
Schlieren

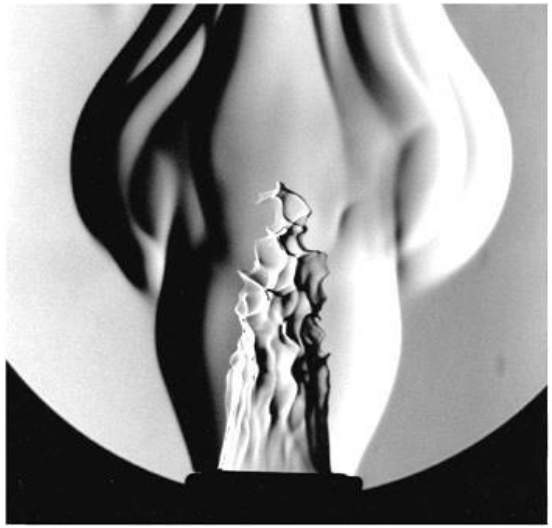
Limitations of Shadowgraph

- A “line-of-sight” technique
  - Information is collected across the entire ray path or line-of-sight
  - Density gradients from the camera to the light source are all imaged, not just from the test section
  - This can sometimes result in odd three-dimensional effects
- Extremely difficult to make the results quantitative, so purely a visualization technique
- Only sensitive to strong variations in the flow
  - For example, cannot visualize expansion fans using shadowgraph
- Size of flow structures visualized in images is diffraction-limited (i.e., shock thickness)

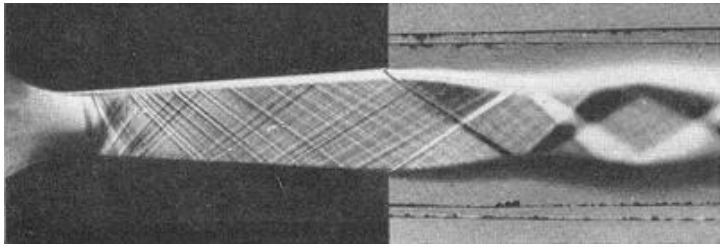
Schlieren

- Means of visualizing density gradients (strong and weak)
- From German *die Schliere* meaning ‘the streak’
- Originally devised to see imperfection in glass and lenses
- Later appropriated by the fluid mechanics community as a flow diagnostic

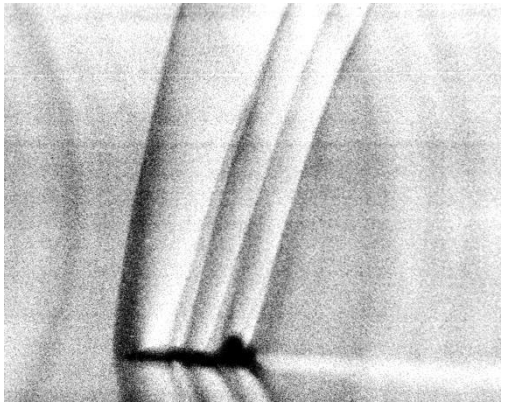
Laminar Diffusion Flame



Supersonic Jet

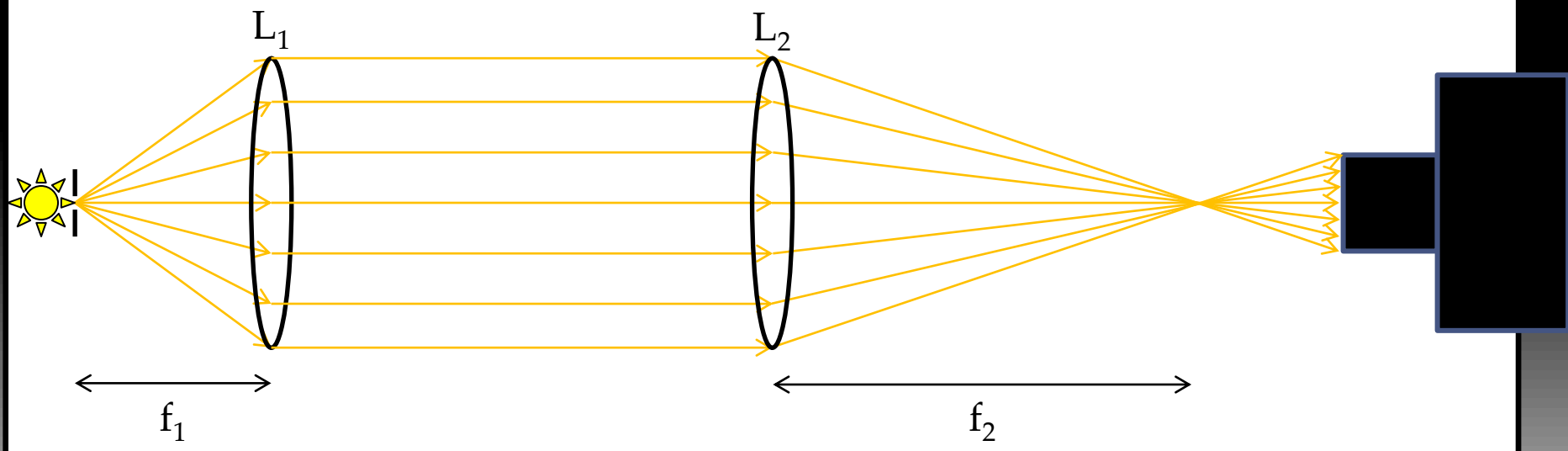


Jet



Experimental Setup

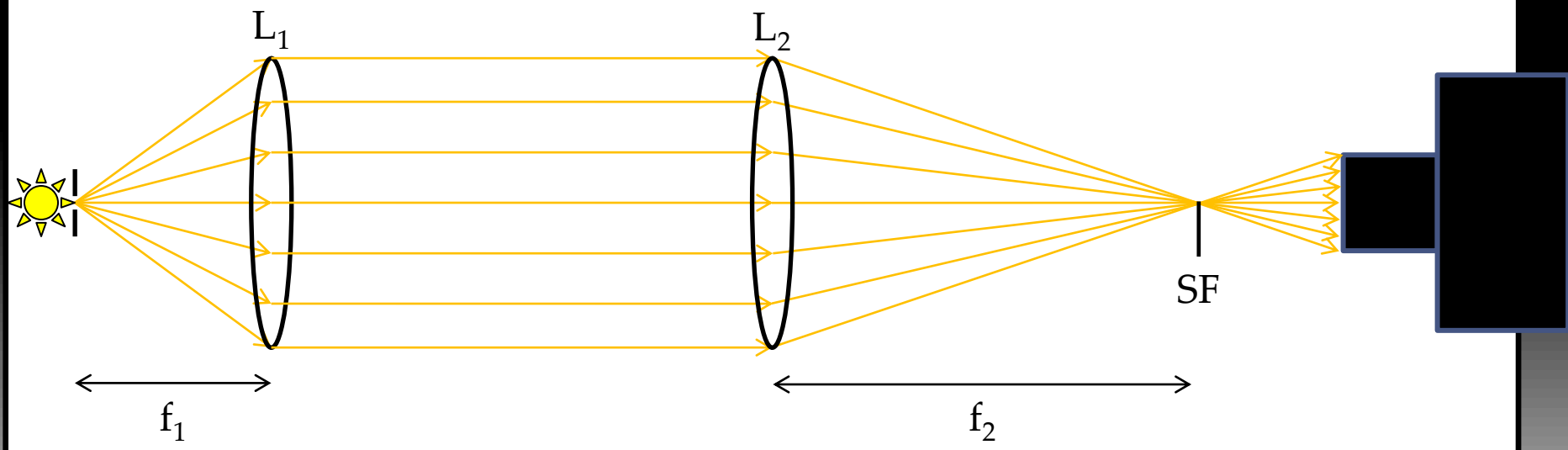
- Let's start from our complete shadowgraph setup
- Note now that the focal lengths of our two lenses/mirrors need not be the same
- Our test section lies between the two lenses/mirrors



Experimental Setup

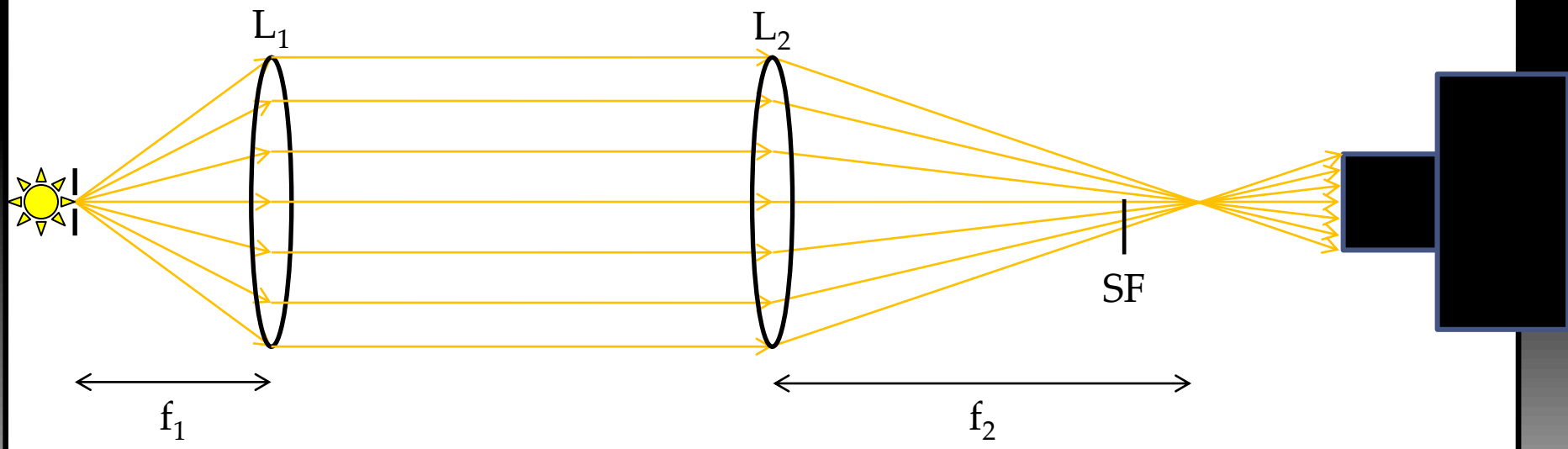
- To get Schlieren from our setup, all we need to do is add a spatial filter at the location of the second focus:

- How does this work?



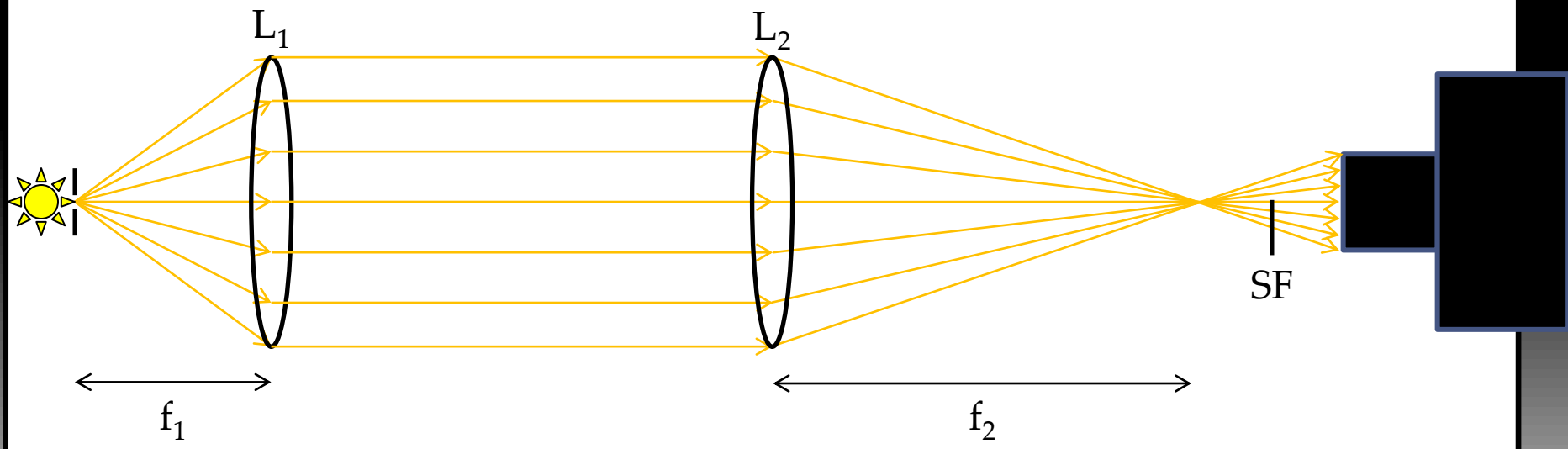
Experimental Setup

- What would happen if we put a sharp spatial filter in front of the focal point?
- Bottom of image is darkened



