GradOptics: Differentiable Ray-Tracer

Simulation Development & Plans

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MAGIS-100 Science & Simulations Meeting
May 17, 2023

SLAC NATIONAL ACCELERATOR LABORATORY
MAGIS-100
Stanford University | U.S. DEPARTMENT OF ENERGY

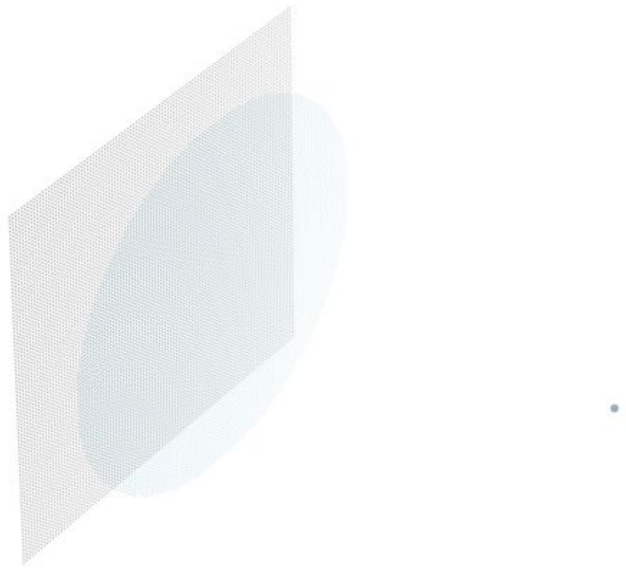
GradOptics: Differentiable Optics via Ray Tracing

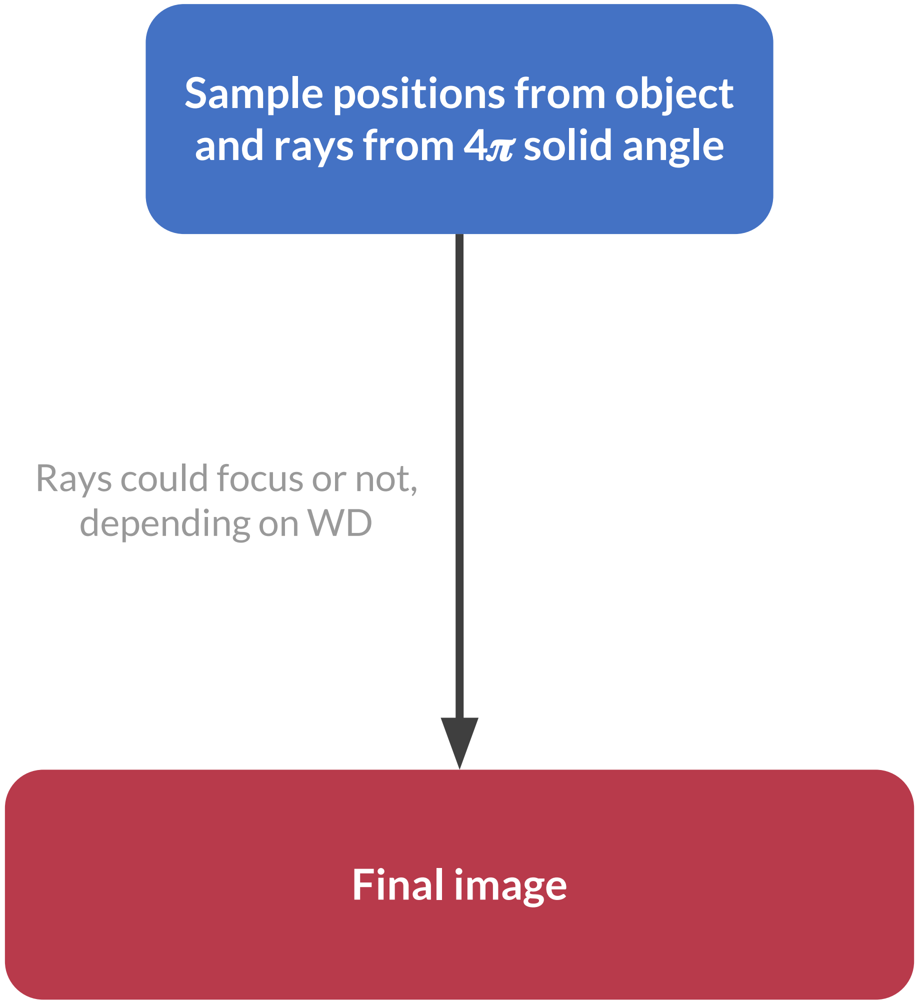
- GitHub Link
- “Differentiable”
  - Allows for gradient-based optimization
  - Implemented with PyTorch
- “Ray Tracing”
  - Geometric optics
  - Defocus (“depth” effect) can be simulated
  - Can do forward & backward tracing
- Applications
  - First-order imaging performance studies
  - Object reconstruction via gradients
  - Imaging design optimization
  - Calibration

