Spectroscopy

Or, the art Gandalf does not approve of.

Luca Sbordone - ESO Chile

"...White cloth may be dyed. The white page can be overwritten; and the white light can be broken."

"In which case it is no longer white," said I. "And he that breaks a thing to find out what it is has left the path of wisdom."

J. R. R. Tolkien

About me

- Italian, almost 51 (ouch)
- ESO Operations Staff Astronomer – Paranal
- UVES instrument Scientist
- Padova – Rome – ESO Chile – Paris – Munich – Heidelberg – PUC Santiago – ESO Chile
- Chemical abundances in FGK stars, chemical evolution, stellar atmospheres, high resolution spectrocospy…

About me

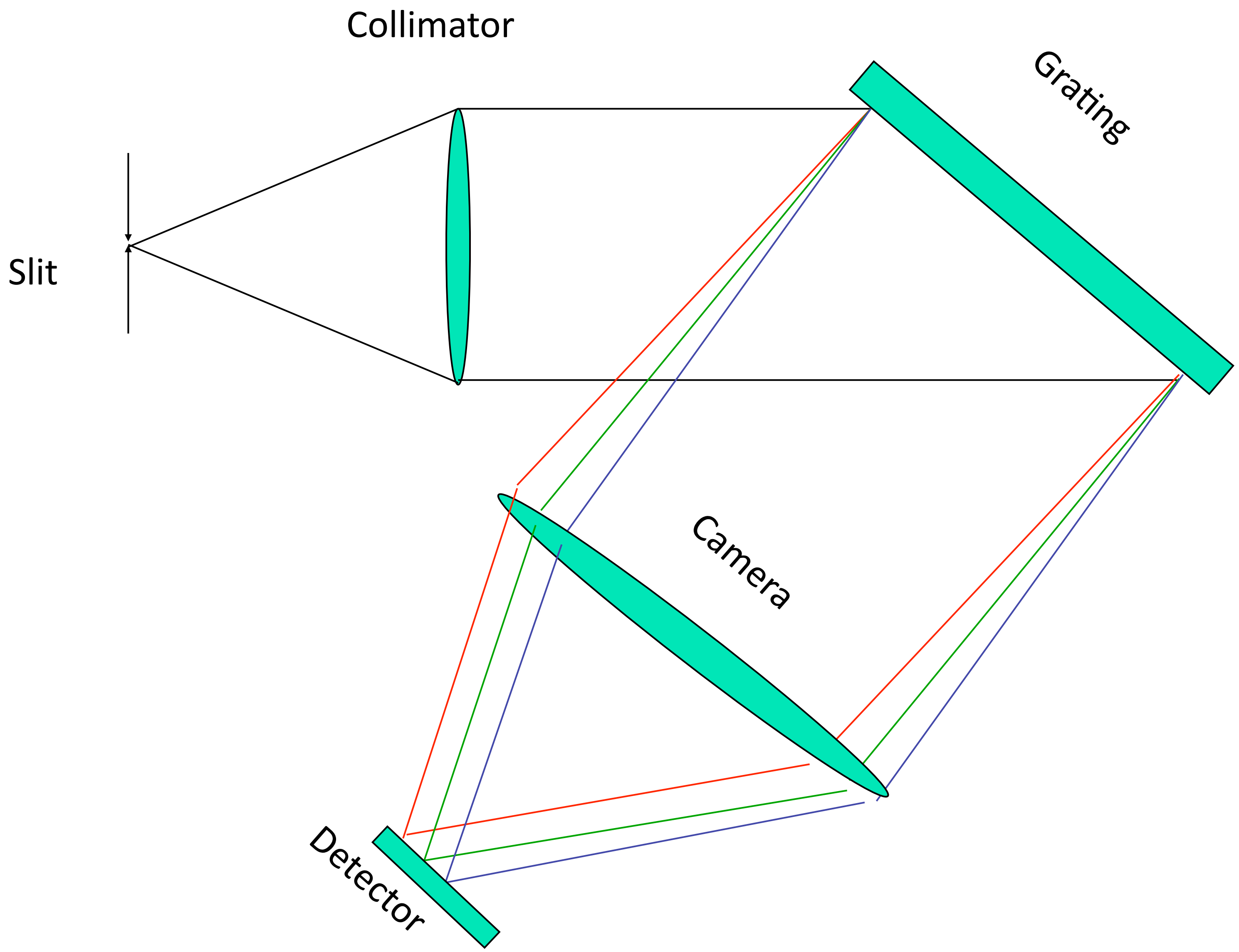
Photography

- Italian, almost 51 (ouch)
- ESO Operations Staff Astronomer – Paranal
- UVES instrument Scientist
- Padova – Rome – ESO Chile – Paris – Munich – Heidelberg – PUC Santiago – ESO Chile
- Chemical abundances in FGK stars, chemical evolution, stellar atmospheres, high resolution spectrocospy…

4 y. o. Unicorn Hybrid

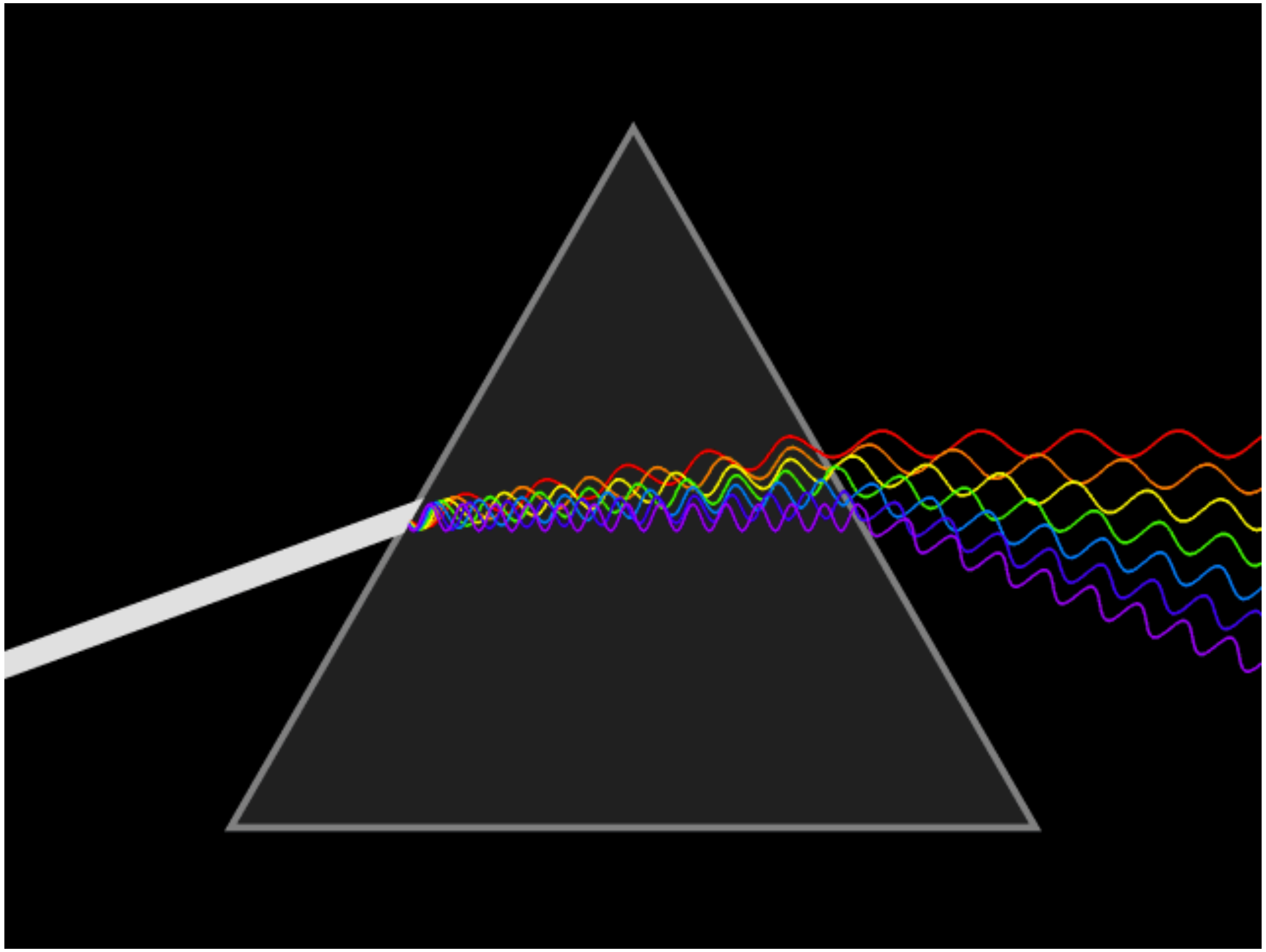
Spectrographs?

- A spectrograph is a **camera** coupled with a **dispersing element**
- Images of the source **at different wavelengths** fall on **different places** in the detector
- The **amount** of light emitted **at each wavelength** can be measured: the **spectrum**



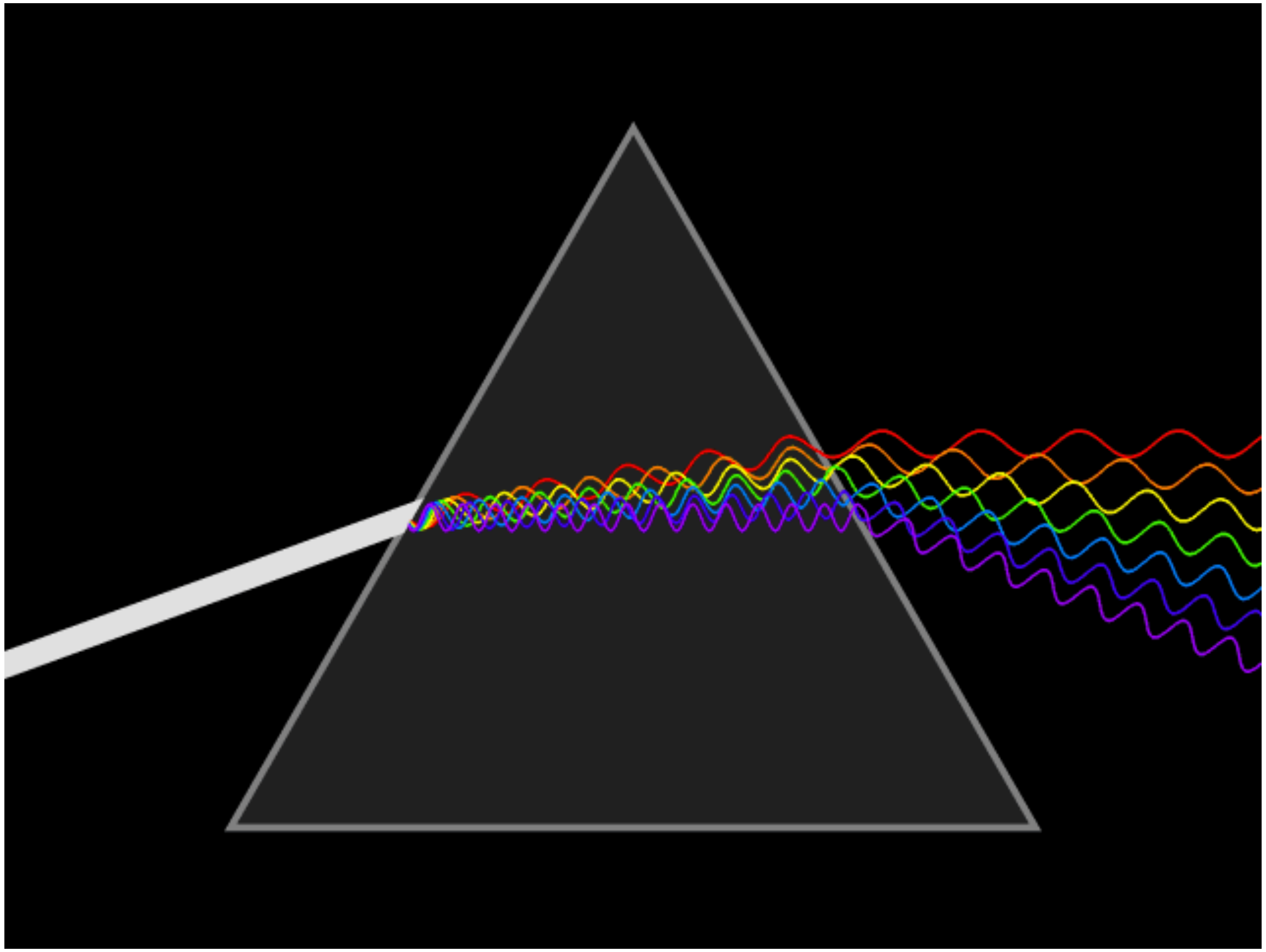
Tools of the trade: the humble prism

- First dispersing element invented/discovered
- Uses the fact that refraction is dependent on light wavelength (any refractive element is chromatic)
- Longer wavelength, redder light is deviated less than bluer, shorter wavelength light.
- In general prisms have low dispersion



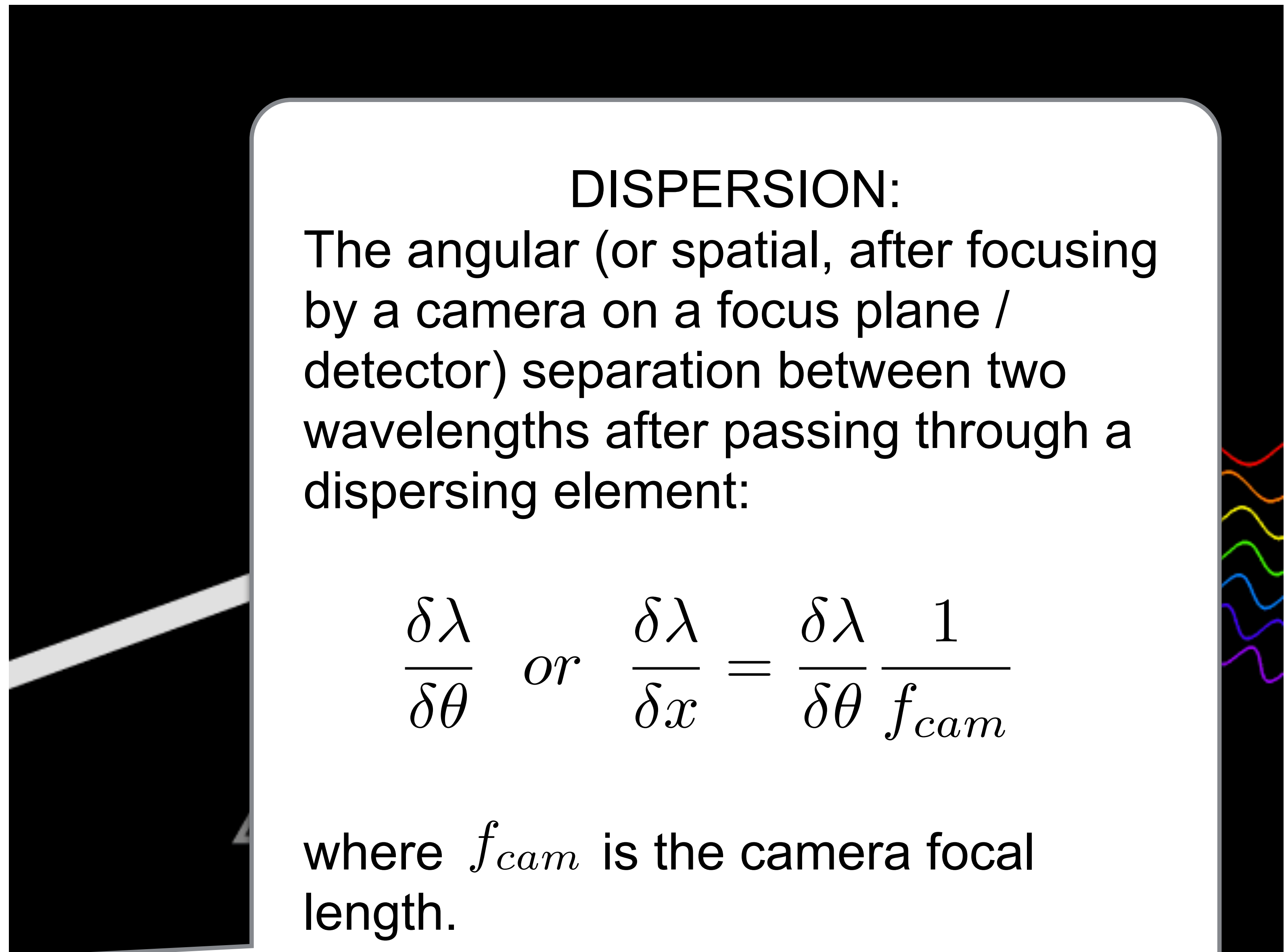
Tools of the trade: the humble prism

- First <u>dispersing element</u> invented/discovered
- Uses the fact that <u>refraction</u> is dependent on light wavelength (any refractive element is <u>chromatic</u>)
- <u>Longer wavelength, redder</u> light is deviated <u>less</u> than bluer, shorter wavelength light.
- In general prisms have low <u>dispersion</u>



Tools of the trade: the humble prism

- First <u>dispersing element</u> invented/discovered
- Uses the fact that <u>refraction</u> is dependent on light wavelength (any refractive element is <u>chromatic</u>)
- <u>Longer wavelength, redder</u> light is deviated <u>less</u> than bluer, shorter wavelength light.
- In general prisms have low <u>dispersion</u>



DISPERSION:

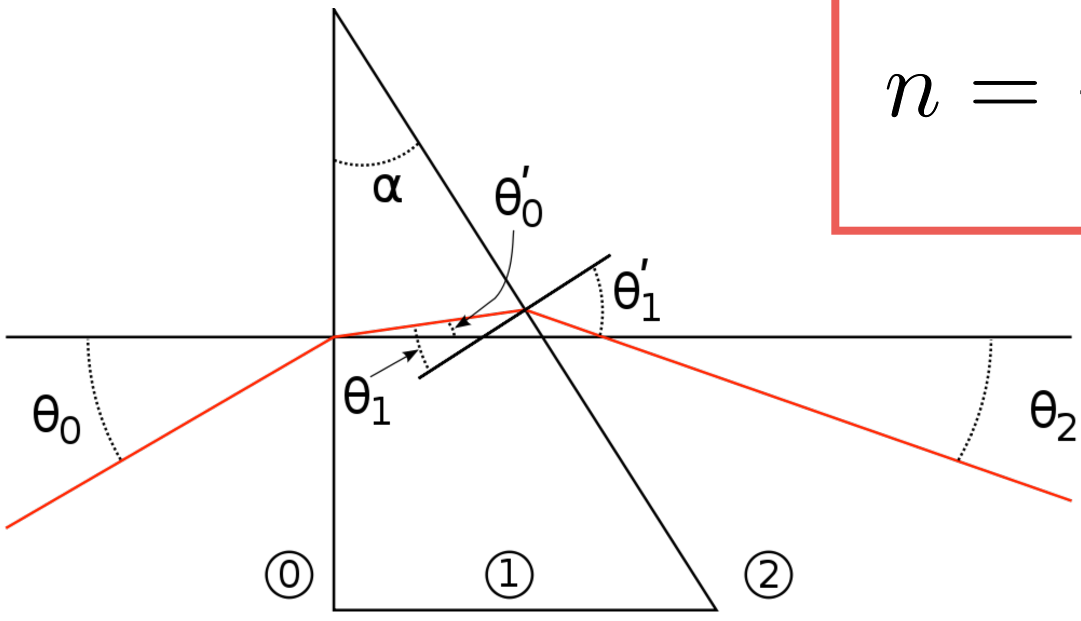
The angular (or spatial, after focusing by a camera on a focus plane / detector) separation between two wavelengths after passing through a dispersing element:

$$\frac{\delta\lambda}{\delta\theta} \quad or \quad \frac{\delta\lambda}{\delta x} = \frac{\delta\lambda}{\delta\theta}\frac{1}{f_{cam}}$$

where f_{cam} is the camera focal length.

Do <u>not</u> confuse it with <u>resolution!</u>

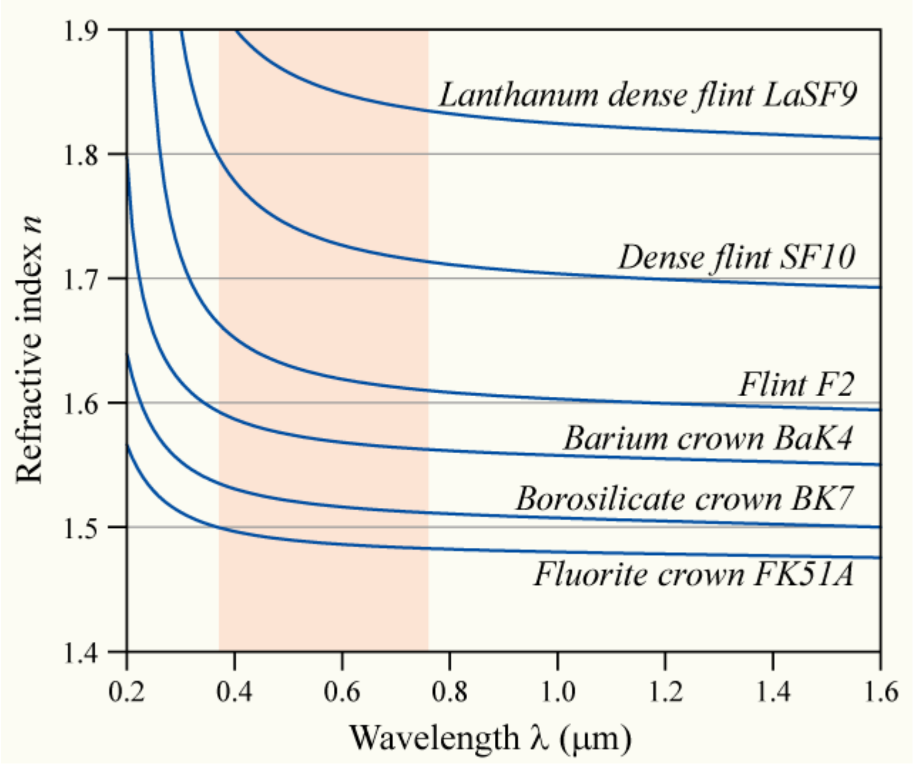
Tools of the trade: the humble prism



Refractive Index

$$n = \frac{c}{v}$$

Light phase velocity in the medium

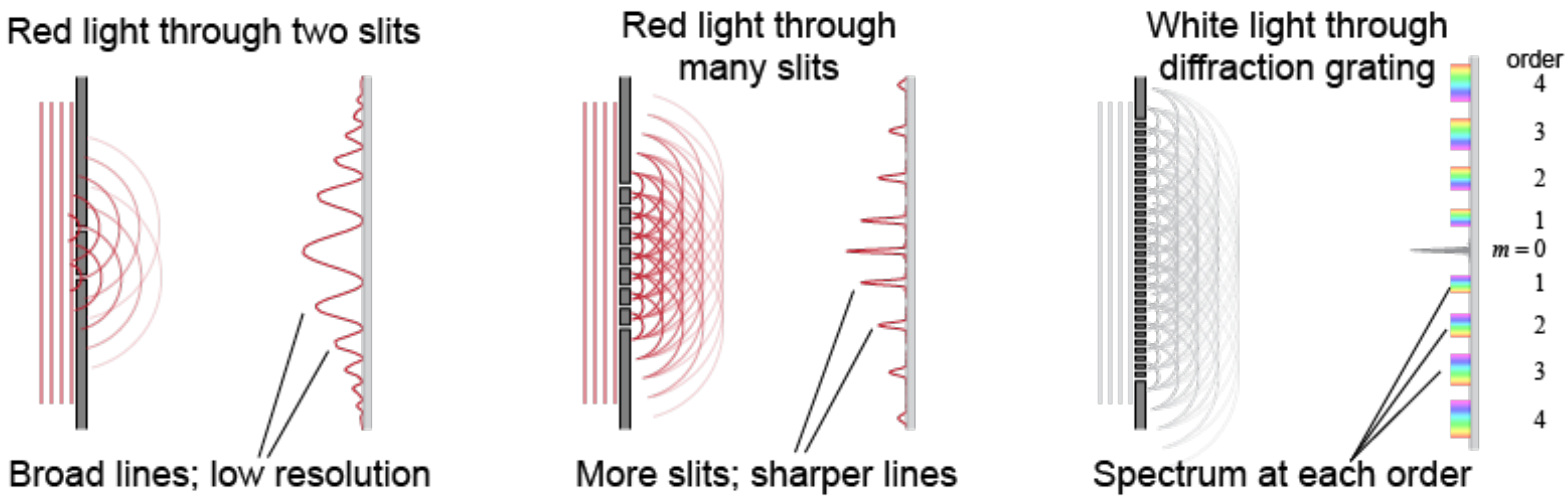


$$n_0 \sin\theta_0 = n_1 \sin\theta_1$$

$$\Rightarrow \delta(\lambda) \approx [n(\lambda) - 1]\,\alpha$$

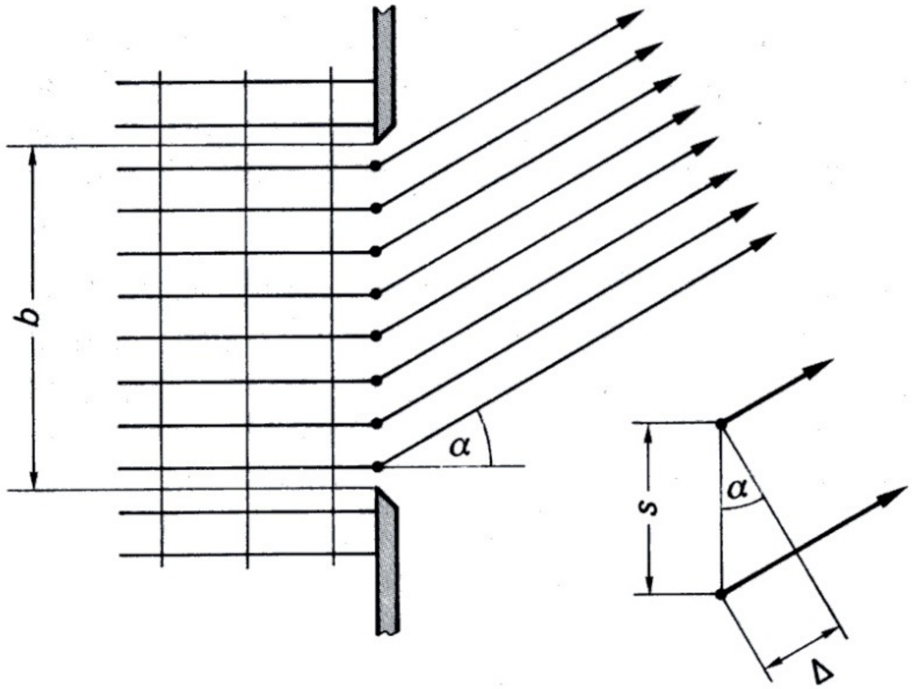
In prisms dispersion is due to the variation of *n* with the wavelength.
Usually then dispersion is not constant with wavelength

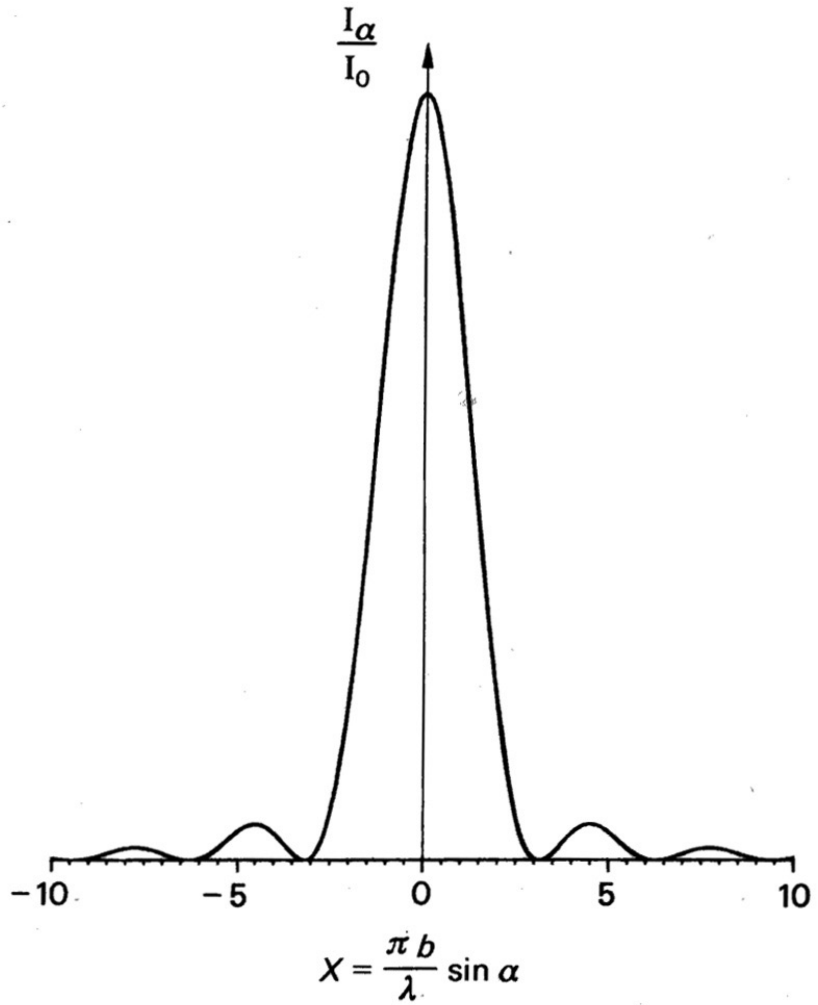
Tools of the trade: the diffraction grating

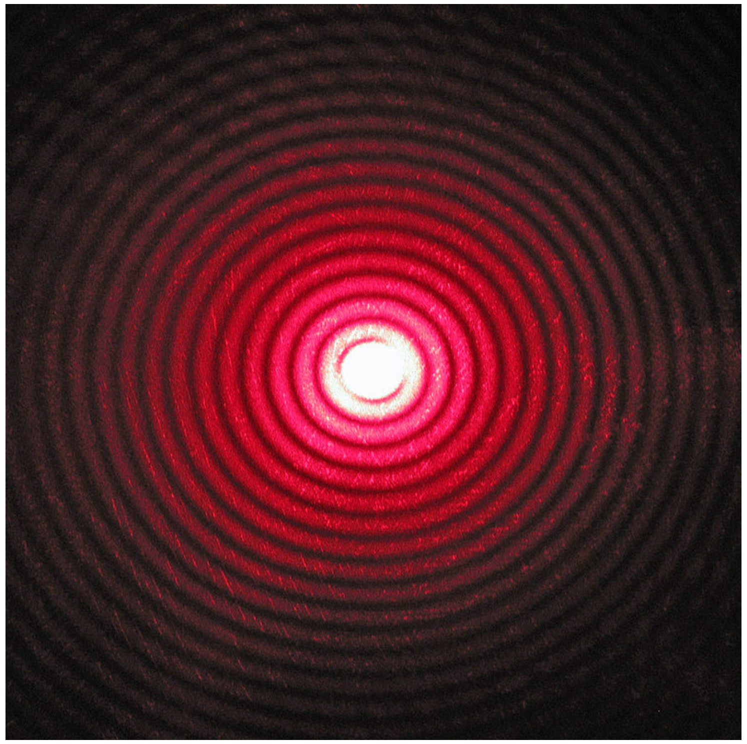


- Diffraction gratings exploit the superposition of diffraction and interference, manifestation of the wave behavior of light.
- Although the pattern is the same for each wavelength, spacing depends on wavelength, hence the dispersion.
- Gratings generate multiple dispersion orders, of increasing dispersion: very high dispersions can be achieved at high orders.
- Red light is dispersed more than blue.

