

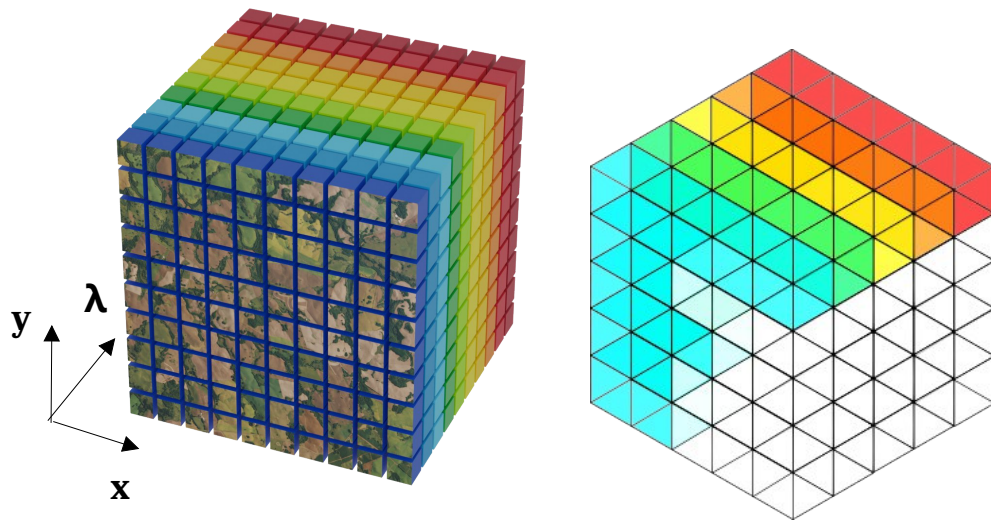
# Differentiable Simulator for Coded-Aperture Spectral Imaging

Léo Paillet<sup>1,2</sup>, Antoine Rouxel<sup>1</sup>, Hervé Carfantan<sup>2</sup>,  
Antoine Monmayrant<sup>1</sup>, Simon Lacroix<sup>1</sup>

leo.paillet@laas.fr

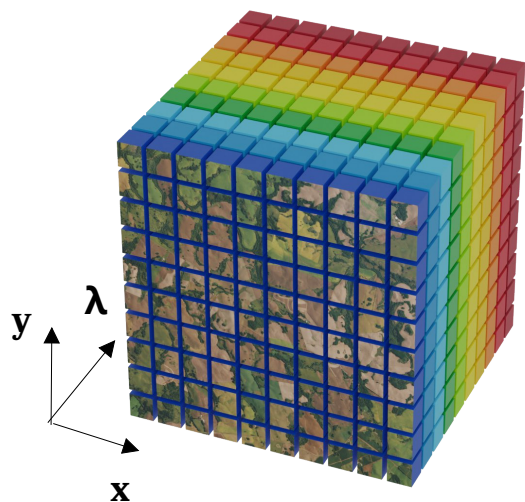
<sup>1</sup>LAAS-CNRS, <sup>2</sup>IRAP  
Toulouse

# Hyperspectral imagery

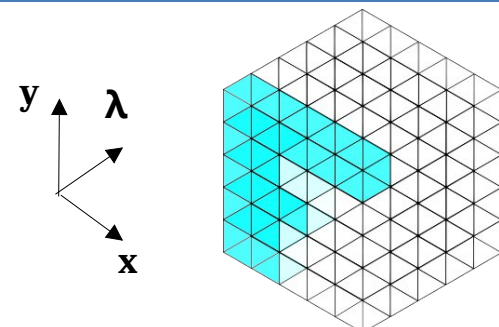
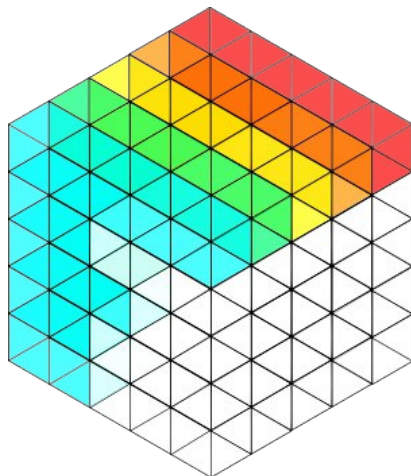


Hyperspectral scene

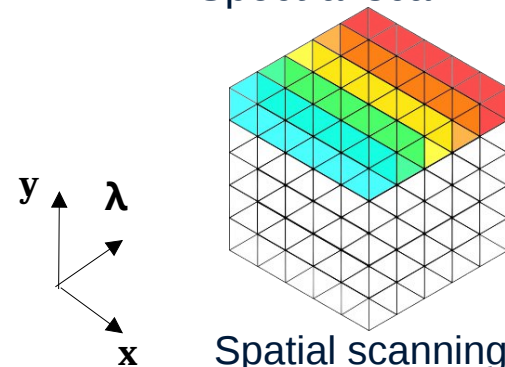
# Hyperspectral imagery



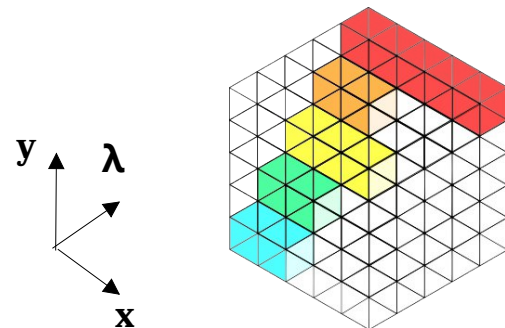
Hyperspectral scene



Spectral scanning

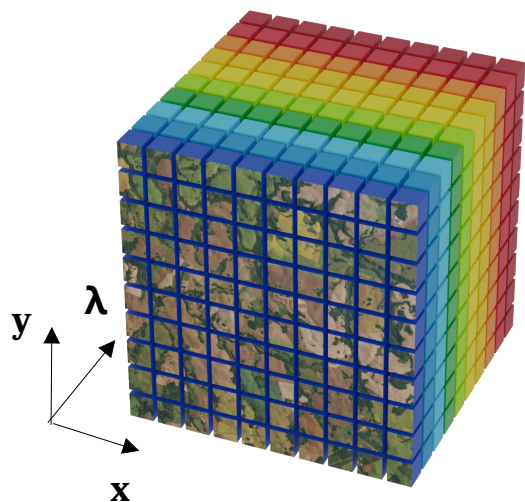


Spatial scanning

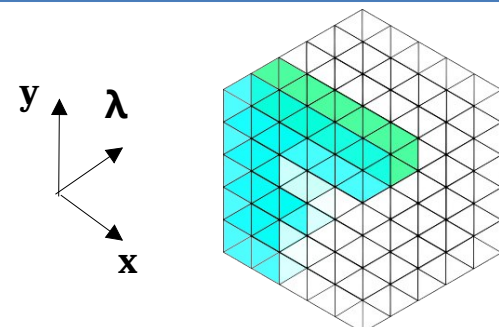
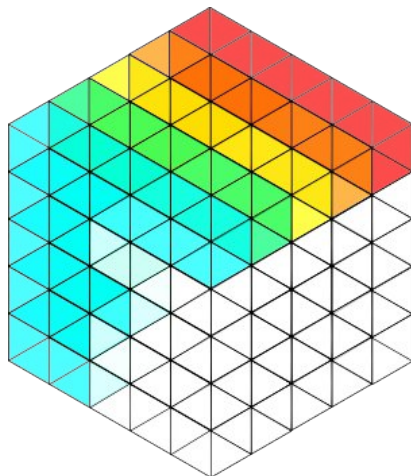


Spectro-spatial scanning

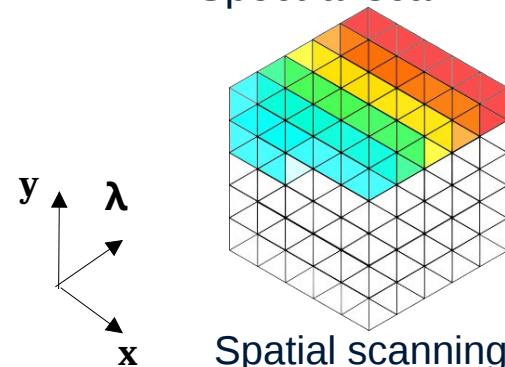
# Hyperspectral imagery



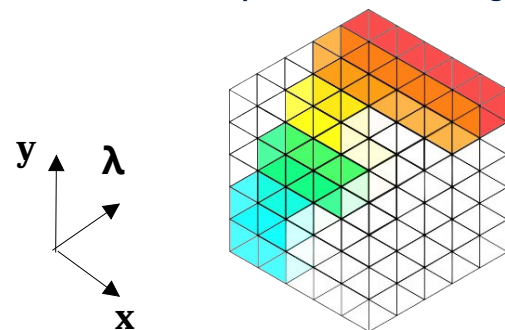
Hyperspectral scene



Spectral scanning

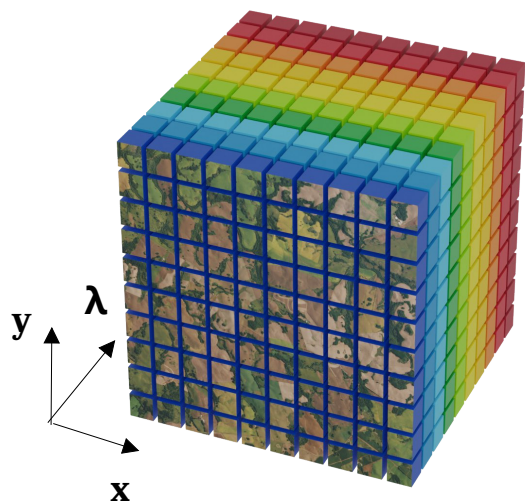


Spatial scanning



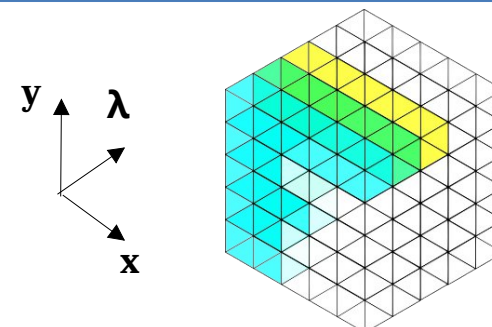
Spectro-spatial scanning

# Hyperspectral imagery

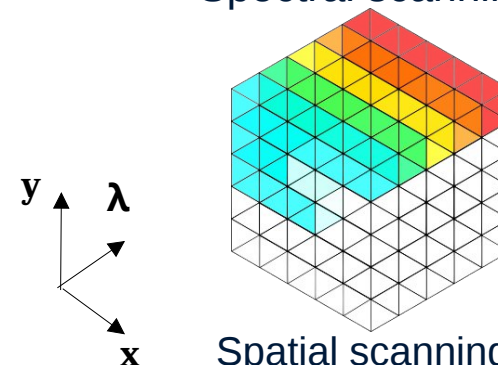


Hyperspectral scene

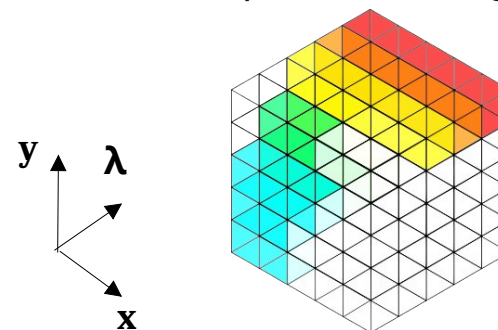
- > High data volume
- > High acquisition time
- > Duplicate information



