

Spectroscopy (Really Just Photometry)

Robert Lupton

2018-01-25

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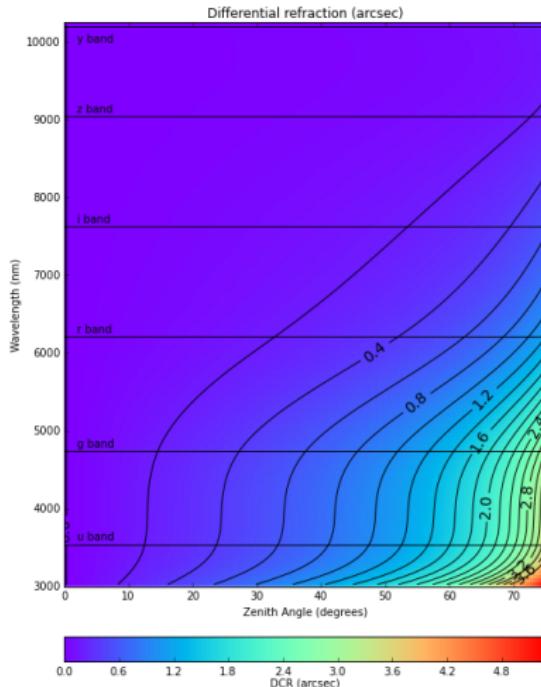
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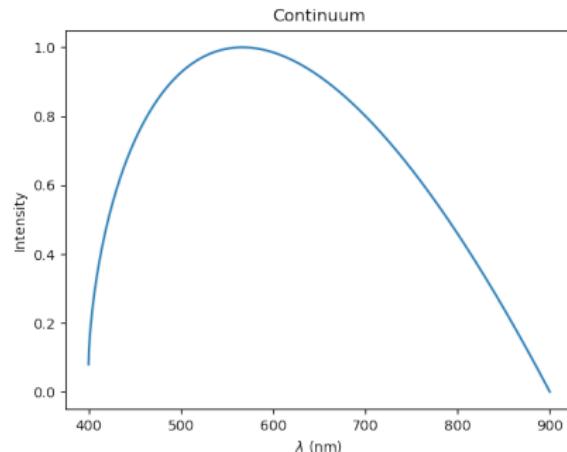
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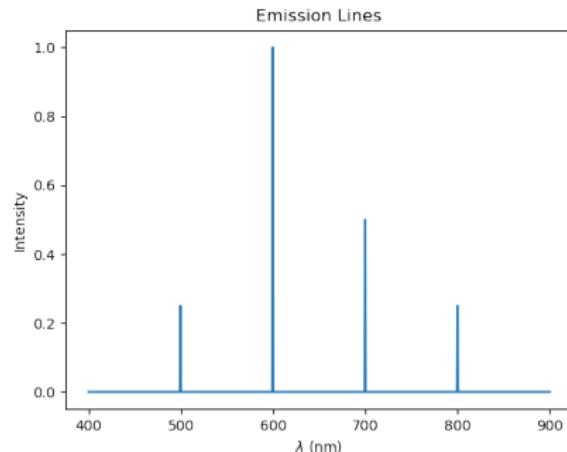


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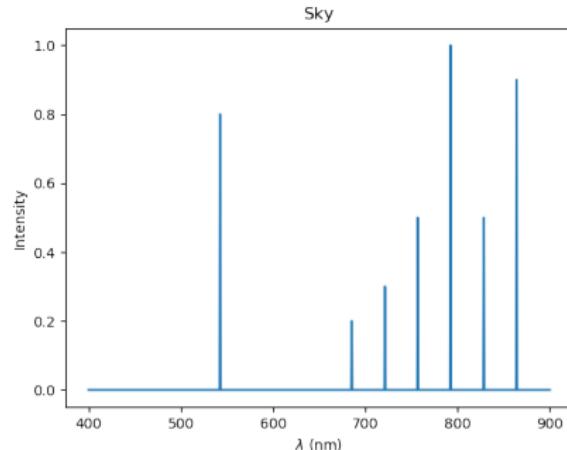


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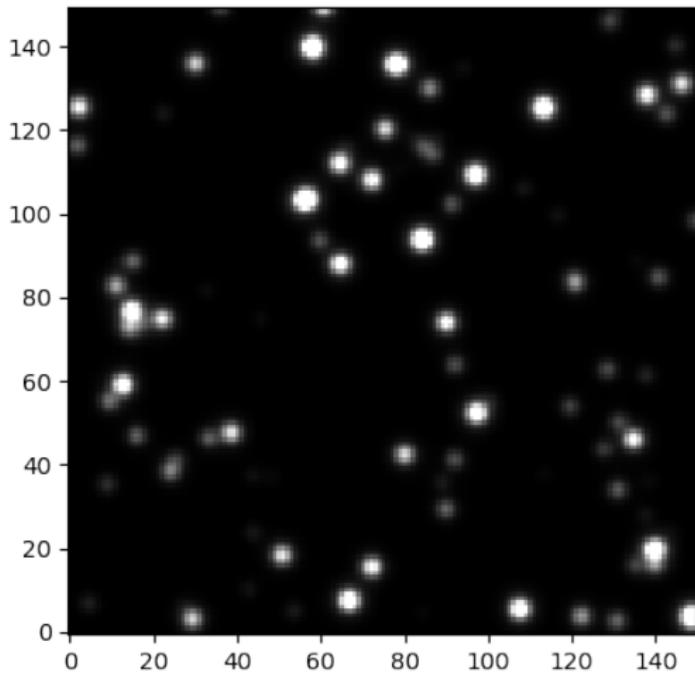


Instrumental Signature Removal

The ISR is similar to an imager's:

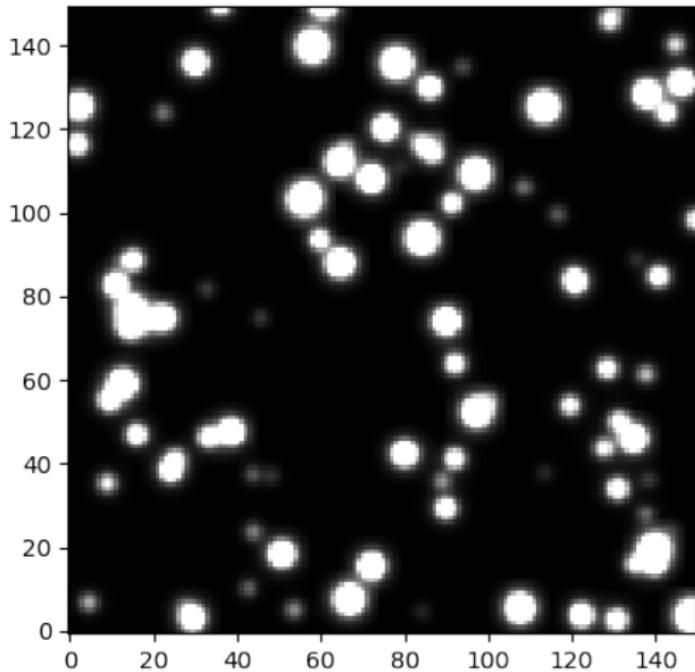
- overscan/bias removal
- dark current subtraction
- linearisation
- flat fielding
 - ▶ Use a dispersed flat -- the QE is in general a function of wavelength
 - ▶ It's not trivial to get a good flat for a fibre spectrograph
- cosmic ray masking/removal

A Star Field



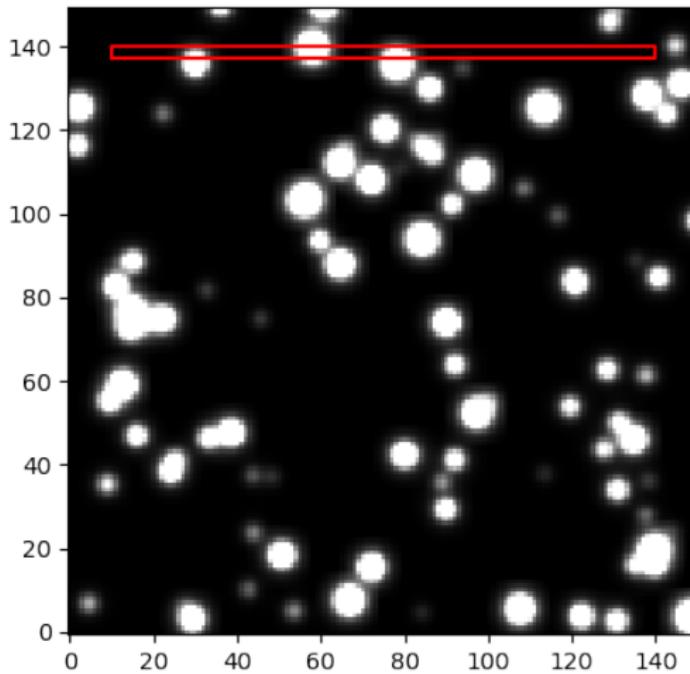
Direct Image

A Star Field



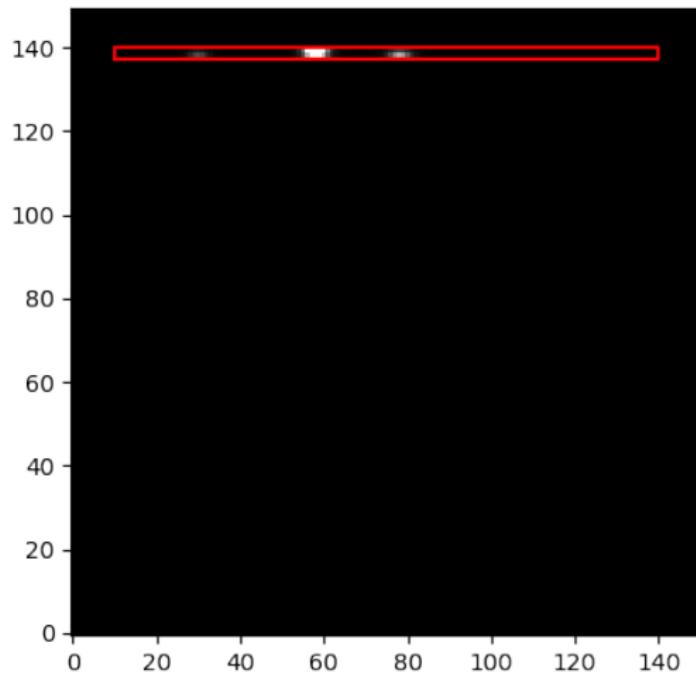
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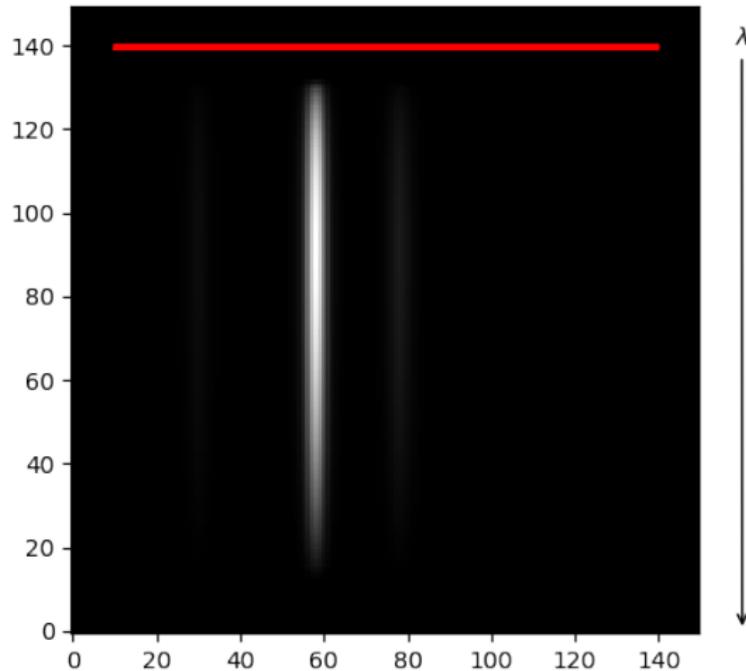
Direct Image with 3-pixel wide slit

