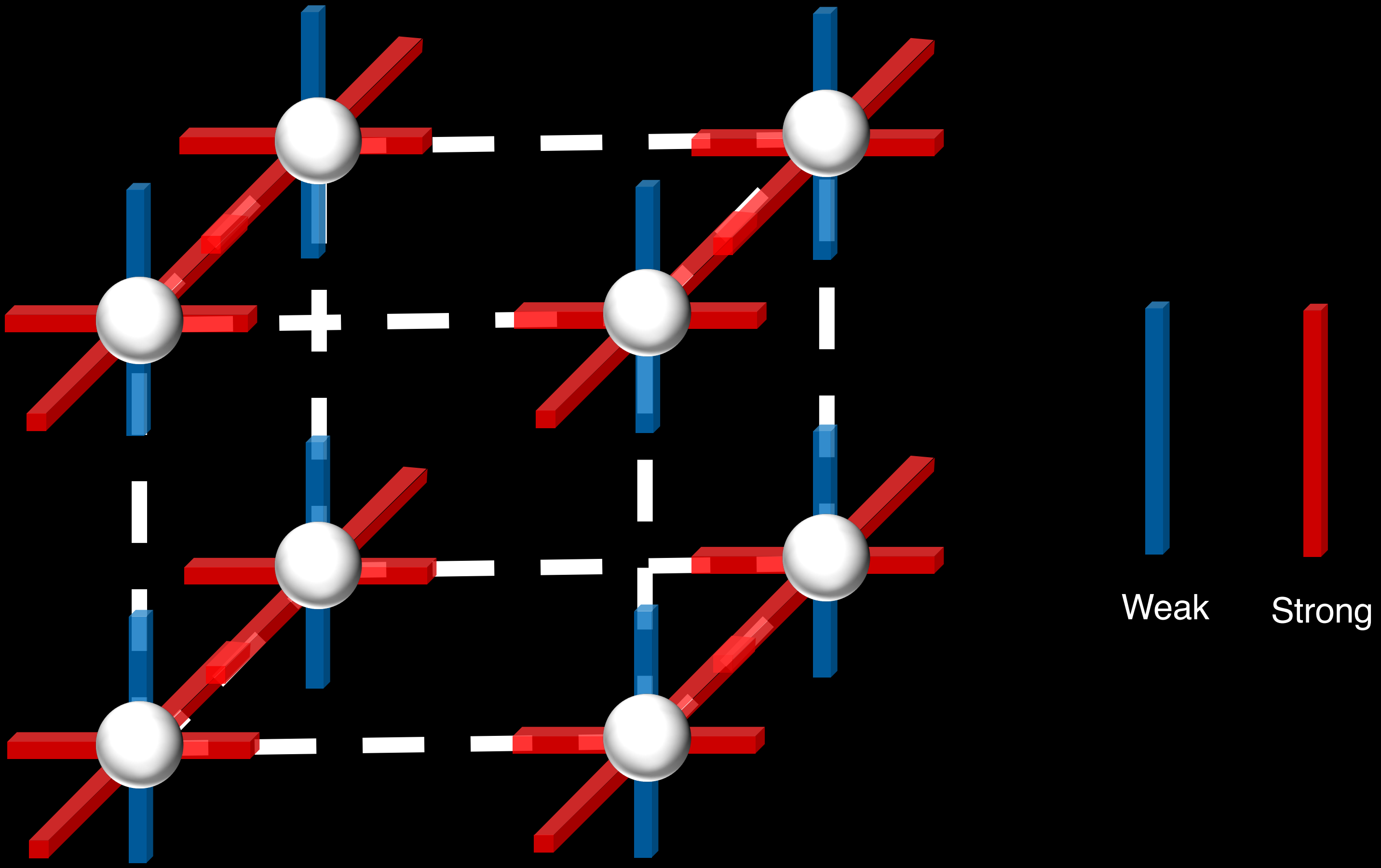


Crystal



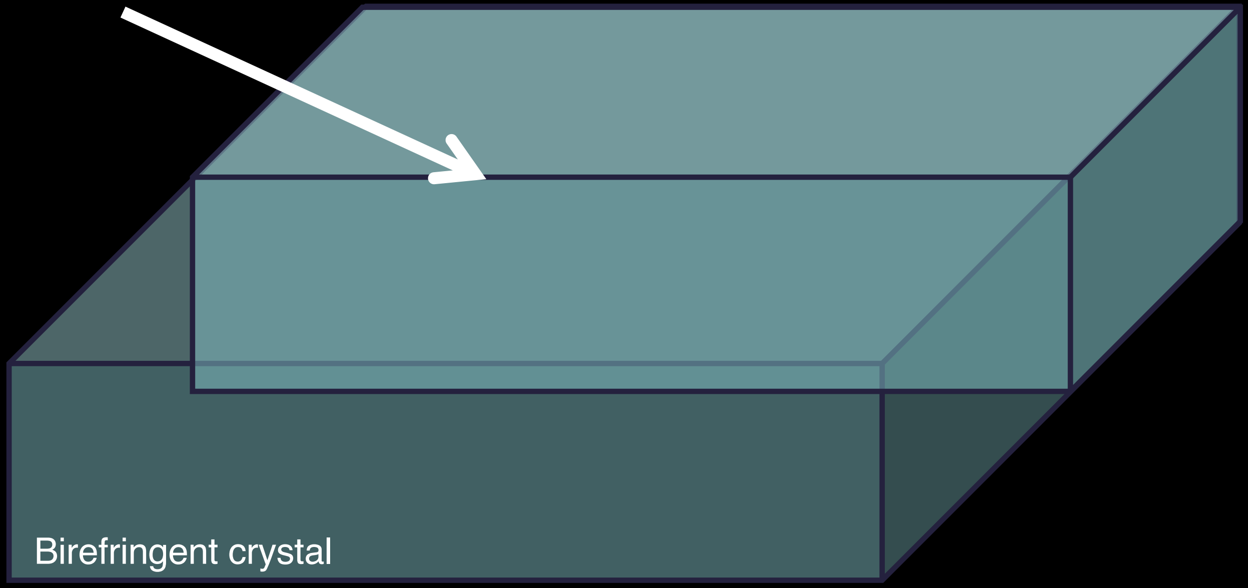
[Hetch, Optics, Addison-Wesley 2002]

Birefringent Crystal

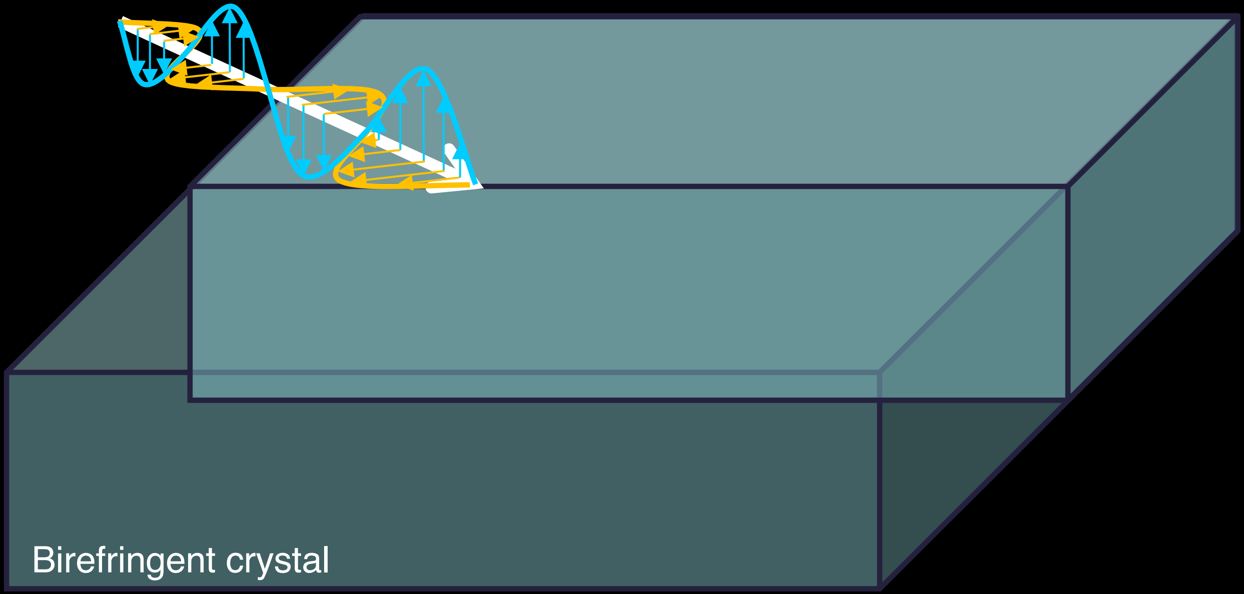


[Hetch, Optics, Addison-Wesley 2002]