Single slit diffraction







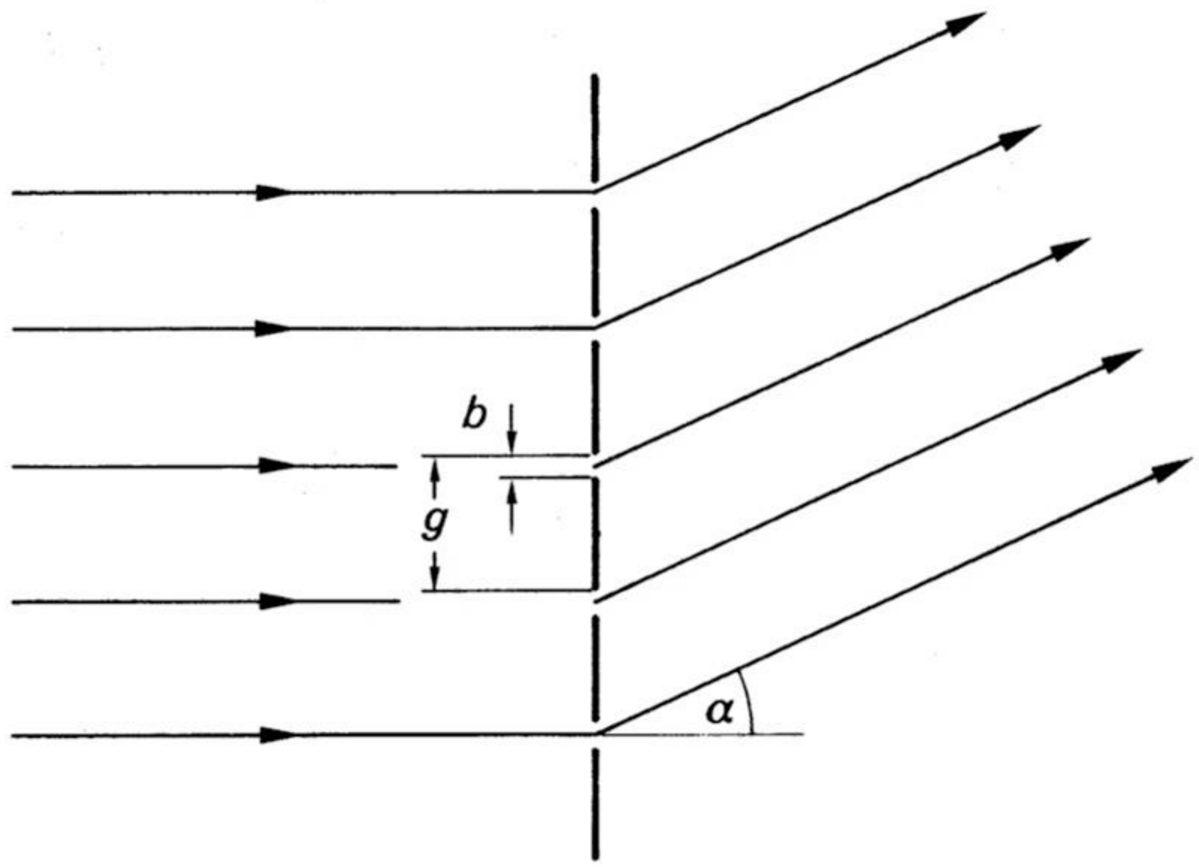
Laser through a single pinhole

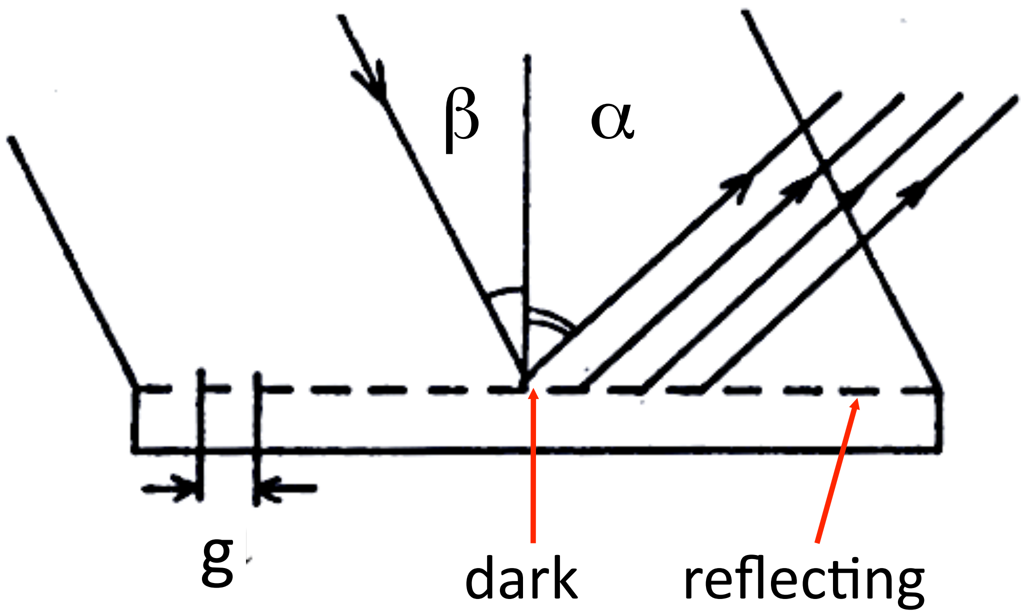
$$\frac{I_\alpha}{I_0} = \left(\frac{\sin\left(\frac{\pi b}{\lambda} \sin \alpha\right)}{\frac{\pi b}{\lambda} \sin \alpha} \right)^2$$

$$\sin \theta \approx 1.22 \frac{\lambda}{b}$$

Angle of 1st zero intensity

Multiple slits interference





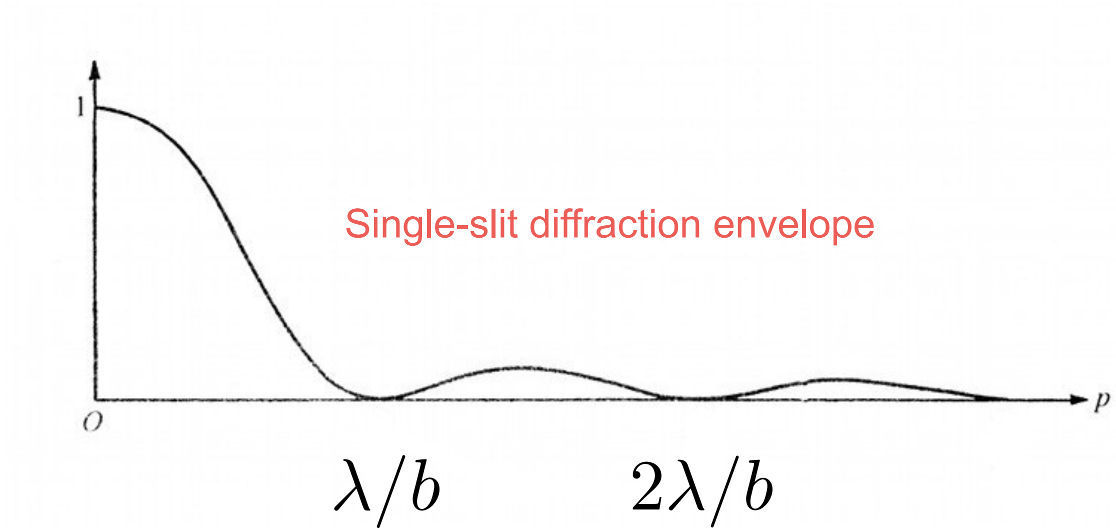
b: slit width

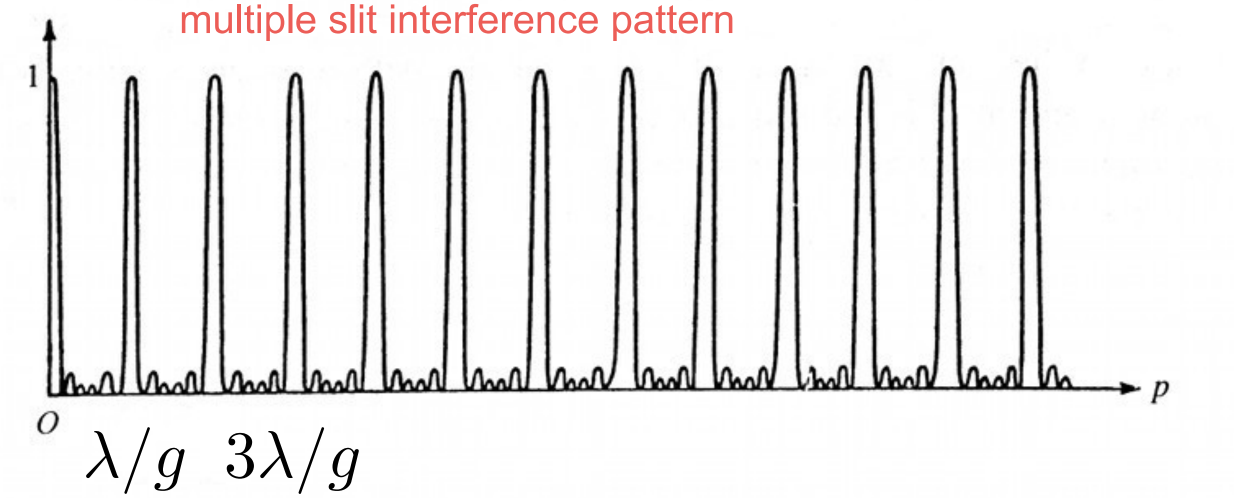
g: period

α: diffraction angle

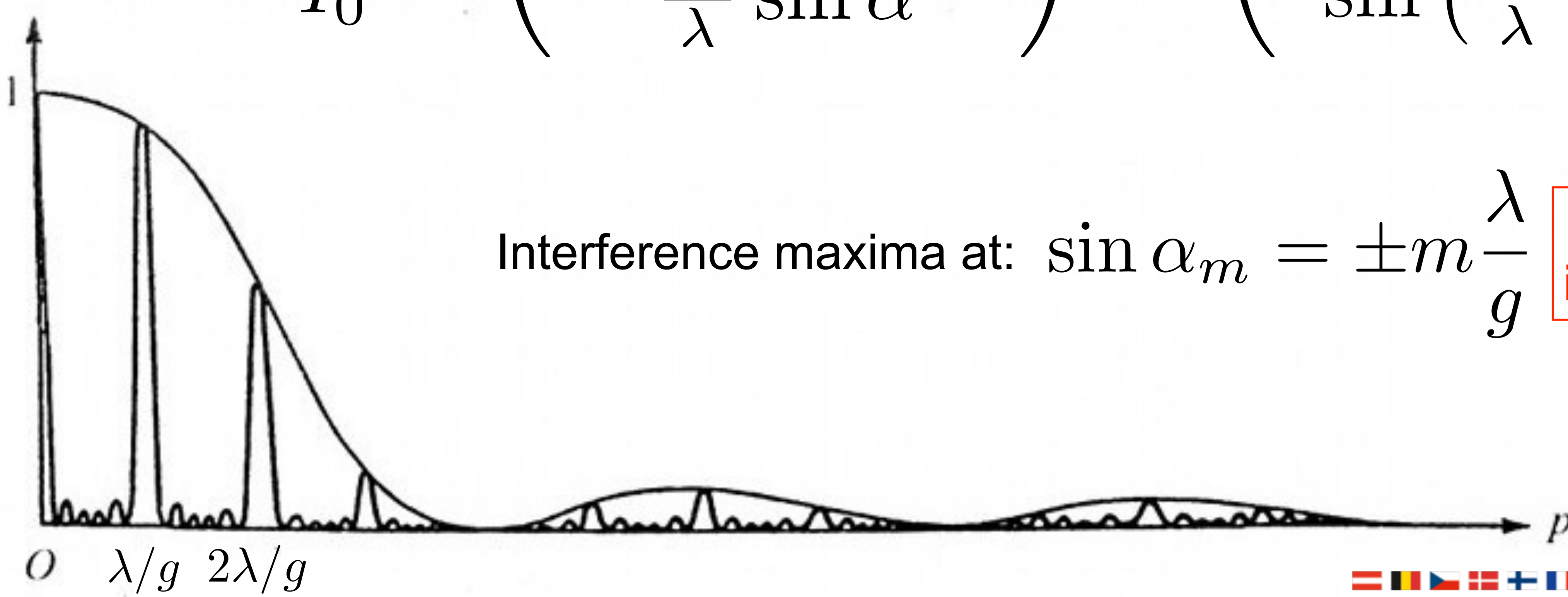
β: angle of incidence

Tools of the trade: the diffraction grating





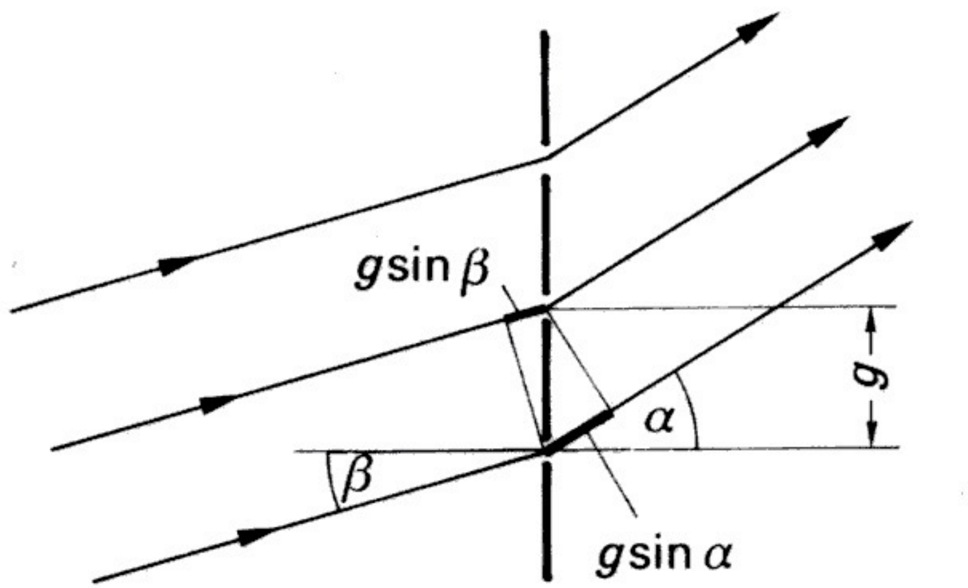
$$\frac{I_\alpha}{I_0} = \left(\frac{\sin\left(\frac{\pi b}{\lambda}\sin\alpha\right)}{\frac{\pi b}{\lambda}\sin\alpha} \right)^2 \times \left(\frac{\sin\left(N\frac{\pi g}{\lambda}\sin\alpha\right)}{\sin\left(\frac{\pi g}{\lambda}\sin\alpha\right)} \right)^2$$

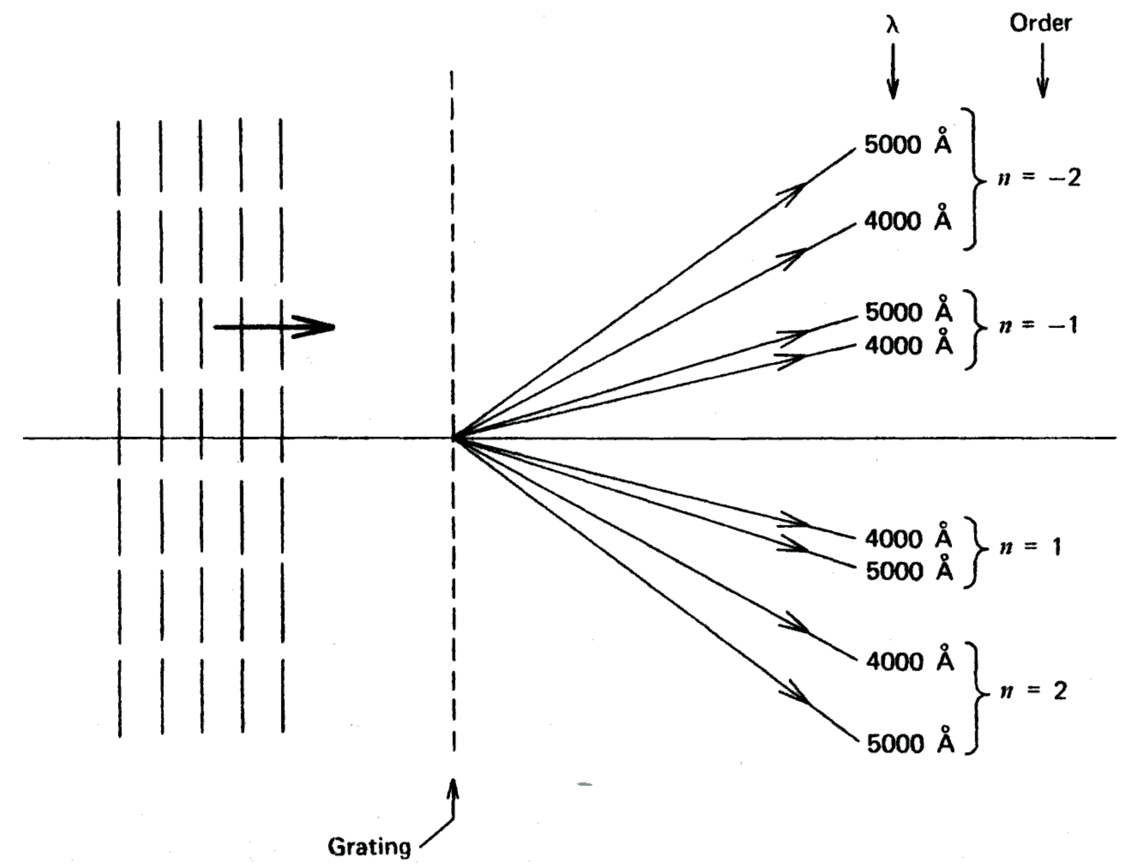


Interference maxima at: $\sin\alpha_m = \pm m\frac{\lambda}{g}$

m is called interference order

The grating equation



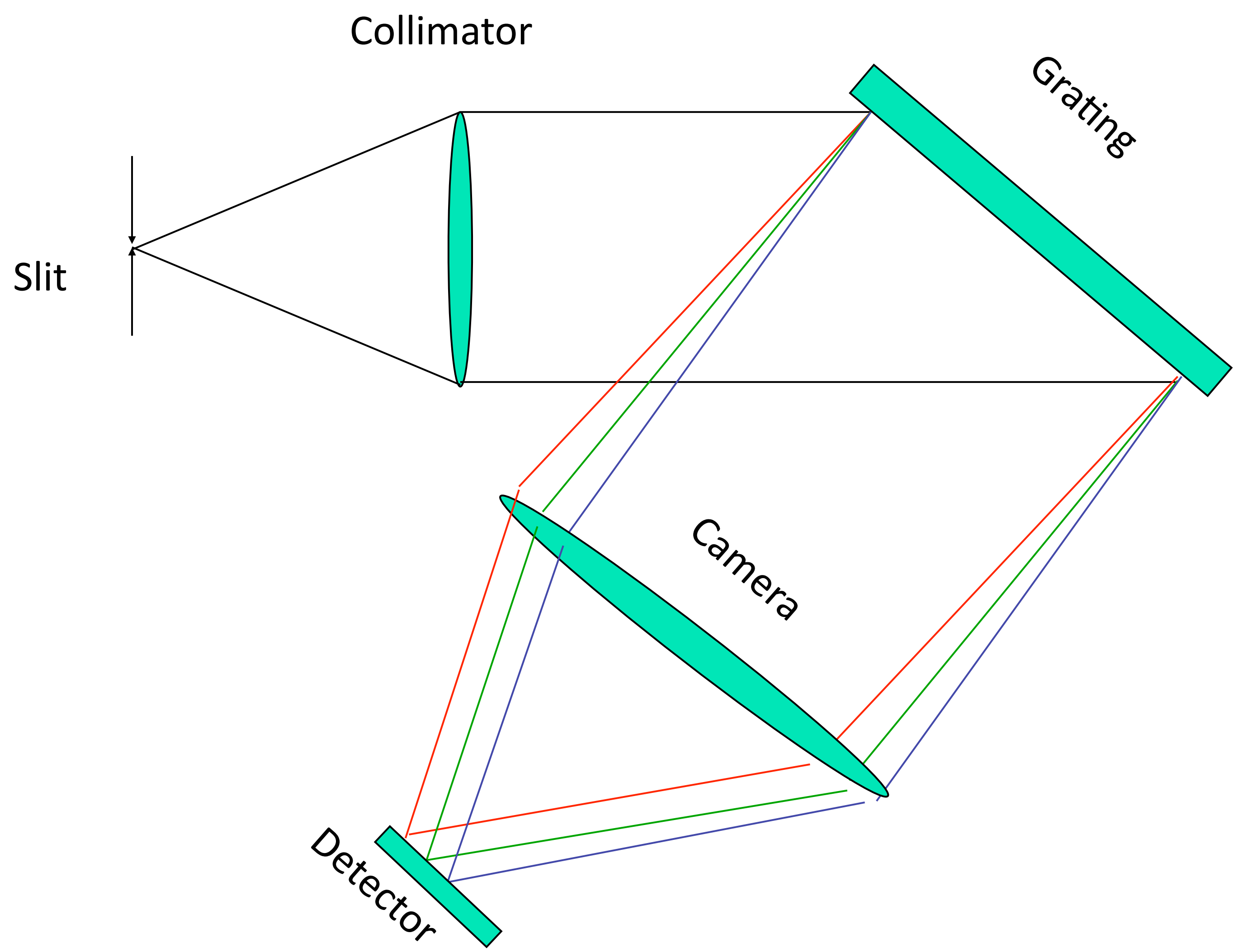


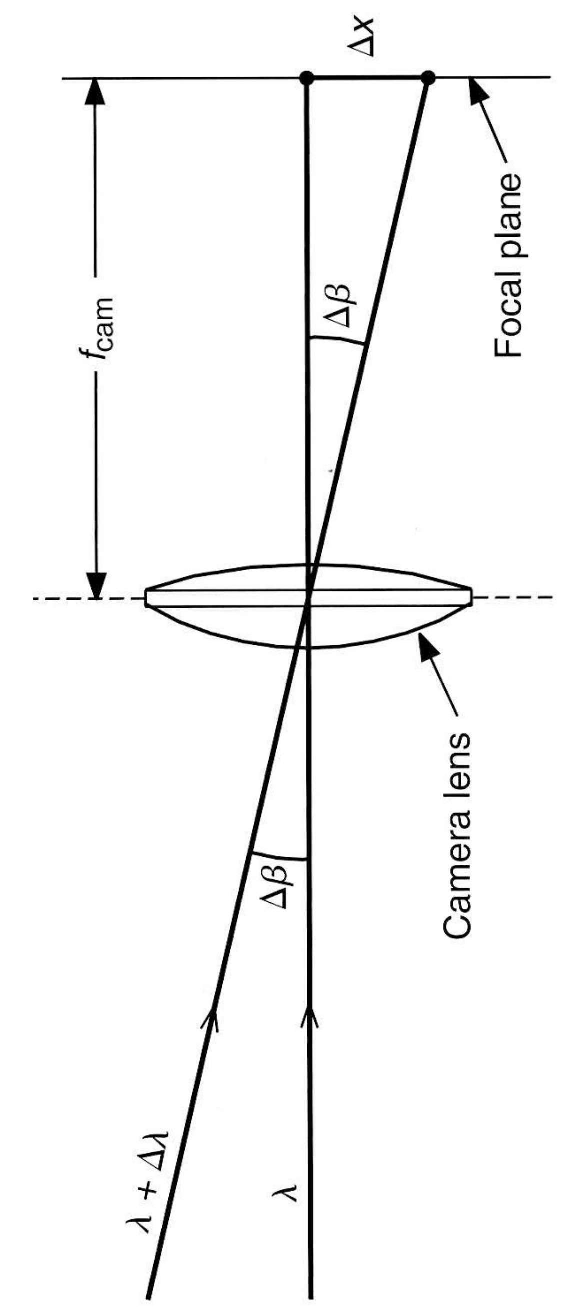
- Deflection is higher for longer wavelengths.
- Dispersion increases as order (m) increases, and period (g) decreases.
- Per order, dispersion is ~linear
- Dispersion does not depend on the size of a single grating “slit” (b)

$$\sin\alpha_m - \sin\beta = \pm m\frac{\lambda}{g}$$

$$\frac{\mathrm{d}\lambda}{\mathrm{d}\alpha} = \frac{g\cos\alpha}{m}$$

Adding the camera



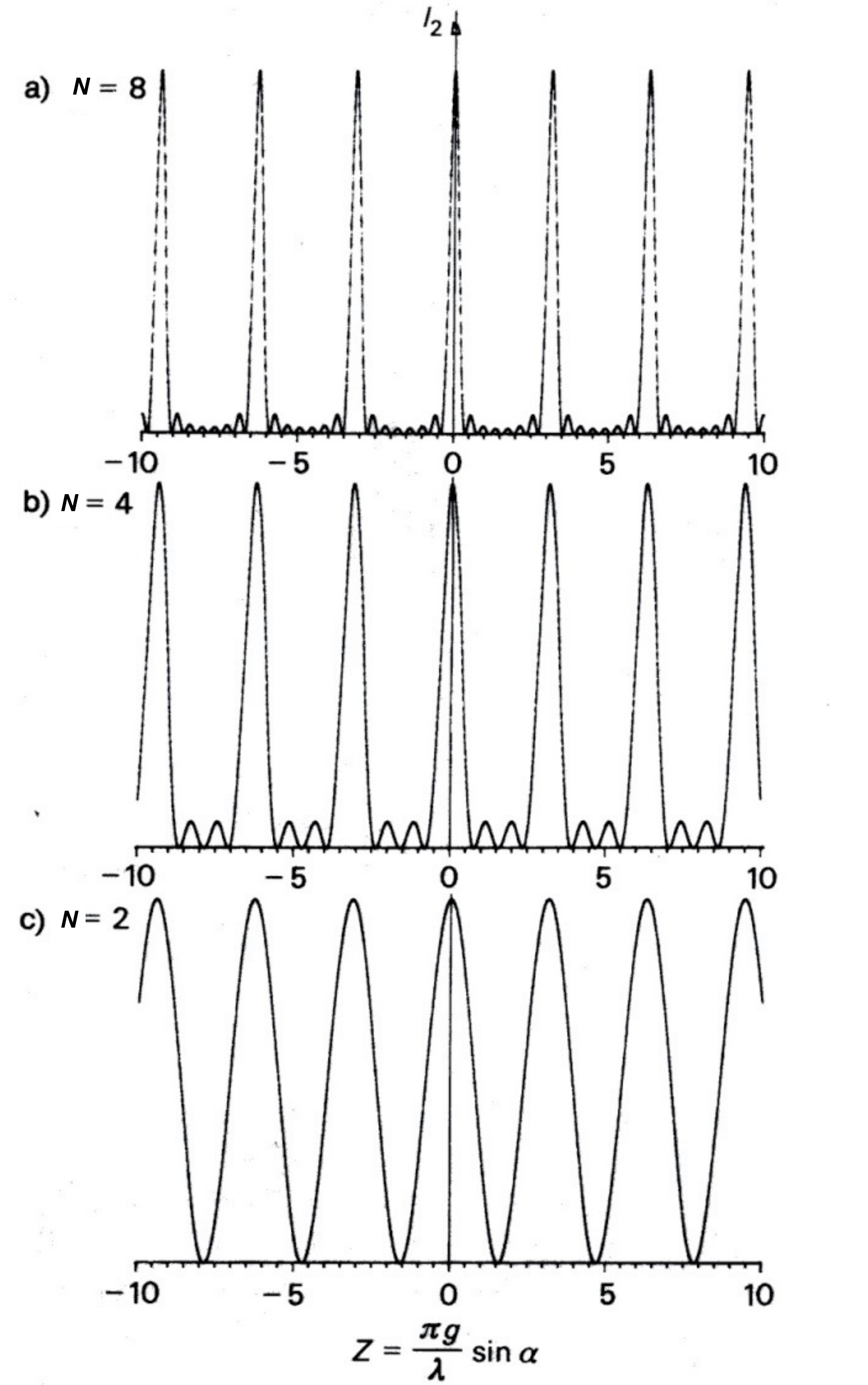


$$\frac{d\lambda}{dx} = \frac{1}{f_{cam}}\frac{d\lambda}{d\alpha} = \frac{g\cos\alpha}{m f_{cam}}$$

