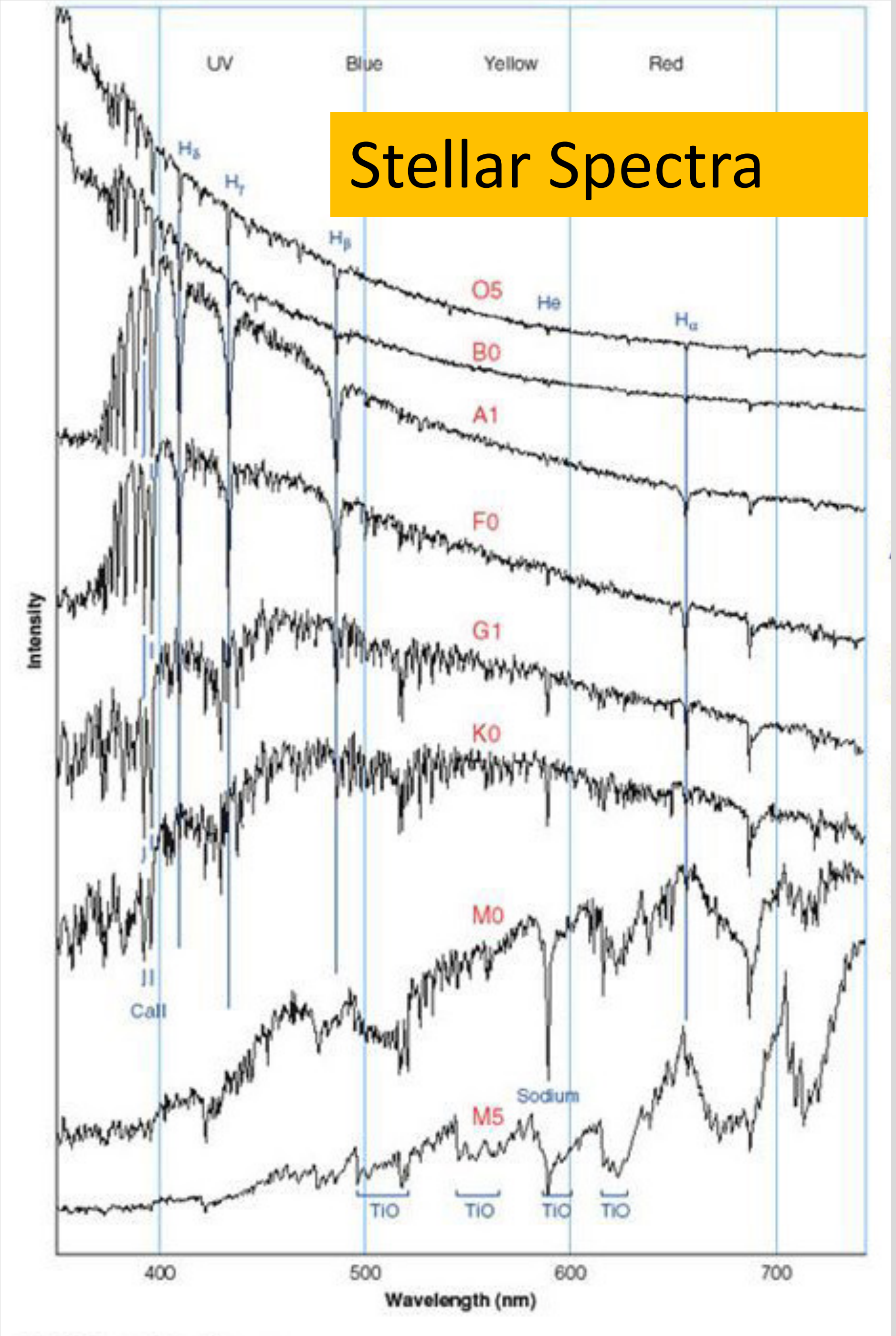
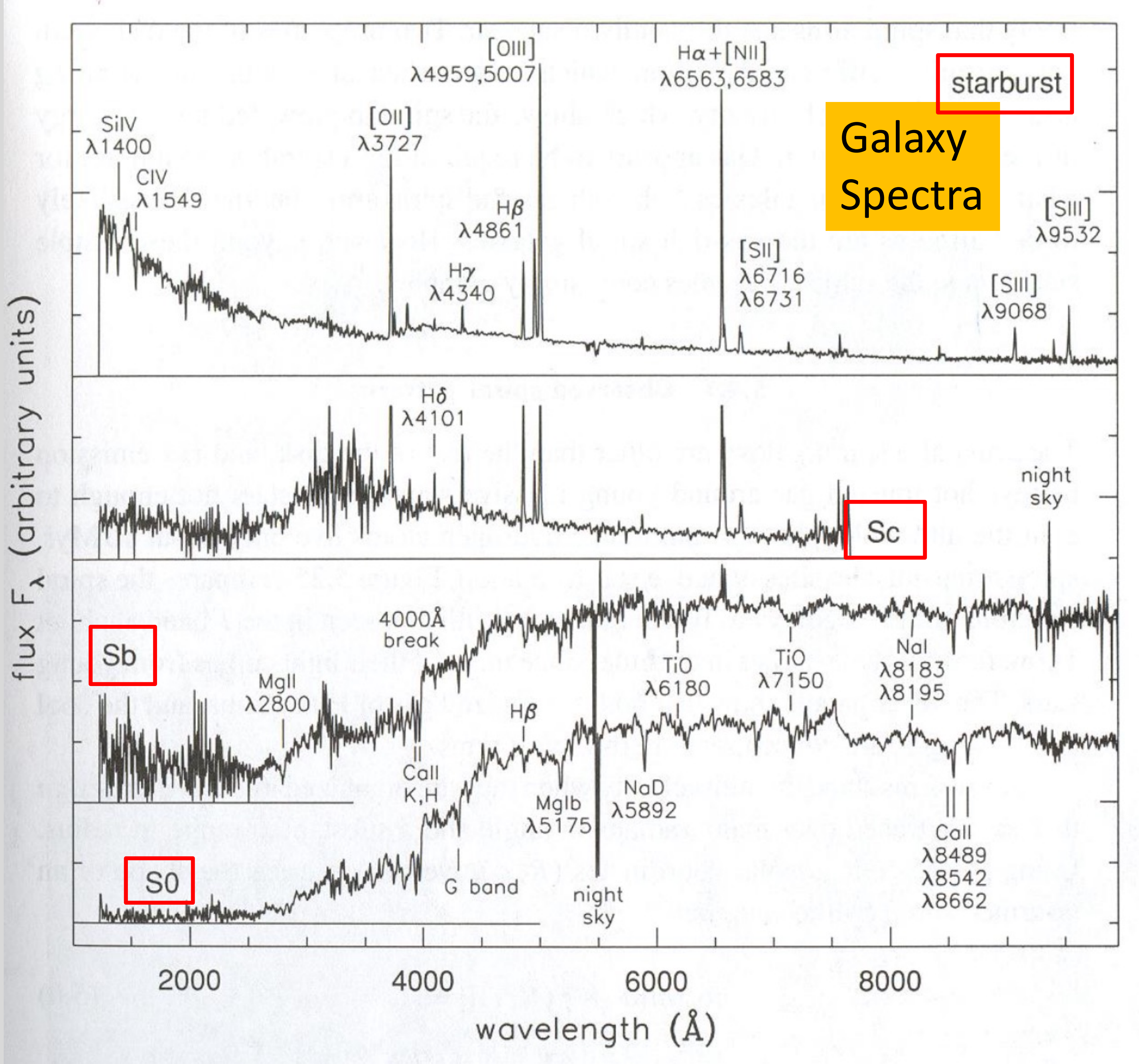
Spectroscopy: Disperse (spread) the light of an object out into its spectrum.

- **Measure spectral lines:** chemical abundances, temperatures, ionization source, density, etc.
- **Measure redshifts**.
- **Measure velocities**.



Spectroscopy: Disperse (spread) the light of an object out into its spectrum.

- **Measure spectral lines:** chemical abundances, temperatures, ionization source, density, etc.
- **Measure redshifts**.
- **Measure velocities**.

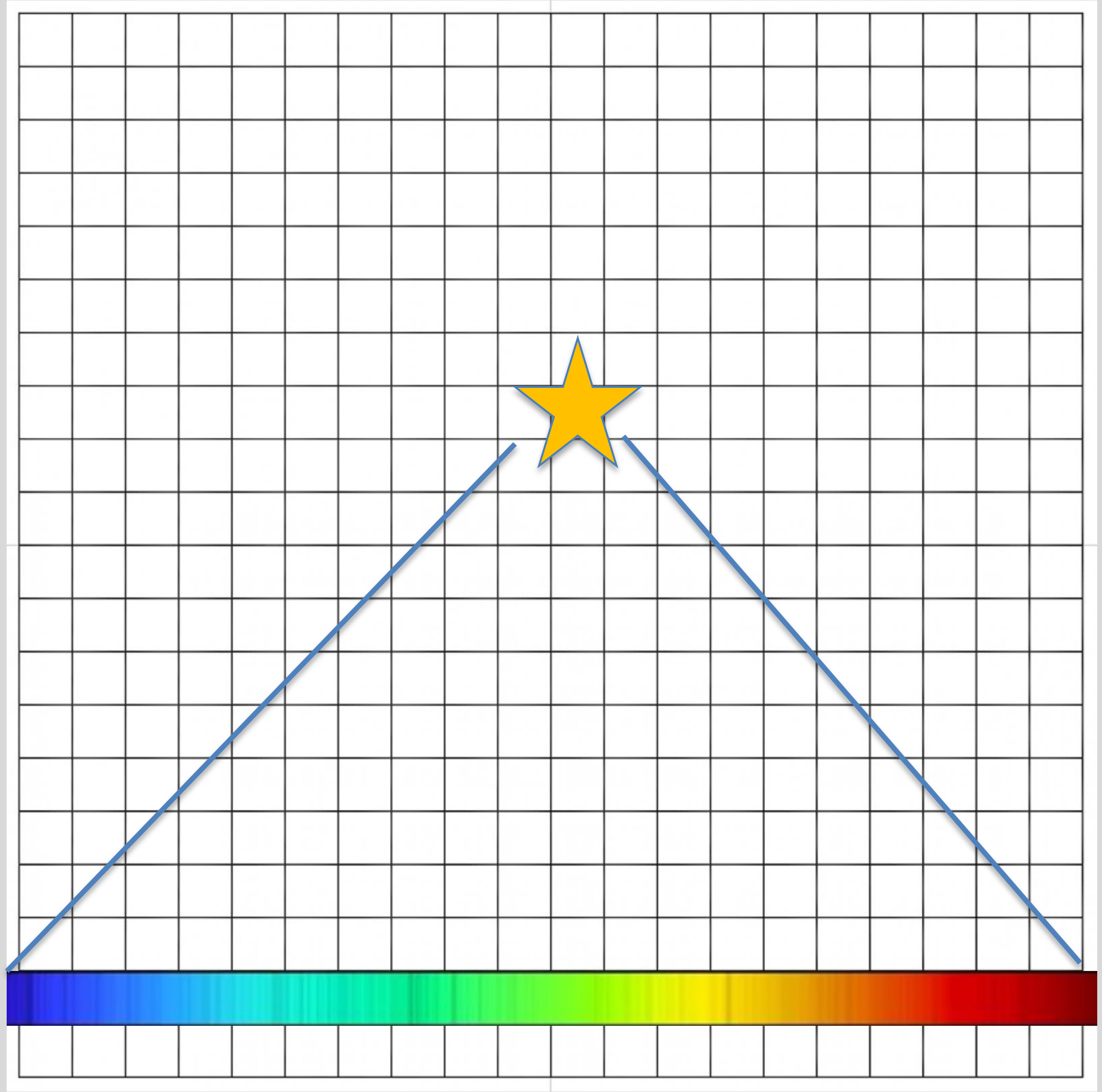


Imaging vs Spectroscopy

Imaging: Take all the light from a star, dump it into a few pixels. Easy to detect even relatively faint sources.

Spectroscopy: Spread the light out in wavelength, dumping it across a whole long swath of pixels. Many fewer photons per pixel, much fainter to measure.

Faint object spectroscopy: the domain of large telescopes.



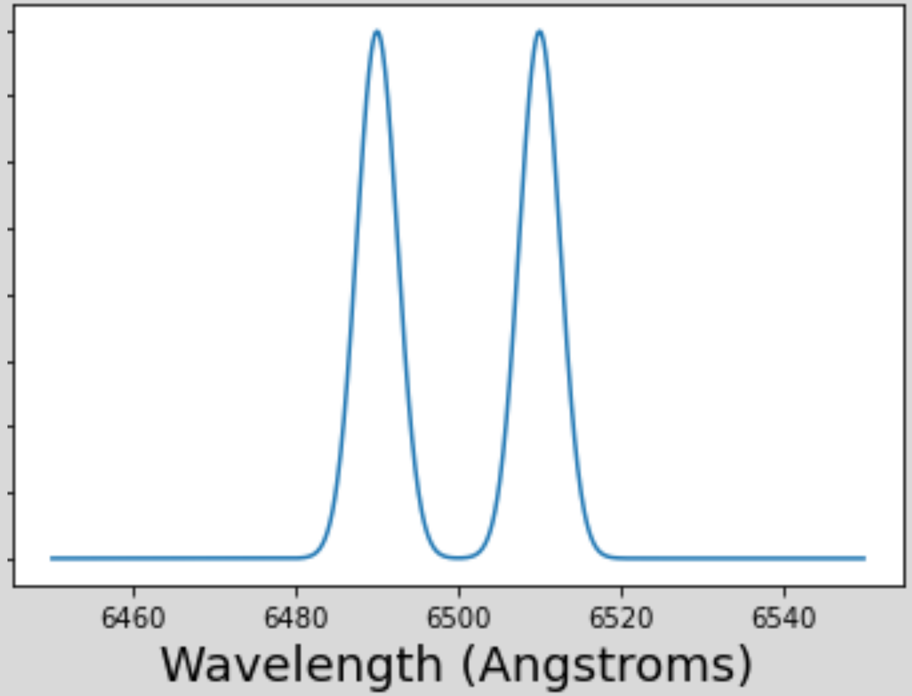
Spectral Resolution

Typically characterized by

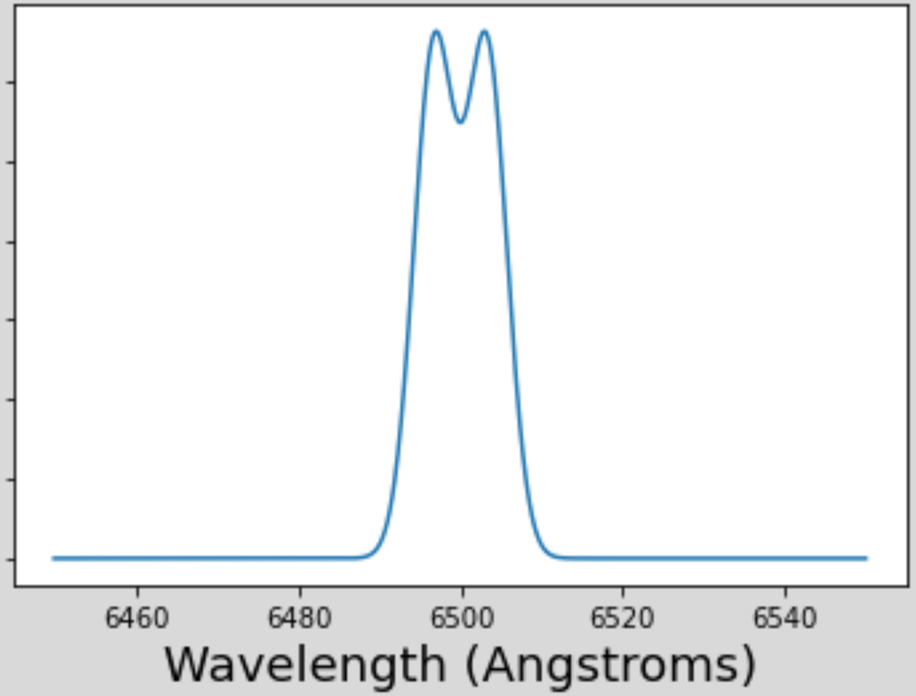
$$R = \lambda/\Delta\lambda$$

where Δλ is the wavelength difference of two spectral lines that can just be distinguished separately.

These two lines at $\lambda = 6490$ Å, 6510 Å ($\Delta\lambda = 20$Å) are easily distinguishable



These two lines at $\lambda = 6496.75$ Å, 6503.25 Å ($\Delta\lambda = 6.5$ Å) are barely distinguishable. So this spectrum has a resolution $R \approx 1000$.



Spectral Resolution

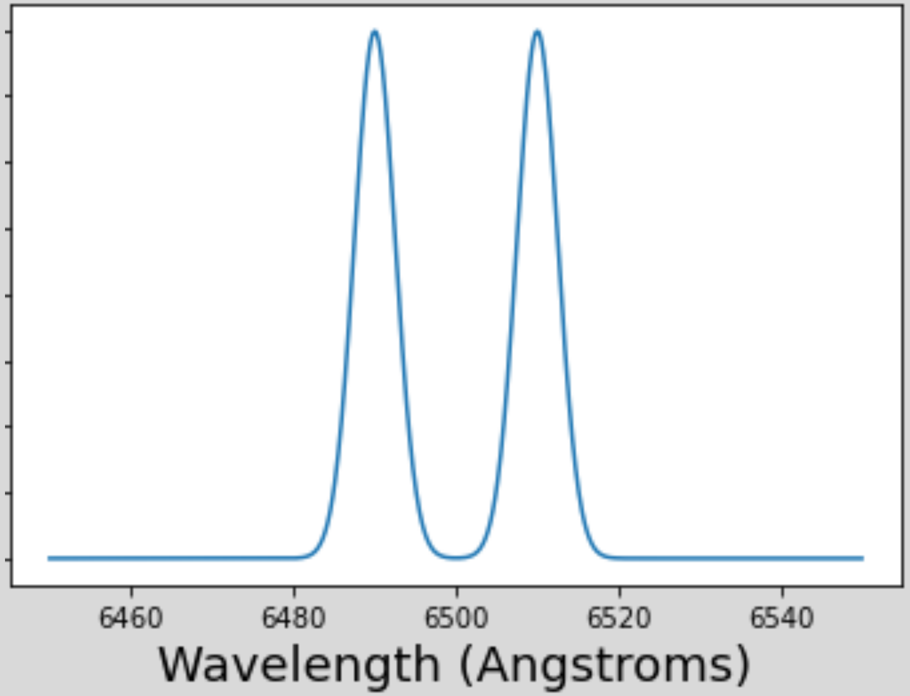
Typically characterized by

$$R = \lambda/\Delta\lambda\ (= c/\underbrace{\Delta v}_{\text{Doppler velocity}})$$

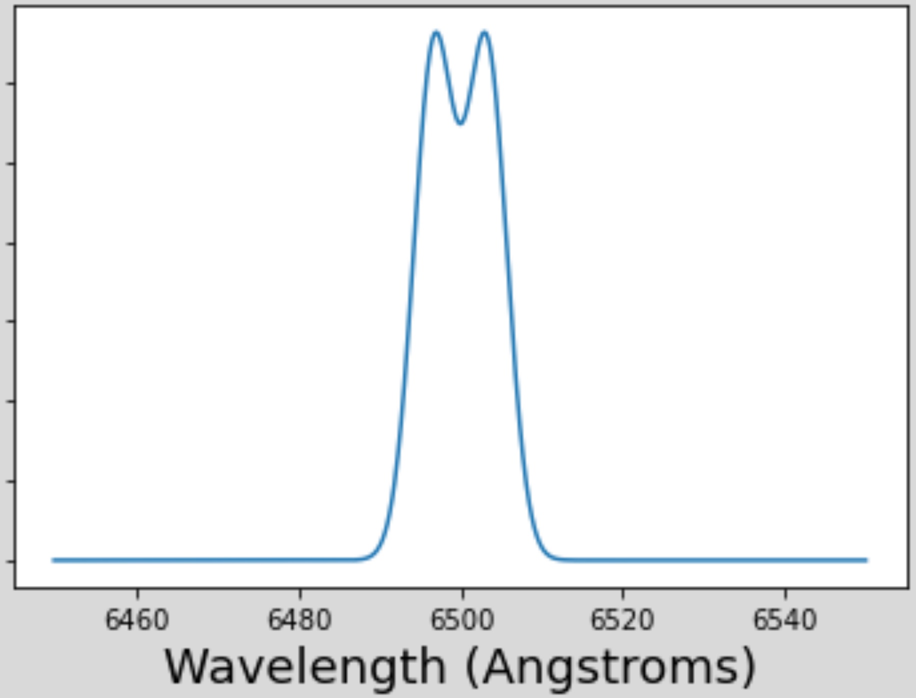
At Hα ($\lambda = 6563$ Å),
$\Delta\lambda = 6.5$ Å $\Rightarrow$ $\Delta v = 300$ km/s

where Δλ is the wavelength difference of two spectral lines that can just be distinguished separately.

These two lines at $\lambda = 6490$ Å, 6510 Å ($\Delta\lambda = 20$Å) are easily distinguishable



These two lines at $\lambda = 6496.75$ Å, 6503.25 Å ($\Delta\lambda = 6.5$ Å) are barely distinguishable.
So this spectrum has a resolution $R \approx 1000$.



Low Resolution (R ~ 600)

At Hα (λ=6563Å):

- Δλ = 6.5Å
- Δv = 500 km/s

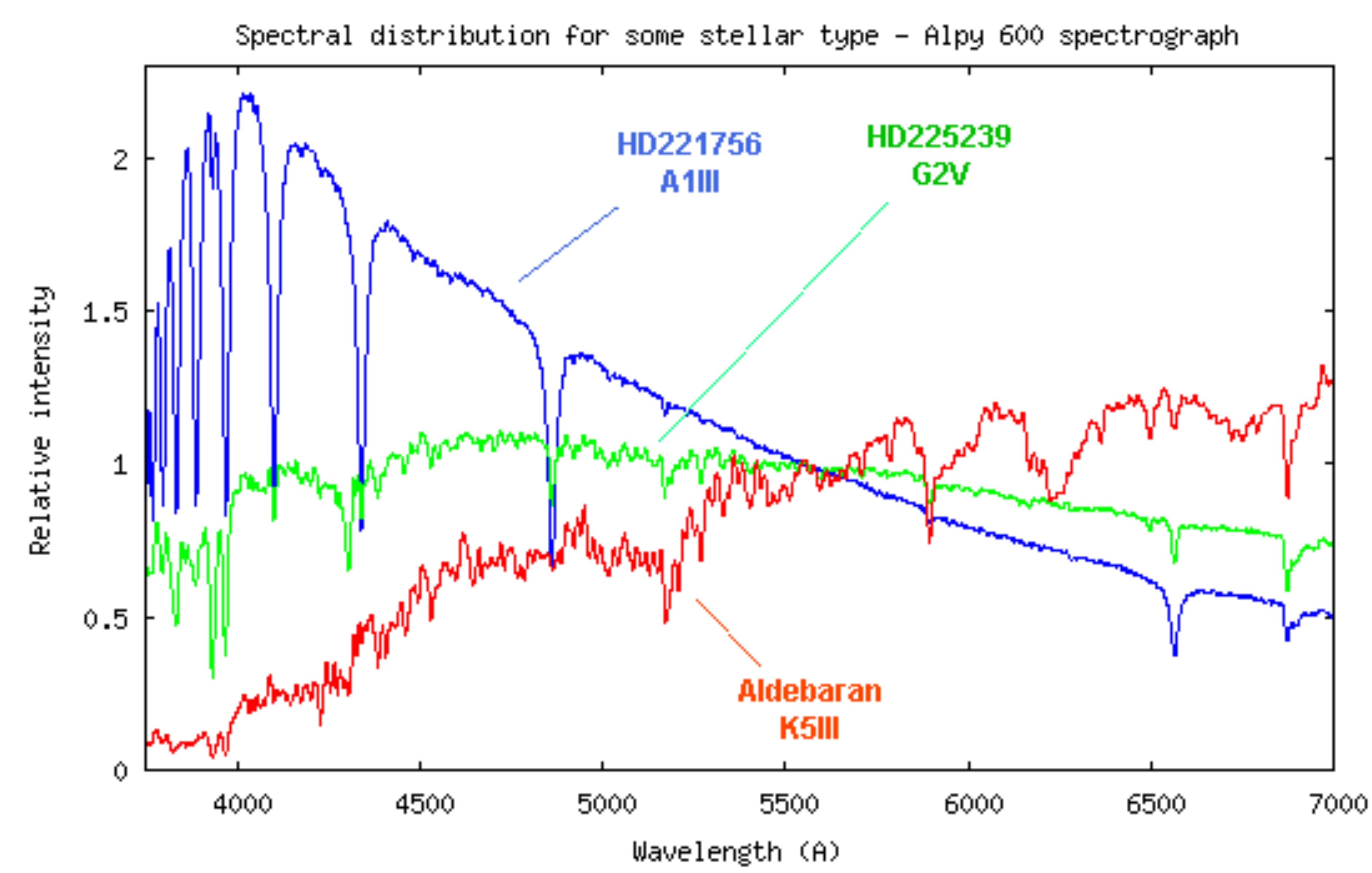
Very broad spectral range

Shows continuum shape

Identifies strong lines

Weak lines are indistinguishable

Gives very crude velocity or redshift information.



Medium Resolution (R ~ 2000)

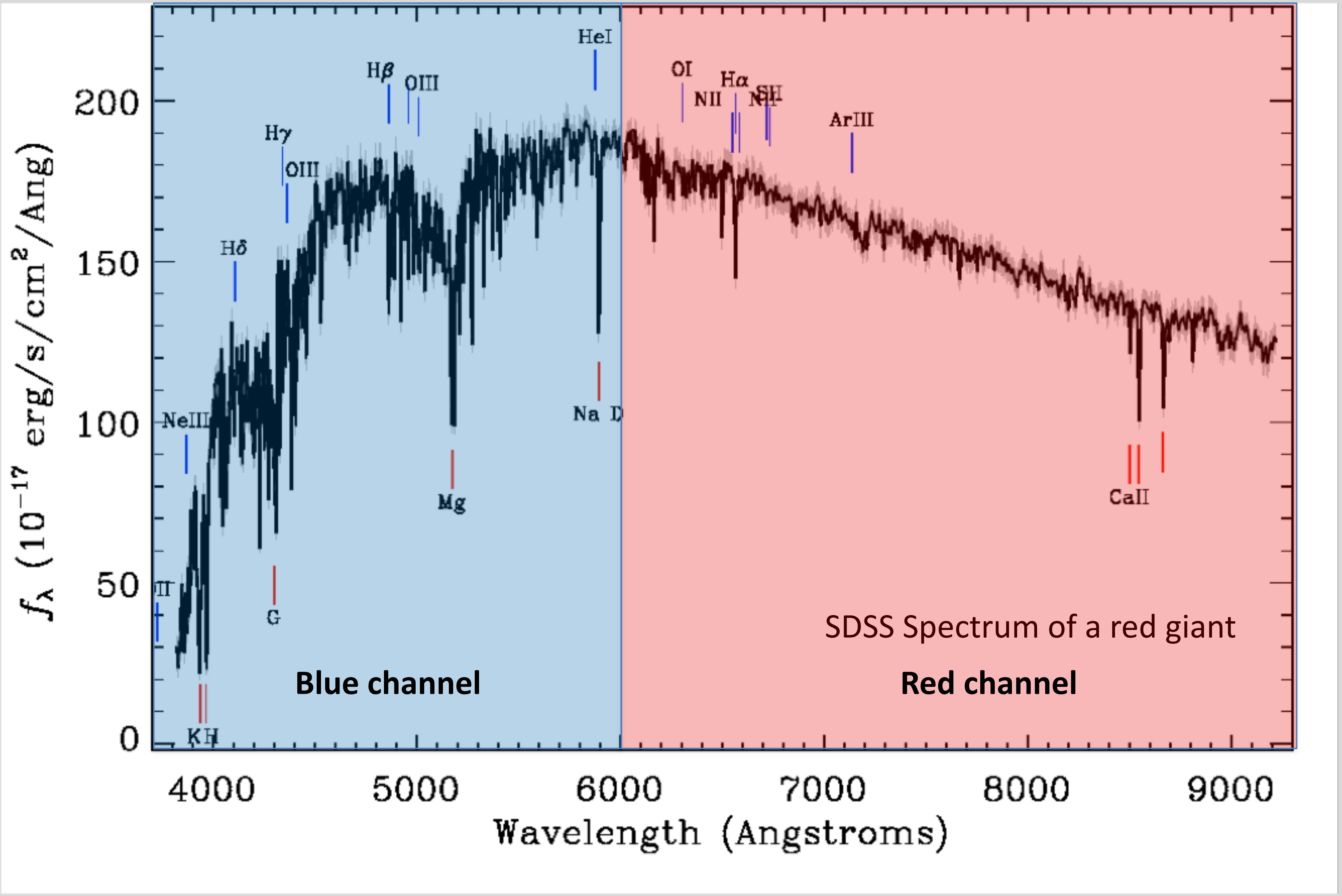
At Hα (λ=6563Å):
- Δλ = 3 Å
- Δv = 150 km/s

Narrower spectral range

Shows continuum shape

Identifies strong lines and moderately weak lines

Gives better velocity or redshift information.



