CS6640 Computational Photography

9. Practical photographic optics

Practical considerations!

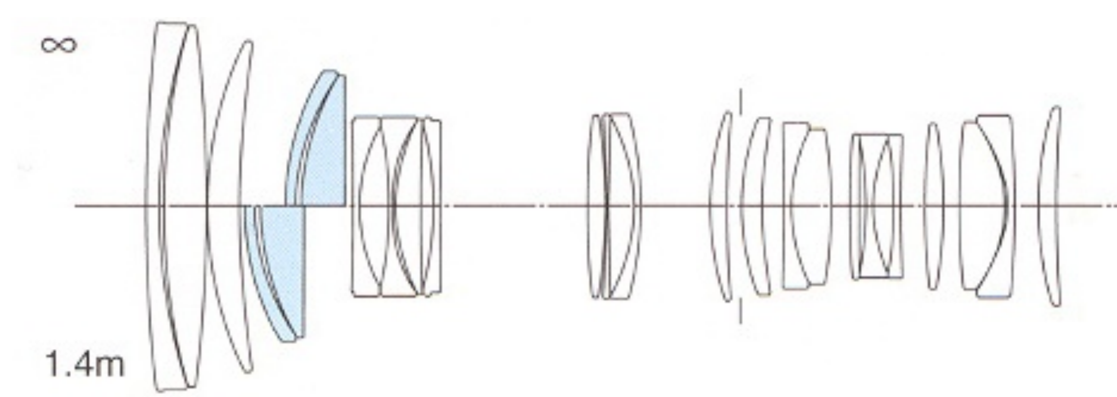
- **First-order optics: what lenses are *supposed* to do**
- **In practice lenses vary substantially in quality**

  where “quality” ≈ “behaves like the first order approximation”

Important question

- **Why is this toy so expensive**
  - EF 70-200mm f/2.8L IS USM
  - $1700

- **Why is it better than this toy?**
  - EF 70-300mm f/4-5.6 IS USM
  - $550
- **Why is it so complicated?**



- **What do these buzzwords and acronyms mean?**

slide by Frédo Durand, MIT

Stanford Big Dish

Panasonic GF1

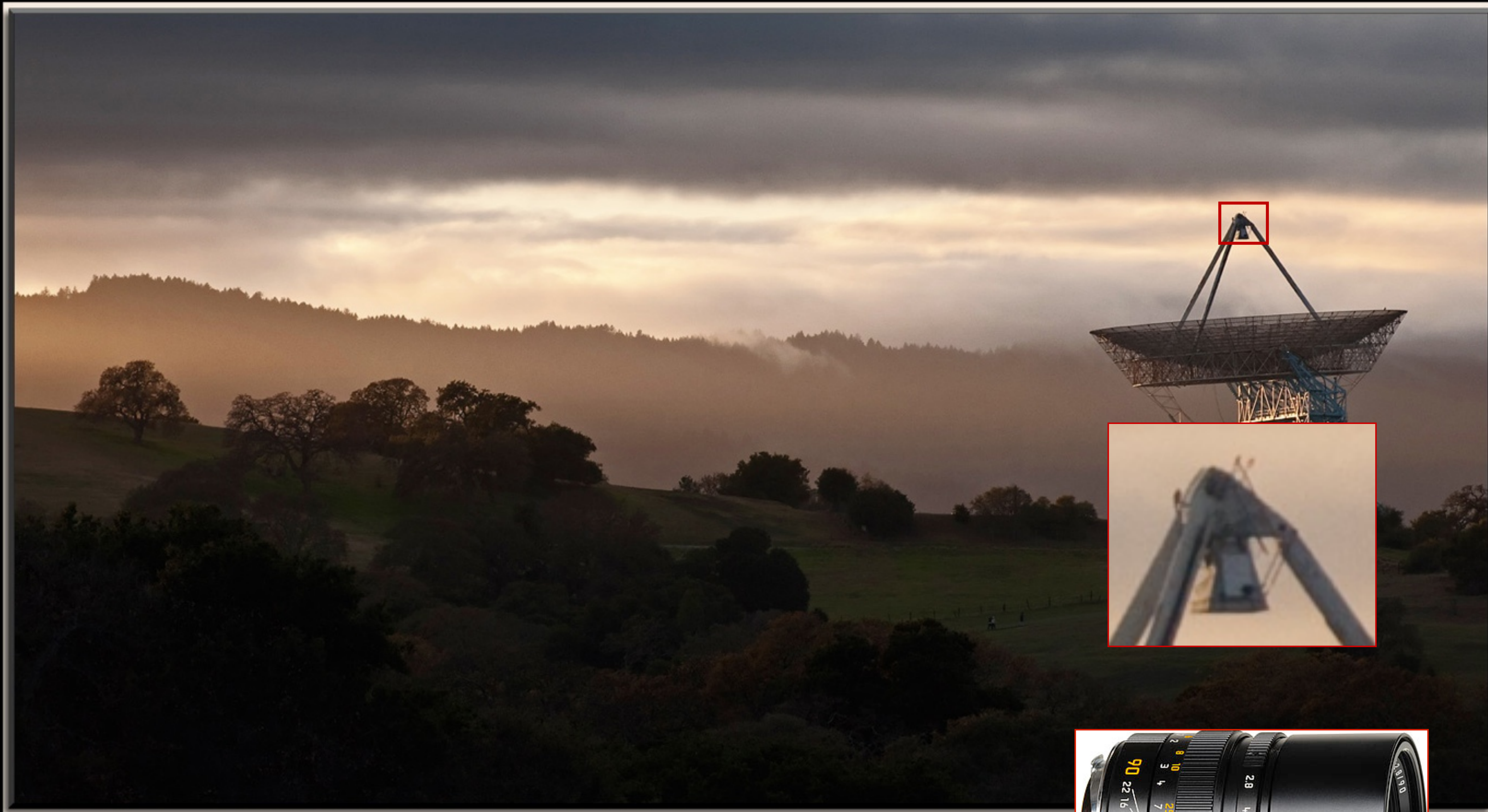
Marc Levoy, Stanford

Stanford Big Dish

Panasonic GF1

Leica 90mm/2.8 Elmarit-M prime, at f/4
$2000

Marc Levoy, Stanford



Leica 90mm/2.8 Elmarit-M
prime, at f/4
$2000

Stanford Big Dish

Panasonic GF1

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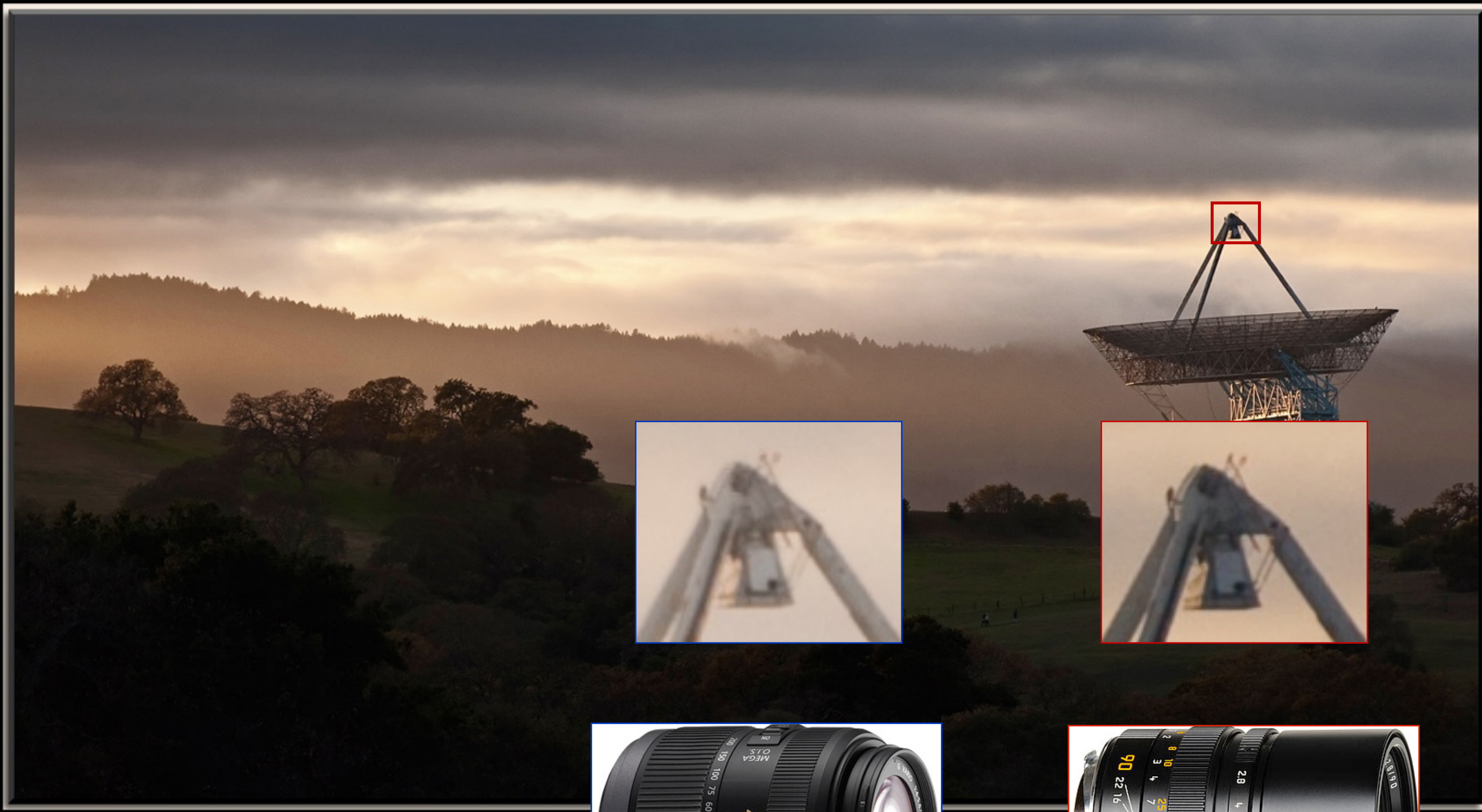

