Making Your Bokeh Fascinating

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

SIGGRAPH 2015 Course

Masaki Kawase

Silicon Studio, Corp.

masa@siliconstudio.co.jp

Introduction

- Basic idea and theory [Kawase08]
  - Only circular aperture
- Practical implementation and optimization [Kawase12]
  - Any kind of aperture shapes

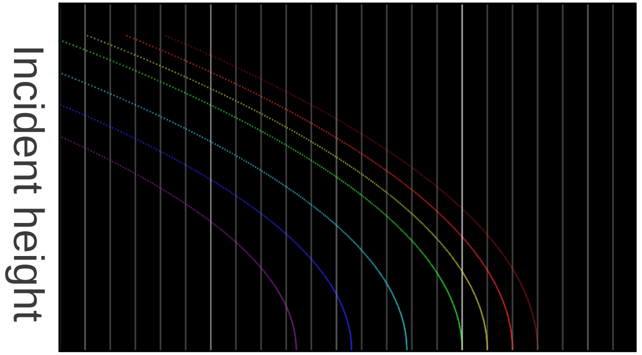
Contents

- Creating the Pencil Map
- Creating the Bundle-of-Light-Ray Map (Pencil Map)
  - “Bundle of Light Rays” or “Pencil Rays” (referred to as “Pencil” here onwards)
- Application to Arbitrary Aperture Shapes
- Scattering or Gathering?
- Results
- Conclusion

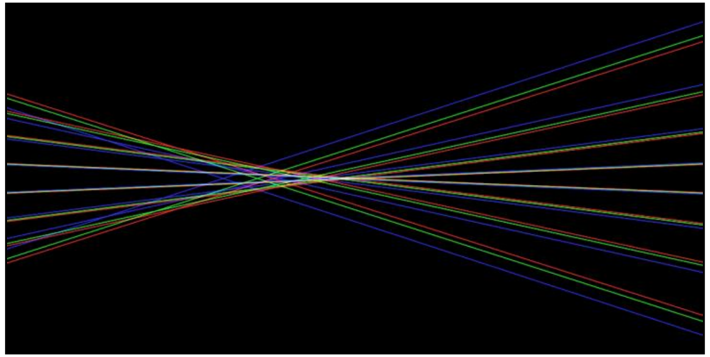
Creating the Pencil Map

Creating the Pencil Map

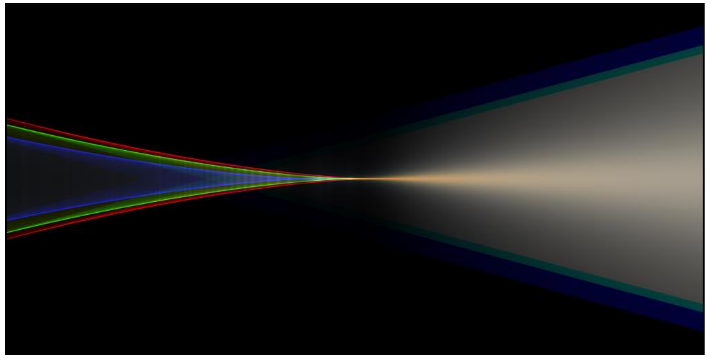
- Precompute light paths from the aberration diagram
  - Takes spherical and axial chromatic aberrations into account



Longitudinal aberration diagram



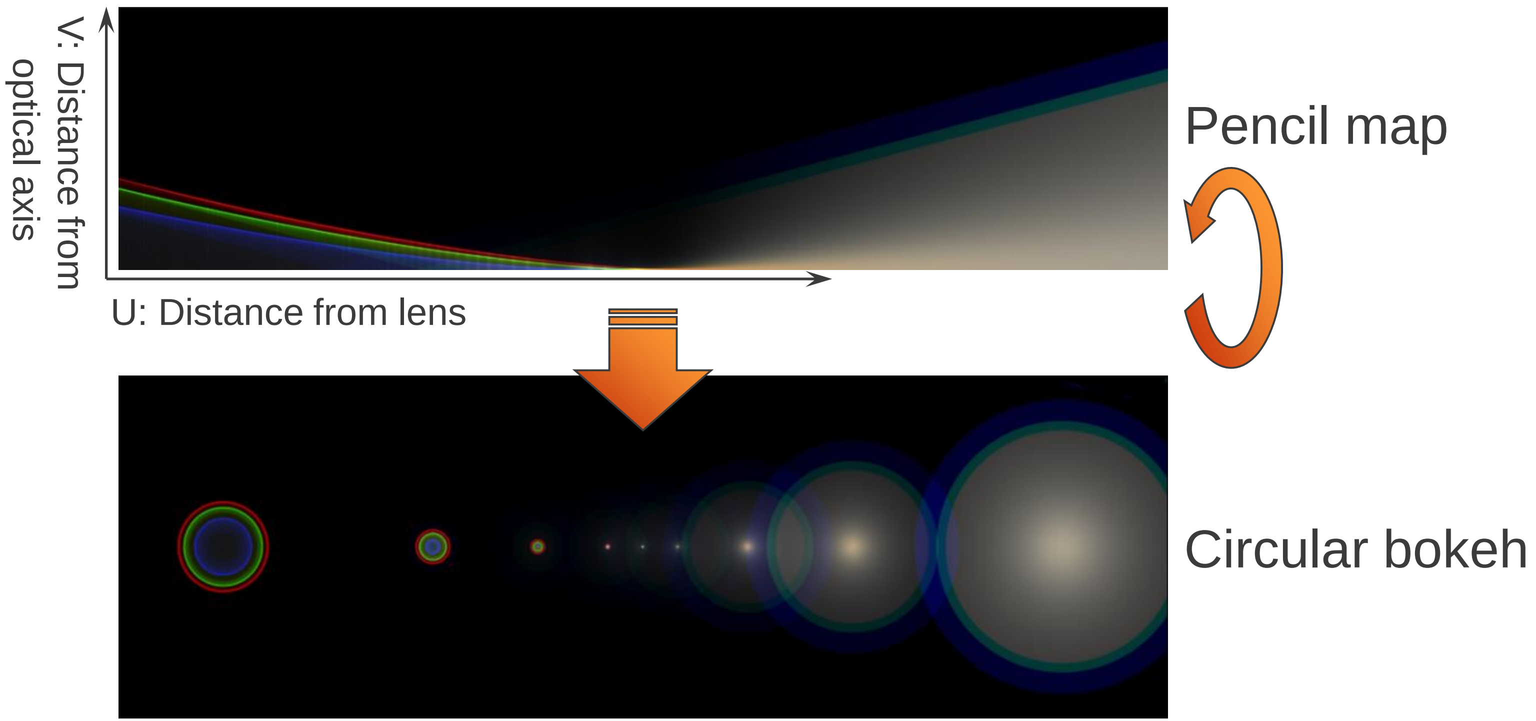
Light paths make up pencil map
(small number of rays)



Pencil map

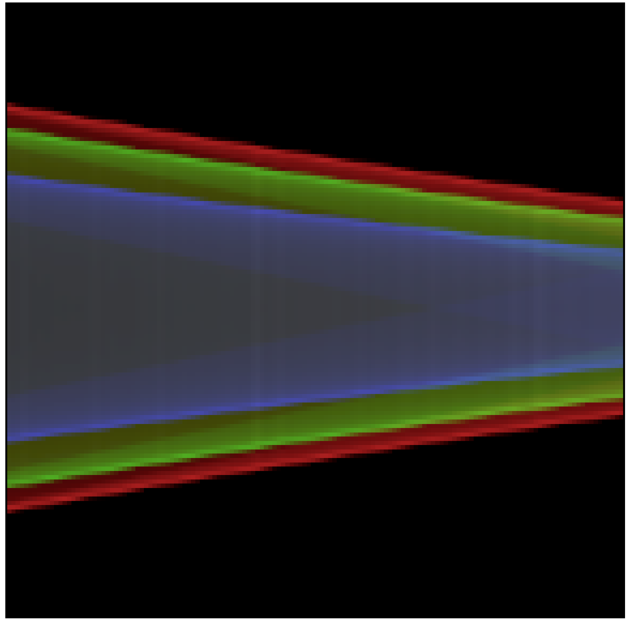
Circular Bokeh Rendering

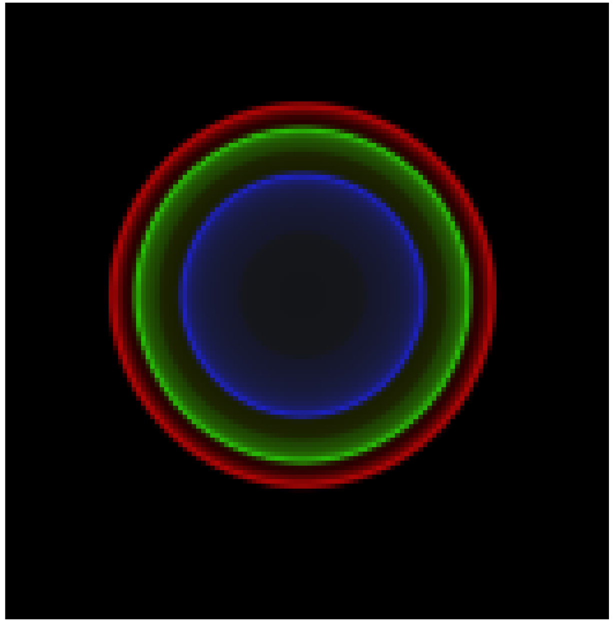
- V coordinate represents the distance from the optical axis
  - Mapping each slice to a circle produces a circular 'bokeh'



Discretized Result…

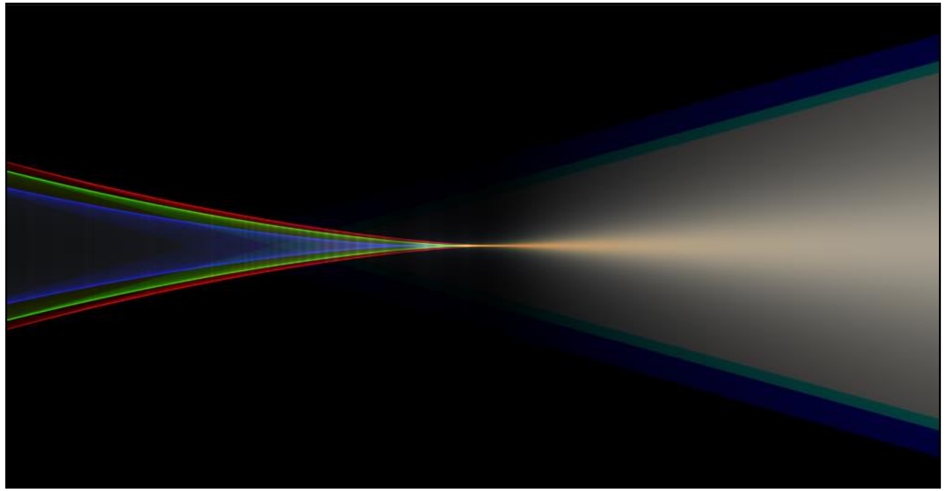
- Chromatic aberration is an issue
- Three wavelengths (R/G/B) are insufficient to represent the dispersion

