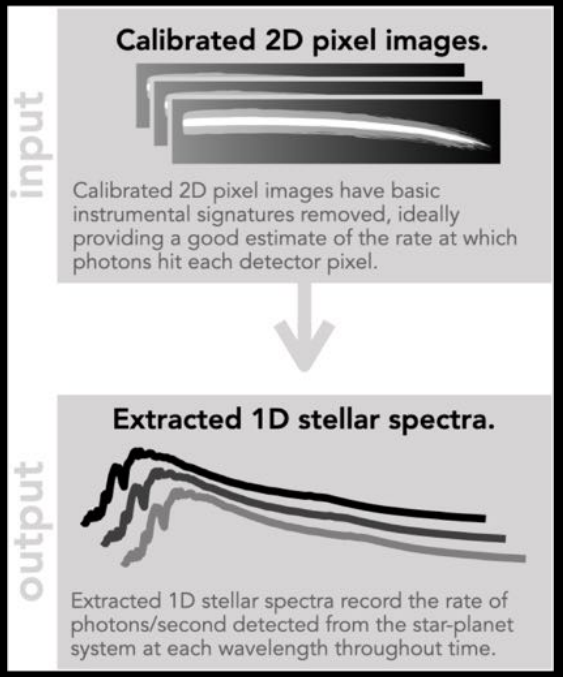
Pixels to spectra

Nicolas Crouzet, Laura Kreidberg

& the ERS Hackathon Team



Outline

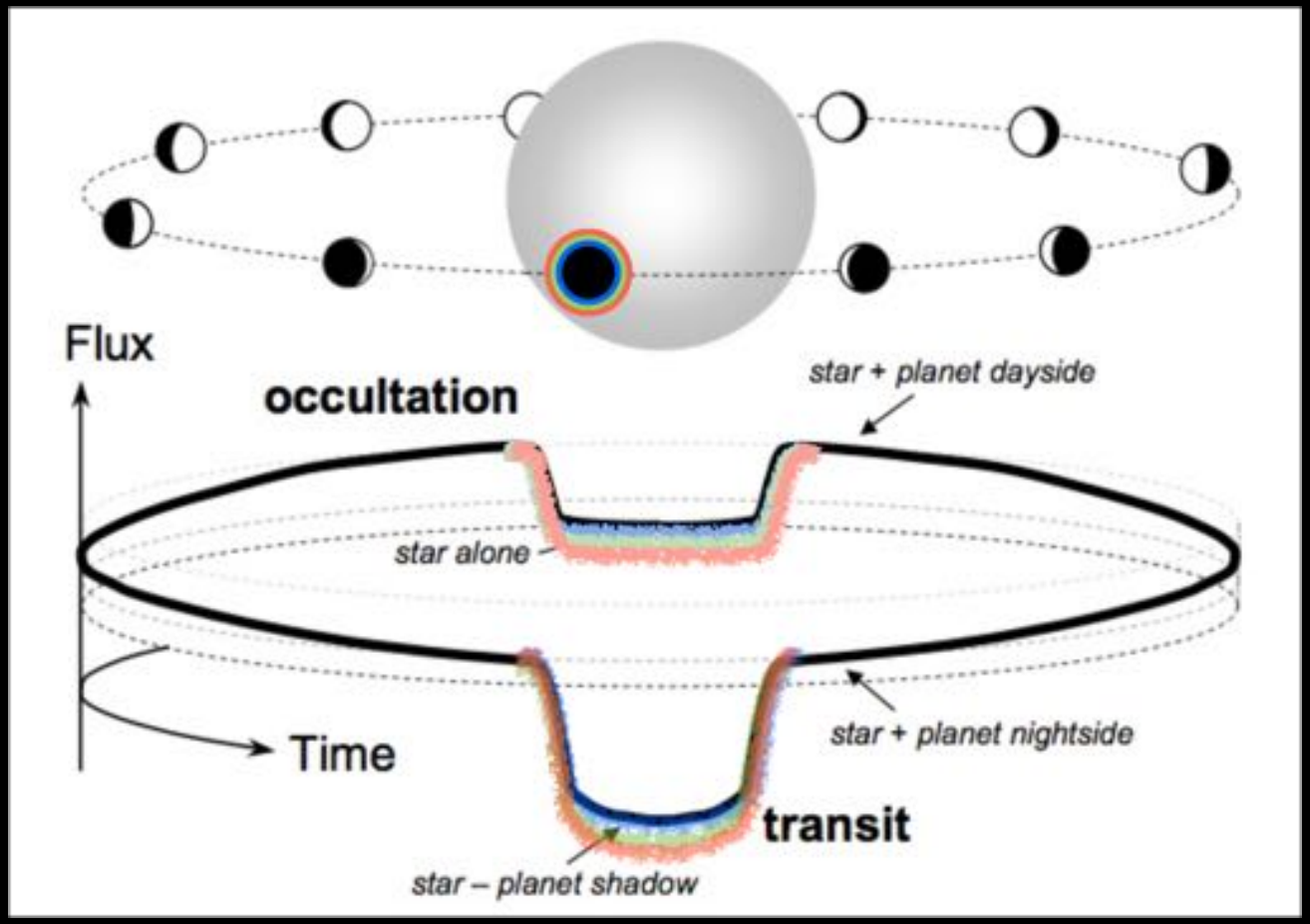
- Pixel to spectra: main steps
- Most common corrections

Outline

- Pixel to spectra: main steps
- Most common corrections

Transit spectroscopy

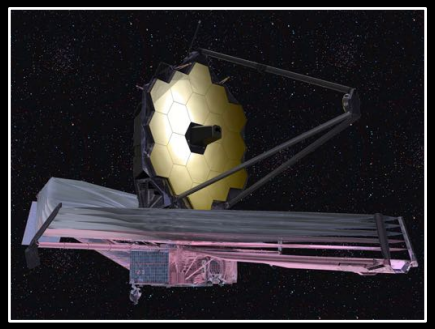
➡ **Measure the transit depth as a function of wavelength**



