Workshop on Observational Techniques

Basic introduction: spectrographs

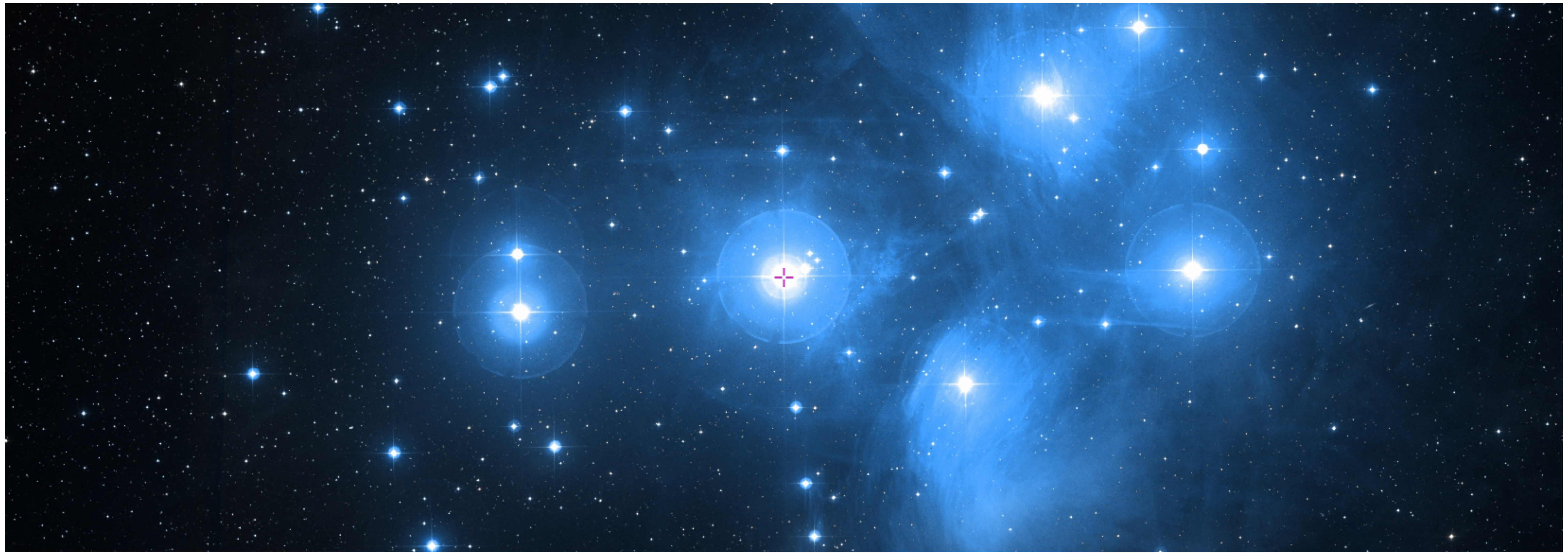
Matti Dorsch[1]

[1]University of Potsdam

4. September 2025

at Ondřejov observatory

What do we want to achieve?



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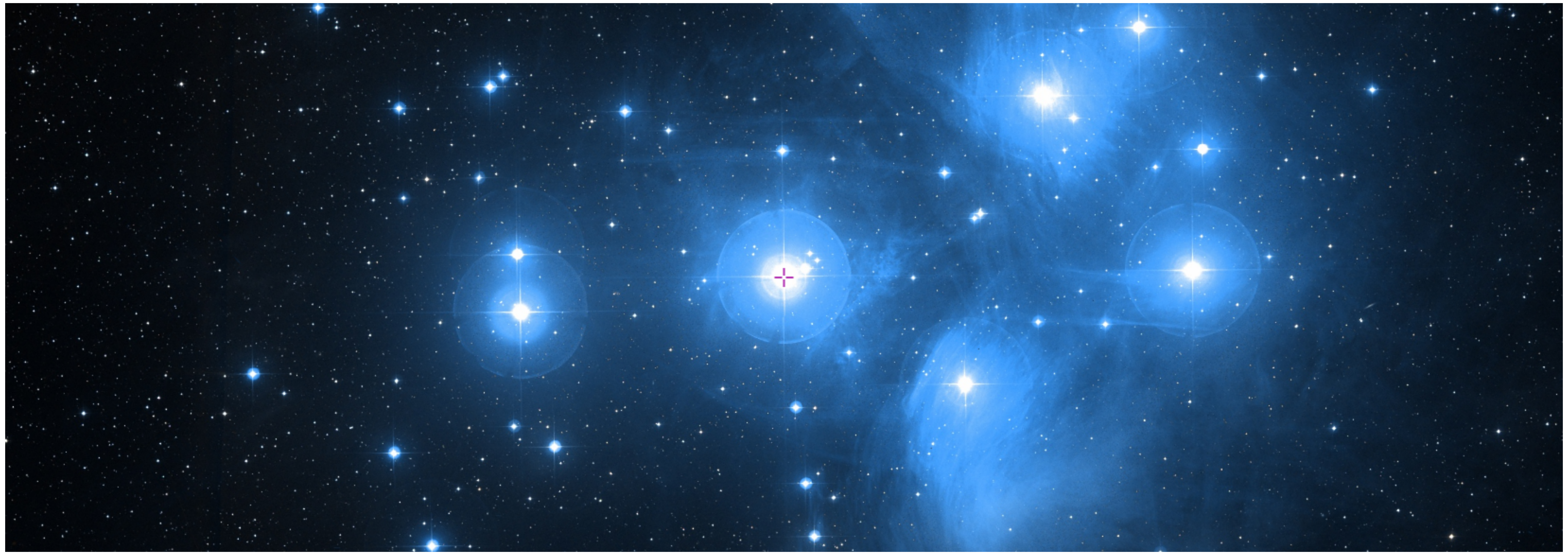

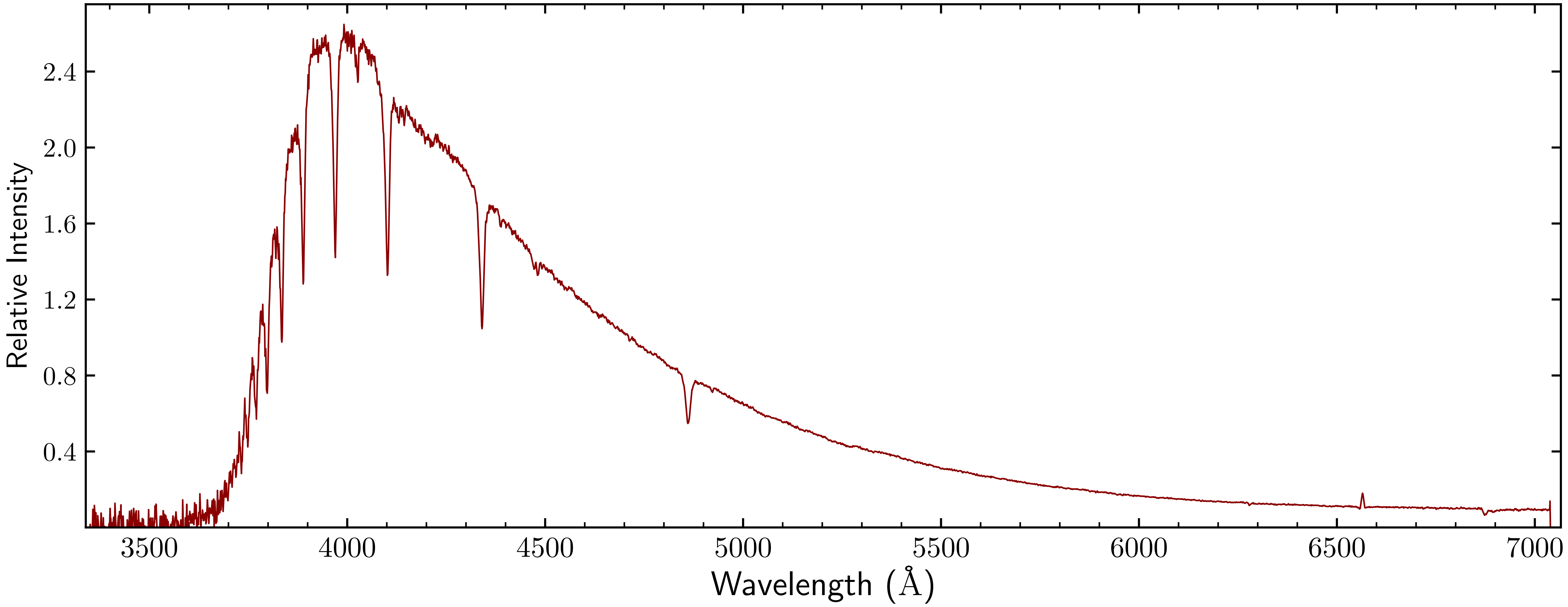

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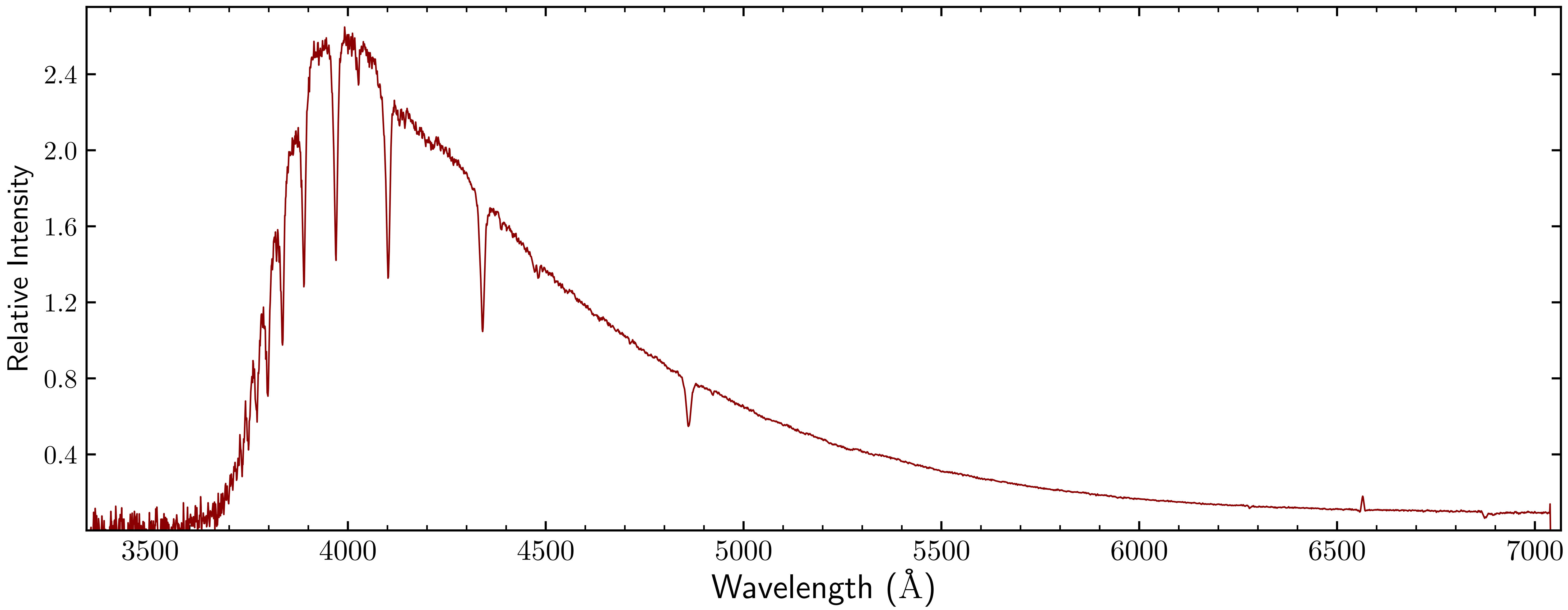


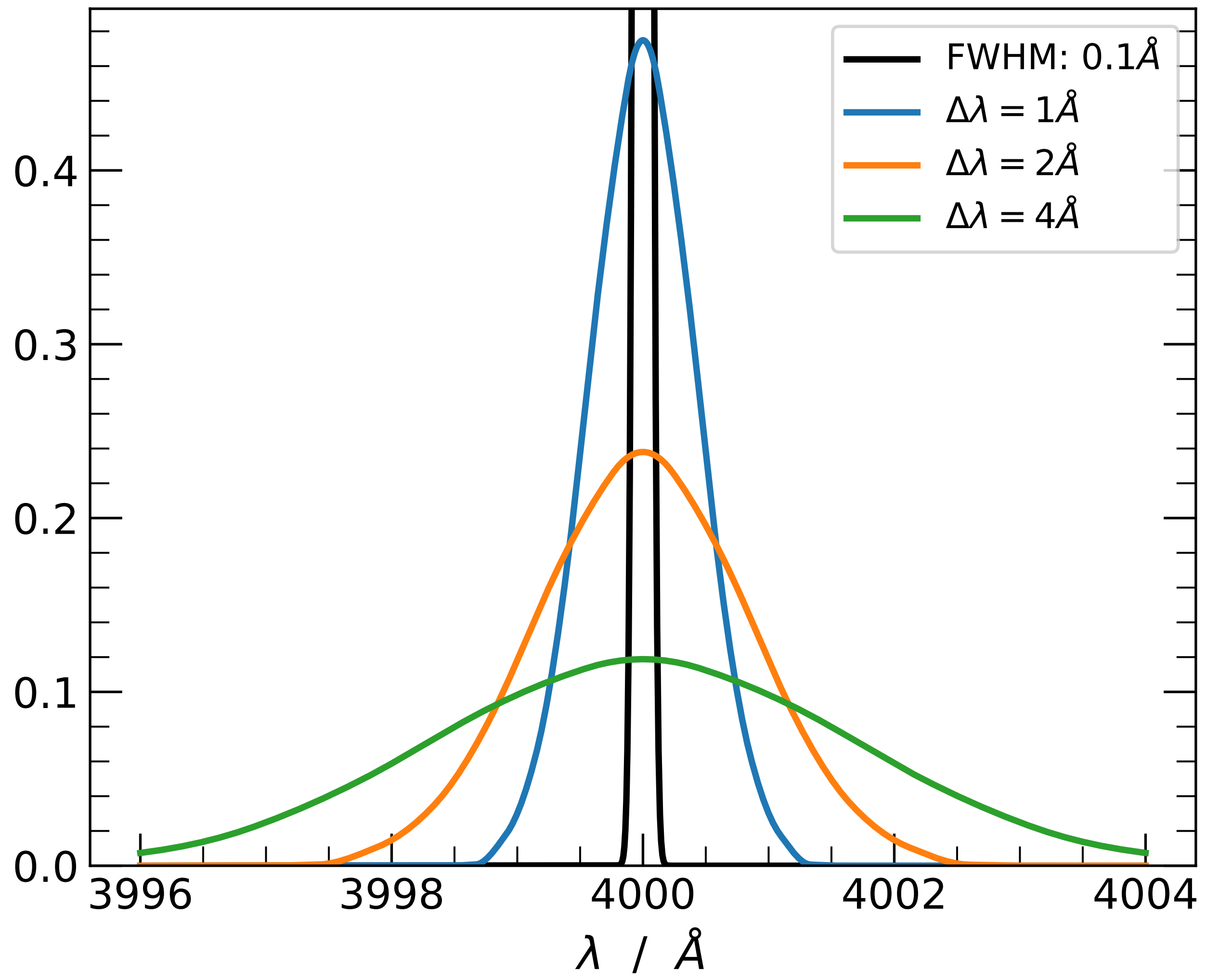
Compromise between

Large wavelength range

High efficiency

High spectral resolving power $R = \lambda/\Delta\lambda$

Accurate wavelength calibration



First-order spectroscopy

Long slit spectrograph

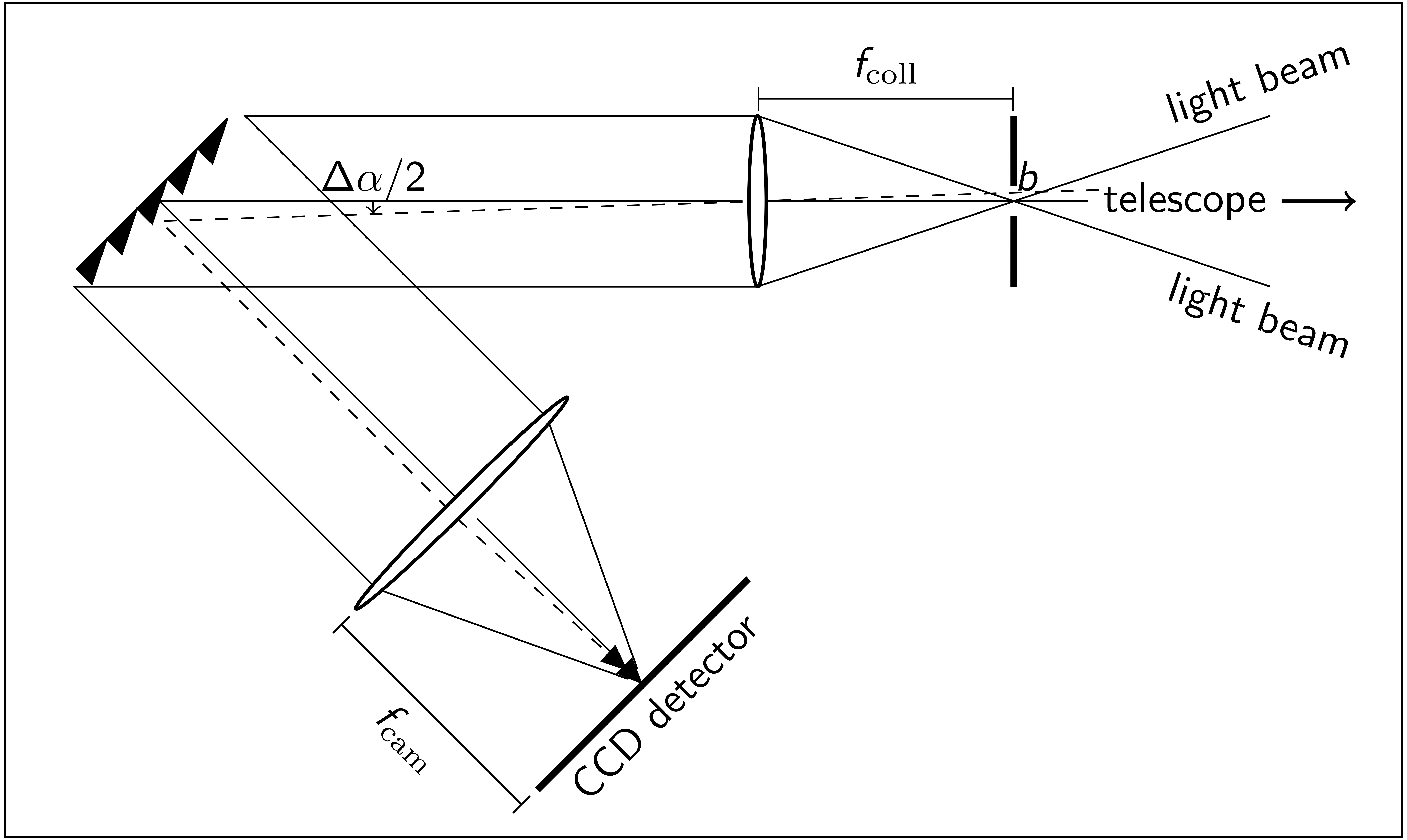
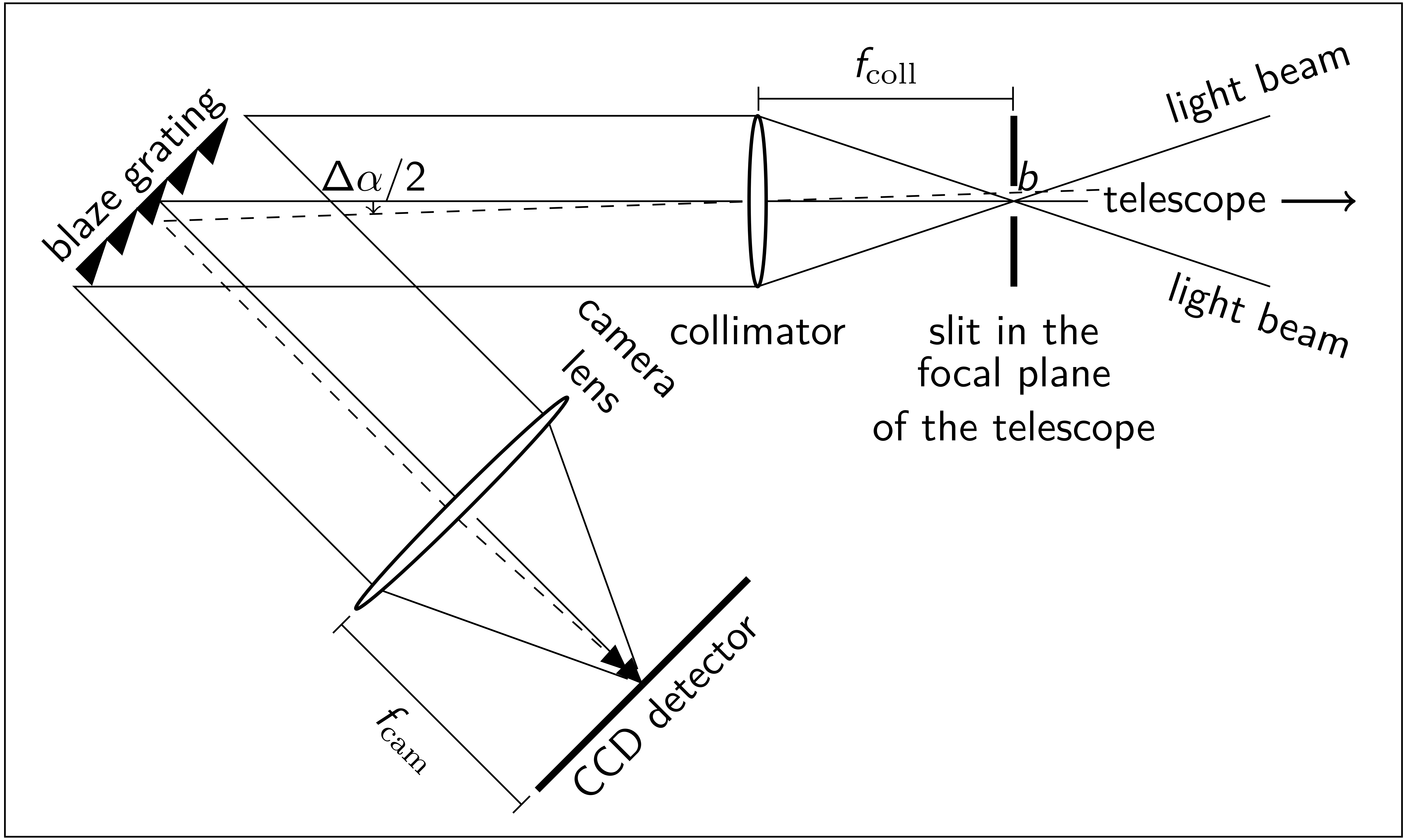


Figure: Schematic beam path in a long slit spectrograph.