From dispersion to resolution

$$\times \left(\frac{\sin\left(N \frac{\pi g}{\lambda} \sin\alpha\right)}{\sin\left(\frac{\pi g}{\lambda} \sin\alpha\right)} \right)^2$$

$$\frac{\mathrm{d}\lambda}{\mathrm{d}\alpha} = \frac{g \cos\alpha}{m}$$



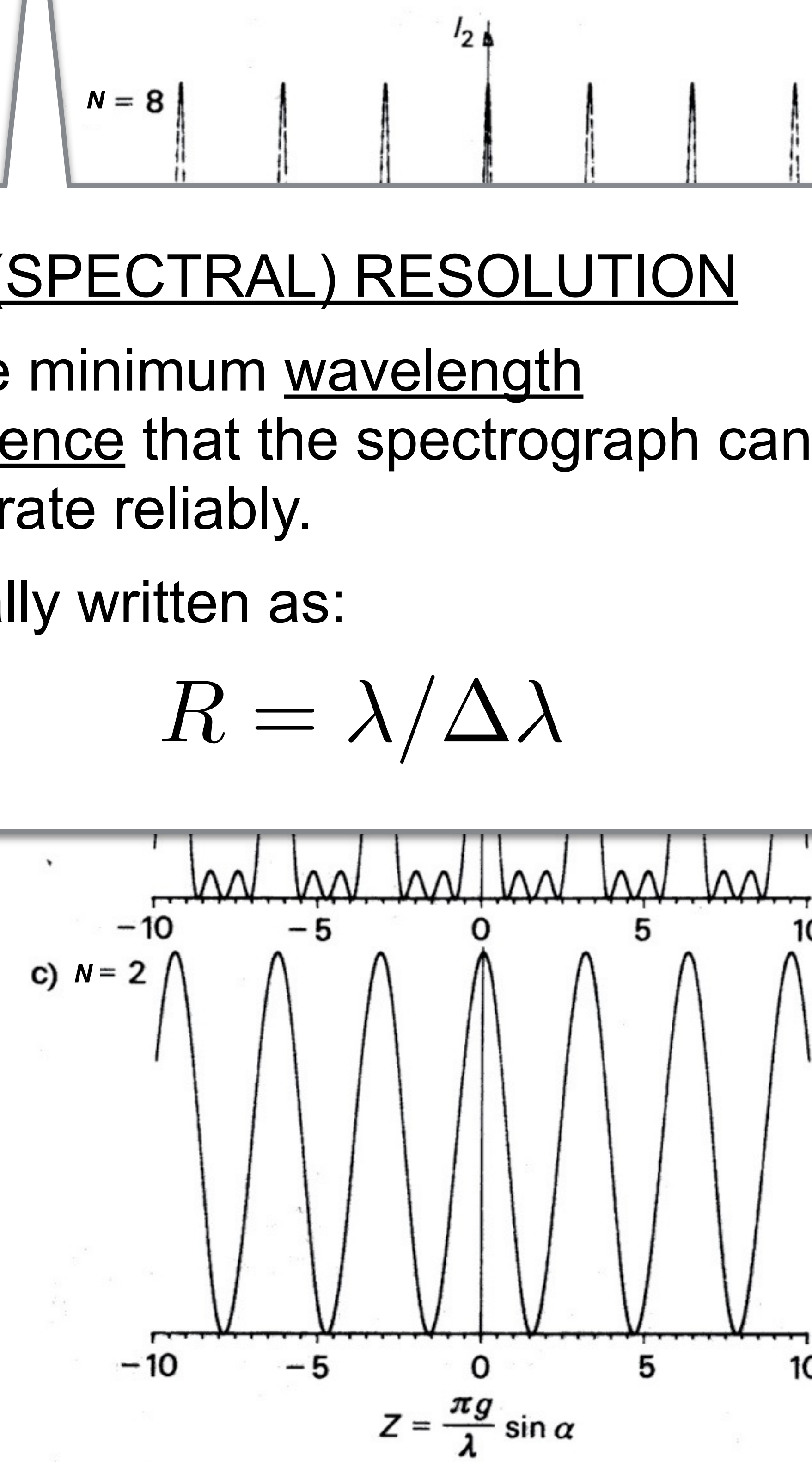
- In the interference term of the grating intensity formula, N is the total number of rules in the spectrograph beam.
- The larger N, the narrower and higher the interference maxima.
- m is the order: the larger m, the larger the dispersion...

From dispersion to resolution

$$\times \left(\frac{\sin\left(N \frac{\pi g}{\lambda} \sin\alpha\right)}{\sin\left(\frac{\pi g}{\lambda} \sin\alpha\right)} \right)^2$$

$$\frac{\mathrm{d}\lambda}{\mathrm{d}\alpha} = \frac{g\,\mathrm{co}}{n}$$

- In the interference term of the grating intensity formula, N is the total number of rules in the spectrograph beam.
- The larger N, the narrower and higher the interference maxima.
- m is the order: the larger m, the larger the dispersion...



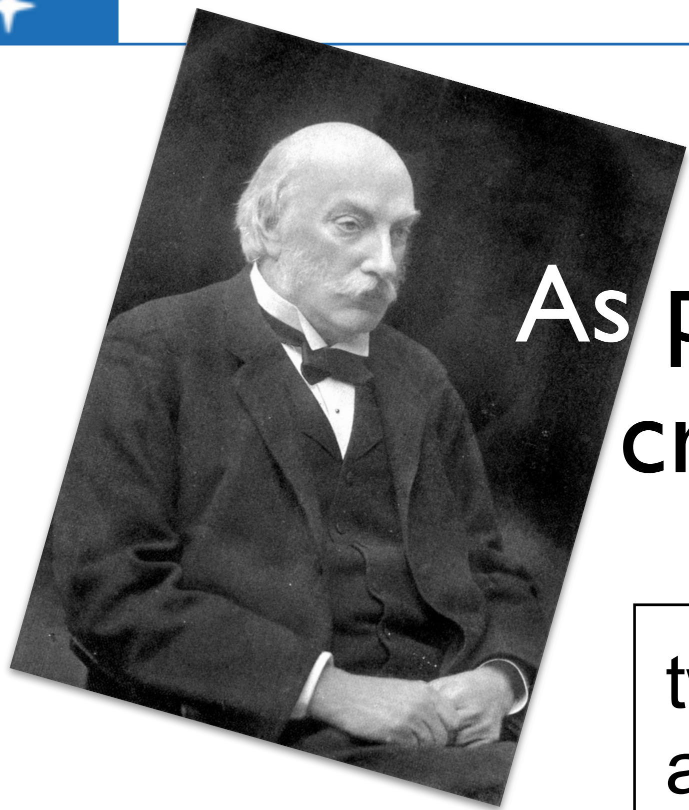
(SPECTRAL) RESOLUTION

Is the minimum wavelength difference that the spectrograph can separate reliably.

Usually written as:

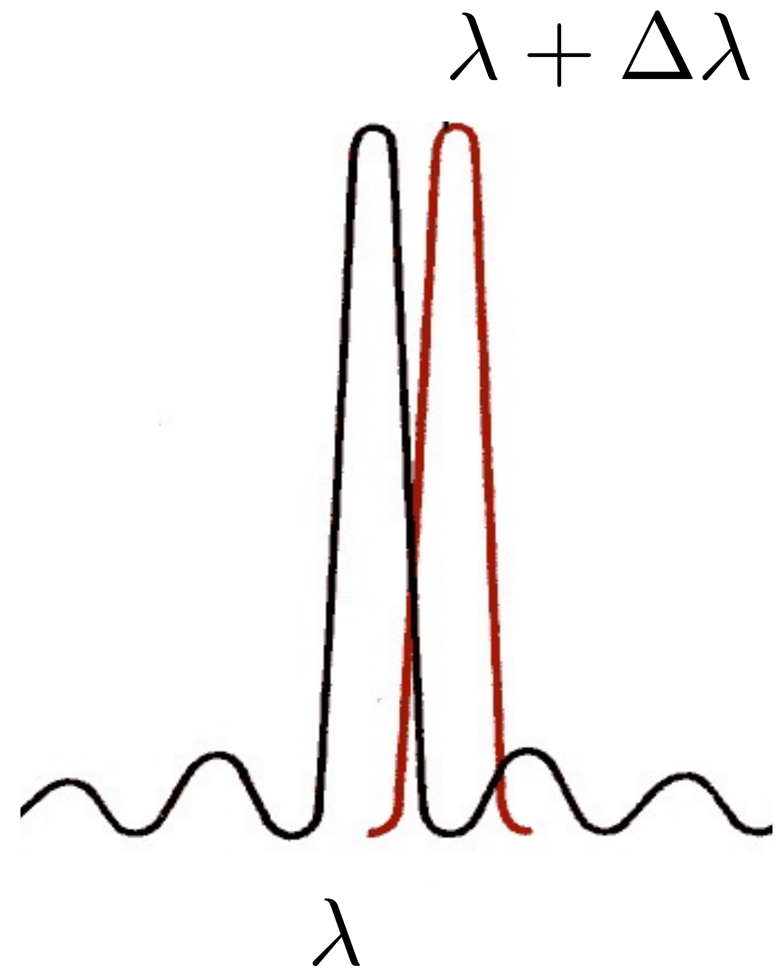
$$R = \lambda/\Delta\lambda$$

From dispersion to resolution



As per Rayleigh criterion....

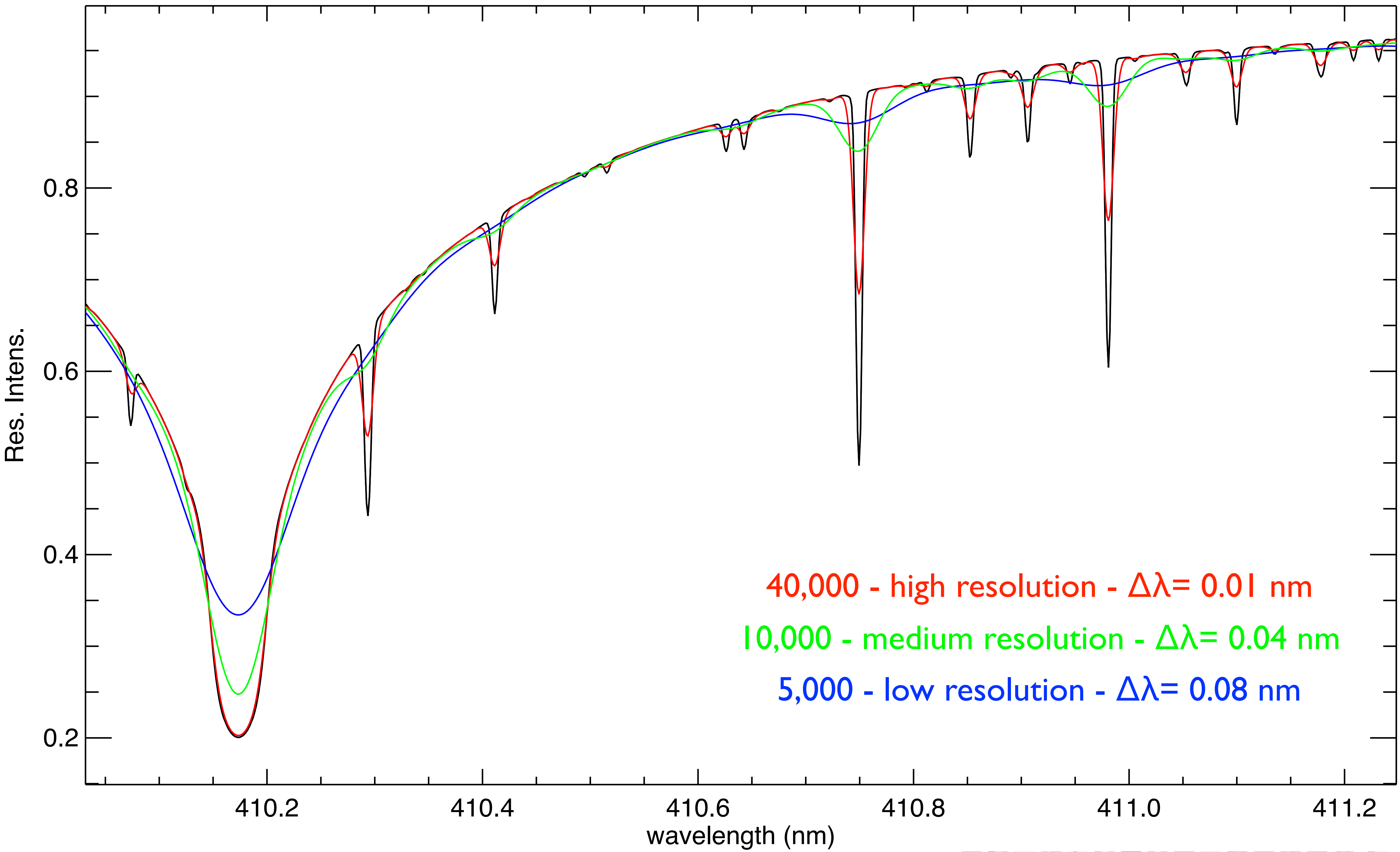
two wavelengths λ and λ+Δλ are barely separable in order *m* if the main intensity maximum of λ+Δλ is located at minimum of λ.



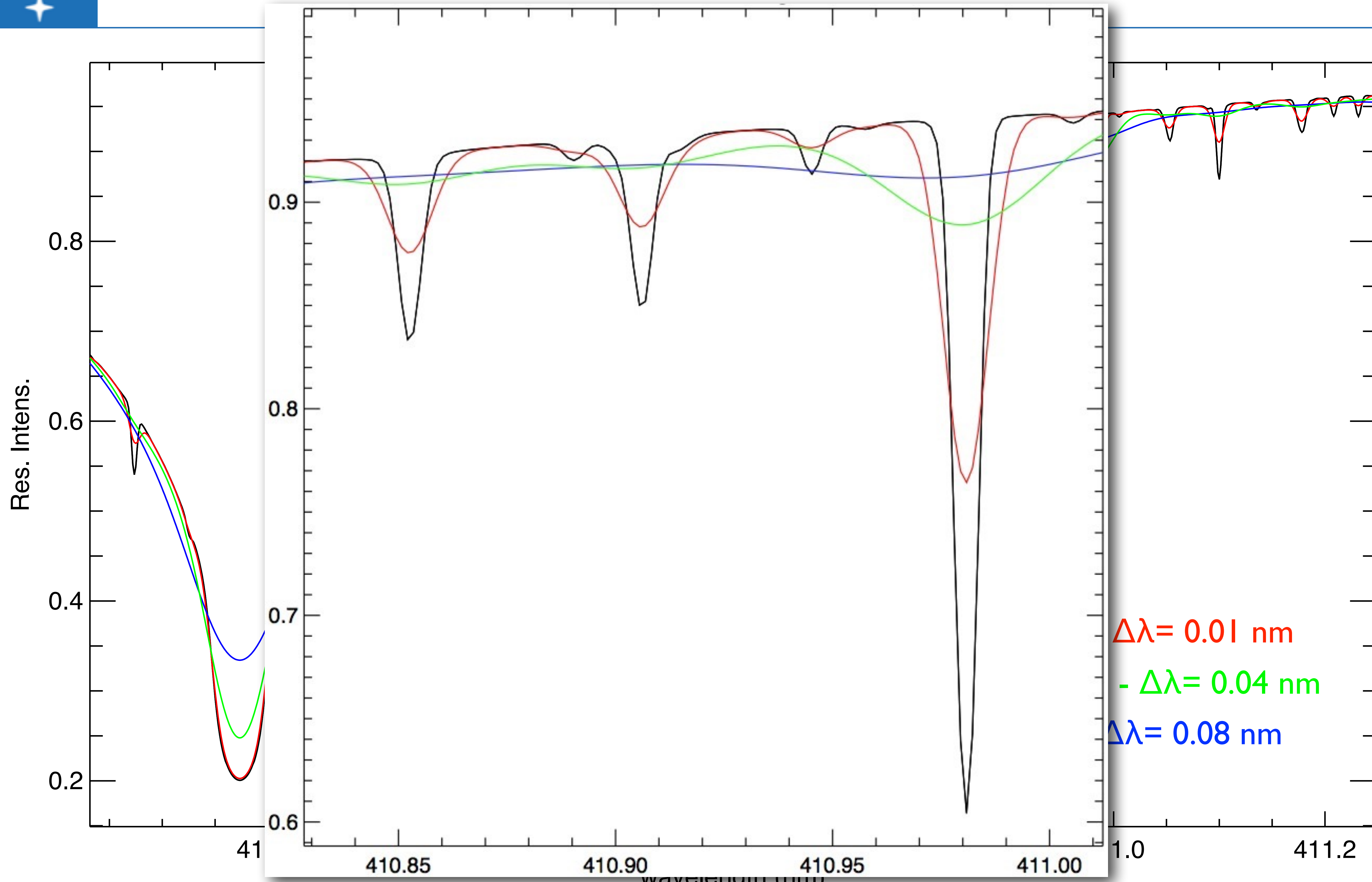
Since *m* determines the dispersion and *N* the width of intensity maxima:

$$R = \frac{\lambda}{\Delta\lambda} = m \times N$$

From dispersion to resolution

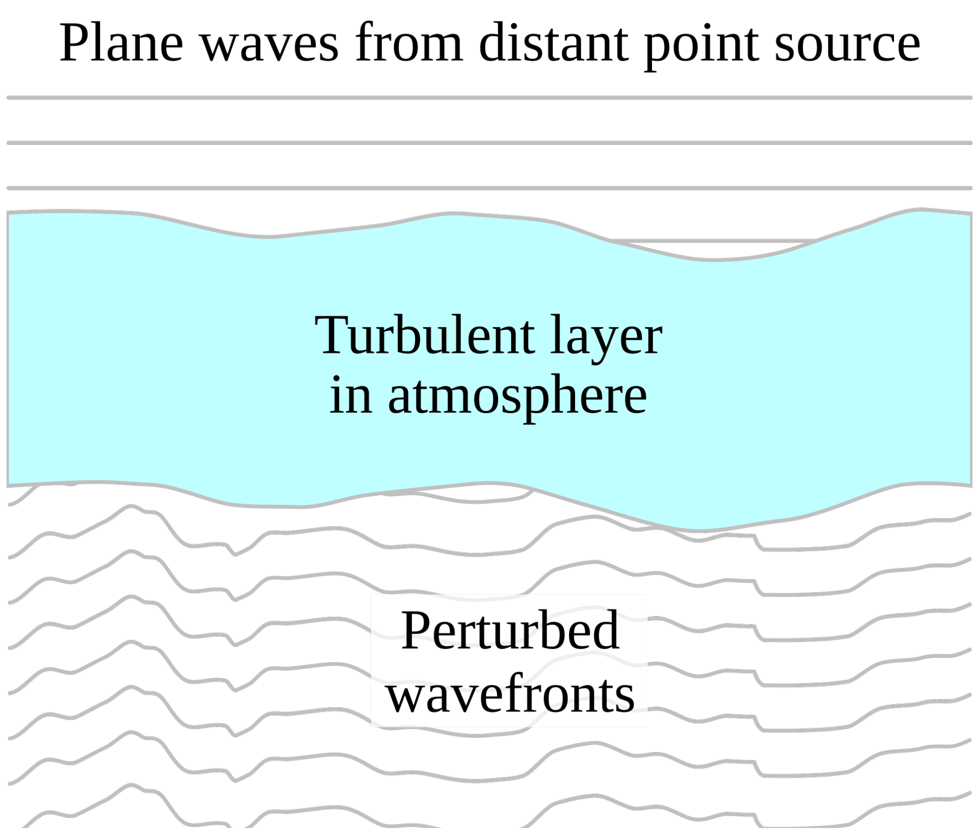


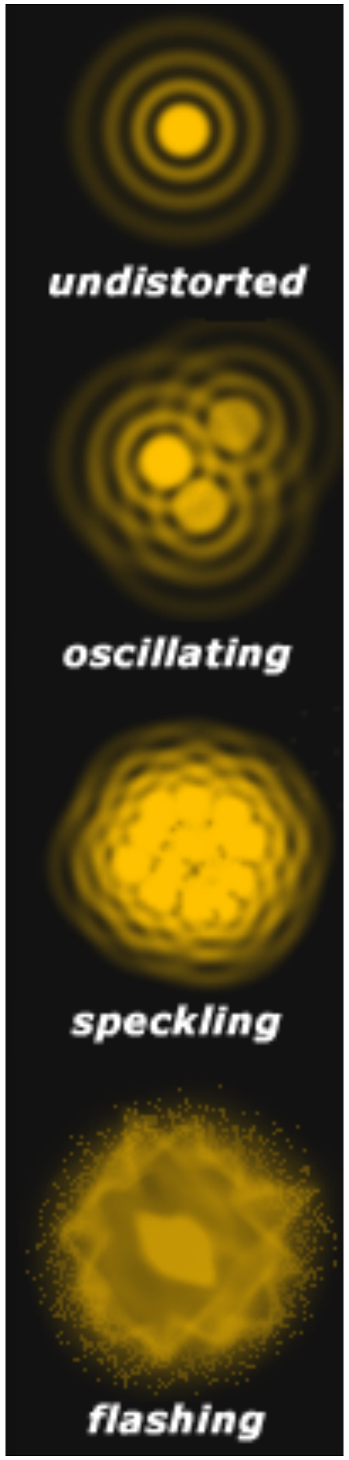
From dispersion to resolution



Introducing seeing

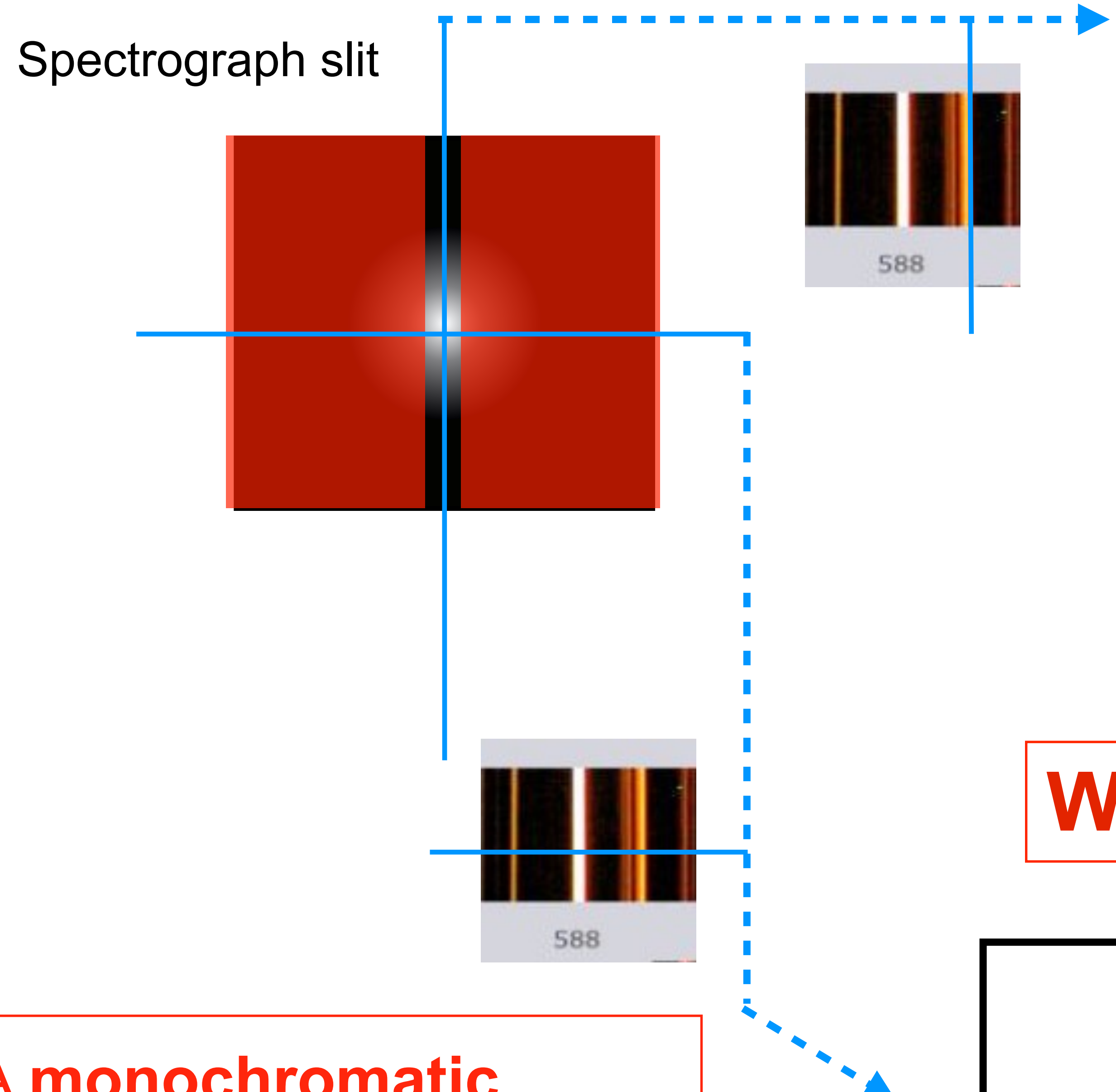
- Seeing is the distortion/ blurring of astronomical images due to the variable light refraction in the turbulent atmosphere
- Refraction —> seeing is a *chromatic* phenomenon: blue light is refracted better, thus seeing is worse in the blue

