Light fields

Computational Photography

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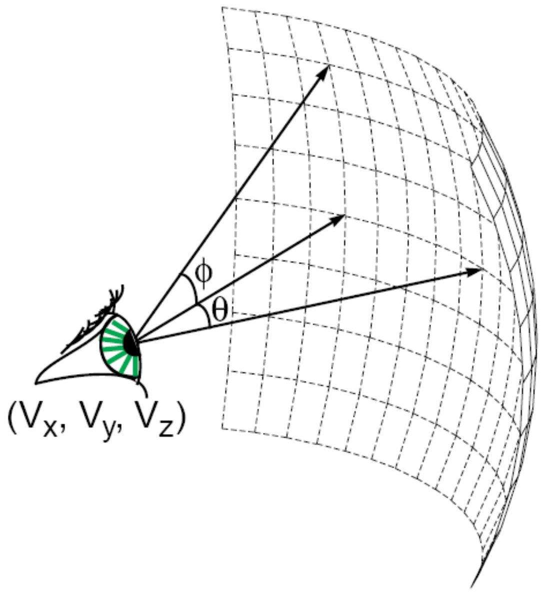
Definition and basic properties

Plenoptic Function

- plenoptic (Latin plenus: full, Greek optic: vision)
- Plenoptic function [Adelson91] describes the radiance at
  - a position in space (3D)
  - in a certain direction (2D)
  - at a particular point in time (1D)
  - in a particular wavelength (1D)
  - $L = P(x, y, z, \theta, \varphi, t, \lambda)$ (7D function)

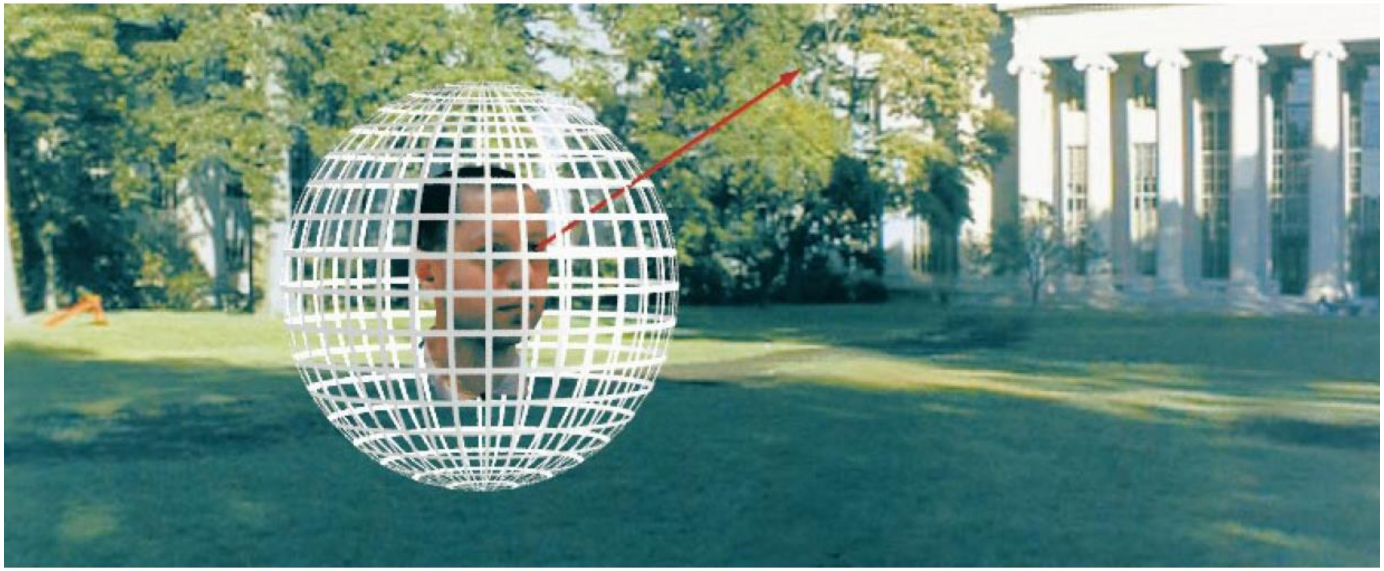


- Imagine a collection of dynamic environment maps covering the whole space

Grayscale snapshot

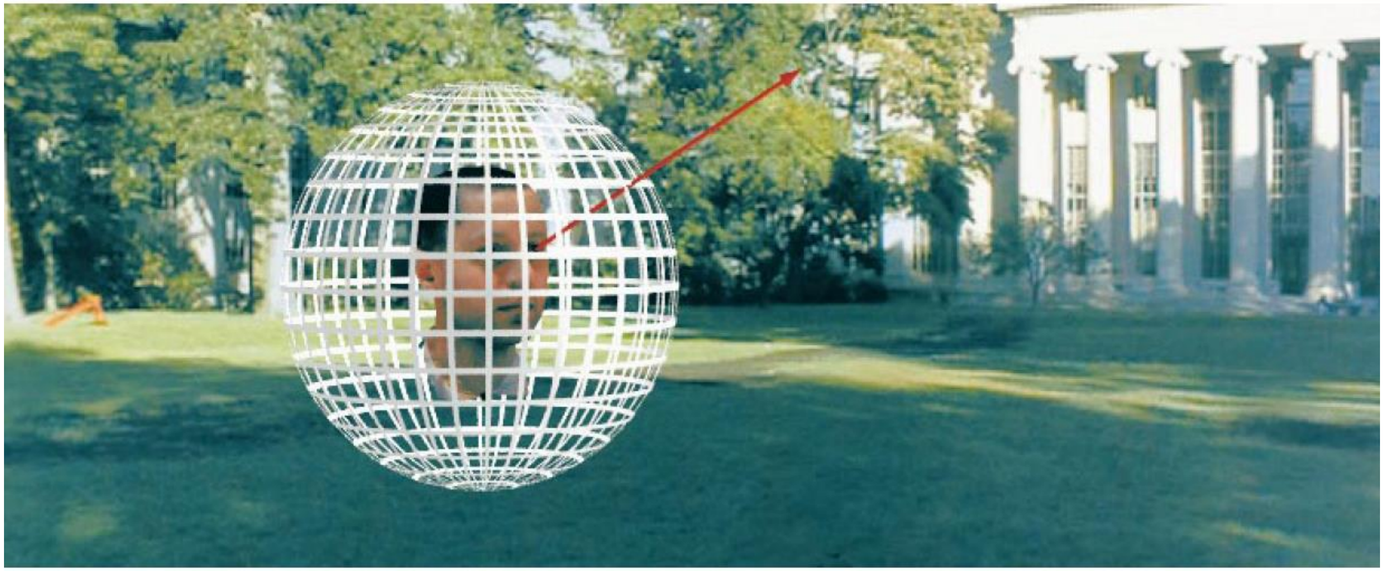
- Intensity of light $P(\theta, \phi)$
  - Seen from a single view point
  - At a single time
  - Averaged over the wavelengths of the visible spectrum
- (can also do $P(x, y)$; spherical coordinates are nicer)

Color snapshot



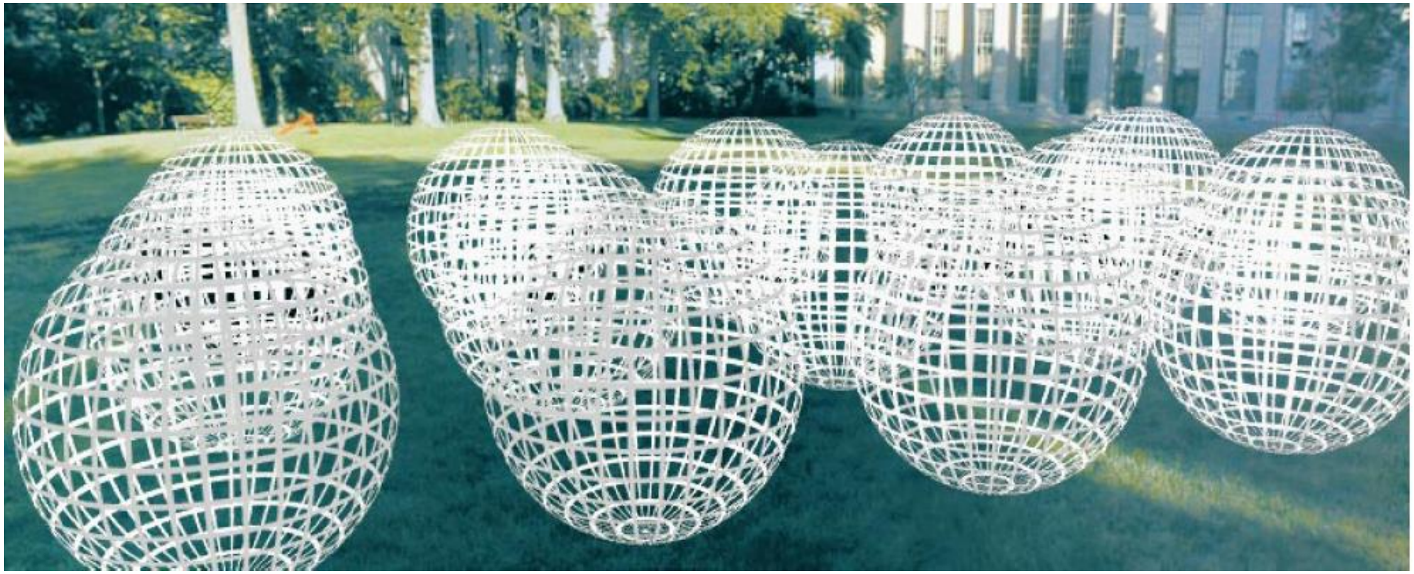
- Intensity of light $P(\theta, \phi, \lambda)$
  - Seen from a single view point
  - At a single time
  - As a function of wavelength

A movie



- Intensity of light $P(\theta, \phi, \lambda, t)$
  - Seen from a single view point
  - Over time
  - As a function of wavelength

Holographic movie



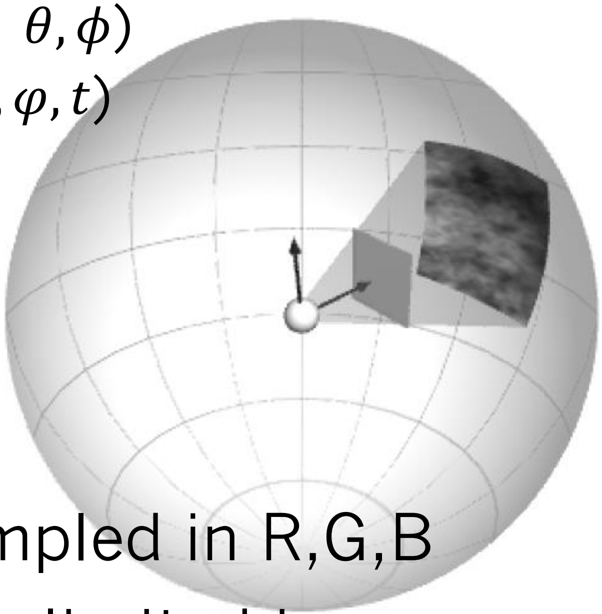
- Intensity of light $P(\theta, \phi, \lambda, t, V_x, V_y, V_z)$
  - Seen from ANY viewpoint
  - Over time
  - As a function of wavelength

Plenoptic Function

- Describes everything that can possibly be seen (and much more)
  - For example, wavelength includes all electromagnetic radiation (not necessarily visible by human observer)
  - Non-physical effects are covered
  - Describes but doesn't explain (for instance, illumination dependency; time variation, wavelength shifting)
- Plenoptic function is unknown, what use does it have?
  - Conceptual tool to group imaging systems according to greater flexibility in view manipulation