Long slit spectrograph



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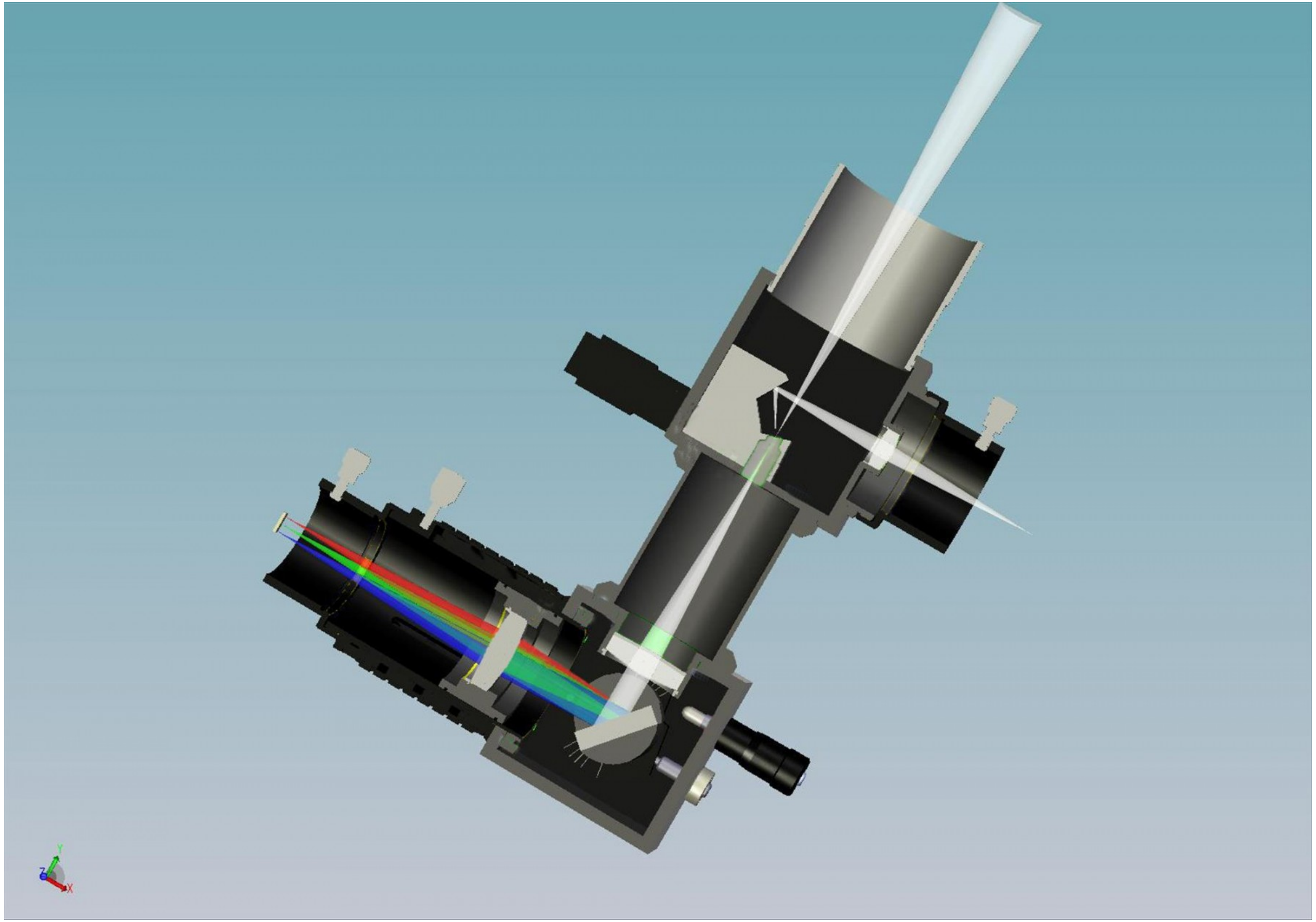
A simple spectrograph



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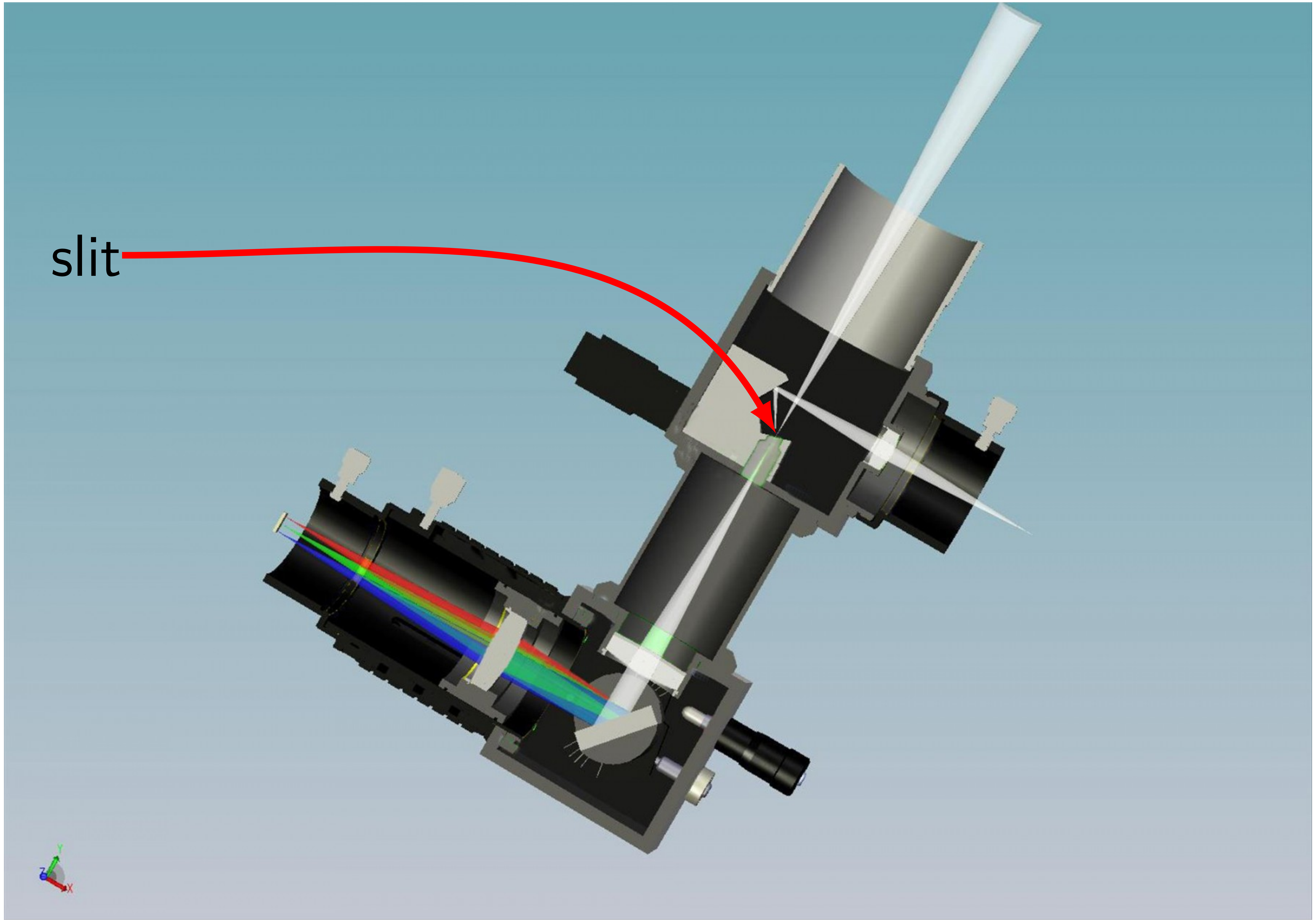

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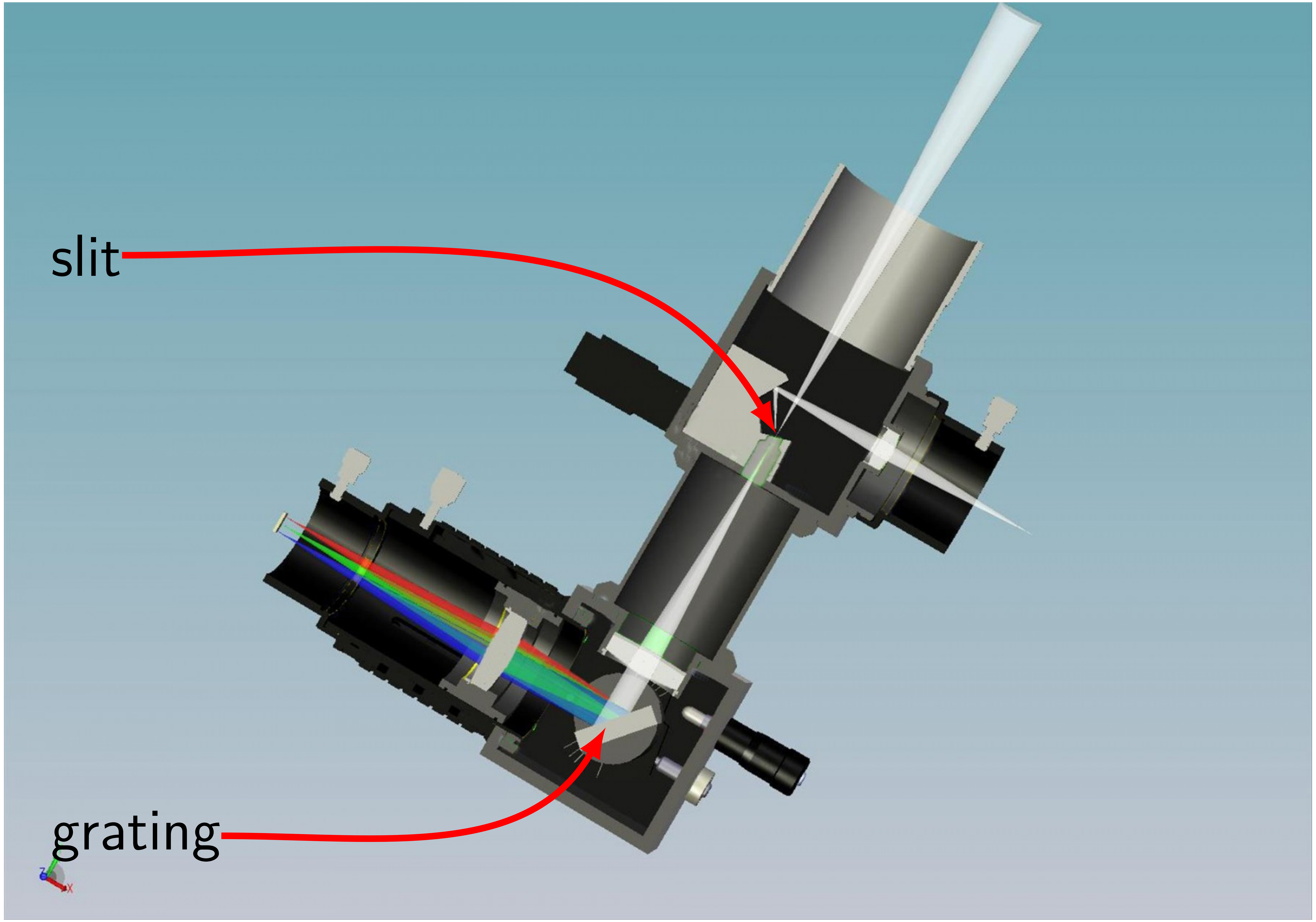

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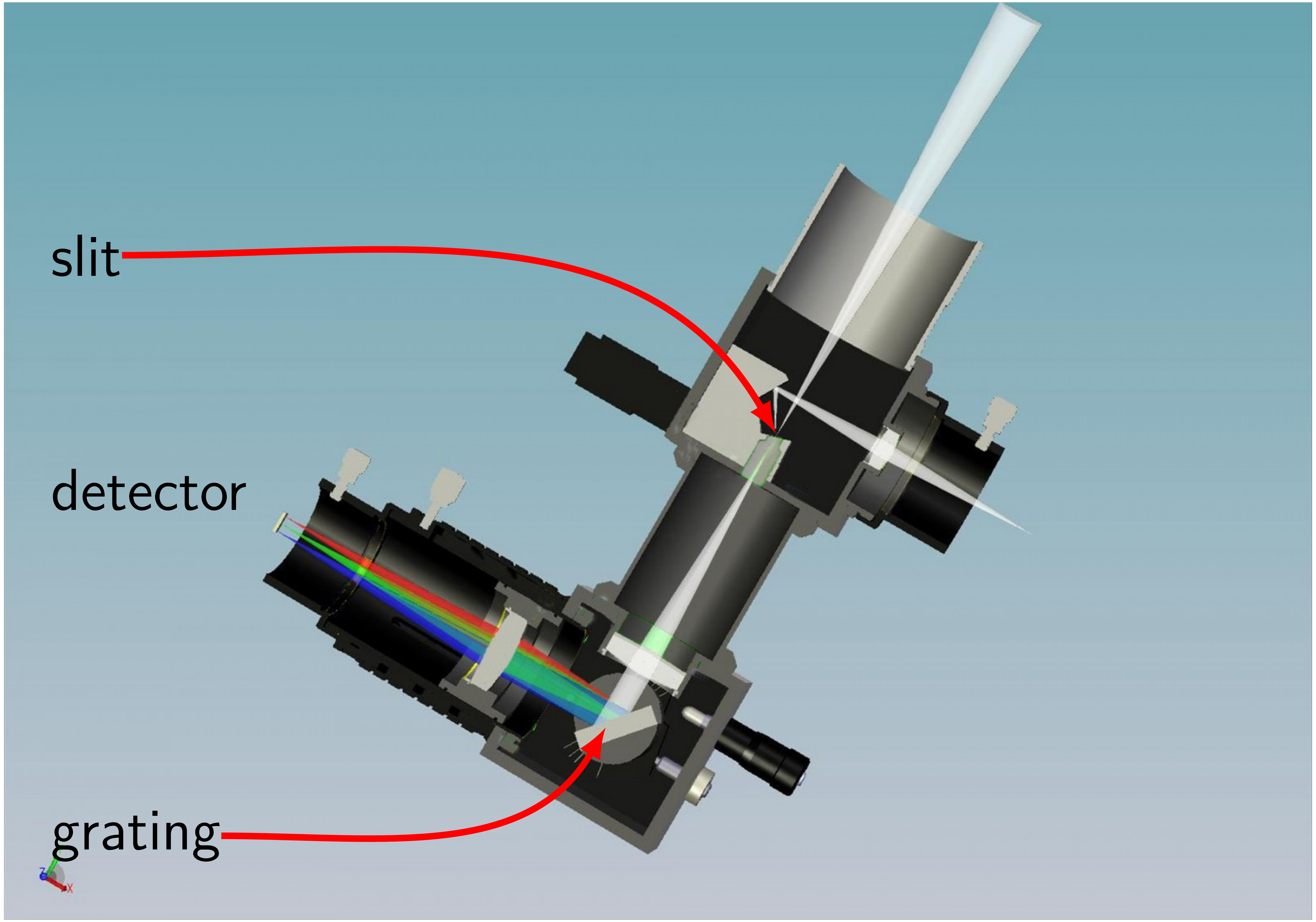
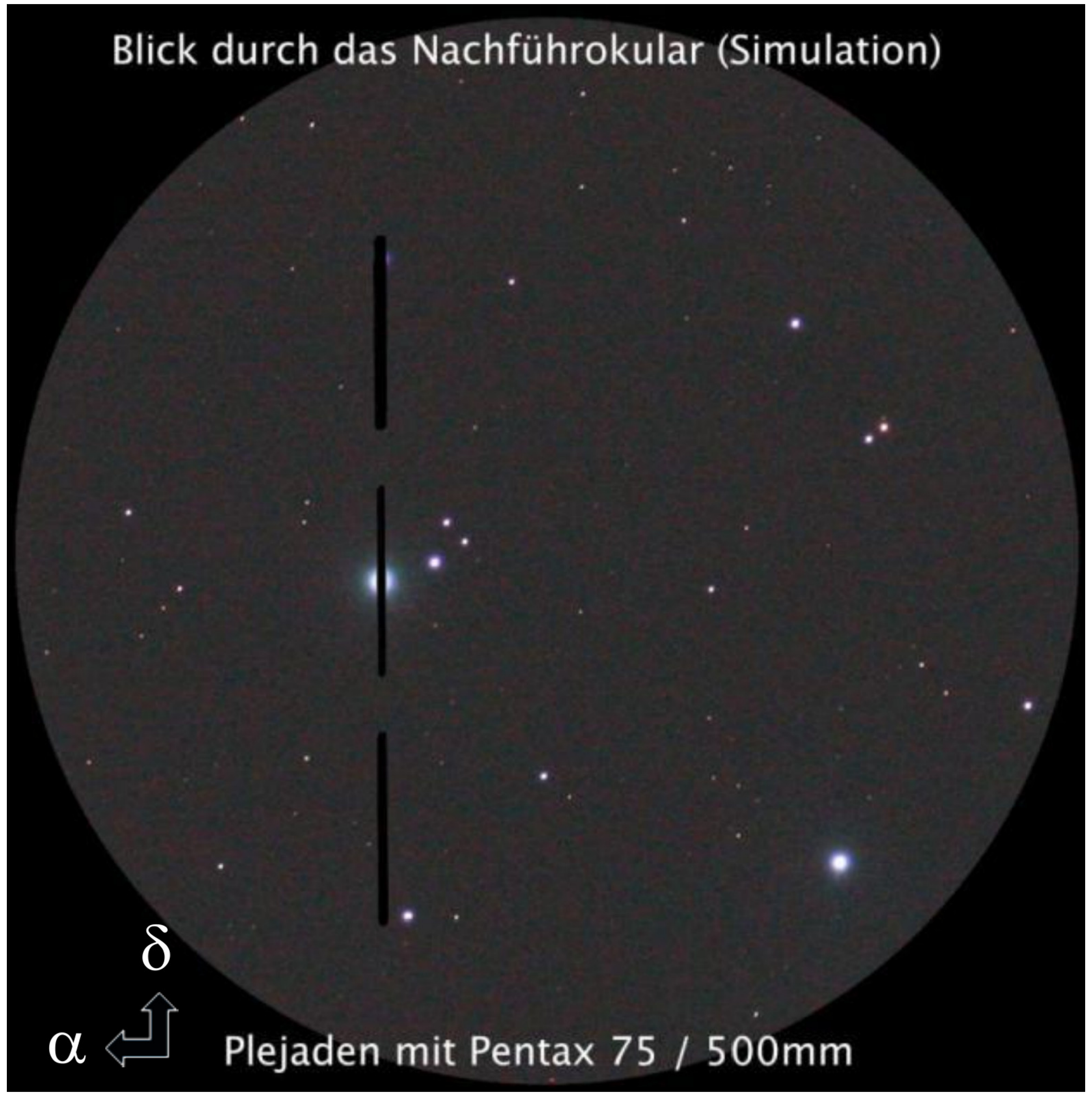


Slits

Why do we need a slit?

Which slit width do we choose?



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Why do we need a slit?