From Winn 2010, adapted by X. Bonfils

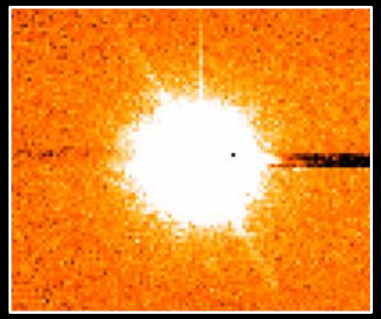
From observations to images

A telescope



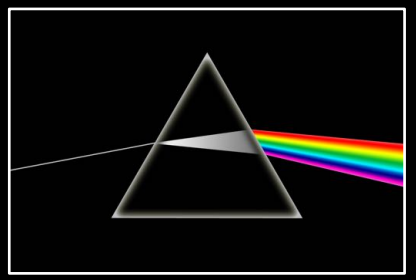
JWST

Image of a star



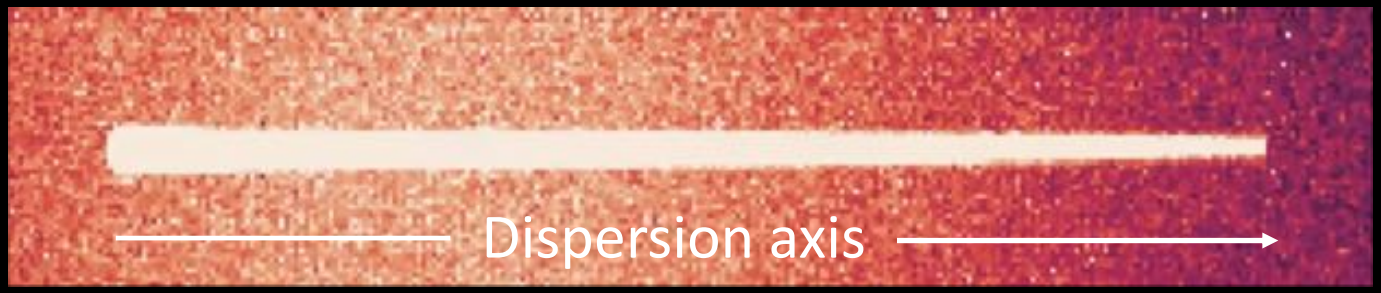
Spread over many pixels

Dispersive element



Inside *JWST* instruments

*



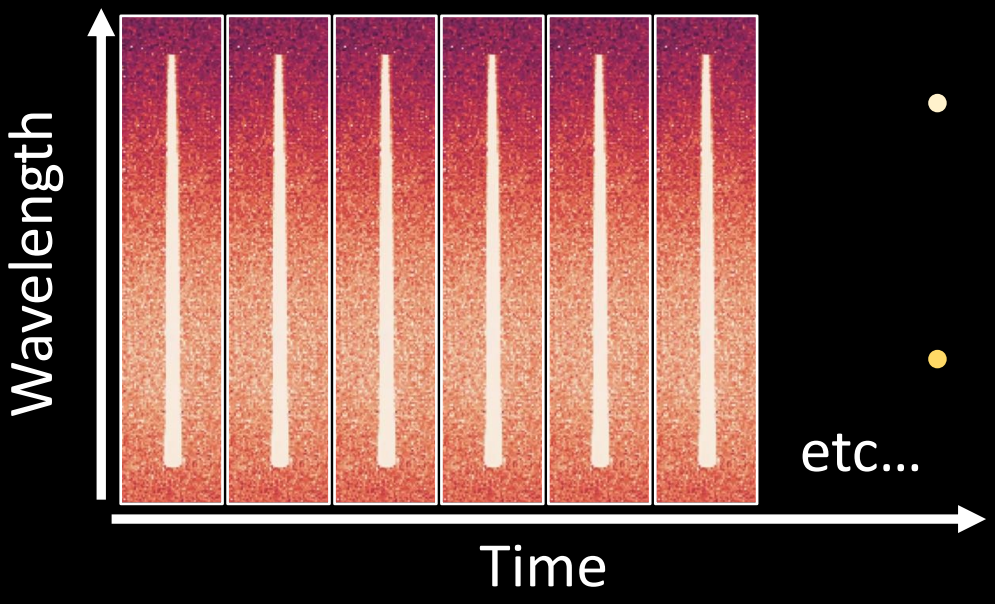
Spectral trace: Star image dispersed in wavelength

* Par Vilisvir — Travail personnel, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=22087094

A series of integrations

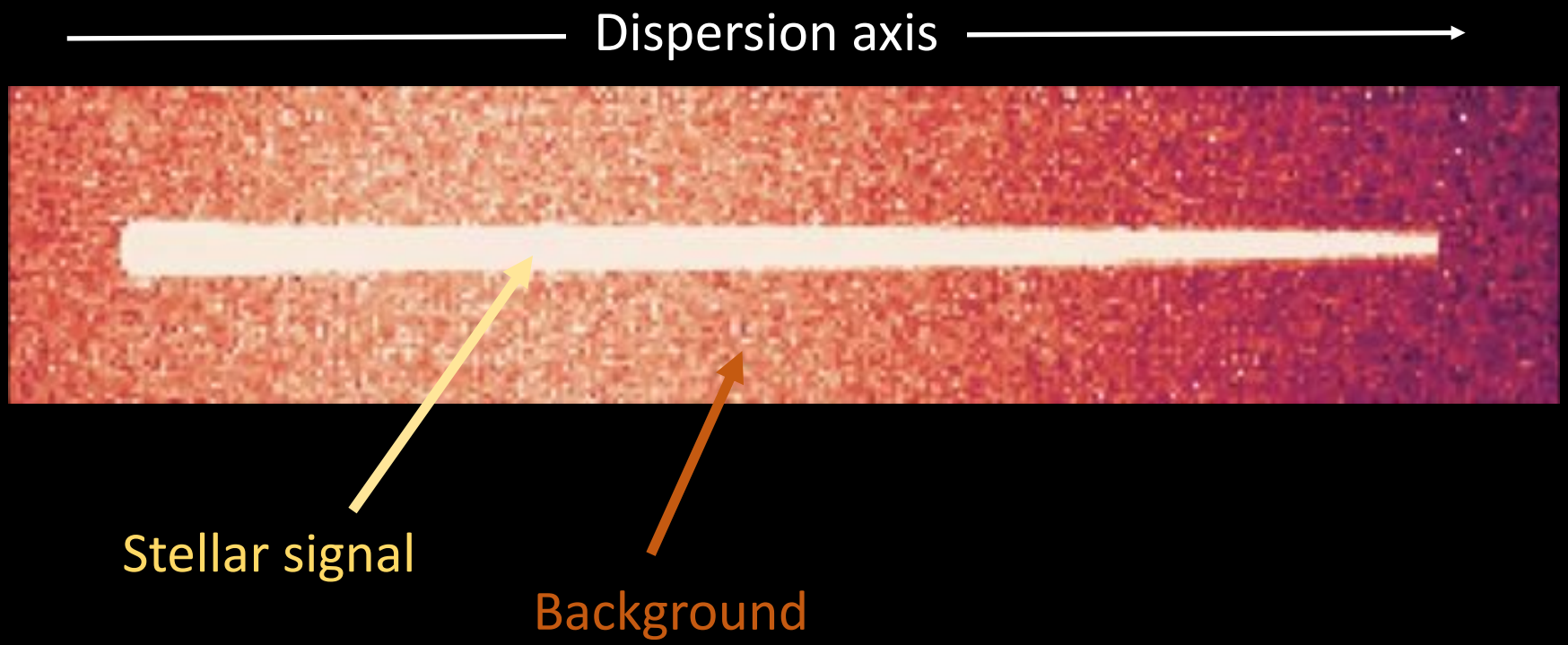
- We want to observe a transit in spectroscopy
- We need to monitor a star for several hours
- Each integration has a finite integration time (seconds to minutes)

➡ **Time-series observations** (TSO)

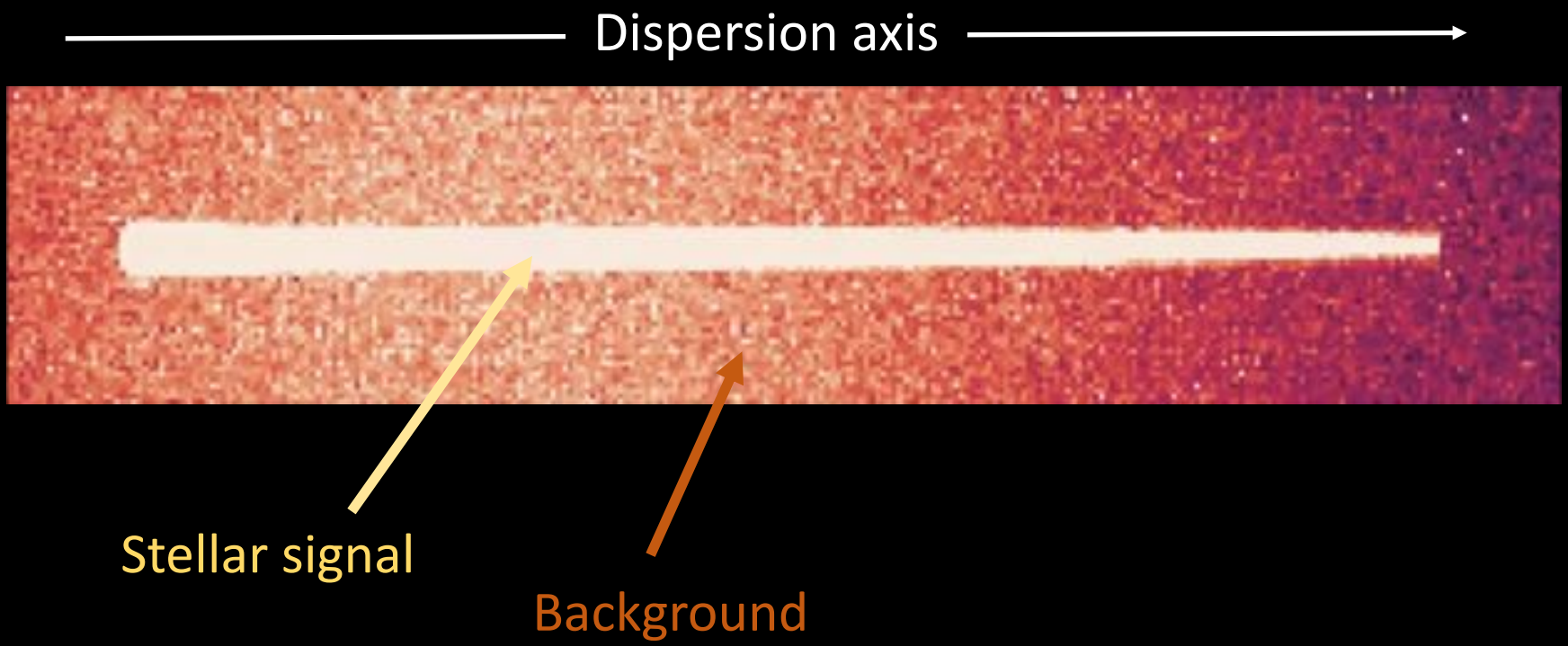


- **A series of integrations of the target's spectral trace**
- **Start point of our analysis**

