Flare

Gregg M. Gallatin

Applied Math Solutions, LLC
ggallatin@odaoptics.com
203-770-7325

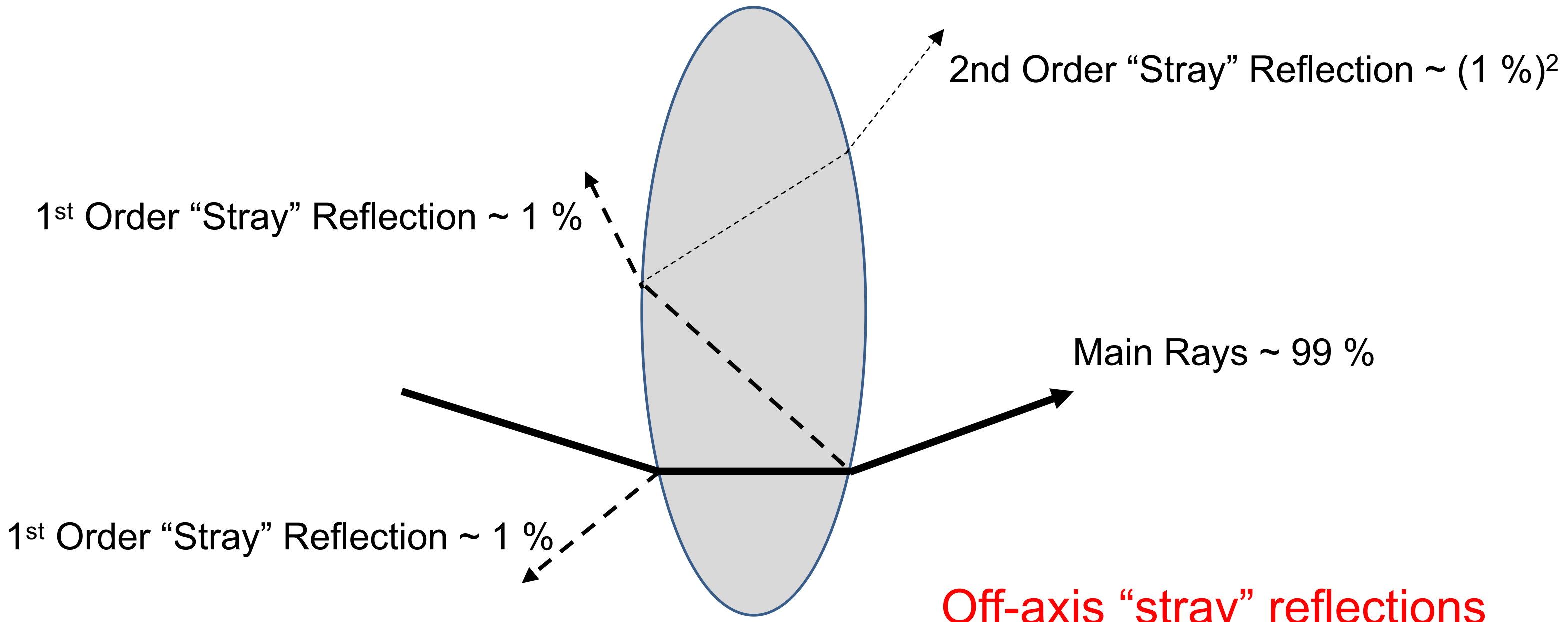
- “Flare” = Scattered light, “stray light”, “ghost images”
  - light that ends up where it shouldn’t
- Caused by
  - Roughness on lens/mirror surfaces
  - Index variations inside lens material
  - AR coating not 100 % ➔ Unintended reflections
  - Scattering off baffles and mechanical structure
- Flare caused by “wavefront roughness” is much longer range than lower-order lens aberrations
  - Low frequency wavefront roughness → Zernike Aberrations

    Range < 1 micron
  - Mid frequency wavefront roughness → “low angle” scattering

    Range ~ 1 to many microns
  - High frequency wavefront roughness → Scatters out of optics

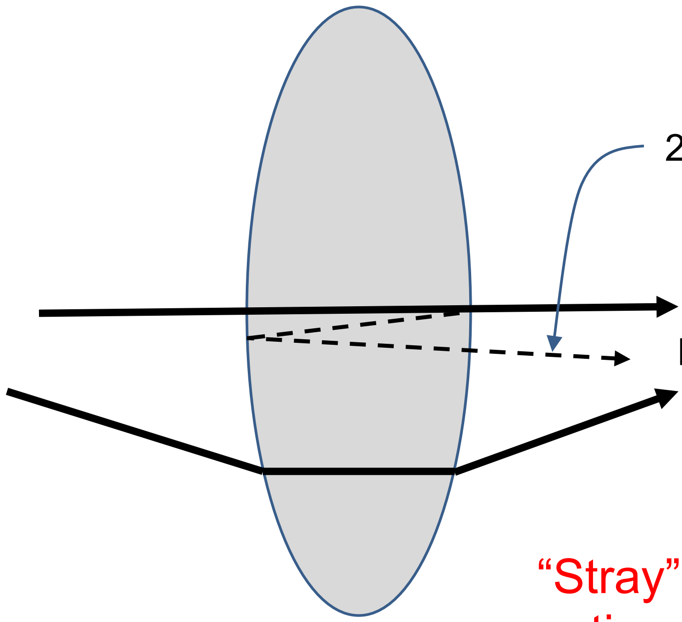
    Energy loss

"Stray" Reflections from AR Coating



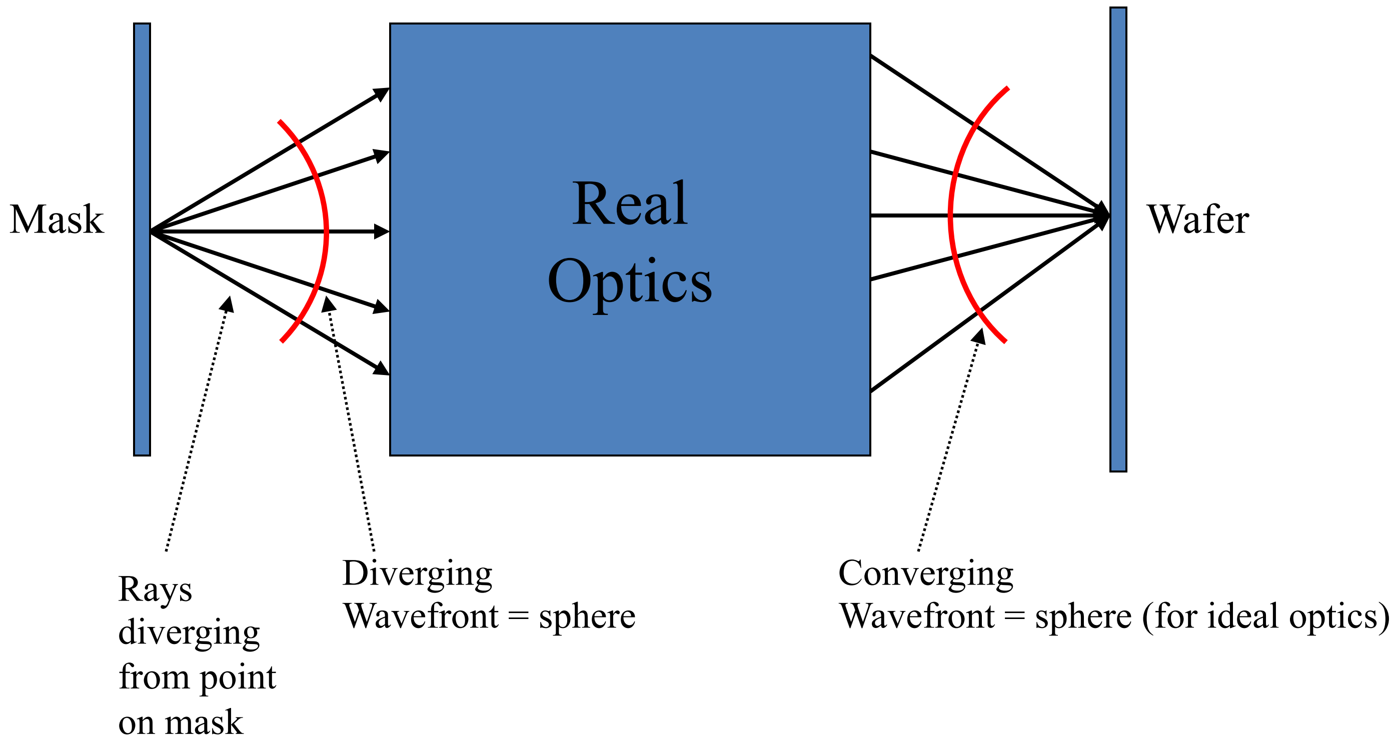
Off-axis "stray" reflections mostly "walk" out of the optics