Spectral scanning



Spatial scanning

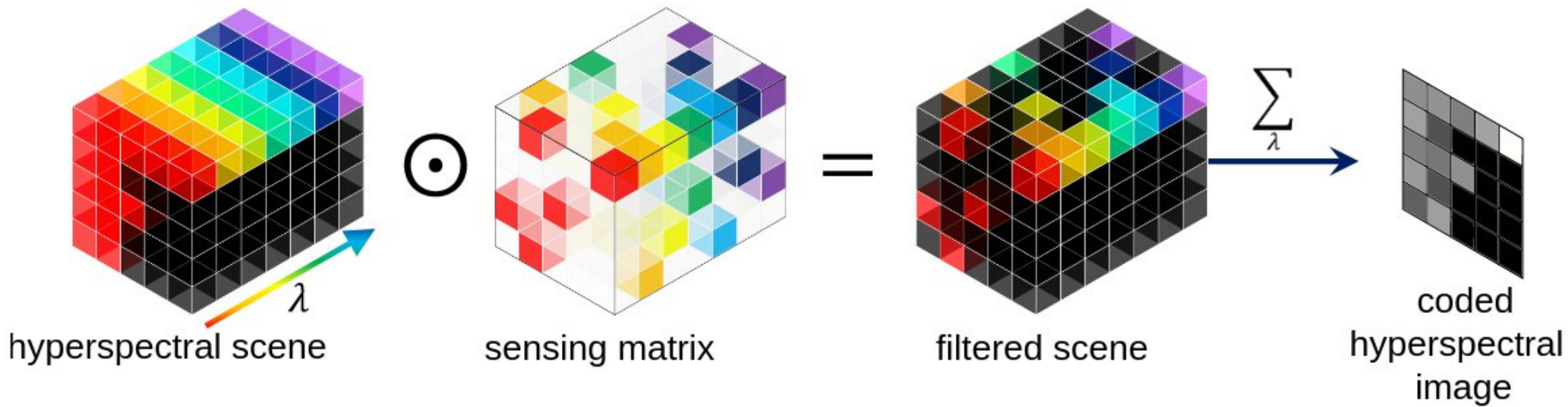


Spectro-spatial scanning

# Coded hyperspectral imagery

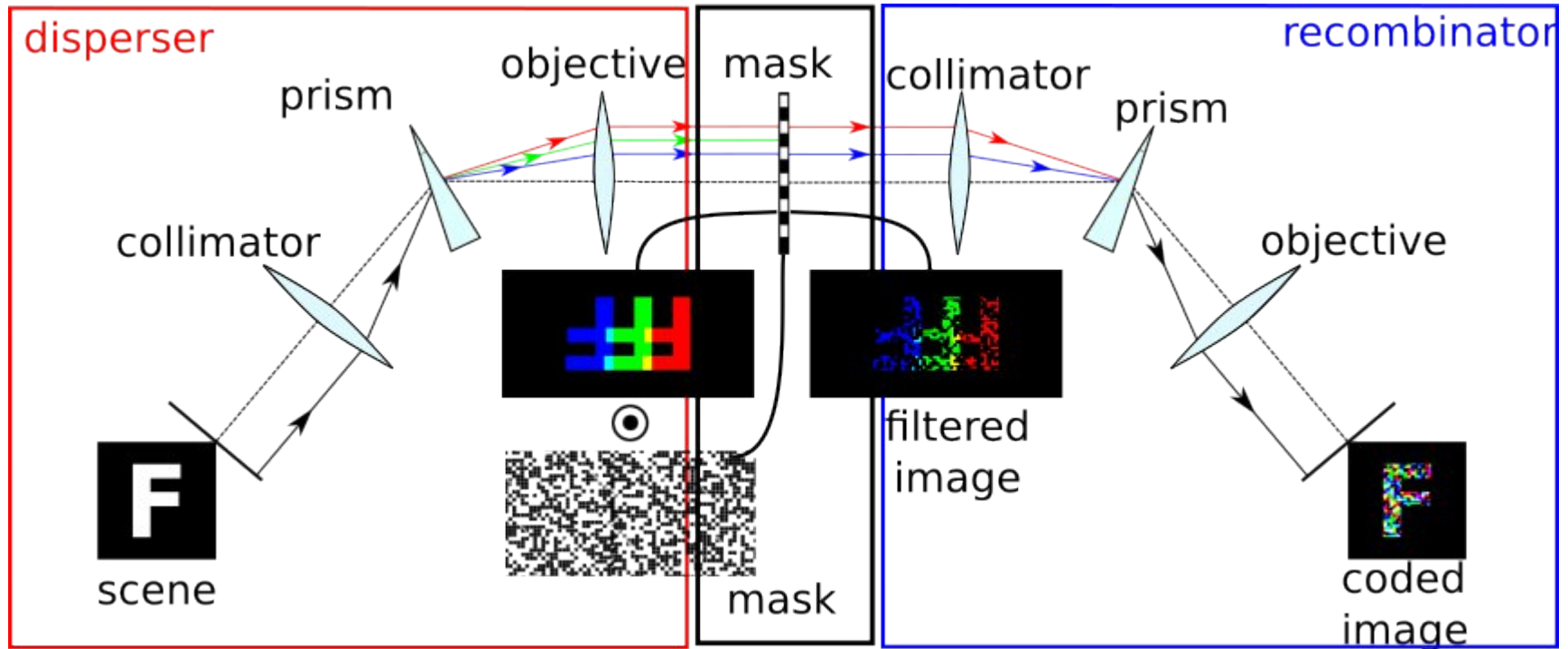
- > Methods inspired by compressed sensing
- > Stands out from traditional methods
- > Based on a coded aperture known as « mask »

# Coded hyperspectral imagery with CASSI



- > Acquisitions depend on optical system and mask's parameters

# Coded hyperspectral imagery with CASSI



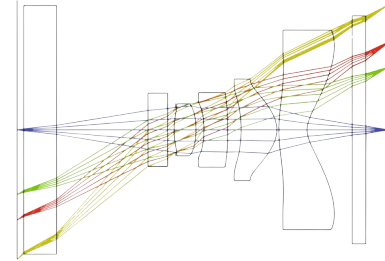
DD-CASSI system: Double Disperser Coded Aperture Snapshot Spectral Imager

- > The sensing matrix is implicitly created by the programmable mask



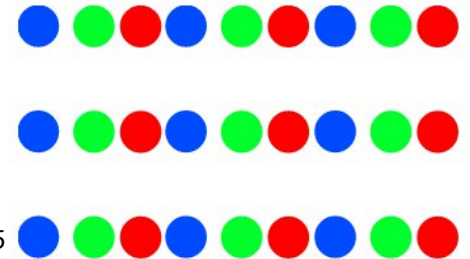
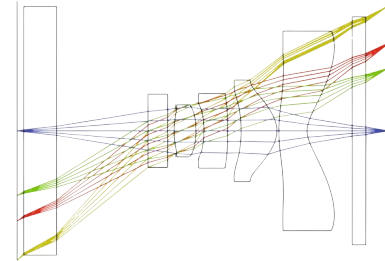
# Existing simulators

- > Zemax: For optical design
  - No image rendering available
  - Cannot be interfaced with processing algorithms



# Existing simulators

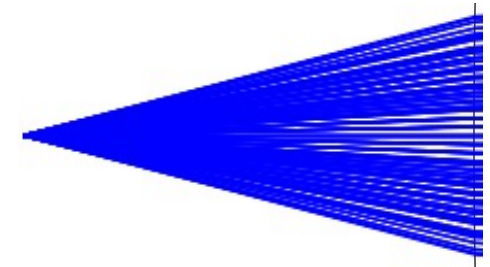
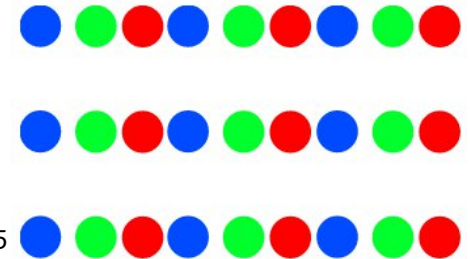
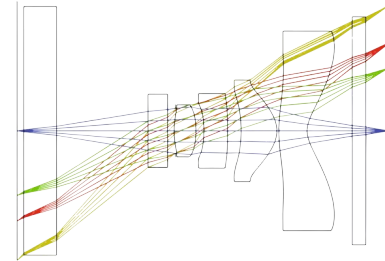
- > Zemax: For optical design
  - No image rendering available
  - Cannot be interfaced with processing algorithms
  
- > Using a simplified propagation model
  - No allowance for optical distortions



J. Bacca, et al. Deep Coded Aperture Design .... 2021. IEEE Transactions on computational imaging. DOI: 10.1109/TCI.2021.3122285

# Existing simulators

- > Zemax: For optical design
  - No image rendering available
  - Cannot be interfaced with processing algorithms
  
- > Using a simplified propagation model
  - No allowance for optical distortions
  
- > Complete and differentiable ray tracing
  - Slow in hyperspectral context

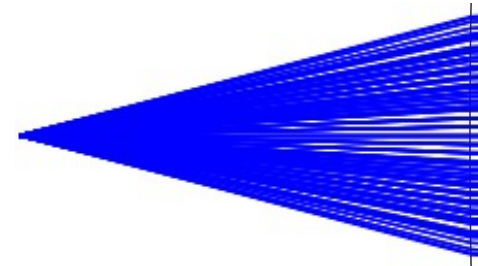
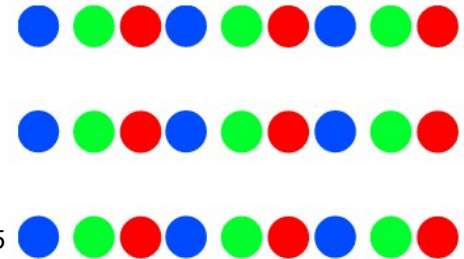
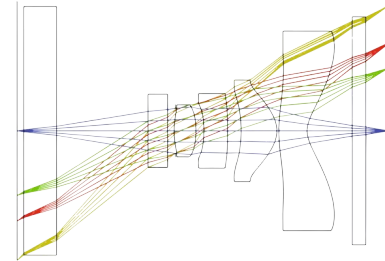


