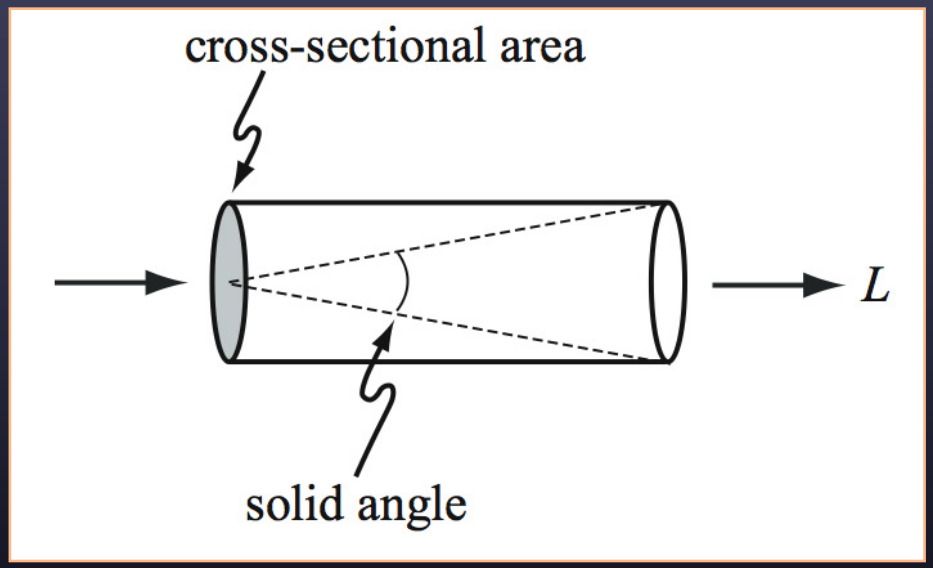
Light field photography and microscopy

Marc Levoy

Computer Science Department
Stanford University

The light field
(in geometrical optics)

Radiance as a function of position and direction in a static scene with fixed illumination

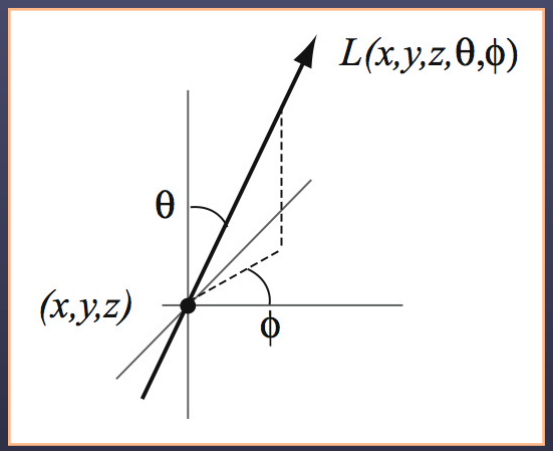


L is radiance in watts / (m^2 steradians)

Dimensionality of the light field

- for general scenes

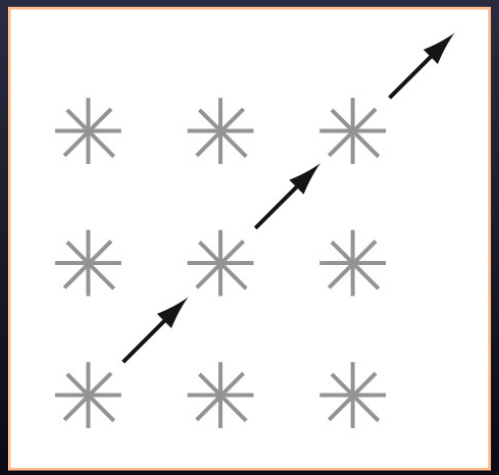
  $\Rightarrow$ 5D function



$L(x, y, z, \theta, \phi)$

- in free space

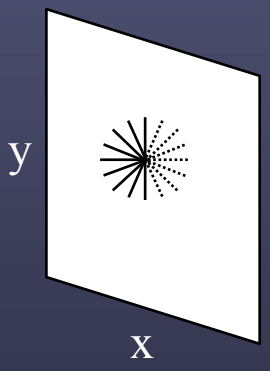
  $\Rightarrow$ 4D function



$L(?)$

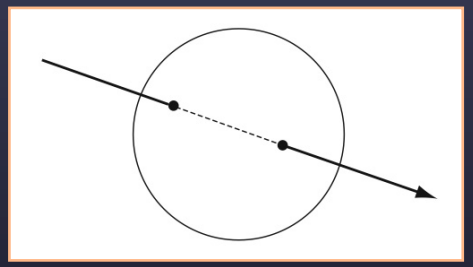
Some candidate parameterizations for the 4D light field

Point-on-plane + direction



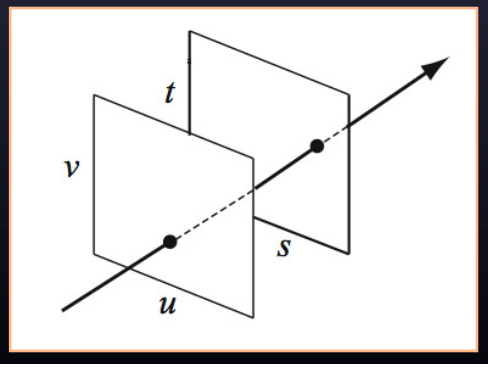
$L (x, y, \theta, \phi)$

Two points on a sphere



$L (\theta_1, \phi_1, \theta_2, \phi_2)$

Points on two planes



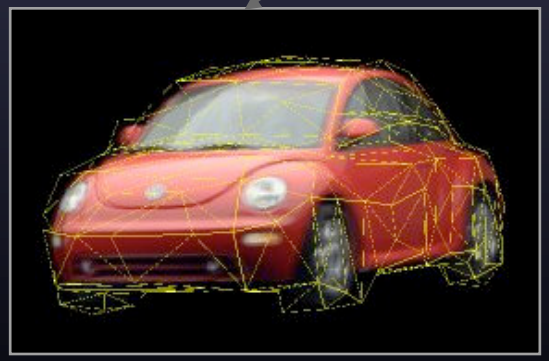
$L (u, v, s, t)$

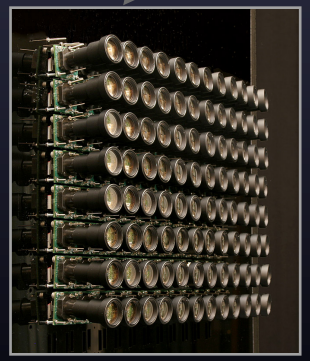
Devices for recording light fields

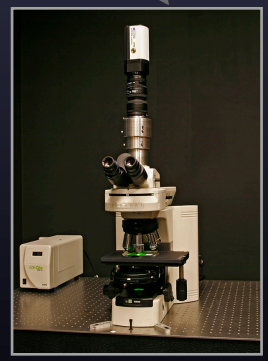
big scenes

small scenes

- handheld camera [Buehler 2001]
- array of cameras [Wilburn 2005]
- plenoptic camera [Ng 2005]
- light field microscope [Levoy 2006]





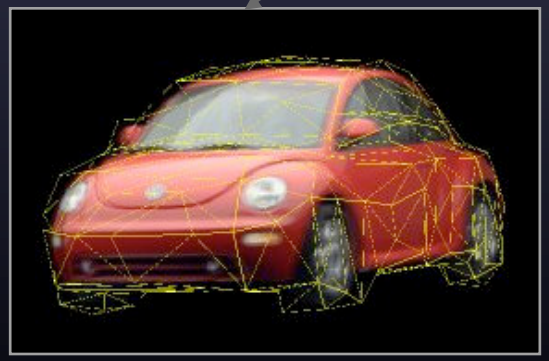
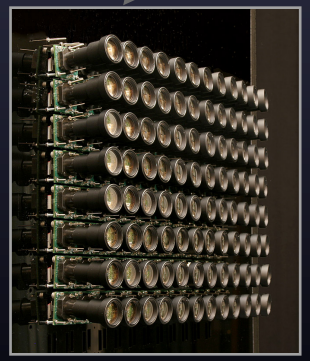


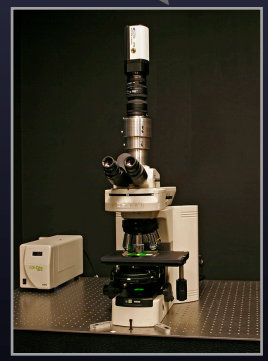
and creating
Devices for recording light fields

big scenes

small scenes

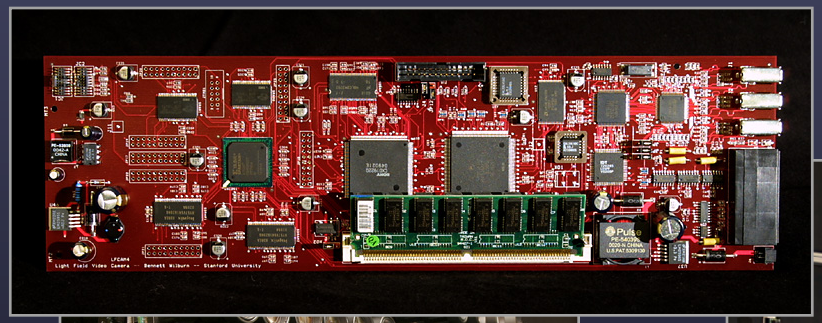
- handheld camera [Buehler 2001]
- array of cameras [Wilburn 2005]
- plenoptic camera [Ng 2005]
- light field microscope [Levoy 2006]
- light field illumination

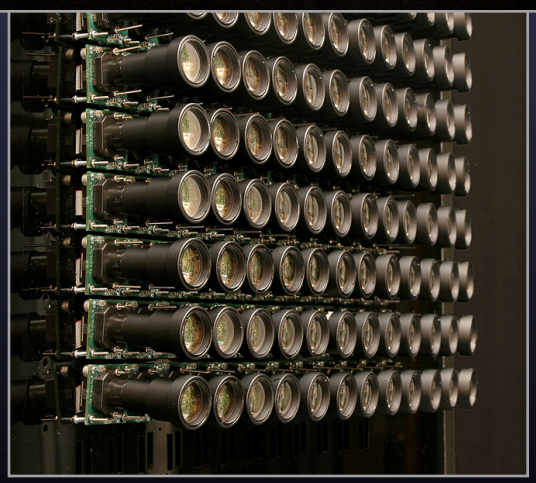



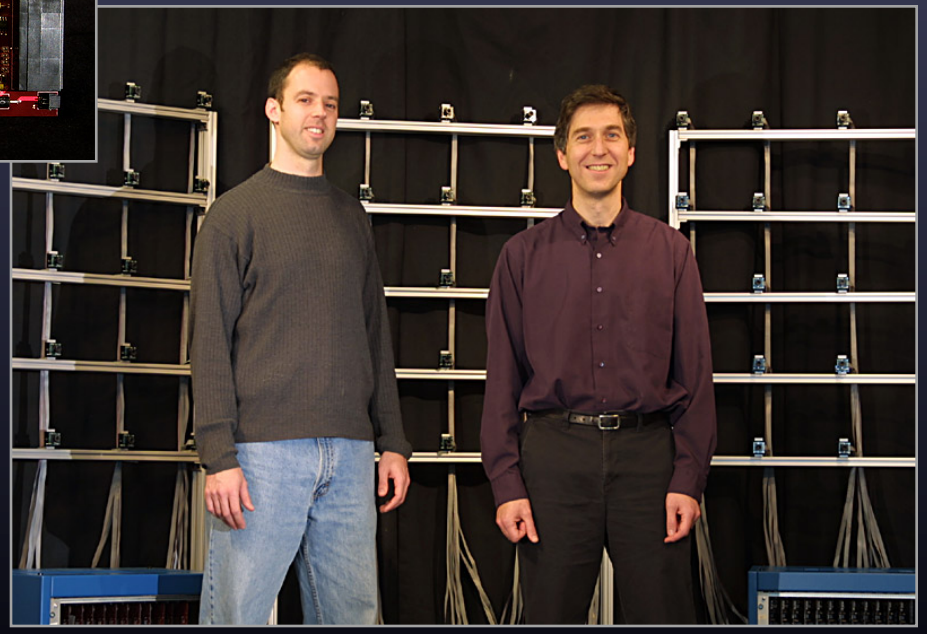


Stanford Multi-Camera Array
[Wilburn SIGGRAPH 2005]

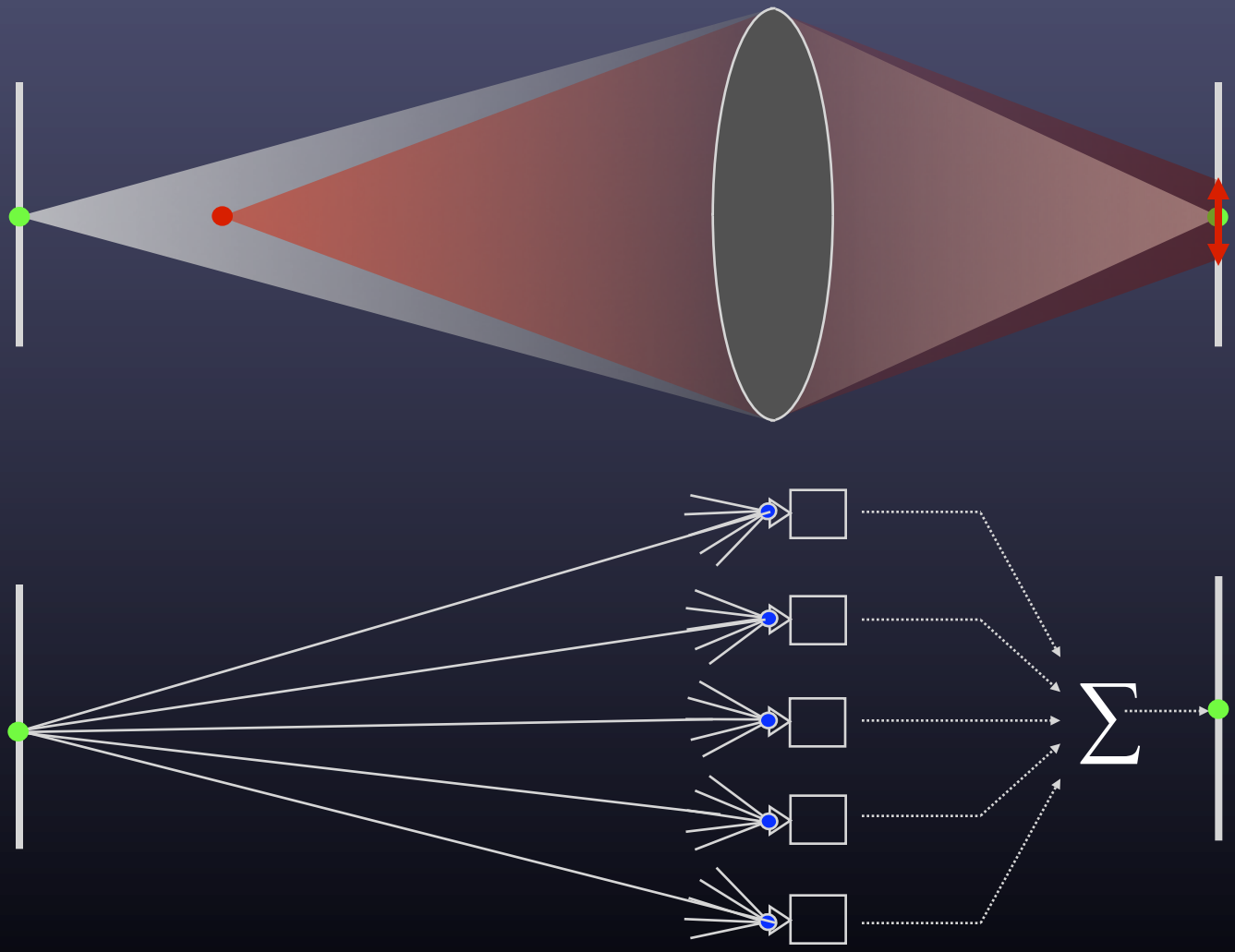
- 640 × 480 pixels × 30 fps × 128 cameras
- synchronized timing
- continuous streaming
- flexible arrangement



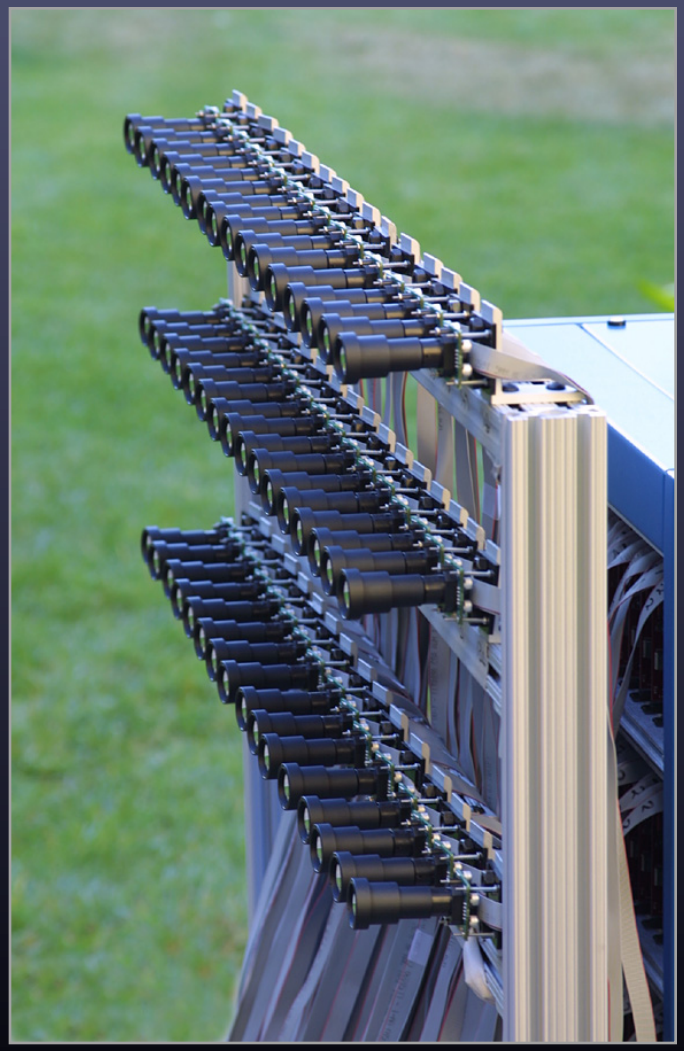


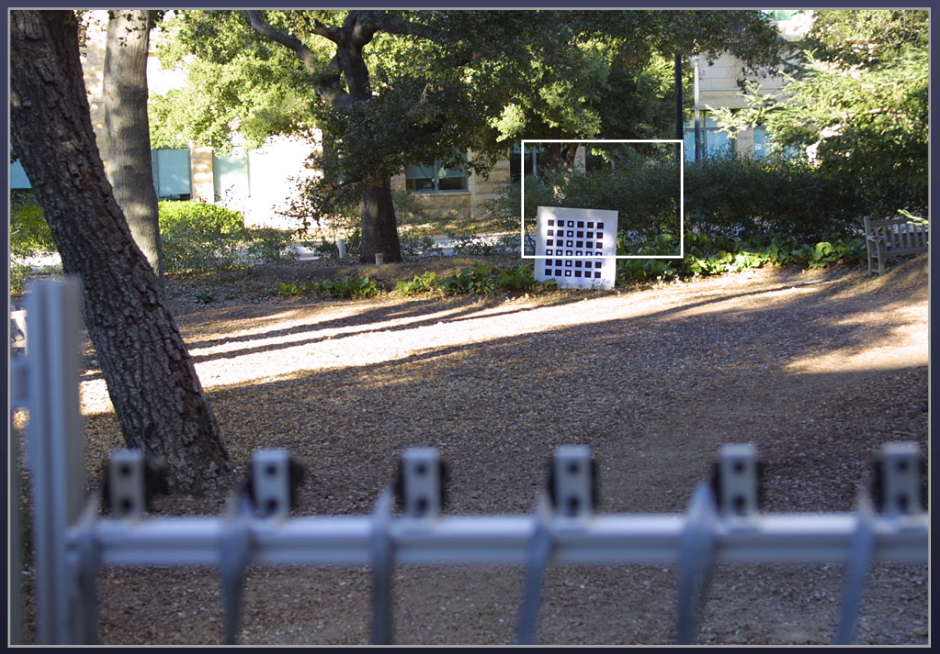


Synthetic aperture photography



Example using 45 cameras
[Vaish CVPR 2004]



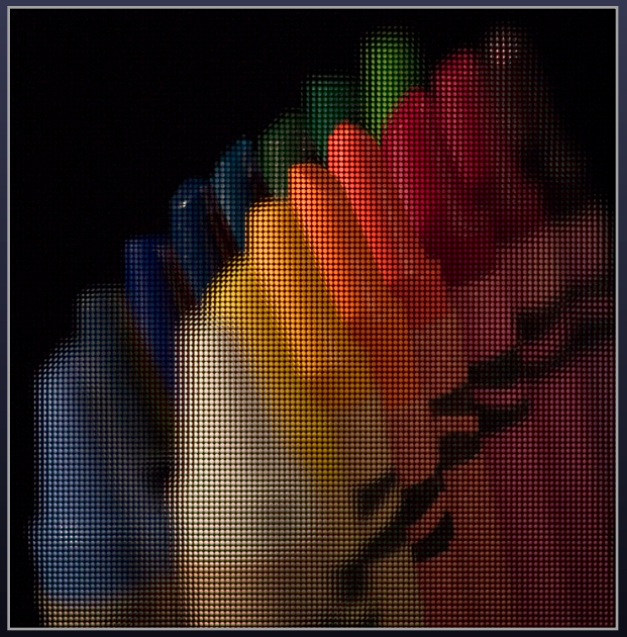


(movie is available at http://graphics.stanford.edu/projects/array)

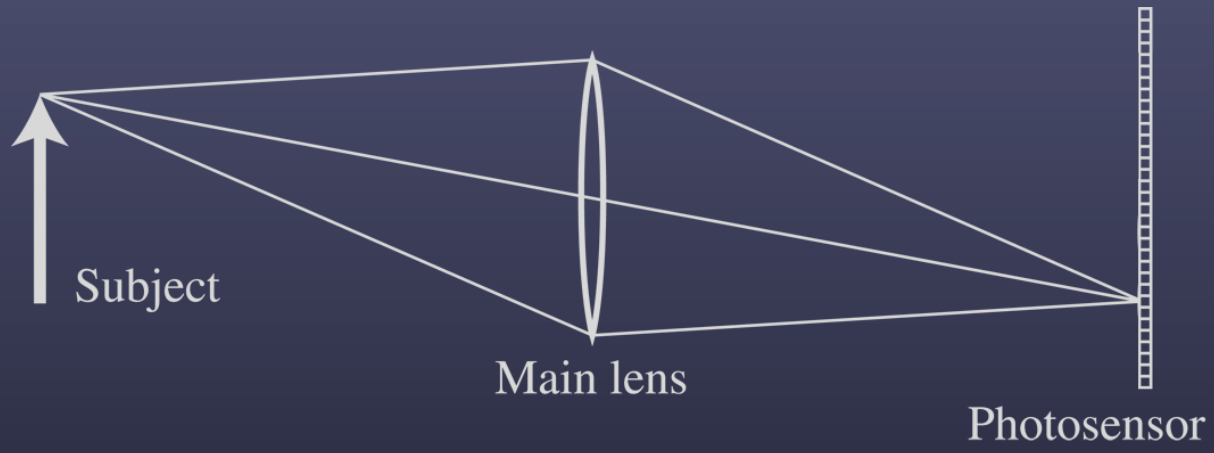
Light field photography using a handheld plenoptic camera

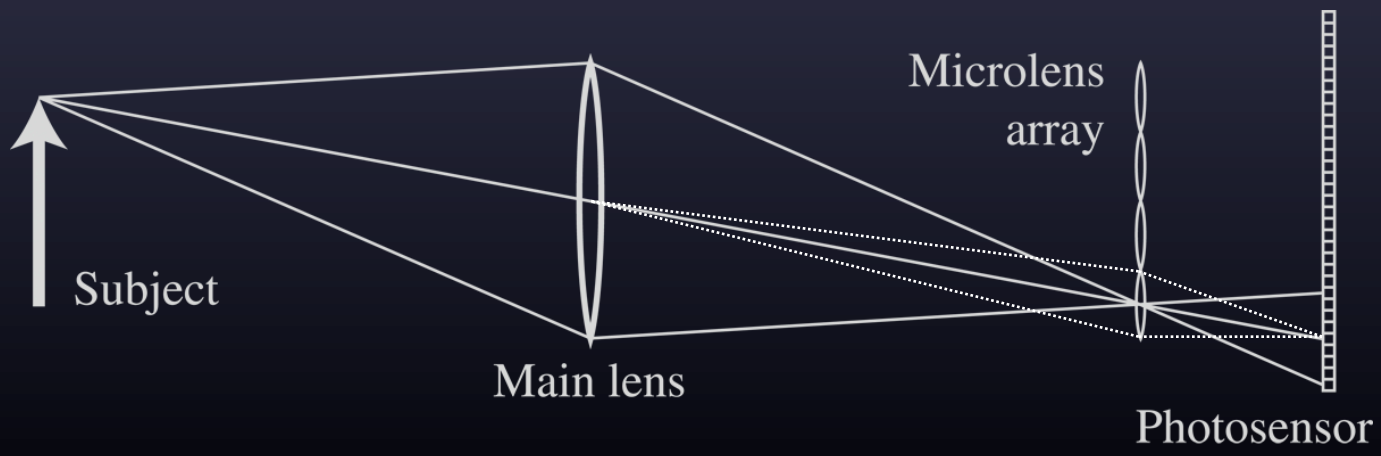
Ren Ng, Marc Levoy, Mathieu Brédif,
Gene Duval, Mark Horowitz and Pat Hanrahan

(Proc. SIGGRAPH 2005
and TR 2005-02)