Panasonic 45-200/4-5.6 zoom, at 200mm f/4.6
$300

Leica 90mm/2.8 Elmarit-M prime, at f/4
$2000

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Panasonic GF1

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Zoom vs. prime

for lots more lens evaluation:
www.slrgear.com
www.photozone.de
www.dpreview.com

17 elements / 14 groups | 7 elements / 6 groups

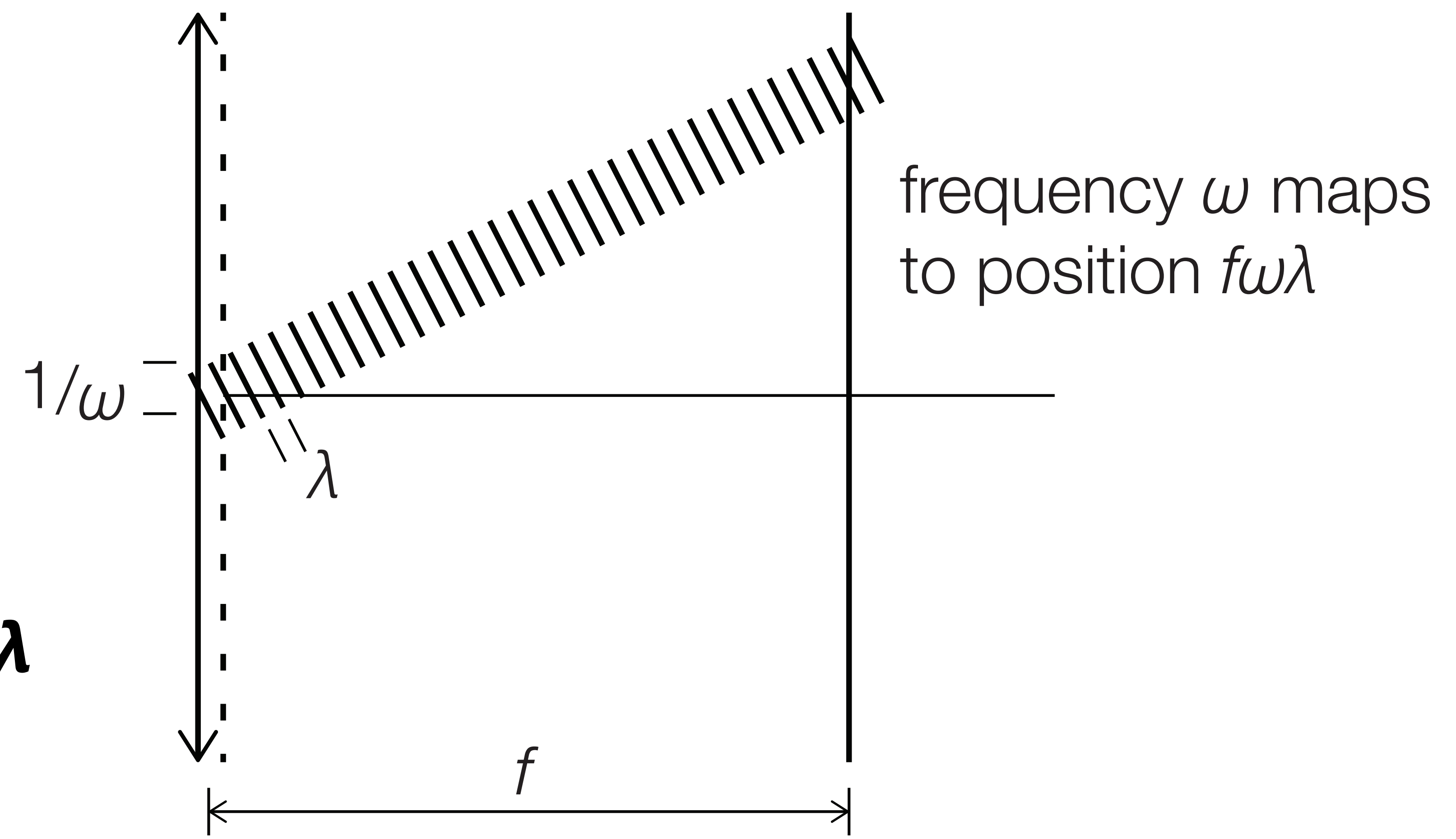
source: the luminous landscape

Sources of blur

- **Diffraction**
  fundamental constraint
- **Aberrations in design**
  deviations in practical glass shape and properties from the ideal
- **Manufacturing tolerances**
  centering and other assembly errors create aberrations

Fourier optics in one slide

- **Thin lens in contact with transparency**
- **In neighborhood of center of lens, sinusoidal grating of frequency ω admits plane wave traveling at angle $\sin \theta = \pm\omega\lambda$**
- **Considering whole lens, focus is at $y \approx f\omega\lambda$**
- **Fourier: represent aperture transparency as sum of sinusoids**
- **Result: intensity at $y = f\omega\lambda$ is proportional to FT of aperture at ω**
- **Focus spot is FT of aperture, scaled up by $f\lambda$**



Diffraction limit

- **Aperture of size *D* produces spot with size about *fλ/D***
- **This is wavelength times *f*-number**

  rule of thumb: f-number in microns, for visible light

  camera with 5-micron pixels limited by diffraction past f/5

  camera with 2-micron pixels limited by diffraction past f/2!

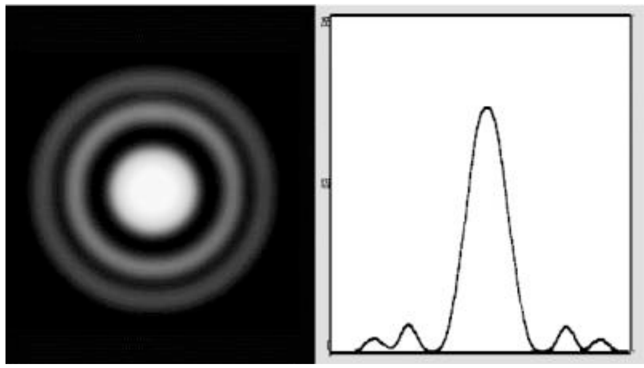
  (not quite this bad, because of color filter array)
- **Practical consequence 1: lenses on smaller cameras don't go to big f-numbers**

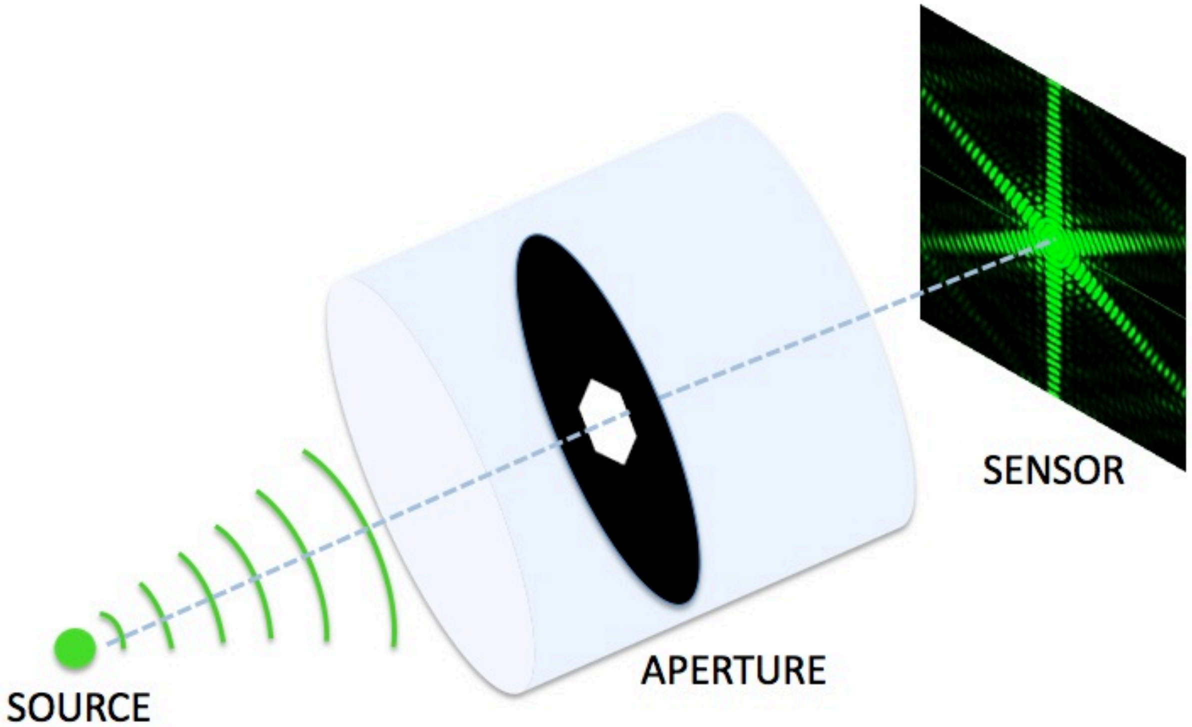
  ≈ 16 for an SLR, 8 for a compact, 4 for a cell phone
- **Practical consequence 2: there's no point reducing aberration-induced blur much past the diffraction spot size**

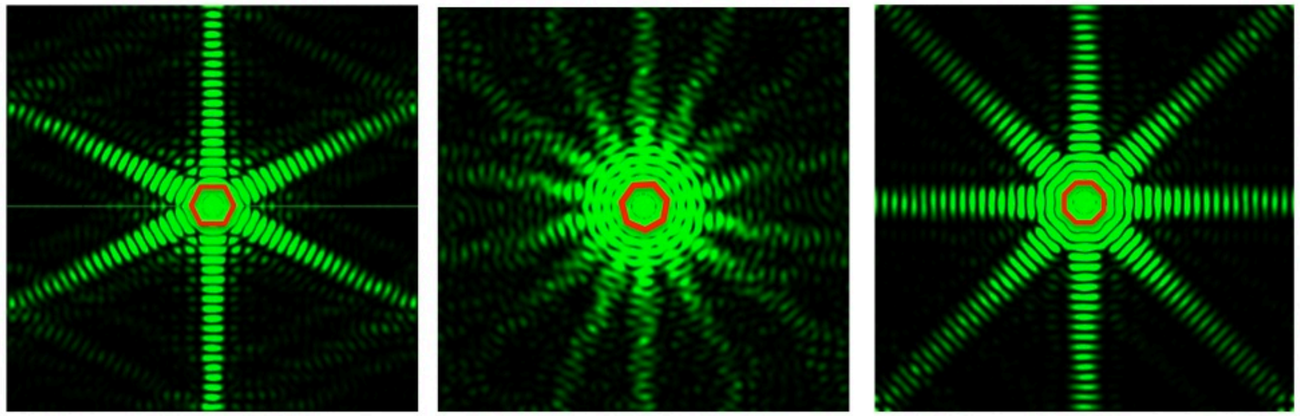
Diffraction spots

- **The blur kernel is the FT of the aperture transparency function**
- **Circular aperture leads to *Airy disk***
  a sinc-like radially symmetric function
- **Apertures with straight edges produce stars**
  every edge orientation produces a linear feature


diglloyd.com






SIX BLADED APERTURE SEVEN BLADED APERTURE EIGHT BLADED APERTURE

cameratechnica.com

Aberrations

- **Chromatic aberration**

  first order effects of dispersion

  - longitudinal **c**hromatic **a**berration

  - **l**ateral **c**olor

- **Third order "Seidel" aberrations**

  nonlinear terms in the expansion to order 3 in (q_x, q_y, p_x, p_y)