J. Bacca, et al. Deep Coded Aperture Design .... 2021. IEEE Transactions on computational imaging. DOI: 10.1109/TCI.2021.3122285

C. Wang, et al. dO: A Differentiable Engine .... 2022. IEEE Transactions on computational imaging. DOI: 10.1109/TCI.2022.3212837

# Existing simulators

- > Zemax: For optical design
  - No image rendering available
  - Cannot be interfaced with processing algorithms
  
- > Using a simplified propagation model
  - No allowance for optical distortions
  
- > Complete and differentiable ray tracing
  - Slow in hyperspectral context
  
- > **Do not allow for co-design**



J. Bacca, et al. Deep Coded Aperture Design .... 2021. IEEE Transactions on computational imaging. DOI: 10.1109/TCI.2021.3122285

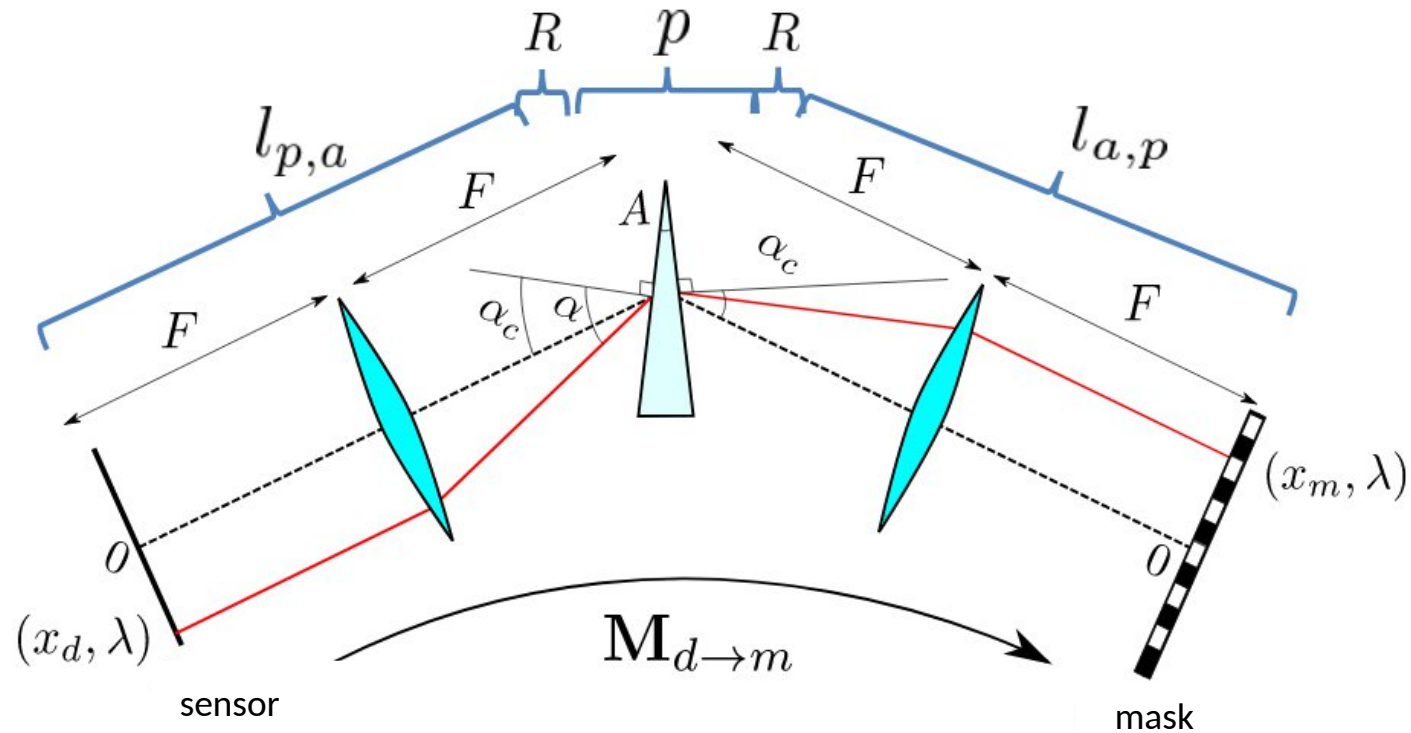
C. Wang, et al. dO: A Differentiable Engine .... 2022. IEEE Transactions on computational imaging. DOI: 10.1109/TCI.2022.3212837

# Our simulator: SIMCA

- > Able to render
- > Accurate propagation model
- > Fast
- > Differentiable
  
- > **Optics and processing co-design**

# Modular optics model

> From sensor to the mask:  $M : (x_d, y_d, \lambda) \rightarrow (x_m, y_m)$



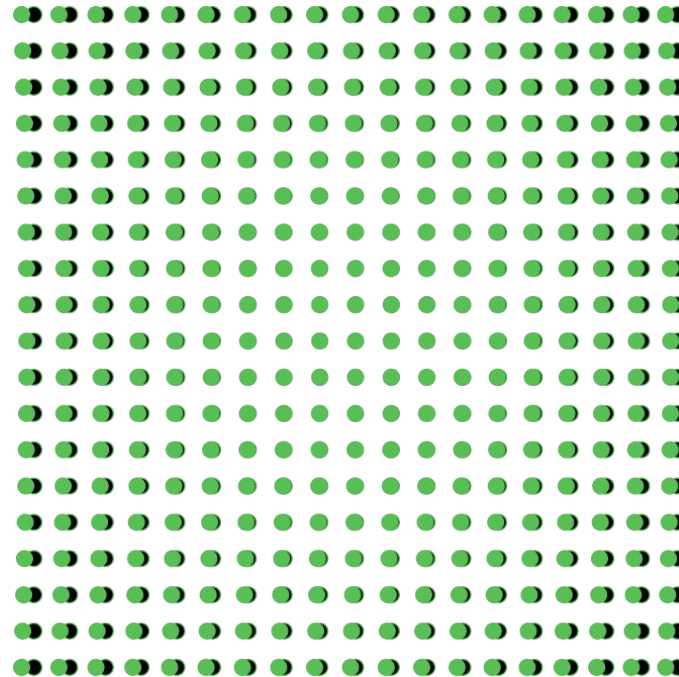
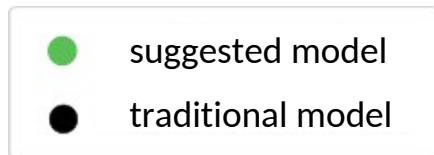
> Suggested model:

- Composition of elementary transformations

$$M_{d \rightarrow m} = l_{a,p} \circ R \circ p \circ R \circ l_{p,a}$$

**Analytical but modular model  
based on ray tracing**

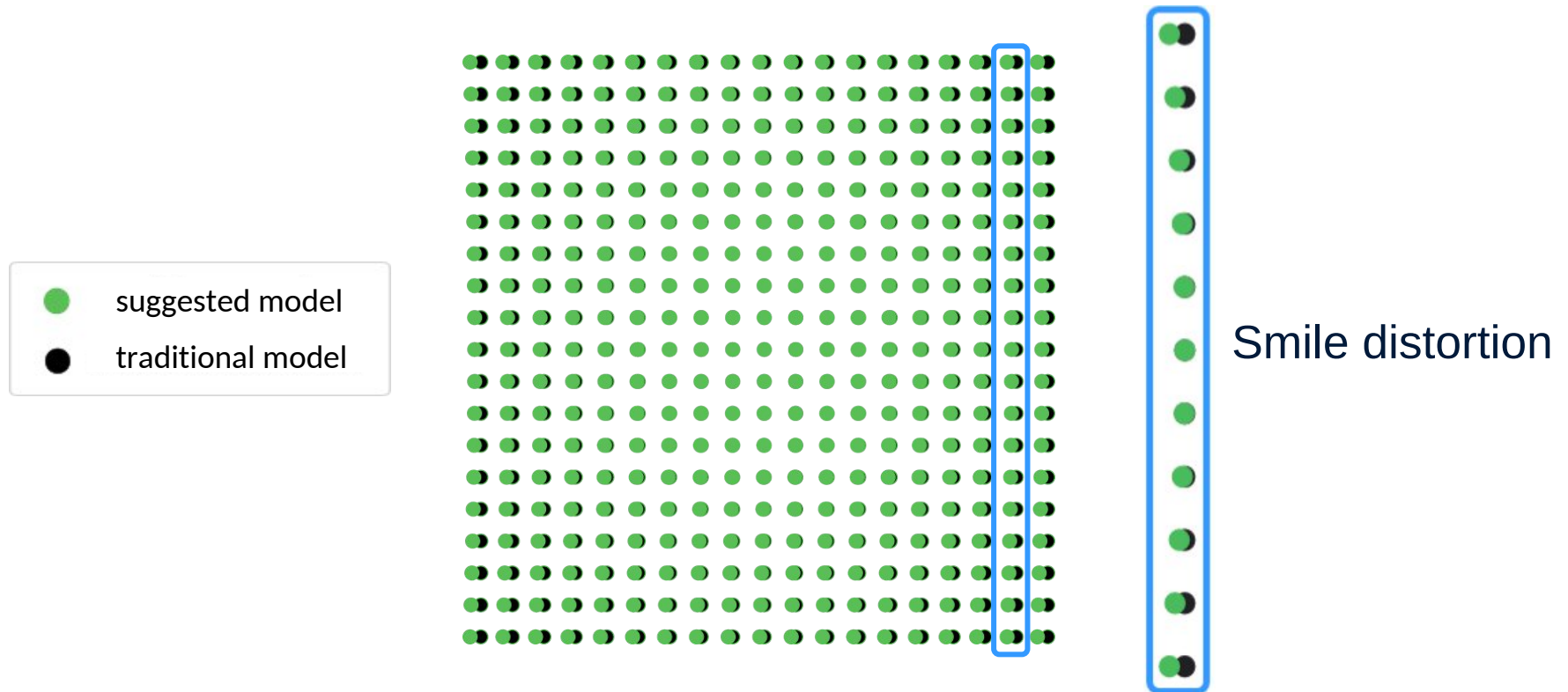
# Taking account of distortions



- > Suggested model:
  - Composition of elementary transformations

$$M_{d \rightarrow m} = l_{a,p} \circ R \circ p \circ R \circ l_{p,a}$$

# Taking account of distortions

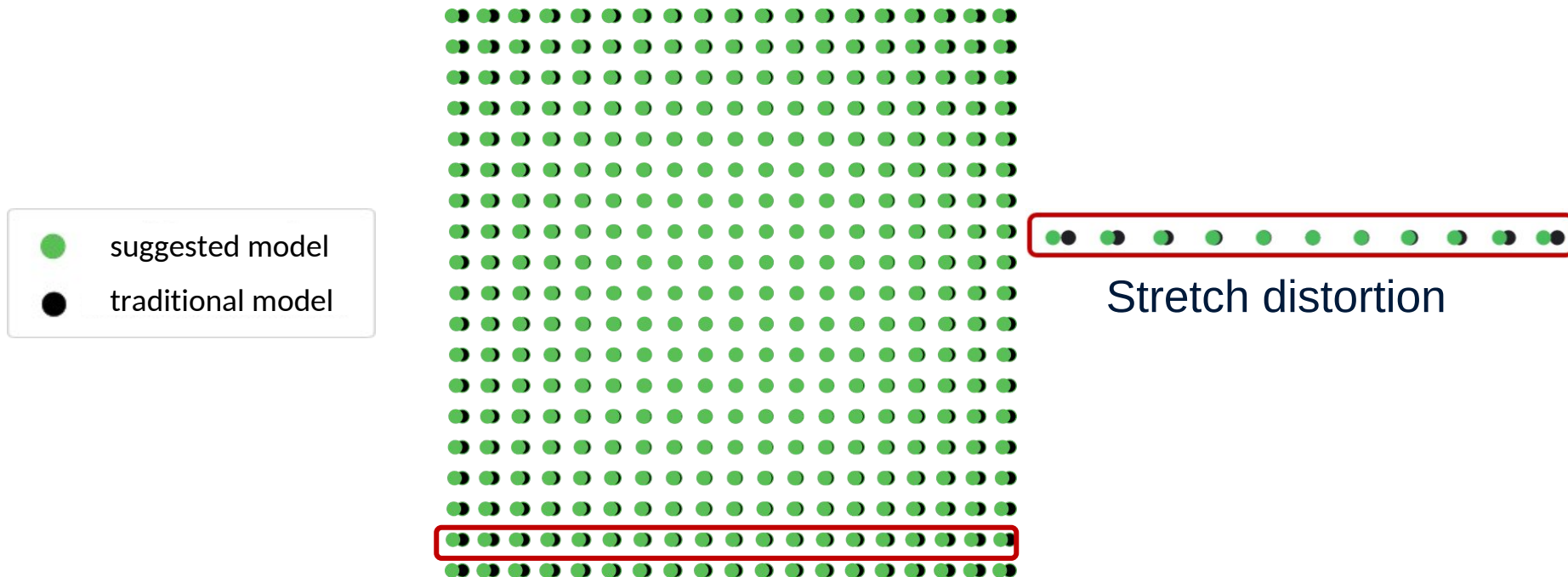


- > Suggested model:
  - Composition of elementary transformations

$$M_{d \rightarrow m} = l_{a,p} \circ R \circ p \circ R \circ l_{p,a}$$



# Taking account of distortions

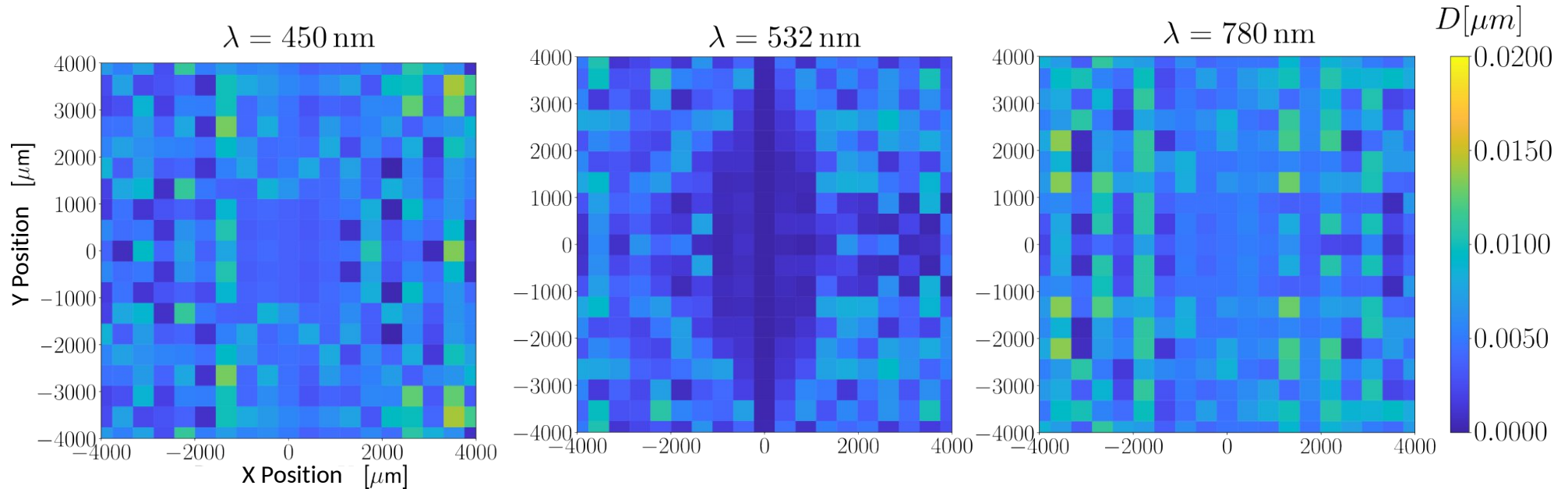


- > Suggested model:
  - Composition of elementary transformations

$$M_{d \rightarrow m} = l_{a,p} \circ R \circ p \circ R \circ l_{p,a}$$

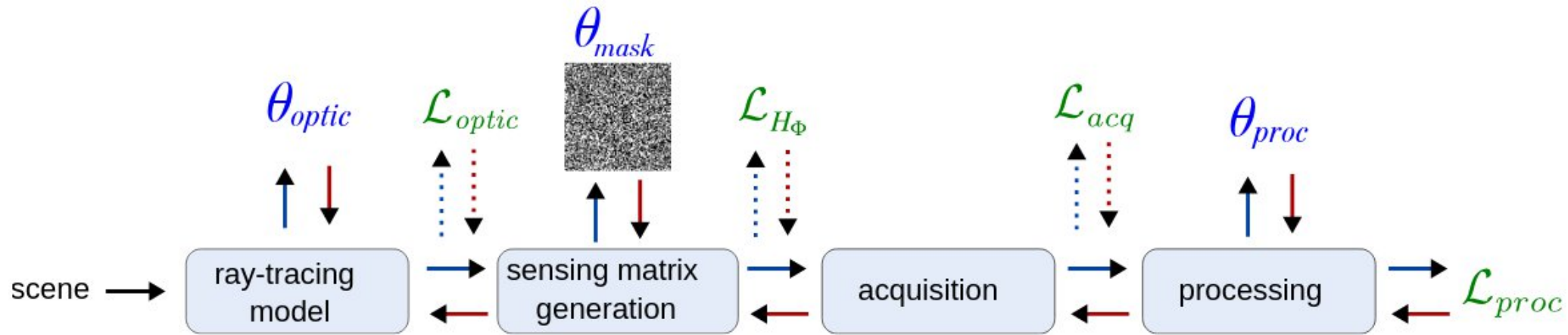
# Validation with Zemax

**Metric** :  $D$  [ $\mu\text{m}$ ], Euclidean distance between the image points of the two models.



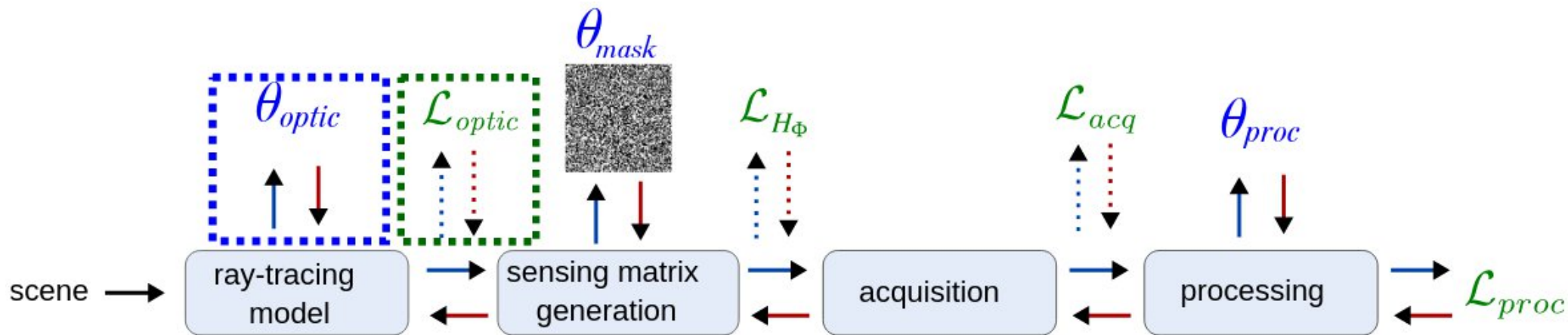
- > Similar accuracy to Zemax
- > Taking care of the PSF: in progress

# Differentiable co-design environment

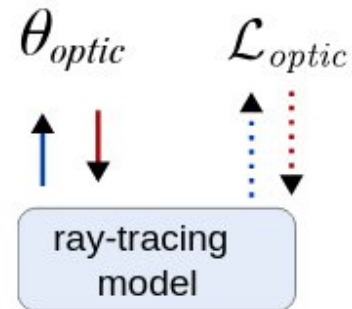


- > Can optimise parameters at each stage of the environment, based on constraints

# Optical parameters optimisation



# Optical parameters optimisation



**Constraint:**  $\mathcal{L}_{optic}$

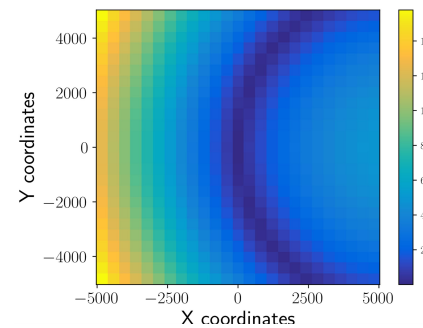
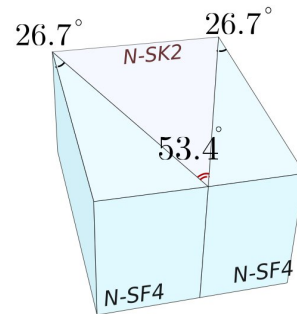
Examples :

- > Spectral dispersion
- > Direct view
- > Compactness
- > Geometric distortions