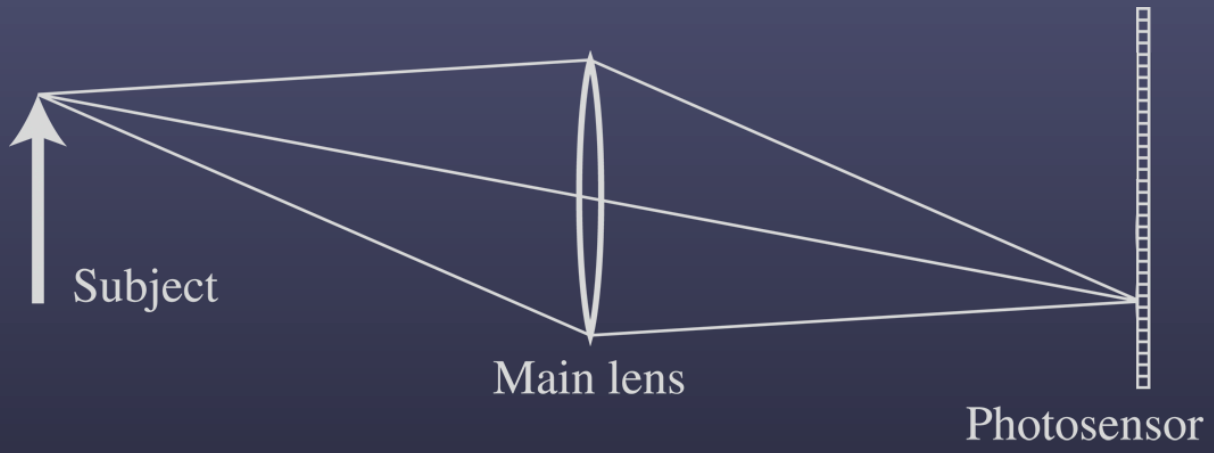


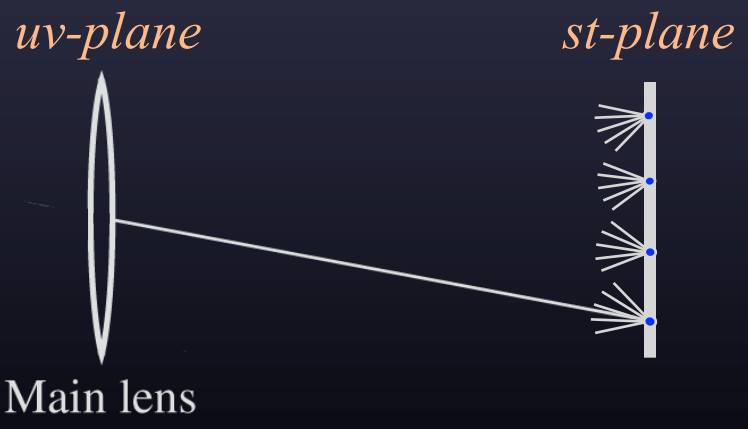
Conventional versus light field camera





Conventional versus light field camera

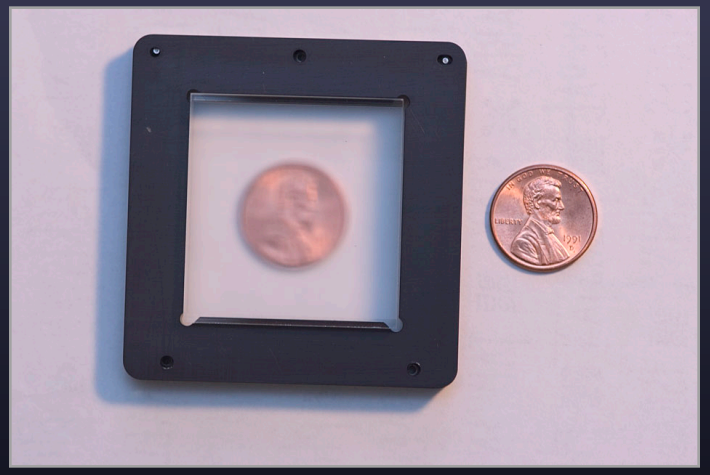




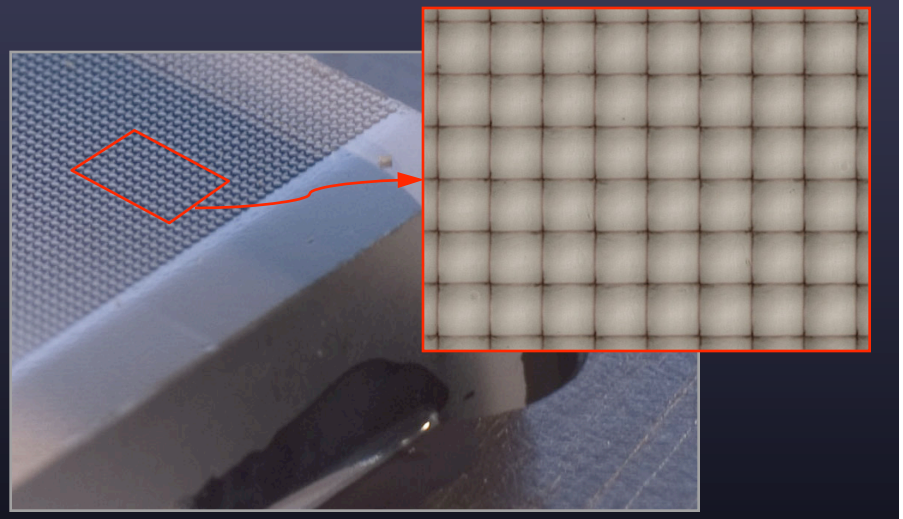
Prototype camera

Contax medium format camera

Kodak 16-megapixel sensor

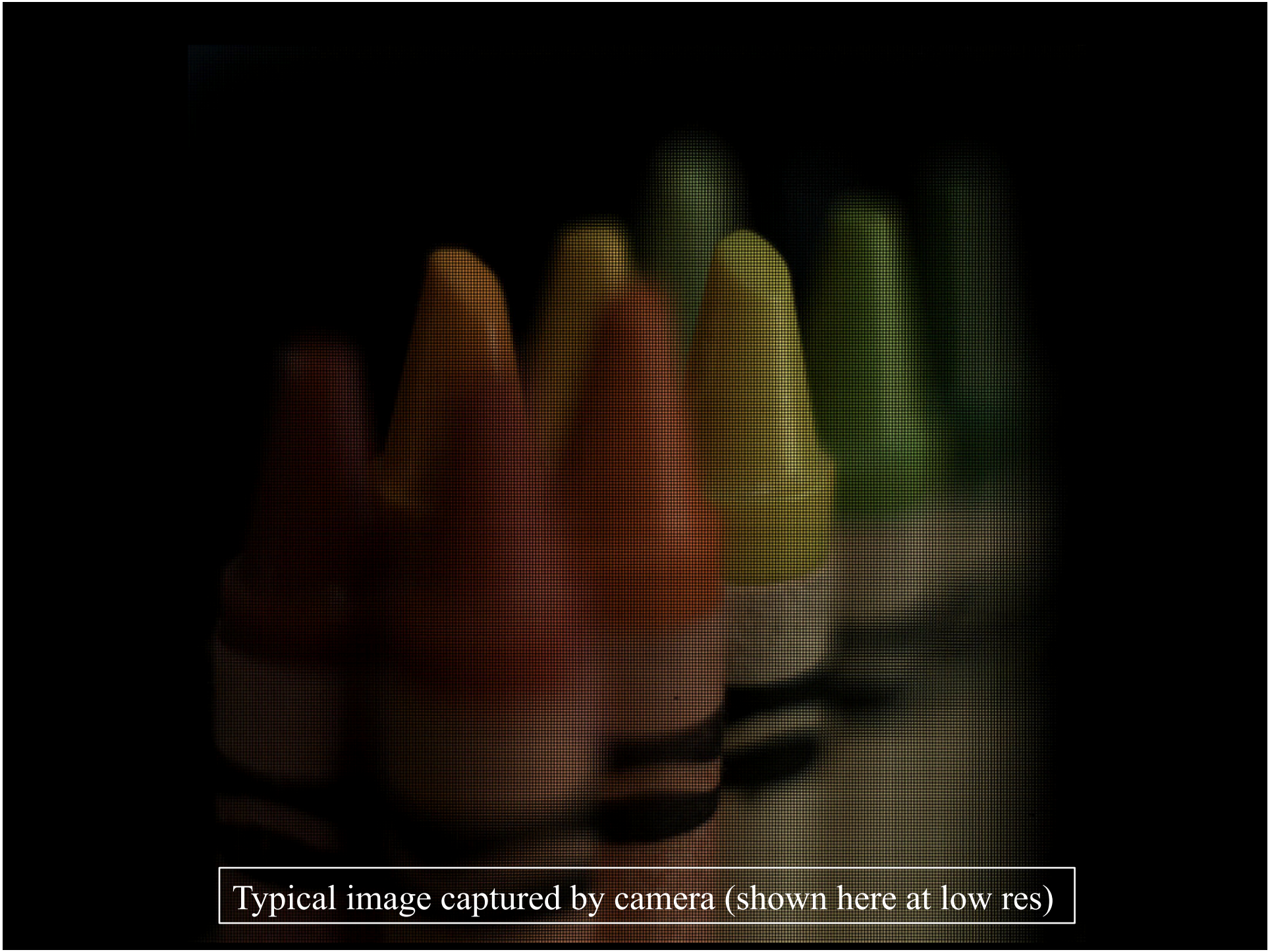


Adaptive Optics microlens array

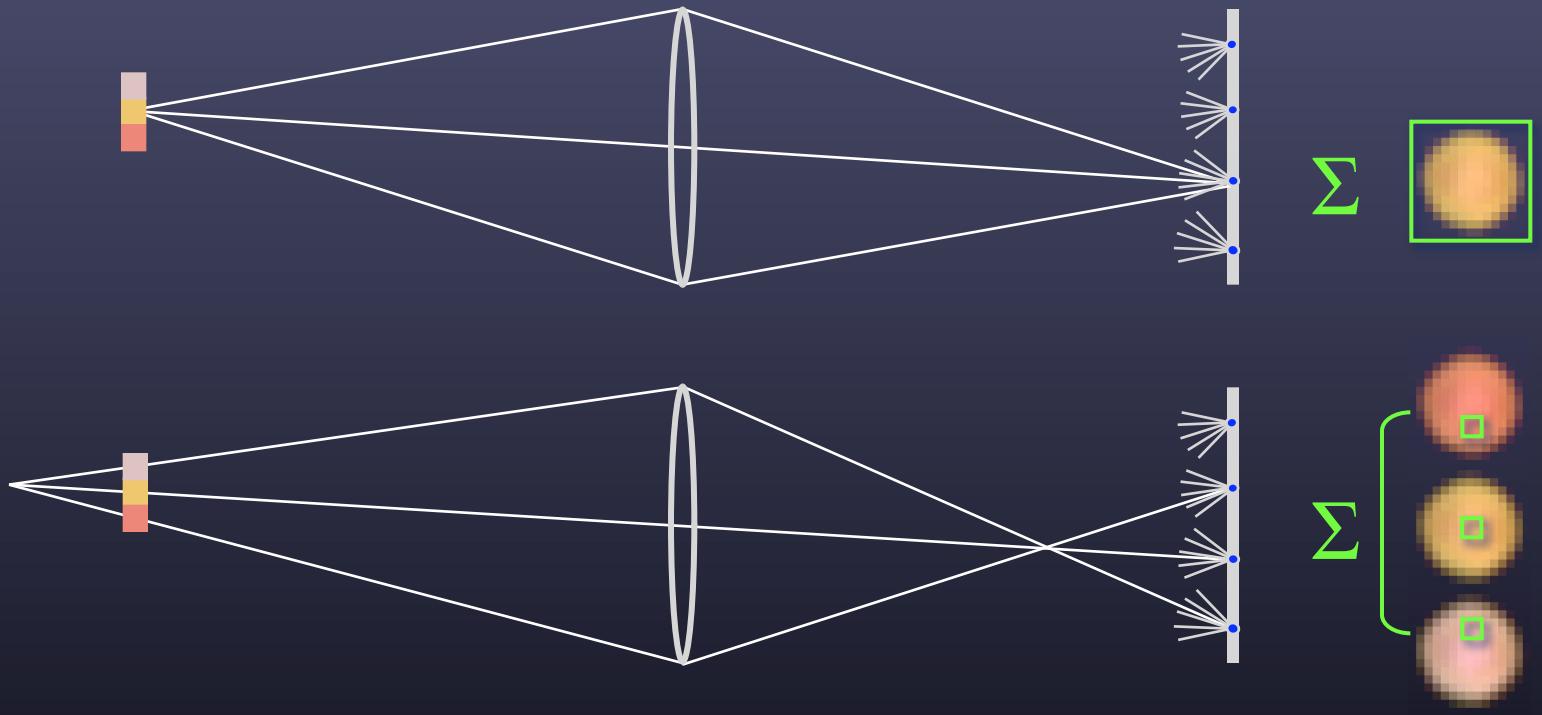


125µ square-sided microlenses

4000 × 4000 pixels ÷ 292 × 292 lenses = 14 × 14 pixels per lens


Typical image captured by camera (shown here at low res)

Digital refocusing



- refocusing = summing windows extracted from several microlenses

Example of digital refocusing

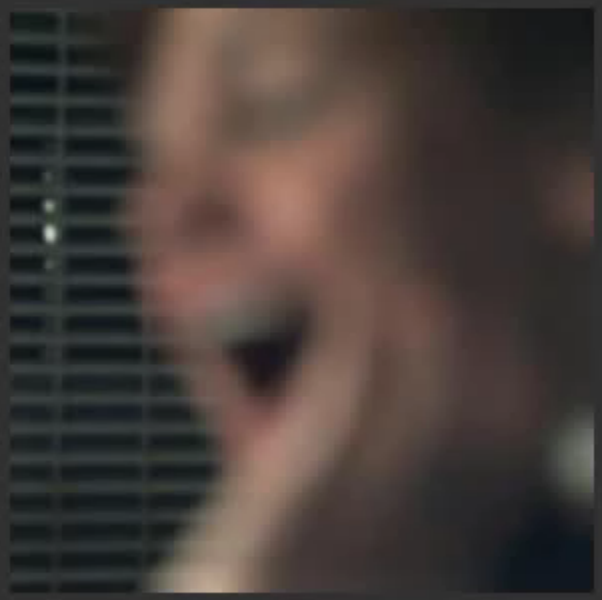
Example of digital refocusing

Example of digital refocusing

Example of digital refocusing

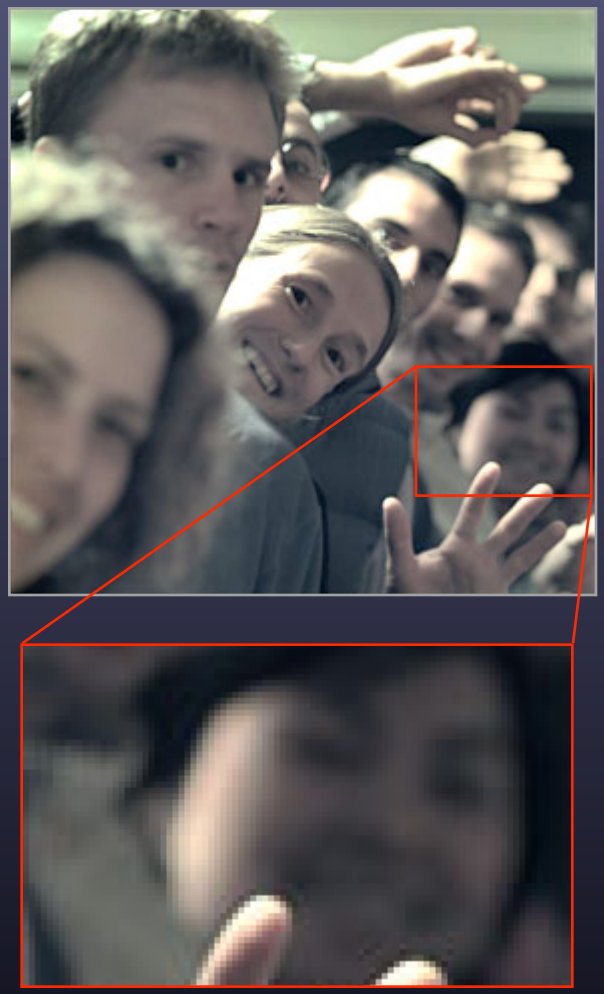
Example of digital refocusing

Refocusing portraits

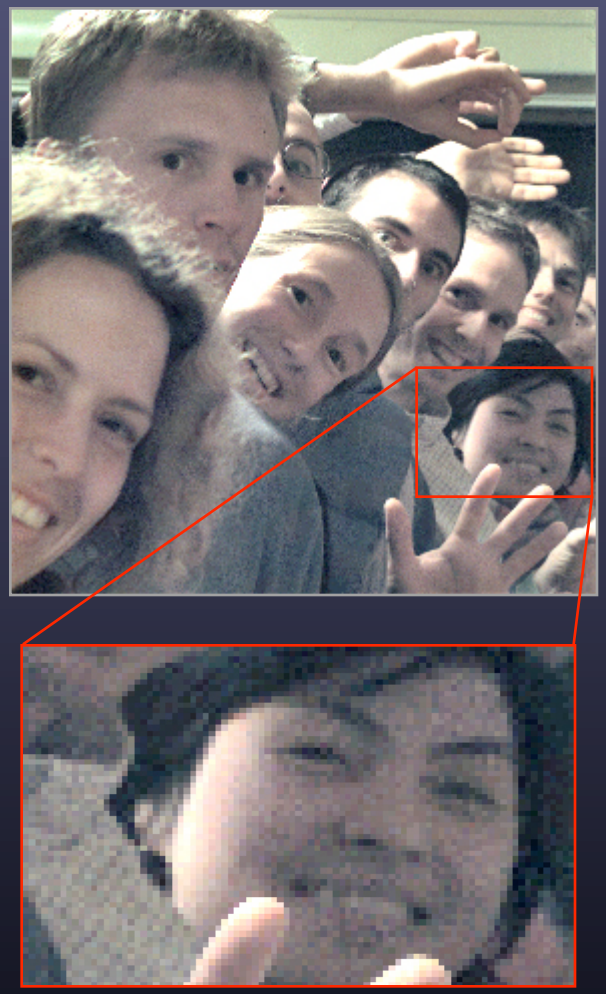


(movie is available at http://refocusimaging.com)

Extending the depth of field



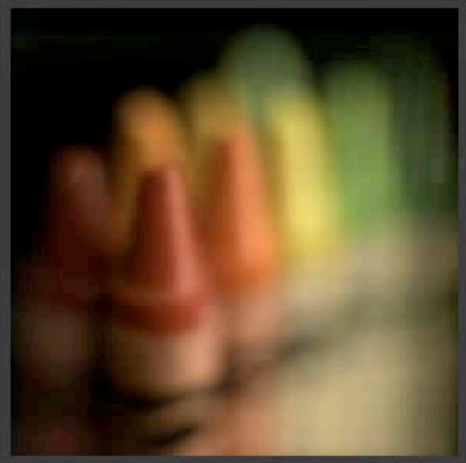
conventional photograph, main lens at f / 4



conventional photograph, main lens at f / 22

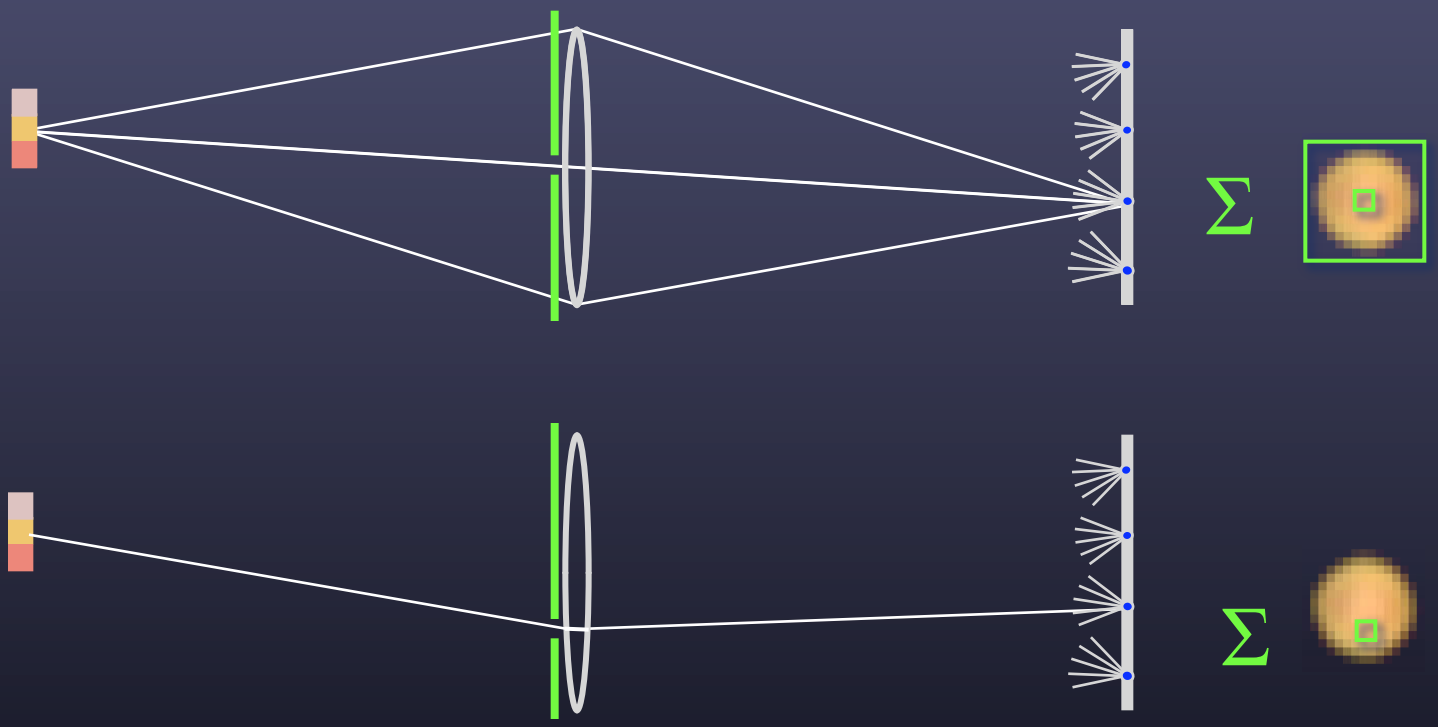
light field, main lens at f / 4, after all-focus algorithm [Agarwala 2004]

Macrophotography



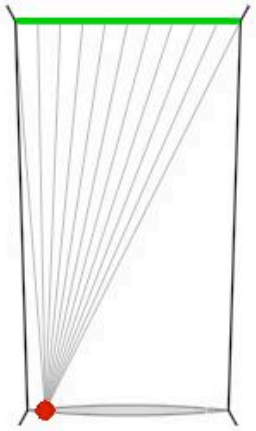
(movie not available online)

Digitally moving the observer

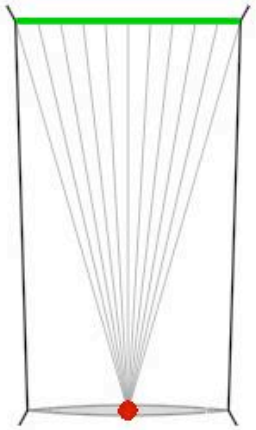


- moving the observer = moving the window we extract from the microlenses

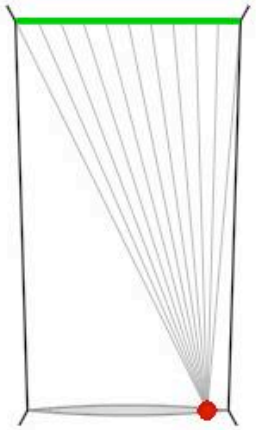
Example of moving the observer



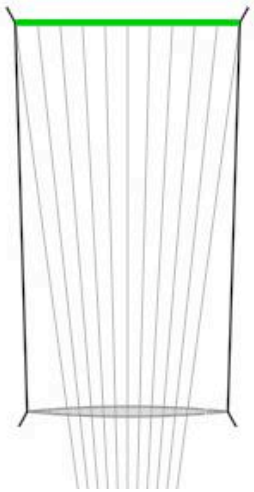
Example of moving the observer



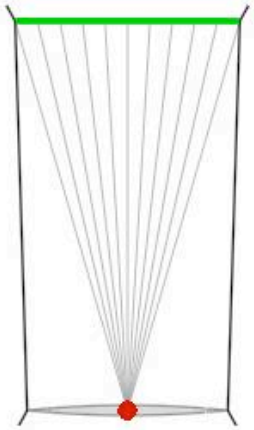
Example of moving the observer



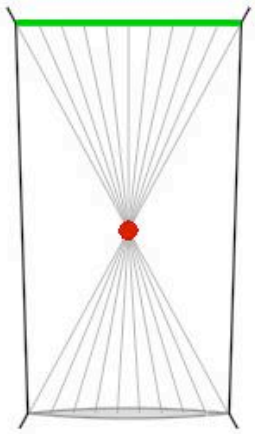
Moving backward and forward



Moving backward and forward



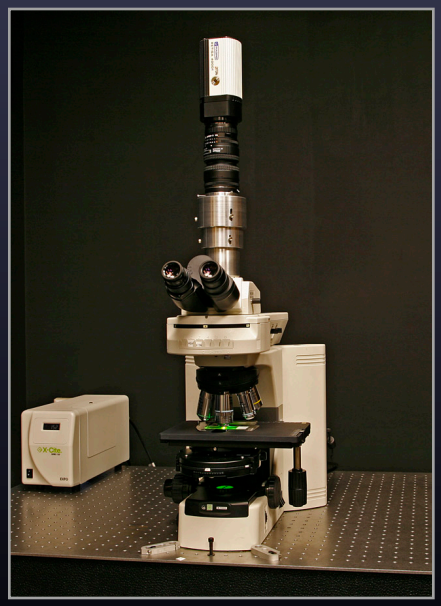
Moving backward and forward

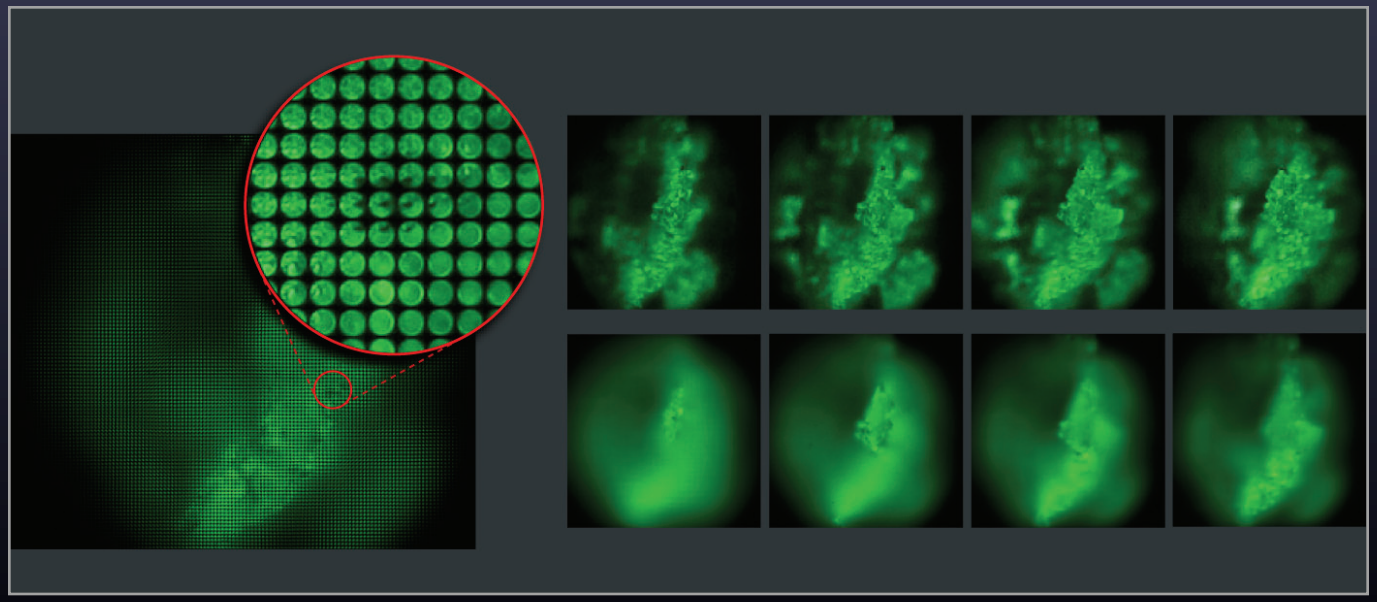


Light Field Microscopy

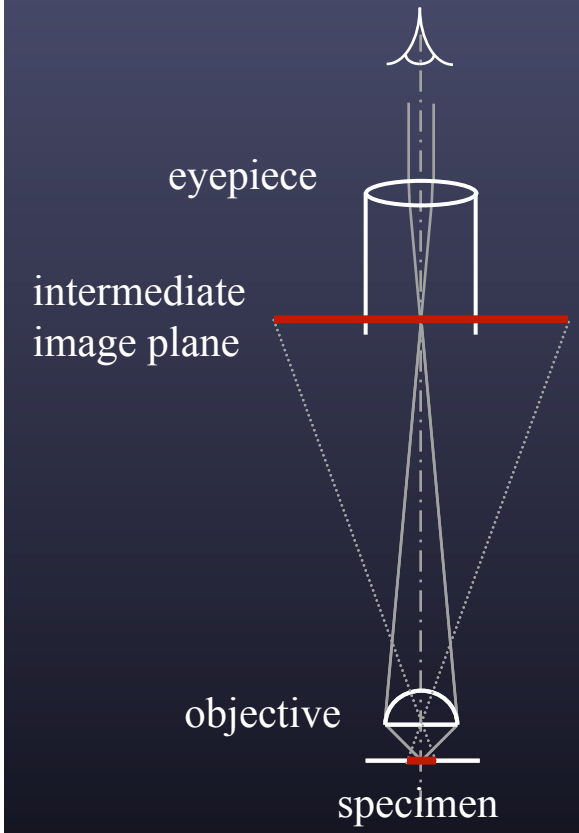
Marc Levoy, Ren Ng, Andrew Adams,
Matthew Footer, and Mark Horowitz