Geometric Ray-tracing

Currently simulate-able effects include:

- **Geometric optics effects with thin lens**
  - **Include defocus if object distance is not nominal WD**
- Quantum efficiency, read-out noise





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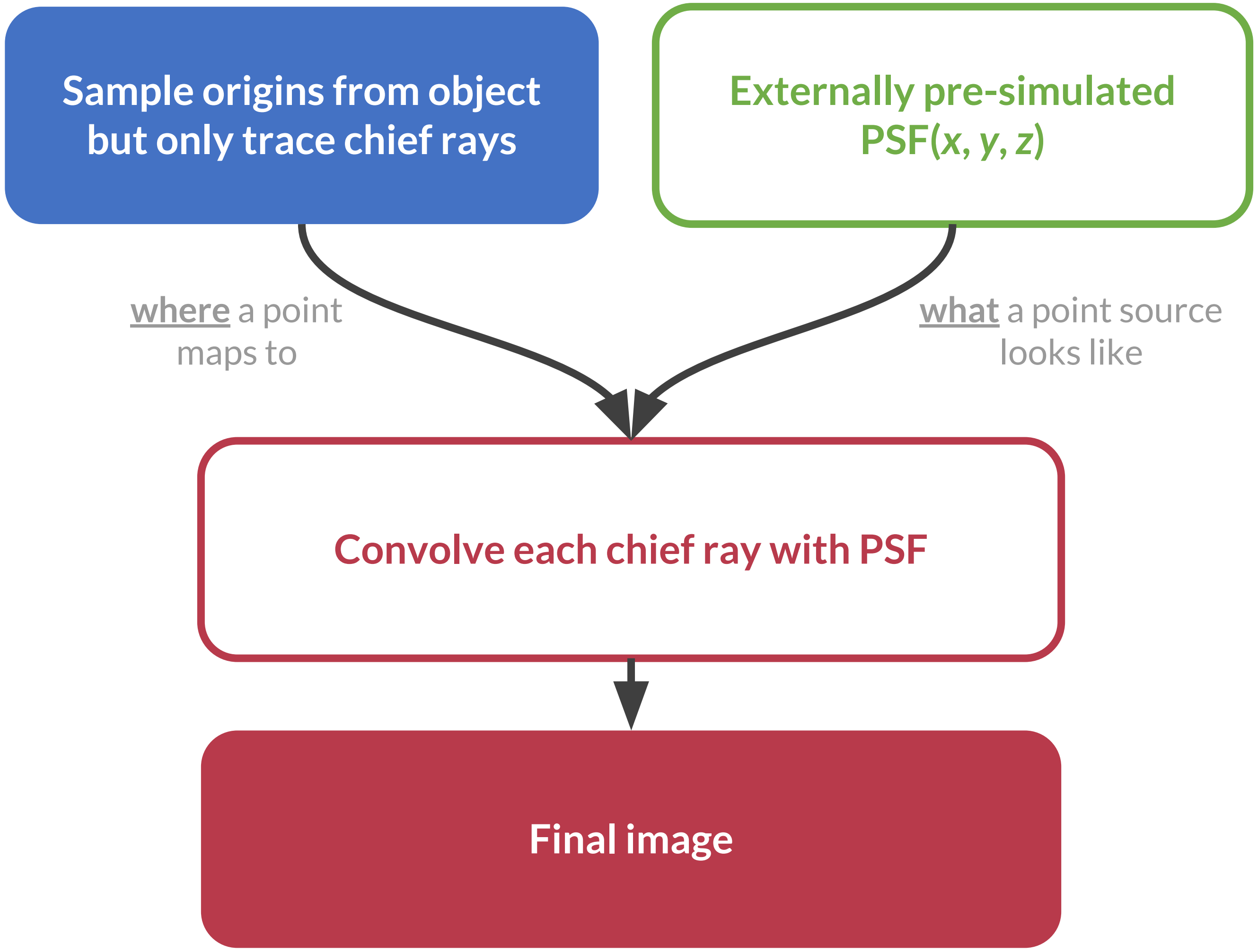
Incorporating PSF

Currently simulate-able effects include:

- Geometric optics effects with thin lens
- Quantum efficiency, read-out noise

(Potentially) Important effects to be added:

- Multi-surface, realistic lens model
  - Requires translating detailed lens models
- **Any physical wave optics effects, e.g. diffraction**
  - **Point Spread Function (PSF)**
    = image of a point source
  - **PSF summarizes geometric AND physical optics effects**