Flux extraction



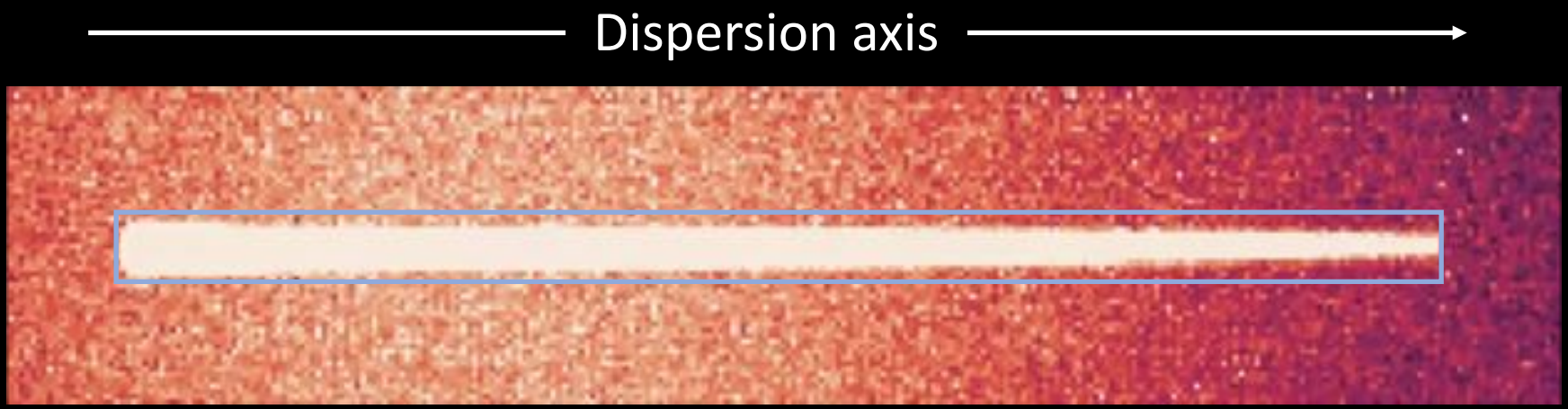
Flux extraction



➡ Sum the pixels containing stellar signal

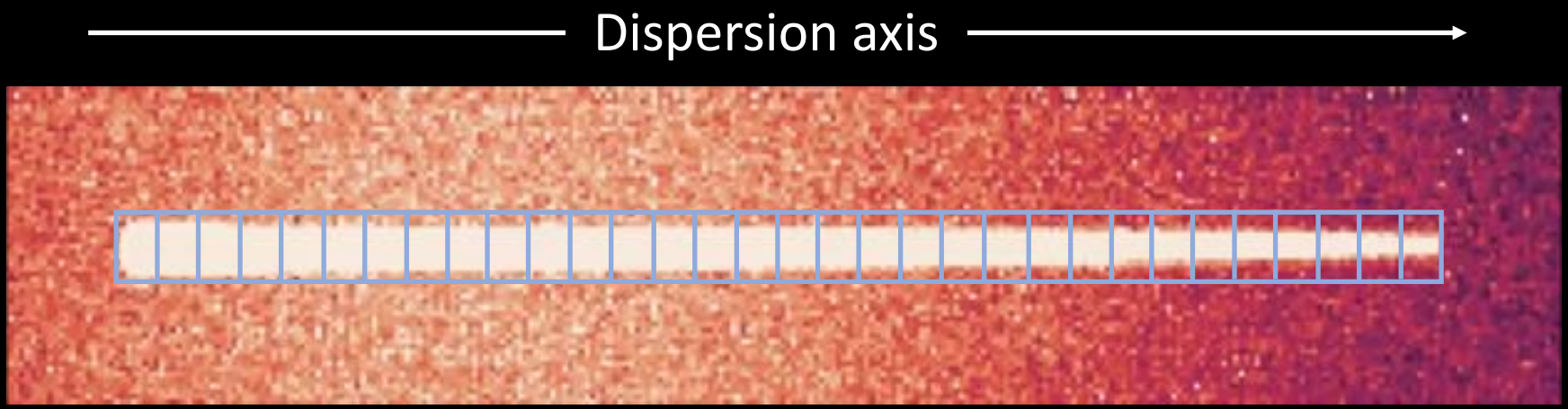
Where is the limit between the star and the background?

Flux extraction



➡ Define a box around the spectral trace ("whitelight")

Flux extraction



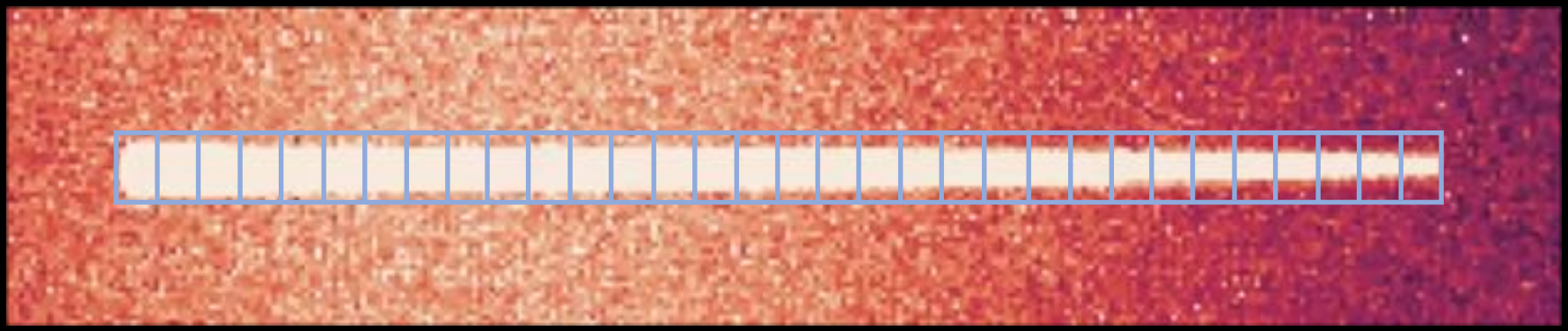
Define a box for each wavelength (“wavelength bins”)

Their size will set the resolution of the spectrum

➡ **Sum the pixels in each bin**

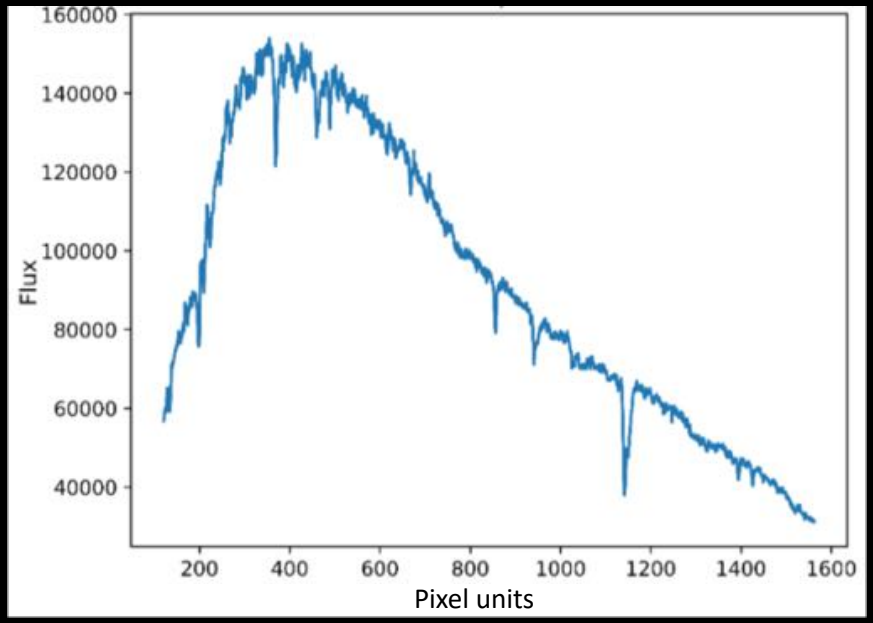
Flux extraction

Dispersion axis



On 1 image:

➡ Stellar spectrum



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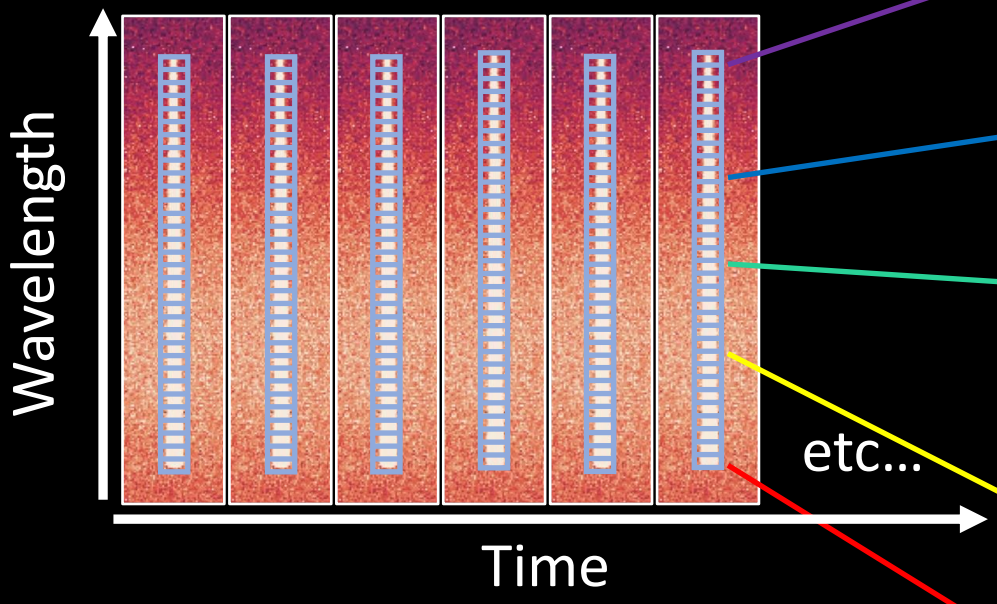
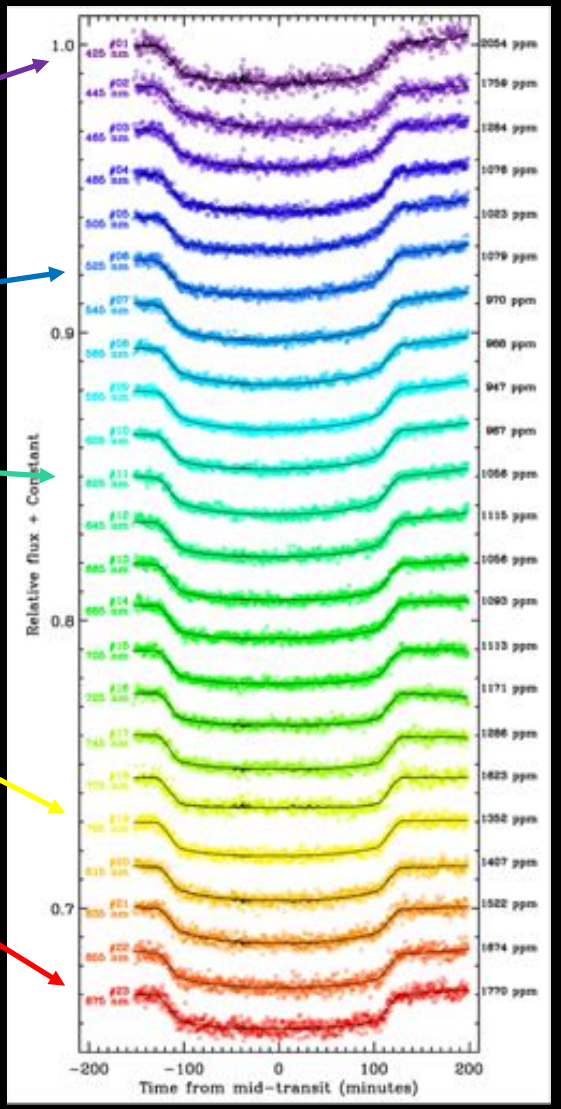
Spectroscopic lightcurves



