Spectroscopy (Really Just Photometry)

Robert Lupton

2018-01-25

What is a Spectrograph?

It's an imager; optics and detectors.

What is a Spectrograph?

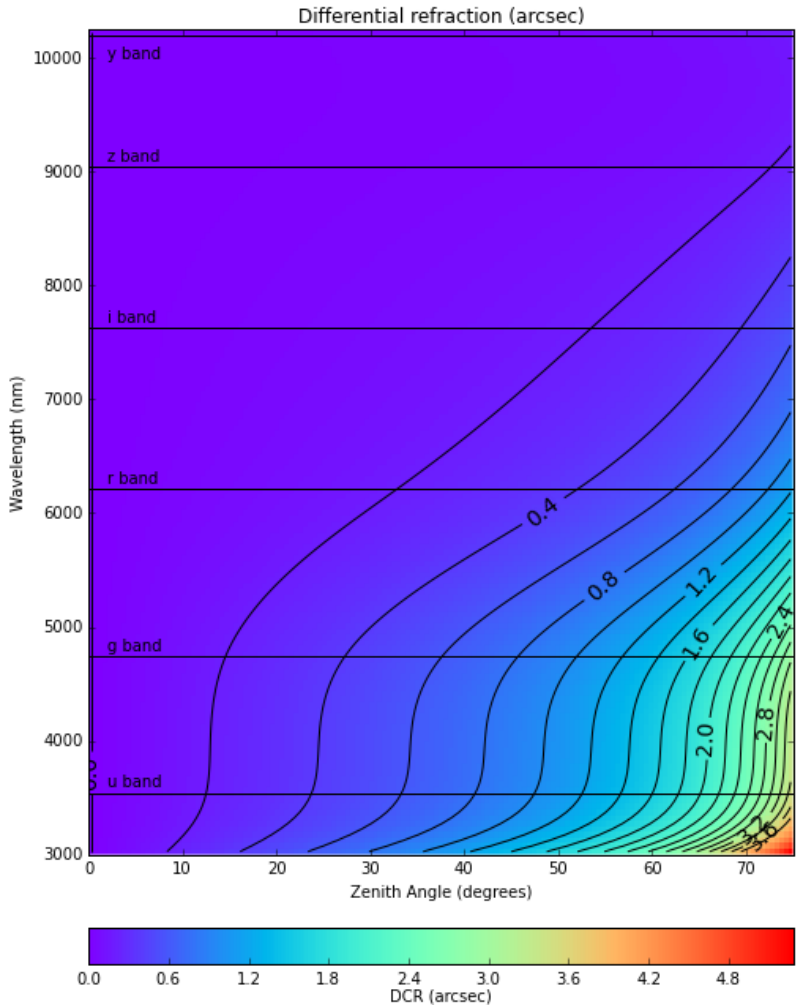
It's an imager; optics and detectors. The only difference is that we add something that *disperses* the light; a prism or a grating

What is a Spectrograph?

It's an imager; optics and detectors. The only difference is that we add something that *disperses* the light; a prism or a grating or a grism.

What is a Spectrograph?

It's an imager; optics and detectors. The only difference is that we add something that *disperses* the light; a prism or a grating or a grism.



What is a Spectrograph?

It's an imager; optics and detectors. The only difference is that we add something that *disperses* the light; a prism or a grating or a grism. Or the atmosphere.

What is a Spectrograph?

It's an imager; optics and detectors. The only difference is that we add something that *disperses* the light; a prism or a grating or a grism.

Generally these days we use "VPH" (Volume Phase Holographic) gratings; they are amazingly efficient.

What is a Spectrograph?

It's an imager; optics and detectors. The only difference is that we add something that *disperses* the light; a prism or a grating or a grism.

Generally these days we use "VPH" (Volume Phase Holographic) gratings; they are amazingly efficient.

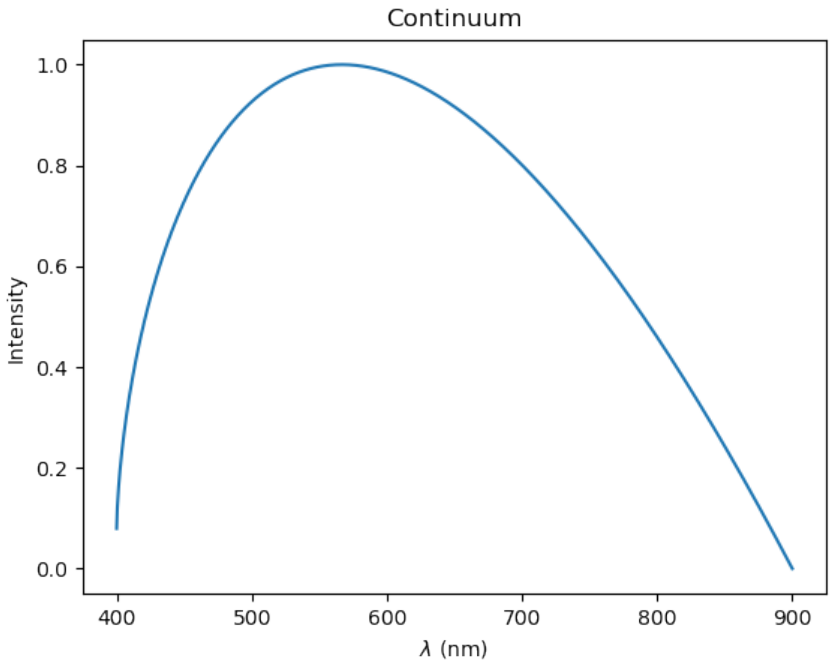
We'll use three (schematic!) spectral energy distributions (SEDs) in the first part of this talk:

What is a Spectrograph?

It's an imager; optics and detectors. The only difference is that we add something that *disperses* the light; a prism or a grating or a grism.

Generally these days we use "VPH" (Volume Phase Holographic) gratings; they are amazingly efficient.

We'll use three (schematic!) spectral energy distributions (SEDs) in the first part of this talk:

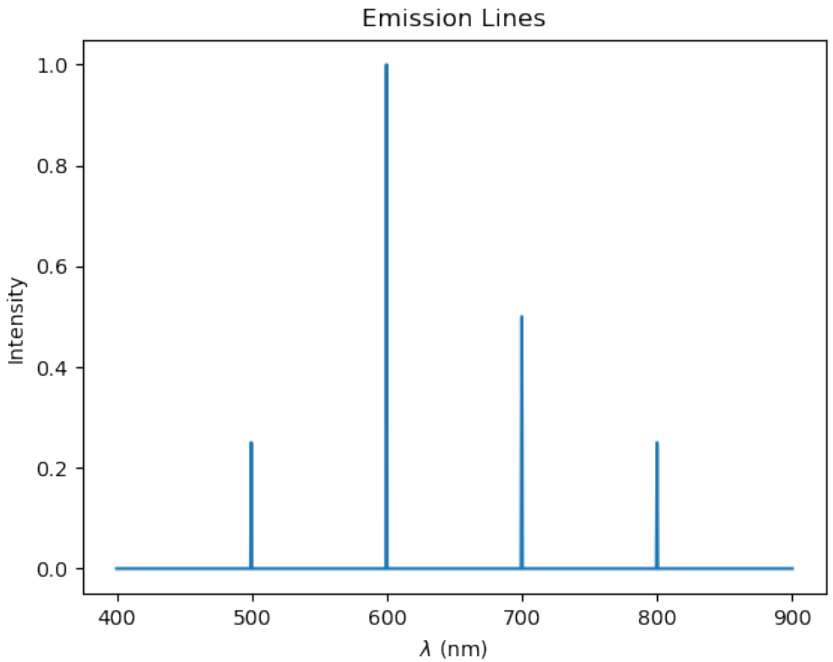


What is a Spectrograph?

It's an imager; optics and detectors. The only difference is that we add something that *disperses* the light; a prism or a grating or a grism.

Generally these days we use "VPH" (Volume Phase Holographic) gratings; they are amazingly efficient.

We'll use three (schematic!) spectral energy distributions (SEDs) in the first part of this talk:

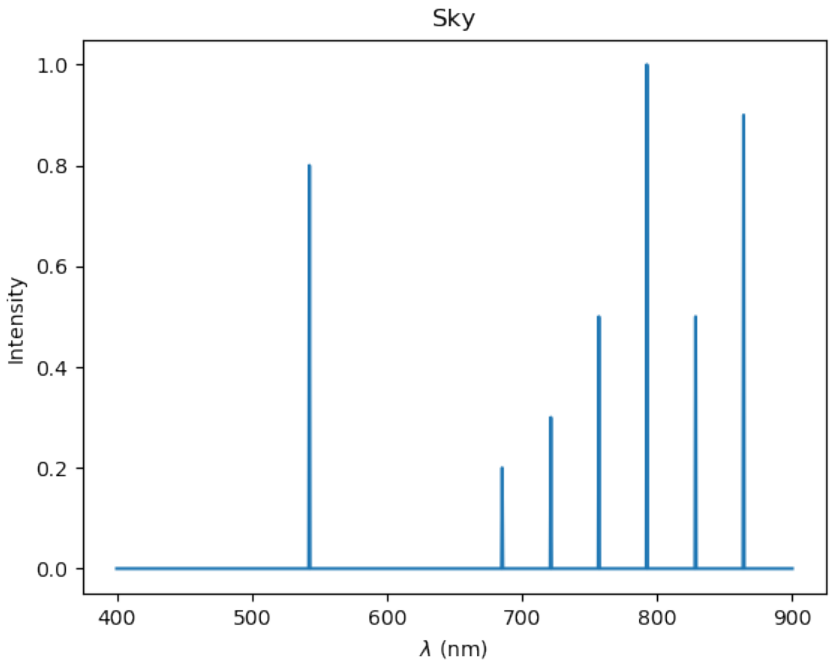


What is a Spectrograph?

It's an imager; optics and detectors. The only difference is that we add something that *disperses* the light; a prism or a grating or a grism.

Generally these days we use "VPH" (Volume Phase Holographic) gratings; they are amazingly efficient.

We'll use three (schematic!) spectral energy distributions (SEDs) in the first part of this talk:

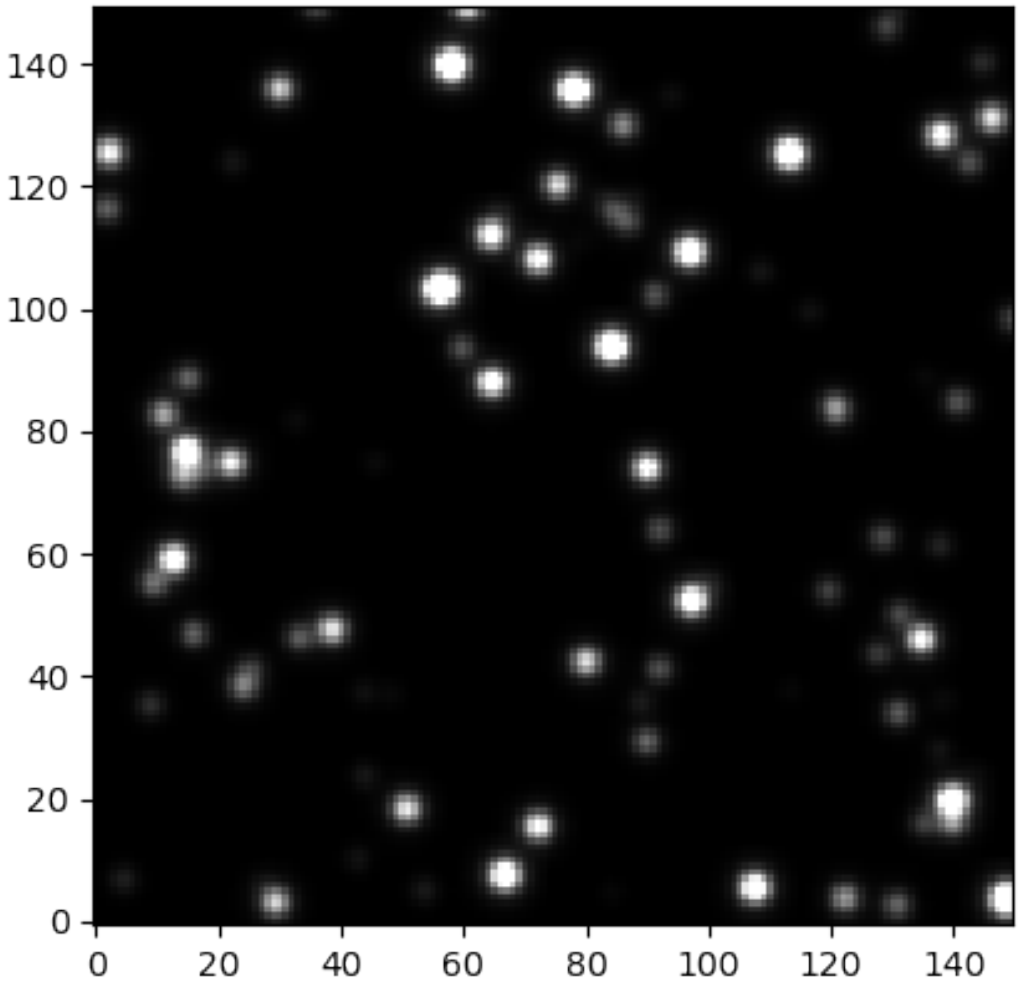


Instrumental Signature Removal

The ISR is similar to an imager's:

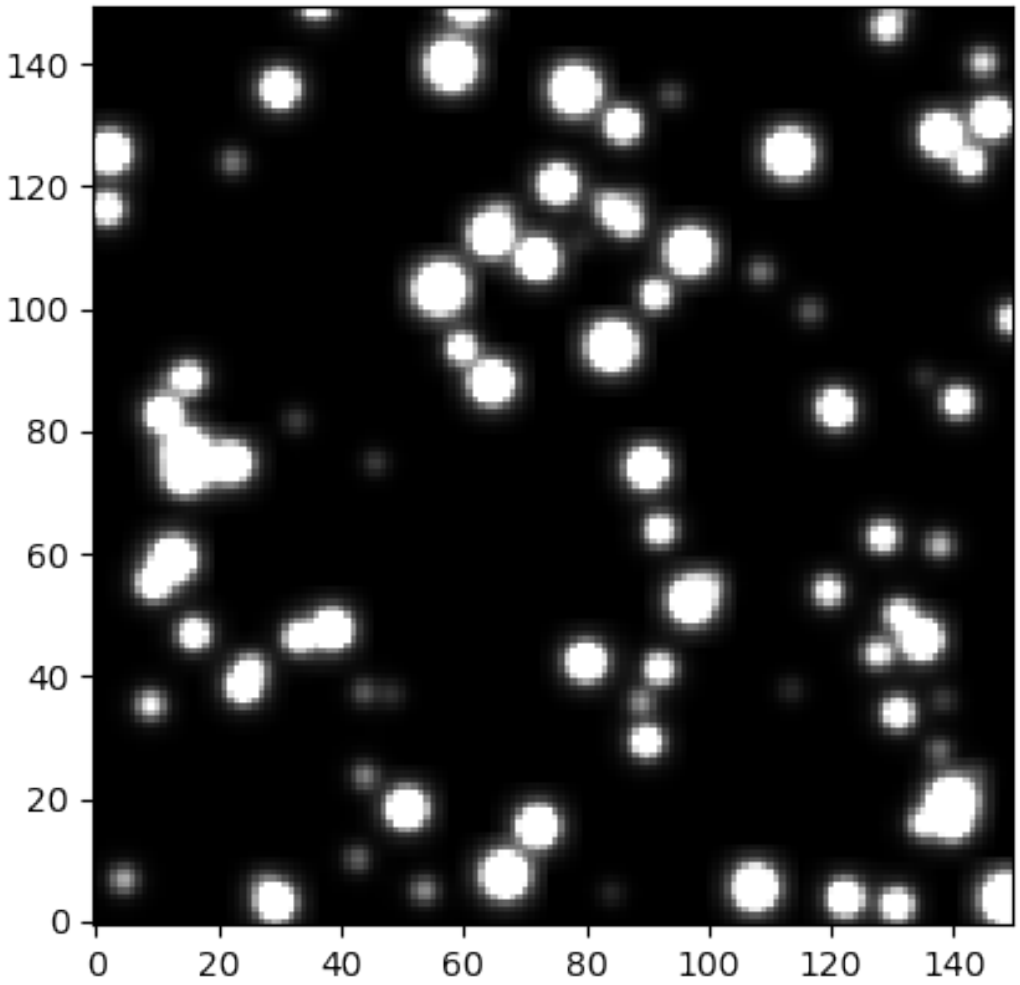
- overscan/bias removal
- dark current subtraction
- linearisation
- flat fielding
  - Use a dispersed flat -- the QE is in general a function of wavelength
  - It's not trivial to get a good flat for a fibre spectrograph
- cosmic ray masking/removal

