MPAGS Astrophysical Techniques 2023

Spectroscopy

Based on materials by
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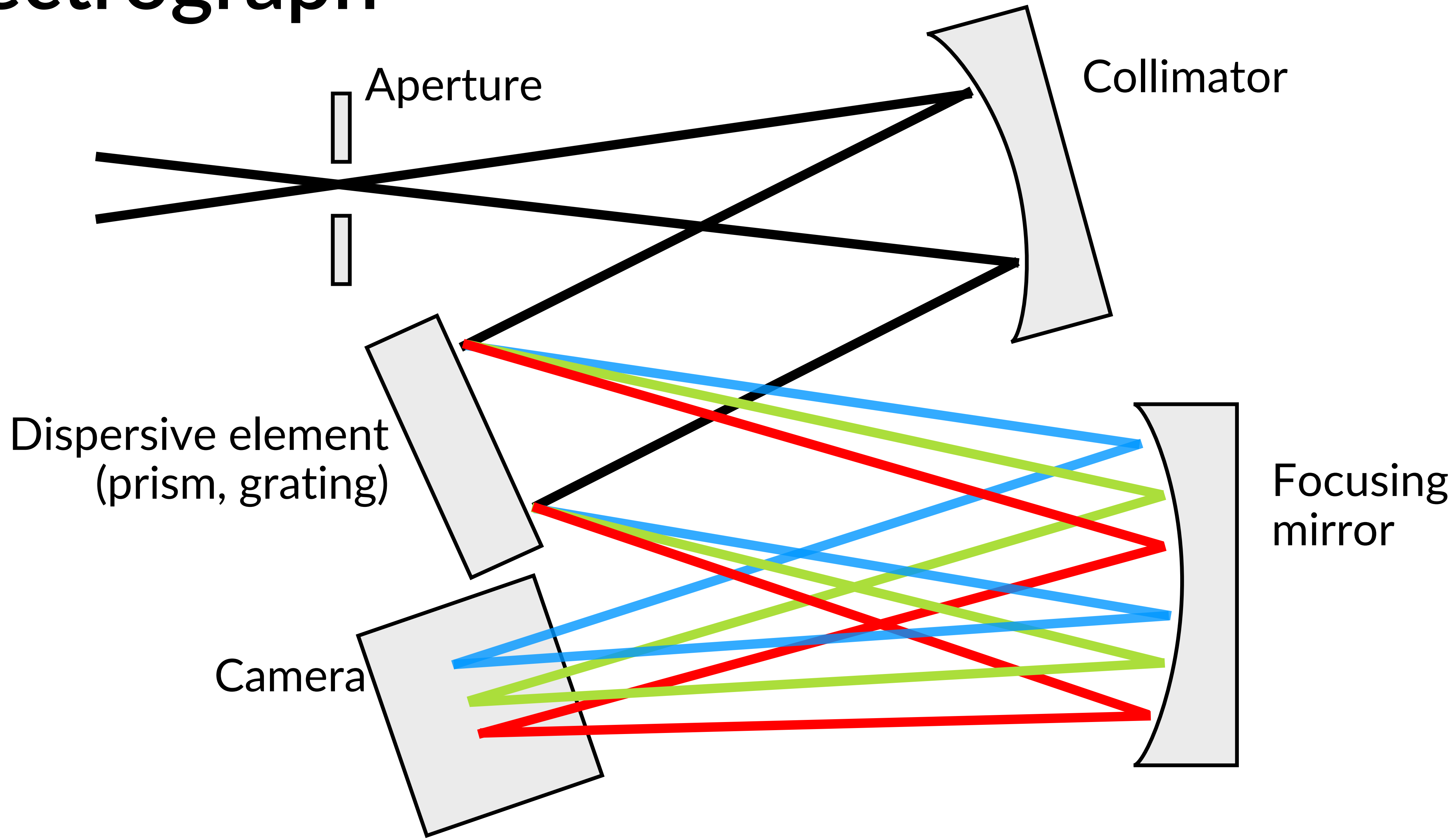
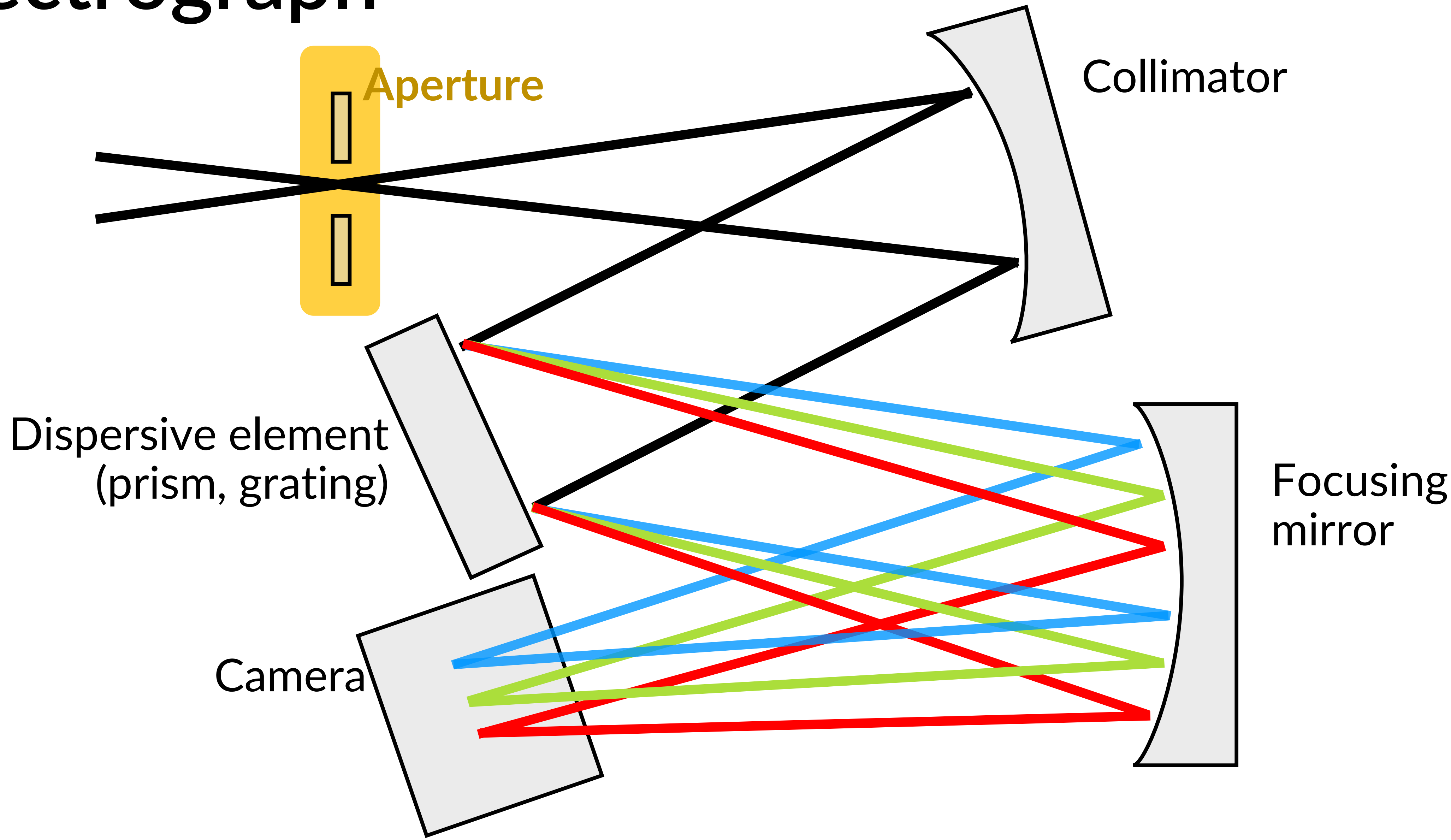
What is a spectrograph?

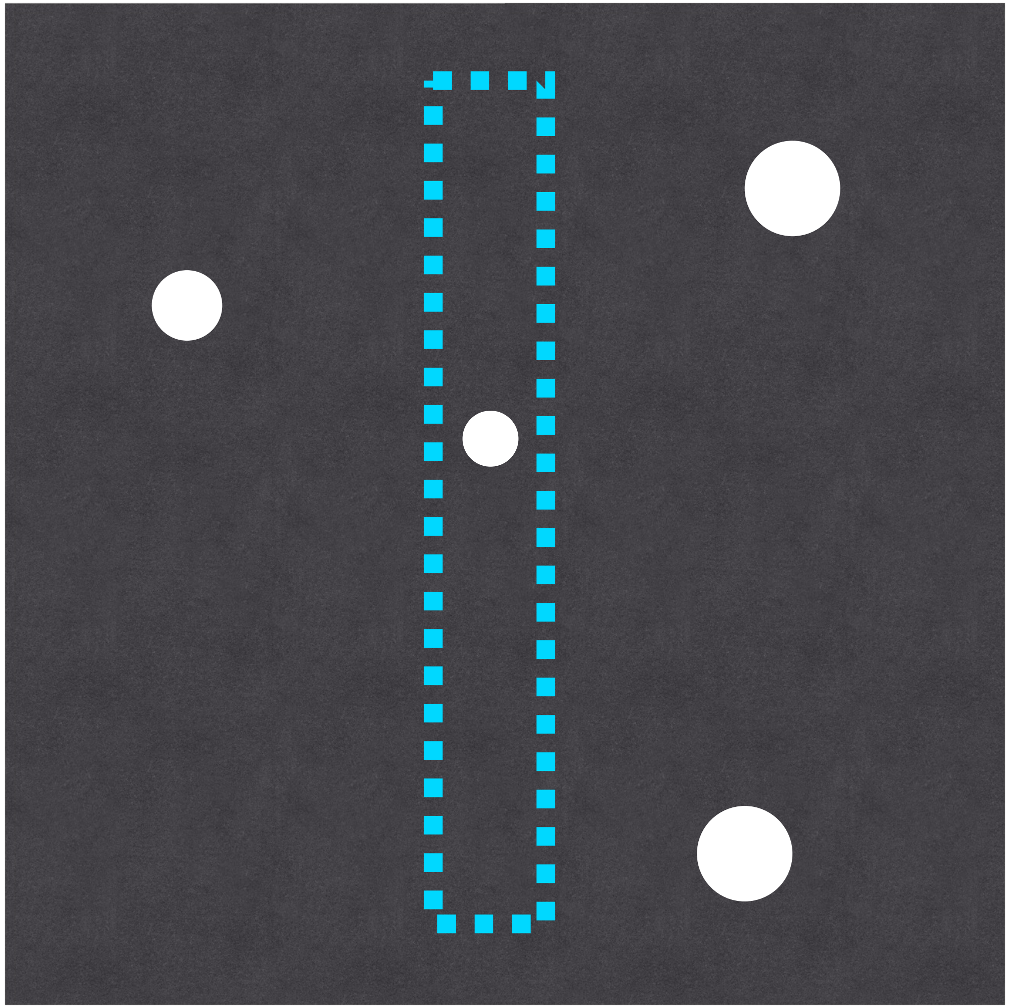
Spectrograph



Spectrograph

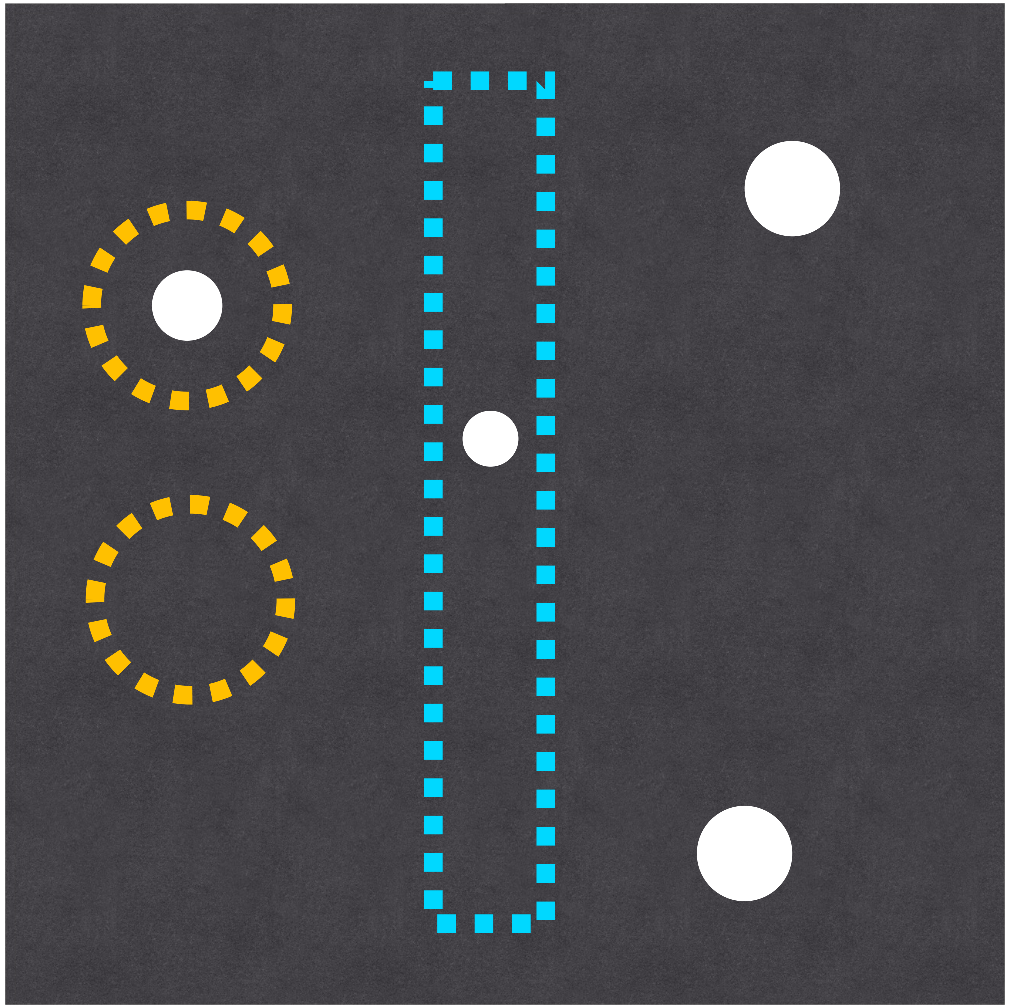


Collecting light



Slit: Mechanical aperture with 2 parallel jaws
- Width can be easily changed
- One spatial direction (along the slit) preserved
- Simultaneous spectrum of the sky
- Typical slit widths: 0.2 – 2.0″

Collecting light



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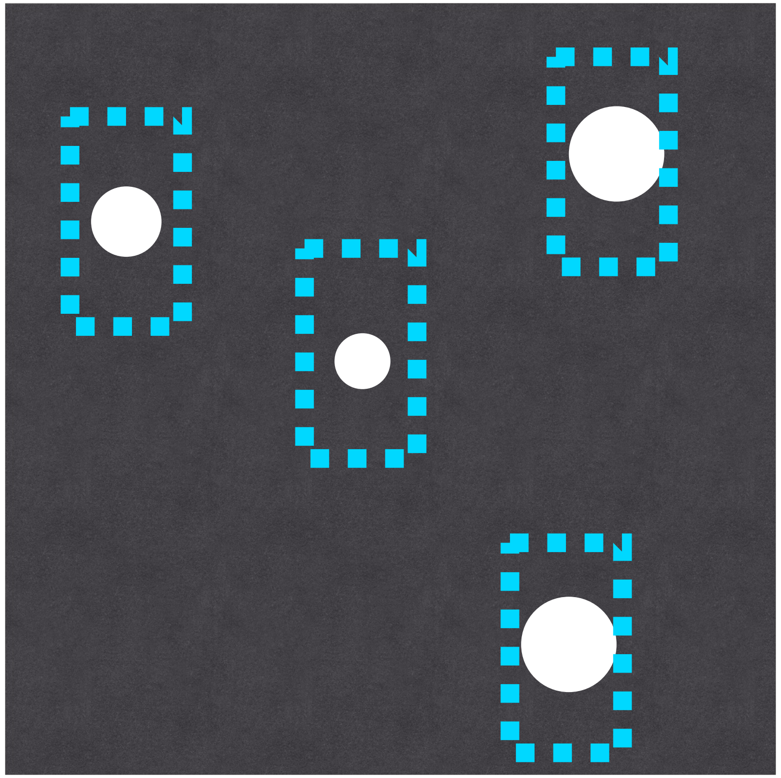
Fibre: Optical guide transmitting light through multiple reflections

- Very constant output (↑ stability)
- Instrument can be moved off-telescope (↑ stability)
- Additional fibre(s) for sky or calibration source
- Typical fibre diameters: 1.0 – 1.5″ (match seeing)

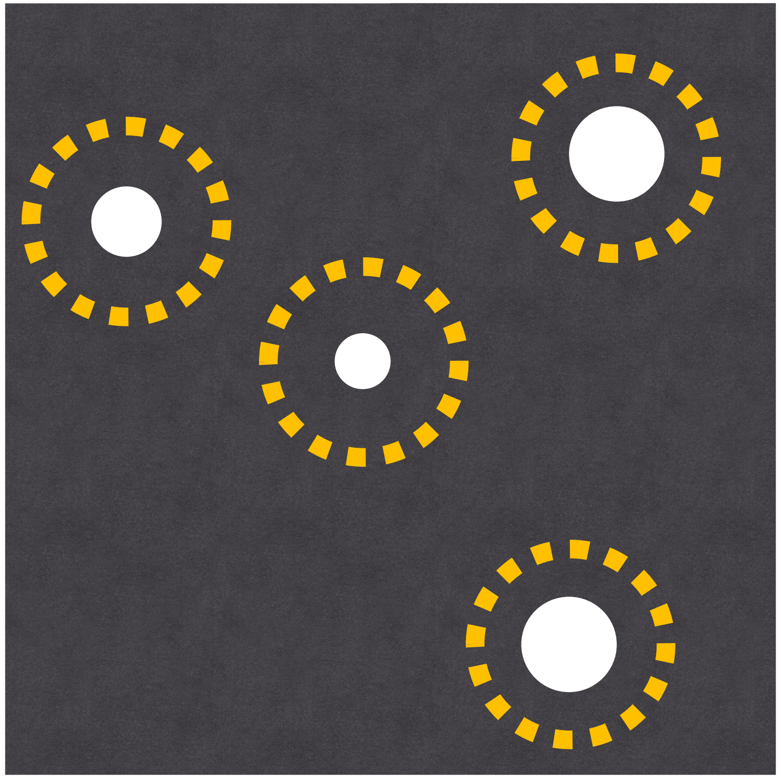
Collecting light

Multiple slits/fibres can be combined to do **multi-object spectroscopy** (MOS)

Differential spectroscopy



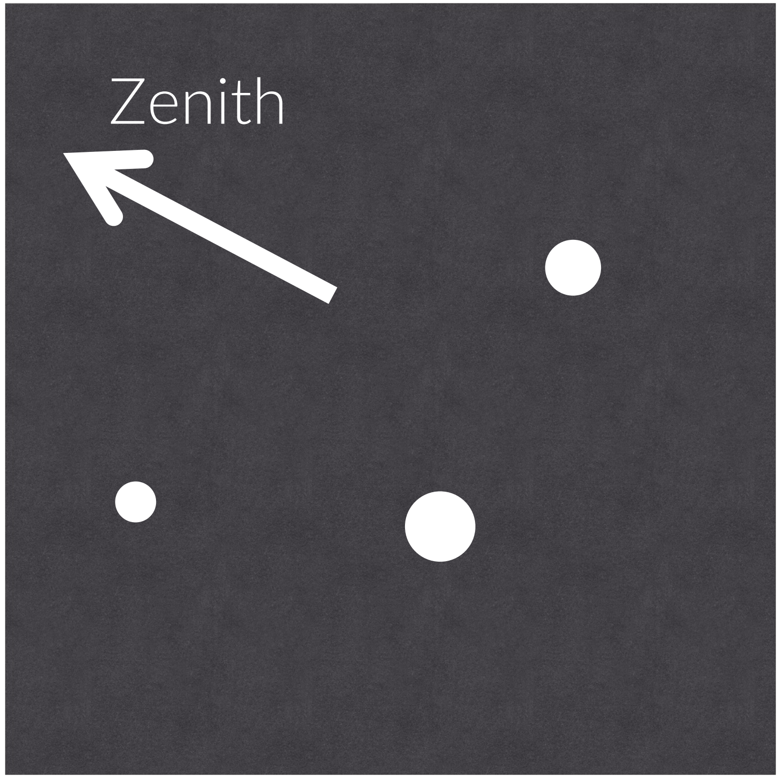
Slit mask



Fibre MOS

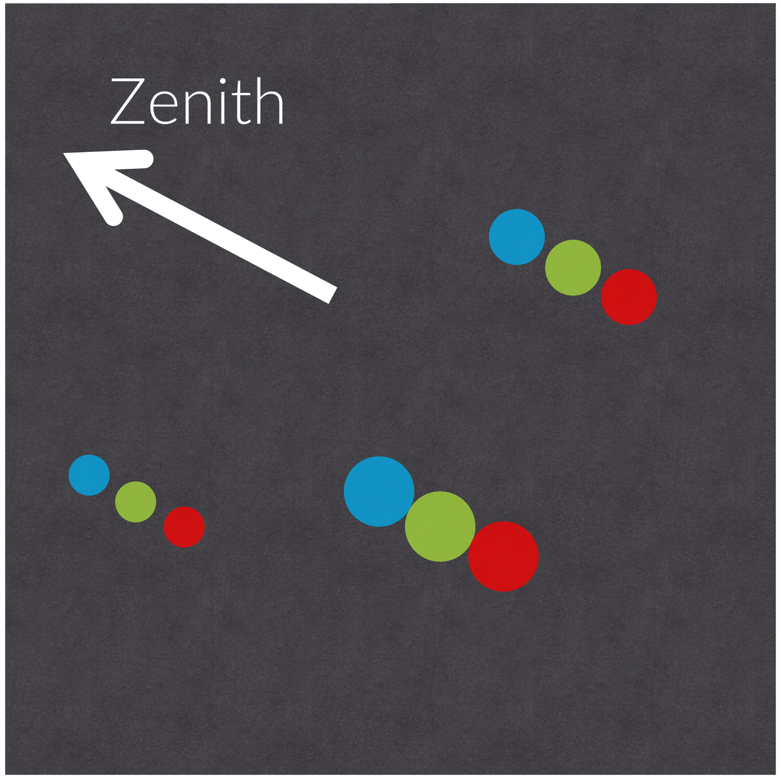
Atmospheric dispersion

- Earth's atmosphere refracts source light ⟹ Sky position of the source is λ-dependent!