High Resolution (R ~ 50,000)

At Hα (λ=6563Å):

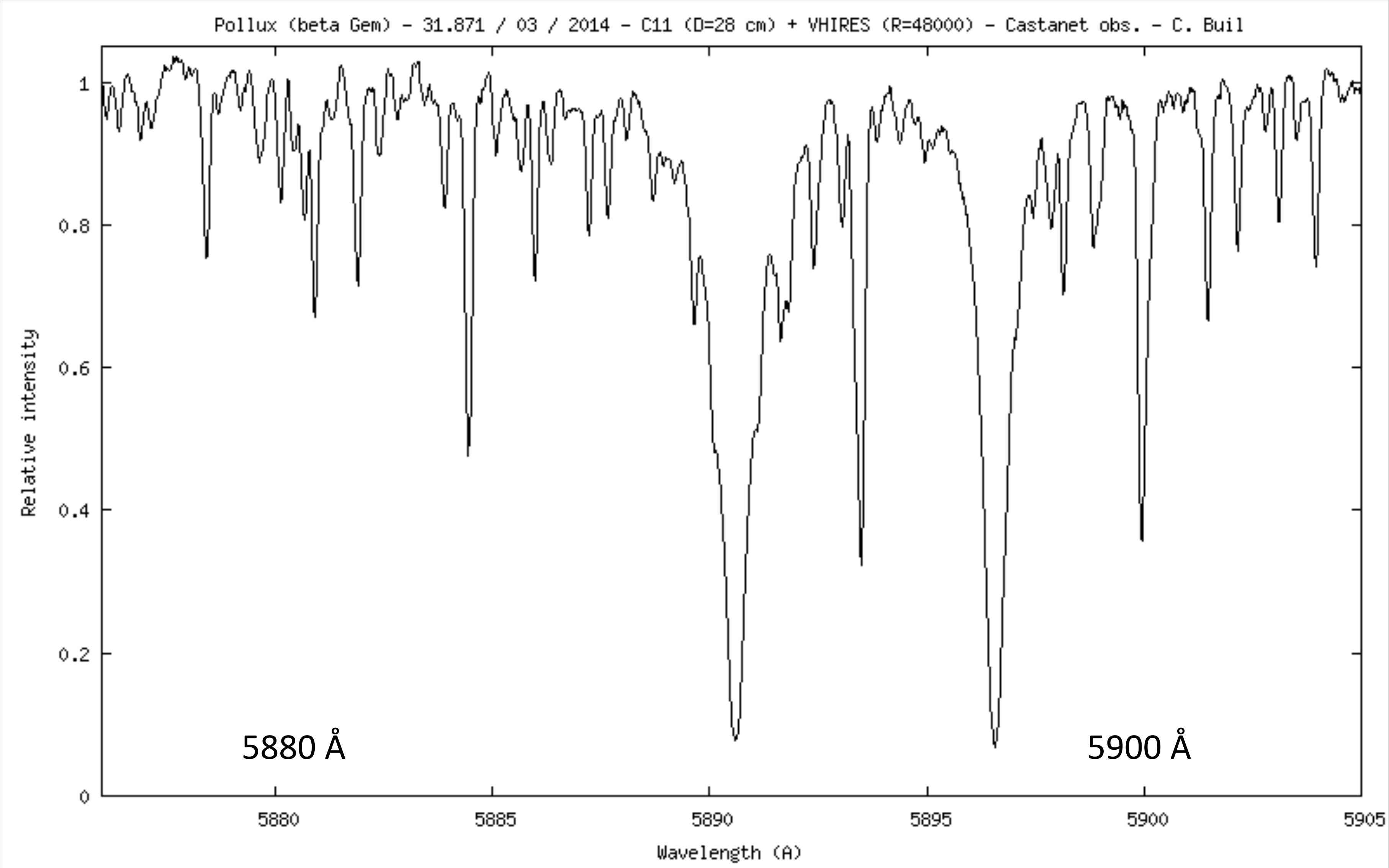
- Δλ = 0.13 Å
- Δv = 6 km/s

Very narrow wavelength range.

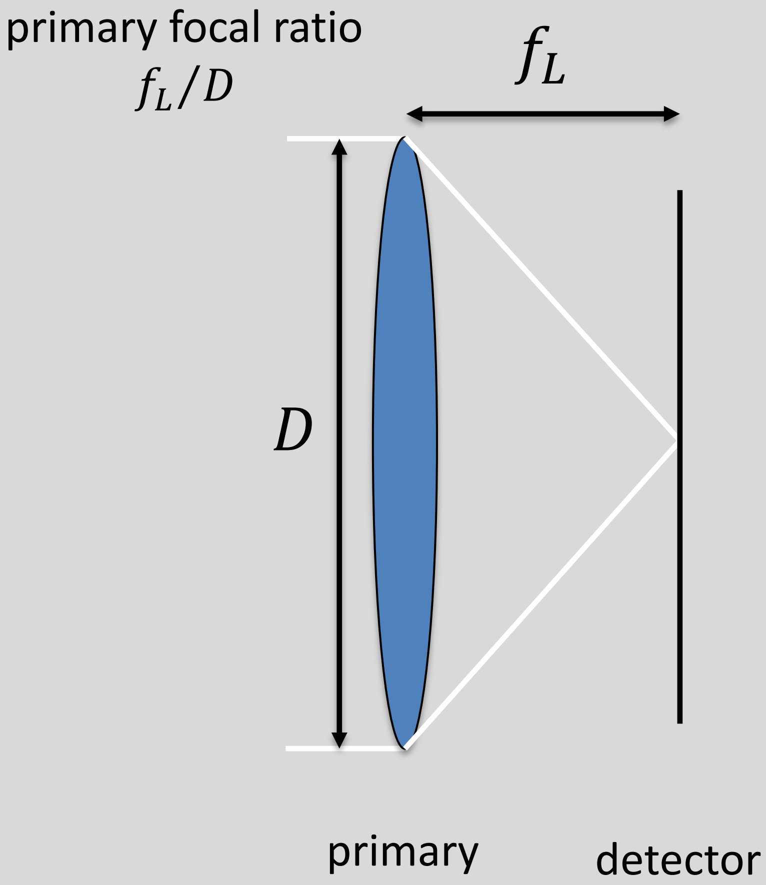
Identifies many weak lines

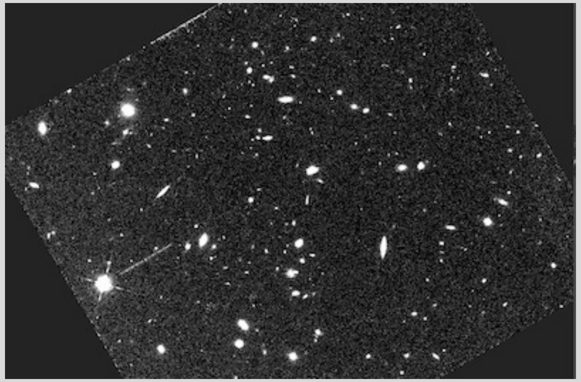
Gives exquisite velocity information.

But because the light is so dispersed in wavelength, the source needs to be very bright or the telescope very big.

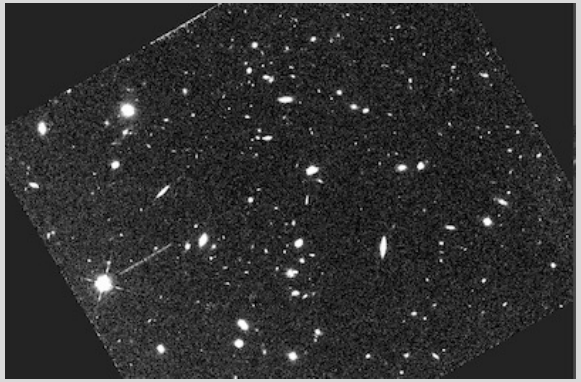


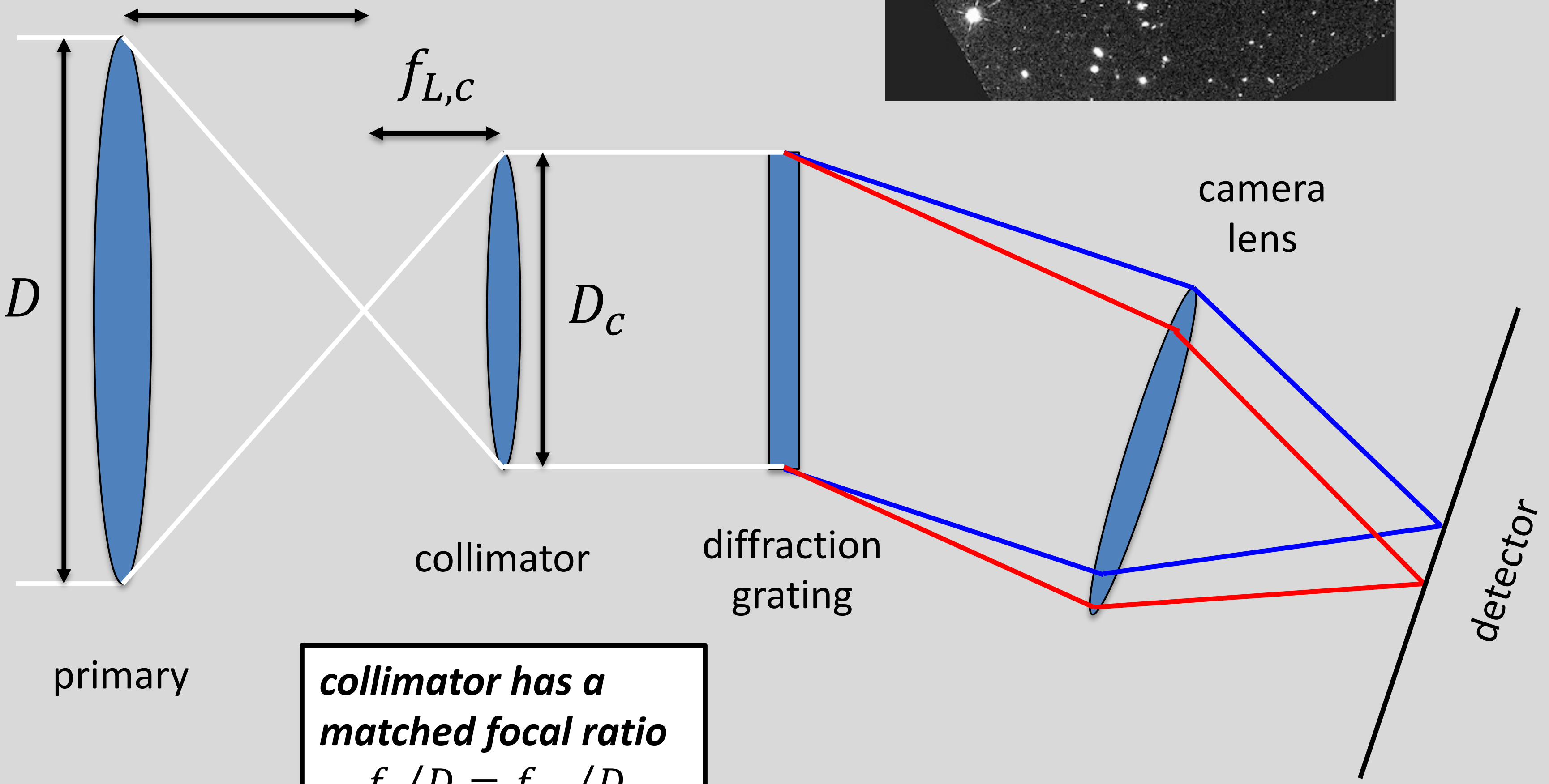
Simple Imaging System





Simple Spectrograph

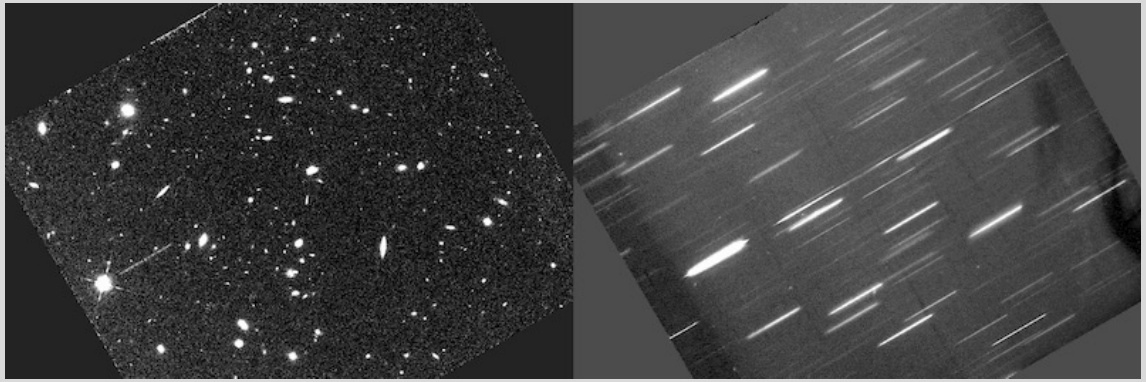


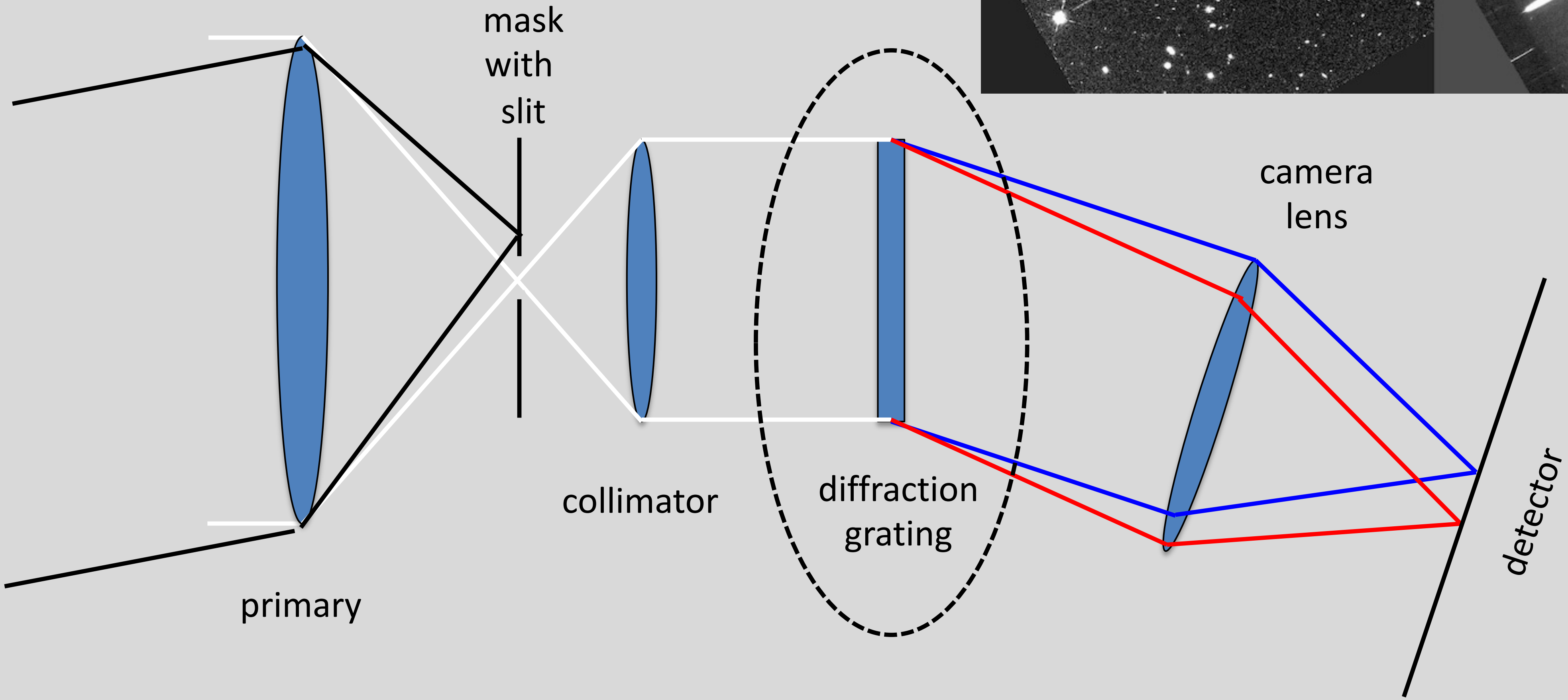


collimator has a matched focal ratio
$f_L/D = f_{L,c}/D_c$

(For ease of sketching, this shows a transmissive system: refracting telescope, transmission grating. Most telescopes and spectrographs actually use a reflecting system.)

Simple Spectrograph





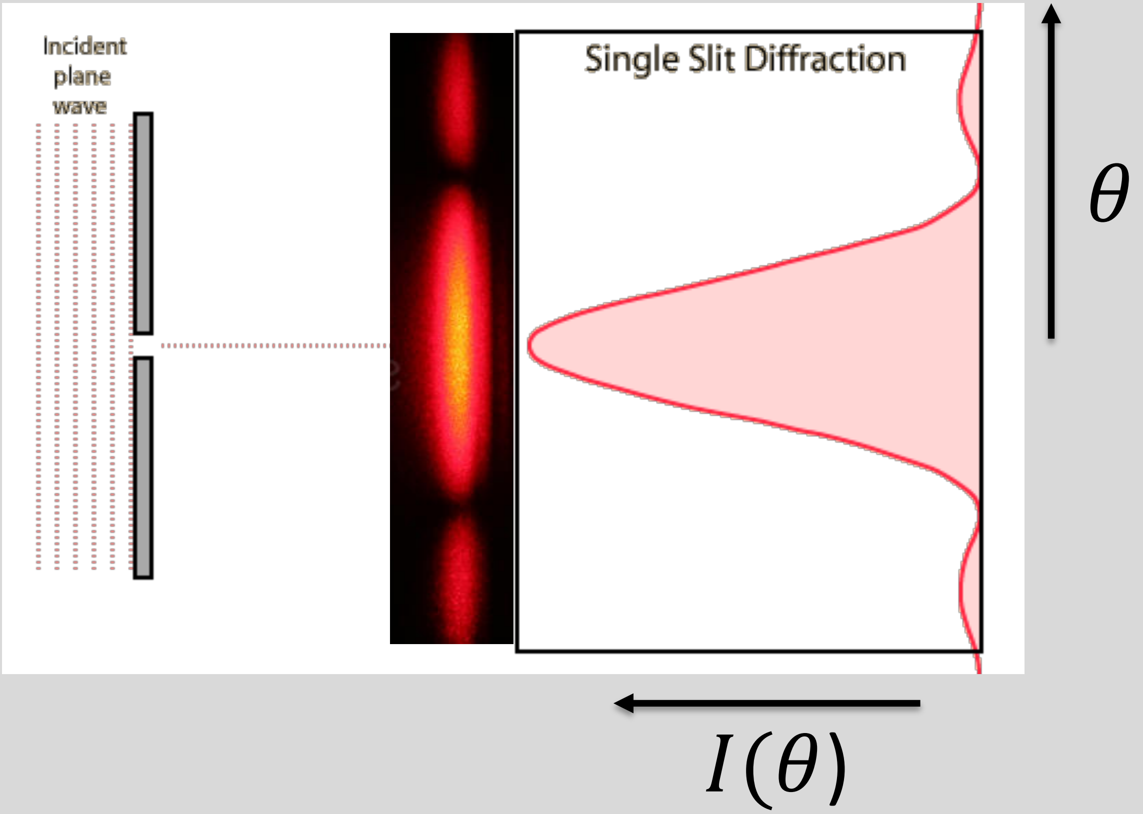
Spectrograph slit: Insert a mask in front of the spectrograph with a small slit that only lets through light from the object you want to take a spectrum of.

Single Slit Diffraction

Remember PHYS 122?

*We're **not** talking about the spectrograph slit here!*

First think about ***diffraction***. Pass a wave through a single slit aperture and you'll get a diffraction pattern:



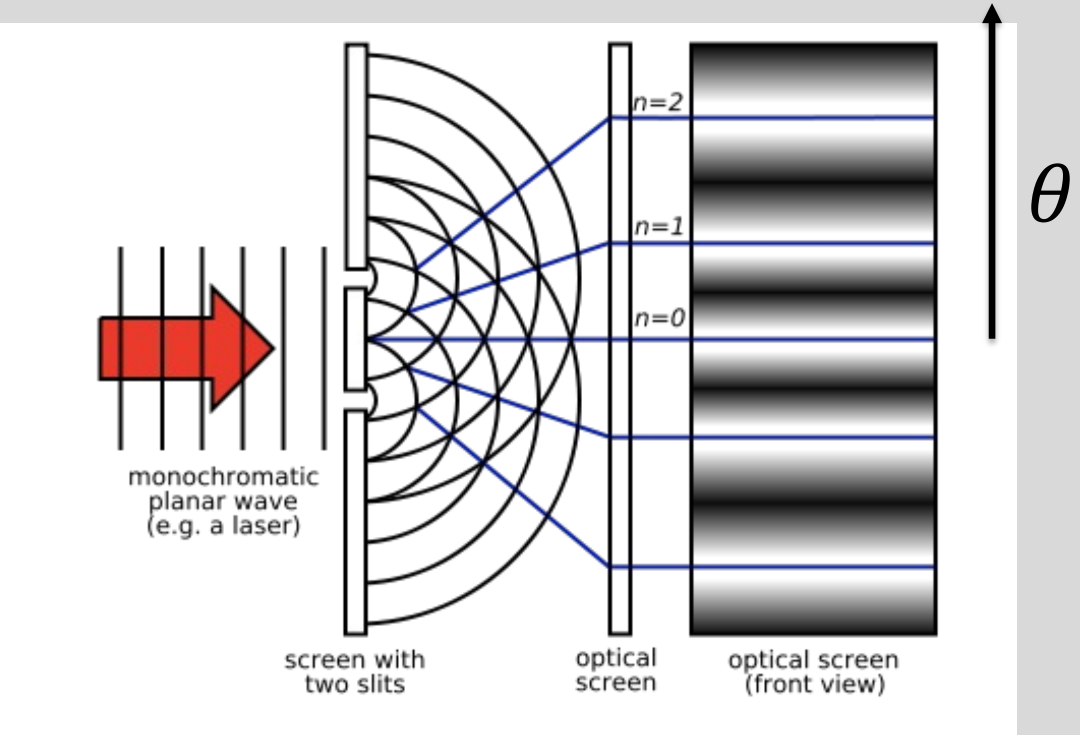
$$I(\theta) = I_0 \frac{\sin^2(\pi\alpha)}{(\pi\alpha)^2}$$

$$\alpha = \frac{a \sin\theta}{\lambda}$$

θ = projected angle from center of peak
a = slit width
λ = wavelength

Two Slit Interference

Now think about two-slit ***interference*** *(again from PHYS 122….)*:



$$I(\theta) = I_0 \cos^2(\pi\delta)$$

$$\delta = \frac{d \sin\theta}{\lambda}$$

θ = projected angle from center of peak
d = distance between slits
λ = wavelength

Condition for intensity peaks:
δ = integer (m, "order")
or
$\sin\theta = m\lambda/d$

Peaks are separated by λ/d

Combined Two-slit diffraction and interference pattern

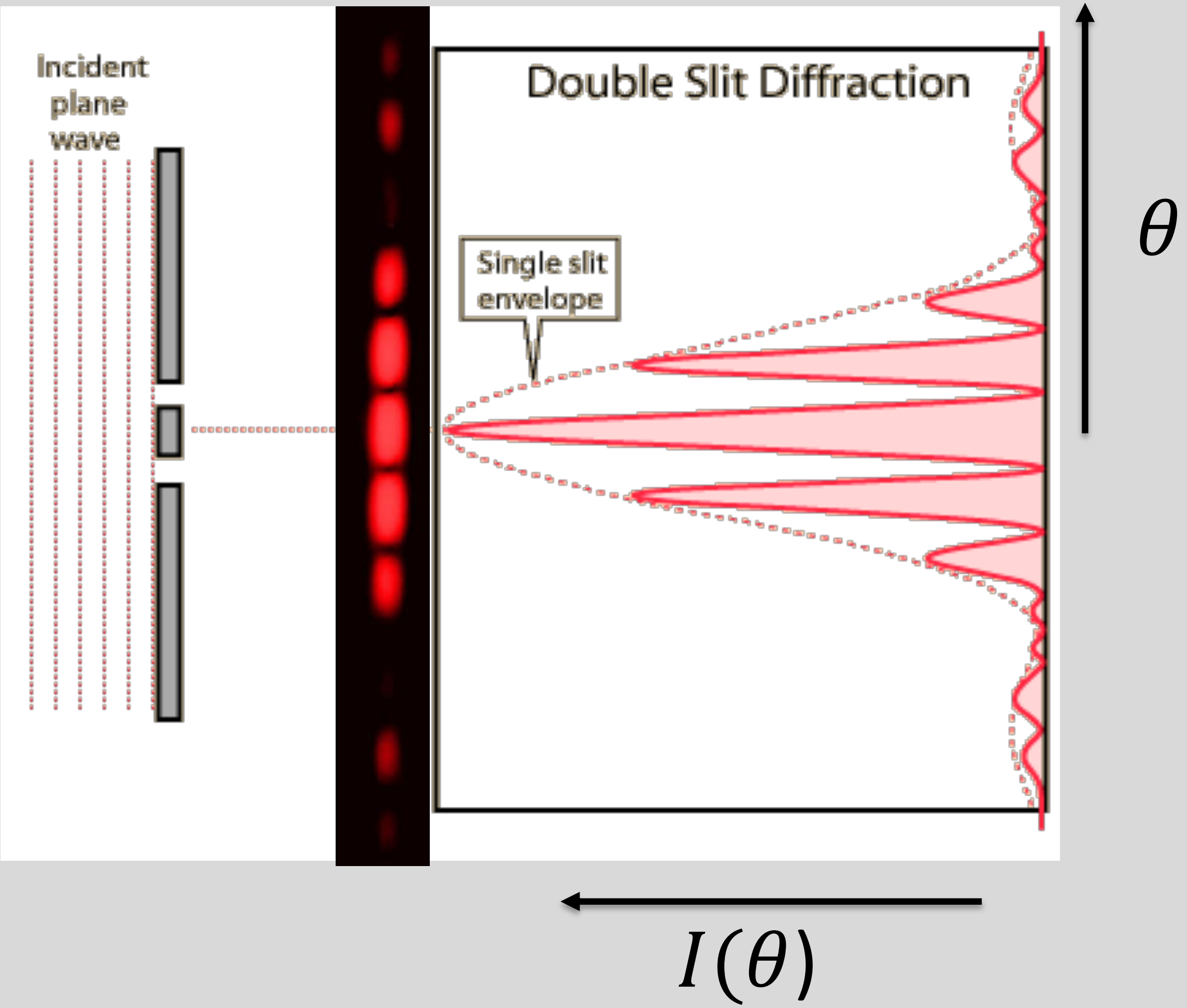
Combine diffraction and interference:

$$I(\theta) = I_0 \underbrace{\frac{\sin^2(\pi\alpha)}{(\pi\alpha)^2}}_{\text{single-slit diffraction}} \times \underbrace{\cos^2(\pi\delta)}_{\text{two-slit interference}}$$

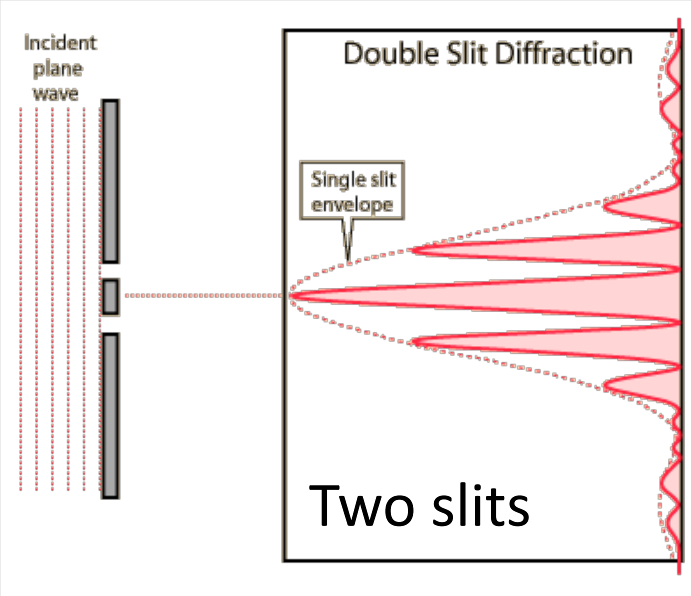
$$\alpha = \frac{a\sin\theta}{\lambda}$$

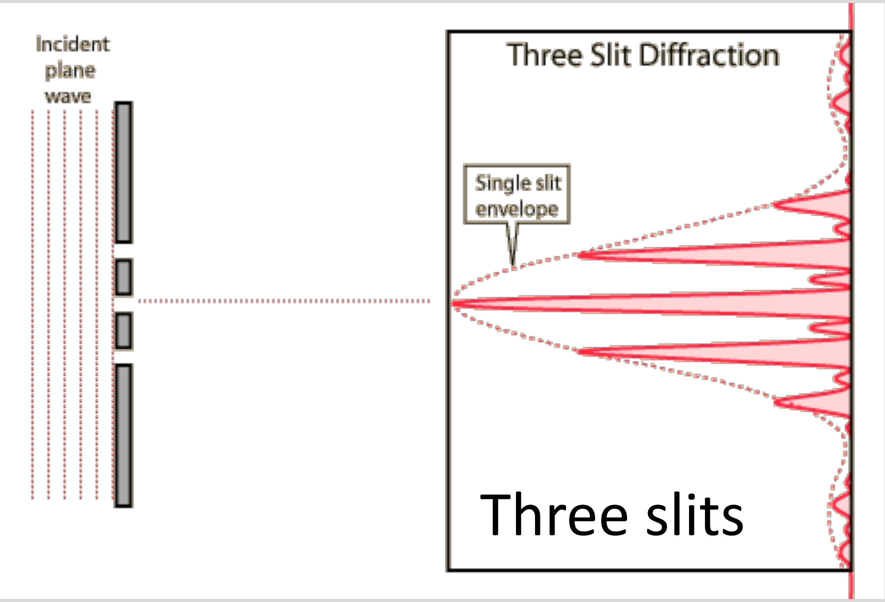
$$\delta = \frac{d\sin\theta}{\lambda}$$

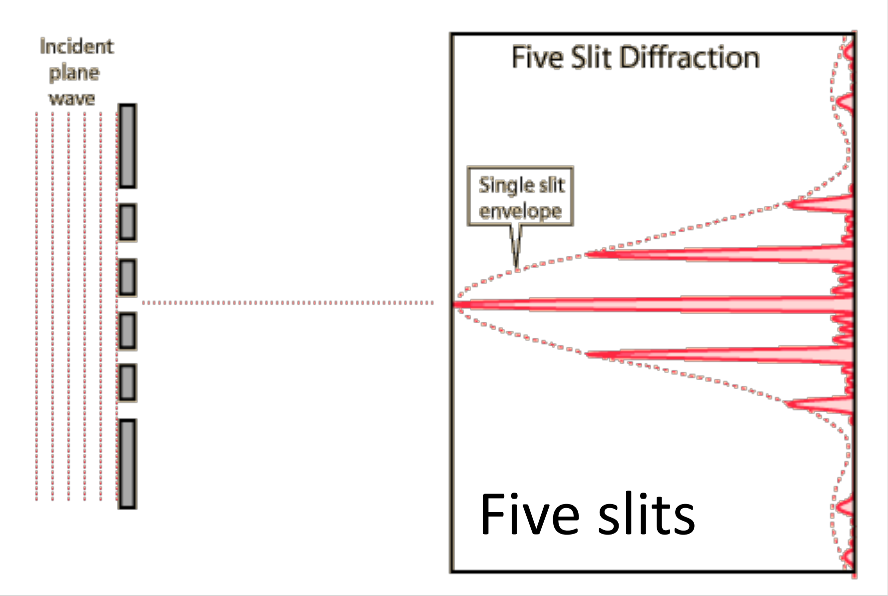
θ = projected angle from center of peak
a = slit width
d = distance between slits
λ = wavelength



Multi-slit interference: Keep adding slits with same width and spacing.