A Star Field



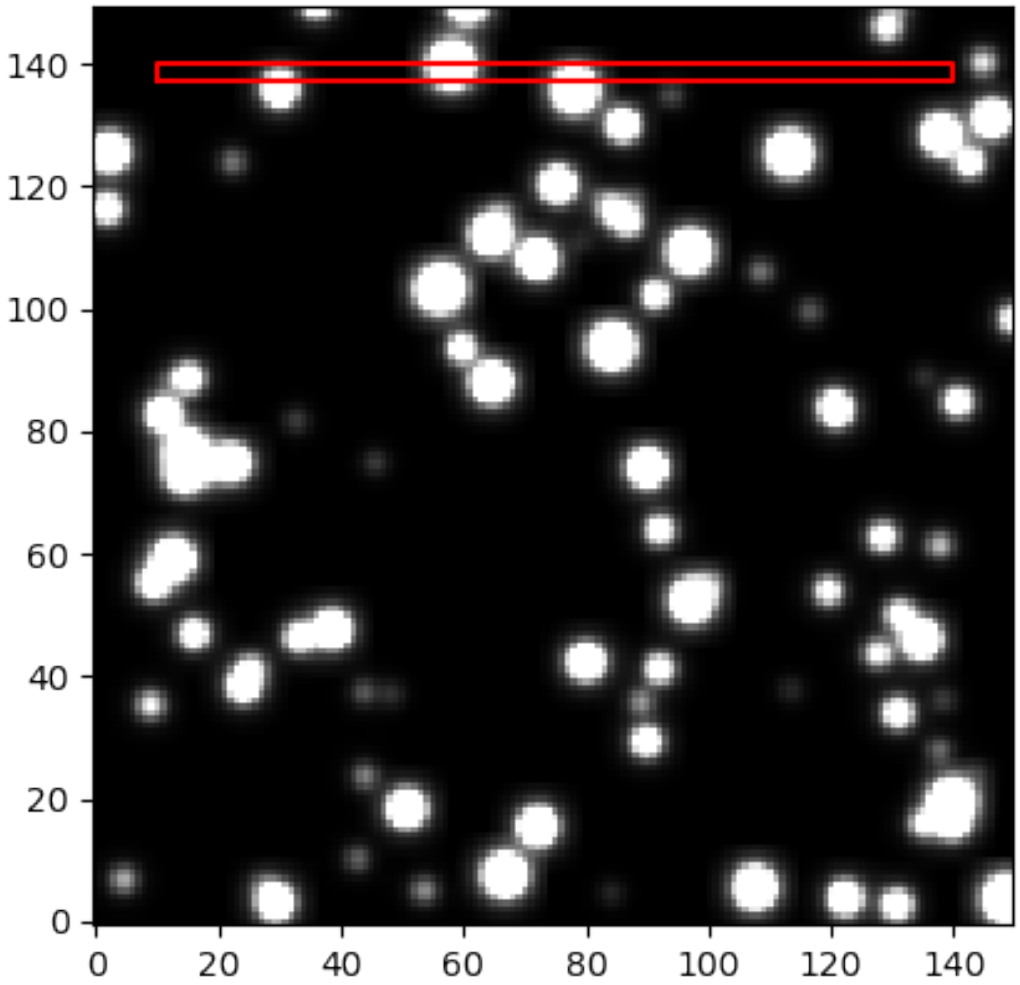
Direct Image

A Star Field



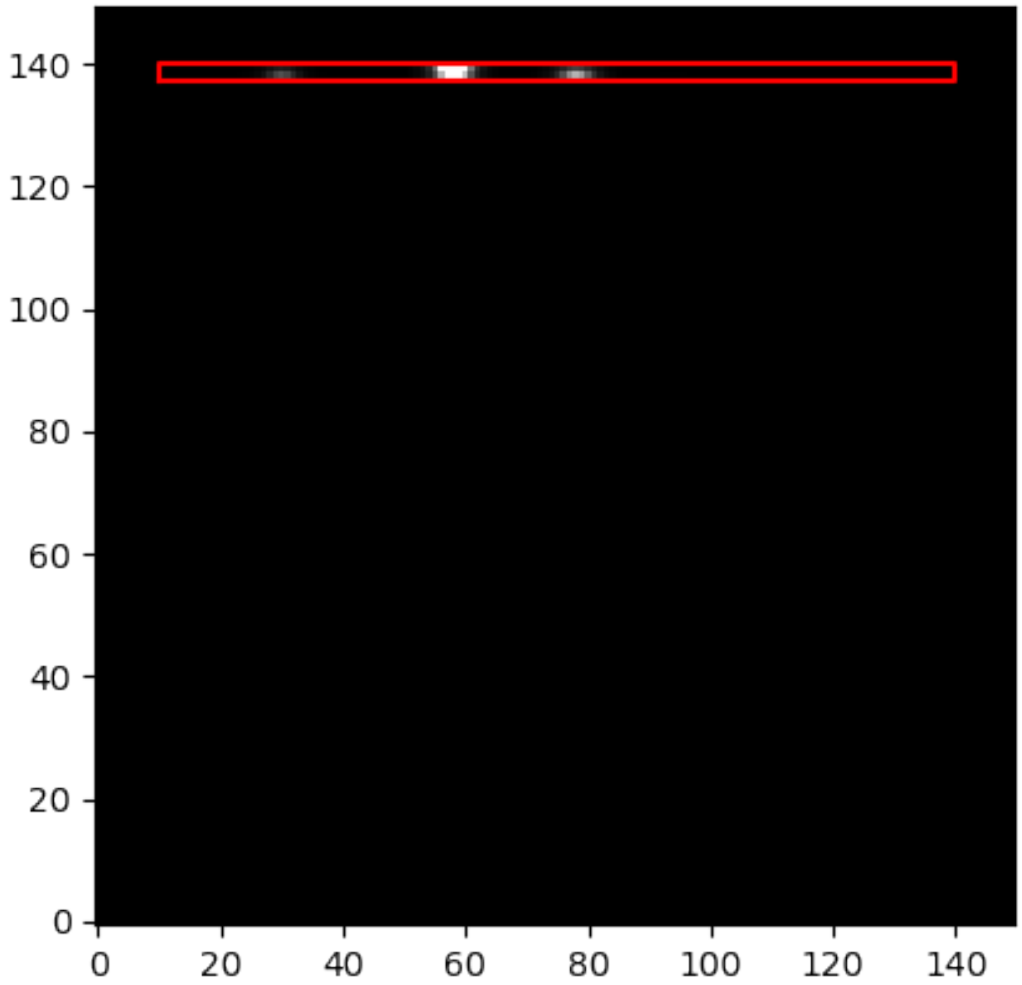
Direct Image

A Star Field



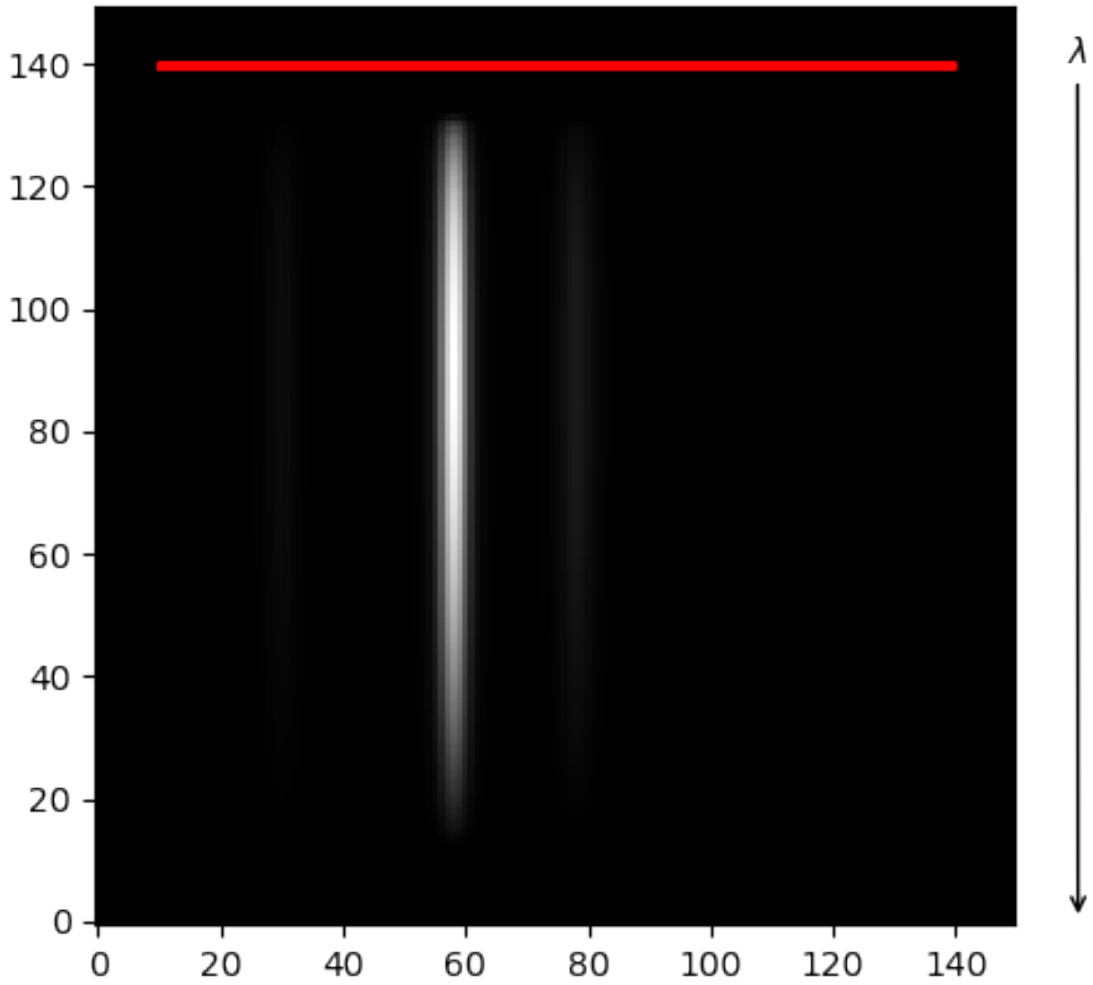
Direct Image with 3-pixel wide slit

A Star Field



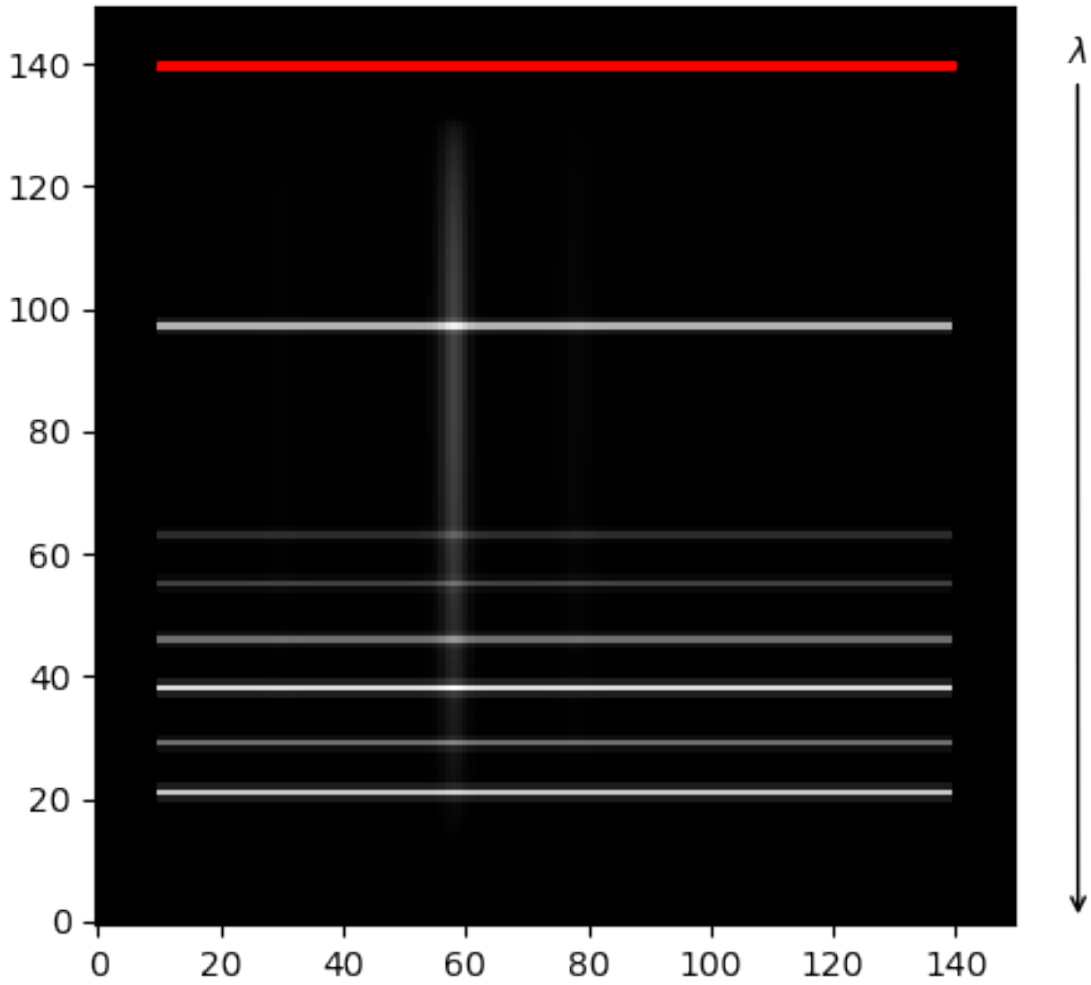
Direct Image with 3-pixel wide slit

A Star Field



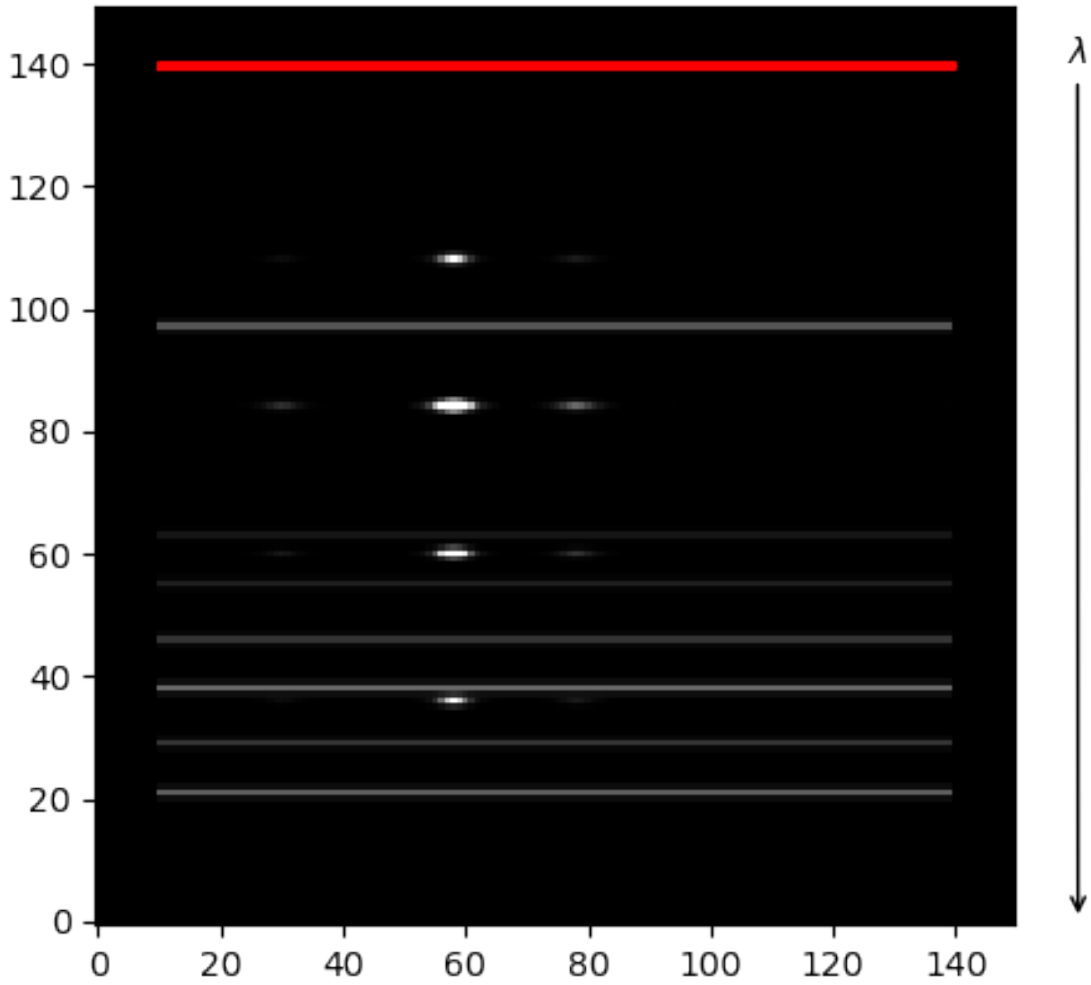
Dispersed 1-pixel wide slit continuum

A Star Field



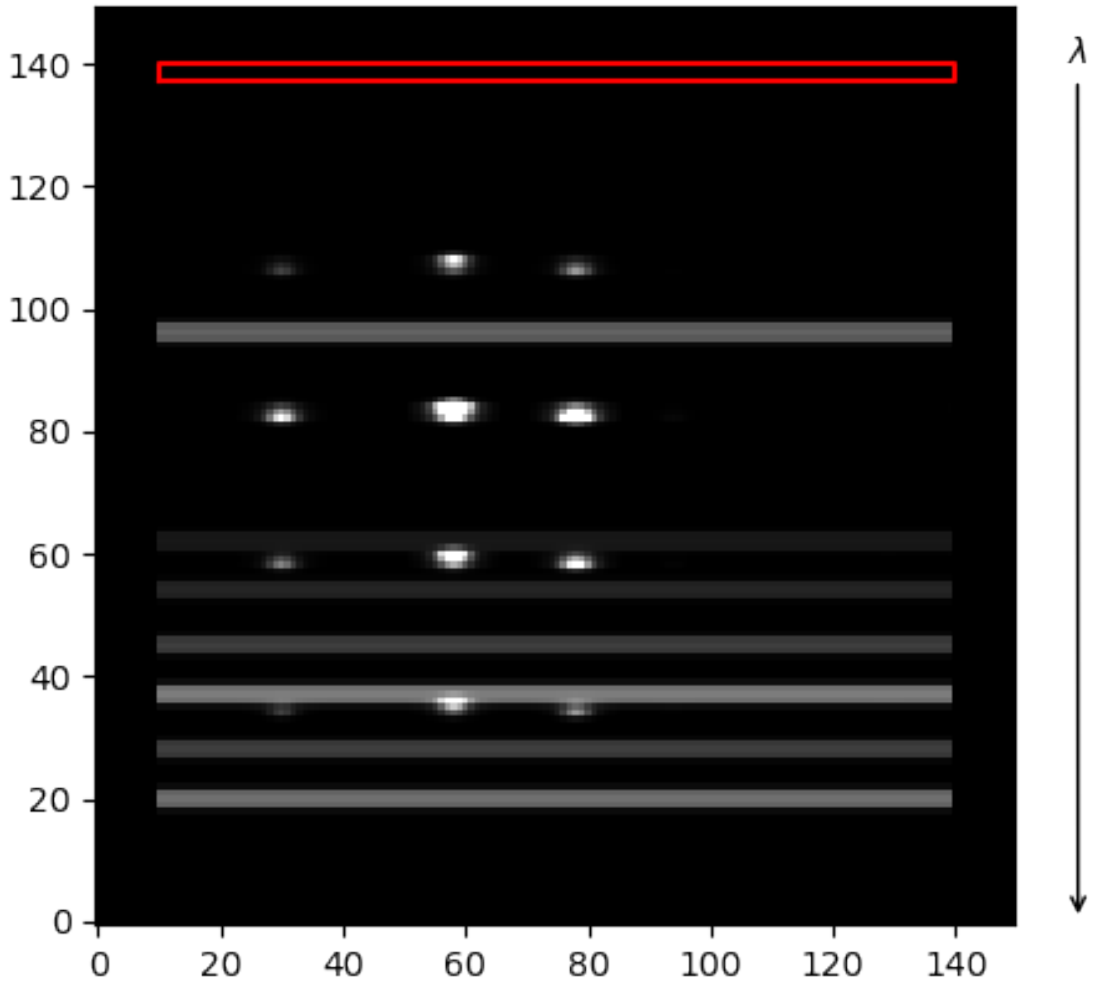
Dispersed 1-pixel wide slit continuum sky

A Star Field



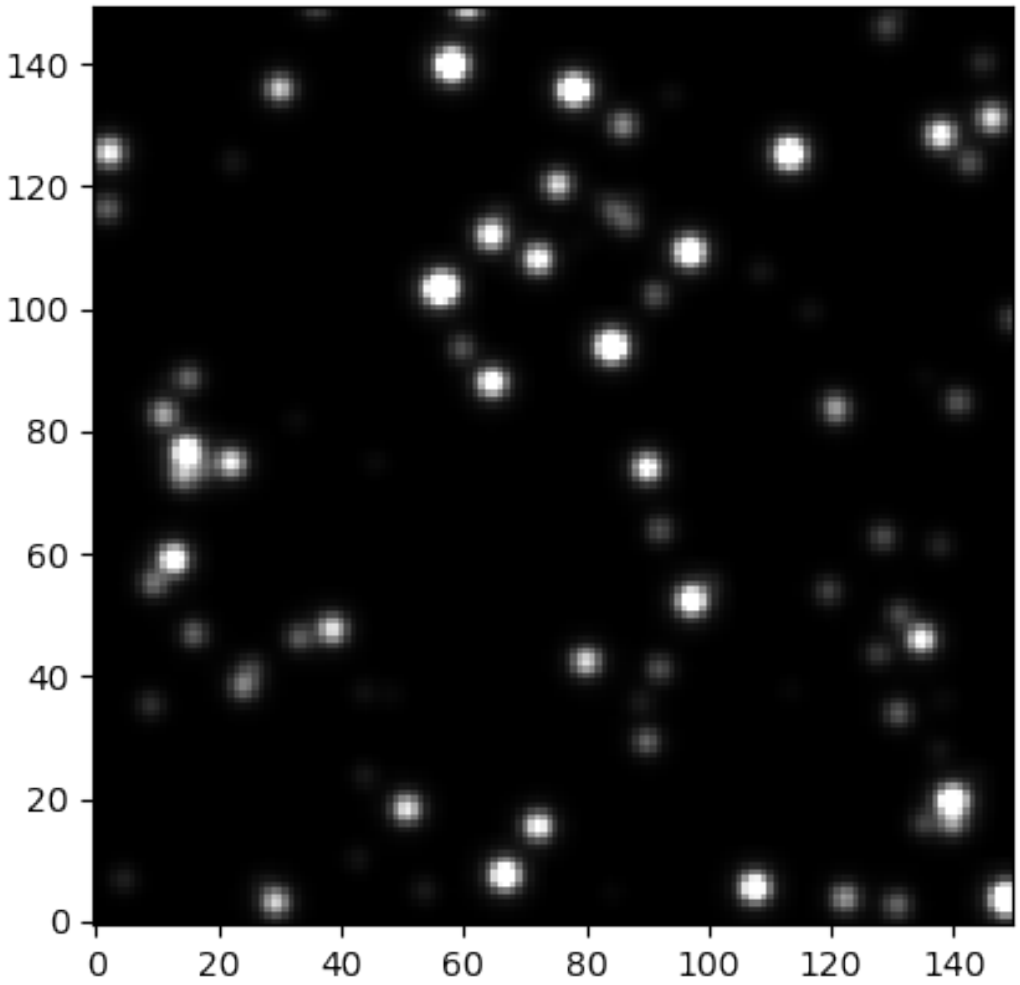
Dispersed 1-pixel wide slit 4 emission lines sky

A Star Field



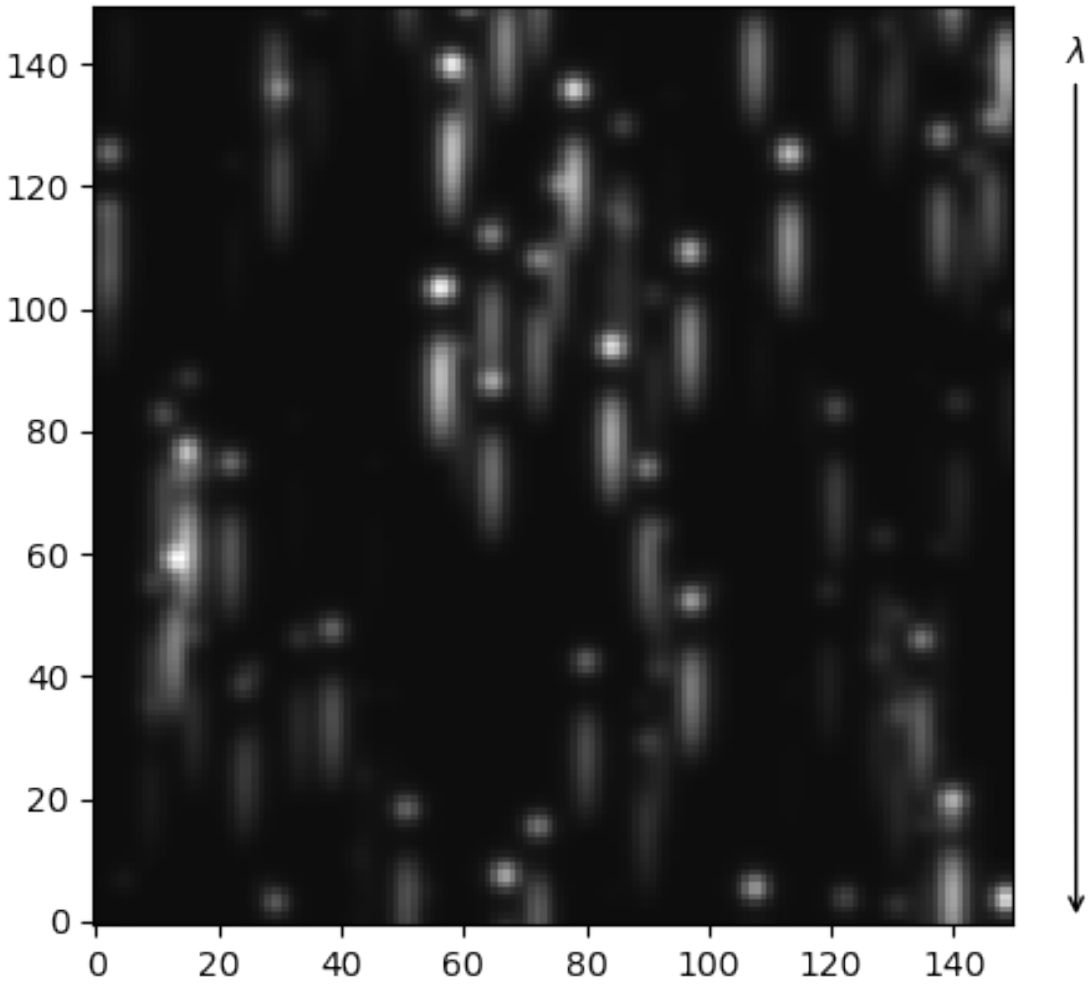
Dispersed 3-pixel wide slit 4 emission lines sky

A Star Field



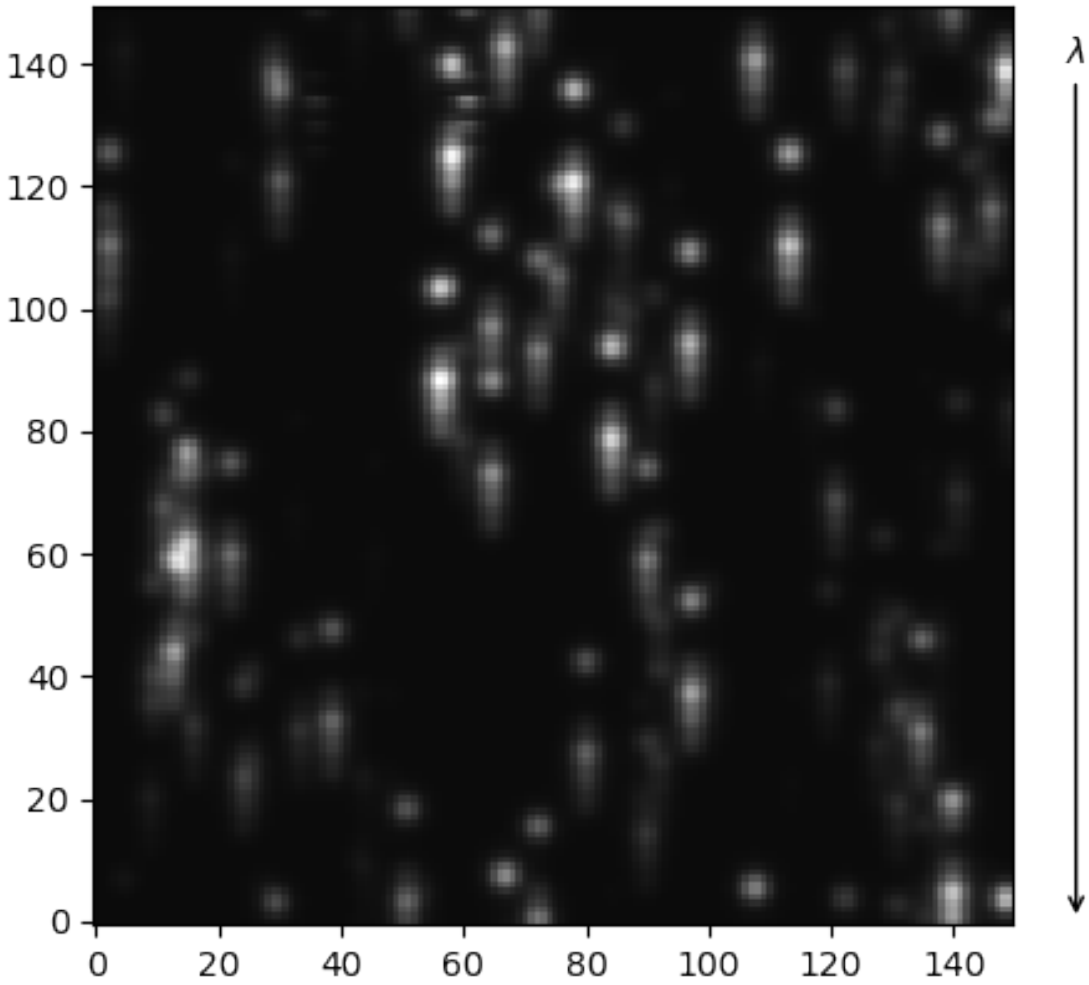
sky

A Star Field



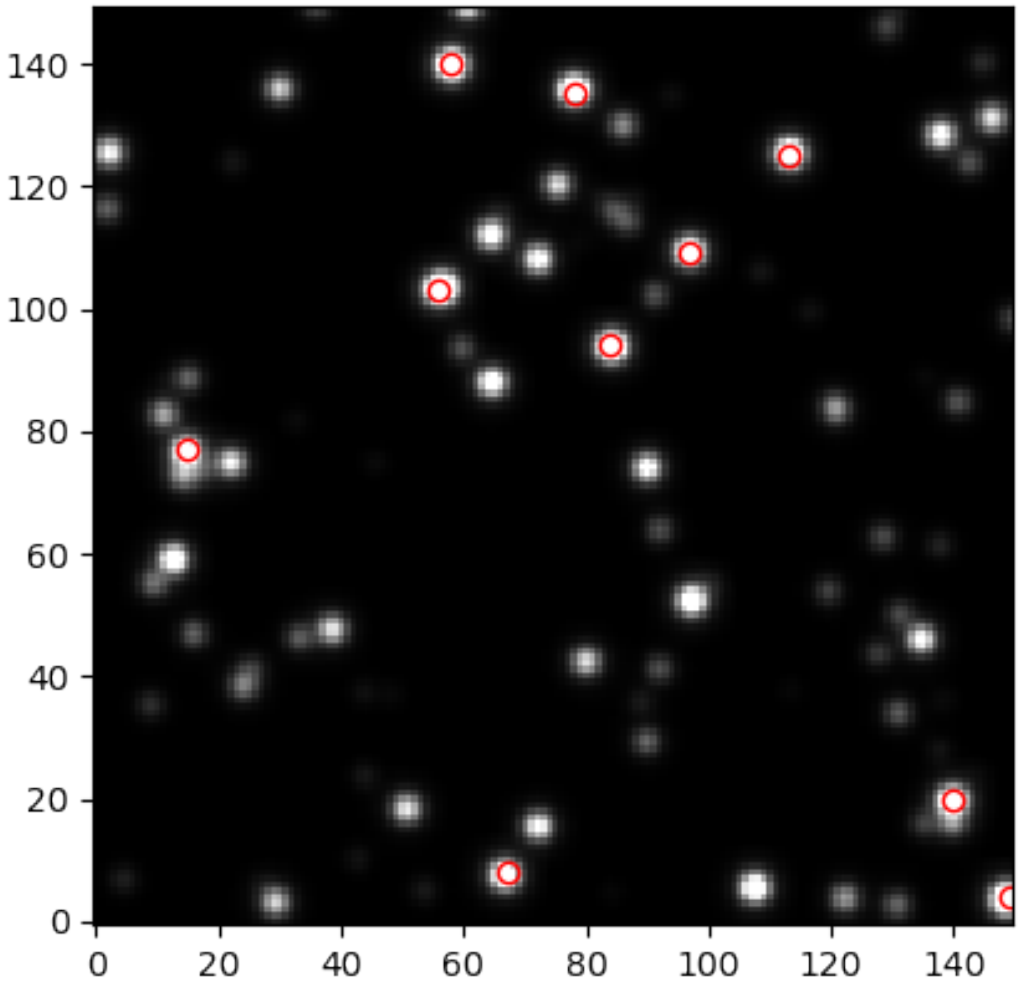
Grism; note 0-order and 1-order images continuum sky

