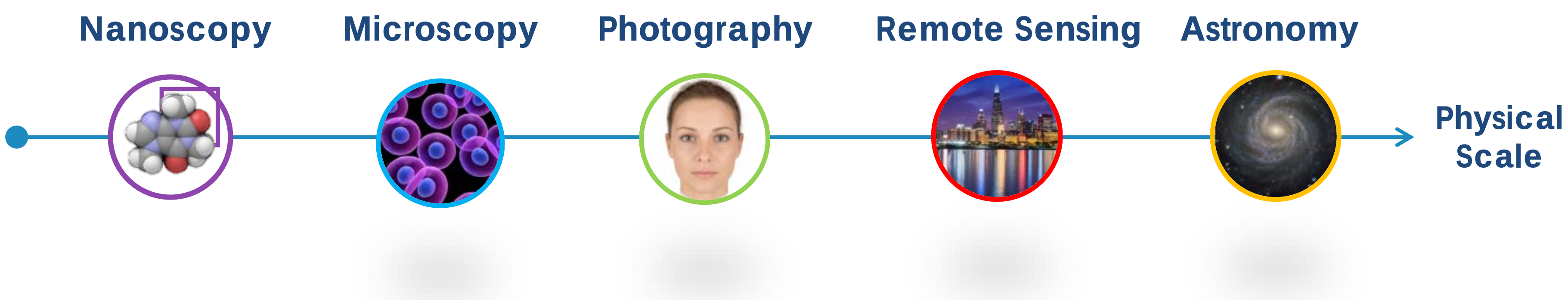
Computational Imaging from Nanoscopic to Astronomical Scales



comp photo lab

iVPL

NU ACCESS

RICE Unconventional Wisdom

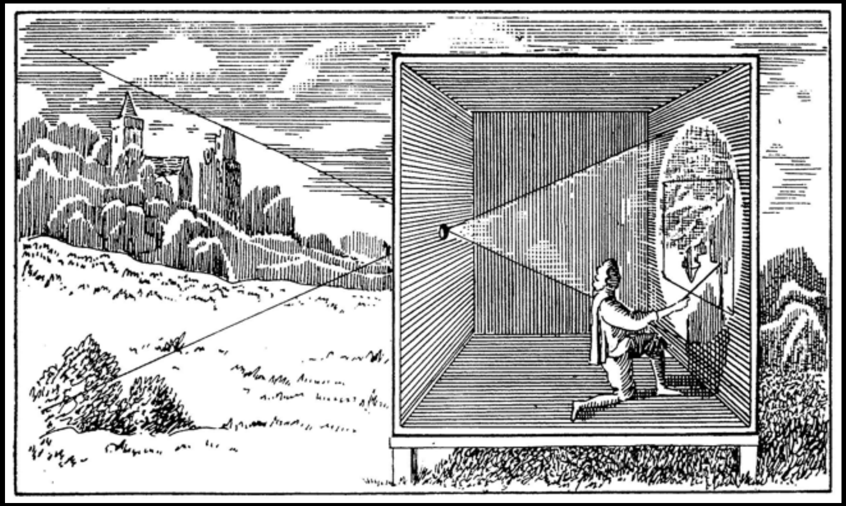
Argonne NATIONAL LABORATORY

THE UNIVERSITY OF CHICAGO

Oliver Cossairt
Assistant Professor
EECS Department
Northwestern University

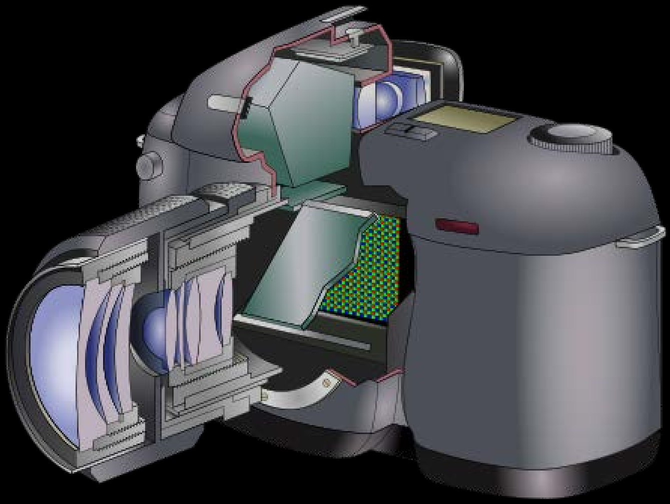
A Centuries Old Design

Camera Obscura



http://www.camerapixela.net

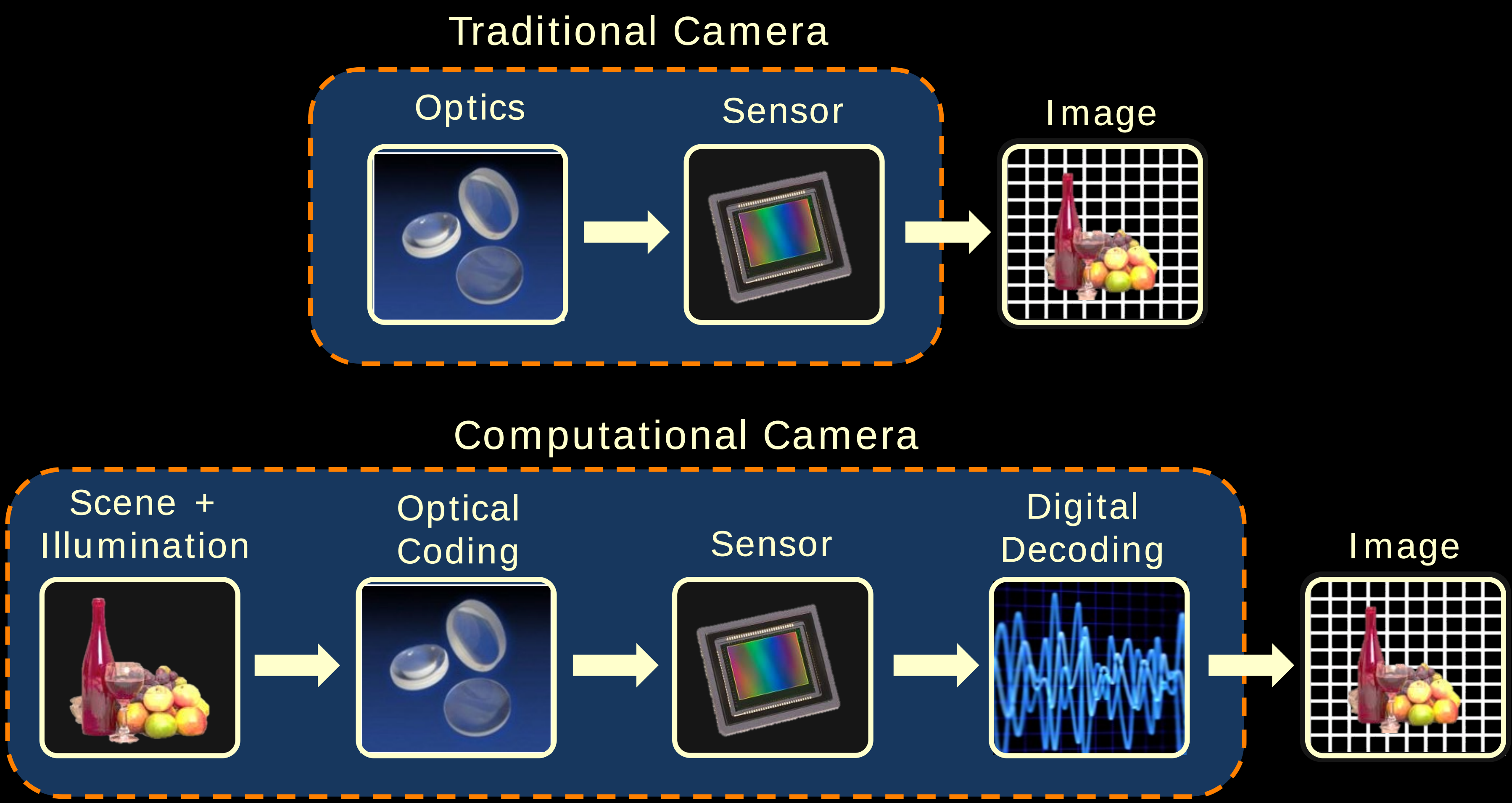
Digital Camera



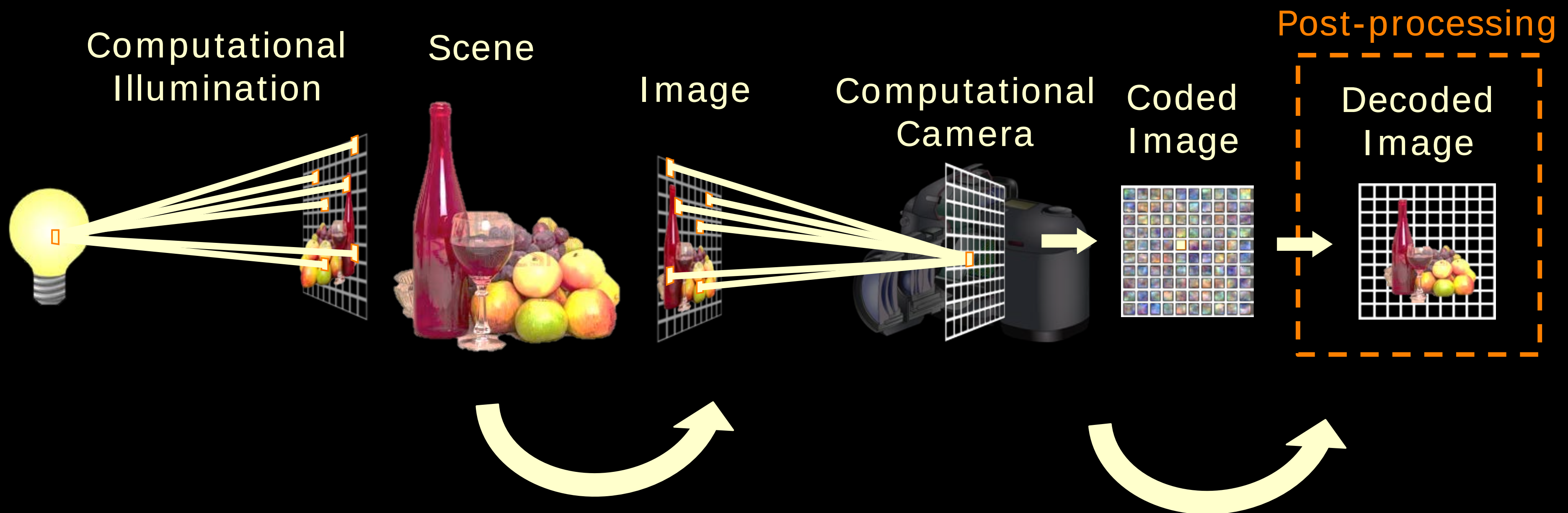
Jean François WITZ

Both cameras produce perspective images

Traditional vs. Computational Imaging



A Generalized Camera Model

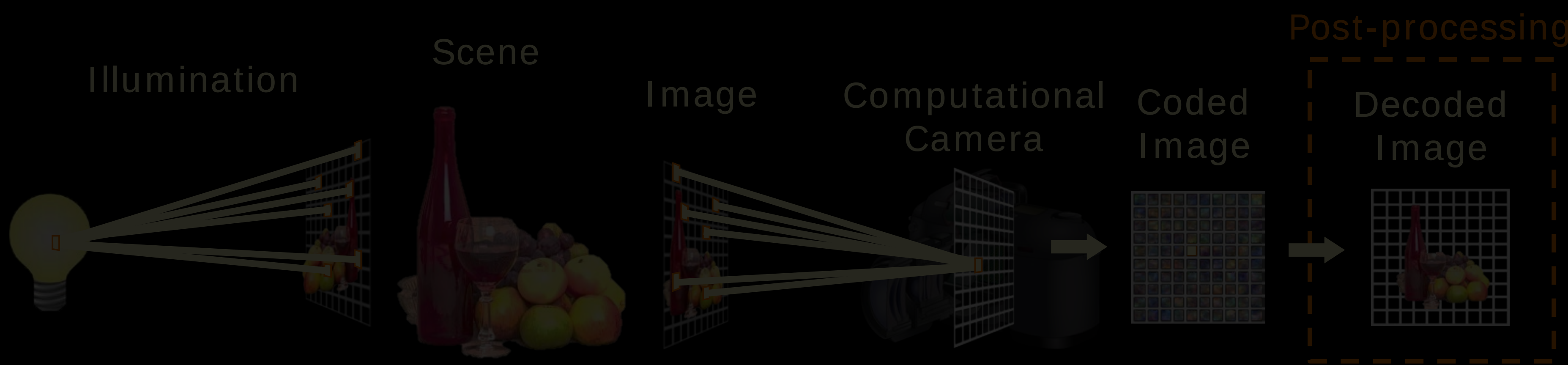


Coded Image	Coding Function	Noise	Decoded Image	Coded Image

$$y = A(x) + n \qquad \hat{x} = A^{-1}(x)$$

Optical Coding Equation — Decoding Equation

A Generalized Camera Model



Incoherent Imaging
(e.g. sun, incandescent, LEDs)

Coded Image — Coding Matrix — Noise

$$y = A \cdot x + n$$

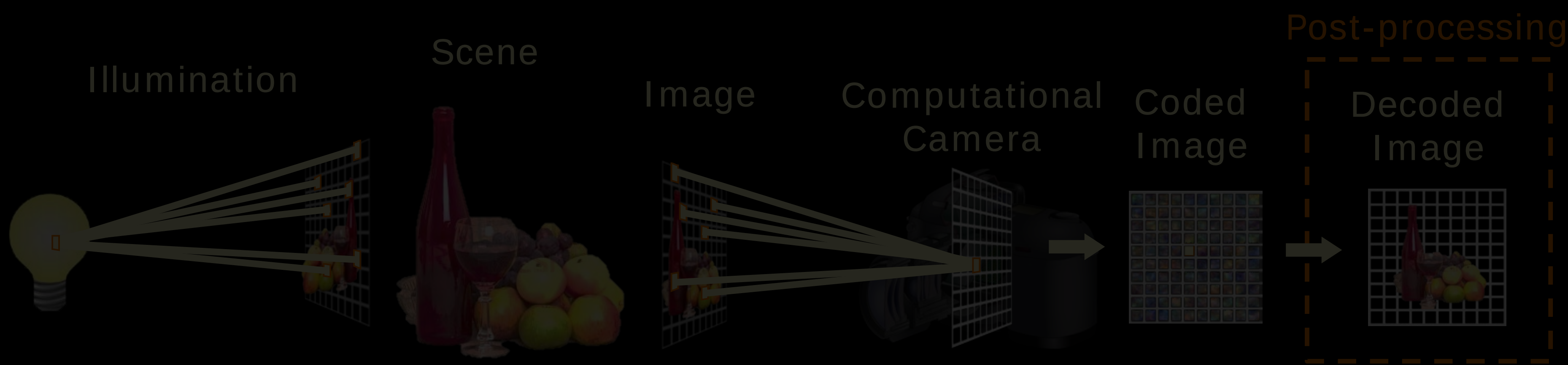
Optical Coding Equation

$$y \in \mathbb{R}_+^M$$

$$x \in \mathbb{R}_+^N$$

$$A \in \mathbb{R}_+^{M \times N}$$

A Generalized Camera Model



Coherent Imaging
(e.g. LASER illumination)

Coded Image — Coding Matrix — Noise

$$y = |A \cdot x|^2 + n$$

Optical Coding Equation

$$y \in \mathbb{R}_+^M$$

$$x \in \mathbb{C}^N$$

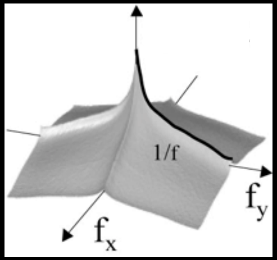
$$A \in \mathbb{C}^{M \times N}$$

Decoding and Image Priors

Assume we have a PDF for images, e.g.

$$P(x) = \exp\left(\|B \cdot x\|^{\alpha}\right)$$

Power Spectra Prior



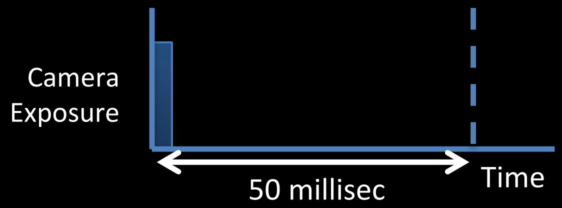
Other priors

- Total Variation (TV)
- Wavelet/sparsity prior
- Learned priors (K-SVD,DNN)

Compute the Maximum A Posteriori (MAP) estimate

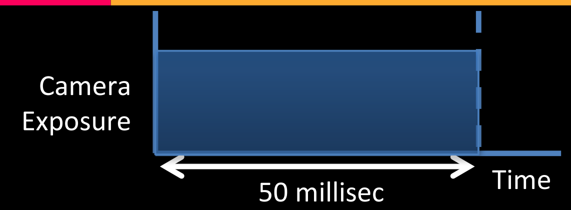
$$x^{*} = \underset{x}{\operatorname{argmax}} \Big(\underbrace{\|y - H \cdot x\|^{2}}_{\text{Data term}} + \underbrace{\|B \cdot x\|^{\alpha}}_{\text{Prior term}} \Big)$$

Previous Work: CI Performance



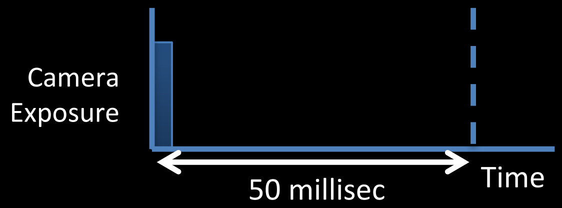
Short Exposure

Vs.



Long Exposure

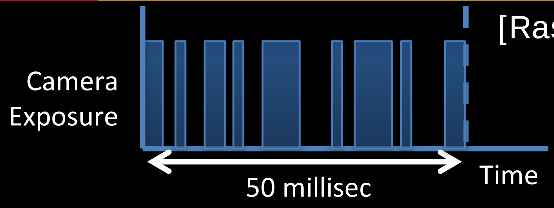
Previous Work: CI Performance

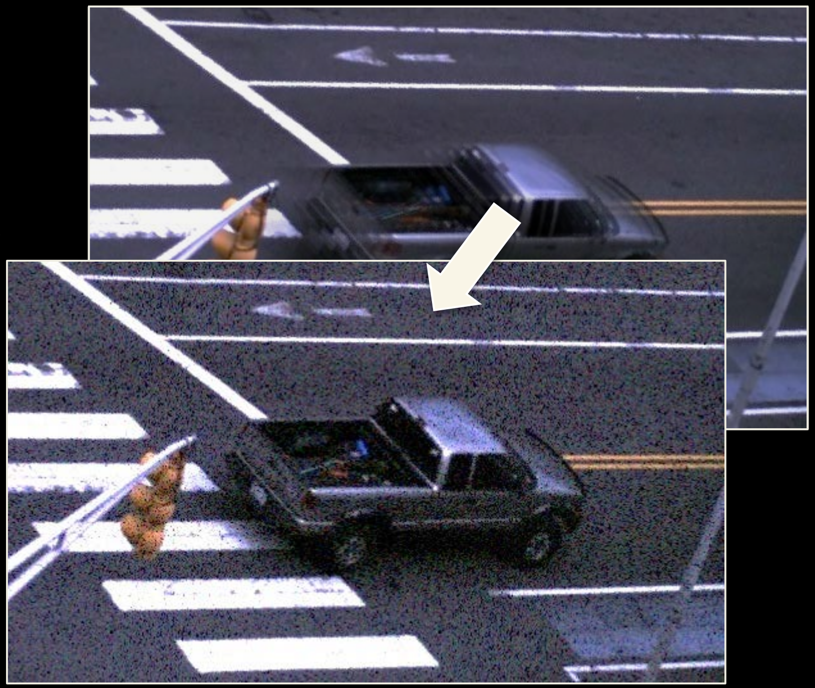


Short Exposure

Vs.

[Raskar ’06]



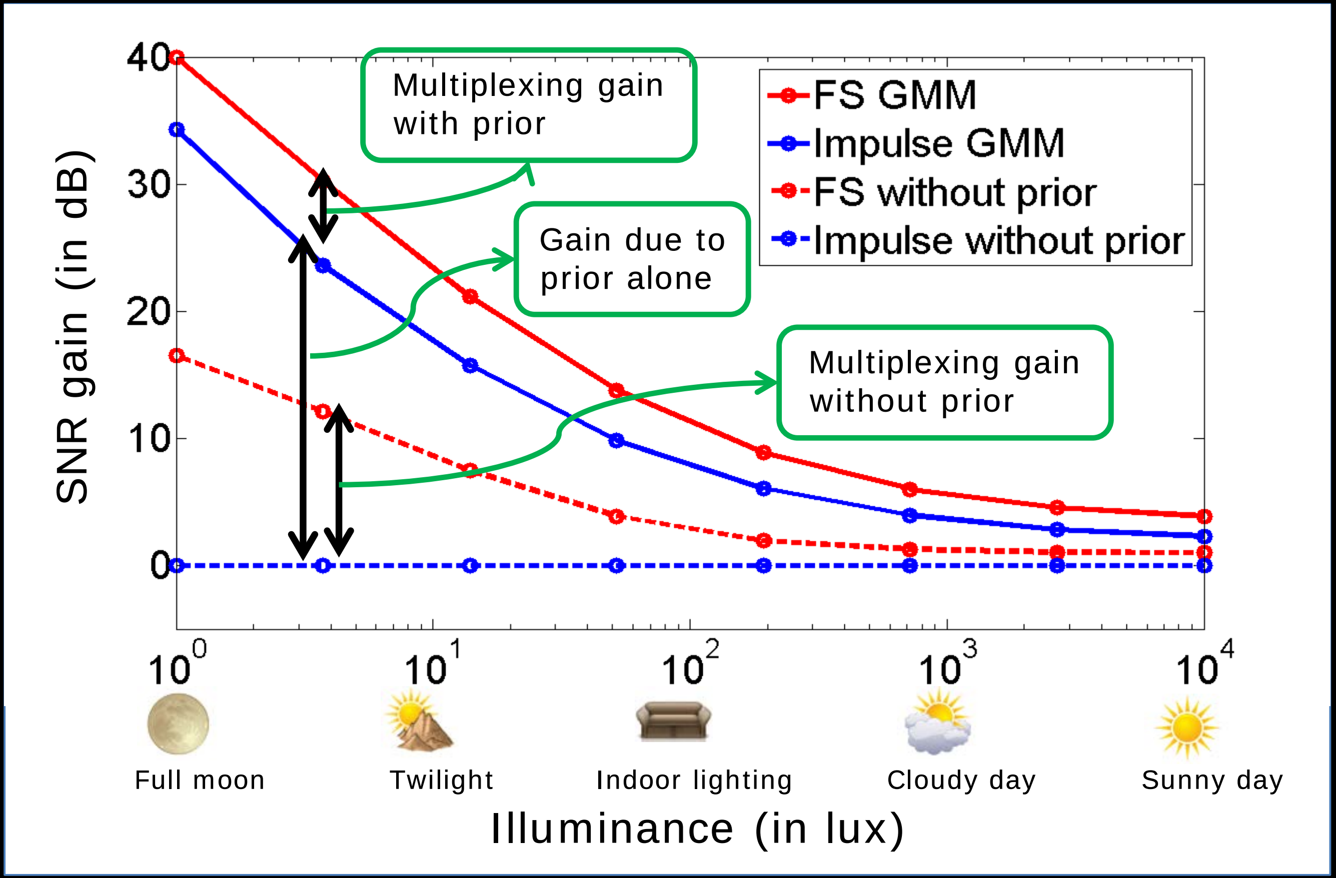


Deblurred Image

When does computational imaging improve performance?