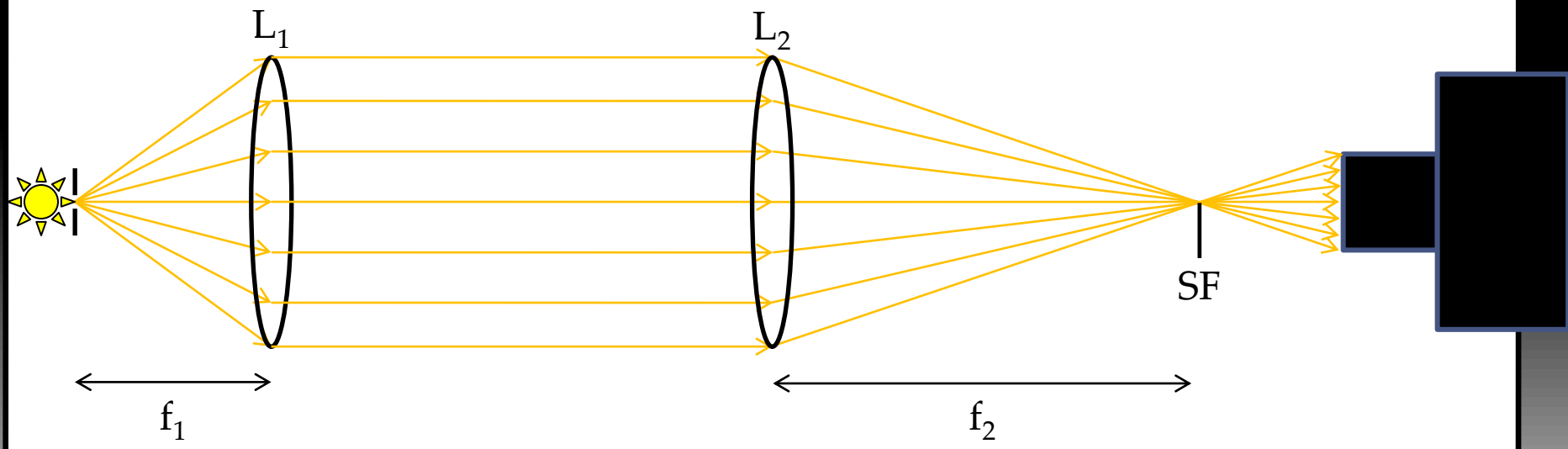
Experimental Setup

- What would happen if we put a sharp spatial filter behind the focal point?
- Top of image is darkened



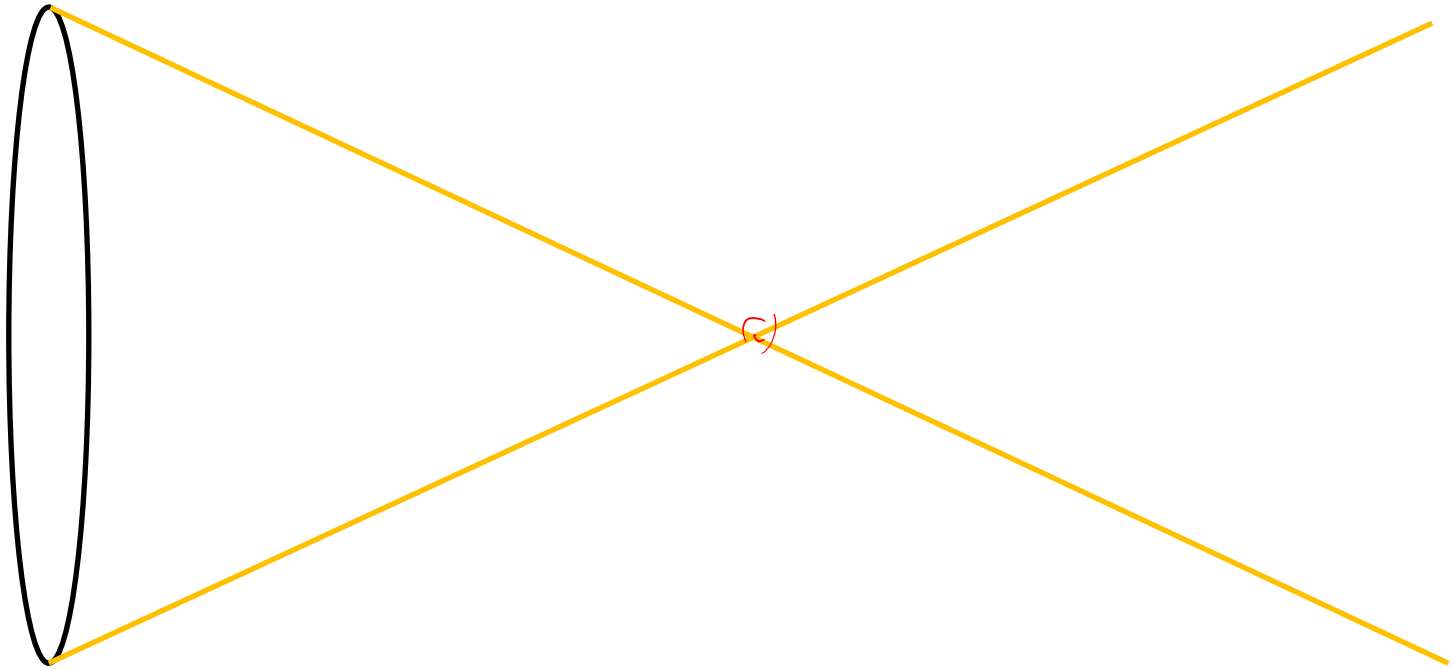
Experimental Setup

- Now, what would happen if we placed it directly at the focal point?
- Need to consider what happens at the focus



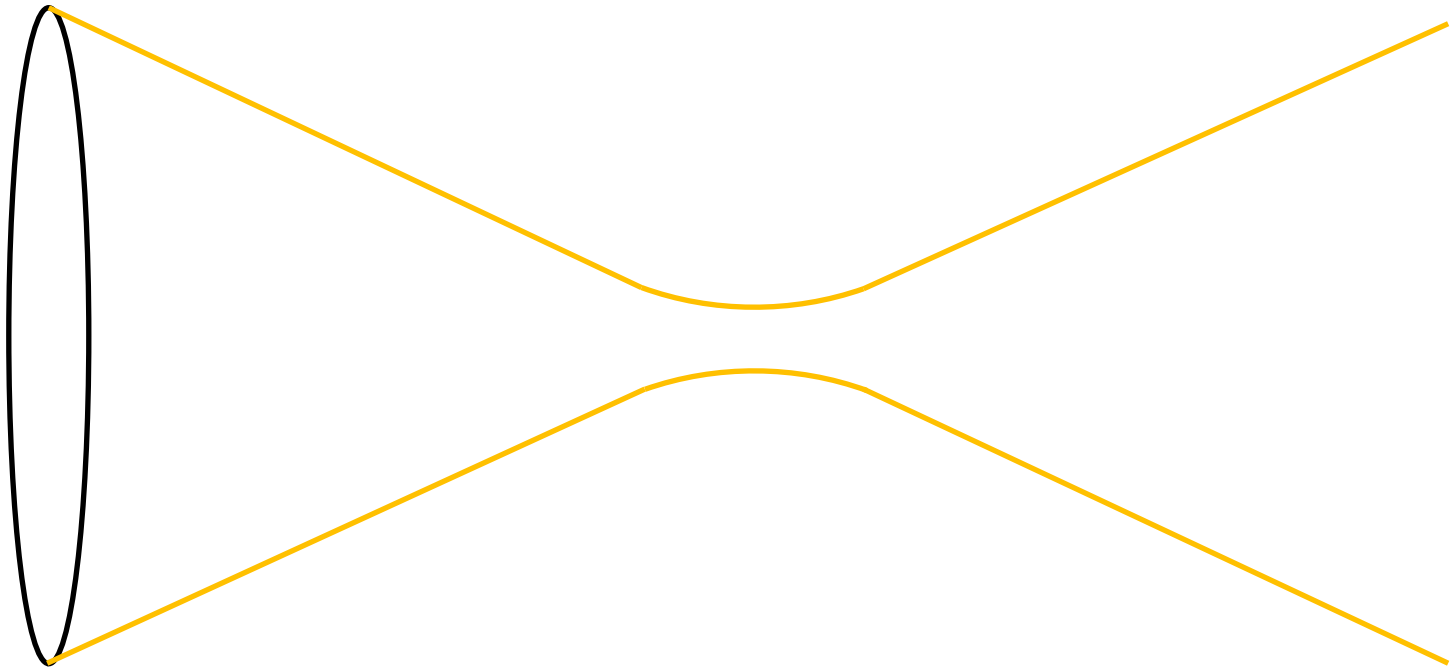
Spatial Filtering

- What is happening at the focus?
- If we go by geometric optics, the focus should be a singular point
- This is not the case however – infinite intensity!



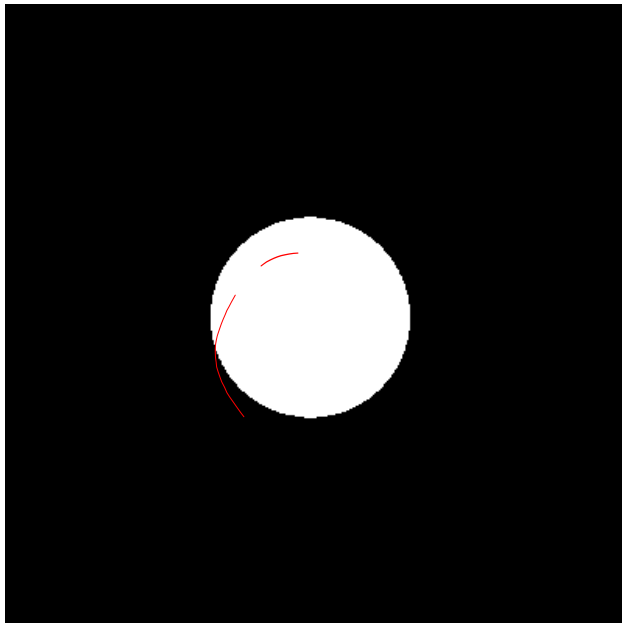
Spatial Filtering

- Diffraction places a lower limit on the possible spot size
  - The lens isn't actually just focusing light down to a point
- Optical aberrations prevent diffraction-limited operation



Spatial Filtering

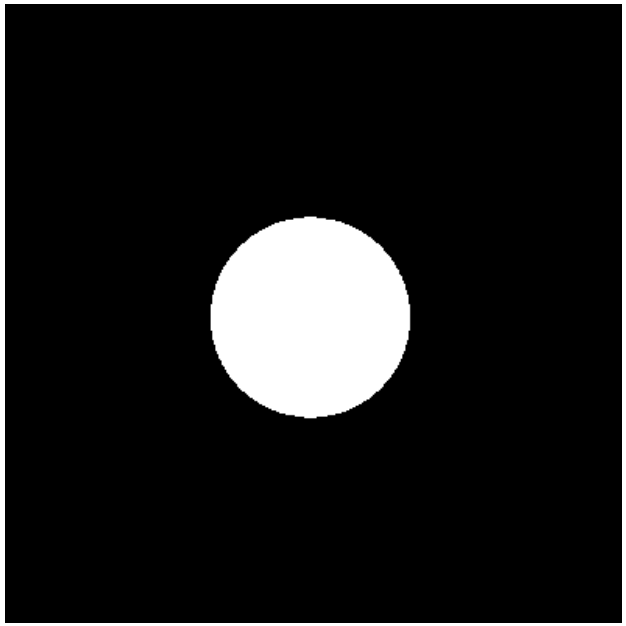
- So what does happen to the light at the focal plane?
- Size of the focal spot is a function of wavelength, image diameter, and focal length of lens
  - $d = 1.22 f \frac{\lambda}{D}$ for diffraction-limited case



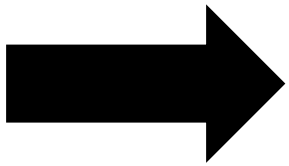
Circular Aperture

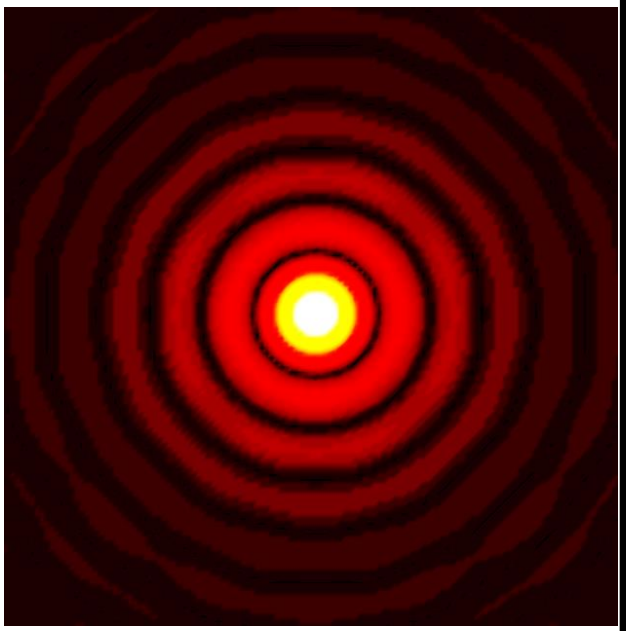
Spatial Filtering

- A lens performs a Fourier transform on the light entering the lens aperture
- The focal plane is often called the transform plane
  - The Fourier transform of the aperture pattern exists in physical space



Circular Aperture

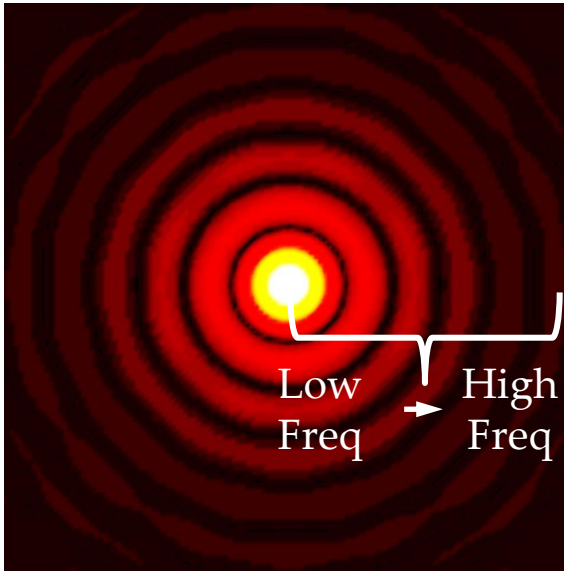




Airy Disk

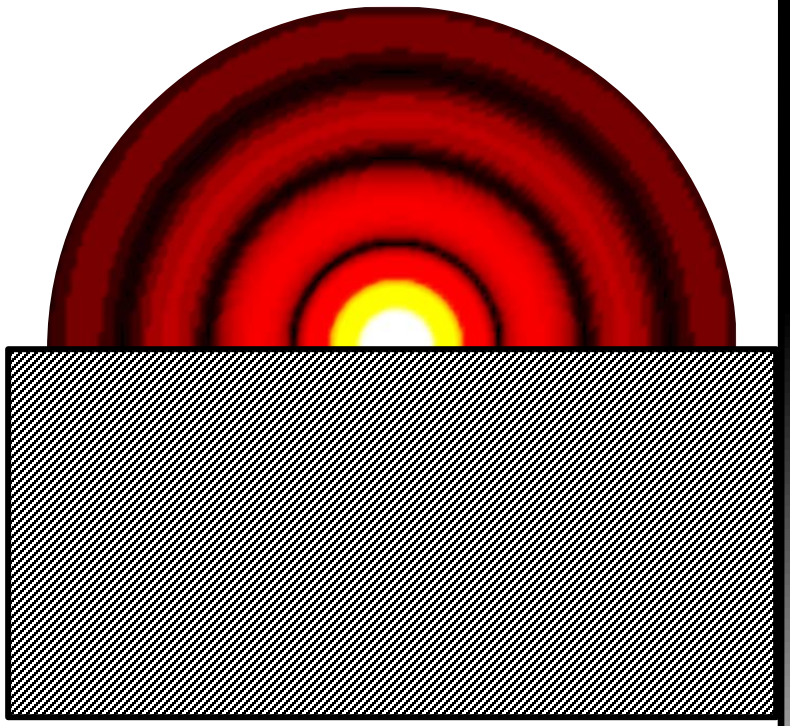
Spatial Filtering

- Why does this matter?
  - The Schlieren effect we're trying to visualize manifests as variations in the spacing and intensity of the diffraction pattern
  - By filtering out part of the content, we are addressing two points:
    - Reducing overall background intensity
    - Preventing destructive interference of anti-symmetric spatial frequencies



