# Methods to mitigate under-sampling problems in stray light analysis

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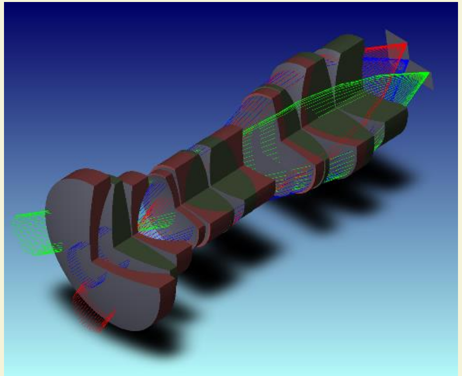
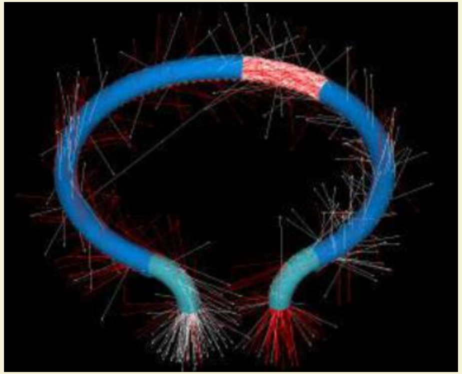
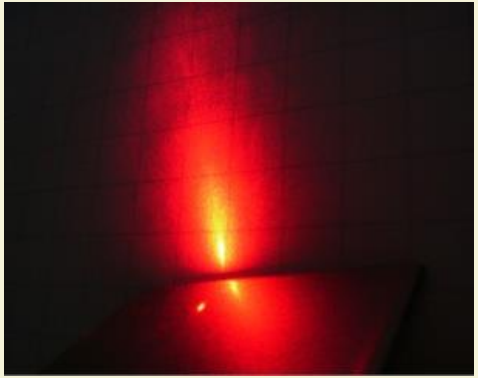
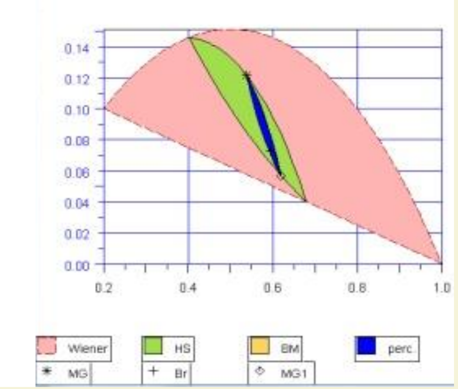
## Key Areas

| Imaging optics | Illumination optics | Straylight analysis | Software development |
|---|---|---|---|


Small innovative engineering company near Nürnberg, Germany

Currently 8 employees: physicists, mathematicians and engineers

Optical design and analysis for customers; strong focus on space applications

Sentinel 3,4,5
MTG-FCI, …

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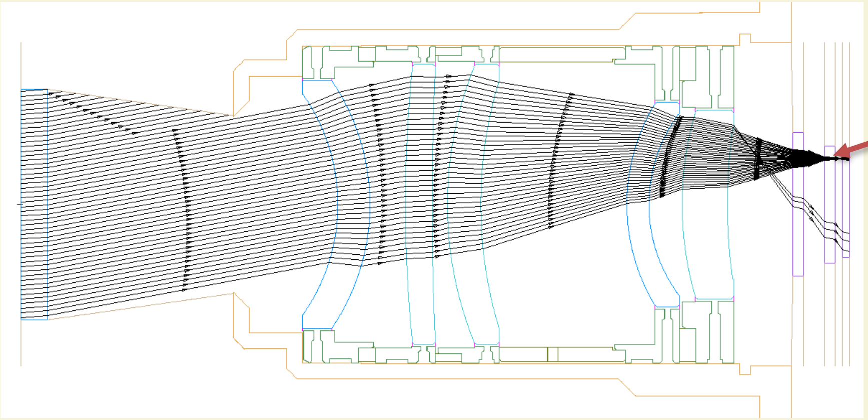
# Introduction

Stray light is unwanted light  entering an optical system, as opposed to nominal light for which the system is designed.



Characteristics of stray light:

- Paths are „unlikely“
- Only few ray will take the stray light paths
- =>Radiometric evaluation is often associated with statistical errors (so called undersampling)

**THIS talk: two methods to reduce noise in stray light calculations – for scattered light and for ghosts**

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Stray light cause 1

# Scattered light



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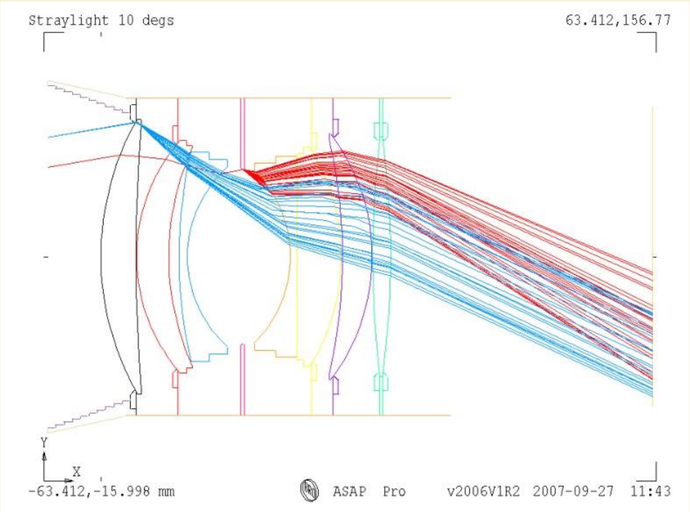
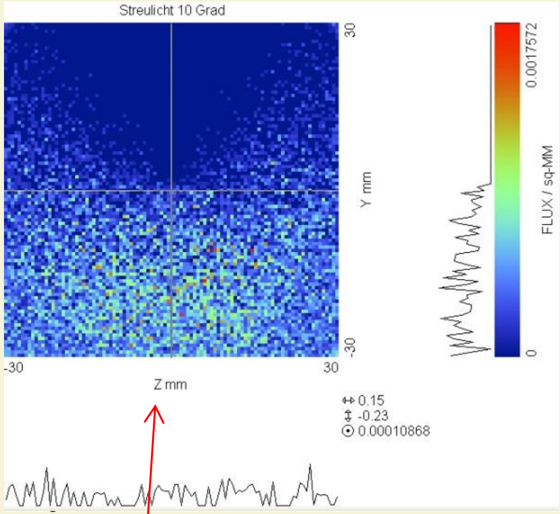
# Stray light cause 1: scattered light




Example:

Light scattering from lens fitting

In most cases this leads to a diffuse background signal in the image plane.

Simulation using Monte-Carlo-Raytracing

Noisy result even when using millions of rays!

