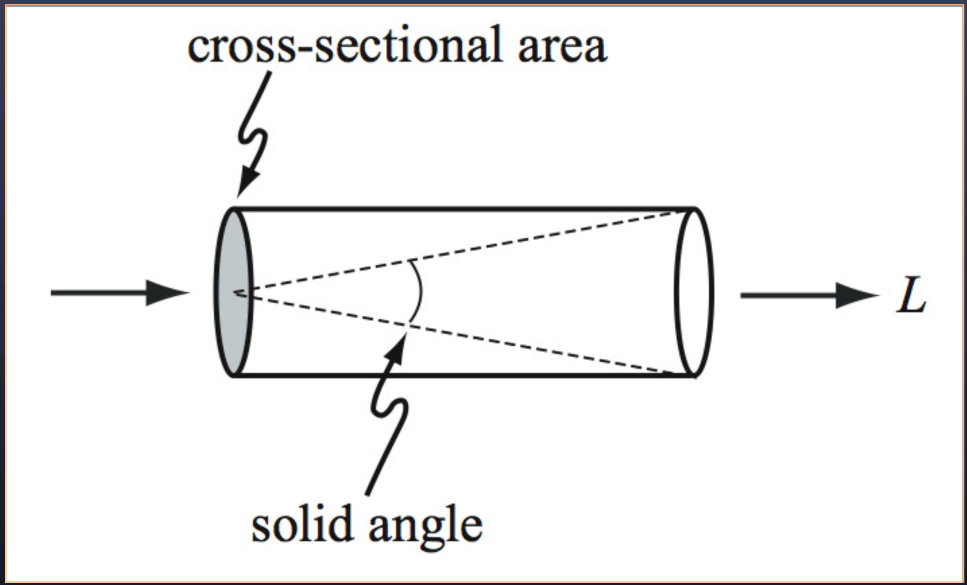
Light field photography

CS 178, Spring 2013

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

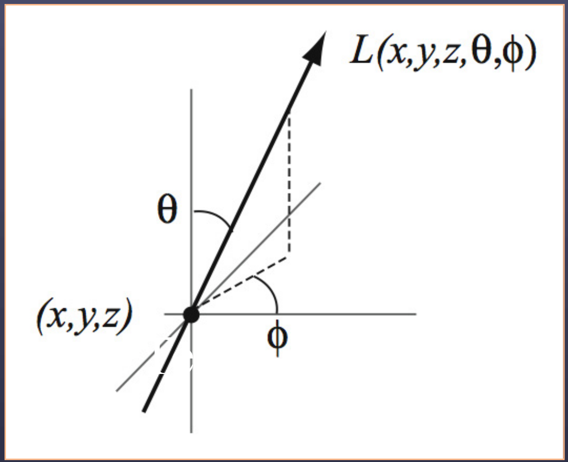


L is radiance in watts / (m^2 steradians)

Dimensionality of the light field

- for general scenes

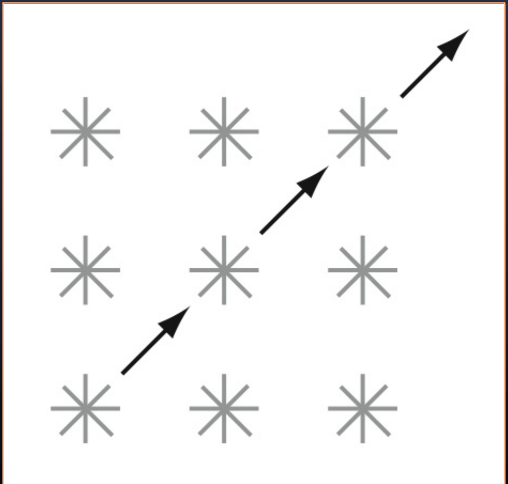
  ⇒ 5D function



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

- in free space

  ⇒ 4D function

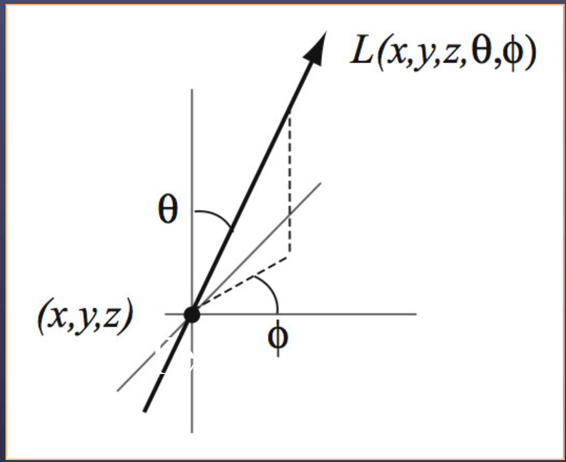


L (?)

Dimensionality of the light field

- for general scenes

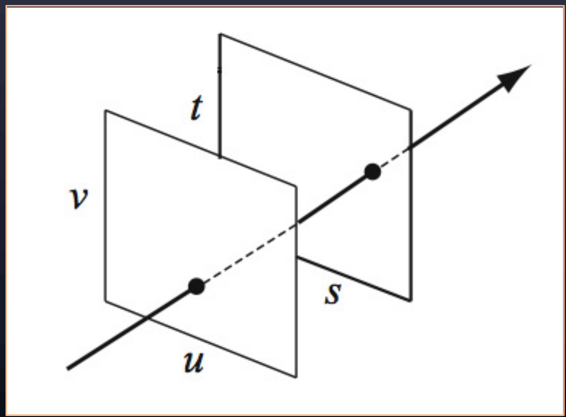
  ⇒ 5D function



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

- in free space

  ⇒ 4D function



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

two-plane parametrization

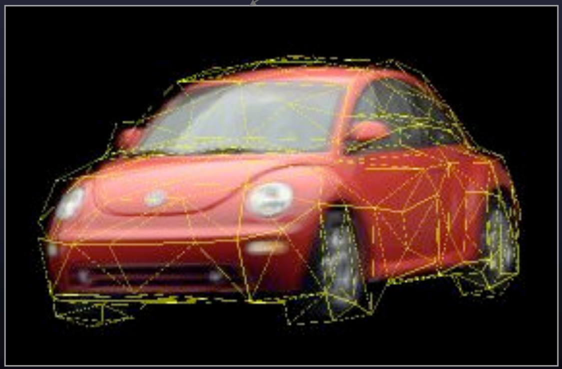
Devices for recording light fields

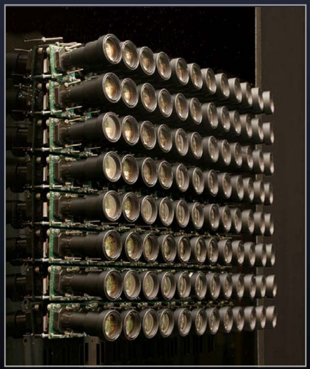
big scenes

↕

small scenes

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





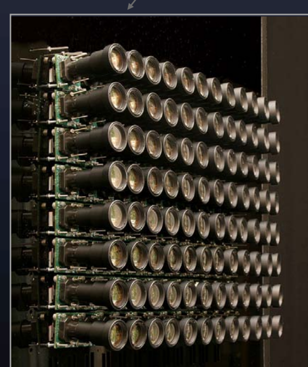
Devices for recording and creating light fields

big scenes

↕

small scenes

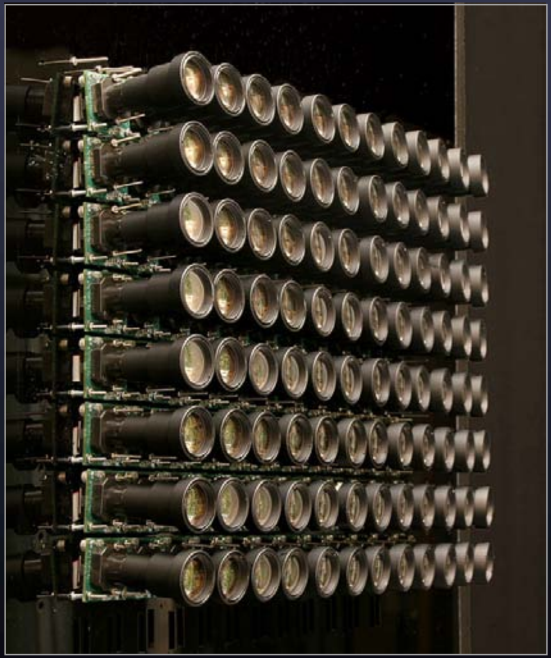
- handheld camera [Buehler 2001]
- → array of cameras [Wilburn 2005]
- → plenoptic camera [Ng 2005]
- → light field microscope [Levoy 2006]
- → light field illumination

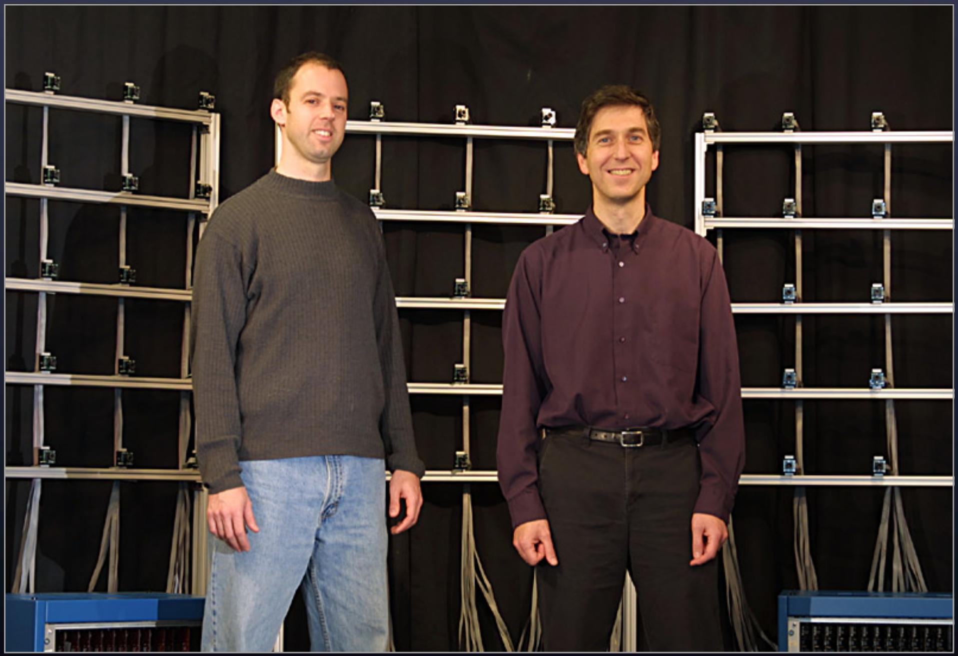


Stanford Multi-Camera Array
[Wilburn SIGGRAPH 2005]