Math more complicated, but as the number of slits (N) increases, subsequent peaks get narrower.

Spacing of maxima: λ/d
Width of peaks: $\lambda/(Nd)$

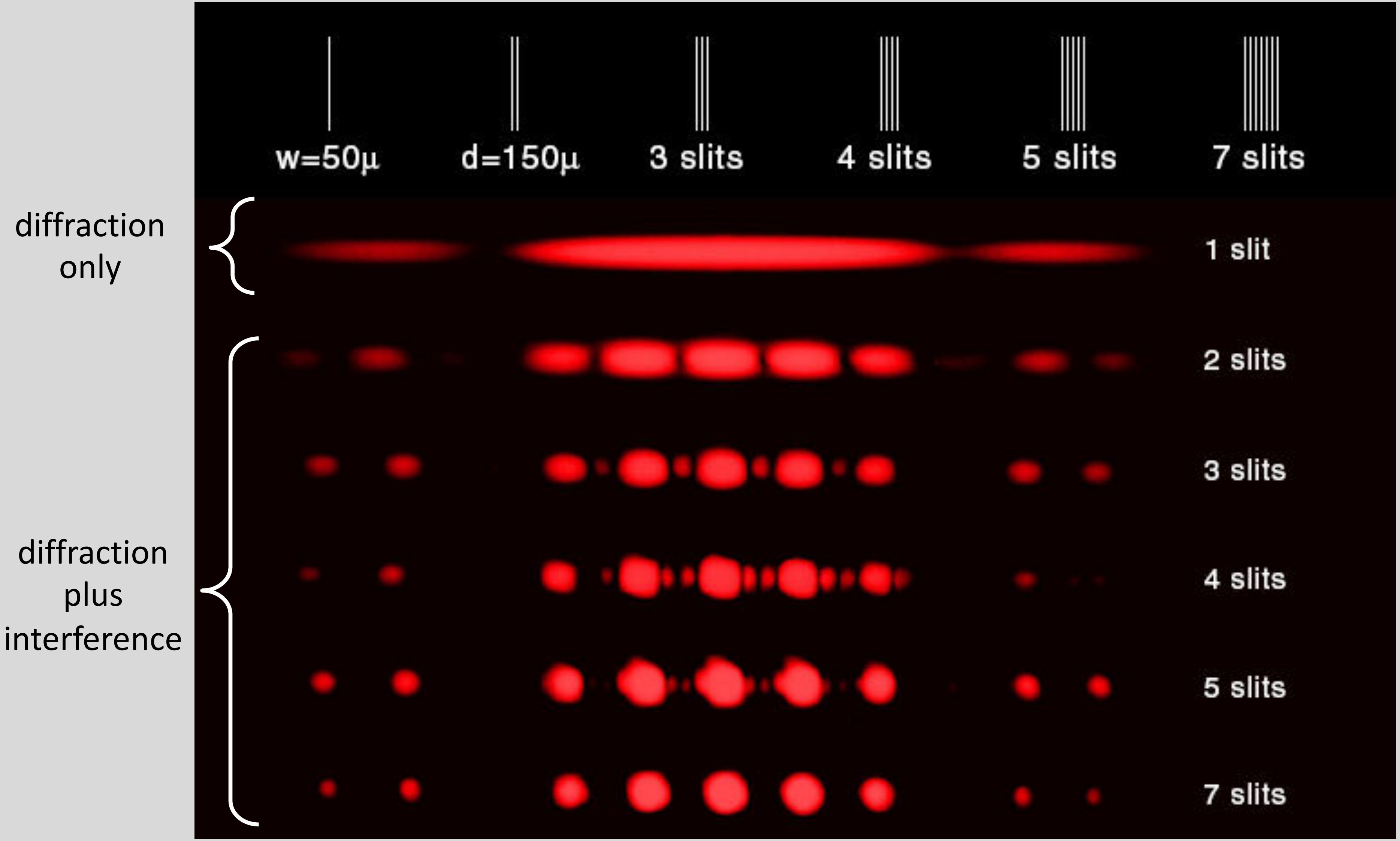
d = distance between slits
λ = wavelength

Important: Spacing/width of peaks is a function of slit separation (d), not slit width!

Slit width (a) affects the overall intensity envelope

Multi-slit interference

Keep adding slits:

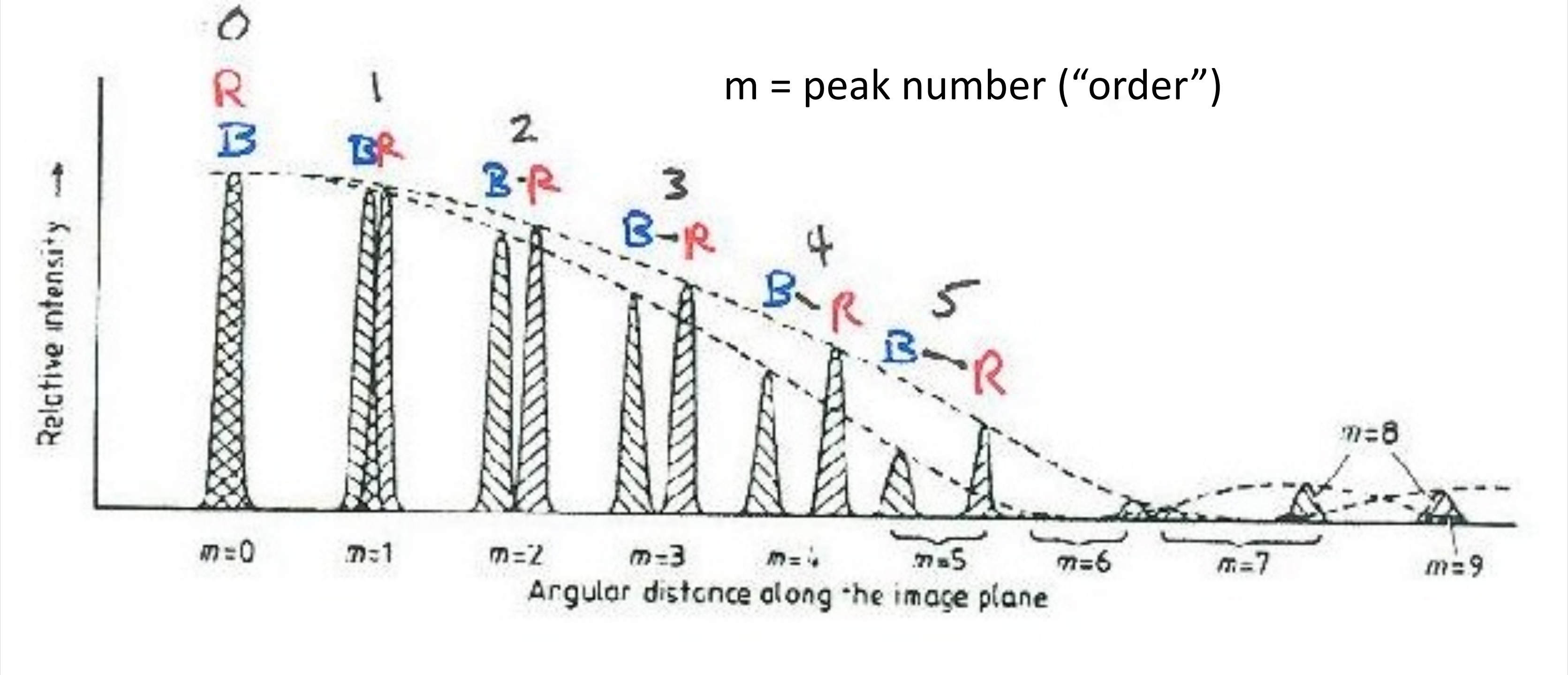


Dispersion in wavelength

So far, we have considered monochromatic light (single fixed λ). Now consider a mythical light source that produces light at two wavelengths only, a blue line and a red line.

Since spacing of peaks is λ/d, blue and red peaks will happen at different places because of the λ-dependence of the interference term.

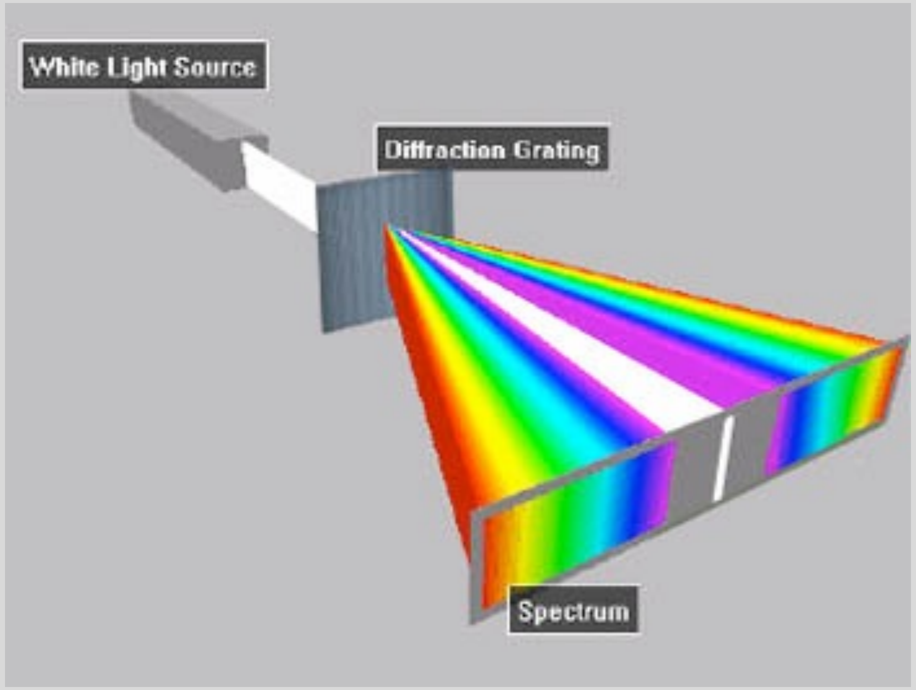
This is referred to as *dispersion*.



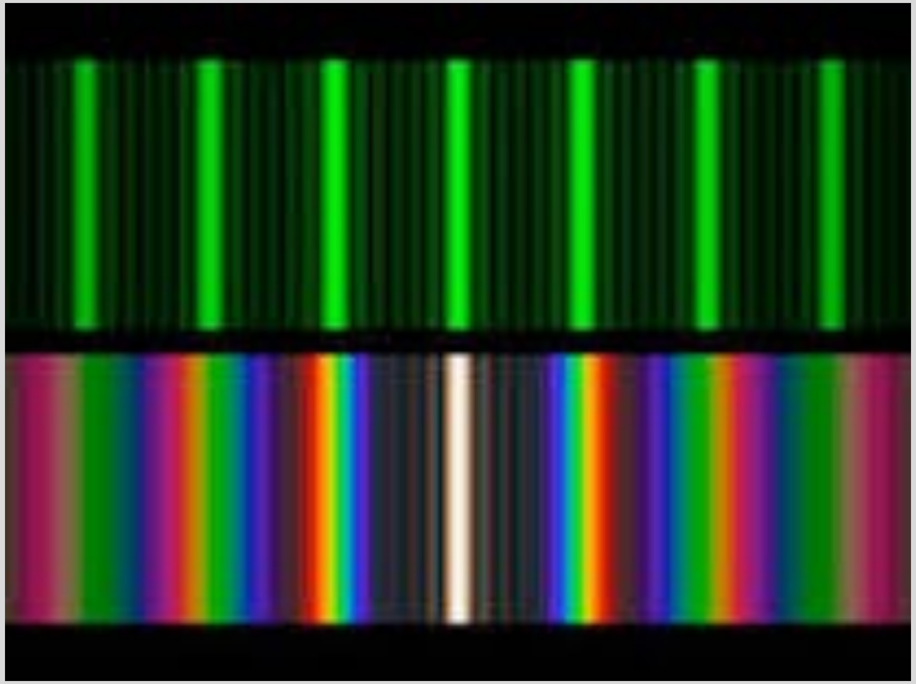
Spectroscopic Instrumentation: Transmission gratings

Now put a continuum (white light) source through a diffraction grating: a transparent medium (film/glass) with fine grooves etched in it.

transmission grating



showing $m = -1, 0, +1$



monochromatic

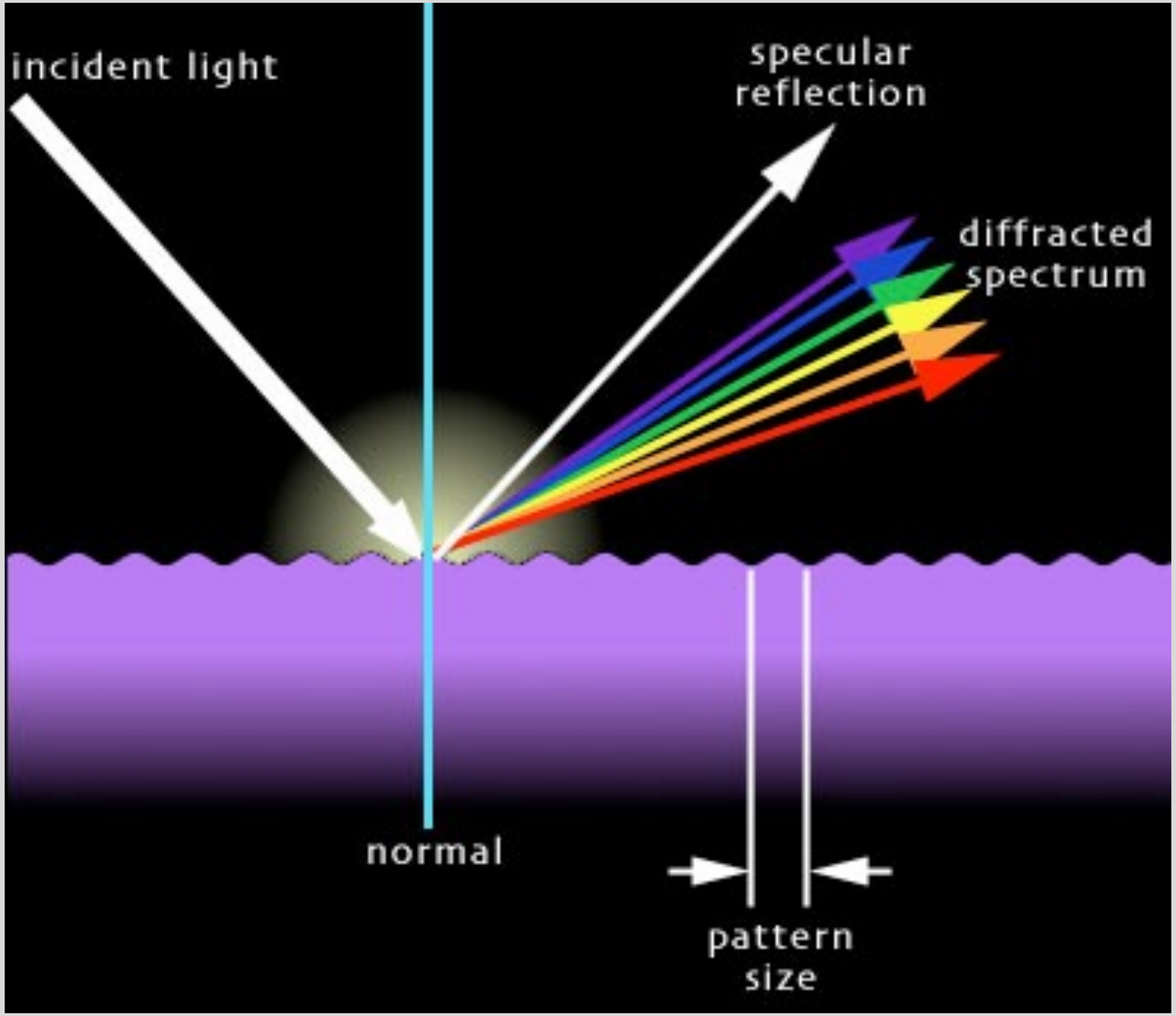
continuum

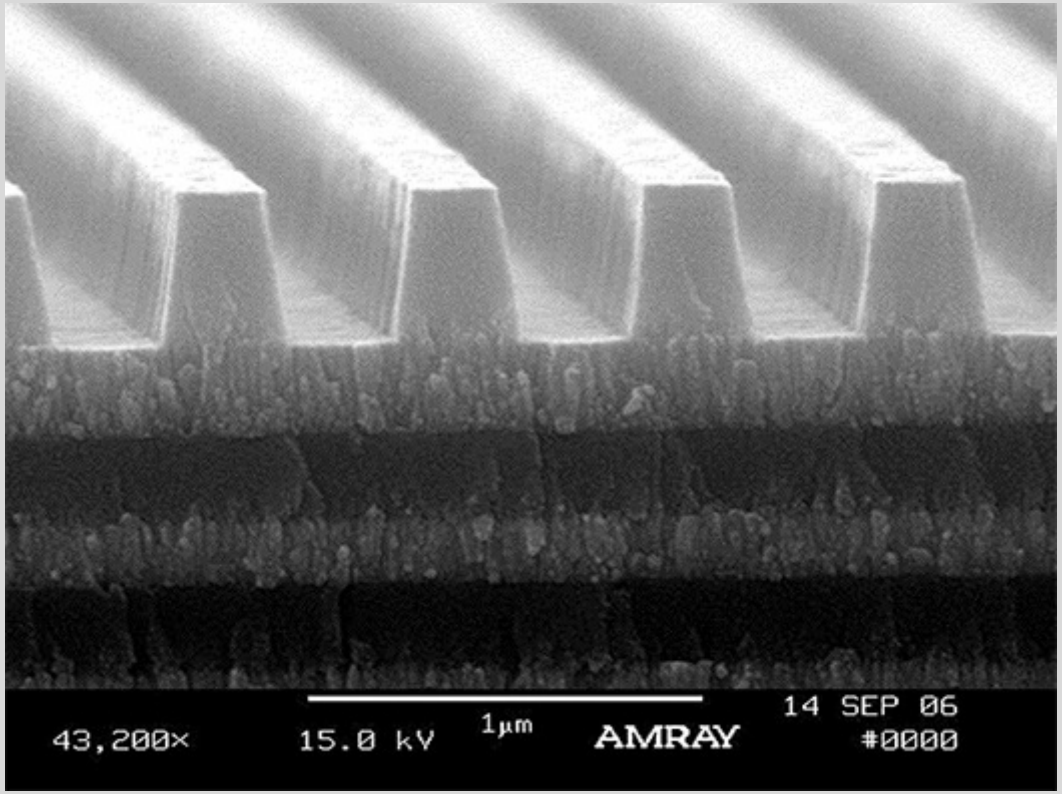
showing $m = -3, -2 - 1, 0, +1, +2, +3$

(Notice increasing dispersion in higher orders!)

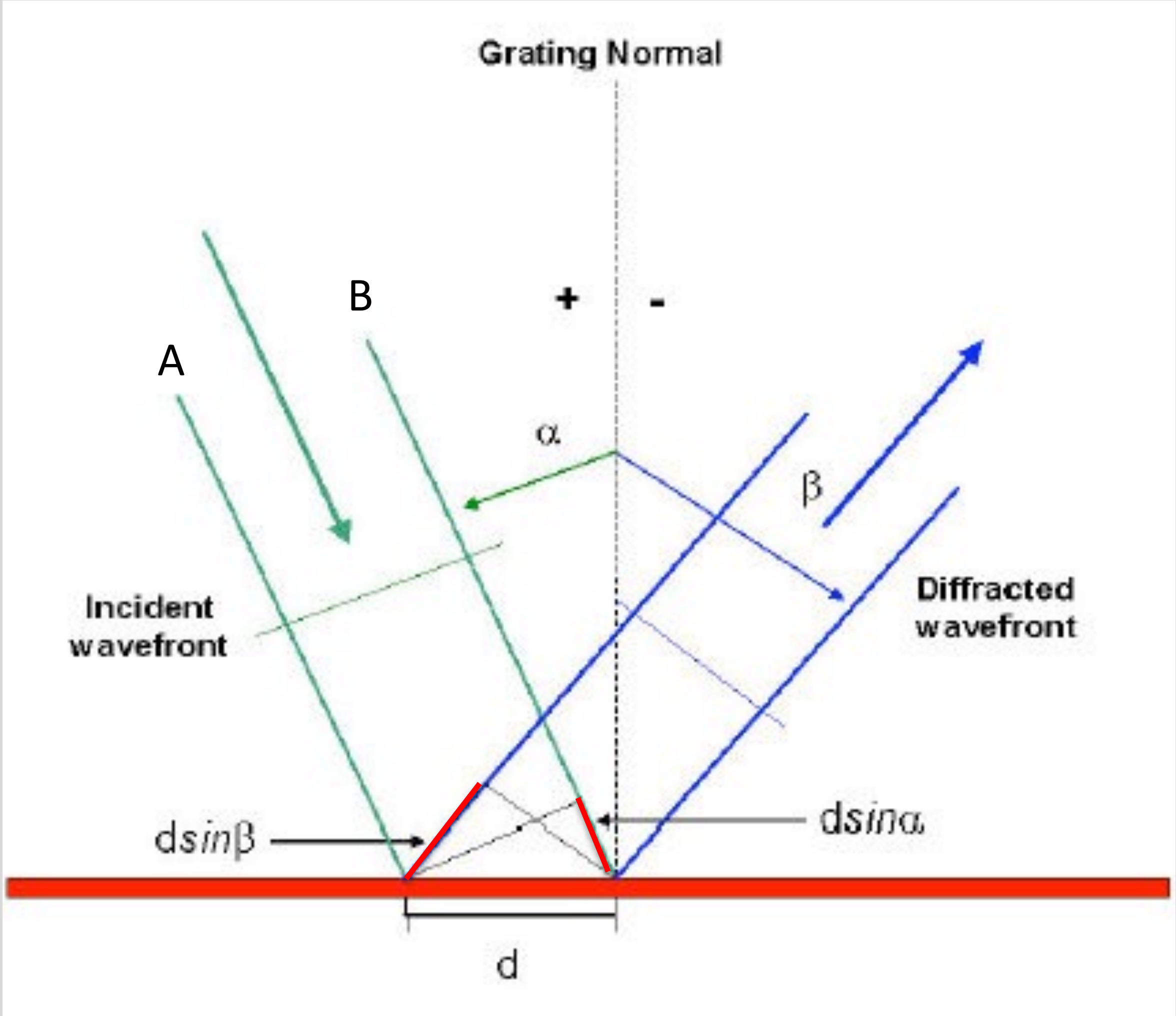
Spectroscopic Instrumentation: Reflection gratings

Alternatively, look at light diffracting off a reflective grooved surface:





Path length differences



α = angle of incidence
β = angle of diffraction
d = groove separation

Consider two rays forming the incoming wavefront, coming in at an angle α and being diffracted out at an angle β.

Ray B has to go an extra distance $d\sin\alpha$ before hitting the grating, and Ray A has to go an extra $d\sin\beta$ after hitting the grating.

Total path length difference is $d\sin\alpha - d\sin\beta$.

But since β is defined to be negative, and sine identities say $\sin(-\beta) = -\sin(\beta)$, we can write this as $d\sin\alpha + d\sin\beta$.

We get **constructive interference** when this path length is an integer multiple of the wavelength:

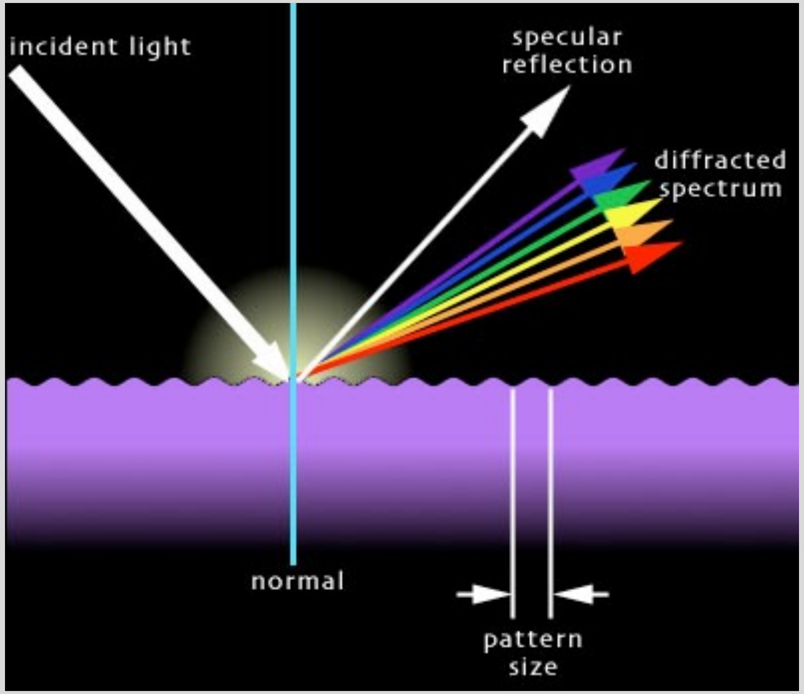
$$\boxed{m\lambda = d\sin\alpha + d\sin\beta}$$

The Grating Equation

$$\boxed{m\lambda = d\sin\alpha + d\sin\beta}$$

for either reflection or transmission gratings!

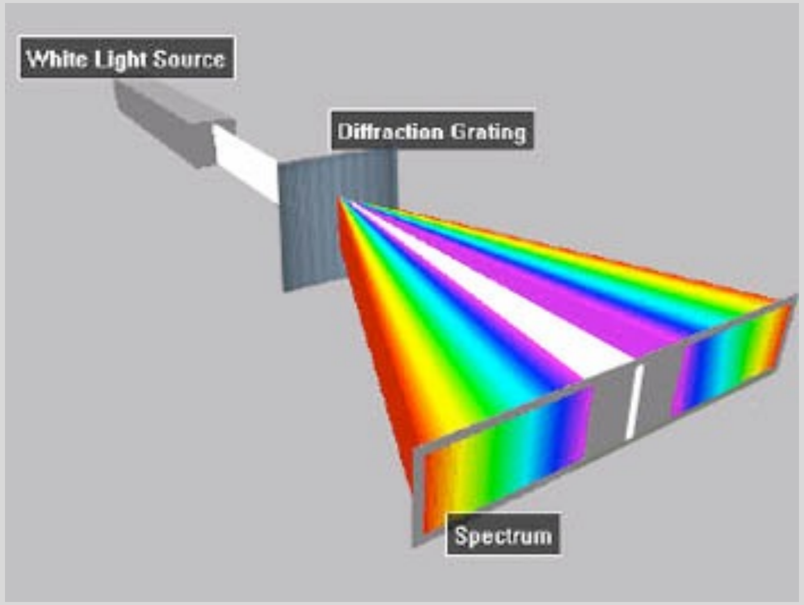
α = angle of incidence
β = angle of diffraction
d = groove separation
m = order
λ = wavelength



Simplifying checks:

"zeroth order": $m = 0, \;\; \text{so } \sin(\alpha) = -\sin(\beta)$
no dispersion, just specular reflection or direct transmission

"normal incidence": $\alpha = 0, \;\; \text{so } m\lambda = d\sin(\beta)$
dispersion pattern symmetric around m=0



Diffraction grating laser lab

(original from B. Weiner…)

$$m\lambda = d \sin\alpha + d \sin\beta$$

alpha, beta in radians

```
beta=np.arcsin(m*wave/d - np.sin(alpha))
```

alpha, beta in degrees

```
beta=np.degrees(np.arcsin(m*wave/d -
                np.sin(np.radians(alpha))))
```

"Normal" incidence: $\alpha = 0$

$$\beta = \sin^{-1}(m\lambda/d)$$

	Green Laser λ = 5320 Å	Red Laser λ = 6350 Å
Grating: 500 lines/mm, d= 1/500 mm = 20,000 Å		
m = 0	$\beta = 0°$	$\beta = 0°$
m = 1	$\beta = 15.4°$	$\beta = 18.5°$
m = 2	$\beta = 32.1°$	$\beta = 39.4°$
m = 3	$\beta = 52.9°$	$\beta = 72.3°$

Off-axis incidence: $\alpha = 15°$

$$\beta = \sin^{-1}(m\lambda/d - \sin\alpha)$$

	Green Laser λ = 5320 Å	Red Laser λ = 6350 Å
Grating: 500 lines/mm, d= 1/500 mm = 20,000 Å		
m = 0	$\beta = -15°$	$\beta = -15°$
m = +1 m = -1	$\beta = 0.4°$ $\beta = -31.7°$	$\beta = 3.4°$ $\beta = -35.2°$
m = +2 m = -2	$\beta = 15.9°$ $\beta = -52.3°$	$\beta = 22.1°$ $\beta = -63.4°$

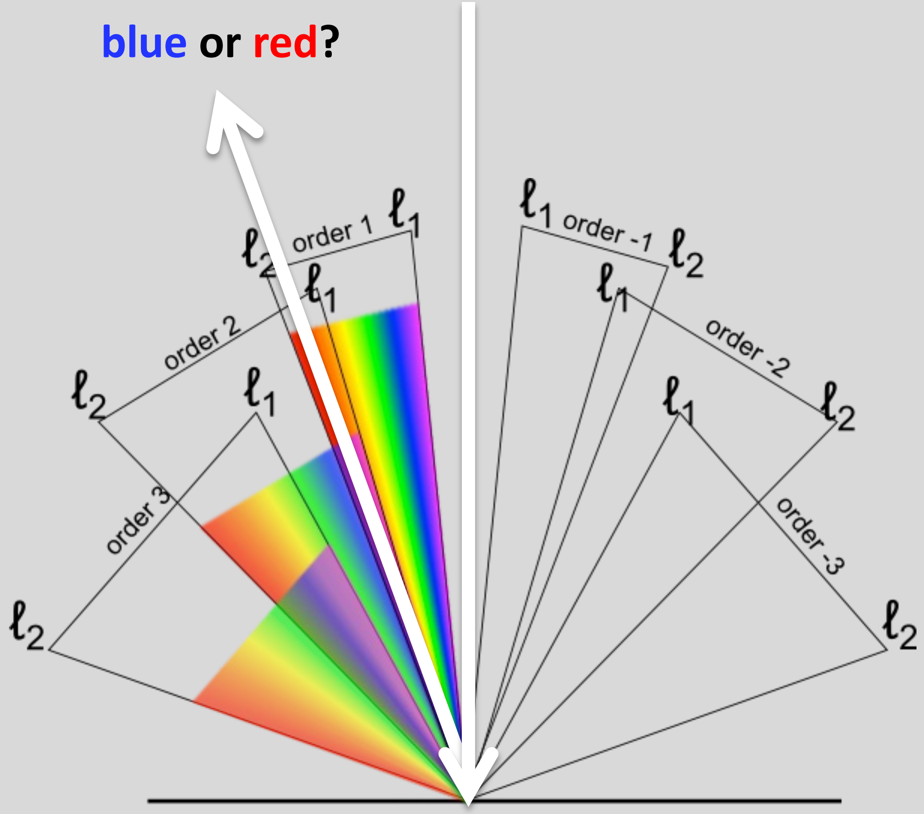
Free Spectral Range

Look at diffracted light in different orders.