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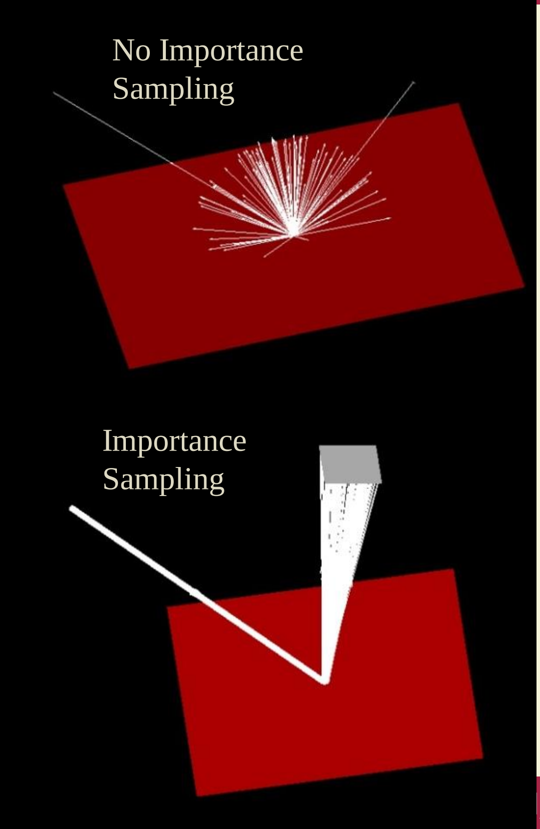
# Standard solution: importance sampling



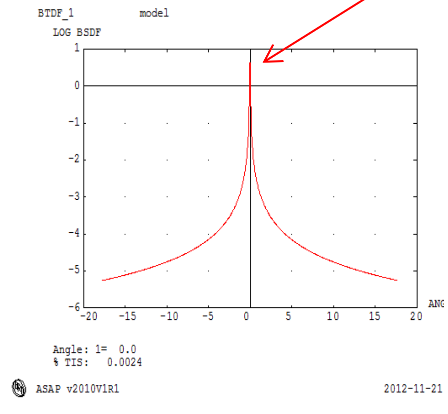

„Brute Force“-Method: scatter light into all direction, using lots of secondary rays. This will almost certainly lead to undersampling problems, because only very few rays will make it to the image plane. This is usually not an option!

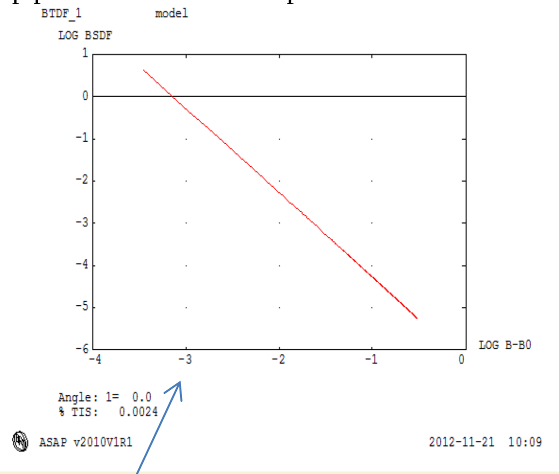
Solution: Importance sampling: create only rays into pre-defined directions which are known to be relevant for the analysis (e.g., rays directed towards the image plane or its images). *Solves many, but not all undersampling problems*.

**… but there is another undersampling problem if the dynamic range of the BSDF is high …**

# Example 1: Surface Roughness

Sharp peak centered about specular direction



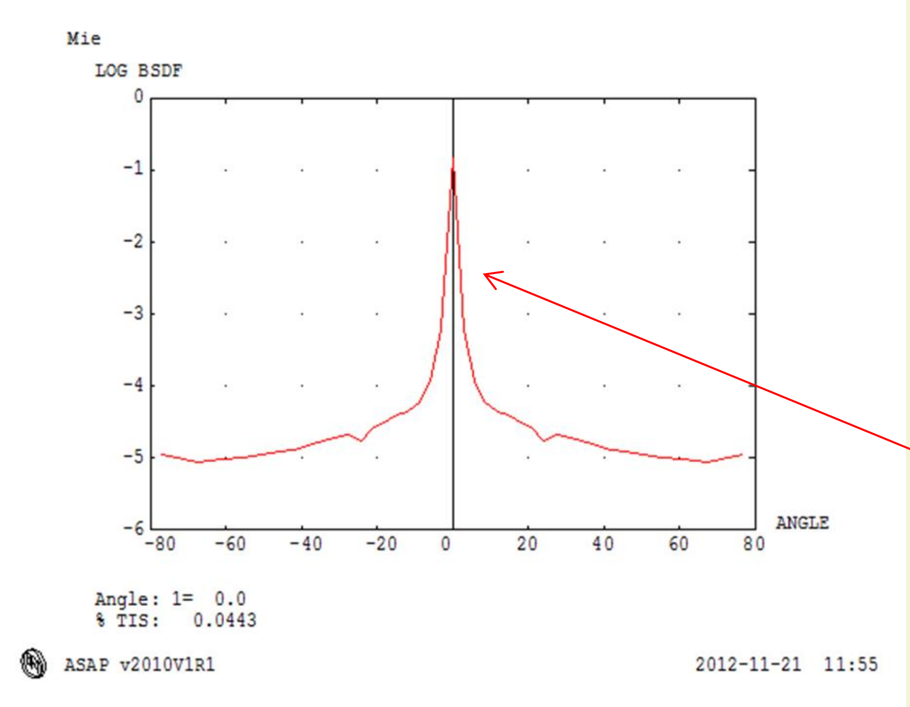

BTDF for perpendicular incidence,
Log-scaled;
Variation over 8 orders of magnitude!

Log-log representation

-3 corresponds to 0.057°

- Example: polished silica, wavelength 0.3µm, RMS roughness=0.5nm
- Note the huge dynamic range of the BSDF which spans more than 8 orders of magnitude
- Scattering is most concentrated within a narrow angular region about the specular peak.

