# Lenses

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

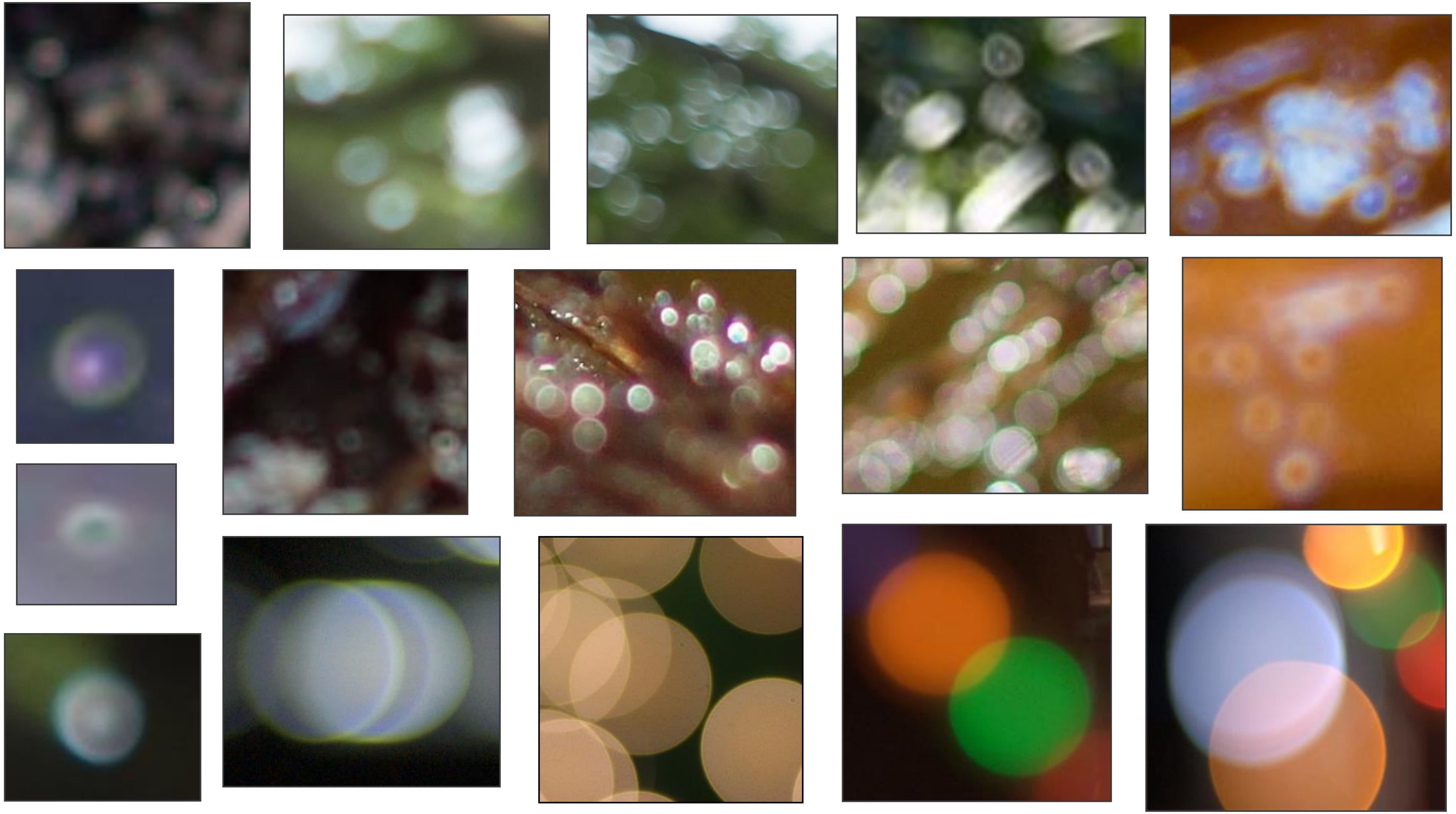
SIGGRAPH 2015 Course

Masaki Kawase

Silicon Studio, Corp.

masa@siliconstudio.co.jp

# 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

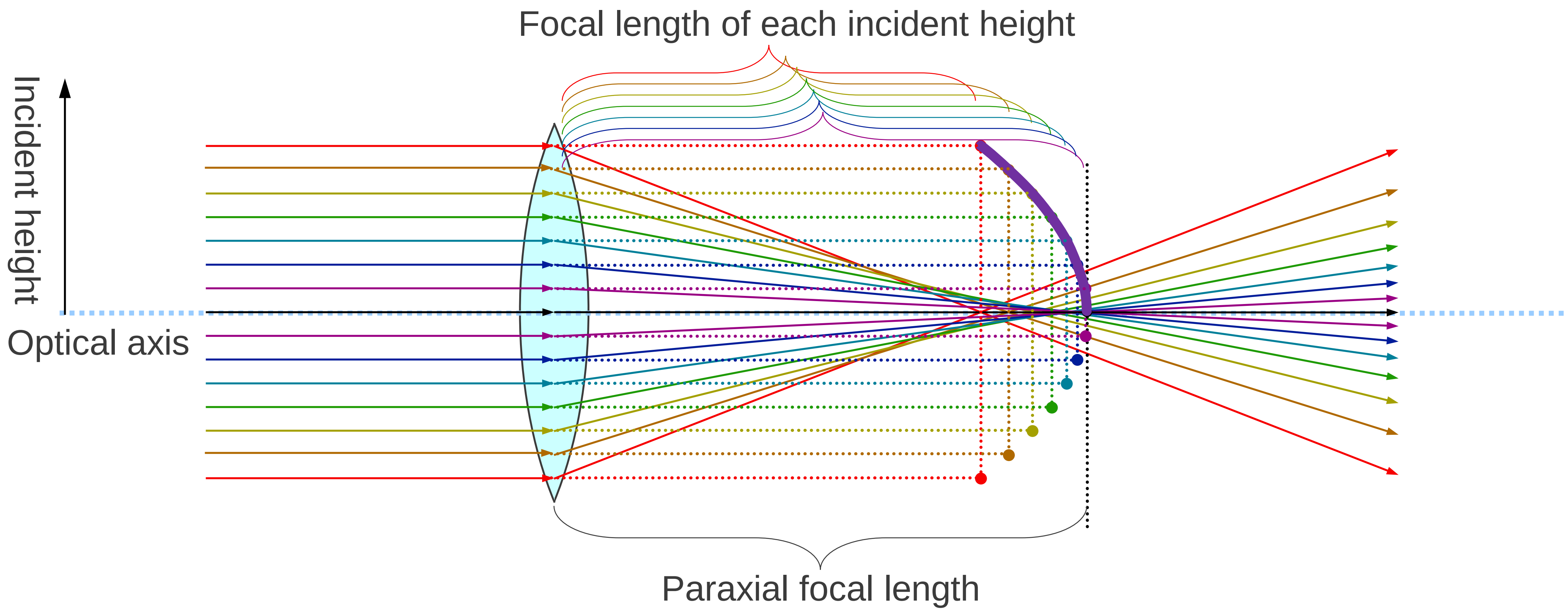
- Monochromatic aberrations (Seidel's five aberrations)
  - Spherical Aberration (SA)
  - Coma
  - Field Curvature
  - Astigmatism
  - Distortion
- Chromatic aberrations (CA)
  - Lateral Chromatic Aberration (CA of Magnification)
  - Longitudinal Chromatic Aberration (Axial CA)

# Details of Important Aberrations Which Affect Bokeh

# Spherical Aberration

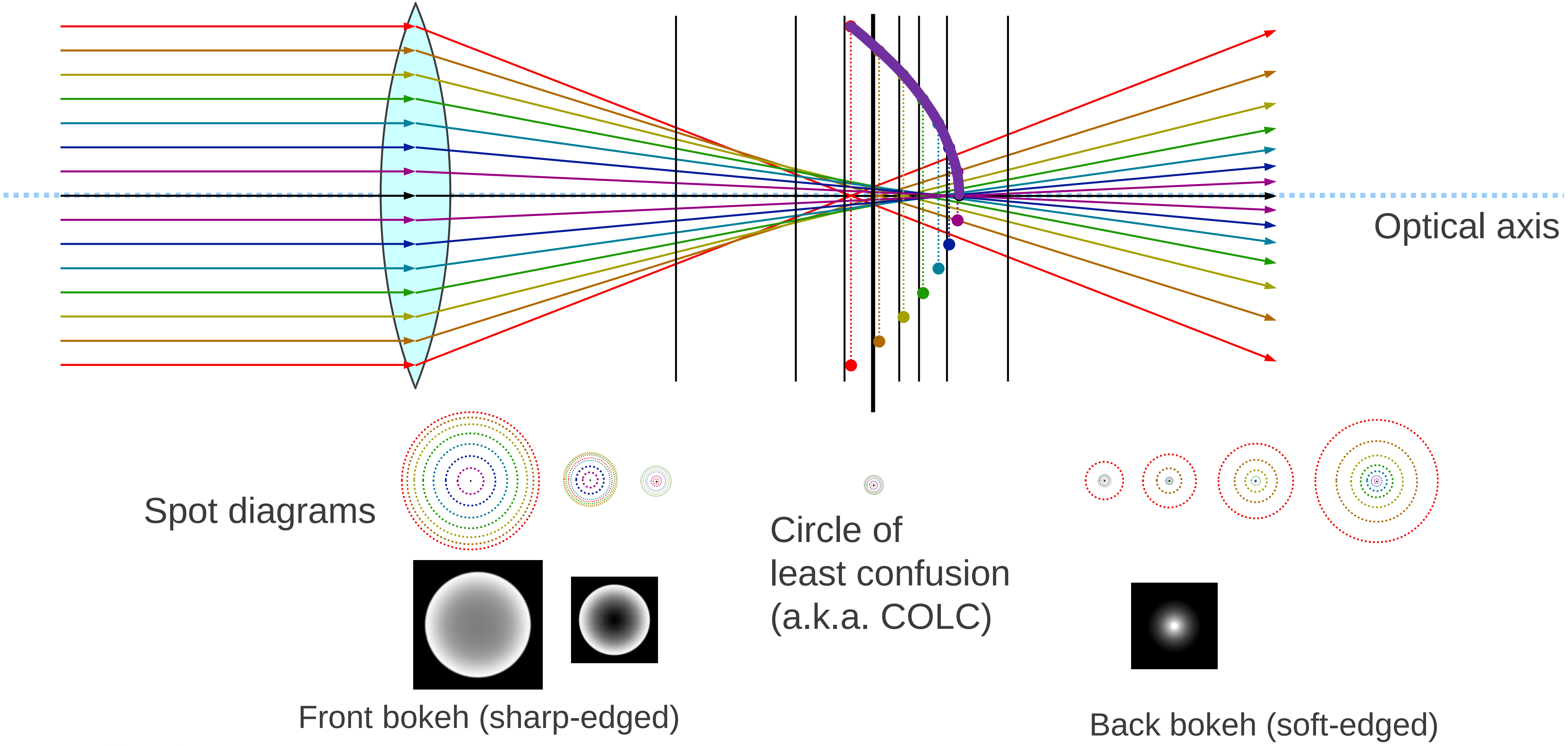
- The focal length deviation of rays parallel to the optical axis
- The aberration is caused by a spherical lens
  - Spherical surfaces are:
    - Not ideal for lenses
    - Commonly used due to the high manufacturability

