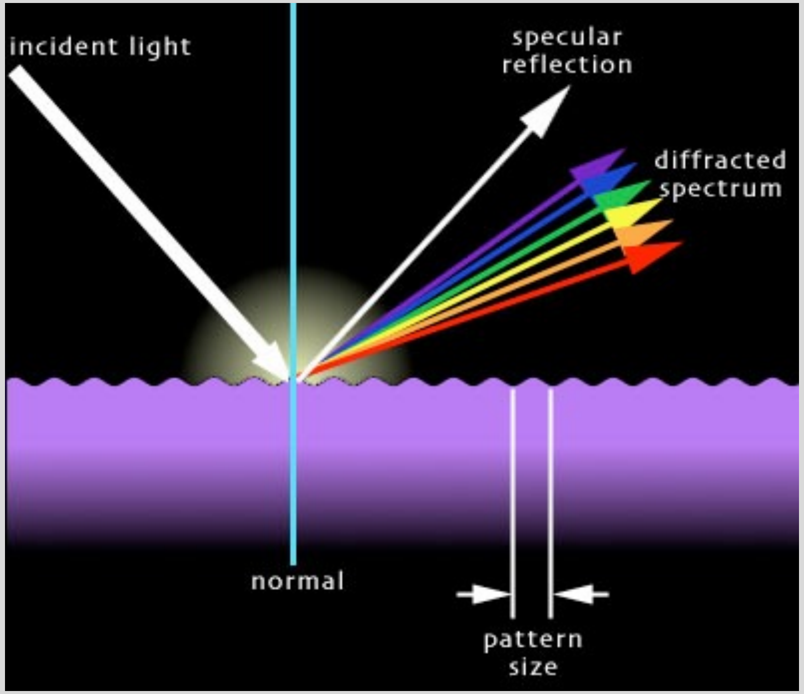
The Grating Equation

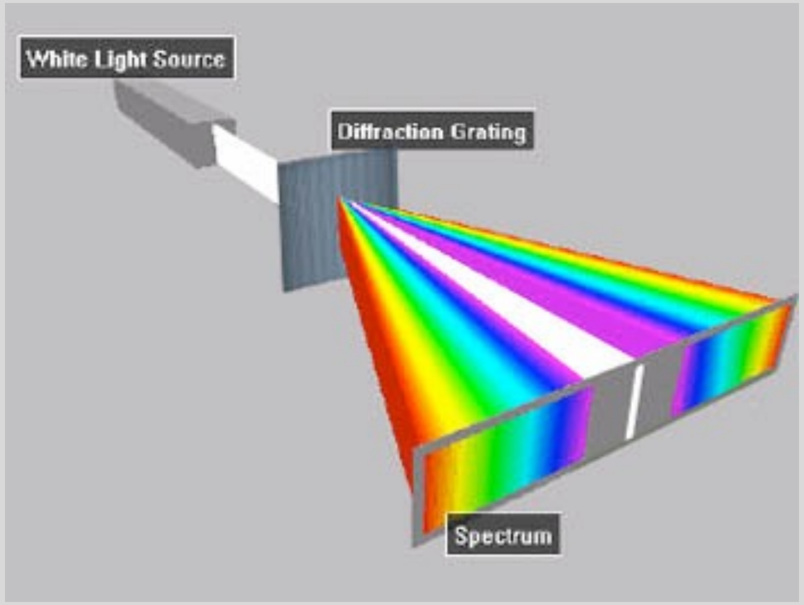
$$\boxed{m\lambda = d\sin\alpha + d\sin\beta}$$

for either reflection or transmission gratings!

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



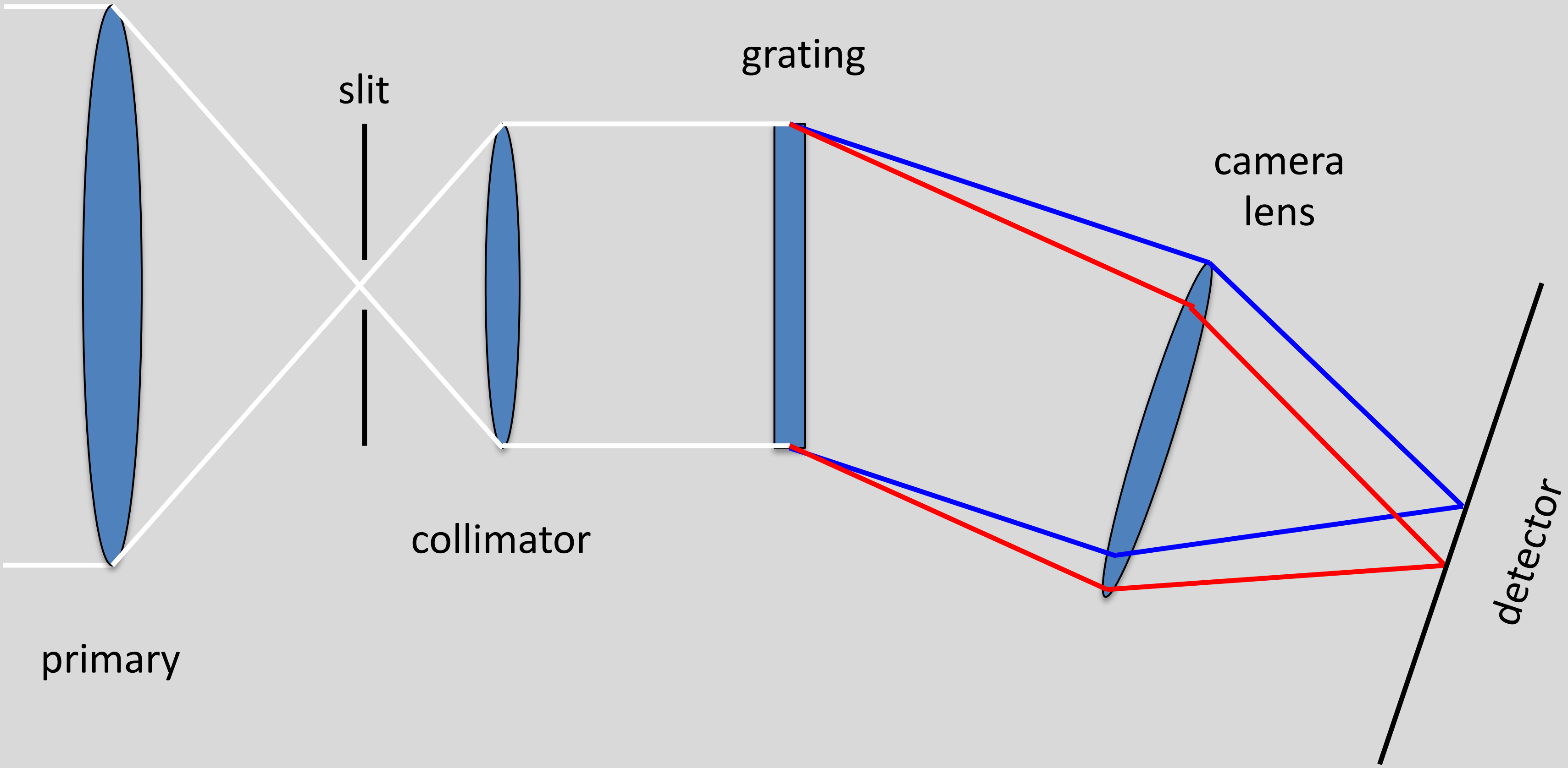
m = −3 −2 −1 0 +1 +2 +3



Remember, higher orders are:

- fainter
- more dispersed

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!

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:

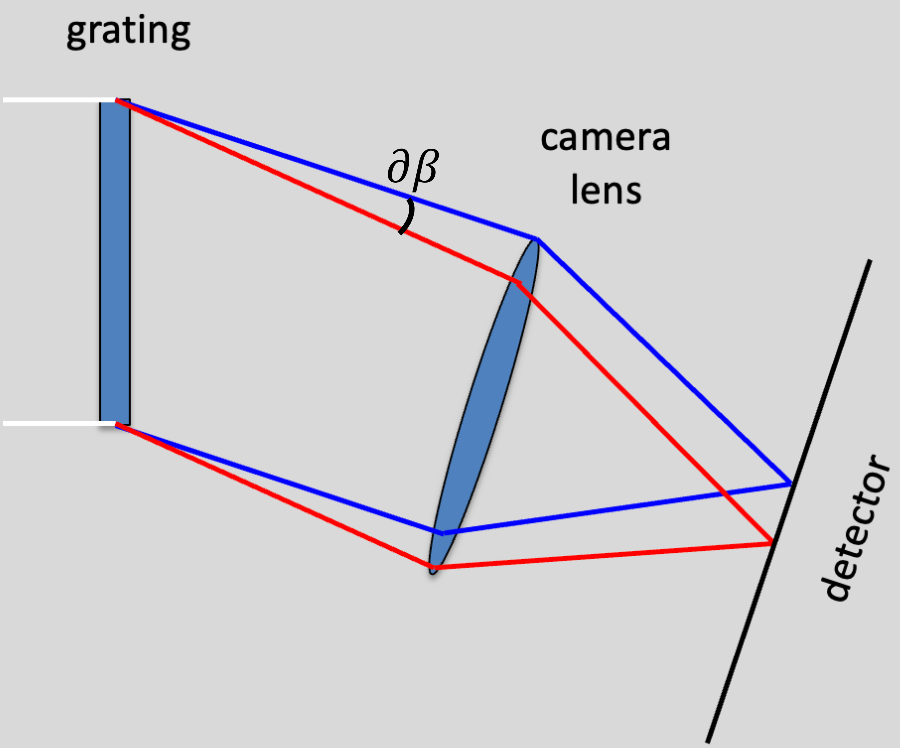
$$m\lambda = d\sin\alpha + d\sin\beta$$

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:

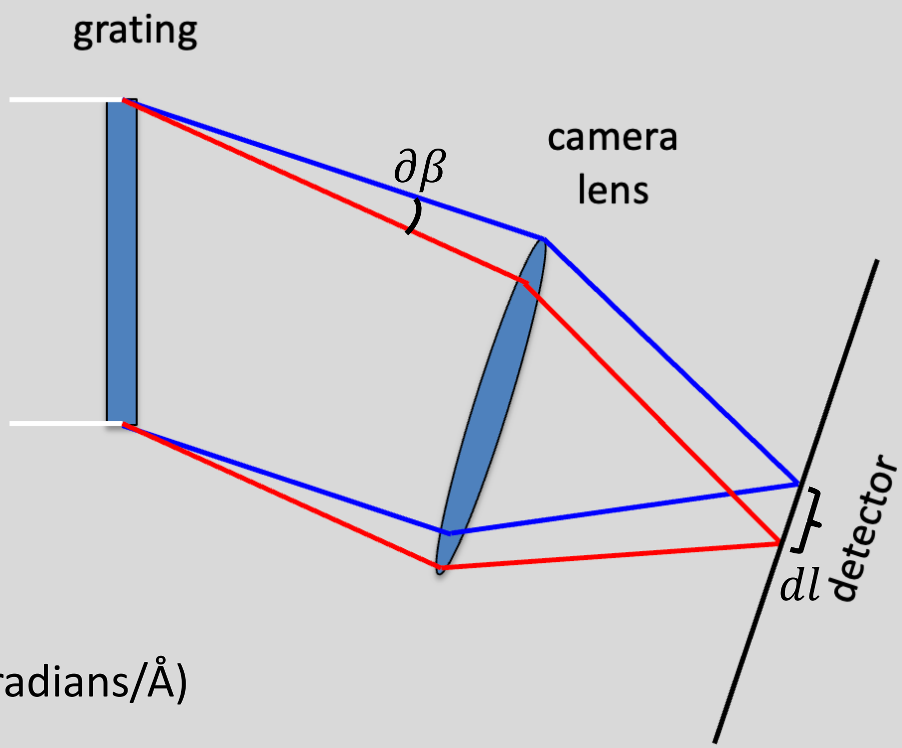
$$\frac{\partial\beta}{\partial\lambda} = \frac{m}{d\cos\beta} = \frac{\sin\alpha + \sin\beta}{\lambda\cos\beta}$$



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)