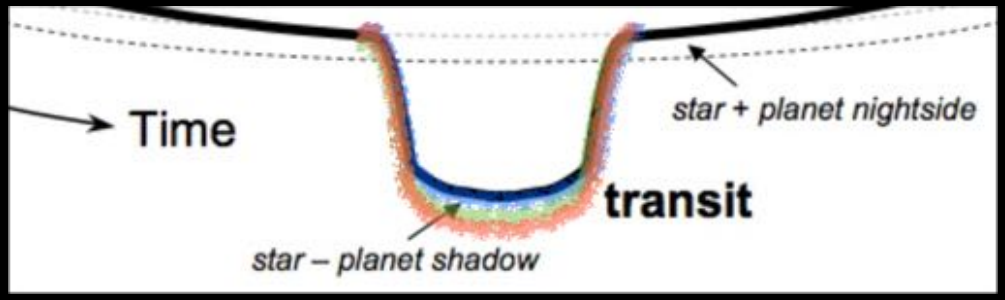


Palle et al. 2017

- Measure the flux in each bin as a function of time

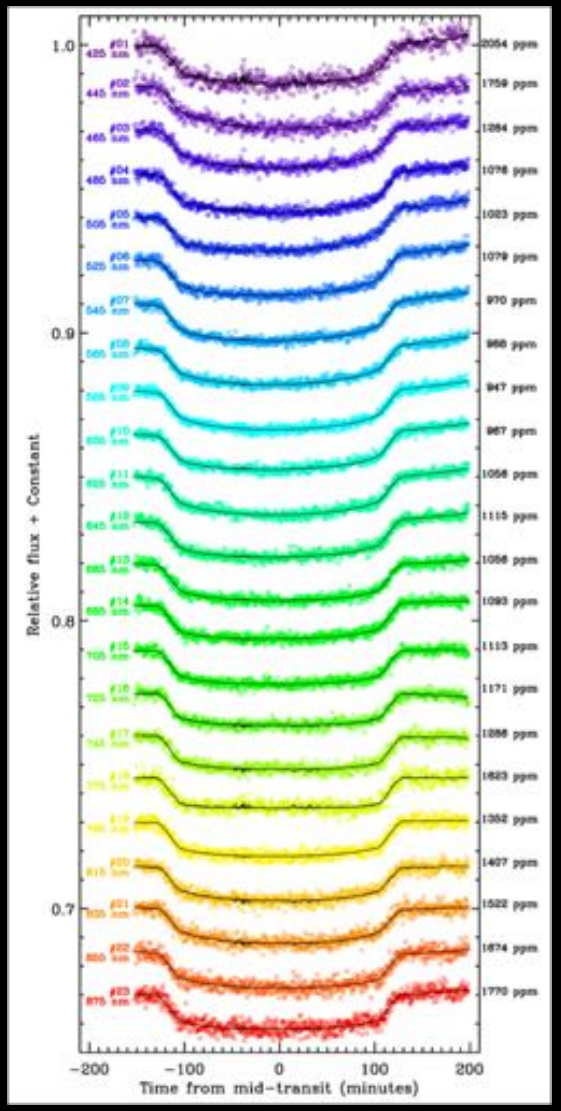
Transit depth

Atmospheric absorption changes the transit depth



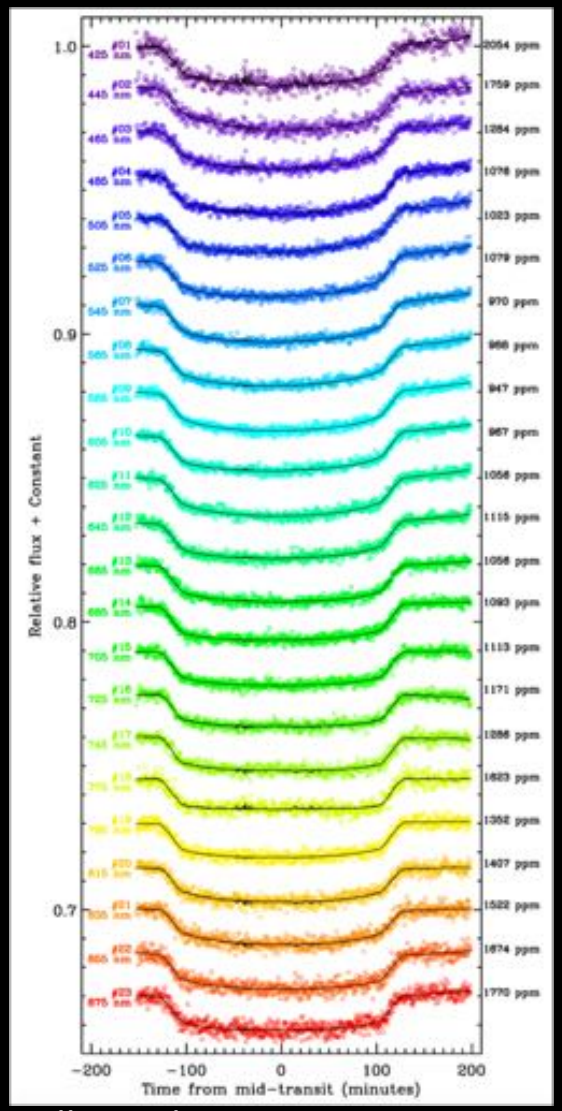
From Winn 2010, adapted by X. Bonfils

Measure the transit depth as a function of wavelength

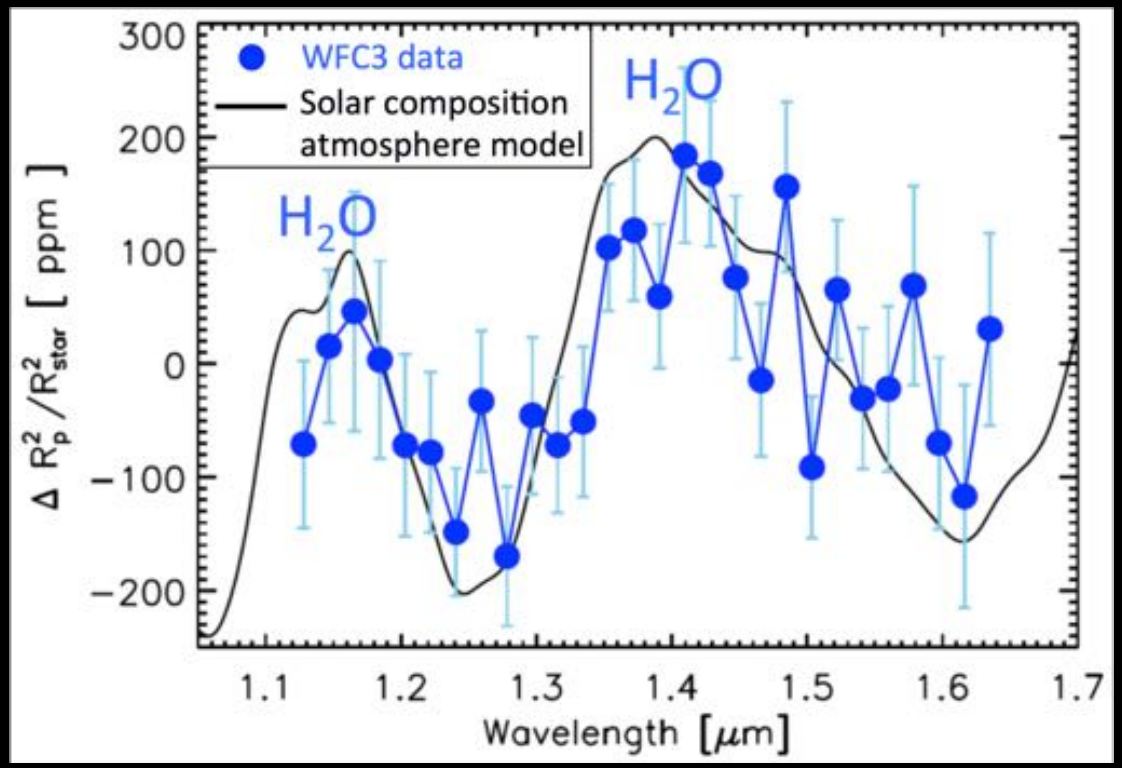


Palle et al. 2017

Absorption spectrum



Palle et al. 2017



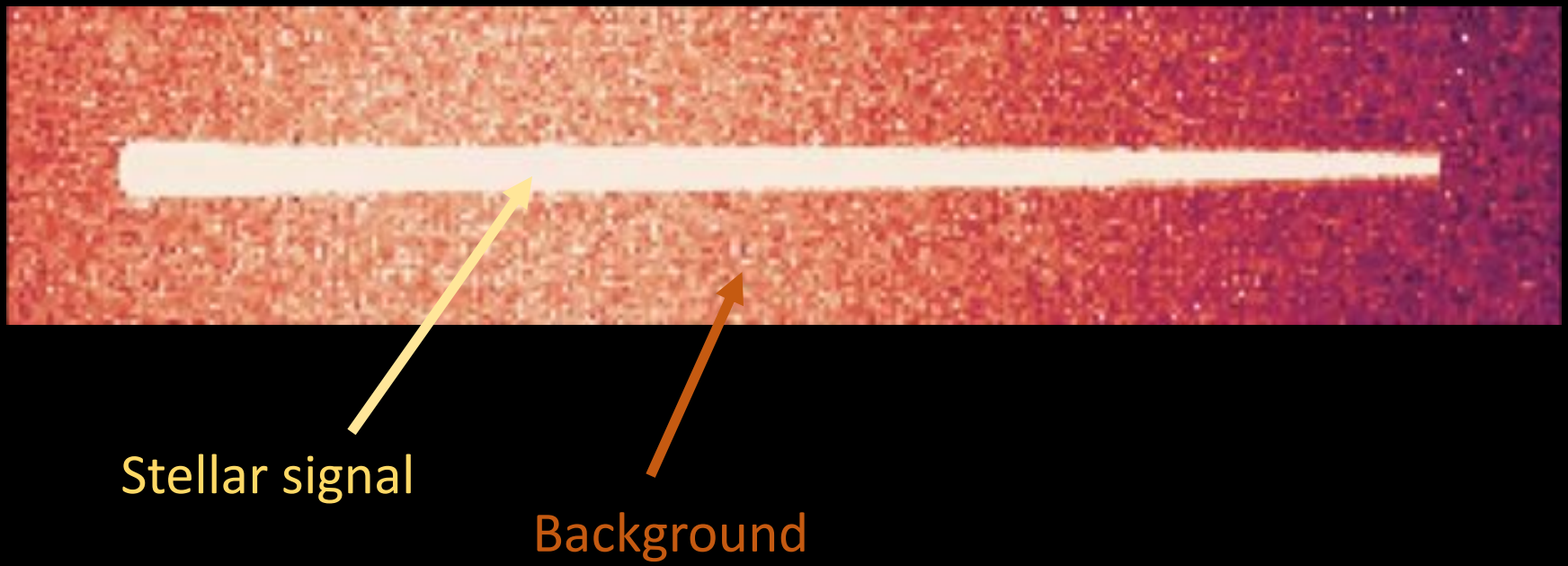
McCullough et al. 2014

⚠ Wavelengths do not match in this example

Outline

- Pixel to spectra: main steps
- Most common corrections

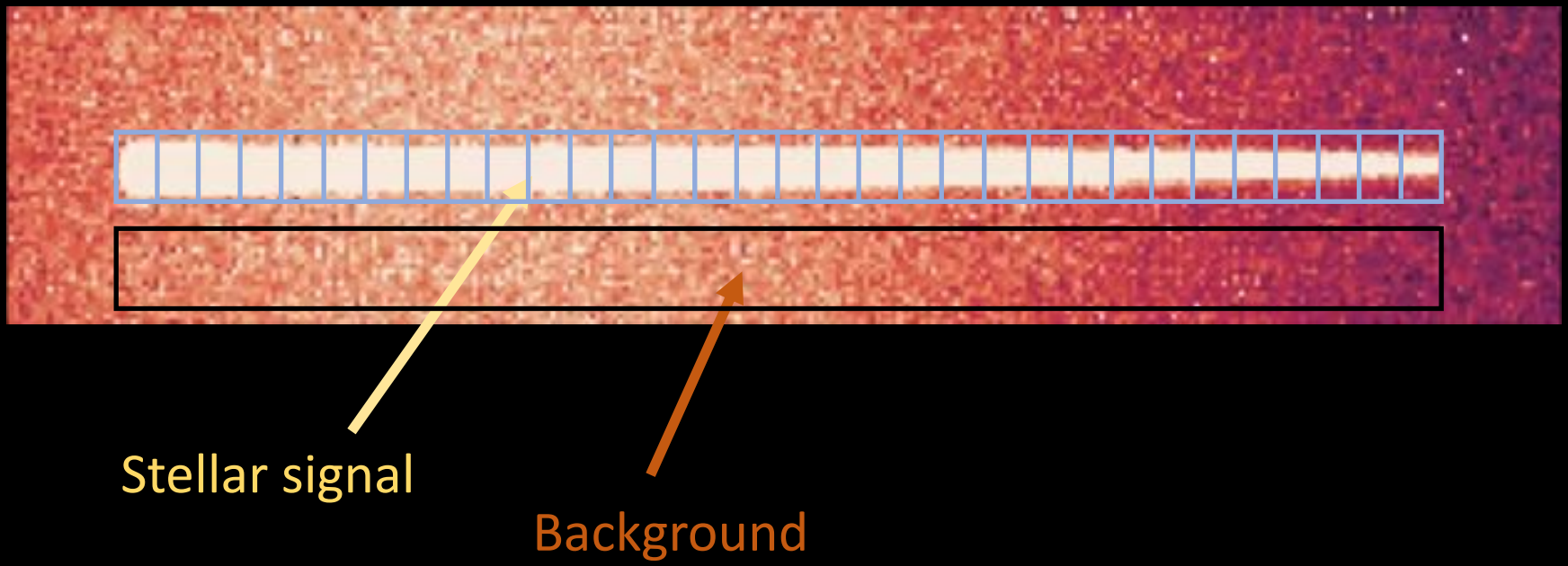
Background