# Example 1– particulate contamination




- Mie scatter
- Angular distribution shows similarities with scattering from roughness
- The larger the particles the higher is the peak close to specular direction
- Just as for roughness, stray light caused by particulate contamination is particularly important for in-field stray light, causing a "halo" about the nominal light

**Dynamic range 4 orders of magnitude; can be much higher depending on particle size distribution**

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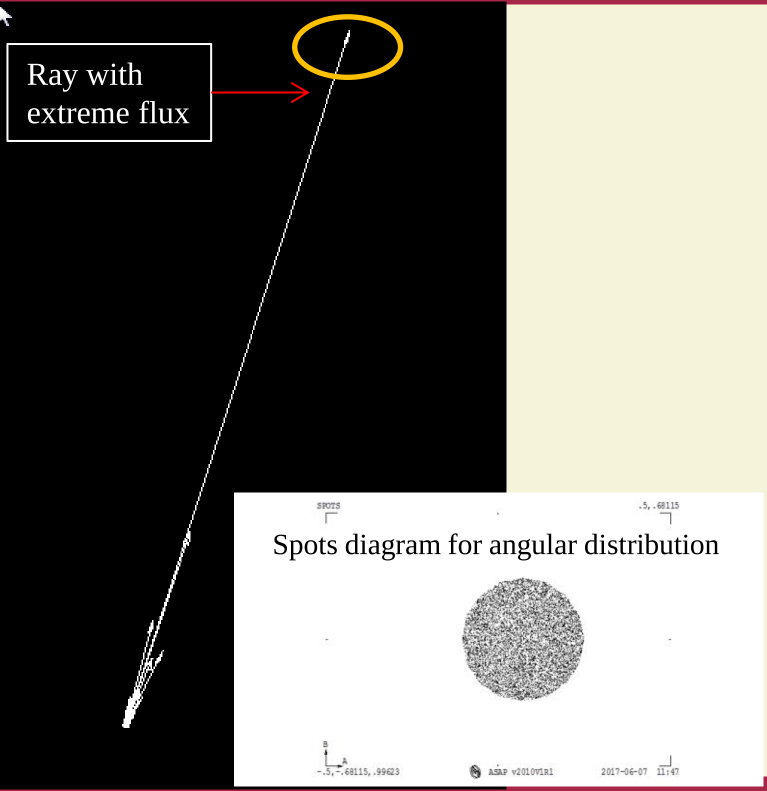
# How is the BSDF modeled in optical software?




- In the context of stray light analysis, we are only interested in modeling the BSDF in combination with Importance Sampling (because the latter is almost always needed!)
- ASAP (and ZEMAX, and possibly most others) do it as follows:
  - First, ray directions are randomly choses such that they sample the important direction homogeneously (or according to a Lambertian law).
  - Aftwards the ray flux gets weighted according to the BRDF in ray direction (so called „Flux weighting“)
- Problem: if the dynamic range of the BSDF is high, the dynamic range of the ray fluxes is also high. This means that a few rays may carry a huge radiant flux, that may even be higher than the flux of the incident ray!

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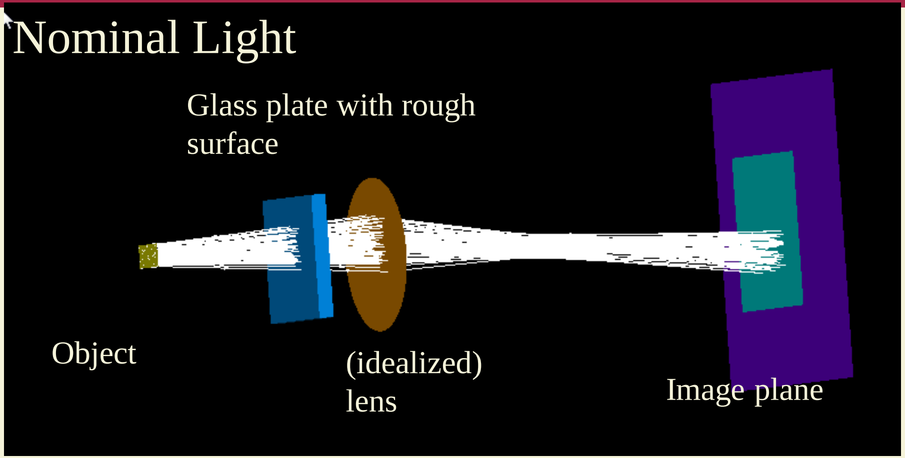
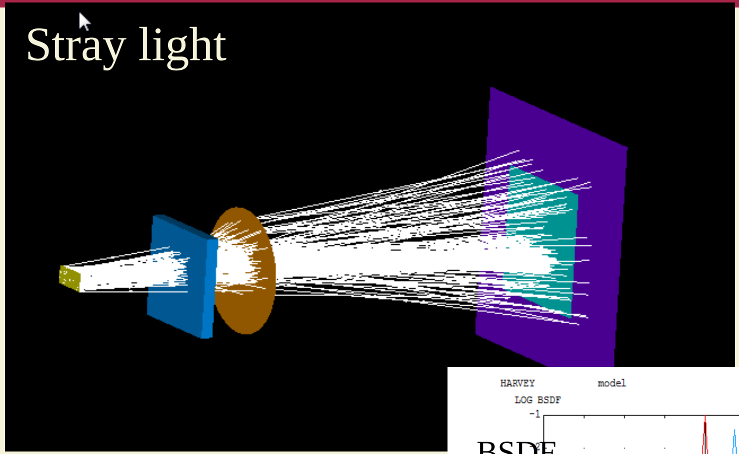
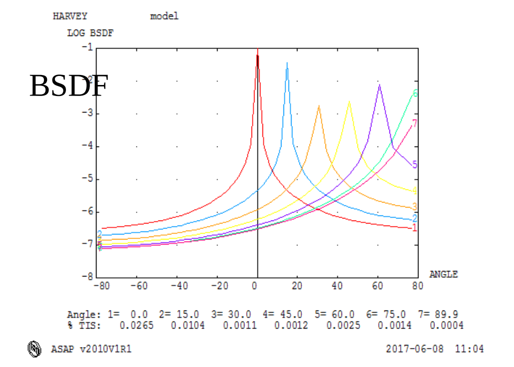
# Worked example: „in-field“-scatter




Ideal (paraxial) lens maps a rectangular object onto the image plane. Between object and lens there is a glass plate with rough surface.