  (order 2 terms all zero by rotational symmetry)

  - **s**pherical aberration

  - **c**oma

  - **a**stigmatism

  - curvature of **f**ield

  - geometric **d**istortion

- **How to reduce them**

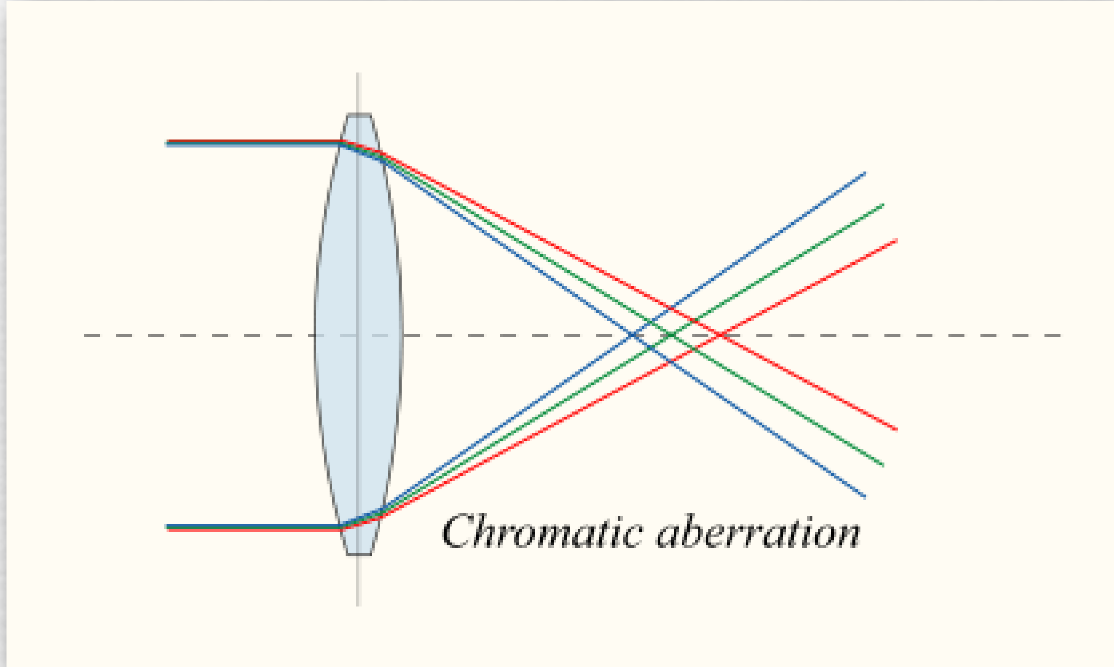
  s,**c**,**a** decreased by stopping down aperture

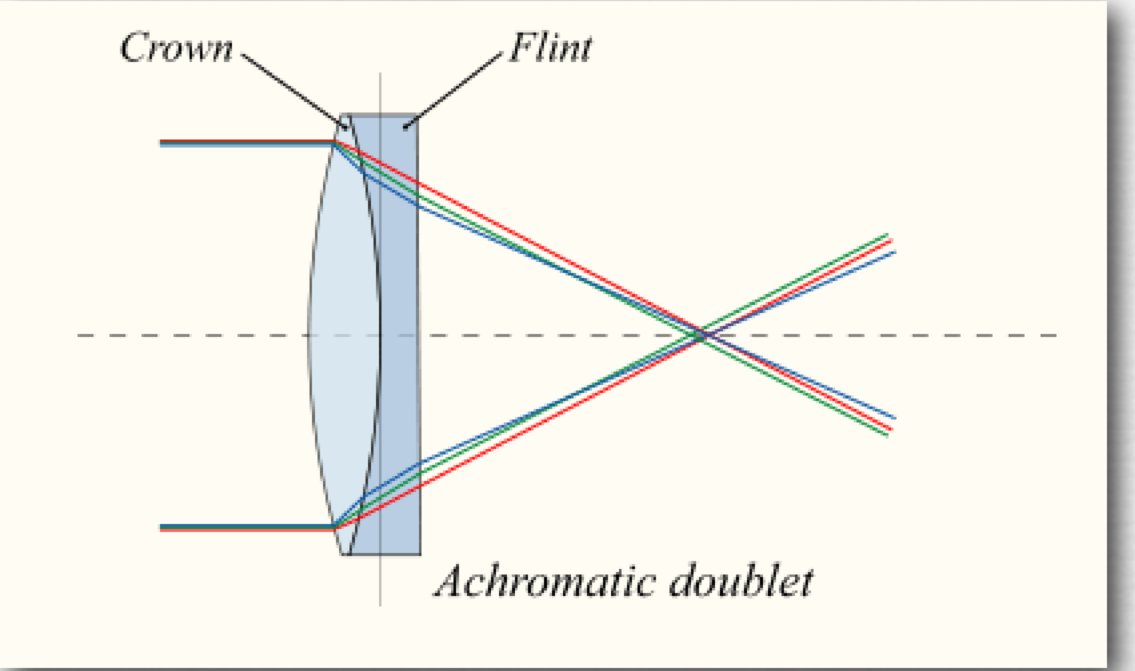
  c,**a**,**f**,**d**,**lc** decreased by narrowing field

  f,**d** do not prevent sharp focusing

  ca you are stuck with

Chromatic aberration



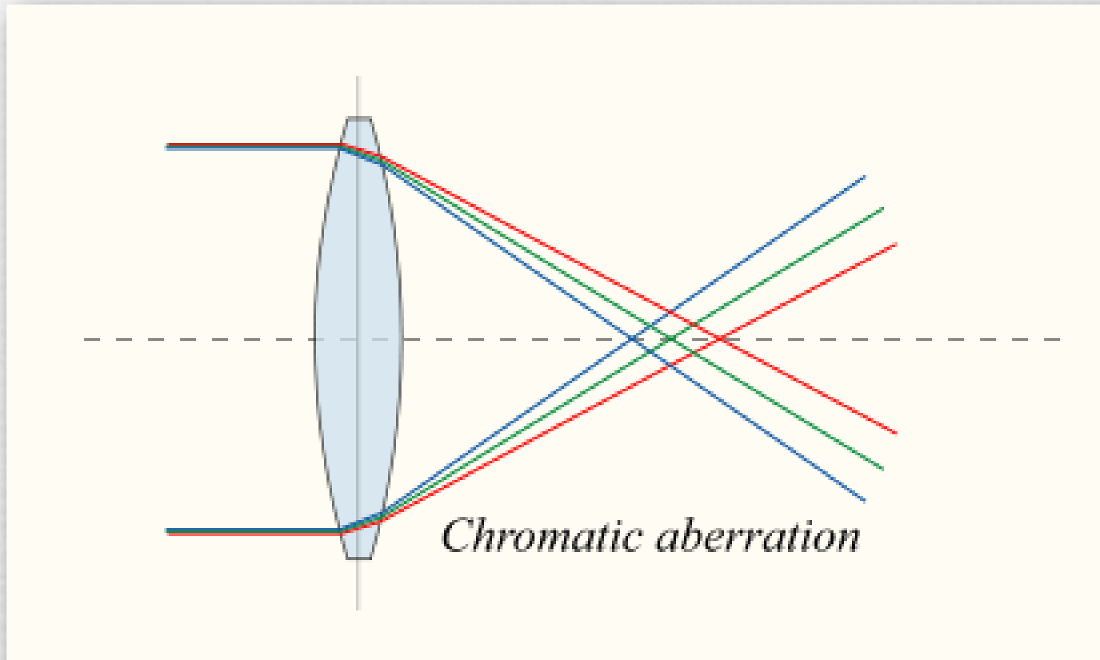


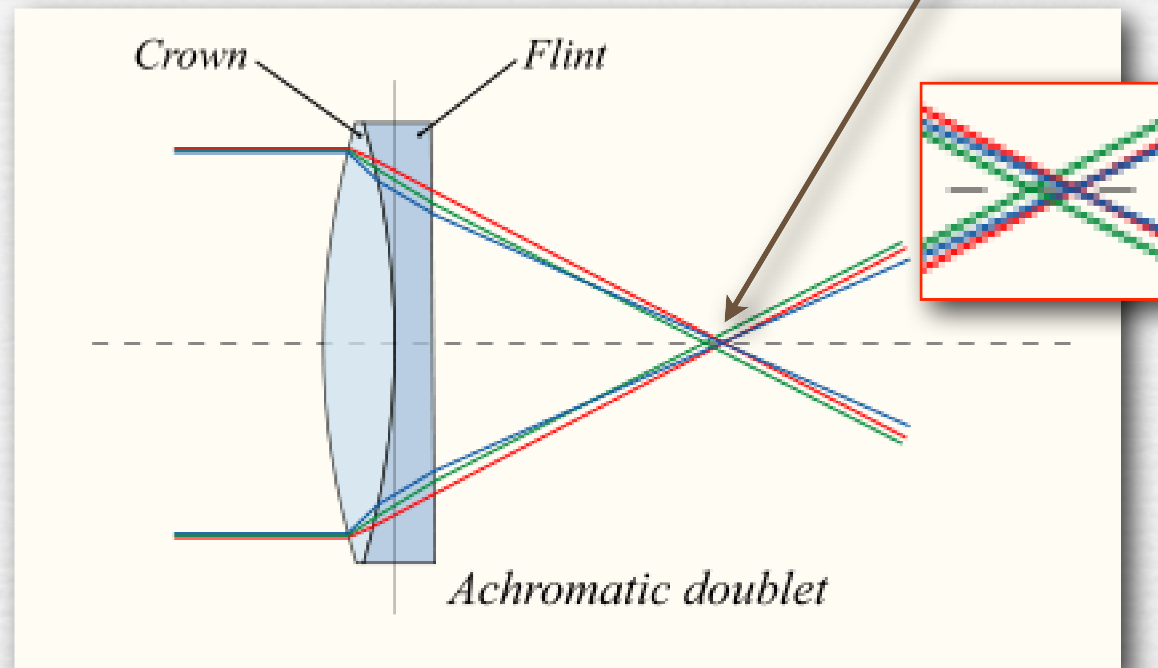
(wikipedia)

- dispersion causes focal length to vary with wavelength
  - for convex lens, blue focal length is shorter
- correct using *achromatic doublet*
  - strong positive lens + weak negative lens = weak positive compound lens
  - by adjusting dispersions, can correct at two wavelengths