(Proc. SIGGRAPH 2006)

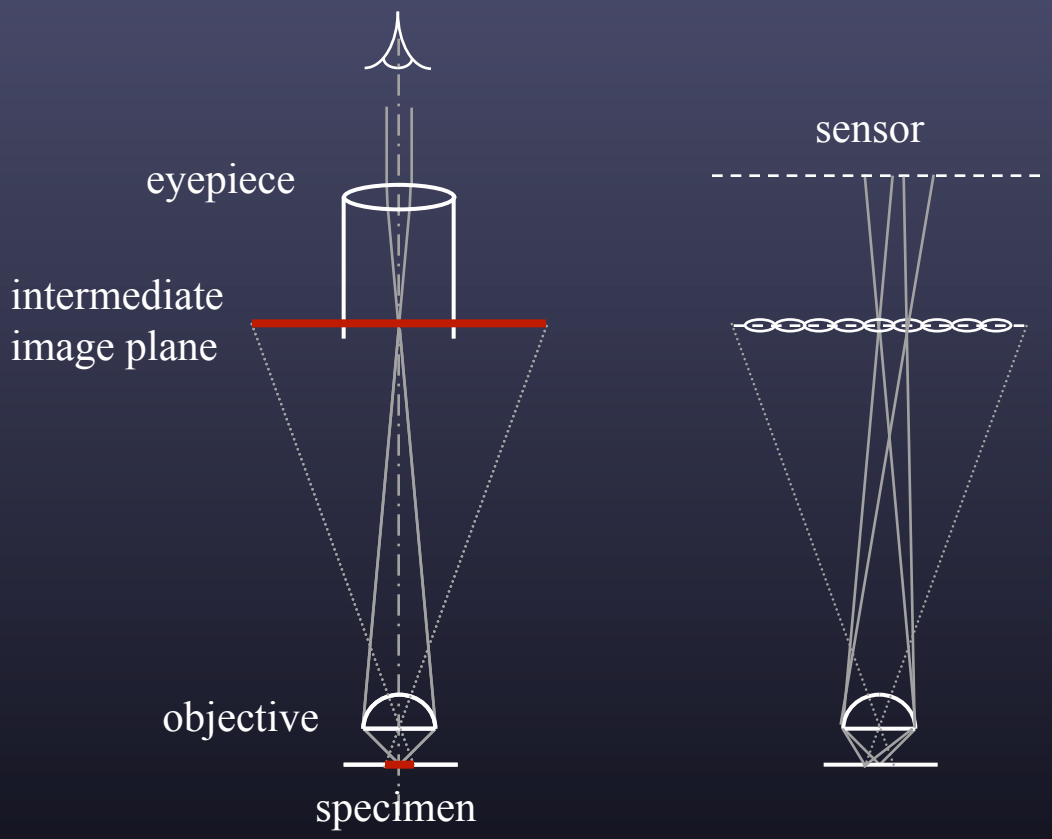




A traditional microscope



A light field microscope (LFM)



- 40x / 0.95NA objective

↓

0.26μ spot on specimen
× 40x = 10.4μ on sensor

↓

2400 spots over 25mm field

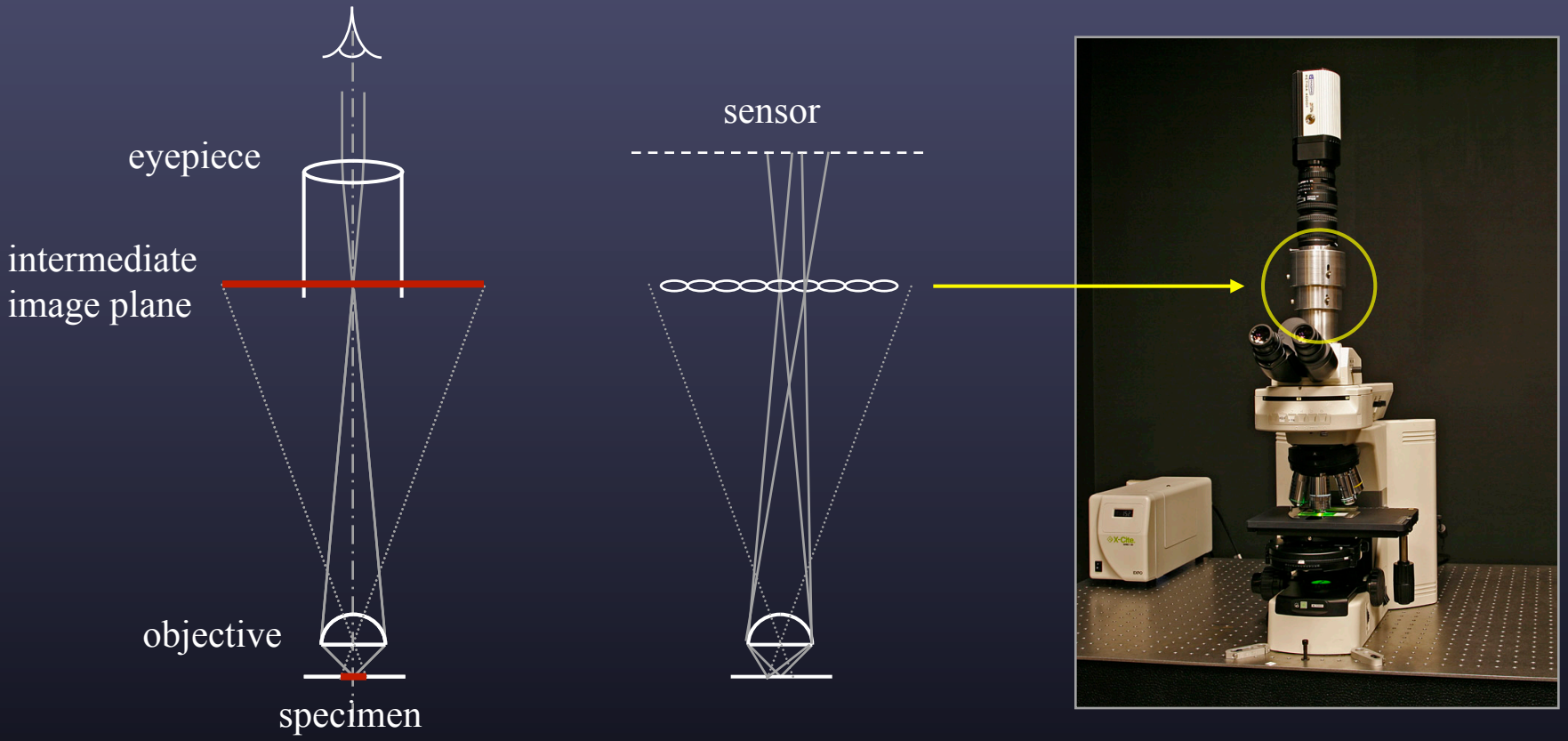
- 125^2-micron microlenses

↓

200 × 200 microlenses with
12 × 12 spots per microlens

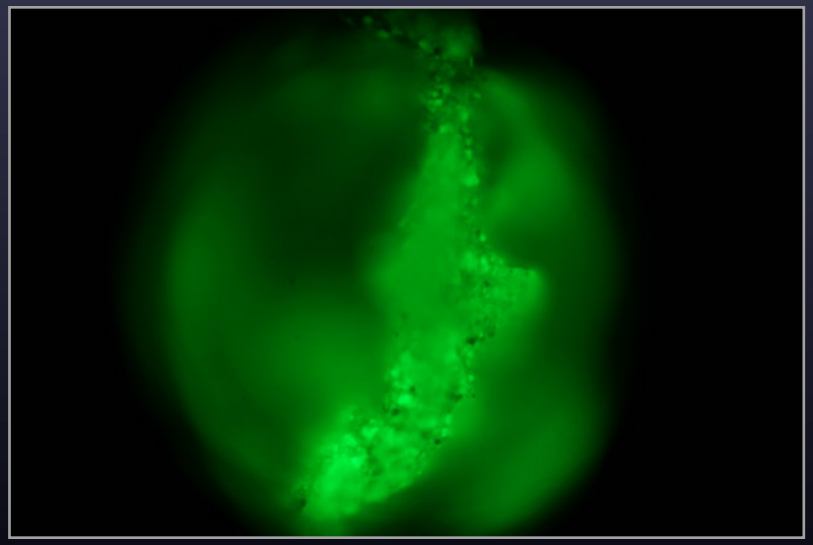
→ reduced lateral resolution on specimen
= 0.26μ × 12 spots = 3.1μ

A light field microscope (LFM)



Example light field micrograph

- orange fluorescent crayon
- mercury-arc source + blue dichroic filter
- 16x / 0.5NA (dry) objective
- f/20 microlens array
- 65mm f/2.8 macro lens at 1:1
- Canon 20D digital camera

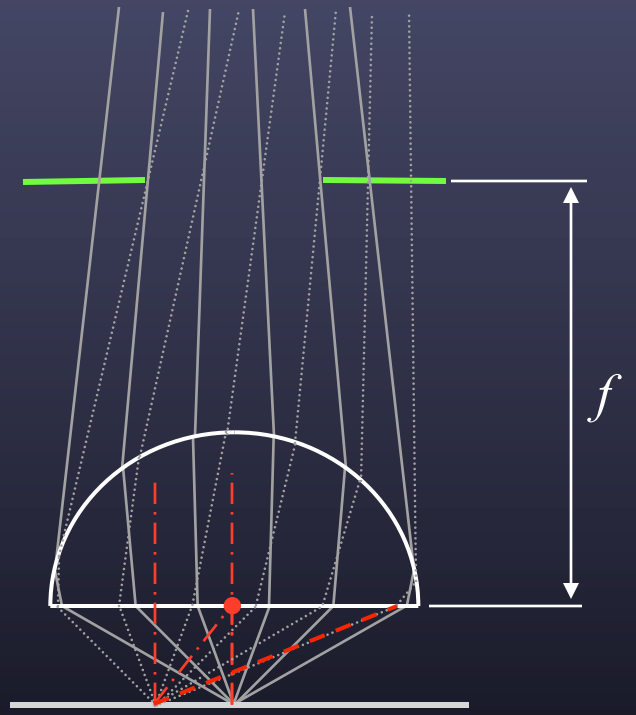


ordinary microscope

Typical image captured by camera (shown here at low res)

light field microscope

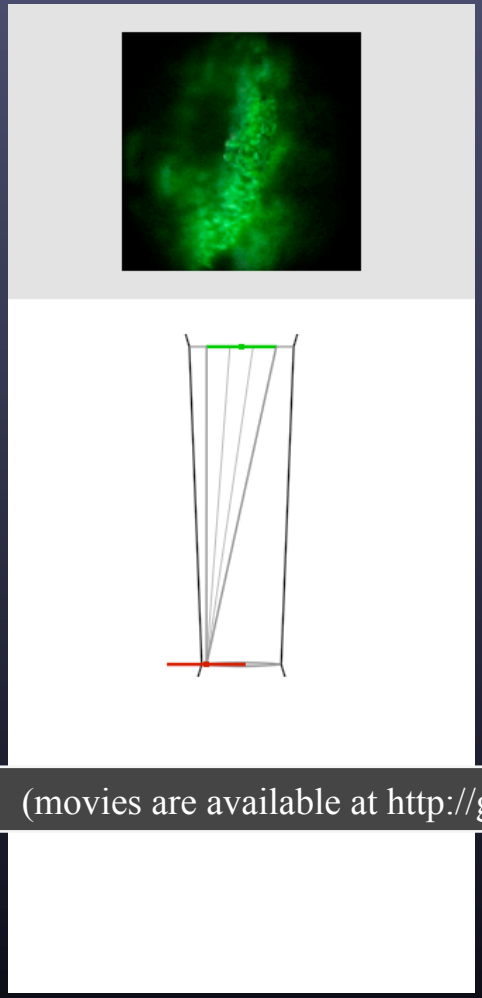
The geometry of the light field in a microscope

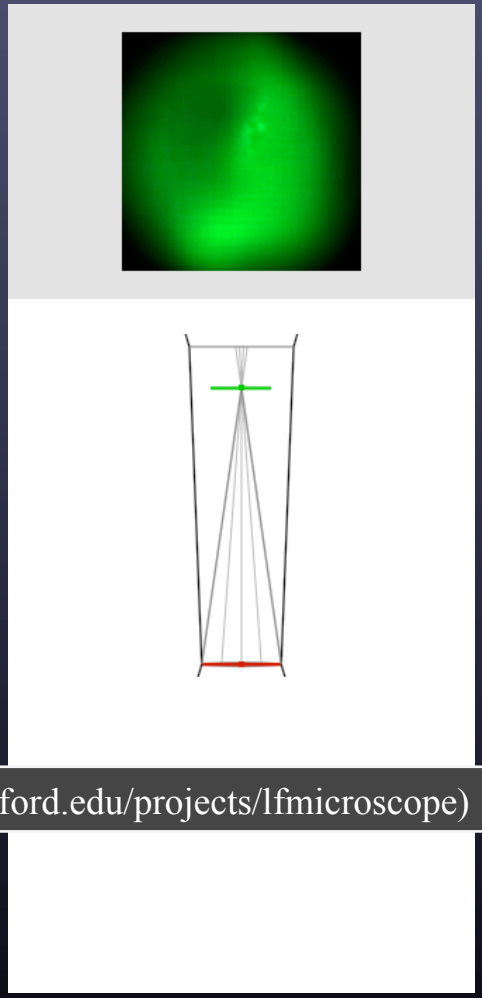


objective lenses are telecentric

- microscopes make orthographic views
- translating the stage in X or Y provides no parallax on the specimen
- out-of-plane features don't shift position when they come into focus
- front lens element size = aperture width + field width
- PSF for 3D deconvolution microscopy is shift-invariant (i.e. doesn't change across the field of view)

Example light field micrograph



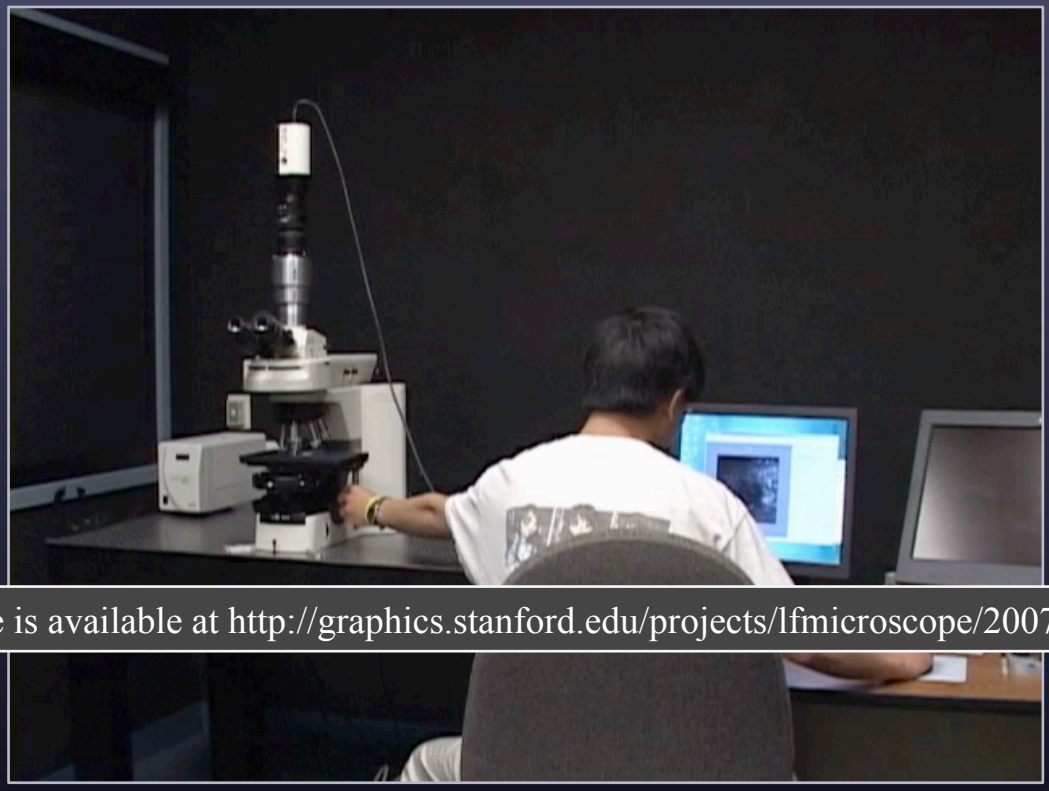


(movies are available at http://graphics.stanford.edu/projects/lfmicroscope)

panning sequence

focal stack

Real-time viewer

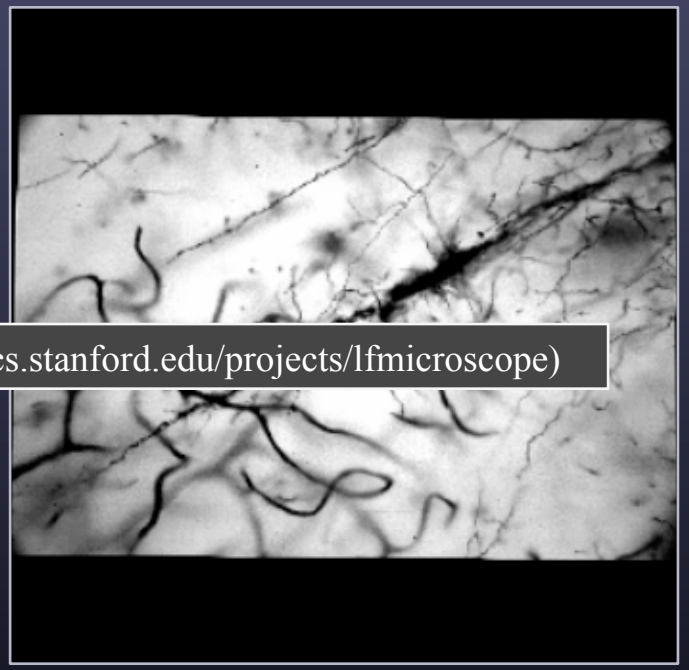


(movie is available at http://graphics.stanford.edu/projects/lfmicroscope/2007.html)

Other examples

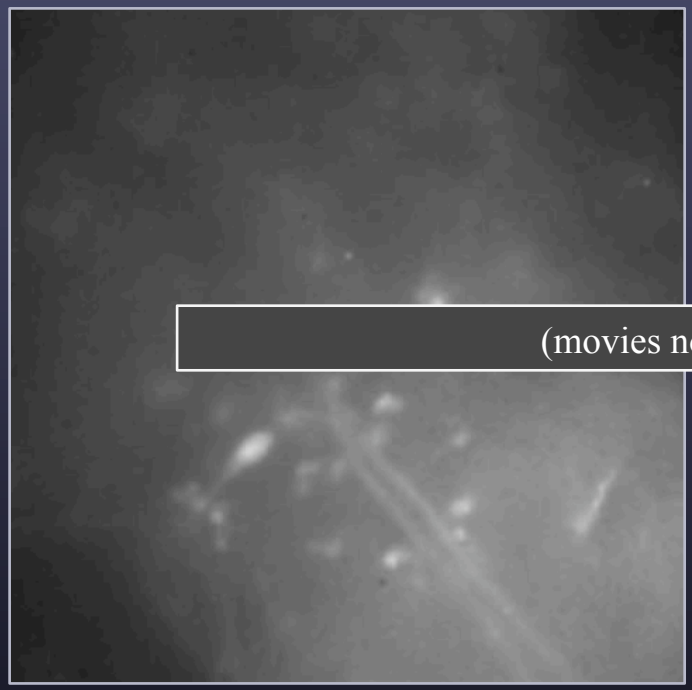
fern spore
(60x, autofluorescence)

(movies are available at http://graphics.stanford.edu/projects/lfmicroscope)

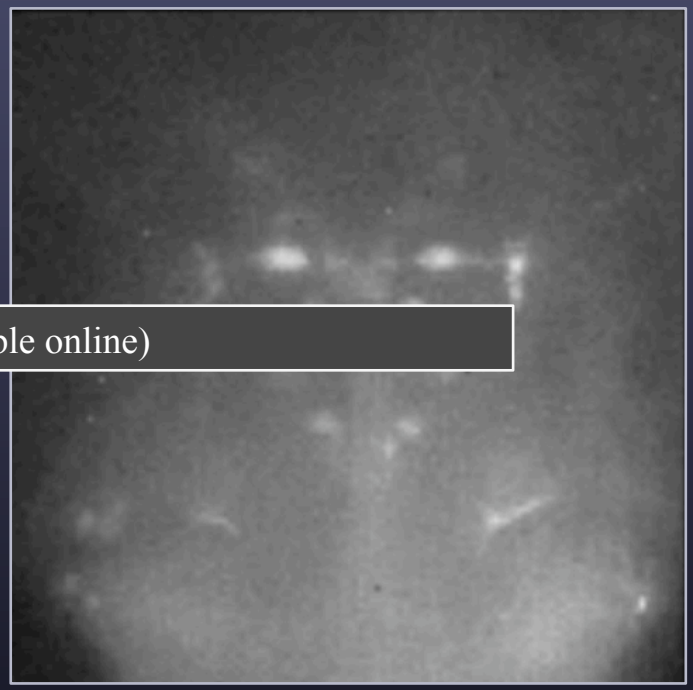


Golgi-stained neurons
(40x)

Zebrafish optic tectum
(collaboration with Florian Engert)



