⊕ ⊖ Computational Photography ⊗ ⊘

Computational Optics

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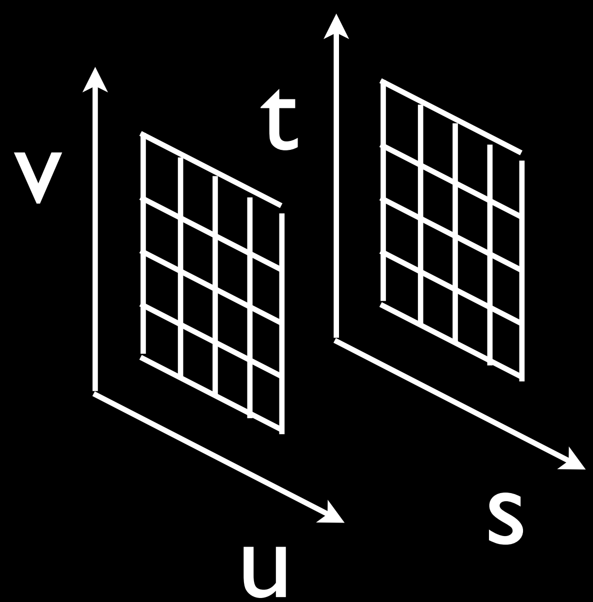
CS 478 Lecture
Feb 29, 2012

Camera as a Black Box

World



4D Light Field

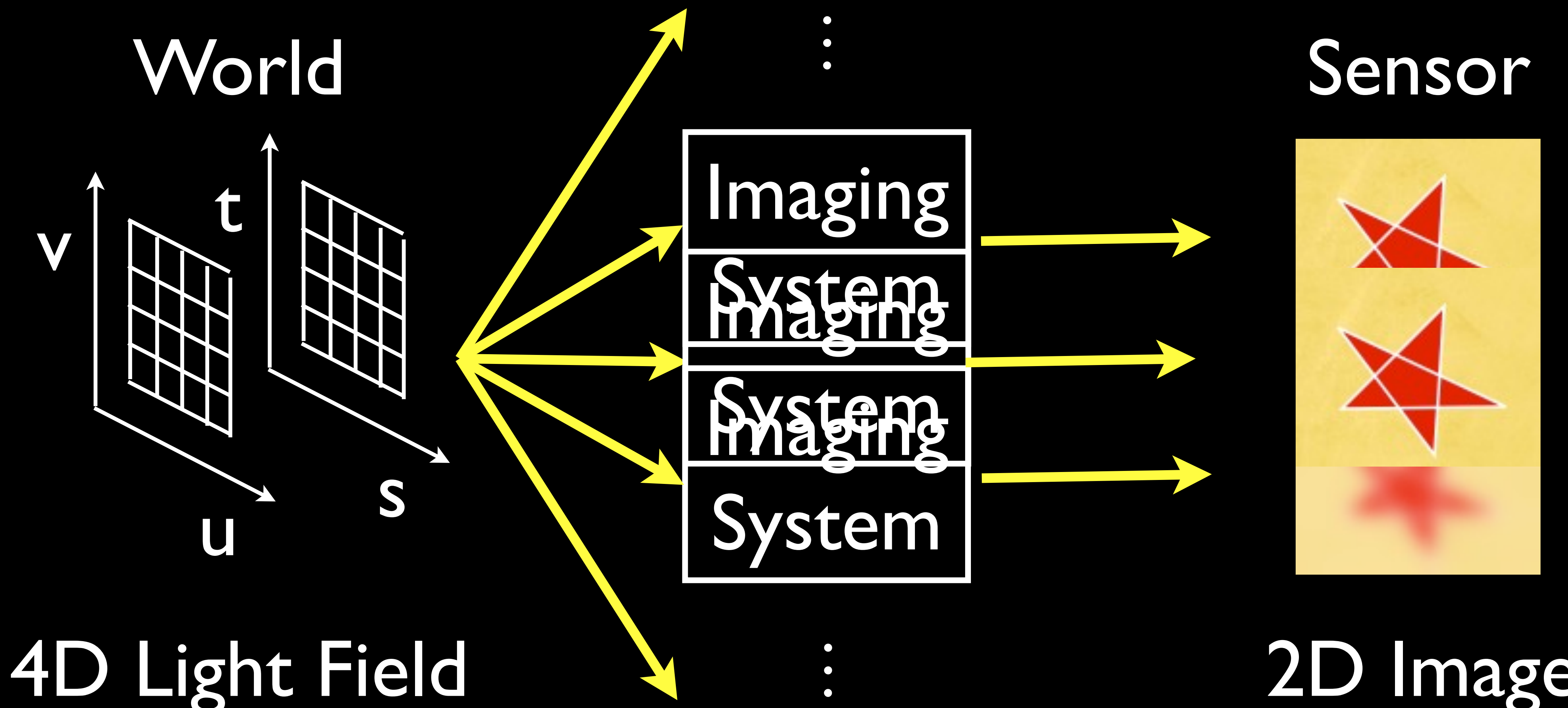
Imaging System

Sensor

2D Image

An imaging system is a function that maps 4D input to 2D output.

Camera as a Black Box



By changing parameters (e.g. focus),
we can obtain a different mapping.

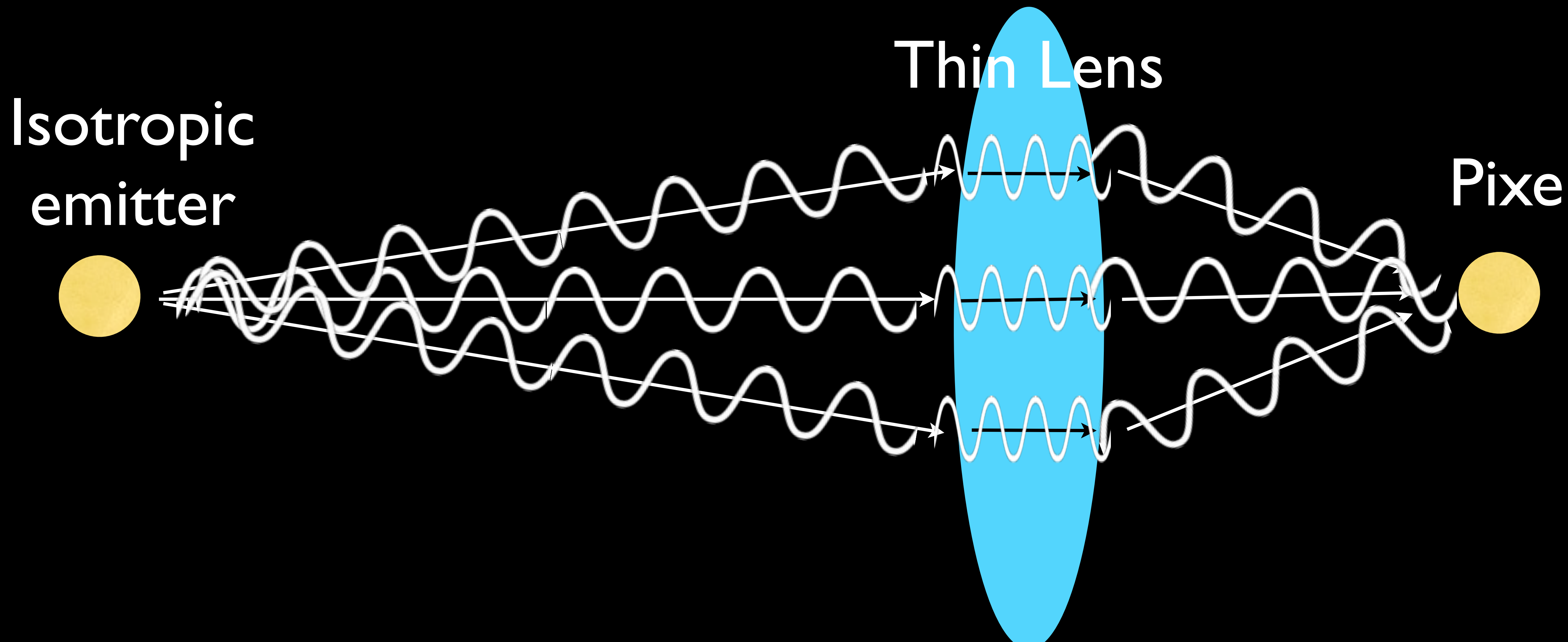
Camera as a Black Box

- What is the space of all mappings we can reasonably obtain?
    - Clearly not all $f:(\mathbb{R}^4 \to \mathbb{R}) \to (\mathbb{R}^2 \to \mathbb{R})$
- Are all mappings useful?
    - Consider $f: x \mapsto (g: y \mapsto 0), \forall x \in (\mathbb{R}^4 \to \mathbb{R})$.
- Do all mappings yield "images"?

Overview

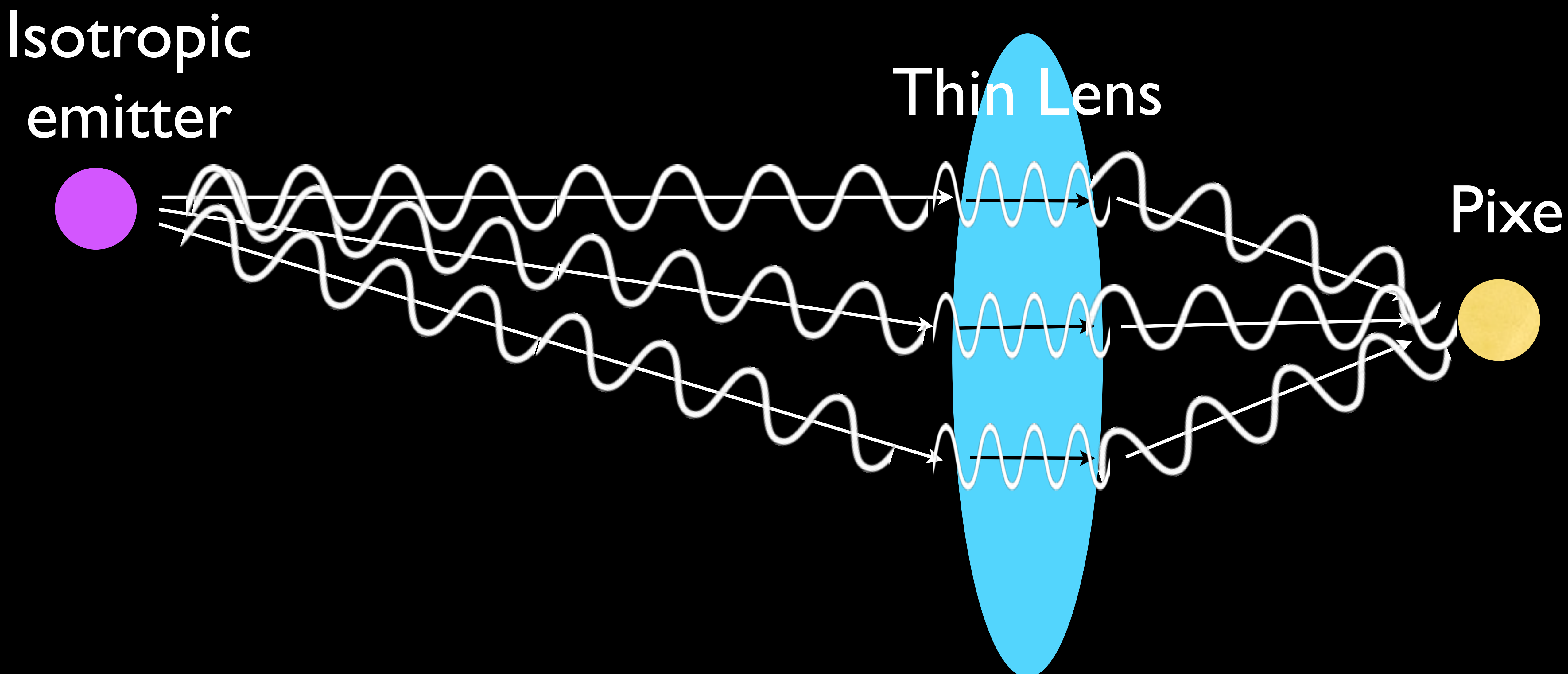
- Coded Aperture
  - Spatial coding
    - Amplitude
    - Phase
- Temporal coding
- Wavelength coding
- Other stuff

"Hand-wavy" Wave Optics Tutorial



We want all these waves to interfere constructively at the pixel.

"Hand-wavy" Wave Optics Tutorial



We want all these waves to interfere destructively at the pixel.

“Hand-wavy” Wave Optics Tutorial

- Lens
  - Controls how wavefronts from the scene interfere at the sensor.
    - Ideally, all wavefronts from a single point source interfere constructively at a pixel, and other wavefronts interfere destructively at that pixel.
      - “Perfect” imaging system.

“Hand-wavy” Wave Optics Tutorial

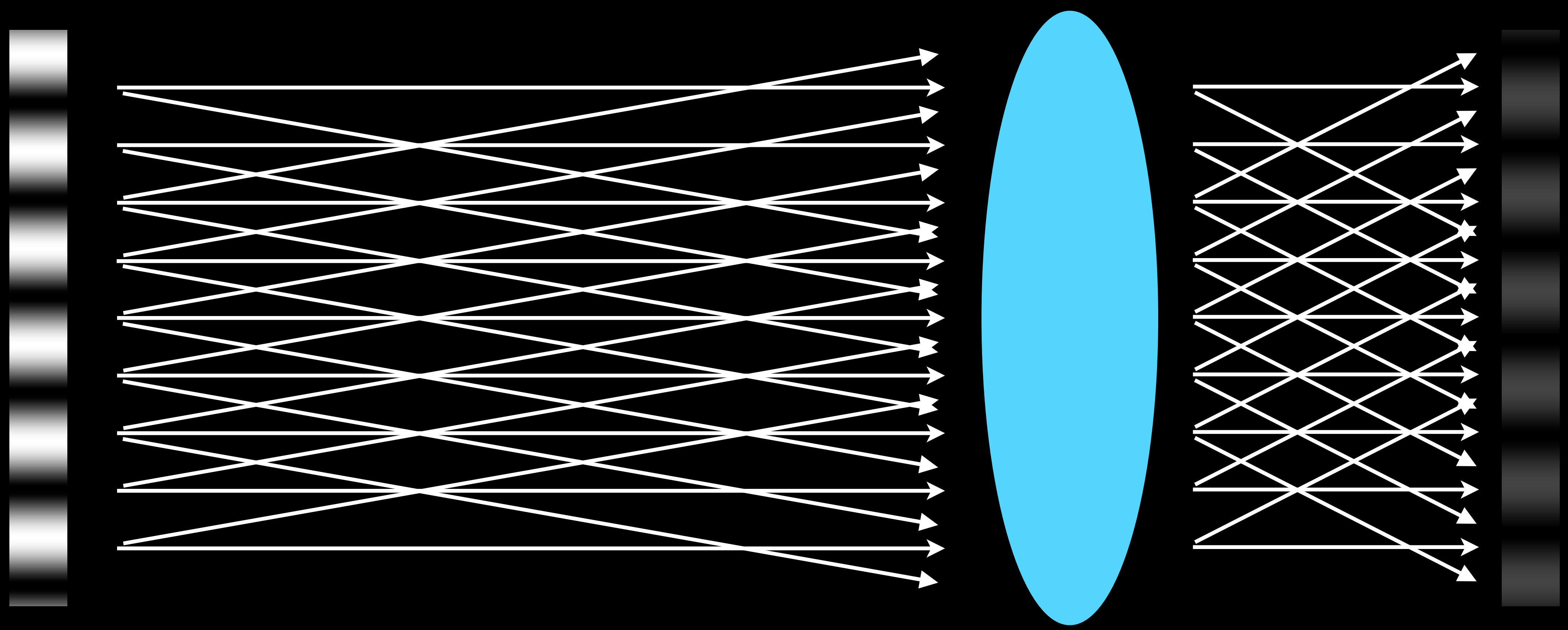
- Perfect imaging system is impossible.
  - Defocus blur: It’s hard to make all the waves interfere 100% constructively, for objects at arbitrary depth.
  - Diffraction: It’s hard to make something interfere 100% constructively, and something ε-away interfere 100% destructively.
- But...

