Lenses

Real-time Rendering of Physically Based Optical Effect in Theory and Practice

SIGGRAPH 2015 Course

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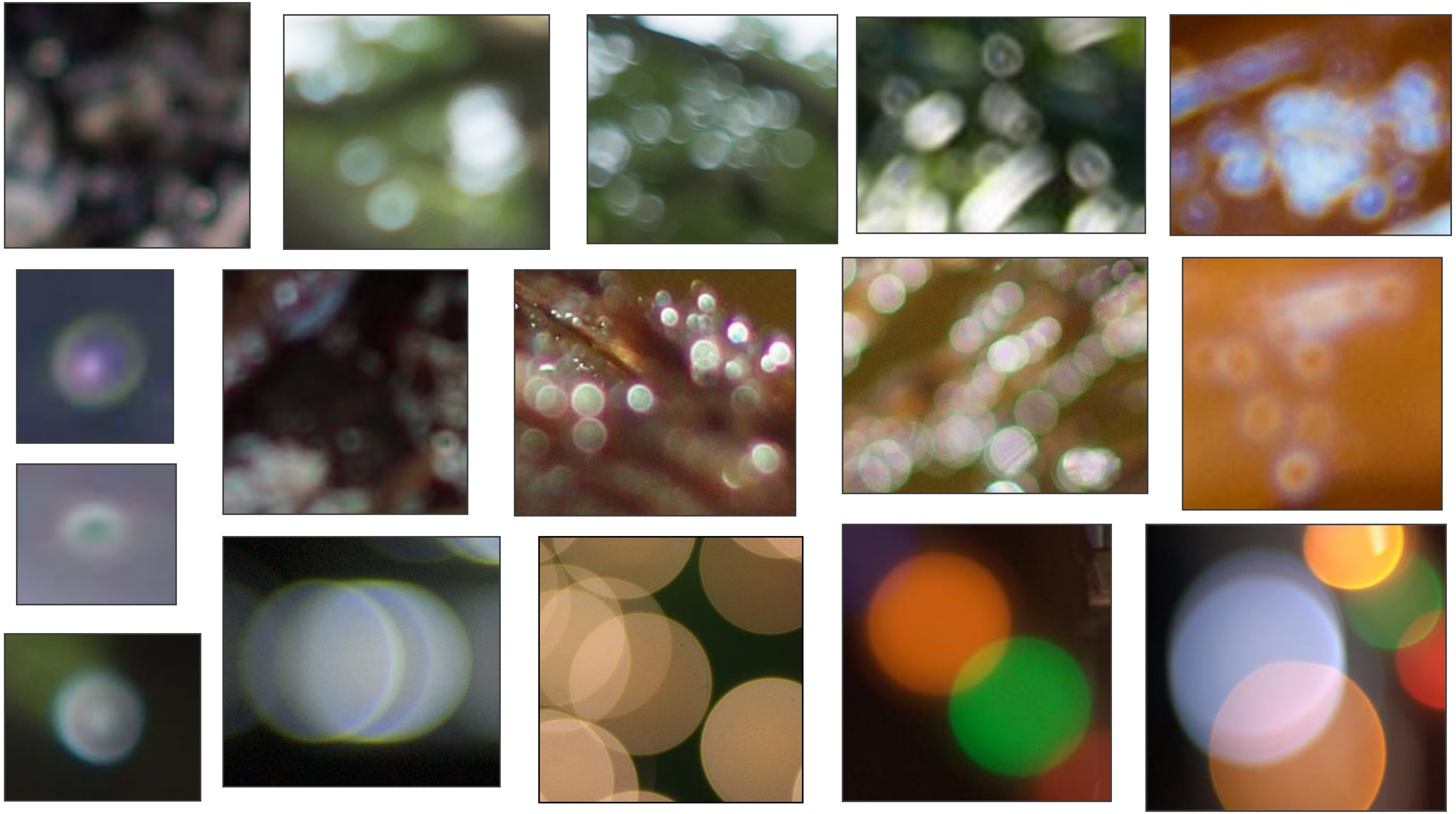
Various Bokeh from Photographs



Contents

Aberrations and Corrections

Optical Aberrations

- Actual lenses do not image ideally
  - Imperfect focus
  - Image distortion
  - Color dispersion
  - And more …

Major Aberrations

- Monochromatic aberrations
  - Occur even with single-wavelength rays
  - Also known as Seidel's five aberrations
- Chromatic aberrations
  - Caused by dispersion
    - The separation of visible light into its different colors
    - Different refractive indices in multi-wavelength rays
  - Caused with multi-wavelength rays but:
    - Occurs as blur in monochrome film
    - Does not occur in color film with single-wavelength rays
      - Such as Sodium-vapor Lamps

Monochromatic and Chromatic Aberrations

- Monochromatic aberrations (Seidel's five aberrations)
  - Spherical Aberration (SA)
  - Coma
  - Field Curvature
  - Astigmatism
  - Distortion

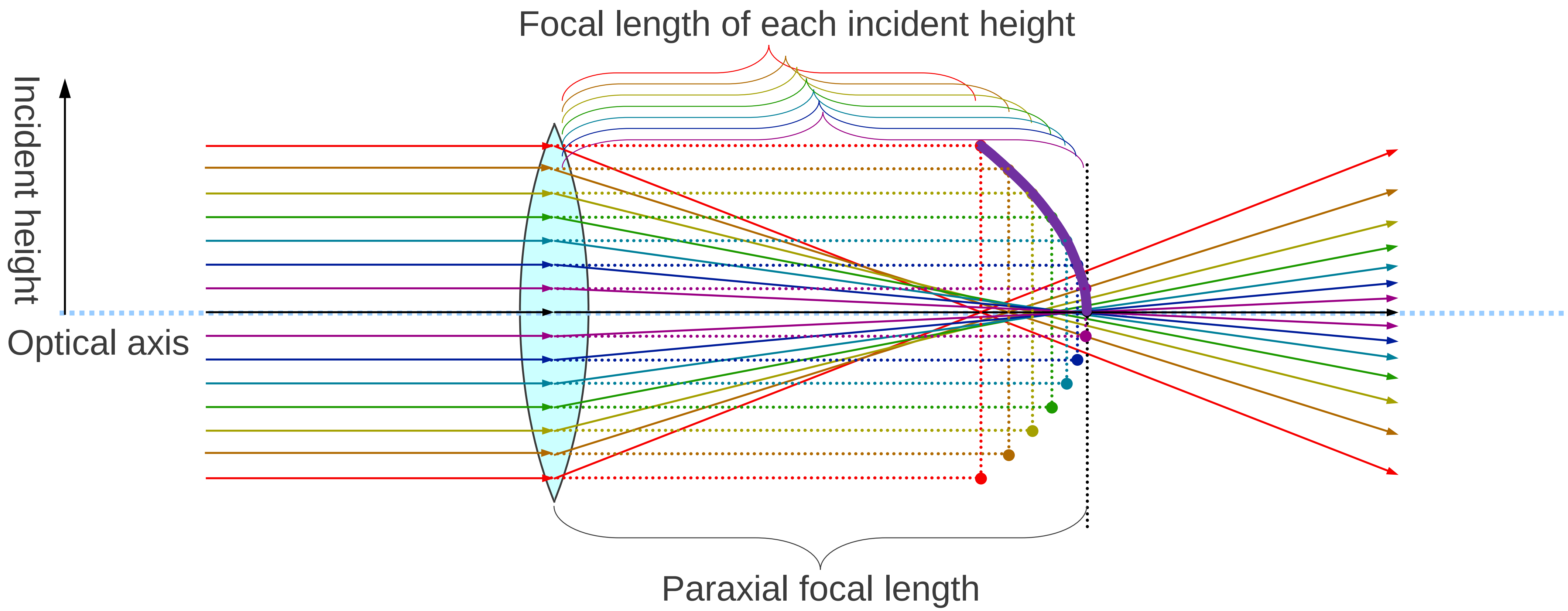
- Chromatic aberrations (CA)
  - Lateral Chromatic Aberration (CA of Magnification)
  - Longitudinal Chromatic Aberration (Axial CA)

Details of Important Aberrations Which Affect Bokeh

Spherical Aberration

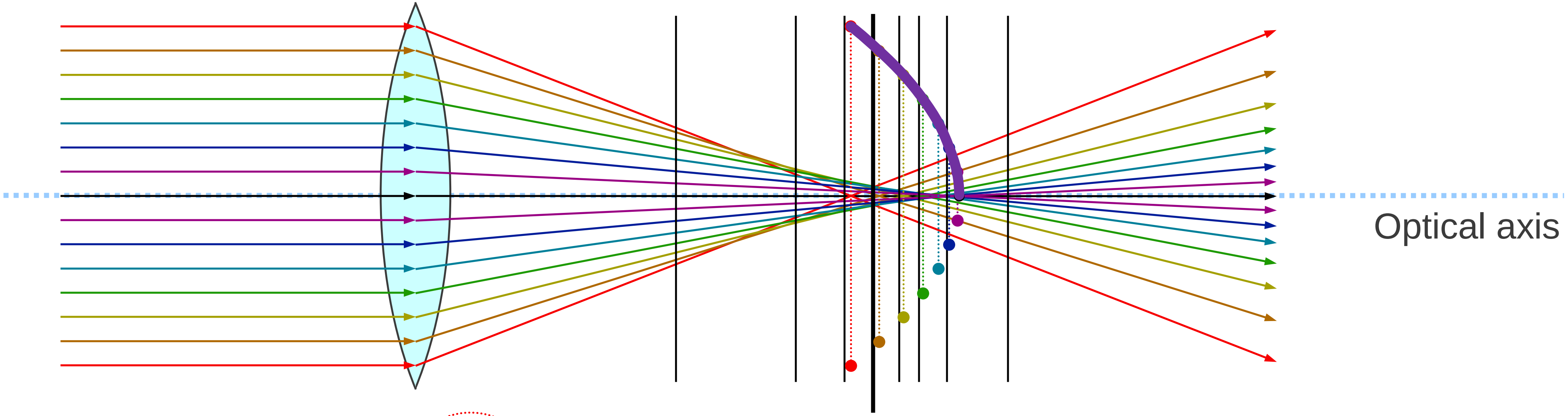
- The focal length deviation of rays parallel to the optical axis
- The aberration is caused by a spherical lens
  - Spherical surfaces are:
    - Not ideal for lenses
    - Commonly used due to the high manufacturability

Principle of Spherical Aberration



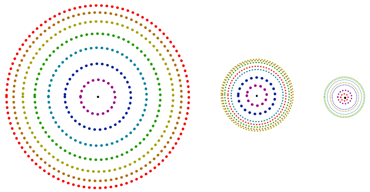
- The farther the rays are from the optical axis, the closer they intersect the optical axis

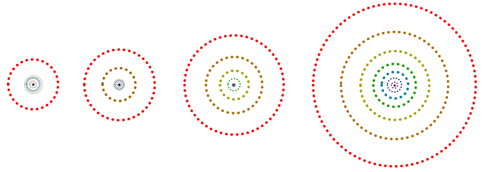
Spherical Lens Bokeh

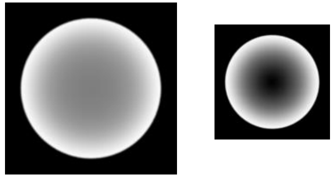


Optical axis

Spot diagrams

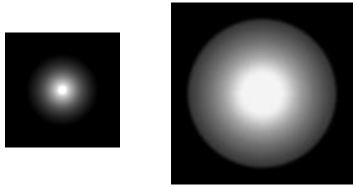






Front bokeh (sharp-edged)

Circle of
least confusion
(a.k.a. COLC)

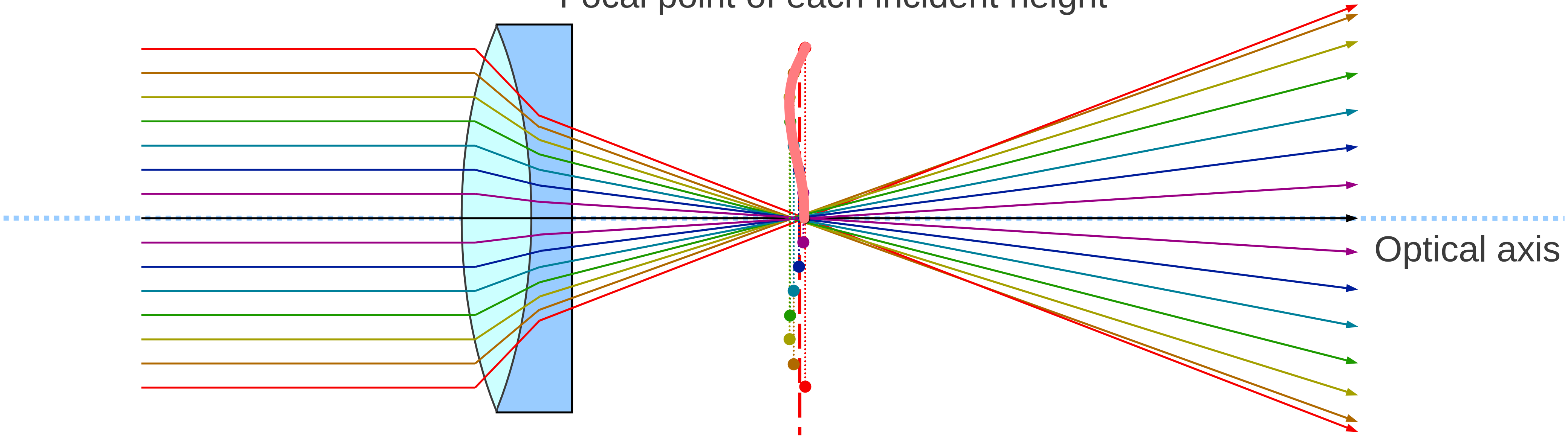


Back bokeh (soft-edged)