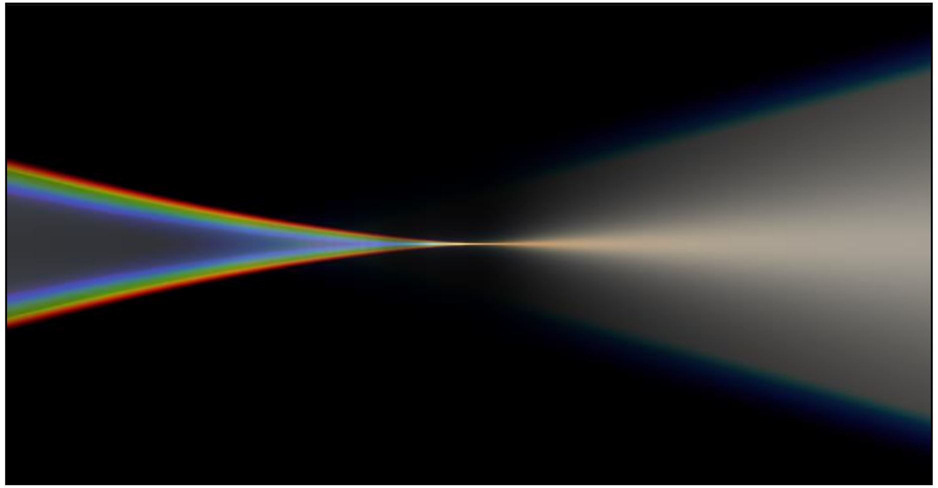




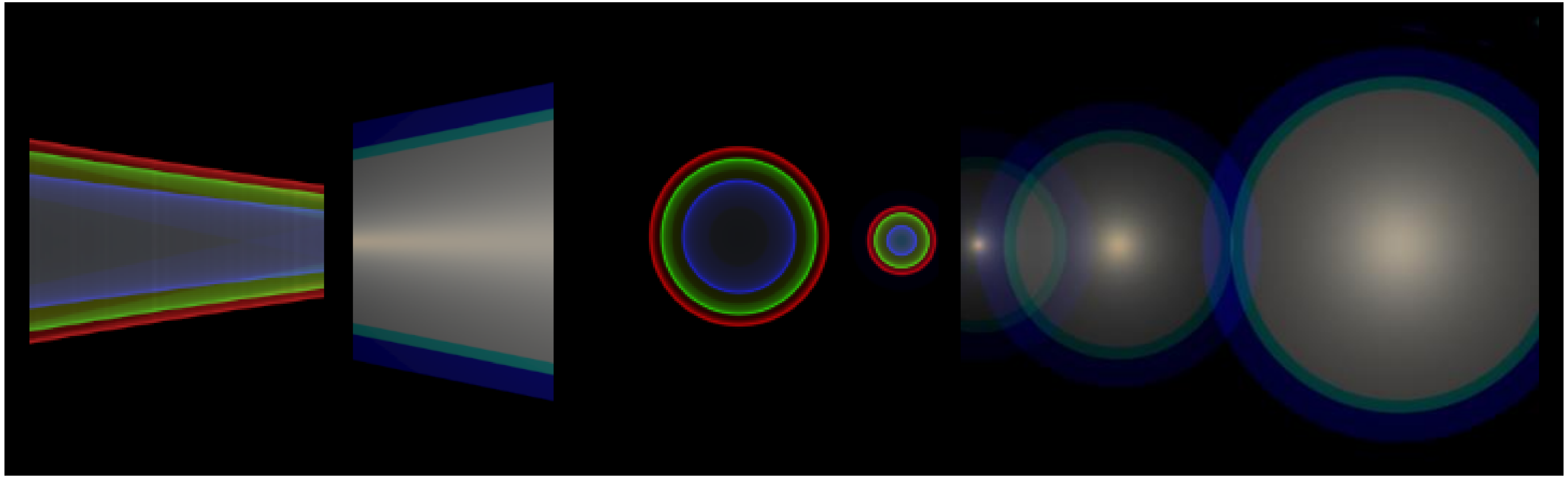
Increasing Wavelength Samplings

- Calculate the map with more wavelengths
- Convert into the RGB space

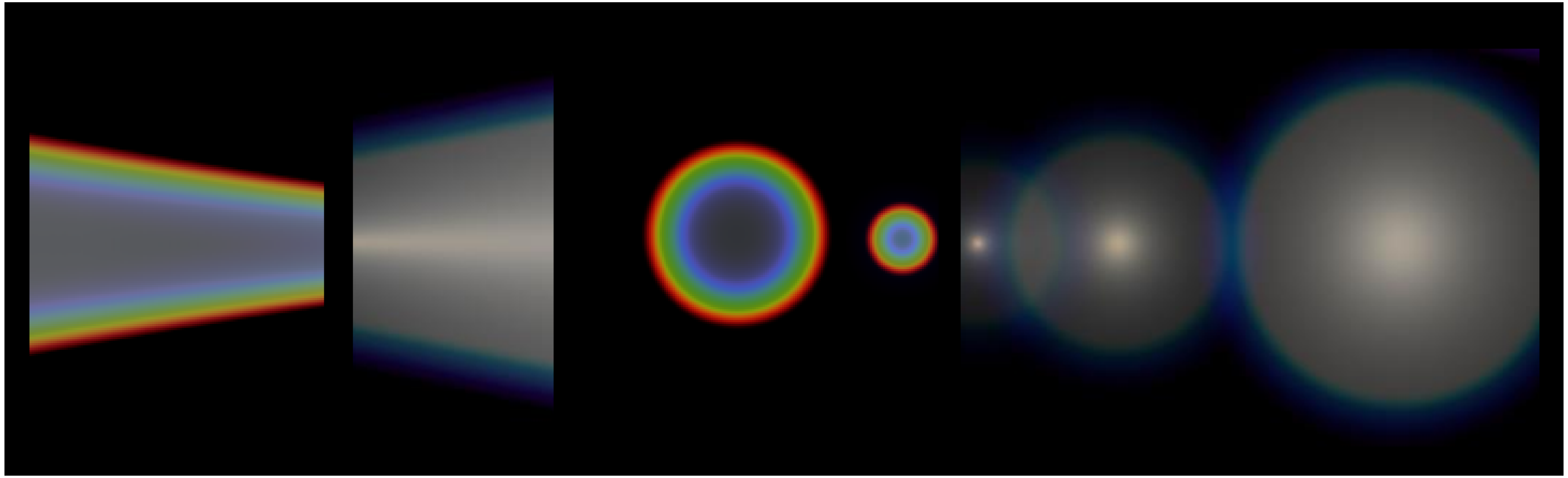




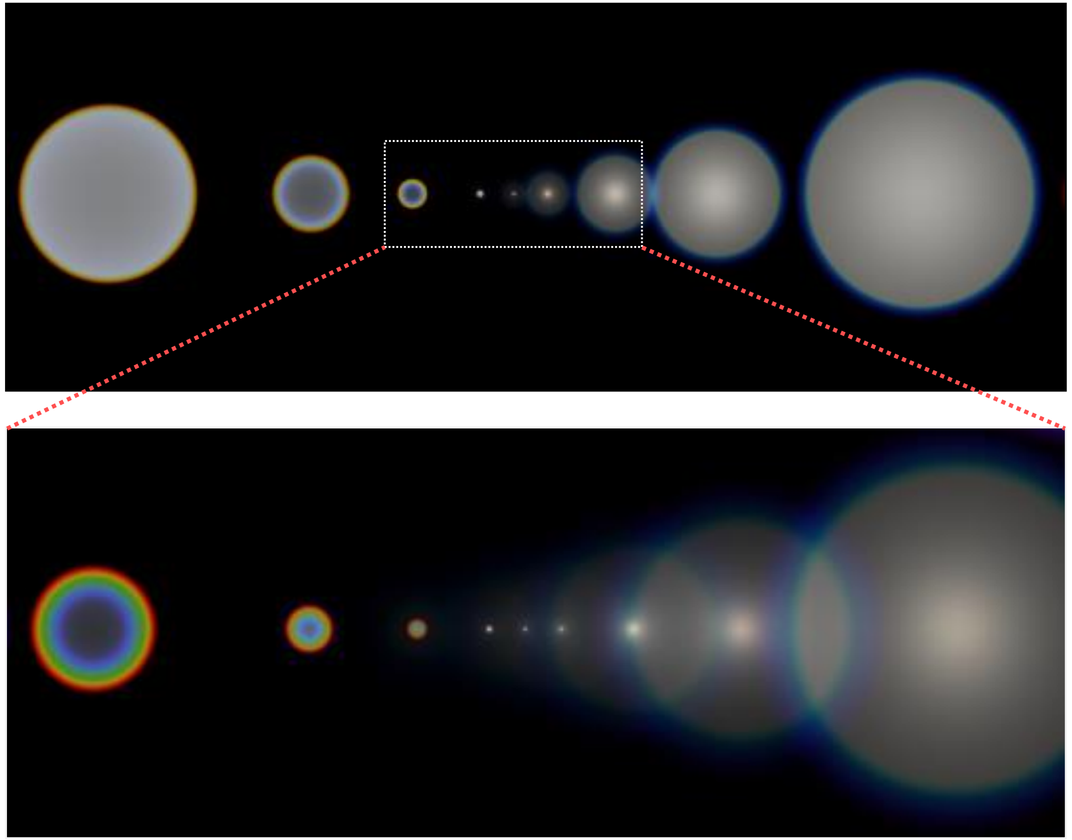
3-Wavelength Samplings



Sufficient Wavelength Samplings



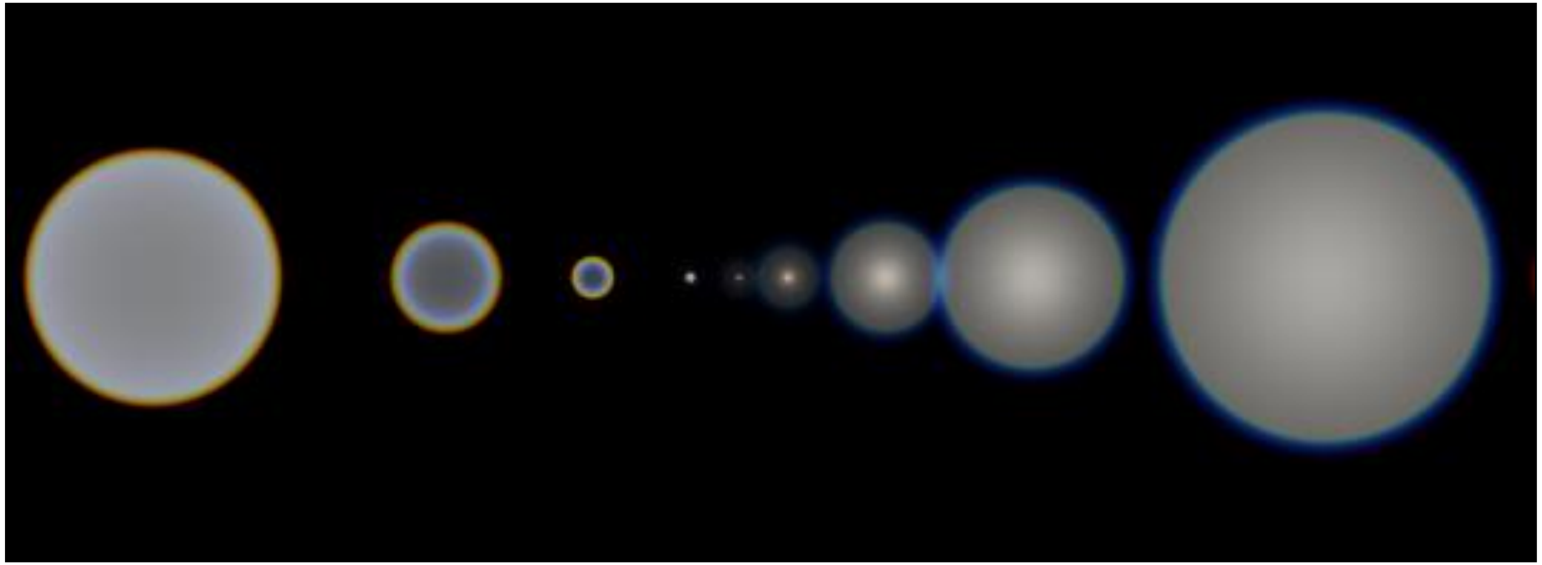
Bokeh with Spherical and Chromatic Aberration



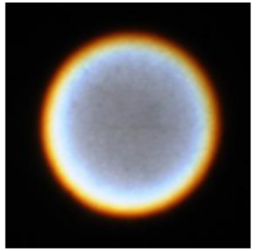
Zoomed-in view around the focal point

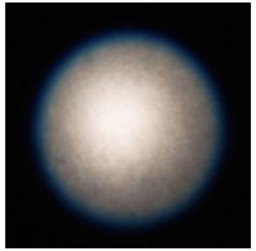
- Imperfect focus
- Front bokeh with red sharp edge
- Back bokeh with blue soft edge

Comparison with photographs



Generated from pencil map

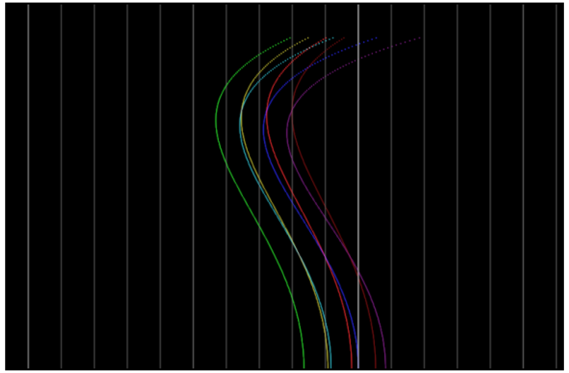




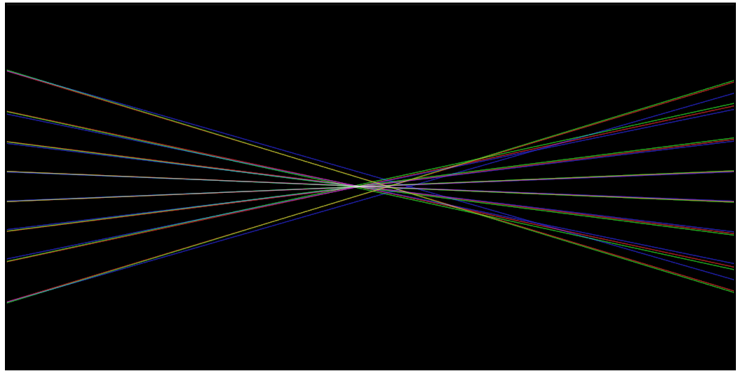
Captured in real photographs

Creating the Pencil Map of Doublet

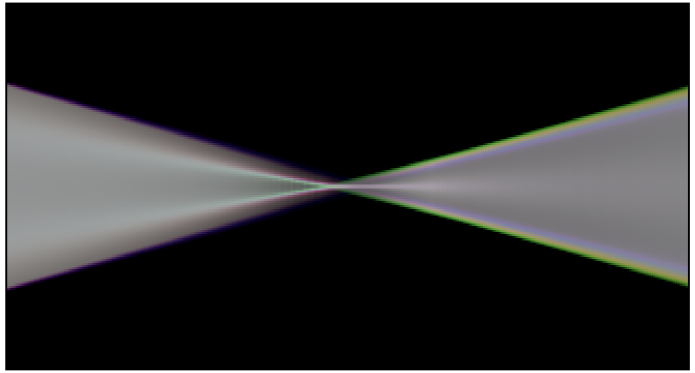
- Calculate the map with the longitudinal aberration diagram
- Using actual lens parameters (if they exist)
  - Only ray paths of each wavelength are required