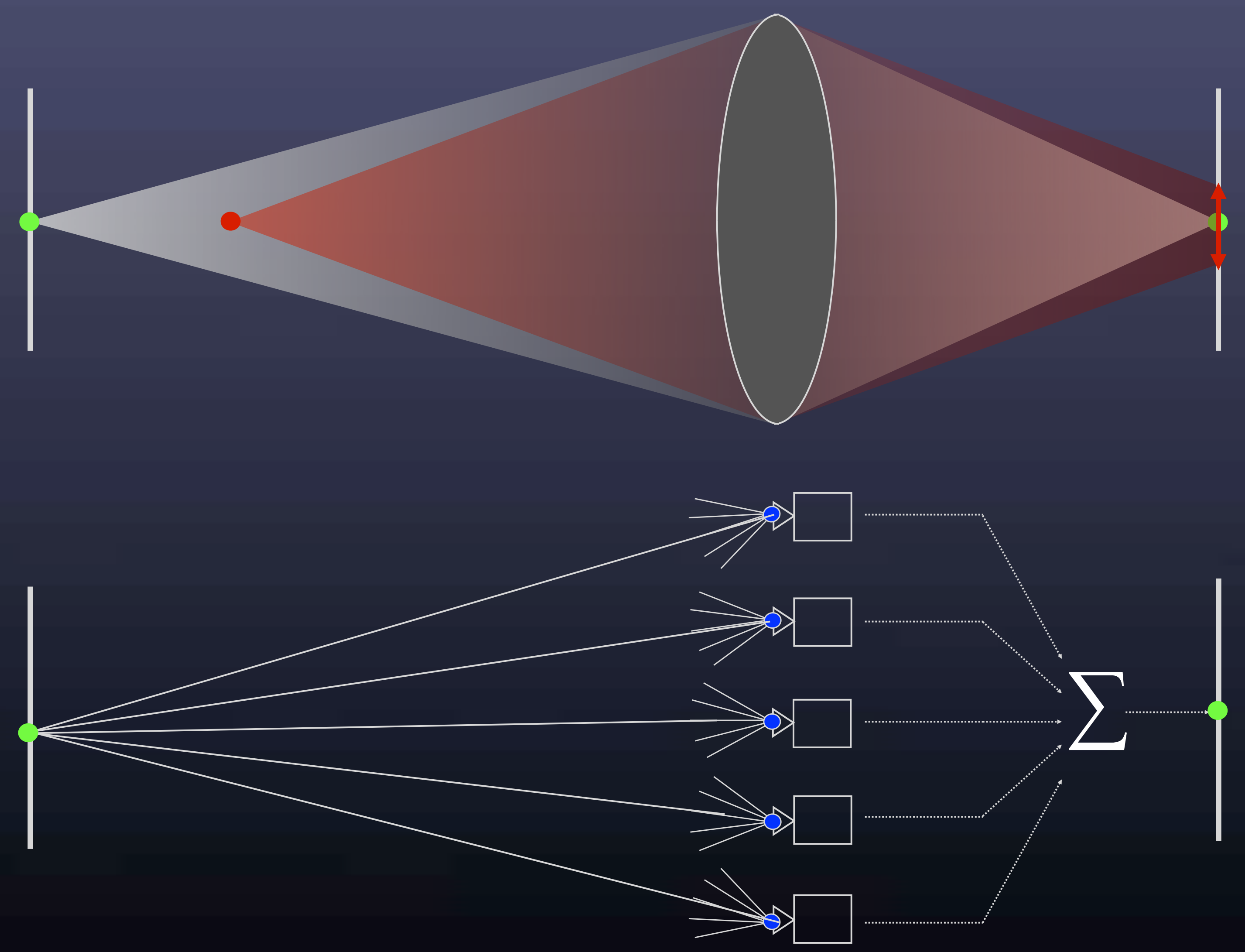
- 640 × 480 pixels × 30 fps × 128 cameras

- synchronized timing
- continuous streaming
- flexible arrangement

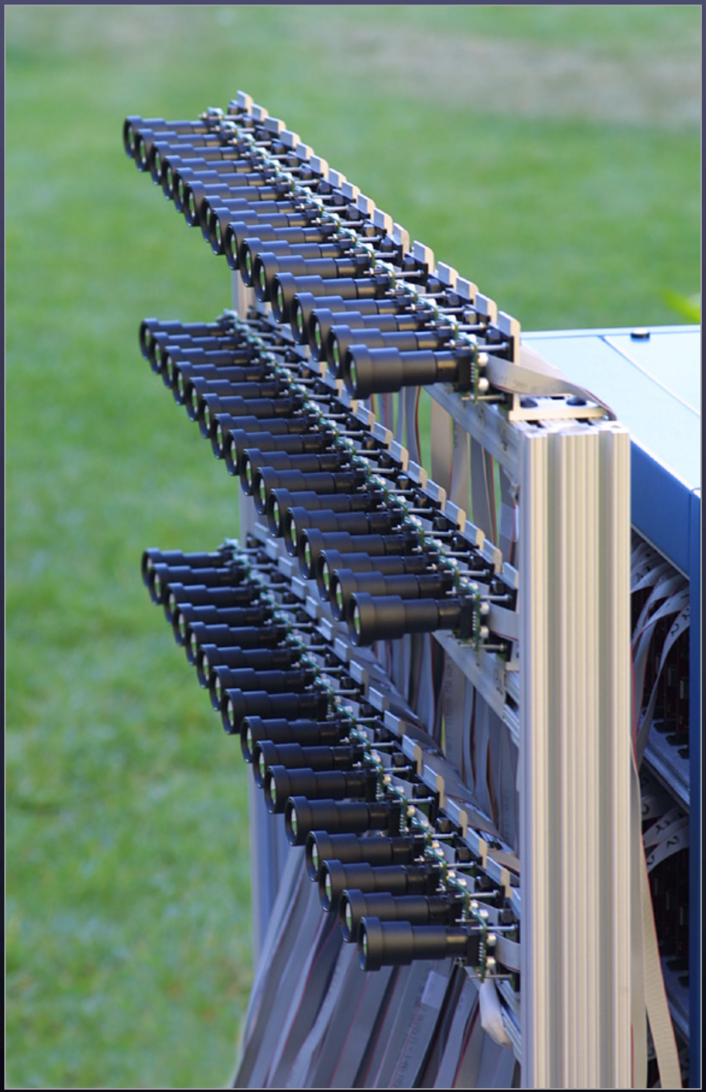


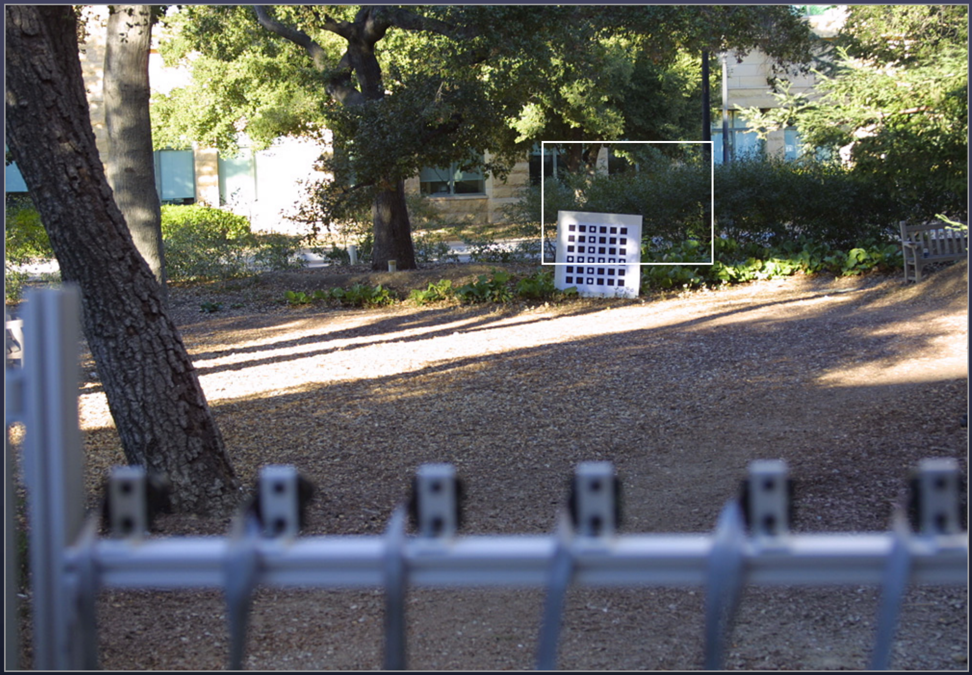


Synthetic aperture photography



Example using 45 cameras
[Vaish CVPR 2004]

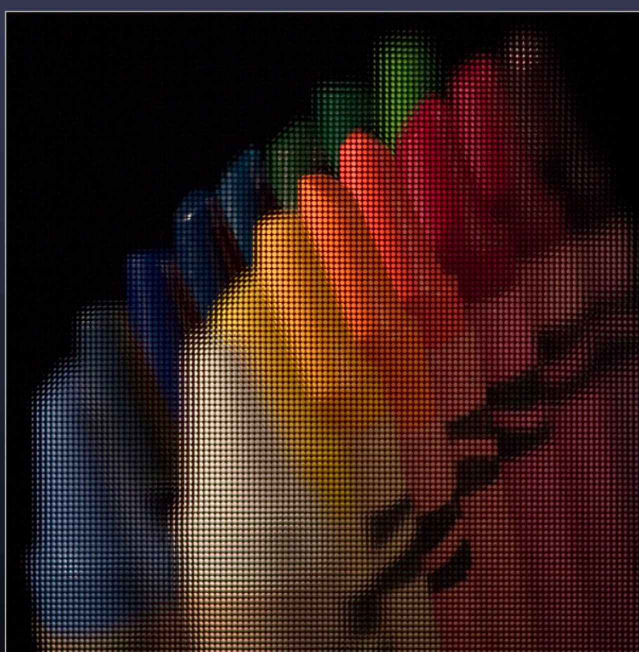




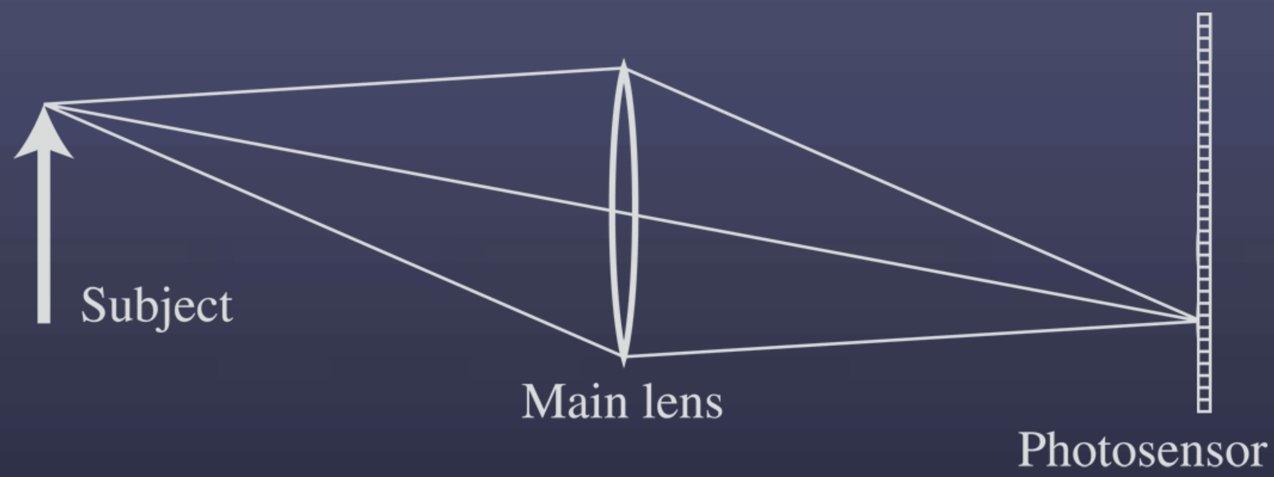
Light field photography using a handheld plenoptic camera