Chromatic aberration

red and blue have the same focal length





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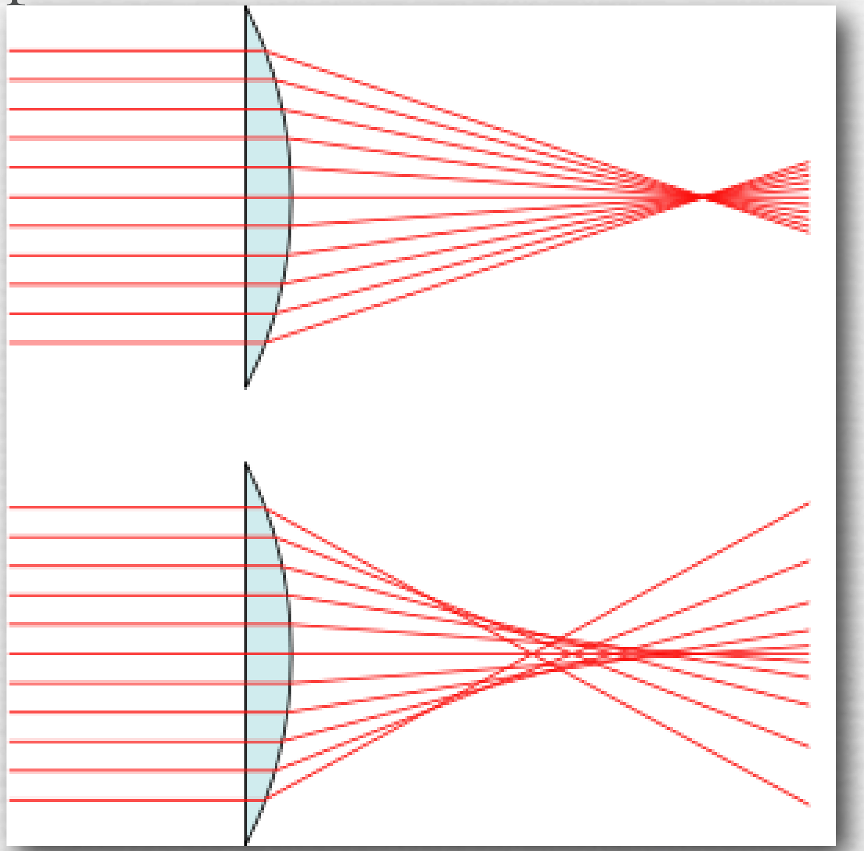
slide by Marc Levoy, Stanford

Spherical aberration

hyperbolic lens



spherical lens (wikipedia)

- focus varies with ray height (distance from optical axis)
- can reduce by stopping down the aperture
- can correct using an aspherical lens
- can correct for this and chromatic aberration by combining with a concave lens of different properties

Examples

(Canon)

sharp

soft focus

Canon 135mm f/2.8 soft focus lens

slide by Marc Levoy, Stanford

Hubble telescope

before correction

slide by Marc Levoy, Stanford

Hubble telescope

before correction

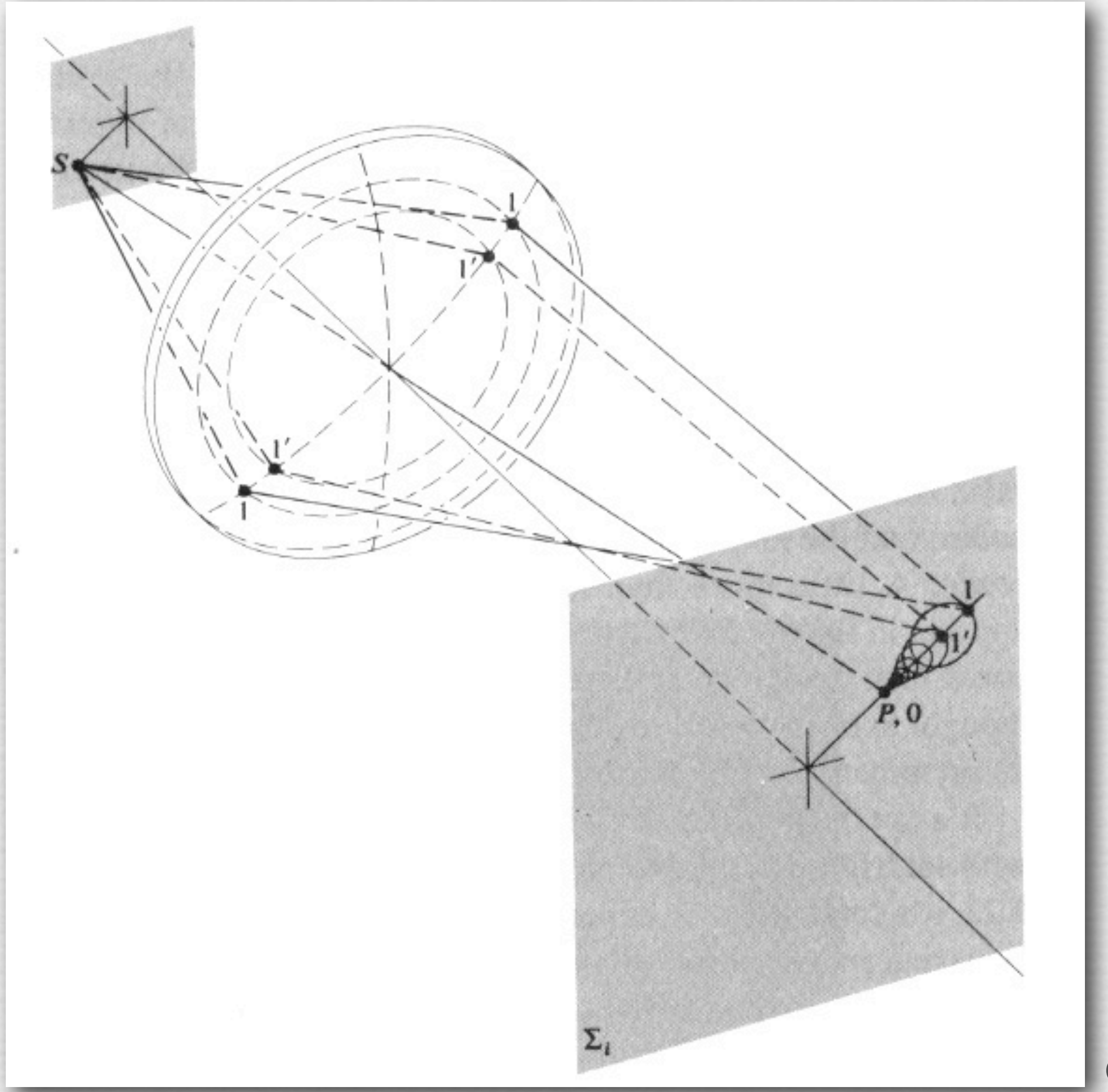
after correction

slide by Marc Levoy, Stanford

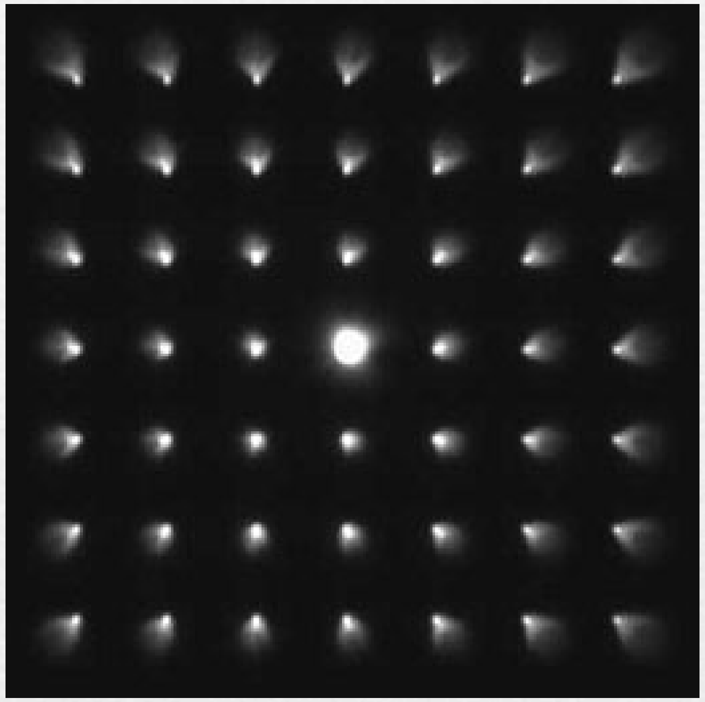
Hubble Space Telescope
Eagle Nebula (NASA)

Marc Levoy, Stanford

Coma



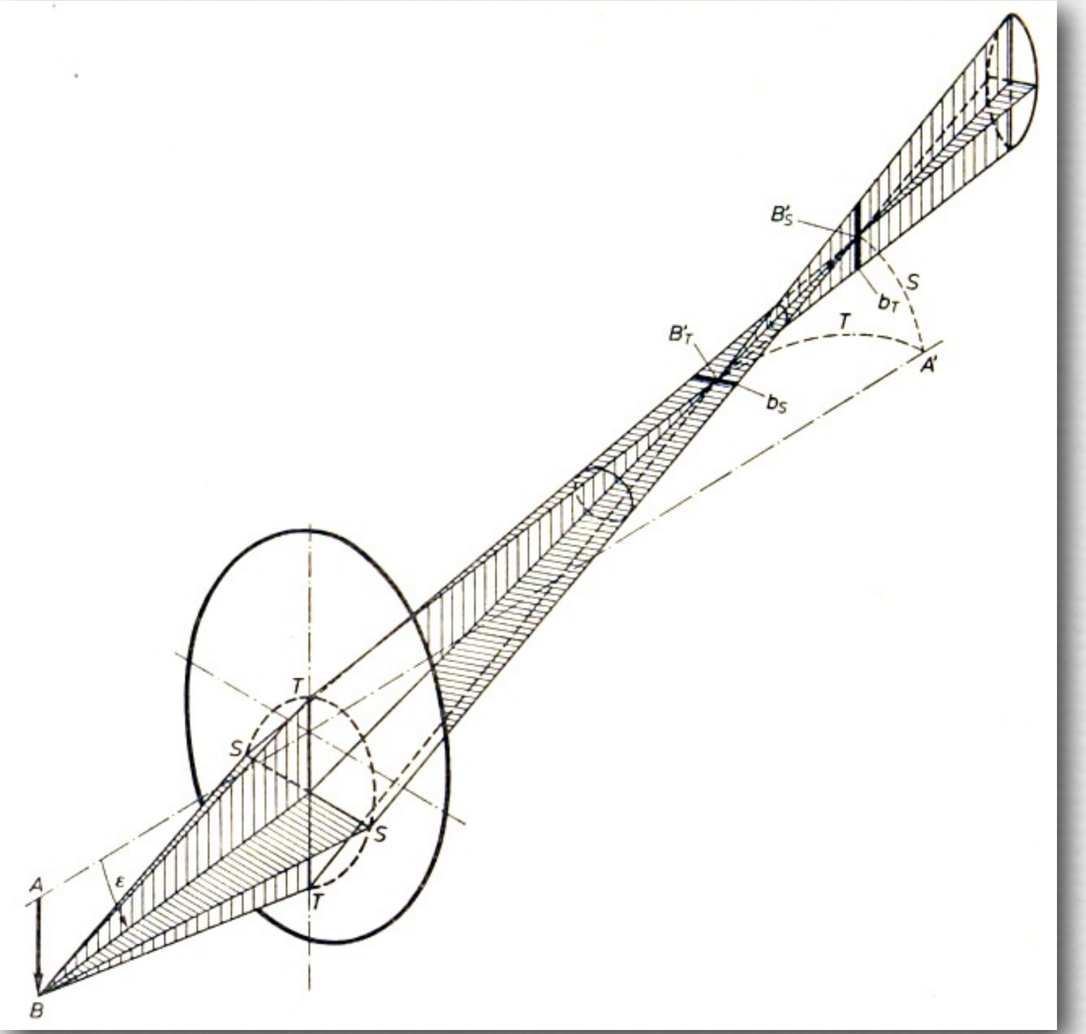
(Hecht)