Longitudinal aberration diagram



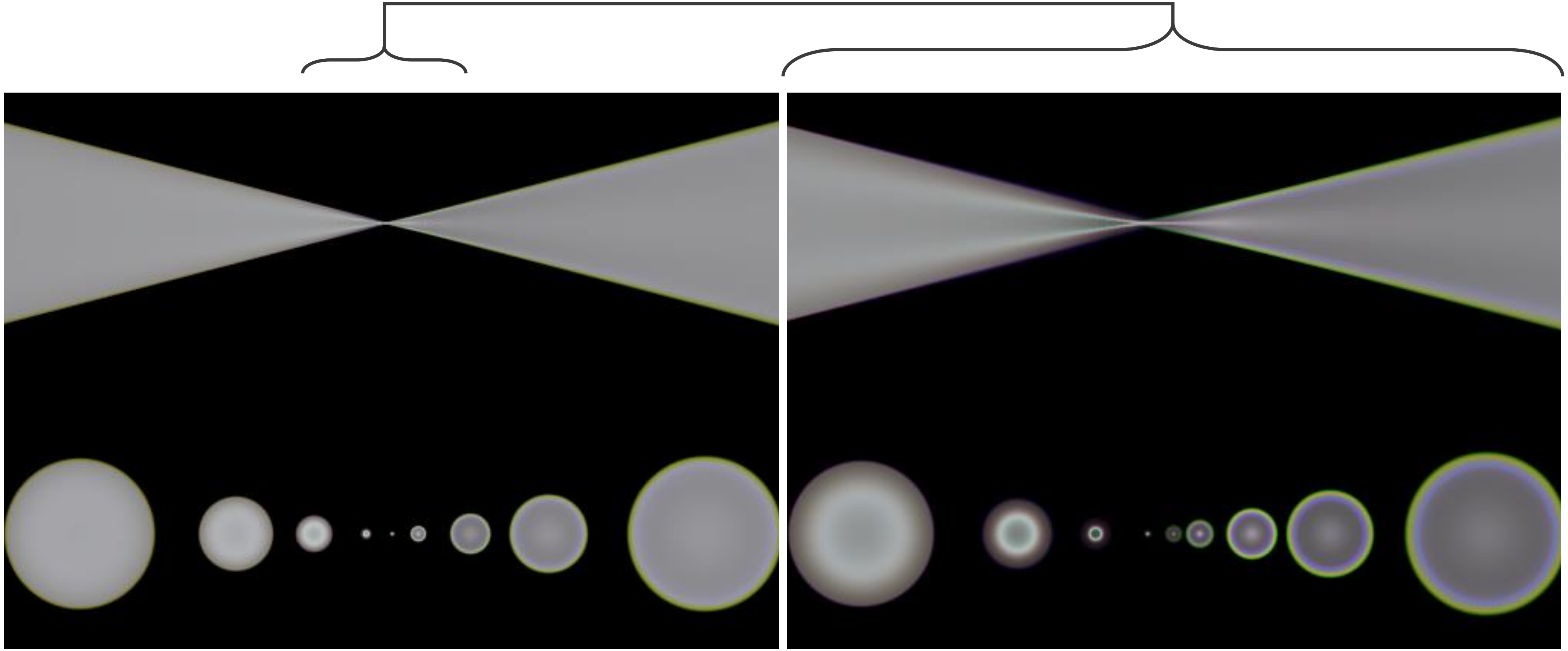
Light paths make up pencil map



Pencil map

Pencil Map of Doublet

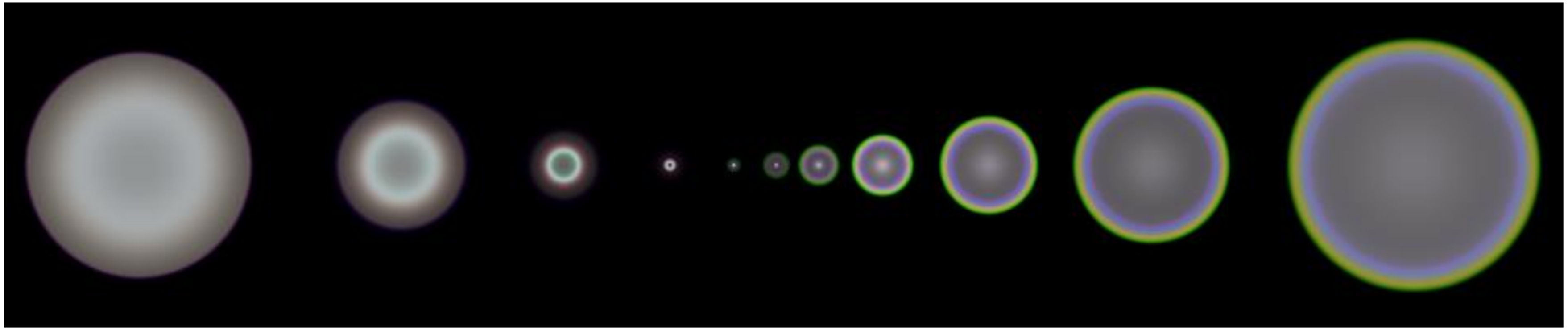
Zoomed-in view around the focal point



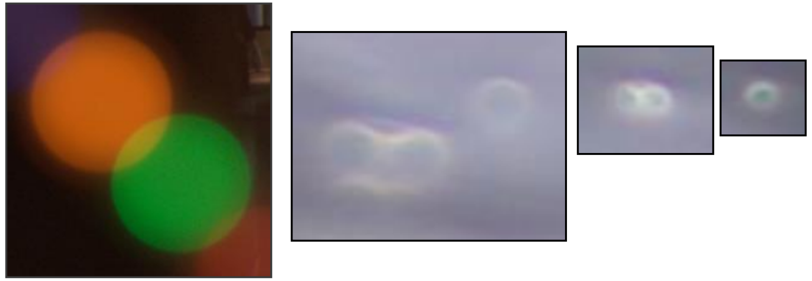
Pencil maps and bokeh

Comparison with photographs

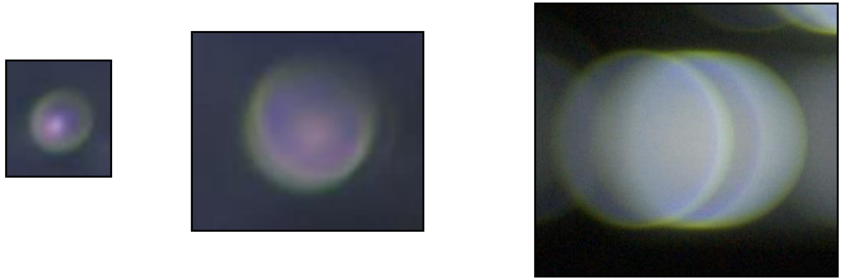
- Typical correction
  - Front bokeh has soft purple edge and the center is darker
  - Back bokeh has sharp green edge and the center is brighter



Front and back Bokeh with Pencil map



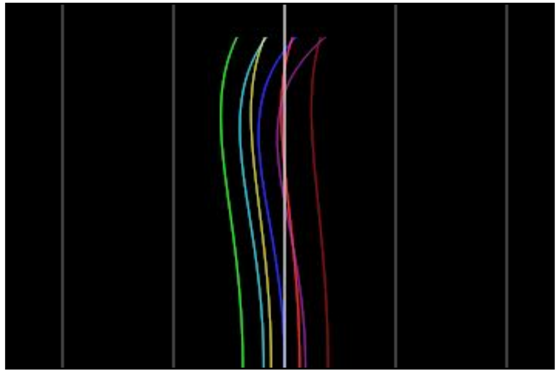
Front bokeh in photographs



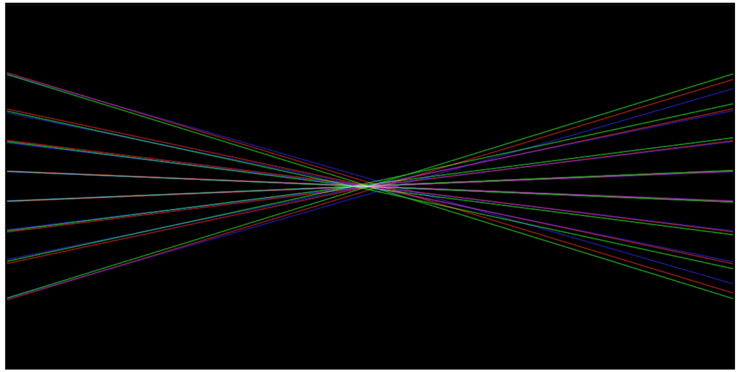
Back bokeh in photographs

Different Type of Doublet

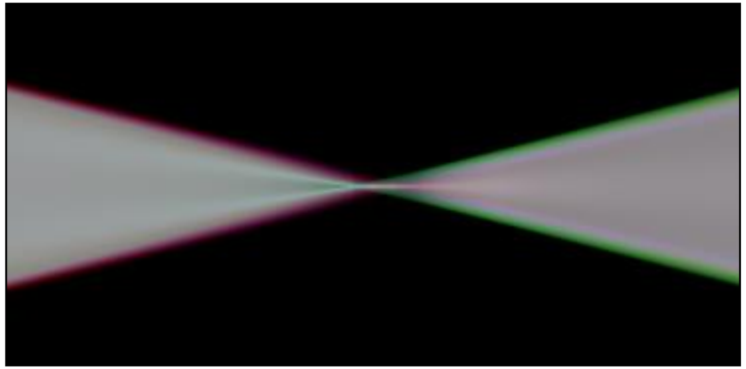
- Residual chromatic aberration is more visible than residual spherical aberration



Longitudinal aberration diagram



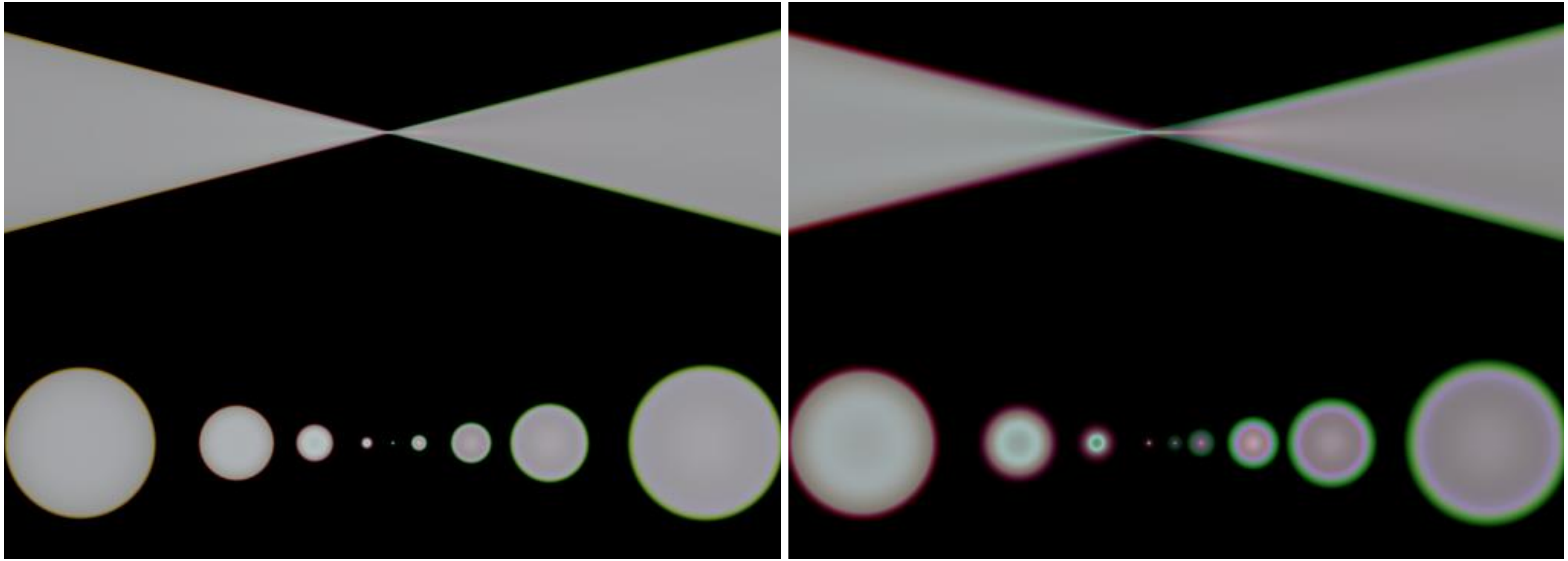
Light paths make up pencil map



Pencil map

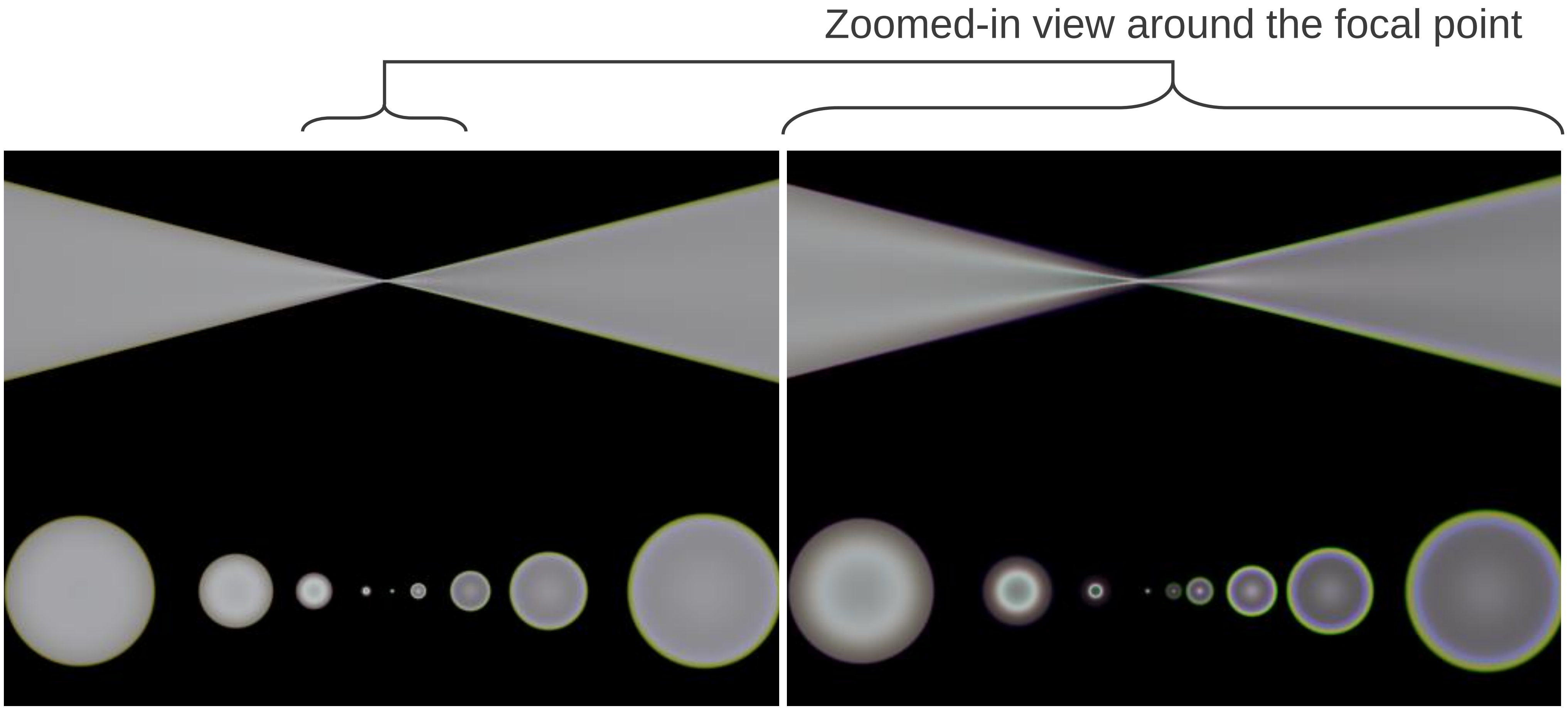
Pencil Map of Doublet (Different Type)

Zoomed-in view around the focal point



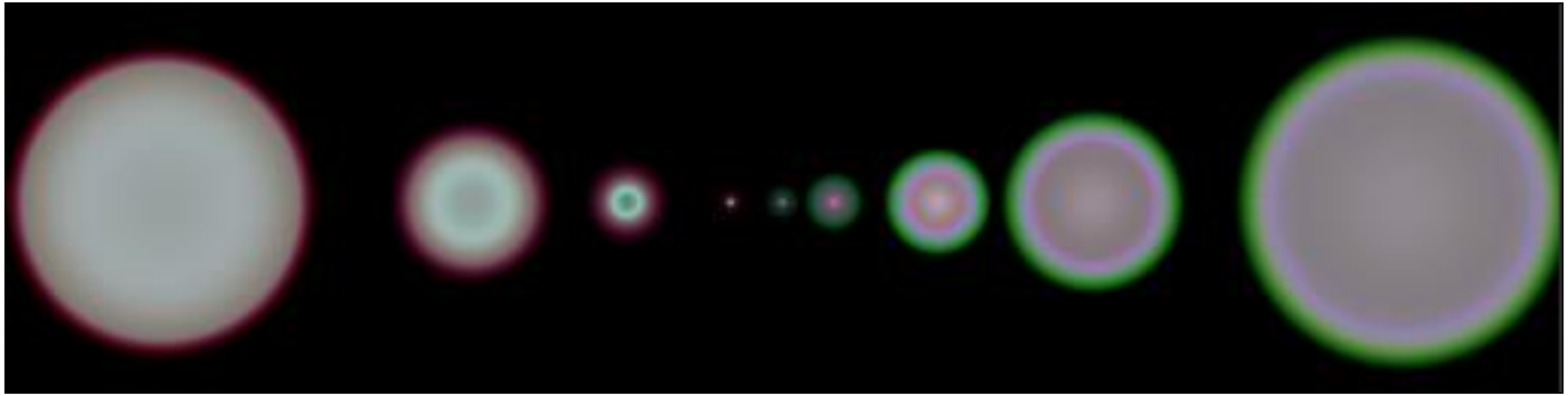
Pencil maps and bokeh

Pencil Map of Doublet (Previous Type)

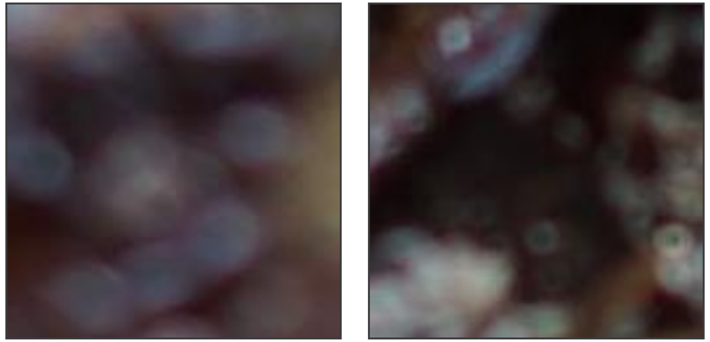


Pencil maps and bokeh

Comparison with photographs



Front and back Bokeh with Pencil map



Front bokeh in photographs

Back bokeh in photographs

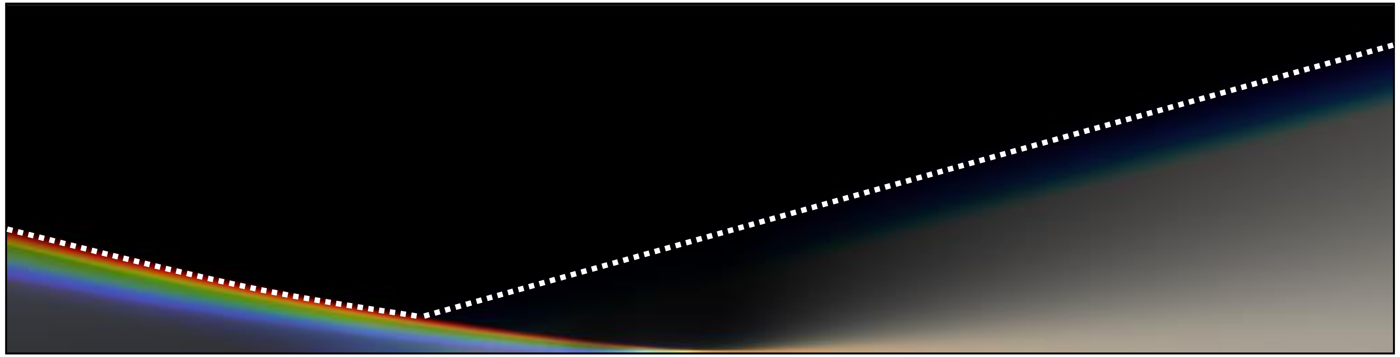
Optimization of Pencil Map

- Wasteful parts in the texture
  - Sparse, many texels are empty
  - There is not enough precision around the more important 'focusing' texels

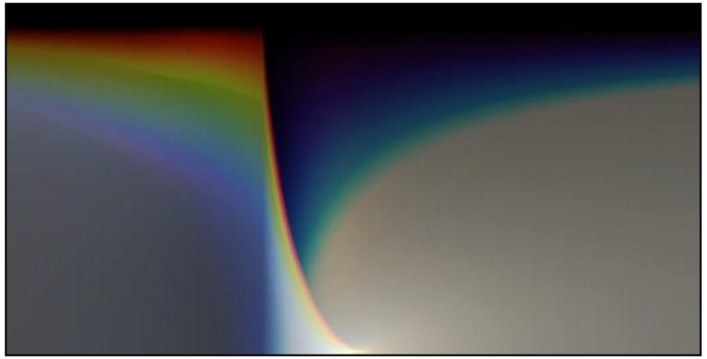
Wasteful pencil map

Optimization of Pencil Map (cont'd)

- Normalizing height of bundle at every distance(u-axis) by the maximum height(bokeh size)
- Less empty texels, and great improvement in precision around focusing texels

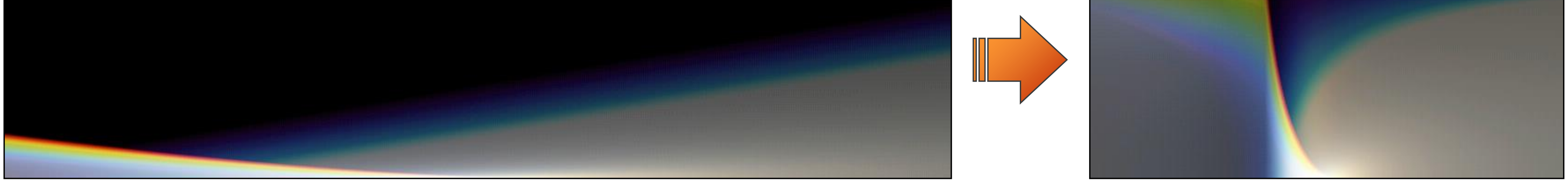


Wasteful pencil map



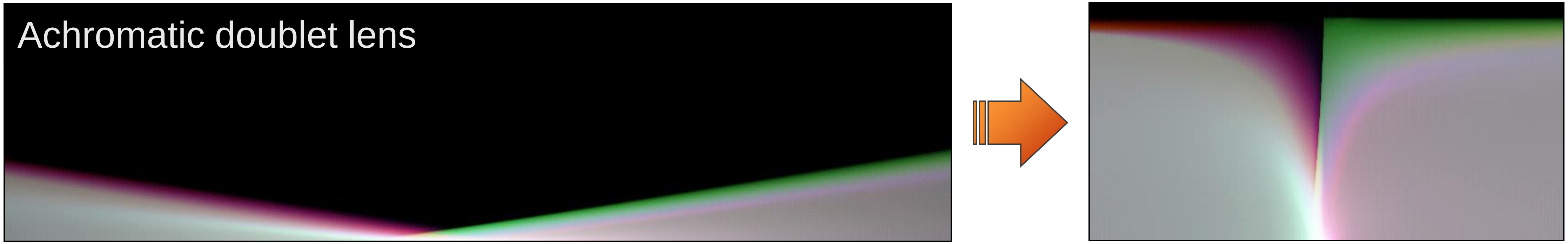
Normalized pencil map

Spherical lens (with no corrections)

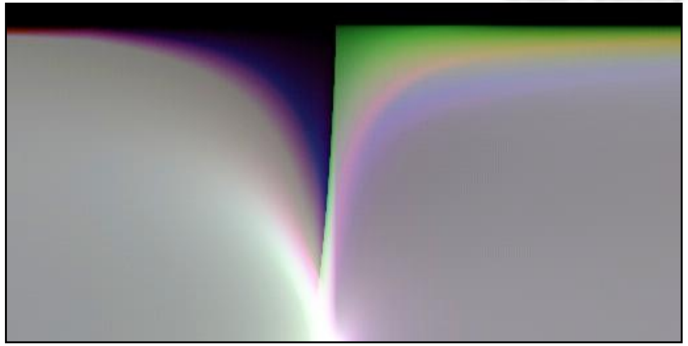


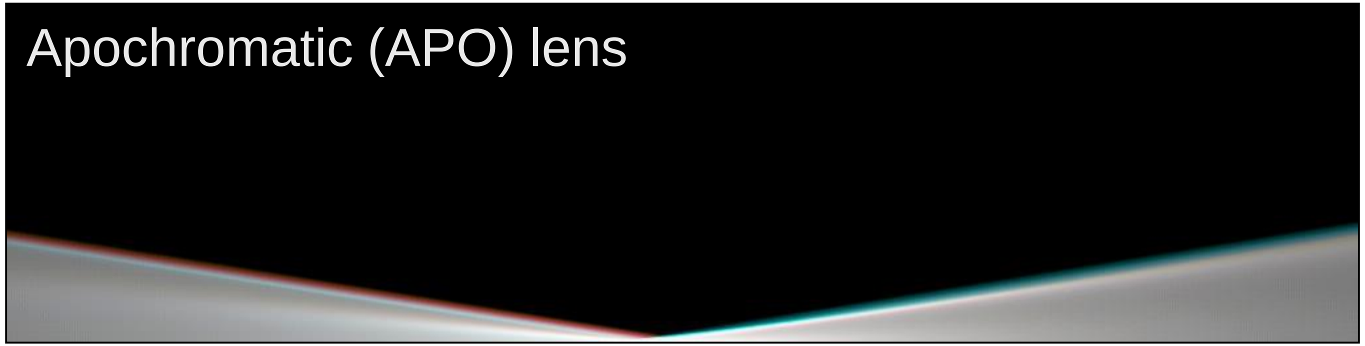
Aspherical lens (chromatic aberration is not corrected)

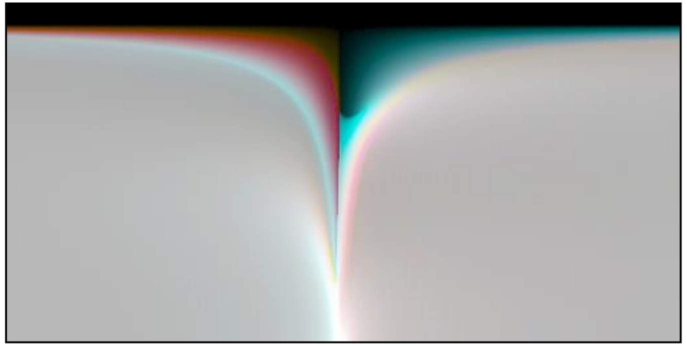
Achromatic doublet lens

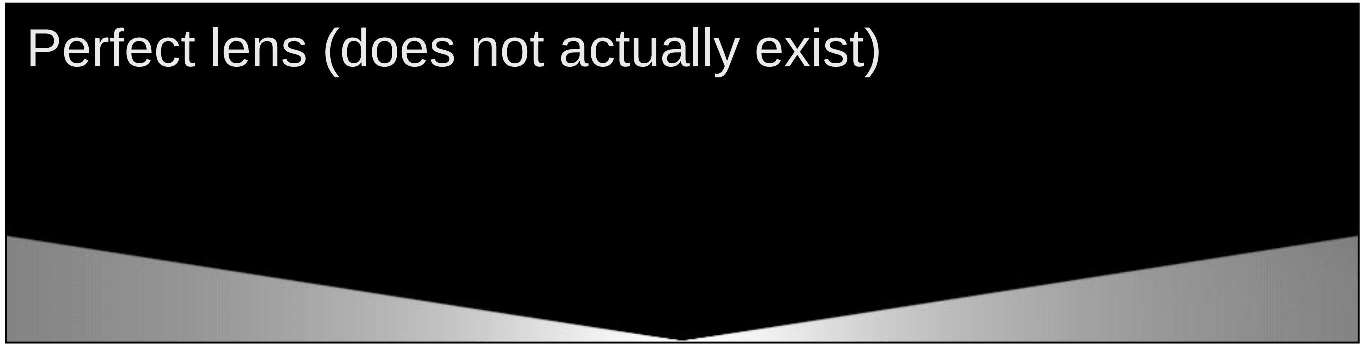


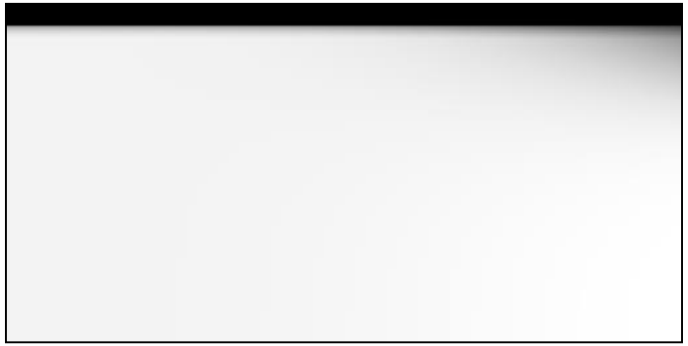

Achromatic doublet lens (different type)




Apochromatic (APO) lens



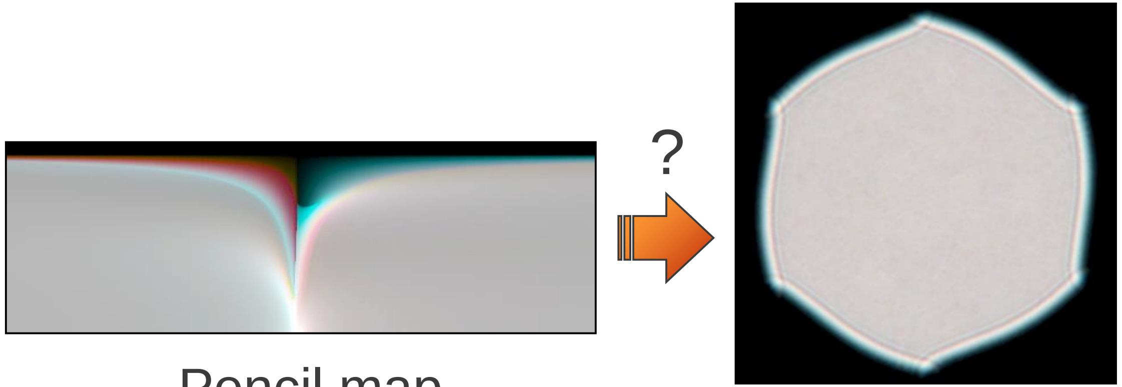

Perfect lens (does not actually exist)



Application to Arbitrary Aperture Shapes

Various Aperture Shapes

- Aperture shape is an important artistic factor
  - Typically 5~9 diaphragm blades
  - Changes from rounded to n-gon
- How to map pencil onto the polygonal aperture shape?
  - 3D Textures?
    - Too large, not practical

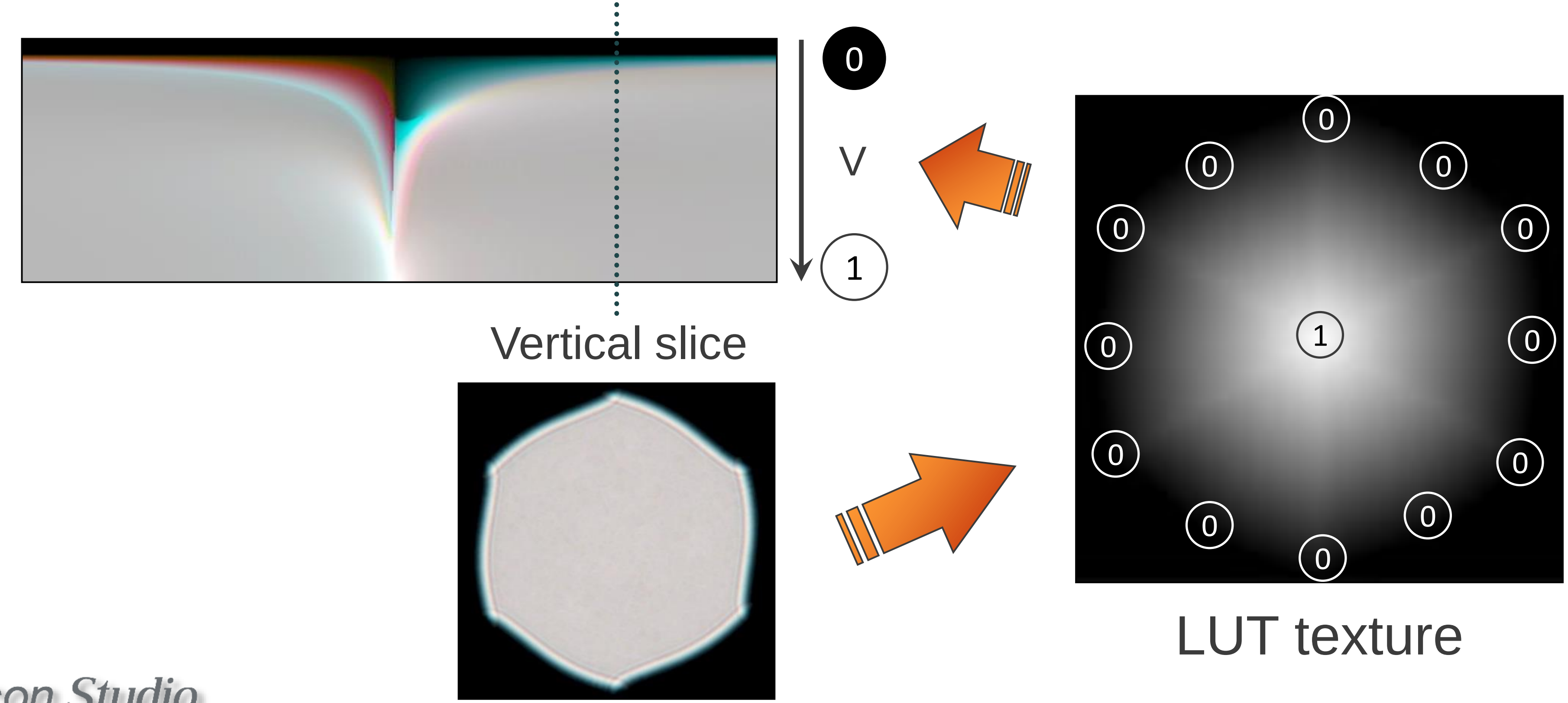


Pencil map

Aperture shape

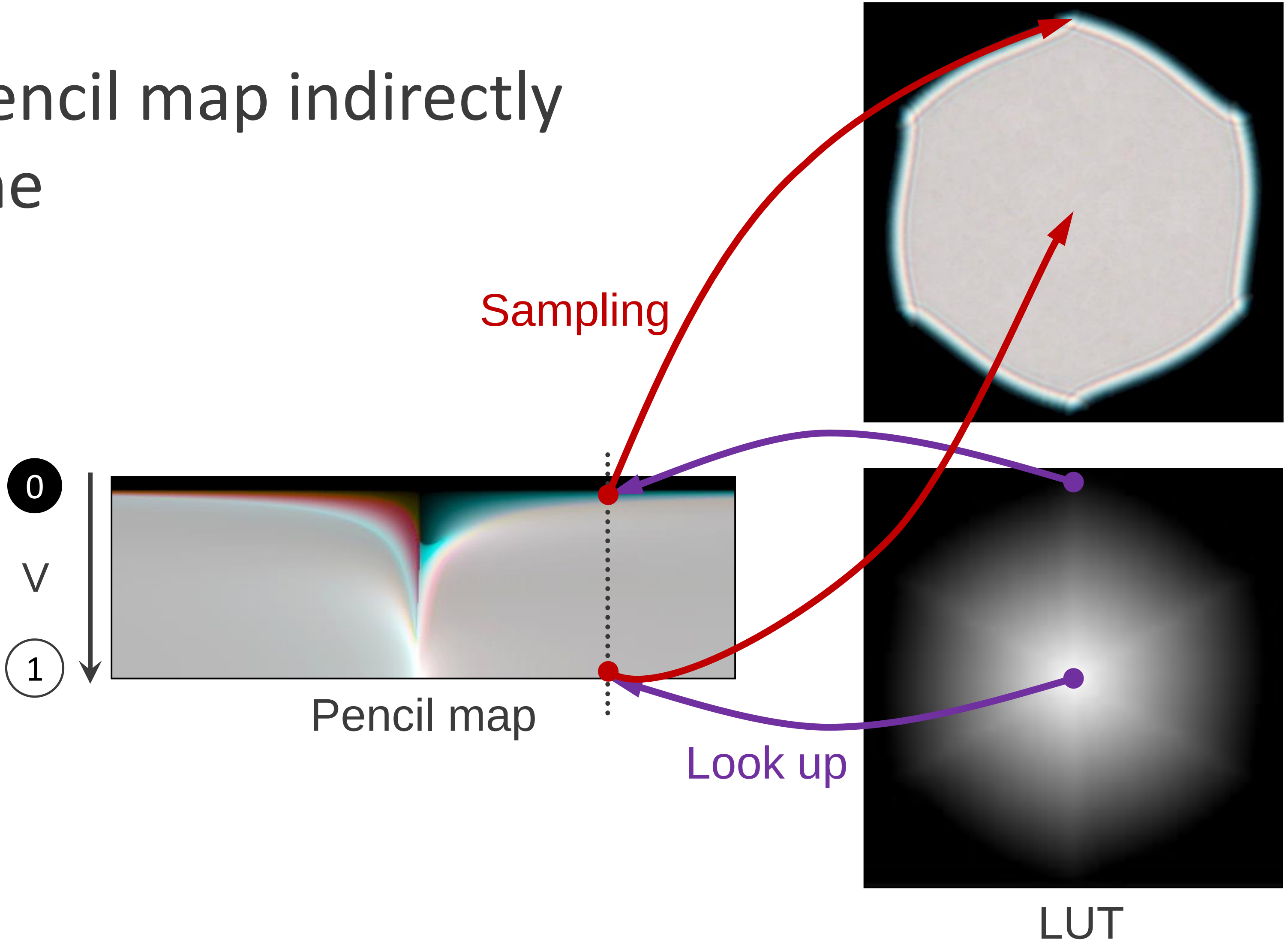
Indirect Reference of Pencil Map

- Precompute an LUT texture that stores V coordinates of pencil map



Indirect Reference of Pencil Map (cont'd)

- Sample pencil map indirectly at run-time

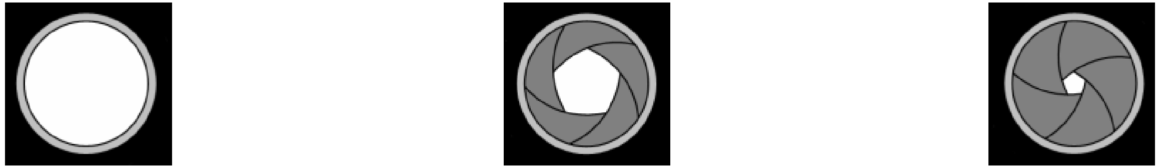


Indirect Reference of Pencil Map (cont'd)

- LUT determines the aperture shape
  - Independent of pencil map
  - Can reproduce curved shapes of a diaphragm blade
    - Prepare a set of LUTs for various diaphragm conditions
  - Other shapes such as stars, hearts, … can be used

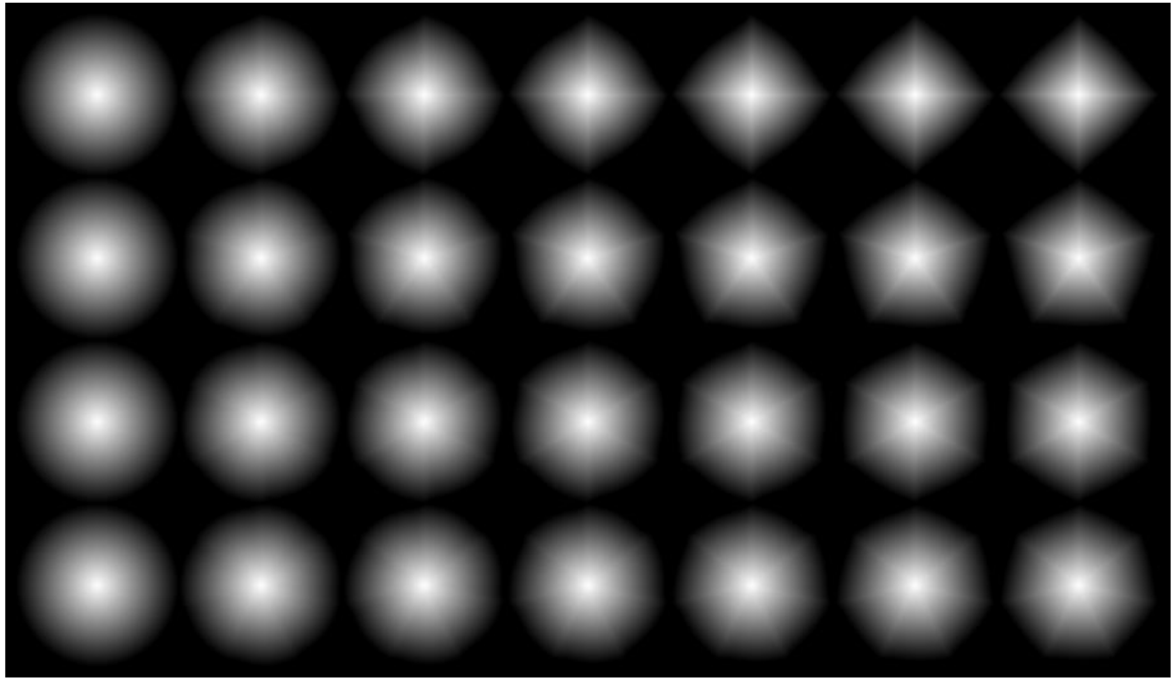
Various LUTs

- For the number of diaphragm blades and opening levels
- Smooth deformation is possible by interpolating between two adjacent LUTs

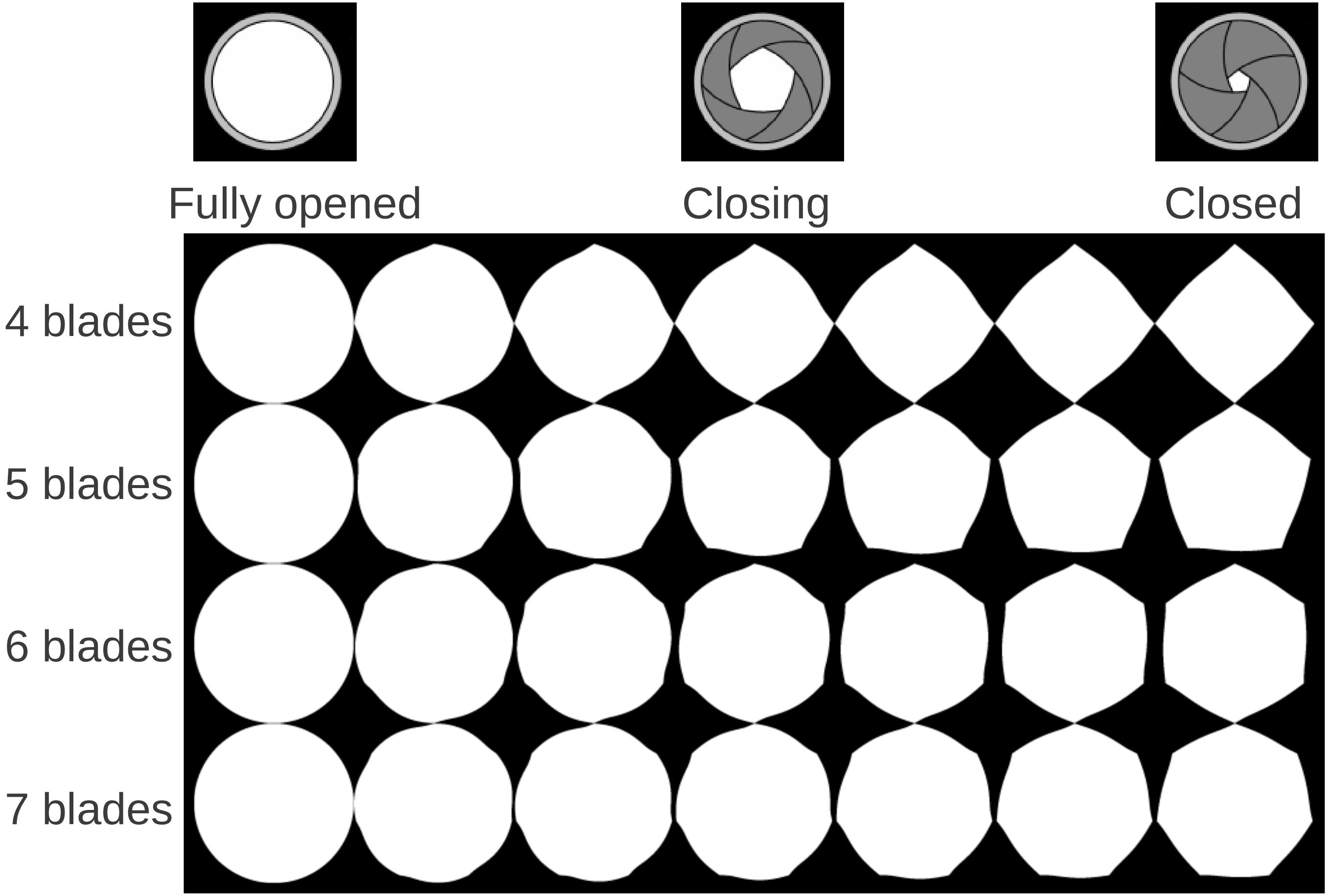


Fully opened　　Closing　　Closed

4 blades
5 blades
6 blades
7 blades



Silhouette LUTs for debug



Scattering or Gathering?

Both can be Implemented

- Better quality by scattering
  - Heavy processing load
- Hybrid method is recommended
  - Both scattering and gathering

Hybrid Method

- To determine which pixels will be scattered or gathered, use:
  - The CoC size
  - Difference in luminance between neighboring pixels

Original

Result (green: gathering pixels)

Gathering

Hybrid of Scattering and Gathering

Optimization

- Use a half resolution buffer for scattering
  - Scattering process can be 16x faster
- Split the process into several passes with hierarchical resolution buffers
  - Use lower resolution for larger bokeh
  - The process at the 1/4 x 1/4 resolution can be 256x faster
- Scatter a pixel every 2x2 pixels
  for relatively larger bokeh in each resolution
  - Pixels that have an especially heavy processing load will be 4x faster

Results

Bokeh Simulation in Real Time

Back bokeh with cyan fringes

Front bokeh with red/purple fringes


Diaphragm Simulation
5-blade Aperture

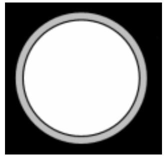
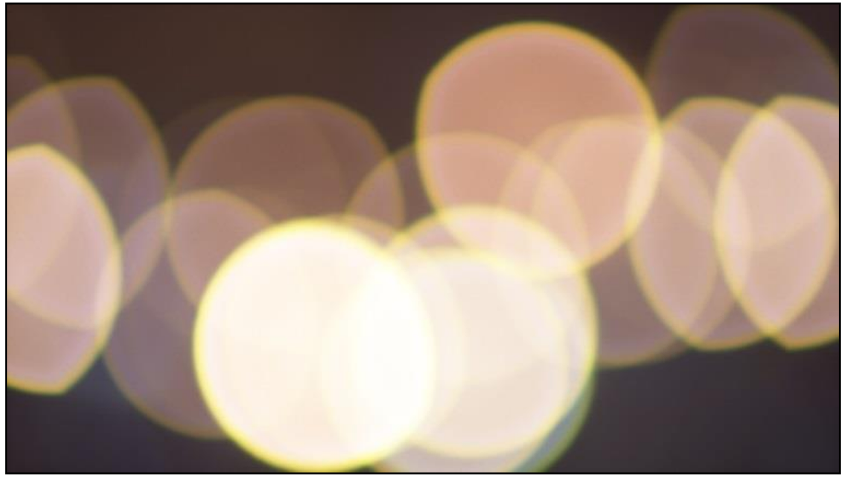

Diaphragm Simulation
6-blade Aperture


Diaphragm Simulation
7-blade Aperture

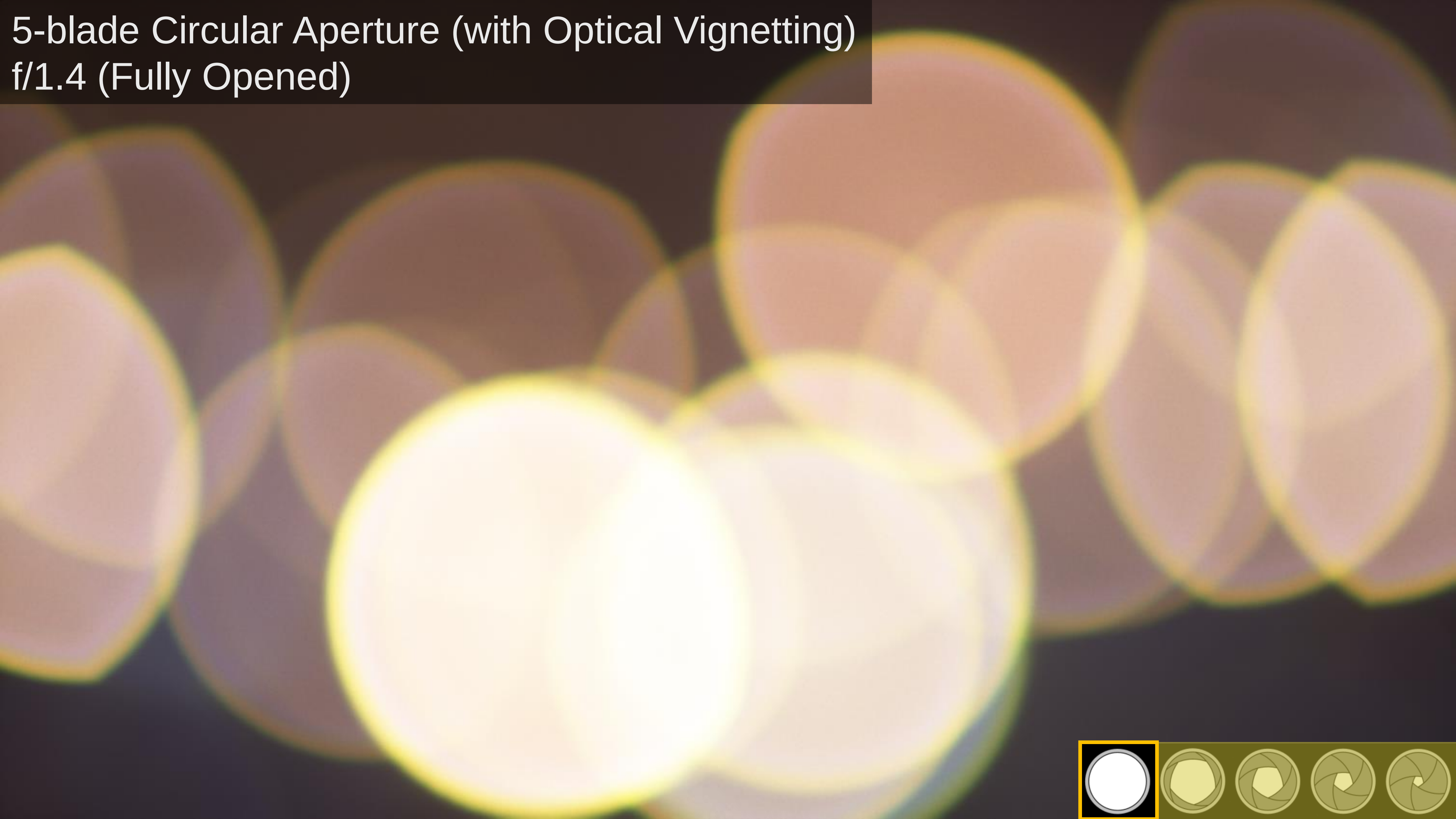

Diaphragm Simulation
8-blade Aperture

Curved Diaphragm and Optical Vignetting

- Opening / Closing
  - Deformation
    - Circular aperture
    - Polygonal aperture
  - Rotation
  - Optical Vignetting
    - Cat’s Eye Effect

5-blade Circular Aperture (with Optical Vignetting)
f/1.4 (Fully Opened)



5-blade Circular Aperture (with Optical Vignetting)

f/2 (1 Stop Closed)

5-blade Circular Aperture (with Less Optical Vignetting)
f/2.8 (2 Stops Closed)

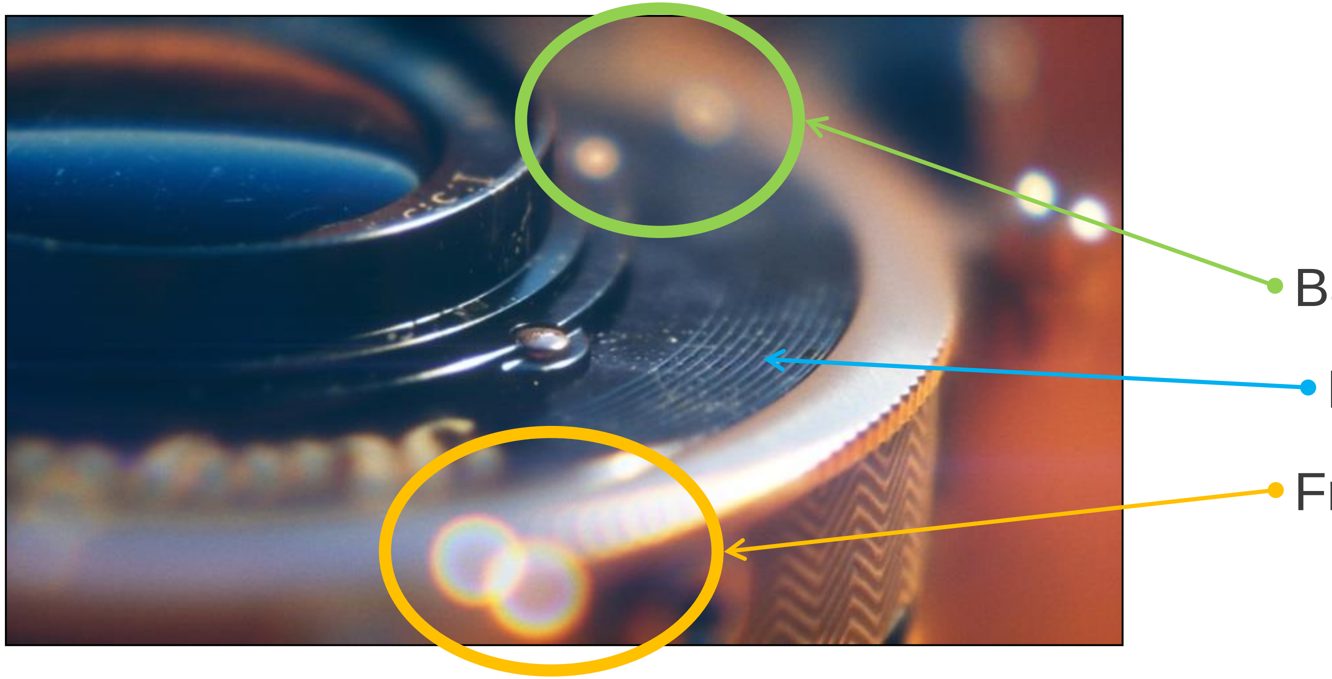
5-blade Circular Aperture (with No Optical Vignetting)
f/5.6 (4 Stops Closed)

5-blade Circular Aperture (with Fake Diffraction Spikes)

f/11 (6 Stops Closed)

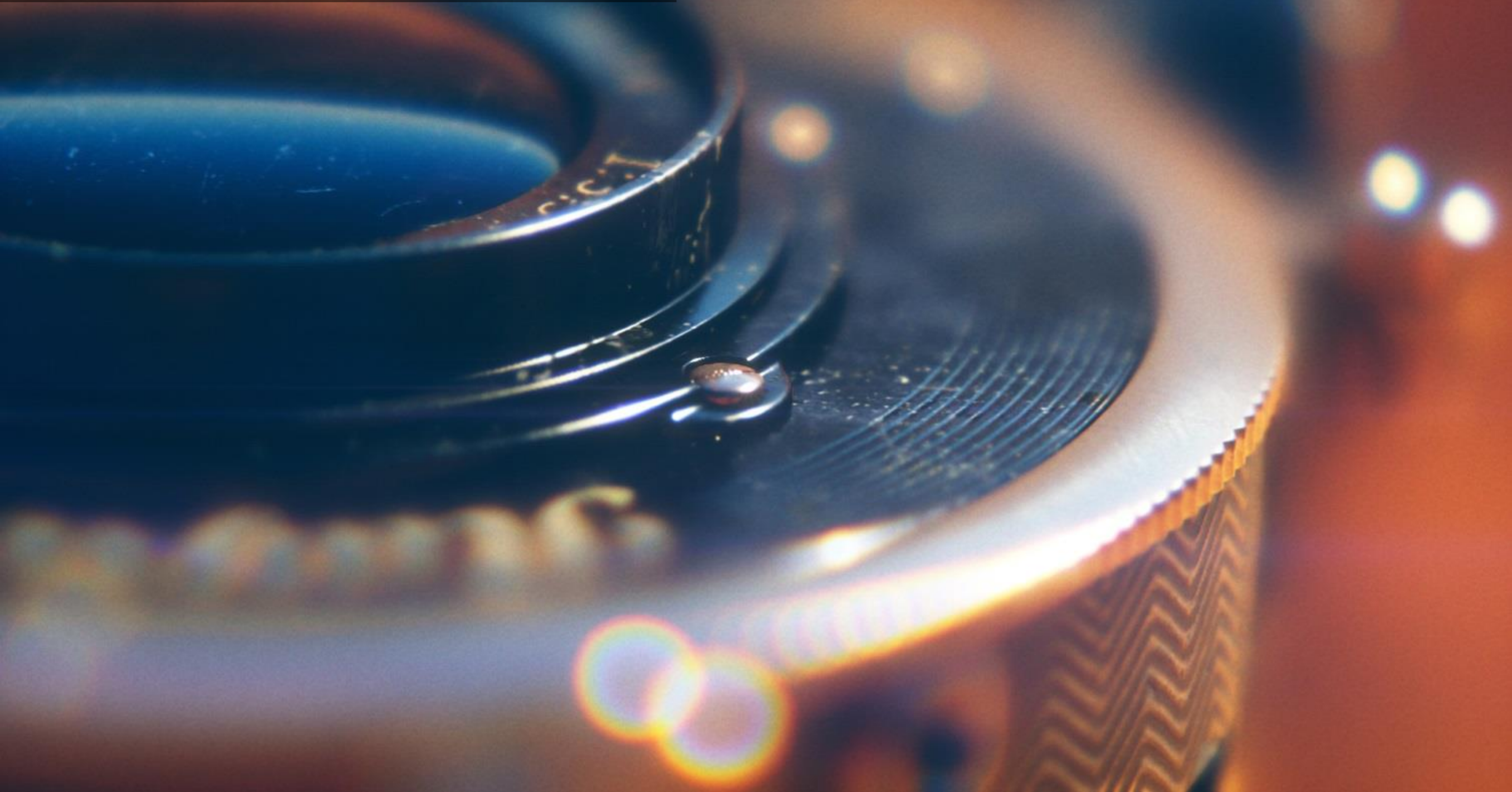
Various Aberrations and Corrections

- Correction of SA and axial CA mostly affect bokeh



Differences between front and back bokeh

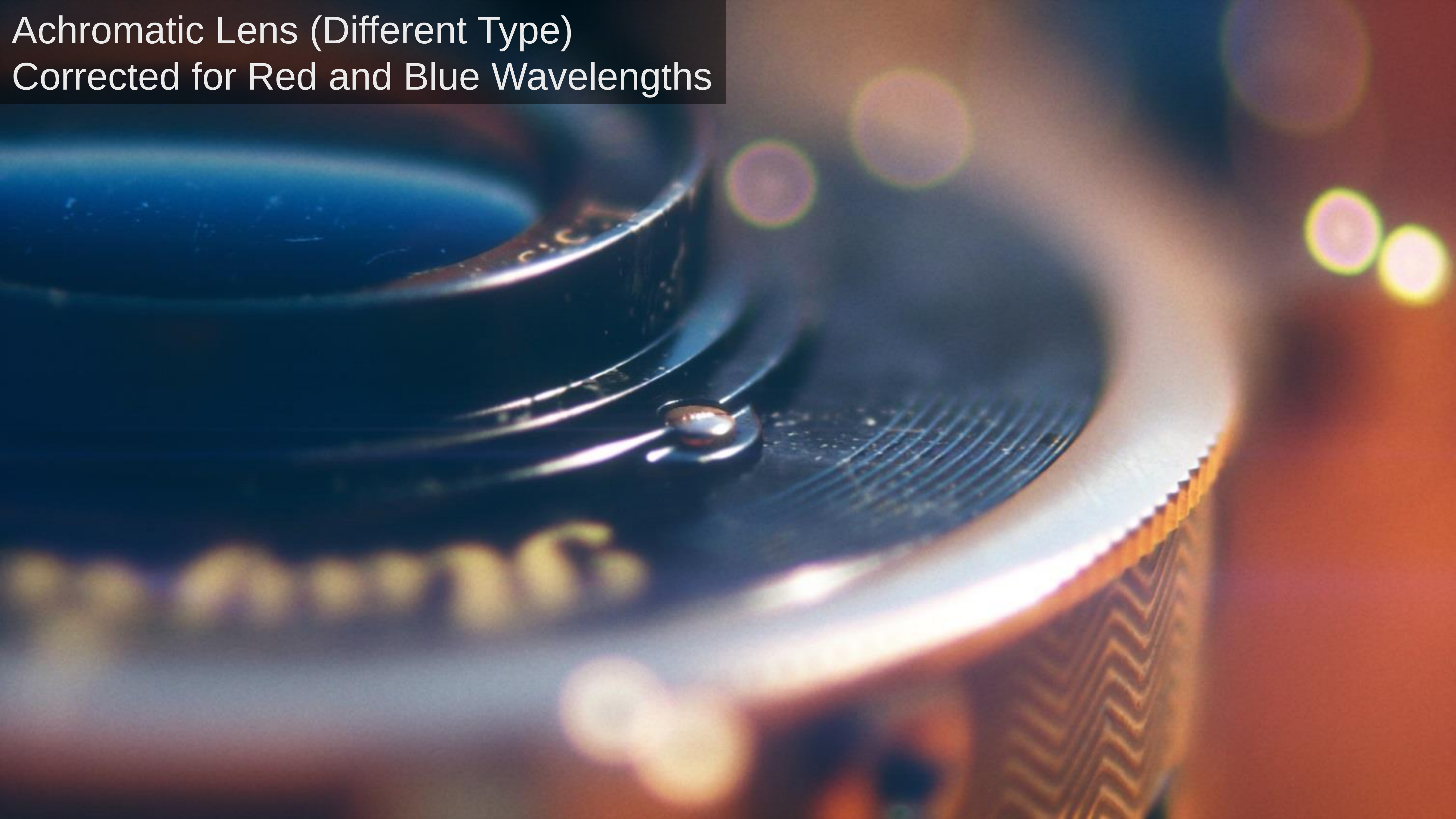
Spherical Lens (with No Corrections)



Aspherical Lens (with Chromatic Aberrations)
Correction of Spherical Aberration

Achromatic Lens
Corrected for Red and Blue Wavelengths

Achromatic Lens (Different Type)
Corrected for Red and Blue Wavelengths



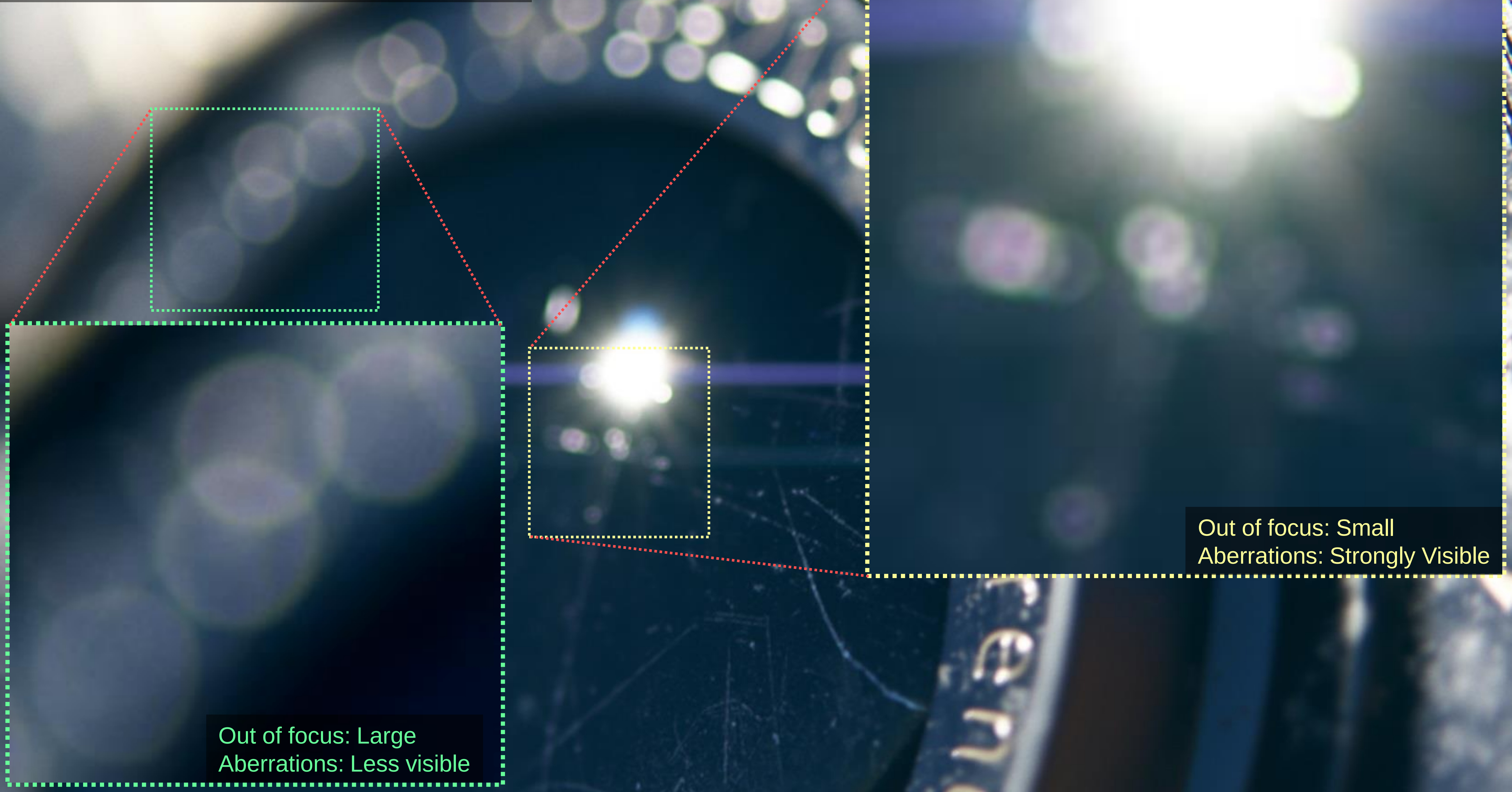
APO (Apochromatic) Lens
Corrected for 3 Wavelengths (More Expensive Lens)

Almost Perfect Lens
Without any Spherical and Longitudinal Chromatic Aberrations

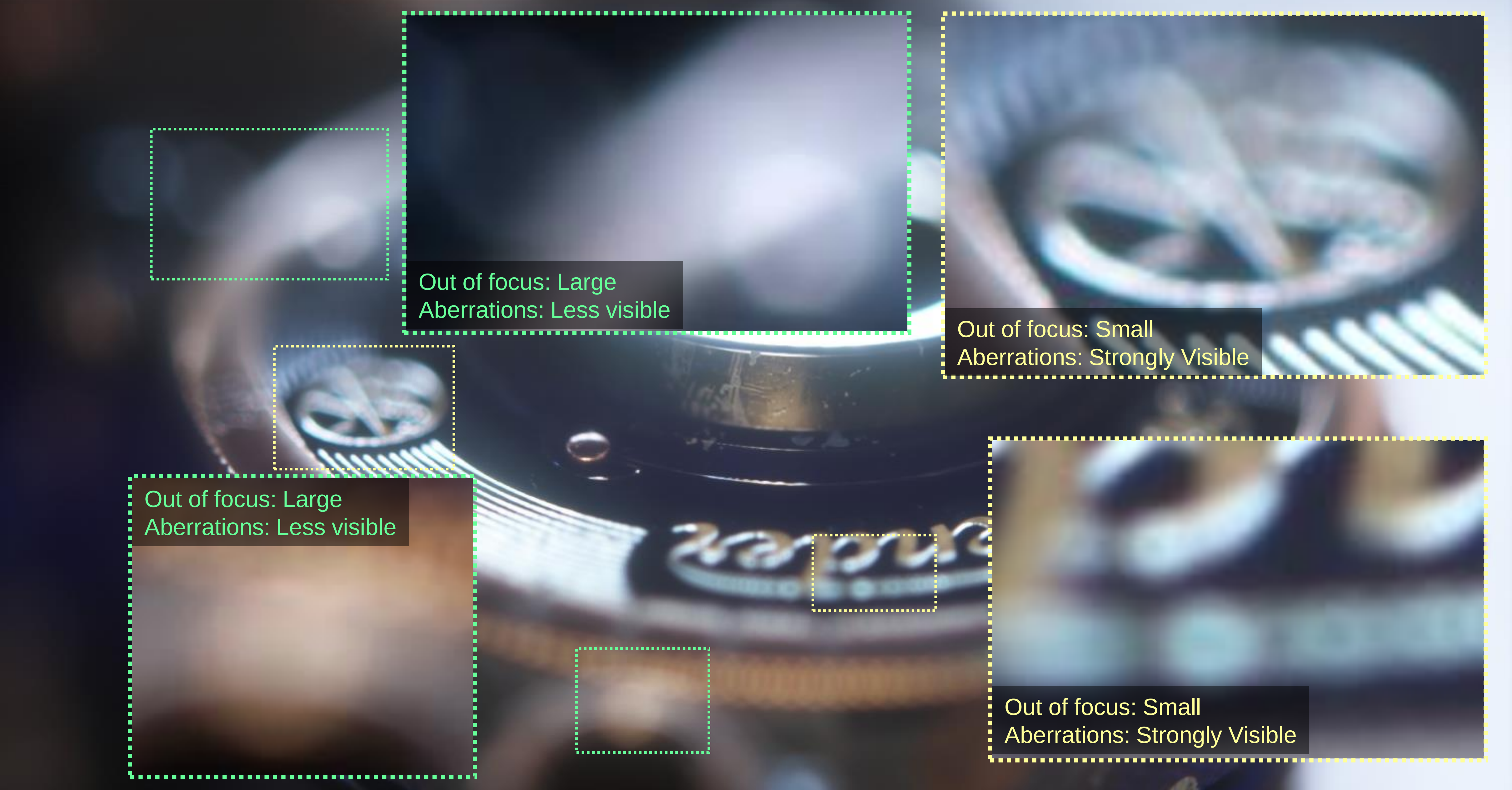
STF (Smooth Transition Focus) Lens
Soft Edged Bokeh by Apodization Optical Element

Radial gradient ND filter

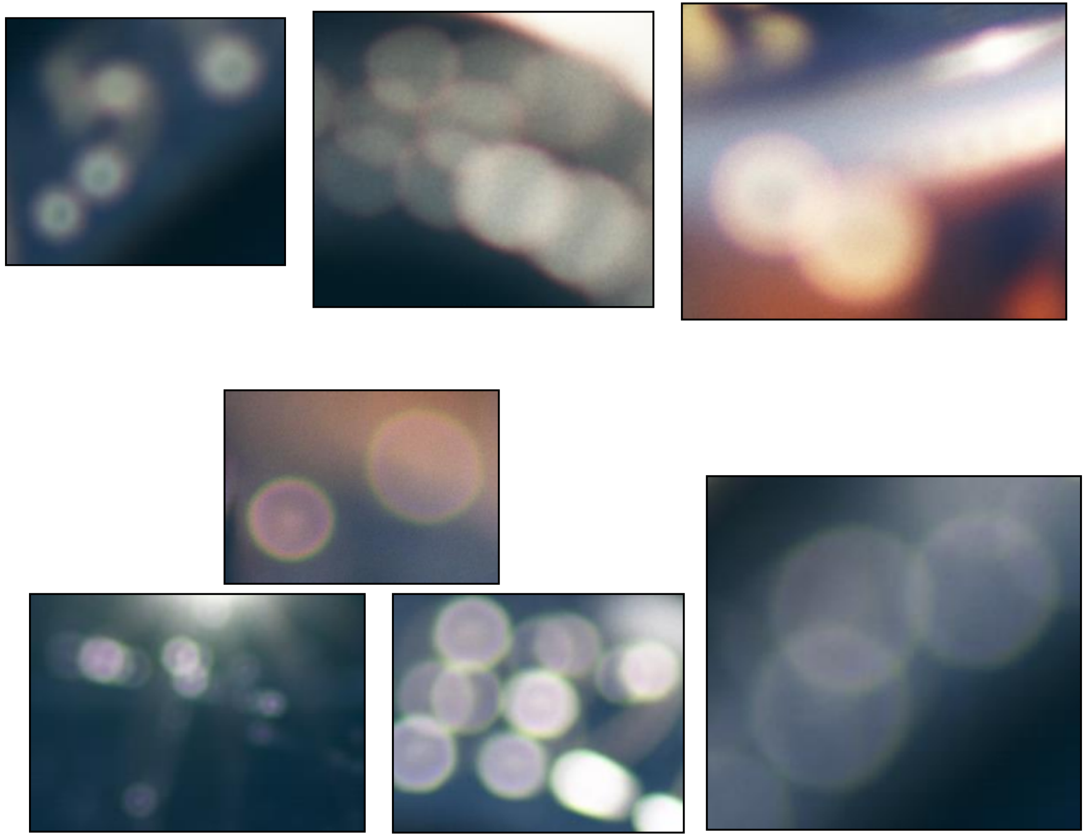
Residual Aberration Visibility



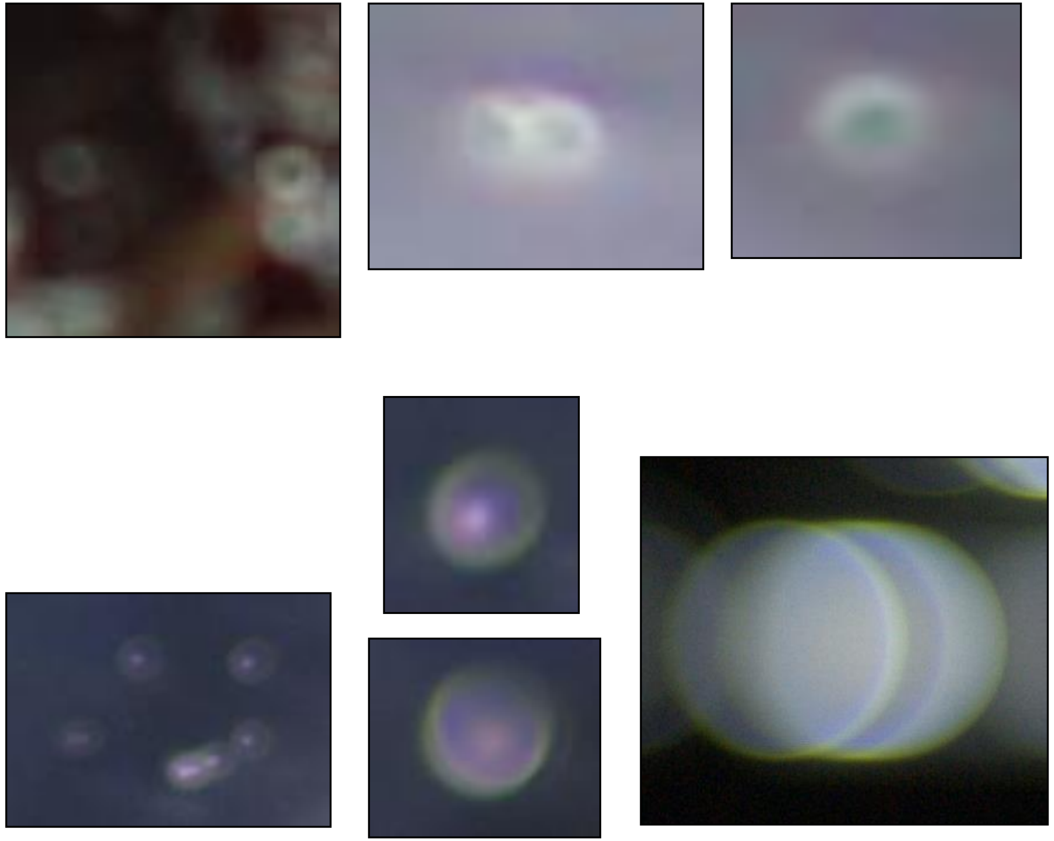
Residual Aberration Visibility



Comparison with Photographs (Achromat)

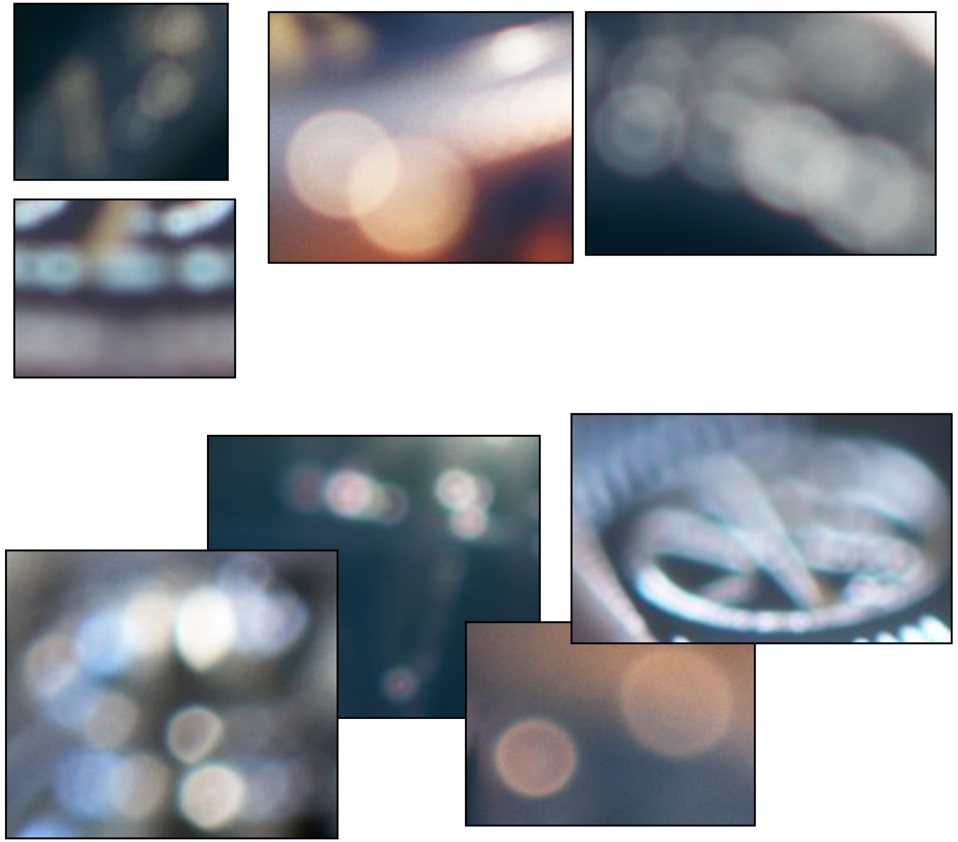


Real-time simulation results

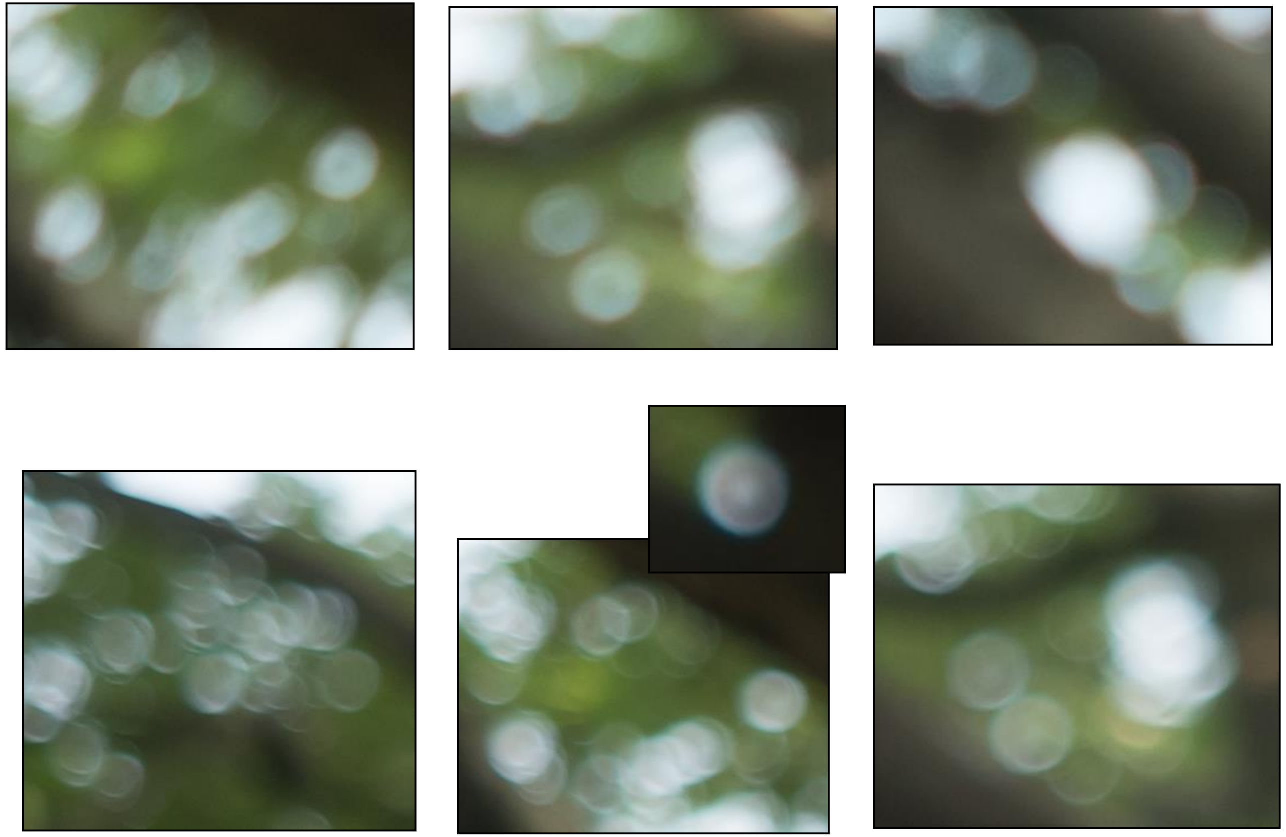


Real photographs with achromatic lens

Comparison with Photographs (APO)



Real-time simulation results



Real photographs with apochromatic lens

Conclusion

Conclusion

- Reproduce photorealistic bokeh with pencil map and LUT
  - Pencil map defines bokeh characteristics
  - LUT defines bokeh shapes
- Optimization
  - Various options available
  - Combinations can be used to improve performance

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