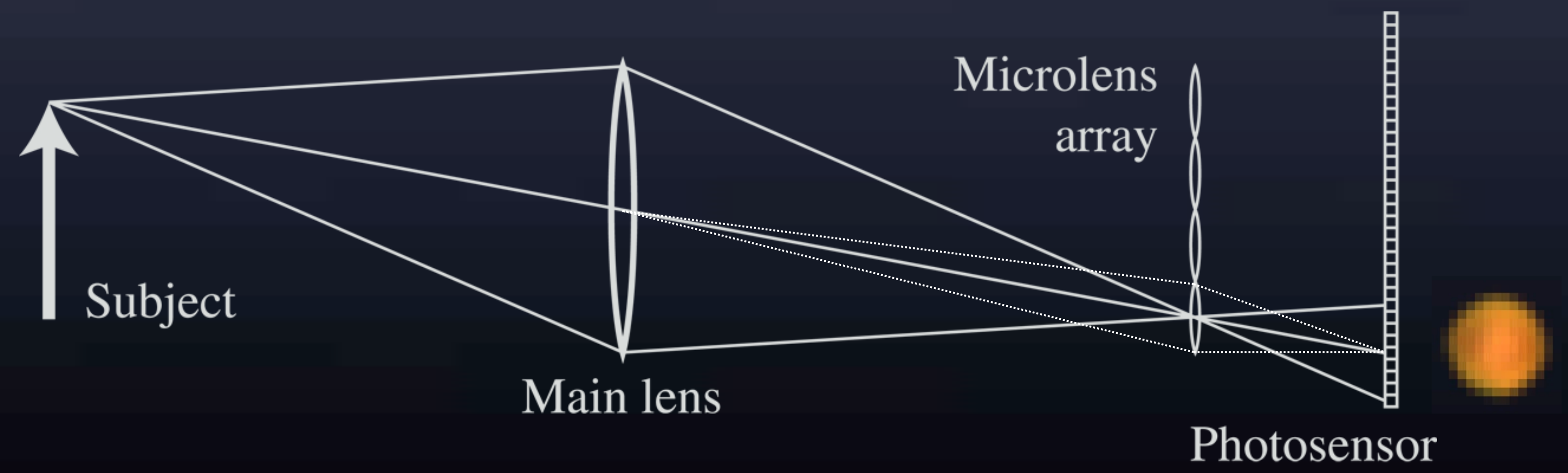
Ren Ng, Marc Levoy, Mathieu Brédif,
Gene Duval, Mark Horowitz and Pat Hanrahan

(Proc. SIGGRAPH 2005
and TR 2005-02)