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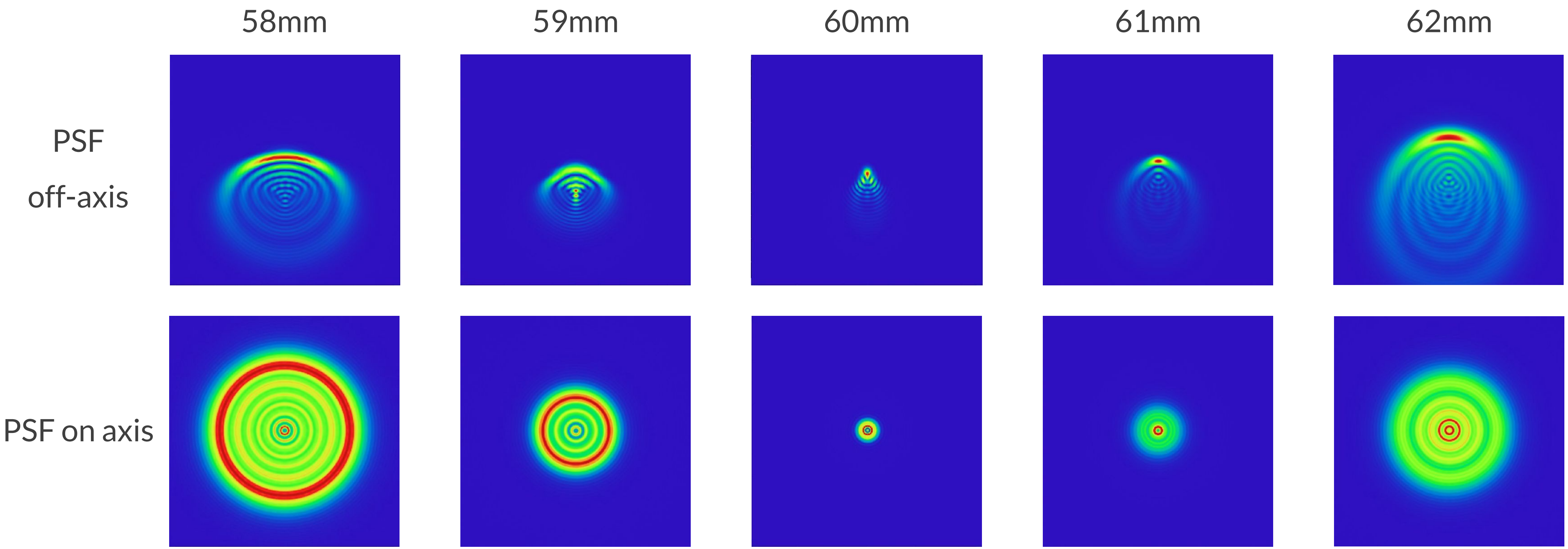
Example PSF's from OpticStudio