"Stray" Reflections from AR Coating

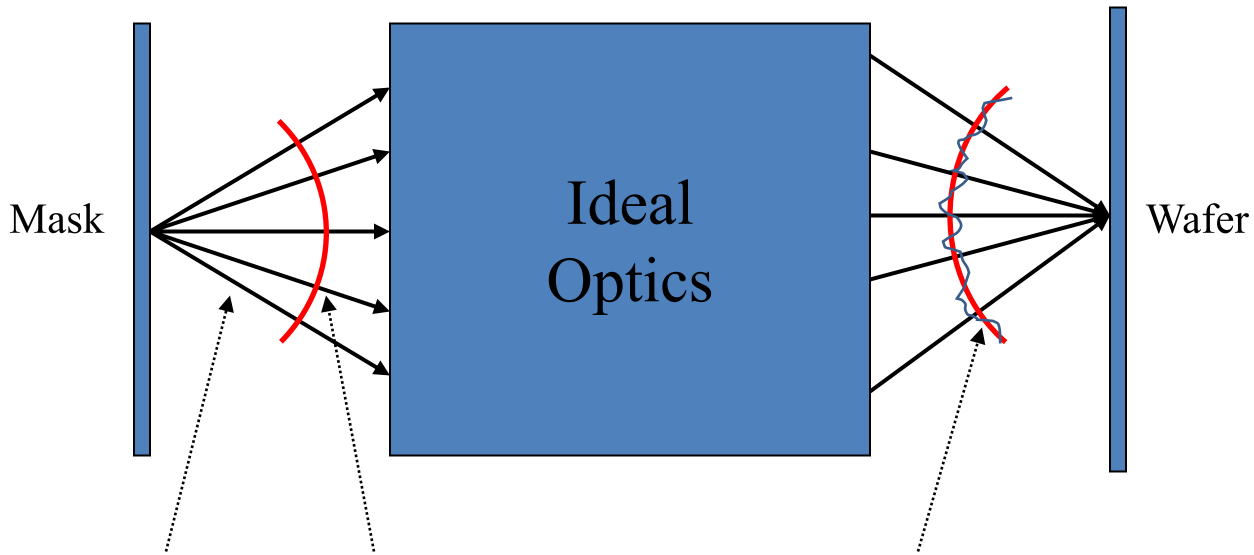


"Stray" reflections close to the optic axis end up in the image.
➔ Worst "ghost" image effect is at the center of the image field.

Ideal optics converts spherical wavefronts to spherical wavefronts



Ideal optics converts spherical wavefronts to spherical wavefronts



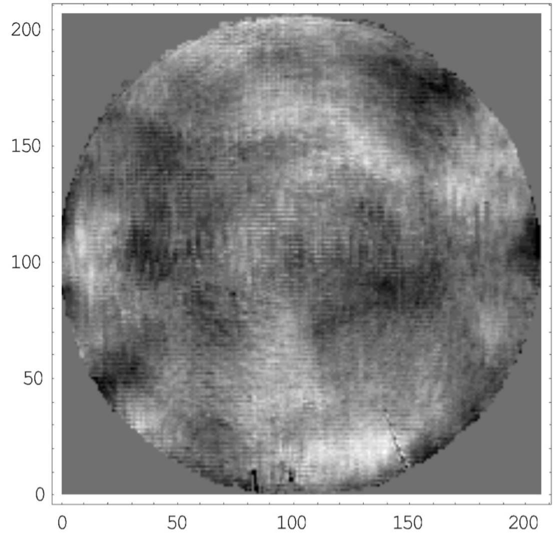
Rays diverging from point on mask

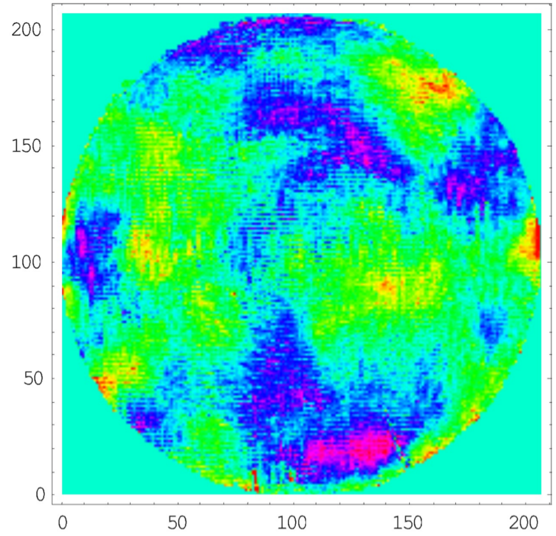
Diverging
Wavefront = sphere

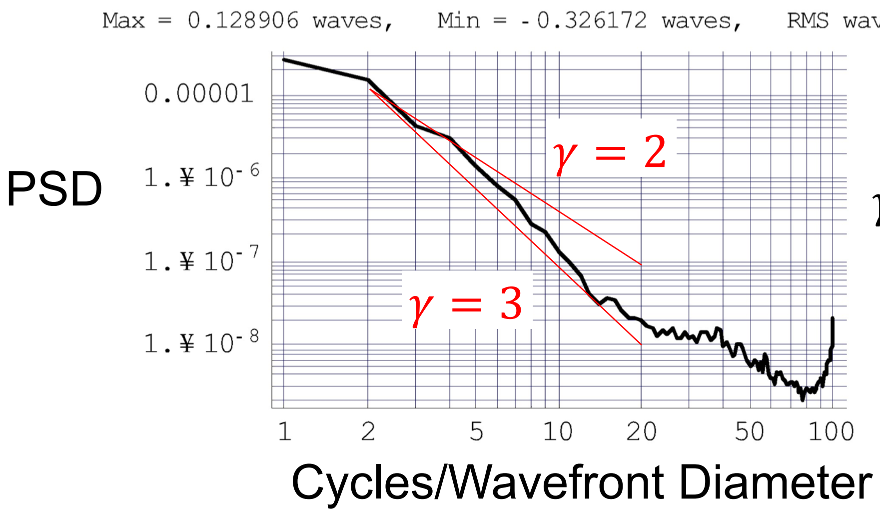
Actual wavefront is NOT spherical
Combination of

- Low spatial frequencies:
  Zernikes ➔ Aberrations
- High spatial frequencies:
  "Roughness" ➔ Flare