We want to measure only the stellar flux

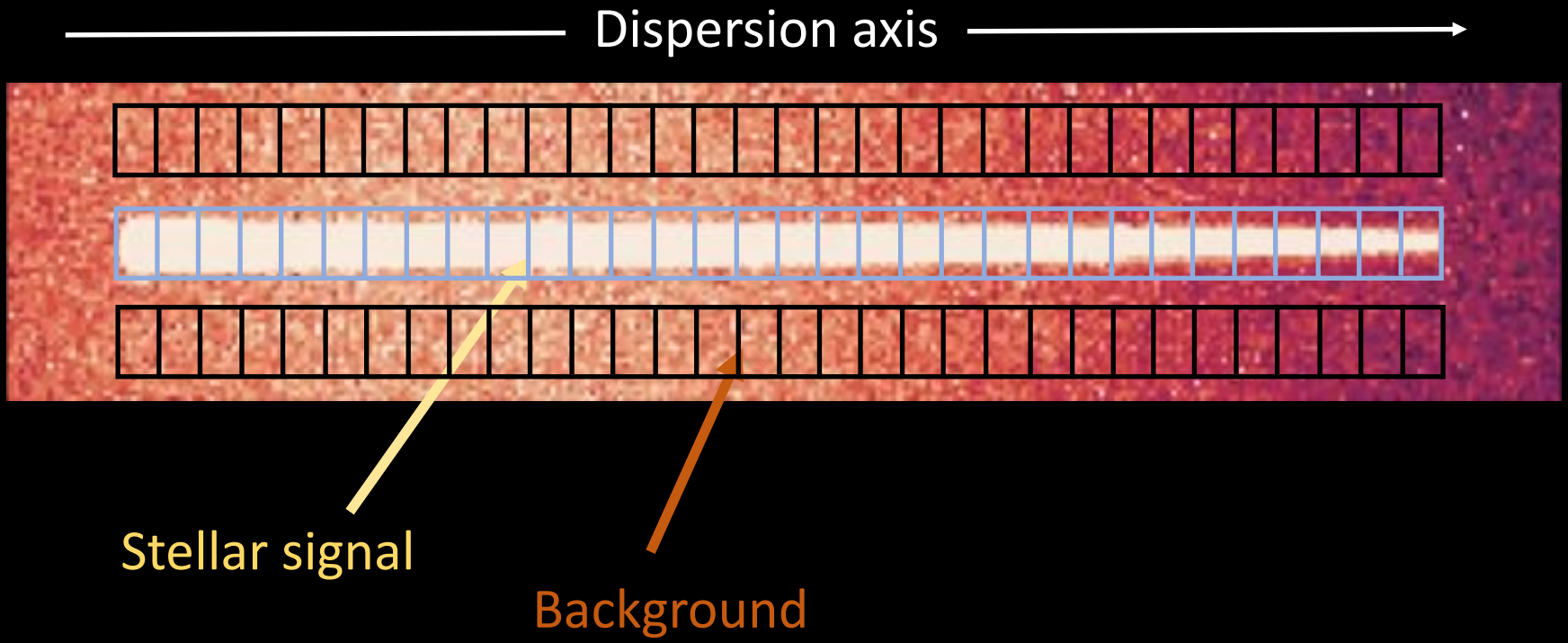
➡ We need to remove the background flux

Background



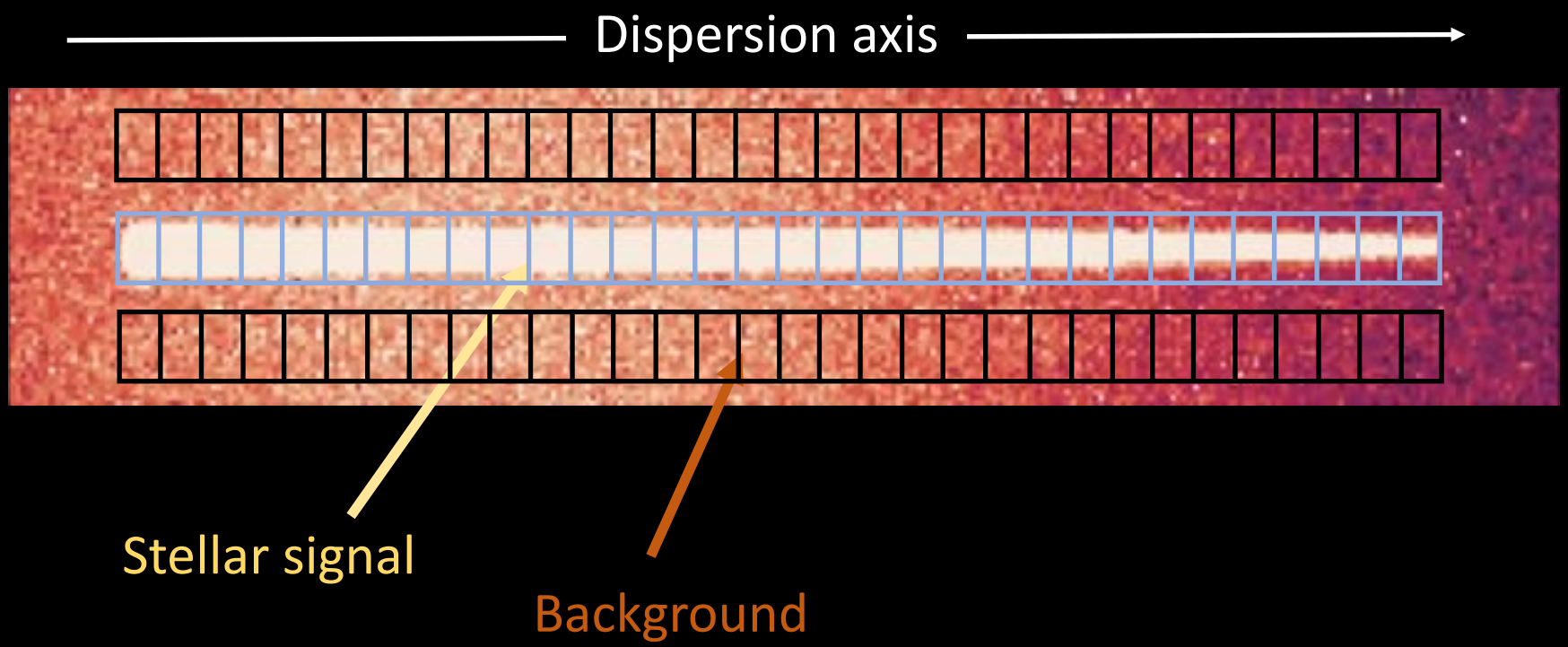
➡ Measure the background flux

Background



➡ Measure the background flux

Background



Subtract the background flux from the stellar flux

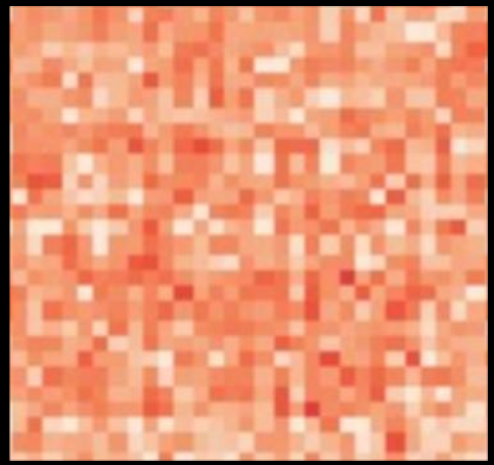
Flat-fielding

- Each pixel has a slightly different response
- Can be measured using "flat fields" (calibration images taken with a source that is uniform in intensity)

➡ **Calibration: Divide the image by a "flat-field"**

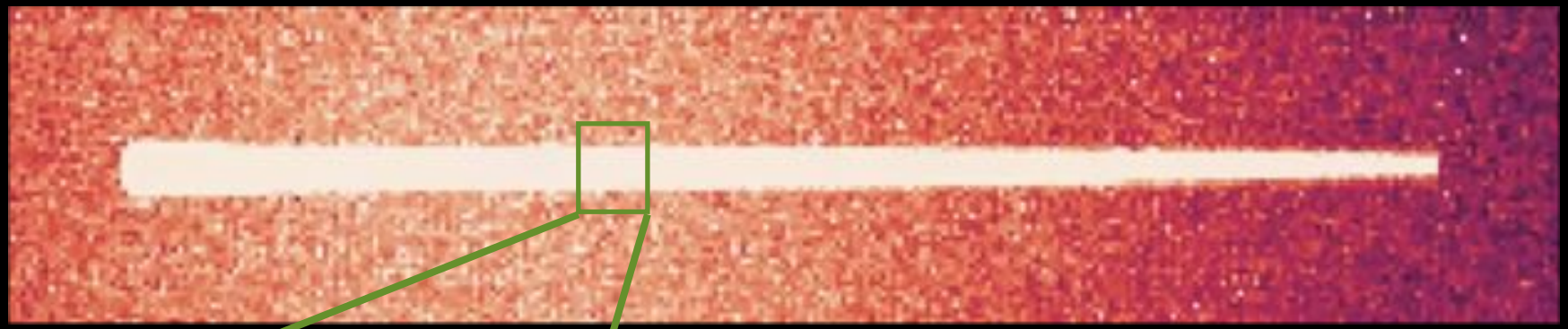
- The flat-field is wavelength dependent
- Might not be useful, might even add noise