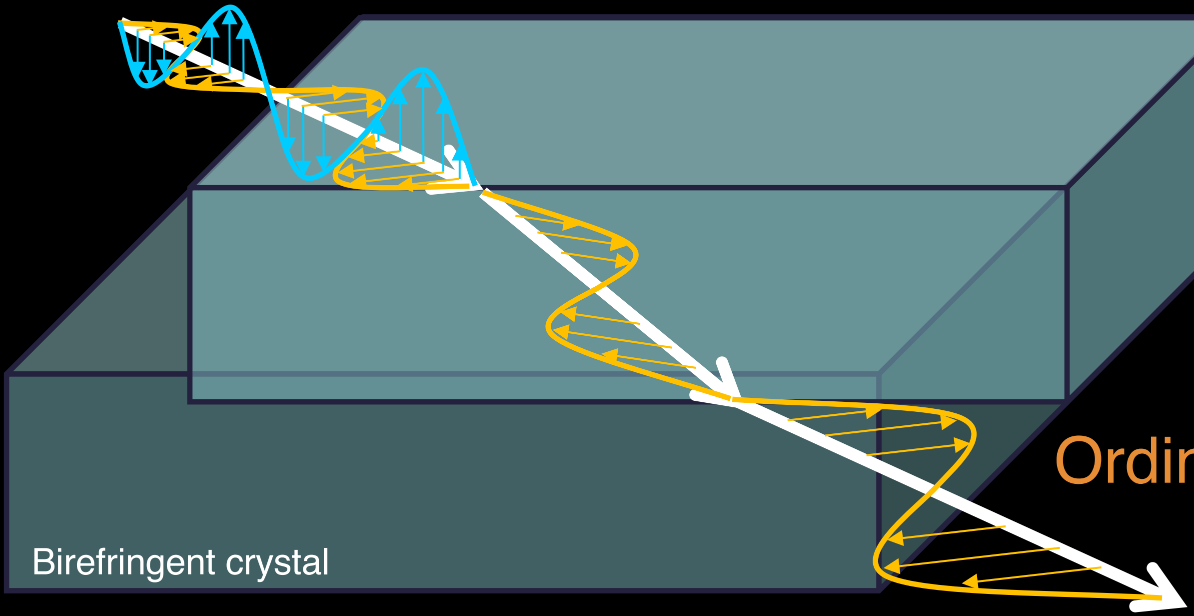
Light Transport



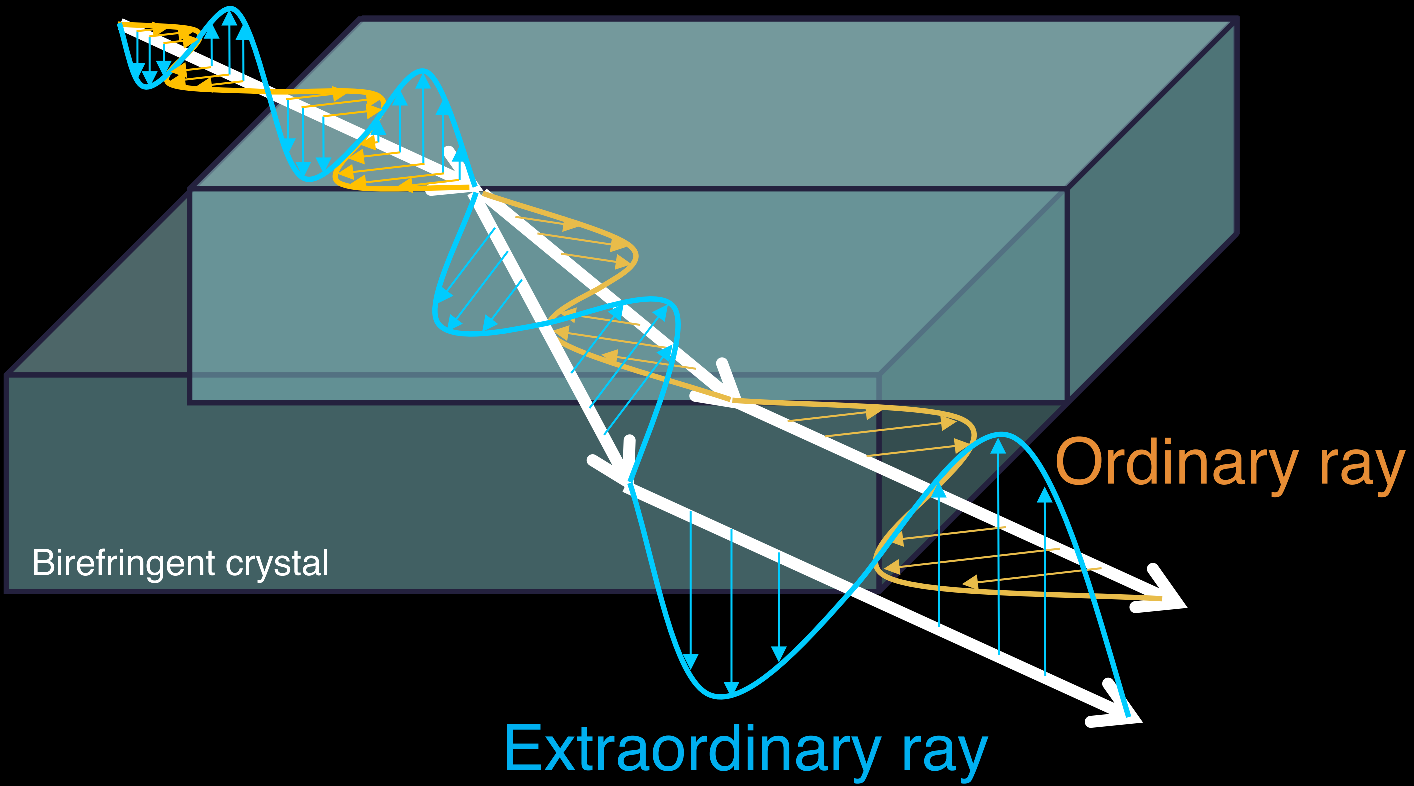
Double Refraction



Double Refraction



Double Refraction



Birefringent Material for Imaging

Conventional camera

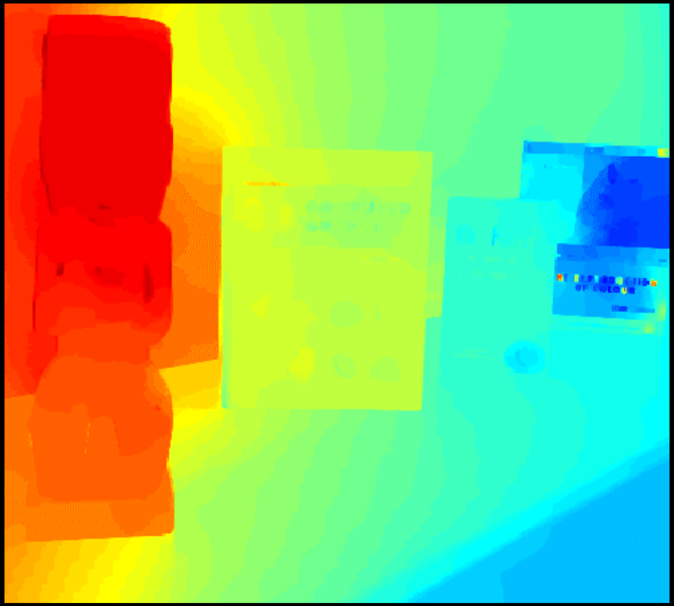
Prototype

Birefringent crystal

Captured image

Corresponding points