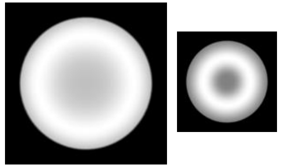
Corrections for Spherical Aberration

- Doublet lens
  - Pair of convex and concave lenses
  - Concave lens aberration cancels convex lens one
  - Cannot cancel perfectly
- Triplet lens
  - An additional lens to doublet
  - Still not perfect, but much better
- Aspherical lens
  - Surface is close to ideal
  - Expensive to make
  - Perfectly remove spherical aberration

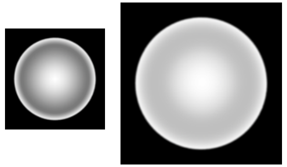
Example of Doublet Lens Correction



- More complicated bokeh than spherical

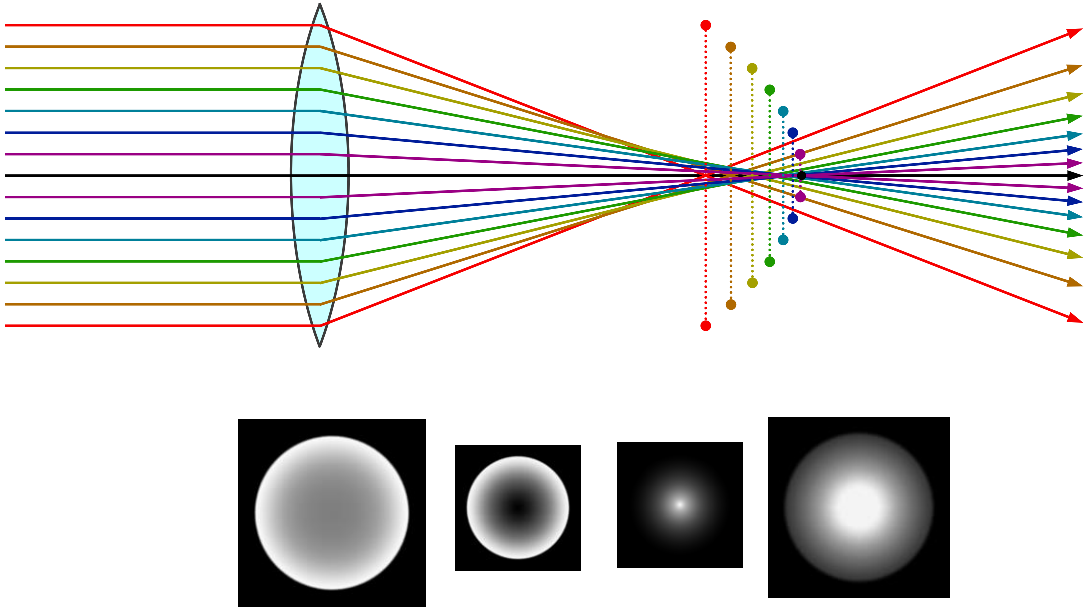


Front bokeh

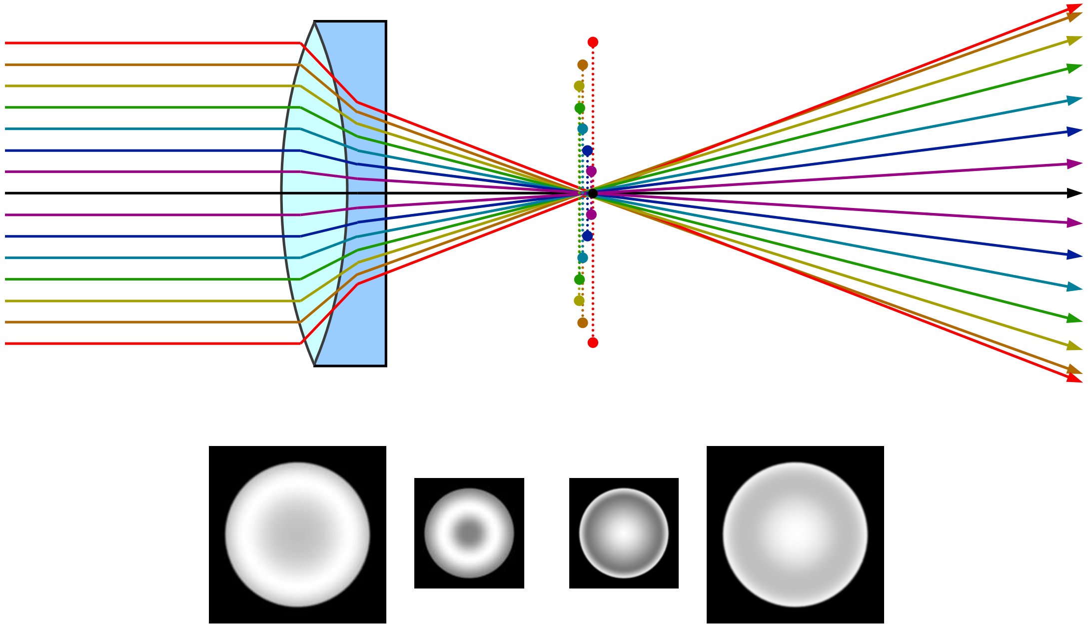


Back bokeh

Comparison

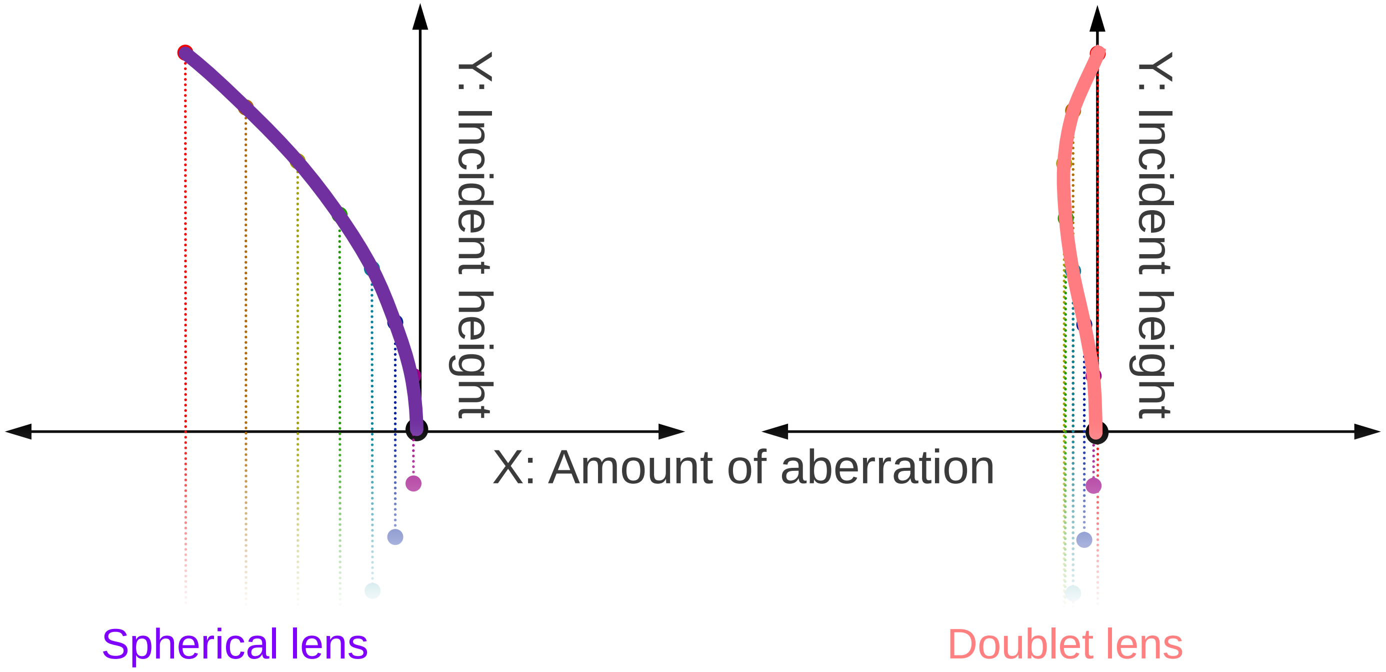


Spherical lens



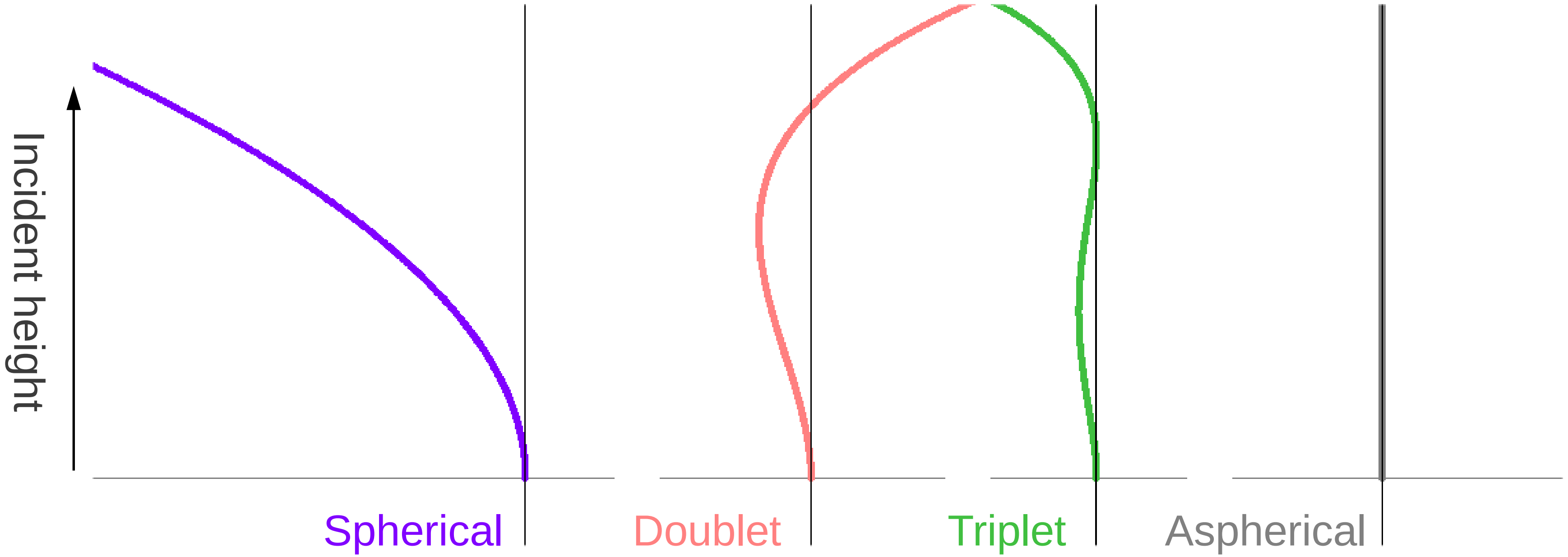
Doublet lens
Sharper focus
Flatter bokeh

Spherical Aberration Charts (Longitudinal Aberration Diagrams)



