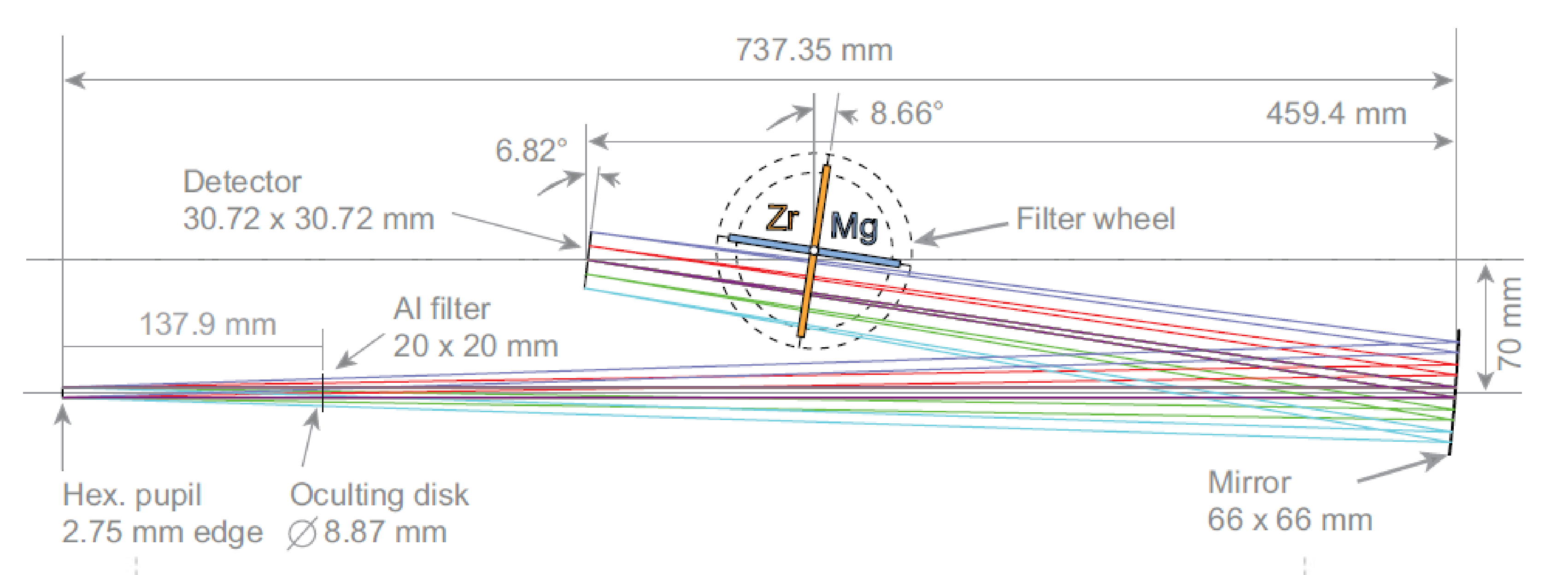
The importance of point spread function corrections in solar physics

Stefan Hofmeister

What is a PSF?

- Describes the imperfections of optical systems
- Describes the diffusion/scattering of light in the system
- Is the impulse response of the instrument

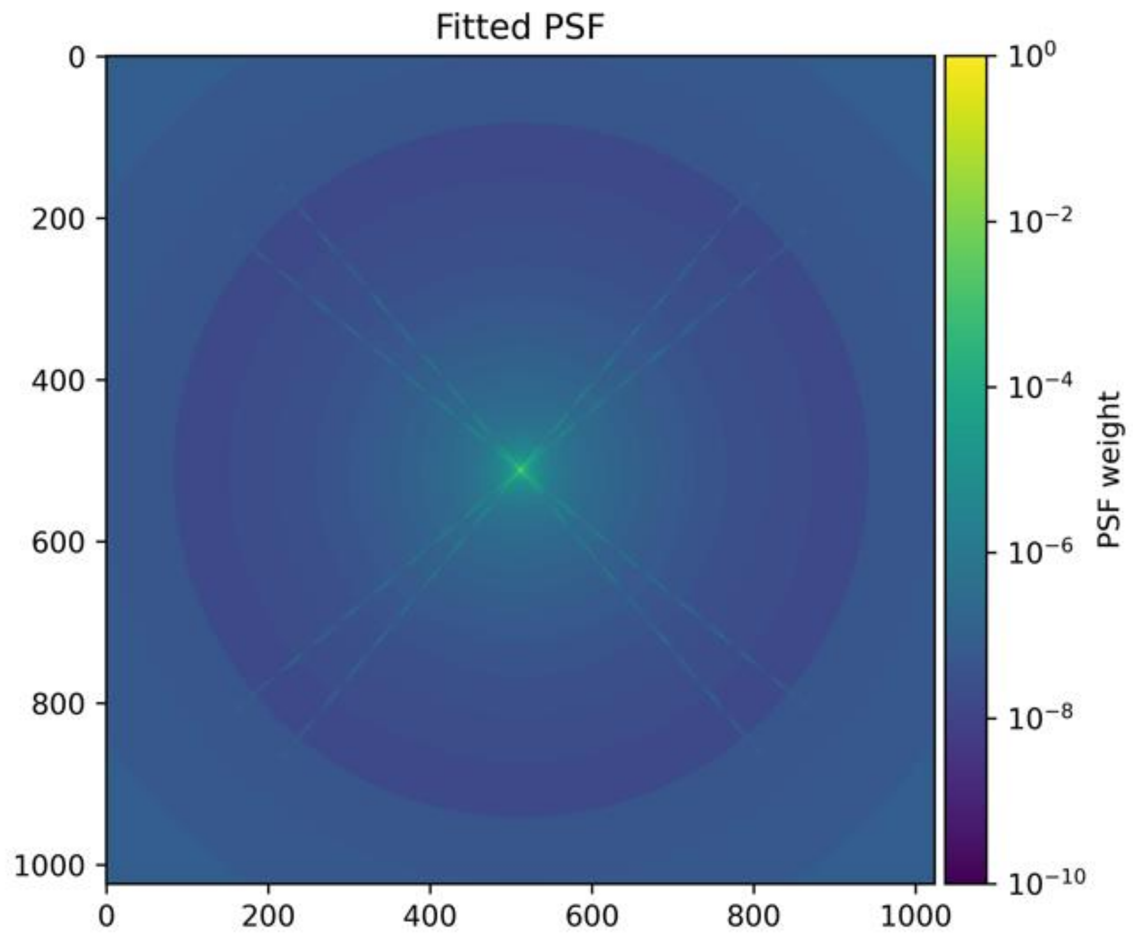
- In simple terms: it is the observed intensity distribution of a point source

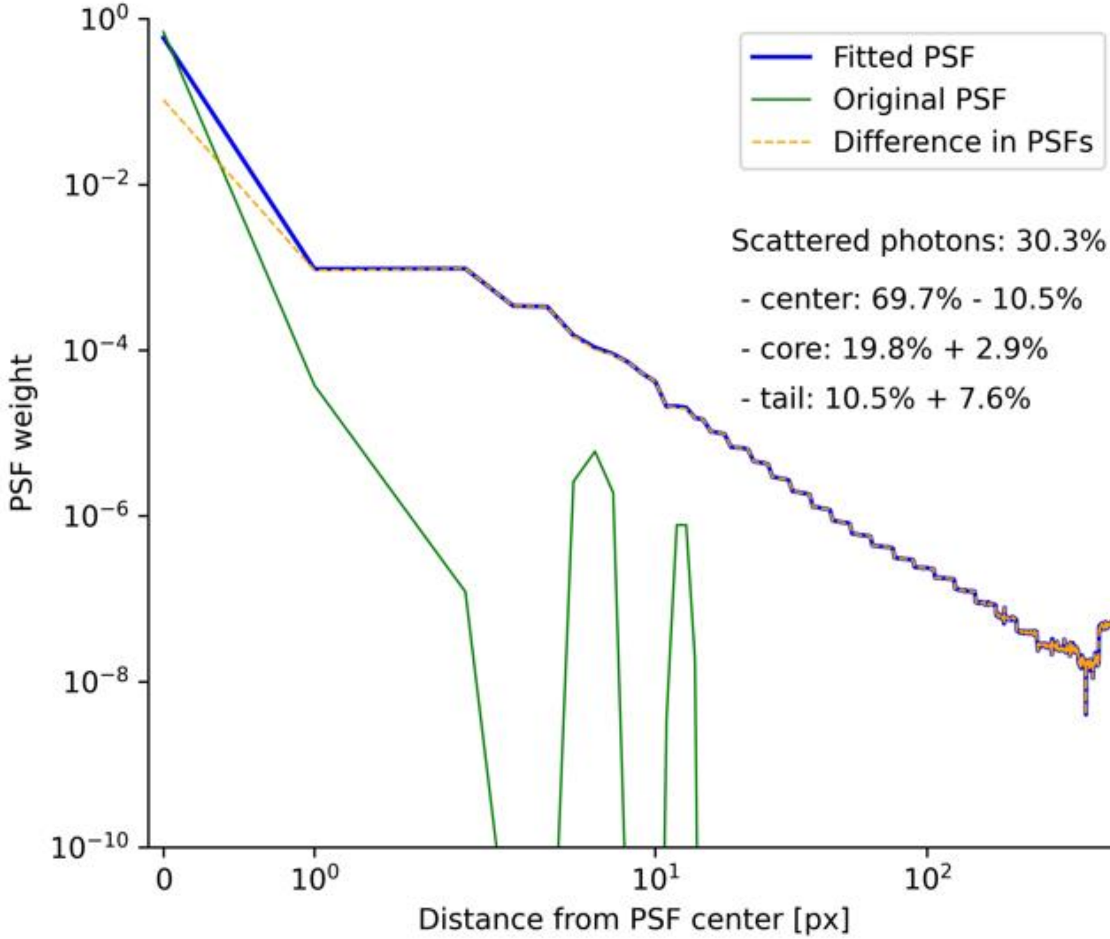


What is a PSF?

- Can contain optical aberrations such as coma, diffraction patterns of
- Can be used to correct images for the imperfections of the imaging system
- Thus, it belongs to the toolset for instrumental calibrations, next to dark current subtractions and flatfield corrections

How does a PSF look like?





How to apply PSF corrections

In IDL: data_dcon = aia_deconvolve_richardsonlucy(float(data), psf)

In Python: smap_dcon = aiapy.psf.deconvolve(smap, psf)

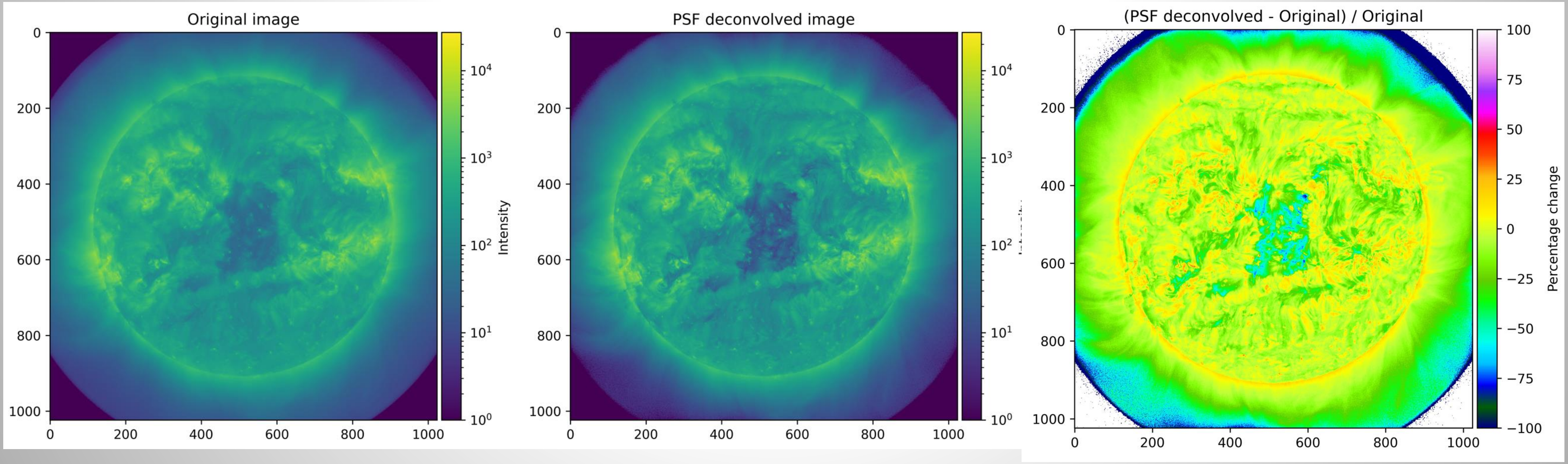
- Both routines work for all images, not only AIA
- It has to be done in the CCD coordinates, i.e., before rotating or rescaling the images
- The Richardson-Lucy Algorithm is applied in the Fourier Domain

  => to break the periodic boundary conditions, the images have to be padded with zeros

  (Both for the PSF and the image, create a PSF/image having the dimension of 1.5*dim(image) filled with zeros, insert the PSF/image in its center, deconvolve the image with the PSF, and cut the deconvolved image out)

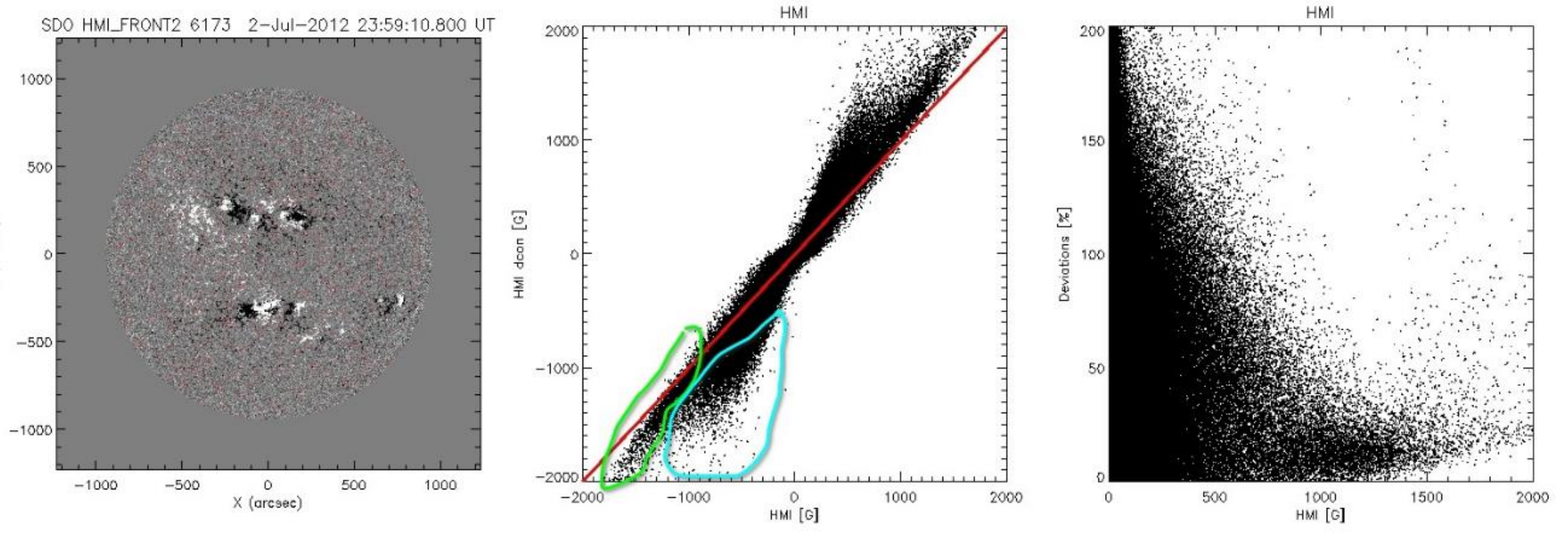
Are PSF corrections important in solar physics?

- Dark regions: coronal holes and the off-limb quiet Sun
- Bright regions: limb brightening, active regions, and flares



Are PSF corrections important in solar physics?

- Data products: magnetic field maps and Dopplermaps



Are PSF corrections important in solar physics?

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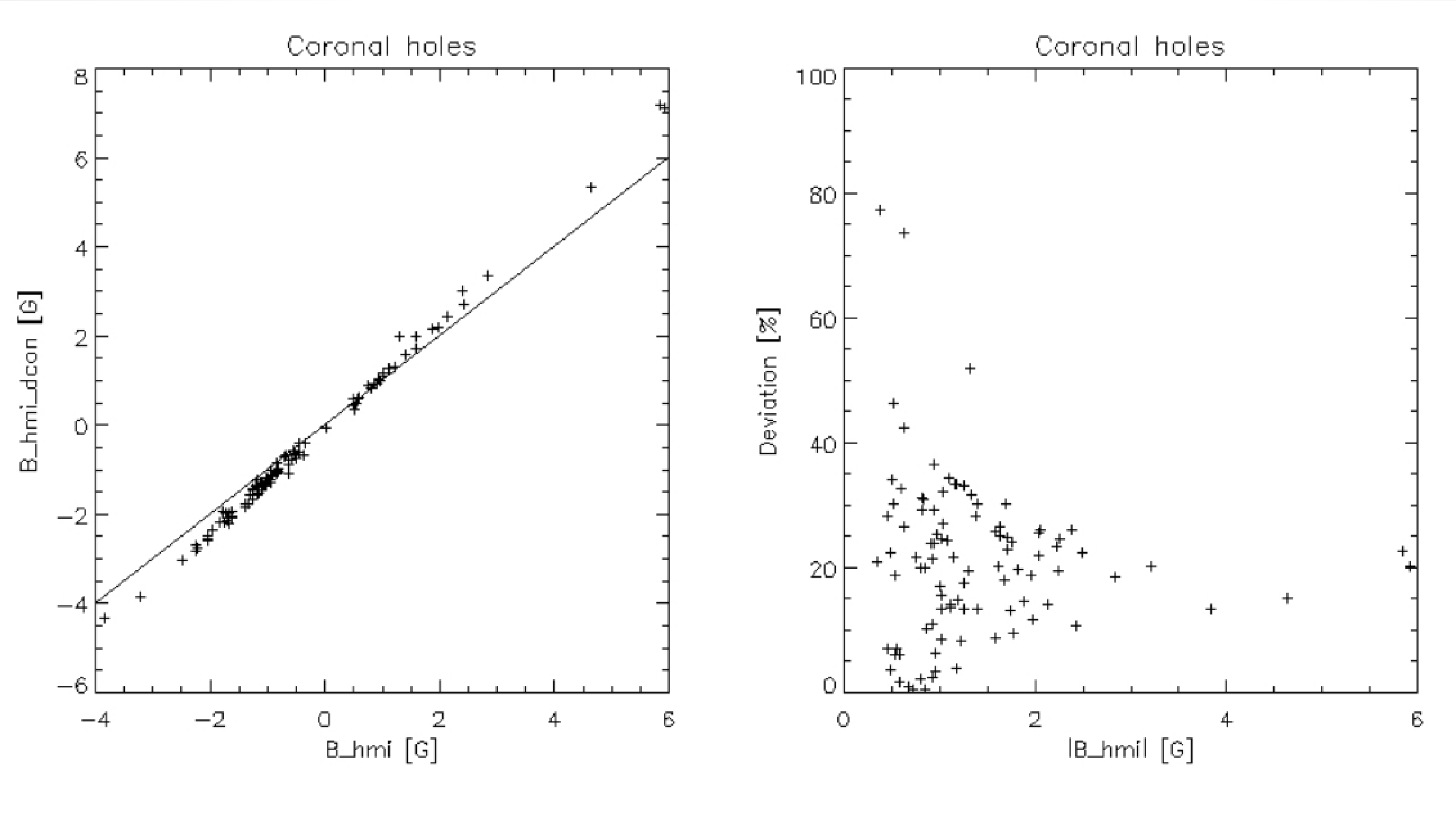

Are PSF corrections important in solar physics?

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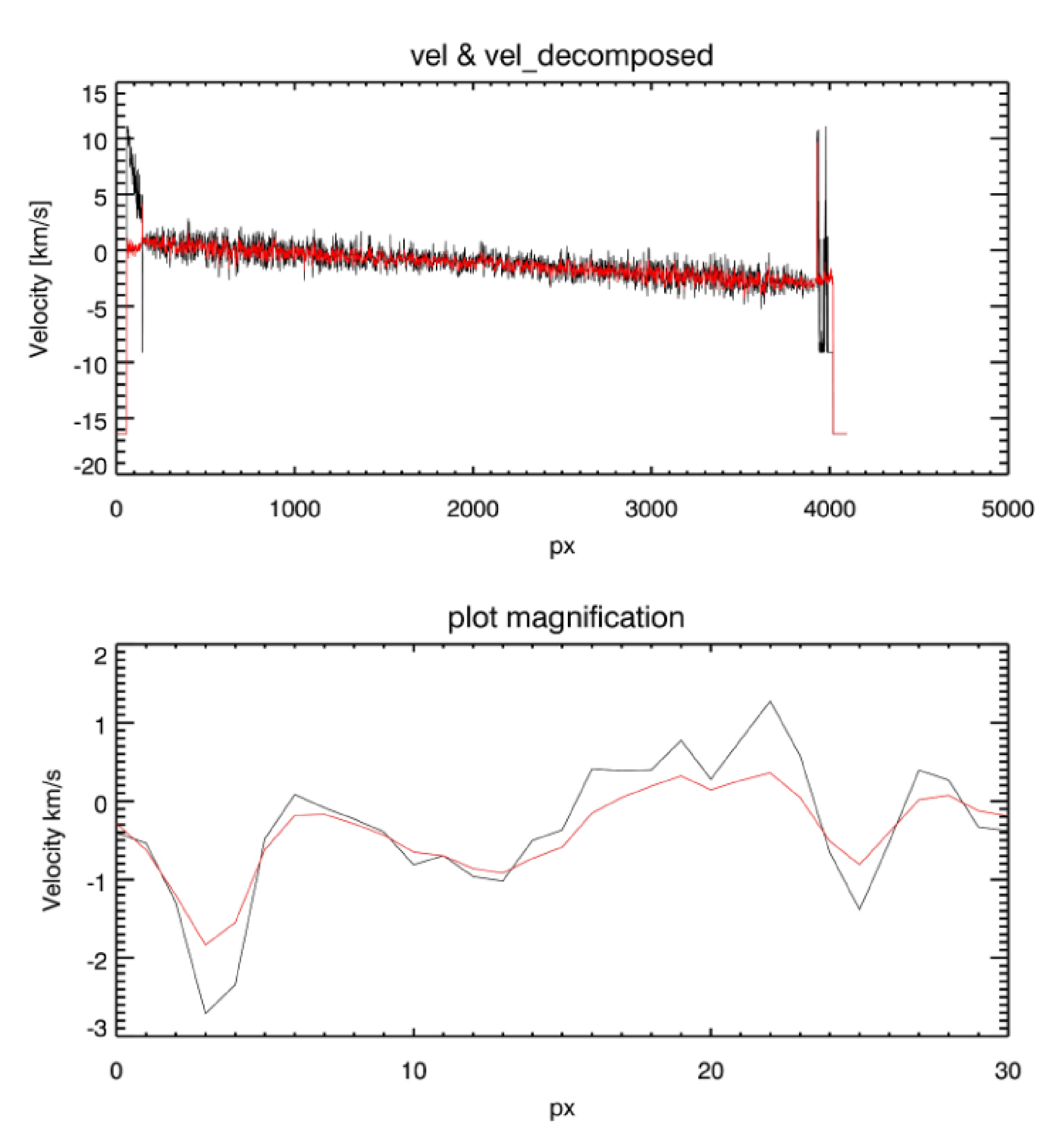


Are PSF corrections important in solar physics?

- Advanced data products: magnetic field extrapolations and wave power spectra

- To be done. But: if the magnetic field strength of magnetic elements and also of larger-scale structures like coronal holes change in a non-linear way, we can expect deviations in the solutions of magnetic field extrapolations

About the issues of applying PSF corrections

Correcting for the PSF is an inverse problem

- theoretically, the solution of the inverse problem is ill-defined
- in practice, for regular images, the solution is close to unique

- The usual deconvolution algorithm for us is the Richardson-Lucy-Algorithm
  - It conserves flux
  - It converges to towards the true image *if it converges*

About the issues of applying PSF corrections

When does the RL algorithm not converge? For noisy images.

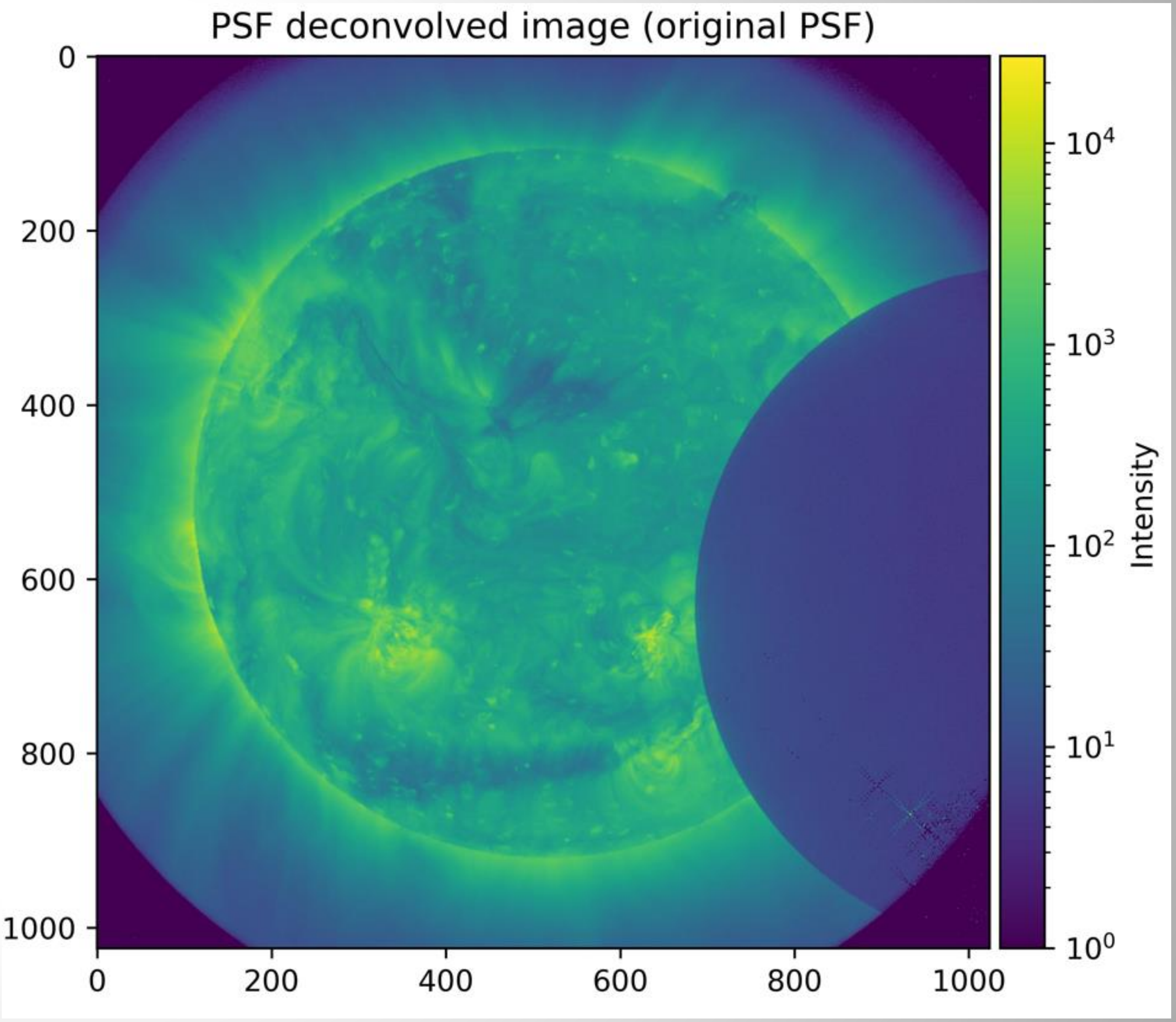
How can it be solved:

increasing the signal to noise => stacking and rebinning of images

⇒This has to be done by the user, as the way of stacking and rebinning depends on the scientific task

⇒For flares, a forward model should be used to find the correct solution

(but do not use the RL algorithm for flares at full resolution images – the bad convergence at noise together with the that the RL algorithm preserves the total counts will underestimate the flare intensities)



Deriving the PSF

<u>4 ways:</u>

- Theoretical modelling of the instrument
  - Can be quite exact
  - But does not include unknown imperfections
- Measuring the PSF from a point source
  - Very exact (if the PSF is shift-invariant)
  - But, due to the limited intensity, one can typically only derive the PSF core
- Using blind deconvolution algorithms
  - High total intensity available
  - But the solution is typically not unique – it depends on the constraints + the initial PSF guess
- Using a blind deconvolution model on eclipse images
  - High total intensity available – allows to fit the PSF tail
  - Often, a presumed functional form of the PSF – a wrong form can create entirely wrong results

Deriving the PSF from partially occulted images

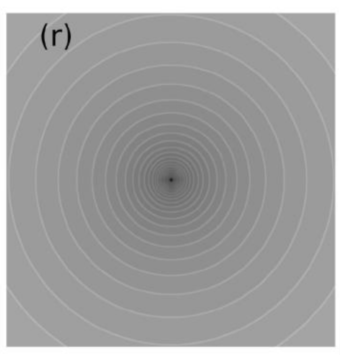
- For details on the algorithm, look at Hofmeister et al., 2022, *Deriving instrumental point spread functions from partially occulted images*, https://opg.optica.org/josaa/abstract.cfm?uri=josaa-39-12-2153&origin=search
- The intensity measured in each pixel in an image is a superposition of the
  - portion of its intrinsic intensity that is not scattered away
  - the scattered photons it receives from all other pixels in the image
  - (+ photon noise).
- As Equation,

$$I_{\mathrm{o},\boldsymbol{r}} = \sum_{\boldsymbol{\Delta r}} I_{\mathrm{t},\boldsymbol{r}-\boldsymbol{\Delta r}}\, \mathrm{psf}_{\boldsymbol{\Delta r}} + \epsilon$$

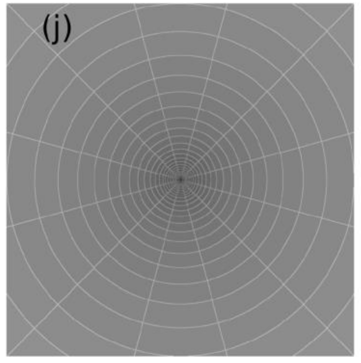
- where the index o stands for observed intensities, t for the unknown true intensities, r for a specific given location of a pixel in the image, delta r a direction vector from that location, and epsilon is the photon noise.

Deriving the PSF from partially occulted images

- *A good discretization of the PSF:*
  - We do not want to determine one psf coefficient for each pixel in the PSF. It is sufficient to derive one coefficient for a PSF segment if it only varies only slightly within that segment.
  - From this follows that we want to have
    - Smaller regions close to the core of the PSF
    - Larger regions in the PSF tail
  - E.g.,



or



  - , where each segment corresponds to one PSF coefficient

Deriving the PSF from partially occulted images

- *A good estimate for the true intensities.*
- We know the true intensities in
  - occulted pixels. There, it is simply zero.
  - pixels in homogenously illuminated regions. There, the observed intensity is equal to the true intensity

$$I_{\mathrm{o},\boldsymbol{r}} = I_{\mathrm{t},\boldsymbol{r}} \sum_{\boldsymbol{\Delta r}} \mathrm{psf}_{\boldsymbol{\Delta r}} = I_{\mathrm{t},\boldsymbol{r}}.$$

  - Thus, if we have a homogeneously illuminated image that is partially occulted, we have a good approximation of the true intensities everywhere except of close to the illuminated edge.

The intensities close to the illuminated edge can be iteratively derived.

Deriving the PSF from partially occulted images

Fitting the PSF iteratively

$$I_{\mathrm{o},\boldsymbol{r}} = I_{\mathrm{t},\boldsymbol{r}} \sum_{\boldsymbol{\Delta r}} \mathrm{psf}_{\boldsymbol{\Delta r}} = I_{\mathrm{t},\boldsymbol{r}}$$

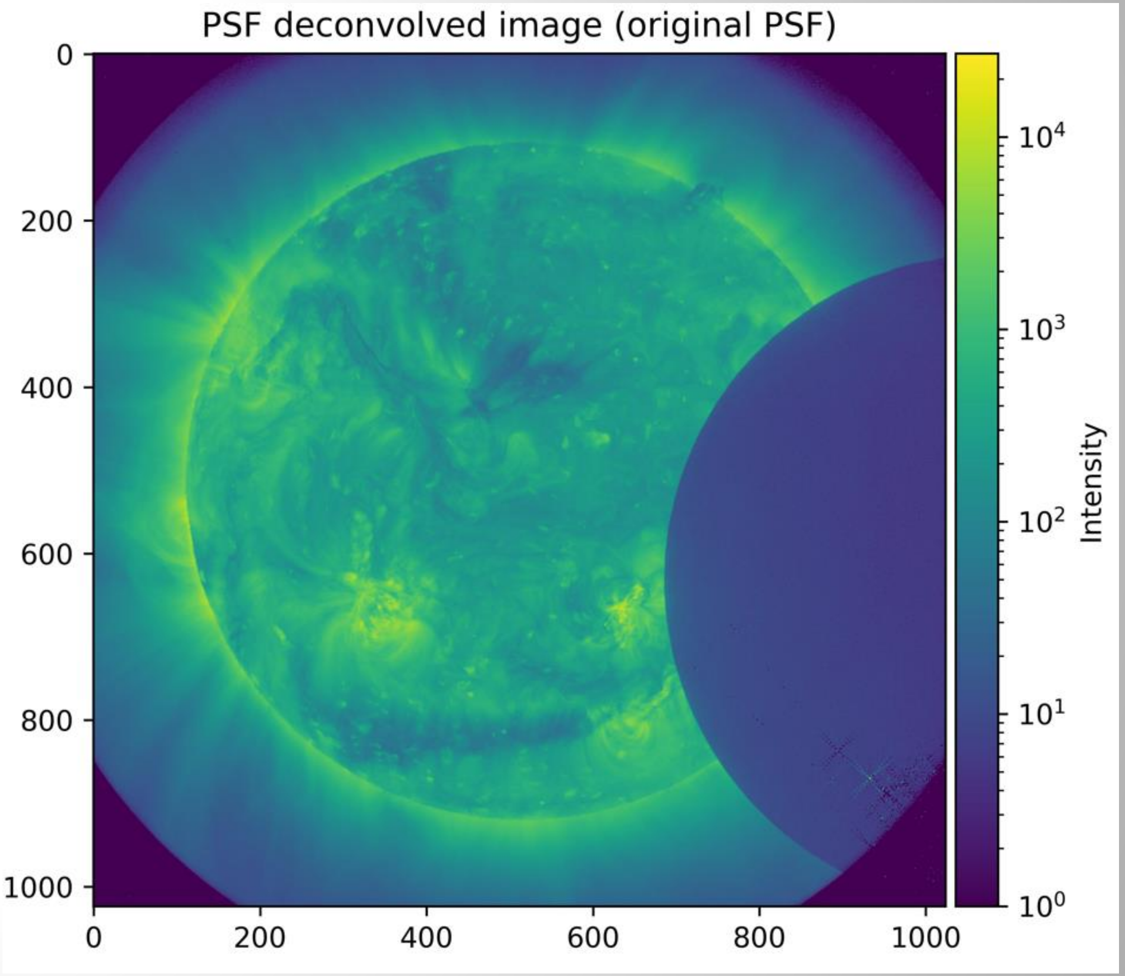
- We fit for the PSF by solving

$$I_{\mathrm{o},\boldsymbol{r}} = \sum_{\boldsymbol{\Delta r}} I_{\mathrm{t},\boldsymbol{r}-\boldsymbol{\Delta r}}\, \mathrm{psf}_{\boldsymbol{\Delta r}} + \epsilon$$

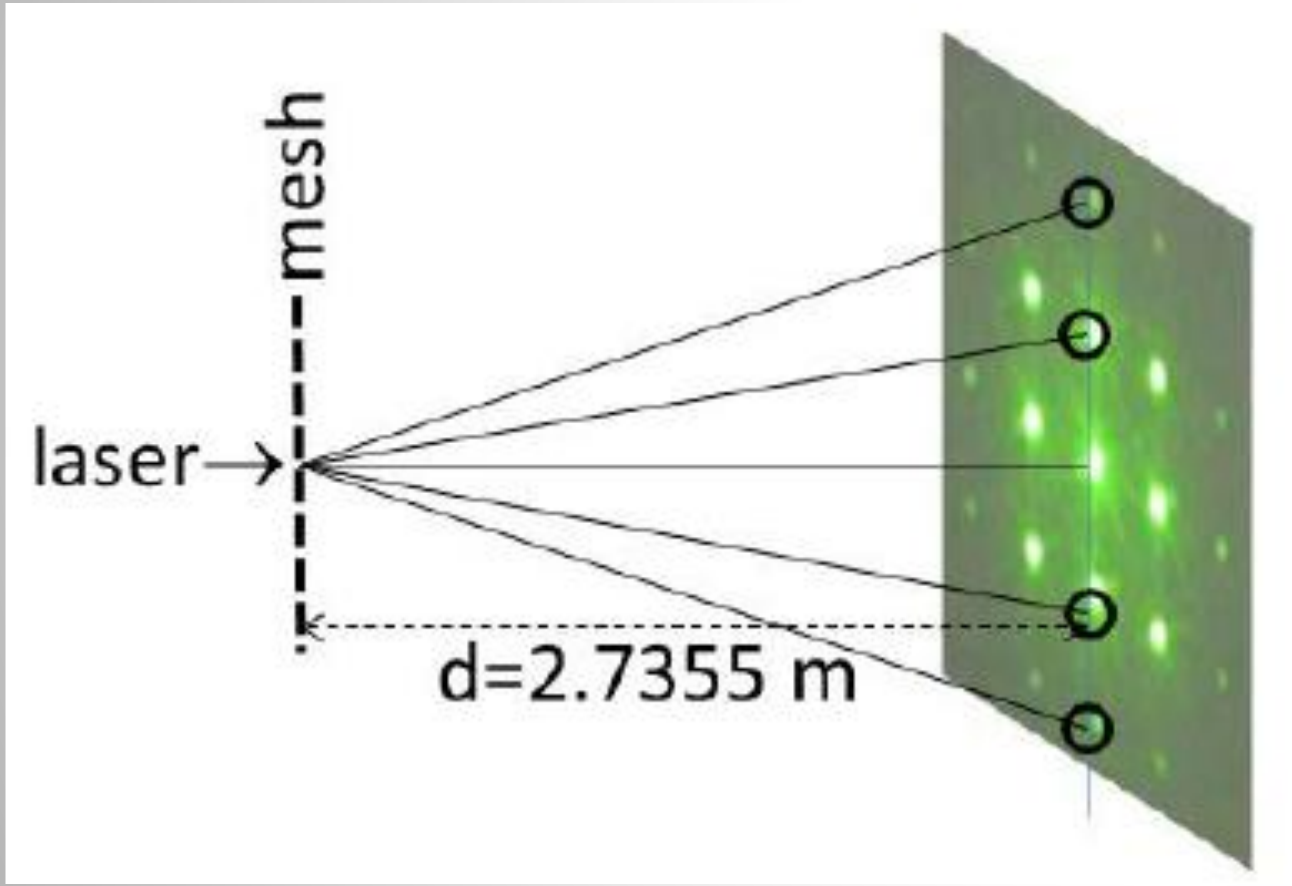
– We use the fitted PSF to reconstruct a better guess of the true intensities close to the eclipse edge

Important note:

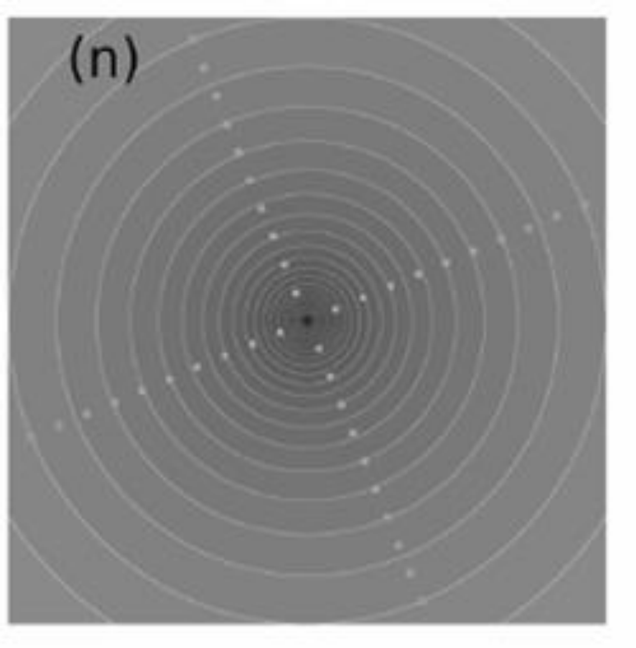
- The PSF coefficients in the tail depend only very slightly on the intensity distribution close to the eclipse edge.
- Thus, for the PSF tail, an iterative approach is not even required – they are always very accurate



What if we have a diffraction pattern from a mesh?



?



Deriving the PSF from partially occulted images

- **The algorithm also allows to revise a PSF.**
- The previous equation,

$$I_{\mathrm{o},\boldsymbol{r}} = \sum_{\boldsymbol{\Delta r}} I_{\mathrm{t},\boldsymbol{r}-\boldsymbol{\Delta r}}\, \mathrm{psf}_{\boldsymbol{\Delta r}} + \epsilon$$

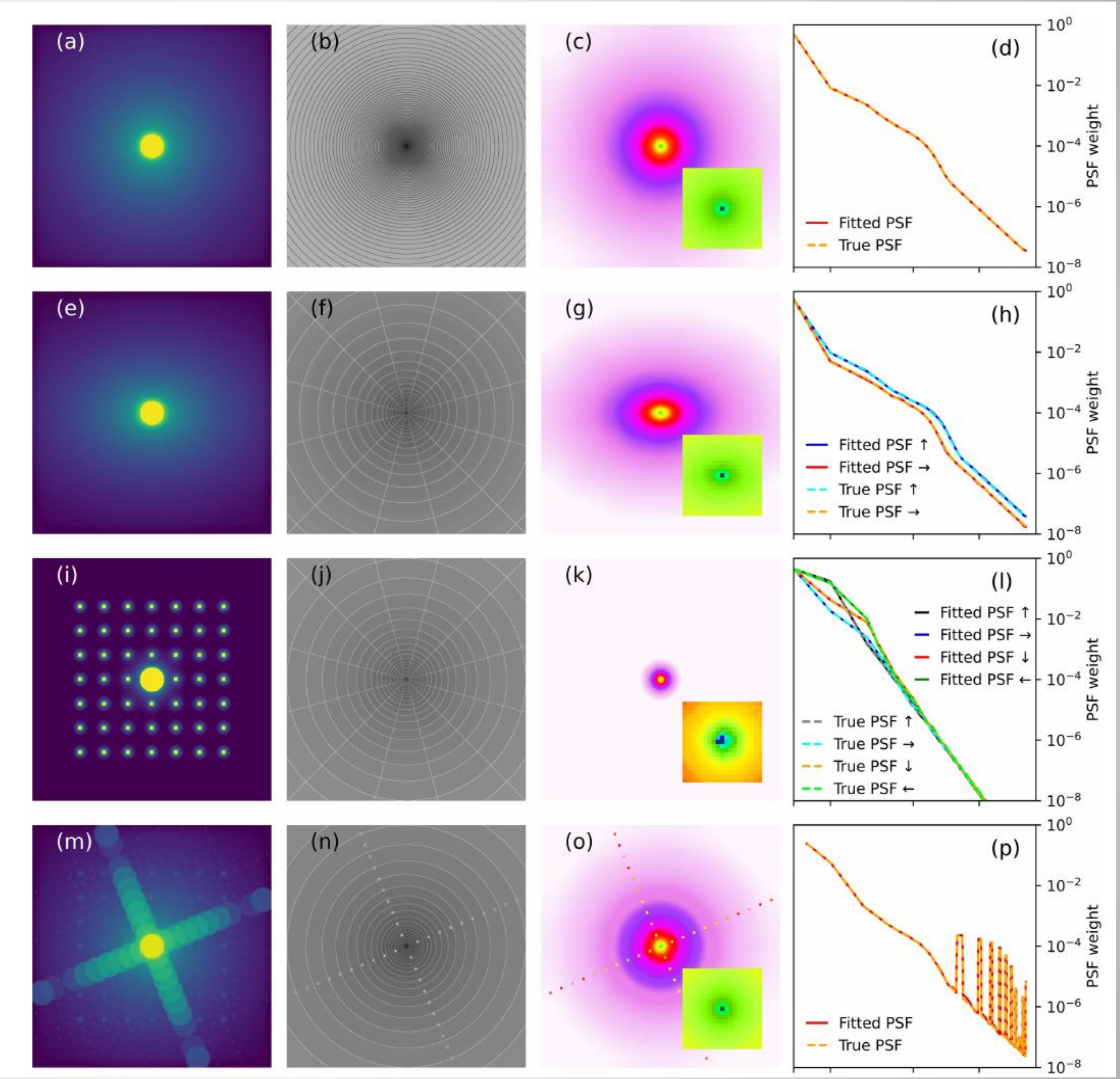
- than changes to:

$$I_{\mathrm{o},\boldsymbol{r}} = \sum_{S} \widetilde{\mathrm{psf}}_S \sum_{\boldsymbol{\Delta r}\ \mathrm{in}\ S} I_{\mathrm{t},\boldsymbol{r}-\boldsymbol{\Delta r}} + \left(1 - \sum_{S} n_S\, \widetilde{\mathrm{psf}}_S\right) \sum_{\boldsymbol{\Delta r}} I_{\mathrm{t},\boldsymbol{r}-\boldsymbol{\Delta r}}\, \overline{\mathrm{psf}}_{\boldsymbol{\Delta r}}. \quad (6)$$

- Bar(psf) is the already existing estimate of the PSF, and tilde(psf) the coefficients we fit for. S relates to a PSF segment, and n_S are the pixels in the segment.

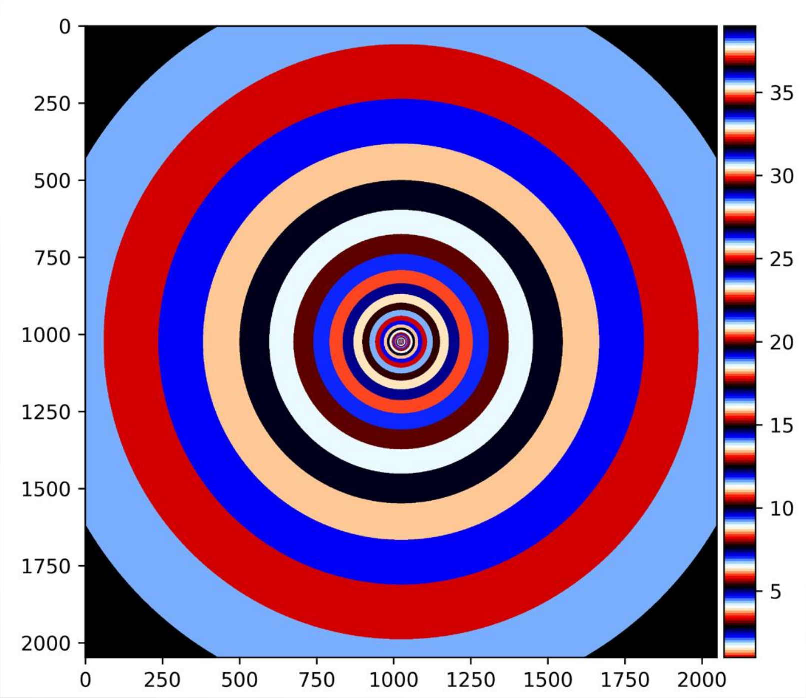
Deriving the PSF from partially occulted images

- **Some examples:**
- Columns from left to right:
  - Observed image
  - PSF discretization
  - Fitted PSF
  - Comparison of the fitted and true PSF along a horizontal slice
- Rows from top to bottom:
  - Cylindrically symmetric PSF
  - Elliptical PSF
  - PSF containing coma and astigmatism aberrations
  - PSF containing a simple diffraction pattern
- For a noise analysis, see the paper.



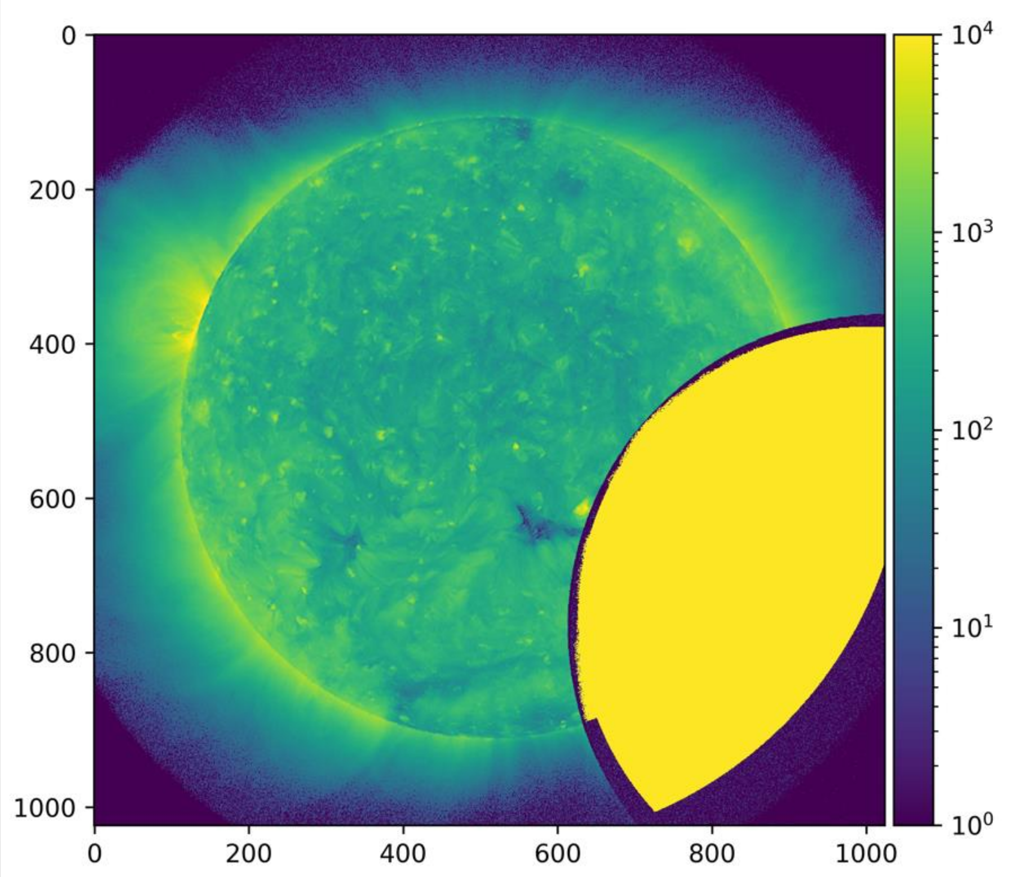
A first (easy...) test bed: AIA

1. Rebin the images to 1k x 1k for speed up
2. PSF segmentation: 40 shells.
   - PSF has to be double the size of the images to allow for scattered light across the entire image -> 2k x 2k



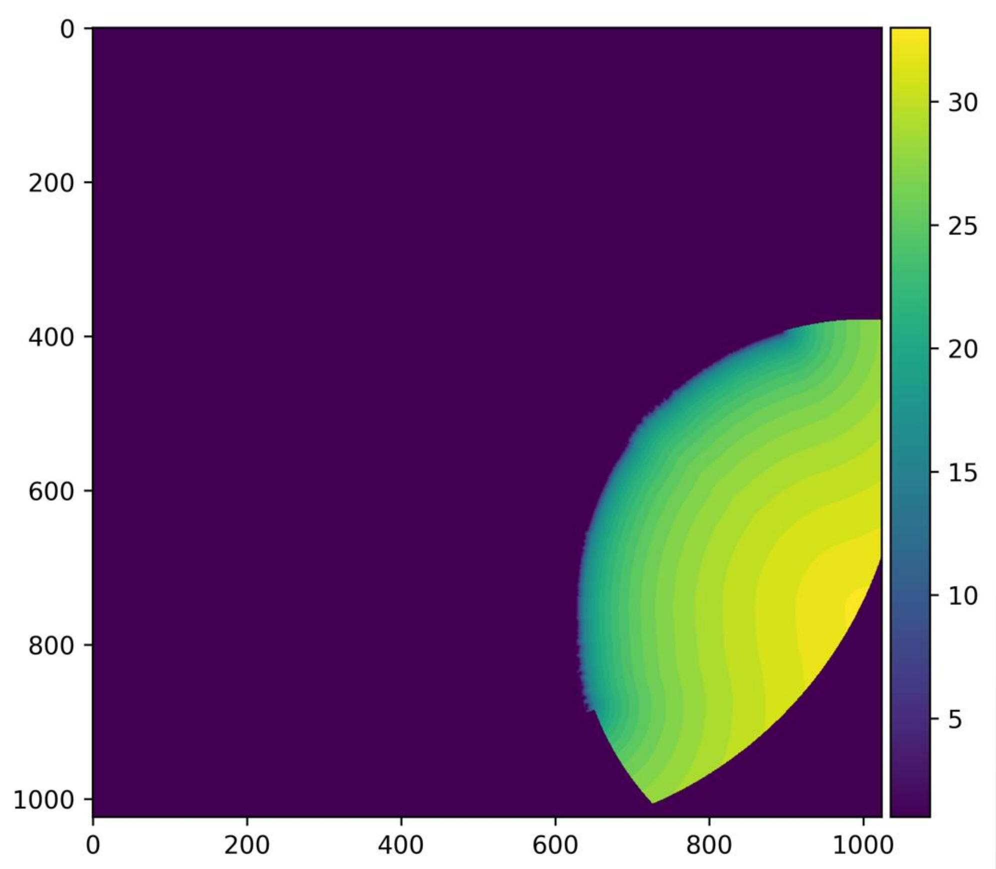
A first (easy...) test bed: AIA

1. Rebin the images to 1k x 1k for speed up
2. PSF segmentation: 40 shells.
3. Identify occulted pixels



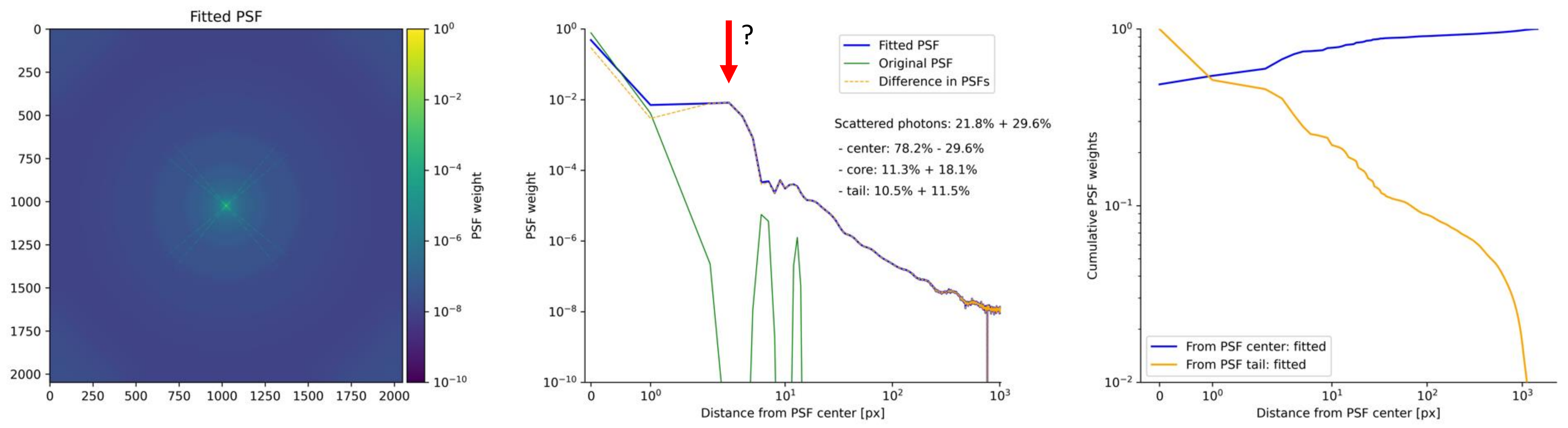
A first (easy…) test bed: AIA

1. Rebin the images to 1k x 1k for speed up
2. PSF segmentation: 40 shells.
4. Select occulted pixels for fitting
    - Stratified choice of 10000 pixels in the eclipse region



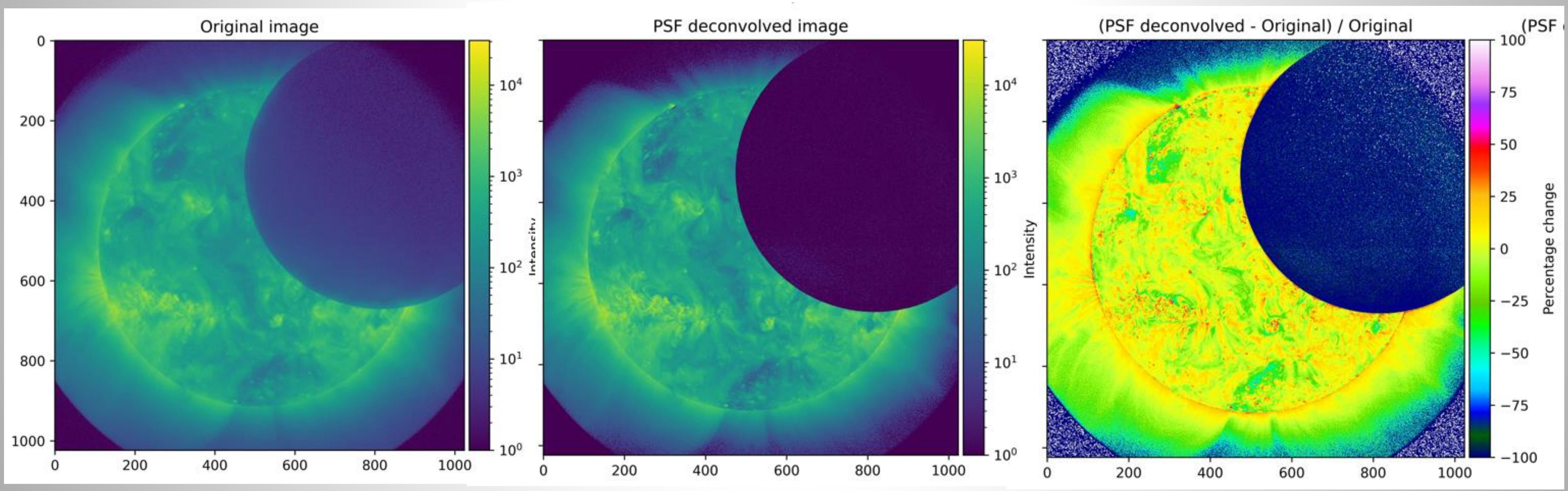
A first (easy...) test bed: AIA

1. Rebin the images to 1k x 1k for speed up
2. PSF segmentation: 40 shells.
4. Select occulted pixels for fitting
5. Fit the PSF, derive updated approximated true images by deconvolving with the PSF, and iterate



A first (easy...) test bed: AIA

How to evaluate the goodness of the fit? – look at the intensity in the eclipse



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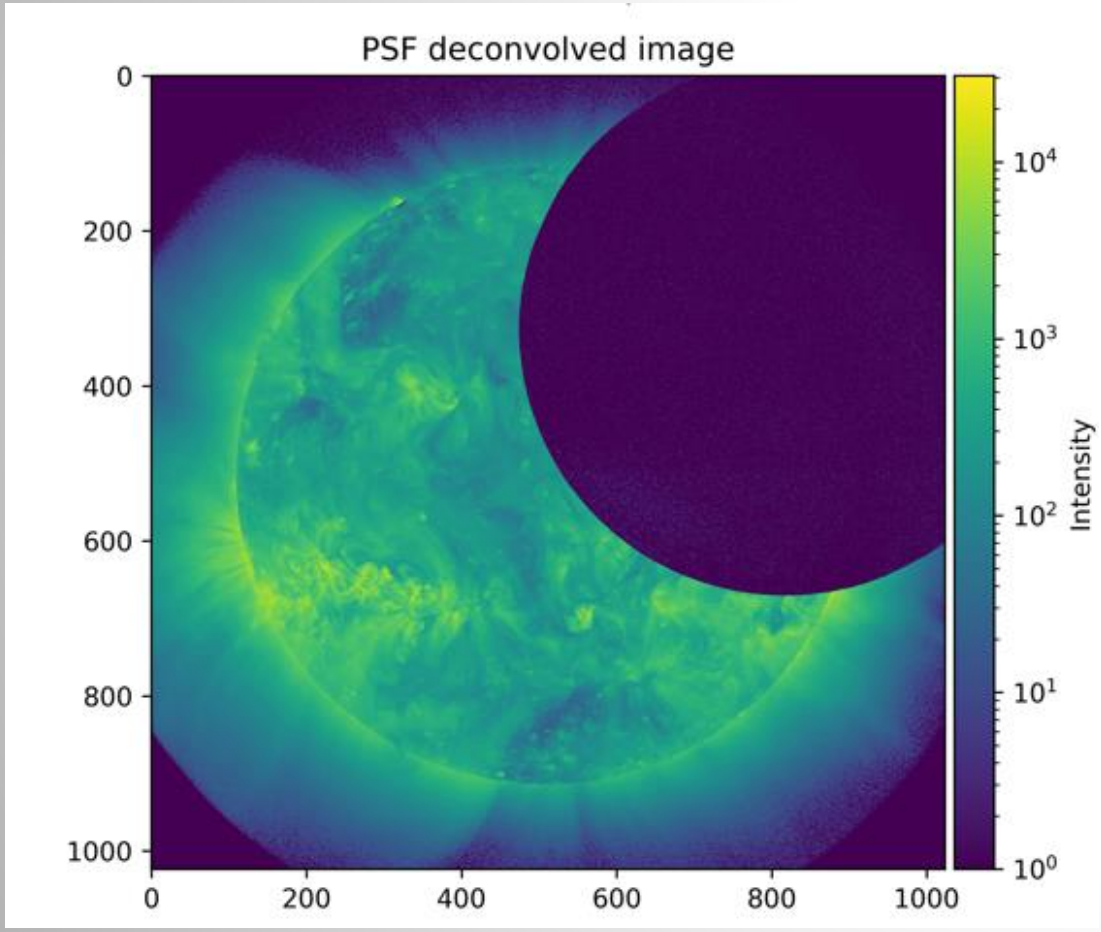
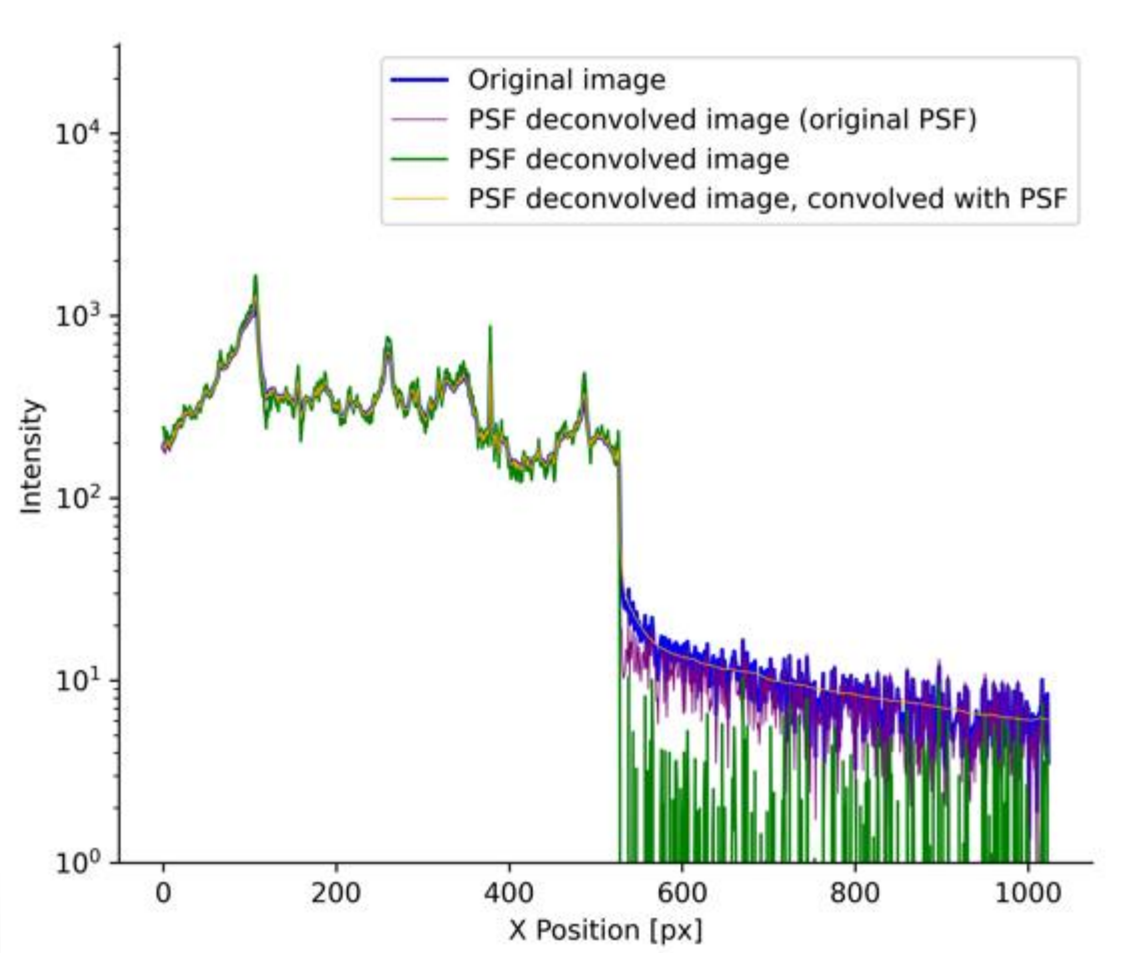
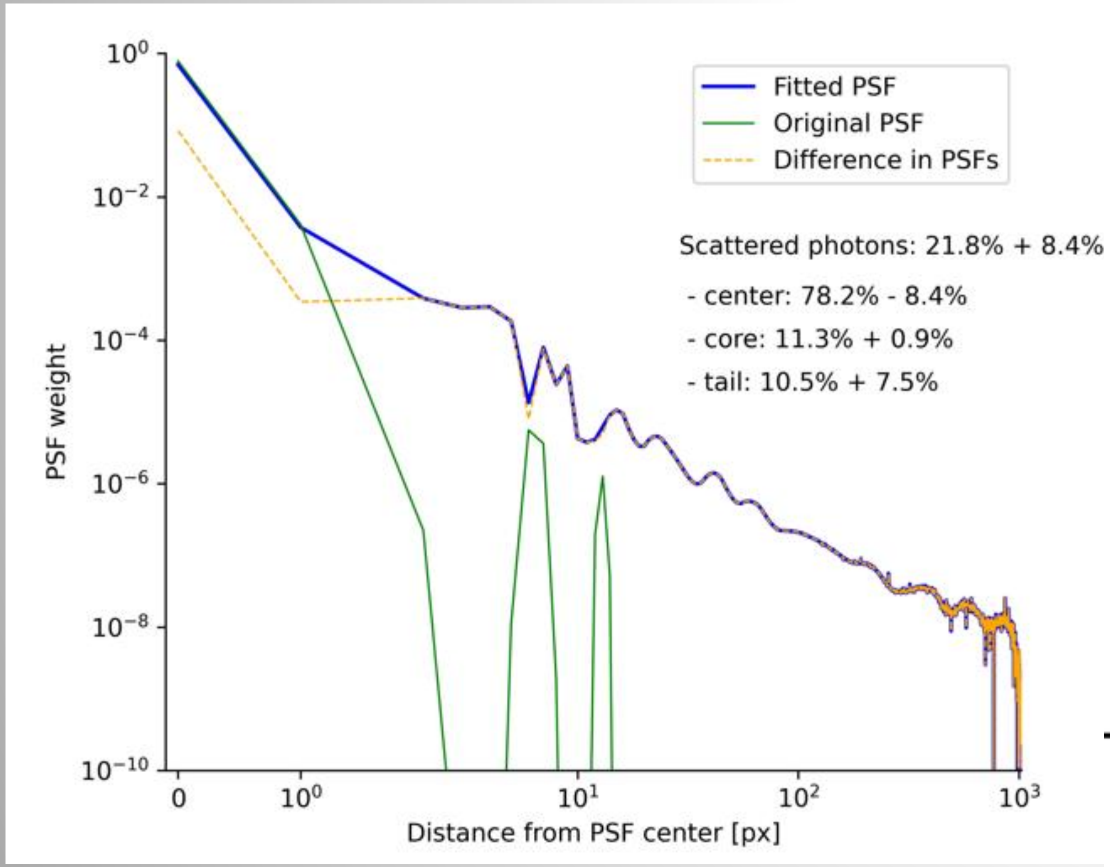
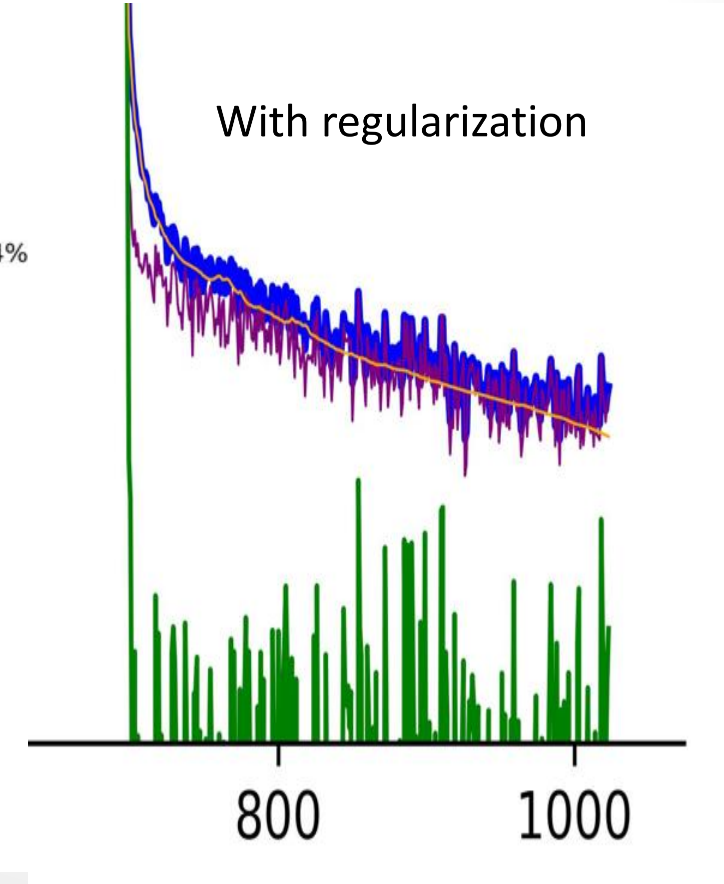


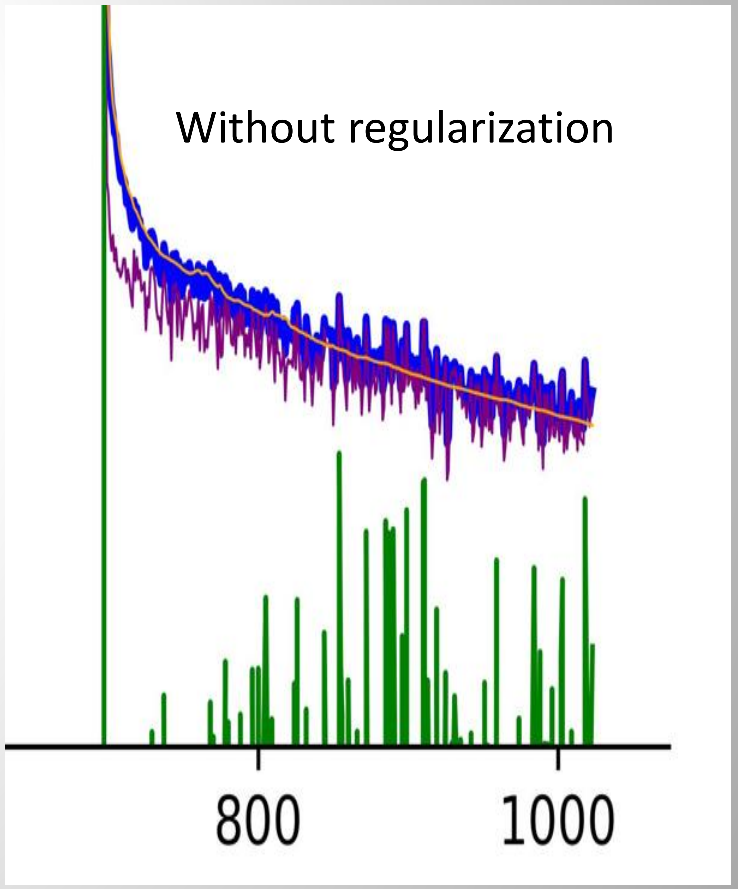


A first (easy...) test bed: AIA

Do you remember the bump in the PSF before? Can we reduce this bump?
- Add the total amount of scattered light as a regularization parameter







Let’s start with EUI HRI 174

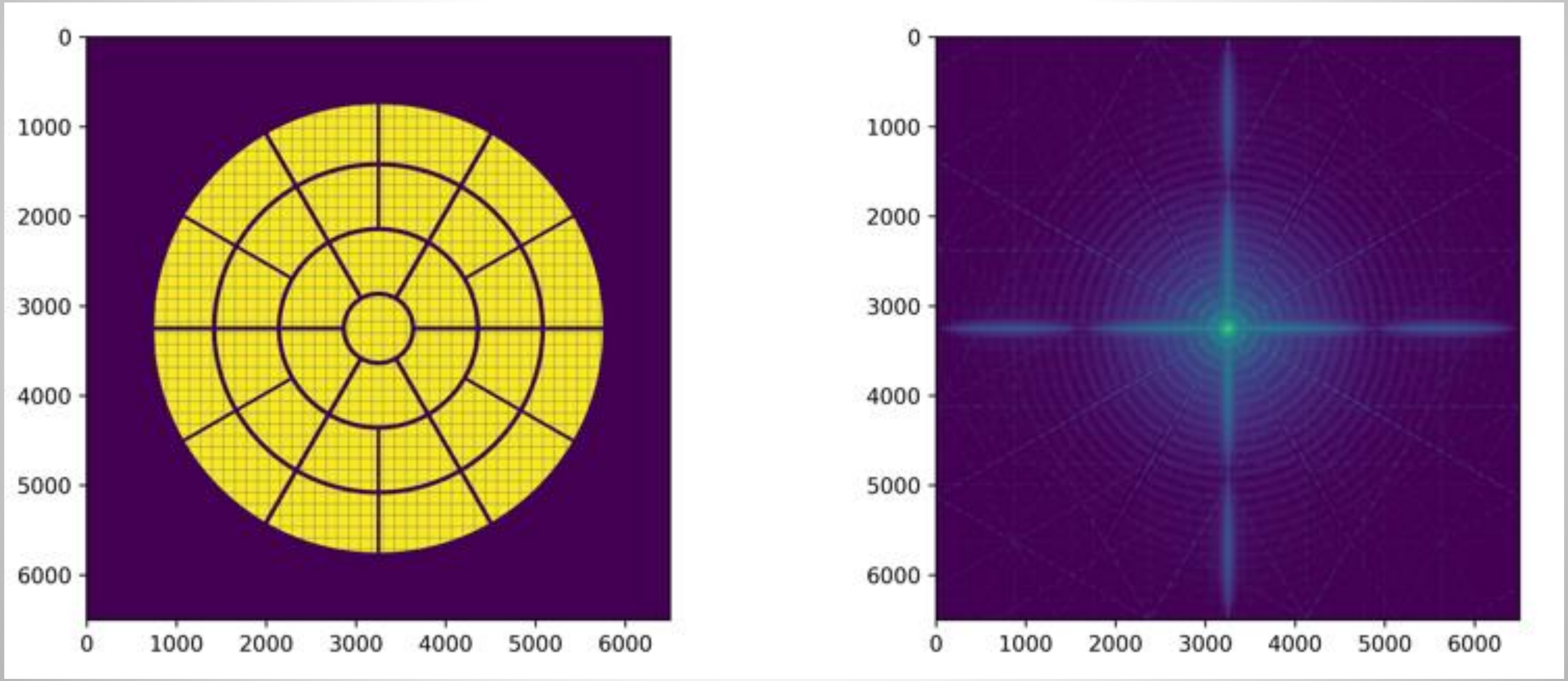
We only have a Mercury transit -> fitting the PSF is more challenging

Let’s fit:

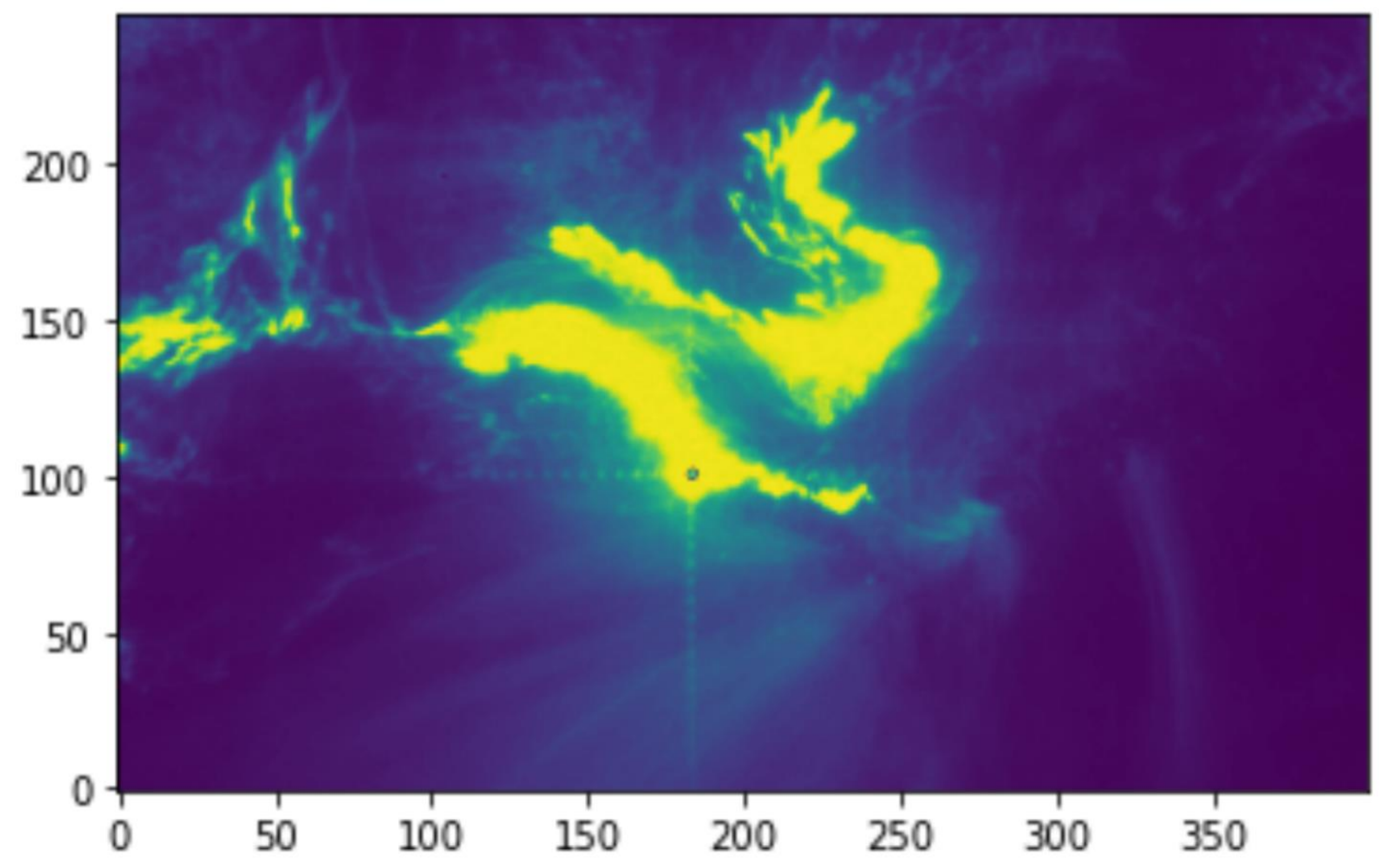
1: The diffraction pattern from a flare
2. The PSF core from the diffraction pattern
3. The PSF tail

Let’s start with EUI HRI 174

What do we expect for the HRI diffraction pattern?



Let’s start with EUI HRI 174



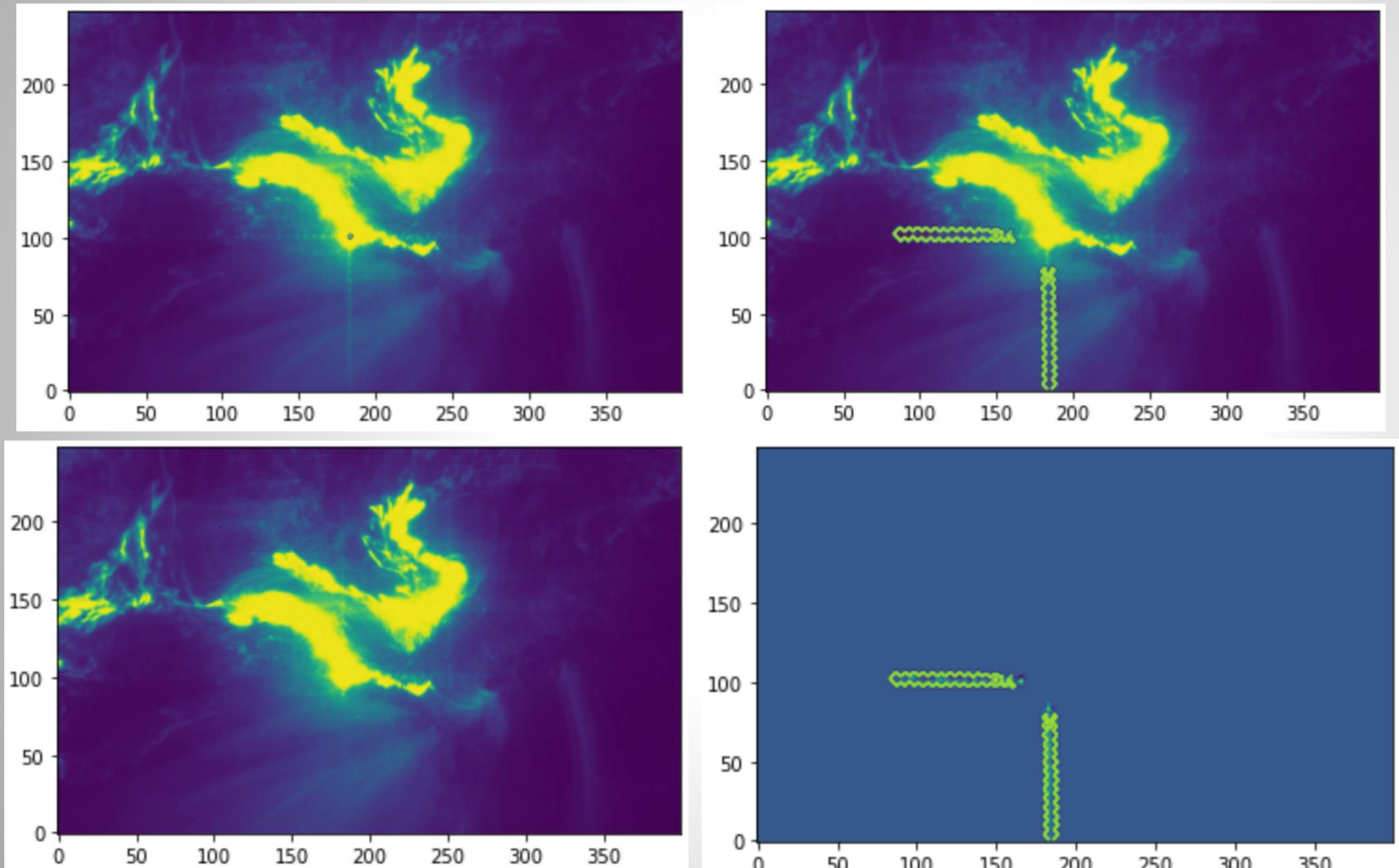
Issues:

- The image is highly saturated
- We do not know the exact location of (the) flaring pixel(s)
- Background without diffraction pattern is not known
- We do not know the intensity of the flaring pixel

But:

- Good enough to calibrate the diffraction pattern

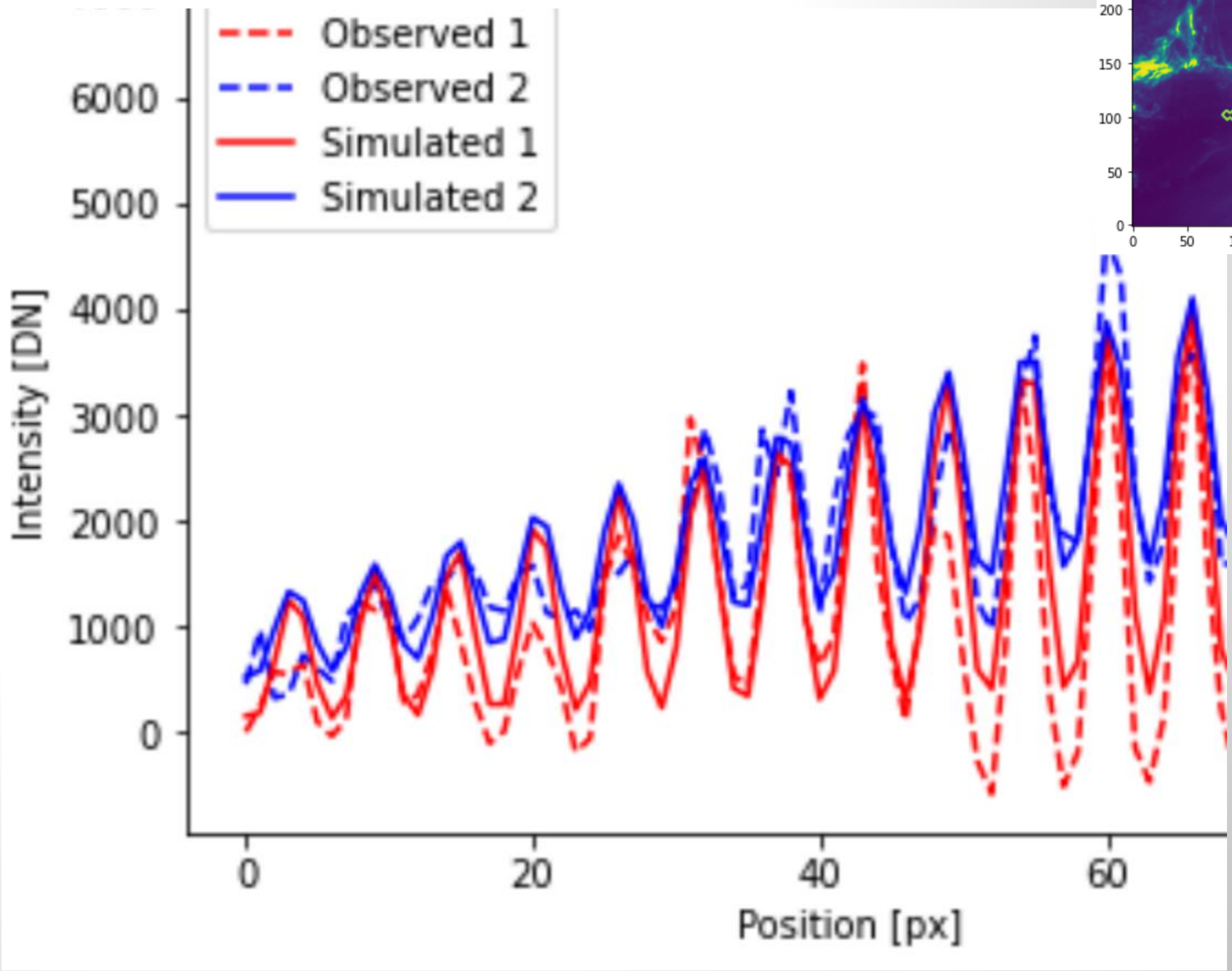
Let’s start with EUI HRI 174

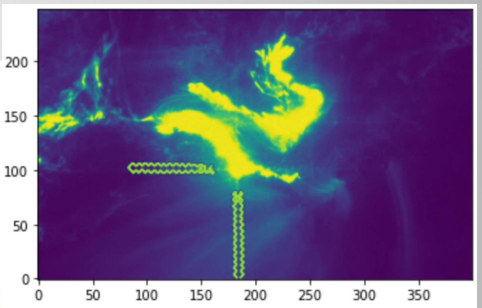


Let’s start with EUI HRI 174

The shape of the PSF core is not only visible in the PSF center,
but due to the convolution with the diffraction pattern around each diffraction peak

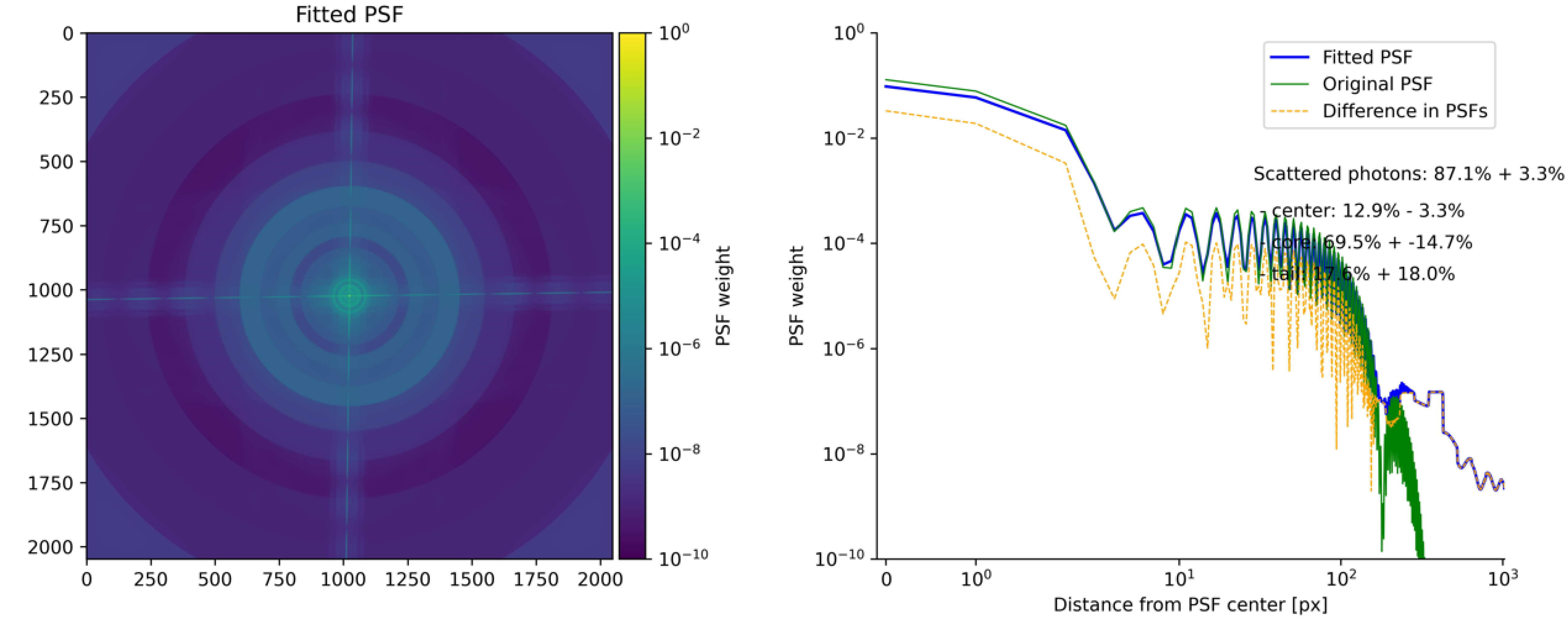
- let’s try to fit it:
  - Sigma_x = 1.1 px
  - Sigma_y = 1.6 px
  - Assymetric PSF core??
  - Or two flaring pixels?..
- Need more time to resolve this





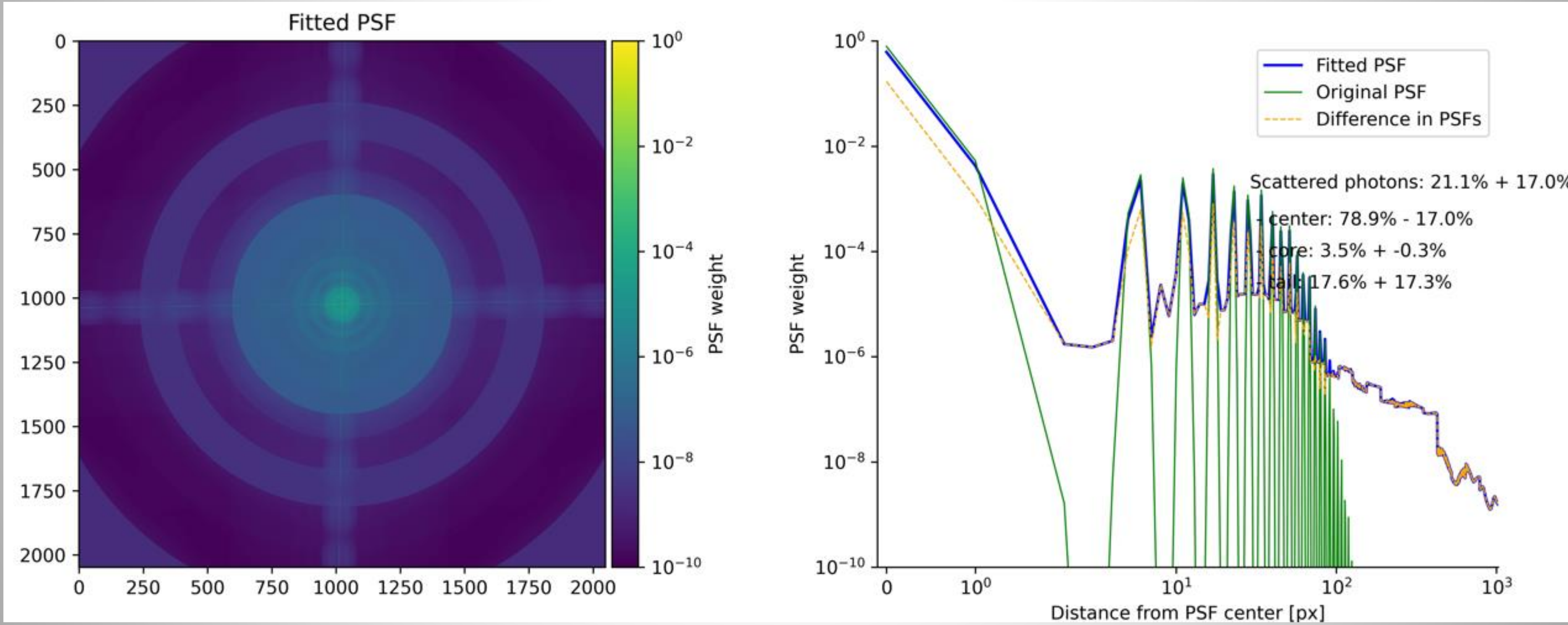
Let’s start with EUI HRI 174

Add the Mercury transit images to fit the tail



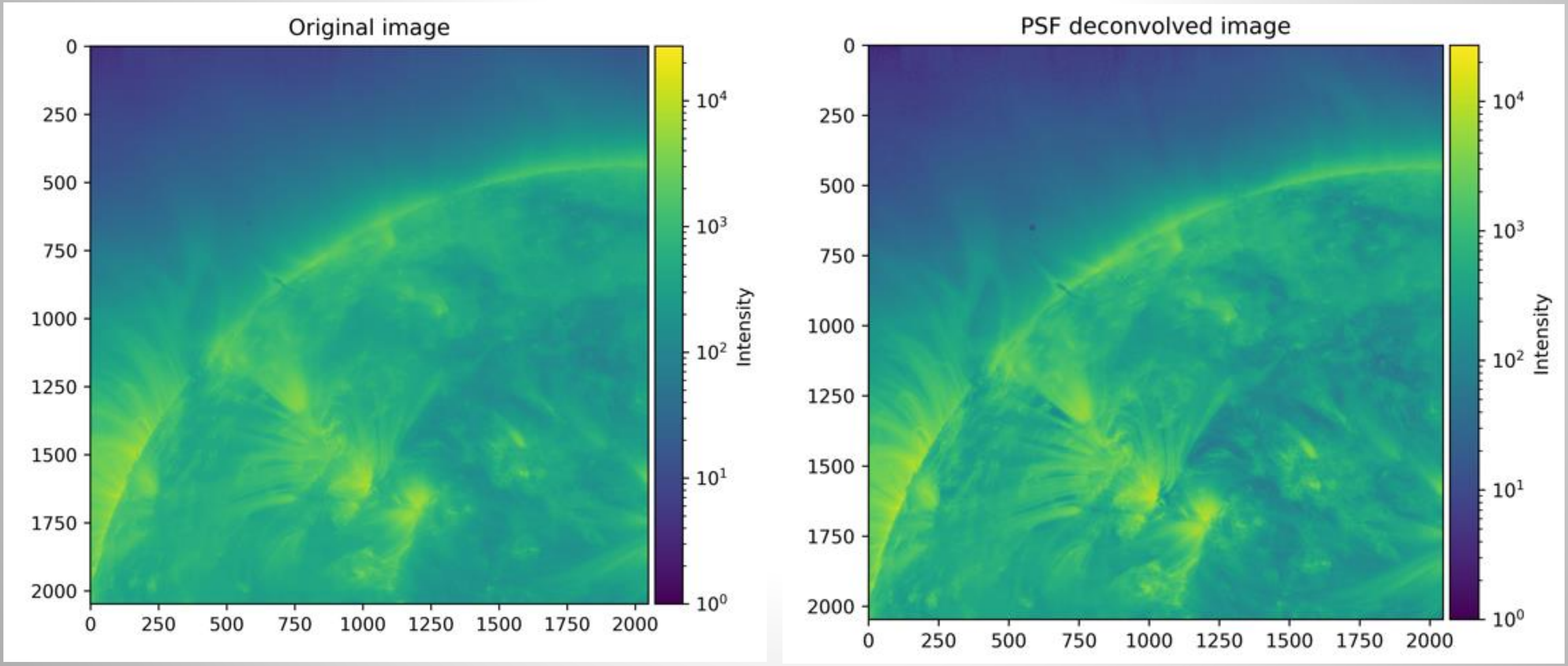
Let’s start with EUI HRI 174

Add the Mercury transit images to fit the tail – without assuming the core



Let’s start with EUI HRI 174

How do the images change?



Let’s start with EUI HRI 174

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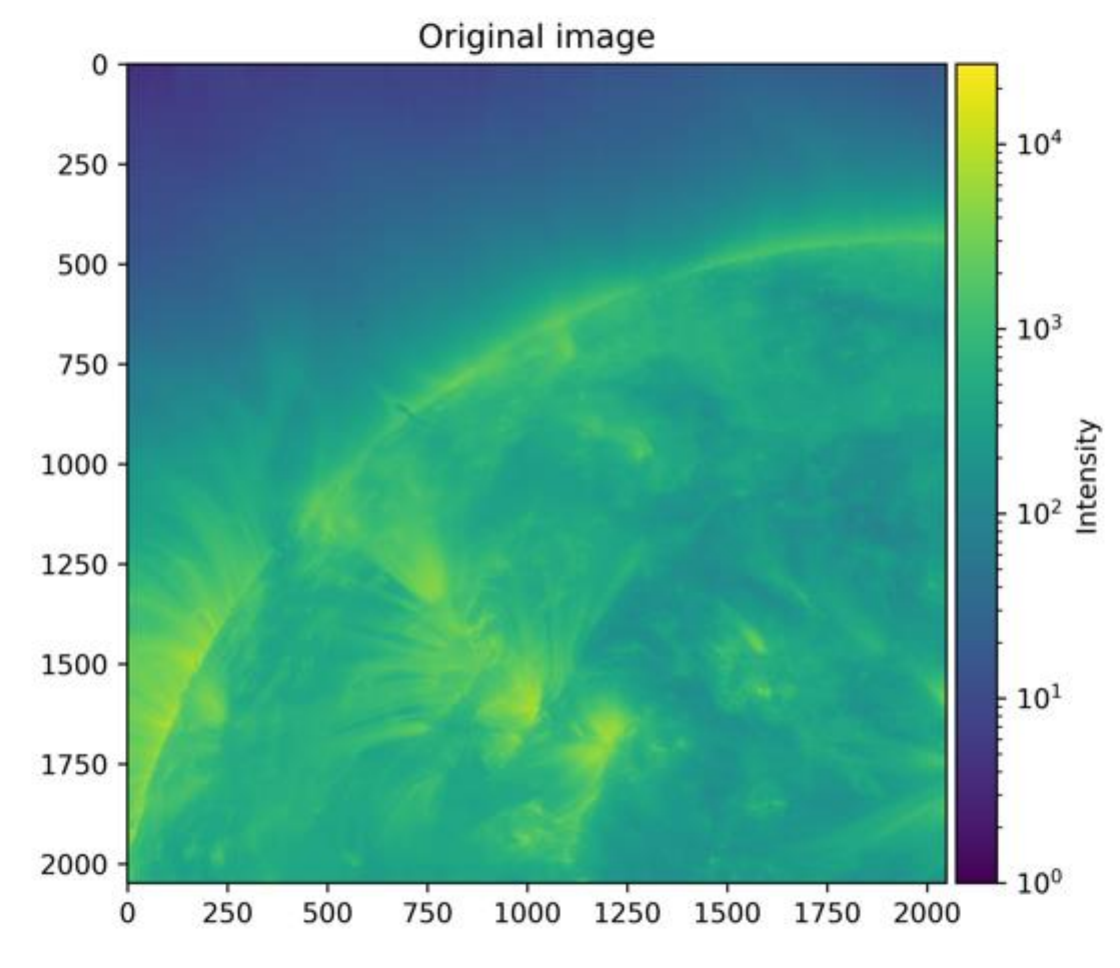

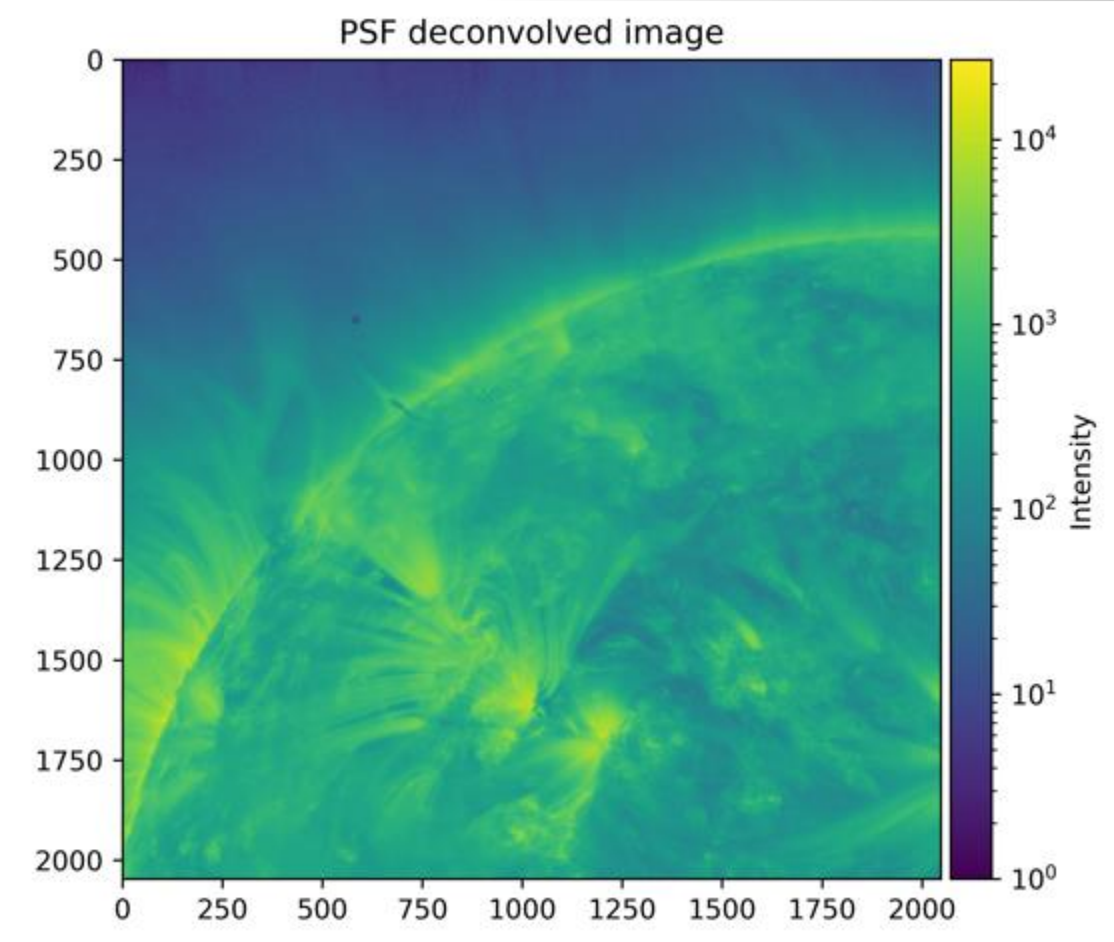

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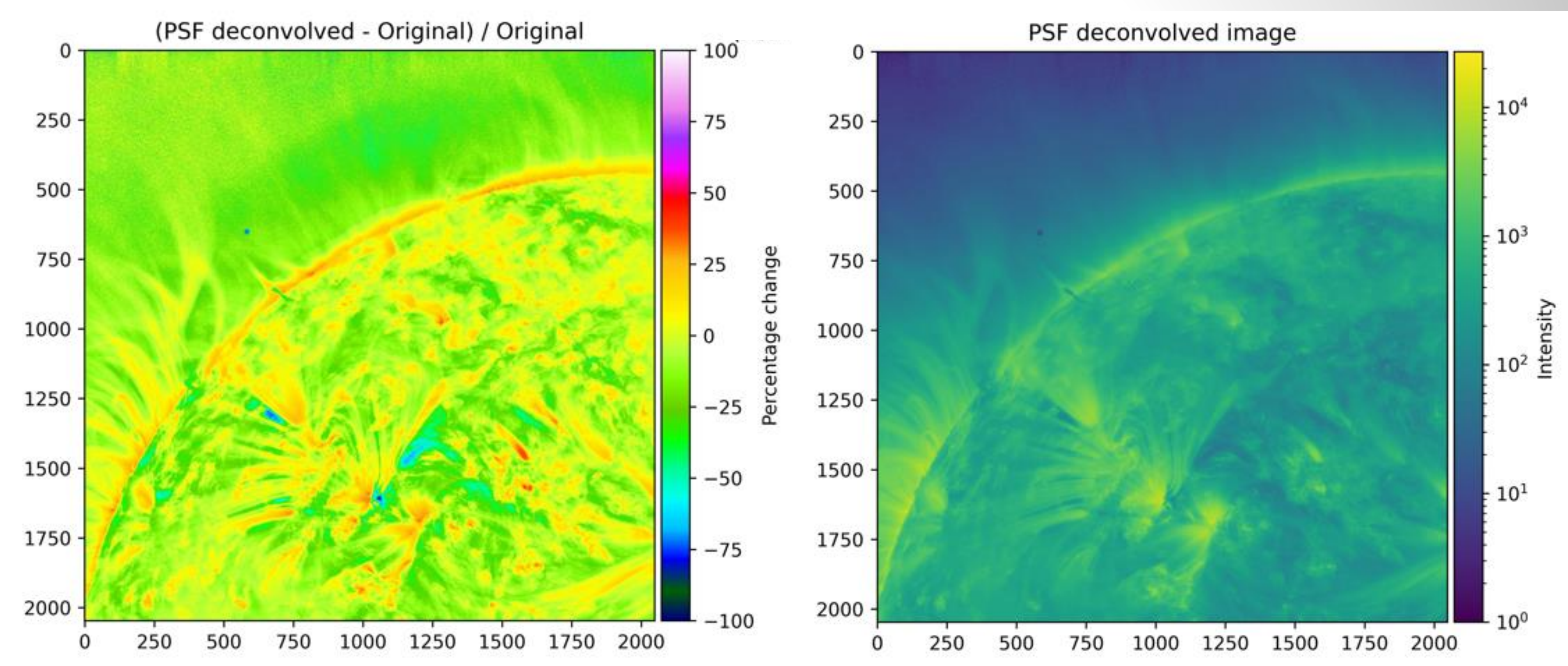

Summary

PSF corrections are important for solar physics

It has the potential to change your results

Deriving the PSF for EUI will be an interesting and challenging task

- we have to combine many different methodologies to derive an accurate PSF

- but it is fun - and a great way to learn a lot about the instrument