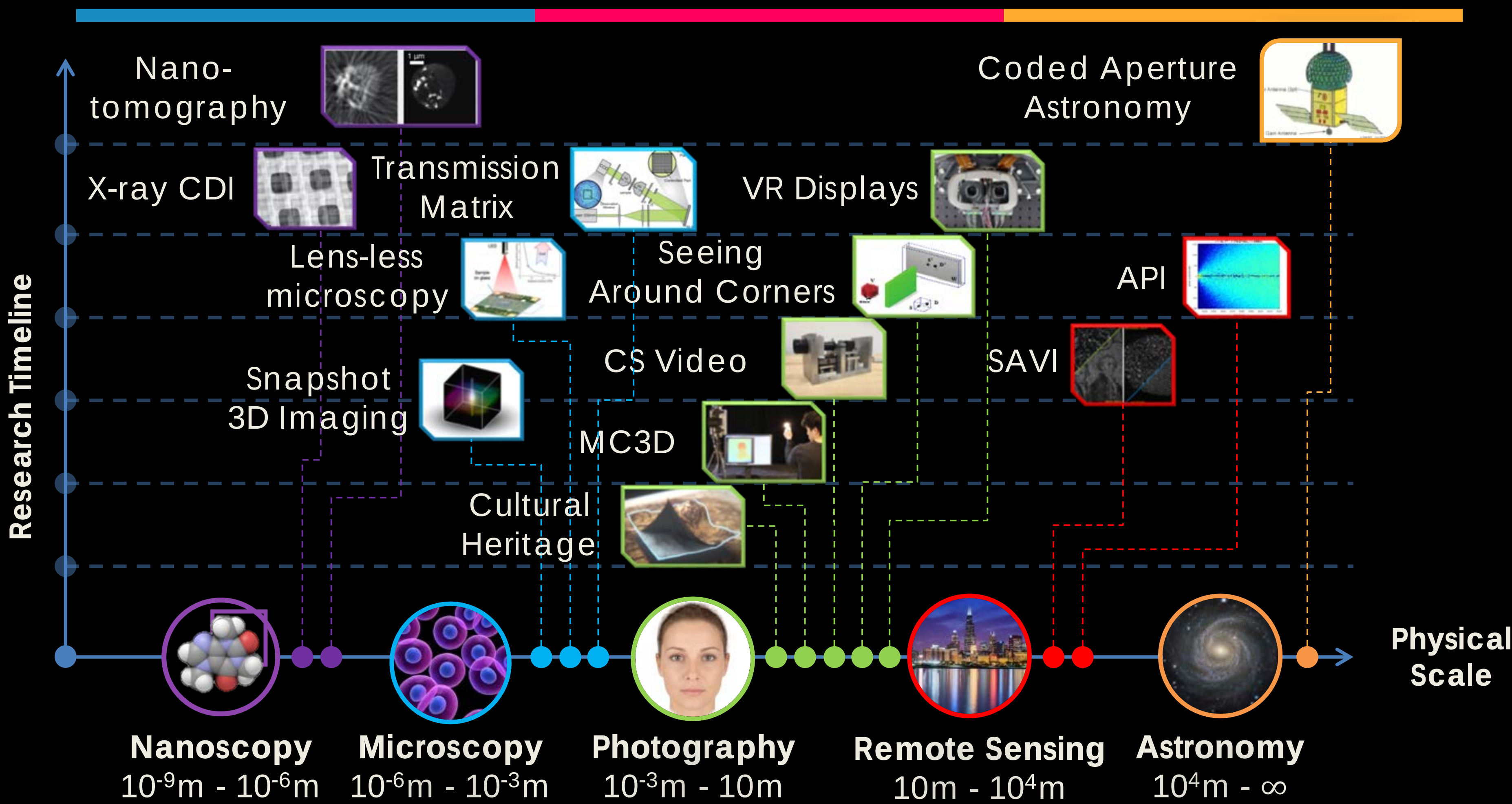
What are the limits of CI Performance?

Stopped Down Camera: *F/11*, Focal Sweep: *F/1* *q=.5, R = .5, t=6ms, p = 1um,* $\sigma_r = 4e^-$

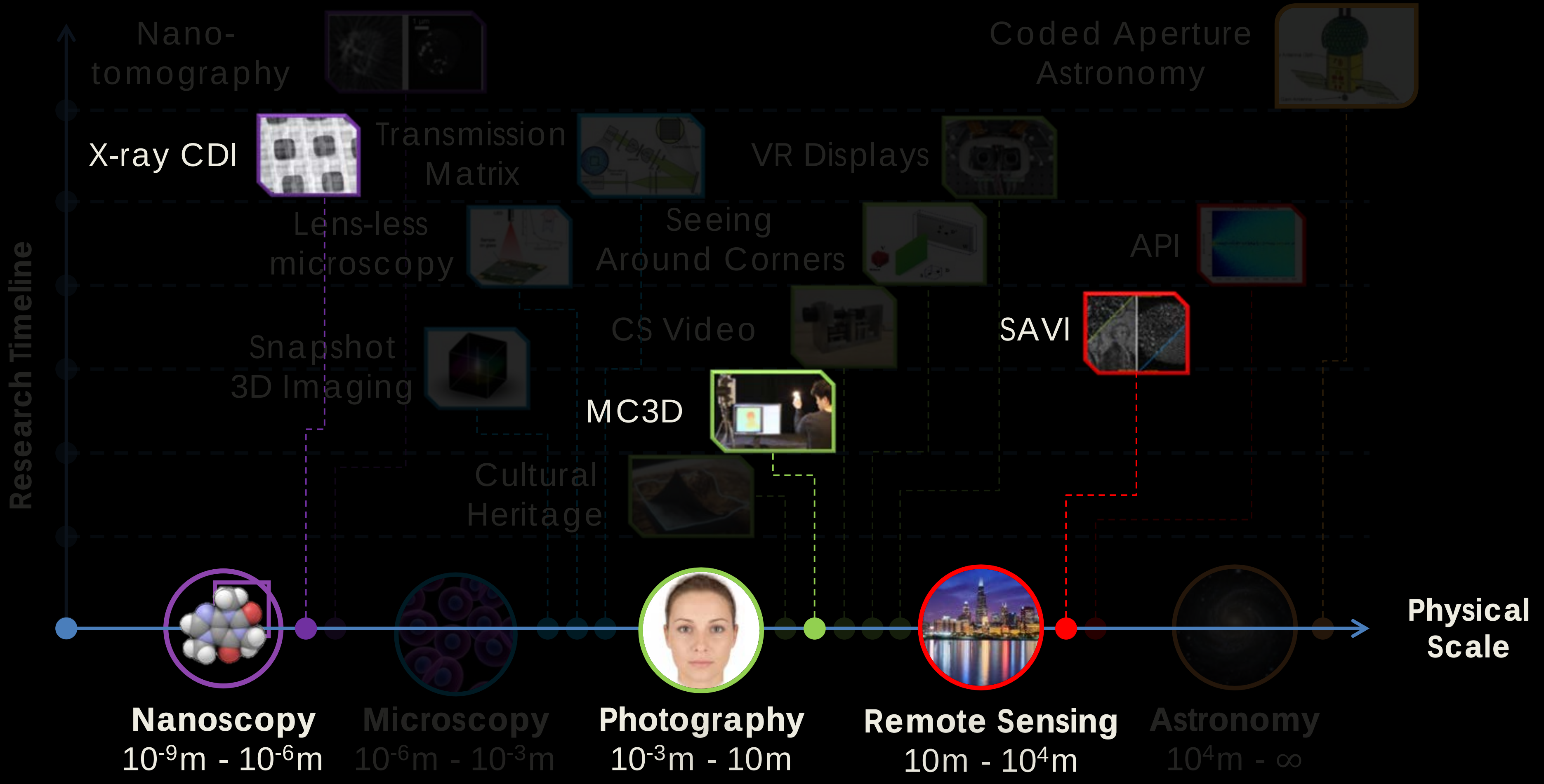


[Mitra et al., PAMI '13]

In this Talk: CI Across Scale



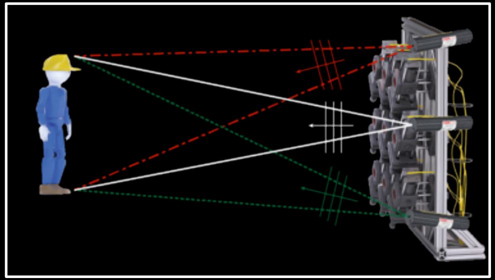
Talk Outline



Talk Outline

X-ray CDI

Synthetic Aperture Visible Imaging (SAVI)

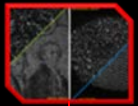


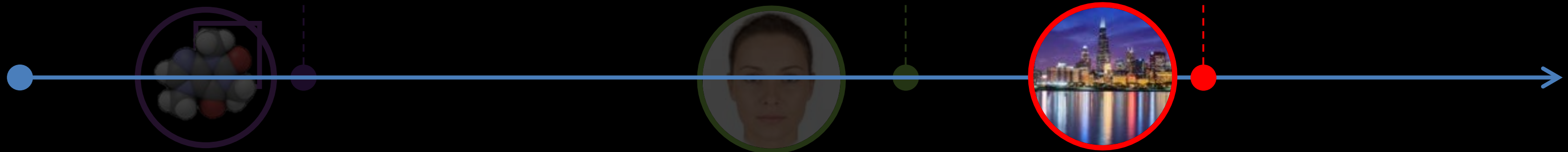
“SAVI: Synthetic apertures for long-range, subdiffraction-limited visible imaging using Fourier ptychography”, Holloway et al. *SCIENCE ADVANCES,* 14 APR 2017.

"Toward Long Distance, Sub-diffraction Imaging Using Coherent Camera Arrays", Holloway et al. IEEE Transactions on Computational Imaging, 2016.

“**PtychNet: CNN-based Fourier Ptychography**”, Kappeller et al. IEEE Conference on Image Processing (ICIP) 2017.

SAVI





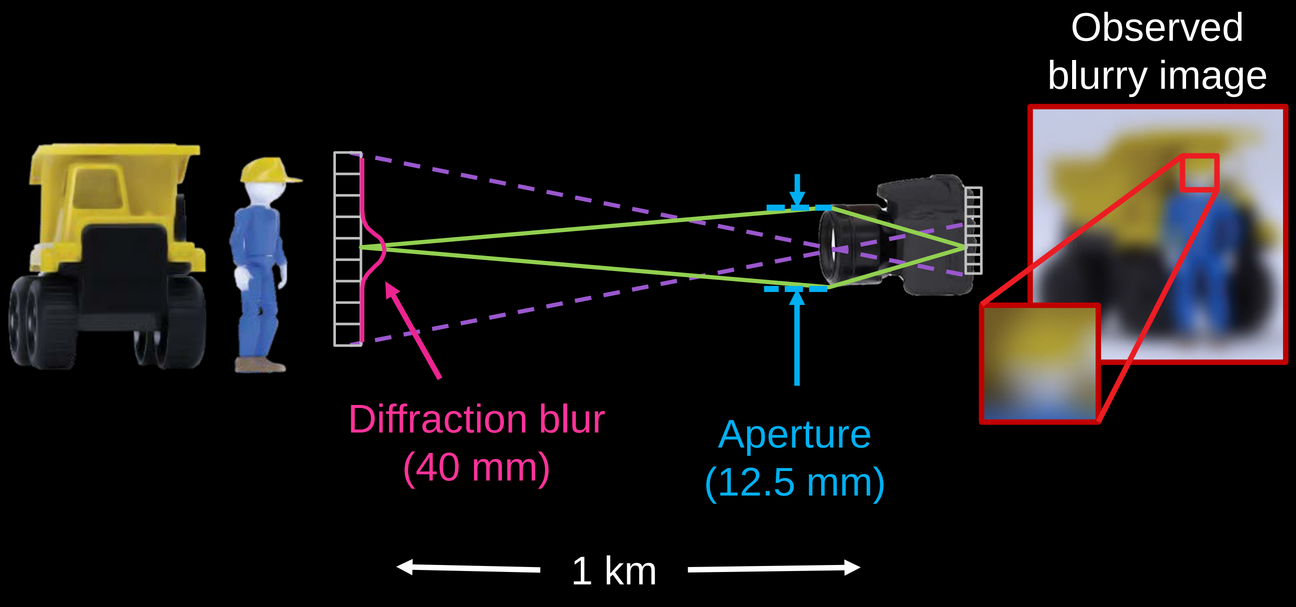
Physical Scale

Nanoscopy
10^{-9}m - 10^{-6}m

Photography
10^{-3}m - 10m

Remote Sensing
10m - 10^{4}m

Goal: Long Distance Imaging

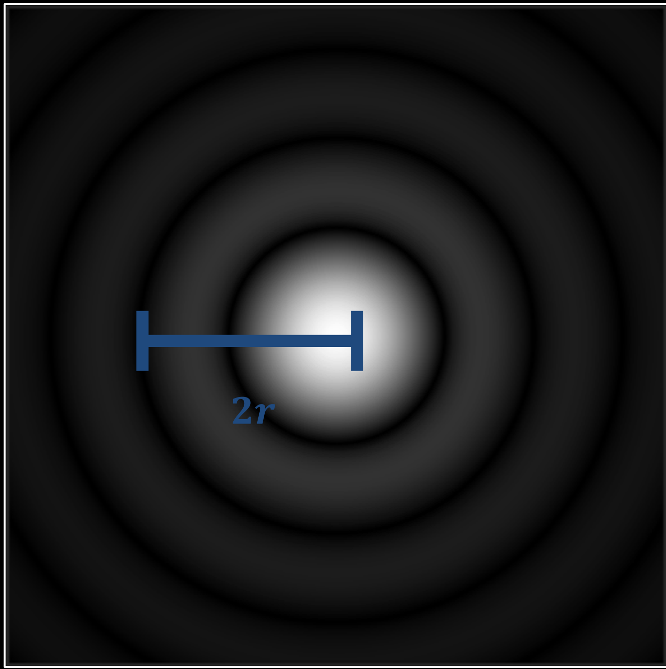


Diffraction Limits Resolution

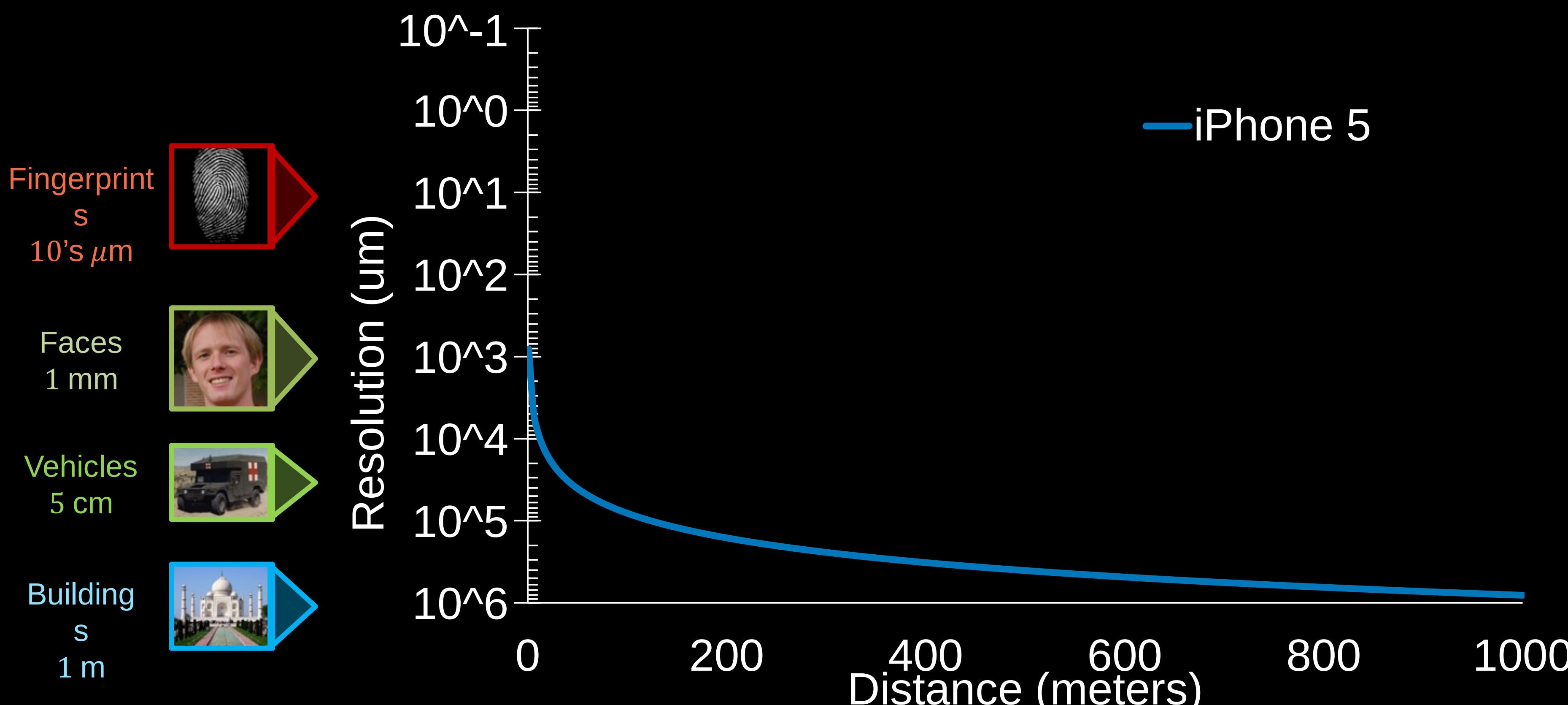
- Light diffracts at the edge of the aperture instead of focusing to a point
- Diffraction is represented by an Airy disk, radius (m)

: wavelength of light (m)
: distance to object (mm)
: aperture diameter (mm)