(ryokosha.com)

- magnification varies with ray height (distance from optical axis)

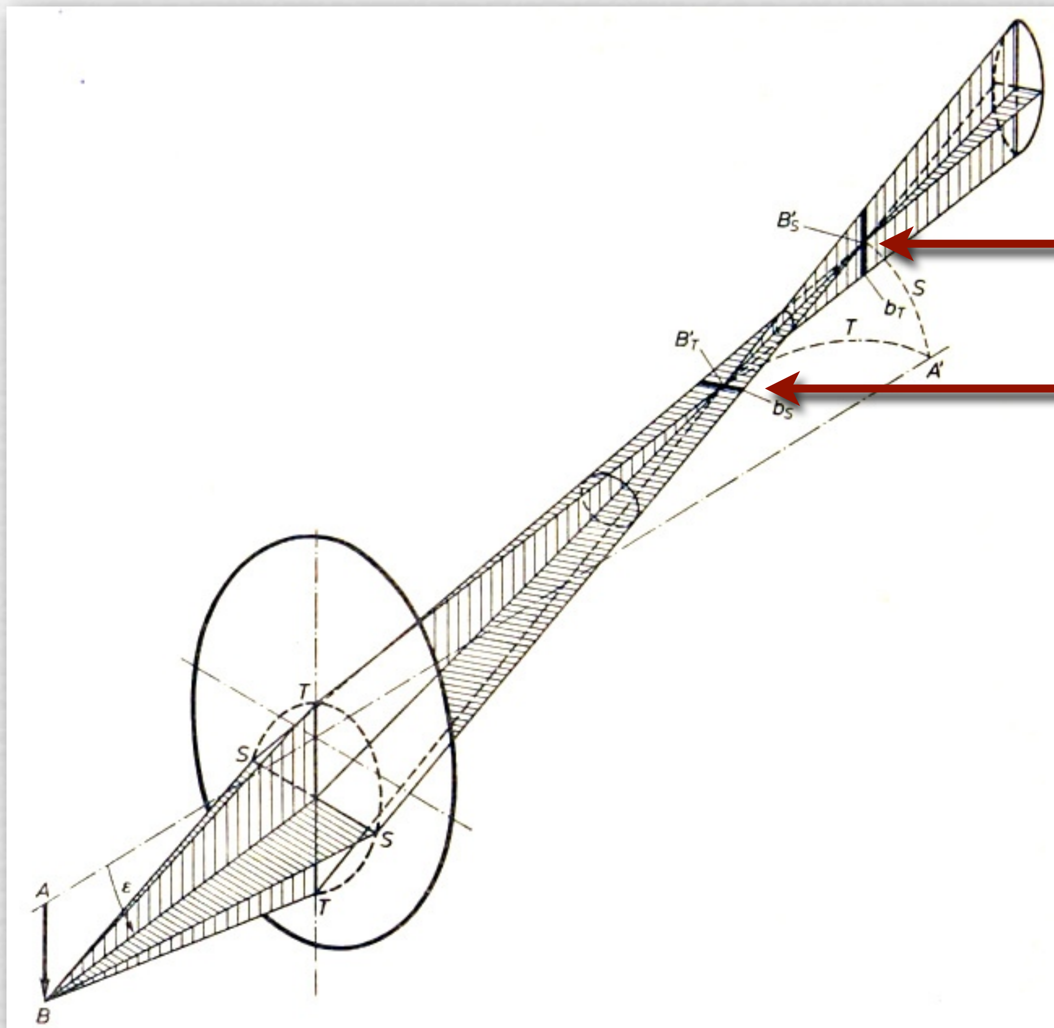
Astigmatism



(Pluta)

- tangential and sagittal rays focus at different depths

Astigmatism



focus of sagittal rays

focus of tangential rays

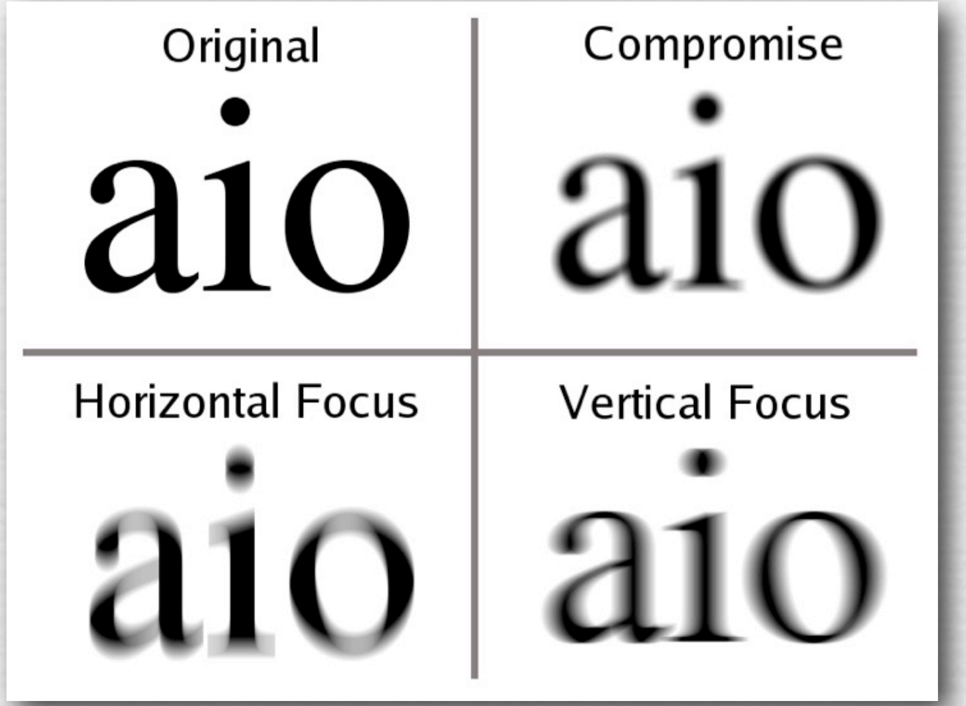
(Pluta)

- tangential and sagittal rays focus at different depths

slide by Marc Levoy, Stanford

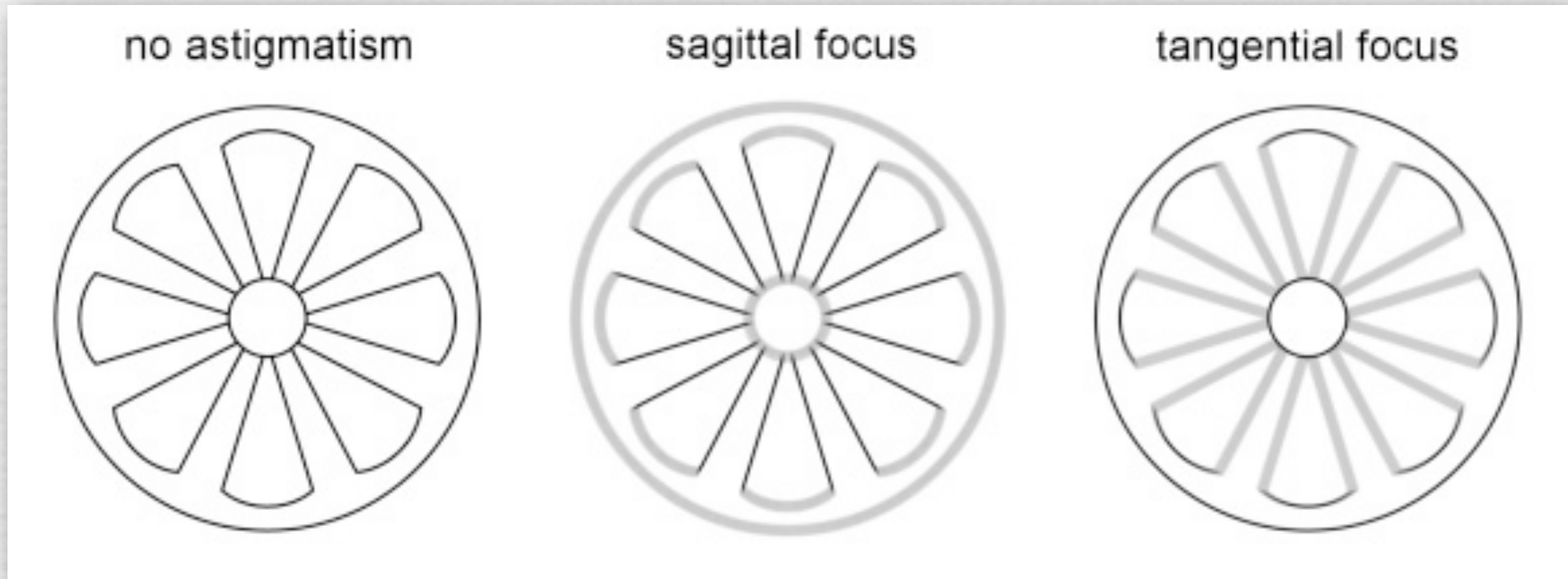
Two kinds of astigmatism

(Wikipedia)



ophthalmic astigmatism
(due to oblong eye)