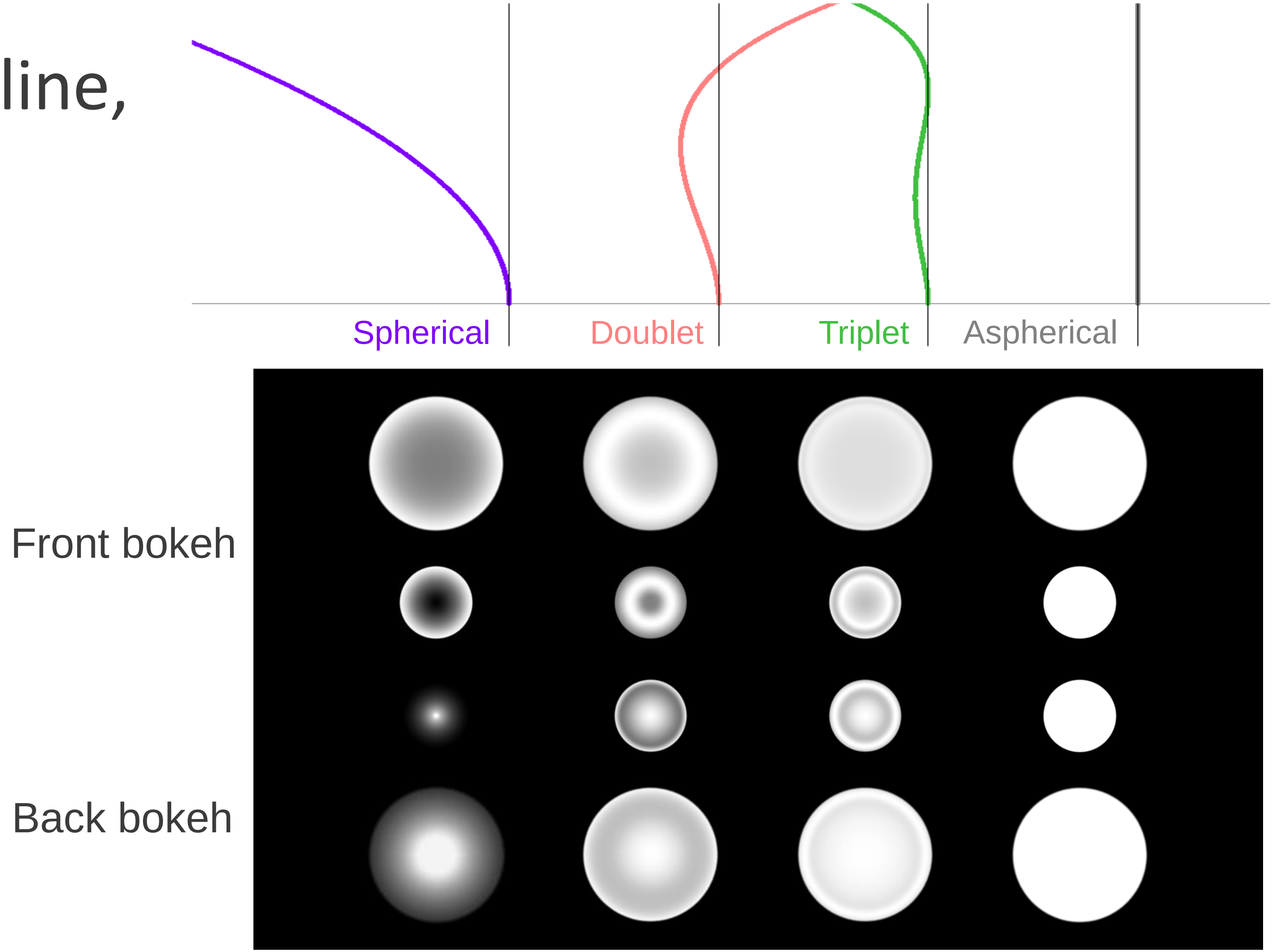
- Y-axis : Incident height (independent variable)
- X-axis : Amount of spherical aberration (dependent variable)

Spherical Aberration Charts (Longitudinal Aberration Diagrams)



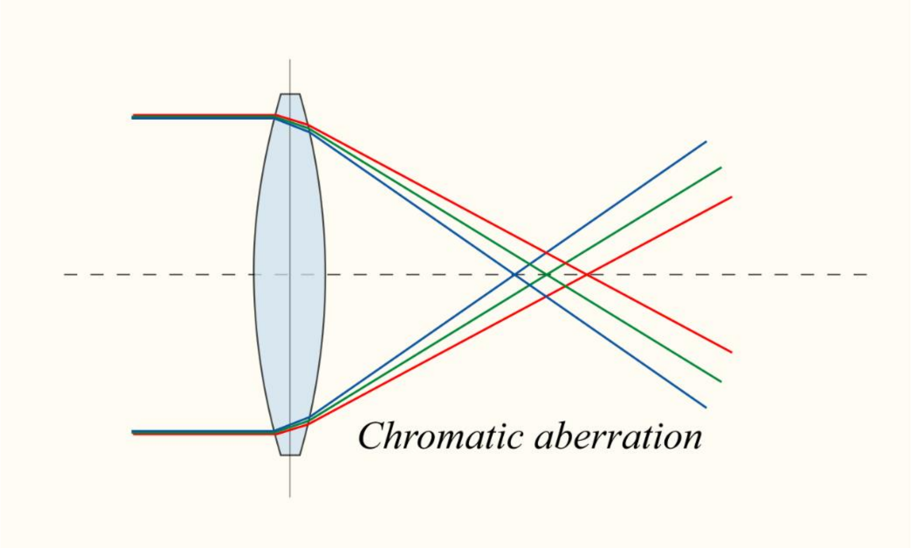
Diagrams and Bokeh

- Closer to vertical line, better correction
  - Sharper focus
  - Flatter bokeh



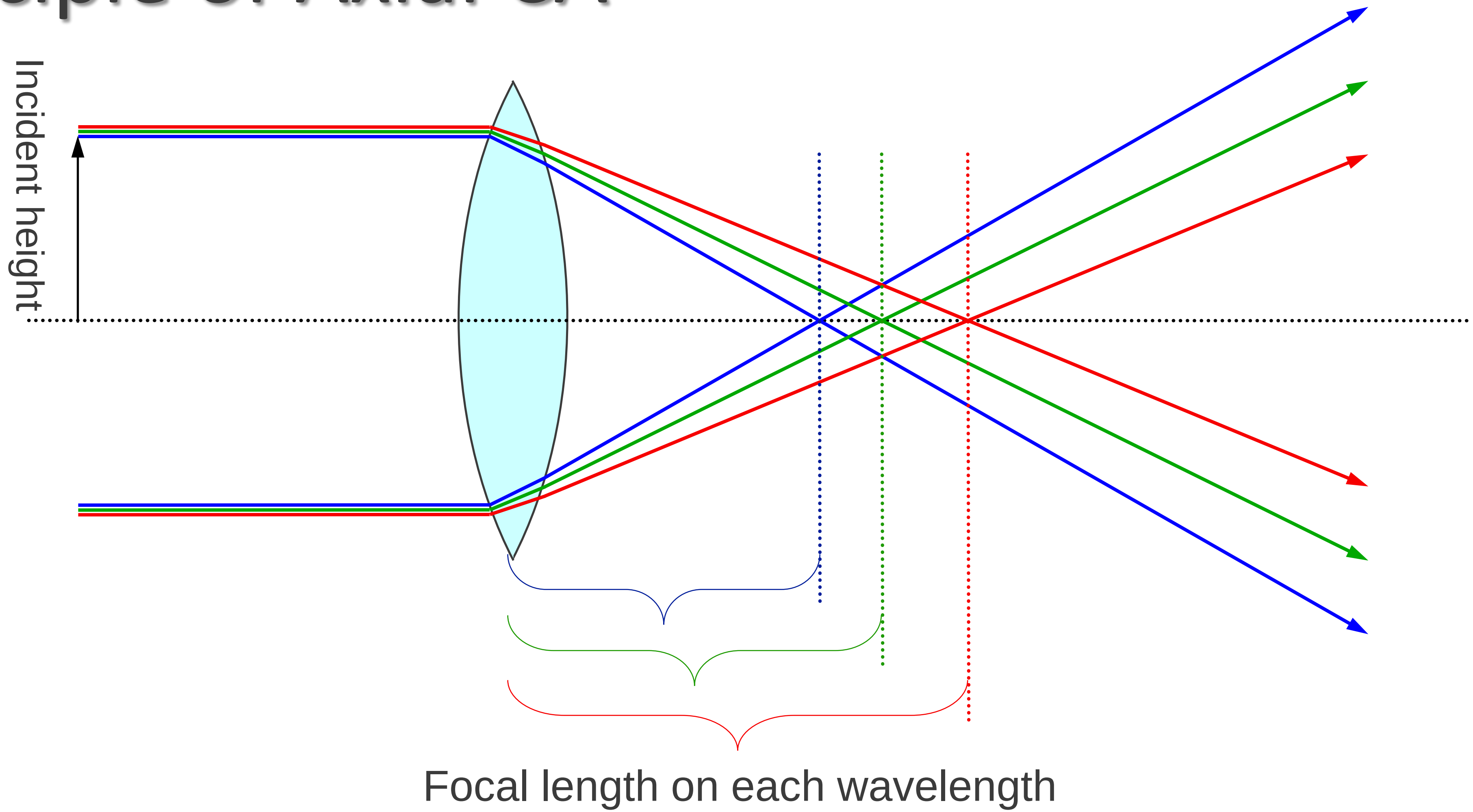
Axial Chromatic Aberration

- Differences of ray wavelengths cause aberration
- Refractive indices differ by wavelengths