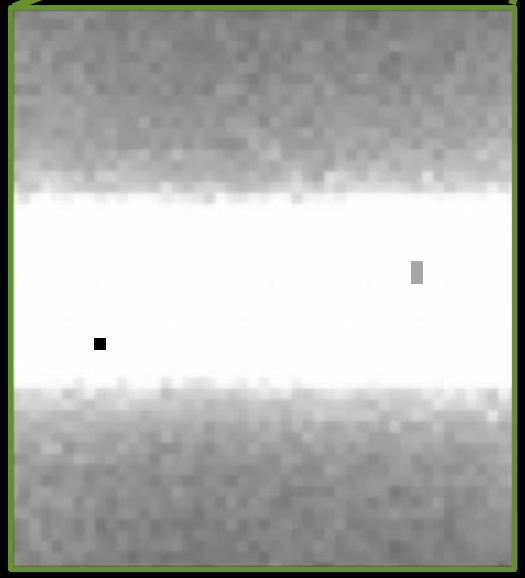
Illustration of a flat-field



Bad pixels

Dispersion axis

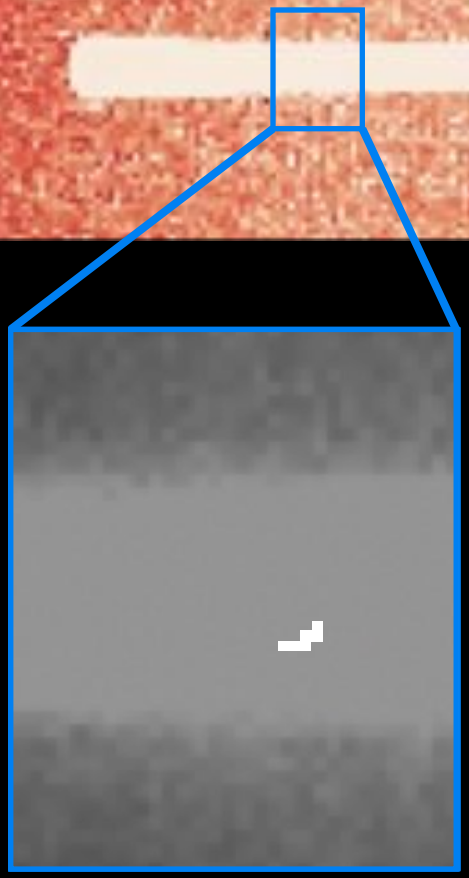




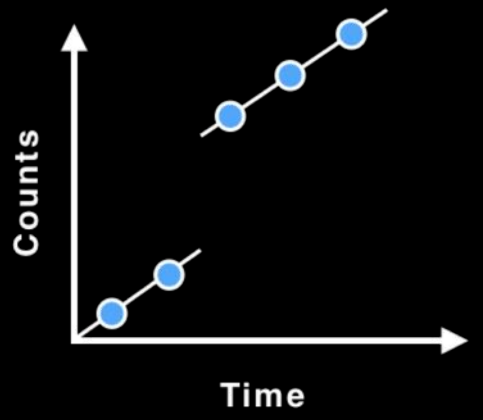
- Identify them
- Check their behaviour in the frames and groups
- Correct for them

Cosmic rays

Dispersion axis



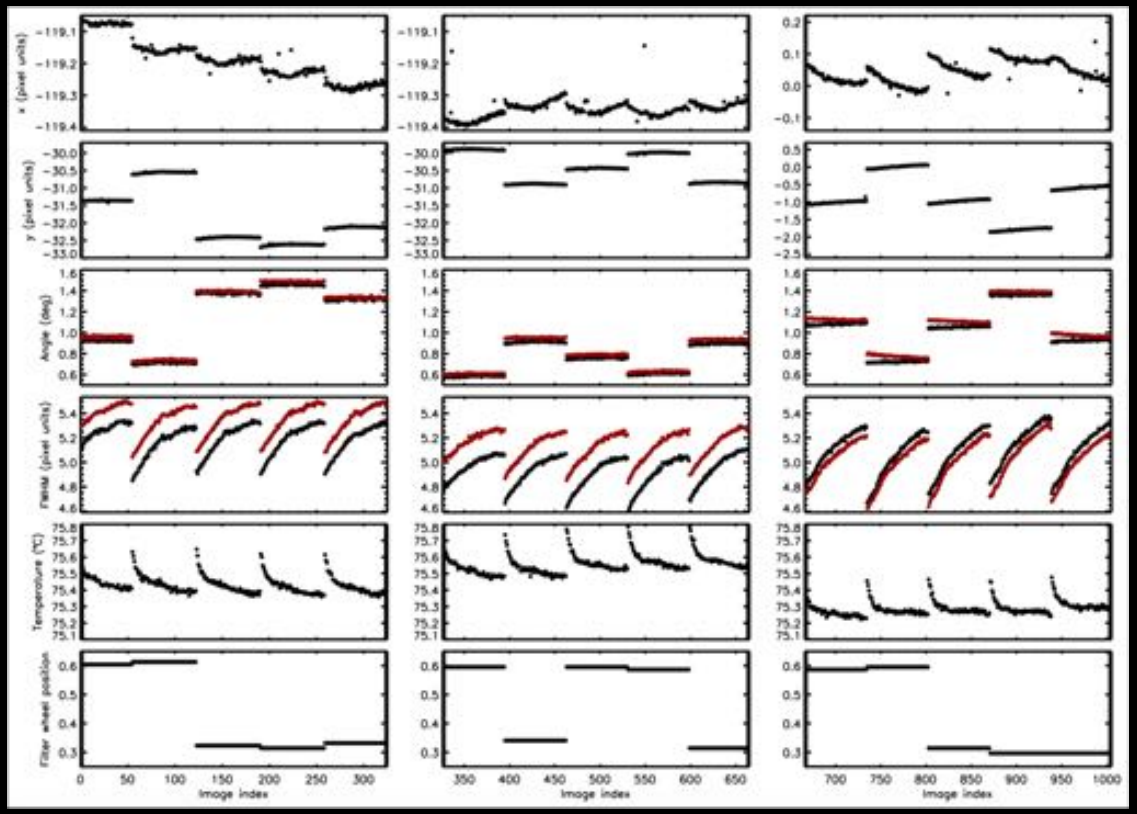
- Identify them
- Correct or discard them



Cosmic rays can be modeled as "jumps" in an up-the-ramp sample.

Diagnostic information

External parameters (spacecraft, instrument) can affect the measured flux: **systematics**



- Position (x, y, angle)
- Width
- Temperature
- Etc…

- Measure them
- Assess their impact
- Decorrelations (or Gaussian processes)

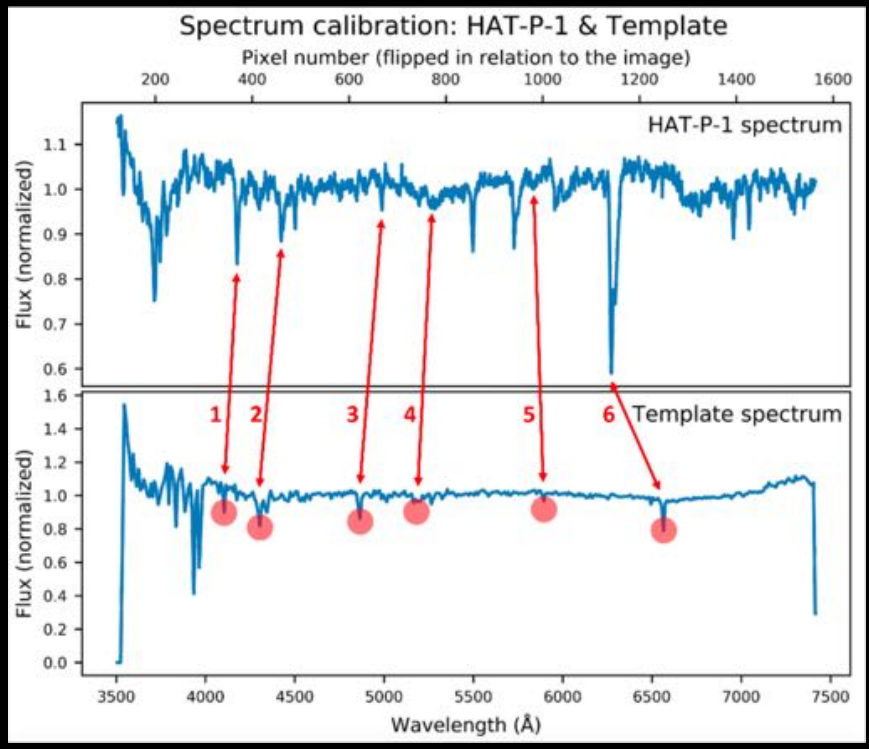
Wavelength calibration

Correspondence between pixels and wavelengths

Dispersion axis in **pixel units**

We want **wavelengths**

- Extract the stellar spectrum
- Compare it to a template of similar spectral type
- Match spectral lines