Plenoptic Function

- Imaging concepts using sub-sets of the plenoptic function
  - Conventional photograph (2D sub-set of θ, ϕ)
  - Panorama [Chen95] (2D – full range of θ, ϕ)
  - Video sequence (3D sub-set of $x, y, z, \theta, \varphi, t$)
  - Light field [Levoy96, Gortler96] (4D sub-set of x, y, z, θ, φ)
  - dynamic light fields [Wilburn05] (5D sub-set of $x, y, z, \theta, \varphi, t$)



- Wavelength is usually discretely sampled in R,G,B
- In real imaging systems, radiance is limited in range
  - LDR for conventional cameras
  - HDR

Plenoptic Function

- Drawback: Many scene parameters molded into time parameter, e.g.
  - dynamic scenes
  - illumination changes
  - light material interaction
- Therefore: difficult to edit

- Alternatives (next lecture):
  - Plenoptic illumination function [Wong02]
  - Reflectance fields [Debevec00]

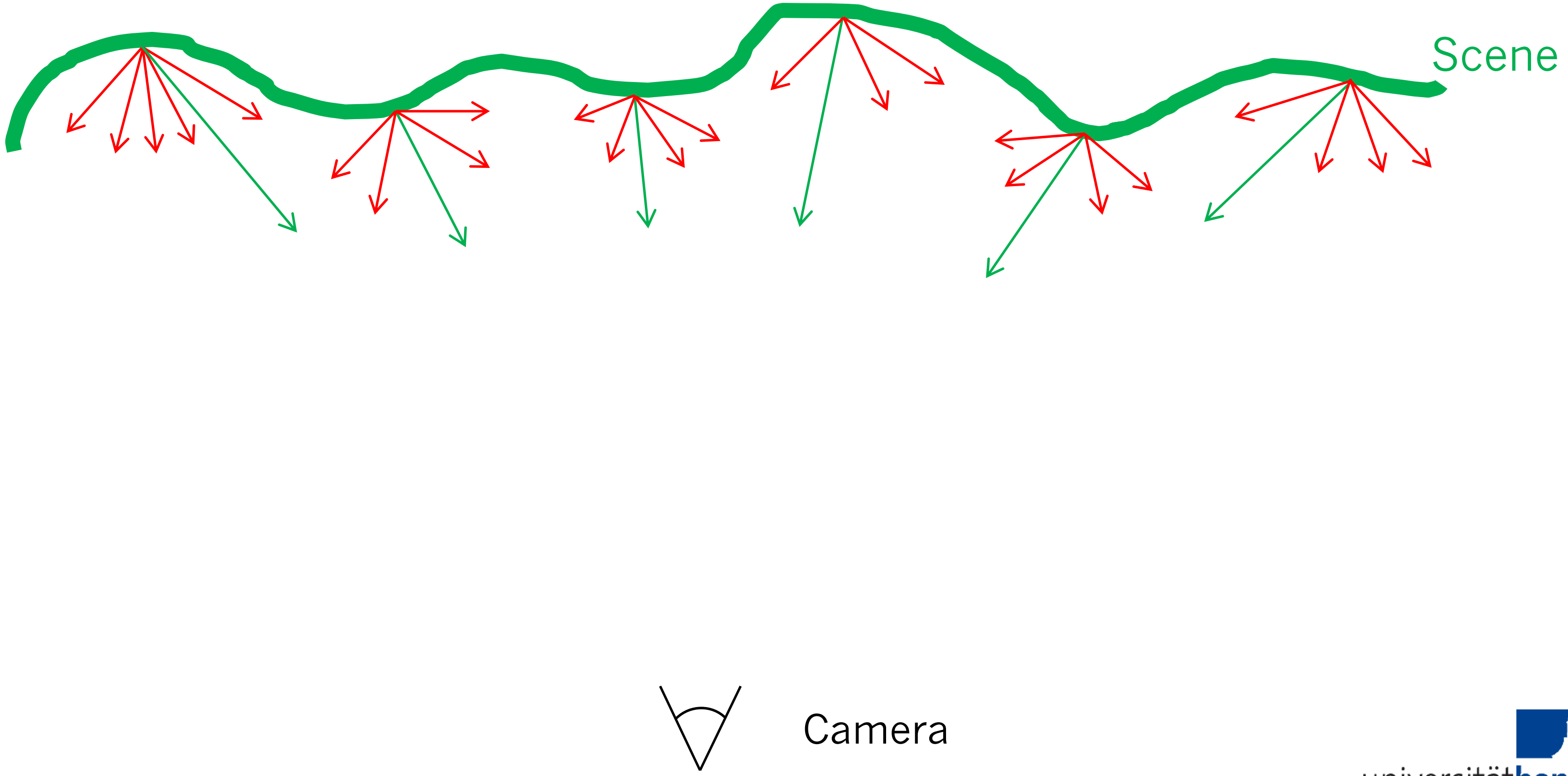
Light Fields

- [McMillan95] use sampled 5D function $(x, y, z, \theta, \varphi)$ on a regular grid
- Interpolate to generate new views

- Light fields are only 4D
  - **Free space assumption**: radiance is constant along a ray

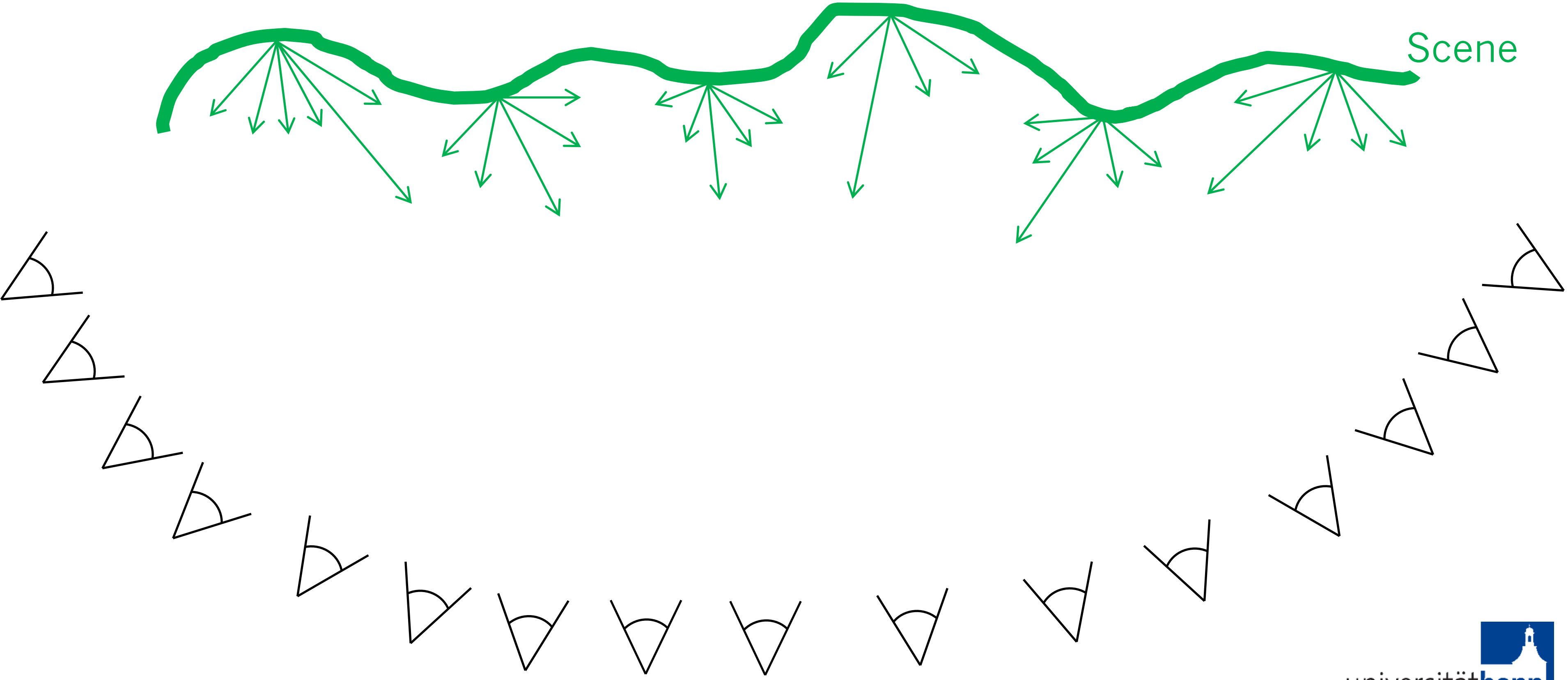
Light Fields

- Normal (2D) photograph



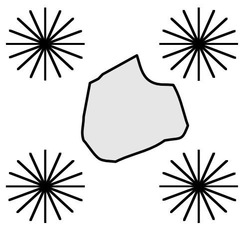
Light Fields

- Light Field (4D)