Benchmark test lens

- 25mm lens, f/2.8, current choice for DIS HM lens
- Focused at 60mm

PSF images drawn
over +/- 64μm range

Validating Chief Ray Tracing

50µm Gaussian cloud

23mm lens, x0.42 mag., f/2, expected DOF +/- 1mm

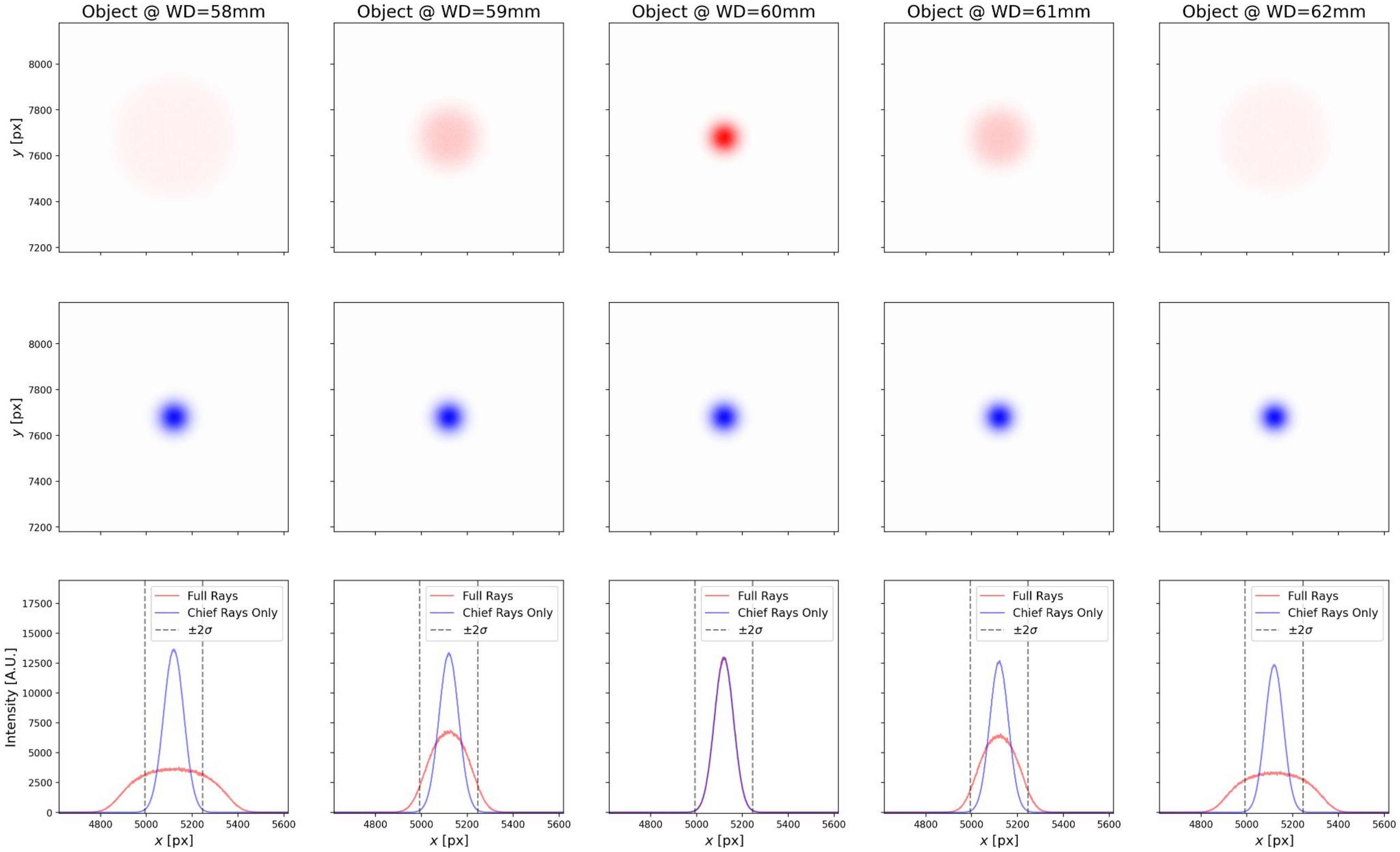
Tracing all rays

simulates geometric defocus

Tracing chief-rays only

always gives focused images,

no geometric OR physical effects



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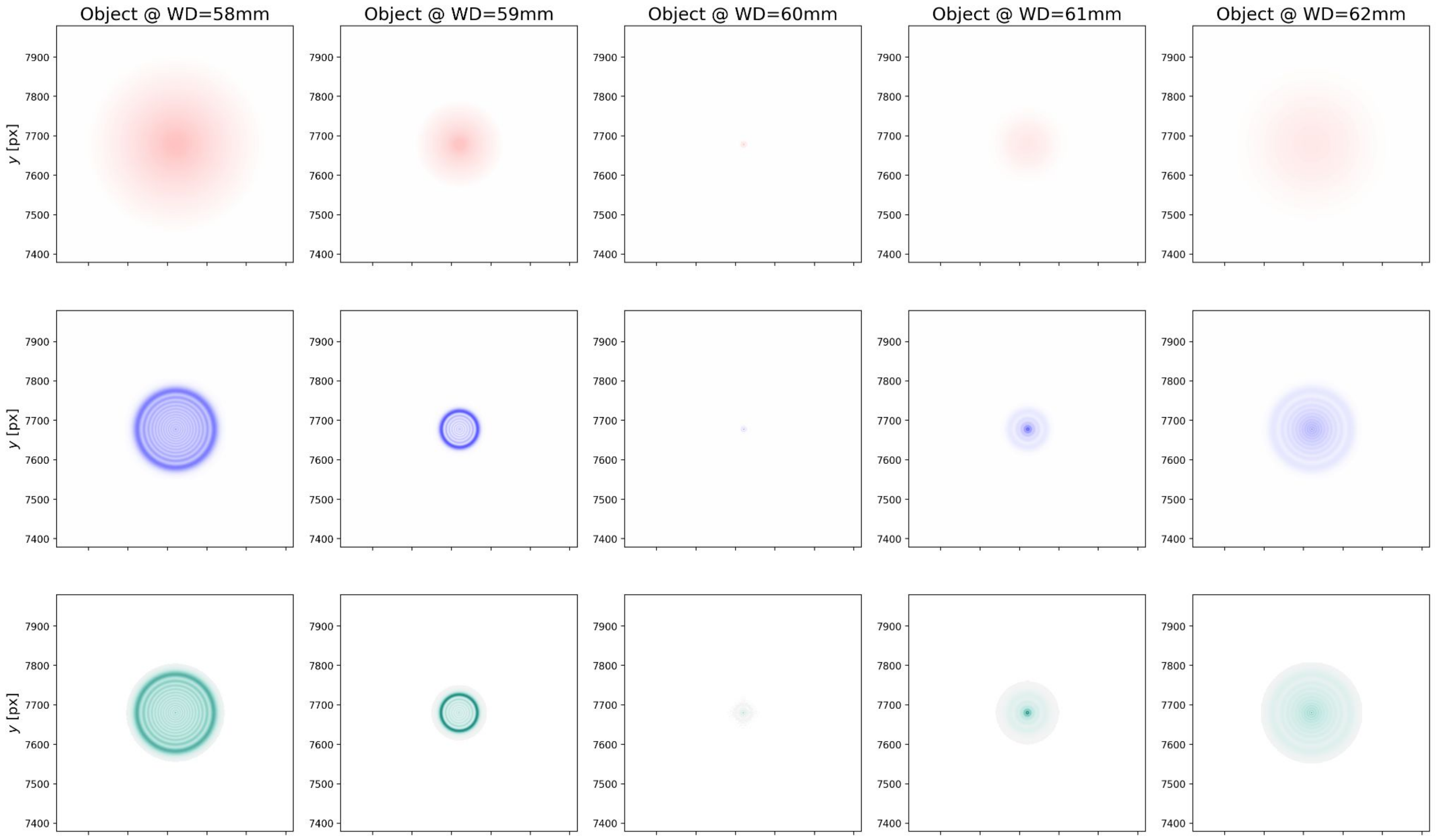
Validating PSF Convolution (1/2)