A Star Field



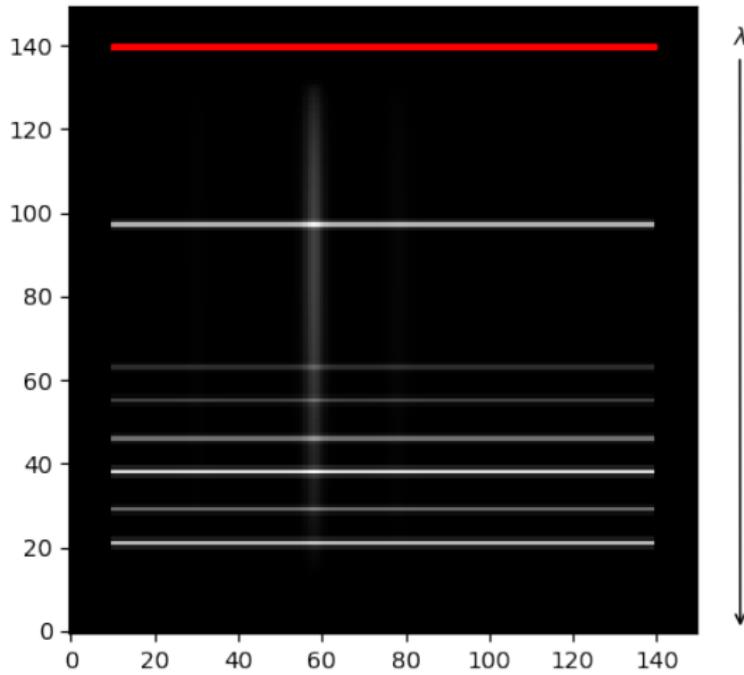
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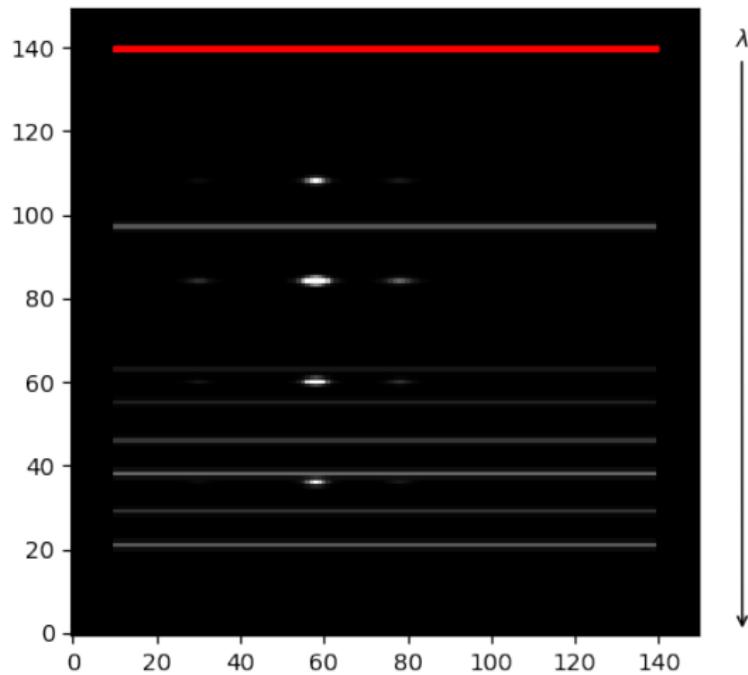
Dispersed 1-pixel wide slit continuum

A Star Field



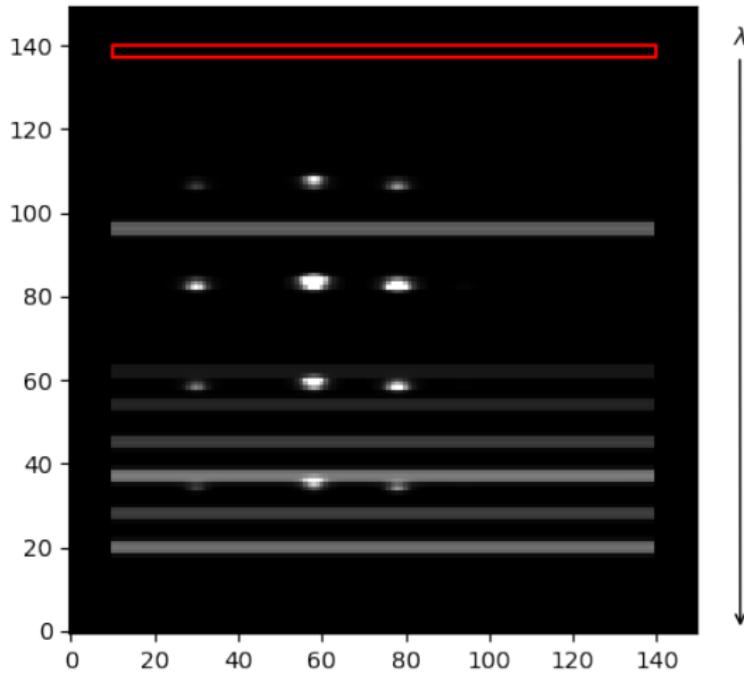
Dispersed 1-pixel wide slit continuum sky

A Star Field



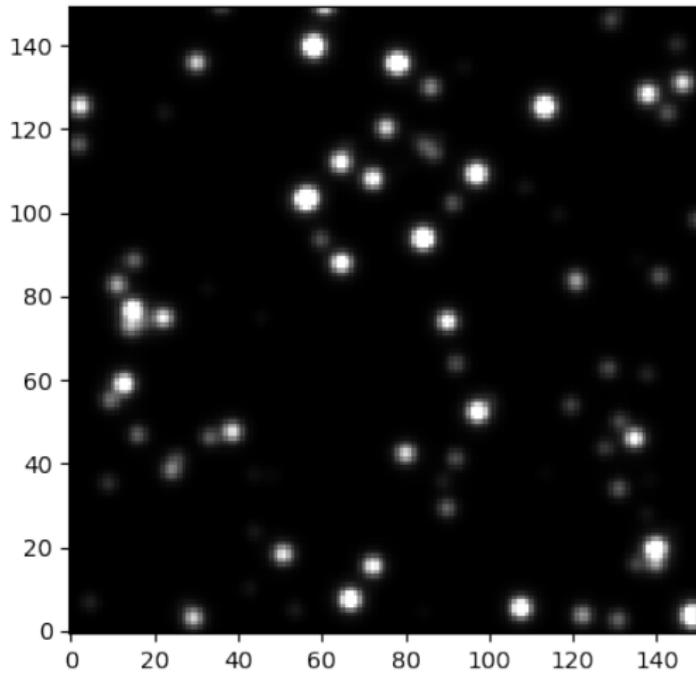
Dispersed 1-pixel wide slit 4 emission lines sky

A Star Field



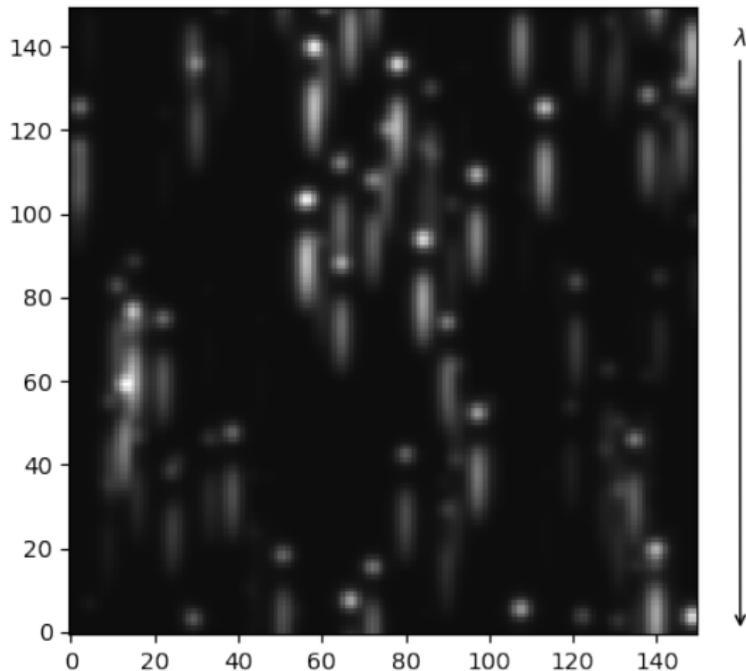
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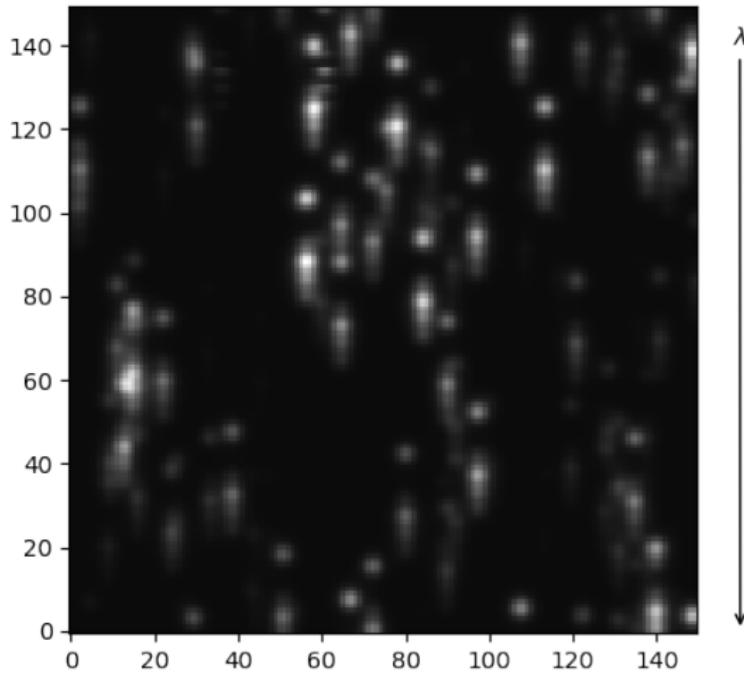
sky

A Star Field



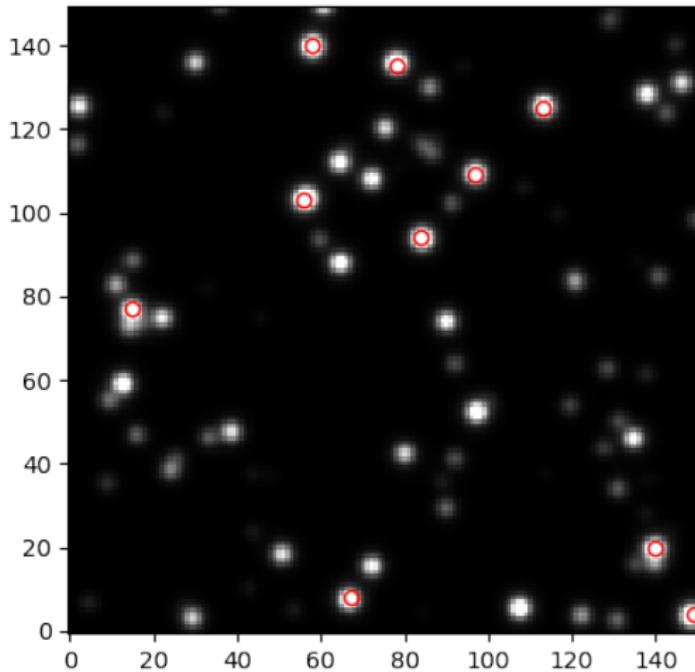
Grism; note 0-order and 1-order images continuum sky

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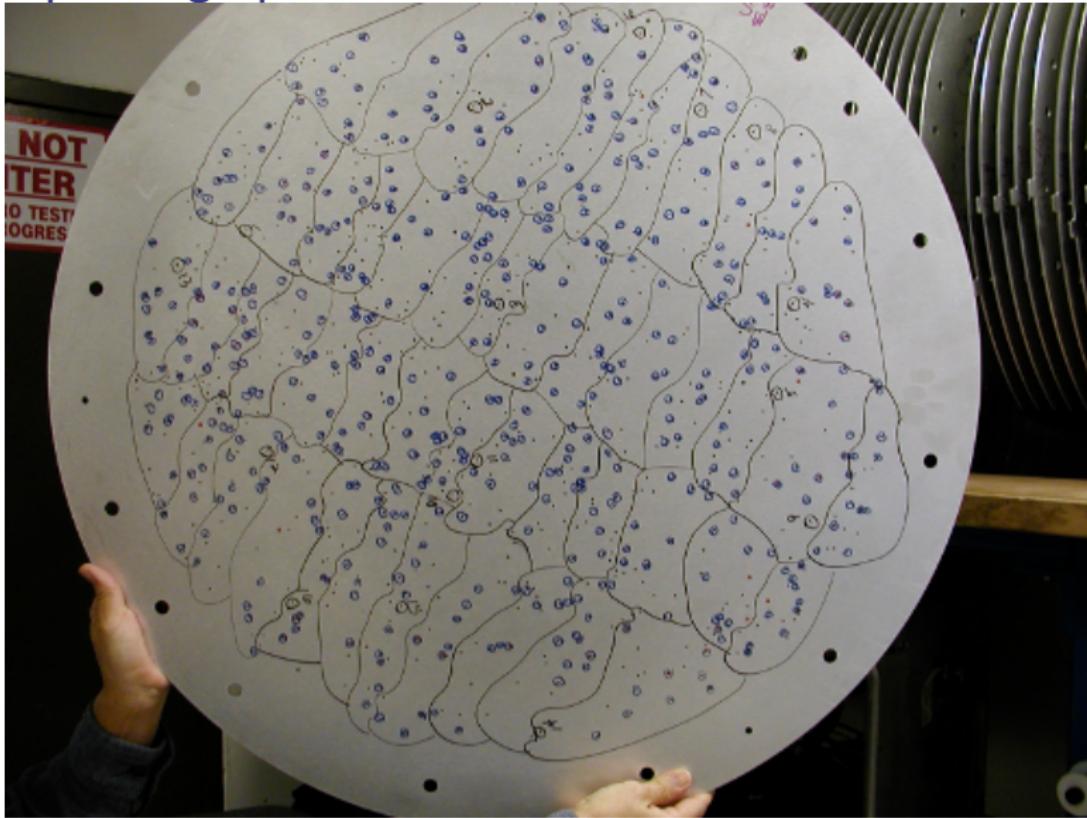
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Fibre Spectrographs