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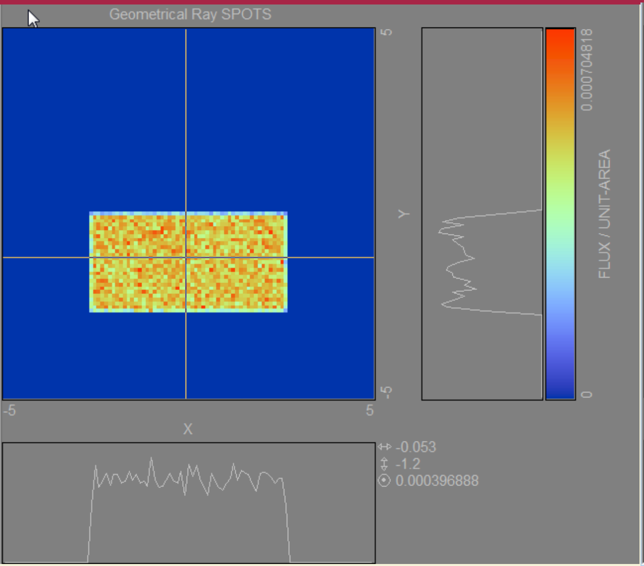
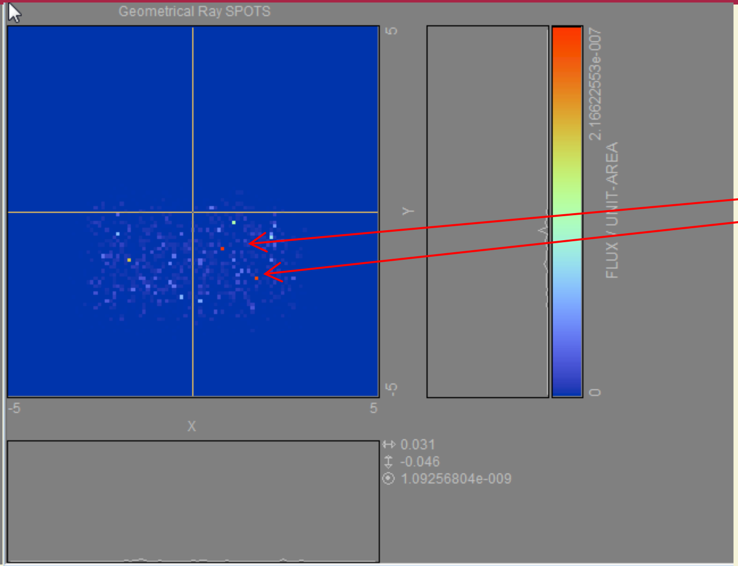
# Resulting irradiance on image plane




Nominal light




Scattered light ($10^5$ rays)

Irradiance distribution on image plane. Stray light distribution is too noisy for evaluation, because single rays (red) dominate. In particular it is impossible to make statements about the maximum irradiance on the image plane.

**More rays!**

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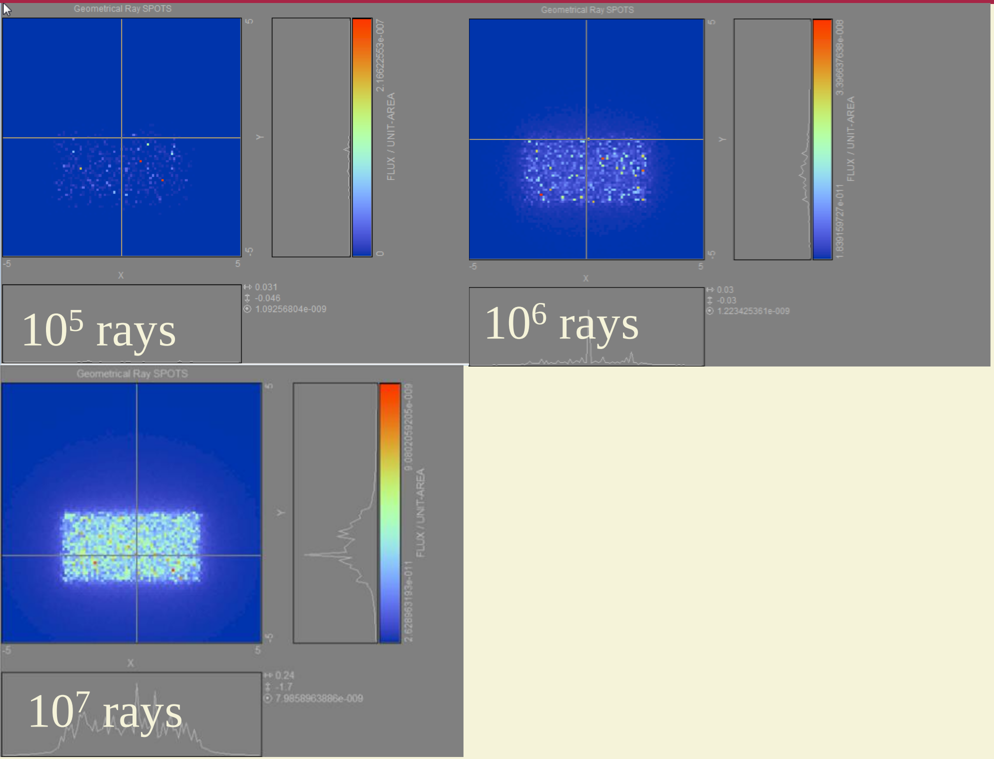
# More rays? Not an option!

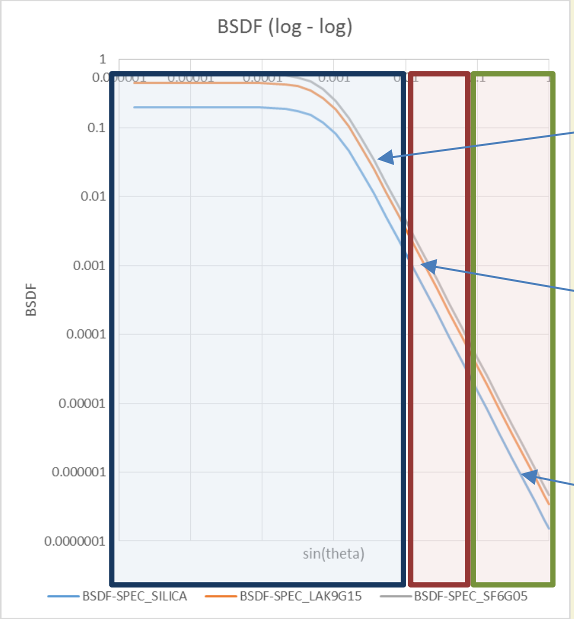


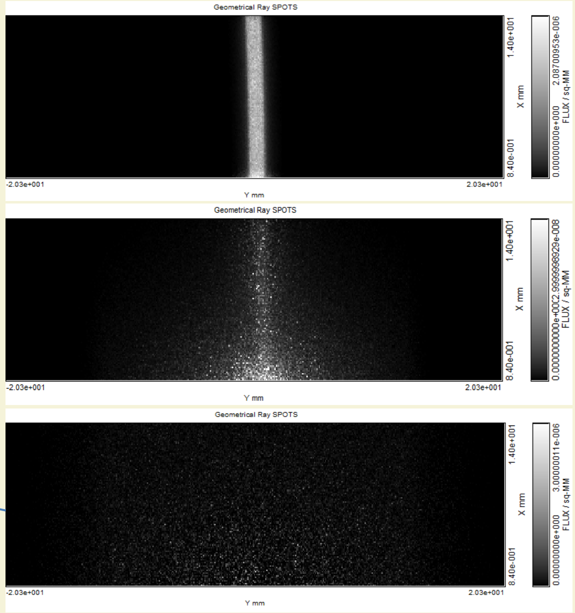

More rays do not solve the problem! The higher the number of rays, the more likely are „extreme“ rays with very high flux. The result simply does not stabilize, unless an extremely high number of rays is used ($10^9$ or more).