Atmospheric dispersion

Case 1: Single object



- Earth's atmosphere refracts source light $\Longrightarrow$ Sky position of the source is λ-dependent!
  - Index of refraction depends on wavelength, temperature, pressure, water vapour
  - Dispersion happens along the horizon-zenith direction (airmass)
  - Dispersion larger for shorter wavelengths
  - Dispersion direction changes with time
- Affects acquisition and slit orientation
- Atmospheric Dispersion Compensator (ADC)

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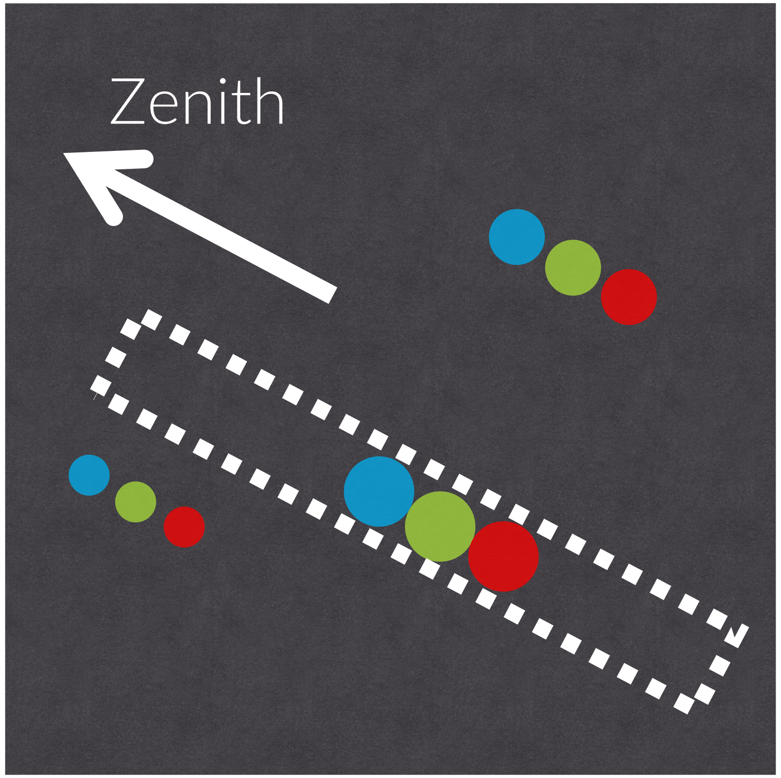

Slit aligned at the parallactic angle

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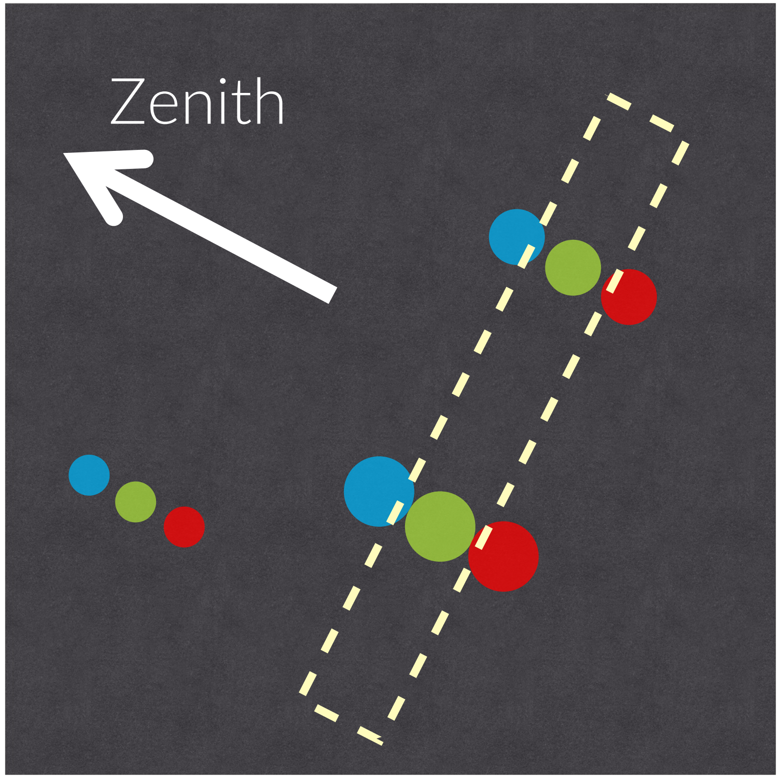

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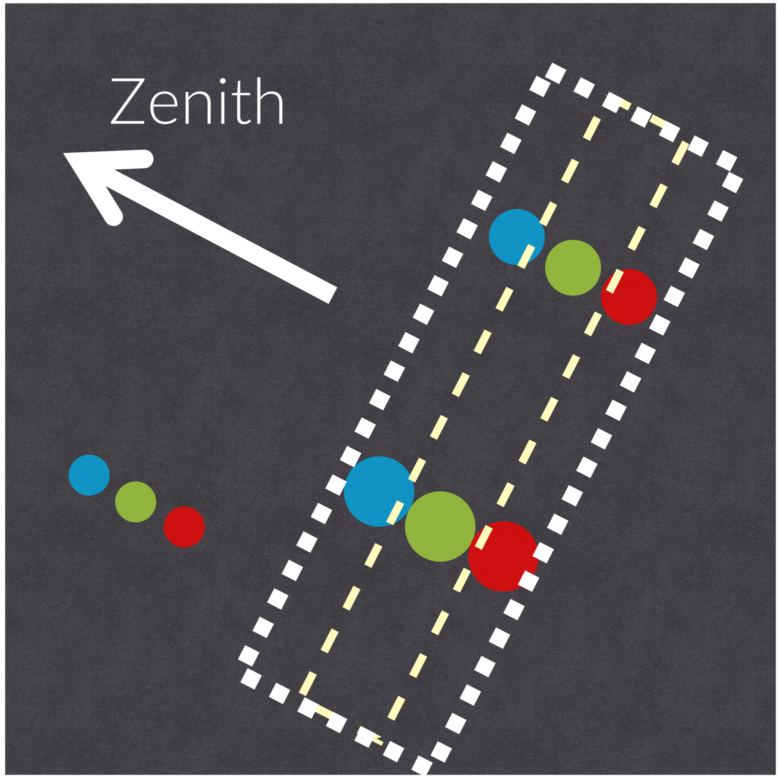
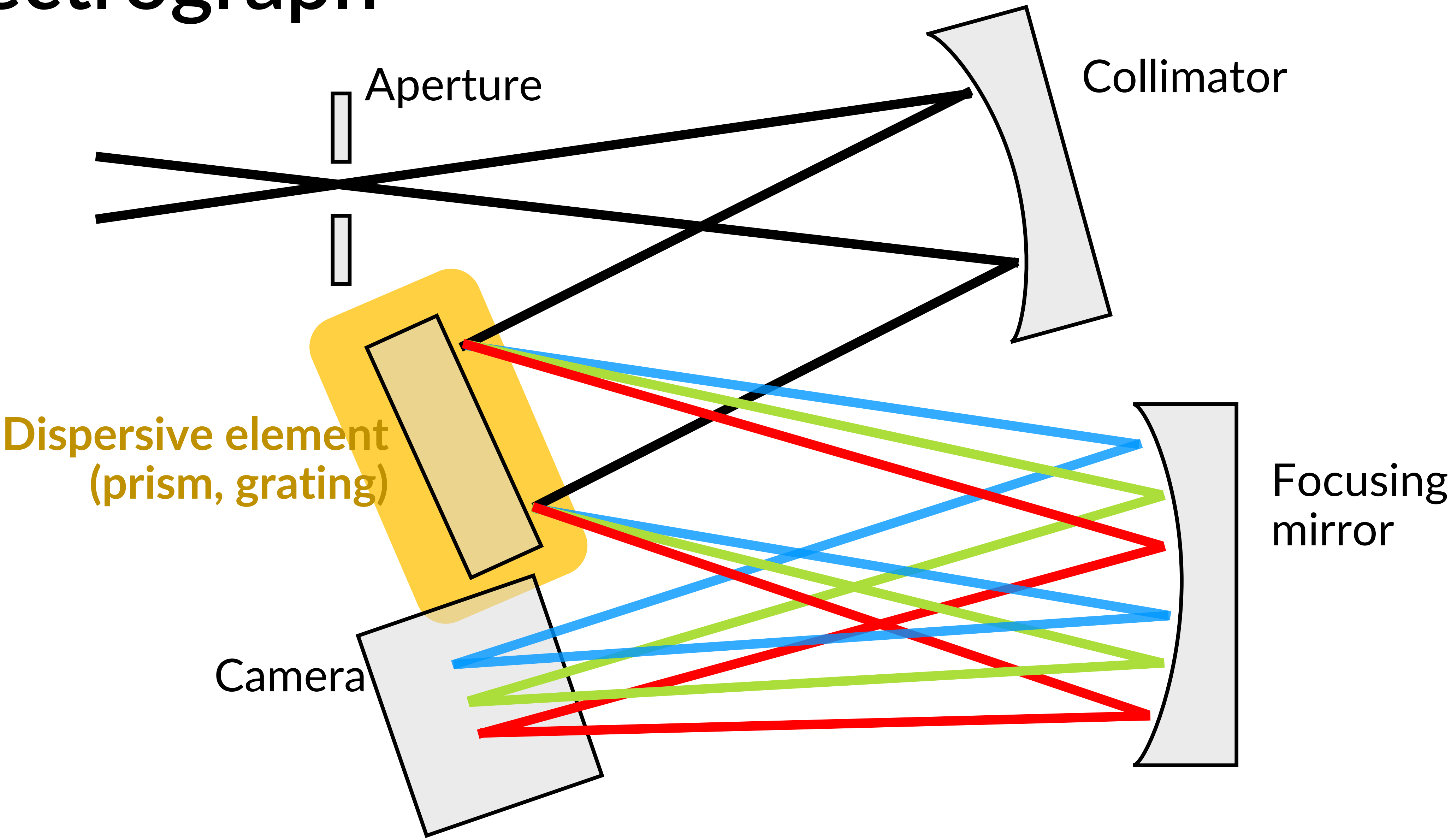


Wider slit to avoid losing light

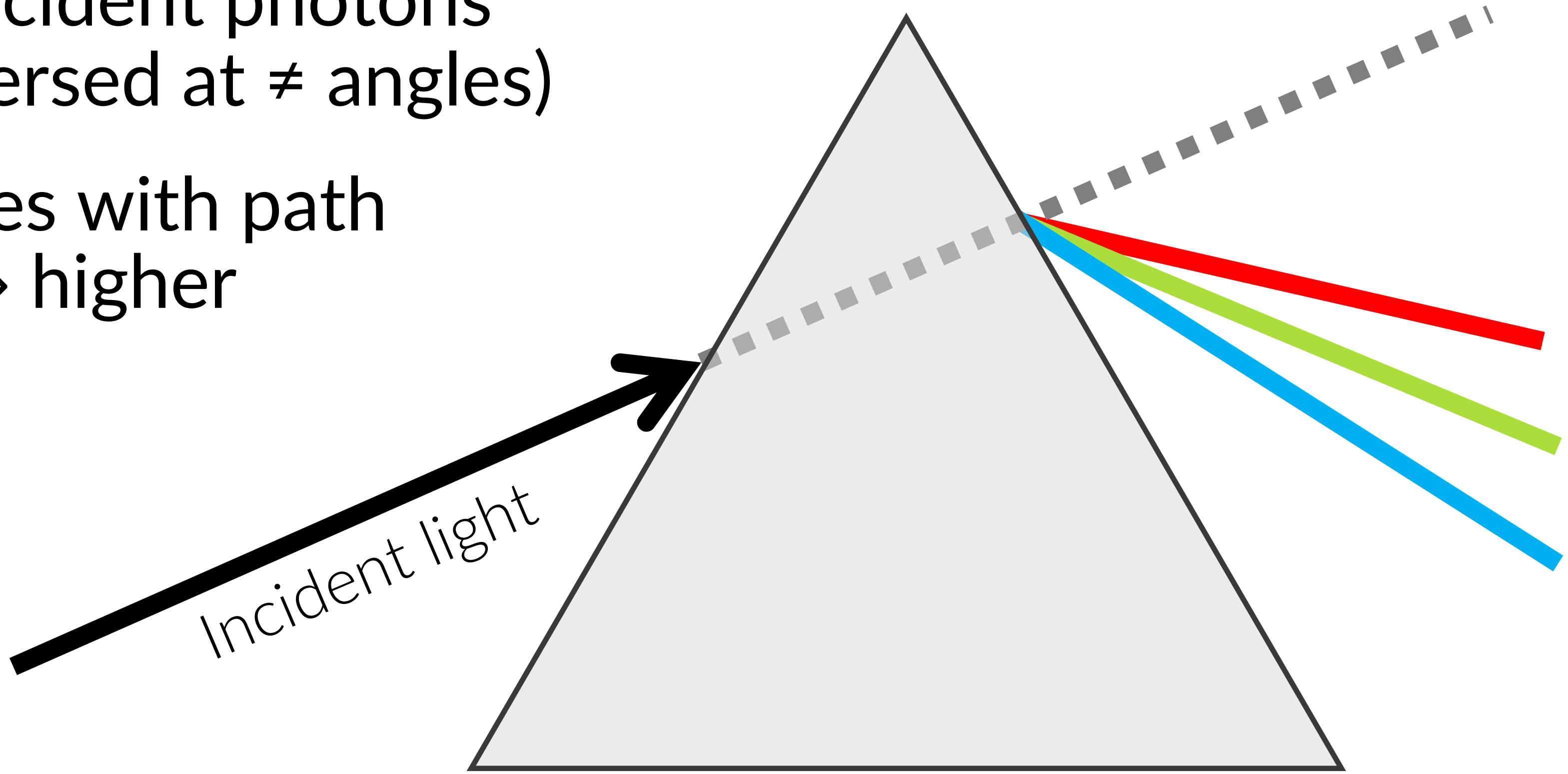
Spectrograph



Dispersing light: prisms, gratings, grisms

Prism

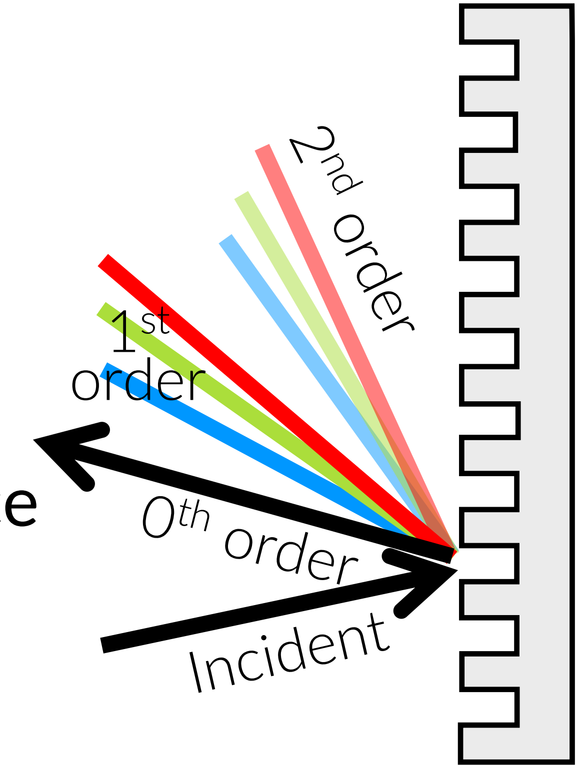
- Uses **variable index of refraction** $\boldsymbol{n(\lambda)}$ to separate incident photons (≠ colours are dispersed at ≠ angles)
- Dispersion increases with path (i.e. larger prism $\Longrightarrow$ higher resolution)



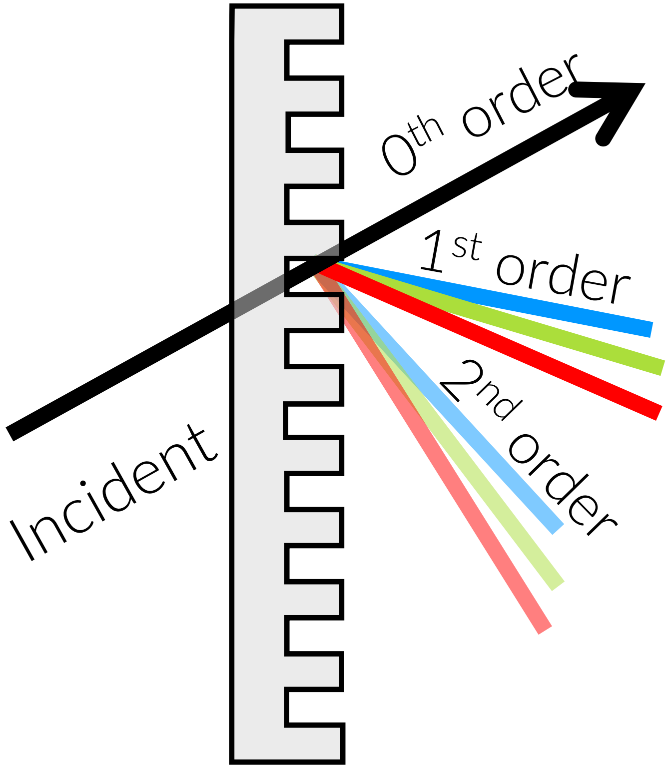
Dispersing light: prisms, gratings, grisms

Diffraction grating

- Uses **diffraction + interference** to separate incident photons
- Periodic carving in material with spacing ~ λ of light
- Diffraction orders at interference maxima
- Resolution ↑ with line density
- Resolution ↑ for higher orders (but intensity ↓)
- Most of the light goes to the first orders



Reflection grating (reflective material)

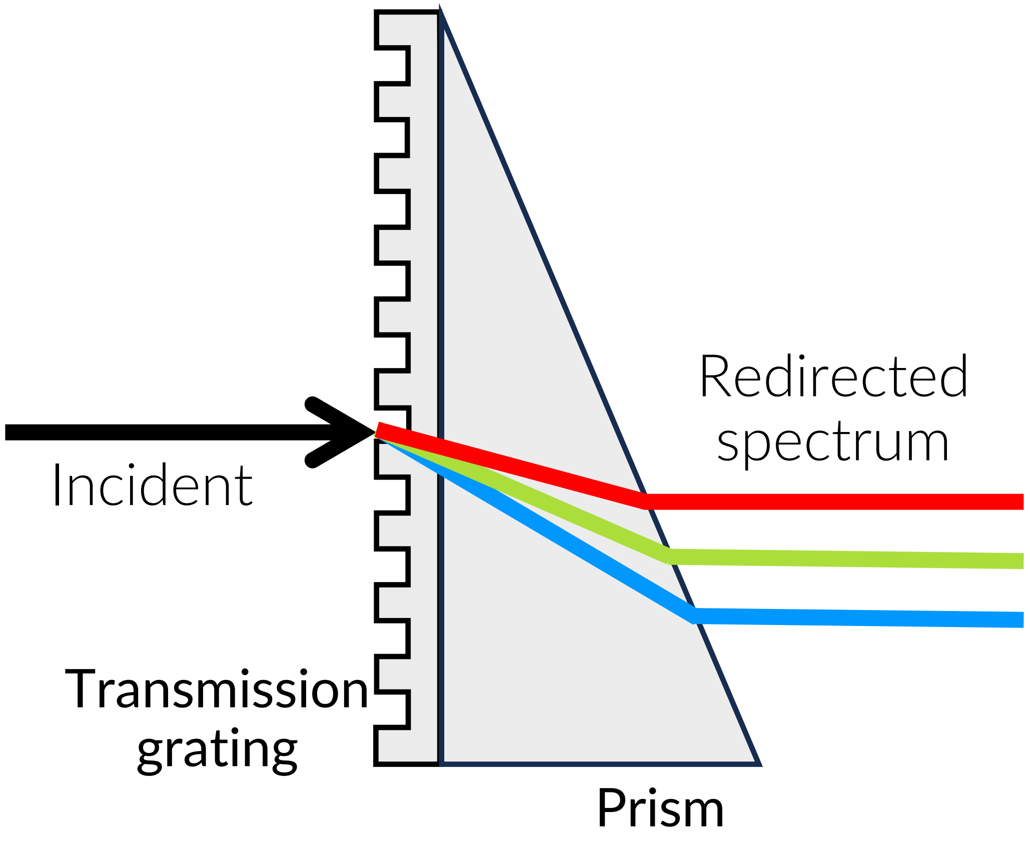


Transmission grating (transmissive material)

Dispersing light: prisms, gratings, grisms

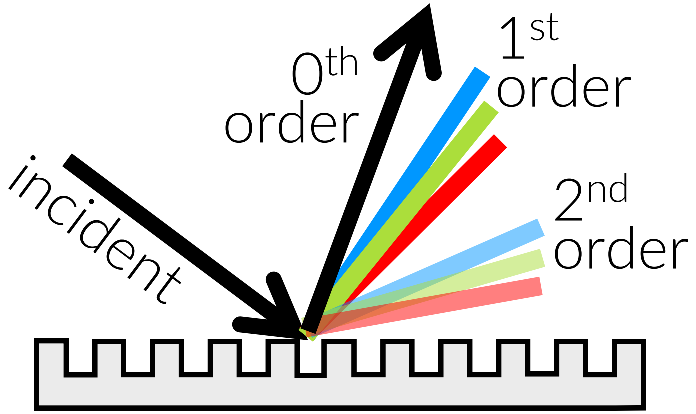
Grism

- Grating mounted on a prism interface
- Useful to correct for the path of diffracted light
  - Smaller instruments
  - Extreme angles (higher orders)