Fibre targets

Fibre Spectrographs



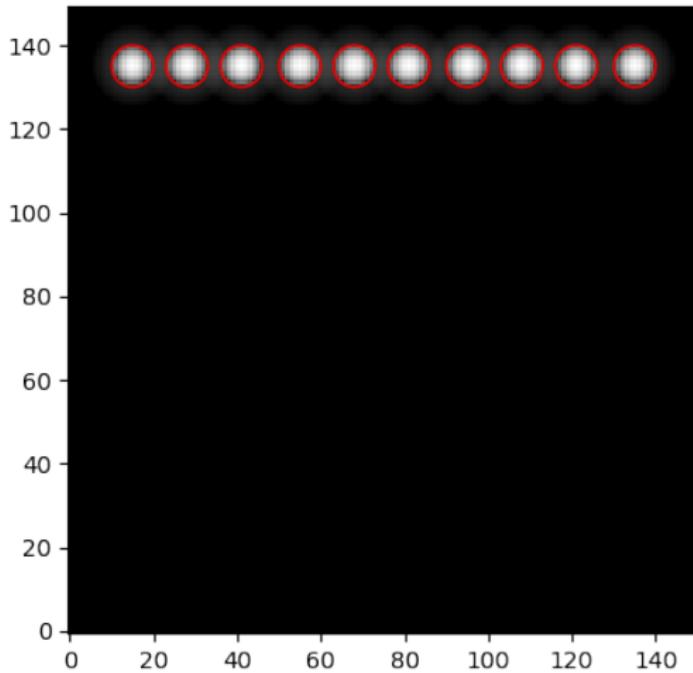
Steel plate into which fibres are plugged

Fibre Spectrographs



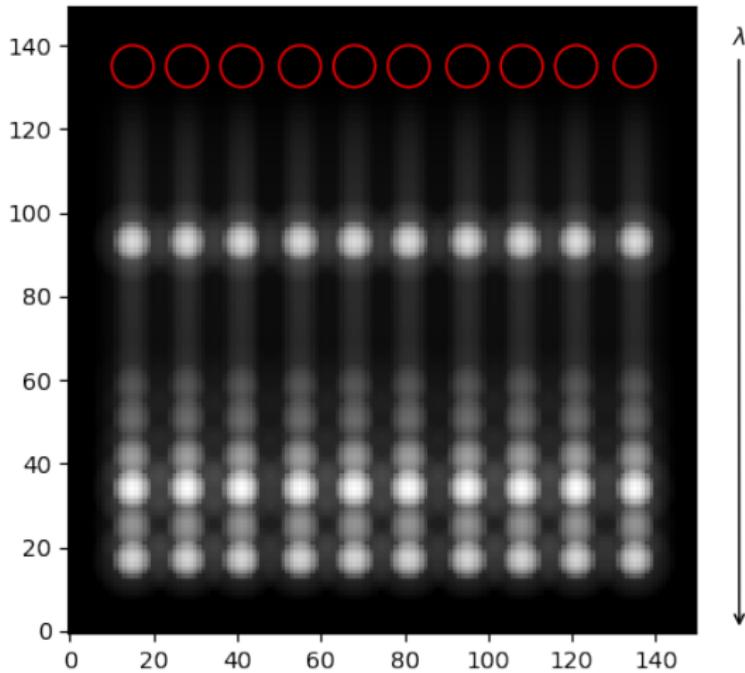
Connecting the sky to the SDSS spectrograph using optical fibres

Fibre Spectrographs



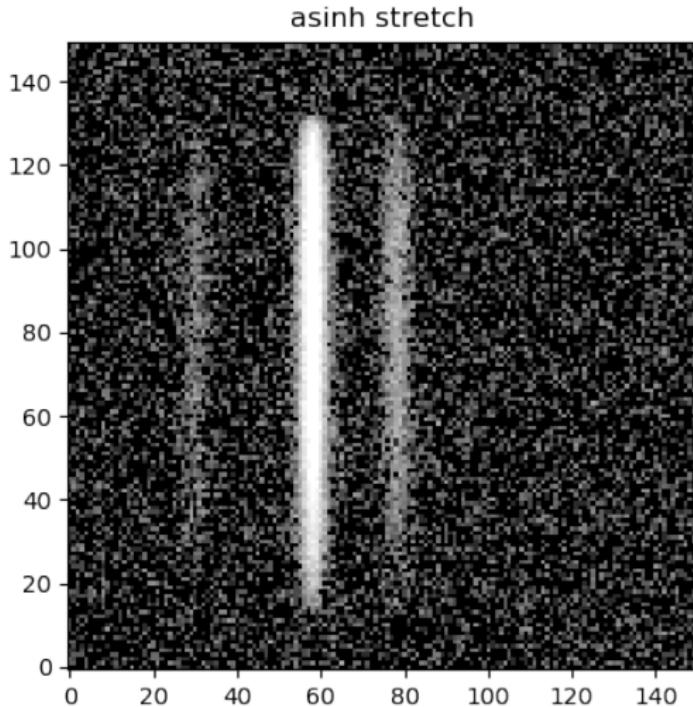
Direct image of fibres

Fibre Spectrographs



Dispersed fibres sky continuum

Extracting Spectra



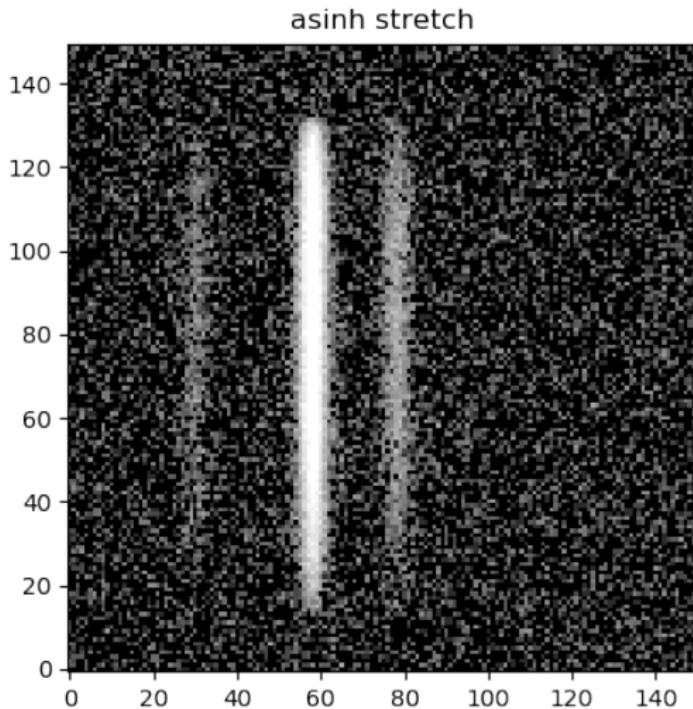
Poisson noise + Gaussian background (readnoise, dark current)

Extracting Spectra

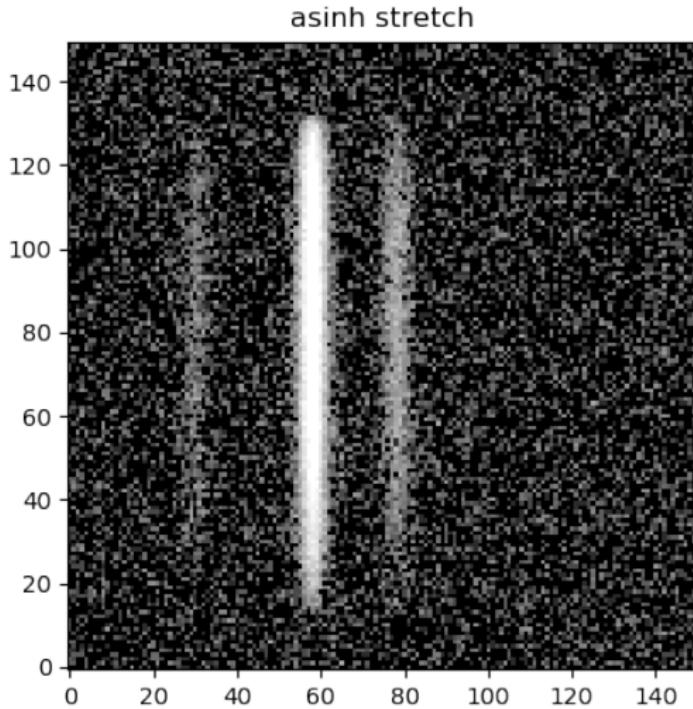
N.b.

$$\text{asinh}(x) = \begin{cases} x & |x| \ll 1 \\ \pm \ln |x| & |x| \gg 1 \end{cases}$$

Extracting Spectra



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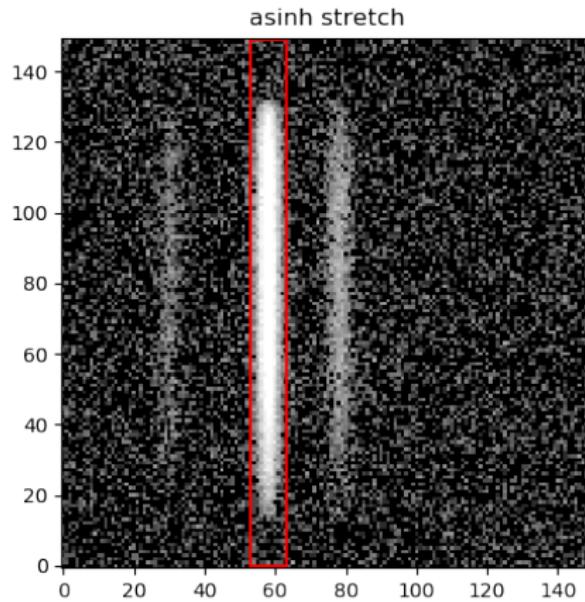
How should we measure those spectra?