=> we need a better solution!

# Approach 1: Decompose scatter model into angular rings and simulate each ring separately

- Advantage : can be implemented directly in commercial software (ASAP, …)
- Disadvantage: useful only for in-field straylight; simulation more complex (and more prone to errors)




Small angles 0-0.5°: Close to nominal light

Intermediate scattering angles 0.5°-5°:

Large angles 5°-180°:

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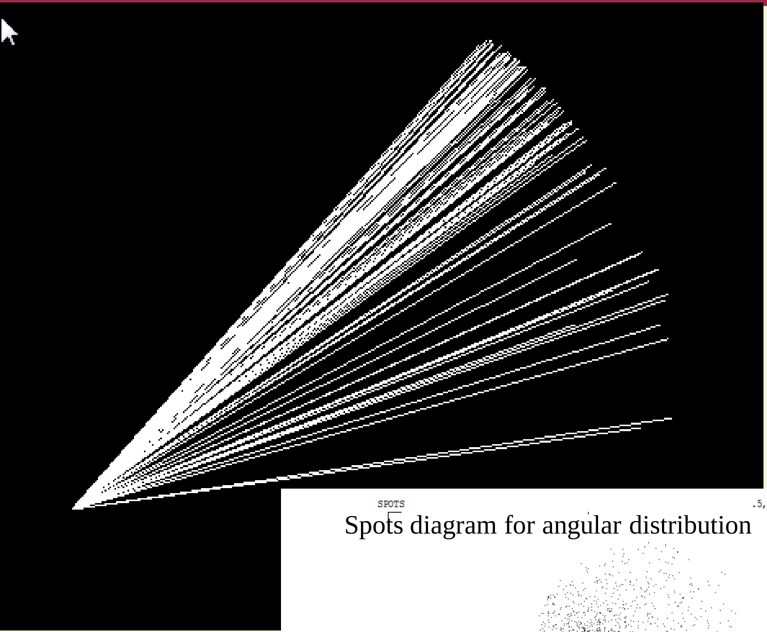
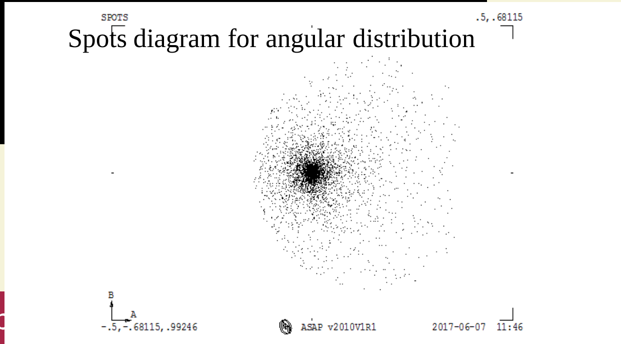
# Approach 2: „Ray density weighting“





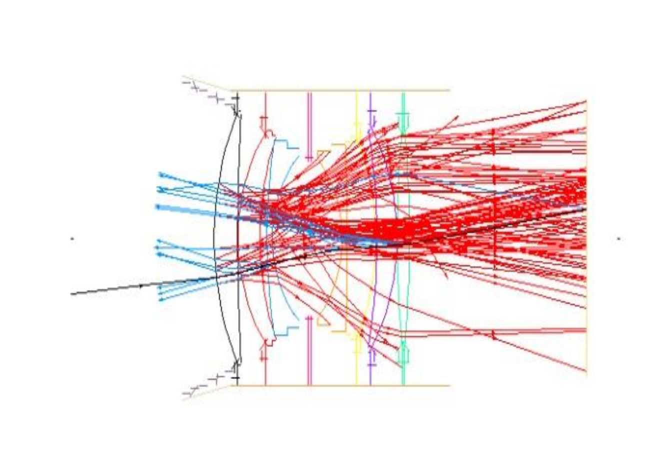

- Secondary rays all have (approximately) the same flux
- More rays are sent into direction with high BSDF
- Advantage: eliminates the problem with „high-flux rays“
- Disadvantages:
  - Must be implemented in external software
  - Does not (yet) work for all BSDFs
  - Software implementation rather tricky
  - Regions with low BSDF values may now be undersampled; maybe a trade-off is needed.

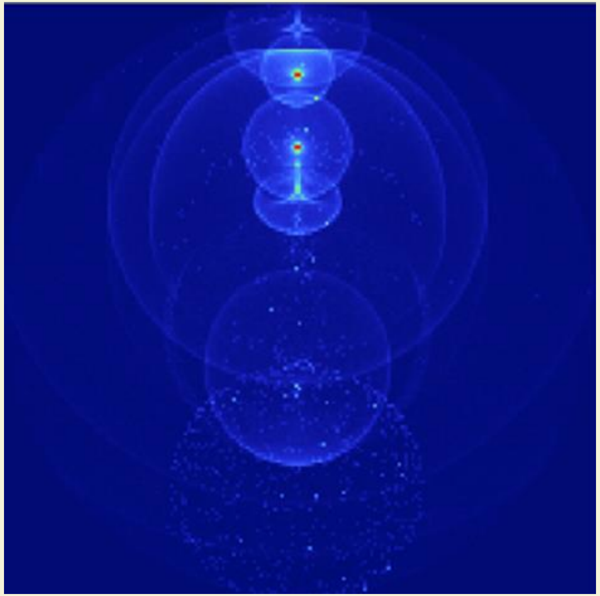
**Currently under development at Hembach Photonik**

Stray light cause 2

# Ghosts

# Stray light cause: Reflections (Ghosts)





Example:

Double-reflection from lens surfaces

Creates pronounced features with hot-spots in the image plane

Simulation is deterministic: this means that importance sampling cannot be used to improve statistics!