Example Wavefront

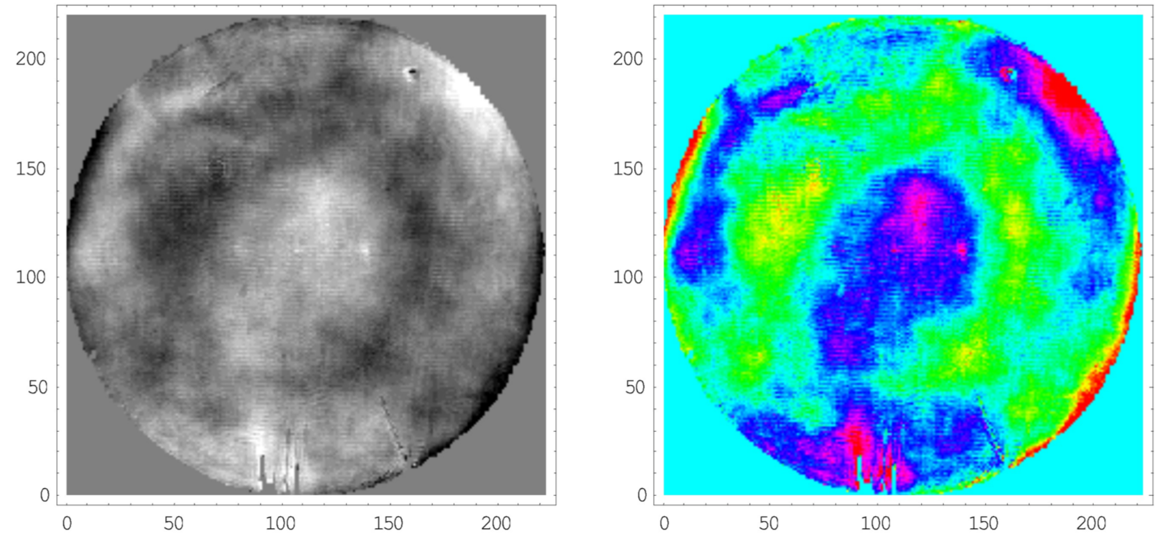




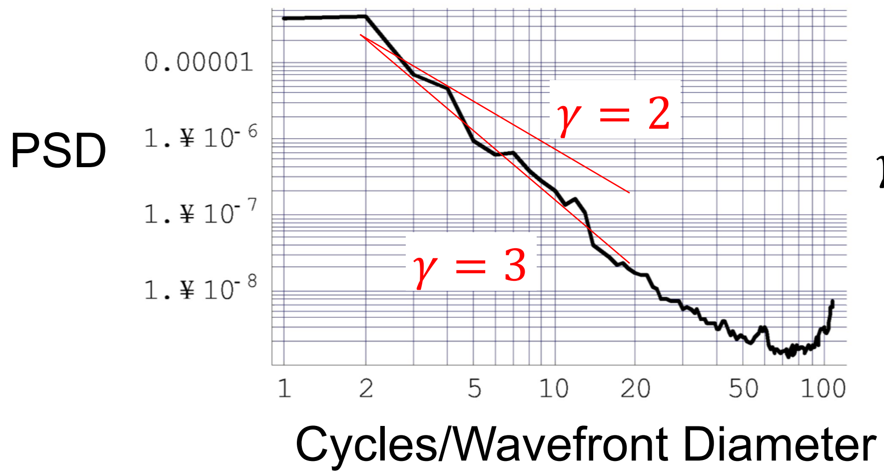


$\gamma = -$ slope on log-log scale

Example Wavefront

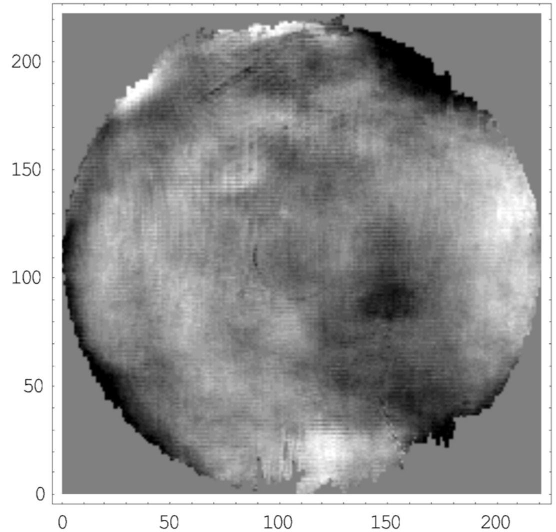


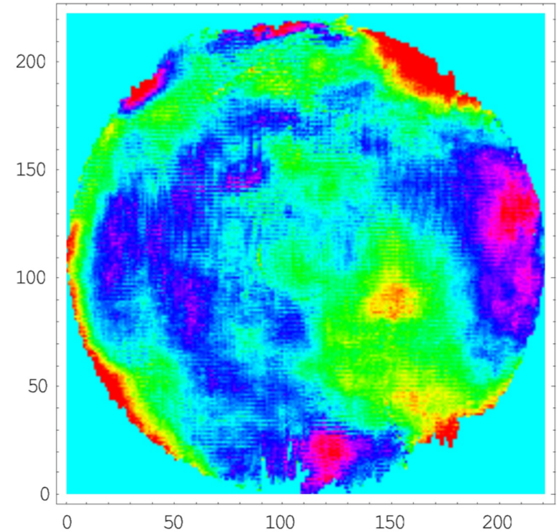
Max = 0.423828 waves, Min = -0.220703 waves, RMS waves = 0.0444123