# Principle of Spherical Aberration




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

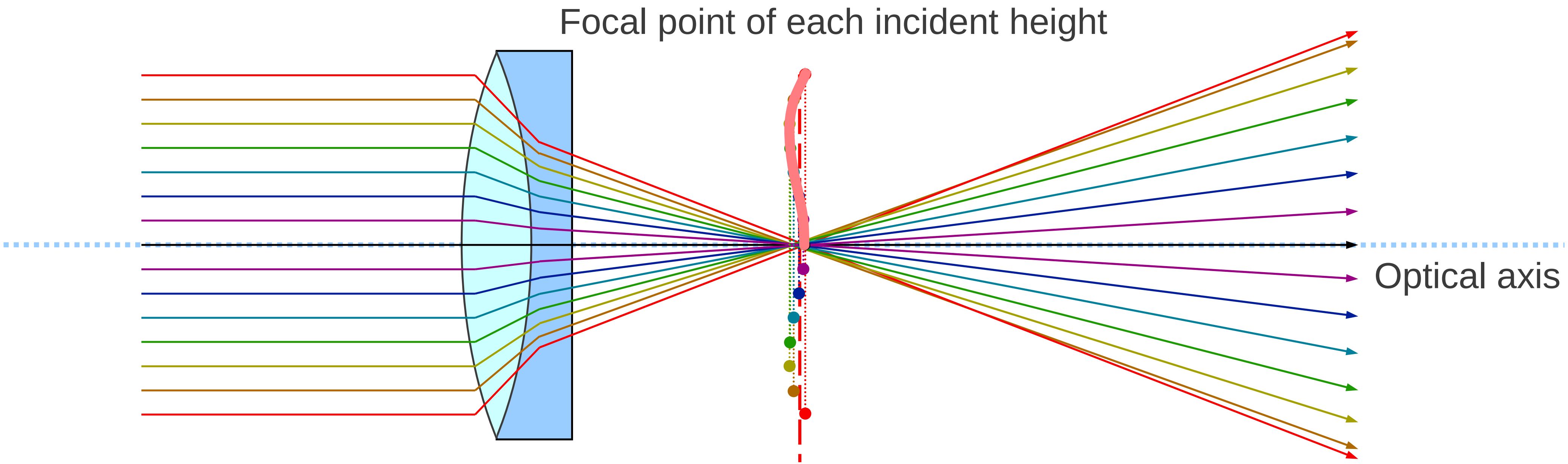
# Spherical Lens Bokeh



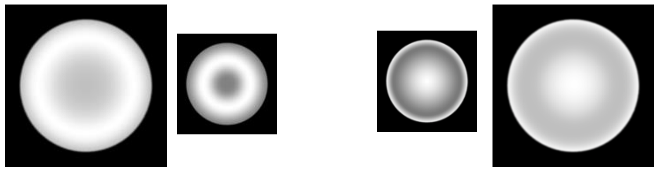
# Corrections for Spherical Aberration

- 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

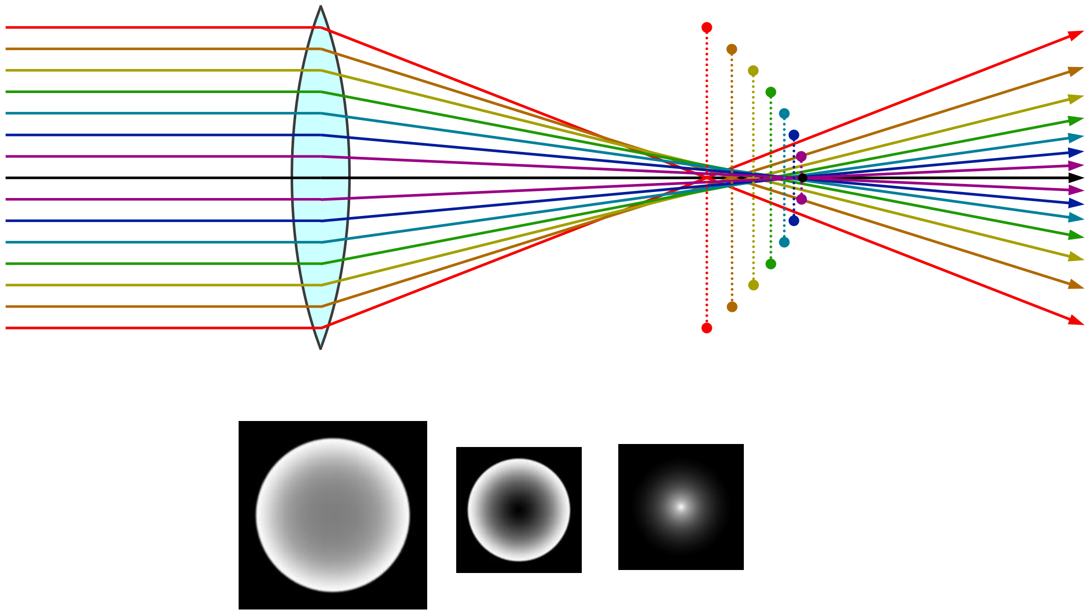
# Example of Doublet Lens Correction



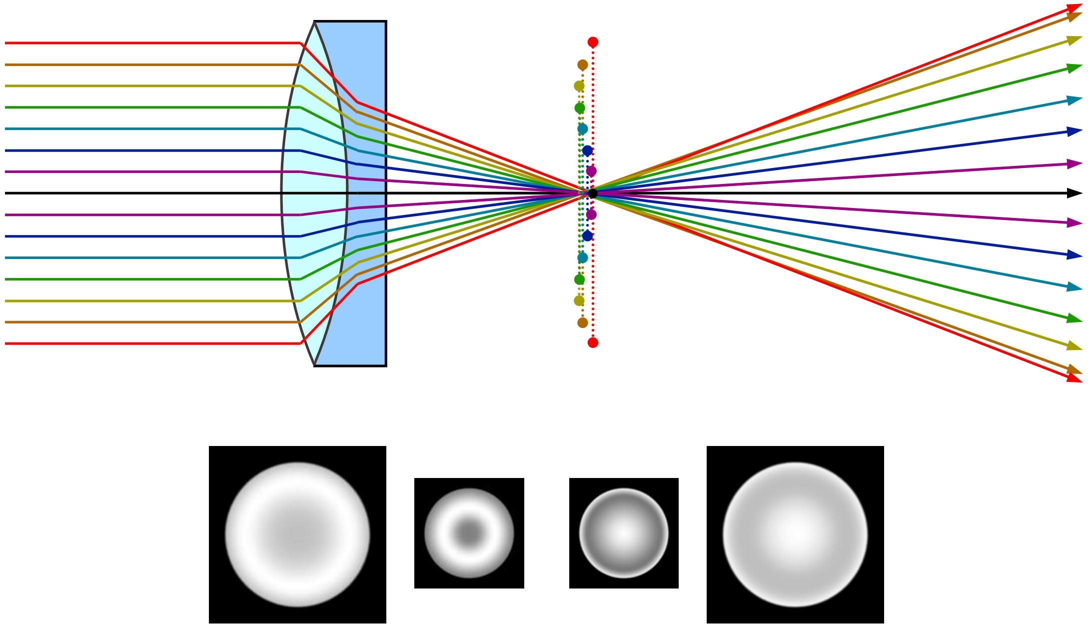

- More complicated bokeh than spherical



# Comparison



Spherical lens

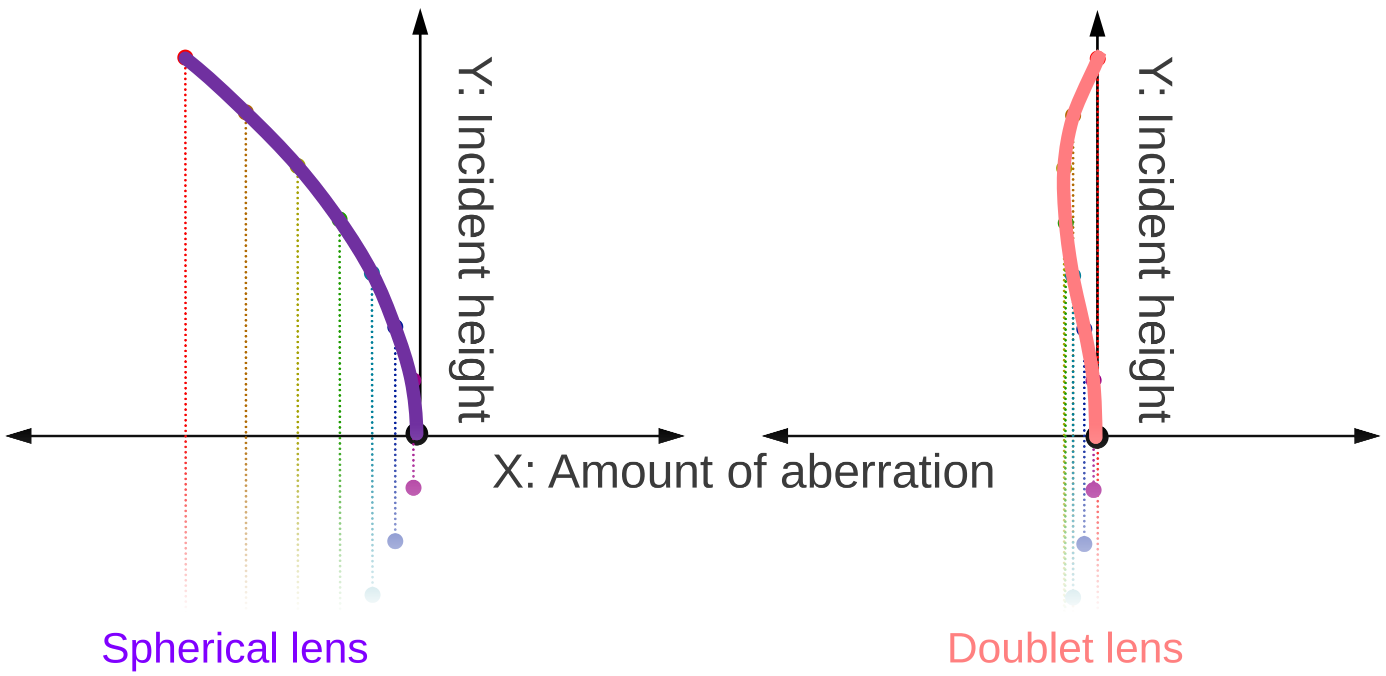


Doublet lens
Sharper focus
Flatter bokeh

Silicon Studio

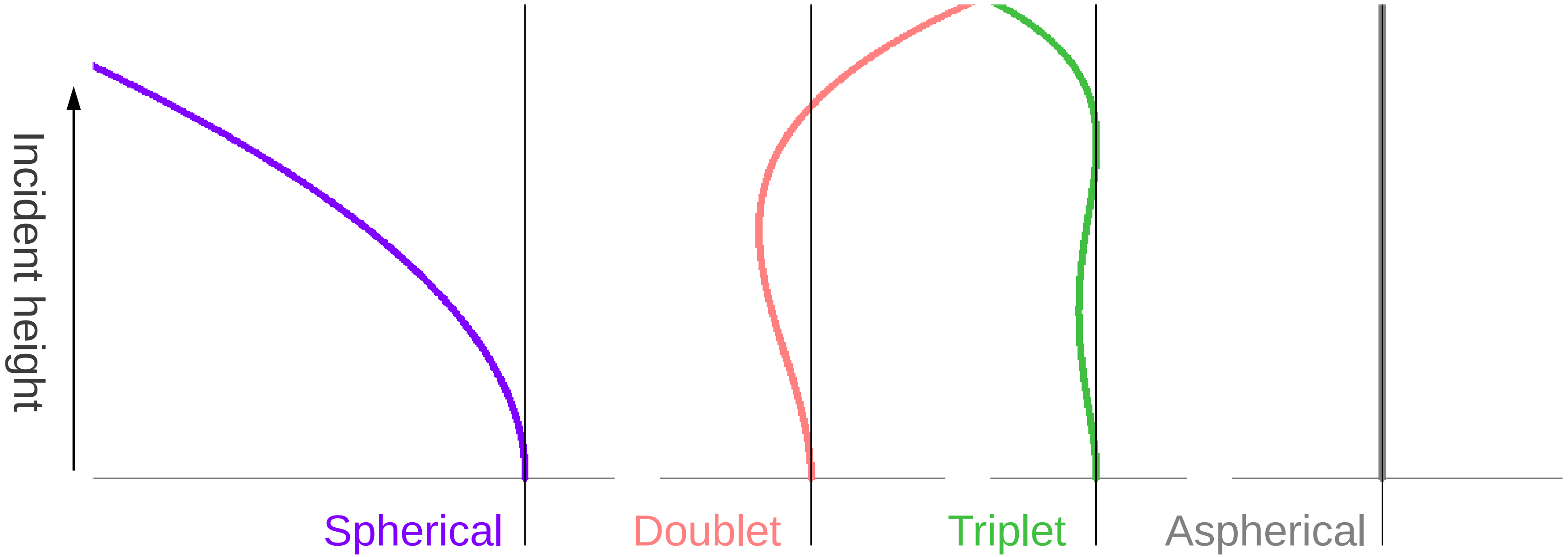
# Spherical Aberration Charts (Longitudinal Aberration Diagrams)