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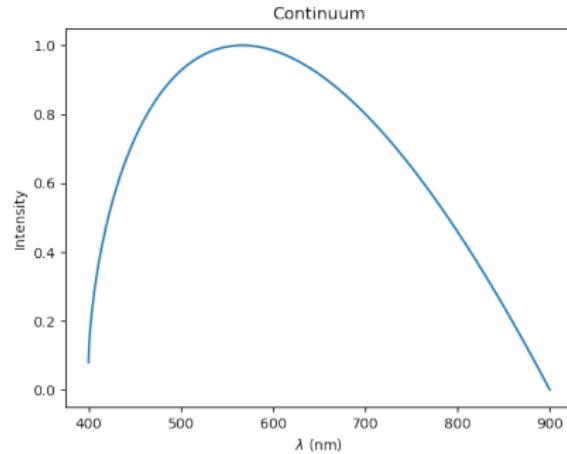
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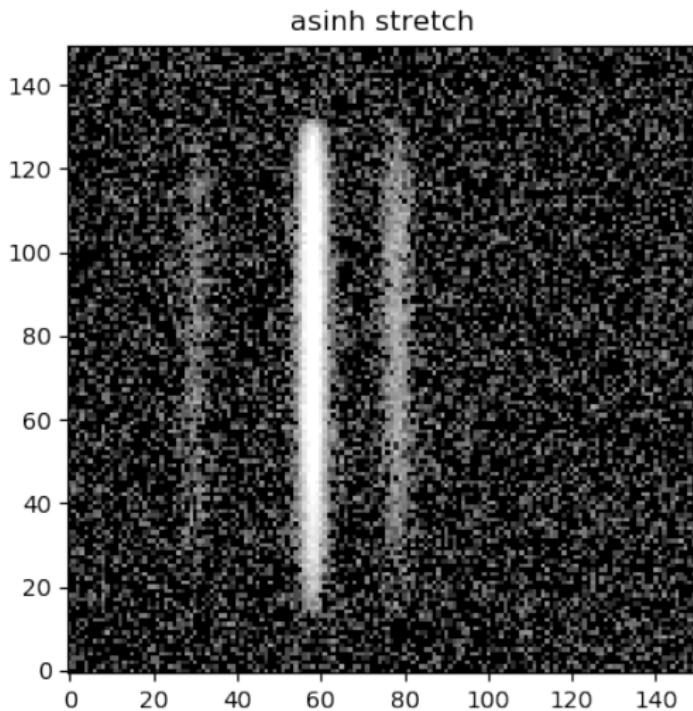
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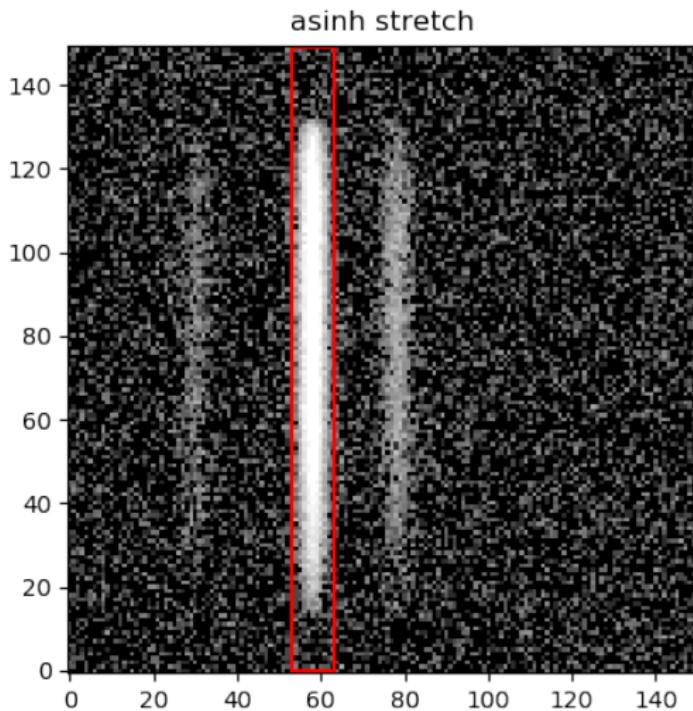
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This doesn't invalidate the estimator \hat{A} , but it does mean that it isn't optimal.

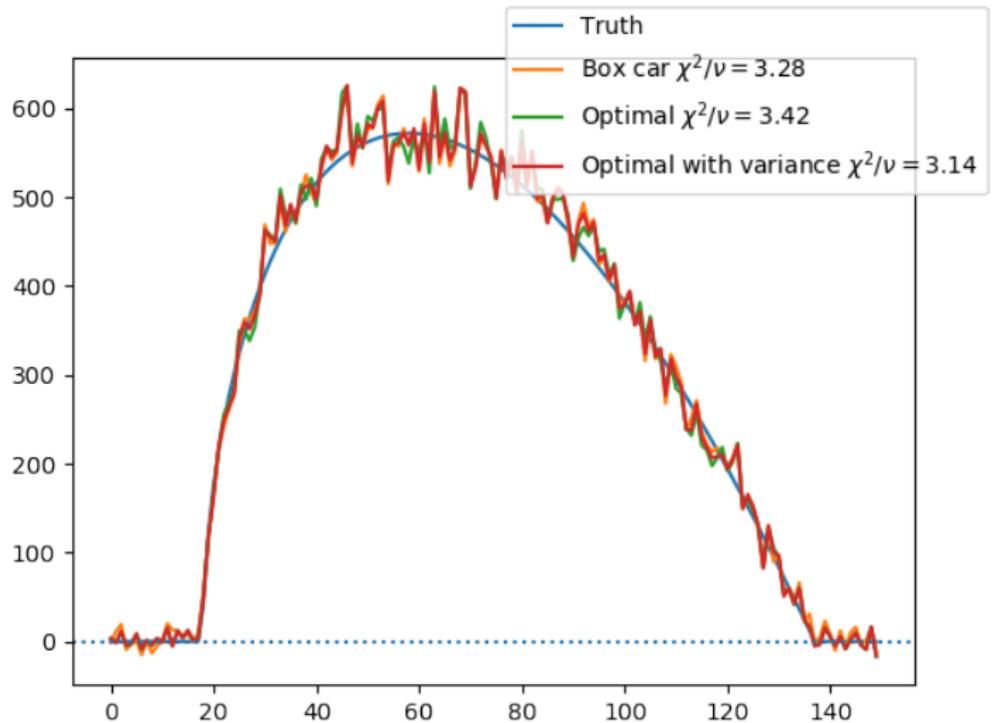
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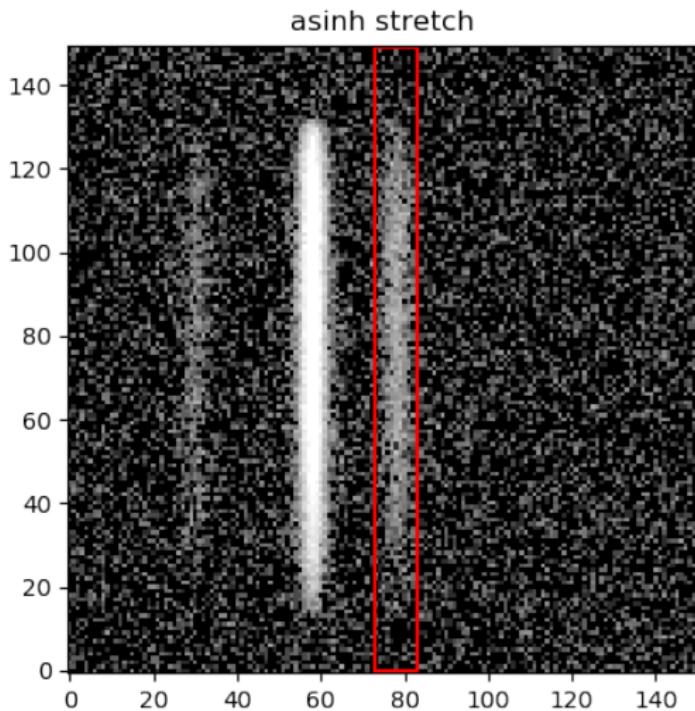
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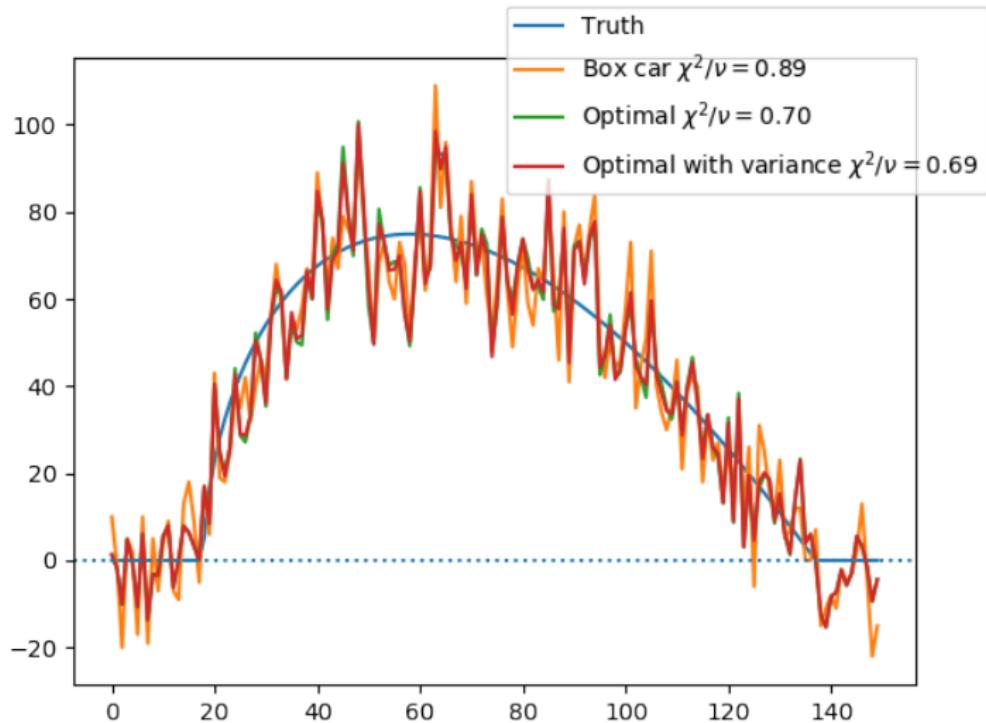
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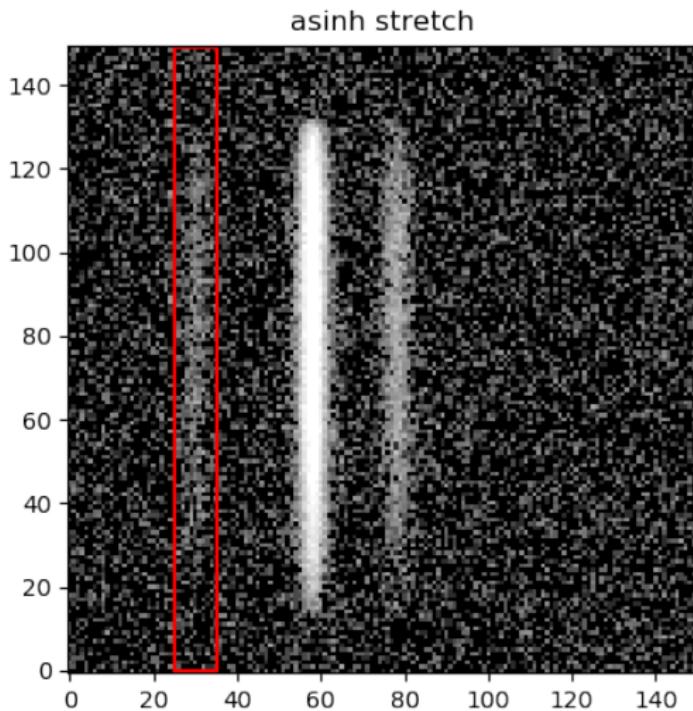
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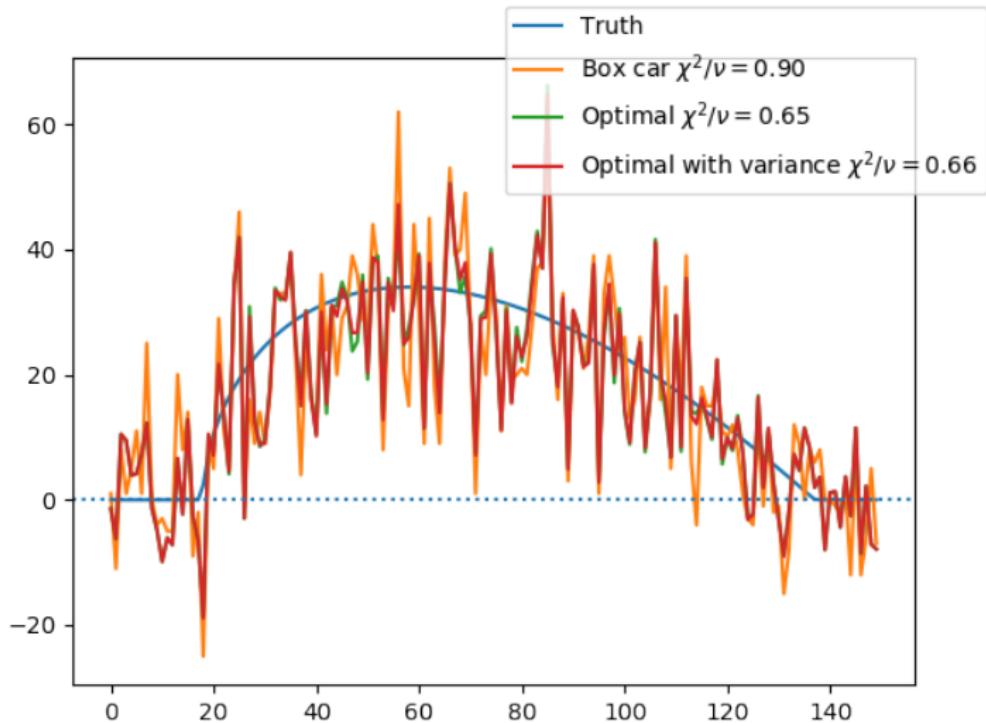
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In reality grism spectra overlap. It helps to take multiple exposures with the grism at a range of positions.