- take spectrum of *one* object

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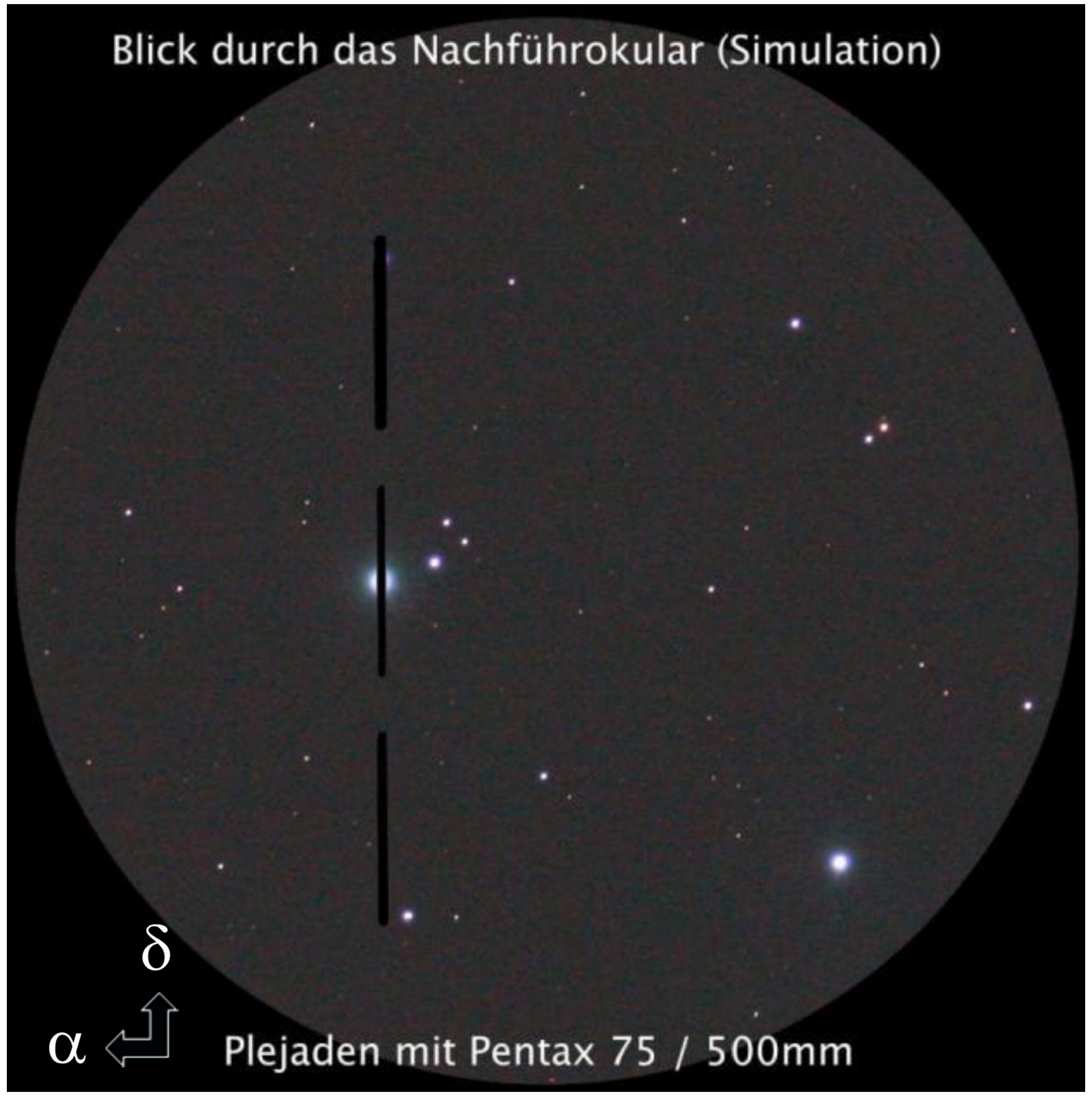
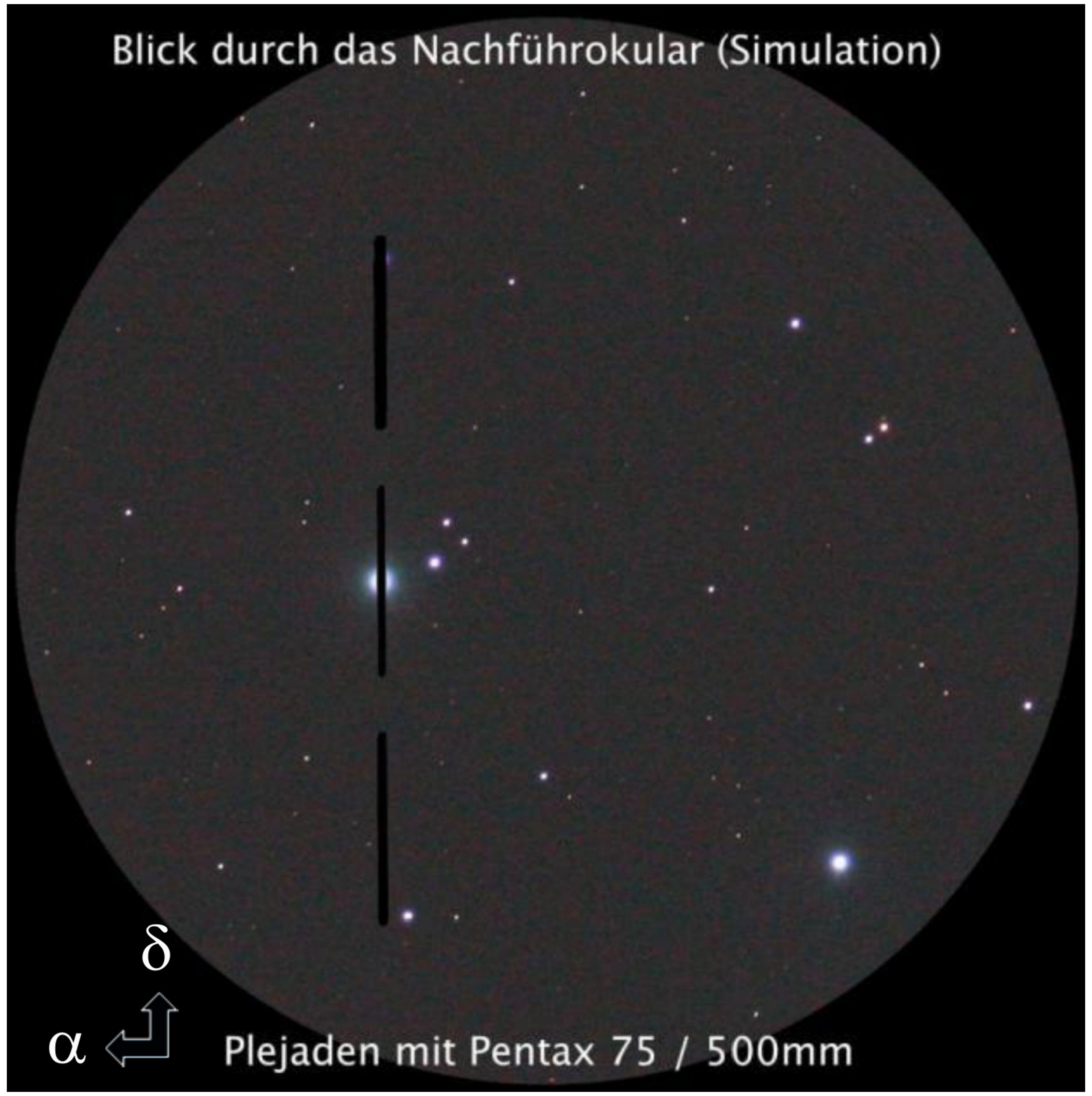


Slits

Why do we need a slit?

- take spectrum of *one* object
- slit width $>$ PSF:
  seeing-limited resolution
- slit width $<$ PSF:
  slit-limited resolution
  (also extended objects)
- Typically: 10 to 1000 μm

Which slit width do we choose?



Slits - light loss

Size of the star on the slit

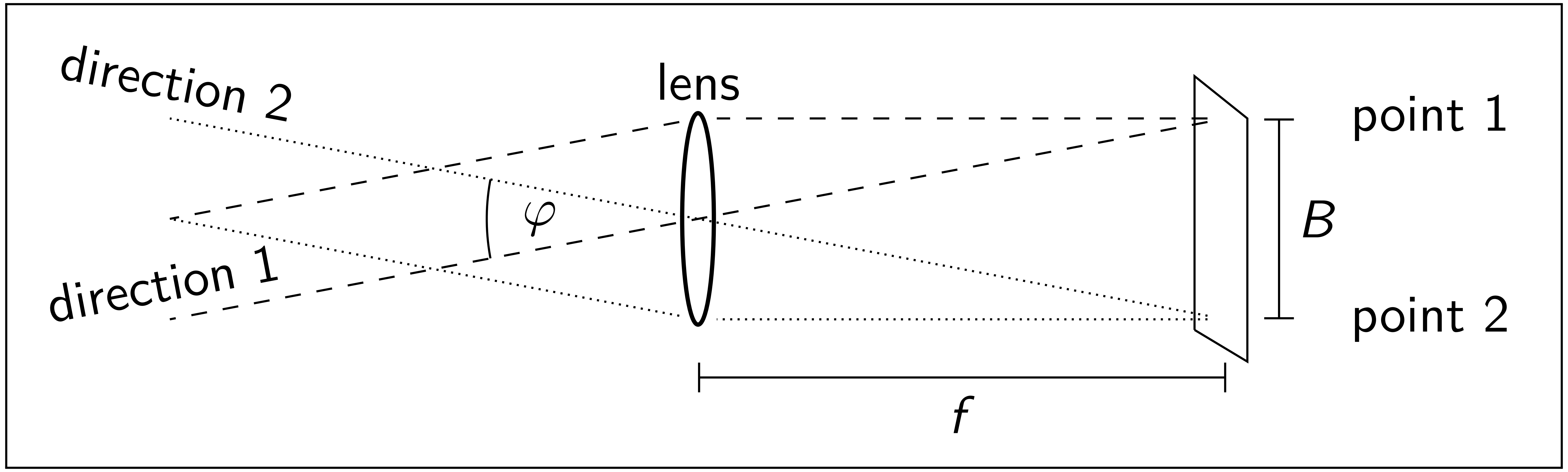


Figure: Image scale for a lens with focal length f and infinite object distance.

$$\frac{\varphi}{2} \approx \tan\frac{\varphi}{2} = \frac{B}{2f} \qquad \rightarrow \qquad B = f \cdot \varphi$$

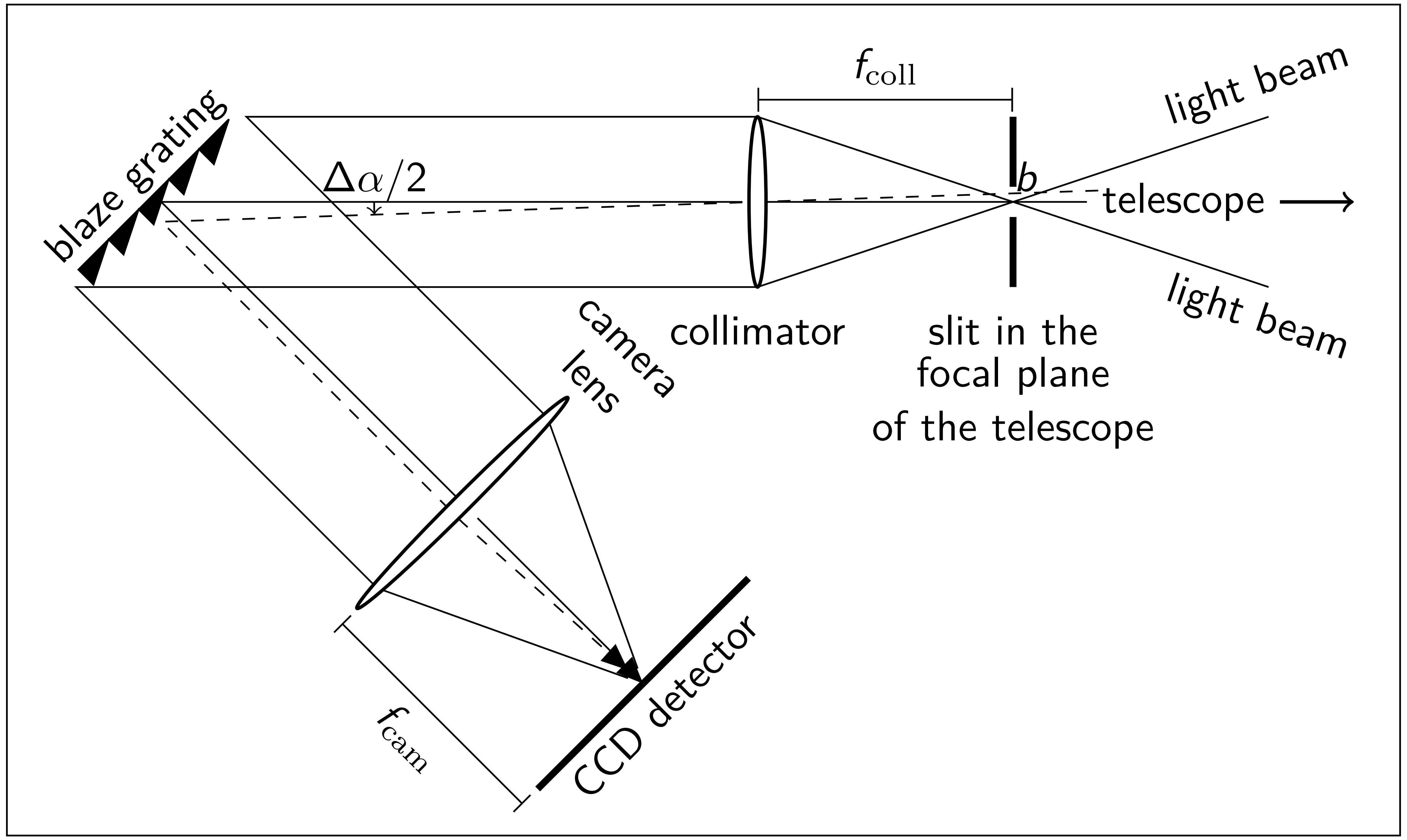
Typical seeing $\rightarrow \varphi \approx 2.5''$

$f_{\mathrm{Perek}} = 63.5\,\mathrm{m}$

Projected size on slit $B \approx 770\,\mu\mathrm{m}$

Slits - resolution

The slit used for OES is $b = 600\,\mu\text{m} < 770\,\mu\text{m}$! Why?



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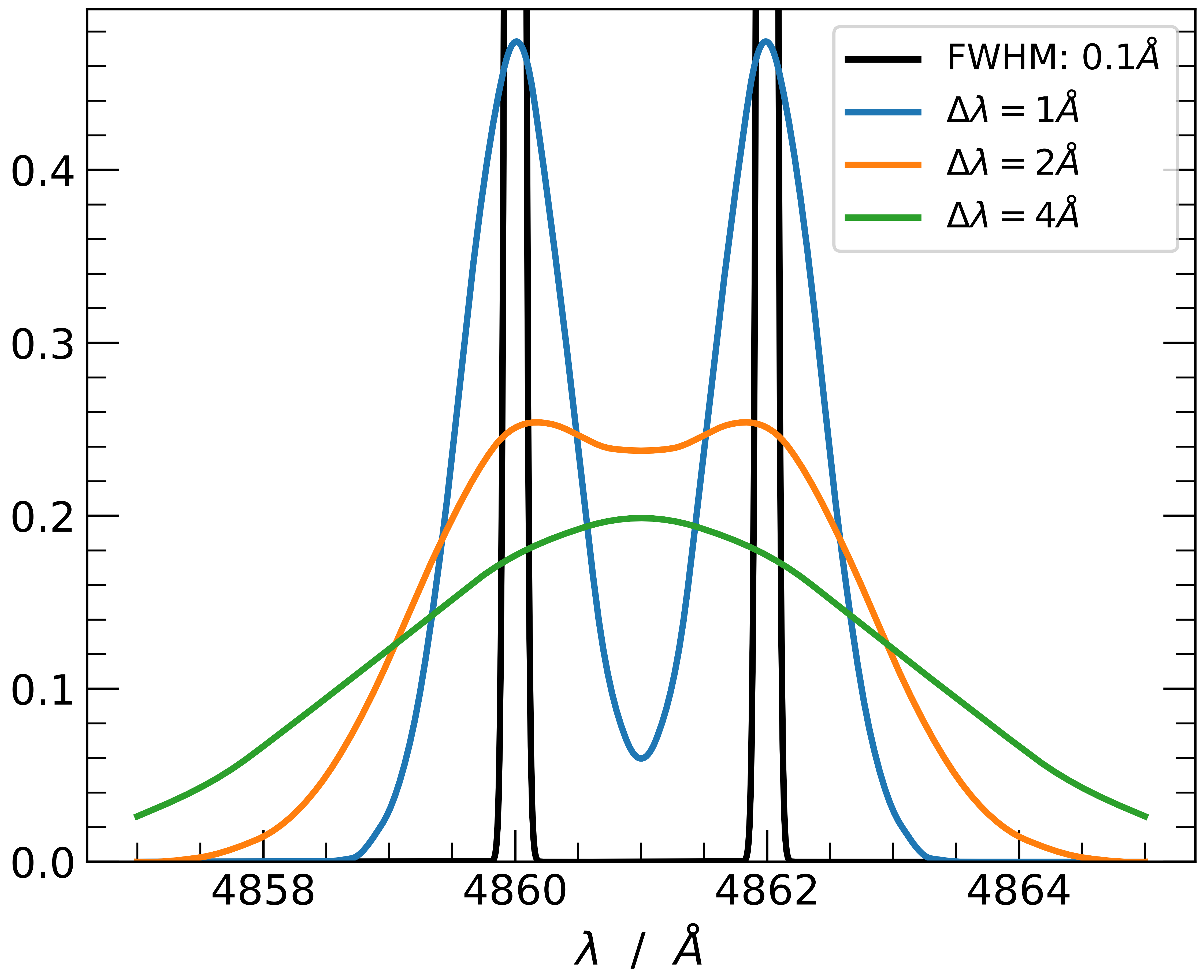

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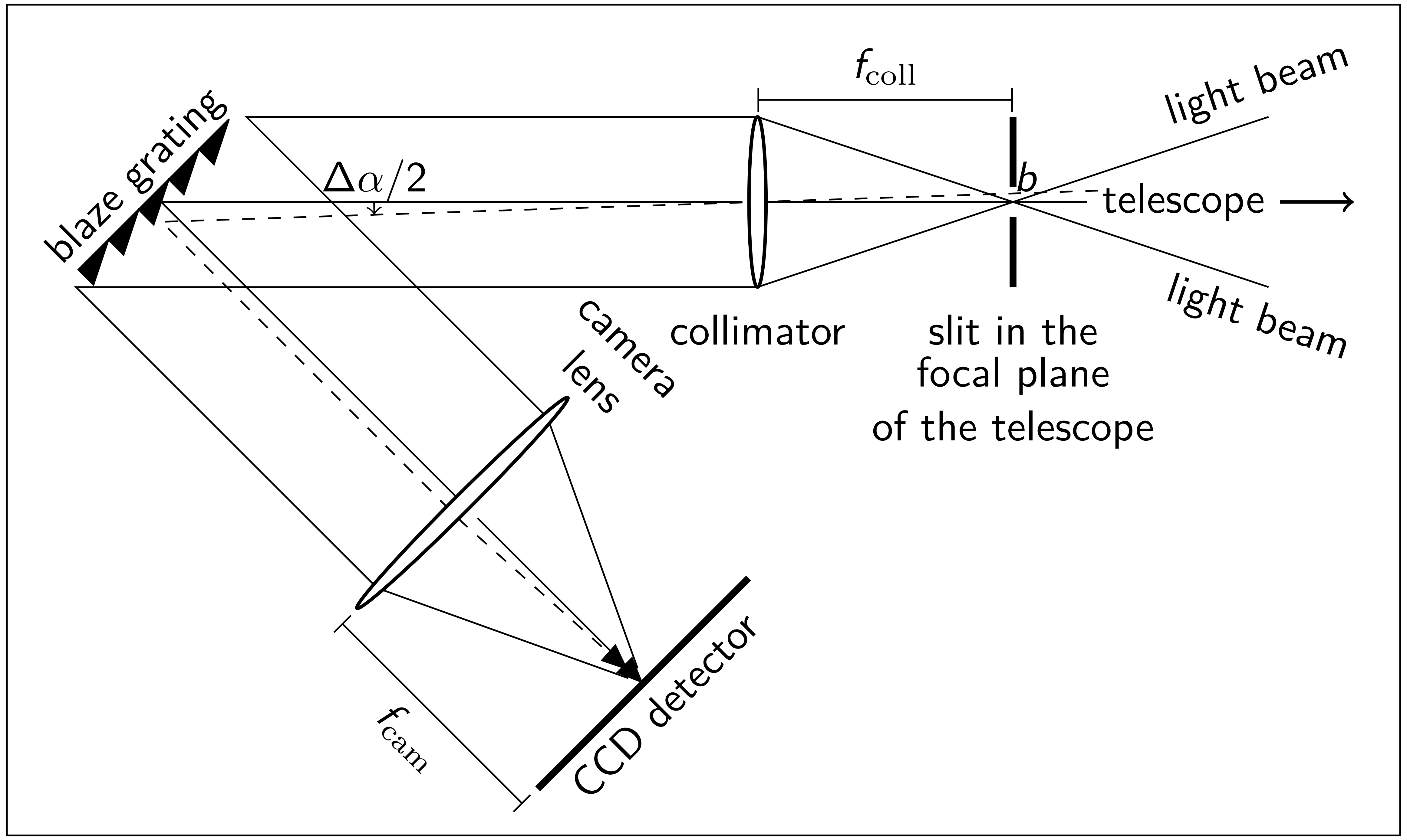

Figure: Schematic beam path in a long slit spectrograph.