A Star Field



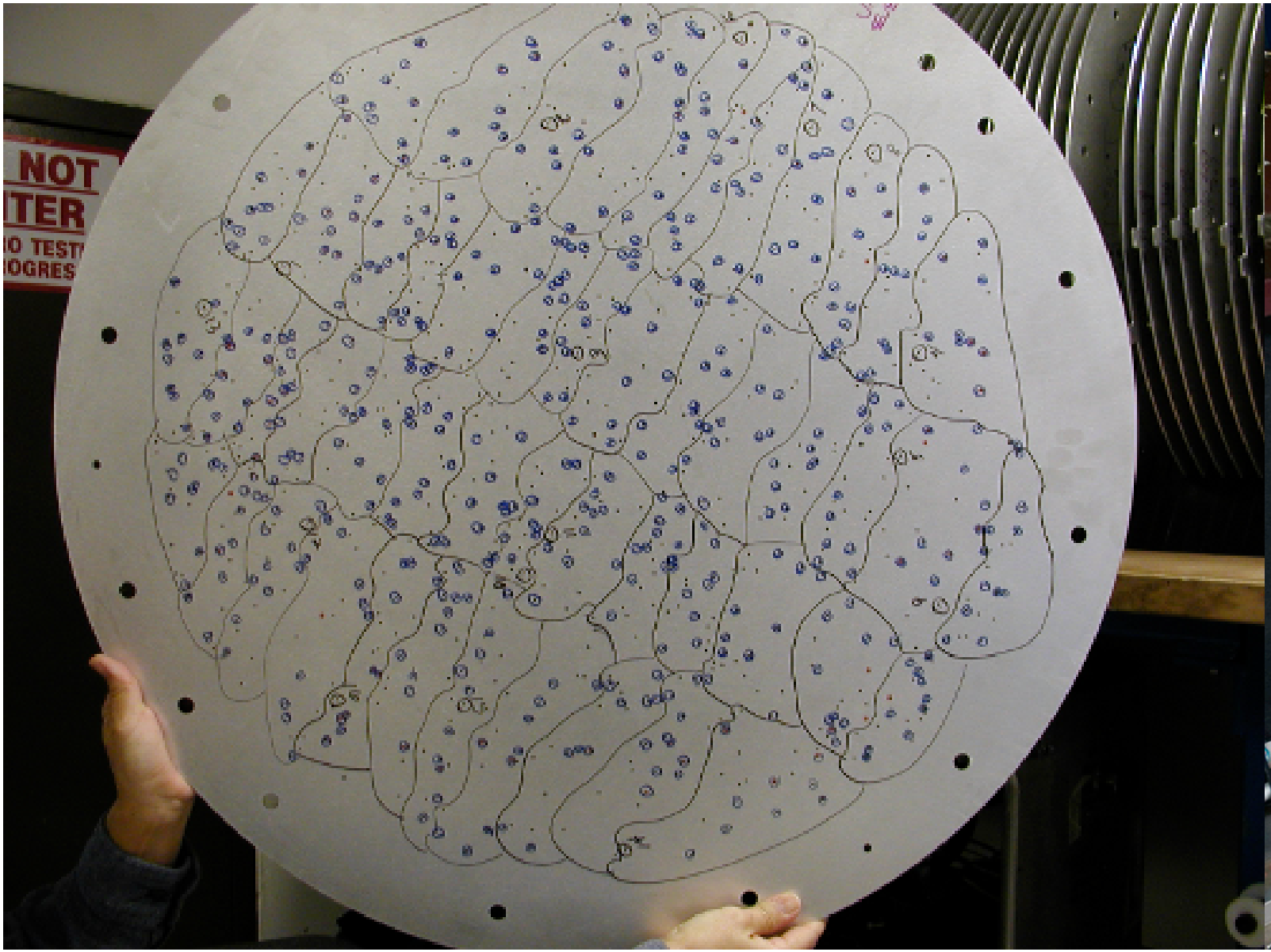
Grism; note 0-order and 1-order images 4 emission lines sky

Fibre Spectrographs

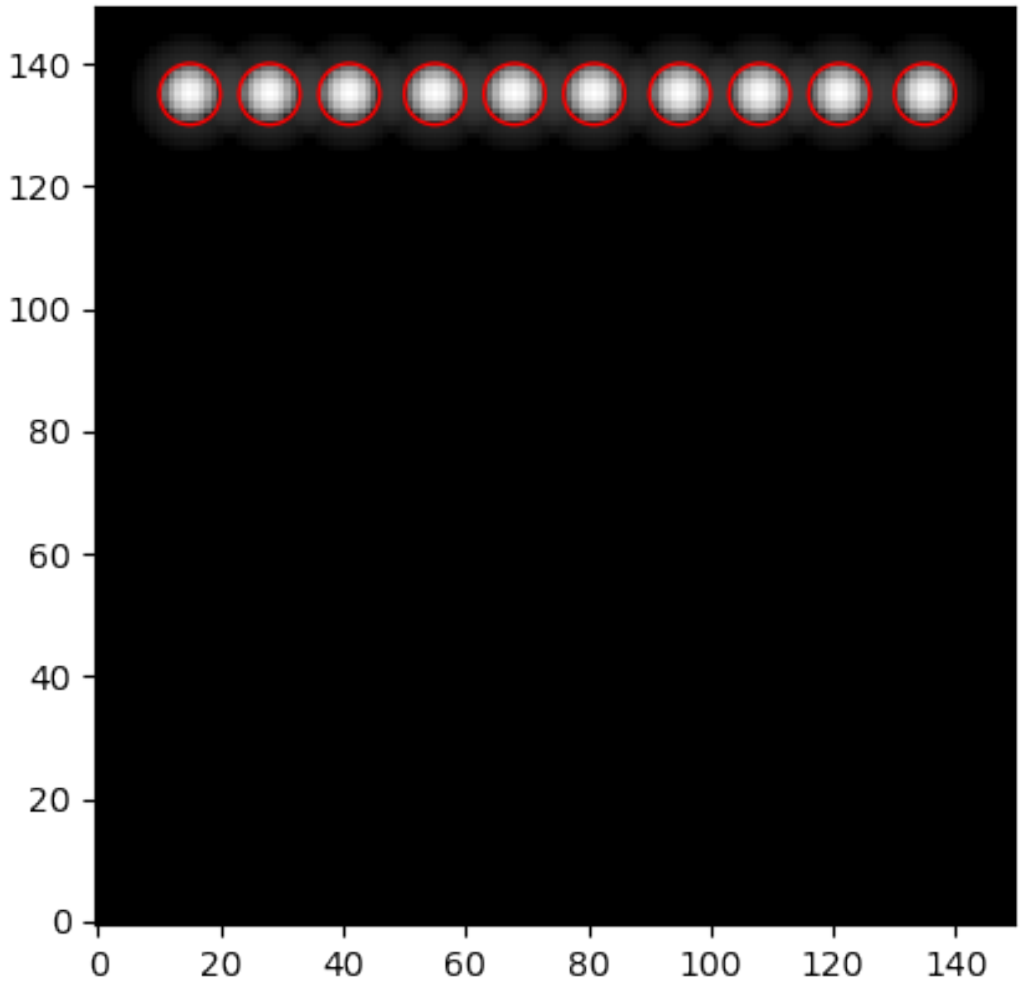


Fibre targets

Fibre Spectrographs

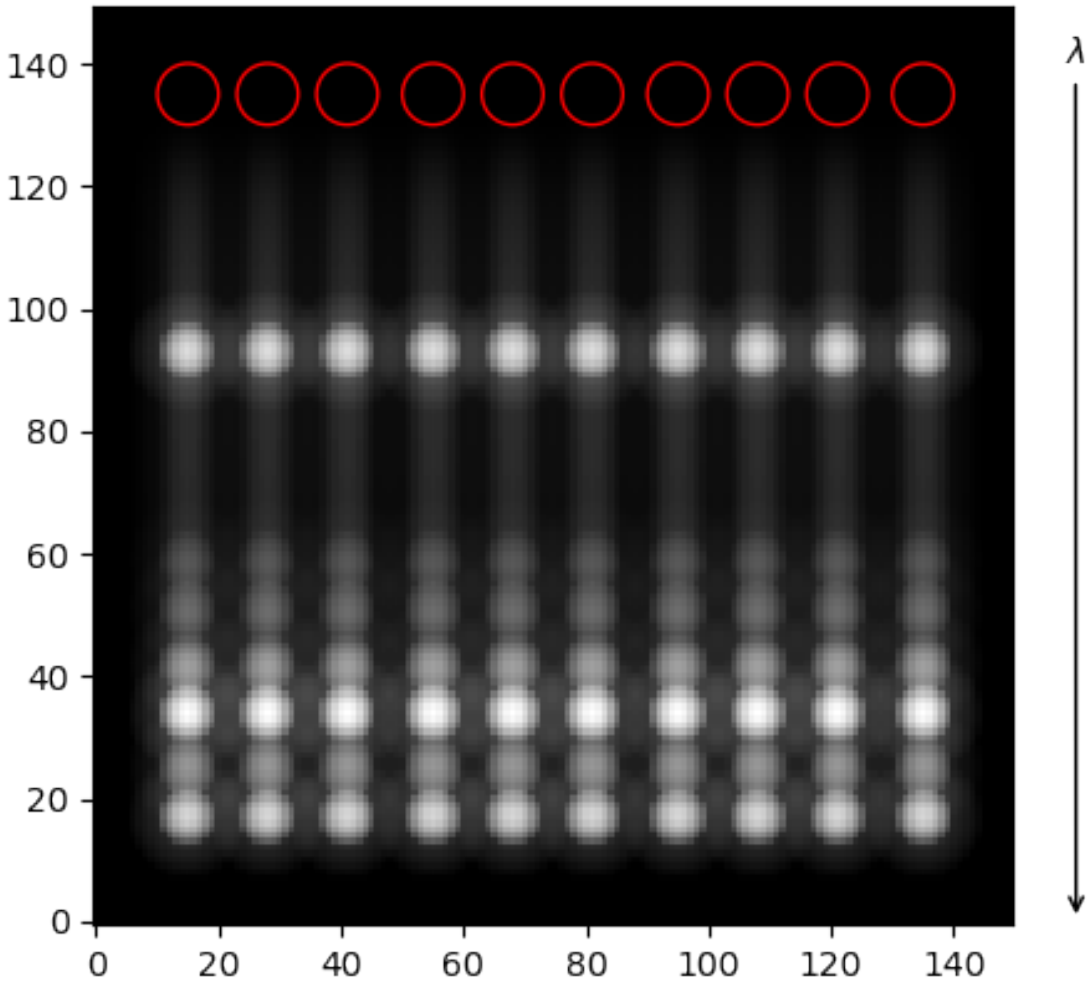


Fibre Spectrographs



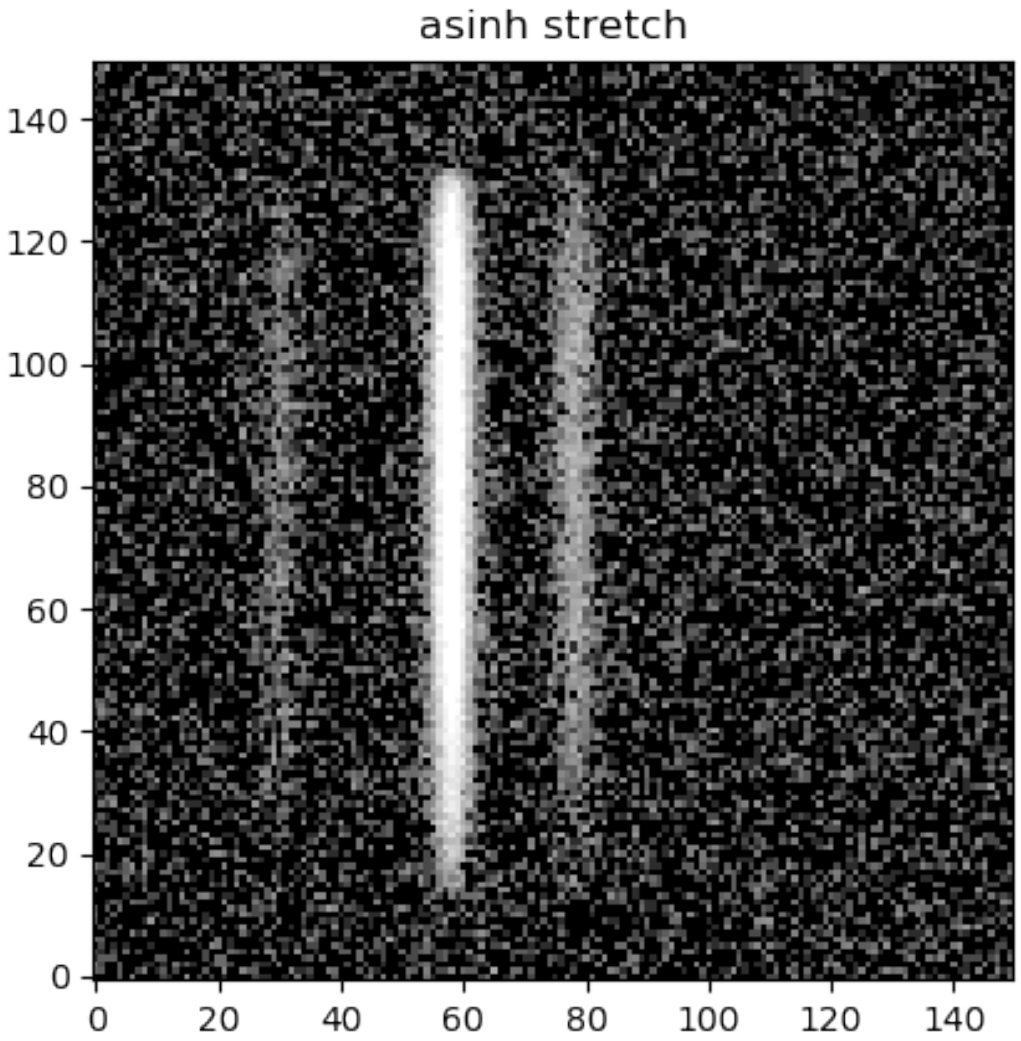
Direct image of fibres

Fibre Spectrographs



Dispersed fibres sky continuum

Extracting Spectra



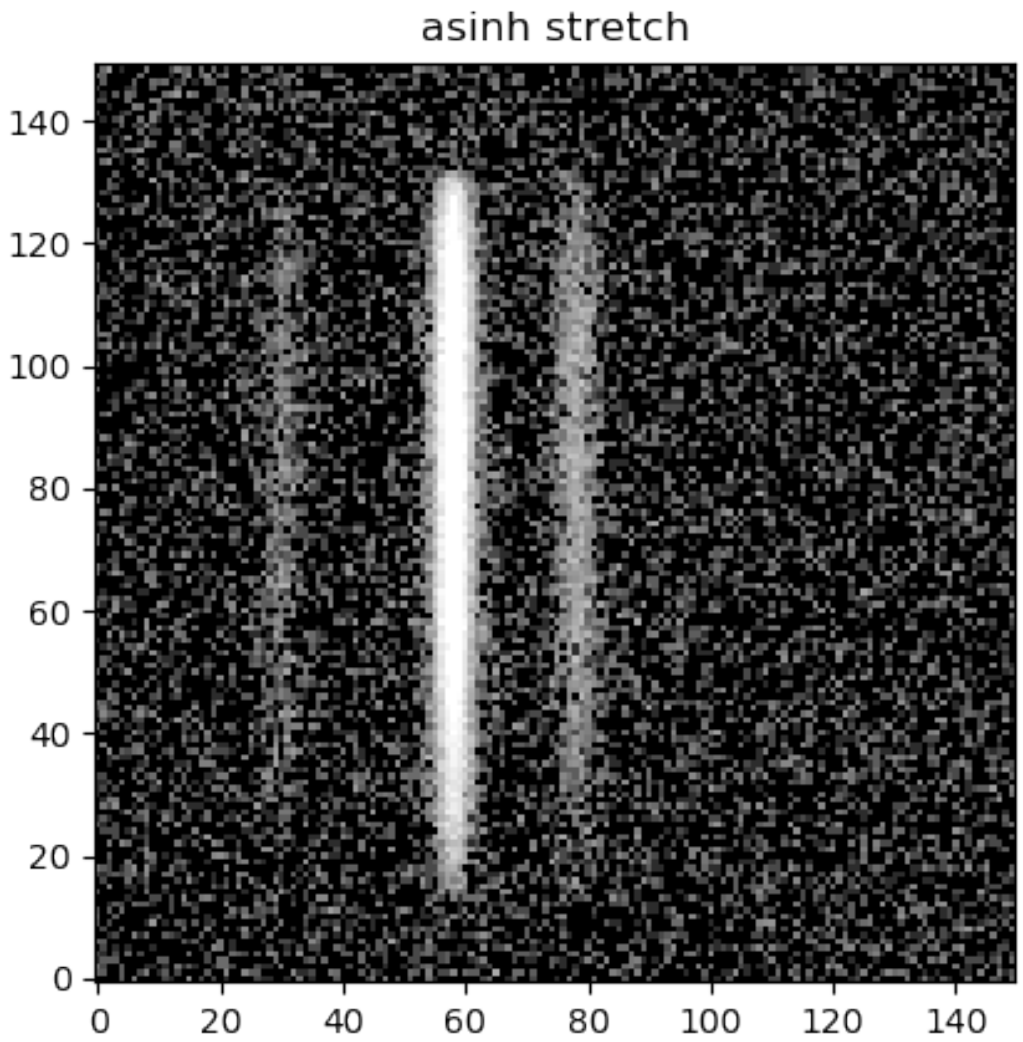
Poisson noise + Gaussian background (readnoise, dark current)

Extracting Spectra

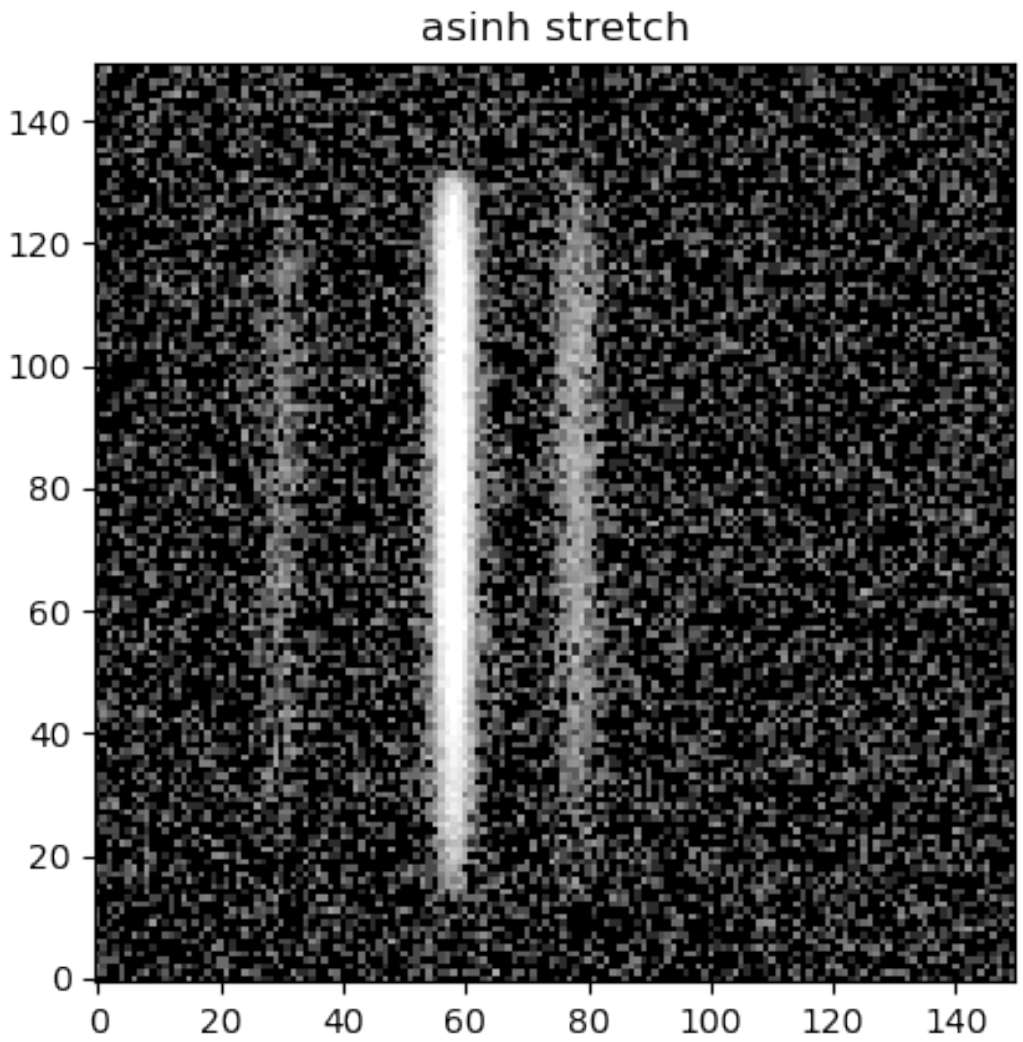
N.b.

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

Extracting Spectra



Extracting Spectra



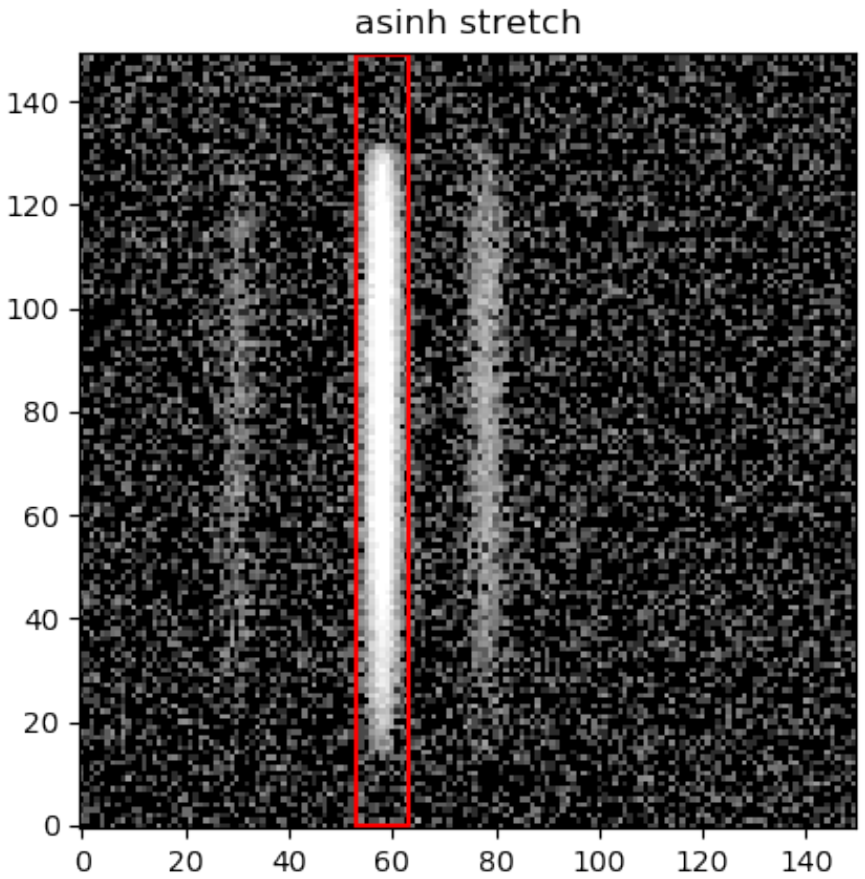
How should we measure those spectra?