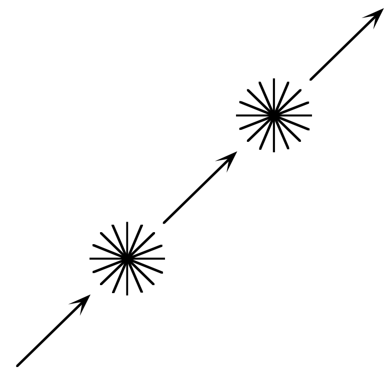


Light Fields

Space with occluders – 5D

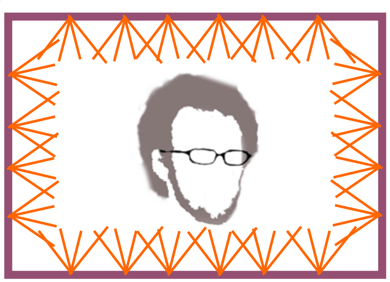


Free space, radiance stays constant along the ray – 4D



Outside – in viewing

Free space



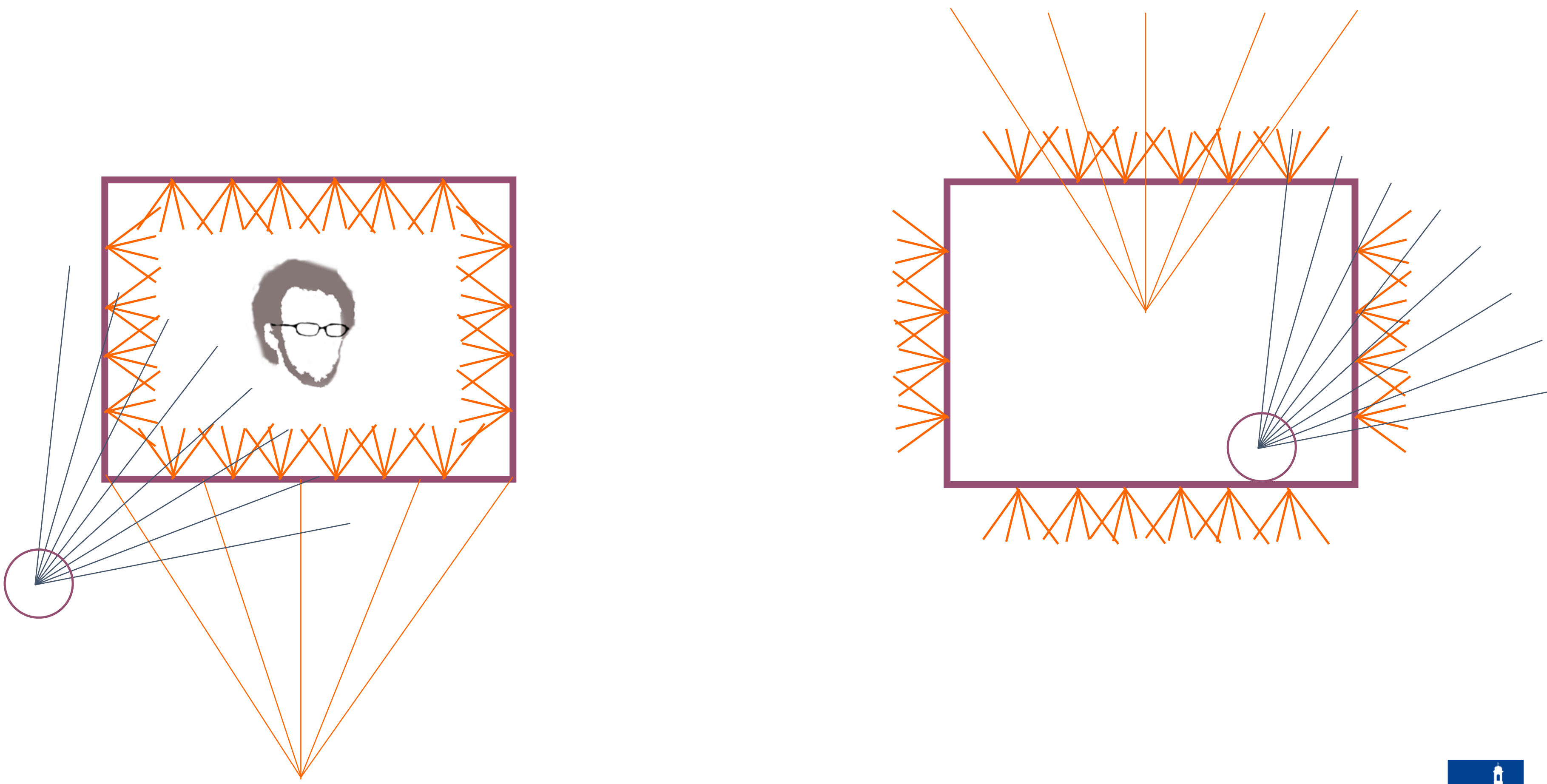
Free space

Free space

Inside – out viewing

Light Fields – Principle of View Synthesis

- Re-arrange ray samples to generate new views



Light Fields – Properties

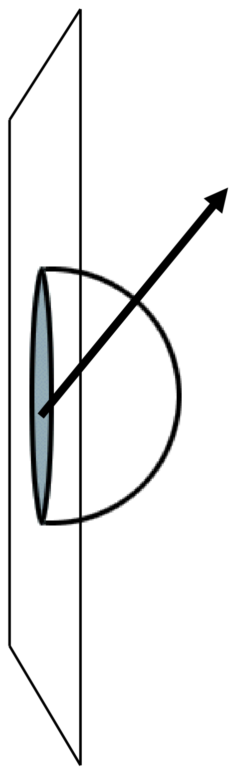
- Advantages
    - Rendering complexity is independent of scene complexity
    - Display algorithms are fast
    - Complex view-dependent effects are simple (no mathematical model required)
- Disadvantages
    - High storage requirements
      (although high correlation between images yields high compression ratios ~120:1 [Levoy96])
    - Difficult to edit (no model)

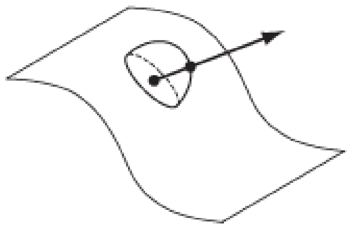
Light Fields – Parameterizations

- Need a way to parameterize rays in space for simple sampling and retrieval
- Should be adapted to sensor geometry
- New view synthesis should be fast
- Let's consider some candidate parametrizations

Light Fields – Parameterizations

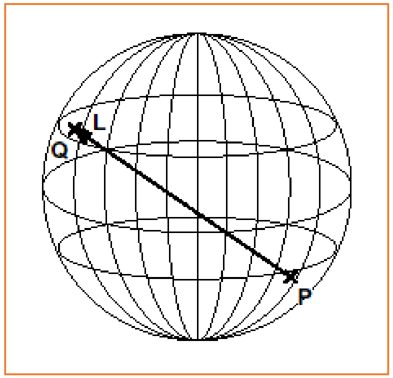
- Point on plane + direction $L(u, v, \theta, \varphi)$
  - Mixture between Cartesian and trigonometric parameters
  - Inefficient to evaluate
  - Non-uniform sampling
  - Directional interpolation difficult
- Alternatively arbitrary surface + direction,
  - Should be convex to avoid duplicates





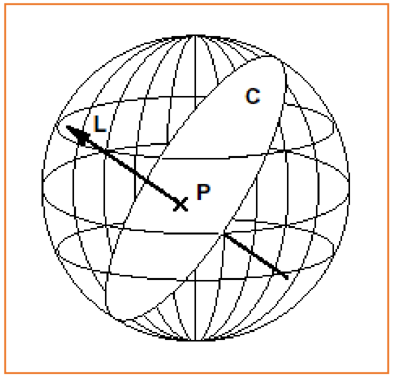
Light Fields – Parameterizations

- Two points on sphere [Camahort98]
  - Uniform sampling
  - Needs a uniform subdivision of sphere into patches
  - Needs a way to sample single rays
    - Difficult for real scenes



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

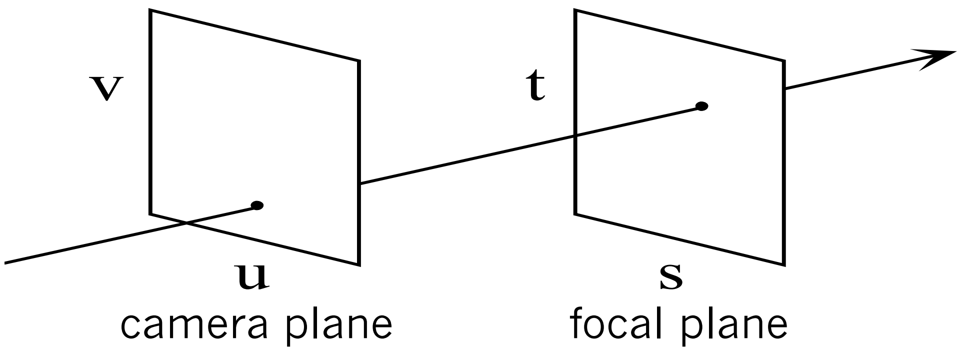
- Great circle + point on disk [Camahort98]
  - Uniform sampling
  - Needs orthographic projections to disk
    - less difficult than 2PS parametrization



$L(u, v, \theta_2, \phi_2)$

Light Fields - Parametrizations

- Two-plane parametrization (**light slab**) [Levoy96]

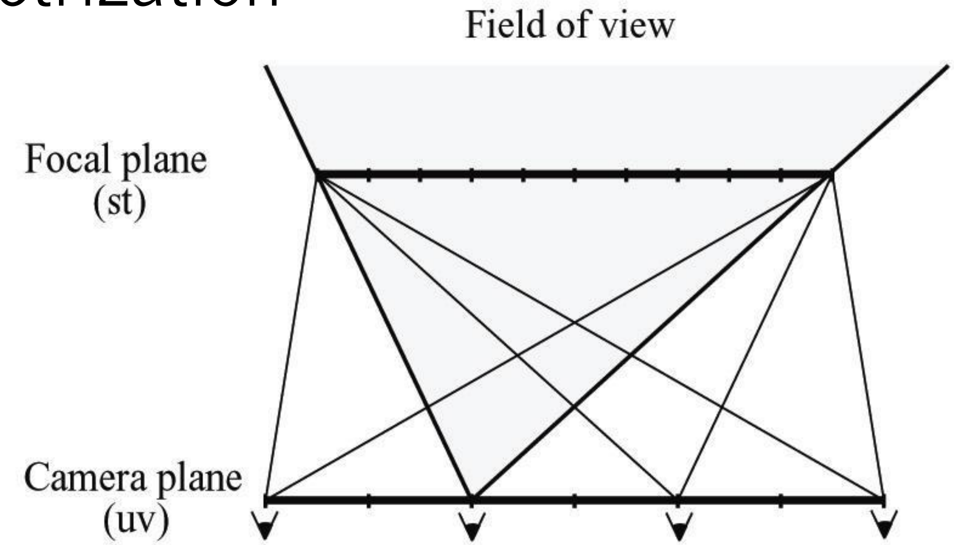


$L(u, v, s, t)$

- Fast display algorithms (projective geometry)
- Simple interpretation (array of images)
- Most commonly used parametrization
- Drawback: only in one major direction
  - Covering 360° requires at least 6 light slabs [Gortler96]
  - Switching from one slab to the next introduces artifacts (disparity problem)

Light Fields – Parametrizations

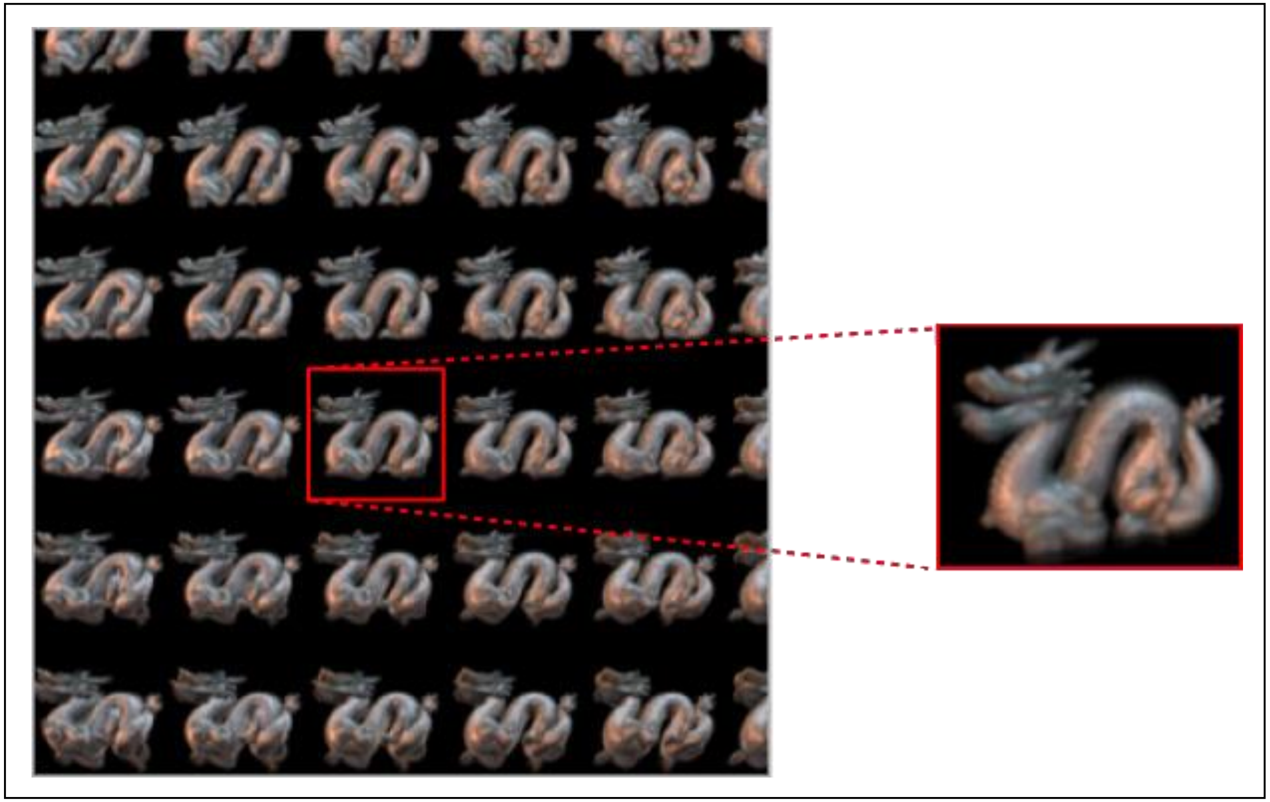
- Light field generation with two-plane parametrization