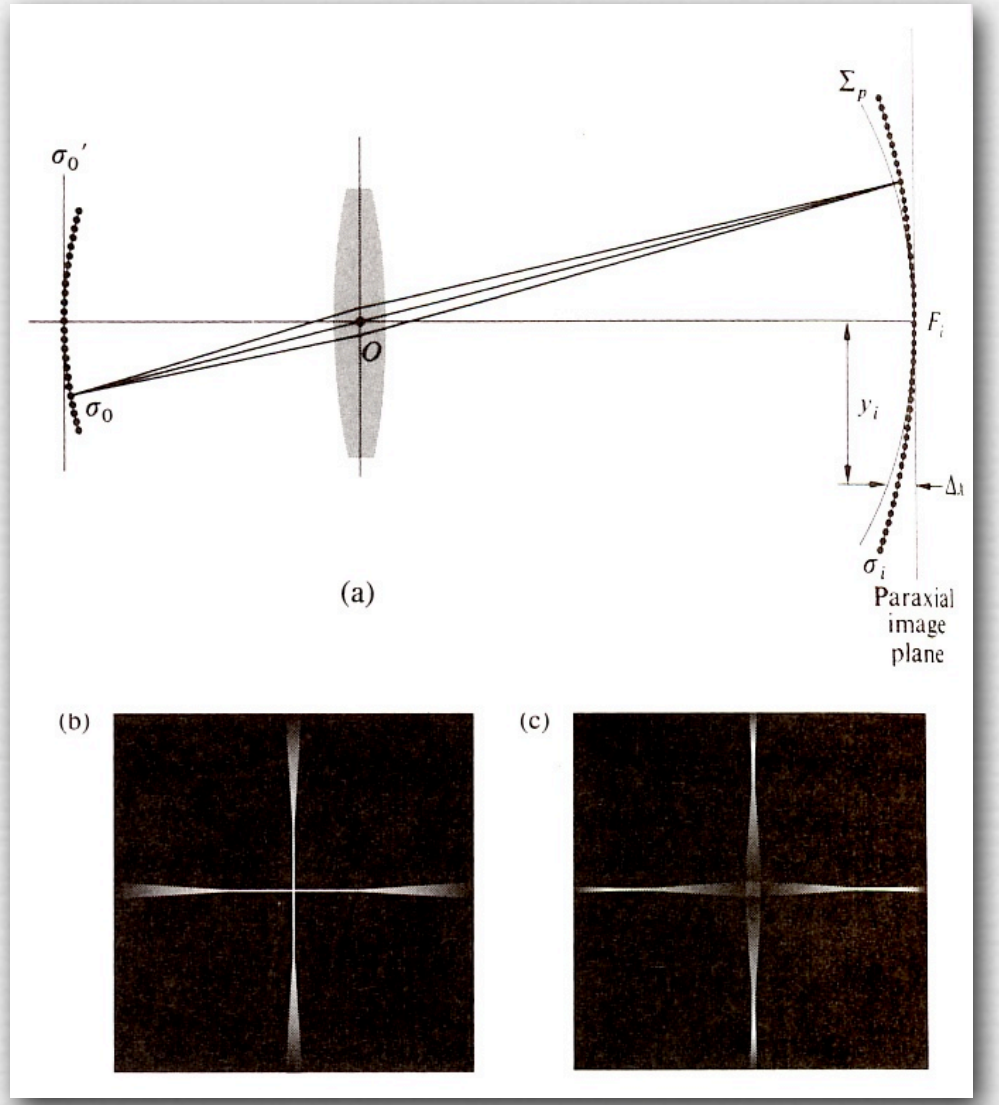
(http://toothwalker.org/optics/astigmatism.html)



third-order astigmatism
(even in rotationally symmetric photographic lenses)

slide by Marc Levoy, Stanford

Field curvature



(Hecht)

- spherical lenses focus a curved surface in object space onto a curved surface in image space
- so a plane in object space cannot be everywhere in focus when imaged by a planar sensor

slide by Marc Levoy, Stanford

Curvilinear/radial distortion

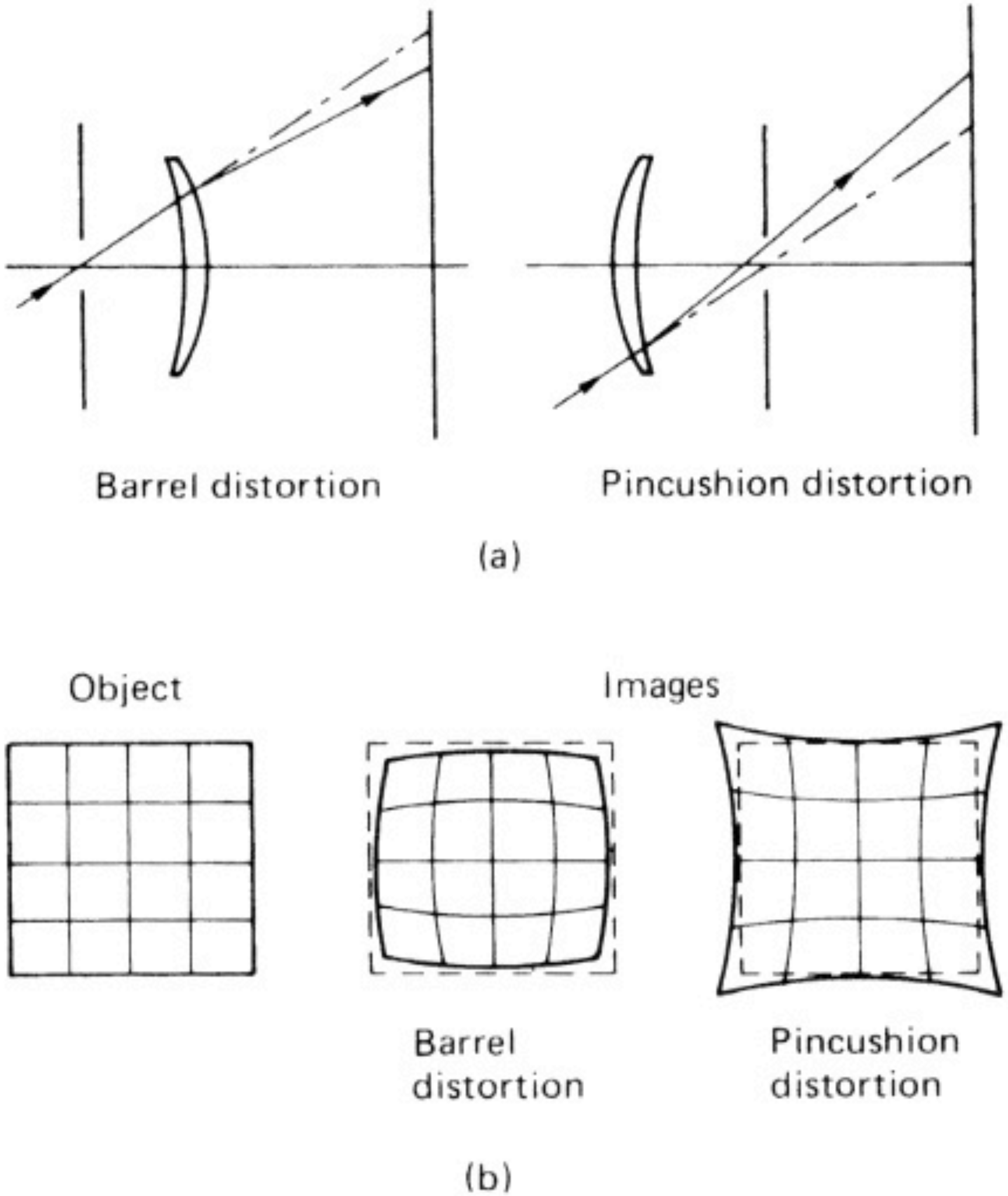


Figure 6.10 The effects of curvilinear distortion. (a) The selection of a geometrically incorrect ray bundle by asymmetric location of the aperture stop. (b) Image shape changes caused by barrel and pincushion distortion

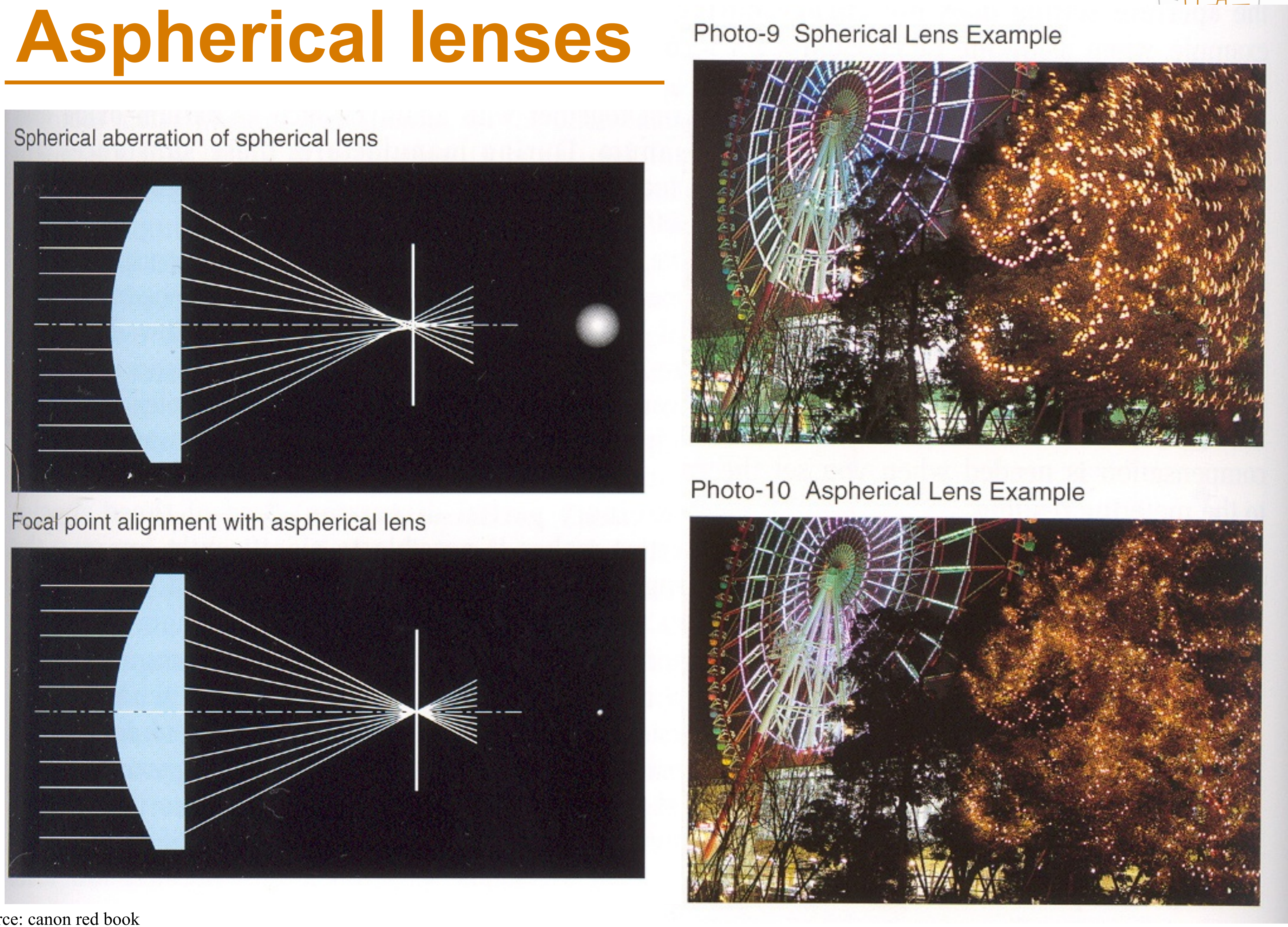
From "The Manual of Photography" Jacobson et al