Corresponding points



Depth

BIREFRACTIVE STEREO MODEL

Image Formation

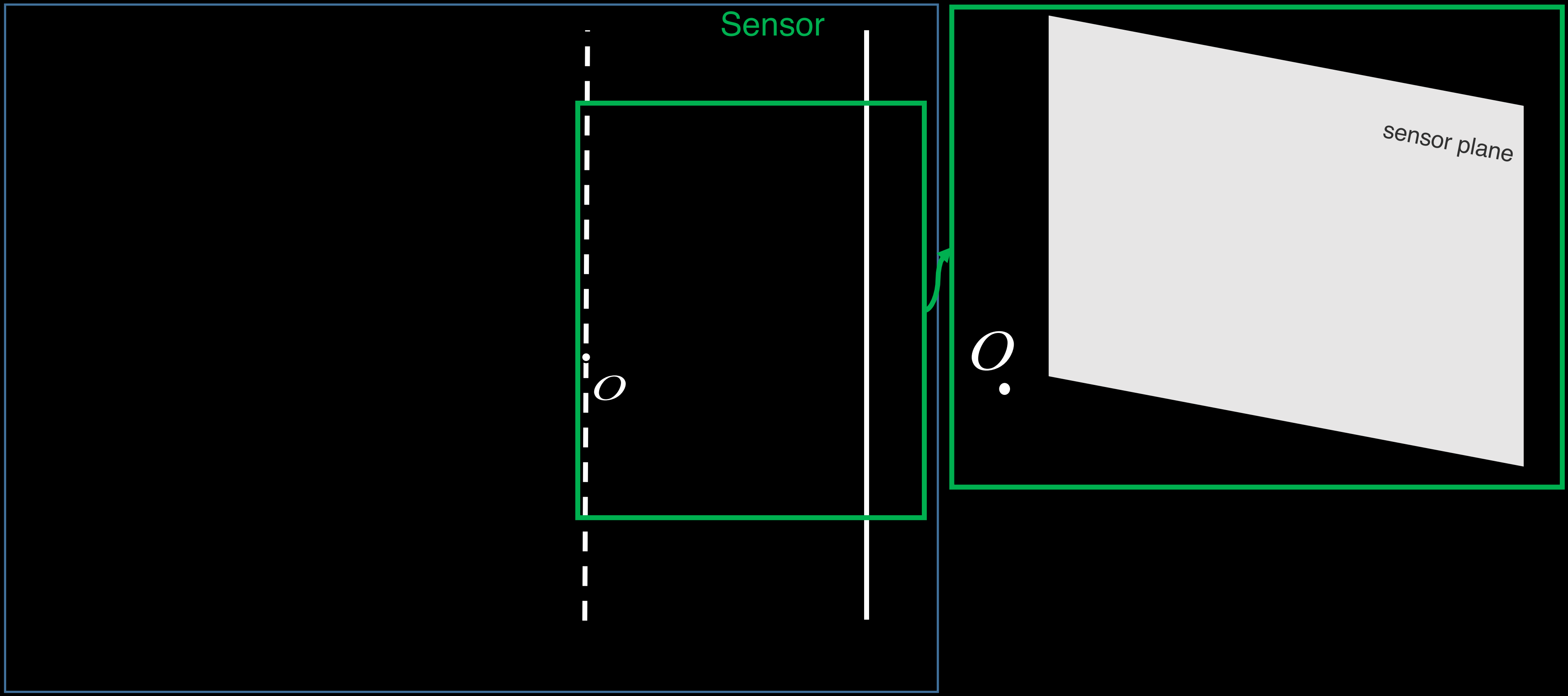


Image Formation

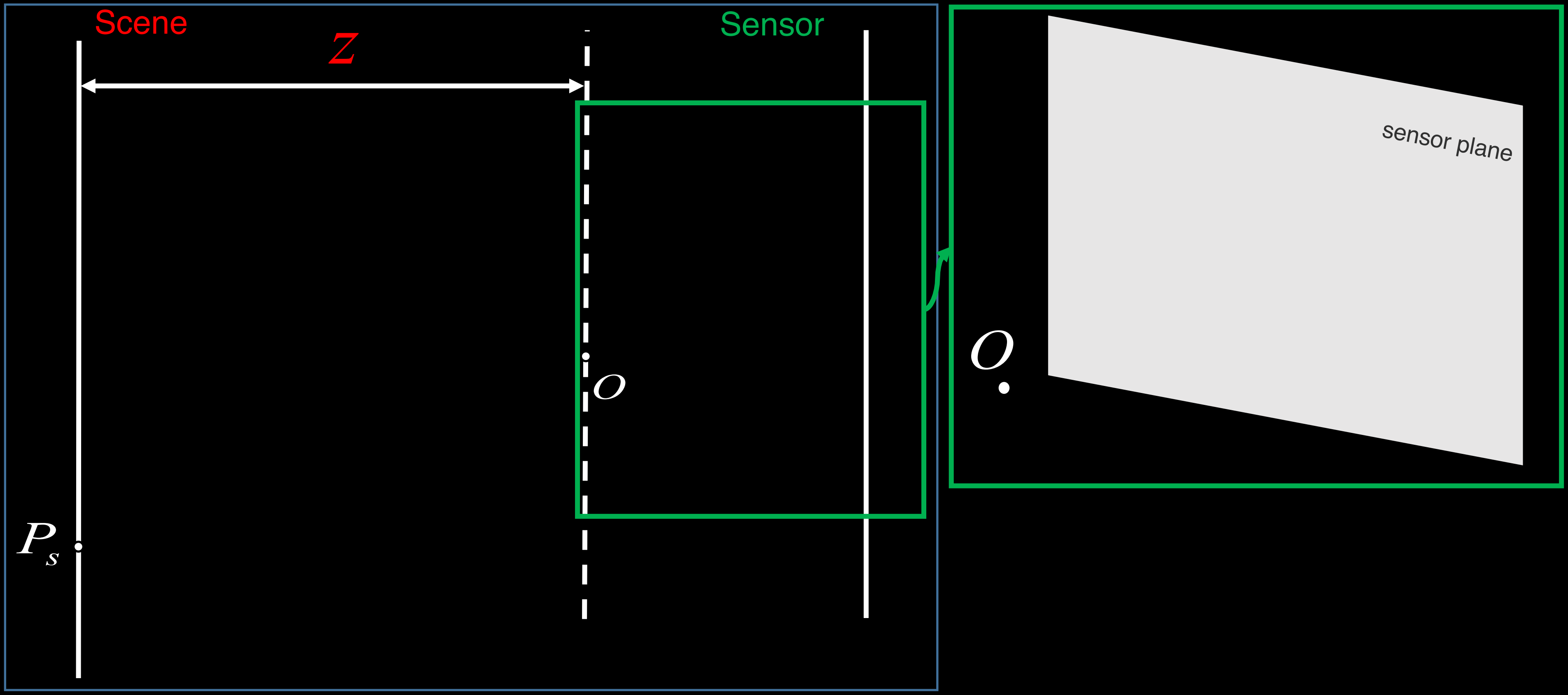


Image Formation

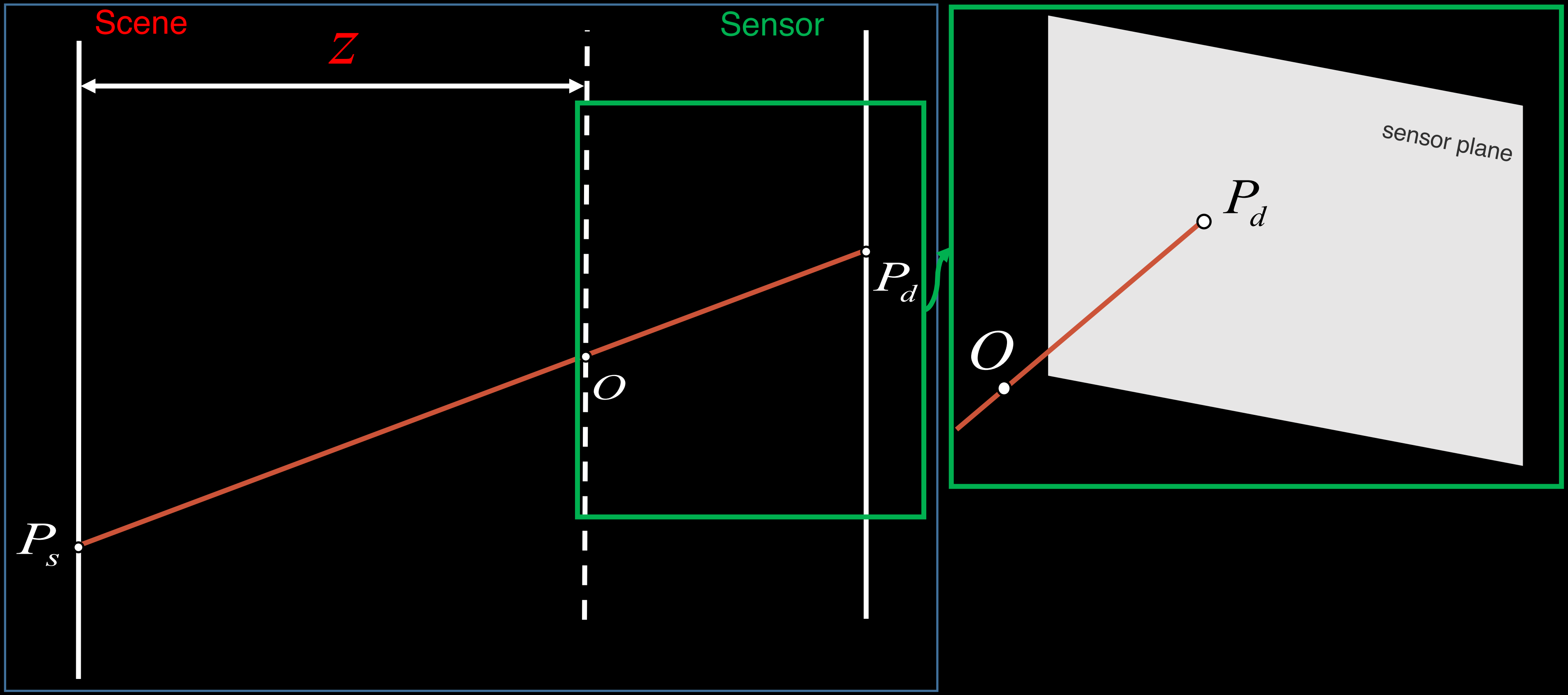
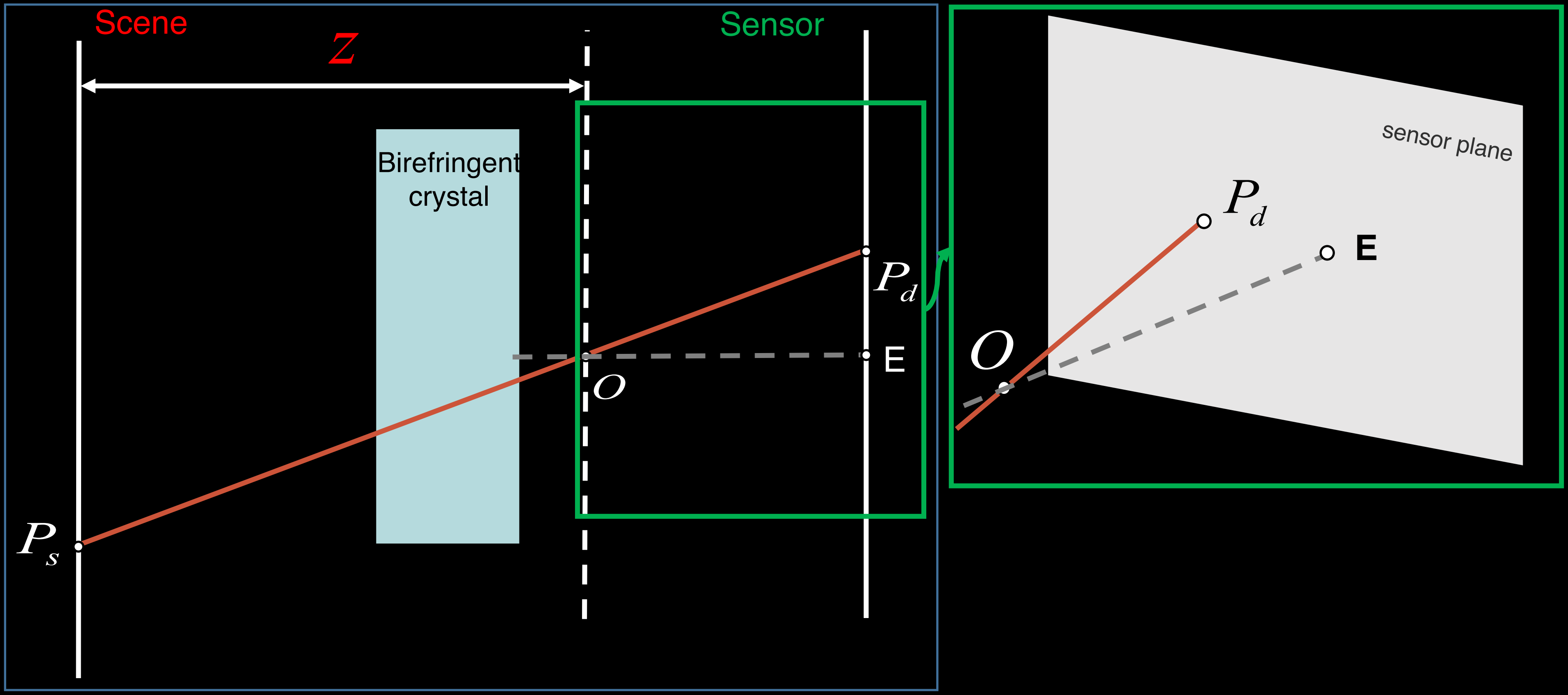
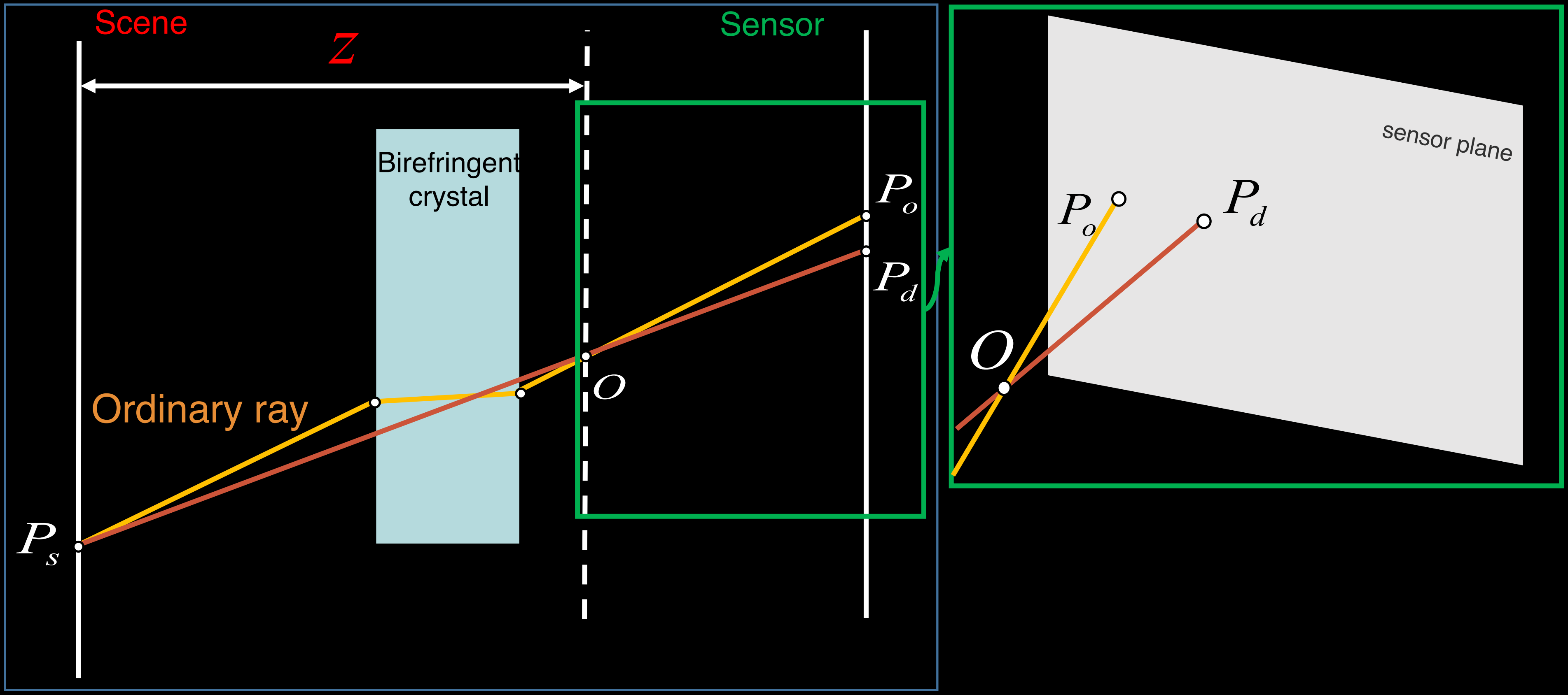