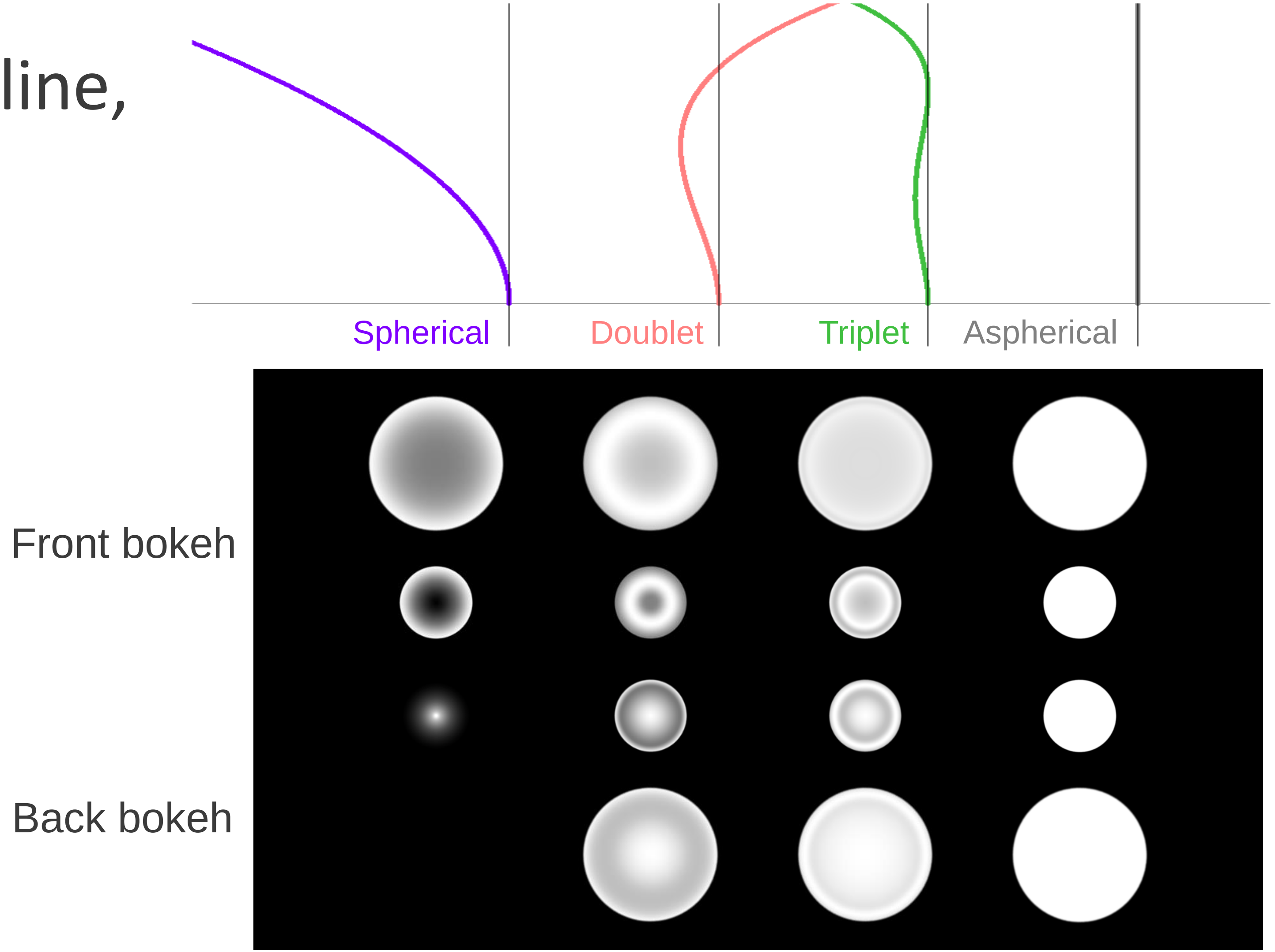

- Y-axis : Incident height (independent variable)
- X-axis : Amount of spherical aberration (dependent variable)