“Hand-wavy” Wave Optics Tutorial

... after some math later ...
(Refer to any optics textbook)

“Hand-wavy” Wave Optics Tutorial

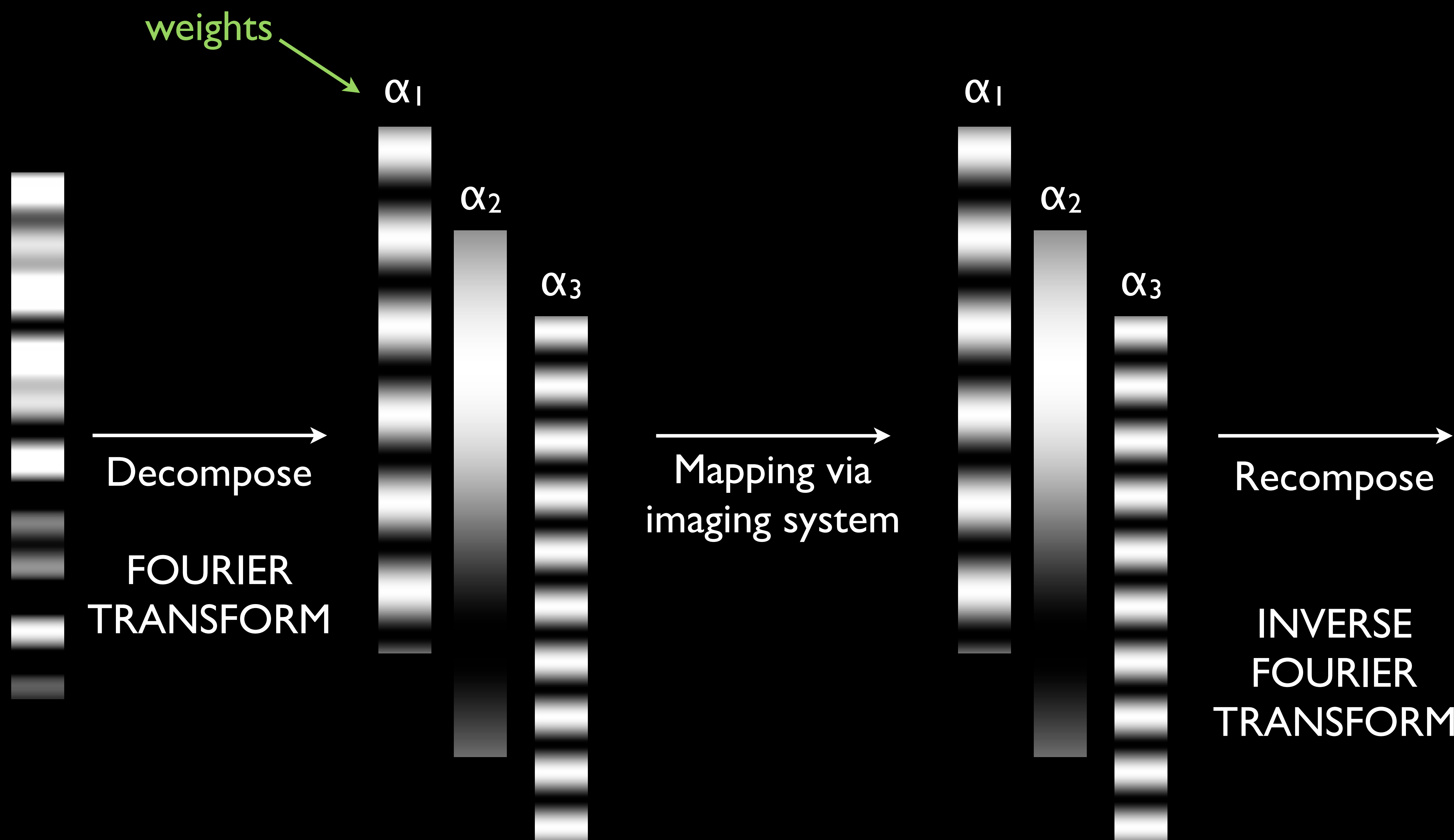
- Sinusoidal patterns are perfectly imaged.
    - Same frequency, potentially lower magnitude



Imaging in Fourier Domain

- Any signal can be written as a sum of sinusoids.
    - We know how each sinusoid is imaged.
    - Imaging is linear.
        - Figure out what the imaging system does to each signal, and add up results!

Imaging in Fourier Domain



Imaging in Fourier Domain

- (Traditional) Imaging system
  - A multiplicative filter in Fourier domain.
    - This filter is called the Optical Transfer Function (OTF).
    - The magnitude of the filter is called the Modulation Transfer Function (MTF).
  - A convolution in the spatial domain.
    - This kernel is called the Point Spread Function (PSF).

Aperture Coding

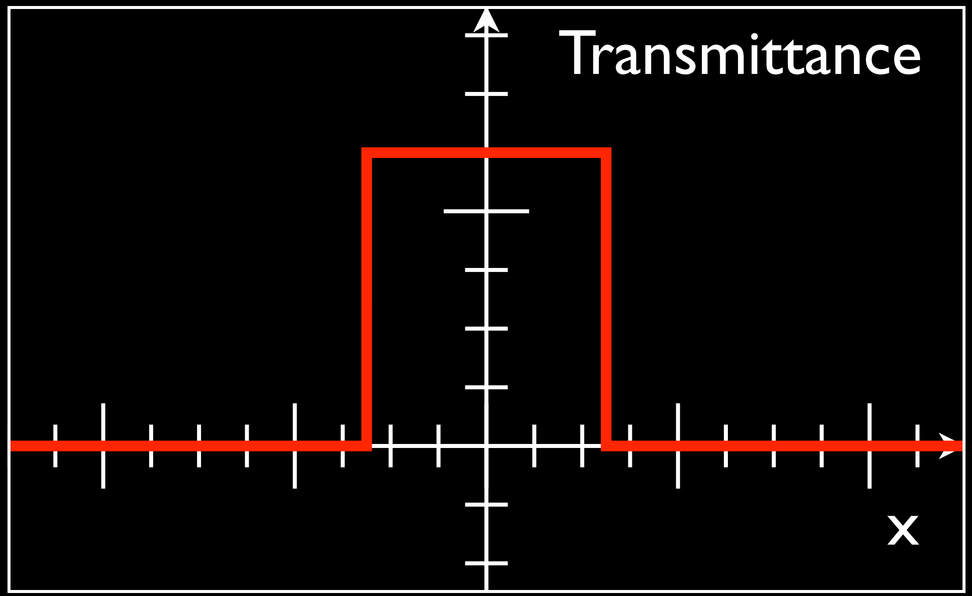
- Why insist on a circular aperture?

(Levin 2007)

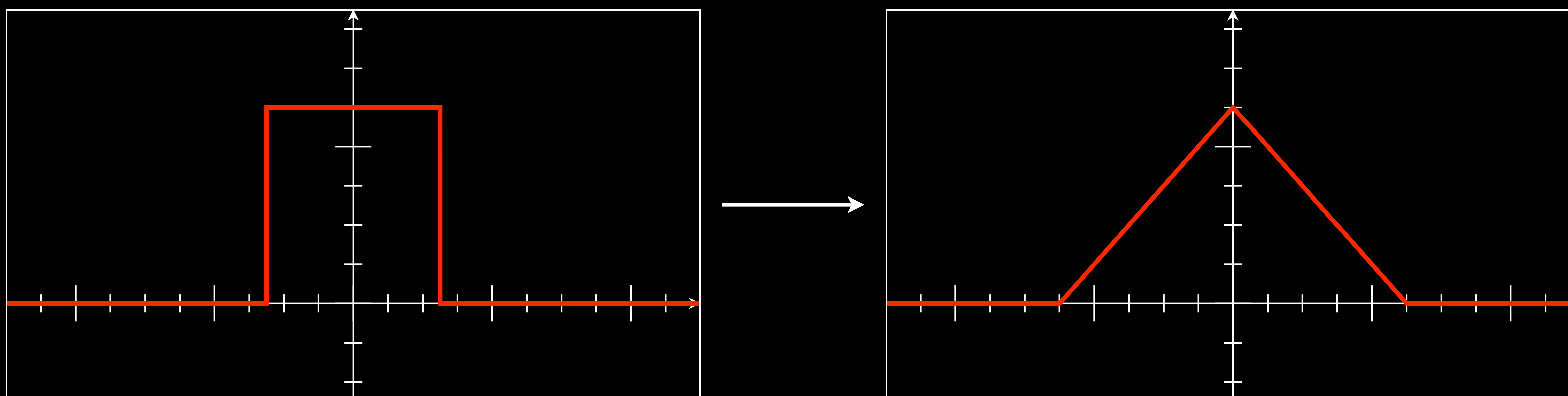
- What kind of aperture should we use?

Circular Aperture

- Let's consider the circular aperture.
- Imagine 2D world.
  - The aperture is now a 1D slit.



Circular Aperture



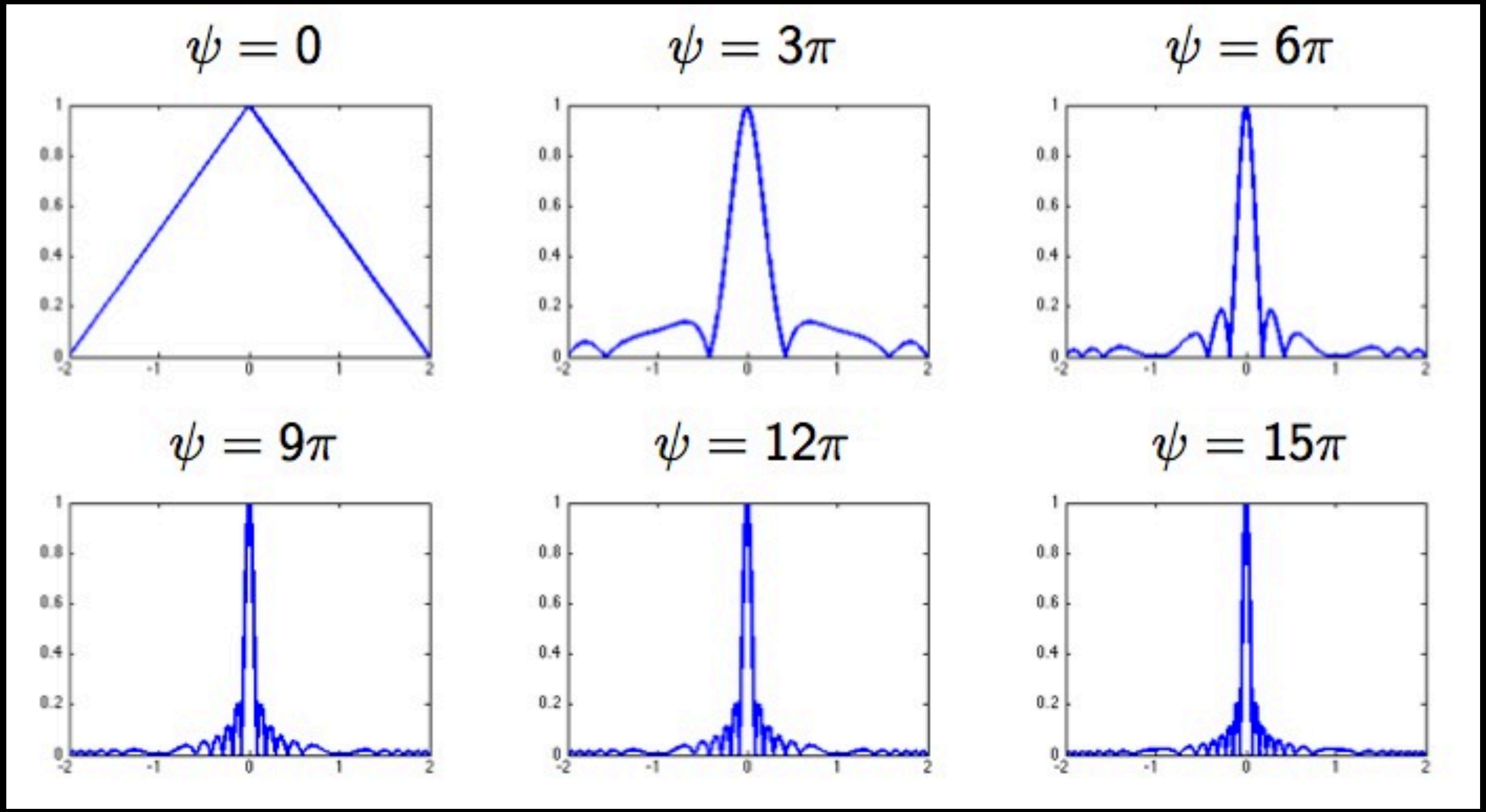
Point Spread Function

Modulation Transfer Function

(Focused)

Circular Aperture

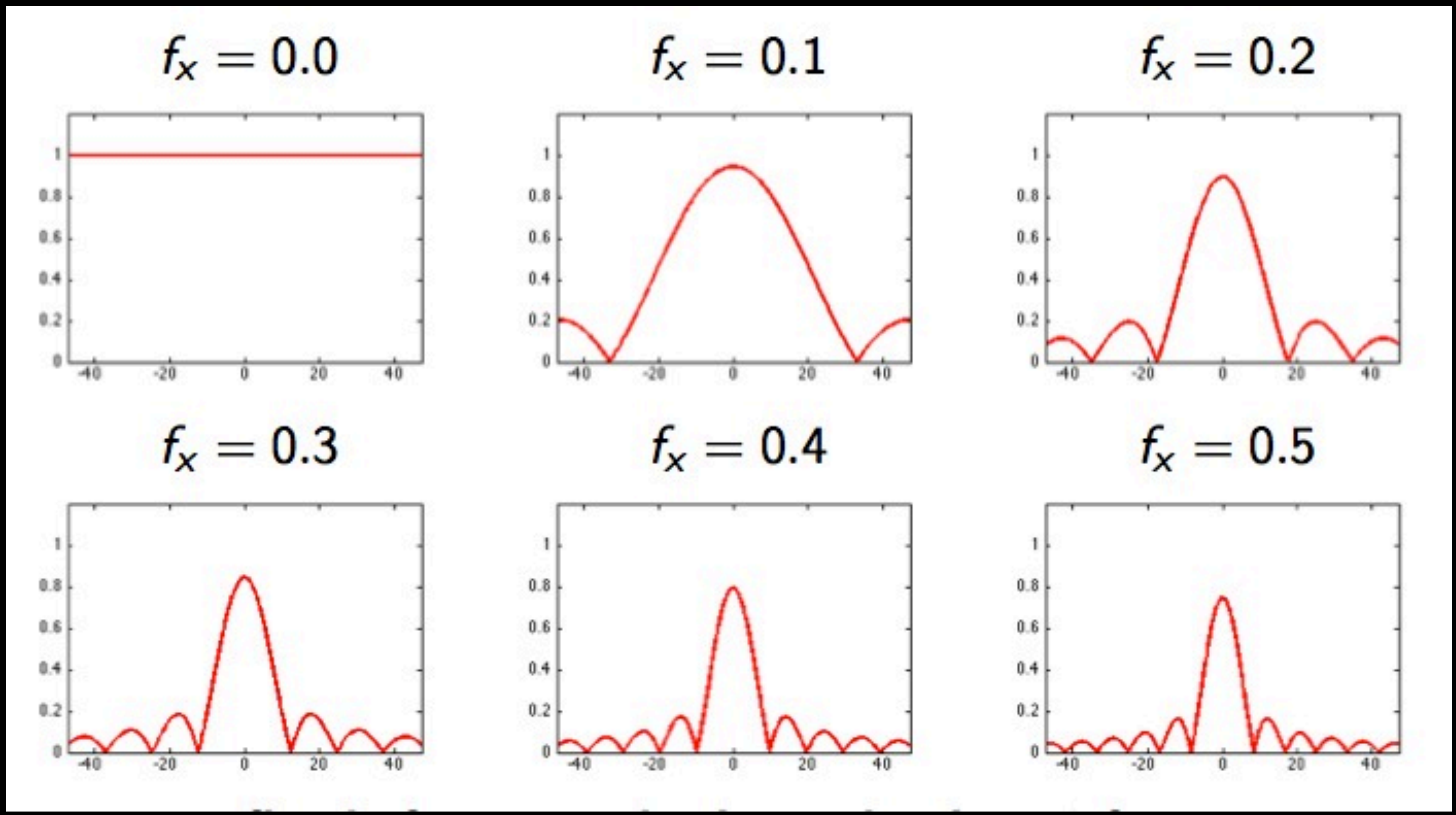
MTF for a 1D slit at various misfocus ψ



(figures stolen from self)

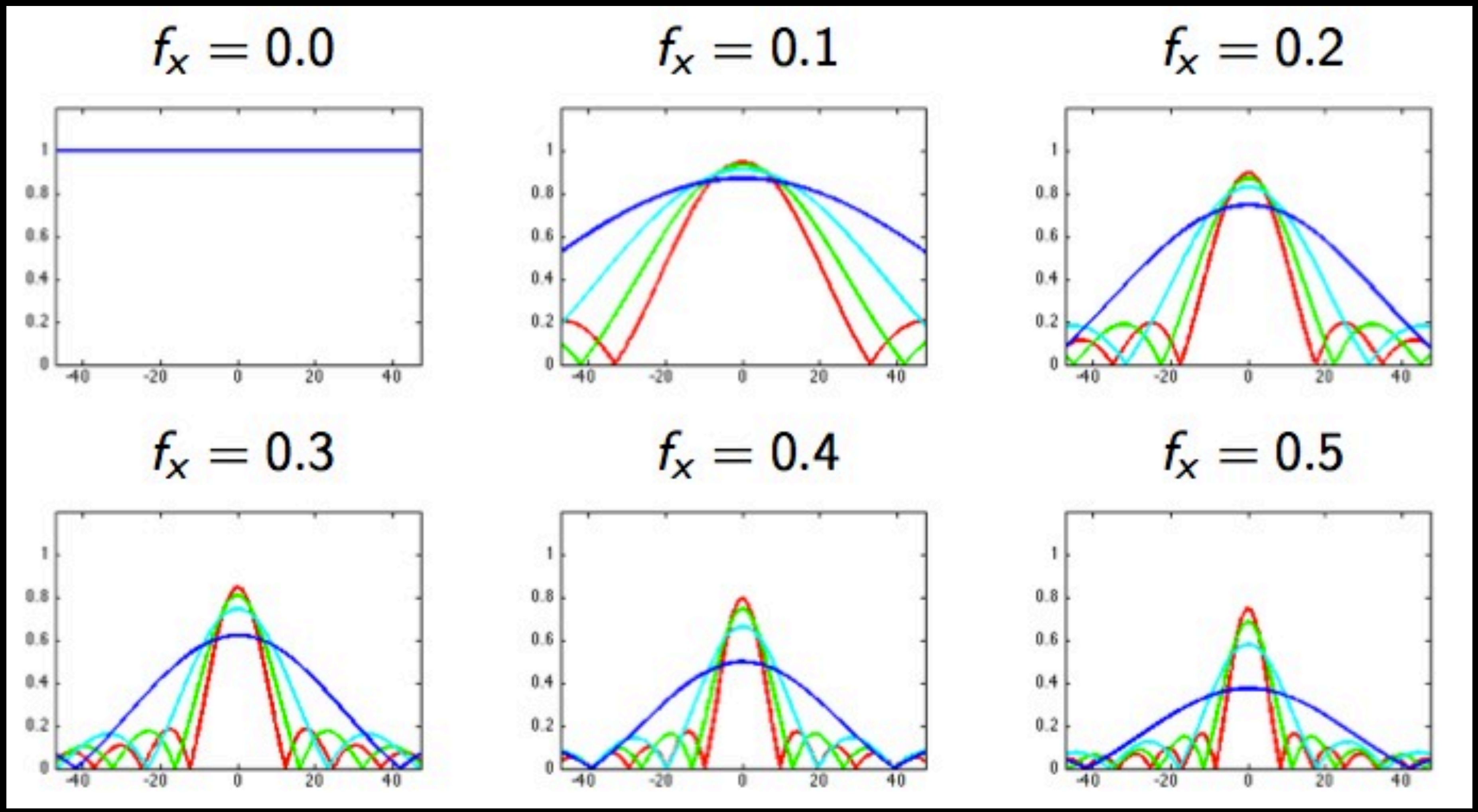
Circular Aperture

MTF as a function of misfocus, at various frequency



Stopping Down

MTF as a function of misfocus, at various frequency



Aperture size at 100%, 80%, 60%, 40% with equal exposure.