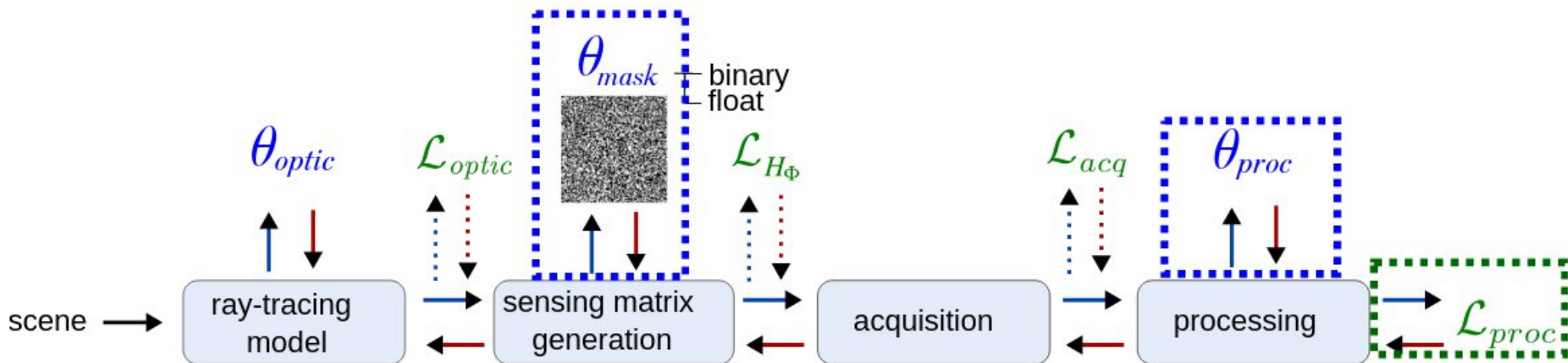
**Parameters:**  $\theta_{optic}$

Examples :

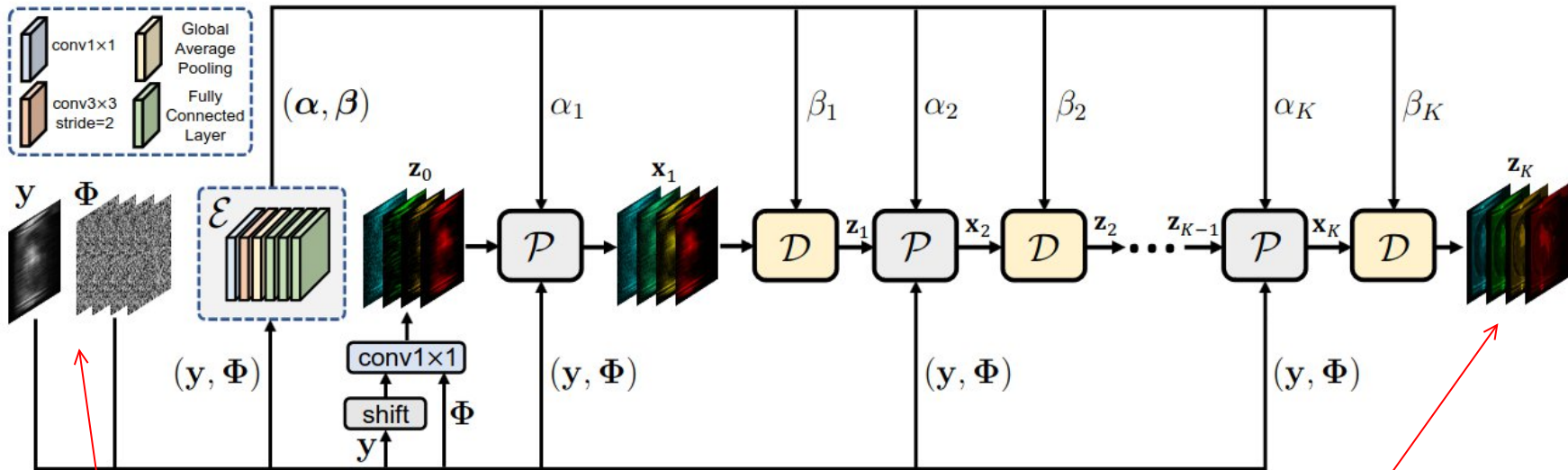
- > Prisms materials
- > Prisms angles
- > Prisms orientation



# Mask optimisation



# Hyperspectral reconstruction with DAUHST



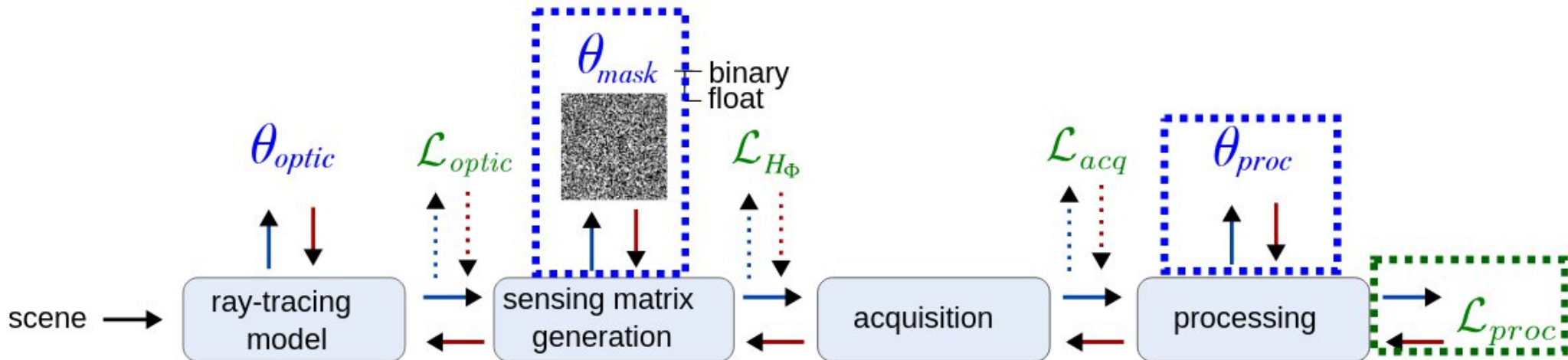
Inputs:

- > Acquisition (112x112)
- > Sensing matrix (112x112x28)

Output:

- > Reconstructed scene (112x112x28)

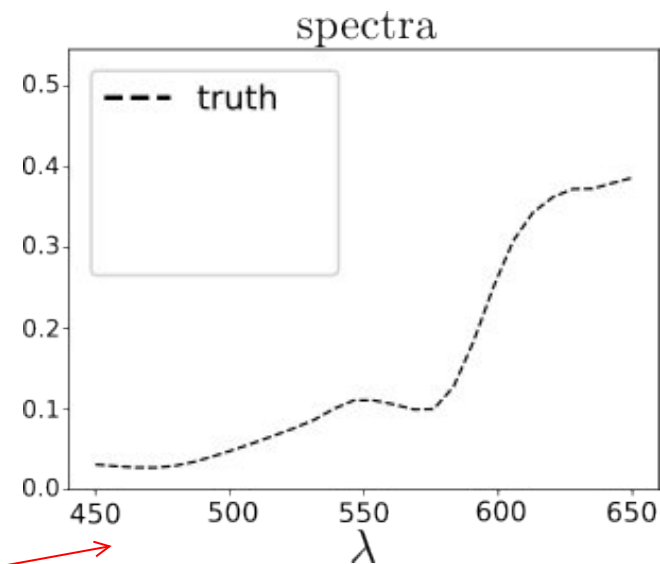
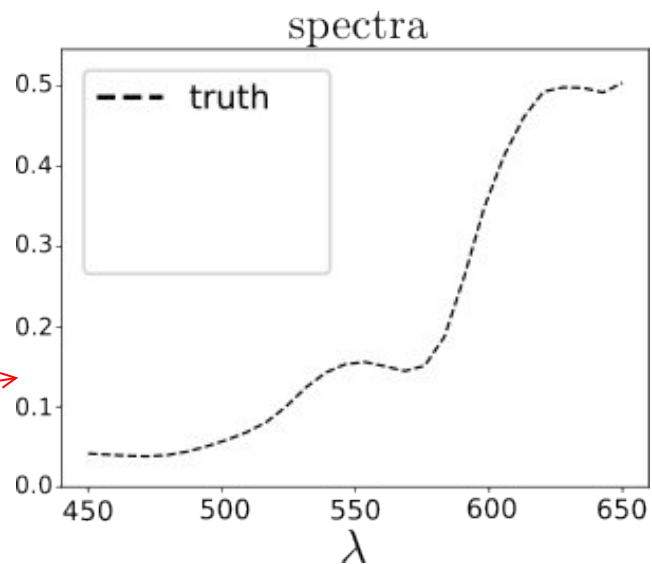
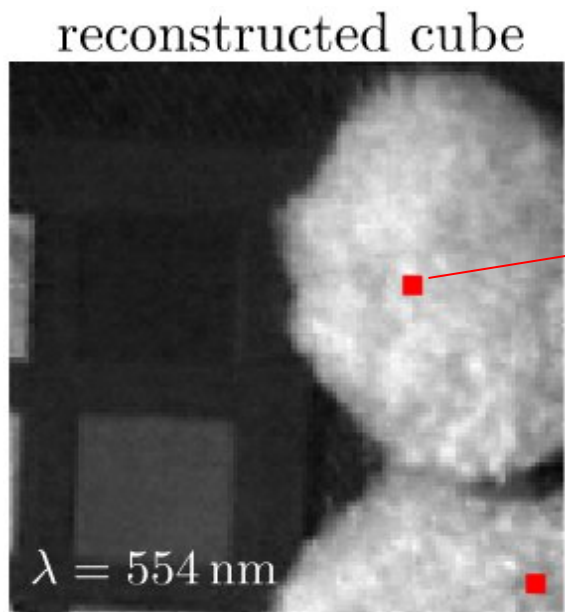
# Mask optimisation