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

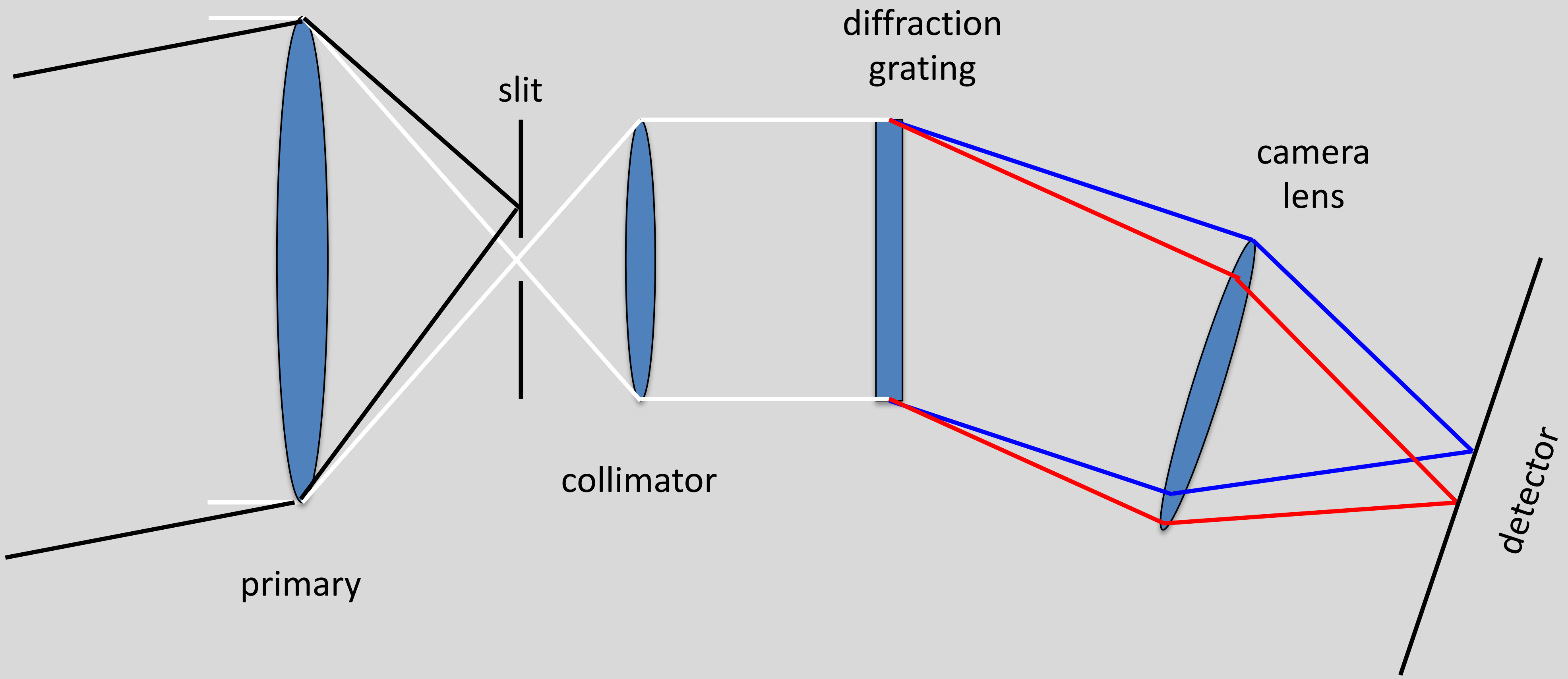
Remember: this is **linear dispersion**, units are (for example) Angstroms/mm

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?

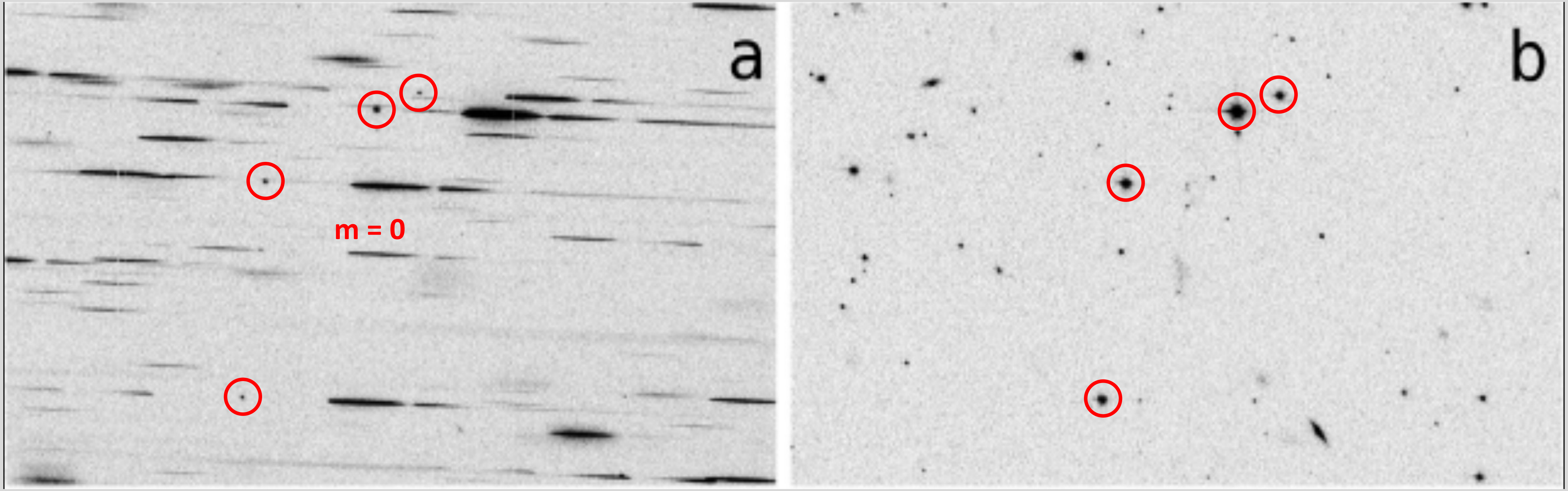
With all else fixed,

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

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

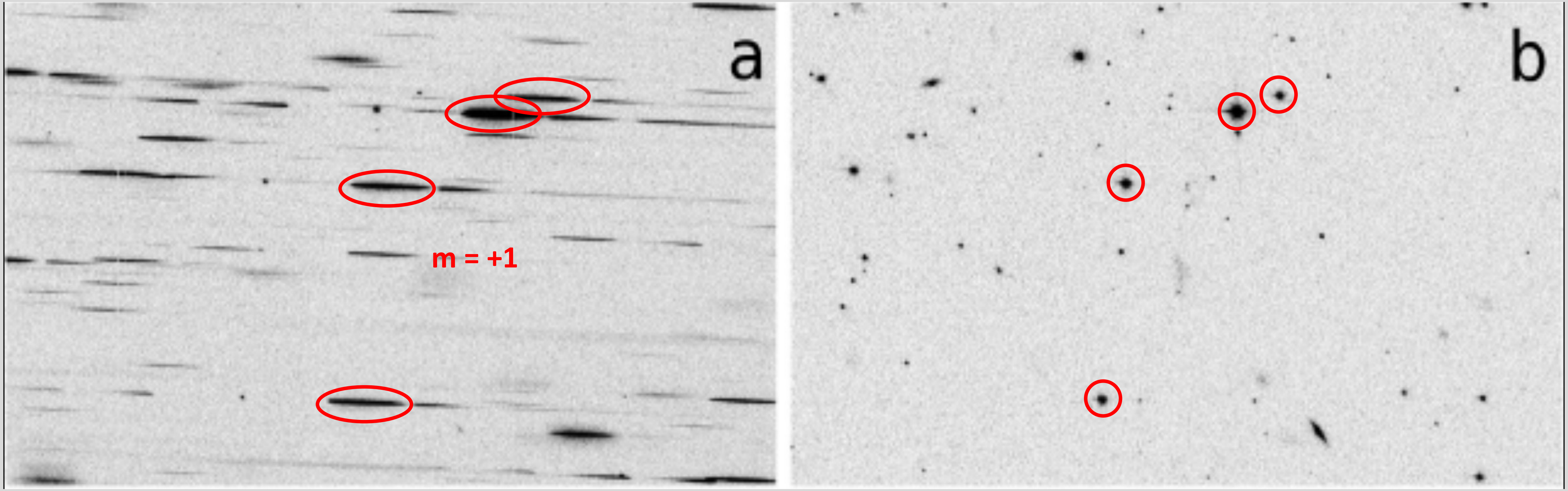
Direct Image

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



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Direct Image

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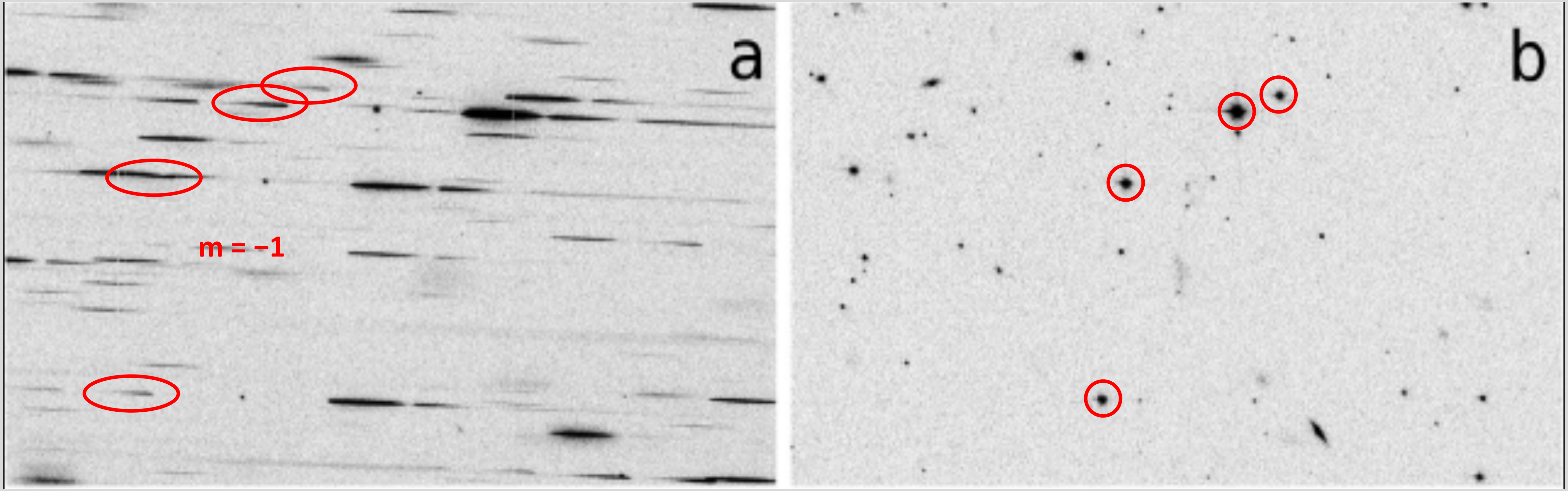
[Kümmel+ 09]

Slitless Spectroscopy



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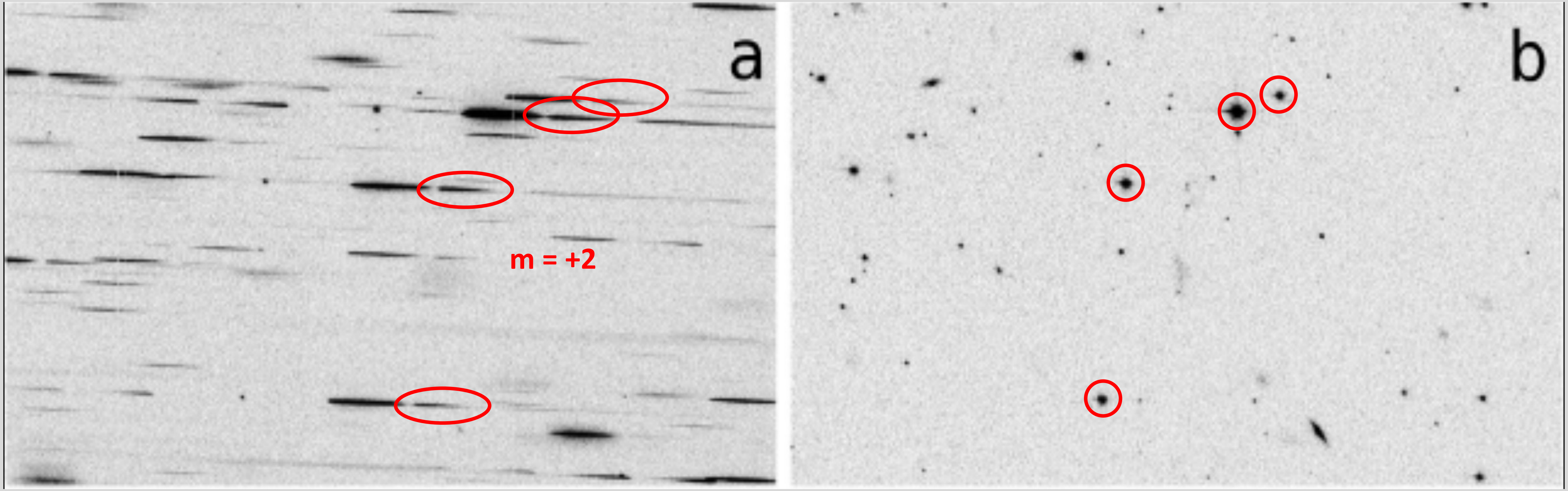
Kümmel+ 09