Simulated Airy pattern



Diffraction Blur For Different Cameras



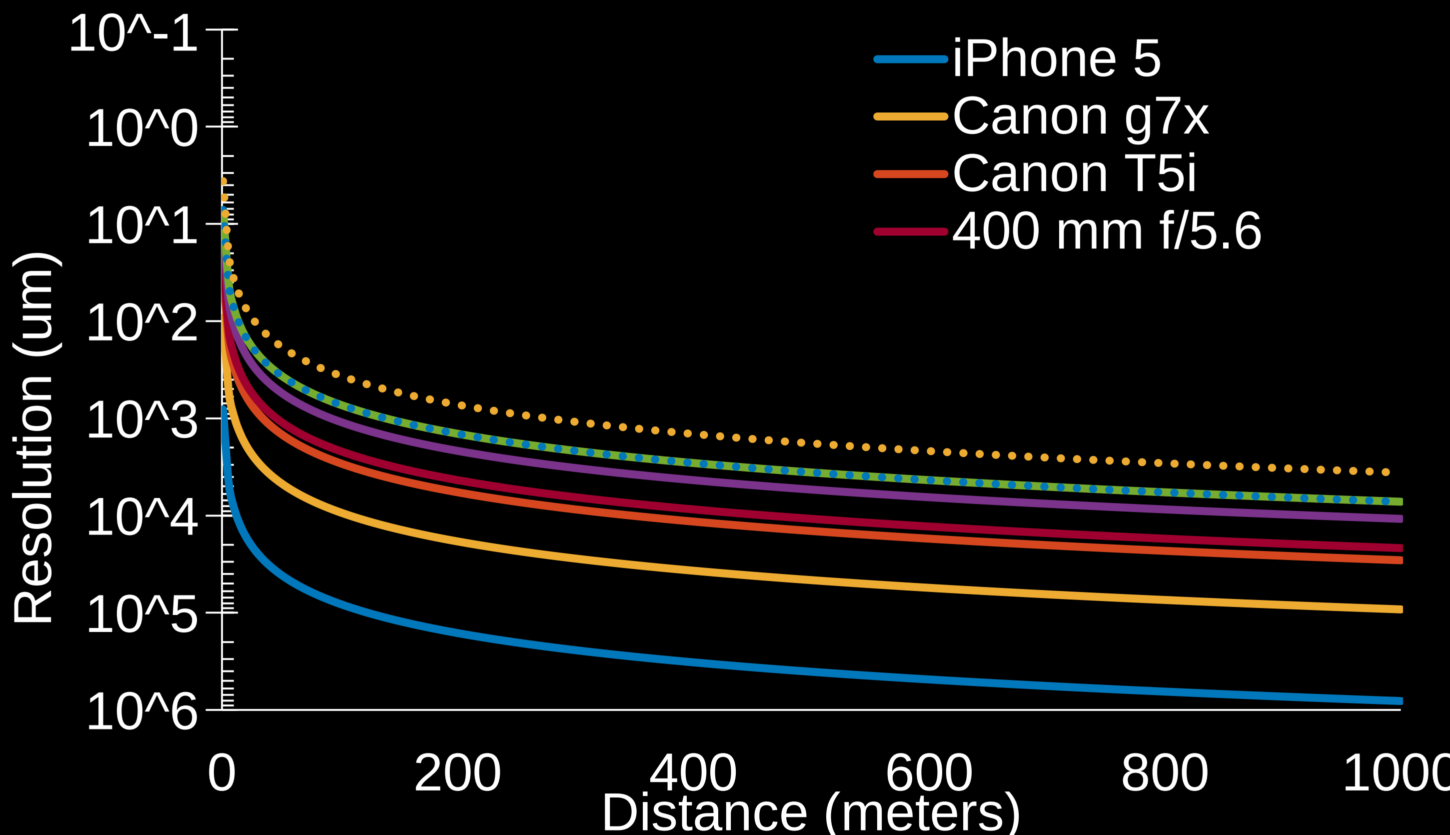
Diffraction Blur For Different Cameras

Fingerprint
s
10's μm

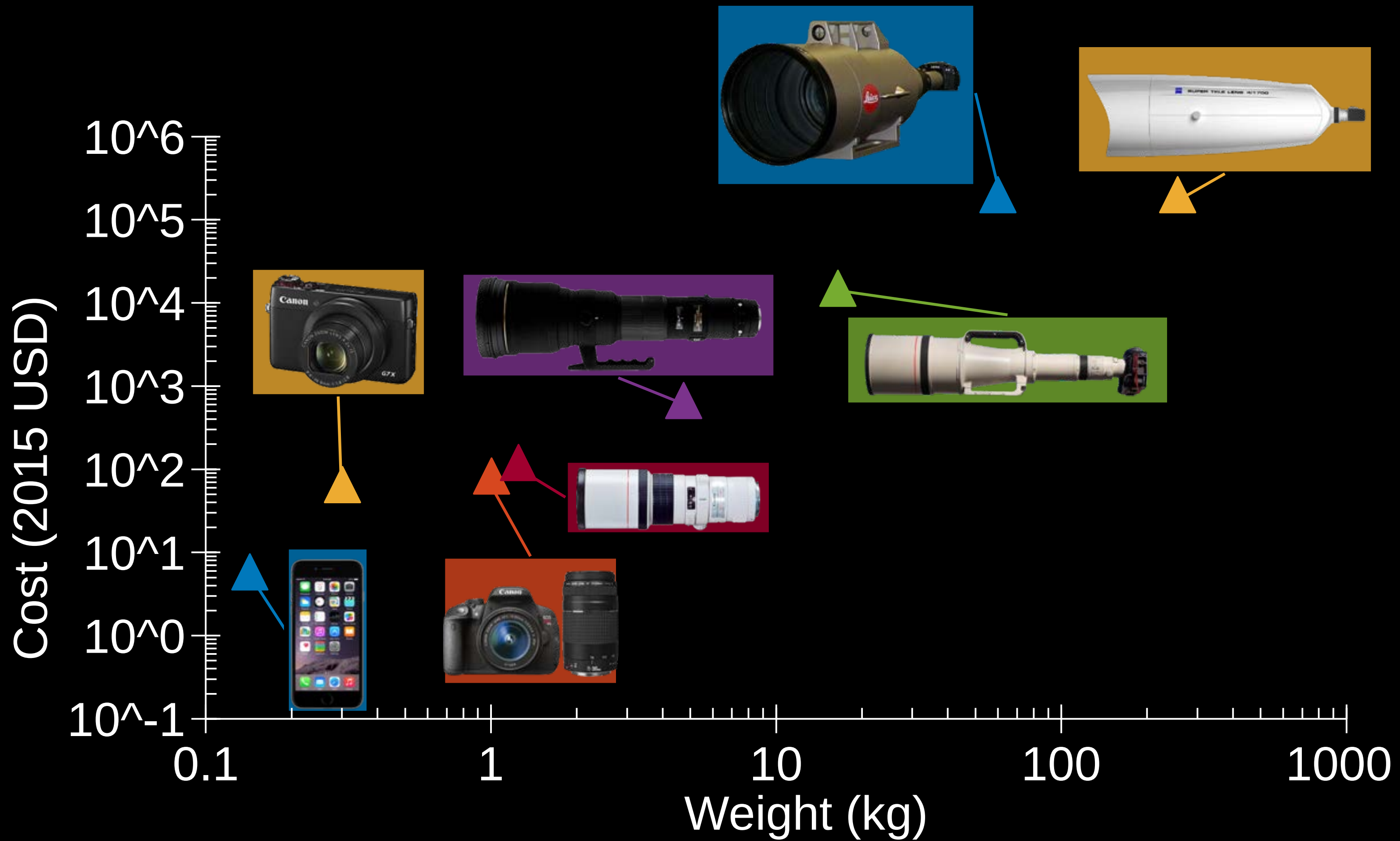
Faces
1 mm

Vehicles
5 cm

Building
s
1 m



Cost Of Using Larger Lenses



Remote Fourier Ptychography Imaging

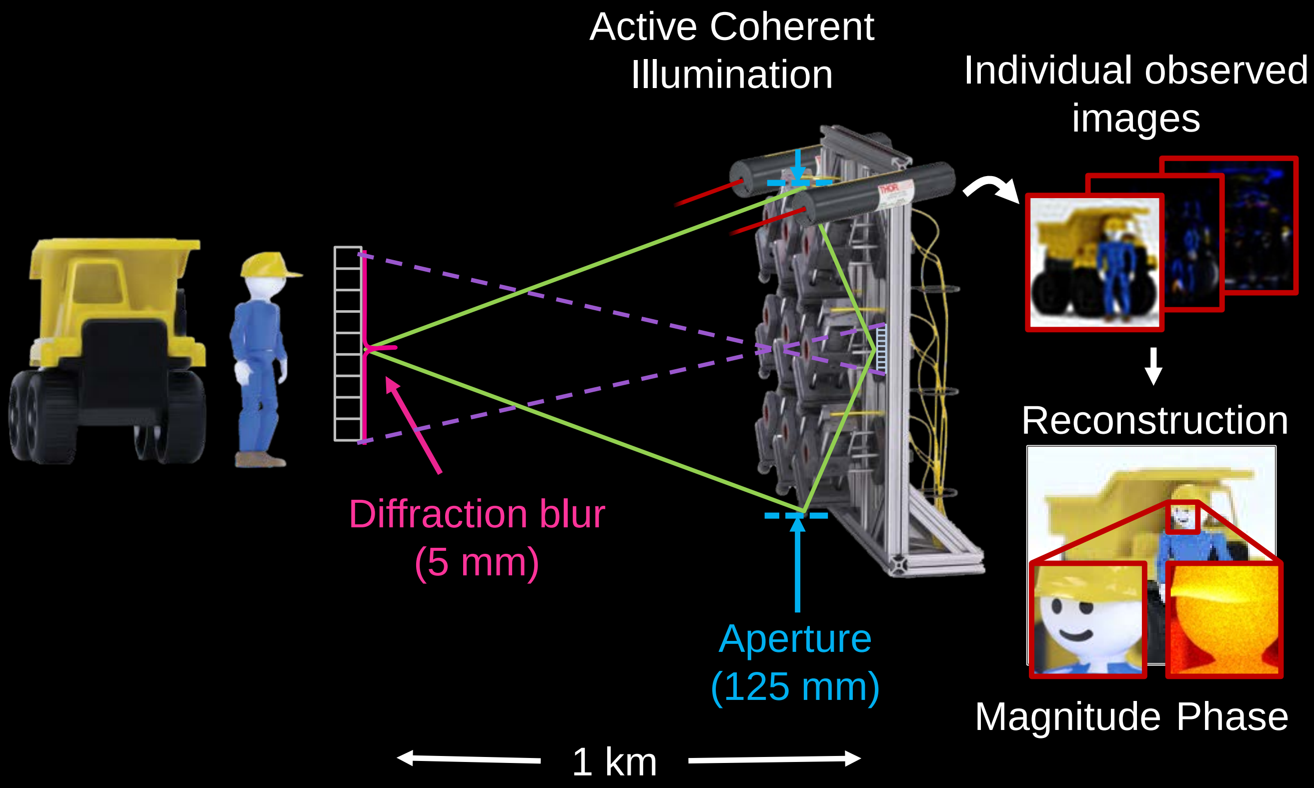
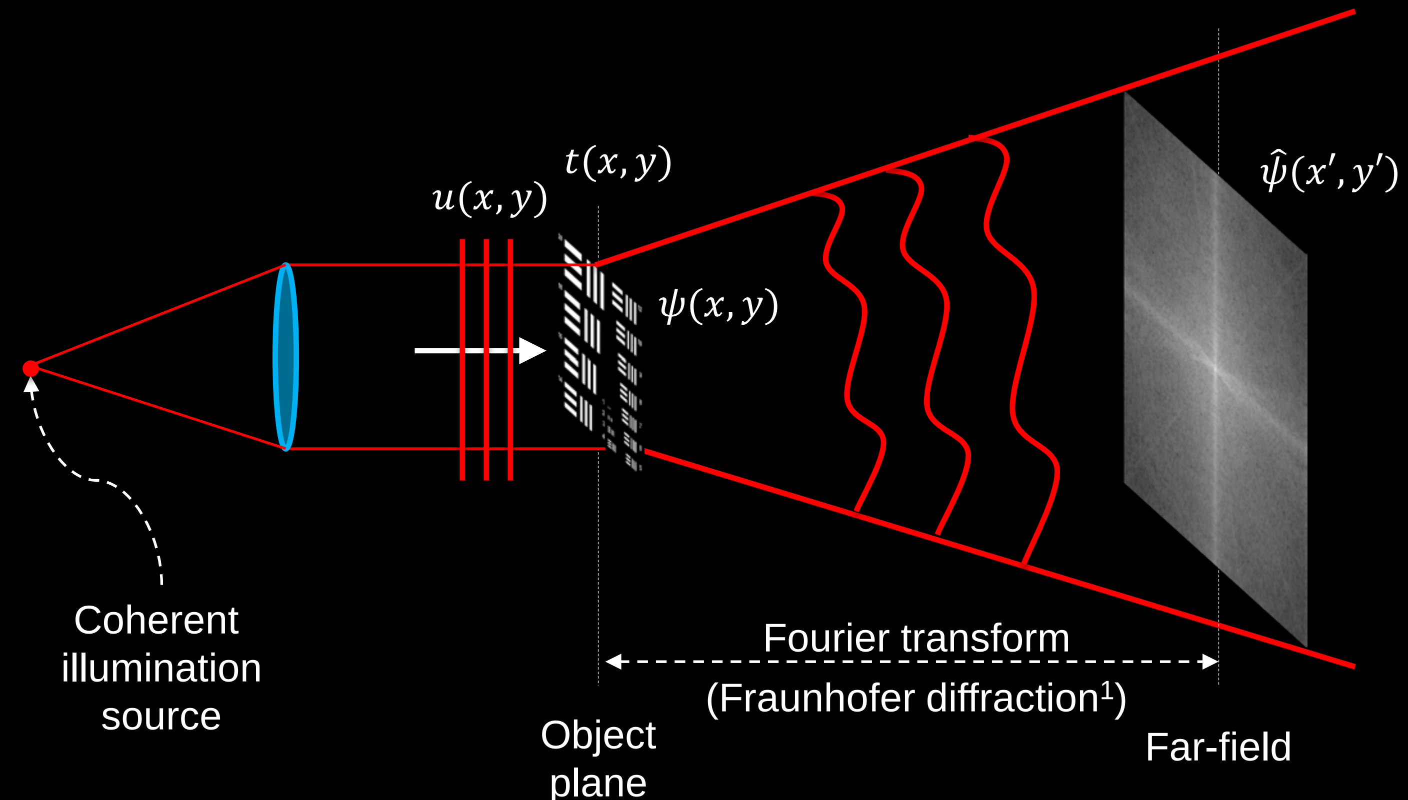


Image Formation Model



[1]Goodman, Joseph W. *Introduction to Fourier optics*. 2005.

Image Formation Model

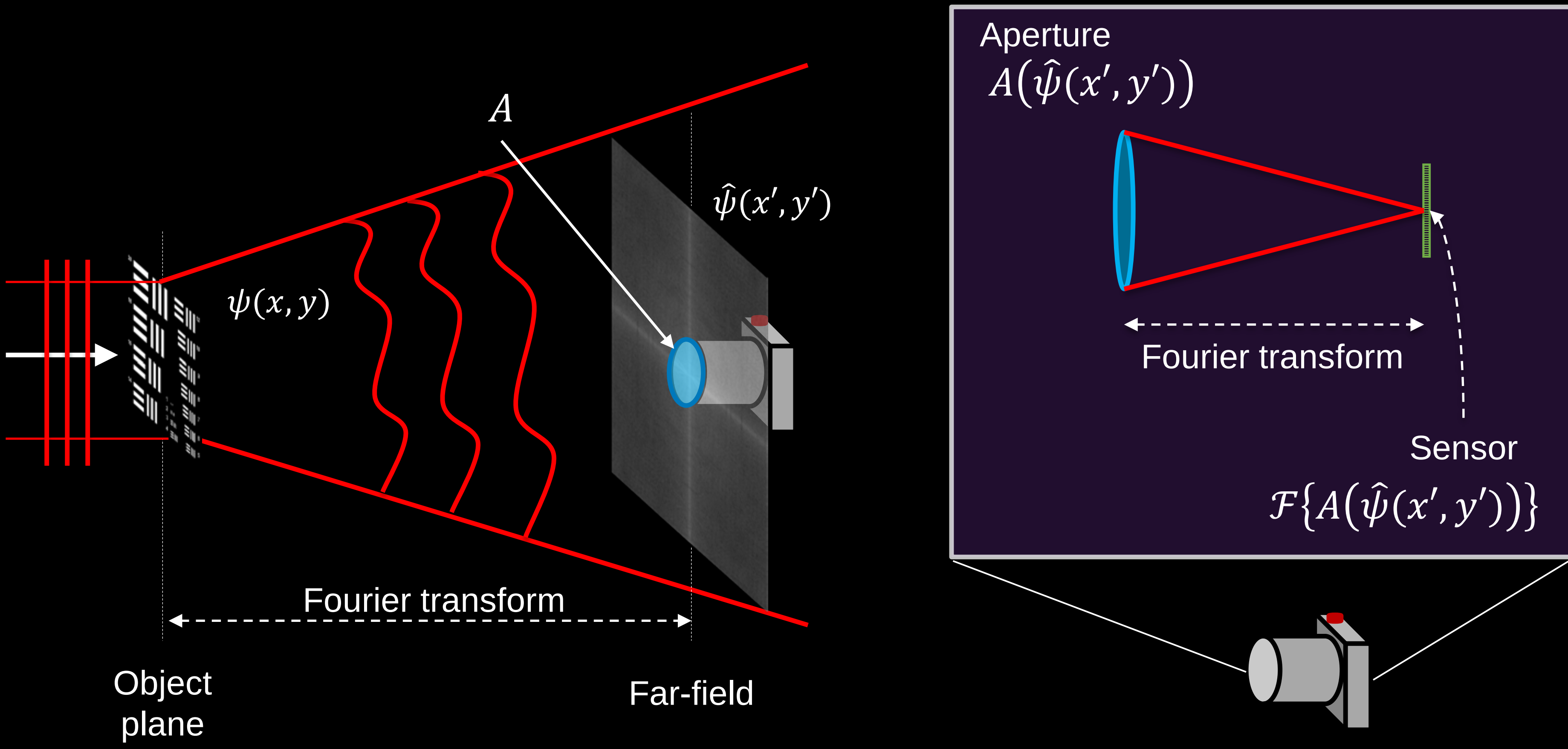


Image Formation Model

- Lens forms the Fourier transform at the sensor plane

$$\mathcal{F}\{A(\hat{\psi}(x',y'))\}$$

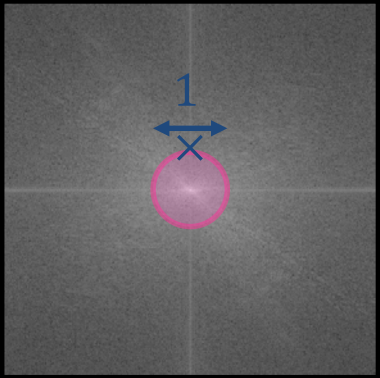
- Sensor captures the squared magnitude

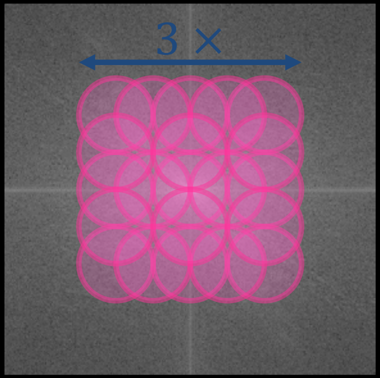
$$I(x',y') \propto \left|\mathcal{F}\{A(\hat{\psi}(x',y'))\}\right|^2$$

Improving Resolution With FP

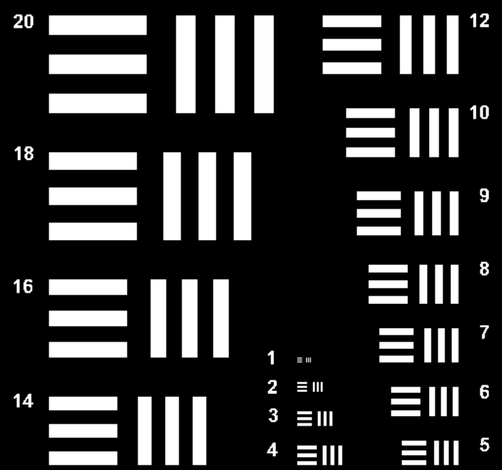
- Individual images are low resolution, combine multiple bandpass regions to improve resolution

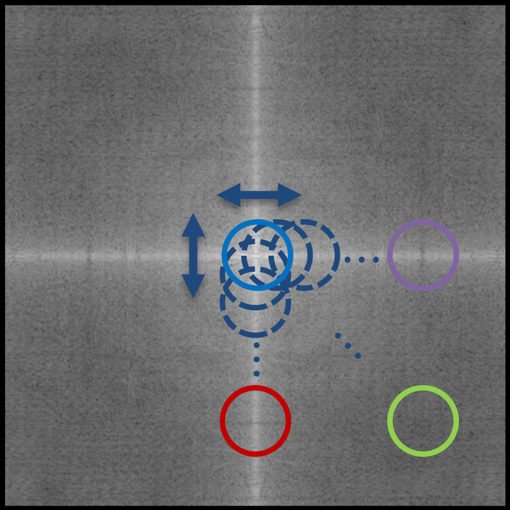
- Move aperture in the Fourier domain to synthetically increase aperture size

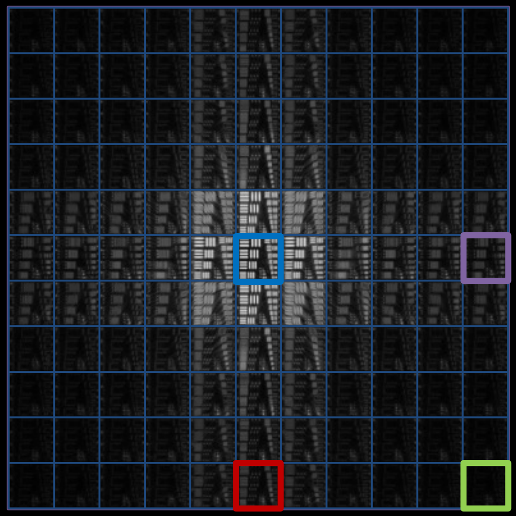




Sampling the Fourier domain







Gerchberg-Saxton Phase Retrieval

– high-resolution Fourier field at the aperture plane
– bandpass operator
– complex field at the camera sensor
– measured image
– index of aperture positions

Goal: Recover

Gerchberg-Saxton Phase Retrieval

Capture images
$I_i = |\phi_i|^2$

Compute complex-field at camera planes
$$\phi_i^{m+1} = \mathcal{F}\{A_i(\hat{\psi}^{m+1})\}$$

Enforce spatial domain magnitudes
$$\phi_i^m = \sqrt{I_i}\angle\phi_i^m$$

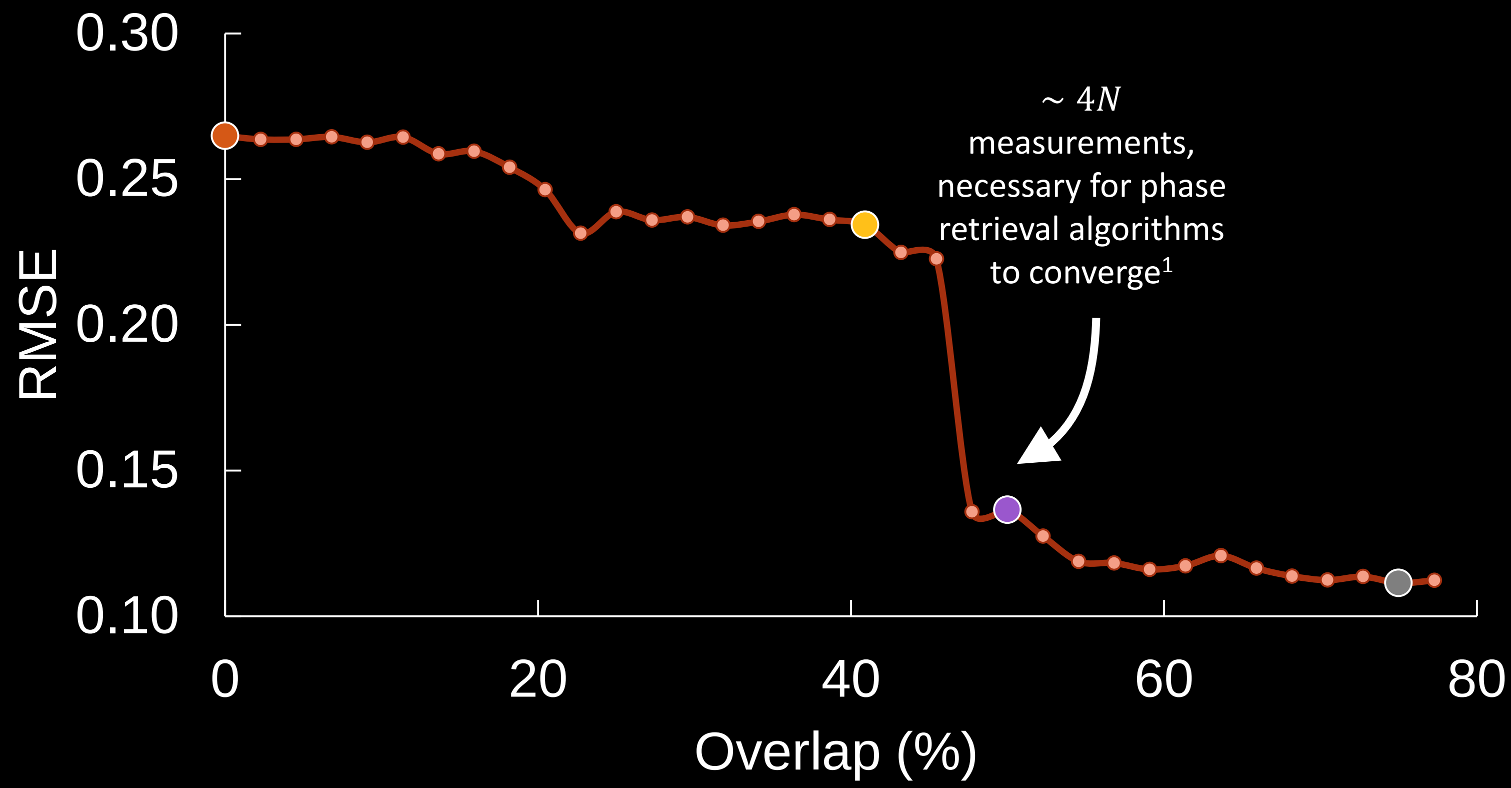
Convert to Fourier domain

Update Fourier estimate and enforce aperture constraint
$$\hat{\psi}^{m+1} \leftarrow \min_{\hat{\psi}} \sum_i \left\| \phi_i^m - \mathcal{F}\{A_i(\hat{\psi}^m)\} \right\|_2 + \tau \left\| \hat{\psi}^m \right\|_2$$

Convert to spatial domain

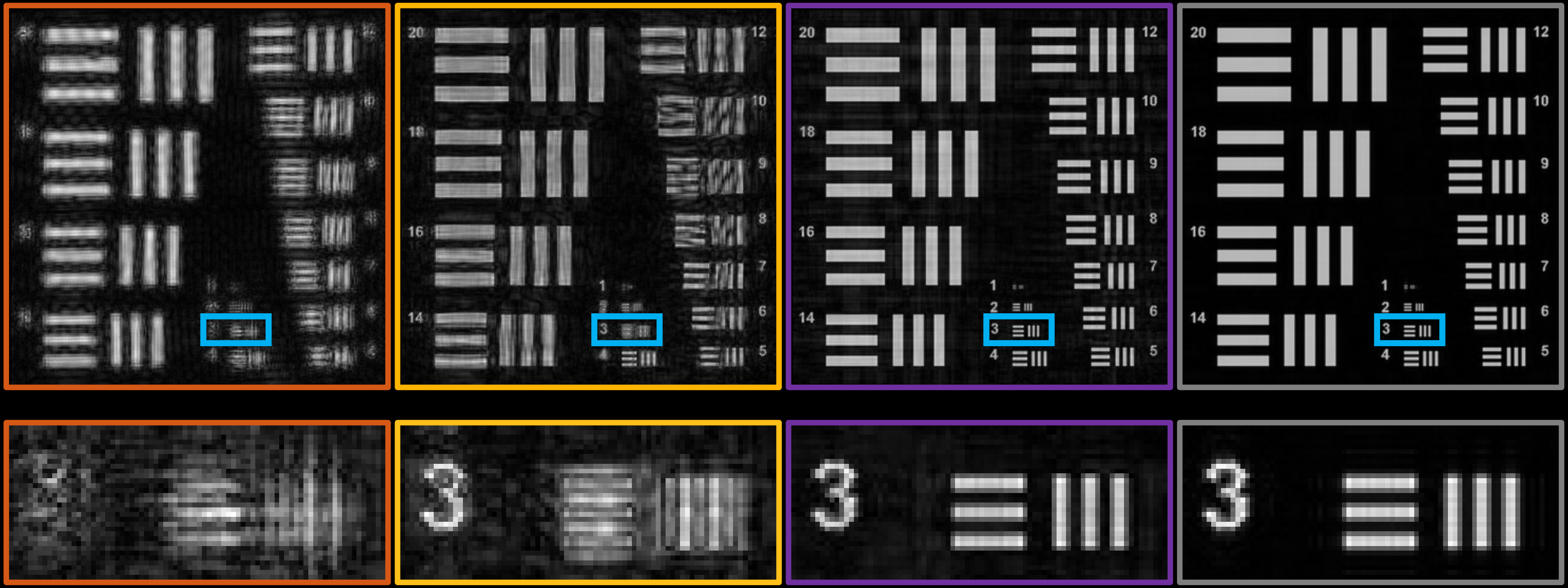
Iterate for $m = 1, \dots, M$ iterations or until convergence

Effect Of Overlap On Reconstruction



[1]Bodmann, Bernhard G., and Nathaniel Hammen. "Stable phase retrieval with low-redundancy frames." *Advances in computational mathematics* 41.2 (2015): 317-331.