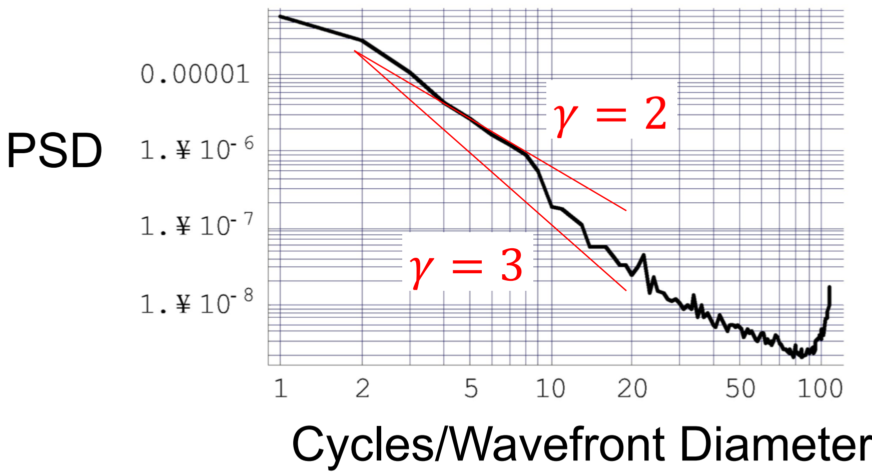
$\gamma = -$ slope on log-log scale

Example Wavefront



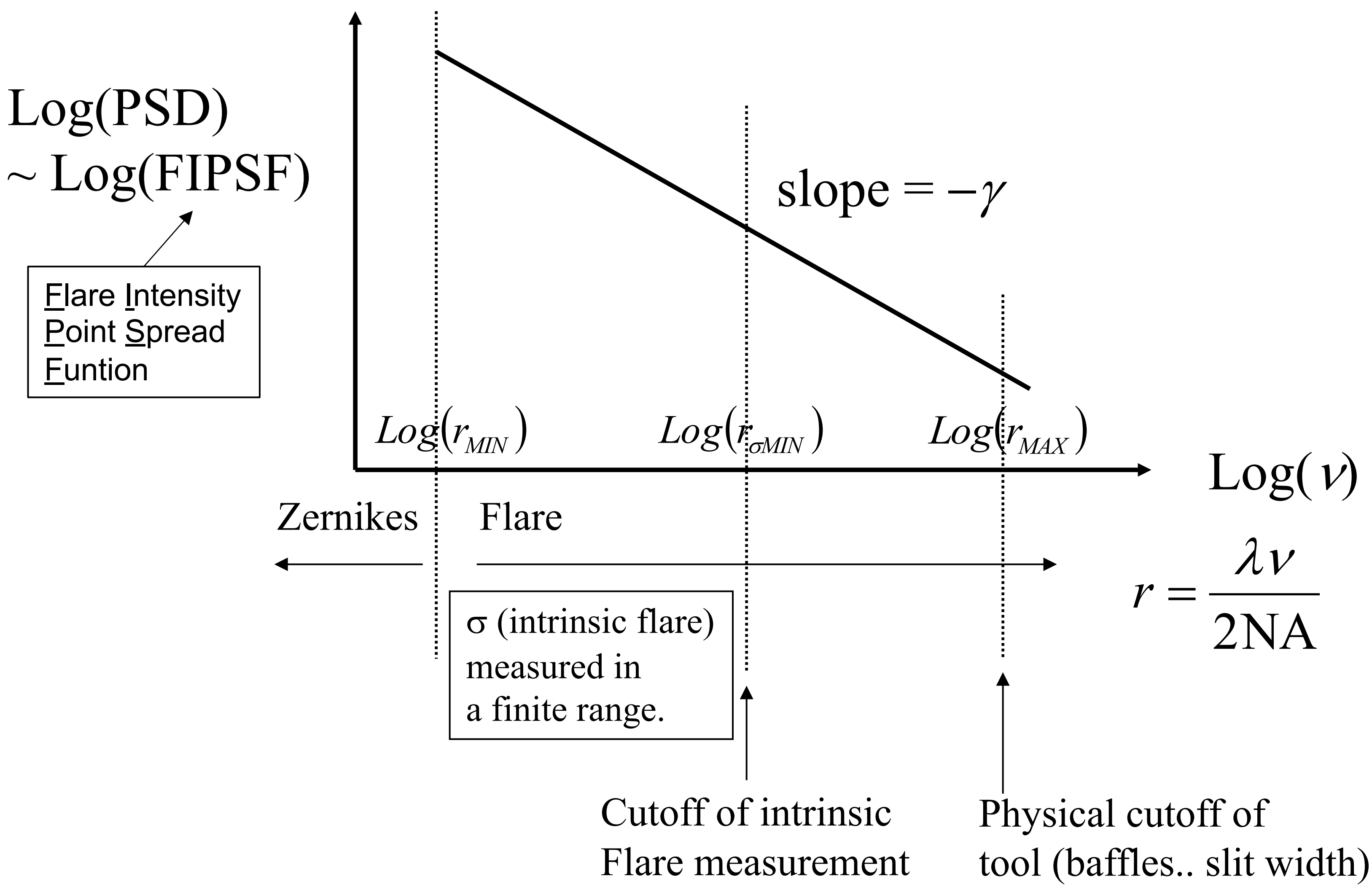


Max = 0.207031 waves, Min = -0.285156 waves, RMS waves = 0.0522661



$\gamma = -$ slope on log-log scale

Spatial Frequency in the pupil ➔ Position in the image



Wavefront Roughness Flare Model

Spatial Frequency in the pupil → Position in the image

$$\text{Flare Intensity Point Spread Function} = \frac{K}{\left|\vec{x}_{obs} - \vec{x}_{source}\right|^{\gamma}}$$ = "Halo" around PSF

$$K = \frac{(2\pi\sigma)^2}{2\pi\left(\dfrac{r_{\sigma MAX}{}^{2-\gamma} - r_{MIN}{}^{2-\gamma}}{2-\gamma}\right)} = \frac{IntrinsicFlare}{2\pi\left(\dfrac{r_{\sigma MAX}{}^{2-\gamma} - r_{MIN}{}^{2-\gamma}}{2-\gamma}\right)}$$

$\sigma = \text{rms wavefront roughness (waves)}$ → Value depends on where Zernikes cut-off.

$\gamma = -\text{LogLogSlope of wavefront PSD} = \text{Positive value} \sim 2\text{ - }3$

$r_{MIN} \sim 1 micron$

$r_{MAX} \sim 10 \text{ of } mm$

$r_{\sigma MAX} = \dfrac{\lambda\nu}{2NA}$ where $\nu =$ Max Cycles/pupil diameter used in intrinsic flare measurement

$$\text{Net Flare} = \text{FIPSF} \otimes \text{Reticle Transmission}$$

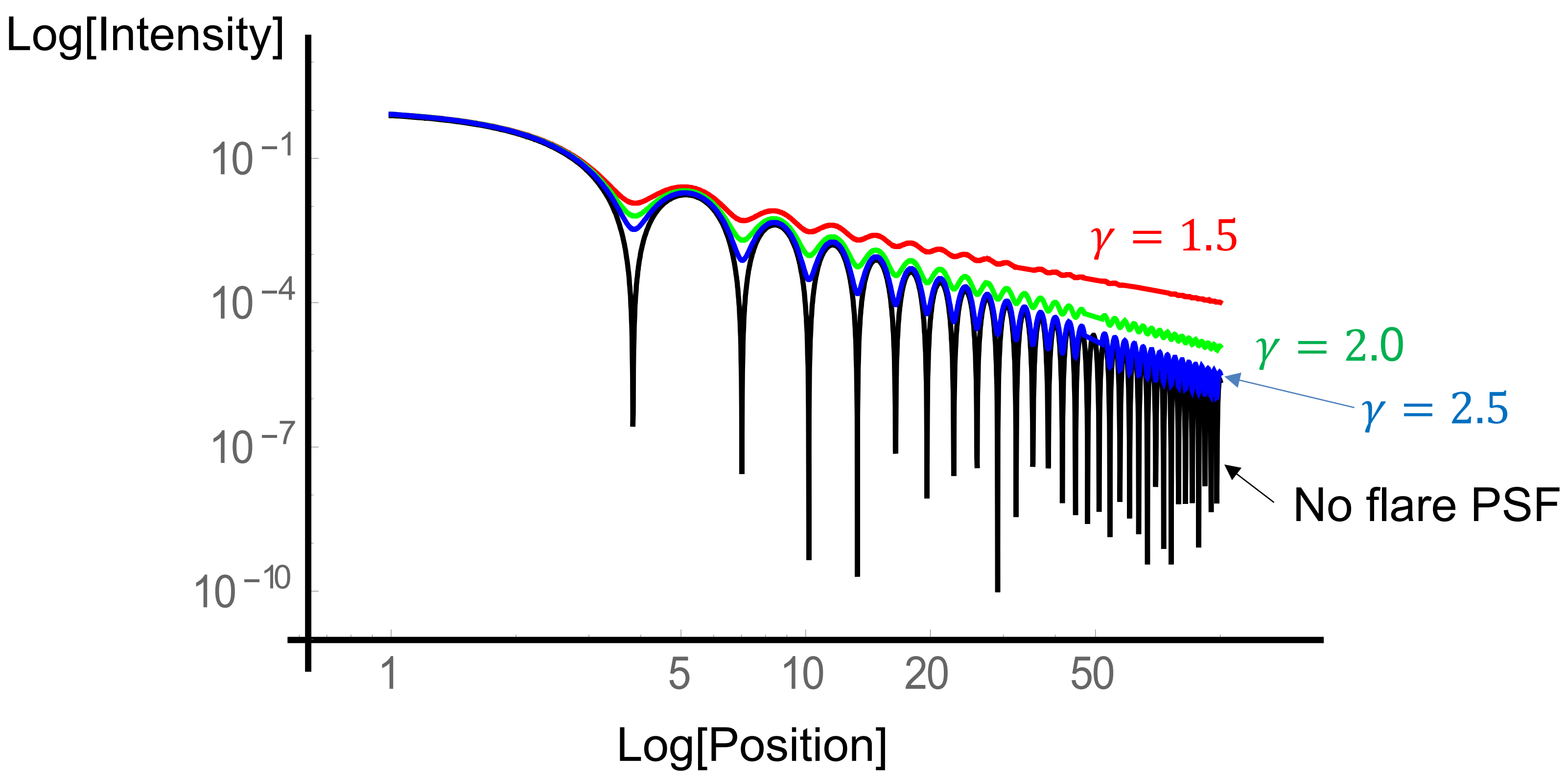
$$\text{Flare}(\vec{x}) = \int_{r_{MIN} \le |\vec{x}-\vec{x}'| \le r_{MAX}} \frac{K}{|\vec{x}-\vec{x}'|^{\gamma}} T_{reticle}(\vec{x}')\, d^2x'$$