Slitless Spectroscopy



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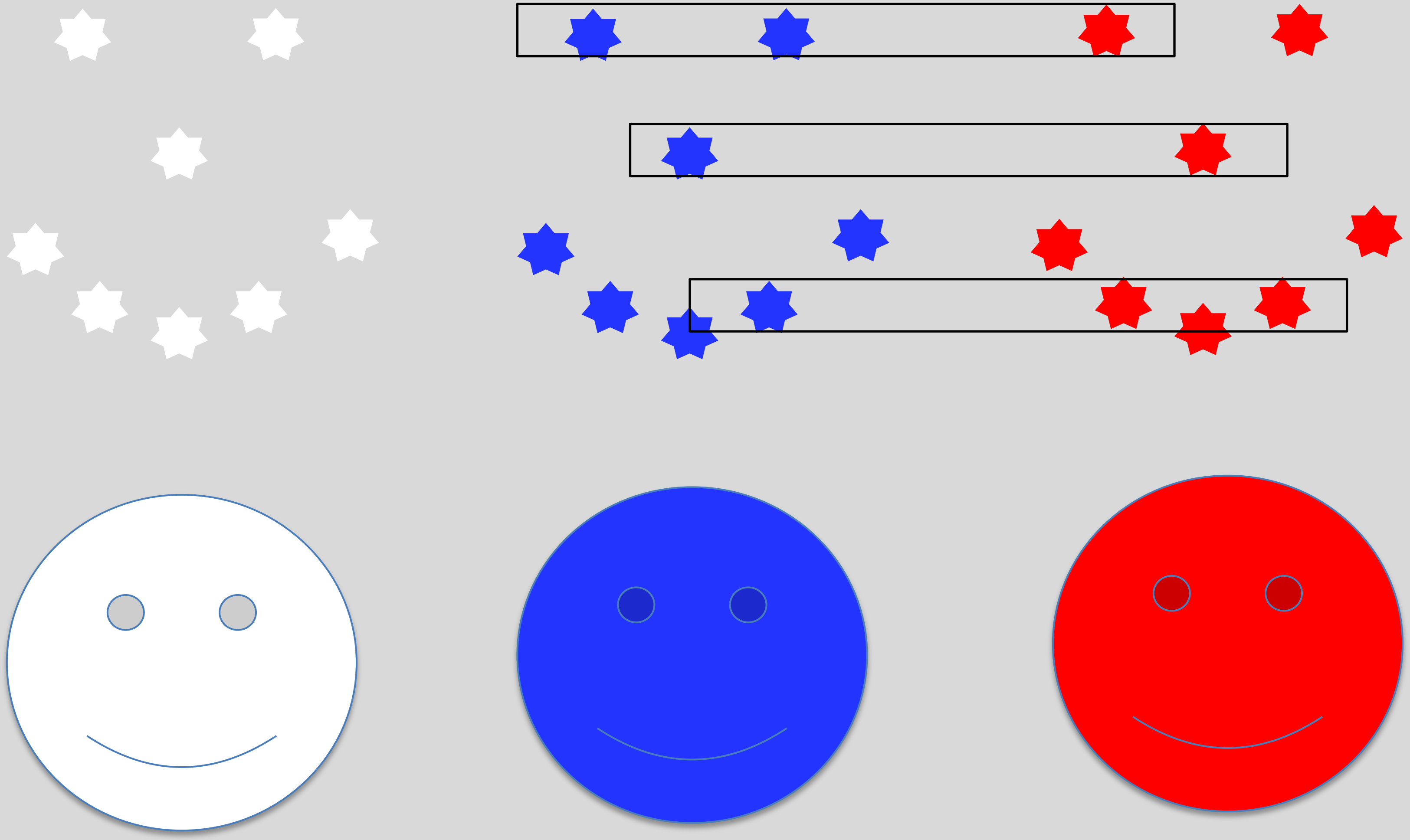
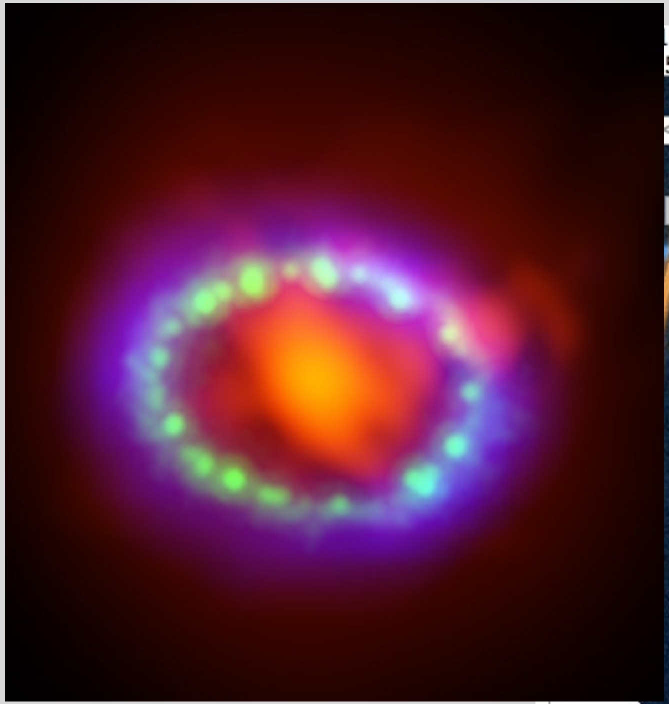
Kümmel+ 09

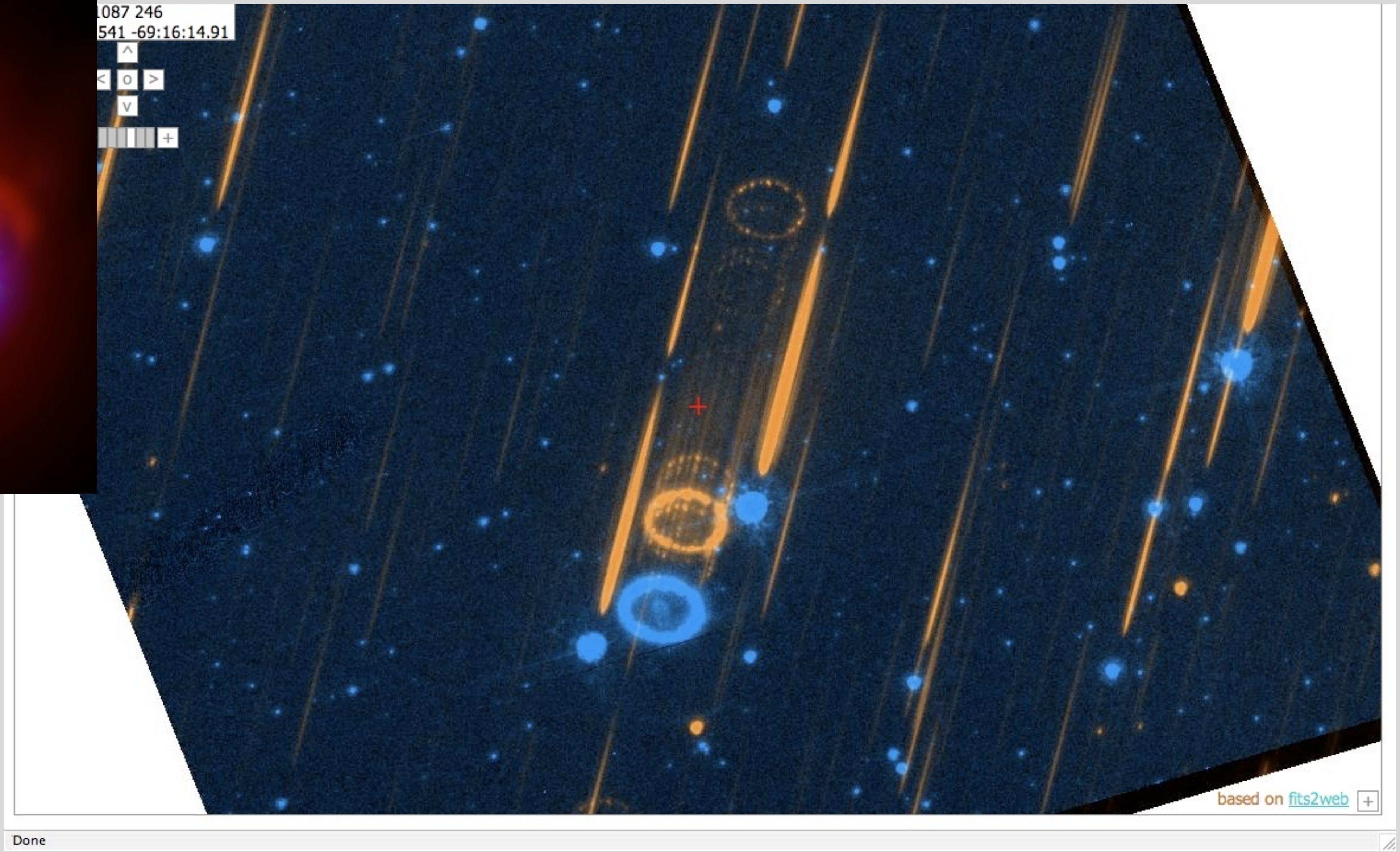
Slitless Spectroscopy: Spectral Images

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

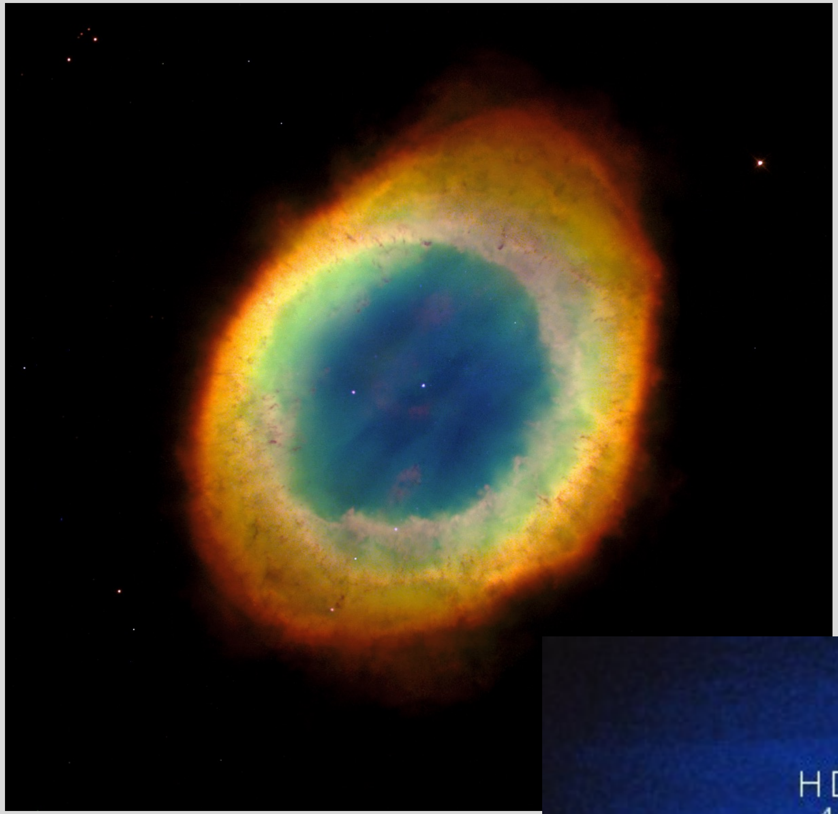


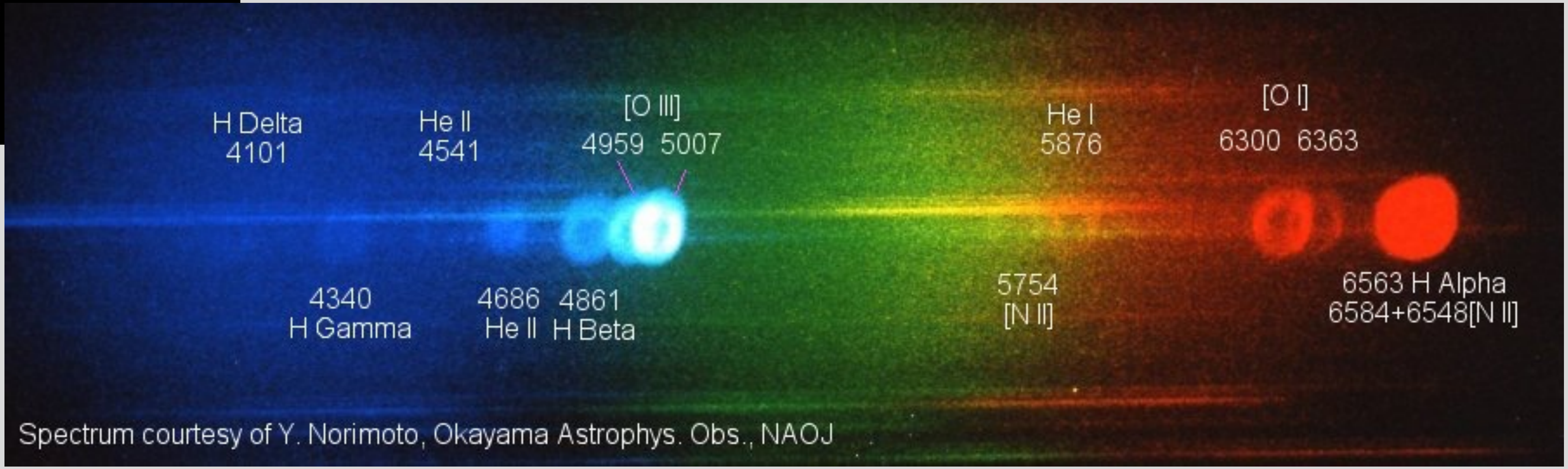
Slitless Spectroscopy: rings around SN1987a