Fibre Spectrographs

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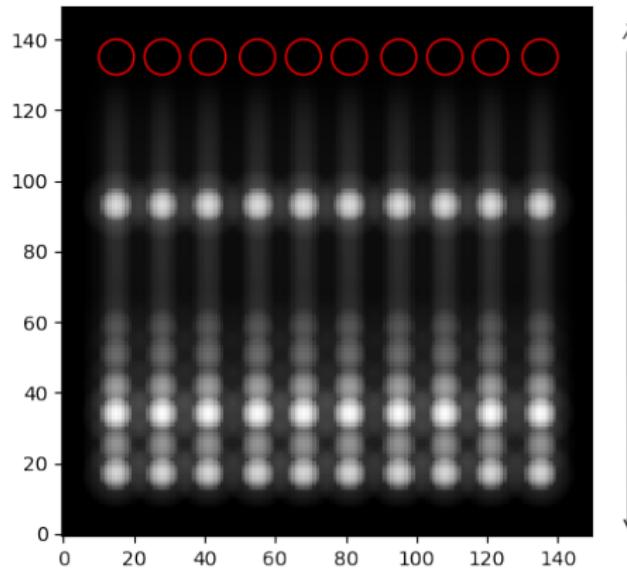
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Unfortunately this is computationally very expensive.

The Sky Spectrum

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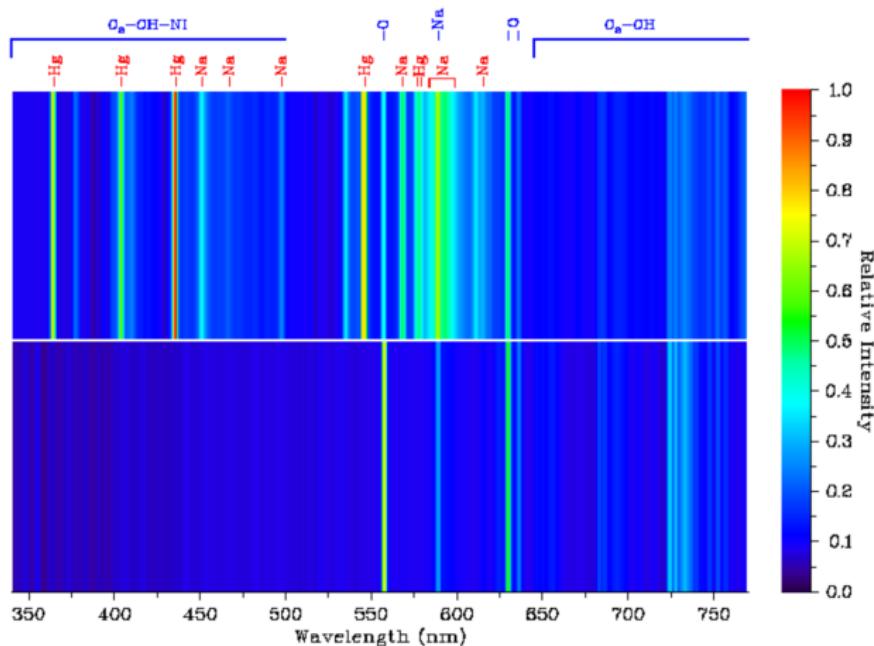
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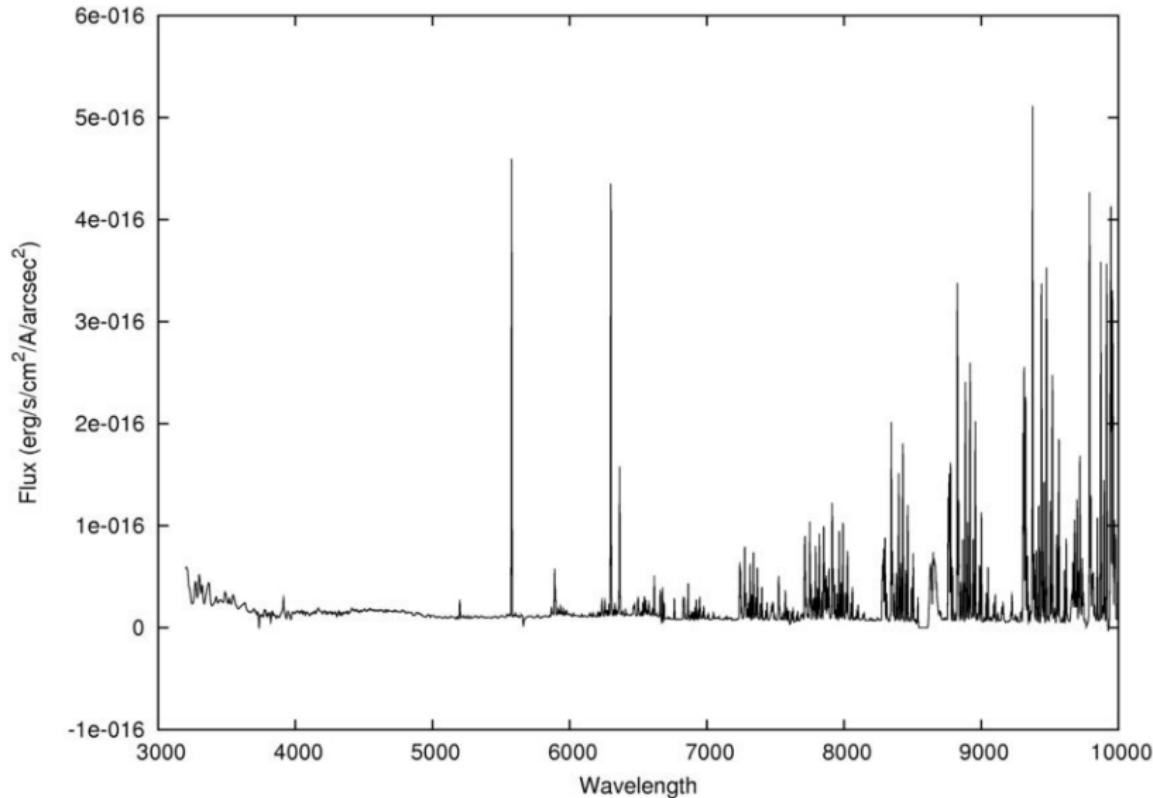
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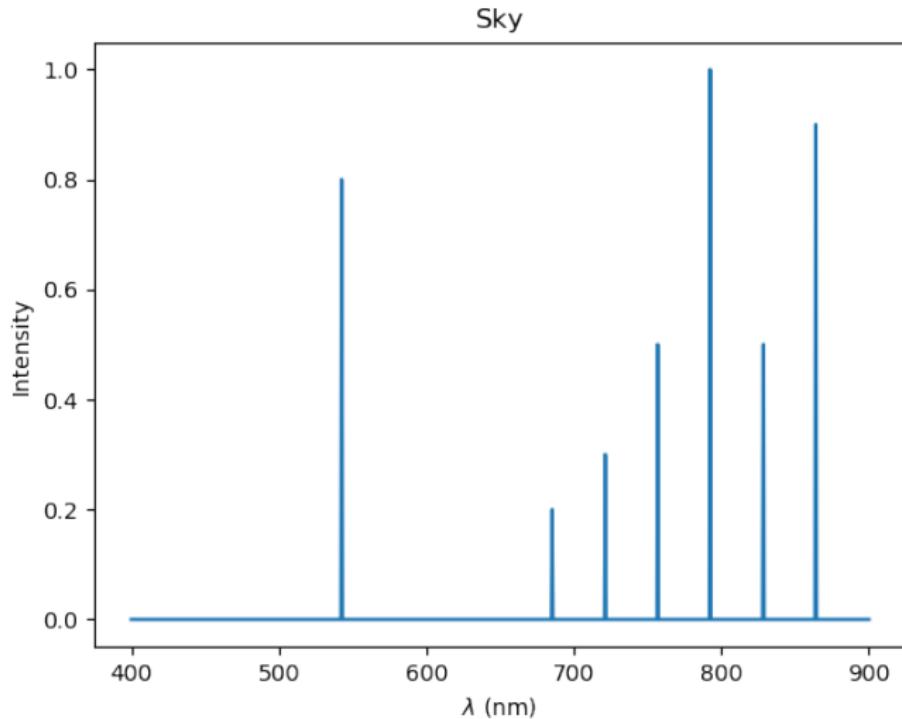
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In the near IR there are *lots* of lines.



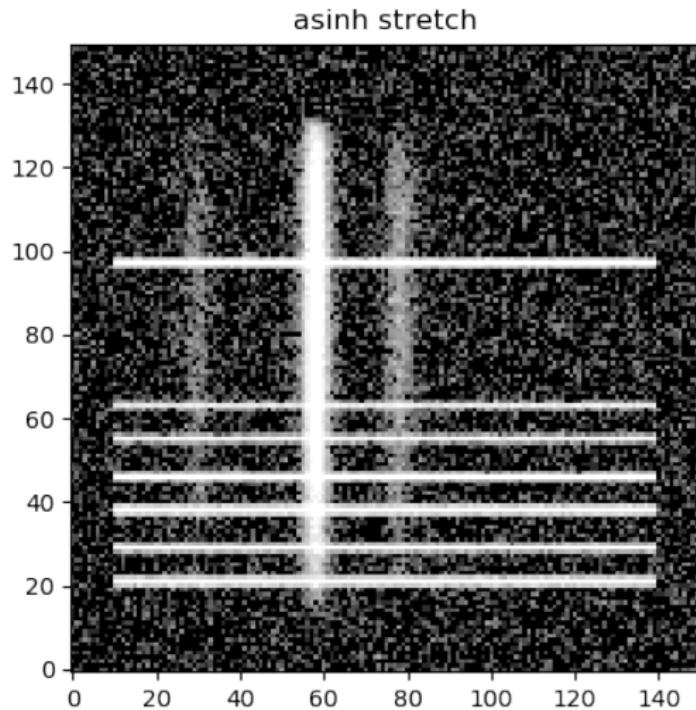
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It's a lot worse than this!