Point source

23mm lens, x0.42 mag., f/2, expected DOF +/- 1mm



Full ray-tracing + PSF

"double-counts" geometric effects

⇒ This is incorrect!

Chief ray-tracing + PSF

accurately reproduces PSF

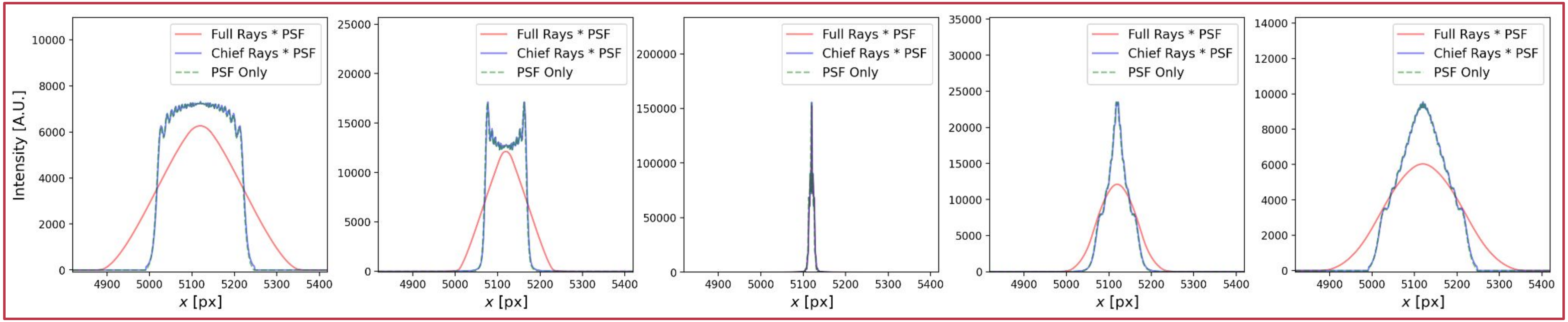
PSF's from Zemax

for reference

Validating PSF Convolution (2/2)

Point source

23mm lens, x0.42 mag., f/2, expected DOF +/- 1mm



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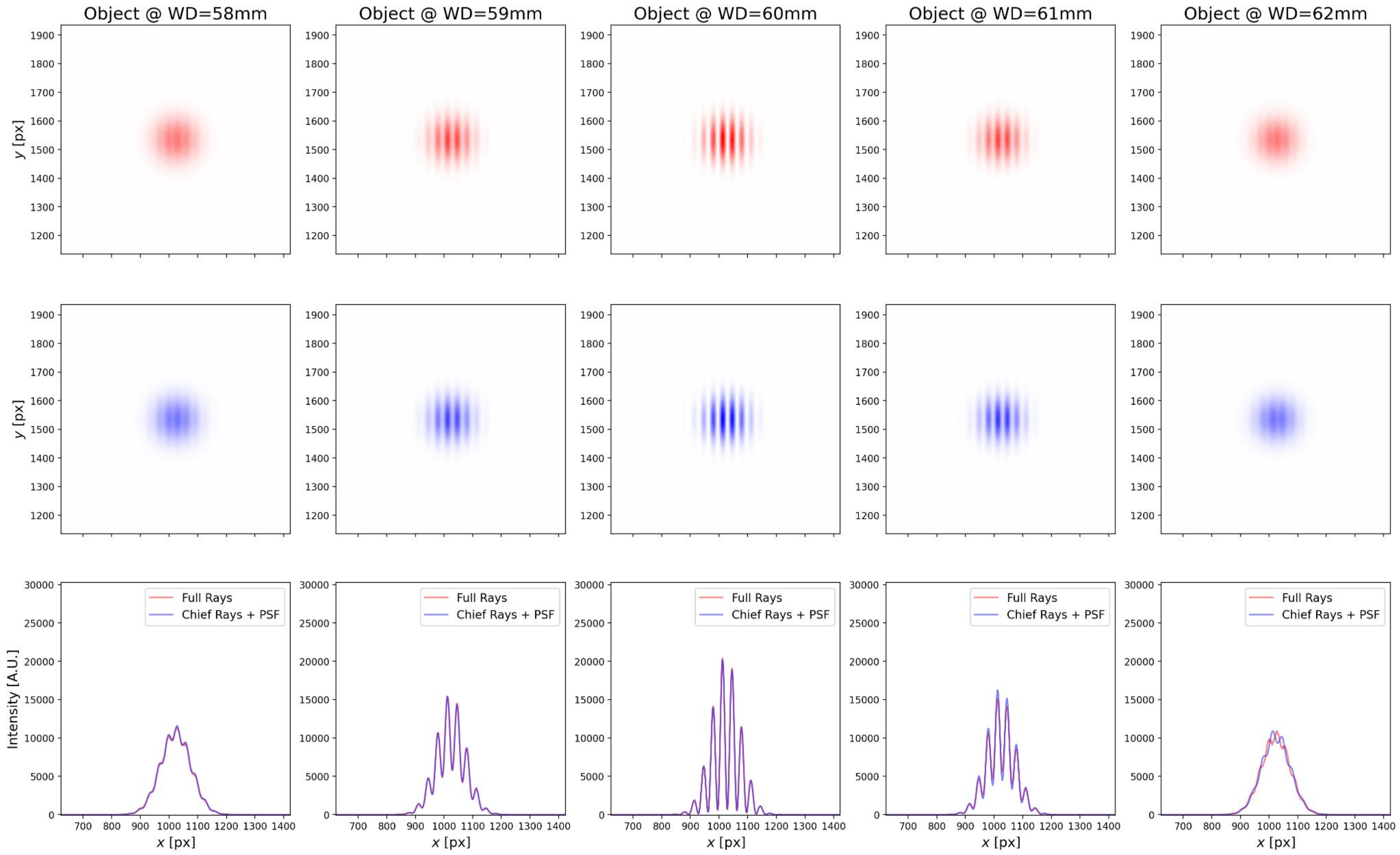
Tests with Realistic Gaussian × Fringes

300µm Gaussian cloud × 200µm fringe

23mm lens, ×0.42 mag., f/2, expected DOF +/- 1mm



Geometric ray-tracing

(geometric effects only, simple thin lens)

Chief ray-tracing + PSF

(physical effects, complex lens)

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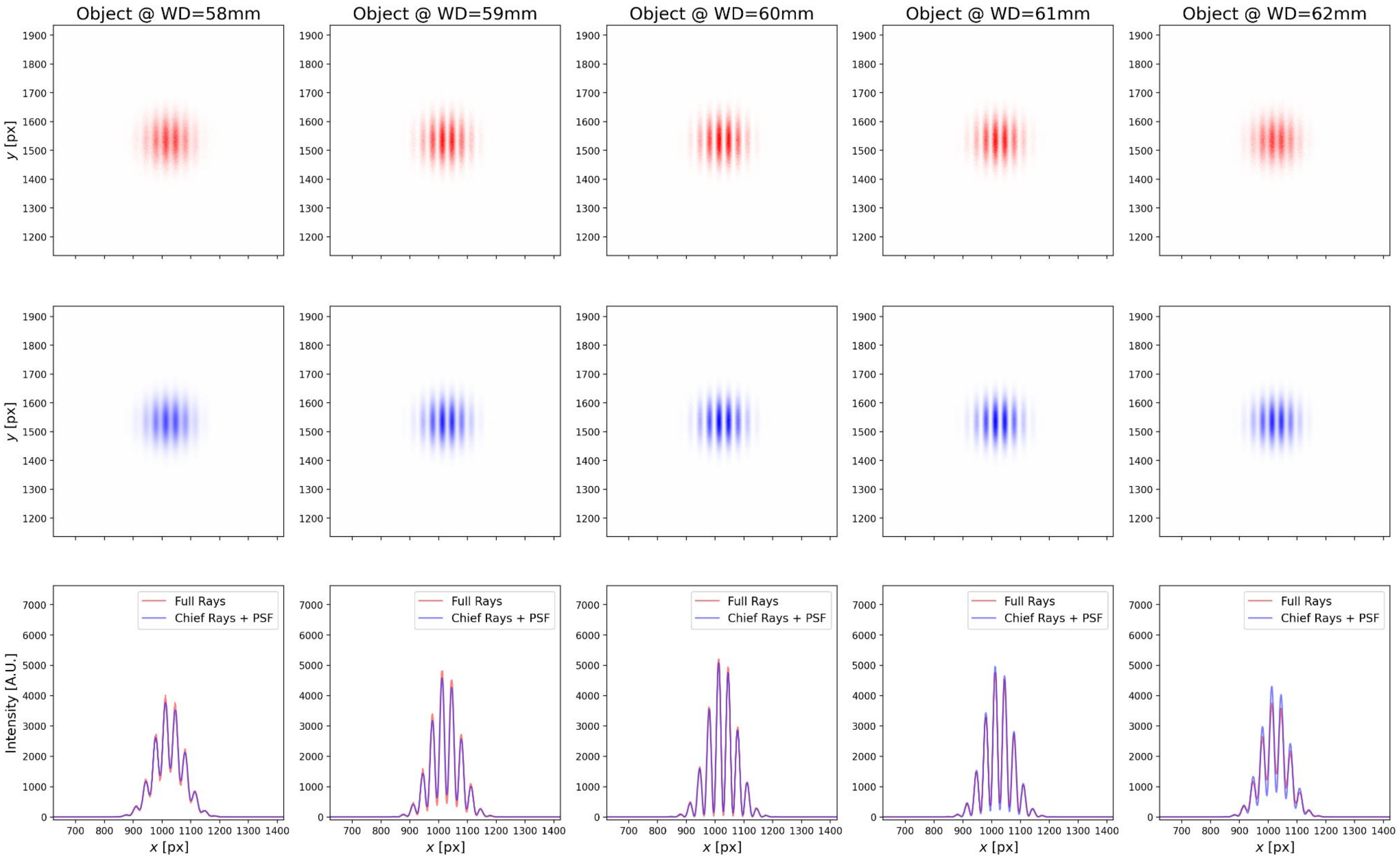
Tests with Realistic Gaussian × Fringes

300μm Gaussian cloud × 200μm fringe

23mm lens, ×0.42 mag., f/4, expected DOF +/- 2mm



Geometric ray-tracing

(geometric effects only, simple thin lens)

Chief ray-tracing + PSF

(physical effects, complex lens)

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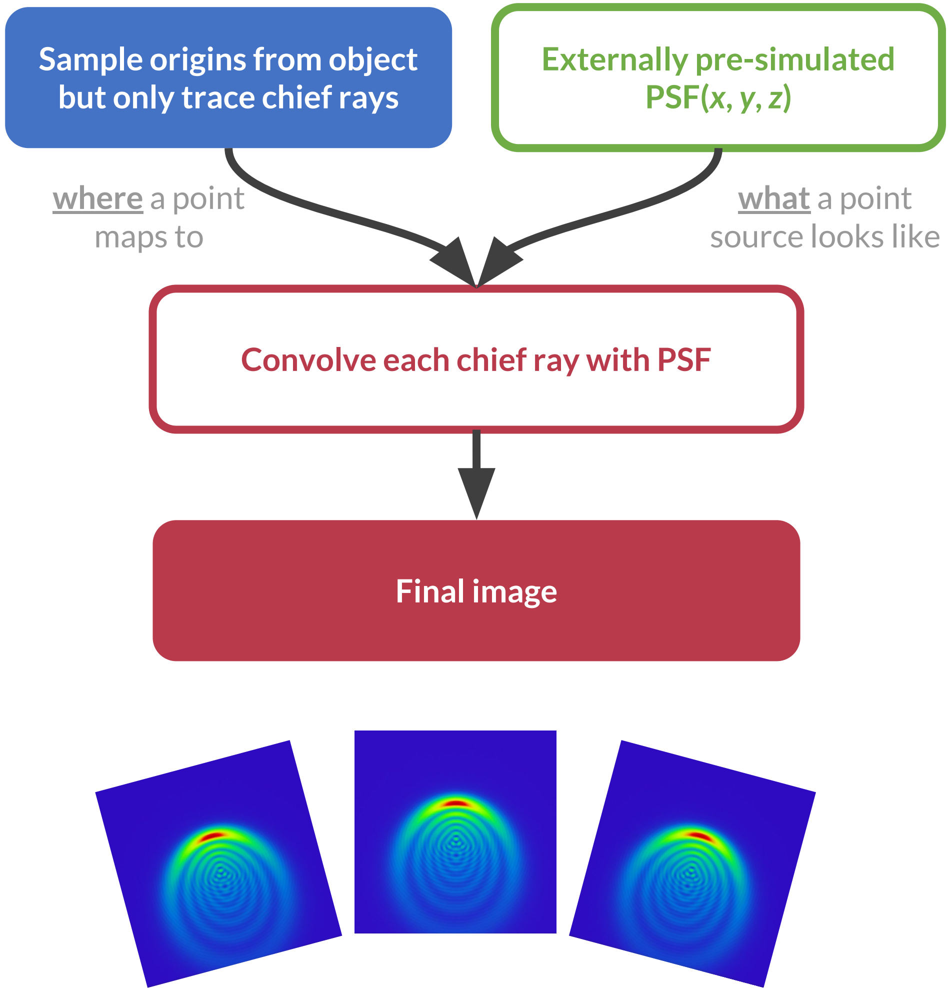
Improving PSF Implementations

Some challenges/limitations currently:

- **Each PSF needs to be simulated externally (via Zemax OpticStudio)**
  - Lens models are often black-box; cannot be opened/investigated by different SW
- **Finely scanning all possible object positions is expensive**
  - Could we scan coarsely and interpolate?
- **We have to apply rotated PSF's**
  - PSF's simulated at some off-axis height
    (PSF image per (x, 0, h) instead of at (x, y, z))
  - In reality, objects are off-axis in different directions
- **Need for parametrizing PSF's**
  - We have some ideas, but suggestions are welcome!
  - Special functions
  - NN-based approach



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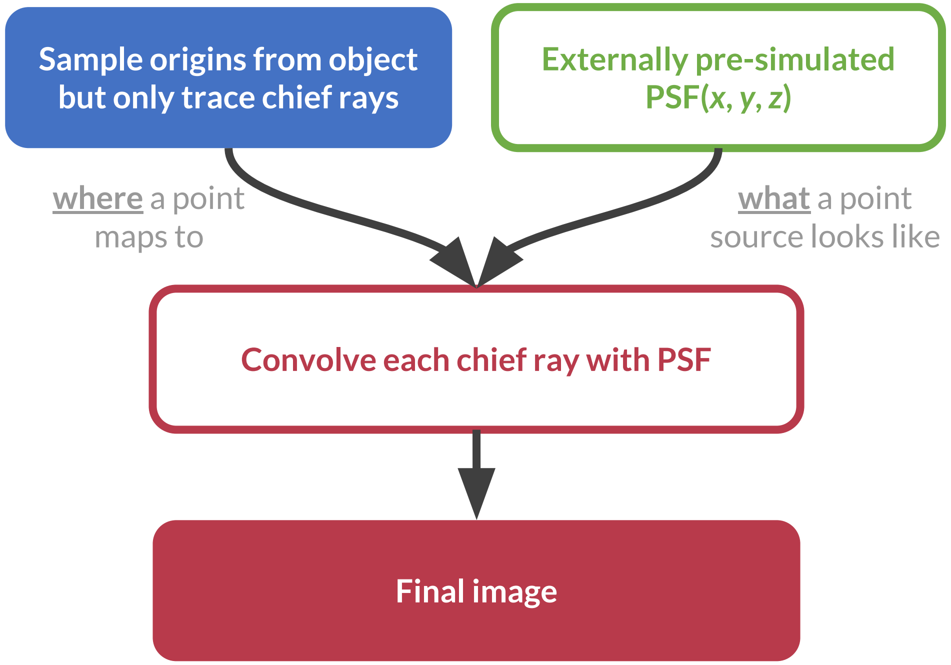
Conclusion

Summary

- Review of GradOptics: differentiable ray-tracer
- **We can now incorporate PSF's**
    - But they need to be externally provided
- Tests with real lenses & their Zemax simulations looking good so far

Next steps

- **Parametrization of PSF's**
    - Special functions, NN's, etc.
    - Will enable more flexible application of PSF's
- **Application to Distributed Imaging System (DIS)**
    - DIS optics design mostly finalized
    - Experimental tests (mostly) done, parameters measured in lab
    - **Physics performance will be further evaluated w/ GradOptics**
    - **Planning to give another S & S talk once this is done!**



Almost-final choice for DIS HM lens

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