The OSA Imaging Optical Design Technical Group Welcomes You!

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Our Technical Group at a Glance

Our Focus

- Physics of linear optical materials, processes, devices, & applications
- 2000 members

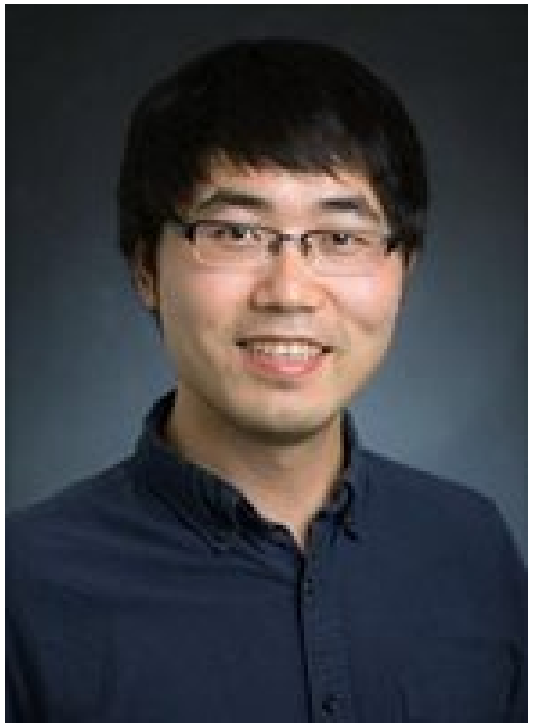
Our Mission

- To benefit *YOU*
- Webinars, social media, publications, technical events, business events, outreach
- Interested in presenting your research? Have ideas for TG events? Contact us at: TGactivities@osa.org.

Where To Find Us

- Website: https://www.osa.org/fd
- Facebook: https://www.facebook.com/groups/OSAImagingOpticalDesign/
- LinkedIn: https://www.linkedin.com/groups/8113351/

Today's Speaker



Prof Liang Gao

Dr. Liang Gao is currently an Assistant Professor at Bioengineering at UCLA. His primary research interests are multidimensional optical imaging, computational optical imaging, and biomedical optics.

Dr. Liang Gao is the author of more than 60 peer-reviewed publications in top-tier journals, such as Nature, Nature Communications, Science Advances, and PNAS. He received his BS degree in Physics from Tsinghua University in 2005 and PhD degree in Applied Physics and Bioengineering from Rice University in 2011. He is a recipient of an NSF CAREER award in 2017 and an NIH MIRA award in 2018.

Today's talk


DEVELOPING NEXT GENERATION
MULTIDIMENSIONAL OPTICAL
IMAGING DEVICES
6 April 2021 • 12:00 EDT (UTC -4:00)
OSA
Imaging
Optical Design
Technical Group

Development of next-generation multidimensional optical imaging devices

Liang Gao
Assistant Professor
Department of Bioengineering
UCLA

UCLA

iOptics Lab

Outline

- Plenoptic function of light
- Multidimensional optical bioimaging
  - Image Mapping Spectrometry (x, y, λ)
  - Ultrafast Compressed Imaging Microscopy (x, y, t)
  - Light field tomography (x, y, θ)
- Summary

- x, y: Spatial coordinates
- θ: Emittance angles
- λ: Wavelength

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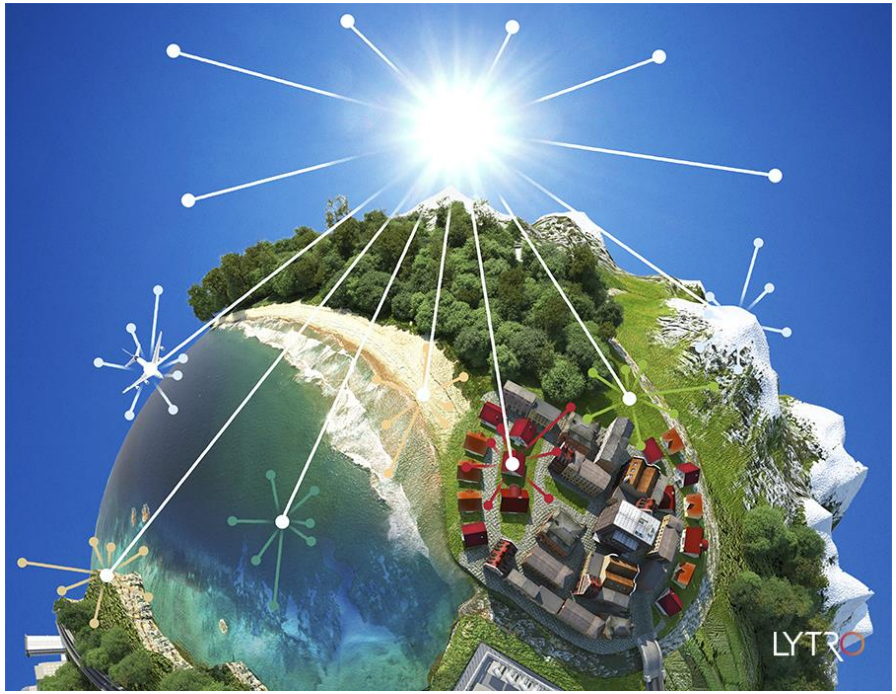
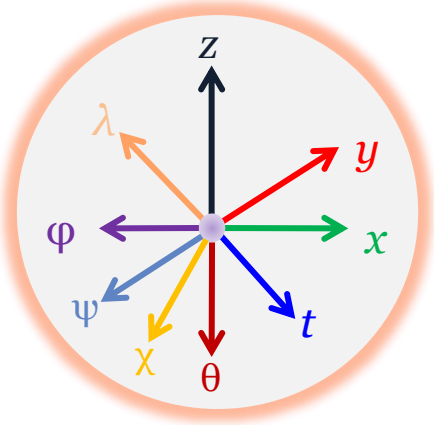
Plenoptic function of light





Plenoptic function of light:

- Spatial information (*x, y, z*)
- Spectral information (λ)
- Temporal information (t)
- Emittance angle (θ, φ)
- Polarization (ψ, χ)

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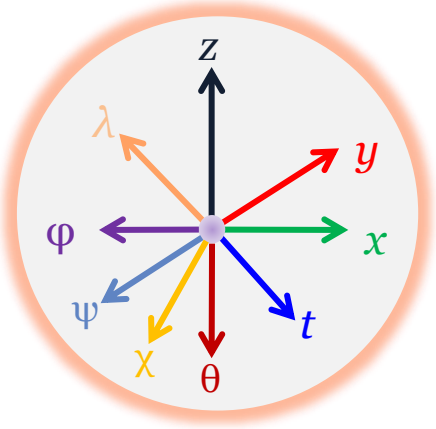
Measurement of a high-dim plenoptic function



Plenoptic function of light:

- Spatial information (x, y, z)
- Spectral information (λ)
- Temporal information (t)
- Emittance angle (θ, φ)
- Polarization (ψ, χ)

Q1: How to make measurement possible?

Q2: How to make measurement efficient?

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Enabling technologies

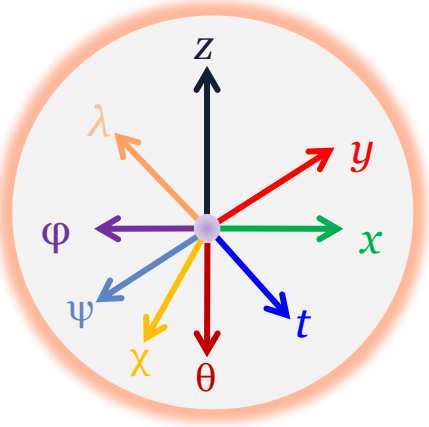
Microfabrication

High-performance computation

Modern detector technologies

Merge

Multidimensional Optical imaging



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Outline

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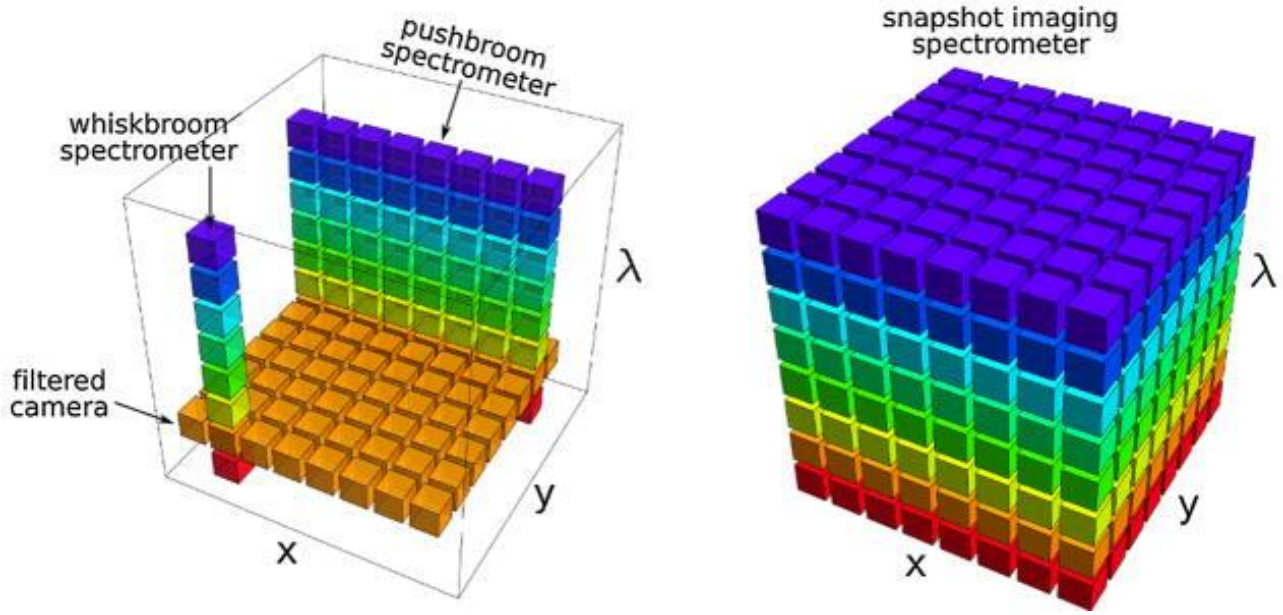
Snapshot hyperspectral imaging

- Motivation
  - Need for dynamic spectral imaging
  - Drawbacks of scanning-based hyperspectral imagers
    - Low throughput
    - Motion artifacts



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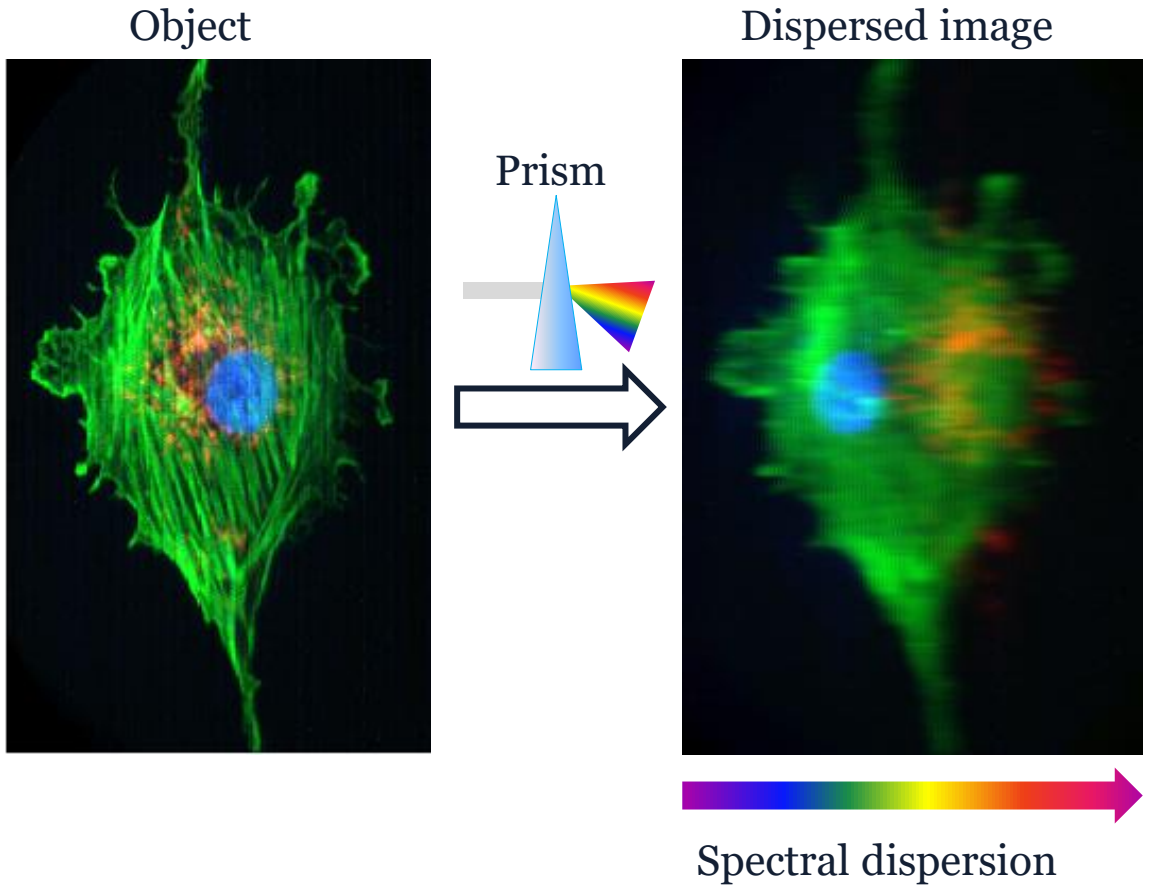
Problem of direct spectral dispersion



- Crosstalk between spatial and spectral information

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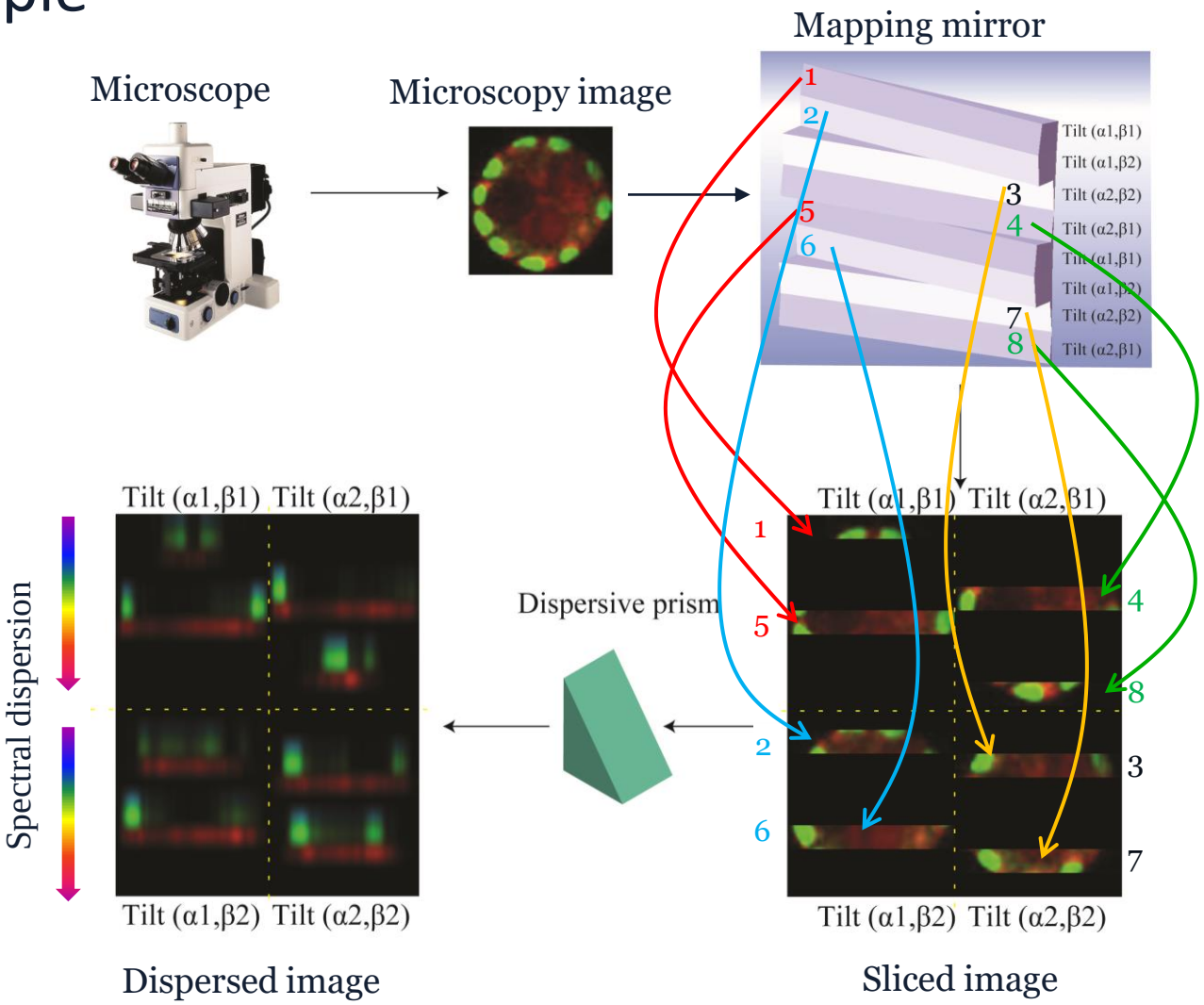
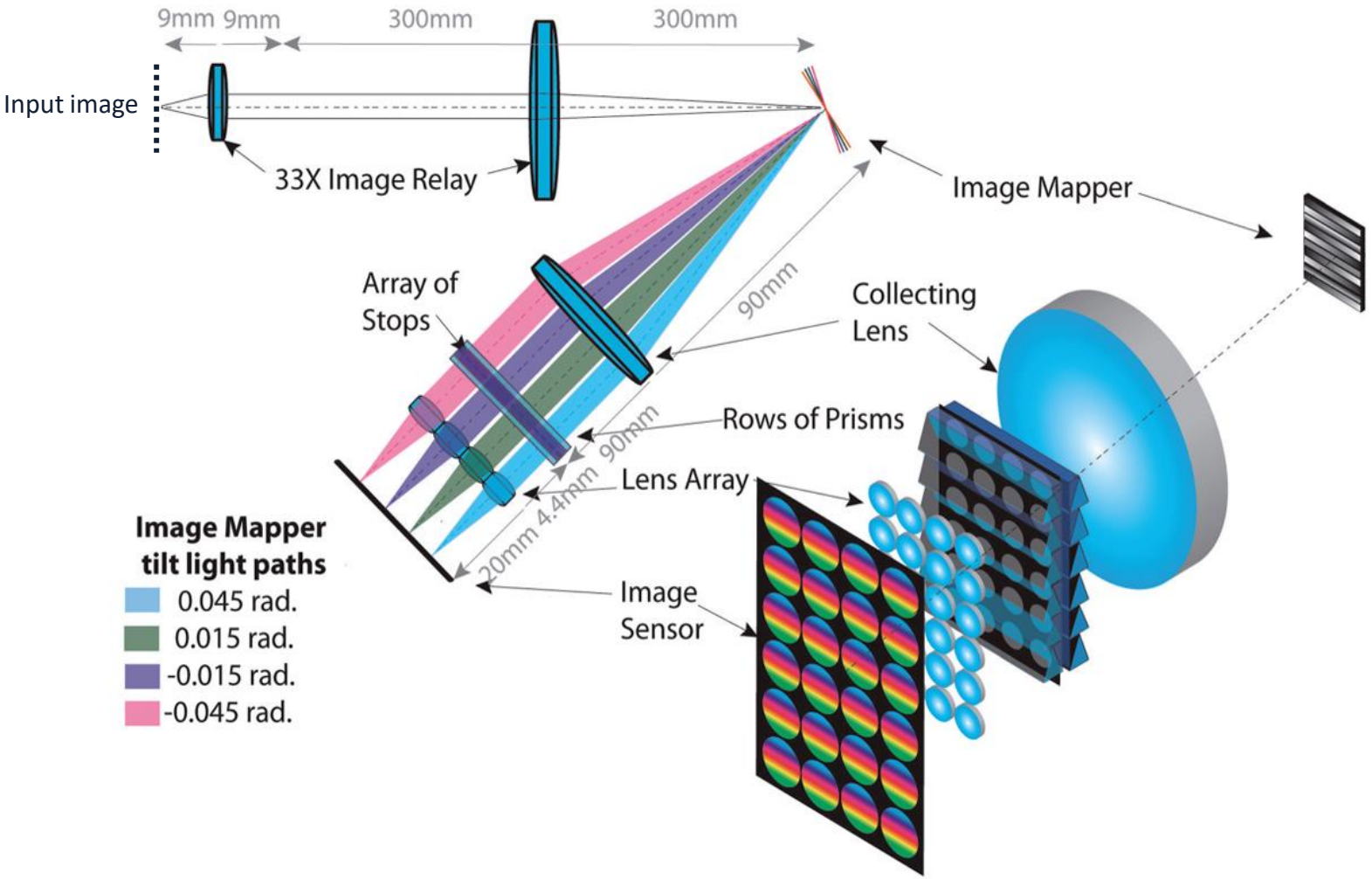
Image Mapping Spectrometry (IMS)