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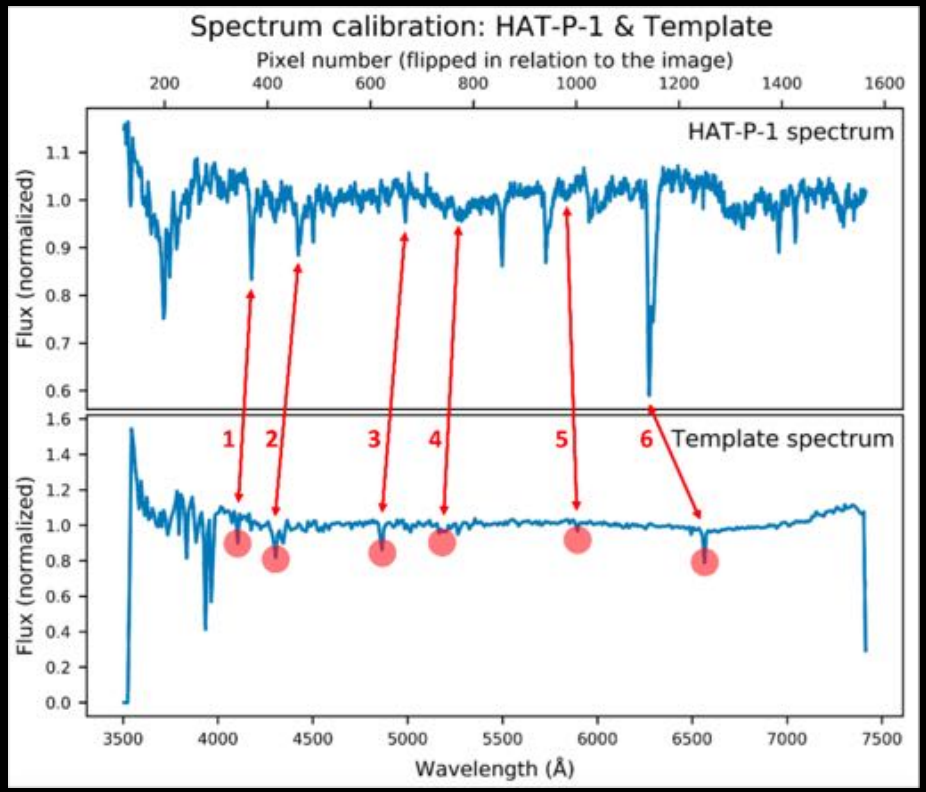
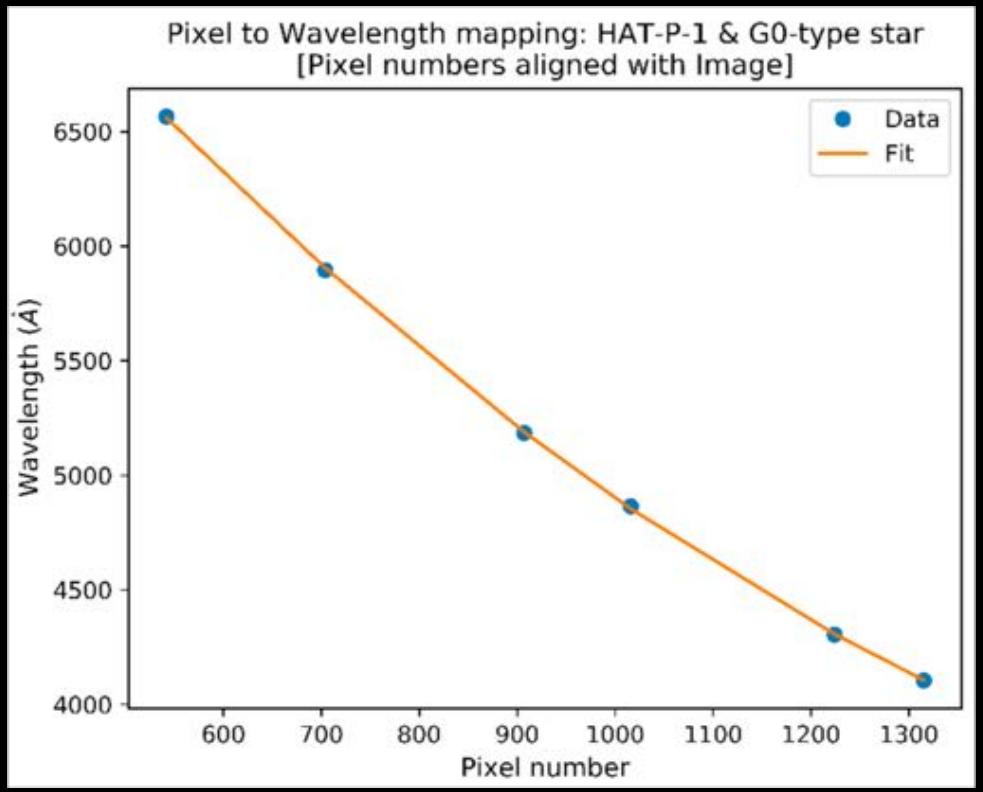
Wavelength calibration

Correspondence between pixels and wavelengths





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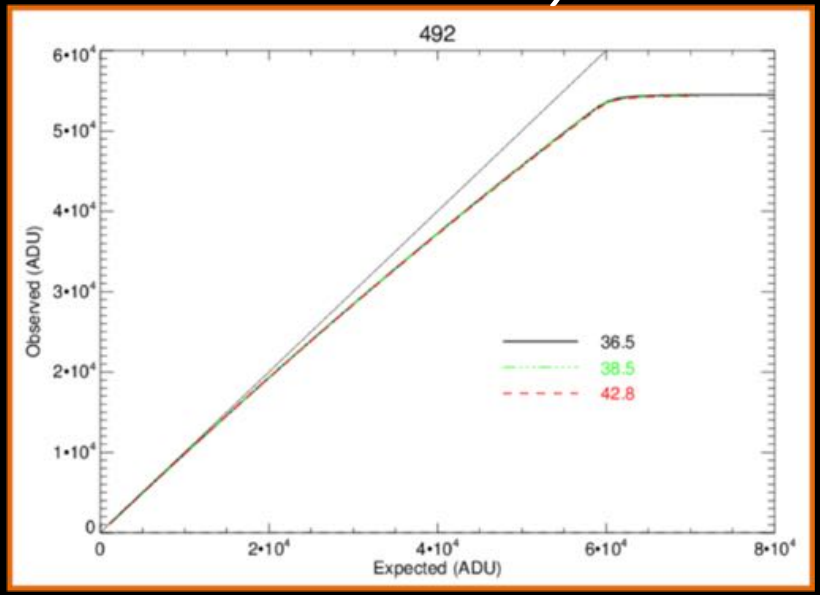
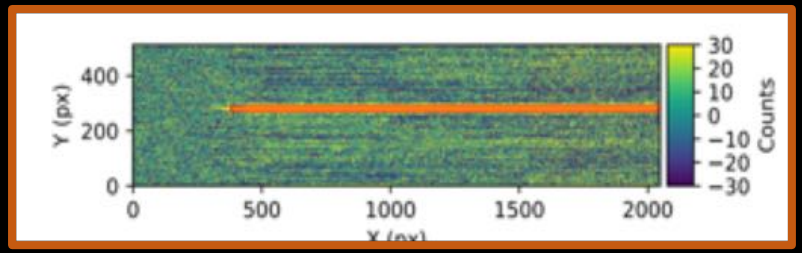
Other effects

- Drifts
- Persistence
- Non-linearity
- 1/f noise
- Unknown effects

Non-linearity



1/f noise



Schlawin 2020, AJ, 160, 231

Summary

- Basics of exoplanet spectrum extraction from spectroscopic time-series observations
- Some common corrections, but most corrections are **different for each telescope and instrument**
- Corrections and calibrations are often (always) **necessary to reveal exoplanet atmosphere signatures**