For simplicity, let's sketch normal incidence (α=0).

At any given β (outgoing angle), there can be light overlapping from various orders.

For example, in this sketch at $\beta = 20°$ we have both $\lambda_{m=1} = 8000$ Å and $\lambda_{m=2} = 4000$ Å.



Free spectral range: region of spectrum free from overlapping orders

How do we get rid of this problem of overlapping orders?

- Put a ***filter*** in front of the spectrograph to only let certain wavelengths through.
- Put in a ***cross-disperser***

Cross-dispersed Echelle Spectrograph

cross dispersal to separate overlapping orders:

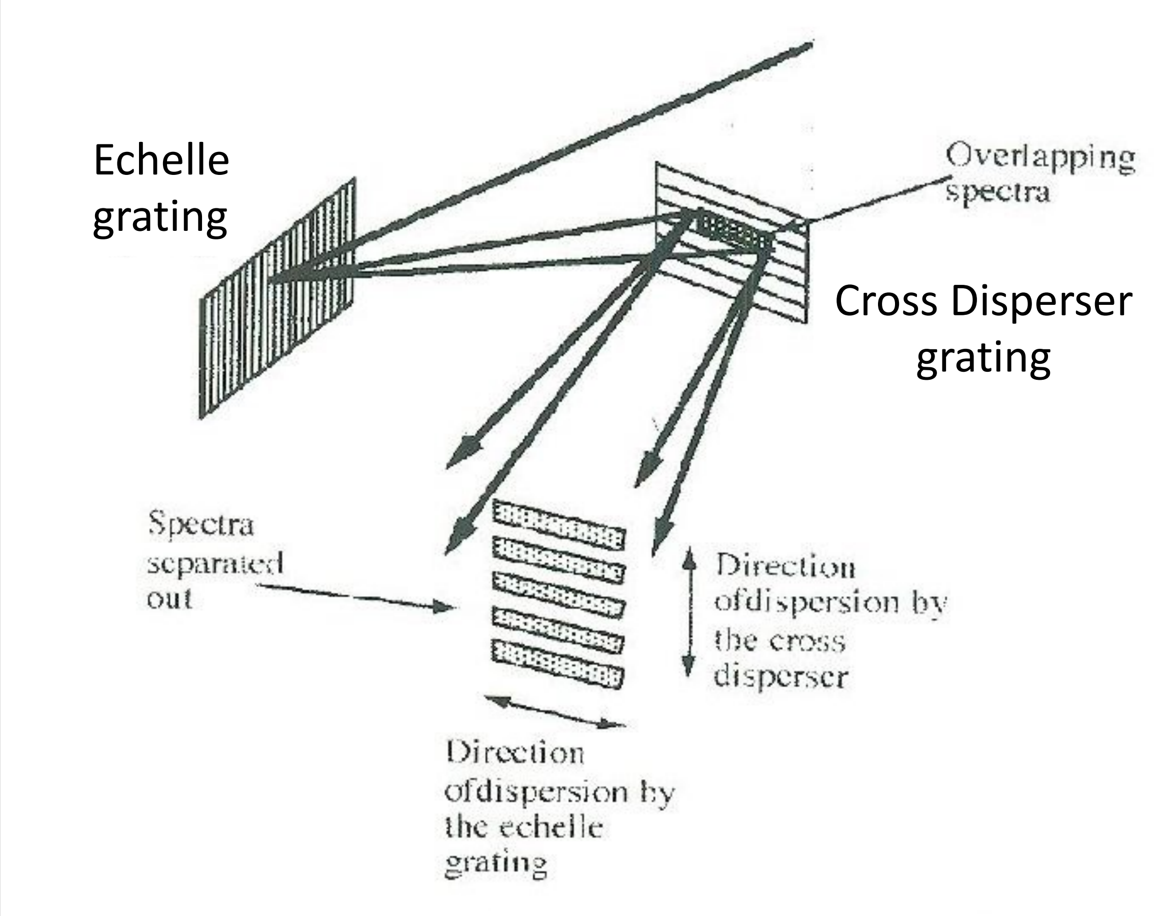
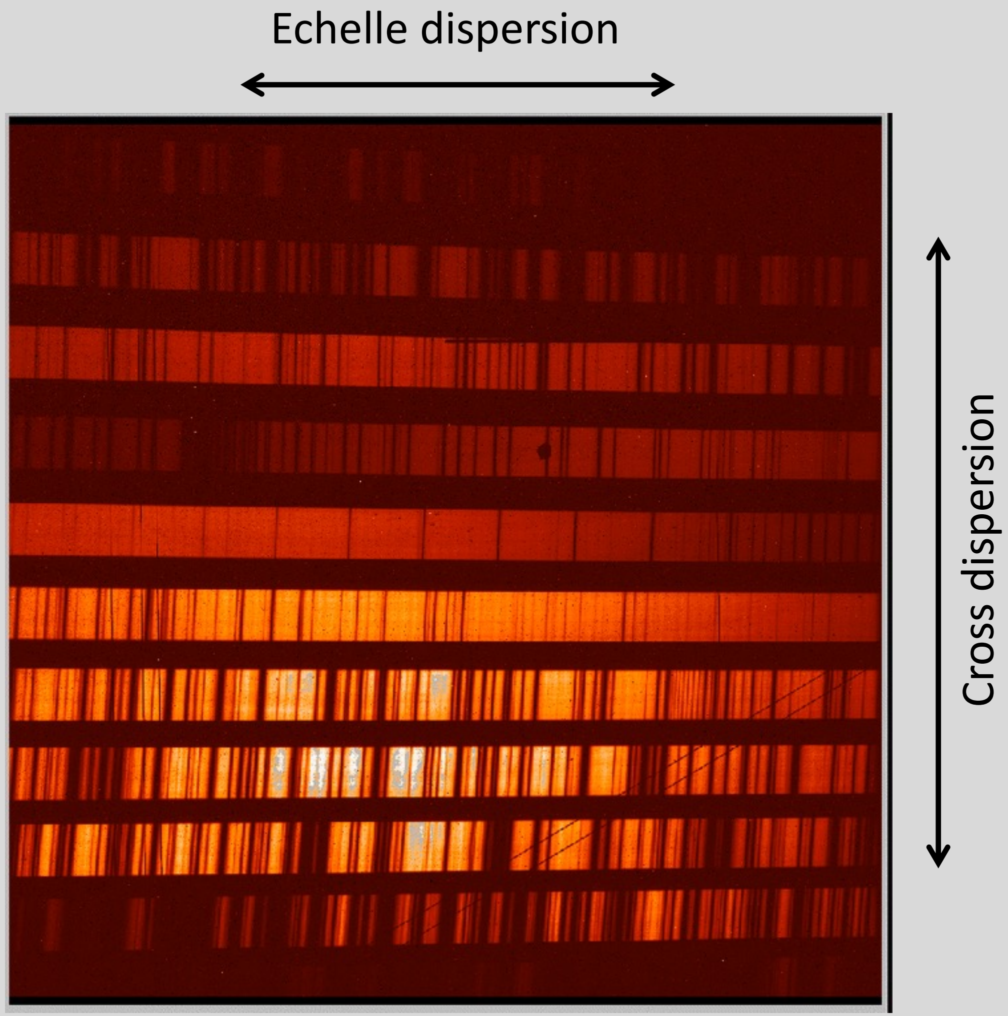


Figure 8.9 Schematic view of an echelle grating and a cross disperser.



Blazing

A grating spreads light out into many orders, and much of which is wasted by not projecting onto the detector.

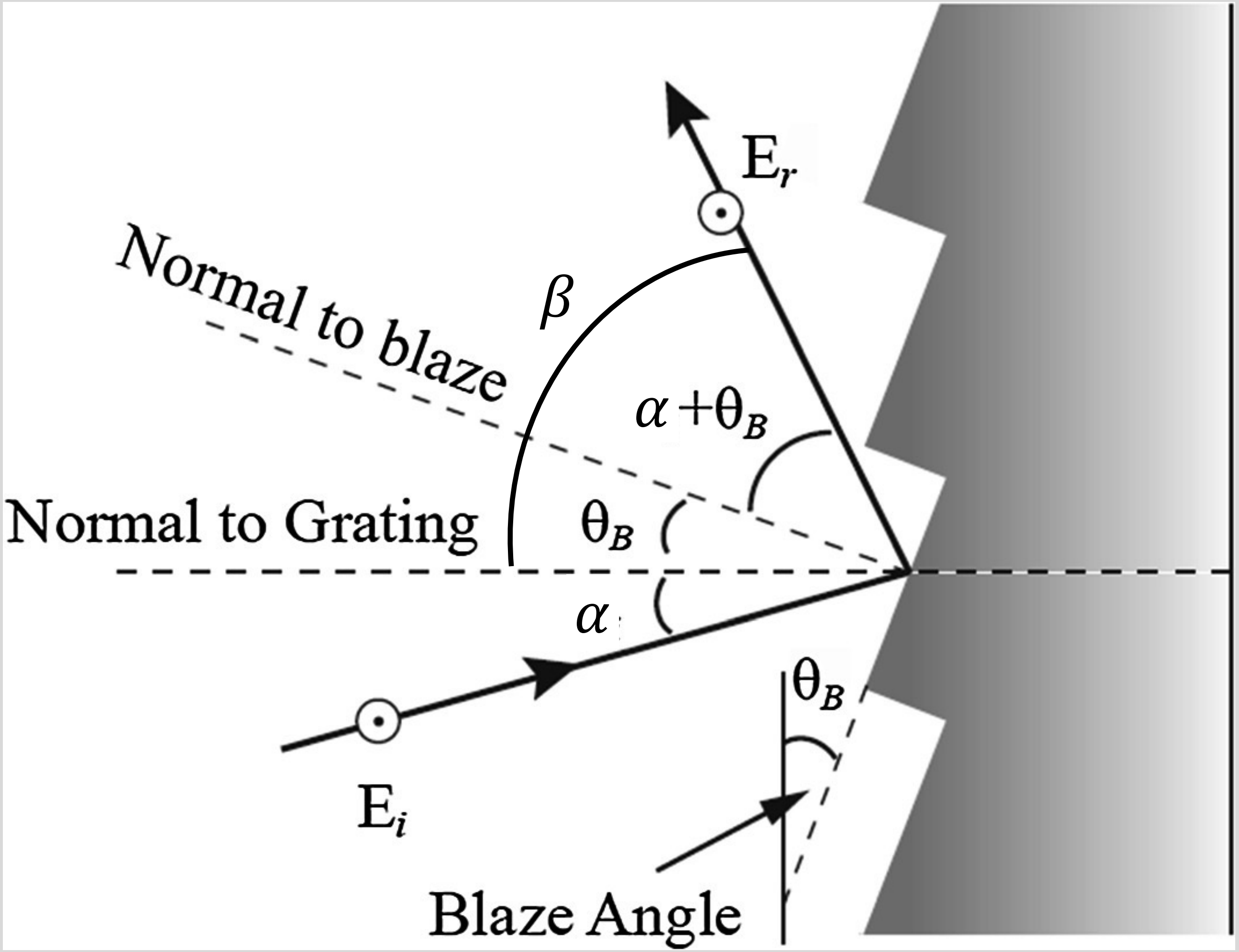
Blazing concentrates ~ 70% light into a particular outgoing angle – a combination of $m\lambda$. Tilt the grooves by an angle θ_B so that the face of the groove points in the direction of the diffraction ray you want to maximize in intensity:

Diffracted light coming out at an angle $\beta = \alpha + 2\theta_B$ will be maximized in brightness. So the "blaze peak" happens when $\alpha + \beta = 2\theta_B$.

(remember that α and β are defined with opposite signs, so in doing the math above, $\alpha - \beta$ becomes $\alpha + \beta$)

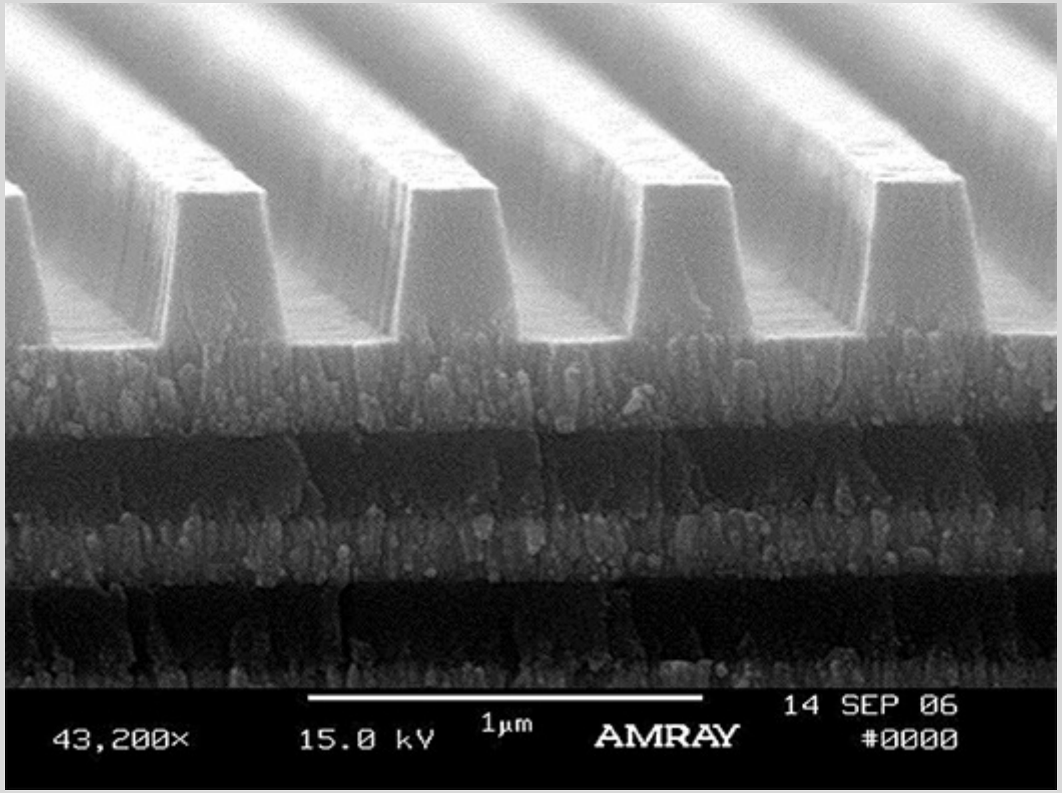
The wavelength that corresponds to that peak brightness is referred to as the blaze wavelength (λ_b) and can be solved using the grating equation to get:

$$m\lambda_b = 2d\cos(\alpha - \theta_B)$$

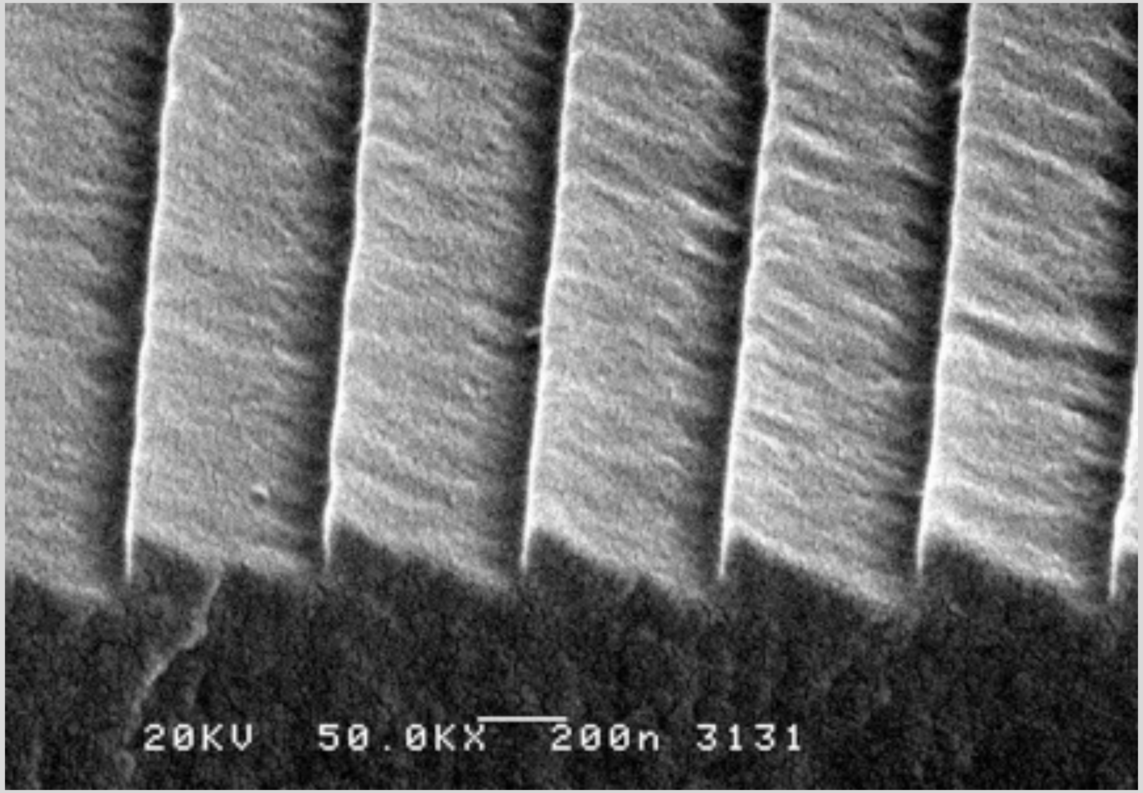


Grating Surfaces

regular (unblazed) grating

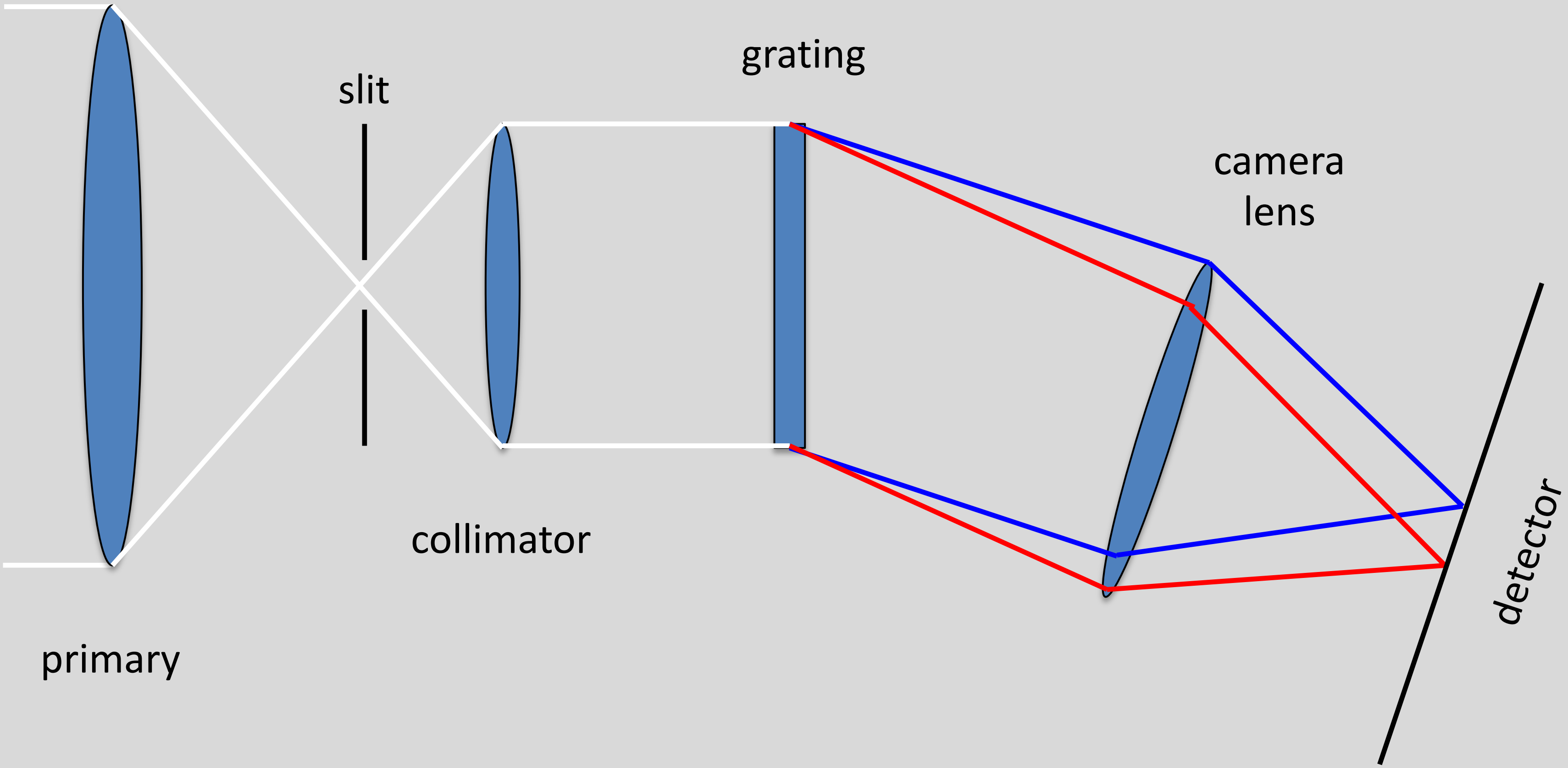


blazed grating



$$m\lambda = d\sin\alpha + d\sin\beta$$

Simple Grating Spectrograph

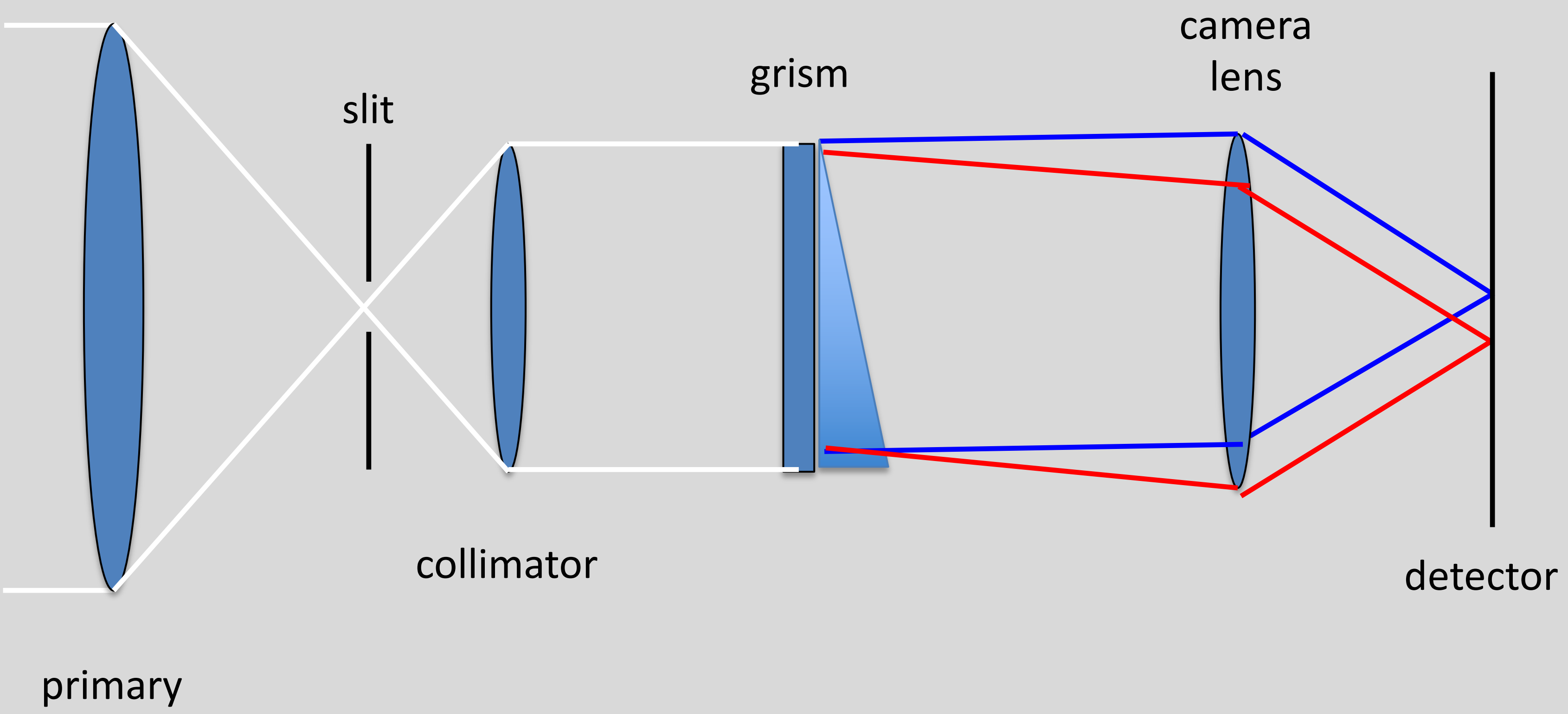


Notes:

1) For ease of sketching, this shows a transmissive system (refracting telescope, transmission grating). Most telescopes use a reflecting system.

2) the focal ratio of primary and collimator must be matched!

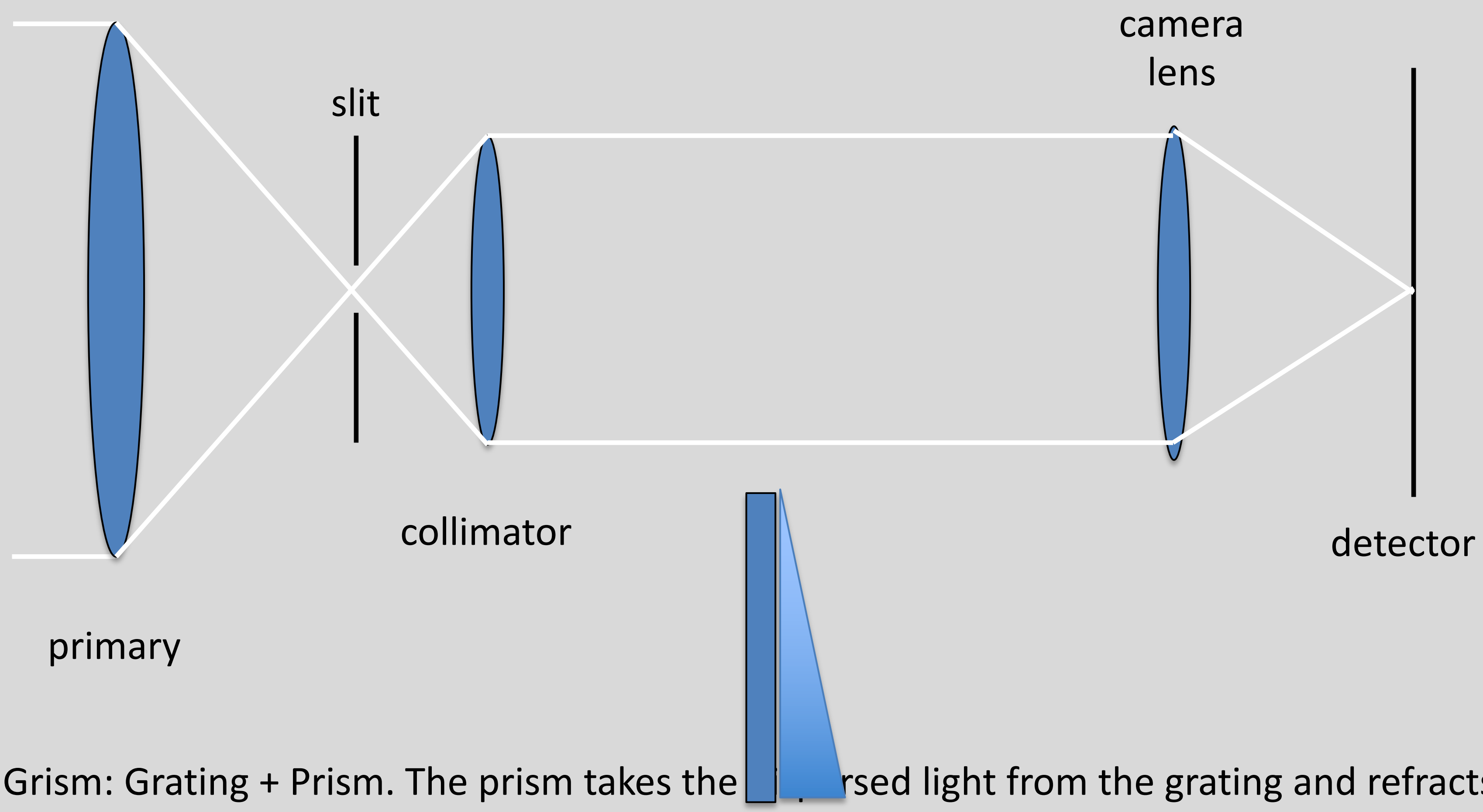
Simple Grism Spectrograph



Grism: Grating + Prism. The prism takes the dispersed light from the grating and refracts it back to a straight-line path.

You can then slide the grism in and out to switch seamlessly between spectroscopy and imaging.

Simple Grism Spectrograph

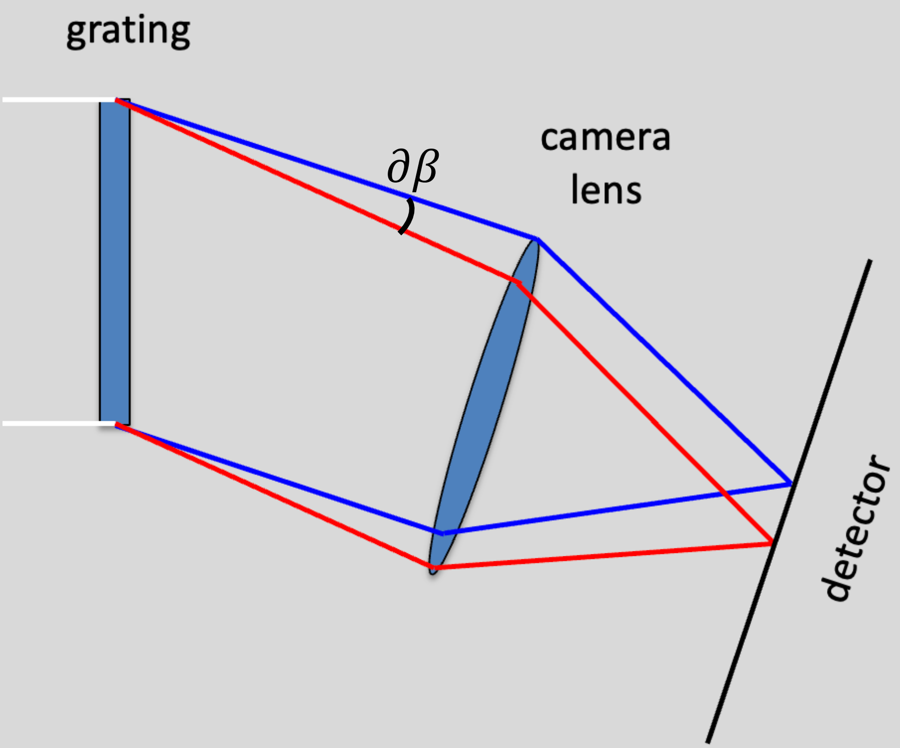


Grism: Grating + Prism. The prism takes the dispersed light from the grating and refracts it back to a straight-line path.

