Compact Single-Shot Hyperspectral Imaging using a Prism

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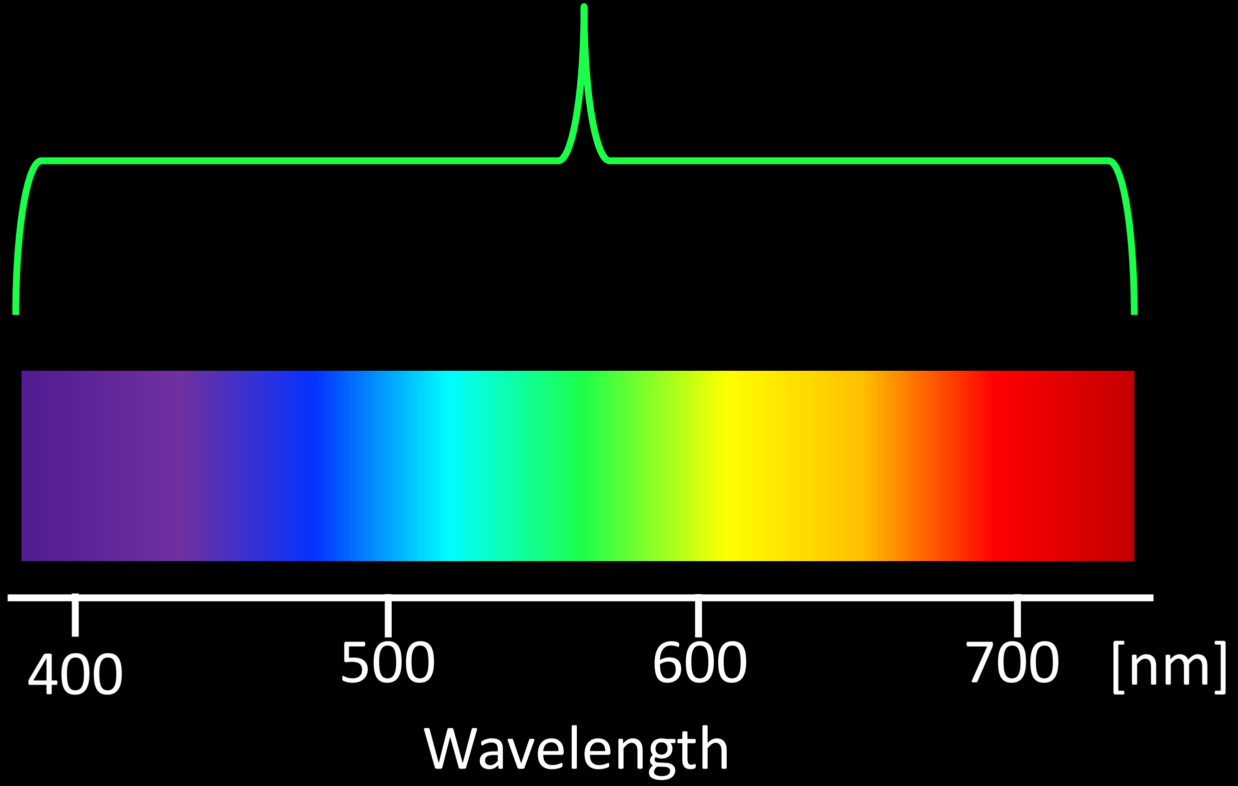
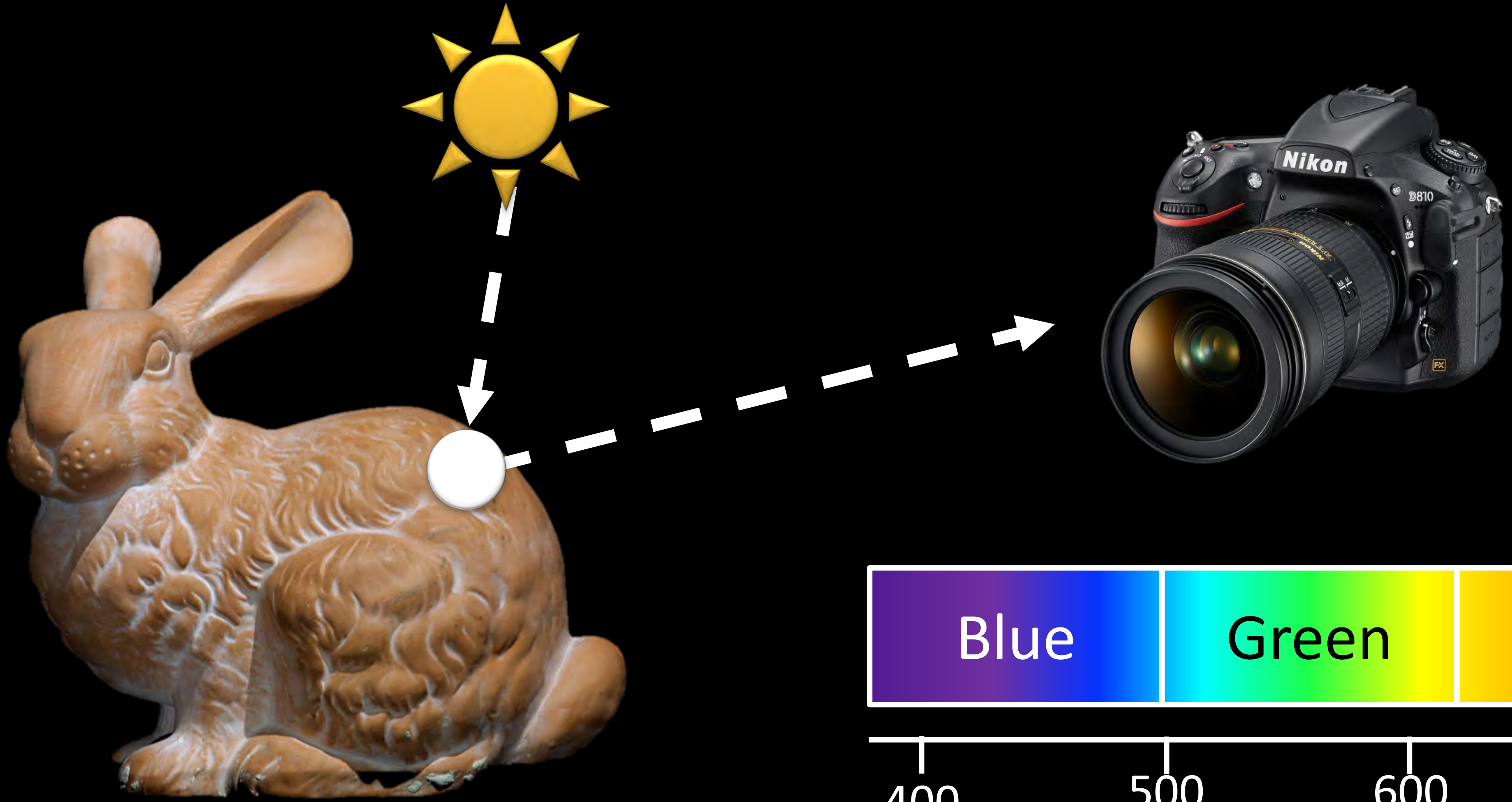
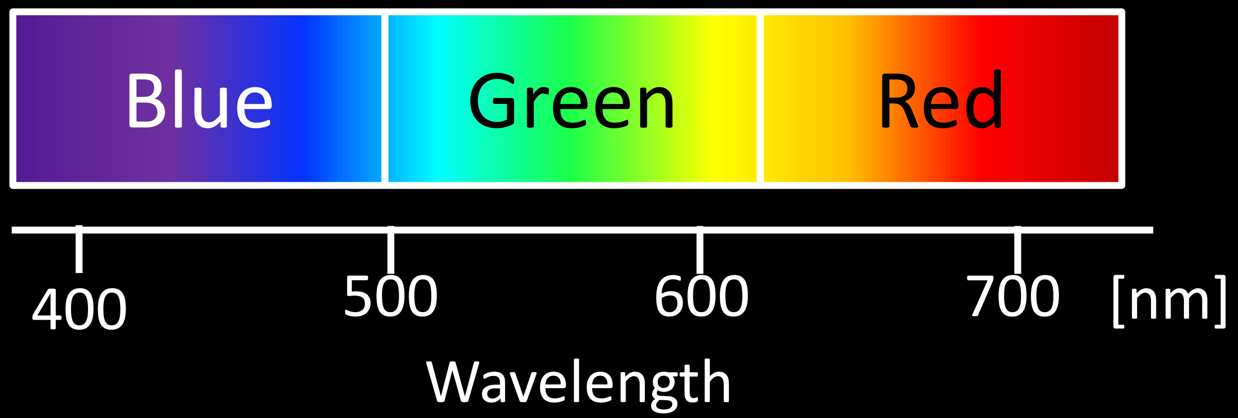
Spectrum

$L(\lambda)$: Spectrum

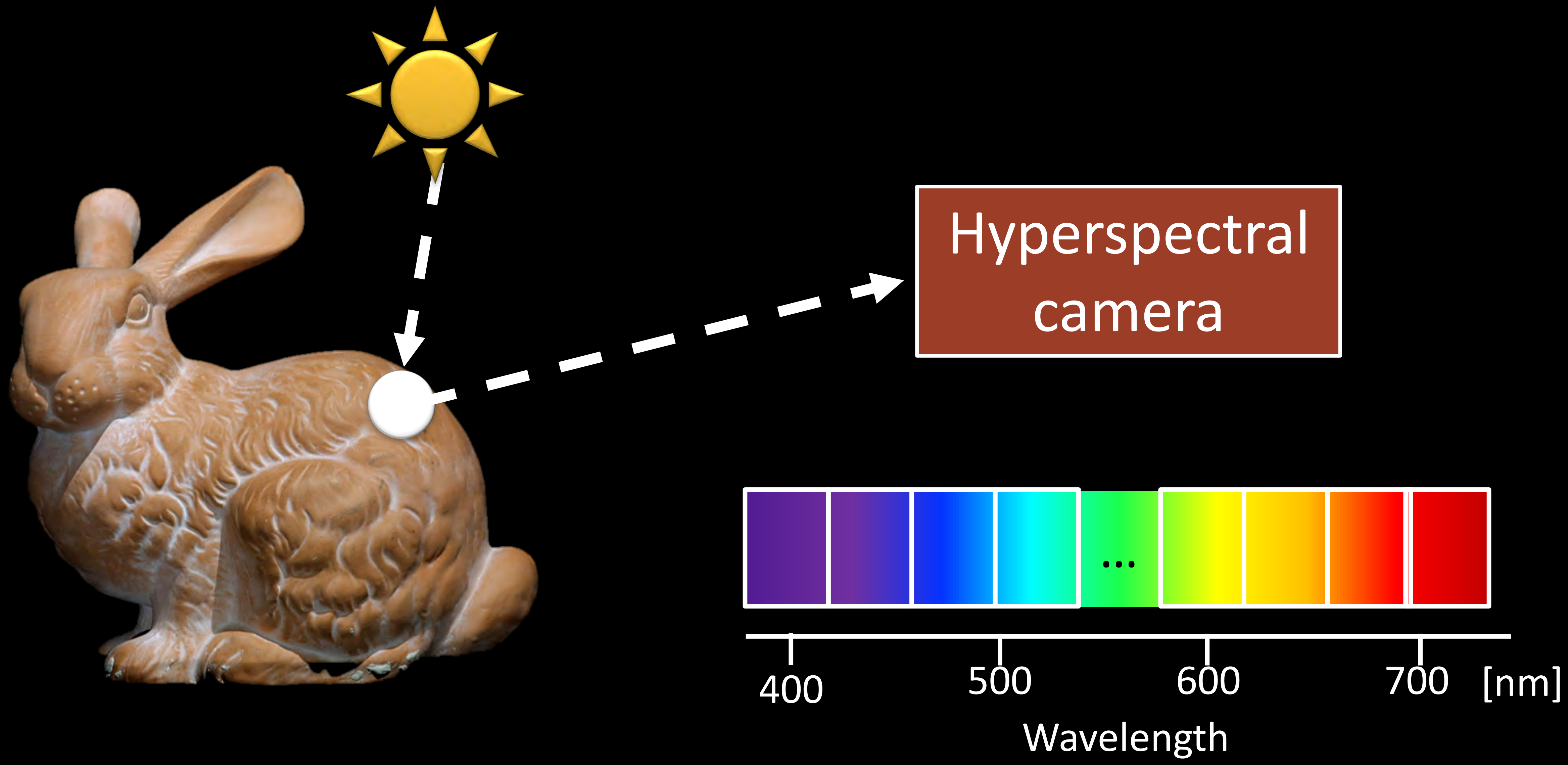


RGB Imaging



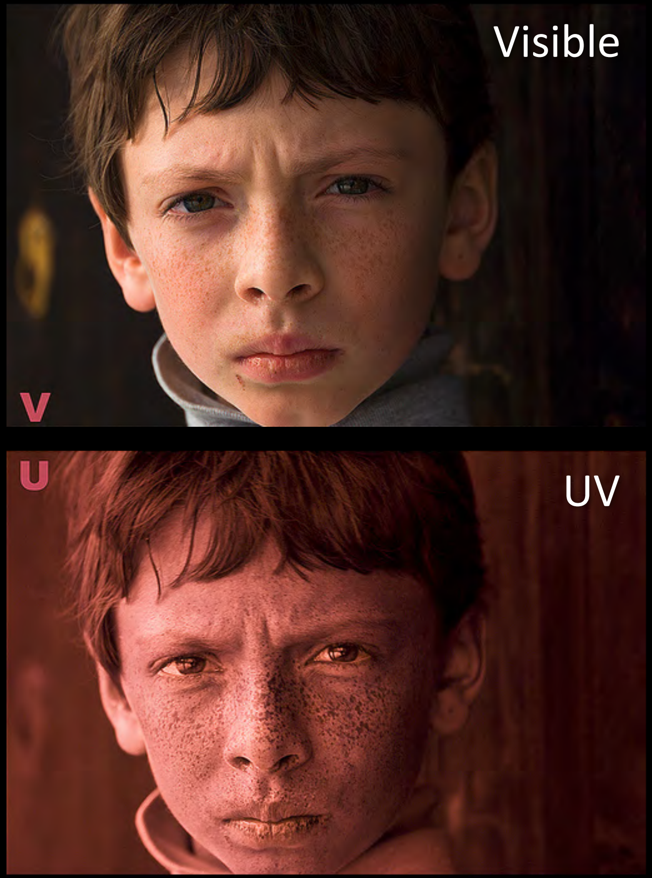


Hyperspectral Imaging

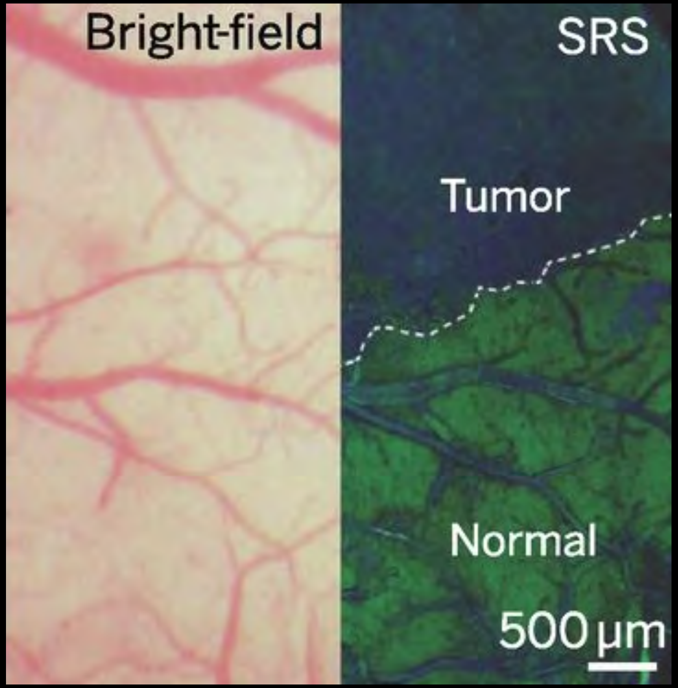


Hyperspectral Imaging

Geology [1]



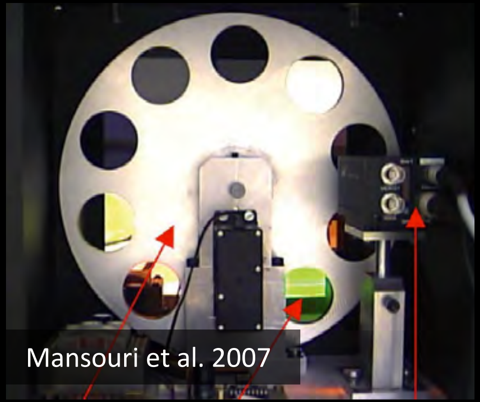
Cosmetics [2]



Biology [3]

[1] NASA
[3] rshephorse, Flickr
[2] Cheng et al., Vibrational spectroscopic imaging of living systems: An emerging platform for biology and medicine, Science 2015

Previous Systems



Mansouri et al. 2007

Spectral scanning

- [Mansouri et al. 2007], [Gat 2000], [Brusco et al., 2006]

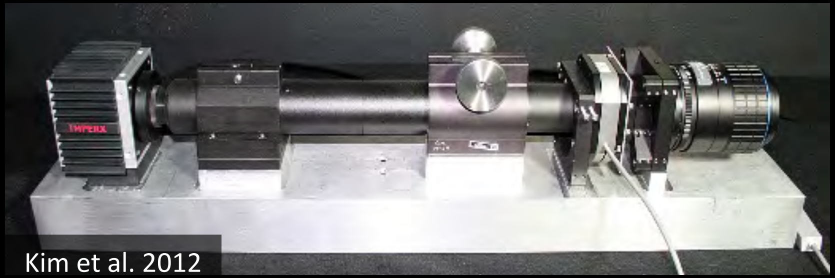
- Static scene only
- Low spectral resolution