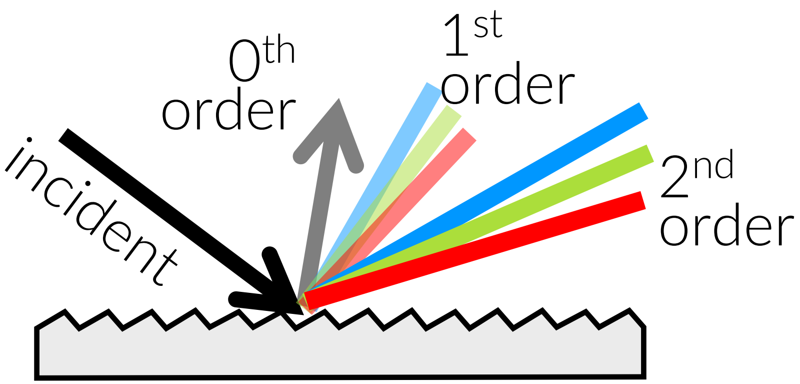


Dispersing light: blazed spectrographs

- Gratings can be ***blazed*** to **concentrate light** away from 0^{th} order and **towards higher orders**
- Reflecting surfaces oriented at a specific *blaze angle* with respect to the surface of the grating
- Called echelette if used for low orders or **echelle** if used for high orders (large blaze angle, > 45°)
- **Order overlap** becomes a problem



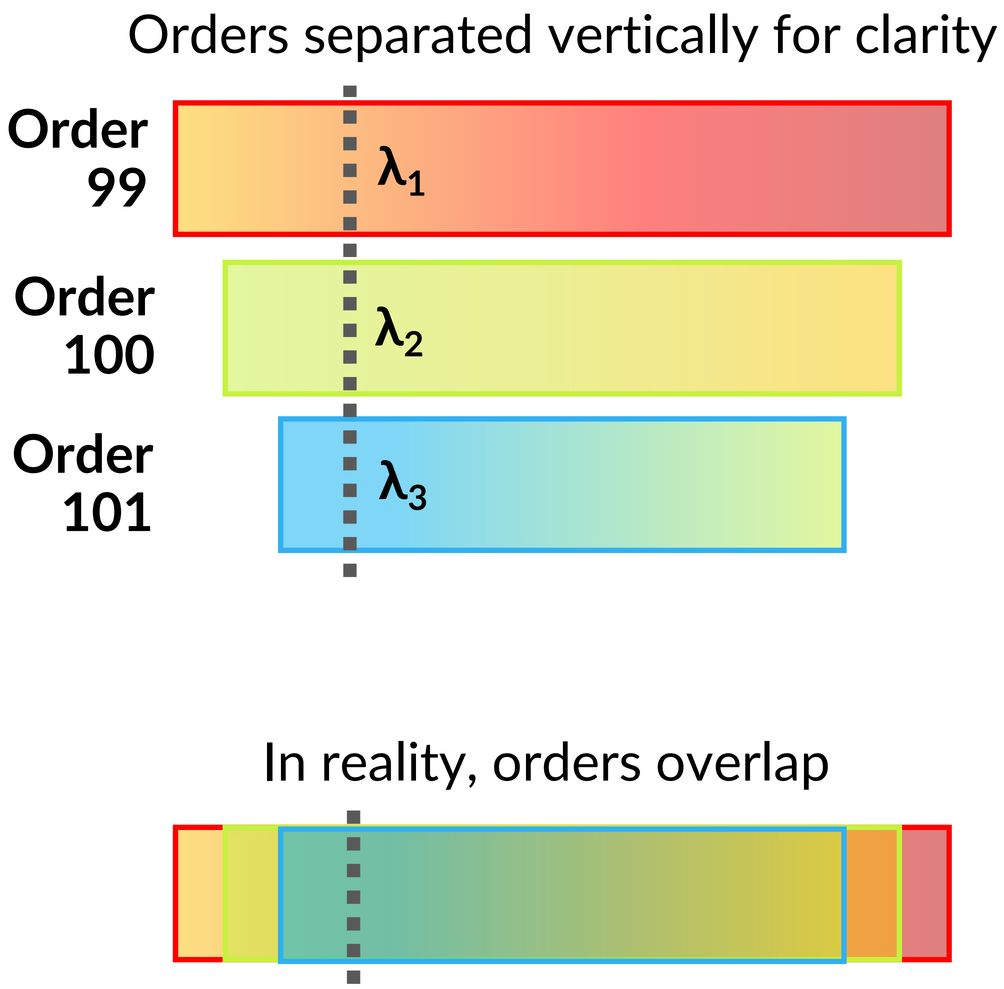
Regular (unblazed) grating



Blazed grating

Dispersing light: cross-dispersion

- The wavelength range of high orders strongly overlaps
- Want to measure λ_1 in order 99, but λ_2 in order 100 and λ_3 in order 101 contaminate your spectra
- Solutions:
  - Bandpass filters to selected desired λ range, but lose light
  - Cross-dispersion perpendicular to the initial spectral dispersion to separate the orders



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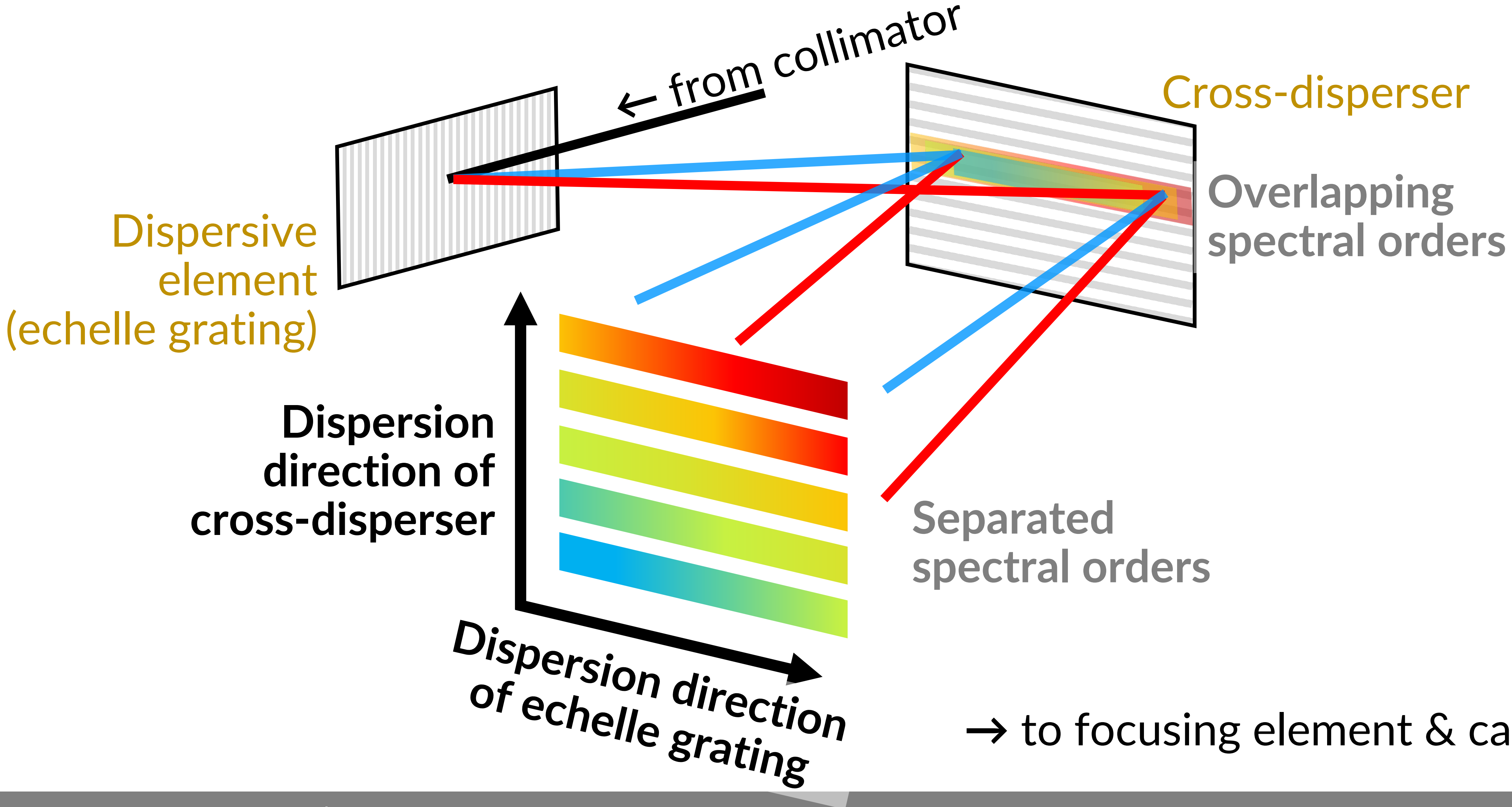


→ to focusing element & camera

Spectral resolution: separating spectral lines

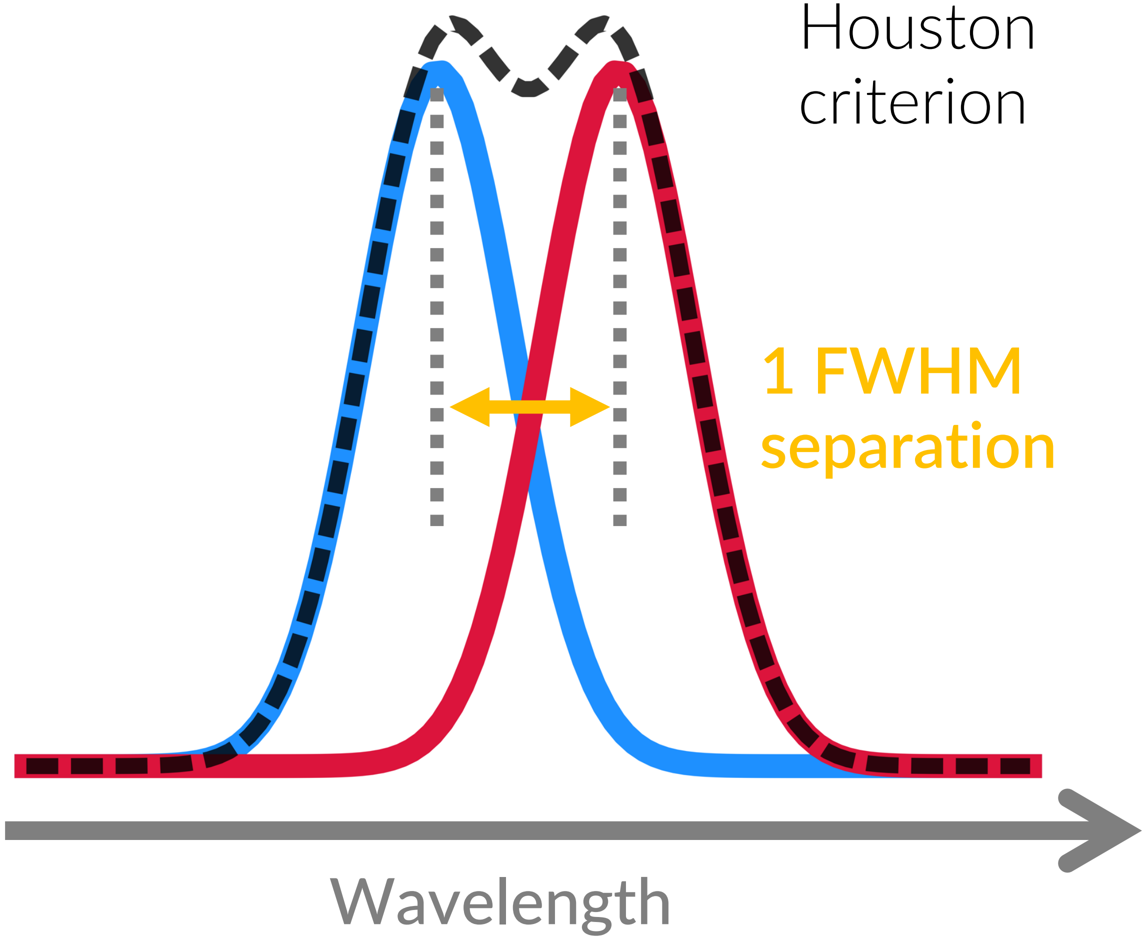
What is the minimum distance between lines ($\Delta\lambda$) to be considered spectrally resolved?

- **Spectral resolution**: $\Delta\lambda$
- **Resolving power**: $\mathrm{R} = \lambda/\Delta\lambda$

Related to **Doppler shift**:

$$\Delta v \sim c/\mathrm{R}$$

E.g. R =100 000 ⟹
Resolve 3 km/s in velocity or
0.005 nm in wavelength at 500 nm

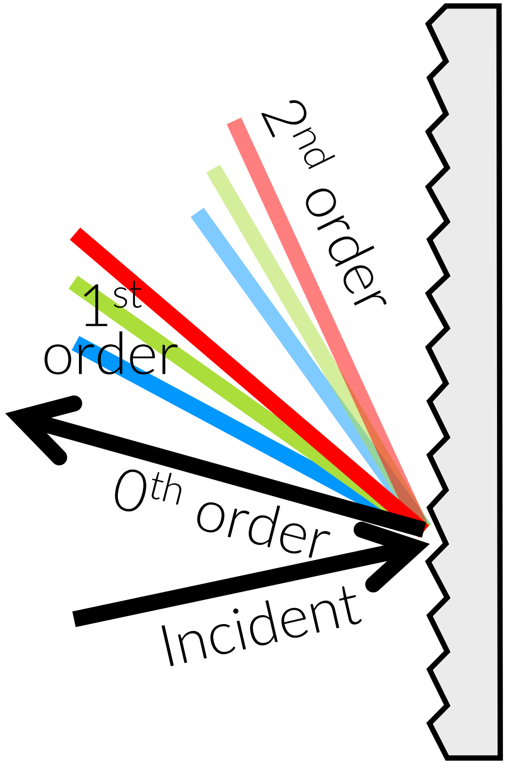


Spectral resolution

Resolution is driven by the **slit width/fibre size** (up to 1”) or by the **seeing** (for wider slits/fibres)

Resolution increases with **density of lines in grating & order number**

How to achieve high resolution?



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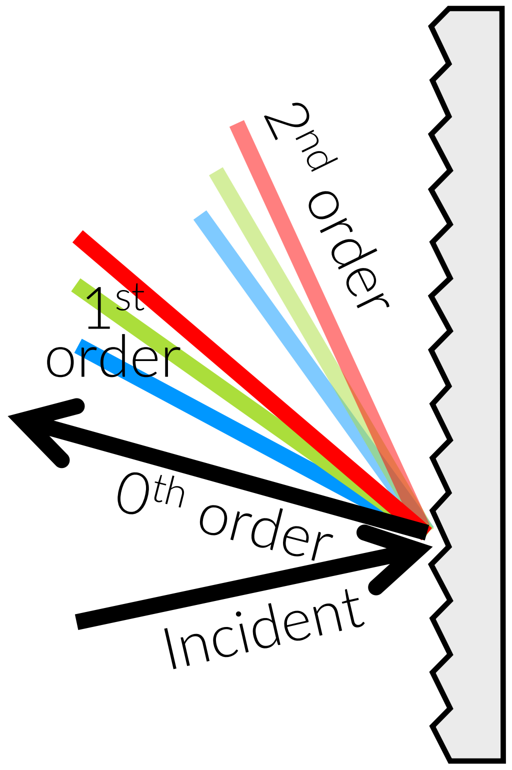
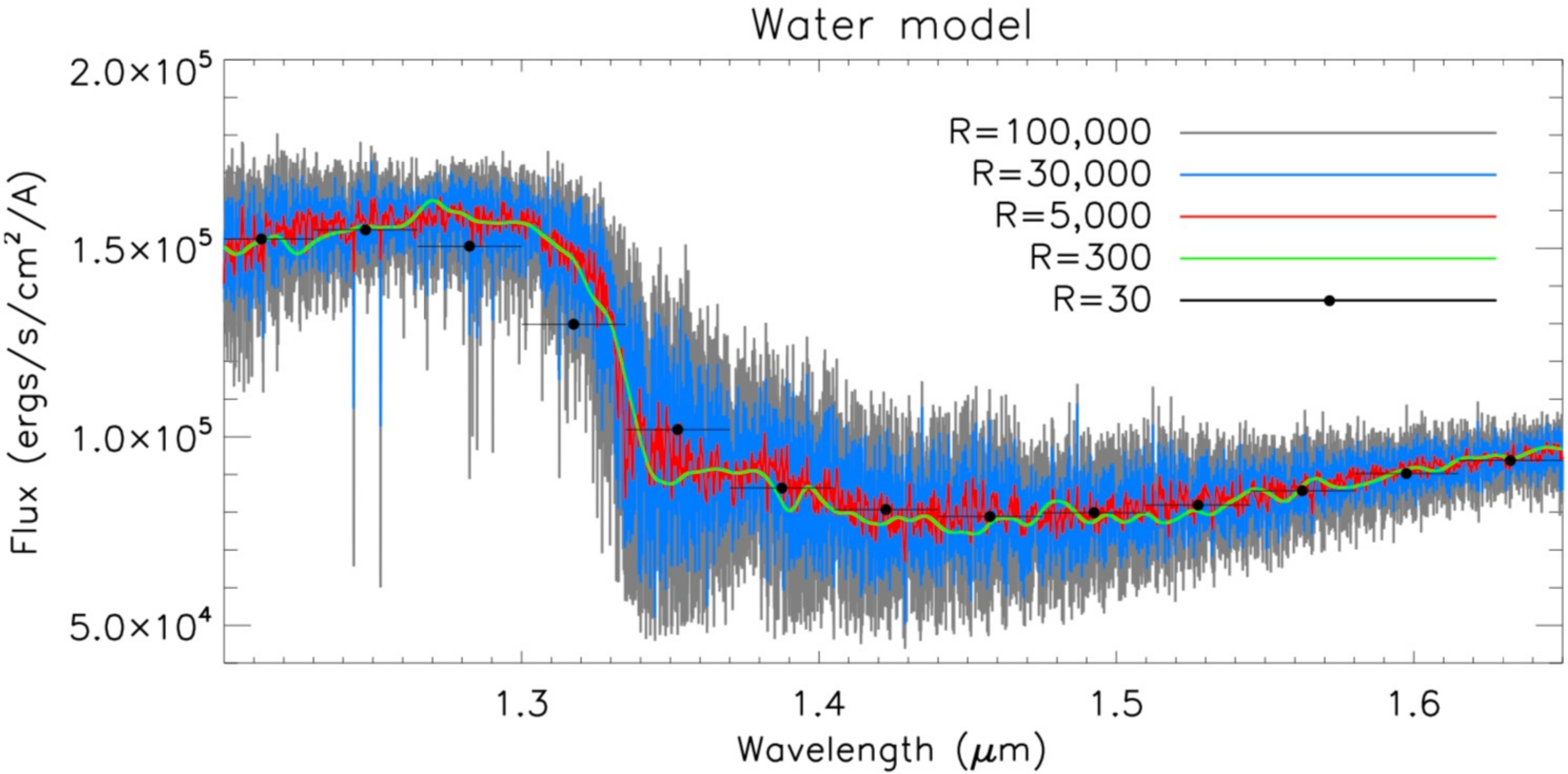
How to achieve high resolution?

- ↓ slit size
- ↑ density of lines in grating
- ↑ order number (high angles)



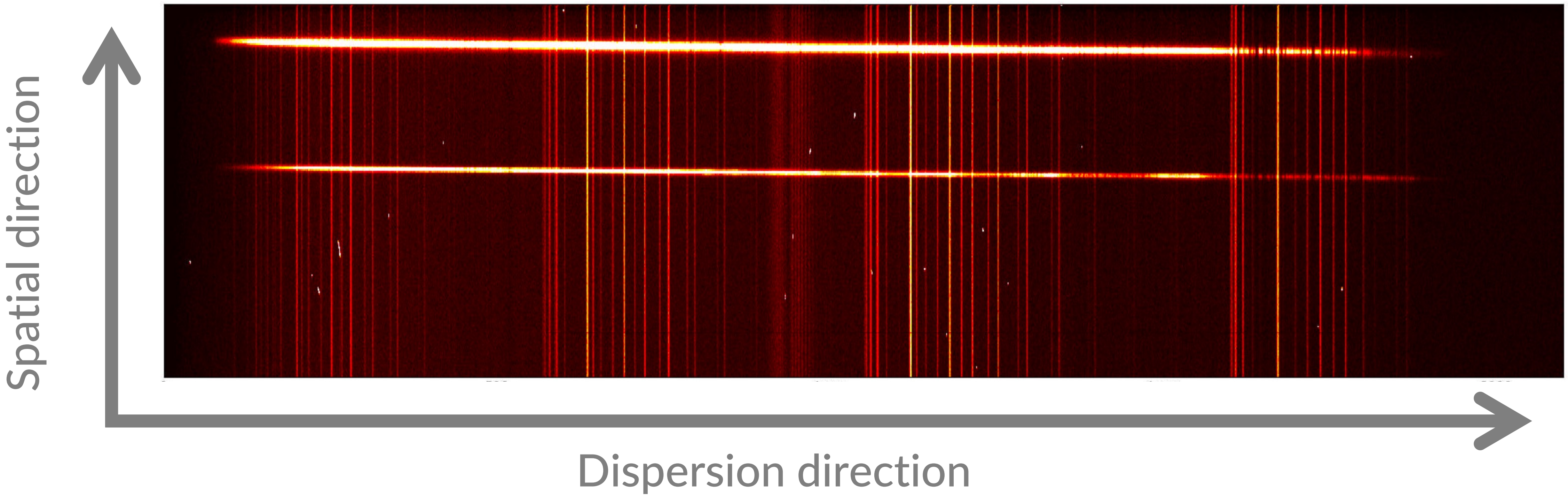
Trade-off between resolution & amount of photons!