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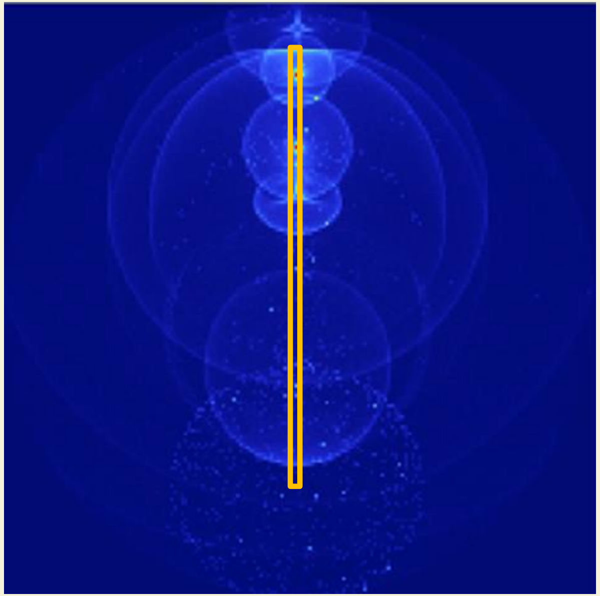
# Ghost analysis and under-sampling



Under-sampling may play a role for example, if:

- Ghost need to be evaluated only within a small region of the image plane, for instance on the slit of a spectrometer
- If there are only very few rays available for analysis, e.g., ghosts in combination with scattering
- If hot spots need to be evaluated in detail (high resolution)

Often only a few rays are left for analysis – far too few for getting a sufficient ray statistics

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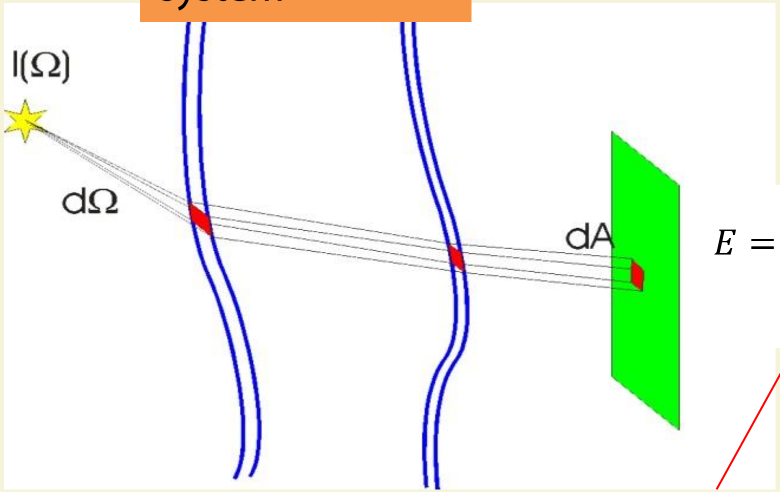
# Solution: differential raytracing

Tracing of infinitesimal ray bundles instead of „normal“ rays.

This allows for:

- Exact radiometry
- Vary rays on the image plane to any location

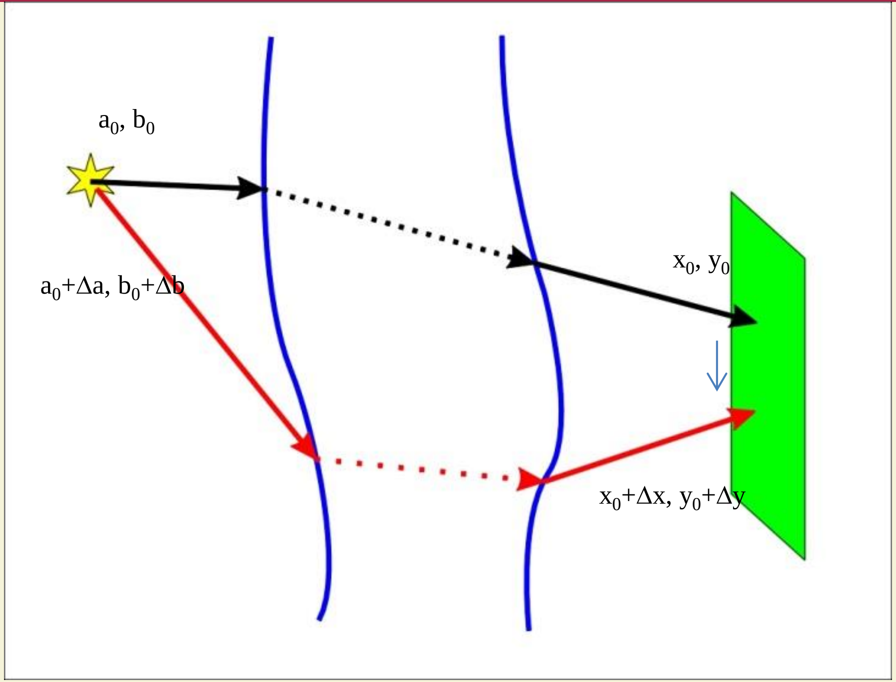
Arbitrary optical system




$$E = \frac{d\,\Omega}{d\,A}\,\mathrm{I}$$

Jacobi determinant

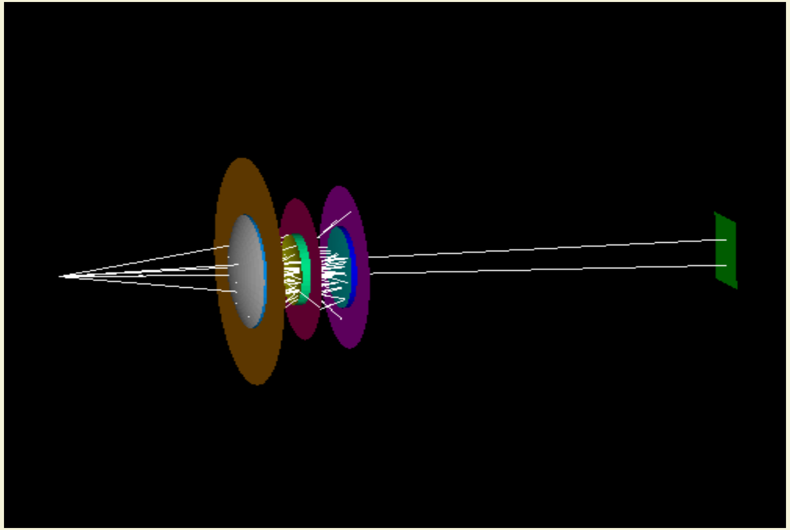
# Ray variation



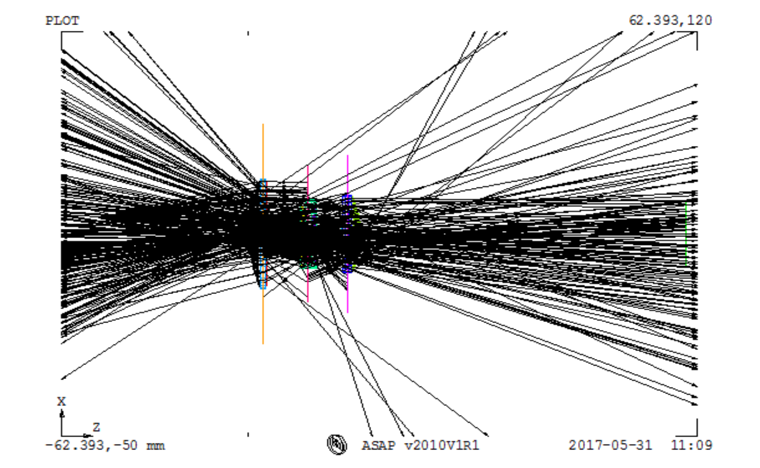

Rays can bee moved to locations of interest on the image plane (e.g., towards the slit of a spectrometer)

Variation uses the differential information contained in the ray bundles.