Habel et al. 2012

Computed Tomography Imaging Spectroscopy (CTIS)

- [Habel et al. 2012], [Johnson et al. 2007], [Okamoto et al. 1993]]

- Large system
- Low spatial resolution



Kim et al. 2012

Compressive Coded Aperture Spectral Imaging (CASSI)

- [Kim et al. 2012], [Wagadarikar et al. 2008]], [Gehm et al.,2007]

- Large system
- Low spatial resolution

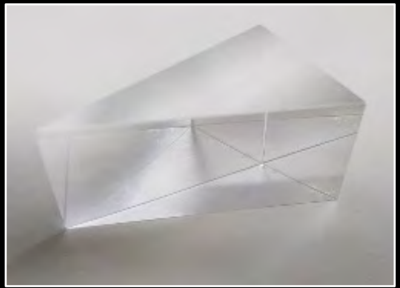
Cao et al. 2011

Prism-Mask Multispectral Video Imaging System (PMVIS)

- [Cao et al. 2011]

- Low spatial resolution

Compact Hyperspectral Camera



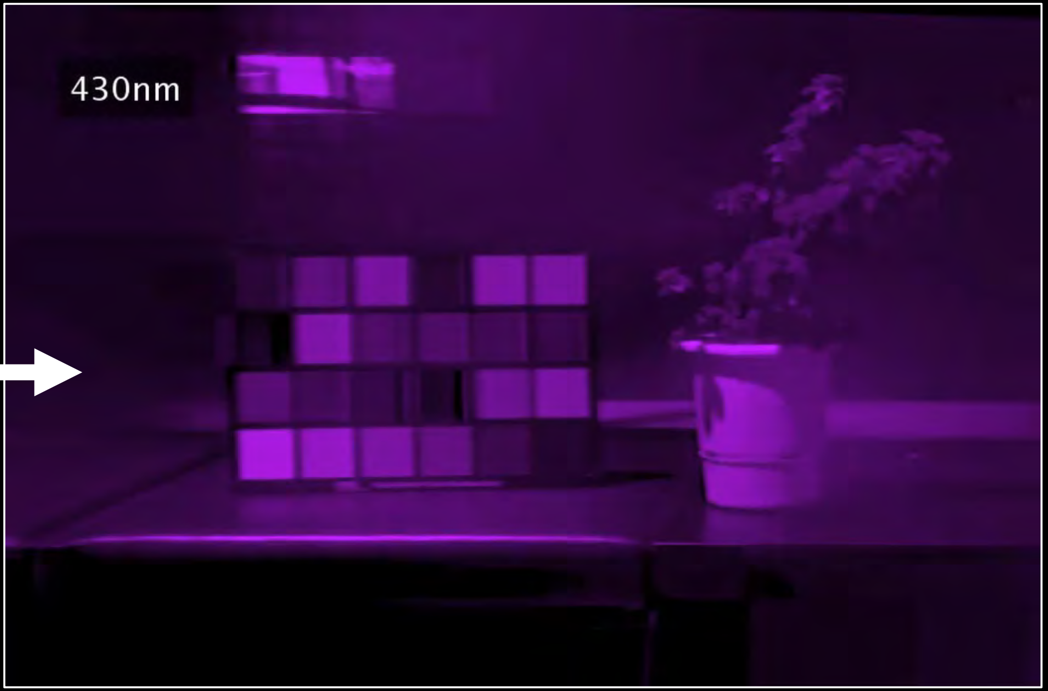
- Compact
- Single-shot
- High spatial/spectral resolution