How Should I Extract a Spectrum?

If the instrumental resolution is high enough, and the slit is narrow enough, then each row samples the object's flux at a single wavelength. How should I extract a 1-D spectrum from my 2-D data?

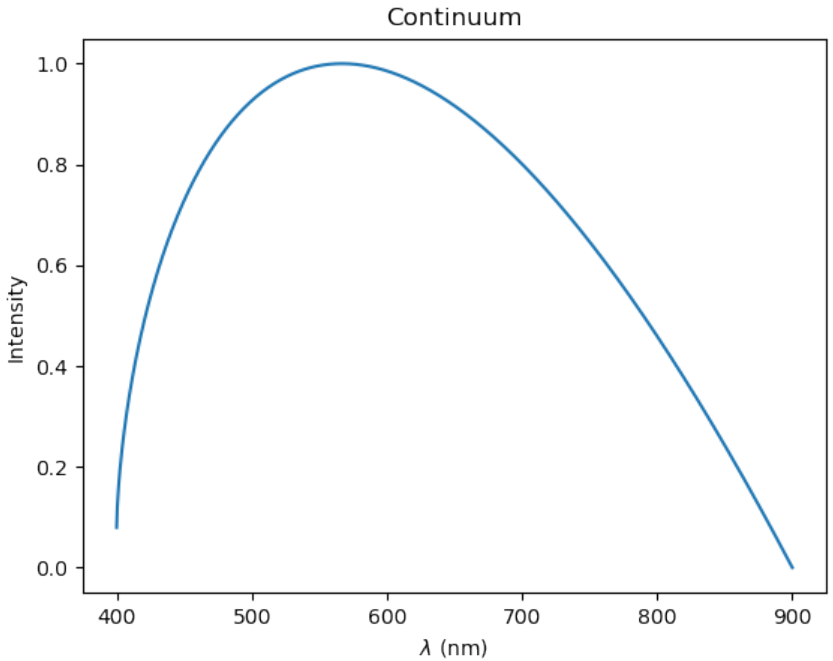
How Should I Extract a Spectrum?

If the instrumental resolution is high enough, and the slit is narrow enough, then each row samples the object's flux at a single wavelength. How should I extract a 1-D spectrum from my 2-D data? *I.e.* Given:



How Should I Extract a Spectrum?

If the instrumental resolution is high enough, and the slit is narrow enough, then each row samples the object's flux at a single wavelength. How should I extract a 1-D spectrum from my 2-D data? I want:



How Should I Extract a Spectrum?

If the instrumental resolution is high enough, and the slit is narrow enough, then each row samples the object's flux at a single wavelength. How should I extract a 1-D spectrum from my 2-D data?

This should seem like a familiar problem!

How Should I Extract a Spectrum?

If the instrumental resolution is high enough, and the slit is narrow enough, then each row samples the object's flux at a single wavelength. How should I extract a 1-D spectrum from my 2-D data?

This should seem like a familiar problem! It's a 1-D photometry problem so I can write down a model and construct an MLE:

$$I_i = B + A\phi_i + \epsilon$$

How Should I Extract a Spectrum?

If the instrumental resolution is high enough, and the slit is narrow enough, then each row samples the object's flux at a single wavelength. How should I extract a 1-D spectrum from my 2-D data?
This should seem like a familiar problem! It's a 1-D photometry problem so I can write down a model and construct an MLE:

$$I_i = B + A\phi_i + \epsilon$$

If the noise ϵ is Gaussian $N(0, \sigma_i^2)$ then we know that the MLE ("optimal extraction") for A is

$$\hat{A} = \frac{\sum_i I_i \phi_i / \sigma_i^2}{\sum_i \phi_i^2 / \sigma_i^2}$$

How Should I Extract a Spectrum?

If the instrumental resolution is high enough, and the slit is narrow enough, then each row samples the object's flux at a single wavelength. How should I extract a 1-D spectrum from my 2-D data?
This should seem like a familiar problem! It's a 1-D photometry problem so I can write down a model and construct an MLE:

$$I_i = B + A\phi_i + \epsilon$$

If the noise ϵ is Gaussian $N(0, \sigma_i^2)$ then we know that the MLE ("optimal extraction") for A is

$$\hat{A} = \frac{\sum_i I_i \phi_i / \sigma_i^2}{\sum_i \phi_i^2 / \sigma_i^2}$$

For photometry Gaussian noise is generally a good assumption, but it's less obvious for spectroscopy:

- The background noise isn't coming from the sky, it's coming from the detector and is relatively small.
- The rest of the noise is Poisson.

How Should I Extract a Spectrum?

If the instrumental resolution is high enough, and the slit is narrow enough, then each row samples the object's flux at a single wavelength. How should I extract a 1-D spectrum from my 2-D data?
This should seem like a familiar problem! It's a 1-D photometry problem so I can write down a model and construct an MLE:

$$I_i = B + A\phi_i + \epsilon$$

If the noise ϵ is Gaussian $N(0, \sigma_i^2)$ then we know that the MLE ("optimal extraction") for A is

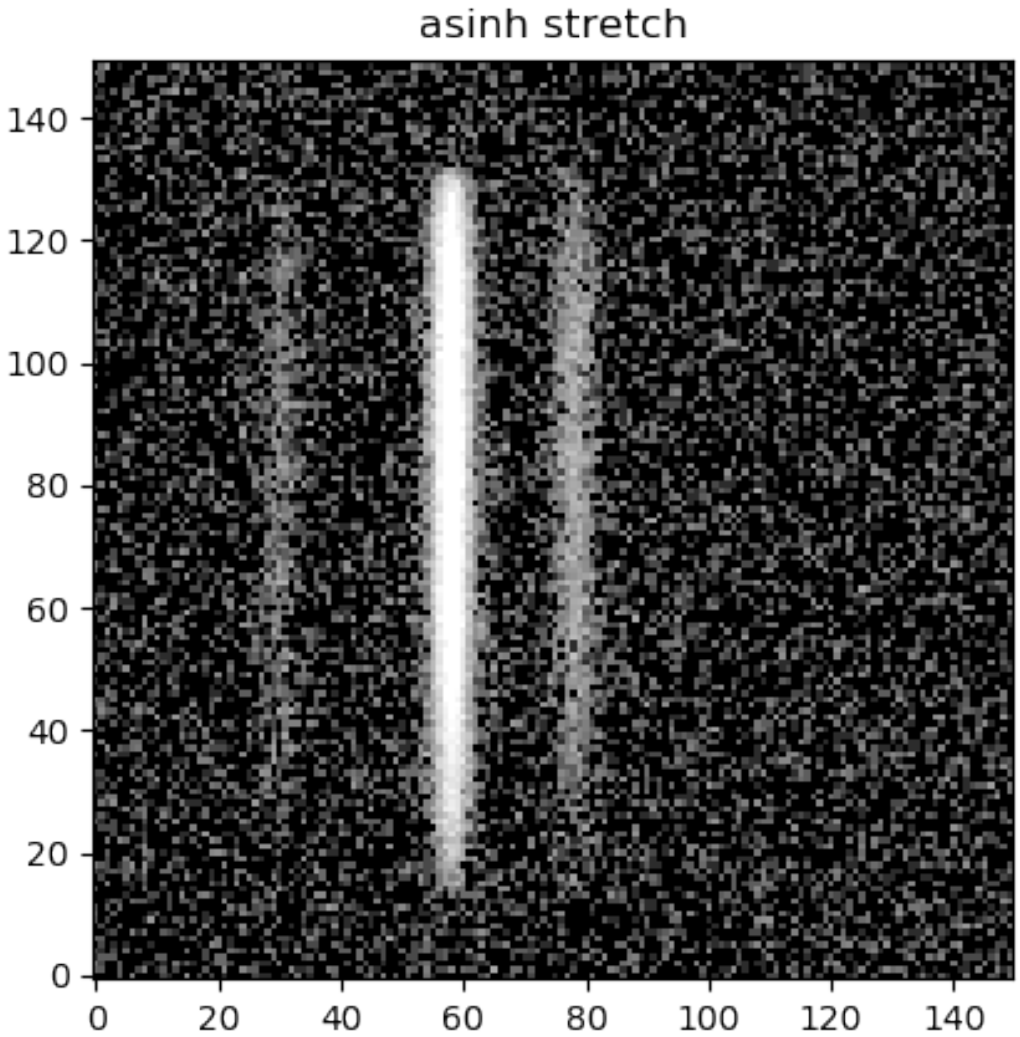
$$\hat{A} = \frac{\sum_i I_i \phi_i / \sigma_i^2}{\sum_i \phi_i^2 / \sigma_i^2}$$

For photometry Gaussian noise is generally a good assumption, but it's less obvious for spectroscopy:

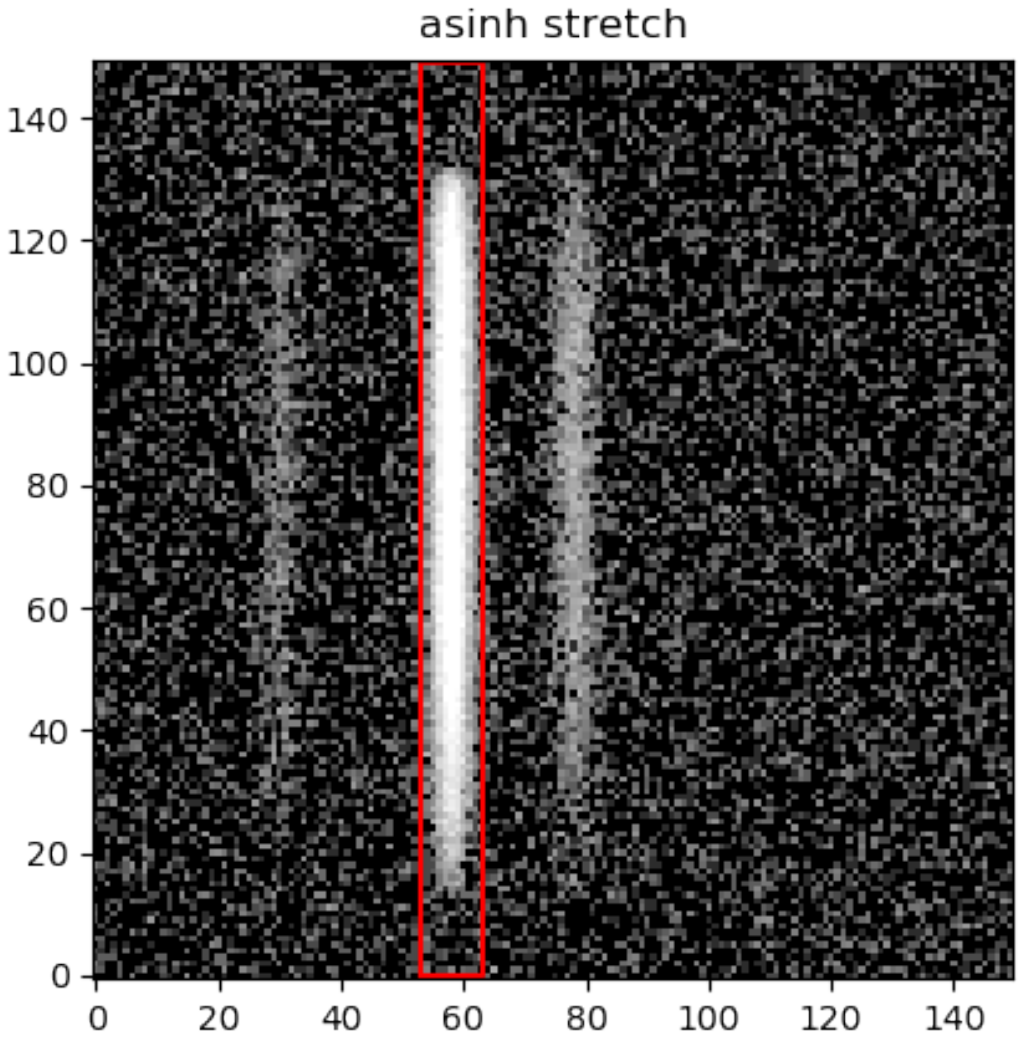
- The background noise isn't coming from the sky, it's coming from the detector and is relatively small.
- The rest of the noise is Poisson.