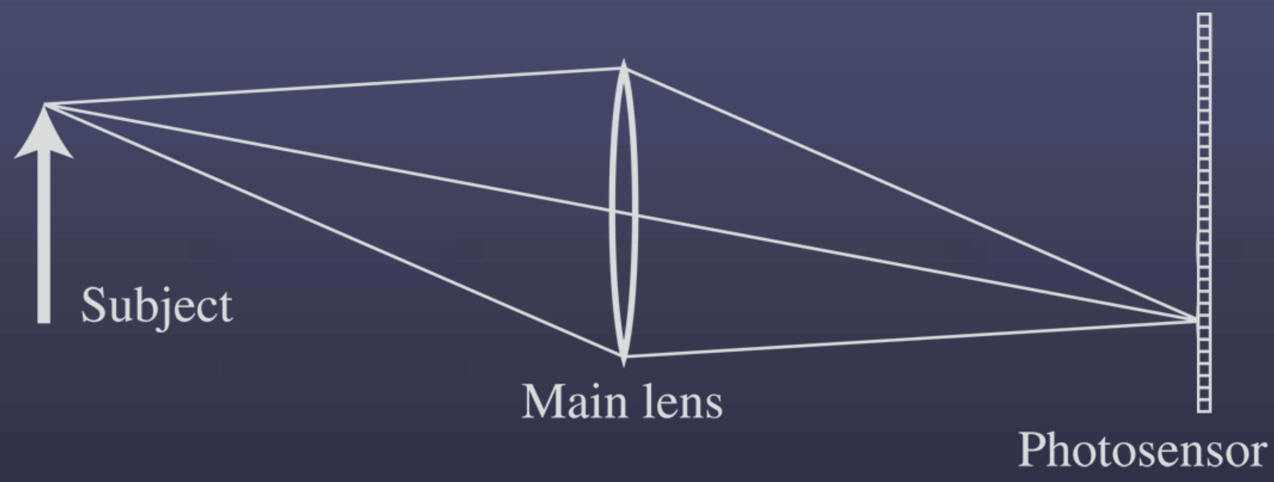


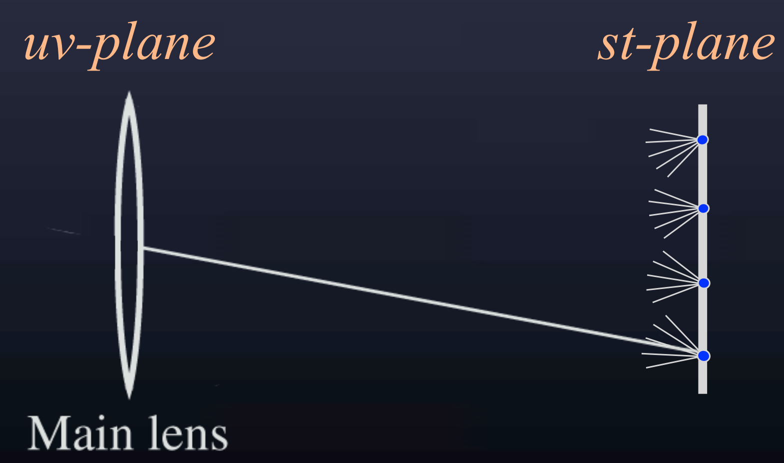
Conventional versus light field camera





Conventional versus light field camera

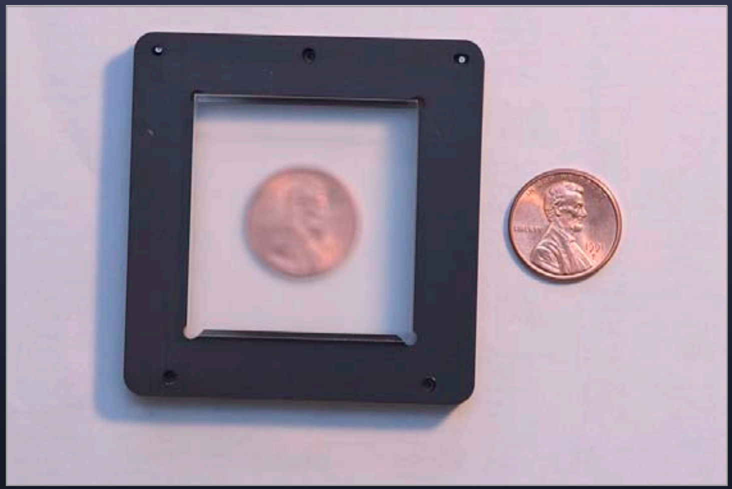


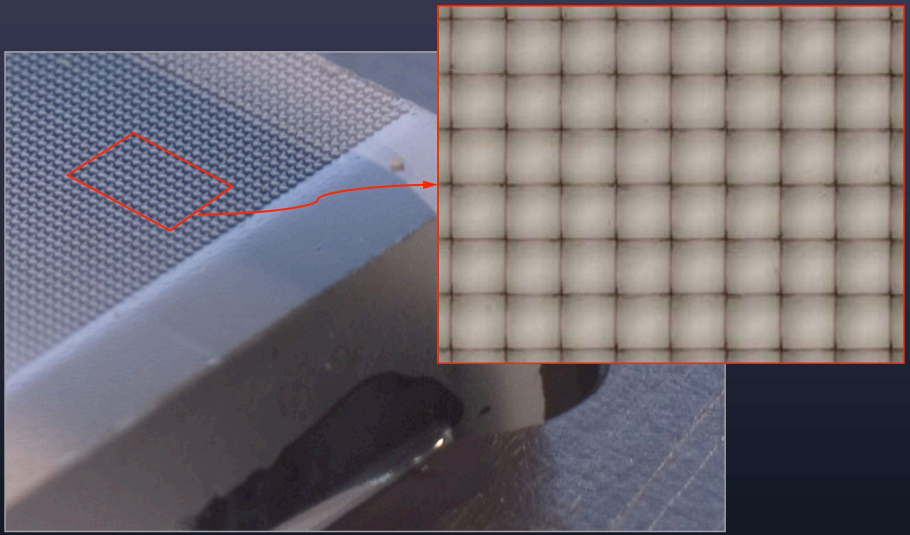


Prototype camera

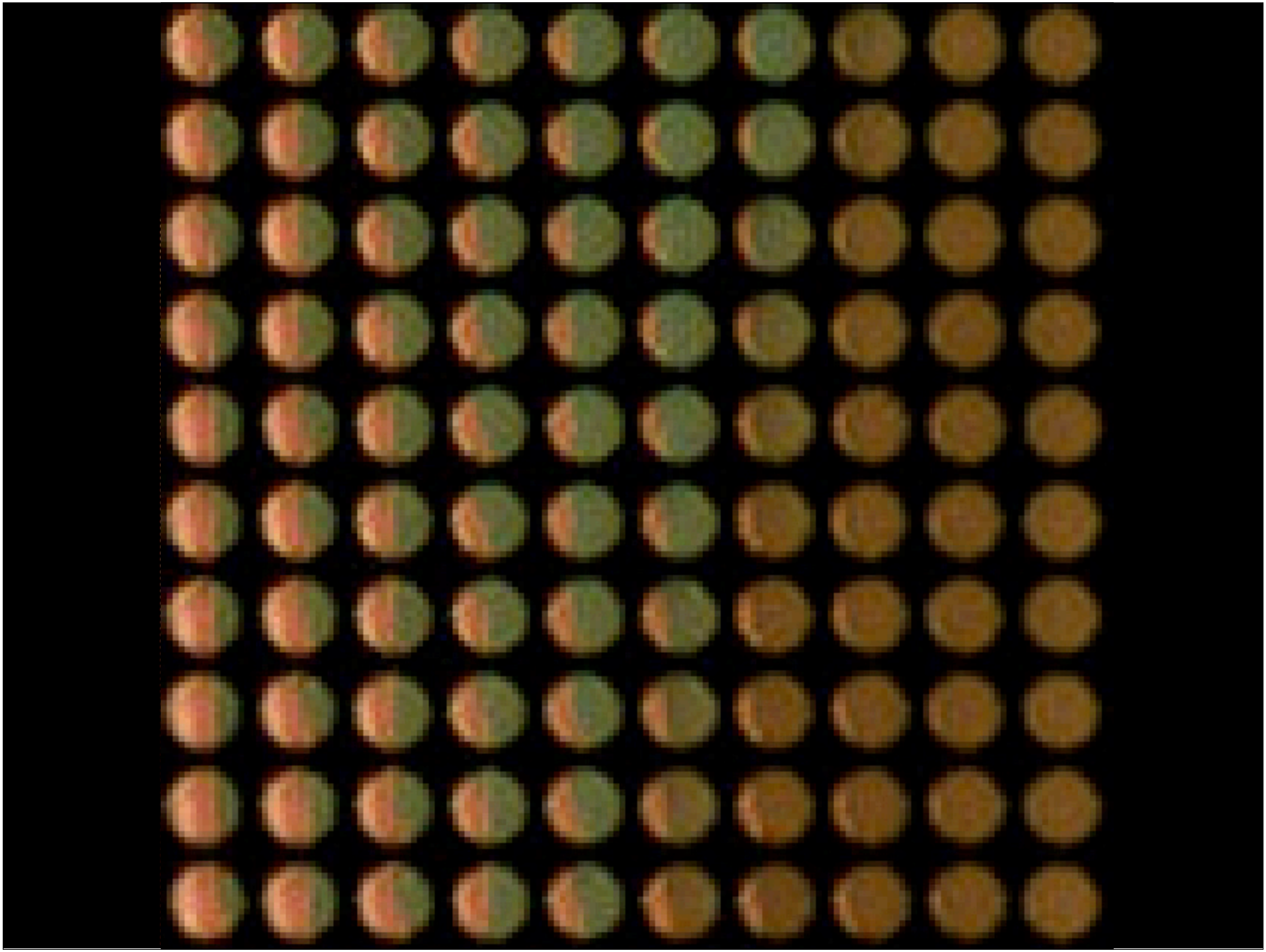
Contax medium format camera


Kodak 16-megapixel sensor

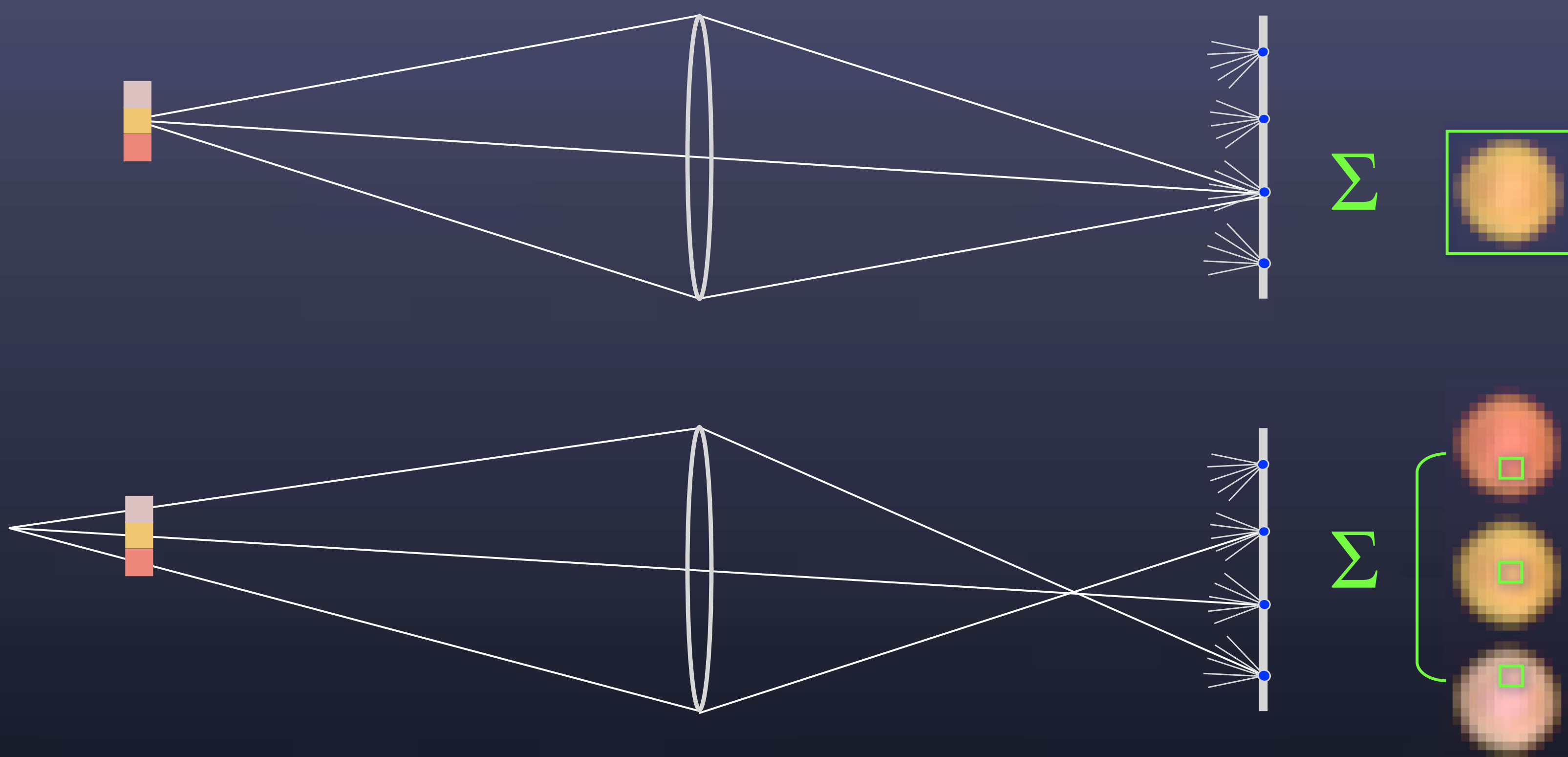

Adaptive Optics microlens array


125µ square-sided microlenses

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



Digital refocusing



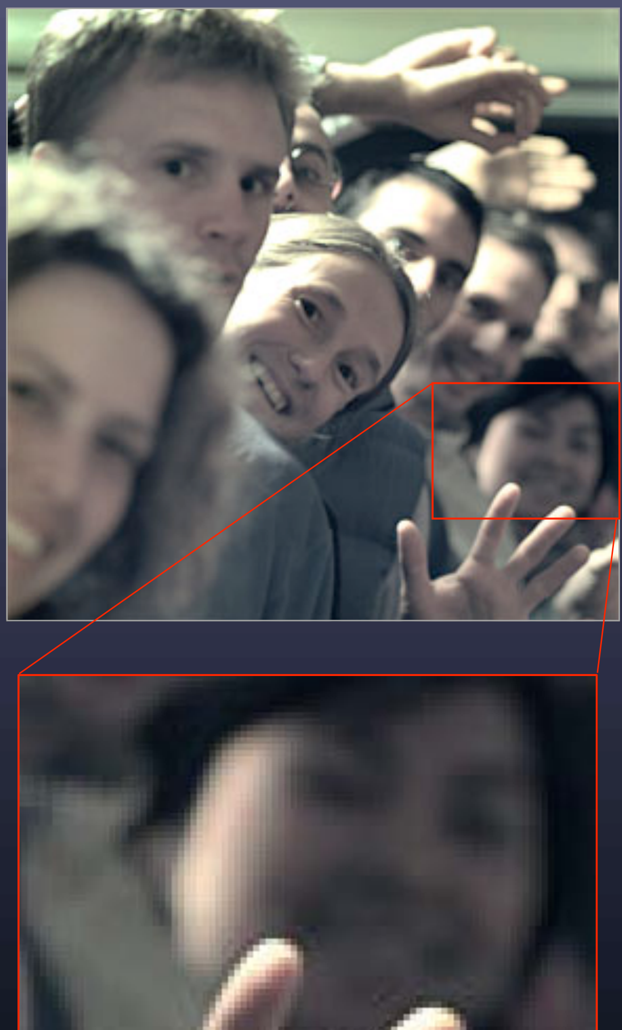
Example of digital refocusing

Refocusing portraits

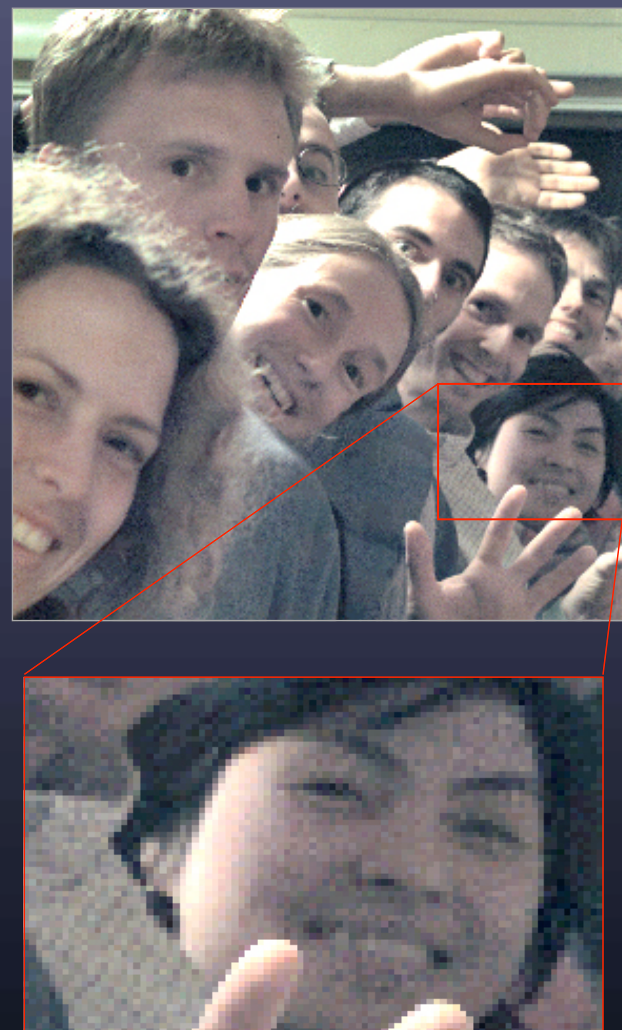
Light field photography

(FLASH DEMO)