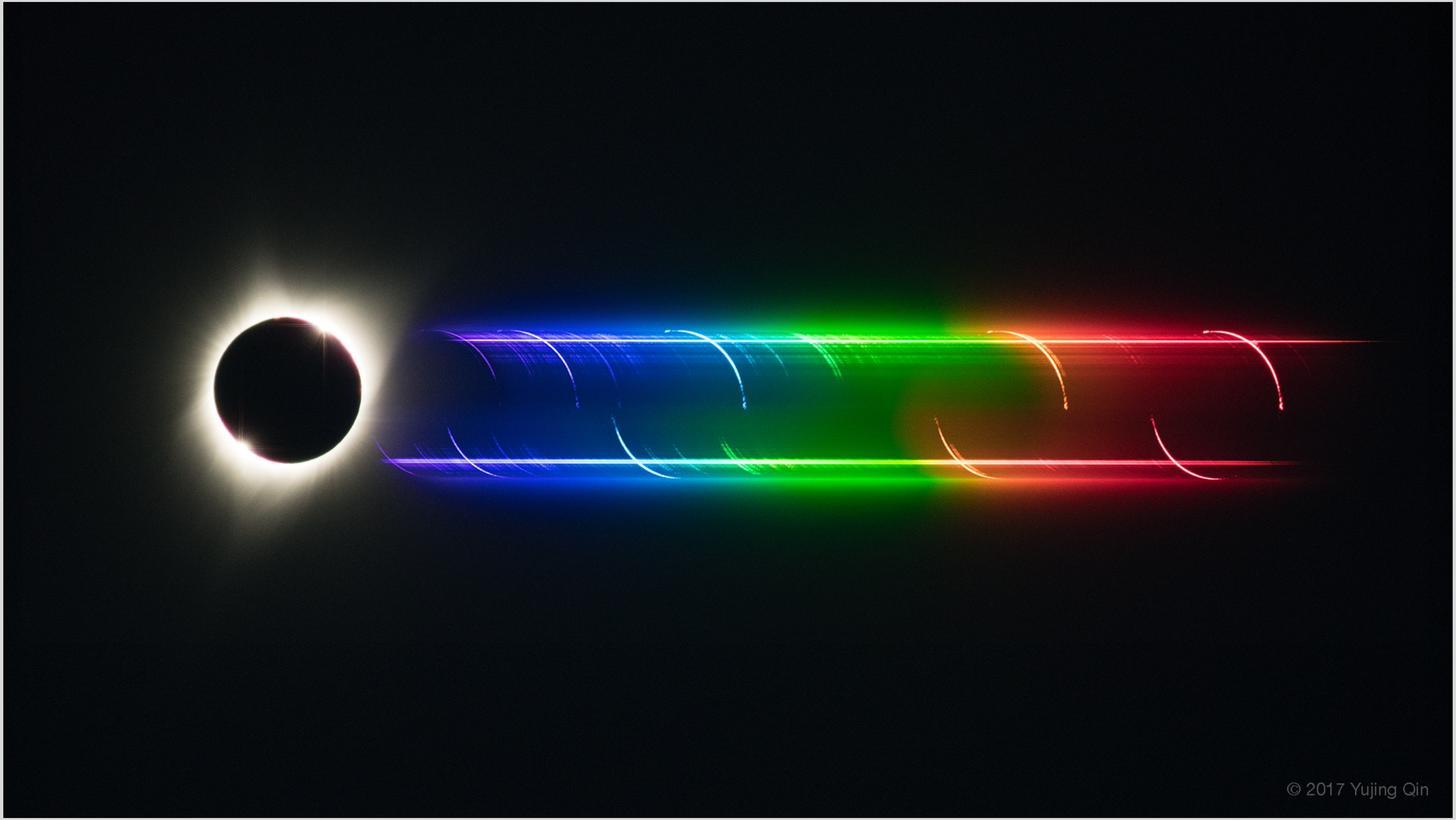


Slitless Spectroscopy: the Ring Nebula (planetary nebula)