Spectral resolution



Let’s have a look at some data

Example of a long-slit spectrum



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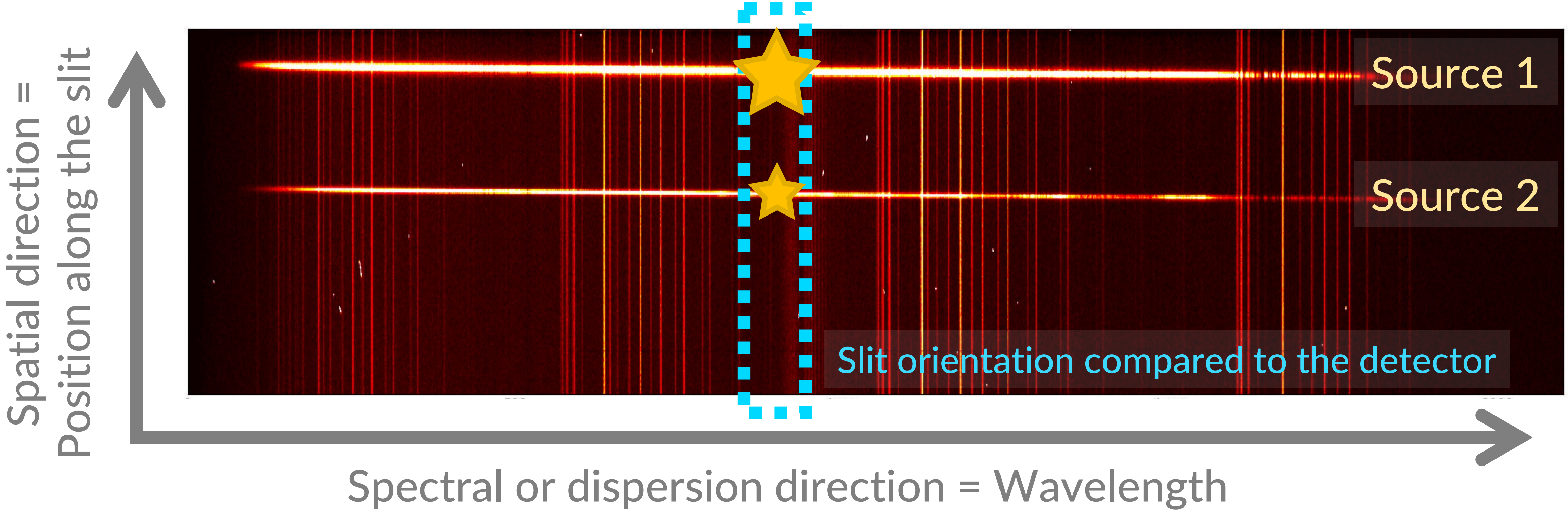

- Light is dispersed perpendicular to the slit ⟹ Spatial information perpendicular to the slit is lost and becomes the spectral direction
- Sources have a specific location on the slit ⟹ Spatial information along the slit is available, spectrum localised at specific spatial positions

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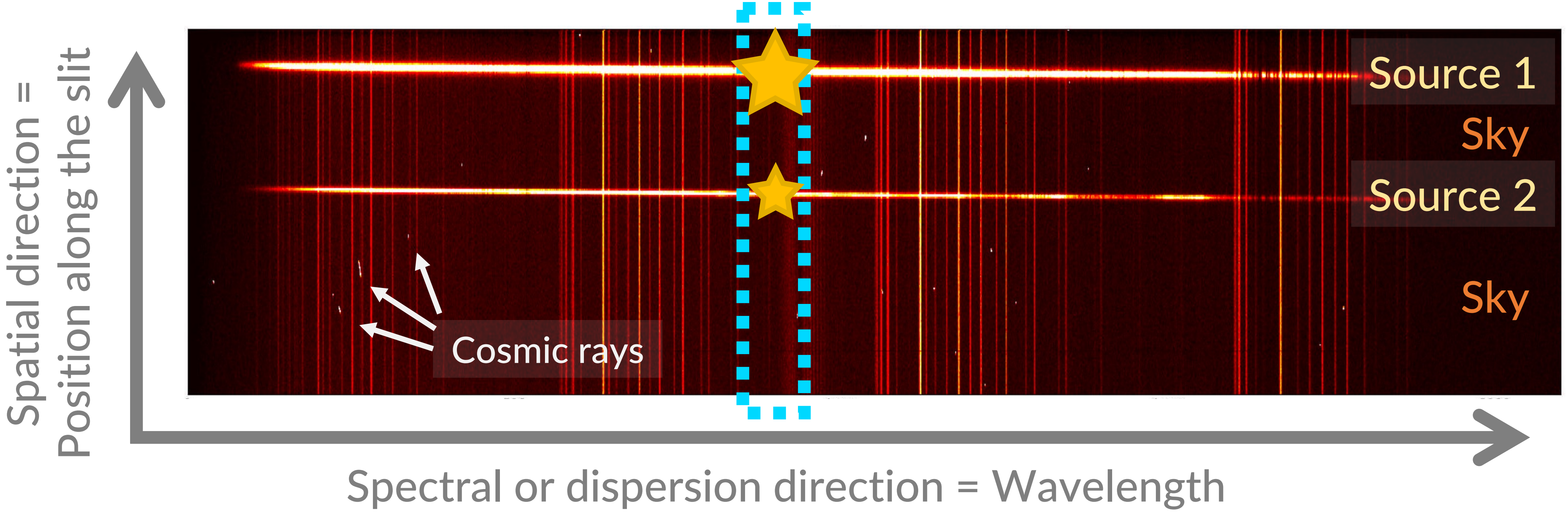

- Sky enters the slit everywhere ⟹ Sky emission lines appear everywhere along the spatial direction

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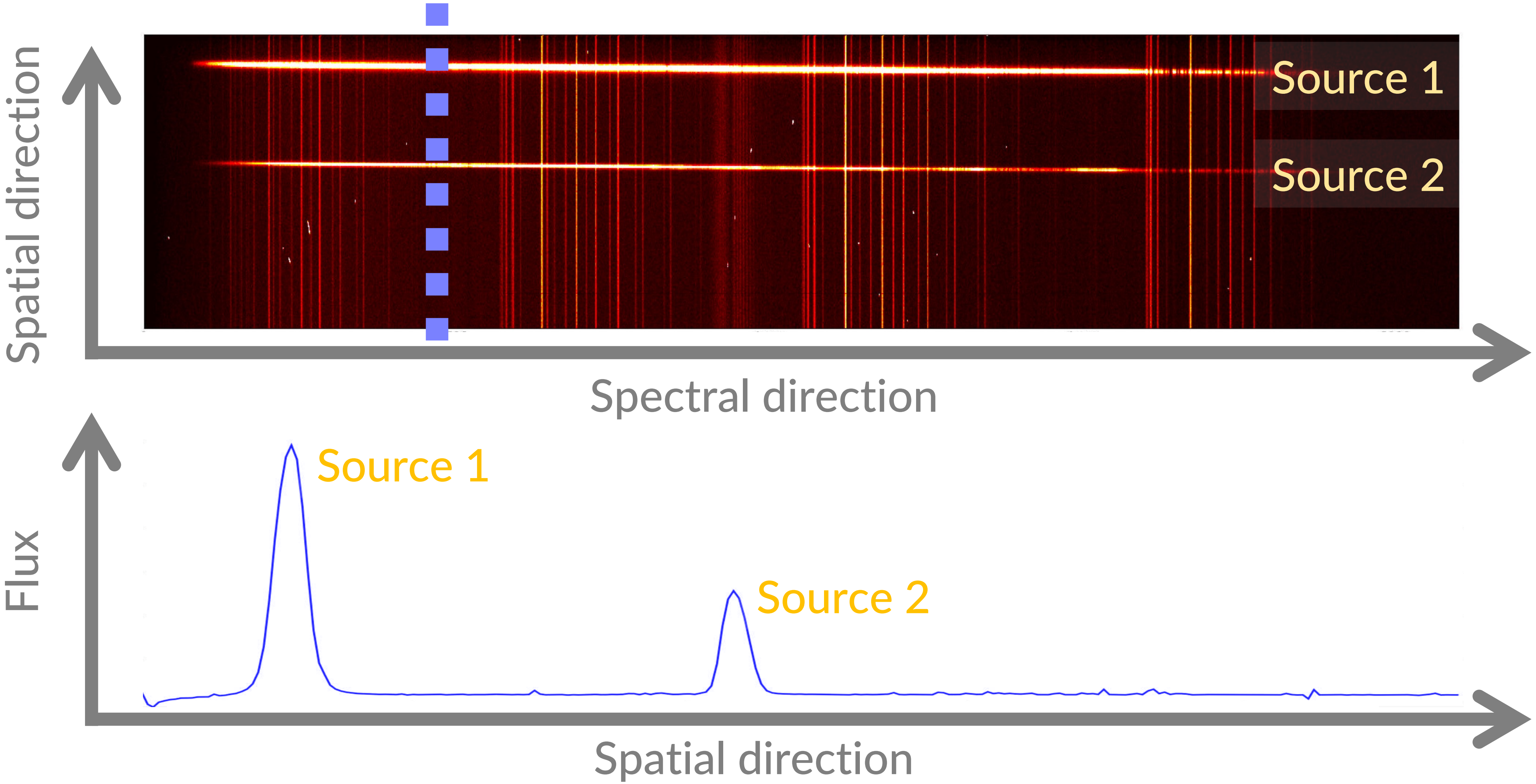

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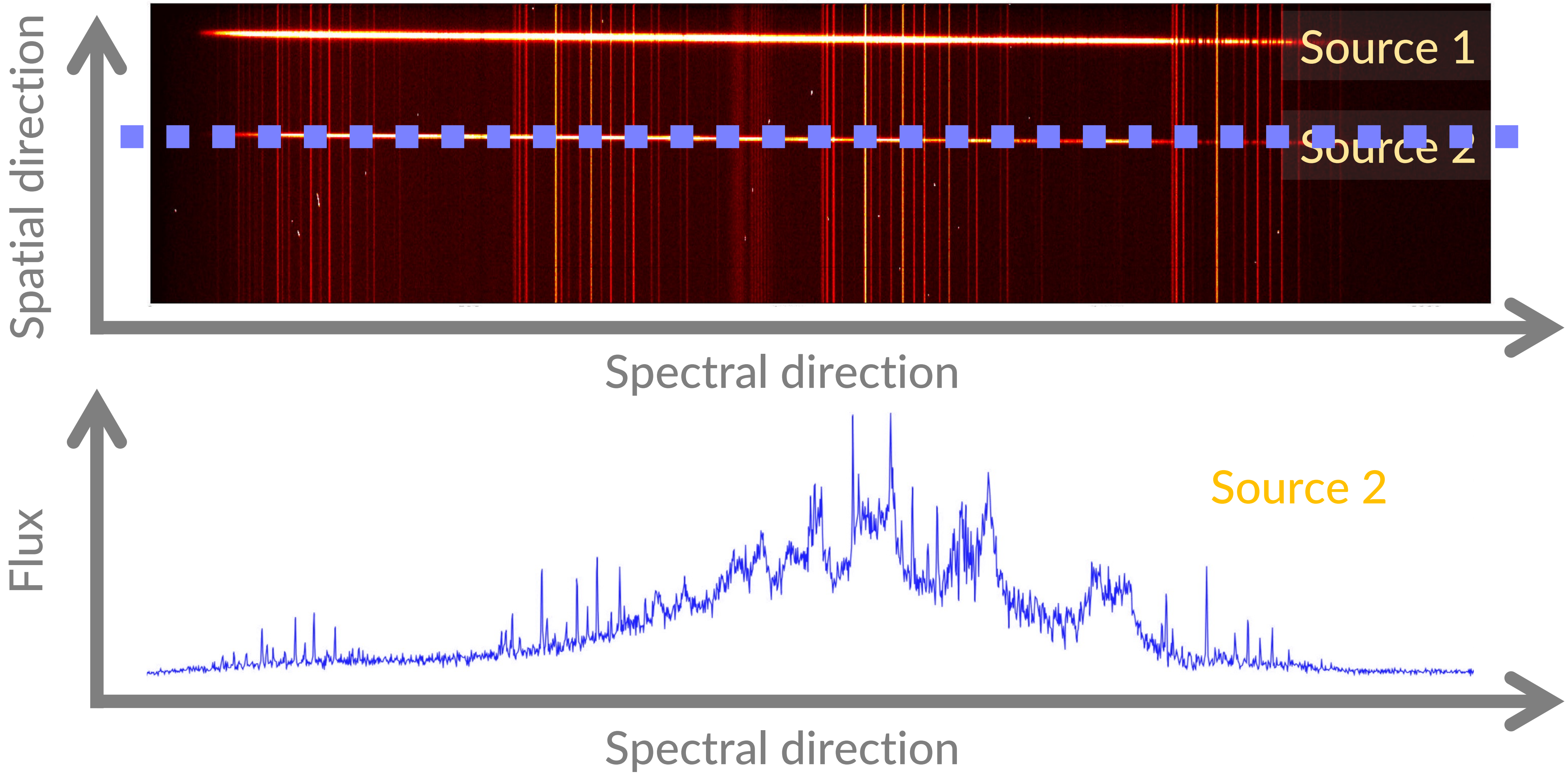
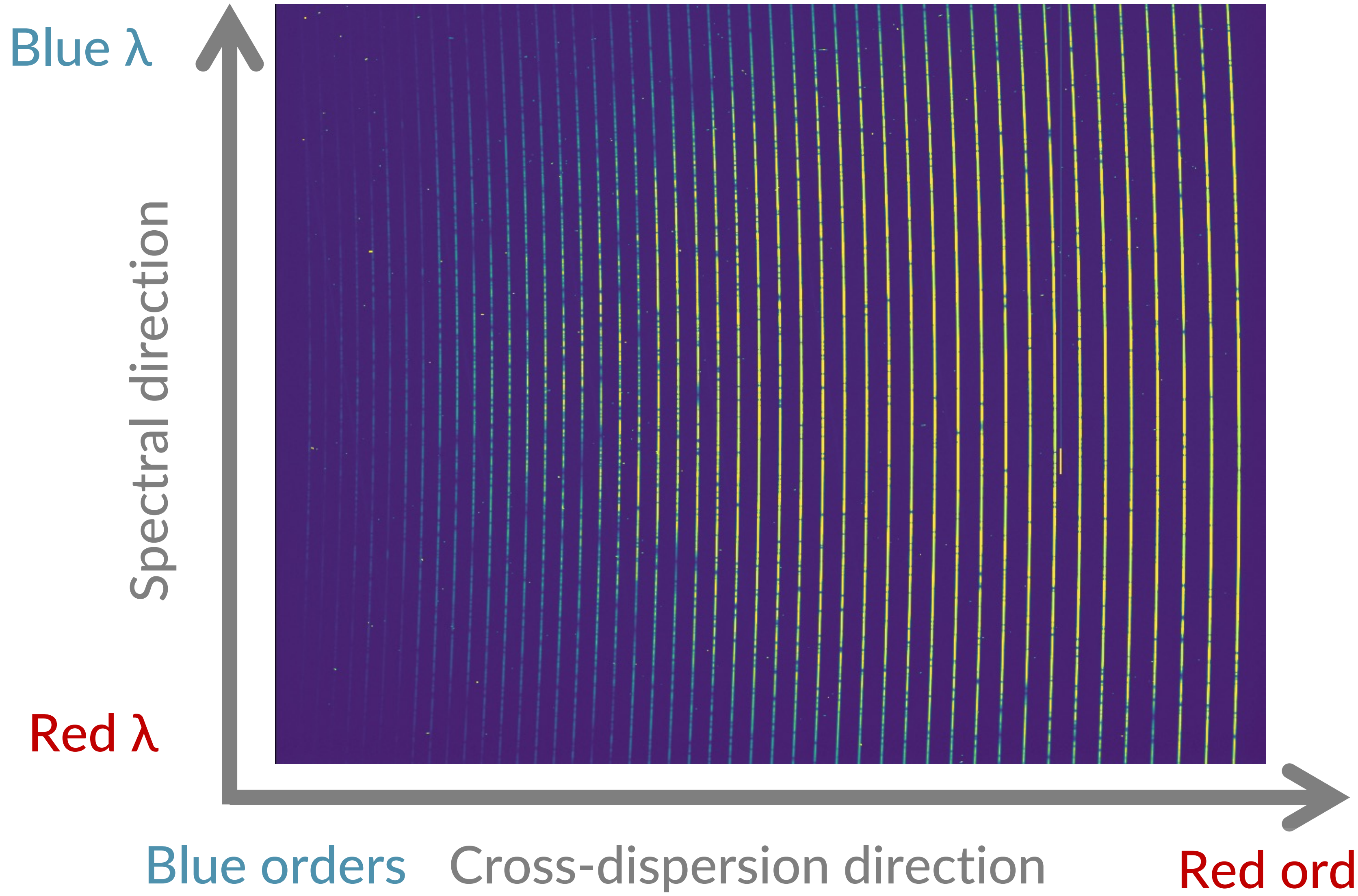


Example of a cross-dispersed spectrum



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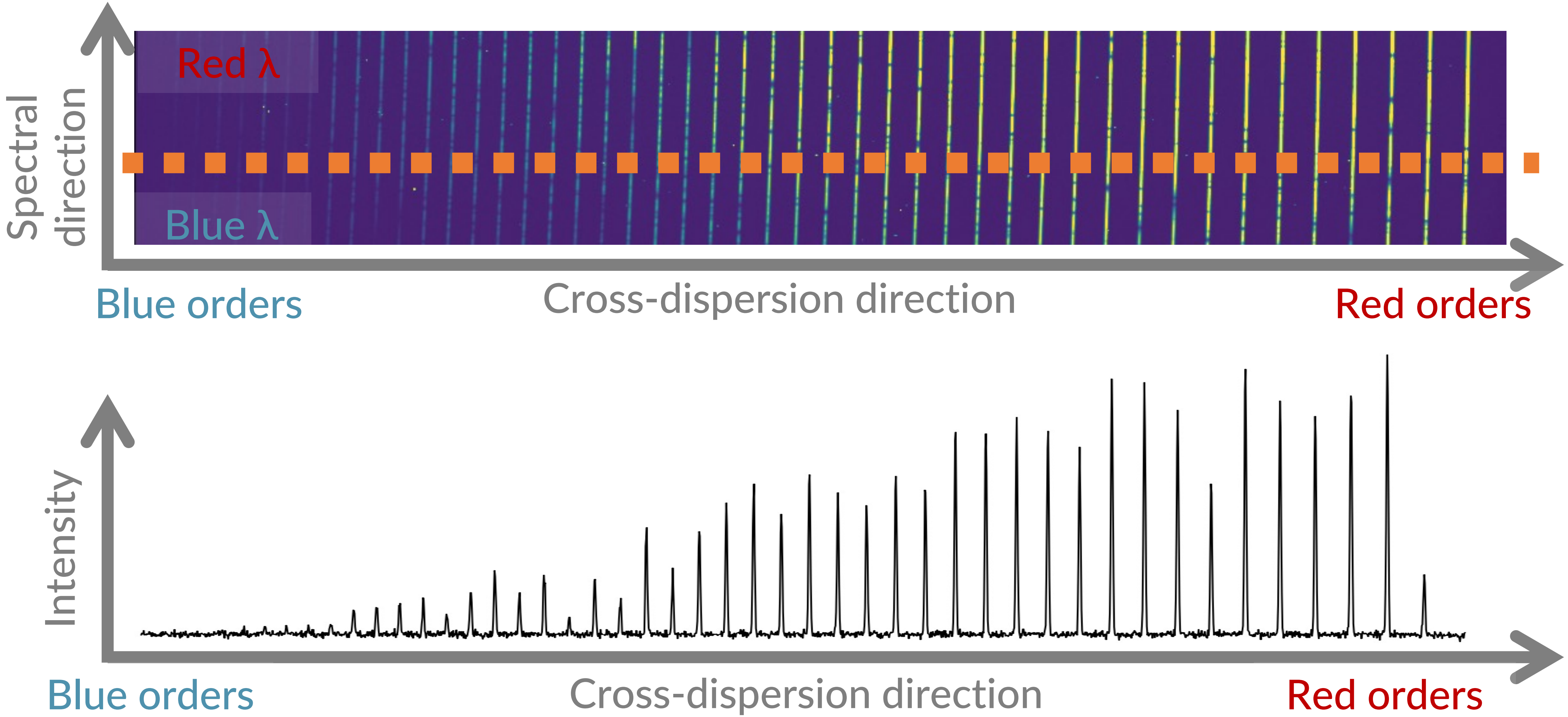