- > **First step:** DAUHST pre-training
  - Improves convergence
  
- > **Second step:** Joint training of parameters



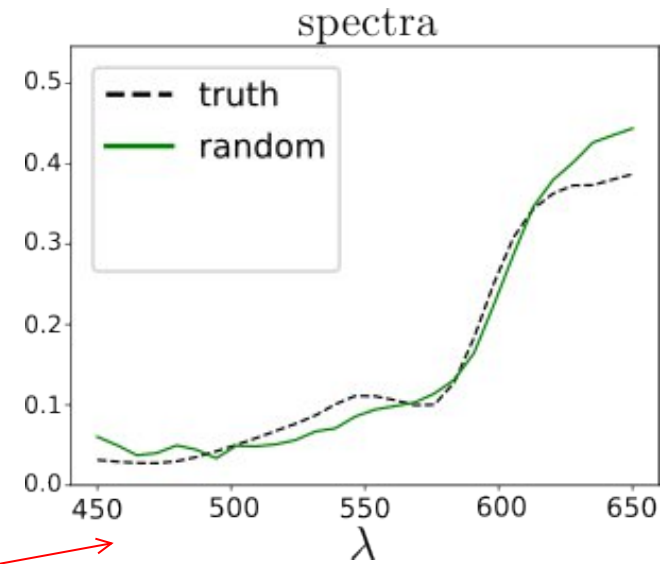
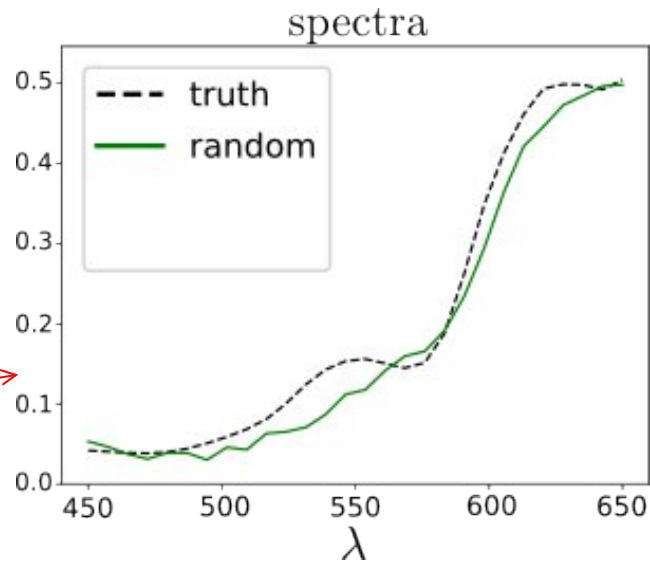
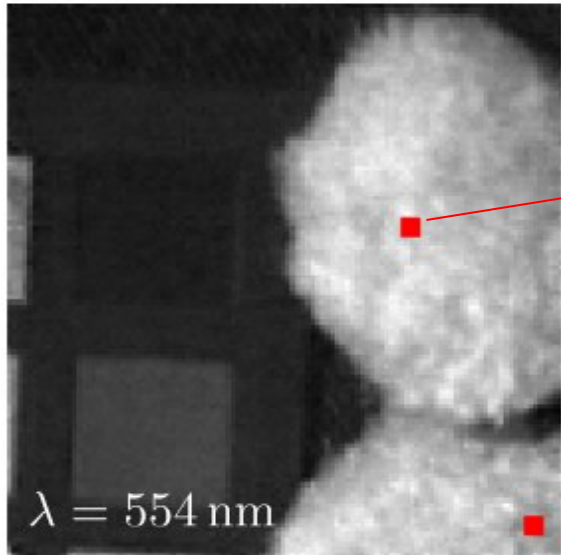
# Results on CAVE dataset



Fumihito Yasuma, et al. CAVE Dataset. <https://www.cs.columbia.edu/CAVE/databases/multispectral/>, 2008.

# Results on CAVE dataset

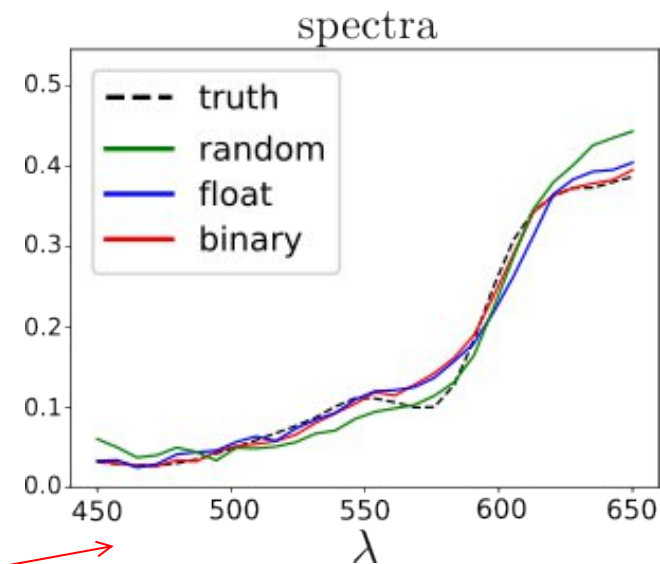
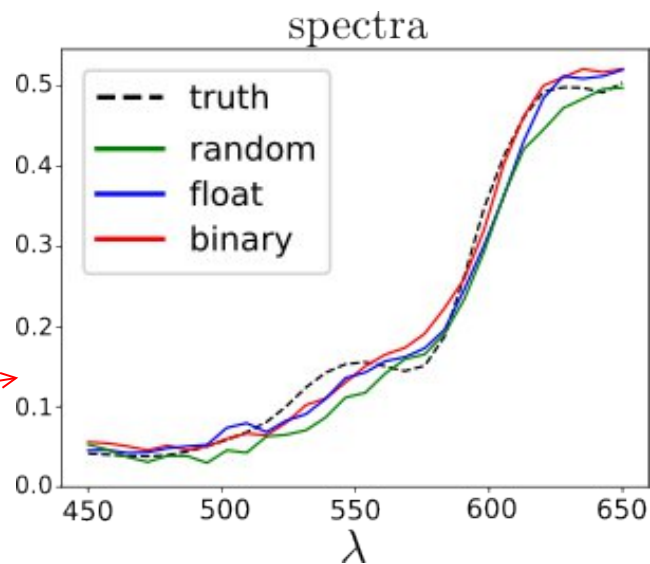
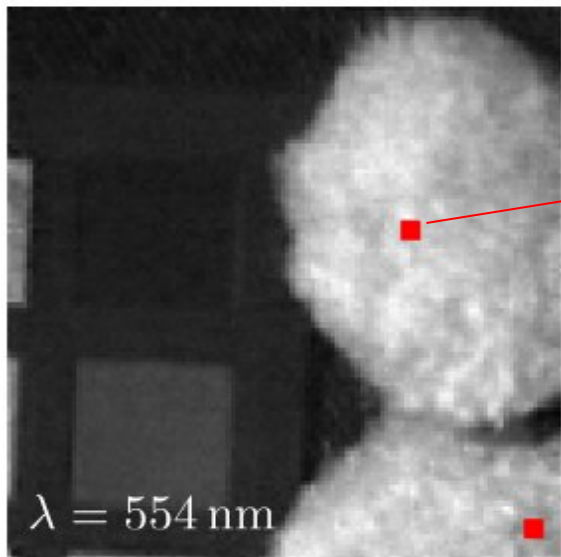
reconstructed cube



Fumihito Yasuma, et al. CAVE Dataset. <https://www.cs.columbia.edu/CAVE/databases/multispectral/>, 2008.

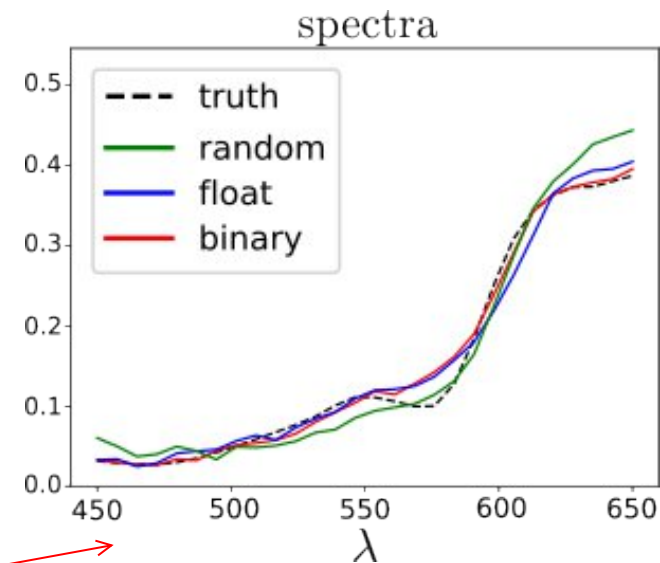
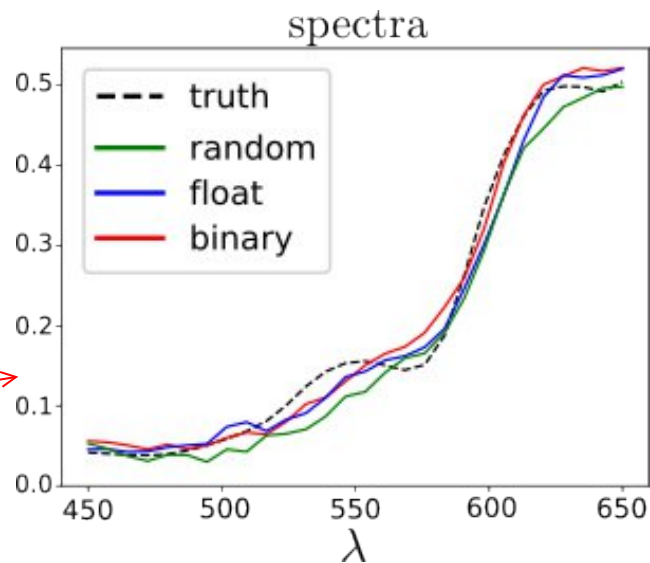
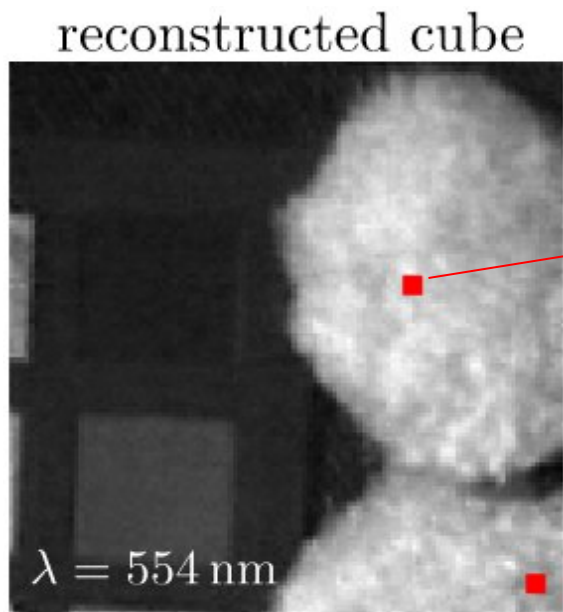
# Results on CAVE dataset

reconstructed cube



Fumihito Yasuma, et al. CAVE Dataset. <https://www.cs.columbia.edu/CAVE/databases/multispectral/>, 2008.