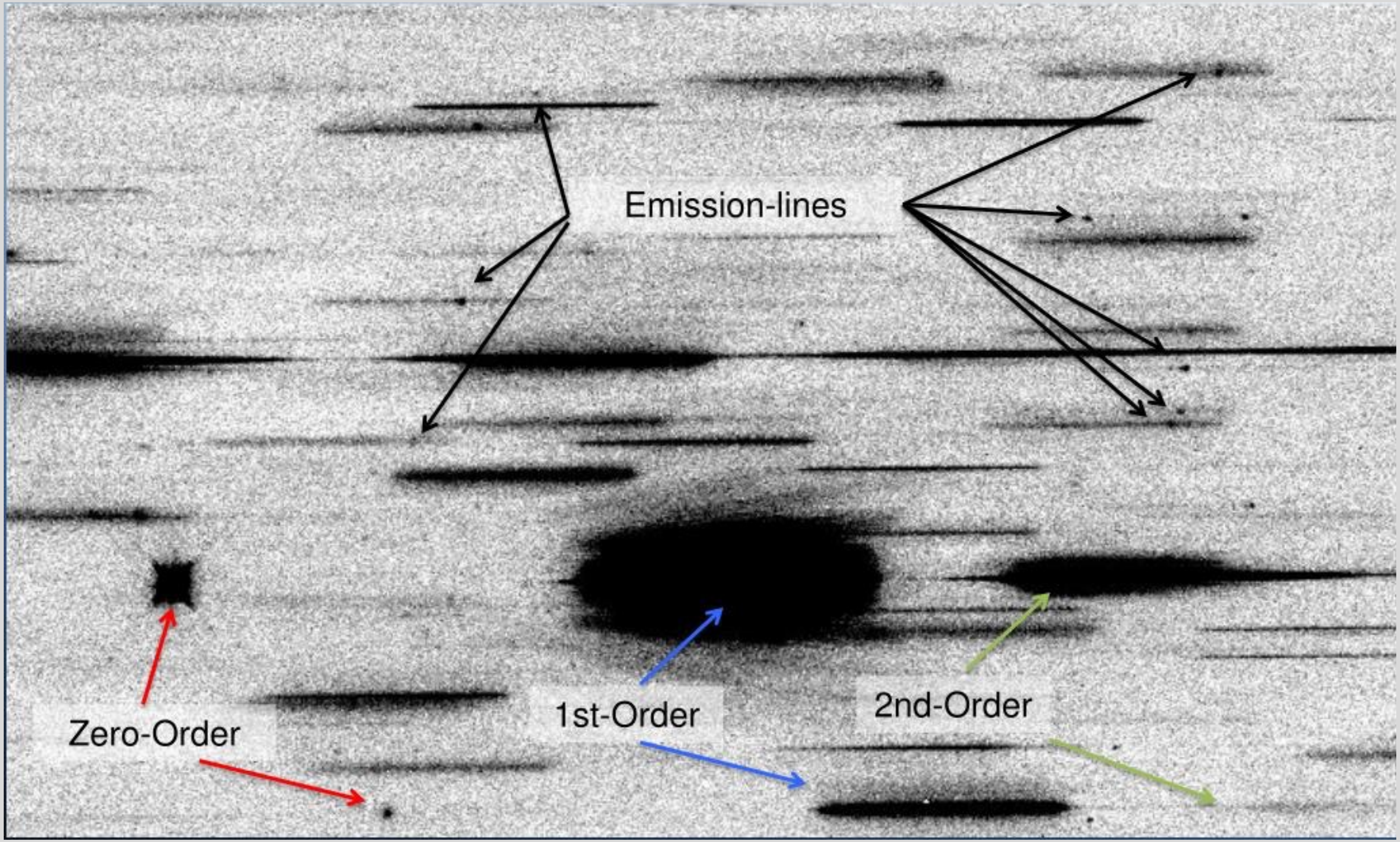




Slitless Spectroscopy: the Solar Corona



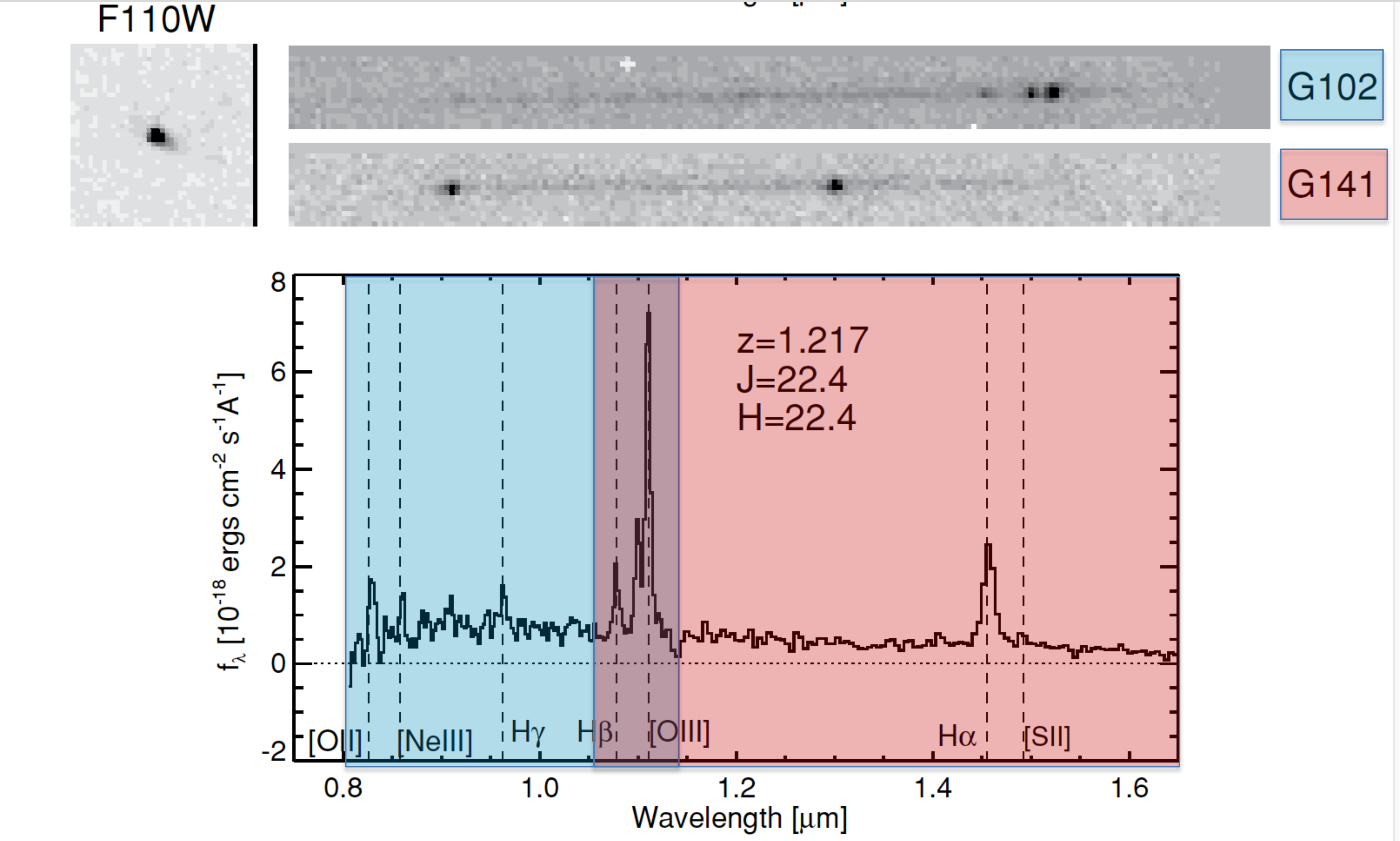
Slitless Spectroscopy: high-z galaxies



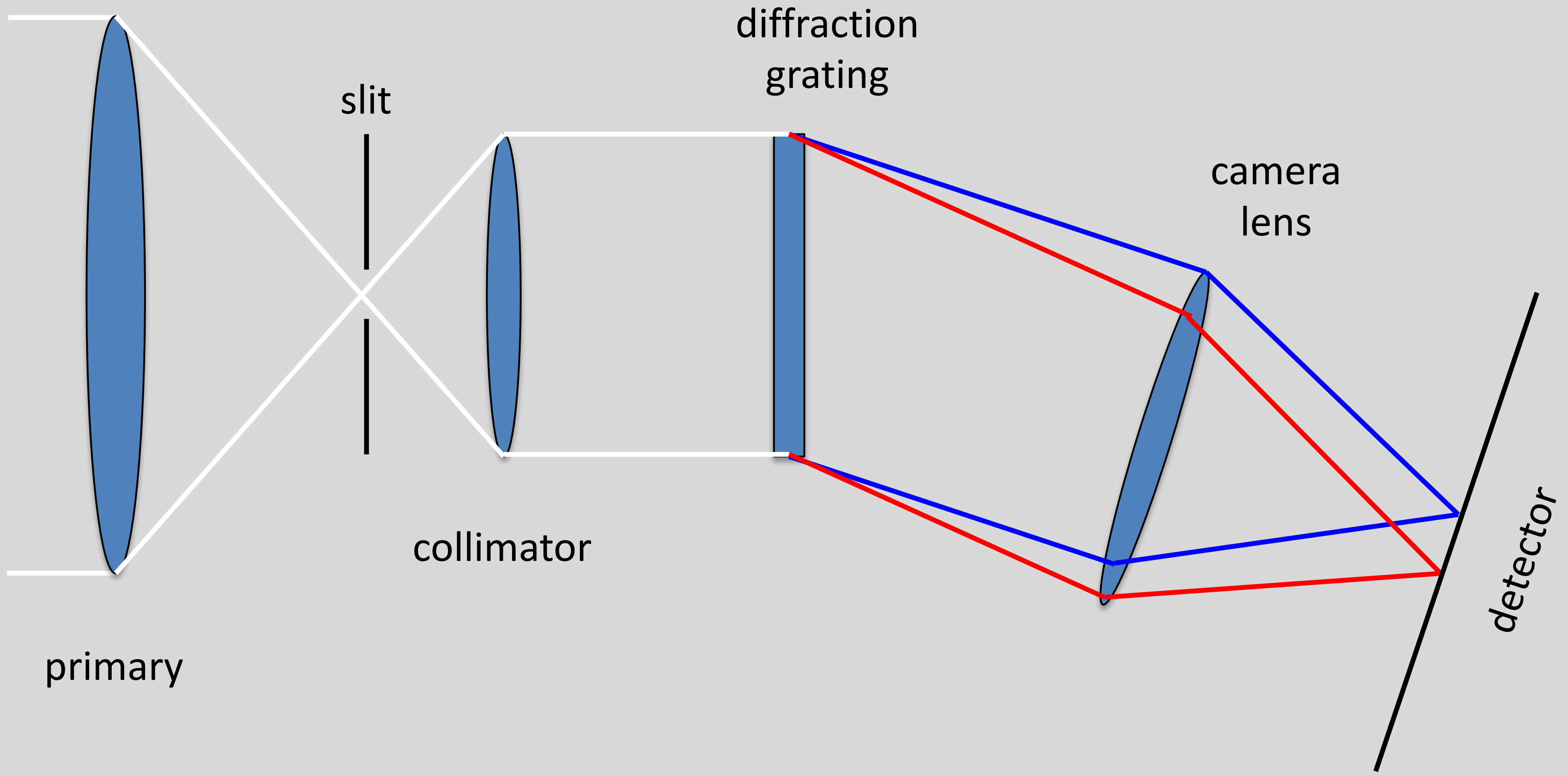
courtesy P McCarthy

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: $\omega_\lambda = \omega' \, d \cos\beta/(mf_{cam})$
- 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)

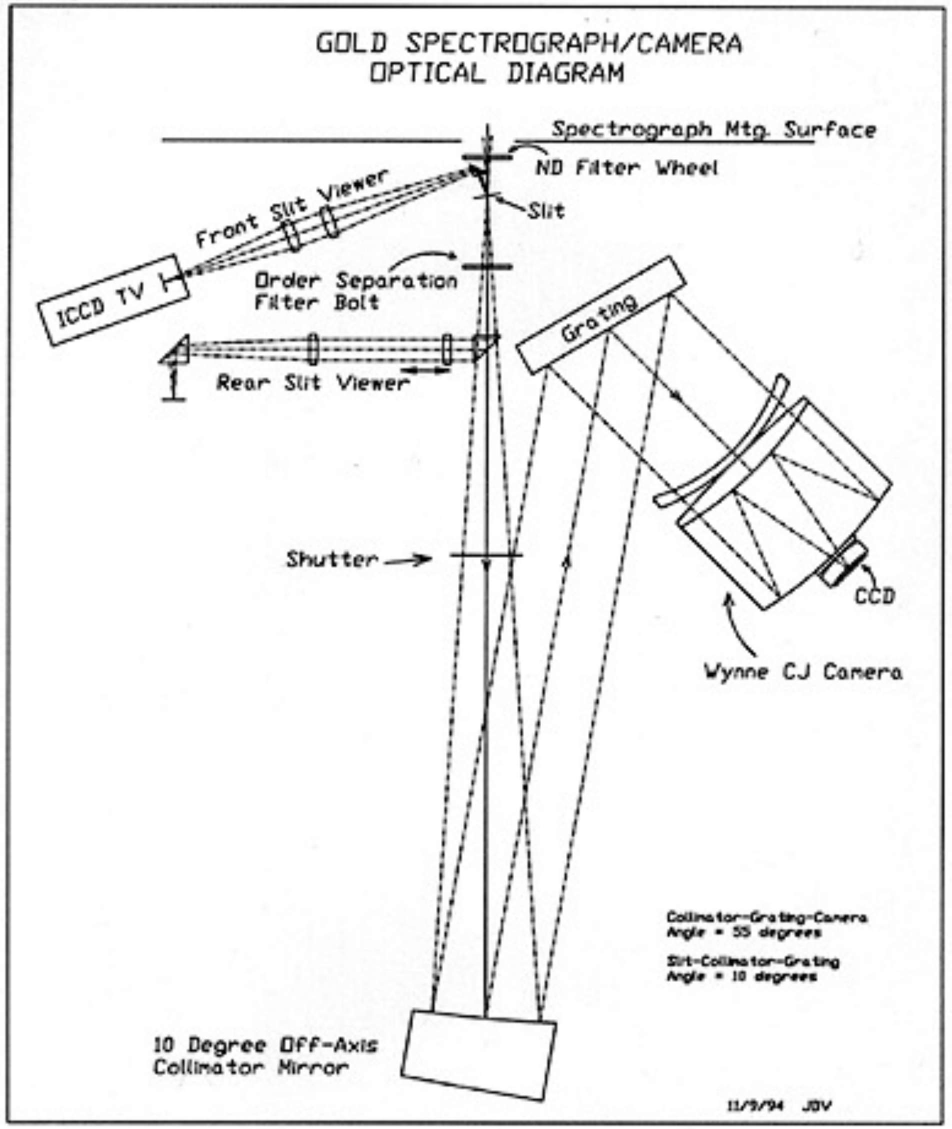
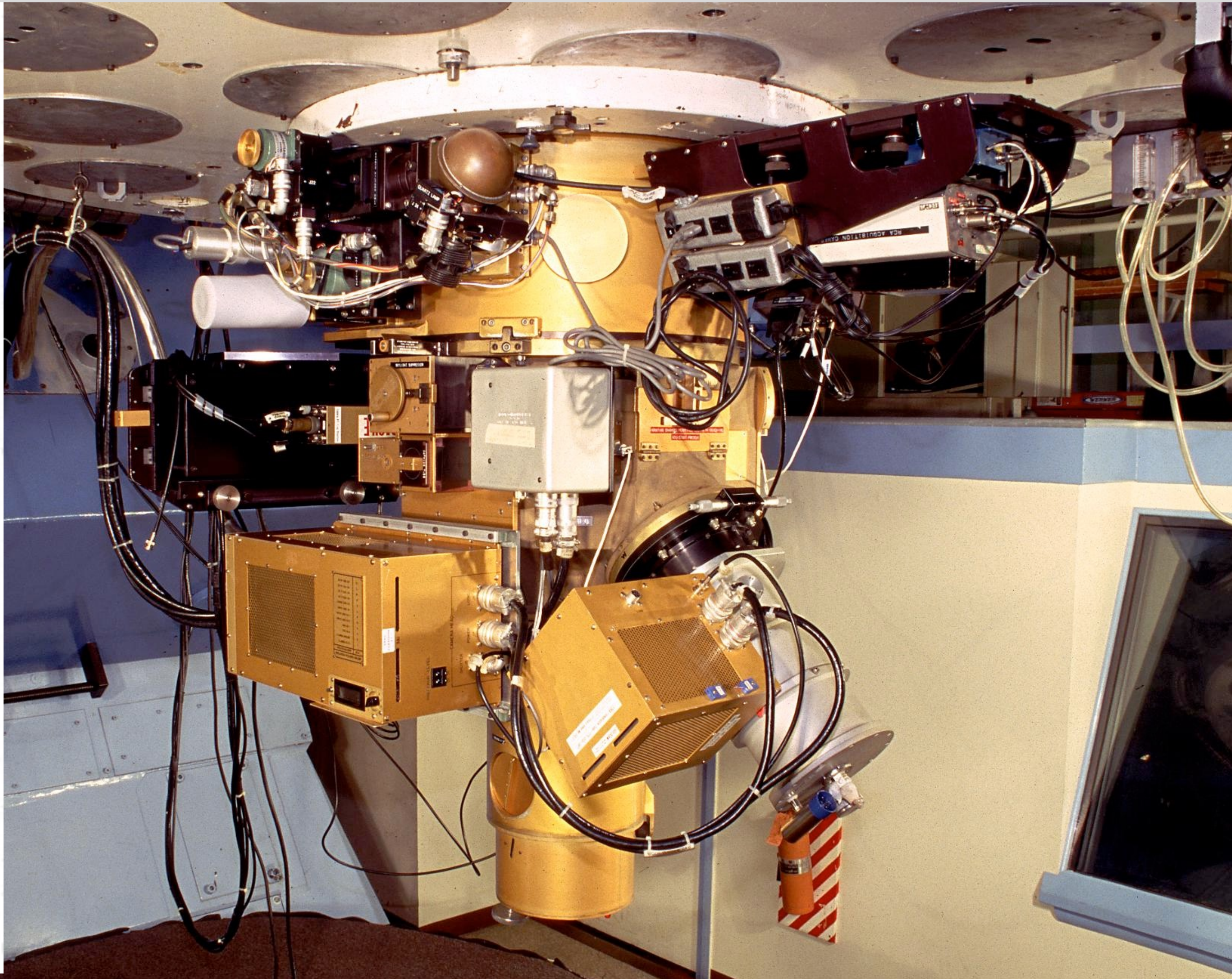
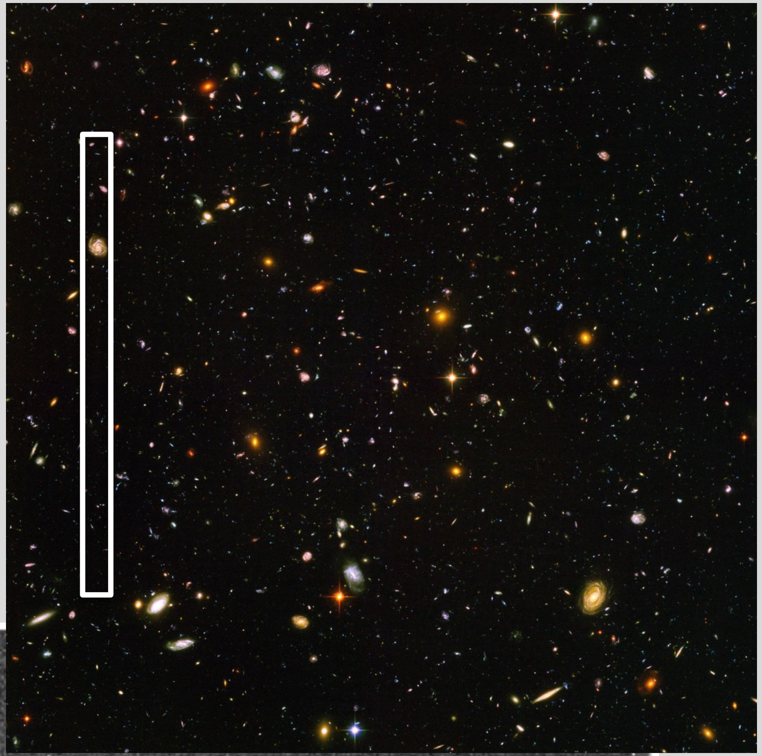