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

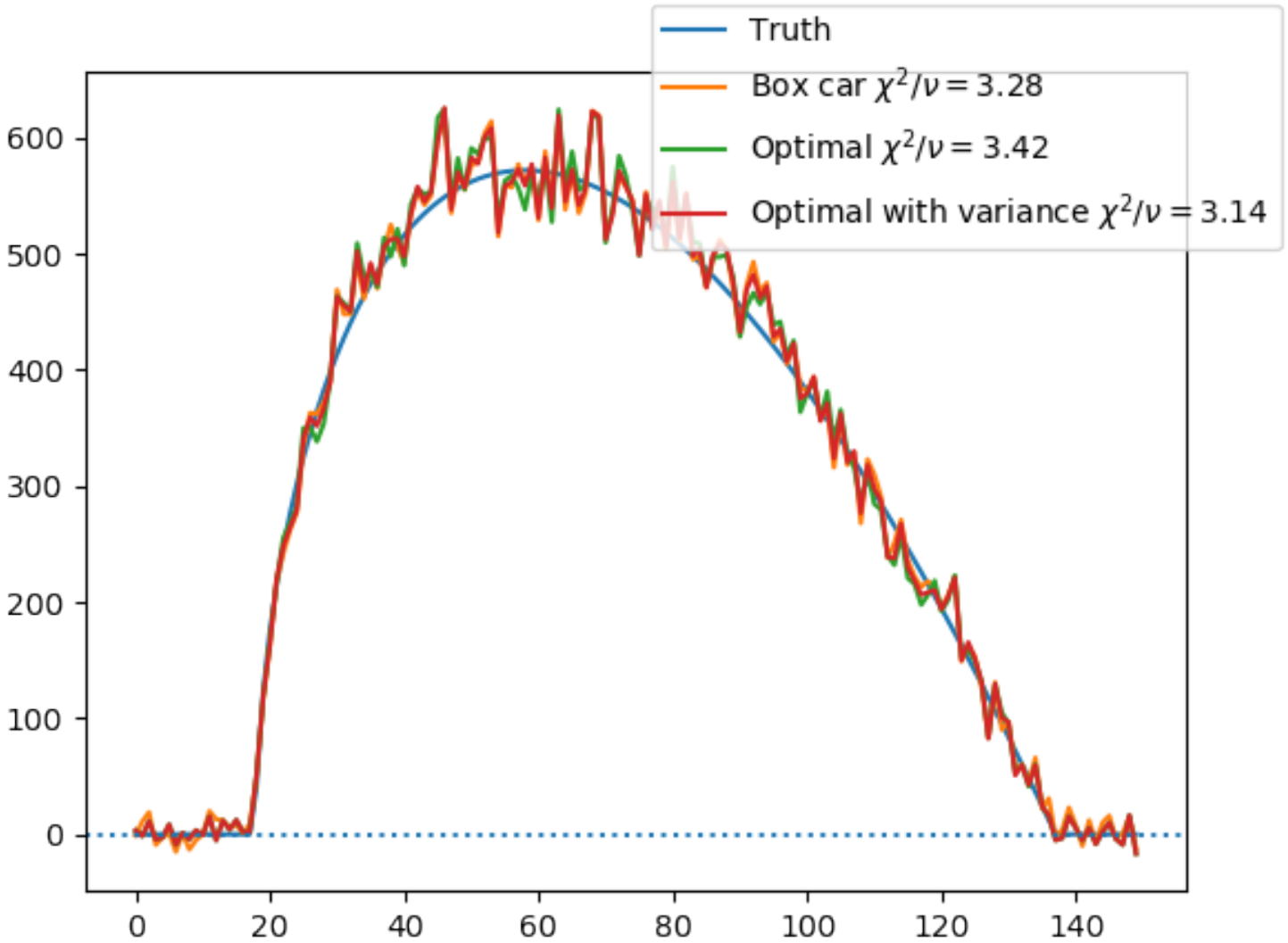
Extracting Spectra



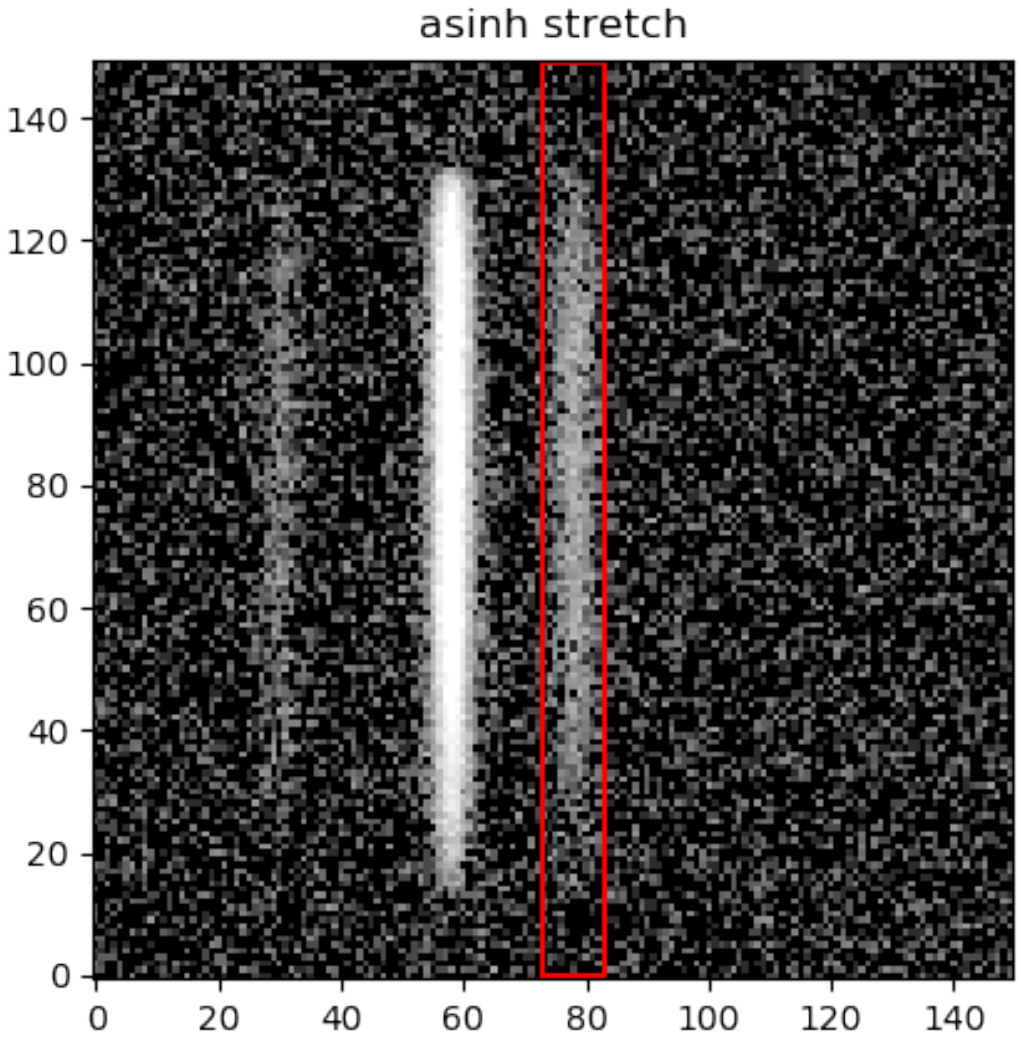
Extracting Spectra



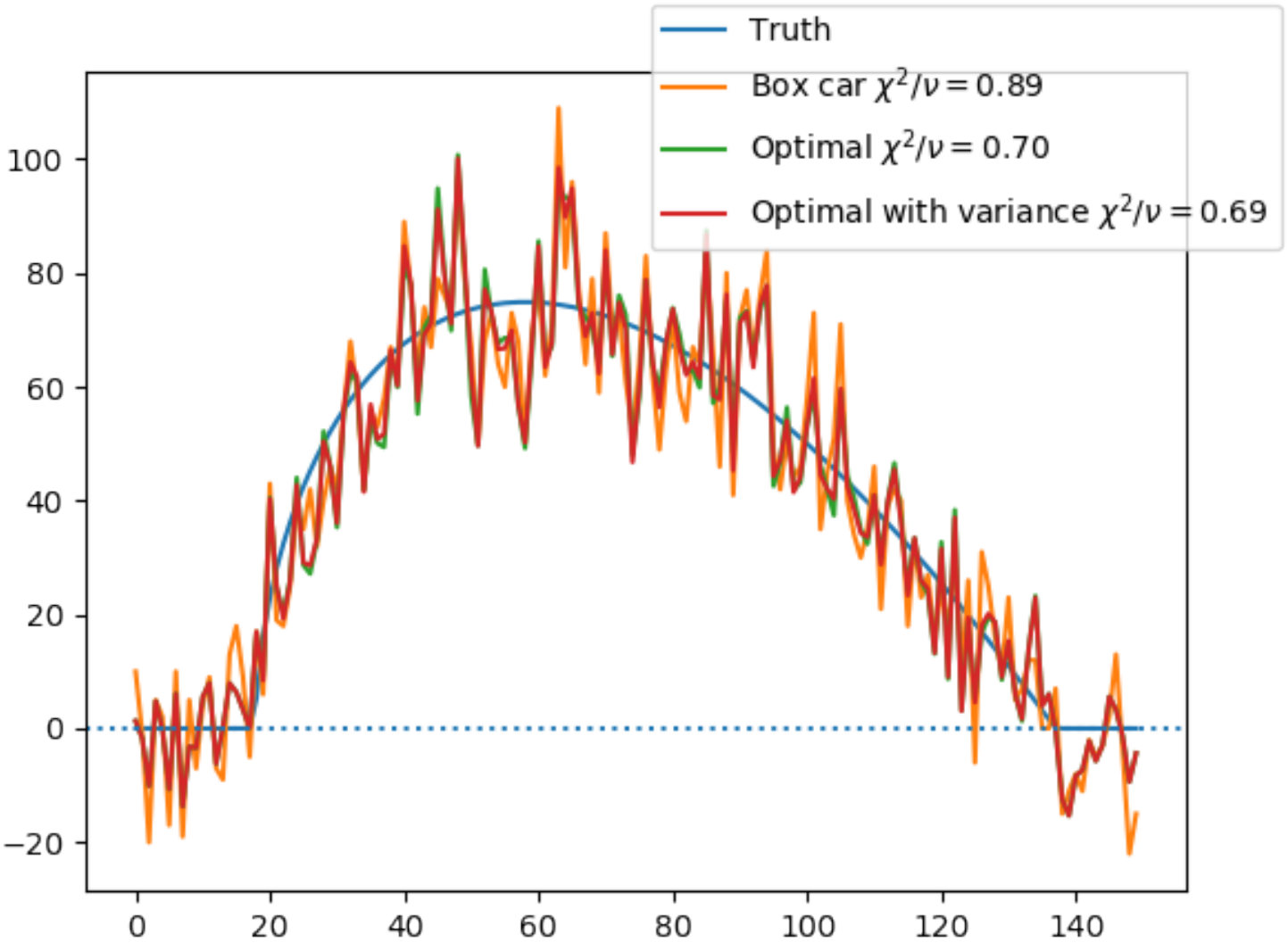
Extracting Spectra



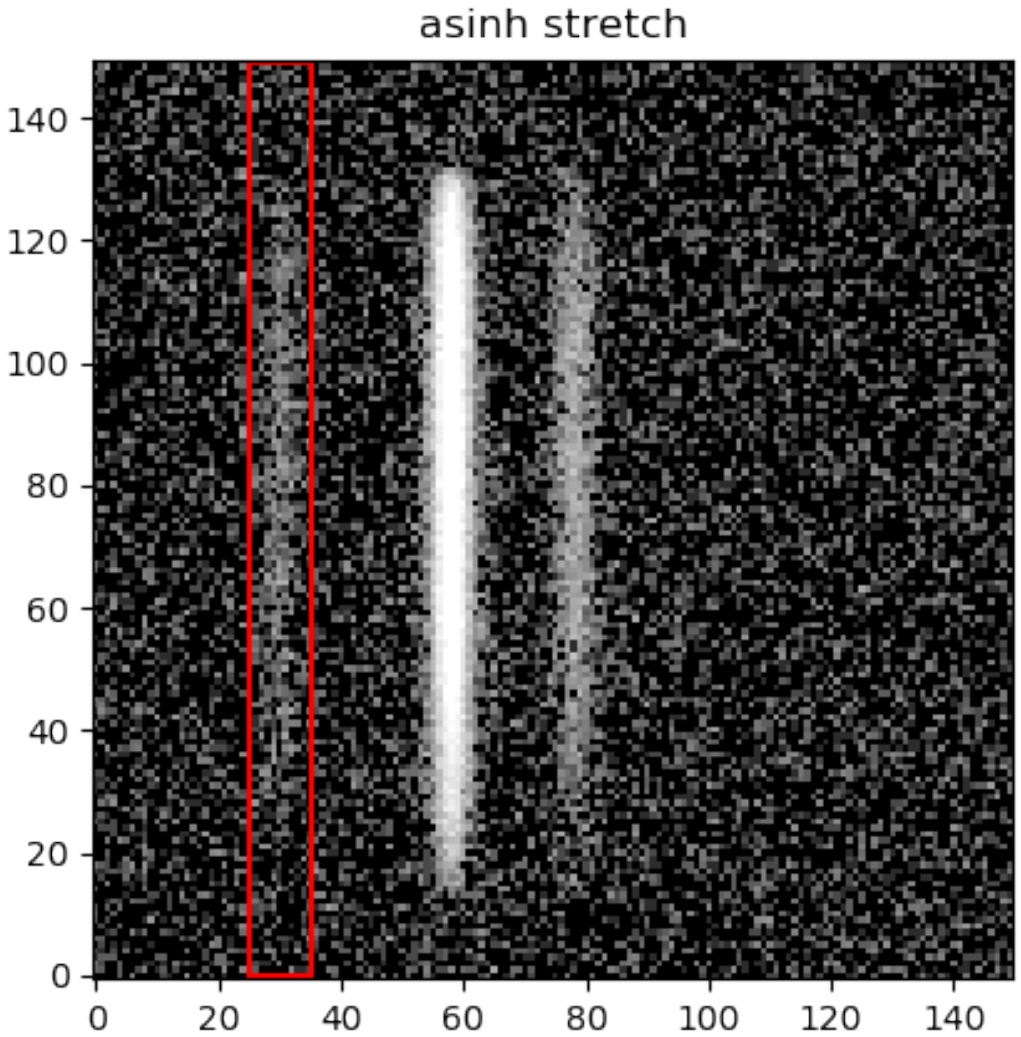
Extracting Spectra



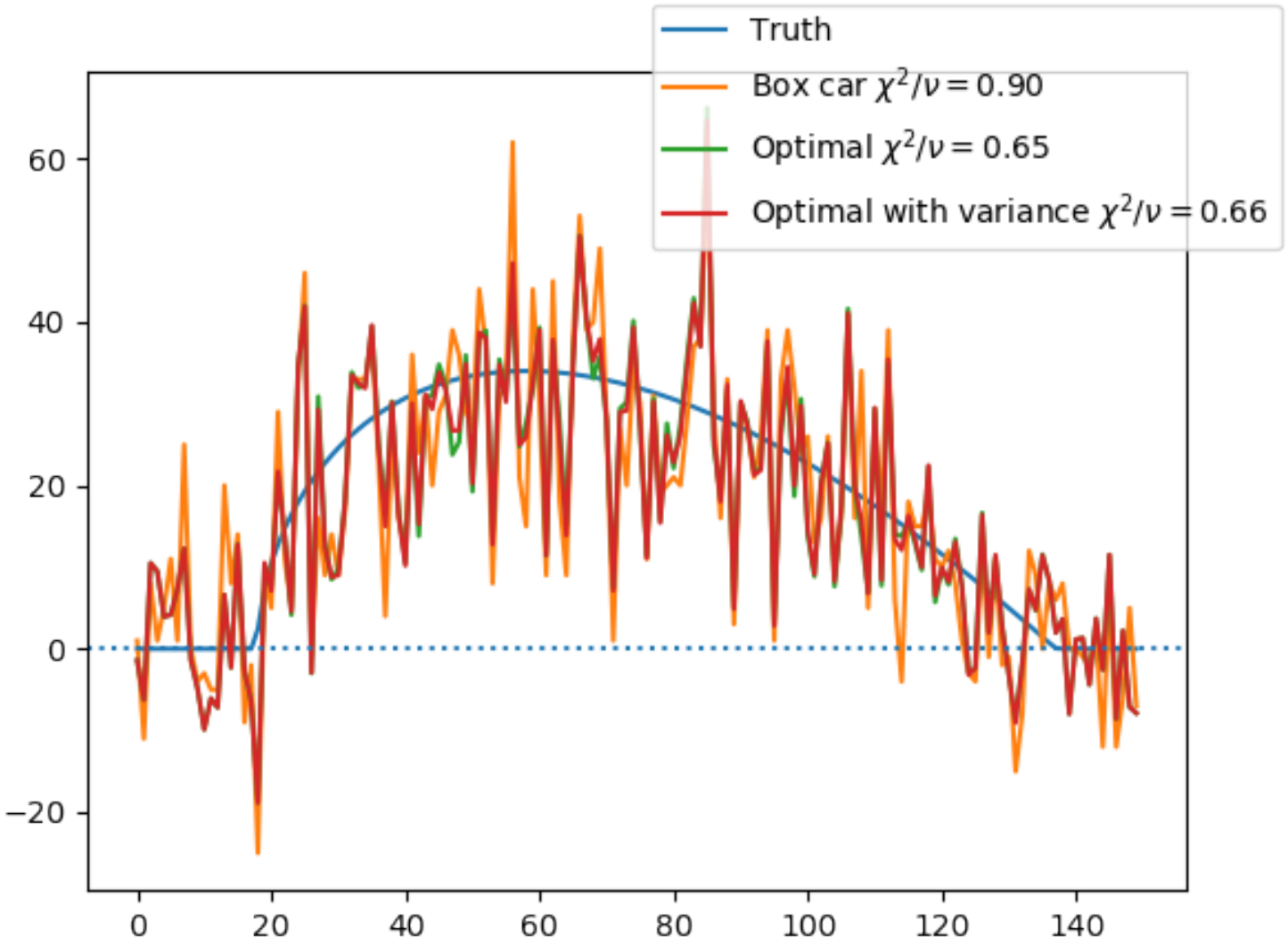
Extracting Spectra



Extracting Spectra



Extracting Spectra



Grisms

If you only had one object in the field, grism extractions would be no harder than long-slit extractions.

Grisms

If you only had one object in the field, grism extractions would be no harder than long-slit extractions.

- The sky signal is spread out uniformly over all pixels, so it isn't a problem

Grisms

If you only had one object in the field, grism extractions would be no harder than long-slit extractions.

- The sky signal is spread out uniformly over all pixels, so it isn't a problem
- except that it generates noise

Grisms

If you only had one object in the field, grism extractions would be no harder than long-slit extractions.

- The sky signal is spread out uniformly over all pixels, so it isn't a problem
- except that it generates noise
- and flat-fielding is impossible as multiple wavelengths fall on each pixel

Grisms

If you only had one object in the field, grism extractions would be no harder than long-slit extractions.

- The sky signal is spread out uniformly over all pixels, so it isn't a problem
- except that it generates noise
- and flat-fielding is impossible as multiple wavelengths fall on each pixel

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

Fibre Spectrographs

We analysed the case:

- If the instrumental resolution is high enough, and the slit is narrow enough, then each row samples the object's flux at a single wavelength.

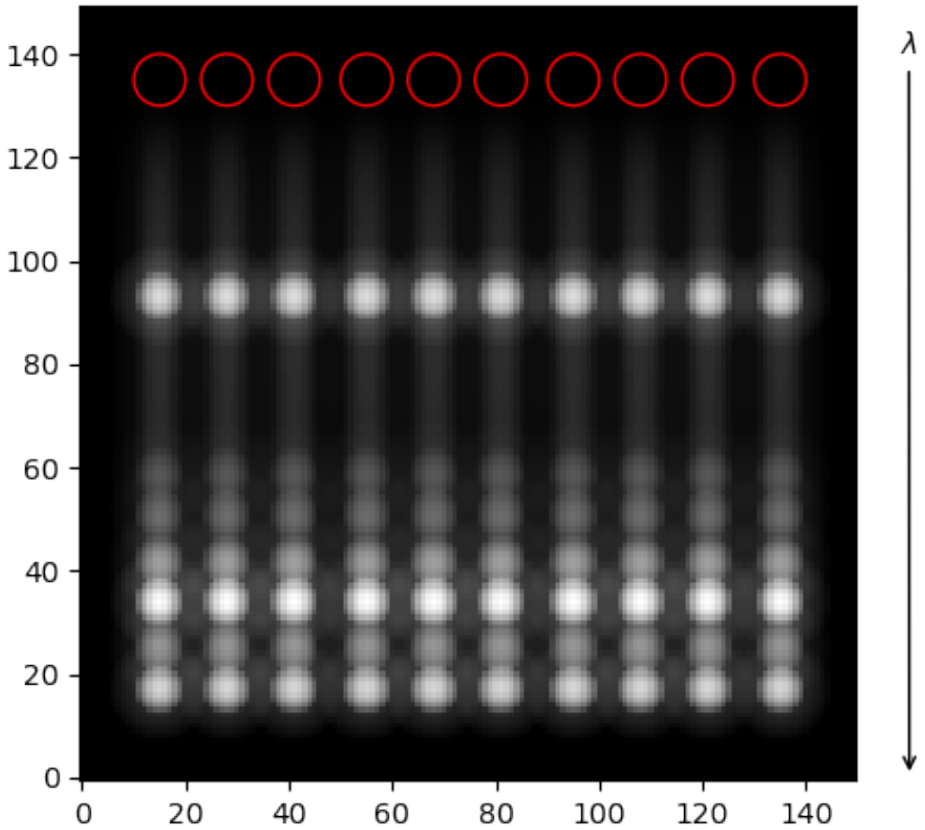
but this isn't satisfied by a fibre spectrograph.

Fibre Spectrographs

We analysed the case:

- If the instrumental resolution is high enough, and the slit is narrow enough, then each row samples the object's flux at a single wavelength.

but this isn't satisfied by a fibre spectrograph. In general the PSF can't be factored into the product of functions in the row- and column- directions.



Fibre Spectrographs

We analysed the case:

- If the instrumental resolution is high enough, and the slit is narrow enough, then each row samples the object's flux at a single wavelength.

but this isn't satisfied by a fibre spectrograph. In general the PSF can't be factored into the product of functions in the row- and column- directions.
People usually ignore this inconvenient fact.

Fibre Spectrographs

We analysed the case:

- If the instrumental resolution is high enough, and the slit is narrow enough, then each row samples the object's flux at a single wavelength.

but this isn't satisfied by a fibre spectrograph. In general the PSF can't be factored into the product of functions in the row- and column- directions.
People usually ignore this inconvenient fact. Bolton and Schlegel (https://arxiv.org/abs/0911.2689) point out that the proper thing to do is to treat the data as a convolution of the spectrum with the *2-dimensional* PSF "spectro-perfectionism".

Fibre Spectrographs

We analysed the case:

- If the instrumental resolution is high enough, and the slit is narrow enough, then each row samples the object's flux at a single wavelength.

but this isn't satisfied by a fibre spectrograph. In general the PSF can't be factored into the product of functions in the row- and column- directions.
People usually ignore this inconvenient fact. Bolton and Schlegel (https://arxiv.org/abs/0911.2689) point out that the proper thing to do is to treat the data as a convolution of the spectrum with the *2-dimensional* PSF
"spectro-perfectionism".
Unfortunately this is computationally very expensive.

The Sky Spectrum

I said:

- The background noise isn't coming from the sky, it's coming from the detector and is relatively small.

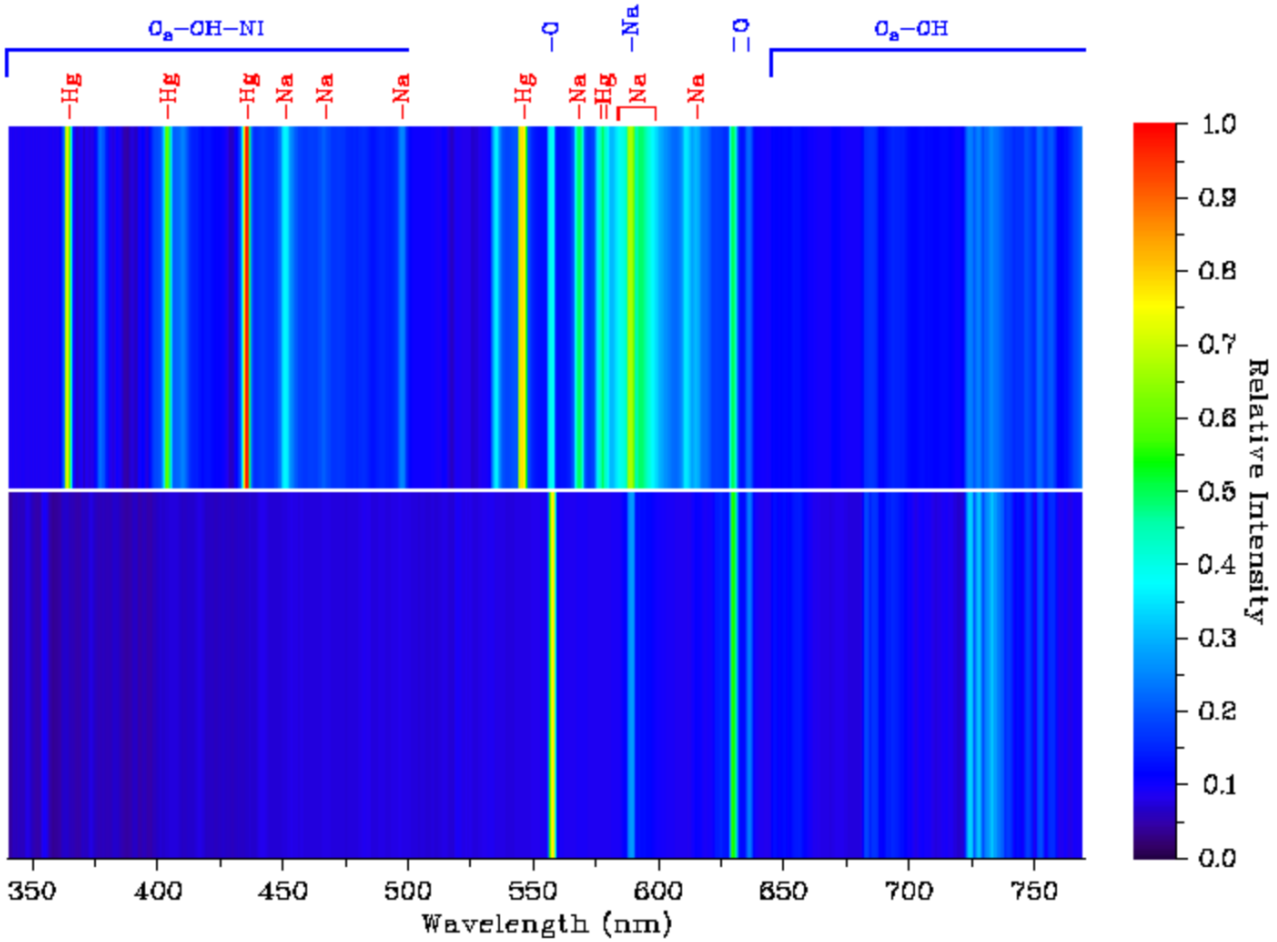
but how did this piece of magic happen?

The Sky Spectrum

I said:

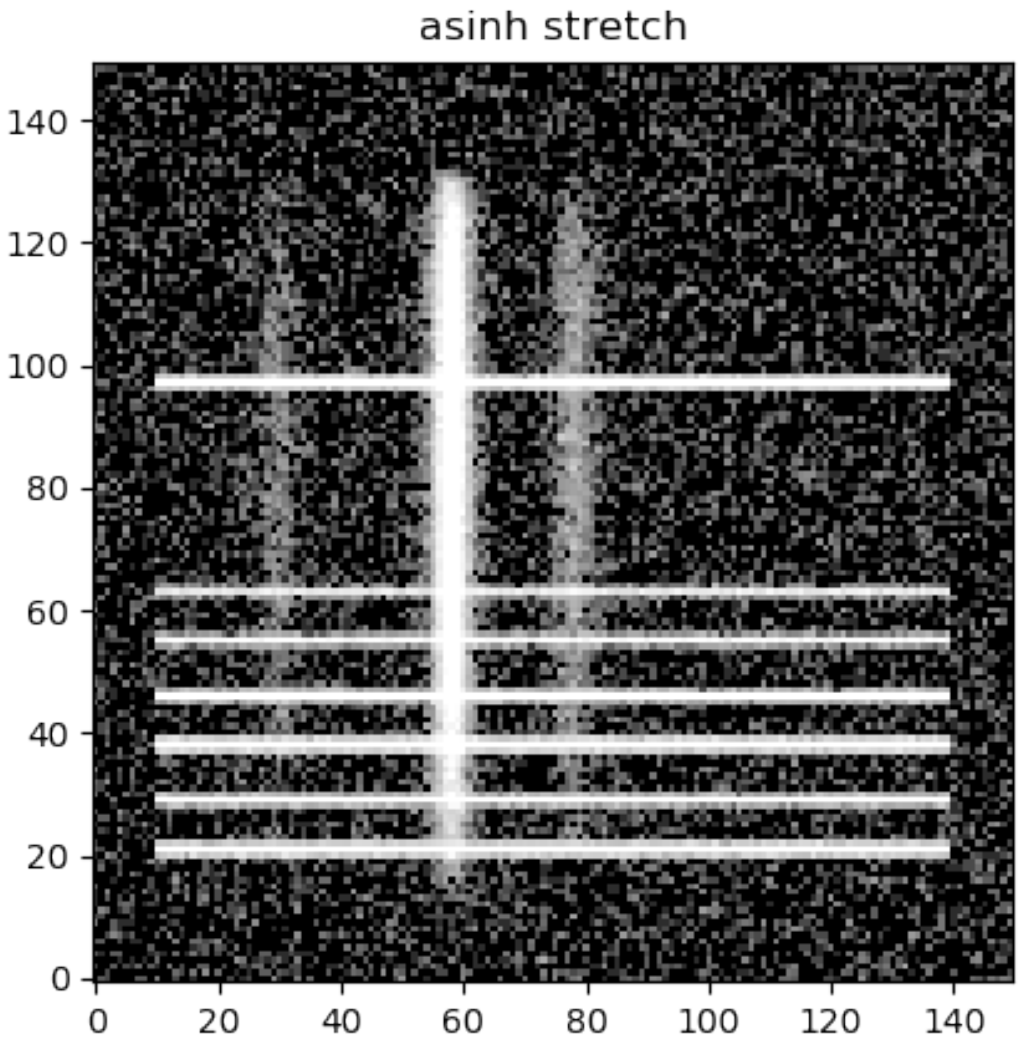
- The background noise isn't coming from the sky, it's coming from the detector and is relatively small.

but how did this piece of magic happen?