# Spherical Aberration Charts (Longitudinal Aberration Diagrams)



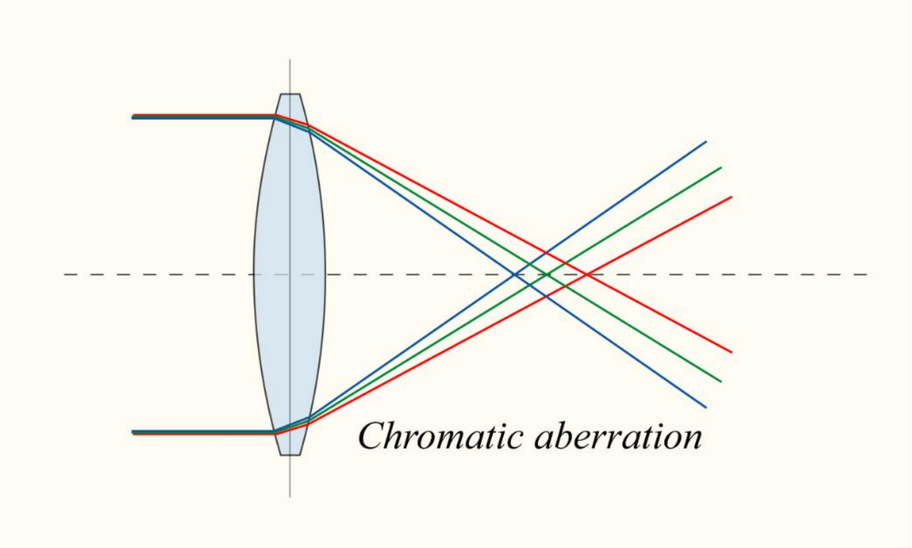
# Diagrams and Bokeh

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



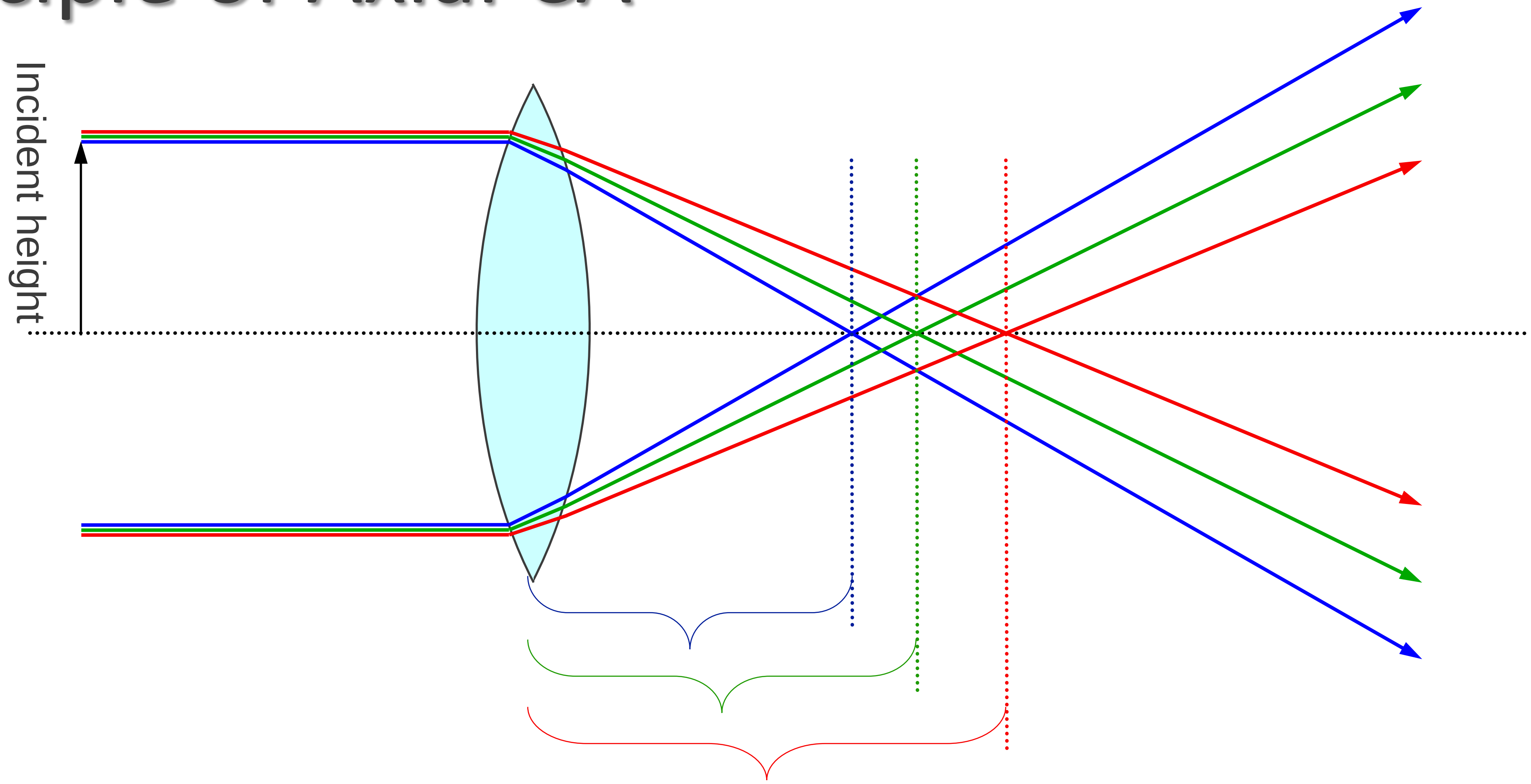
# Axial Chromatic Aberration

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




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

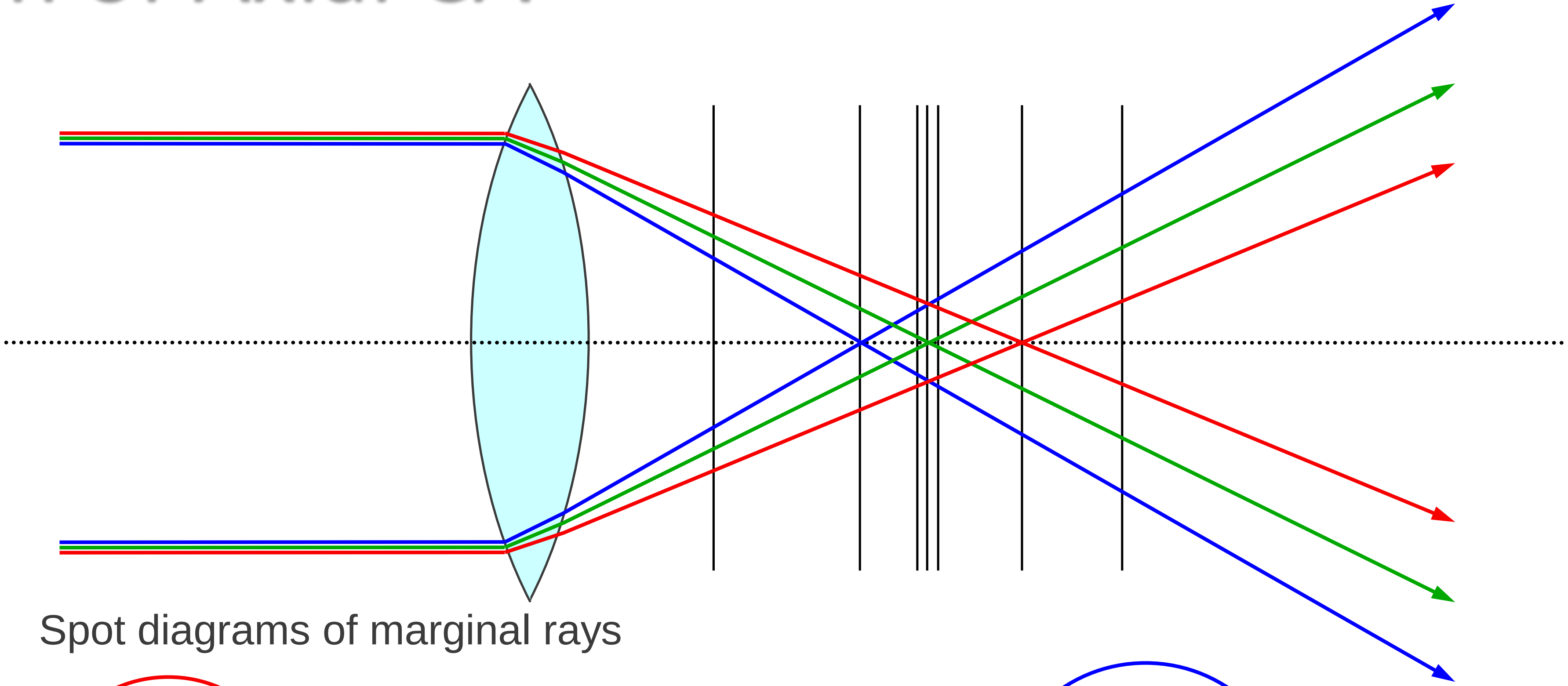
# Principle of Axial CA



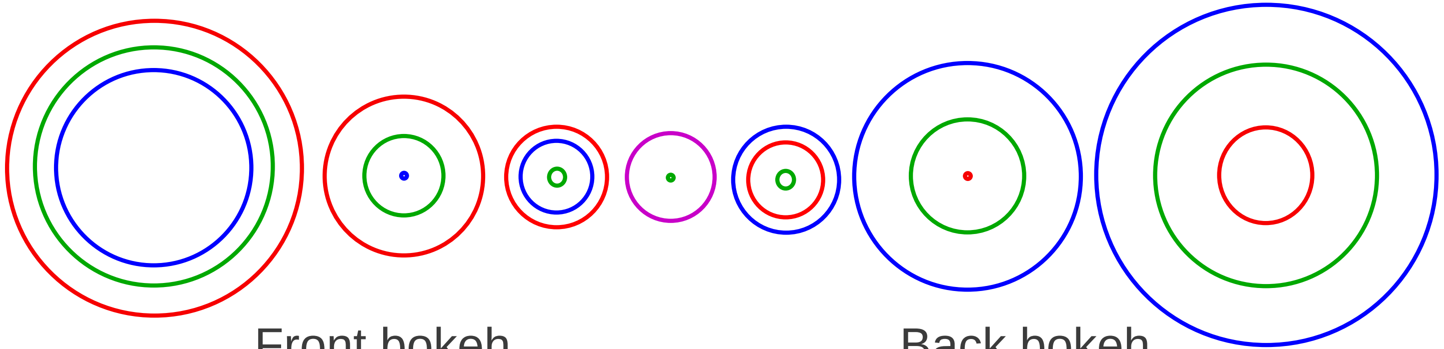

Focal length on each wavelength

SIGGRAPH2015 Xroads of Discovery

# Bokeh of Axial CA



Spot diagrams of marginal rays

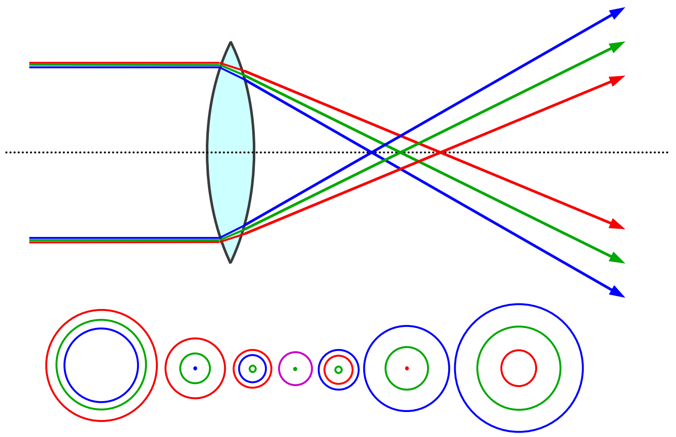


Front bokeh

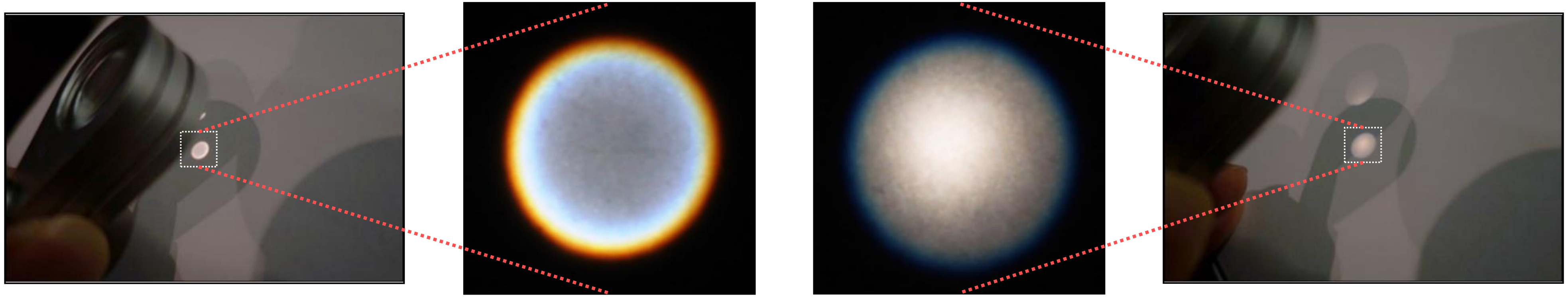
Back bokeh

Silicon Studio

# 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

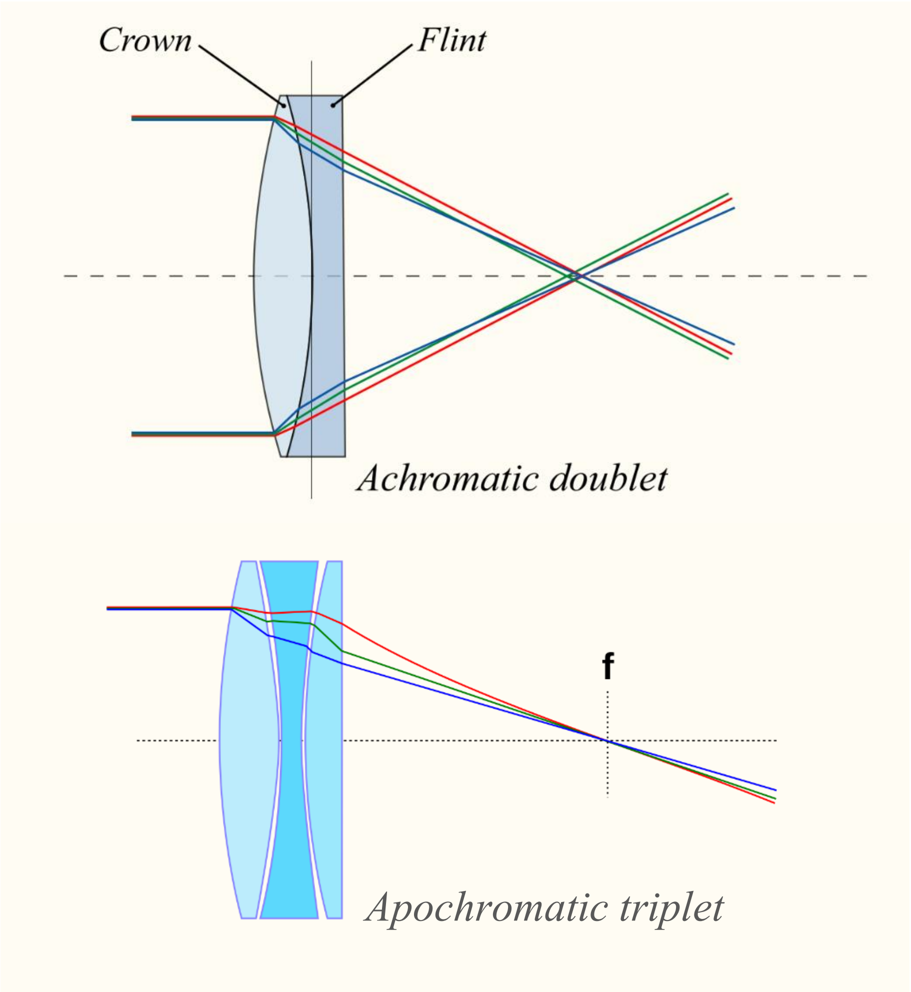
Out-of-focus images made by a magnifier

# 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

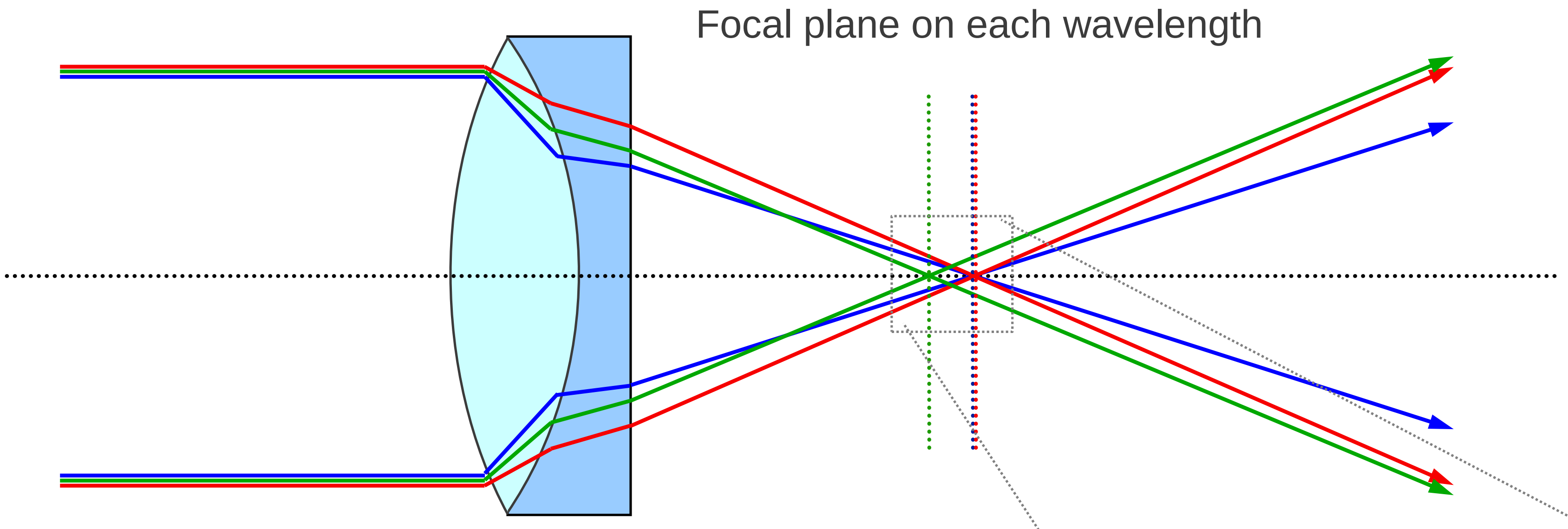
# Achromatic Lens

- 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

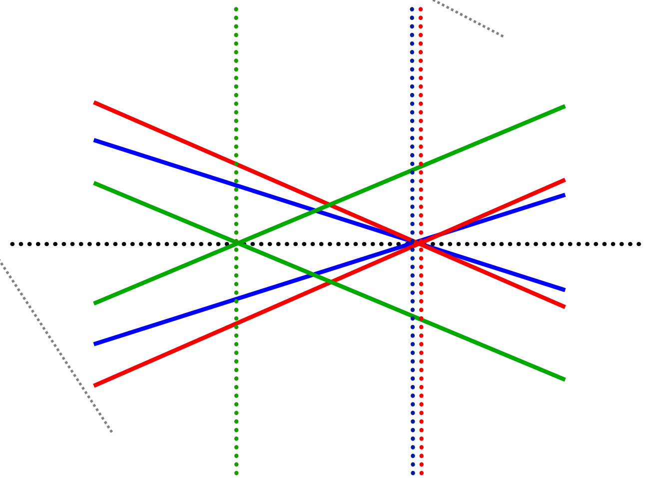



DrBob, https://commons.wikimedia.org/wiki/File:Lens6b-en.svg
Egmason, https://commons.wikimedia.org/wiki/File:Apochromat_2.svg

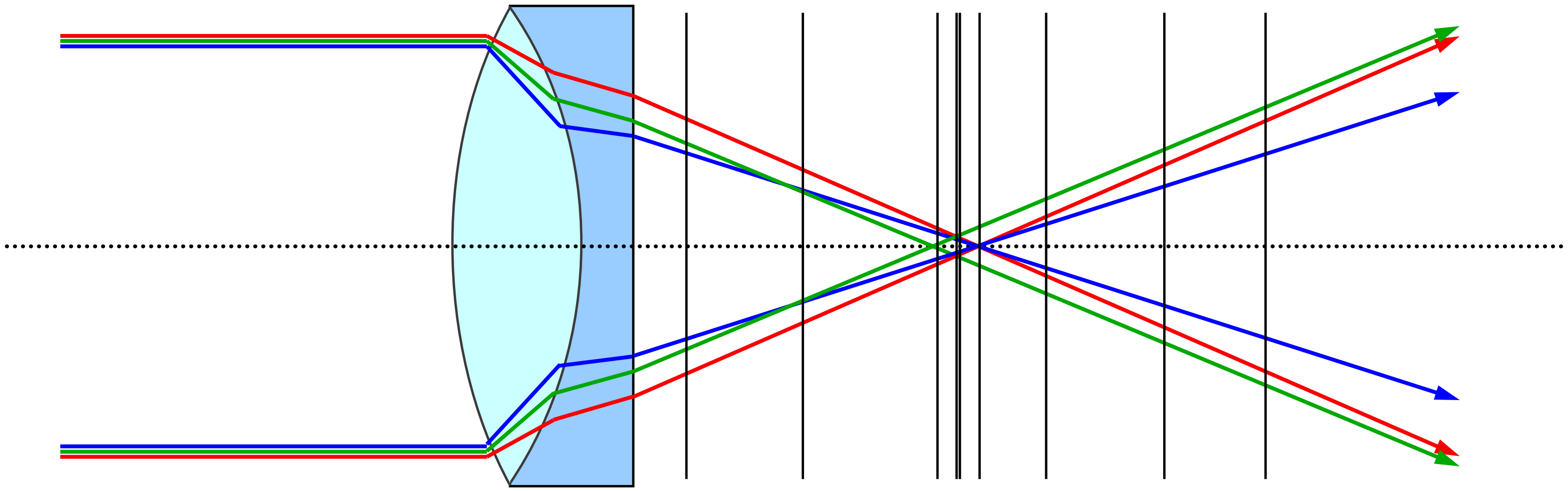
# Example of Achromatic Doublet Correction