Desiderata

- Given an aperture, we can generate these plots mathematically*.
  - What kind of aperture do we want?
  - What kind of plot is ideal?

*Are you sure you want to know?

$$OTF(x, y, \psi) = \iint p(t_1 - f_x/2, t_2 - f_y/2)\, p^*(t_1 + f_x/2, t_2 + f_y/2)\, e^{2i(t1fx+t2fy)\psi}\, dt_1\, dt_2.$$

For aperture with large features, one can estimate the PSF by the aperture shape, scaled by misfocus.

Depth Invariance?

- Do we want the frequency response to be constant w.r.t. misfocus (equivalently, depth)?
  - Would be useful for all-focus image.
- Do we want the frequency response to vary wildly w.r.t. misfocus (equivalently, depth)?
  - Would be useful as depth cues, for depthmap generation.

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Image and Depth from a Conventional Camera with a Coded Aperture

Levin et al., SIGGRAPH 2007

- Pick an aperture whose OTF varies much with depth.
  - Random search.
  - Restrict search to binary 11x11 patterns.
  - Maximize K-L divergence among OTFs.
- Calculate PSF for each depth.

Image and Depth from a Conventional Camera with a Coded Aperture

Levin et al., SIGGRAPH 2007

- Steps
  - Take a picture.

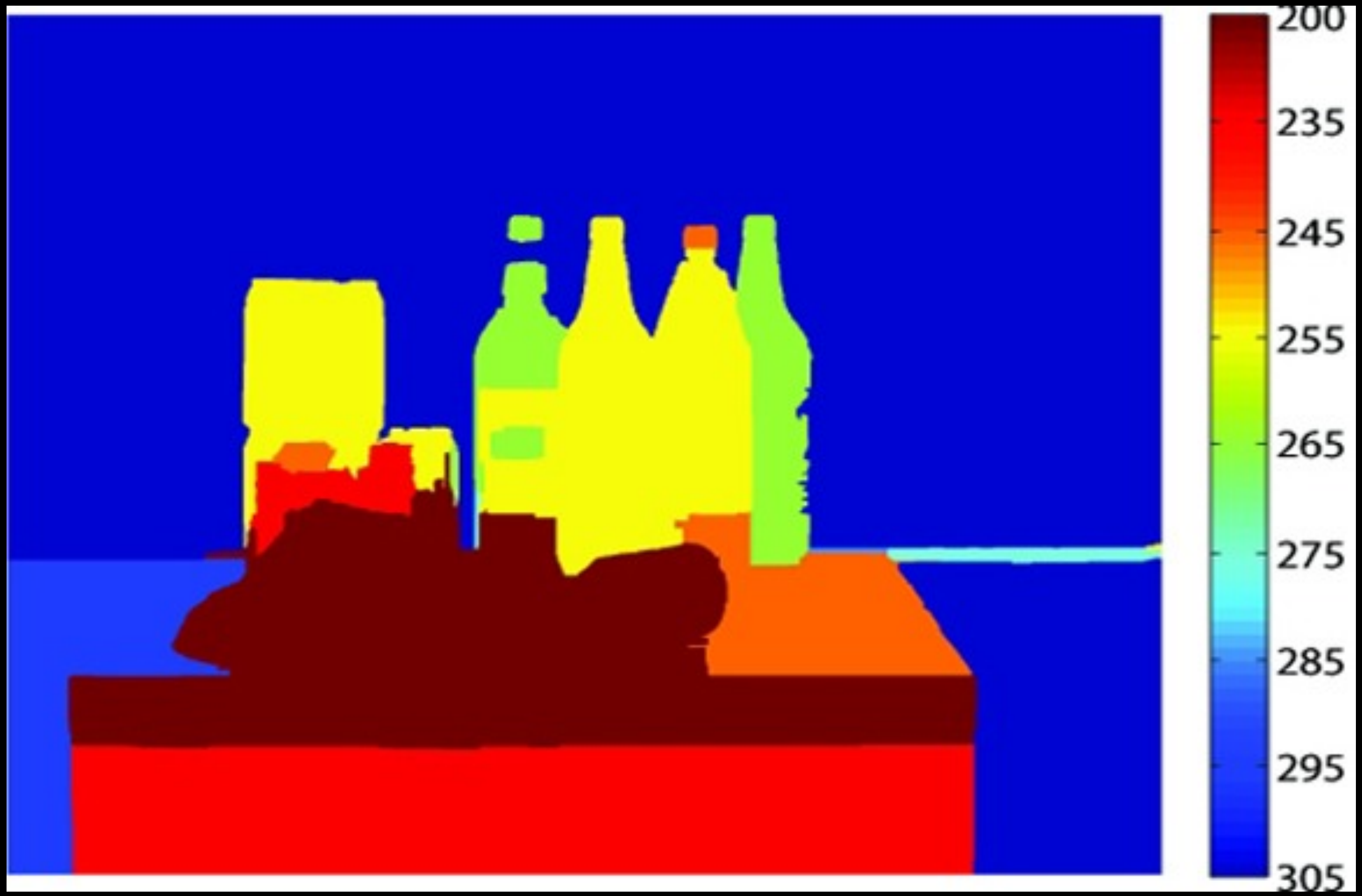
Image and Depth from a Conventional Camera with a Coded Aperture

Levin et al., SIGGRAPH 2007

- Steps
  - Try *deconvolving* with each candidate PSF.
  - Convolve again with PSF, subtract from picture to compute error.
  - For each region, pick the PSF (hence depth) that gives the minimal error.
  - Regularize depthmap.

Image and Depth from a Conventional Camera with a Coded Aperture

Levin et al., SIGGRAPH 2007



Resulting Depthmap

Image and Depth from a Conventional Camera with a Coded Aperture

Levin et al., SIGGRAPH 2007

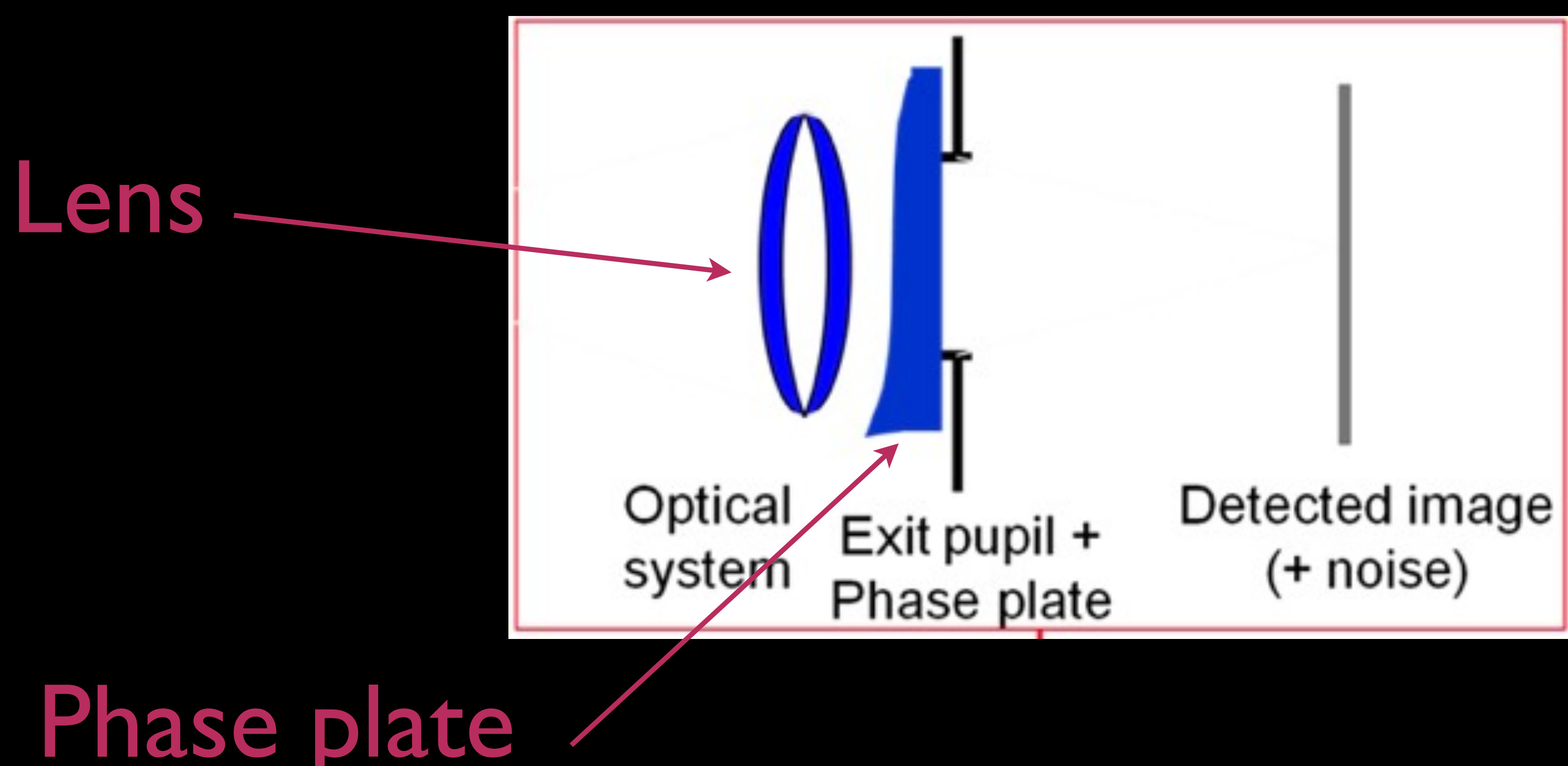
- You can do all this with a circular aperture.
  - The result won't be as good, though.

Next Step

- Instead of modulating the aperture amplitude (transmittance), we could modulate the phase as well.
  - Upside: No light lost.
  - Downside: Larger space of unknowns.

Phase Coding

- (Parabolic) Lens already modulates the phase.
  - Add an additional refractive element.



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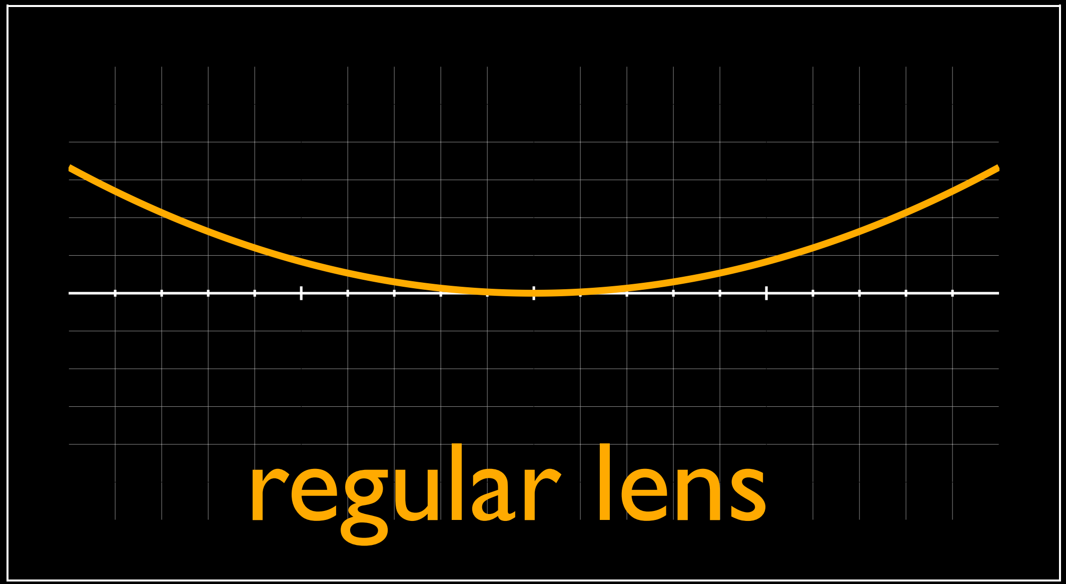
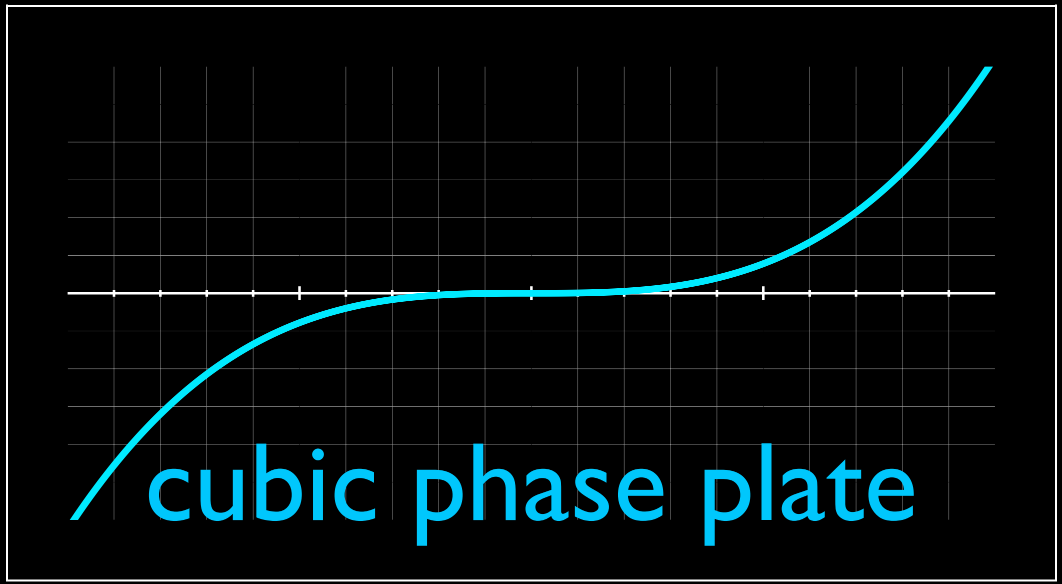
Extended Depth of Field through Wavefront Coding

Dowski et al., Applied Optics 1995

- Design a phase plate such that the MTF is the same across depth.
  - A regular lens is parabolic, or quadratic.
  - Instead, use a lens whose profile is cubic.

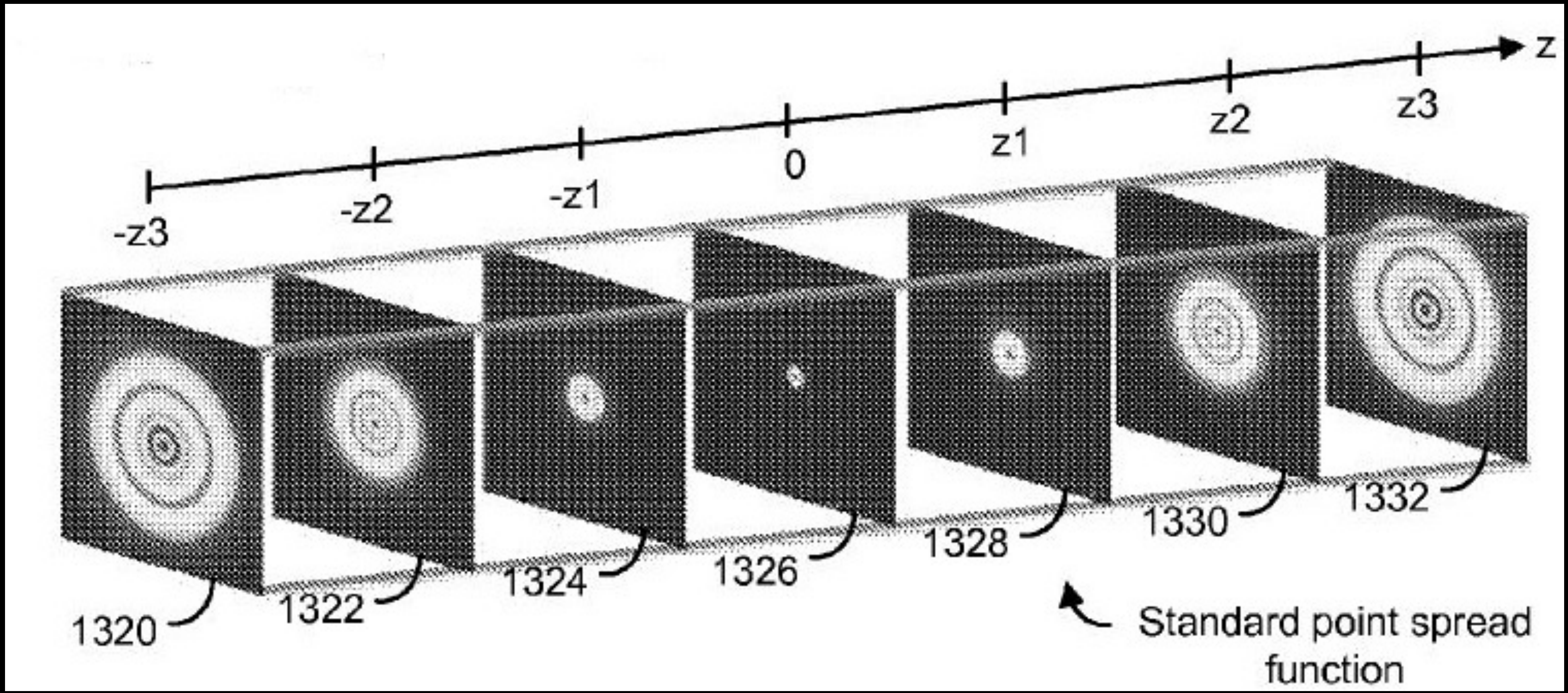




Extended Depth of Field through Wavefront Coding

Dowski et al., Applied Optics 1995

- How does it work?
  - A regular lens is parabolic, or quadratic.
    - The 2nd derivative determines plane of focus.