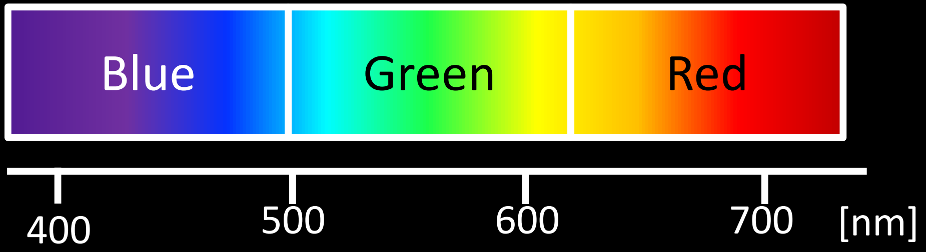
Input & Output

Input

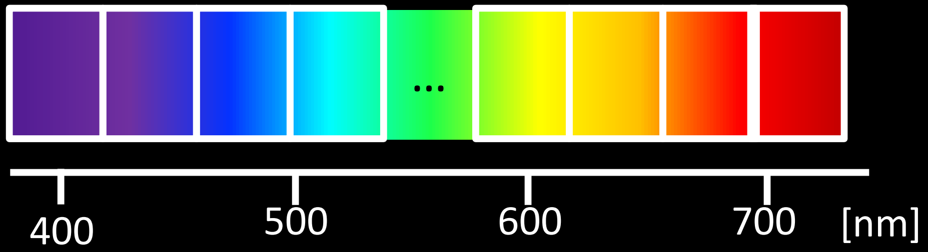
Computational method

Output



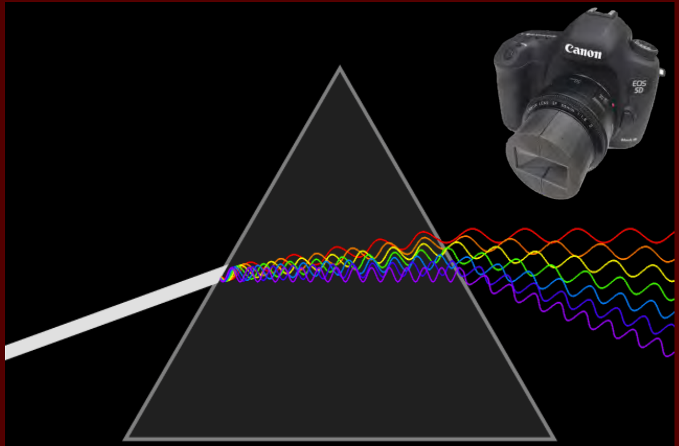


# of channels: 3



# of channels: 23

Challenges



Prism

Dispersion

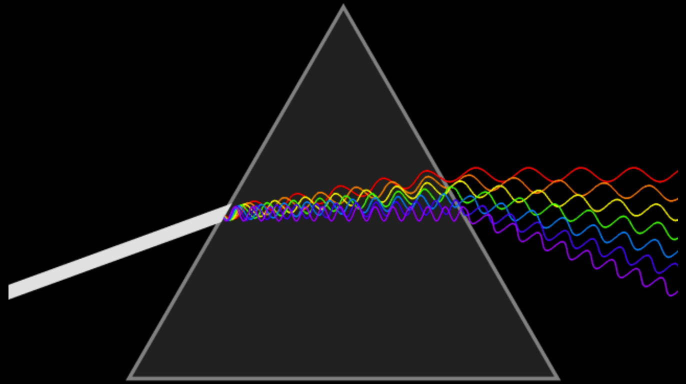
Hyperspectral image

1. How to model the dispersion accurately?

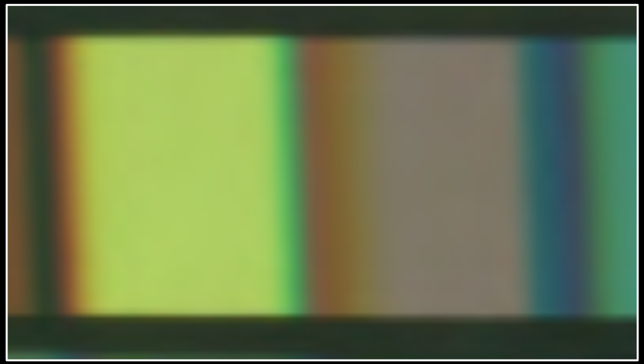
➔ Spatially-varying dispersion model

2. How to reconstruct hyperspectral images?

➔ Gradient-based reconstruction



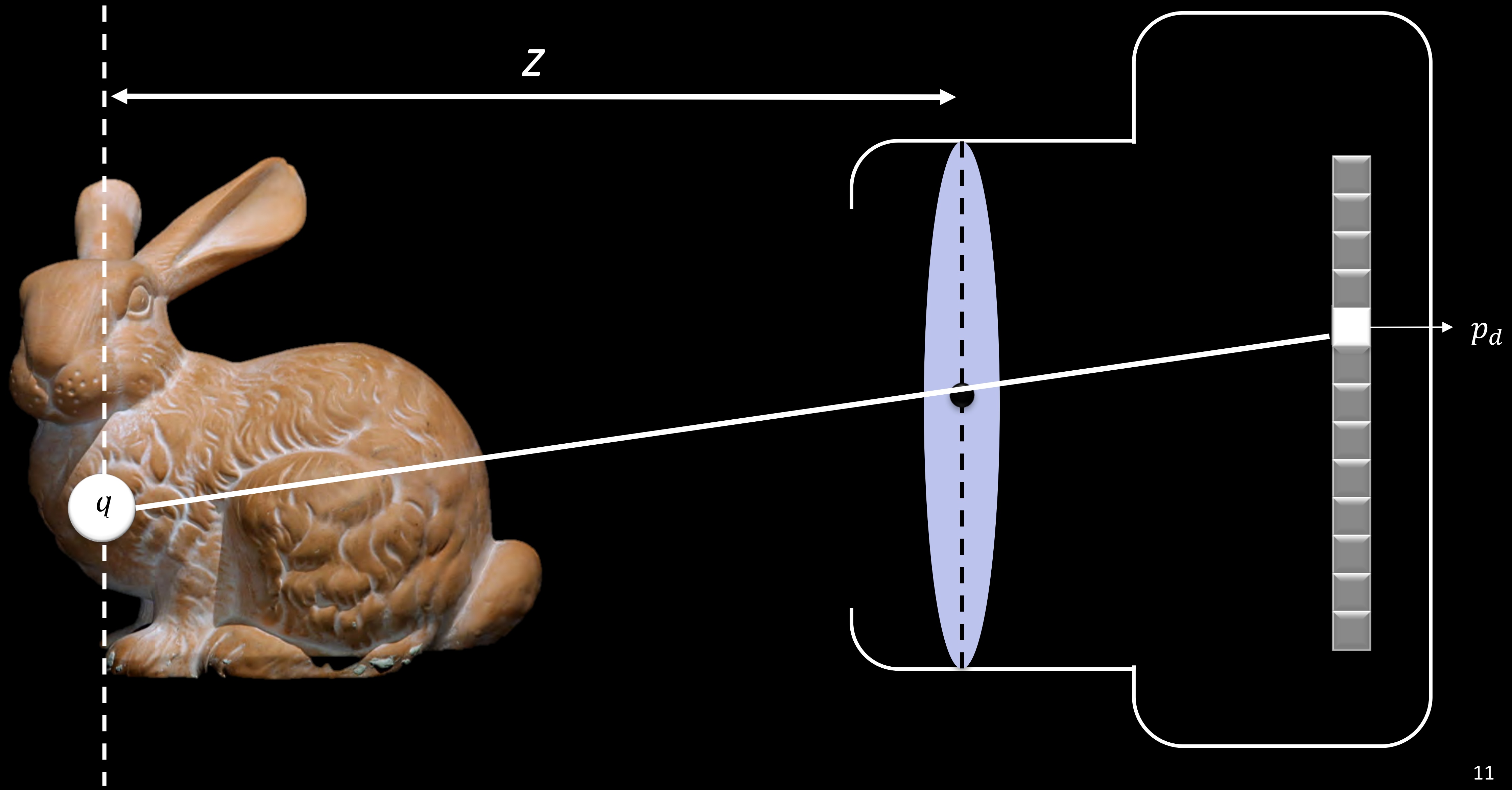
Prism



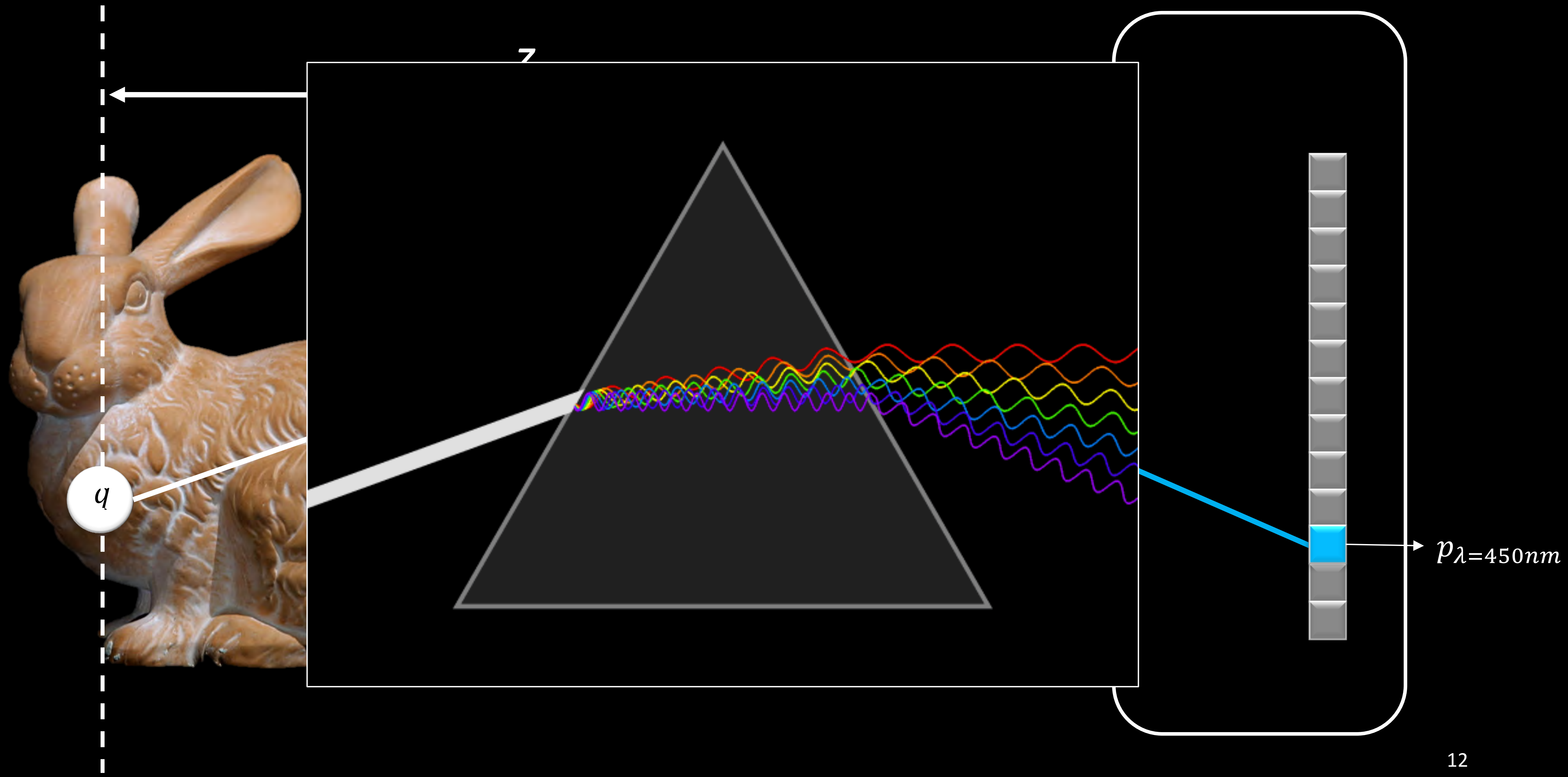
Dispersion

DISPERSION MODEL

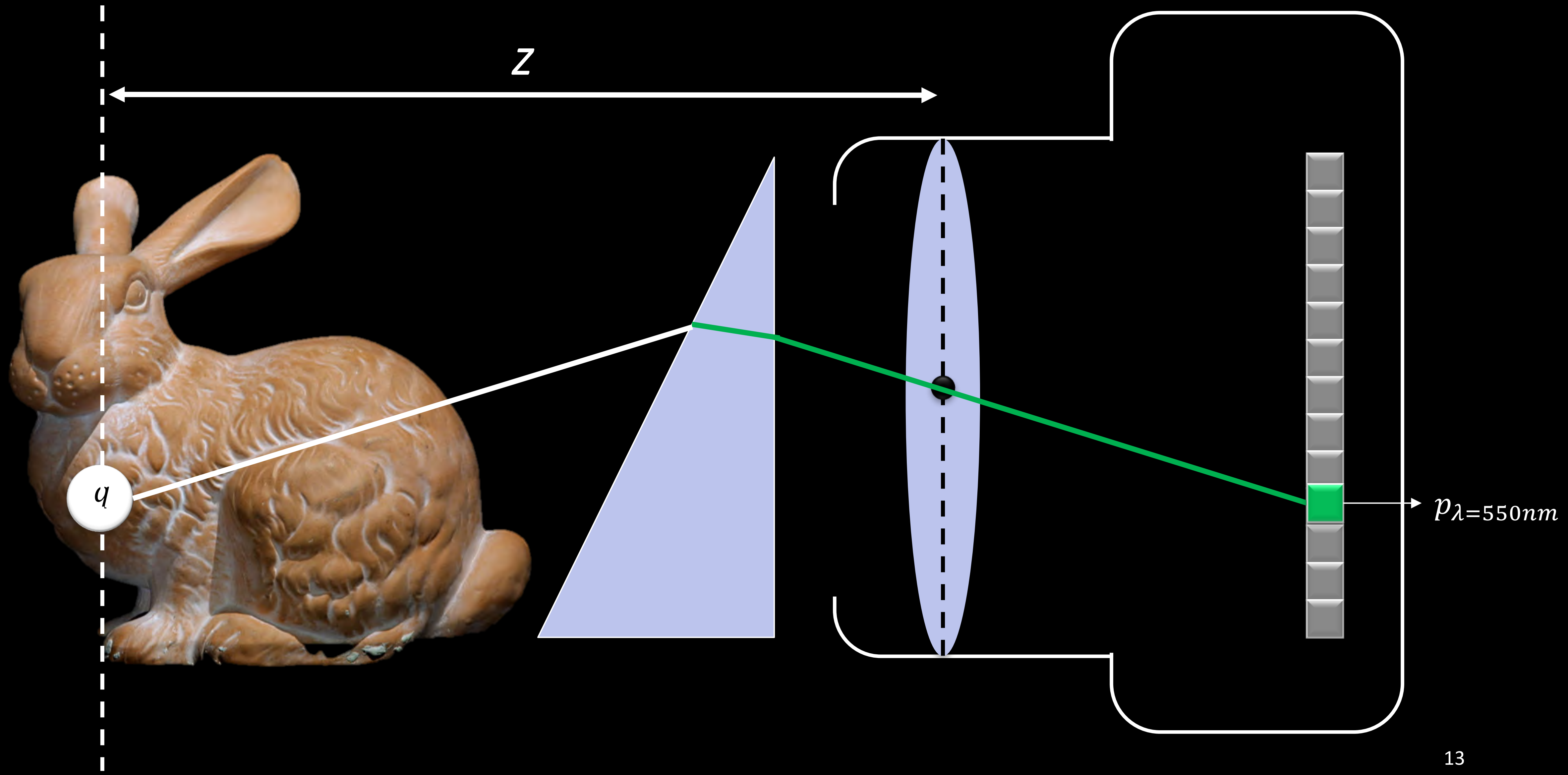
Without a Prism



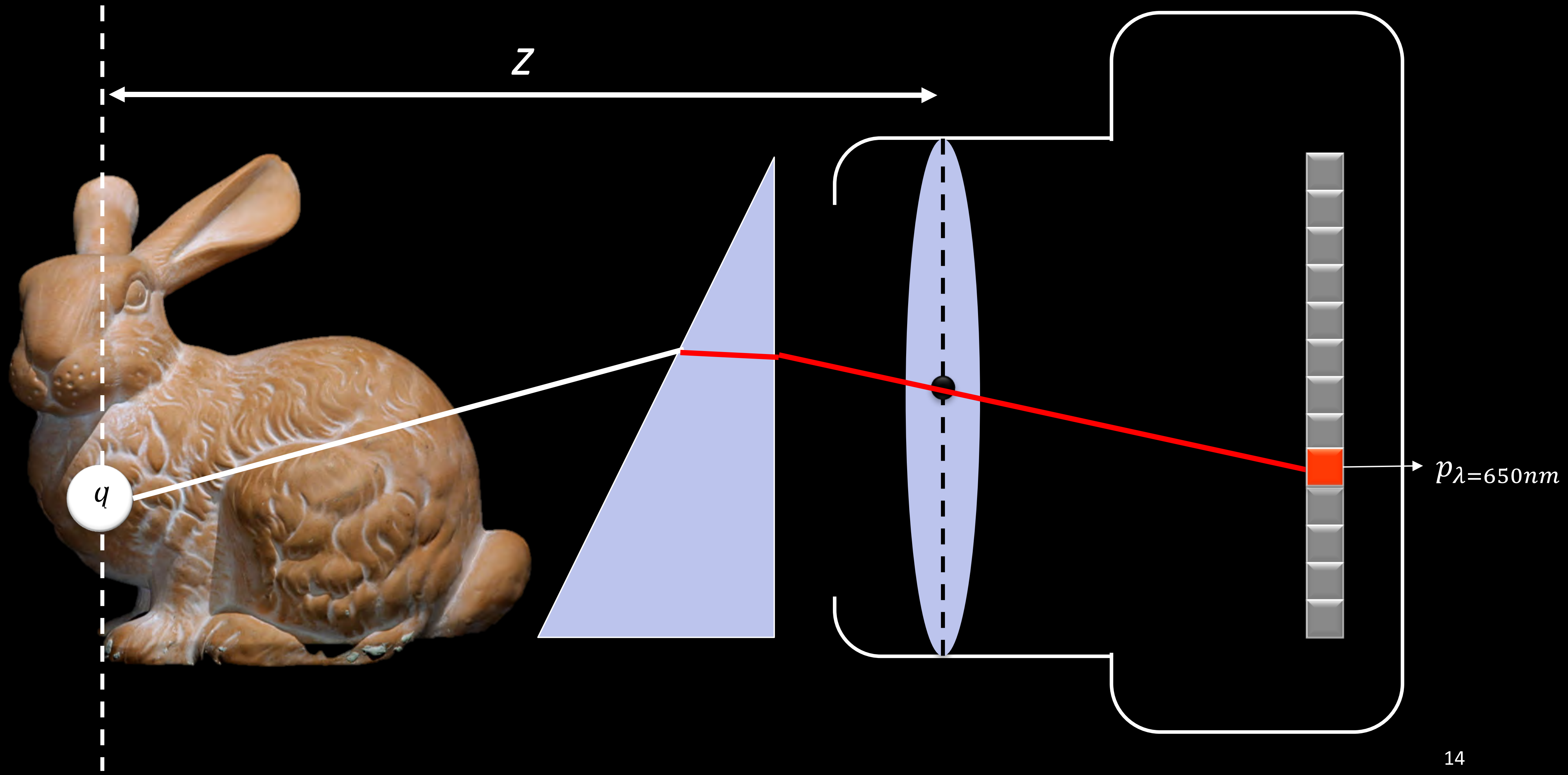
With a Prism



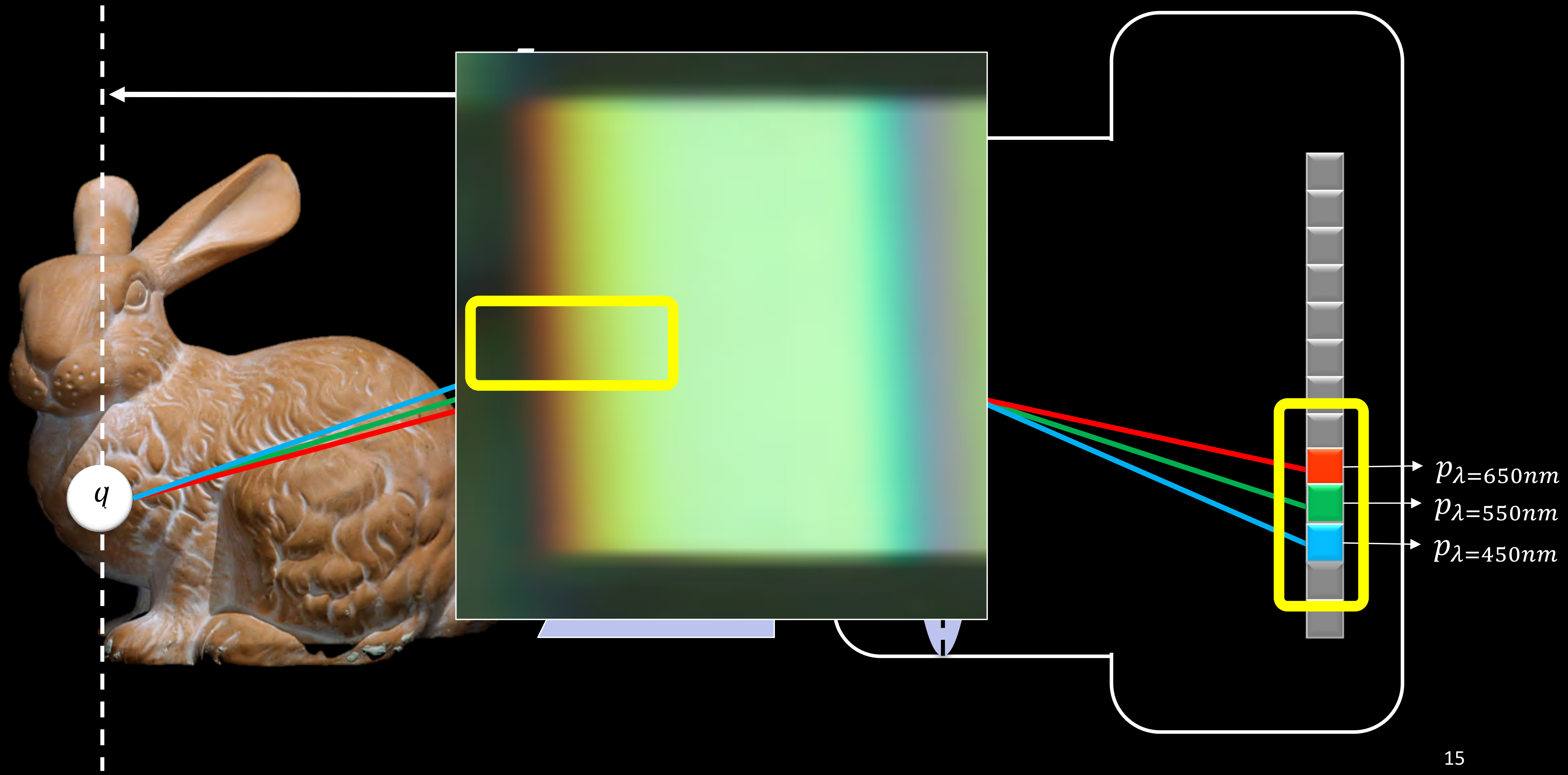
With a Prism



With a Prism



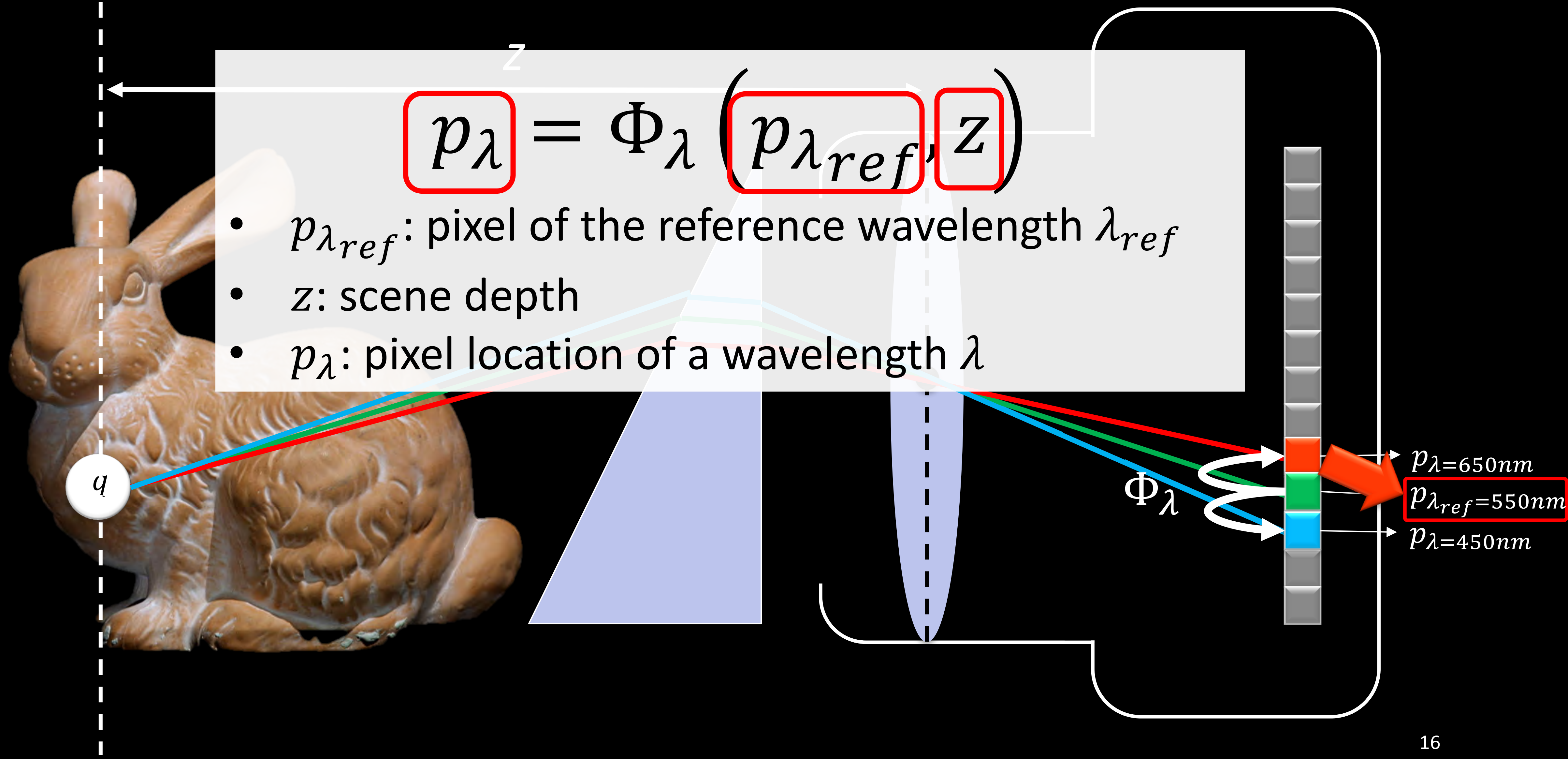
With a Prism



Dispersion Model

$$\boxed{p_\lambda} = \Phi_\lambda\left(\boxed{p_{\lambda_{ref}}}, \boxed{z}\right)$$

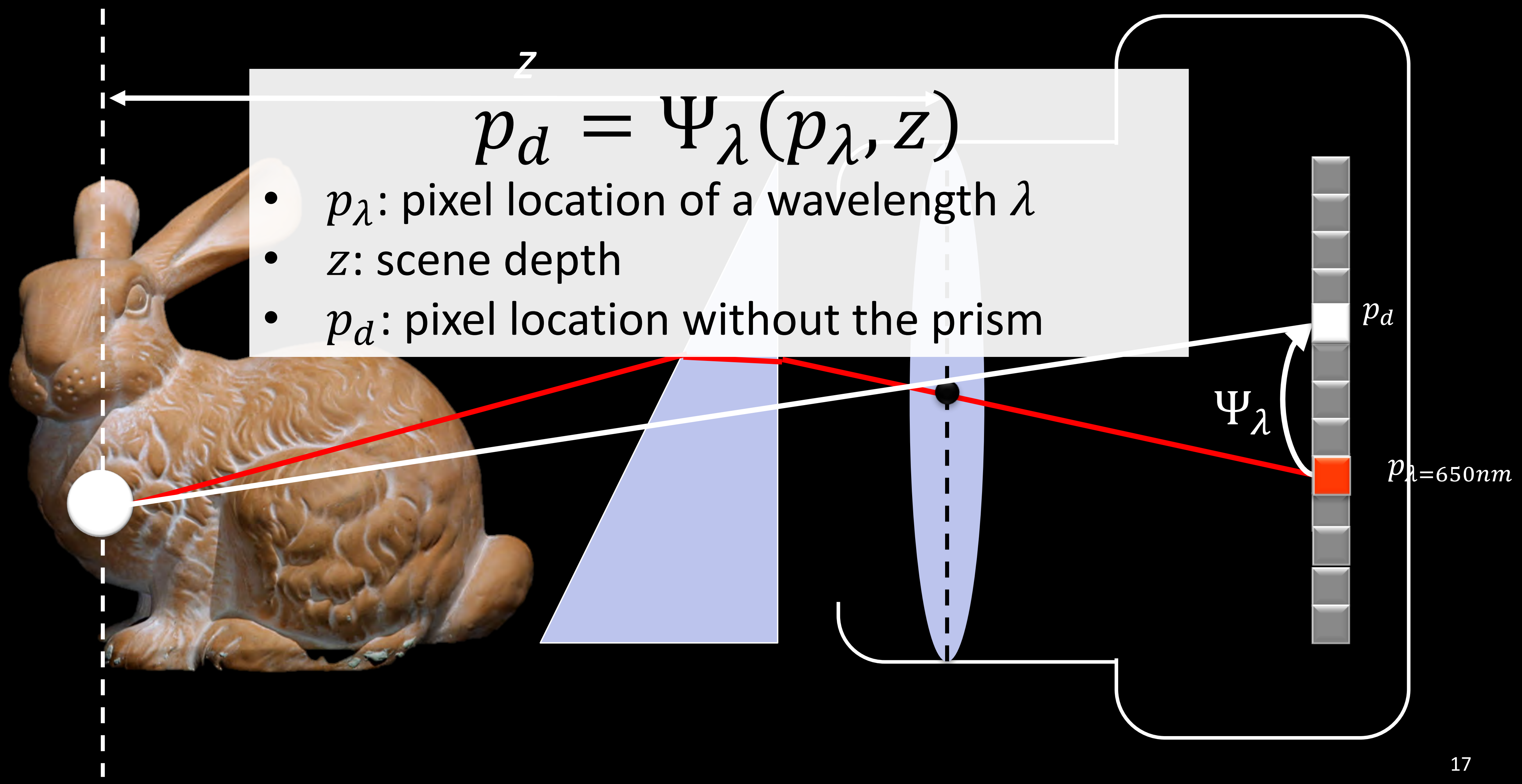
- $p_{\lambda_{ref}}$: pixel of the reference wavelength λ_{ref}
- z: scene depth
- p_λ: pixel location of a wavelength λ



Refraction Model

$$p_d = \Psi_\lambda(p_\lambda, z)$$

- p_λ: pixel location of a wavelength λ
- z: scene depth
- p_d: pixel location without the prism