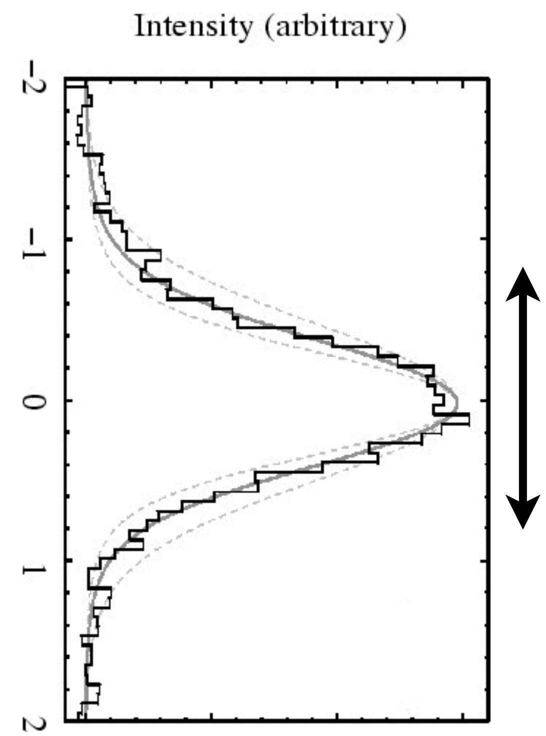




- 8m-class telescopes have ~0.01” diffraction-limited images (V band), median seeing in Paranal is 0.8” (x80)
- Adaptive Optics can recover (most) seeing *in the extreme red and infrared,* but not in the blue

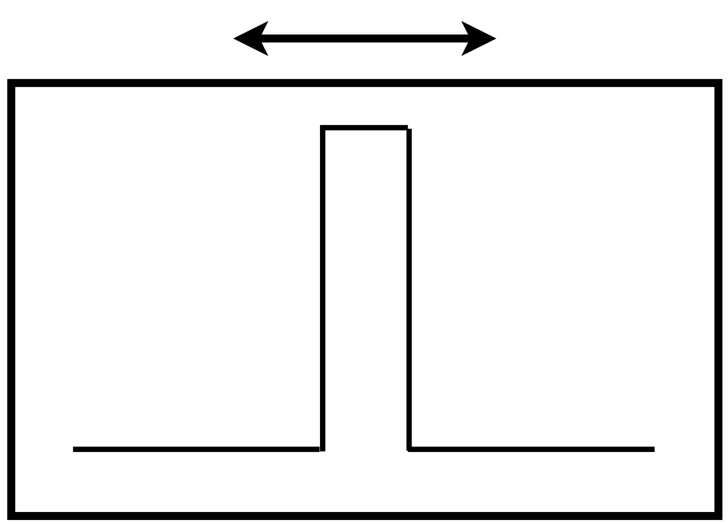
Enter the spectrograph slit…





normal to dispersion:
Stellar seeing image

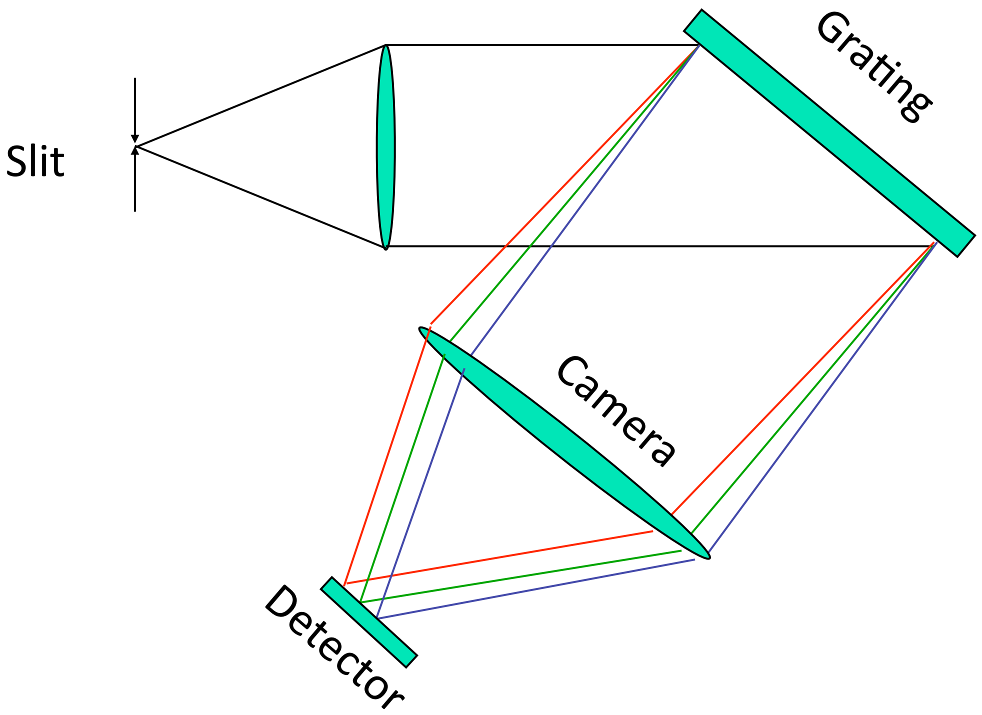
Wavelength!



parallel to dispersion:
Stellar seeing image convoluted with slit transmission (square func + diffraction)

A **monochromatic image of the slit** is produced on the detector at the position of every wavelength

Slit and resolution

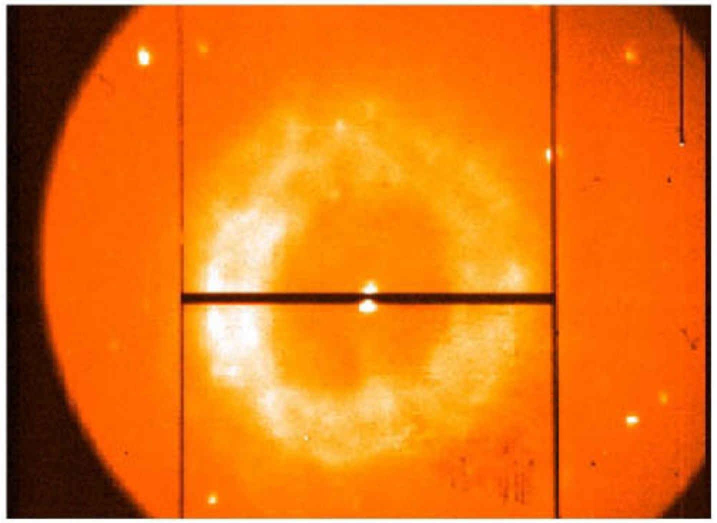


$$s' = \frac{f_{\rm cam}}{f_{\rm coll}} \cdot s$$

$$\frac{d\lambda}{dx} = \frac{g \cos \alpha}{m f_{cam}}$$

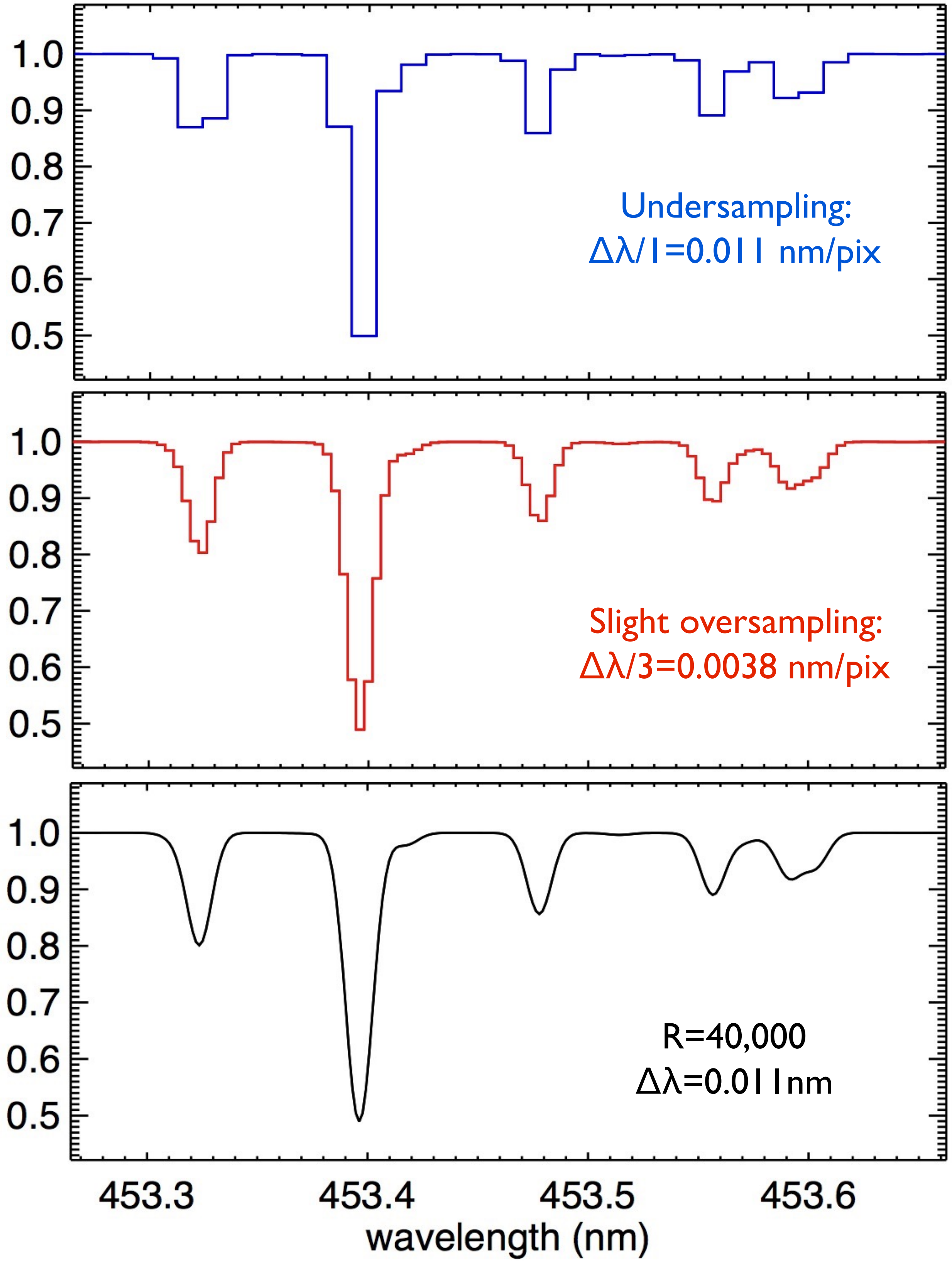
$$\Rightarrow R = \frac{m\lambda}{g \cos \alpha} \frac{f_{coll}}{s}$$

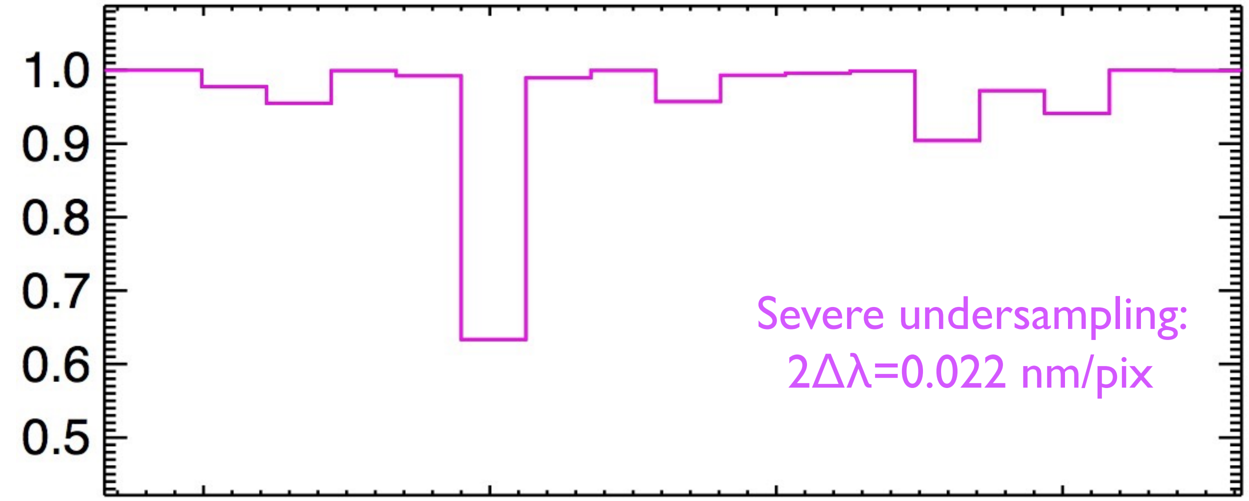
Slit width on the sky (in arcsec.) is limited by the need not to lose too much light, hence depends on typical site seeing. The spectrograph has to be designed accordingly, engineering constraints on f_{cam}/f_{col} permitting: the longer f_{col}, the larger the grating, and the spectrograph.



VLT-UVES Slit viewer

Detector and resolution

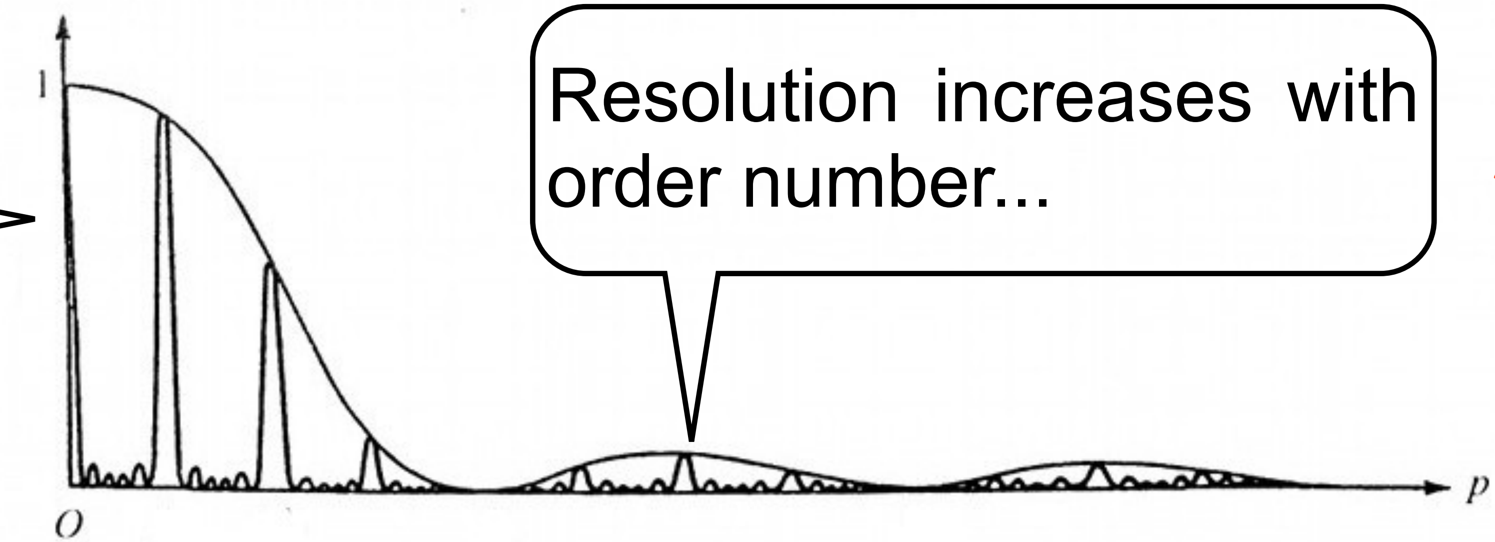




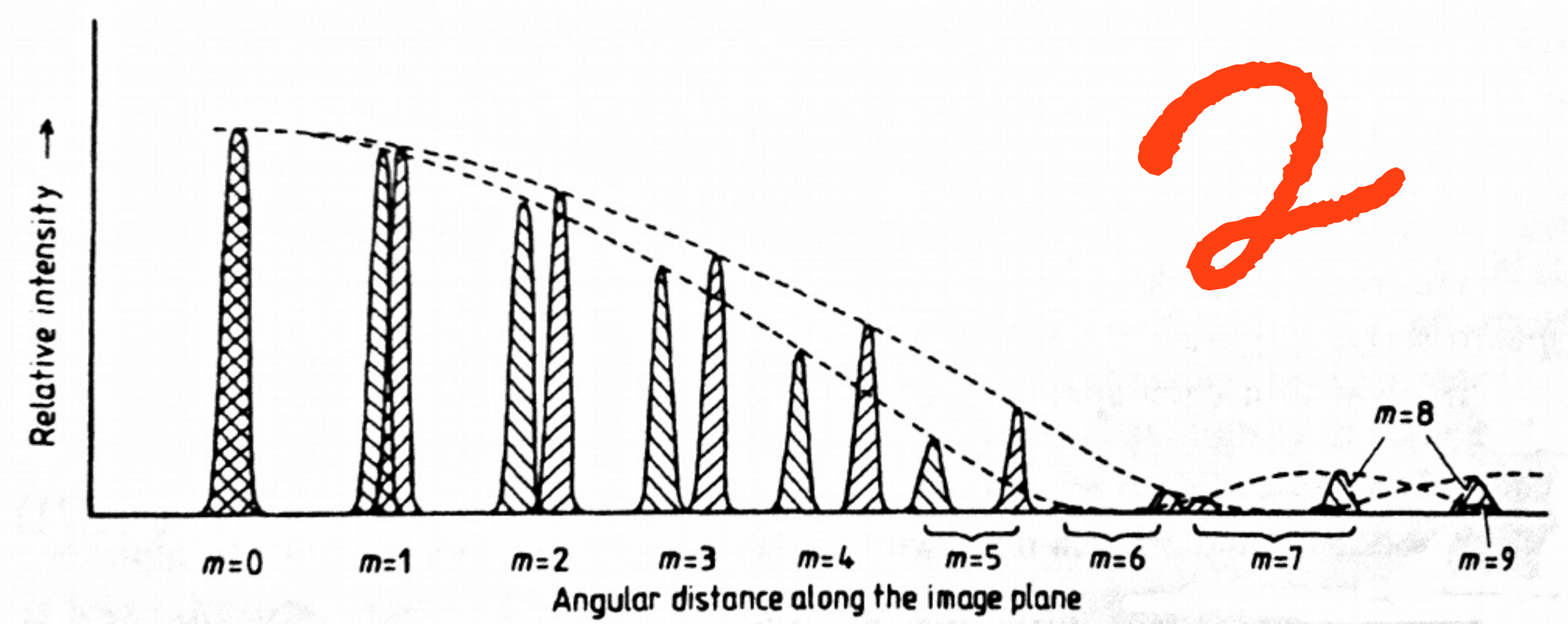
<u>Nyquist criterion</u>:
to properly recover line profile one needs at least 2 samples (=pixels) per resolution element.
This has to be matched with available detector (pixels ~15 μm, CCD size) and optical/mechanical constraints (size of corrected camera field, f_{cam}/f_{col}, full instrument size...)

Problems!!!

Diffraction modulation sends most light to low orders!



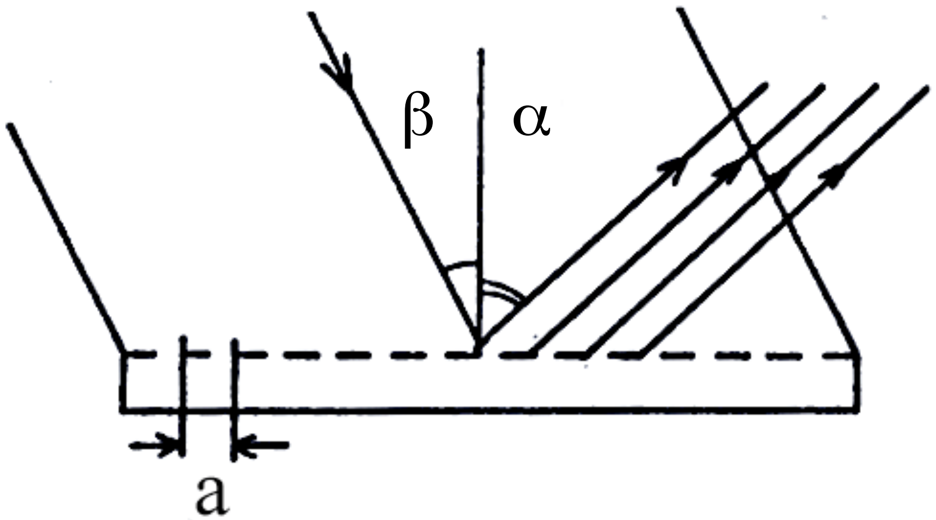
Resolution increases with order number...

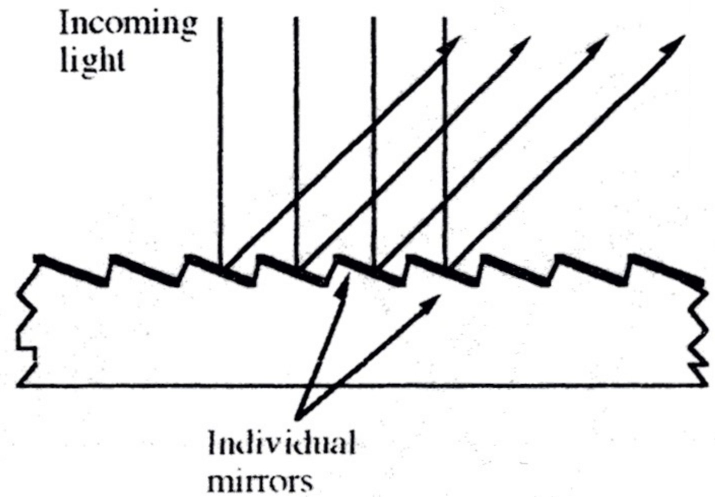


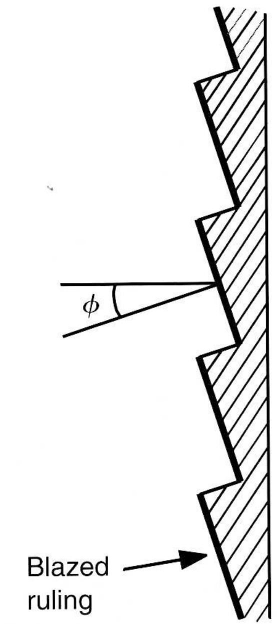
As order number increases, longer wavelengths from order m-1 overlap with shorter from order m...
The free spectral range Σ decreases with increasing order

$$\sin^{-1}(m\lambda_1/d) = \sin^{-1}[(m+1)\lambda_2/d] \Rightarrow \Sigma = \lambda_1 - \lambda_2 = \lambda_2/m$$

Solution: Blazed Grating

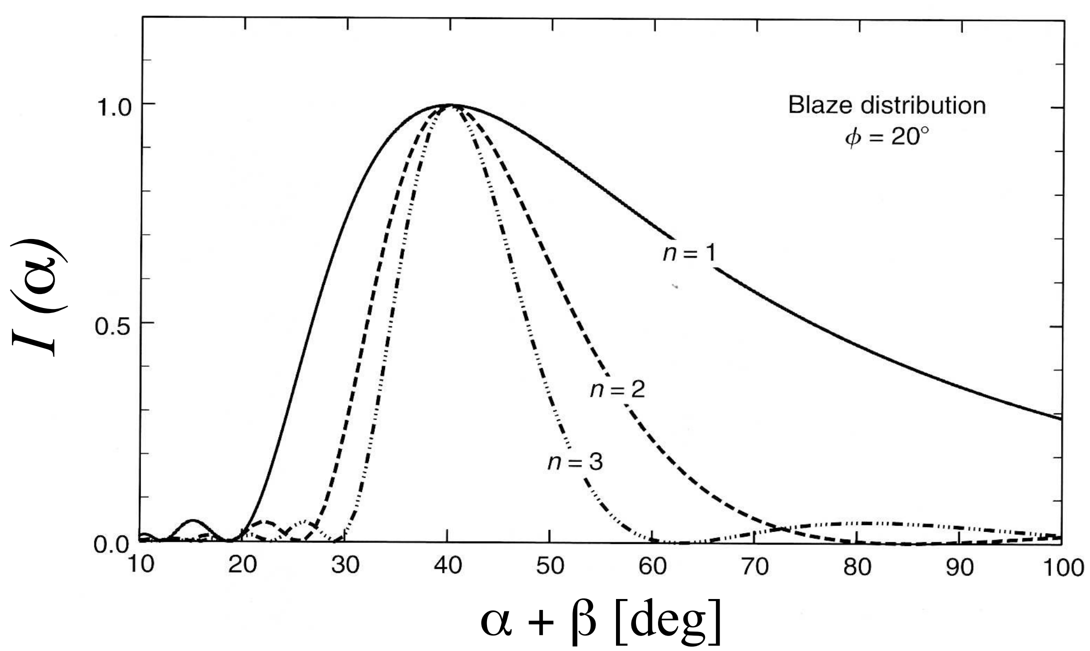


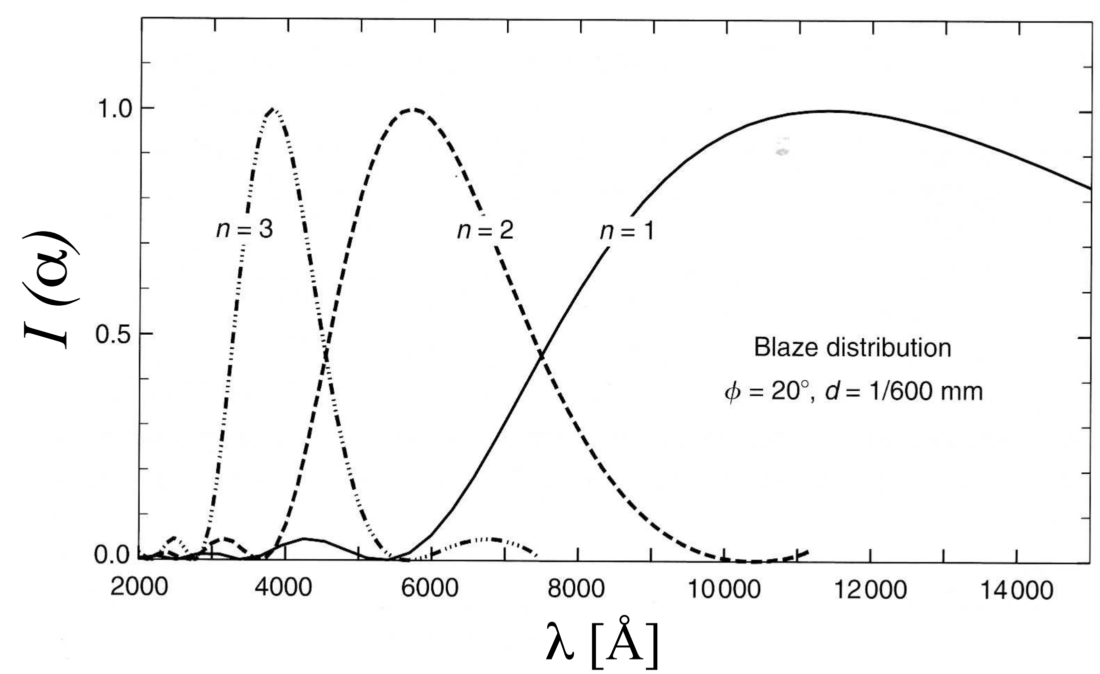




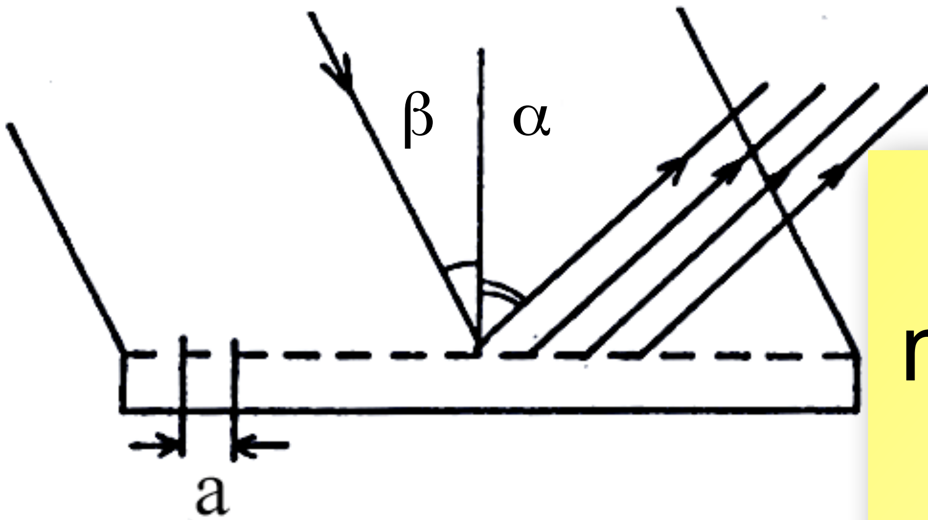
Single-slit diffraction envelope for blazed grating

$$I(\beta) = \left[\frac{\sin\{(\pi b/\lambda)\left[\sin(\alpha+\phi) + \sin(\beta+\phi)\right]\}}{(\pi b/\lambda)\left[\sin(\alpha+\phi) + \sin(\beta+\phi)\right]} \right]^2$$