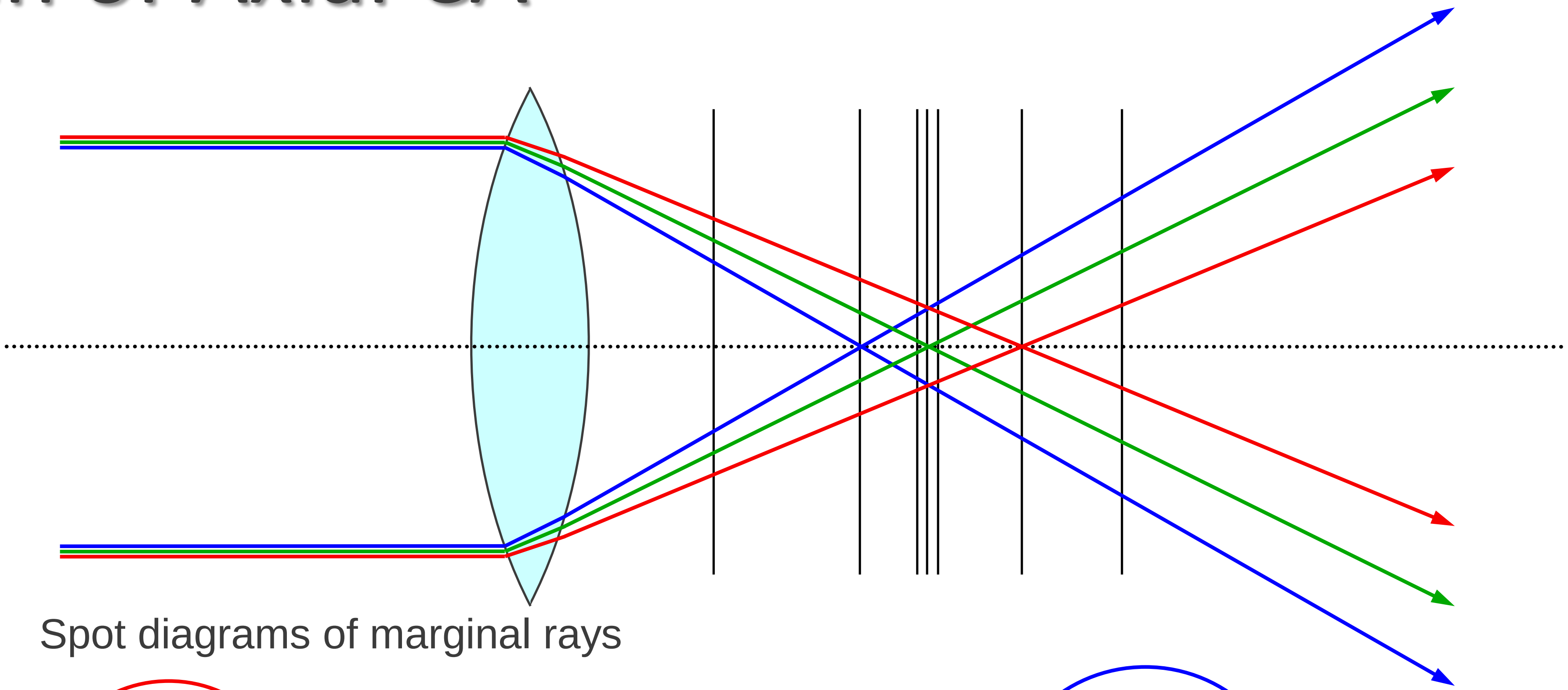


DrBob, https://en.wikipedia.org/wiki/File:Chromatic_aberration_lens_diagram.svg

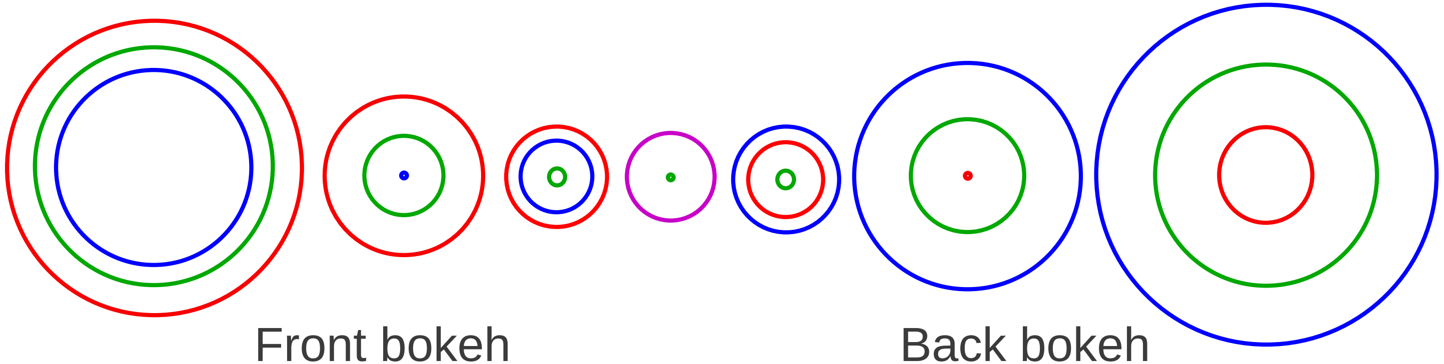
Principle of Axial CA



Bokeh of Axial CA



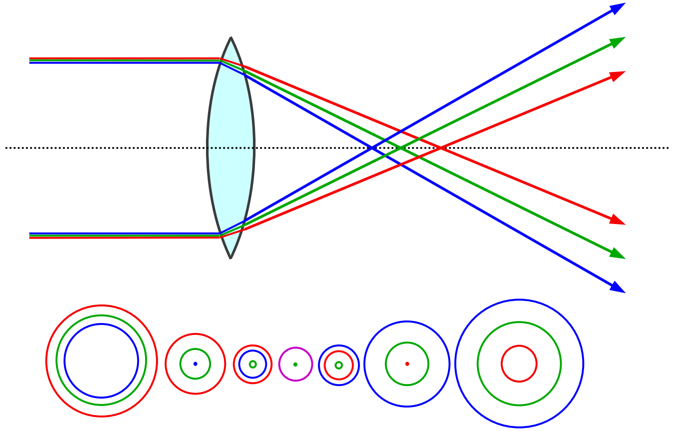
Spot diagrams of marginal rays



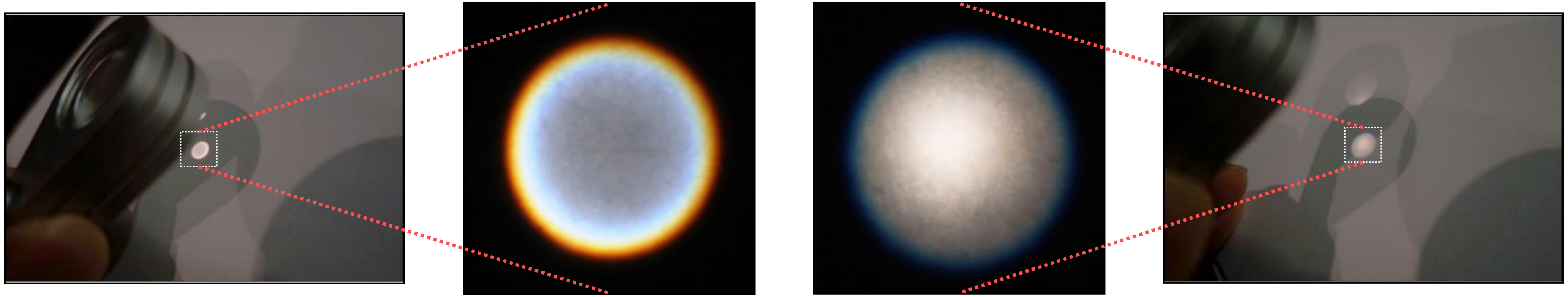
Front bokeh

Back bokeh

Effects of Axial CA



- Front bokeh shows red fringe
- Back bokeh shows blue fringe
- Relatively larger fringe around the focal point



Front bokeh

Back bokeh

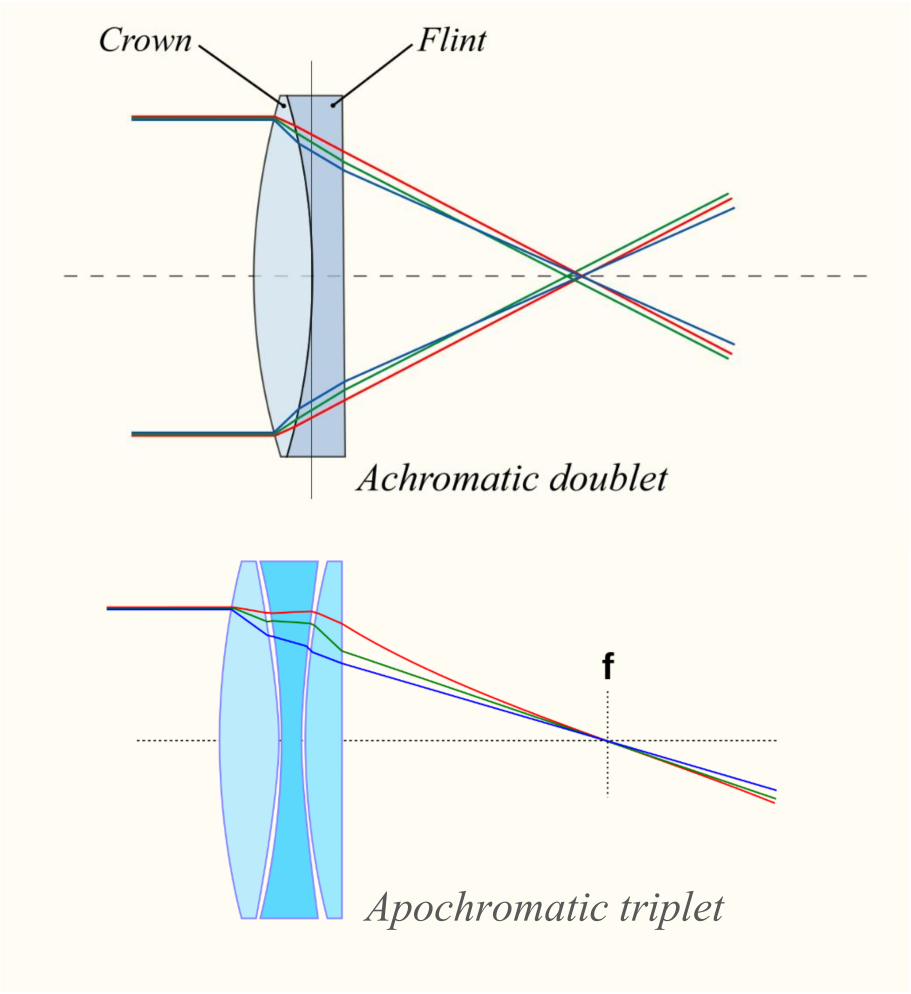
Out-of-focus images made by a magnifier

Correction of Axial Chromatic Aberration

- Achromatic lens
  - Correction with doublet or triplet etc.
    - Coupling of different dispersion property lenses
    - Focusable multi-wavelength rays on a single point
    - Cannot correct perfectly on all wavelengths

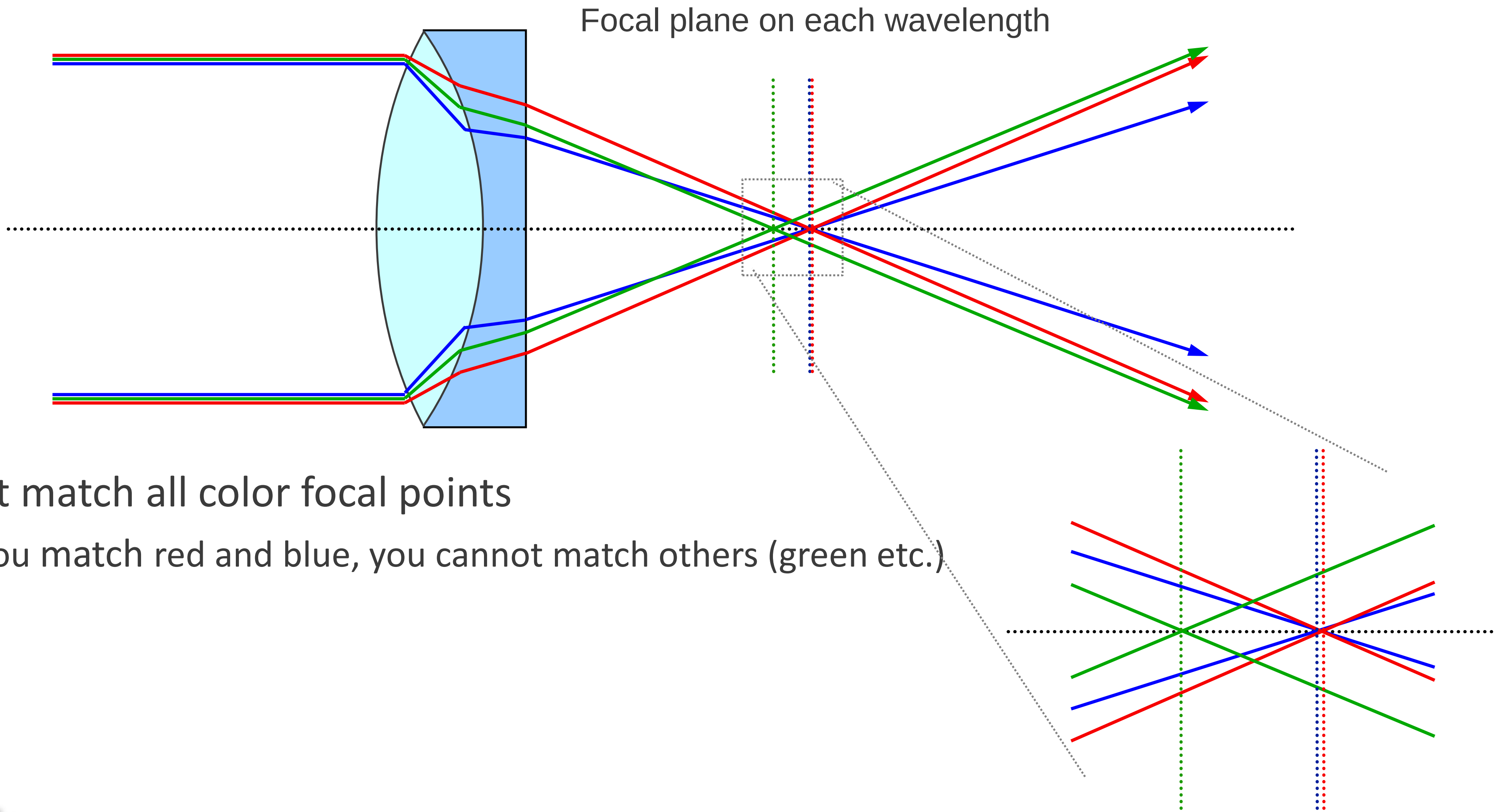
Achromatic Lens

- Achromatic lens (Achromat)
  - Achromatic doublet etc.
  - Focusable two wavelength rays on the same point
    - e.g. red and blue
- Apochromatic lens (APO)
  - Apochromatic triplet etc.
  - Generally focusable three wavelength rays
    - e.g. red, green and blue



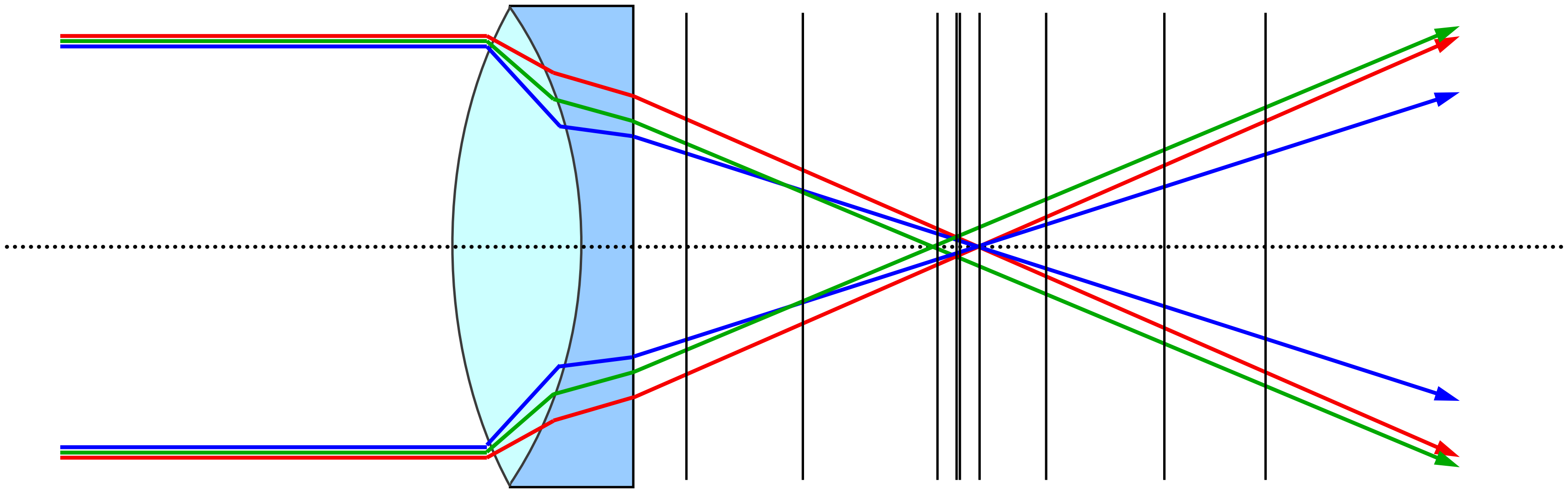
DrBob, https://commons.wikimedia.org/wiki/File:Lens6b-en.svg
Egmason, https://commons.wikimedia.org/wiki/File:Apochromat_2.svg

Example of Achromatic Doublet Correction

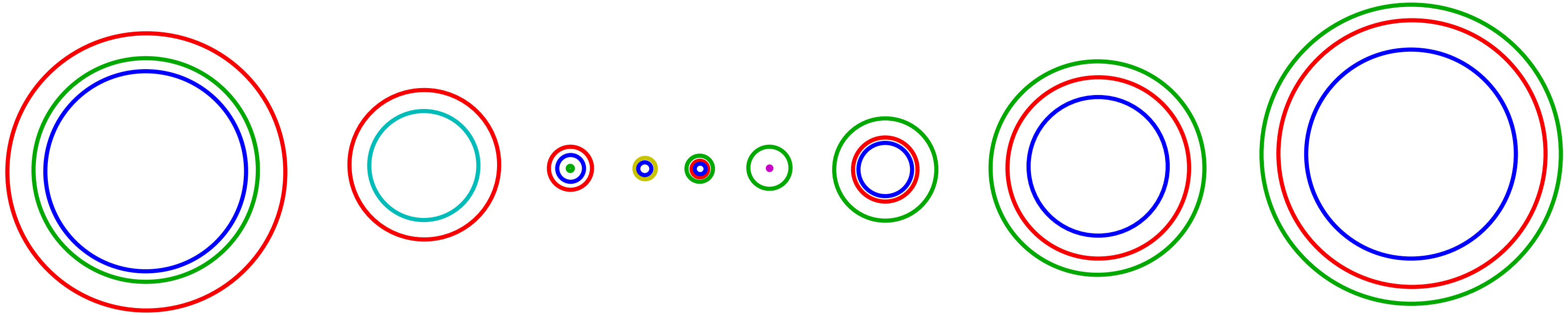


- Cannot match all color focal points
  - If you match red and blue, you cannot match others (green etc.)