Dispersion Model from Refraction Models

Refraction model

$$p_d = \Psi_\lambda(p_\lambda, z)$$

Dispersion model

$$p_\lambda = \Phi_\lambda\left(p_{\lambda_{ref}}, z\right)$$

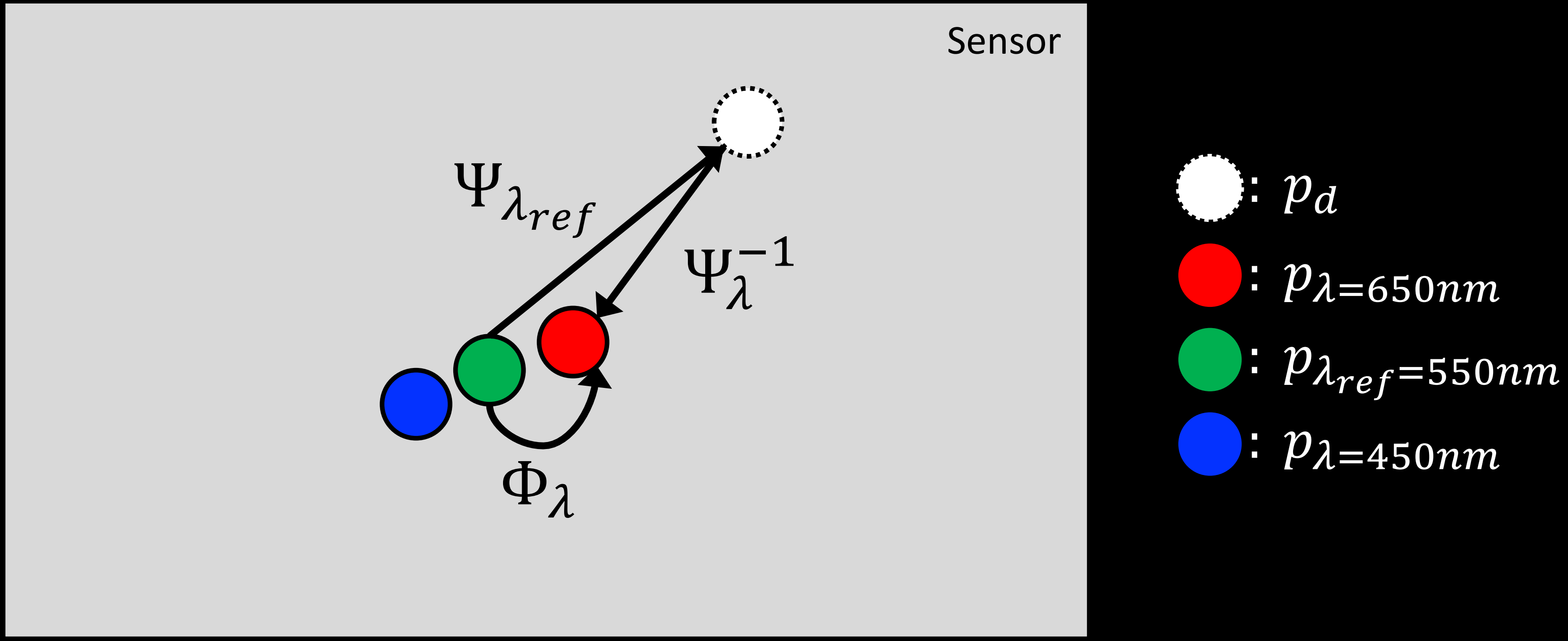
Dispersion Model from Refraction Models

Refraction model

$$p_d = \Psi_\lambda(p_\lambda, z)$$

Dispersion model

$$p_\lambda = \Phi_\lambda\left(p_{\lambda_{ref}}, z\right)$$



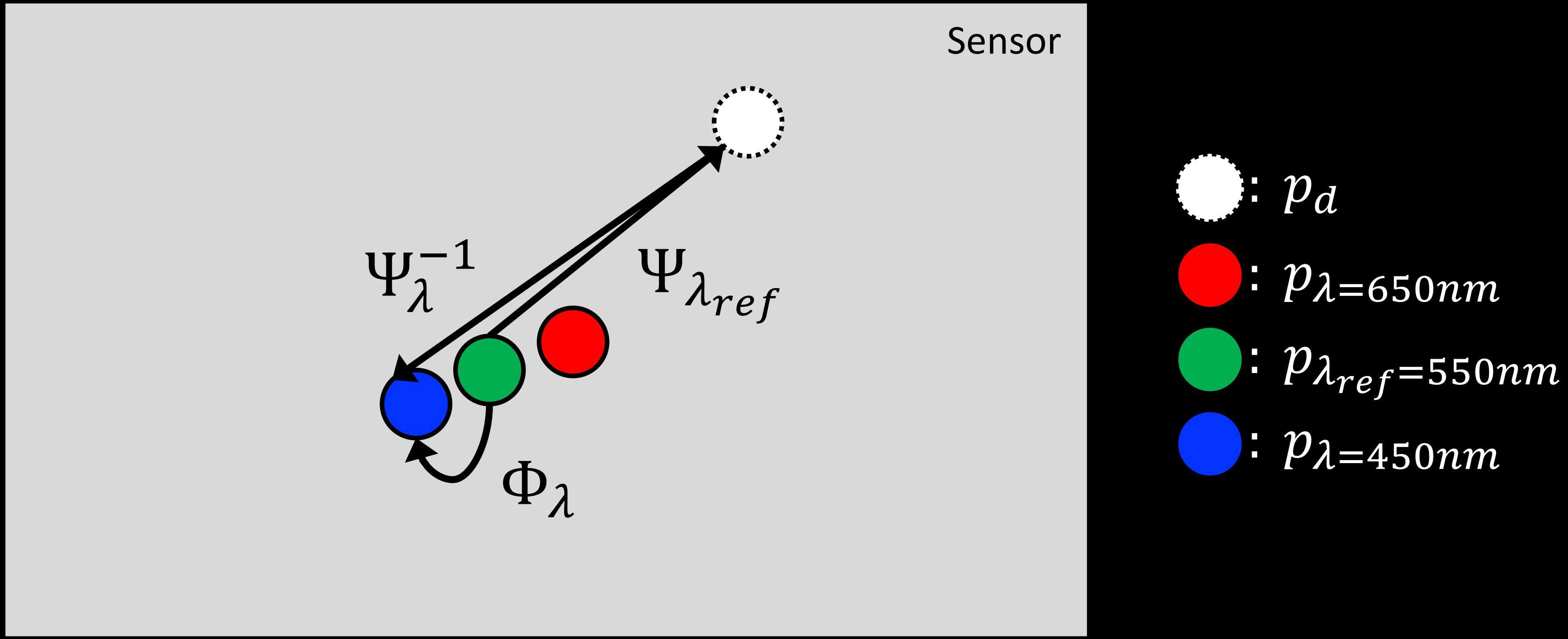
Dispersion Model from Refraction Models

Refraction model

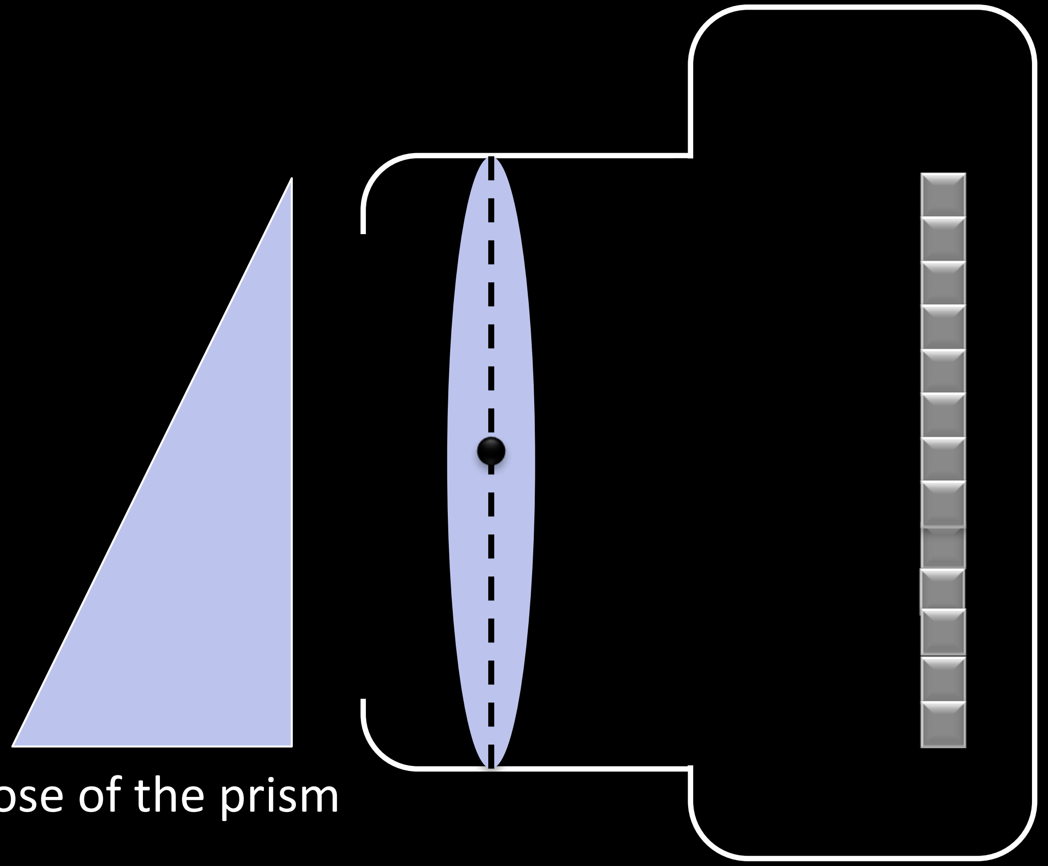
$$p_d = \Psi_\lambda(p_\lambda, z)$$

Dispersion model

$$p_\lambda = \Phi_\lambda\left(p_{\lambda_{ref}}, z\right)$$



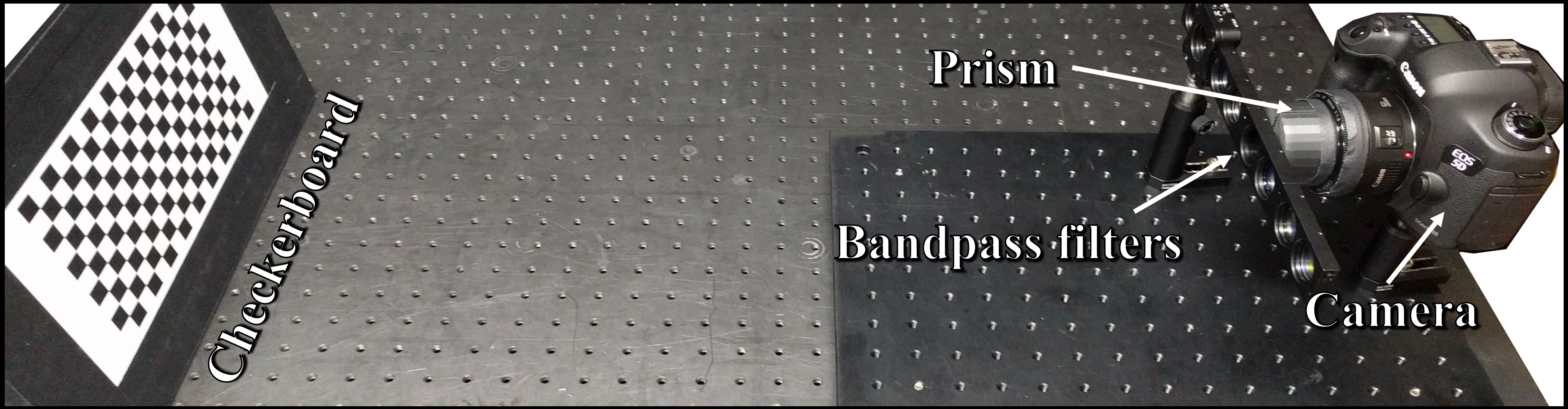
PRISM CALIBRATION

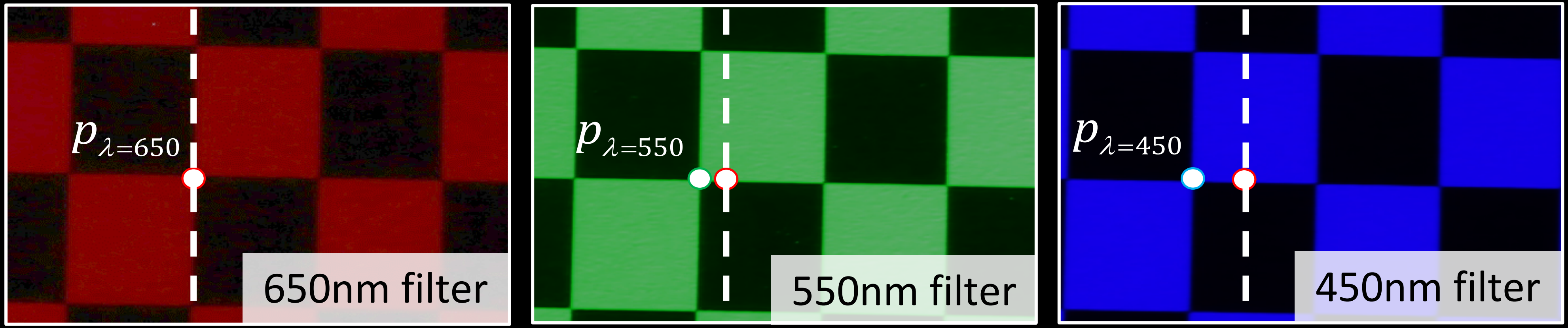


Pose of the prism

* Camera geometric and radiometric calibrations are performed first without the prism

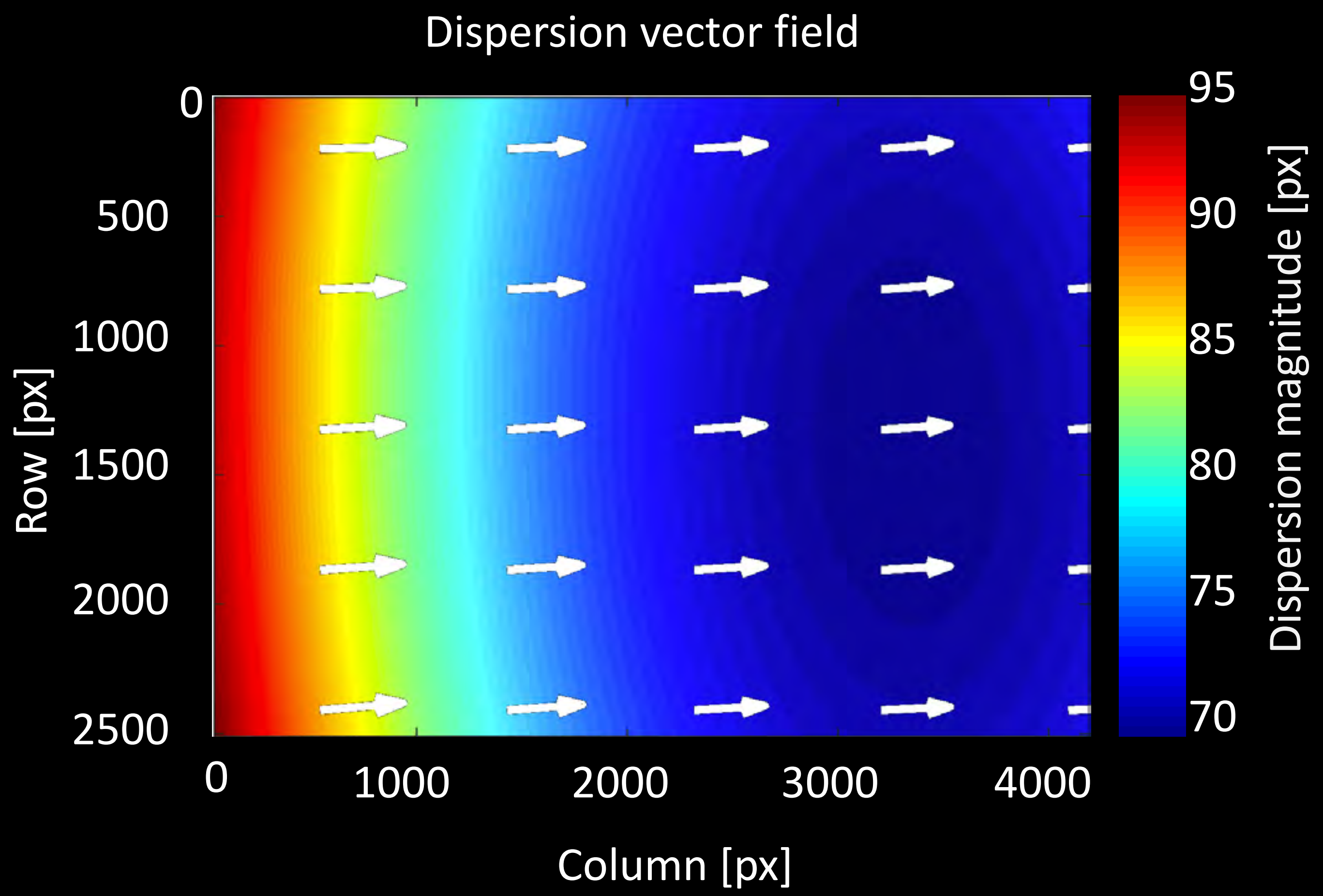
Prism Pose Calibration





- Find the pose of the prism which explains the observed dispersion best
- Estimated pose of the prism ➔ refraction model Ψ ➔ dispersion model $\boldsymbol{\Phi}$