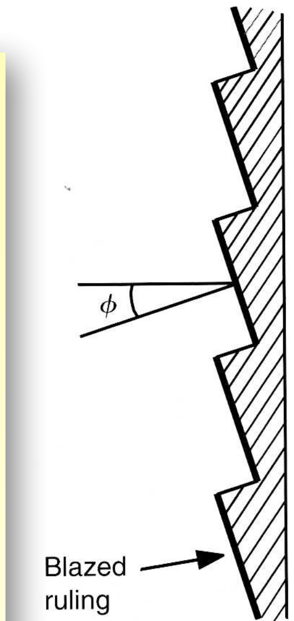
Solution: Blazed Grating

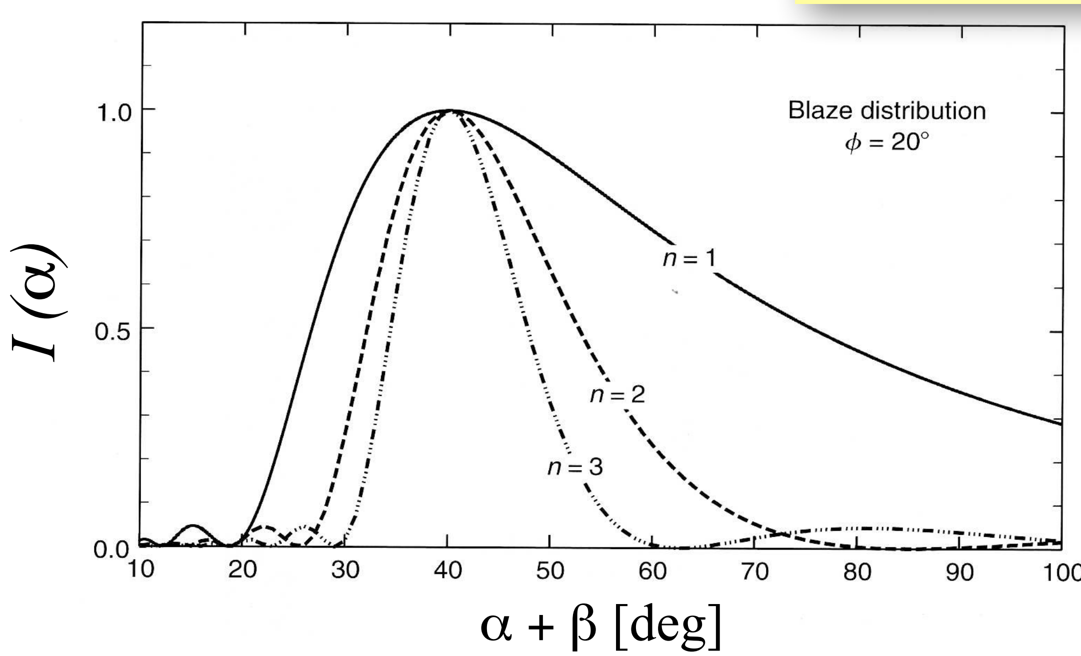


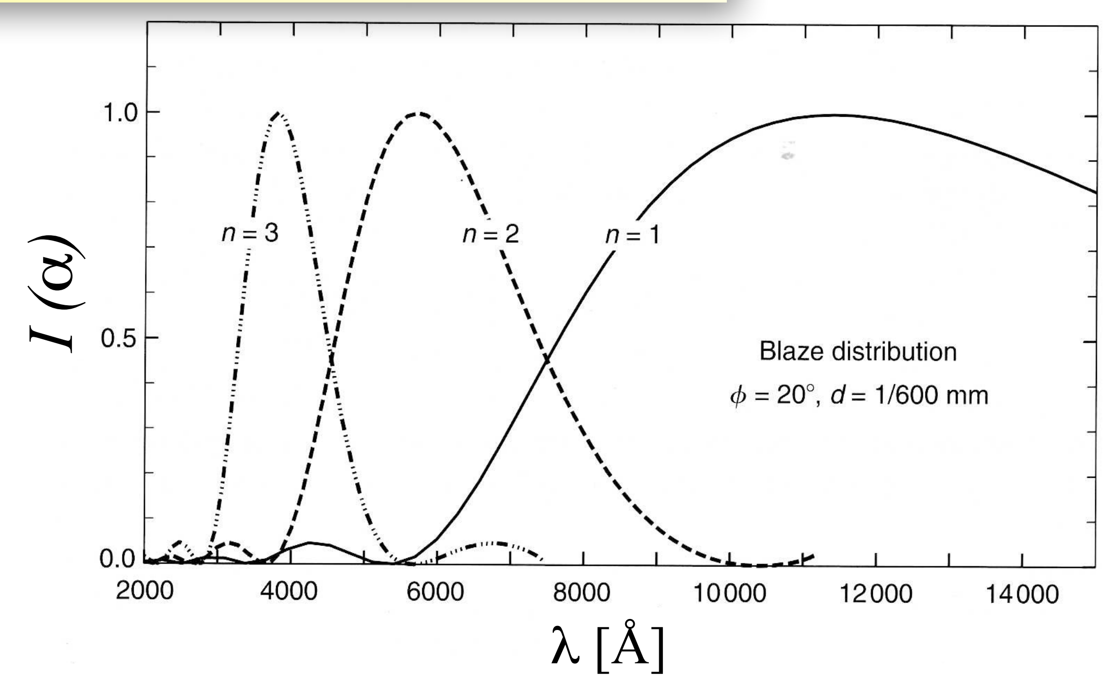
Single-slit diffraction envelope fo

$$I(\beta) = \left[\frac{\sin\{(\pi b/\lambda)[\mathrm{si}}{(\pi b/\lambda)[\sin} \right.$$

Blazing the grating moves the angle at which the <u>diffraction</u> peak is placed, leaving the <u>interference</u> pattern unaffected

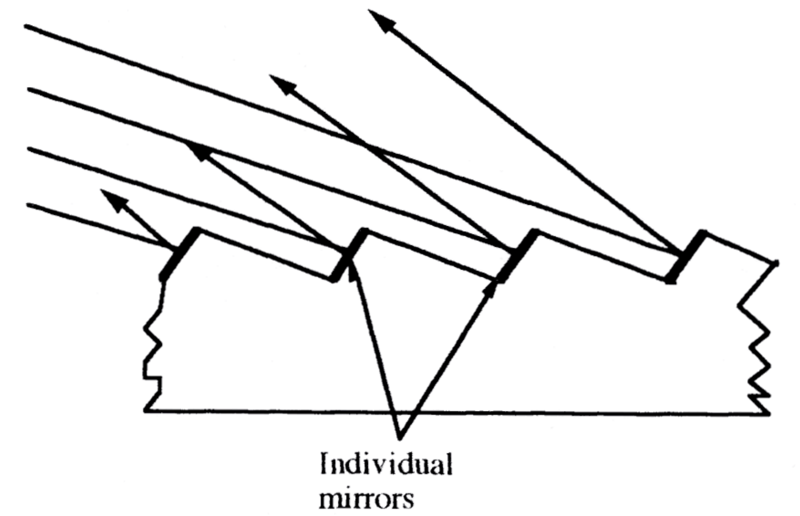


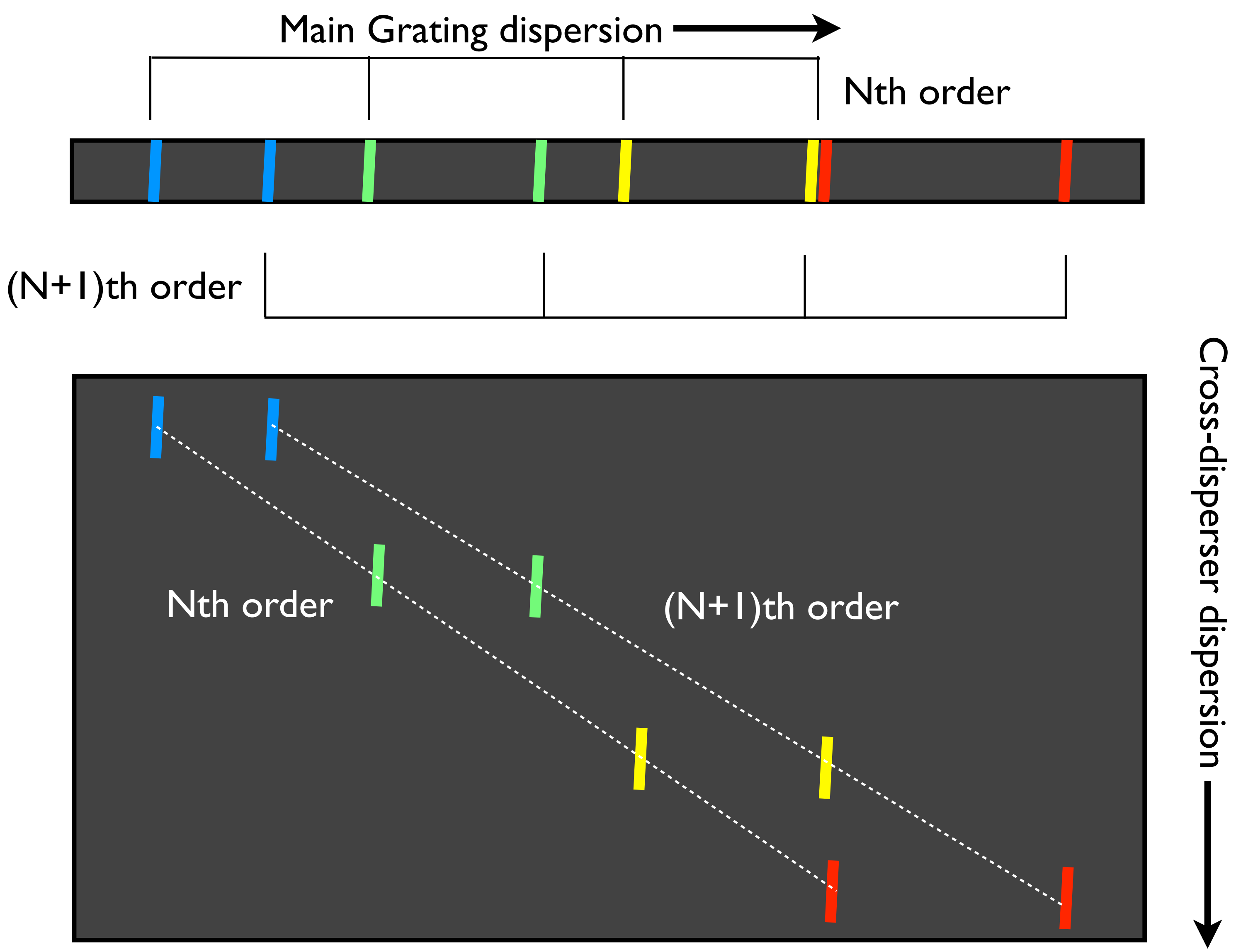


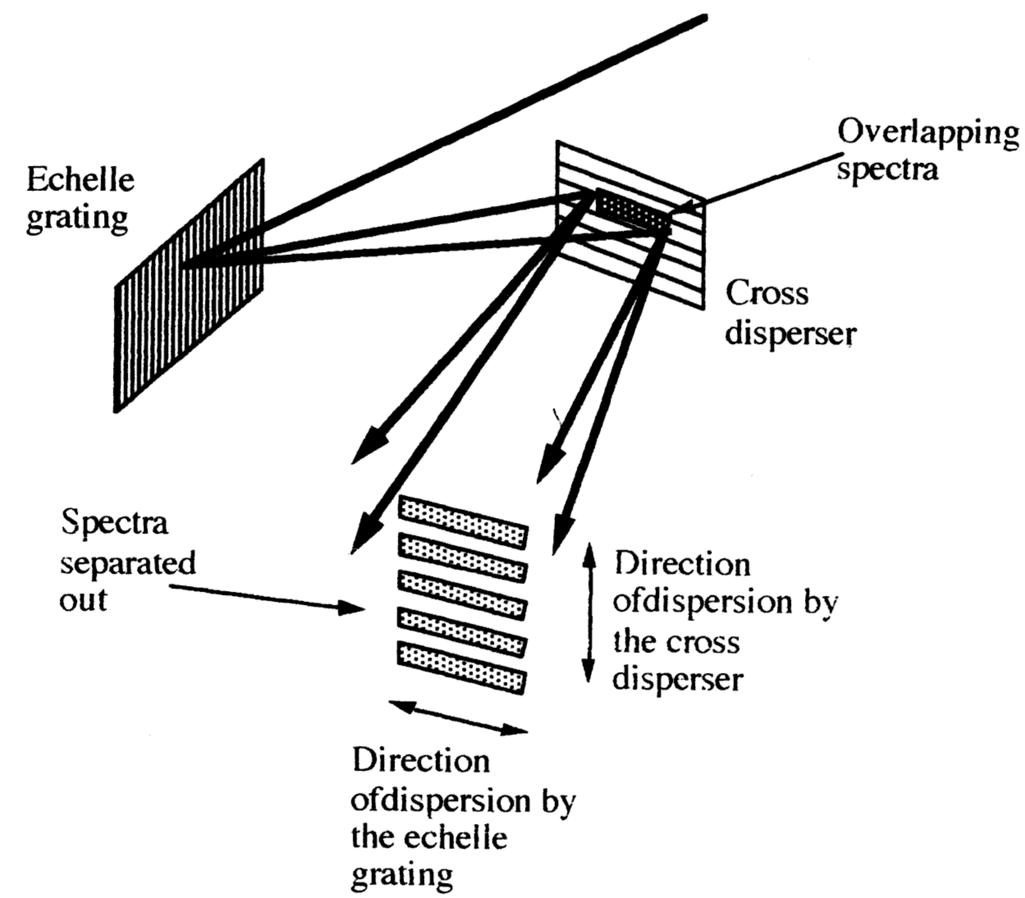


The èchelle cross-dispersed spectrograph

- No shadowing, very high orders (100+), high dispersion
- Order overlap avoided by cross-dispersion

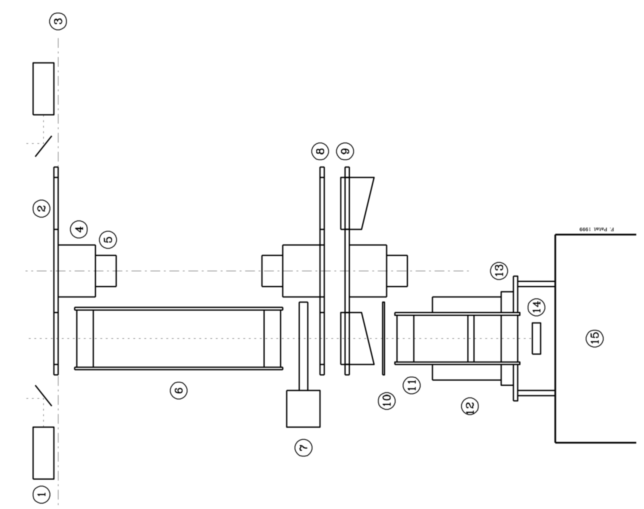


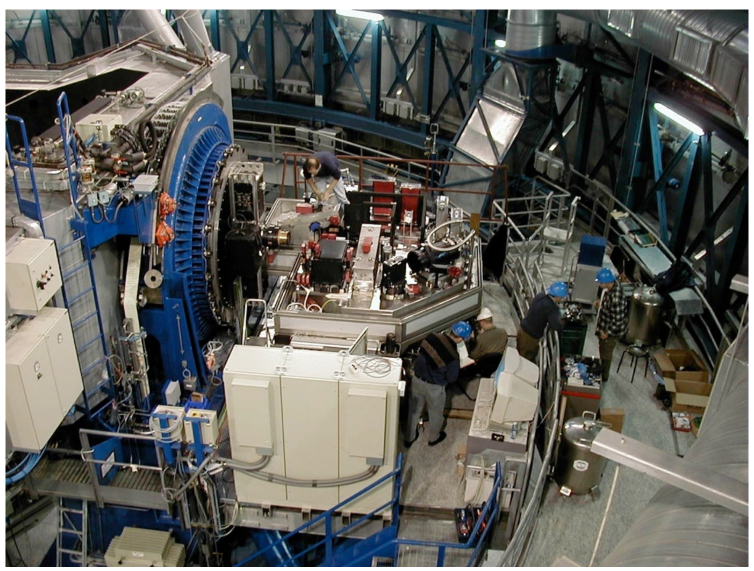




Flavors of spectrographs: single object

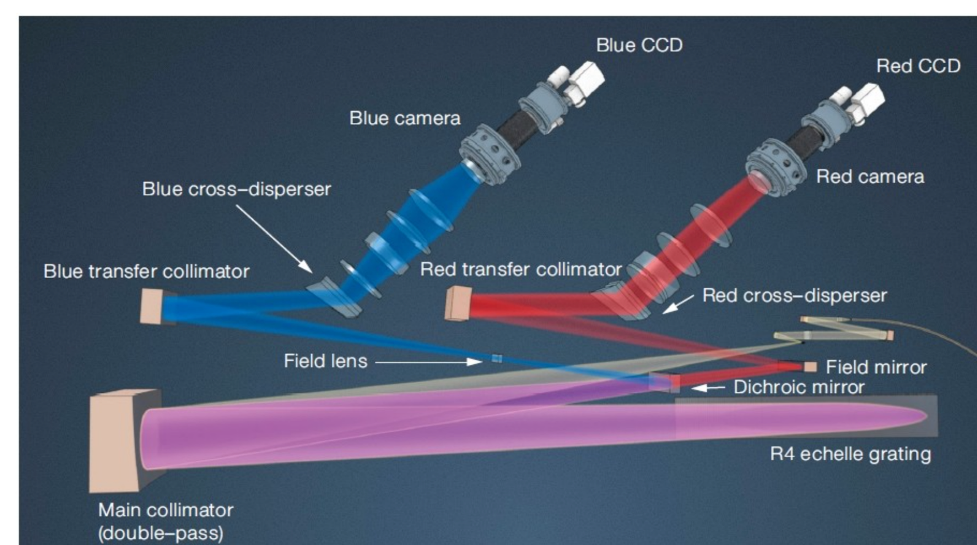
- **“Long slit” low/mid resolution:** EFOSC, FORS. R<5k (~100 km/s), 100+nm coverage, high efficiency, often multi-mode (imager, MOS, LSS…)





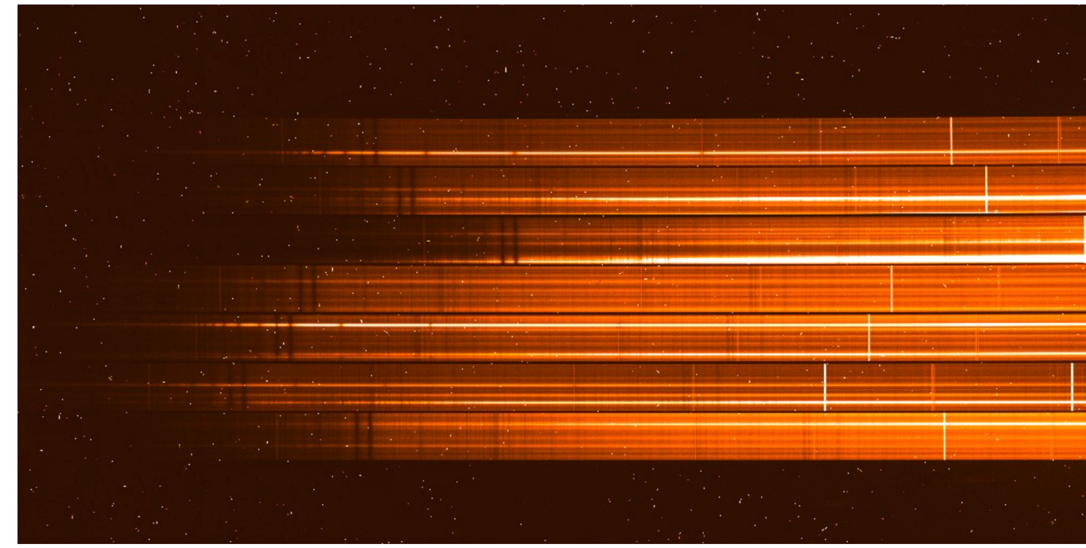
- **Echelle mid-to-high resol.:** X-Shooter, UVES, FEROS. R=10k - 120k (30-2.5 km/s), cross-dispersed, short-slit or fiber-fed, 100 - 700 nm coverage, multi-arm, low-to-mid efficiency

- **Echelle high-res, high-stability:** HARPS, ESPRESSO, R=100k-200k (up to 1.2 km/s), 100+nm coverage, fiber-fed, thermally stabilized, 10 cm/s long-term precision, multi-arm, low efficiency.



Flavors of spectrographs: Multi-Object

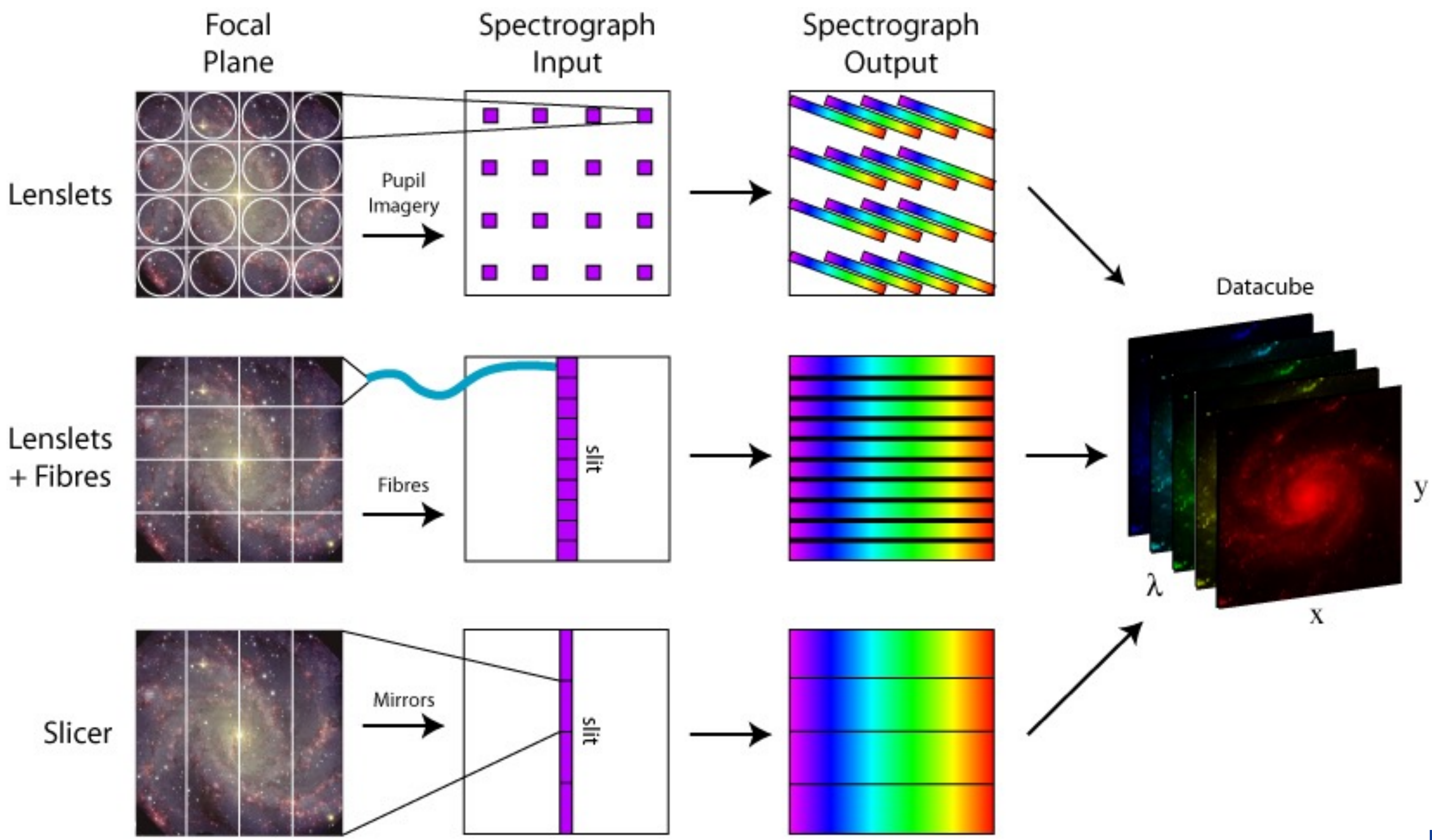
- **“On-Chip” low/mid resolution:** EFOSC, FORS, (VIMOS). Same as long slit, but multiple “slitlets” via masks. Field < 10’, 10s-100s objects.