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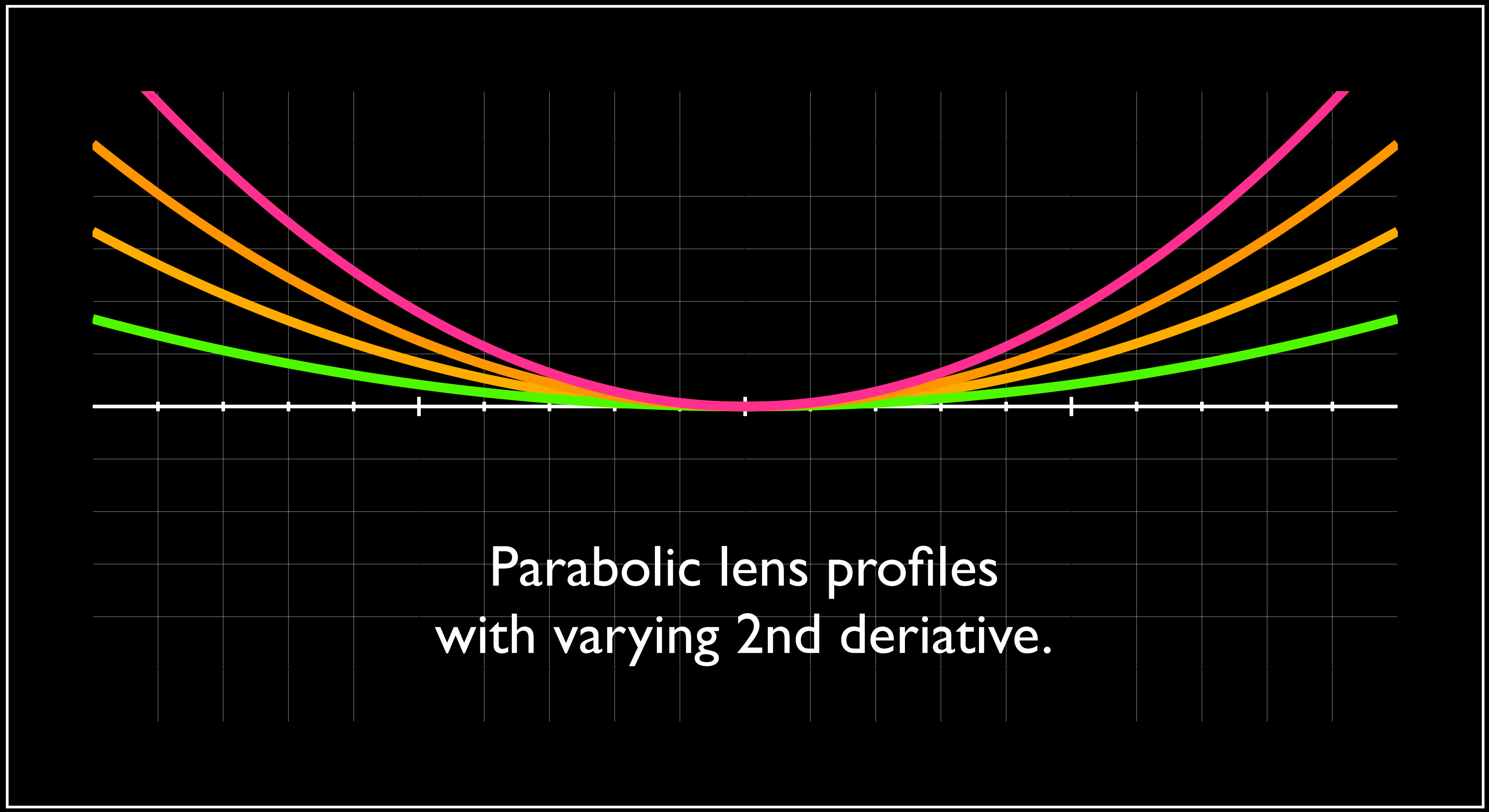


Extended Depth of Field through Wavefront Coding

Dowski et al., Applied Optics 1995

- How does it work?
  - A regular lens is parabolic, or quadratic.
    - The 2nd derivative determines plane of focus.
  - A cubic lens is locally quadratic with varying 2nd derivative.
    - Different parts of the lens “focus” at different depth!

Extended Depth of Field through Wavefront Coding

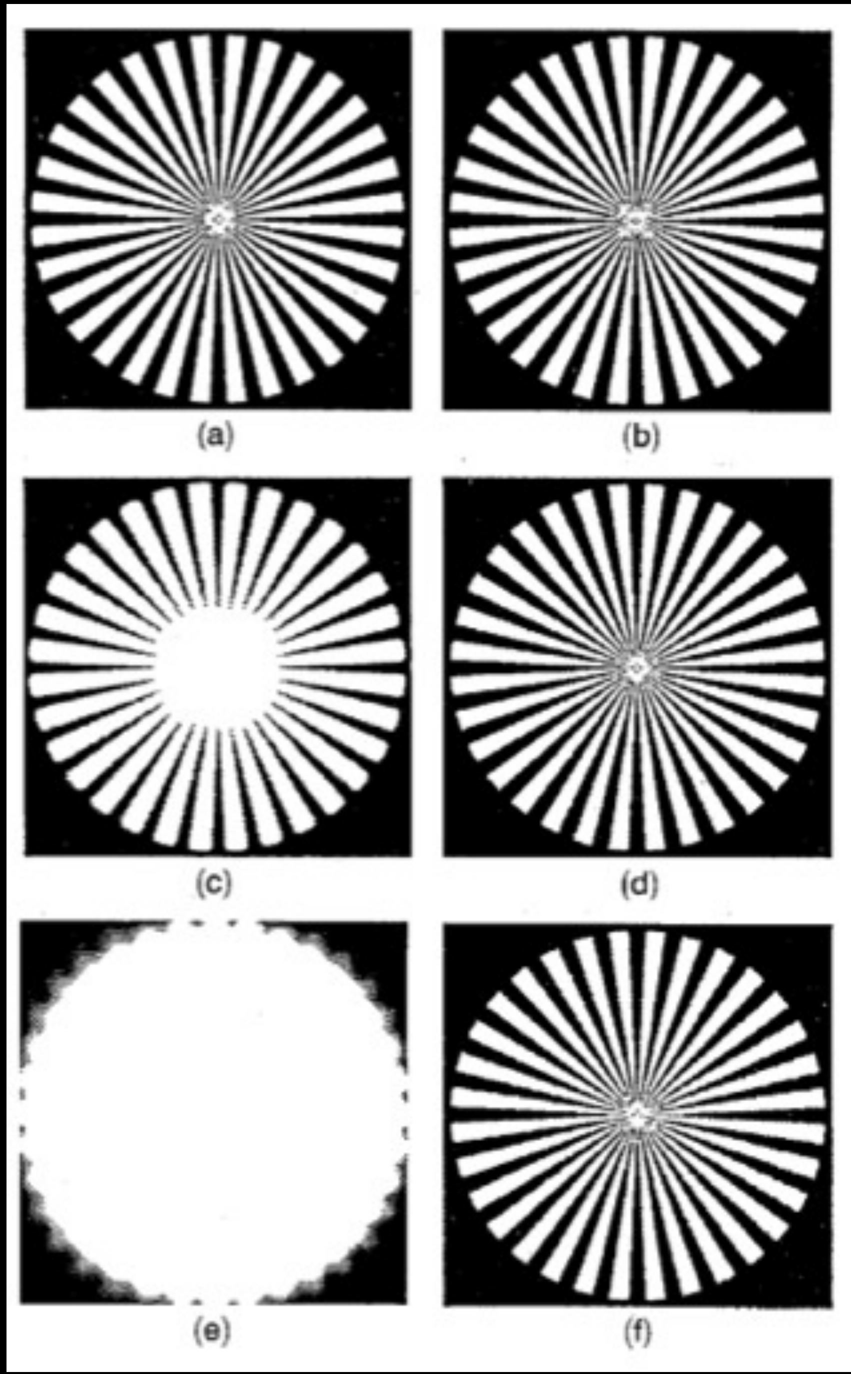
Dowski et al., Applied Optics 1995

- How does it work?
  - Therefore, regardless of depth, the object will be:
    - in focus (small PSF) for some parts of the lens
    - blurry (large PSF) for other parts of the lens
  - The overall PSF will be the sum.
    - More or less depth-invariant.
    - Deconvolve with a single PSF to recover scene.

Extended Depth of Field through Wavefront Coding

Dowski et al., Applied Optics 1995

Regular lens

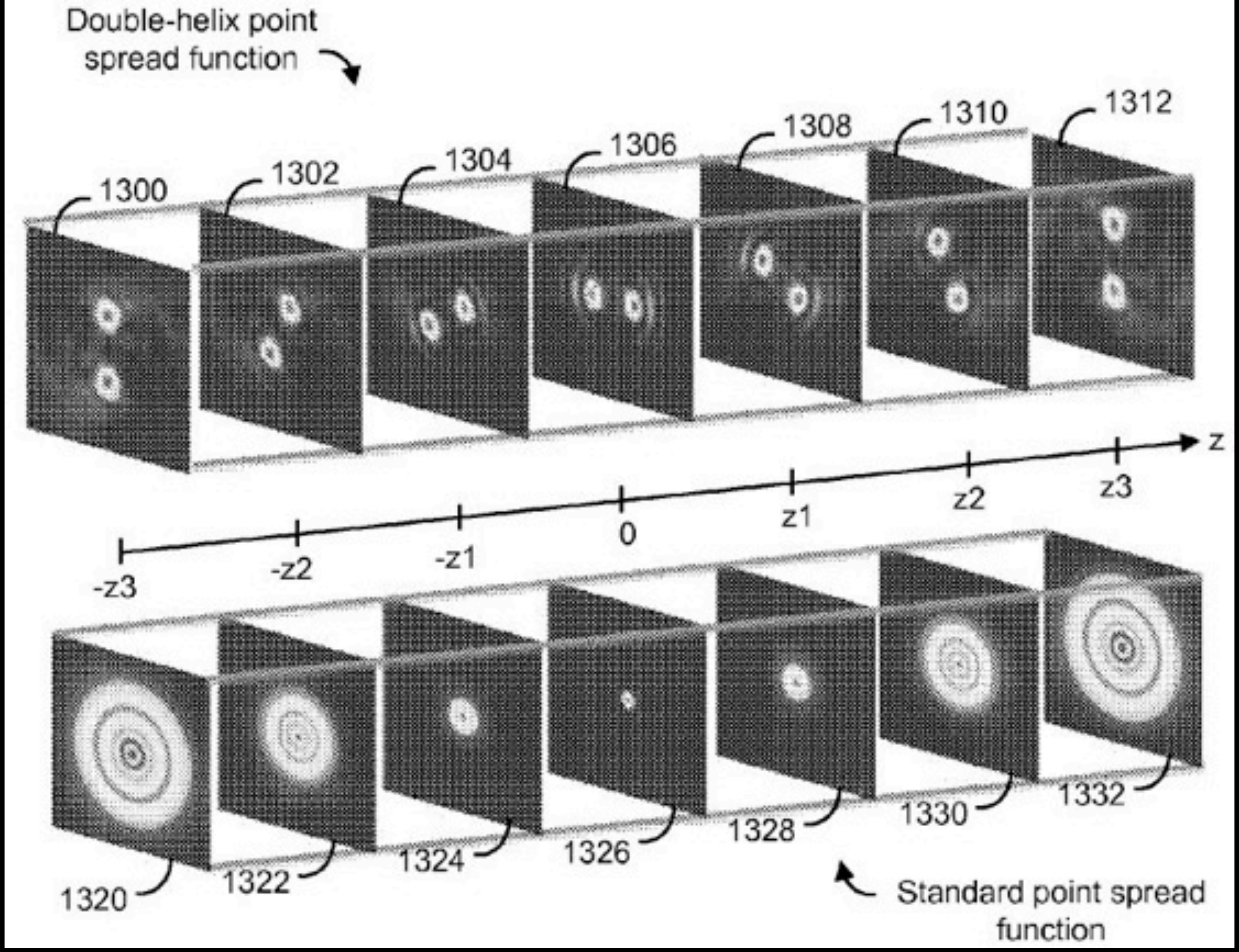


Cubic phase plate (deblurred)

Depth from Diffracted Rotation

Greengard et al., Optics Letters 2006

Aside: Can also design phase plate to be depth-variant.



4D Frequency Analysis of Computational Cameras for Depth of Field Extension

Levin et al., SIGGRAPH 2009

- Similar idea
  - Have parts of the lens focus at different depths.

“Lattice Focal Lens”

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Levin et al., SIGGRAPH 2009

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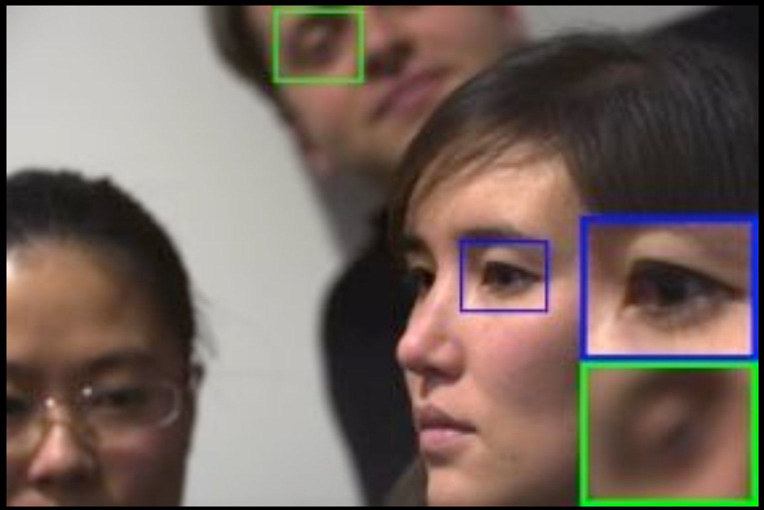
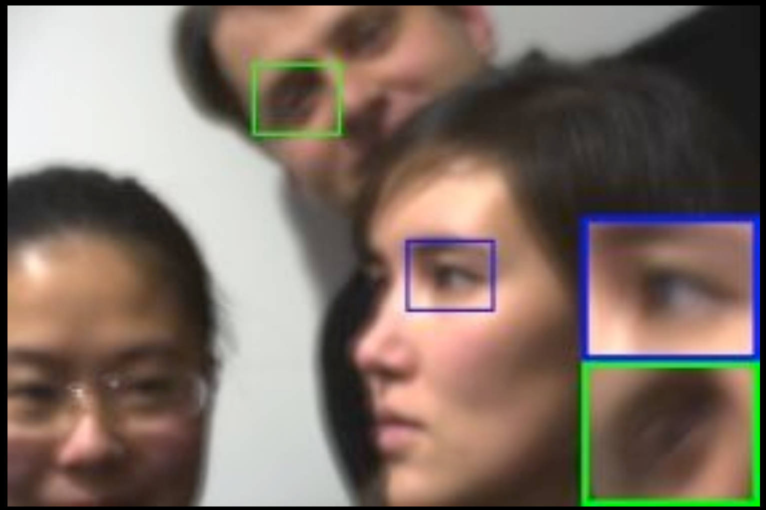
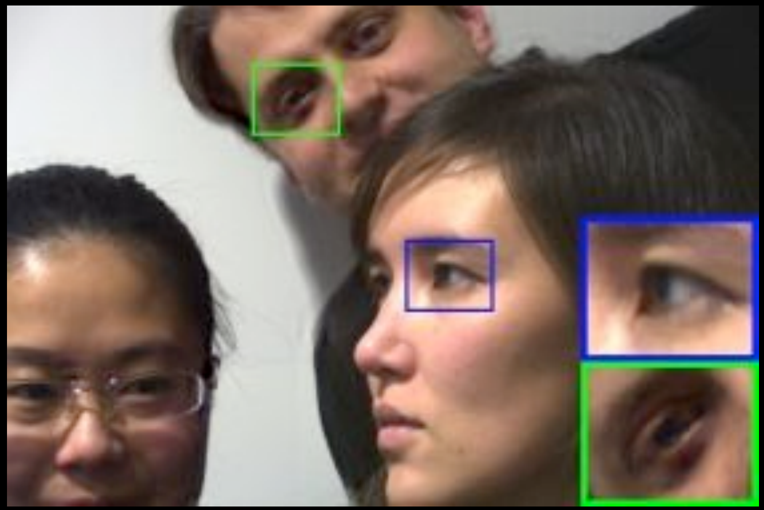