http://www.dxo.com/us/photo/dxo_optics_pro/optics_geometry_corrections/distortion

http://en.wikipedia.org/wiki/Distortion_(optics)

slide by Frédo Durand, MIT

Aspherical lenses

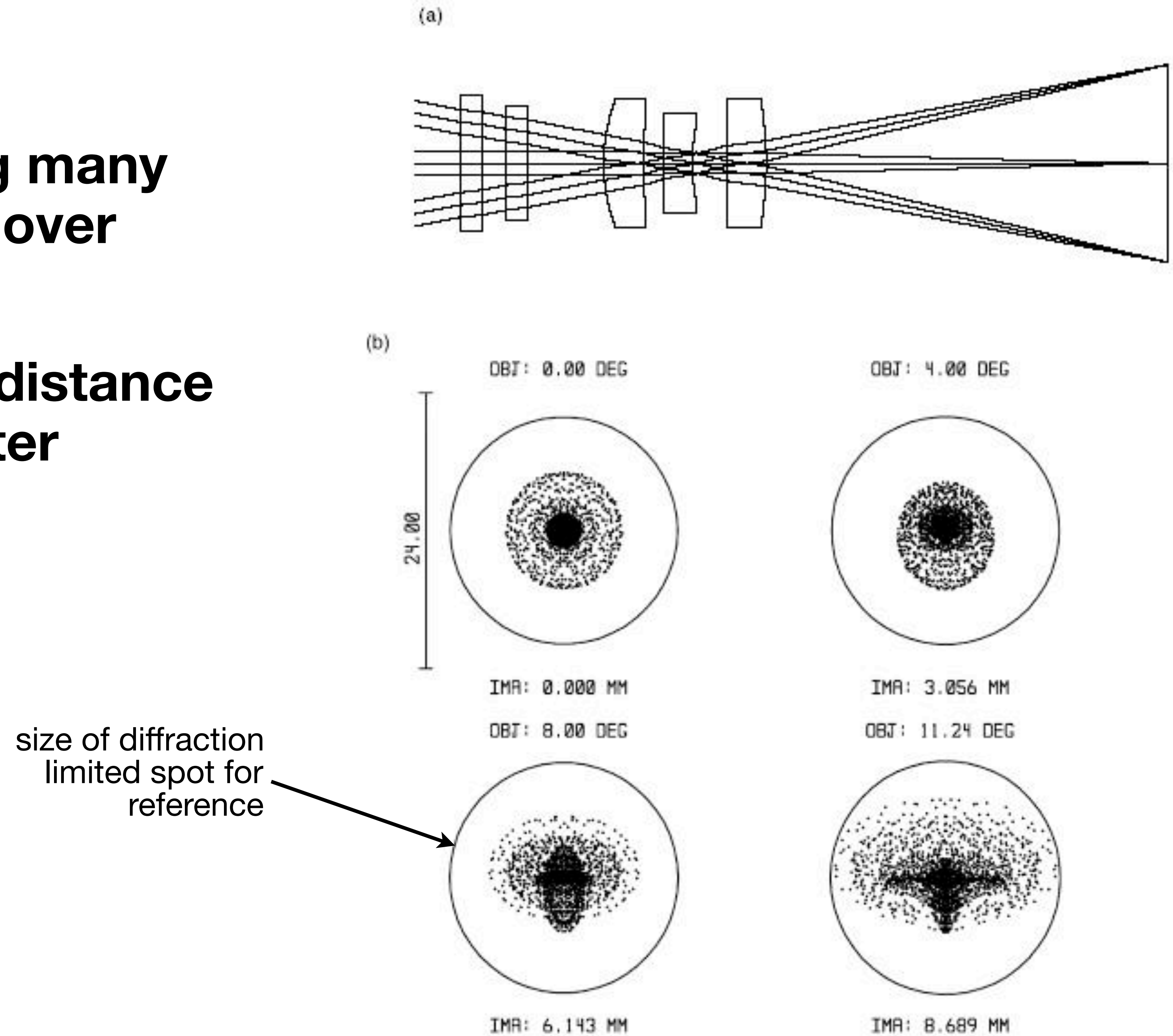


slide by Frédo Durand, MIT

source: canon red book

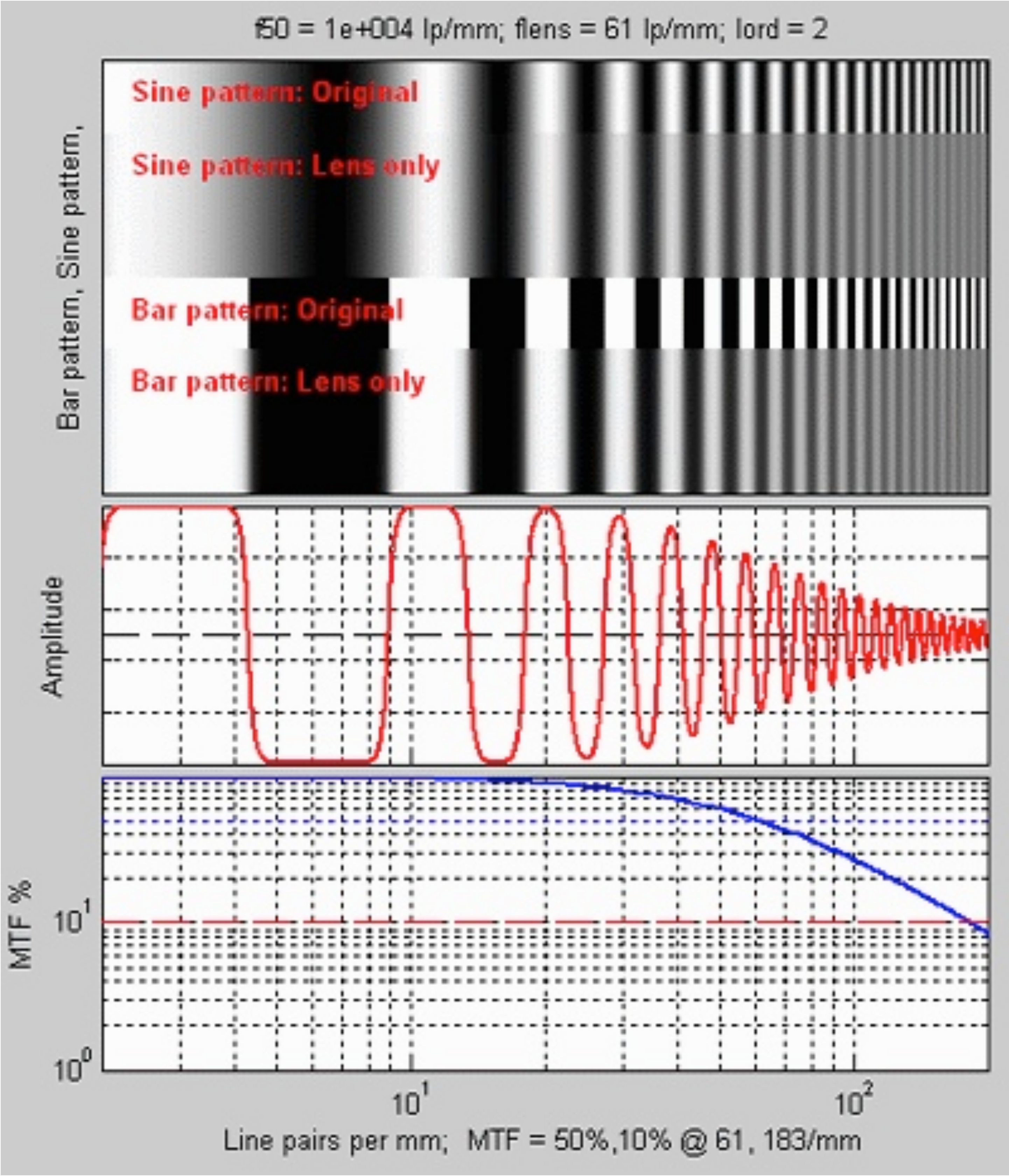
Describing lens performance in space

- **Spot diagrams**
- **Result of tracing many rays distributed over the aperture**
- **Results vary by distance from image center**



Zemax corp. | Mars Rover panoramic camera lens (f:20)

Describing lens performance in frequency



Modulation transfer function (MTF)

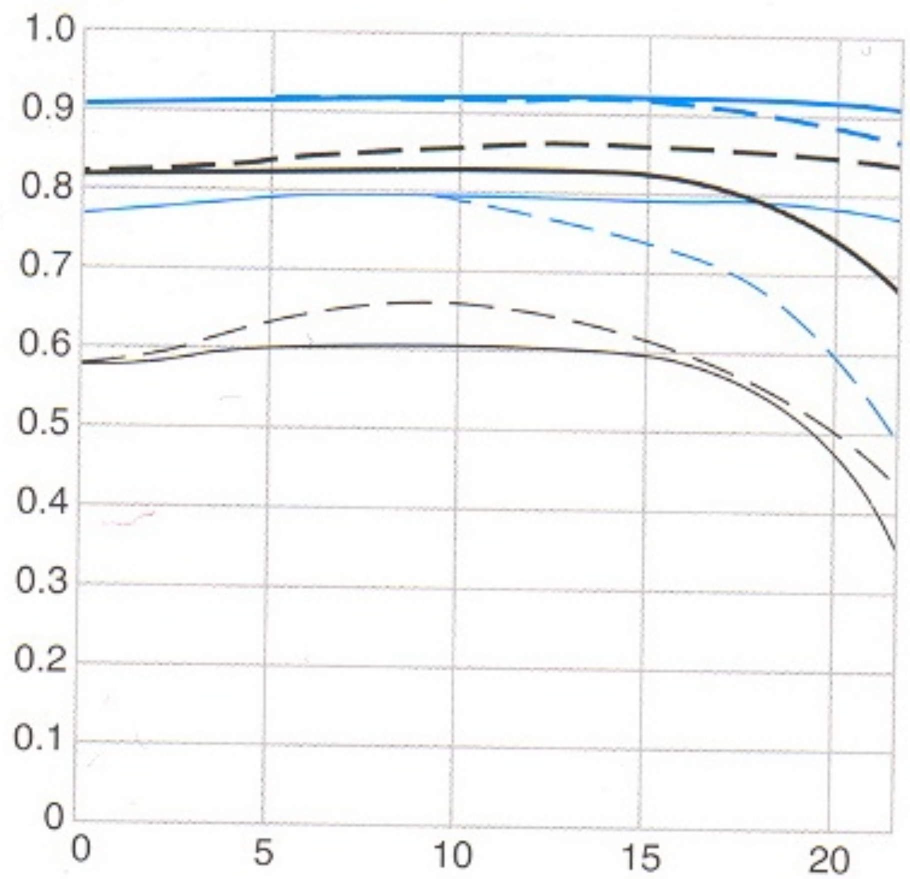
- **Function of spatial frequency and image position**