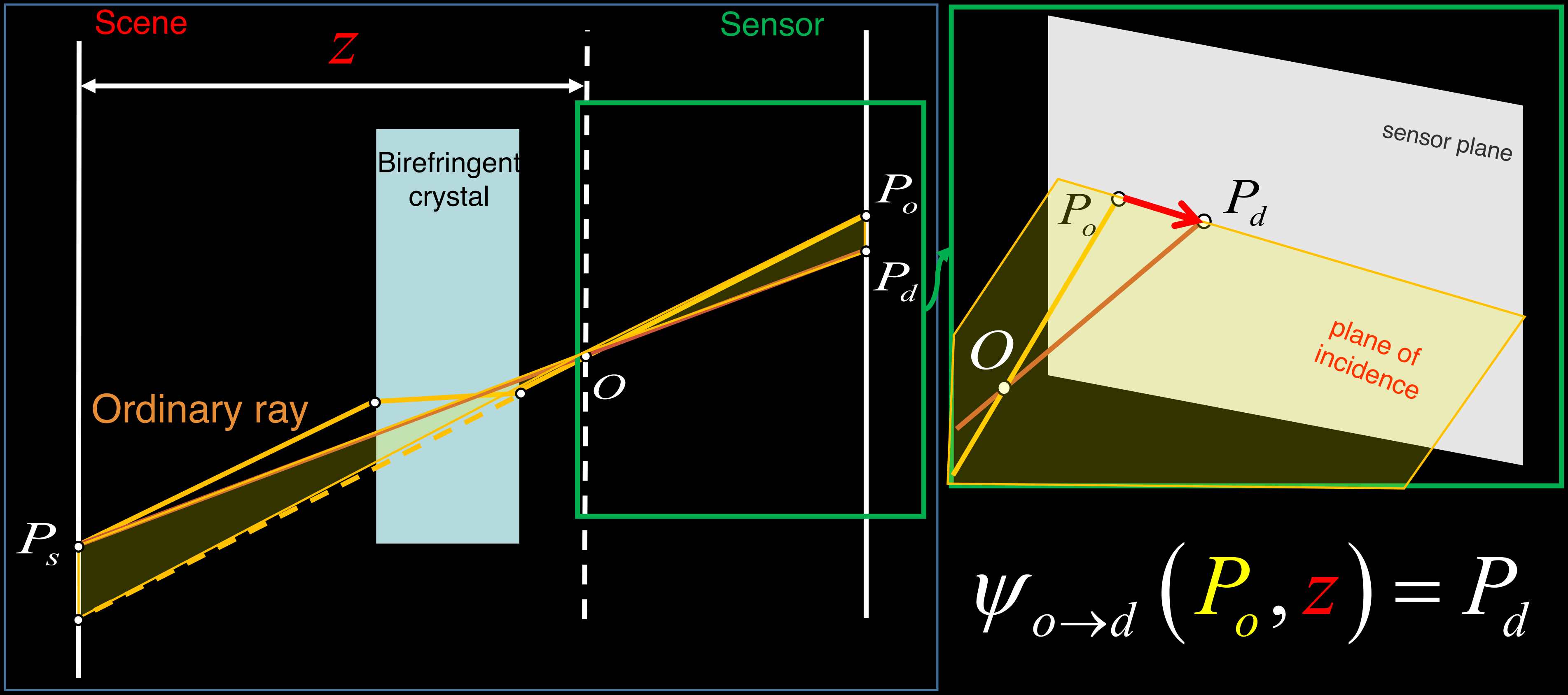
Image Formation



Ordinary Ray Model

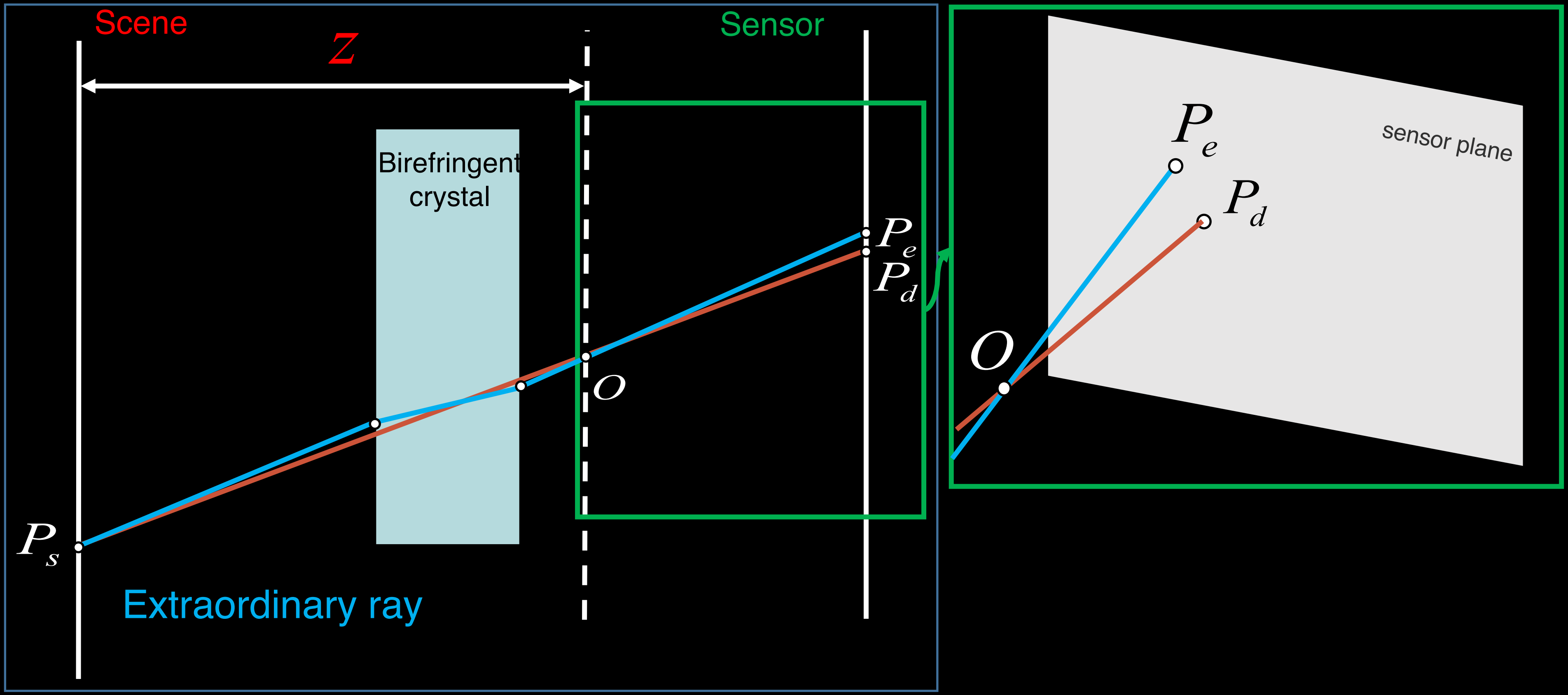


Ordinary Ray Model

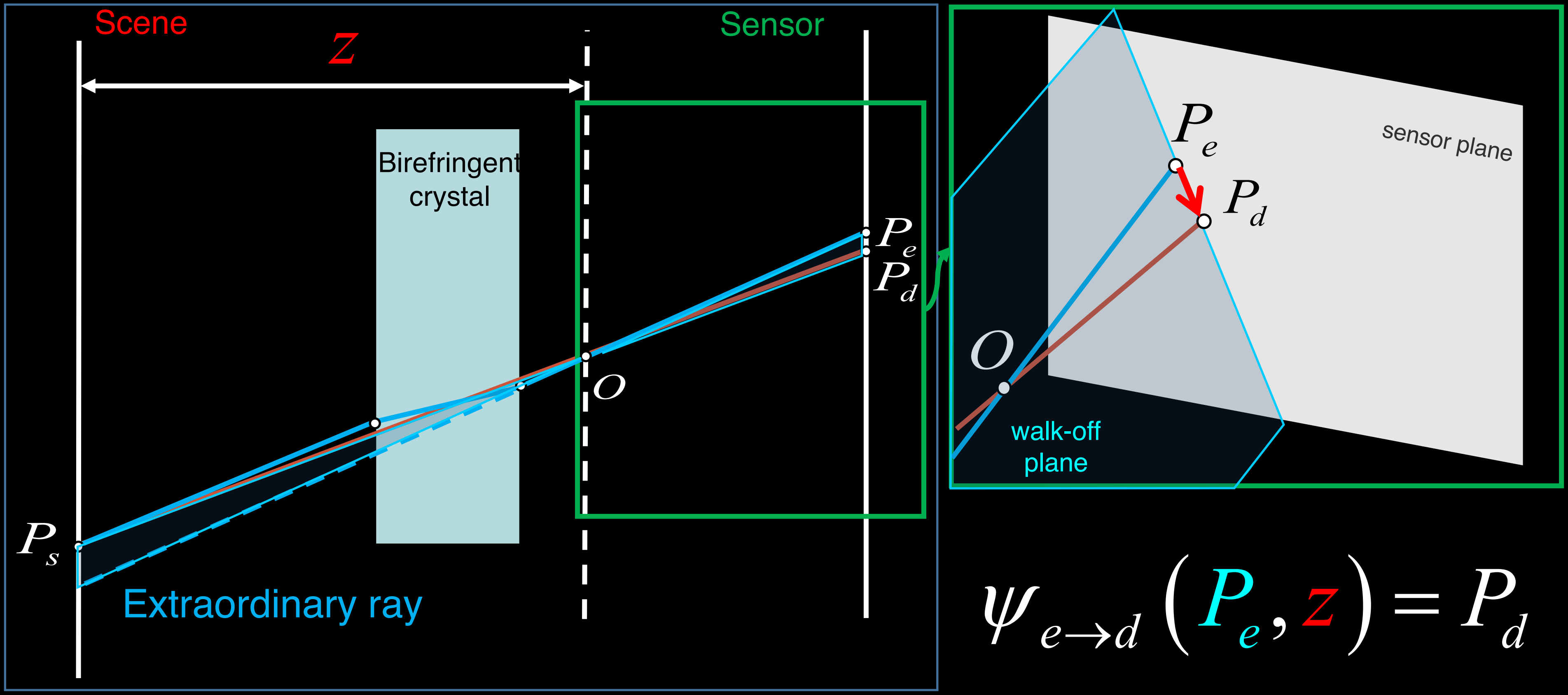


$$\psi_{o\to d}\left(P_o, z\right) = P_d$$

Extraordinary Ray Model

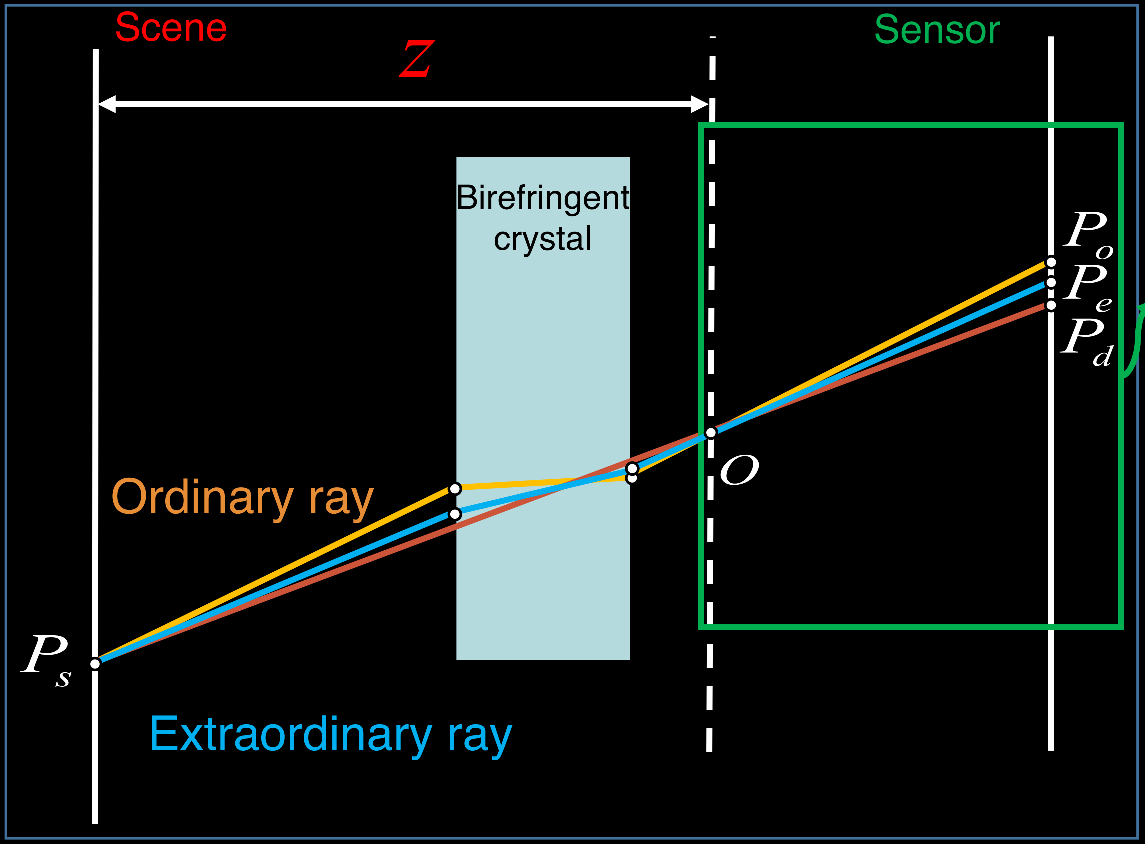


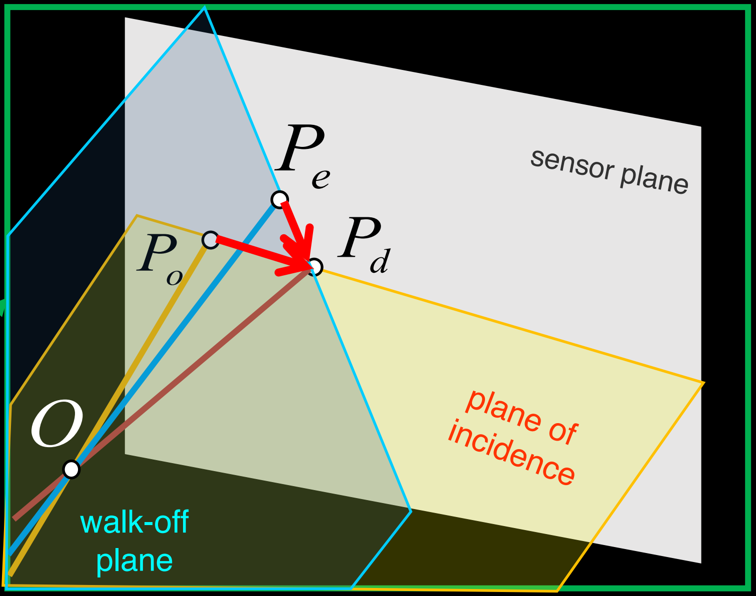
Extraordinary Ray Model



$$\psi_{e\to d}\left(P_e, z\right) = P_d$$

Birefractive Stereo Model

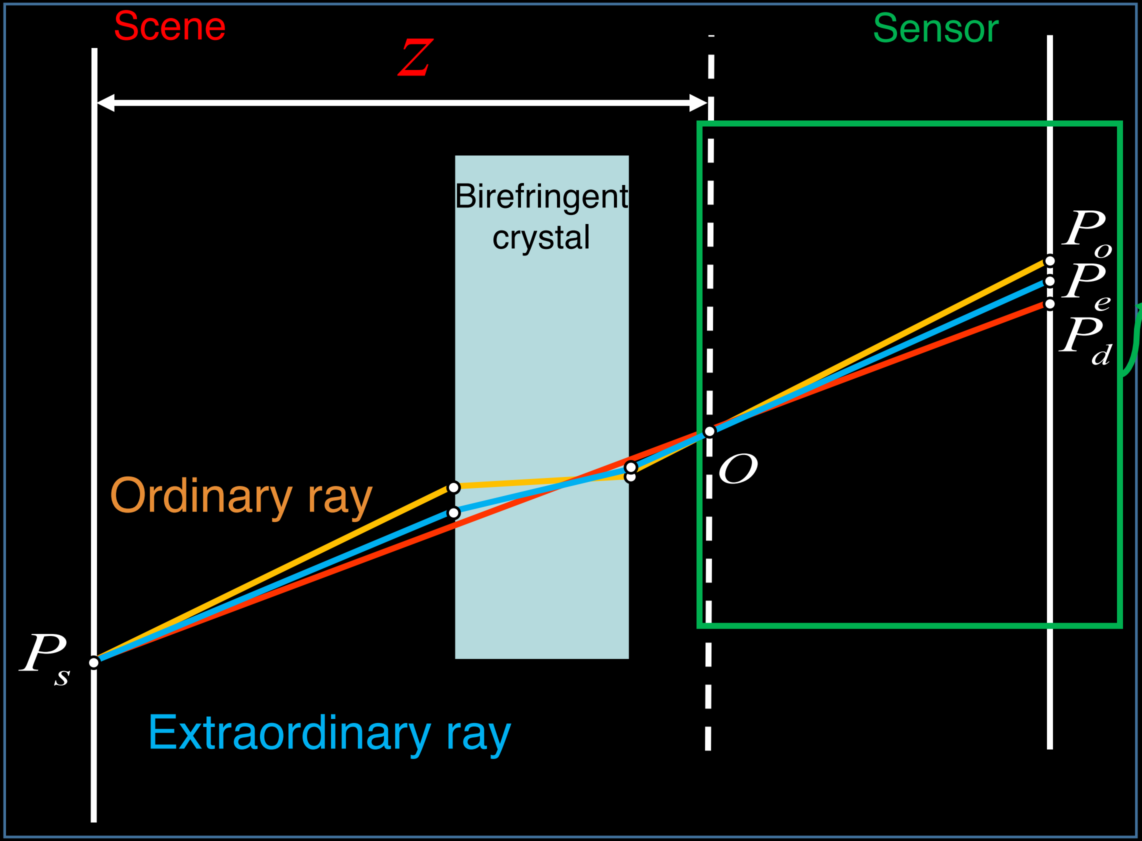


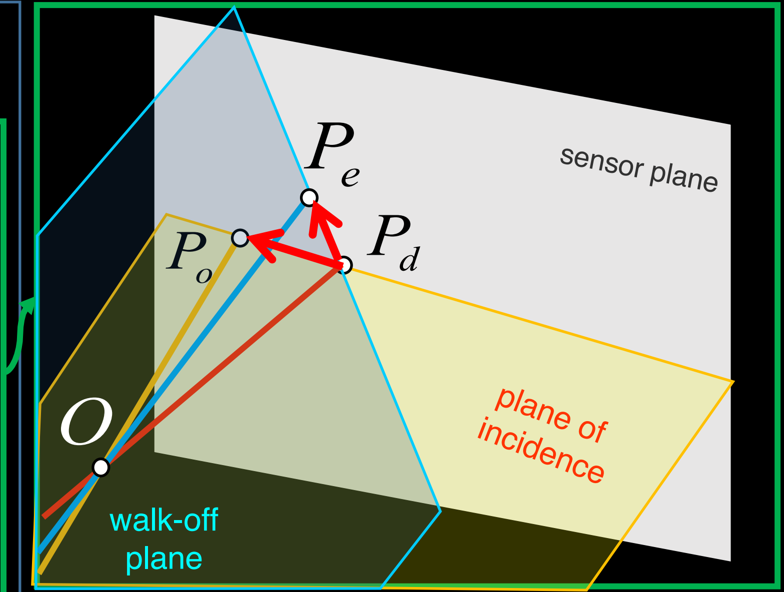


$$\psi_{o\rightarrow d}\left(P_o, z\right) = \boxed{P_d}$$

$$\psi_{e\rightarrow d}\left(P_e, z\right) = \boxed{P_d}$$

Birefractive Stereo Model

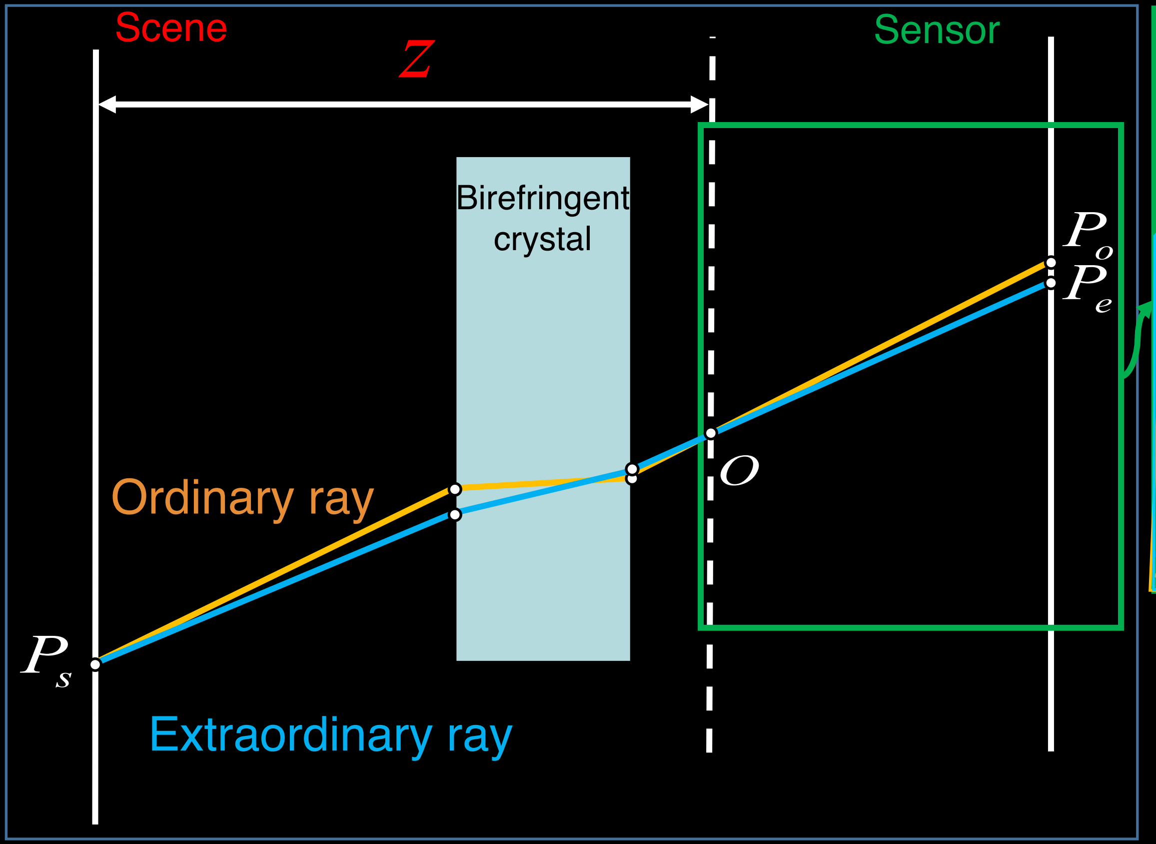


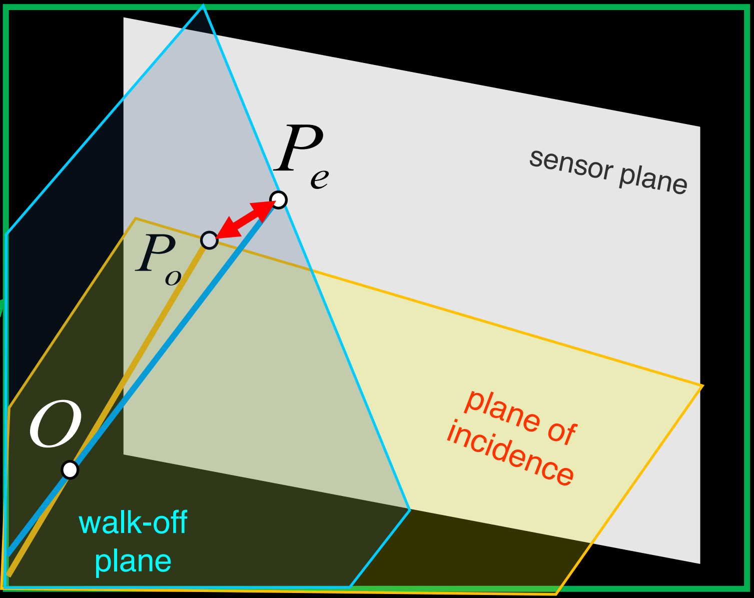


$$\psi_{d\to o}\left(P_d, z\right) = P_o$$

$$\psi_{d\to e}\left(P_d, z\right) = P_e$$

Birefractive Stereo Model

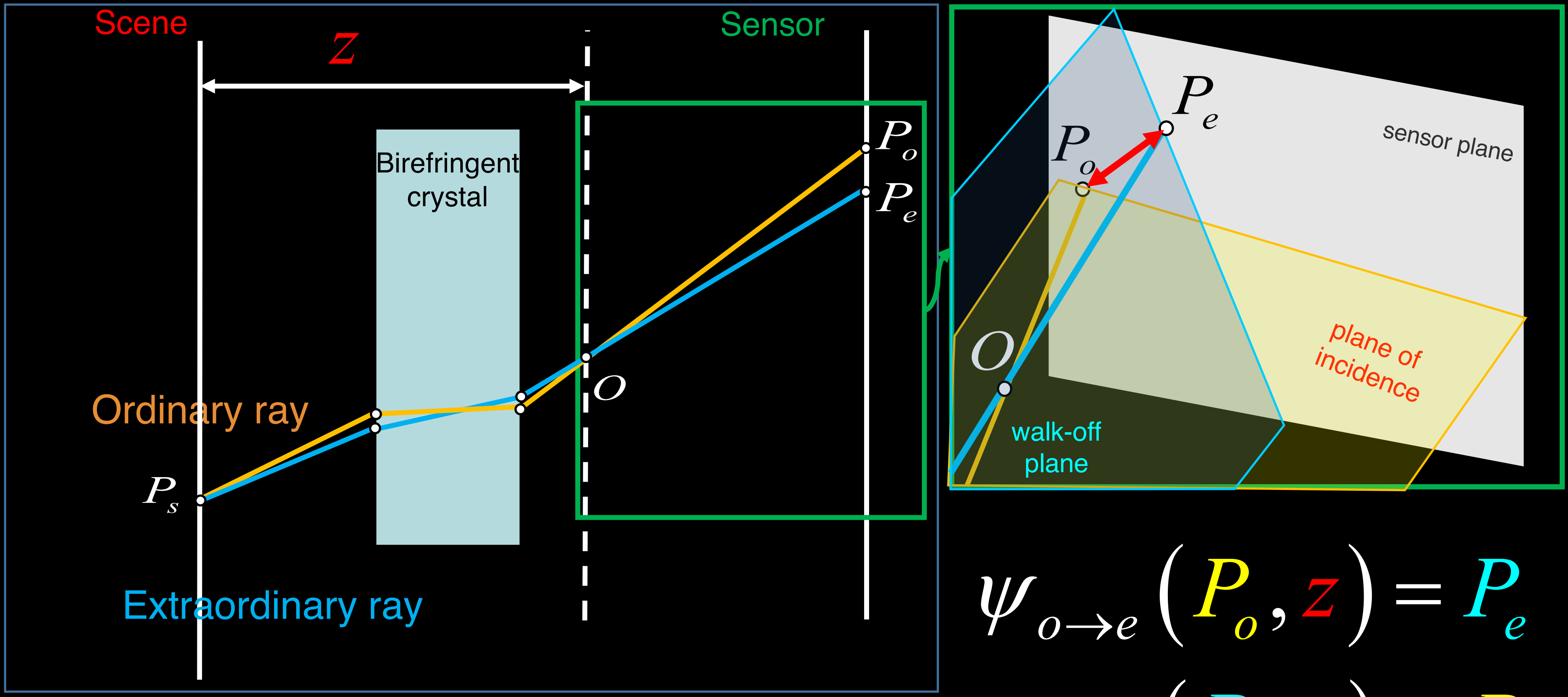




$$\psi_{o\rightarrow e}\left(P_o, z\right) = P_e$$

$$\psi_{e\rightarrow o}\left(P_e, z\right) = P_o$$

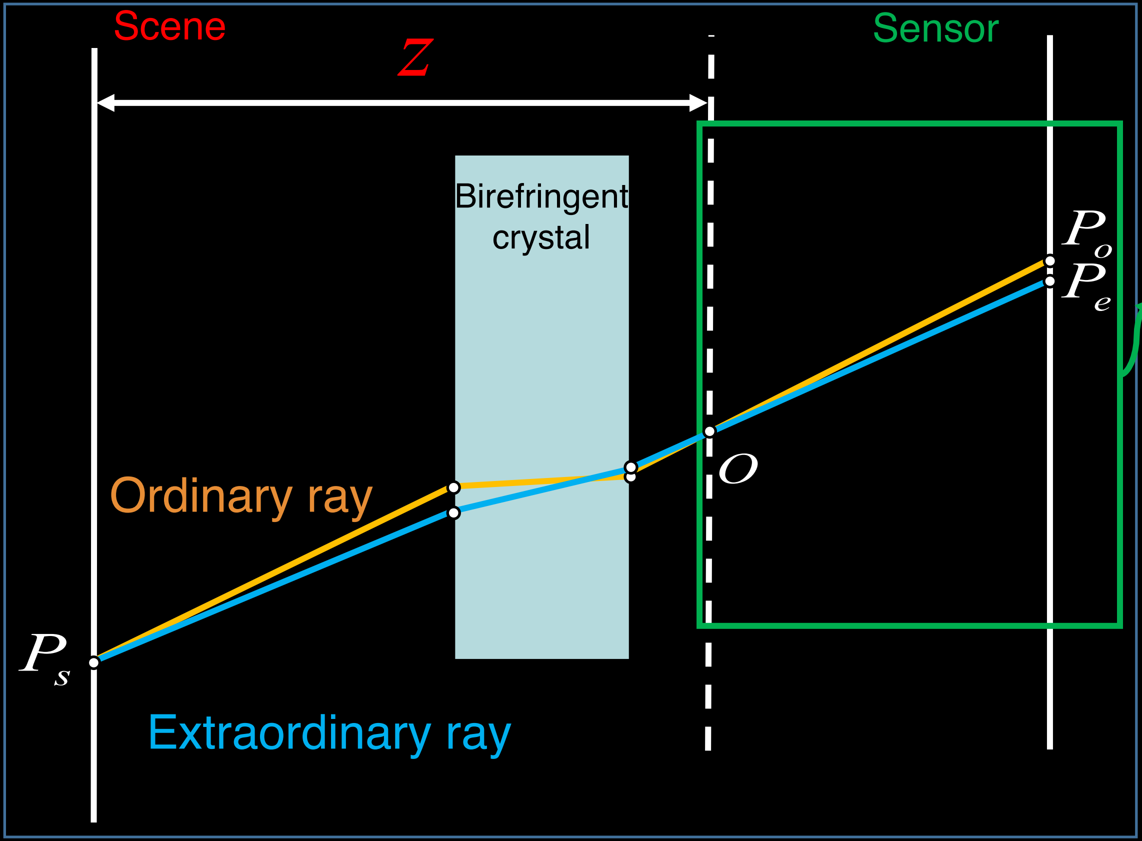
Birefractive Stereo Model

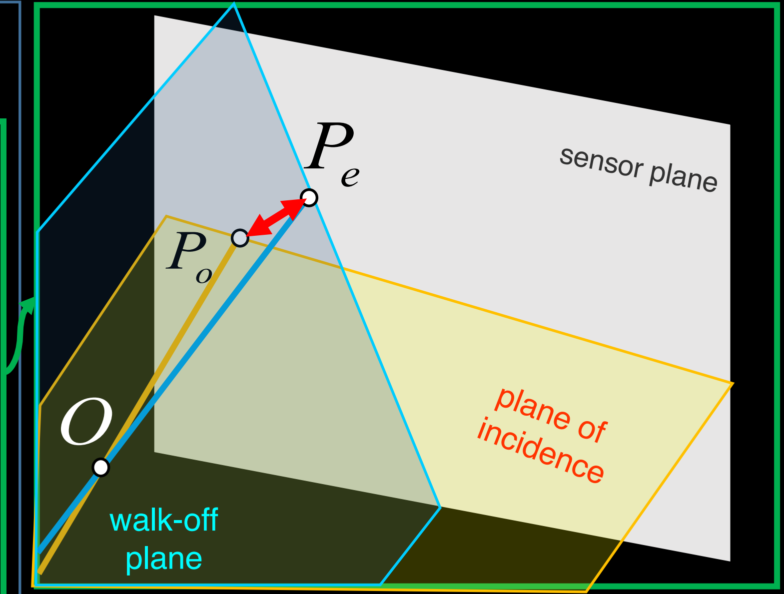


$$\psi_{o\rightarrow e}\left(P_o, z\right) = P_e$$

$$\psi_{e\rightarrow o}\left(P_e, z\right) = P_o$$

Birefractive Stereo Model

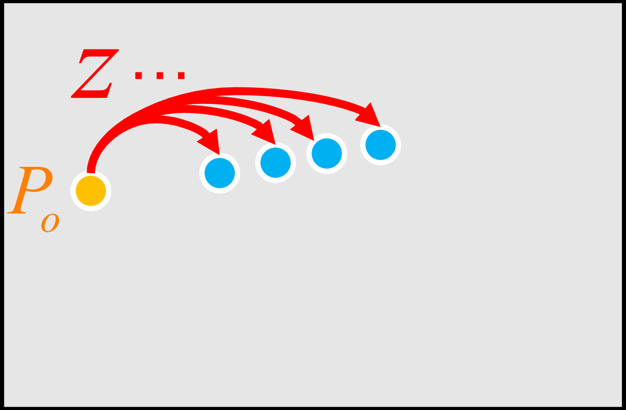




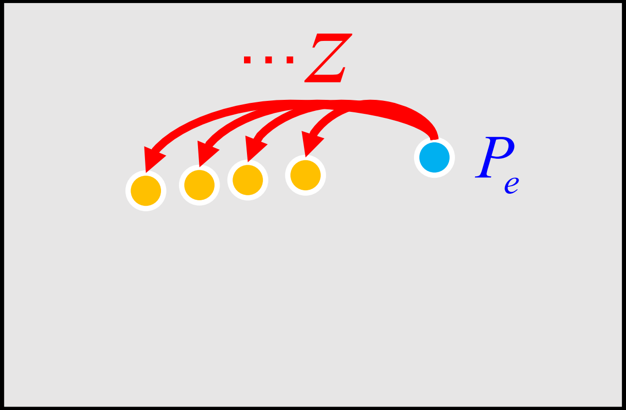
$$\psi_{o\rightarrow e}\left(P_o, z\right) = P_e$$

$$\psi_{e\rightarrow o}\left(P_e, z\right) = P_o$$

Birefractive Stereo Model

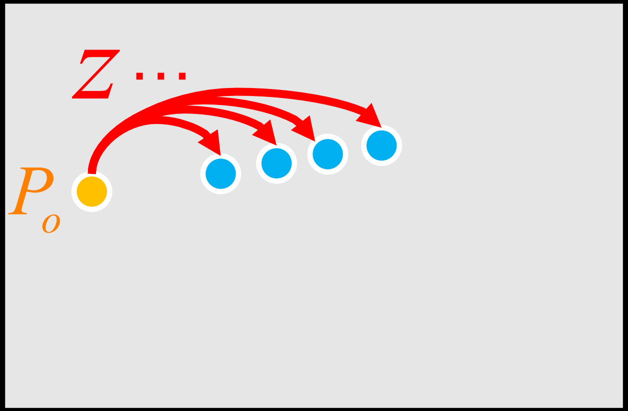


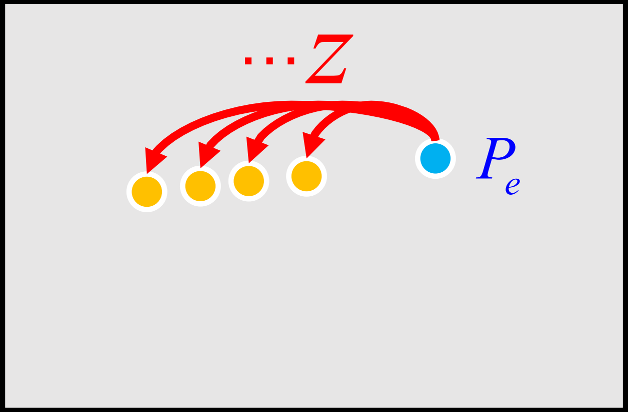
$$\psi_{o\rightarrow e}\left(P_o, z\right) = P_e$$



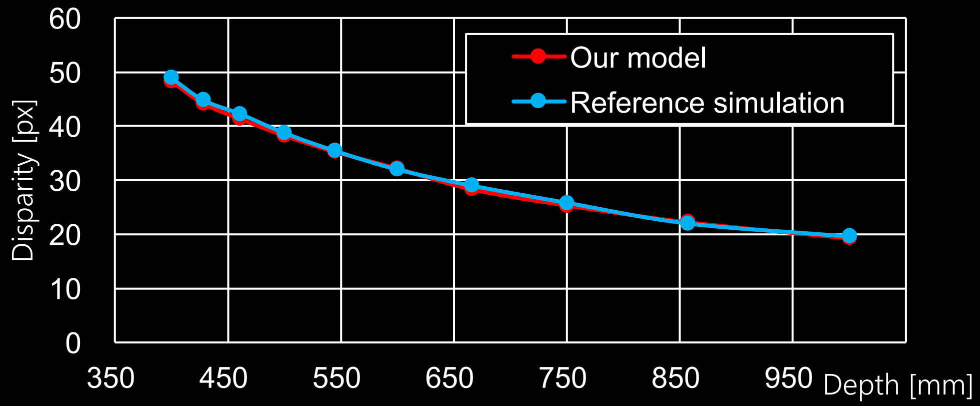
$$\psi_{e\rightarrow o}\left(P_e, z\right) = P_o$$