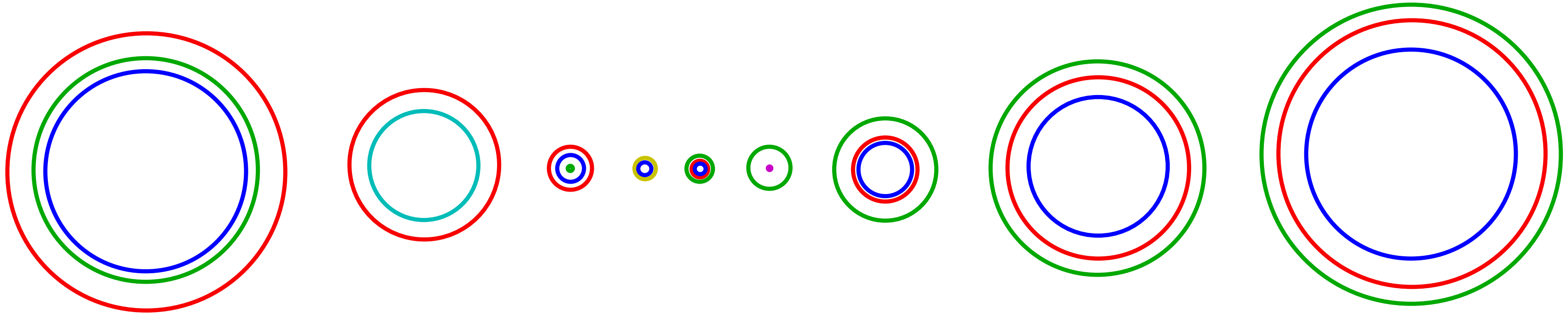

- Cannot match all color focal points
  - If you match red and blue, you cannot match others (green etc.)



# Example of Achromatic Doublet Bokeh



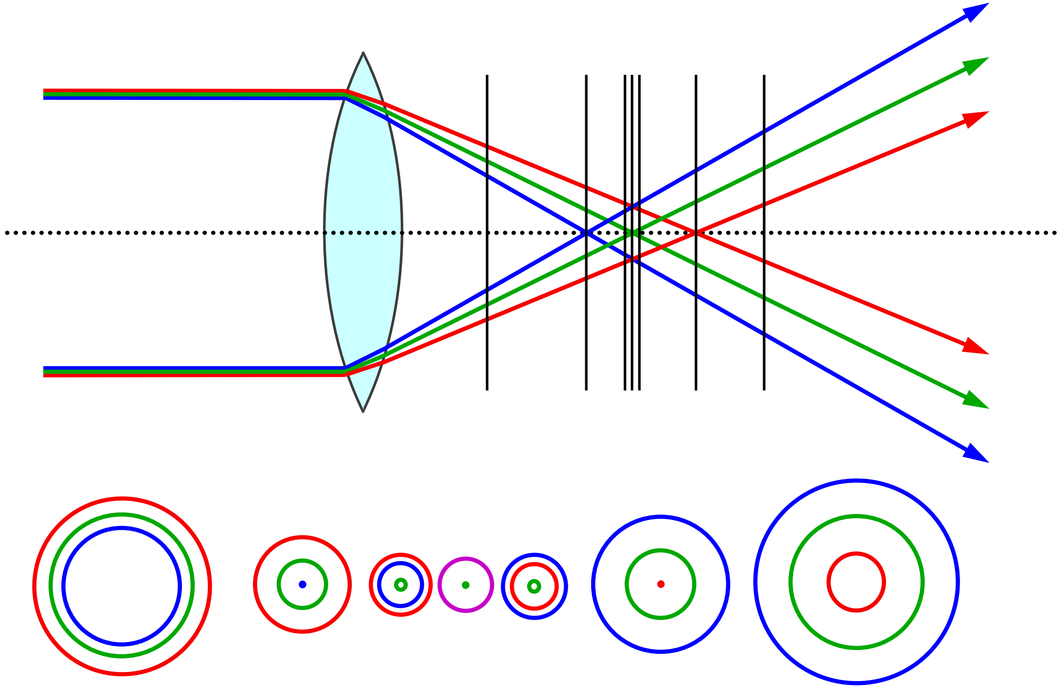
Spot diagram of marginal rays



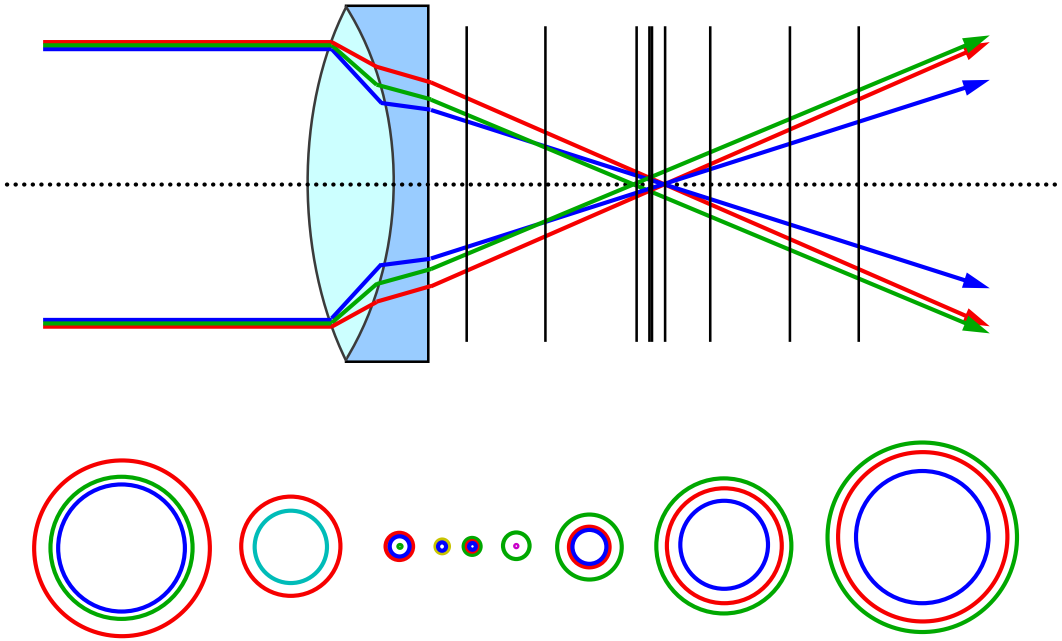
Front bokeh

Back bokeh

# Comparison



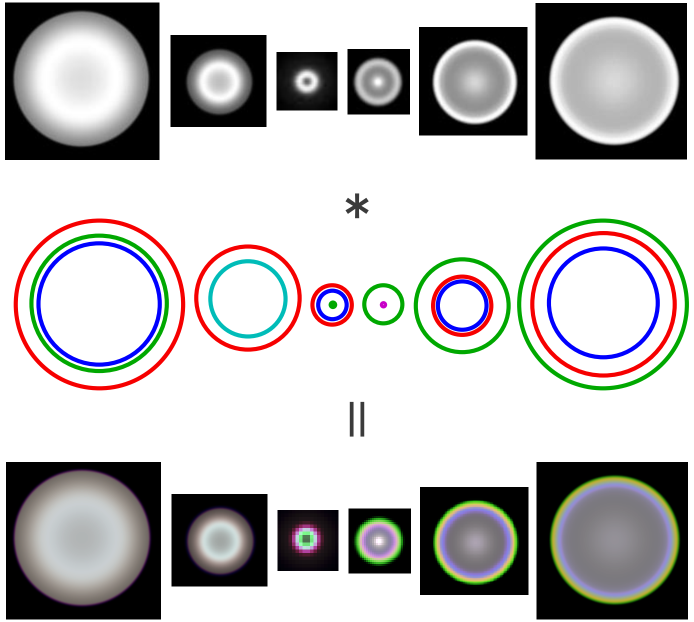
Axial chromatic aberration



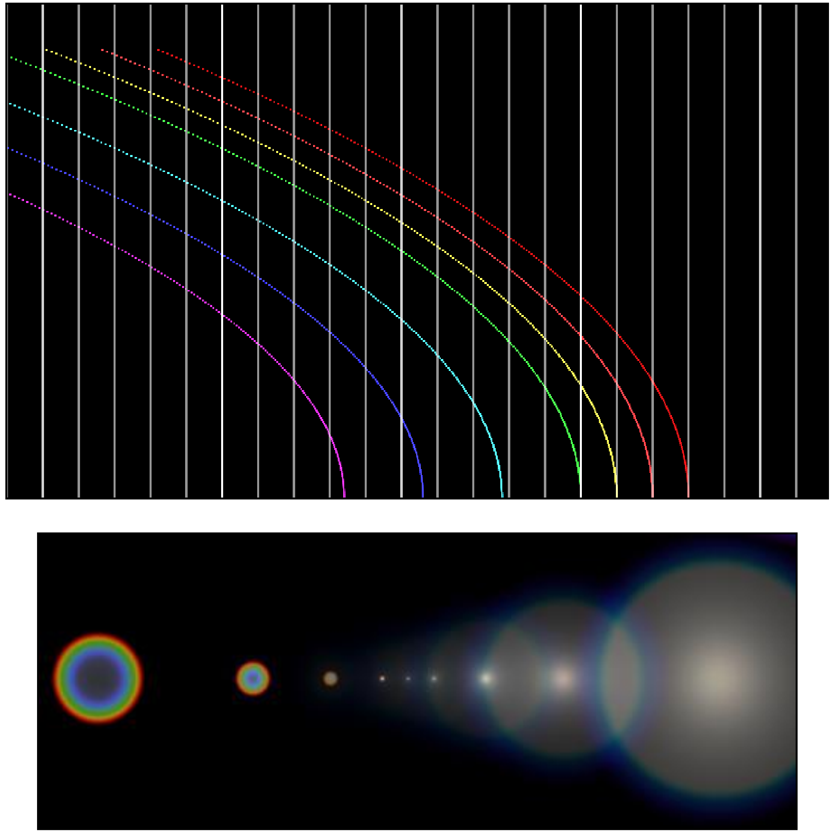
Residual chromatic aberration
a.k.a. secondary spectrum

# Correction by Achromatic Doublet

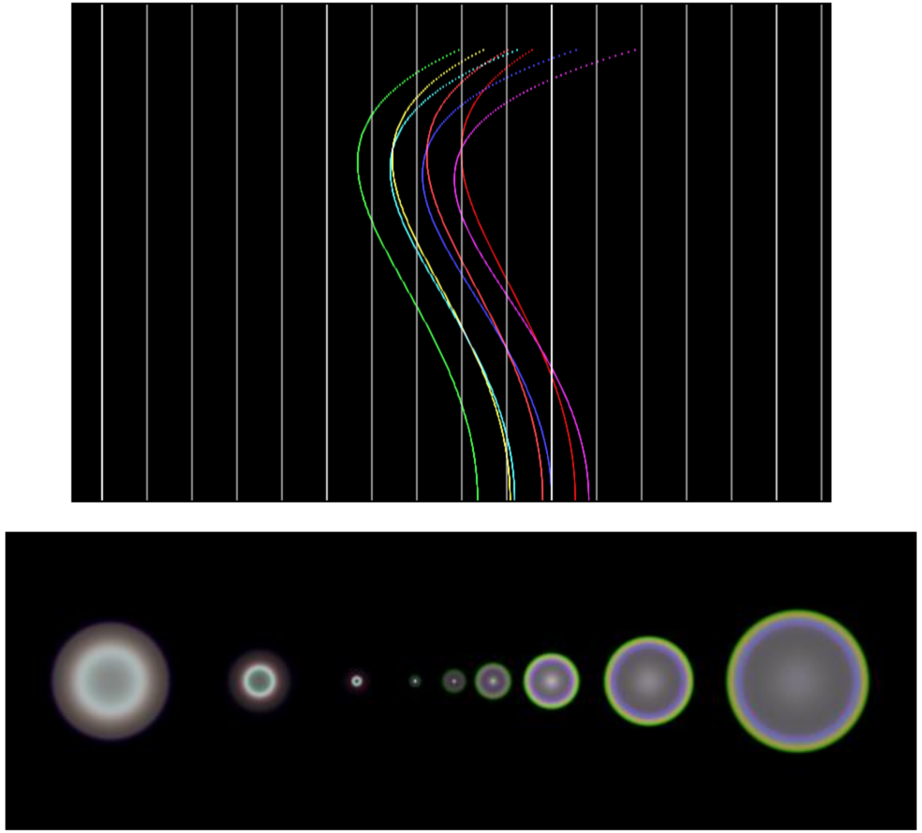
- Doublet also corrects spherical aberration
- Combination bokeh of each character
  - Residual aberration of spherical aberration
    - Soft / Sharp edge
    - Dark center / sharp peak
  - Residual aberration of axial chromatic aberration
    - Concentric colored circles
- ⇒Complicated gradation