Spatial Filtering

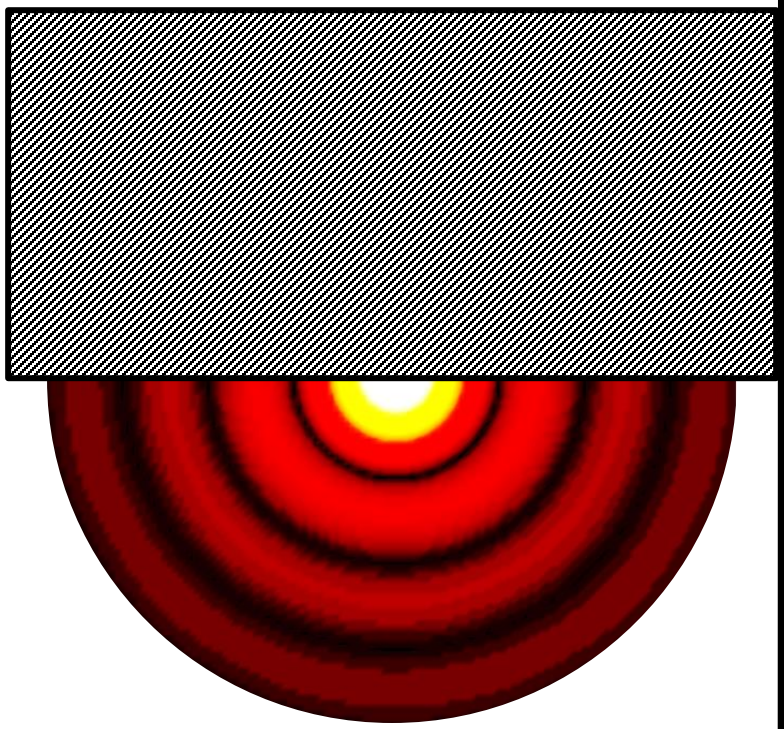
- What kind of spatial filters can be used?
- Heaviside filter (knife edge)
  - Removes high- and low- frequency content
  - Background uniformly dimmed
  - Density gradients perpendicular to KE appear lighter or darker depending on direction



Focal Spot

Spatial Filtering

- What kind of spatial filters can be used?
- Heaviside filter (knife edge)
  - Removes high- and low- frequency content
  - Background uniformly dimmed
  - Density gradients perpendicular to KE appear lighter or darker depending on direction
  - If KE is moved to opposite side of focal spot, intensity pattern is reversed

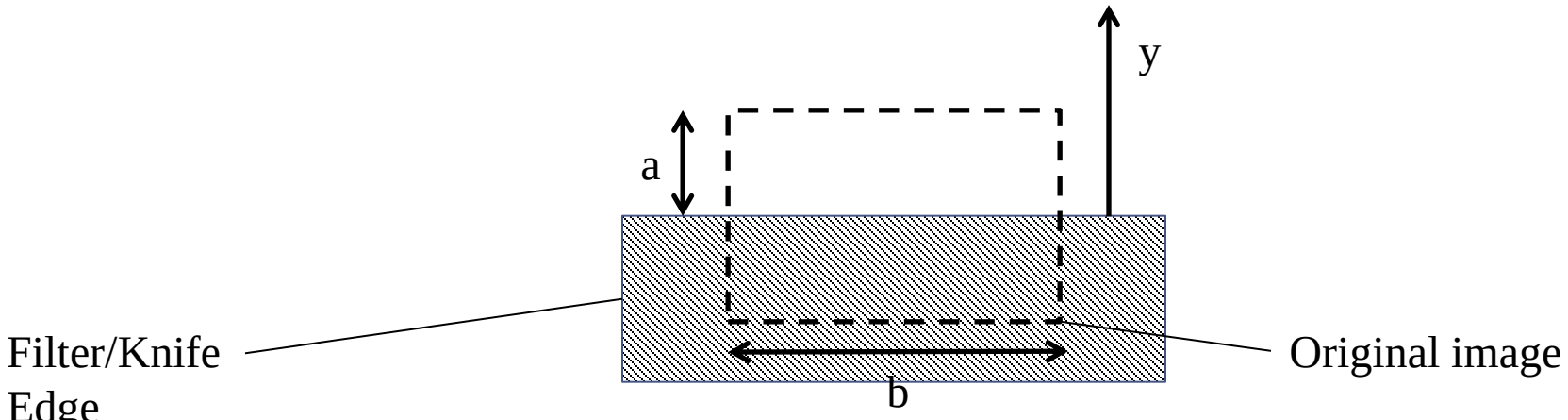


Focal Spot

Schlieren Equation

- The governing equation for Schlieren

$$\frac{\Delta I}{I} = \frac{f_2 \kappa}{a} \int \frac{\partial \rho(x,y,z)}{\partial y} dz$$



f_2 = focal length of focusing optic

κ = Gladstone-Dale constant

Schlieren Equation

$$\frac{\Delta I}{I} = \frac{f_2 \kappa}{a} \int \frac{\partial \rho(x,y,z)}{\partial y} dz$$

- What we can learn from this:
  - Schlieren is sensitive to the first derivative of density
    - Expansions and subtle density changes can now be visualized
  - Schlieren is sensitive to density gradients perpendicular to direction of filter
  - Sensitivity increases:
    - As slit half-height (a) decreases
      - Pushing filter further into focal spot increases sensitivity
    - With larger gradient path lengths (dz)
    - With longer focal length (f_2) Schlieren head
    - With a more intense light source (I)
  - Sensitivity does not depend on distance from test section to Schlieren head

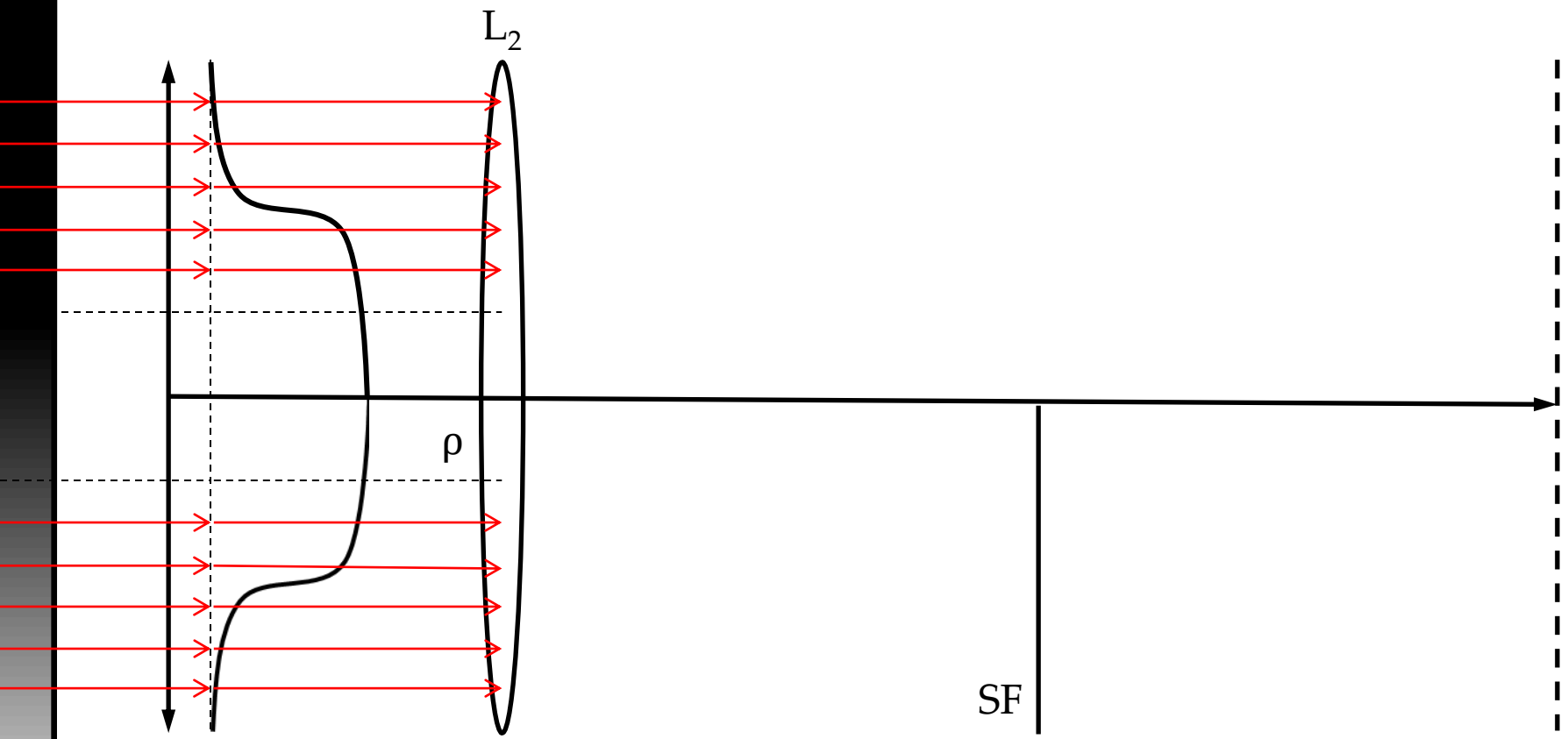
Schlieren vs. Shadowgraph

- Common differences between Schlieren and shadowgraph images

Schlieren	Shadowgraph
Sharp, detailed features, more sensitive	Sometimes “out of focus,” less detail, less sensitive
Symmetry of light/dark regions dependent on KE position	Always the same light/dark pattern (shocks are black/white stripe)
Expansion fans visible	Structures with linear density variation not visible

Schlieren Ray Tracing

- Ray Tracing
  - As before, plot density profile and draw undisturbed light rays