Regular lens



Lattice Focal Lens

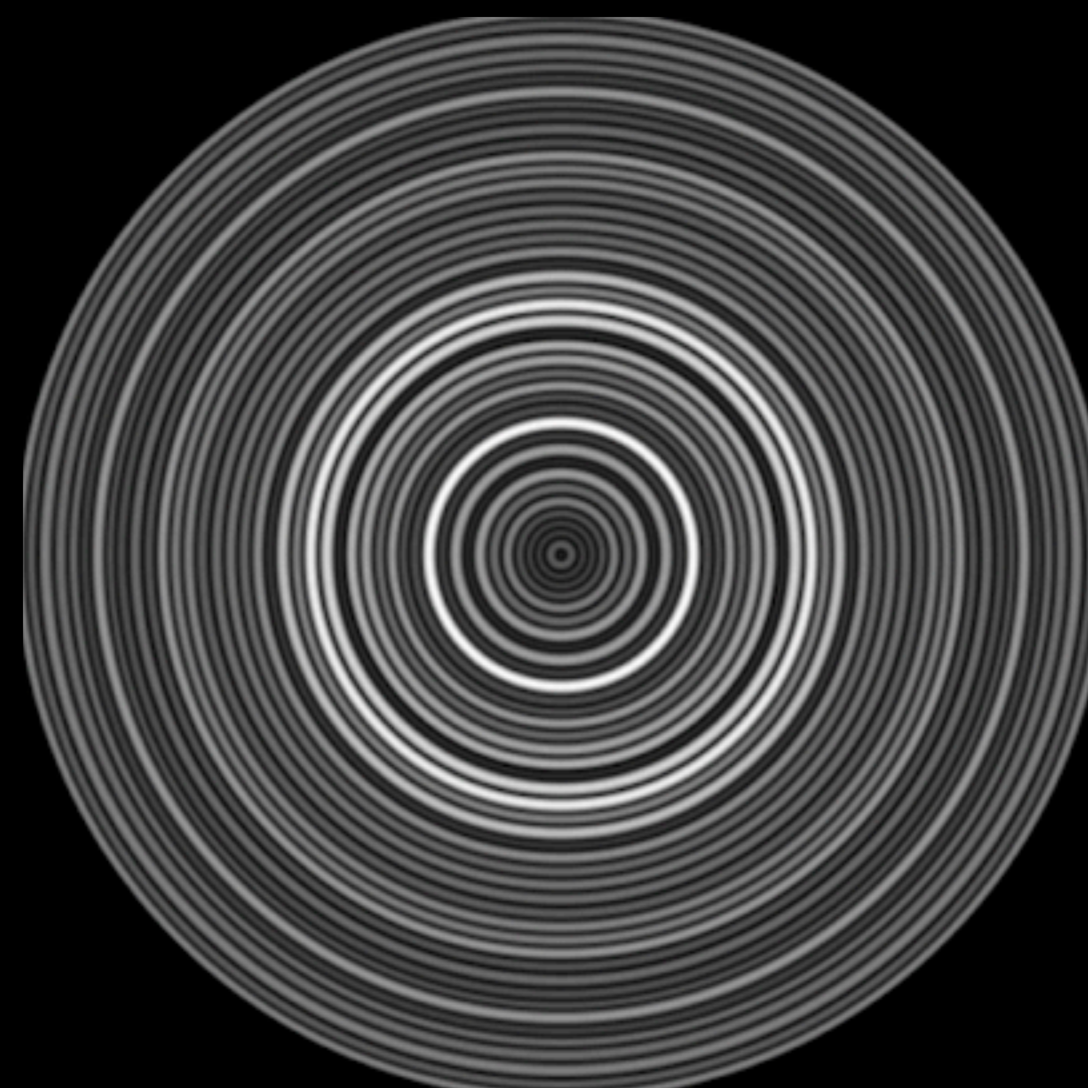


Deconvolved

Diffusion Coded Photography for Extended Depth of Field

Cossairt et al., SIGGRAPH 2010

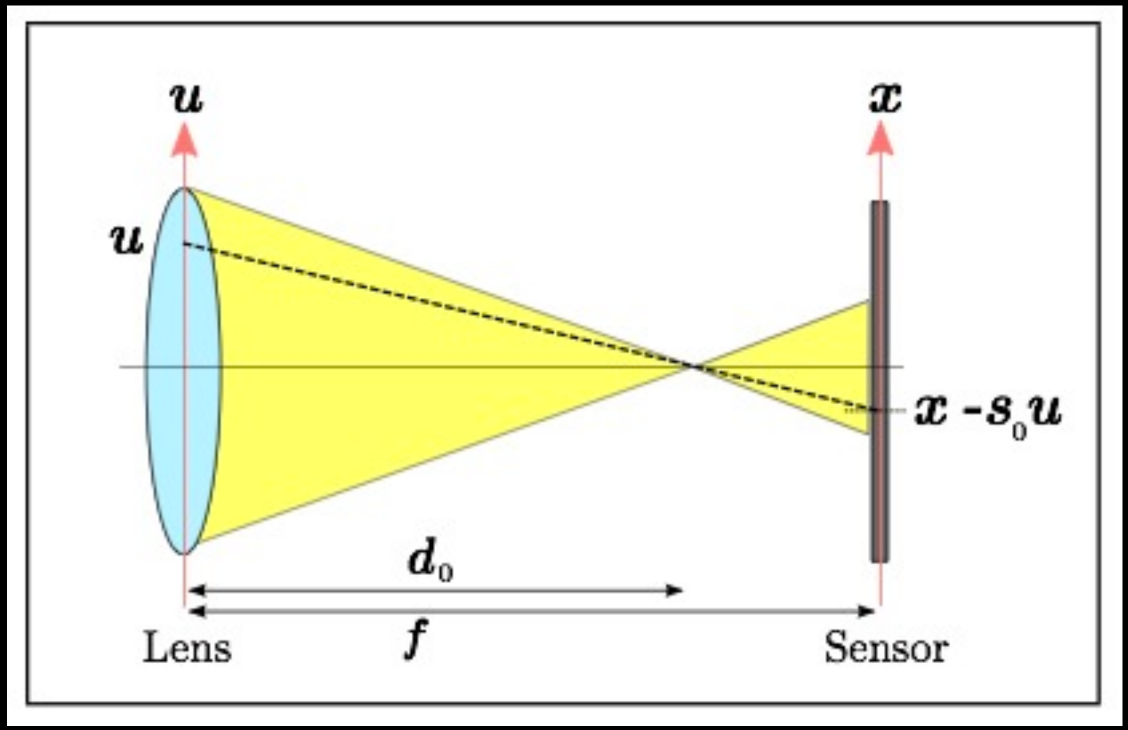
- Put a radial diffuser in front of the lens.

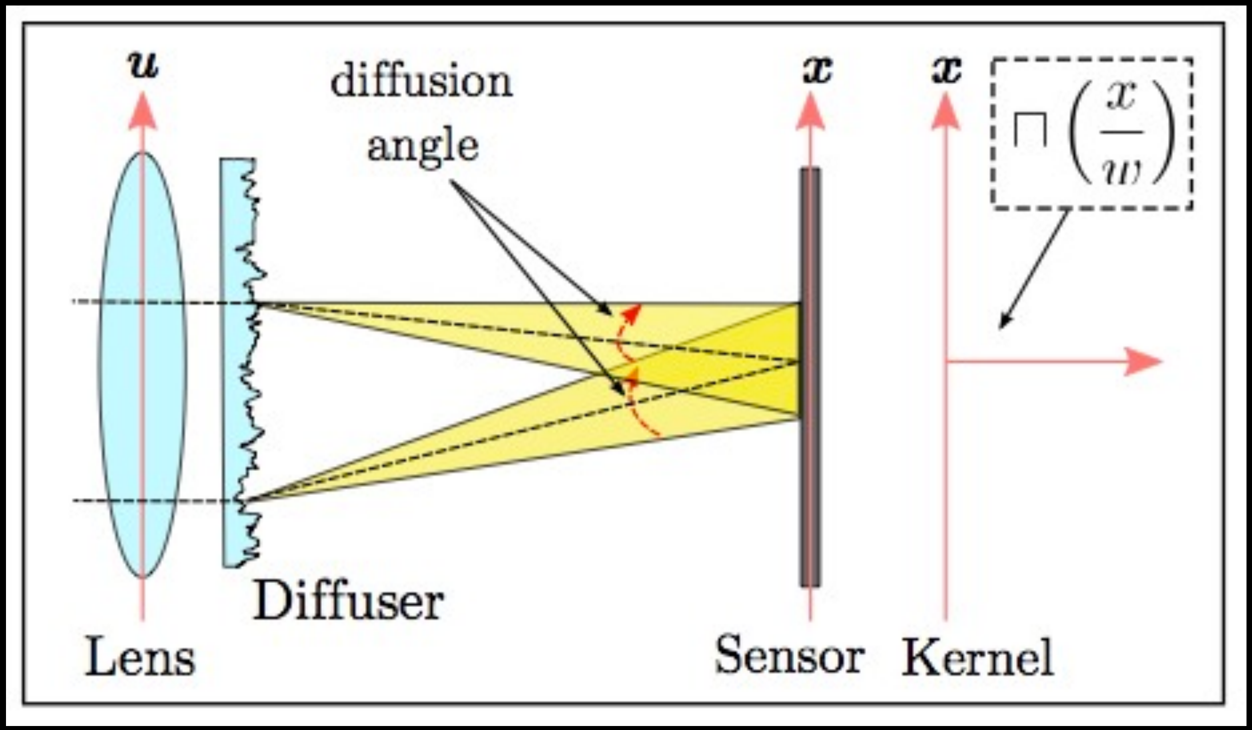


Diffusion Coded Photography for Extended Depth of Field

Cossairt et al., SIGGRAPH 2010

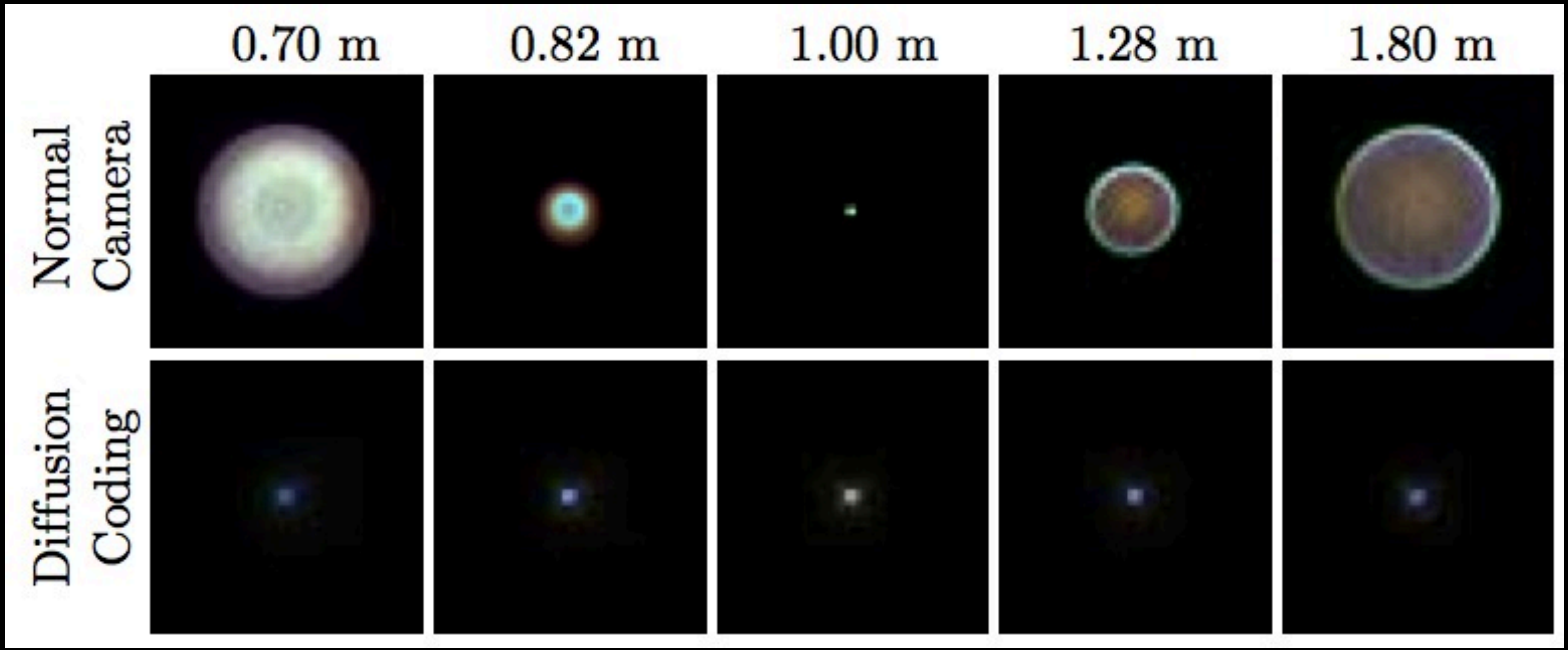
- Idea
  - Add a random diffuser (surface gradient is sampled randomly from a probability distribution)
  - This makes the PSF stochastic, and ultimately less dependent on ray angles, leading to depth invariance.





Diffusion Coded Photography for Extended Depth of Field

Cossairt et al., SIGGRAPH 2010



PSF is indeed depth-invariant.

Diffusion Coded Photography for Extended Depth of Field

Cossairt et al., SIGGRAPH 2010

Regular photos

Deblurred output

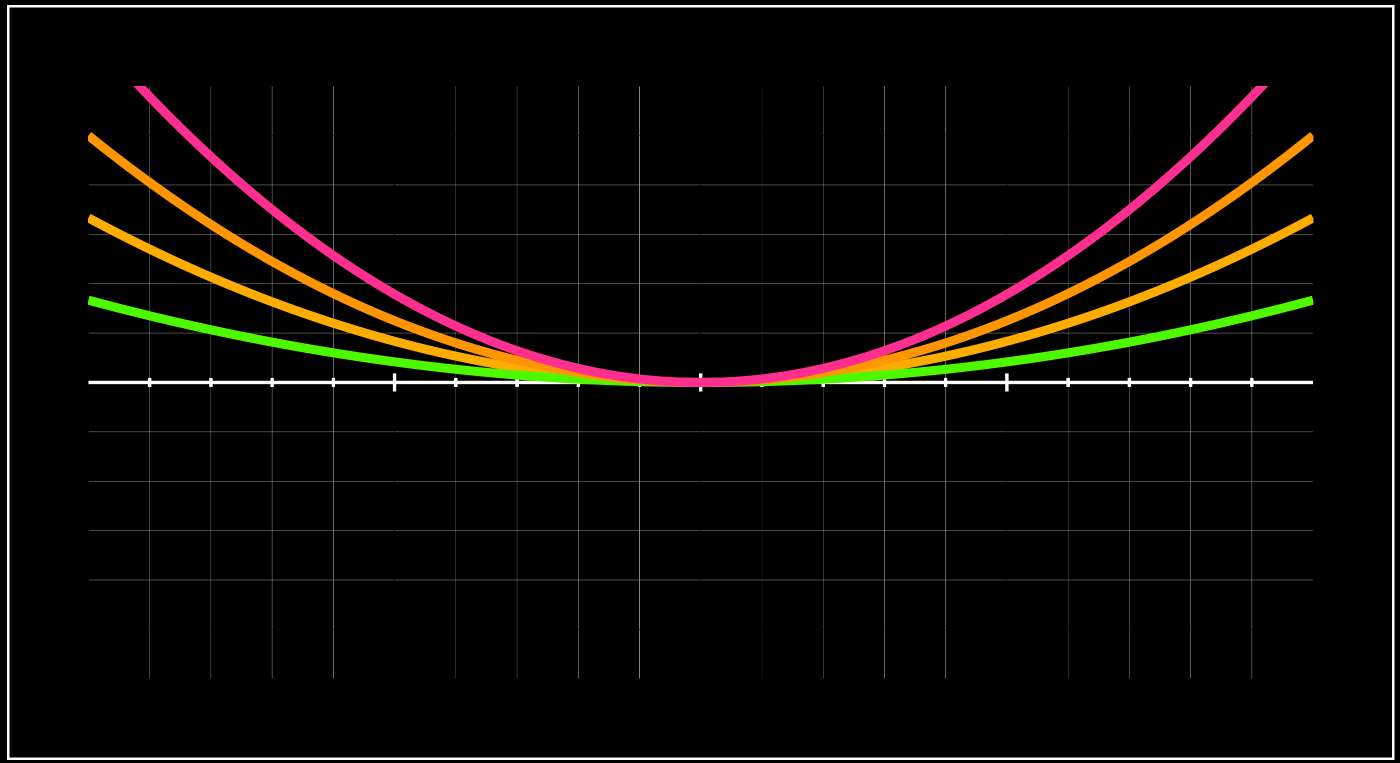
Next Step

- We've looked at techniques that modulate the aperture spatially.
- Why not try temporally?
  - Change modulation over time.

Flexible Depth of Field Photography

Nagahara et al., ECCV 2008

- Translate the sensor over the exposure time.
  - Equivalent to simulating lens of different focal lengths over time.