# Results on CAVE dataset



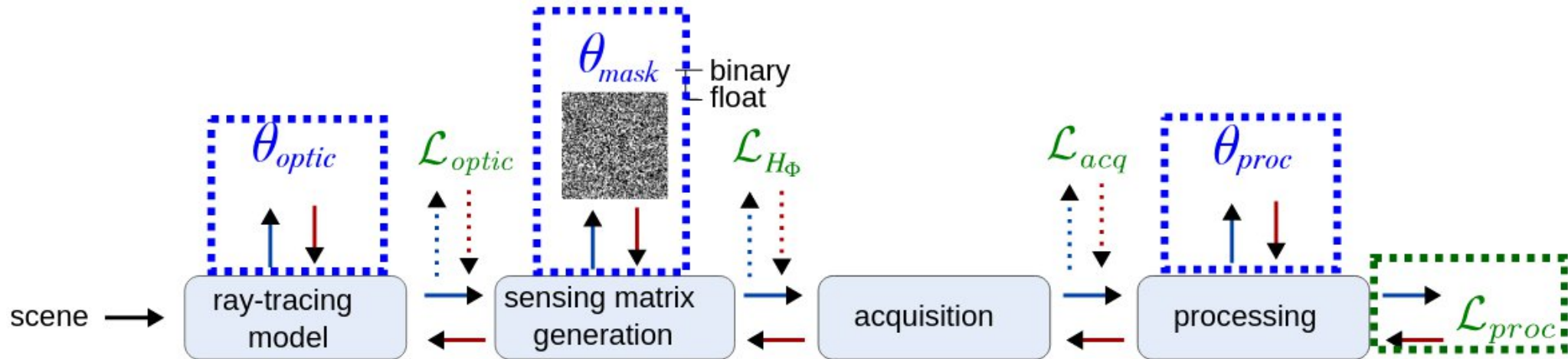
CAVE 1024 (test)

Methods	SSIM↑	PSNR↑	RMSE↓
Random	0.960	33.5	11.0
Optim. Float	0.969	34.8	9.65
Optim. Binary	0.976	35.4	8.86

Fumihito Yasuma, et al. CAVE Dataset. <https://www.cs.columbia.edu/CAVE/databases/multispectral/>, 2008.

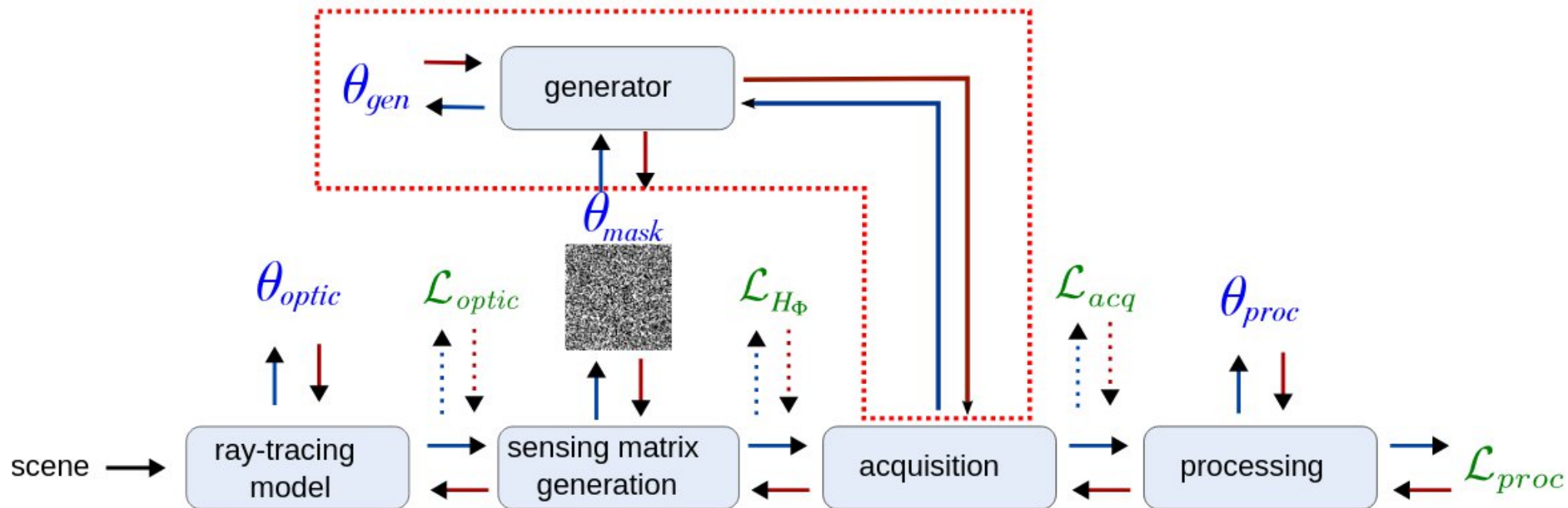
- > Realistic optical model of propagation
  
- > Differentiable co-design environment:
  - Optics design
  - Simulation of coded hyperspectral acquisitions
  - Acquisitions processing
  - Joint optimisation optics-processing

# Prospects: Towards full co-design



- > Joint optimisation of optical, mask, and acquisition processing parameters

# Prospects: Towards active perception



> Adaptive mask generation for each scene

# Thank you for your attention

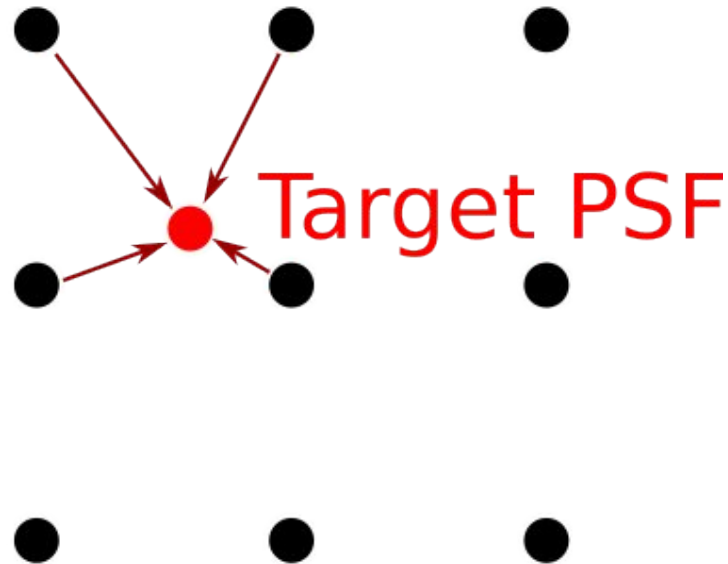
Léo Paillet  
PhD student

[leo.paillet@laas.fr](mailto:leo.paillet@laas.fr)



# PSF estimation (impulse response)

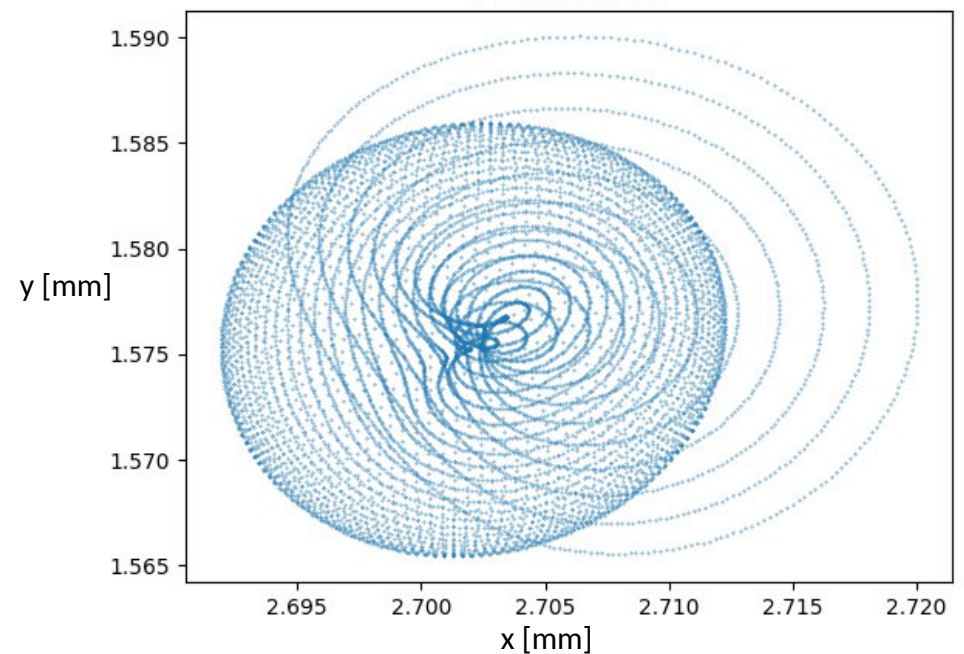
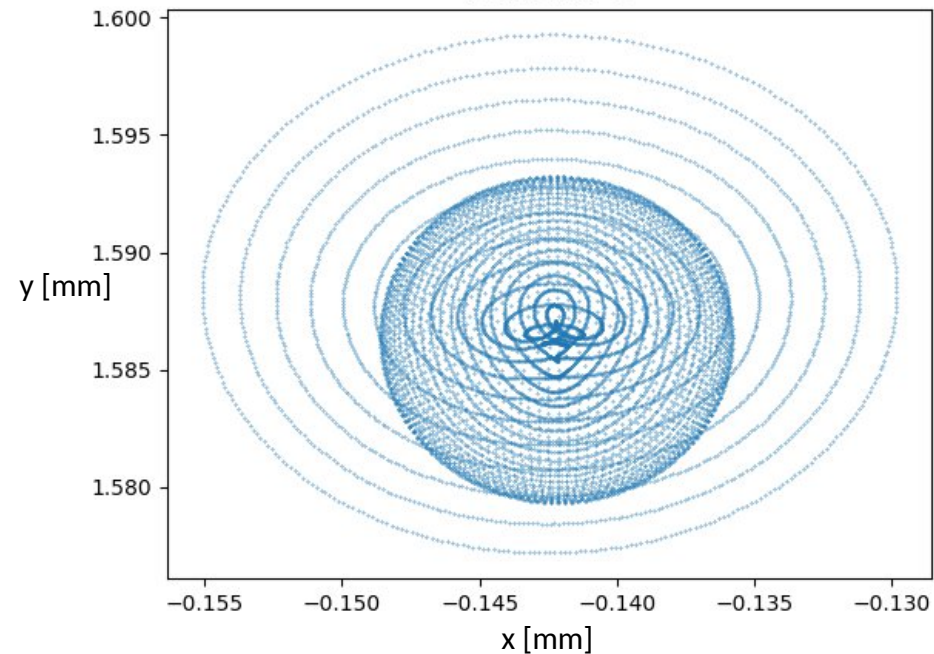
PSFs samples



- > Regular PSFs database for a fixed optical system
- > Database compression with SVD, NMF, ...
- > Bilinear interpolation to estimate PSFs at required locations