➔ Flare level is proportional to bright area in the image

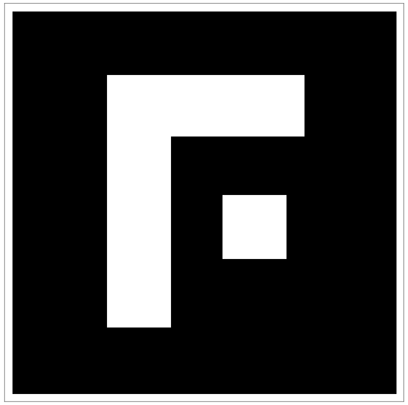
NOTE: In 2 dimensions $\Rightarrow \sim \int \frac{rdr}{r^{\gamma}} \sim r^{2-\gamma}$

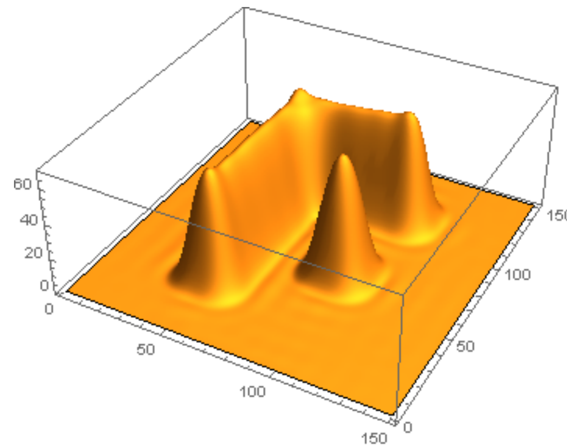
$$\Rightarrow \text{Divergent for } -\gamma = |\gamma| \le 2$$