Reminder: $\Delta\alpha \overset{\mathrm{b \ll f_{coll}}}{=} \frac{b}{f_{\mathrm{coll}}}$, $n\lambda \overset{\mathrm{interference}}{=} d \cdot (\sin\alpha + \sin\beta)$

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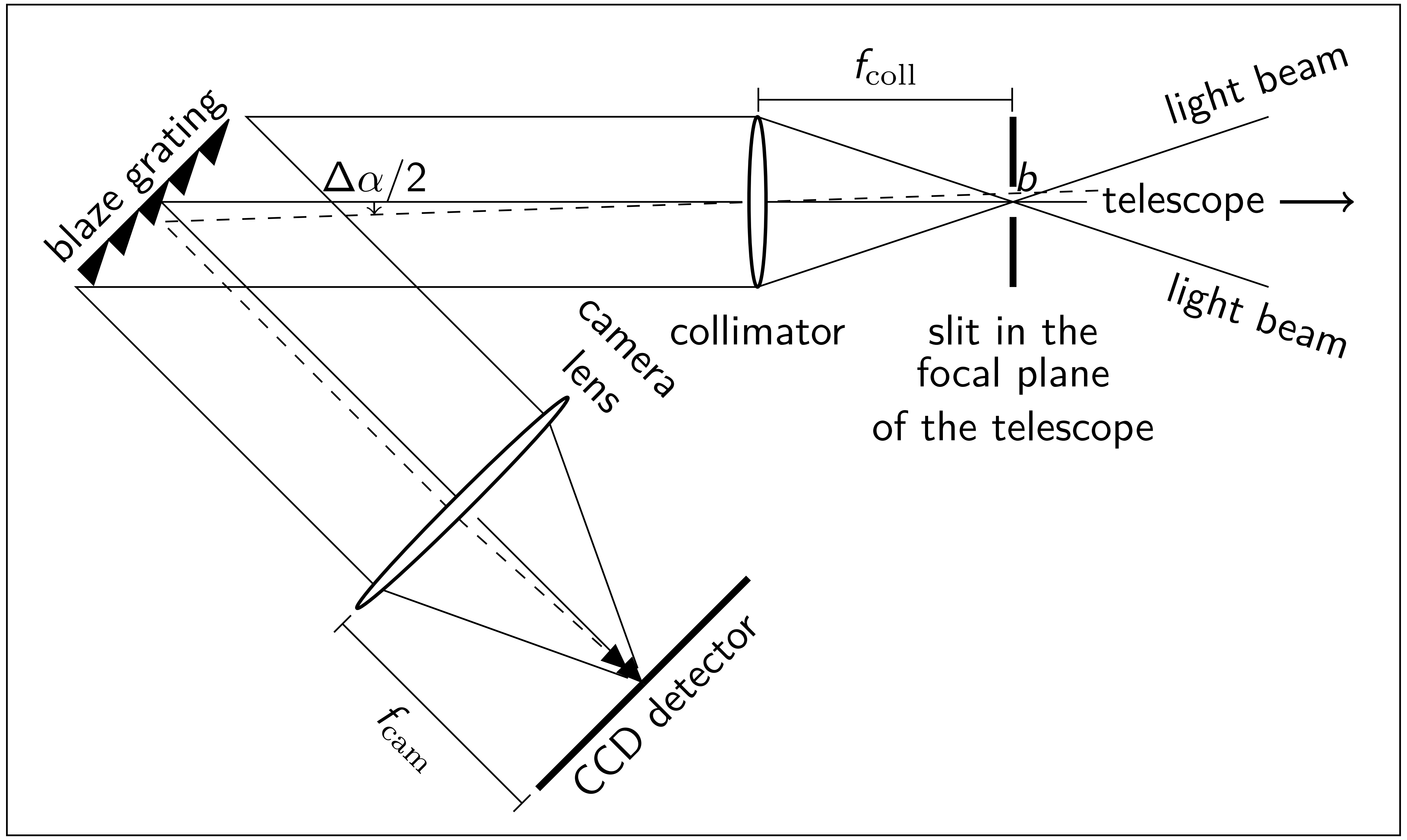


Figure: Schematic beam path in a long slit spectrograph.

Reminder: $\Delta\alpha \overset{b \ll f_{coll}}{=} \frac{b}{f_{coll}} \rightarrow \Delta\lambda \overset{lin.}{\approx} \frac{\partial\lambda}{\partial\alpha}\Delta\alpha = \frac{d}{n}\cos\alpha\Delta\alpha \overset{n=1}{=} \mathrm{const.}$

Slits - resolution

The slit used for OES is $b = 600\,\mu\mathrm{m} < 770\,\mu\mathrm{m}$! Why?

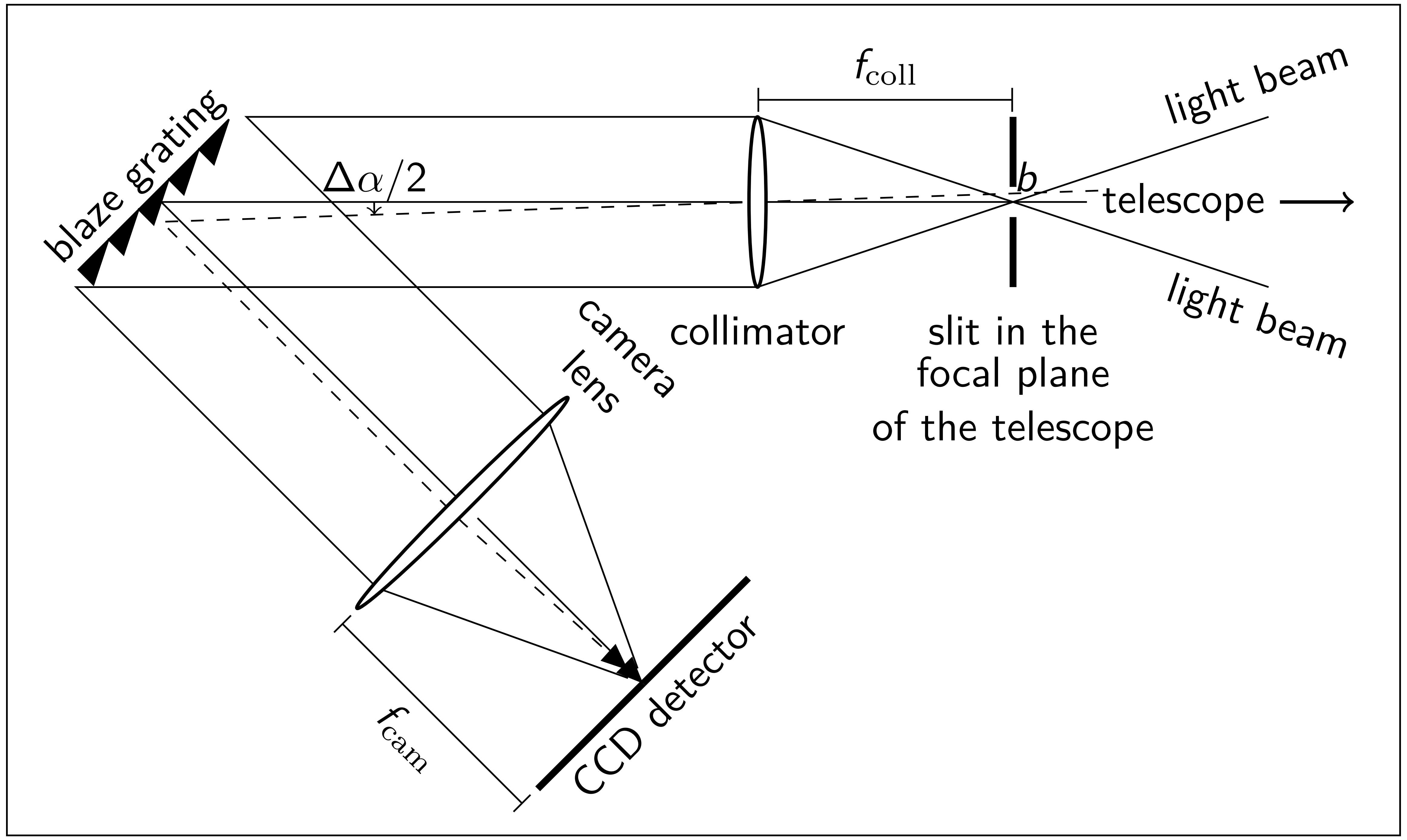
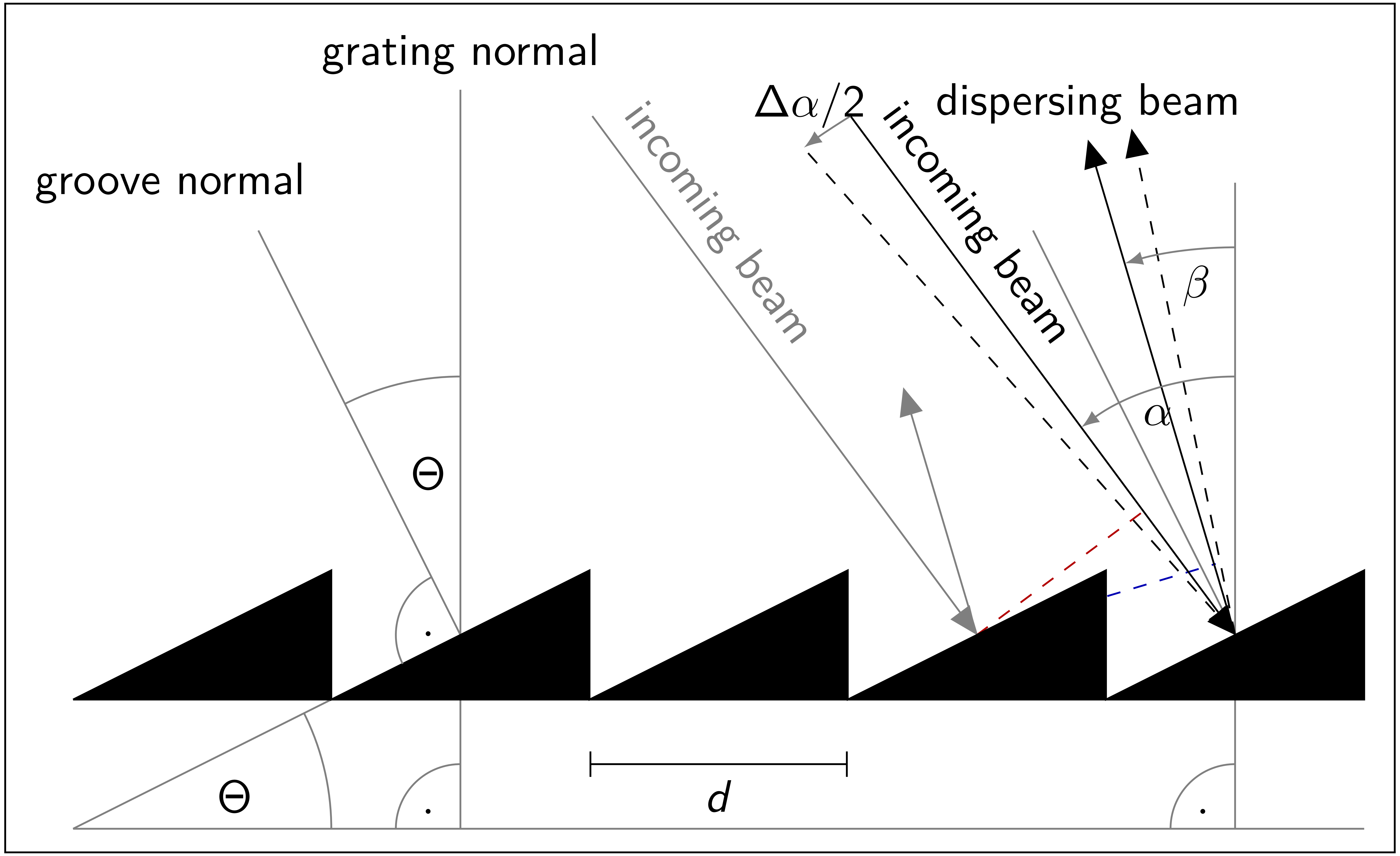


Figure: Schematic beam path in a long slit spectrograph.

Reminder: $\Delta\alpha \stackrel{\mathrm{b}\ll\mathrm{f_{coll}}}{=} \frac{b}{f_{\mathrm{coll}}} \rightarrow R_{\mathrm{slit}} = \frac{\lambda}{\Delta\lambda_{\mathrm{slit}}} = \frac{n f_{\mathrm{coll}}}{d\,b\cos\alpha}\lambda$

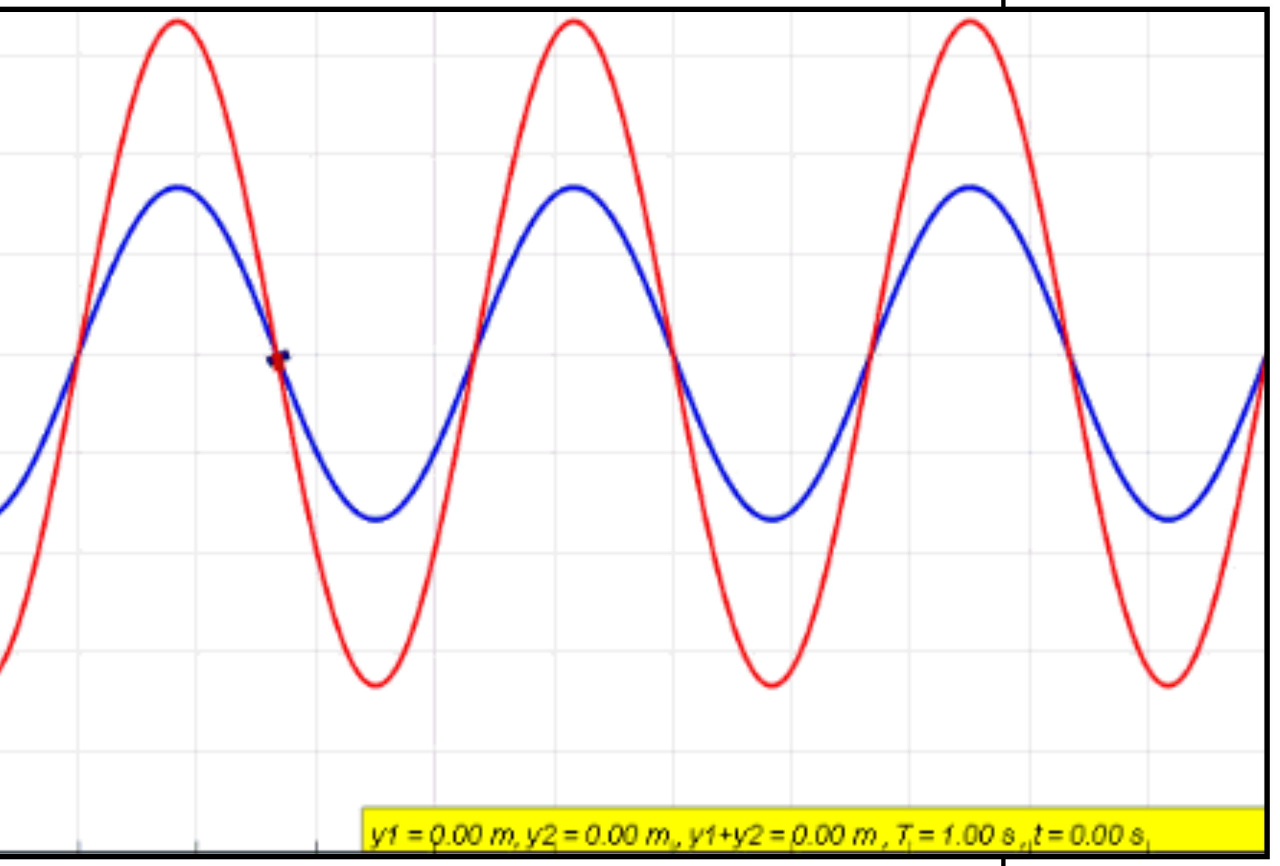
Blaze grating - interference condition



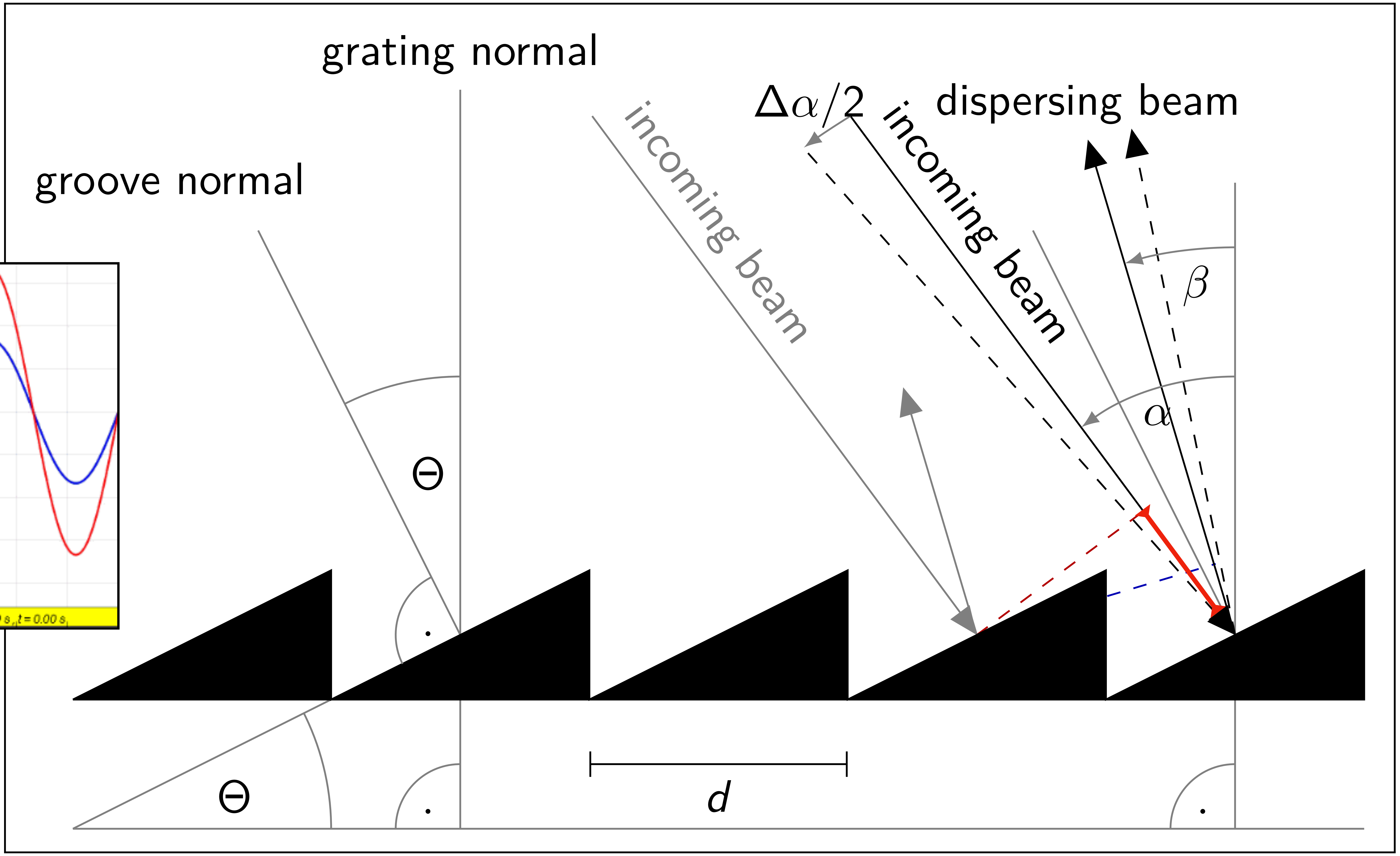
$$\boxed{n\lambda \overset{\text{interference}}{=} \Delta s = d \cdot (\sin\alpha + \sin\beta)}, \text{ order } n \in \mathbb{N};\ \alpha + \beta \overset{\text{class.}}{=} 2\Theta_B$$

Δs: path difference between each groove

Blaze grating - interference condition



Constructive interference
↔ same phase



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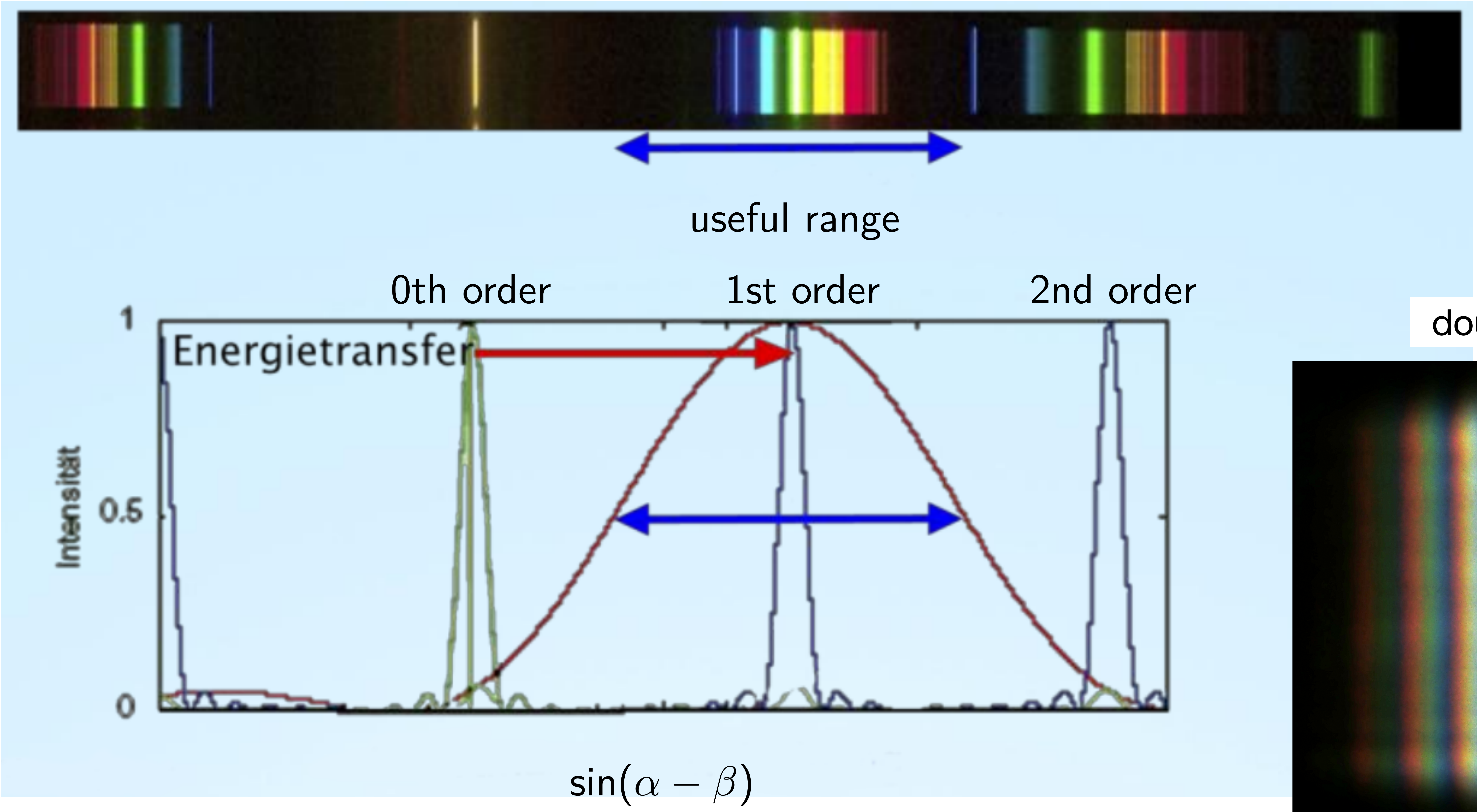
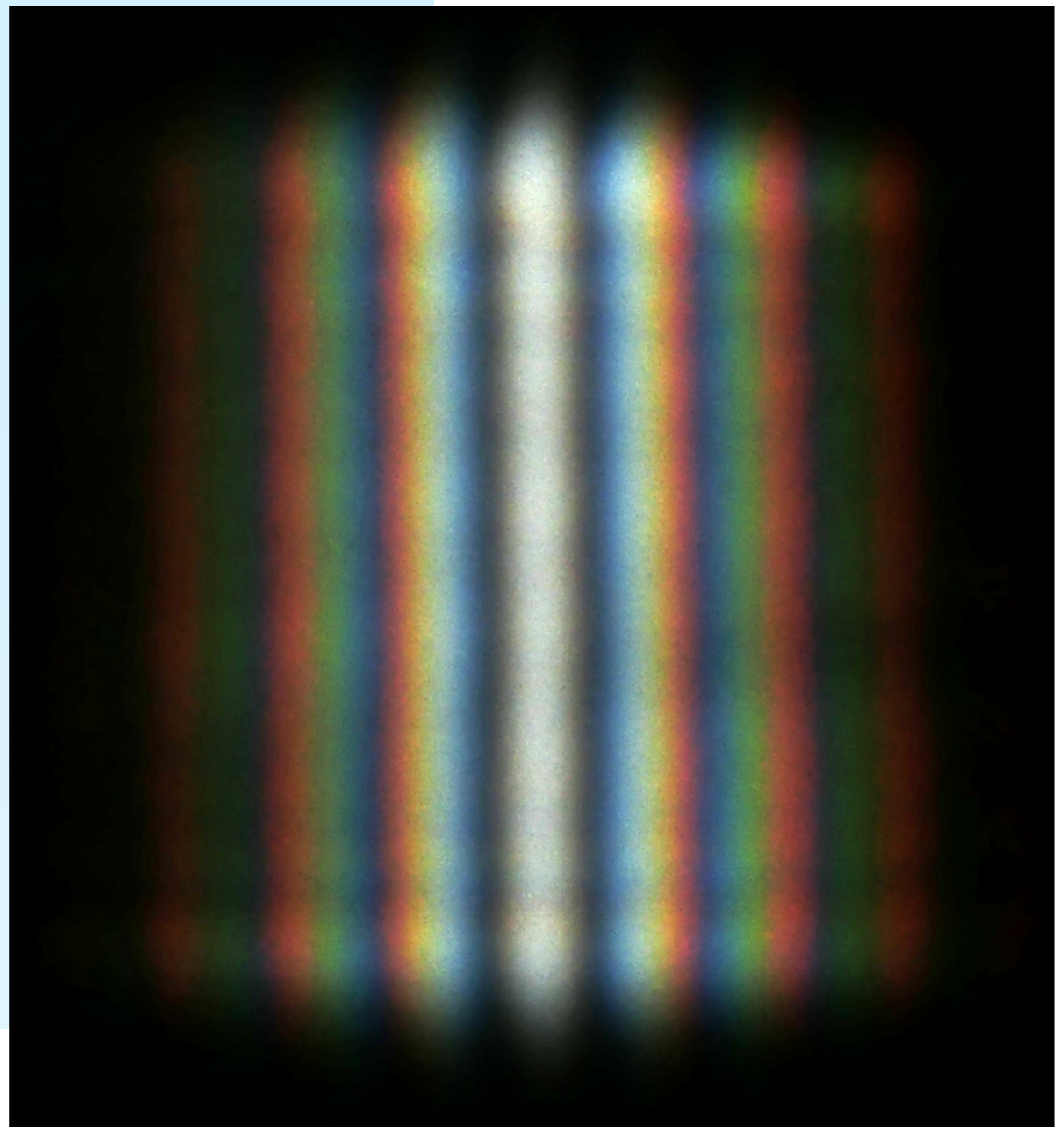
Blaze grating - diffraction orders