Spatial Dependency

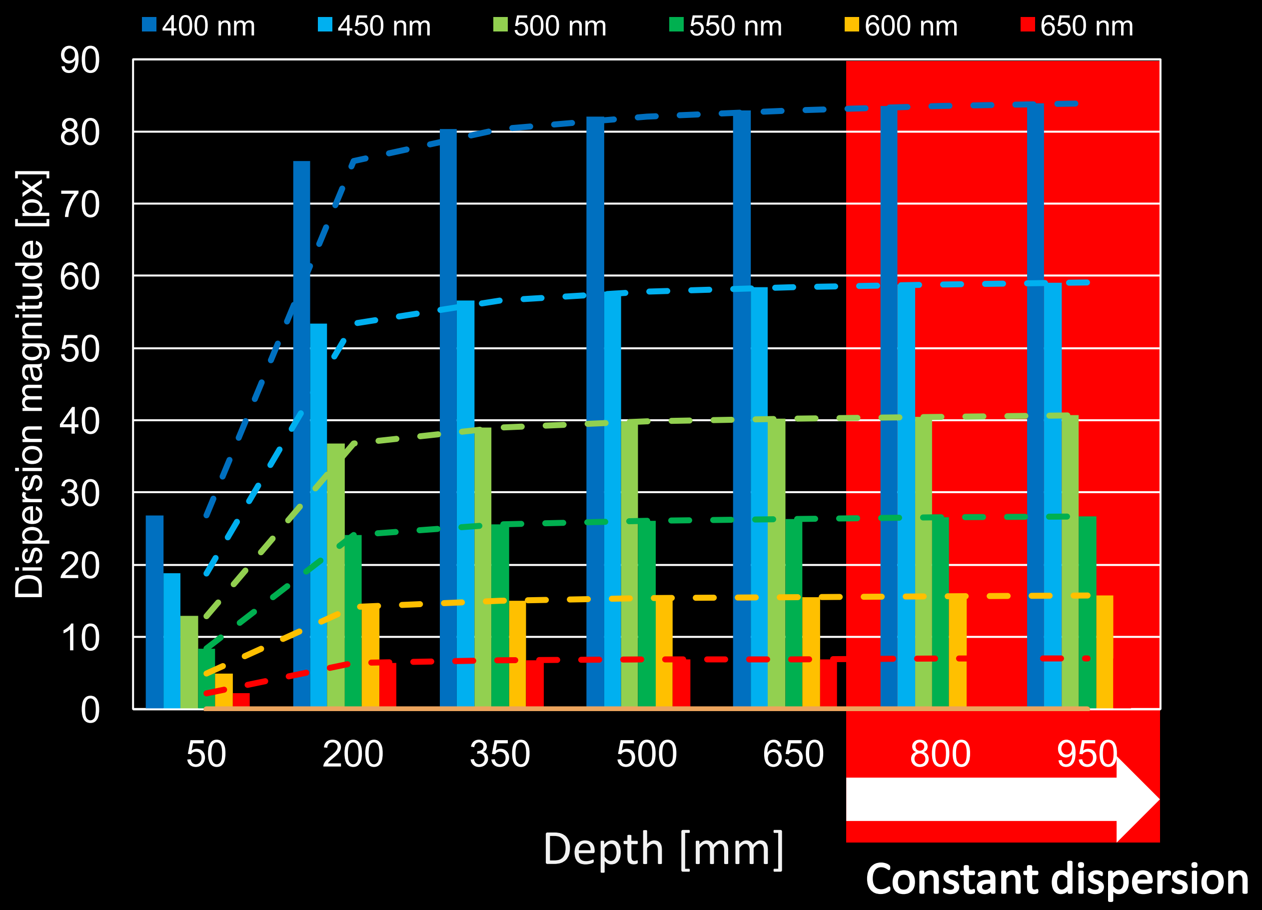


- Dispersion direction is nearly invariant to the spatial position
- Dispersion magnitude has large dependency on the spatial position

➔ Spatially-varying dispersion

$$p_\lambda = \Phi_\lambda\left(p_{\lambda_{ref}}, z\right)$$

Depth Dependency



- For depth over ~700mm, dispersion profile becomes nearly constant.

➔ Depth-invariant dispersion

$$p_\lambda = \Phi_\lambda\left(p_{\lambda_{ref}}\right), \text{ for } z > 700mm$$

Dispersion

Hyperspectral image

HYPERSPECTRAL IMAGE RECONSTRUCTION

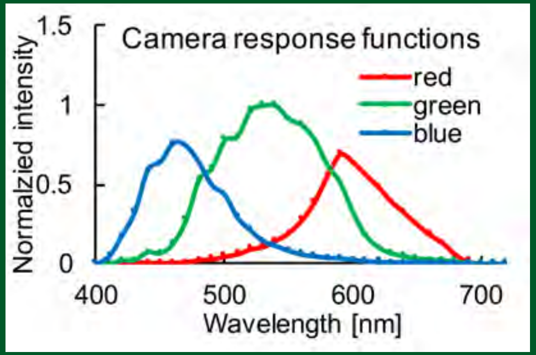
Image Formation

$$j = \Omega \Phi i$$

Dispersed RGB image

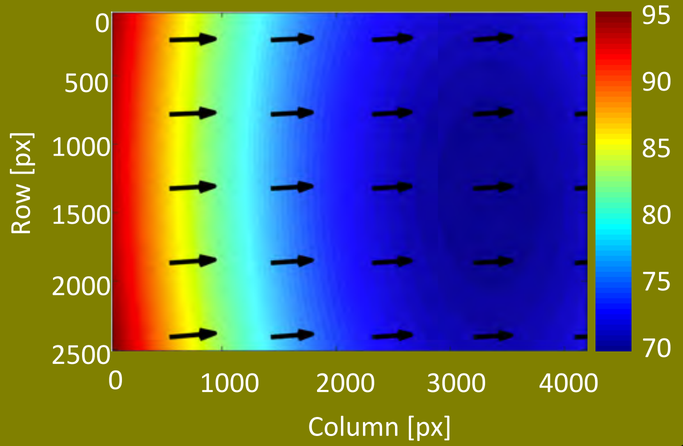
=

Camera response function



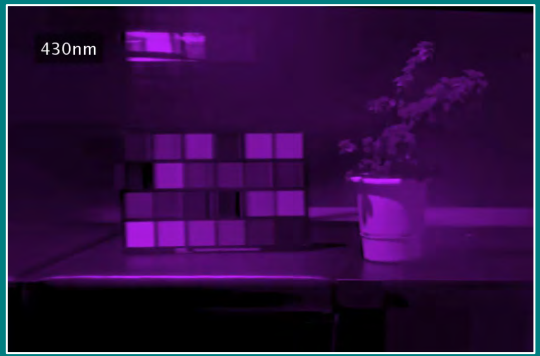
x

Dispersion matrix



x

Hyperspectral image



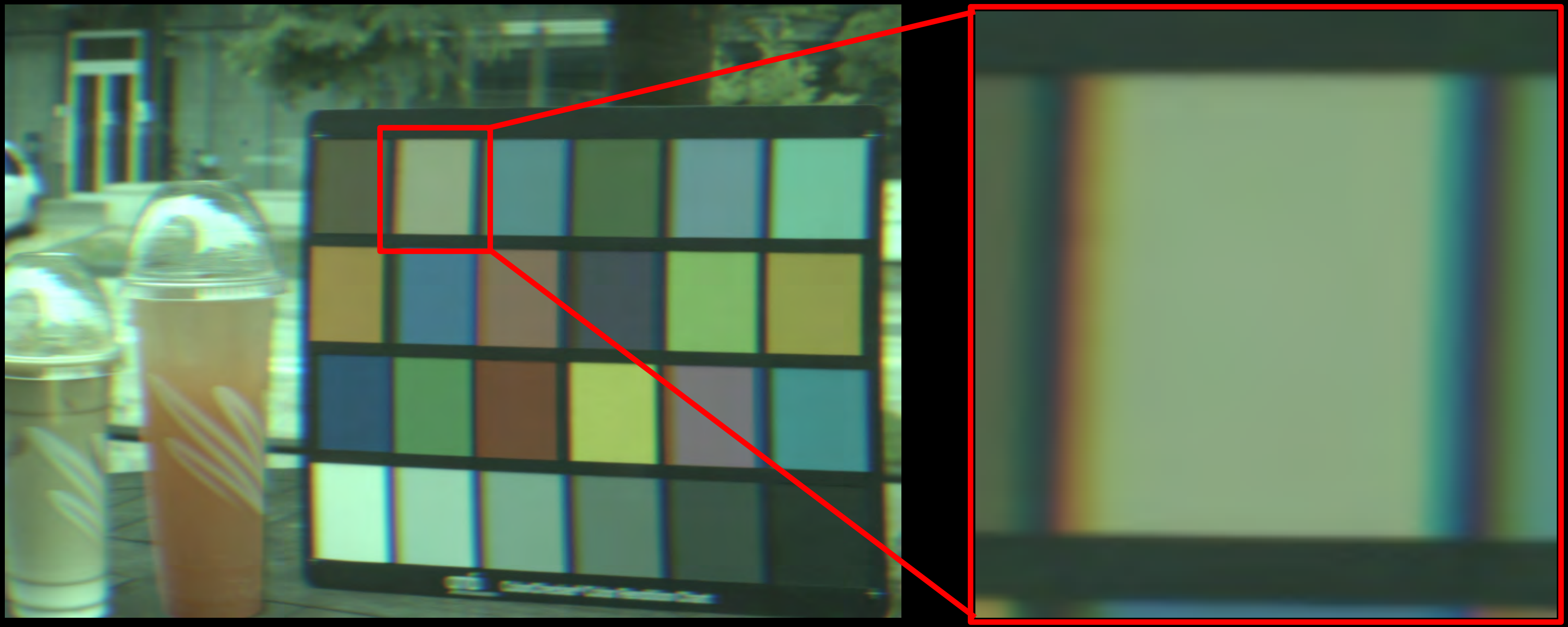
Known

Known

Known

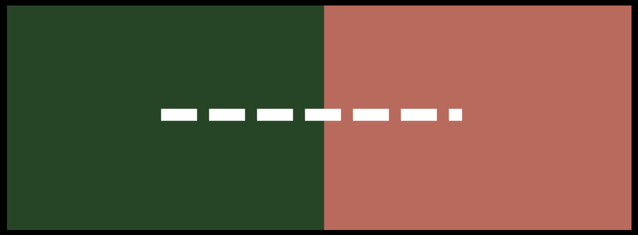
Unknown

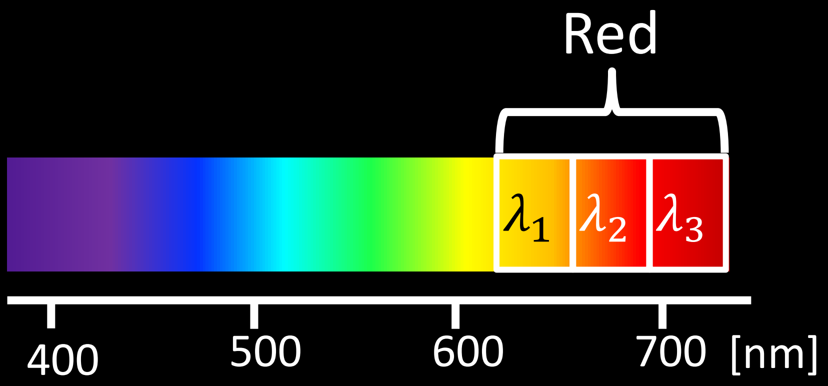
Sparse Spectral Cues

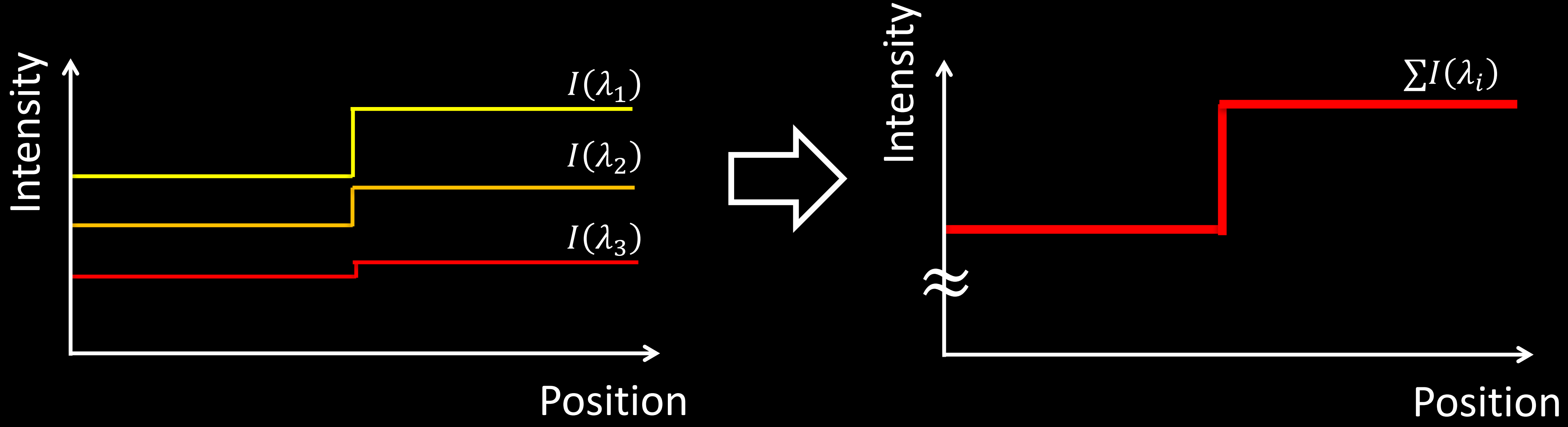


- Spectral cues only exist around edges
- Direct reconstruction is severely ill-posed