FIPSF = Ideal PSF + Flare



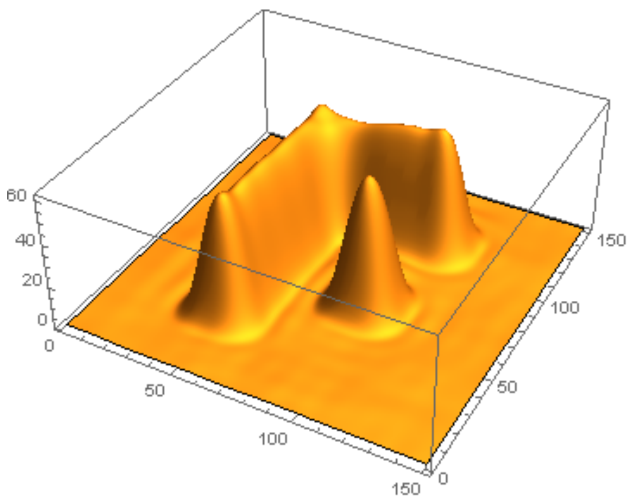
Object



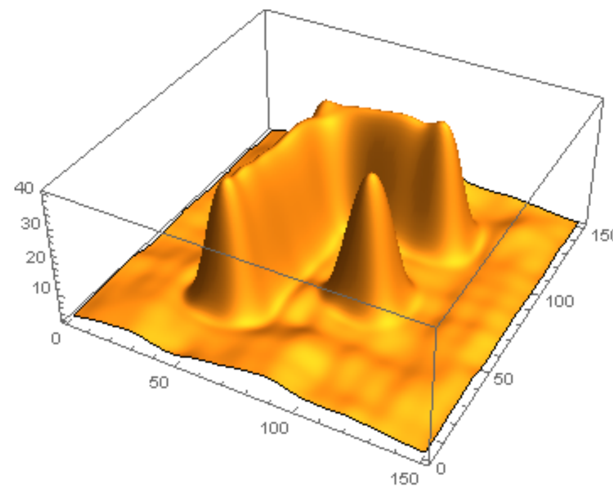


No Flare

$\gamma = 2.3, 0.03$ RMS WFR



$\gamma = 2.3, 0.1$ RMS WFR

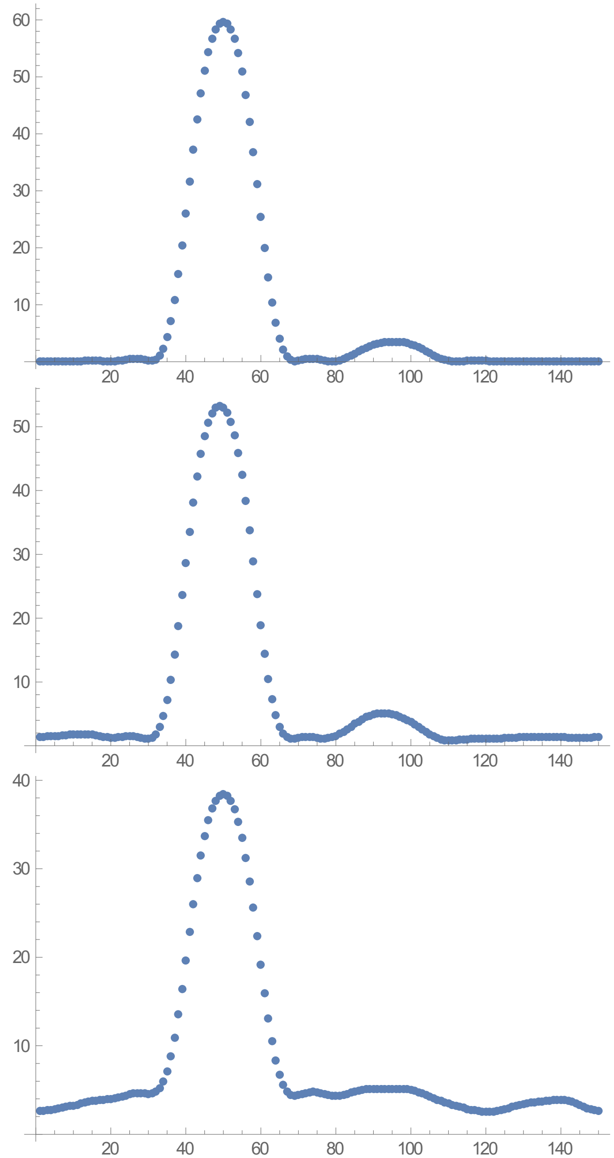


Slice through Image

No Flare

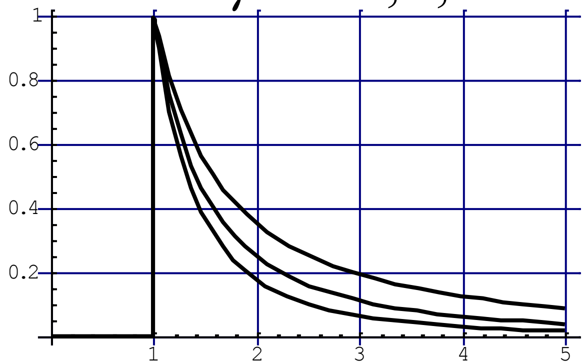
$\gamma = 2.3, 0.03$ RMS WFR

$\gamma = 2.3, 0.1$ RMS WFR

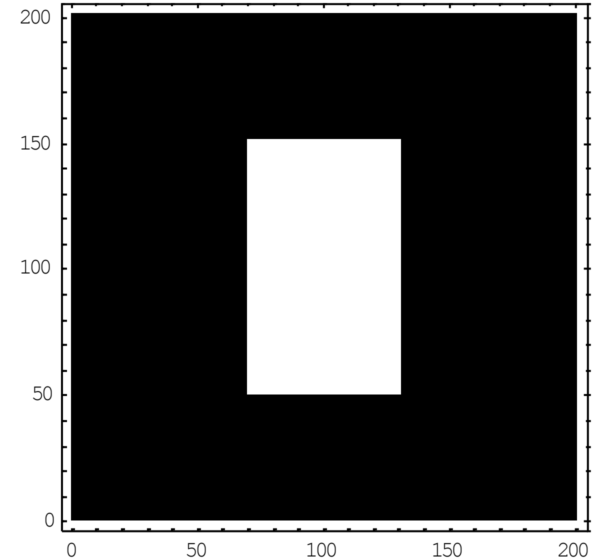


$$FIPSF = 1/r^{\gamma}$$

for $\gamma = 1.5, 2, 2.5$

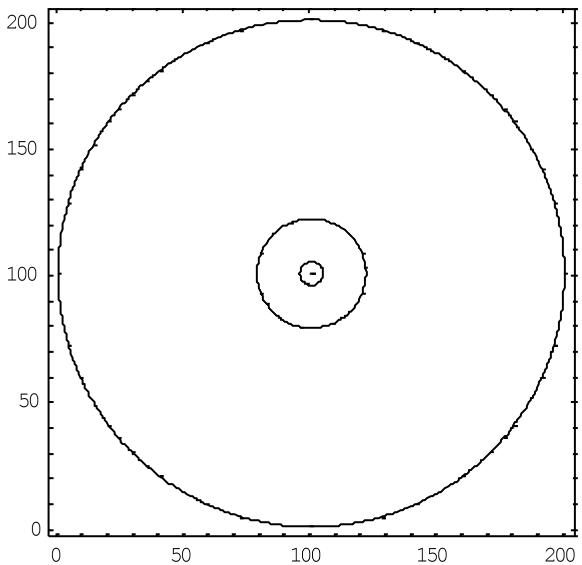


Field

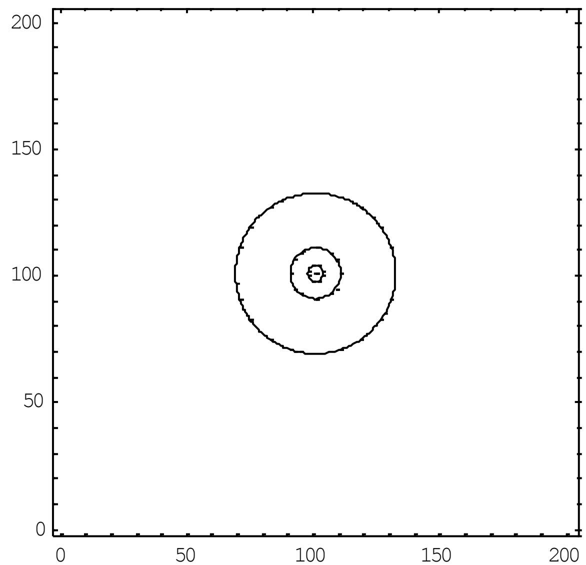


Contour plots of FIPSF: Contours = 0.001, 0.01, 0.1 in each case

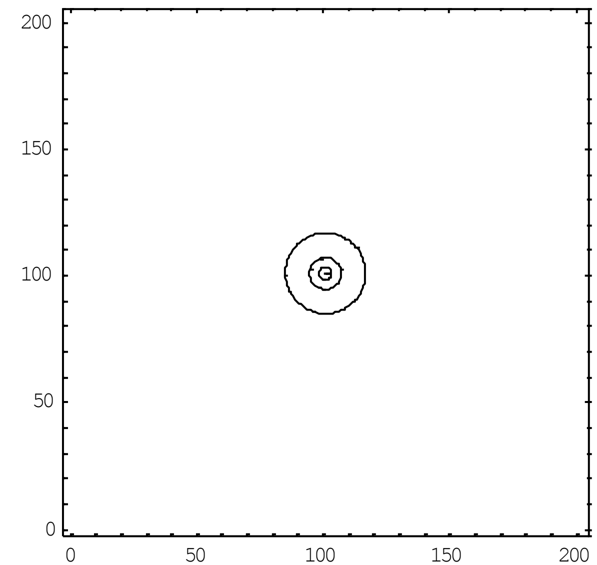
$\gamma = 1.5$



$\gamma = 2$



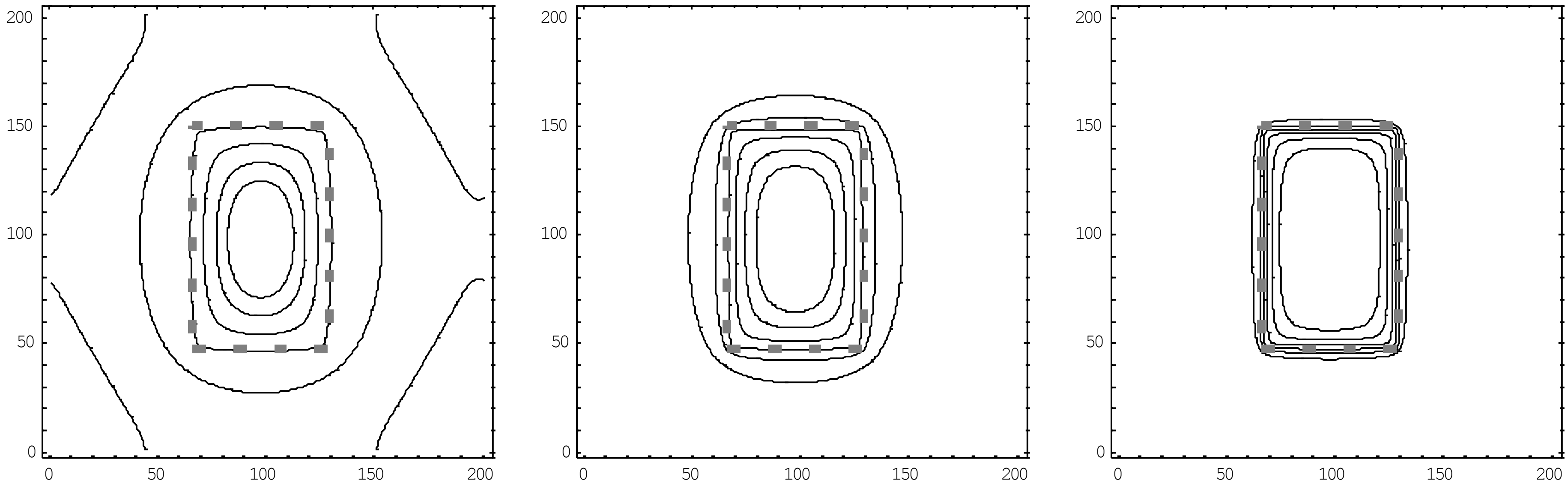
$\gamma = 2.5$



$FIPSF \otimes$ Clear Field Transmission

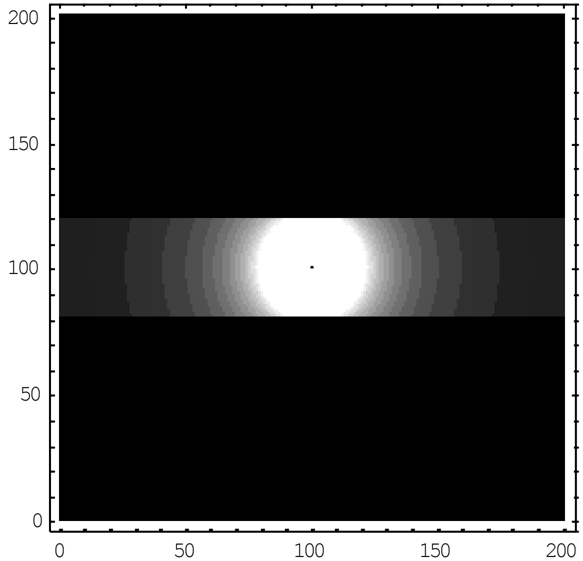
Contours are 10%, 20%, 50%, 80%, 90%, and 95% of max flare value in each case.
Note that the 50% contour generically follows the field edge (gray dashed rectangle)