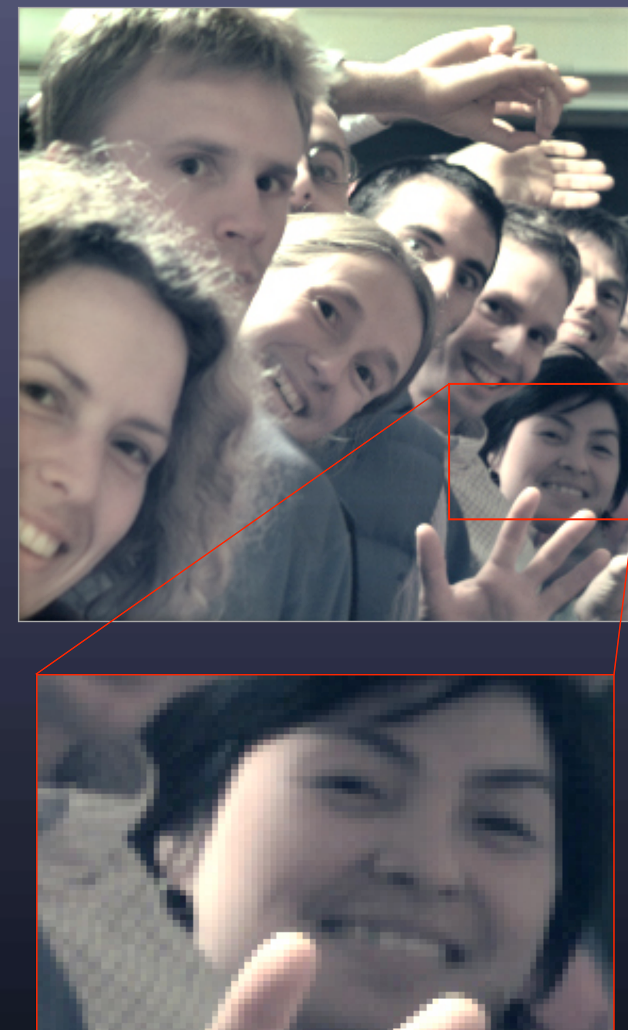
Extending the depth of field



conventional photograph,
main lens at $f/4$

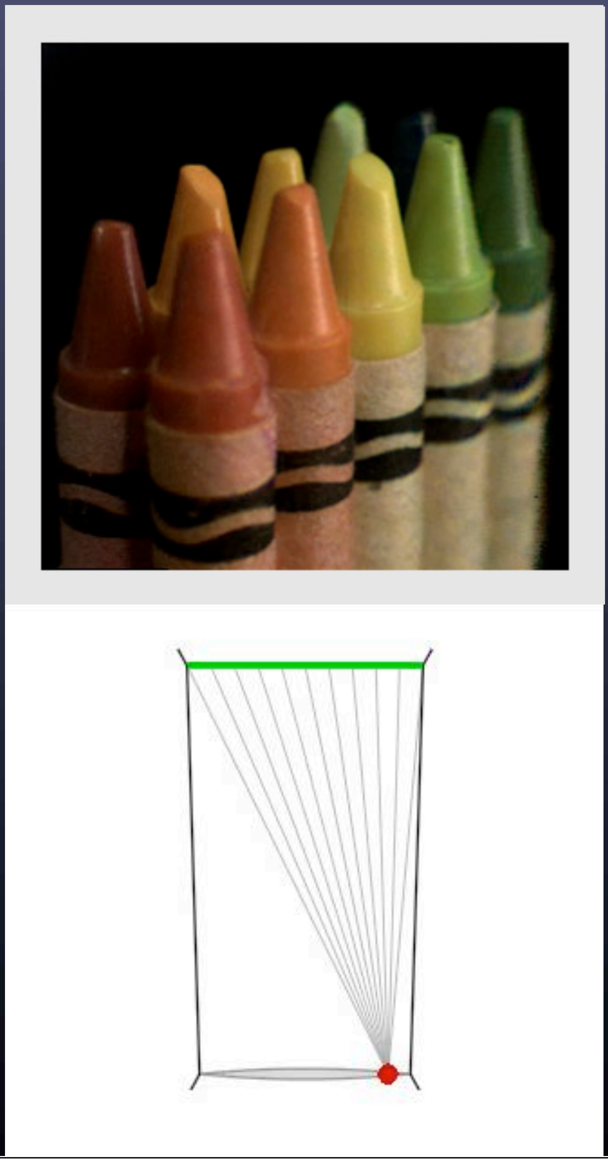


conventional photograph,
main lens at $f/22$

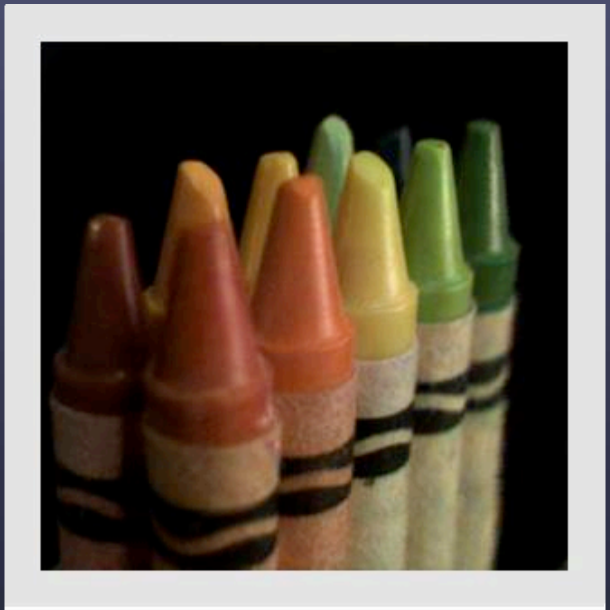


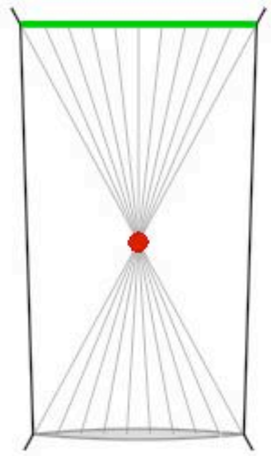
light field, main lens at $f/4$,
after all-focus algorithm
[Agarwala 2004]

Example of moving the observer



Moving backward and forward





Commercialization

LYTRO

- trades off (excess) spatial resolution for ability to refocus and adjust the perspective

- sensor pixels should be made even smaller, subject to the diffraction limit, for example:

    36mm × 24mm ÷ 2.5μ pixels = 266 Mpix

    20K × 13K pixels

    4000 × 2666 pixels × 20 × 20 rays per pixel

  or

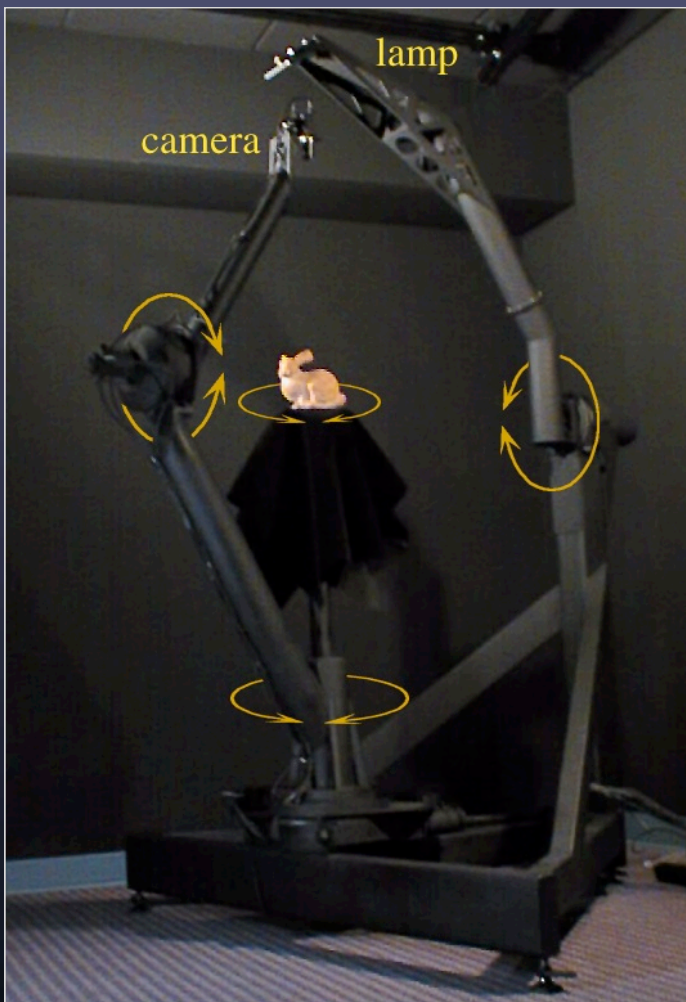
    2000 × 1500 pixels × 3 × 3 rays per pixel = 27 Mpix

Other devices for capturing light fields

Manex's bullet time array

Stanford Multi-Camera Array

Other devices for capturing light fields

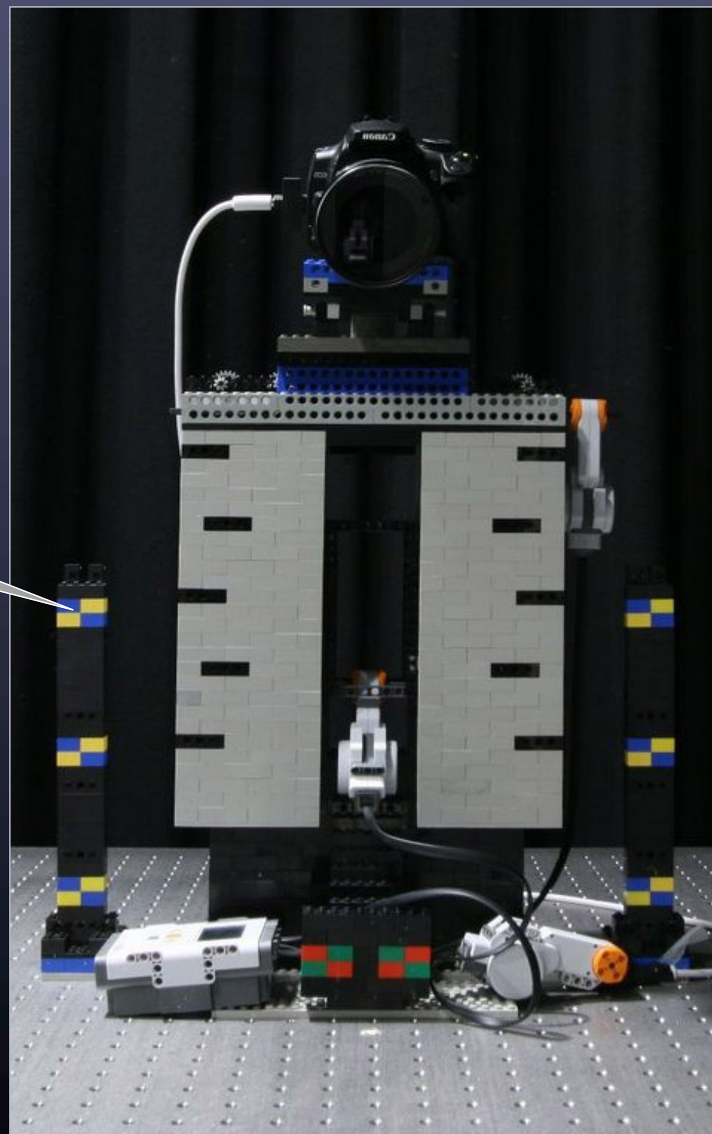


Stanford Spherical Gantry

used to measure light scattering
for rendering translucent materials

Lego gantry for capturing light fields
(built by Andrew Adams)