# Worked example: Ghosts in Cooke Triplet



- Point source at (5, 0, -40)
- 10000000 rays
- Detector: 201x201 Pixels




ASAP: „normal“ ray tracing

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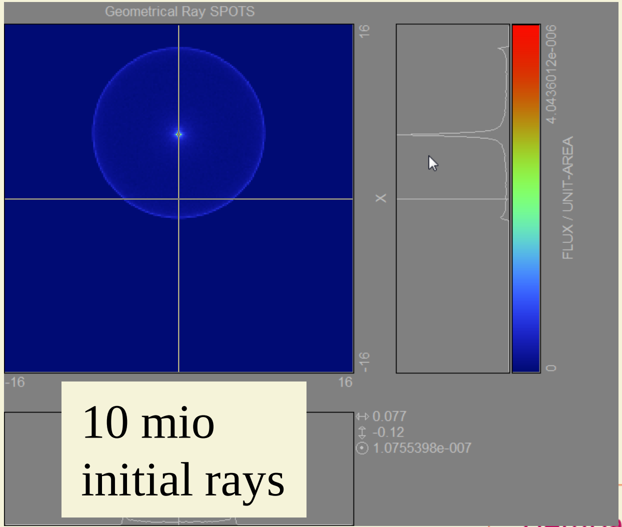
# Analysis in ASAP

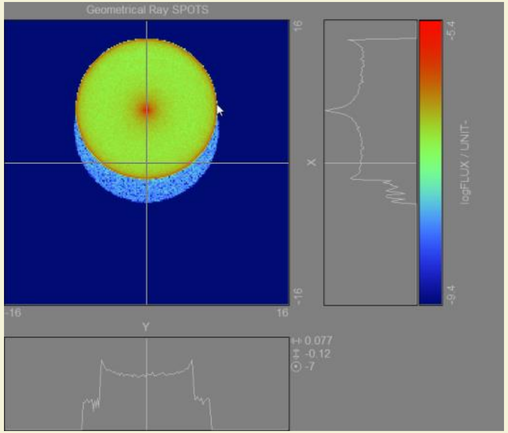
## Ray paths in ASAP

| Path | Rays | SumTOTA | Percent | Hits | Curr | Prev | Split/Scatter ... | | |
|---|---|---|---|---|---|---|---|---|---|
| 3 | 24725 | 3.43E-04 | 35.48 | -17 | 13 | 10 | 1.100 | 10.100 | 0.000 |
| 4 | 9226 | 1.94E-04 | 20.07 | -9 | 13 | 10 | 2.100 | 5.100 | 0.000 |
| 7 | 5370 | 1.13E-04 | 11.68 | -9 | 13 | 10 | 6.100 | 9.100 | 0.000 |
| 15 | 3476 | 7.52E-05 | 7.79 | -9 | 13 | 10 | 1.100 | 2.100 | 0.000 |
| 6 | 4405 | 7.40E-05 | 7.67 | -13 | 13 | 10 | 1.100 | 6.100 | 0.000 |
| 5 | 1986 | 3.72E-05 | 3.86 | -11 | 13 | 10 | 1.100 | 5.100 | 0.000 |
| 8 | 1525 | 2.56E-05 | 2.65 | -13 | 13 | 10 | 5.100 | 10.100 | 0.000 |
| 13 | 1239 | 1.92E-05 | 1.99 | -15 | 13 | 10 | 1.100 | 9.100 | 0.000 |
| 14 | 977 | 1.83E-05 | 1.90 | -11 | 13 | 10 | 6.100 | 10.100 | 0.000 |
| 17 | 727 | 1.57E-05 | 1.63 | -9 | 13 | 10 | 9.100 | 10.100 | 0.000 |
| 18 | 664 | 1.03E-05 | 1.07 | -15 | 13 | 10 | 2.100 | 10.100 | 0.000 |
| 9 | 8150 | 8.86E-06 | 0.92 | -10 | 13 | 10 | 5.100 | 6.100 | 0.000 |
| 16 | 381 | 7.76E-06 | 0.80 | -9 | 13 | 10 | 5.100 | 6.100 | 0.000 |
| 10 | 371 | 6.98E-06 | 0.72 | -11 | 13 | 10 | 2.100 | 6.100 | 0.000 |
| 12 | 390 | 6.78E-06 | 0.70 | -13 | 13 | 10 | 2.100 | 9.100 | 0.000 |
| 11 | 267 | 5.02E-06 | 0.52 | -11 | 13 | 10 | 5.100 | 9.100 | 0.000 |
| 1 | 177 | 3.61E-06 | 0.37 | -9 | 13 | 10 | 6.100 | 0.000 | |
| 2 | 1879 | 1.74E-06 | 0.18 | -14 | 13 | 10 | 2.100 | 9.100 | 0.000 |

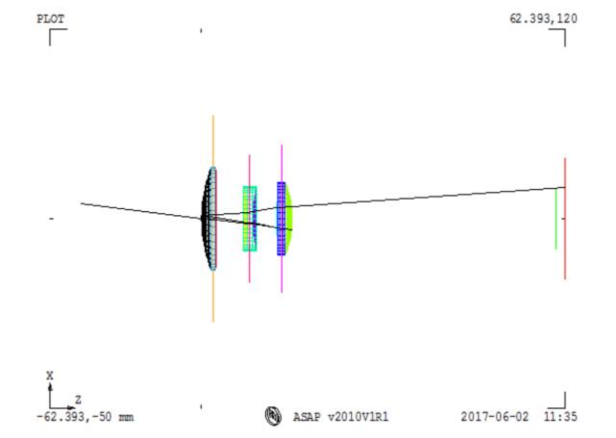
Let us consider only the ghost generated by reflection by the first and last lens surface; let us also analyze it using differential ray tracing.



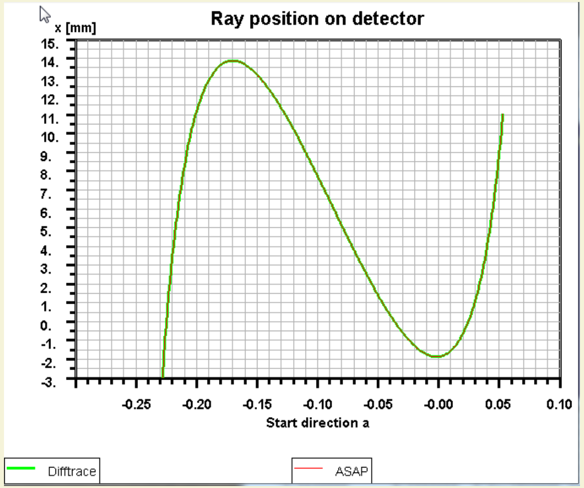
# A closer look at the ghost: Caustics




Log-scale representation: ghost consists of more than one component; why?