$\gamma = 1.5$ $\gamma = 2$ $\gamma = 2.5$

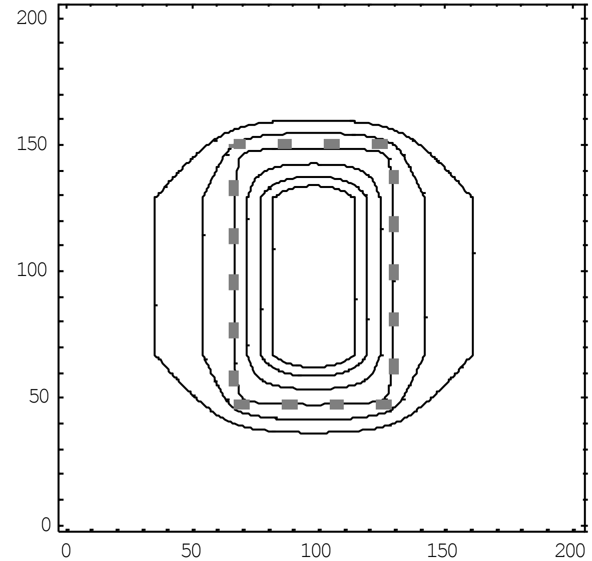


Thank you and questions

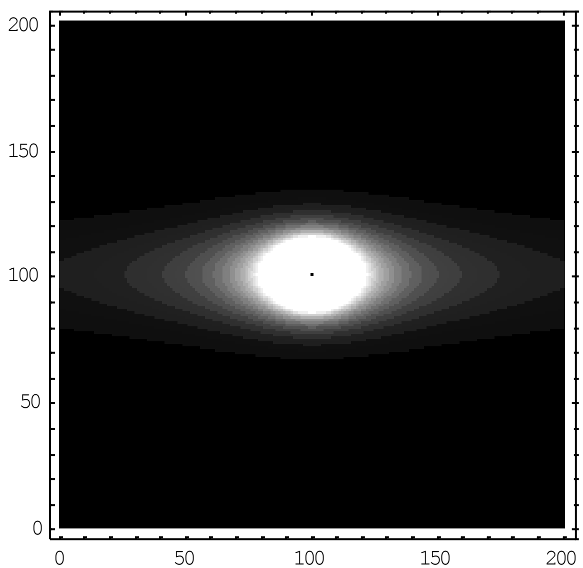
谢谢你和问题



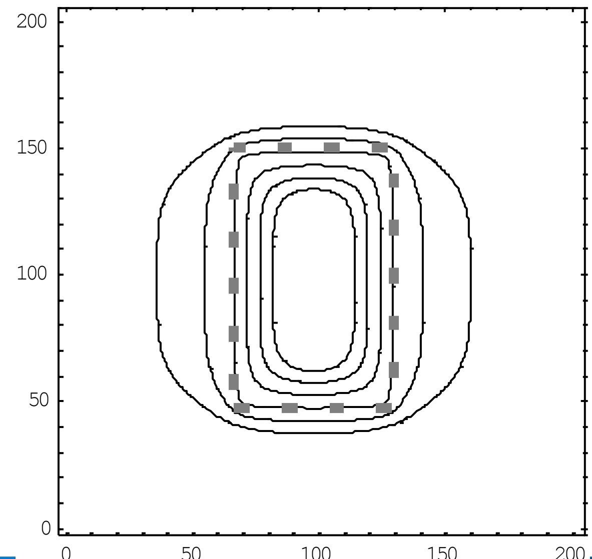
Sharp Cutoff → Field Flare



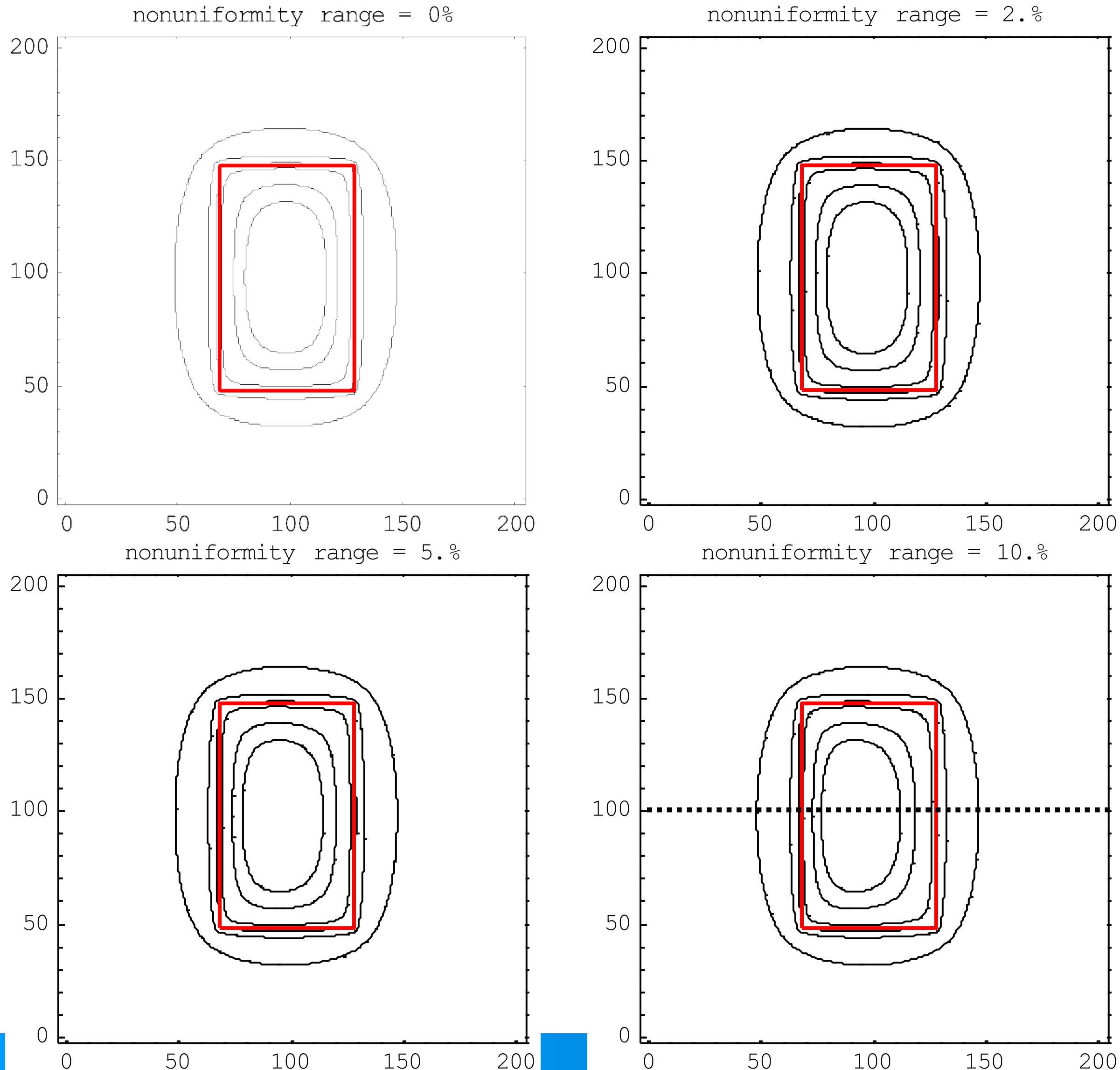
$$\gamma = 2$$



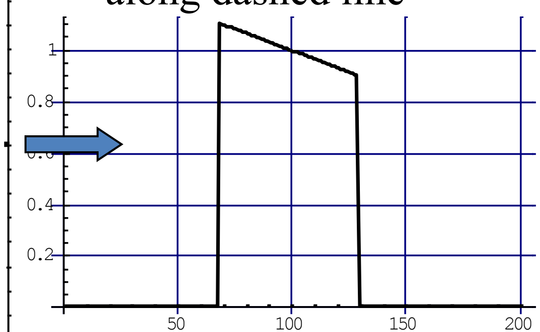
Gaussian Cutoff → Field Flare



$\gamma = 2$, Contours = 10,25,50,75,90,95%. Red rectangle is the field.
No cutoff but included a linear ramp of dose or equivalently K in x (slit) direction.
Nonuniformity number indicates total range of intensity or K variation = (Max – Min)%