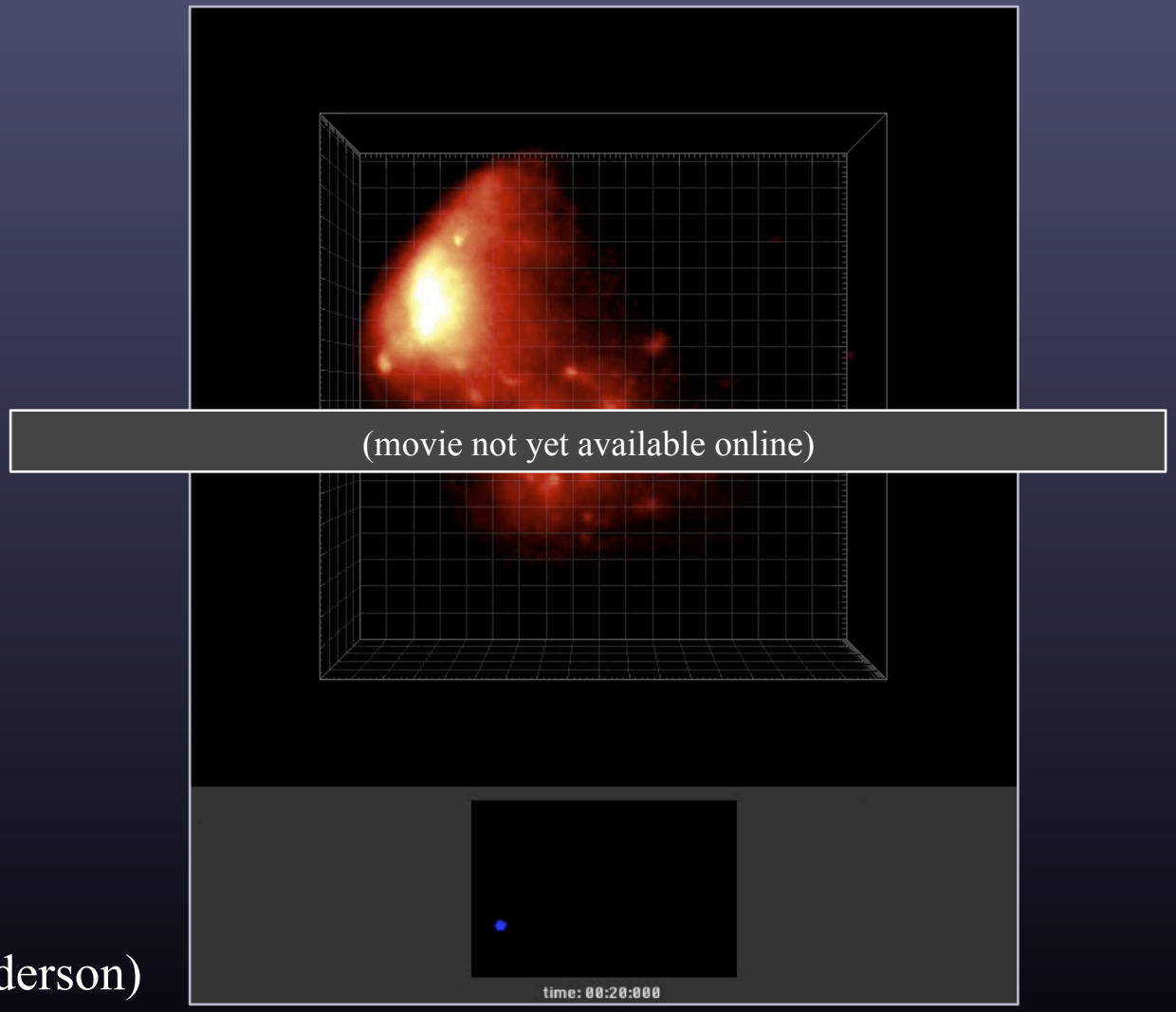
(movies not yet available online)



genetically modified
to express GFP
(40x)

calcium imaging
of neural activity
(40x)

Calcium imaging under visual stimulation
(collaboration with Stephen Smith)

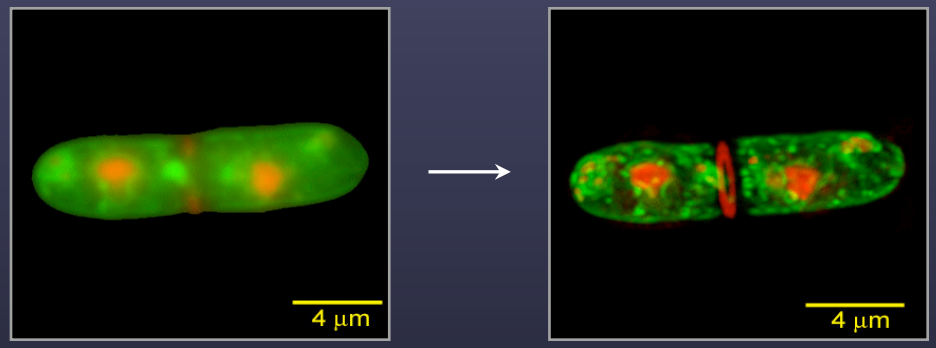


(Todd Anderson)

3D reconstruction

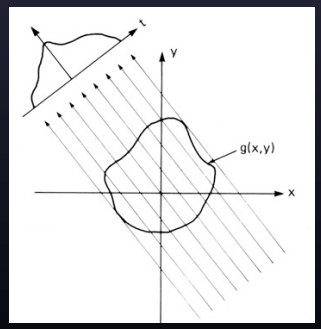
- 4D light field → *digital refocusing* →
  3D focal stack → *deconvolution microscopy* →
  3D volume data

(DeltaVision)



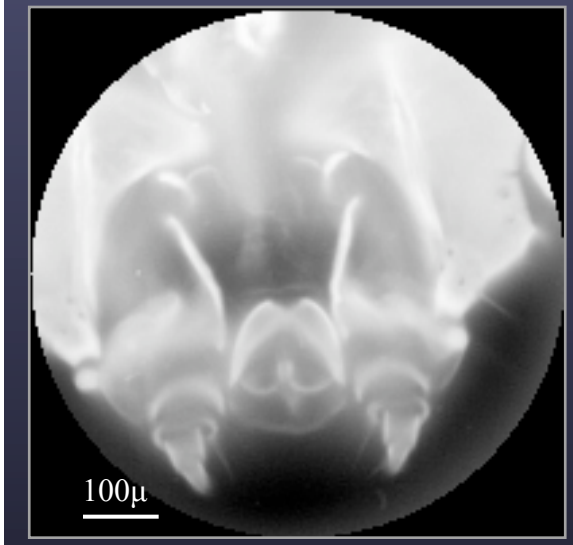
- 4D light field → *tomographic reconstruction* →
  3D volume data

(from Kak & Slaney)

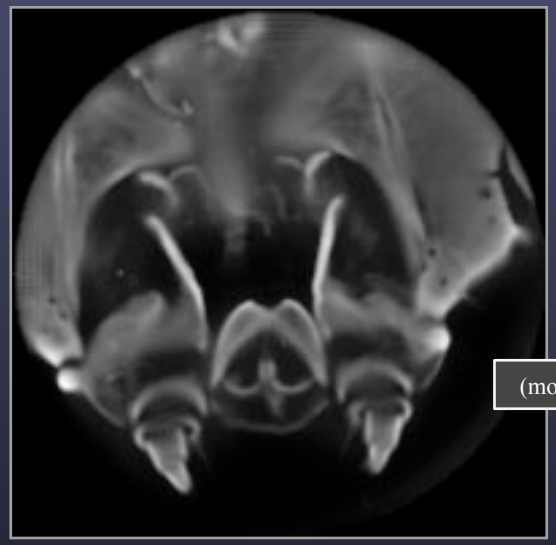


Silkworm mouth

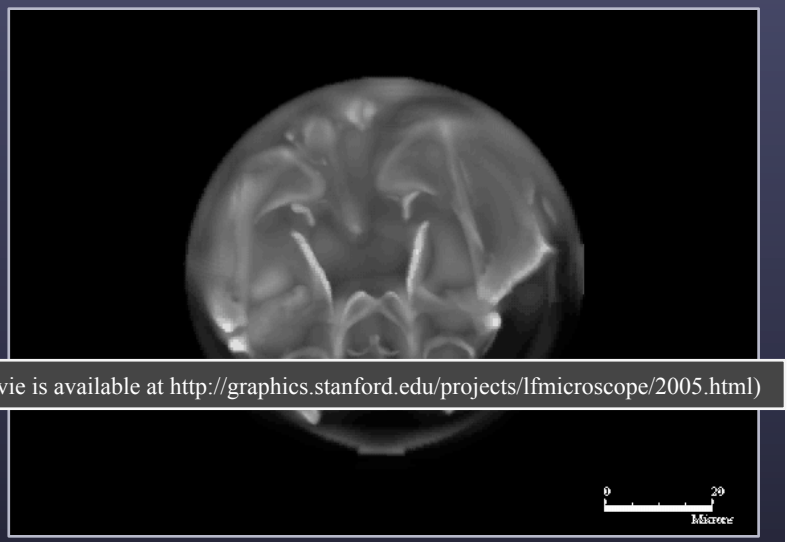
(40x / 1.3NA oil immersion)



slice of focal stack



slice of volume

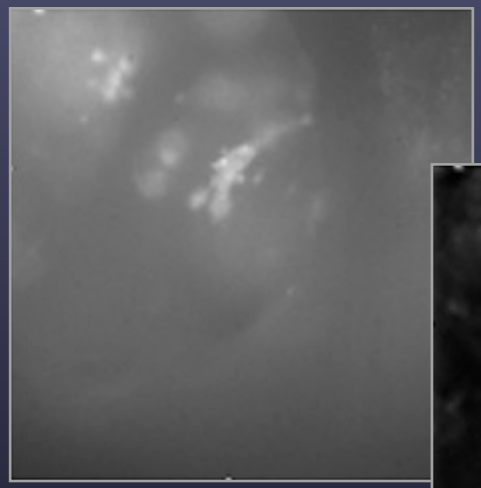


(movie is available at http://graphics.stanford.edu/projects/lfmicroscope/2005.html)

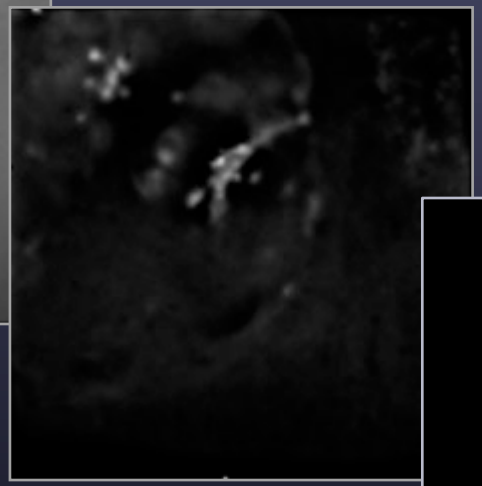
volume rendering

GFP-labeled zebrafish neurons

(40x / 0.8NA water immersion)



focal stack

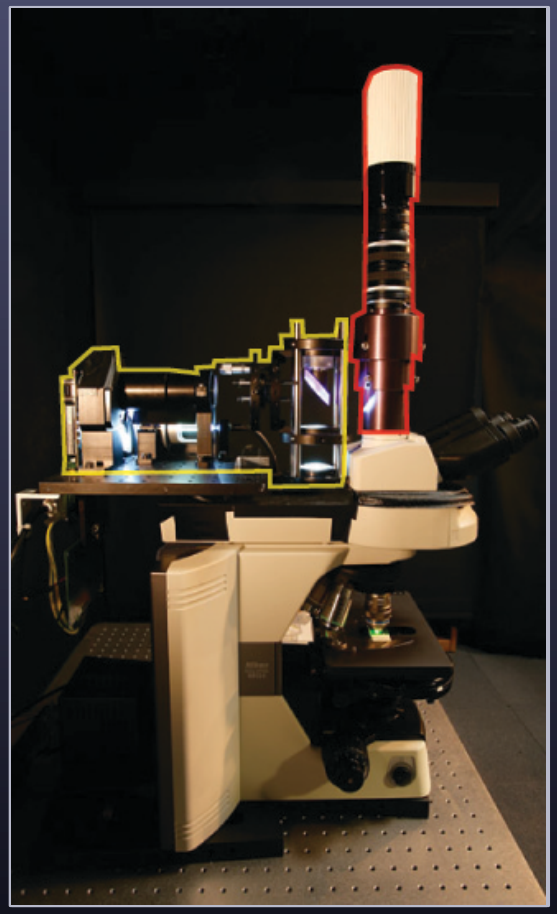


deconvolved

volume rendering

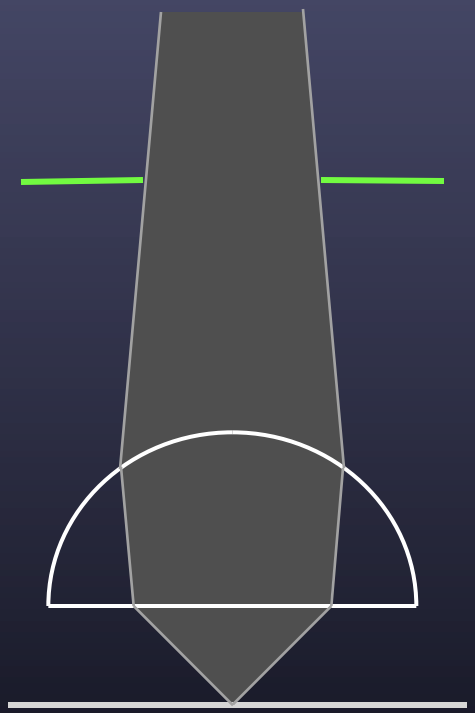
Combined light field microscope (LFM) and light field illuminator (LFI)

[To appear in Journal of Microscopy, 2009]



- applications:
  - exotic microscope illumination
  - reducing scattering using 3D "follow spots"
  - characterizing and correcting for aberrations
  - microscopic structured light rangefinding
  - gonioreflectometer for opaque surfaces
  - optical stimulation of neural tissues in 3D

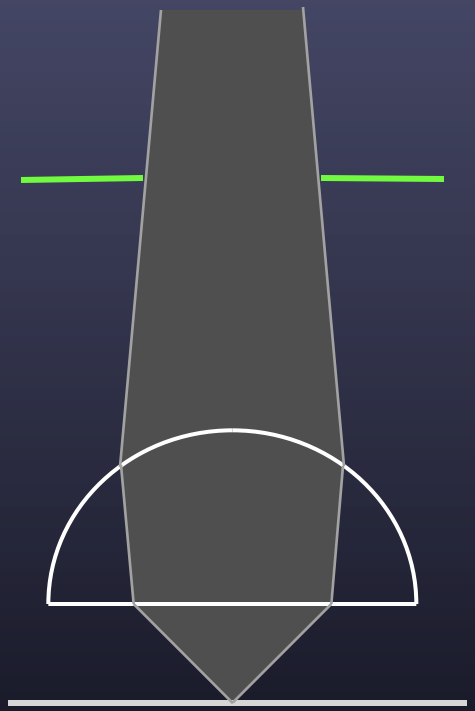
Angular control over lighting



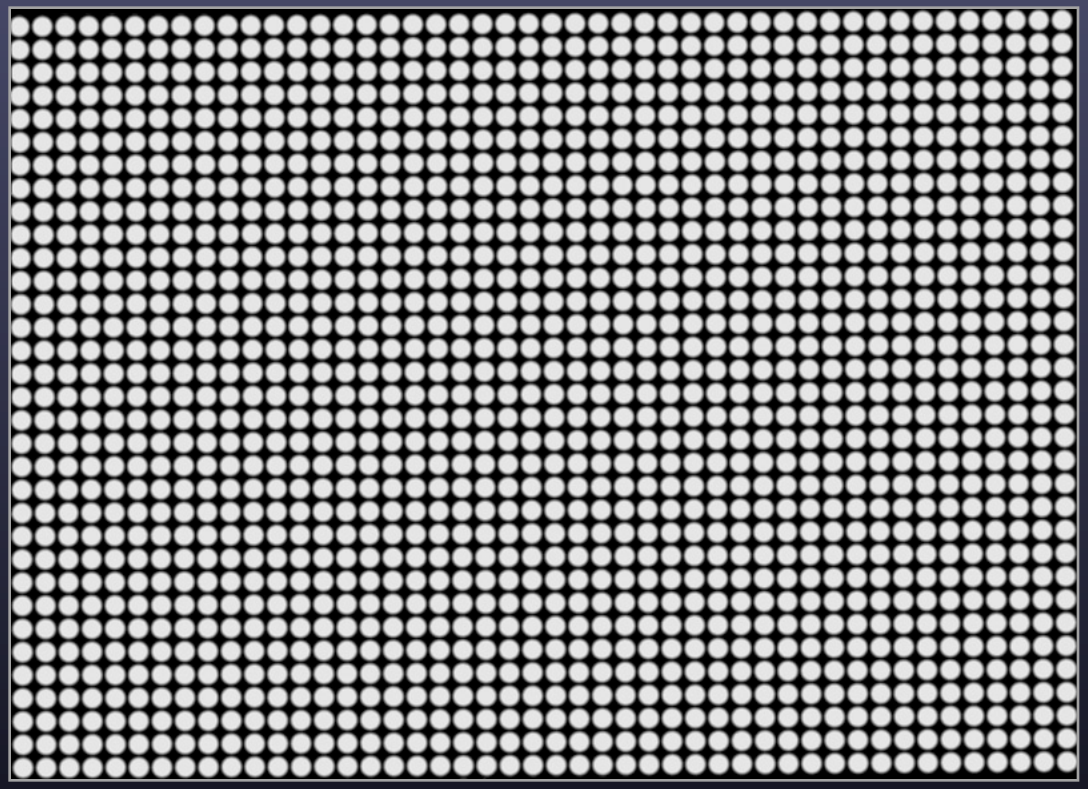
brightfield

image sent to projector's graphics card

Angular control over lighting

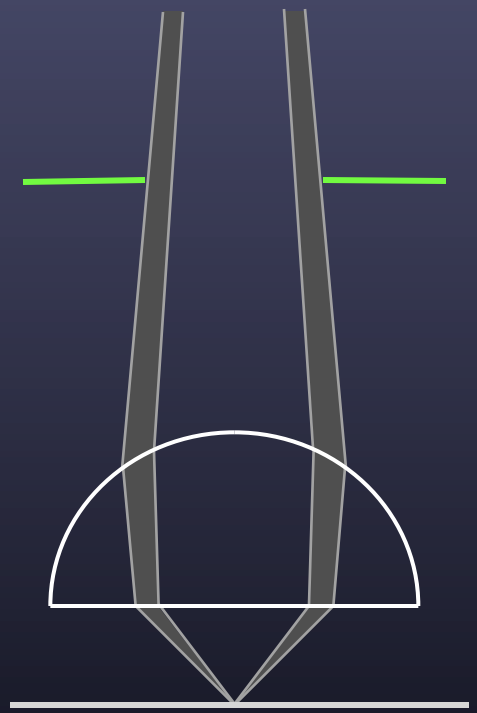


brightfield

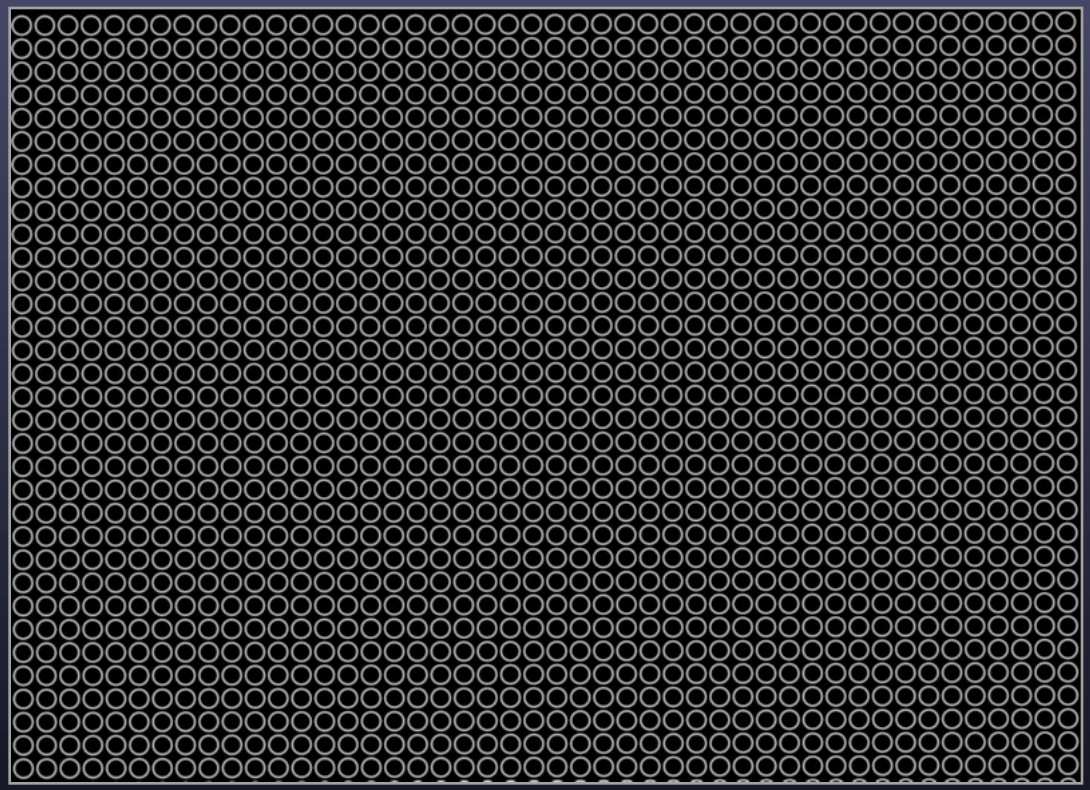


(tilt due to imperfect placement of microlenses)

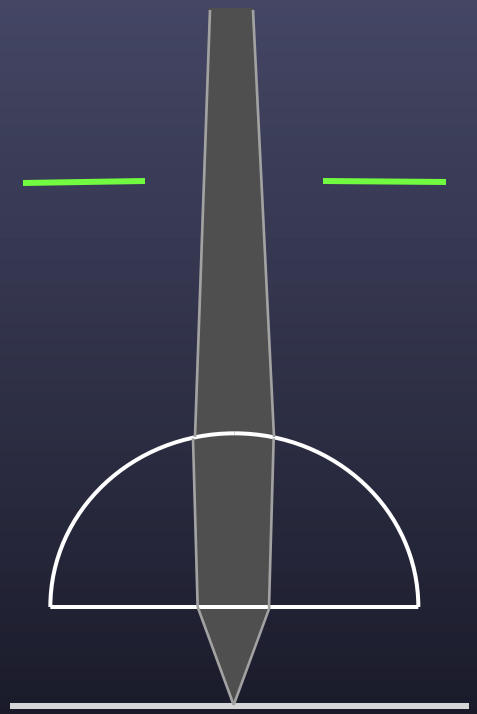
Angular control over lighting



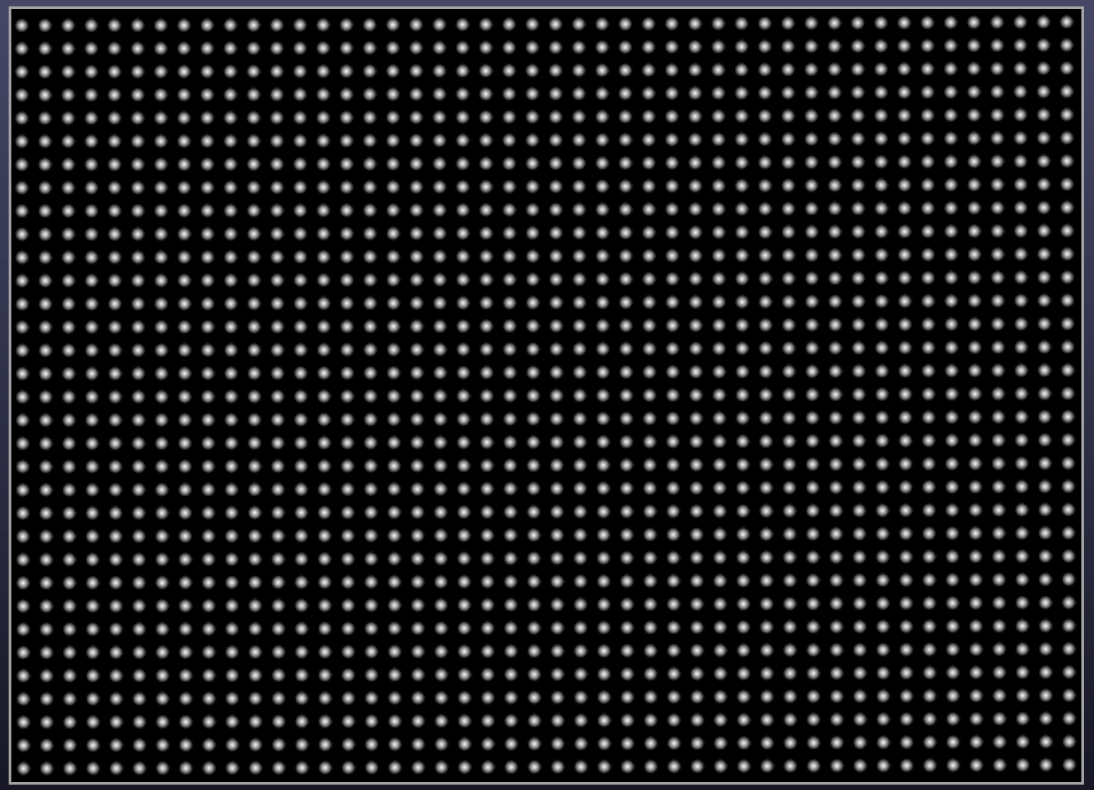
“darkfield”