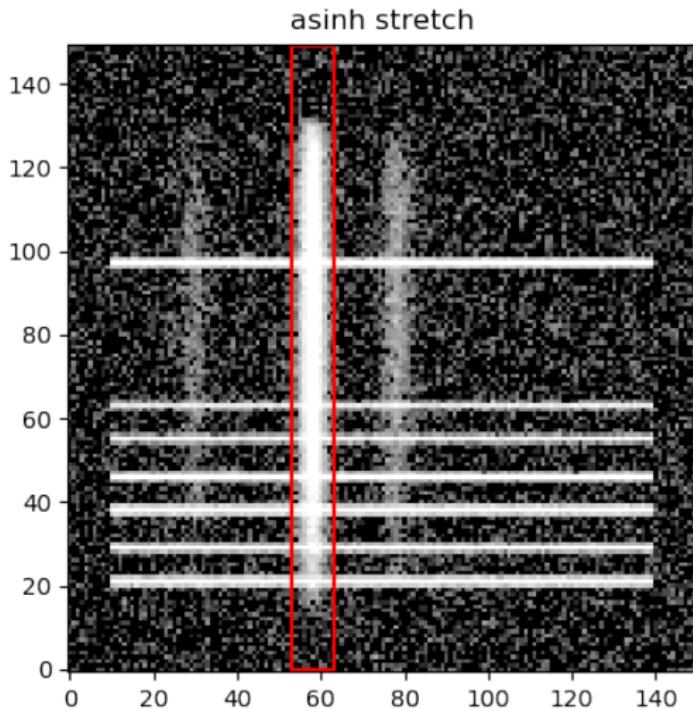


Sky Subtraction

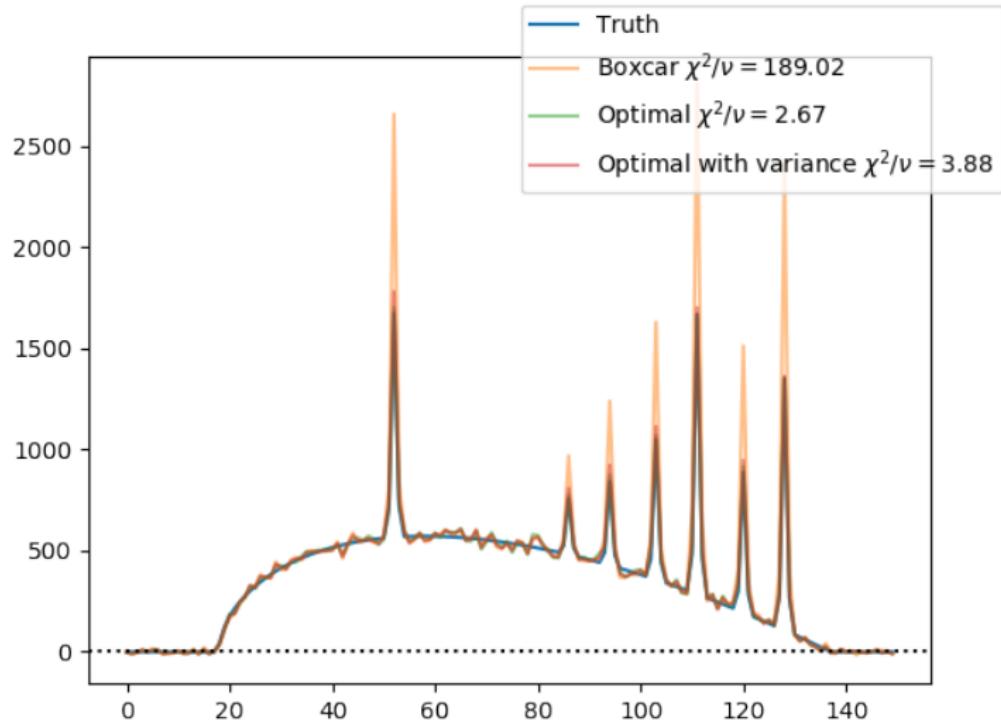
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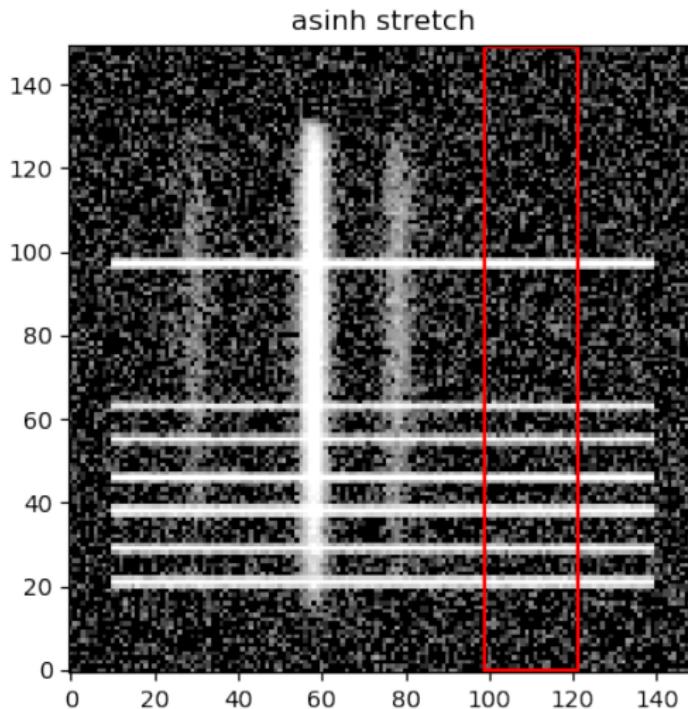


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We can then extract the sky in an uncontaminated part of the slit:

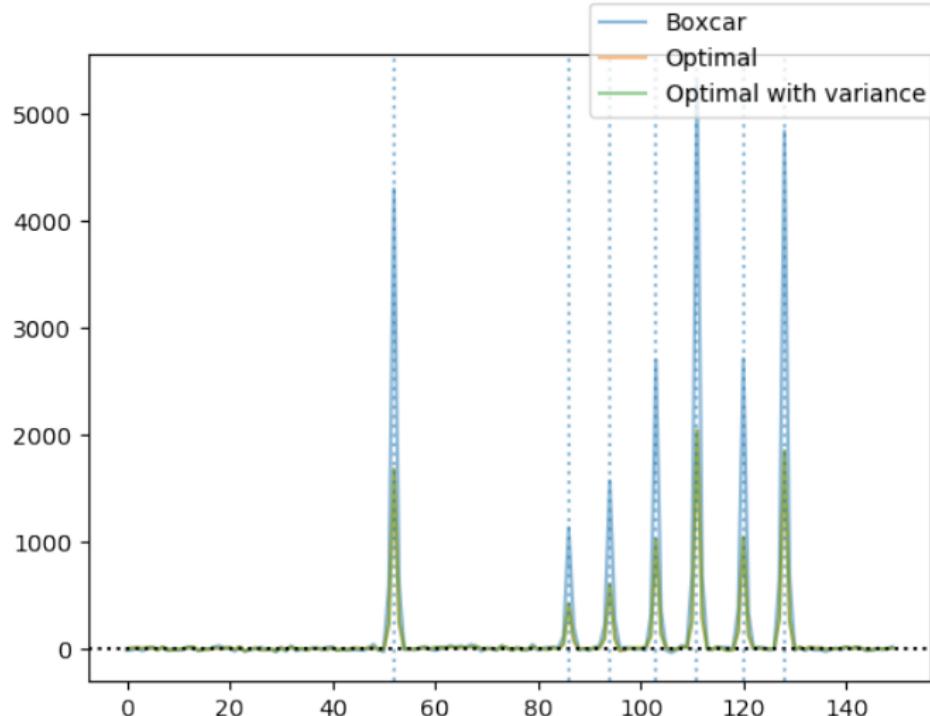
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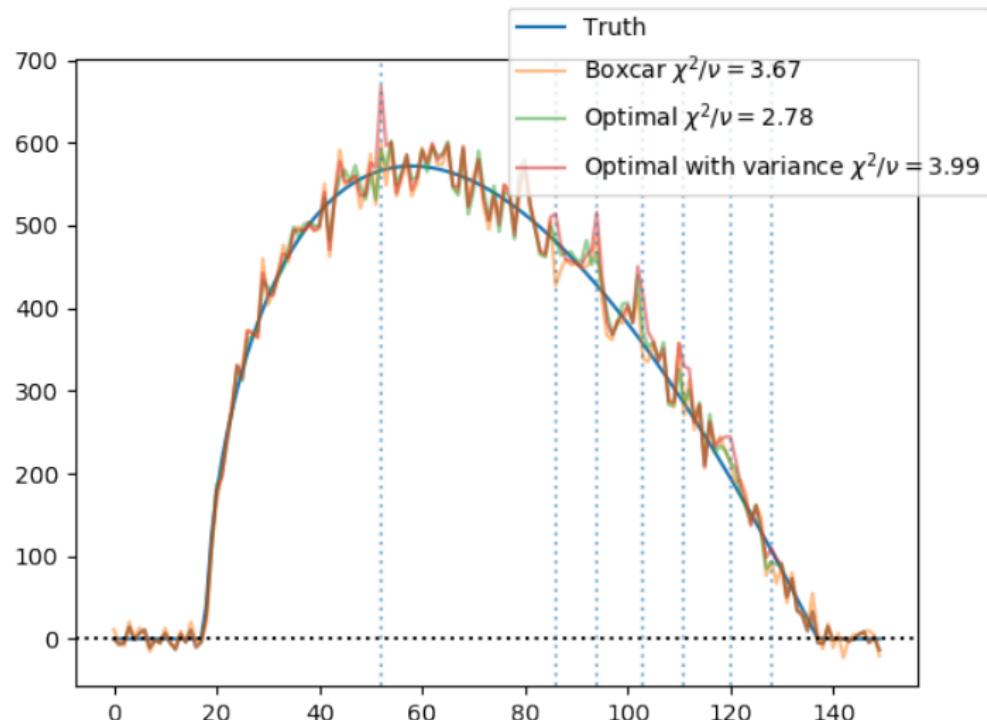


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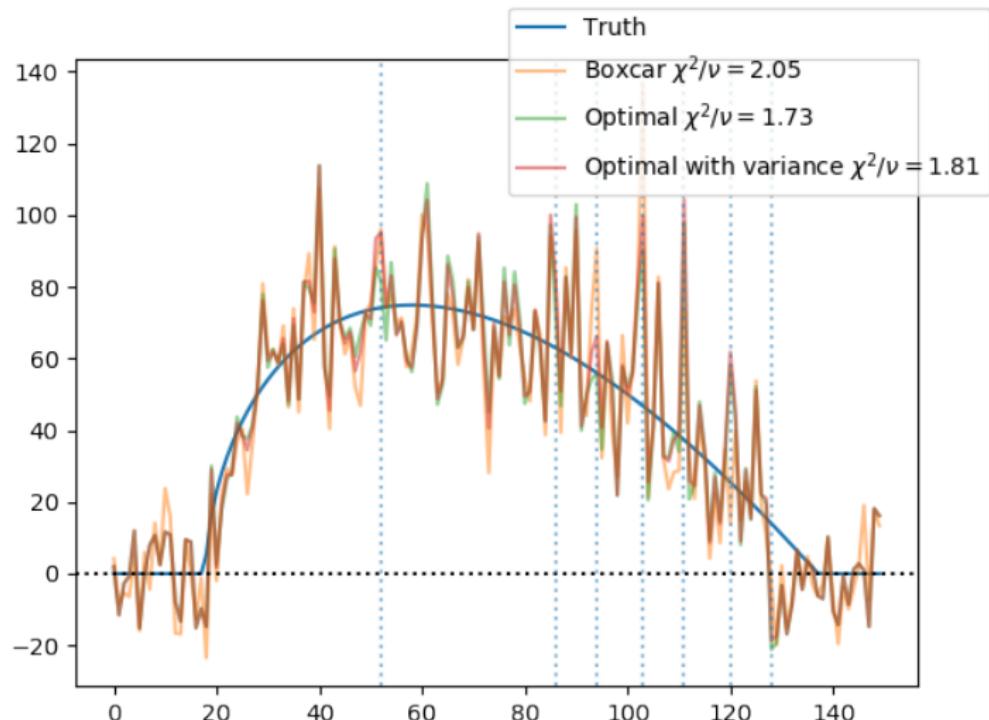
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Note the residuals near the sky lines in the "Optimal with variance" spectrum

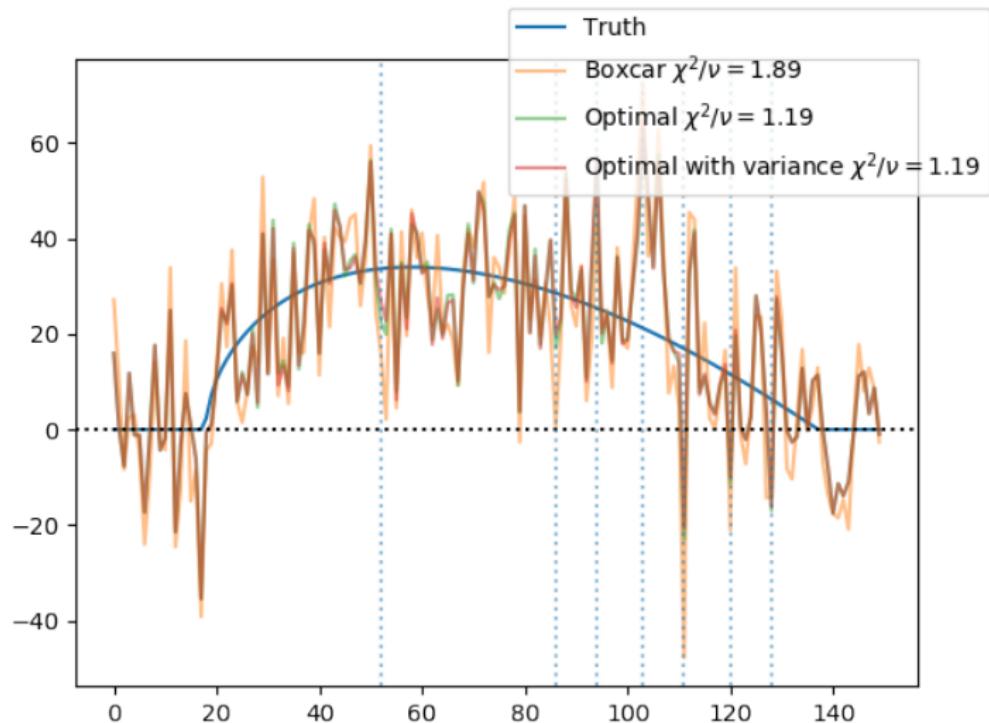
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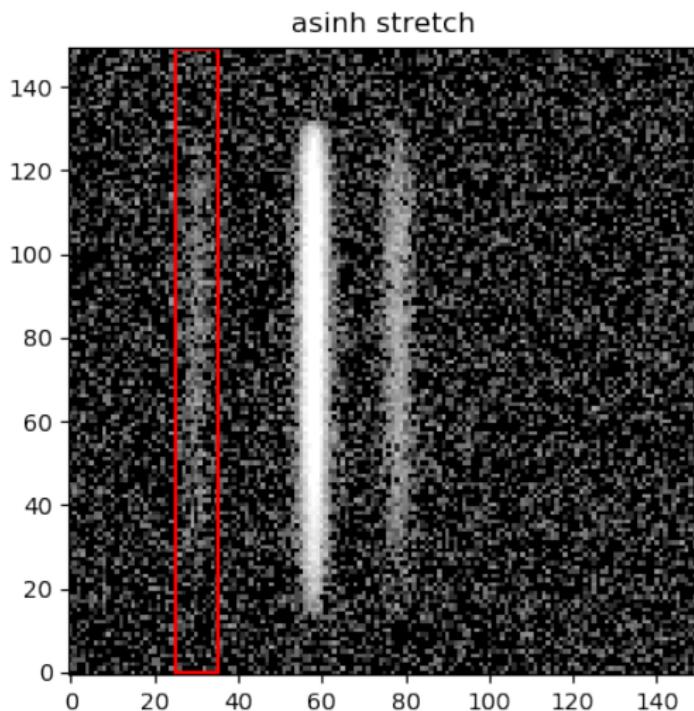