# Diagrams and Bokeh with Multiple Wavelengths



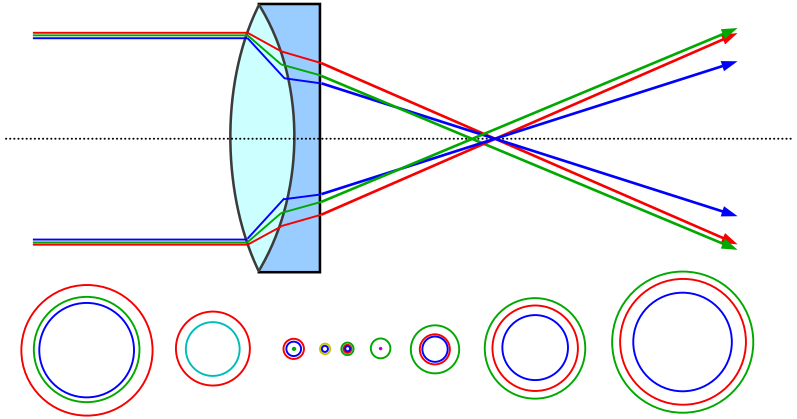
Spherical lens
without correction



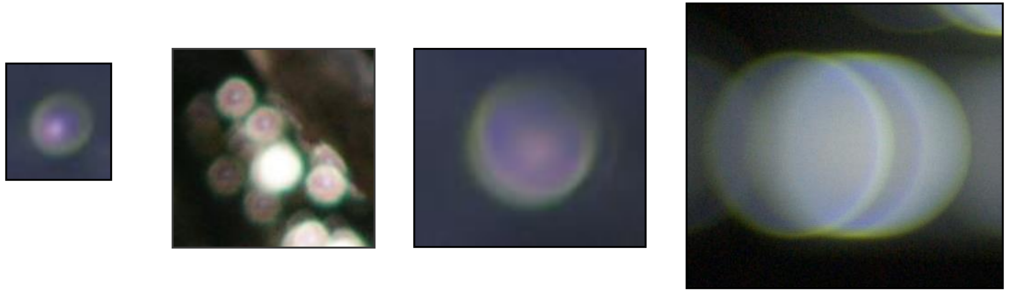
Doublet lens

# 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

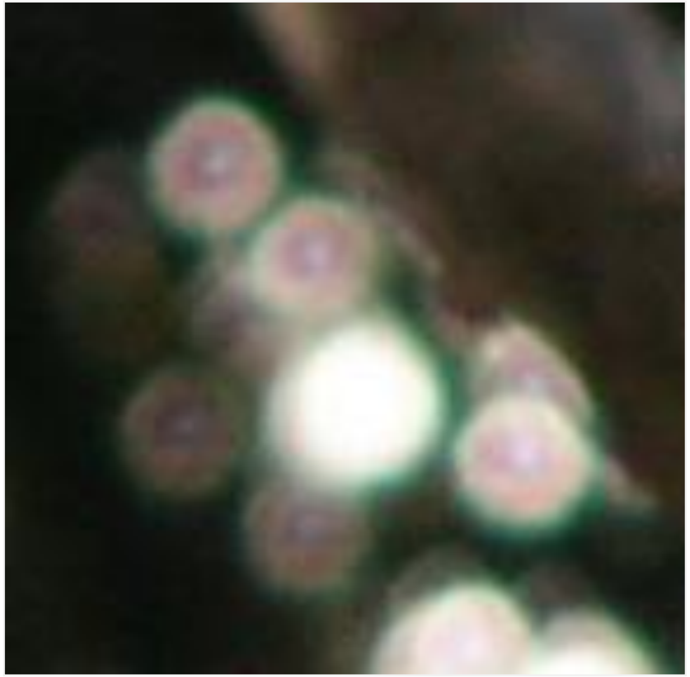


Back bokeh in photographs

# Front Bokeh with Purple Fringe

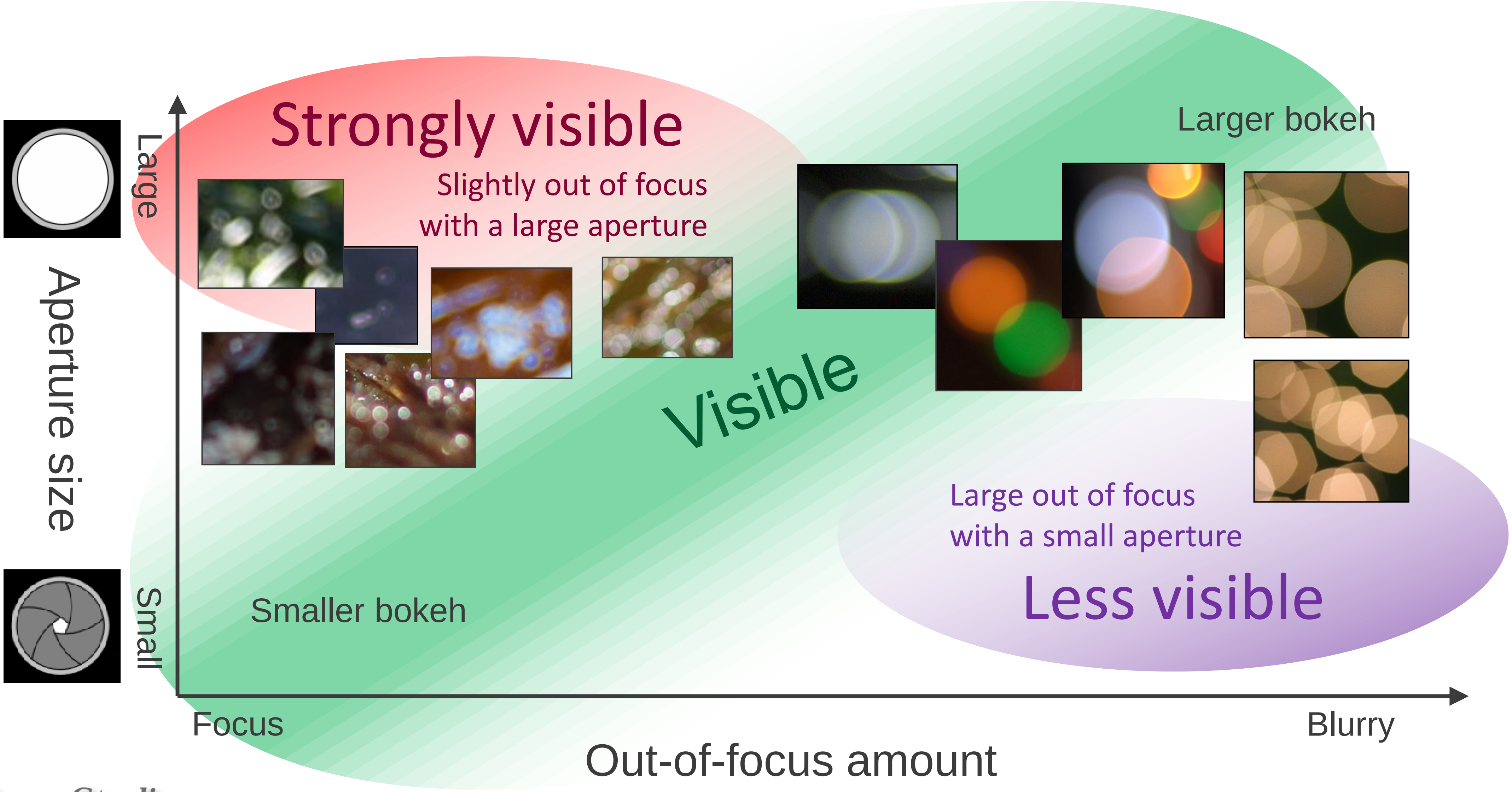
Front bokeh in photographs

# Back Bokeh with Green Fringe



Back bokeh in photographs

# Is Residual Aberration Visible or Not?



# Is Residual Aberration Visible or Not? (Cont'd)

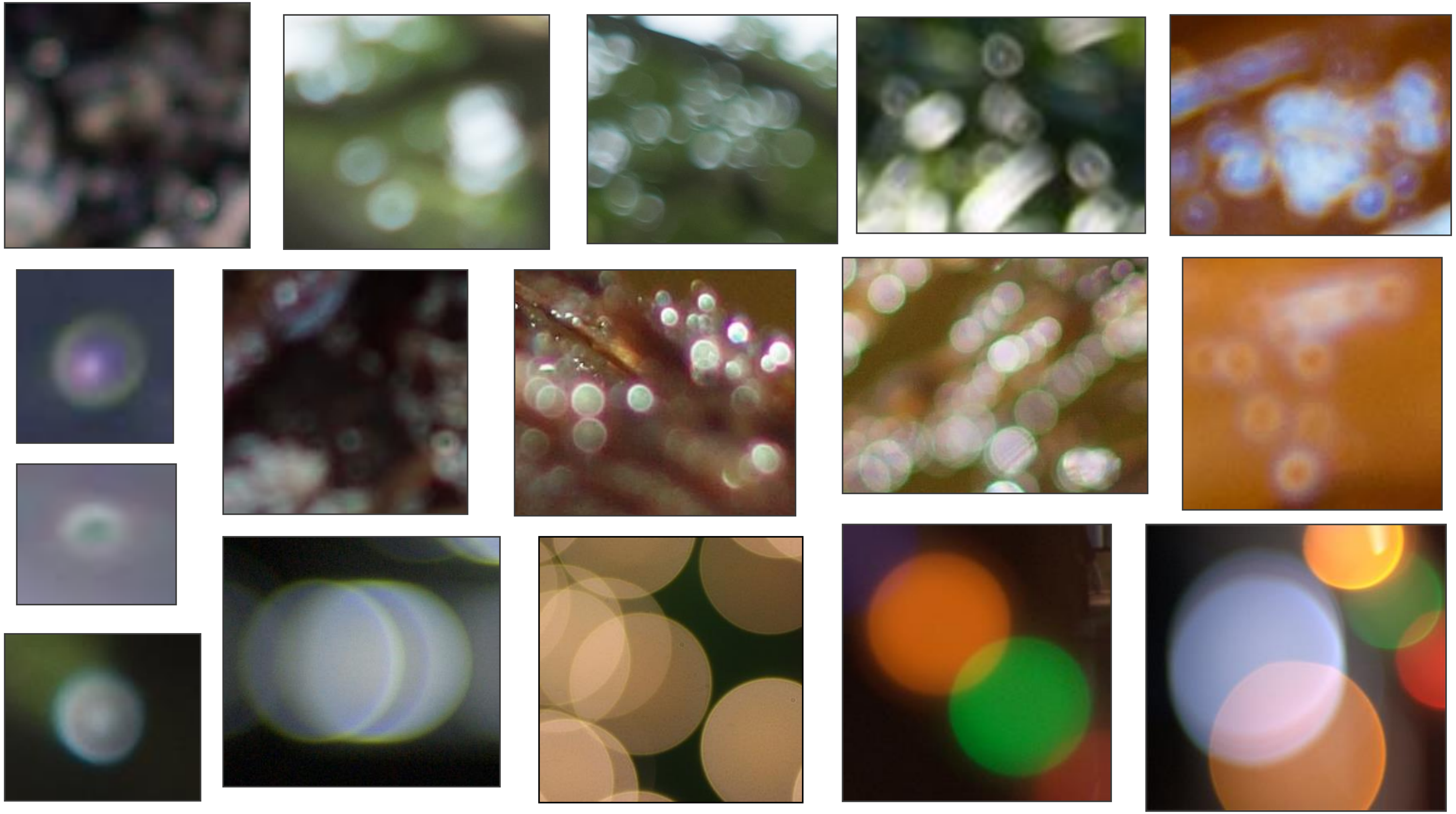
- Strongly visible
  - Slightly out of focus with a large aperture
- Less visible
  - Large out of focus with a small aperture