- Off-axis perspective projections
- Normal camera images need (simple) re-sampling

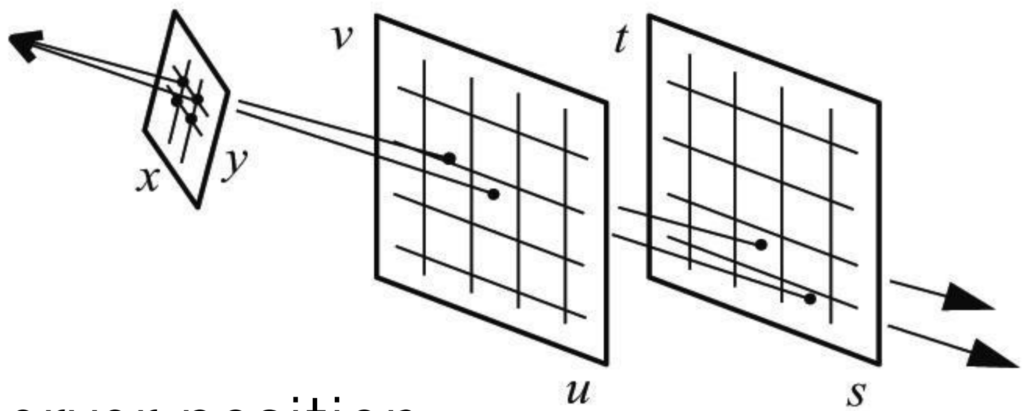
Light Fields – Parametrizations

- A two-plane parametrized light field is basically a collection of images



Light Fields – Parametrizations

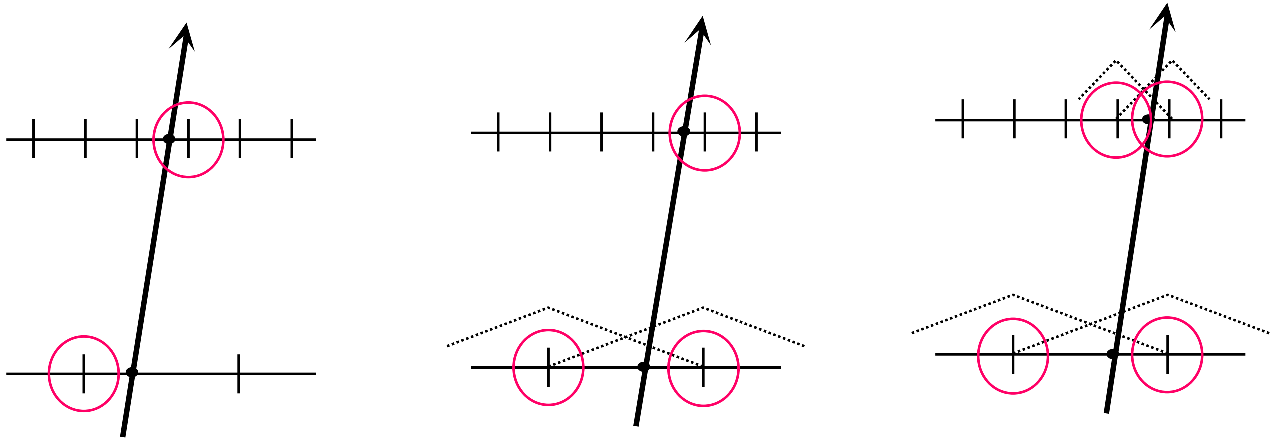
- View generation from two-plane parametrization



- At an observer position
  - Project (u, v) and (s, t) parameter planes into virtual view (x, y)
  - For each pixel in virtual view use projected (u, v, s, t) to look up radiance $L(u, v, s, t)$
  - Two perspective projections and one look-up determine virtual view → efficient rendering

Light Fields – Rendering 2D

involved samples



nearest neighbor uv bilerp uv and st bilerp

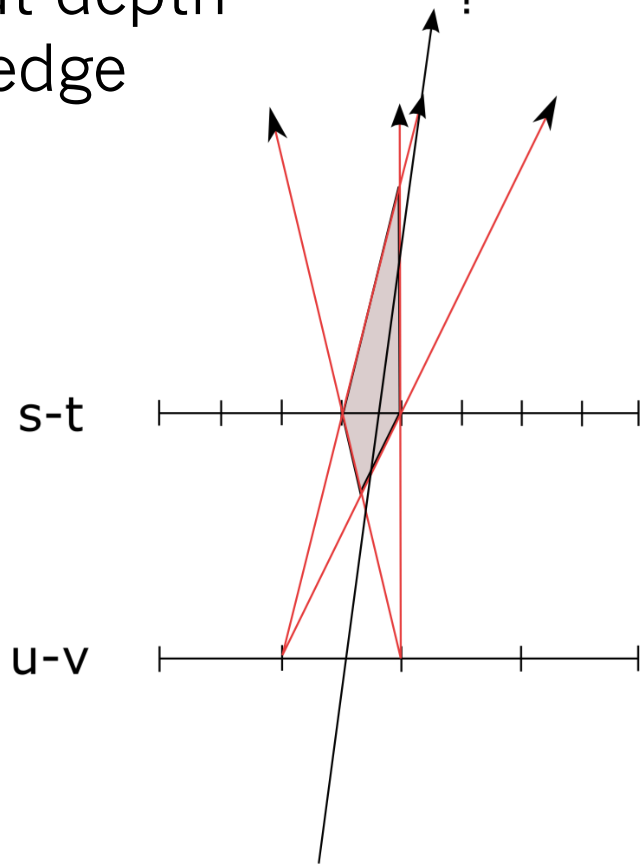
Light Field Rendering – Examples [Levoy1996]

16x16 images
1 slab

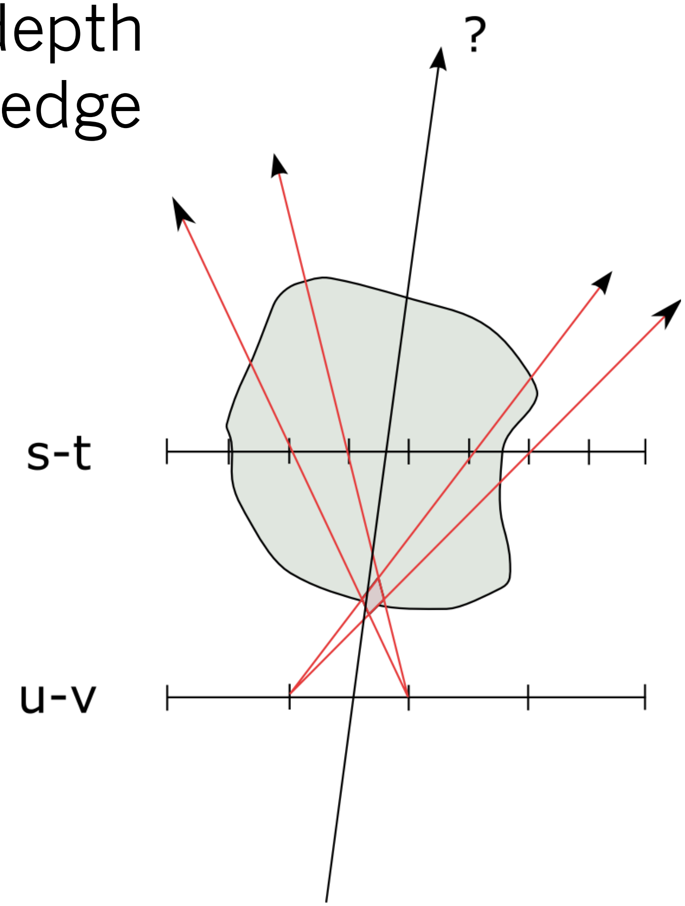
32 x 16 images
4 slabs

Depth Assisted Light Fields [Gortler96]

without depth knowledge



with depth knowledge



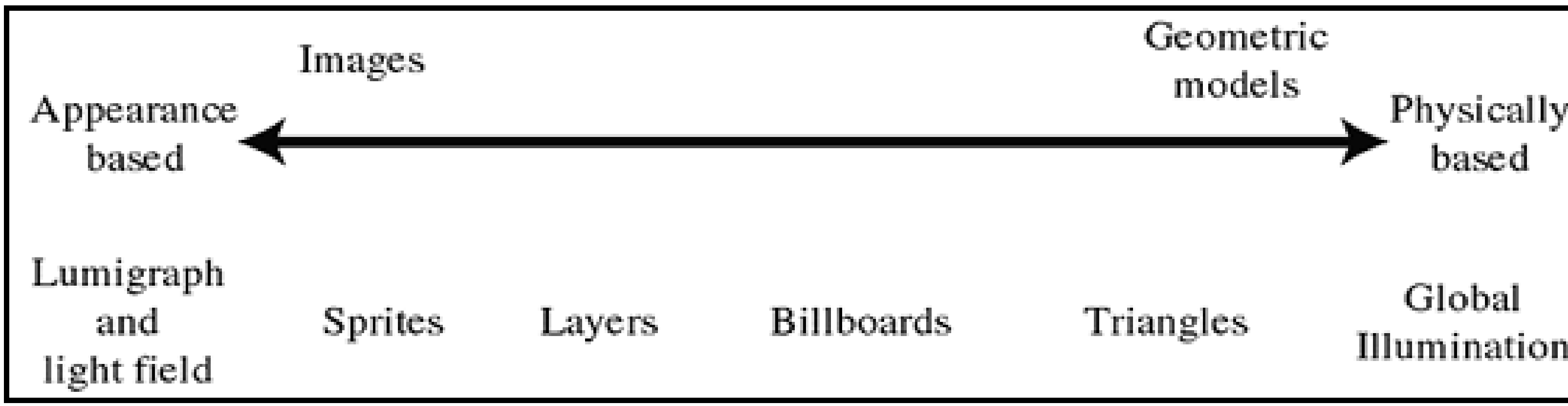
different pixels have to be interpolated !

Image-based vs. Model-based Rendering

- trade-off between image-based and model-based rendering approaches

Images Only

Mathematical
Descriptions



more data
less computation

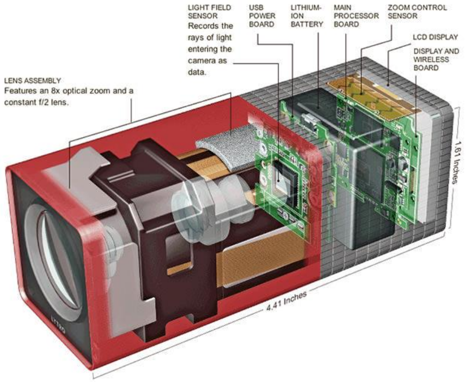
less data
more computation

- Is there a way to find a good trade-off ?
- need some signal processing for analysis

Capturing light fields

- Using calibrated gantries [Levoy1996]

- Using camera arrays [Wilburn2005]



- Using lenslet arrays [Ng2005]

- Using hand-held devices [Gortler1996, Davis2012] (requires camera tracking)

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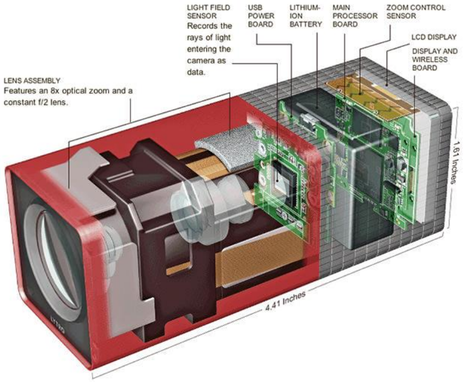
Capturing light fields

- Using calibrated gantries [Levoy1996]

- Using camera arrays [Wilburn2005]

- Using lenslet arrays [Ng2005]



- Using hand-held devices [Gortler1996, Davis2012] (requires camera tracking)

“Plenoptic camera”

- Integral photography [Lippmann 1908]

donc un large faisceau qui converge vers A (voir *fig.* 1) : c’est un faisceau large, puisqu’il a pour base toute la plaque sensible, ou du moins toute la partie de cette plaque d’où le point A était visible (1).