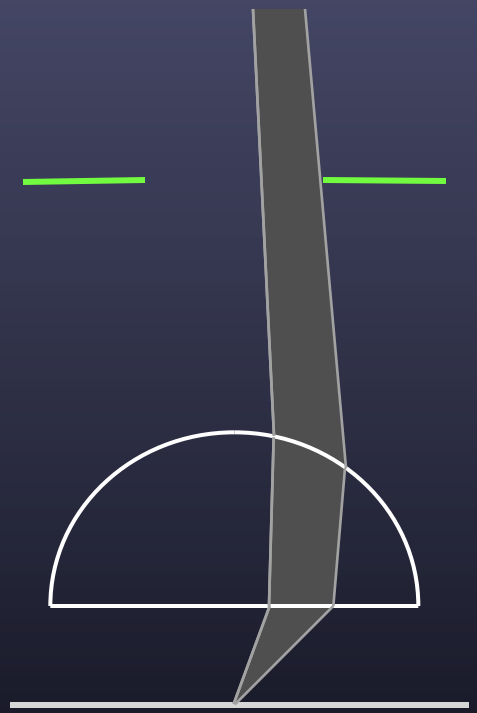
Angular control over lighting



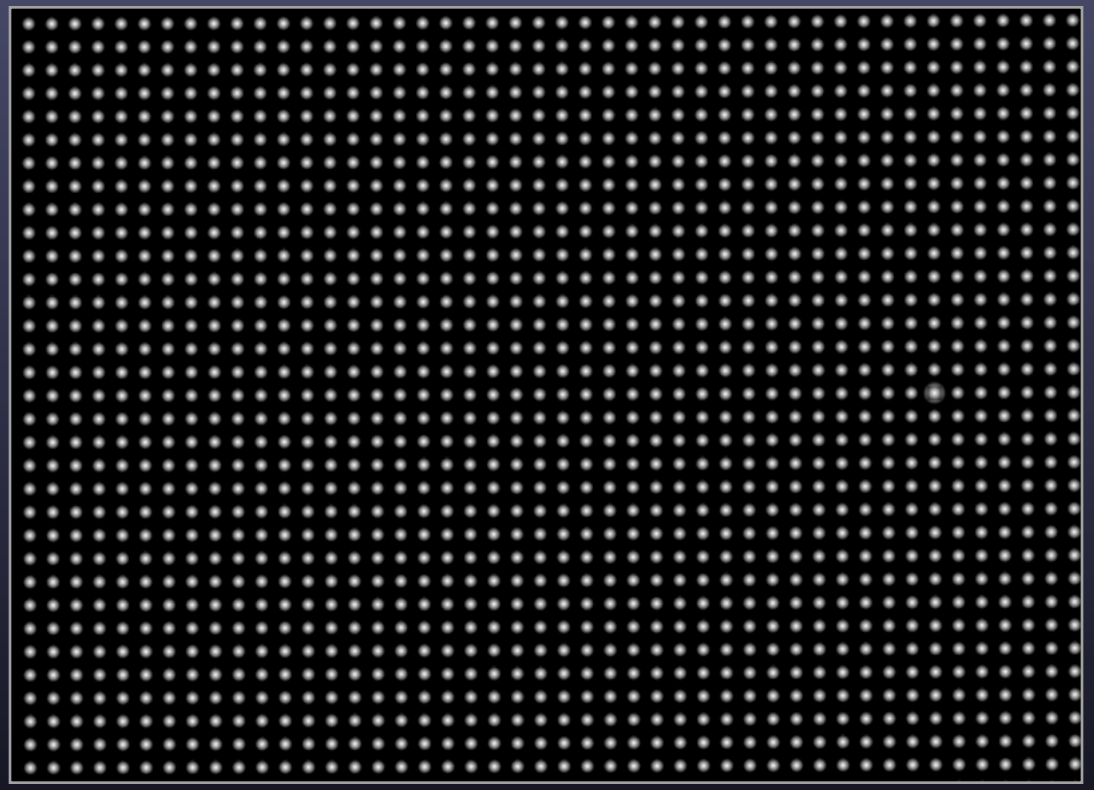
headlamp



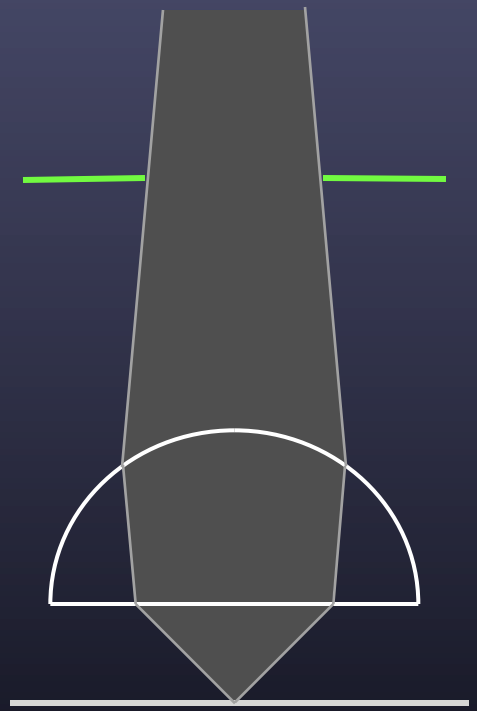
Angular control over lighting



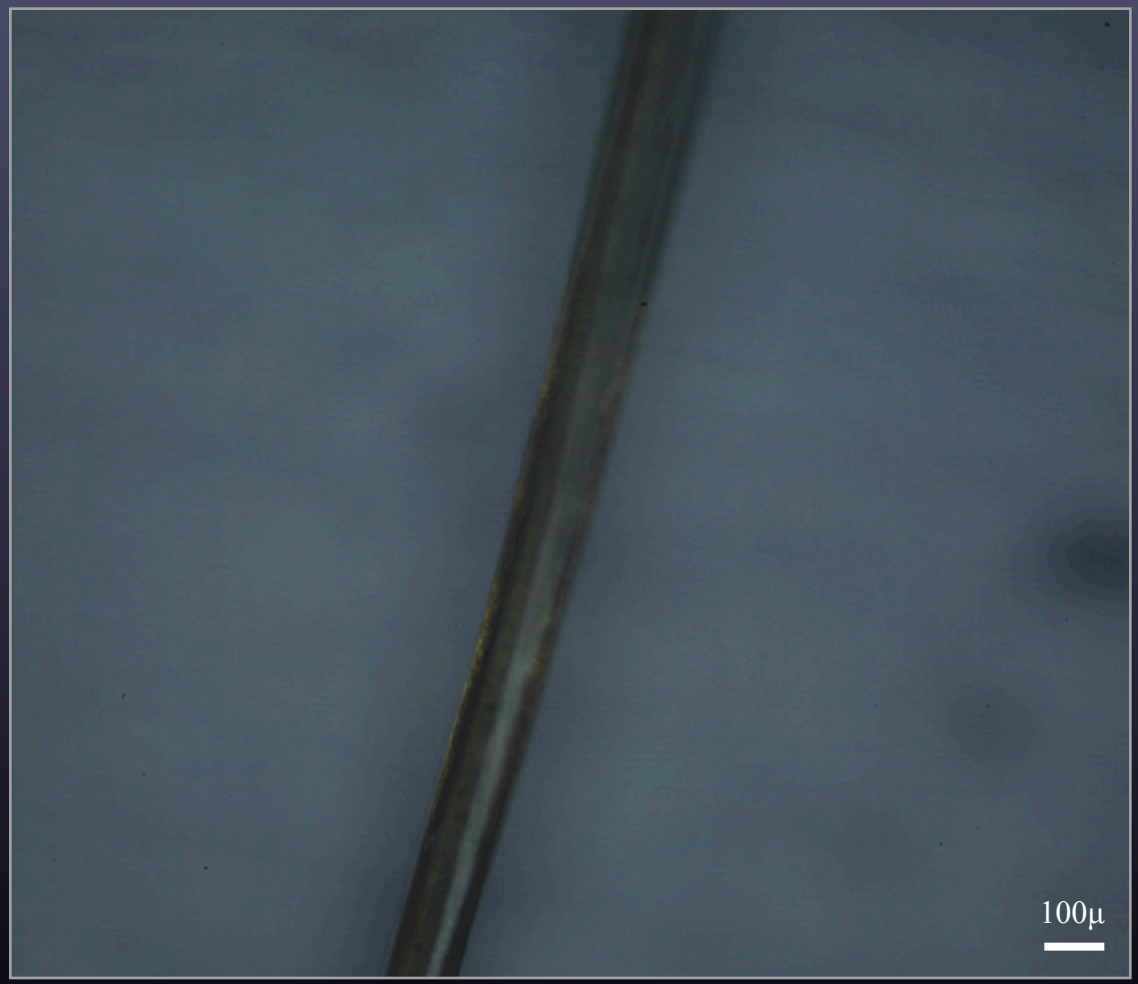
oblique



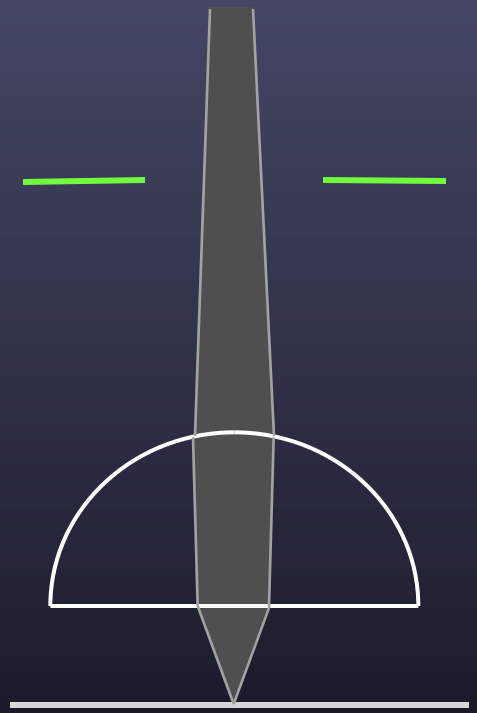
Single blond hair (10x/0.45NA)



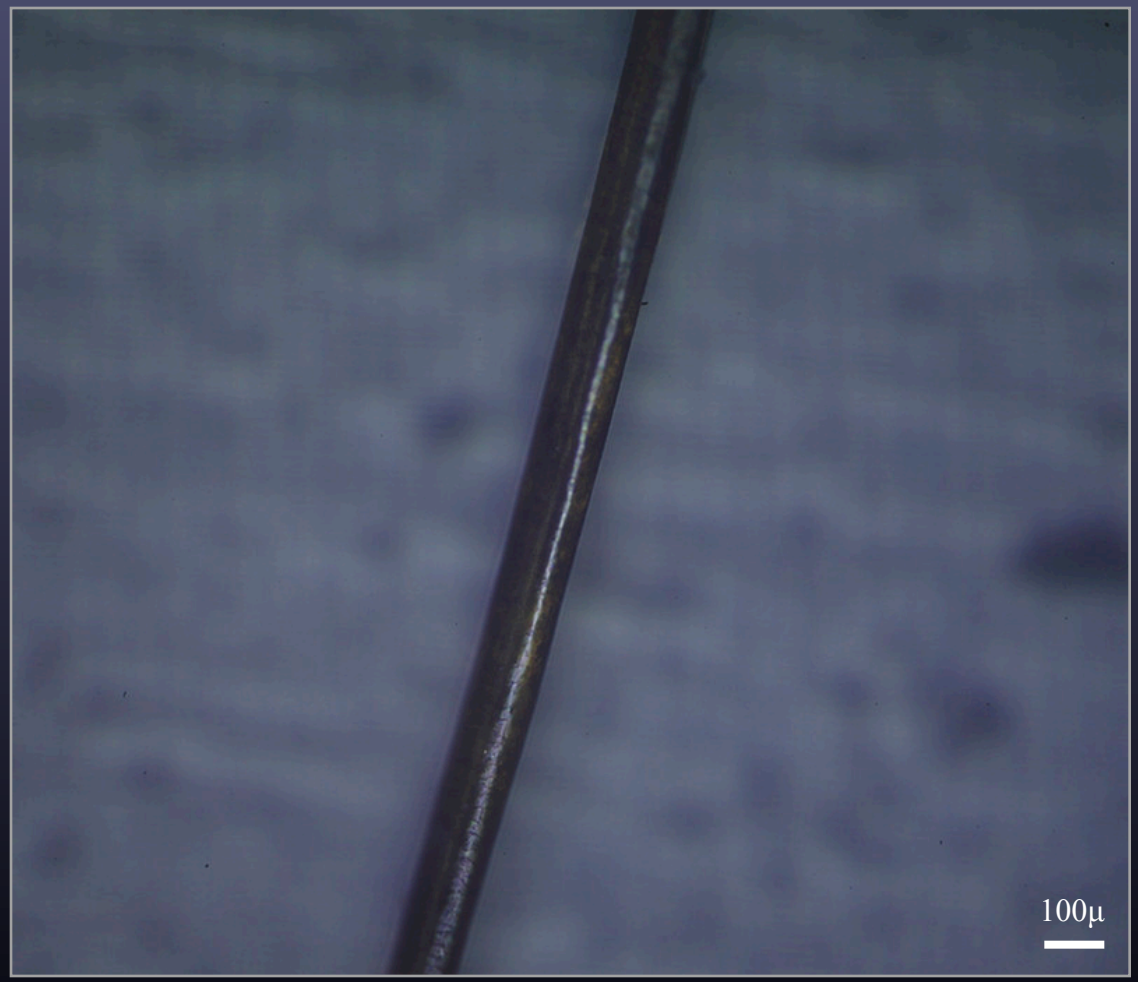
brightfield



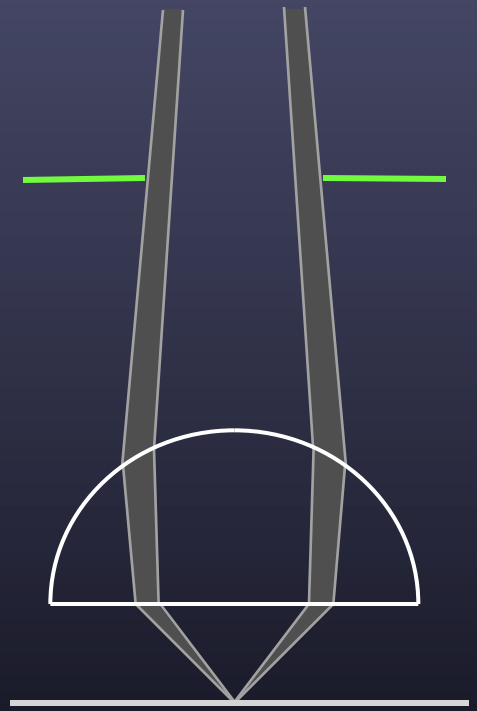
Single blond hair (10x/0.45NA)



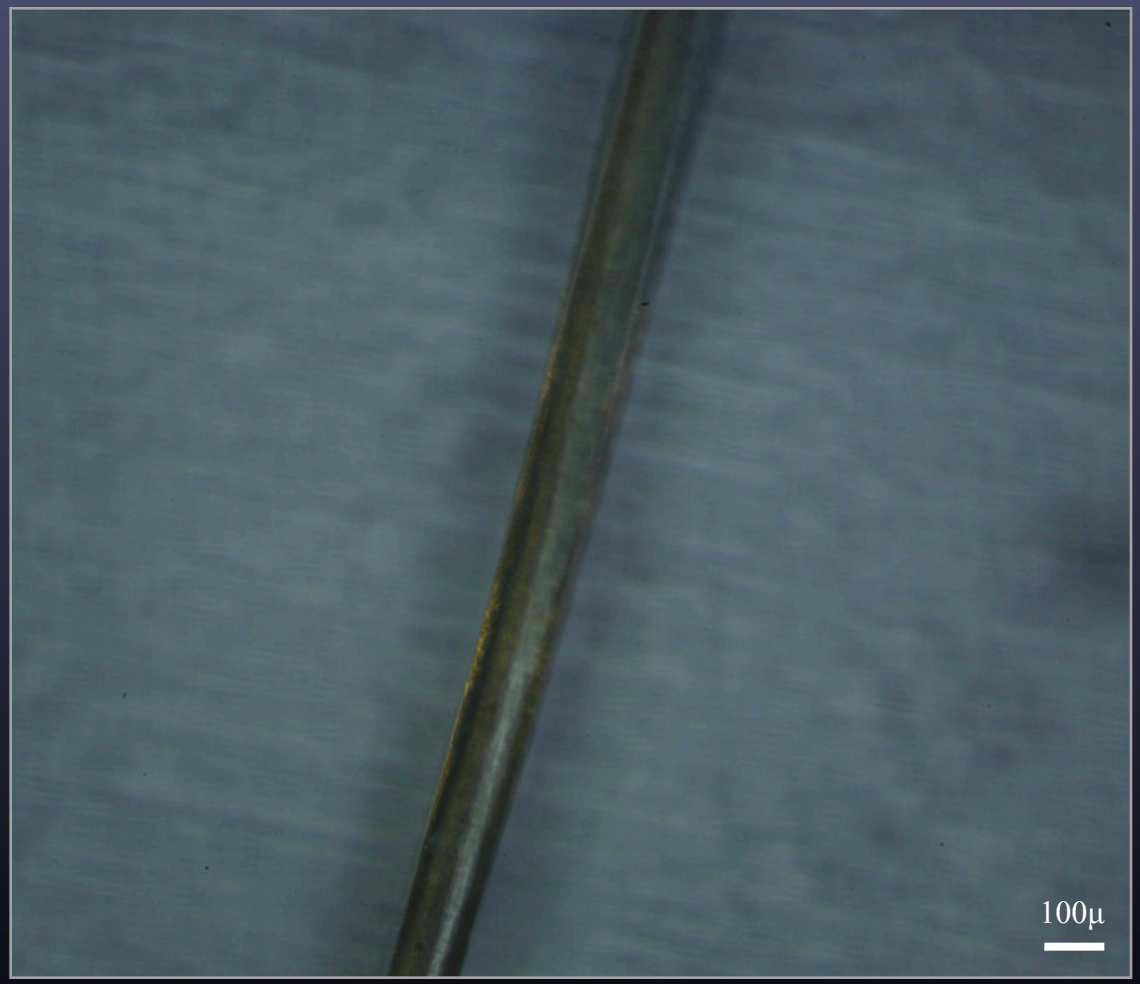
headlamp



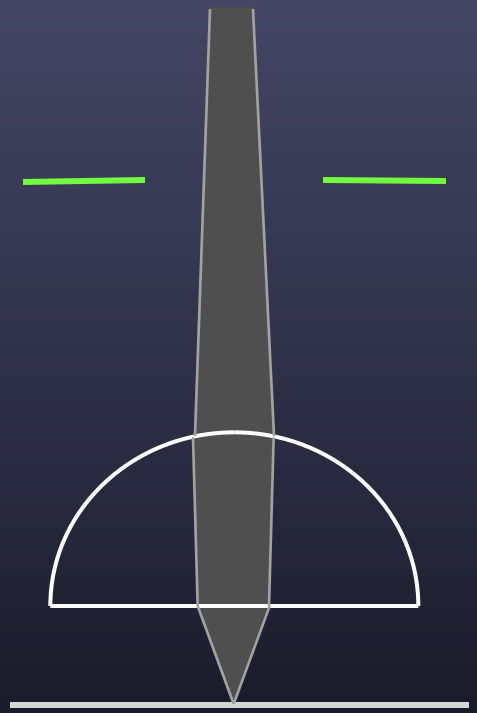
Single blond hair (10x/0.45NA)



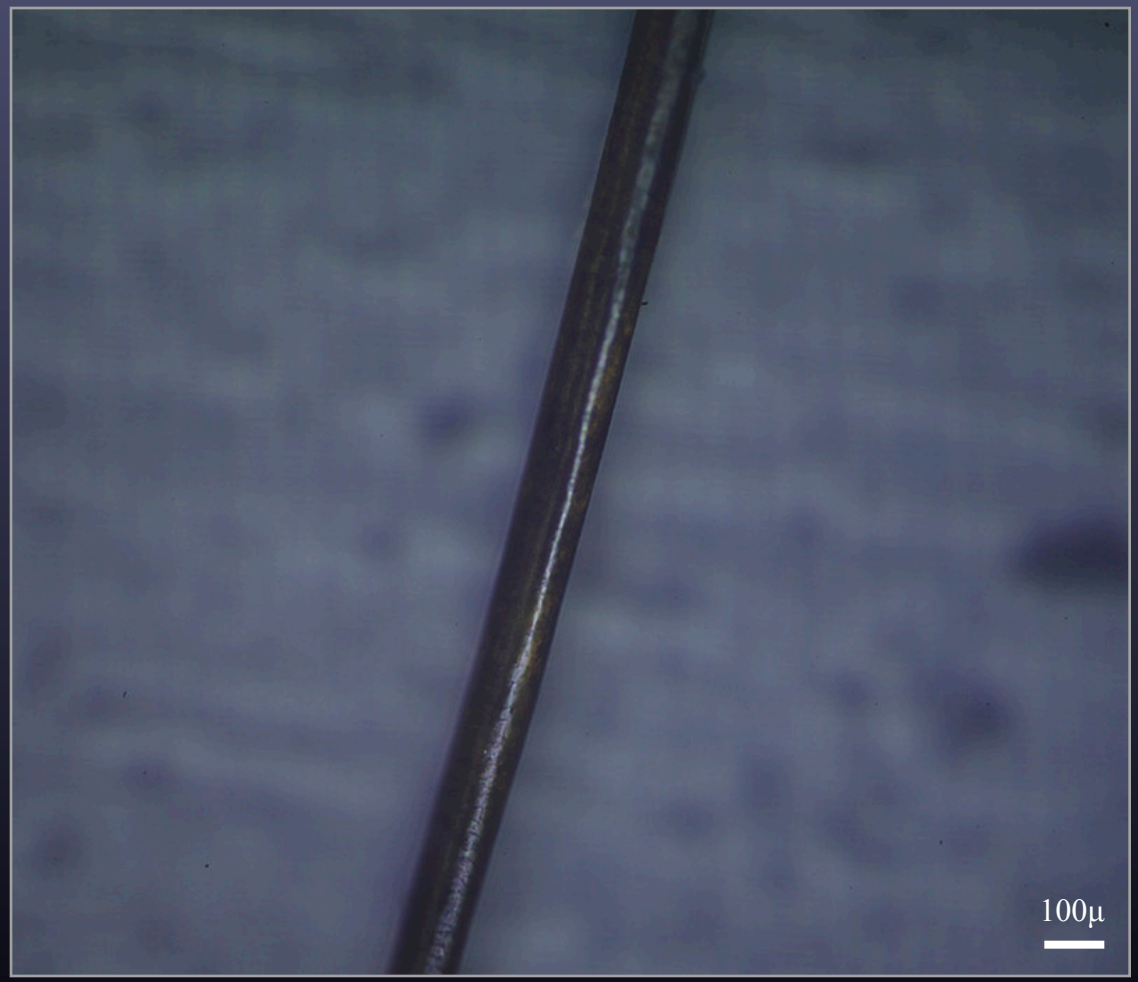
darkfield



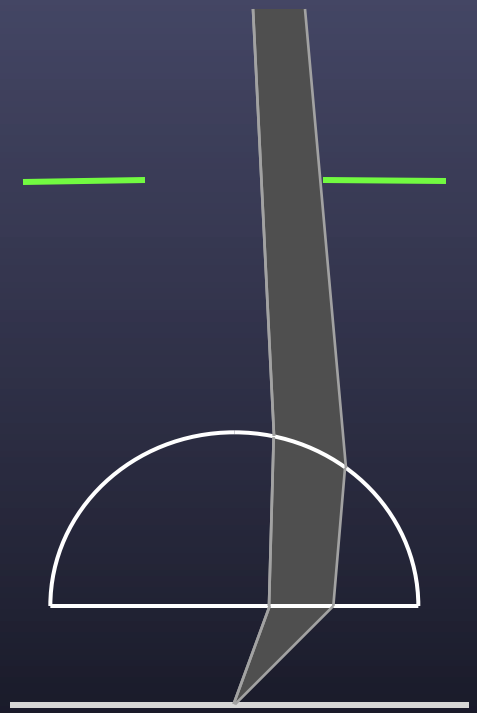
Single blond hair (10x/0.45NA)



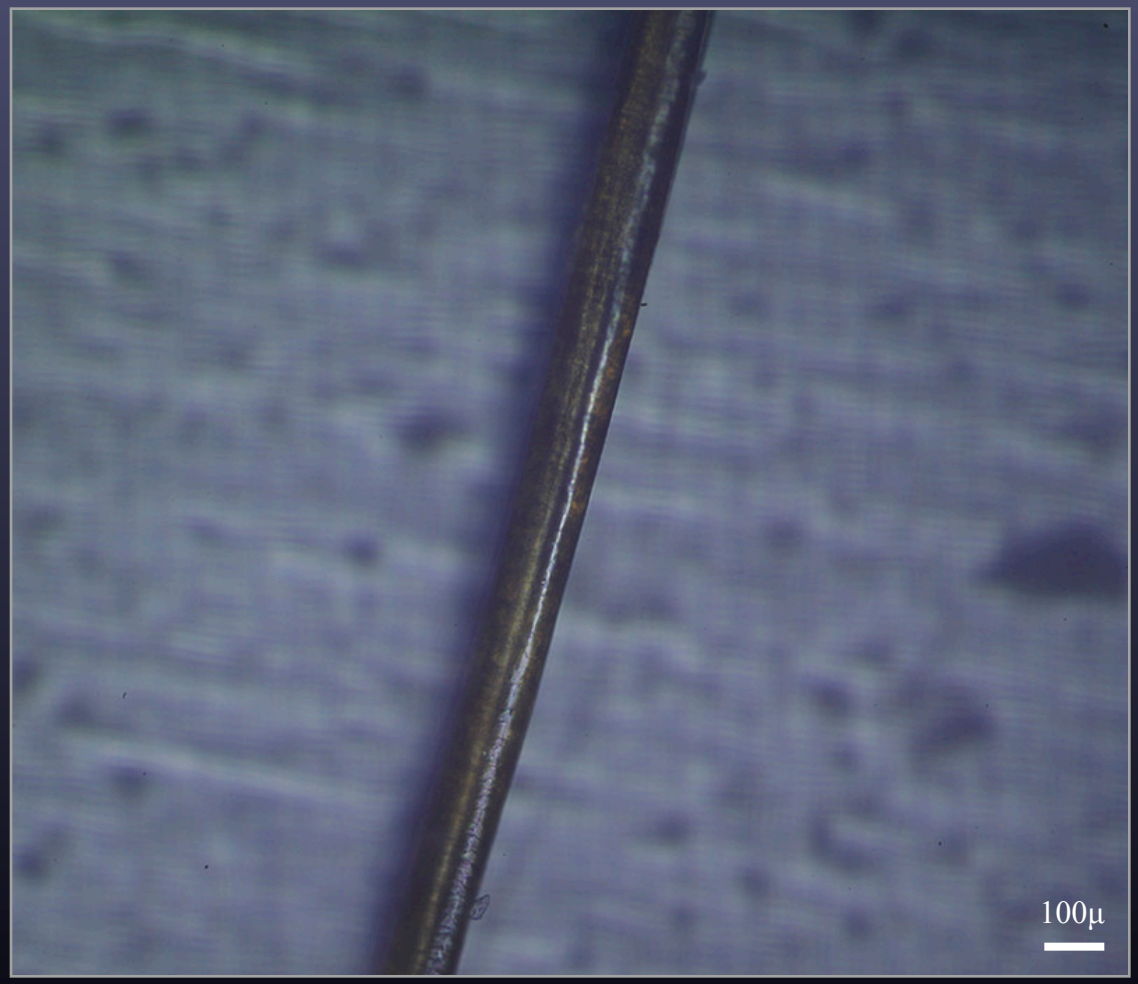
headlamp



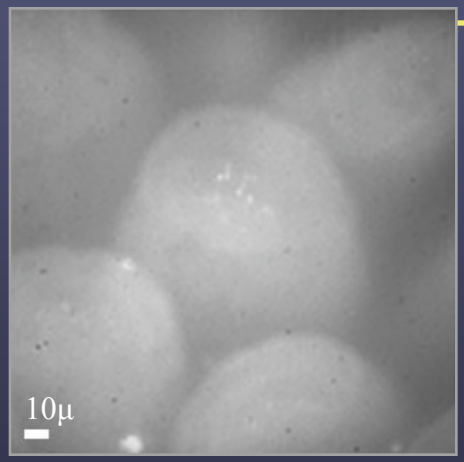
Single blond hair (10x/0.45NA)