You can then slide the grism in and out to switch seamlessly between spectroscopy and imaging.

Spectral Dispersion

Remember β is the outgoing angle of diffraction. At fixed spectrograph setup (i.e, for fixed spectograph tilt (α) and grating (d)), the spectral dispersion tells you how broadly dispersed the spectrum is: $\partial\beta/\partial\lambda$



Start with the grating equation:

$$m\lambda = d\sin\alpha + d\sin\beta$$

Differentiate with respect to λ (holding α fixed, it's the incoming angle) :

$$m\partial\lambda = d\cos\beta\,\partial\beta$$

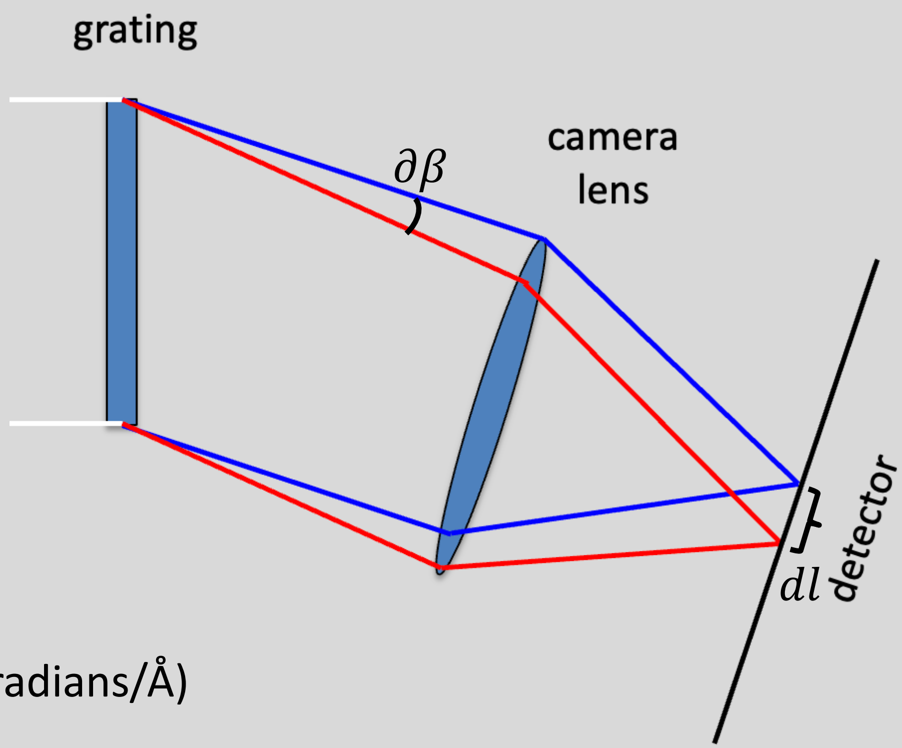
and solve for spectral dispersion:

$$\frac{\partial\beta}{\partial\lambda} = \frac{m}{d\cos\beta} = \frac{\sin\alpha + \sin\beta}{\lambda\cos\beta}$$

Remember: this is **angular dispersion,** units are radians/wavelength (i.e.,radians/Å if λ is expressed in Angstroms).

Linear Dispersion

Coming off the grating, the light has to be refocused onto the detector via a camera lens. This maps the angular dispersion onto linear dispersion (Å/mm) on the detector. We want to work out $\partial\lambda/\partial l$ where dl is size on the detector.



Remember imaging: the imaging plate scale was determined solely by the focal length of the telescope: $S = 1/f_L$ (in radians/mm).

The same thing holds for the spectrograph camera: $S_{cam} = 1/f_{cam}$

Conversion via unit analysis:

Linear dispersion (Å/mm) = plate scale (radians/mm) / spectral dispersion (radians/Å)

$$\frac{d\lambda}{dl} = \frac{S_{cam}}{d\beta/d\lambda} = \frac{d\cos\beta}{mf_{cam}}$$

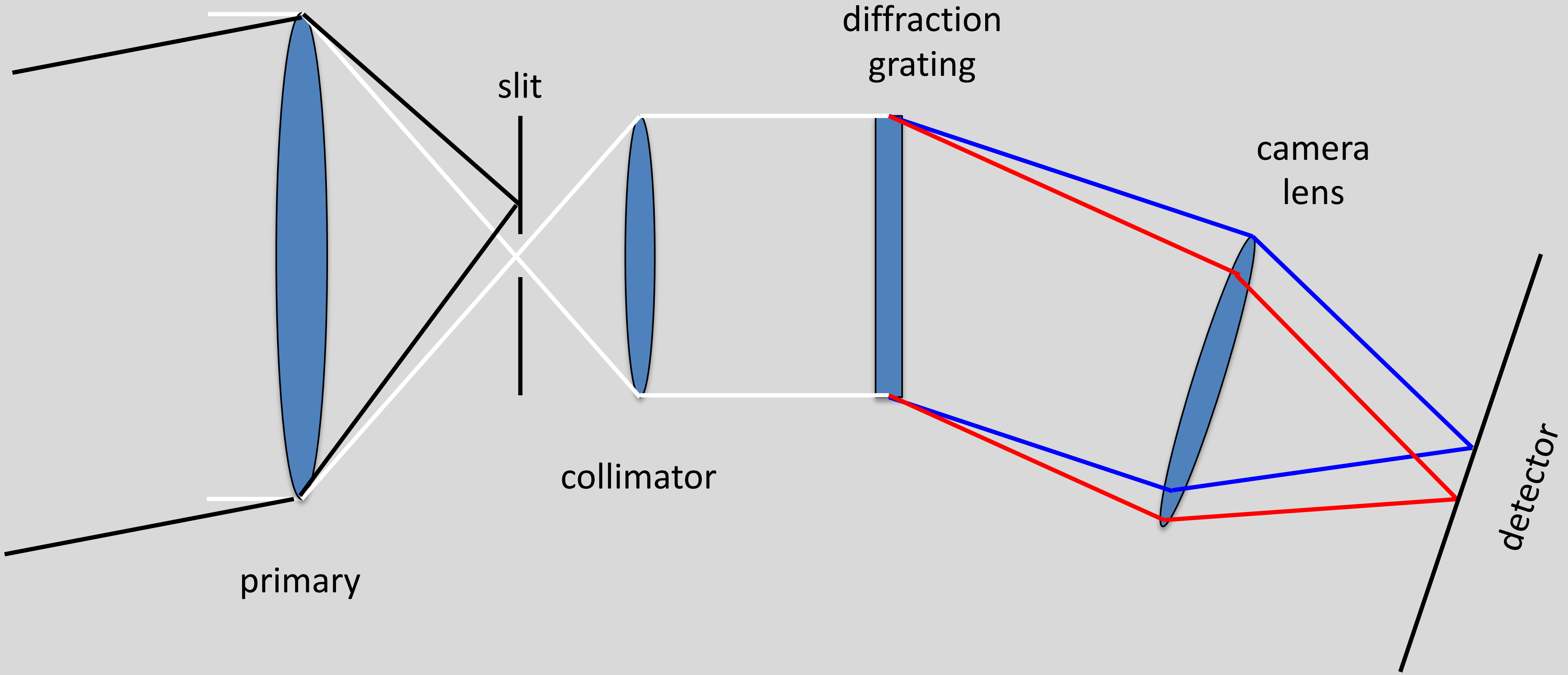
Remember: this is **linear dispersion**, units are (for example) Angstroms/mm

Given the physical pixel size you can then turn that into Angstroms/pixel

Slitless Spectrograph

The spectrograph slit blocks all but the object you are interested in.

Removing the slit means you are letting in light from any object in the field, coming in at a different angle.



Slitless Spectroscopy

In slitless spectroscopy, you let light in from everything in the field of view. This means you are feeding the grating light with a range of input angles (since objects are scattered across the angular field of view).

Look at the grating equation: $m\lambda = d \sin\alpha + d \sin\beta$

If you vary the incoming angle (α), how does the outgoing angle (β) change?

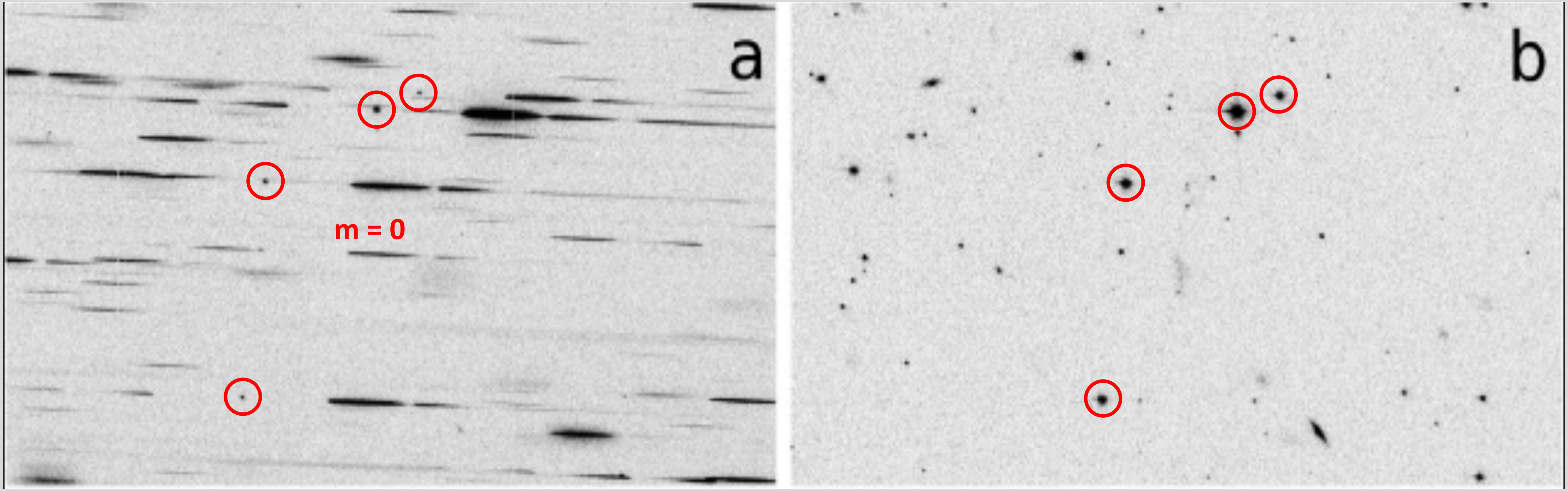
With all else fixed,

$$\frac{\partial\beta}{\partial\alpha} = \frac{\cos\alpha}{\cos\beta} \sim 0.5 - 1$$

for typical spectroscopic setups. So light coming in at a slightly different angle will have its diffracted spectrum shifted outwards by a similar amount.

So two objects in the field will produce two spectra, shifted on the detecter proportional to their position shift.

Slitless Spectroscopy



Spectral Image

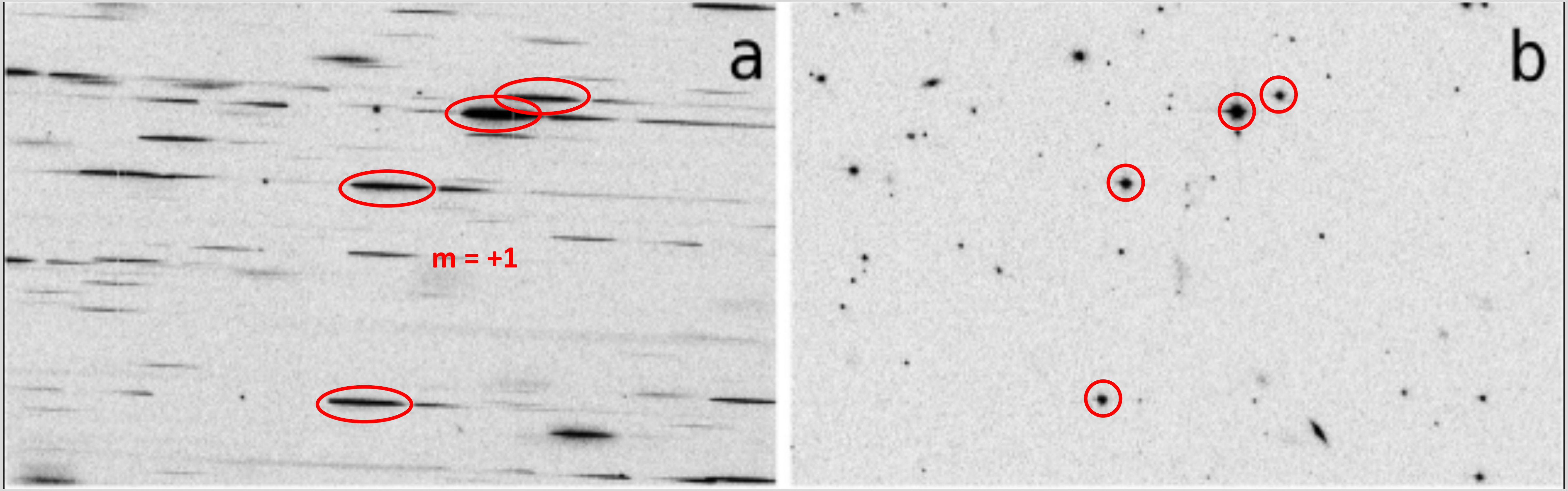
Direct Image

notice:

- “dots” on the spectral image are $m = 0$: undiffracted “white light” images of the stars.
- +/- orders are symmetric: $\alpha = 0$
- $m = +1$ is brightest: this grism is blazed to put power in $m = +1$

Kümmel+ 09

Slitless Spectroscopy



Spectral Image

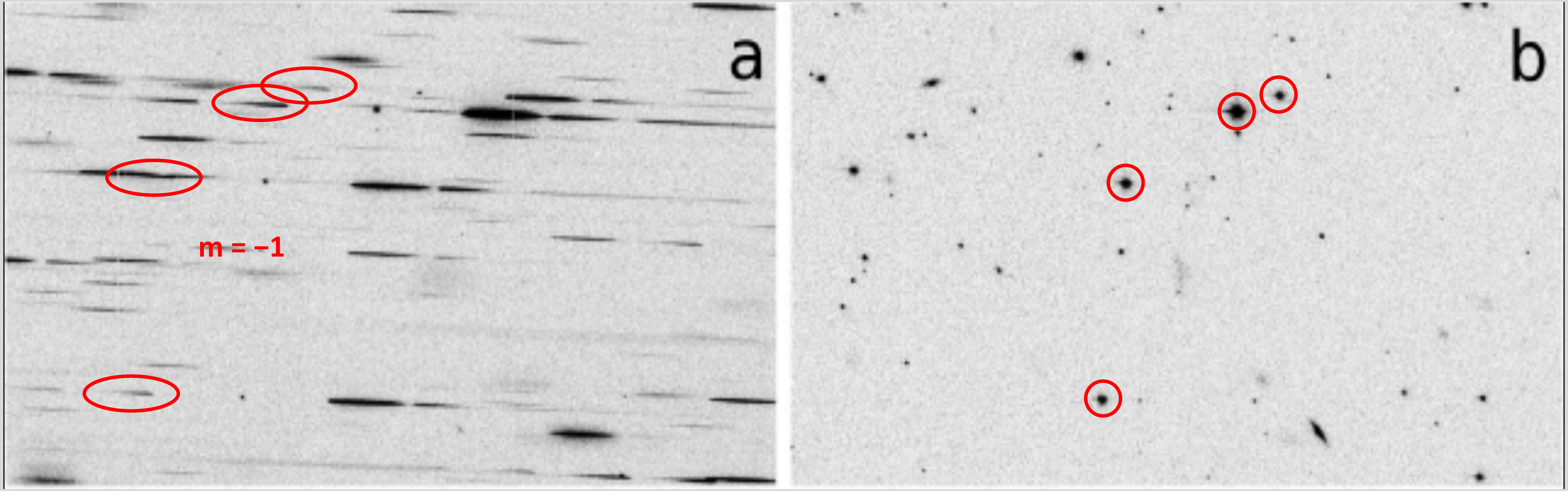
Direct Image

notice:

- “dots” on the spectral image are $m = 0$: undiffracted “white light” images of the stars.
- +/- orders are symmetric: $\alpha = 0$
- $m = +1$ is brightest: this grism is blazed to put power in $m = +1$

Kümmel+ 09

Slitless Spectroscopy



Spectral Image

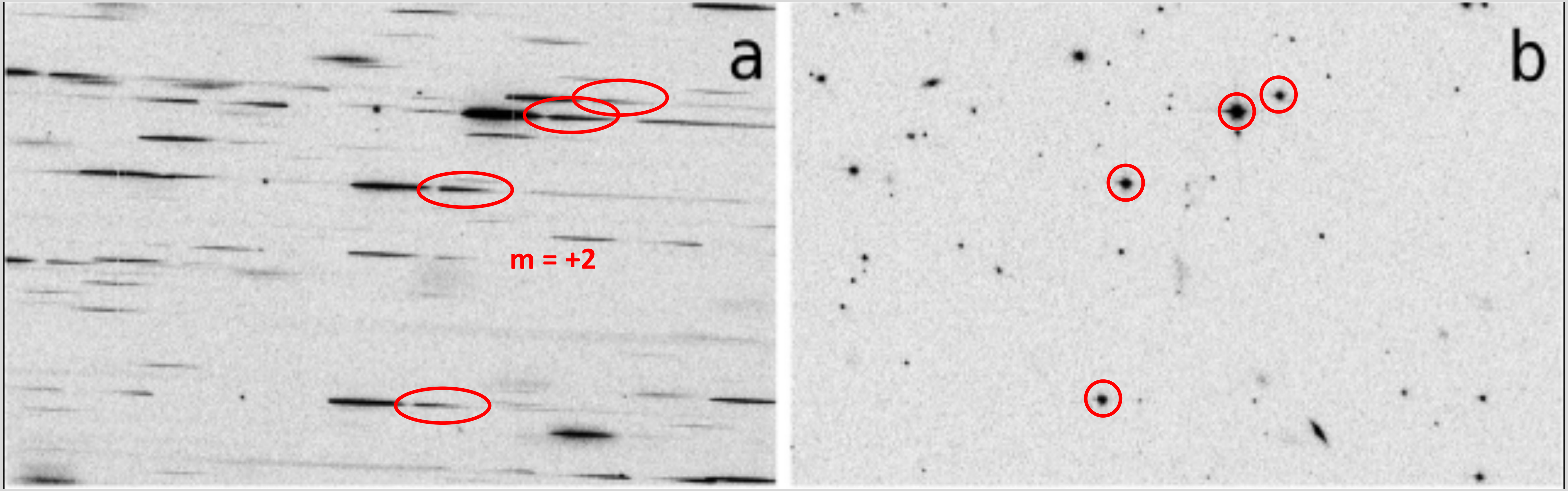
Direct Image

notice:

- “dots” on the spectral image are $m = 0$: undiffracted “white light” images of the stars.
- +/- orders are symmetric: $\alpha = 0$
- $m = +1$ is brightest: this grism is blazed to put power in $m = +1$

Kümmel+ 09

Slitless Spectroscopy



Spectral Image

Direct Image

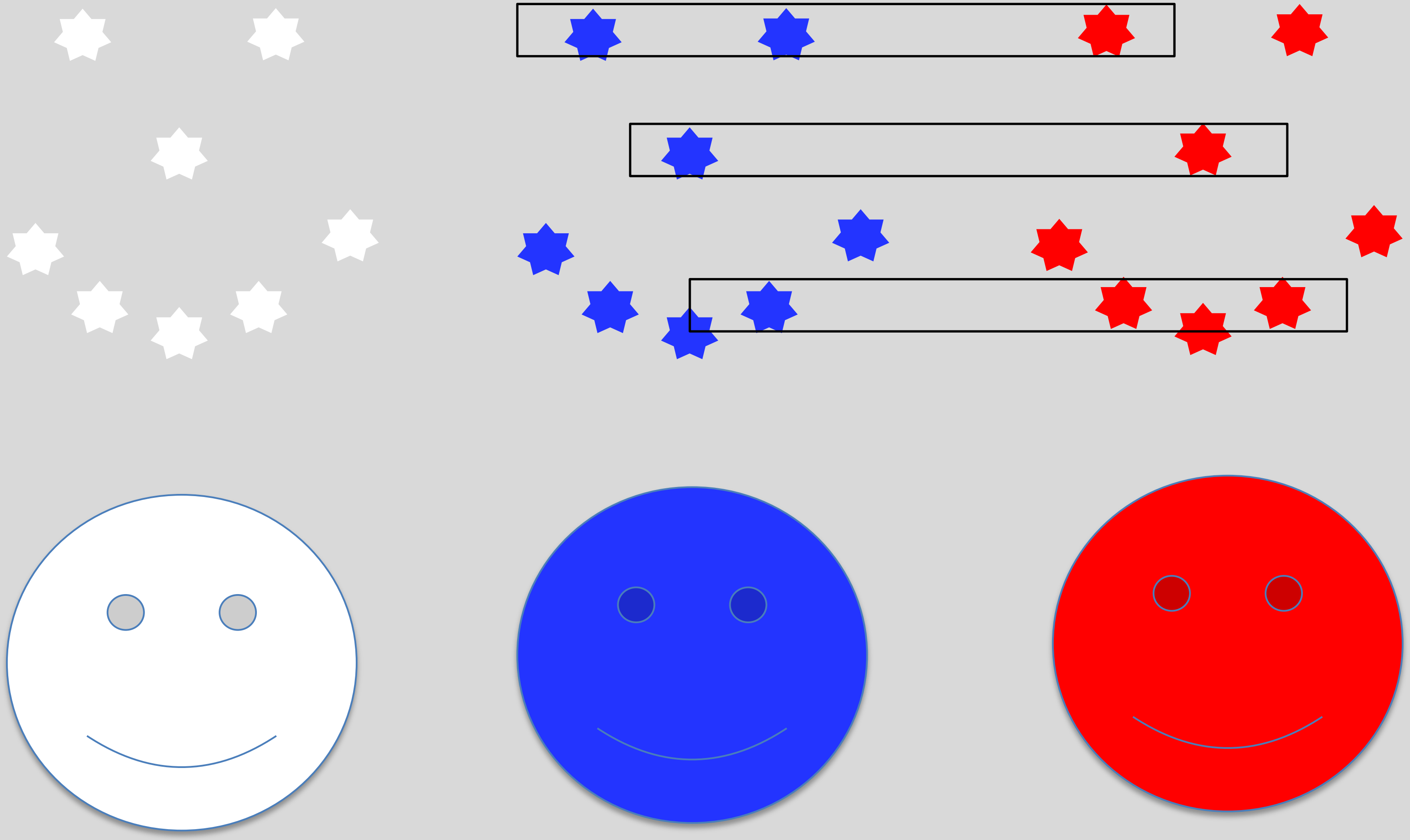
notice:

- “dots” on the spectral image are $m = 0$: undiffracted “white light” images of the stars.
- +/- orders are symmetric: $\alpha = 0$
- $m = +1$ is brightest: the grism is blazed to put power in $m = +1$

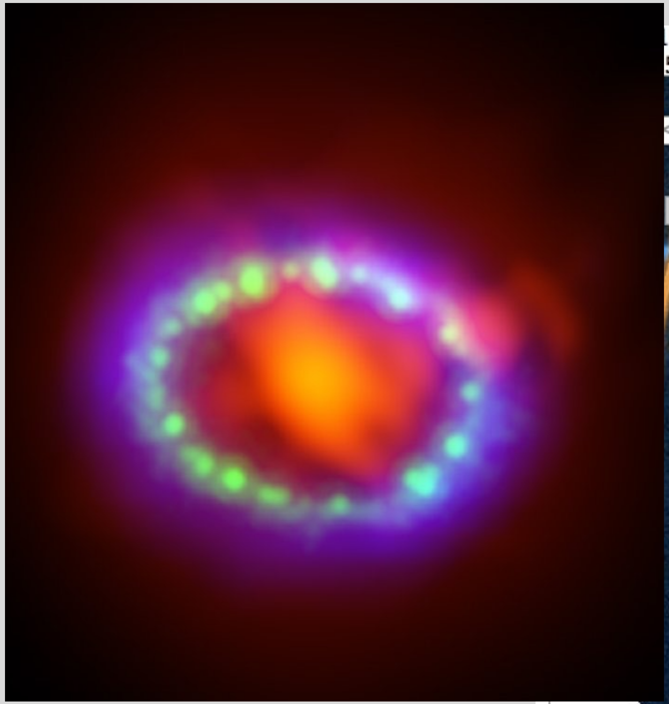
Kümmel+ 09

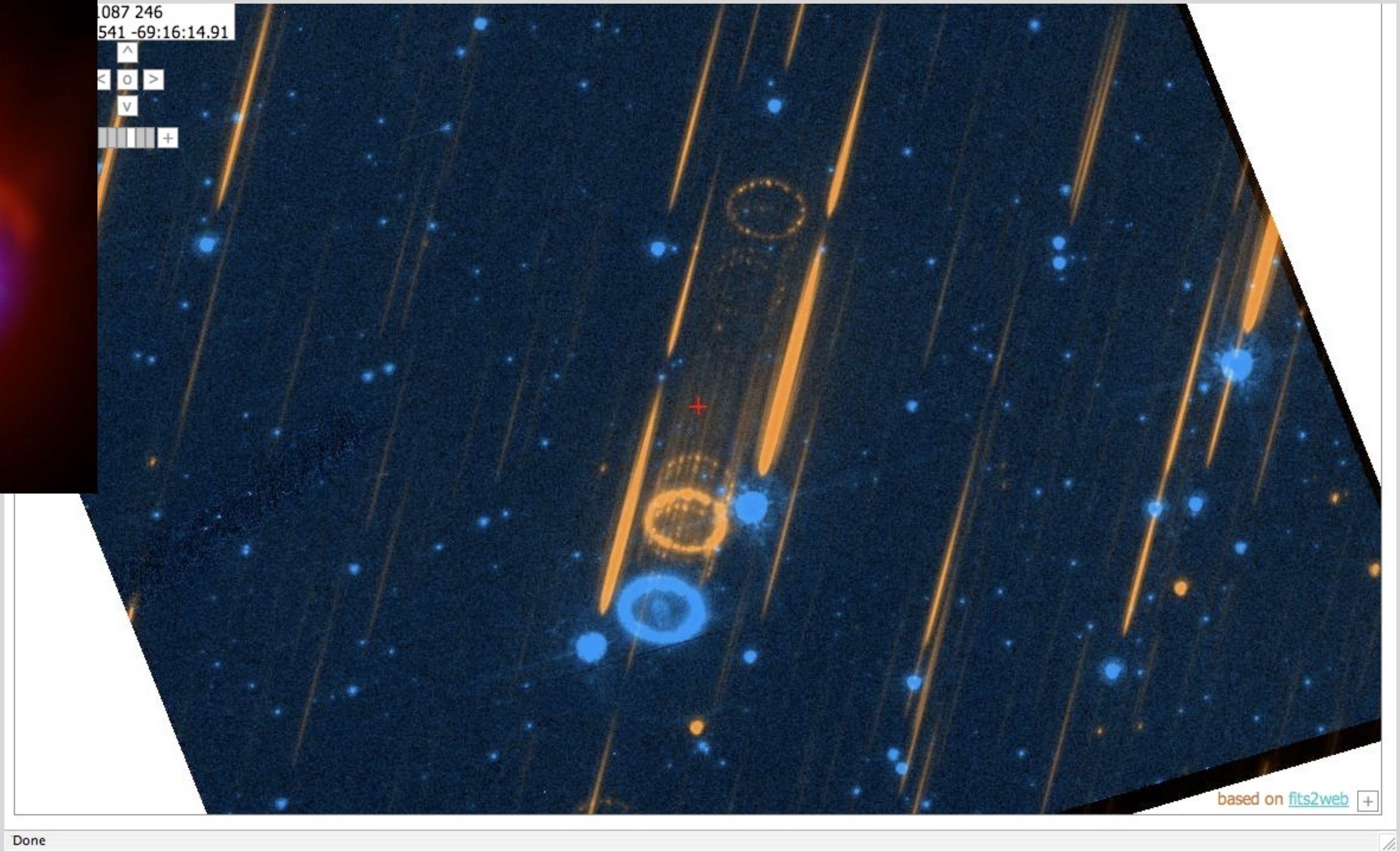
Slitless Spectroscopy: Spectral Images

Imagine a source that produces two emission lines only: blue and red. What does it look like in slitless spectroscopy?