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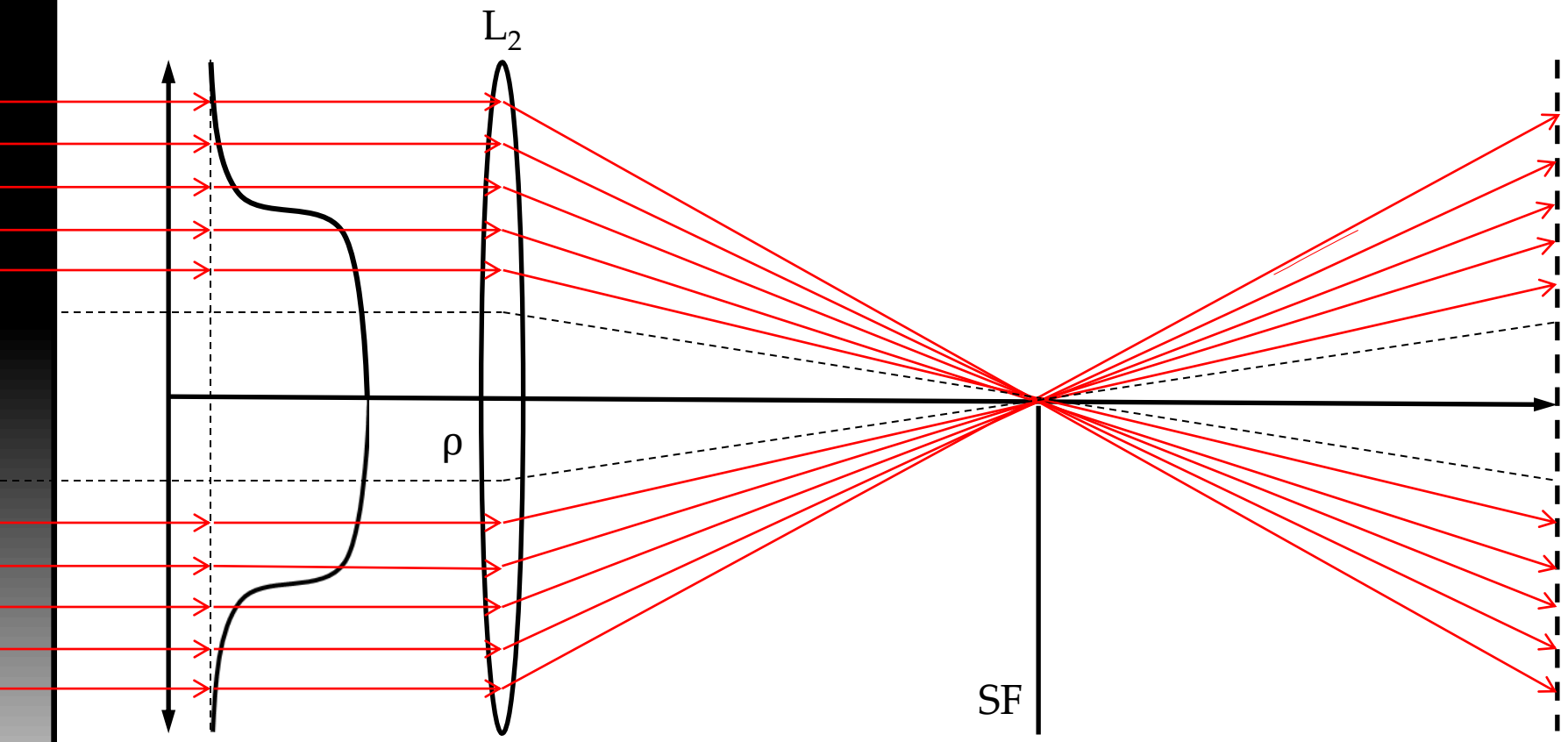
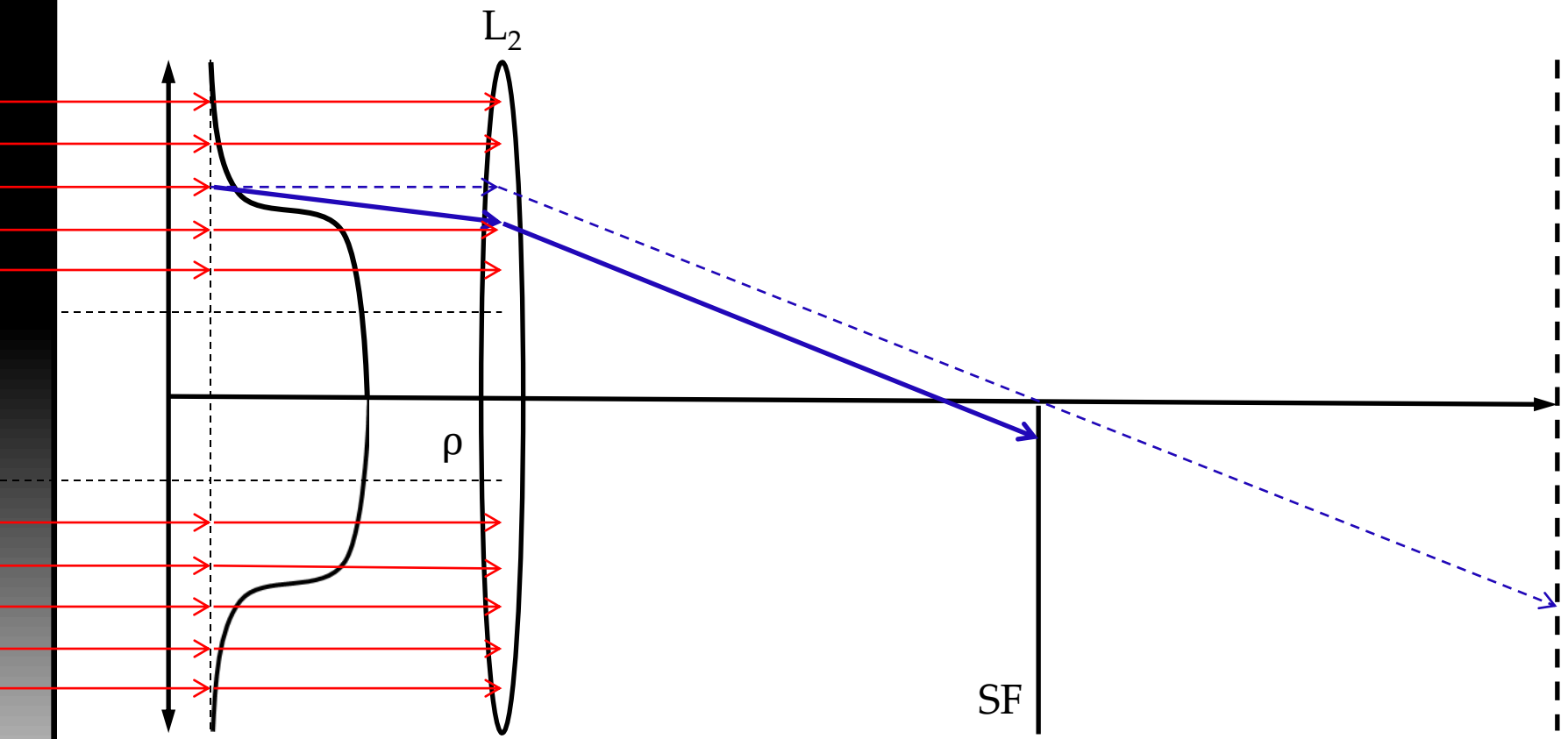


Schlieren Ray Tracing

- Ray Tracing
  - Deflect rays as with shadowgraph before L_2



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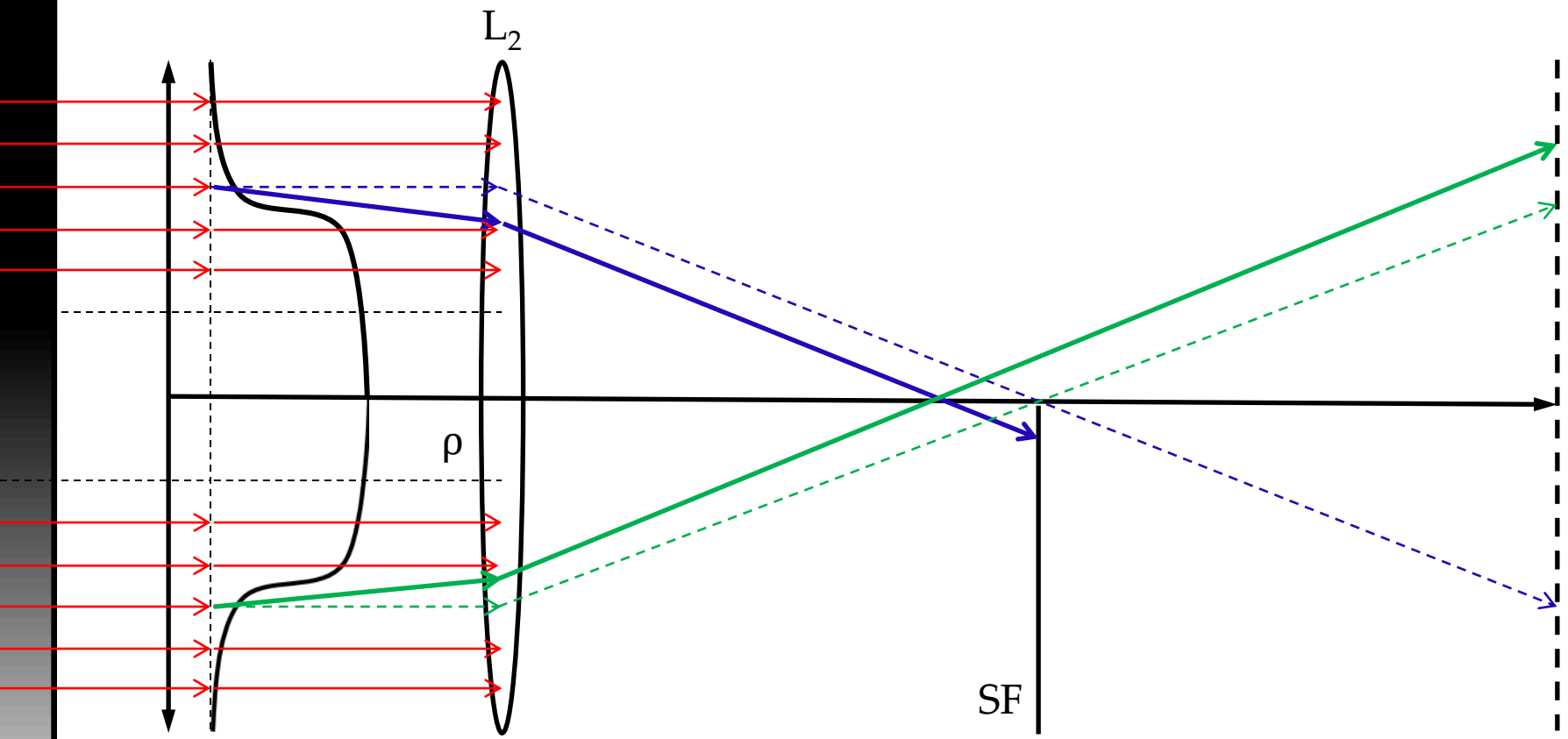
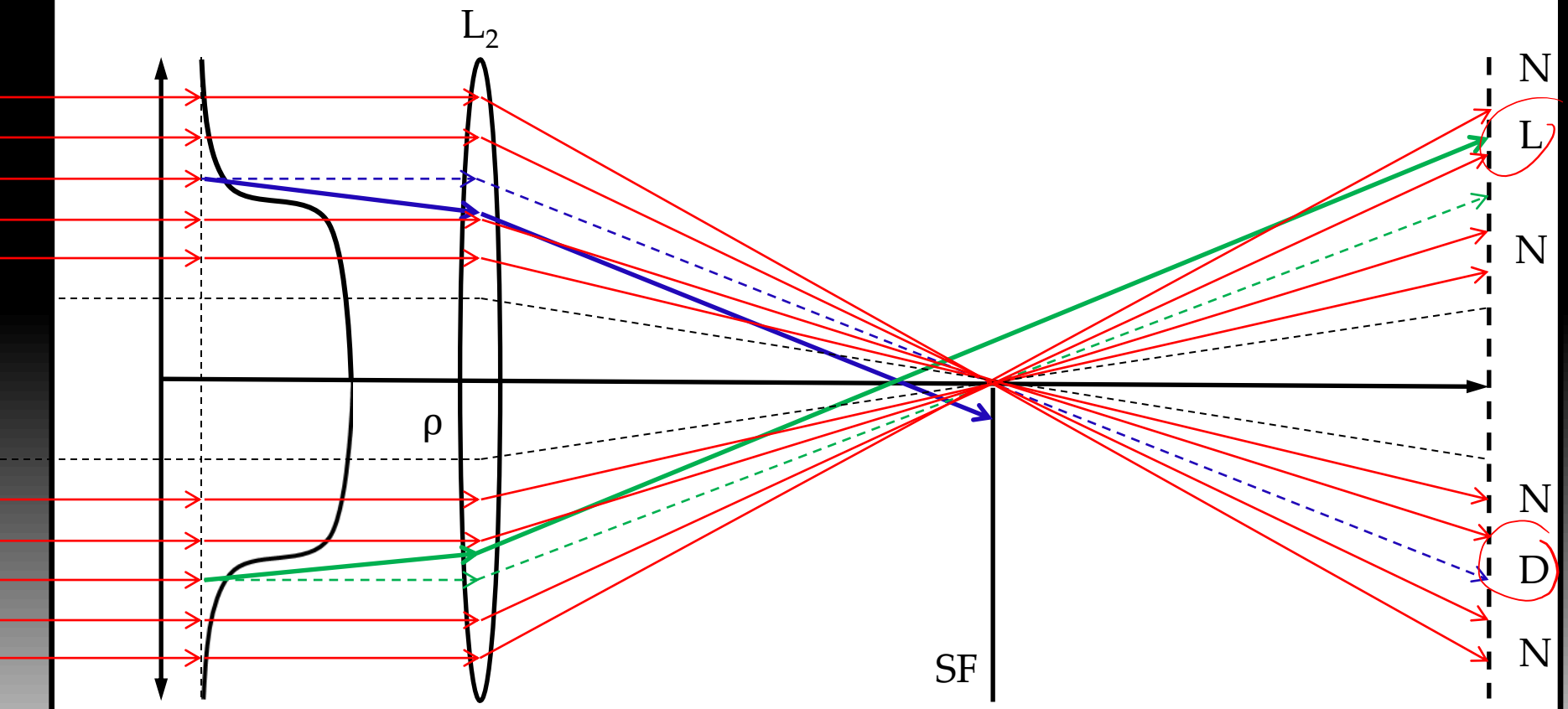


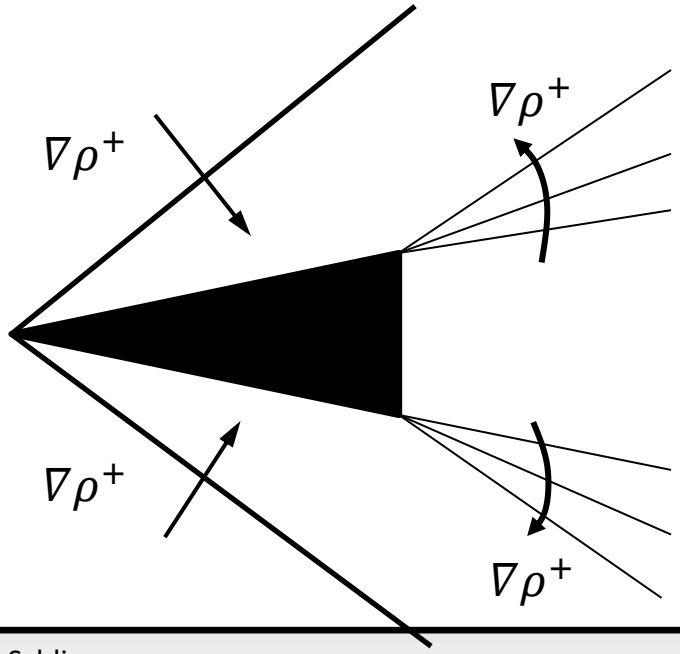
Schlieren Ray Tracing

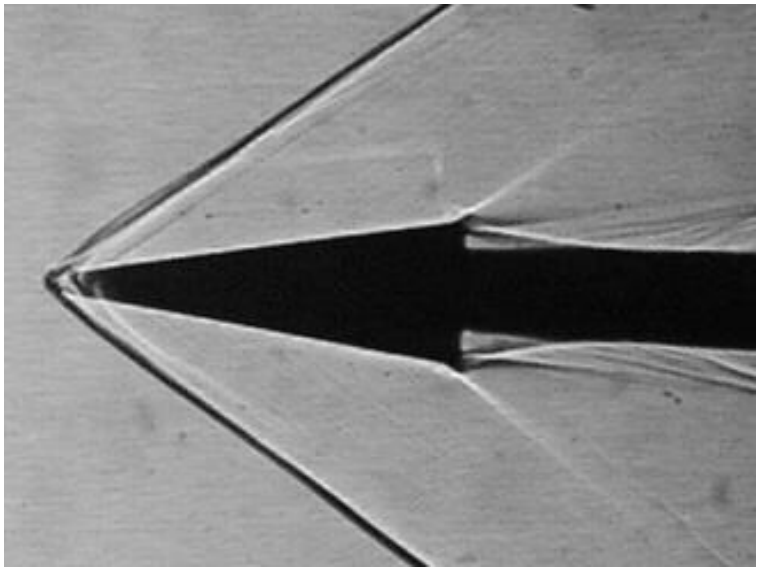
- Ray Tracing
  - We end up with an intensity pattern