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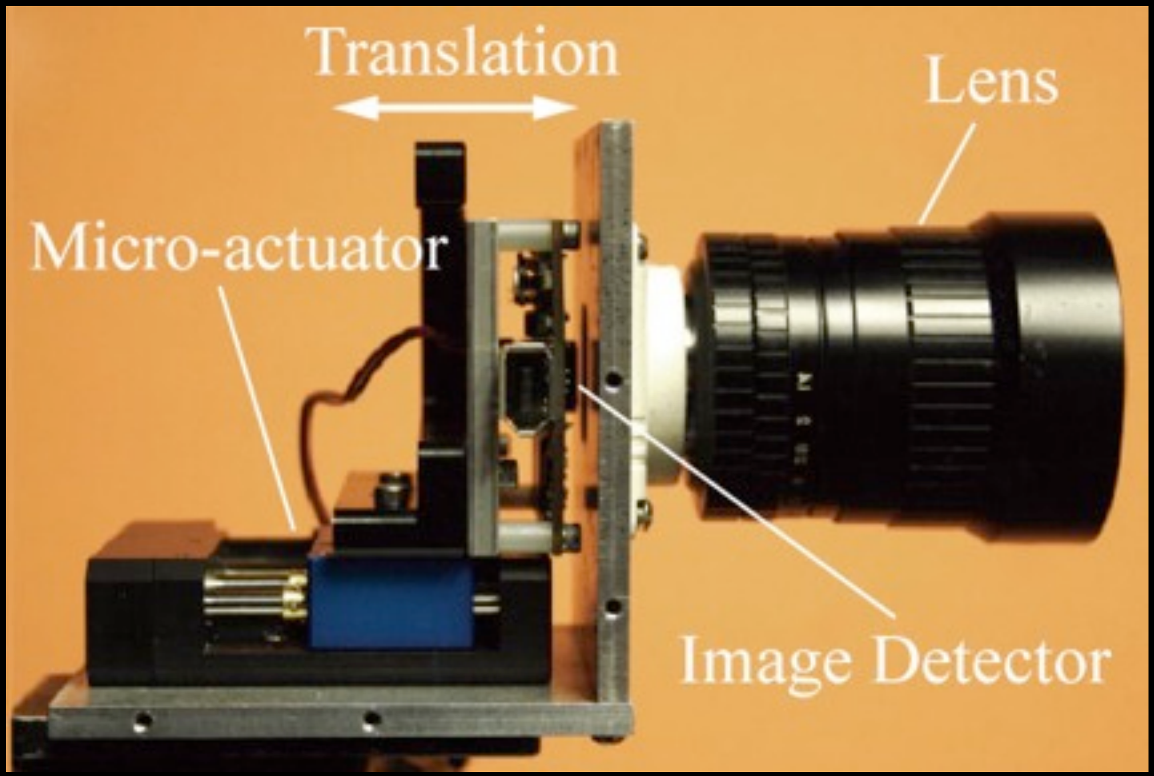


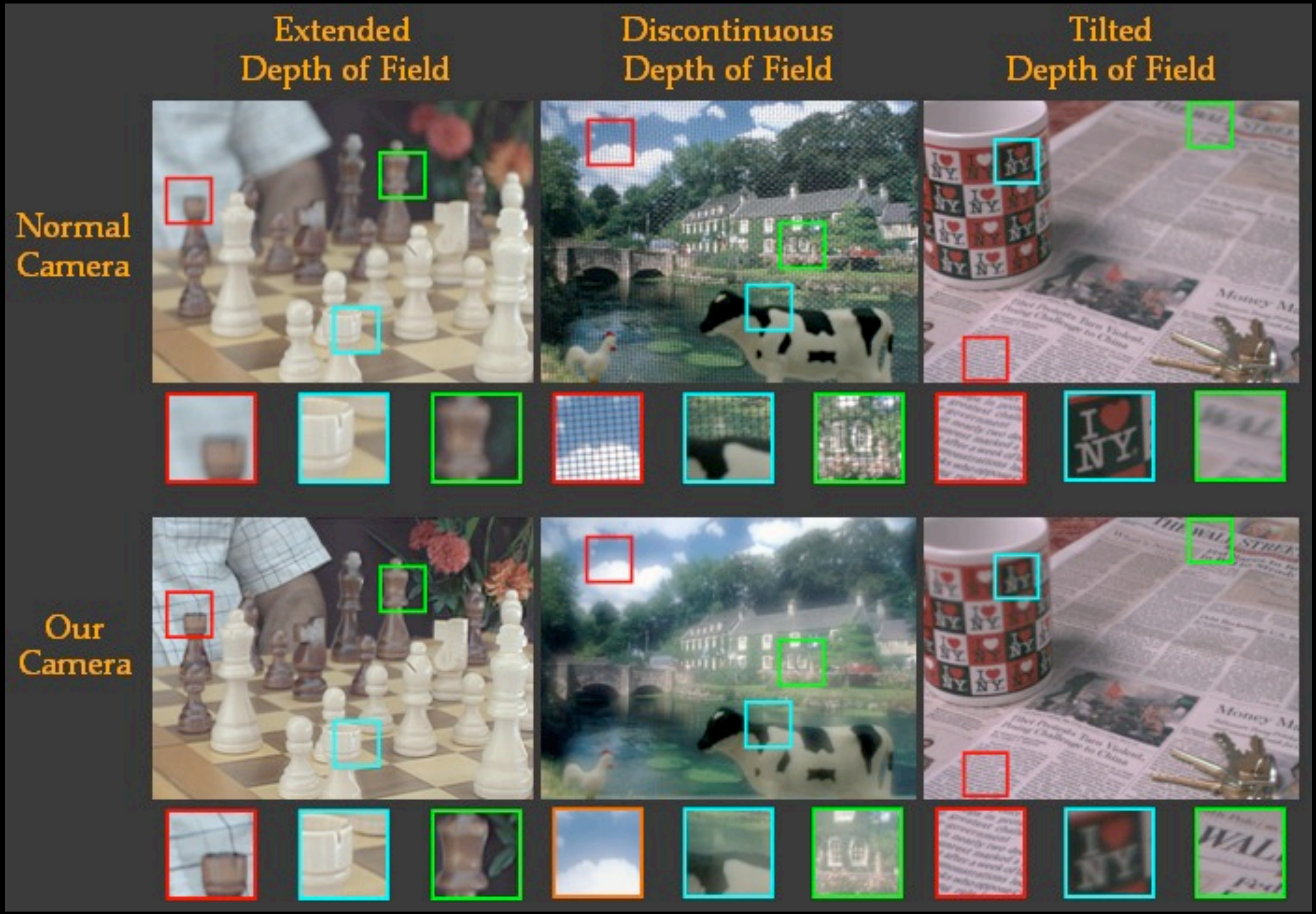
Flexible Depth of Field Photography

Nagahara et al., ECCV 2008

- Other applications
  - Could move the sensor non-linearly
    - Discontinuous depth of field?
  - Combine with rolling shutter
    - Tilt-shift

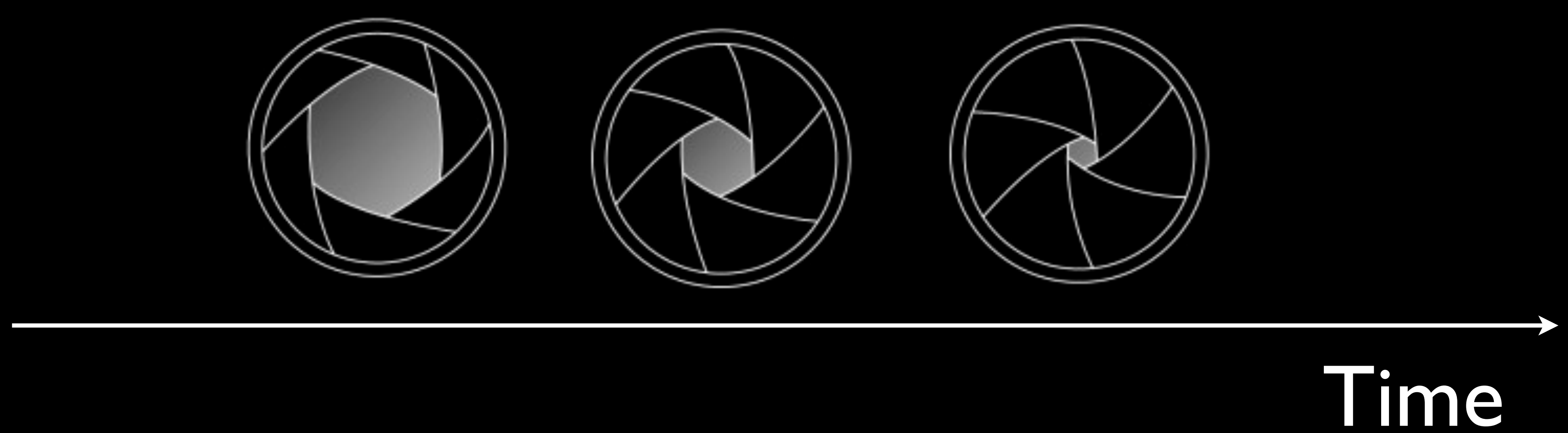
Flexible Depth of Field Photography

Nagahara et al., ECCV 2008



More ways for Temporal Coding

- One can also temporally code aperture by engaging the shutter over time.
  - Could even use electronic shutter.



Coded Exposure Photography: Motion Deblurring using Fluttered Shutter

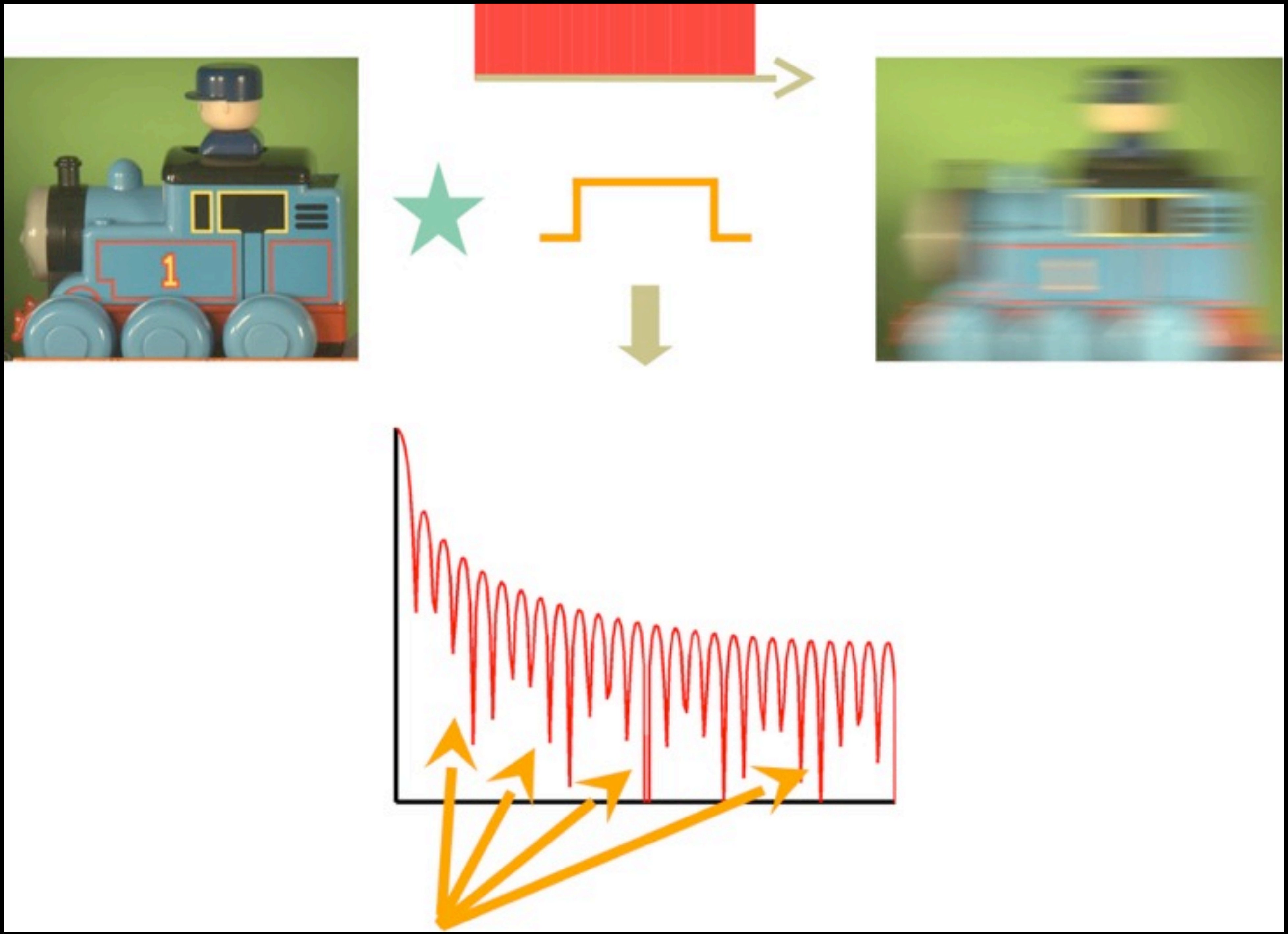
Raskar et al., SIGGRAPH 2006

- LCD shutter flutters in order to block/unblock light during exposure.

Coded Exposure Photography: Motion Deblurring using Fluttered Shutter

Raskar et al., SIGGRAPH 2006

slide stolen from Ramesh Raskar



Coded Exposure Photography: Motion Deblurring using Fluttered Shutter

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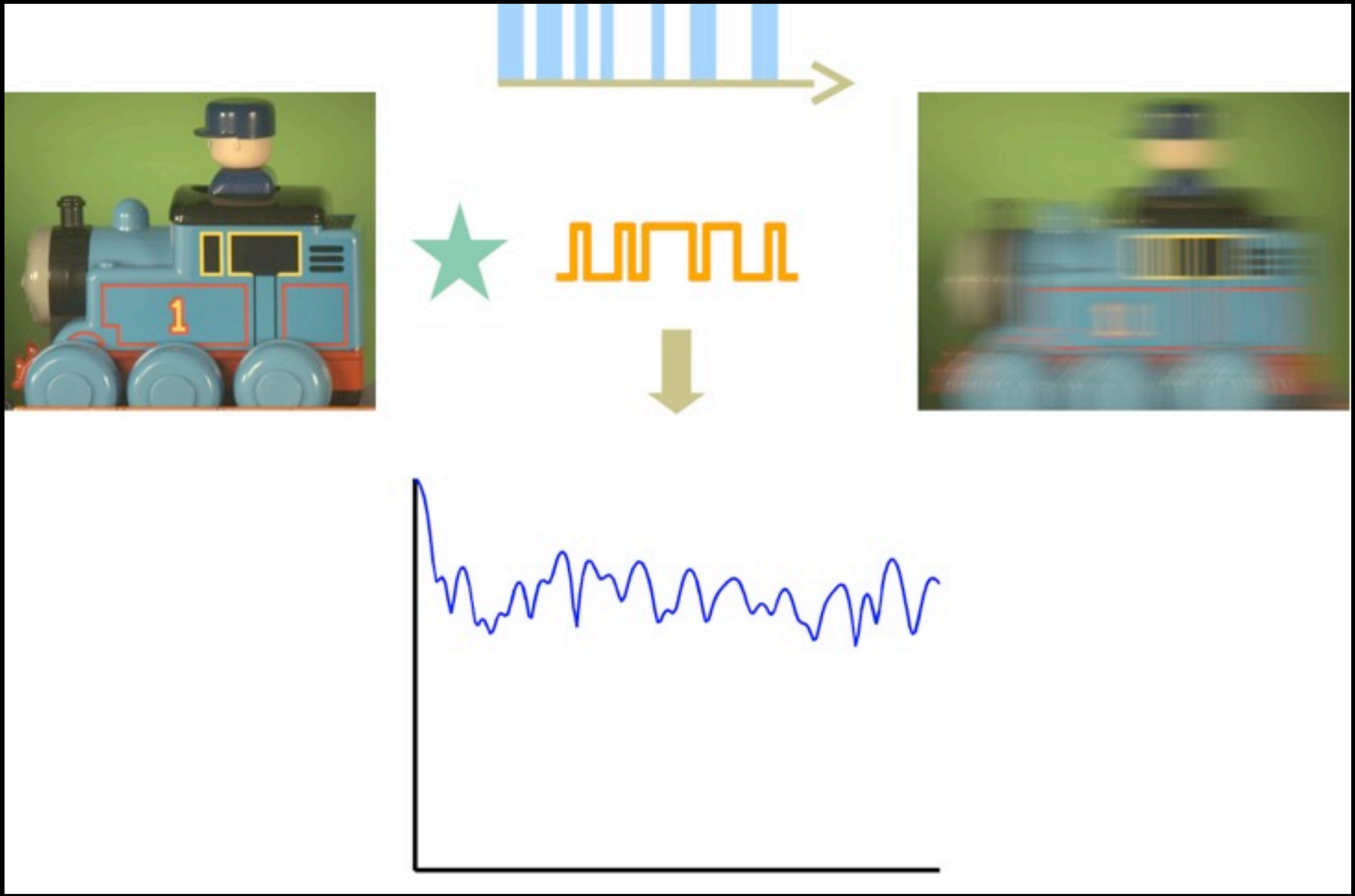
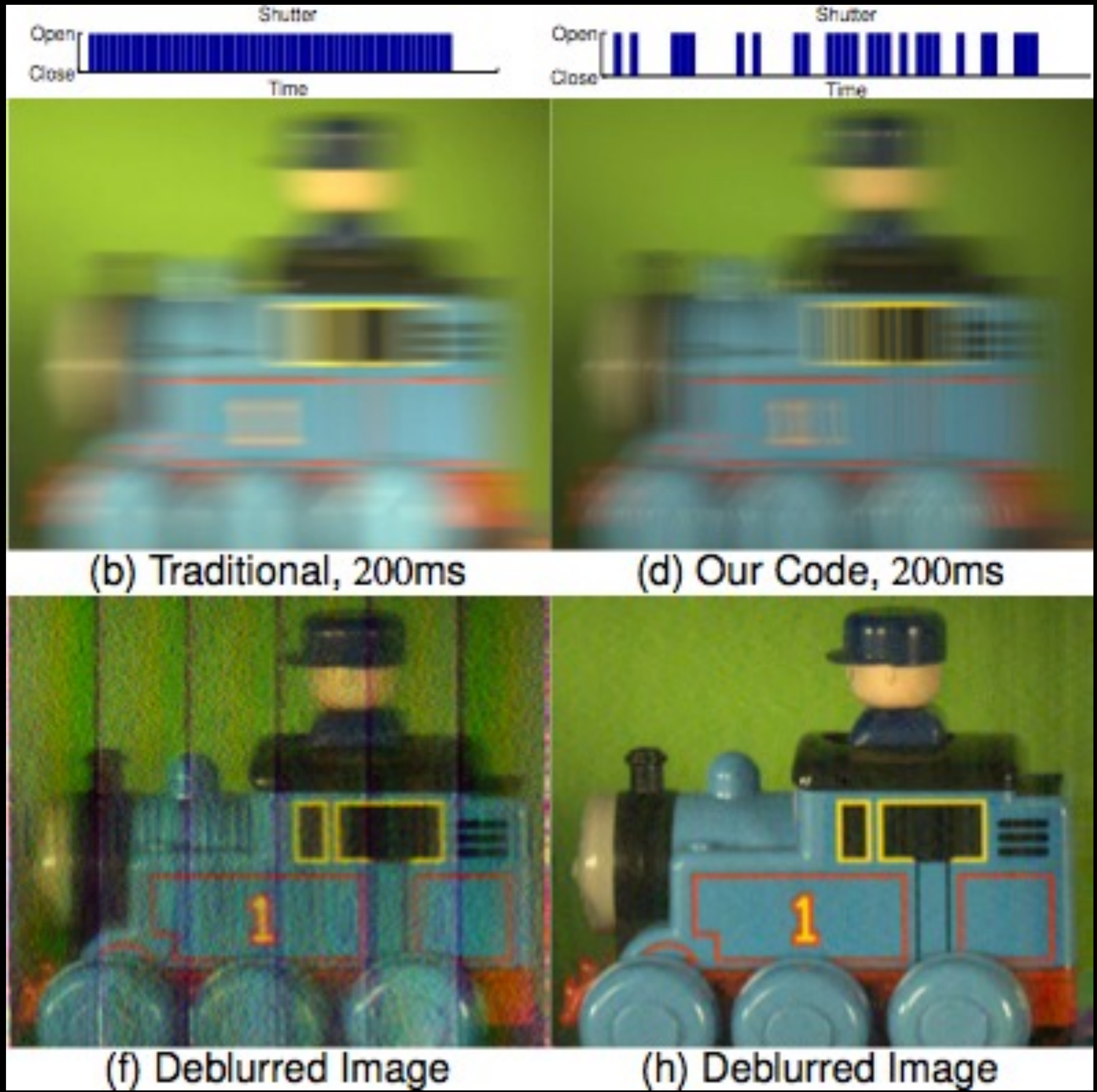
slide stolen from Ramesh Raskar