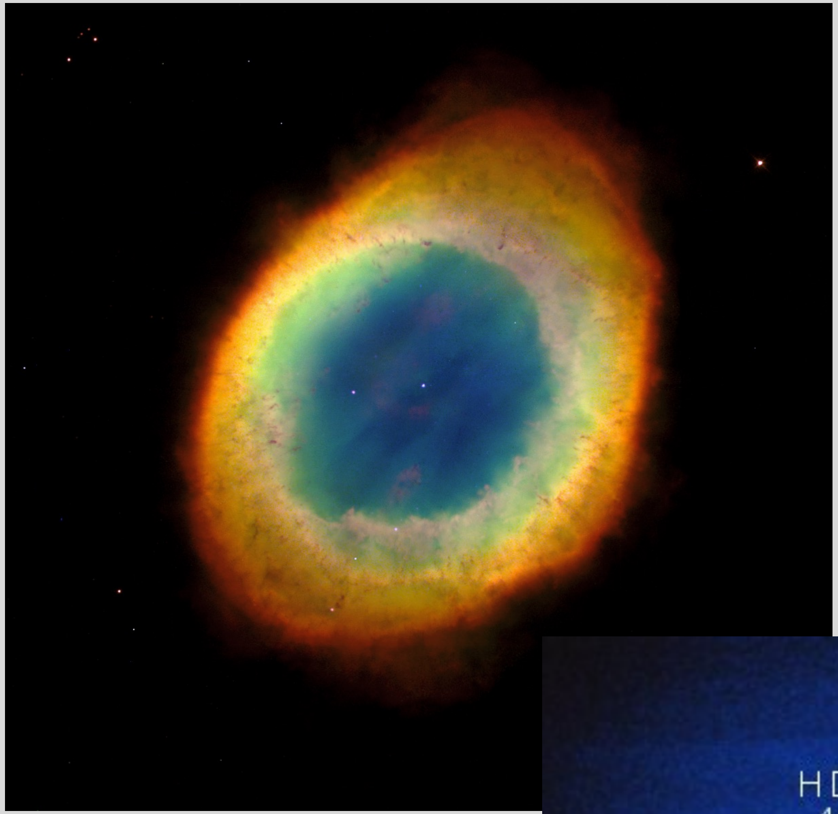


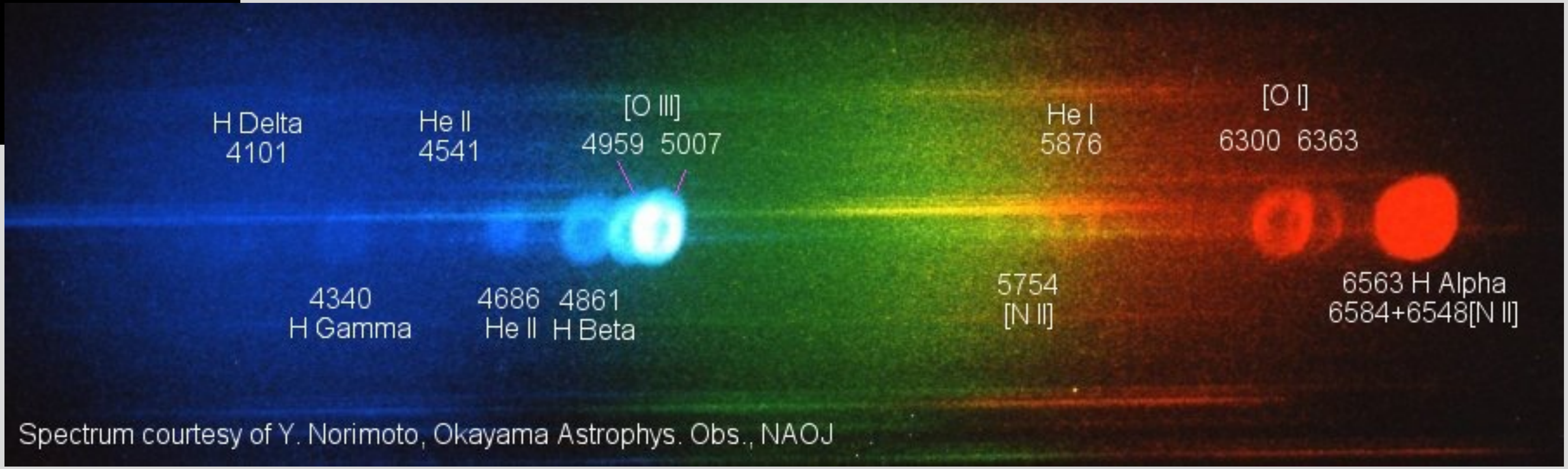
Slitless Spectroscopy: rings around SN1987a



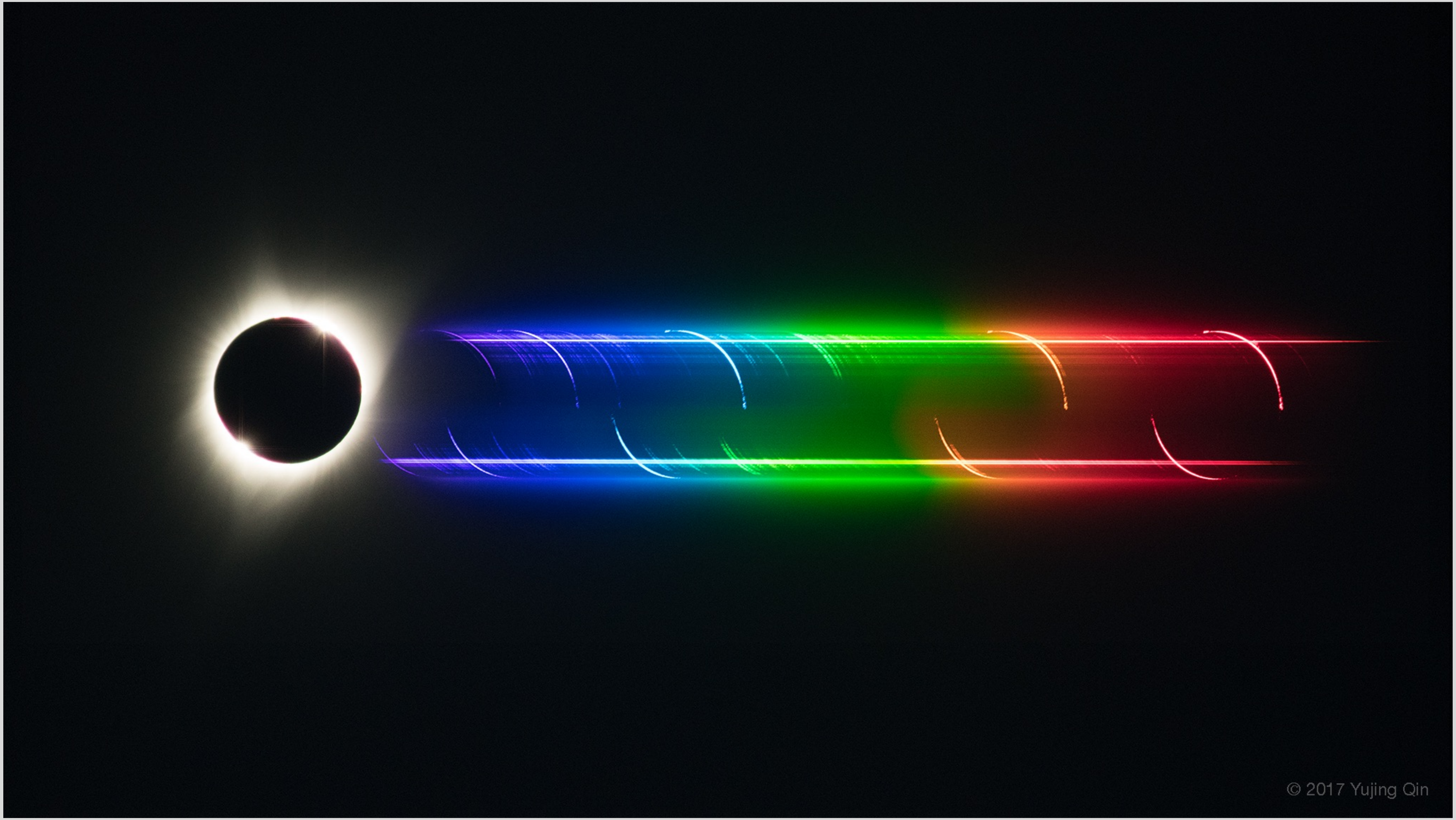


Slitless Spectroscopy: the Ring Nebula (planetary nebula)

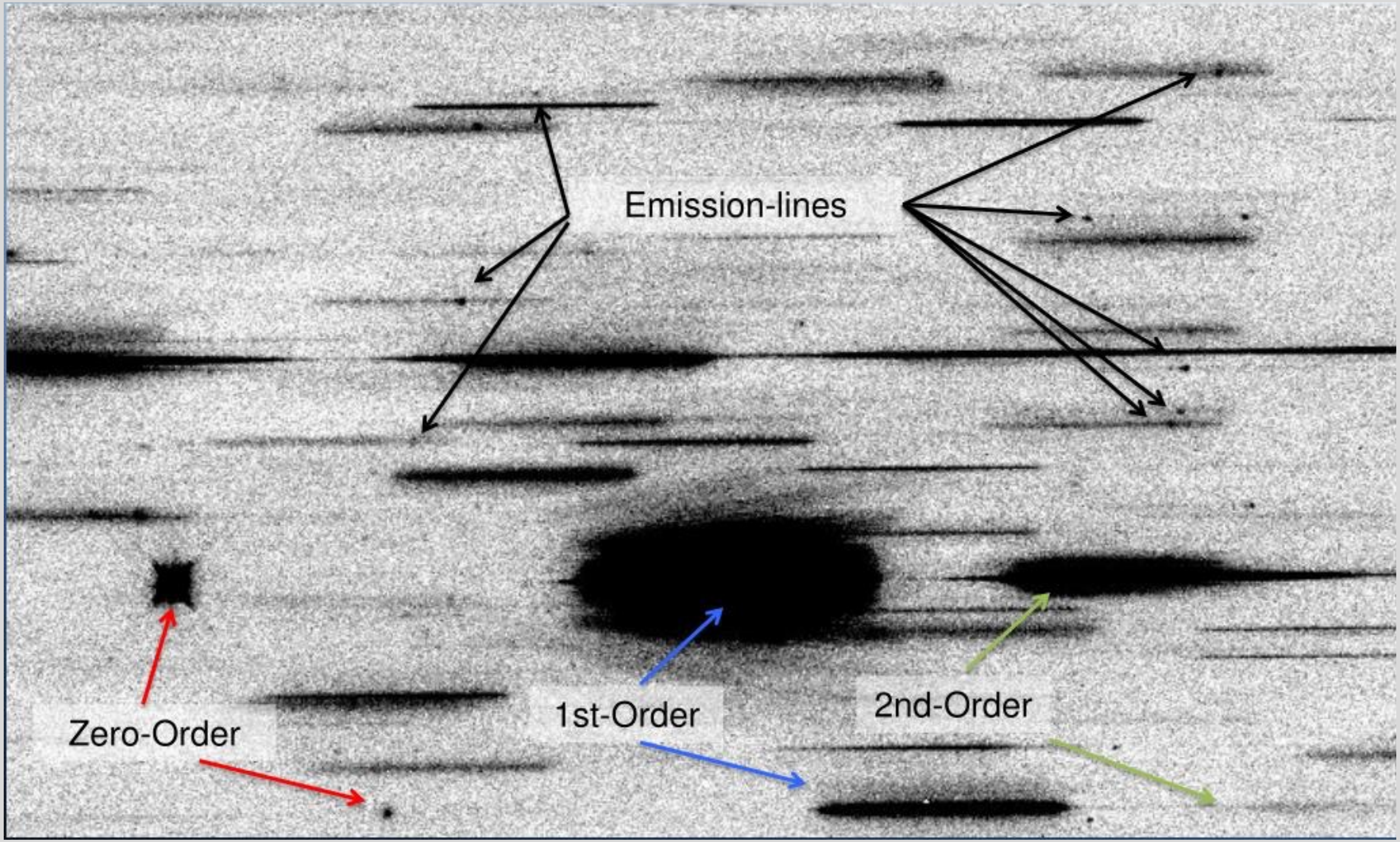




Slitless Spectroscopy: the Solar Corona



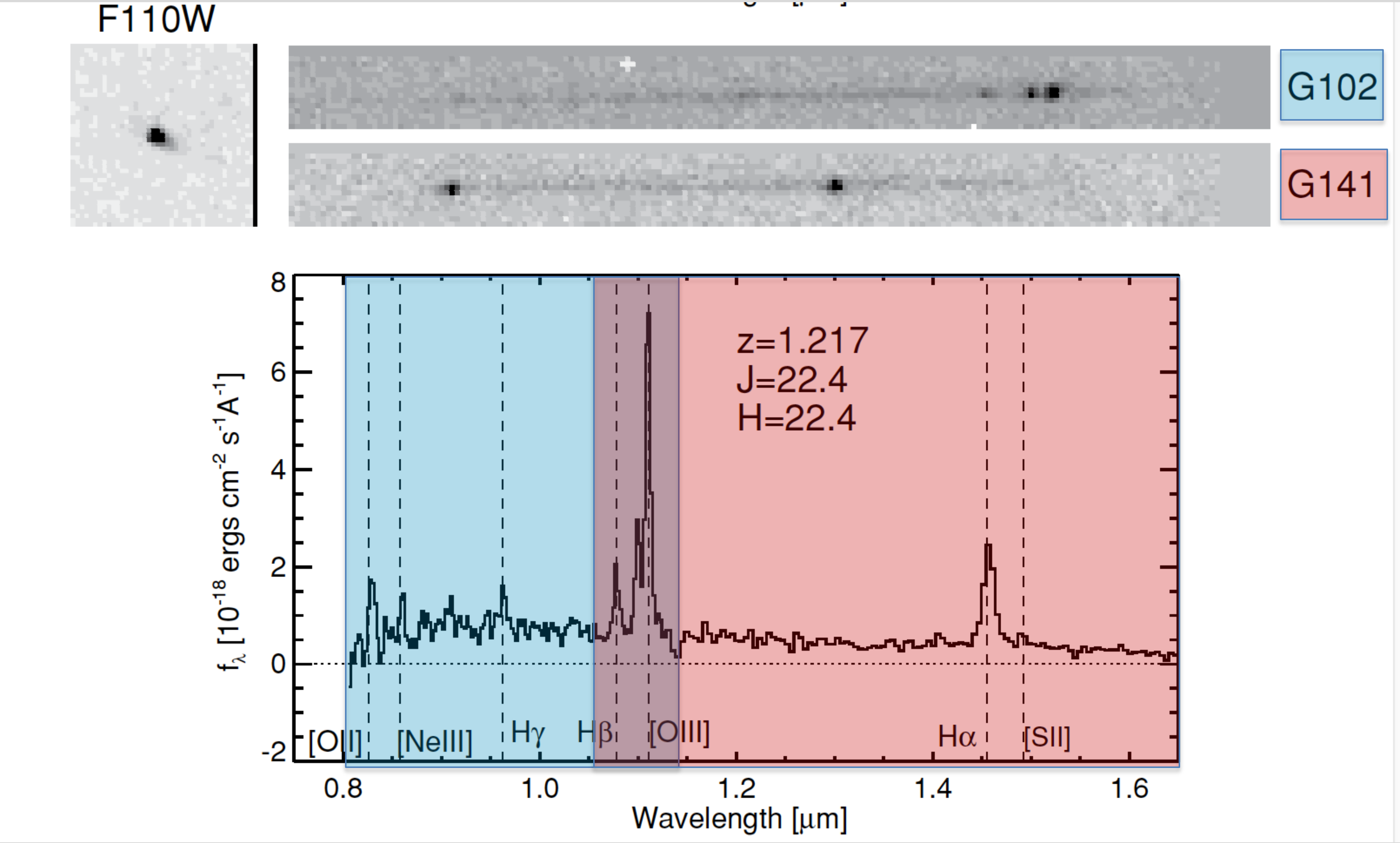
Slitless Spectroscopy: high-z galaxies



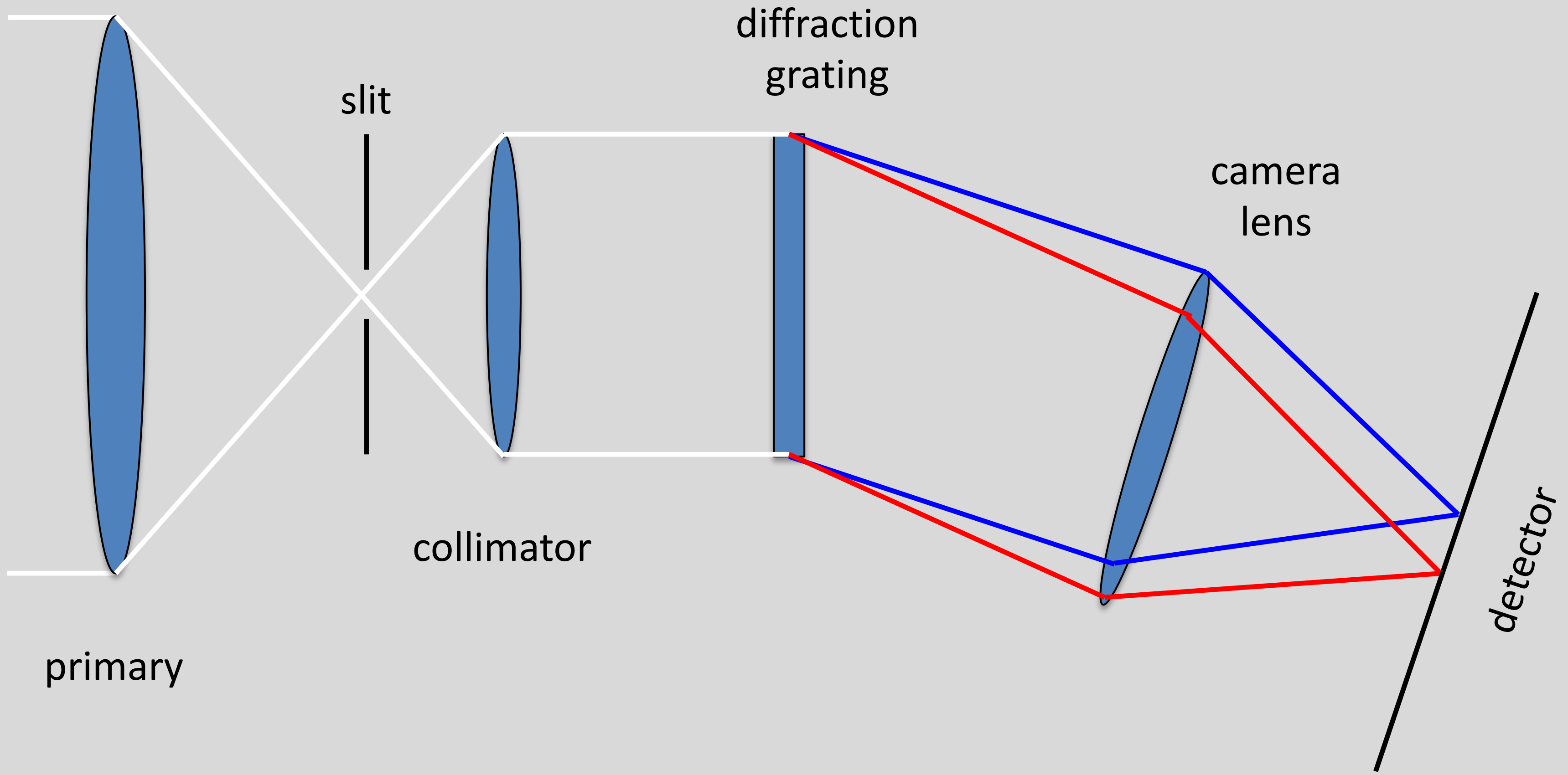
courtesy P McCarthy

Slitless Spectroscopy: high-z galaxies

Atek+ 20



Slit Spectrograph



(For ease of sketching, this shows a transmissive system: refracting telescope, transmission grating. Most telescope/spectrographs actually use a reflecting system.)

The Spectrograph Slit

The width of the slit determines the range of angles that get into the spectrograph. A wide slit allows a broader range of incoming angles, so it blurs the outgoing dispersed light and limits the spectral resolution.

Characterizing slit width

- Physical size (**linear**): true size of slit, ω (for example, in mm)
- Projected width on the sky (**angular**): just like image size, it depends on the focal length of the telescope, $\omega_\theta = \omega / f_L$ (remember, if ω and f_L are measured in the same units, this will come out in radians!)
- Projected width on the detector (**linear**): depends on the focal length of the camera and collimator lenses: $\omega' = \omega(f_{cam}/f_{col})$

  also possibly a term due to anamorphic (de-)magnification (Schweizer 1979): r = |dβ/dα| = cos(α)/cos(β)
- Projected width on the detector (**wavelength resolution**): use linear dispersion to convert microns to Angstroms: $\omega_\lambda = \omega' \, d \cos\beta / (m f_{cam})$
- Width in velocity (**velocity resolution**): use Doppler equation: $\omega_v = \omega_\lambda (c/\lambda)$

Caution: always work through unit analysis when using these expressions to make sure you're using consistent units!

Tradeoffs

Wide Slit: lets more light in, but reduces spectral resolution.

Narrow slit: less light gets in, but better spectral resolution.

GoldCam Spectrograph (KPNO 2m)

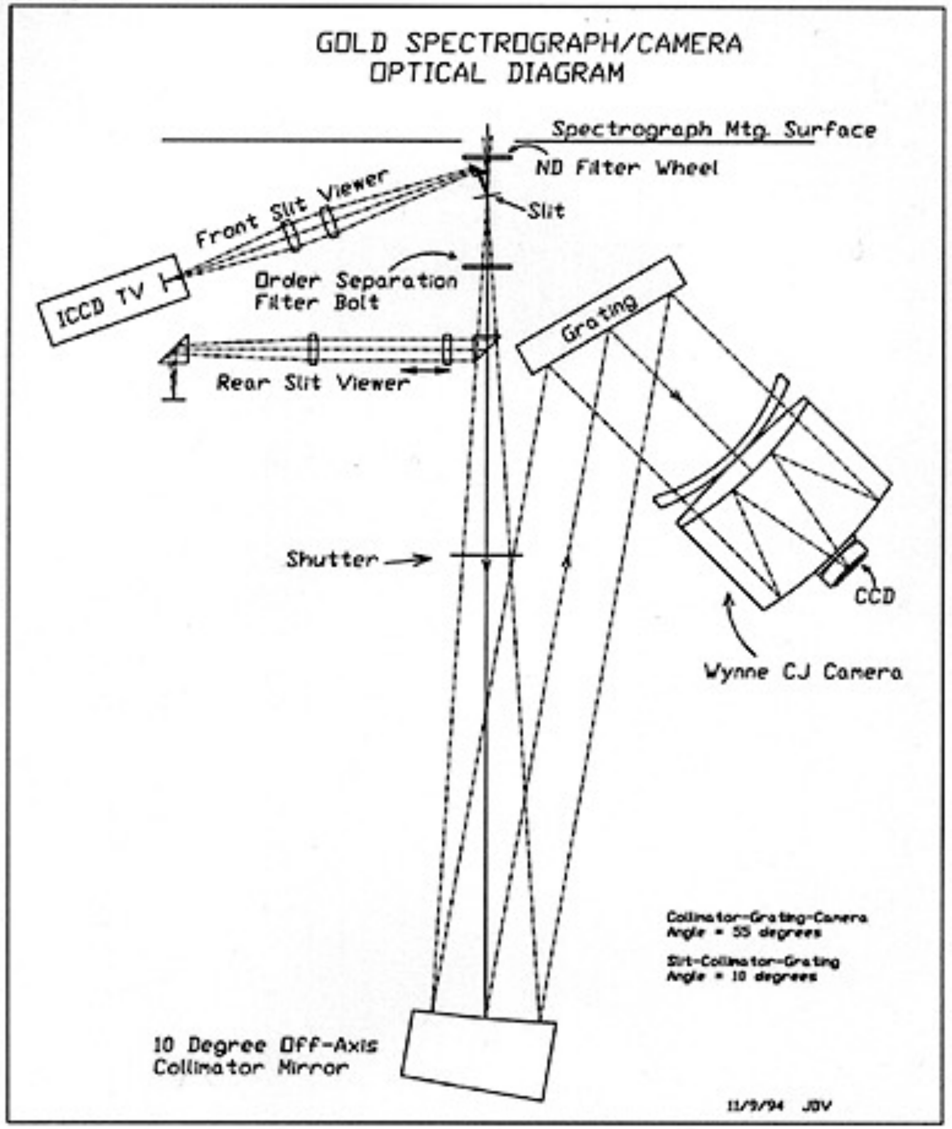
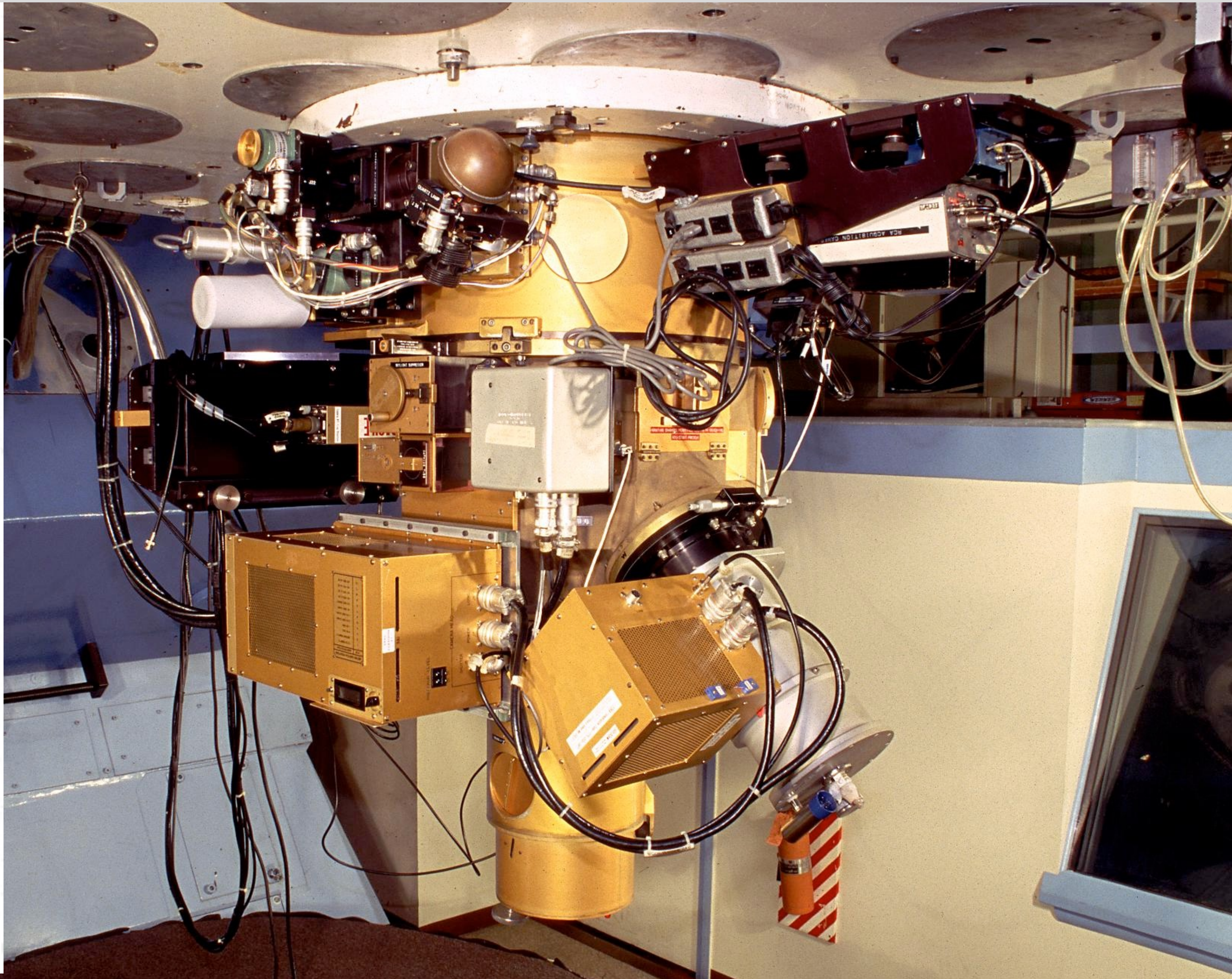
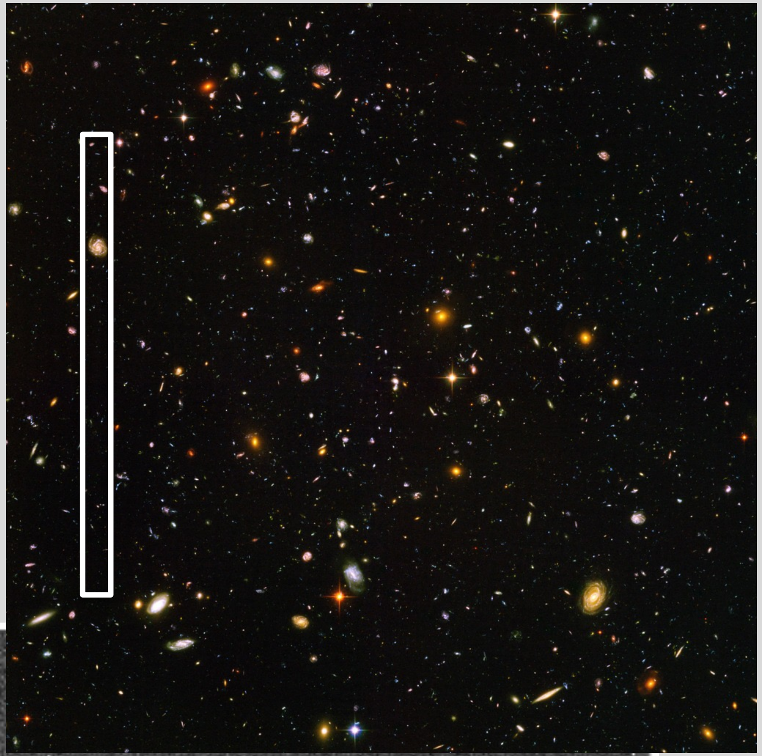


Figure 1: GCAM Spectrograph Optical Diagram

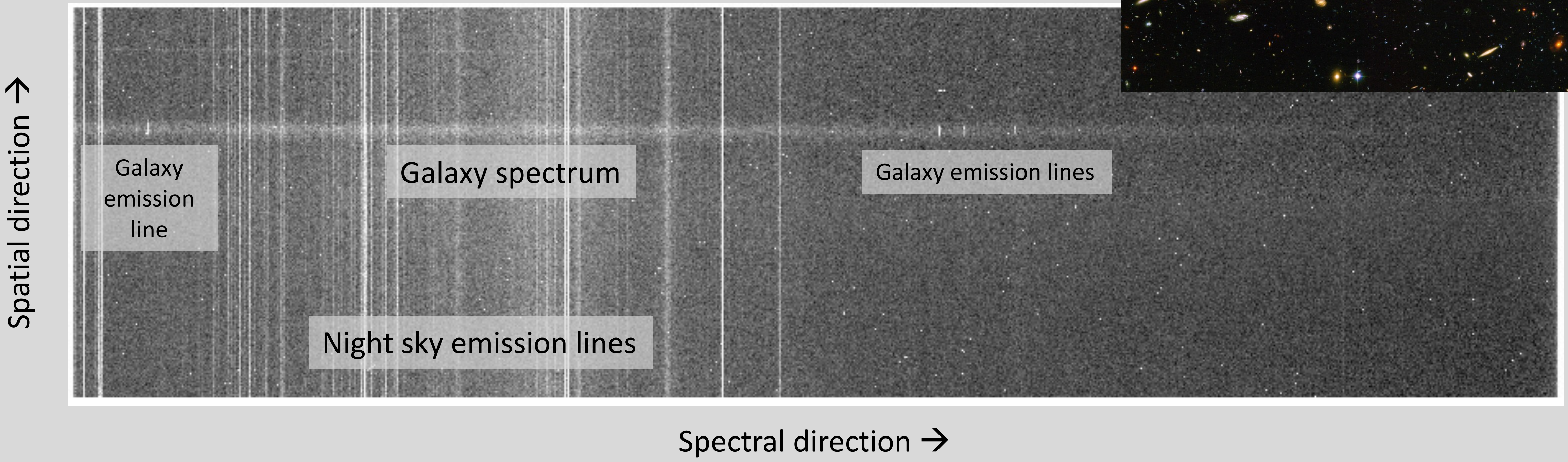


Longslit Spectroscopy

For a long slit that passes through the small object (i.e., a distant galaxy)...