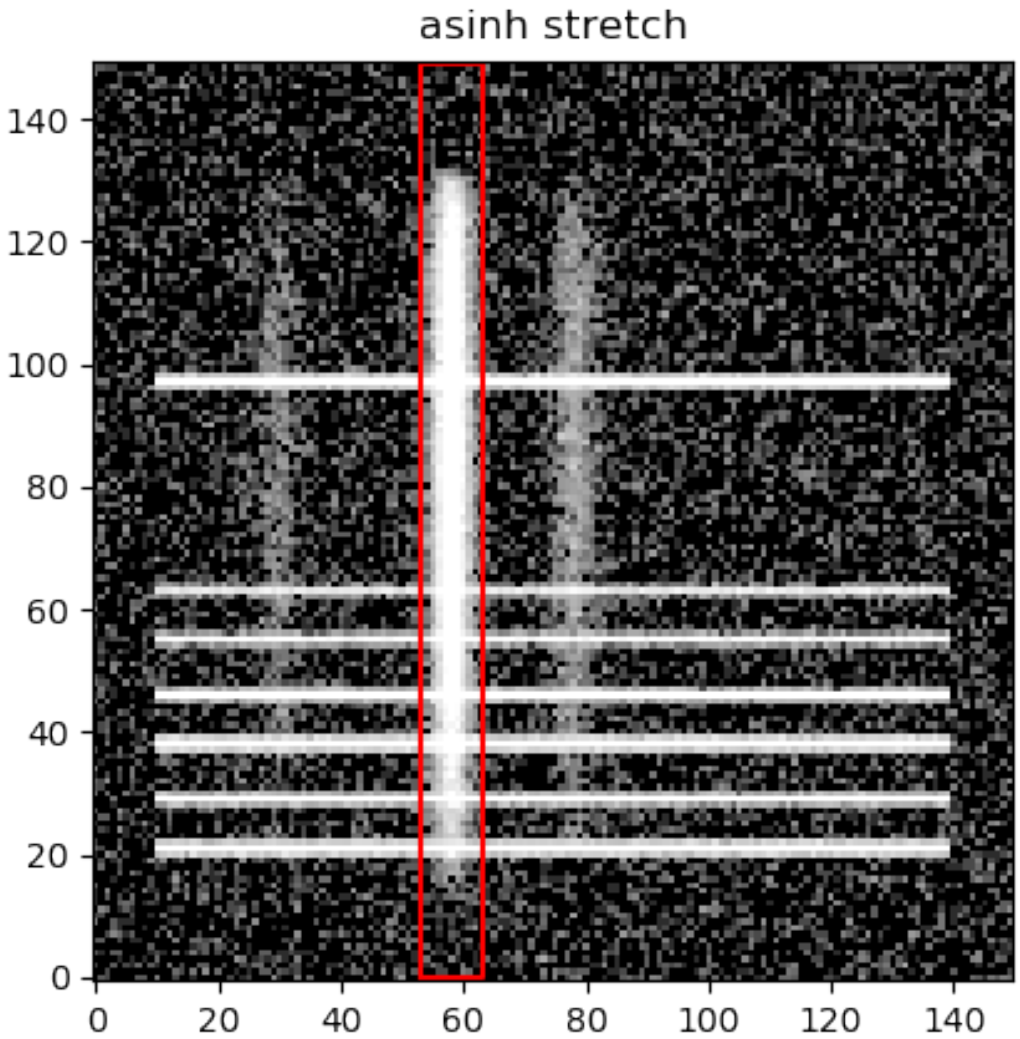


Sky Subtraction

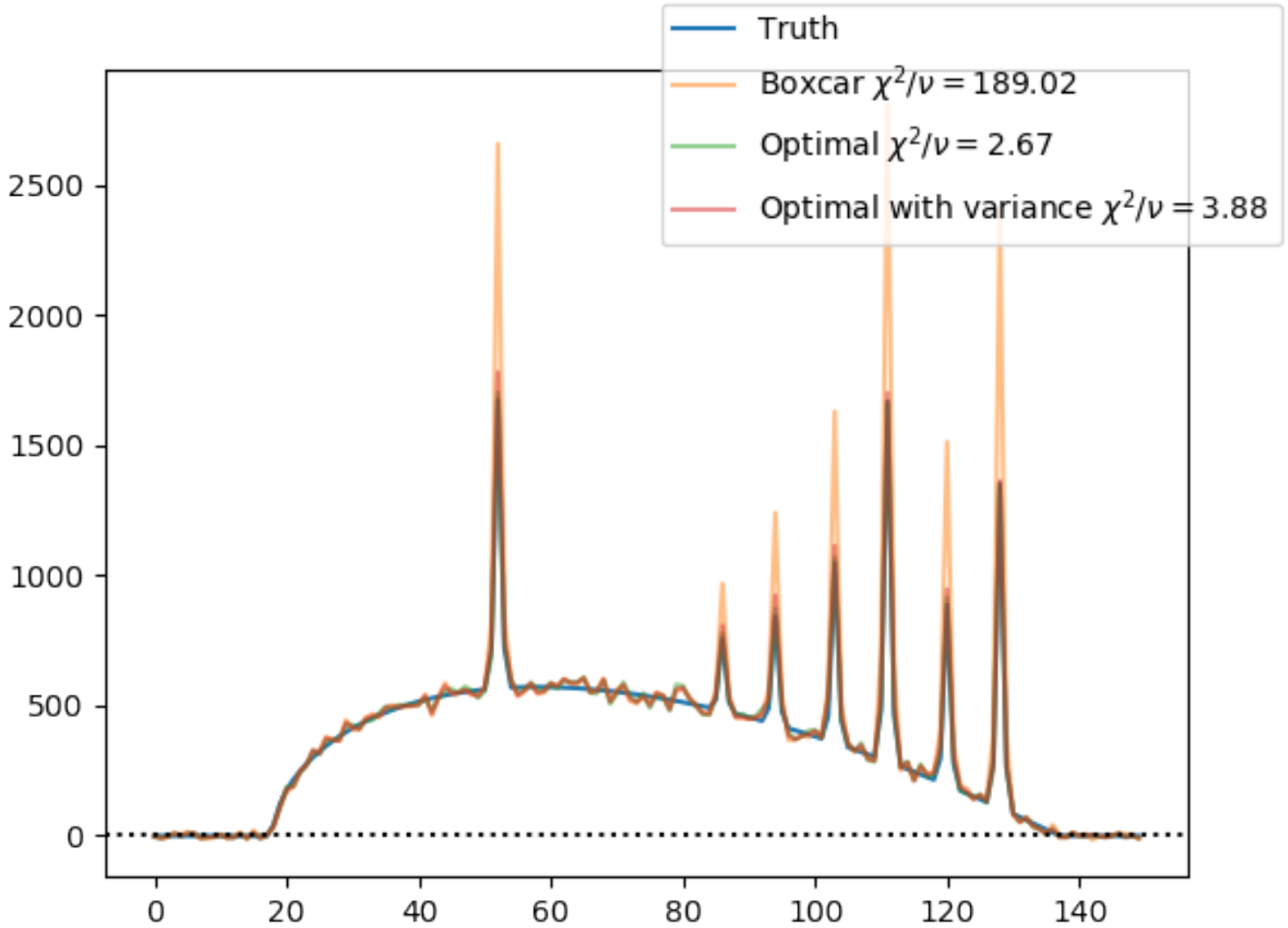
Sky Subtraction



Sky Subtraction



Sky Subtraction

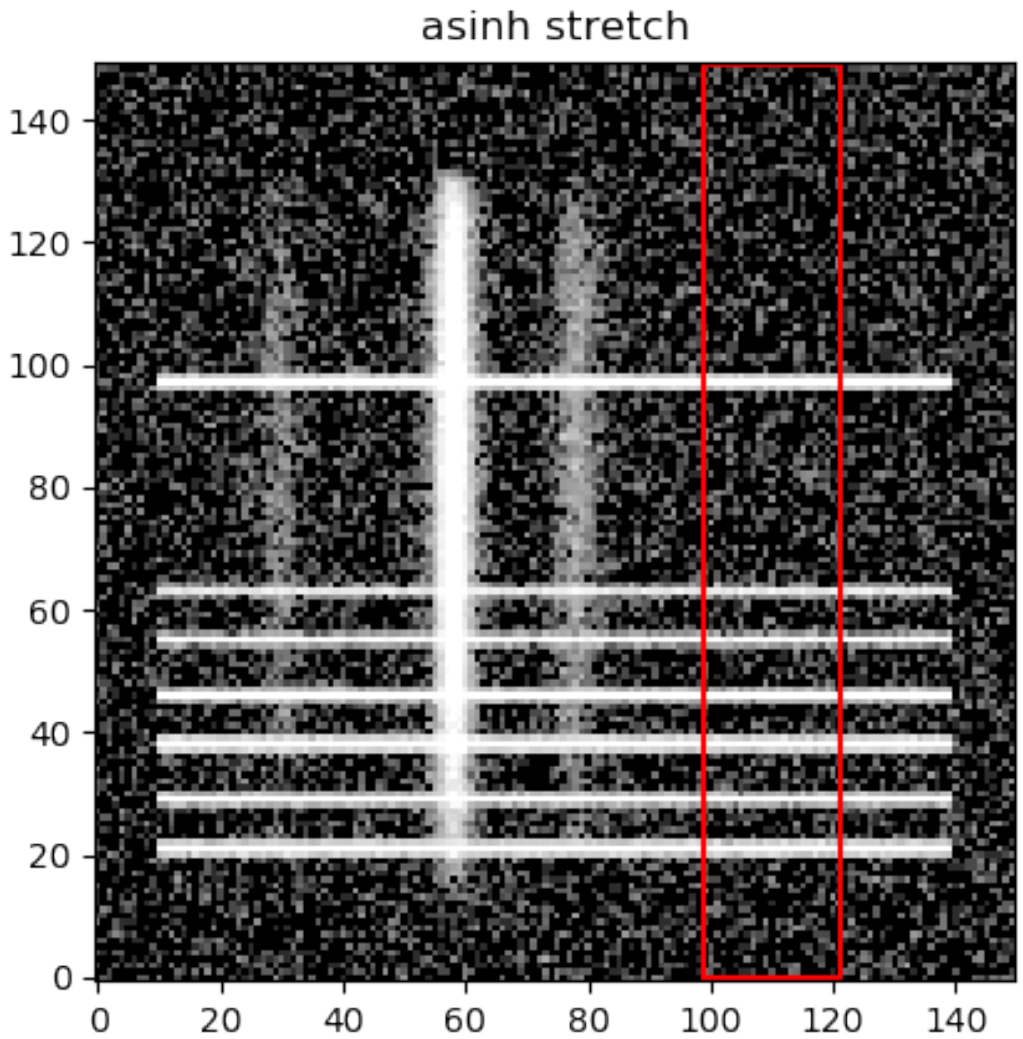


Sky Subtraction

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

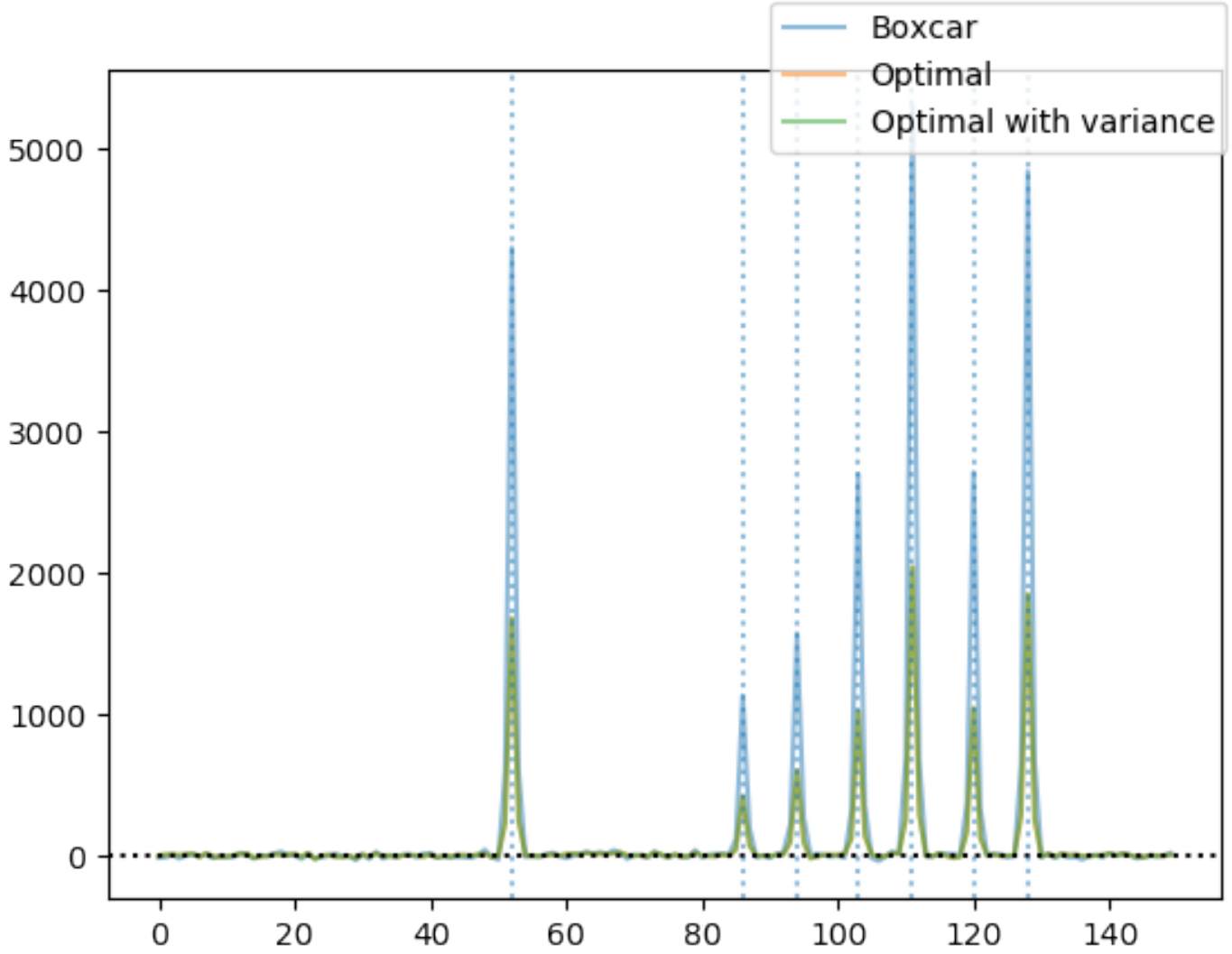
Sky Subtraction

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



Sky Subtraction

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

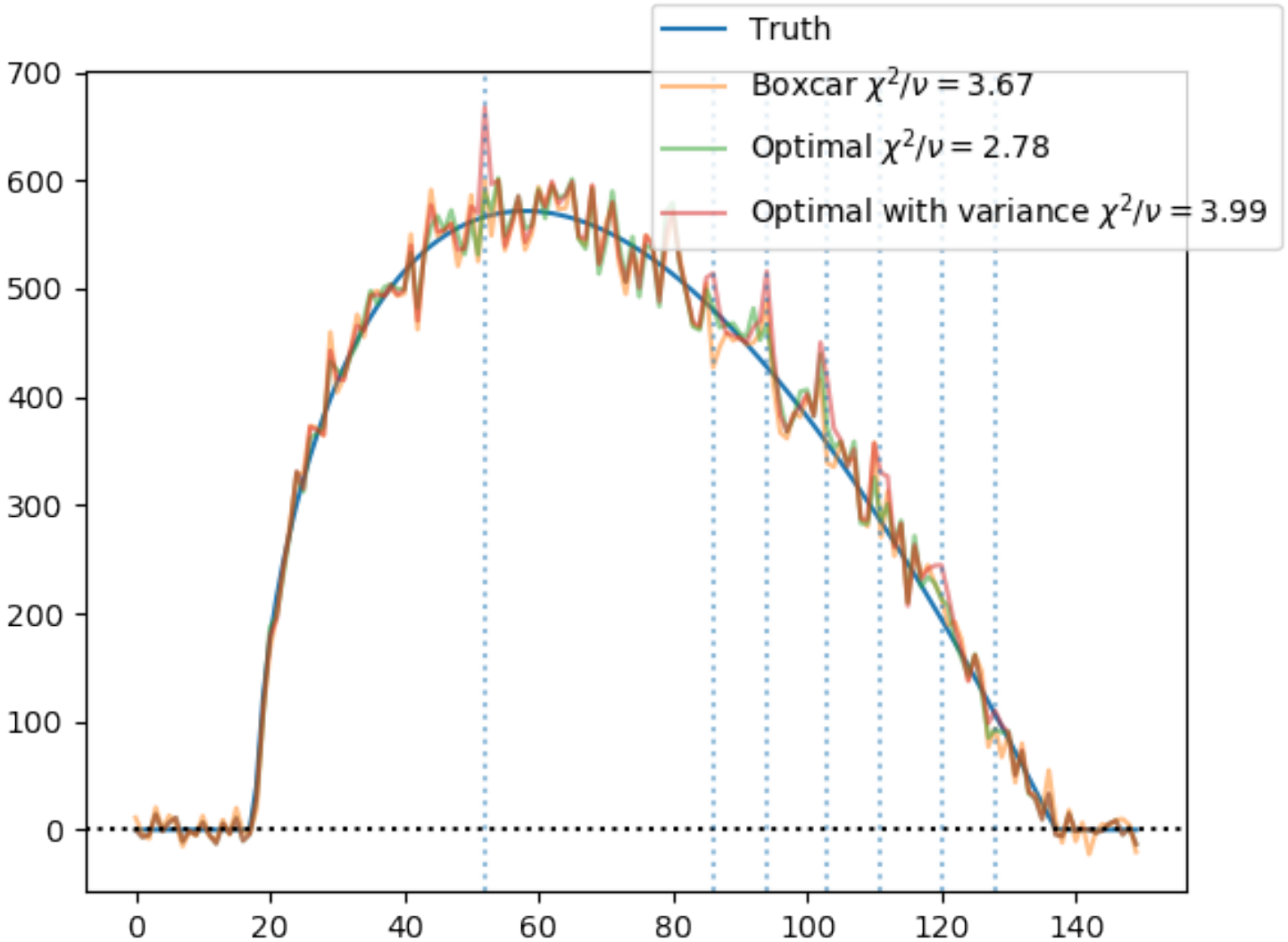


Sky Subtraction

With our sky spectrum in hand we can subtract it from our data:

Sky Subtraction

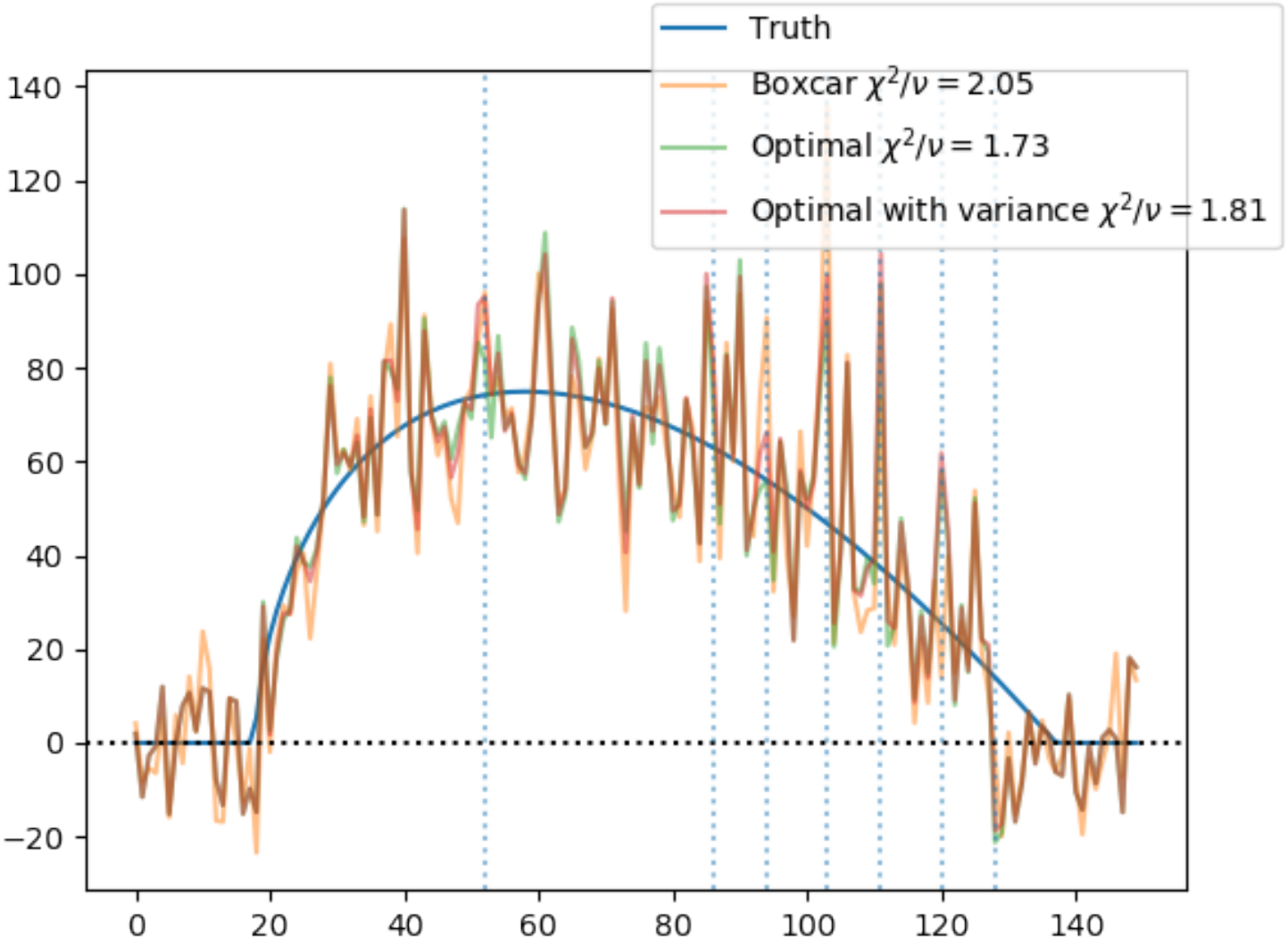
With our sky spectrum in hand we can subtract it from our data:



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

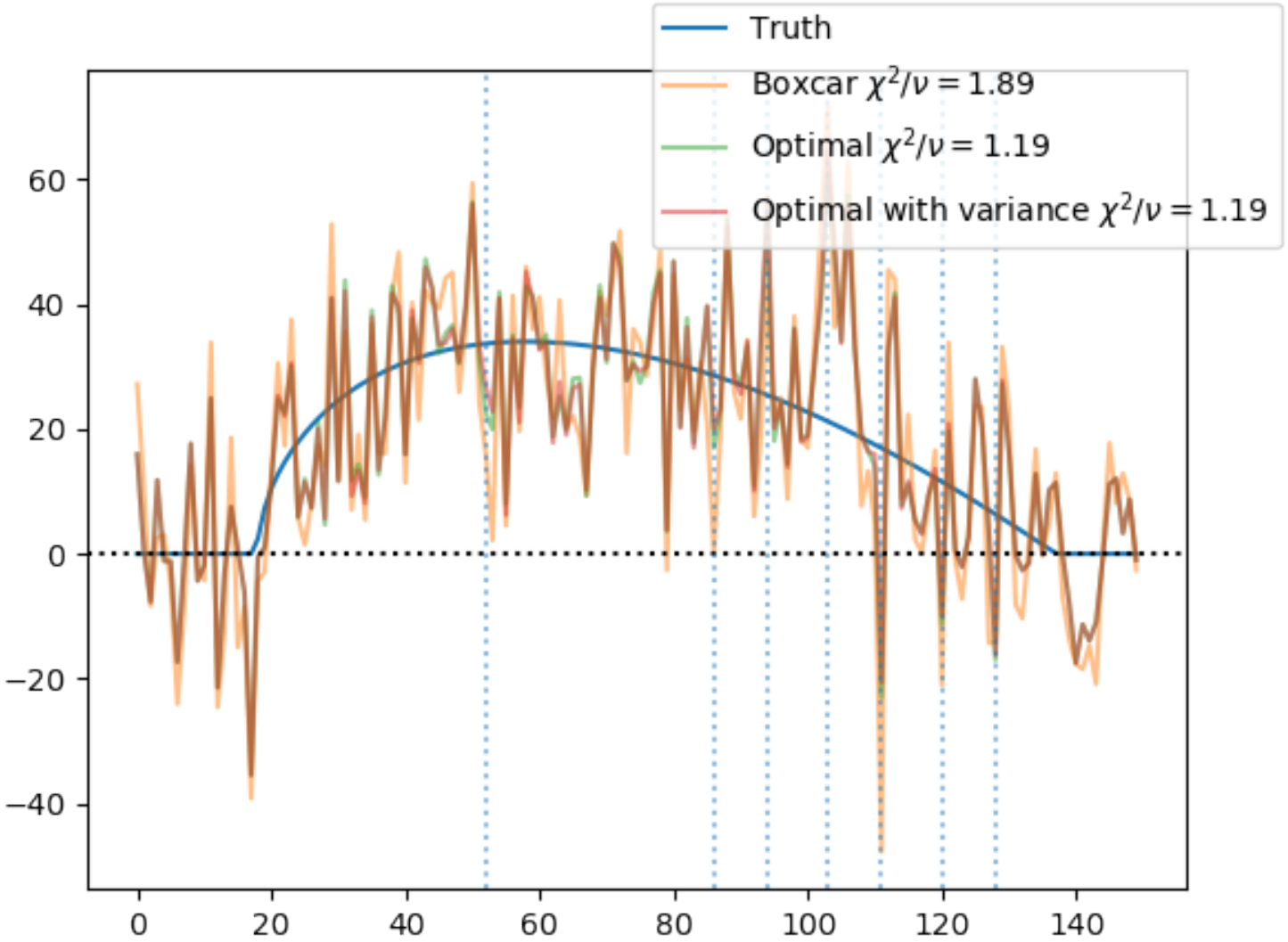
Sky Subtraction

With our sky spectrum in hand we can subtract it from our data:

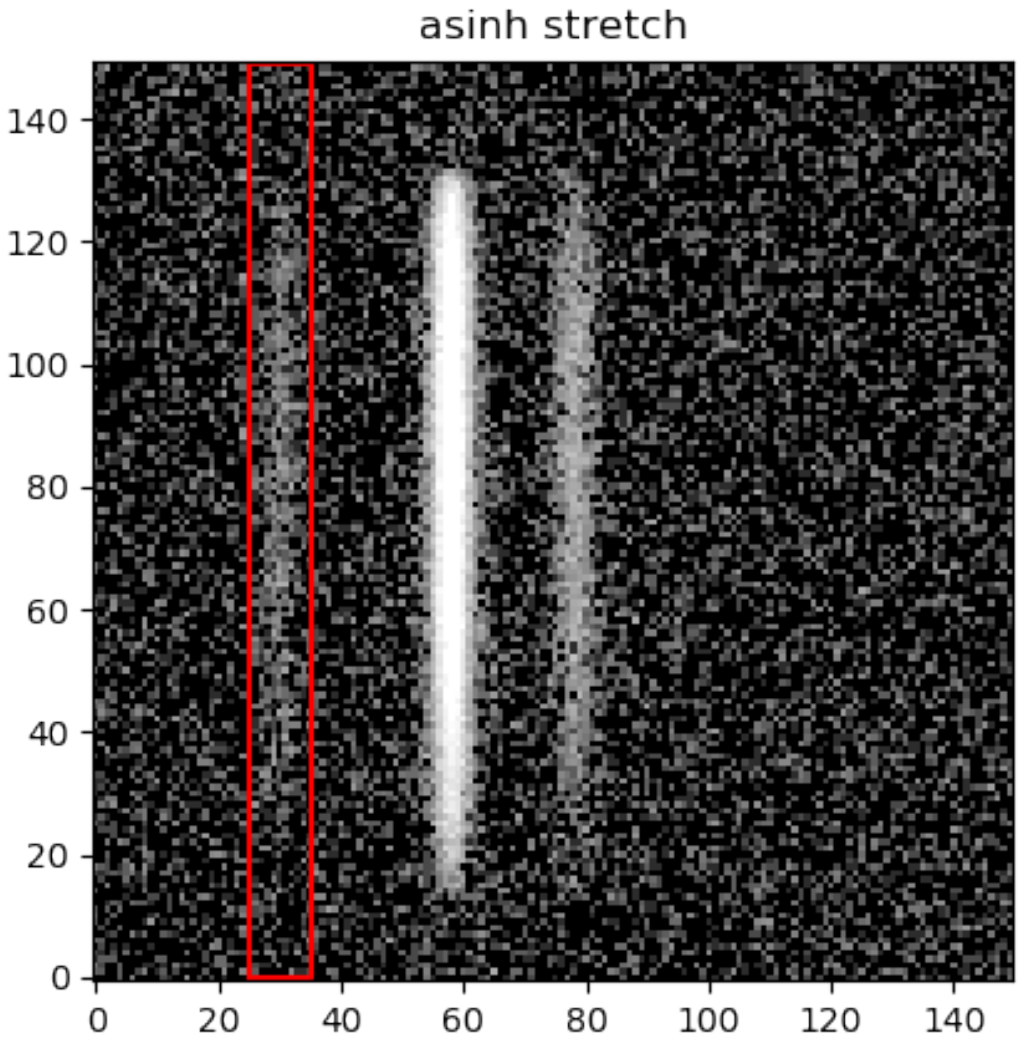


Sky Subtraction

With our sky spectrum in hand we can subtract it from our data:



Sky Subtraction



Fibres

You put some fibres on empty parts of the sky, and then use long-slit style subtractions.

Fibres

You put some fibres on empty parts of the sky, and then use long-slit style subtractions. Unfortunately sky subtraction is notoriously difficult in fibre spectrographs.