Creates a better-conditioned motion blur!

Coded Exposure Photography: Motion Deblurring using Fluttered Shutter

Raskar et al., SIGGRAPH 2006



Motion blur can be inverted easily!

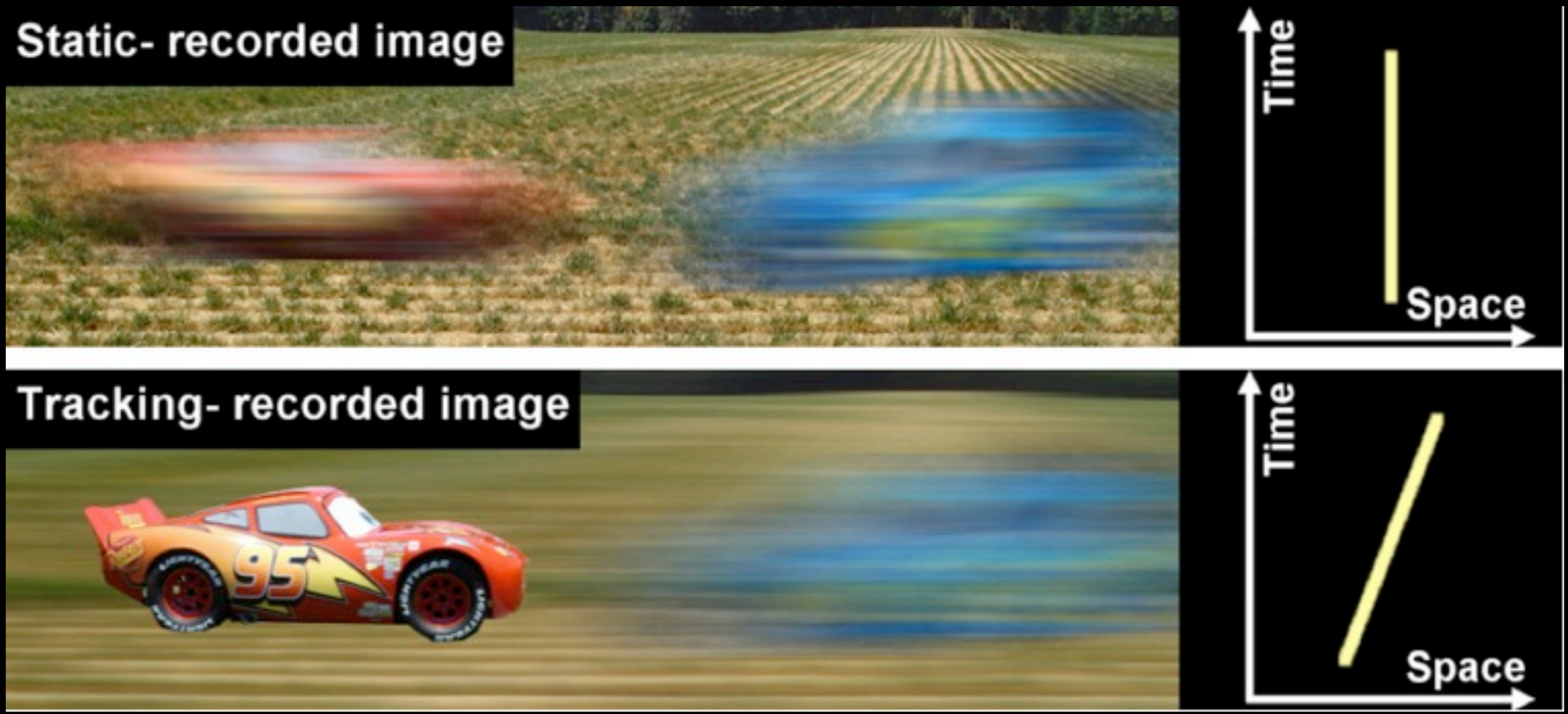
Next Step

- We've tried modulating capture based on
  - where the ray passes through the aperture
  - when the ray passes through the aperture
- Instead, let's move the entire camera.

Motion Invariant Photography

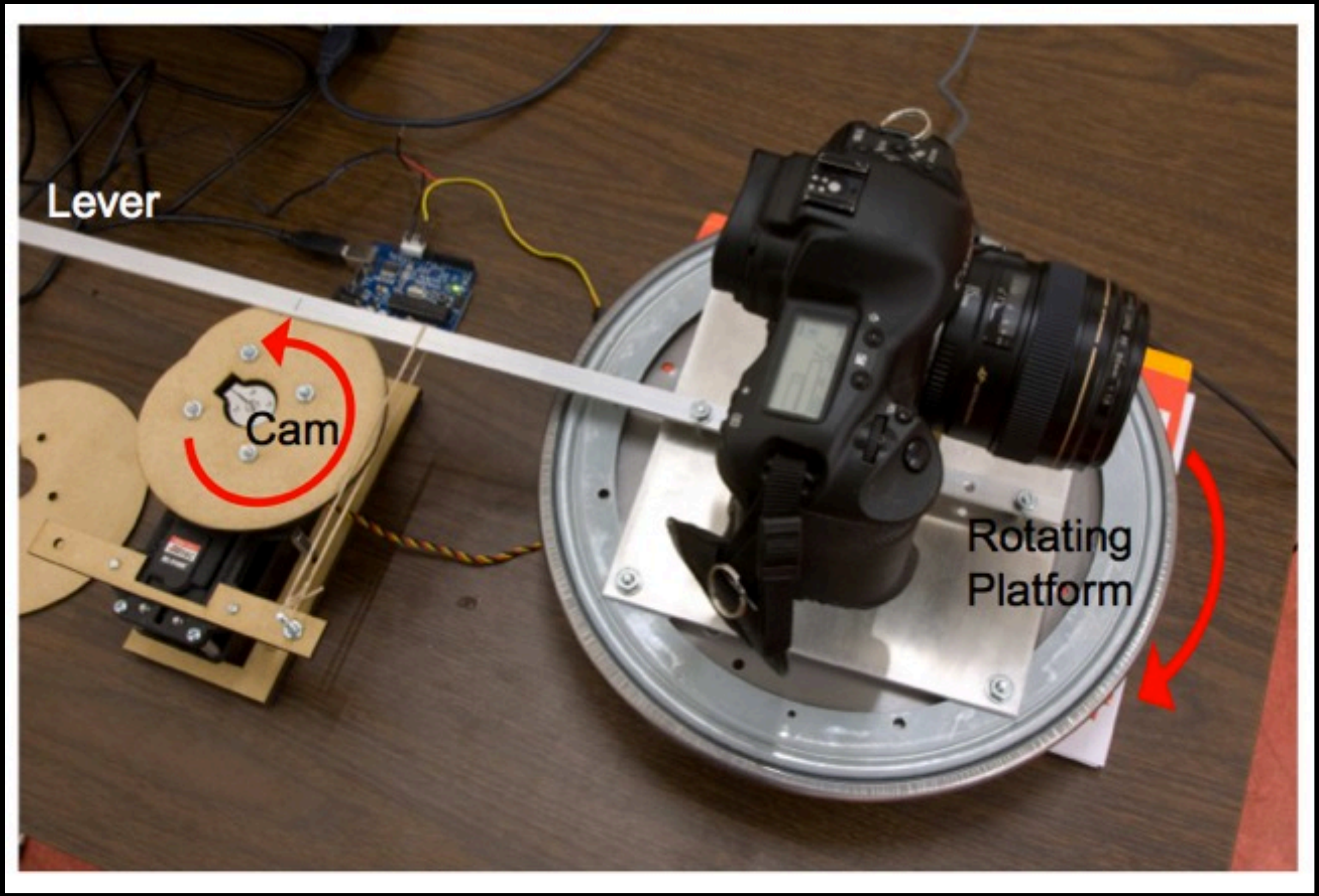
Levin et al., SIGGRAPH 2008

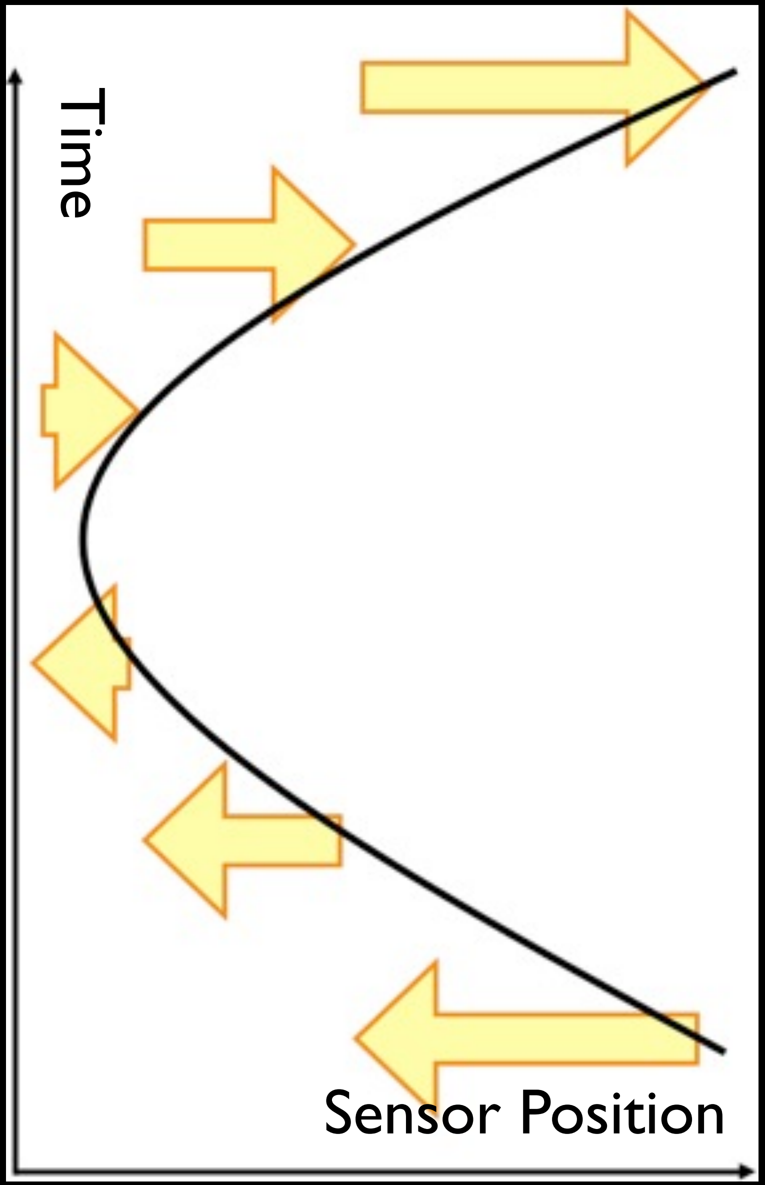
- Motivation
  - If there is an object that travels at a constant speed, you can image it sharply by moving the camera linearly at some velocity.



Motion Invariant Photography
Levin et al., SIGGRAPH 2008

- The entire camera moves during exposure in a parabola.





Motion Invariant Photography

Levin et al., SIGGRAPH 2008

- If there is an object that travels parallel to the image plane, at some point in time the camera motion will mirror the object *exactly*.
  - Object is momentarily imaged sharply.
  - At other times, it will be somewhat blurry, blurry, very blurry, etc.
- Above happens independent of object speed!
  - Motion-invariant motion blur!

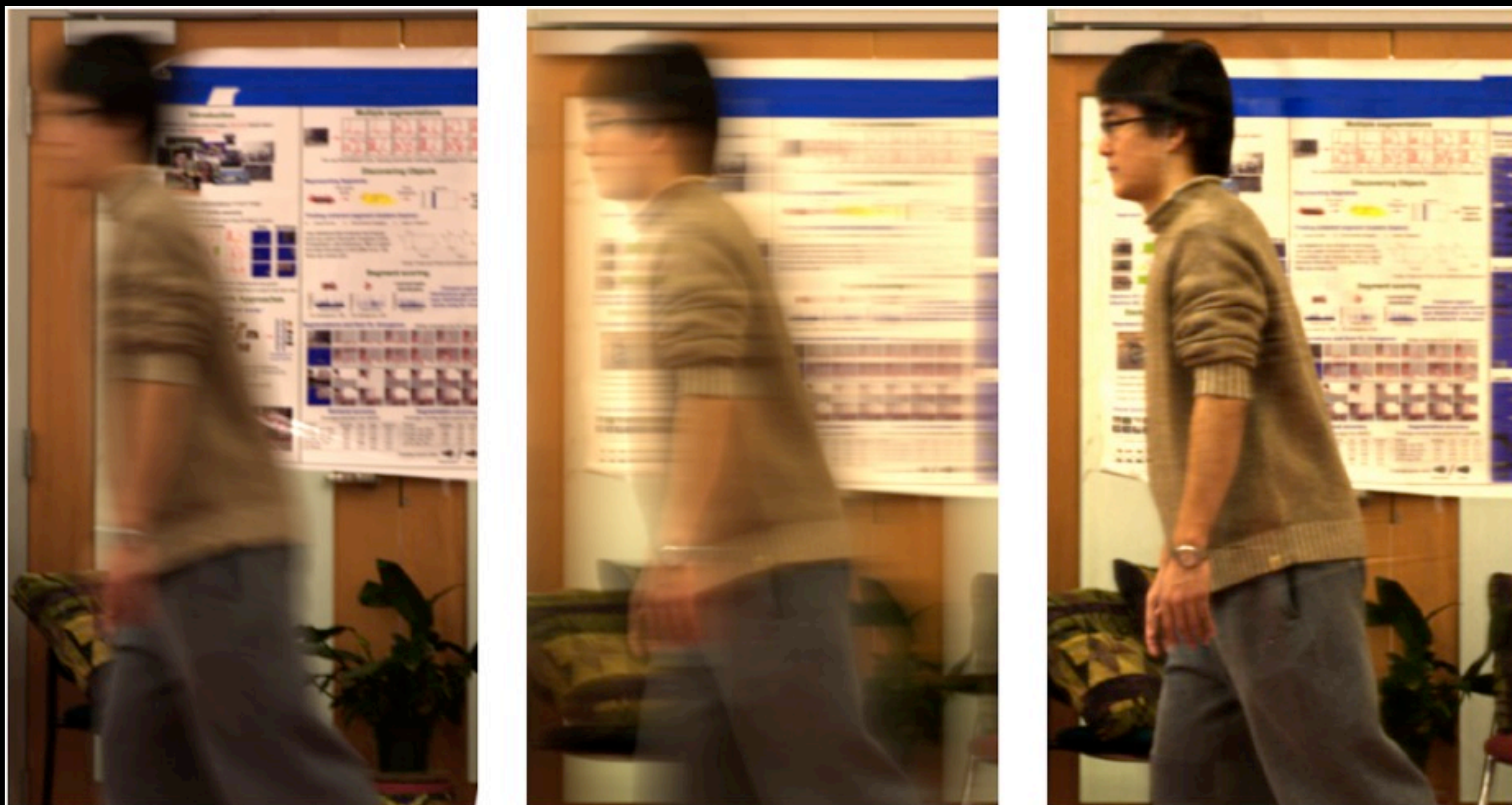
Motion Invariant Photography

Levin et al., SIGGRAPH 2008

Alt-tab to video?