lens from hw3

Table-3

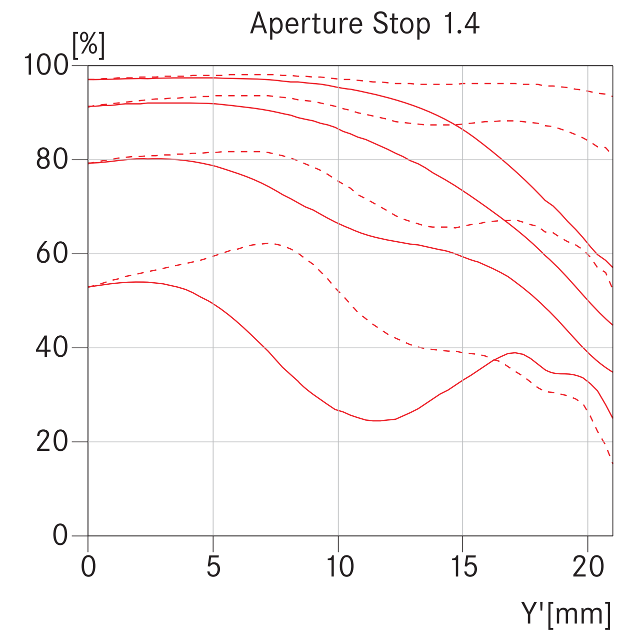
Spatial frequency	Maximum aperture		F 8	
	S	M	S	M
10 lines/mm				
30 lines/mm				

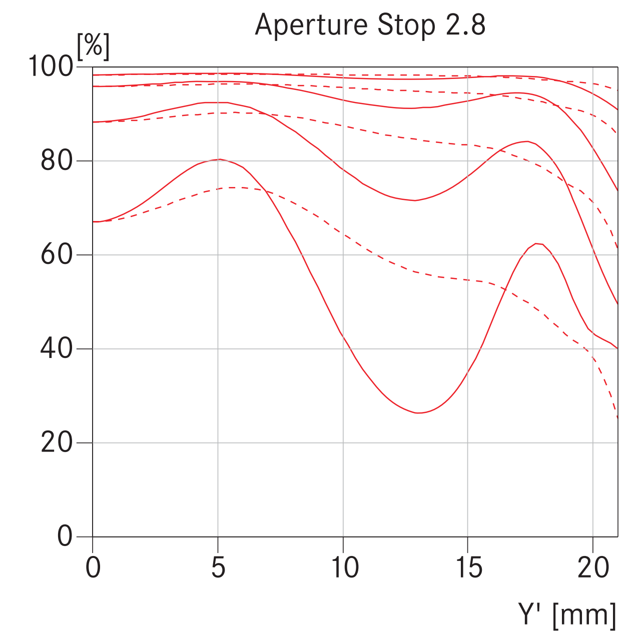
Graph-5 MTF Characteristics

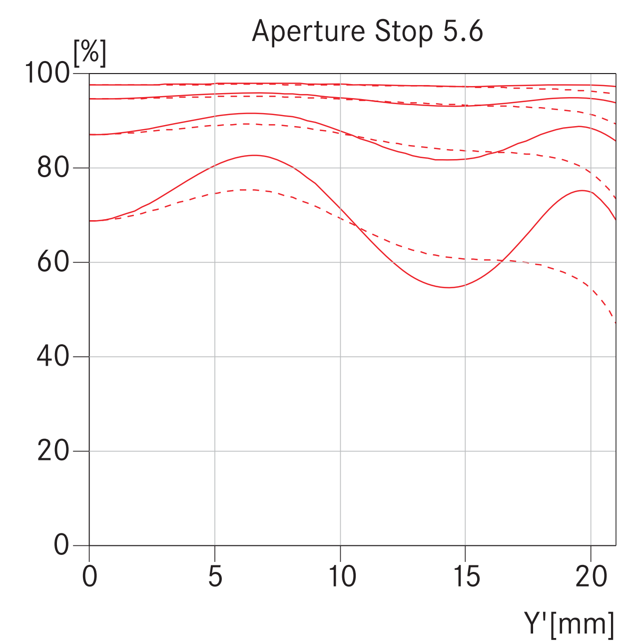


source: canon red book

LEICA SUMMILUX-M 35 mm f/1.4 ASPH.







The MTF is indicated at full aperture, at f/2.8 and at f/5.6 at long taking distances (infinity). Shown is the contrast in percentage for 5, 10, 20 and 40 lp/mm accross the height of the 35 mm film format, for tangential (dotted line) and sagittal (solid line) structures, in white light. The 5 and 10 lp/mm will give an indication regarding the contrast ratio for large object structures.The 20 and 40 lp/mm records the resolution of finer and finest object structures.

sagittal structures

tangential structures

Fighting aberrations

- **Add more elements**
- **Use aspherical surfaces**

  introduces more DOFs without adding more surfaces
- **Stop when aberrations are smaller than Airy disk**

  then the lens is "diffraction limited"

  lenses become diffraction limited when you stop them down far enough

Stray light

- **Reflections from optical surfaces (lens flare)**
  classic "lens flare" with images of aperture
  planar filters cause annoying reflections of objects
- **Diffuse reflections from other parts (lens flare and camera flare)**
  leads to general loss of contrast
- **Reduced by use of lens hoods**
  goal: exclude bright sources outside the image
  useless when the source is in the image

Reducing stray light

- **Paint everything black**

  inside of lens barrel, edges of lenses, inside of camera, …

- **Use of knife-edge baffles**

  use geometry to eliminate single-bounce diffuse paths

- **Anti-reflection coatings on optical surfaces**

  fancy and highly developed technology

  old: 1/4 wave coating

  current: optimized multilayer coatings

  newest: nanostructured coatings

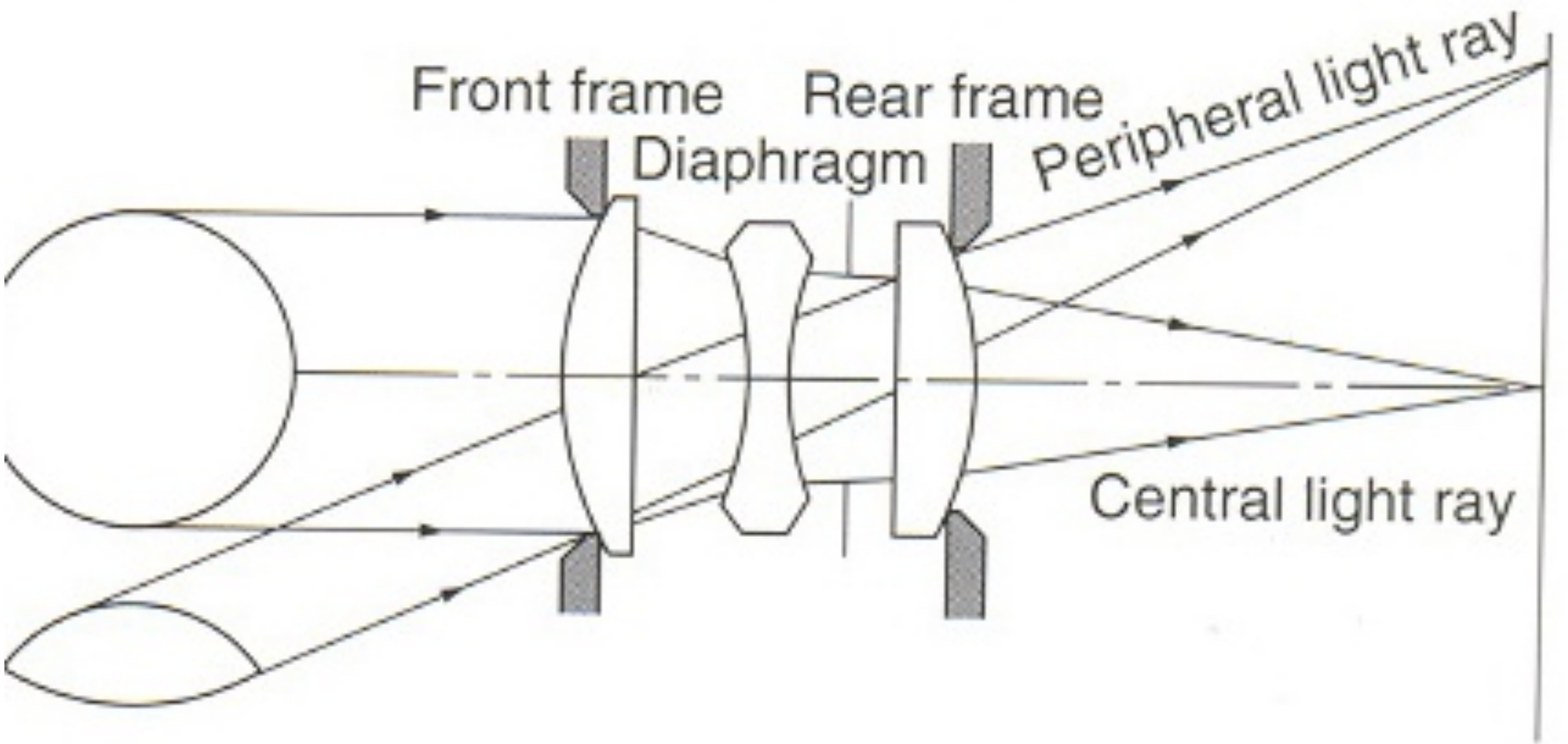
Other issues

- **Vignetting**
- **Shading**

Vignetting

- **Occlusion by lens elements**
- **The periphery does not get as much light**

Figure-28 Vignetting



Source: canon red book

slide by Frédo Durand, MIT

Vignetting correction (ACR)

Before

After

slide by Frédo Durand, MIT

Characteristics of lenses

- **Basic: focal length, min f number**
- **Zoom range**
- **Minimum focus distance**
  - if very close, it's a "macro" lens
  - requires extra optimization to work at all distances
- **Principal planes**
- **Entrance and exit pupils**
- **Geometric distortion**
- **Actuation**
  - aperture
  - autofocus
  - image stabilization

Quality of lenses

- **Center sharpness** (IMO over-emphasized)
  how well it resolves small features
  only of interest relative to the size of pixels
  all modern lenses are very sharp in the center
  affected by some aberrations but not others
- **Corner sharpness**
  affected by all aberrations
  generally noticeably worse than center sharpness
- **Contrast** (IMO under-appreciated)
- **Lateral color**