Fibres

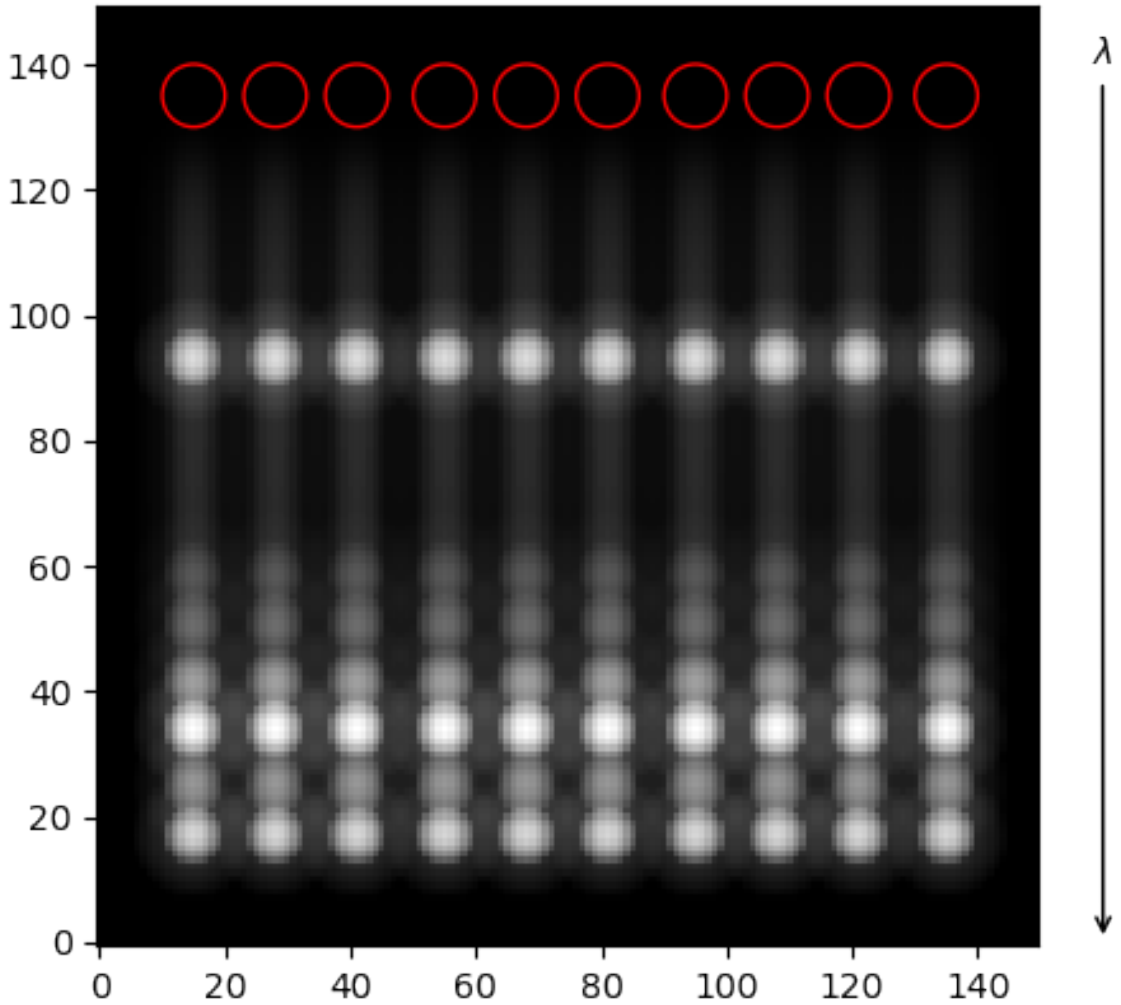
You put some fibres on empty parts of the sky, and then use long-slit style subtractions. Unfortunately sky subtraction is notoriously difficult in fibre spectrographs. The problems come from variations in throughput between the sky and the object fibres, spatial structure in the sky spectrum, and the effects of the 2-D PSF.

Fibres

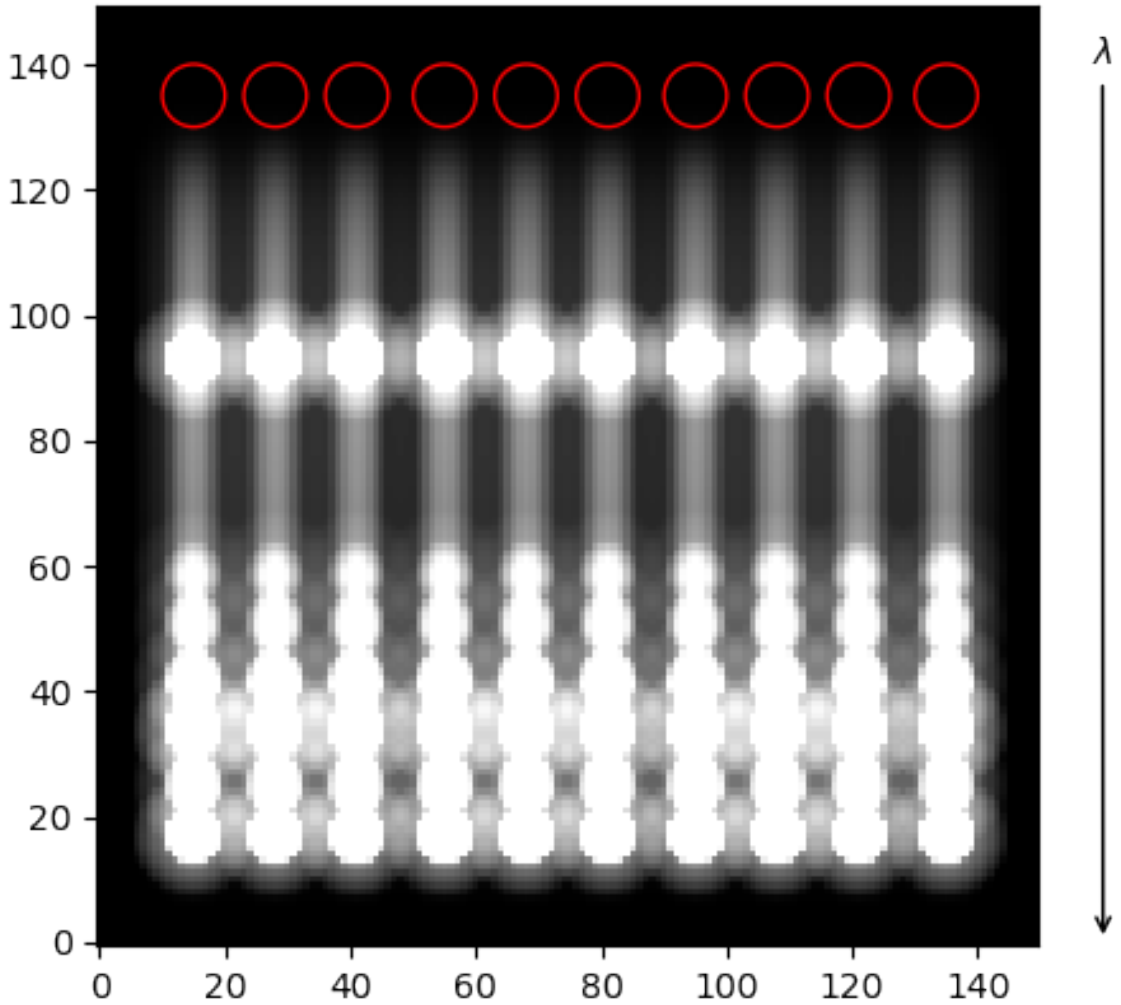
You put some fibres on empty parts of the sky, and then use long-slit style subtractions. Unfortunately sky subtraction is notoriously difficult in fibre spectrographs. The problems come from variations in throughput between the sky and the object fibres, spatial structure in the sky spectrum, and the effects of the 2-D PSF.

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

Fibres



Fibres



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

A proposal

The right thing to do is spectro-perfectionism; but that is expensive and needs regularisation.

A proposal

The right thing to do is spectro-perfectionism; but that is expensive and needs regularisation.
For the Prime Focus Spectrograph I have another plan.

A proposal

The right thing to do is spectro-perfectionism; but that is expensive and needs regularisation.
For the Prime Focus Spectrograph I have another plan. What's the Prime Focus Spectrograph?

A proposal

The right thing to do is spectro-perfectionism; but that is expensive and needs regularisation.
For the Prime Focus Spectrograph I have another plan. What's the Prime Focus Spectrograph?

- 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

A proposal

The right thing to do is spectro-perfectionism; but that is expensive and needs regularisation.
For the Prime Focus Spectrograph I have another plan. What's the Prime Focus Spectrograph?

- 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

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

A proposal

The right thing to do is spectro-perfectionism; but that is expensive and needs regularisation.
For the Prime Focus Spectrograph I have another plan. What's the Prime Focus Spectrograph?

- 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

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

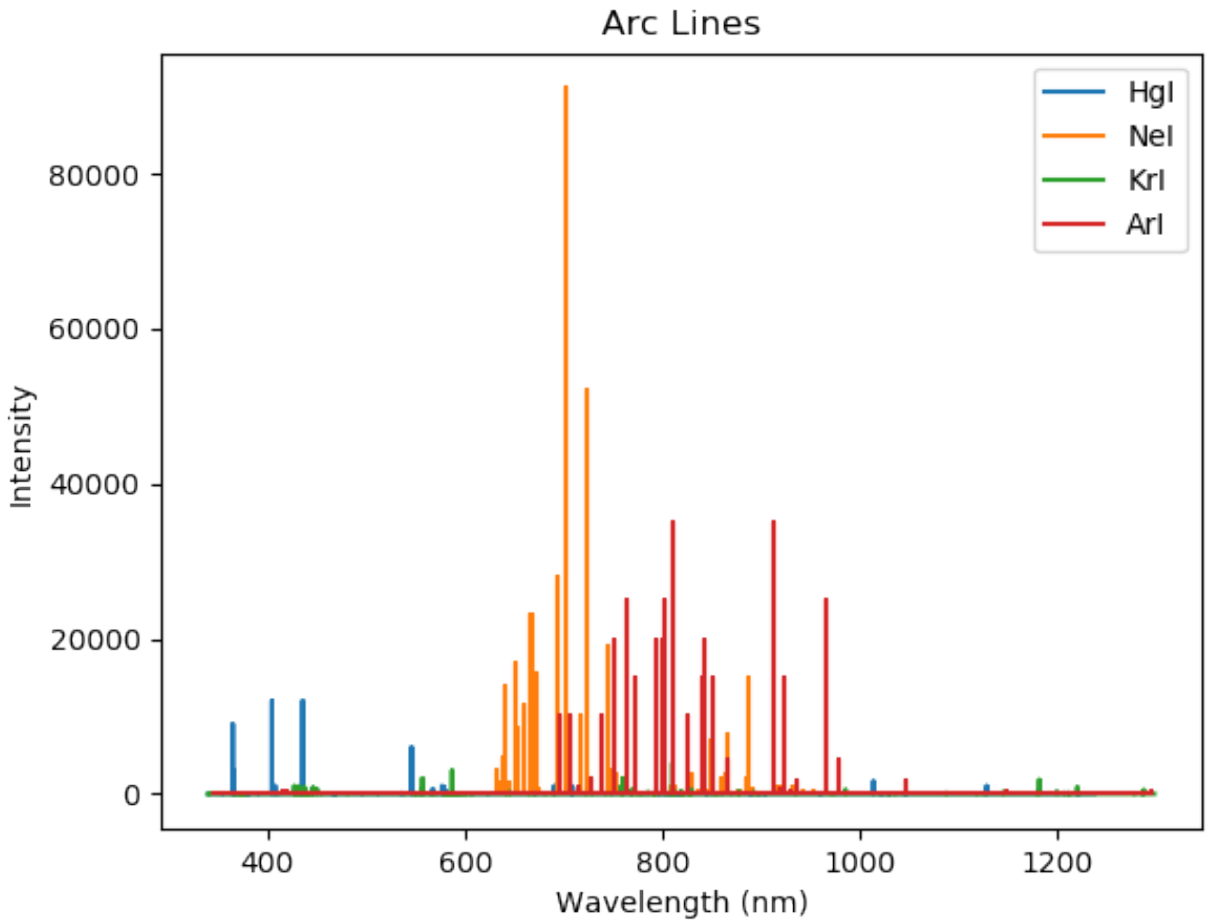
Wavelength Solutions

I plotted all these spectra with the x-axis in pixels; how to I convert them to wavelengths?

Wavelength Solutions

I plotted all these spectra with the x-axis in pixels; how to I convert them to wavelengths?

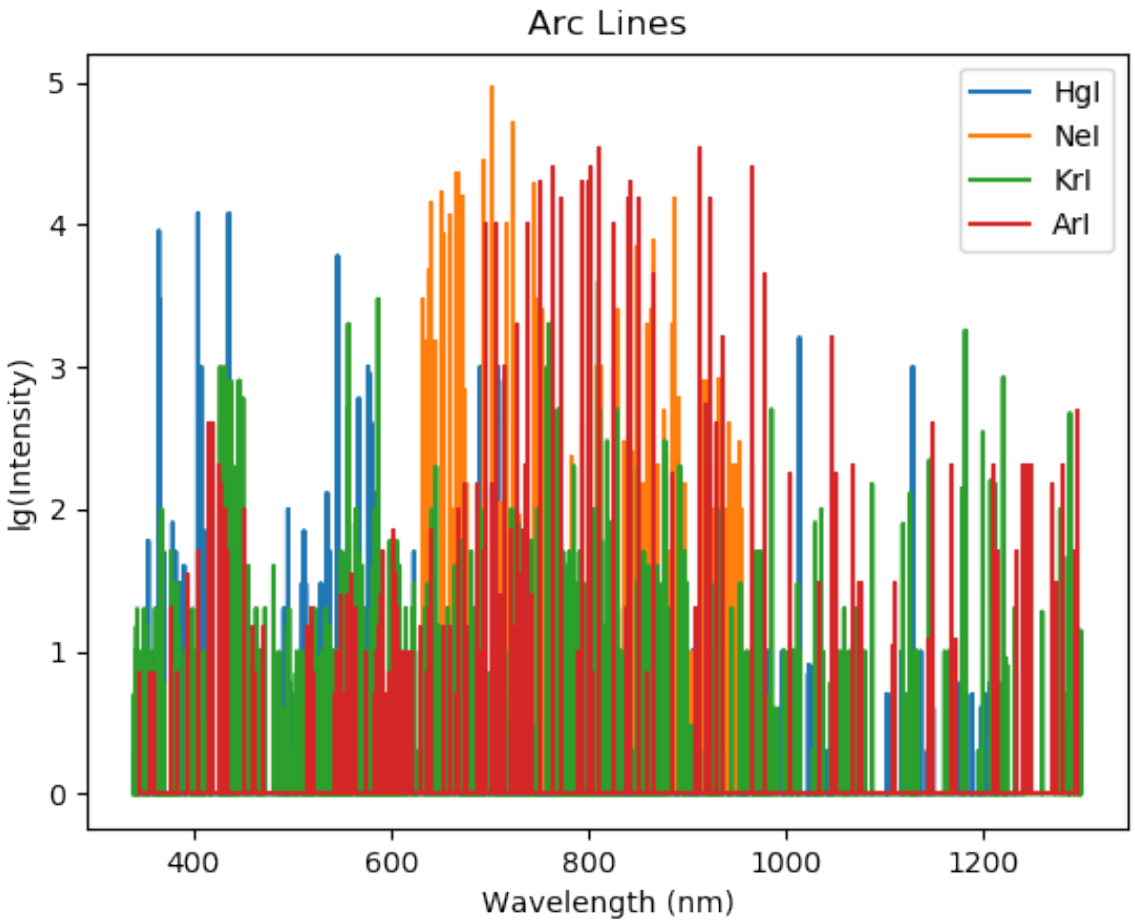
The solution is to illuminate the spectrograph with an arc emission lamp.



Wavelength Solutions

I plotted all these spectra with the x-axis in pixels; how to I convert them to wavelengths?

The solution is to illuminate the spectrograph with an arc emission lamp.



Wavelength Solutions

I plotted all these spectra with the x-axis in pixels; how to I convert them to wavelengths?
The solution is to illuminate the spectrograph with an arc emission lamp. Popular elements include

- He
- Ne
- Ar
- Kr
- Xe
- Hg + Cd

Wavelength Solutions

I plotted all these spectra with the x-axis in pixels; how to I convert them to wavelengths?
The solution is to illuminate the spectrograph with an arc emission lamp. Popular elements include

- He
- Ne
- Ar
- Kr
- Xe
- Hg + Cd

For high-accuracy radial velocity spectrographs *laser combs* are becoming popular.

Wavelength Solutions

I plotted all these spectra with the x-axis in pixels; how to I convert them to wavelengths?
The solution is to illuminate the spectrograph with an arc emission lamp. Popular elements include

- He
- Ne
- Ar
- Kr
- Xe
- Hg + Cd

For high-accuracy radial velocity spectrographs *laser combs* are becoming popular.

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

Polynomials

You might hope that

$$\lambda(x) = a_0 + a_1 x$$

Polynomials

You might hope that

$$\lambda(x) = a_0 + a_1 x$$

but you're likely to be disappointed.

Polynomials

You might hope that

$$\lambda(x) = a_0 + a_1 x$$

but you're likely to be disappointed.
You might think, "Easy! I'll go to higher order:"

$$\lambda(x) = \sum_{r=0}^{n-1} a_r x^r$$

but you're likely to be unhappy.

Polynomials

You might hope that

$$\lambda(x) = a_0 + a_1 x$$

but you're likely to be disappointed.
You might think, "Easy! I'll go to higher order:"

$$\lambda(x) = \sum_{r=0}^{n-1} a_r x^r$$

but you're likely to be unhappy.

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 $x \in [-1, 1]$:

$$T_0(x) = 1$$
$$T_1(x) = x$$
$$T_2(x) = 2x^2 - 1$$
$$T_3(x) = 4x^3 - 3x$$
$$T_4(x) = 8x^4 - 8x^2 + 1$$

Chebyshev Polynomials

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

$$T_0(x) = 1$$
$$T_1(x) = x$$
$$T_2(x) = 2x^2 - 1$$
$$T_3(x) = 4x^3 - 3x$$
$$T_4(x) = 8x^4 - 8x^2 + 1$$

In general,

$$T_n(x) = \cos(n \arccos(x))$$

so $-1 \leq T_n(x) \leq 1$

Chebyshev Polynomials

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

$$T_0(x) = 1$$
$$T_1(x) = x$$
$$T_2(x) = 2x^2 - 1$$
$$T_3(x) = 4x^3 - 3x$$
$$T_4(x) = 8x^4 - 8x^2 + 1$$

In general,

$$T_n(x) = \cos(n \arccos(x))$$

so $-1 \leq T_n(x) \leq 1$ and

$$\lambda(x) = \sum_{r=0}^{n-1} a_r T_r(x)$$

is bounded by

$$\lambda(x) = \sum_{r=0}^{n-1} |a_r|$$

Chebyshev Polynomials

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

$$T_0(x) = 1$$
$$T_1(x) = x$$
$$T_2(x) = 2x^2 - 1$$
$$T_3(x) = 4x^3 - 3x$$
$$T_4(x) = 8x^4 - 8x^2 + 1$$

In general,

$$T_n(x) = \cos(n \arccos(x))$$

so $-1 \leq T_n(x) \leq 1$ and

$$\lambda(x) = \sum_{r=0}^{n-1} a_r T_r(x)$$

is bounded by

$$\lambda(x) = \sum_{r=0}^{n-1} |a_r|$$

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

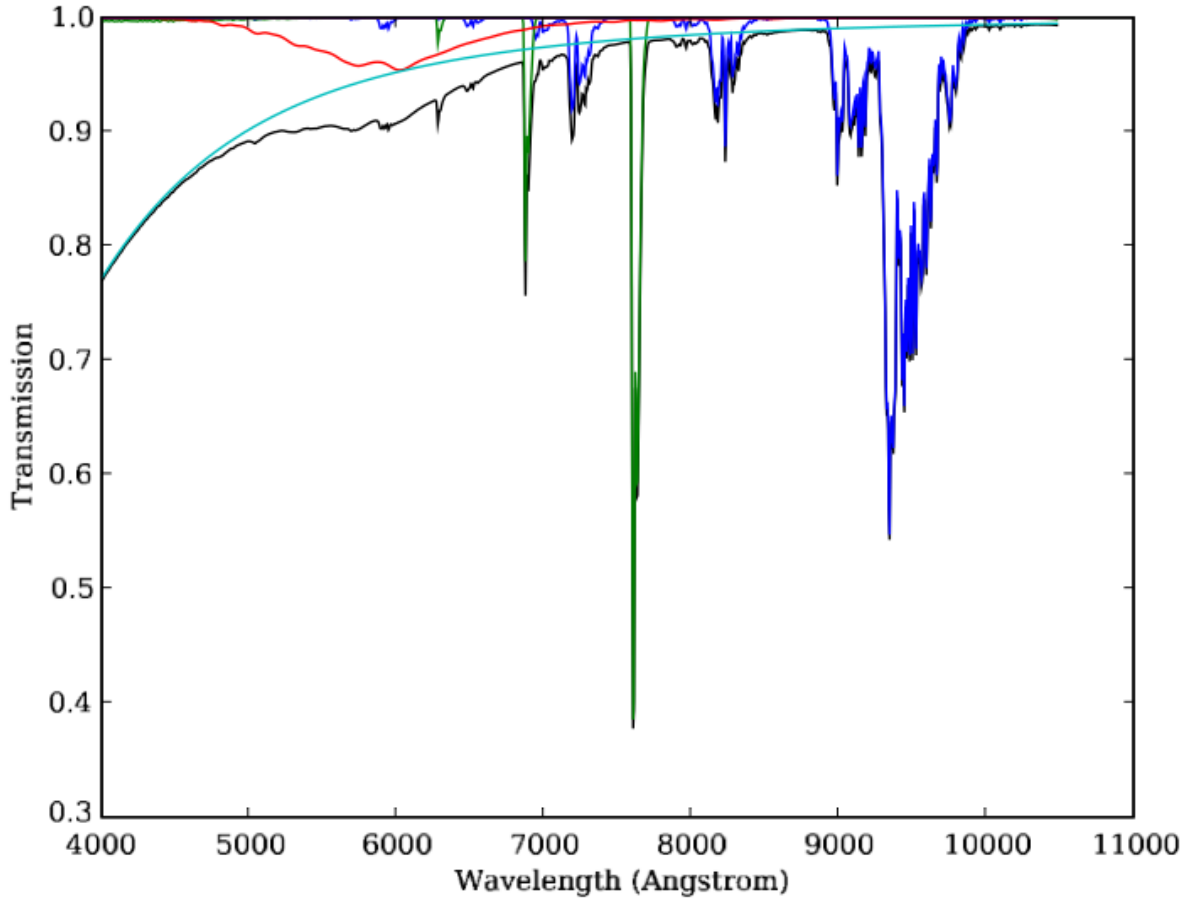
Scattering and absorption both remove light from the target:

- Gray: Clouds
- Chromatic: Aerosols (τ, n), O_3, O_2, H_2O

The Atmosphere

Scattering and absorption both remove light from the target:

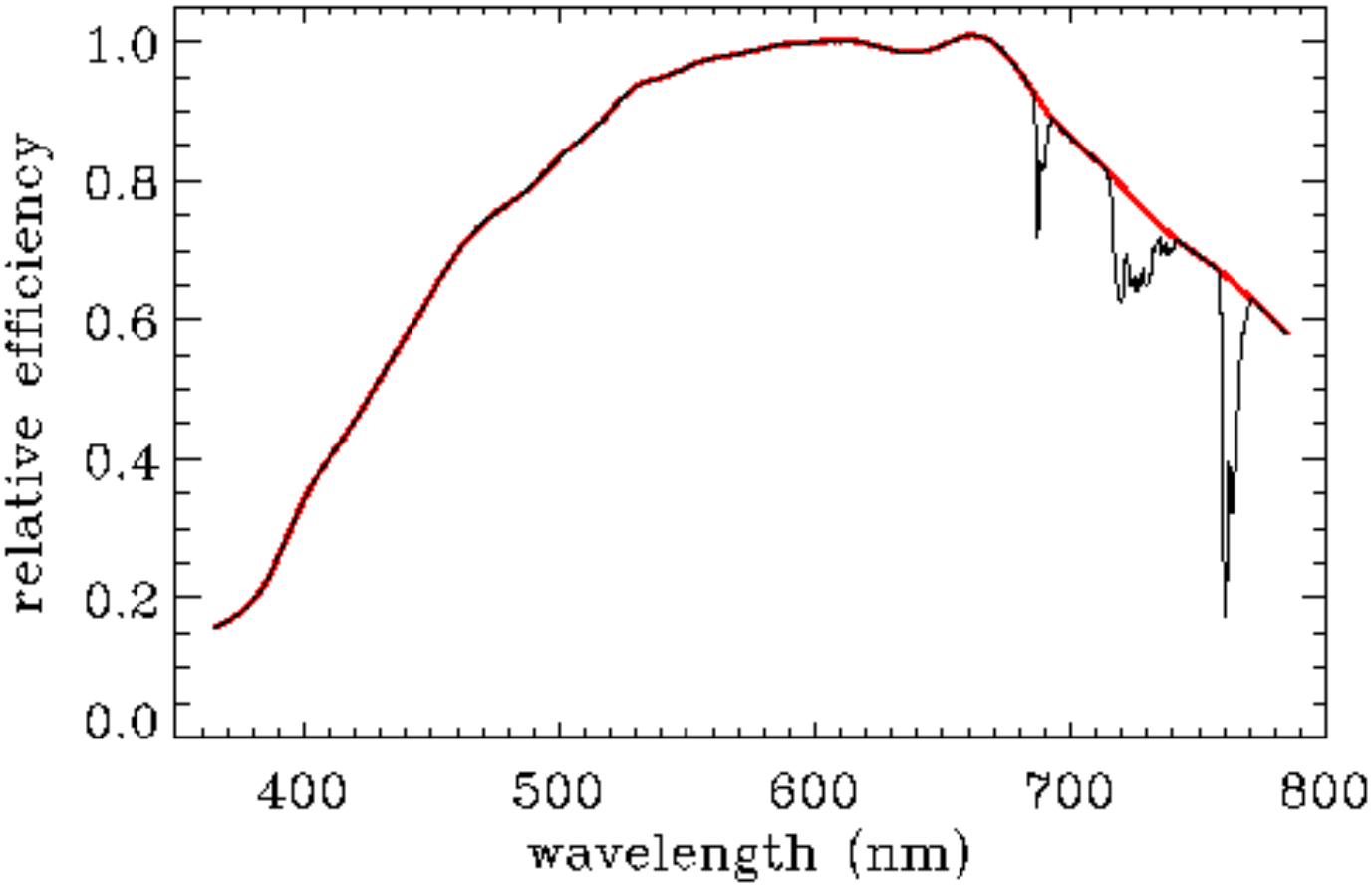
- Gray: Clouds
- Chromatic: Aerosols (τ, n), O_3, O_2, H_2O