Example of Achromatic Doublet Bokeh

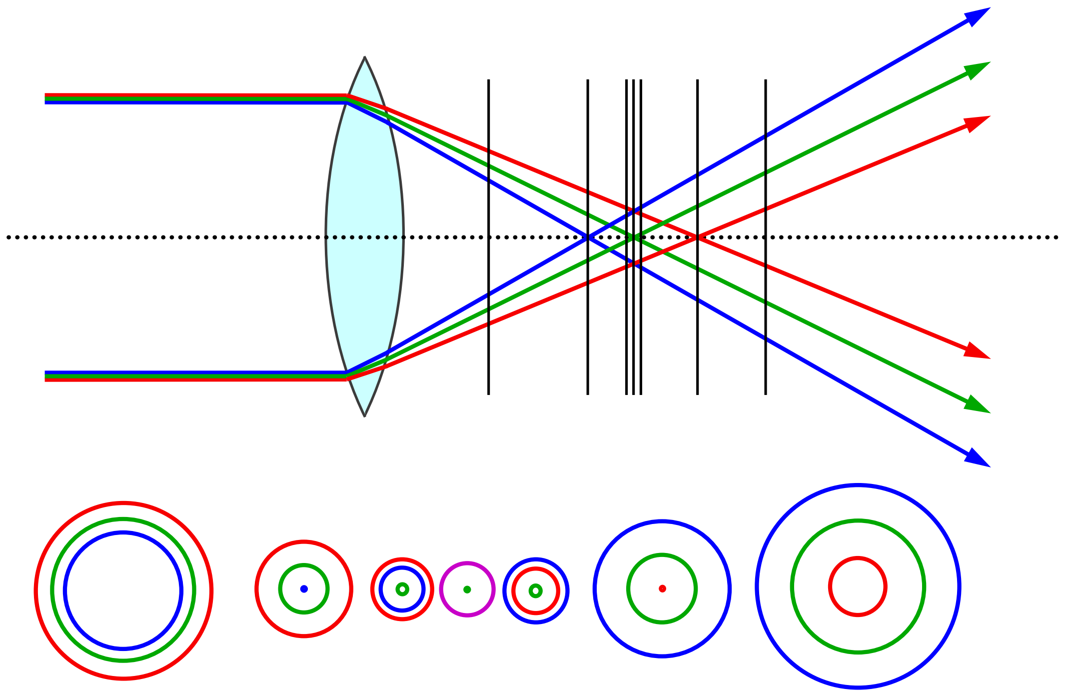


Spot diagram of marginal rays

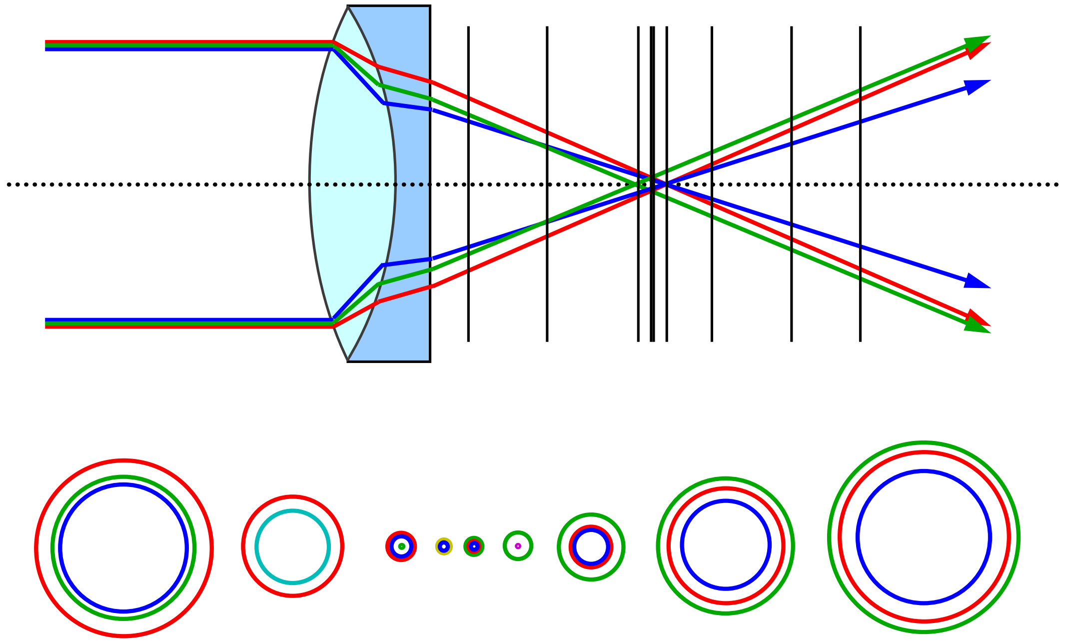


Front bokeh   Back bokeh

Comparison



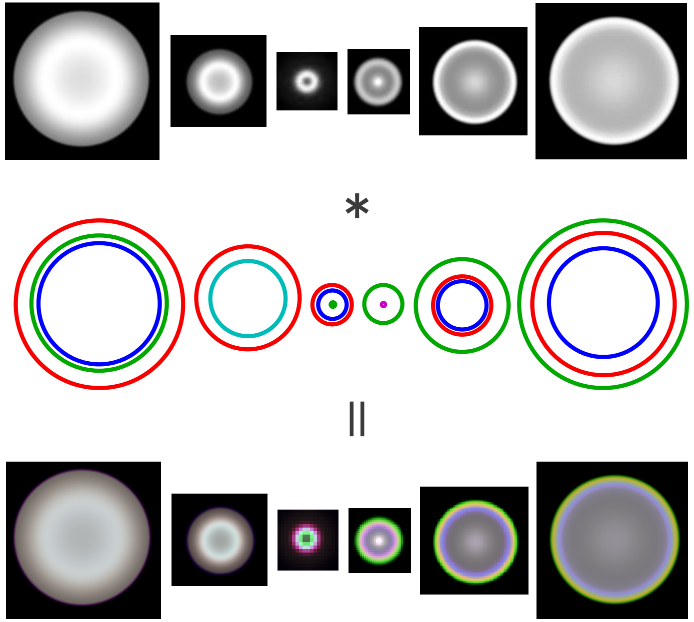
Axial chromatic aberration



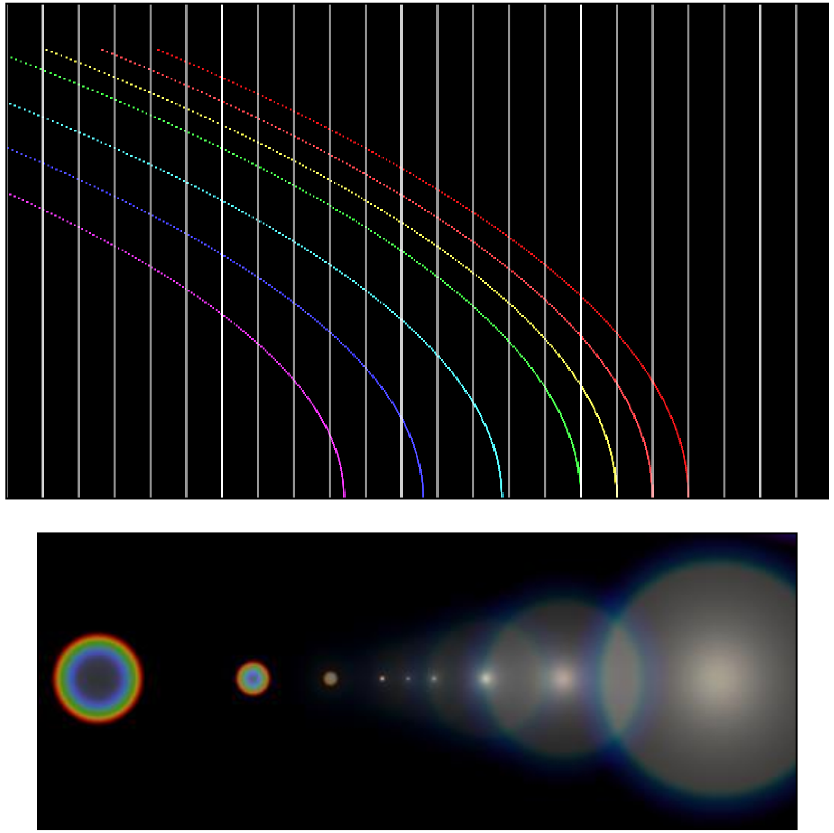
Residual chromatic aberration
a.k.a. secondary spectrum

Correction by Achromatic Doublet

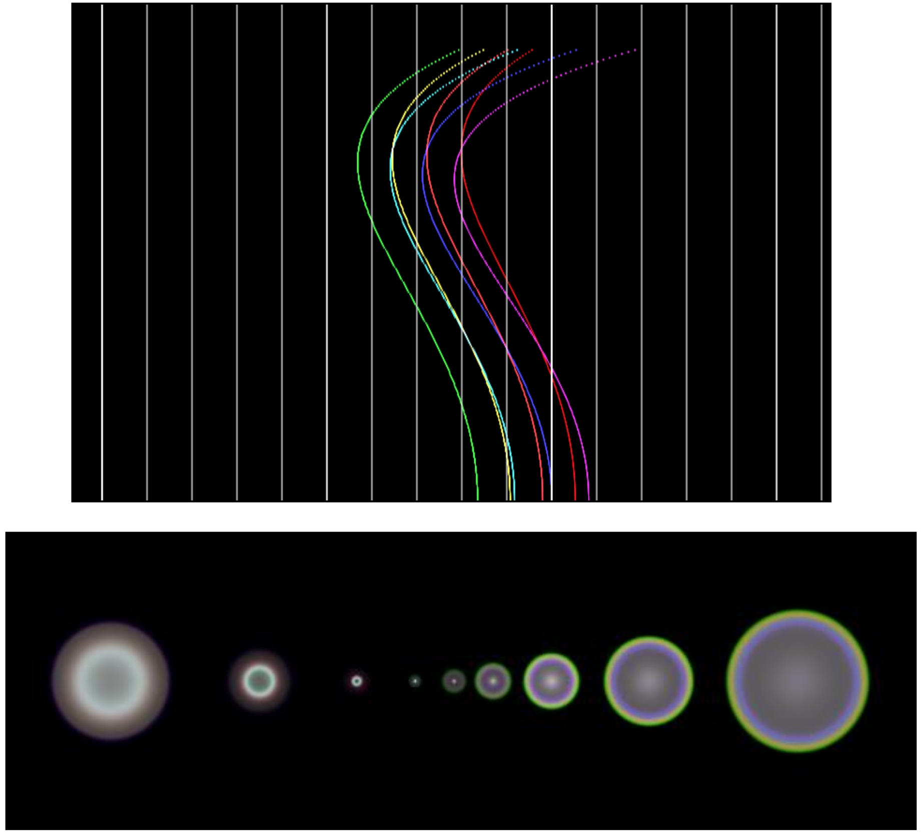
- Doublet also corrects spherical aberration
- Combination bokeh of each character
  - Residual aberration of spherical aberration
    - Soft / Sharp edge
    - Dark center / sharp peak
  - Residual aberration of axial chromatic aberration
    - Concentric colored circles
- ⇒Complicated gradation