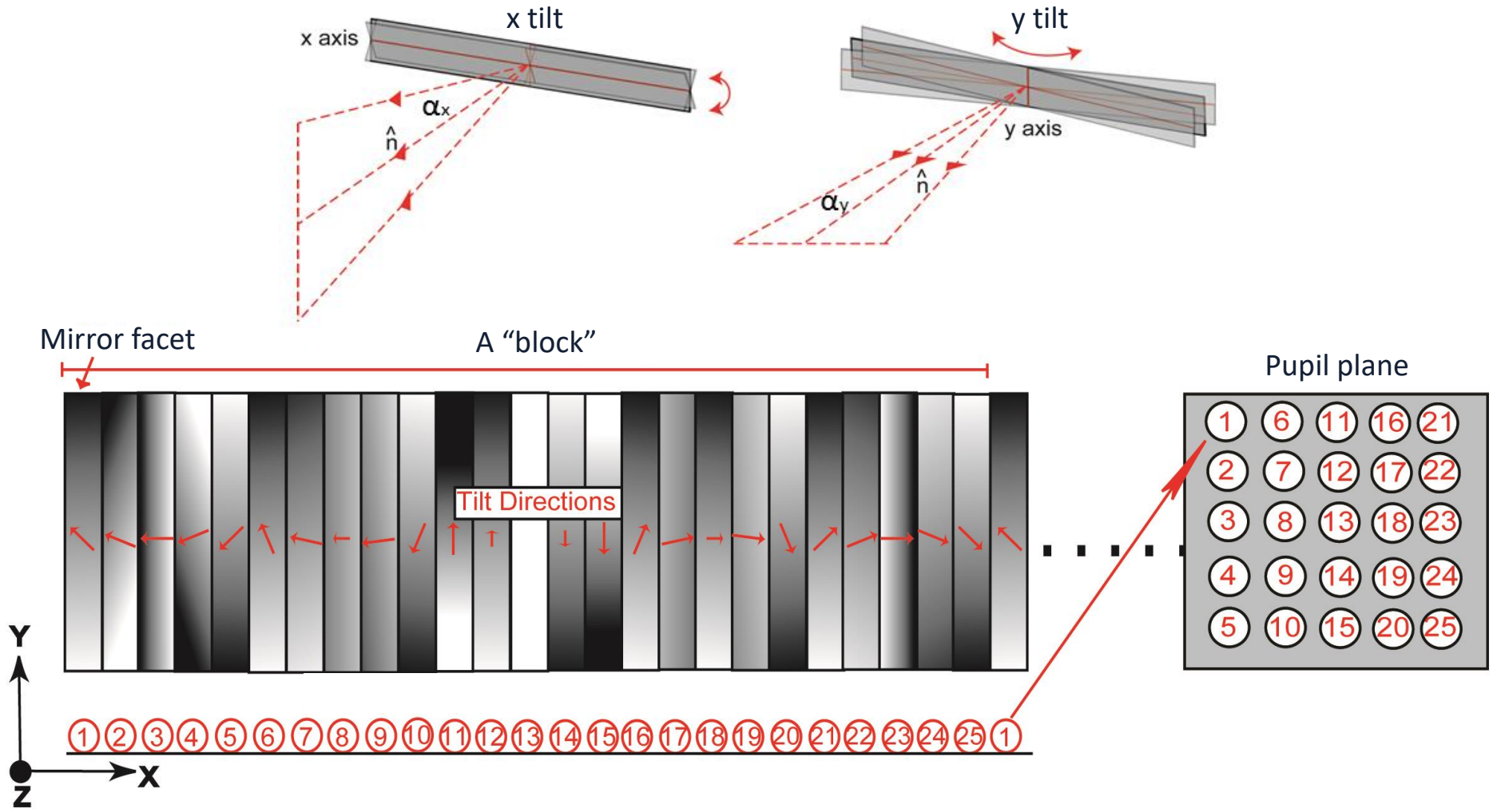
- Principle



Optical setup

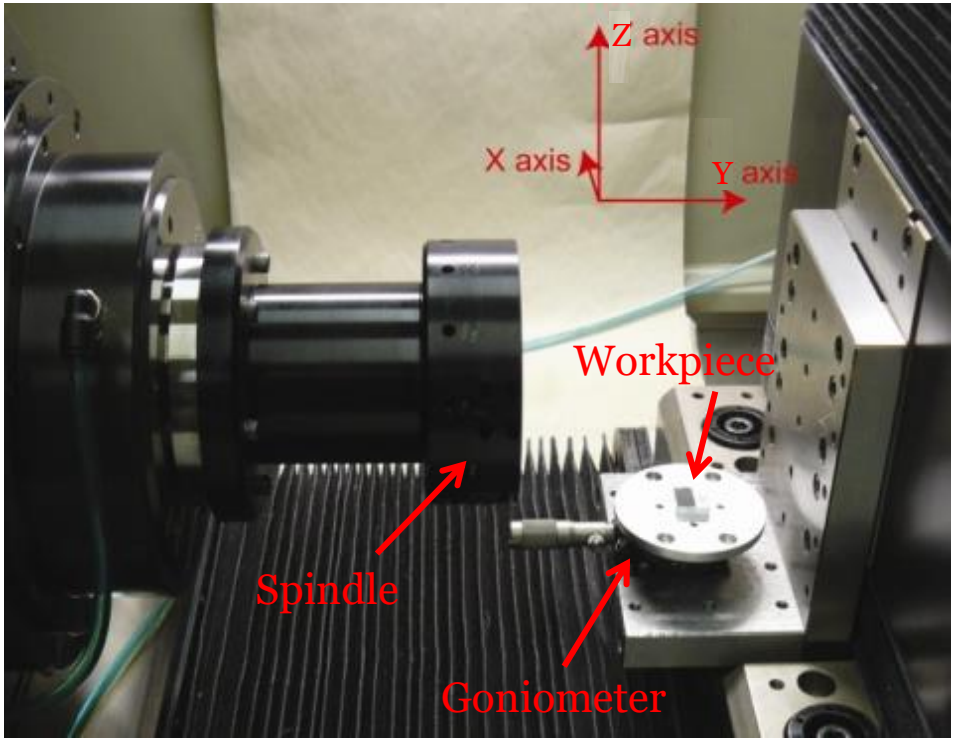


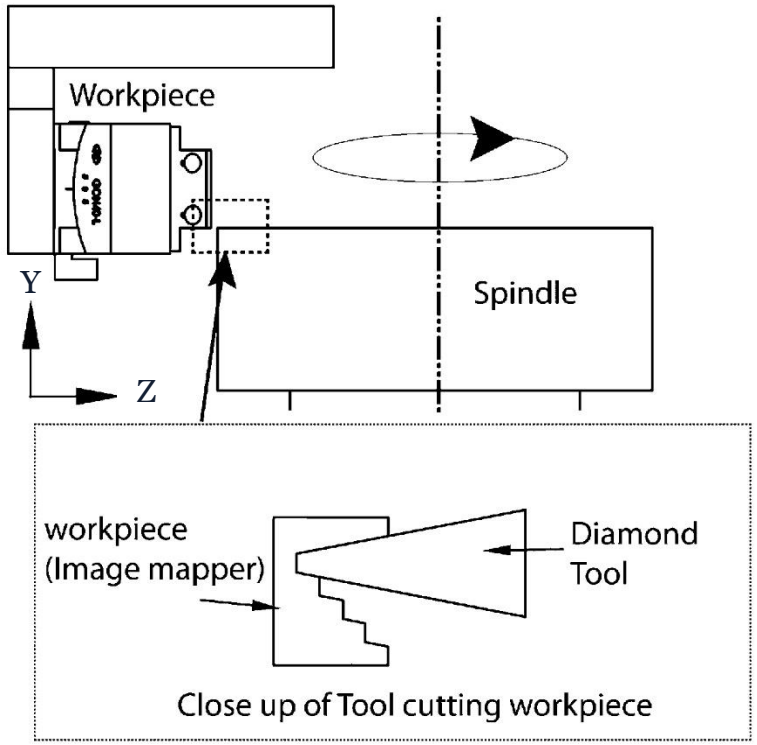
Design of the mapping mirror



- Each mirror facet has a two-dimensional (x, y) tilt.
- The mirror facets are grouped into repetitive "blocks" based on their tilt angles.

Fabrication of the mapping mirror





The mapping mirror was fabricated on a nano-precision lathe (Nanotech 250UPL) by raster-fly cutting.

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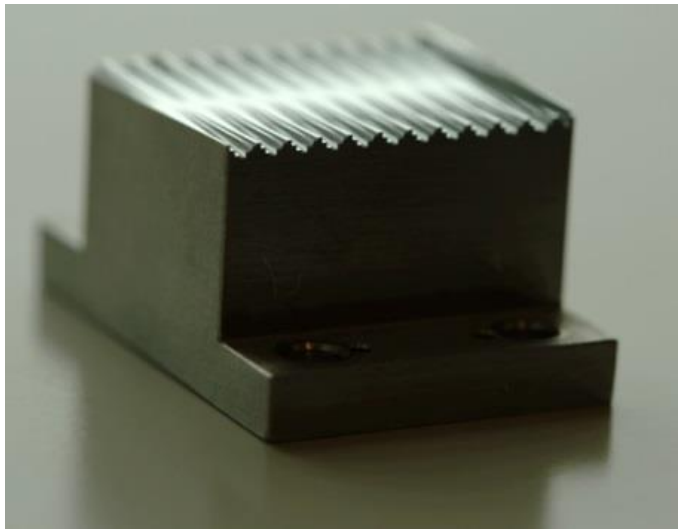
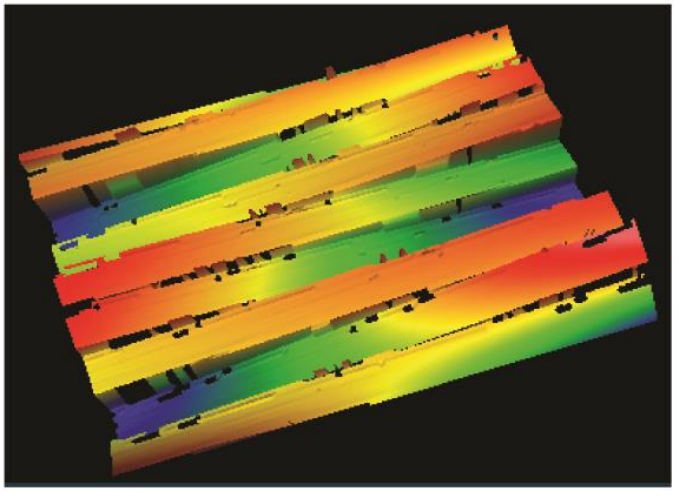
Mapping mirror

Photograph image



White-light interferometer image



- Substrate size: 25 mm × 25 mm
- Mirror facet size: 25 mm × 70 μm

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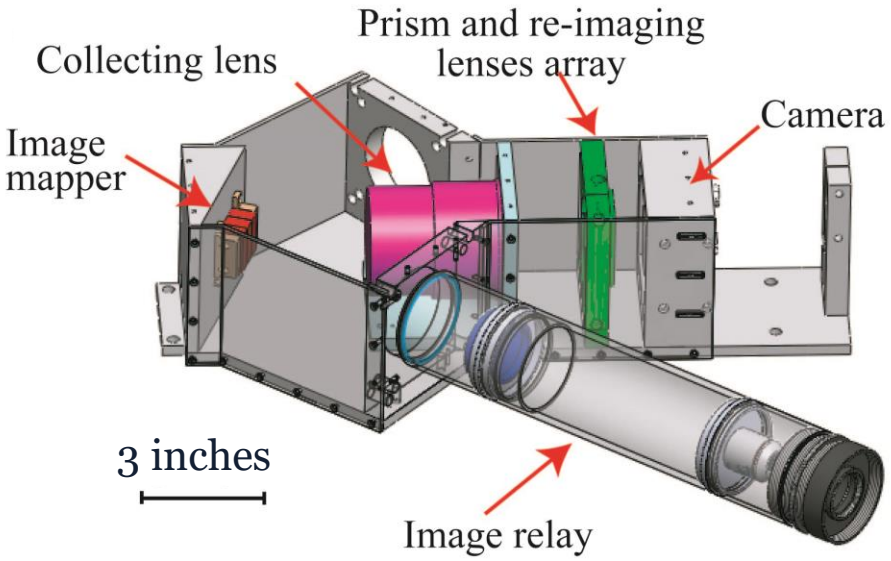
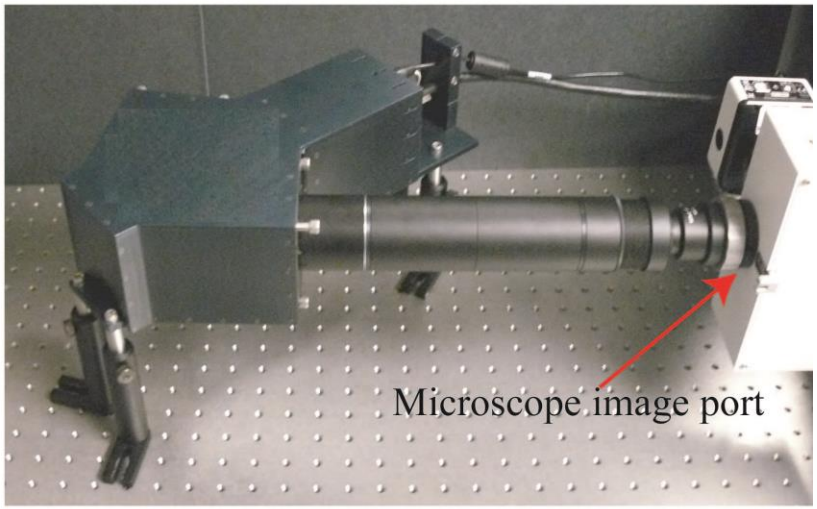
Image Mapping Spectrometer

3D model



IMS coupled to a microscope



J. Cell. Sci. 125, 4833 (2012)

- Instrument size: 20 inches x 5 inches x 3 inches
- Datacube size: 350 × 350 × 48 (x, y, λ)
- Datacube acquisition rate: up to 7.2 fps
- Spectral range: 460 nm – 700 nm
- Spectral resolution: ~ 7 nm