double slit



$$n\lambda_n^0 = d \cdot (\sin\alpha + \sin(2\Theta_B - \alpha)),\ \lambda_n^0 = \text{blaze wavelength (max. intensity)}$$

Blaze grating - blaze function

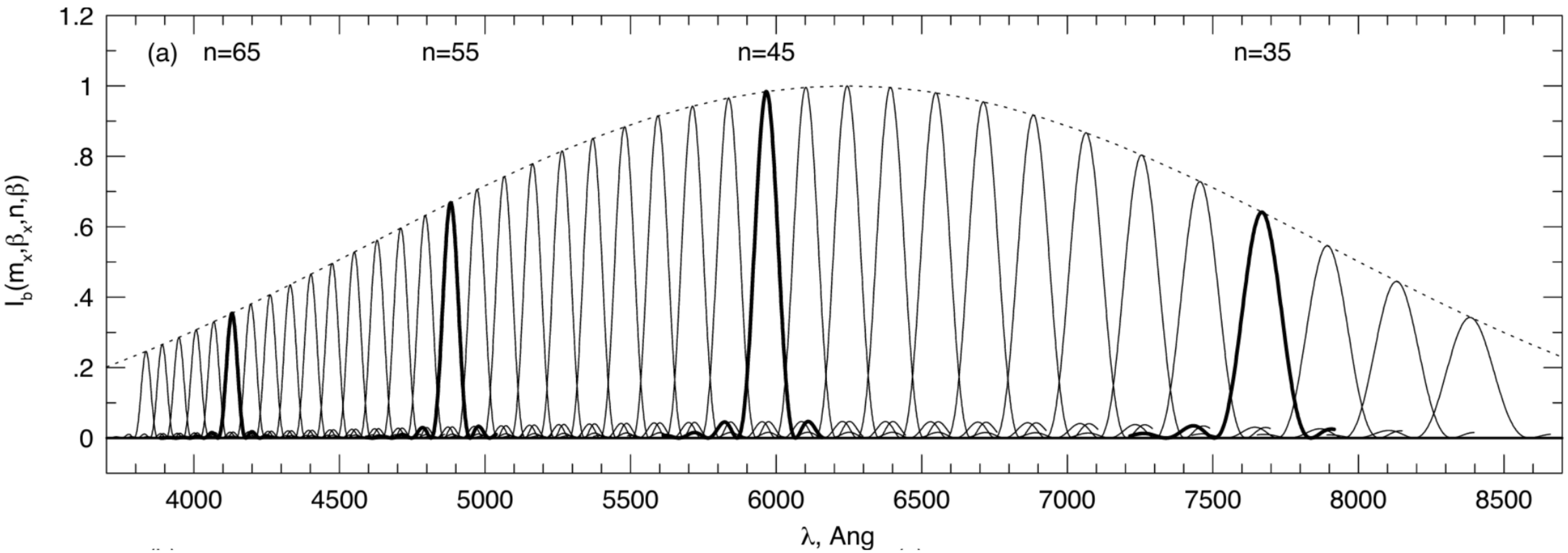
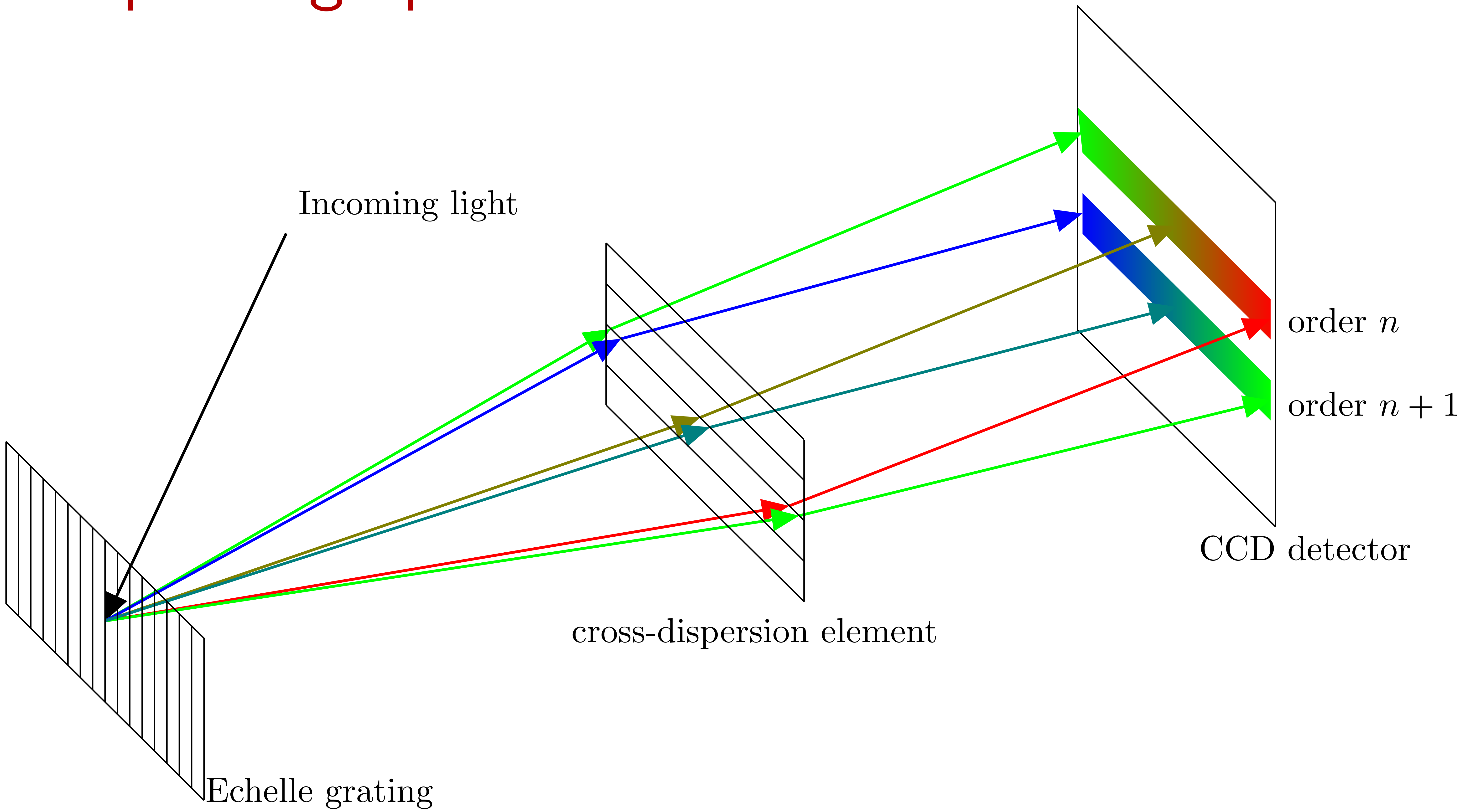


Figure: Dispersion and Blaze function $(\sin(x)/x)^2$ for a cross-dispersed échelle spectrograph.

Higher-order spectrograph, similar to OES.
All of these orders overlap after the first grating!

Échelle spectrograph



- separate overlapping orders by cross-dispersion element
- optimized for high incidence angles and high orders: $\Theta_B = 69^\circ$ for OES

$$R_{\text{Échelle}} \approx \frac{f_{\text{coll}}}{b \cos\alpha}[\sin\alpha + \sin(2\Theta_B - \alpha)] \approx \text{constant} \approx 50000$$

Blaze grating - efficiency

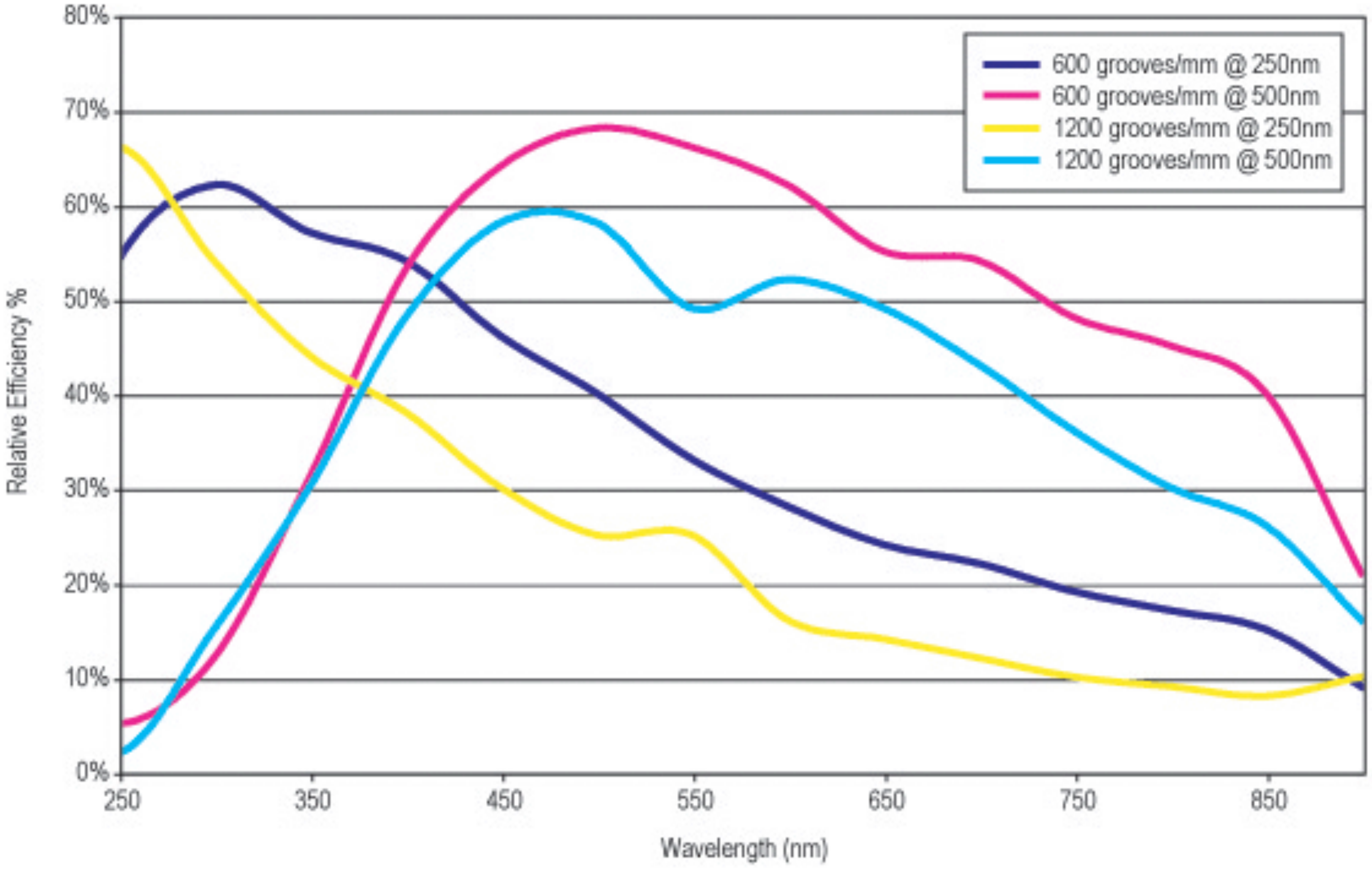


Figure: Typical efficiency curves for blazed holographic gratings (edmundoptics).

CCD detector - efficiency

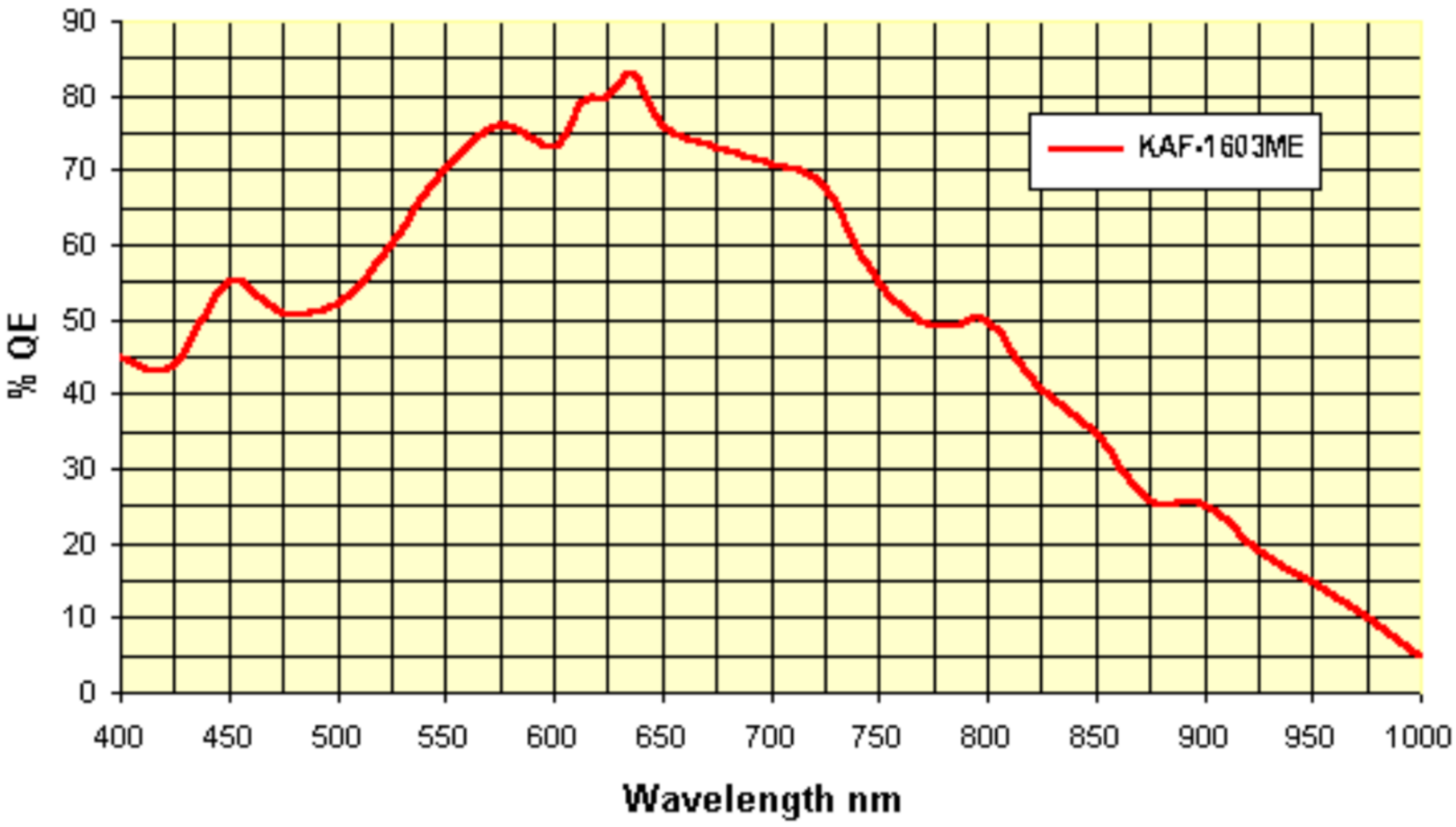


Figure: Quantum efficiency = % incident photons detected (SBIG ST-8XME).