Diagrams and Bokeh with Multiple Wavelengths



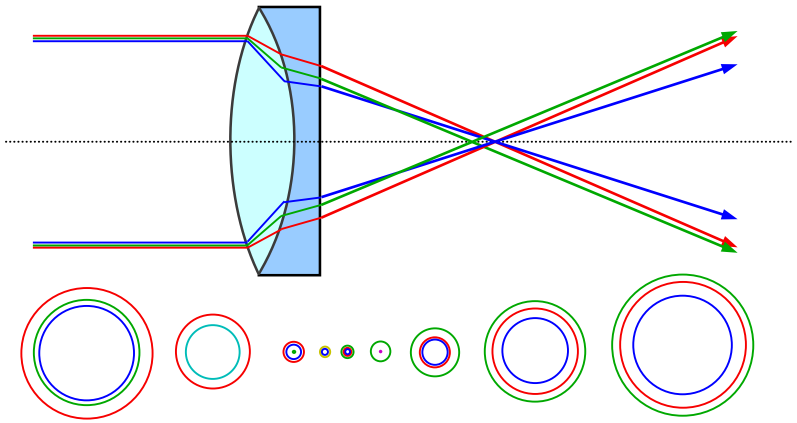
Spherical lens
without correction



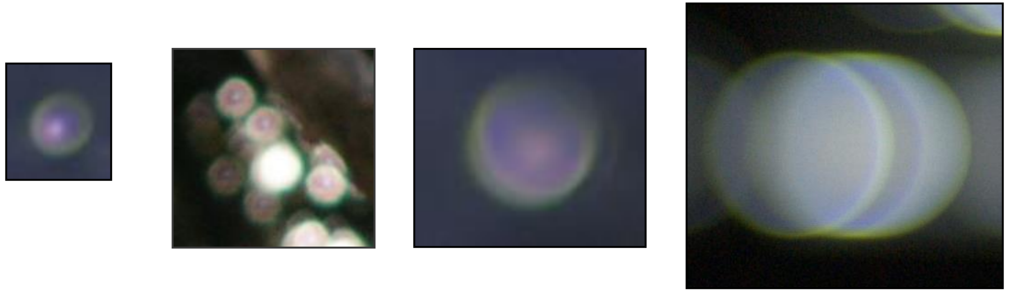
Doublet lens

Corrected Bokeh from Aberrations

- Correction by achromatic doublets
  - Widely used
  - Typical correction example
    - Soft purple fringe on front bokeh
    - Sharp green fringe on back bokeh



Front bokeh in photographs

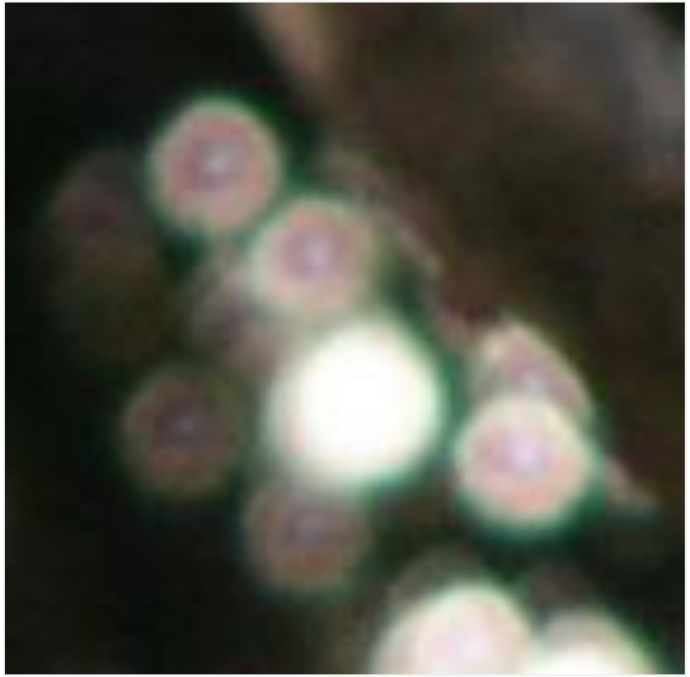


Back bokeh in photographs

Front Bokeh with Purple Fringe

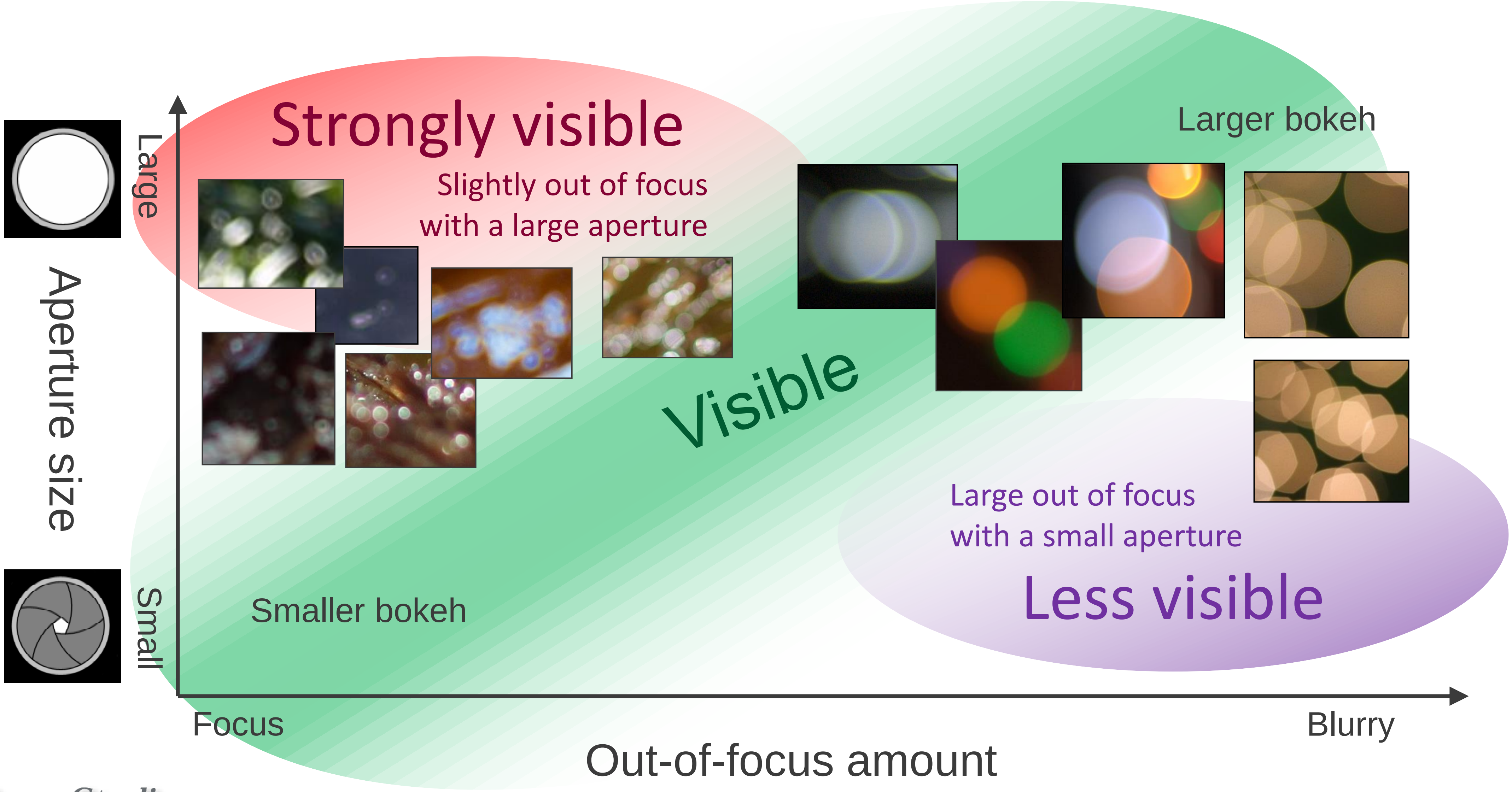
Front bokeh in photographs

Back Bokeh with Green Fringe



Back bokeh in photographs

Is Residual Aberration Visible or Not?



Is Residual Aberration Visible or Not? (Cont’d)

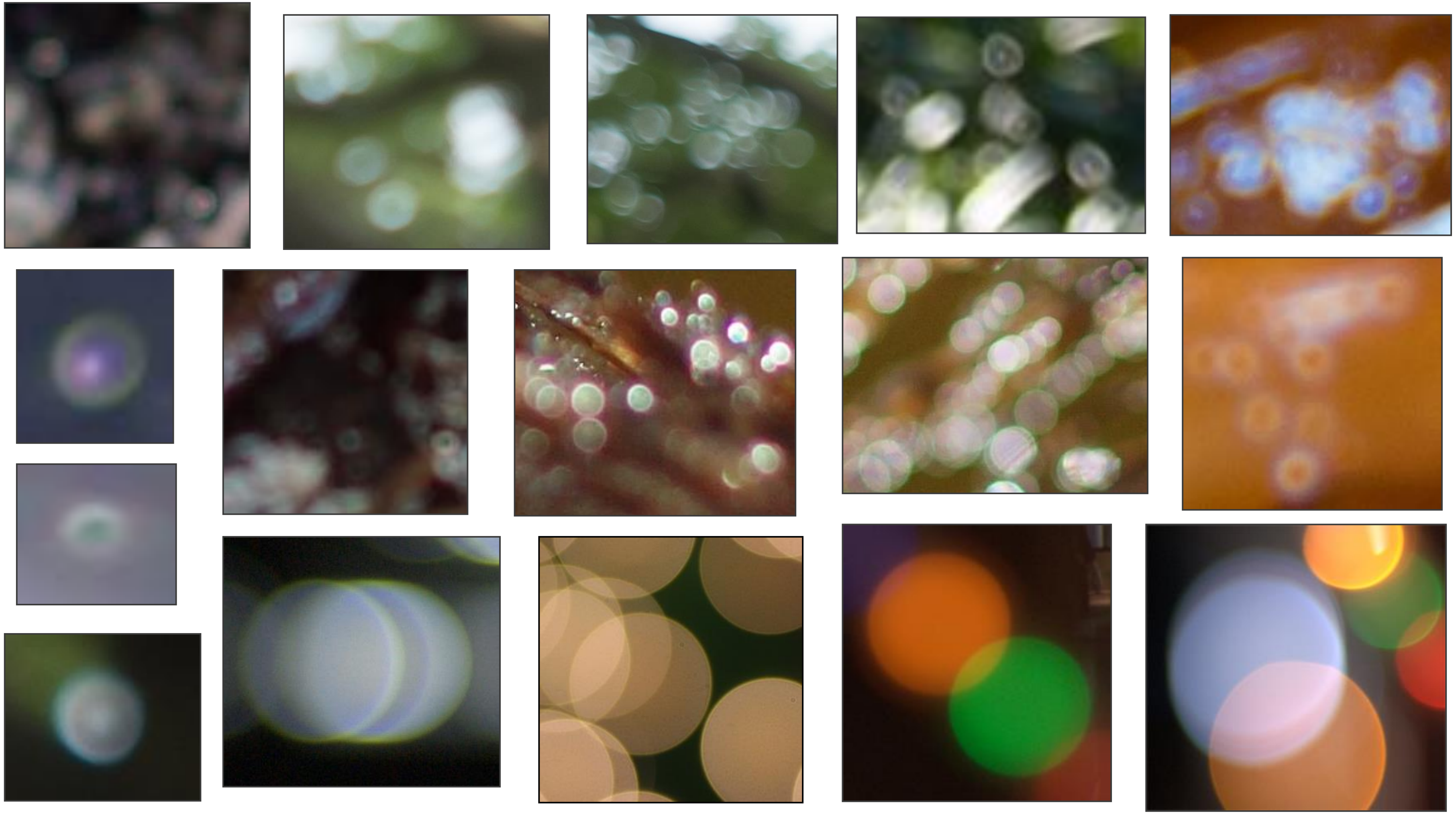
- Strongly visible
  - Slightly out of focus with a large aperture
- Less visible
  - Large out of focus with a small aperture

Residual Aberrations and Bokeh Characteristics

Bokeh Characteristics

- Bokeh Characteristics vary by:
  - Aberrations
  - Residual aberrations
    - Different corrections make different characteristics
- Residual aberrations are essentially undesired
  - But they are characteristics of real photos

Various Bokeh from Photographs



Phenomena of Multiple-Lens Systems

Multiple-Lens Systems

- Actual optical system is composed of multiple lenses in order to:
  - Correct aberrations
  - Zoom
  - Reduce focus breathing
  - Others

Multiple-Lens vs. Single-Lens

- More complex aberrations
- Various bokeh characteristics
- Different focus breathing
- Variable maximum aperture
- Optical Vignetting
- And more …

Focus Breathing

- Focus breathing
  - FOV varies when focusing

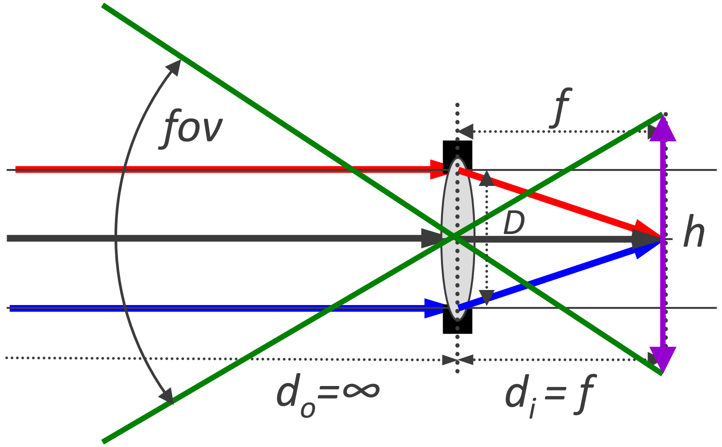
- Types of focus breathing
  - Single Lens
    - Focusing by shifting lens or sensor
      - Focal length is constant and independent of focus distance
    - At close focus, FOV becomes narrower
      - In spite of constant focal length
        - » Extend image distance (between lens and sensor)
        - » While the F-number is the same, the effective F-number is larger (darker)

  - Multiple-lens system
    - Breathing varies by the focusing mechanism

Focal Length, Sensor Size and FOV

- Field of view is often explained as…
  – Depends on the ratio of sensor size and focal length
    - $fov = \text{atan}(h / 2f) * 2$
    - $f = h / (\tan(fov / 2) * 2)$