Figure 1: GCAM Spectrograph Optical Diagram

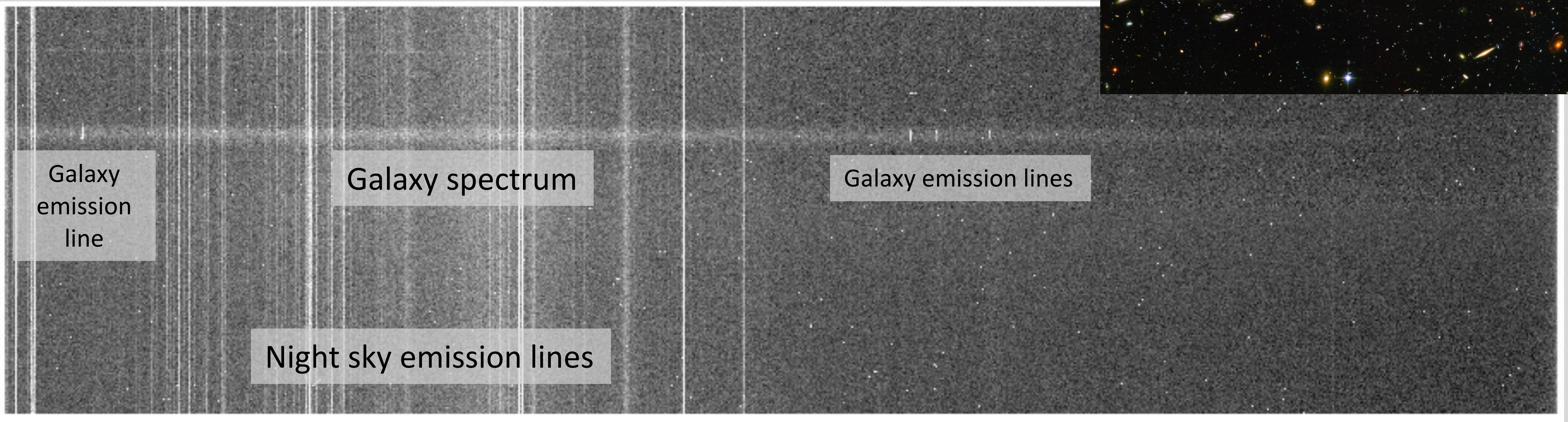


Longslit Spectroscopy



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

we get a spectral image that looks like this



Spatial direction →

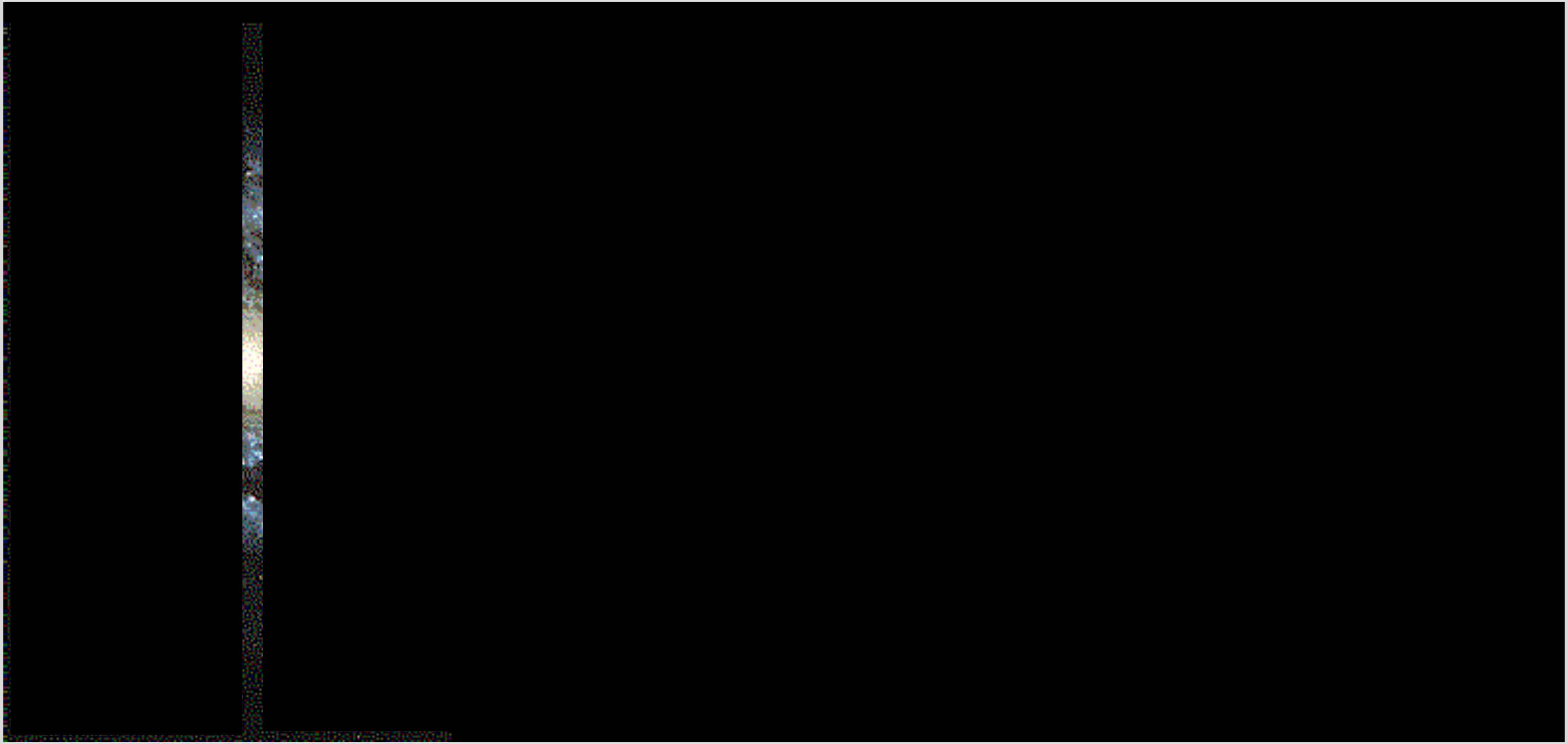
Spectral direction →

Longslit Spectroscopy

Extended source (nearby galaxy)

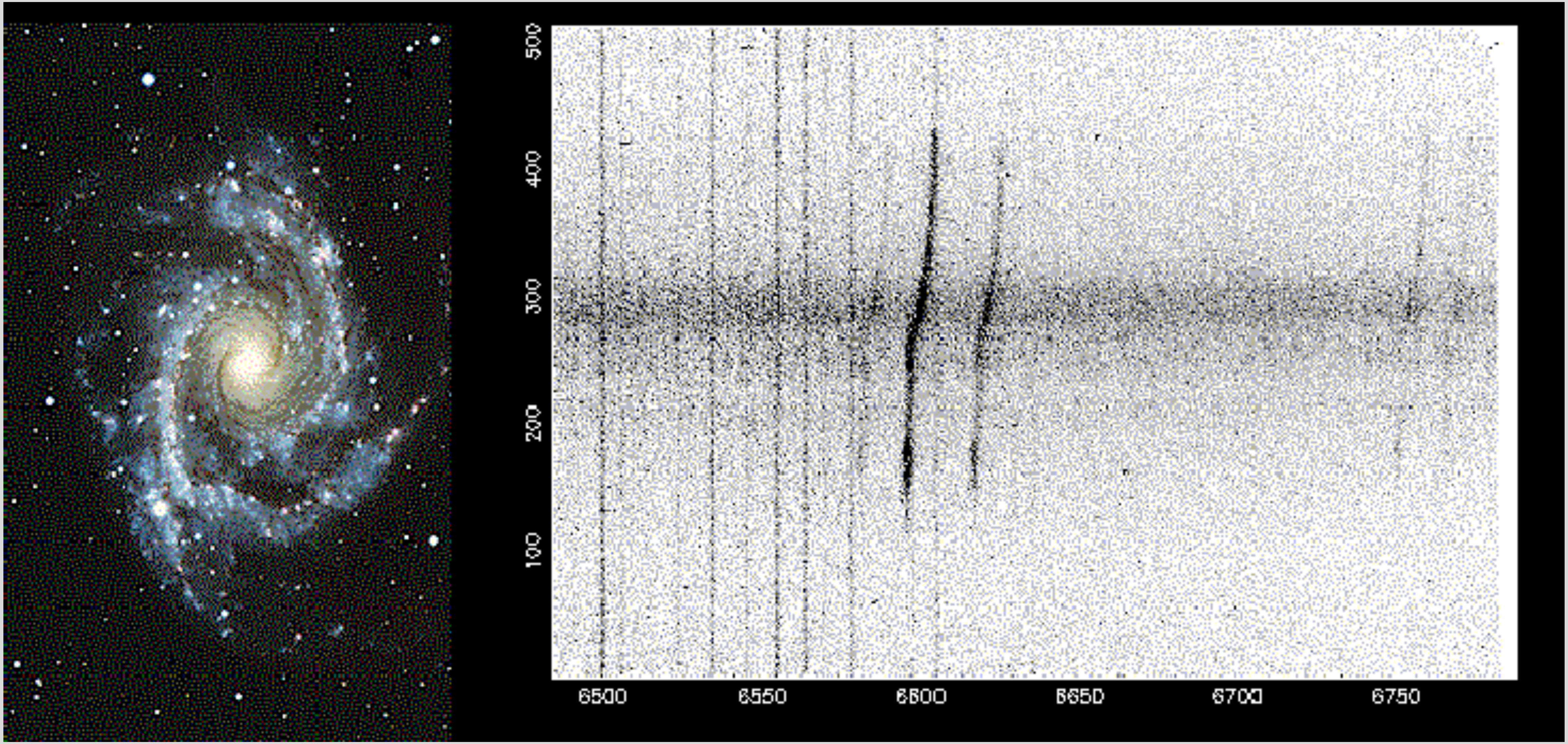
Longslit Spectroscopy

Extended source (nearby galaxy)



Longslit Spectroscopy

Extended source (nearby galaxy)



Multi-object spectroscopy: Slitmasks

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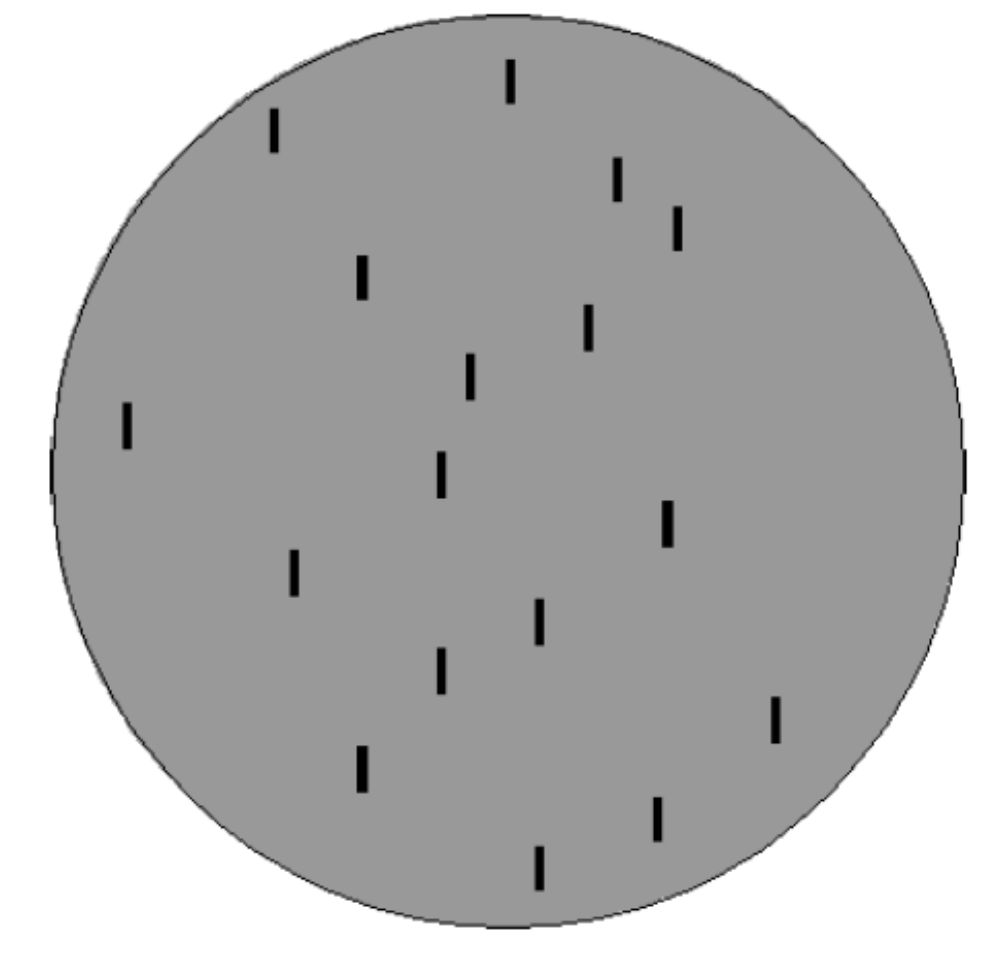


Metal plate with slits cut at the position of stars.