Observation

Raw images

Raw images

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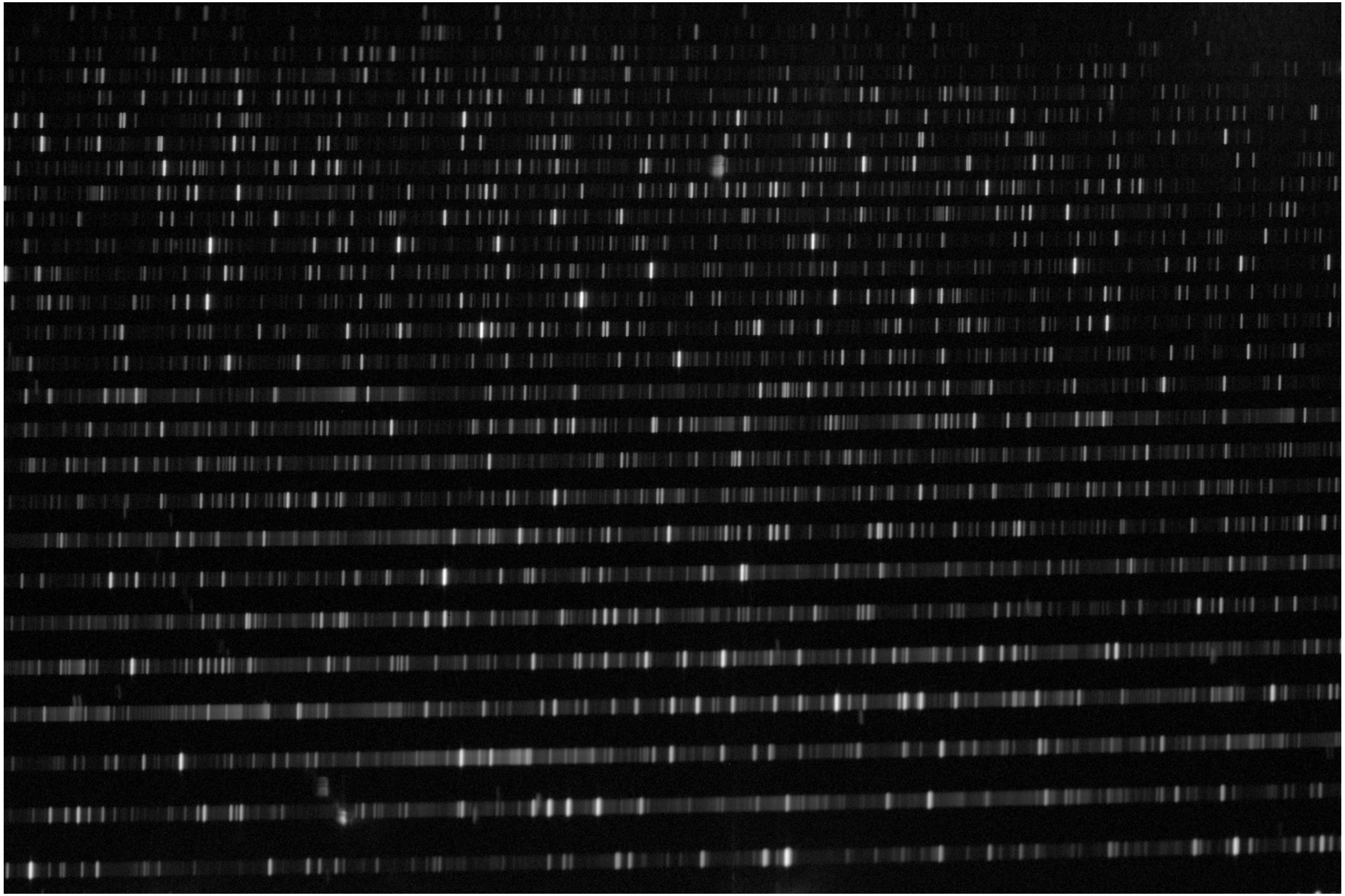
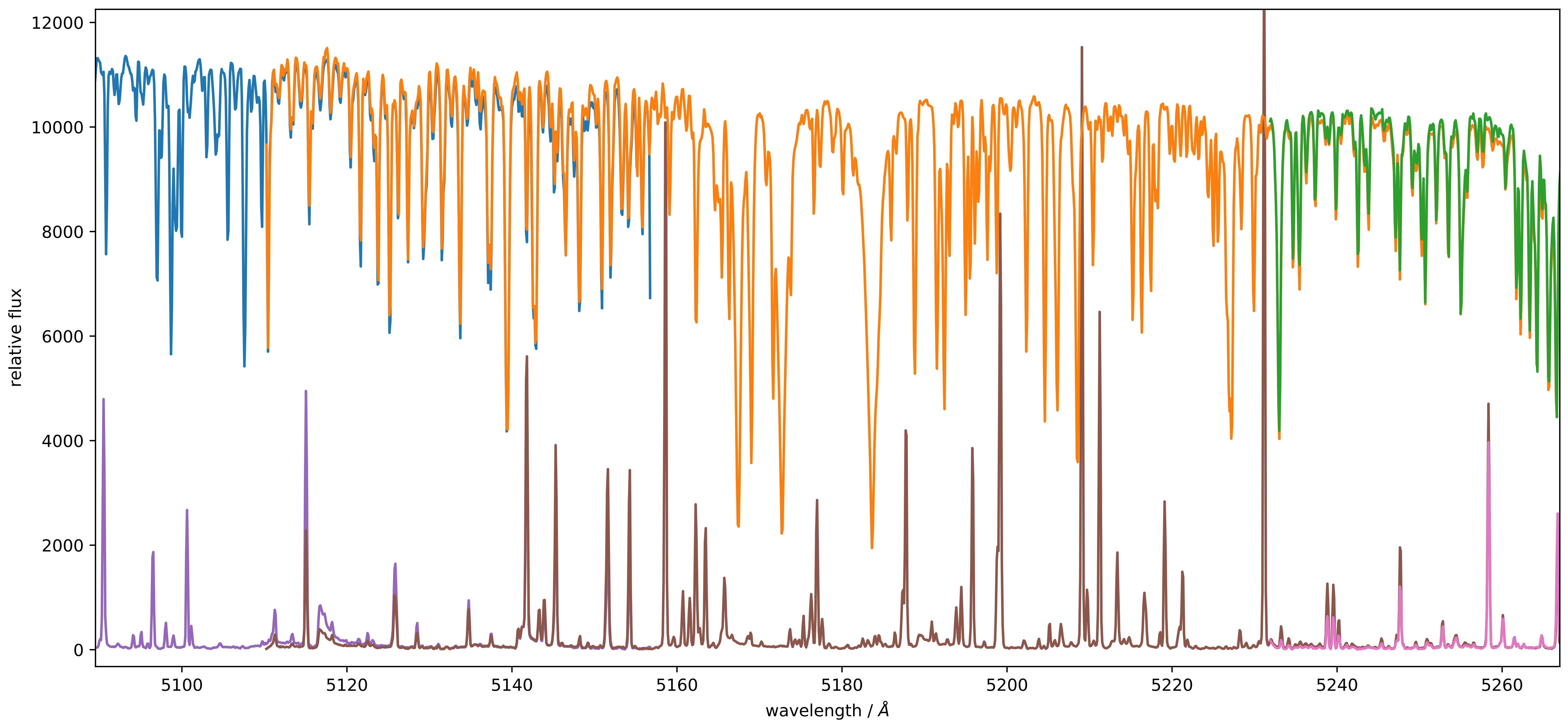


Raw images



12000
10000
8000
6000
4000
2000
0
relative flux
5100
5120
5140
5160
5180
5200
5220
5240
5260
wavelength / Å

Raw data summary

To produce a calibrated, 1-d spectrum, we need:

- *Science* frame

For each of these:

Raw data summary

To produce a calibrated, 1-d spectrum, we need:

- *Science* frame
- *Flat-field* frame

For each of these:

Raw data summary

To produce a calibrated, 1-d spectrum, we need:

- *Science* frame
- *Flat-field* frame
- *Calibration (arc)* frame

For each of these:

Raw data summary

To produce a calibrated, 1-d spectrum, we need:

- *Science* frame
- *Flat-field* frame
- *Calibration (arc)* frame

For each of these:

- *Bias* frame:
  - used to remove the CDD *readout signals*, including constant offset
  - taken with shortest exposure time and closed shutter
  - included in dark frame, required if $t_{\mathrm{exp,dark}} \neq t_{\mathrm{exp,science}}$

Raw data summary

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  - taken with shortest exposure time and closed shutter
  - included in dark frame, required if $t_{\mathrm{exp,dark}} \neq t_{\mathrm{exp,science}}$
- *Dark* frame:
  - thermal excitation of electrons in the CCD leads to a constant background noise
  - also: hot/cold pixels/columns
  - taken with the same exposure time and temperature as science frame
  - has to be subtracted from science frame

Reduction steps

Bias frame

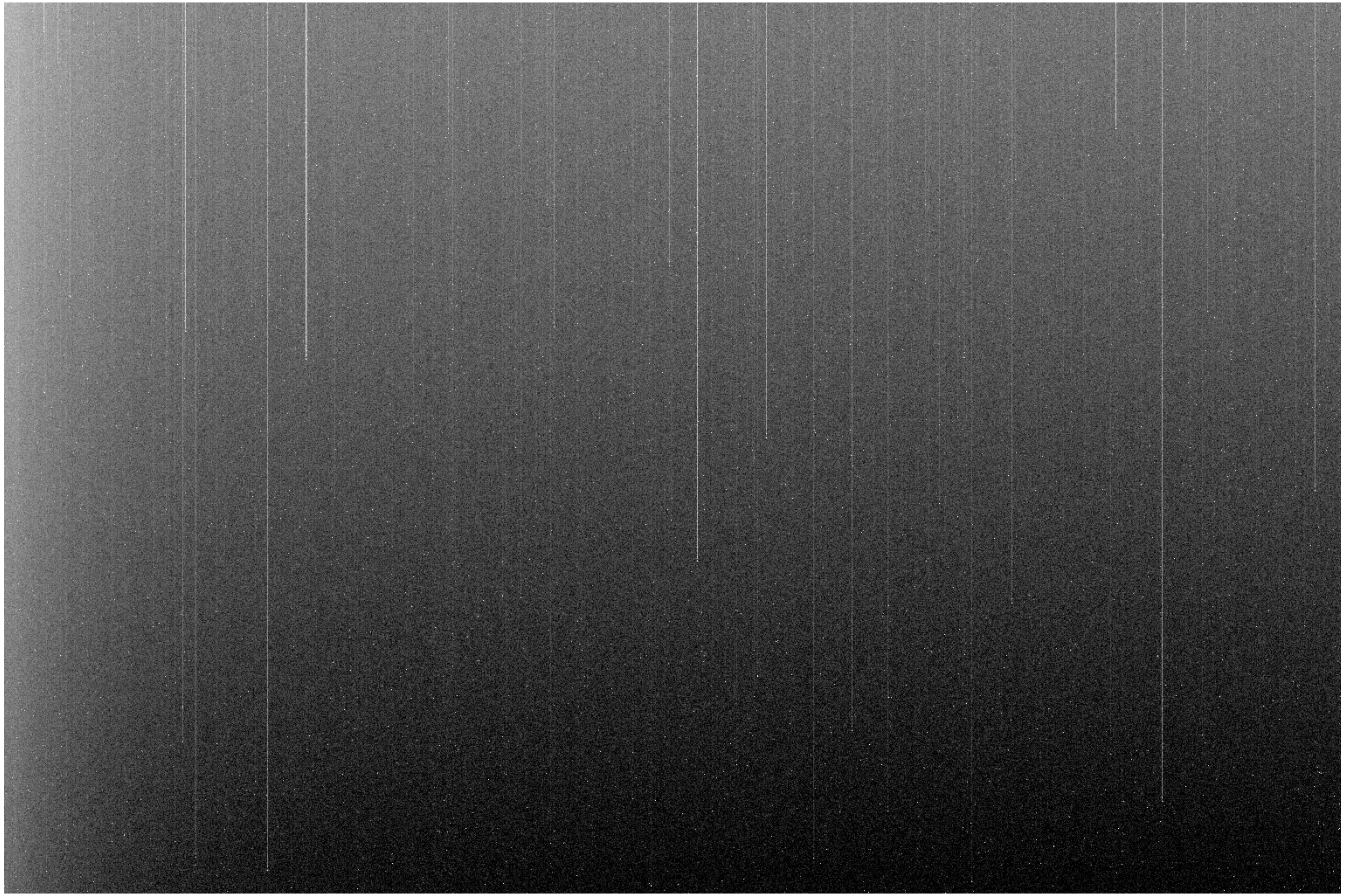
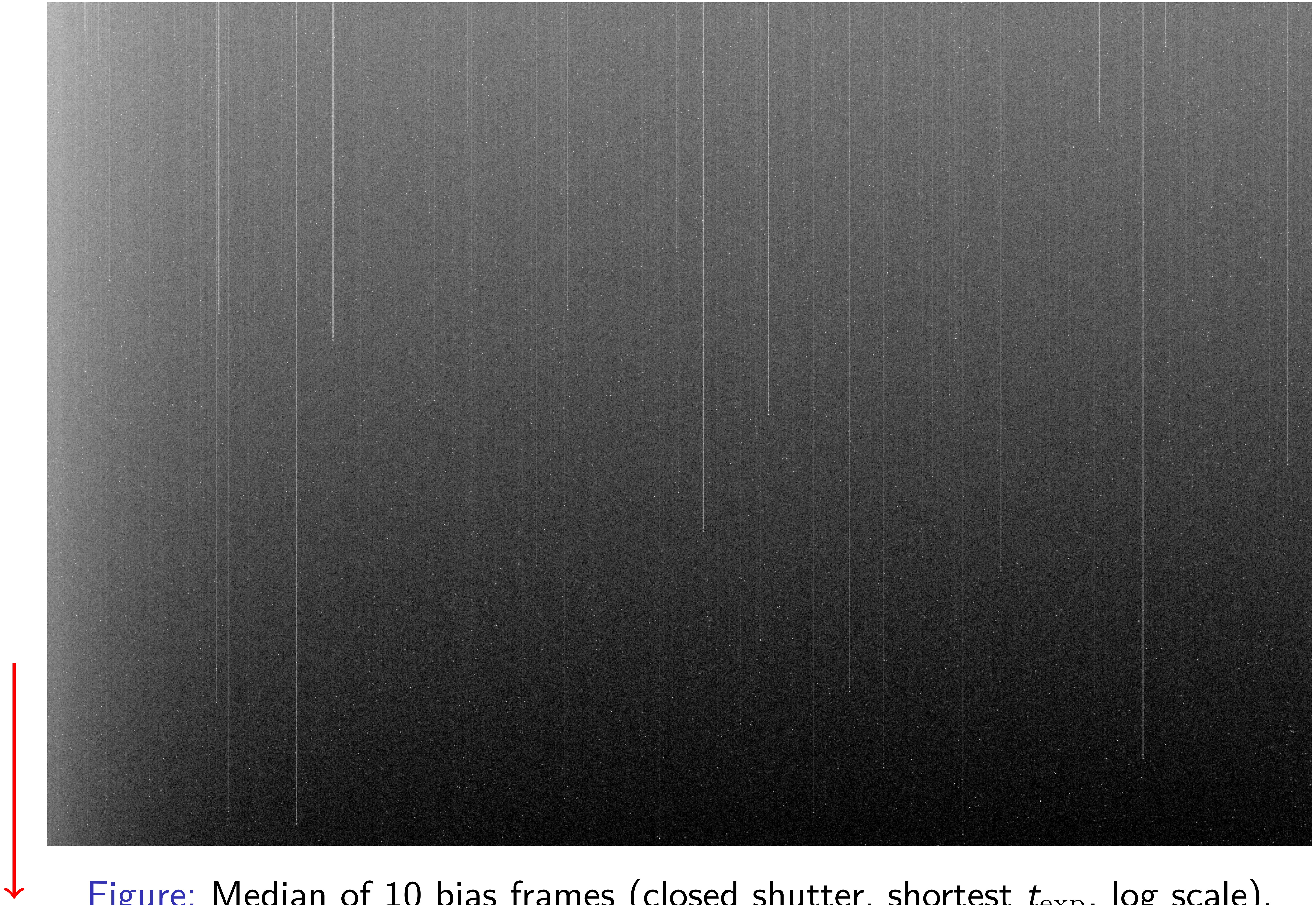


Figure: Median of 10 bias frames (closed shutter, shortest $t_{\rm exp}$, log scale).

Bias frame



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Dark frame / Cosmics

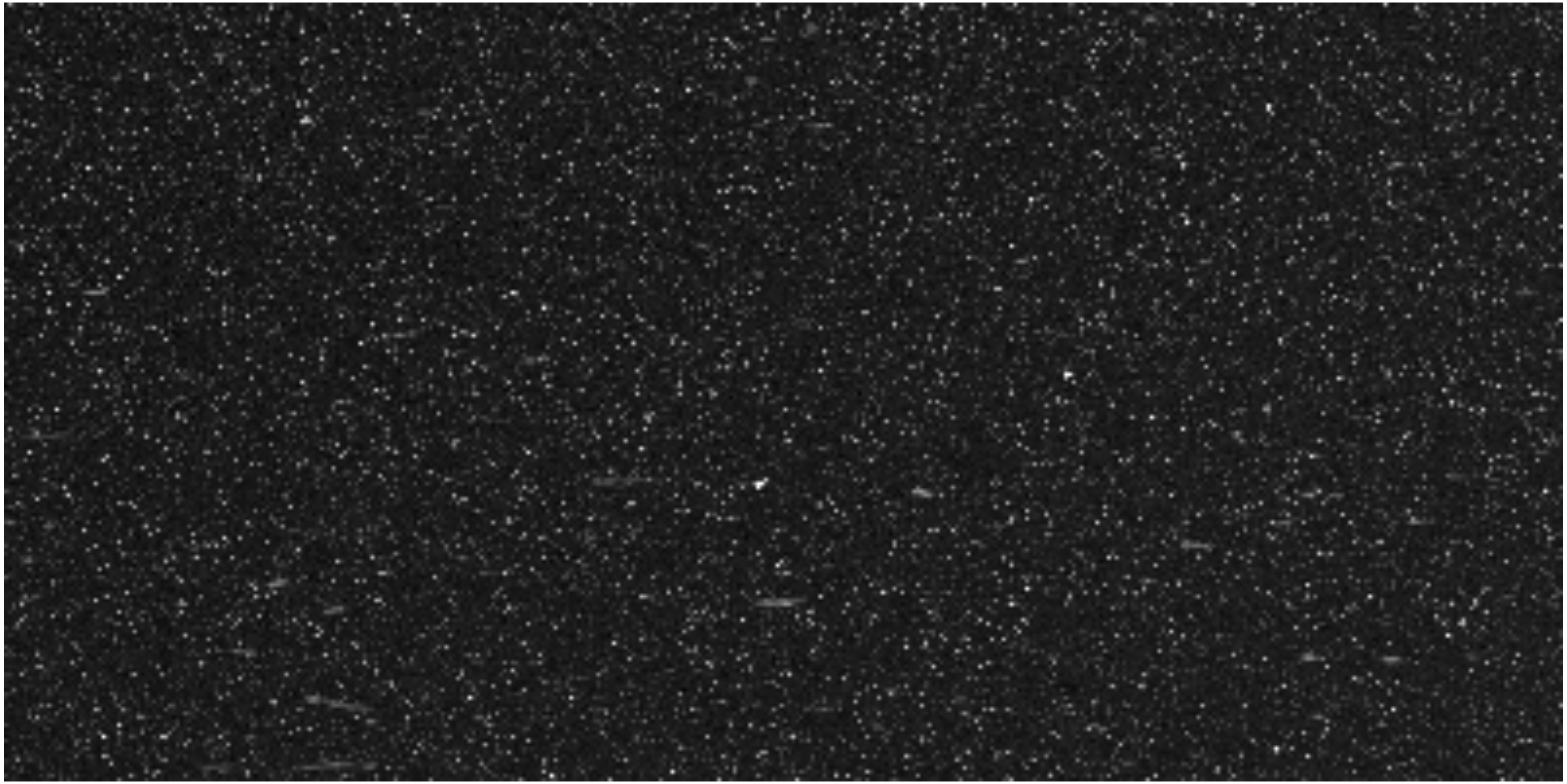


Figure: Dark frame detail, 3600s exposure (log scale).

Dark frame / Cosmics

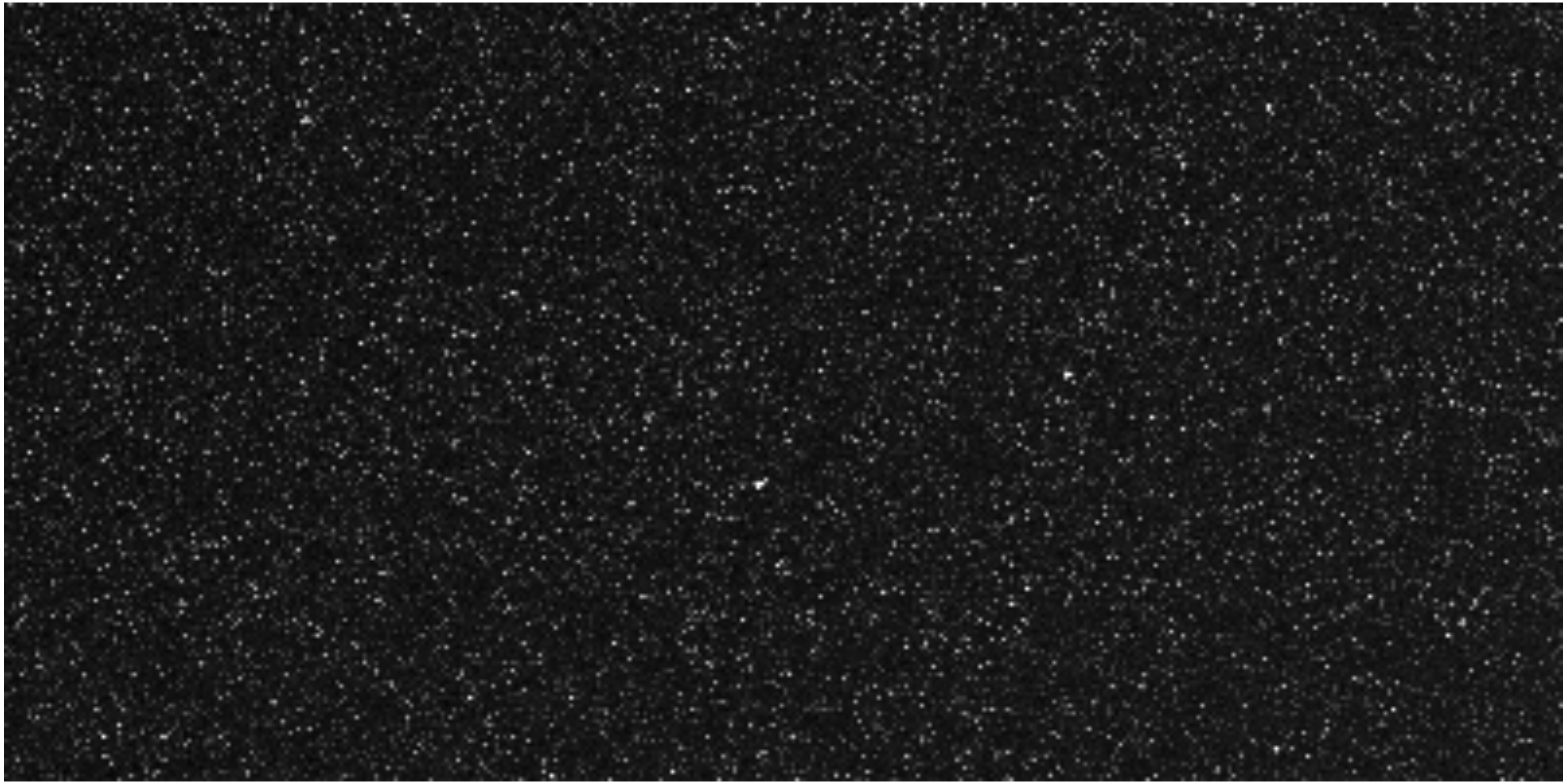


Figure: Dark frame detail: median of five 3600s exposures (log scale).