Schlieren: Rules of Thumb

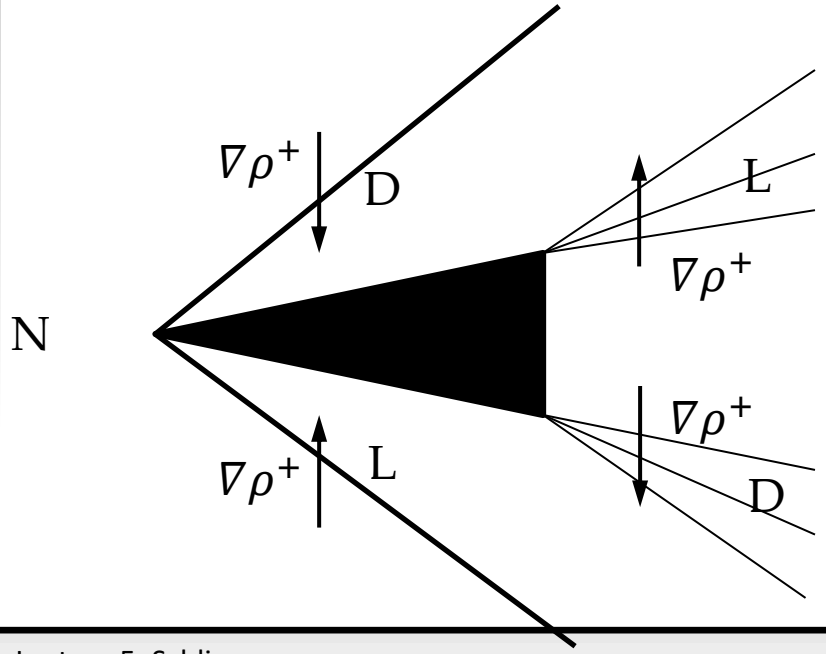
- Visualization of density gradients a function of filter orientation
- Any density gradient perpendicular to knife edge will be accentuated
- Consider supersonic flow over a wedge
- First, a shadowgraph image

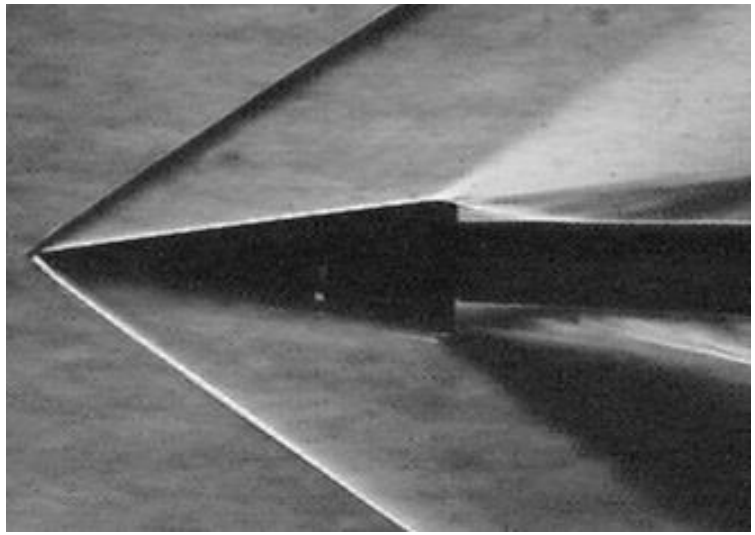




Schlieren: Rules of Thumb

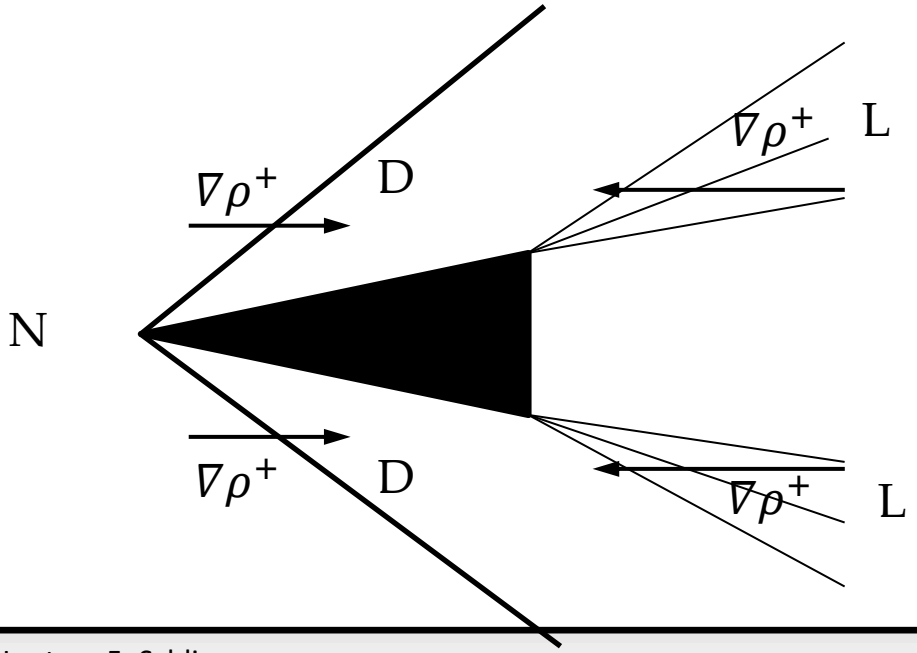
- Horizontal filter – vertical component of gradients are accentuated
- Downward (+) gradients – appear dark in image
- Upward (+) gradients – appear light in image

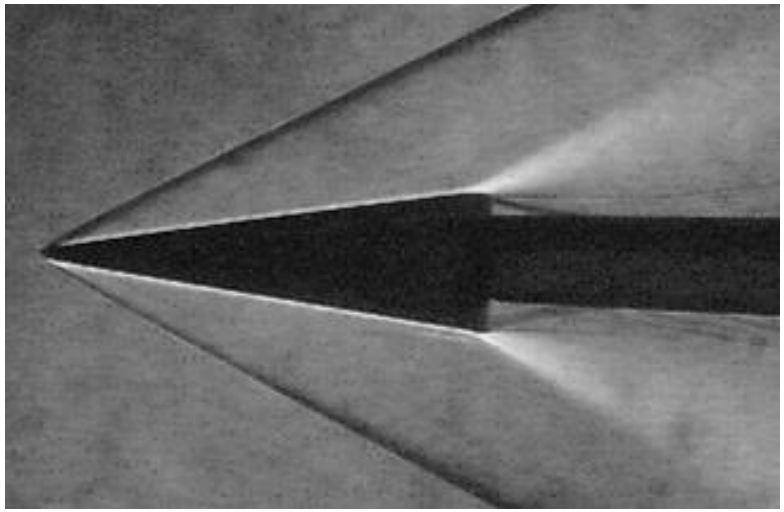




Schlieren: Rules of Thumb

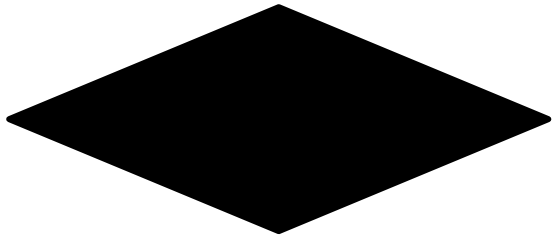
- Change orientation of spatial filter
- Vertical orientation – visualize horizontal gradients