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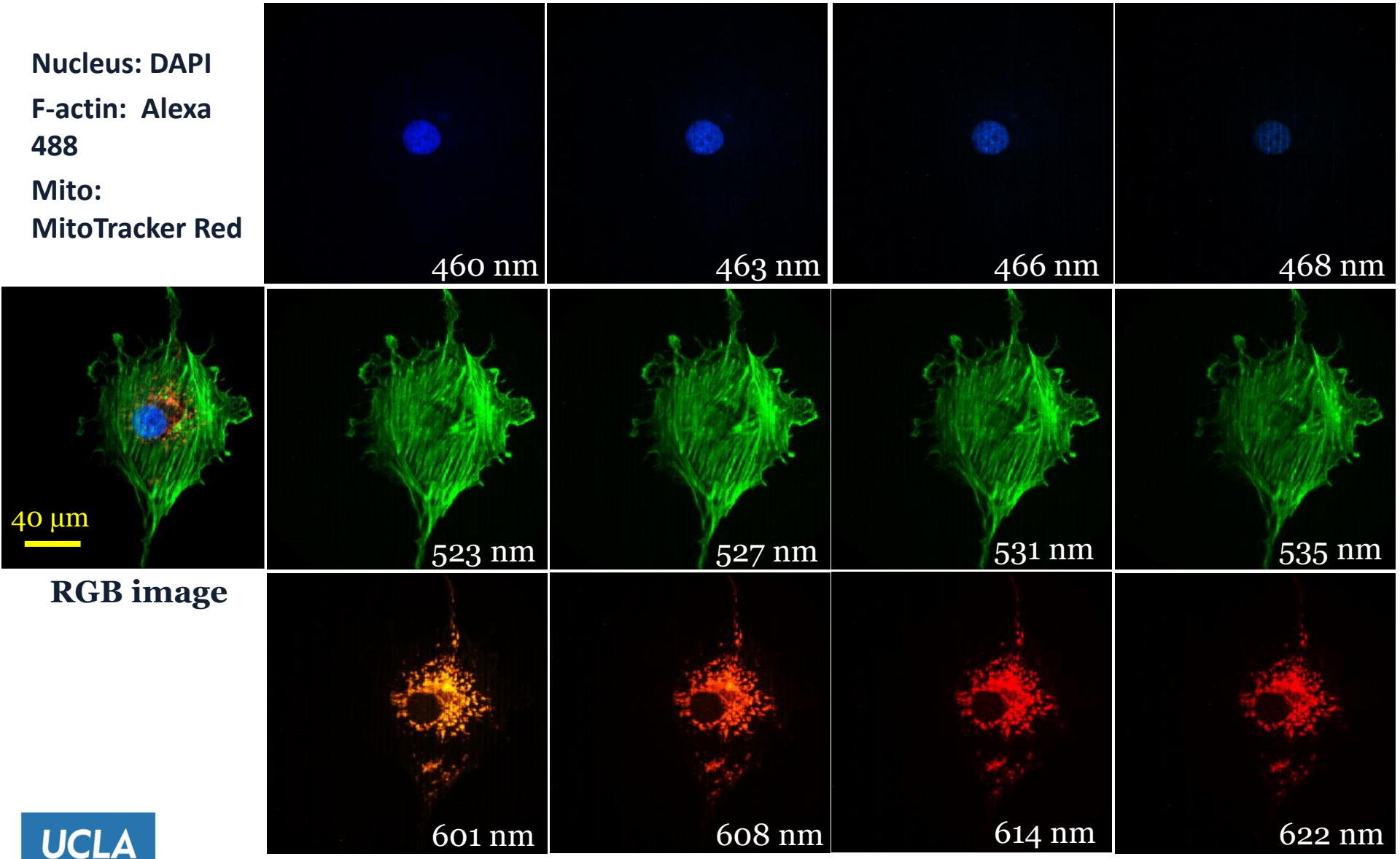
Hyperspectral imaging of triple-labeled bovine pulmonary artery endothelial cells

Nucleus: DAPI

F-actin: Alexa 488

Mito: MitoTracker Red



RGB image

Spectral channel images

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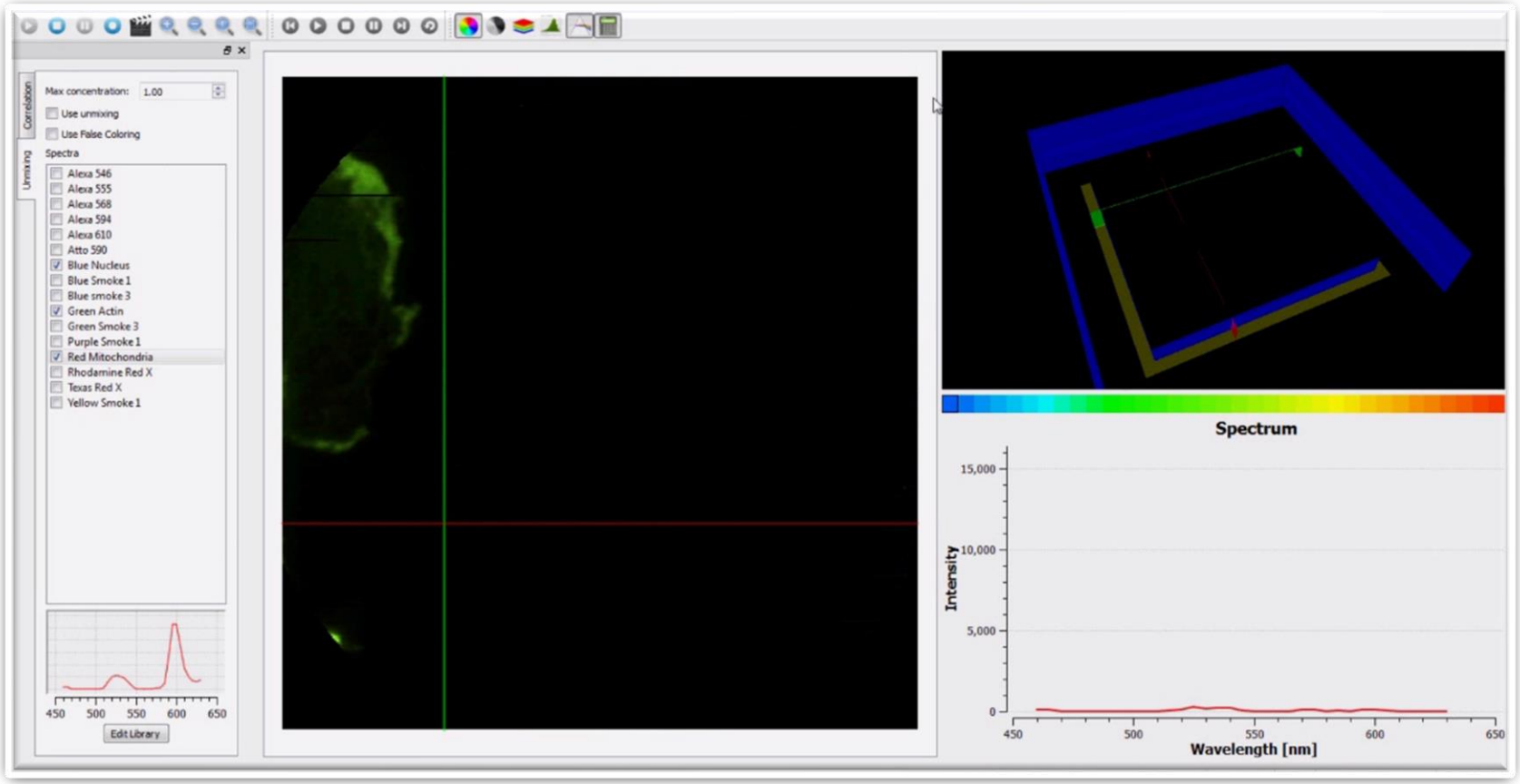
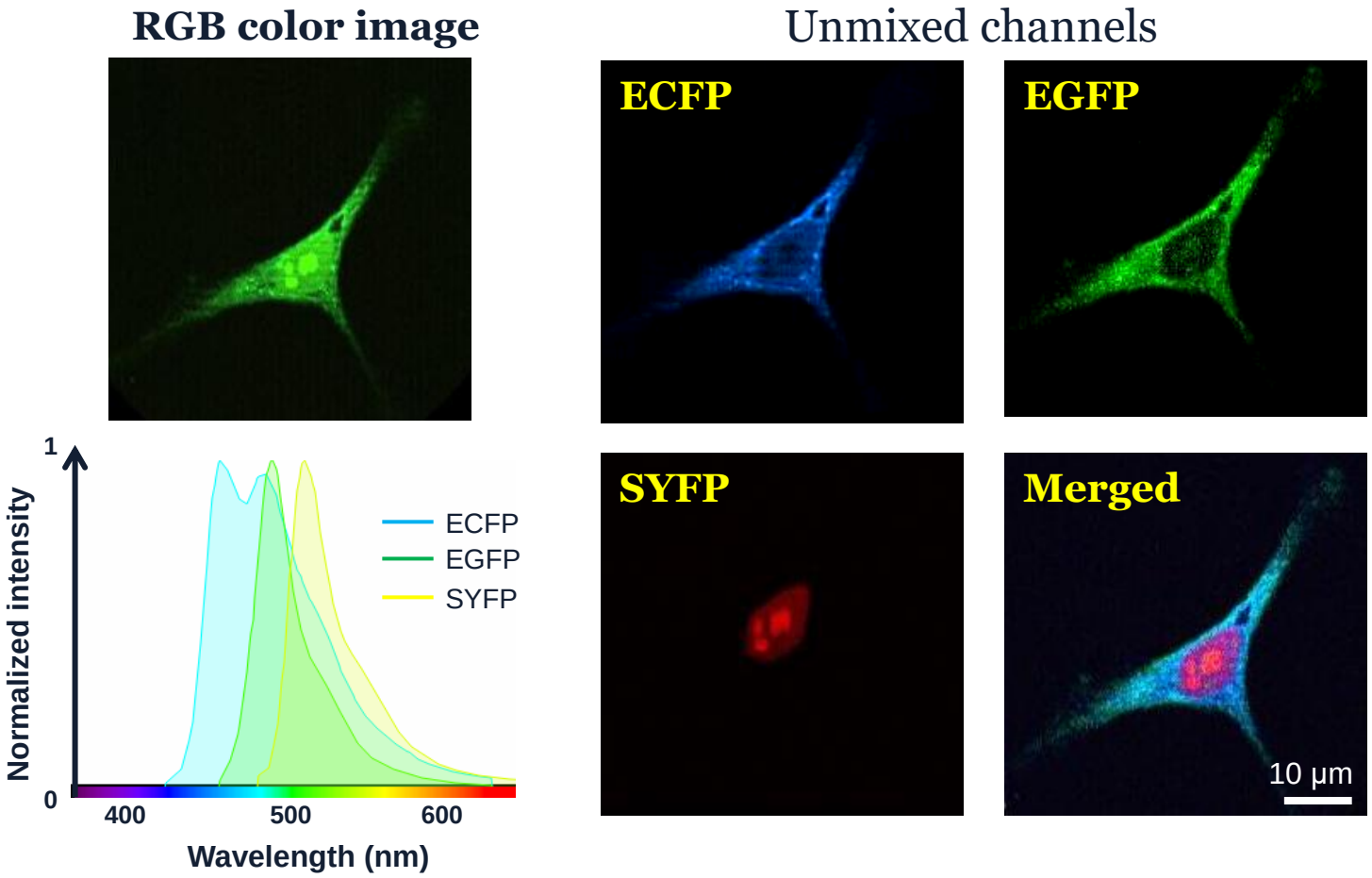
Real-time hyperspectral imaging



Spectral unmixing of triple-labeled Hela cells



- Mitochondria: ECFP
- Plasma membrane: EGFP
- Nucleus: SYFP

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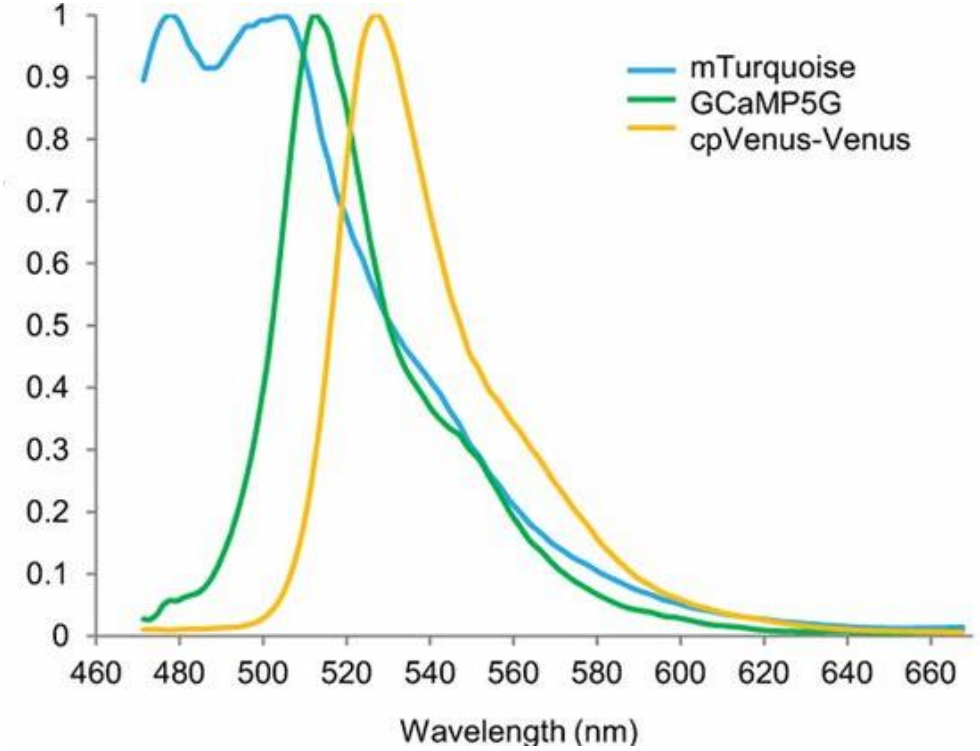
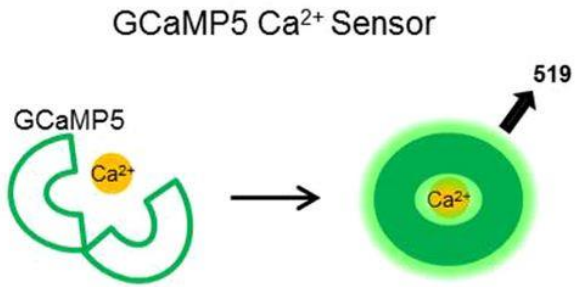
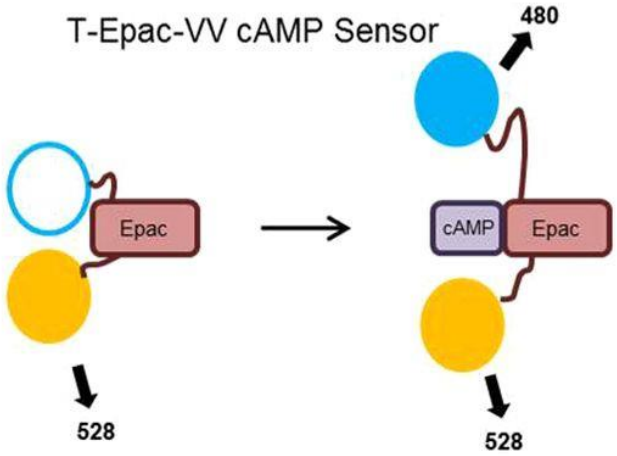
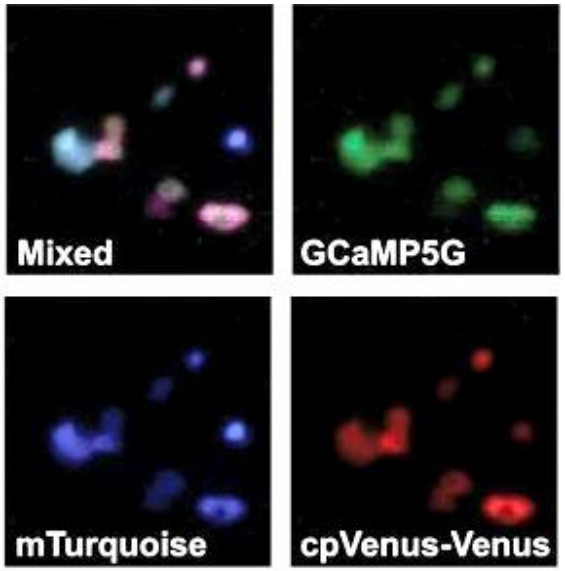
[Ca^{2+}] and cAMP signaling in MIN6 cells