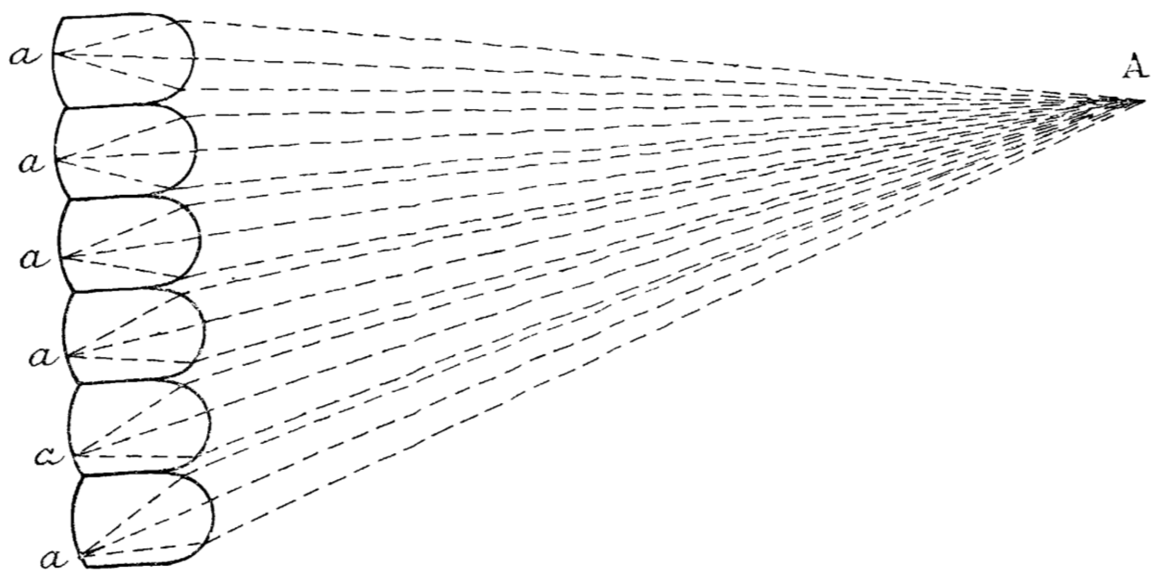
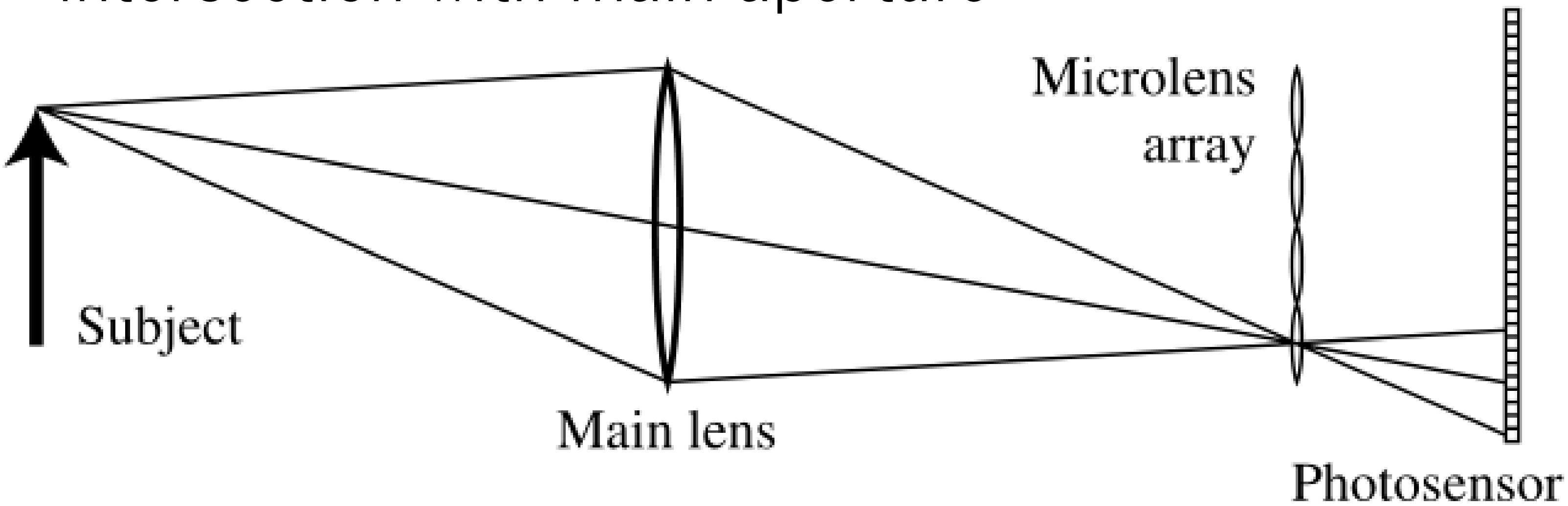


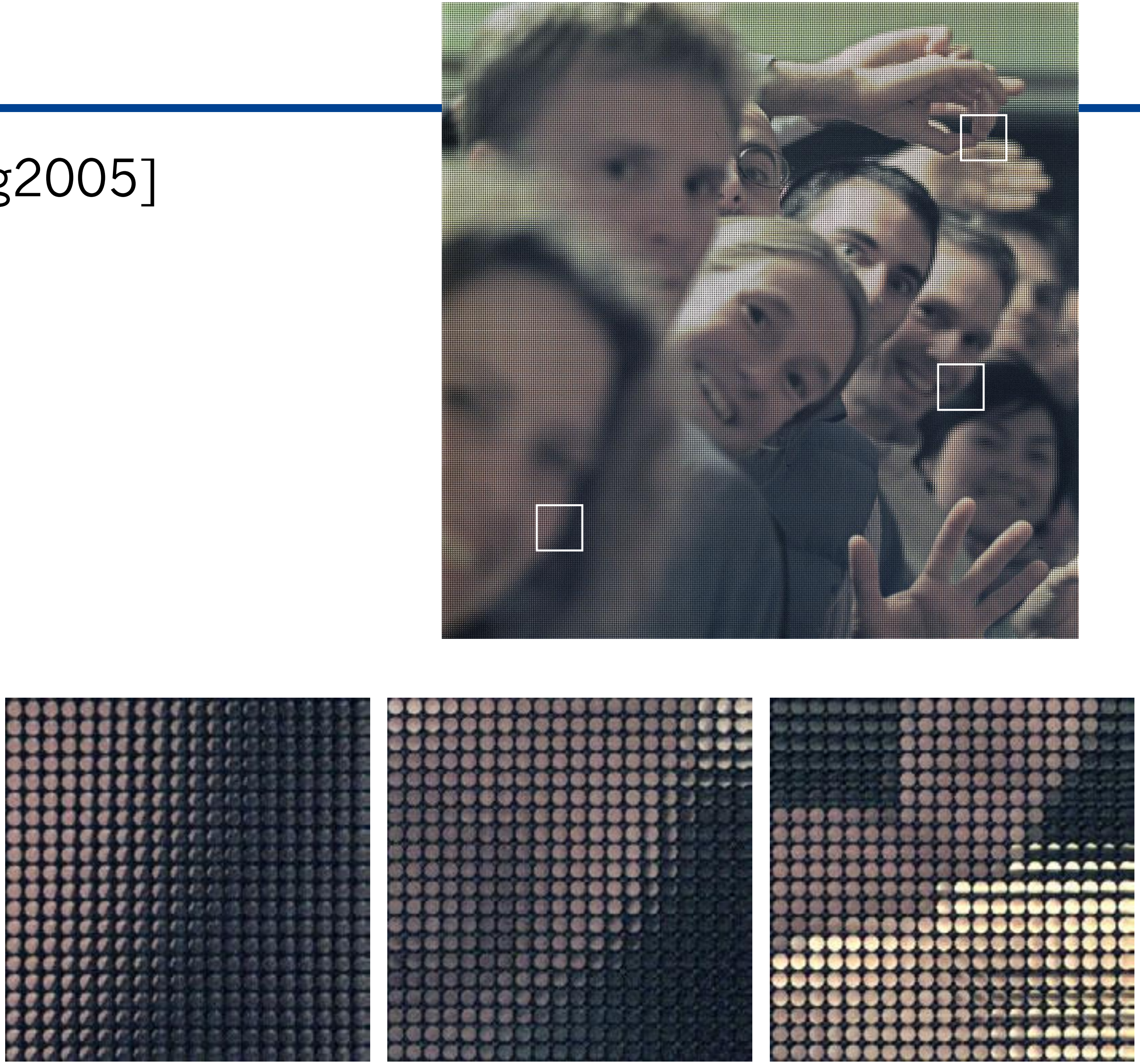
Fig. 1.

“Plenoptic camera” [Ng2005]

- Lenslet array resolves pixels by direction, or intersection with main aperture



[Ng2005]