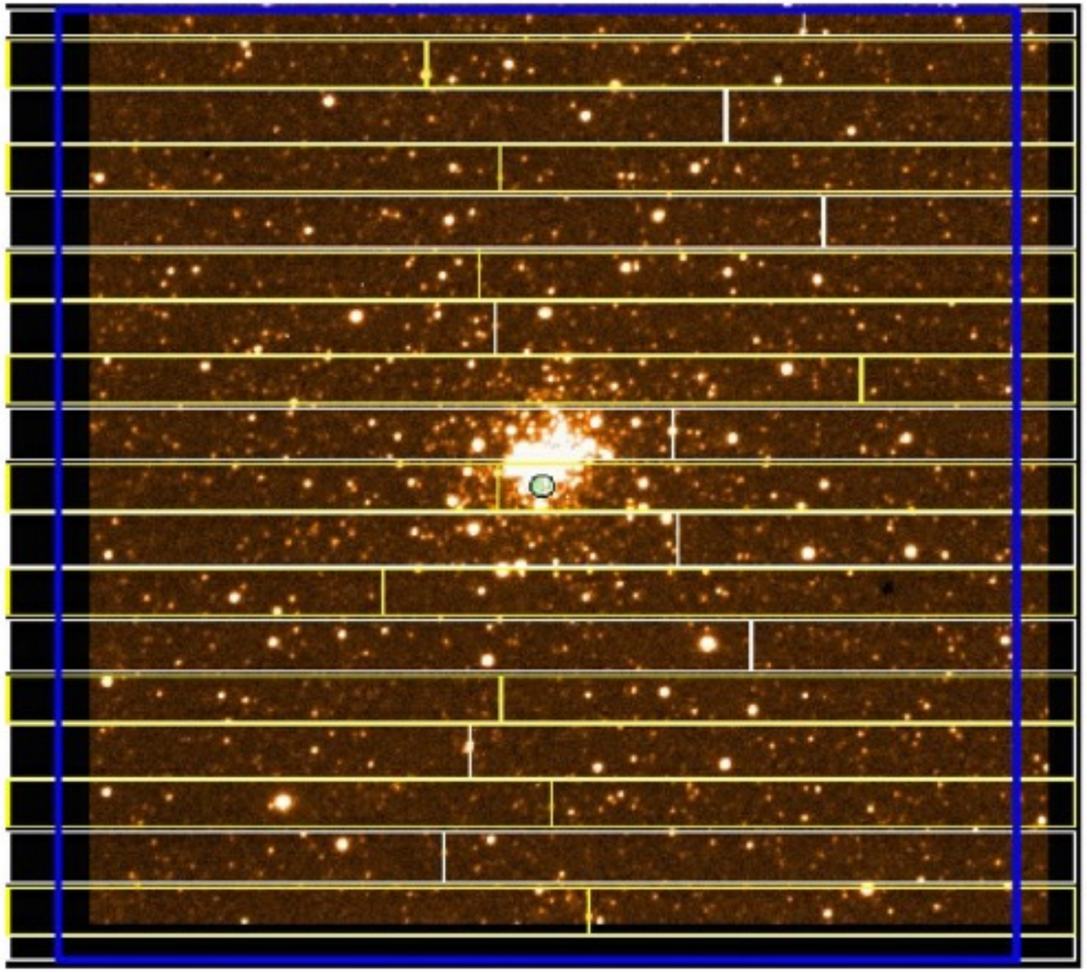
Put at focal plane of telescope; star light passes through slit onto grating.

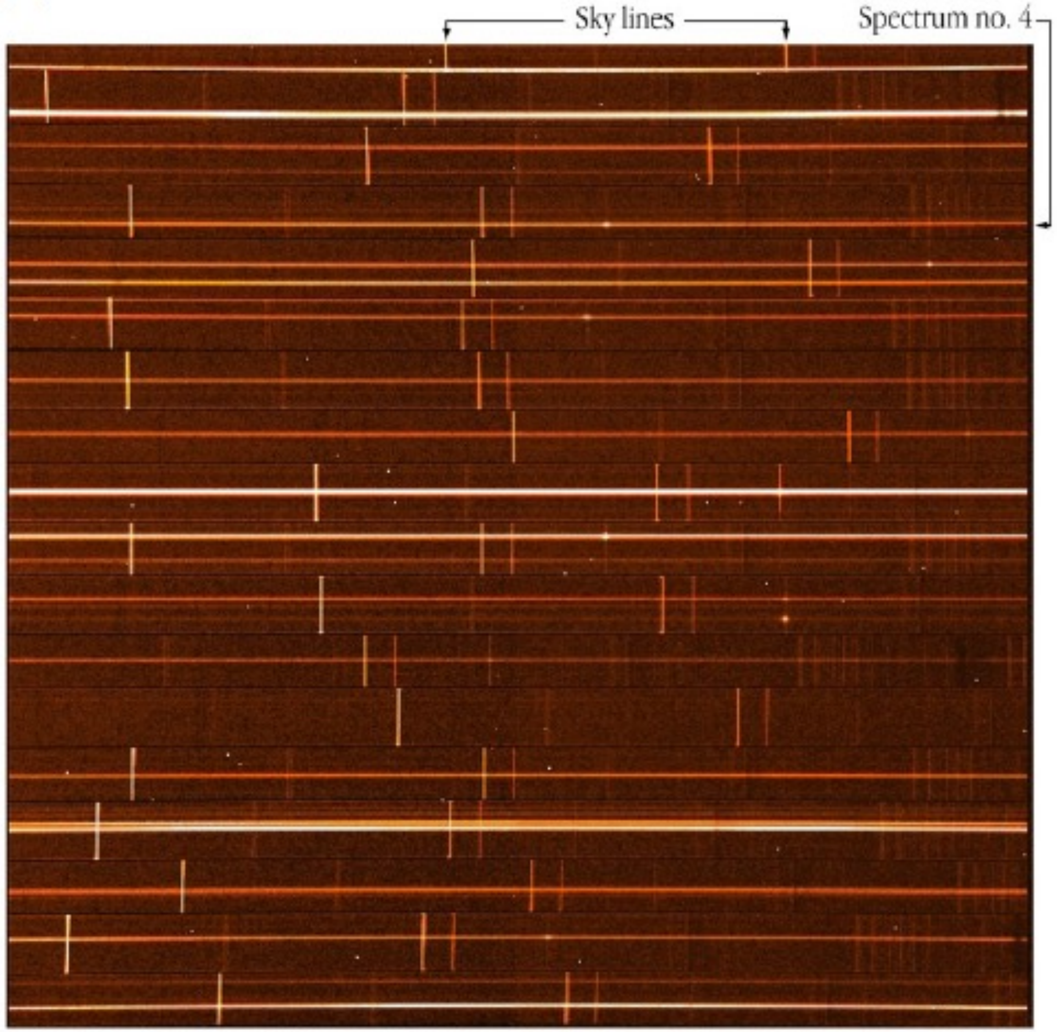
Forms a series of spectra, one for each star.

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

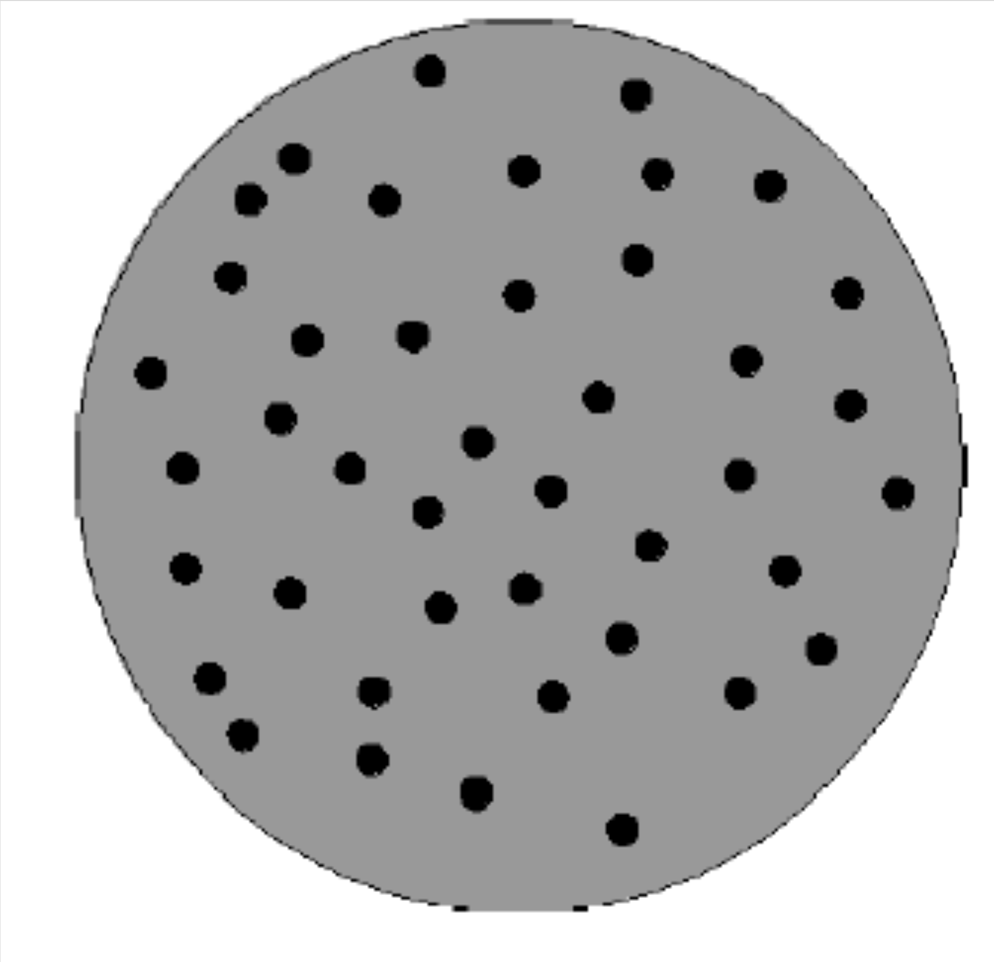
Slits must not overlap in Y! (otherwise spectra will overlap)

Multi-object spectroscopy: Slitmasks





Multi-object spectroscopy: Fiber fed spectrographs

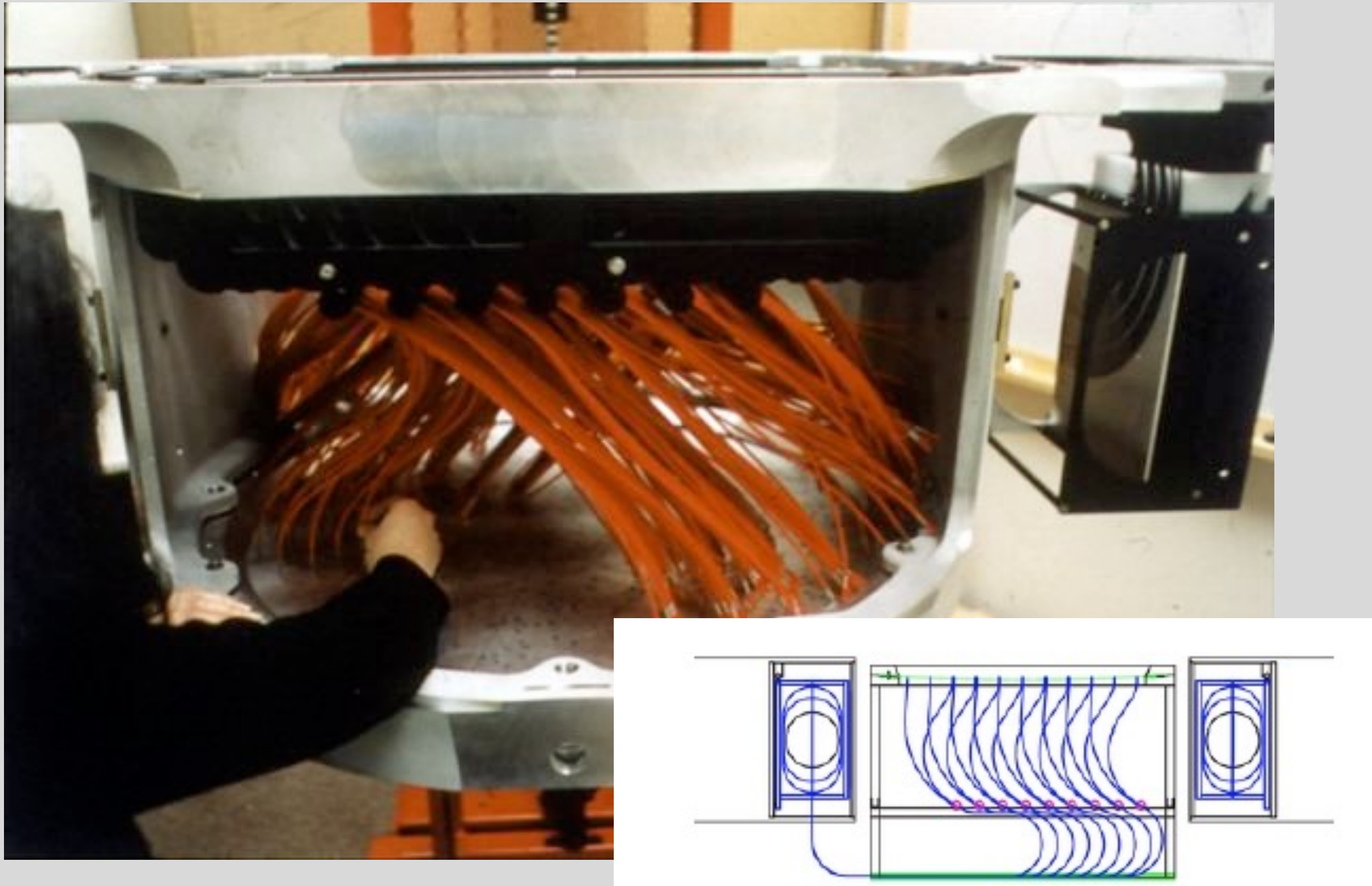


Metal plate with holes cut at the position of stars.