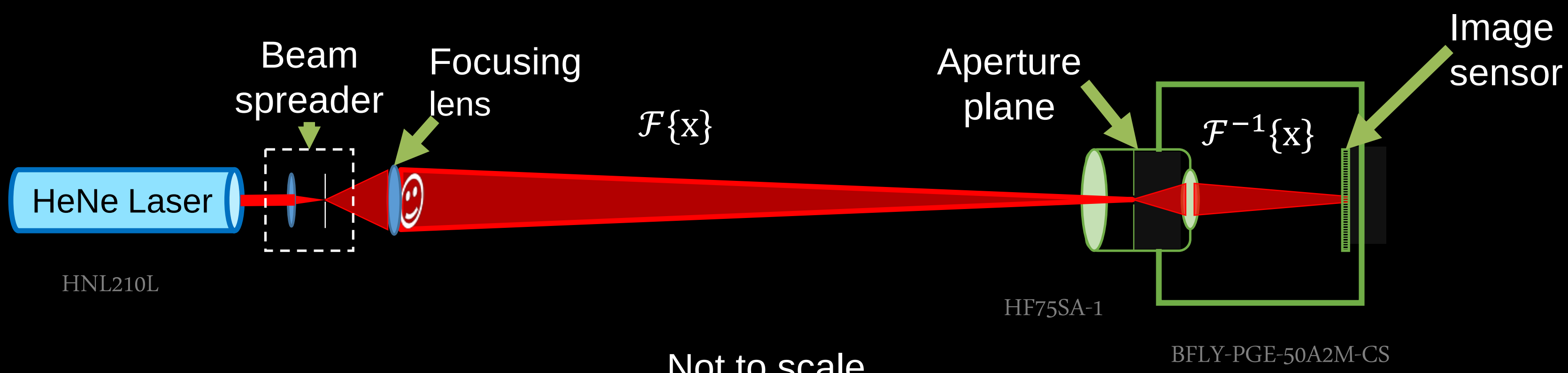
Effect Of Overlap On Reconstruction



0% 41% 50% 75%

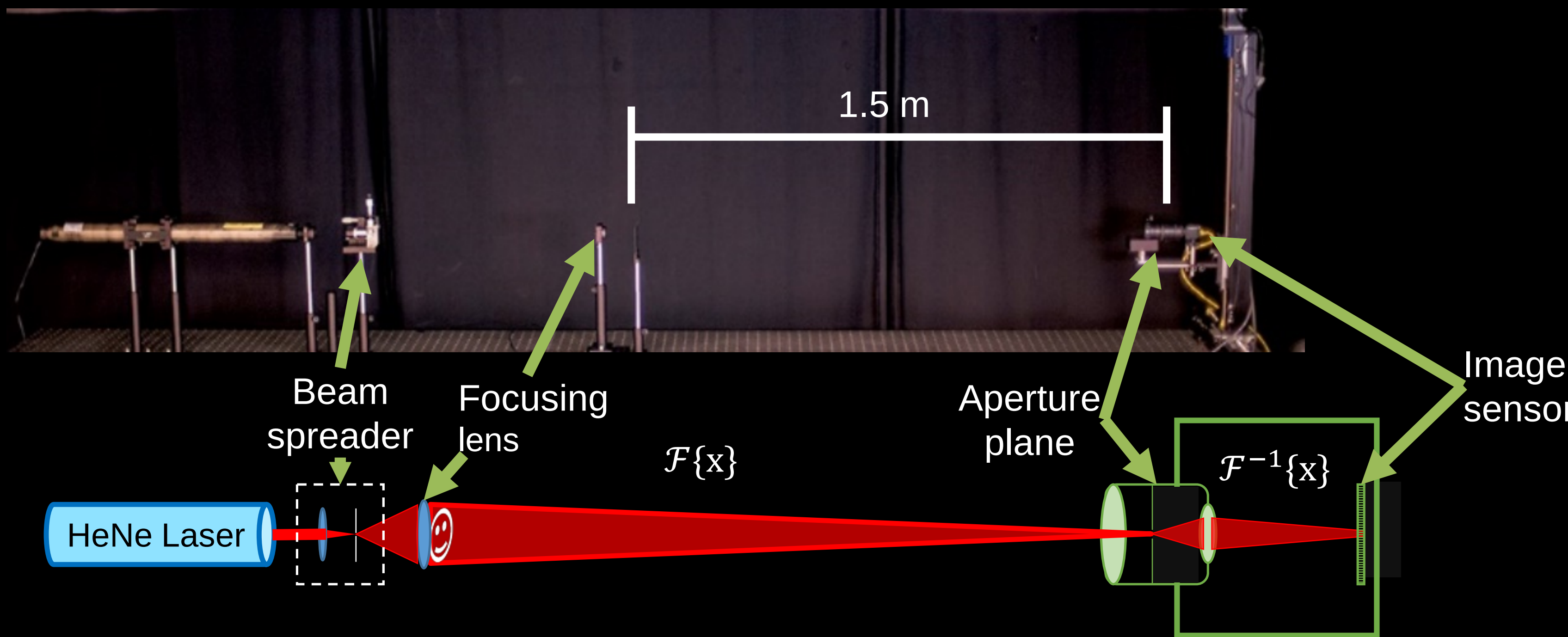
Experimental Setup For Macroscopic FP

- Camera: Blackfly Camera from Point Grey, 2.2 μm pixels
- Fujinon Lens: 75 mm focal length, 2.3 mm aperture ($f/32$)
- Laser: Helium Neon laser from Thorlabs, $\lambda = 633$ nm
- Diffraction: Spot size on sensor = 49 μm ~ 20 pixels