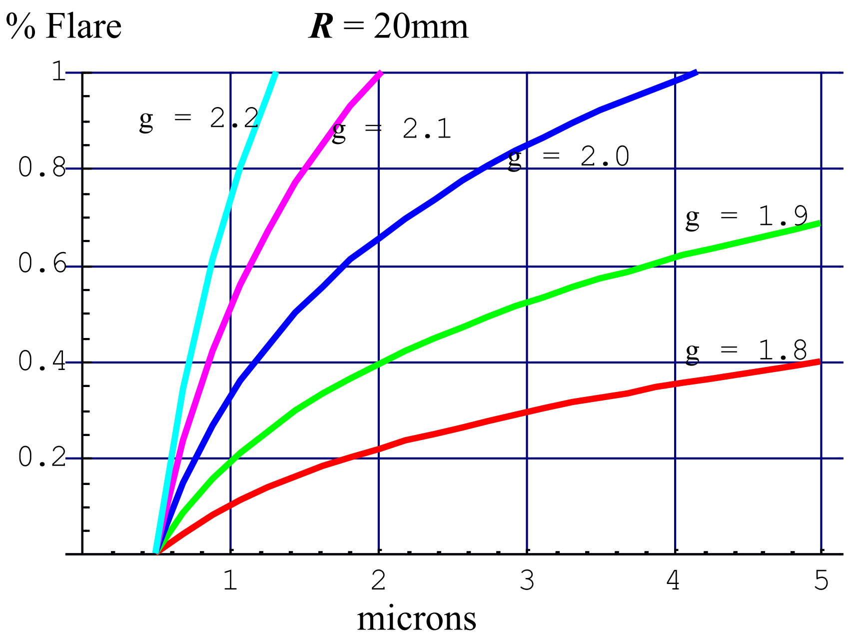
Intensity or K variation along dashed line

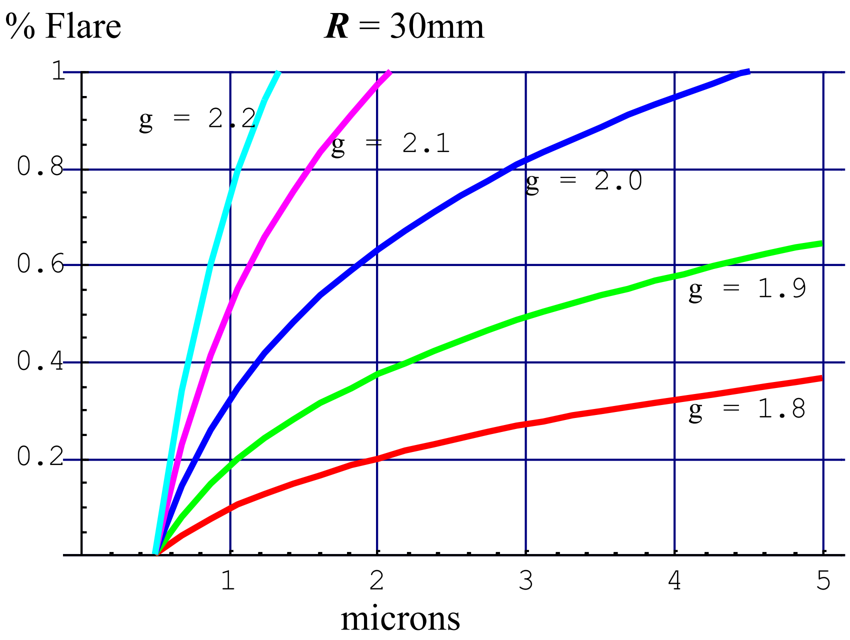


Assume 5% intrinsic flare (total integrated value) over range ½ micron to 20 or 30mm.
i.e., power law kernel normalized so that

$$2\pi K \int_{1/2\mu m}^{20 or 30mm} \frac{r\,dr}{r^{\gamma}} = 5\%$$

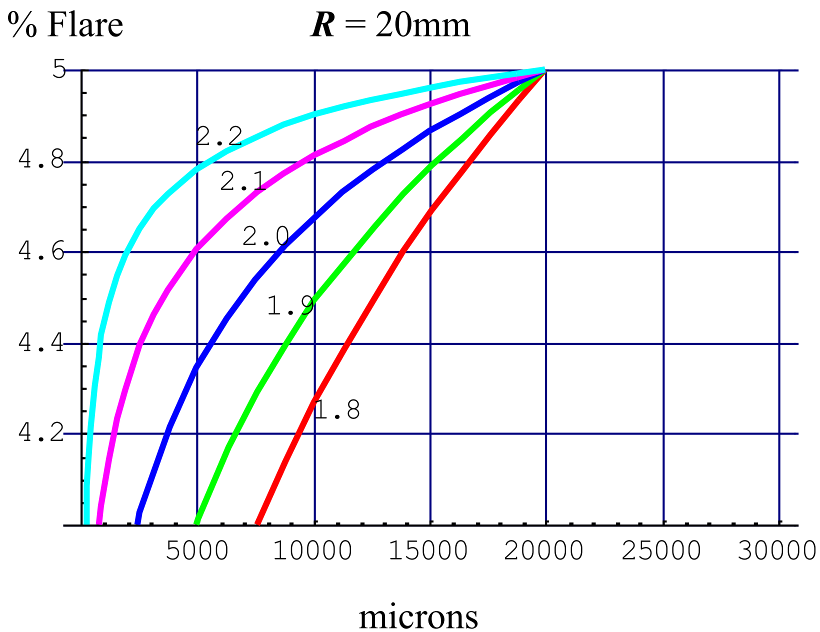
How much of the 5% is generated within a few microns of the ROI center as a function of γ and R?

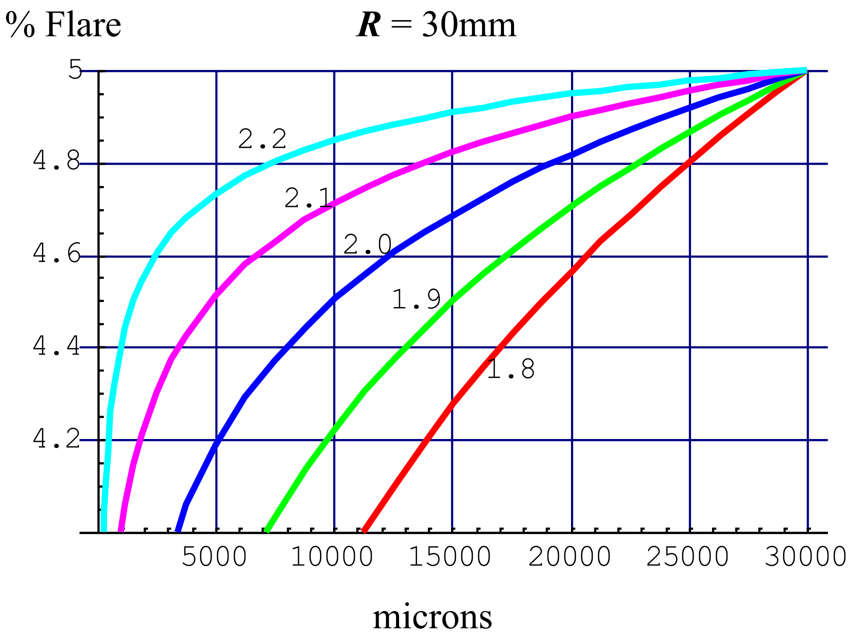




Max Error of ~ 1% in total flare value if we ignore the range from ½ to 2 microns in the integration for γ < 2.1.

How far out does the integration need to go to capture all but 0.5% of the flare?





Need only integrate out to ~ 2/3 nominal flare range to incur a max error of 0.2% in the total flare value for $\gamma < 2.1$.