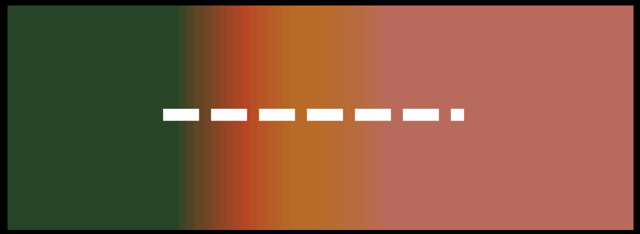
Spectral Cues around the Edge Region


Without dispersion

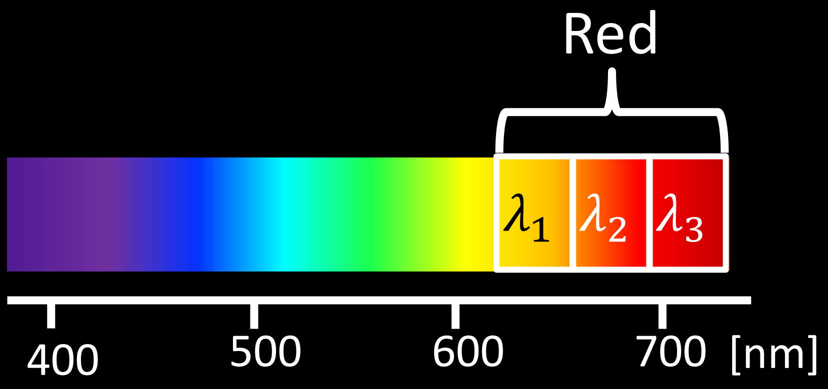


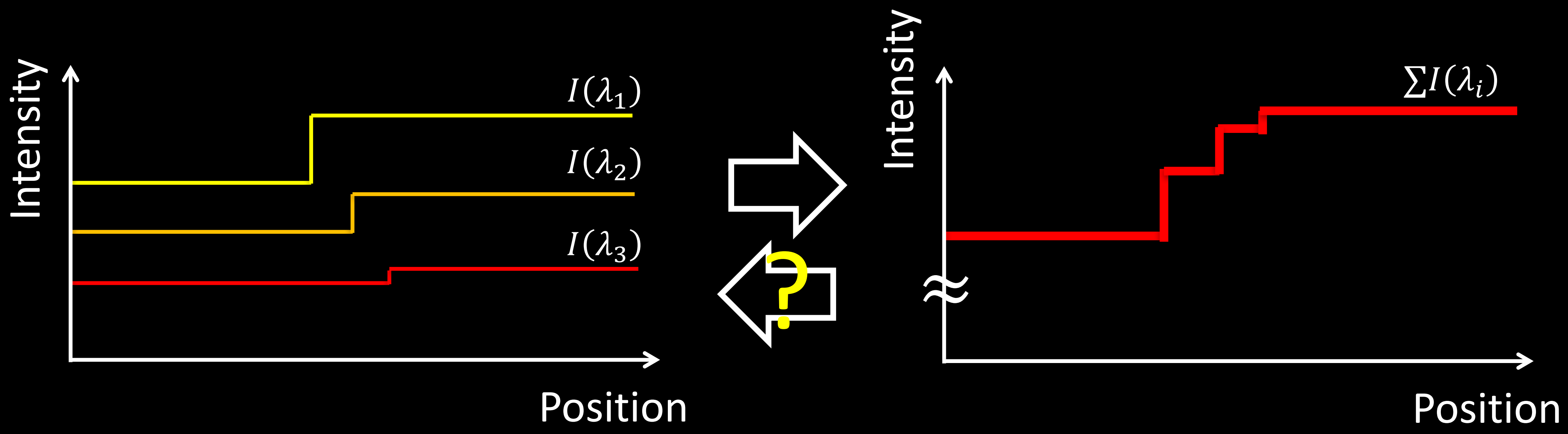


Spectral Cues on the Edge Region

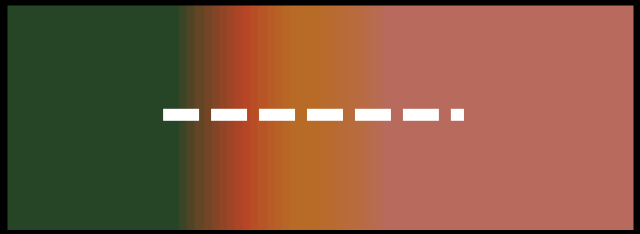


With dispersion

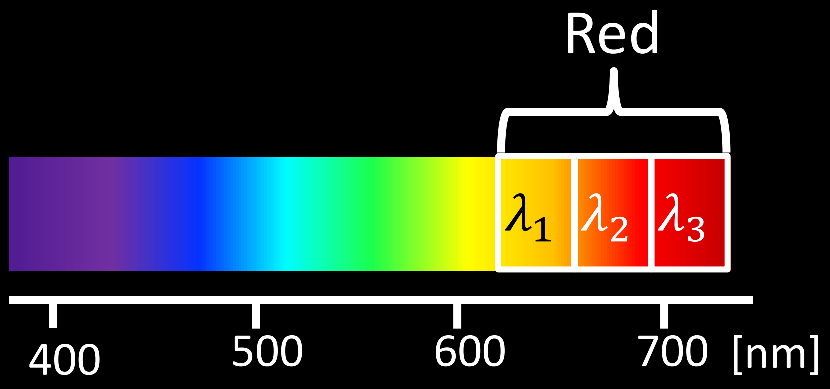


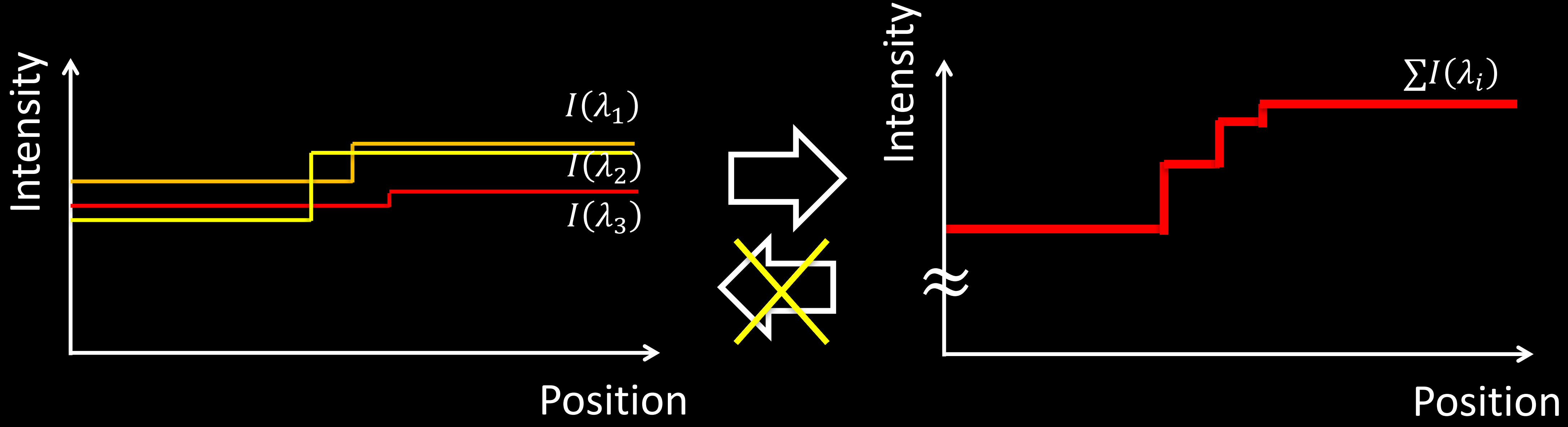


Spectral Cues on the Edge Region



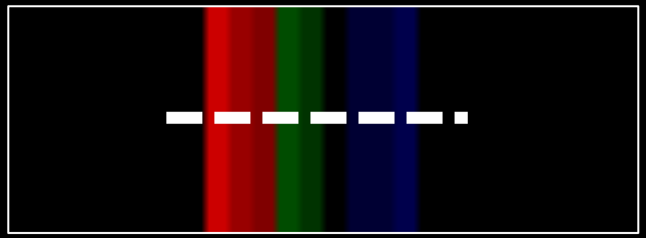
With dispersion



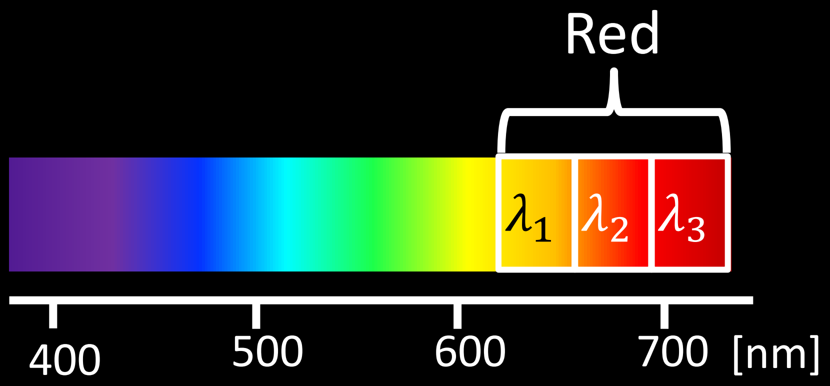


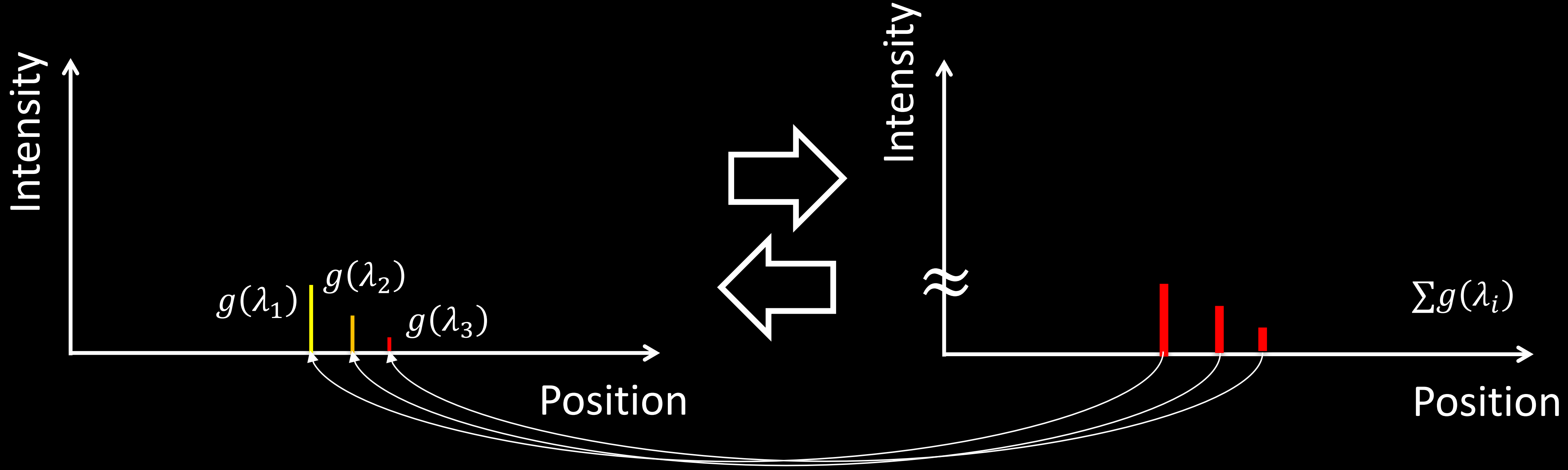
- For edge regions, there could be many solutions which give the same observation

Gradient Domain



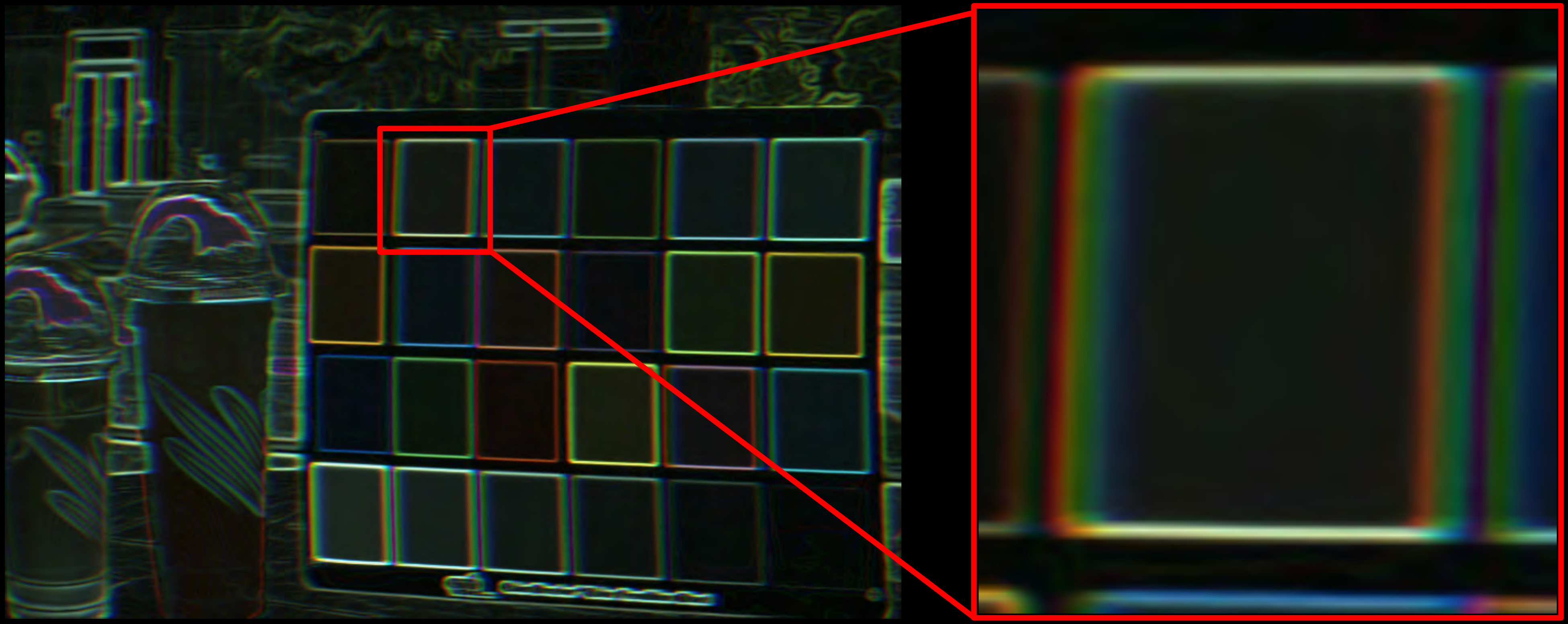
With dispersion





- For edge regions, we can mitigate ill-posedness in the gradient domain

Edges and Gradient Domain

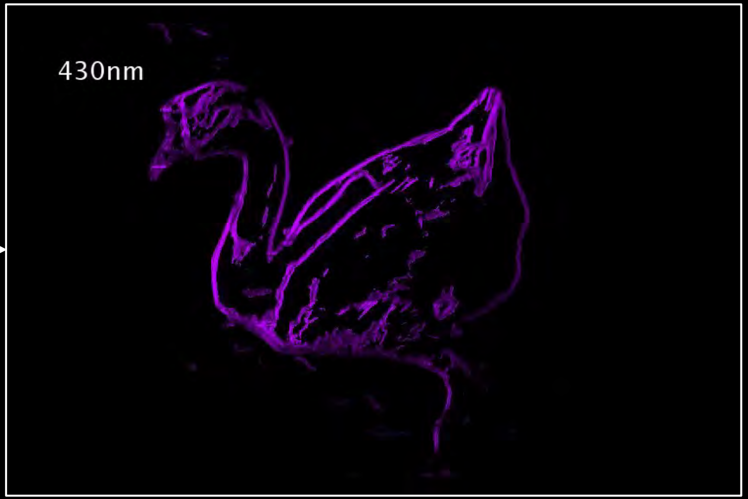


1. Reduce the region of interests on the pixels around edges
2. Solve the problem in the gradient domain

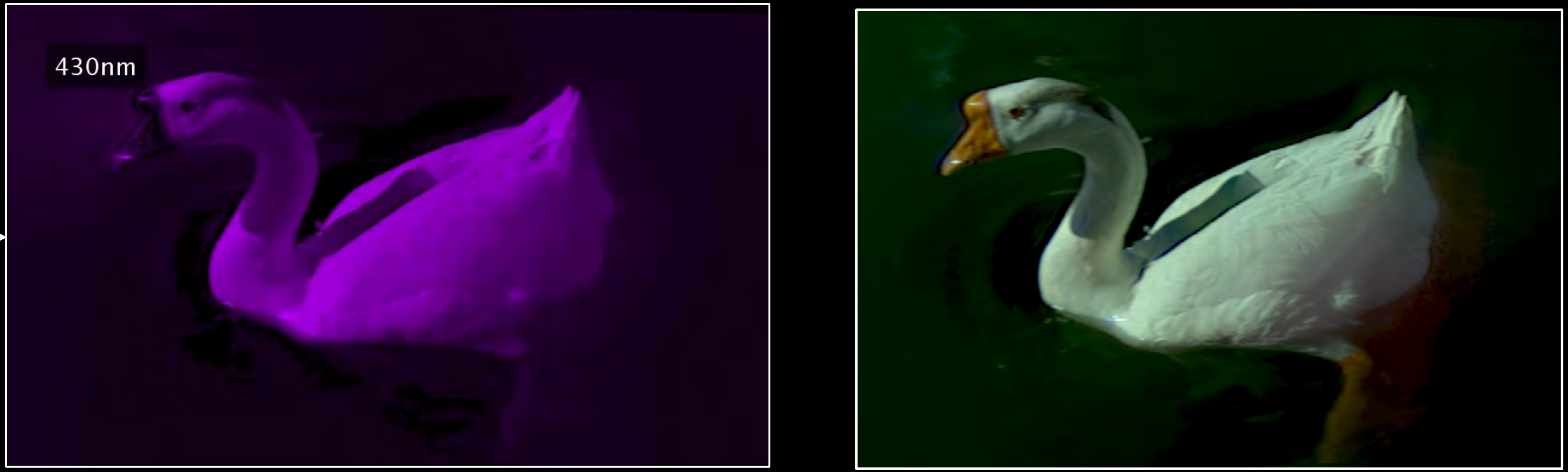
Workflow

Input

Edge restoration



Spectrum in the gradient domain

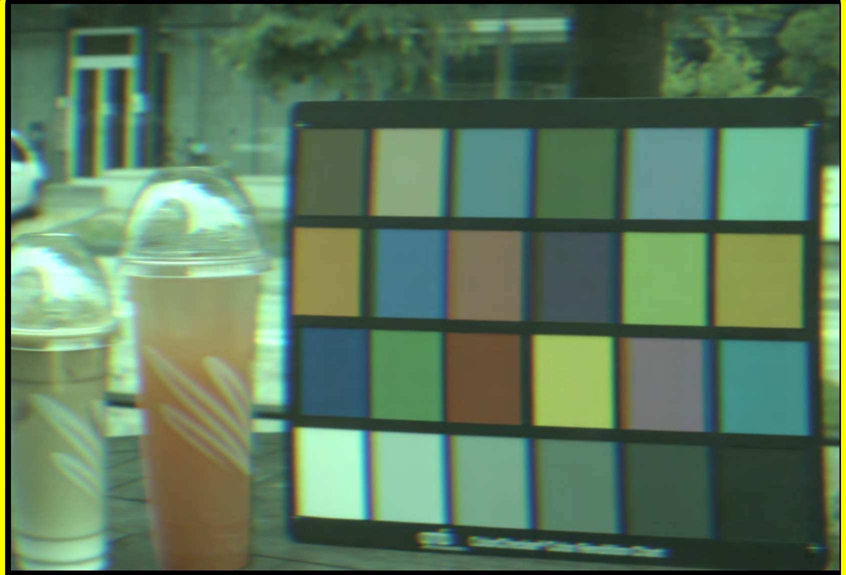


Spectrum estimation in the intensity domain

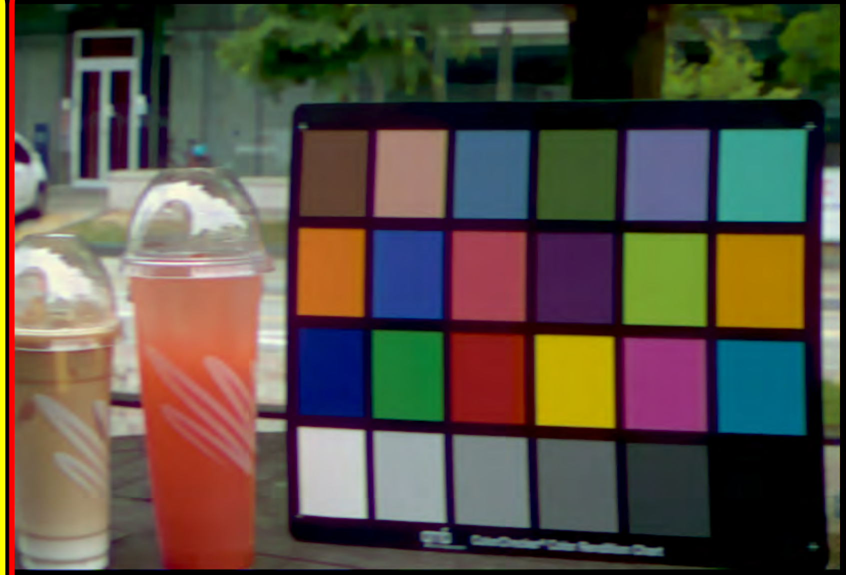
Edge Restoration for Detecting Region of Interests

Input

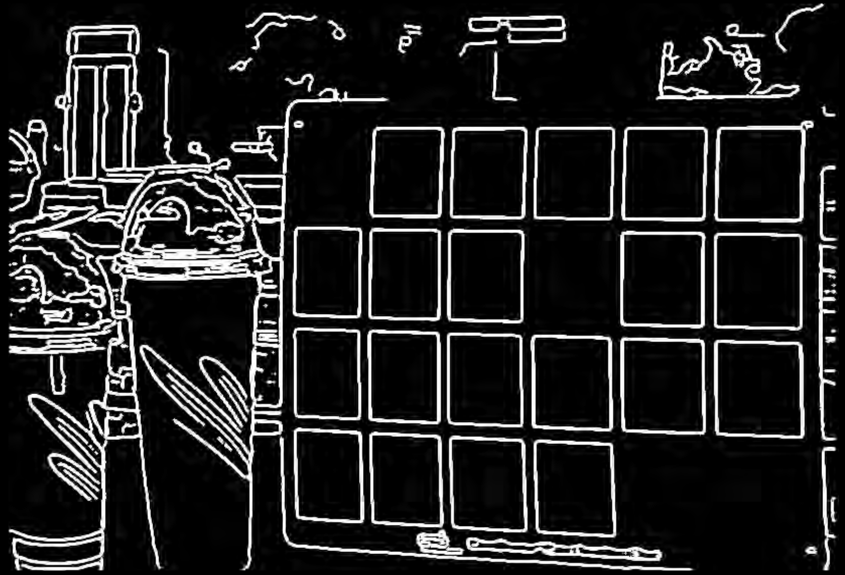
Output



Input image with dispersion



Restored image without dispersion



Detected edge position

$$\mathbf{i}_{\text{aligned}} = \arg\min_{\mathbf{i}} \boxed{\left\| \boldsymbol{\Omega\Phi}\mathbf{i} - \mathbf{j} \right\|_2^2}$$

Data term

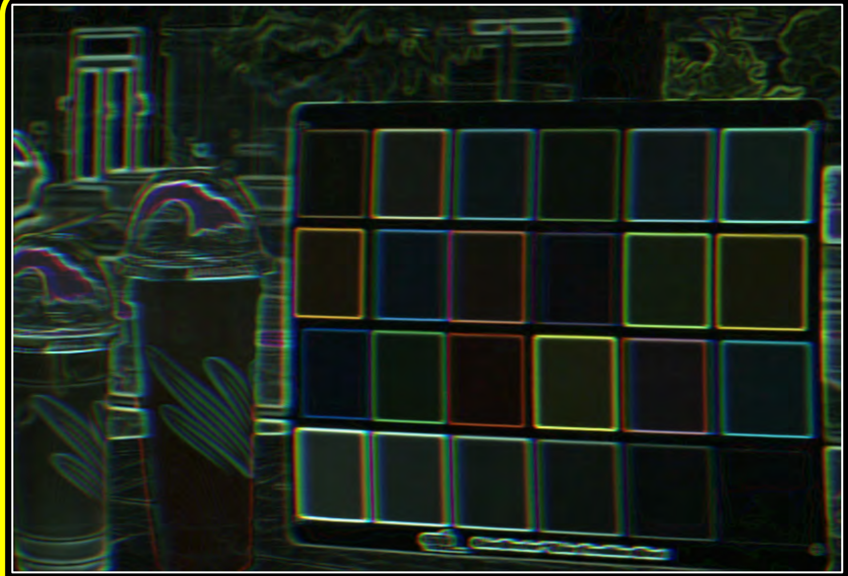
TV prior

Cross-channel prior

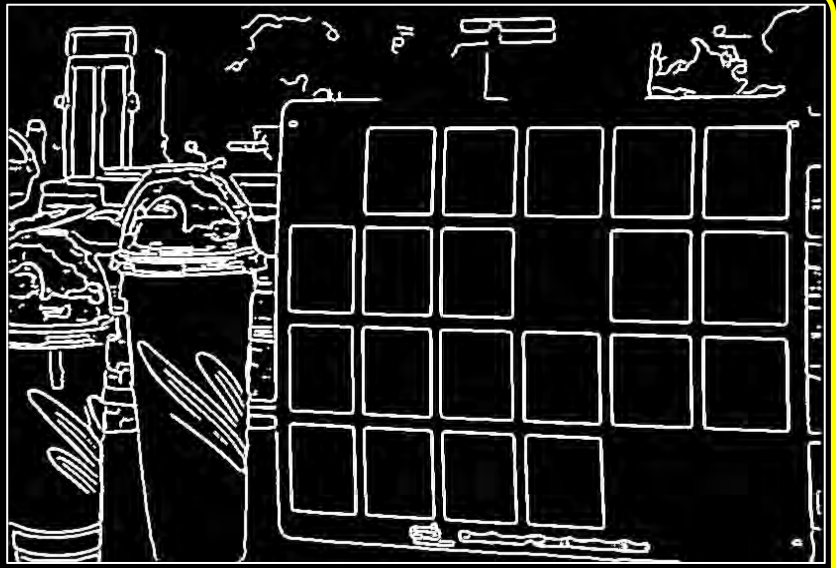
- Remove dispersion around edges
- Cross-channel prior → image without dispersion

Gradient Reconstruction

Input

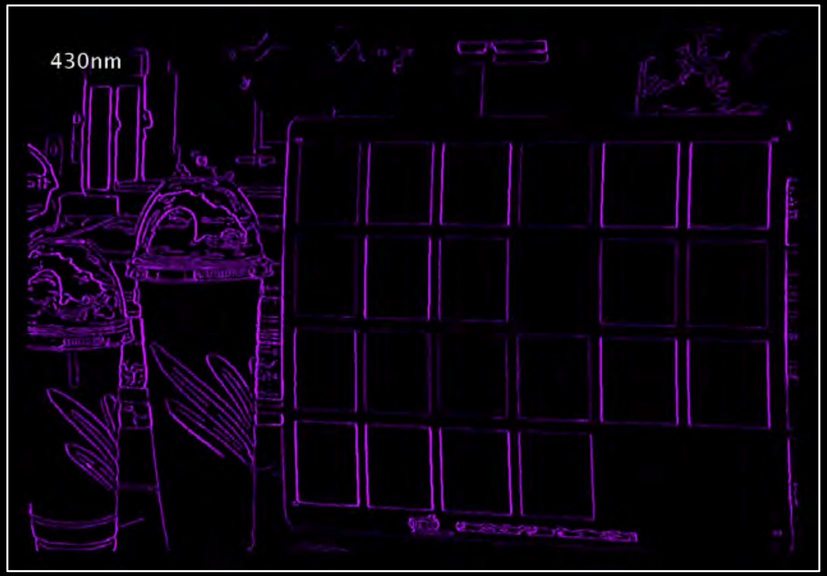


Spatial gradient with dispersion



Detected edge position

Output



Estimated spatial gradient

$$\hat{\mathbf{g}}_{xy} = \arg\min_{\mathbf{g}_{xy}} \boxed{\left\| \mathbf{\Omega\Phi g}_{xy} - \nabla_{xy}\mathbf{j} \right\|_2^2}$$

Data term in the gradient domain

Spectral sparsity of the spatial gradient

Smoothness of the spatial gradient

- Estimate spatial gradient which explains the dispersion best
- Restrict reconstruction on the edge pixels only

Reconstructing the Spectral Images

Input

Input image with dispersion

Estimated spatial gradient

Output

Hyperspectral image

$$\mathbf{i}_{opt} = \arg\min_{\mathbf{i}} \left\| \mathbf{\Omega\Phi i} - \mathbf{j} \right\|_2^2$$

Intensity data term

Gradient data term

Smoothness of
the spectral curvature

- Gradient-aided hyperspectral reconstruction

Reconstruction Summary

Edge Restoration

↓

Spectral Gradient Reconstruction

↓

Spectral Image Reconstruction

RESULTS

Real Scene with a ColorChecker

Input

Output

Input

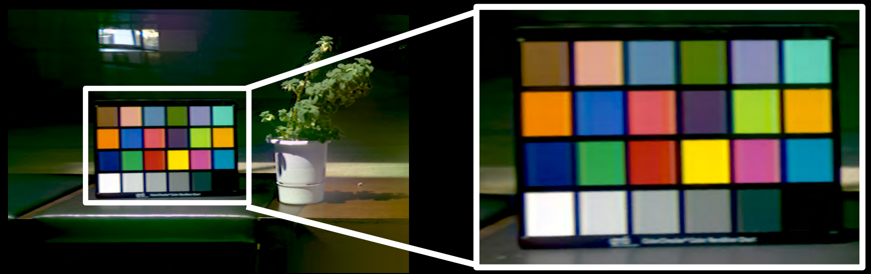
Reconstructed spectral images

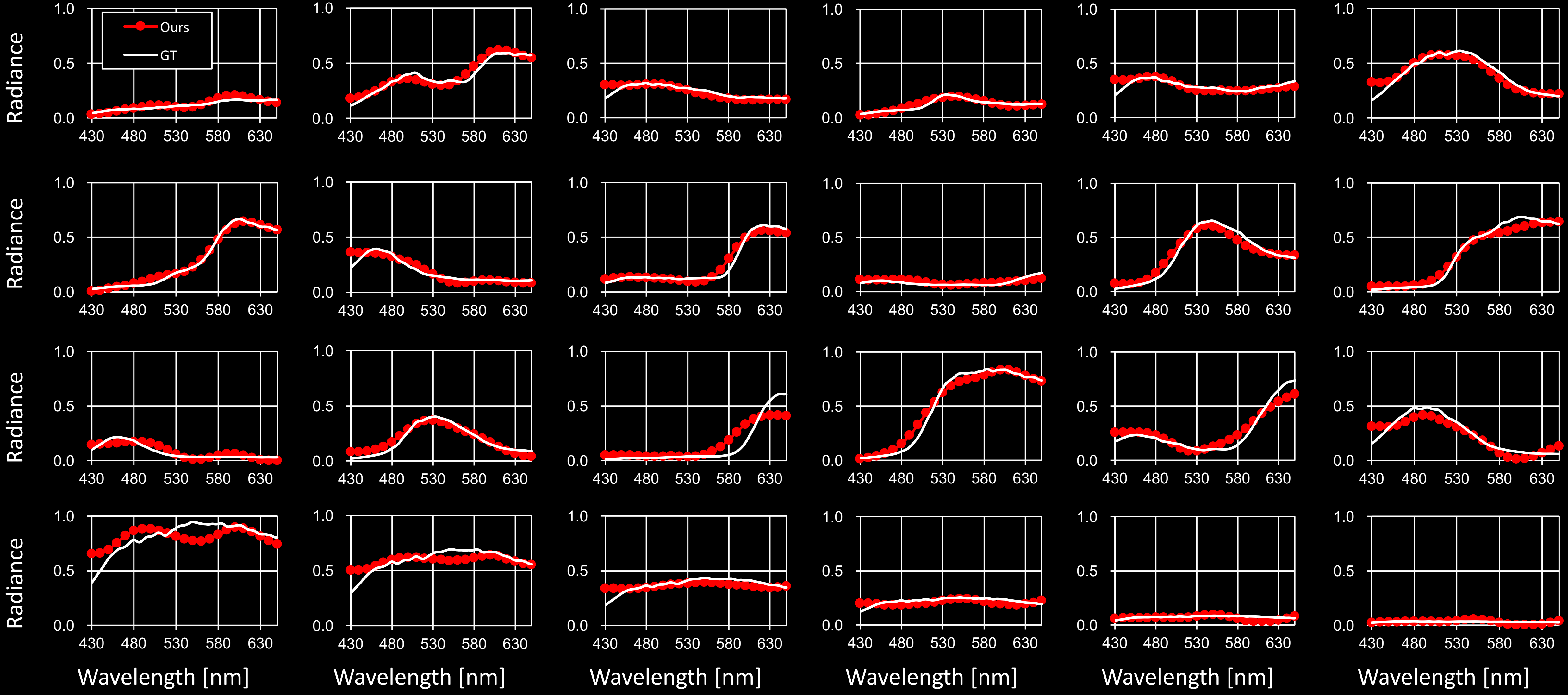
Reconstructed sRGB

- Ground-truth spectrum is measured for each color patch using a spectro-radiometer

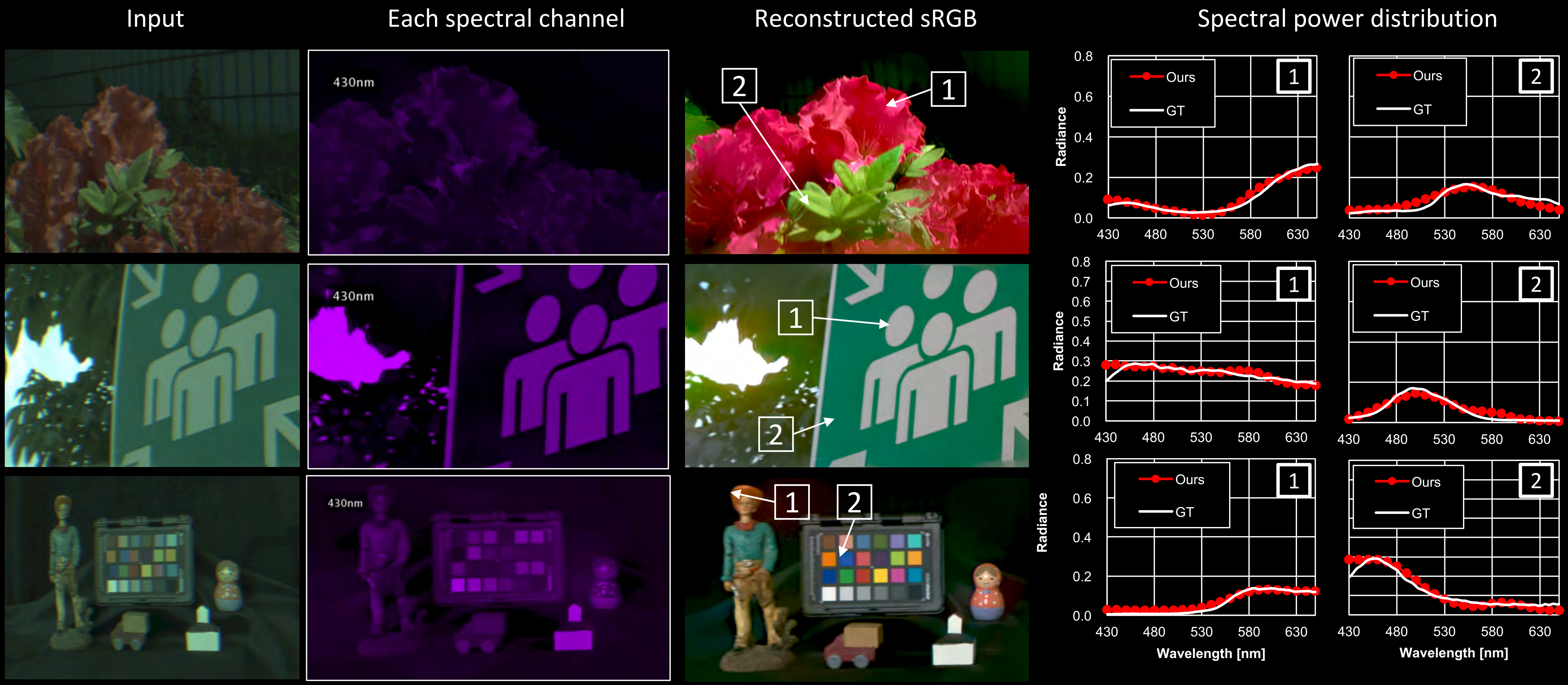
Reconstruction vs. Ground truth

(Red) (White)