Not to scale

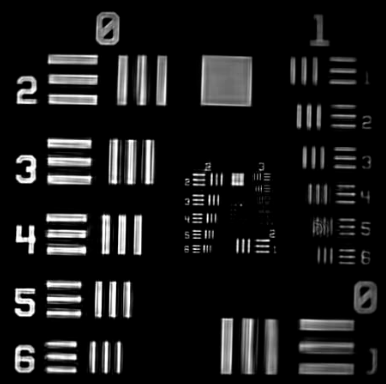
Experimental Setup For Macroscopic FP



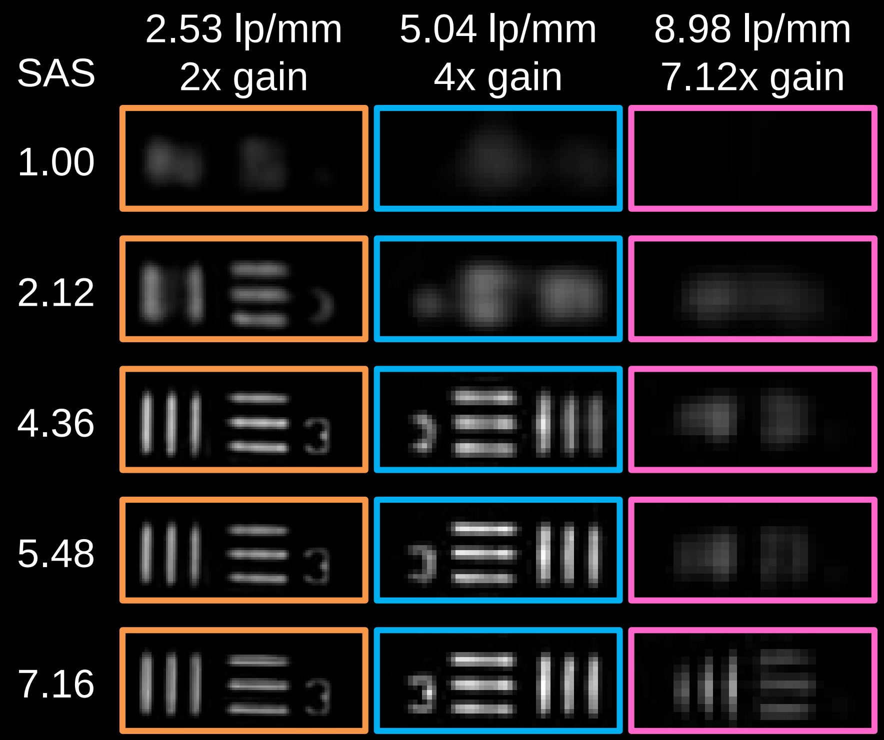
Not to scale

USAF Target

Observed Image
$f/32$

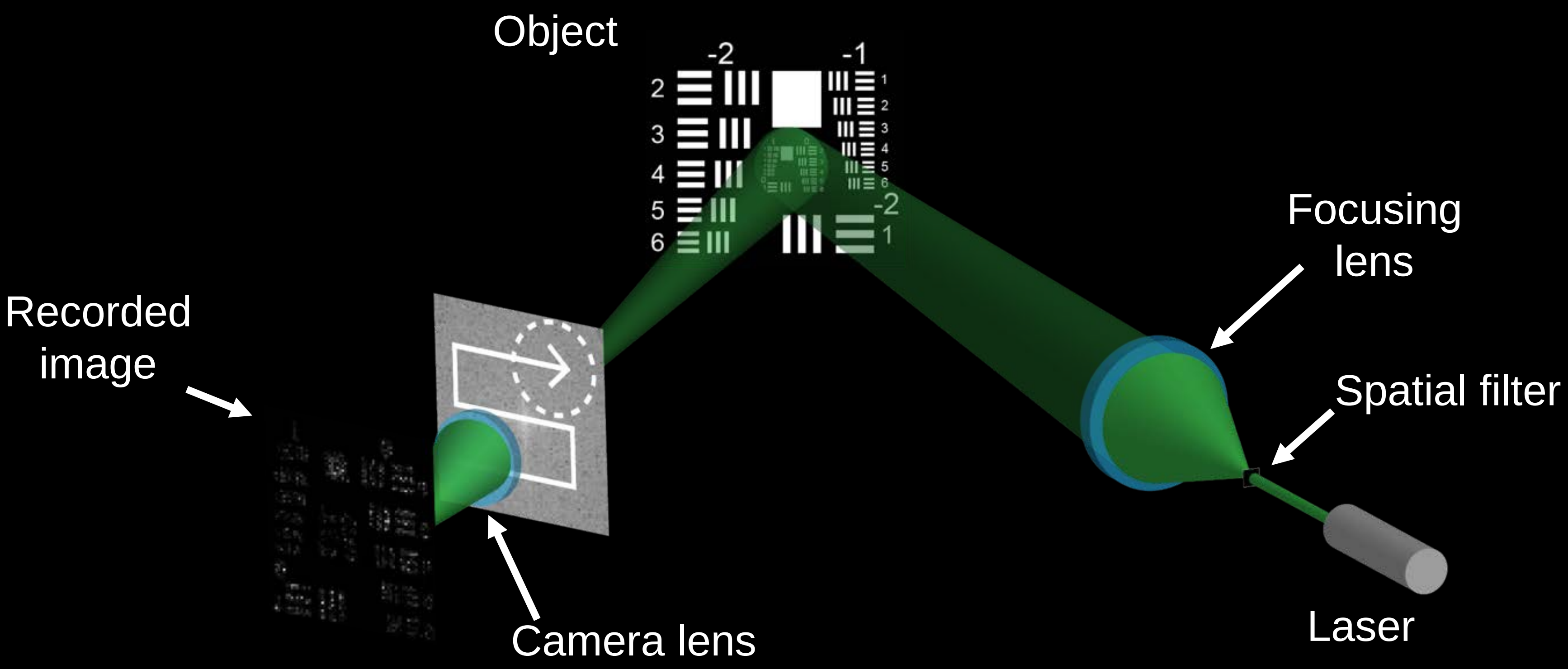


Recovered Image
$f/4.4$

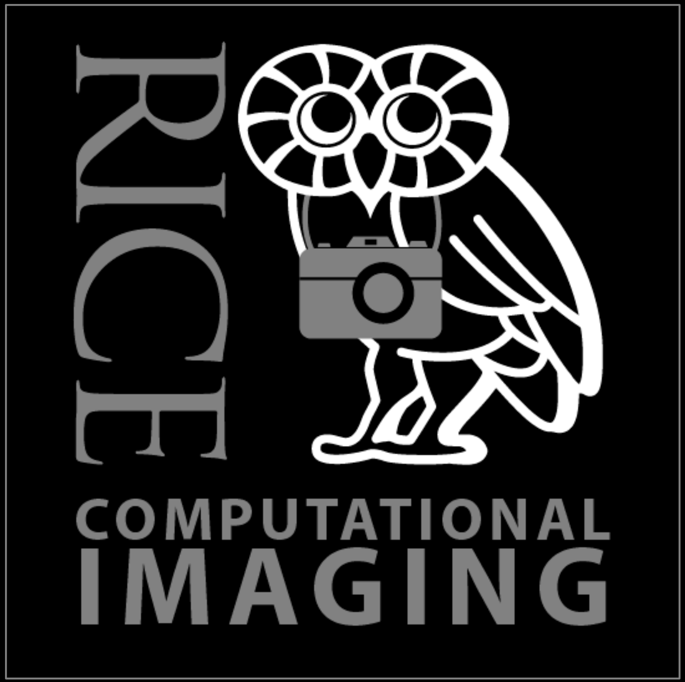


- Overlap: 72%
- Resolution Gain: $1\times - 7.12\times$

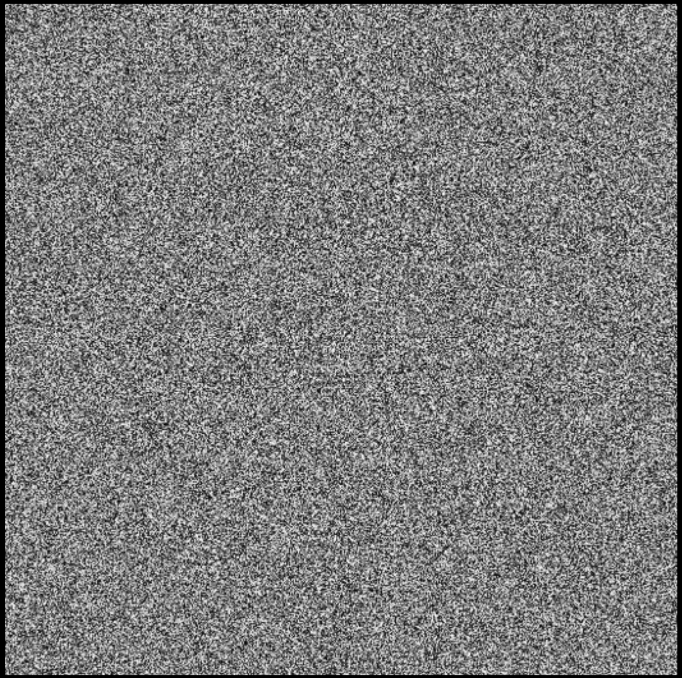
Reflection Mode Imaging Geometry



Rough Surfaces and Random Phase

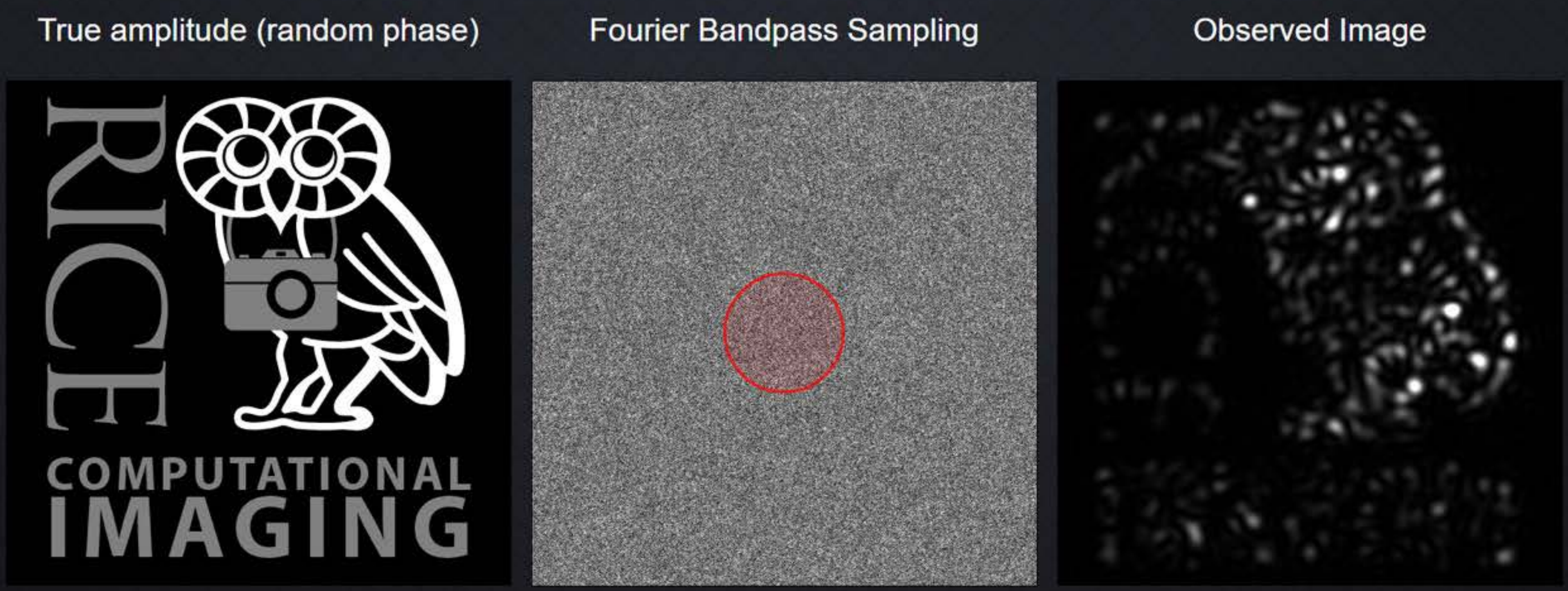


Amplitude

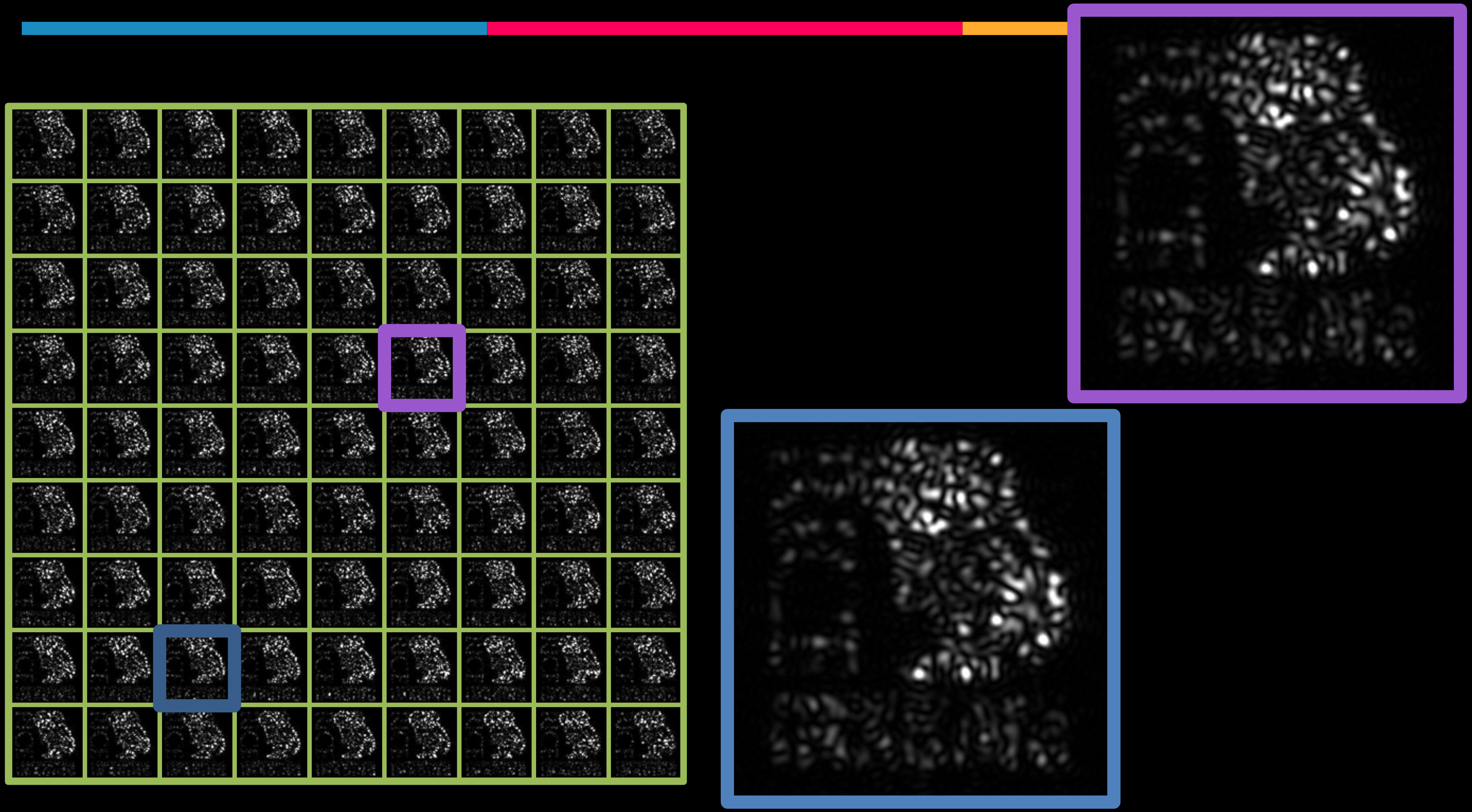


Phase

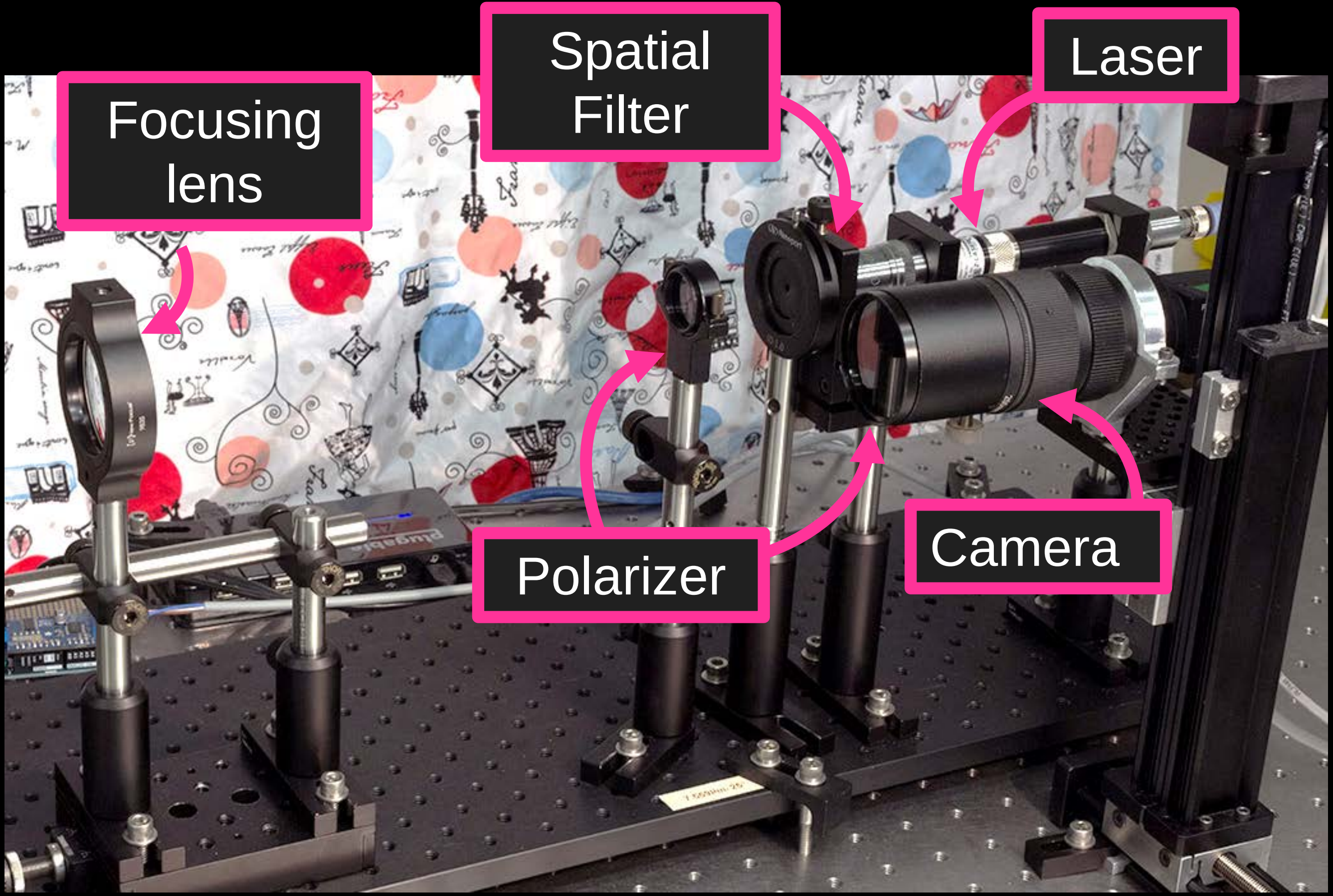
Rough Surfaces and Random Phase



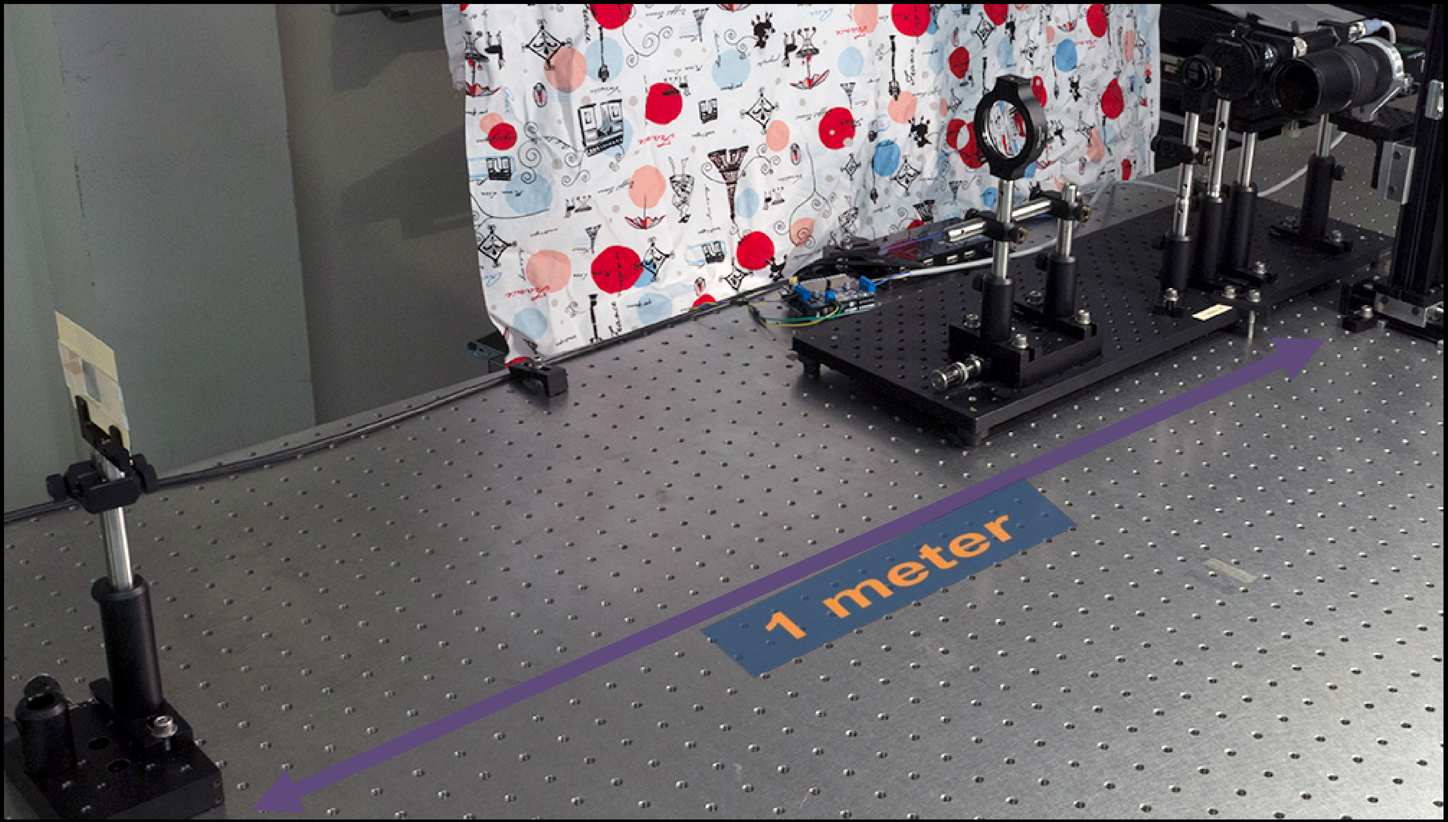
Captured Images for a Diffuse Object



Experimental Setup

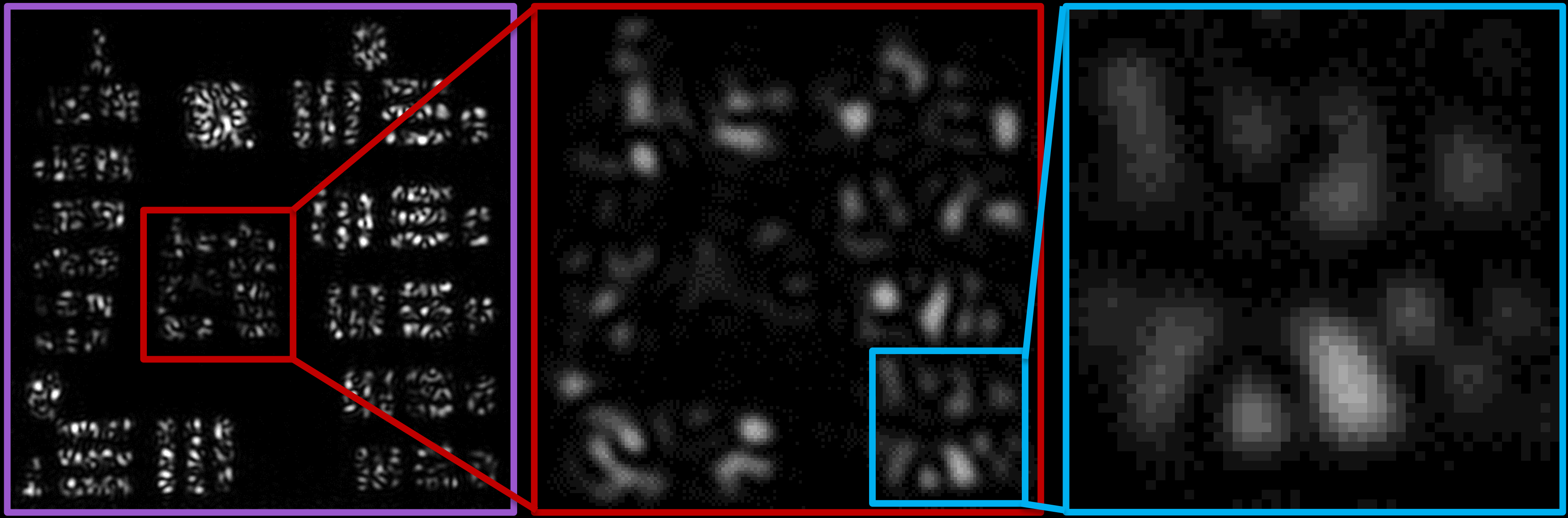


Experimental Setup



Diffuse USAF Resolution Target

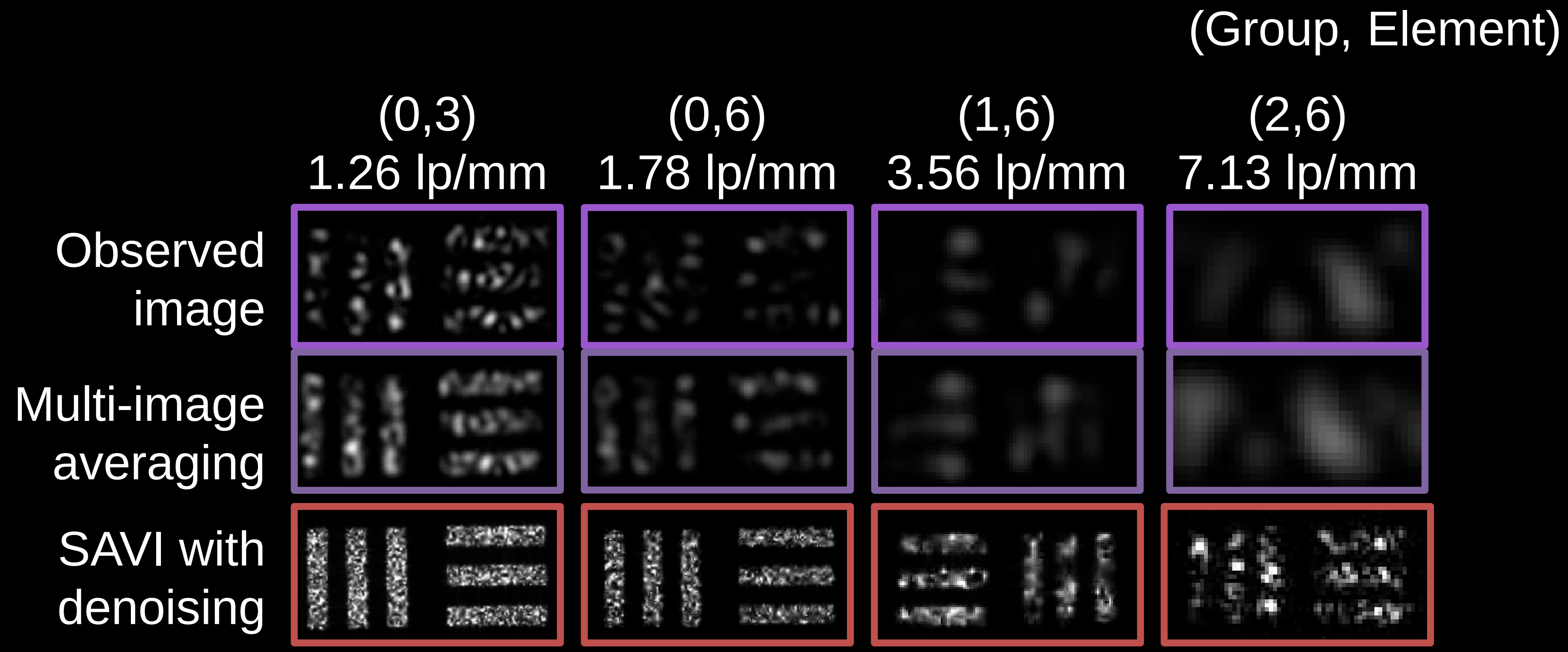
Example captured image



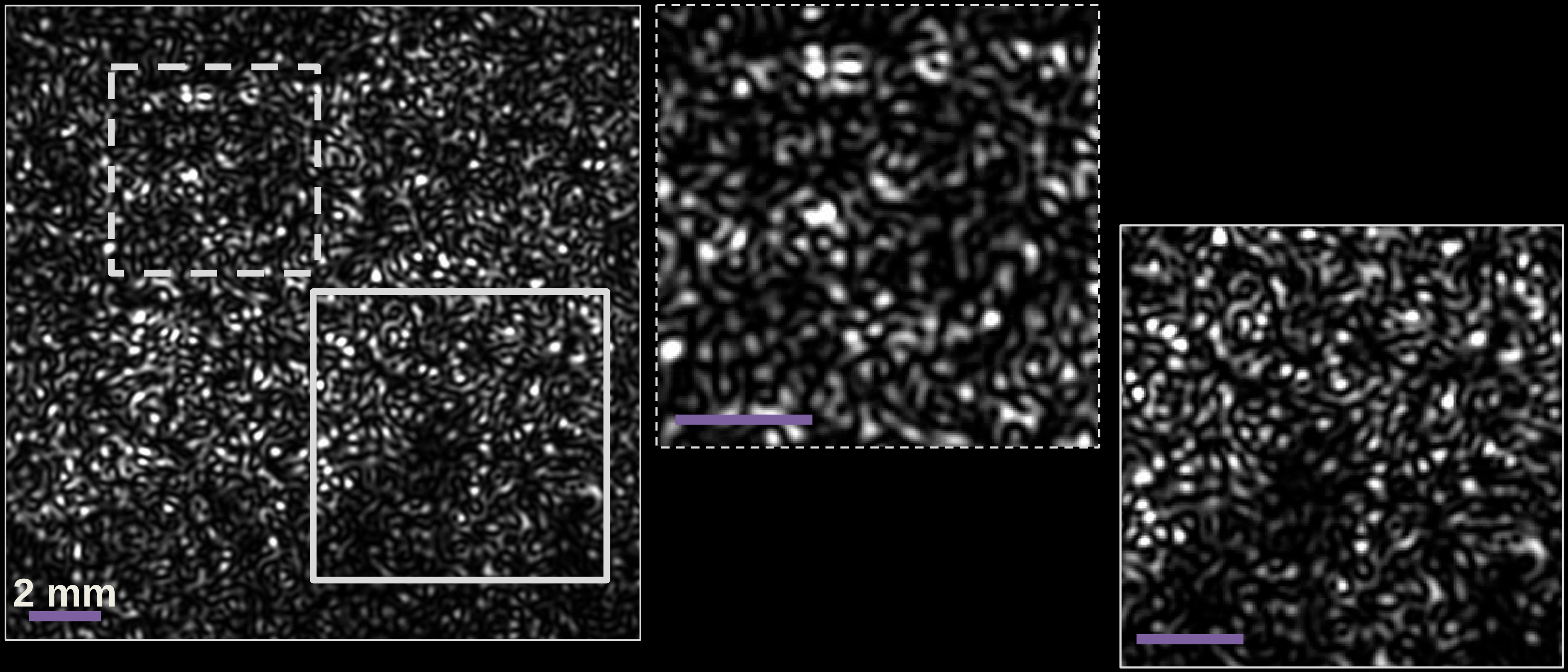
Diffuse USAF Resolution Target

SAVI reconstruction

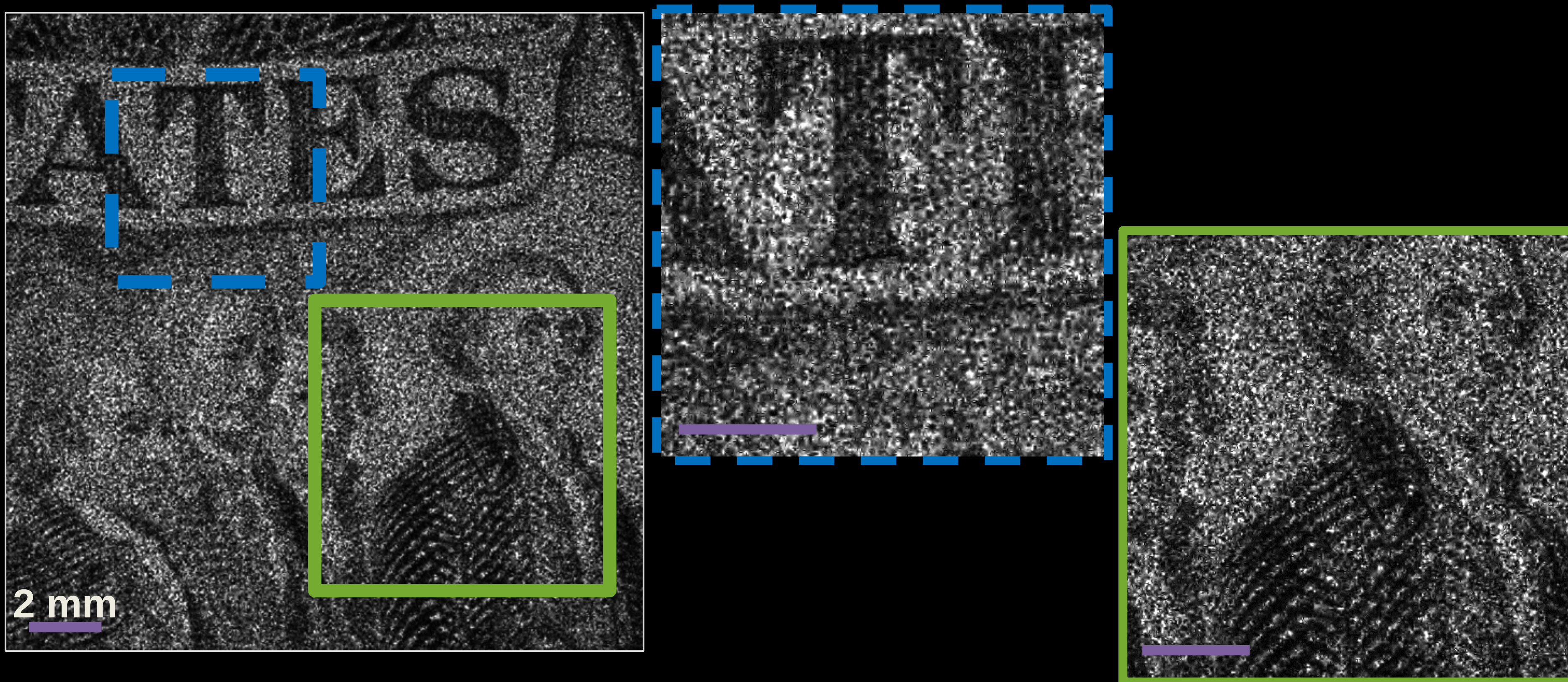
Resolution Improvement with SAVI



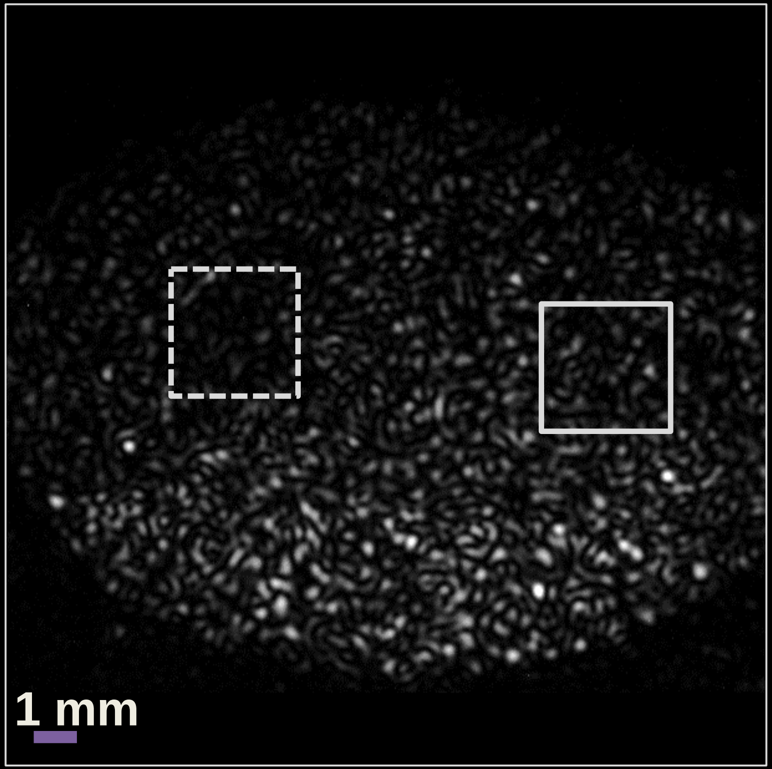
Diffuse Everyday Objects – Mystery Object #1

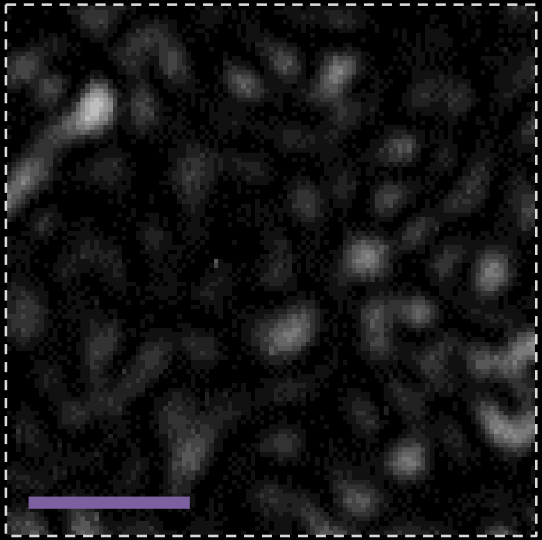


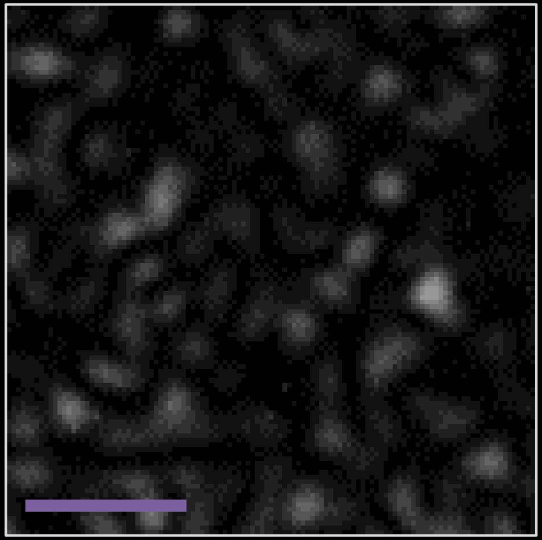
Diffuse Everyday Objects – Mystery Object #1



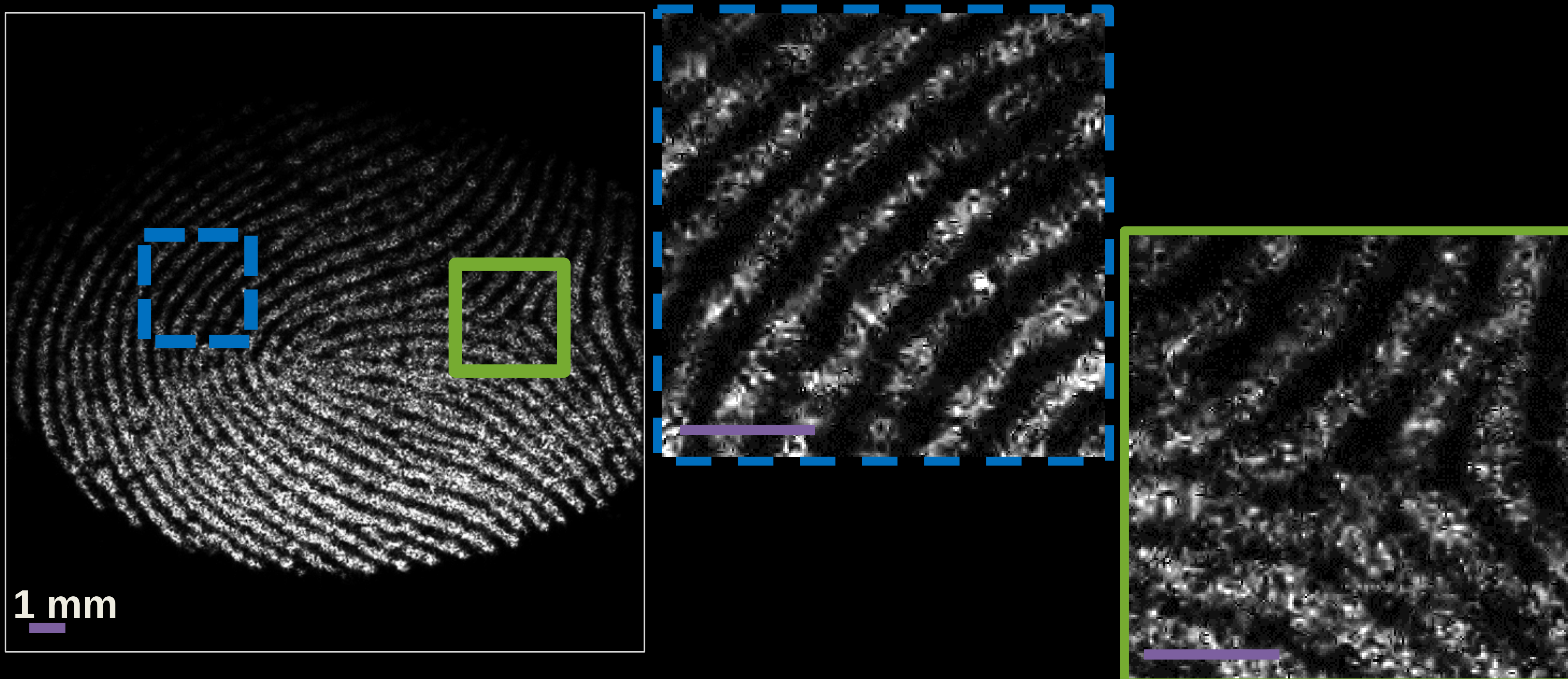
Diffuse Everyday Objects – Mystery Object #2