Birefractive Stereo Model

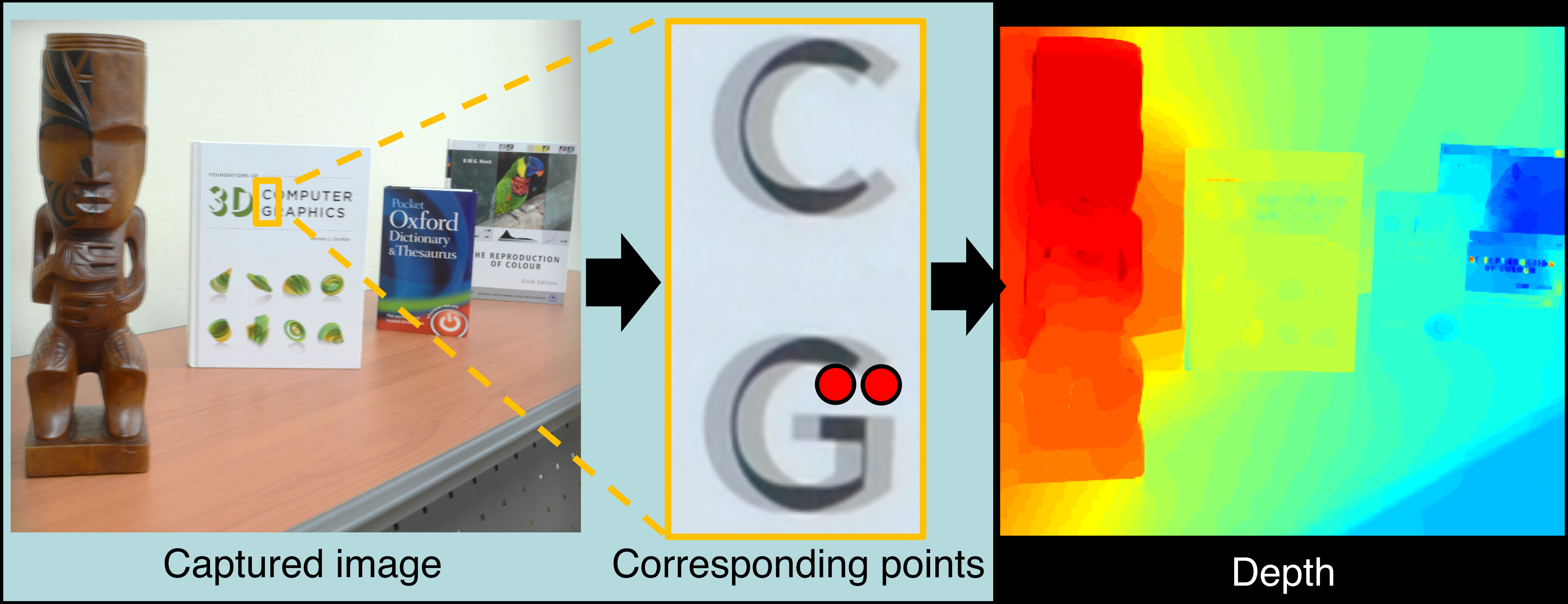




$$\psi_{o \to e}\left(P_o, z\right) = P_e$$



$$\psi_{e \to o}\left(P_e, z\right) = P_o$$



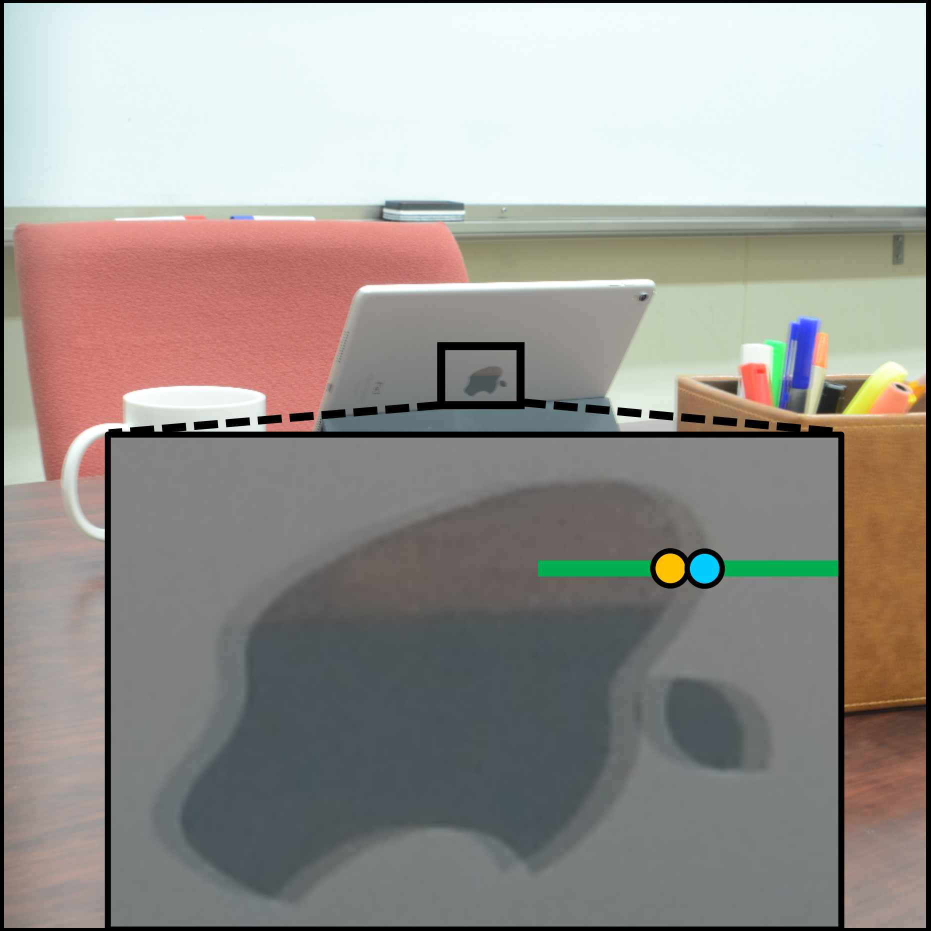
Captured image

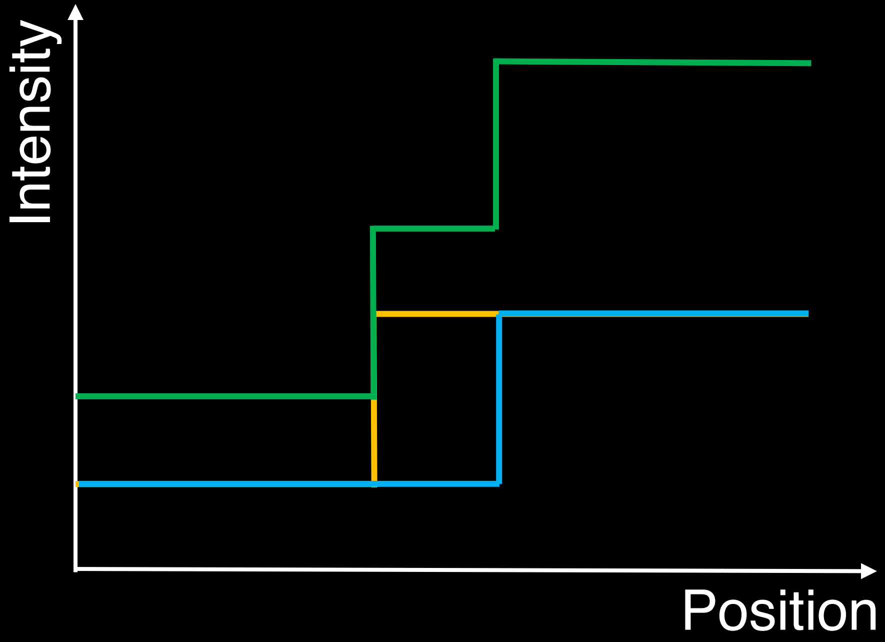
Corresponding points

Depth

CORRESPONDENCE ESTIMATION

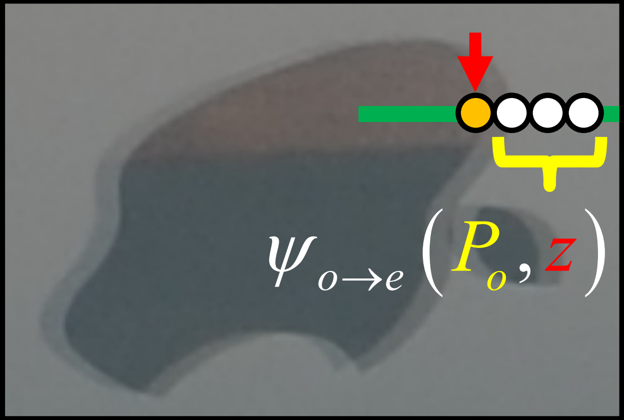
Correspondence from a Double-refraction Image

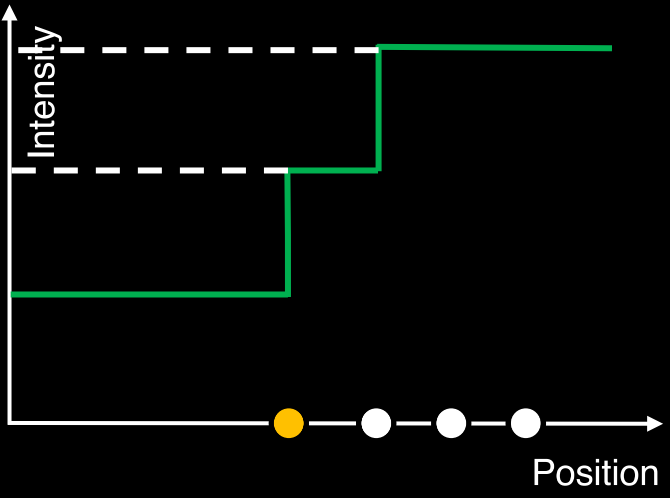


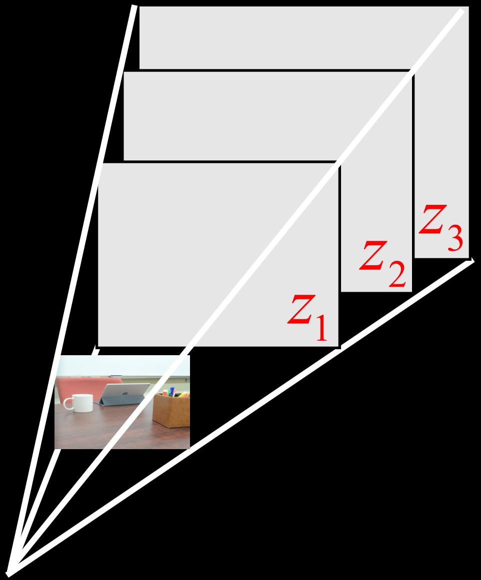


Captured image = ordinary image + extraordinary image

Correspondence Metric





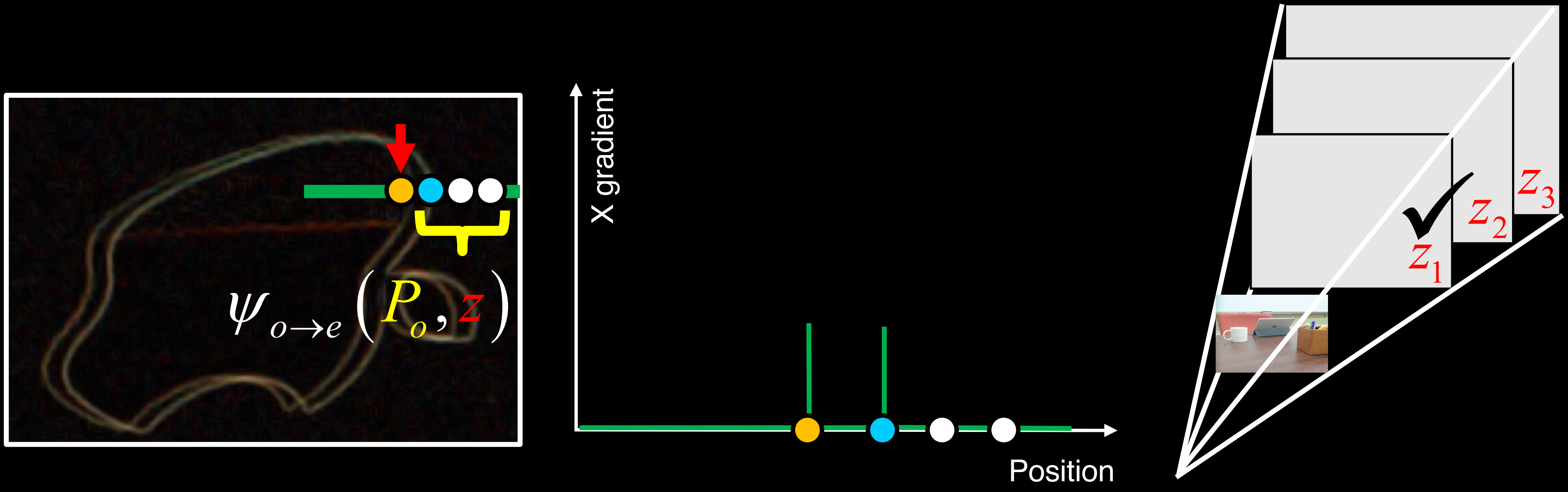


$$I(P_o) \neq I(\psi_{o\rightarrow e}(P_o, z))$$

Intensity of an o-ray pixel

Intensity of the corresponding e-ray pixel

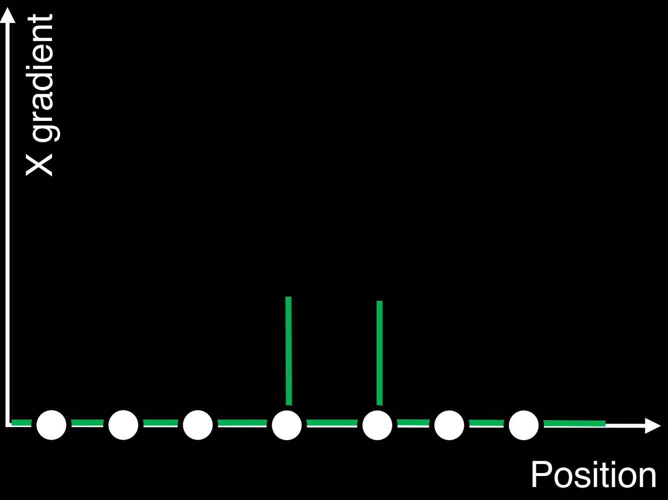
Gradient-domain Metric

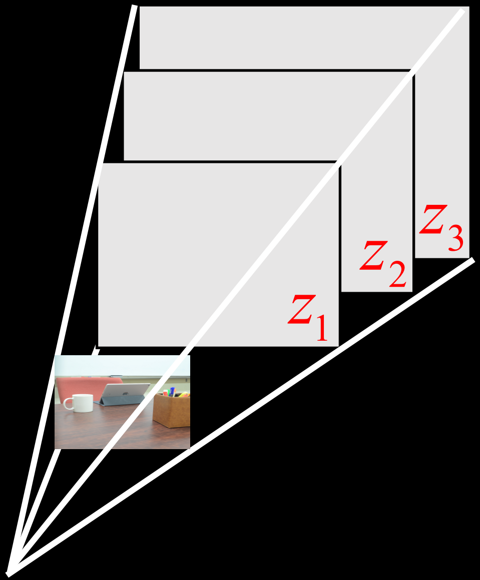


$$C_o(P_o, z) = \left\| \partial I(P_o) - \partial I\left(\psi_{o\to e}(P_o, z)\right) \right\|_1$$

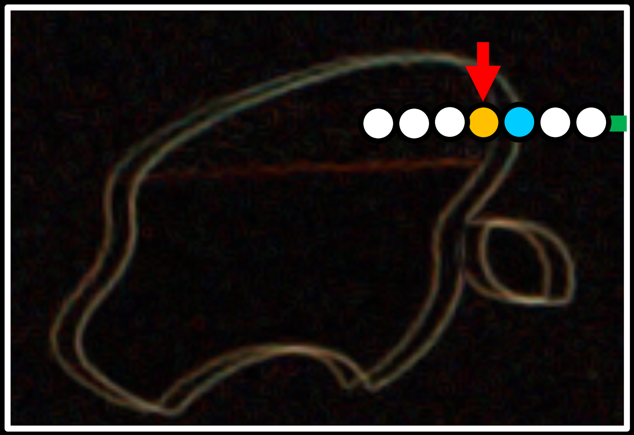
Difference of the gradient profiles
of the corresponding o-ray and e-ray pixels

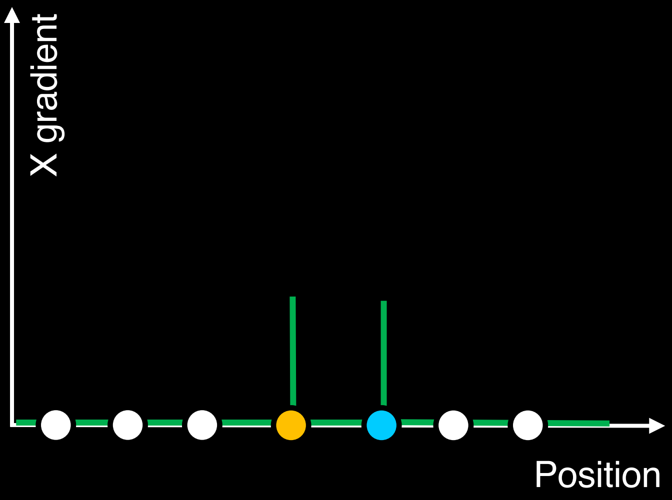
Ambiguity from Superposition

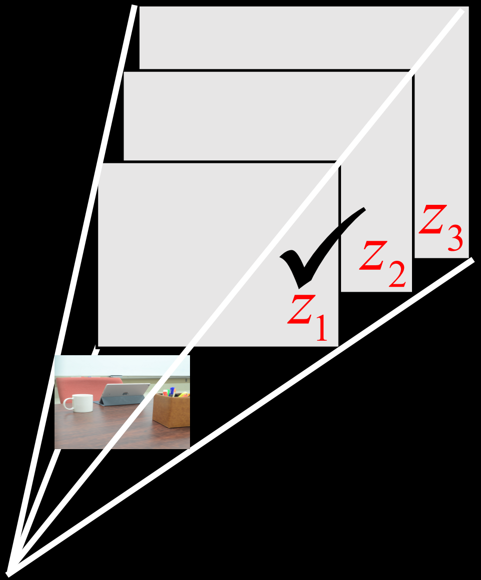




Dual Matching Cost

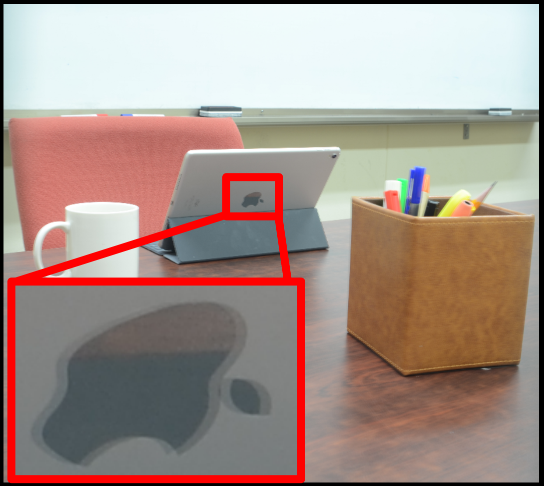






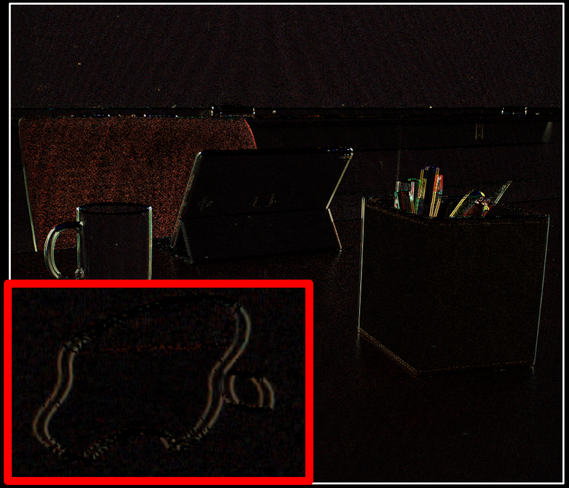
$$C(P,z)=\begin{cases} C_o(P,z), \text{if} \min C_o(P,z_\forall) \le \min C_e(P,z_\forall) \\ C_e(P,z), \text{otherwise} \end{cases}$$

