

2D point spread function characterization for Prime Focus Spectrograph

Neven Caplar

Robert Lupton, James Gunn, Princeton DRP team and PSF collaboration



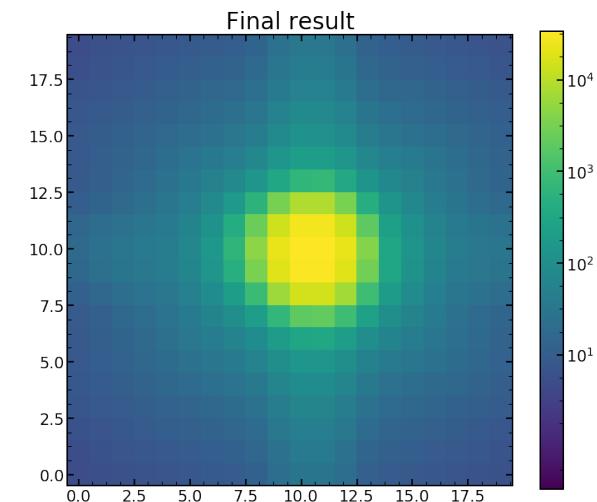
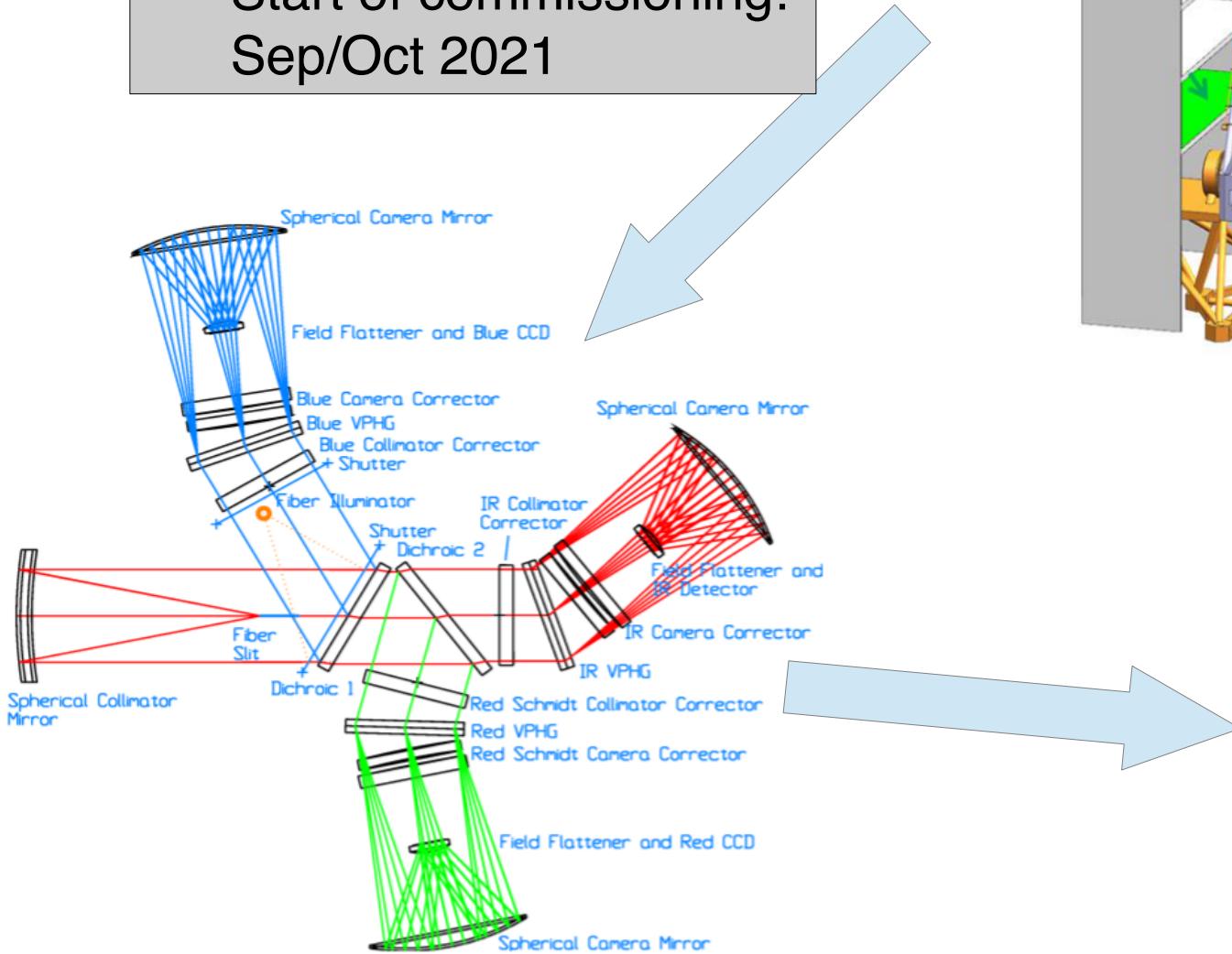
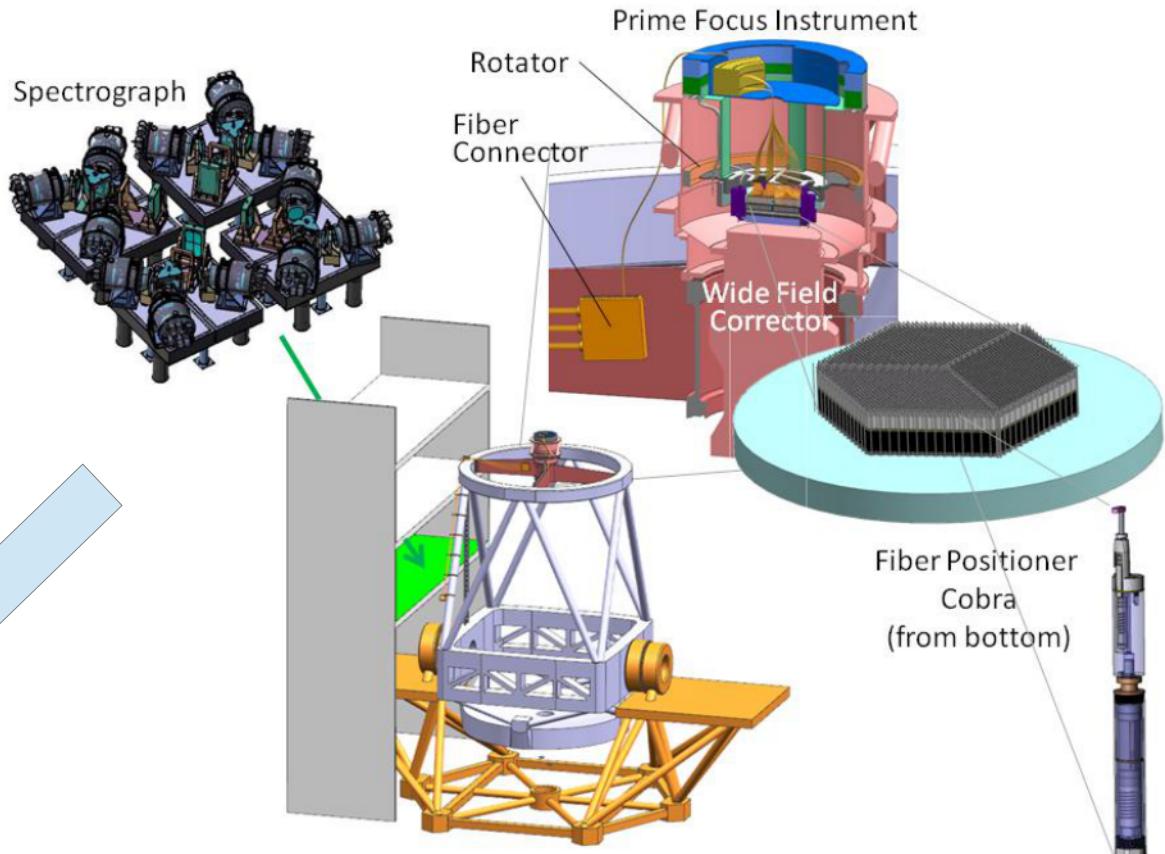
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UNIVERSITY

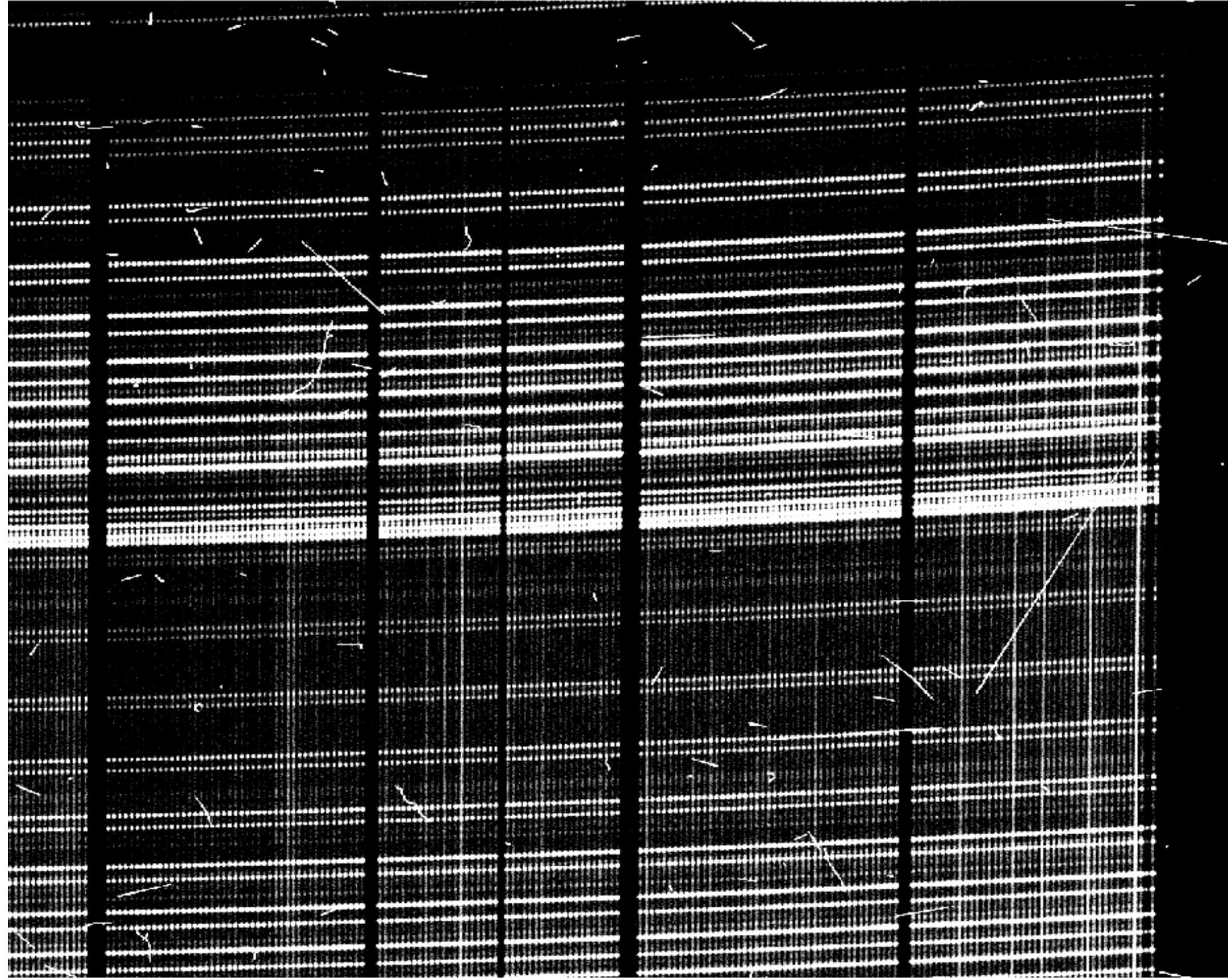


Contents

- Overview of the spectrograph
- Sky subtraction
 - 2d point-spread function algorithm
 - Analysis of defocused images
 - Behavior of wavefront and comparison to Zemax
- Current real world challenges
 - Centering and line properties
 - Problems in red
 - Non continuous solutions

- 2394 fibers on 8.2 meter Subaru Telescope
- 360 nm – 1260 nm
- 1.6 to 2.7 Angstrom resolution
- Start of commissioning: Sep/Oct 2021





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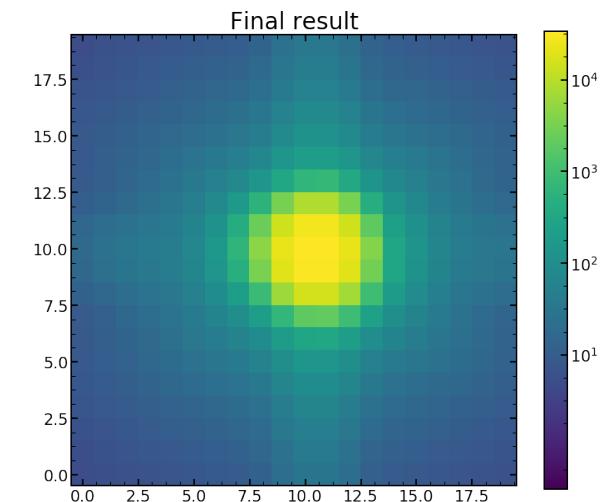
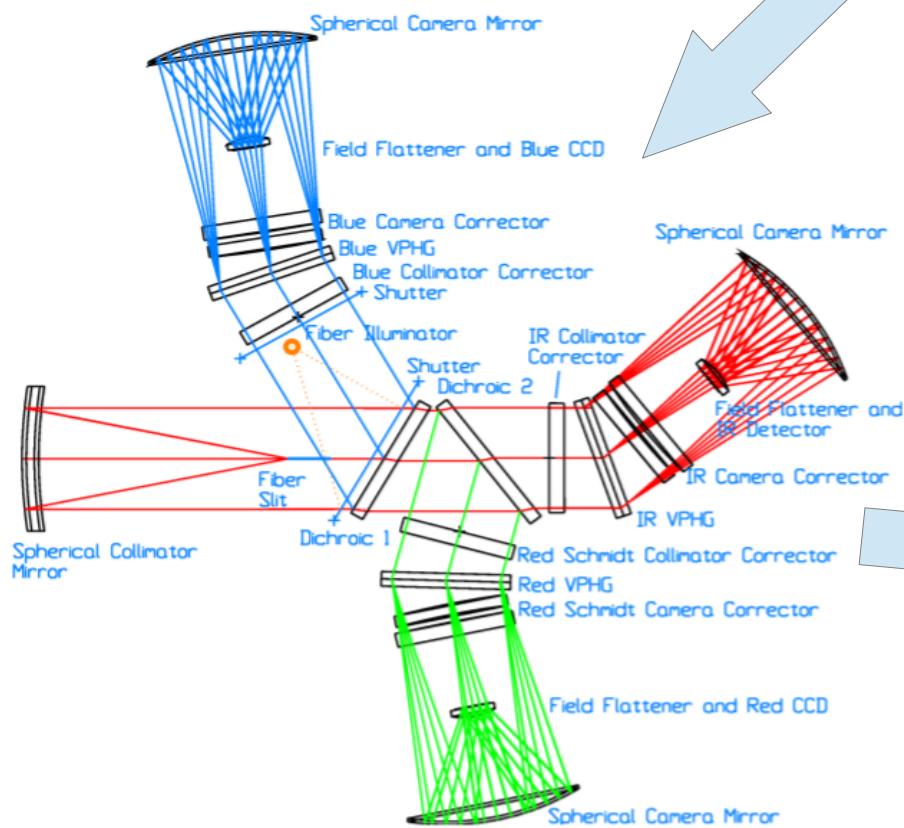
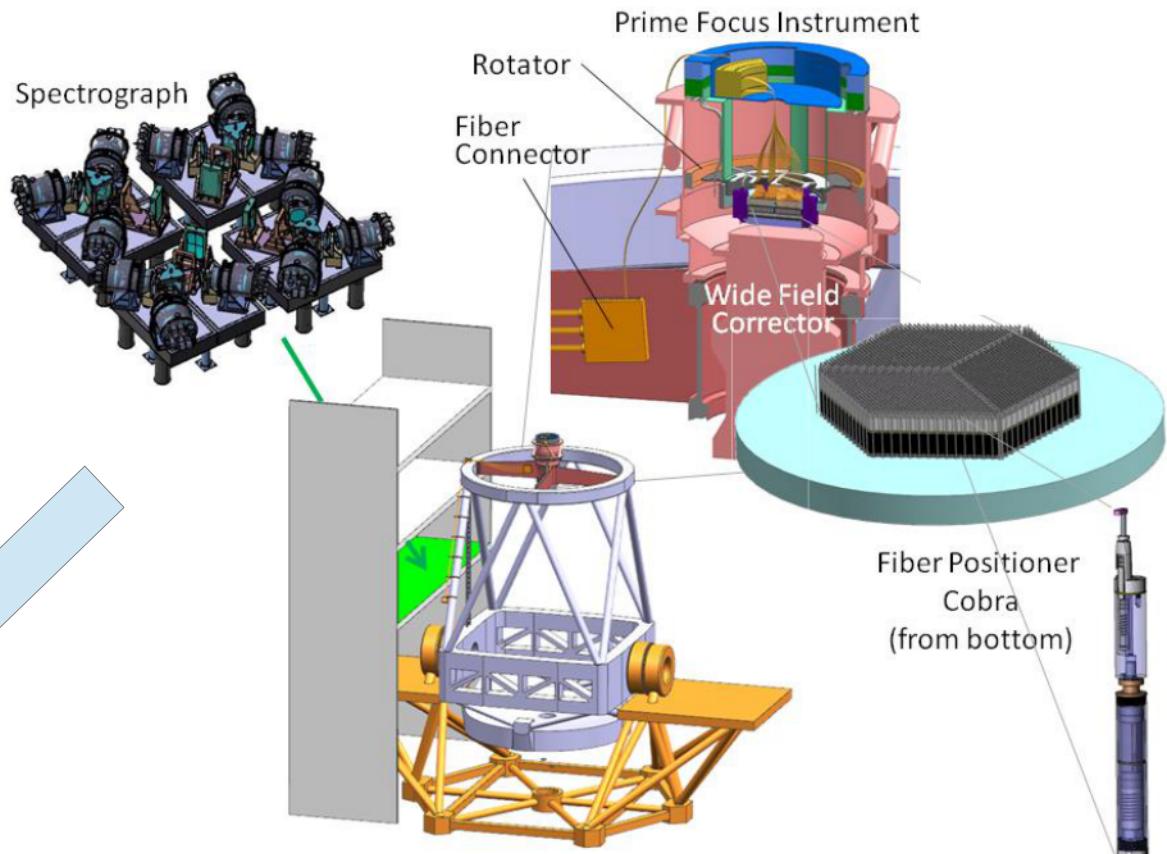
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3 components to the PSF

- Telescope pupil illumination
- Focal ratio degradation in the fibres
- Spectrograph cameras



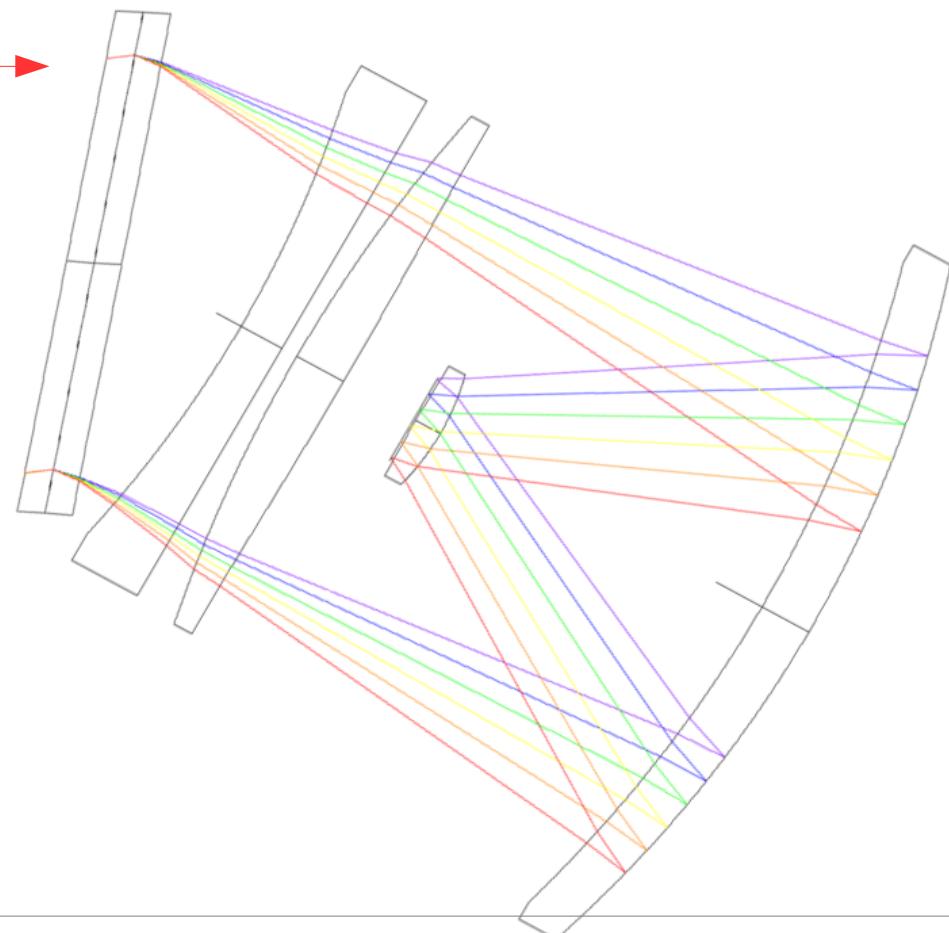
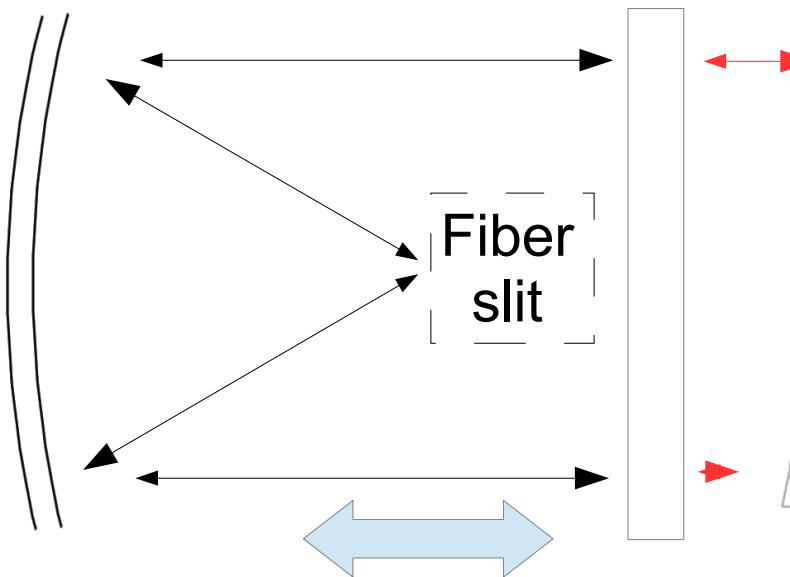
3 components to the PSF

- Telescope pupil illumination

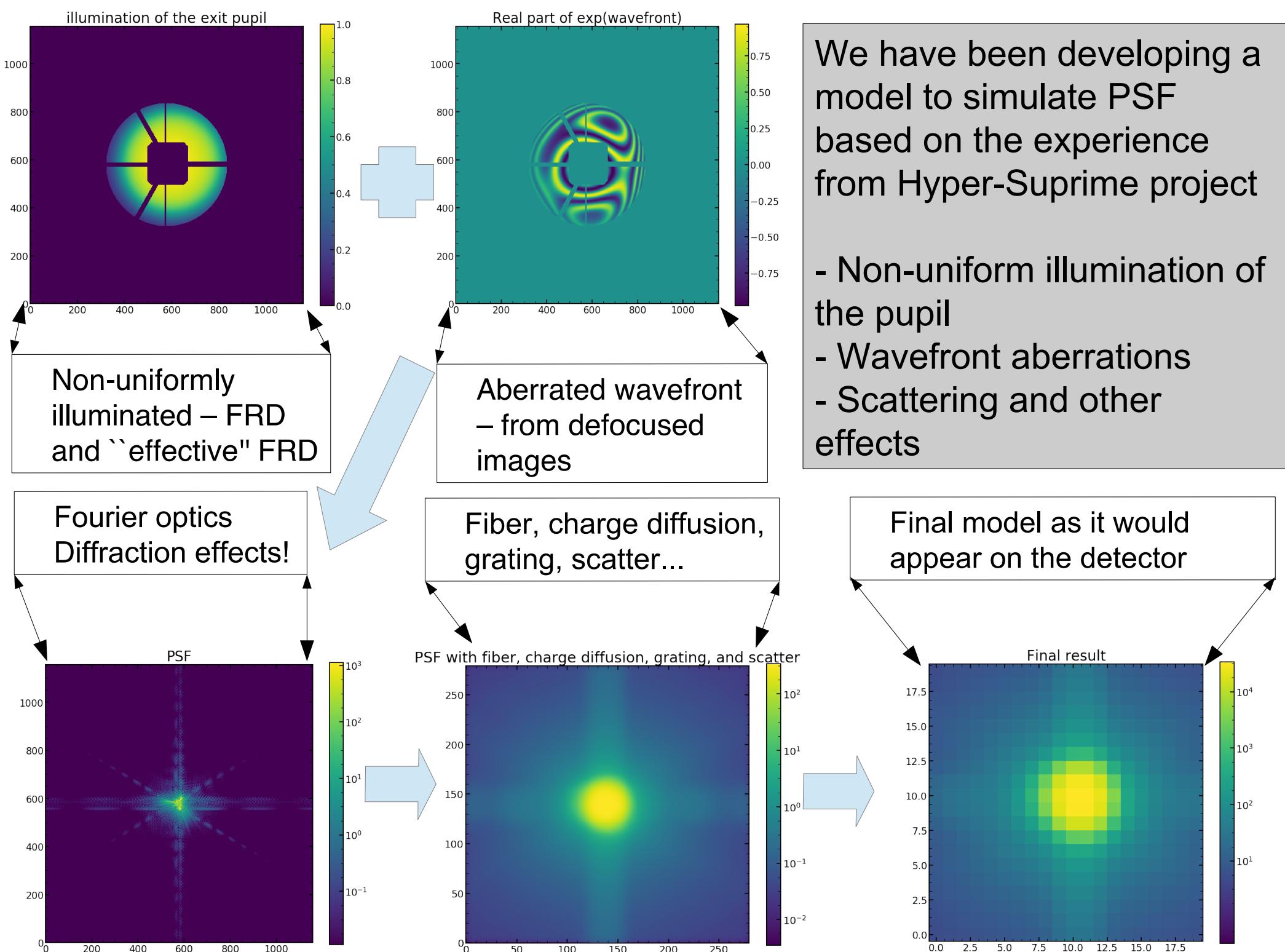
- Focal ratio degradation in the fibres

- Spectrograph cameras

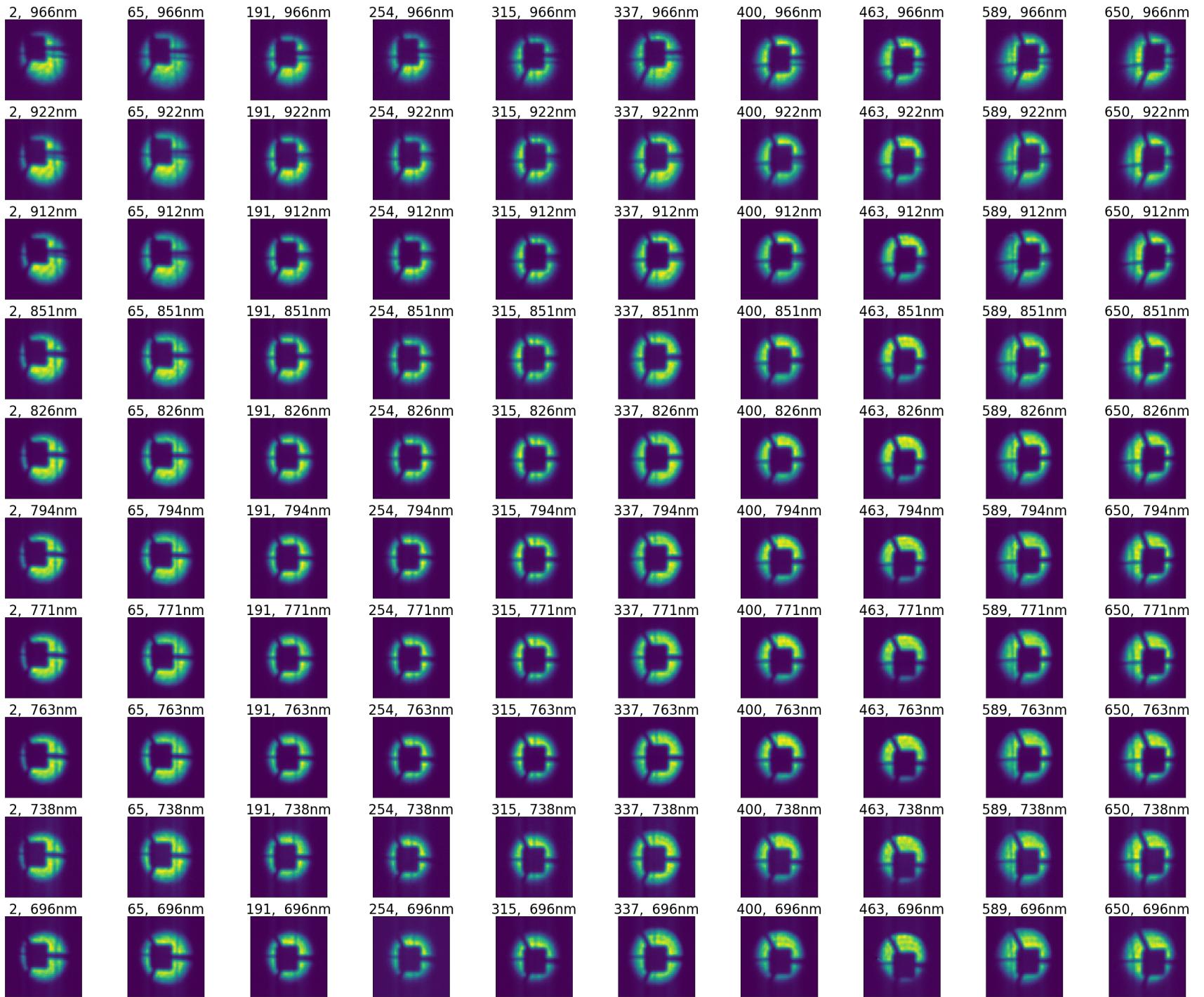
- Separate these 3 components (vignetting, fibers & camera) causing aberrations in the PSF by working in wavefront space
- We aim to characterize contribution of camera imperfections to PSF by modelling optical performance using defocused data



Single camera

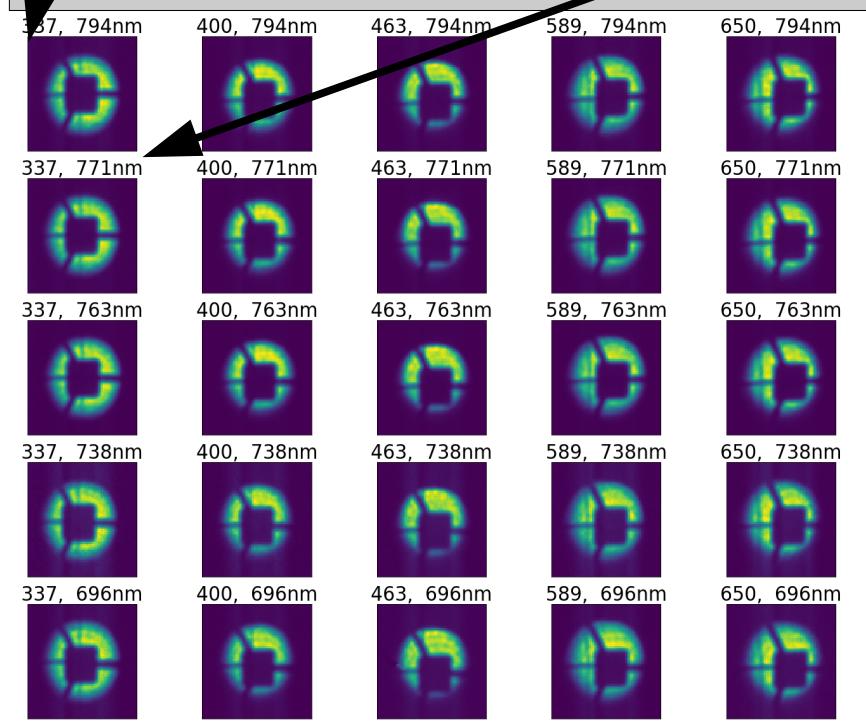
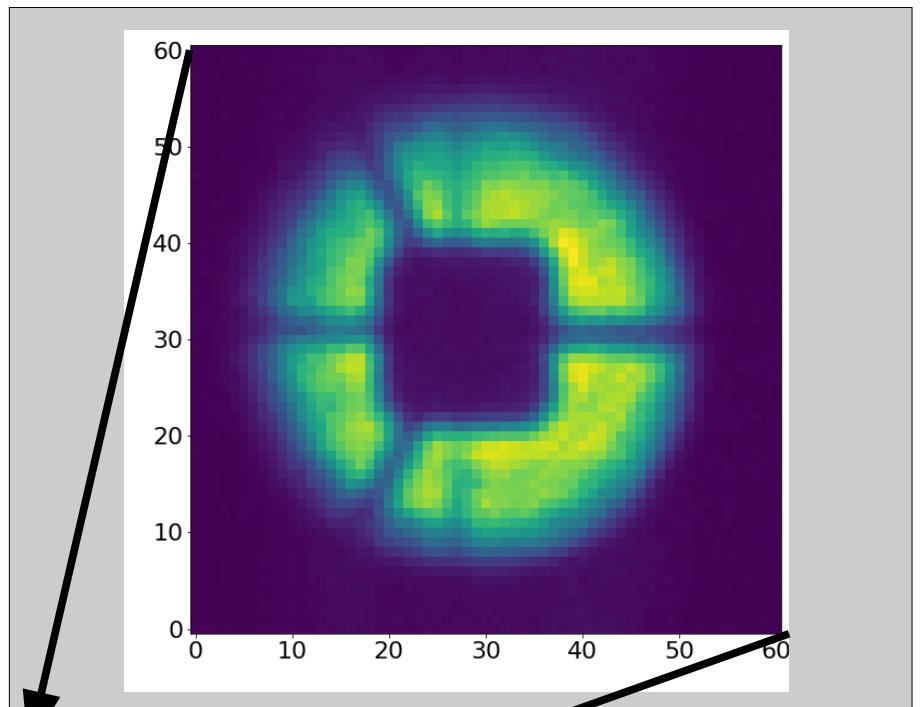
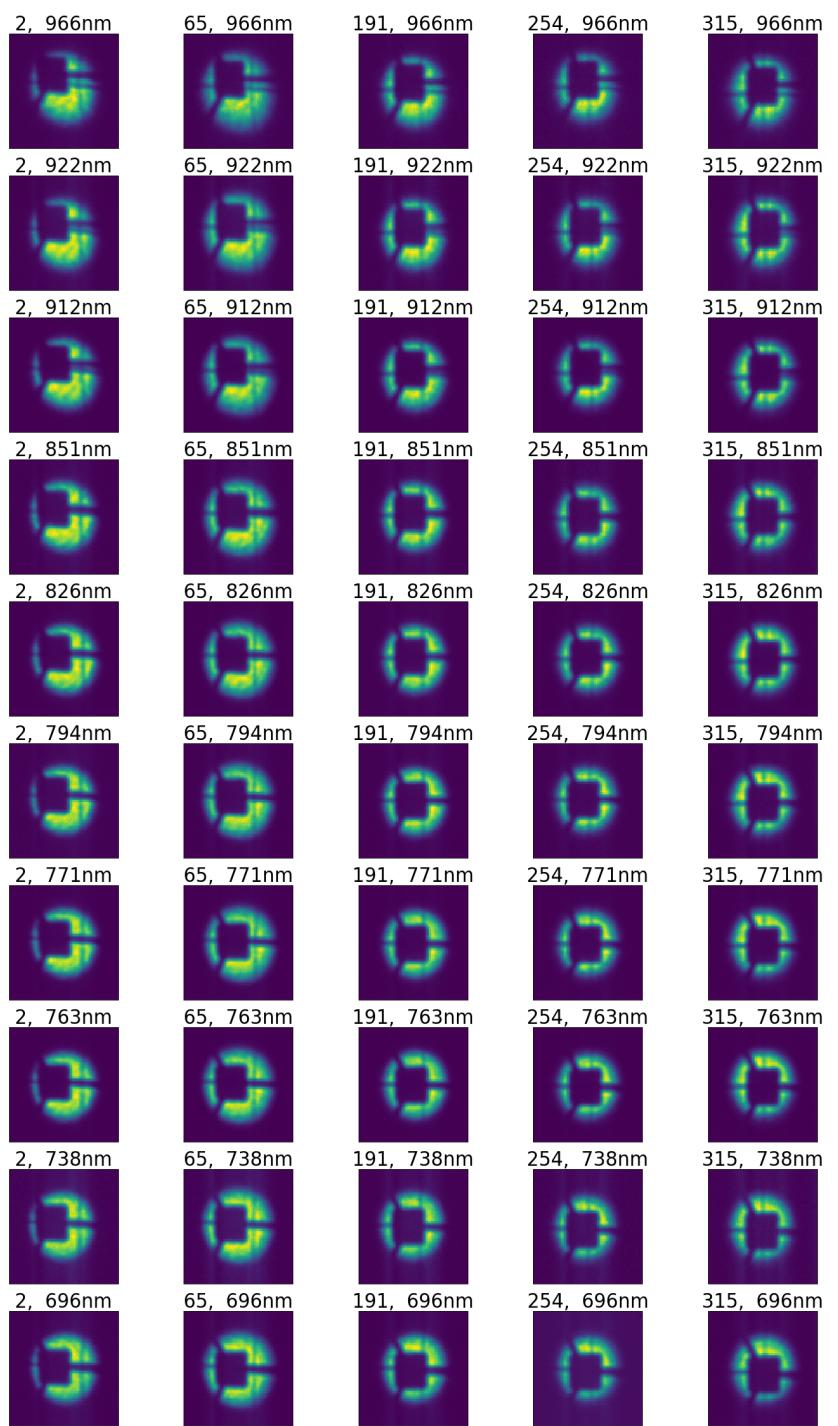


Wavelength



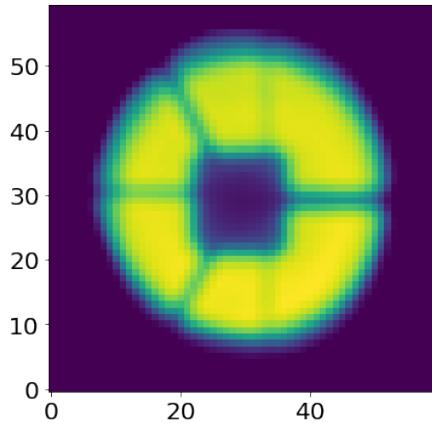
Different fibers

Wavelength

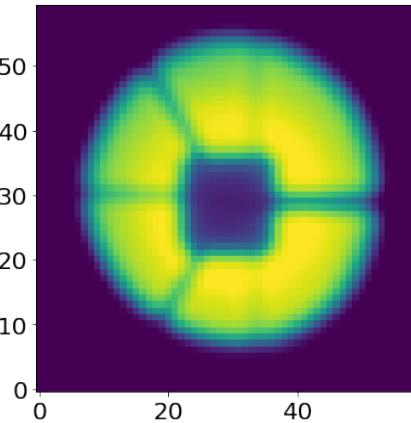


Different fibers

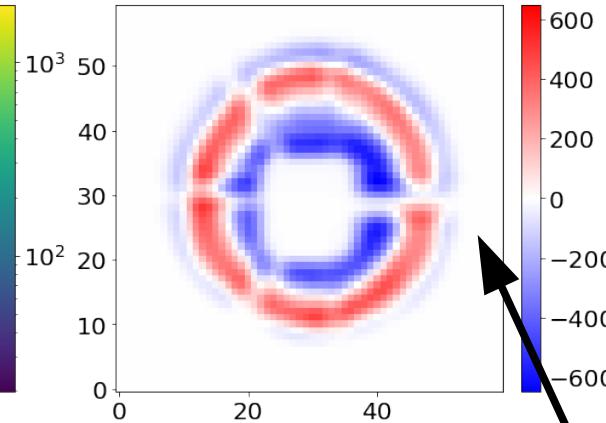
fiber 401



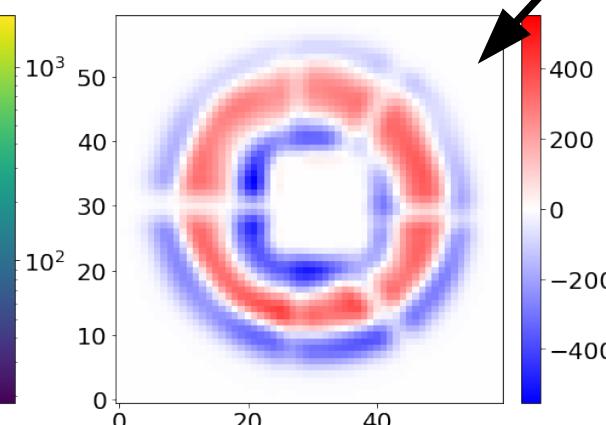
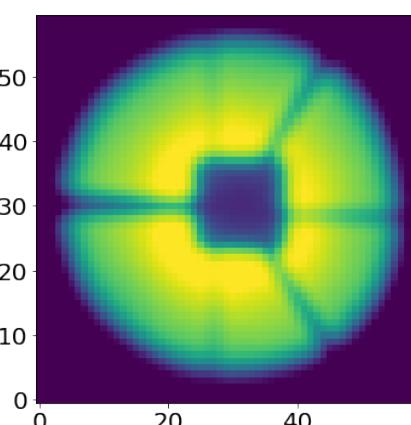
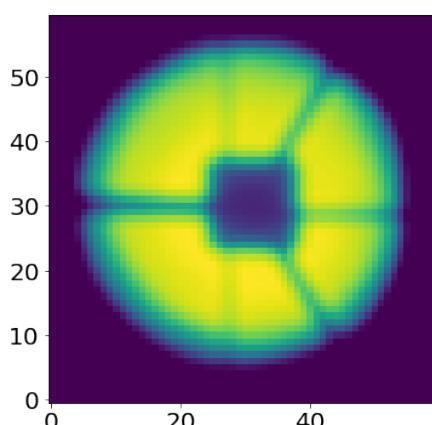
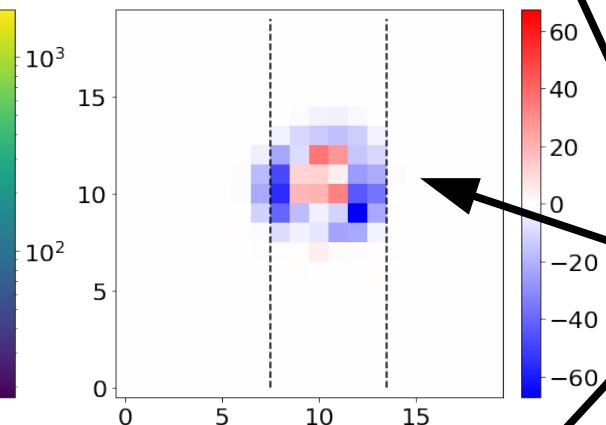
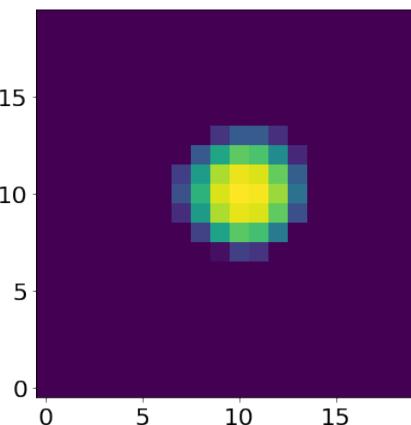
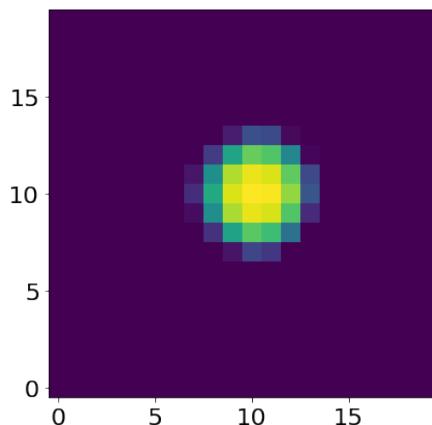
fiber 400



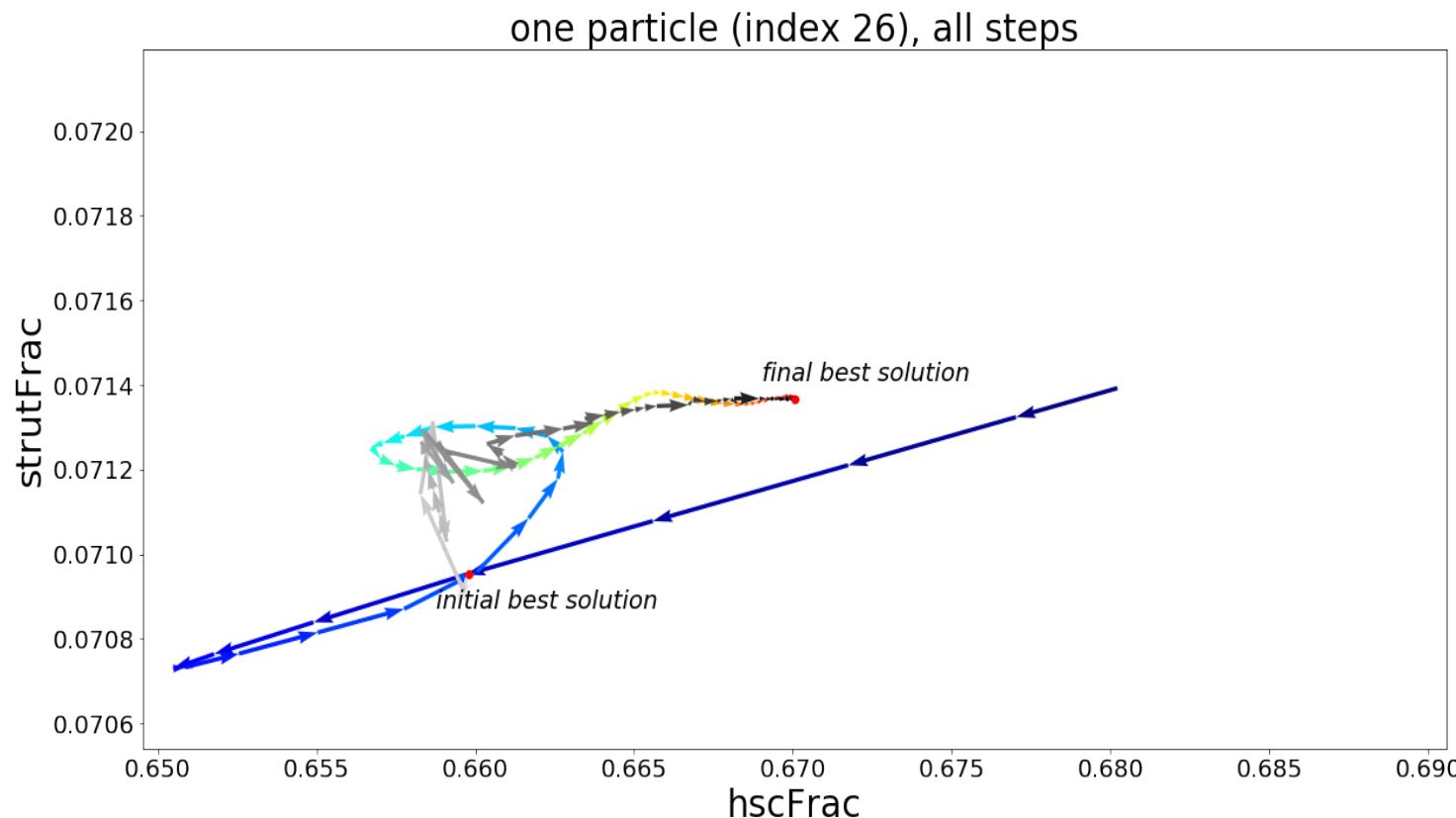
fiber 401 - fiber 400



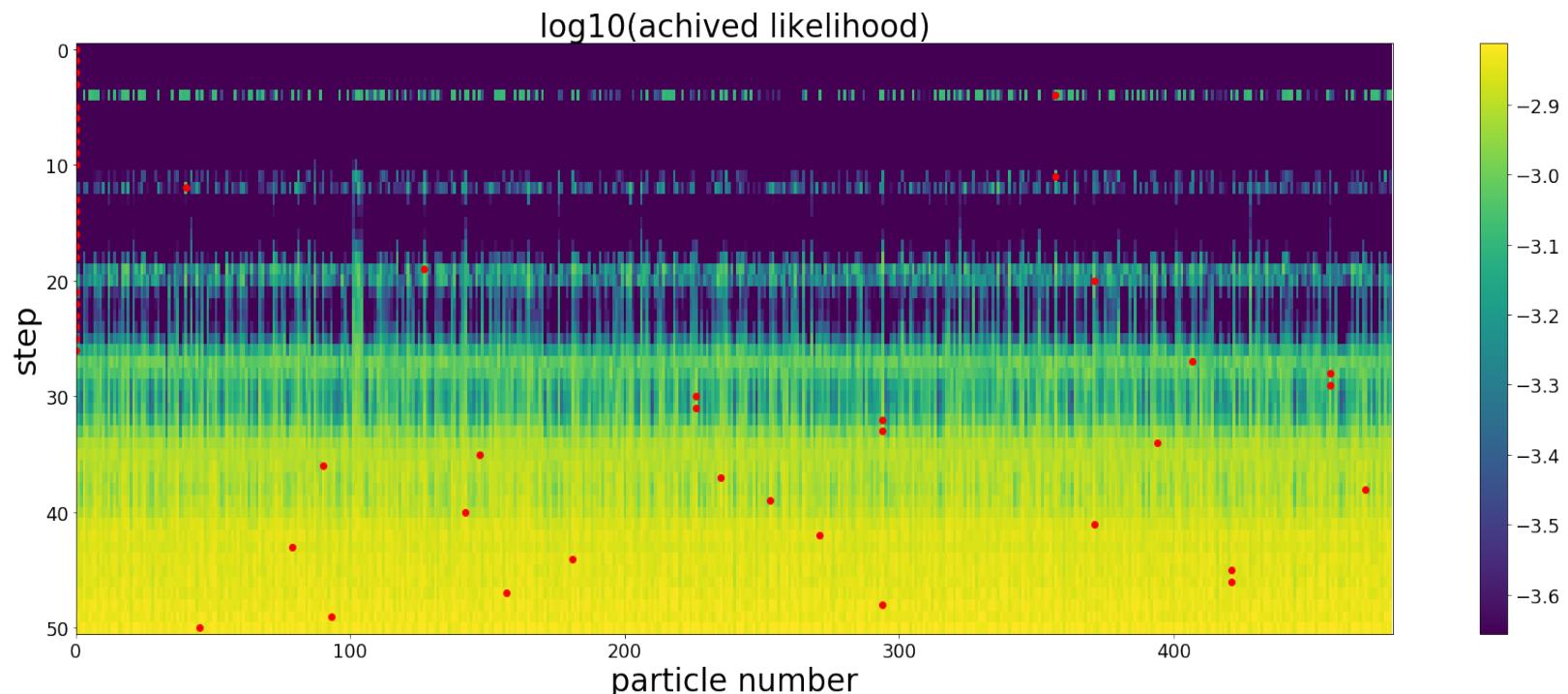
- Neighbouring fibers
- Possible to illuminate and defocus separately
- Wavefront is practically identical
- Only difference is the fiber illumination

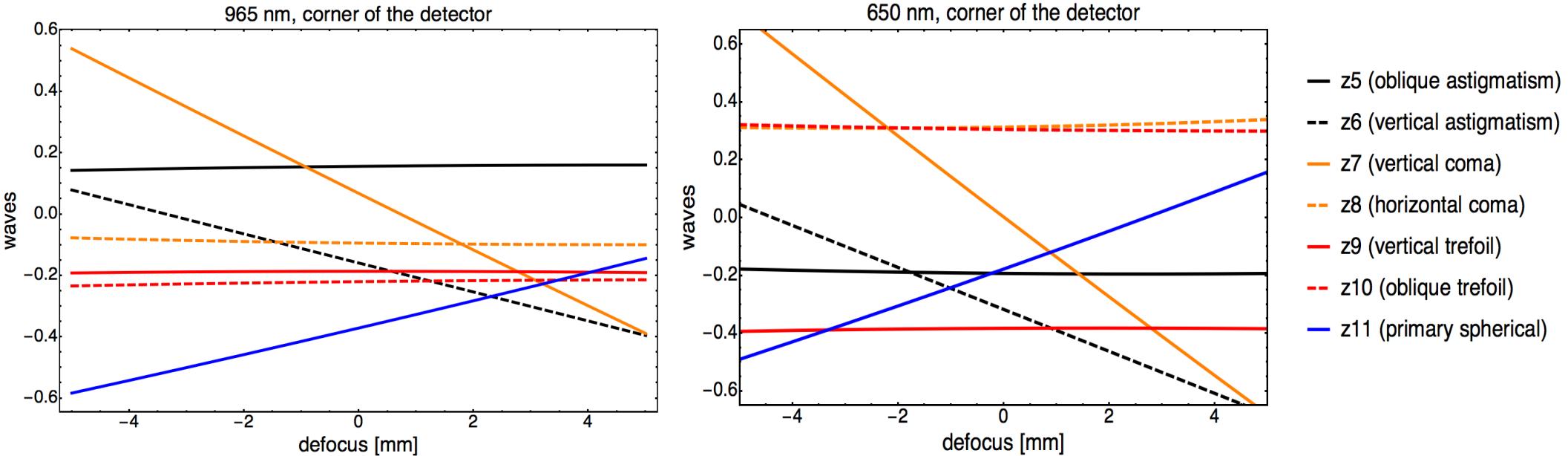


- ``Global parameters'' (such as illumination details) are fit with Particle Swarm Optimizer (<http://cosmo-docs.phys.ethz.ch/cosmoHammer/>)
- For each particle, at each step run wavefront algorithm from Tokovinin & Heathcote (2006PASP..118.1165T)
 - Compute small changes in the final image by varying Zernike parameters by a small amount
 - Use the same computation for all particles to save time
 - In least square sense, solve for the coefficients which multiply each change made by changing Zernike parameter
 - Continue until no more improvement



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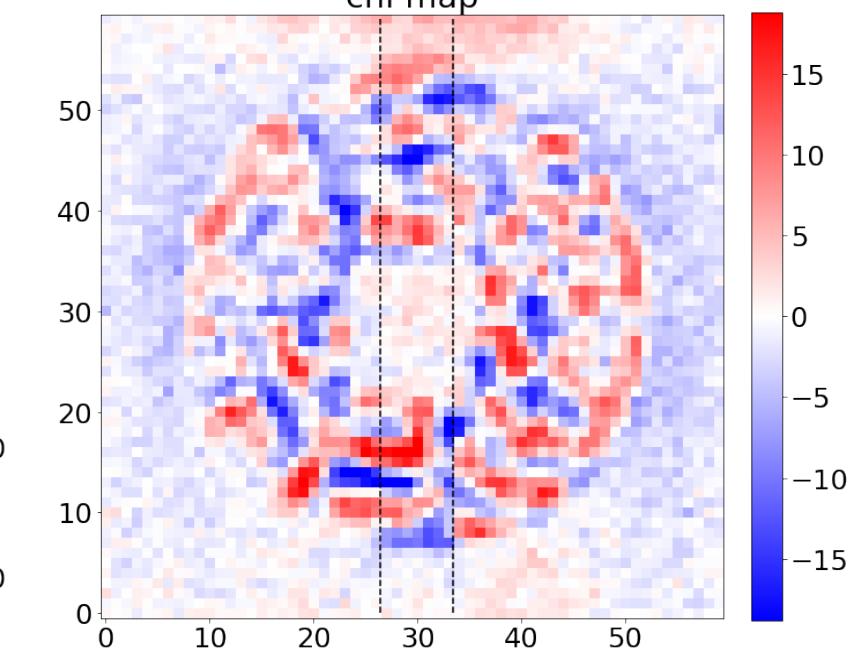
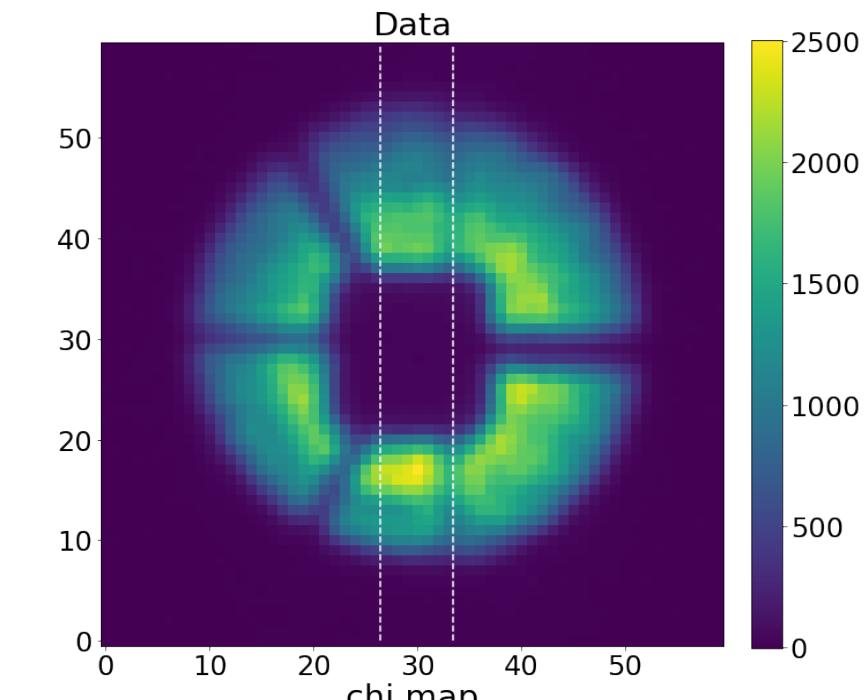
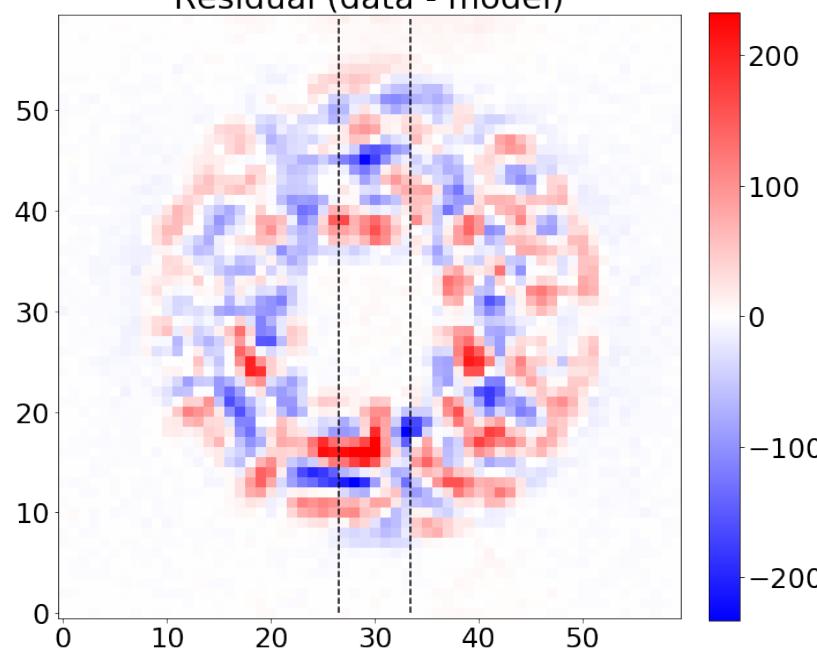
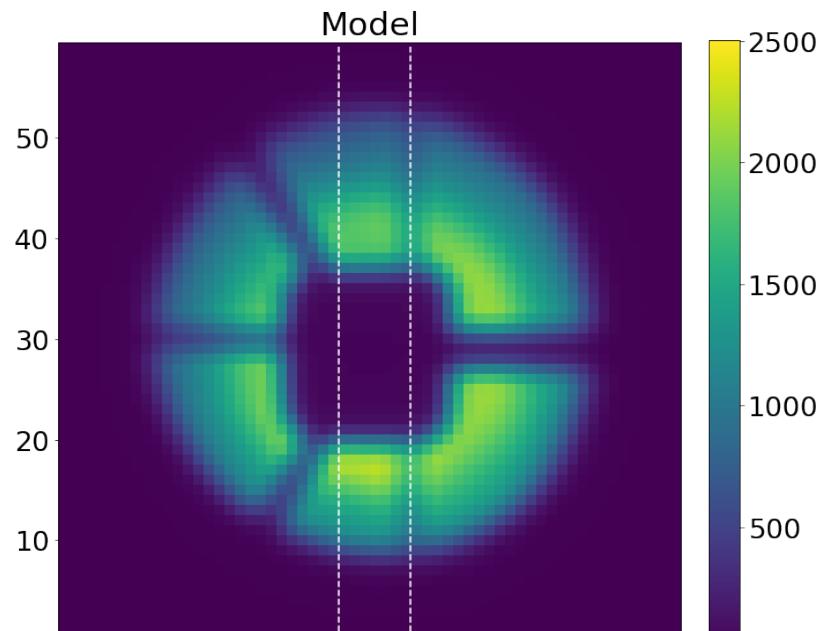




Wavefront aberrations as function of defocus (Zemax)

- We wish to deduce/reproduce these curves from the data
- Model wavefront aberrations at each position in the detector

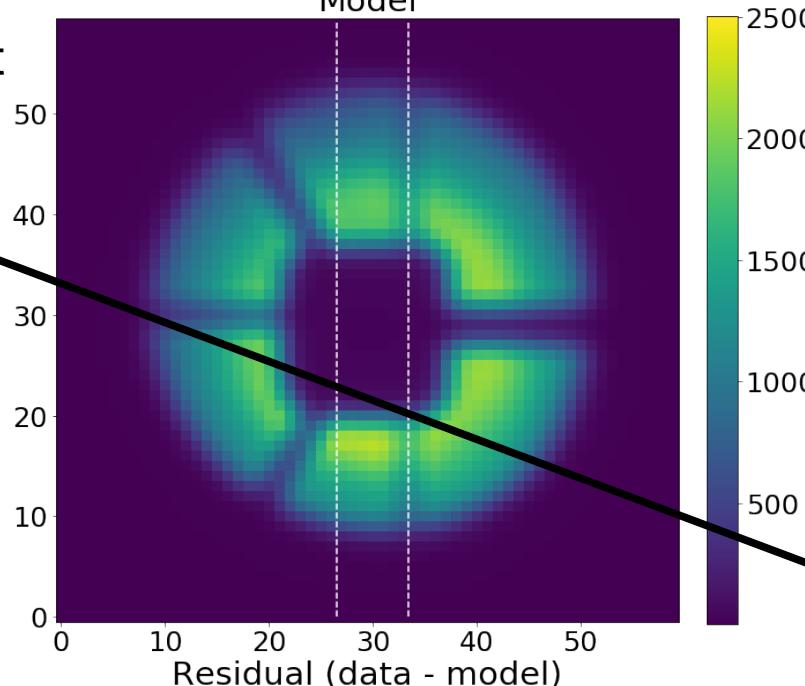
Defocused
data,
example with
linear scaling



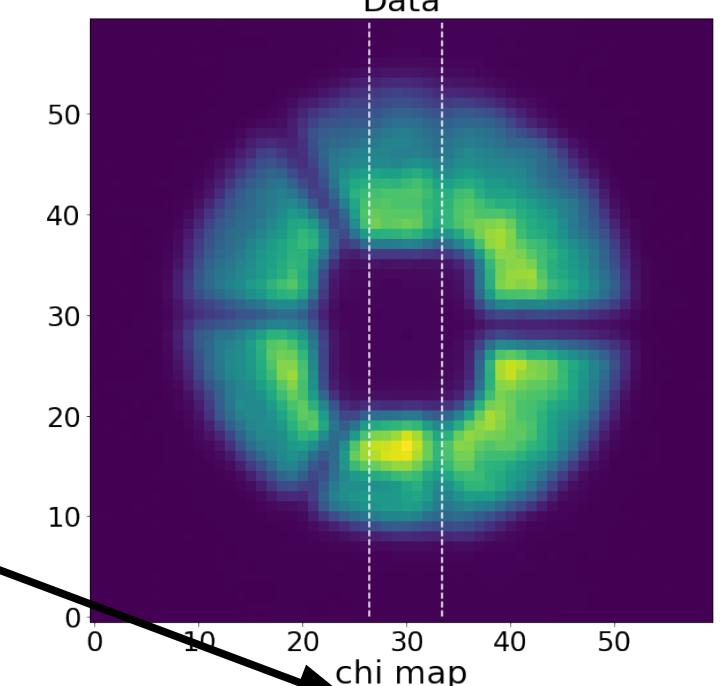
- Next source at the edge of the image, seen in the residual

Defocused data,
example with linear scaling

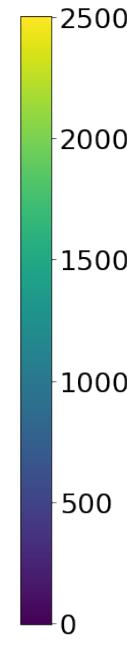
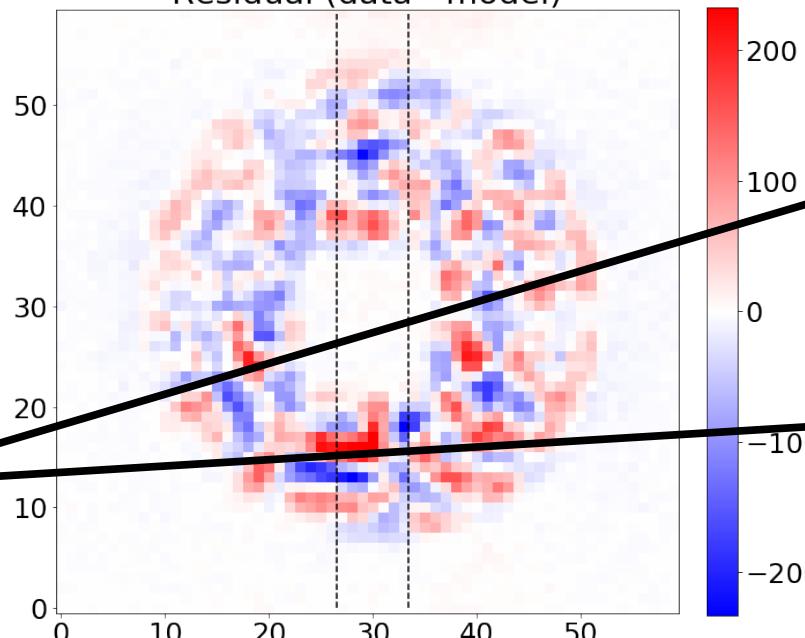
Model



Data

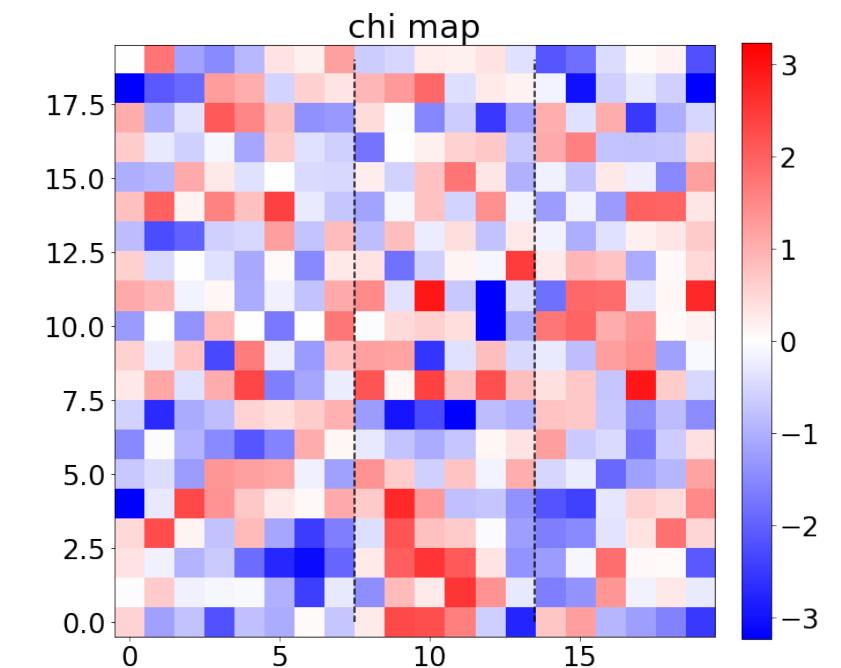
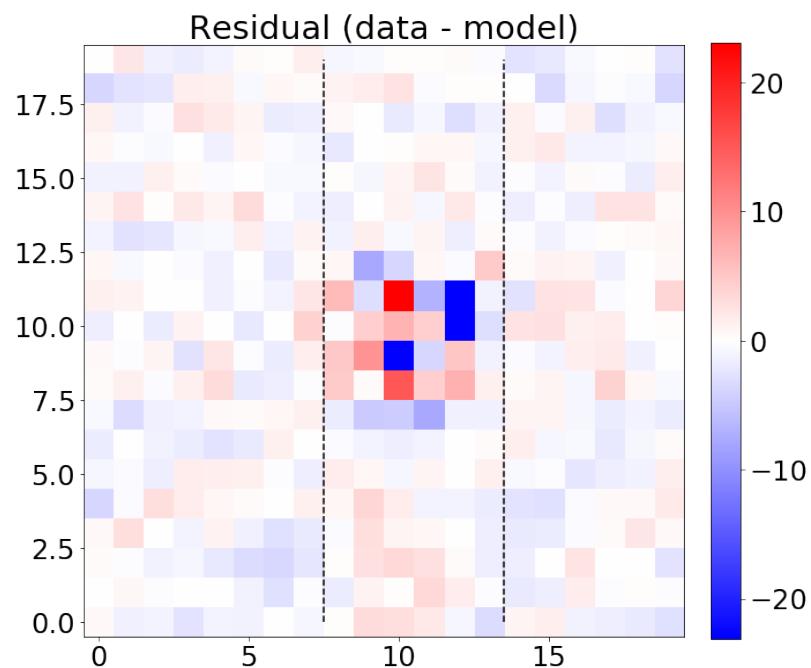
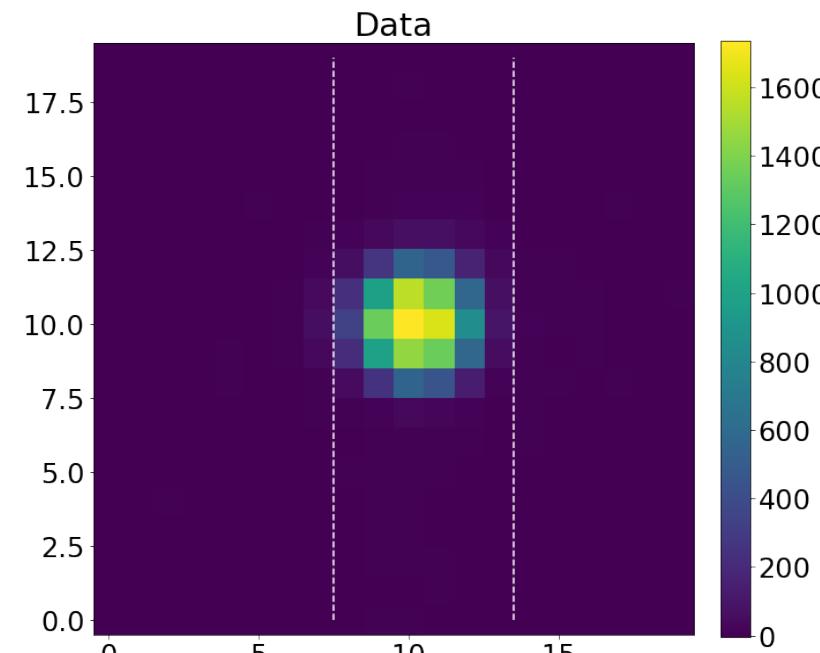
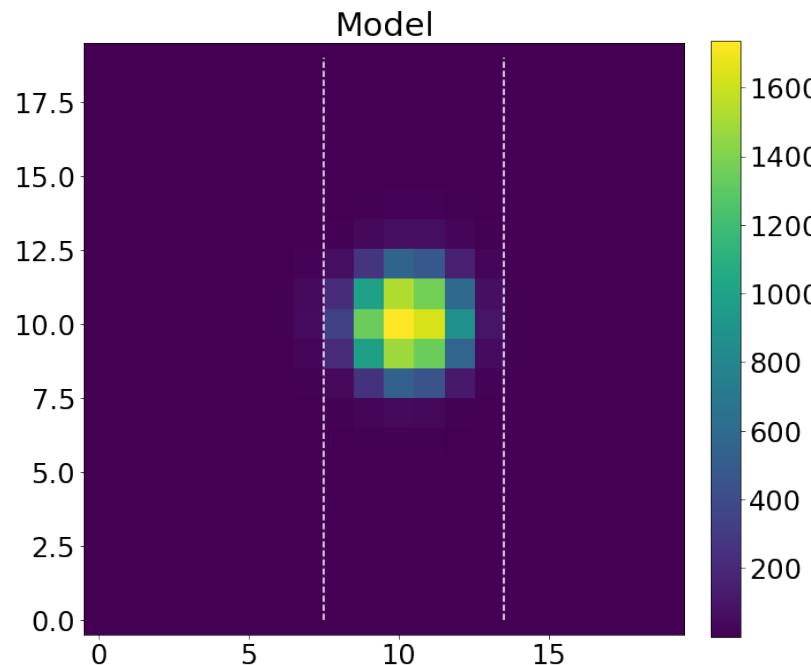


Residual (data - model)

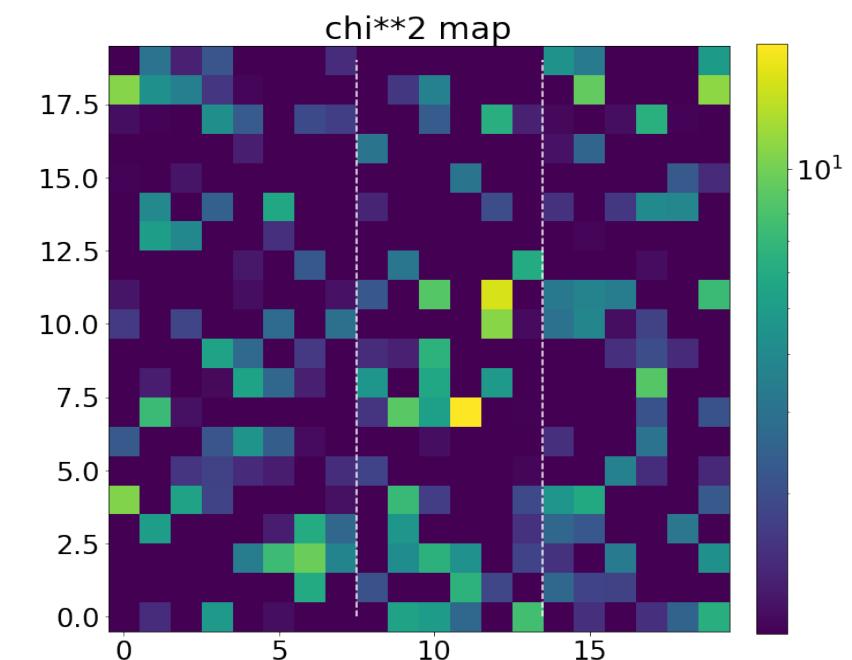
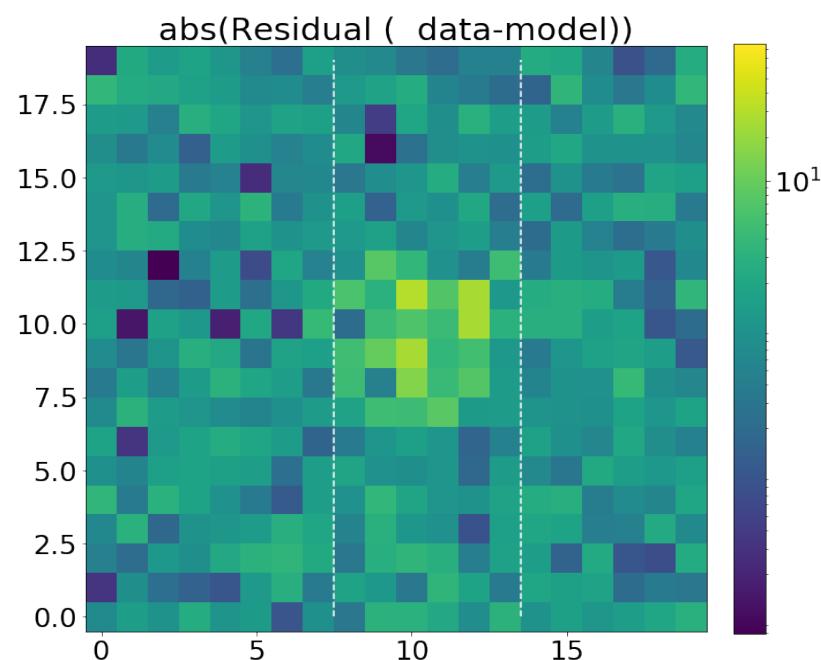
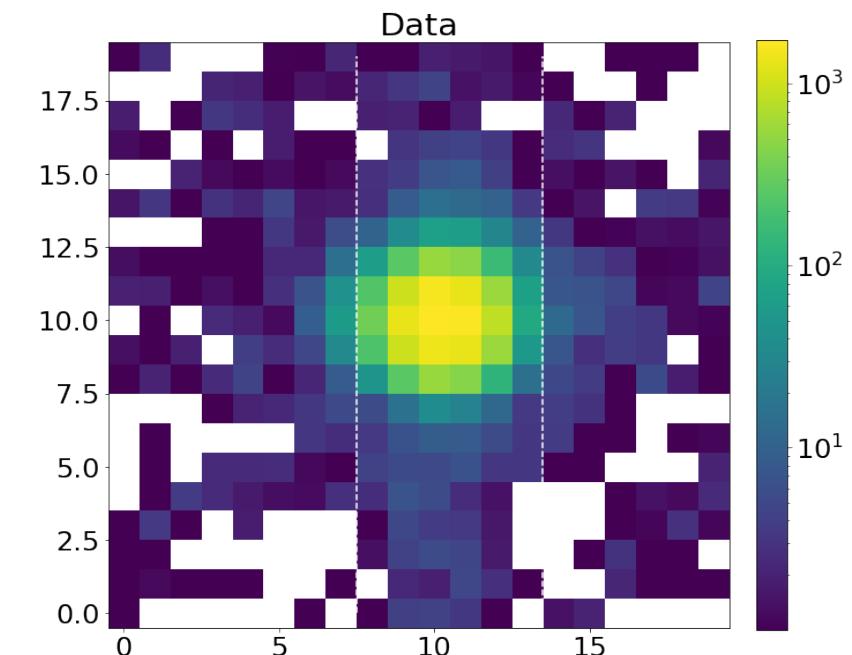
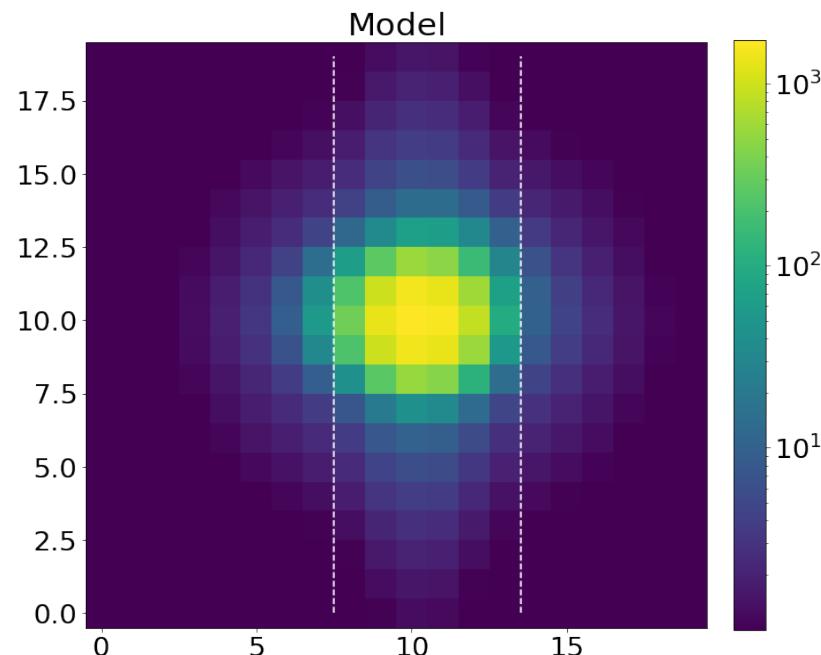


- Too much scattering for defocused image?

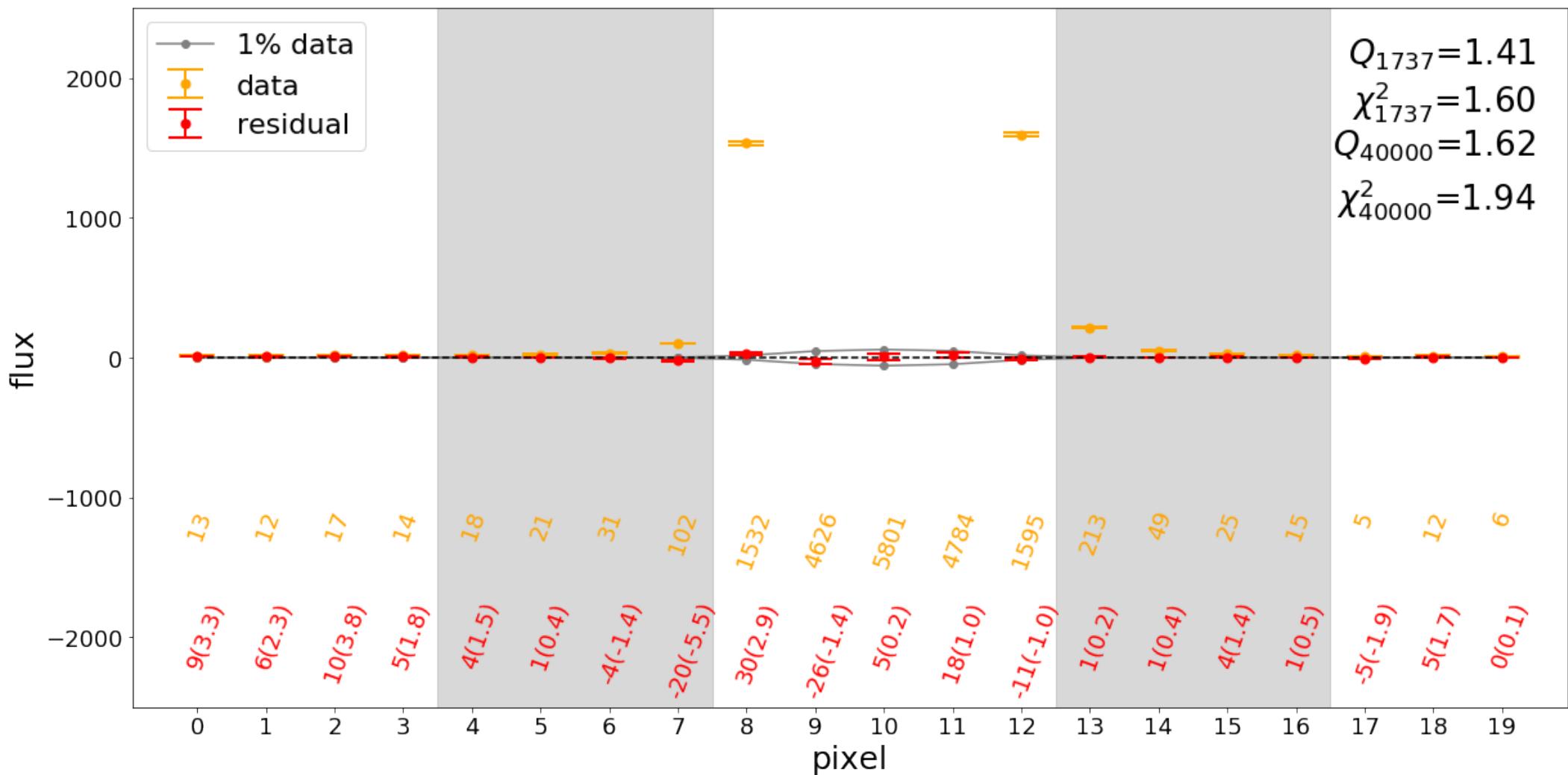
Focused
data,
example with
linear scaling



Focused
data,
example with
log scaling

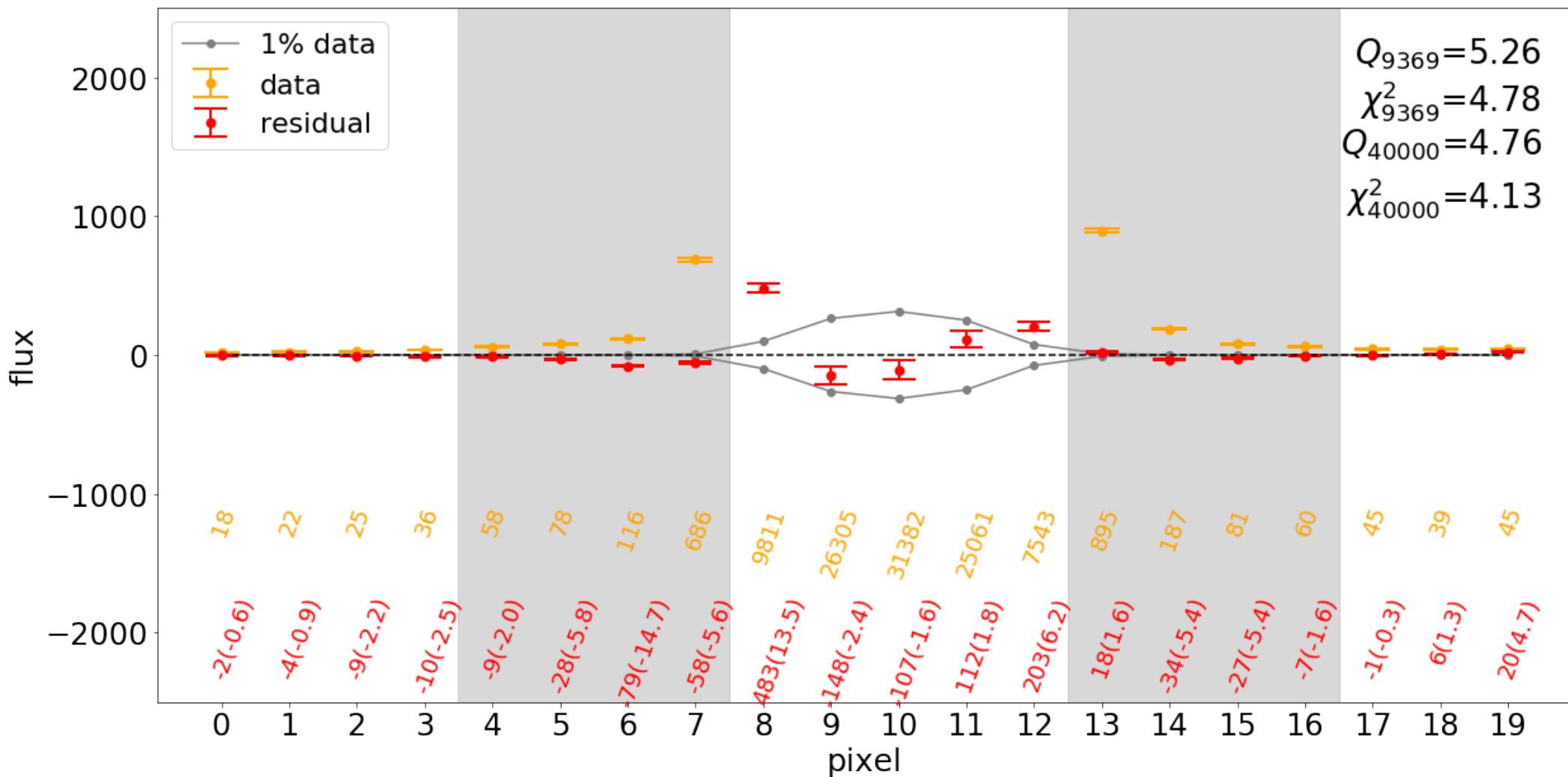


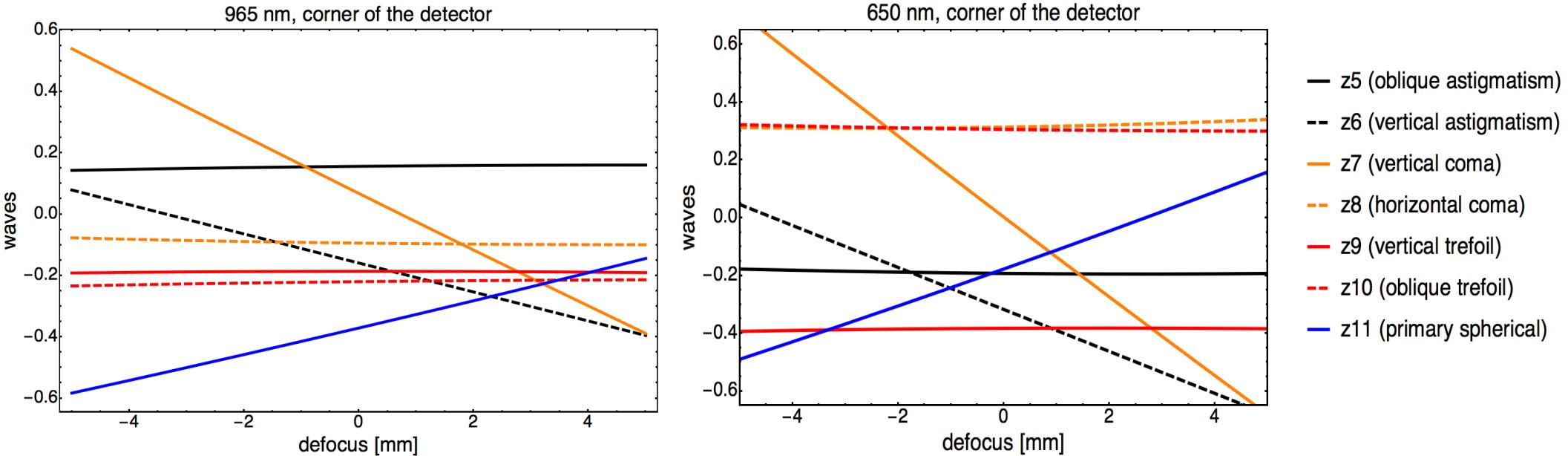
- Ultimate goal is quality of 1d extraction (closely related but not necessarily completely equivalent to the quality 2d subtraction)
- Provisional goal is 1% subtraction
 - In particular, outside of the core of the lines (gray areas below)



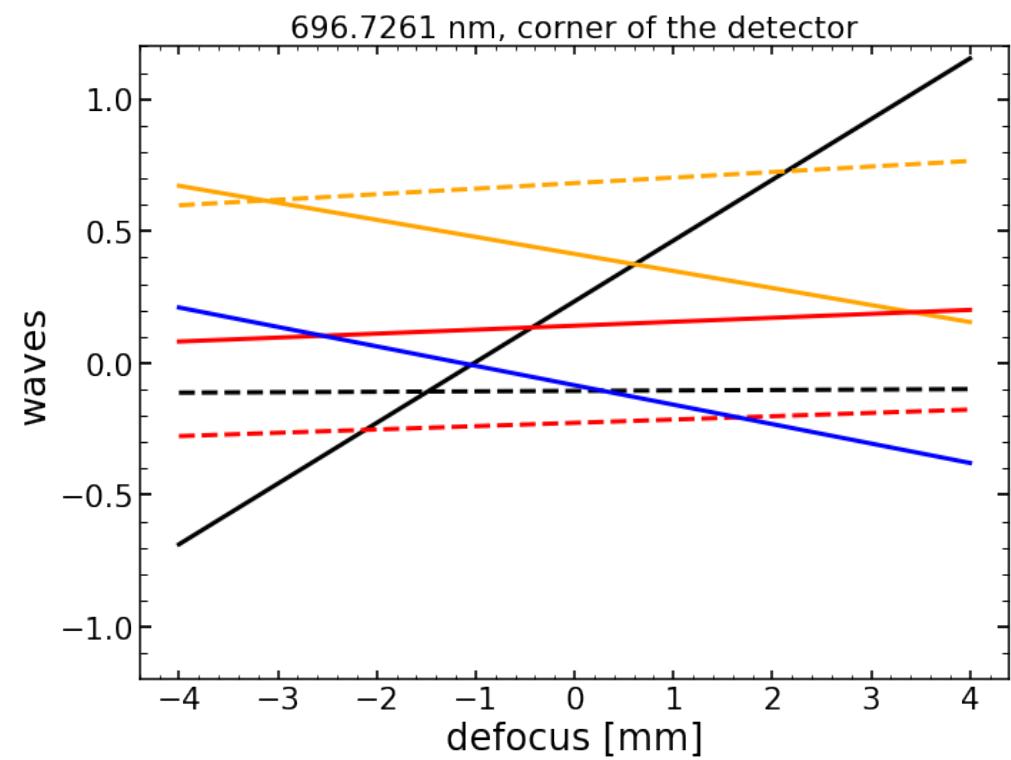
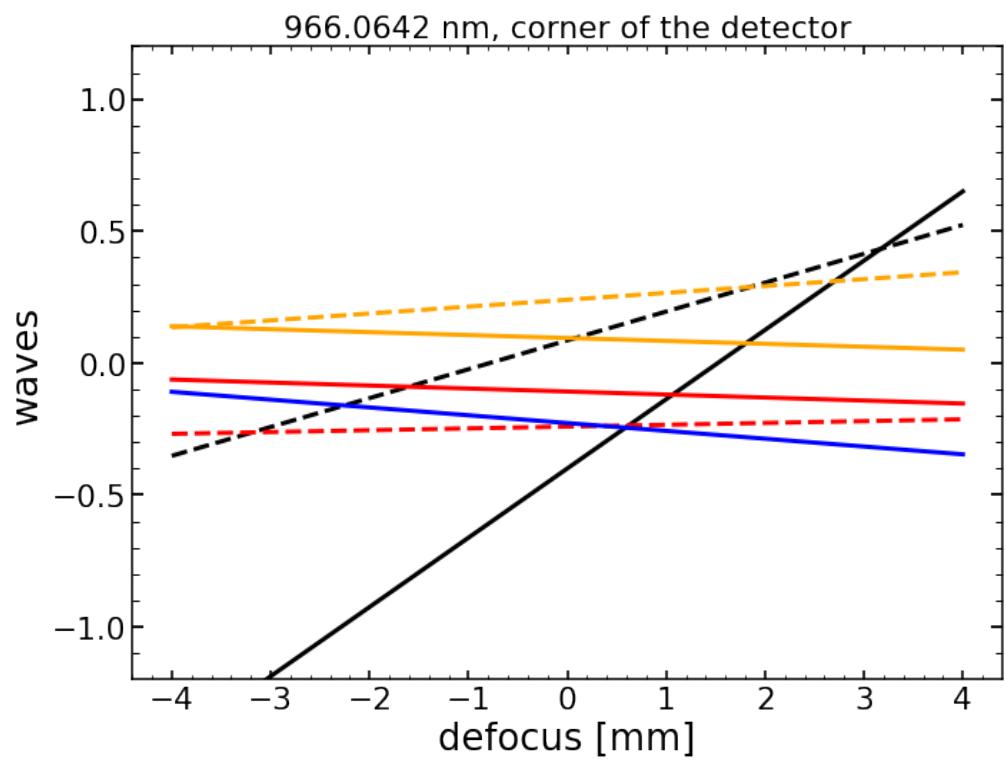
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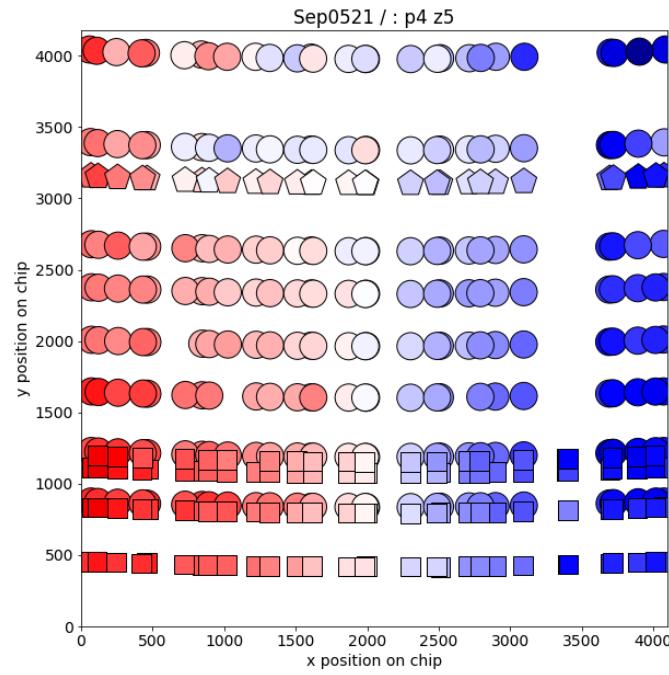
Higher flux example



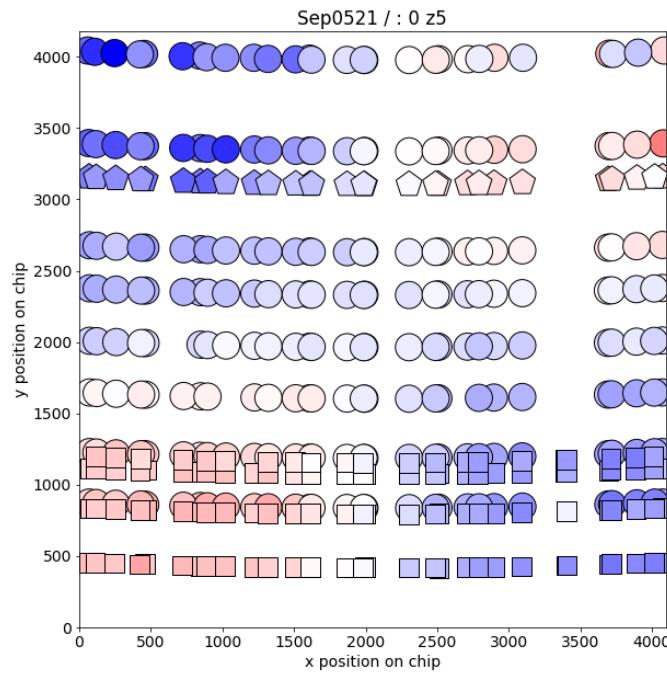
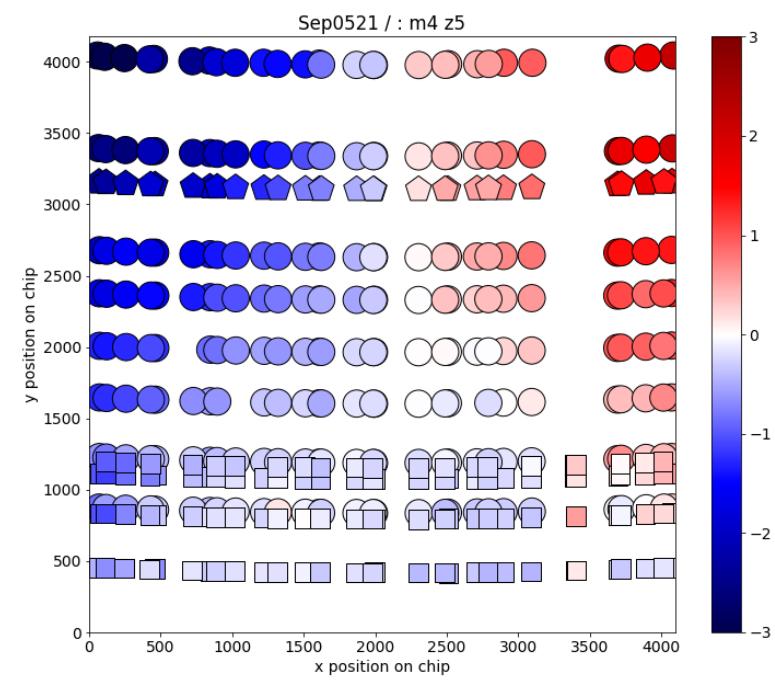


- Example from modelling of the experimental data below
(not exactly the same location as above, but observe large difference)



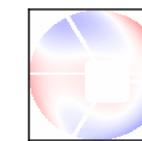
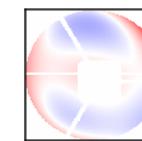
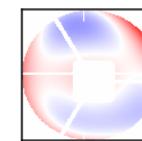
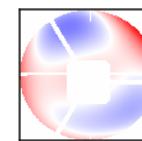
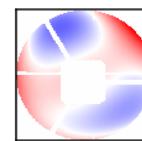
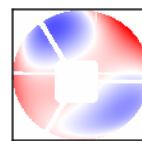
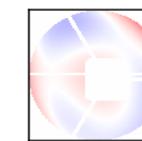
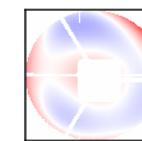
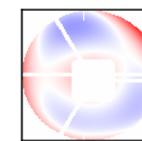
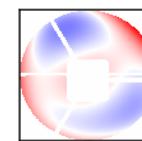
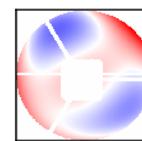
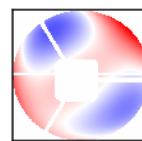
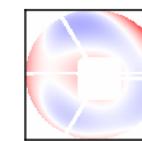
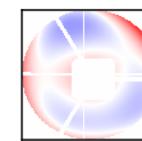
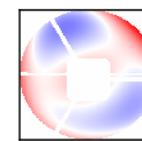
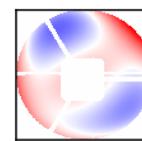
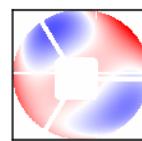
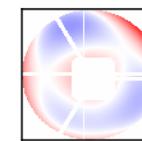
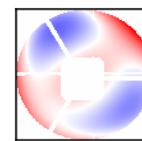
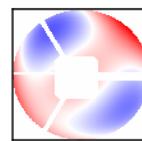
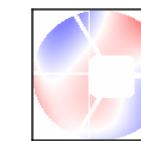
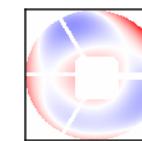
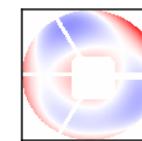
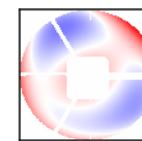
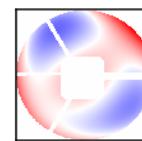
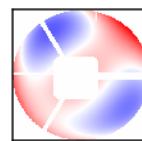
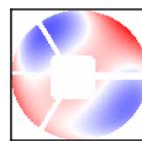
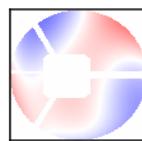
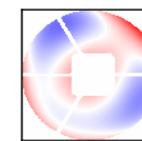
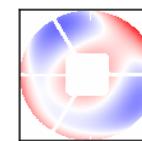
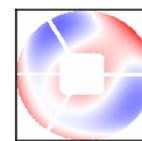
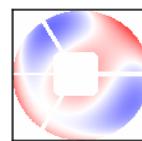
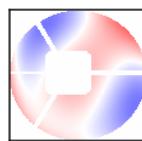
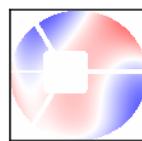
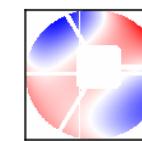
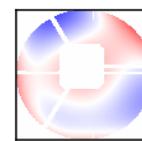
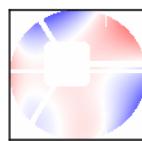
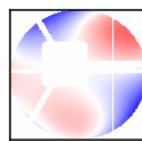
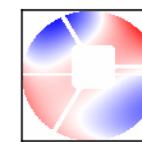
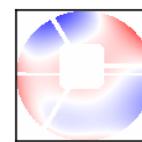
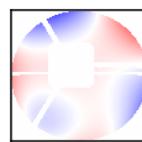
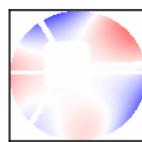
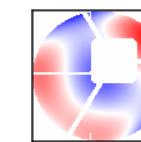
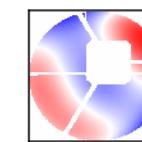
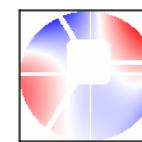
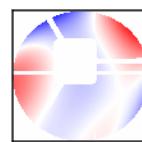
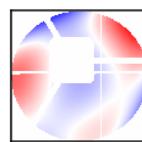
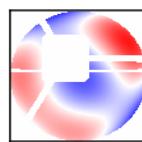


Change of single component
(oblique astigmatism)

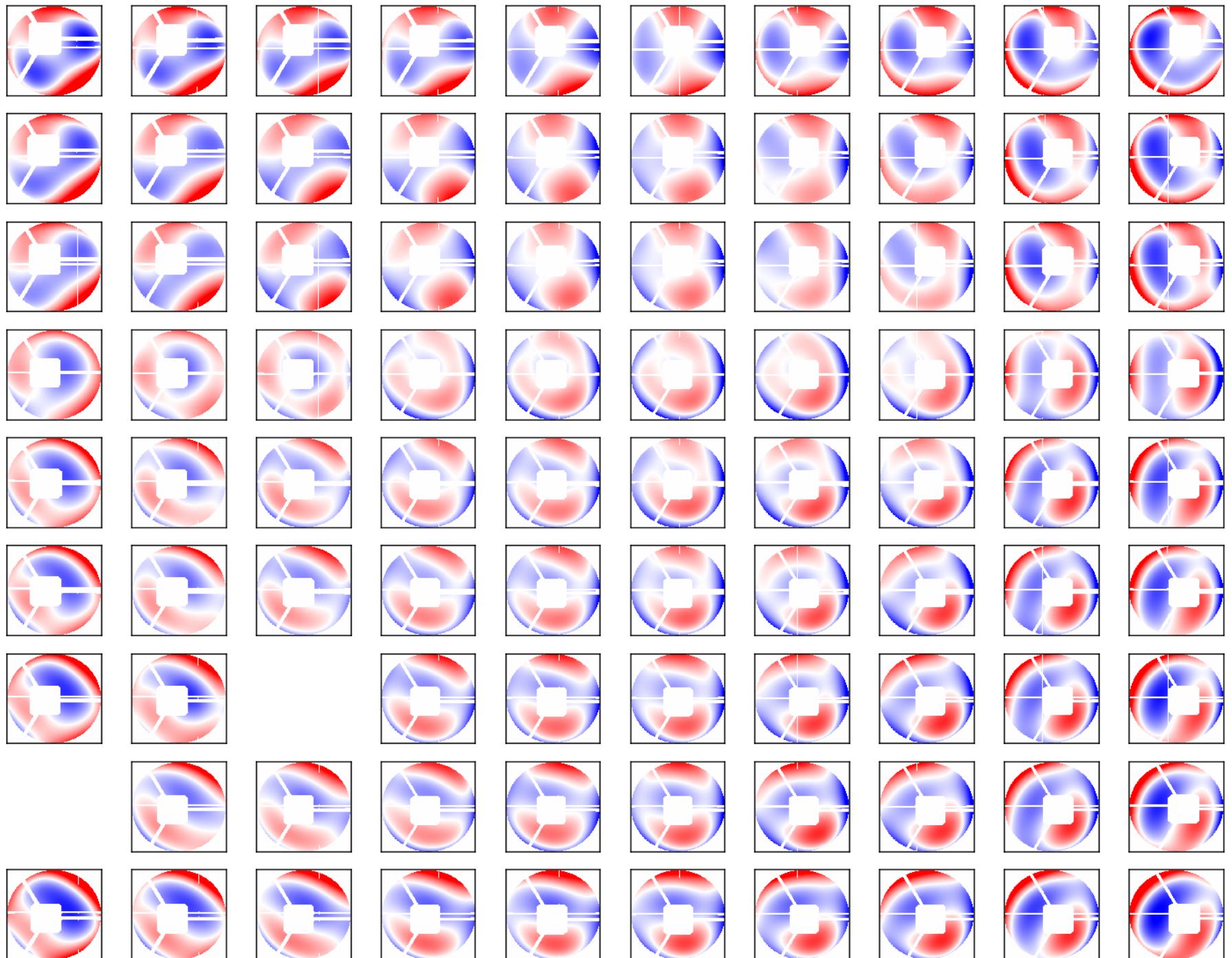


Changing defocus

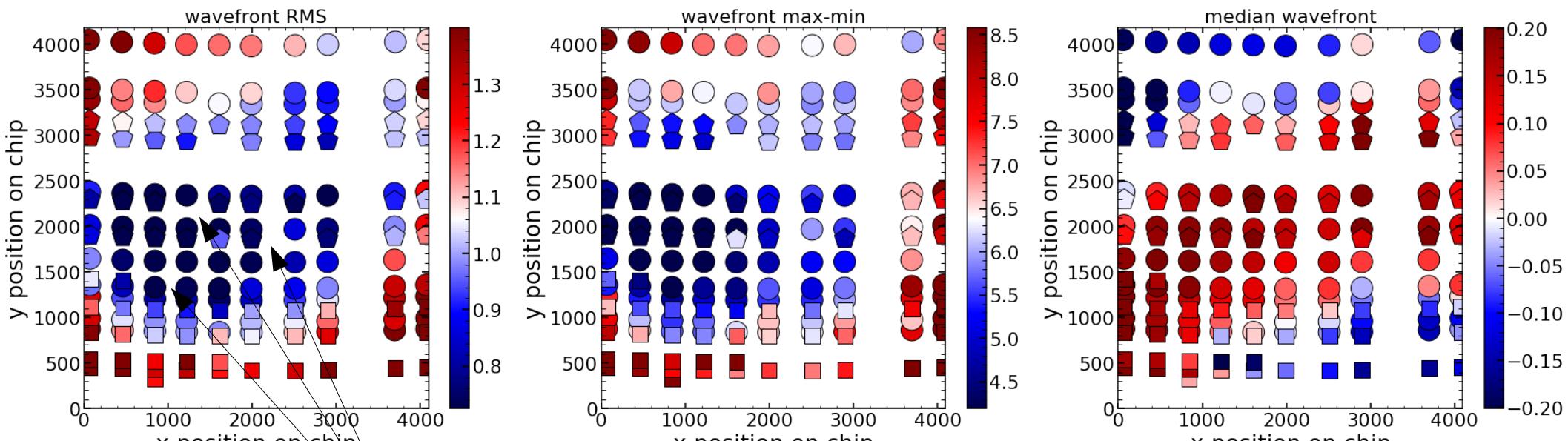
Wavefront - Zemax



Wavefront – reality

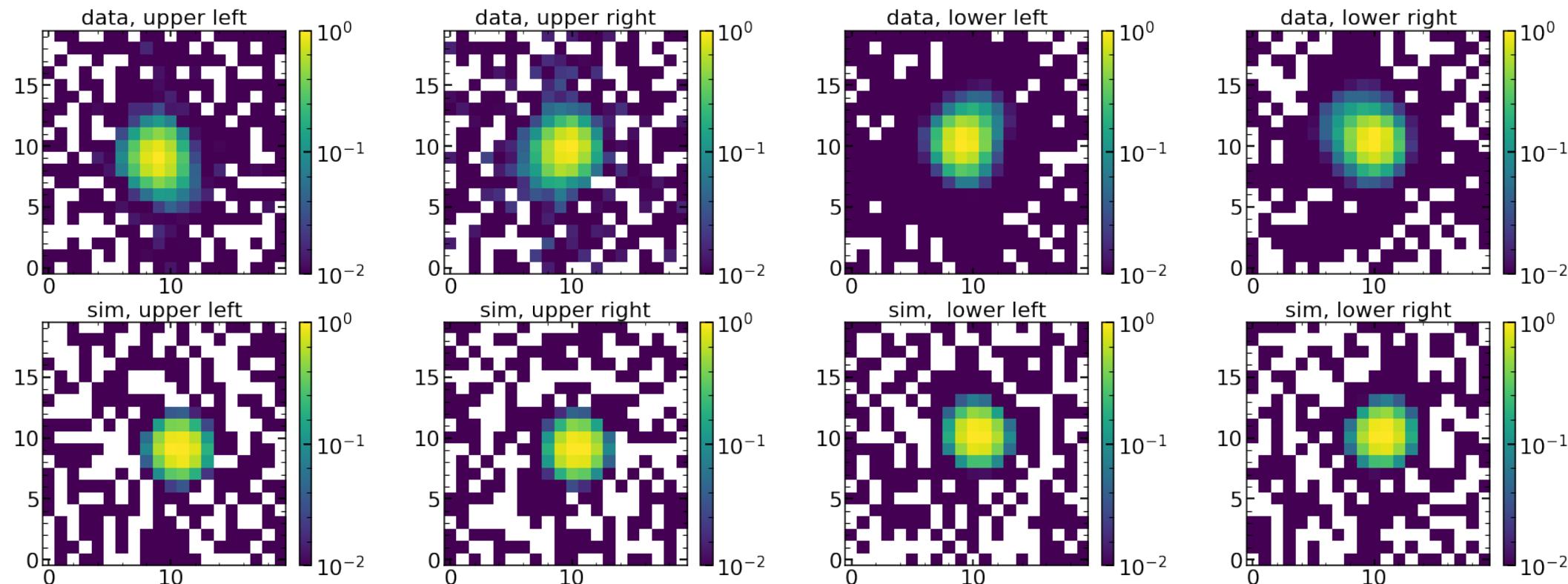


Wavefront rms across the detector

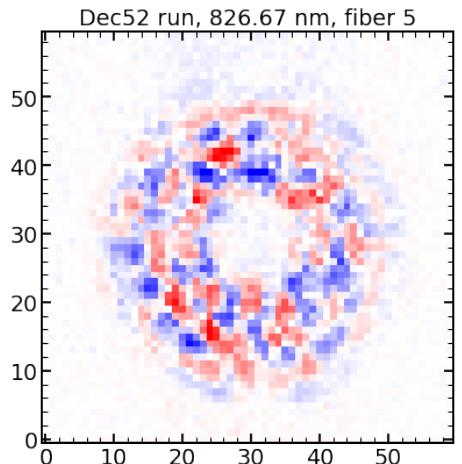


Not in the center of the detector –
probably because it was centered from
available data

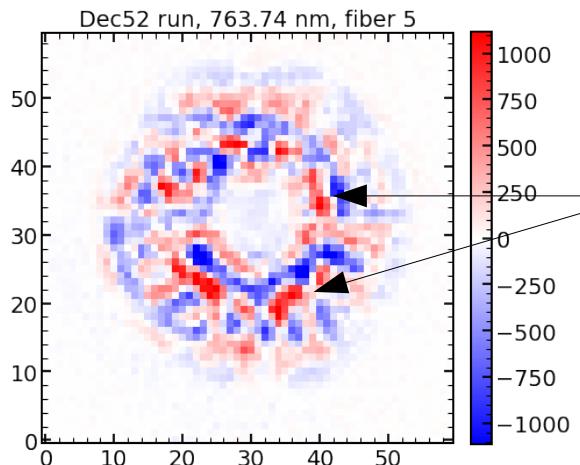
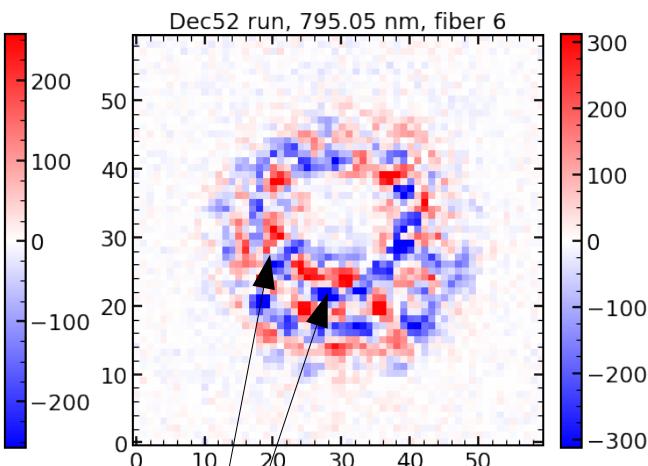
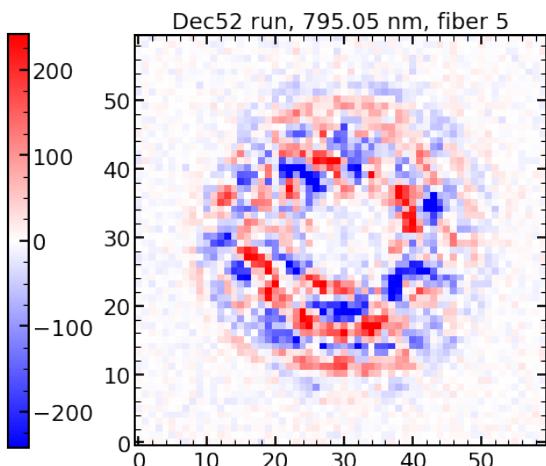
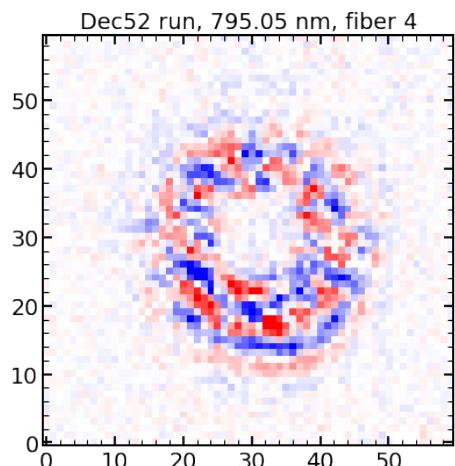
Zemax & real data



Residuals of fits to the data - defocus



Residuals scaled to
5% of the maximal flux
in the data



Speckles – can be
"removed" by fitting
higher order
wavefront
abberations

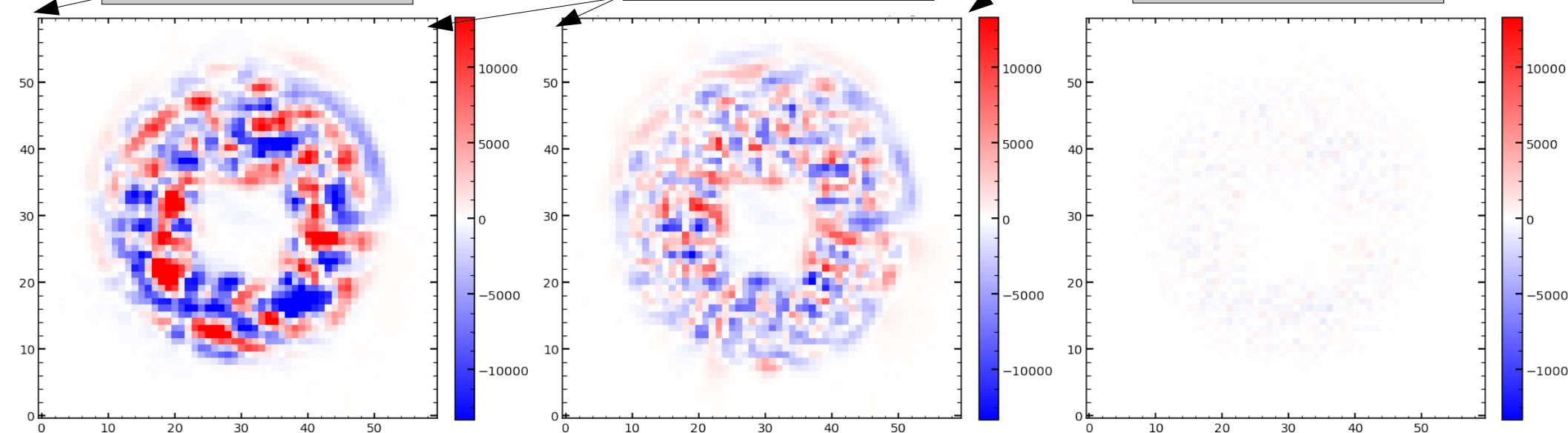
Direct Fits

Up to z22

Up to z254

Perfection

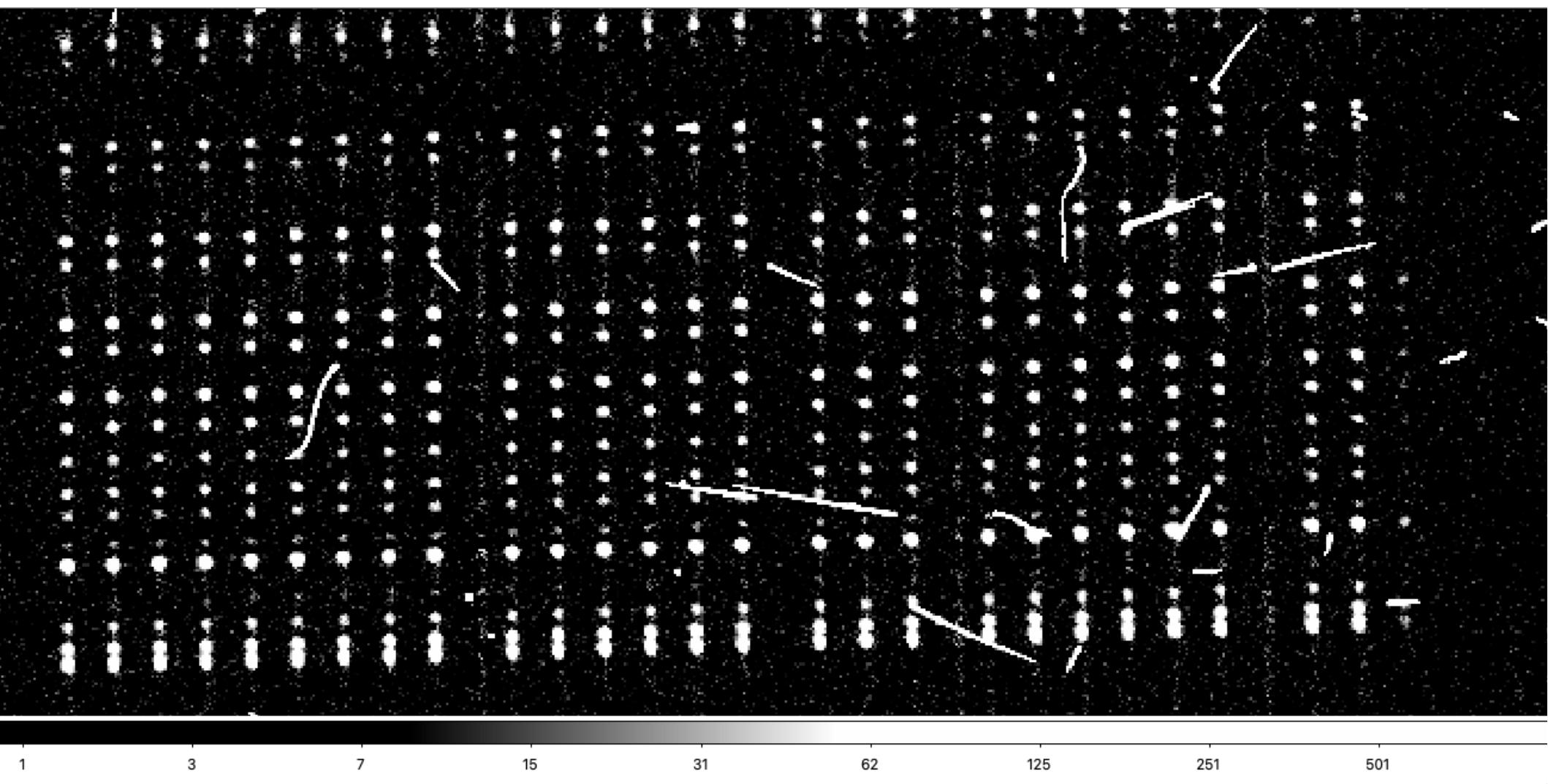
Residuals scaled to
5% of the maximal flux
in the data



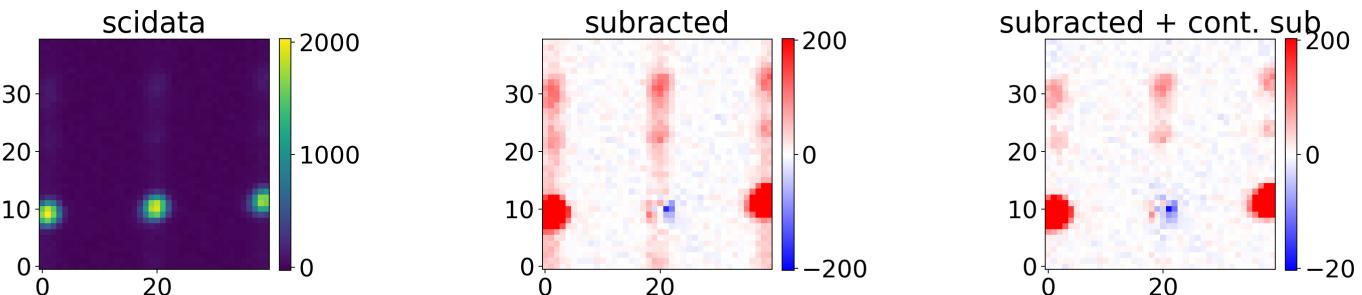
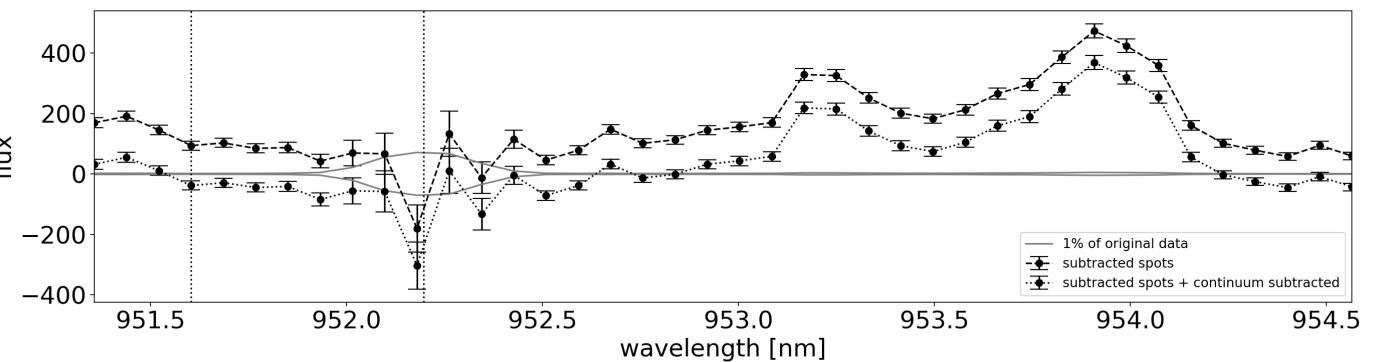
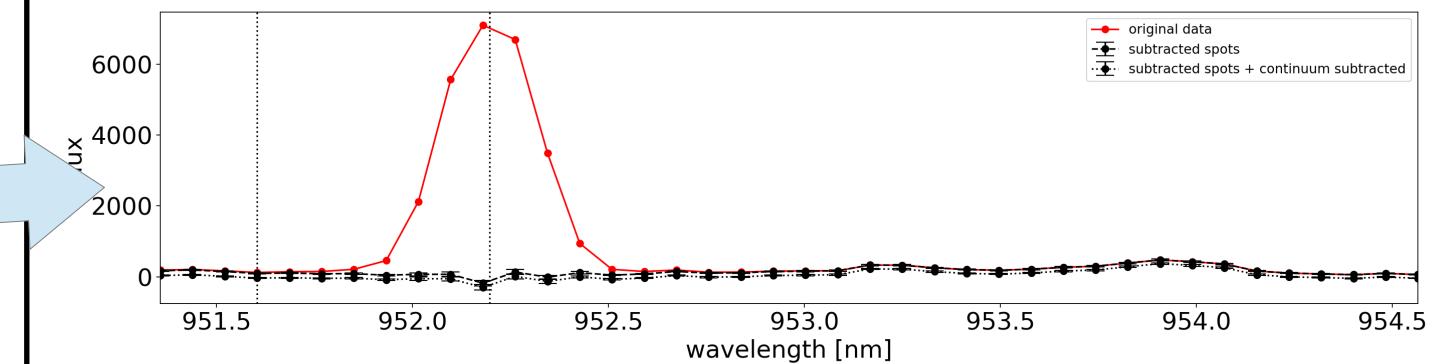
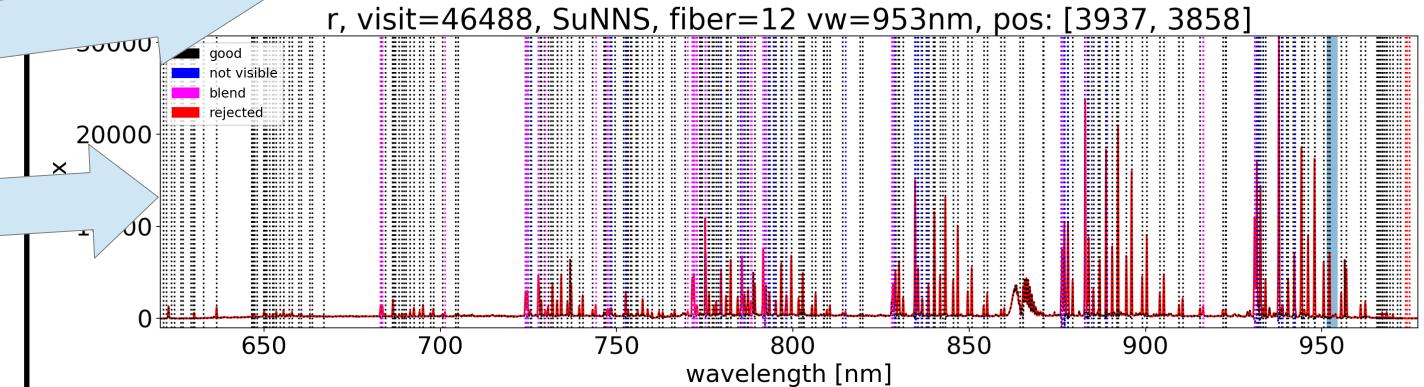
High order
aberrations do not
vary as a position of
the detector? (if they
come from glass
imperfections)

Speckles – can be
``removed" by fitting
higher order
wavefront aberrations

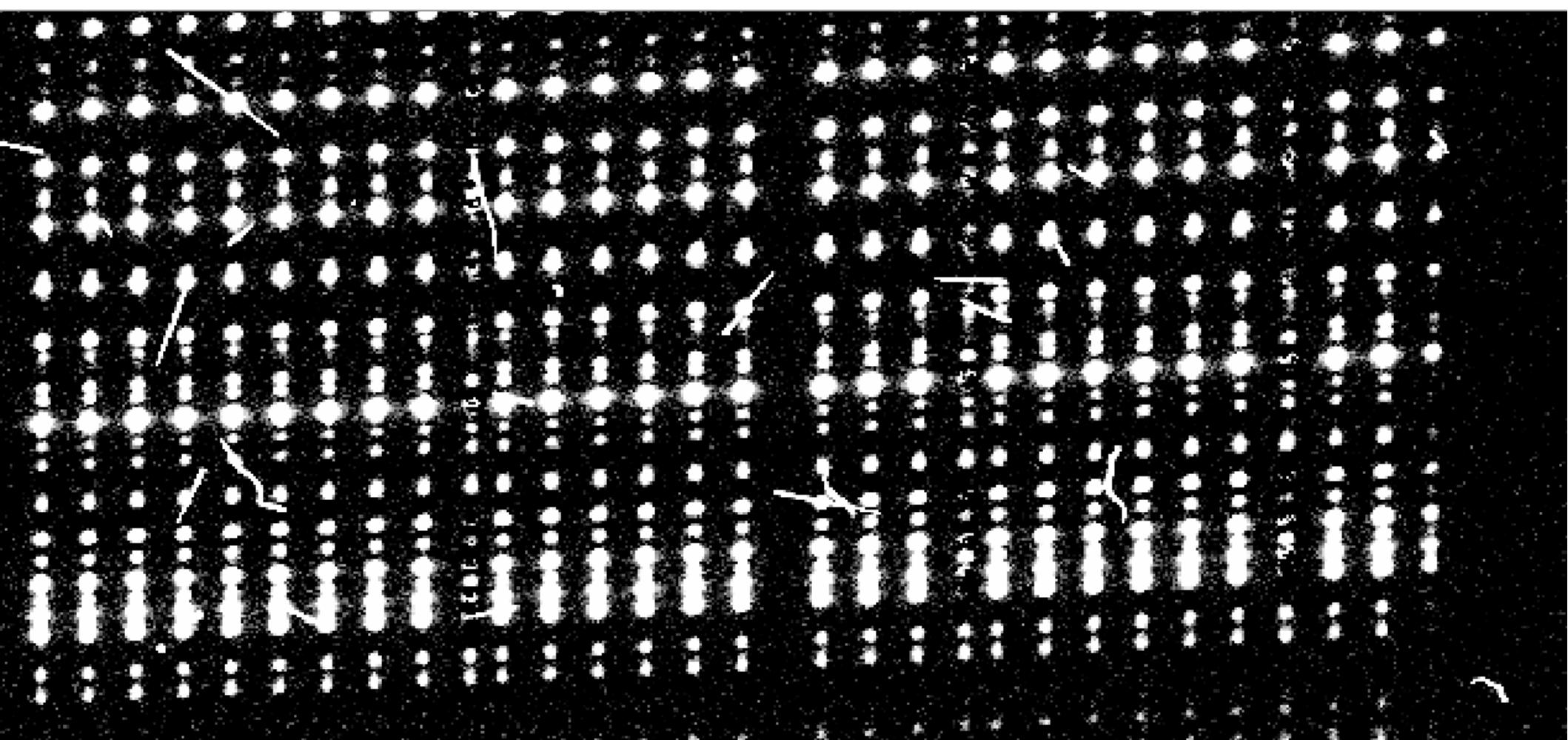
Problems – centering, full
list of lines, strength of
lines....



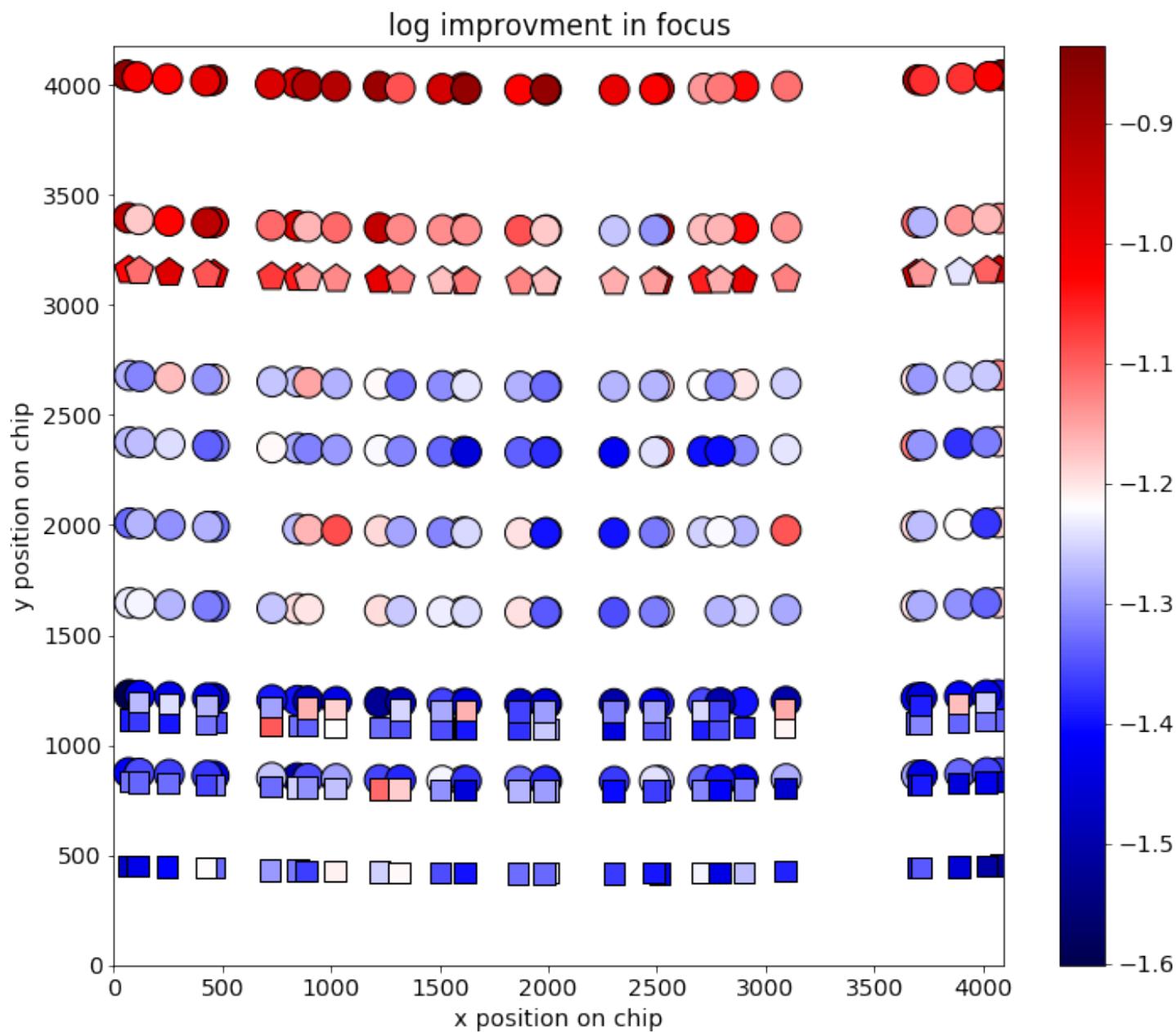
- Example
- Fiber, wavelength
- Full spectrum with all lines
- Shaded region shows the region of interest
- Zoom in on the region of interest. Red shows the data, dashed after subtraction of spots dotted after continuum subtraction as well.
- Zoom in on the region of interest, on the subtracted spectrum. The gray line shows $\pm 1\%$ of the data.
- 2d images of the region of interest. Left: original data, middle after spot subtraction, right after cont sub as well. Scaled to 10% of original image.



Problems in red



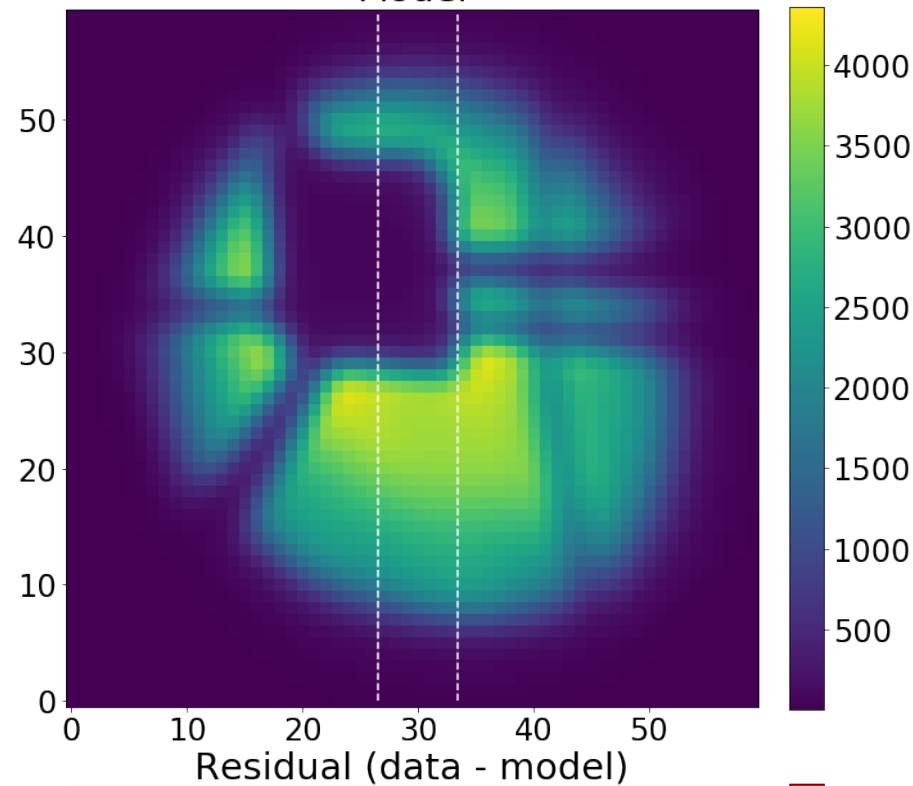
Problems in red



Measure of the quality of the fit, for images in focus

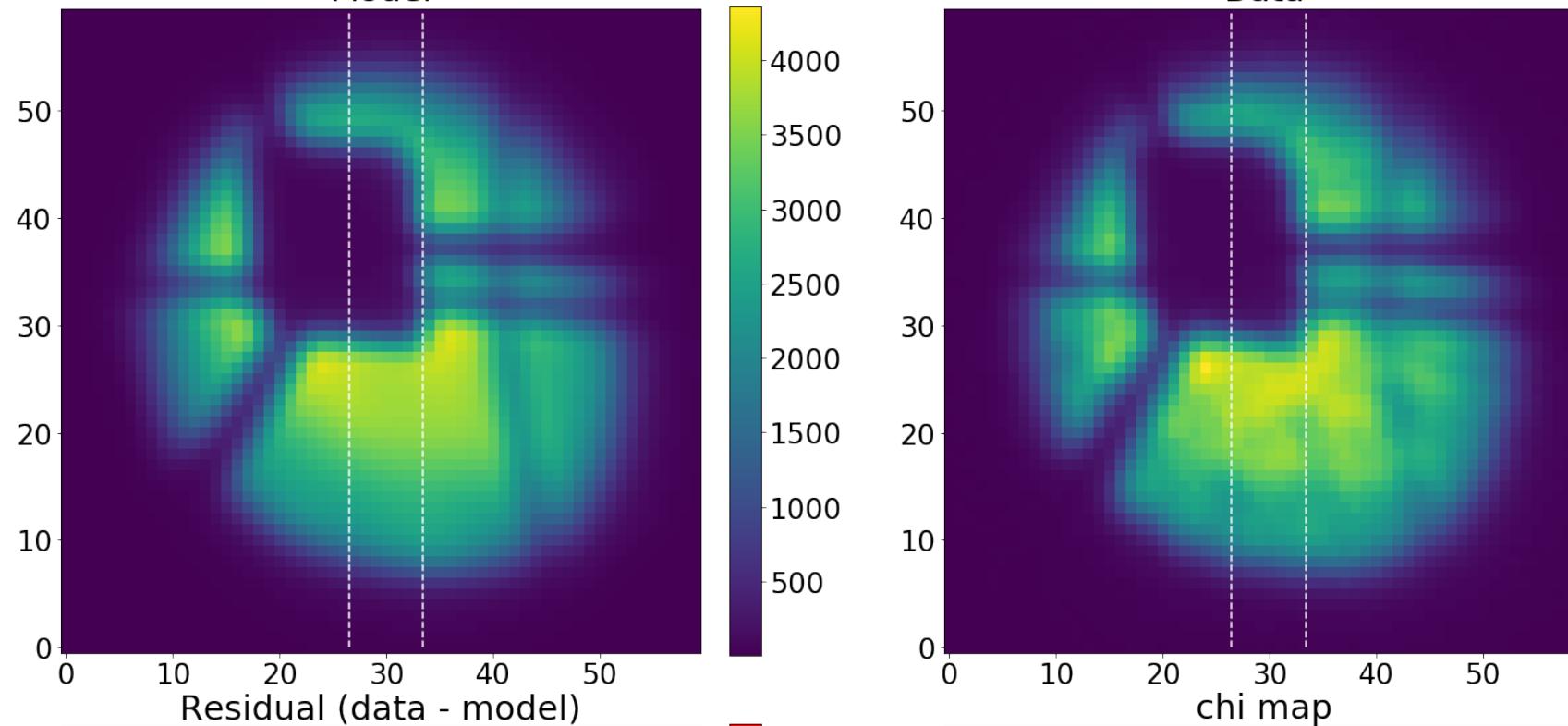
Clearly worse fits for images at the top of the detector (redder wavelengths)

Model

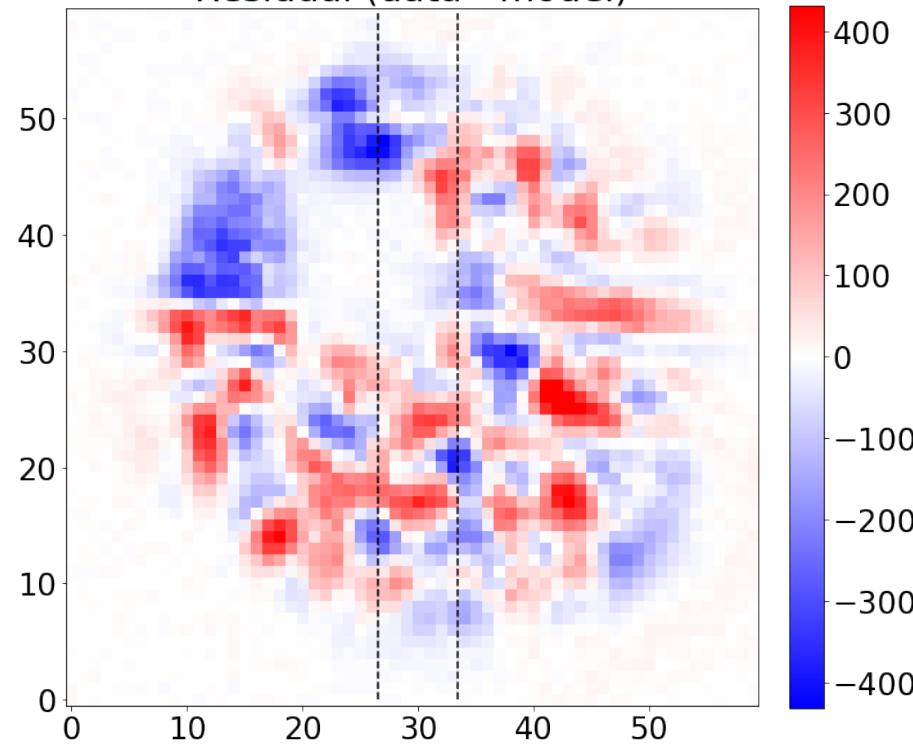


Residual (data - model)

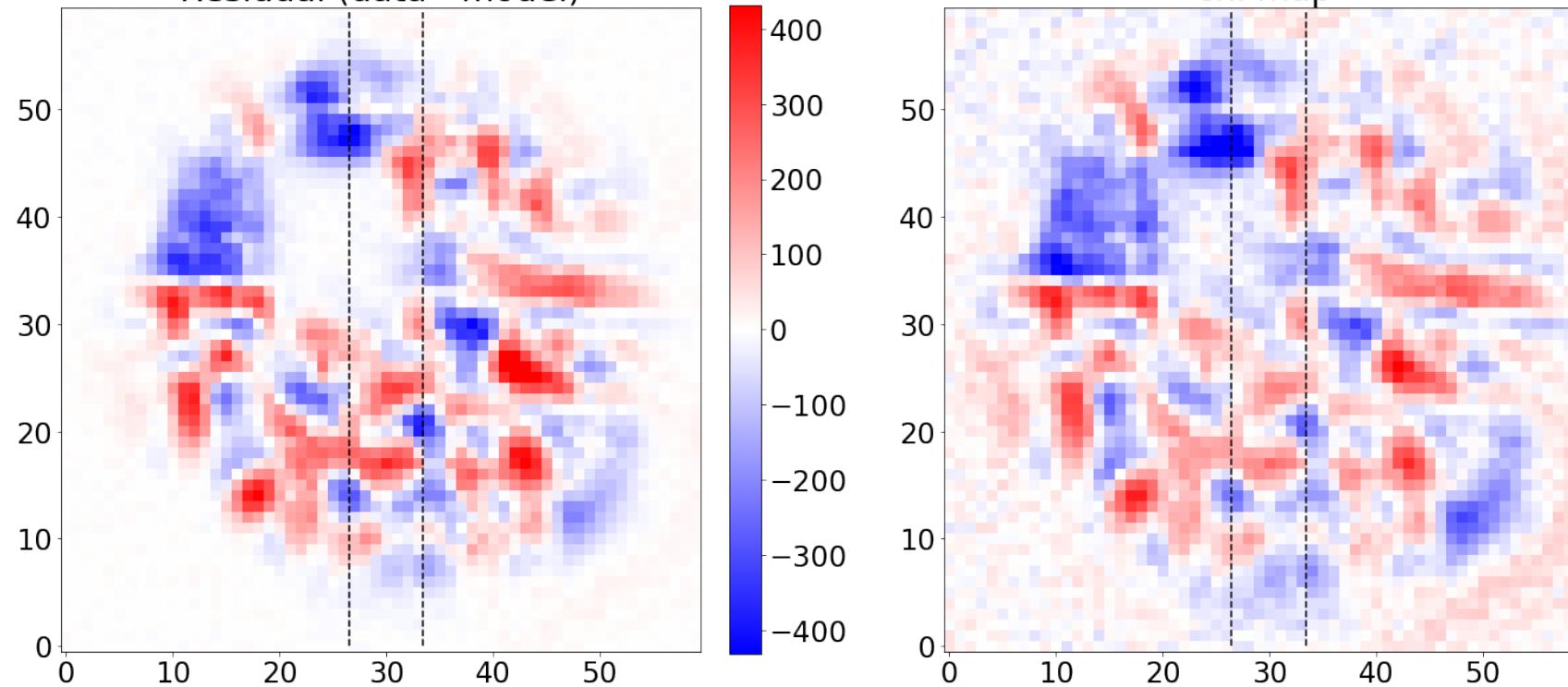
Data



chi map

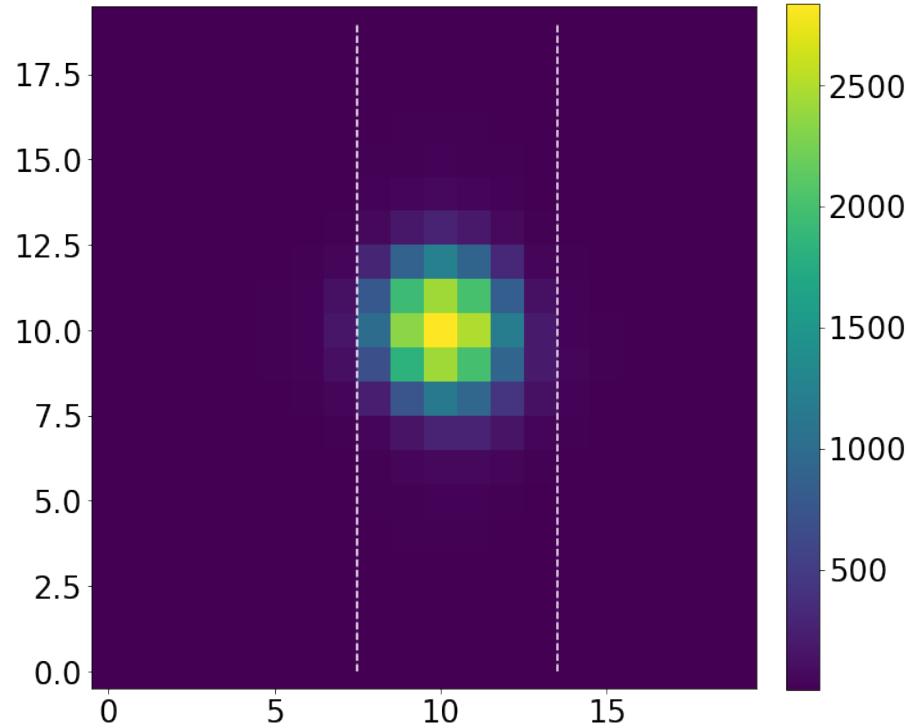


Residual (data - model)

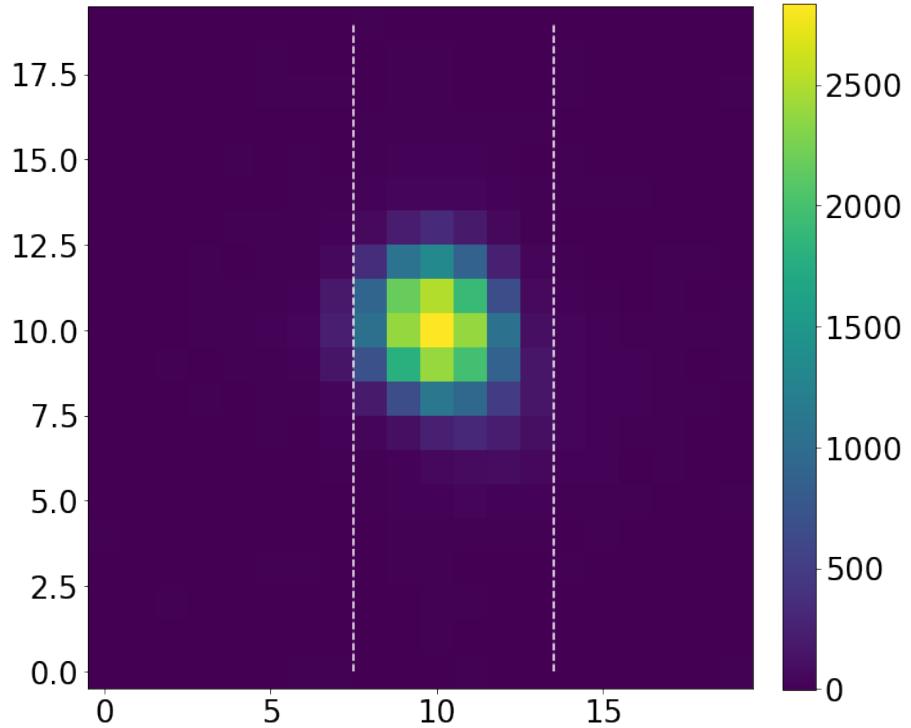


chi map

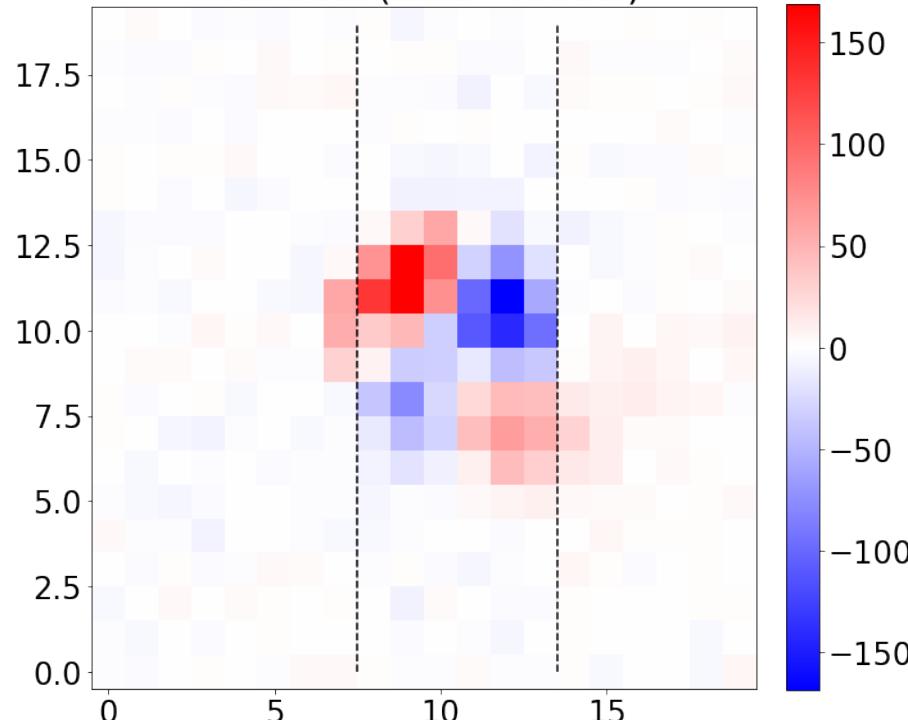
Model



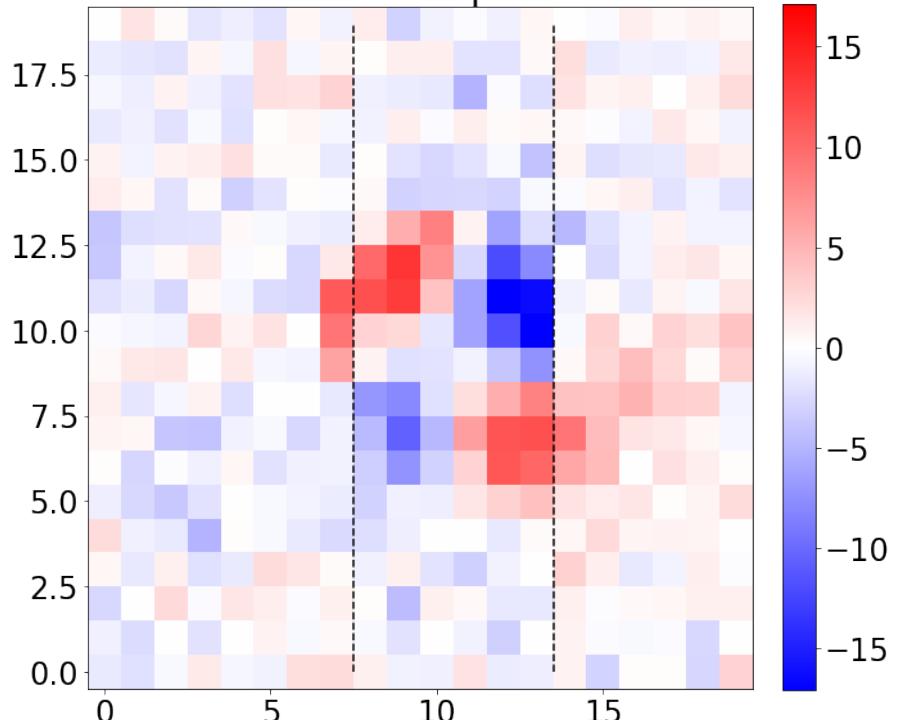
Data



Residual (data - model)

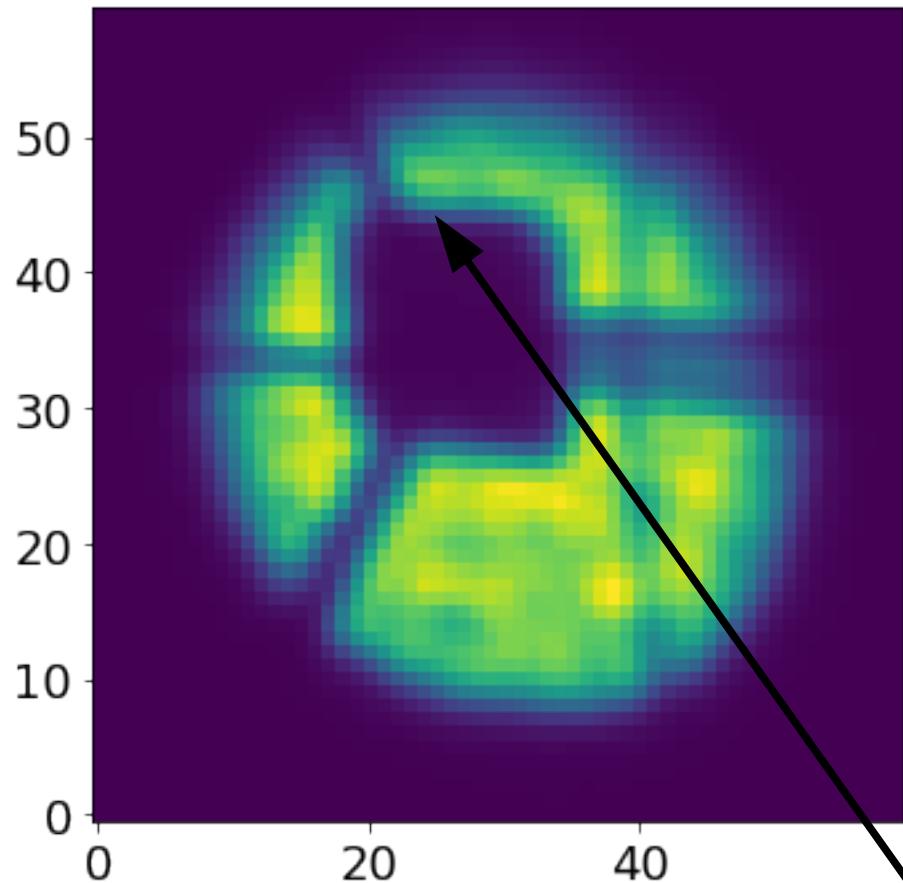


chi map

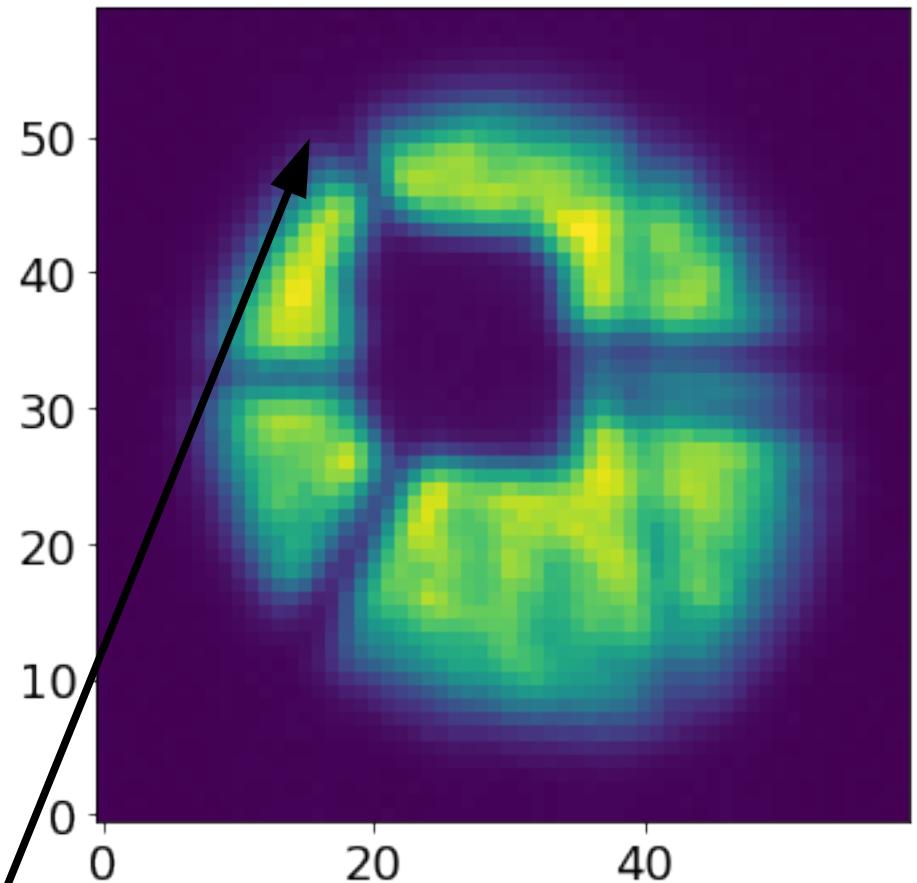


Problems in red

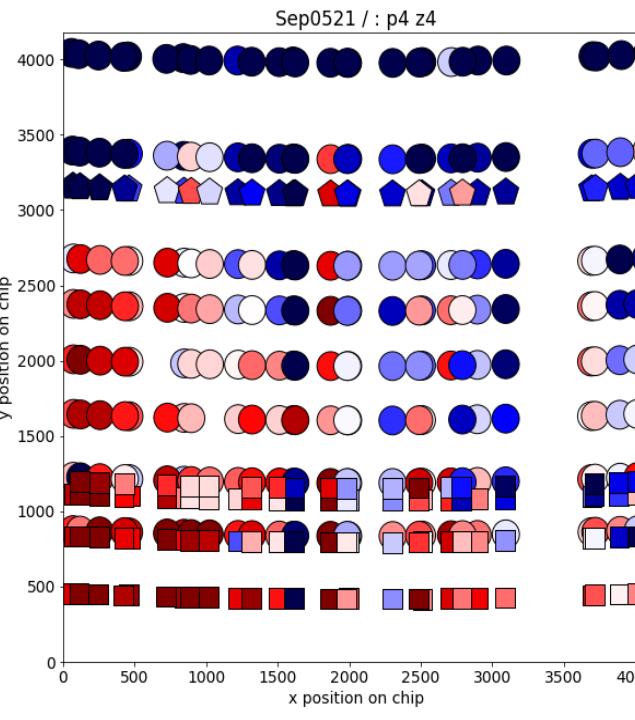
SM1



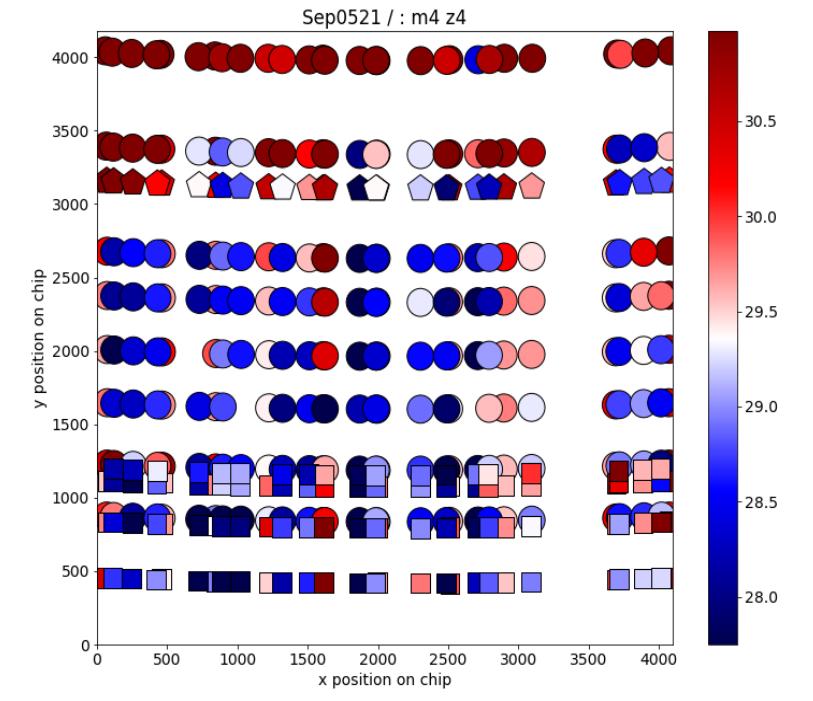
SM2



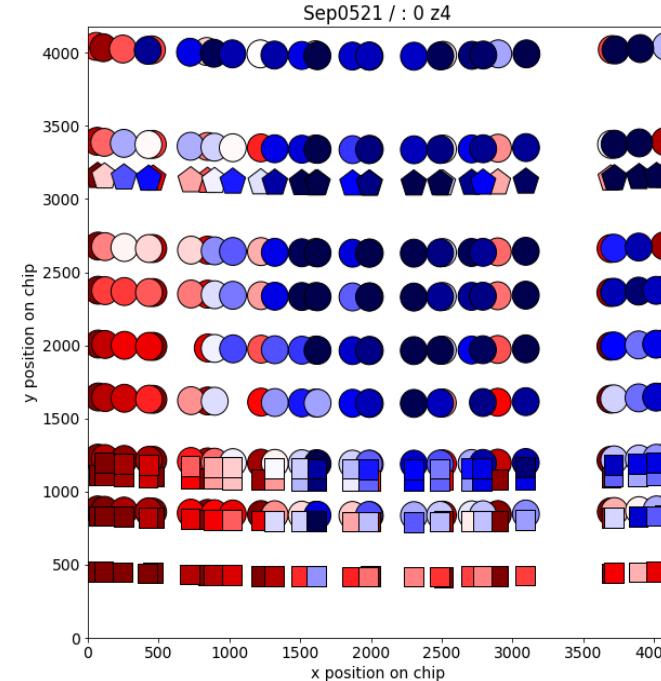
- Soon – data from spectrograph modules 2 and 3
- Same spot, same defocus, same optics



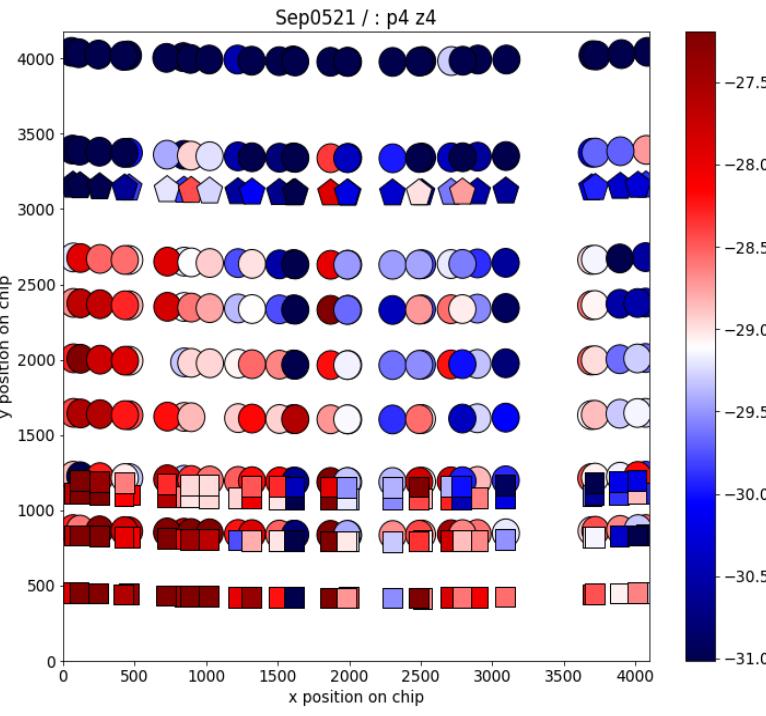
Change of single component (z4, defocus)



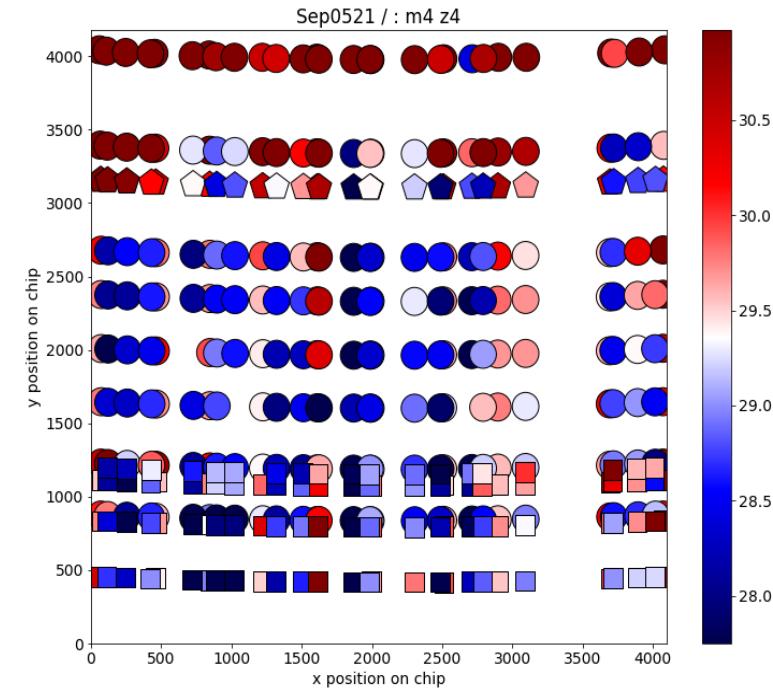
Problem – non continuous solutions



Changing defocus



Change of single component (z4, defocus)



Problem – non continuous solutions

- First step – fit multiple spots in the same fiber, with illumination pattern same in all spots
- Ultimate step - Global solution of Zernike parameters across the whole detector plane

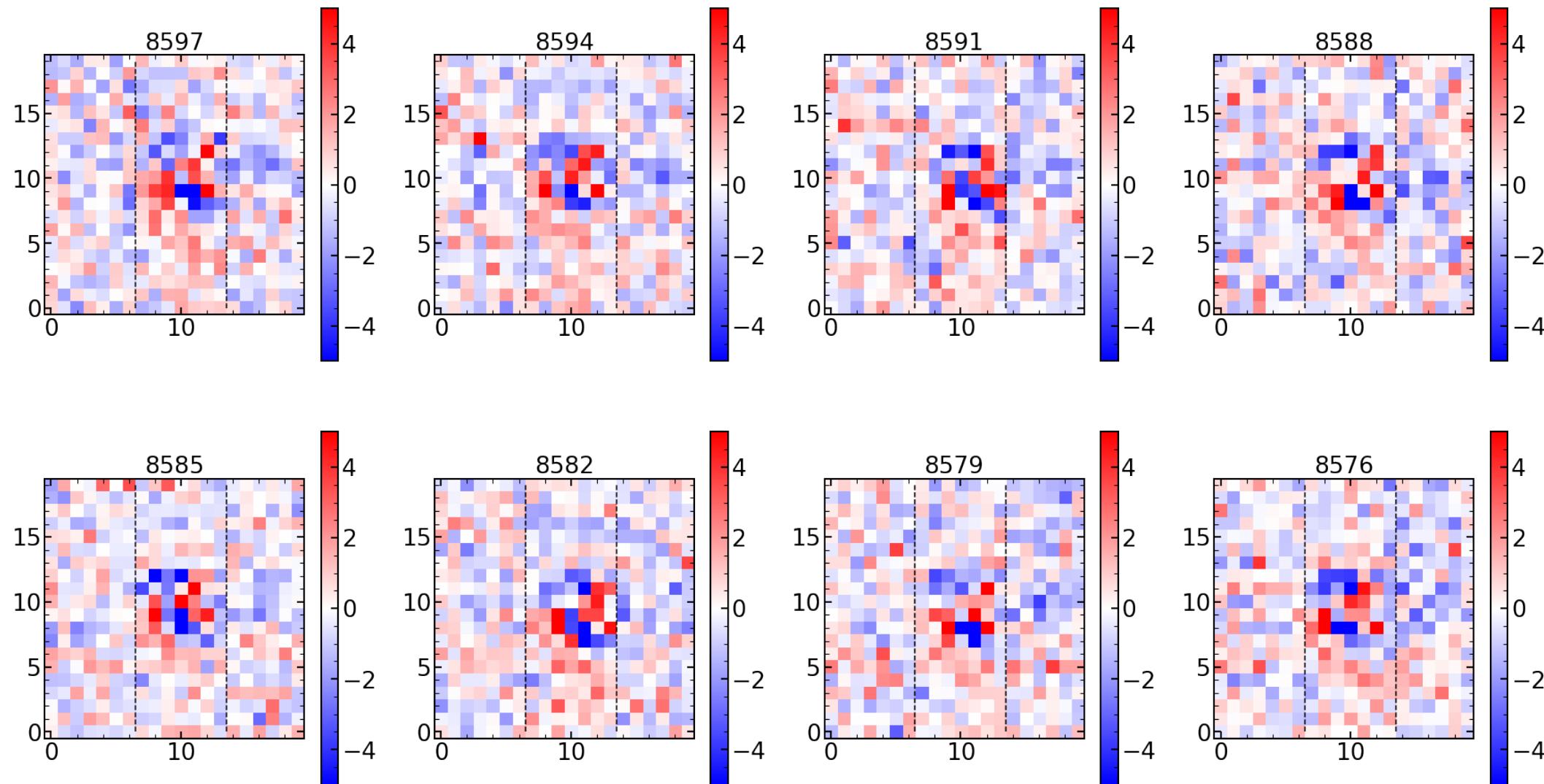
Summary

- Prime Focus Spectrograph – 2394 fibers, 380nm-1260nm, being installed on Subaru
- 3 components of the point spread function
 - Telescope pupil illumination
 - Focal ratio degradation in the fibres
 - Spectrograph cameras
- Characterize contribution of camera imperfections to the point spread function by modelling optical performance using defocused data
 - 1% subtraction achievable across the large parts of the field
- Poor agreement with Zemax predictions
- Poor subtractions in parts of the field
- Need to construct continuous solutions, both for illumination and wavefront parameters

Extra slides

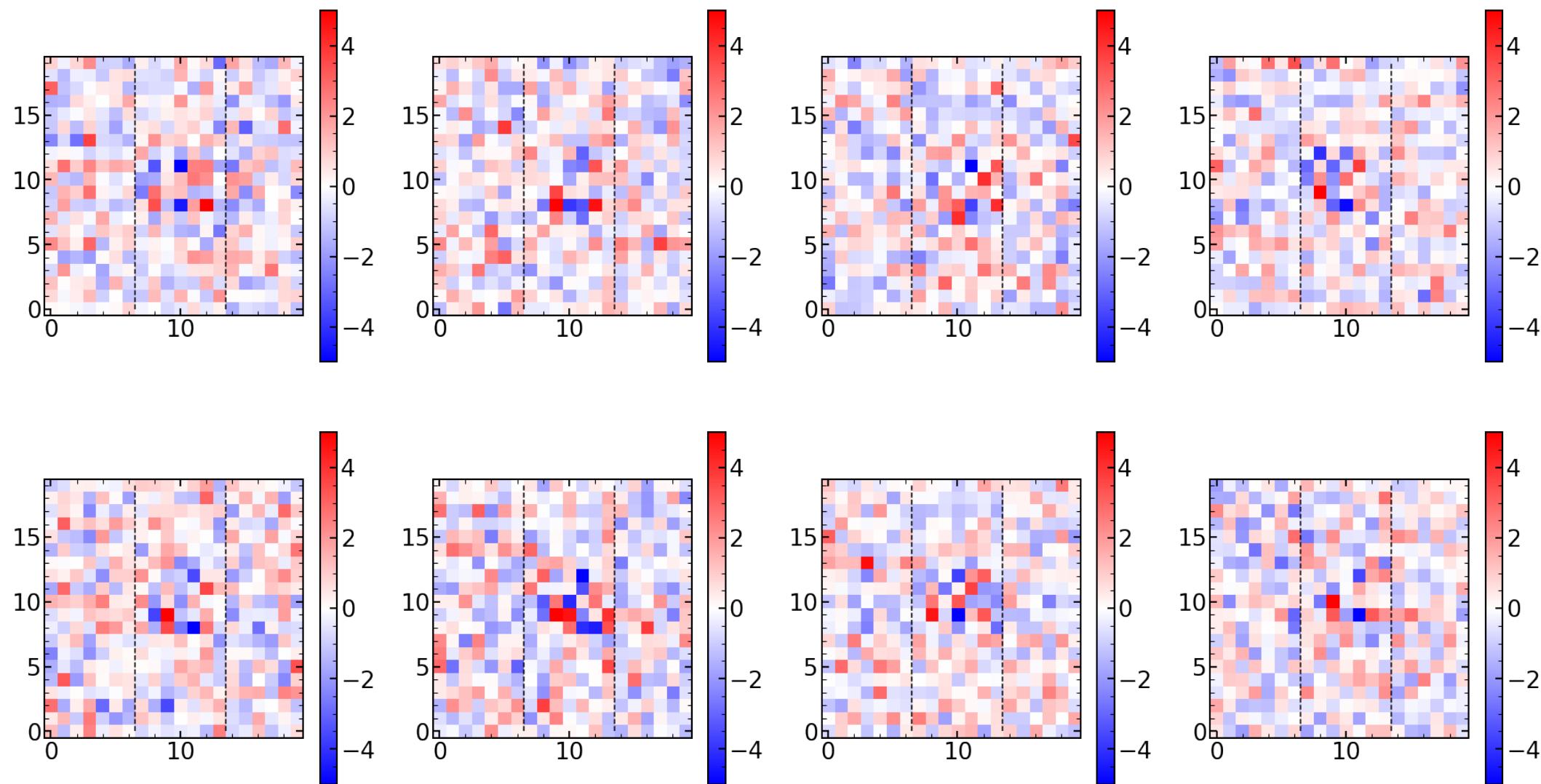
Residuals in the focused data, 8 different dithering positions

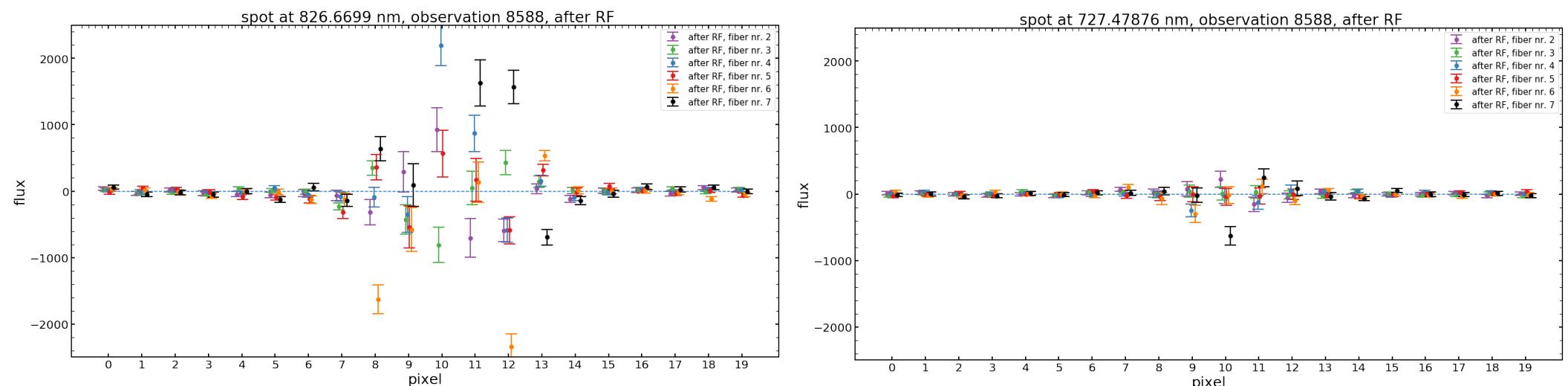
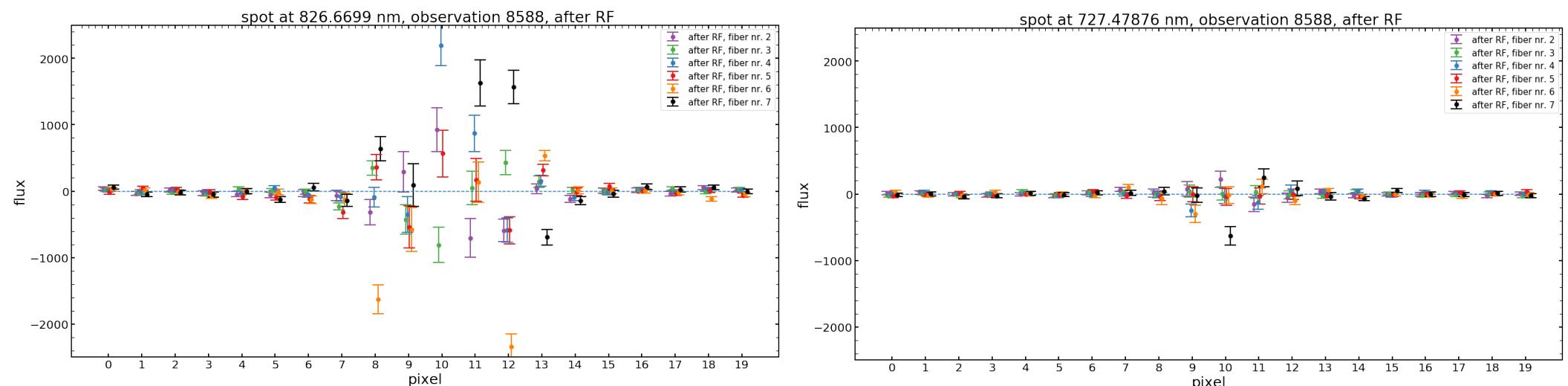
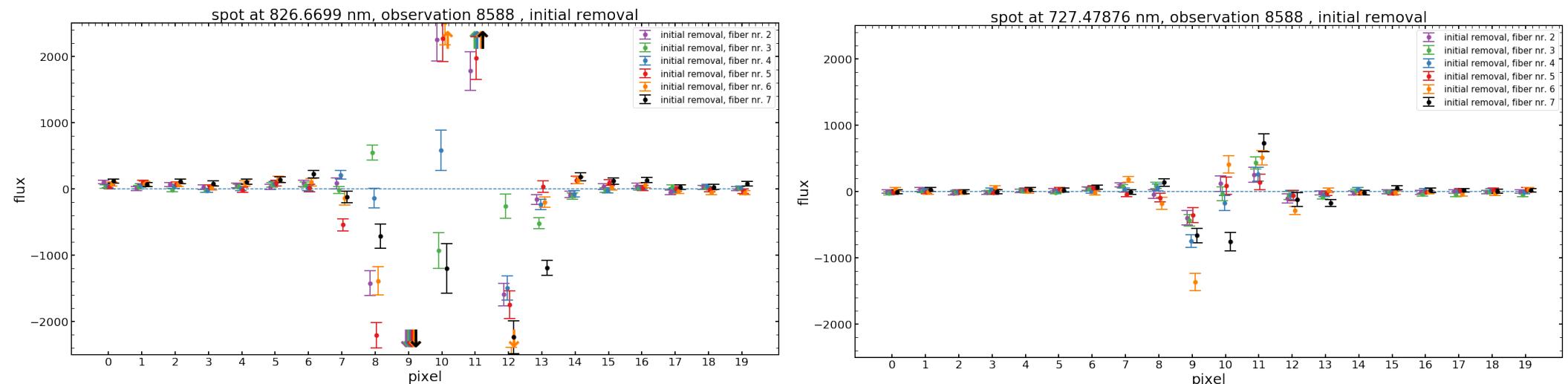
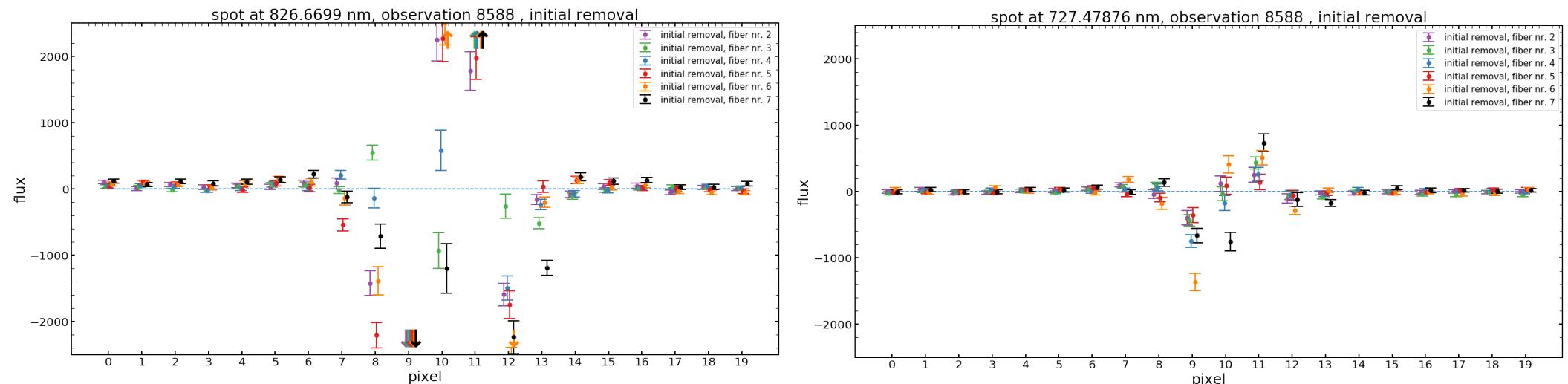
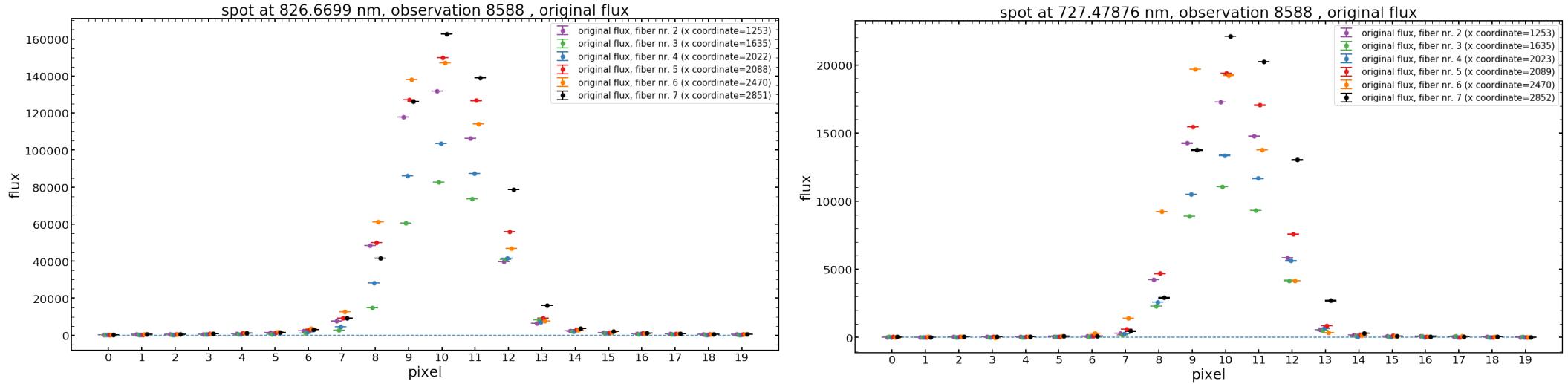
Residuals, up to Zernike 22 and Jan 15 modifications to centering



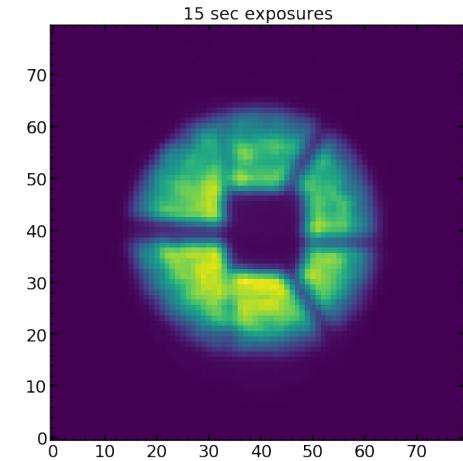
Residuals in the focused data, 8 different dithering positions, after Random forest cleaning applied

up to Zernike 22, Jan 15 modifications to centering, and Random Forest postprocessing

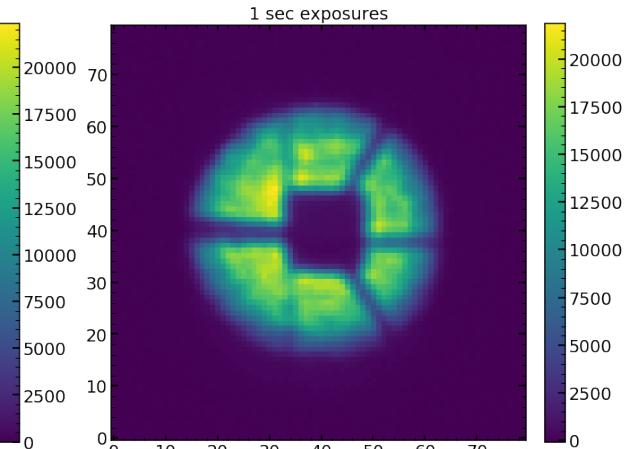




15 sec exposures

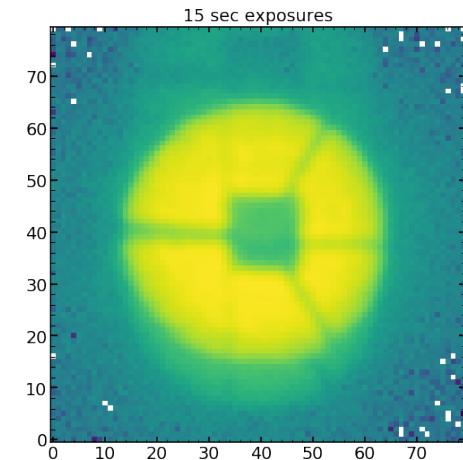


1 sec exposures

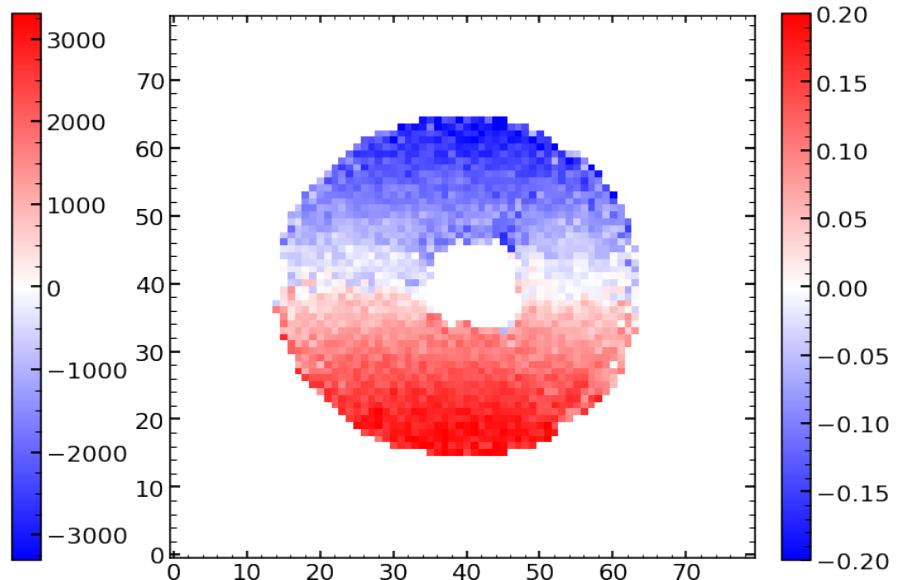
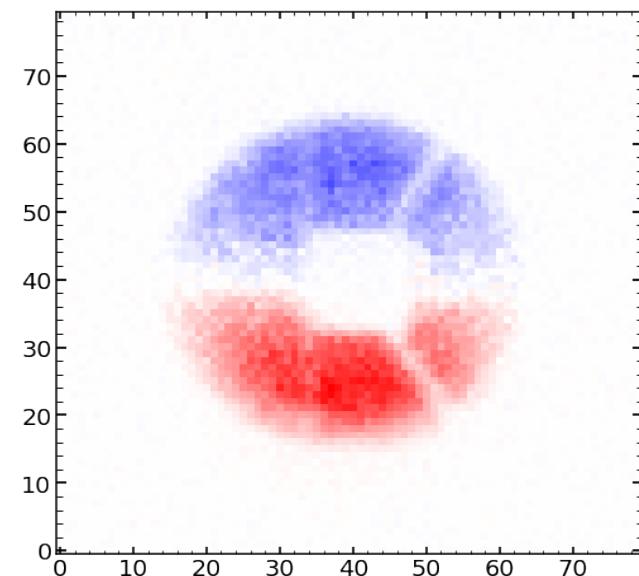
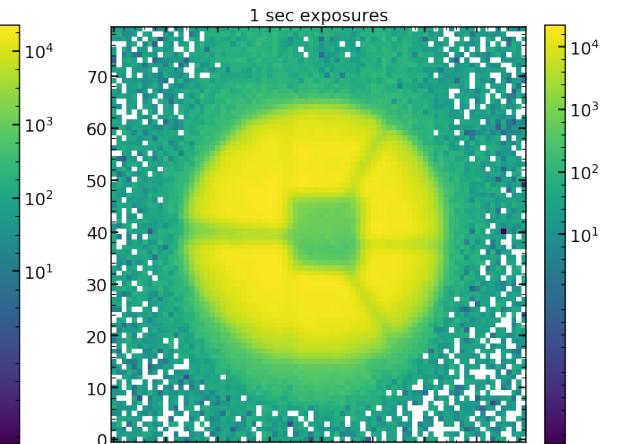


Shutter and flux control

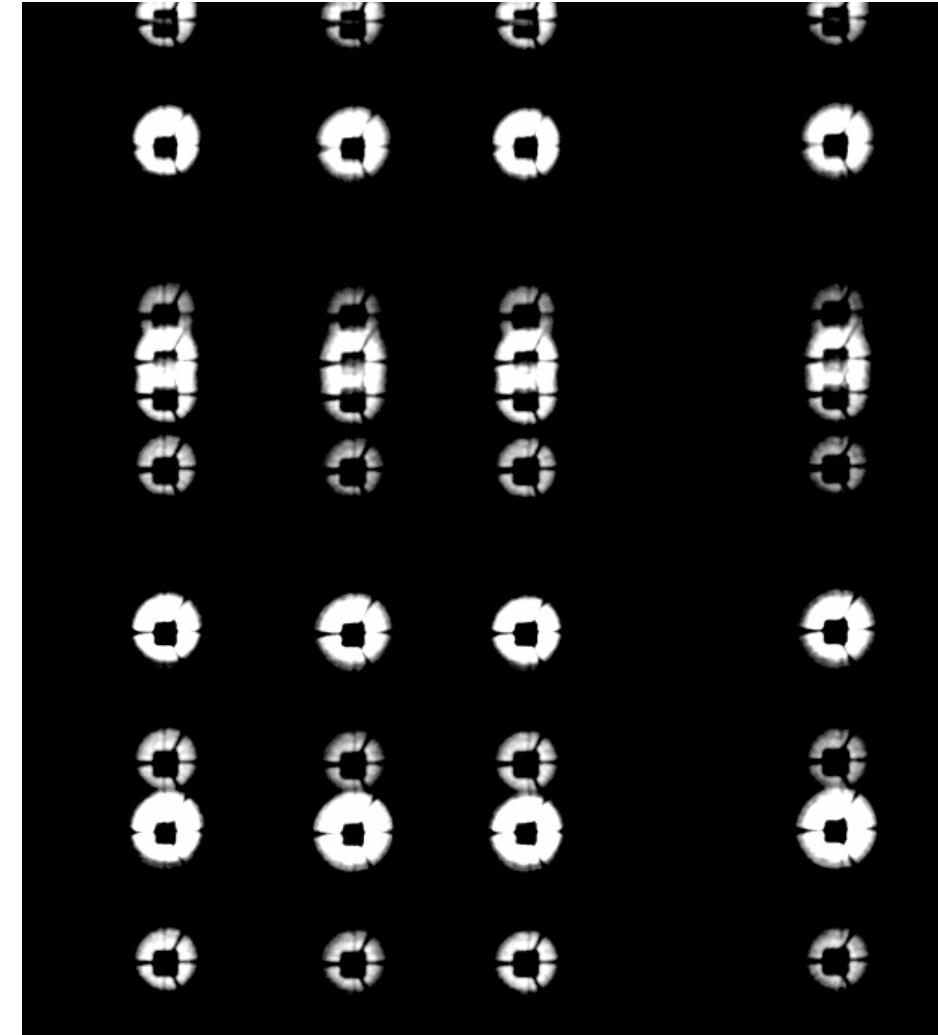
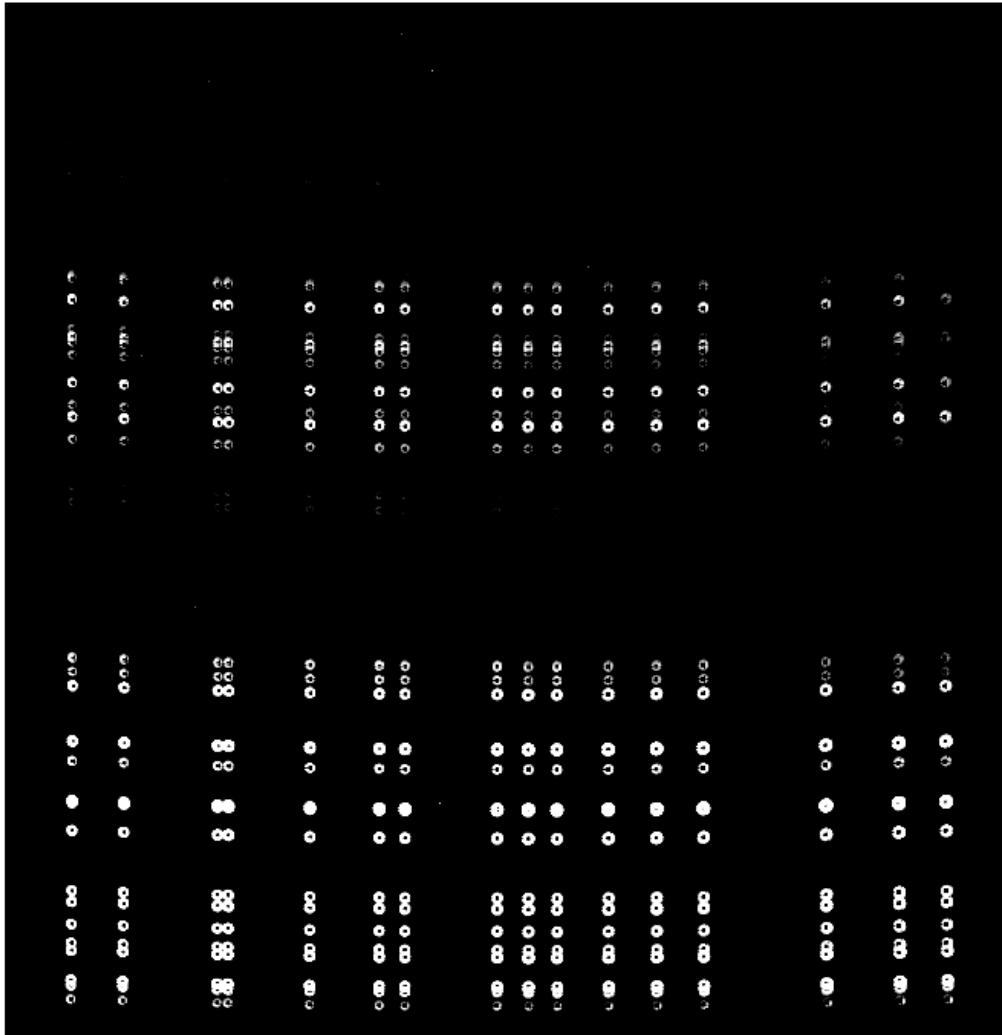
15 sec exposures



1 sec exposures



Selected topics – Overlap of spots



Partially mitigated by algorithm improvement, creating two identical
models with an offset and adding them together

Parameter fitting