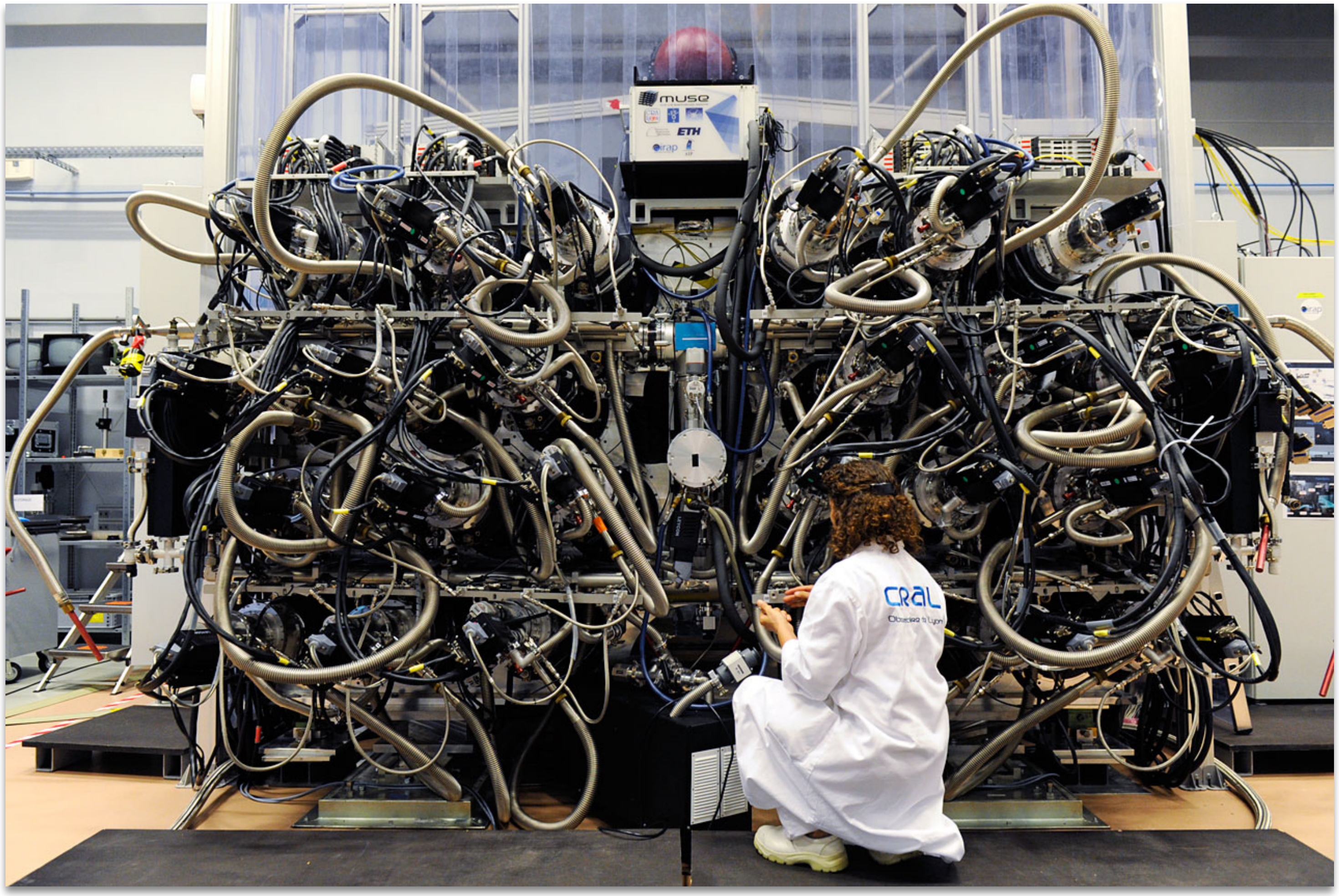
- **Positionable-fiber-fed:** FLAMES MEDUSA, (4MOST), R=2k-20k, 100-1000 spectra, 25’ to 1 degree field, 10-500 nm range (dep. on res.). Complex positioner mechanics, survey-optimized, “blind” pointing, no spatial resolution

Flavors of spectrographs: Integral Field

- FLAMES ARGUS/IFU, MUSE. Cover an area (up to ~1') with spctrograph "pick-ups" (fibers / slicers). 100 - 1000 spectra, multi-spectrograph, spectral resol. / spatial resol. / spectral coverage trade-off



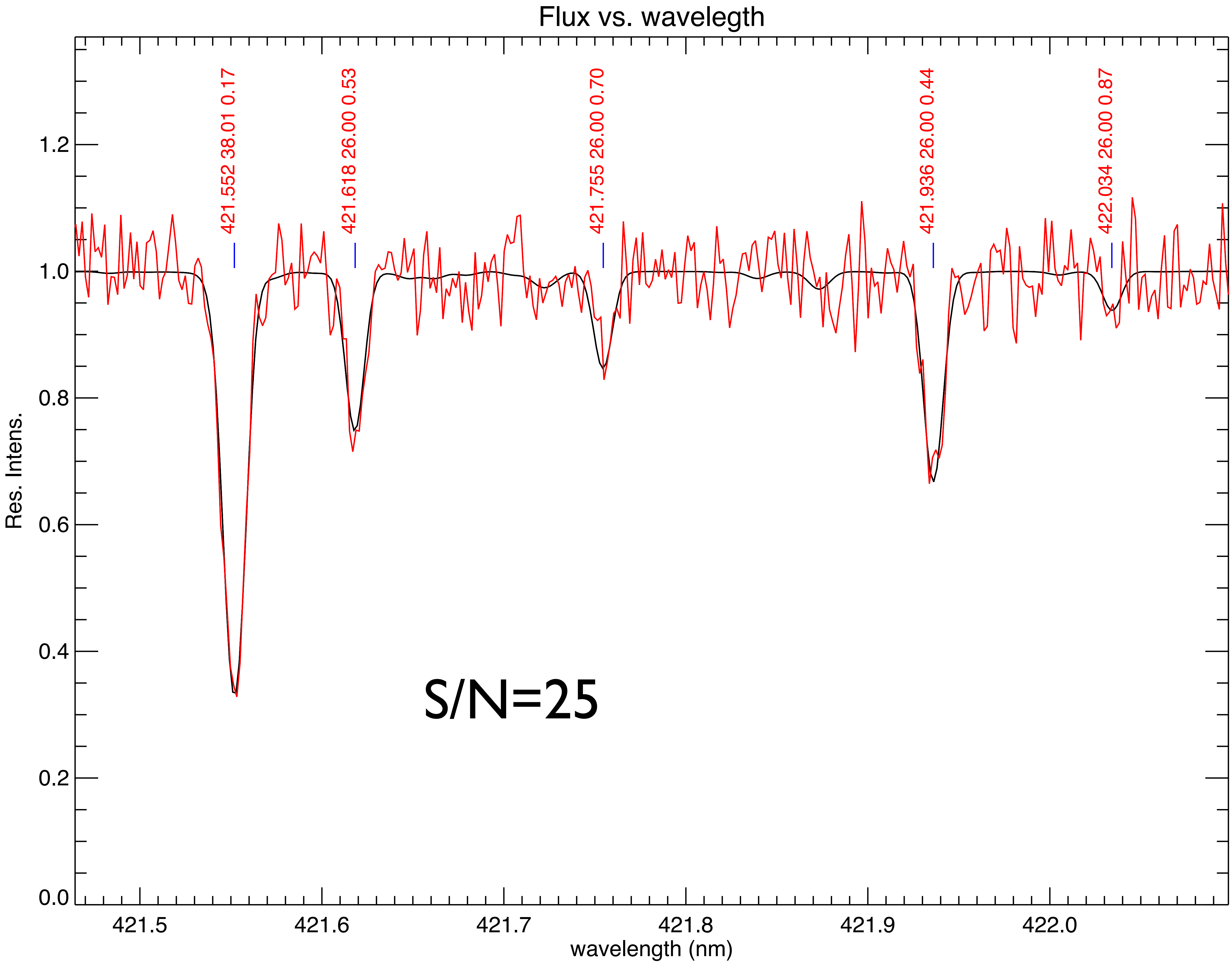
Flavors of spectrographs: Integral Field

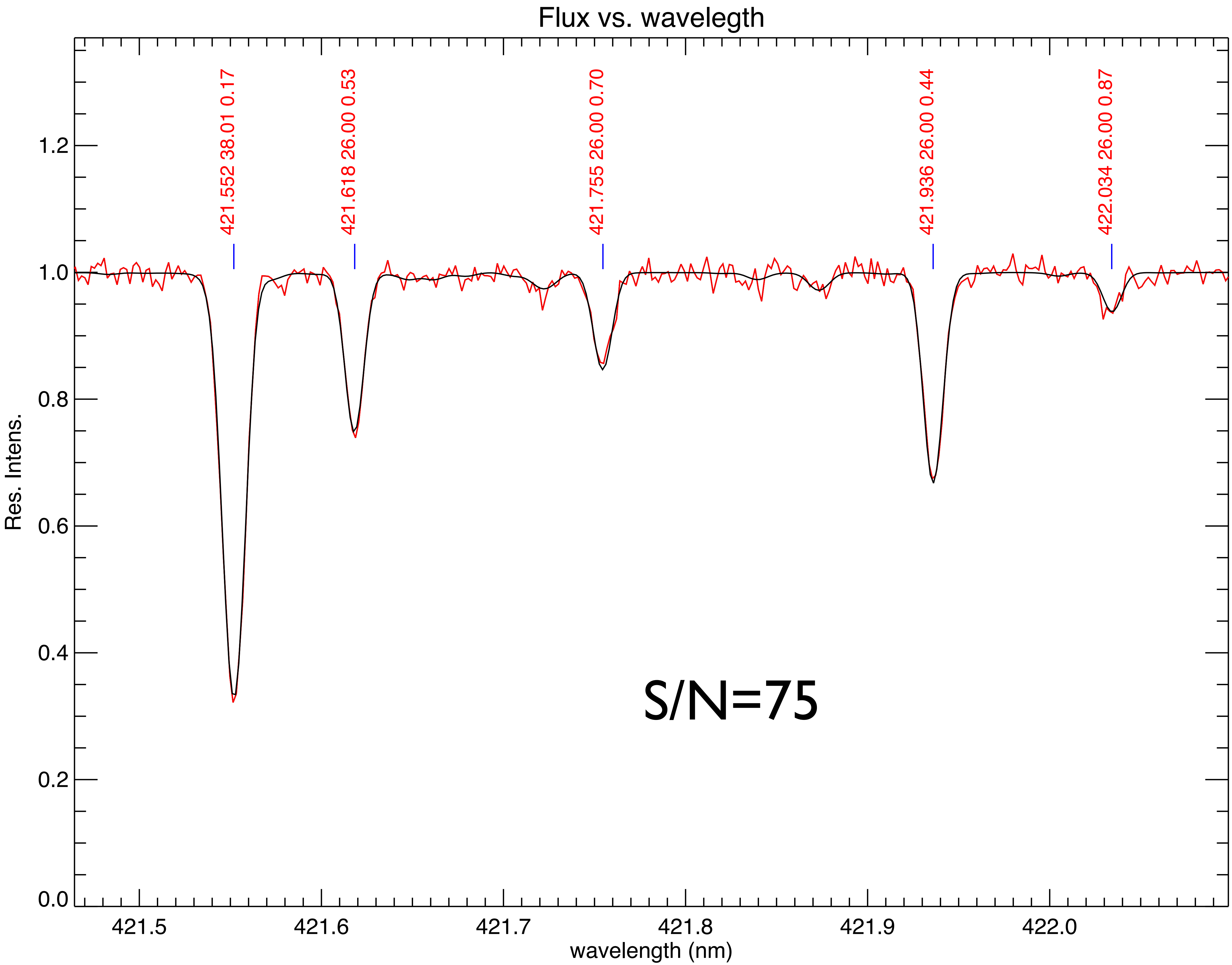


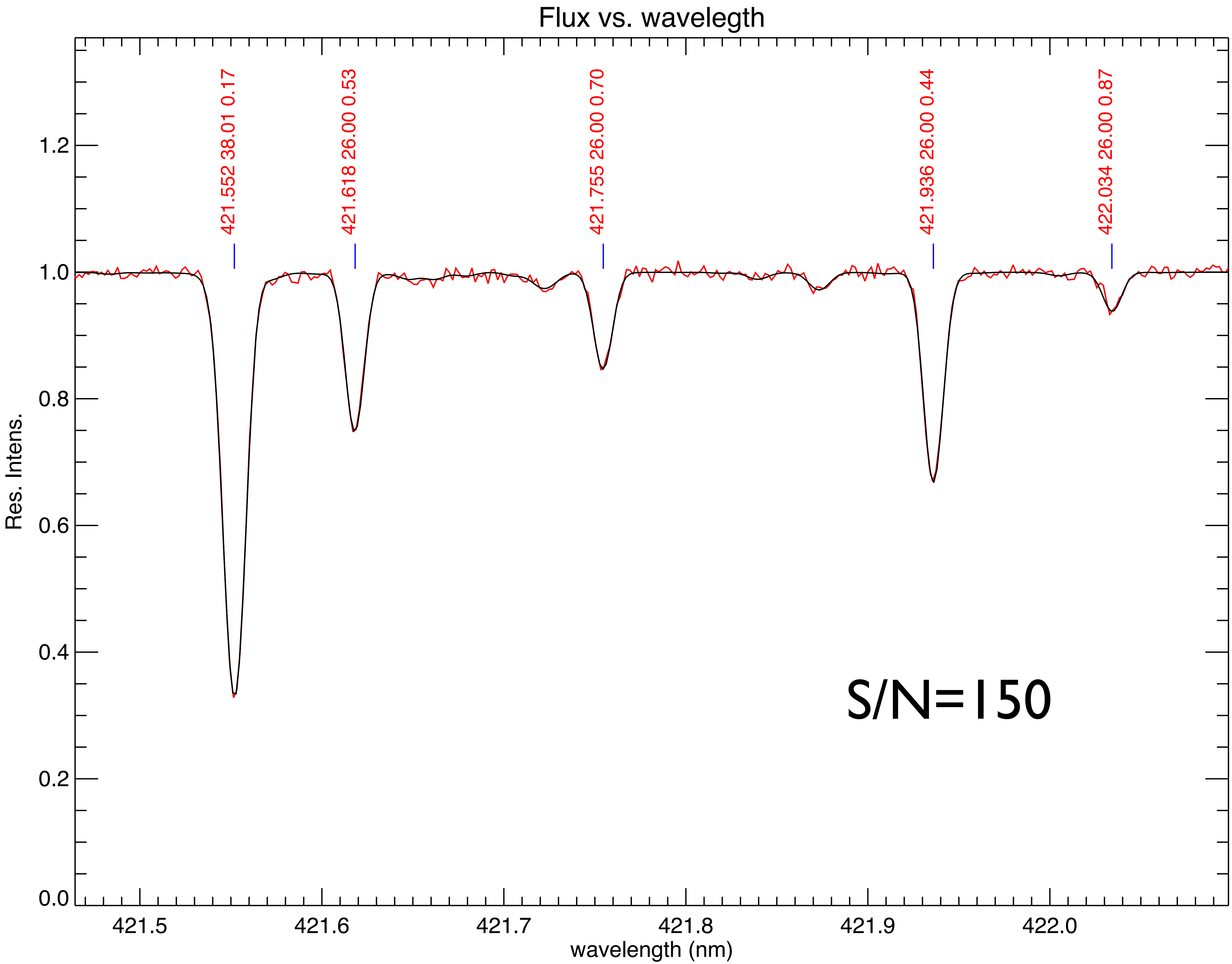
- MUSE: Field of view: 60”x60”; “pixel” size 0.2”; 1152 “slices”; Resolution ~ 2500; 480 nm —> 930 nm, 24 spectrographs, 48 spectra each.

Getting the spectra you need

- **Spectral range:** must contain the features you need (+ redshift / radial velocity) or enough features of the type you need
- **Resolution:** sufficient to resolve otherwise blended features / to resolve the radial velocity you need
- **Slit length:** is the source extended? Do you need a good sky subtraction? (a.k.a. spatial resolution, see also "number of spectra")
- **Signal-to-noise:** adequate to detect / measure features of strength X with Y uncertainty (may correlate w. available features number)
- **Number of targets/spectra:** how many do you need for the science goal? Quality vs. quantity? Is multiplexing viable? Time sampling needed? Spatial sampling needed (see also "slit length")?


Flux vs. wavelegth
421.552 38.01 0.17
421.618 26.00 0.53
421.755 26.00 0.70
421.936 26.00 0.44
422.034 26.00 0.87
S/N=25
Res. Intens.
wavelength (nm)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
421.5
421.6
421.7
421.8
421.9
422.0

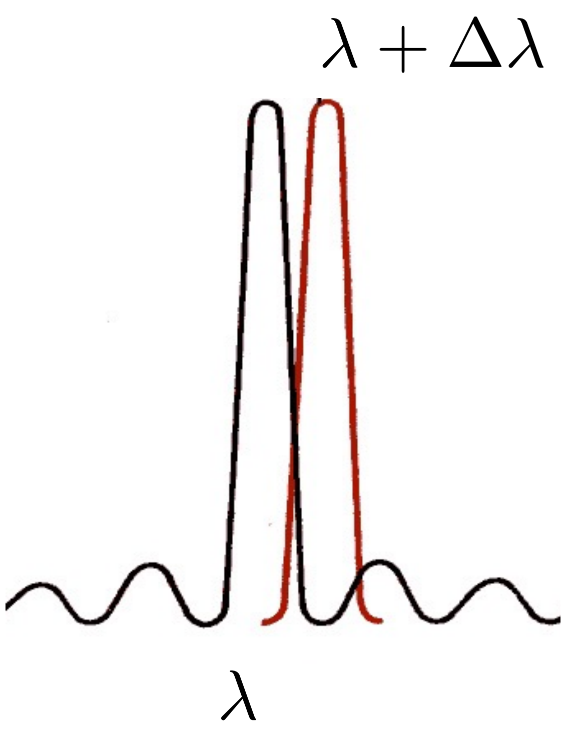

Flux vs. wavelegth
421.552 38.01 0.17
421.618 26.00 0.53
421.755 26.00 0.70
421.936 26.00 0.44
422.034 26.00 0.87
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Res. Intens.
S/N=75
421.5
421.6
421.7
421.8
421.9
422.0
wavelength (nm)


Flux vs. wavelegth
421.552 38.01 0.17
421.618 26.00 0.53
421.755 26.00 0.70
421.936 26.00 0.44
422.034 26.00 0.87
Res. Intens.
1.2
1.0
0.8
0.6
0.4
0.2
0.0
421.5
421.6
421.7
421.8
421.9
422.0
wavelength (nm)
S/N=150

S/N vs. resolution

- **S/n, spectral resolution, and sampling** are the three main parameters defining spectral **quality**.

- They set the **uncertainty** with which features can be measured: **lower** resolution requires **higher S/N** to achieve same result.



- **Optimal-** or **over-sampling** must be mantained. Higher sampling decreases S/N **per pixel** but more fitting points compensate for it.

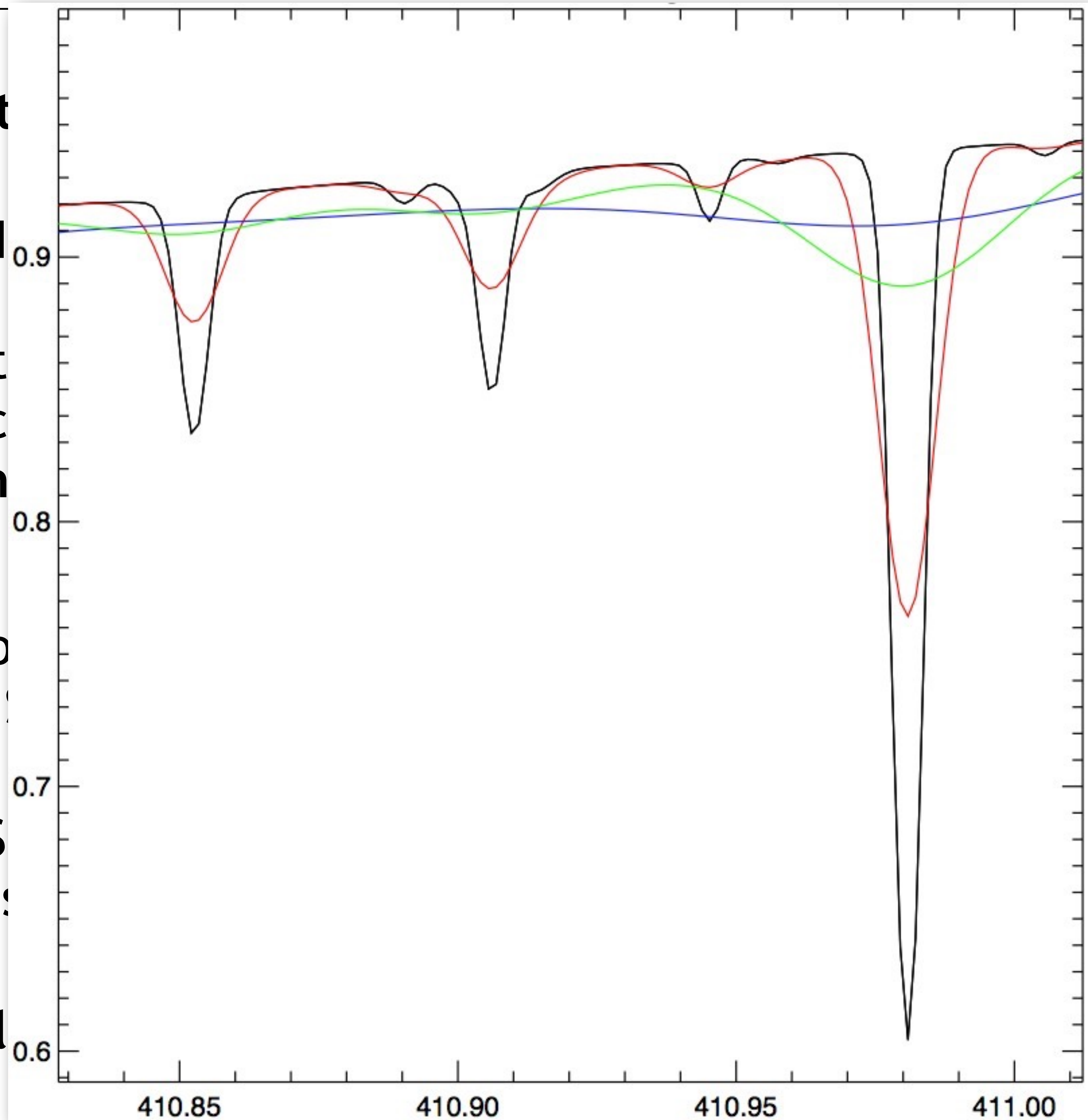
- Same for S/N and resolution (@optimal sampling): lower R —> higher S/N but just enough to compensate for loss of line strength.

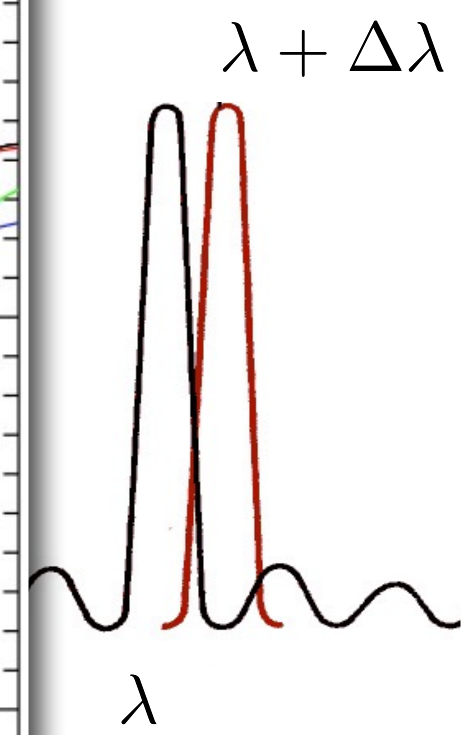
- **Be careful about blending!!**

S/N vs. resolution

- **S/n, spect**
  the three
  spectral **q**

- They set t
  features c
  requires **h**

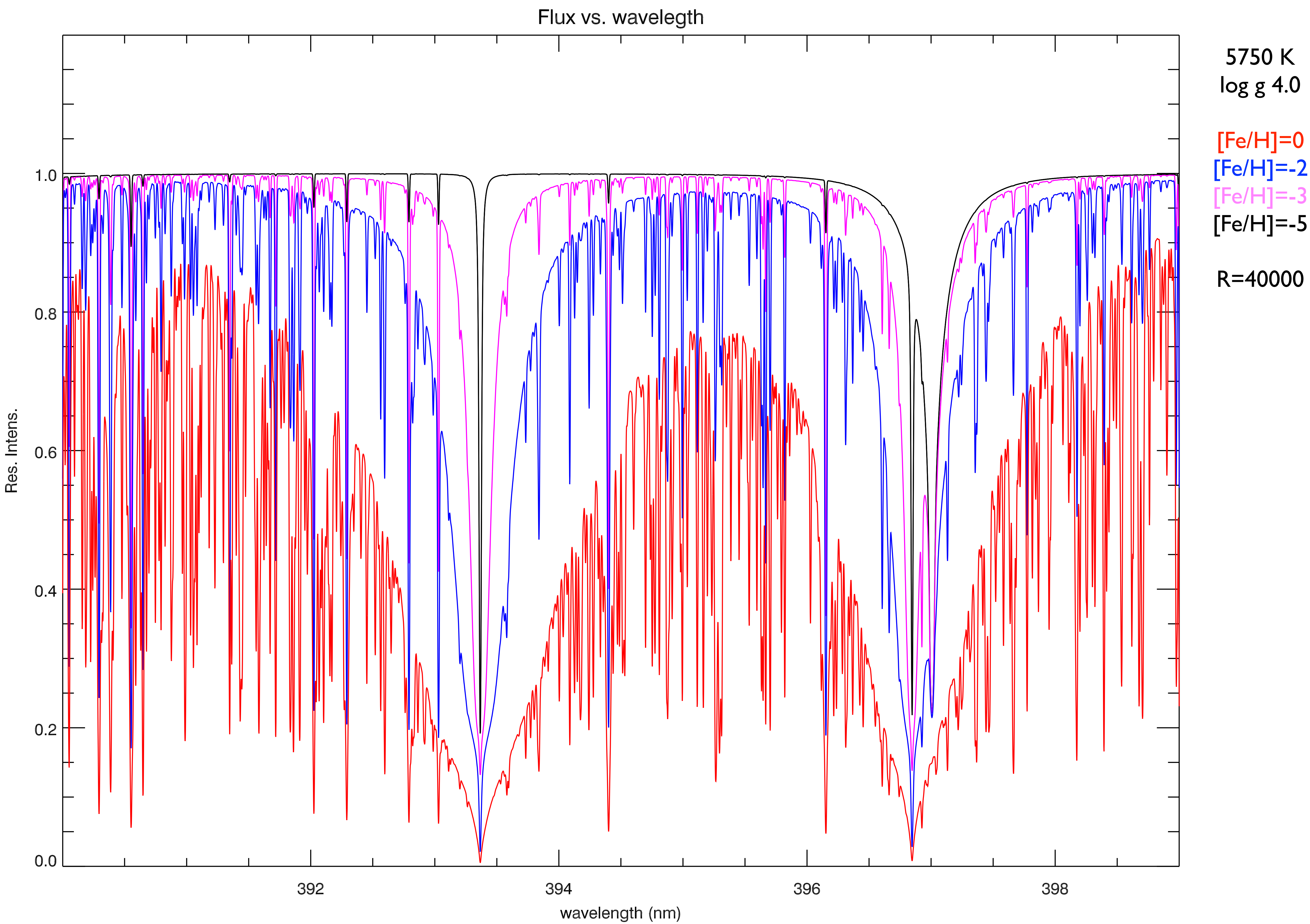




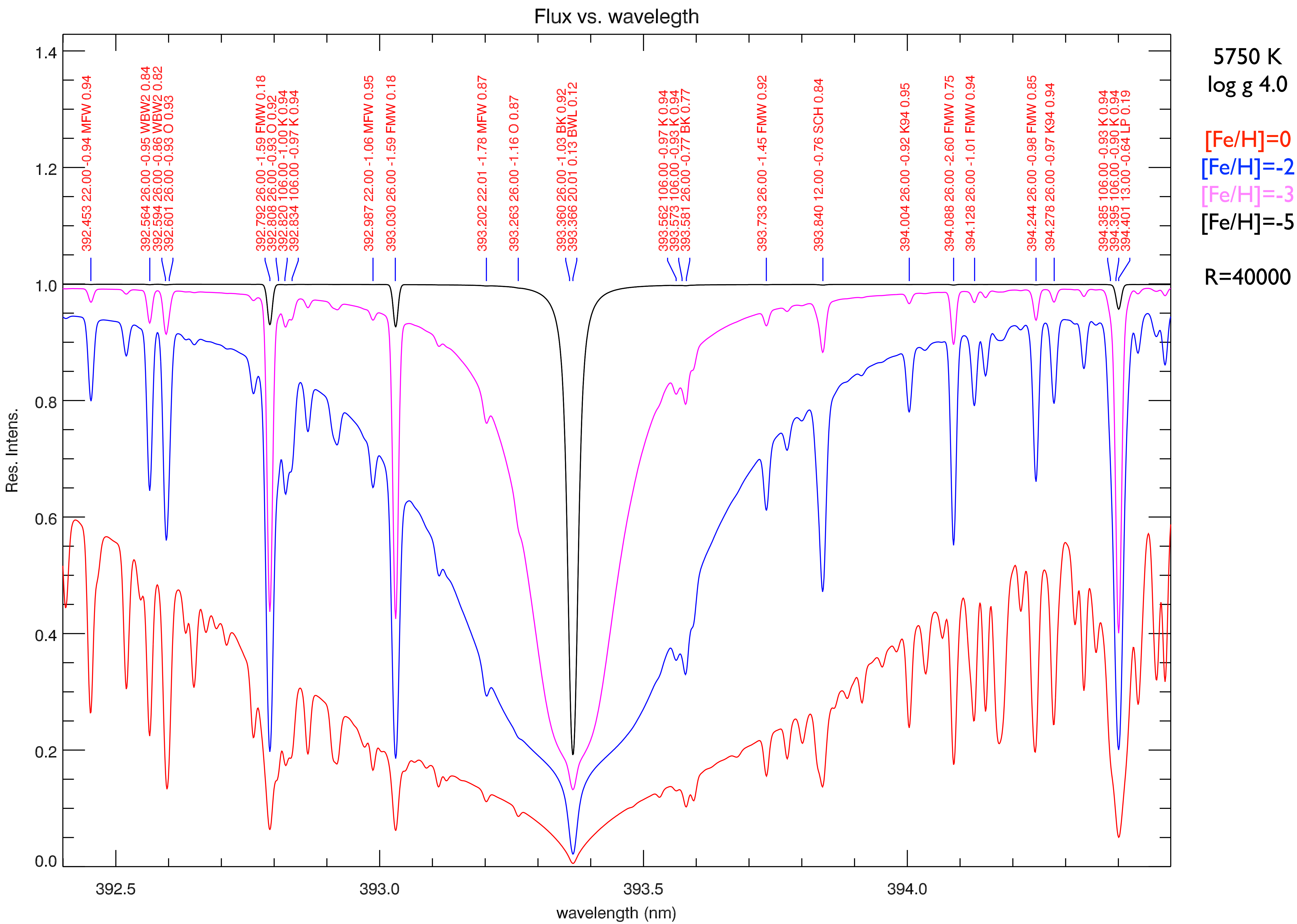
- **Optimal-** o … ampling
  decreases … ate for it.