Average frames

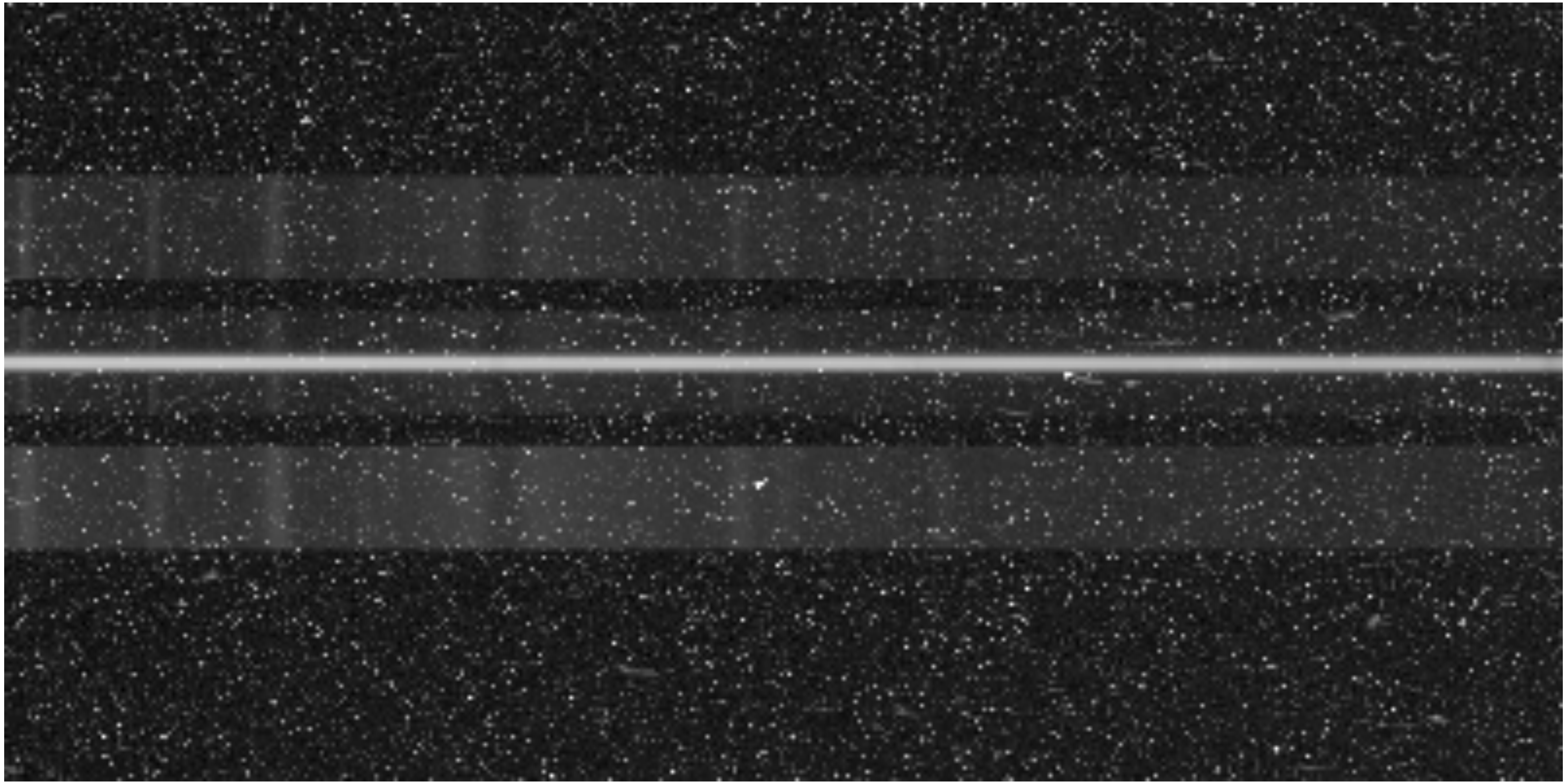


Figure: Science frame detail: 3600s exposure of BD+53 2790 (log scale).

Average frames

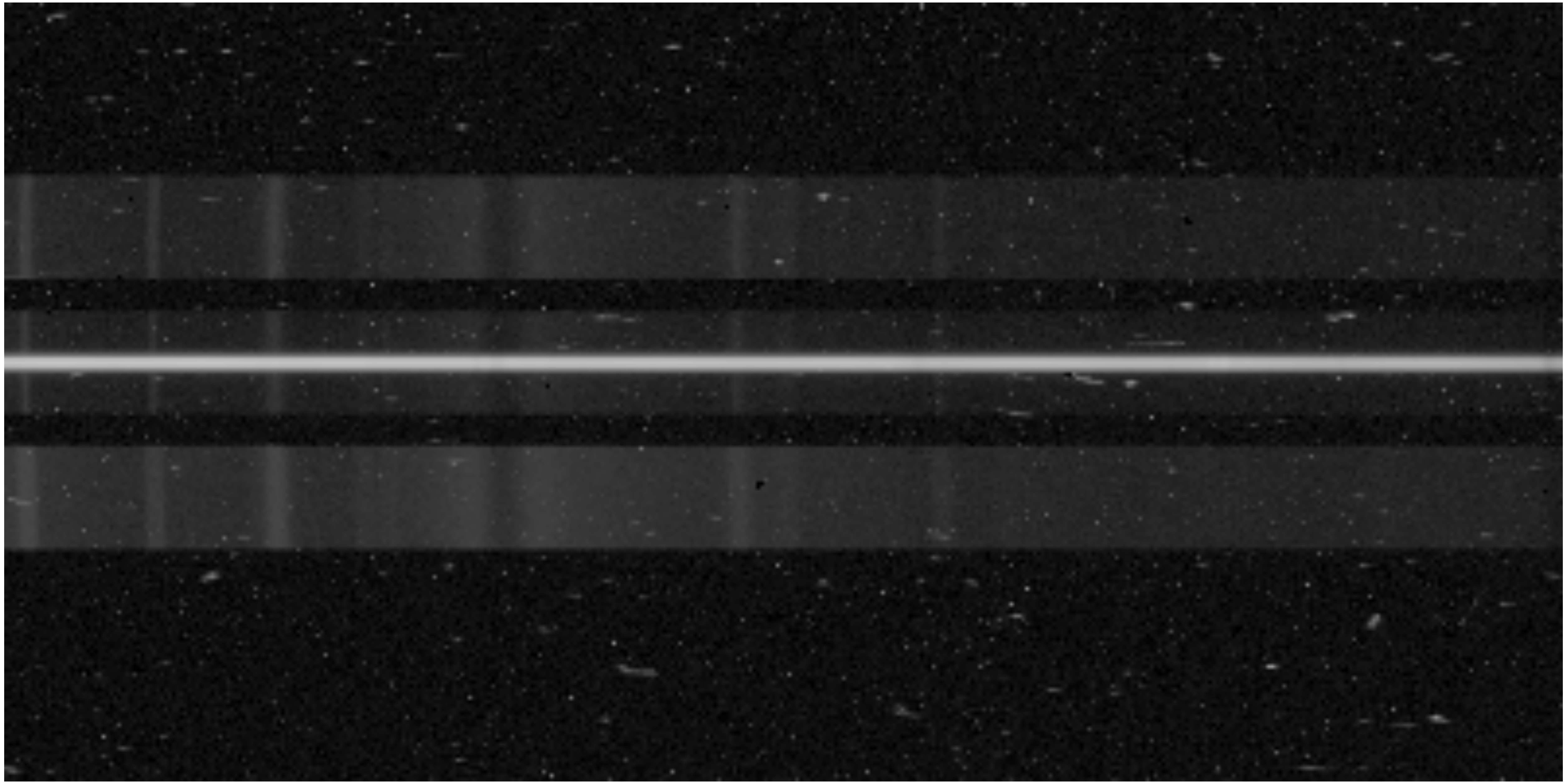


Figure: Science frame detail: dark frame subtracted.

Average frames

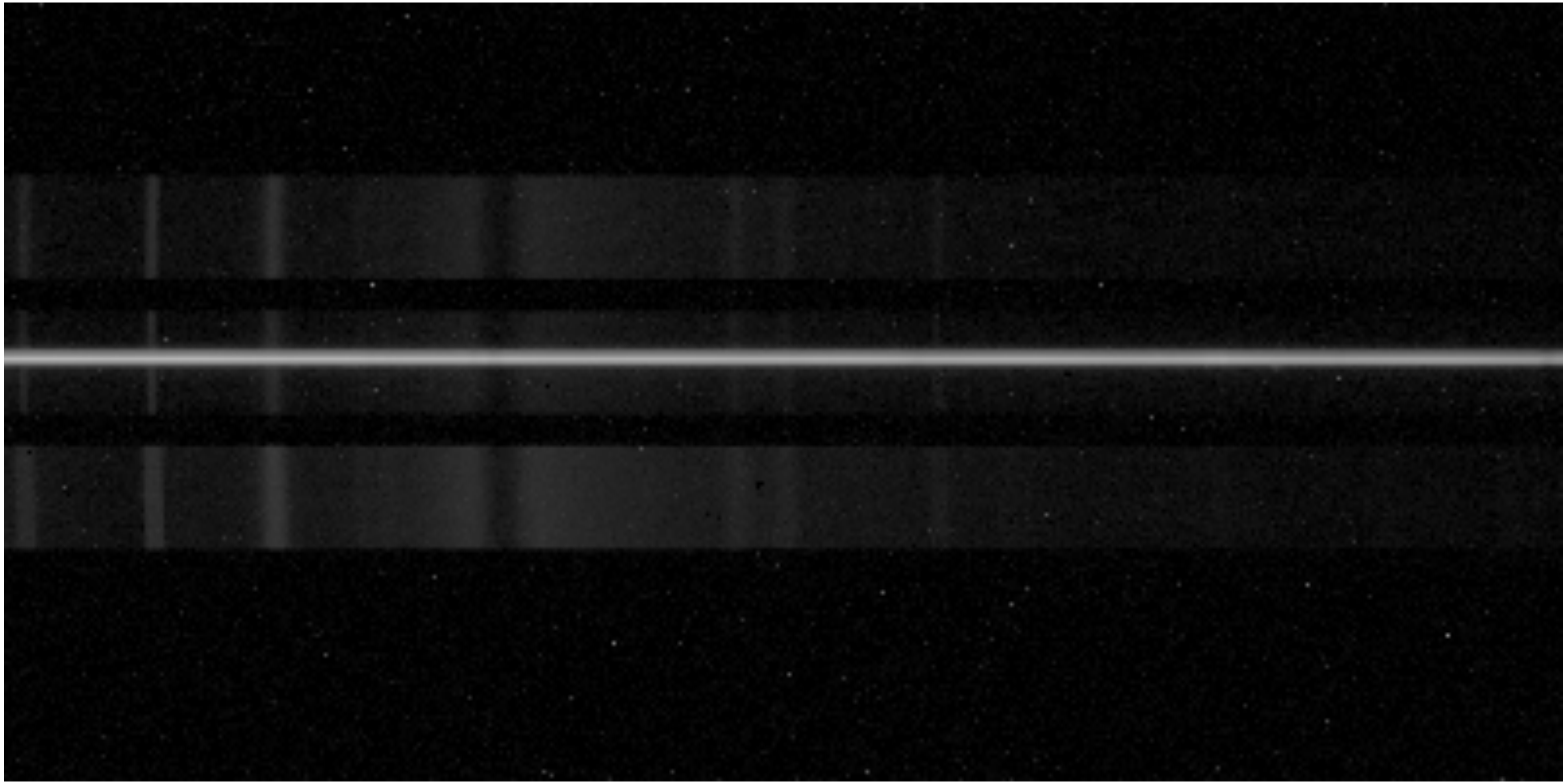
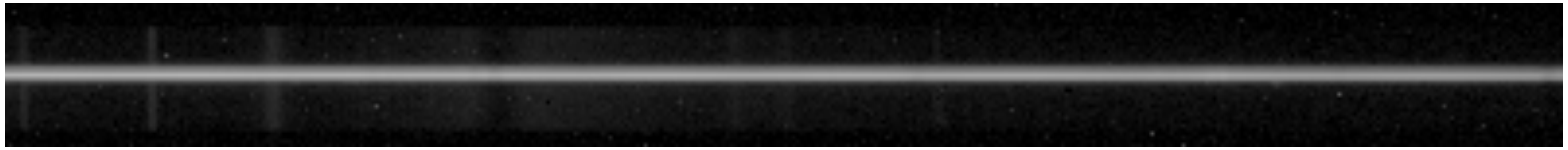


Figure: Science frame detail: dark frame subtracted, median of six exposures.

Sky background



Even the night sky is not completely black! Relevant for dark targets:

- air glow (emission lines due to chemical reactions in Earth's atmosphere, mainly at low altitudes $< 10^\circ$)
- scattered sunlight (astronomical twilight if Sun $< 18^\circ$ below horizon)
- moonlight
- *light pollution* (Potsdam, Berlin)
- in case of bad luck: planes (Tegel, Schönefeld)

Sky background

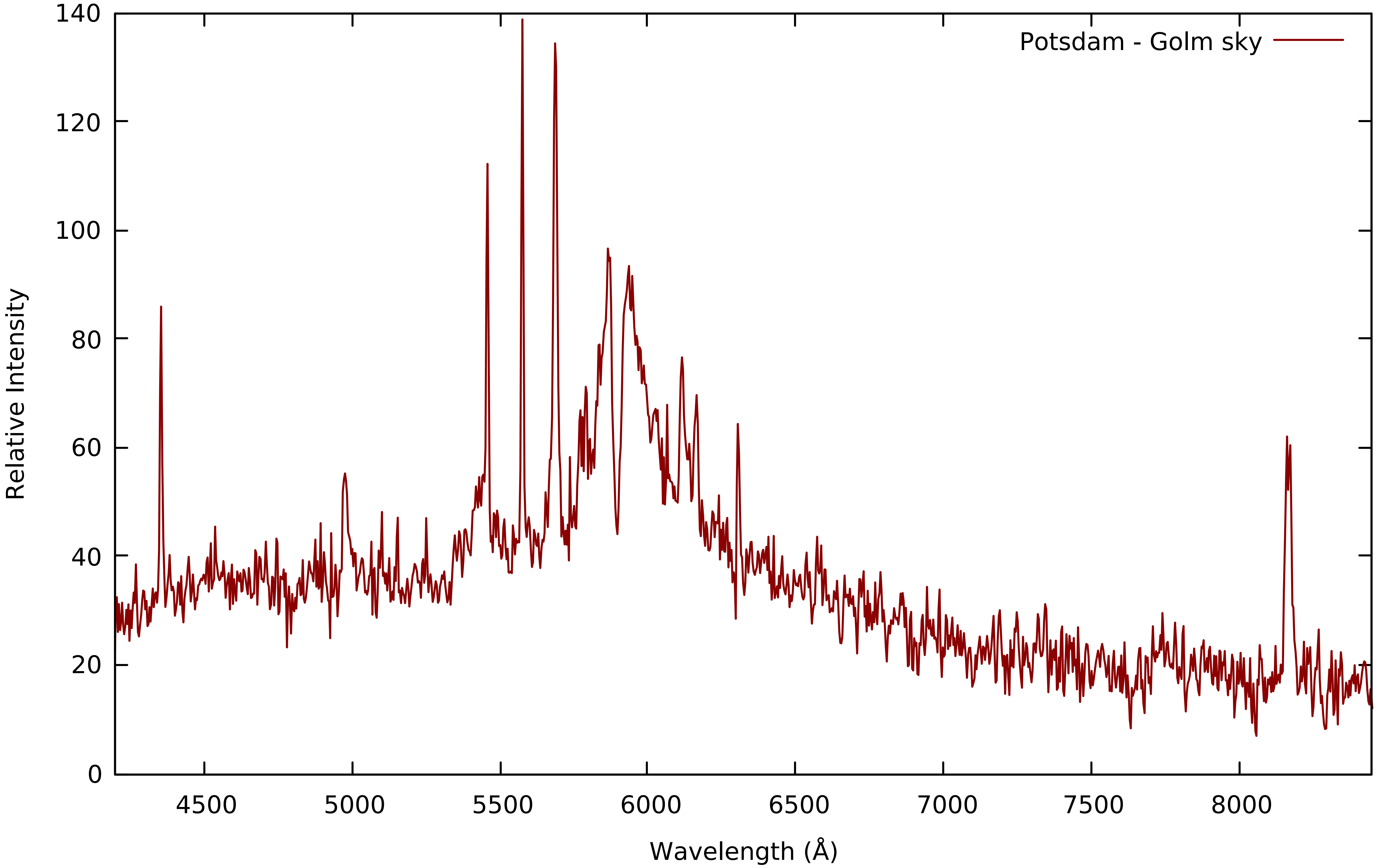
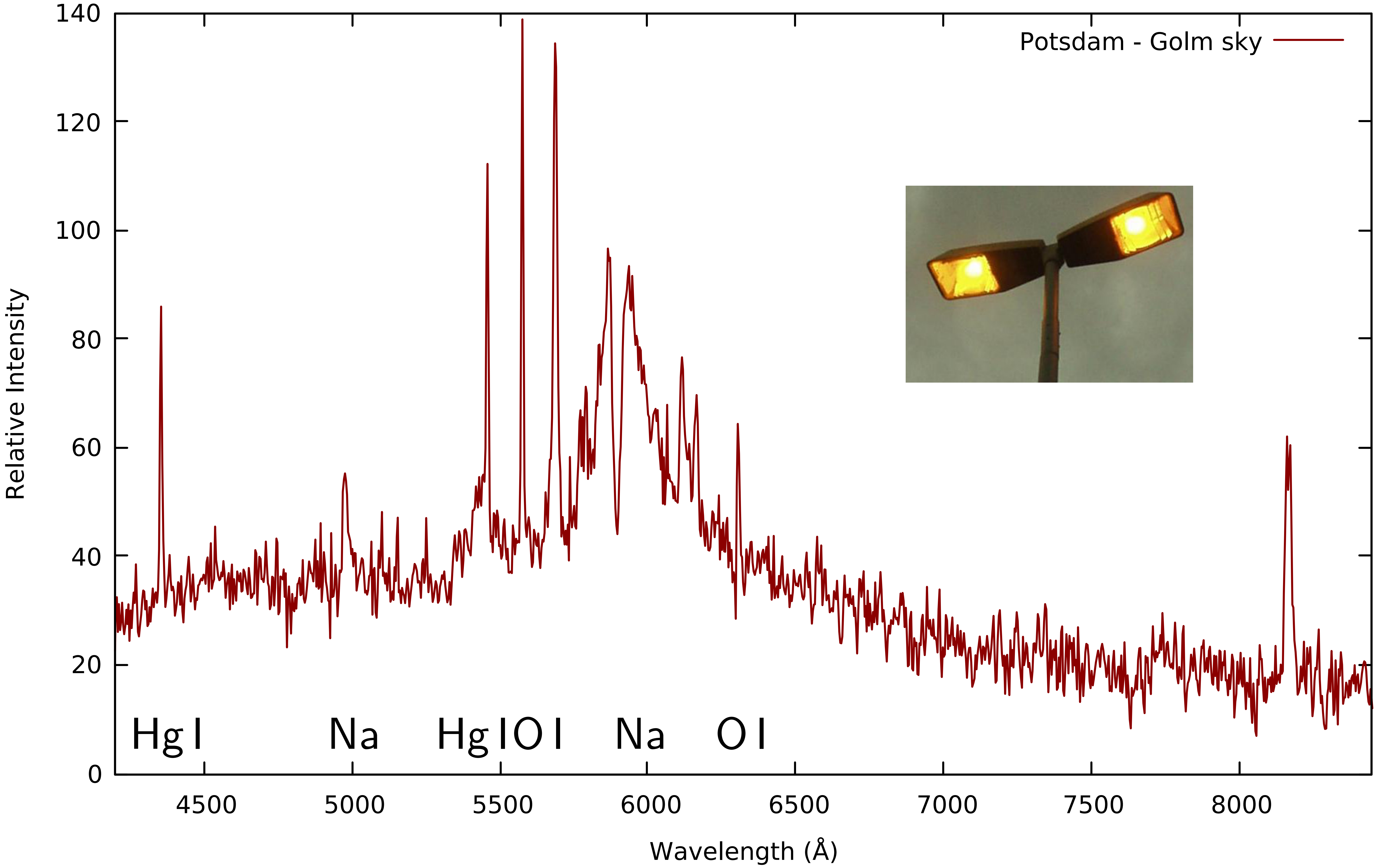


Figure: Potsdam sky background seen by DADOS (3h exposure average).

Sky background



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Dispersion relation

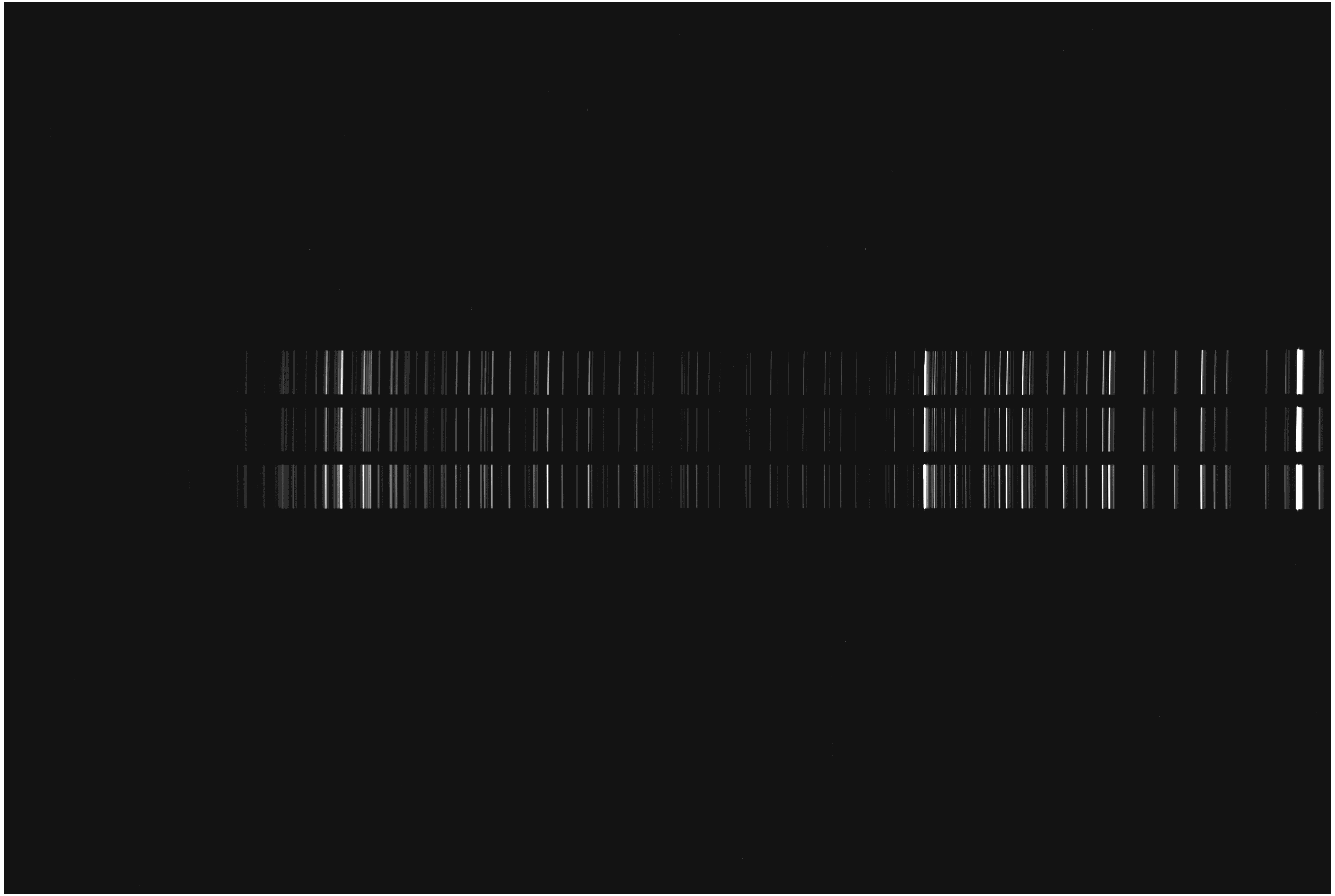

Figure: NeAr calibration frame.