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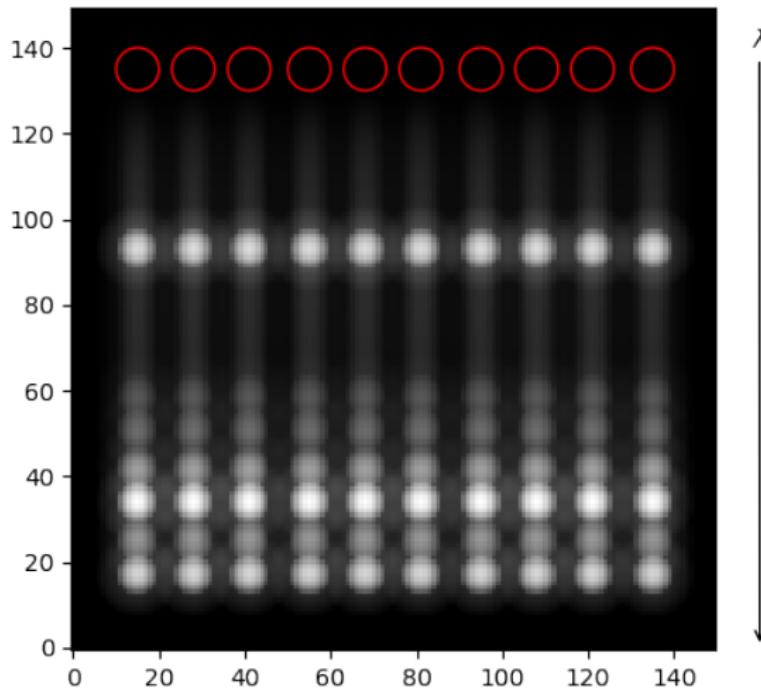
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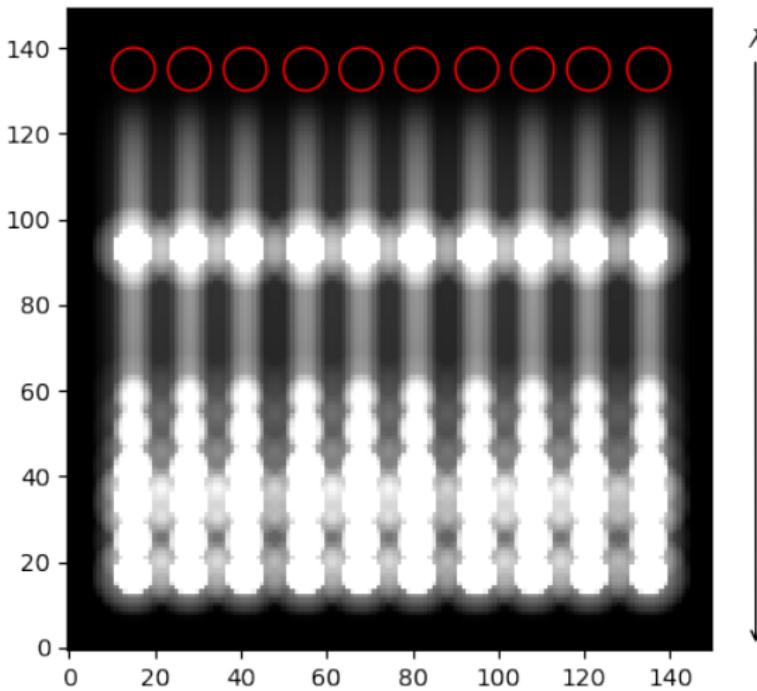
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One successful technique is to do a PCA decomposition of all the sky spectra and use those components to subtract sky.

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Note that the wings of the PSF extend to the neighbouring fibres.

A proposal

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- a terrible acronym (PFS)
- a spectrograph (being built) on the 8m Subaru telescope with
 - ▶ 2394 fibres
 - ▶ a 1.3 deg^2 field
 - ▶ four spectrographs, three arms
 - ▶ coverage from 380 -- 1250 nm

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Only the sky lines are bright enough to cause problems, but we know where they are.

So I'm planning to:

- Measure the 2-D PSF
- Fit the PSF to the sky lines
- Subtract the models from the 2-D image
- Proceed with optimal extraction

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 - ▶ four spectrographs, three arms
 - ▶ coverage from 380 -- 1250 nm

Only the sky lines are bright enough to cause problems, but we know where they are.

So I'm planning to:

- Measure the 2-D PSF
- Fit the PSF to the sky lines
- Subtract the models from the 2-D image
- Proceed with optimal extraction

Wait a year or two, than ask me if it works

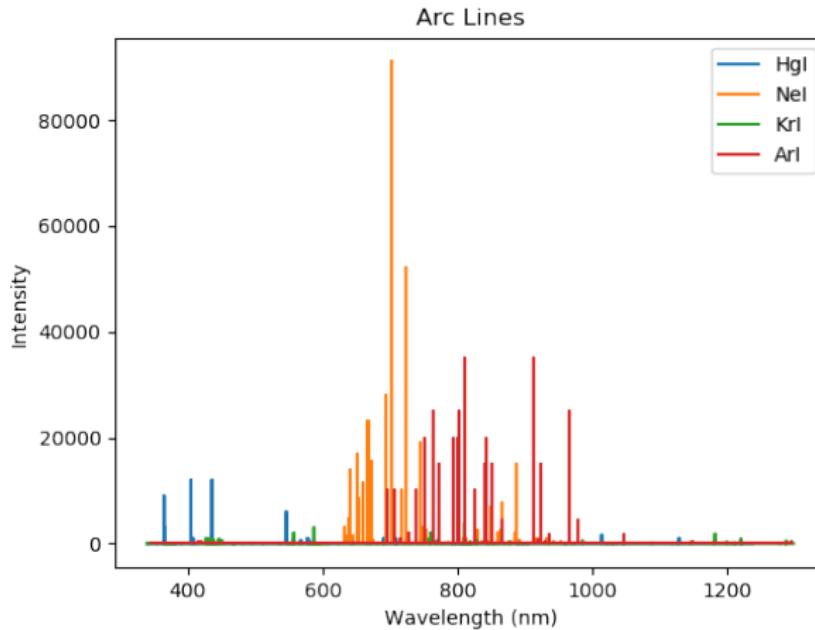
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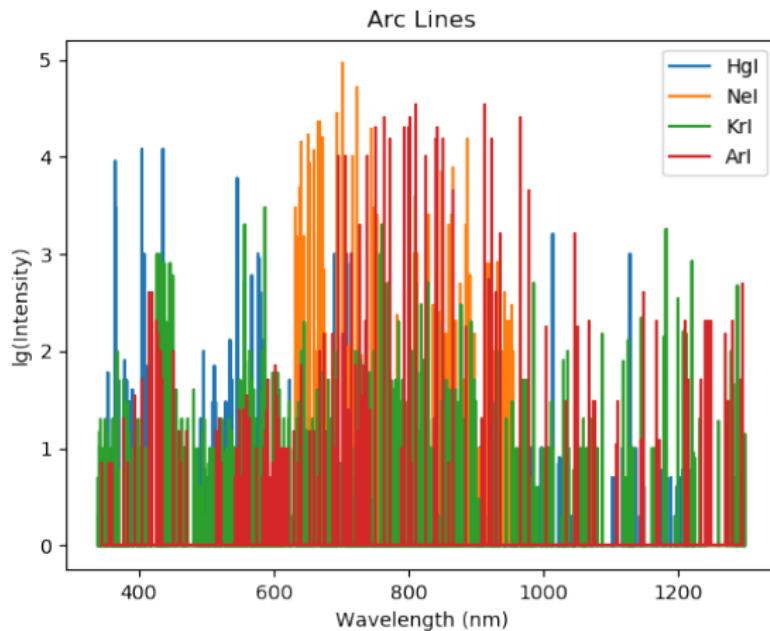
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You then take a spectrum, find the lines (whose wavelengths you know), and estimate the mapping $x \rightarrow \lambda$.

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The problem is that high-order polynomials fitted to noisy data tend to be *very* badly behaved between the data points.

Chebyshev Polynomials

Instead, use Chebyshev polynomials, valid for $x \in [-1, 1]$:

$$T_0(x) = 1$$

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E.g. `np.polynomial.chebyshev.Chebyshev`

Photometric Calibration

We've fixed the x-axis; what about the y-axis? This is tricky for two reasons:

- We don't know the sensitivity of the instrument (telescope, grating, detector, ...) as a function of lambda
- We don't know what the atmosphere does