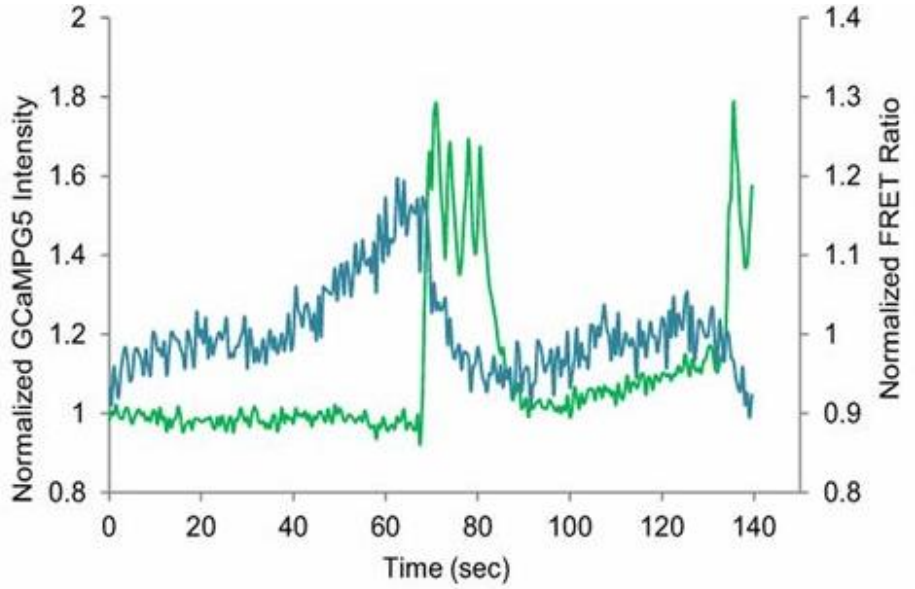


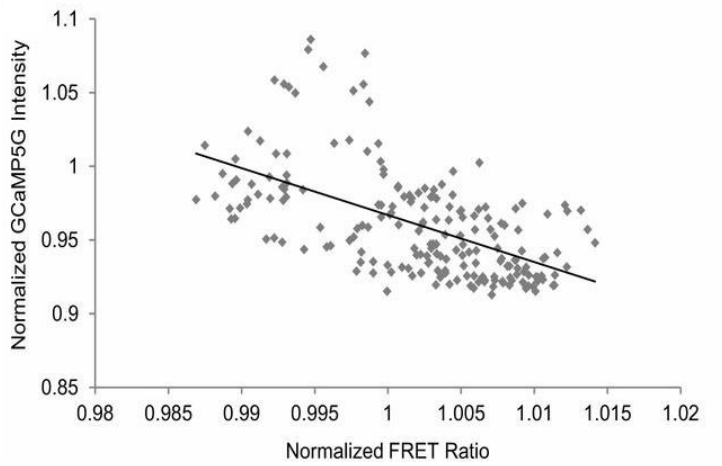




Hyperspectral imaging of [Ca^{2+}] and cAMP oscillations in MIN6 cells



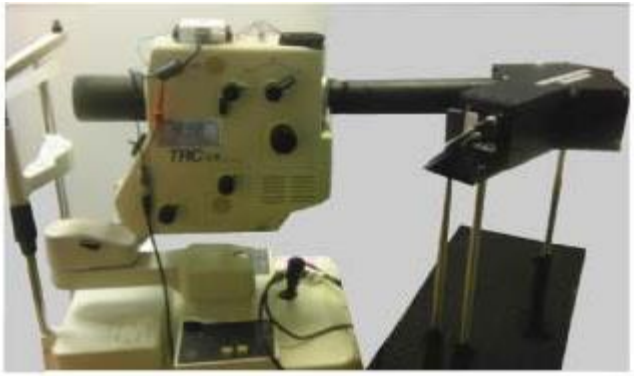




J. Cell. Sci. 125, 4833 (2012)

Hyperspectral retinal imaging in vivo

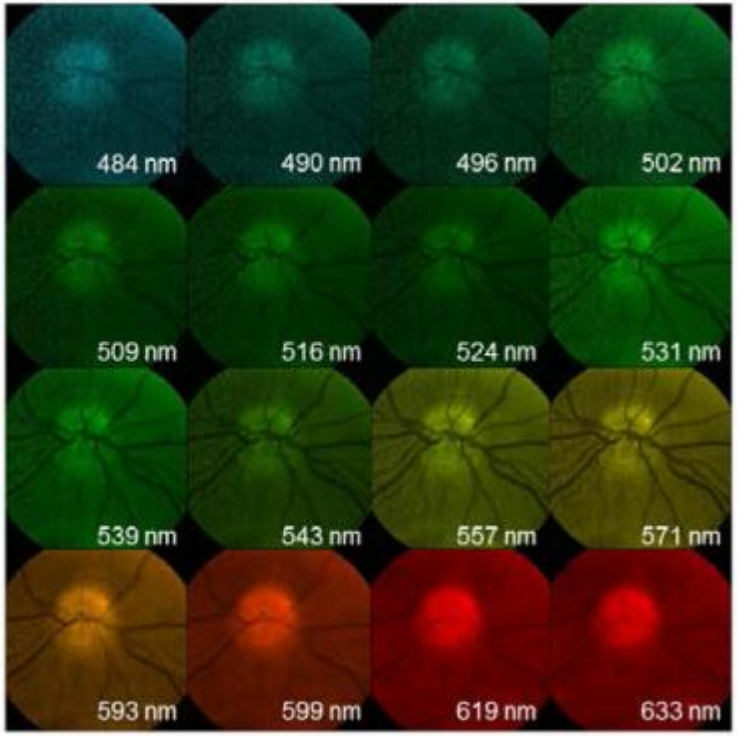
Hyperspectral fundus camera



Panchromatic image

Reference image

Representative spectral channel images



Biomed. Opt. Express 3, 48 (2012)

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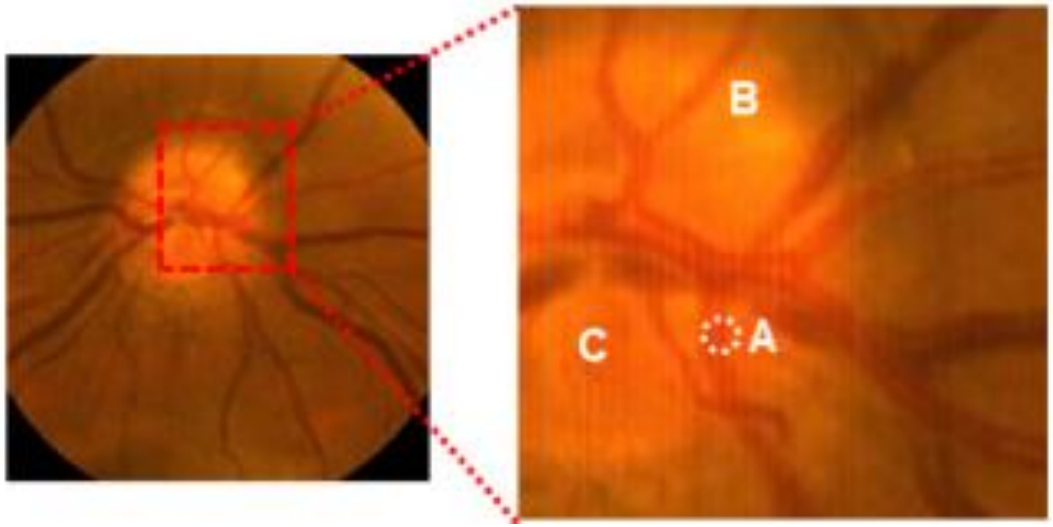
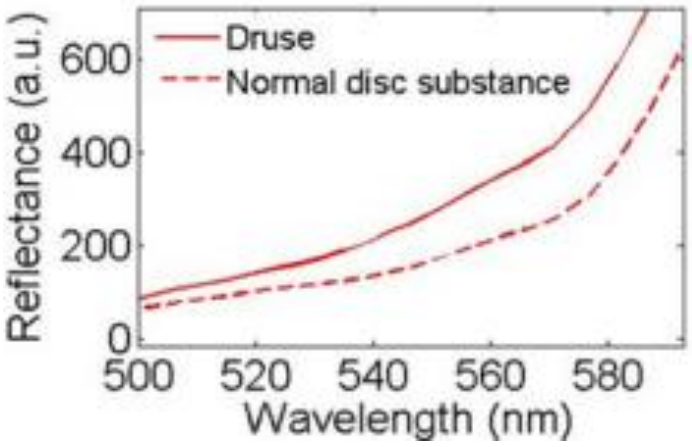
Hyperspectral imaging of drusen in vivo





Biomed. Opt. Express 3, 48 (2012)

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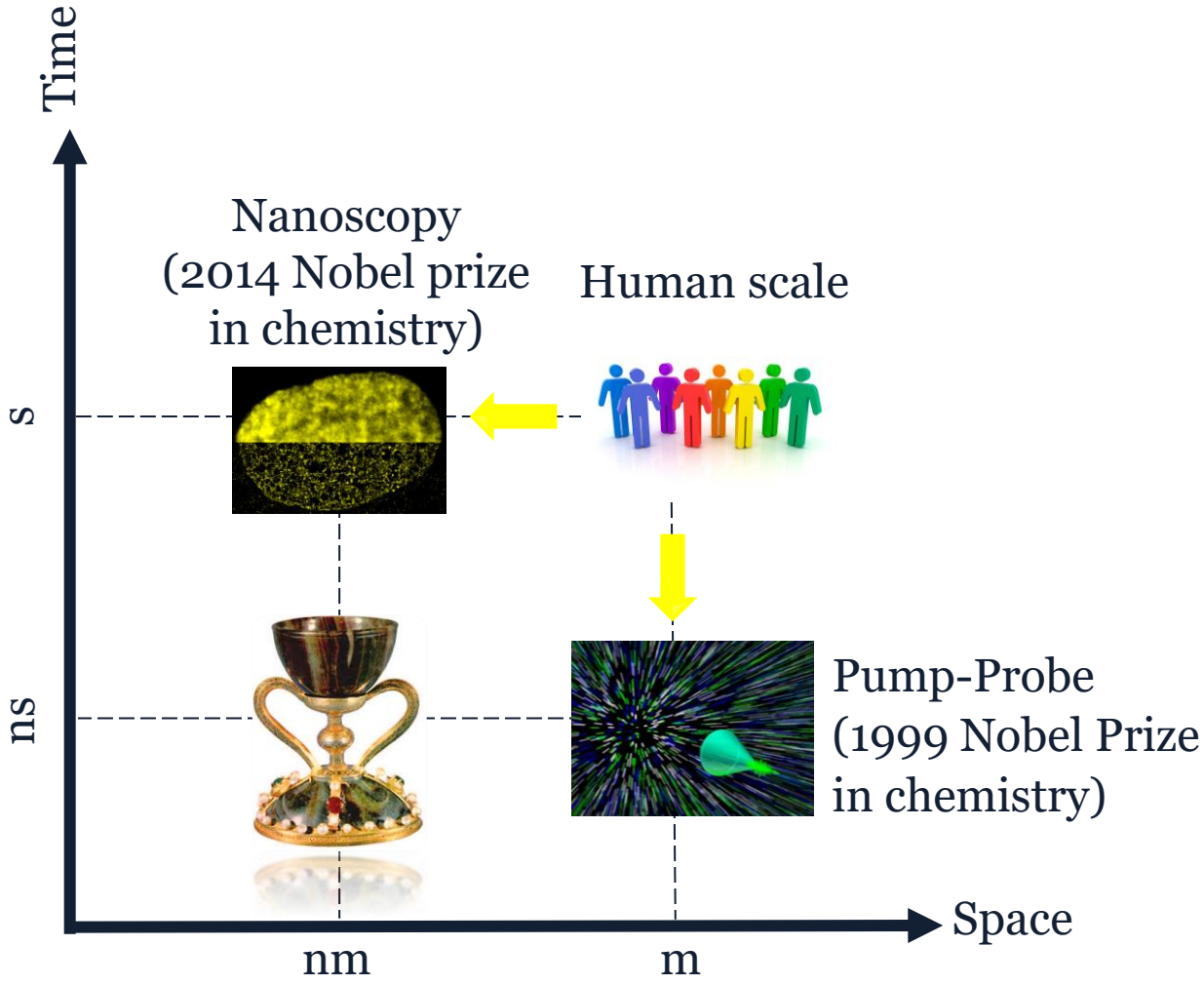
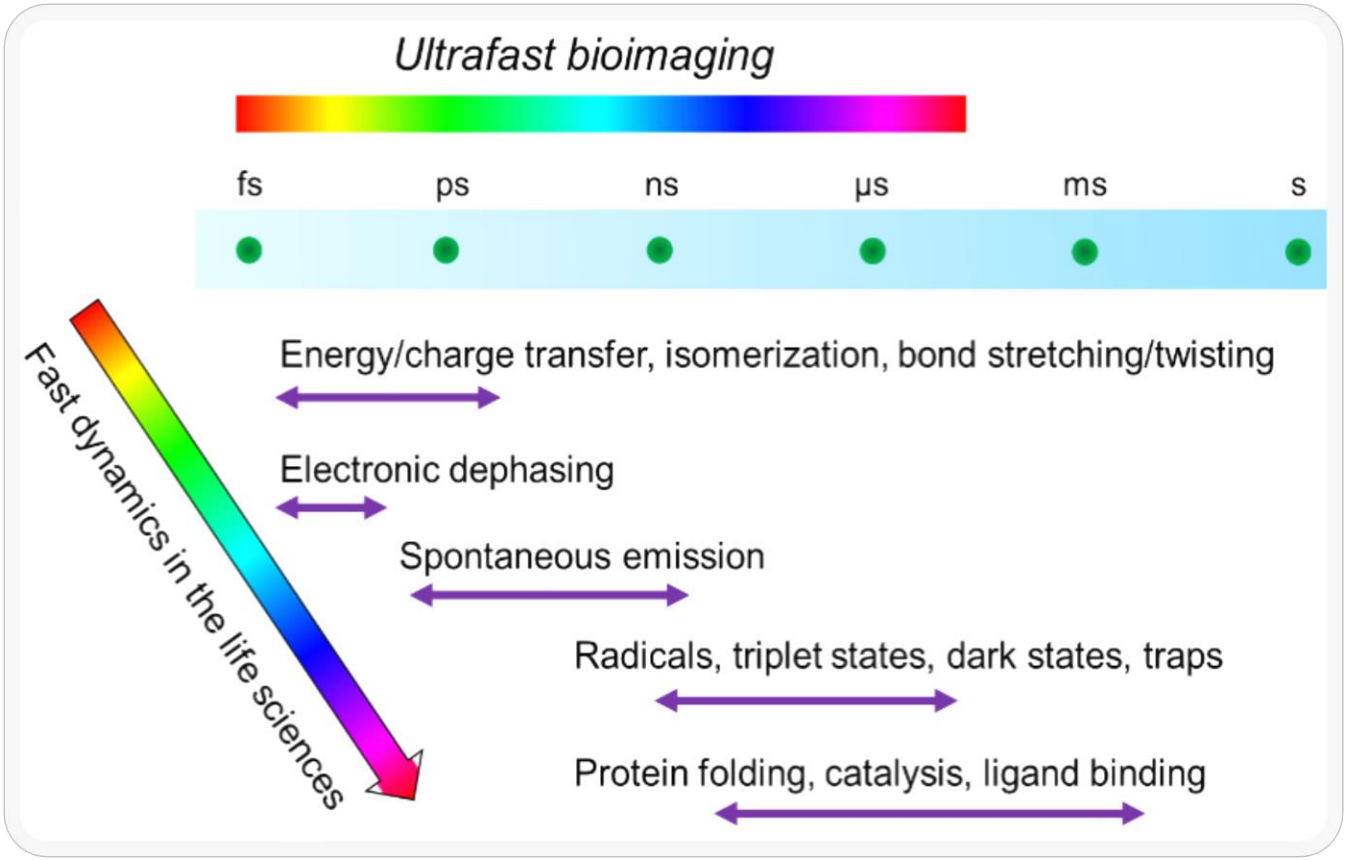
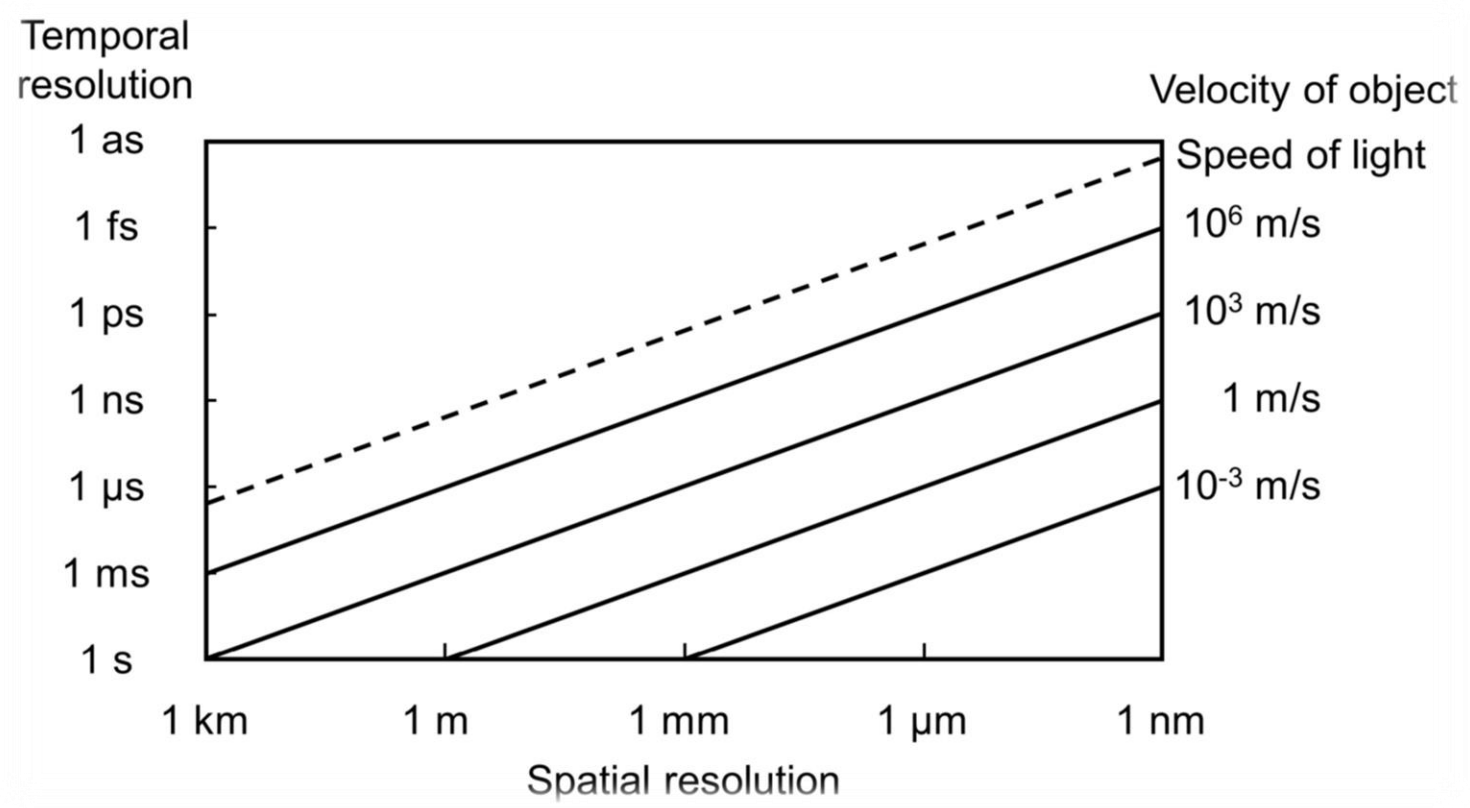
Ultrafast imaging