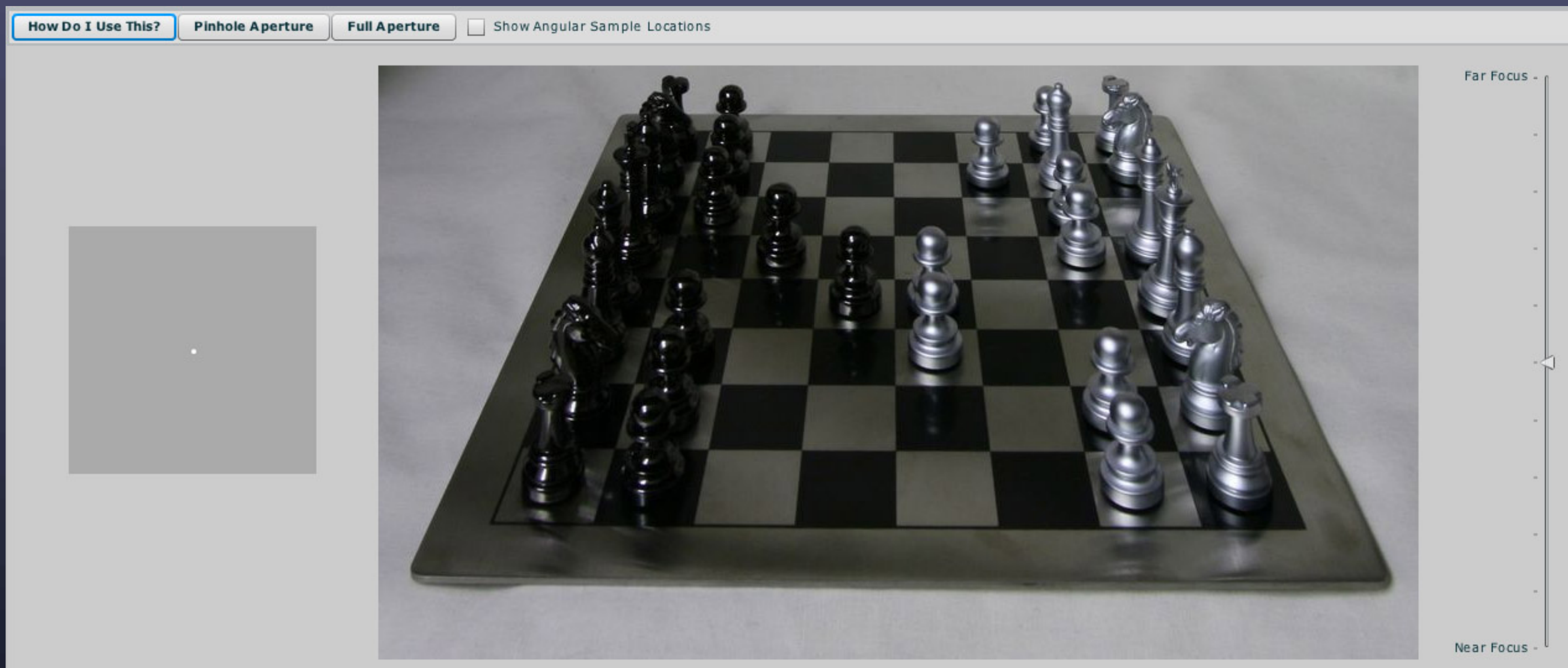
calibration point



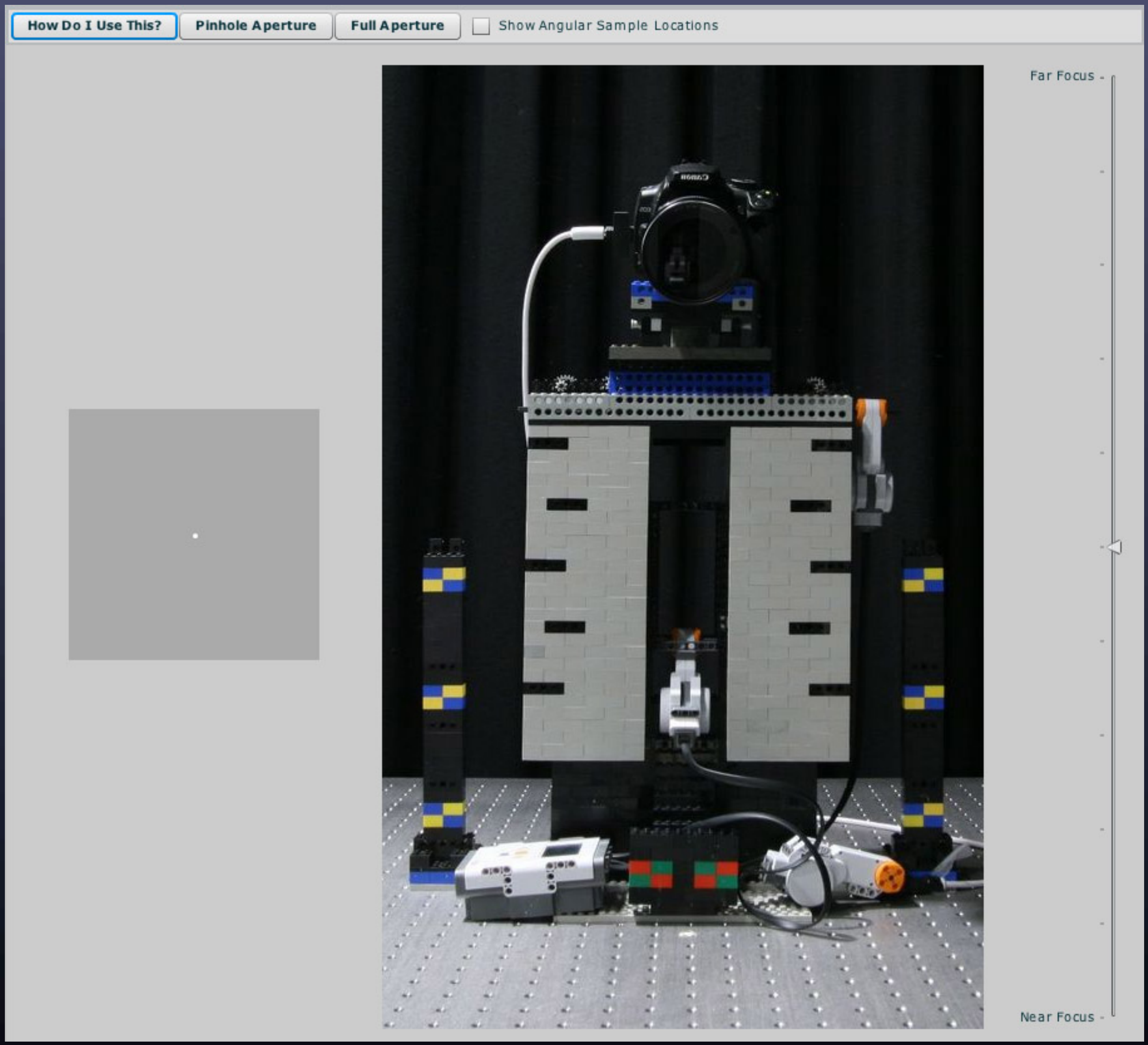
Flash-based viewer for light fields
(written by Andrew Adams)

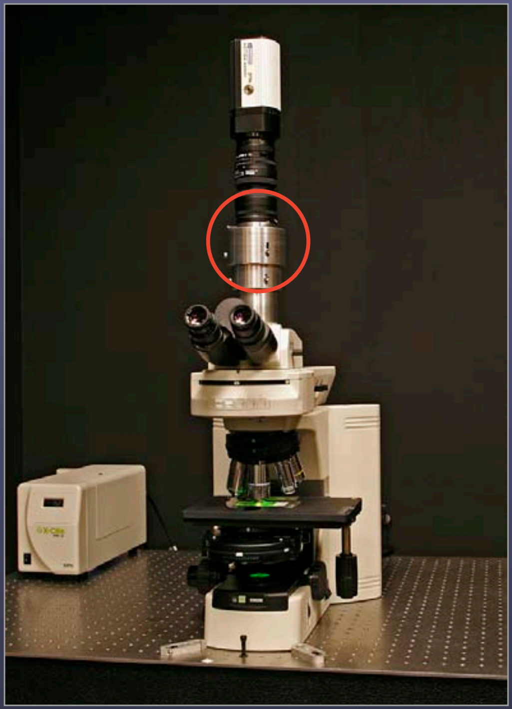
Try it yourself at http://lightfield.stanford.edu/

Flash-based viewer for light fields
(written by Andrew Adams)