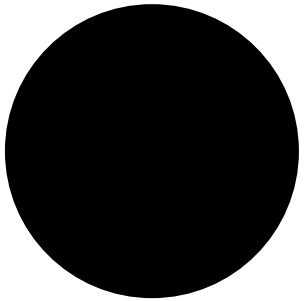
Let's Try Drawing Schlieren

M > 1 →



Vertical KE from left

M > 1 →



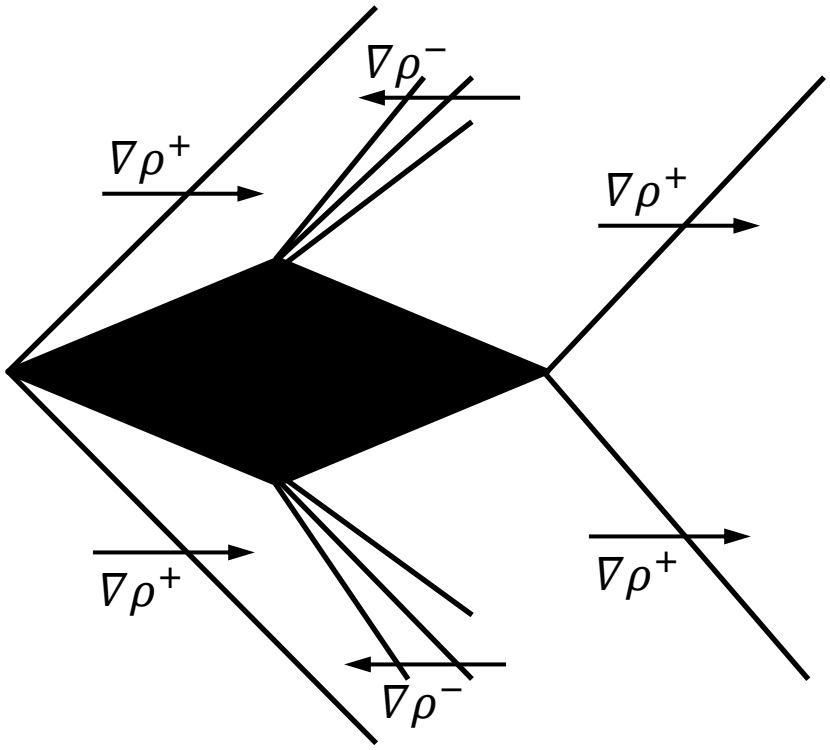
Vertical KE from right

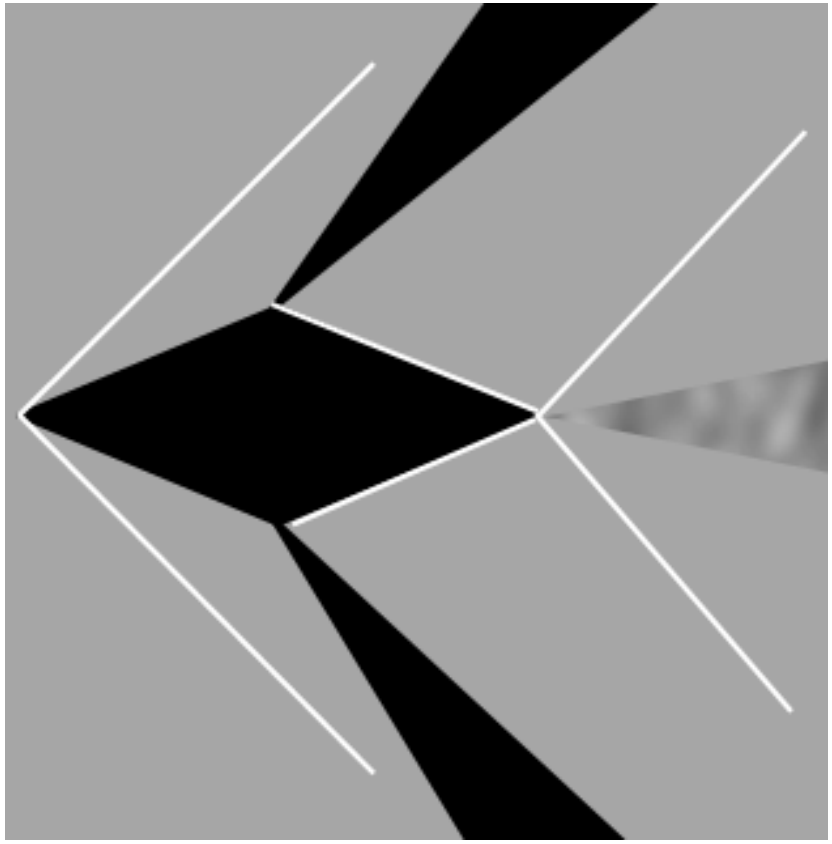
M >> 1 →

Horizontal KE from bottom

Let's Try Drawing Schlieren

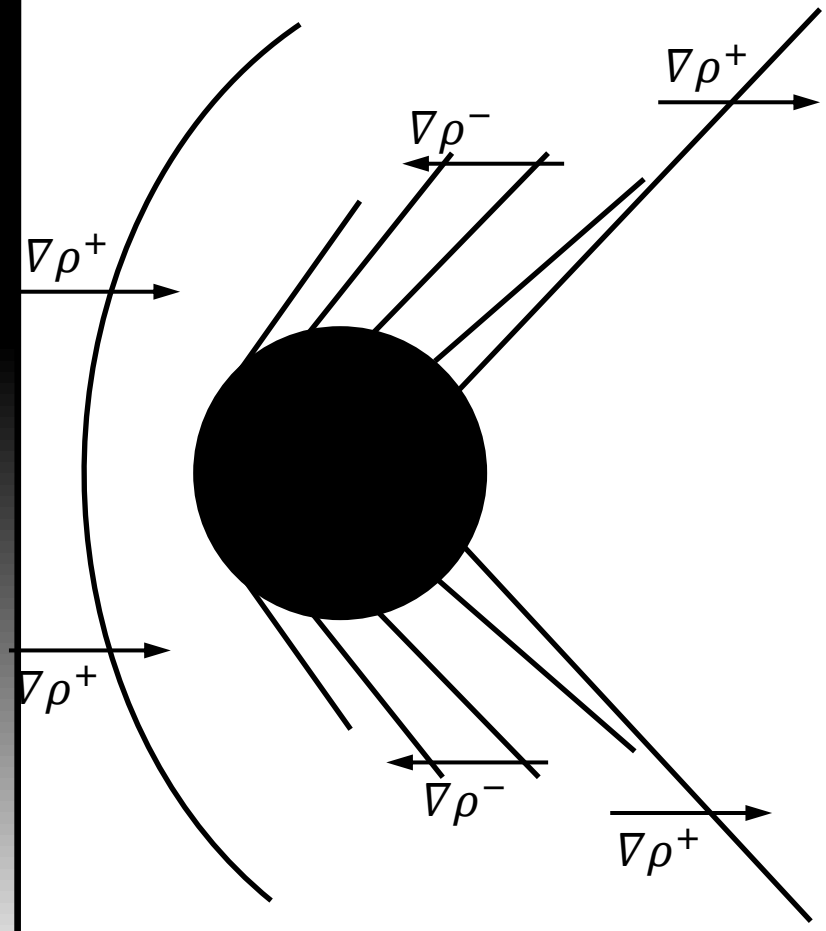
- With vertical KE from left

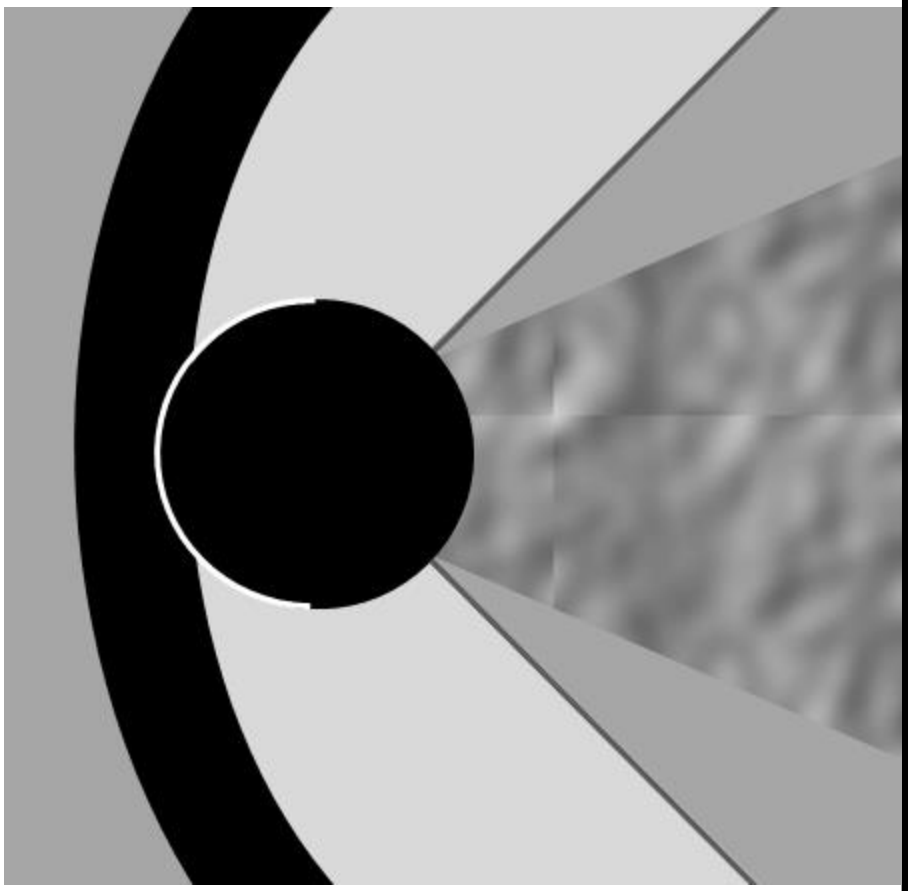




Let's Try Drawing Schlieren

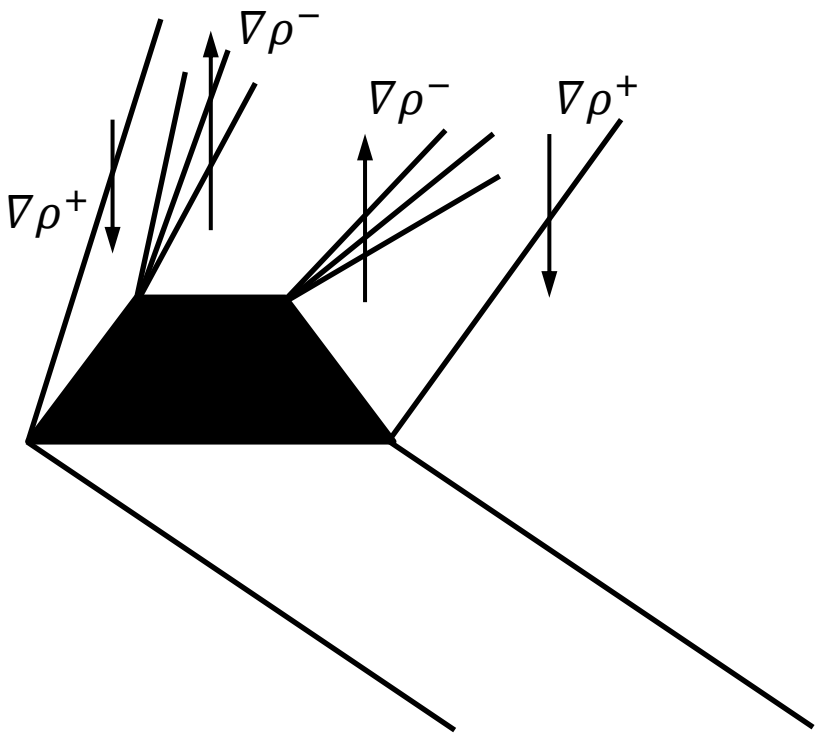
- With vertical KE from right

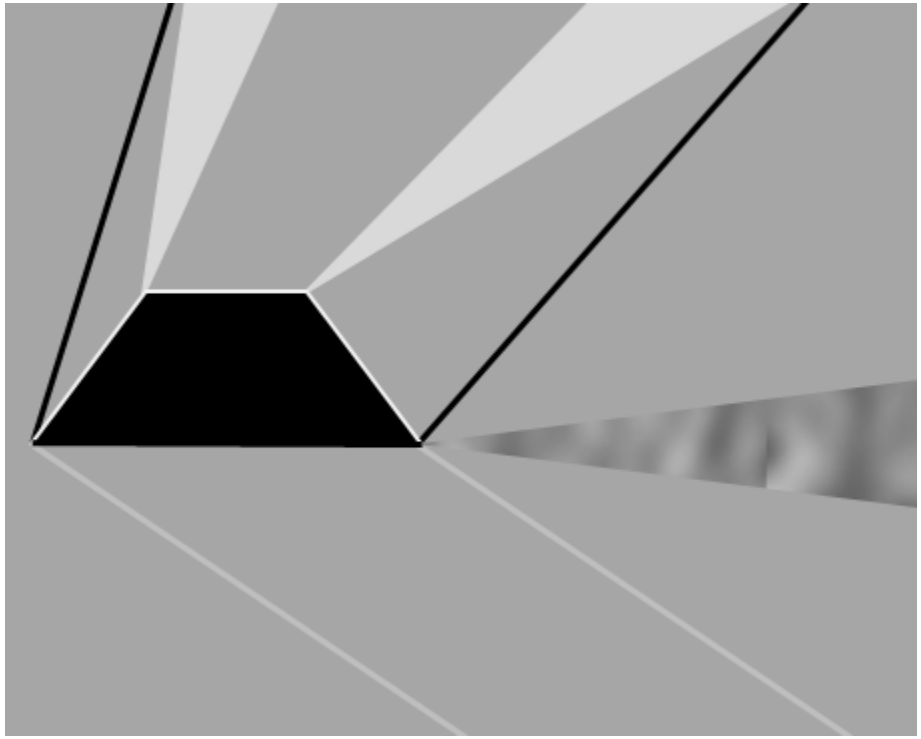




Let's Try Drawing Schlieren

- With horizontal KE from bottom





Schlieren Shortcomings

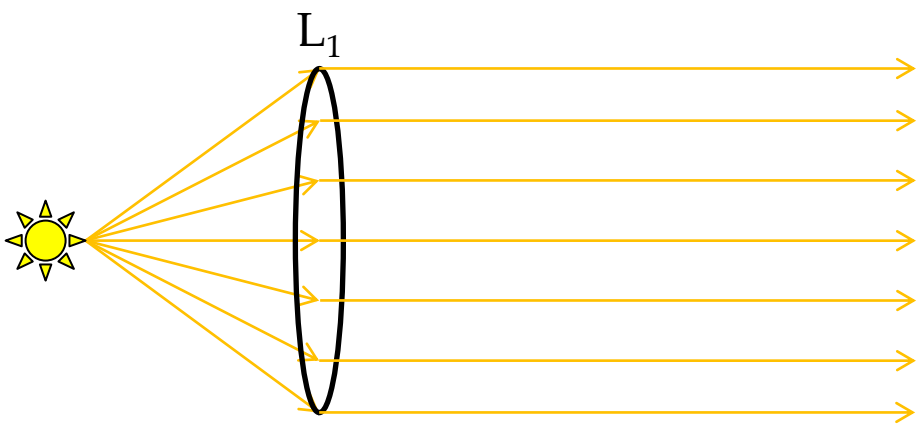
- Extremely sensitive to changes in index of refraction
  - Any change can cause distorted images – including smudges or pitting of glass and distortion of windows
- In the presence of *very* strong density gradients, Schlieren effect is often too weak to overcome shadowgraph without blocking a substantial part of the focal spot (75% or greater)
- Since the technique relies on diffraction, any secondary diffraction results in terrible images
  - Schlieren with a laser can look bad since laser light is coherent

Schlieren Overview

- Schlieren is a modification of the shadowgraph technique which enhances the visualization of refracted light rays
- Images often have a distinct anti-symmetry in intensity
- Schlieren is much more sensitive than shadowgraph and allows for visualization of weaker density gradients within the flow
- Schlieren also contains information about the direction of density gradients
- Ray tracing is similar, but must account for the presence of the Schlieren head and spatial filter
- Can deduce coloration of Schlieren image a priori by checking direction of expected density gradients versus the filter orientation

Schlieren: Image Quality

- Quality of images dependent on several factors
  - Quality of initial point source
    - Most light sources are too diffuse, even ones that approximate point sources (e.g., flash lamps, LEDs)



Schlieren: Rules of Thumb

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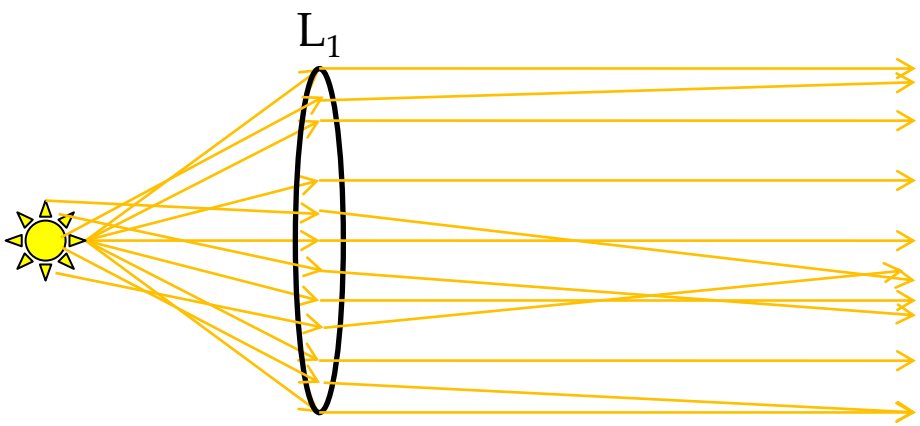

Schlieren: Rules of Thumb

- Quality of images dependent on several factors
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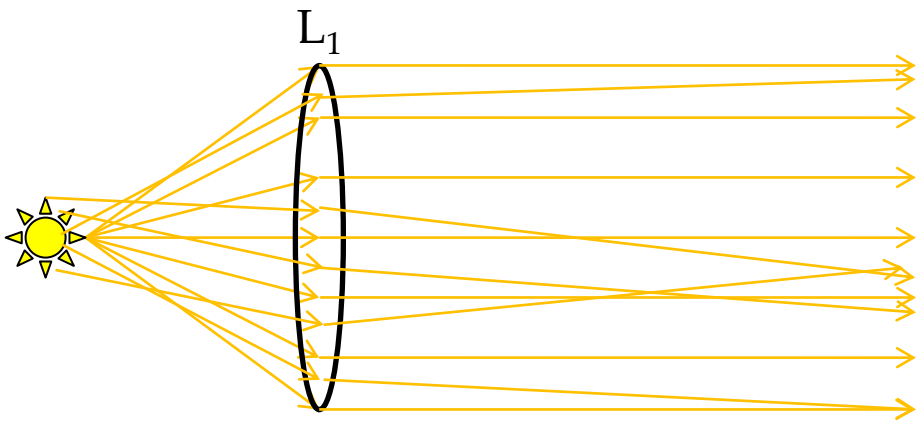
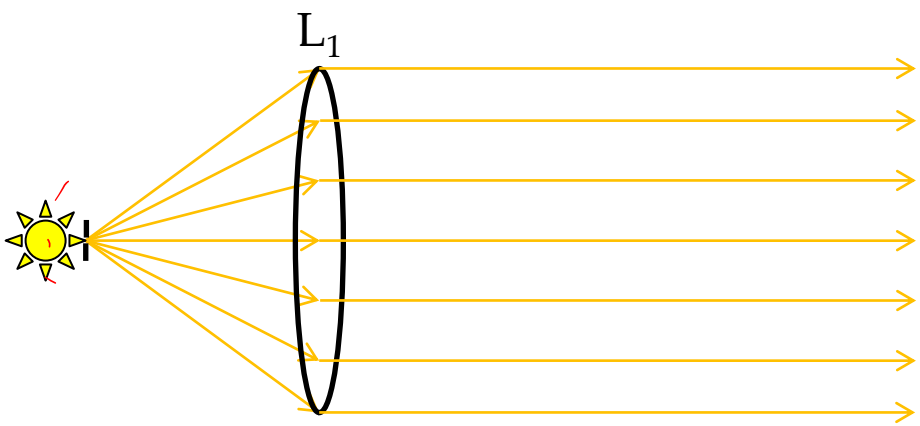
    - Several corrections can be made