Ultrafast bioimaging

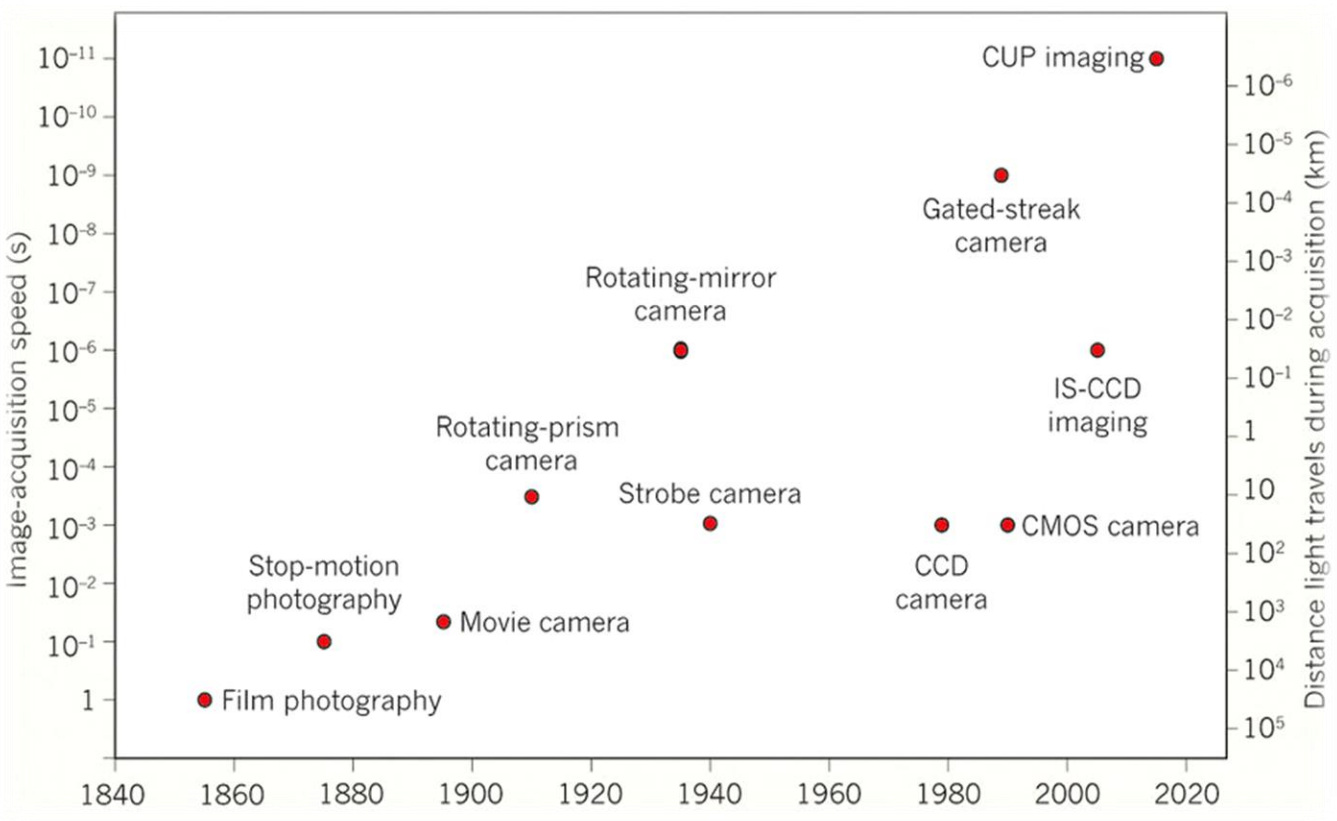


The need for ultrafast imaging at the microscopic scale



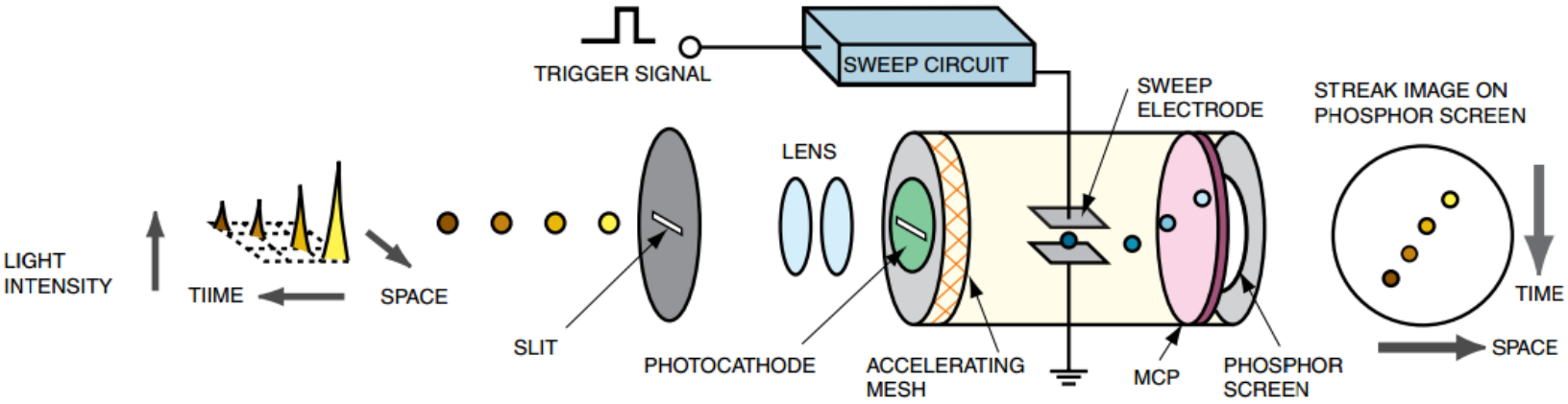
Nanophotonics, 5, 98-110 (2016)

Milestones



Nature **516**, 46-47 (2014)

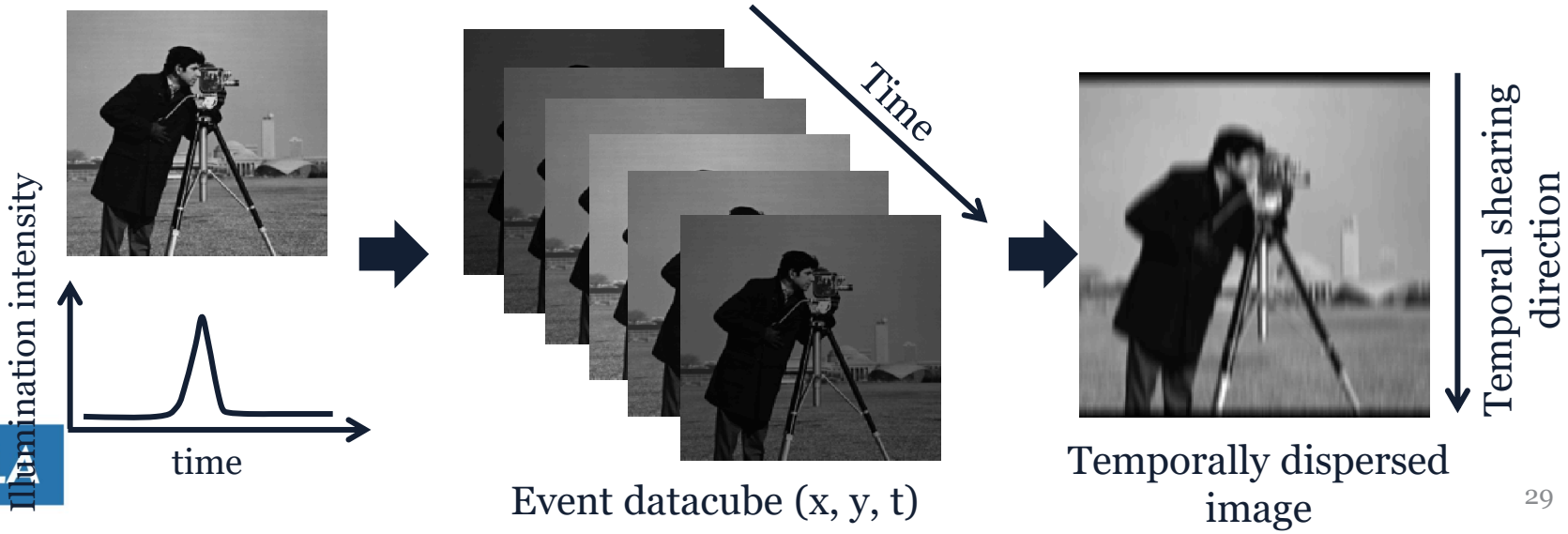
Streak camera



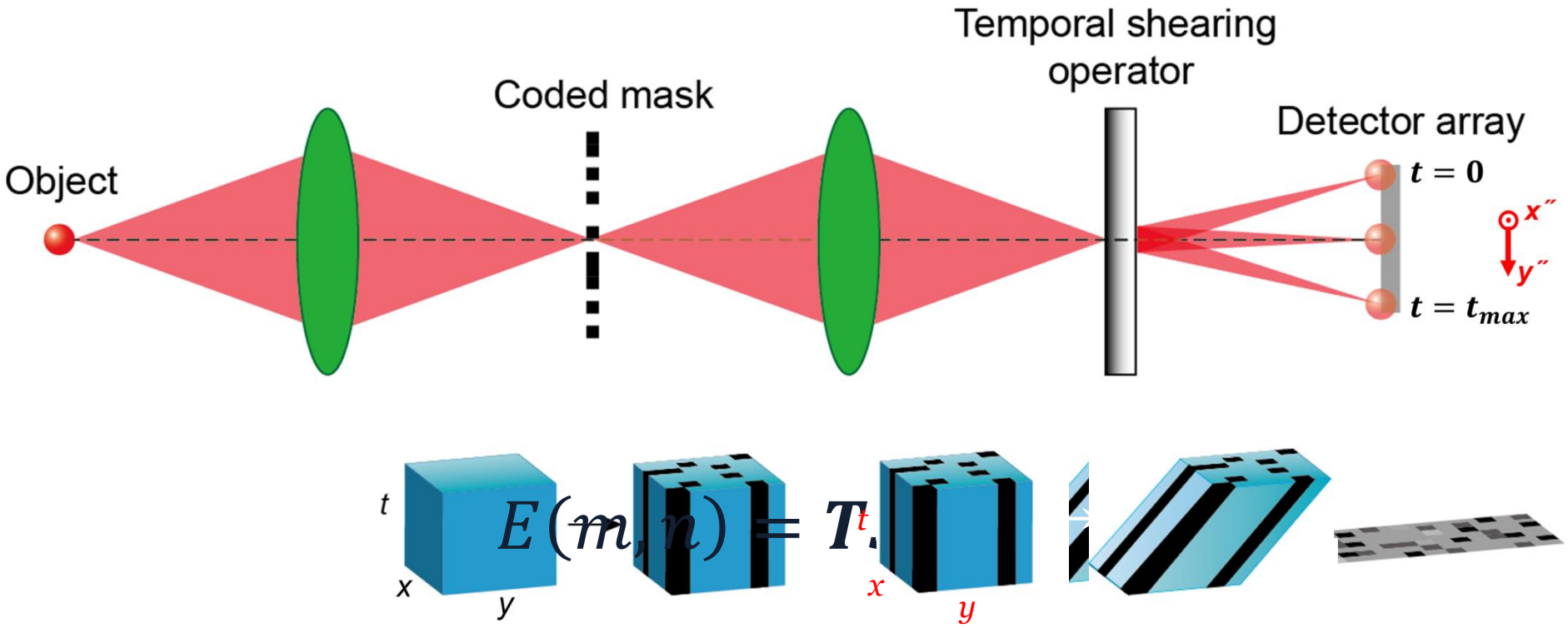
- Frame rate up to one trillion fps
- Problem:
  - 1D imaging only!

Snapshot ultrafast imaging

- Goal: convert a streak camera to a snapshot 2D imaging device
- Solution: fully open the entrance slit of a streak camera
- Problem: spatiotemporal mixing along the temporal shearing direction



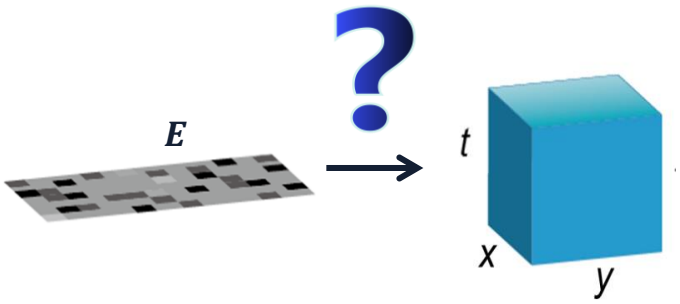
Compressed ultrafast photography (CUP)



- Image encoding (operator *C*)
- Temporal shearing (operator *S*)
- Spatiotemporal integration (operator *T*)
- $\boldsymbol{E(m,n)}$: optical energy measured at pixel *m*, *n* on the detector array
- $\boldsymbol{I(x,y,t)}$:Event datacube

$\boldsymbol{x,y}$: spatial coordinates; $\boldsymbol{t}$: time.

Image Reconstruction

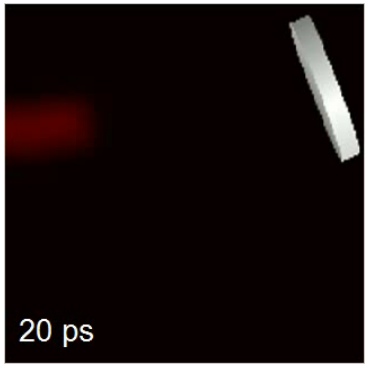


- Inverse problem formation: $\arg\min\{\frac{1}{2}\|E-\boldsymbol{O}I\|^2+\beta\Phi(I)\}$
  - Operator $\boldsymbol{O}=\boldsymbol{TSC}$
    - $\boldsymbol{T}$: spatiotemporal integration operator
    - $\boldsymbol{S}$: temporal shearing operator
    - $\boldsymbol{C}$: Image encoding operator
  - $\boldsymbol{E}$: optical energy
  - $\boldsymbol{I}$: event datacube
  - $\boldsymbol{\beta}$: regularization parameter
  - $\boldsymbol{\Phi(I)}$: regularization function (total variation)

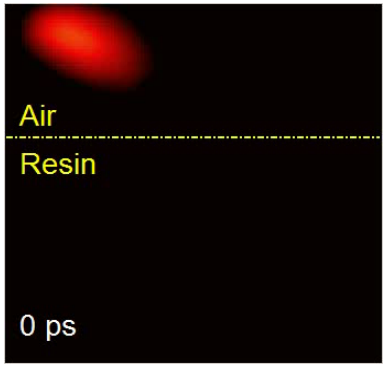
Solution: Two-Step Iterative Shrinkage/Thresholding (TwIST) algorithm