Ray hitpoint on detector (vertical direction) as function of initial direction (Animation)




Ray hitpoint as function of initial direction: two turning points indicate **caustics => ghosts consists of three contributions (equivalence classes)**

Things are more complicated than expected!



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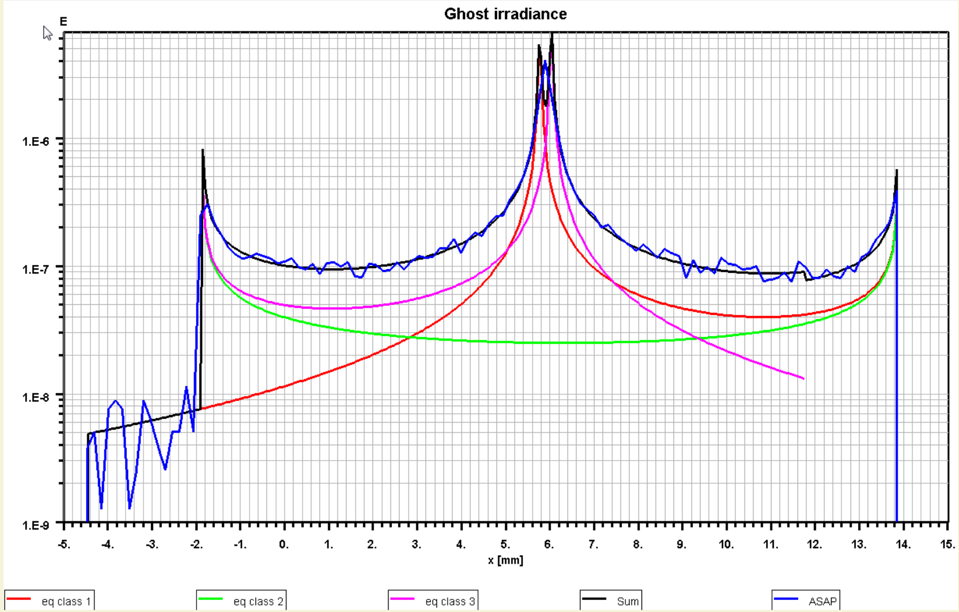
# Comparison between ASAP and differential ray tracing




Calculation done with software currently developed by Hembach Photonik

Vertical cut through irradiance distribution

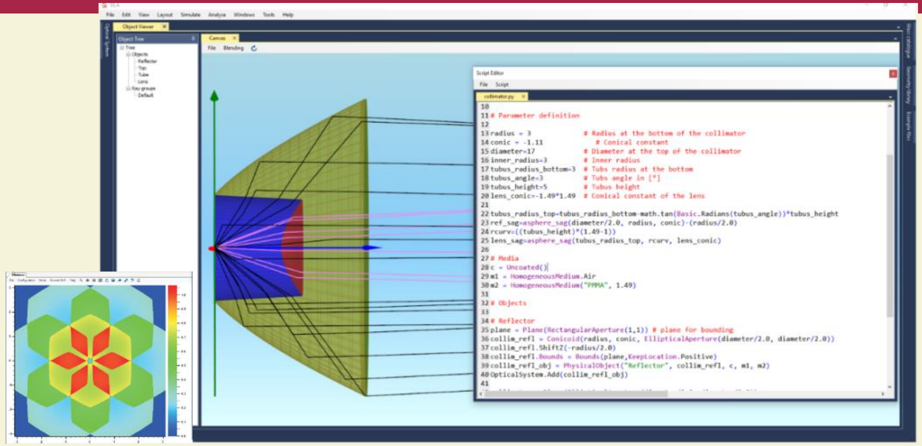
Differential ray tracing has to sum three contributions (the three equivalence classes) to end up with the total irradiance.

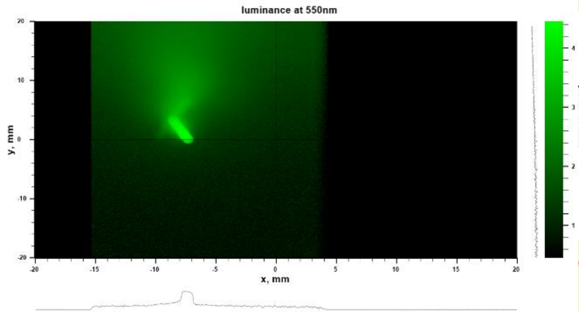
Result is noise-free and has an arbitrarily fine resolution.

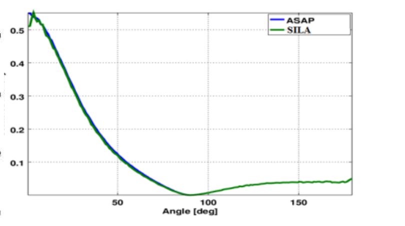
Caution: irradiance at caustic is incorrect (actually, differential raytracing predicts an infinite value), because geometrical optics is invalid there!

# Summary and conclusion

- Undersampling is one key problem for stray light analysis
- For scattered light, ray density weighting can help reduce this problem in addition to standard methods such as importance sampling.
- Undersampling of ghost light can be avoided using differential ray tracing.
- Hembach is currently developing ray tracing software to address these problems.





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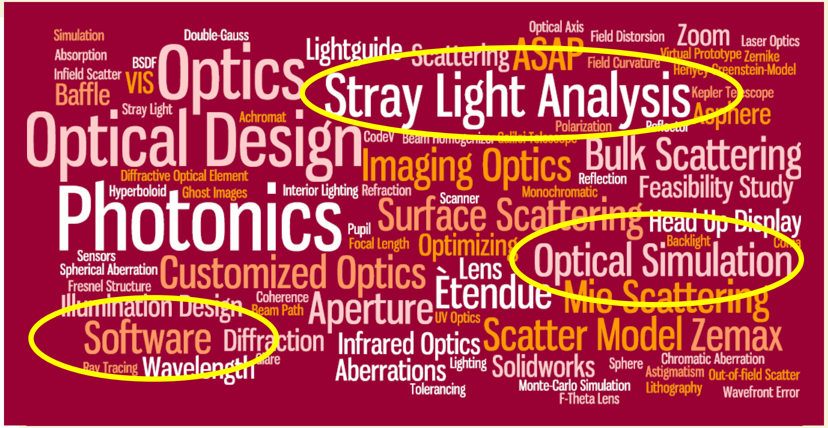


# THANK YOU!

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