Find dispersion relation

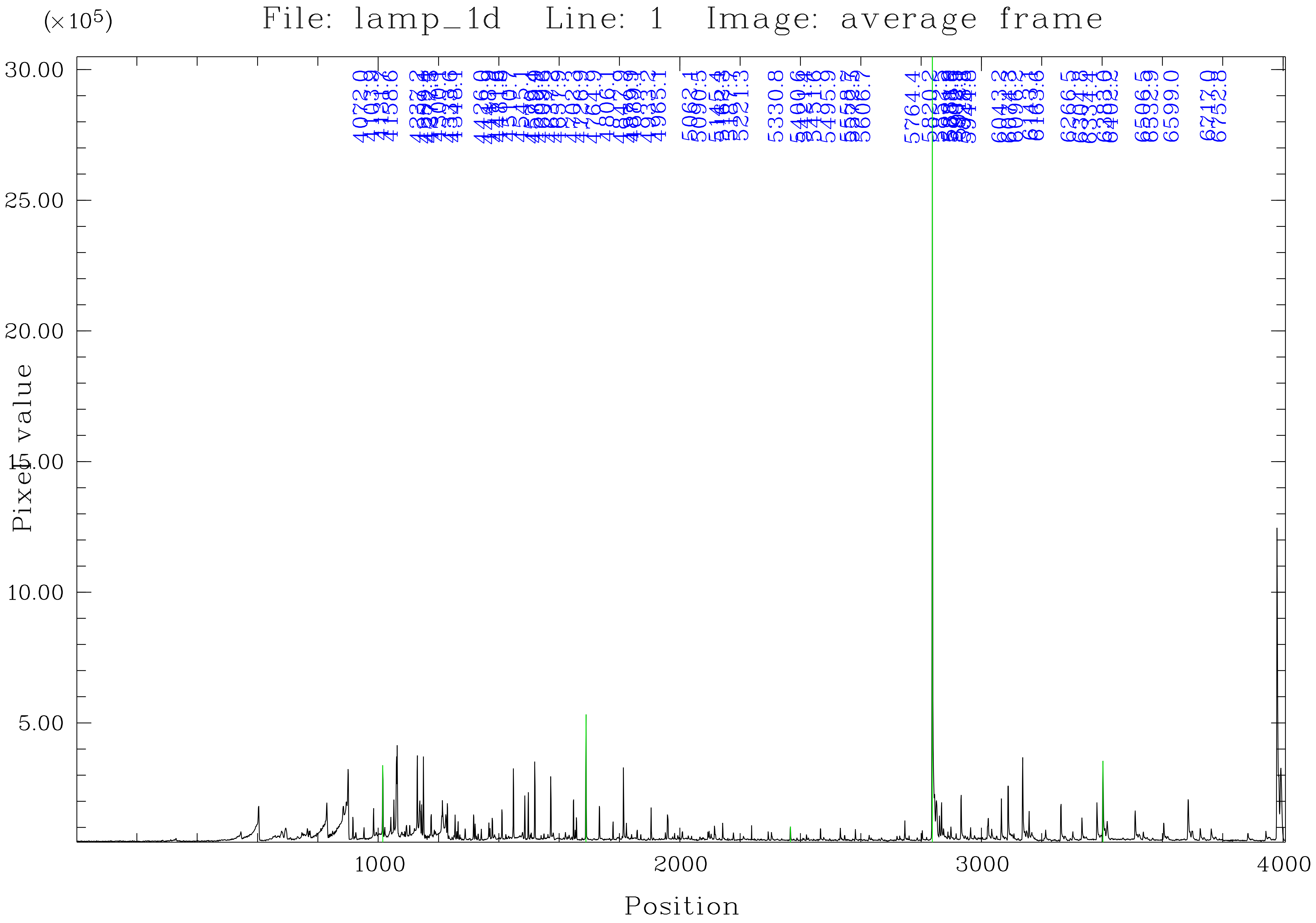

Figure: Semi-automatic emission line identification (NeXe lamp).

Find dispersion relation

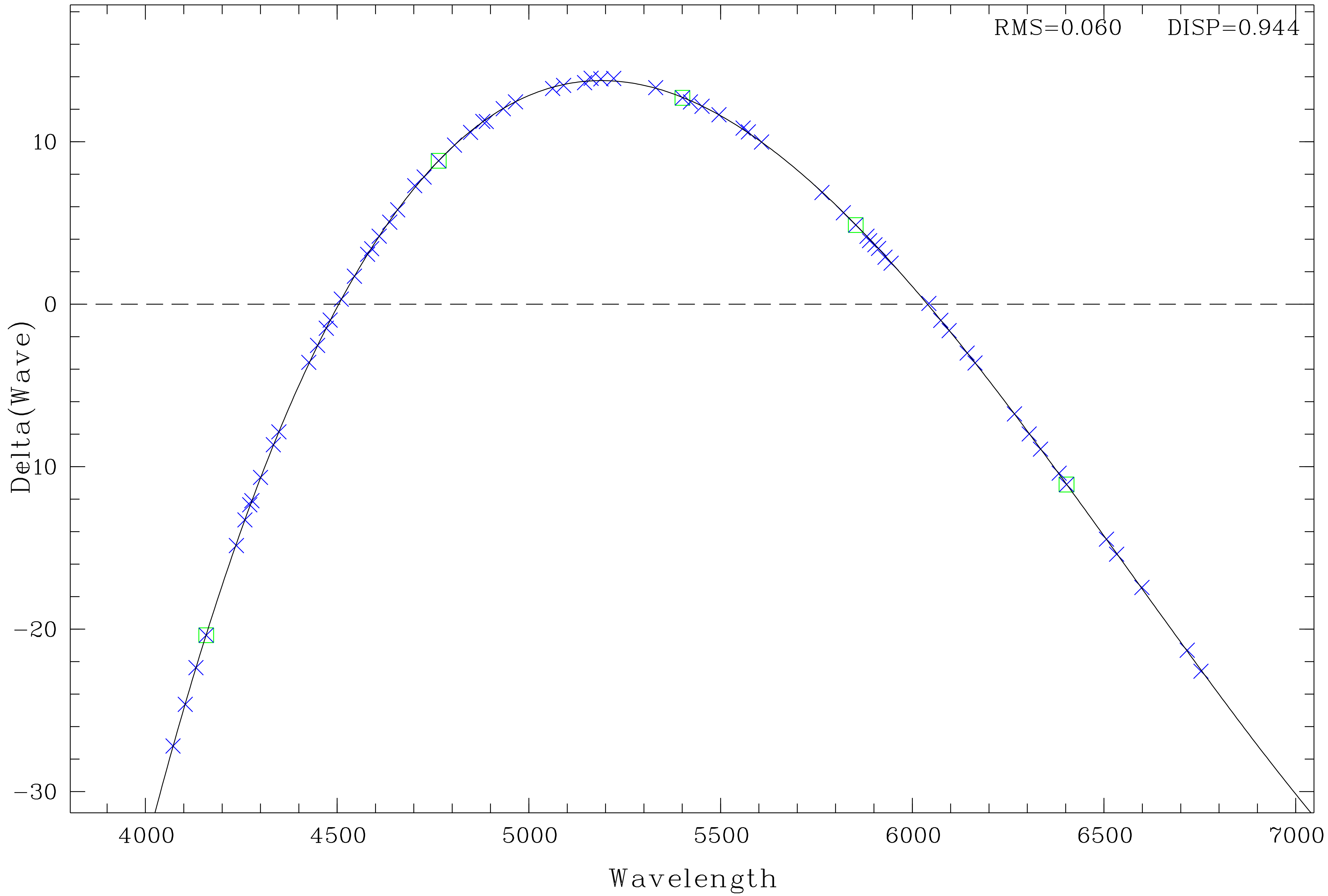

Figure: Dispersion relation as deviation from a linear relation between pixel and wavelength (NeXe lamp).

Find dispersion relation

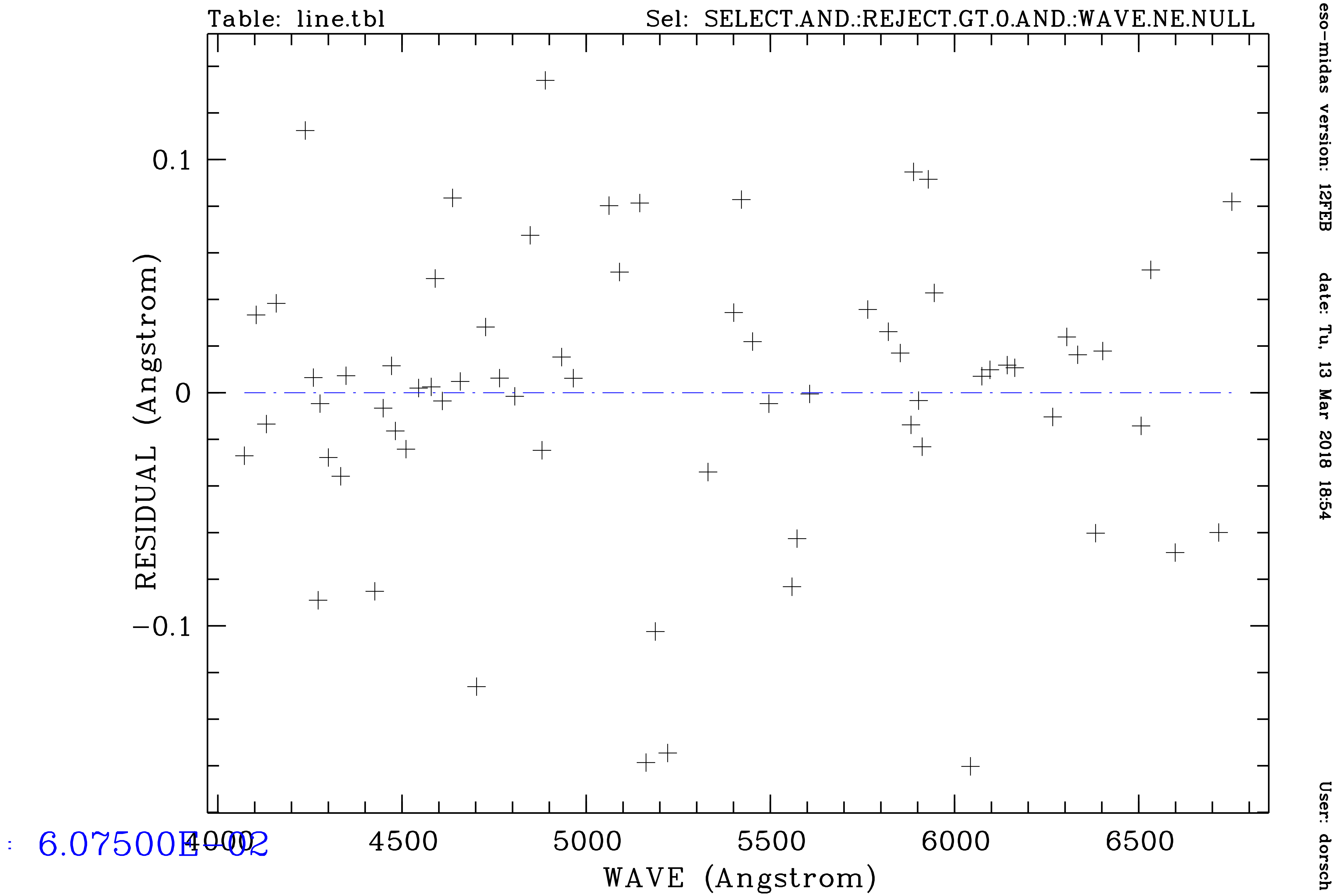

Figure: Deviations from the fitted dispersion relation (NeXe lamp).

Step-by-step summary

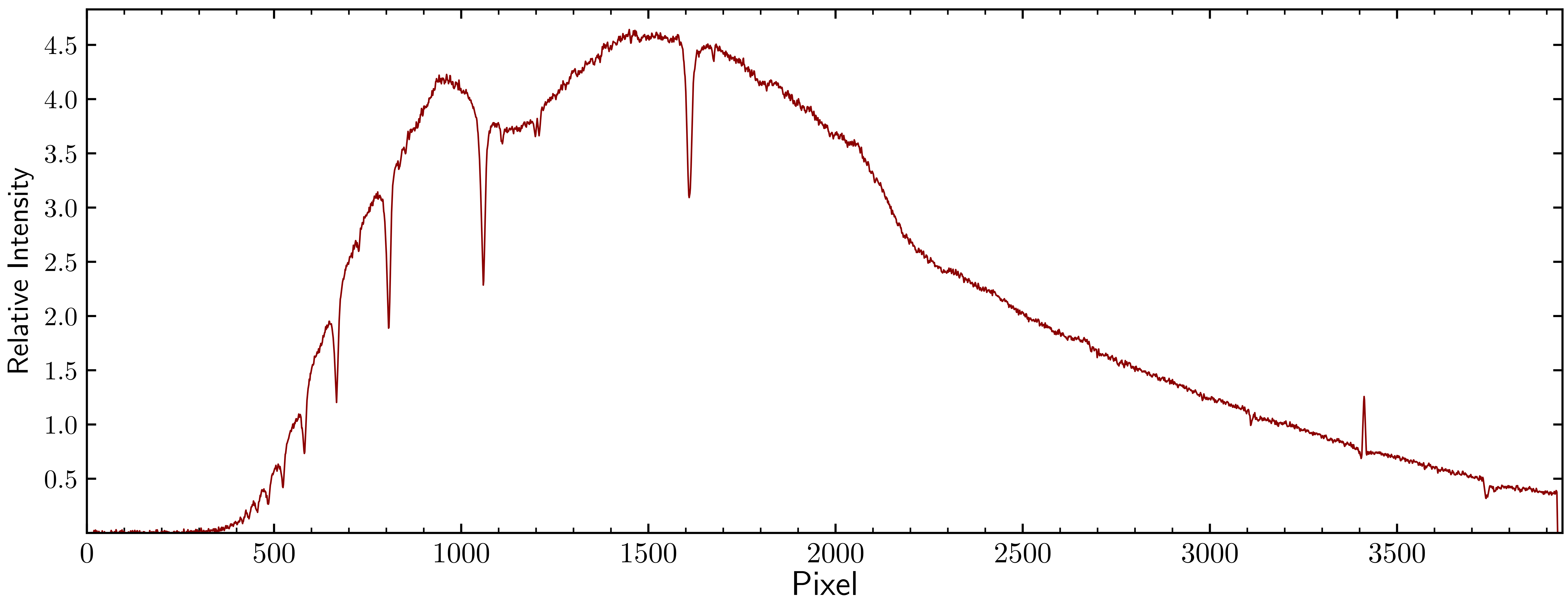

Figure: DADOS spectrum of Alcyone: dark, averaged.

Step-by-step summary

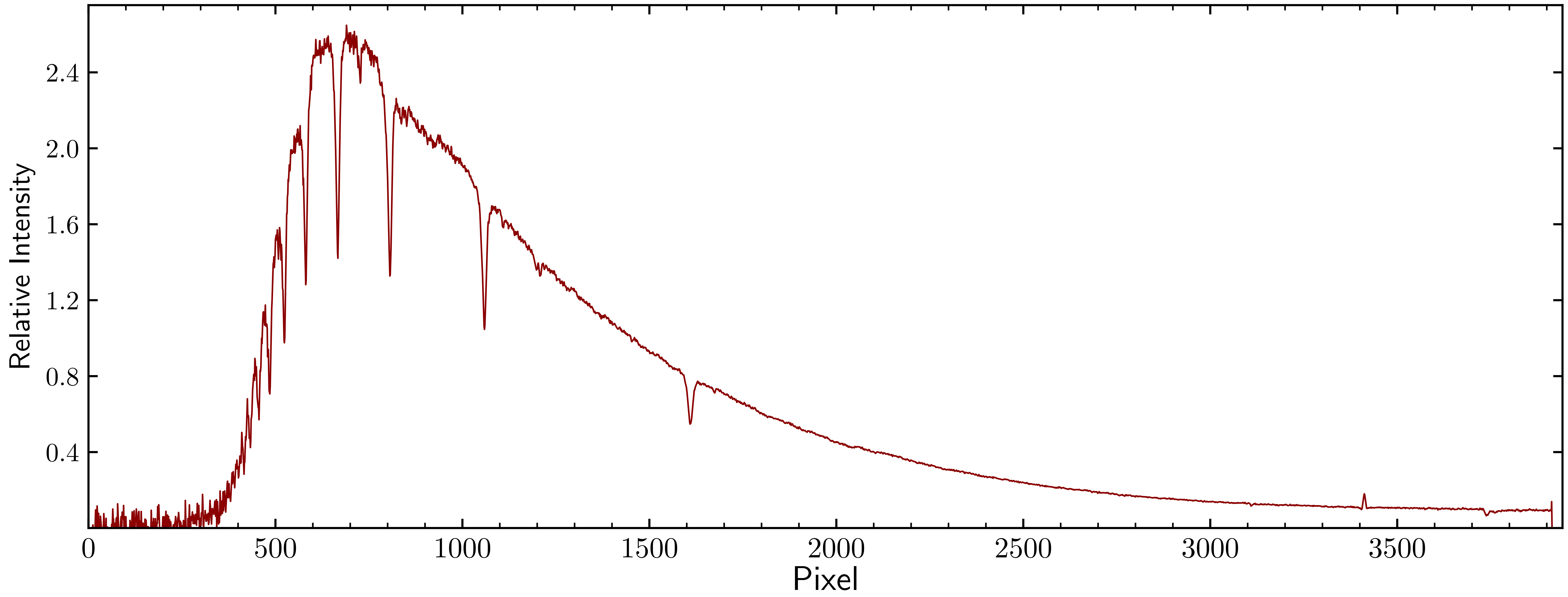

Figure: DADOS spectrum of Alcyone: dark, averaged, flat.

Step-by-step summary

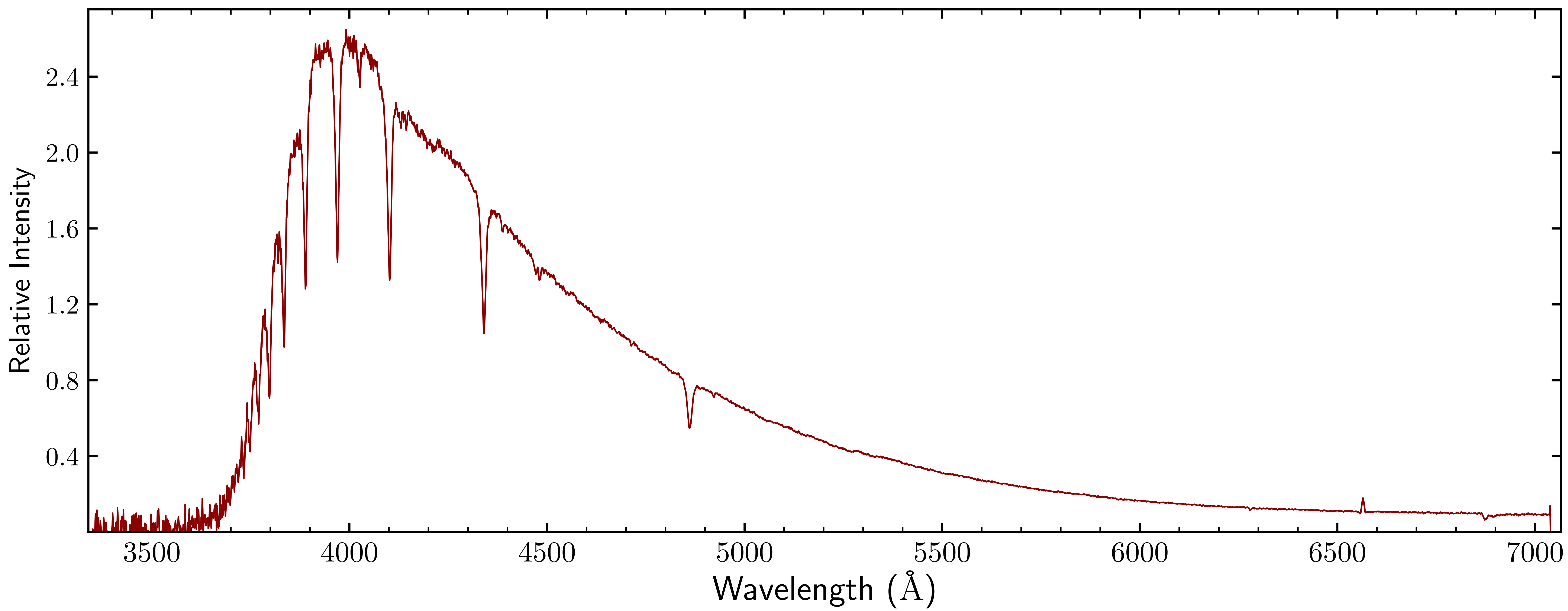

Figure: DADOS spectrum of Alcyone: dark, averaged, flat, calibrated.