# 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

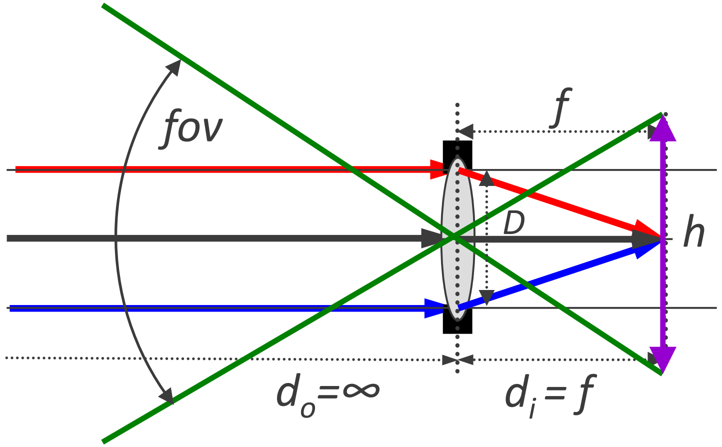
- Types of focus breathing
  - Single Lens
    - Focusing by shifting lens or sensor
      - Focal length is constant and independent of focus distance
    - At close focus, FOV becomes narrower
      - In spite of constant focal length
        - » Extend image distance (between lens and sensor)
        - » 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* = atan(*h* / 2*f*) * 2
    - *f* = *h* / (tan(*fov* / 2) * 2)

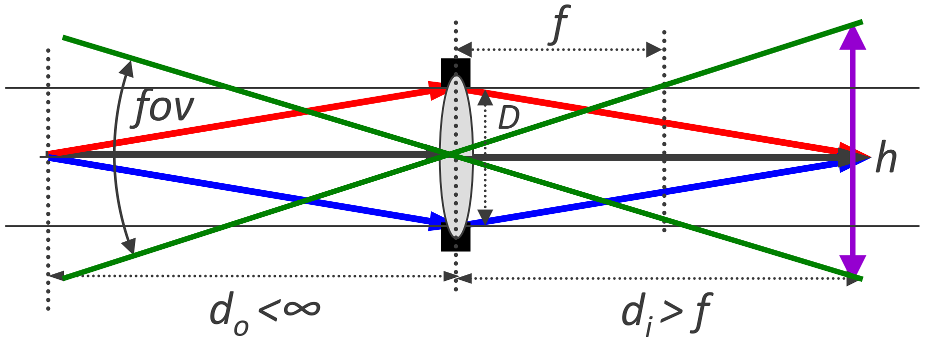
    - *fov* : field of view
    - *h* : sensor size




- 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

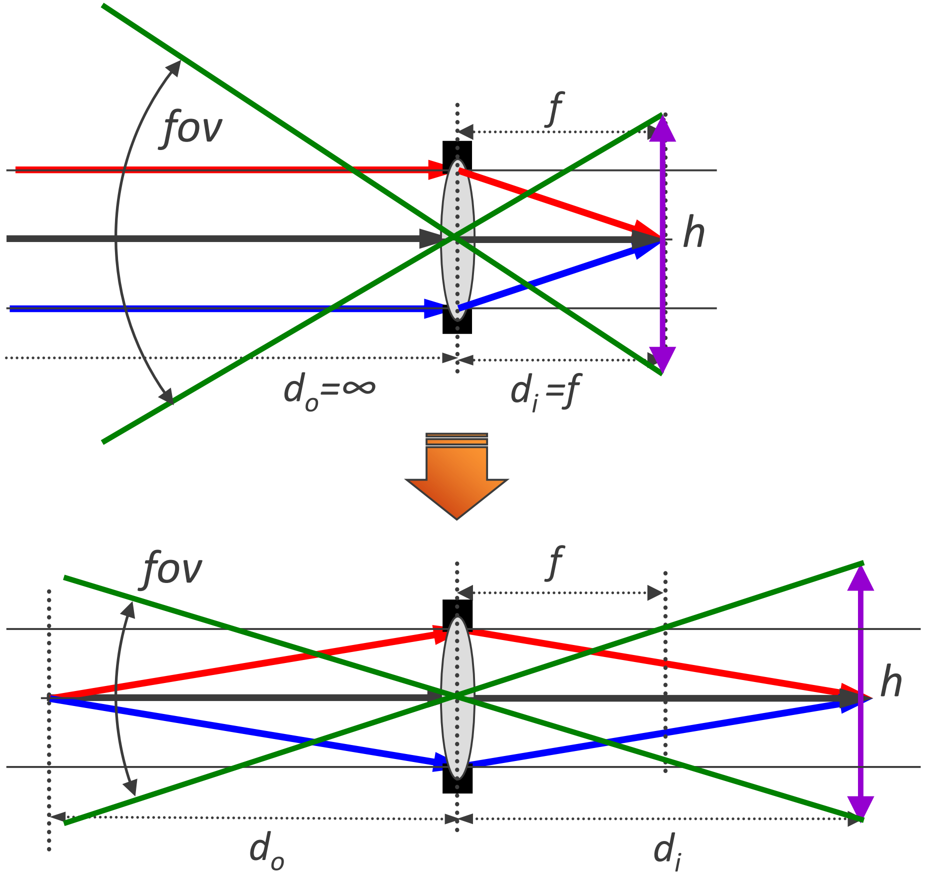
# Focusing Mechanism and Breathing Examples

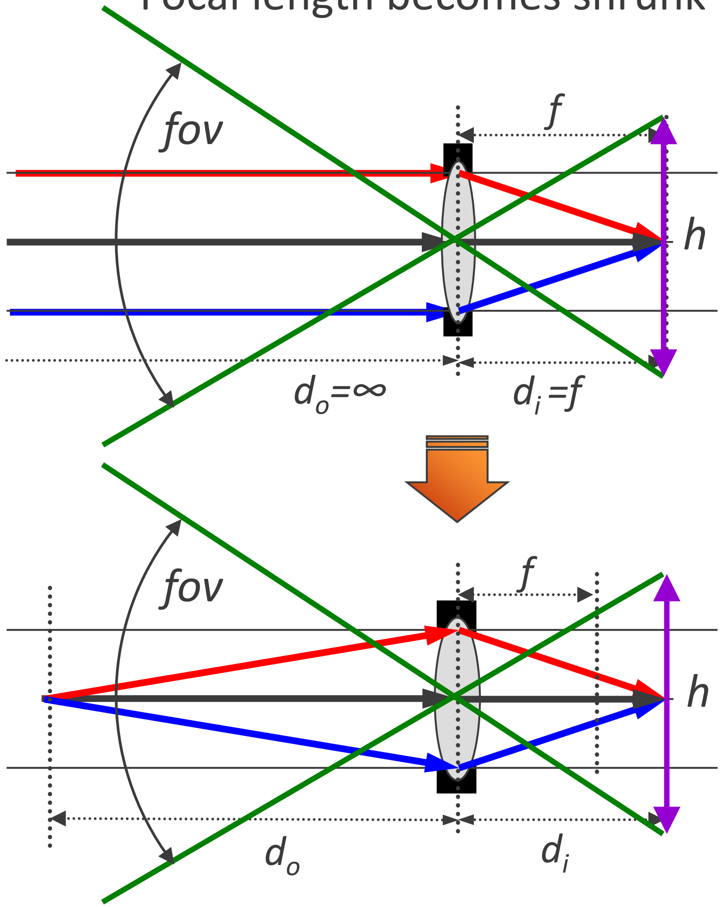
All-Group / Film-Back Focusing
FOV becomes narrower

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

Infinite focus

Close focus



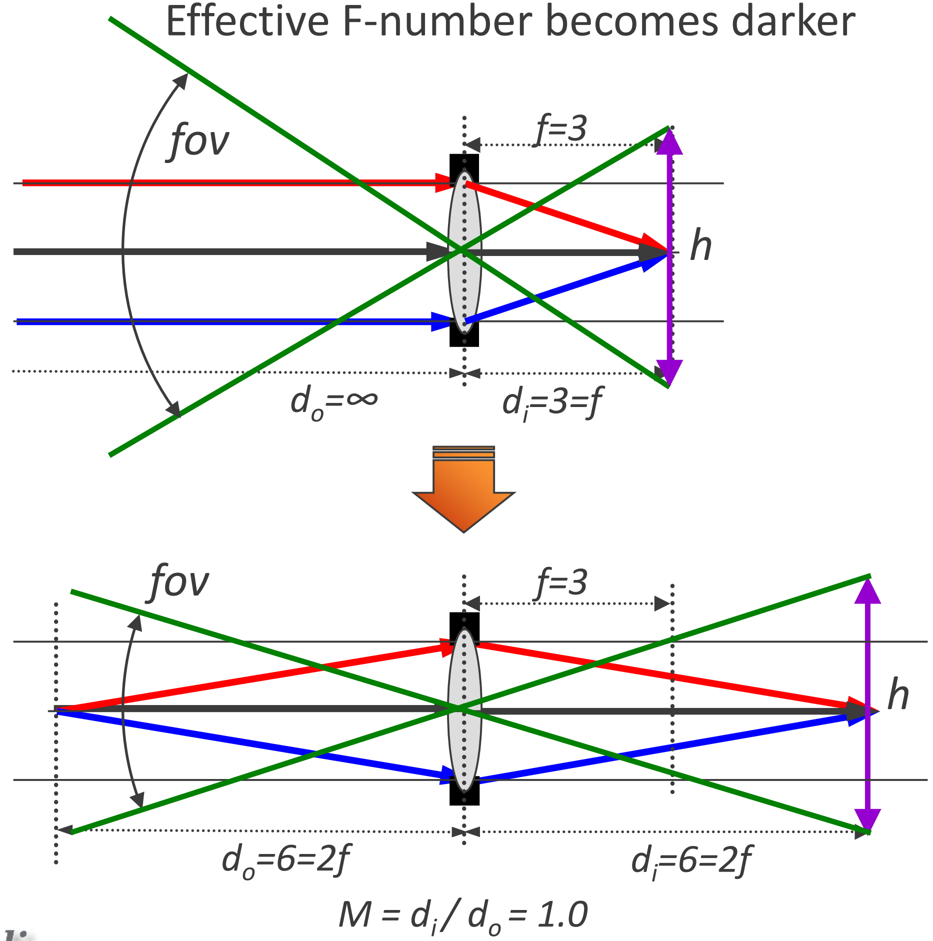
# Focusing Mechanism and Breathing Examples

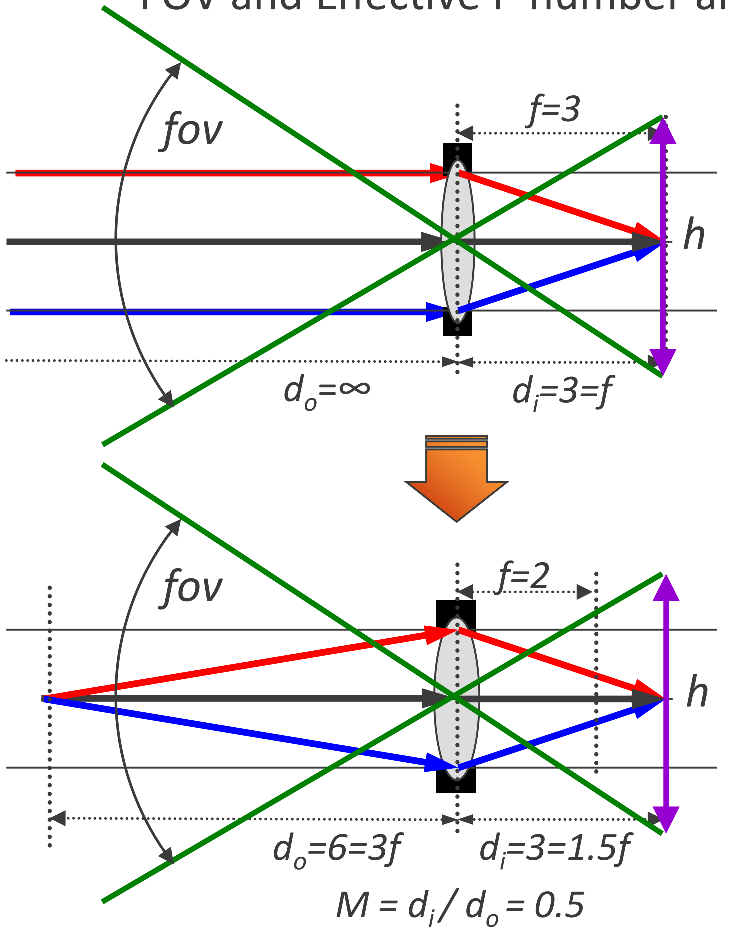
Shift sensor to backward 2f (or shift lens)
Focal length is constant
Effective F-number becomes darker