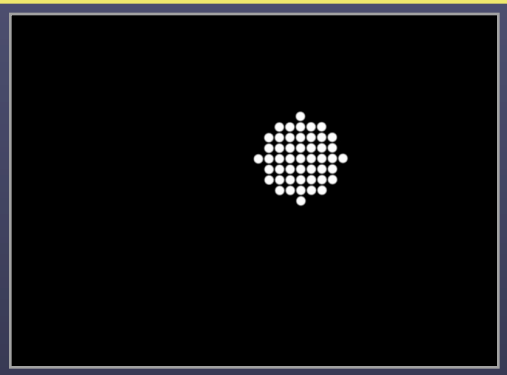


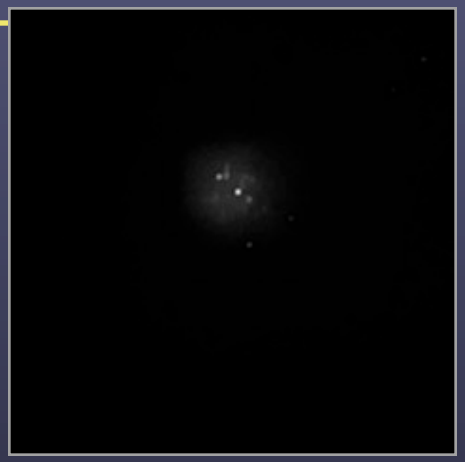
oblique



Spatial control over lighting
(collaboration with Julie Theriot)

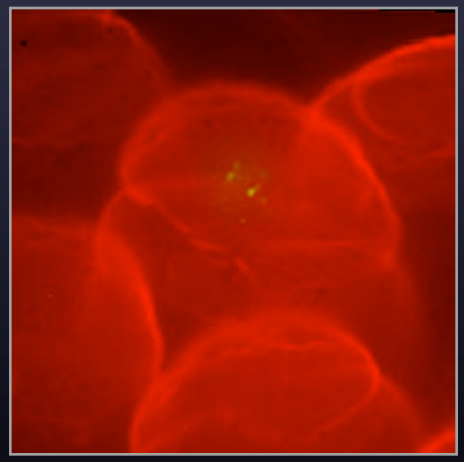


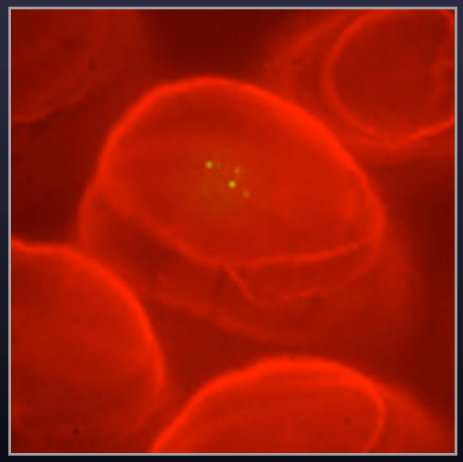


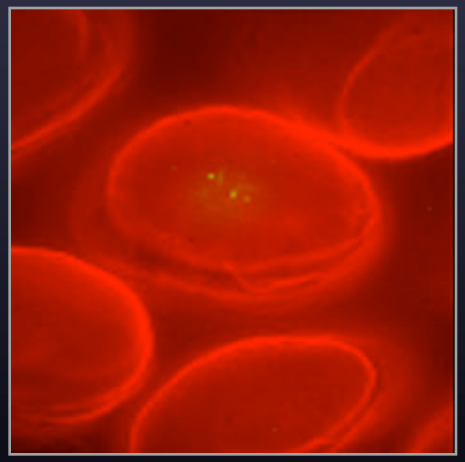


Listeria monocytogenes
in mouse intestine villus

6x improvement in contrast

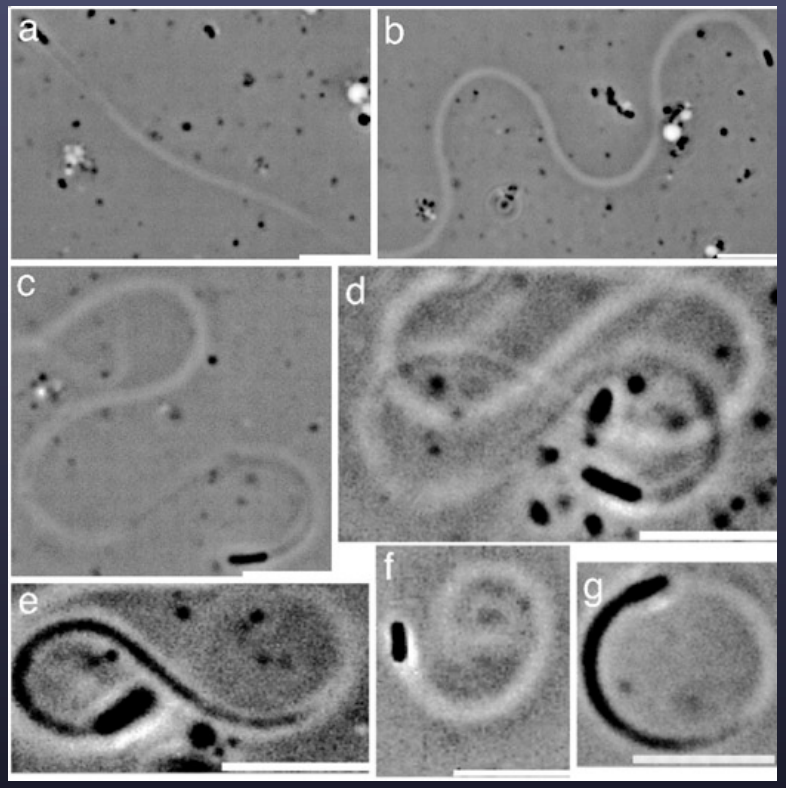






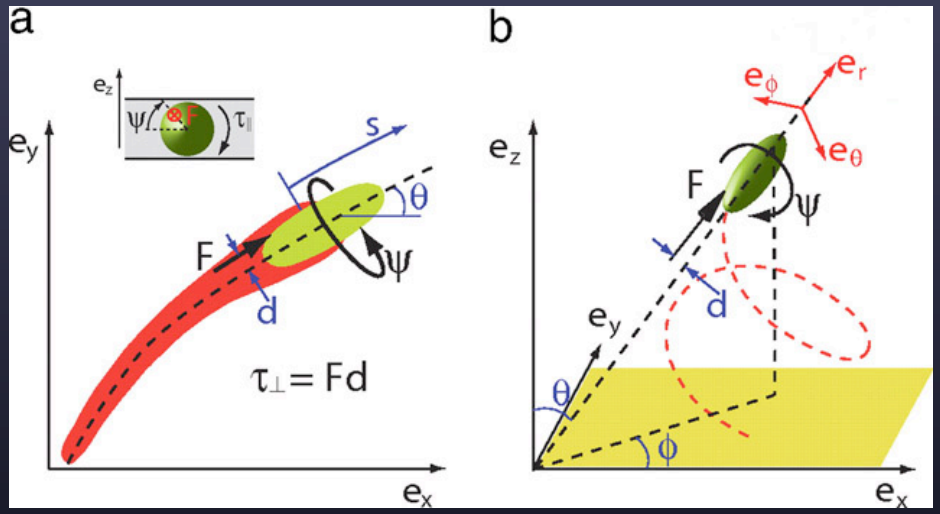
color composite with green = GFP, red = rhodamine-phalloidin

Tracking 3D bacterial motions using "follow spotlights"



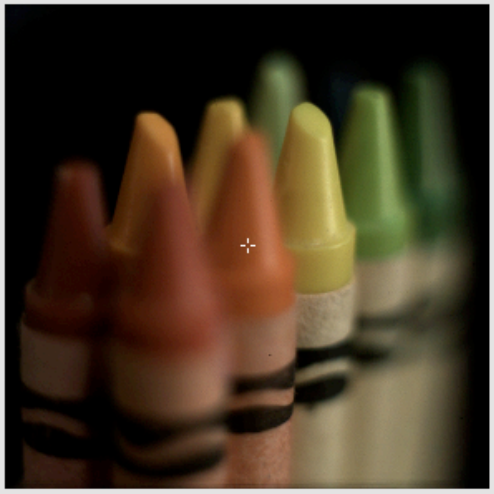
motion of *Listeria monocytogenes* imaged in 2μ thick chamber

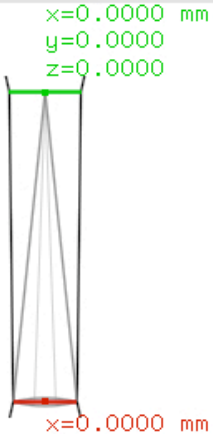
[Shenoy and Theriot]

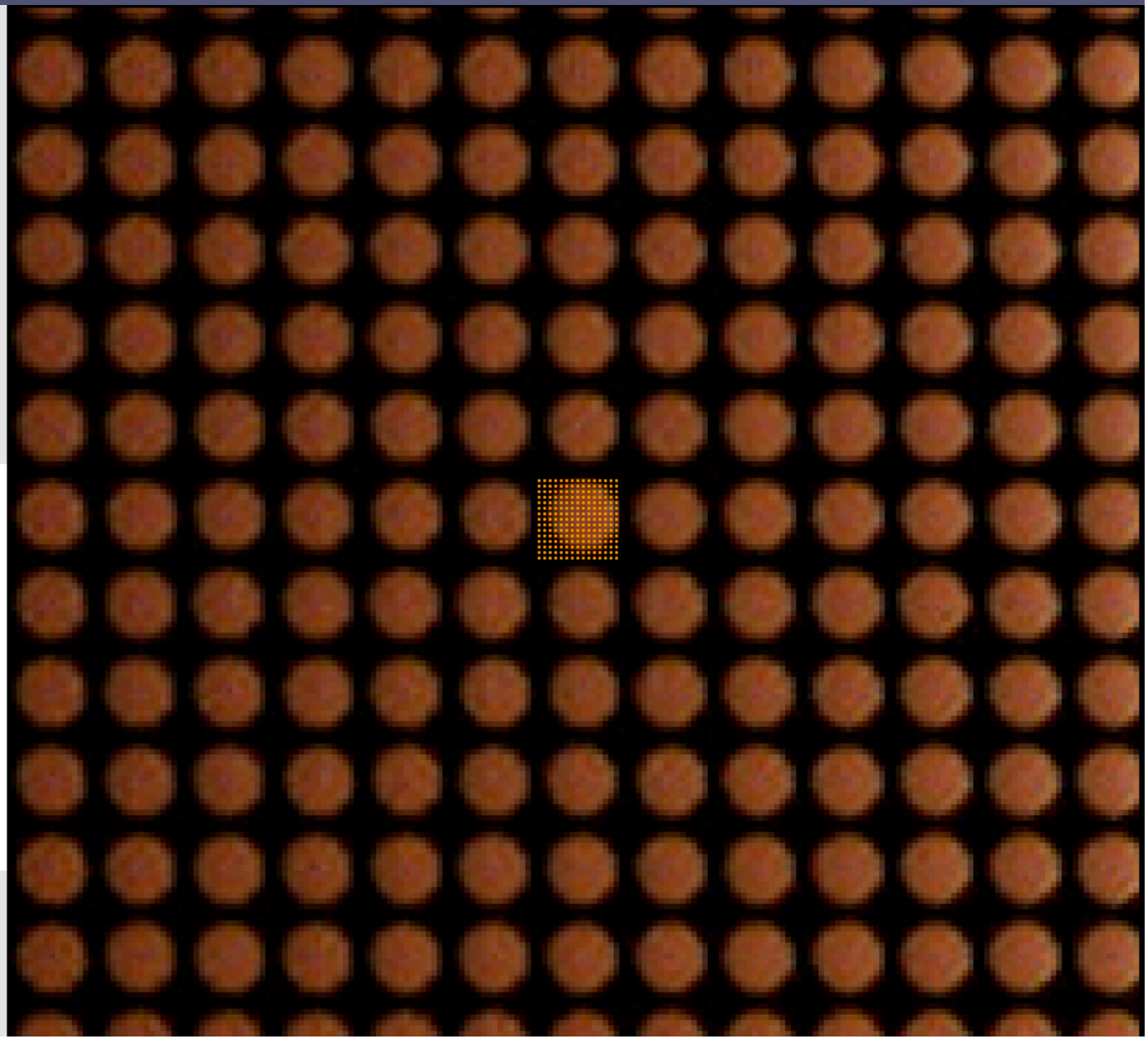


geometry of bacterial trajectories in 2D and 3D

Which rays contribute to a pixel as the plane of focus is changed?







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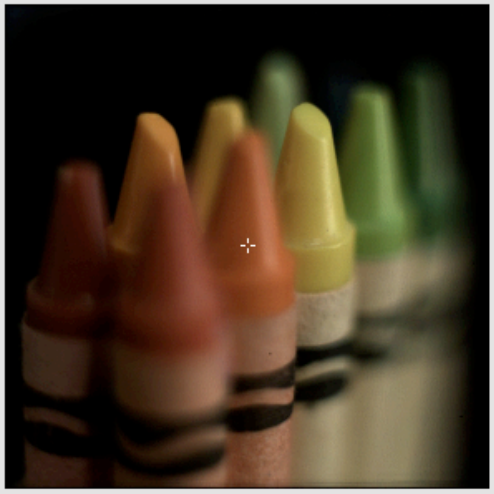
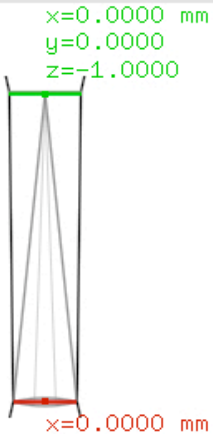
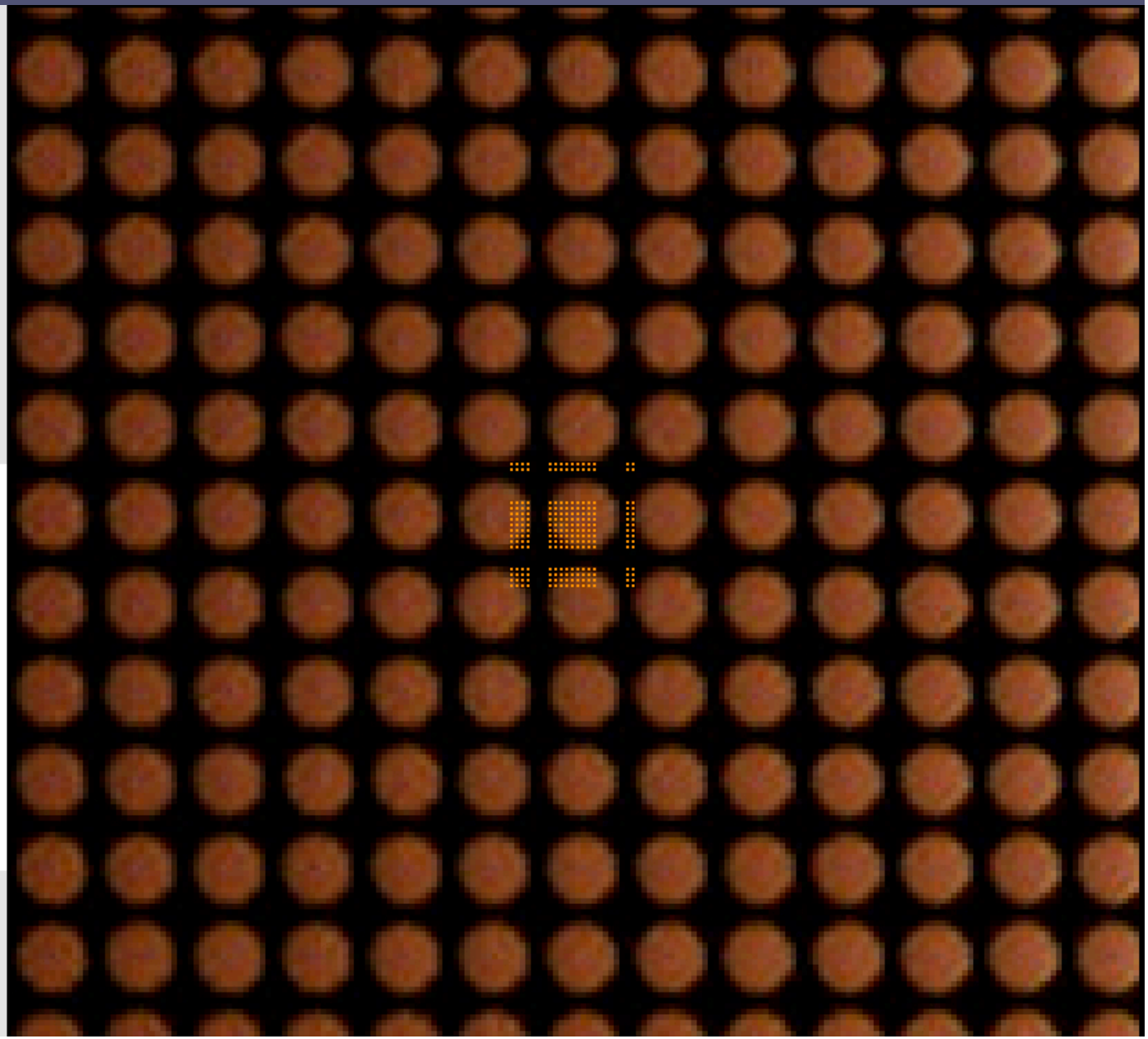
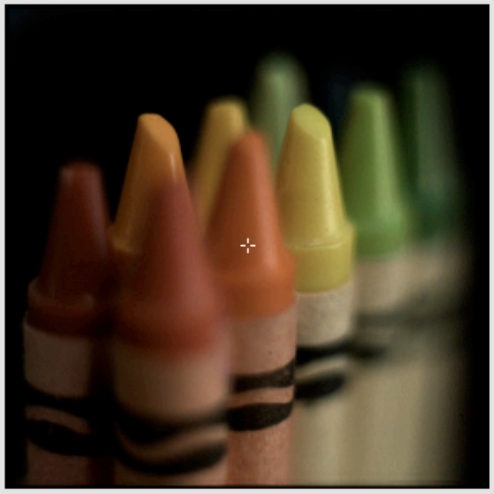
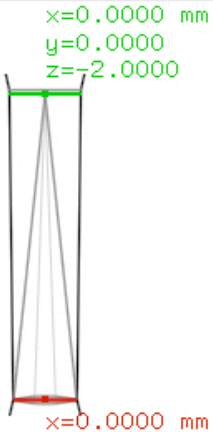


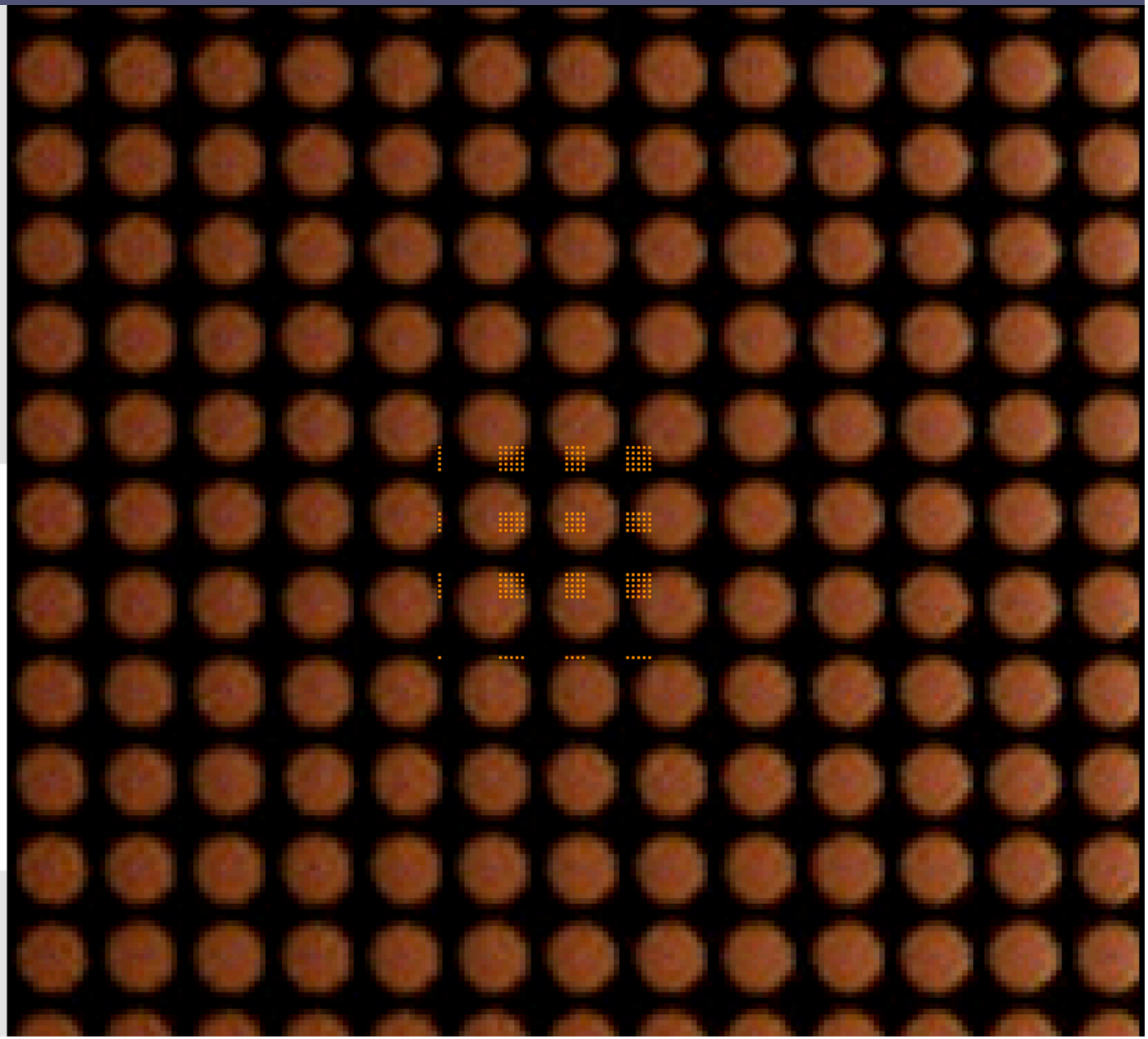




Which rays contribute to a pixel as the plane of focus is changed?







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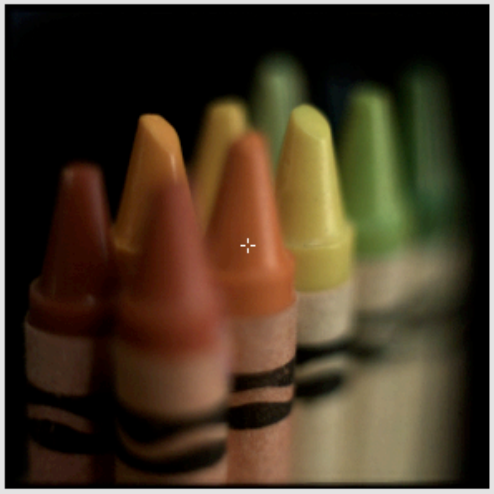
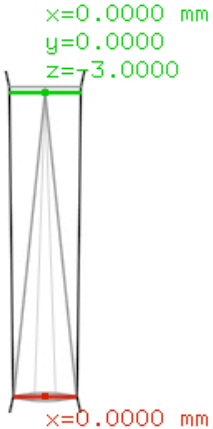
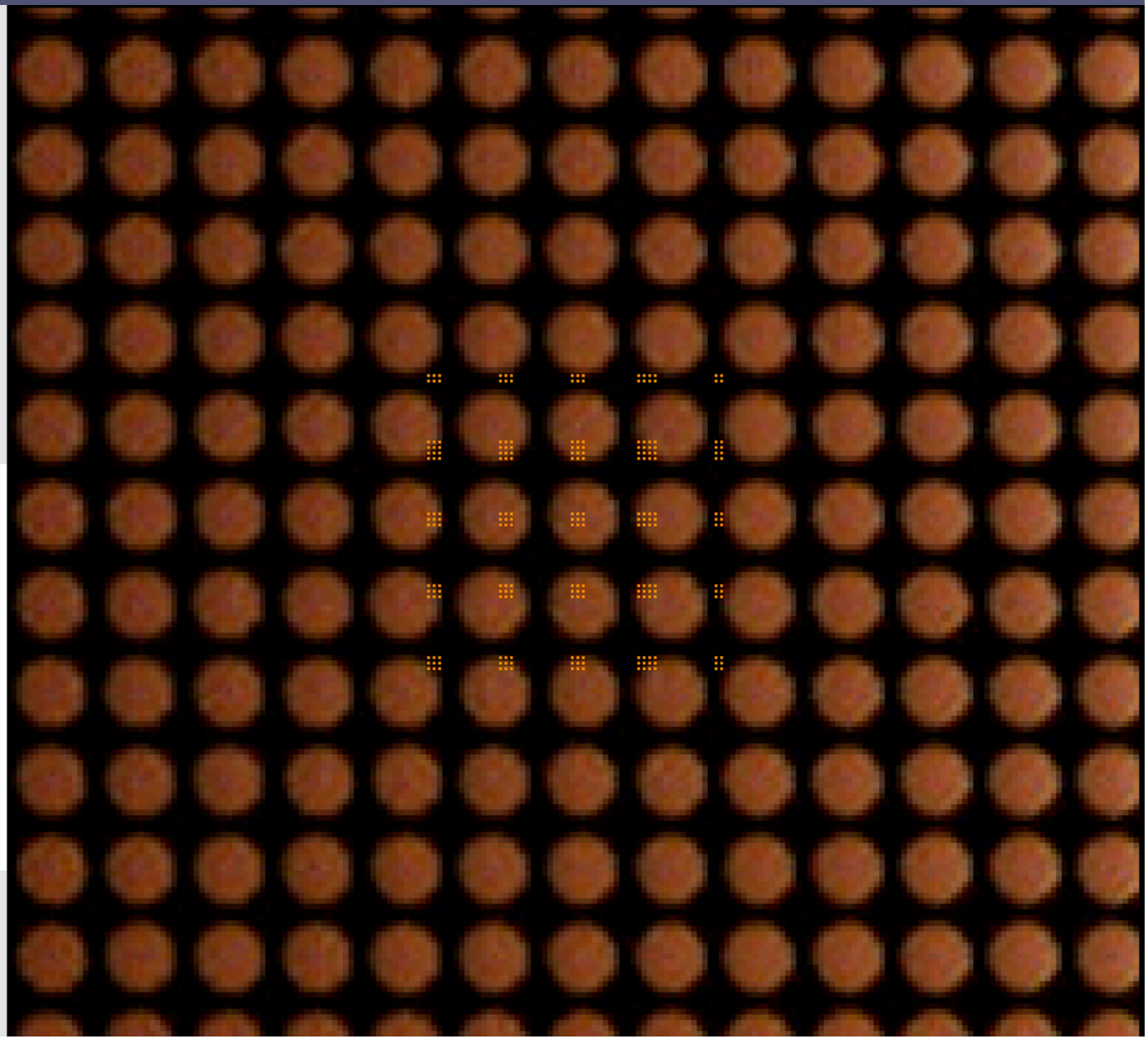
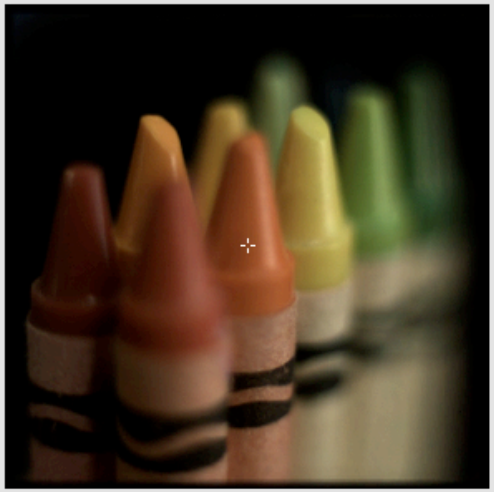
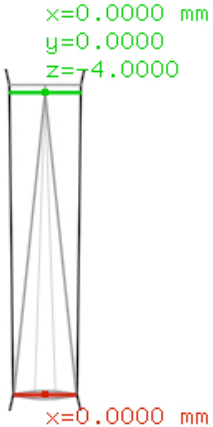