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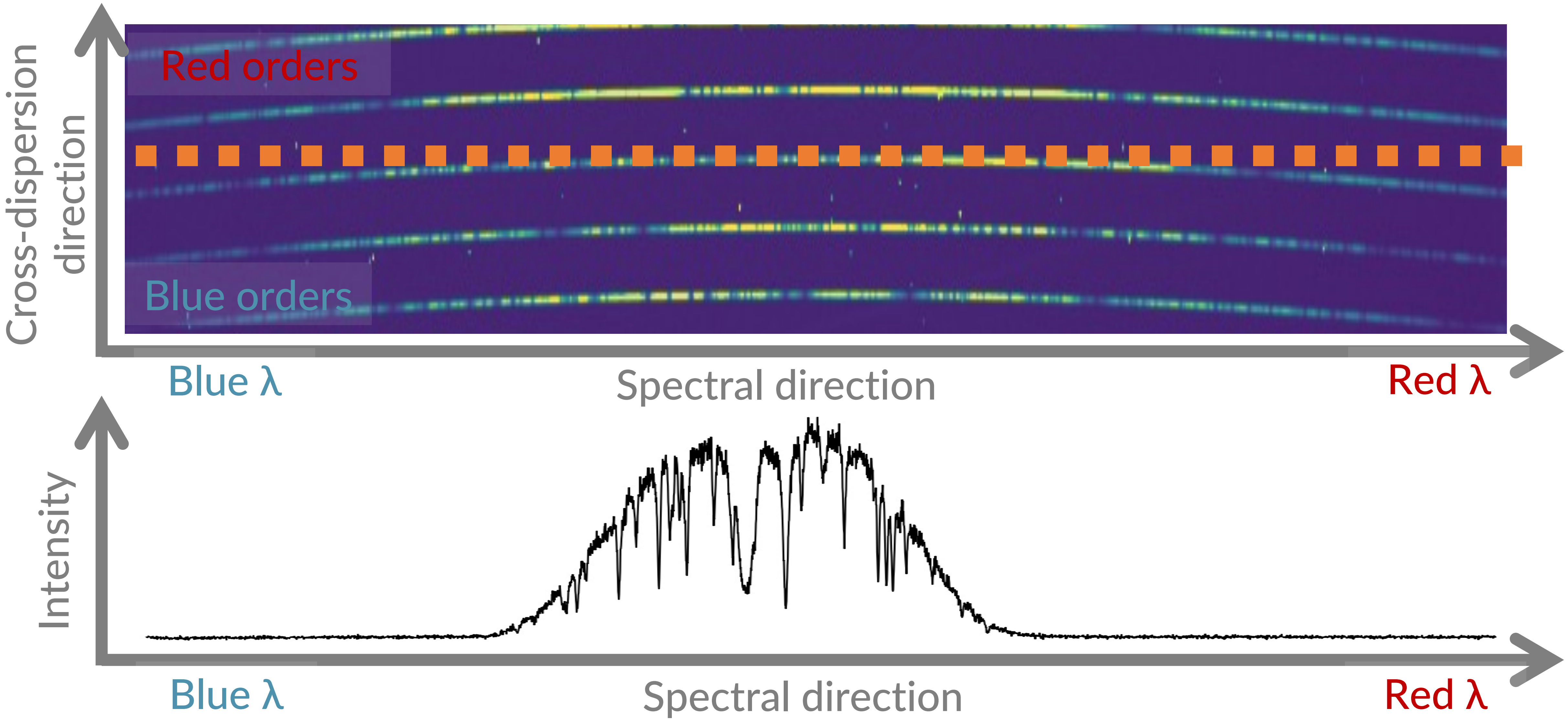
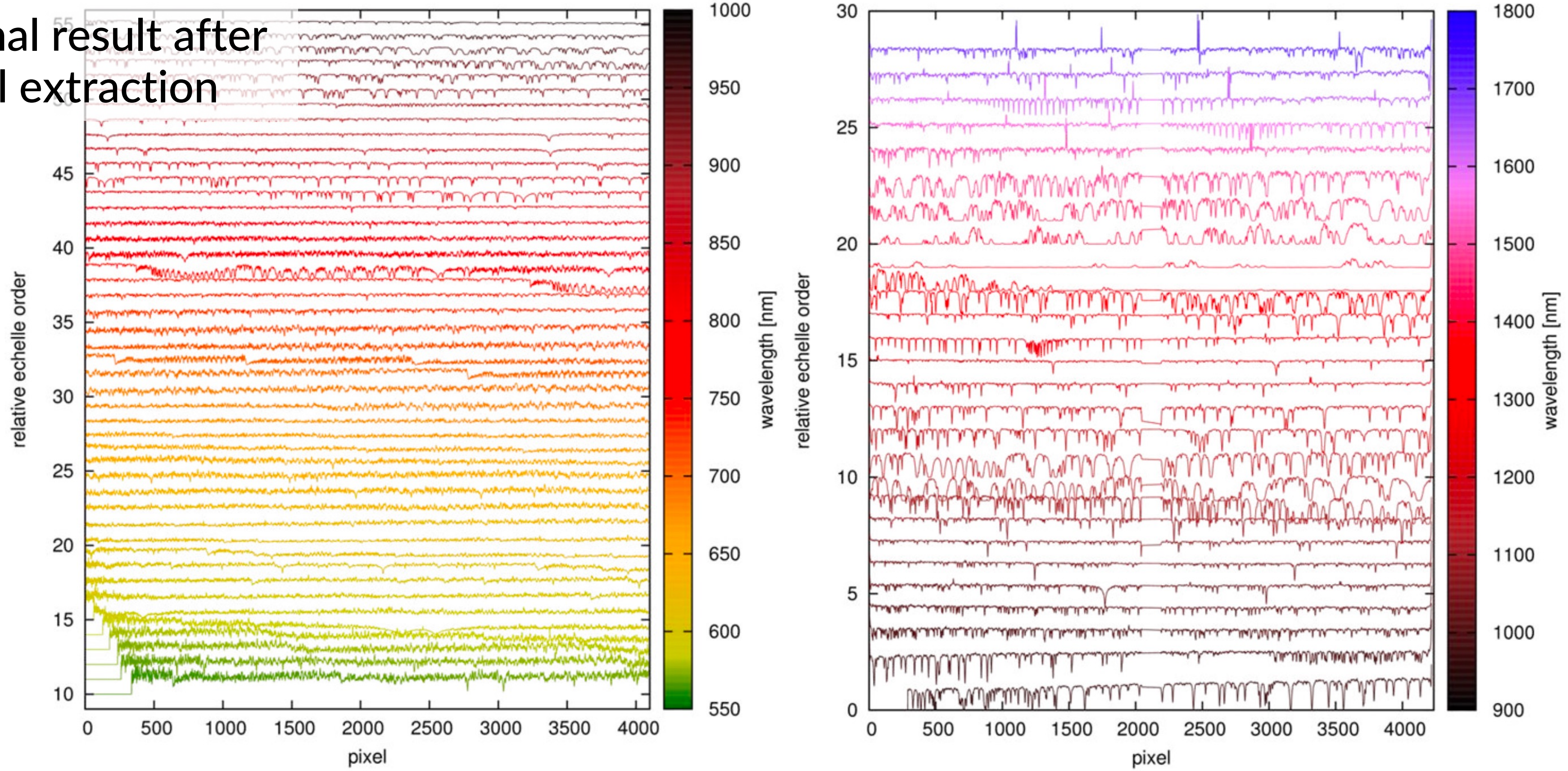


Example of a cross-dispersed spectrum

Final result after full extraction

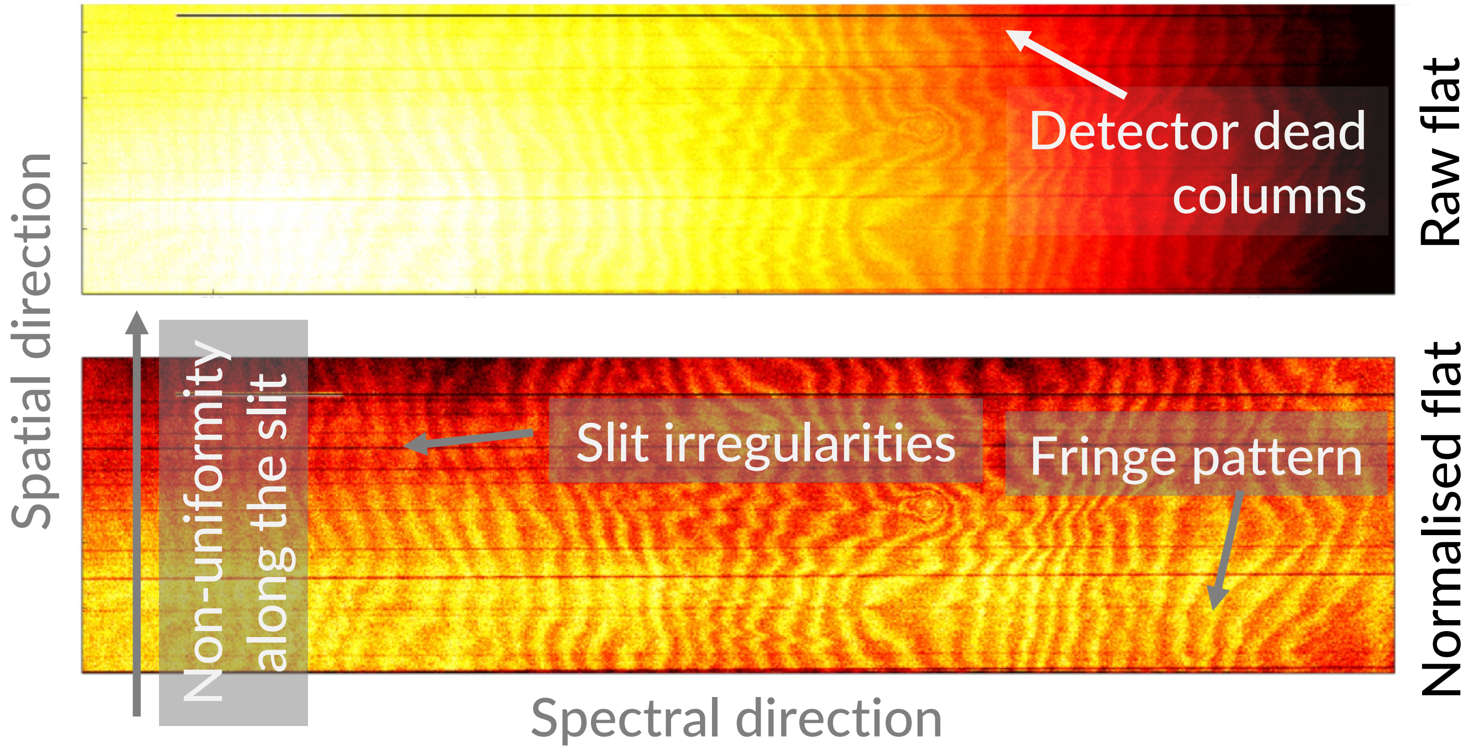


Quirrenbach et al. 2016

Extracting the spectrum

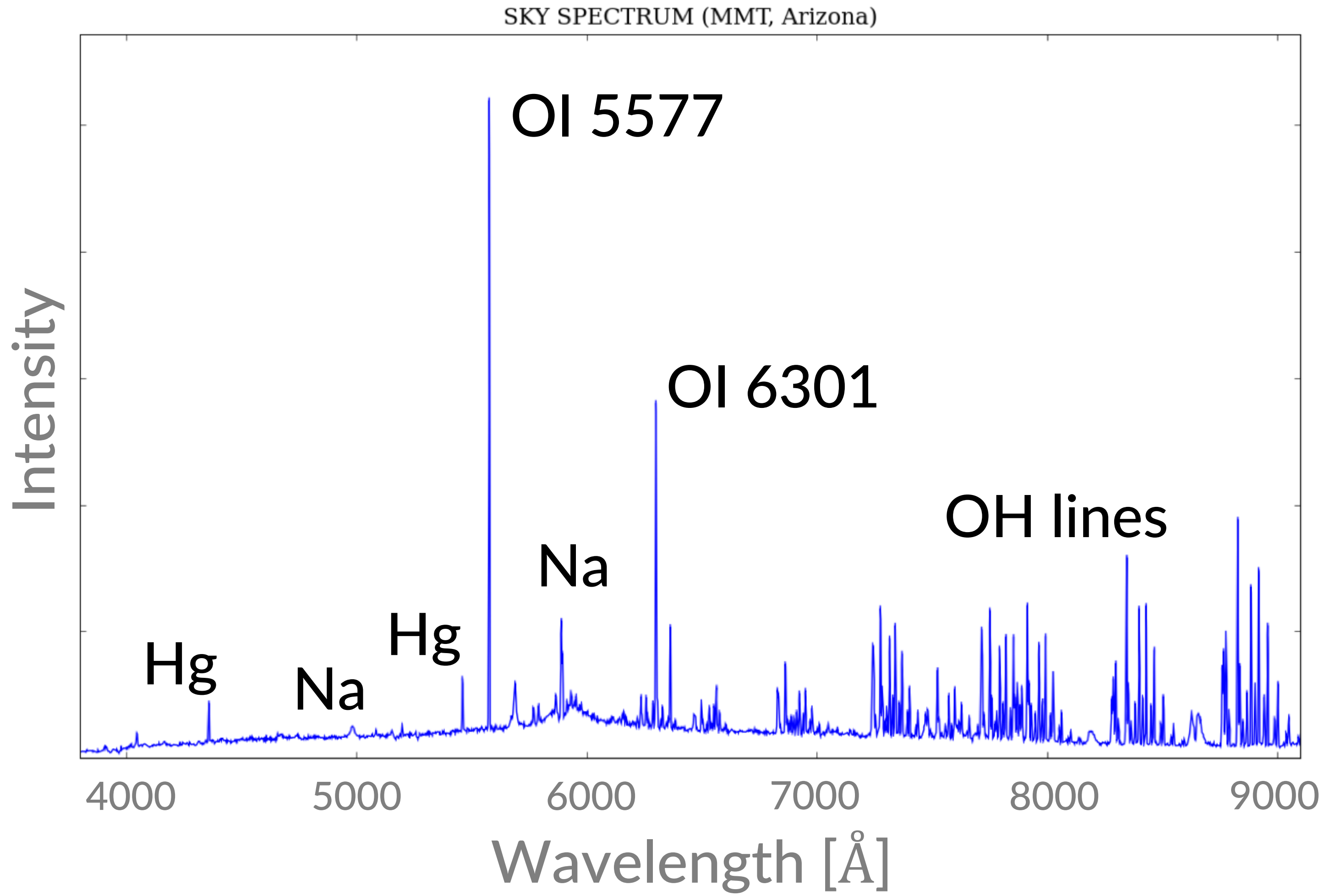
Calibrating the detector

- **Bias** & **Dark** frames are treated in the same way as for imaging
- Spectroscopic **flats** (with slit, light path as close as science observations)
  - Uniform illumination along slit & in the dispersion direction ⟹ Light source with a smooth and simple spectrum (e.g. tungsten lamp)
  - Correct by e.g. averaging along the spatial direction, fitting the spectrum, dividing out
  - Dome or twilight-sky flats for non-uniformity in spatial direction (do not help in spectral direction, with or without slit)
  - Creating a proper spectroscopic flat is complicated!
  - Sometimes flat-fielding can worsen the data



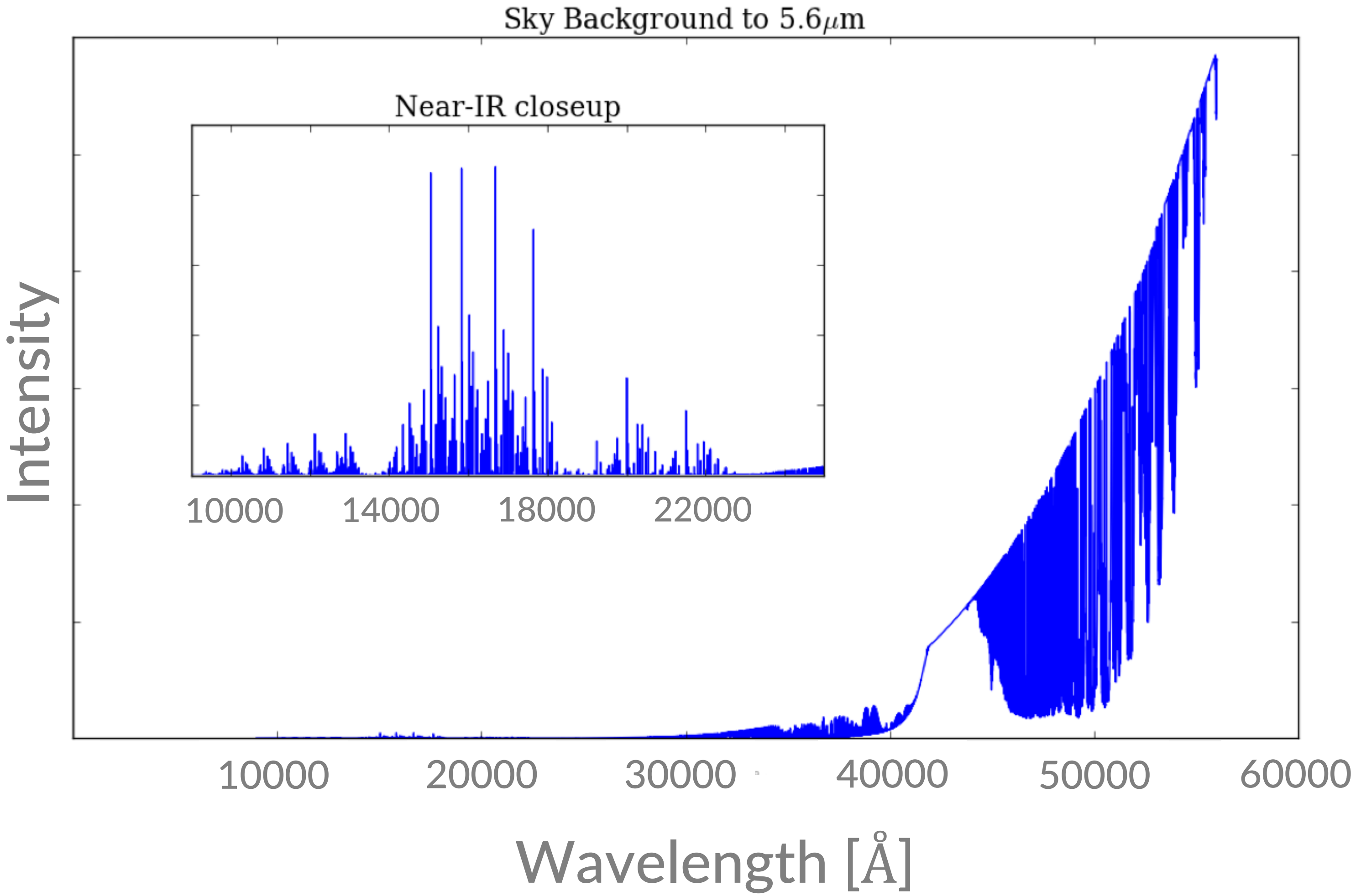
Sky background: Optical

- Background has contributions from many sources
  - Air glow: Strong, discrete emission lines (fluorescence of atmospheric OH, O, Na, & city lights Hg)
  - Zodiacal light
  - Sun/Moonlight
  - Auroare
  - Light pollution
  - Thermal emission from sky, telescope and buildings
  - Non-resolved astronomical background



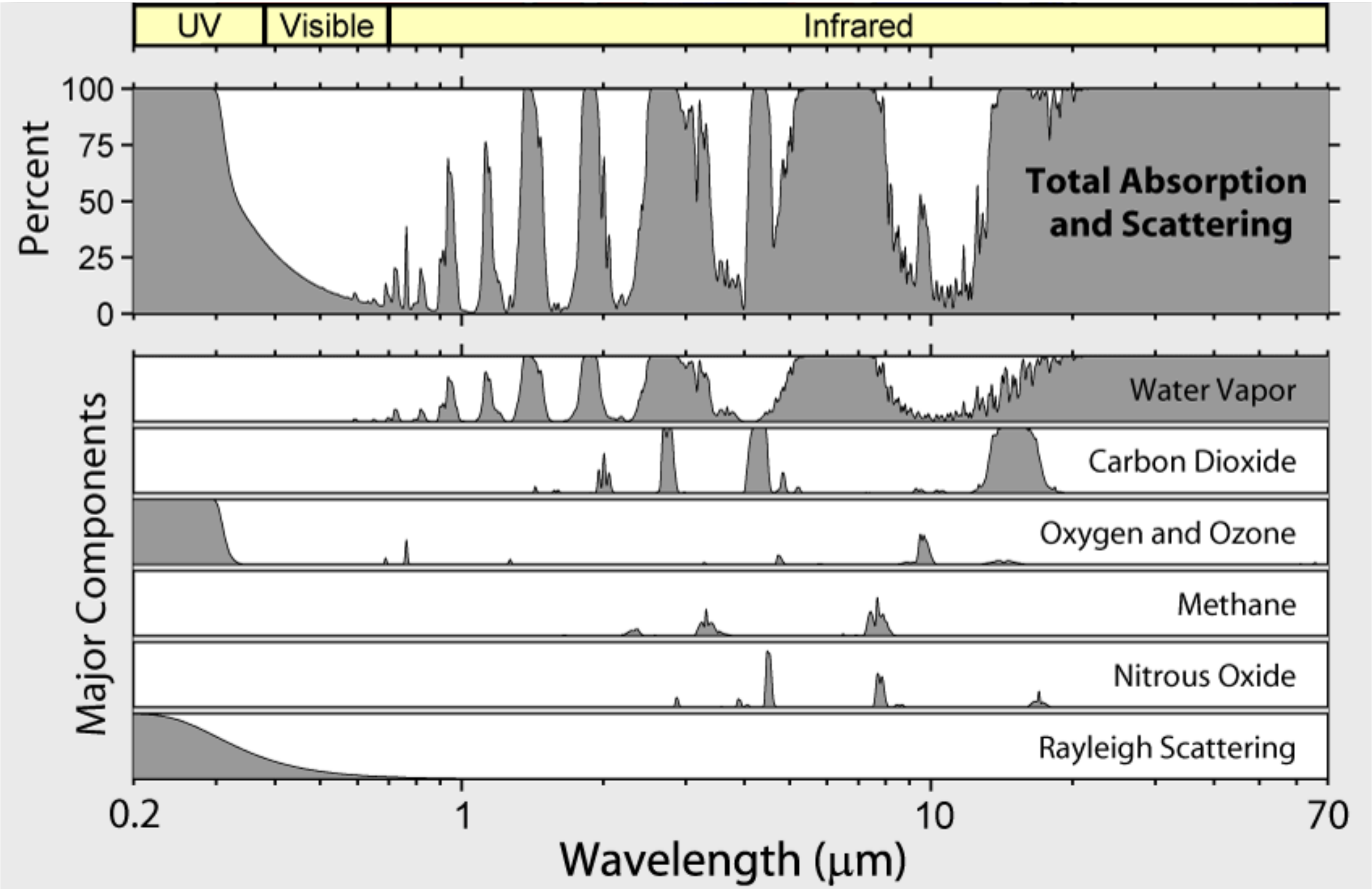
Sky background: Infrared

- Thermal emission from the sky, ground and telescope dominates
- Observations become very challenging for. $\lambda > 5\ \mu m$