How to make the best use of sensor pixels

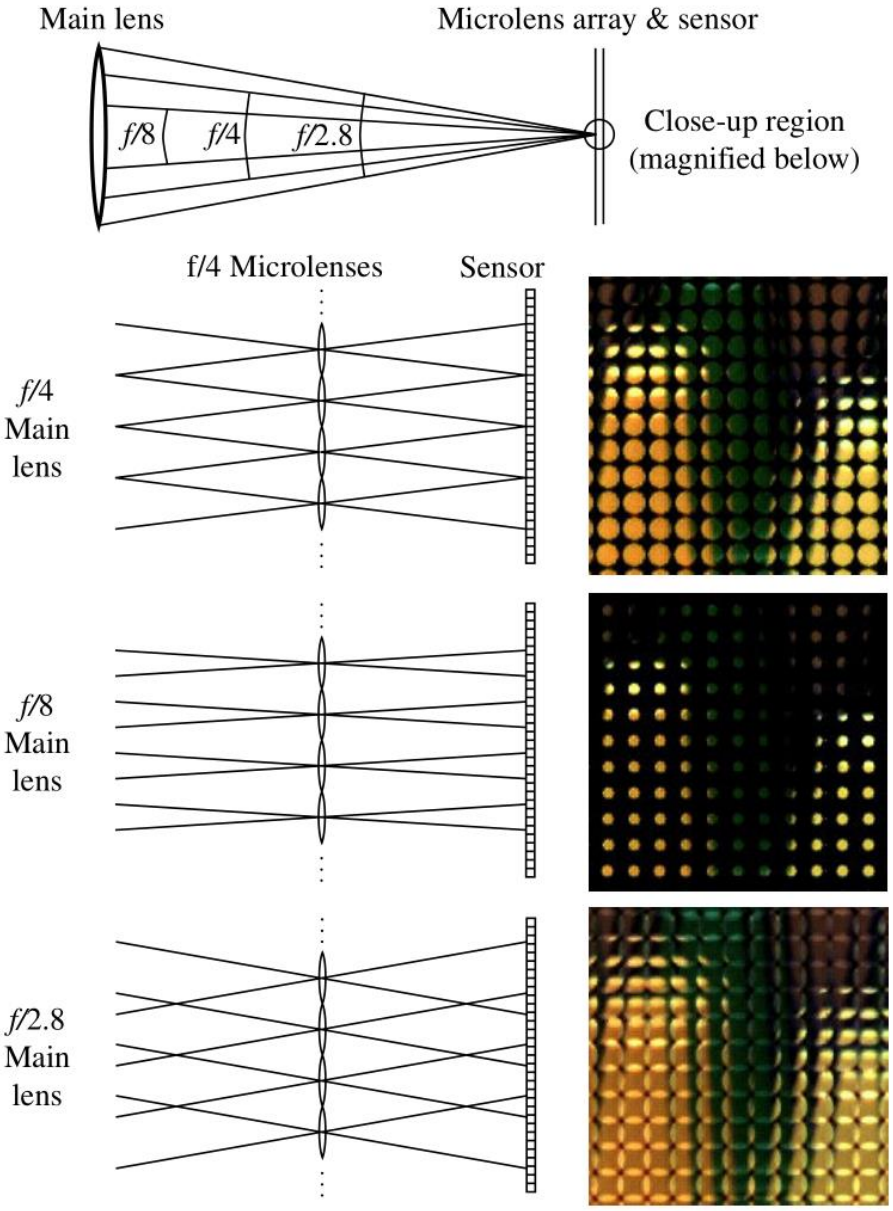


Figure 2: Illustration of matching main lens and microlens f-numbers. *Top*: Extreme convergence rays for a main lens stopped down to $f/2.8$, $f/4$ and $f/8$. The circled region is shown magnified for each of these f-stops, with the extreme convergence rays arriving at microlenses in the manigifed region. The images show close-ups of raw light field data collected under conditions shown in the ray diagrams. When the main lens and microlens f-numbers are matched at $f/4$, the images under the microlenses are maximal in size without overlapping. When the main lens is stopped down to $f/8$, the images are too small, and resolution is wasted. When the main lens is opened up to $f/2.8$, the images are too large and overlap.

- [Ng2005]

Mathematical analysis of light fields

- Epipolar-plane images (EPI)
- Frequency-domain analysis
- Fourier slice theorem

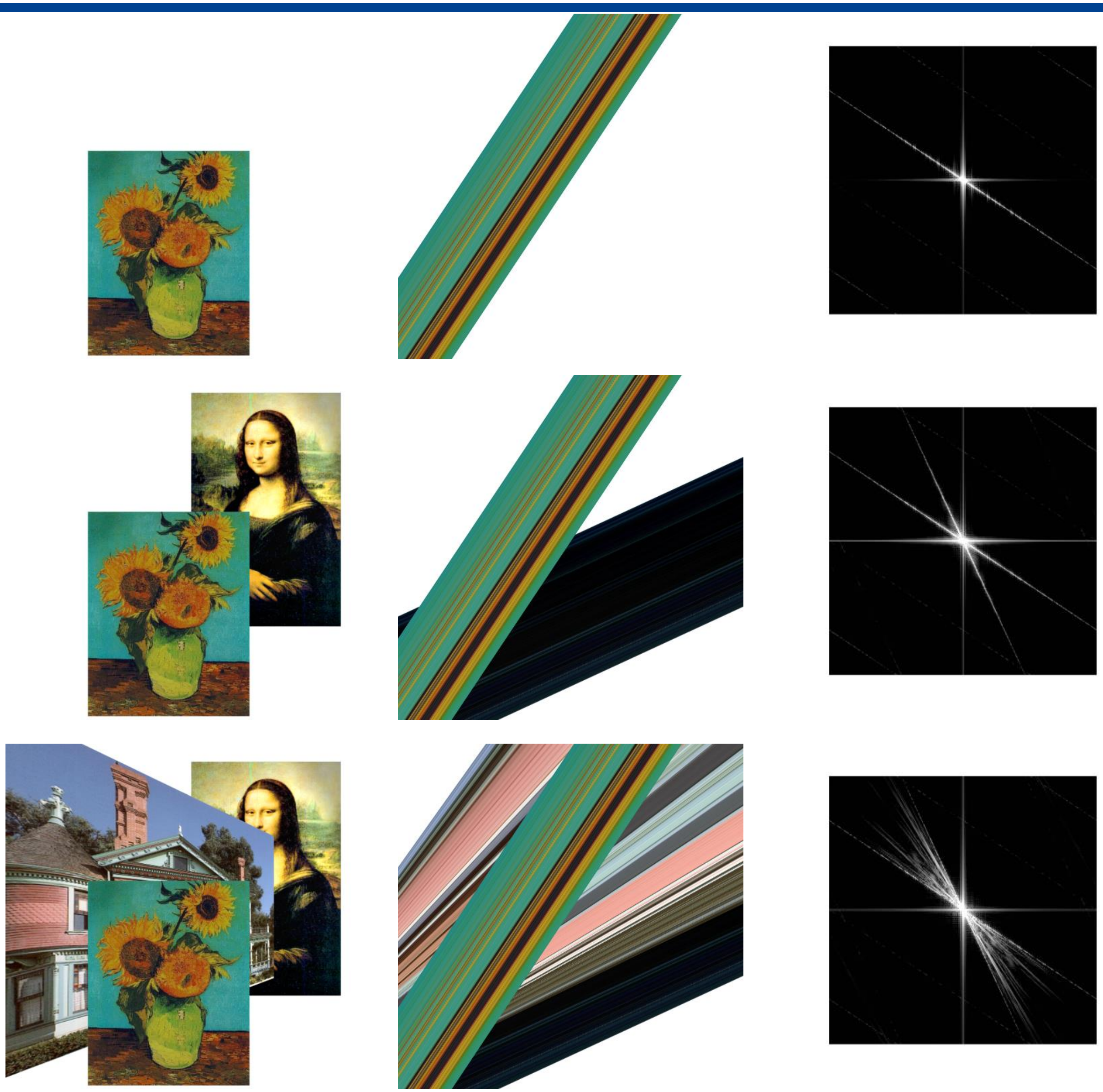
Epipolar plane images (EPI) [Bolles1987]

- 2D Light field mapped out over two-plane parameters:

- Slope = depth

Images from [Kim2013]

EPI in Fourier domain [Chai2000]



Scene image | Epipolar-plane img. | Freq. spectrum of EPI

Depth from EPI [Wanner2013]

- Use *structure tensor* J to extract depth from epipolar-plane image:

$$J = \begin{bmatrix} G_\sigma * (S_x S_x) & G_\sigma * (S_x S_y) \\ G_\sigma * (S_x S_y) & G_\sigma * (S_y S_y) \end{bmatrix} = \begin{bmatrix} J_{xx} & J_{xy} \\ J_{xy} & J_{yy} \end{bmatrix}$$

G_σ: Gaussian smoothing kernel

$S_{x,y}$: Gradient components

The direction of the local level lines can then be computed via [5]

$$\boldsymbol{n}_{y^*,t^*} = \begin{bmatrix} \Delta x \\ \Delta s \end{bmatrix} = \begin{bmatrix} \sin(\varphi) \\ \cos(\varphi) \end{bmatrix}$$
$$\text{with } \varphi = \frac{1}{2} \arctan\left(\frac{J_{yy} - J_{xx}}{2J_{xy}} \right), \tag{5}$$

from which we derive the local depth estimate via equation (3) as

$$Z = -f \frac{\Delta s}{\Delta x}. \tag{6}$$

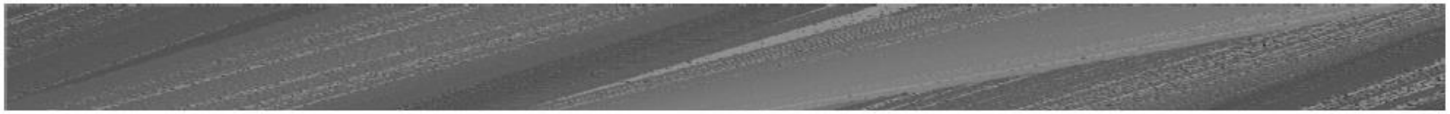
f = distance between planes

Disparity: $d_{y^*,t^*} = \frac{f}{Z} = \frac{\Delta x}{\Delta s} = \tan\phi$: pixel shift of a scene point when moving between the views

Denoising [Wanner2013]

- Filter local disparity estimate to obtain global depth estimate u for each view (s,t):

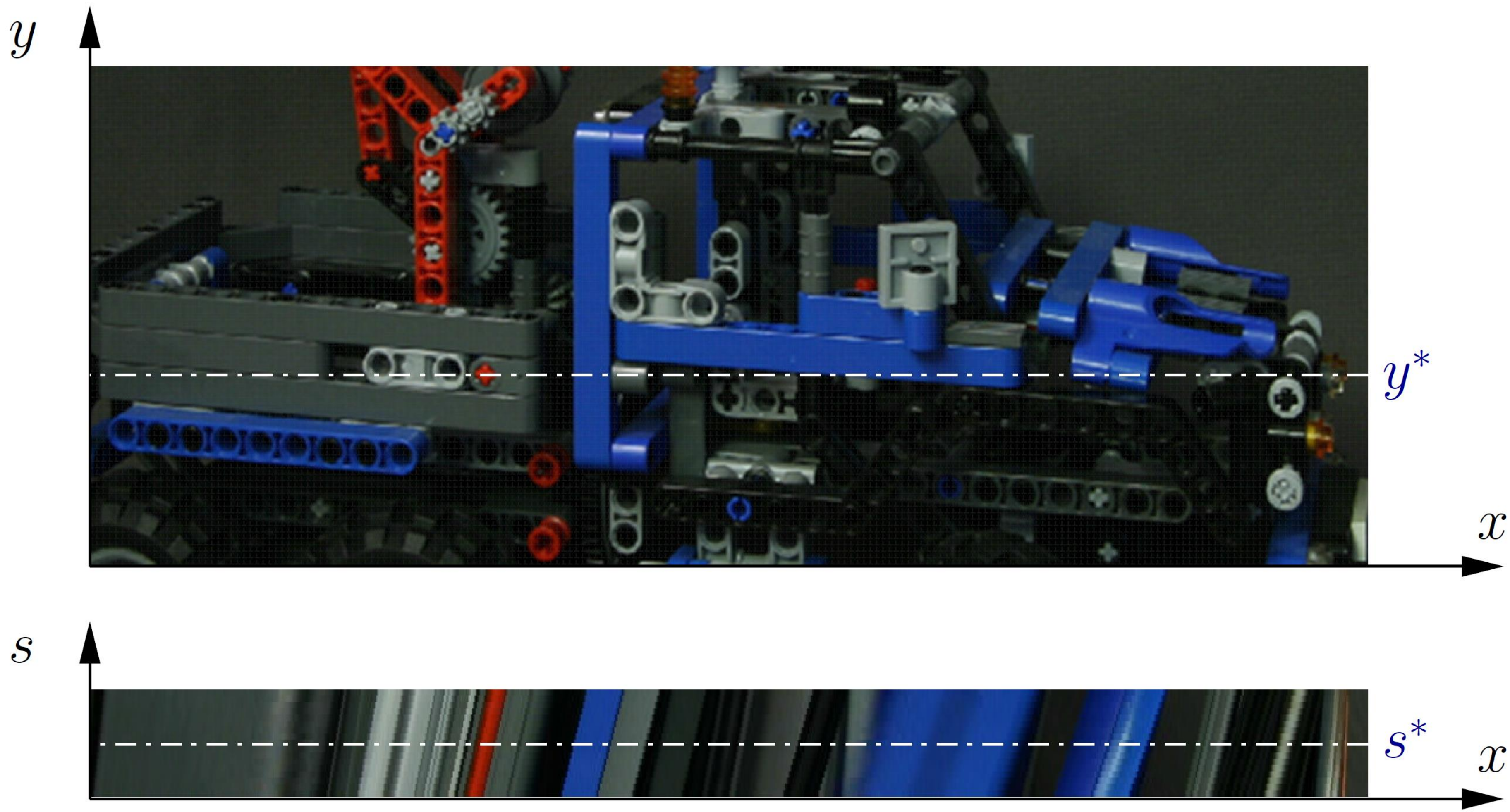
(a) Typical epipolar plane image S_{y^*,t^*}