The Atmosphere

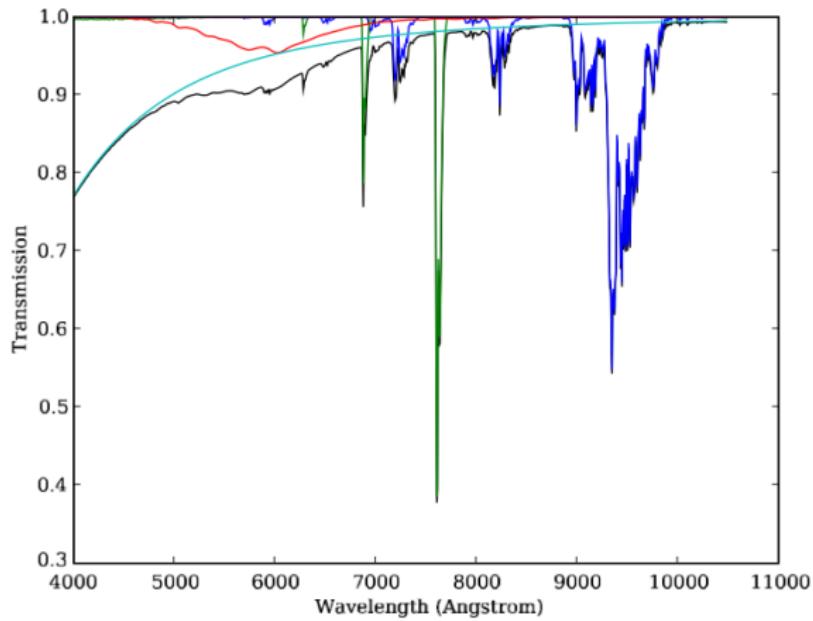
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- Gray: Clouds
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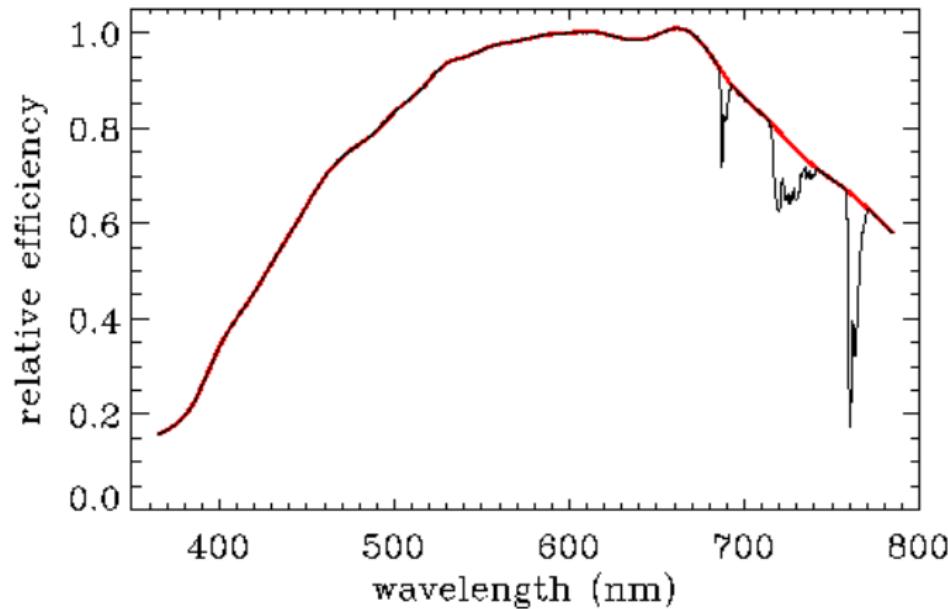
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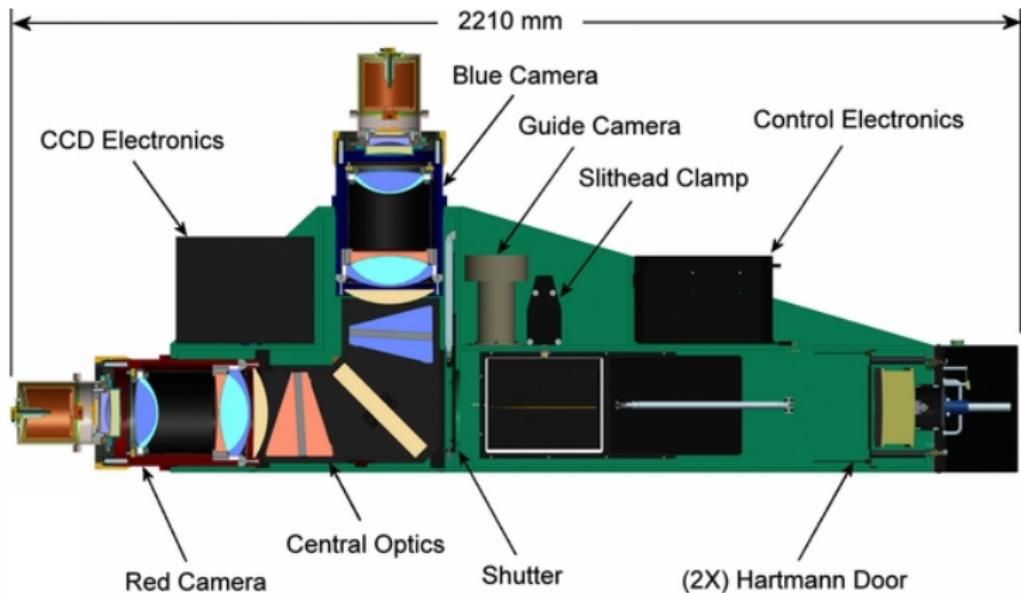
Credit: 2DF Survey

Multi-arm Spectrographs

Many spectrographs have too large a spectral range to only use one detector; the usual solution is to split the light into 2 (or more) paths using *dichroics*.

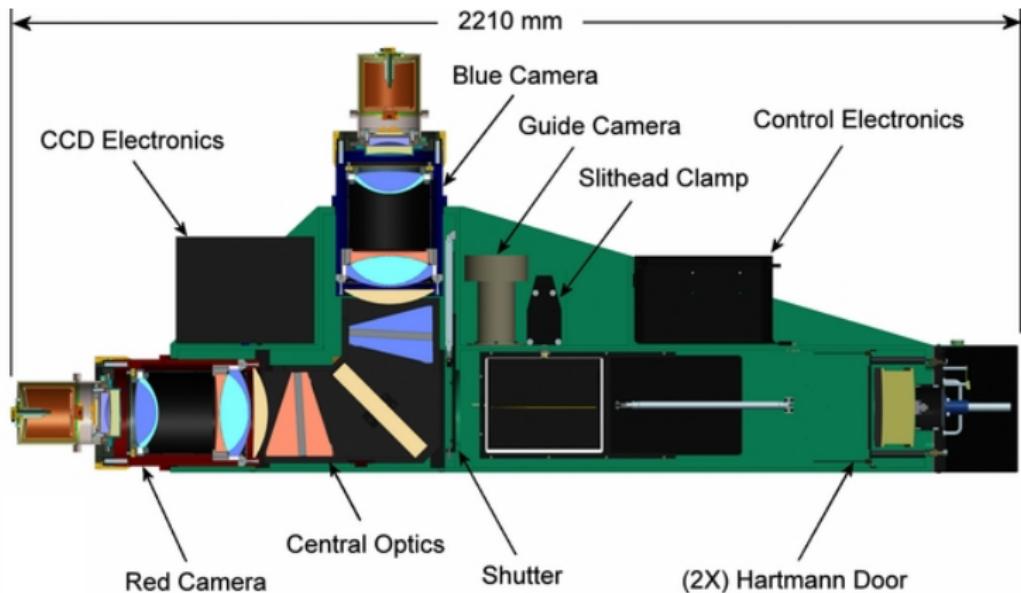
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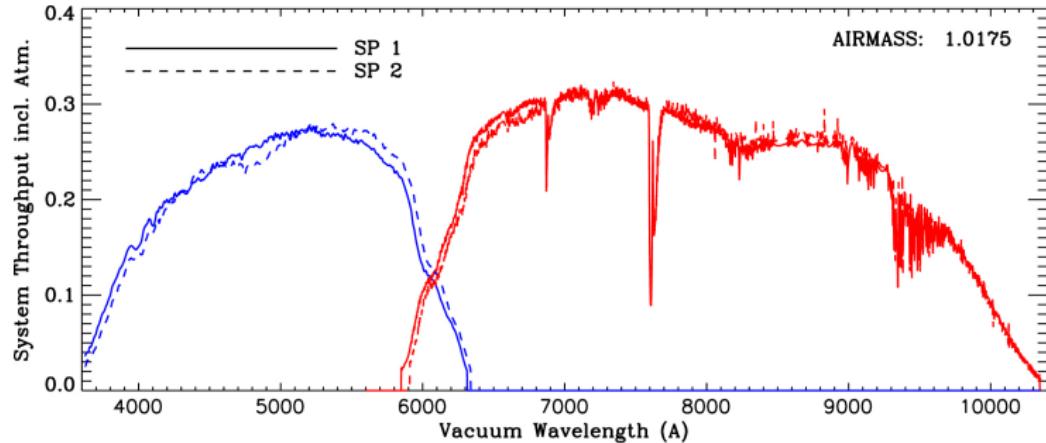
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Now we have a new problem: how do we tie the two arms together?

Photometric Calibration



An SDSS Spectrograph

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The solution is to observe objects of known spectrum; ideally

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Objects at a variety of redshifts with known spectra (*e.g.* Luminous Red Galaxies) provide a way to check for features in our spectro-photometric standards that we failed to fit/model.

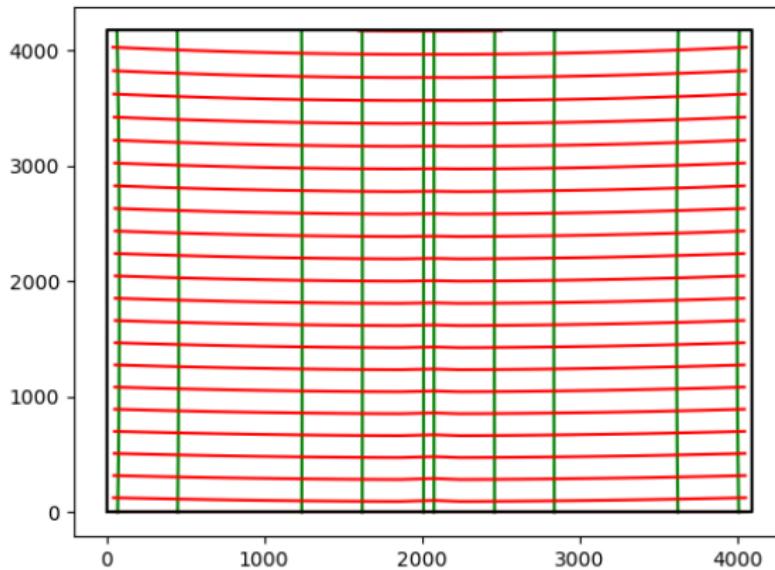
Real Fibre Spectrographs

In the real world fibre spectra don't lie nicely up-and-down the chip, and sky lines don't run along rows of the CCD.

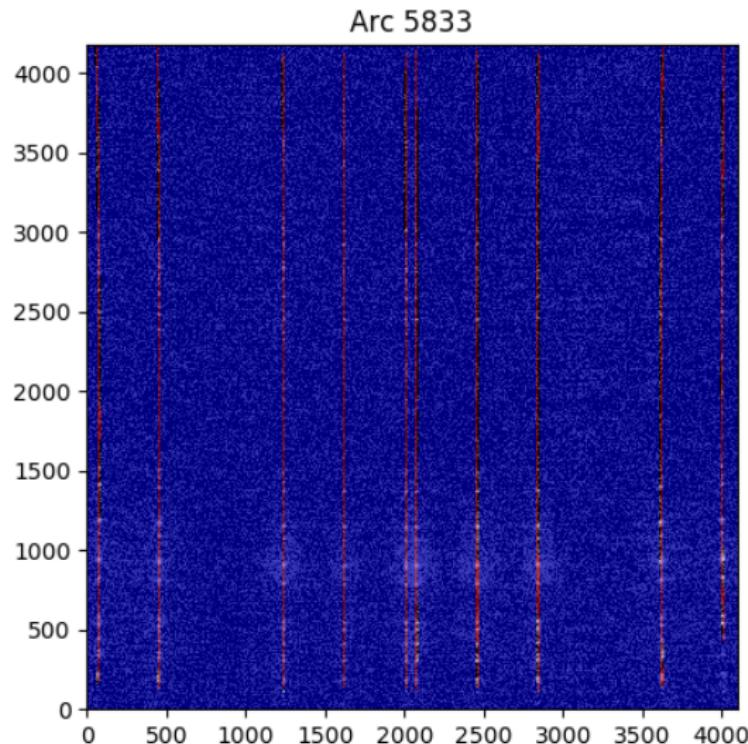
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Here's the model that the PFS pipeline uses of the 10 fibres that are currently illuminated in the first spectrograph (it's "r1" -- red arm, spectrograph 1),

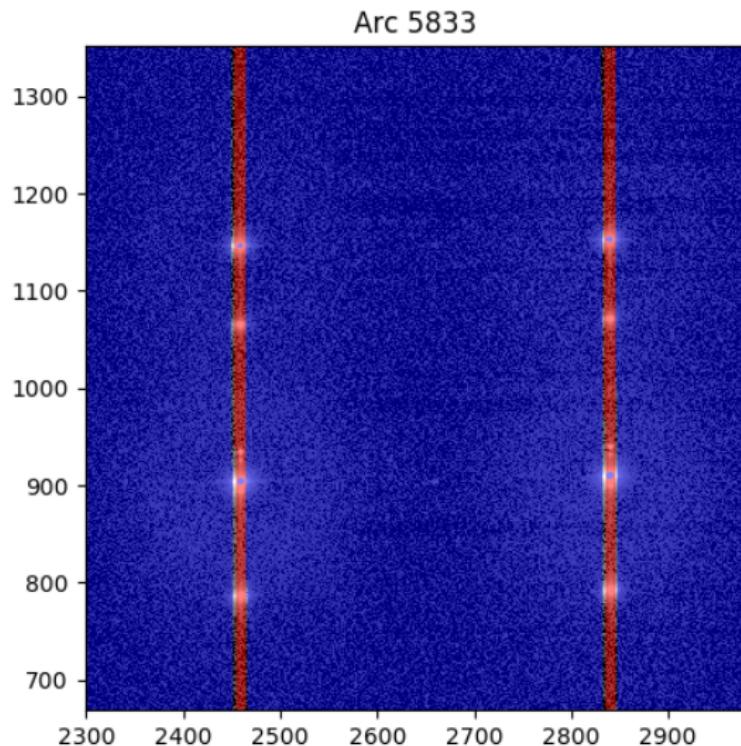


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- Calibrated the spectrum relative to standard stars
- If we know the absolute flux of the spectro-photometric standards (*e.g.* by comparison with the CALSPEC Standards), calibrated the spectrum to absolute units (nJy)
- We still have to understand the spectra, *e.g.*
 - ▶ classify the objects (stars, galaxies, QSOs)
 - ▶ fit redshifts
 - ▶ fit metallicities, gravities (if appropriate)
 - ▶ fit equivalent widths of emission and absorption lines
 - ▶ ...