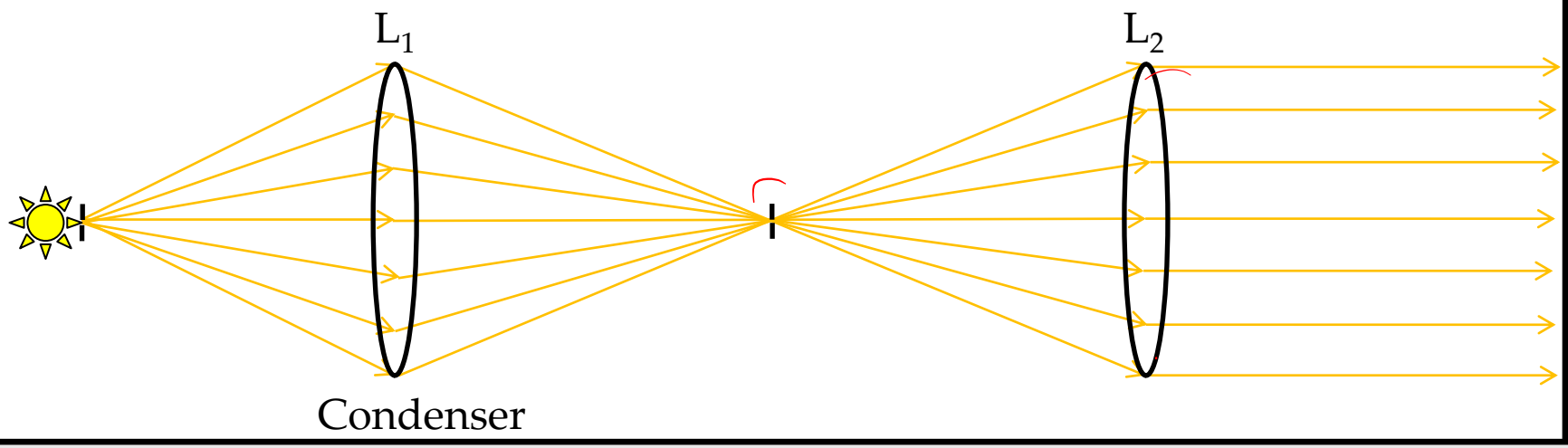
Schlieren: Rules of Thumb

- Quality of images dependent on several factors
  - Quality of initial point source
    - Most light sources are too diffuse, even ones that approximate point sources (e.g., flash lamps, LEDs)
    - Several corrections can be made
      - Iris after light source – reduces the solid angle of light emitted, reduces number of diffuse rays that reach first lens/mirror
        - The smaller the iris aperture, the more effective the filtering



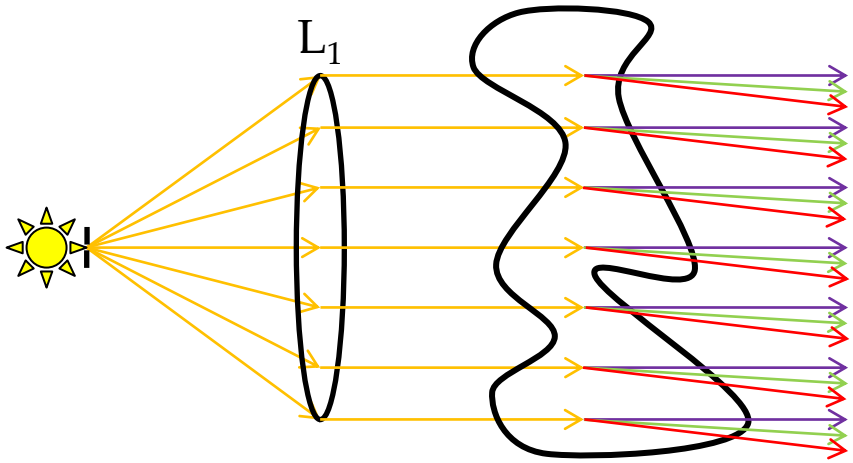
Schlieren: Rules of Thumb

- Quality of images dependent on several factors
  - Quality of initial point source
    - Most light sources are too diffuse, even ones that approximate point sources (e.g., flash lamps, LEDs)
    - Several corrections can be made
      - Condenser – second stage of reduction.
        - Iris after light source followed by a lens.
        - Lens refocuses light, at which point a second, smaller iris is placed
        - The light then goes through a second lens and is collimated



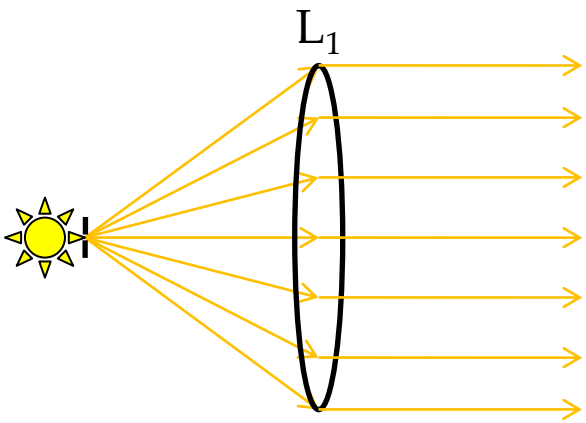
Schlieren: Rules of Thumb

- Quality of images dependent on several factors
  - Quality of initial point source
    - Narrow bandwidth light
      - White light is not ideal
        - Since index of refraction is a function of wavelength, index of refraction gradients cause dispersion of light
        - As a result, Schlieren images can become blurry even if light is perfectly collimated
      - Narrow bandwidth sources are better, such as LEDs
      - Can also use a white source with colored glass filters



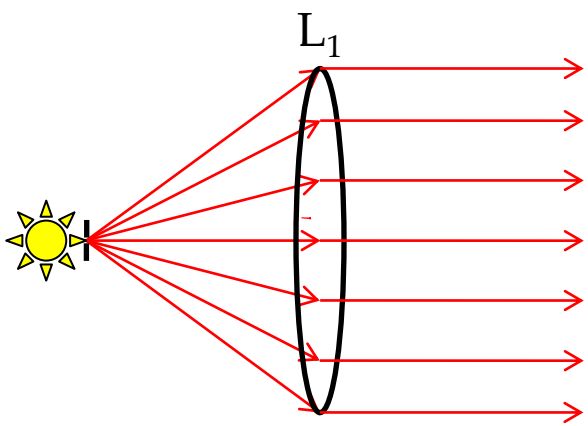
Schlieren: Rules of Thumb

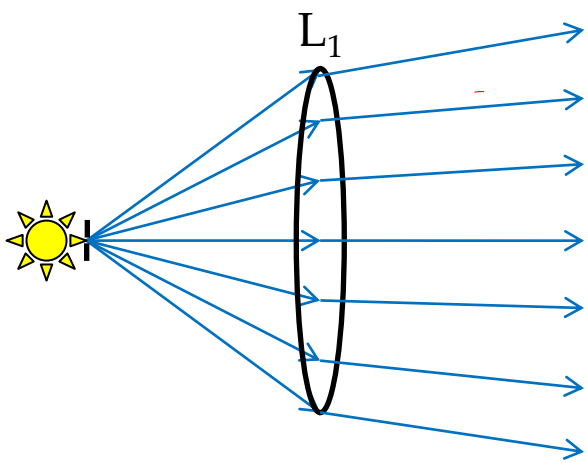
- Quality of images dependent on several factors
  - Optical arrangement is critical
    - Mirrors and lenses have drawbacks
      - Lenses possess optical aberrations that are a function of wavelength of light (chromatic aberrations)



Schlieren: Rules of Thumb

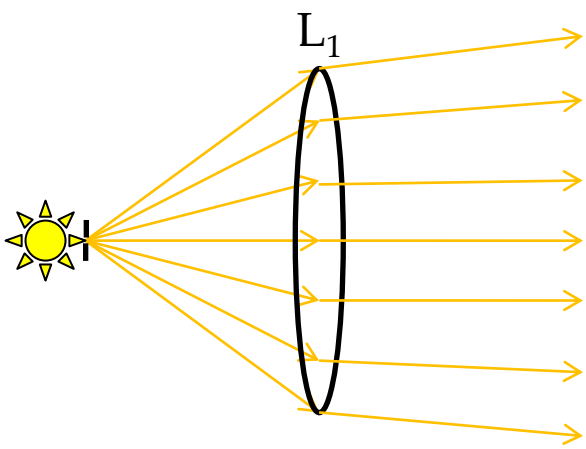
- Quality of images dependent on several factors
  - Optical arrangement is critical
    - Mirrors and lenses have drawbacks
      - Lenses possess optical aberrations that are a function of wavelength of light (chromatic aberrations)





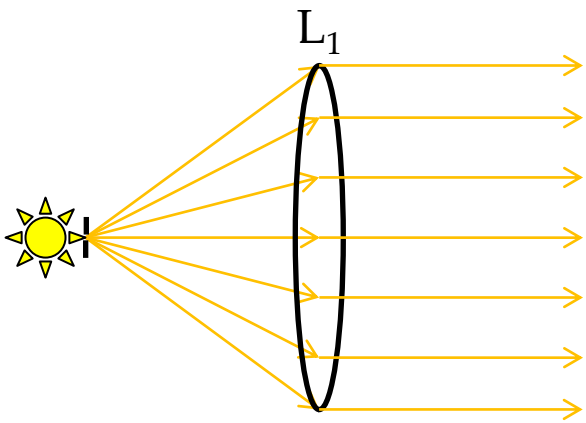
Schlieren: Rules of Thumb

- Quality of images dependent on several factors
  - Optical arrangement is critical
    - Mirrors and lenses have drawbacks
      - Lenses possess optical aberrations that are a function of wavelength of light (chromatic aberrations) and radial position of incident rays (spherical aberrations)



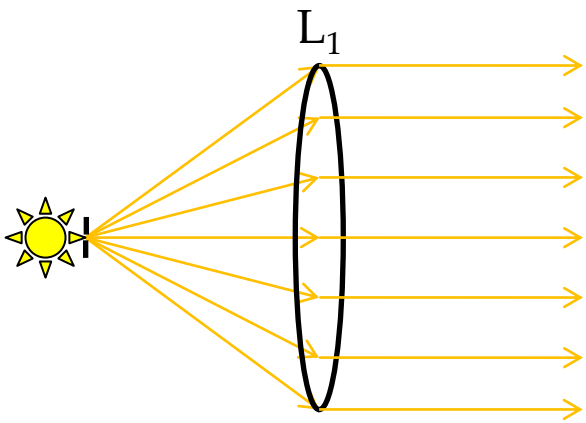
Schlieren: Rules of Thumb

- Quality of images dependent on several factors
  - Optical arrangement is critical
    - Mirrors and lenses have drawbacks
      - Lenses possess optical aberrations that are a function of wavelength of light (chromatic aberrations) and radial position of incident rays (spherical aberrations)
      - Aberrations become worse as lens size increases