Depth Estimation Process

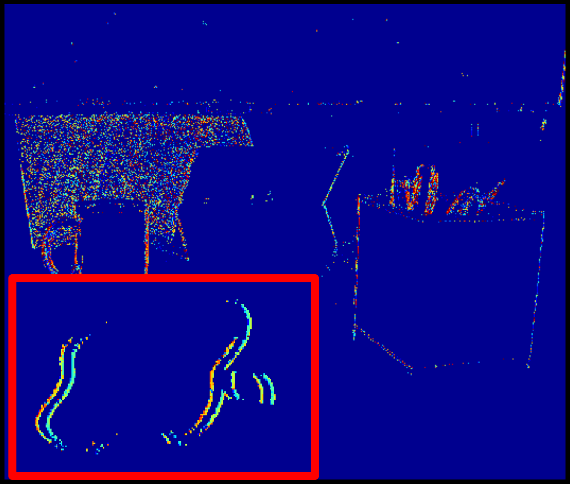


Double-refraction image

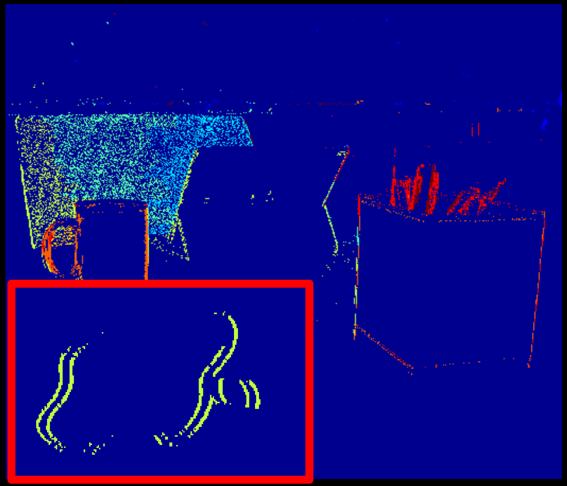
Gradient profile



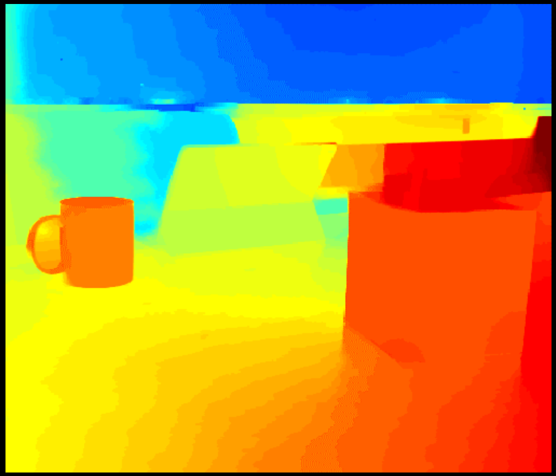
Handling ambiguous pixels



Sparse depth map
without cost aggregation



Sparse depth map
with cost aggregation



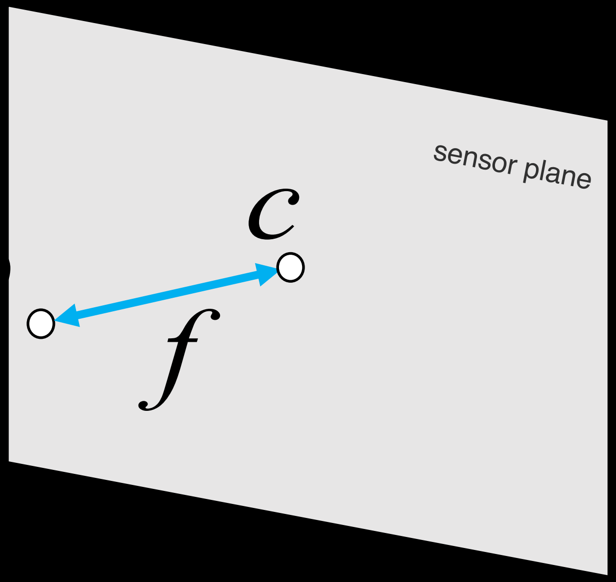
Dense depth map

BIREFRACTIVE STEREO

CALIBRATION

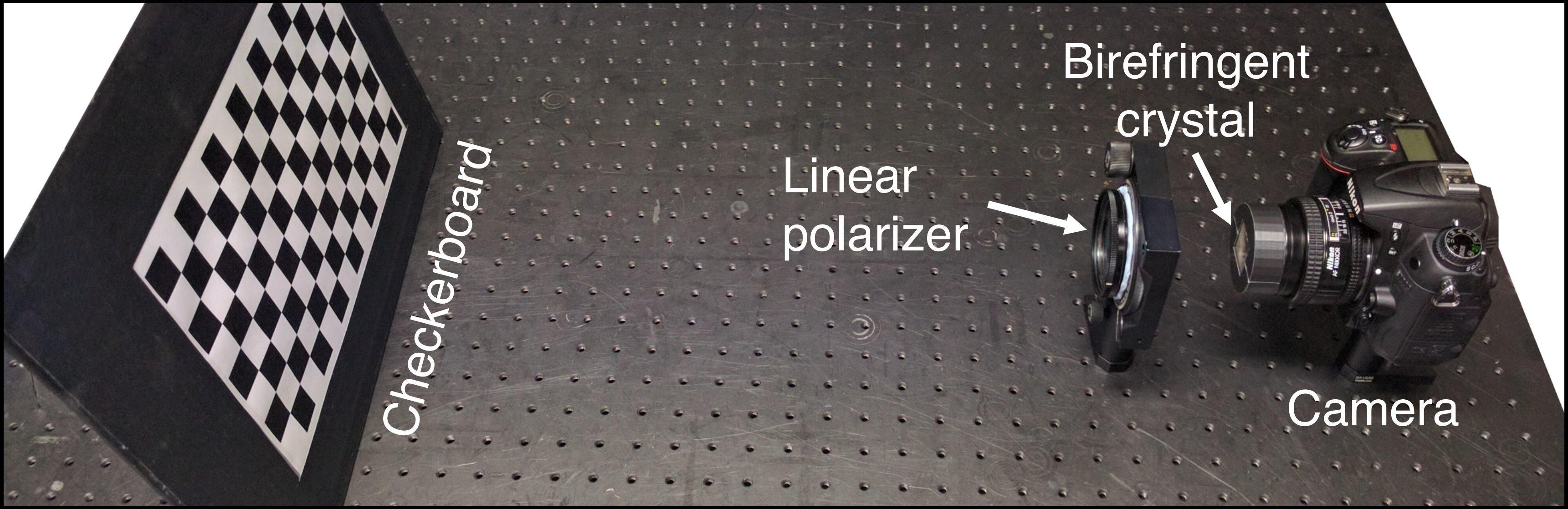
Camera Calibration

- Camera
  - –Intrinsic parameters
    - Focal length and center of projection of the camera [Zhang 2000]



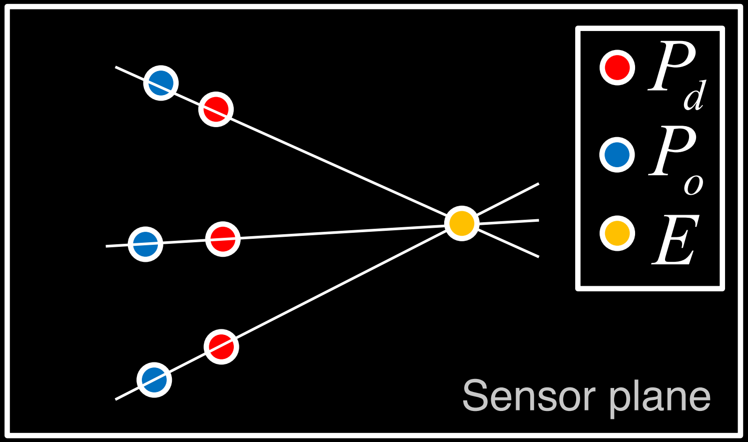
Birefringent Crystal Calibration

- Orientation of the crystal w.r.t. the camera (essential point: **E**)
- Optical anisotropy of the crystal (optical axis: **a**)

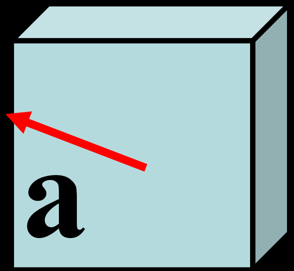


Birefringent Crystal Calibration

- Orientation of the crystal w.r.t. the camera (essential point: **E**)



- Optical anisotropy of the crystal (optical axis: **a**)

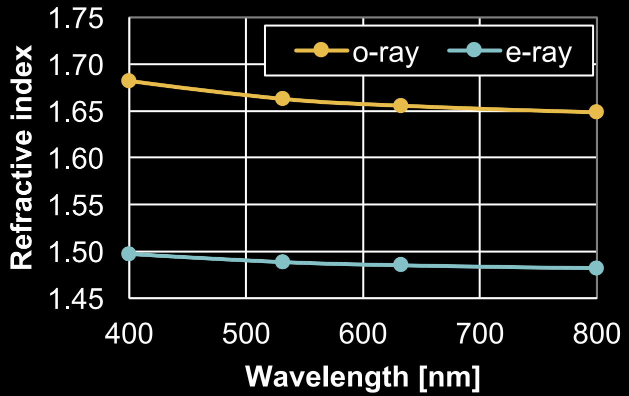


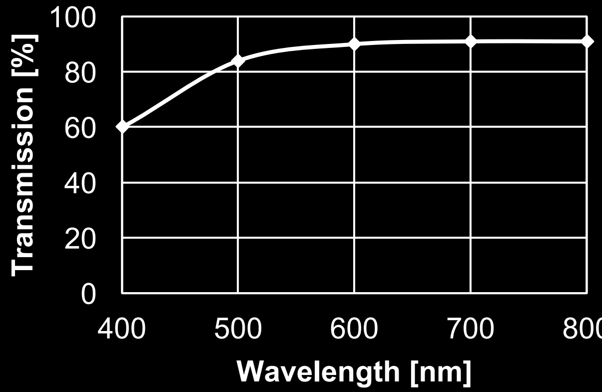
$$\underset{\mathbf{a}}{\text{minimize}} \sum_{\{P_d, P_e\}\in\Pi} \left\| P_d - \psi_{e\to d}\left(P_e, z; \mathbf{a}\right) \right\|_2$$