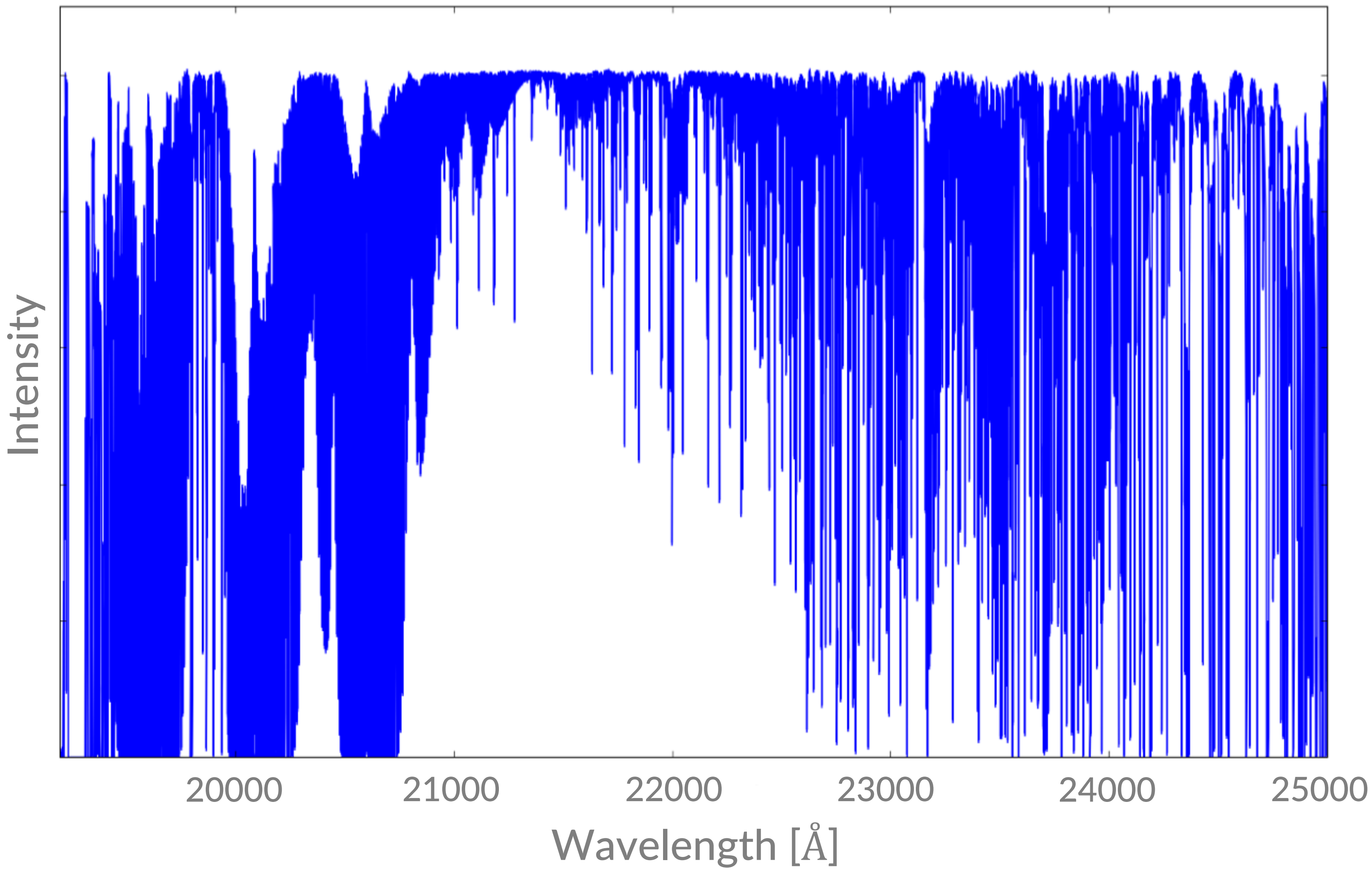


Atmospheric transmission

- Atmospheric transmission strongly depends on λ
- Source spectrum will be imprinted by Earth's transmission spectrum
- At visible wavelengths Earth atmosphere almost transparent



Atmospheric transmission: Telluric spectrum



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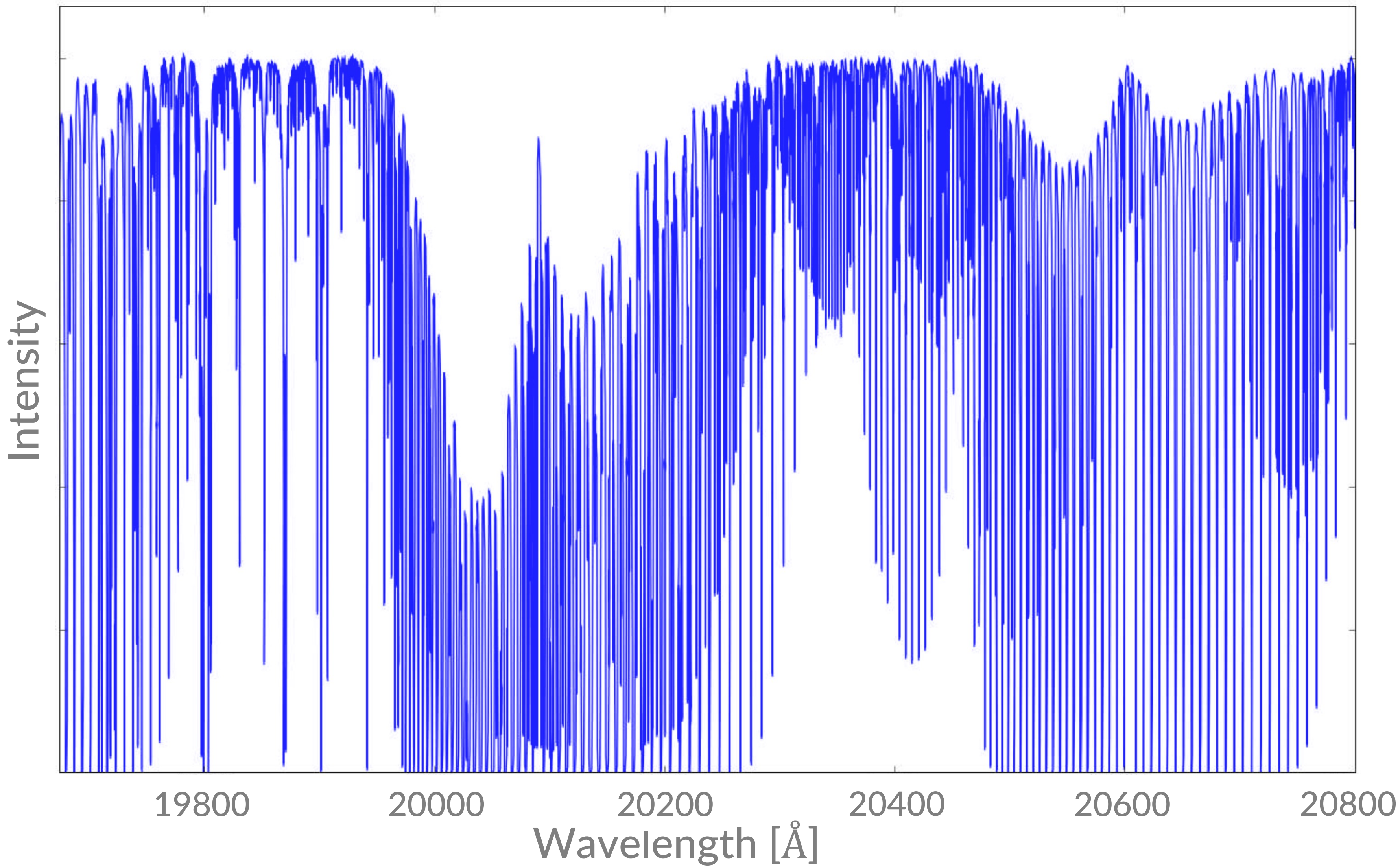
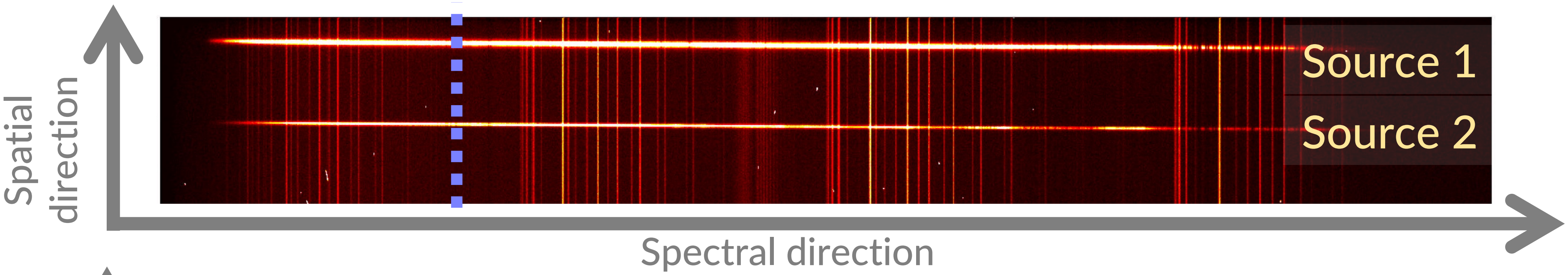
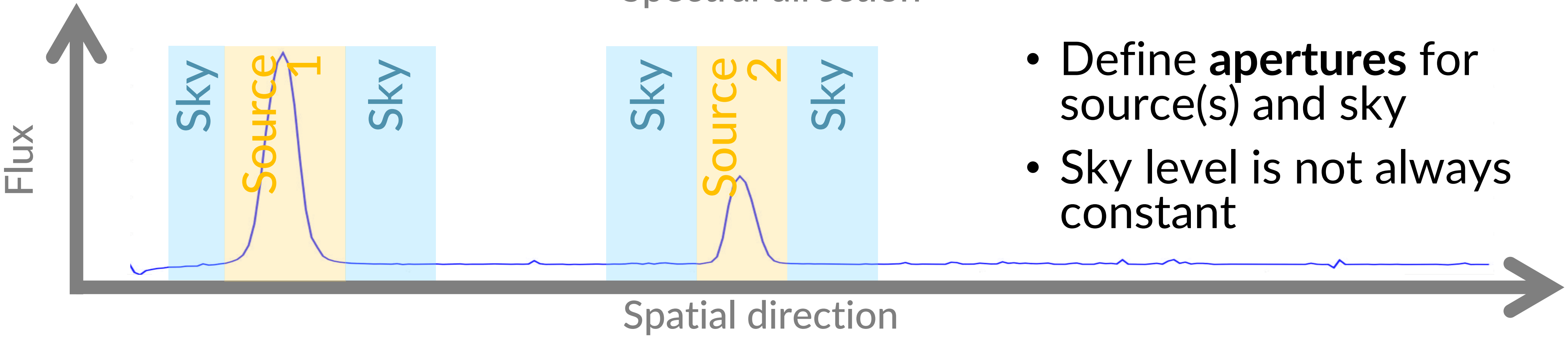


Extracting long-slit spectra



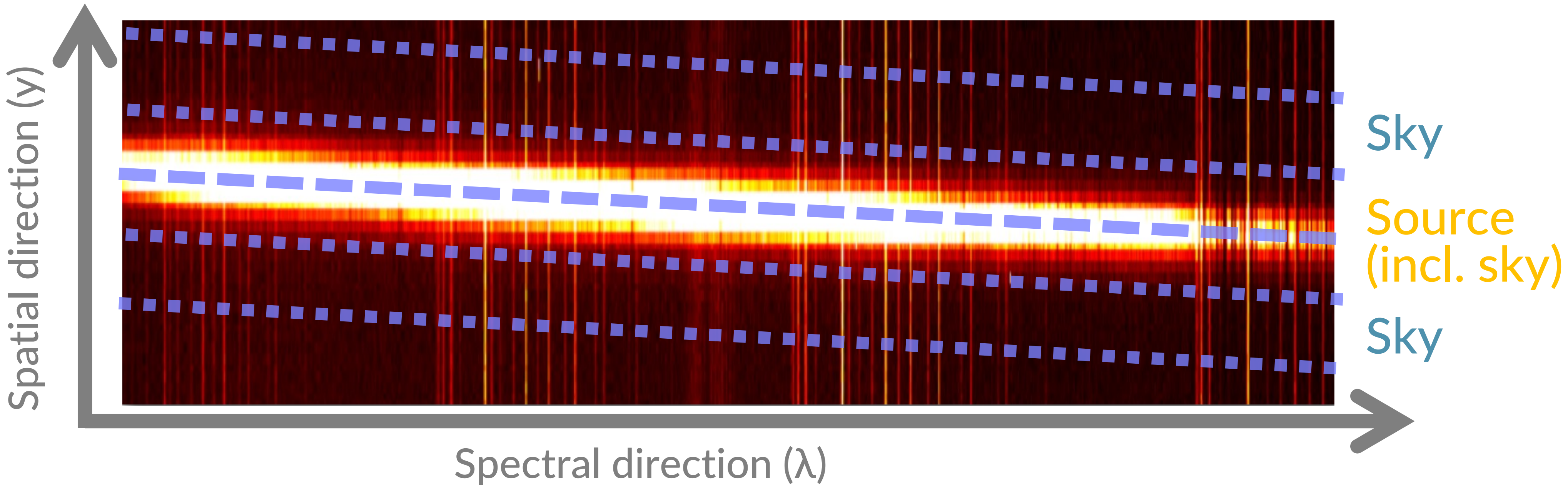


- Define **apertures** for source(s) and sky
- Sky level is not always constant

$$\text{Signal} = (\text{object} + \text{background}) - \text{background}$$

Source | Sky

Extracting long-slit spectra



$$\text{Spectrum}(\lambda) = \sum_{y,aperture}\left[\left(source(y,\lambda) - sky(y,\lambda)\right) * weight(y,\lambda)\right]$$

- Challenge: **Spectral trail** can be **tilted** with respect to the spectral direction
- Challenge: **Sky lines** can be **tilted** with respect to the spatial direction
- Optimal extraction: weight by a smoothed 2D profile (Horne 1986)

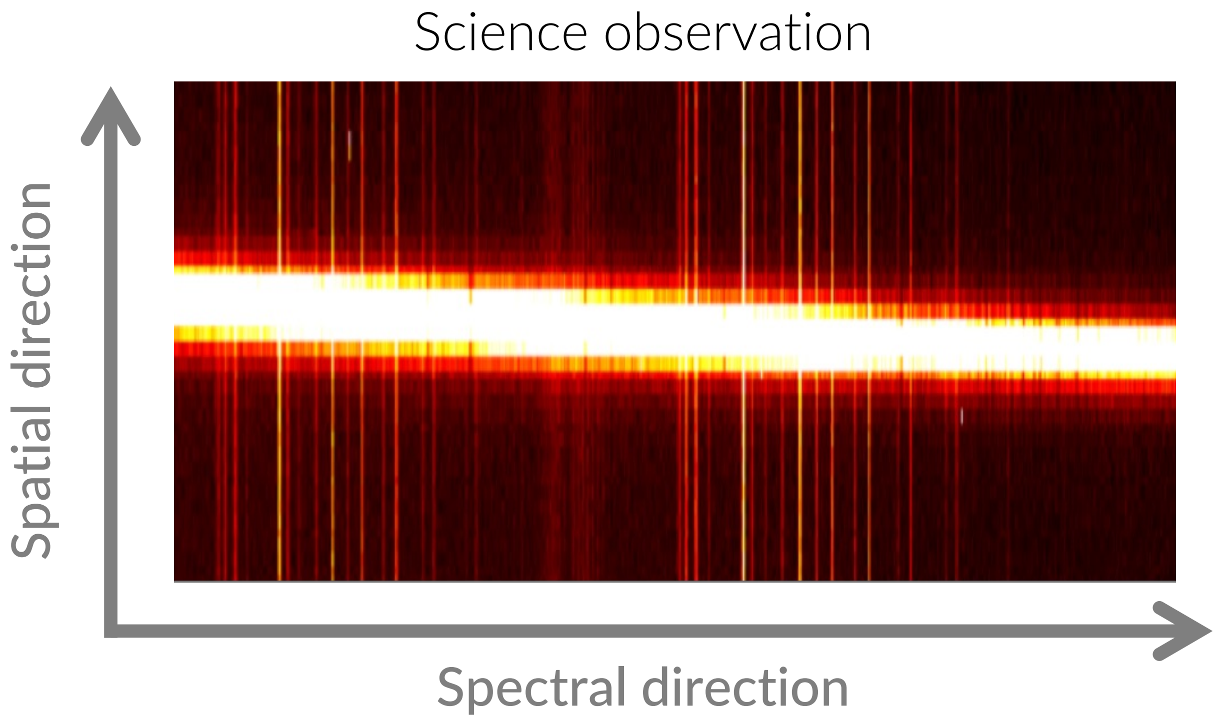
Wavelength calibration: from pixel to λ

- Associate a wavelength to each of the pixels along the spectral direction
- Requires a **reference spectrum** with known wavelengths

Sky emission lines
- Simultaneous, observer reference frame
- Not accurate with very wide slits

Sky absorption lines
- Simultaneous, observer reference frame
- Few lines in optical, fine in near-infrared

Stellar spectral lines
- Simultaneous, stellar frame



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Gas absorption cell in optical path
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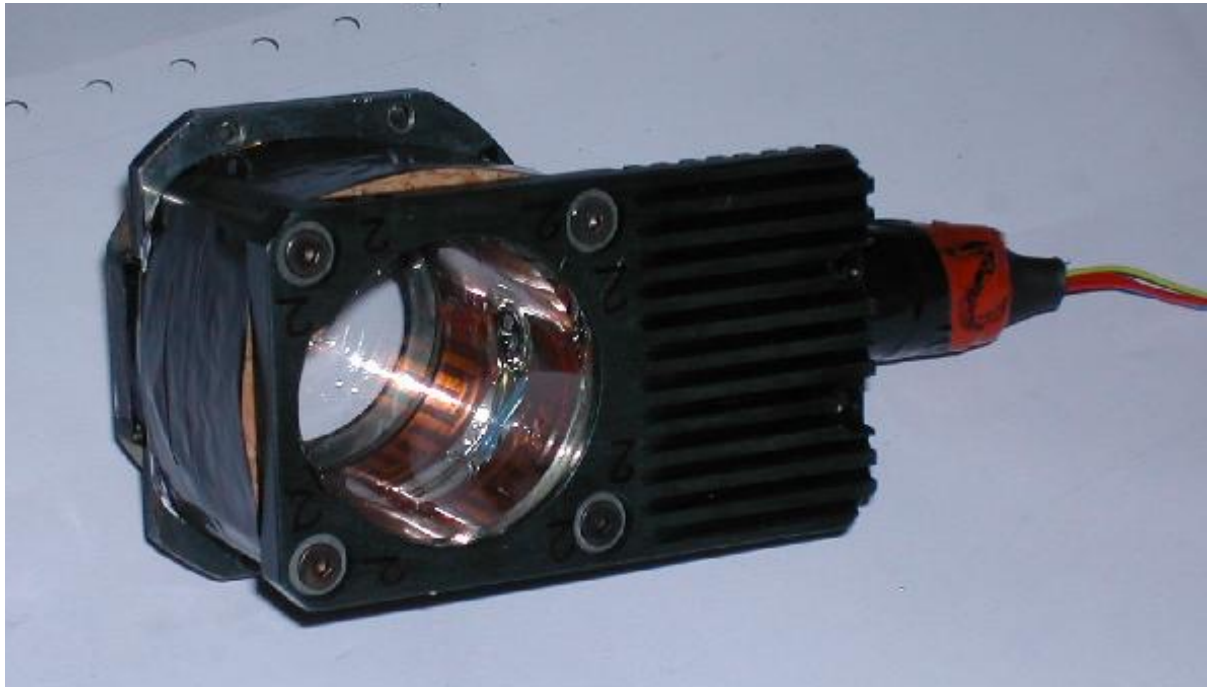
- Reduces amount of photons from source
- Very accurate (m/s)

HARPS Iodine cell



https://www.eso.org/sci/facilities/lasilla/instruments/harps/inst/description.html

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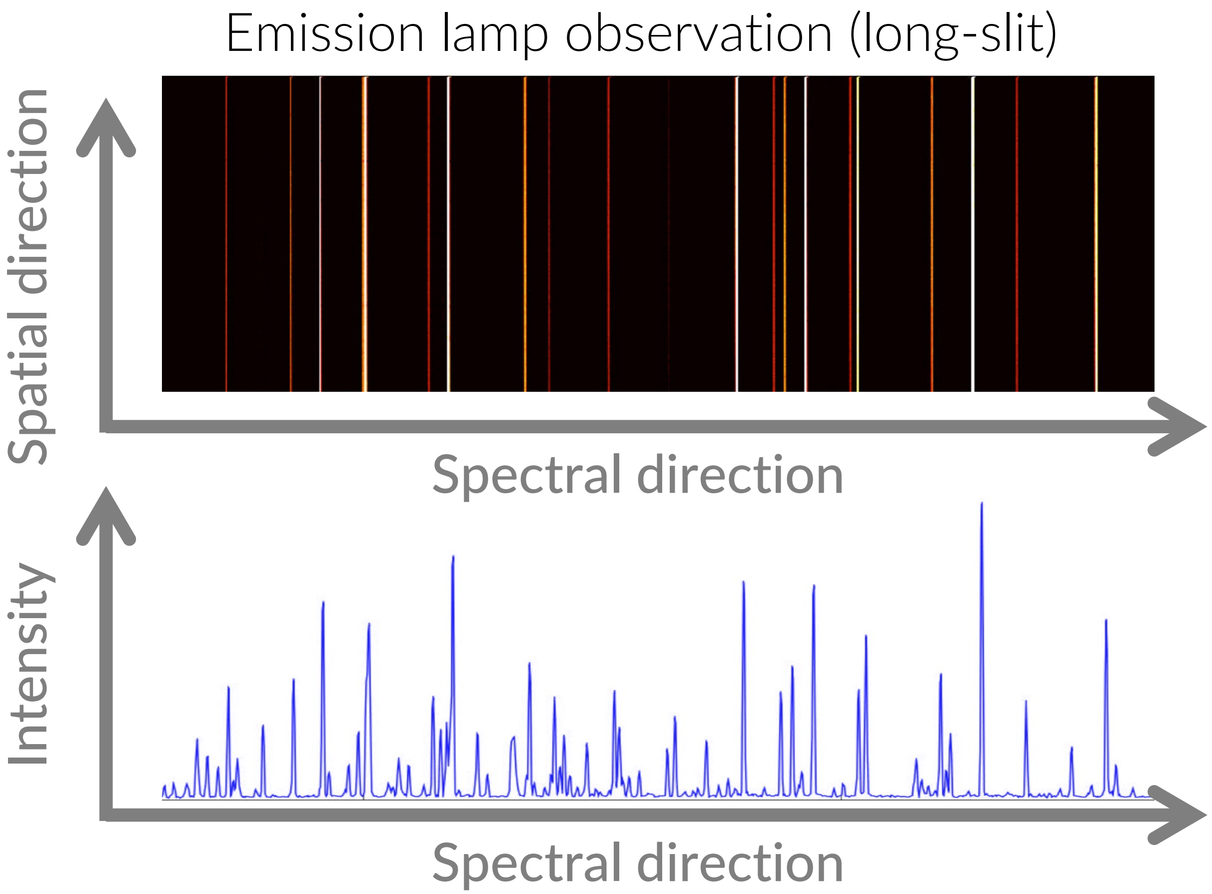
Emission line lamps (arcs): Ar, Th, He, Ne, Cu…
- Not always simultaneous, observer reference frame
- Stable source, very accurate (m/s)