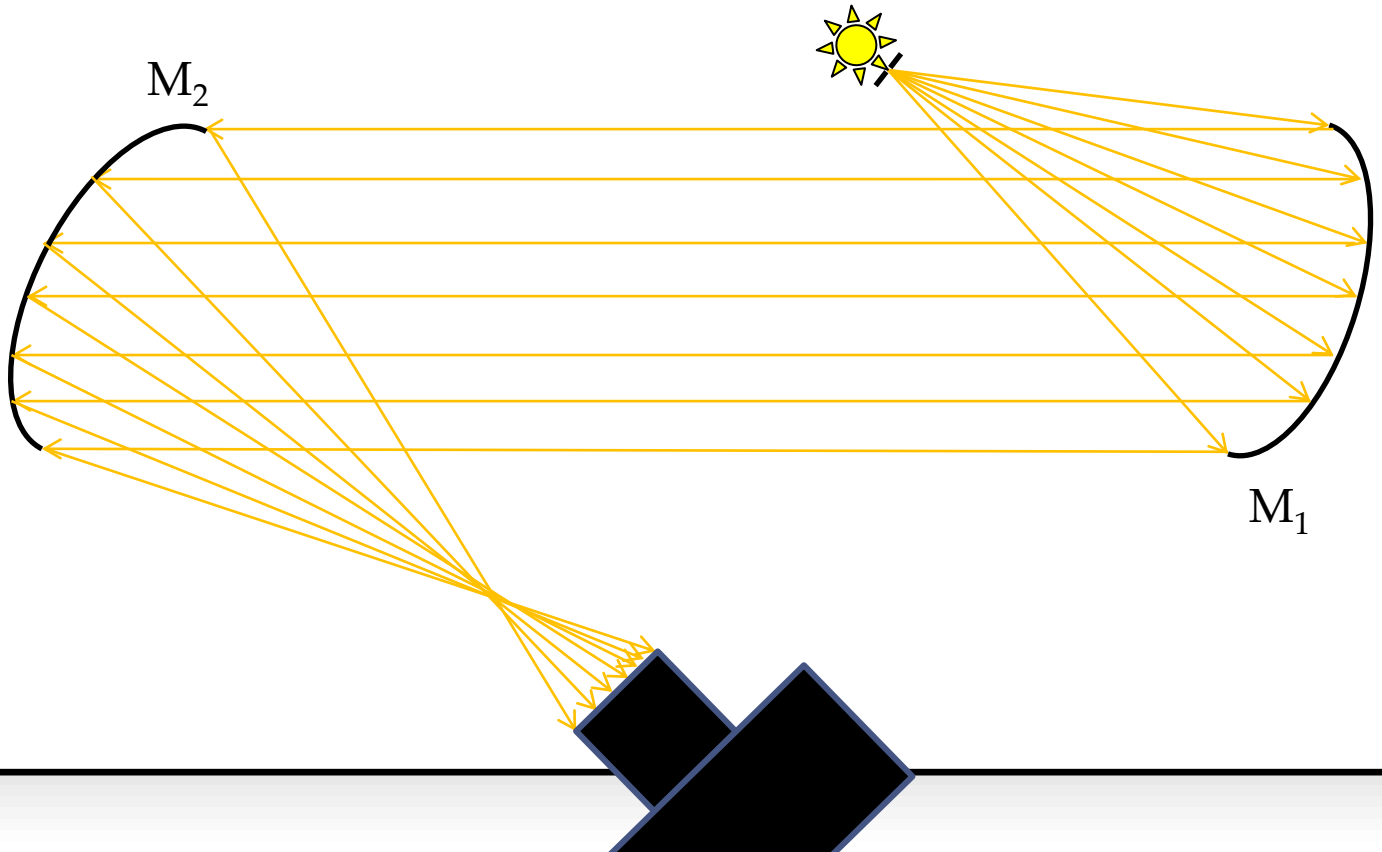
Schlieren: Rules of Thumb

- Quality of images dependent on several factors
  - Optical arrangement is critical
    - Mirrors and lenses have drawbacks
      - Lenses possess optical aberrations that are a function of wavelength of light (chromatic aberrations) and radial position of incident rays (spherical aberrations)
      - Aberrations become worse as lens size increases
      - Lenses become very expensive as they become larger
        - For larger fields of view, mirrors are almost always necessary



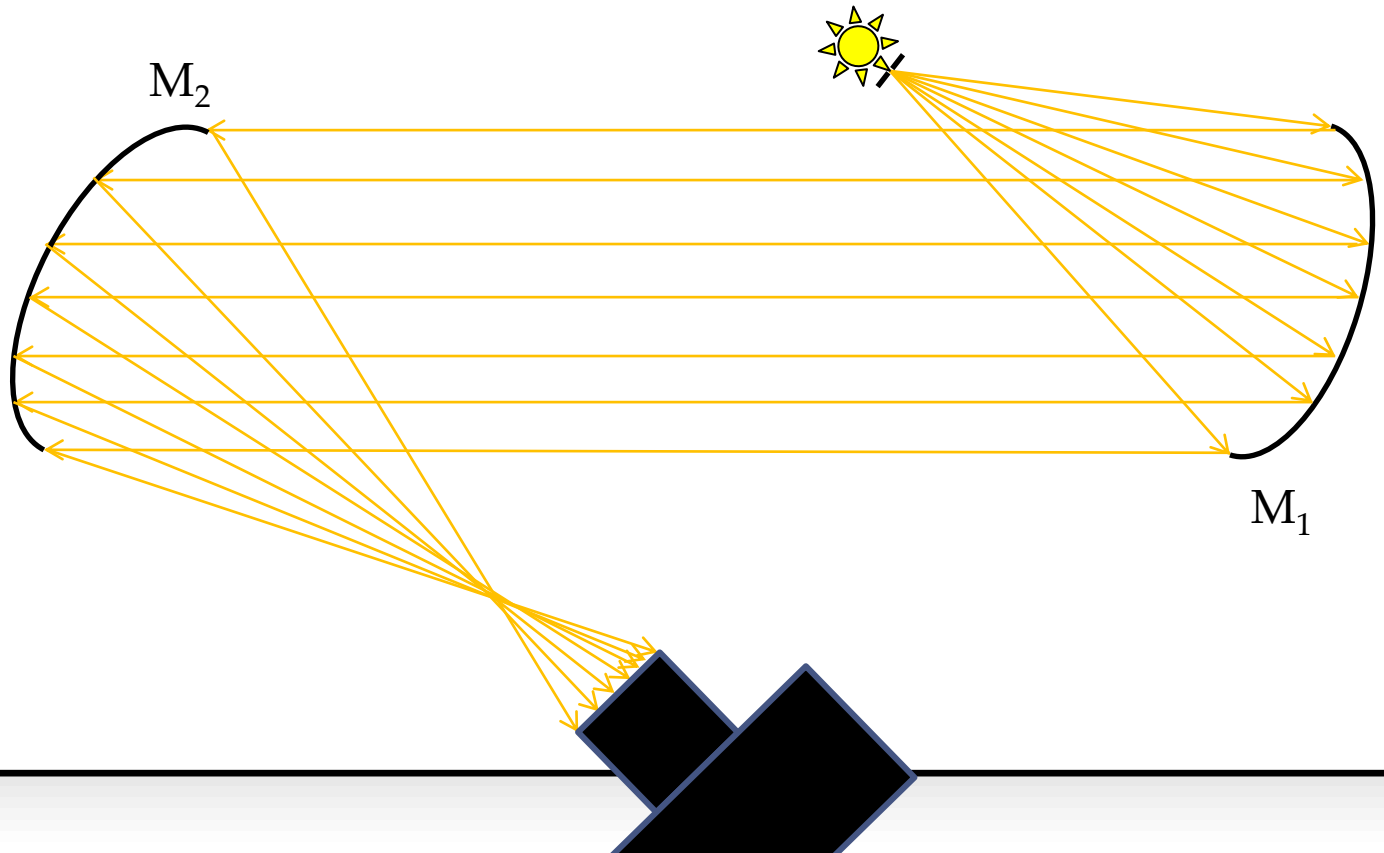
Schlieren: Rules of Thumb

- Quality of images dependent on several factors
  - Optical arrangement is critical
    - Mirrors and lenses have drawbacks
      - Mirrors have to be run off-axis



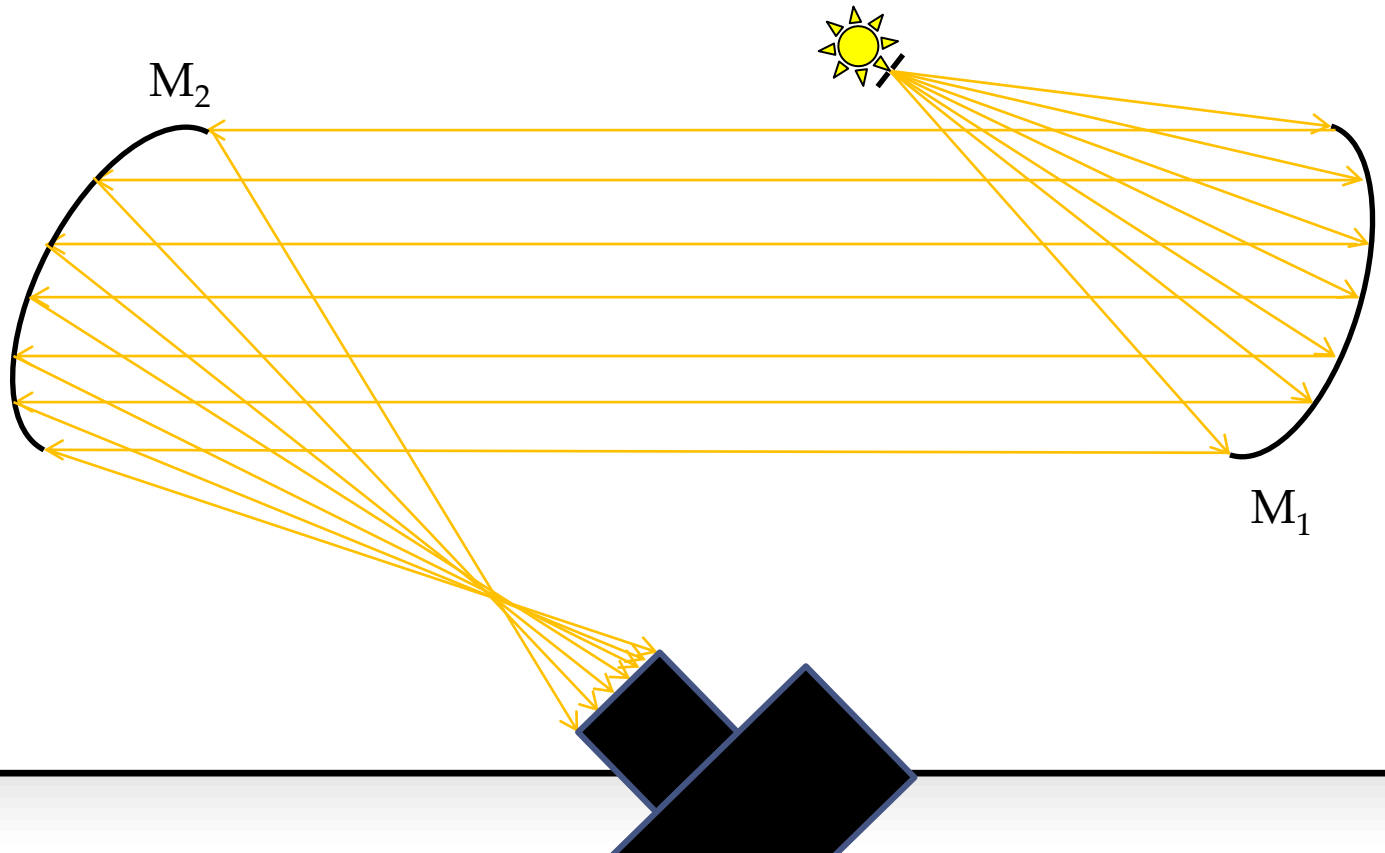
Schlieren: Rules of Thumb

- Quality of images dependent on several factors
  - Optical arrangement is critical.
    - Mirrors and lenses have drawbacks
      - Introduces astigmatic aberrations – changes focal spot to focal volume
        - Images distorted



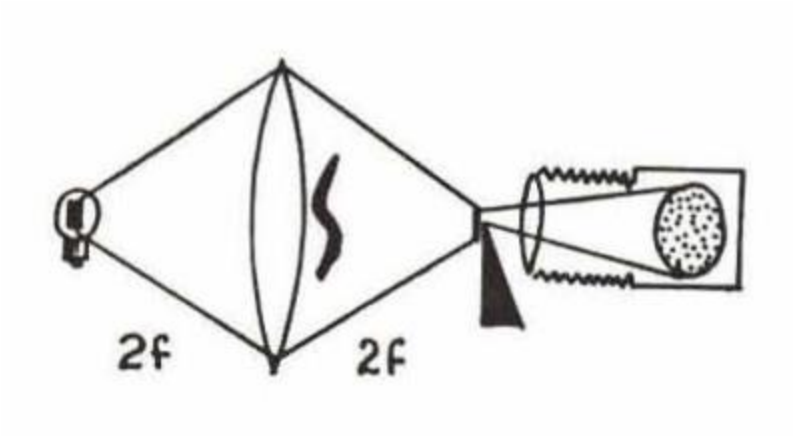
Schlieren: Rules of Thumb

- Quality of images dependent on several factors
  - Most importantly – all optical surfaces must be clean and free of distortion!
    - Schlieren enhances any and all changes in index of refraction

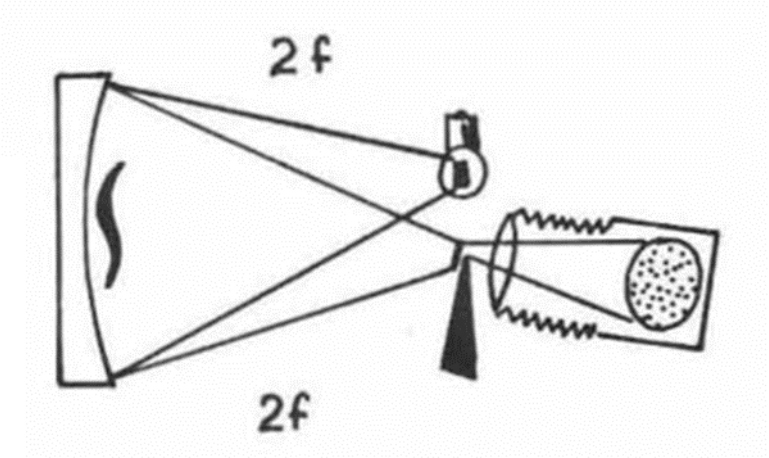


Schlieren Setups

- Single-Lens Systems:

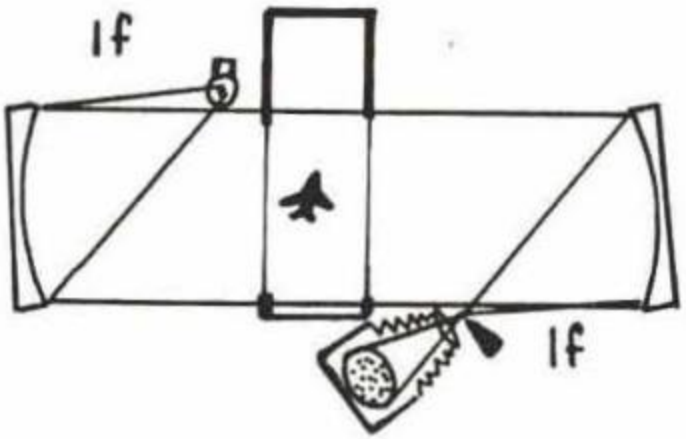


- Single-Mirror Systems:



Schlieren Systems

- Dual Mirror-Systems:



- Dual Lens Systems: