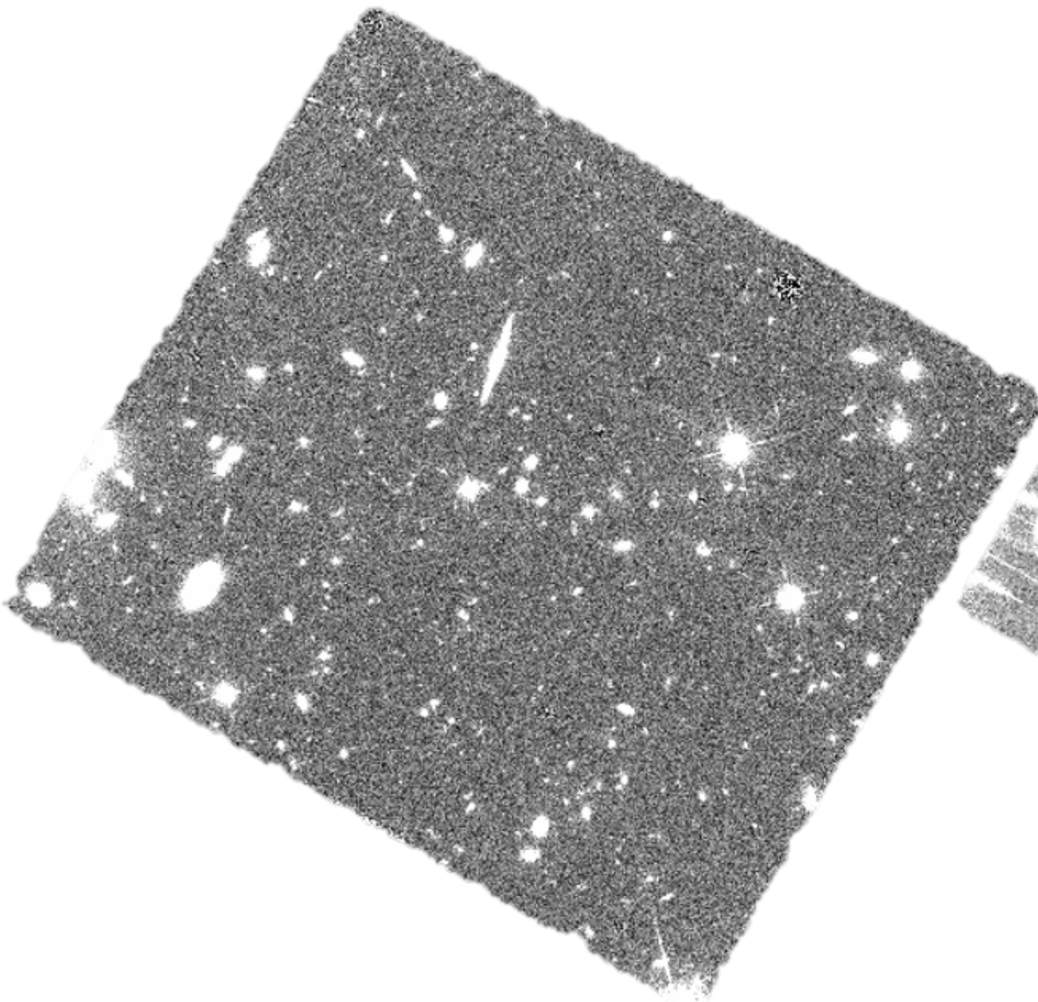
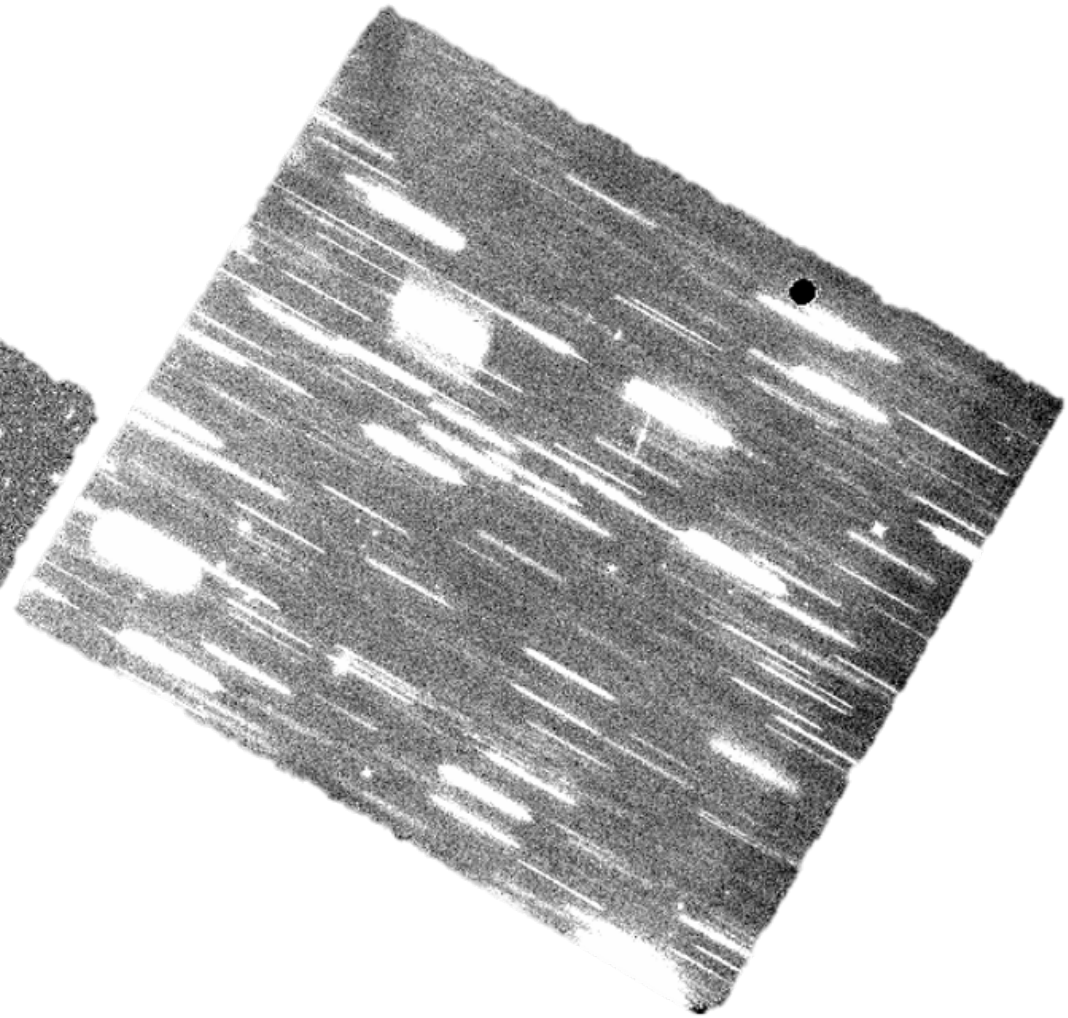
Introduction to spectroscopic data reduction

Jens-Kristian Krogager | IFAS10 | 3 – 10 Nov 2025, IUCAA, Pune, India

Different types of data

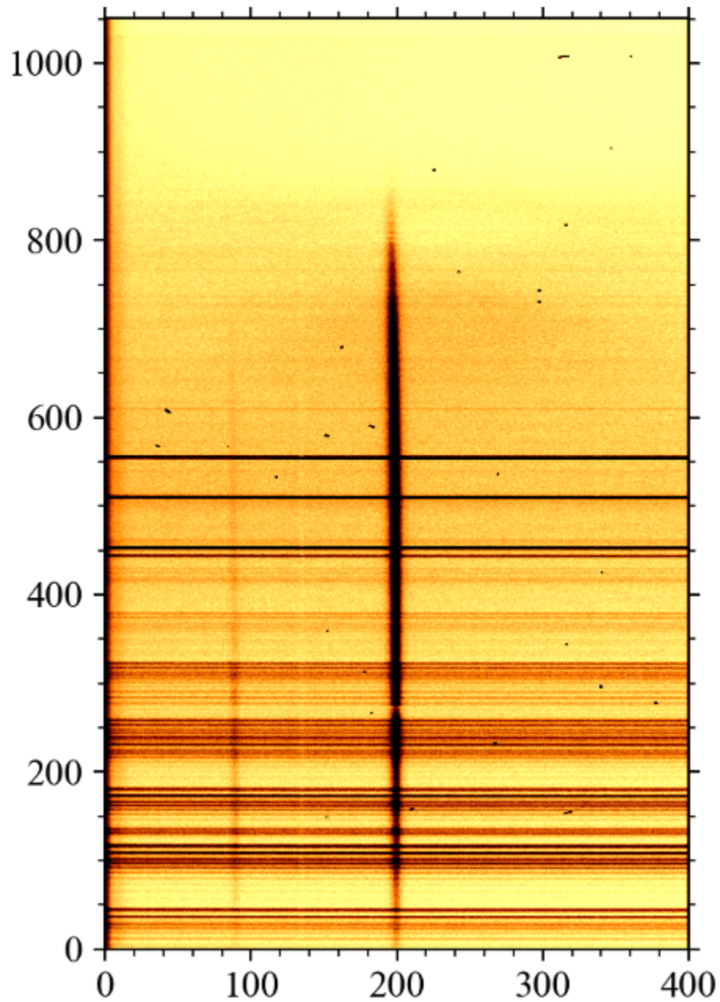
Slit-less spectroscopy



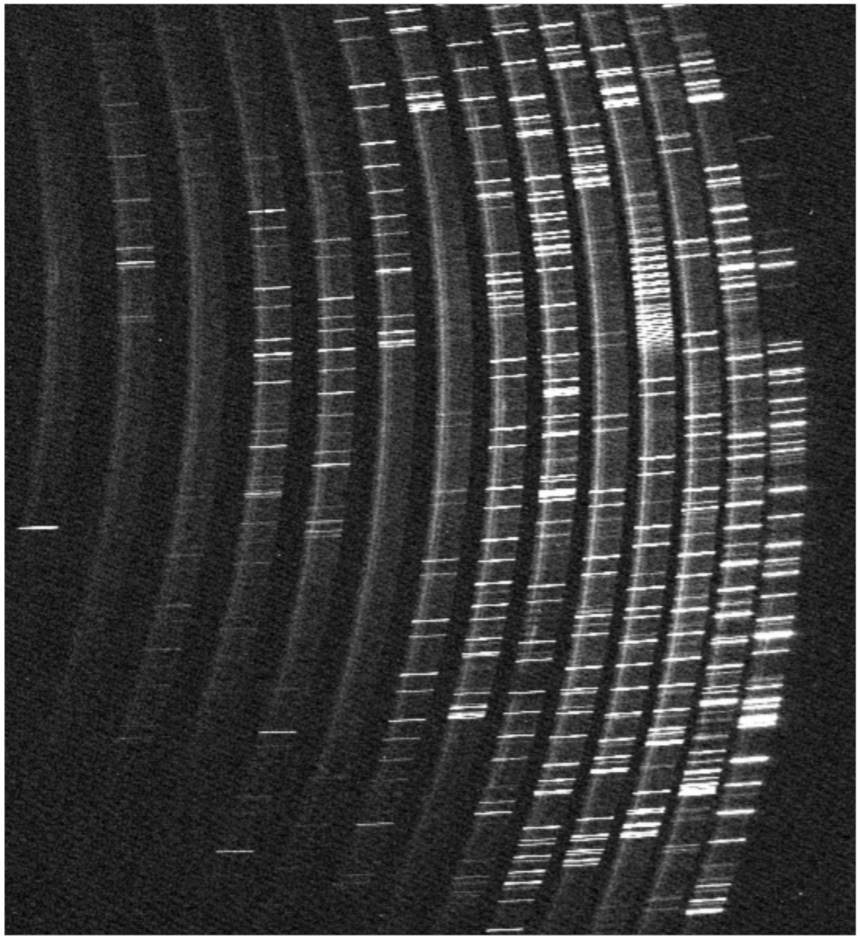


Different types of data

Long-slit spectroscopy

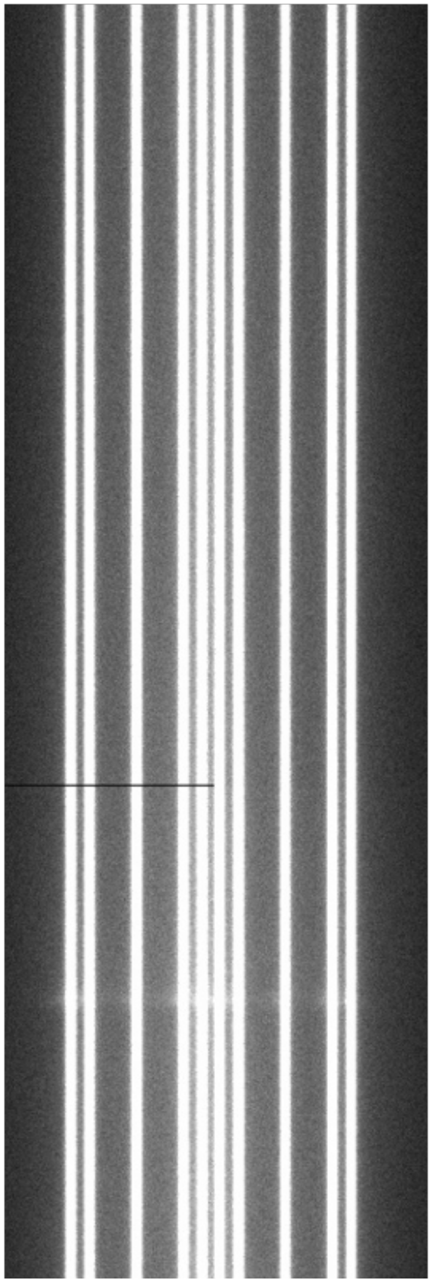


Echelle spectroscopy

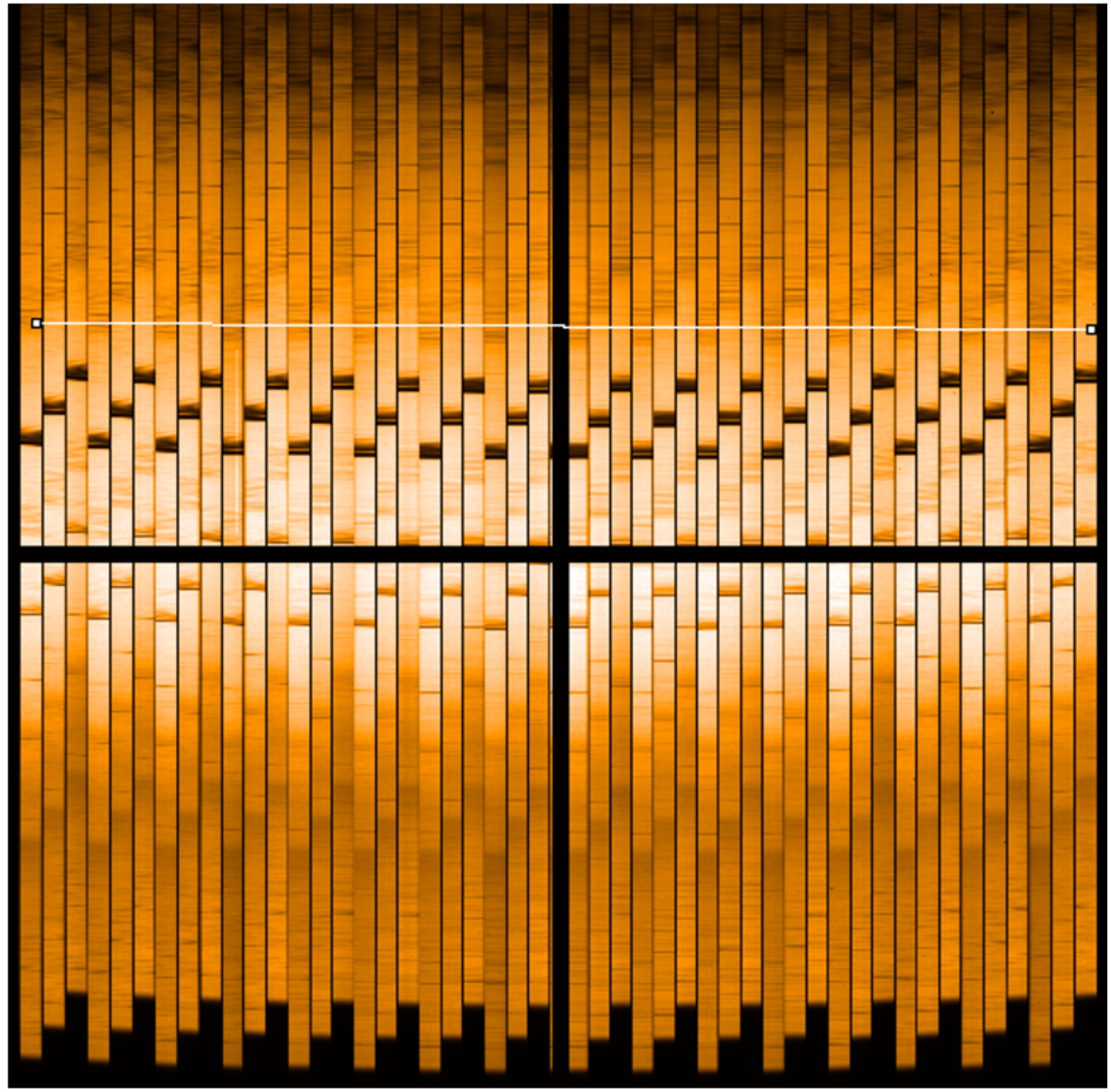


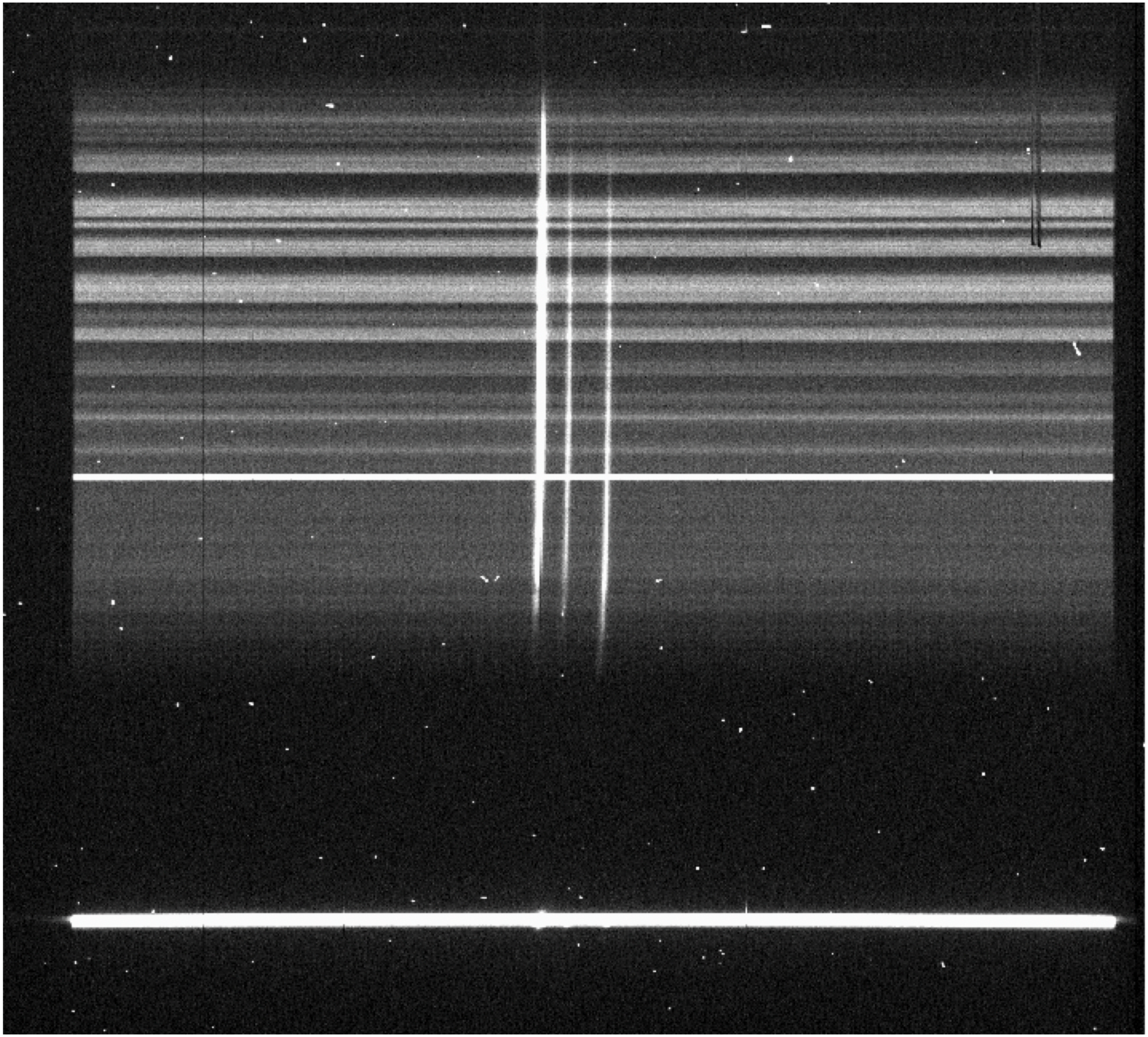
Different types of data

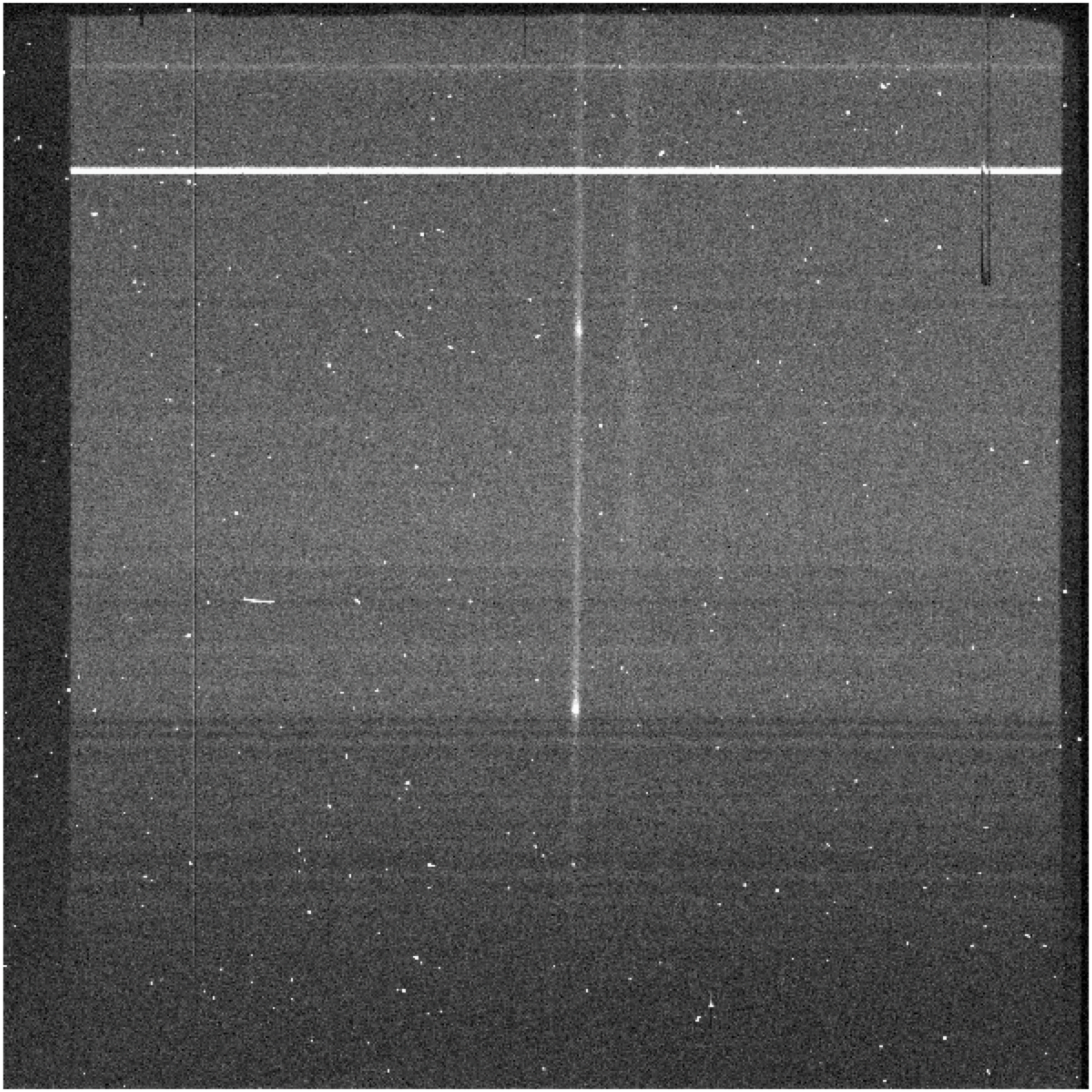
Multi-Object fibre spectroscopy



MUSE integral-field spectroscopy







Data reduction basics

Remove detector artefacts

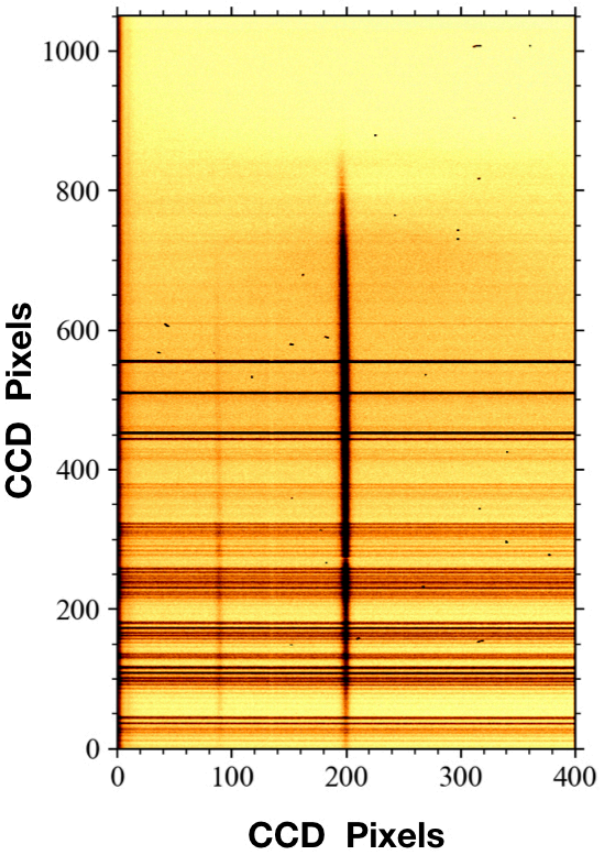
Remove instrumental effects

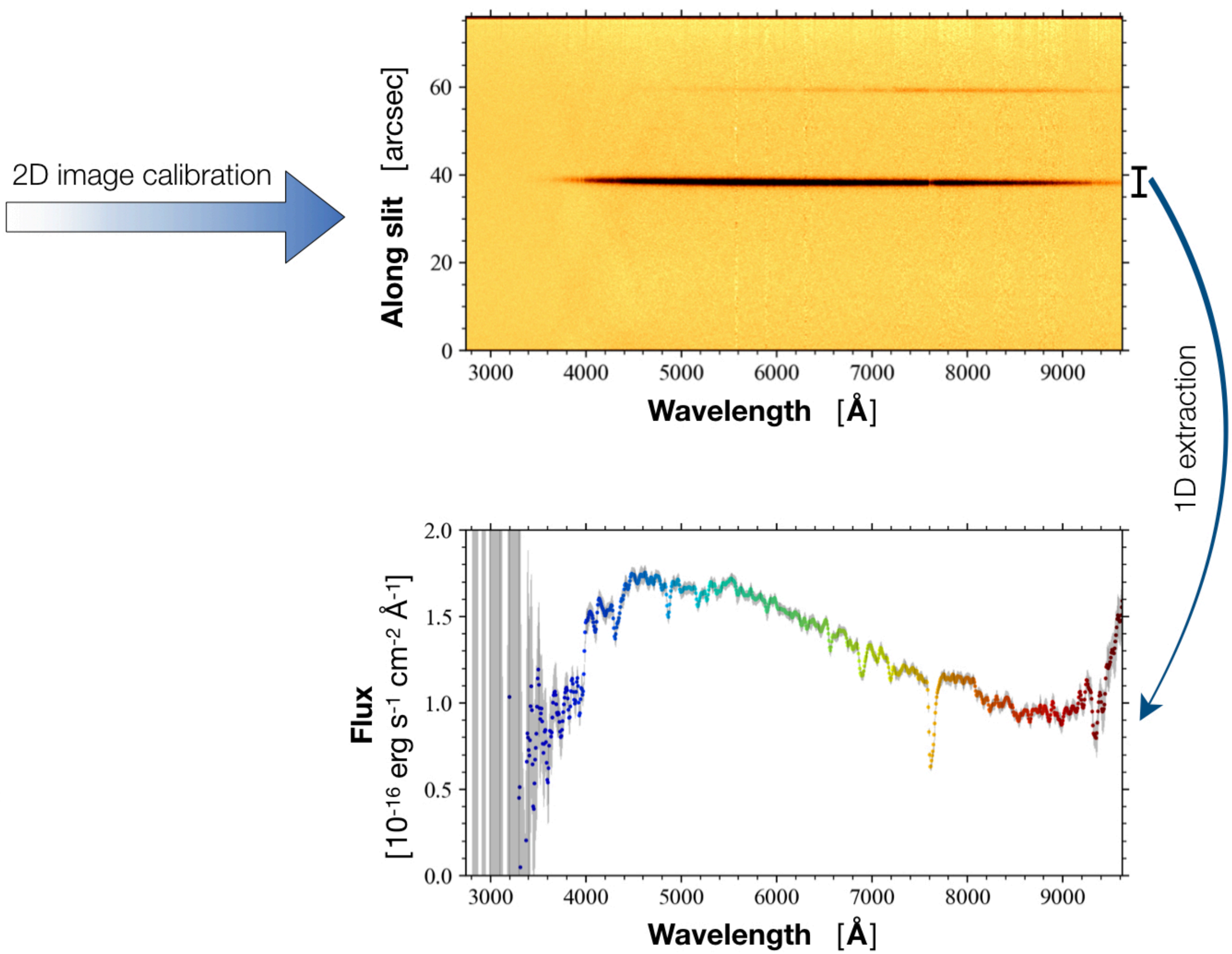
Remove atmospheric features

```
pip install PyNOT-redux
```

PyNOT :: spex

Spectroscopic Data Processing





What does our detector give us?

The observed pixel value from the detector is given as:

$$I_{i,j} = (D_{i,j} + S_{i,j}) \cdot s_{i,j} + B_{i,j}$$

Physical flux received from object and atmosphere (sky)

Pixel-to-pixel variations in sensitivity (<*s*> = 1)

Detector bias level (or zero level)

What about uncertainties?

The observed pixel value from the detector is given as:

$$I_{i,j} = (D_{i,j} + S_{i,j}) \cdot s_{i,j} + B_{i,j}$$

photons received, Poisson stat.
Var(I) = I

Mean of N images
Var(B) = RON / sqrt(N)

RON : Read-out Noise

Mean of M images:
Var(s) ≈ RON / sqrt(M)

Detector Artefacts

CCD Bias Level / overscan

Flag bad pixels / cosmic ray hits

Flatfield

Detector Artefacts

CCD Bias Level (Zero Level):

Why do we keep the CCD at a non-zero voltage?

`pynot bias`

Detector Artefacts

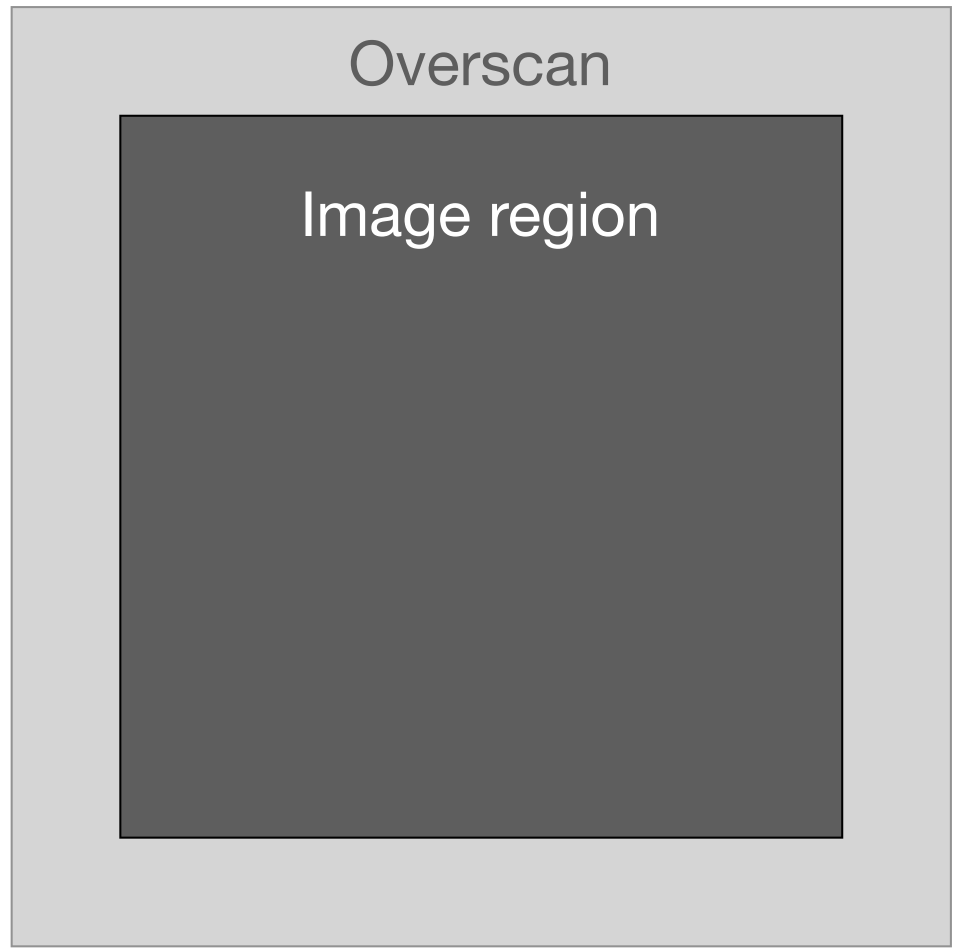
CCD Bias Level:

Estimated with shutter closed and 0 exposure time

Combine N read-outs (median or sigma clipped)

- For each exposure:
  - Subtract median of overscan
  - Trim overscan regions

Then combine all exposures
–> reduces read-noise contribution



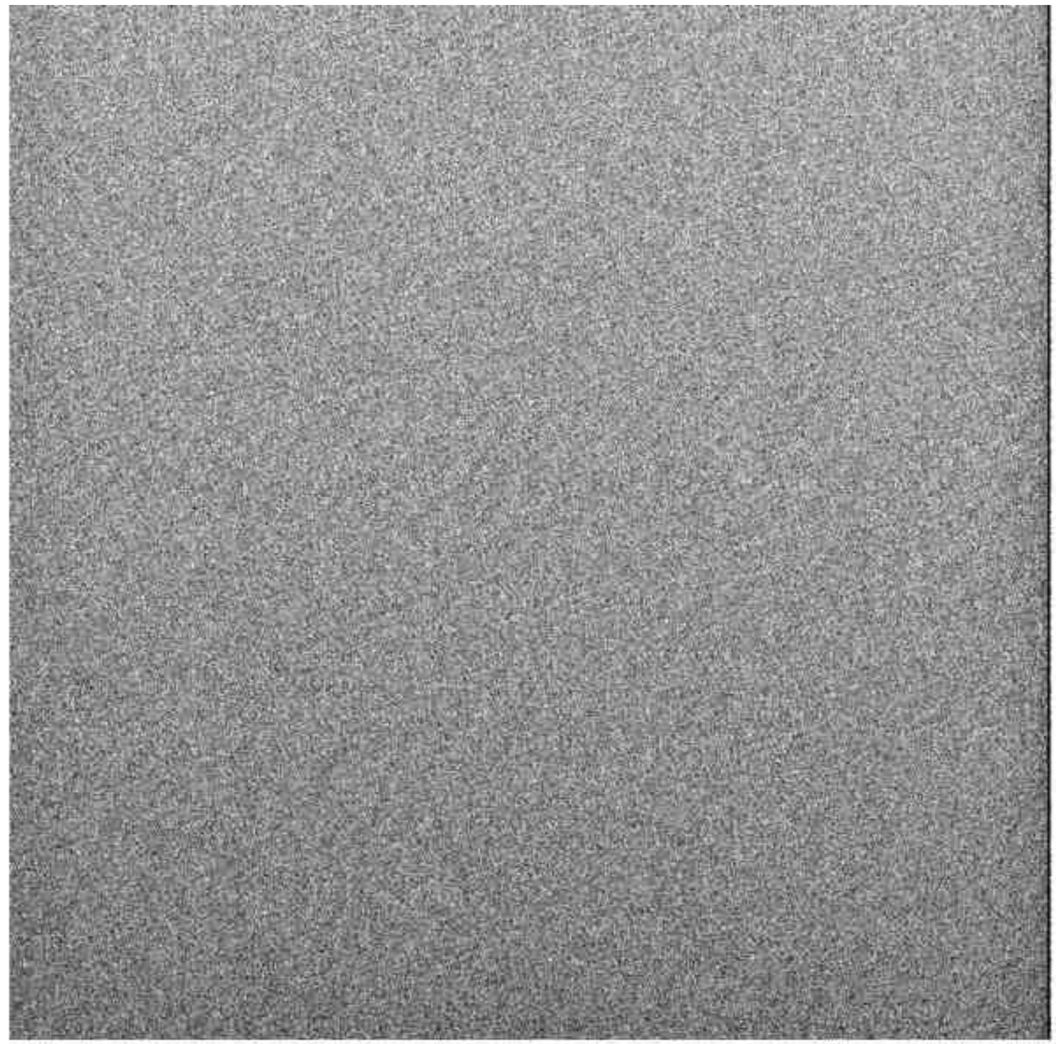
`pynot bias`

Detector Artefacts

CCD Bias Level:

Estimated with shutter closed and 0 exposure time

NTT/EFOSC2 MASTER BIAS



Detector Artefacts

Dark current:

Thermal excitation of electrons in the CCD
induces a current even if the detector is not exposed.

Detector Artefacts

Dark current:

Thermal excitation of electrons in the CCD
induces a current even if the detector is not exposed.

In optical data this is usually negligible with modern CCDs.

Two options:

1) Obtain exposures with same exposure time as science
2) Obtain long exposures and normalize by exposure time

Detector Artefacts

Dark current:

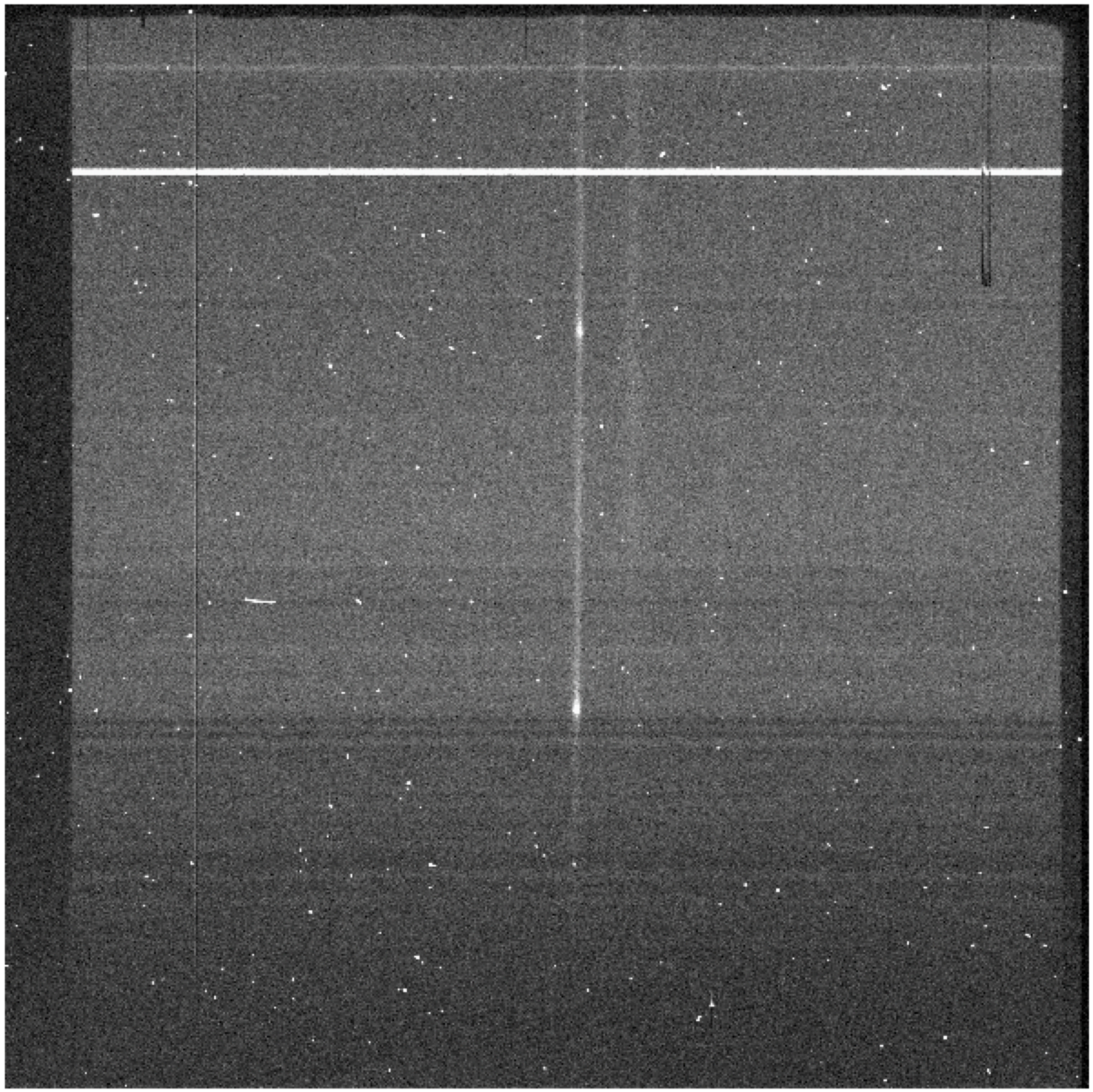
1) **Matched exposure times**
- Obtain N frames with the same t_exp as your science target
- Subtract median of overscan and trim overscan regions
- Subtract master bias
- Combine N exposures

2) **Normalized master dark**
- Obtain long exposures with closed shutter
- Same as above
- Divide the combined frame by the exposure time

```
pynot crr
```

Detector Artefacts

Flag bad pixels / cosmic ray hits

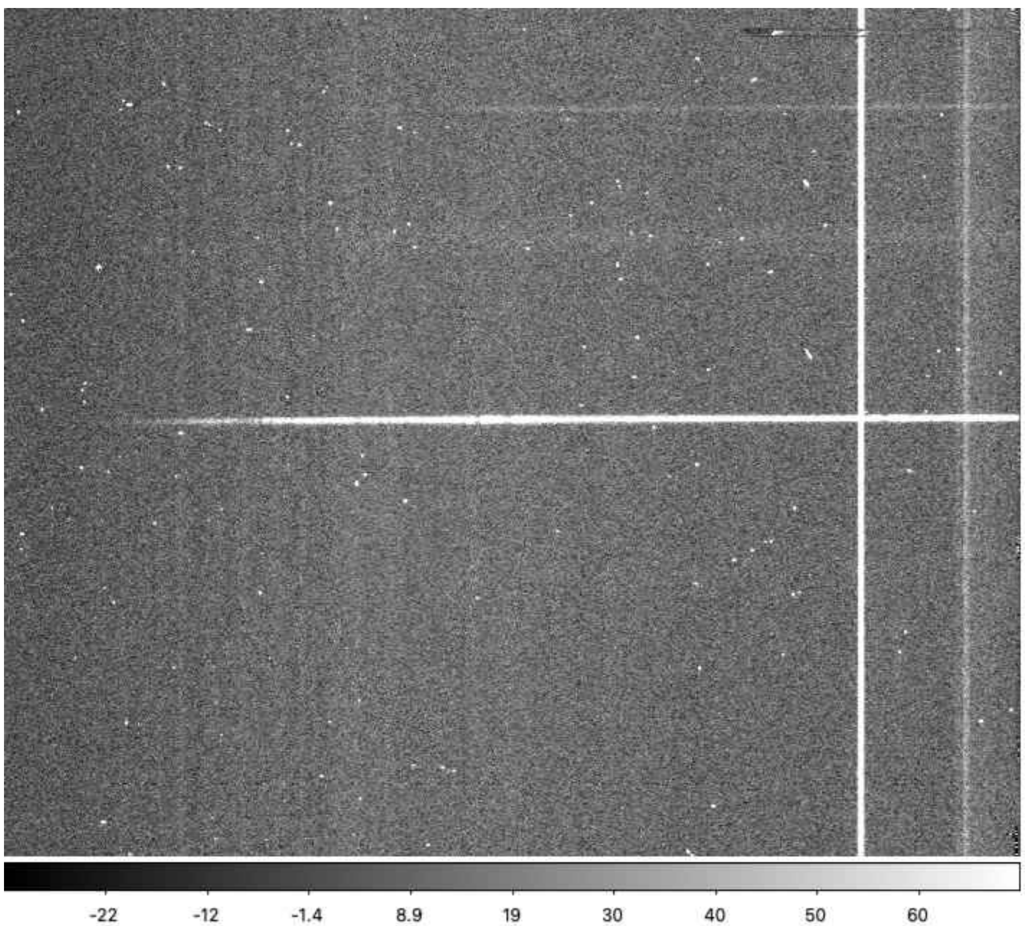


pynot crr

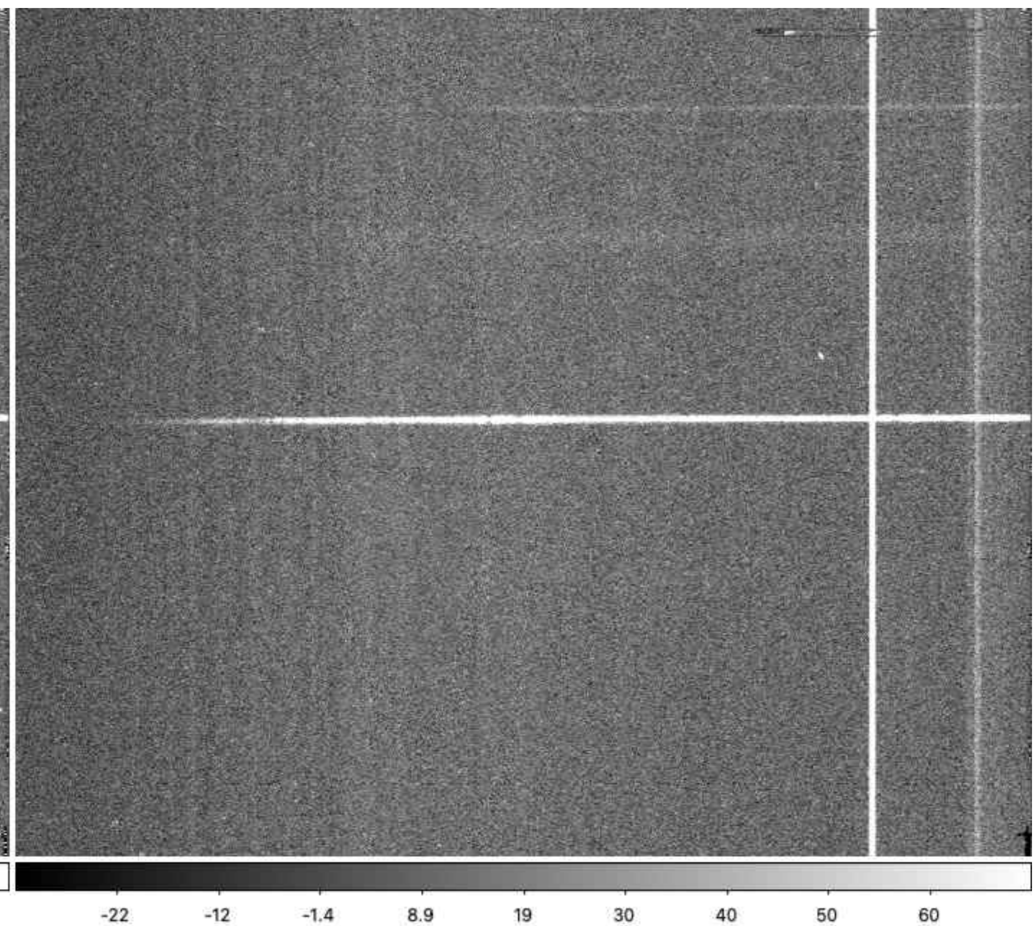
Detector Artefacts

```
pynot crr image1.fits -o crr_image1.fits [options…]
```

Before Correction



After Correction

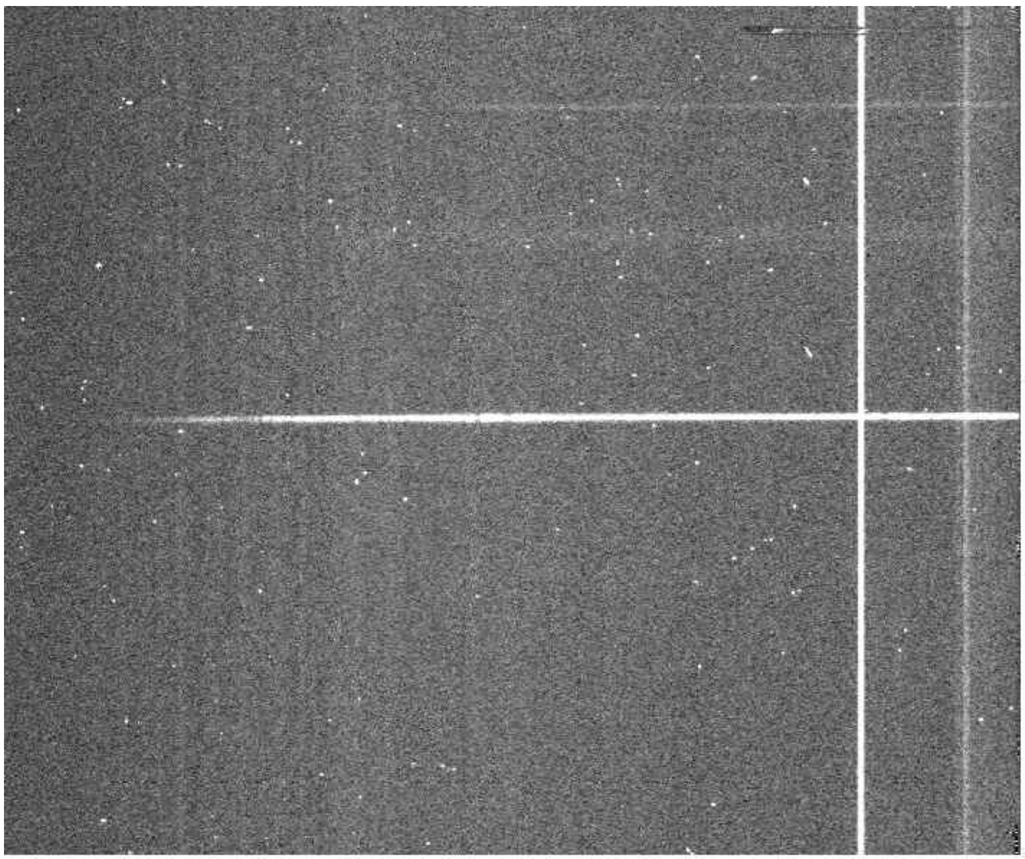


pynot crr

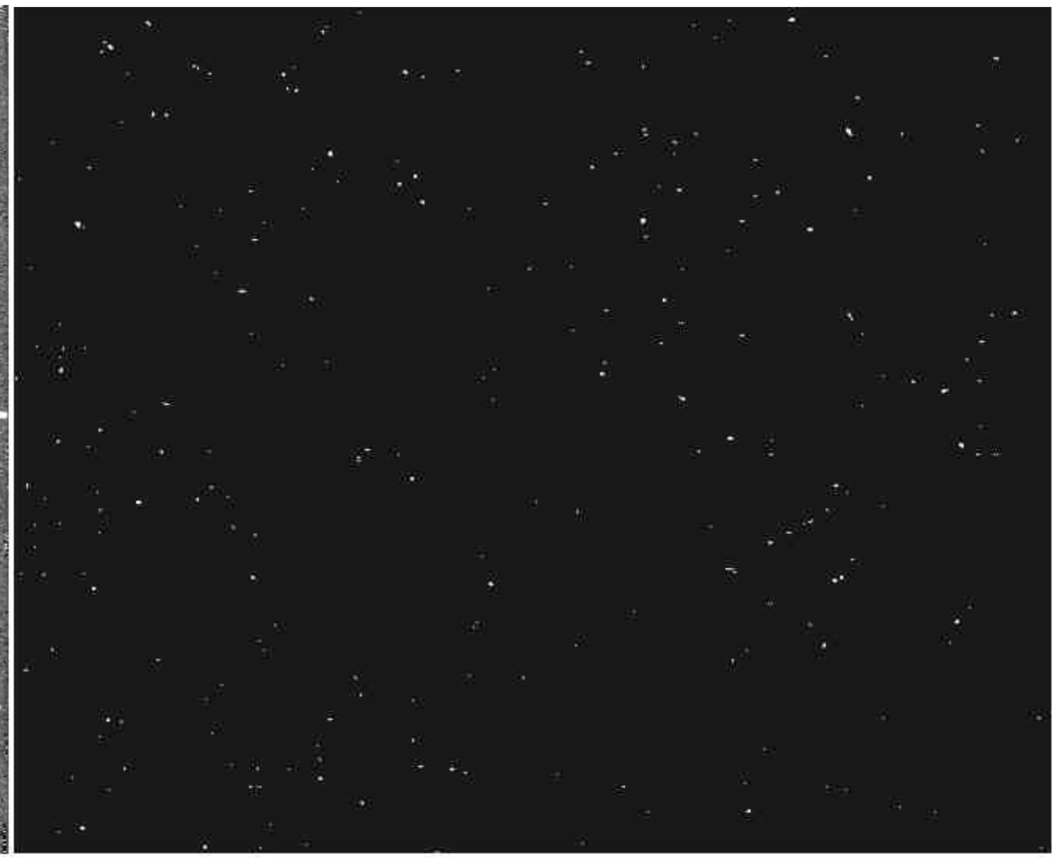
Detector Artefacts

```
pynot crr image1.fits -o crr_image1.fits [options…]
```

Before Correction



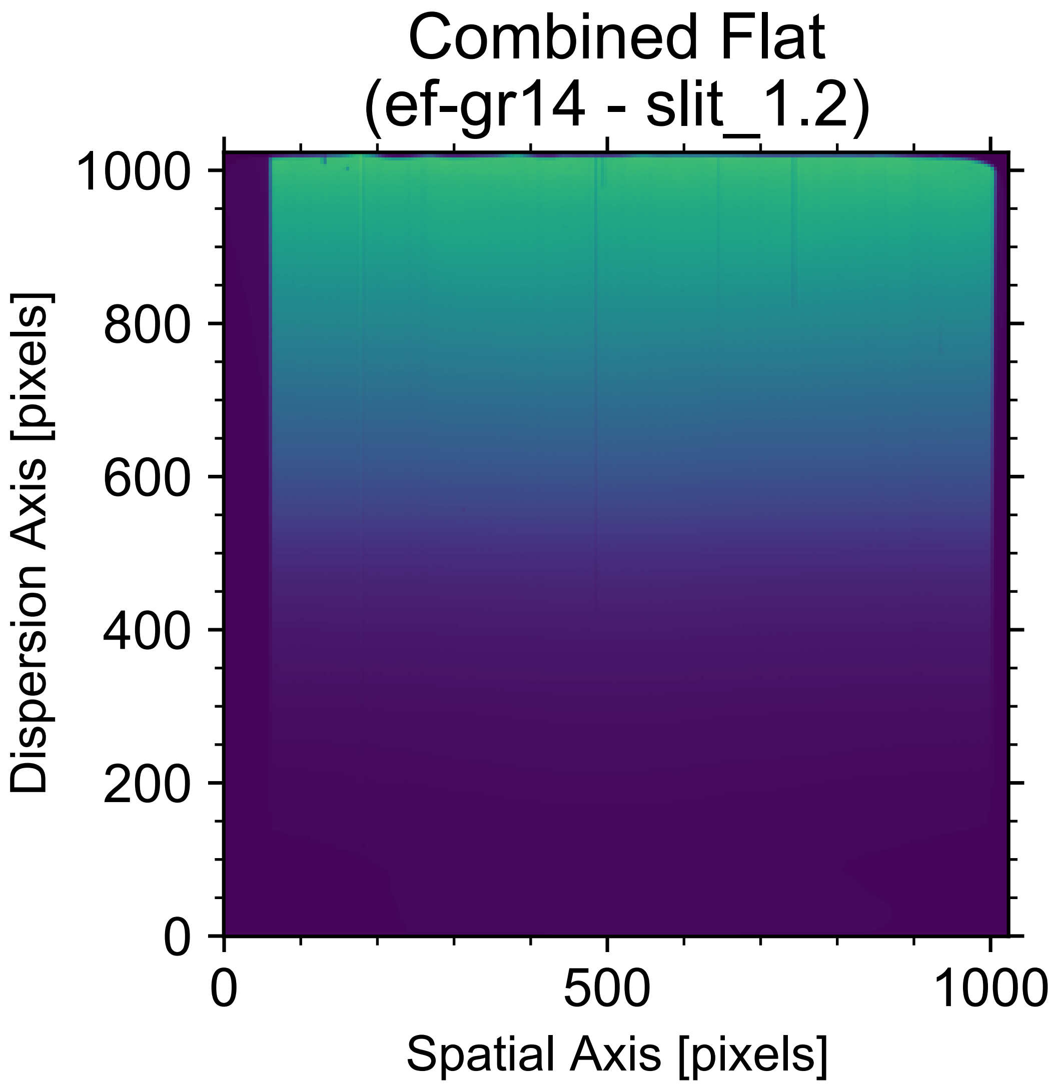
Pixel Mask After Correction



Detector + Instrument Artefacts

Flatfield

Estimated with
with open shutter
and uniform illumination!

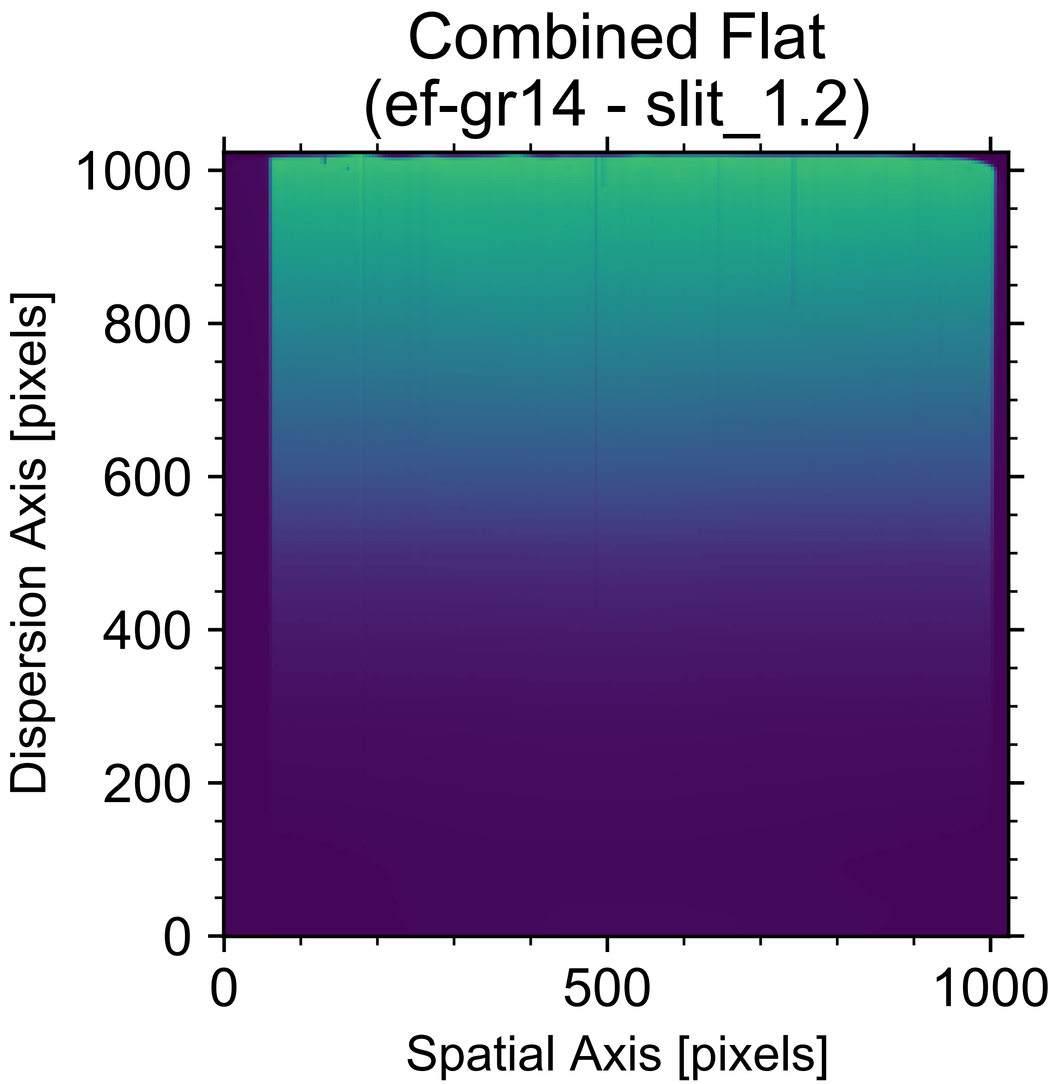


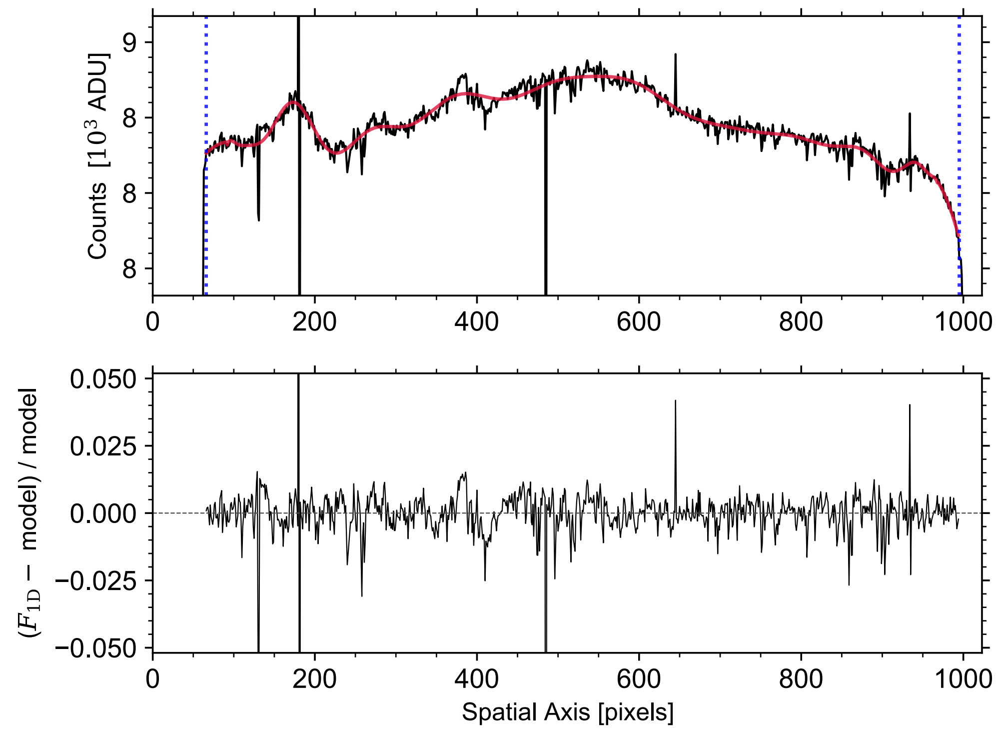
This is very tricky business
and depends heavily on the setup
and the science case!

Good discussion available here:
http://arxiv.org/abs/1010.5270v1

Detector + Instrument Artefacts

Flatfield

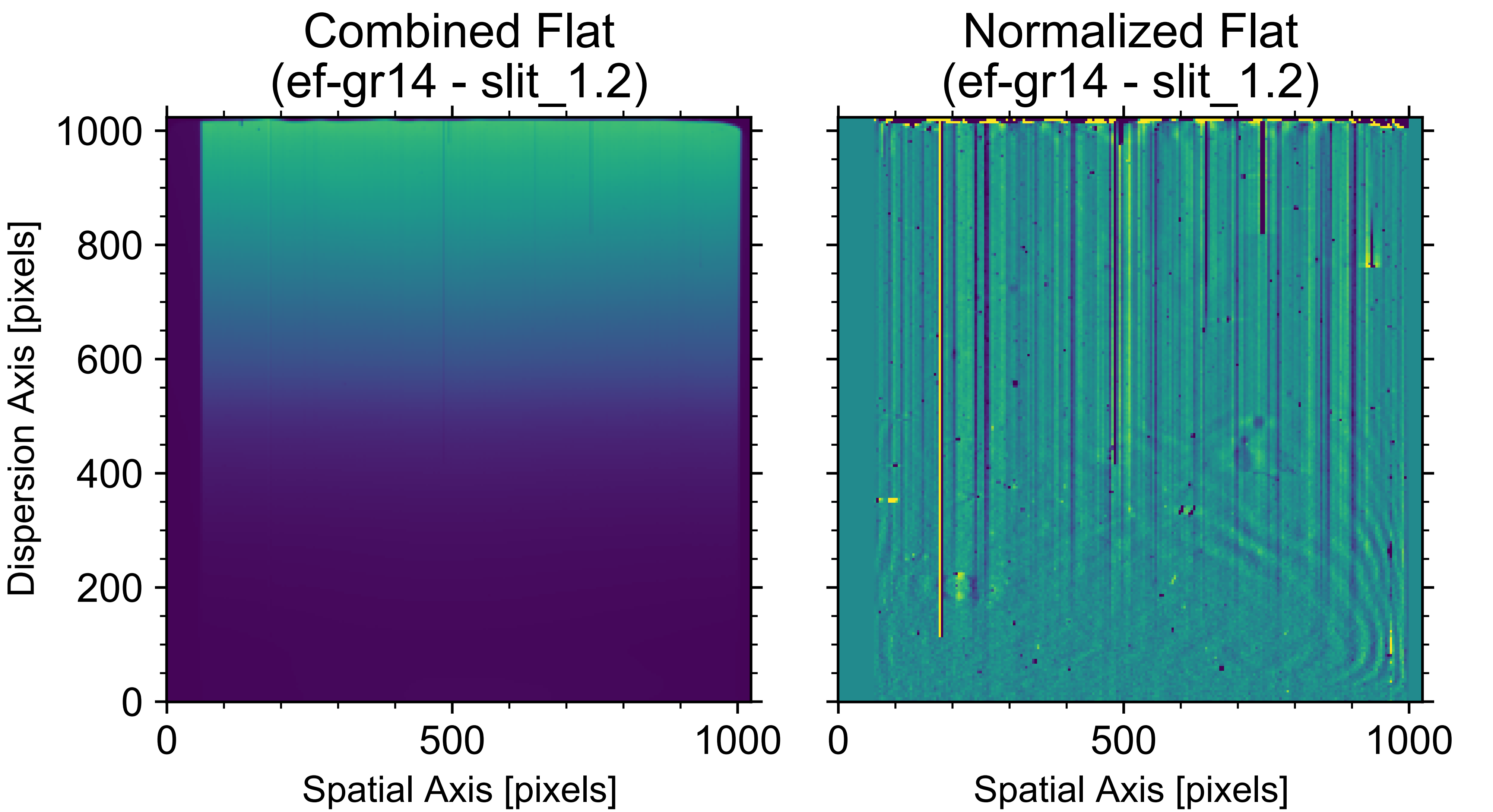




```
pynot sflat
```

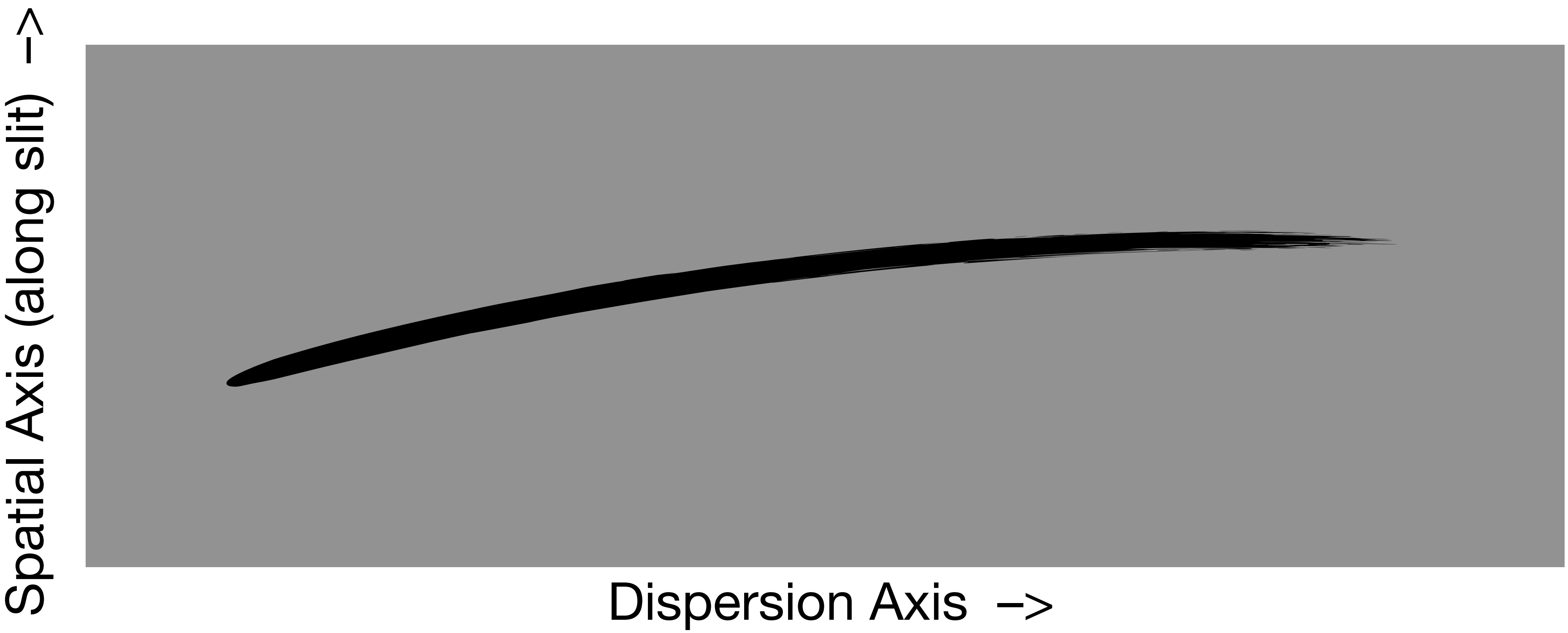
Detector + Instrument Artefacts

Flatfield



Object Extraction

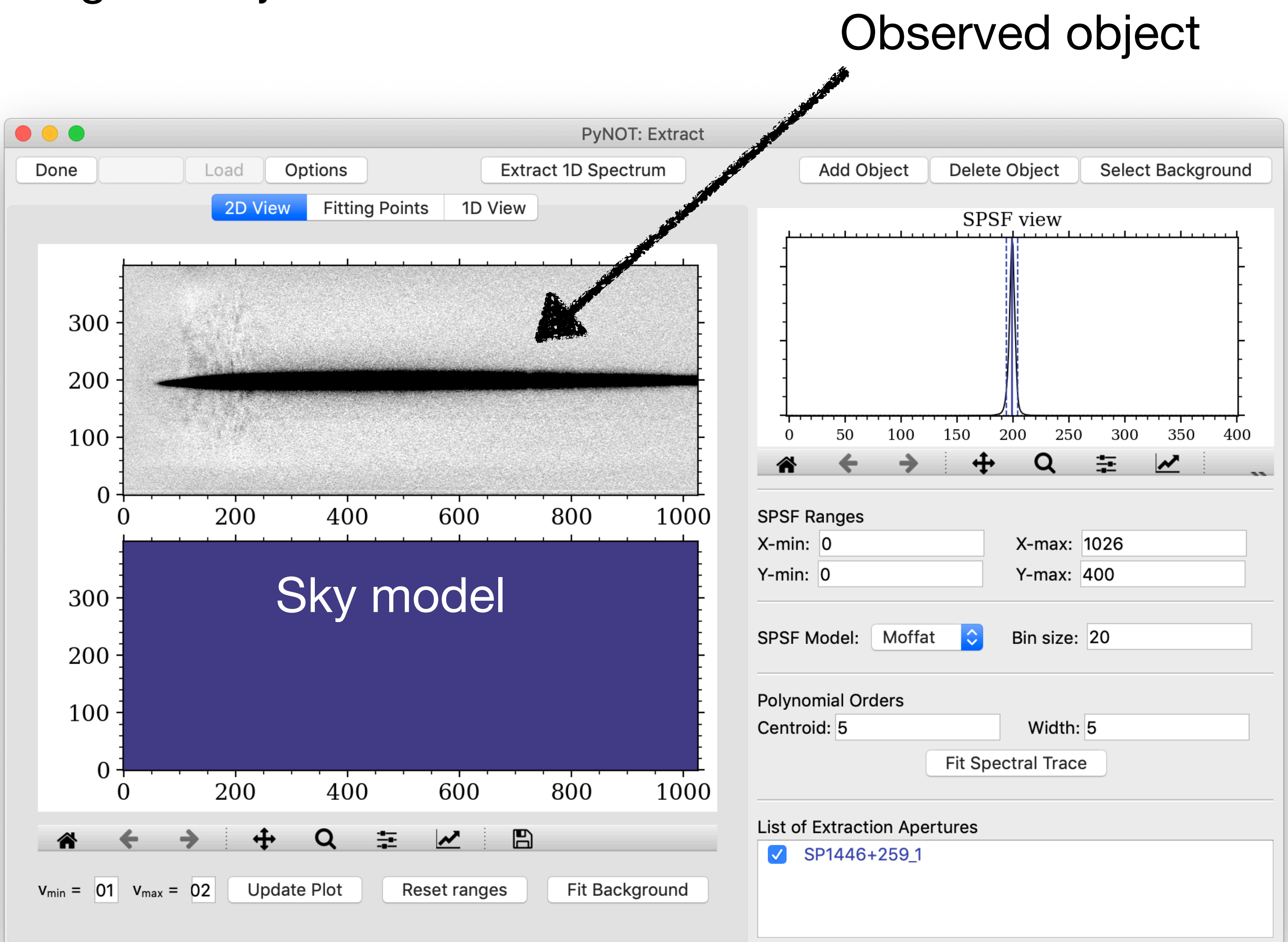
- Tracing the object
- Optimal extraction? Aperture extraction?



`pynot extract`

Object Extraction

- Tracing the object

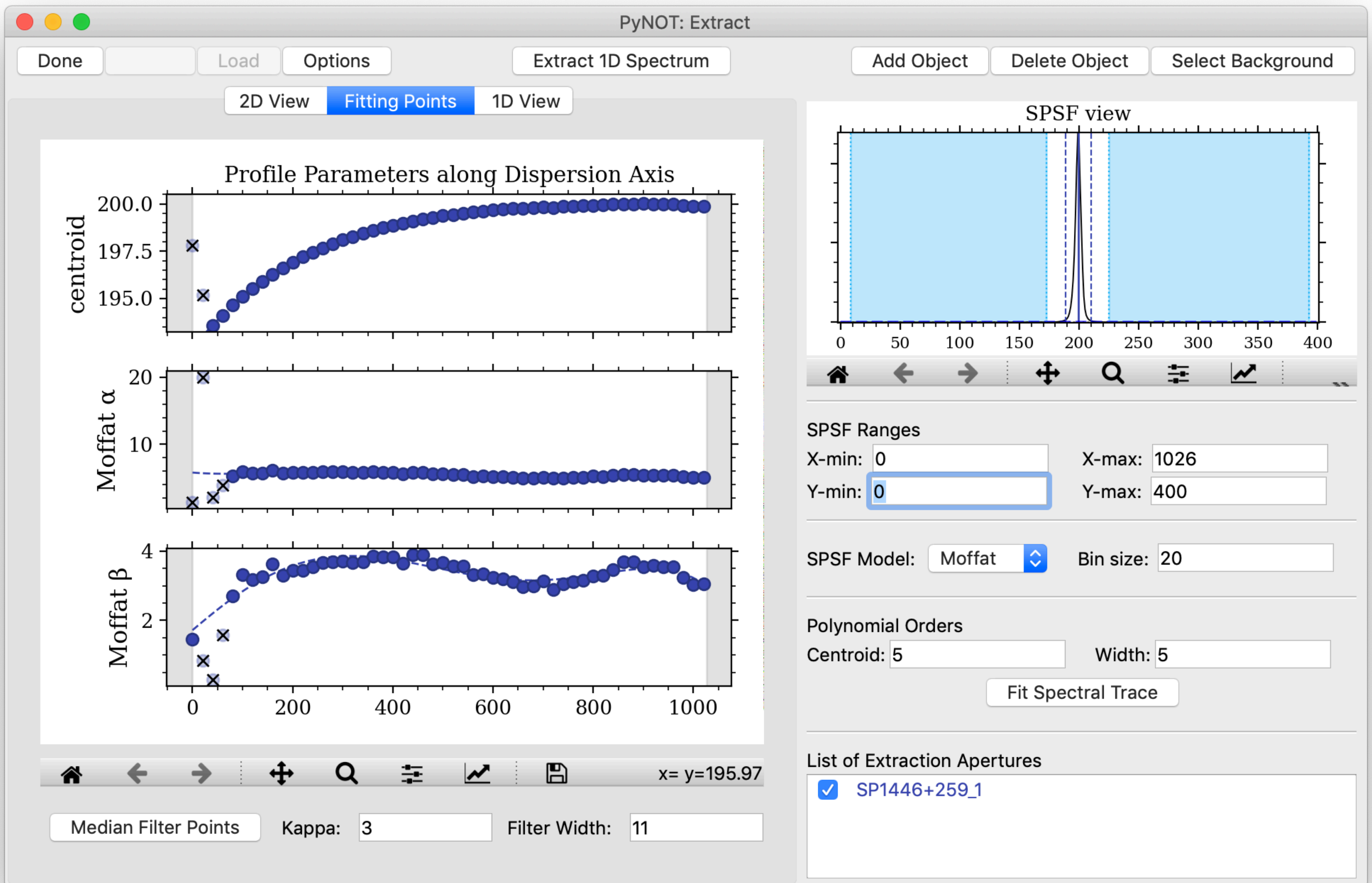


`pynot extract`

Object Extraction

- Tracing the object

Fit the centroid and width as function of wavelength



Object Extraction

- Optimal extraction? Aperture extraction?

Sum up the flux from the object in each wavelength bin

Two options:

1) Simply sum all pixel values inside a range (aperture)

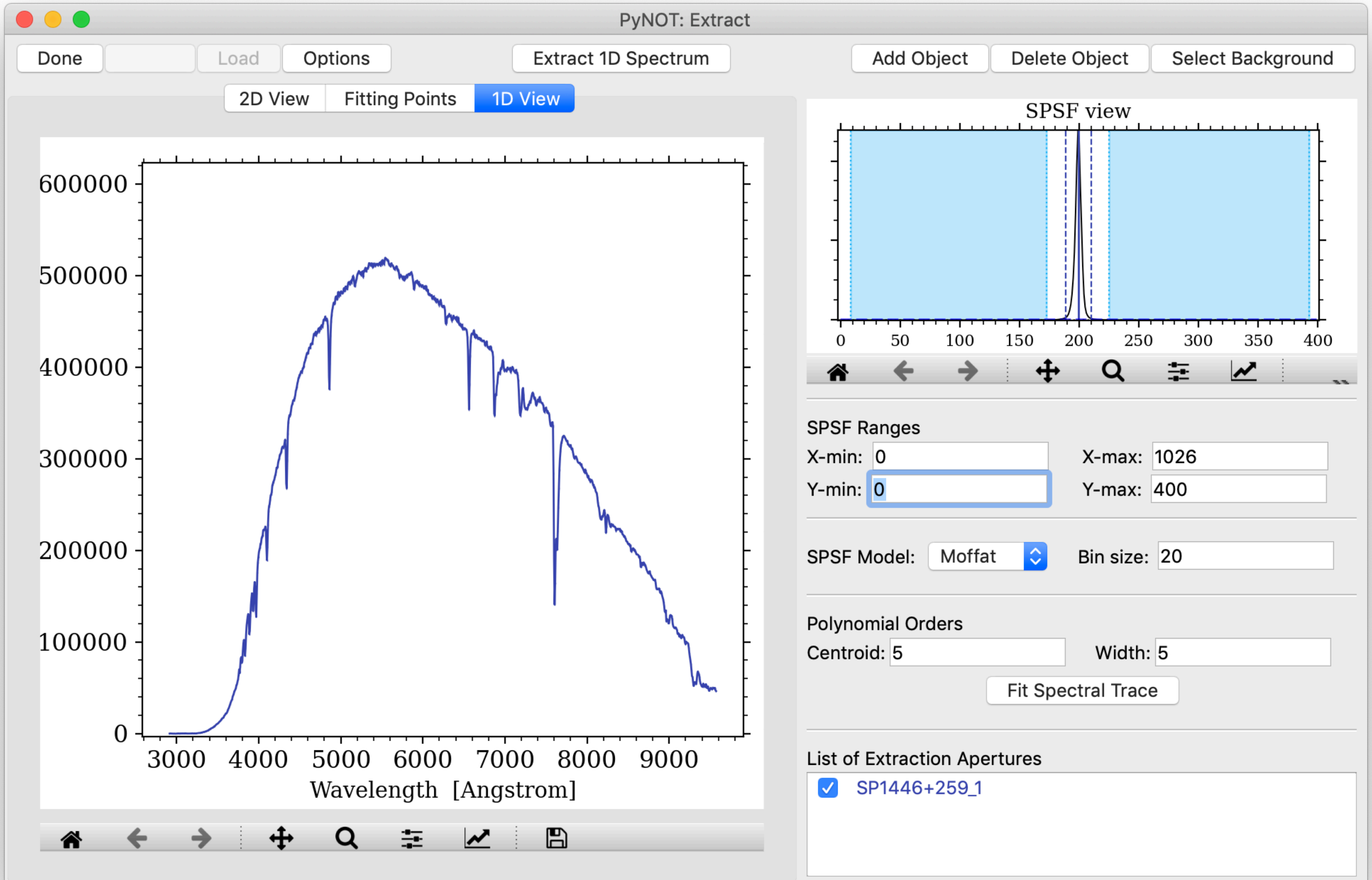
2) Perform weighted sum (aka. optimal extraction)

$$f_i = \sum_j \frac{P_j \; M_{i,j} \left(D_{i,j} - S_{i,j} \right)}{P_j^2 \; M_{i,j}}$$ (see Horne 1986 for details)

where P_j is the normalized spatial profile (which may vary with wavelength),
D and S are the source and sky flux at spectral pixel i and spatial pixel j.
M is a binary pixel mask where bad pixels have a value of 0 and good pixels 1.
Can also weight each pixel by inverse variance $(1 \,/\, V_{i,j})$

Object Extraction

The final 1D spectrum

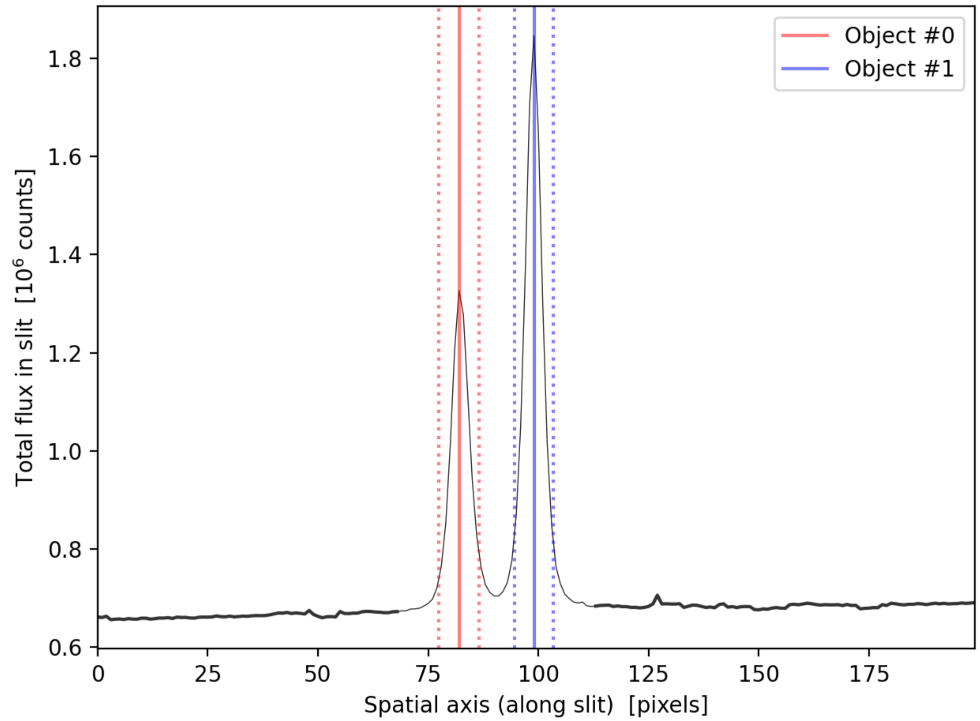


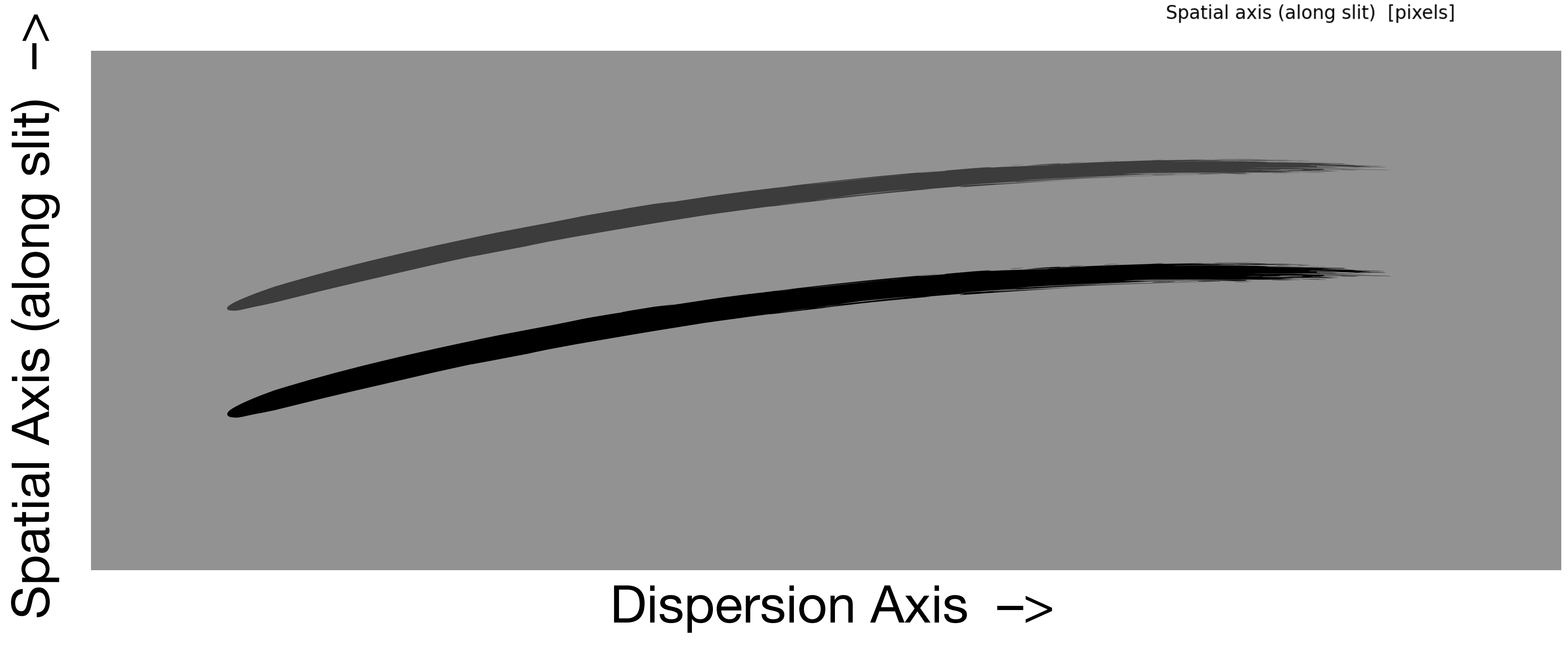
pynot extract

Object Extraction

- Tracing the object

One or multiple objects in the slit?

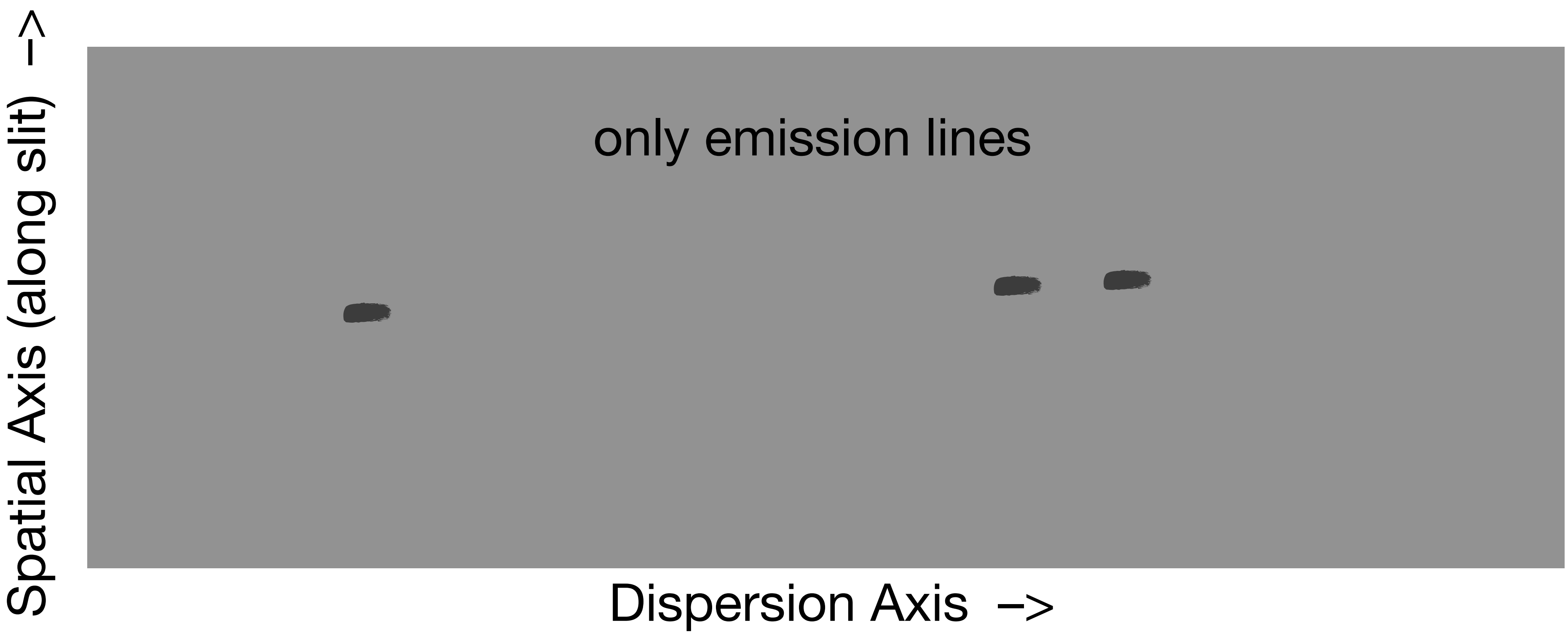




Object Extraction

- Tracing the object

What if there's no continuum?

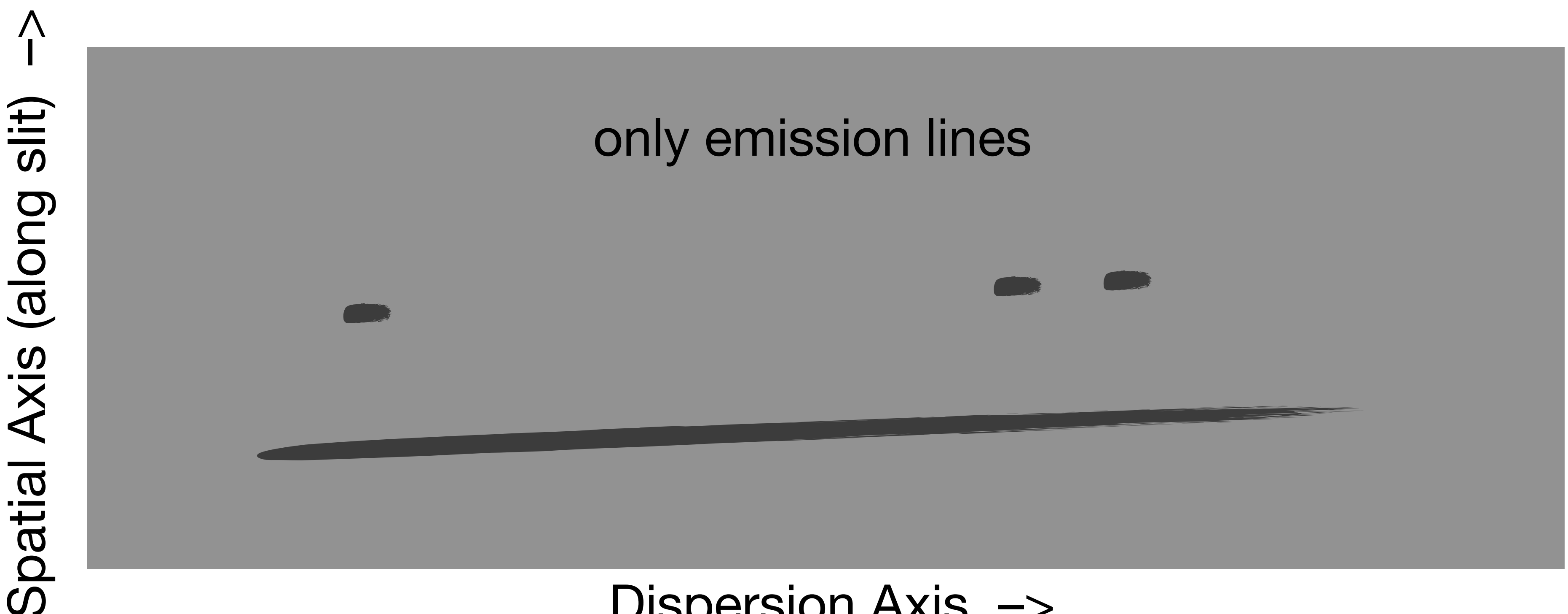


Object Extraction

- Tracing the object

What if there's no continuum?

We can try to observe a reference object offset along the slit

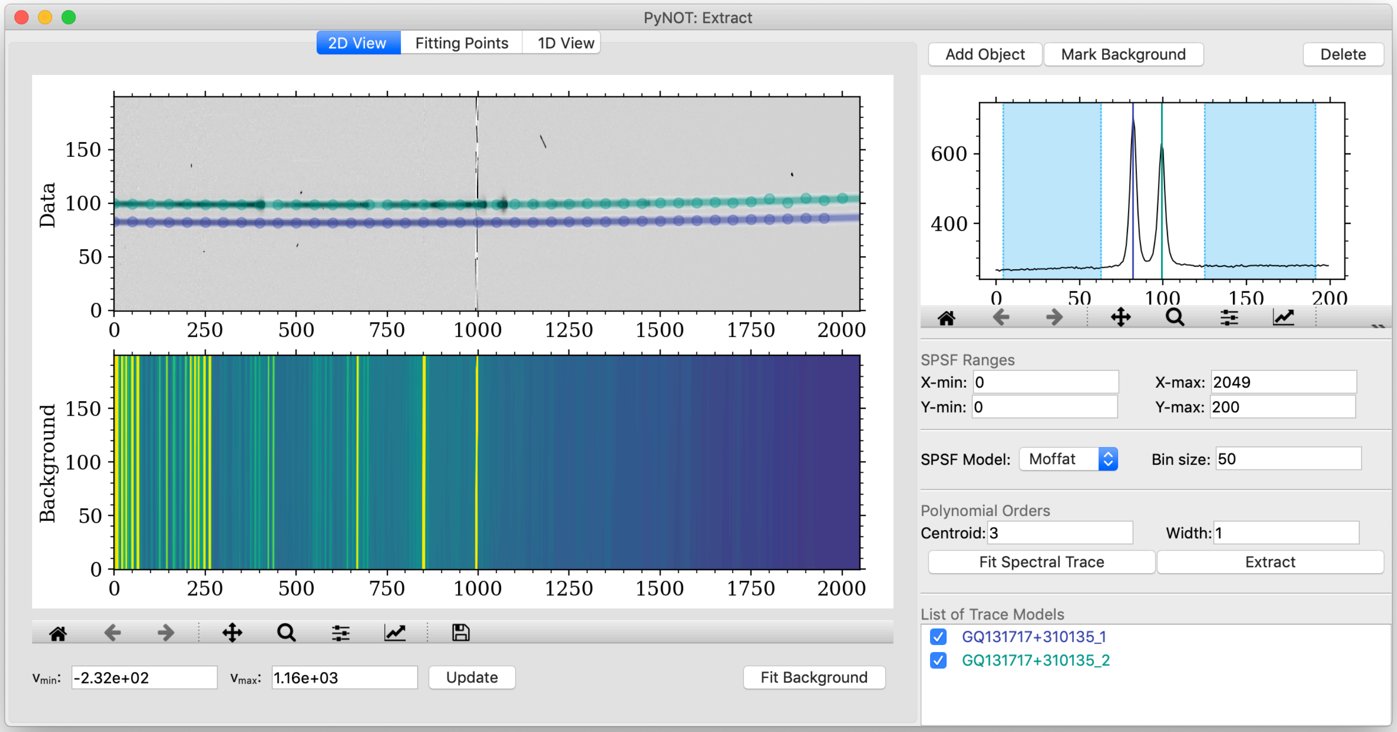


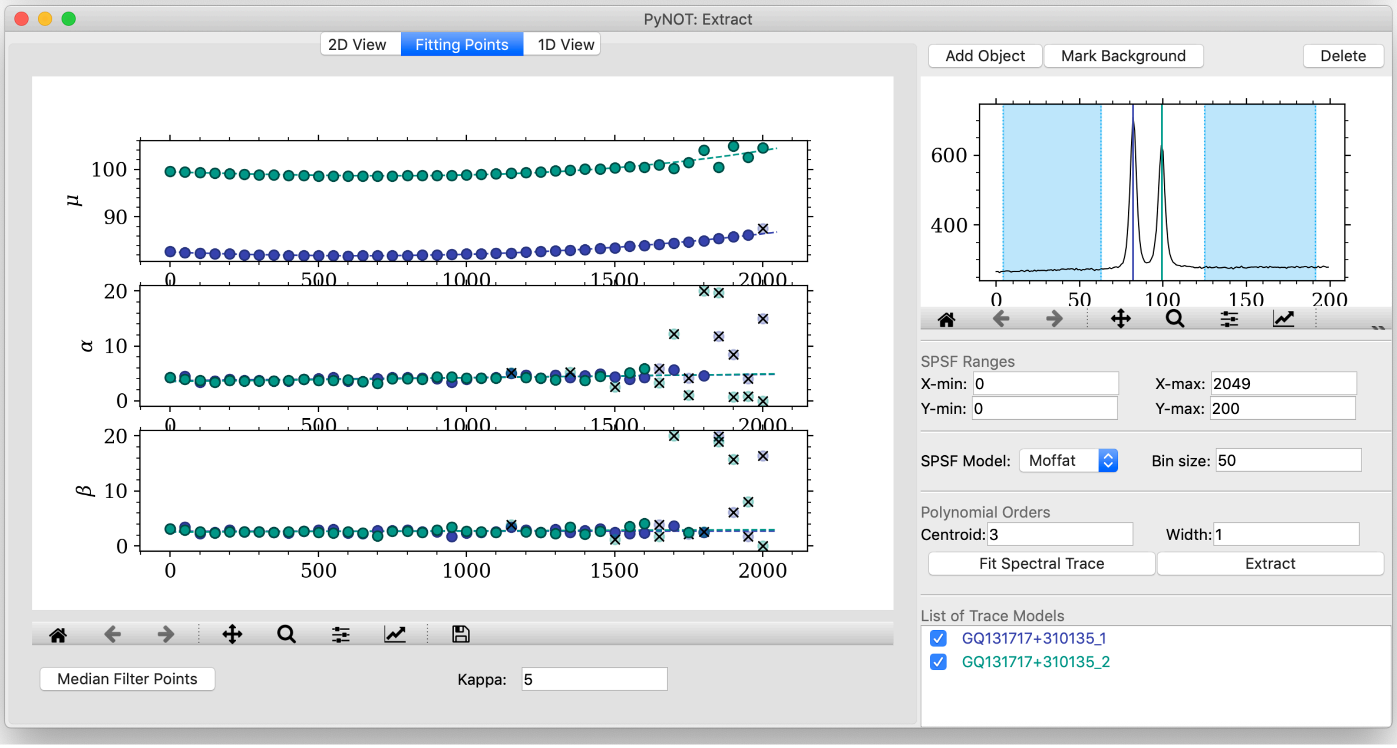
Object Extraction

Using `pynot extract`

We can copy an aperture from one source to another

and drag it to the desired position along the slit





Instrumental Artefacts

- Wavelength Calibration *(and 2D rectification)*
- Flux Calibration

Instrumental Artefacts

<u>- Wavelength Calibration</u>

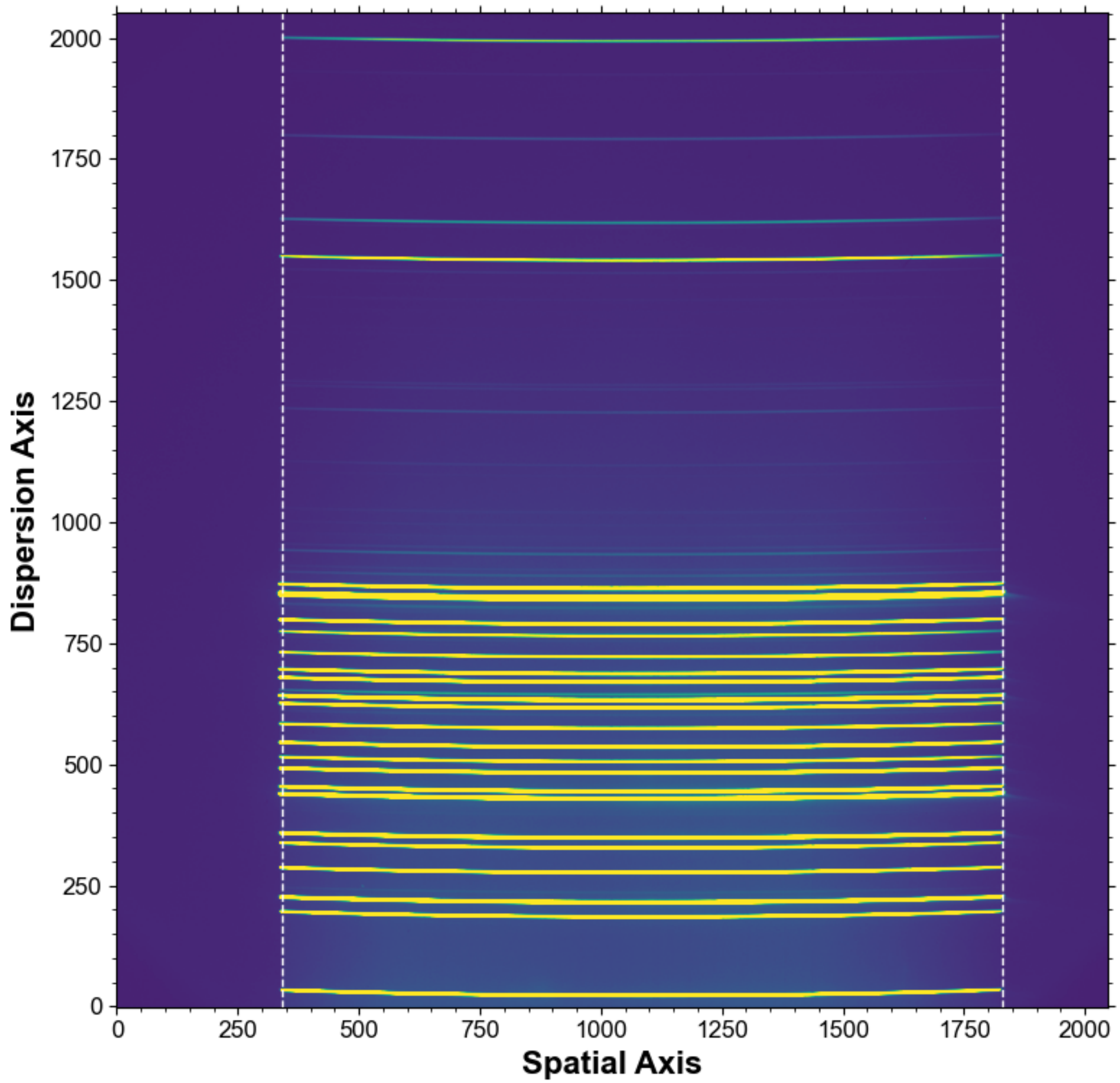
Arc frames:

Taken with a lamp

(HeNe/ThAr)

Important:

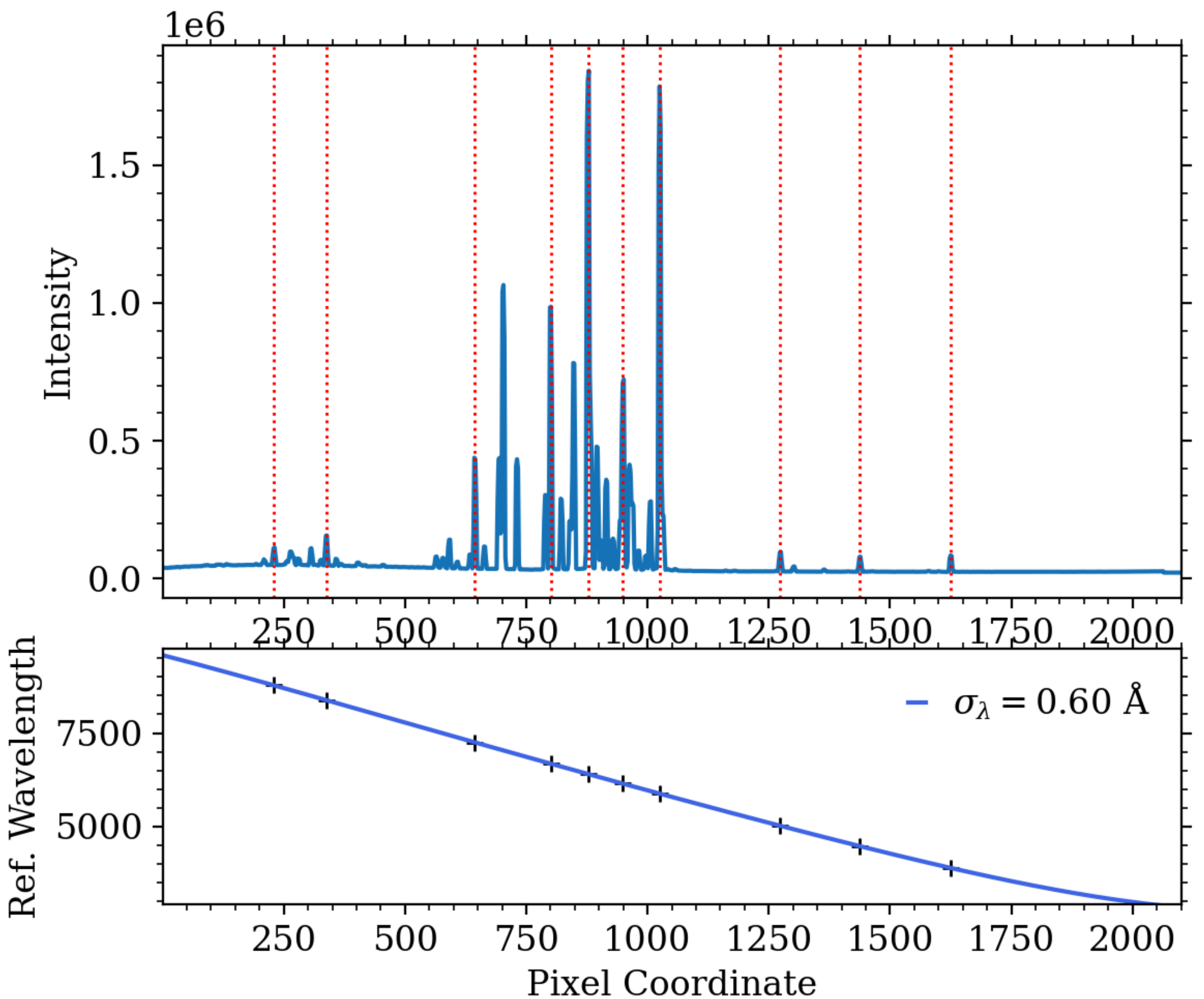
known emission lines!

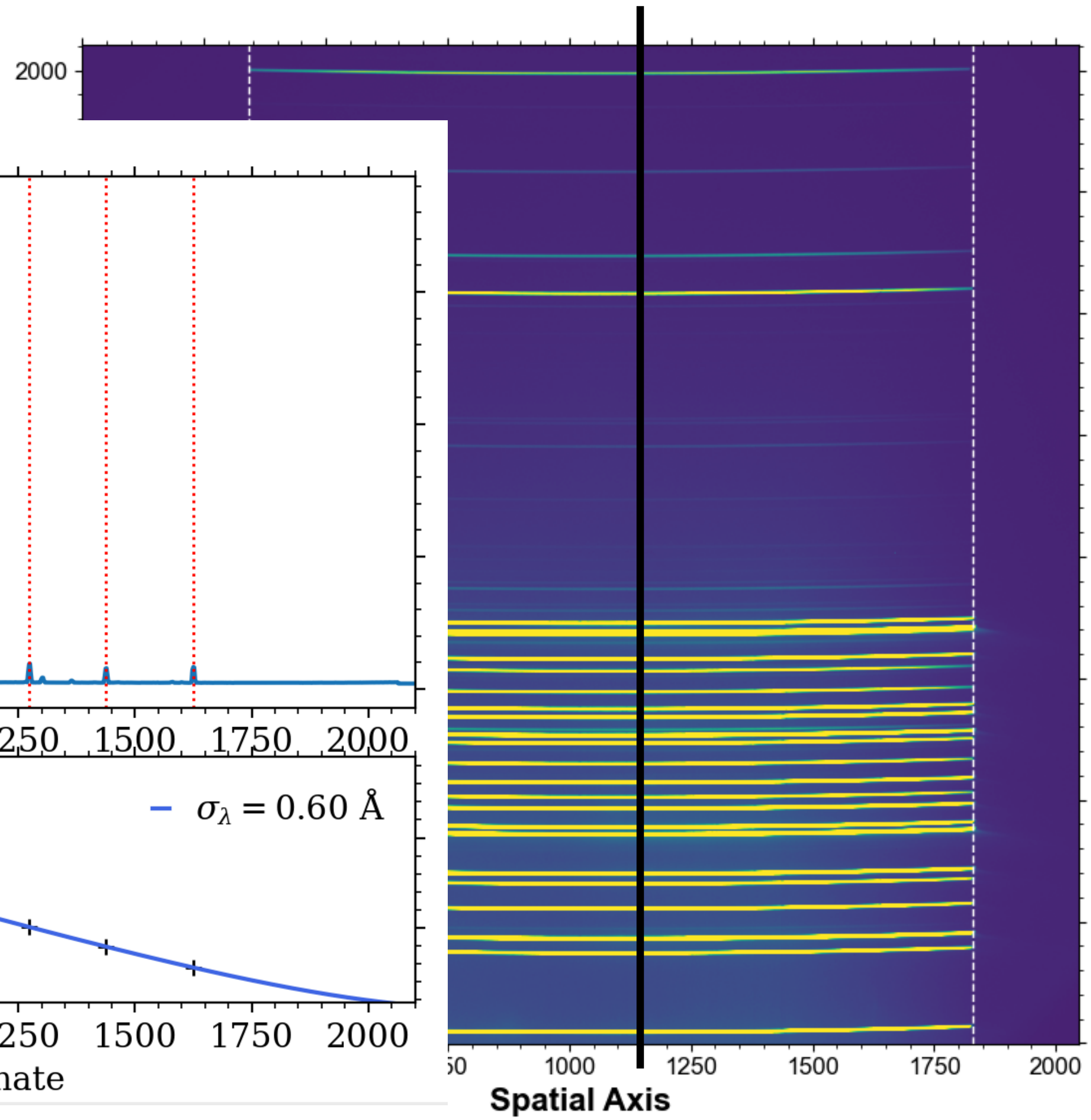


`pynot identify`

Instrumental Artefacts

<u>- Wavelength Calibration</u>

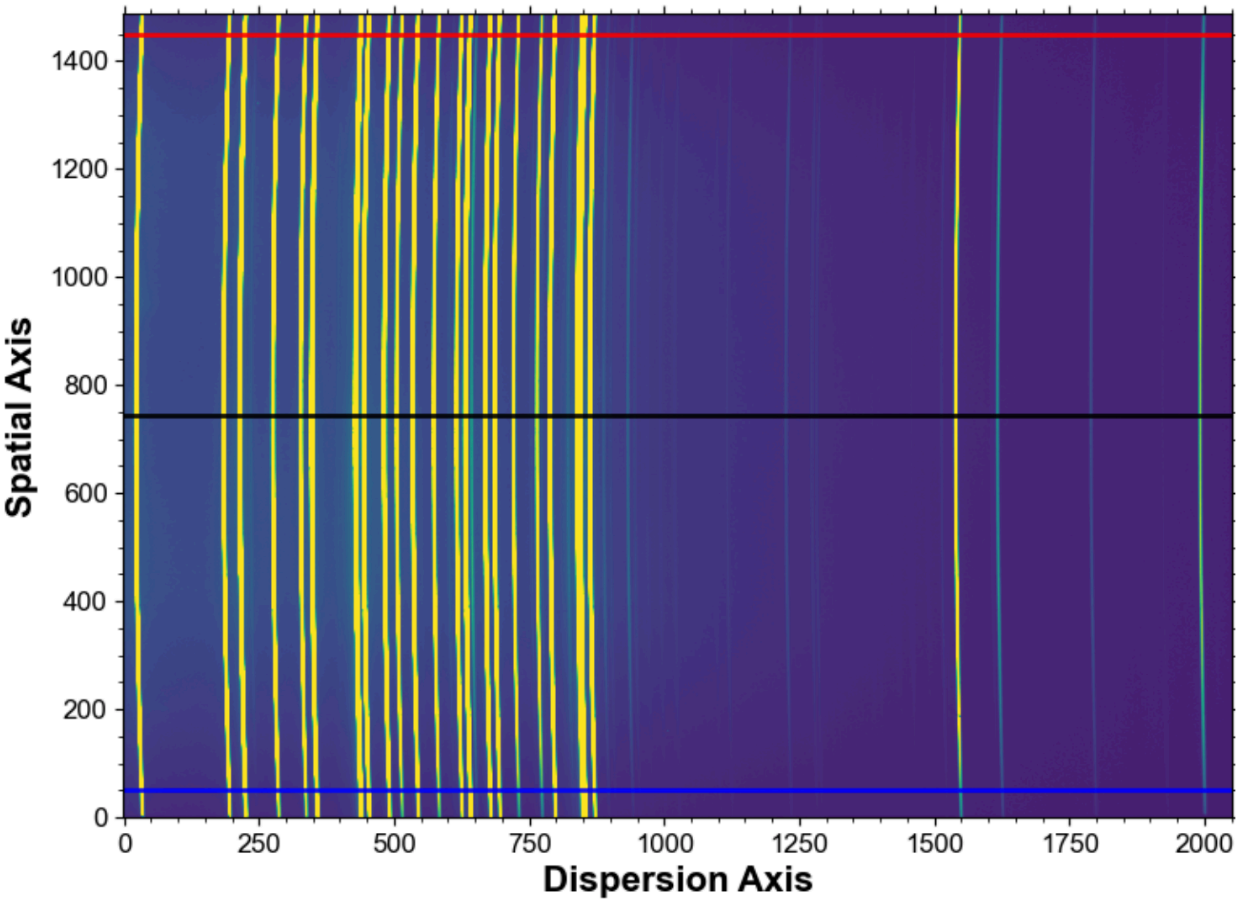


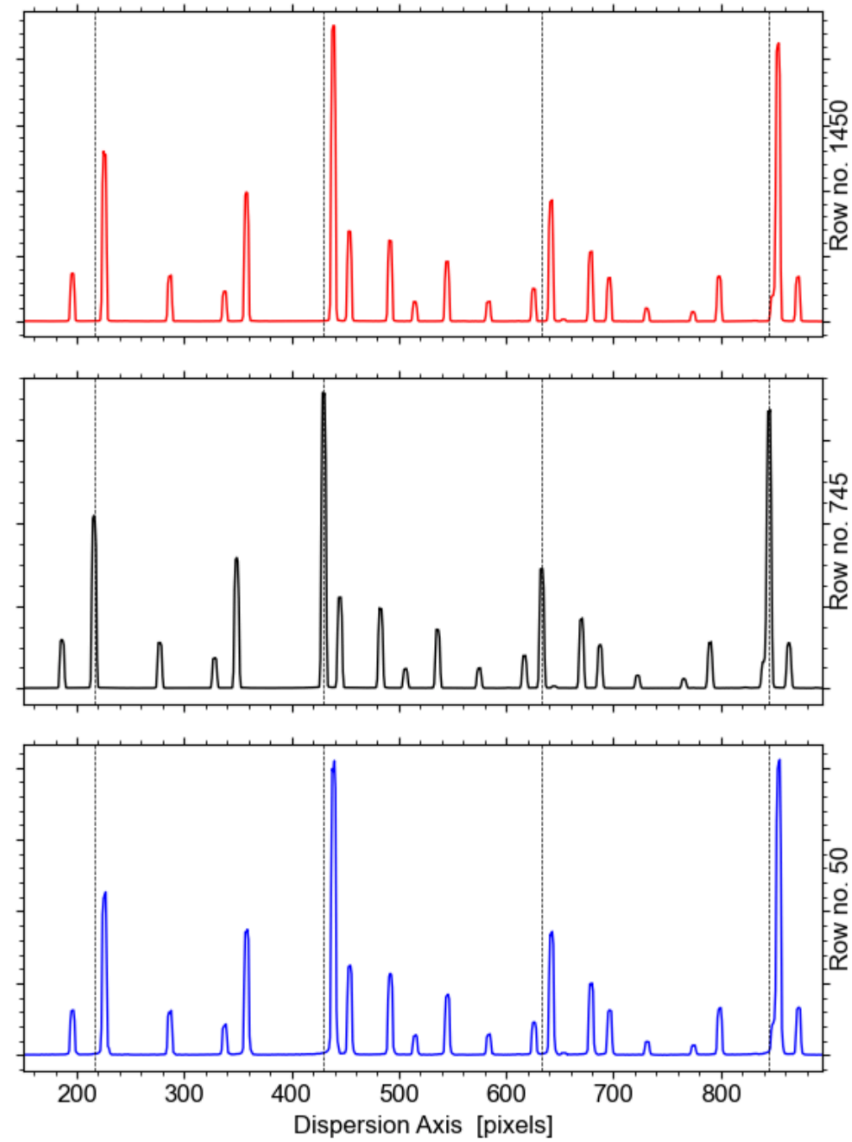


`pynot wave2d`

Instrumental Artefacts

- Wavelength Calibration

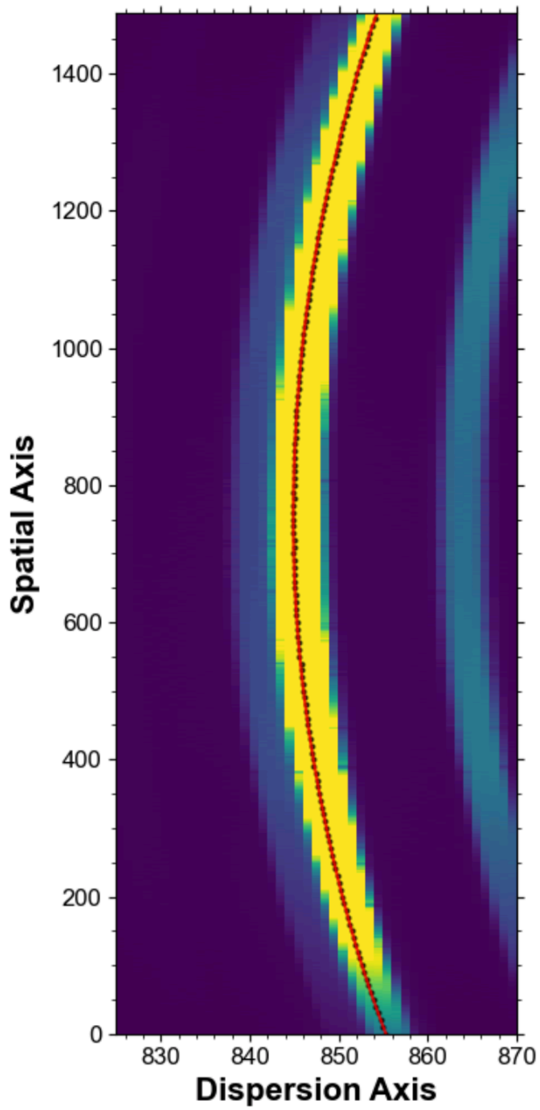


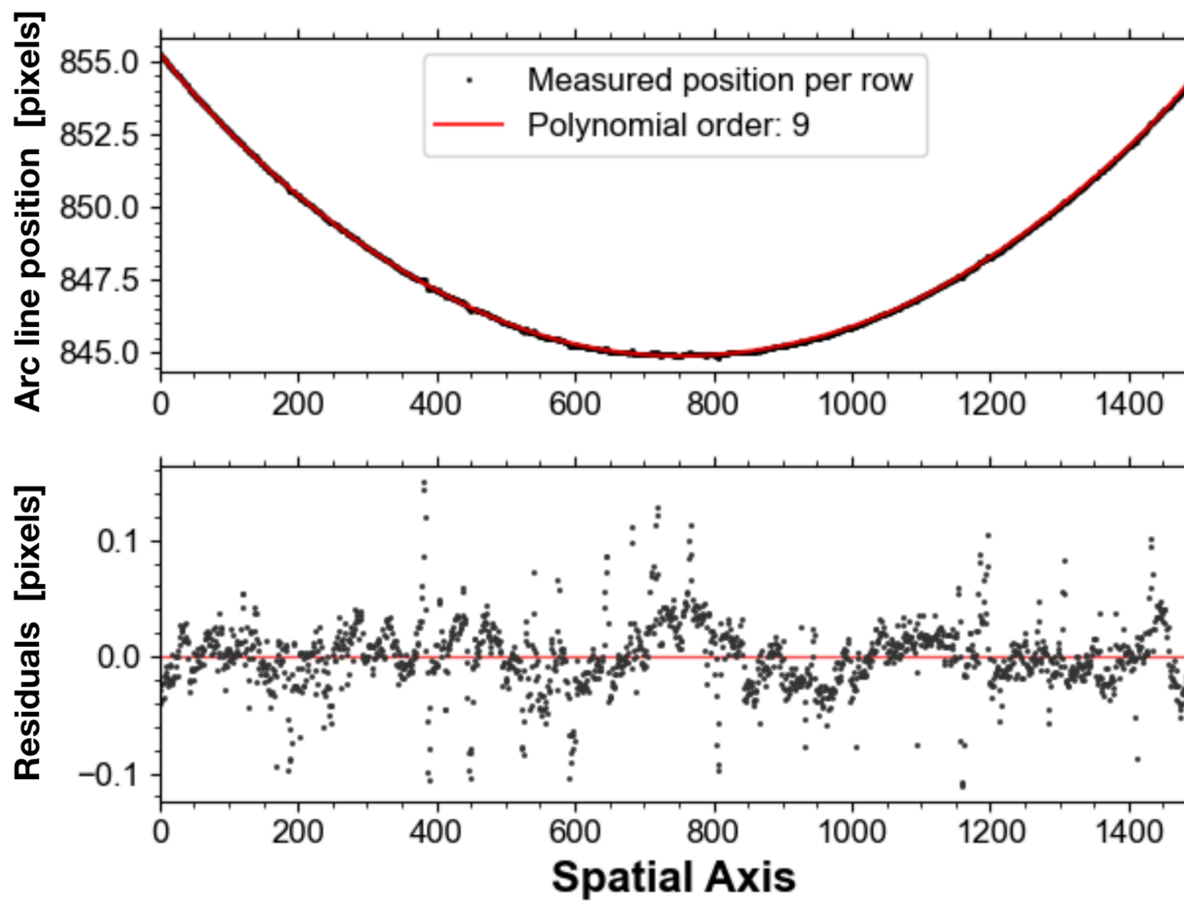


pynot wave2d

Instrumental Artefacts

- Wavelength Calibration

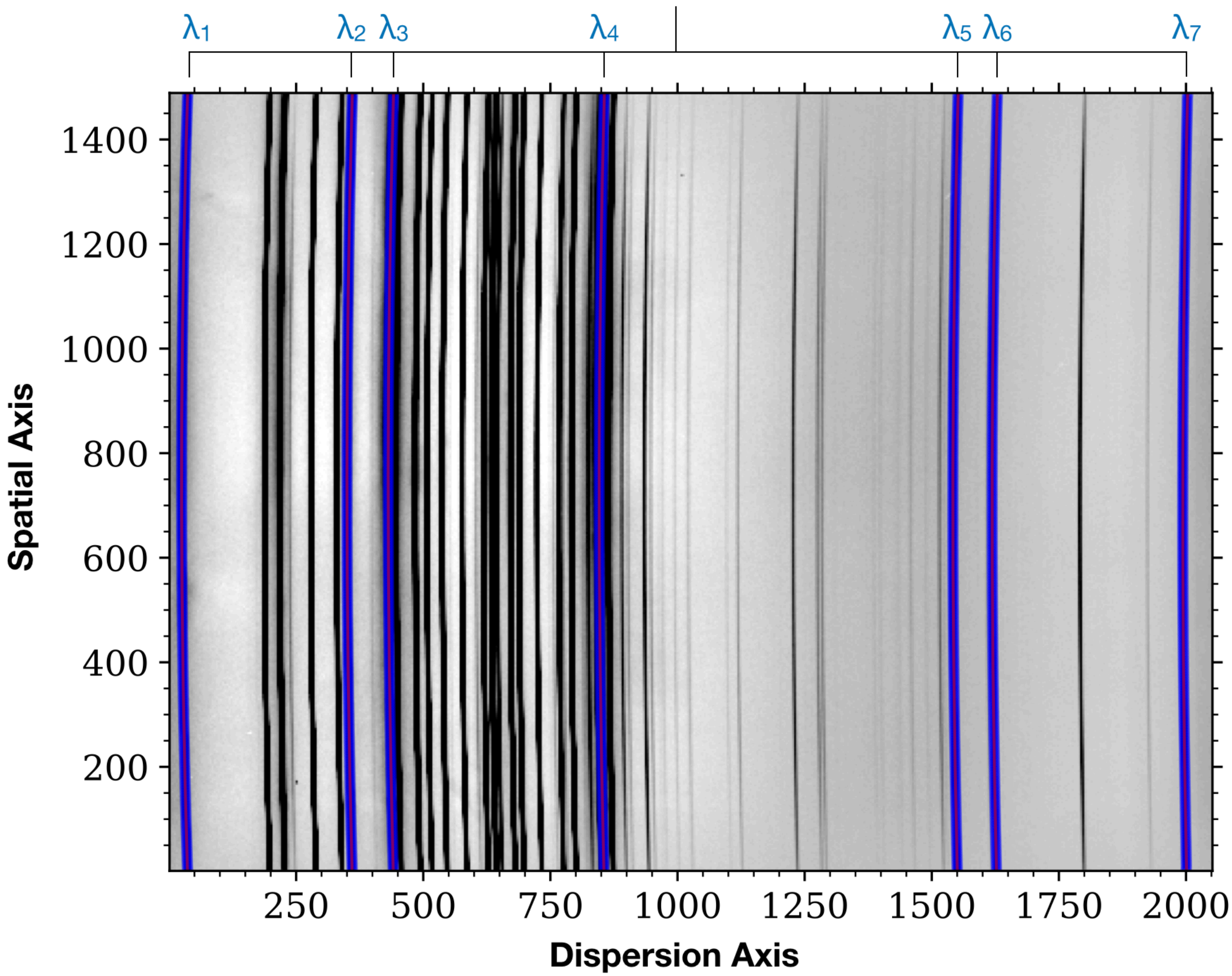




```
pynot wave2d
```

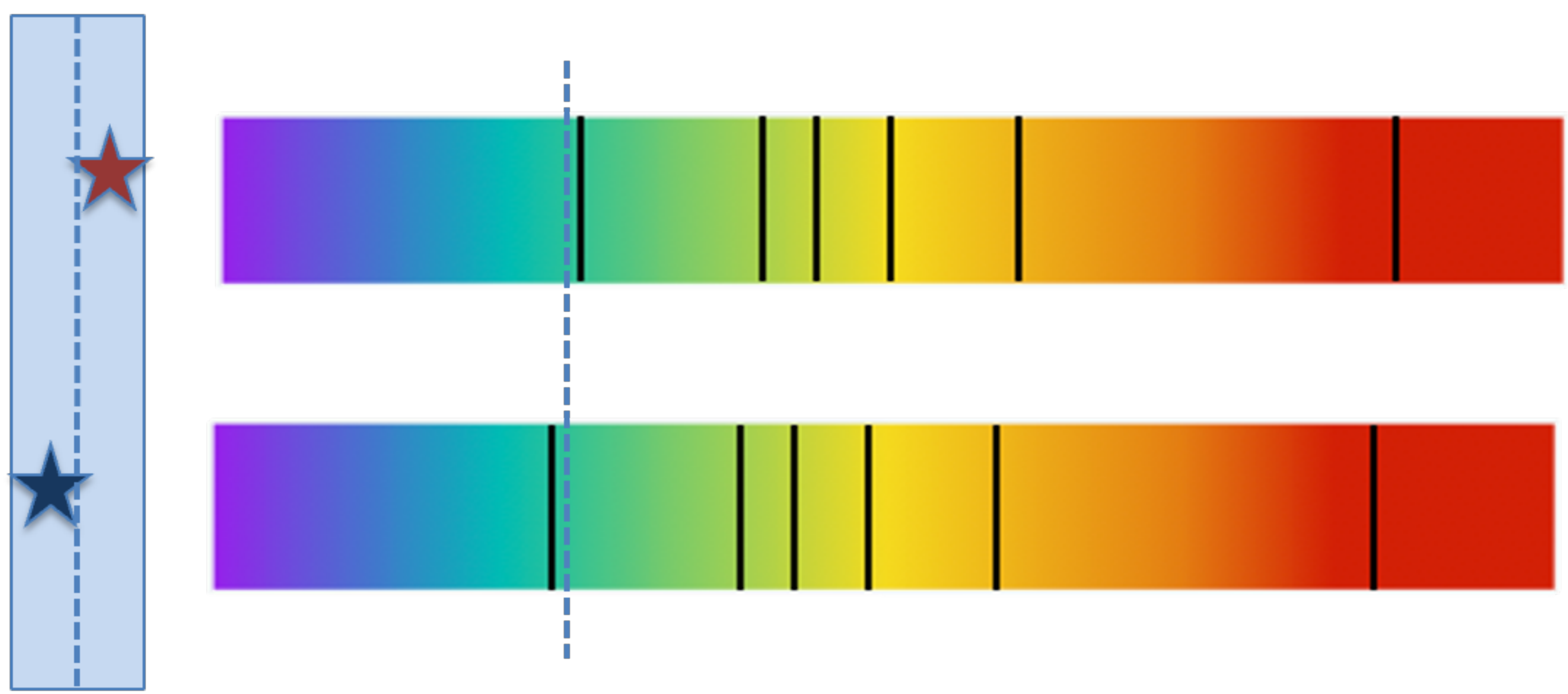
Instrumental Artefacts

- Wavelength Calibration



Wavelength Precision

Things to pay attention to:
How was an object observed? Using a fibre? Slit? How wide is the slit/aperture? Is the object centered?



Instrumental Broadening (spectral resolution)

The spectrograph adds further broadening due to the limited spectral resolving power.

$$R = \lambda/\Delta\lambda$$

$\Delta\lambda$: FWHM of resolution element

For most instruments, the spectral line spread function (LSF) is very close to Gaussian.
(deviations can often be neglected,
except for some HST instruments e.g., COS)

Often depends on wavelength:

Simple Grating Spectra: constant $\Delta\lambda$
Resolving power varies with wavelength!

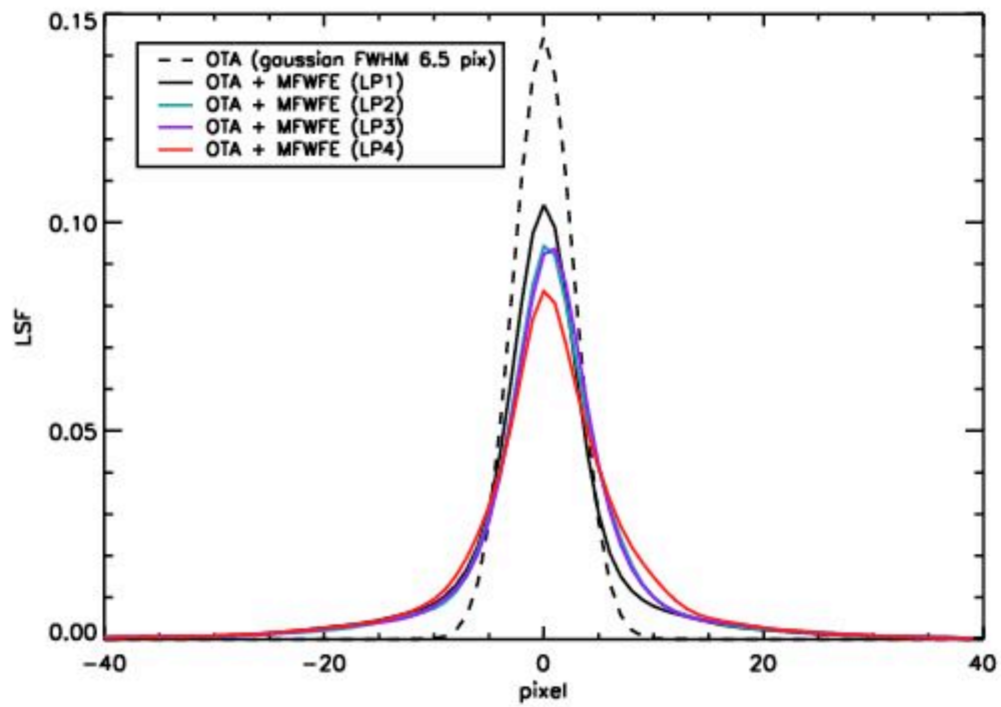
Echelle Spectra: constant R

R is often given in units of km/s:

$$\mathbf{R_{vel} = c / R}$$

for R = 10,000, $R_{vel} \approx 30$ km/s

example: HST/COS



Instrumental Artefacts

- Wavelength Calibration

- Air to vacuum

- Heliocentric motion

Instrumental Artefacts

- Flux Calibration

Standard stars:

Stars with very well-known flux at various wavelengths

Two parts to the calibration:

Relative

Is the spectral shape recovered?

Absolute

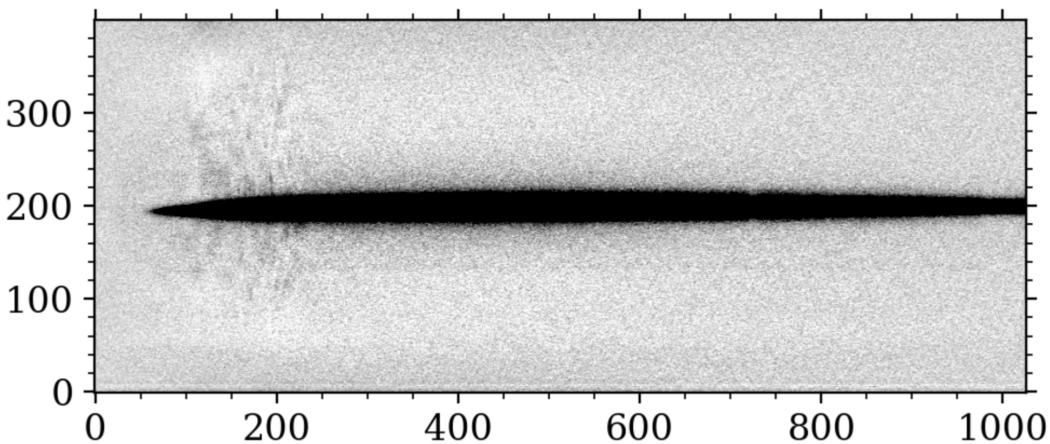
Is the overall amount of flux recovered?

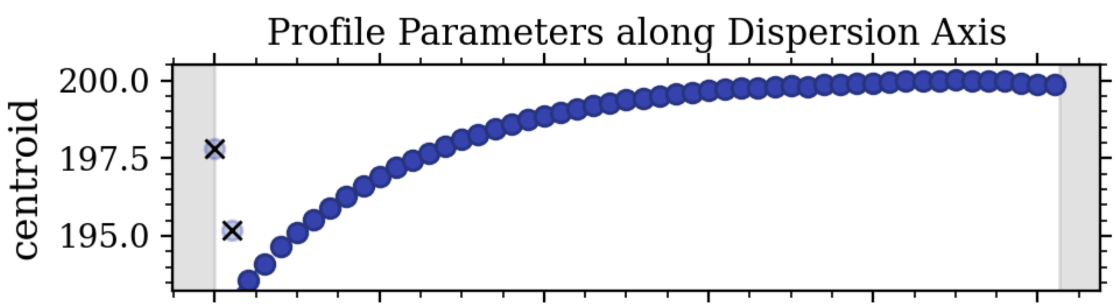
`pynot response`

Instrumental Artefacts

- Flux Calibration

Go through same steps as before





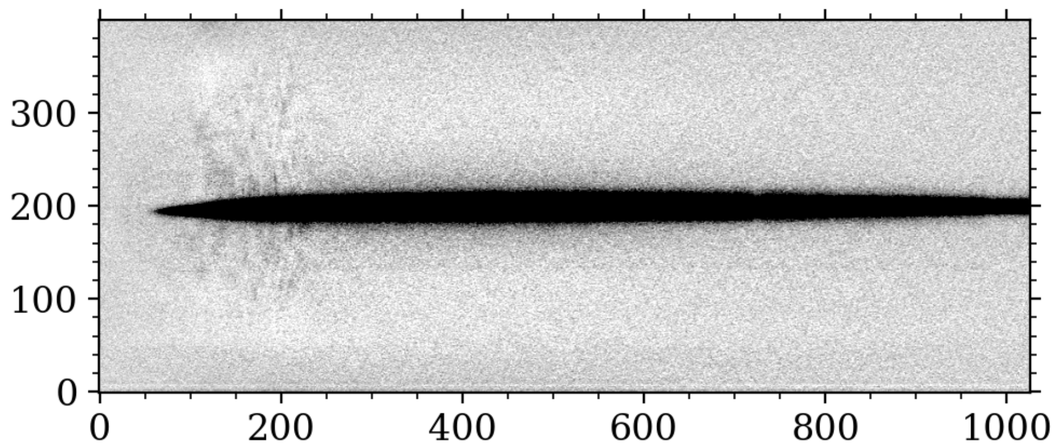
pynot response

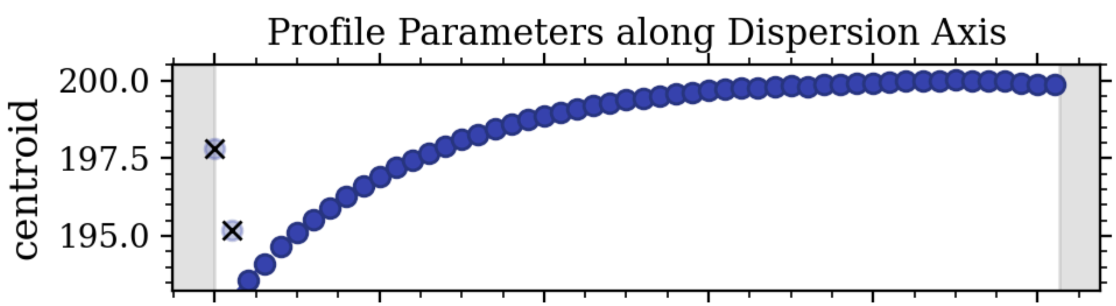
Instrumental Artefacts

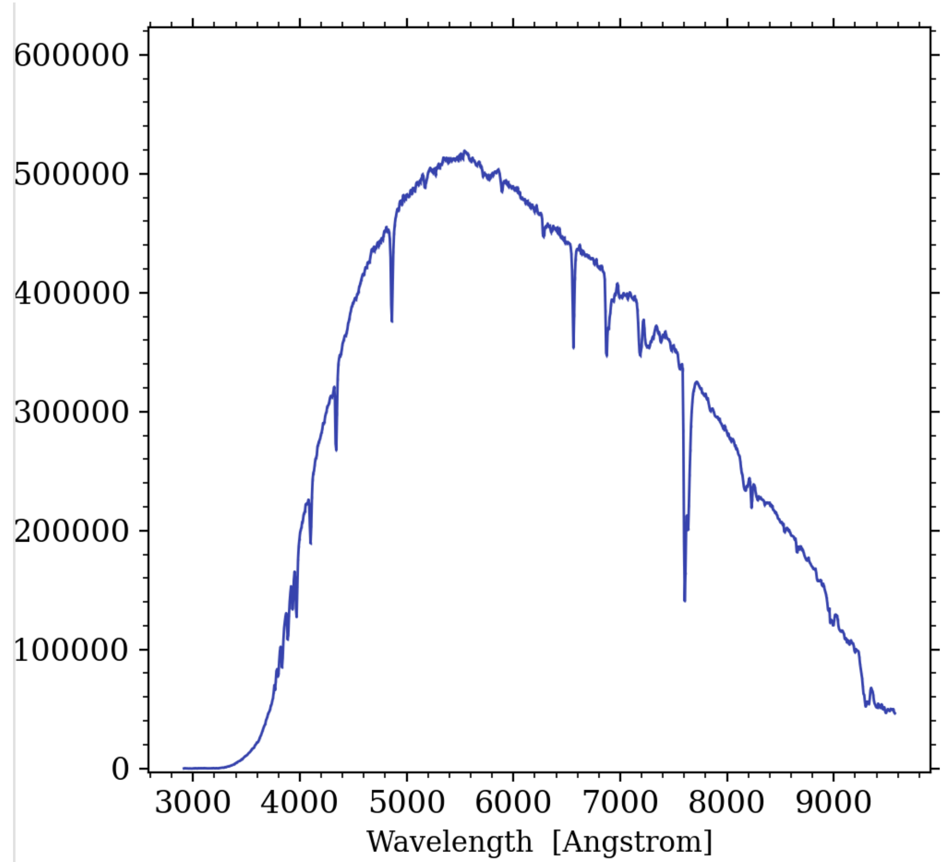
- Flux Calibration

Go through same steps as before

Extracted number of counts as function of wavelength







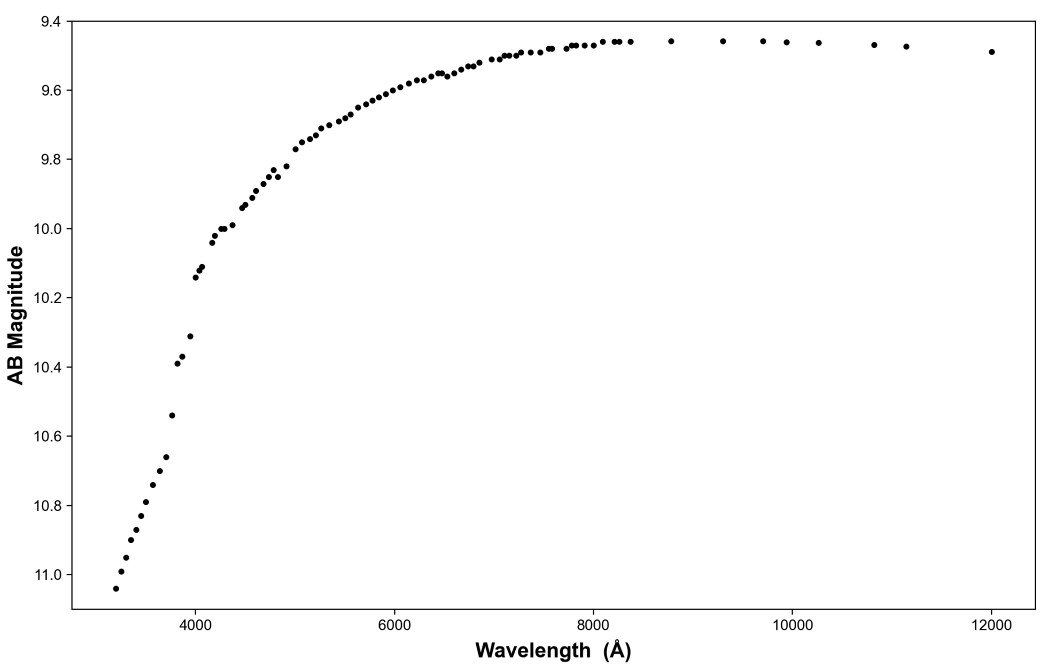
```
pynot response
```

Instrumental Artefacts

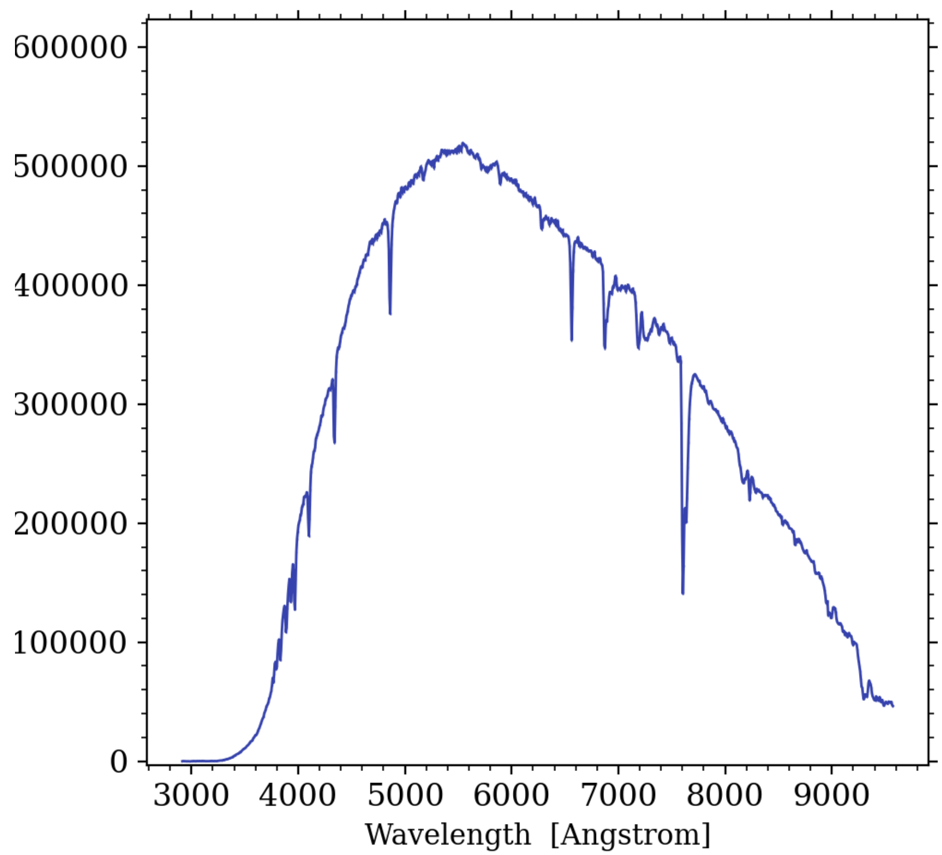
- Flux Calibration

Compare with known fluxes

Known magnitude in narrow bands as function of wavelength



Extracted number of counts as function of wavelength



`pynot response`

$m = -2.5 \log_{10}(F_\nu) - 48.6$

For F_ν in erg / s / cm^2 / Hz

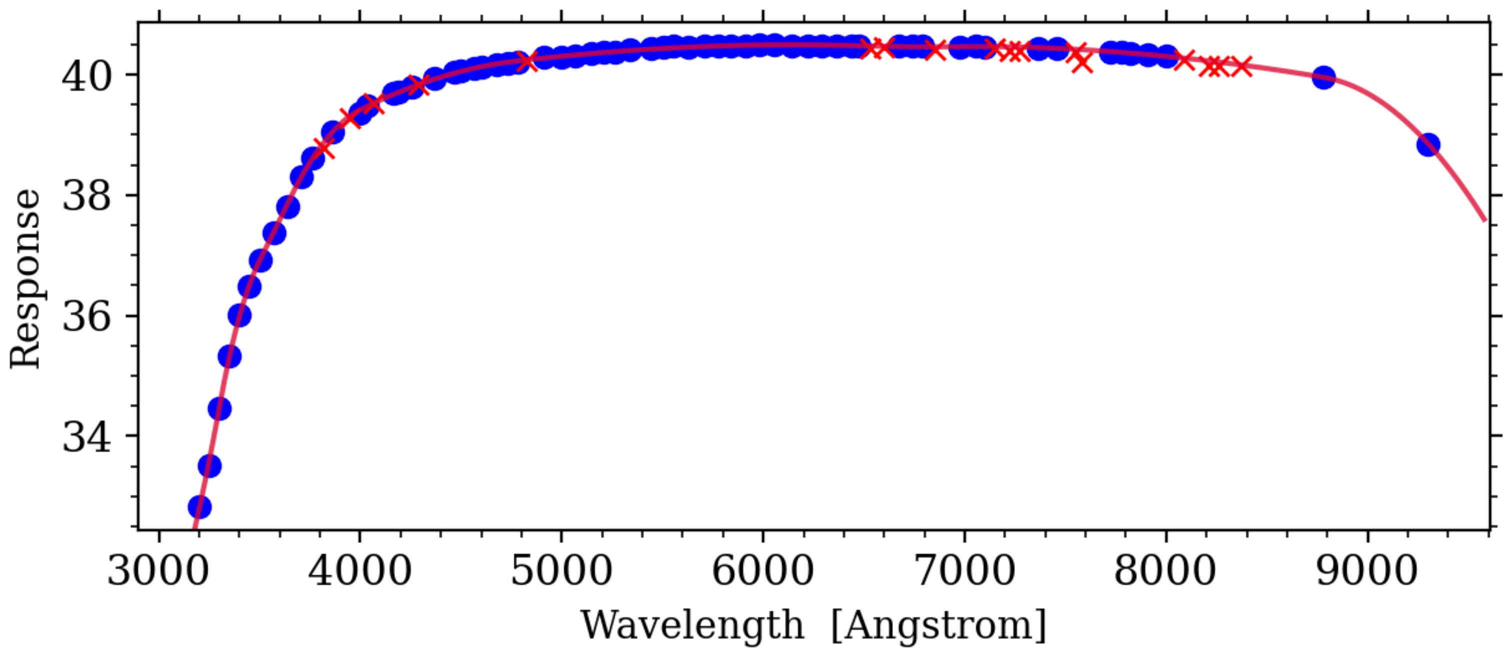
Instrumental Artefacts

$S_i = 2.5 \log_{10} [N_{i,ref} / (t_{exp} \; \Delta\lambda \; F_{\lambda i,ref})] + \text{airmass} \cdot A_i$

- Flux Calibration

Compare with known fluxes —> instrument response

Counts —> F_λ (erg s^{-1} cm^{-2} Å^{-1})



To apply the response function:

```
pynot flux2d
pynot flux1d
```

```
pynot response
```

$m = -2.5 \log_{10}(F_\nu) - 48.6$

For F_ν in erg / s / cm^2 / Hz

Instrumental Artefacts

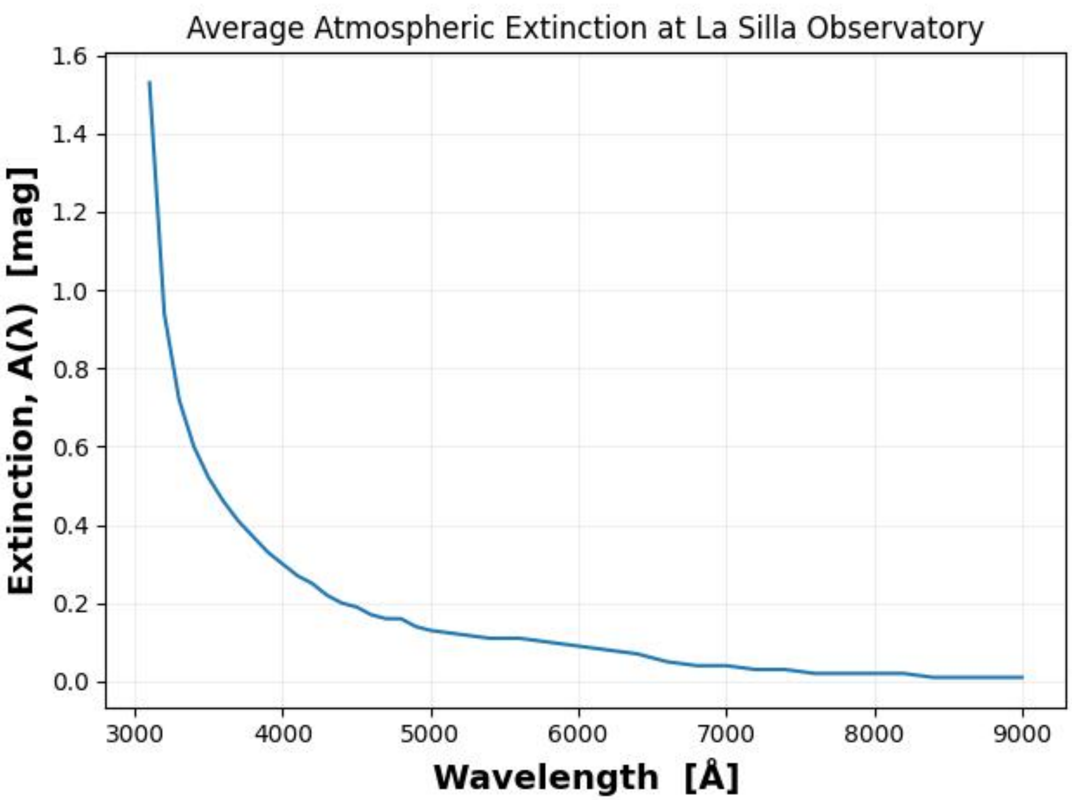
$S_i = 2.5 \log_{10} [N_{i,ref} / (t_{exp}\ \Delta\lambda\ F_{\lambda i,ref})] + \text{airmass} \cdot A_i$

- Flux Calibration

Compare with known fluxes —> instrument response

Counts —> F_λ (erg s^{-1} cm^{-2} Å^{-1})

Atmospheric Extinction in the ith spectral bin at wavelength λ_i.

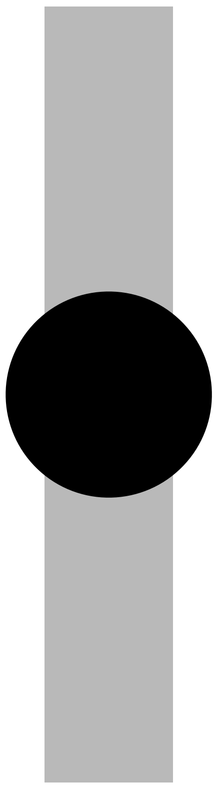


Instrumental Artefacts

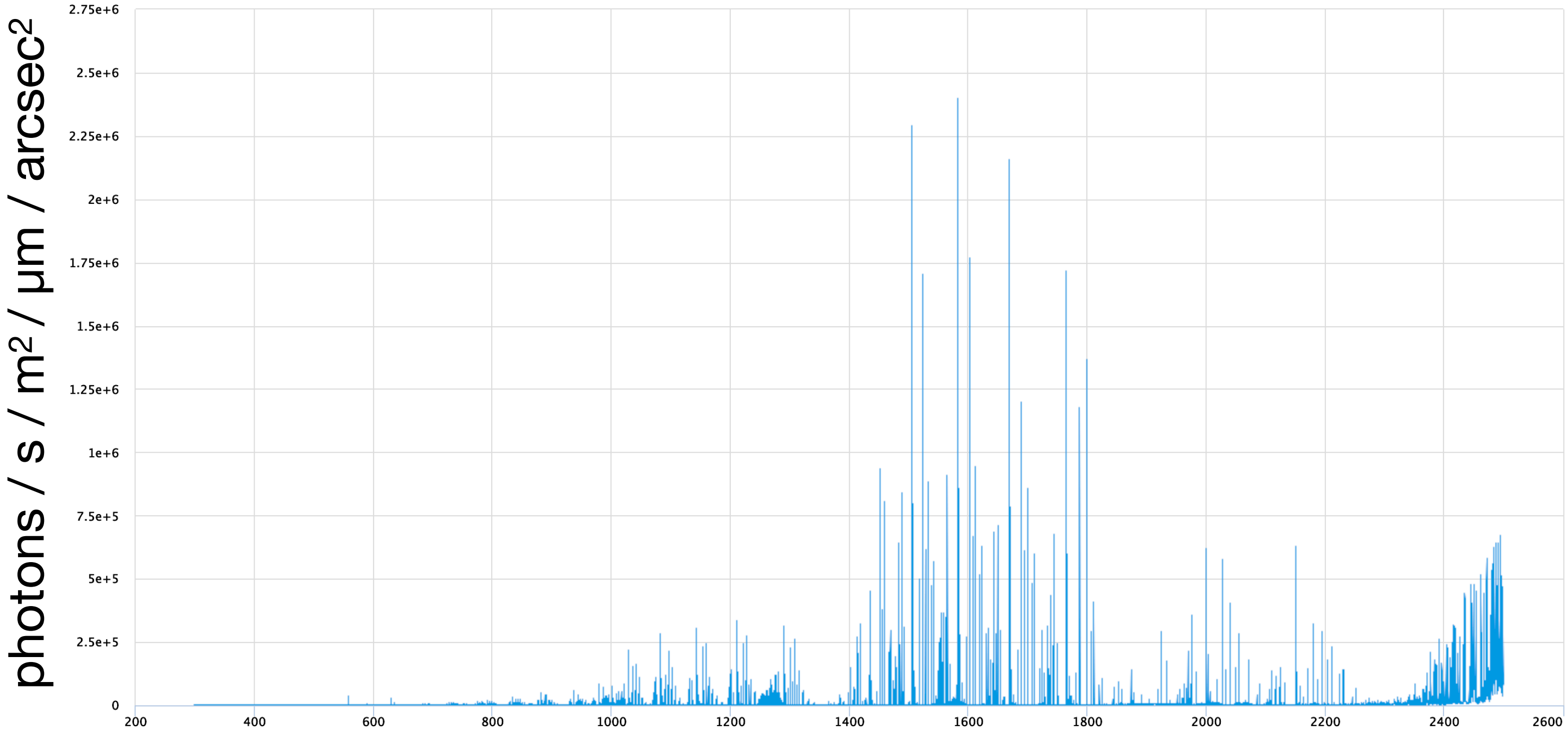
Aperture effects:

Is the object centred in the slit?

Is the seeing bigger/smaller than the slit?

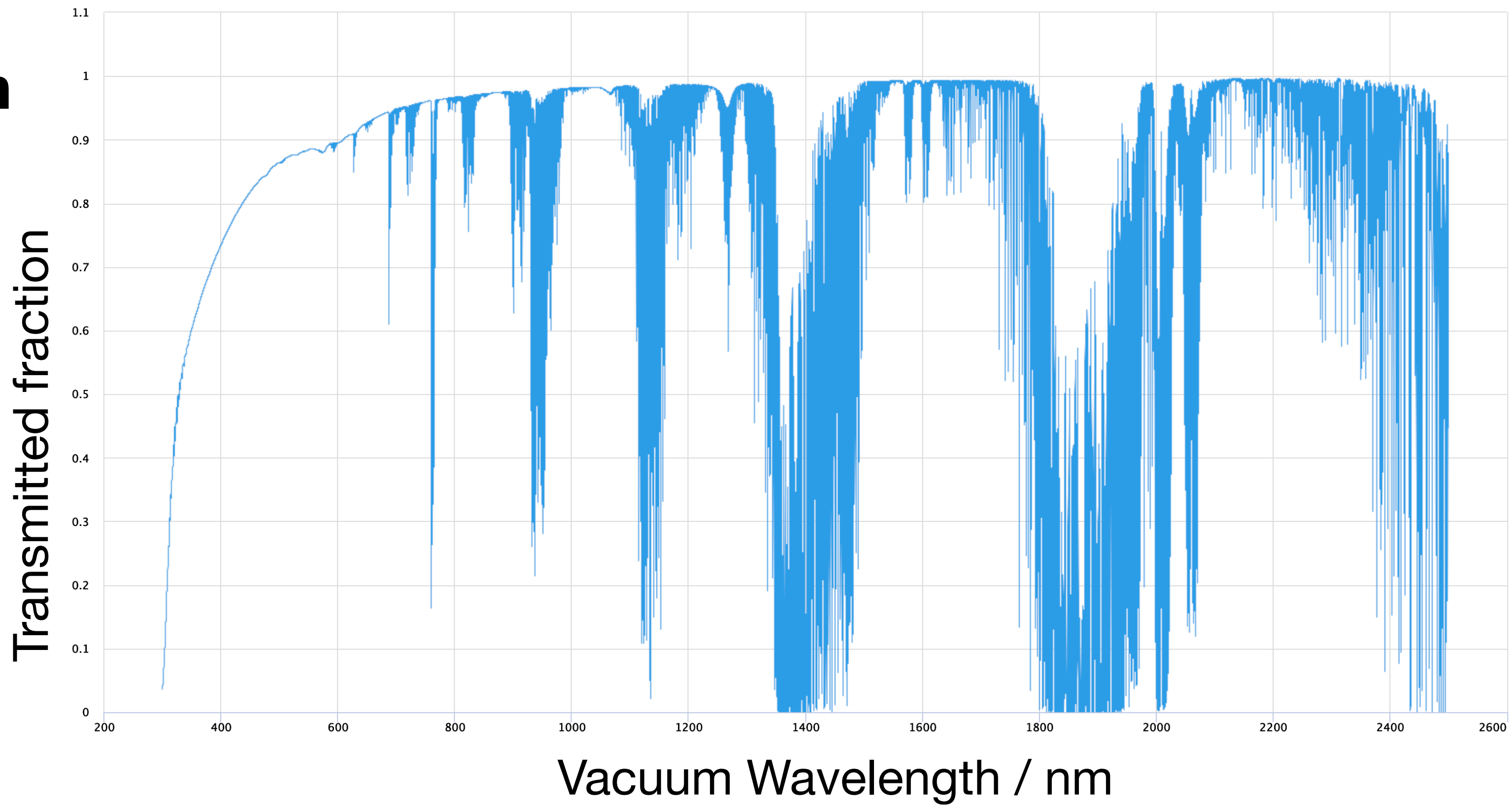


Atmospheric Emission



Telluric Absorption

Not covered today

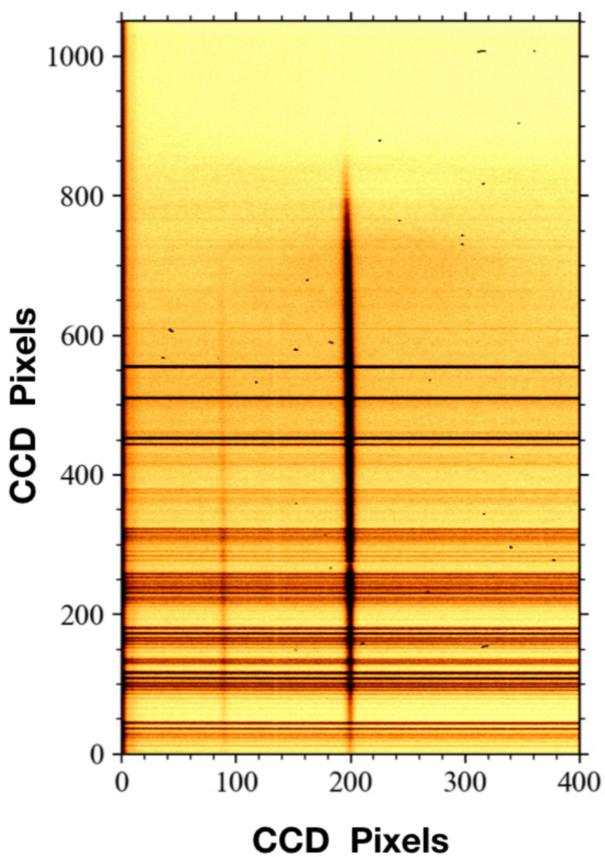


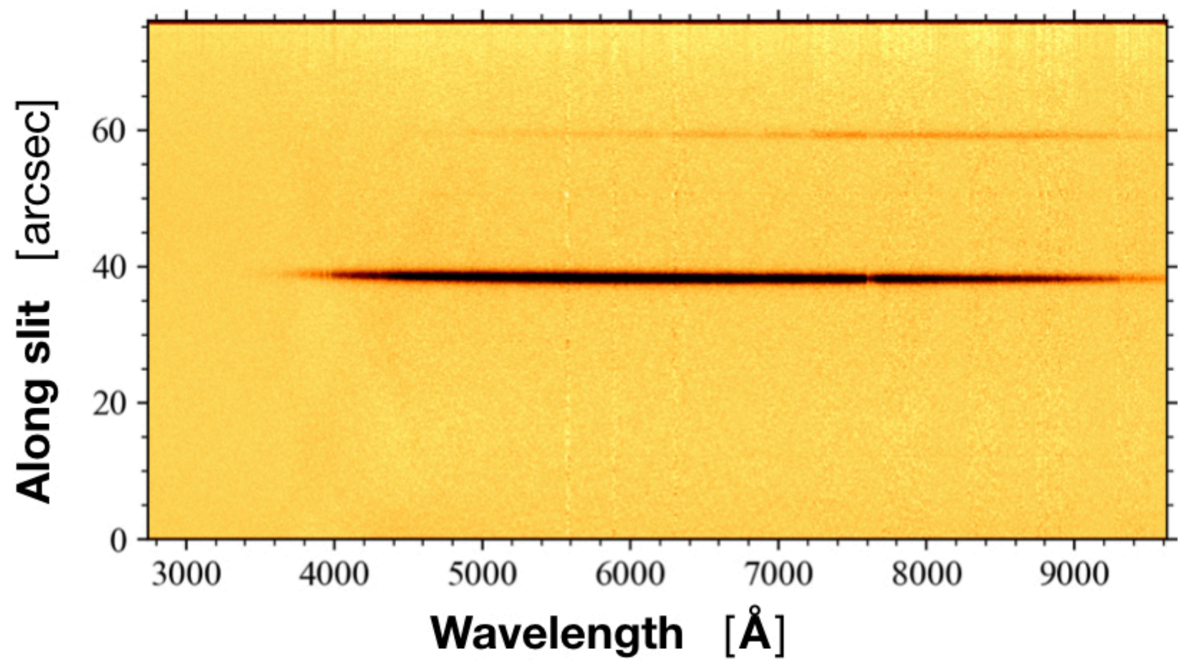
`pynot skysub` or `pynot extract`

Atmospheric Artefacts

- Sky background

Estimating the sky background in 2D:





Atmospheric Artefacts

- Sky background

Dithering : offset the target along the slit and subtract frames

Using pynot operate to subtract images:

```
pynot operate ‘a - b’ a=image1.fits b=image2.fits output=AB.fits

pynot operate ‘b - a’ a=image1.fits b=image2.fits output=BA.fits
```

and then shift and combine using scombine:

```
pynot scombine AB.fits BA.fits -o skysub.fits
```

Atmospheric Artefacts

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What if my object is very extended?