The Atmosphere

Scattering and absorption both remove light from the target:

- Gray: Clouds
- Chromatic: Aerosols (τ, n), O_3, O_2, H_2O



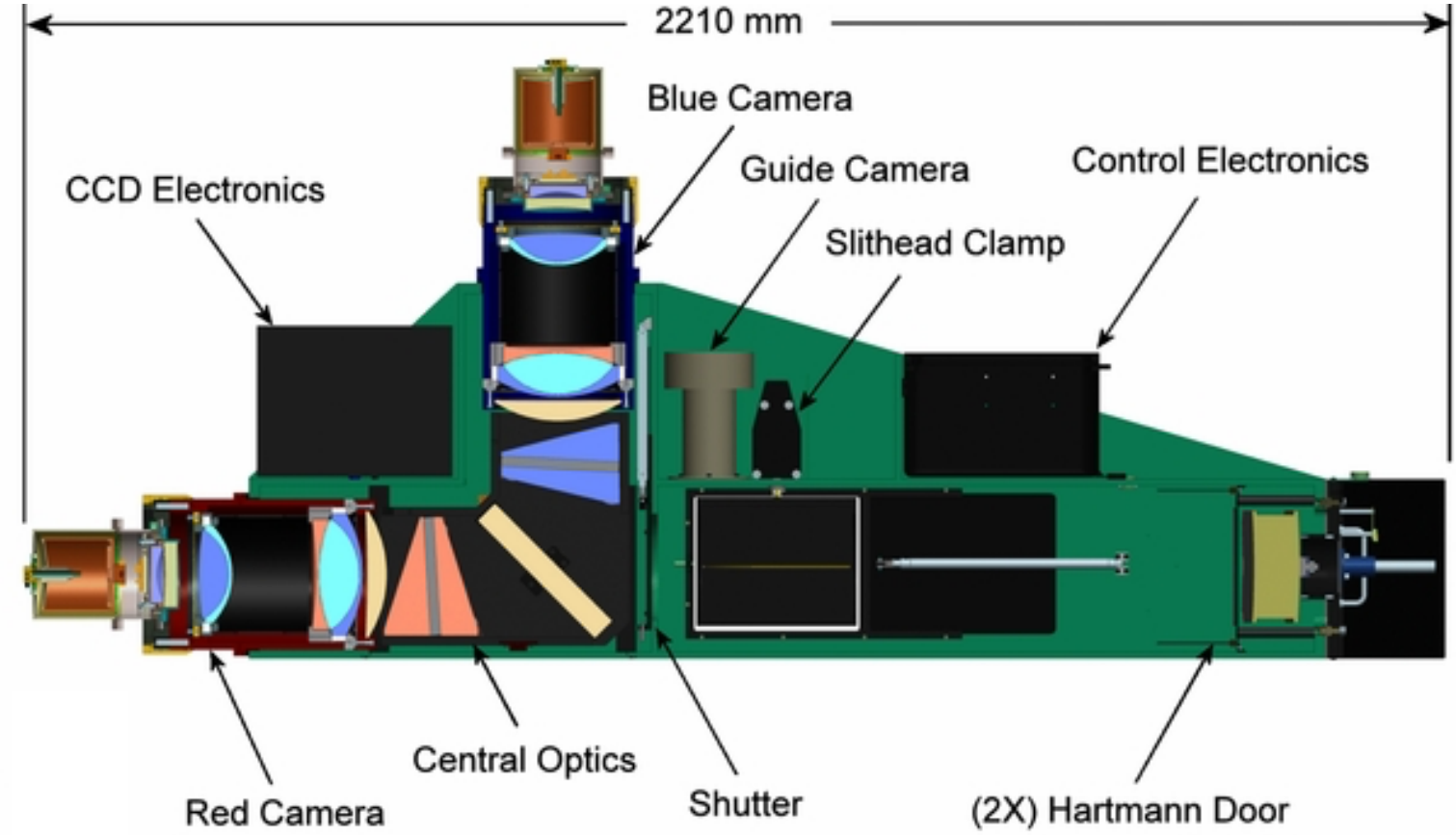
Credit: 2DF Survey

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*.

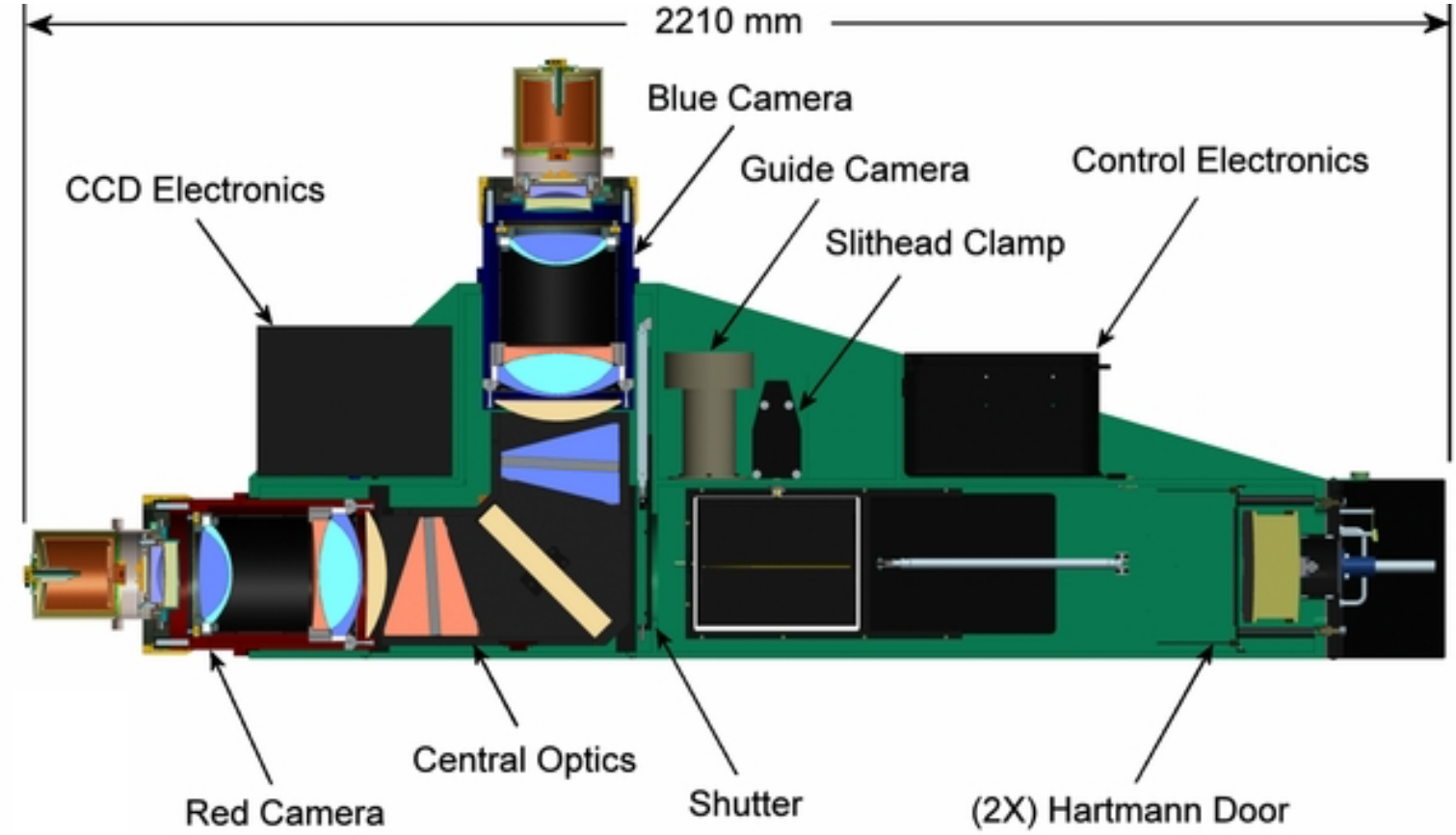
Multi-arm Spectrographs

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*.
For example, the SDSS spectrographs use one dichroic and two cameras:



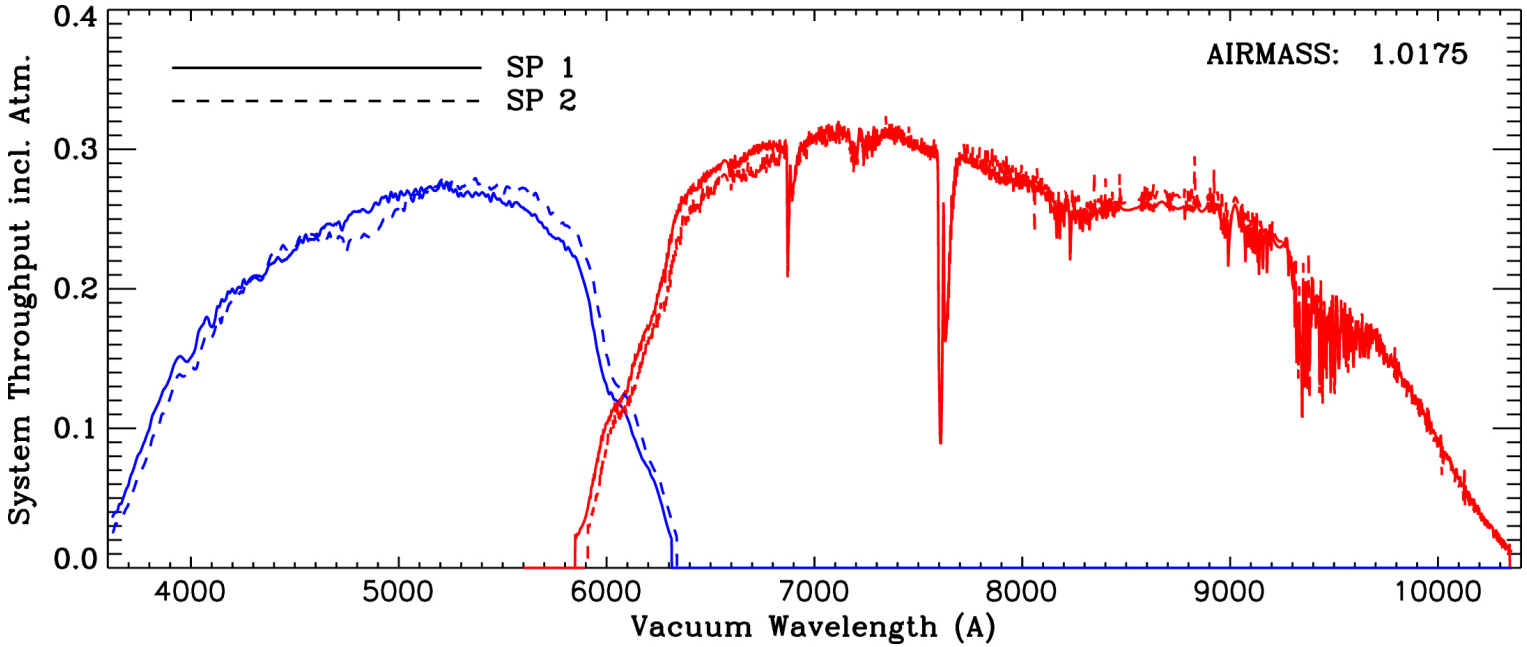
Multi-arm Spectrographs

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*.
For example, the SDSS spectrographs use one dichroic and two cameras:



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

Photometric Calibration



An SDSS Spectrograph

Spectro-Photometric Standards

The solution is to observe objects of known spectrum; ideally

- with a smooth well-known spectrum
- bright
- near your science target

Spectro-Photometric Standards

The solution is to observe objects of known spectrum; ideally

- with a smooth well-known spectrum
- bright
- near your science target

One popular candidate is low-metallicity F subdwarfs.

Spectro-Photometric Standards

The solution is to observe objects of known spectrum; ideally

- with a smooth well-known spectrum
- bright
- near your science target

One popular candidate is low-metallicity F subdwarfs. We fit or model the spectrum (metallicity, gravity, velocity) and *divide* it into our data.

Spectro-Photometric Standards

The solution is to observe objects of known spectrum; ideally

- with a smooth well-known spectrum
- bright
- near your science target

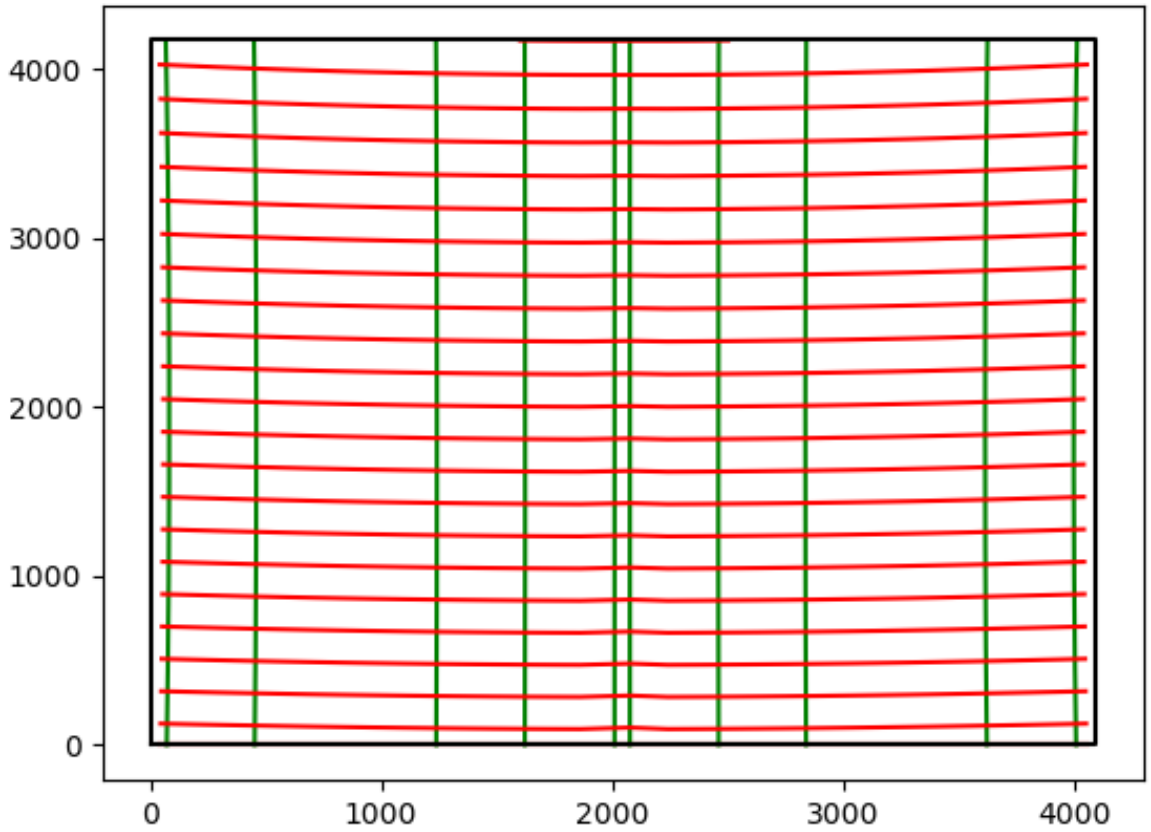
One popular candidate is low-metallicity F subdwarfs. We fit or model the spectrum (metallicity, gravity, velocity) and *divide* it into our data.
Objects at a variety of redshifts with known spectra (*e.g.* Luminous Red Galaxies) provide a way to check for features in our spectro-photometric standards that we failed to fit/model.

Real Fibre Spectrographs

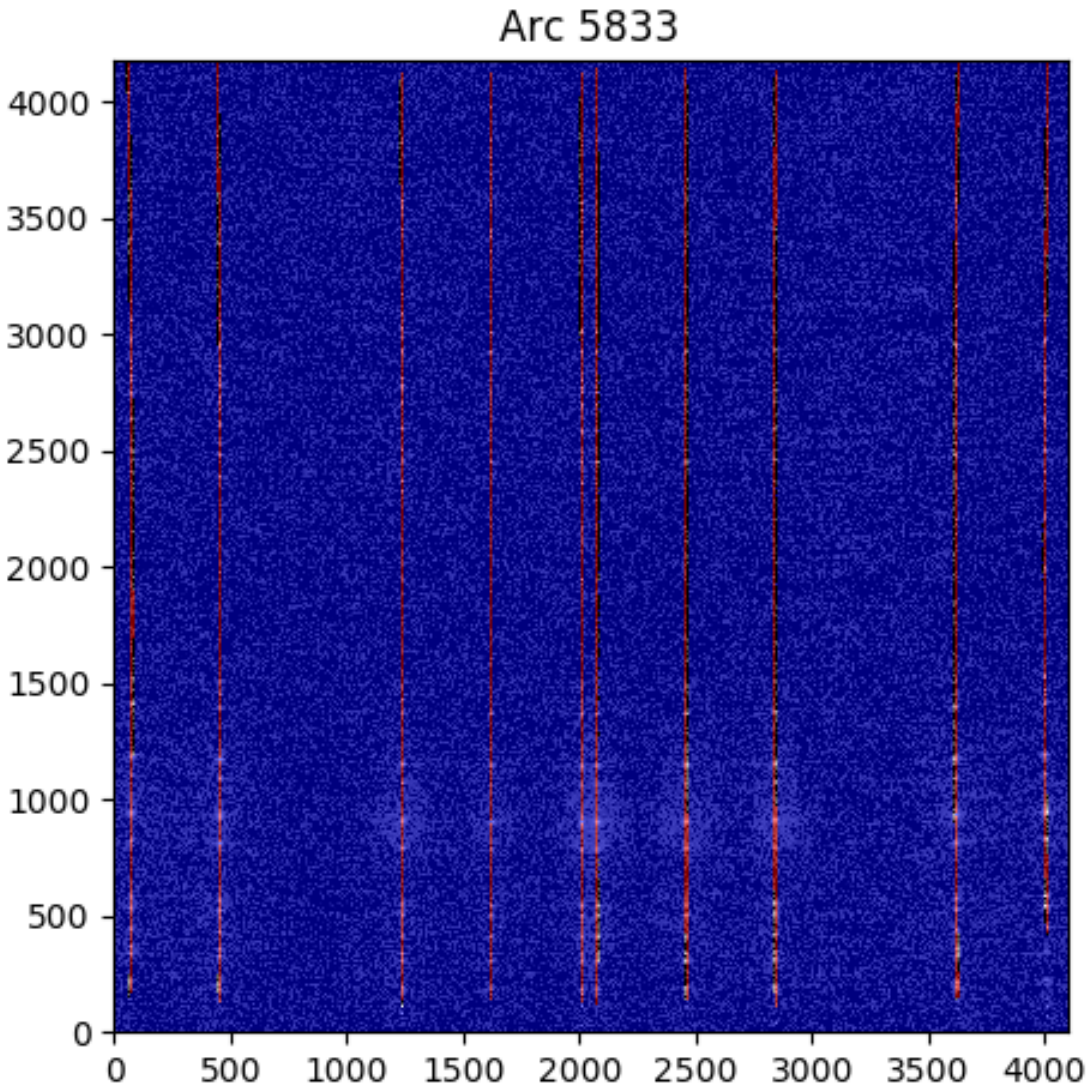
In the real world fibre spectra don't lie nicely up-and-down the chip, and sky lines don't run along rows of the CCD.

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.
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),

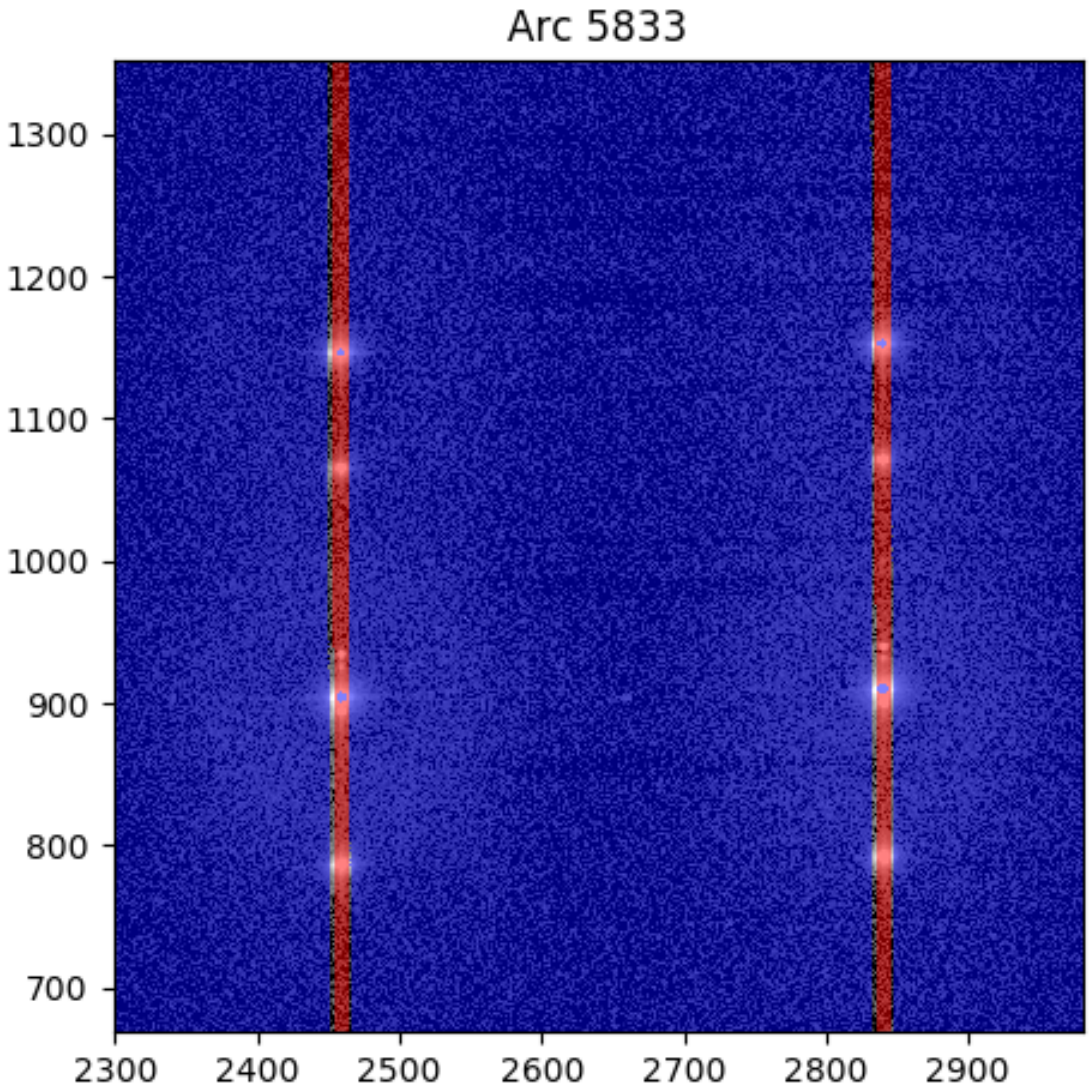


What does the data look like?



Ne arc

What does the data look like?



Ne arc

Summary

What have we achieved?

Summary

What have we achieved? We've

- Extracted the spectra from the 2-D image
- Subtracted the sky
- Put the spectrum on an absolute wavelength scale
- Calibrated the spectrum relative to standard stars

Summary

What have we achieved? We've

- Extracted the spectra from the 2-D image
- Subtracted the sky
- Put the spectrum on an absolute wavelength scale
- 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*)

Summary

What have we achieved? We've

- Extracted the spectra from the 2-D image
- Subtracted the sky
- Put the spectrum on an absolute wavelength scale
- 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
  - …