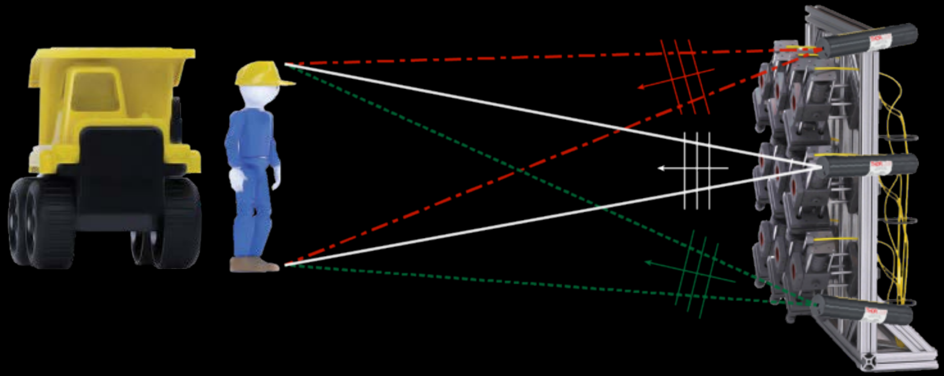


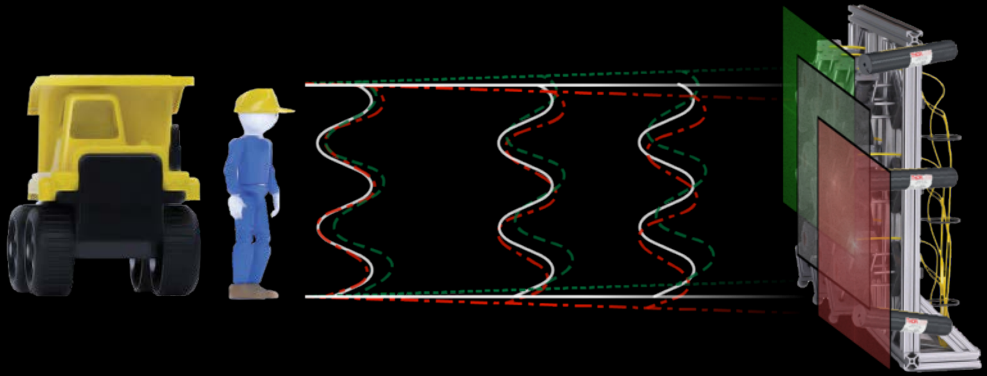
Diffuse Everyday Objects – Mystery Object #2



Future Work

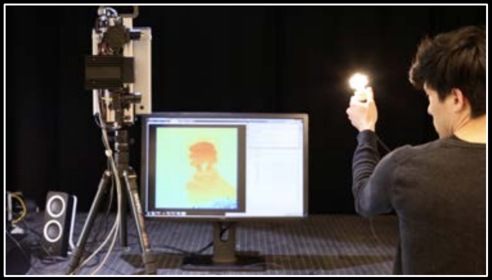
- Capturing long distance FP data in a snapshot
- Camera array to simultaneously acquire images
- Multiplexed lasers to fill in gaps in Fourier domain





Talk Outline

Motion Contrast 3D Scanning (MC3D)

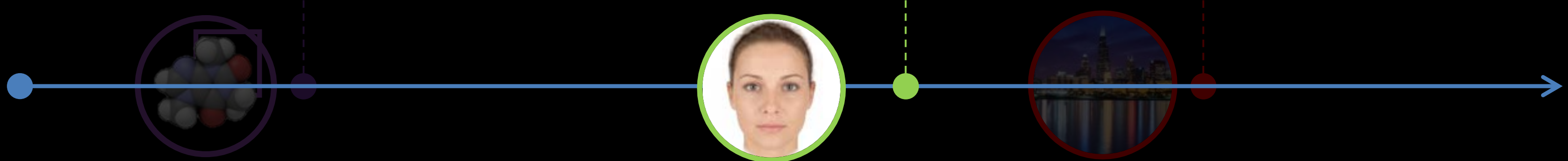


X-ray CDI

"MC3D: Motion Contrast 3D Scanning", Matsuda et al., IEEE Conference on Computational Photography (ICCP), 2016.

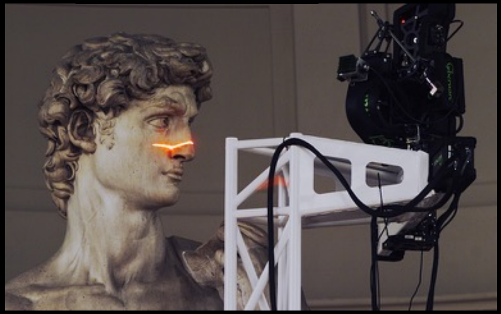
"**Fluorescence lifetime estimation using a dynamic vision sensor**." I et al., Proc. SPIE, Computational Imaging II, 2017.

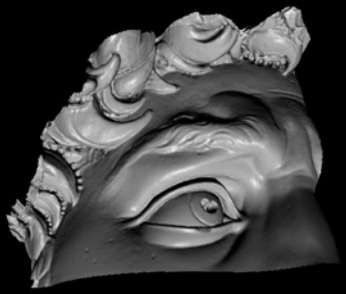
SAVI



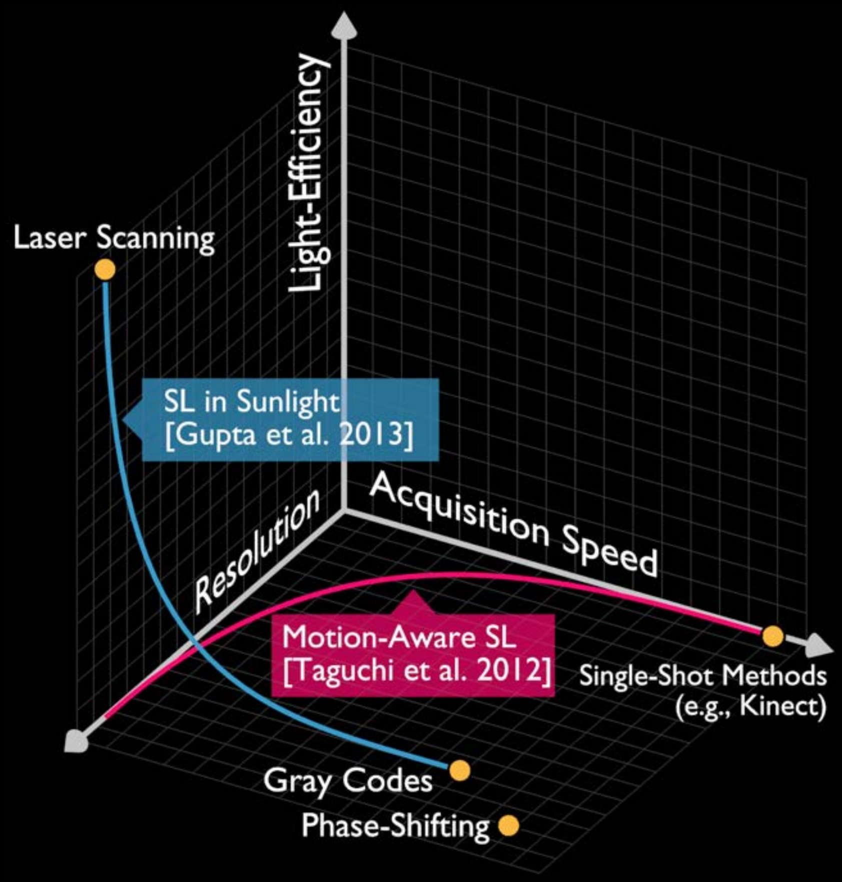
Different Methods for 3D capture

- Passive – stereo, DFF/DFD
- Active – Scanning, Structured Light (SL), ToF

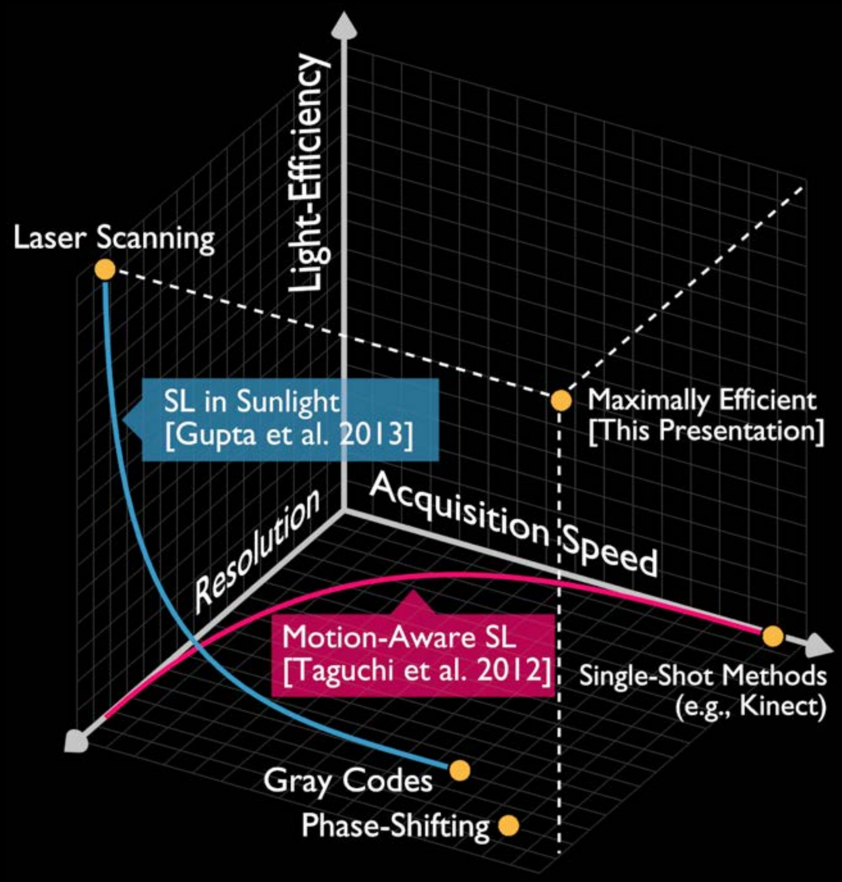




Tradeoffs in SL

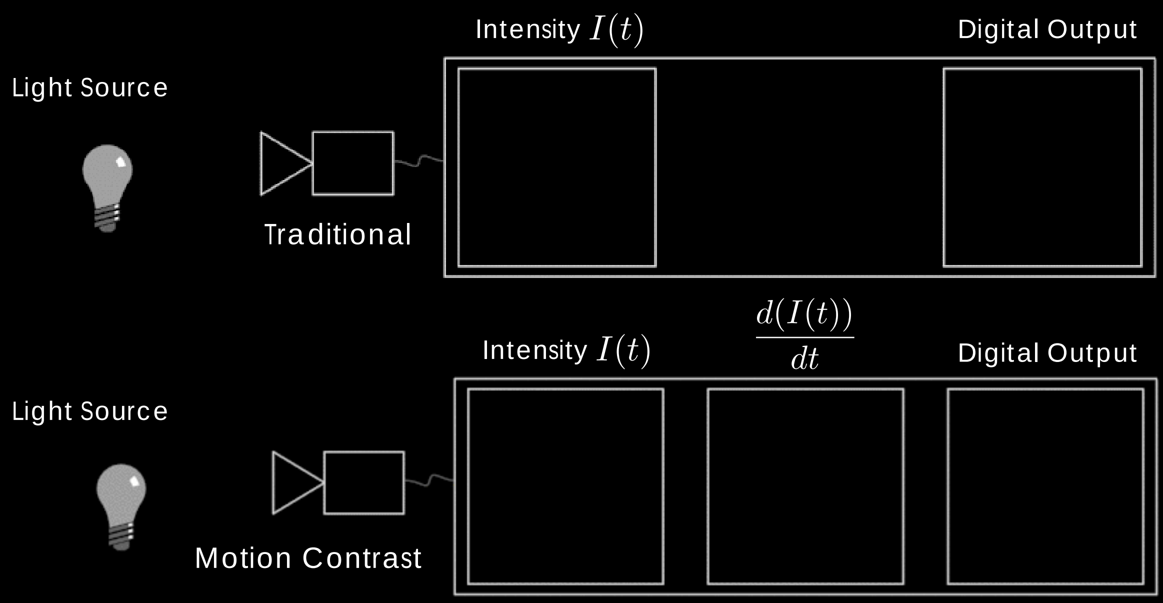


Optimal SL System



Motion Contrast Principle

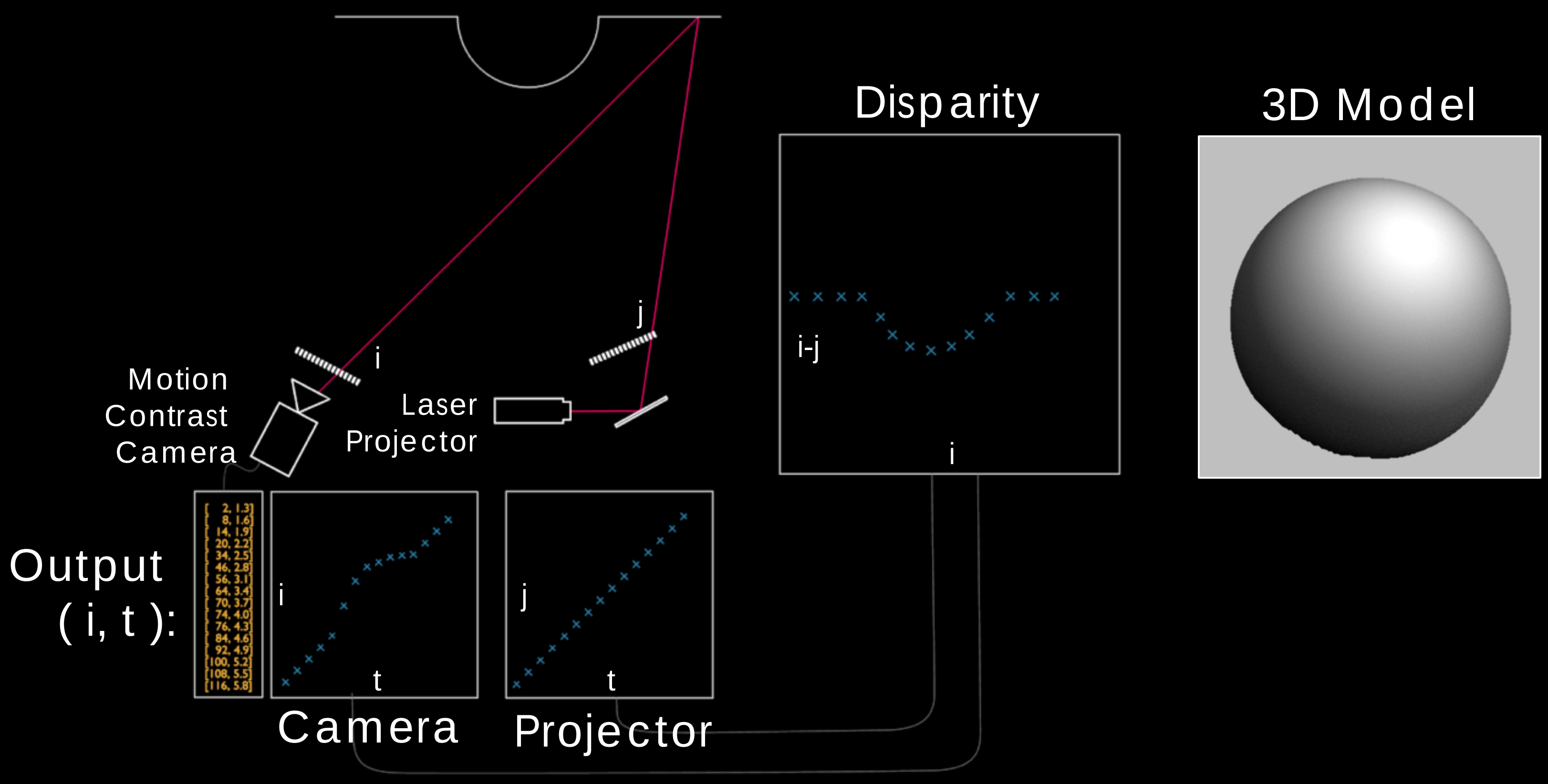
- Traditional photo sensor continually outputs values
- Motion contrast sensor measures temporal changes



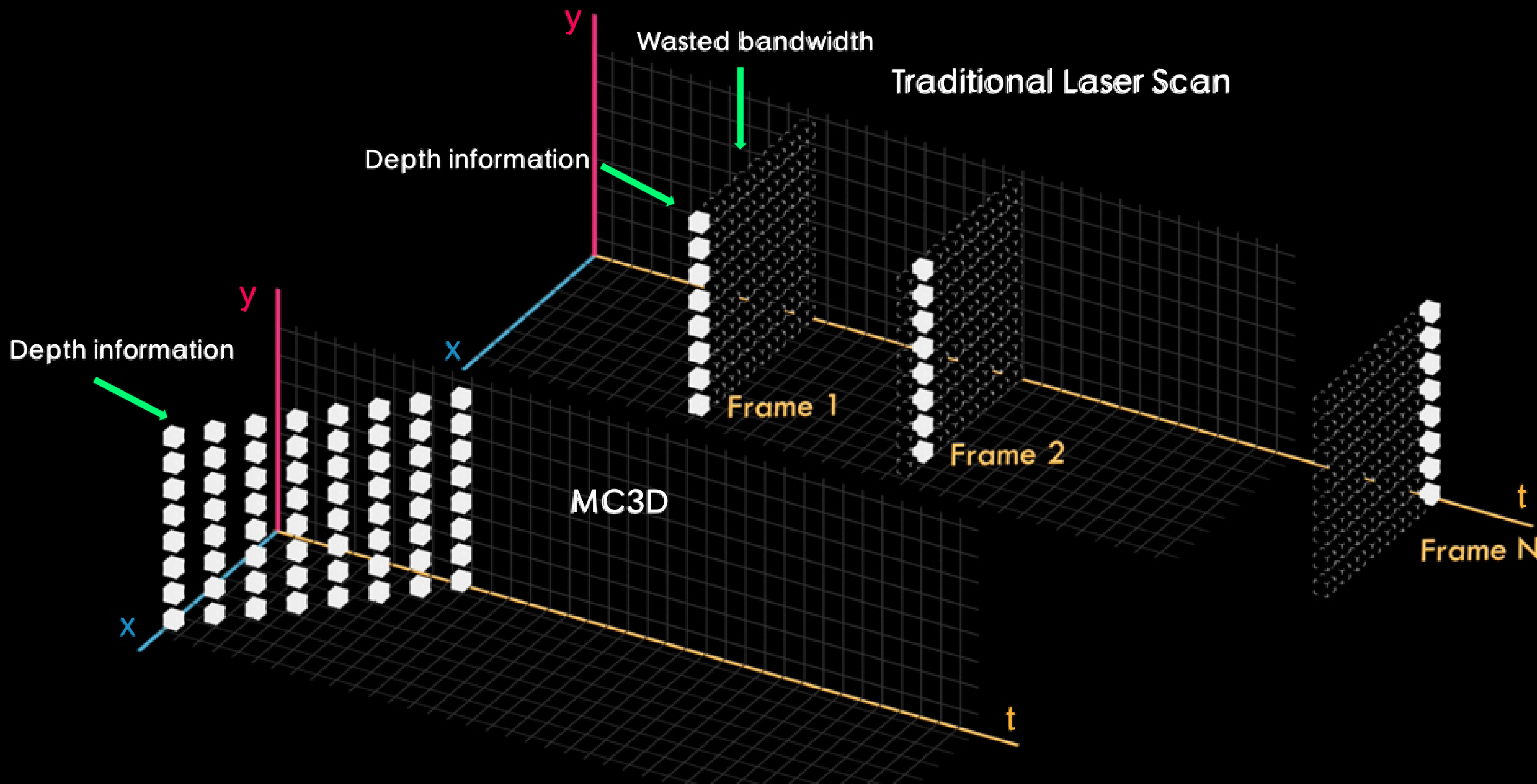
Motion Contrast Capture

- Same bandwidth for Video and motion contrast
- Video frames are dense, temporal resolution is low
- Motion contrast stream is sparse in space and time