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

Infinite focus

Focus on *2f*



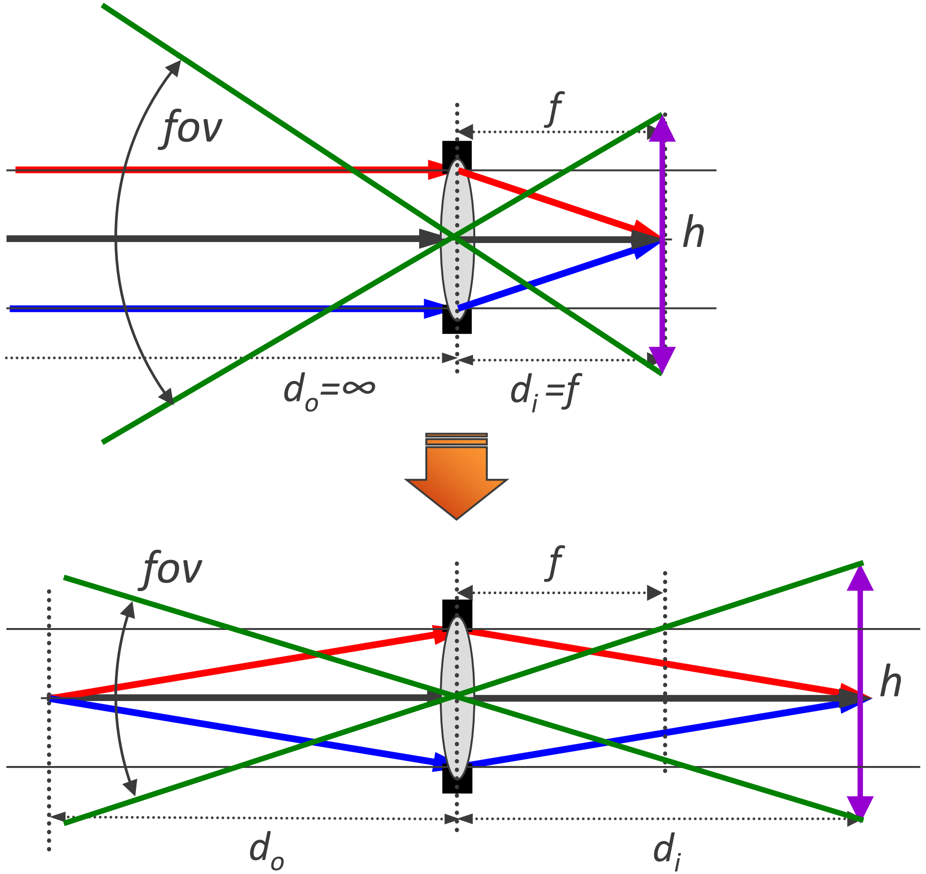
# Focusing Mechanism and Breathing Examples

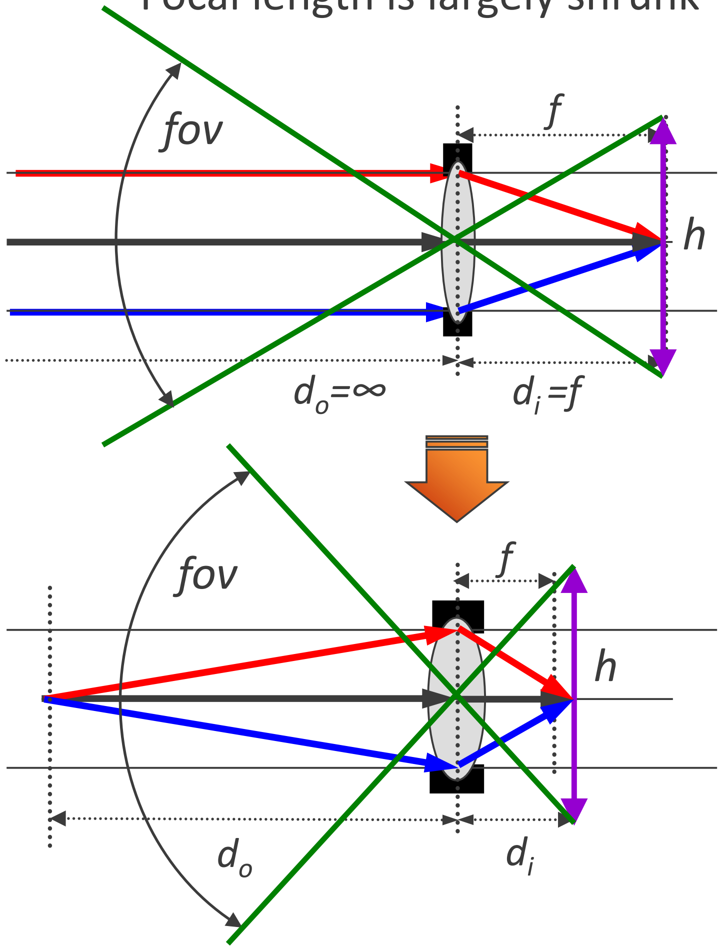
All-Group / Film-Back Focusing
FOV becomes narrower

Typical Inner Focusing
FOV becomes wider
Focal length is largely shrunk

Infinite focus

Close focus



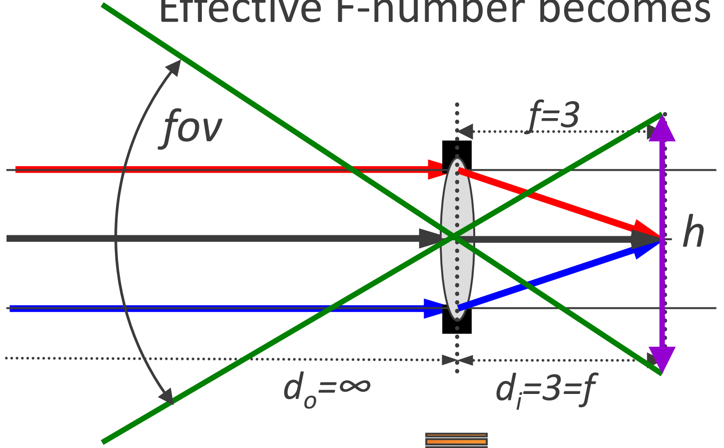



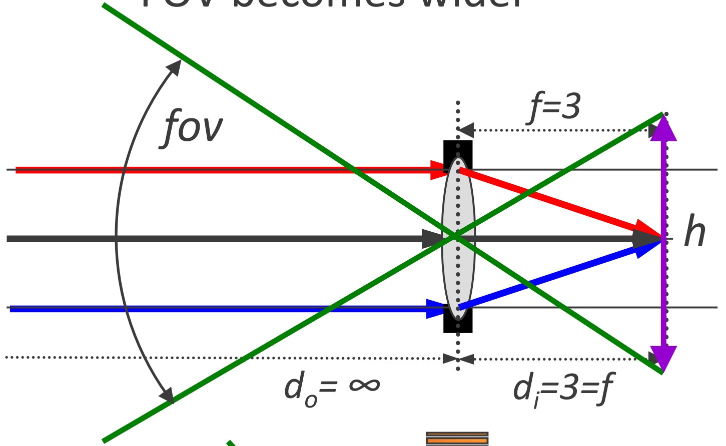
# Focusing Mechanism and Breathing Examples

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

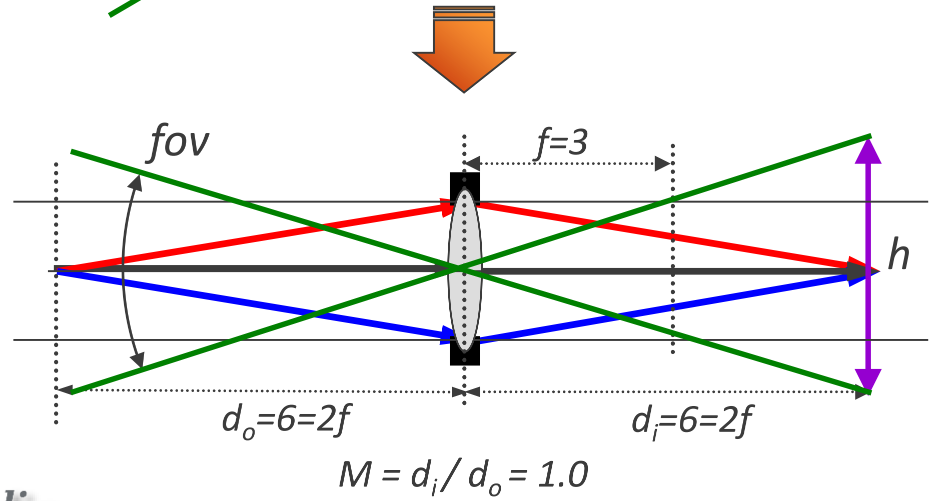
Focal length is shrunk to 40% in this case
Image distance is also shrunk to 50%
FOV becomes wider

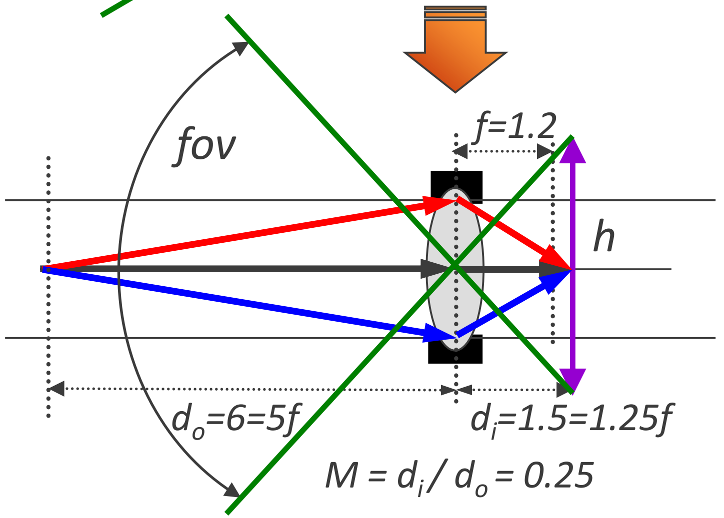
Infinite focus




Focus on *2f*



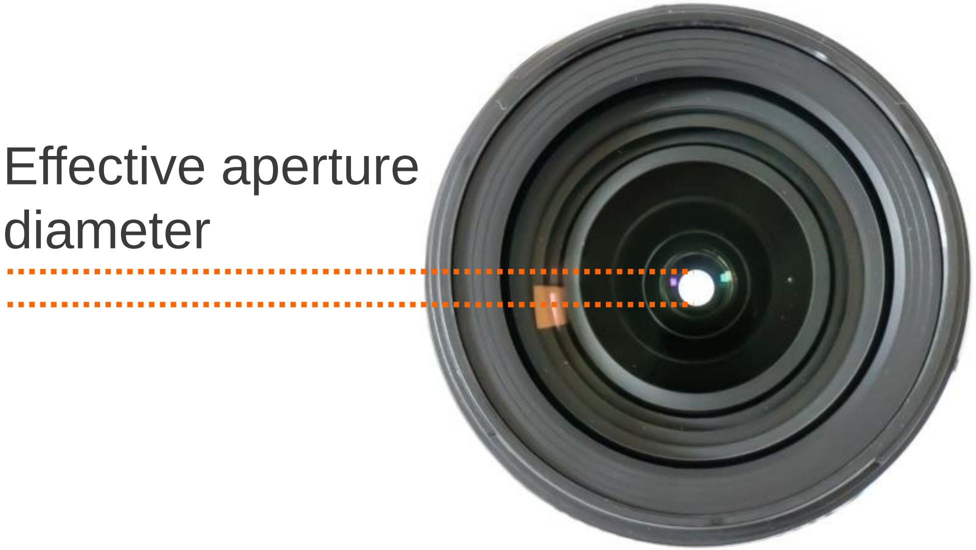
# Variable Aperture Zoom Lenses

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

# References


- Kawase, M. “Camera, Optics Theory and Post Effects for Renderists.” *Computer Entertainment Developers Conference, 2007.*
- Kawase, M. “Optics Knowledge to Achieve Attractive Images.” *Computer Entertainment Developers Conference, 2010.*
- Trávník, J. “On Bokeh.” *Jakub Trávník's resources*. http://jtra.cz/stuff/essays/bokeh/index.html
- 安藤幸司 『光と光の記録「レンズ編」』 *AnfoWorld* http://www.anfoworld.com/LensMF.html
- 吉田正太郎（1997）『カメラマンのための写真レンズの科学』地人書館.
- 永田信一（2002）『図解　レンズがわかる本』日本実業出版社.