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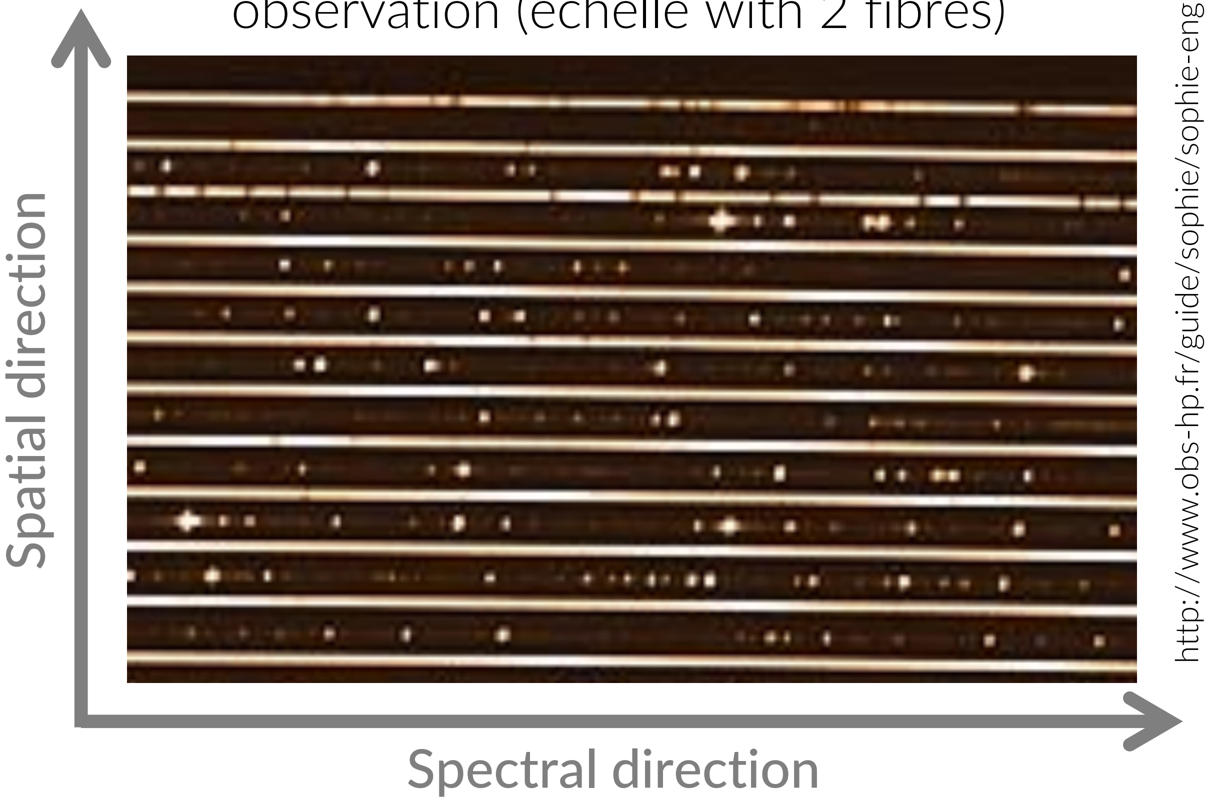
Simultaneous target and emission lamp observation (echelle with 2 fibres)



http://www.obs-hp.fr/guide/sophie/sophie-eng.shtml

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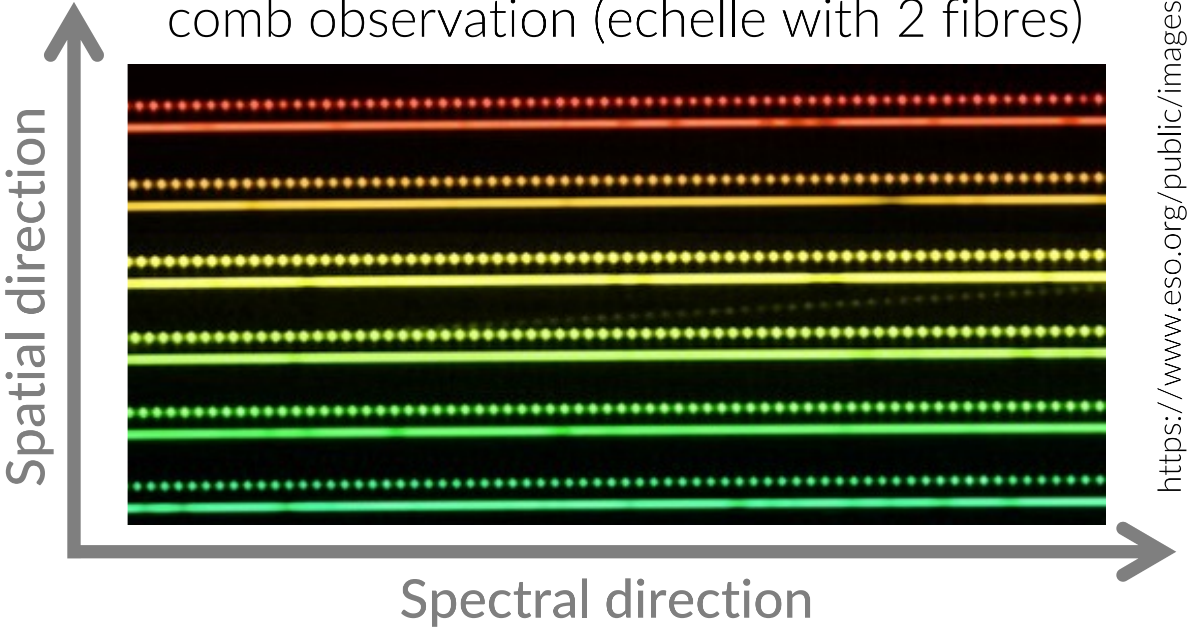
Fabry-Perot & Laser frequency comb
- Simultaneous, observer reference frame
- Very stable, very accurate

Simultaneous target and laser frequency comb observation (echelle with 2 fibres)



https://www.eso.org/public/images/ann12037a/

Wavelength calibration: from pixel to λ

- Associate a wavelength to each of the pixels along the spectral direction
- Requires a **reference spectrum** with known wavelengths

Sky emission lines
- Simultaneous, observer reference frame
- Not accurate with very wide slits

Sky absorption lines
- Simultaneous, observer reference frame
- Few lines in optical, fine in near-infrared

Stellar spectral lines
- Simultaneous, stellar frame

Gas absorption cell in optical path
- Simultaneous, observer reference frame
- Reduces amount of photons from source
- Very accurate (m/s)

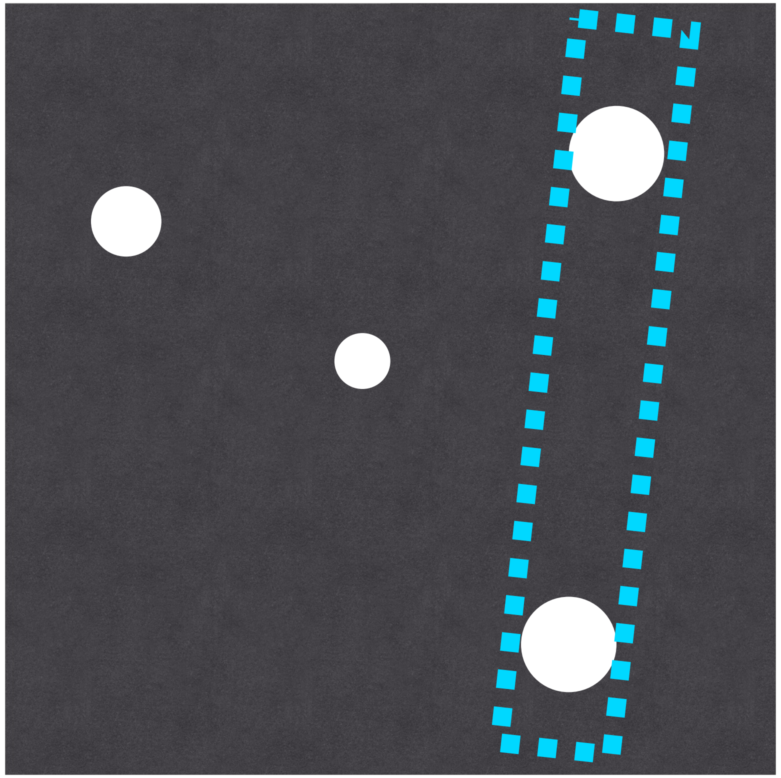
Emission line lamps (arcs): Ar, Th, He, Ne, Cu…
- Not always simultaneous, observer reference frame
- Stable source, very accurate

Fabry-Perot & Laser frequency comb
- Simultaneous, observer reference frame
- Very stable, very accurate

Instrument flexures, seeing/pointing variations, temperature and pressure changes… all influence the wavelength solution

Flux calibration: from counts to flux

- Convert the measured counts into fluxes
- Requires a reference spectrum with known fluxes as a function of λ (spectrophotometric standard star), usually a hot star
- Differential spectrophotometry
- Also useful for correcting telluric absorption (hot star spectrum is almost featureless)



Dos & don’ts when working with data

- **Instrument manuals** are the best resource to learn about spectrographs (also **literature** using the same instrument)
- Always **visually inspect** calibration and science frames for quality check (**plot, plot, plot!**)
- **Instrument pipelines** & software packages are extremely useful, but do not use them as **black boxes** (but do not reinvent the wheel either)
- **Tune** the reduction/analysis to your science
- Know your **noise** (read-out noise + Poisson noise + background noise + systematics) and S/N regime

Assignment

Long-slit spectroscopy with

ACAM (Auxiliary-port CAMera)

at the 4.2 m WHT
(William Herschel Telescope)

in La Palma, Canary Islands, Spain

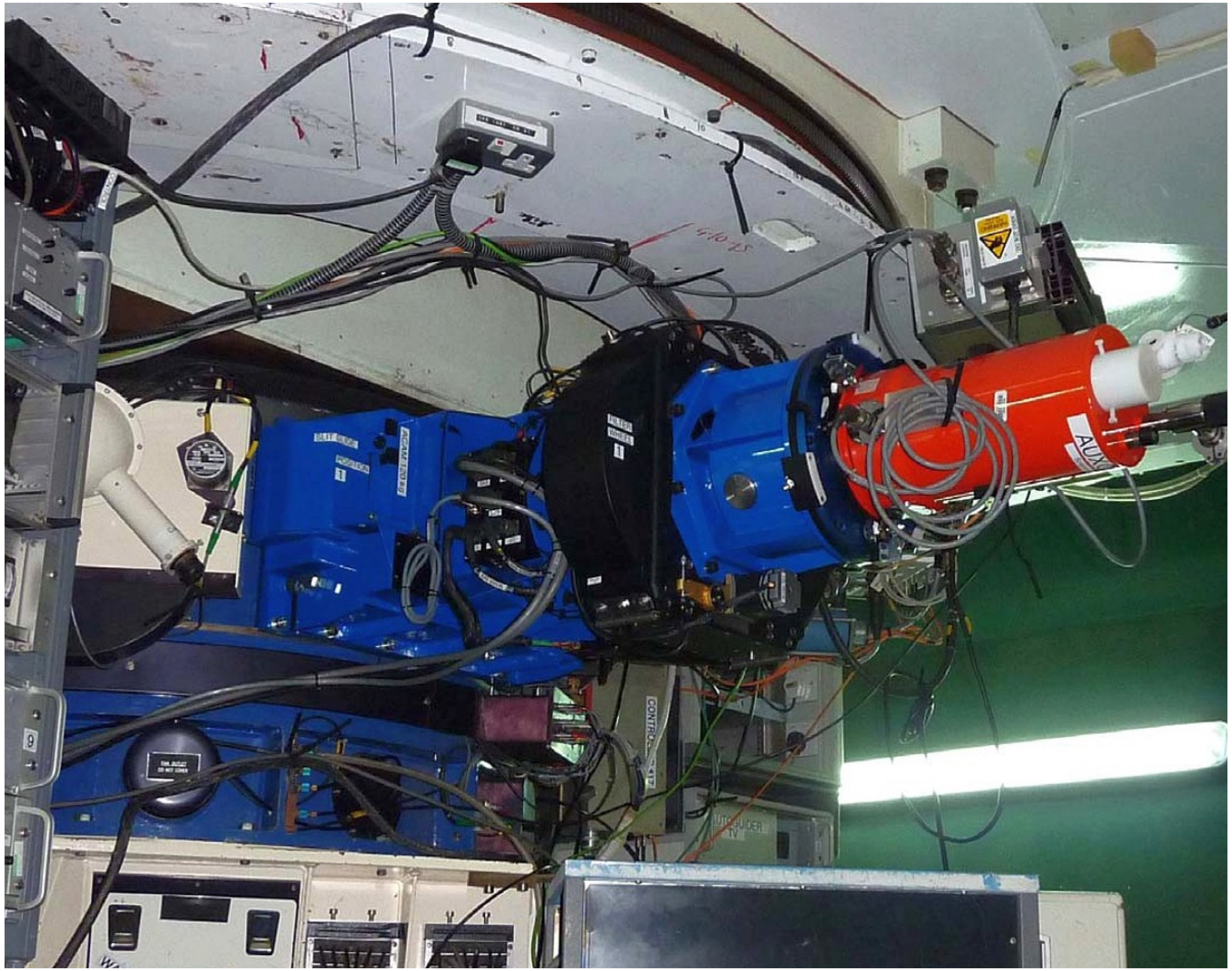
- ACAM mounted at WHT Cassegrain focus → flexures during telescope pointing
- ACAM does photometry (variety of filters) and low-resolution spectroscopy (**R < 900**) between **350 and 940 nm**

https://www.ing.iac.es/Astronomy/instruments/acam/

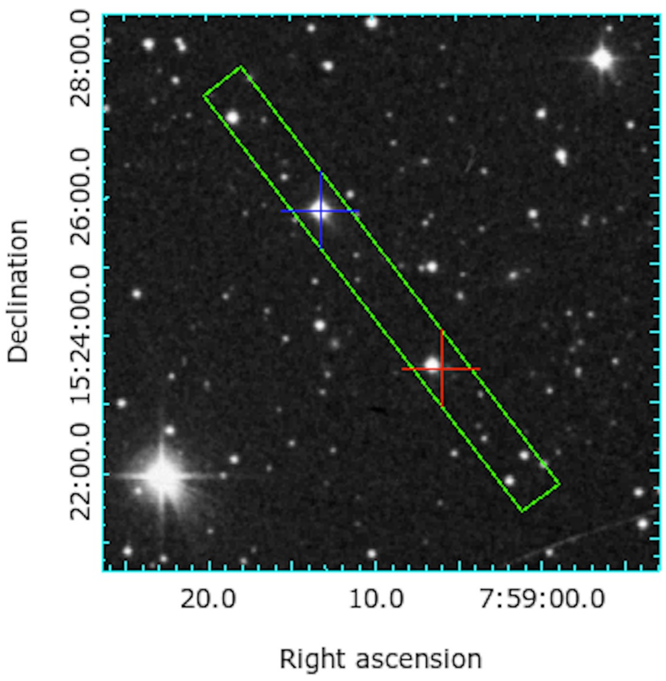
https://www.ing.iac.es/Astronomy/instruments/acam/spectroscopy.html

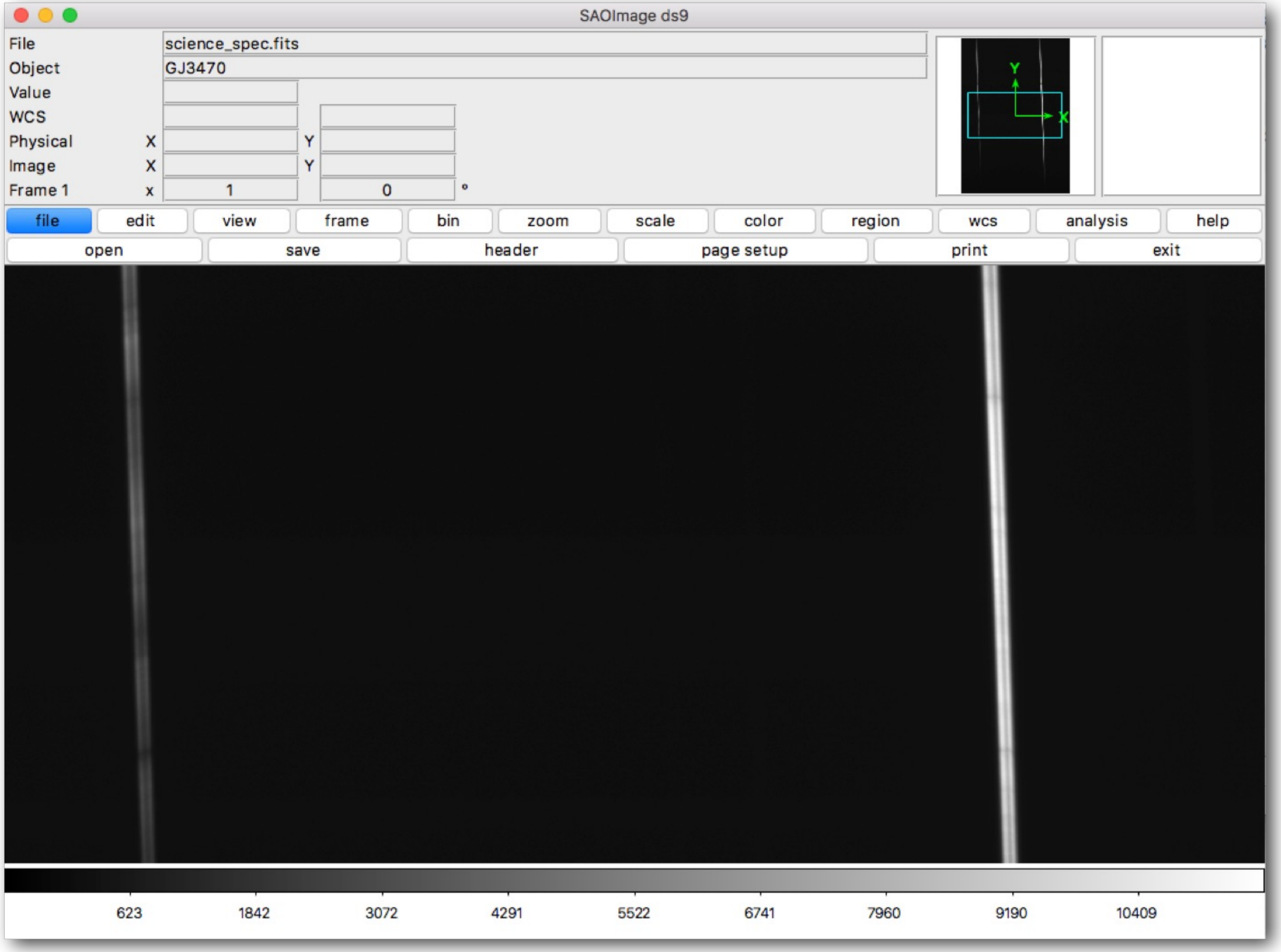
https://www.ing.iac.es/Astronomy/telescopes/wht/