The world's fastest passive camera tops 100 billion frames per second

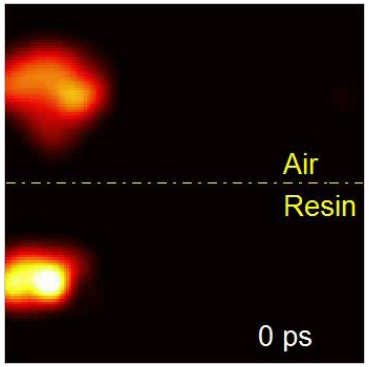
Reflection



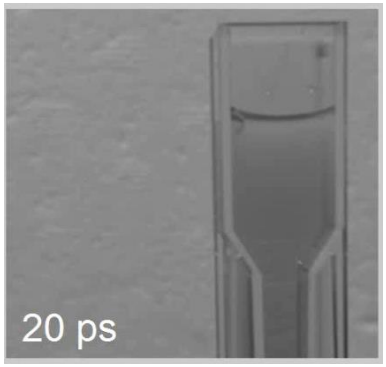
Refraction

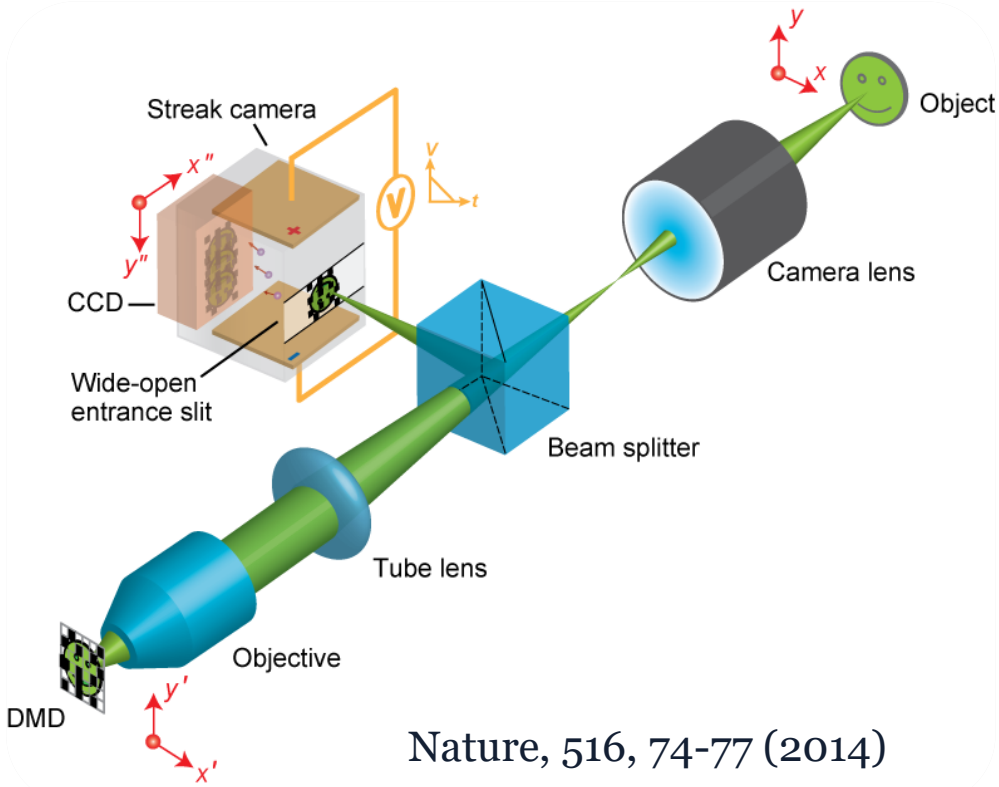


Laser pulse racing



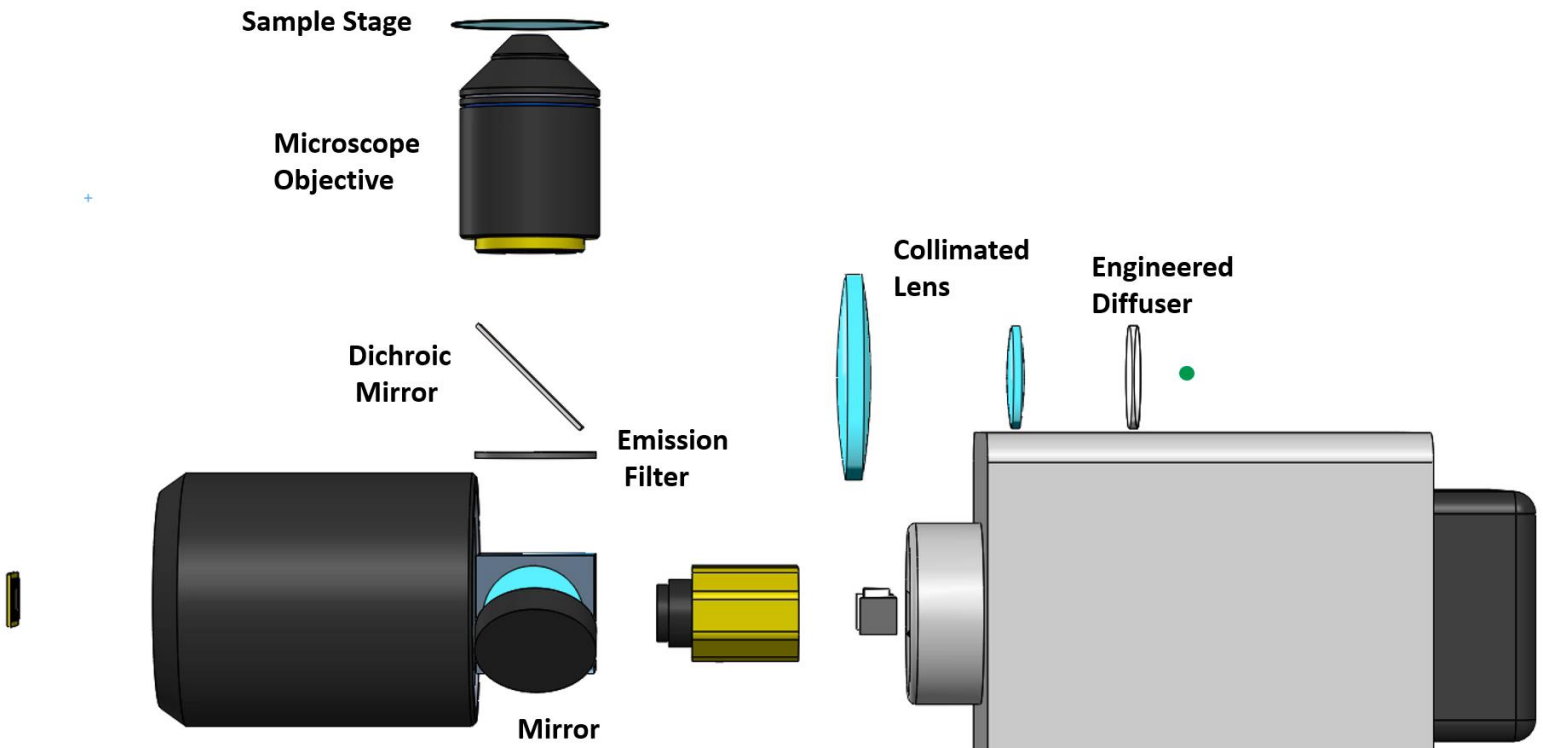
Fluorescence





Nature, 516, 74-77 (2014)

Ultrafast compressed imaging microscopy



Side view of compressed FLIM

Channel outputs:

$E_{CUP\_1} = \boldsymbol{TSC_1}(1-\eta)I(x,y,t)$

$E_{CUP\_2} = \boldsymbol{TSC_2}1-\eta)I(x,y,t)$

$\boldsymbol{T}$: spatiotemporal integration operator
$\boldsymbol{S}$: temporal shearing operator
$\boldsymbol{C}$: Image encoding operator, $\boldsymbol{C_1} + \boldsymbol{C_2} = \boldsymbol{J}$, where $\boldsymbol{J}$ is a matrix of ones

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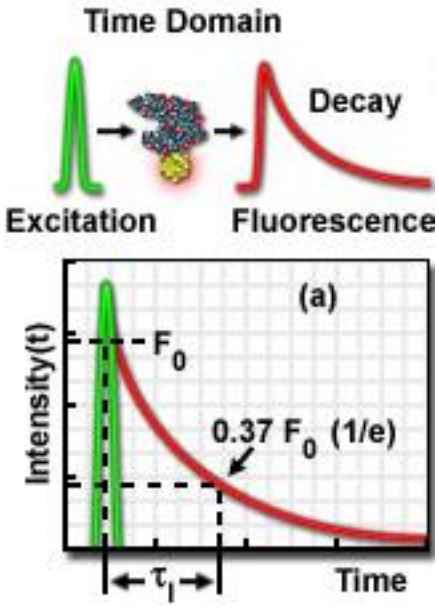
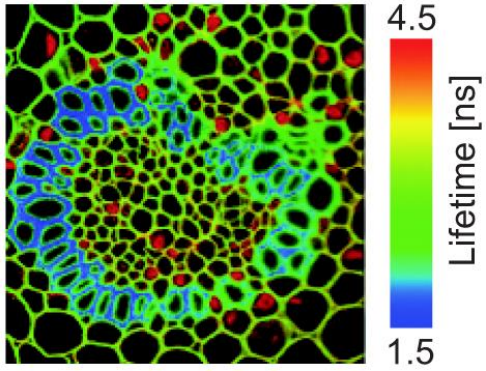
Fluorescence imaging lifetime microscopy (FLIM)





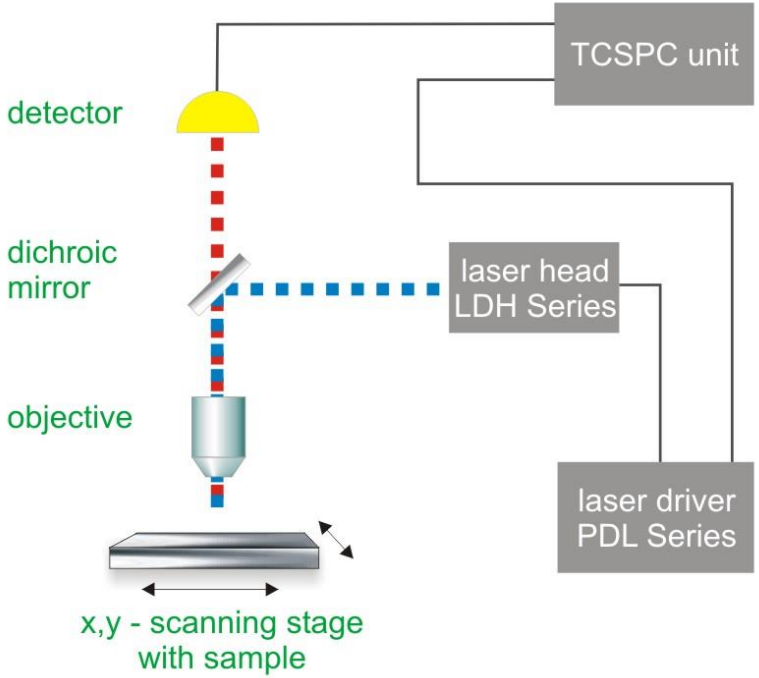
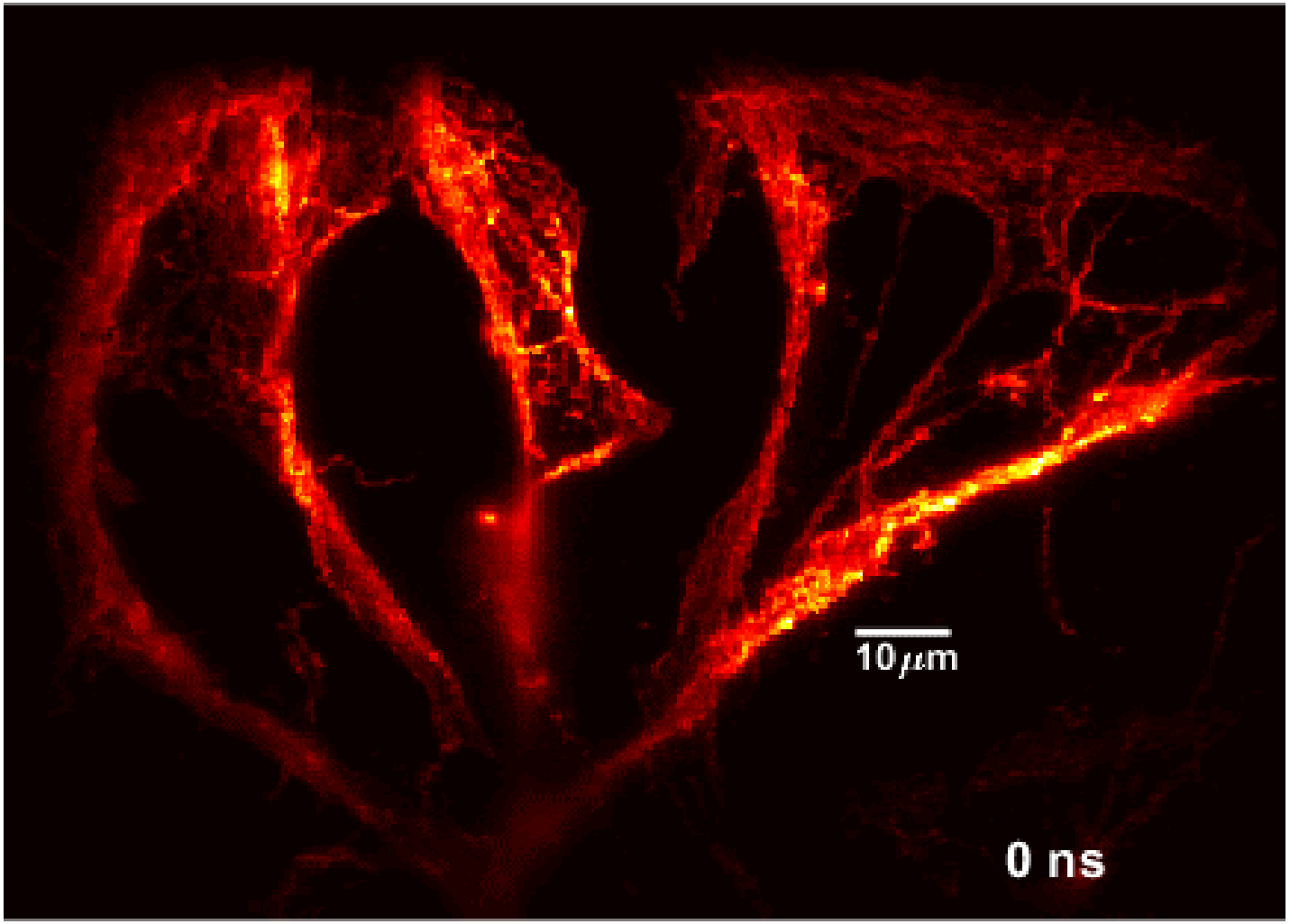


Image Courtesy of PICOQUANT

Time-lapse fluorescence decay after pulsed excitation (neuron imaging)



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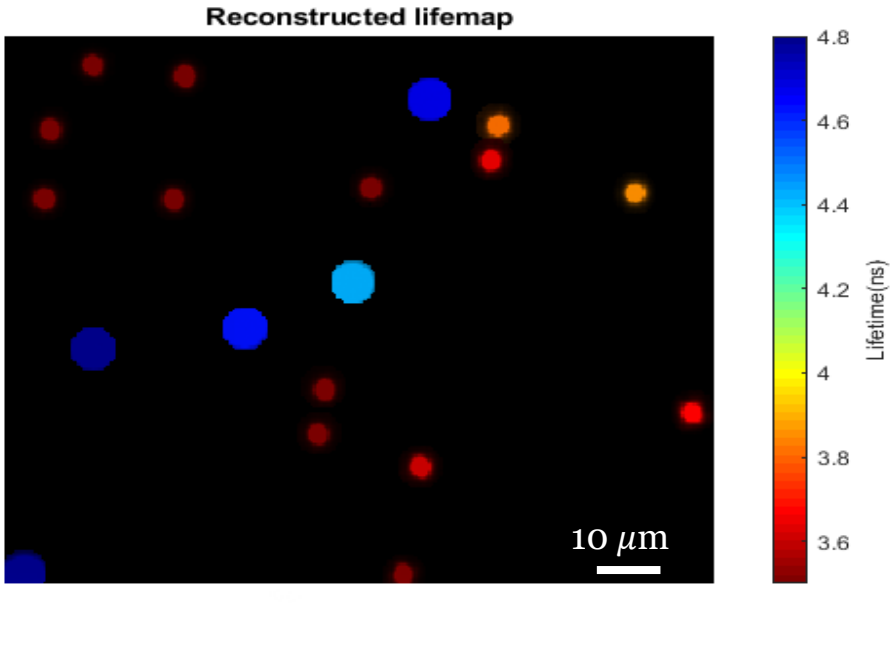
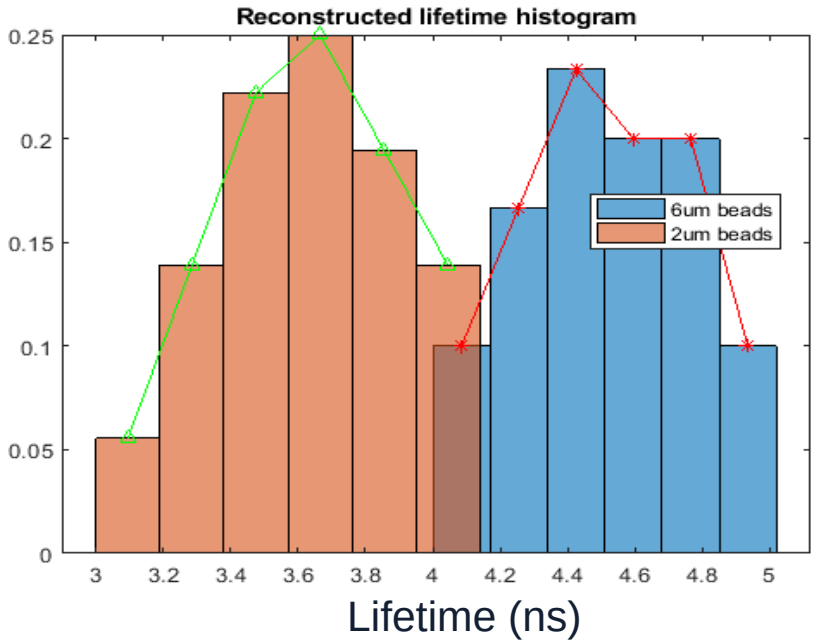
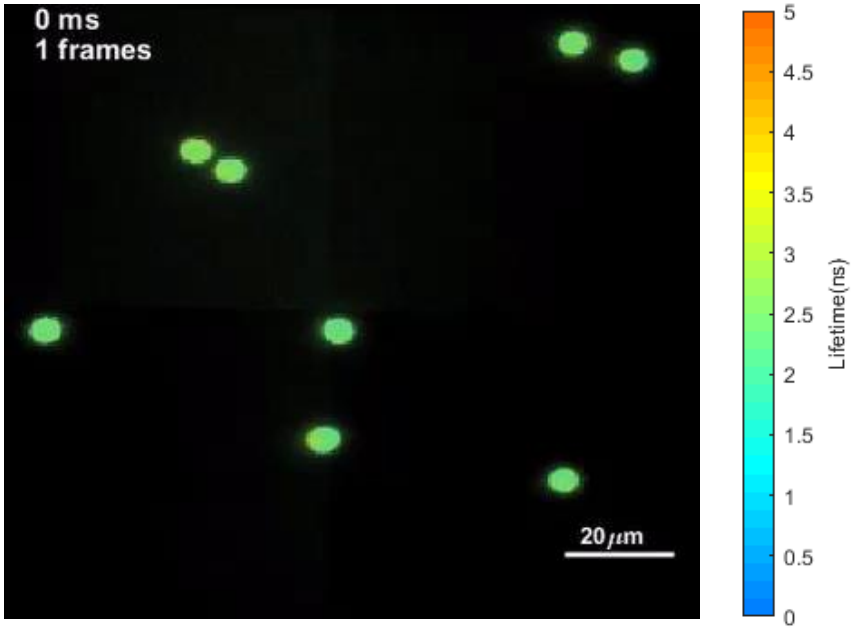
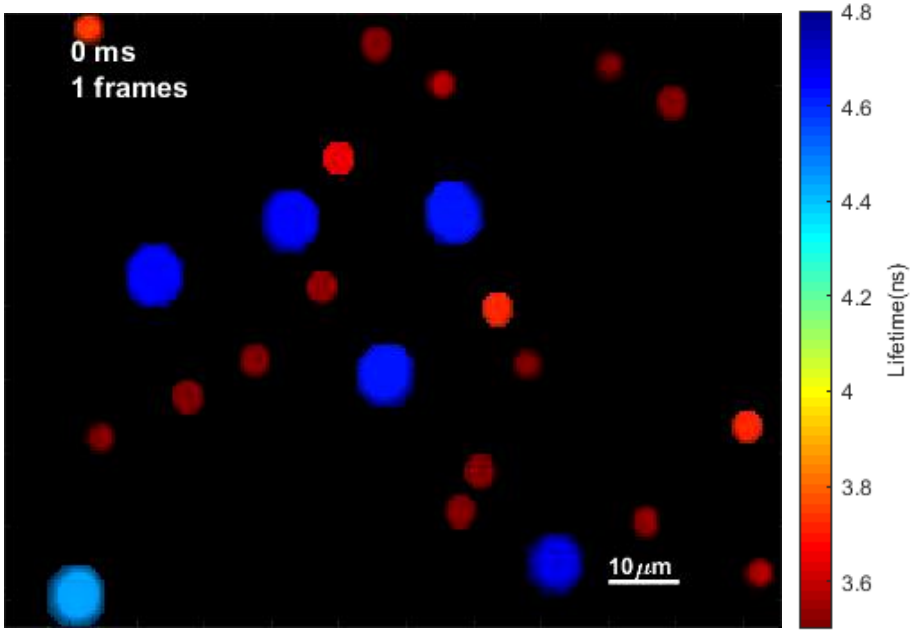
Snapshot lifetime imaging of fluorescence beads