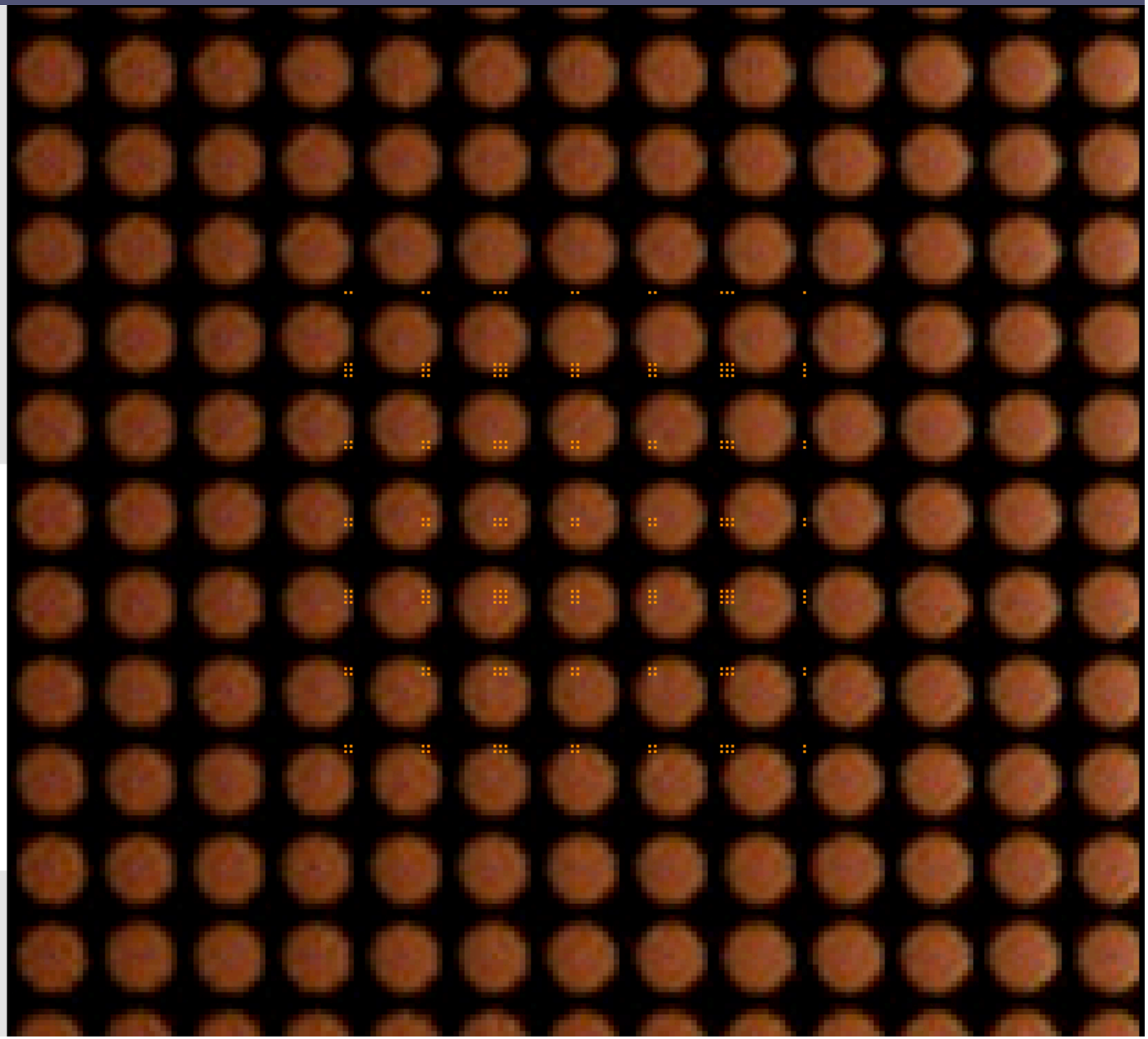




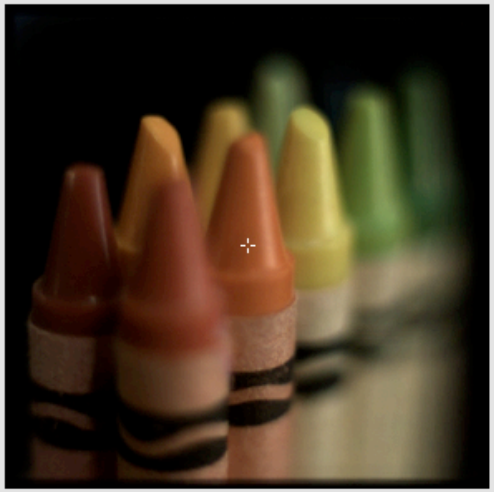
Which rays contribute to a pixel as the plane of focus is changed?

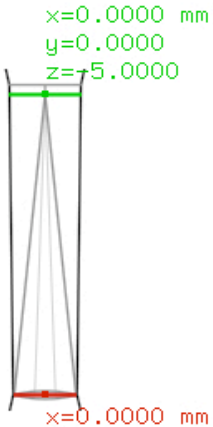


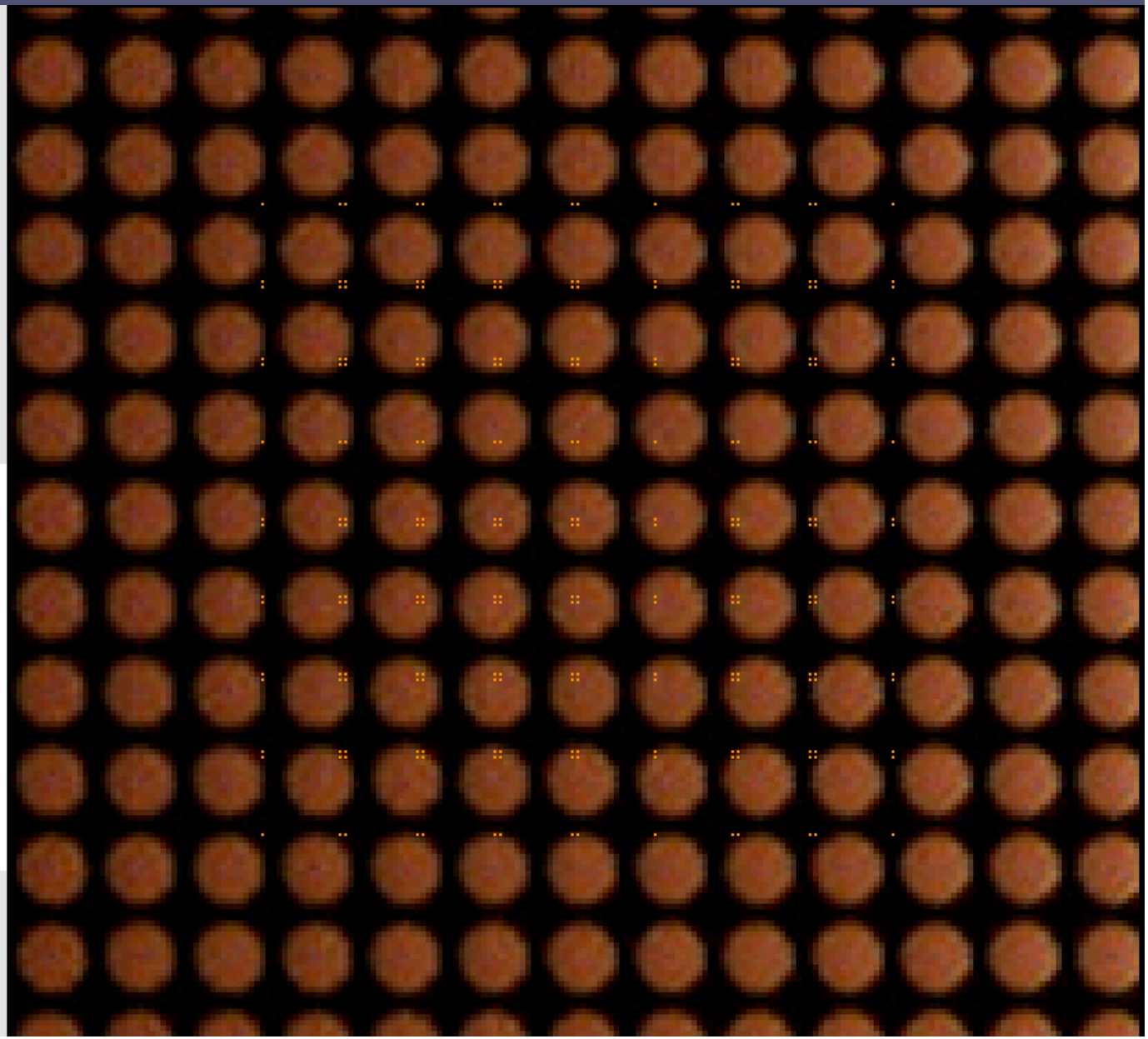




Which rays contribute to a pixel as the plane of focus is changed?







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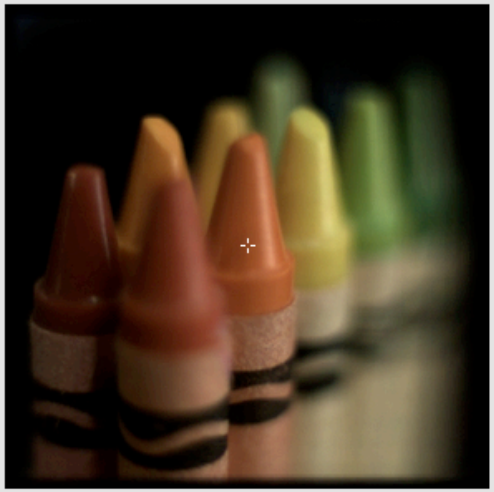
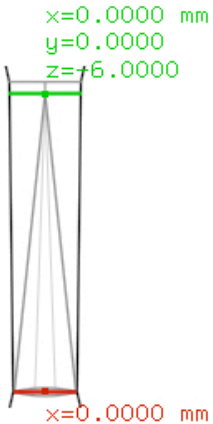
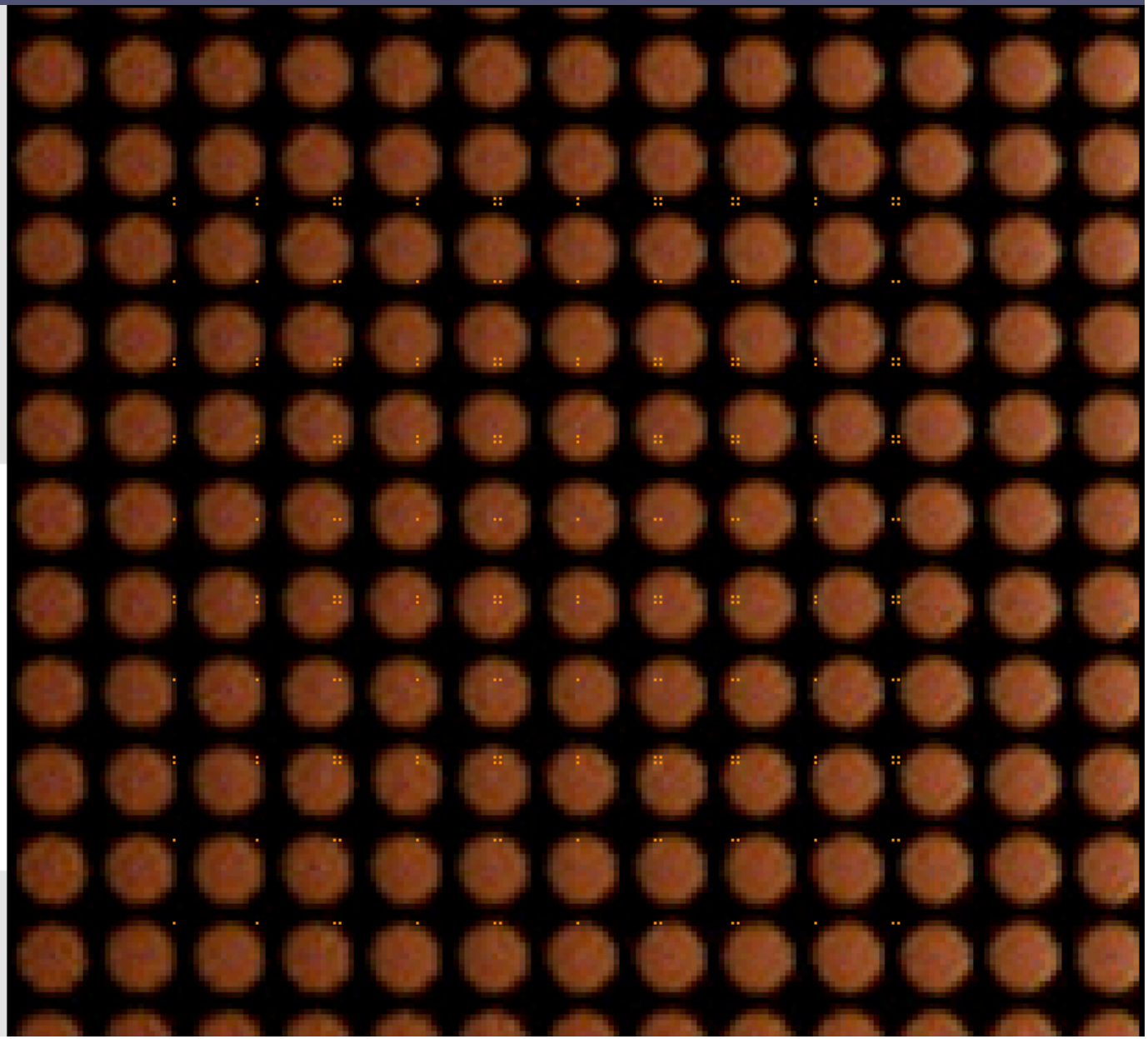
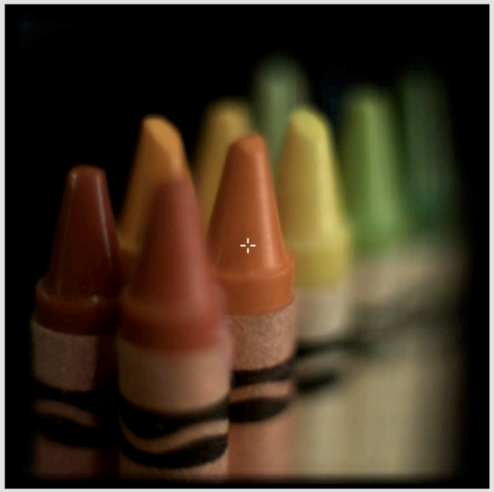
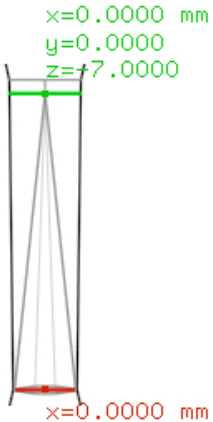


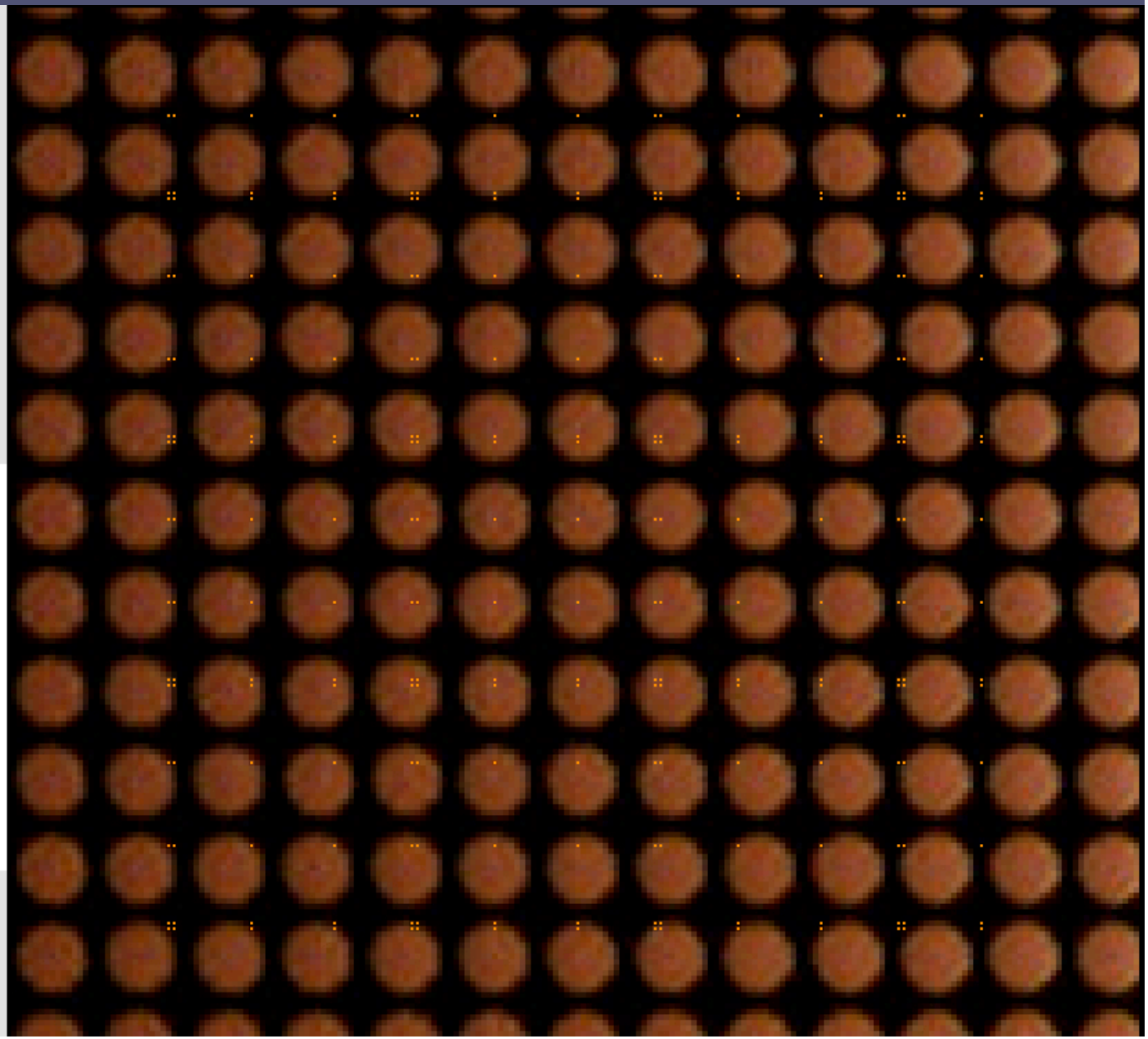




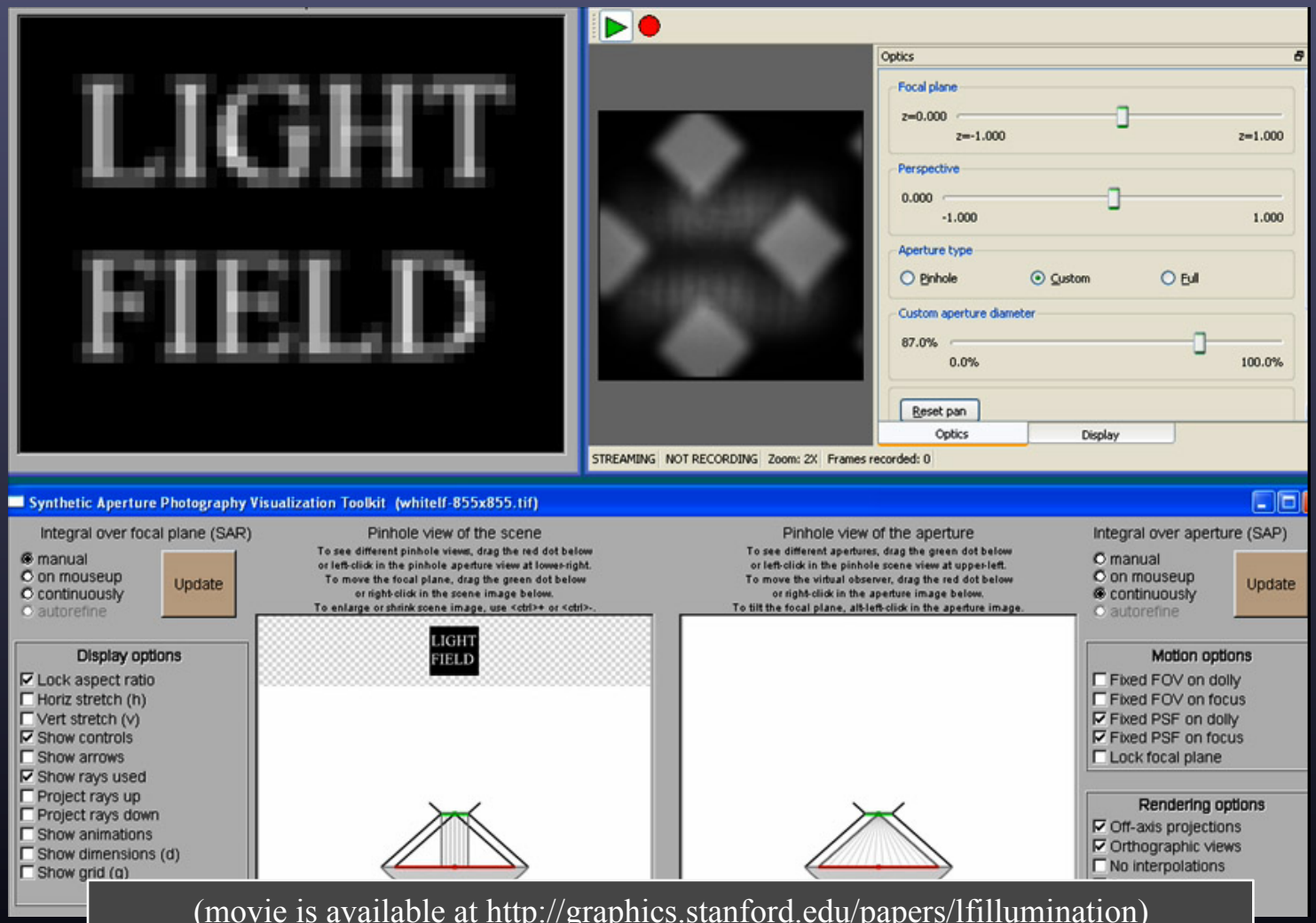
Which rays contribute to a pixel as the plane of focus is changed?