- Same for S … R —> higher
  S/N but ju … gth.

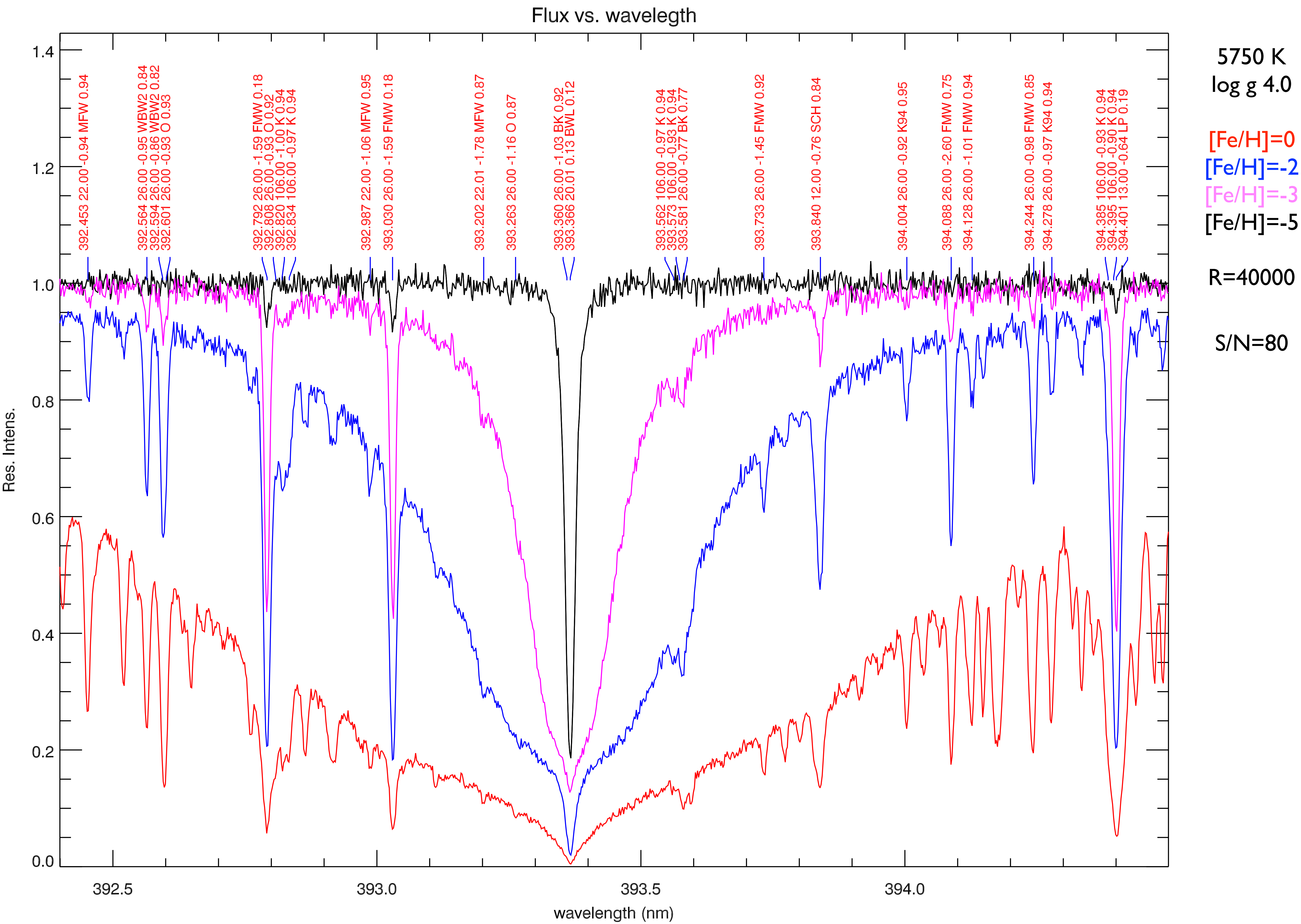
- **Be careful**



Flux vs. wavelegth
Res. Intens.
1.0
0.8
0.6
0.4
0.2
0.0
392
394
396
398
wavelength (nm)
5750 K
log g 4.0
[Fe/H]=0
[Fe/H]=-2
[Fe/H]=-3
[Fe/H]=-5
R=40000

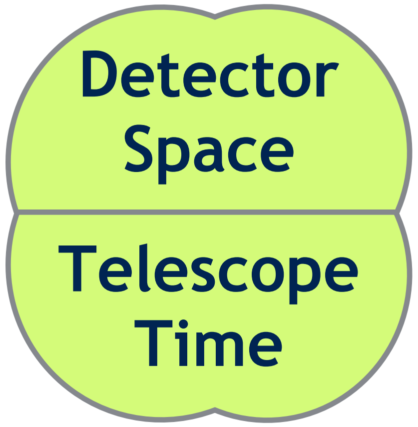


Flux vs. wavelegth
5750 K
log g 4.0
[Fe/H]=0
[Fe/H]=-2
[Fe/H]=-3
[Fe/H]=-5
R=40000
Res. Intens.
wavelength (nm)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
392.5
393.0
393.5
394.0
392.453 22.00 -0.94 MFW 0.94
392.564 26.00 -0.95 WBW2 0.84
392.594 26.00 -0.86 WBW2 0.82
392.601 26.00 -0.93 O 0.93
392.792 26.00 -1.59 FMW 0.18
392.808 26.00 -0.93 O 0.92
392.820 106.00 -1.00 K 0.94
392.834 106.00 -0.97 K 0.94
392.987 22.00 -1.06 MFW 0.95
393.030 26.00 -1.59 FMW 0.18
393.202 22.01 -1.78 MFW 0.87
393.263 26.00 -1.16 O 0.87
393.360 26.00 -1.03 BK 0.92
393.366 20.01 0.13 BWL 0.12
393.562 106.00 -0.97 K 0.94
393.573 106.00 -0.93 K 0.94
393.581 26.00 -0.77 BK 0.77
393.733 26.00 -1.45 FMW 0.92
393.840 12.00 -0.76 SCH 0.84
394.004 26.00 -0.92 K94 0.95
394.088 26.00 -2.60 FMW 0.75
394.128 26.00 -1.01 FMW 0.94
394.244 26.00 -0.98 FMW 0.85
394.278 26.00 -0.97 K94 0.94
394.385 106.00 -0.93 K 0.94
394.395 106.00 -0.90 K 0.94
394.401 13.00 -0.64 LP 0.19

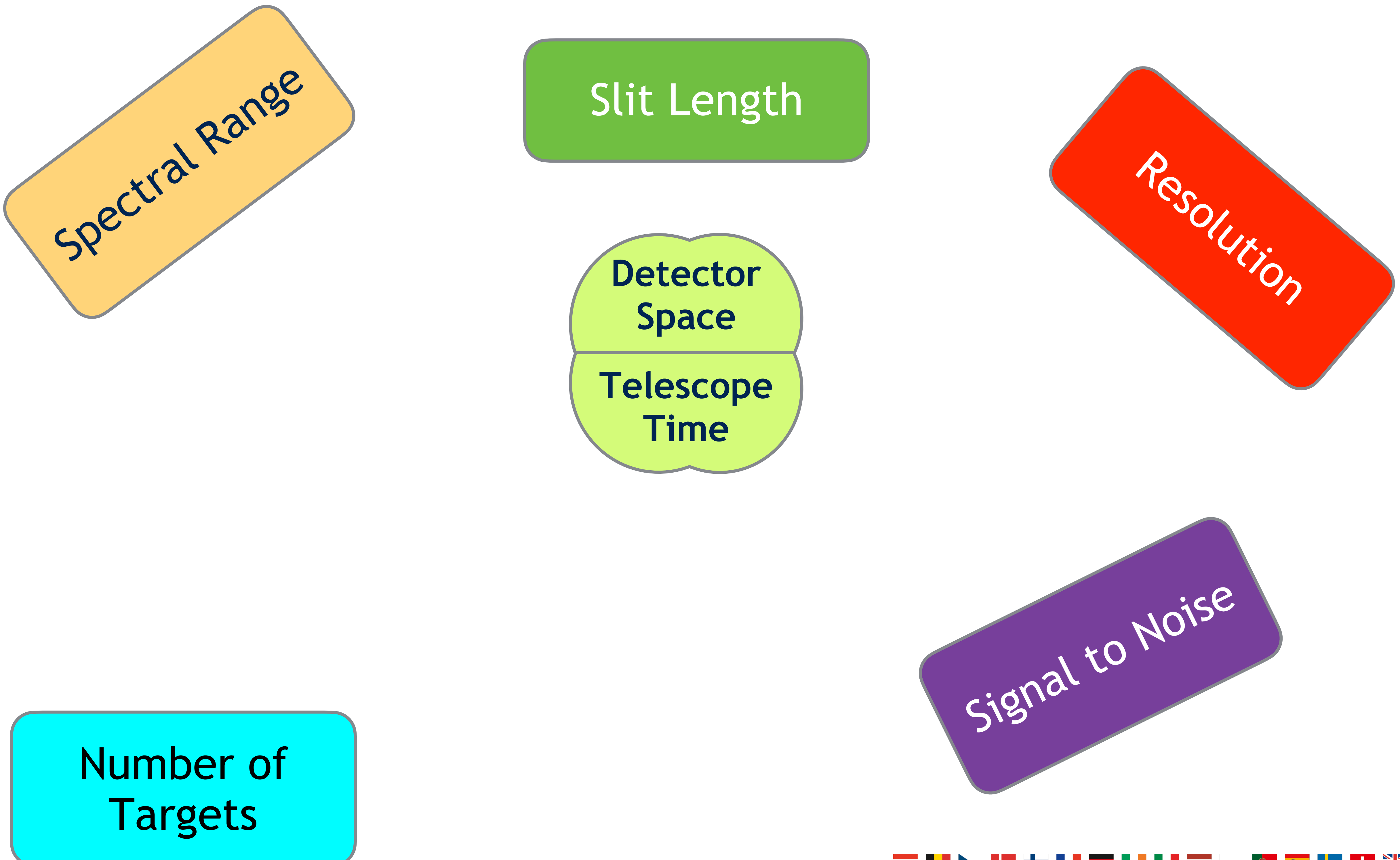


Flux vs. wavelegth
Res. Intens.
wavelength (nm)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
392.5
393.0
393.5
394.0
392.453 22.00 -0.94 MFW 0.94
392.564 26.00 -0.95 WBW2 0.84
392.594 26.00 -0.86 WBW2 0.82
392.601 26.00 -0.93 O 0.93
392.792 26.00 -1.59 FMW 0.18
392.808 26.00 -0.93 O 0.92
392.820 106.00 -1.00 K 0.94
392.834 106.00 -0.97 K 0.94
392.987 22.00 -1.06 MFW 0.95
393.030 26.00 -1.59 FMW 0.18
393.202 22.01 -1.78 MFW 0.87
393.263 26.00 -1.16 O 0.87
393.360 26.00 -1.03 BK 0.92
393.366 20.01 0.13 BWL 0.12
393.562 106.00 -0.97 K 0.94
393.573 106.00 -0.93 K 0.94
393.581 26.00 -0.77 BK 0.77
393.733 26.00 -1.45 FMW 0.92
393.840 12.00 -0.76 SCH 0.84
394.004 26.00 -0.92 K94 0.95
394.088 26.00 -2.60 FMW 0.75
394.128 26.00 -1.01 FMW 0.94
394.244 26.00 -0.98 FMW 0.85
394.278 26.00 -0.97 K94 0.94
394.385 106.00 -0.93 K 0.94
394.395 106.00 -0.90 K 0.94
394.401 13.00 -0.64 LP 0.19
5750 K
log g 4.0
[Fe/H]=0
[Fe/H]=-2
[Fe/H]=-3
[Fe/H]=-5
R=40000
S/N=80

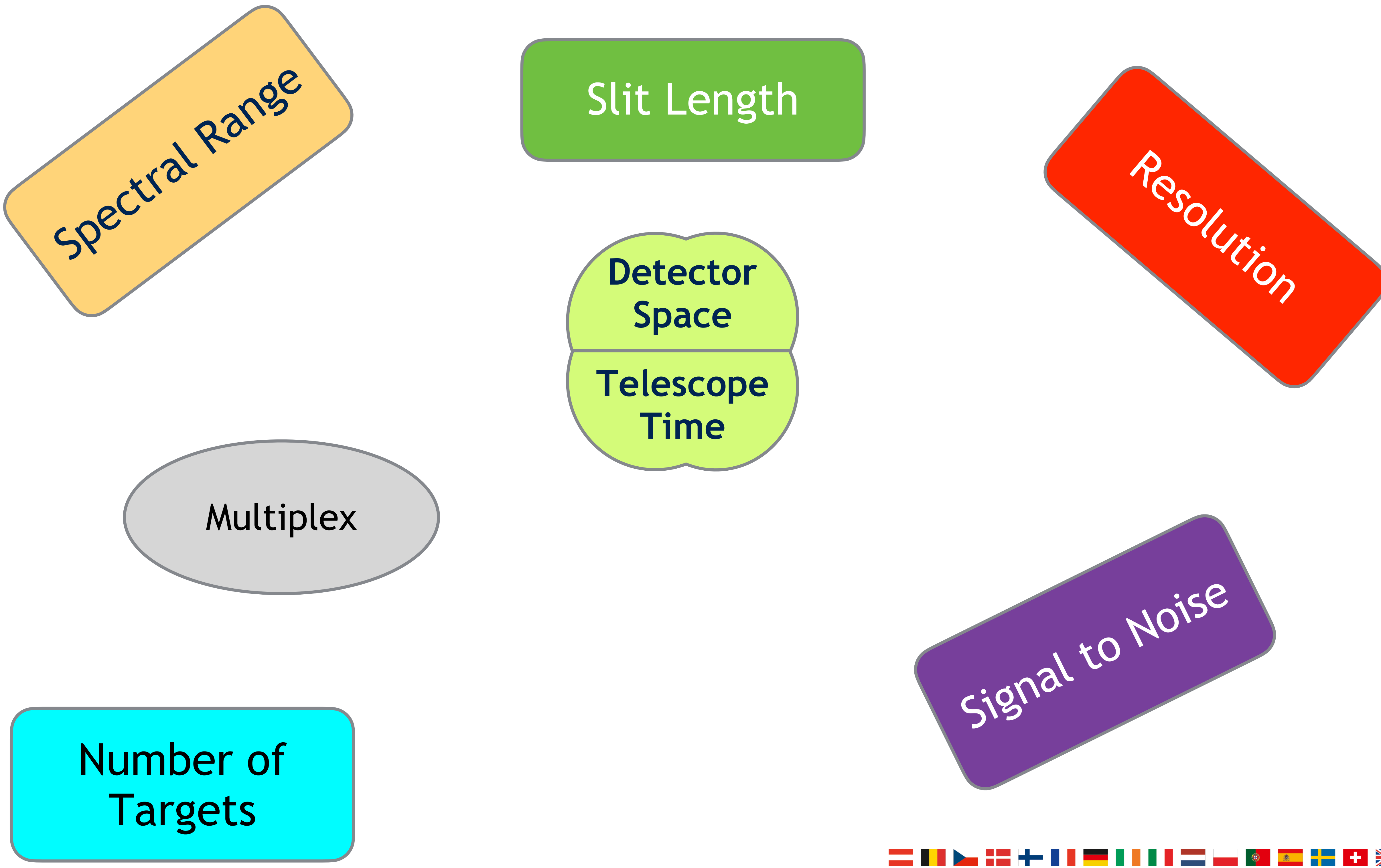
Spectroscopy Choices Confusogram



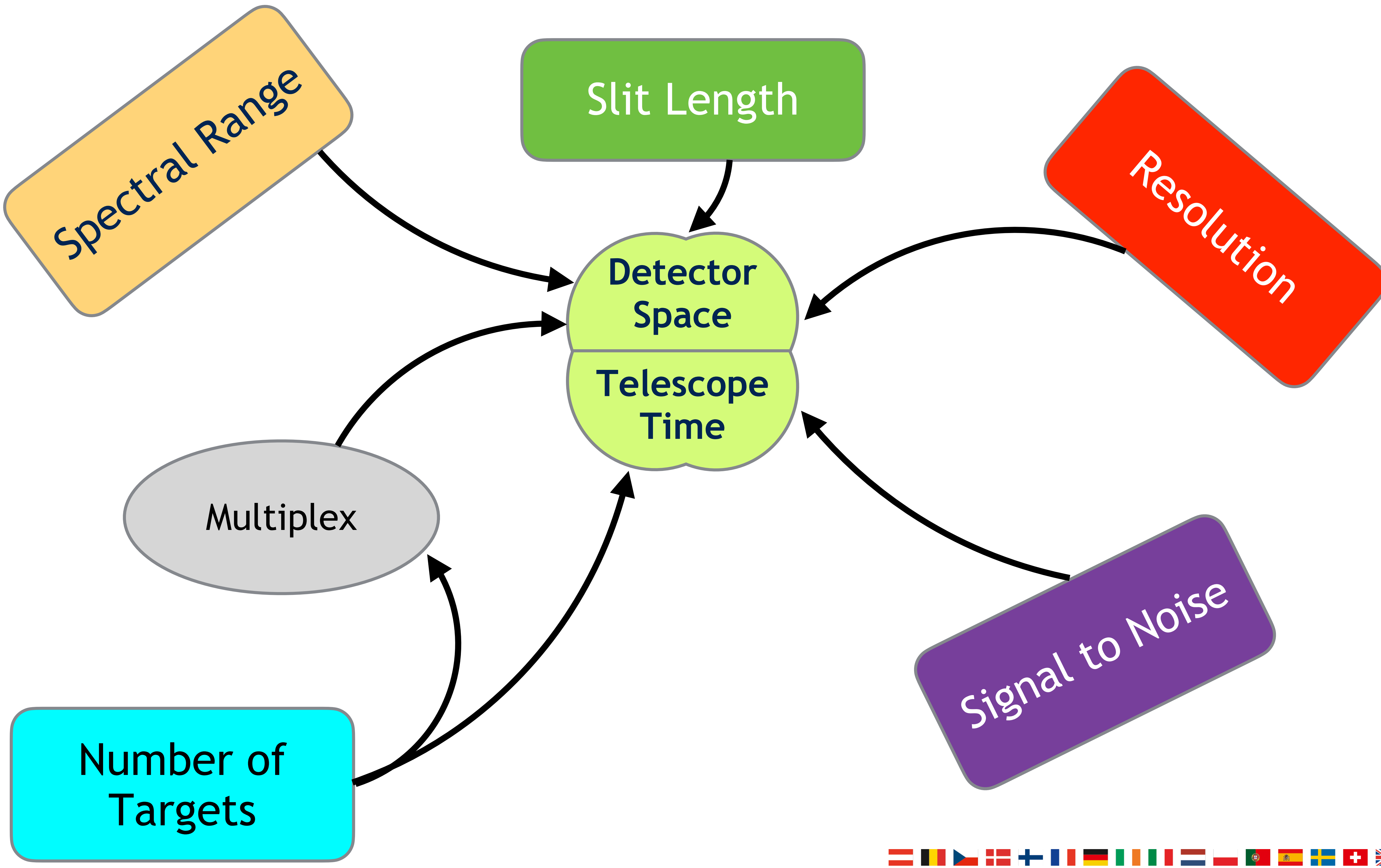
Spectroscopy Choices Confusogram



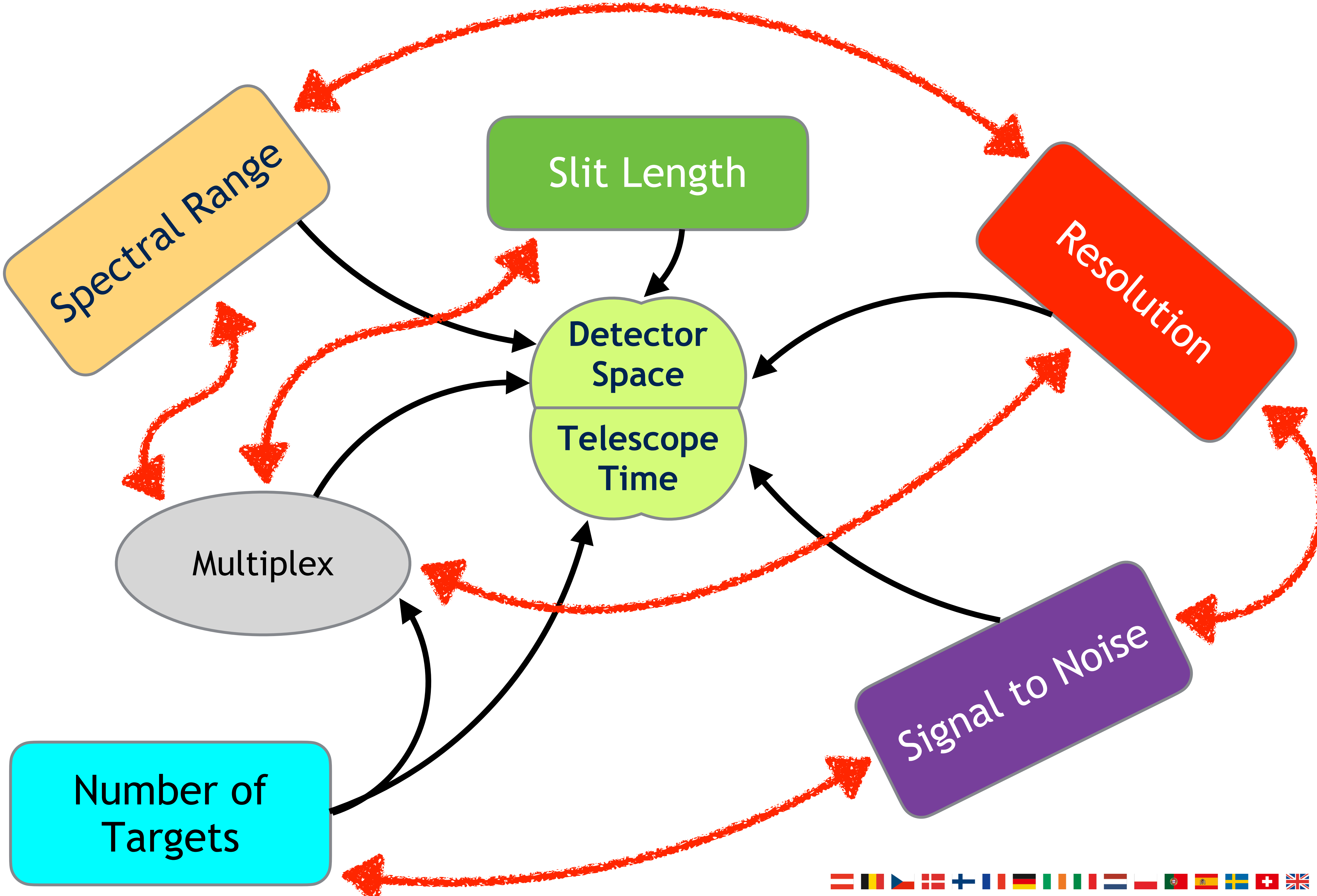
Spectroscopy Choices Confusogram



Spectroscopy Choices Confusogram



Spectroscopy Choices Confusogram



Spectrograph data reduction

- **Bias subtraction:** detector calibration to remove readout bias, same as for imaging.

- **Order/slitlet trace:** Position of orders/slits centers across wavelength on the detector are traced and stored.

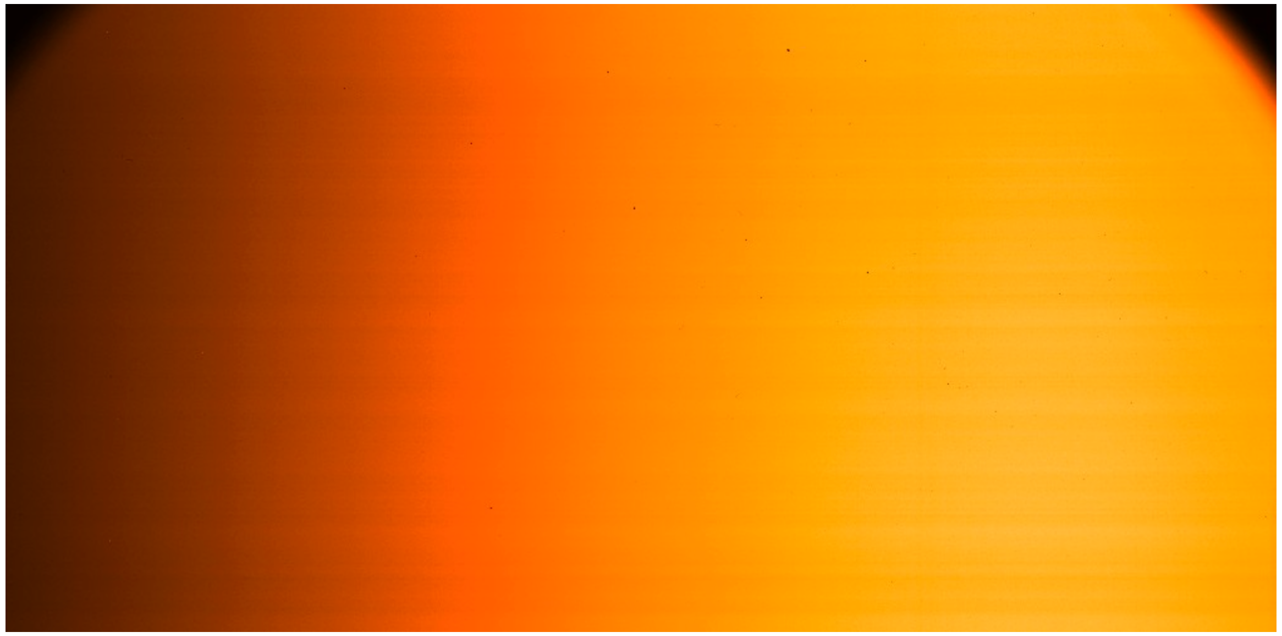
- **Flat-field correction:** through-spectrograph flat field used to correct for illumination variations (blaze, vignetting) and pix-to-pix inhomogeneity. Per-order (-slitlet).