The Lego gantry captures a light field of itself

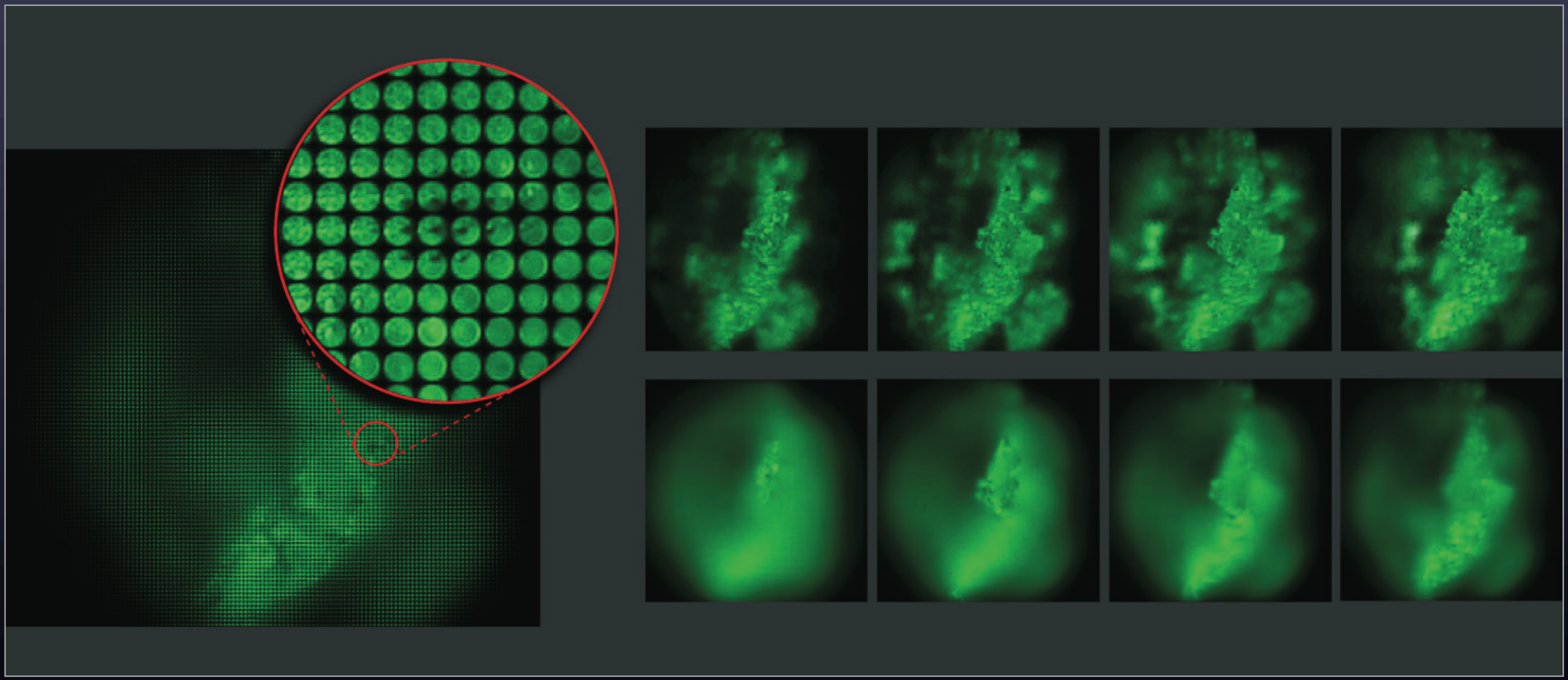




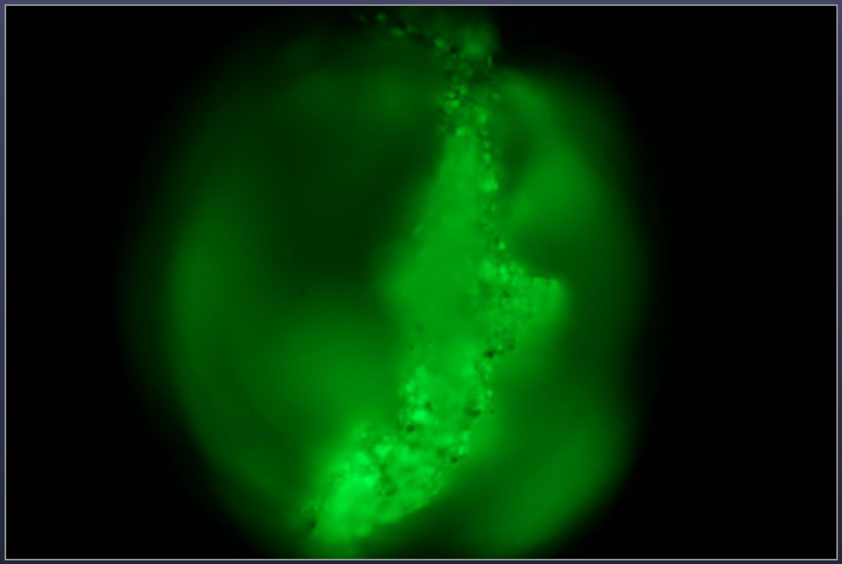
Light Field Microscopy

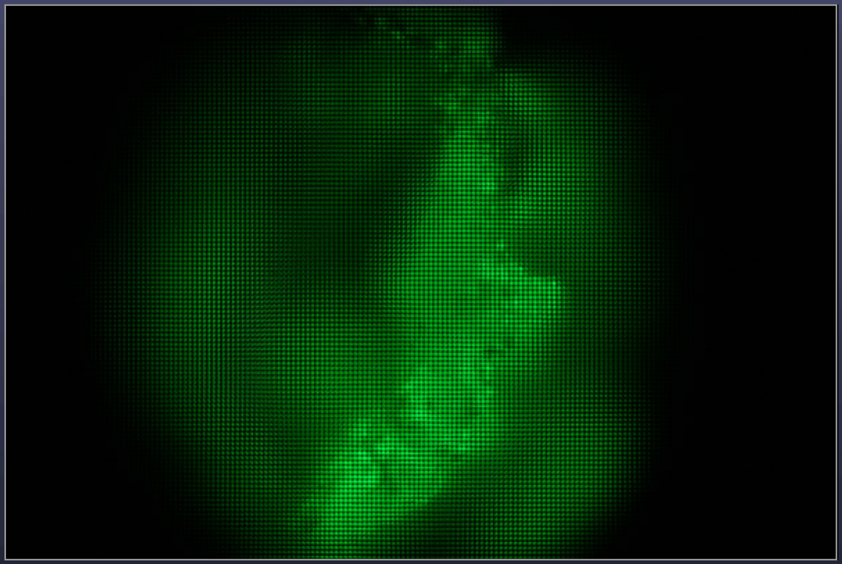
Marc Levoy, Ren Ng, Andrew Adams, Matthew Footer, and Mark Horowitz

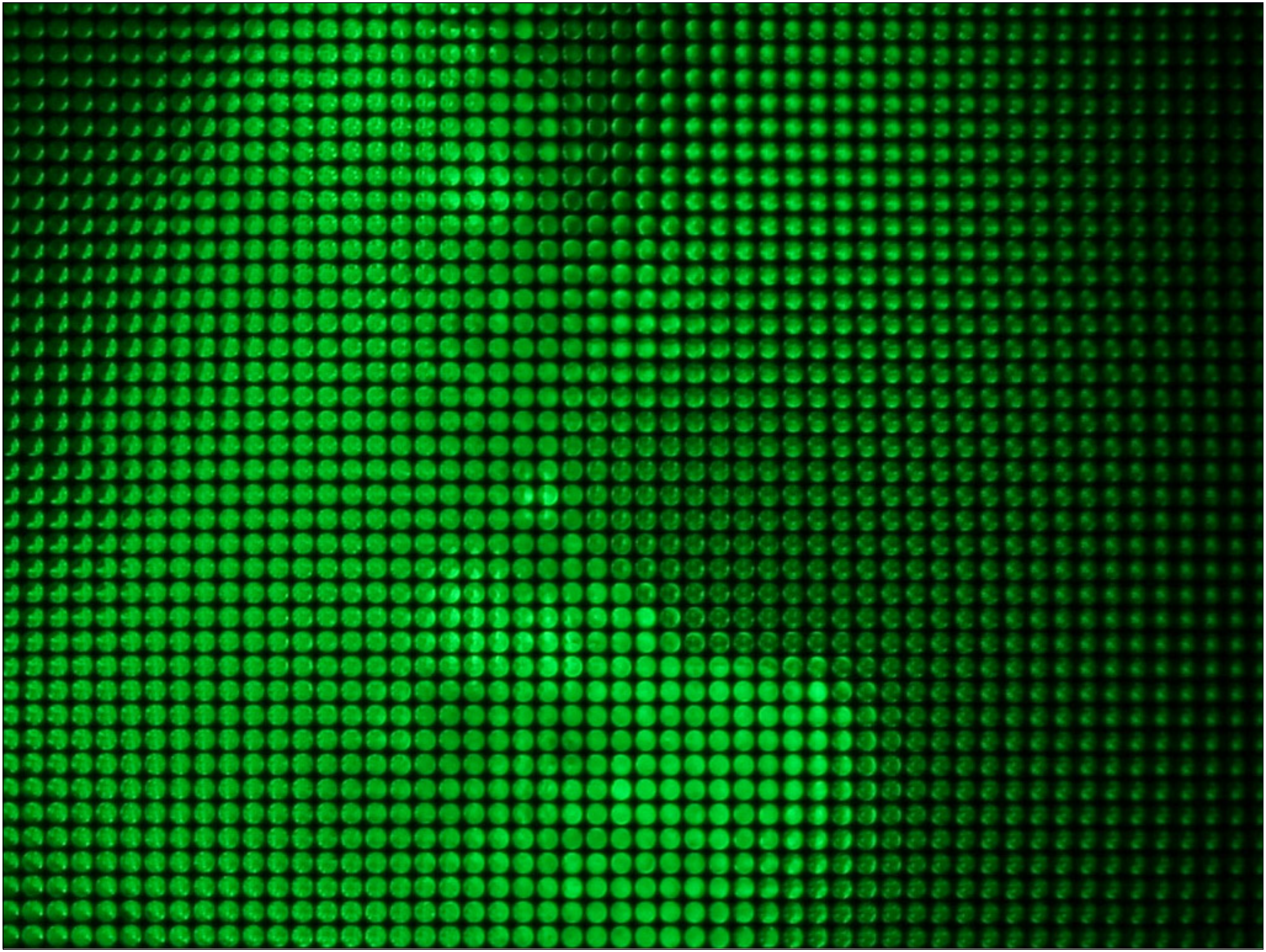
(Proc. SIGGRAPH 2006)