MC3D Principle



MC3D Advantage: Bandwidth

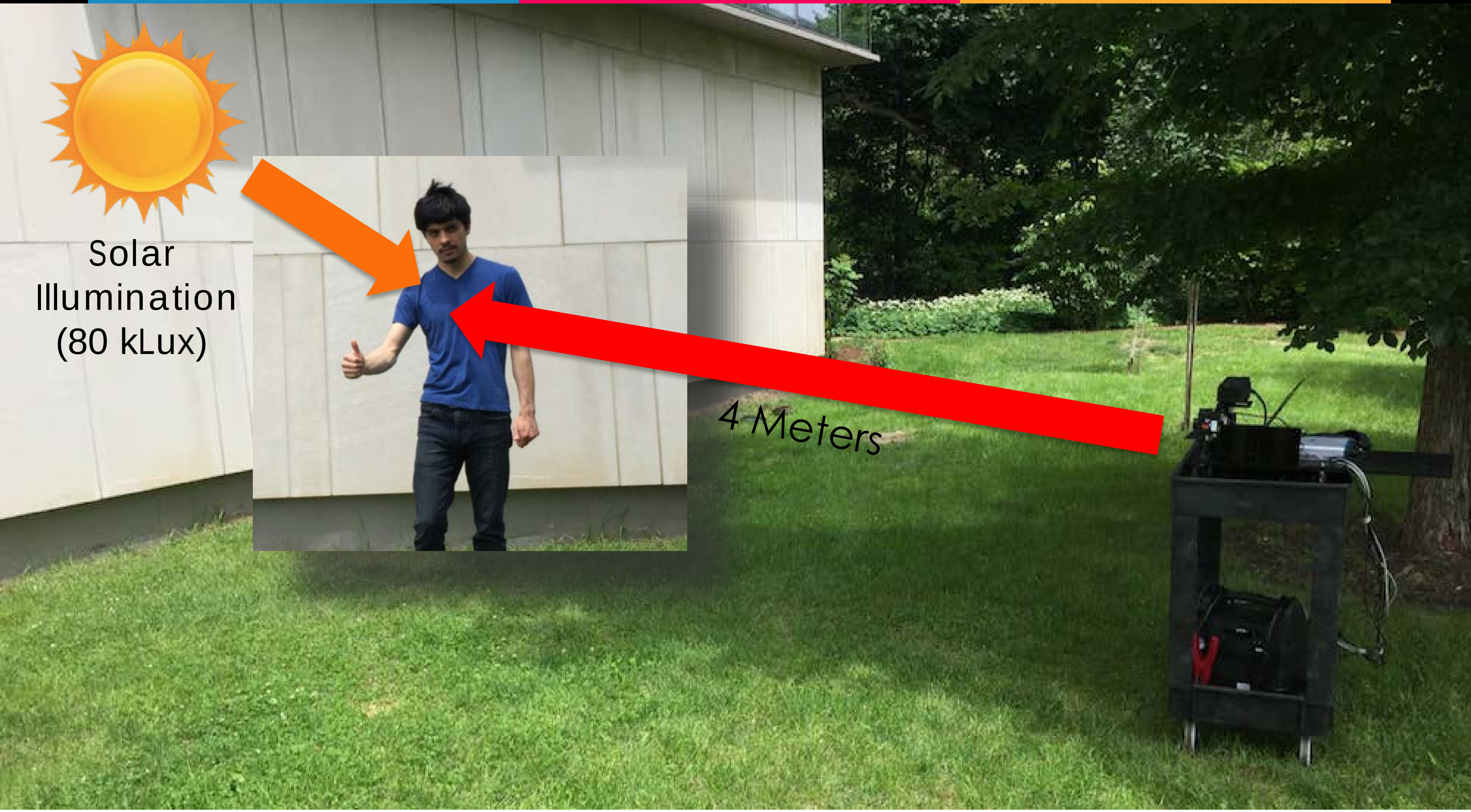


- Requires only one measurement per pixel

Results: Ambient Illumination

- Second Generation MC3D works with 50,000lux

Live Outdoor 3D Scanning



Live Outdoor 3D Scanning

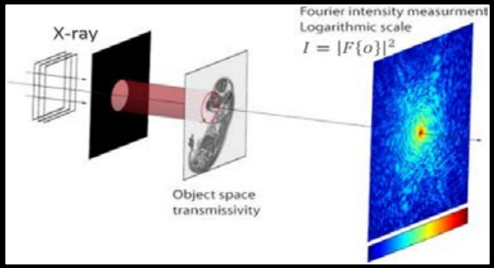
Kinect2 | MC3D (Zoom Lens) | IR Image

- MC3D works with 80,000 lux at 4m stand-off distance

Talk Outline

X-ray CDI

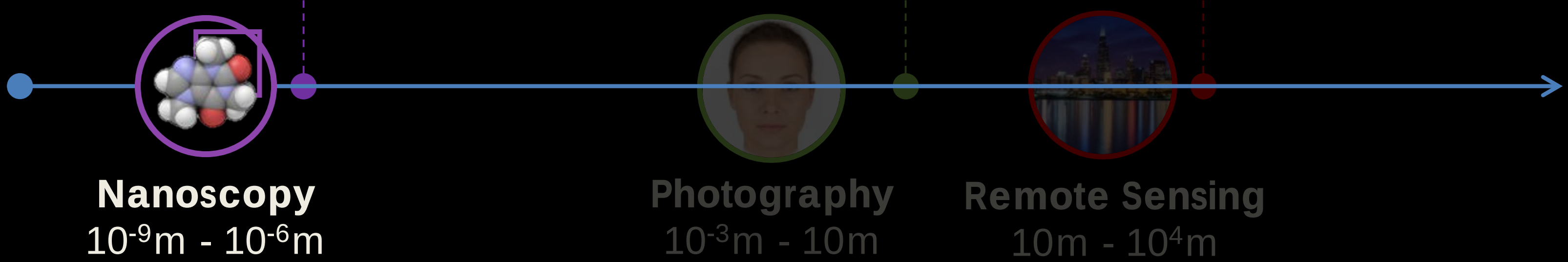
X-Ray Coherent Diffraction Imaging



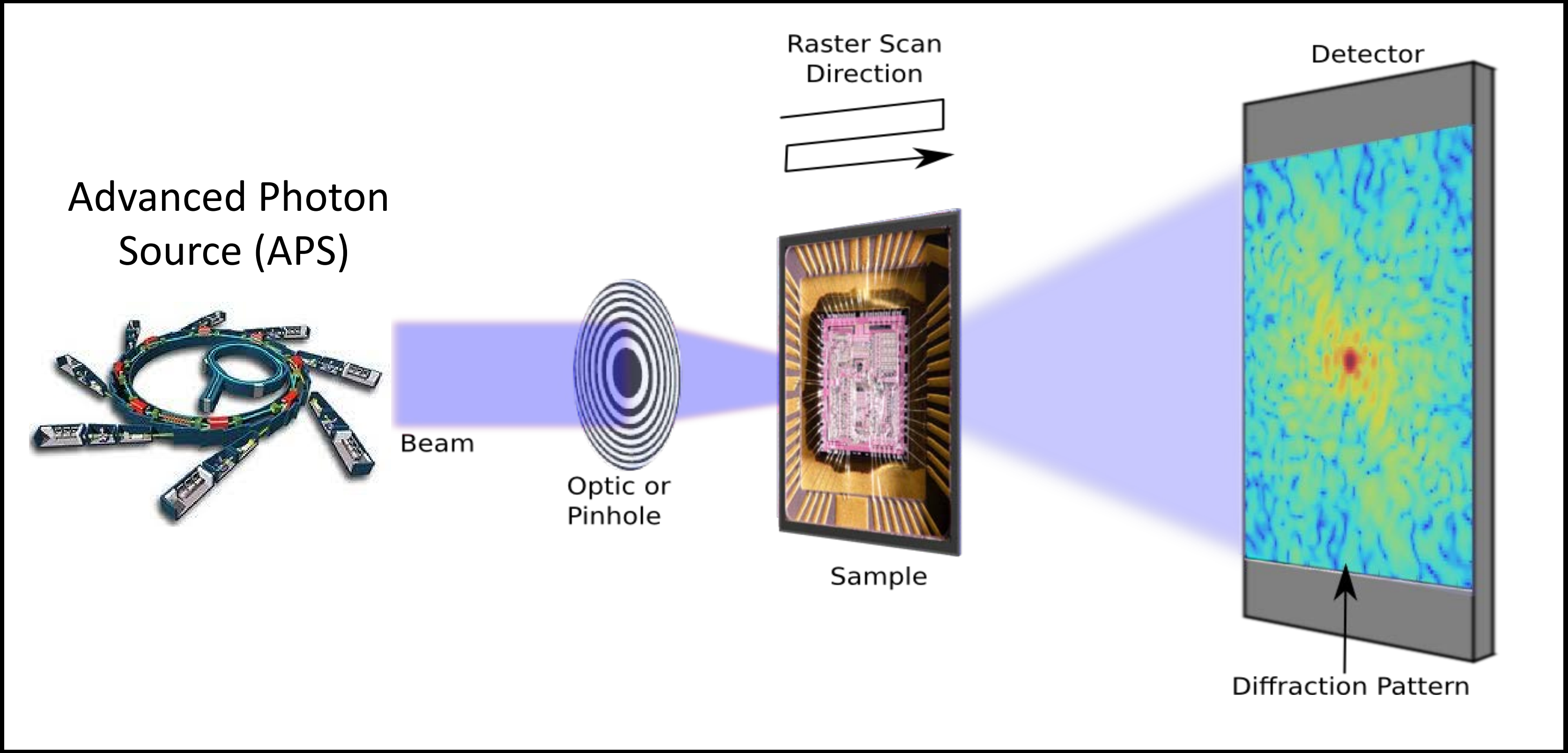
"High Dynamic Range Coherent Imaging Using Compressed Sensing", He et al., Optics Express, November 2015.

"A Compressed Sensing Approach to Solving the Dynamic Range Problem in Fourier Transform Holography", He et al., Imaging and Applied Optics 2015, OSA Technical Digest (online) (Optical Society of America, 2015), paper CW2F.3.

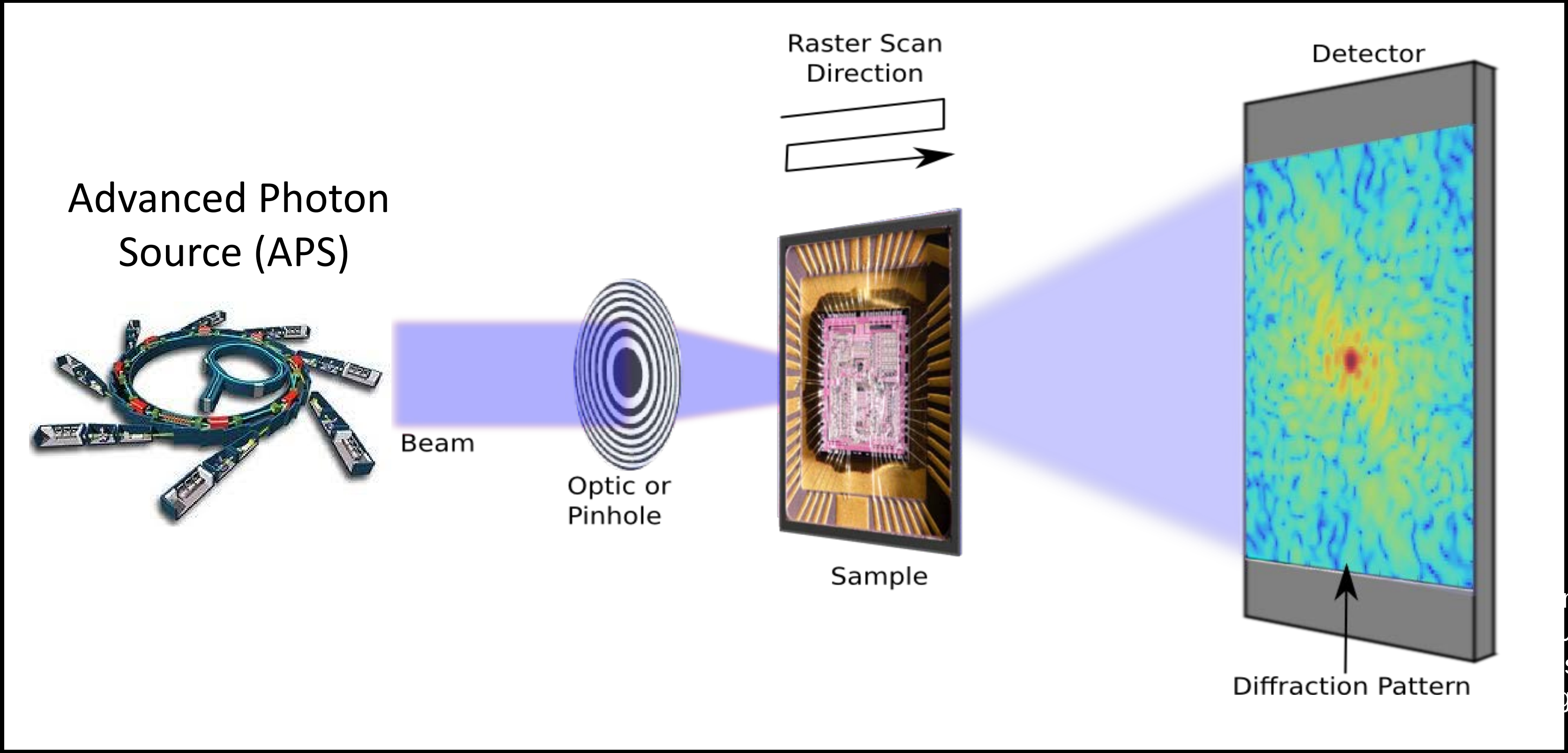
"Nanoscale x-ray imaging of circuit features without wafer etching", Deng et al. PHYSICAL REVIEW B 95, 104111 (2017).



X-ray Ptychography at ANL



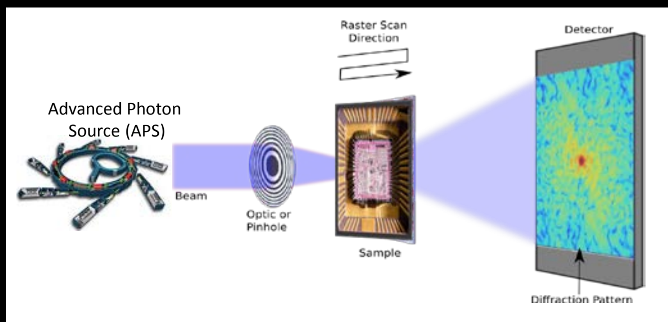
X-ray Ptychography at ANL



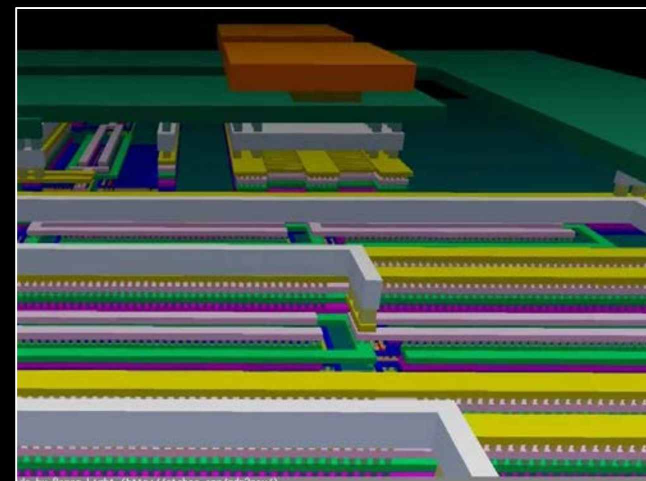
nology.
um. (b)
scaling
22nm

IARPA RAVEN / PRISMA

X-Ray Ptychography



GDSII Design File

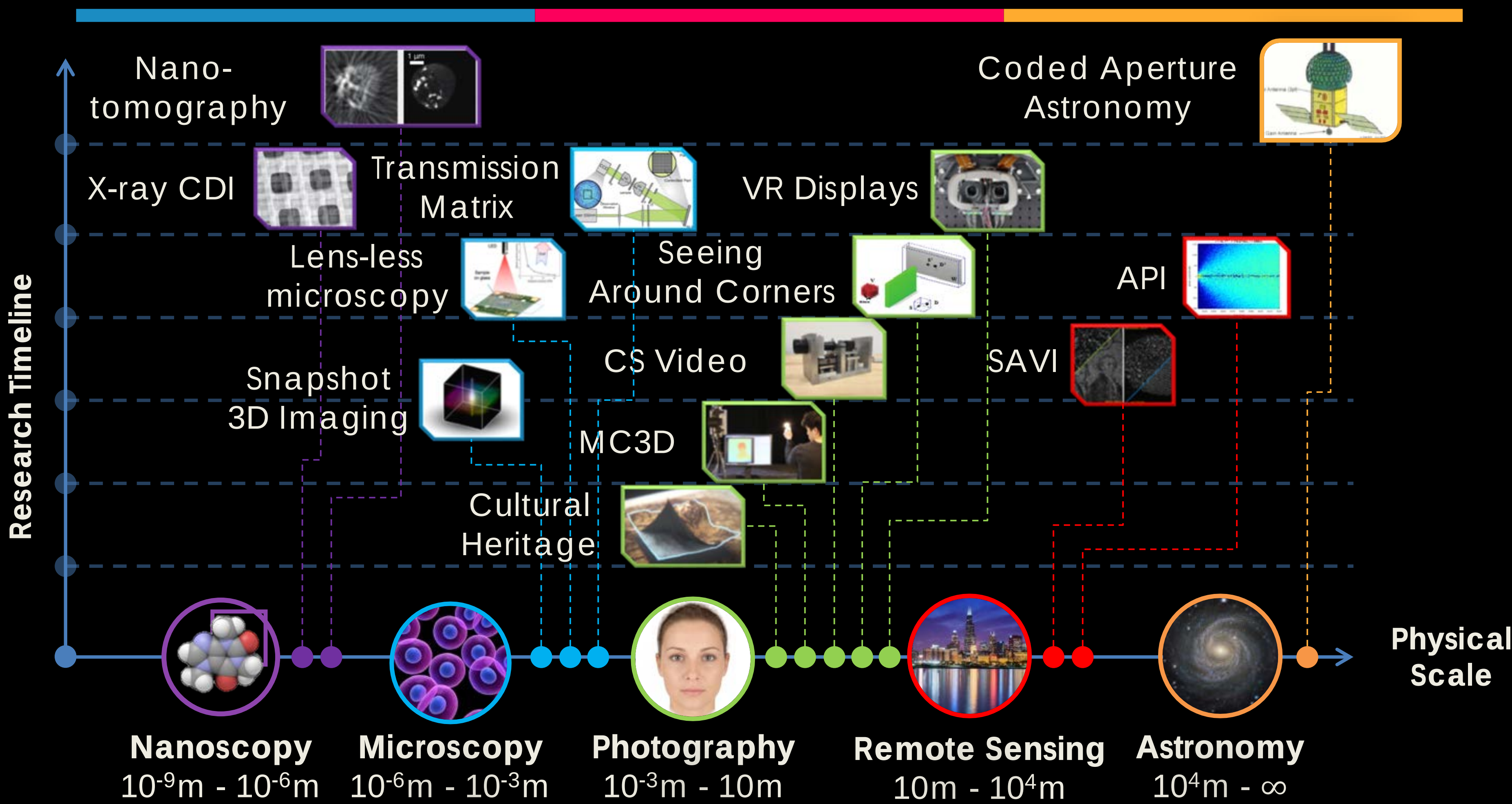


RAVEN / PRISMA Goals:

- Non-invasive IC chip imaging.
- 10nm resolution over 1cm x 1cm FoV.
- 3D reconstruction of 10-15 layers.
- Capture + Reconstruction within 25 days.

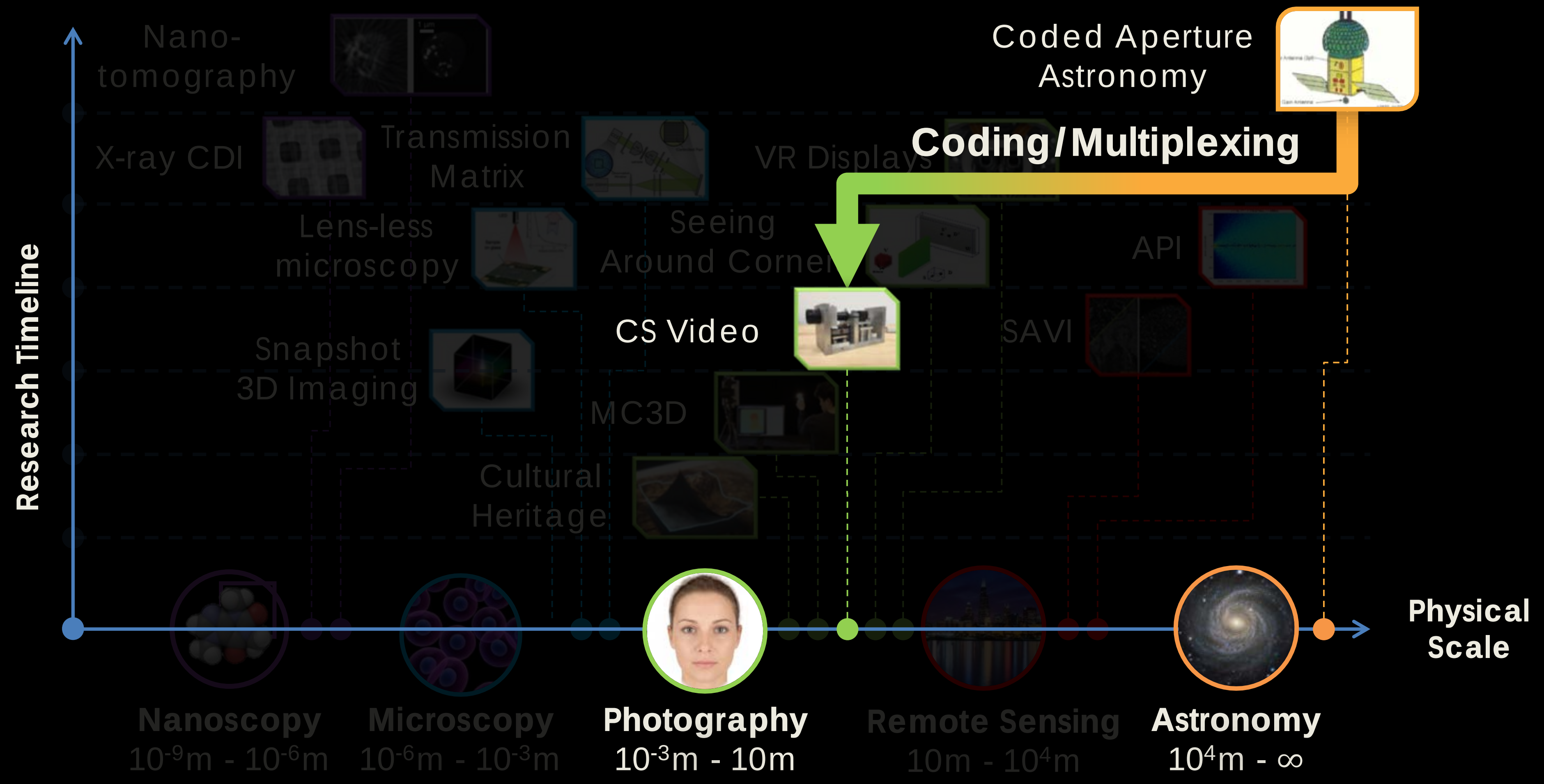
USC | ISI Information Sciences Institute | Argonne NATIONAL LABORATORY | PAUL SCHERRER INSTITUT PSI | Stanford University

Big Picture



Nano-tomography
Coded Aperture Astronomy
X-ray CDI
Transmission Matrix
VR Displays
Lens-less microscopy
Seeing Around Corners
API
CS Video
SAVI
Snapshot 3D Imaging
MC3D
Cultural Heritage
Research Timeline
Physical Scale
Nanoscopy
10^{-9}m - 10^{-6}m
Microscopy
10^{-6}m - 10^{-3}m
Photography
10^{-3}m - 10m
Remote Sensing
10m - 10^{4}m
Astronomy
10^{4}m - ∞

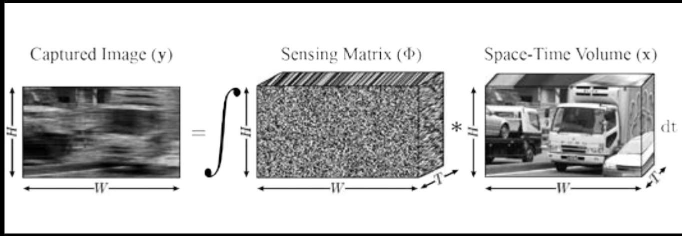
Connection 1: Coding



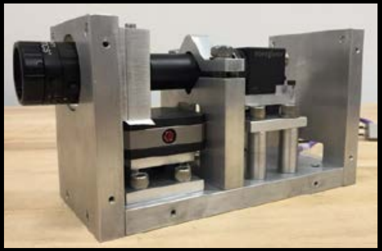
Connections I: Coding

Compressed Sensing Video

Measurement Model:

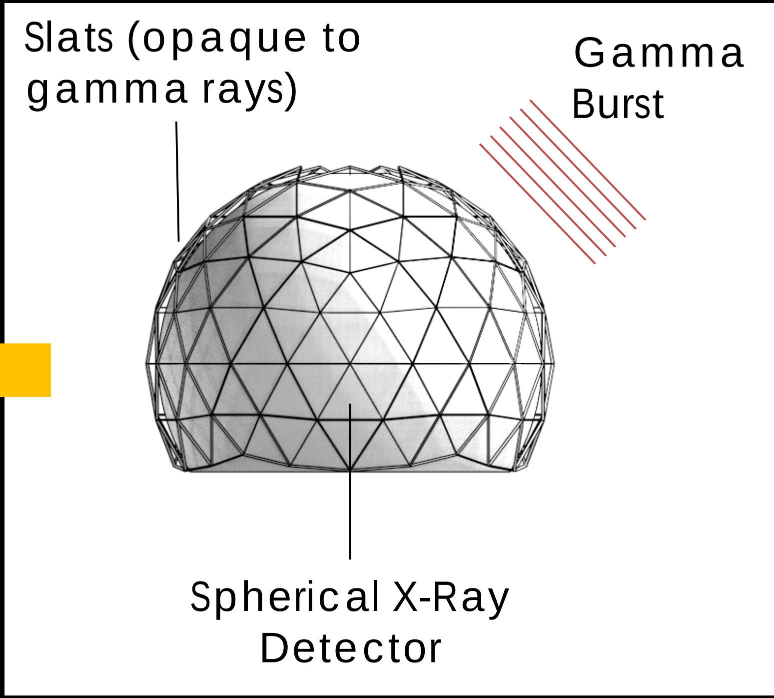


CS Video Camera:

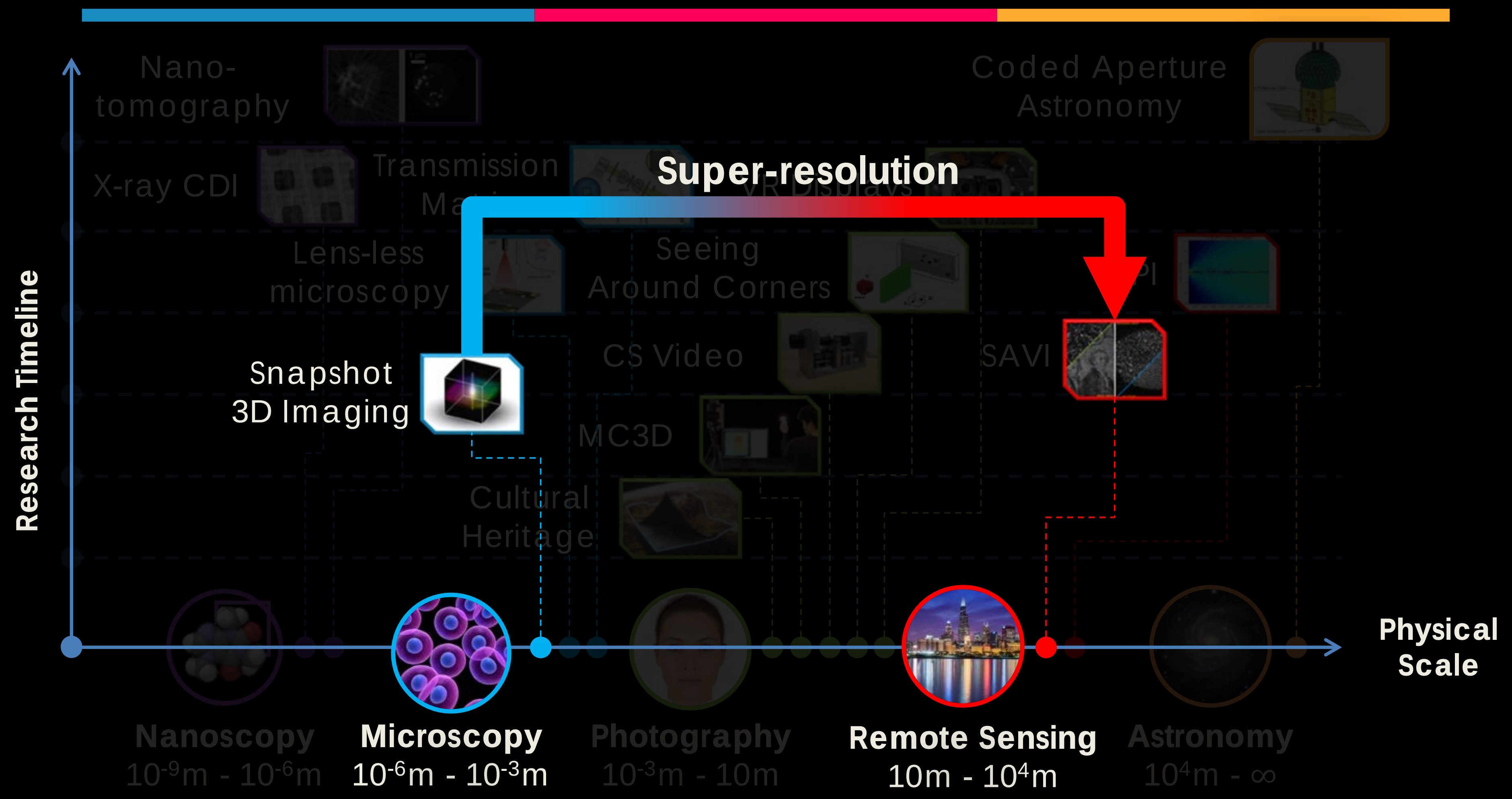


Snapshot Video Reconstructions:

Coded Aperture Astronomy



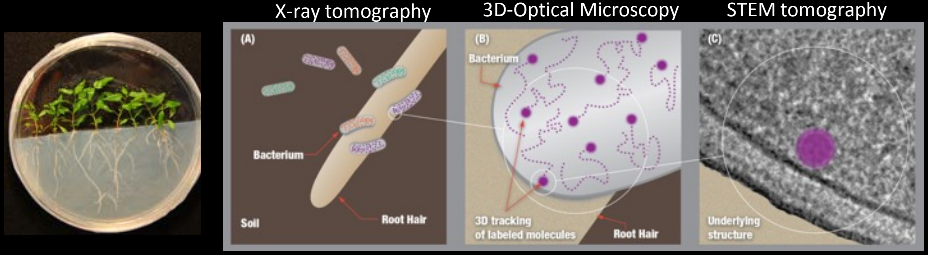
Connections 2: Super-resolution



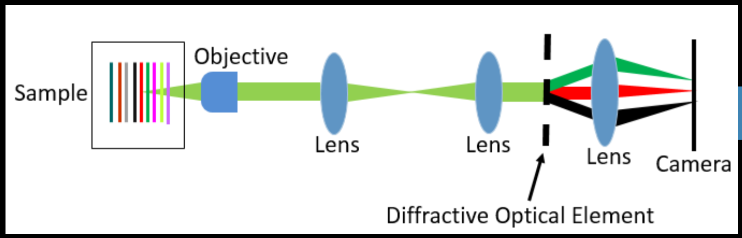
Connections 2: Super-resolution

Snapshot 3D Microscopy

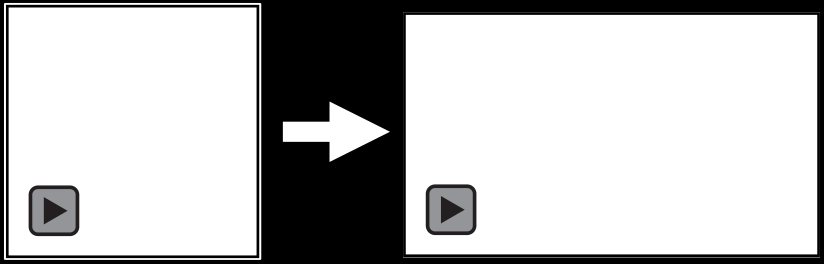
Small Worlds DOE Project :



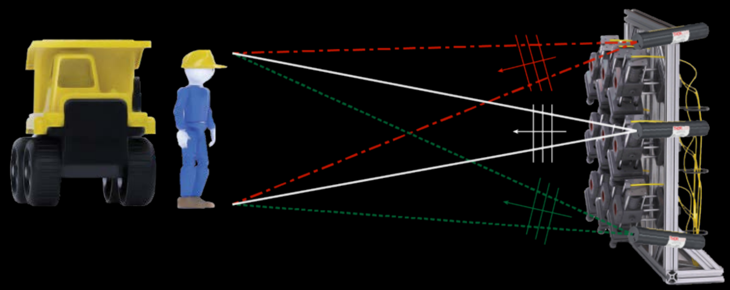
MultiFocal Microscopy (MFM):

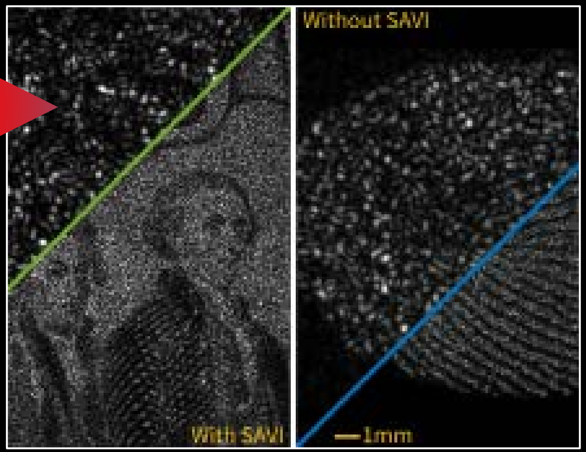


Snapshot 3D Reconstructions:

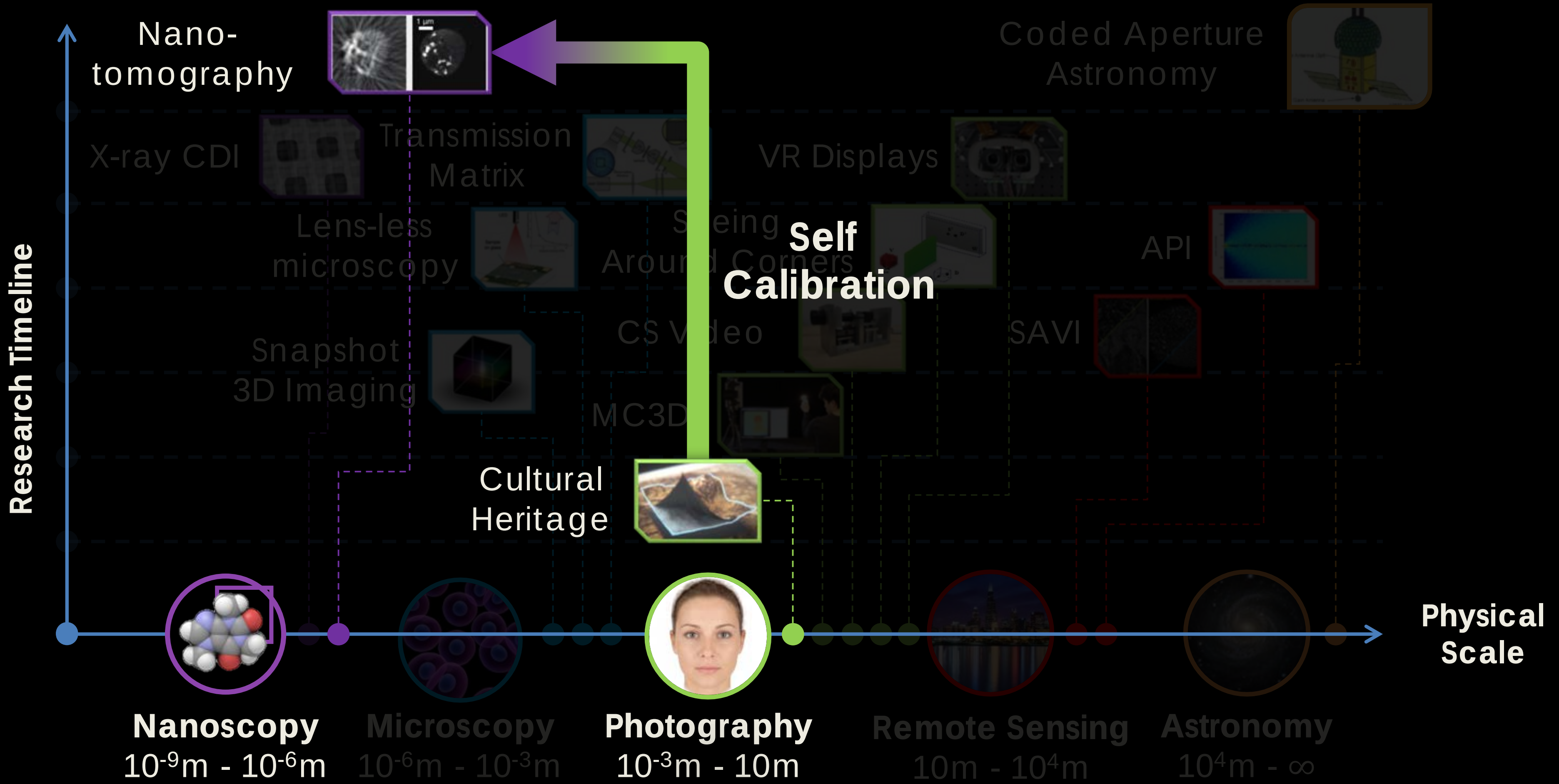


Synthetic Aperture Visible Imaging





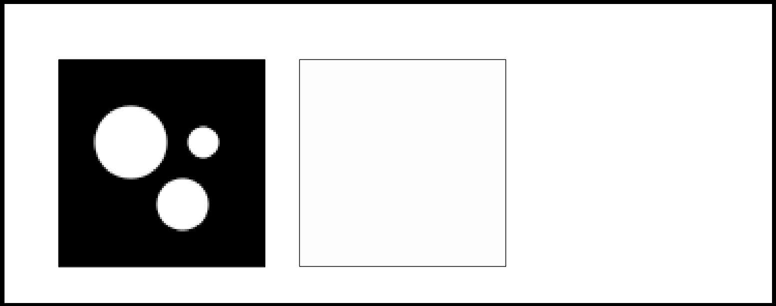
Connections 3: Self-calibration



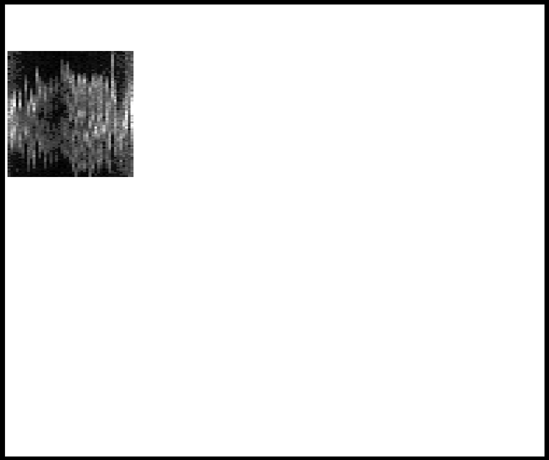
Connections 3: Self-calibration

Uncalibrated X-Ray Tomography

Unknown Projection Angles:

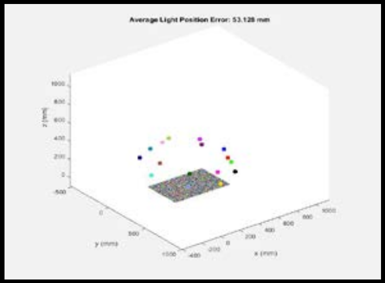


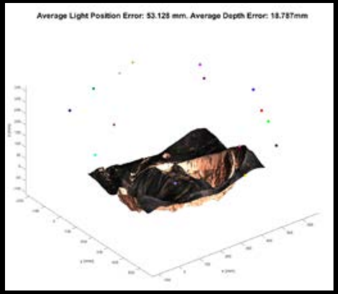
Calibrated Projection Angles



Cultural Heritage Imaging

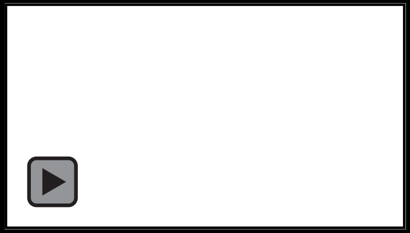
Uncalibrated Photometric Stereo:





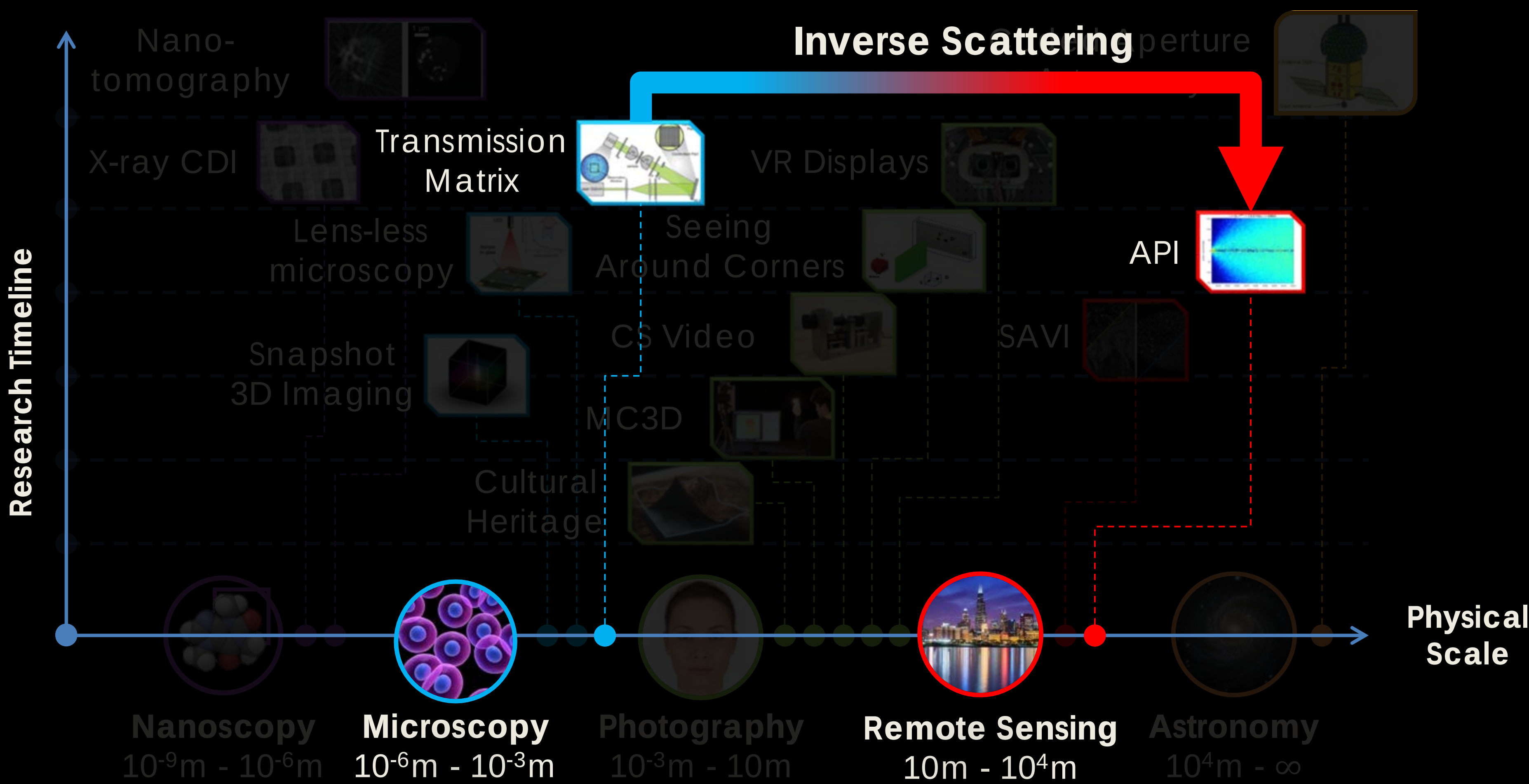
Gauguin Surface Measurement:

3D Surface Reconstruction



Drawing Reconstruction

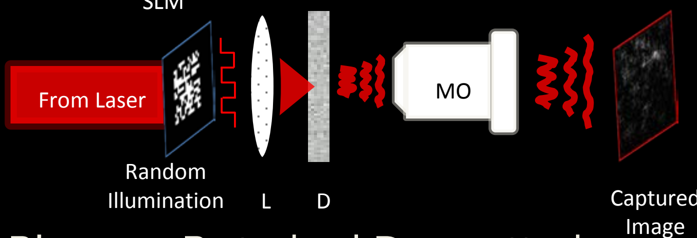
Connections 4: Scattering



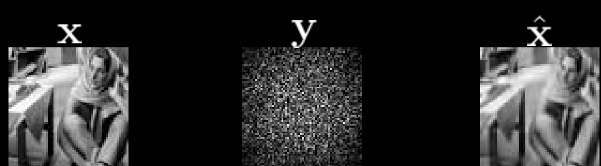
Connections 4: Scattering

Transmission Matrix Descattering

Experimental TM Measurement :

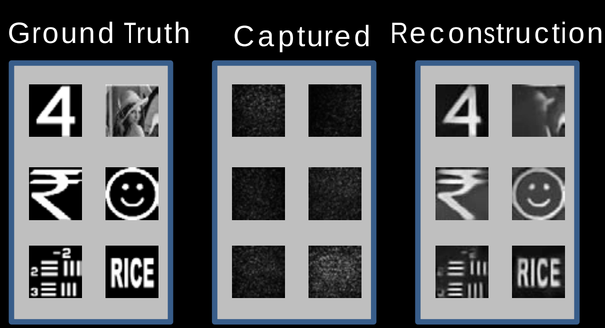


Phase + Retreival Descattering:



$\mathbf{y} = |\mathbf{A}\mathbf{x}|$ $\hat{\mathbf{x}} = \mathrm{PR}(\mathbf{y}, \hat{\mathbf{A}})$

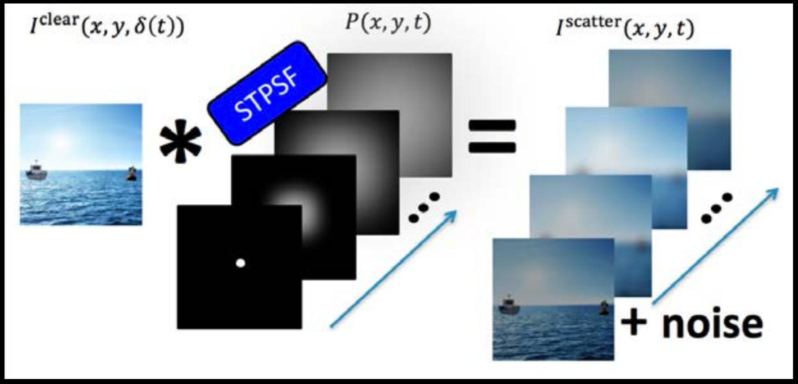
Results:



All Photon Imaging

ToF Imaging through Fog/Rain:

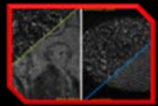
Model 3D STPSF Response:



Summary

- Advantages of Computational Imaging
  - Reduce hardware complexity
  - Photon efficient imaging
  - Introduce new functionality

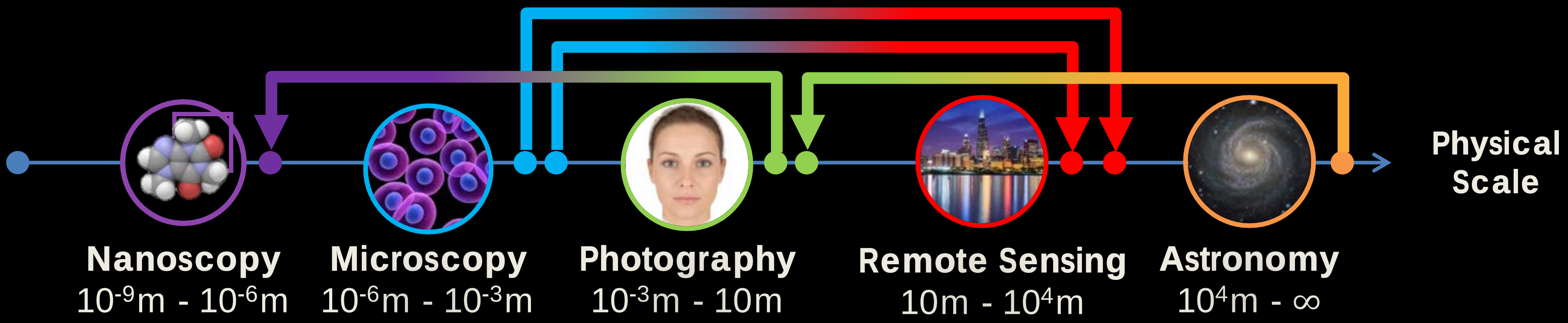
SAVI



MC3D

X-ray CDI

Many common problems across large range of physical scales



Aknowledgements

Northwestern

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