Motion Invariant Photography

Levin et al., SIGGRAPH 2008



Scene Captured Deblurred

Next Step

- While we are at it, let’s move both lens and the sensor, independently.

Image Destabilization: Programmable Defocus using Lens and Sensor Motion

Mohan et al., ICCP 2009

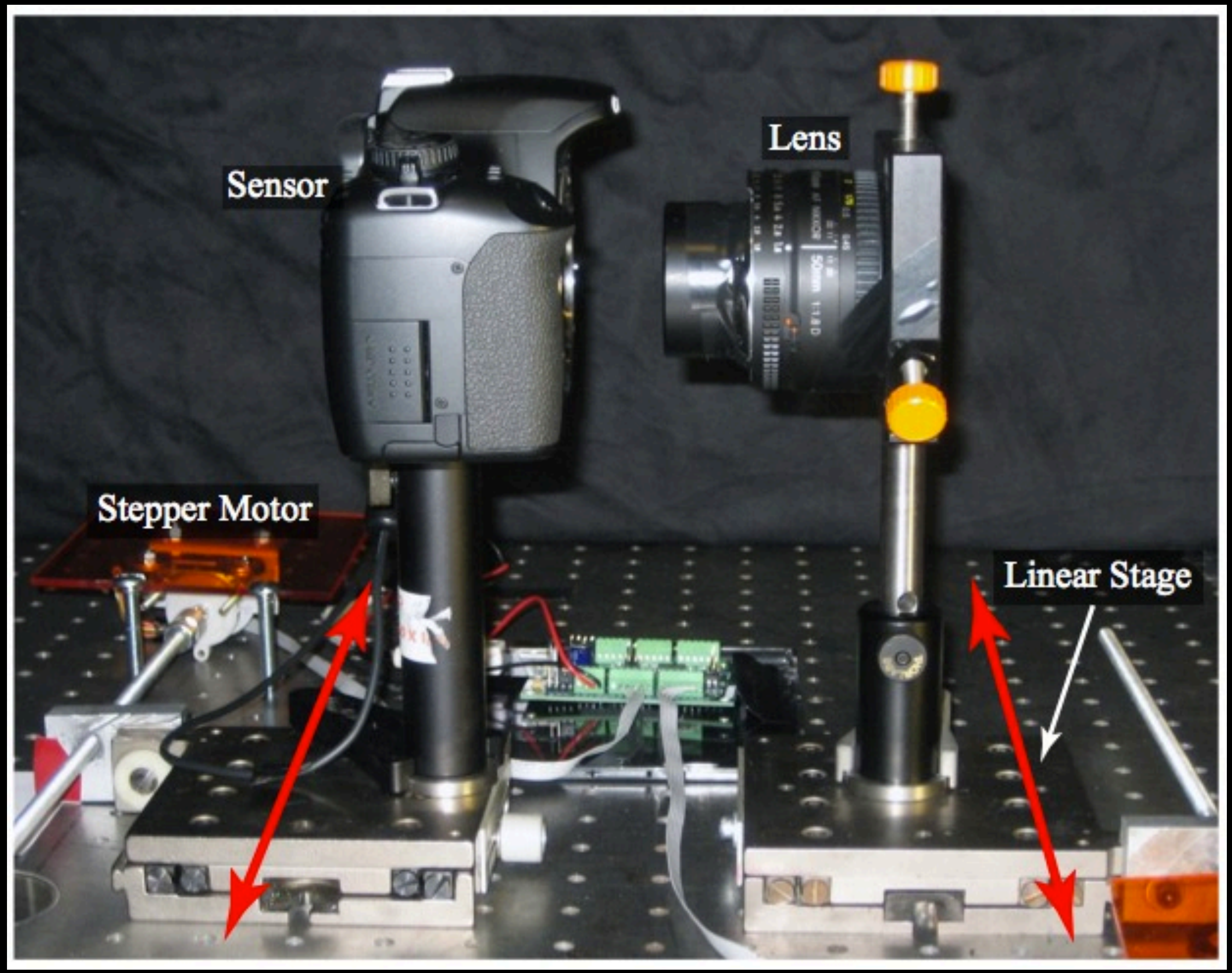


Image Destabilization: Programmable Defocus using Lens and Sensor Motion

Mohan et al., ICCP 2009

- Translate both the lens and the sensor laterally.
  - Depending on their relative speed, there exists a 3D point in the scene that is imaged by the same pixel.
    - Remains sharp.
  - Other points are effectively motion-blurred

Image Destabilization: Programmable Defocus using Lens and Sensor Motion

Mohan et al., ICCP 2009

regular camera

result

Next Step

- Can we modulate capture based on something entirely different?
  - Wavelength?

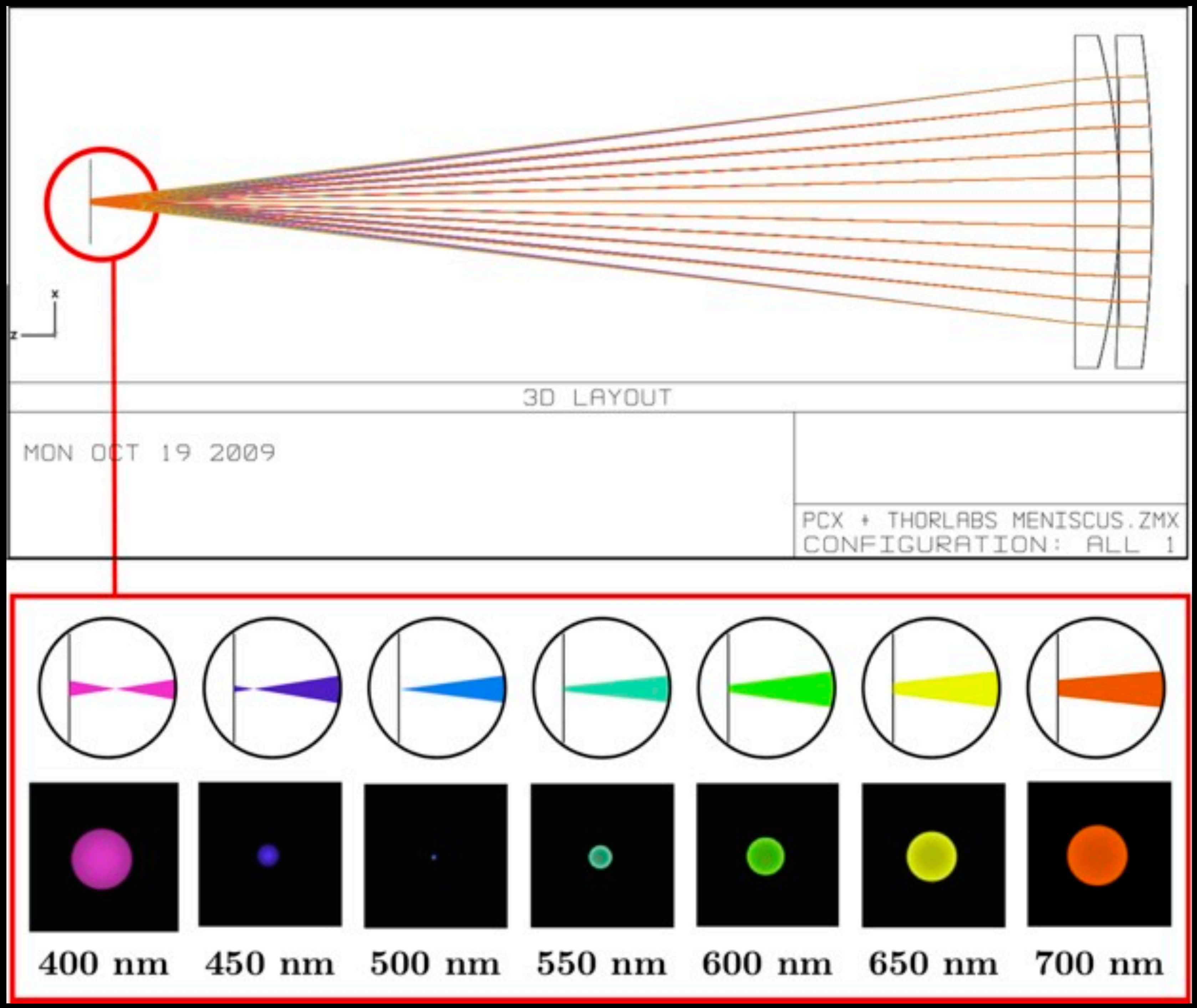
Spectral Focal Sweep: Extended Depth of Field from Chromatic Aberration

Cossairt et al., ICCP 2010

- Have a lens that maximizes axial chromatic aberration.
  - Different wavelength focuses at different depth!
- If the scene spectrum is broadband,
  - We're effectively doing a focal sweep!

Spectral Focal Sweep: Extended Depth of Field from Chromatic Aberration

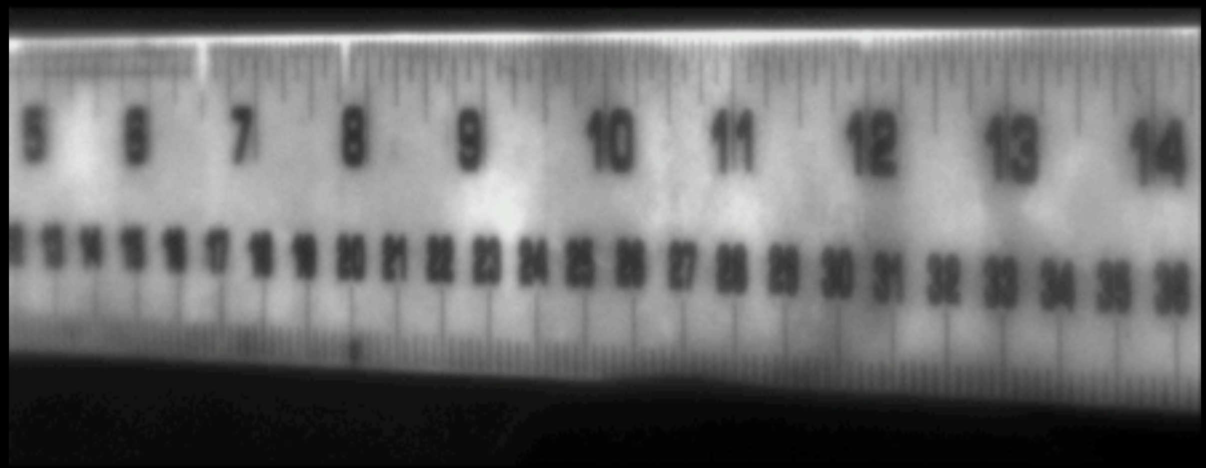
Cossairt et al., ICCP 2010



Spectral Focal Sweep: Extended Depth of Field from Chromatic Aberration

Cossairt et al., ICCP 2010

Conventional camera



SFS Lens

Deblurred output

Spectral Focal Sweep: Extended Depth of Field from Chromatic Aberration

Cossairt et al., ICCP 2010

Conventional camera

Deblurred output

For color, transform to YUV and deblur Y only.

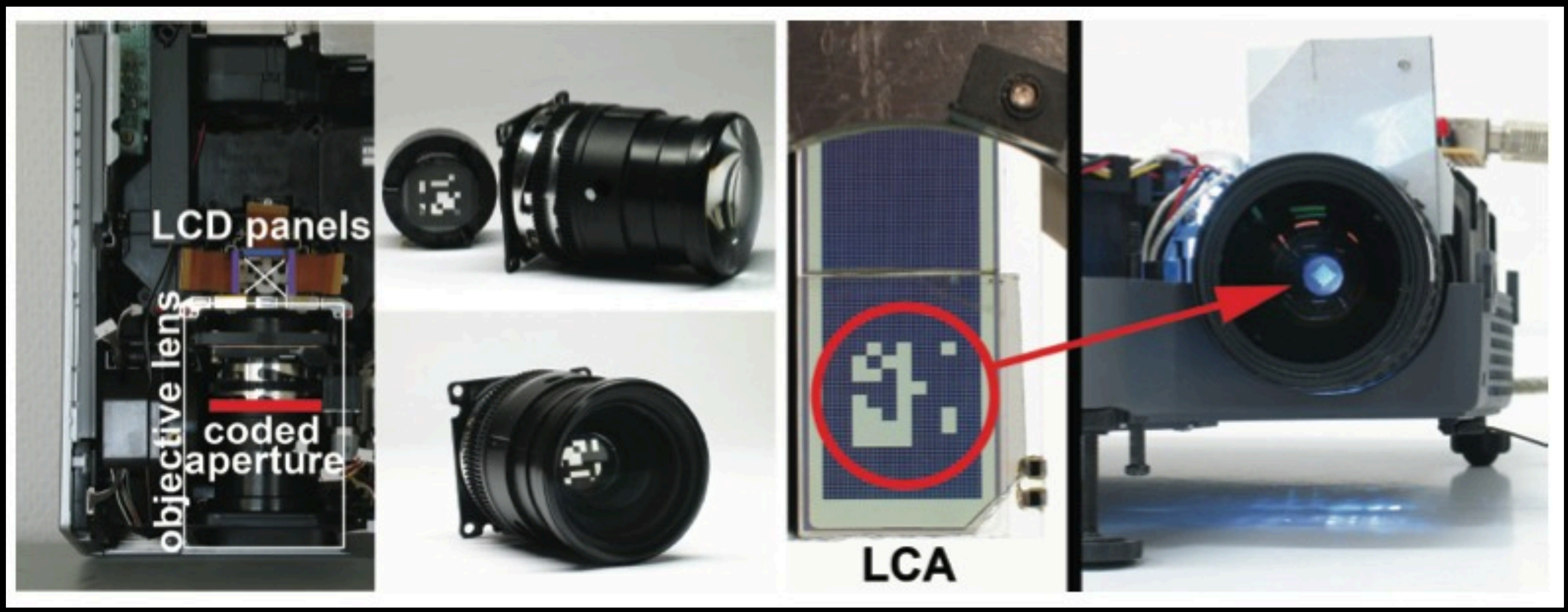
Other Cool Stuff

- Coded aperture projection
- Periodic motion
  - http://www.umiacs.umd.edu/~dikpal/Projects/codedstrobing.html
- Interaction with rolling shutter

Coded Aperture Projection

Grosse et al., SIGGRAPH 2010

- Pick coded aperture that creates depth-invariant blur.
  - Could be adaptive.
- Before projecting, convolve image with the inverse of that aperture. (Ensures that the image looks fine.)



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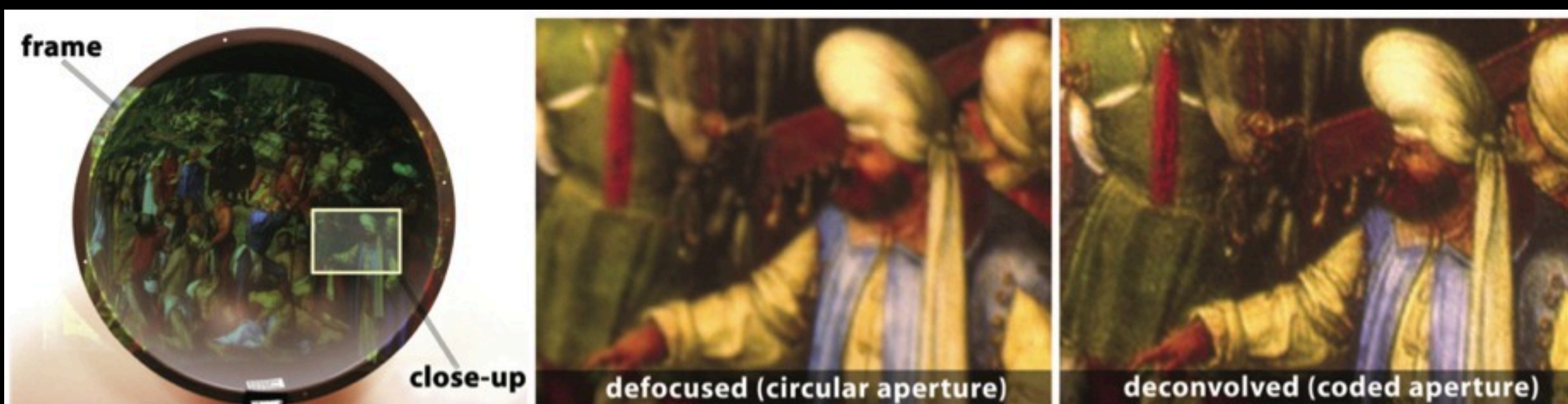

Depth of field increased!

Questions?

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