we get a spectral image that looks like this

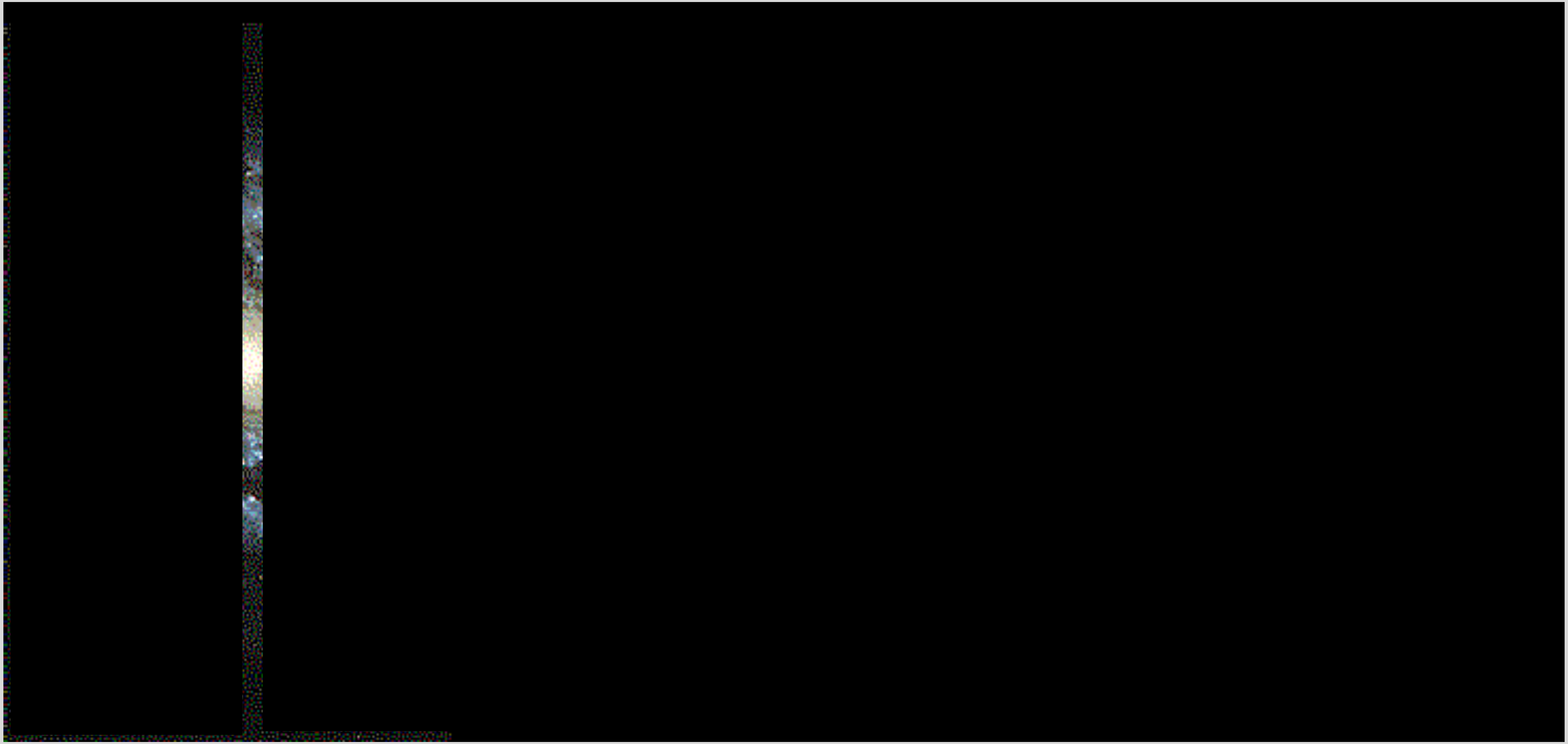


Longslit Spectroscopy

Extended source (nearby galaxy)

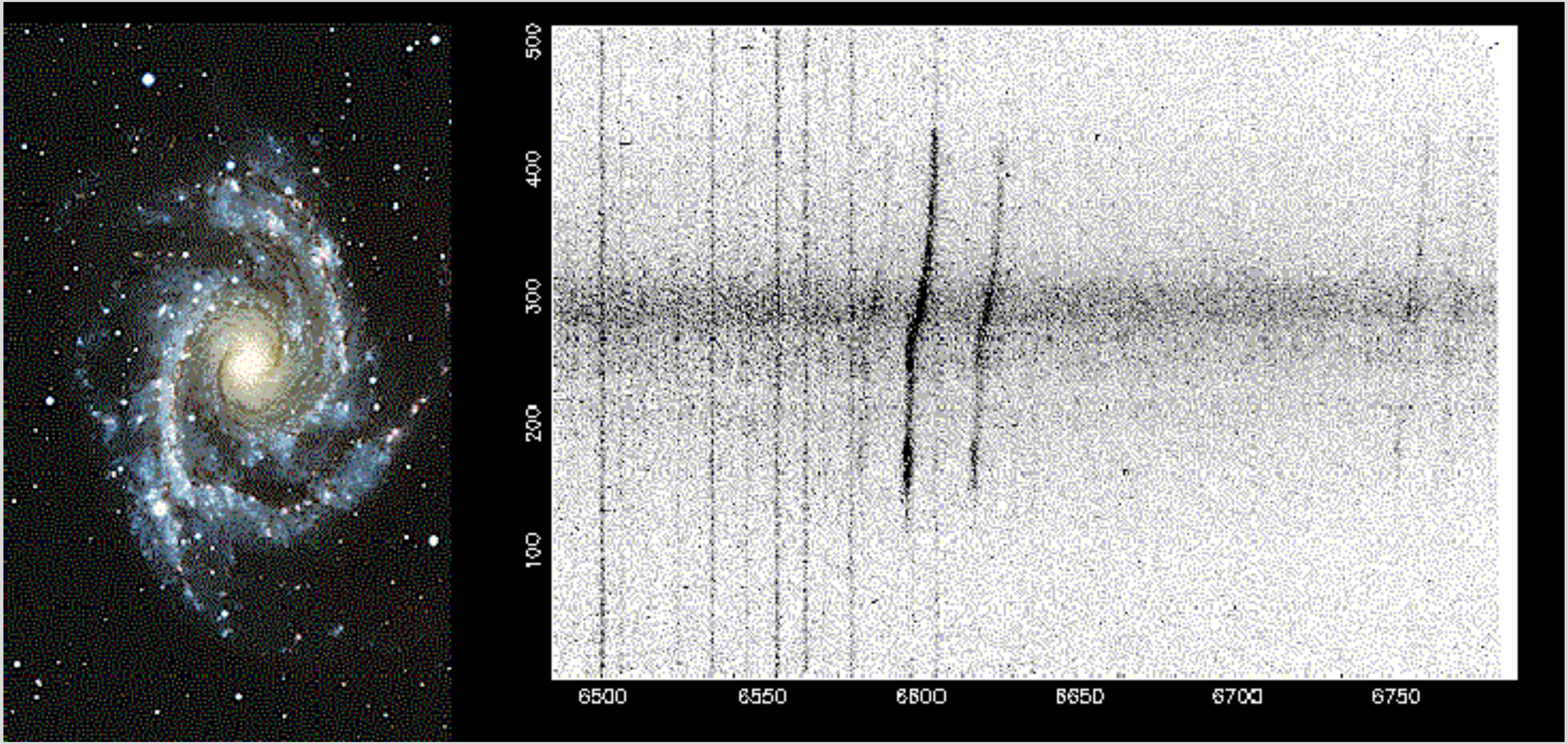
Longslit Spectroscopy

Extended source (nearby galaxy)



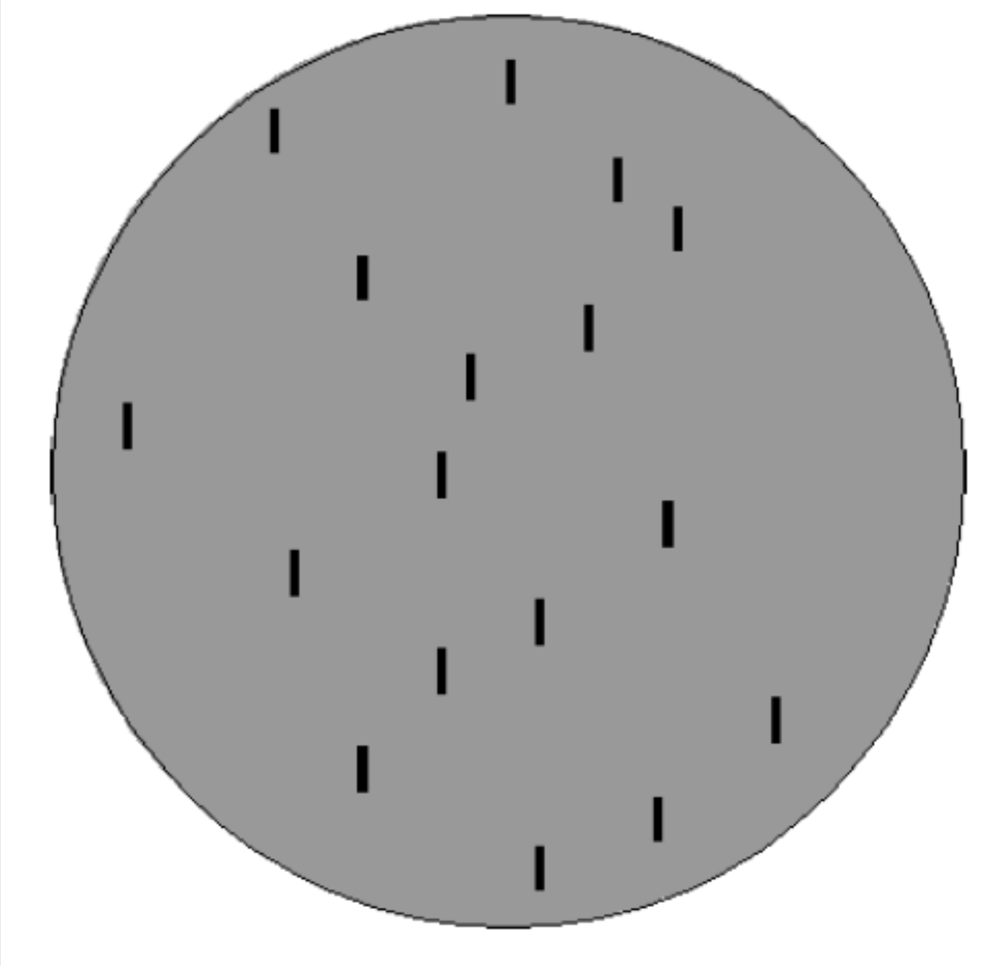
Longslit Spectroscopy

Extended source (nearby galaxy)



Multi-object spectroscopy: Slitmasks

Multi-object spectroscopy: Slitmasks



Metal plate with slits cut at the position of stars.

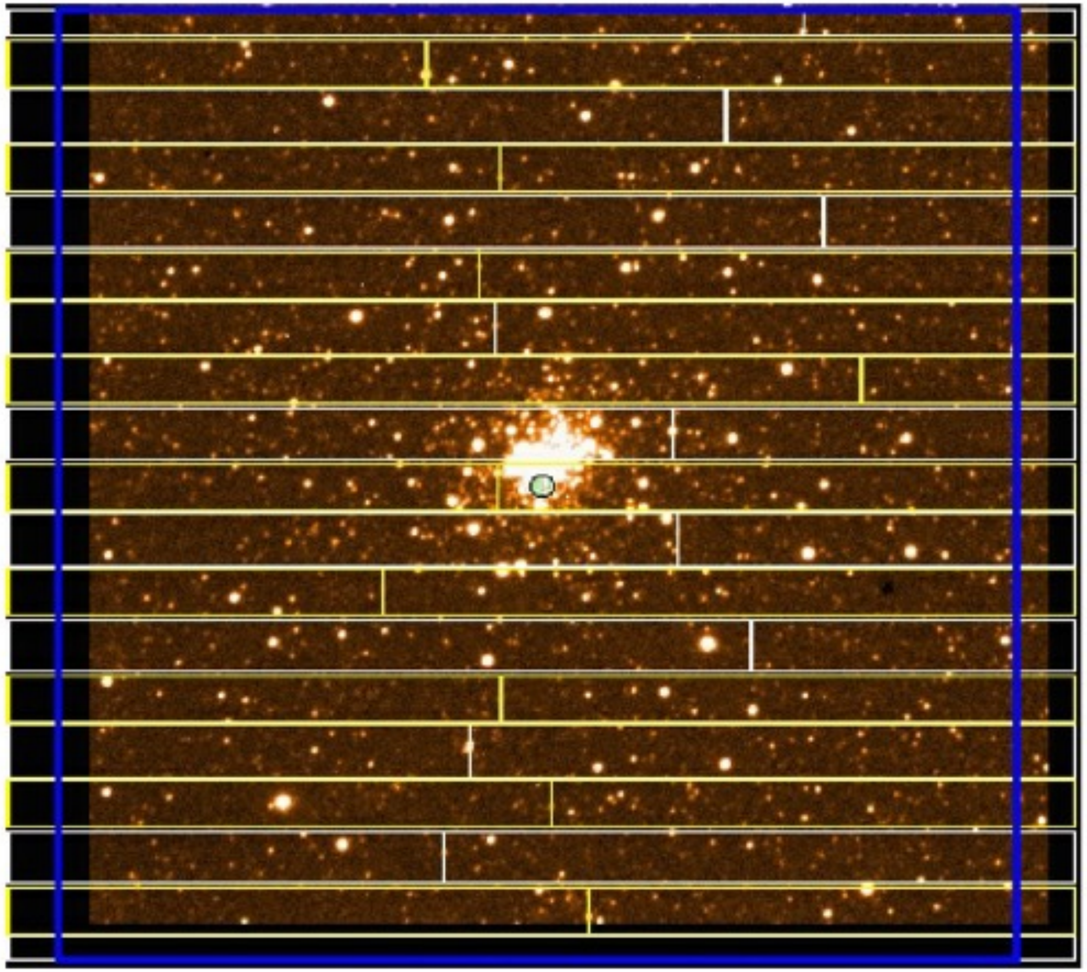
Put at focal plane of telescope; star light passes through slit onto grating.

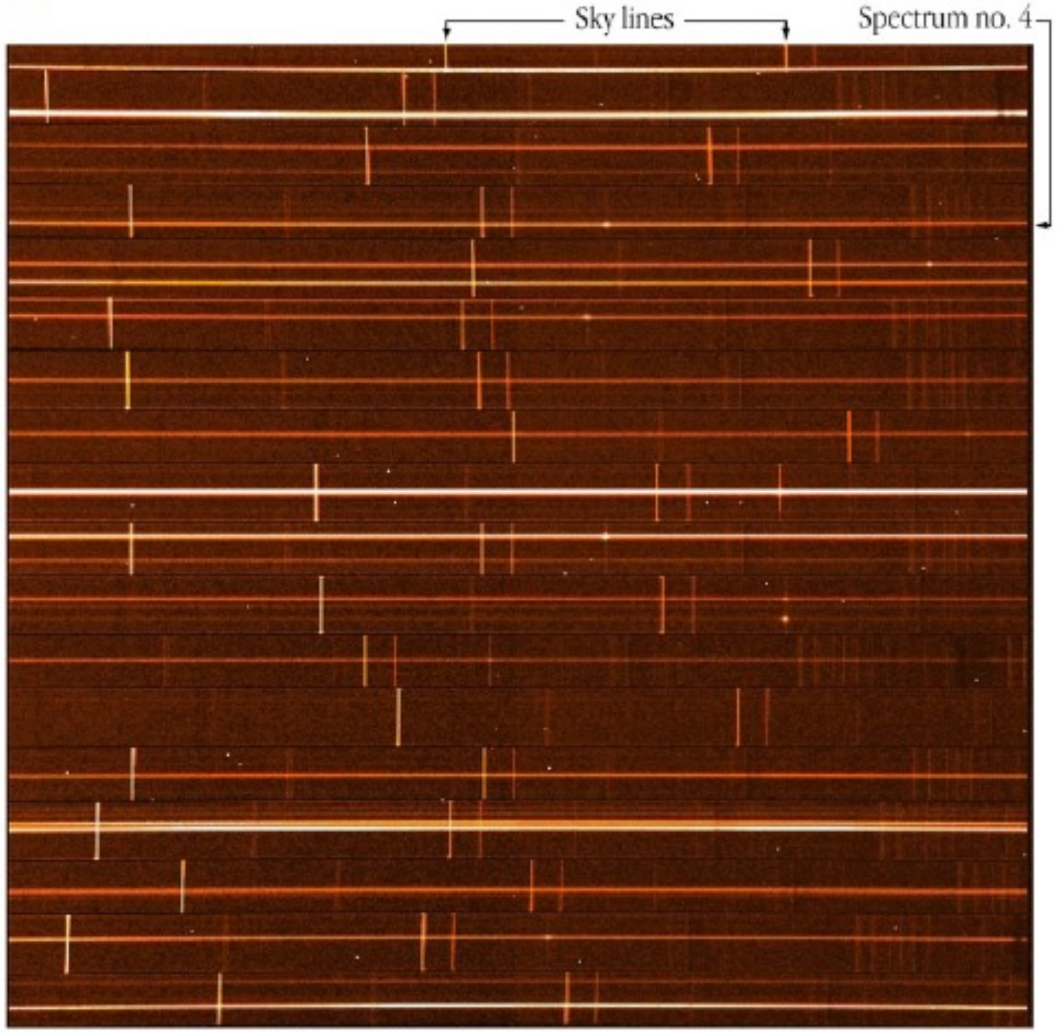
Forms a series of spectra, one for each star.

Spectra are offset in the spectral direction from each other, due to different X-positions of slits.

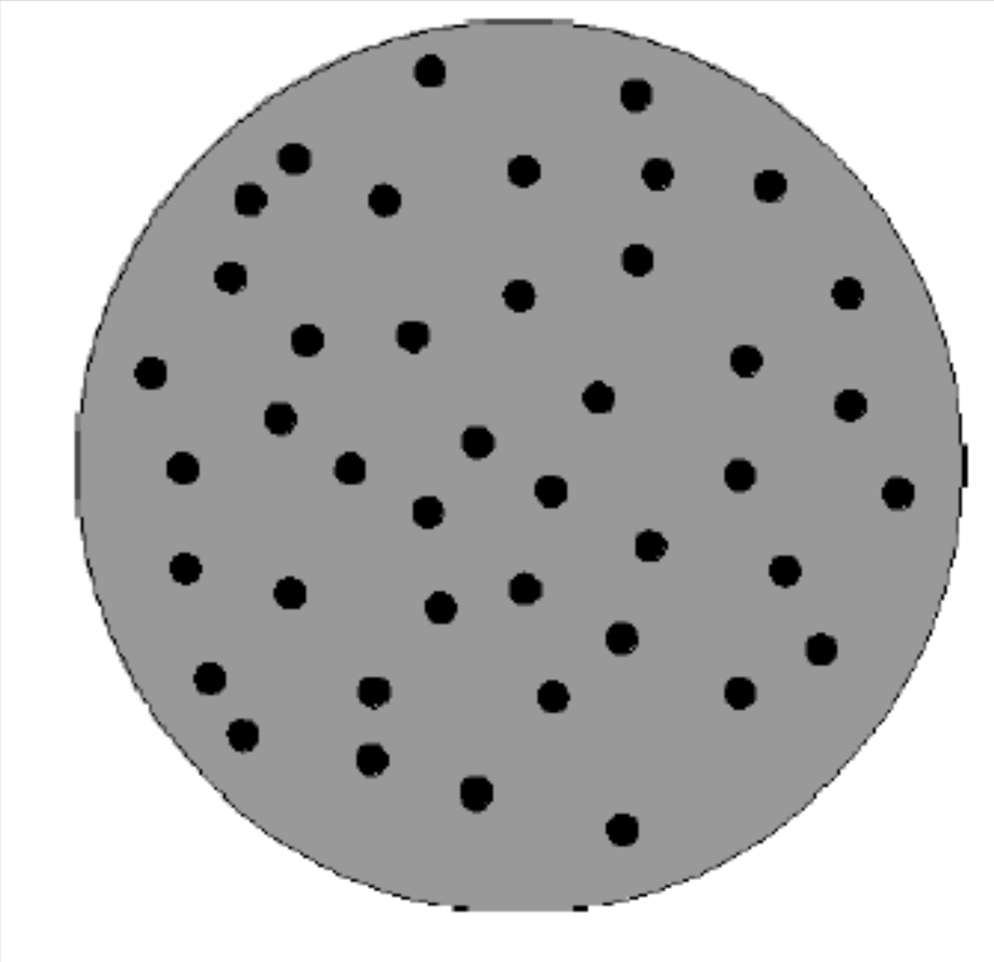
Slits must not overlap in Y! (otherwise spectra will overlap)

Multi-object spectroscopy: Slitmasks





Multi-object spectroscopy: Fiber fed spectrographs

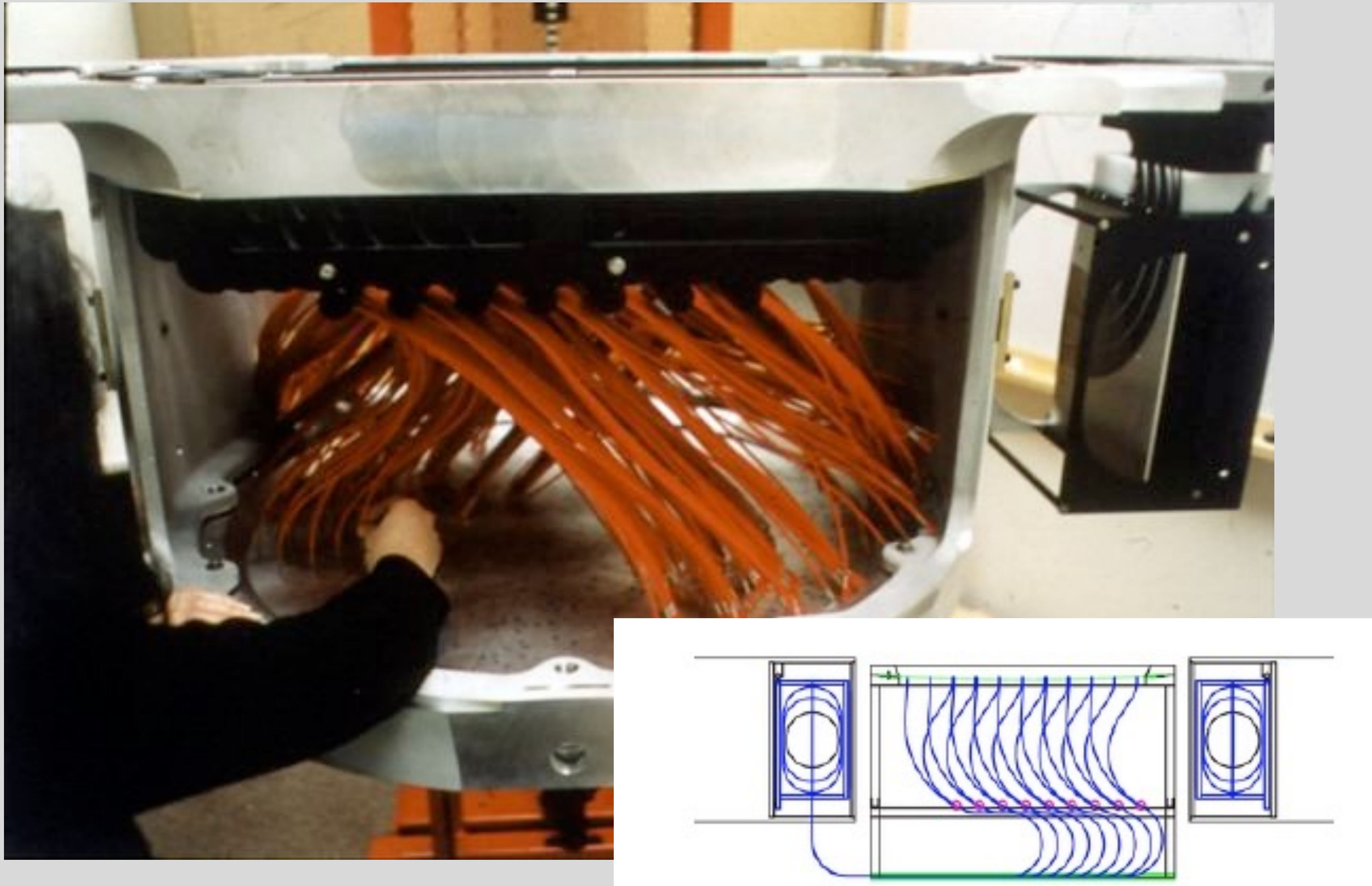


Metal plate with holes cut at the position of stars.

Put an optical fiber in each hole to carry the light down to the spectrograph.

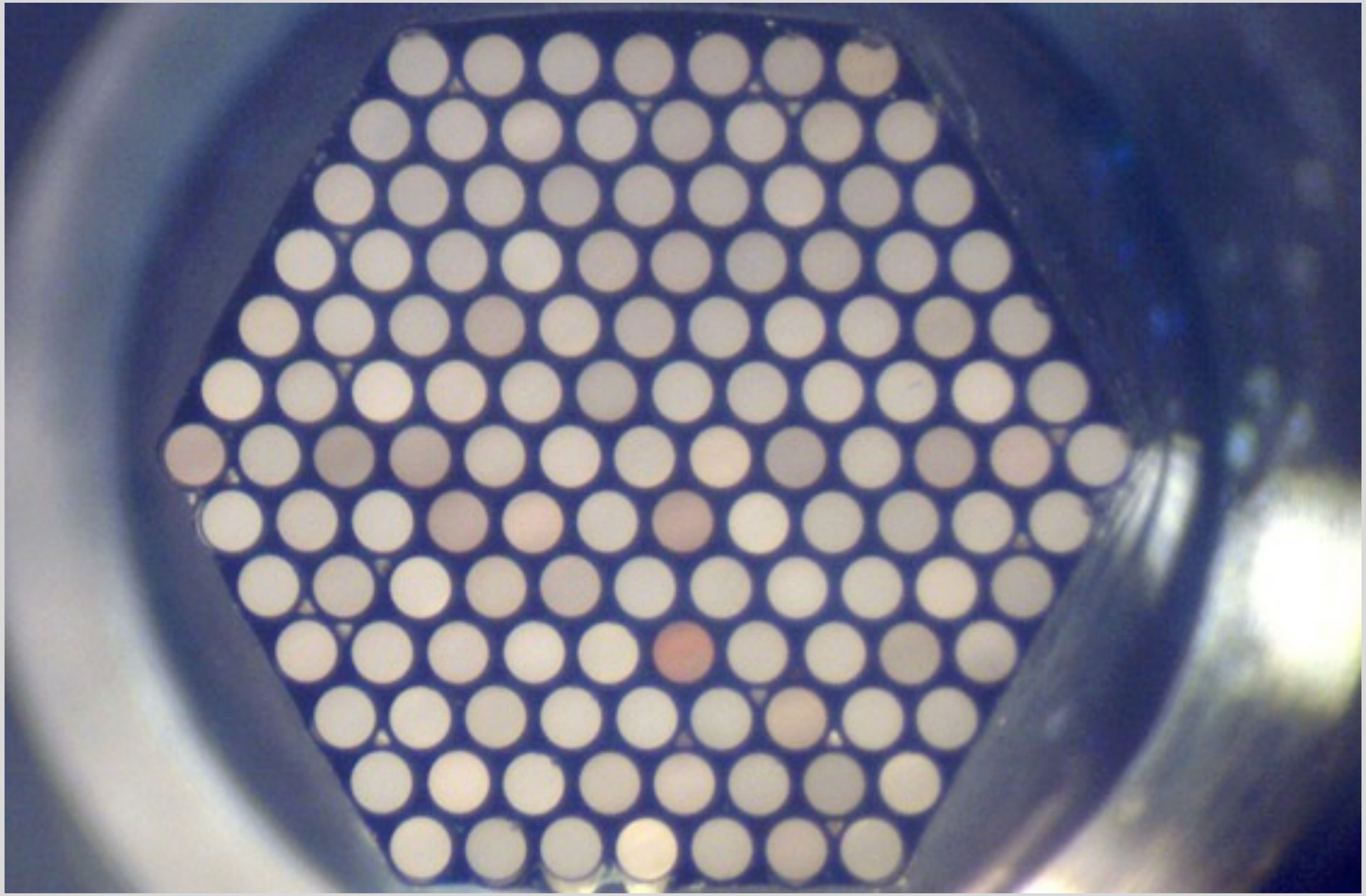
Produce many spectra, no constraints on fiber positions (other than they can't be too close spatially).