Dynamic lifetime imaging of bead diffusion at 75 Hz





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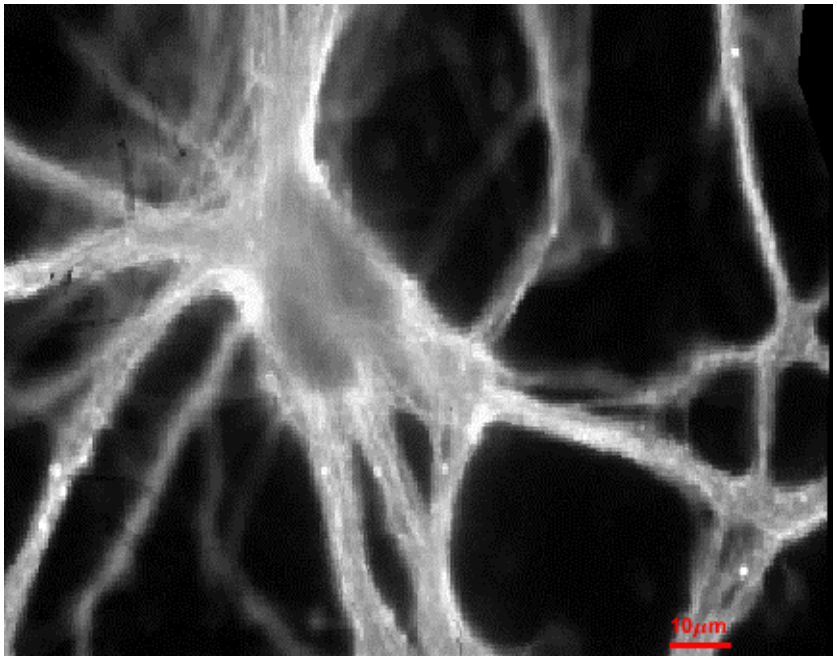
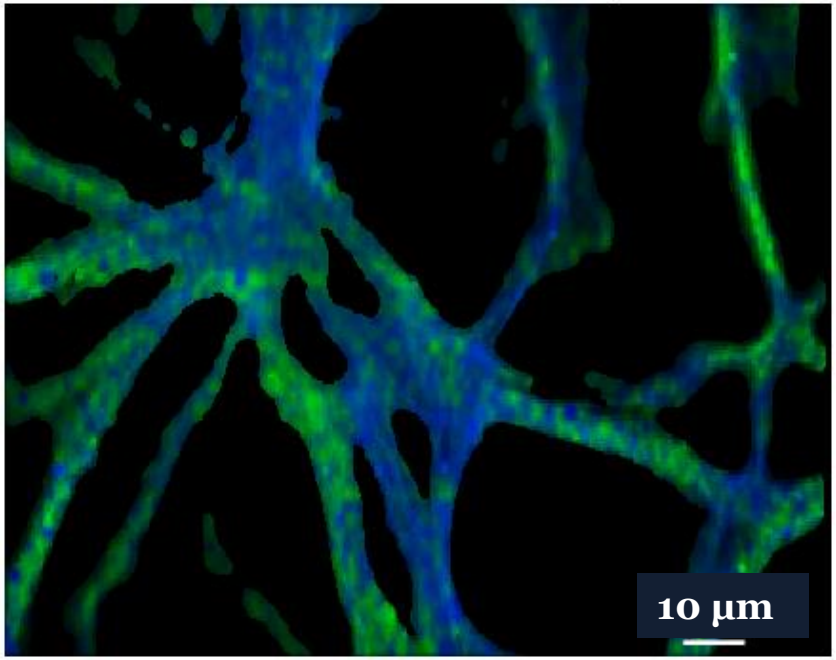
Ma, Y., Lee, Y., Best-Popescu, C. & Gao, L. High-speed compressed-sensing fluorescence lifetime imaging microscopy of live cells. ***PNAS*** 118, e2004176118 (2021)

Lifetime unmixing of double-labeled neurons



Intensity image



Unmixed image

Cytoskeleton: Alex 546 and Alex 555

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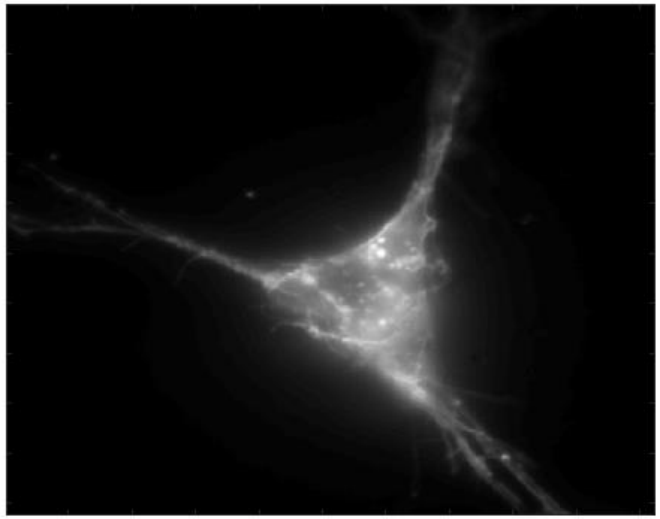
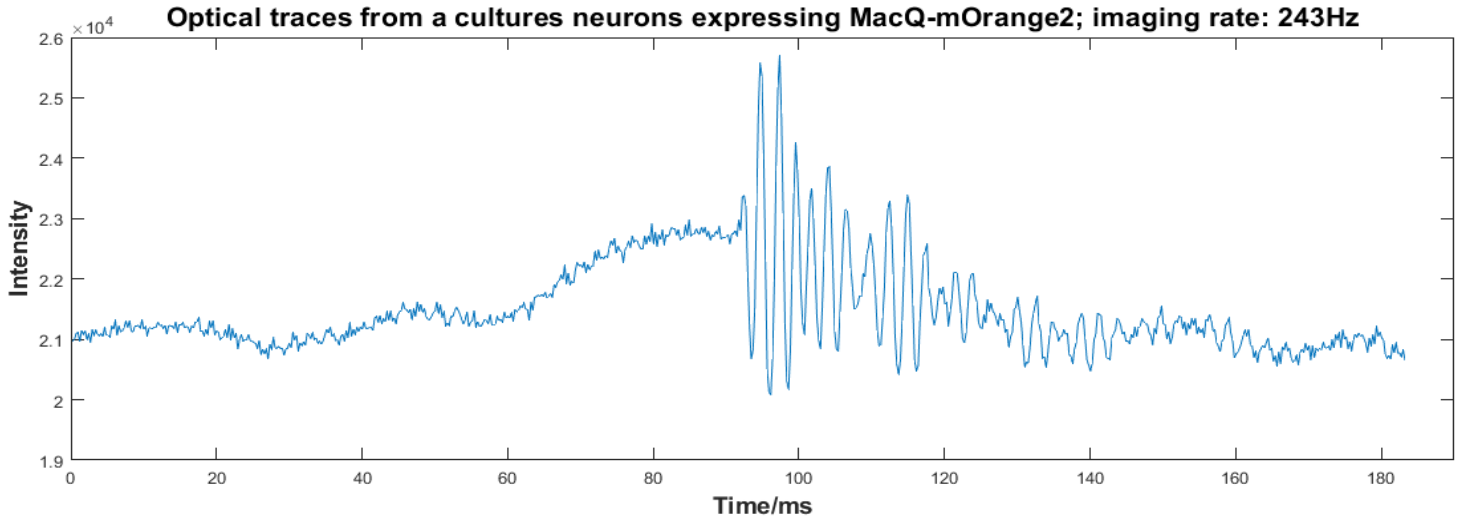
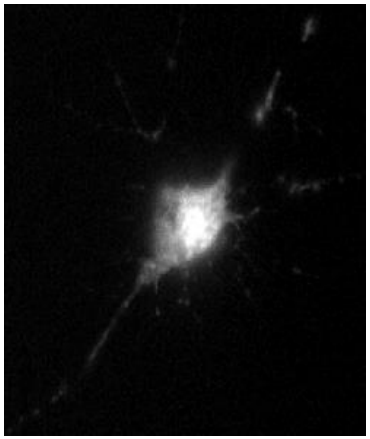
Ma, Y., Lee, Y., Best-Popescu, C. & Gao, L. High-speed compressed-sensing fluorescence lifetime imaging microscopy of live cells. ***PNAS*** 118, e2004176118 (2021)

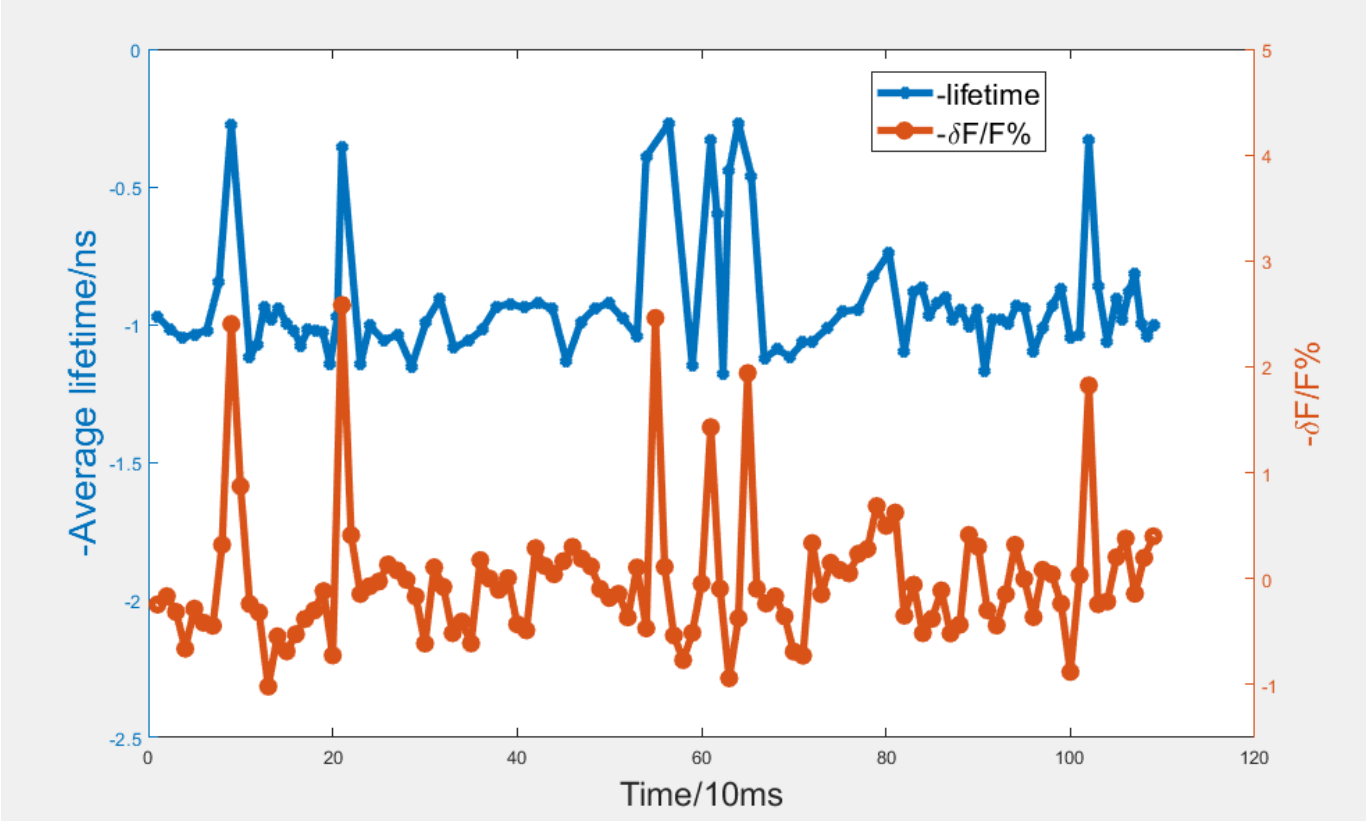
Fluorescence signals from neurons labelled with MacQ-mOrange2





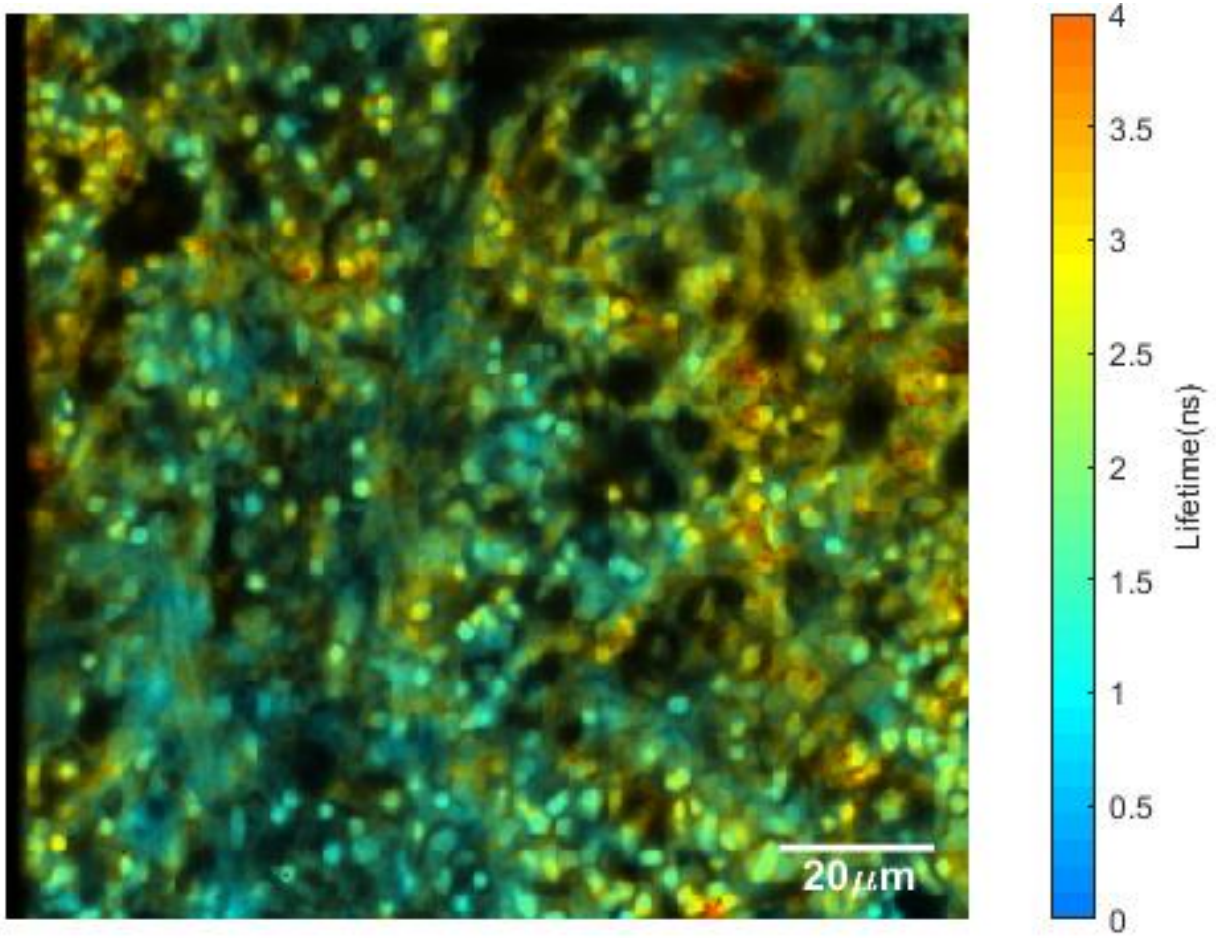
High-speed FLIM of neuron spiking (100 fps)





Ma, Y., Lee, Y., Best-Popescu, C. & Gao, L. High-speed compressed-sensing fluorescence lifetime imaging microscopy of live cells. ***PNAS*** 118, e2004176118 (2021)

Lifetime imaging of fluorescence quenching in living tissue



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Outline

- Plenoptic function of light
- Multidimensional optical bioimaging
  - Image Mapping Spectrometry (x, y, λ)
  - Ultrafast Compressed Imaging Microscopy(x, y, t)
  - Light field tomography (x, y, θ)
- Summary