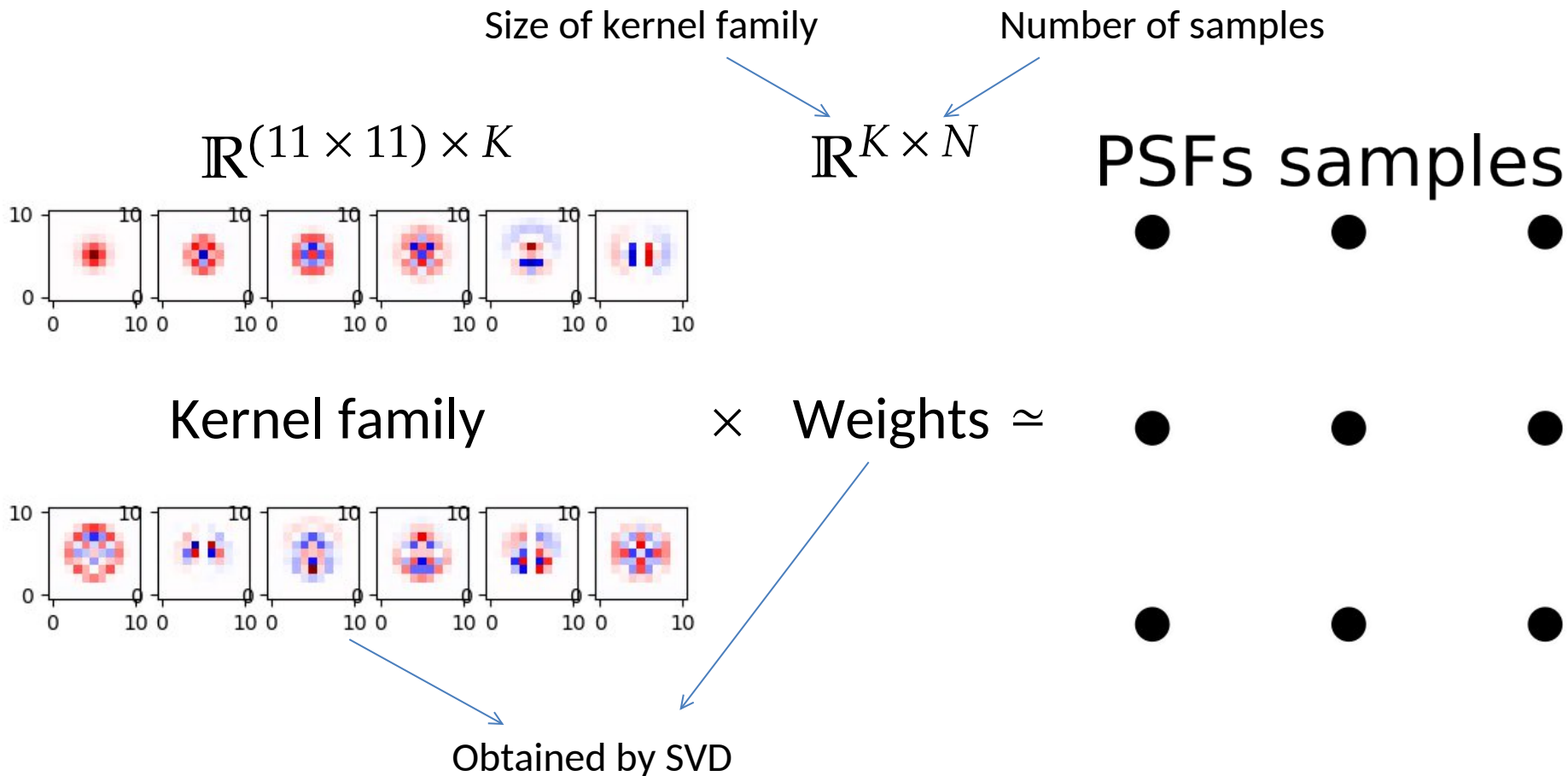
Yanny, K., Antipa, N., Liberti, W. et al. Miniscope3D: optimized single-shot miniature 3D fluorescence microscopy. *Light Sci Appl* 9, 171 (2020). <https://doi.org/10.1038/s41377-020-00403-7>  
 Zhang, Y., Song, X., Xie, J. et al. Large depth-of-field ultra-compact microscope by progressive optimization and deep learning. *Nat Commun* 14, 4118 (2023).  
<https://doi.org/10.1038/s41467-023-39860-0>

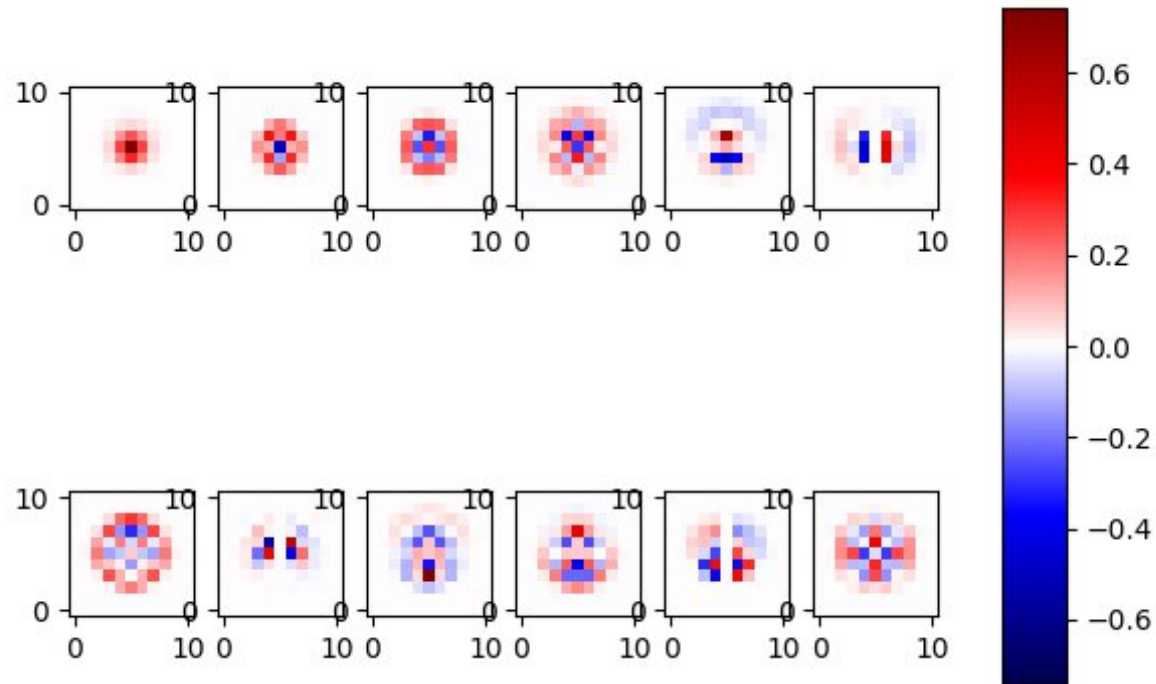
## > Examples of PSFs



## > Database generation by discretizing their distribution

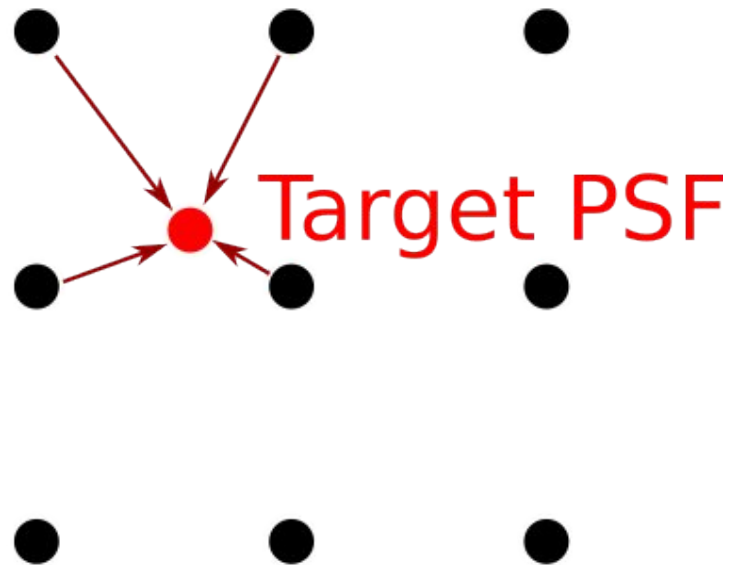
# PSF generating family with SVD



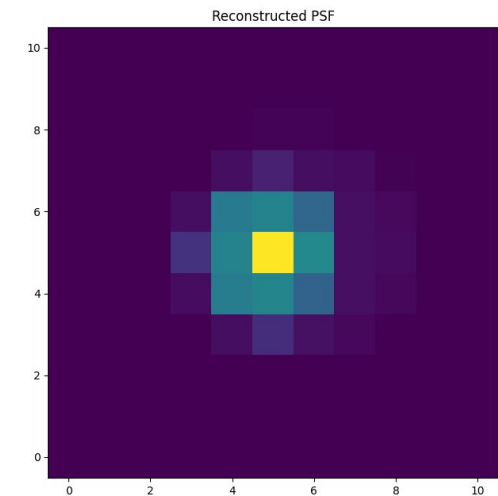
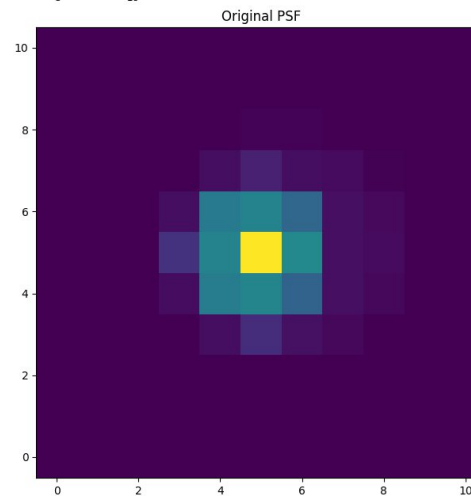
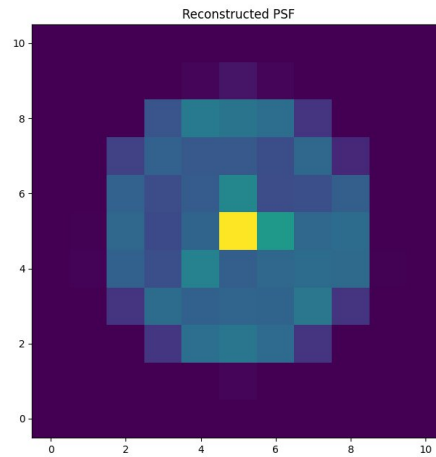
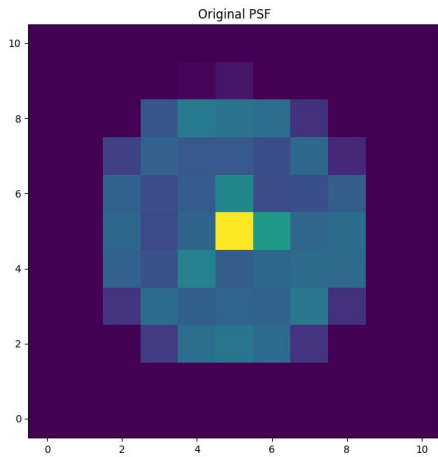


- > Higher frequencies are seen in higher-ranking family members

- > Bilinear interpolation with the 4 known neighbours



## > Error between original and estimated PSFs



- > Error between original and estimated PSF throughout the field of view