Multi-object spectroscopy: Fiber fed spectrographs

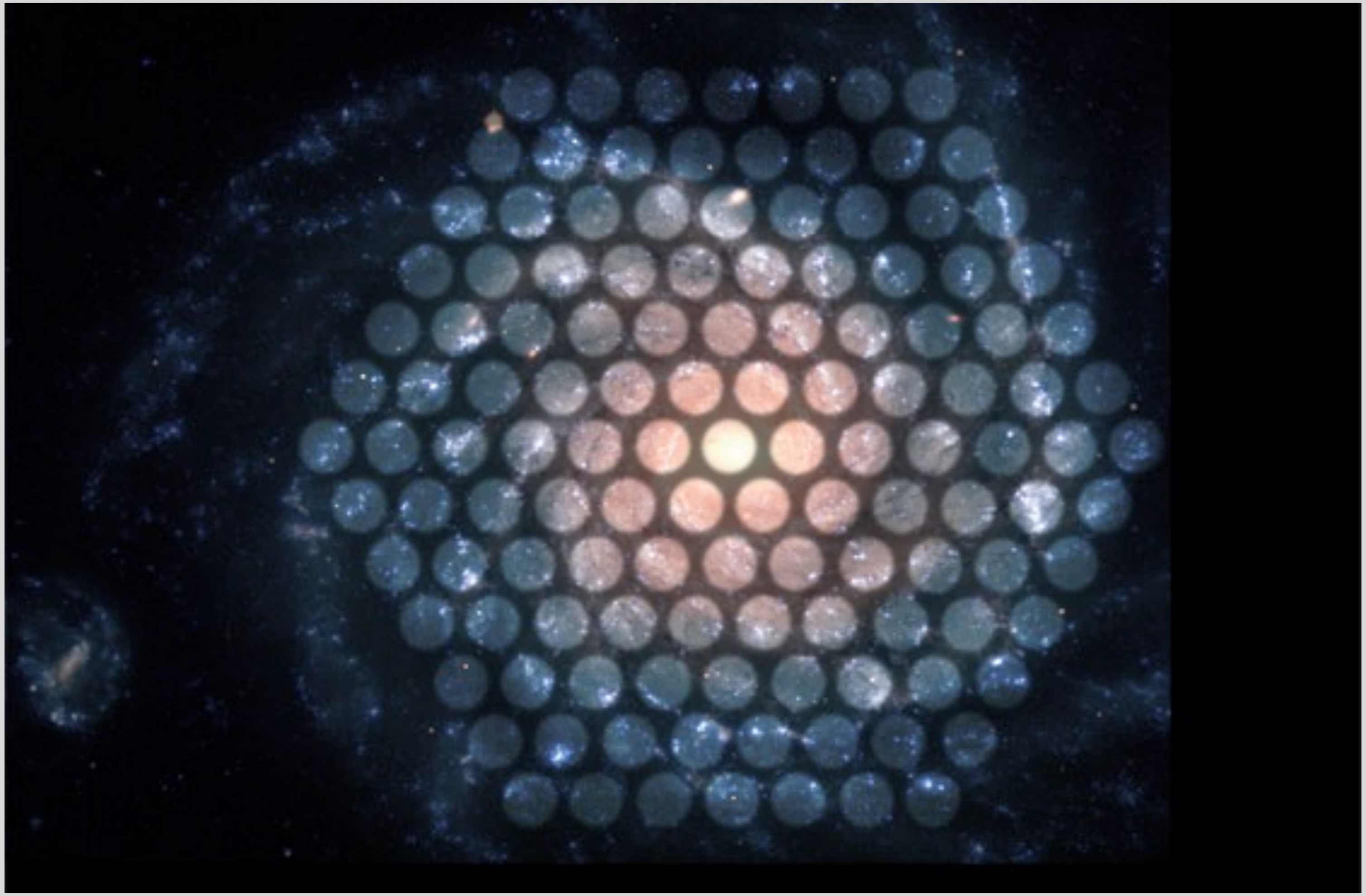


Side View
(only 9 fiber harnesses shown)

Multi-object spectroscopy: Integral Field Units (IFUs)

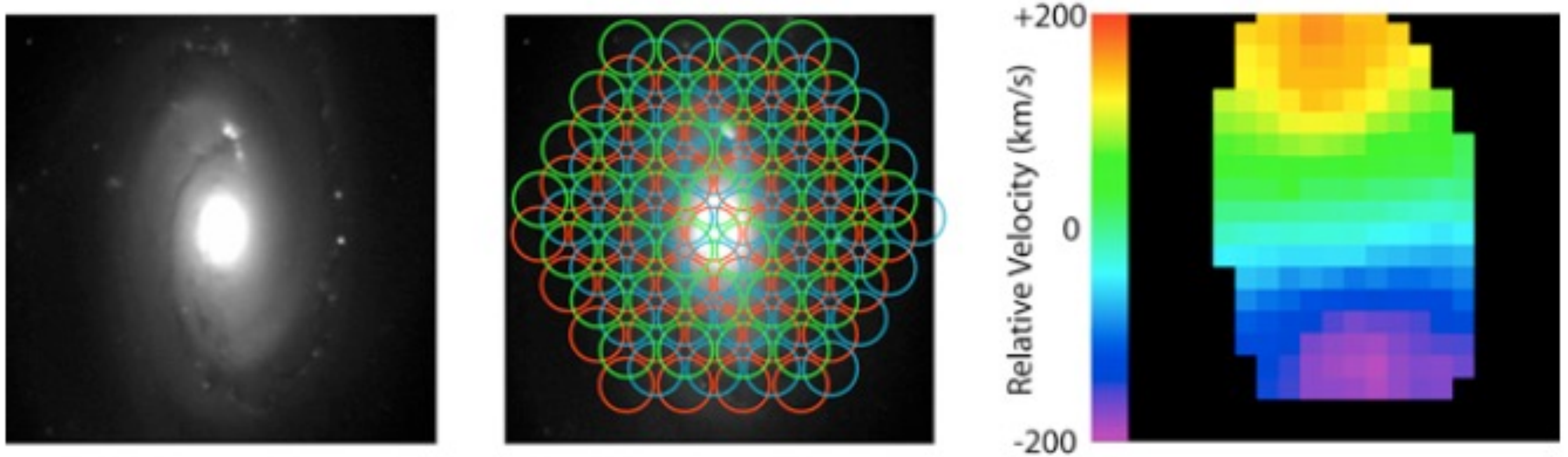


Multi-object spectroscopy: Integral Field Units (IFUs)



Multi-object spectroscopy: Integral Field Units (IFUs)

Dithering to get full coverage

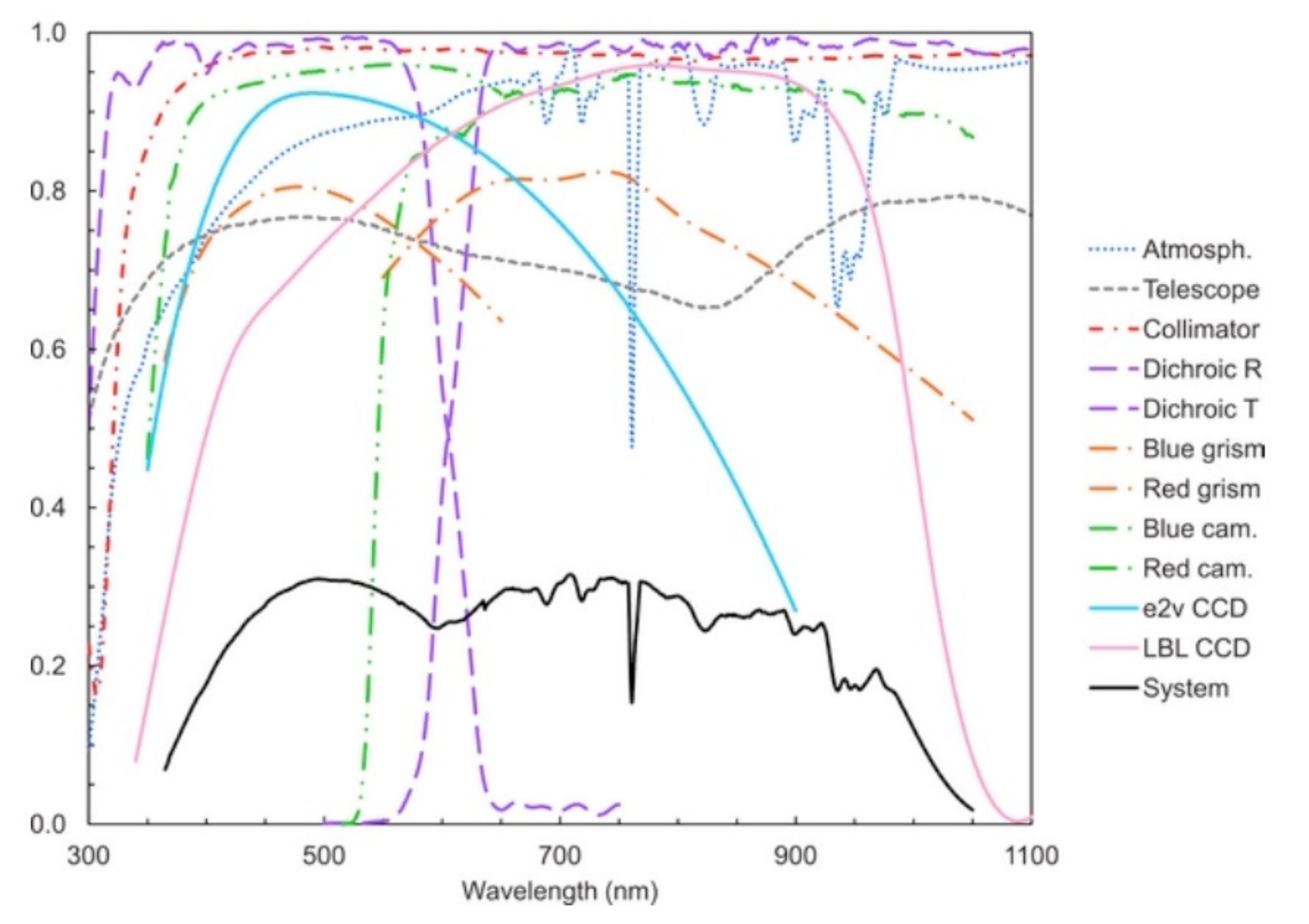


Hα image of NGC 4450

MaNGA fiber bundle
(with 3 dither positions)

Recovered velocity map

Spectroscopic Throughput



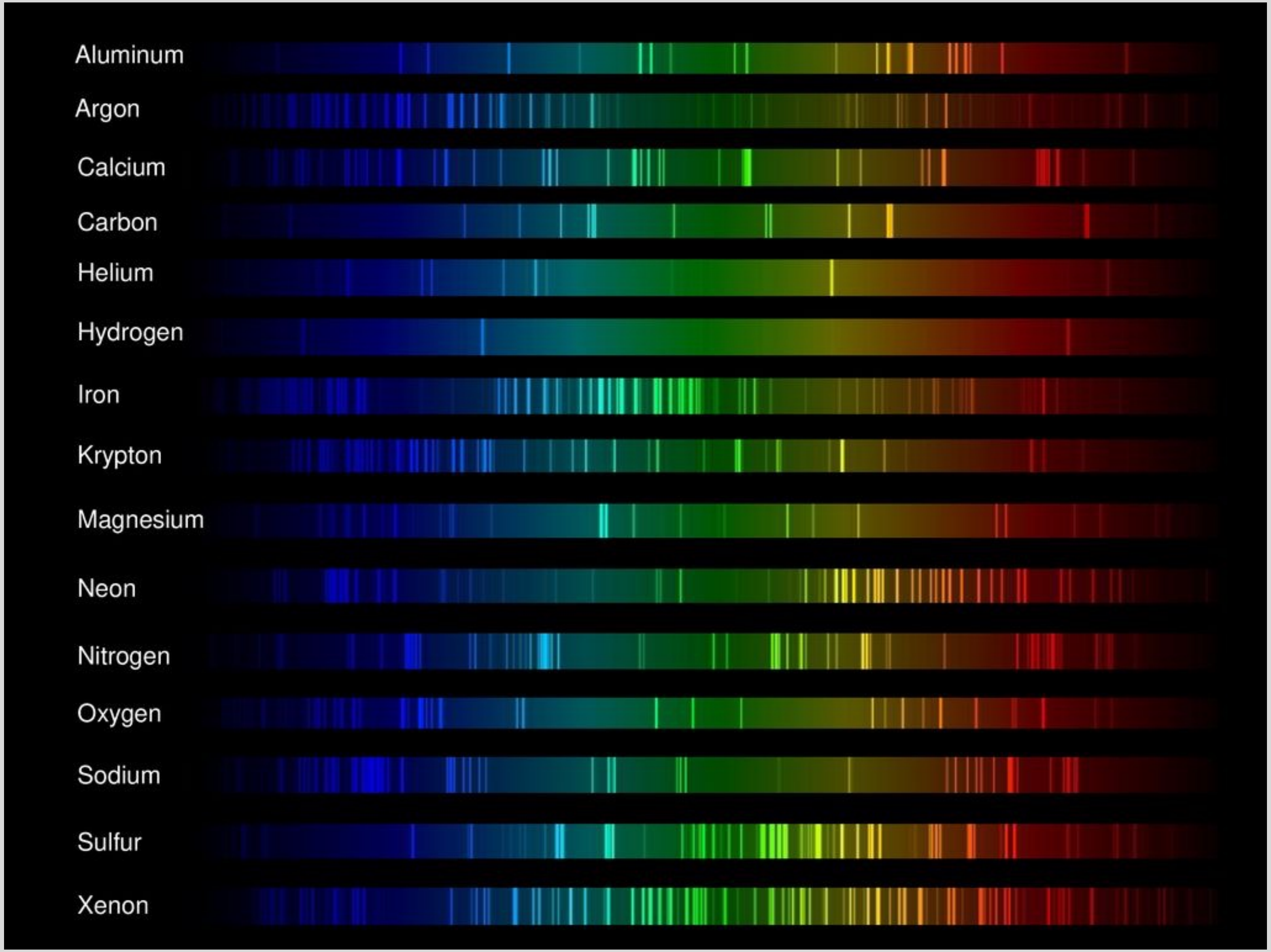
Wavelength Calibration

Take spectra of an arc-lamp: flourescent tube filled with known gas (Argon, Neon, etc).

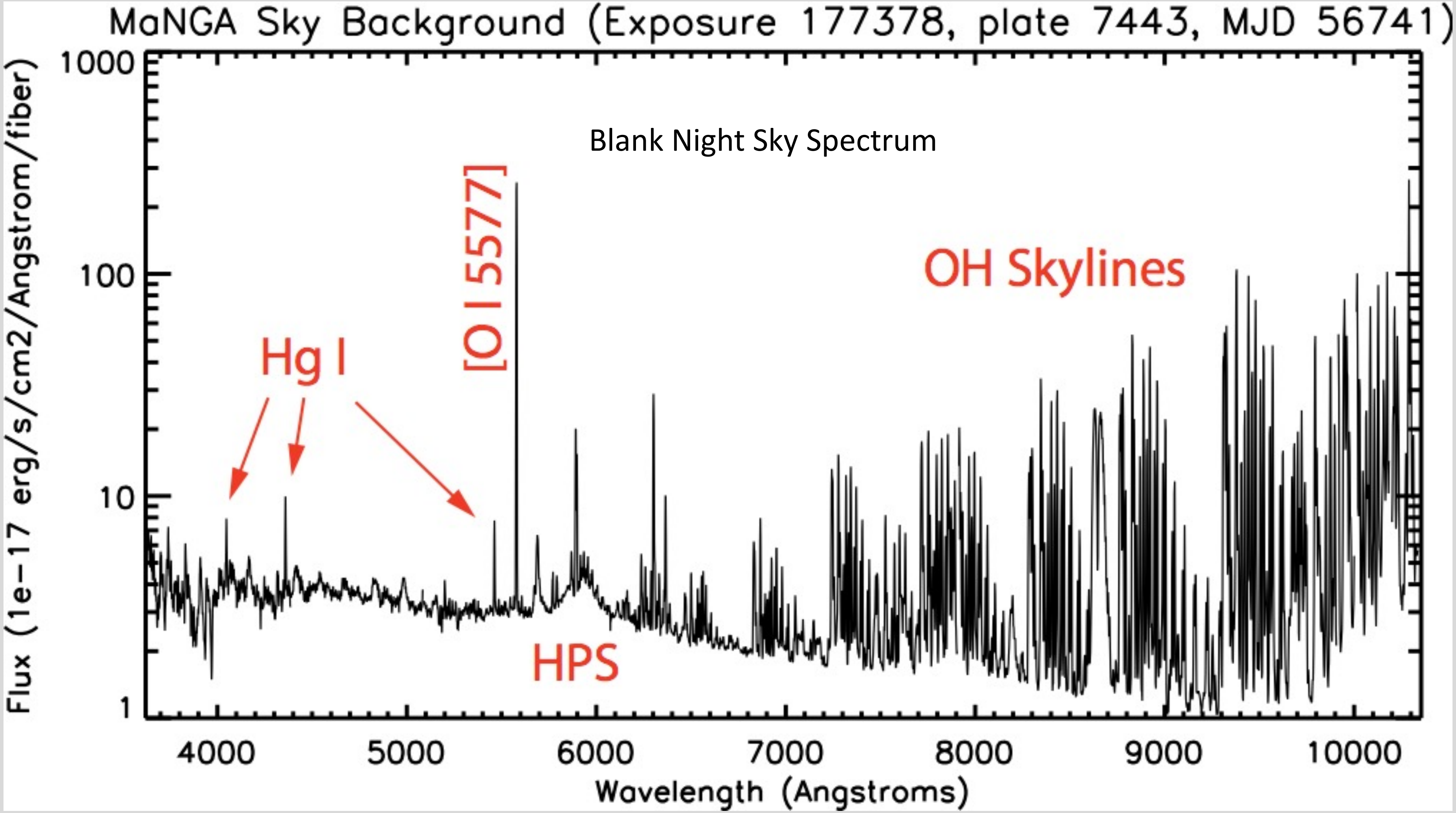
Measure the X position of the lines, fit a high order polynomial function given the known wavelengths:

$$\lambda = f(X)$$

Typically do this several times a night (or more frequently) to account for changes in the spectrograph over time.



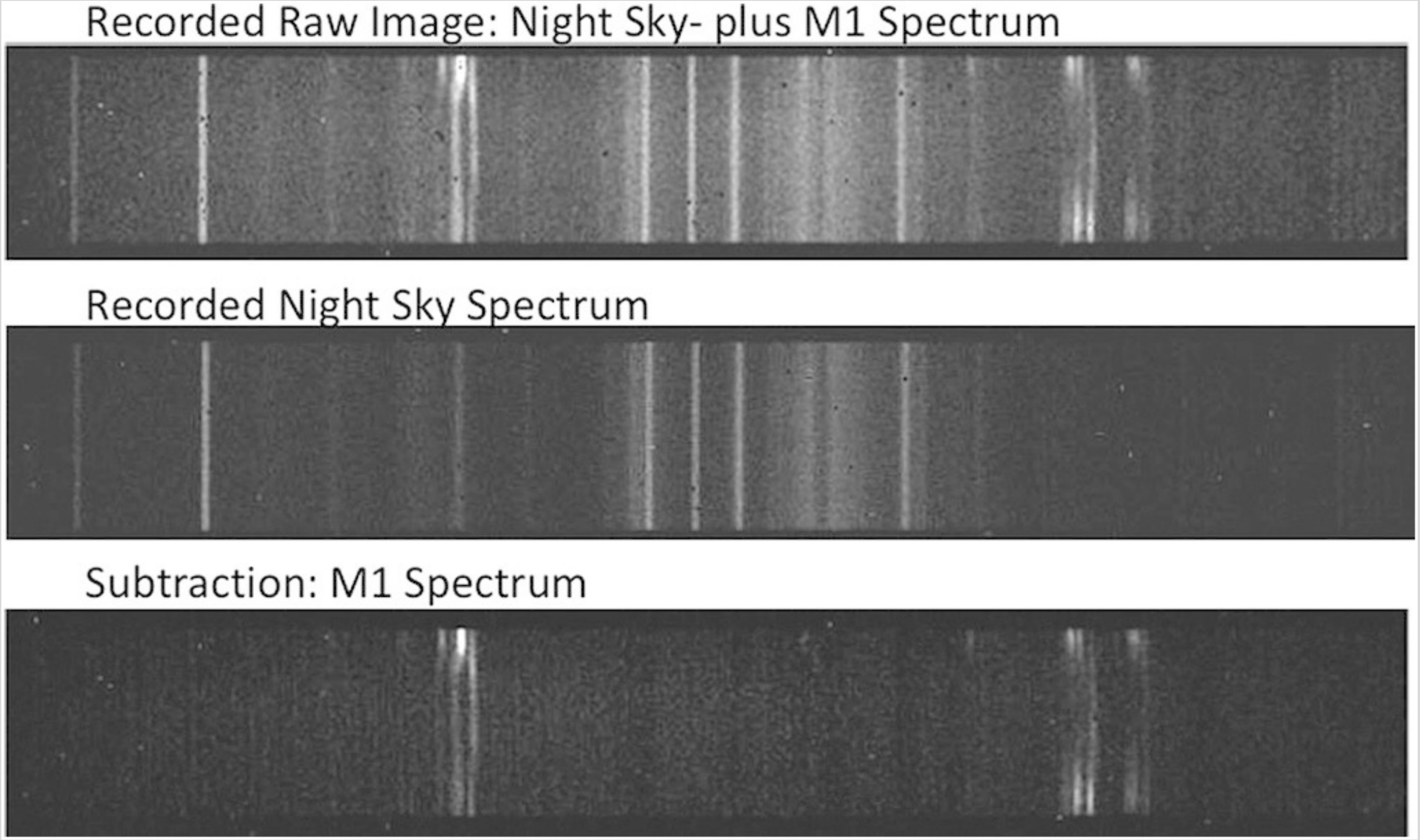
Spectroscopic Sky Subtraction



Spectroscopic Sky Subtraction

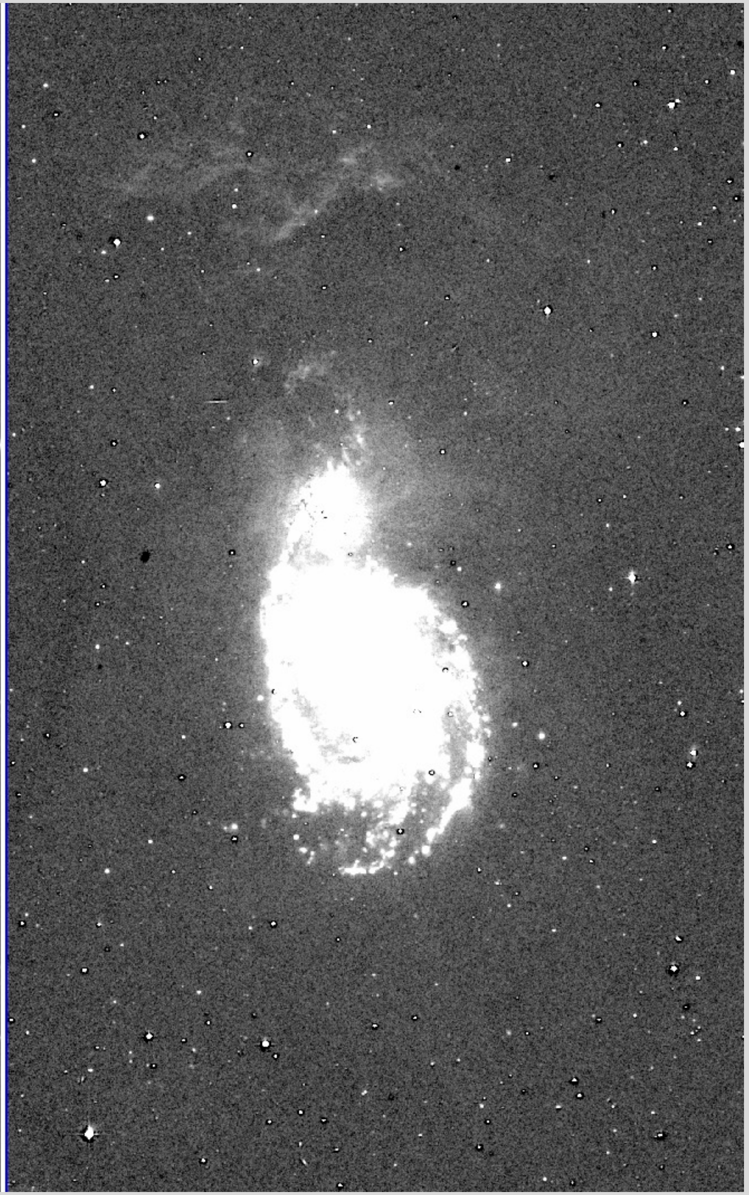
Take blank sky spectra and subtract:

Night sky lines can vary in intensity over time, so ideally get blank sky spectra at the same time as spectrum of target.



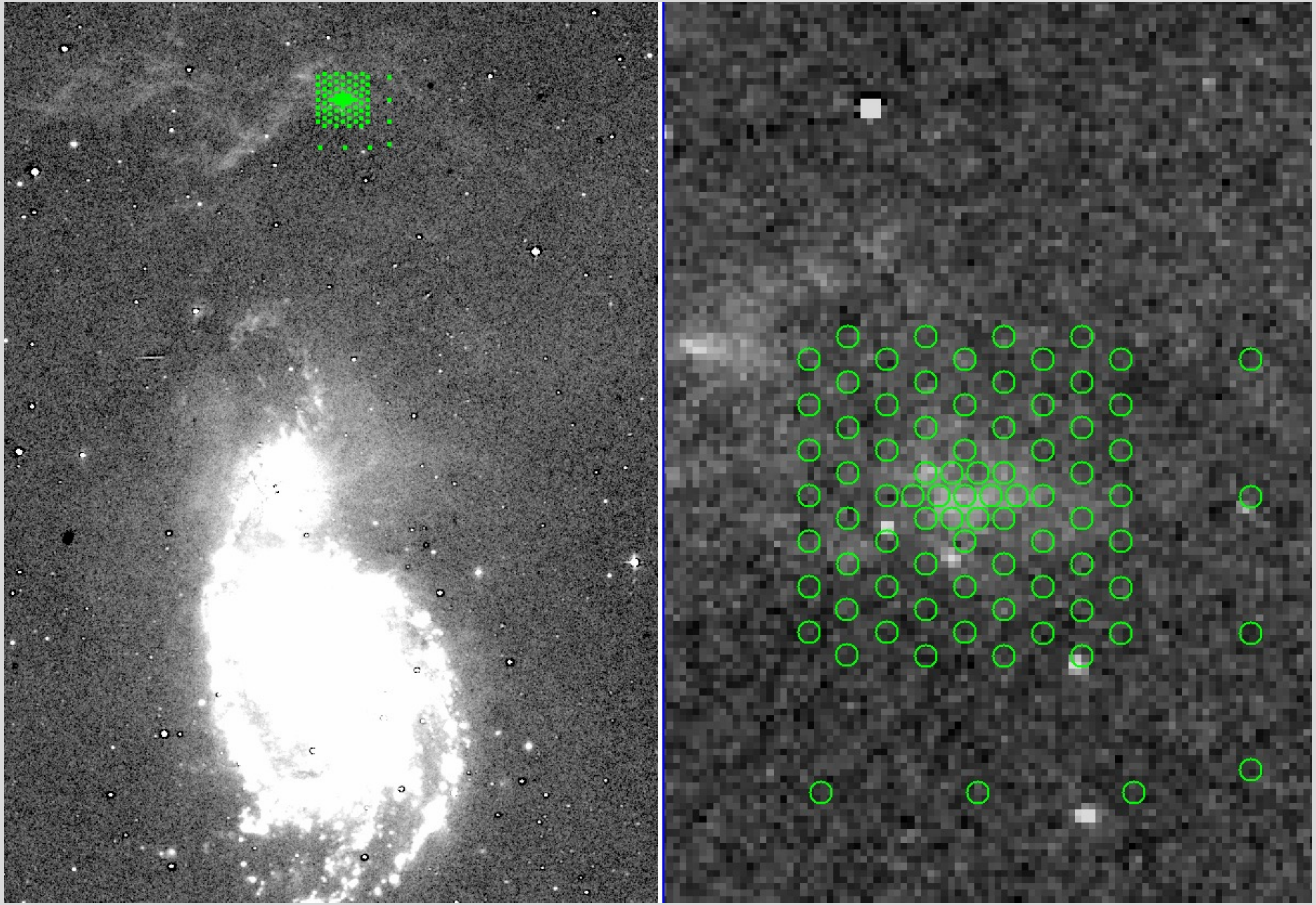
Spectroscopic Sky Subtraction

M51 (B)



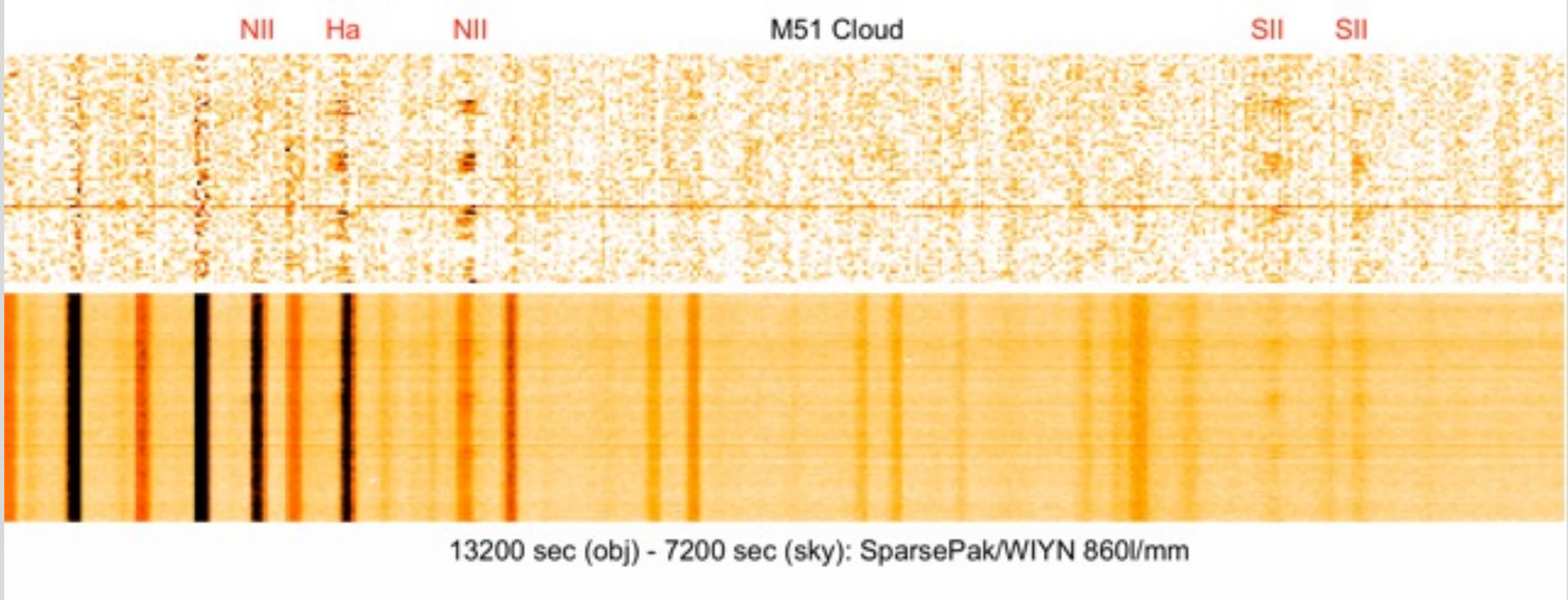
M51 (Hα)

Spectroscopic Sky Subtraction



WIYN/Sparsepak pointing

Spectroscopic Sky Subtraction



Spectroscopic Sky Subtraction