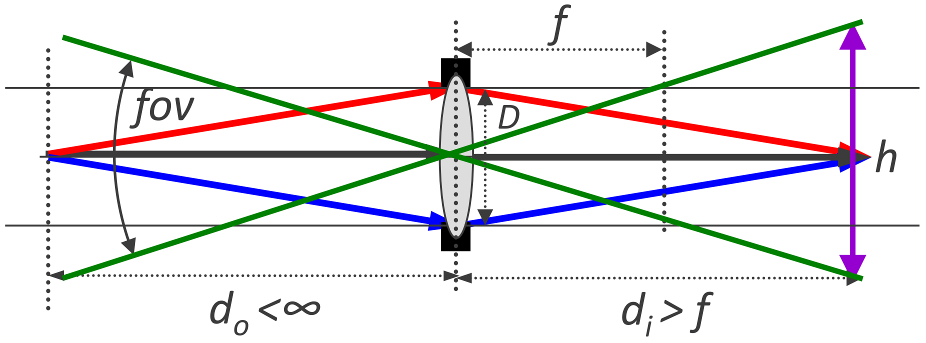
    - fov : field of view
    - h : sensor size



- Not accurate
  – Accurate only when focusing on infinite distance

Accurate FOV Calculation

- Field of view
  - Depends on the ratio of sensor size and image distance
    - $fov = \mathrm{atan}(h / 2d_i) * 2$
    - $d_i = h / (\tan(fov / 2) * 2)$
  - Effective calculation only when a lens exists
    - $fov = \mathrm{atan}(h\,(d_o - f) / 2d_o f) * 2$
    - $f = (d_o h / 2) / (\tan(fov / 2) * d_o + h / 2)$
- Effective F-number
  - $F_e = d_i / D$
  - Effective calculation only when a lens exists
    - $F_e = (1 + M)\,F$
    - $F_e = (d_i / f)\,F$



Optical magnification ‘M’
$M = d_i / d_o$
$M = f / (d_o - f) = d_i / f - 1$

- Focus distance is also required in order to calculate correctly
  - If the focal length is constant, FOV becomes narrower with finite focus

Focusing Mechanisms

- All-Group Focusing / Film-Back Focusing
  - Same mechanism as single-lens system
  - Used in old lenses
  - FOV becomes narrower when close focus
    - An Effective F-number becomes decreased
- Front-Group Focusing
  - Used in old lenses
  - Usually FOV becomes narrower when close focus
    - An Effective F-number becomes decreased
- Inner (Internal) / Rear Focusing
  - a.k.a. IF / RF
  - Used in recent zoom lenses
  - Usually FOV becomes wider when close focus (less expensive lenses)
  - No-breathing focus (relatively expensive lenses)
    - An Effective F-number is constant

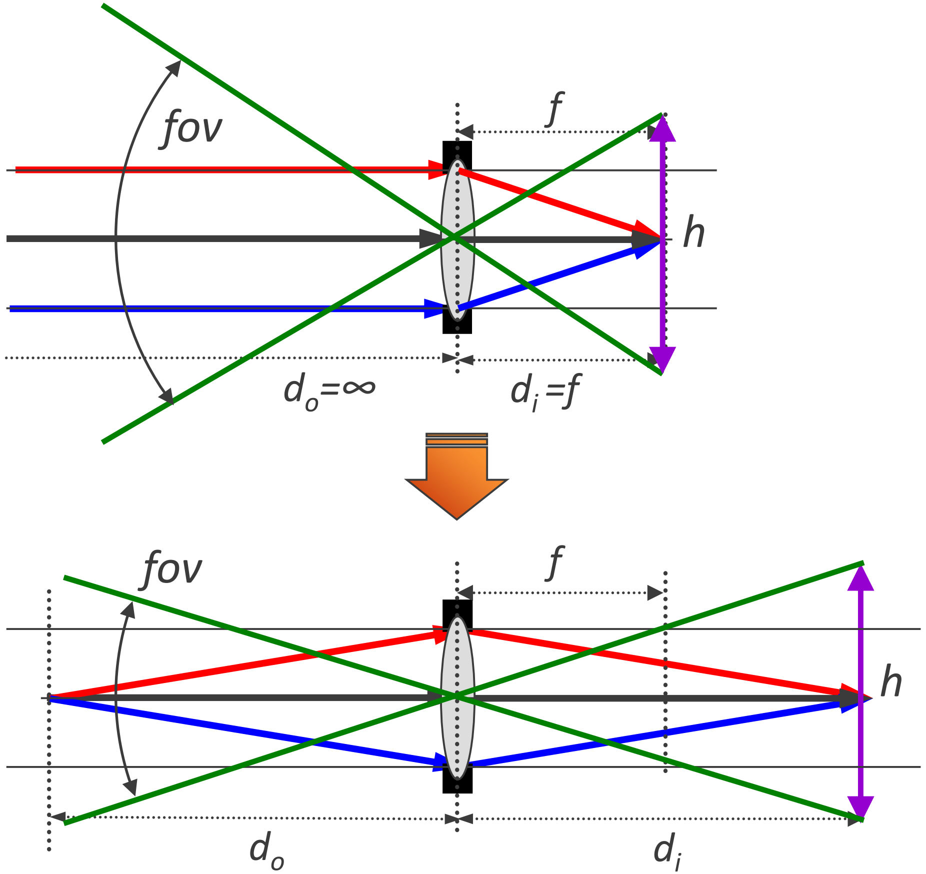
Focusing Mechanism and Breathing Examples

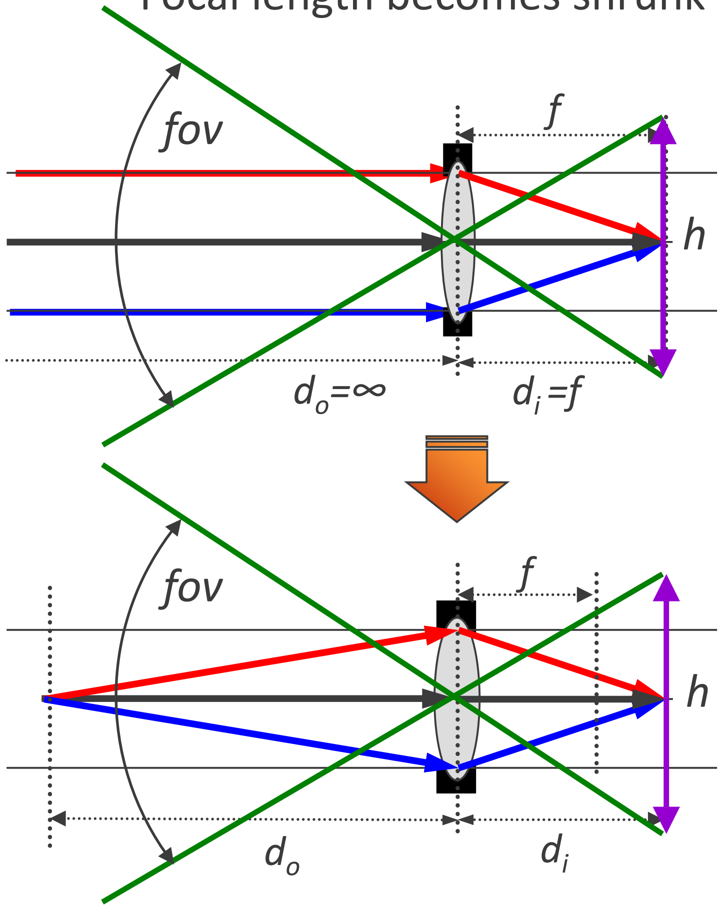
All-Group / Film-Back Focusing
FOV becomes narrower

Inner Focusing (expensive lens)
No breathing
Focal length becomes shrunk

Infinite focus

Close focus





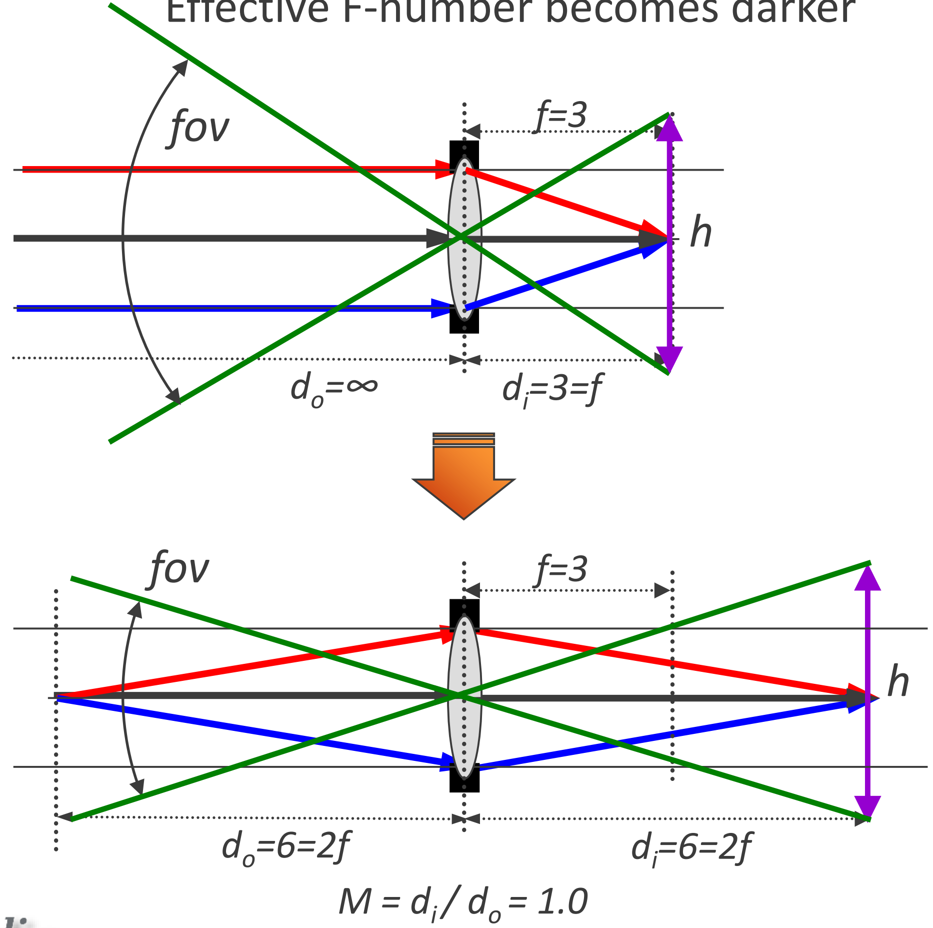
Focusing Mechanism and Breathing Examples

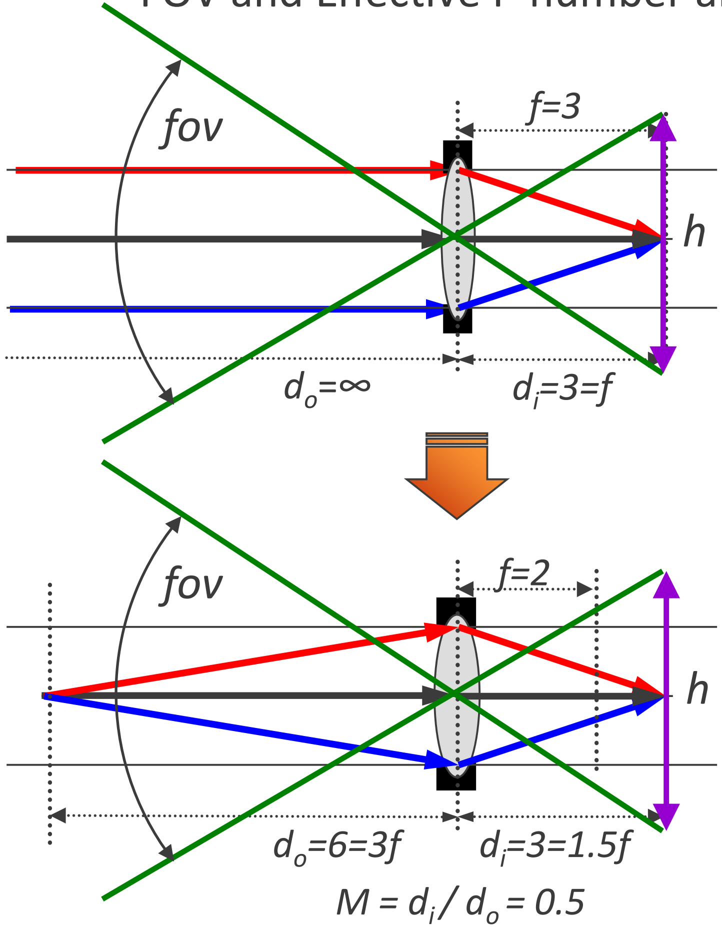
Shift sensor to backward 2f (or shift lens)
Focal length is constant
Effective F-number becomes darker

Image distance is fixed
Focal length is shrunk to 66.7%
FOV and Effective F-number are constant