(b) Noisy local depth estimate

(c) Consistent depth estimate after optimization

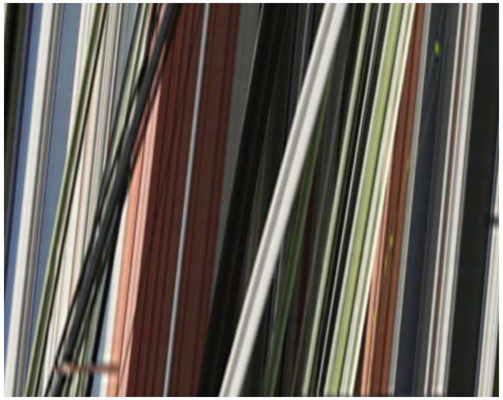
Non-Lambertian (non-diffuse) scenes



Light field manipulation

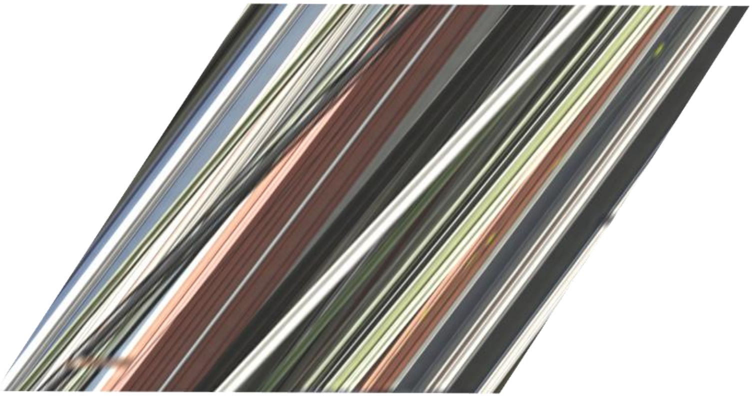
- **Propagation** shears EPI (direction stay the same; positions change proportionally to direction)

Angle



Position

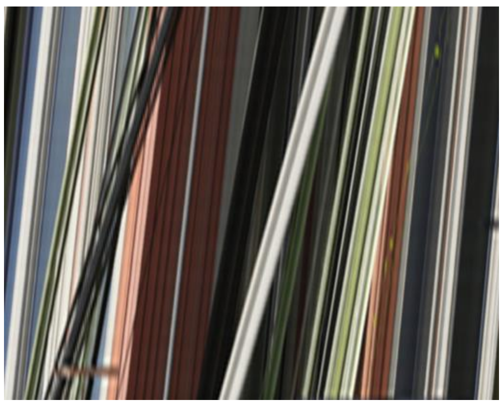
Angle

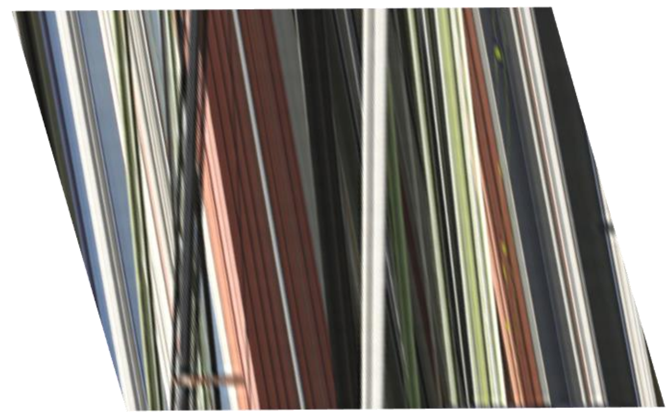


Position

Light field manipulation

- **Taking an in-focus image**: Propagate (shear) EPI until features become vertical! Then project down

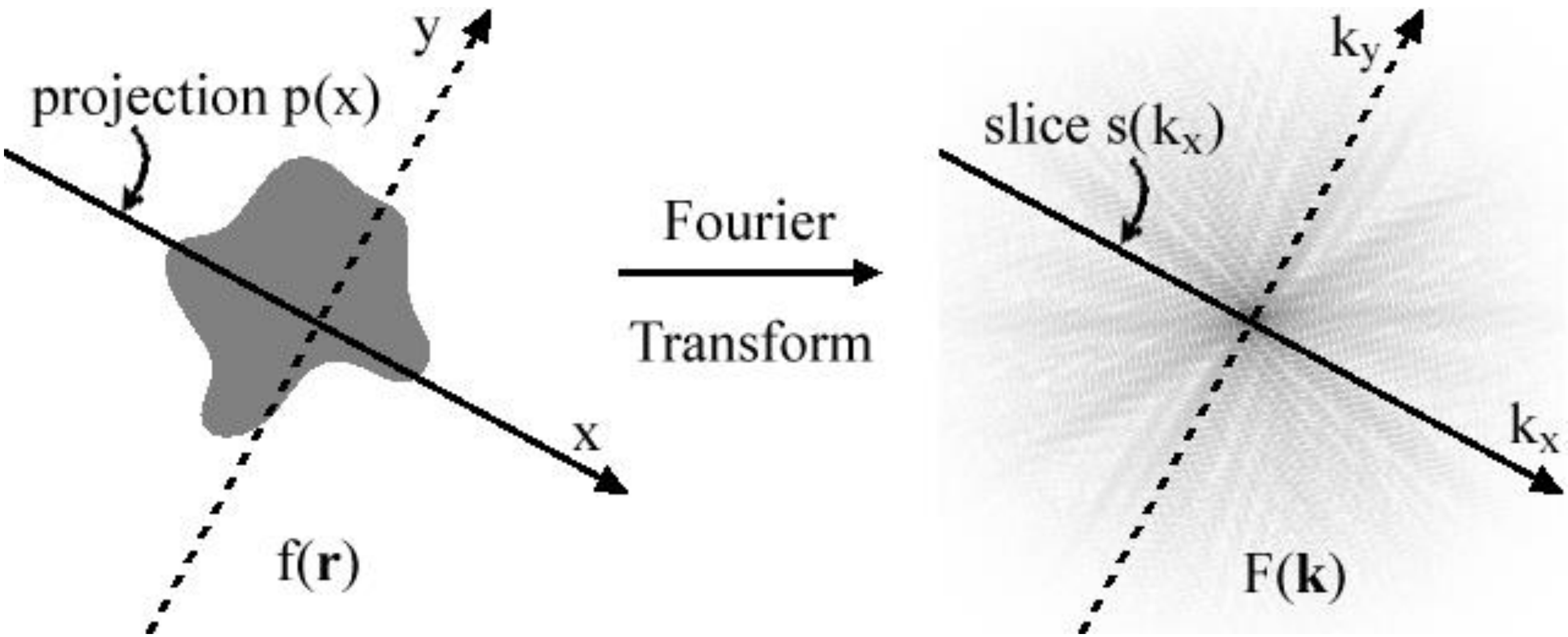




- Alternatively, project along slanted direction

Fourier slice theorem (projection-slice theorem)

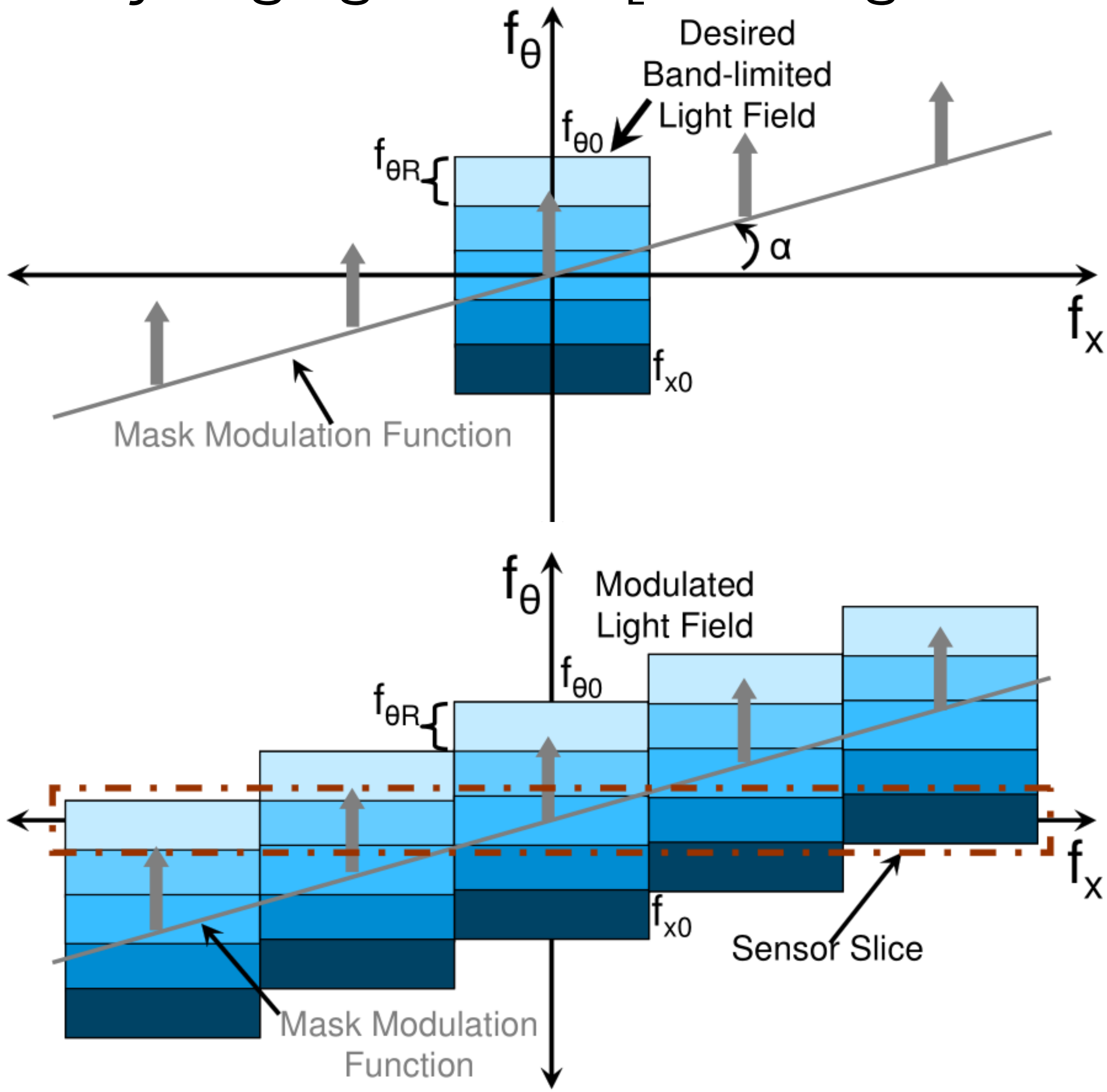
- Remember the convolution theorem?
- Focus (projection) can be expressed the same way