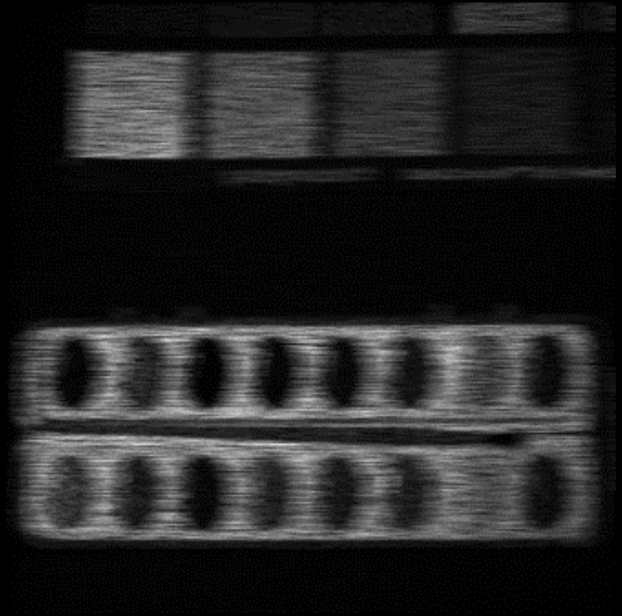


Results on Various Scenes

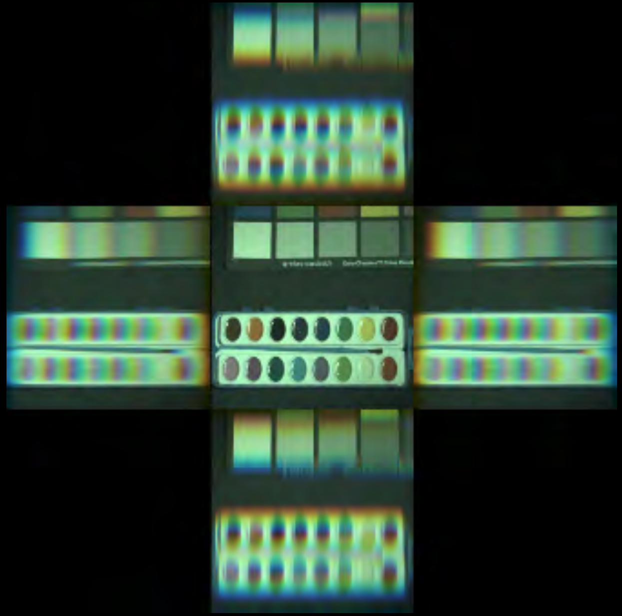


Comparison with Other Hyperspectral Imaging Systems

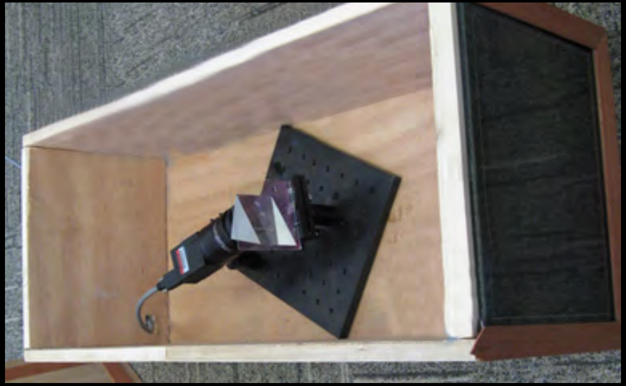
CASSI

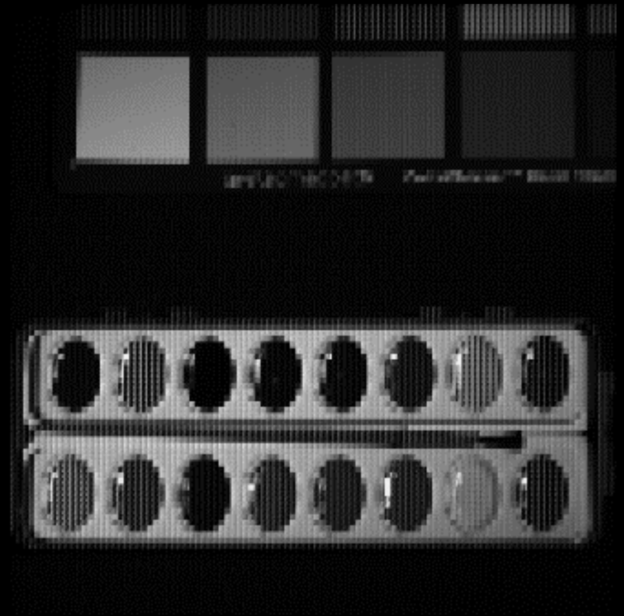


CTIS

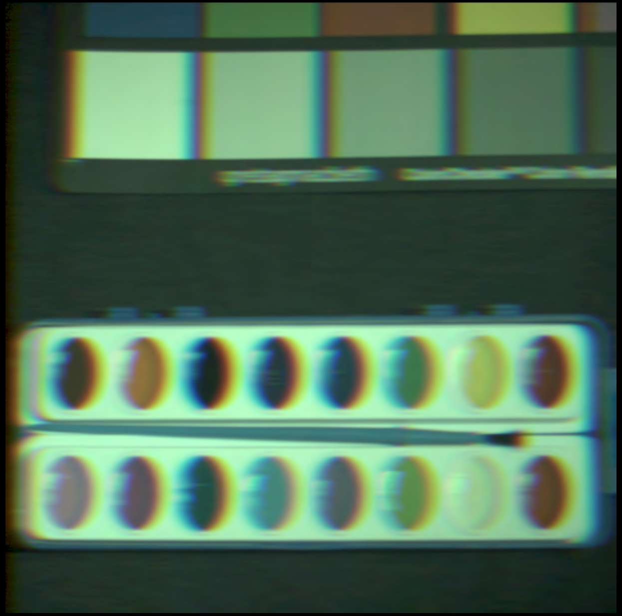


PMVIS

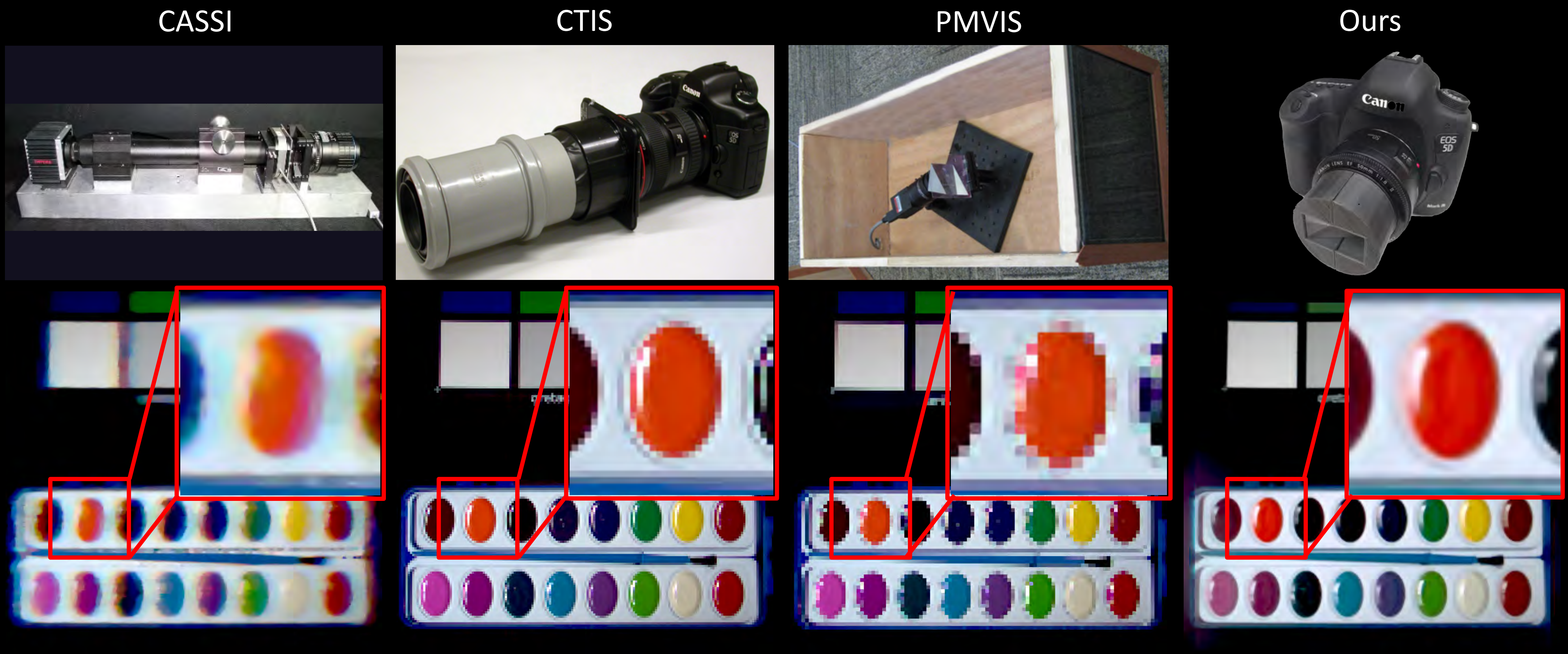




Ours



Comparison with Other Hyperspectral Imaging Systems



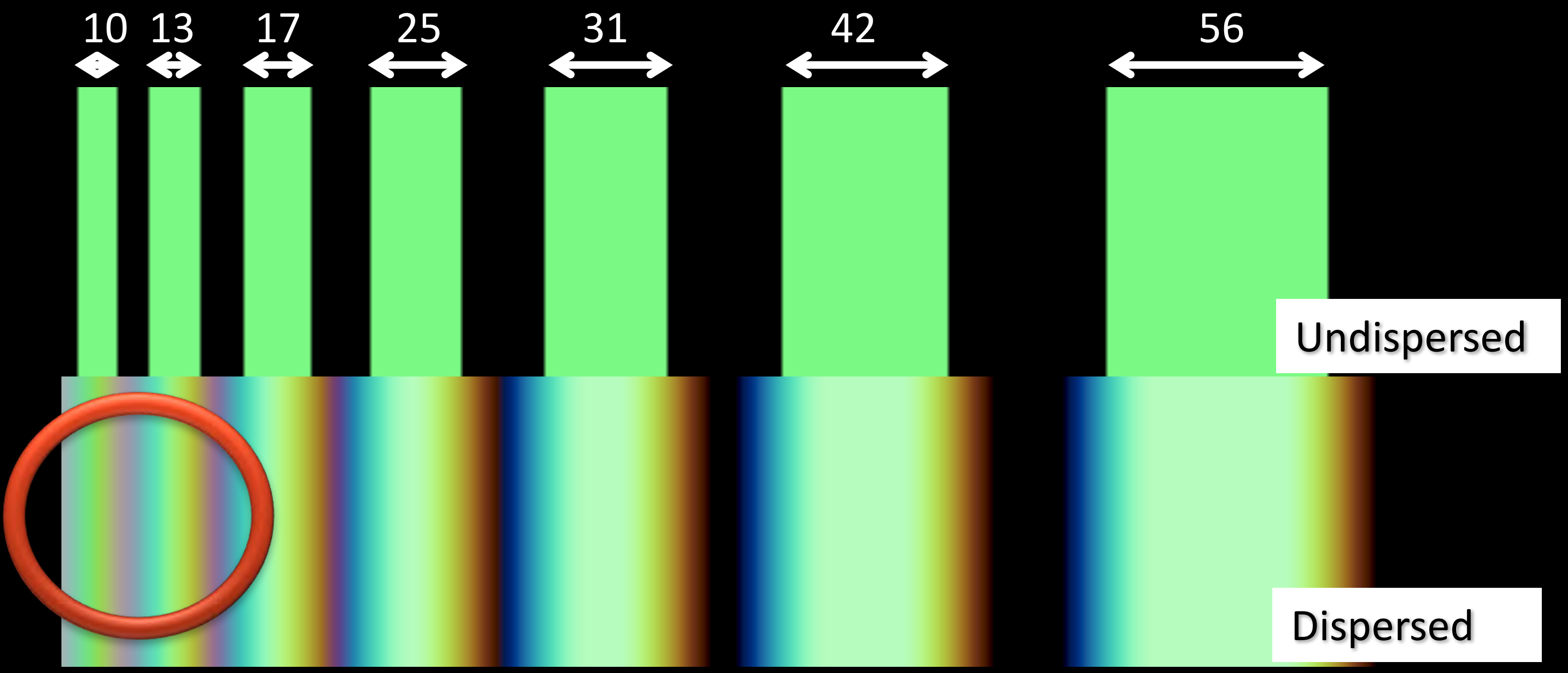
PSNR: 22.99dB/ SSIM: 0.82

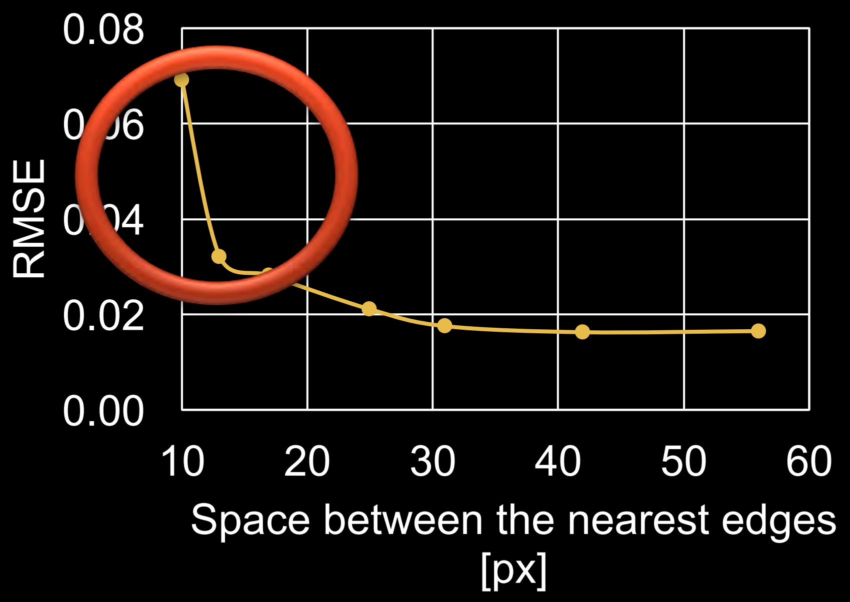
PSNR: 24.41dB/ SSIM: 0.70

PSNR: 19.98dB/ SSIM: 0.73

PSNR: 27.63dB/ SSIM: 0.88

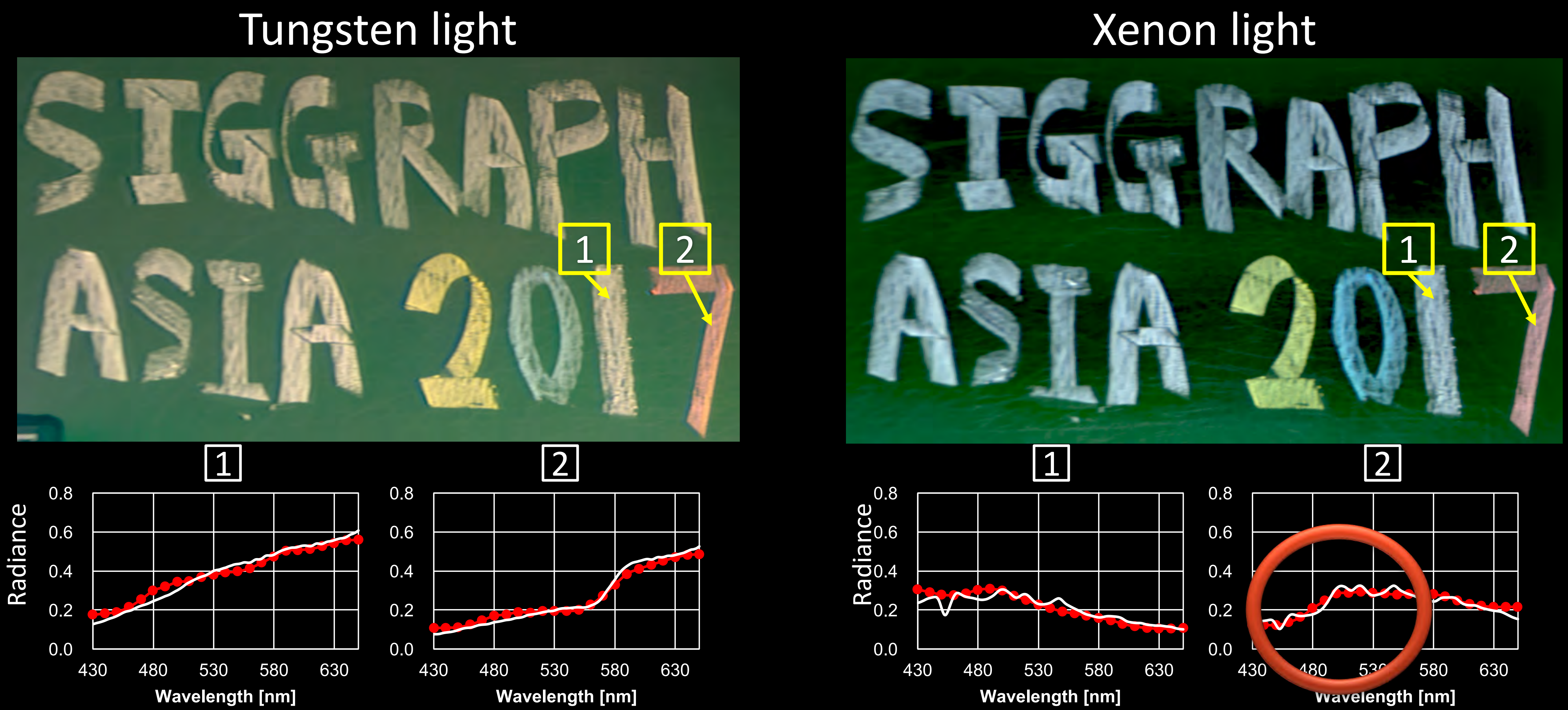
Limitations: High-frequency Spatial Structures





- Reconstruction accuracy degrades severely when the dispersion profiles of neighboring edges become overlapped

Limitations: High-frequency Spectral Information



- Our method cannot capture the high-frequency spectral details

Future Work

- Reconstruction algorithm for various edge structures
  - Deep priors for hyperspectral images

- Depth from dispersion
  - Estimate depth from dispersion

- Integration with CTIS
  - Better reconstruction algorithm for CTIS

Compact Single-Shot Hyperspectral Imaging using a Prism

Seung-Hwan Baek Incheol Kim Diego Gutierrez Min H. Kim

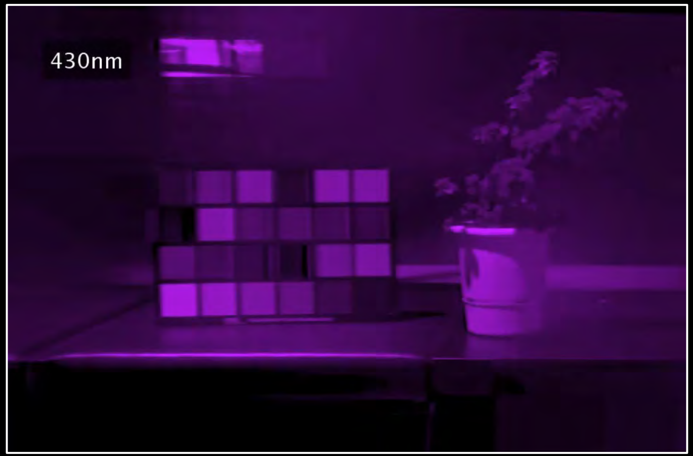
Simple camera setup

+

Dispersion modeling

Reconstruction algorithm

Computational method



Hyperspectral image

Acknowledgements

- VCLAB members, Adrian Jarabo, Belen Masia and anonymous reviewers

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