Assignment

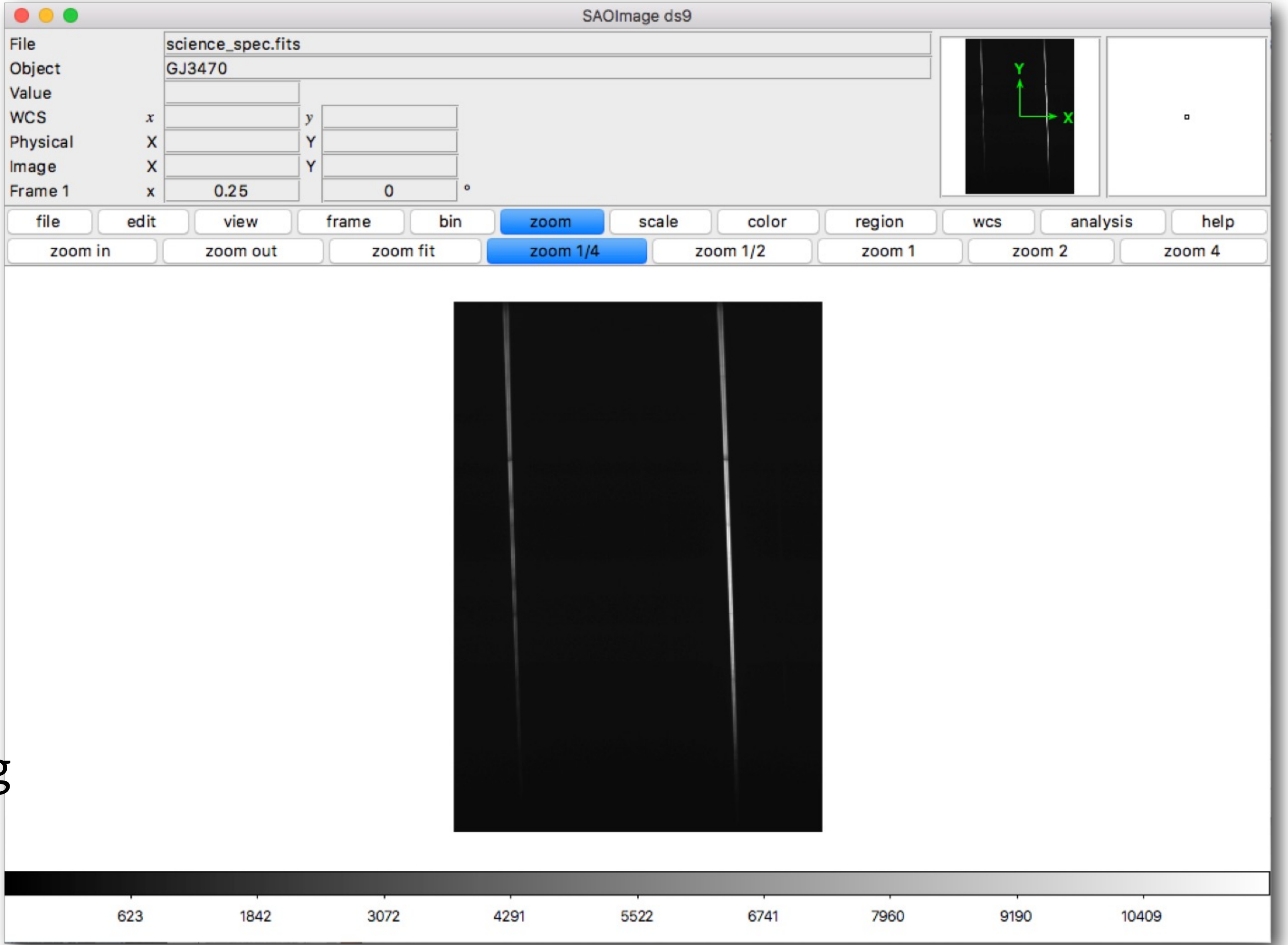


Assignment



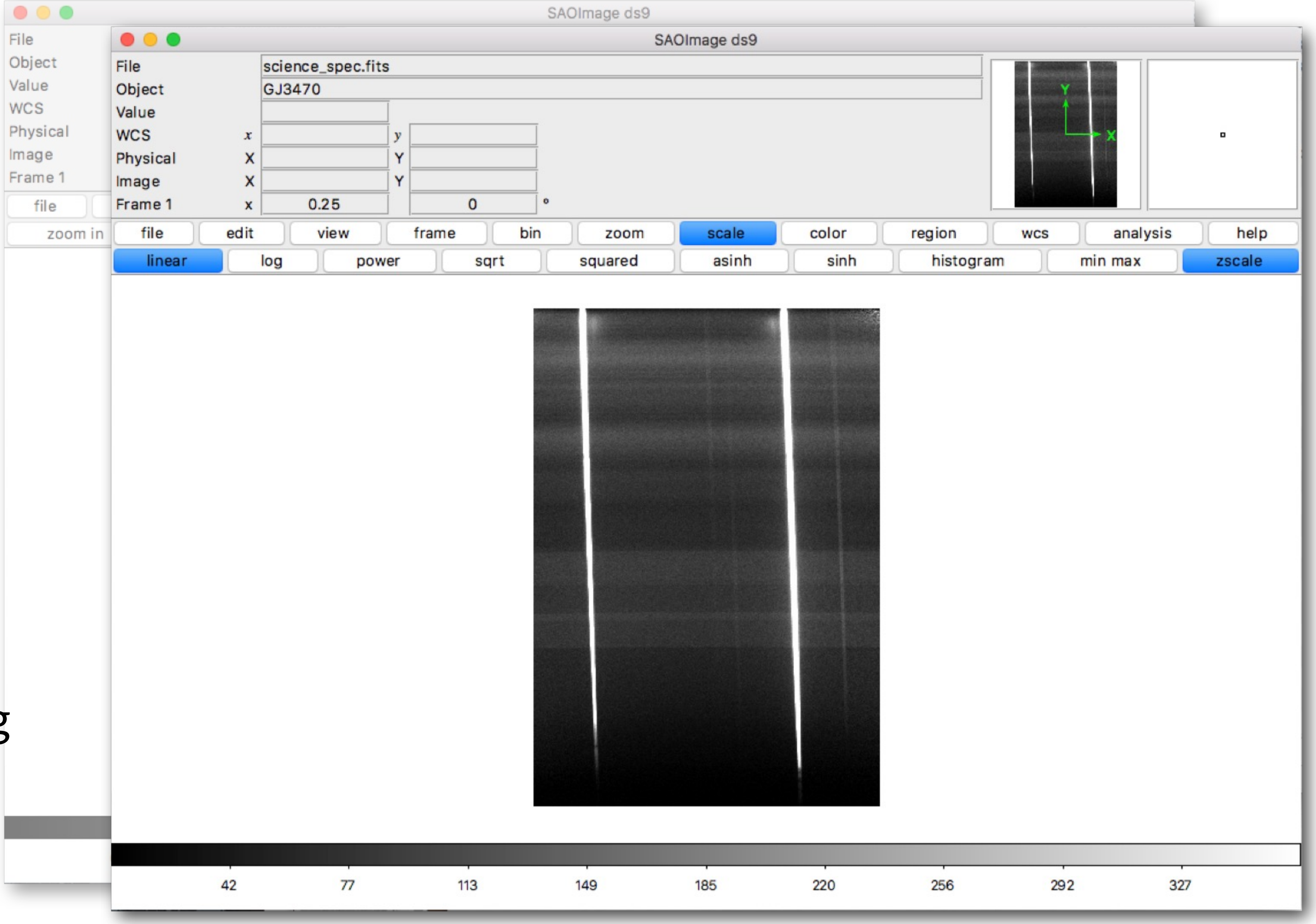


Visualising ACAM spectra in DS9

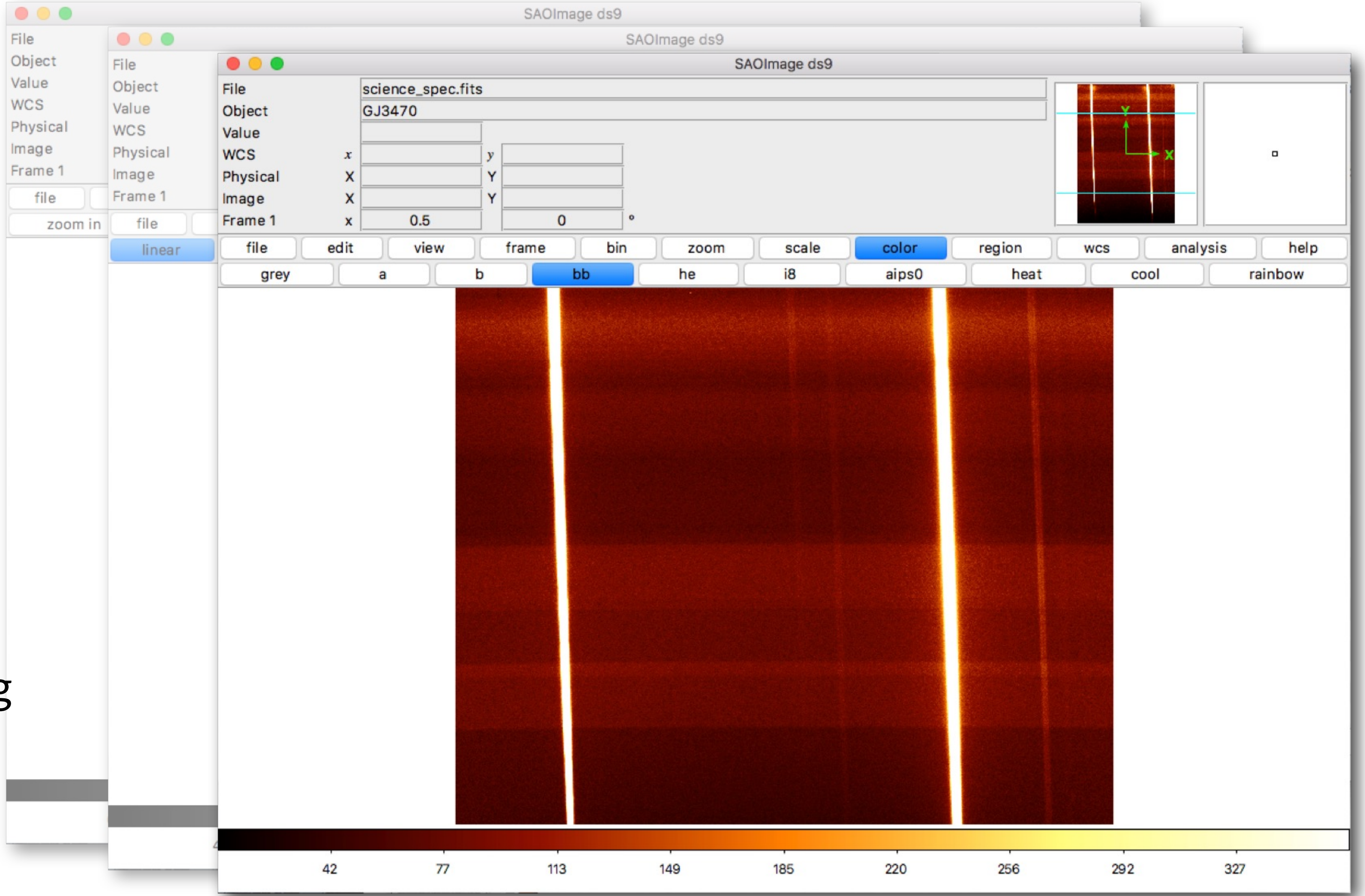


Visualising ACAM spectra in DS9

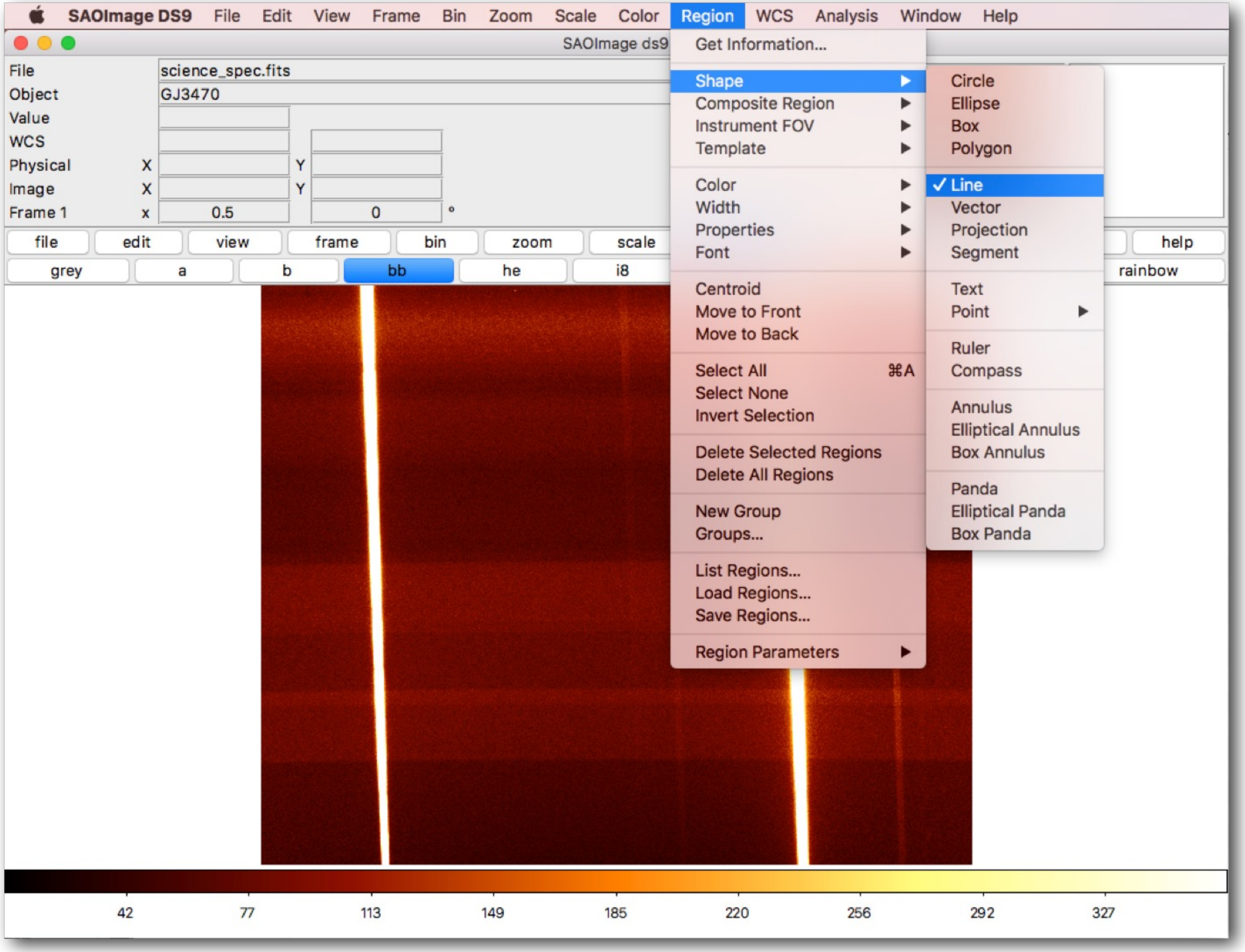
Visualising ACAM spectra in DS9



Visualising ACAM spectra in DS9



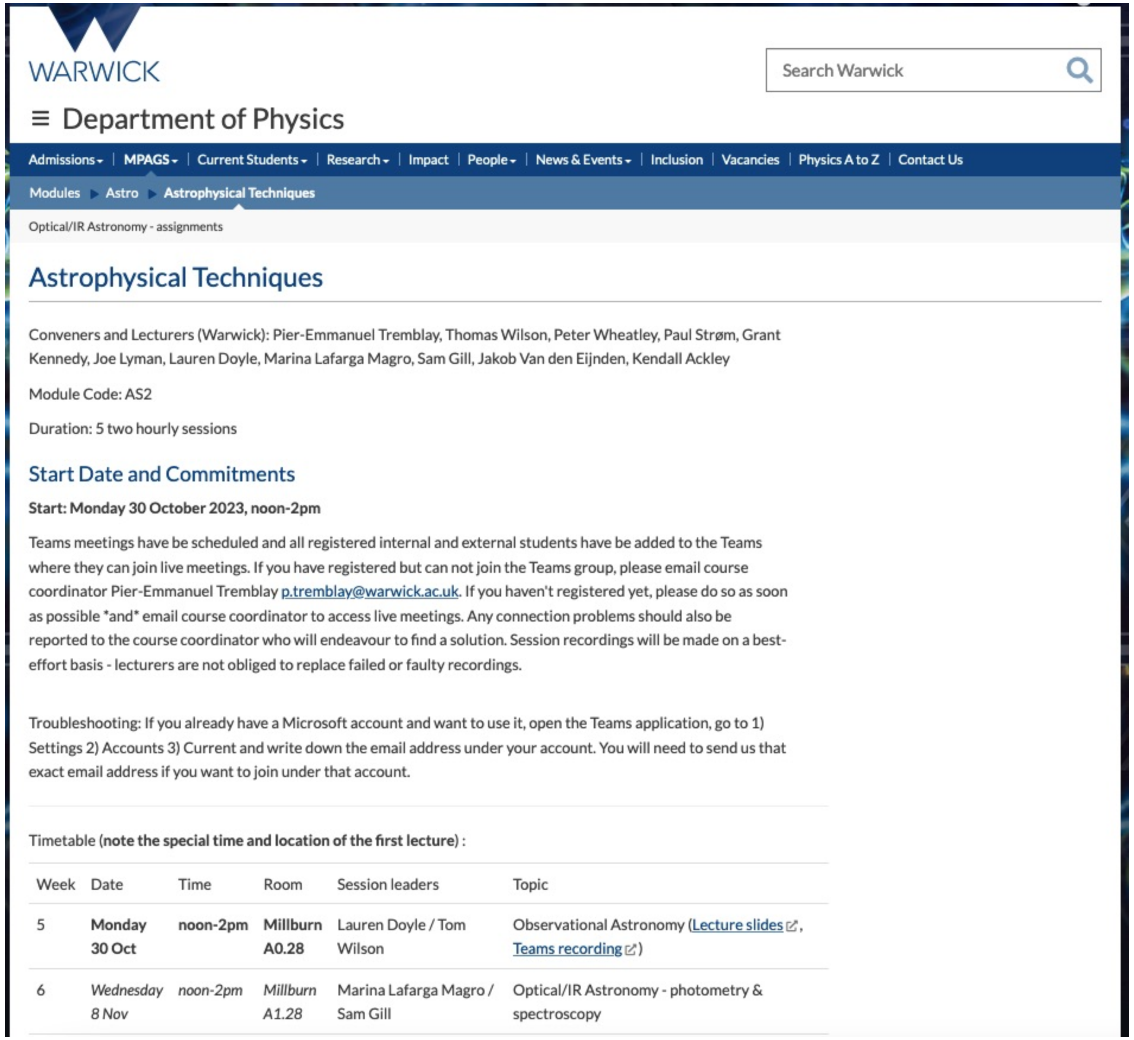
Useful DS9 tools: Regions



Assignment checklist

- Have **DS9** and **Python** installed (code written in Python 3)
- **DS9** self-explanatory: just play around with the interface and try different options
- All the instructions and questions to answer are in the Jupyter notebook
- Make sure you have basic python libraries (**numpy** for manipulating arrays, **matplotlib** for plotting)

https://warwick.ac.uk/fac/sci/physics/mpags/modules/astro/at/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Modules ▸ Astro ▸ Astrophysical Techniques

Optical/IR Astronomy - assignments

Astrophysical Techniques

Conveners and Lecturers (Warwick): Pier-Emmanuel Tremblay, Thomas Wilson, Peter Wheatley, Paul Strøm, Grant Kennedy, Joe Lyman, Lauren Doyle, Marina Lafarga Magro, Sam Gill, Jakob Van den Eijnden, Kendall Ackley

Module Code: AS2

Duration: 5 two hourly sessions

Start Date and Commitments

Start: Monday 30 October 2023, noon-2pm

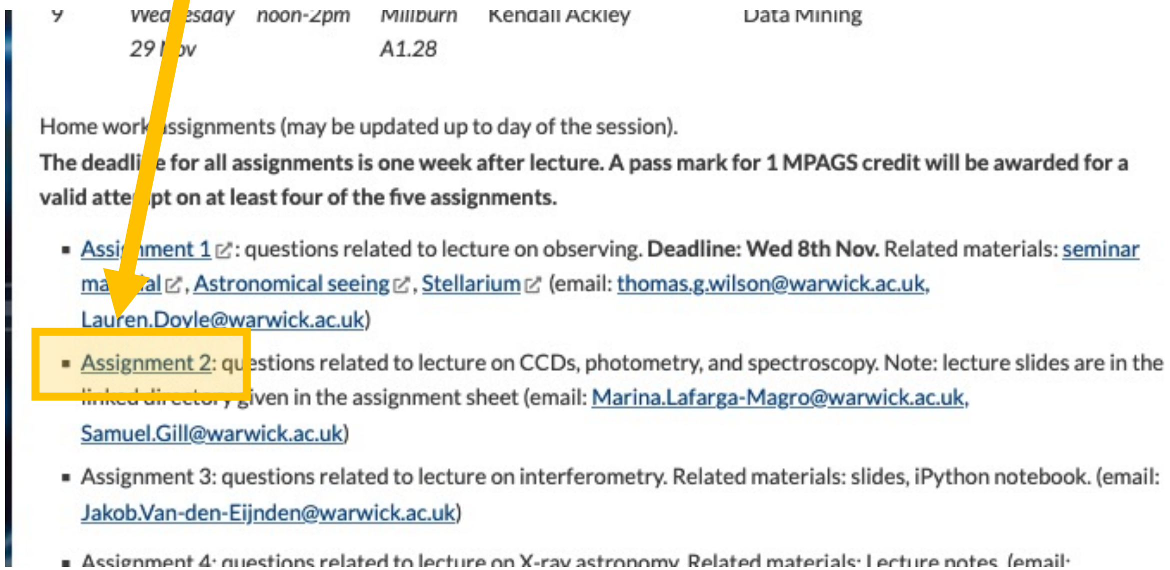
Teams meetings have be scheduled and all registered internal and external students have be added to the Teams where they can join live meetings. If you have registered but can not join the Teams group, please email course coordinator Pier-Emmanuel Tremblay p.tremblay@warwick.ac.uk. If you haven't registered yet, please do so as soon as possible *and* email course coordinator to access live meetings. Any connection problems should also be reported to the course coordinator who will endeavour to find a solution. Session recordings will be made on a best-effort basis - lecturers are not obliged to replace failed or faulty recordings.

Troubleshooting: If you already have a Microsoft account and want to use it, open the Teams application, go to 1) Settings 2) Accounts 3) Current and write down the email address under your account. You will need to send us that exact email address if you want to join under that account.

Timetable (**note the special time and location of the first lecture**) :

Week	Date	Time	Room	Session leaders	Topic
5	**Monday 30 Oct**	**noon-2pm**	**Millburn A0.28**	Lauren Doyle / Tom Wilson	Observational Astronomy (Lecture slides, Teams recording)
6	*Wednesday 8 Nov*	*noon-2pm*	*Millburn A1.28*	Marina Lafarga Magro / Sam Gill	Optical/IR Astronomy - photometry & spectroscopy

Scroll to the bottom of the page, the assignment materials are here


9	*Wednesday 29 Nov*	*noon-2pm*	*Millburn A1.28*	Kendall Ackley	Data Mining

Home work assignments (may be updated up to day of the session).

The deadline for all assignments is one week after lecture. A pass mark for 1 MPAGS credit will be awarded for a valid attempt on at least four of the five assignments.

- Assignment 1: questions related to lecture on observing. **Deadline: Wed 8th Nov.** Related materials: seminar material, Astronomical seeing, Stellarium (email: thomas.g.wilson@warwick.ac.uk, Lauren.Doyle@warwick.ac.uk)
- Assignment 2: questions related to lecture on CCDs, photometry, and spectroscopy. Note: lecture slides are in the linked directory given in the assignment sheet (email: Marina.Lafarga-Magro@warwick.ac.uk, Samuel.Gill@warwick.ac.uk)
- Assignment 3: questions related to lecture on interferometry. Related materials: slides, iPython notebook. (email: Jakob.Van-den-Eijnden@warwick.ac.uk)
- Assignment 4: questions related to lecture on X-ray astronomy. Related materials: Lecture notes. (email:

https://warwick.ac.uk/fac/sci/physics/mpags/modules/astro/at/mpags_2023_optical_photometry_assignment/

Optical/IR Astronomy - assignments

Optical/IR Astronomy - photometry assignment

For the photometry assignment, you will need Python and be able to run a jupyter notebook (have a look online here if you need help).

For this assignment, you will take a night of binned observations from the Next Generation Transit Survey and perform aperture photometry to extract a light curve.

You will need to download:

1. The jupyter notebook
2. The MJD file.
3. The FLUX file.
4. The WCS file.

I would like you to work through the Jupyter notebook, fill in the missing RA and Dec values, and make the plots. I would then like you to send me 2 of the plots, and a comment on what you can see in the final lightcurve.

Please send your results to samuel.gill@warwick.ac.uk

Optical/IR Astronomy - spectroscopy assignment

For the spectroscopy assignment, you will also need Python and be able to run a jupyter notebook, as well as the software DS9 (you can download and install it from here https://sites.google.com/cfa.harvard.edu/saoimageds9/download).

In this assignment, you will extract the long-slit spectra of two stars with DS9 and some python code. To do that you will need to download:

1. The jupyter notebook
2. The science observation in FITS format (to be read with DS9)
3. The same science observation in .npy format (ready to be read in python)

You have all the instructions to complete the assignment and the questions to be answered in the jupyter notebook. Let me know if you have any issues with anything and send your results to marina.lafarga-magro@warwick.ac.uk