Infinite focus

Focus on *2f*



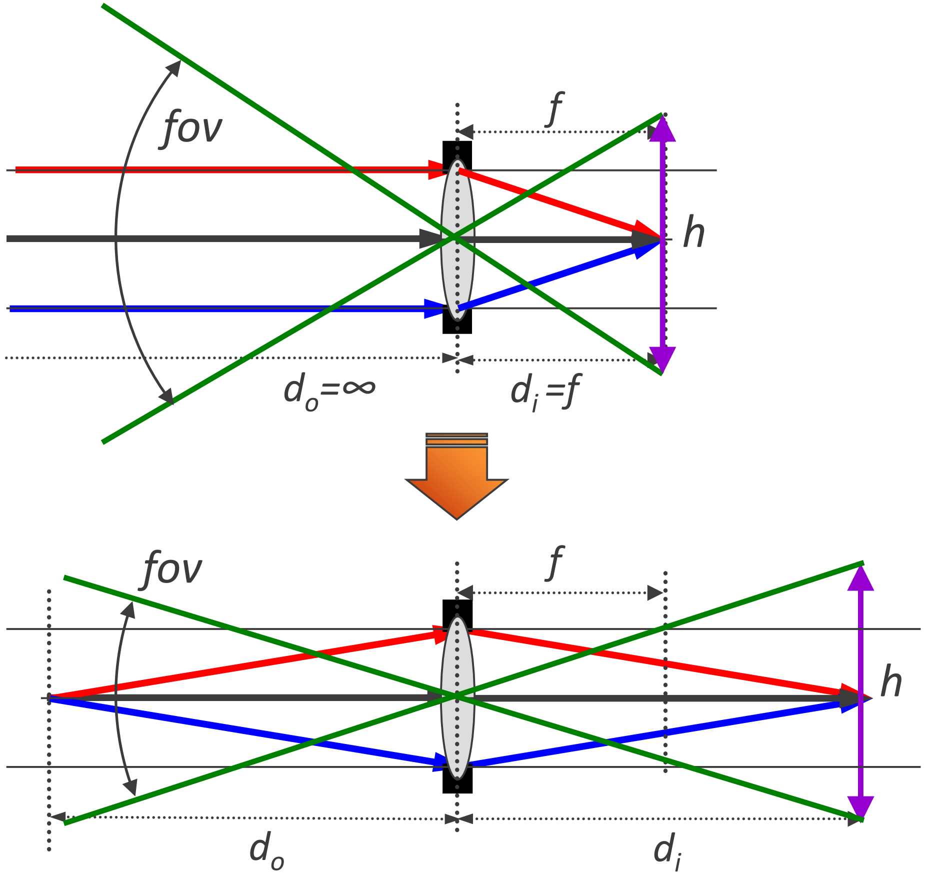


Focusing Mechanism and Breathing Examples

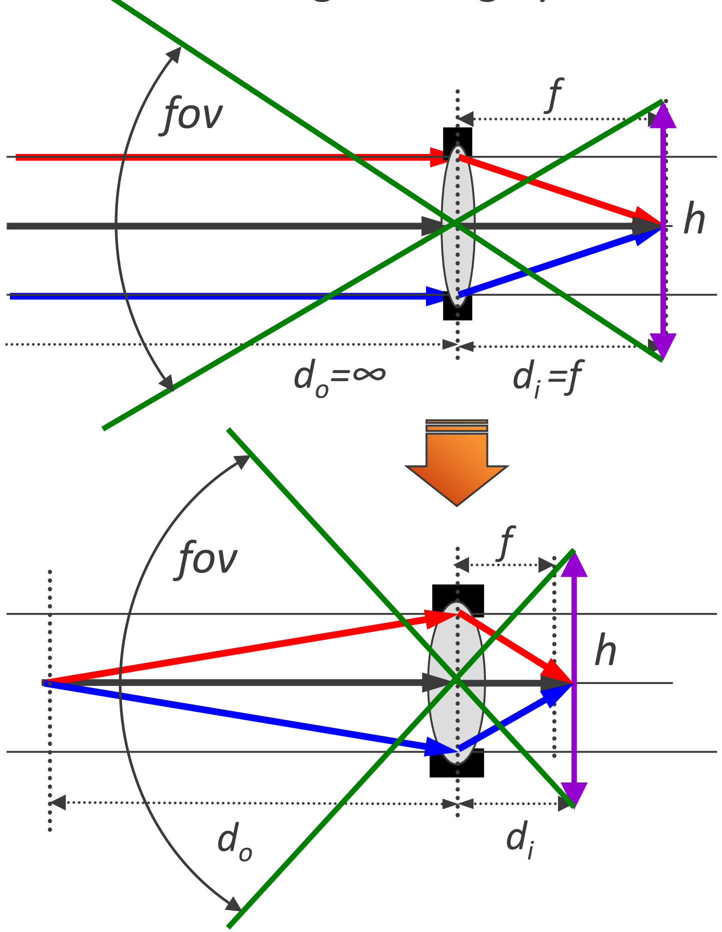
All-Group / Film-Back Focusing
FOV becomes narrower

Infinite focus

Close focus



Typical Inner Focusing
FOV becomes wider
Focal length is largely shrunk



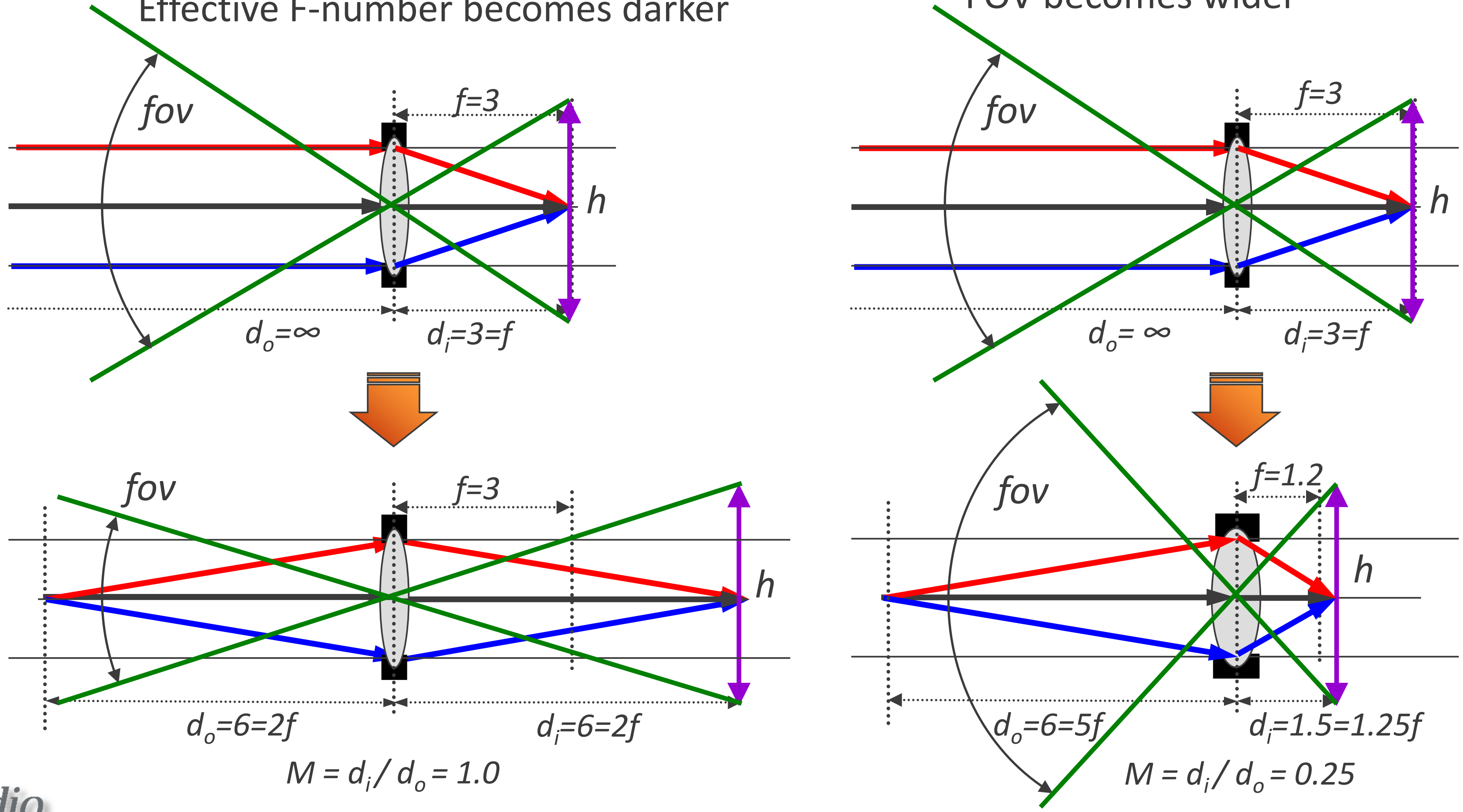
Focusing Mechanism and Breathing Examples

Shift sensor to backward 2f (or shift lens)
Focal length is constant
Effective F-number becomes darker

Focal length is shrunk to 40% in this case
Image distance is also shrunk to 50%
FOV becomes wider

Infinite focus

Focus on *2f*



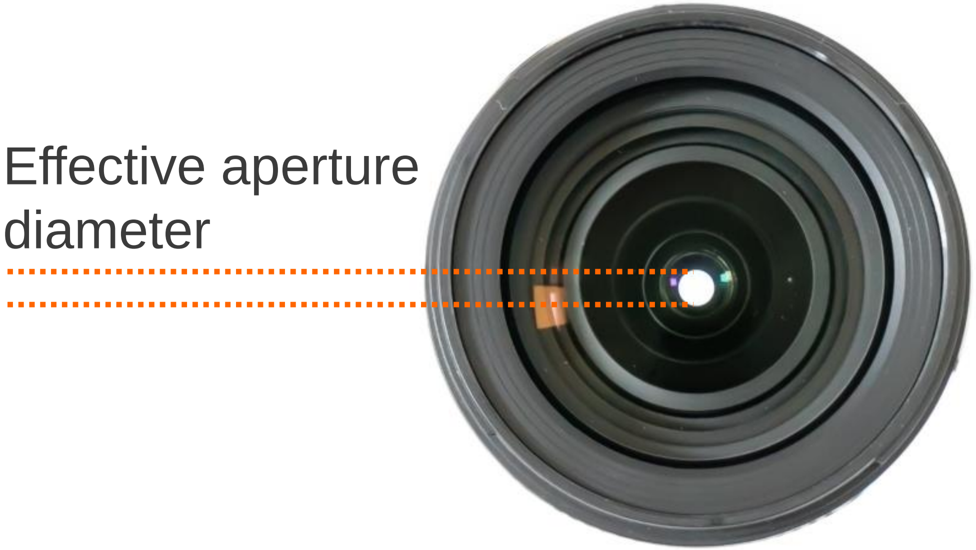
Variable Aperture Zoom Lenses

Wide (12mm)
Maximum aperture is f/2.8

Narrow (60mm)
Maximum aperture is f/4.0

Effective Aperture Diameter *'D'*

- Diameter of "Entrance Pupil"
  - Virtual image of the aperture as seen from the front
  - NOT a physical aperture diameter



Zooming Varies Virtual Image Diameter

- To keep the exposure, narrower FOV requires larger diameter

$$D = f / F$$

Zoom lens
12-60mm F2.8-4.0

Wide (12mm) f/2.8
D = 12/2.8 = ~4.2mm

Narrow (60mm) f/4
D = 60/4 = 15mm

Zoom Lens Types

- Fixed Aperture Zoom Lens
  - Minimum F-number is constant over the entire zoom range
  - Effective diameter is proportional to focal length ($D = f / F$)

- Variable Aperture Zoom Lens
  - Minimum F-number becomes larger as the FOV becomes narrower
  - Effective diameter is not proportional to focal length

*Note that the “Minimum F-number” means the “Maximum Aperture”

Wide (12mm)
f/2.8

Narrow (60mm)
f/4.0

Examples of Zoom Lens Products

- OLYMPUS D.ZUIKO (4/3“)
  - 14-42mm F3.5-5.6
  - 12-60mm F2.8-4.0
  - 35-100mm F2.0 Fixed aperture
- CANON EF-S (APS-C)
  - 17-55mm F2.8 Fixed aperture
  - 18-135mm F3.5-5.6
  - 55-250mm F4.0-5.6
- DX NIKKOR (APS-C)
  - 17-55mm F2.8 Fixed aperture
  - 18-140mm F3.5-5.6
  - 55-200mm F4.0-5.6
- CANON EF (35mm)
  - 24-70mm F2.8 Fixed aperture
  - 70-200mm F2.8 Fixed aperture
  - 100-400mm F4.5-5.6
- FX NIKKOR (35mm)
  - 24-70mm F2.8 Fixed aperture
  - 70-200mm F2.8 Fixed aperture
  - 80-400mm F4.5-5.6

Tendency of Actual Lenses

- Lower magnification zoom
- More expensive "Brighter lens"

→ Minimum F-number varies a little

- Higher magnification zoom
- Less expensive "Darker lens"

→ Minimum F-number varies a lot

Conclusion

Conclusion

- Actual lenses have various aberrations
  - Many solutions correct aberrations
  - Aberrations cannot be completely corrected
    - Residual aberrations give bokeh its character
- Bokeh is rich in variety
  - Different corrections show different representations
  - Color fringes and gradation vary between front and back bokeh
  - Conspicuousness: smaller out-of-focus > larger out of focus

Conclusion (cont'd)

- Actual optical system is composed of multiple lenses in order to:
  - Correct aberrations
  - Zoom
  - Reduce focus breathing

- Many phenomena do not conform to single lens rules
  - Different focus breathing
  - Different zooming aperture varying

  } by different mechanisms

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