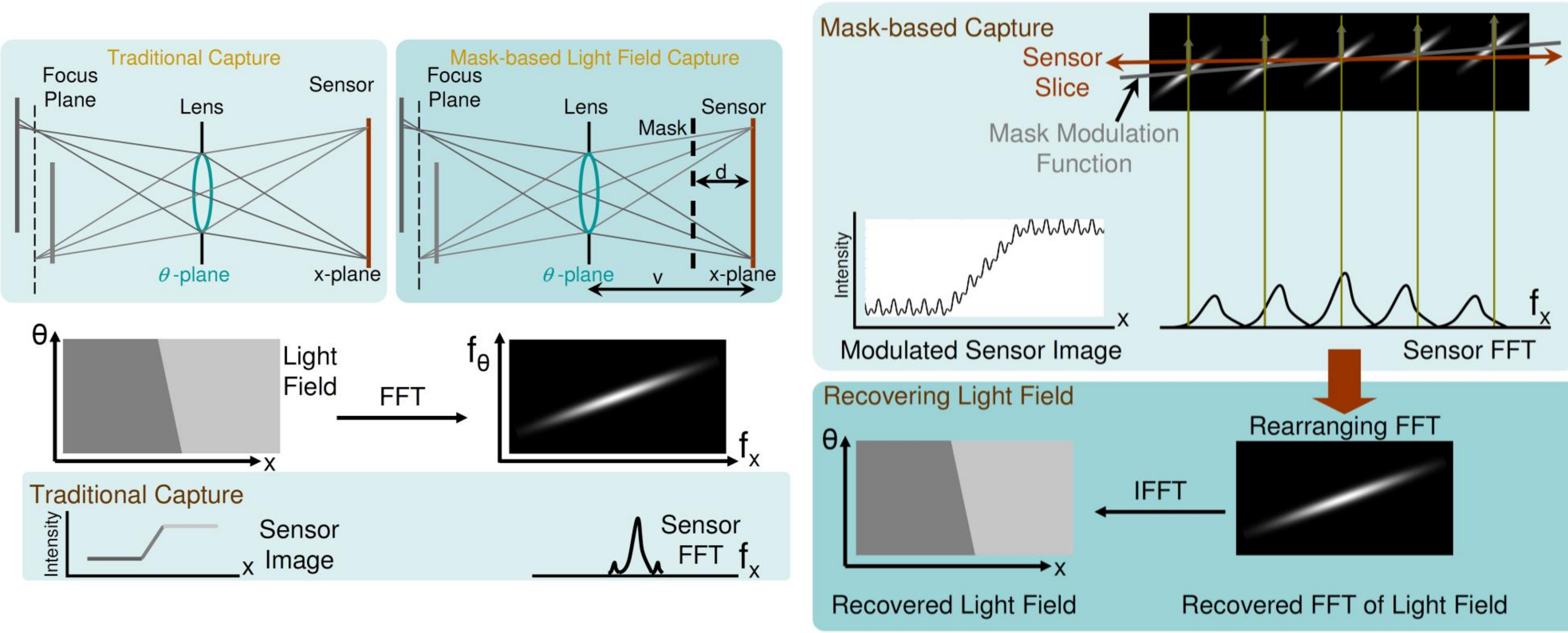
- **Projection** in one domain maps to **slicing** in other domain [Ng2005]

Example of Fourier-space manipulation

- Heterodyning light fields [Veeraraghavan2007]

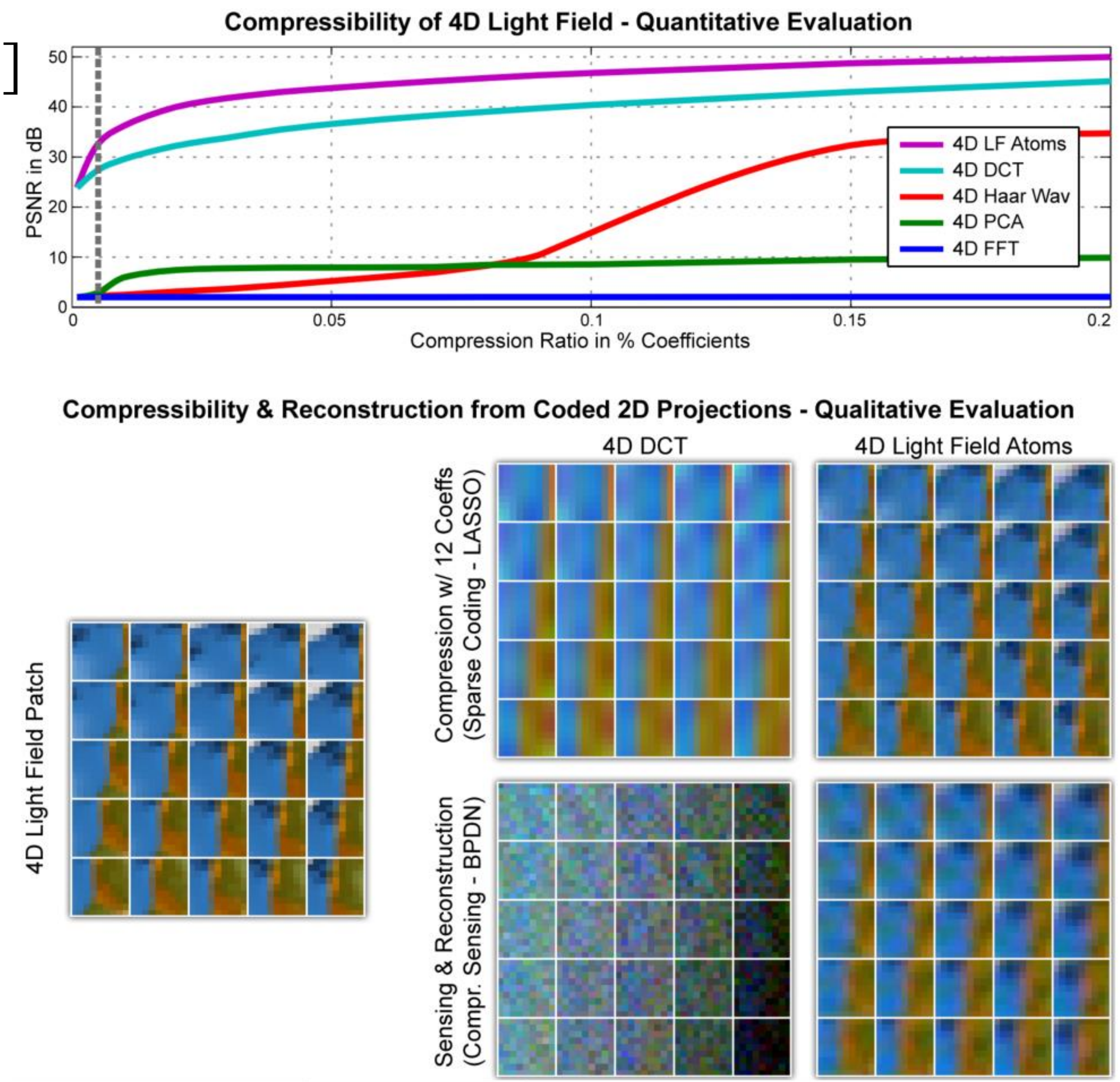


Heterodyning by multiplicative mask



Compressive acquisition of light fields

- [Marwah2013]



Compressive LF photography [Marwah2013]

- Setup very similar to mask-based LF camera – but operated differently:

  use multiple random mask patterns, solve linear system

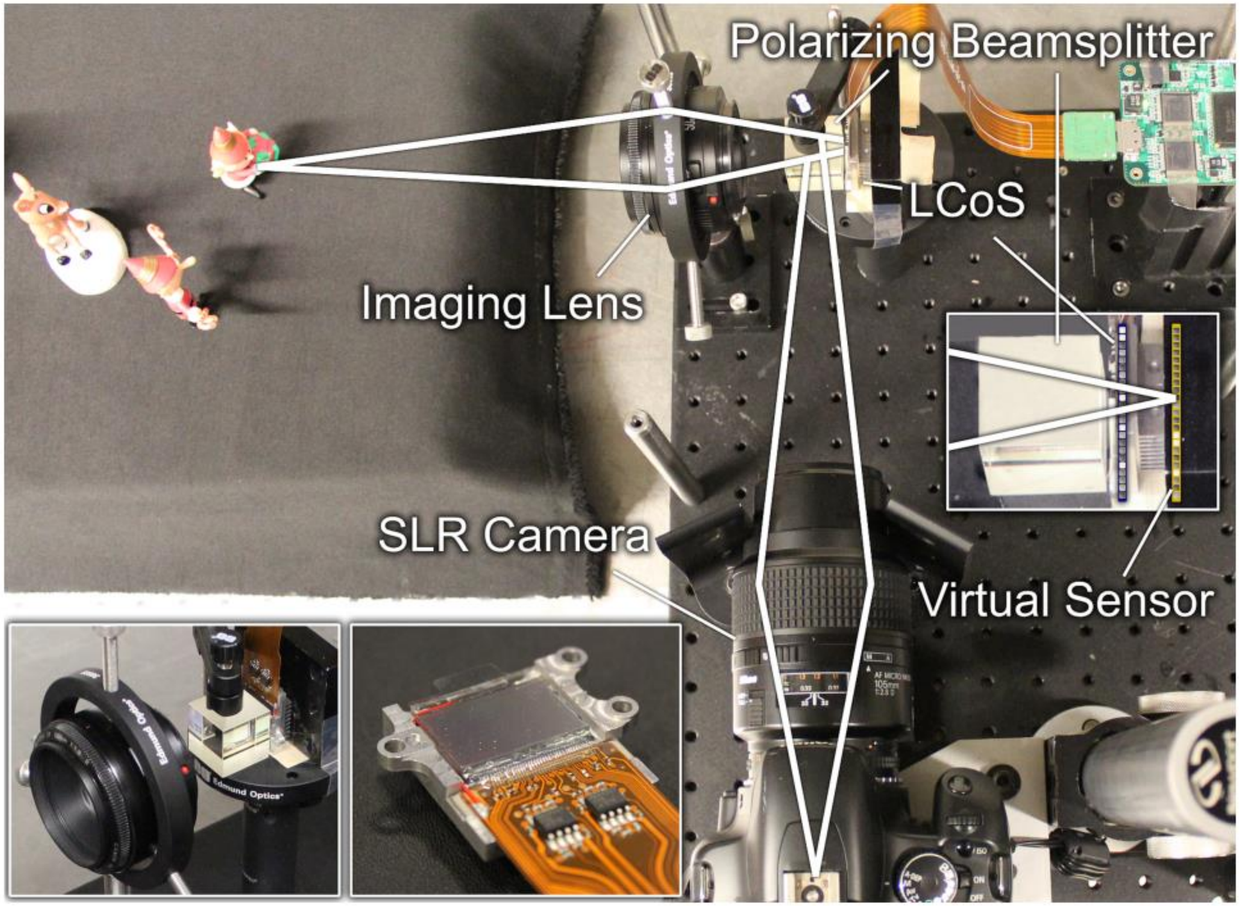


Figure 9: *Prototype light field camera. We implement an optical relay system that emulates a spatial light modulator (SLM) being mounted at a slight offset in front of the sensor (right inset). We employ a reflective LCoS as the SLM (lower left insets).*

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