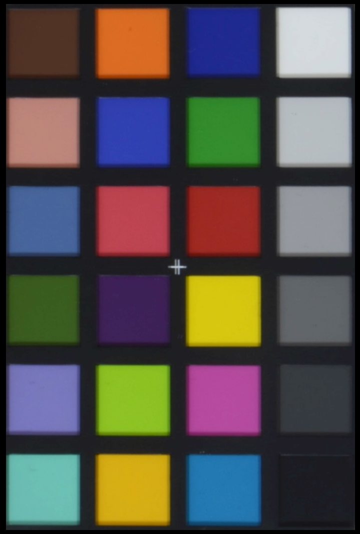
Calcite Characterization

Calcite

Prototype



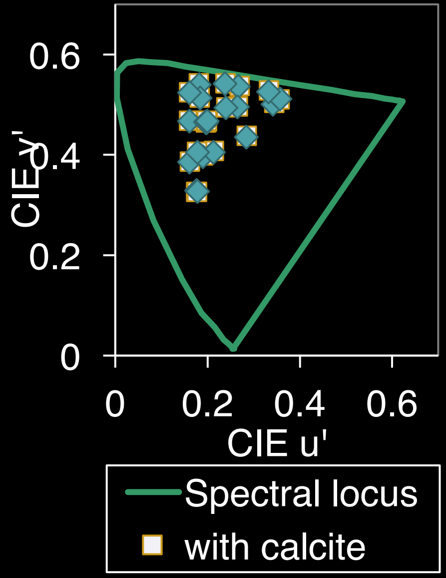




With calcite

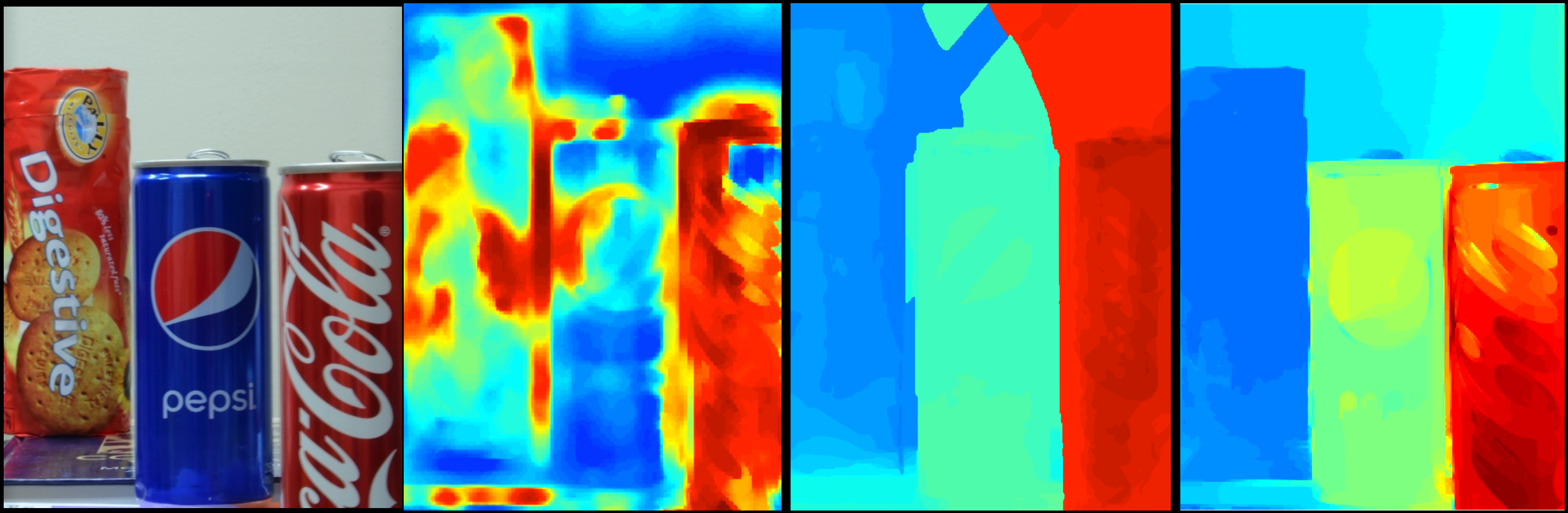
Without calcite

Color comparison



RESULTS

Single-shot Depth Imaging vs. Ours



Depth-from-defocus

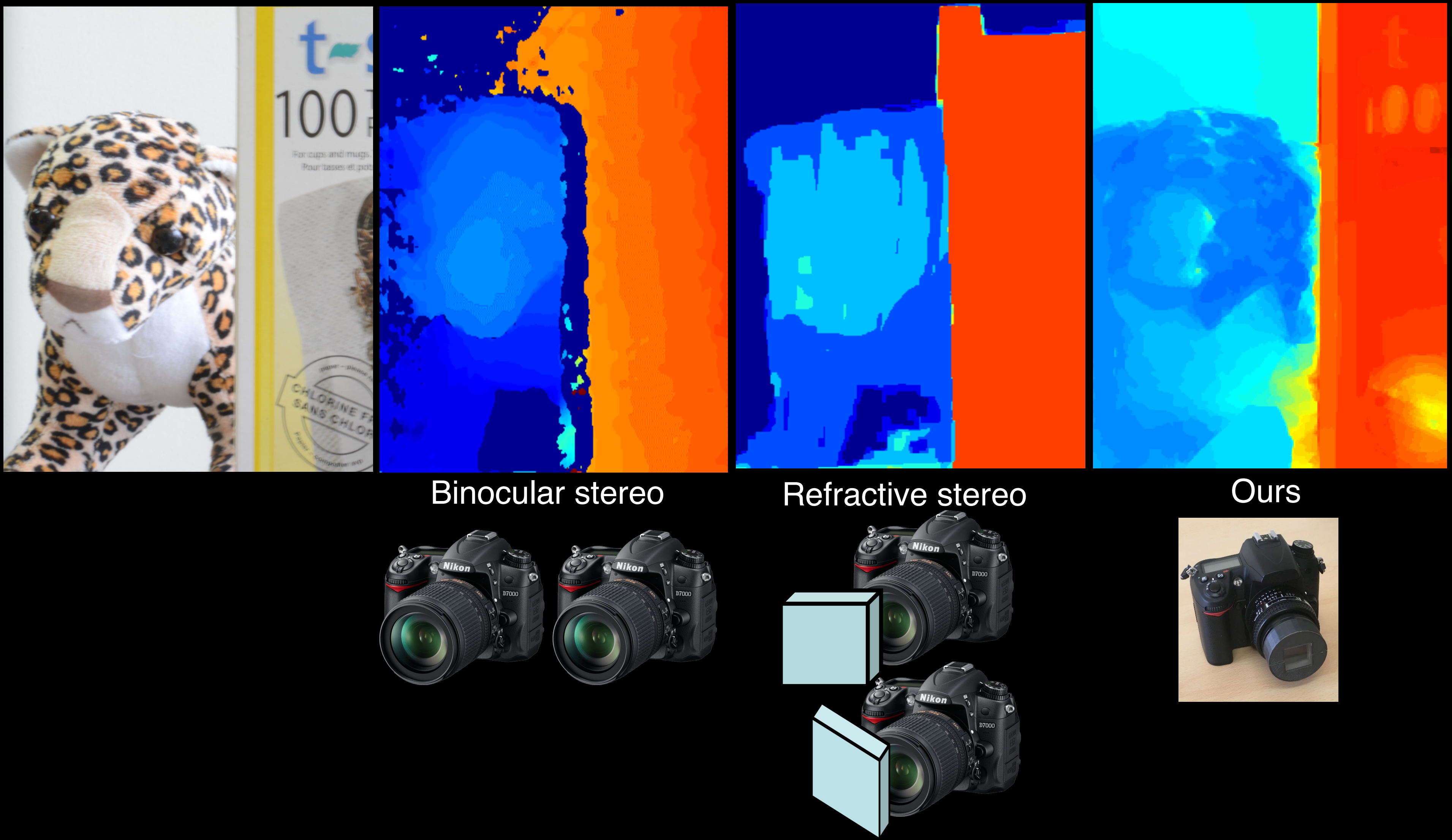
Lytro Illum: Light-field camera

Ours

Low accuracy

Large sensor

Two-shot Depth Imaging vs. Ours

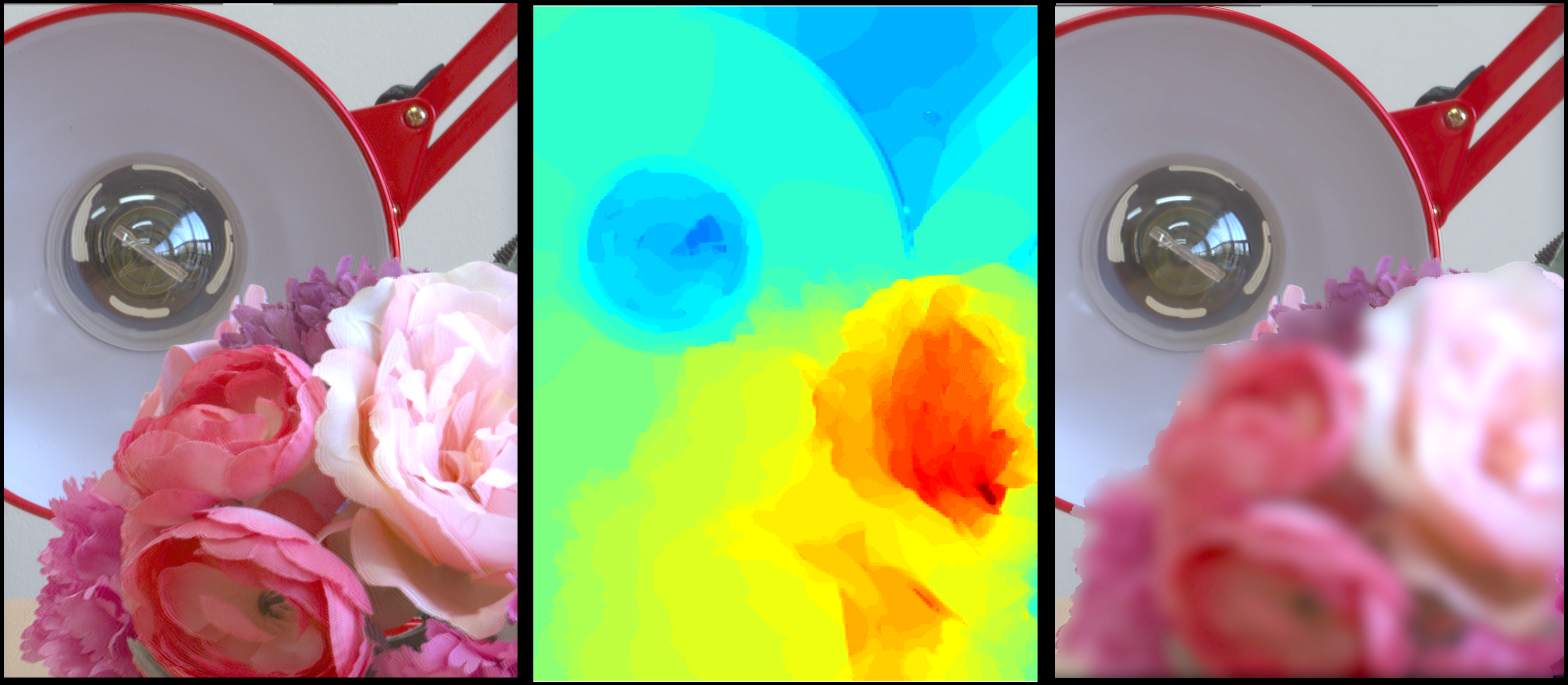


Binocular stereo

Refractive stereo

Ours

Refocusing



Image

Depth map

Refocusing

Decolorization via RGBD Segmentation

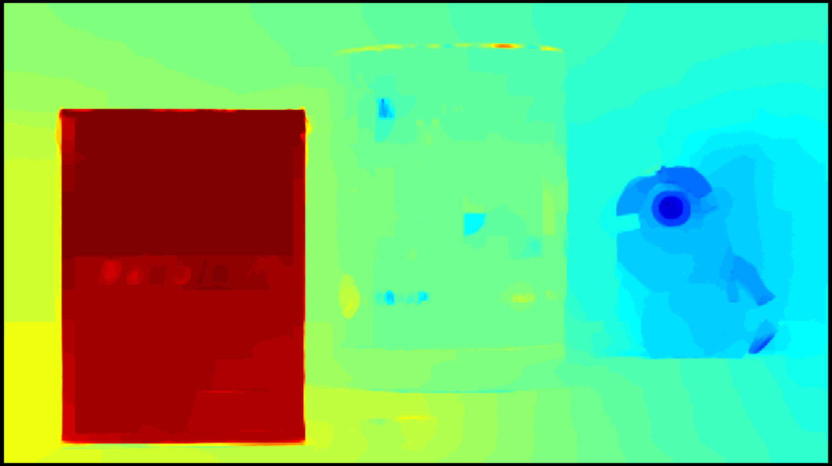
Image

Depth map

Decolorization

Generating 3D Anaglyph Stereo Images

Image



Depth map

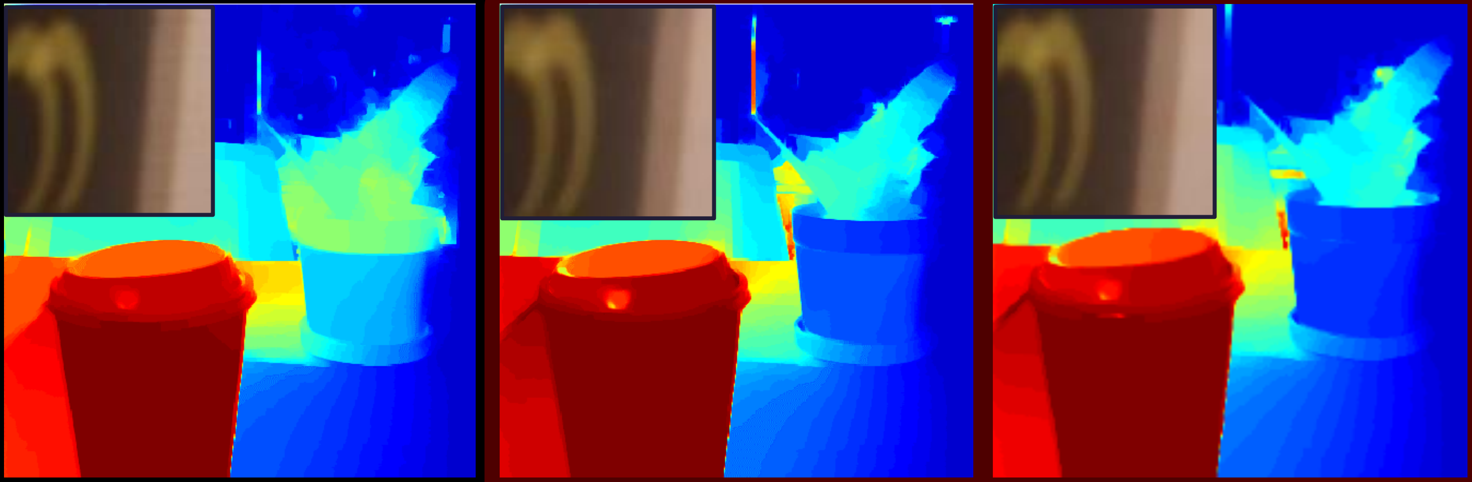
Image of the displaced view point

3D anaglyph photo

DISCUSSION AND CONCLUSION

Limitation: Impact of Noise

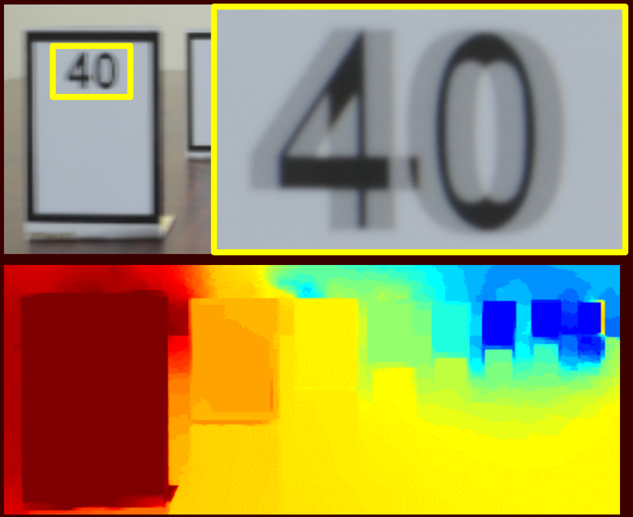
Double refraction ISO 800 ISO 1600



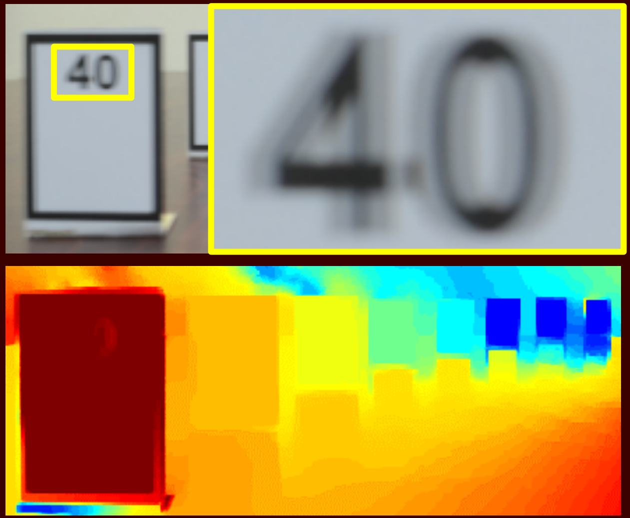
ISO 100 ISO 800 with denoising ISO 1600 with denoising

Limitation: Impact of Depth-of-field

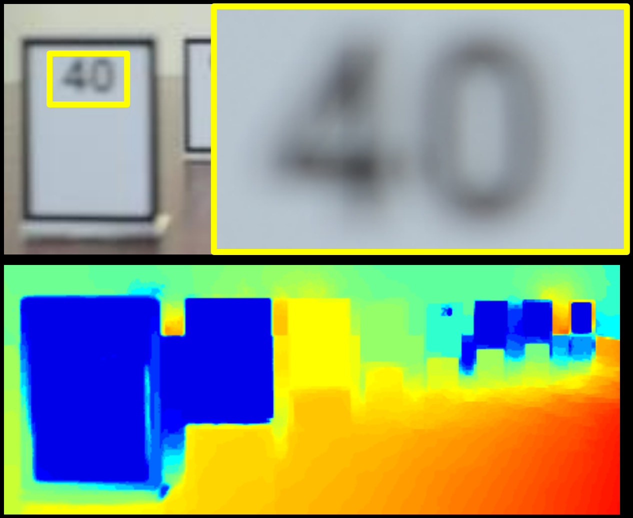
f/22



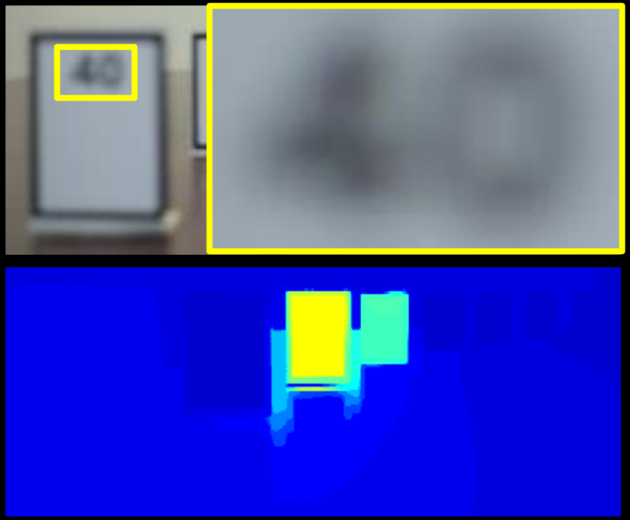
f/11



f/5.6



f/2.8



Conclusion

- Birefractive stereo imaging
  - Birefractive stereo model
  - Correspondence matching algorithm
  - Birefractive stereo calibration

- Acknowledgements
  - KAIST VCLAB members, Andrian Jarabo and anonymous SIGGRAPH reviewers