- x, y: Spatial coordinates
- θ, φ: Emittance angles
- λ: Wavelength

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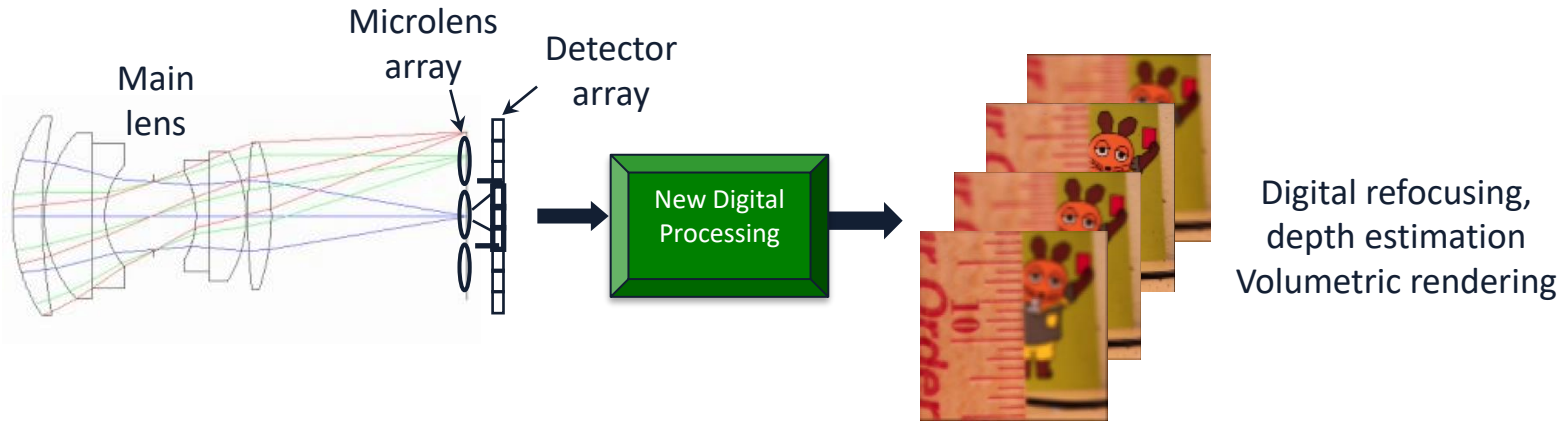
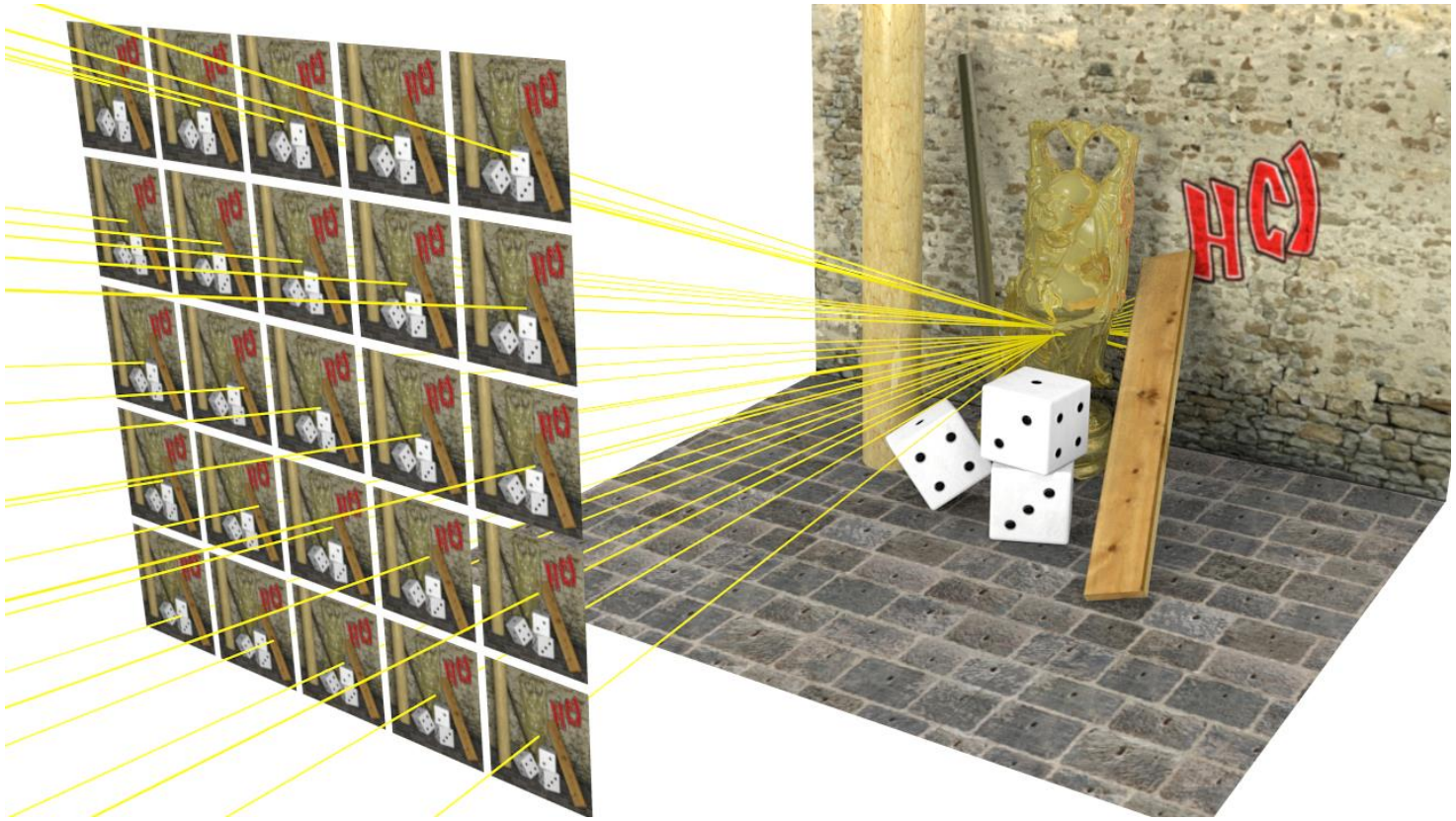
Light field cameras (x, y, θ, φ)



Data redundance in light field imaging



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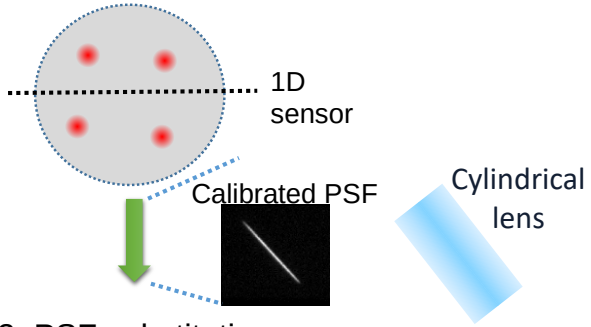
Light field tomography (LIFT)

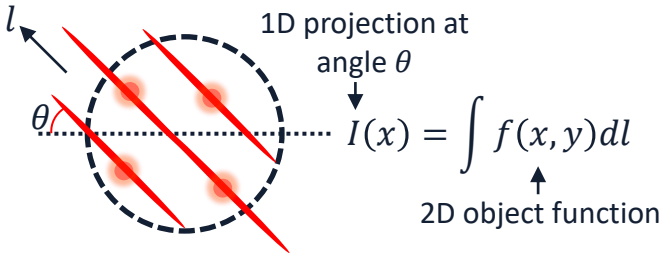
Problems to solve: **High-speed** light field imaging with only a **1D detector array**

Core idea: Reformulate **3D imaging** as a **sparse-view computed tomography (CT) problem** by using **cylindrical lenses** to acquire *en-face* parallel beam projections of the object.

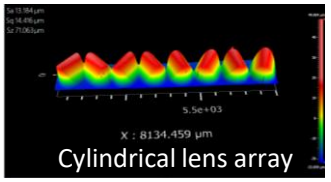
1. Geometric imaging model

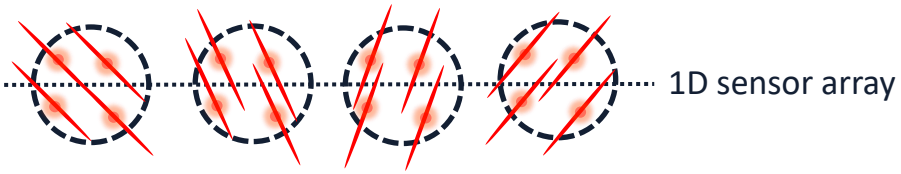


2: PSF substitution



3. Acquisition of multiple projections





4. Calculation of Depths from the light field

If each subfield images the same scene from different perspectives, the disparity can be extracted for calculating depths.

Light-field data readout by a 1D sensor array!
Full-fledged light field imaging capabilities: numerical refocusing, extended depth of field, 3D reconstruction, etc.

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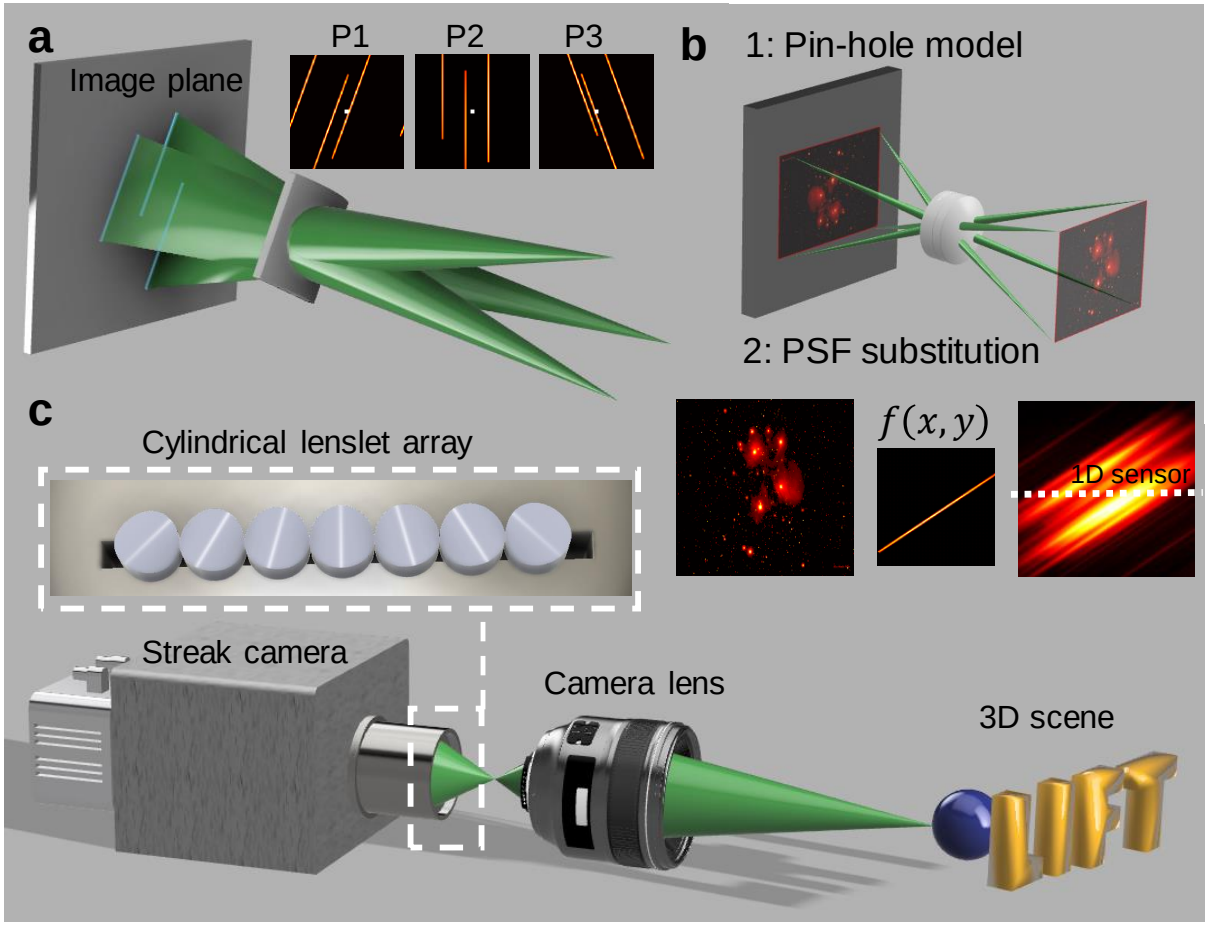
Ultrafast light field tomography (LIFT)



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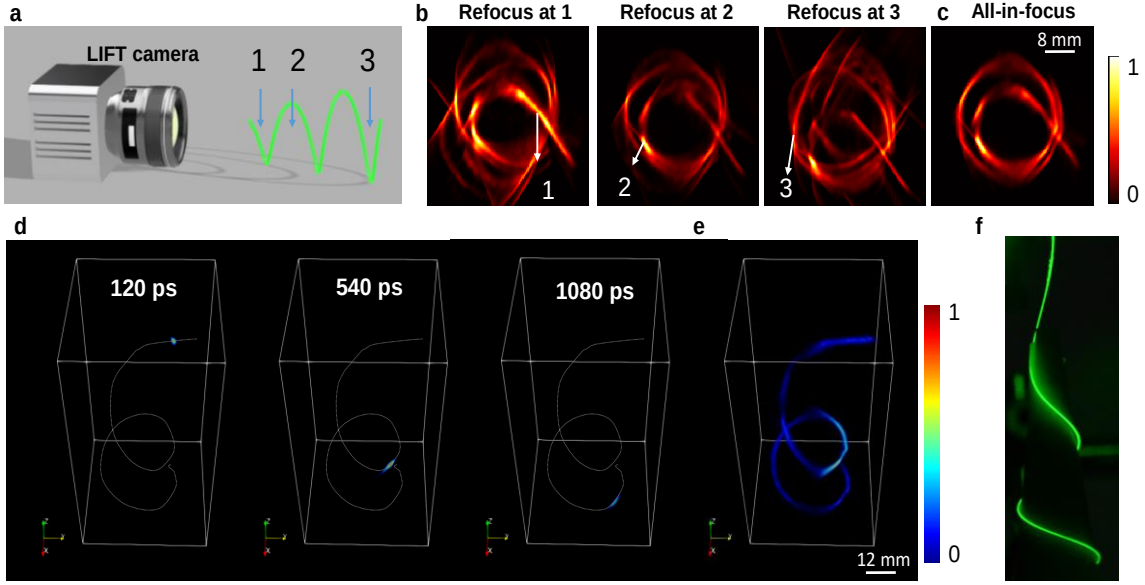
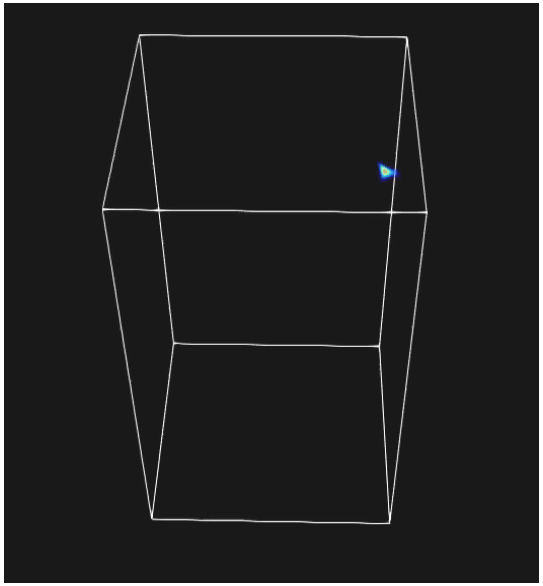
Xiaohua Feng, Liang Gao, "Ultrafast light field tomography for snapshot transient and non-line-of-sight imaging", ***Nature Communications***, in press (2021) .

Ultrafast 3D imaging of a laser pulse propagation in a helical fiber





Xiaohua Feng, Liang Gao, "Ultrafast light field tomography for snapshot transient and non-line-of-sight imaging", ***Nature Communications***, in press (2021) .

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Summary

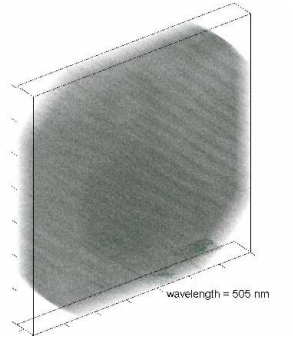
Microfabrication

High-performance computation

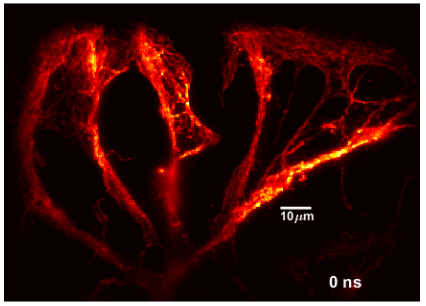
Modern detector technologies

Merge

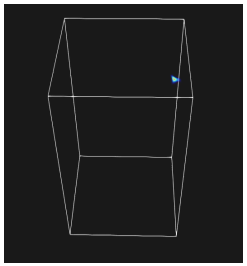
Hyperspectral imaging (x, y, λ)



Ultrafast imaging (x, y, t)



Light field imaging (x, y, θ)



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Summary

Q1: How to make measurement possible?

Q2: How to make measurement efficient?

	Q1 (Dim reduction)	Q2 (Sampling)
IMS	(x, y, λ) to (x', y')	Nyquist sampling
CUP	(x, y, t) to (x', y')	Compressed sensing
LIFT	(x, y, θ) to x'	Compressed sensing

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Acknowledgement

Postdocs:

- Xiaohua Feng
- Jongchan Park

Graduate Students:

- Yayao Ma
- Jorge Mora
- Qi Cui
- Xiaoxi Du

Multiple openings for PhD students and Postdocs!

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Development of next-generation multidimensional optical imaging devices

Liang Gao
Assistant Professor
Department of Bioengineering
UCLA

UCLA

iOptics Lab