- **Wavelength calibration:** (per-order) wavelength values along dispersion direction determined via known emission-line spectrum (Th-Ar lamp, Fabry-Perot etalon, Laser Frequency Comb), wavelength solution computed, per order/slitlet and at different points along slit

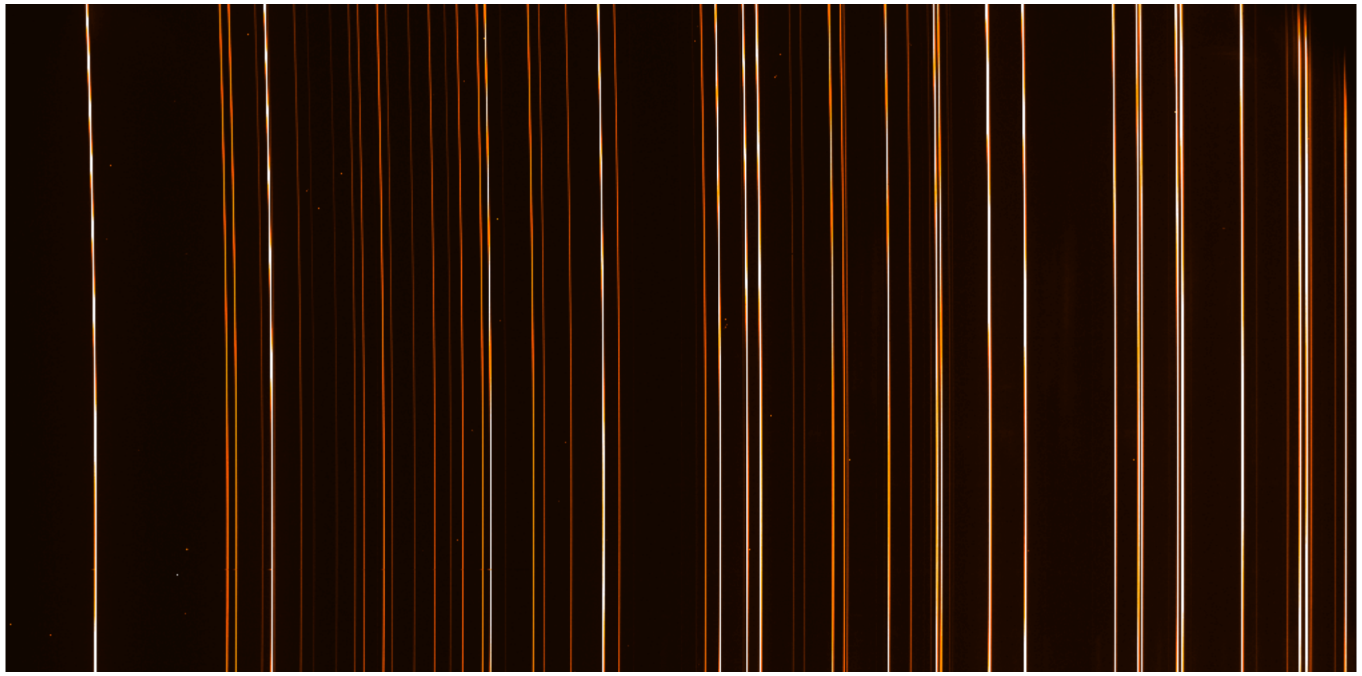
- **Science spectrum extraction:** using defined spectrum geometry science spectra are extracted, rectified, flat-fielded, wavelength calibrated and resampled. If echelle, orders are merged. Background (“sky”) is subtracted from slit edges / sly fiber(s) if LSS, Echelle

Spectrograph data reduction

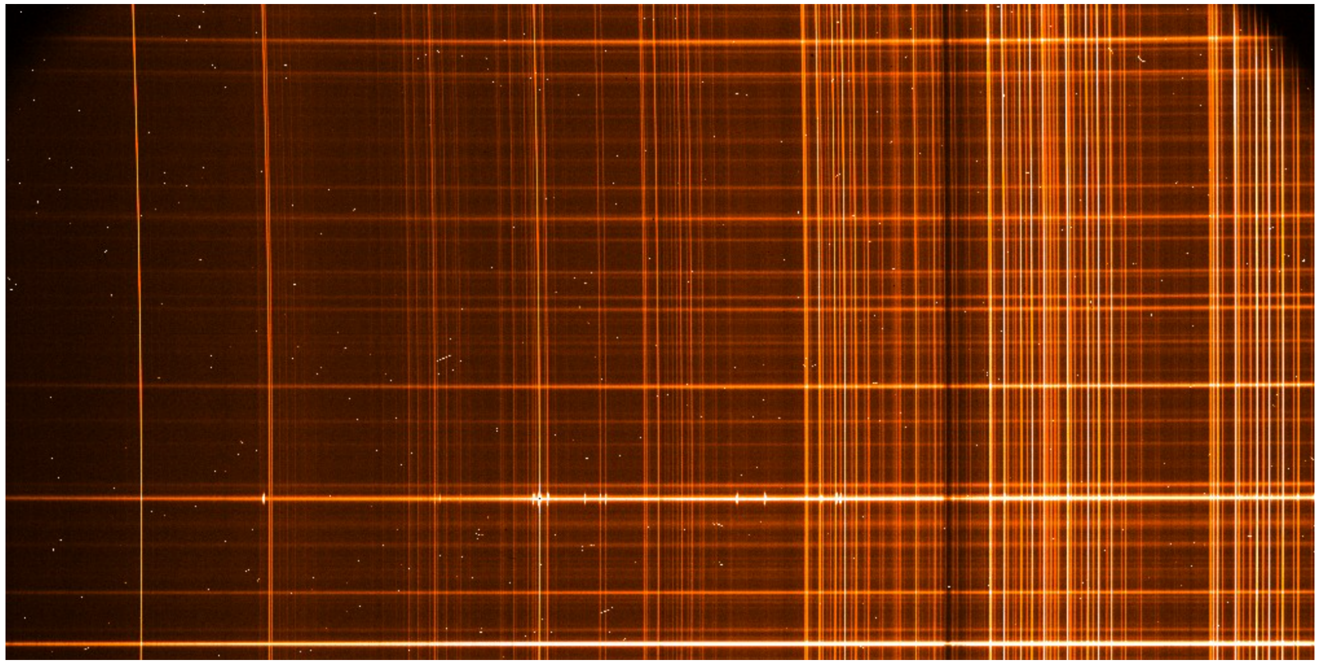
- Long Slit Flat Field frame



- Long Slit Wavelength Calibration (ThAr) lamp frame

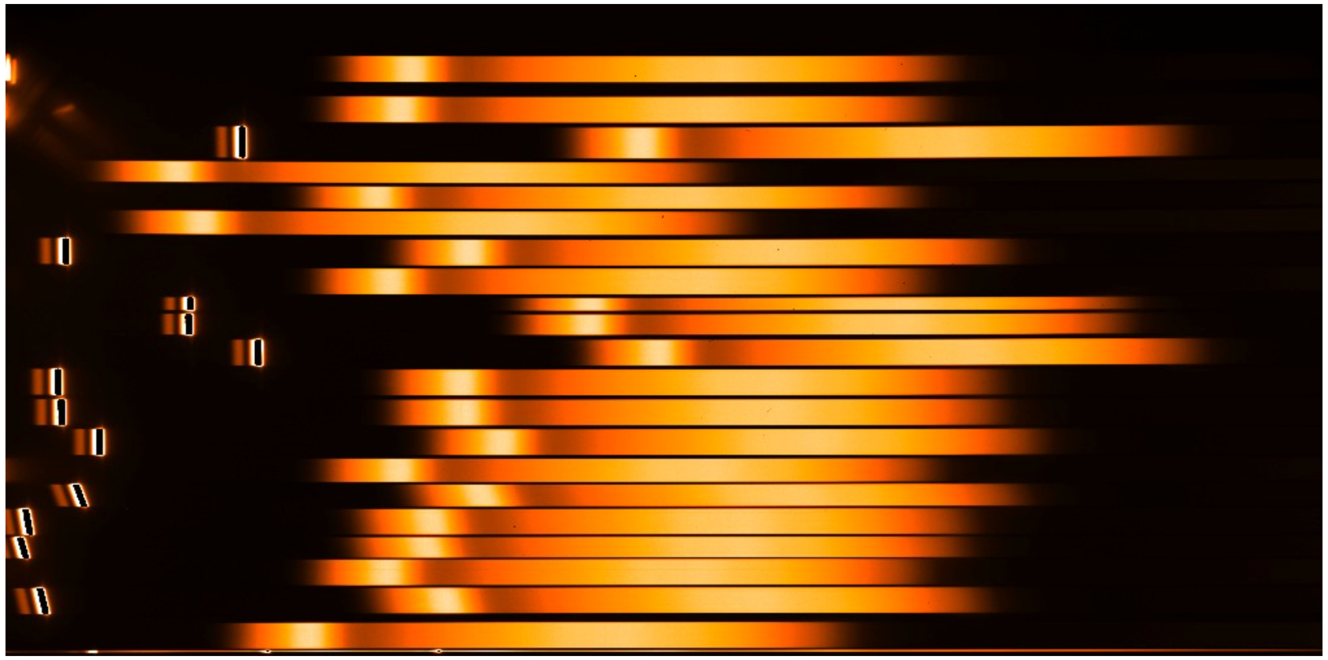


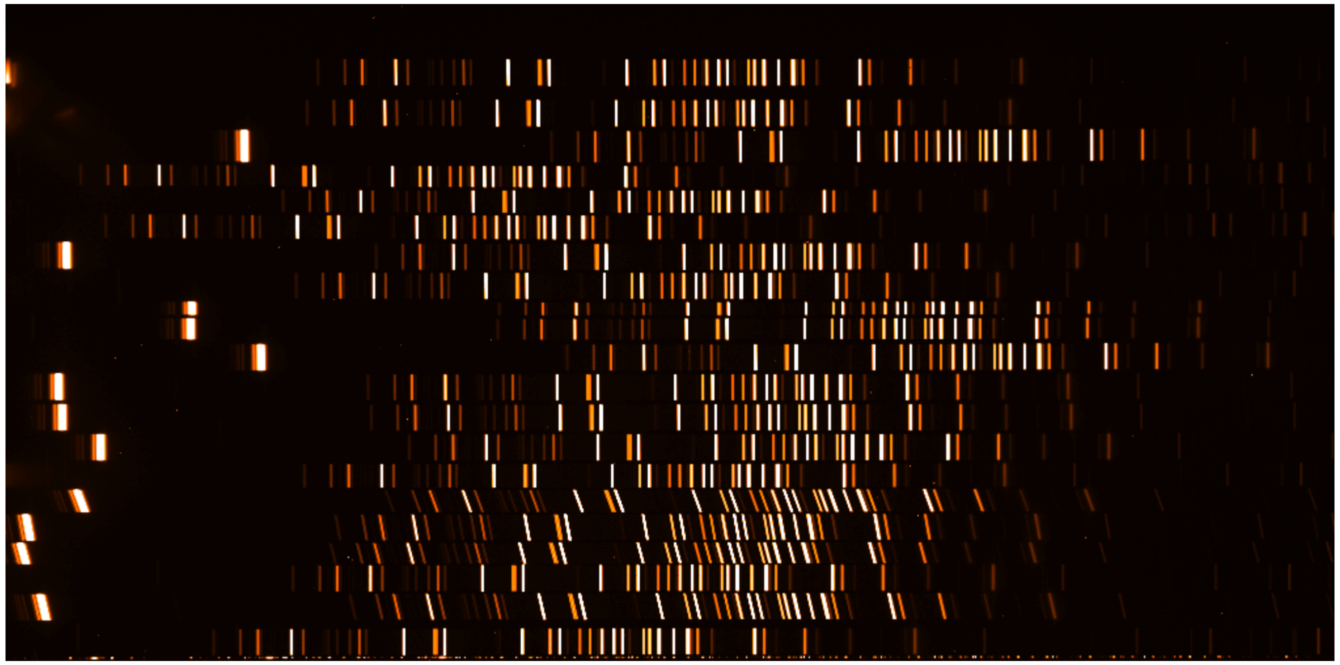
- Long Slit Science frame



Spectrograph data reduction

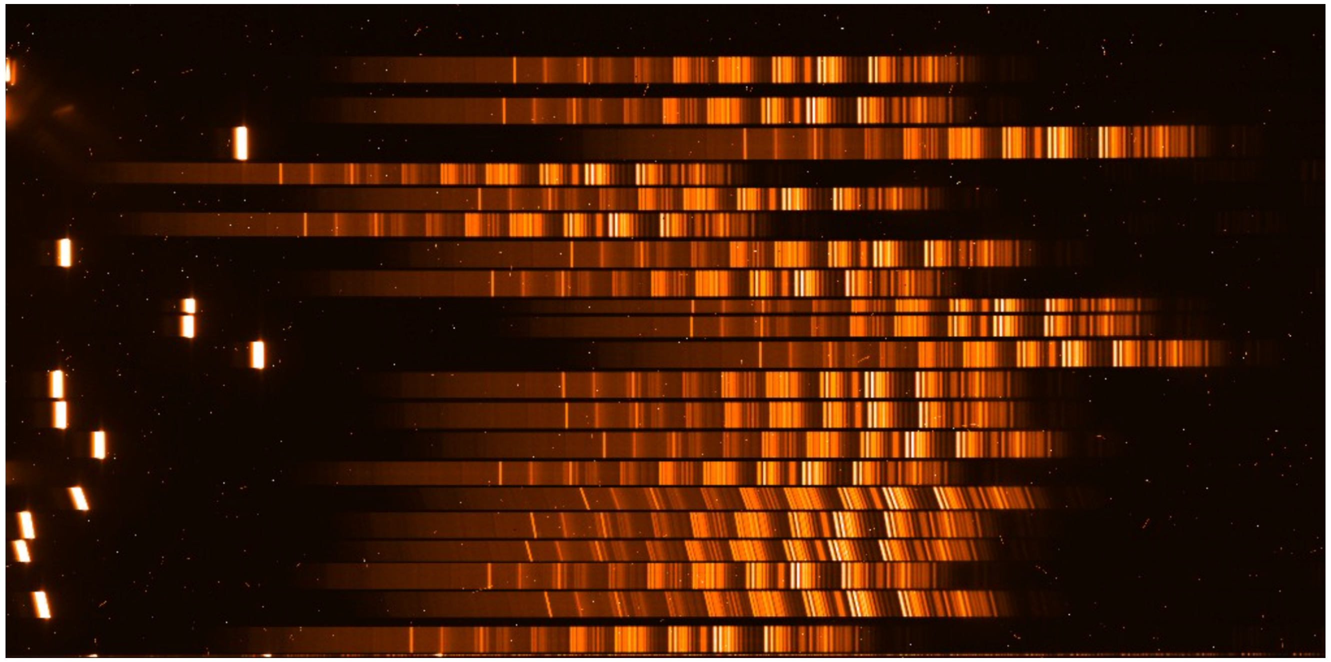
- MXU Flat Field frame



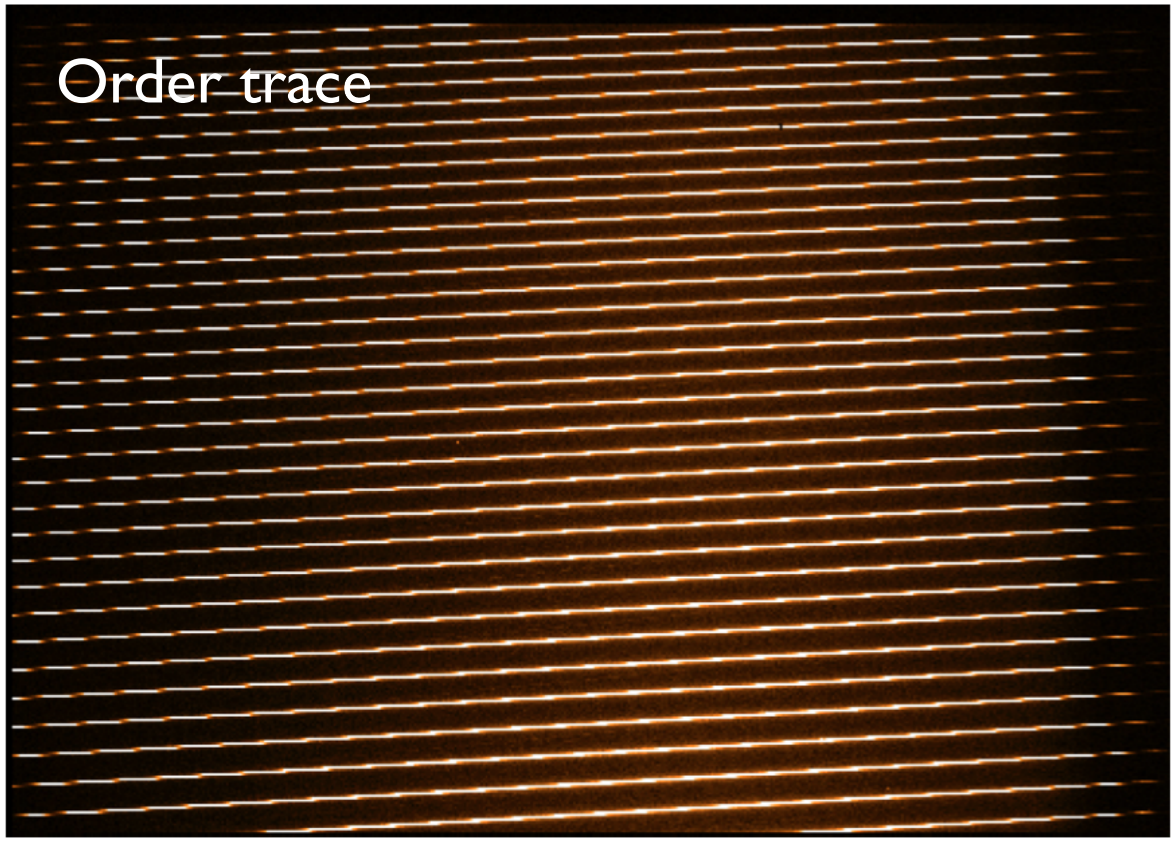


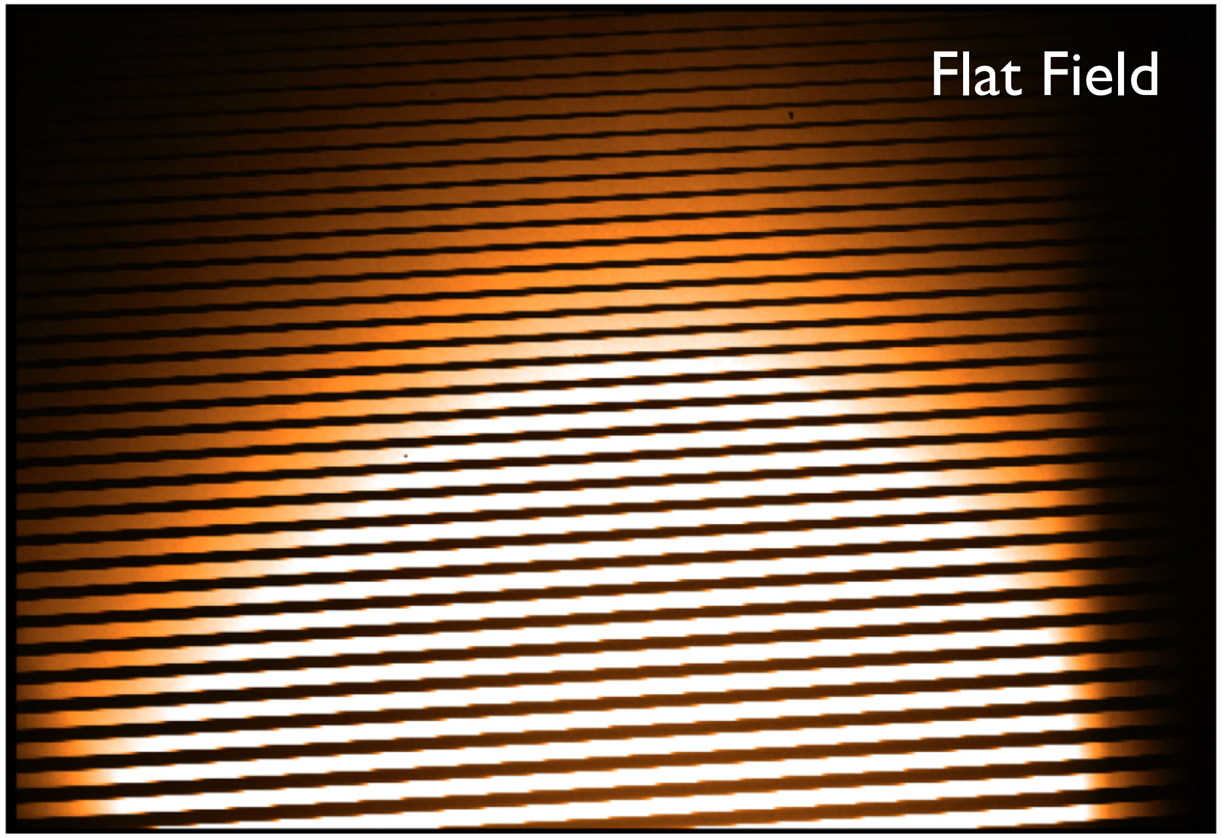
- MXU Wavelength Calibration (ThAr) lamp frame

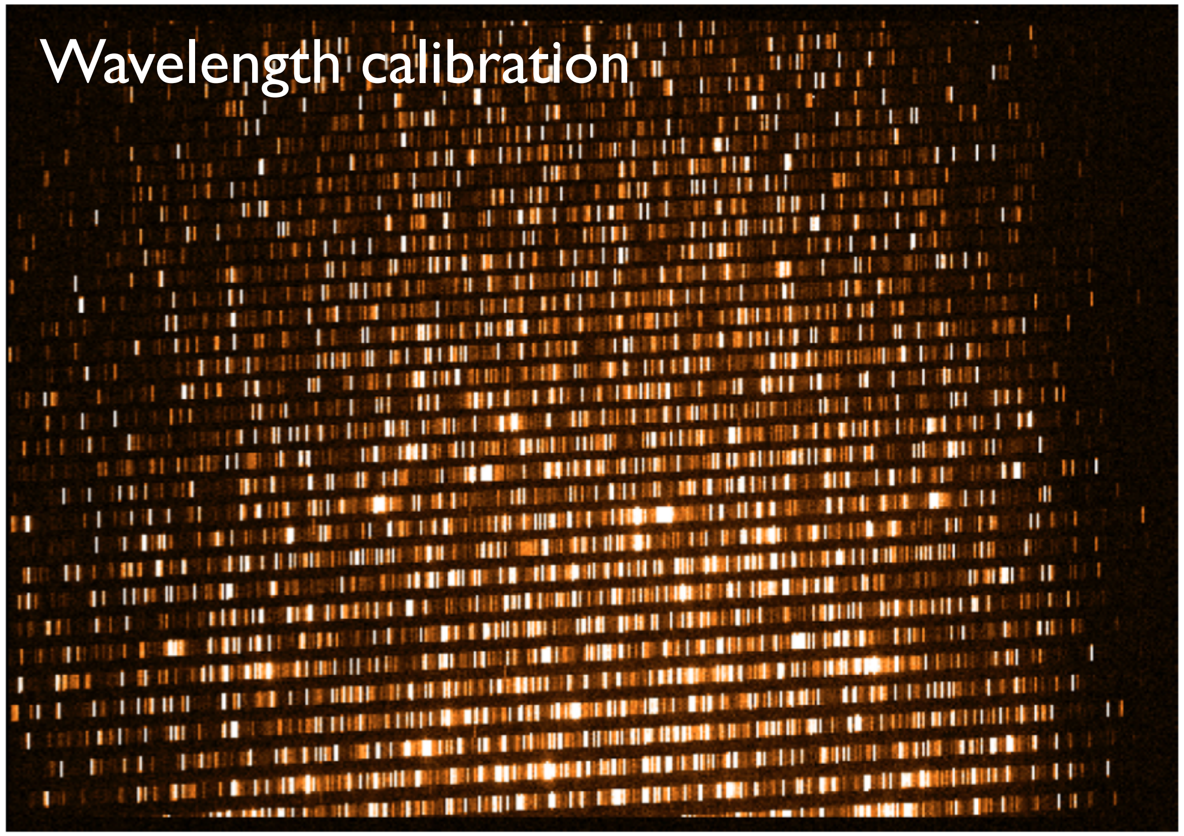
- MXU Science frame



Spectrograph data reduction

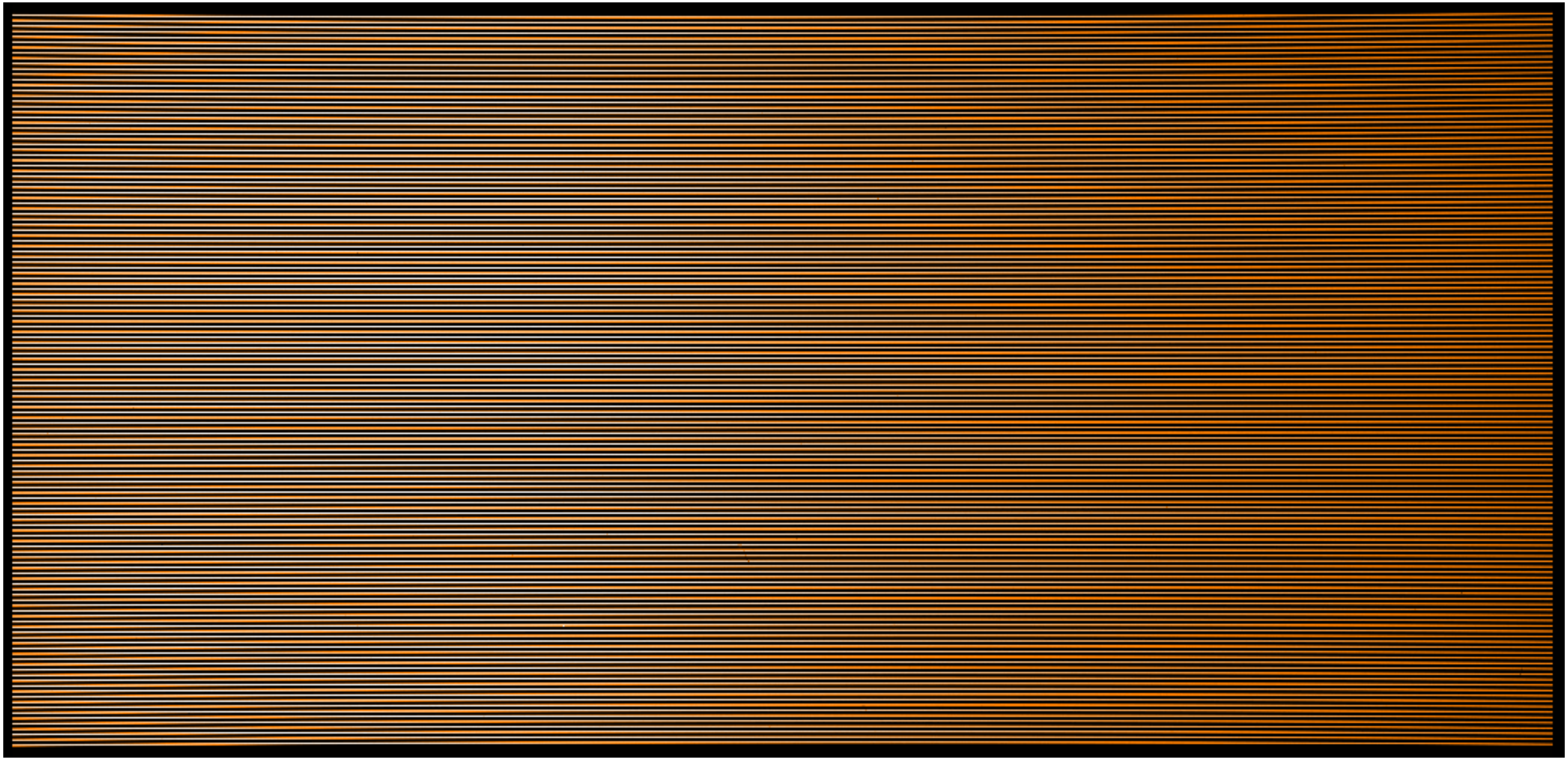






- Echelle spectra require **order tracing** because orders are tilted, and often curved. FF & Wave need to be **extracted and rectified** before applying to science. **Inter-order background** needs to be fitted

Spectrograph data reduction



- **Positionable fiber-fed (FLAMES) Flat Field frame:** single-order spectra, flat field, from the 131 fibres

Thank you!