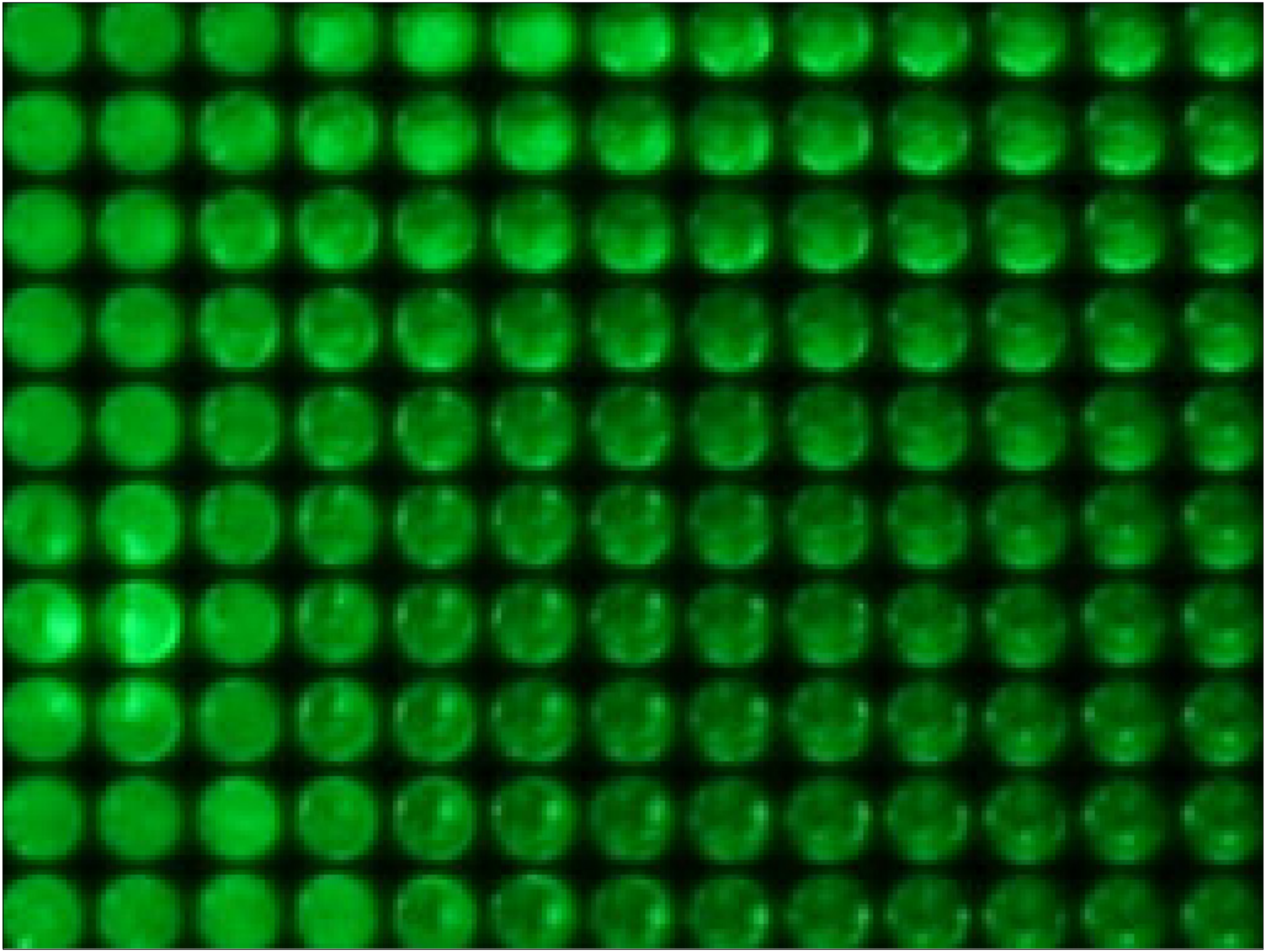


Example light field micrograph

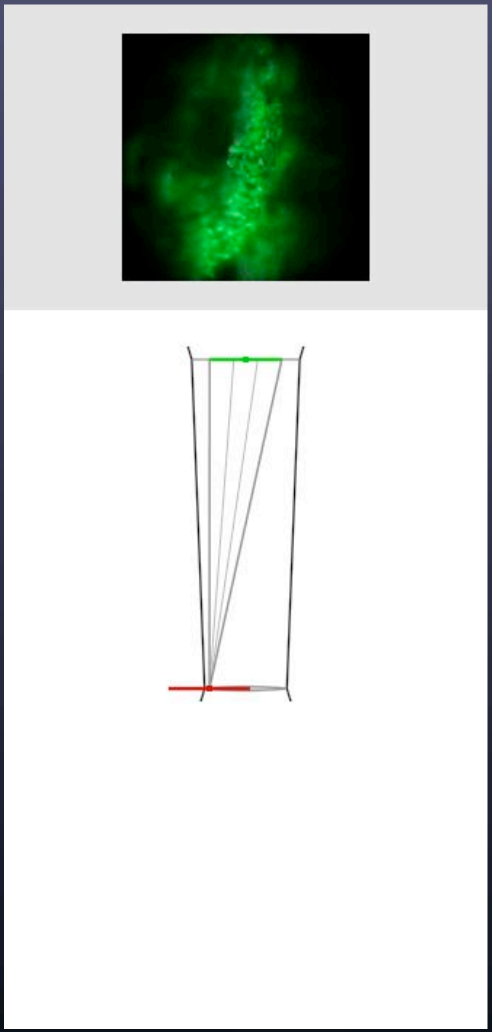

ordinary microscope


light field microscope

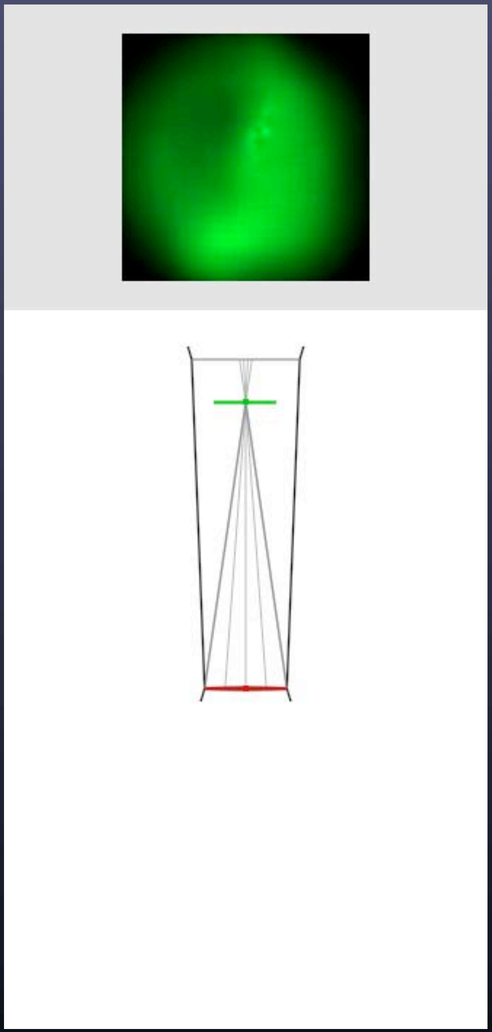




Example light field micrograph

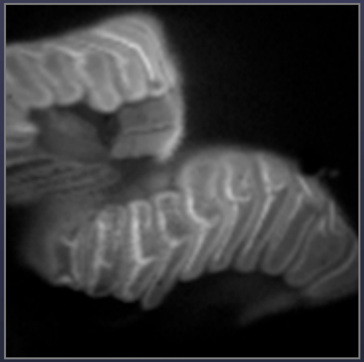


panning sequence

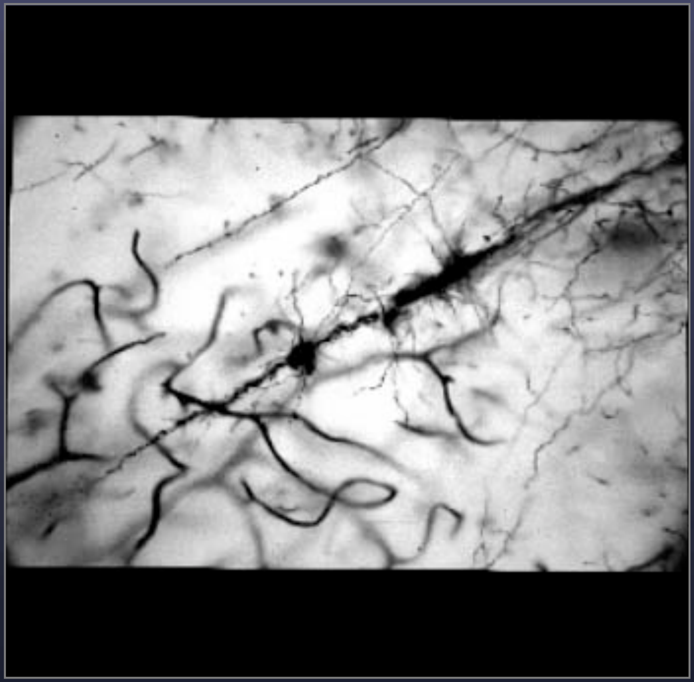


focal stack

Examples

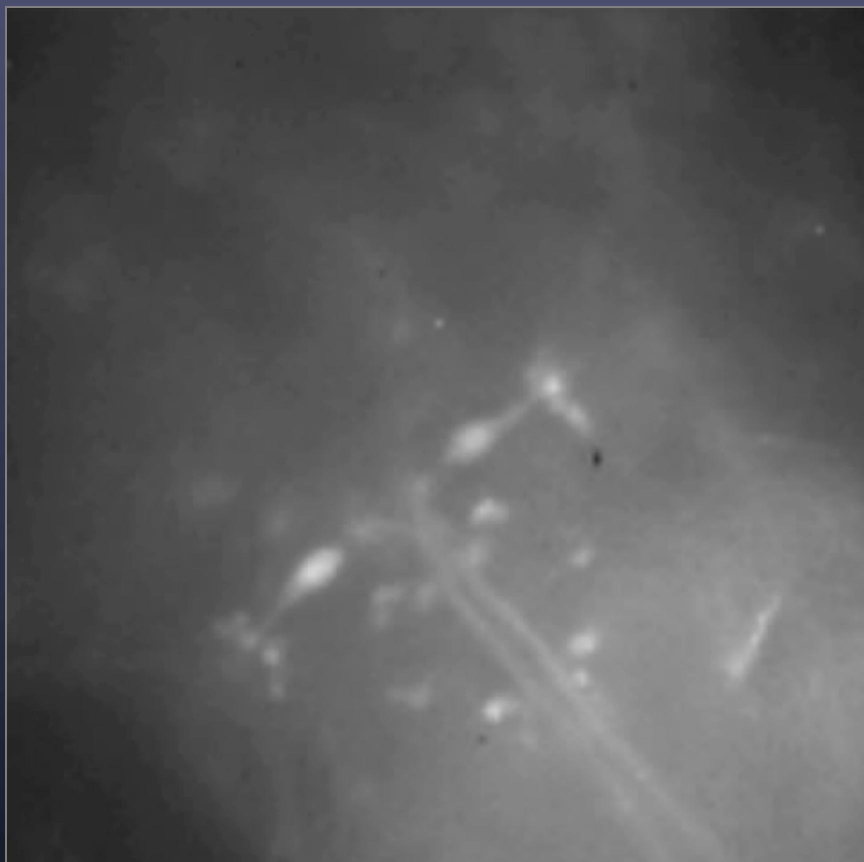


fern spore
(60x, autofluorescence)



Golgi-stained neurons
(40x)

Zebrafish optic tectum
(Florian Engert / Ruben Portugues)



genetically modified
to express GFP
(40x)

calcium imaging
of neural activity
(40x)

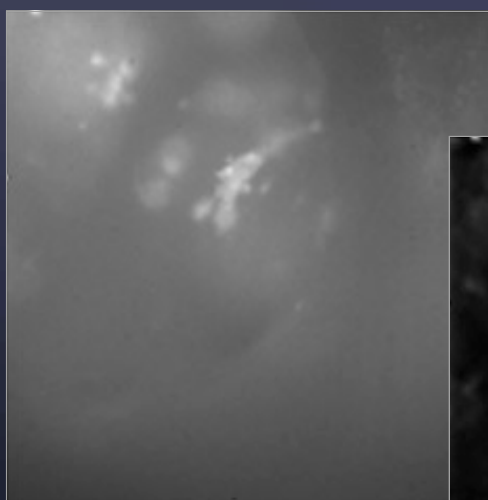
3D reconstruction

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

3D reconstruction
(Stephen Smith / Todd Anderson)

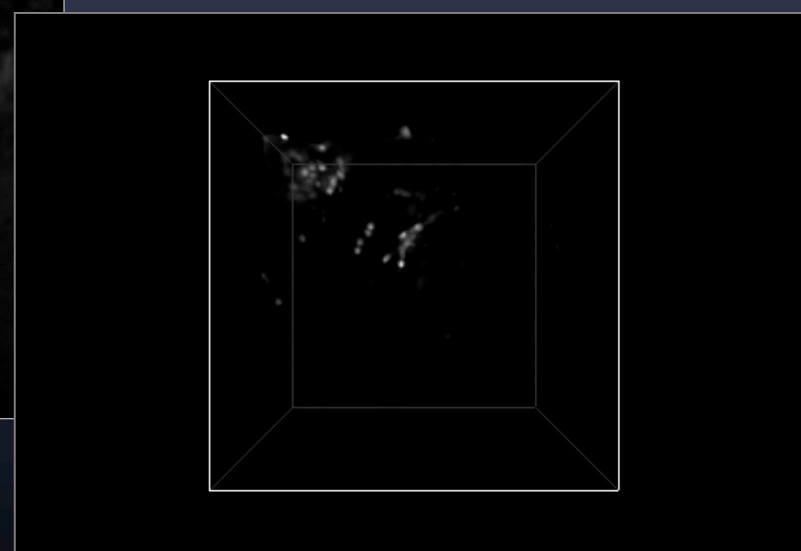
- 4D light field → *digital refocusing* → 3D focal stack → *deconvolution microscopy* → 3D volume data

GFP-labeled zebrafish neurons
(40x / 0.8NA water immersion)



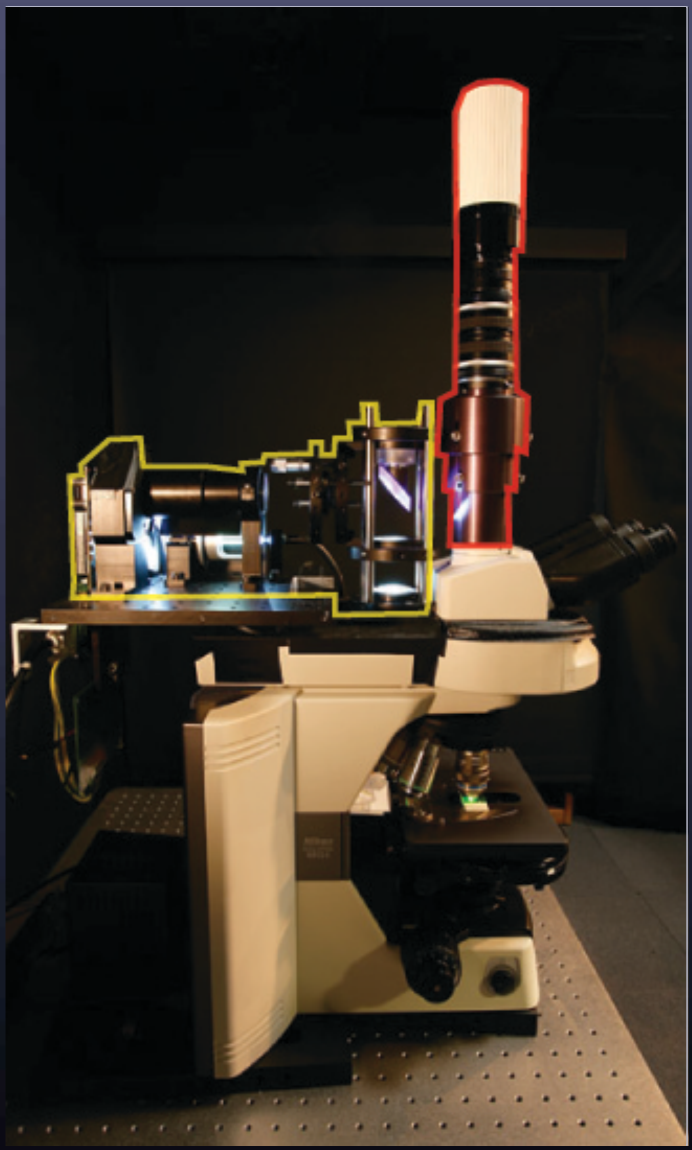
slice of
focal stack

slice after 3D
deconvolution



volume rendering

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



Marc Levoy,
Zhengyun Zhang,
Ian McDowall
(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**