Digitally refocusing the illumination

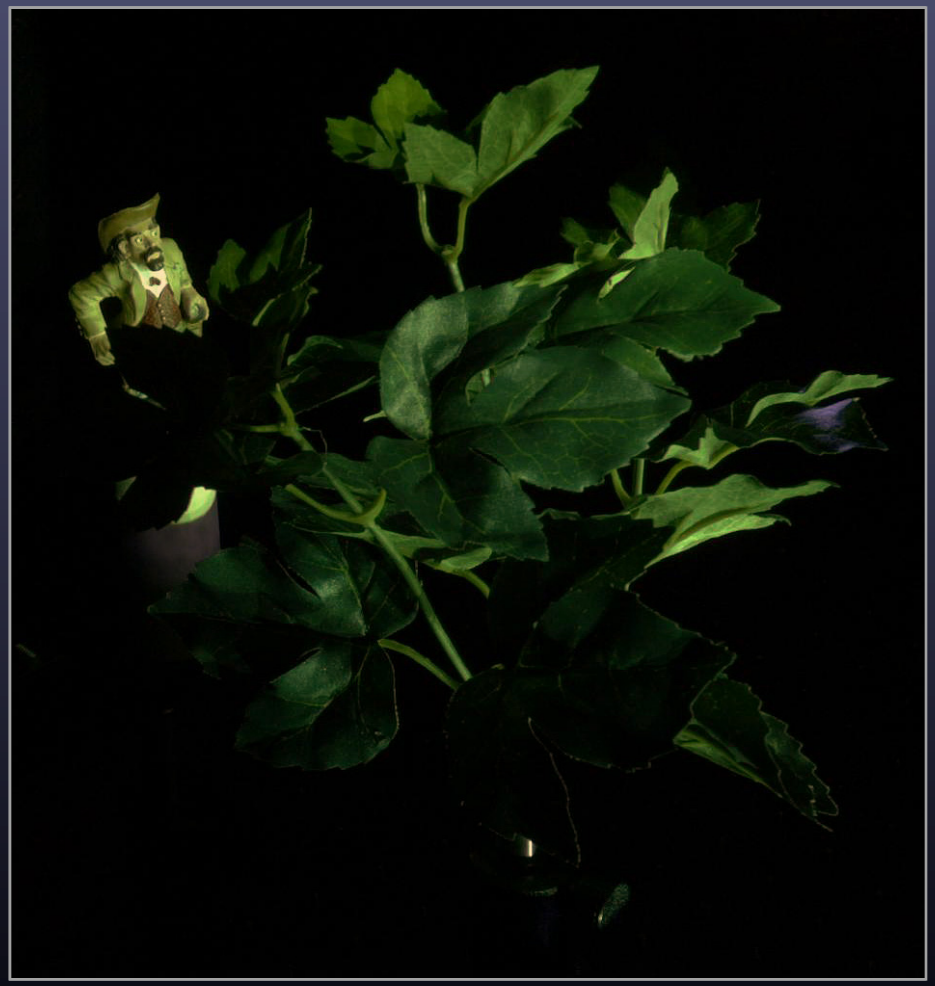


(movie is available at http://graphics.stanford.edu/papers/lfillumination)

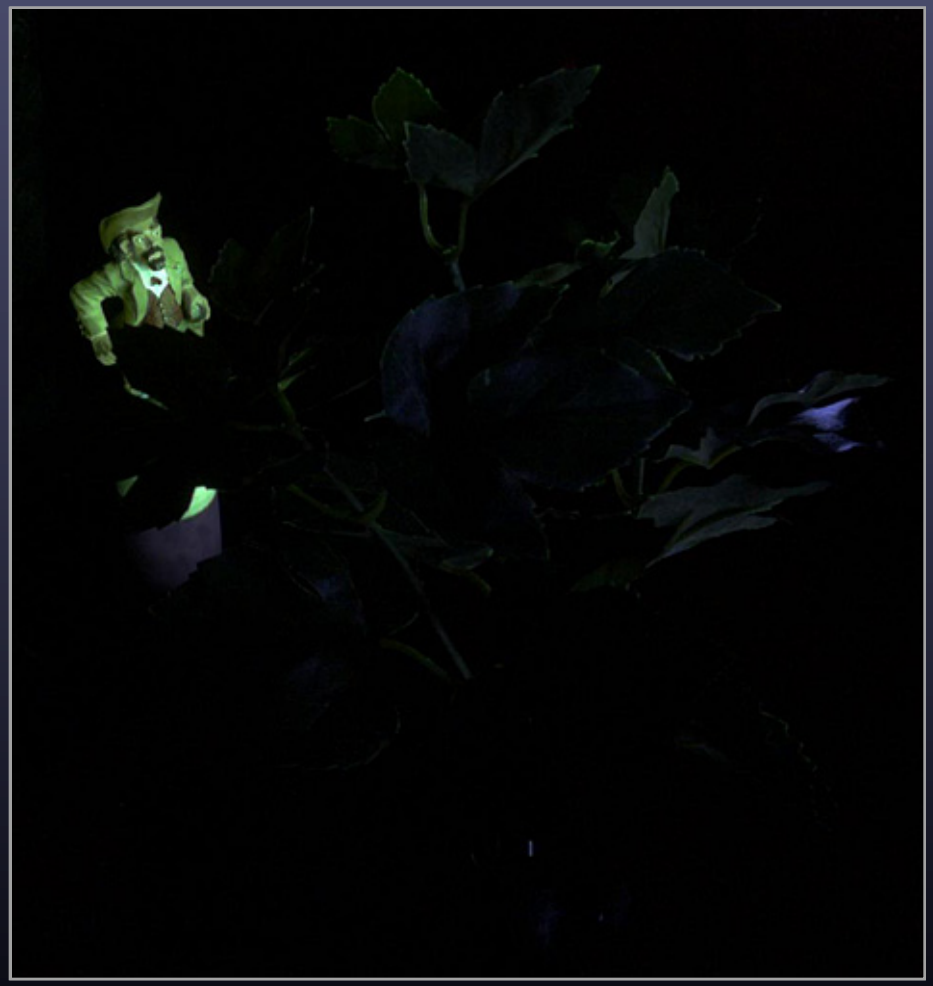
Other ideas

- maximize illumination over selected voxels
  - while minimizing illumination over other voxels
  - use algorithms from radiation treatment planning?

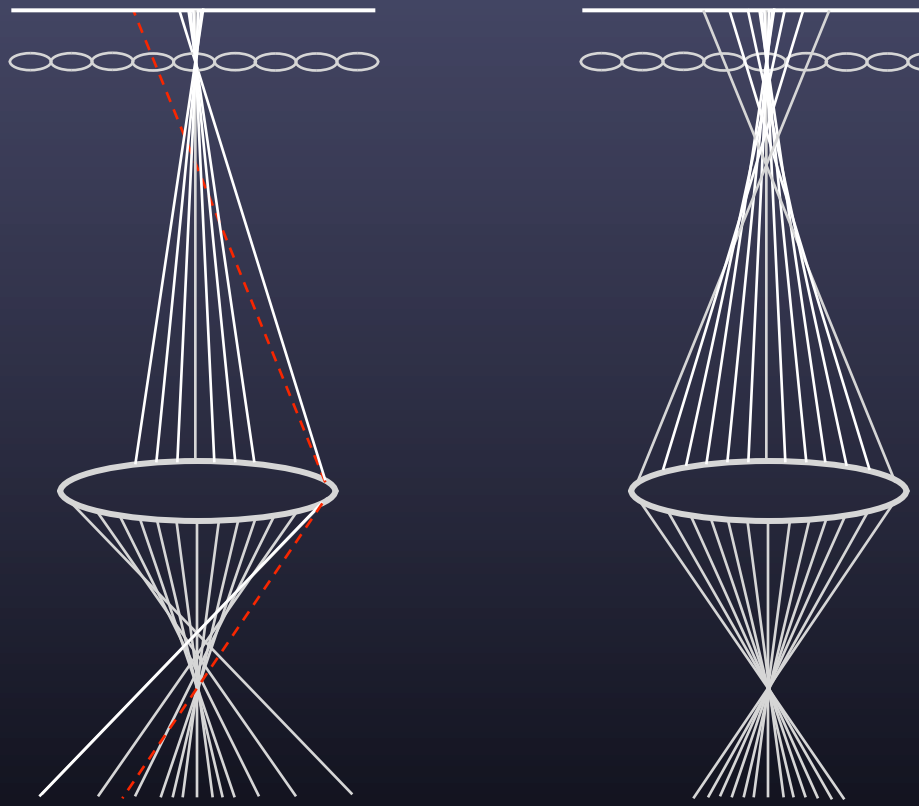
“4D designer lighting”
(from [Levoy 2004])



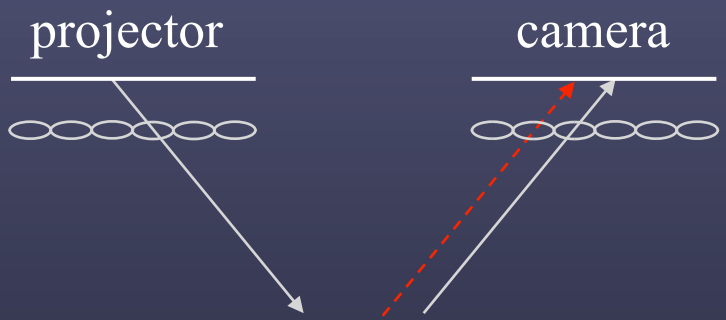
“4D designer lighting”
(from [Levoy 2004])



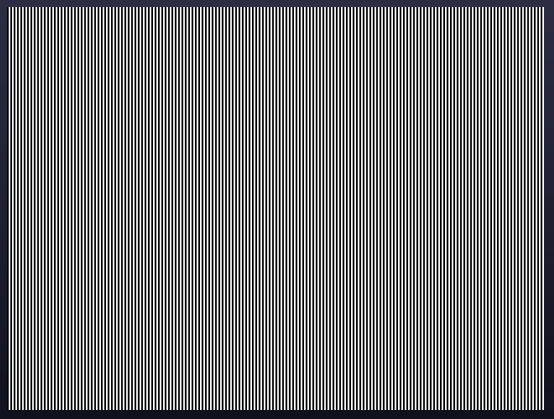
Correcting spherical aberrations digitally using light fields



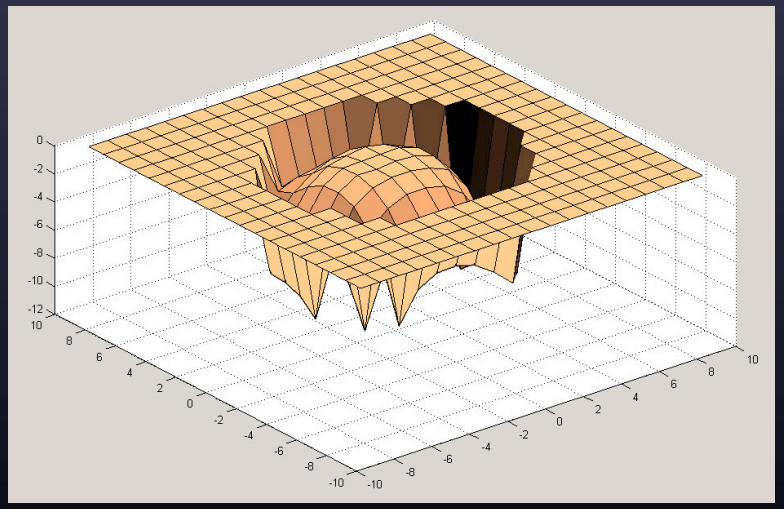
Creating guide stars using programmable illumination



...and using the LFM as a Shack-Hartmann sensor



Gray codes



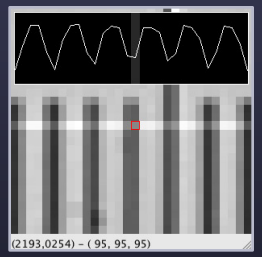
aberration as a function of pupil position

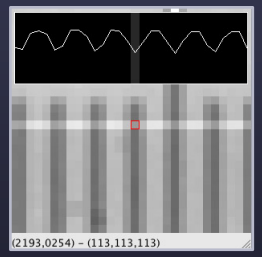
Digital correction of aberrations
(60× / 1.0 NA dipping objective)

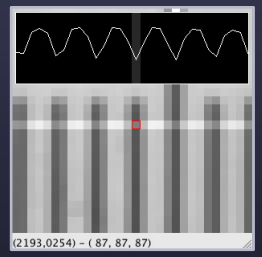
distilled water

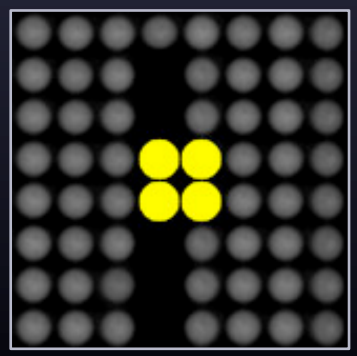
10% glycerol uncorrected

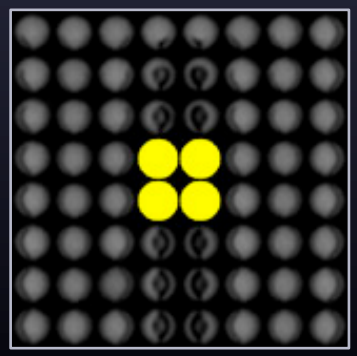
digitally corrected

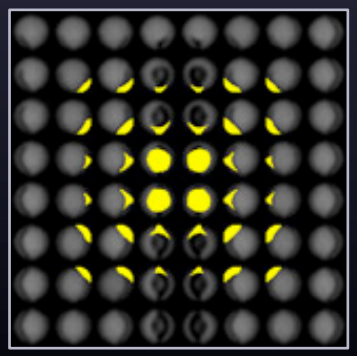




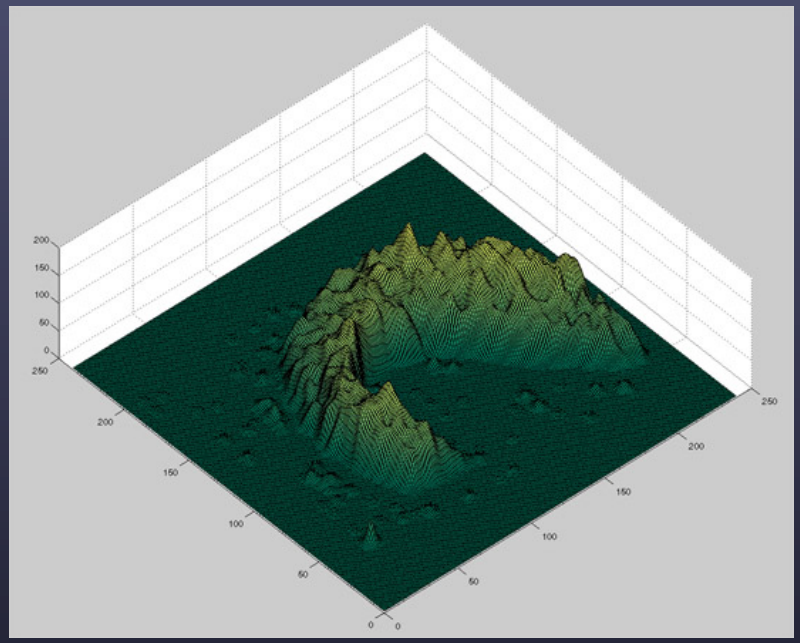








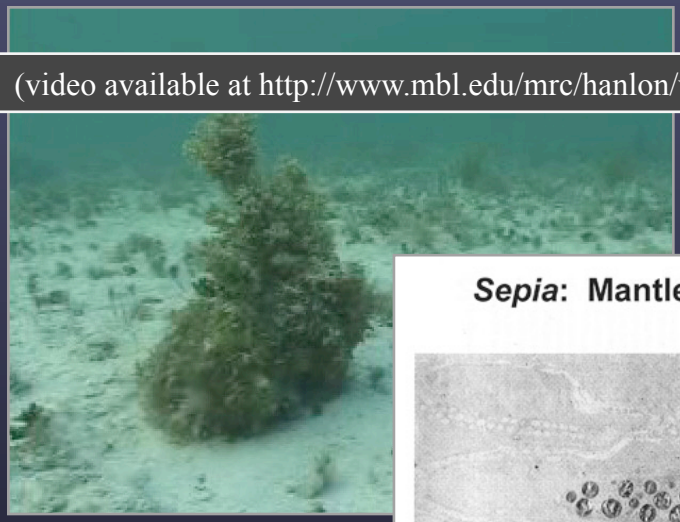
Structured light rangefinding



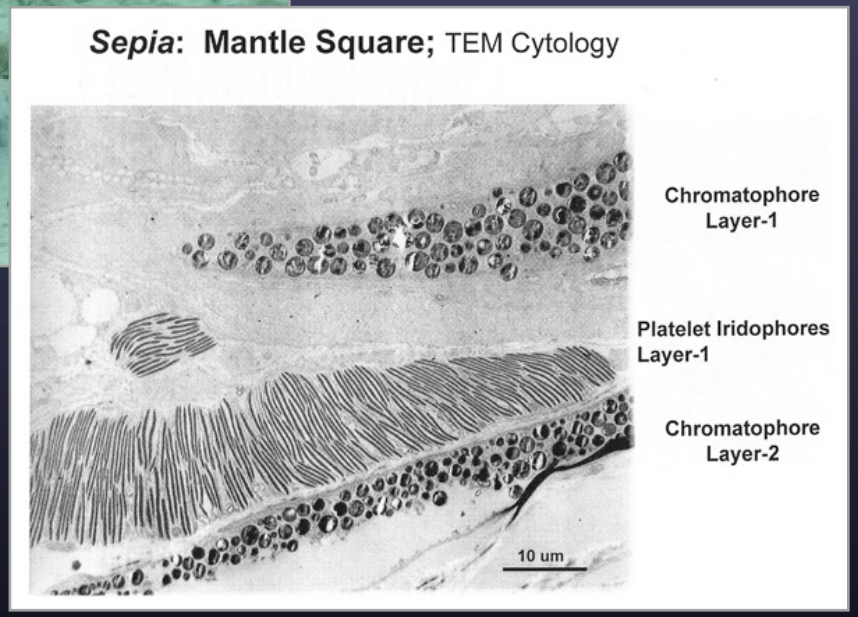
- spatial resolution = microlens count → crude 3D model
- combine with BRDFs / BSSRDFs to measure or parameterize new models of material appearance

Reflectance properties of biological objects

(video available at http://www.mbl.edu/mrc/hanlon/video.html)

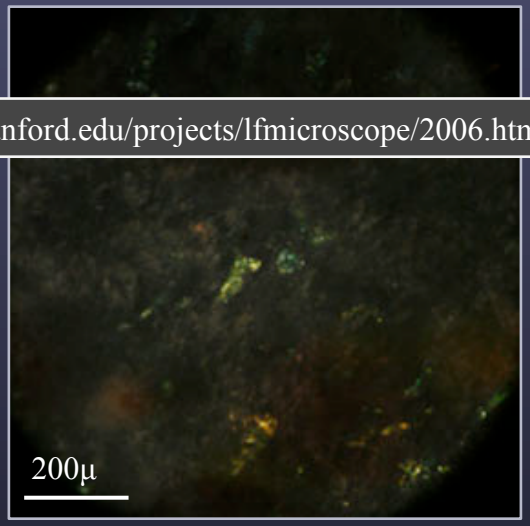


(Roger Hanlon)



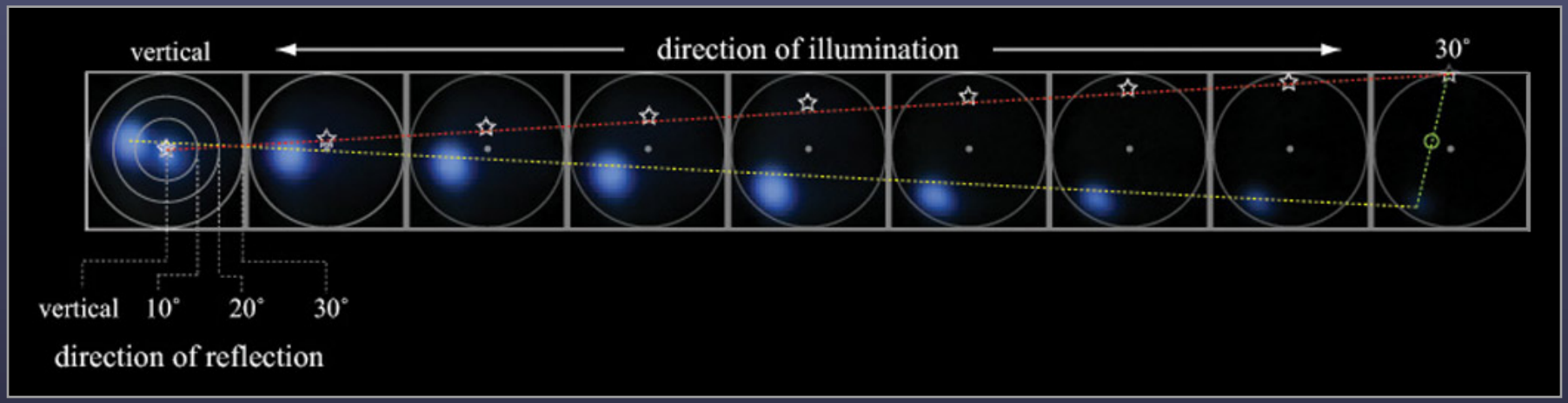
(Lydia Mathger)

(movie is available at http://graphics.stanford.edu/projects/lfmicroscope/2006.html)

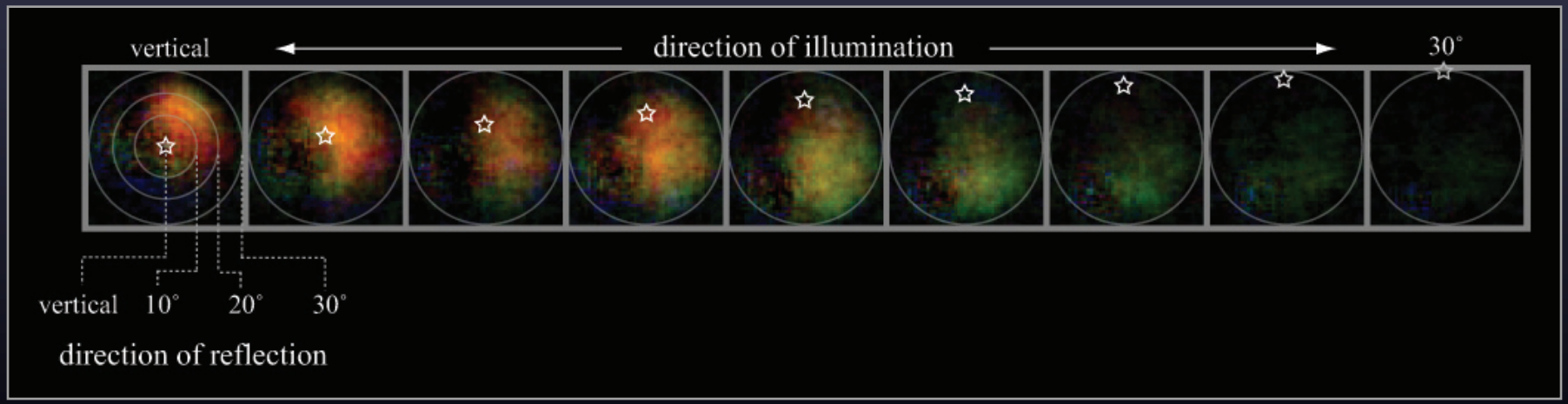


single iridiphores in live skin sample of *Loligo pealeii*

Slice of BSSRDF of single squid skin iridiphore

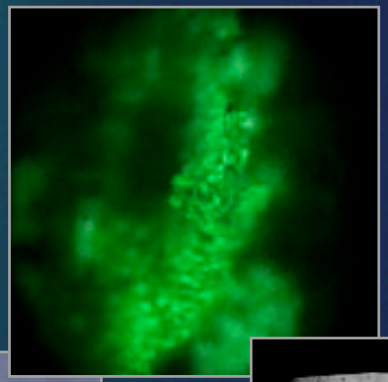
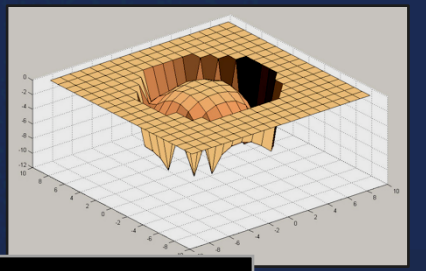
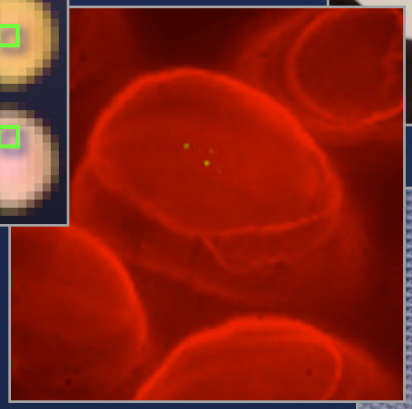
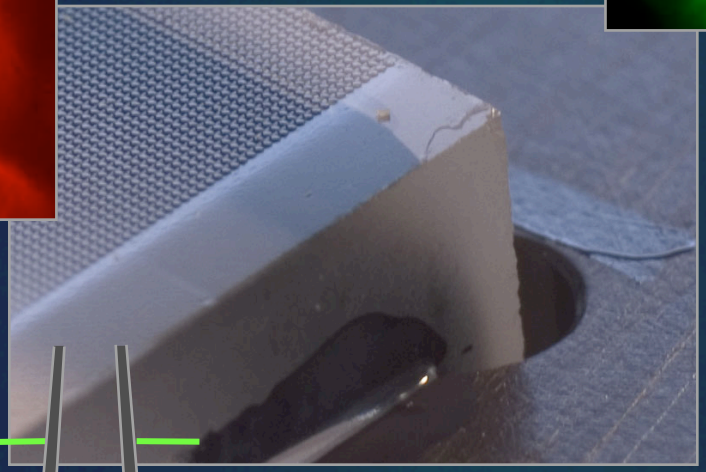
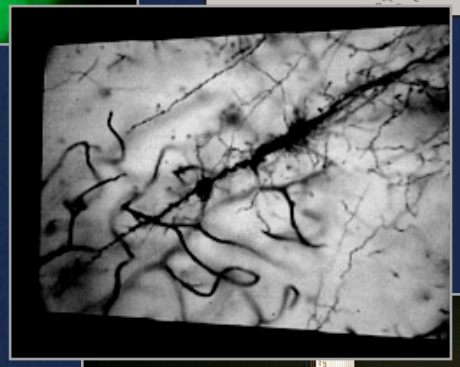


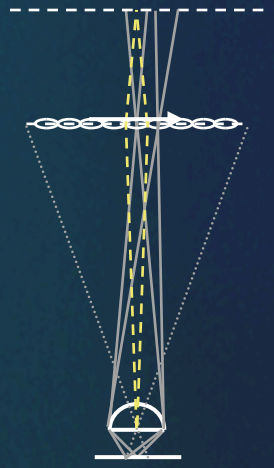
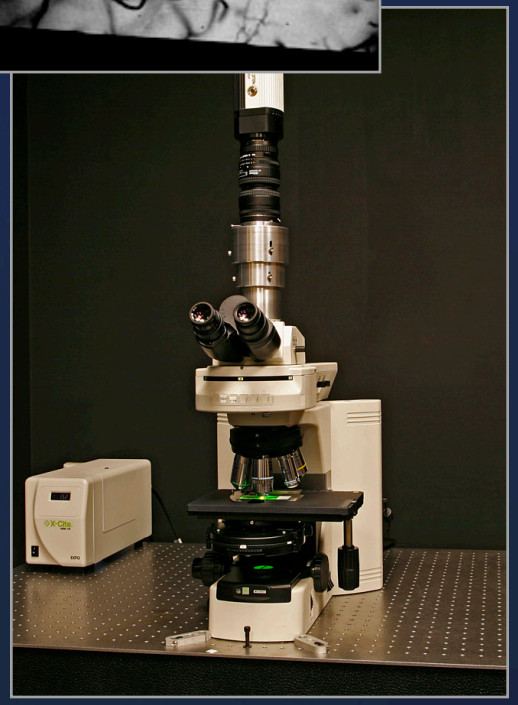
specular component



iridescence component



http://graphics.stanford.edu