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

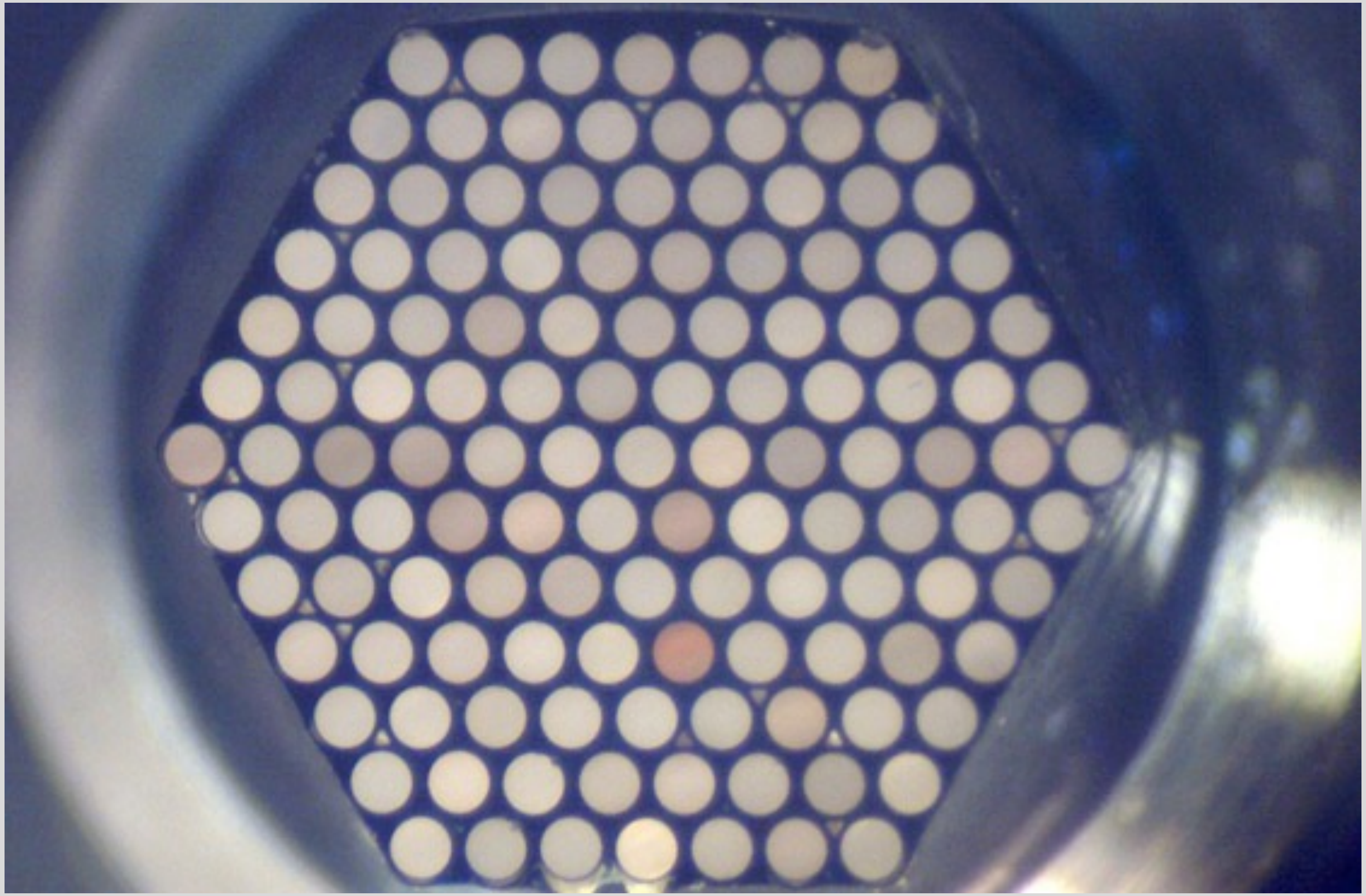
Produce many spectra, no constraints on fiber positions (other than they can't be too close spatially).

Multi-object spectroscopy: Fiber fed spectrographs

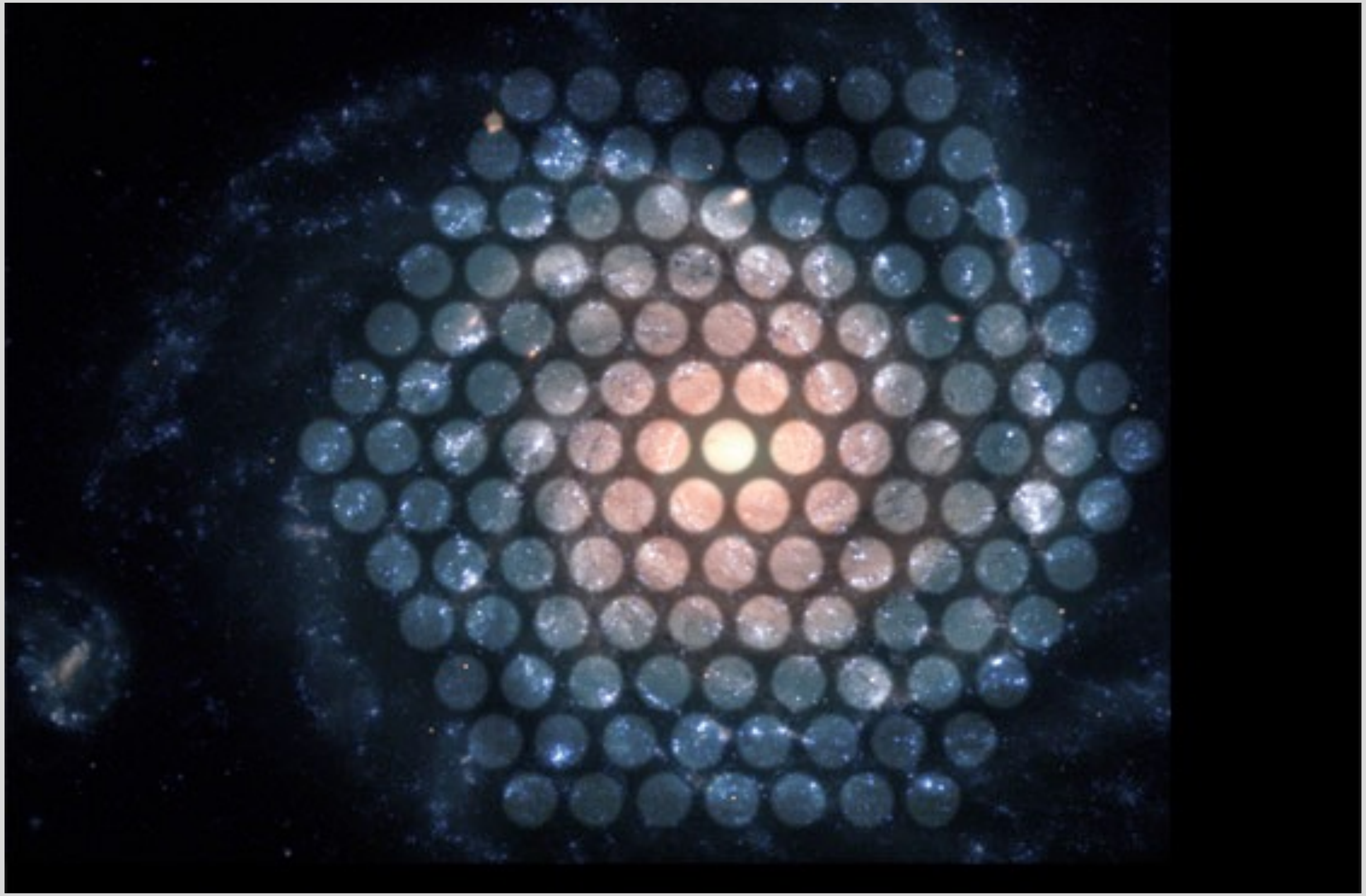


Side View
(only 9 fiber harnesses shown)

Multi-object spectroscopy: Integral Field Units (IFUs)

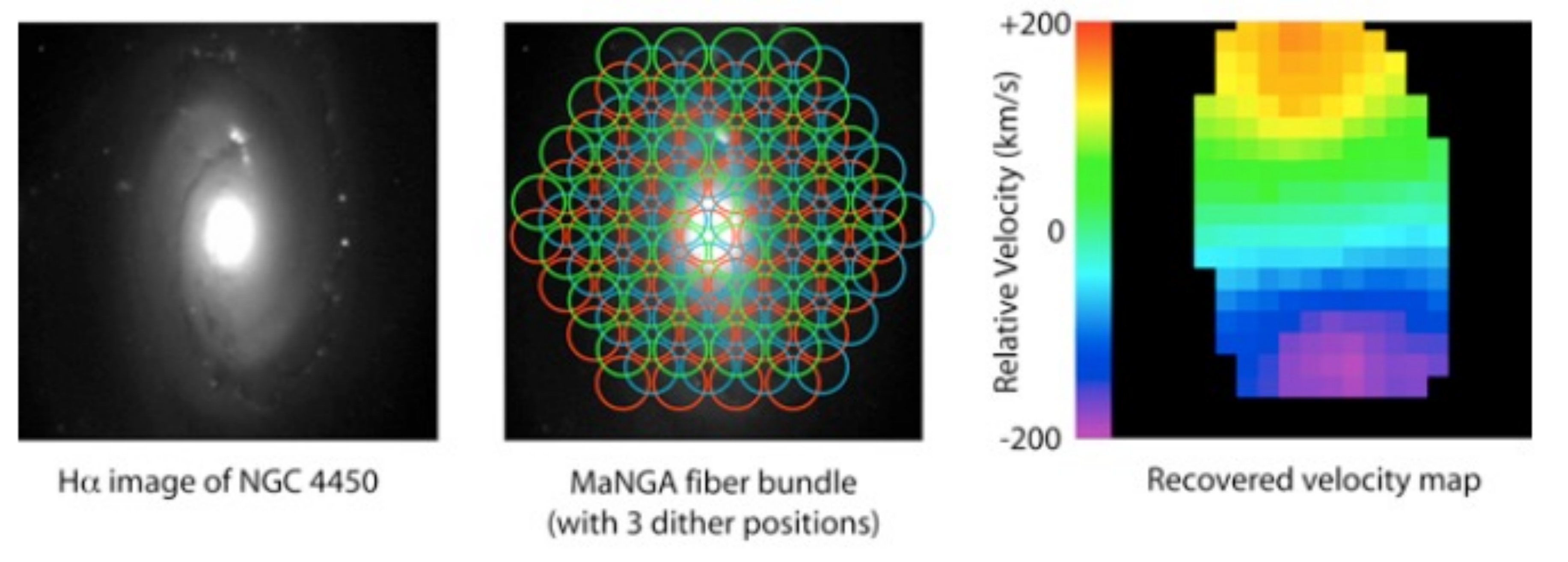


Multi-object spectroscopy: Integral Field Units (IFUs)

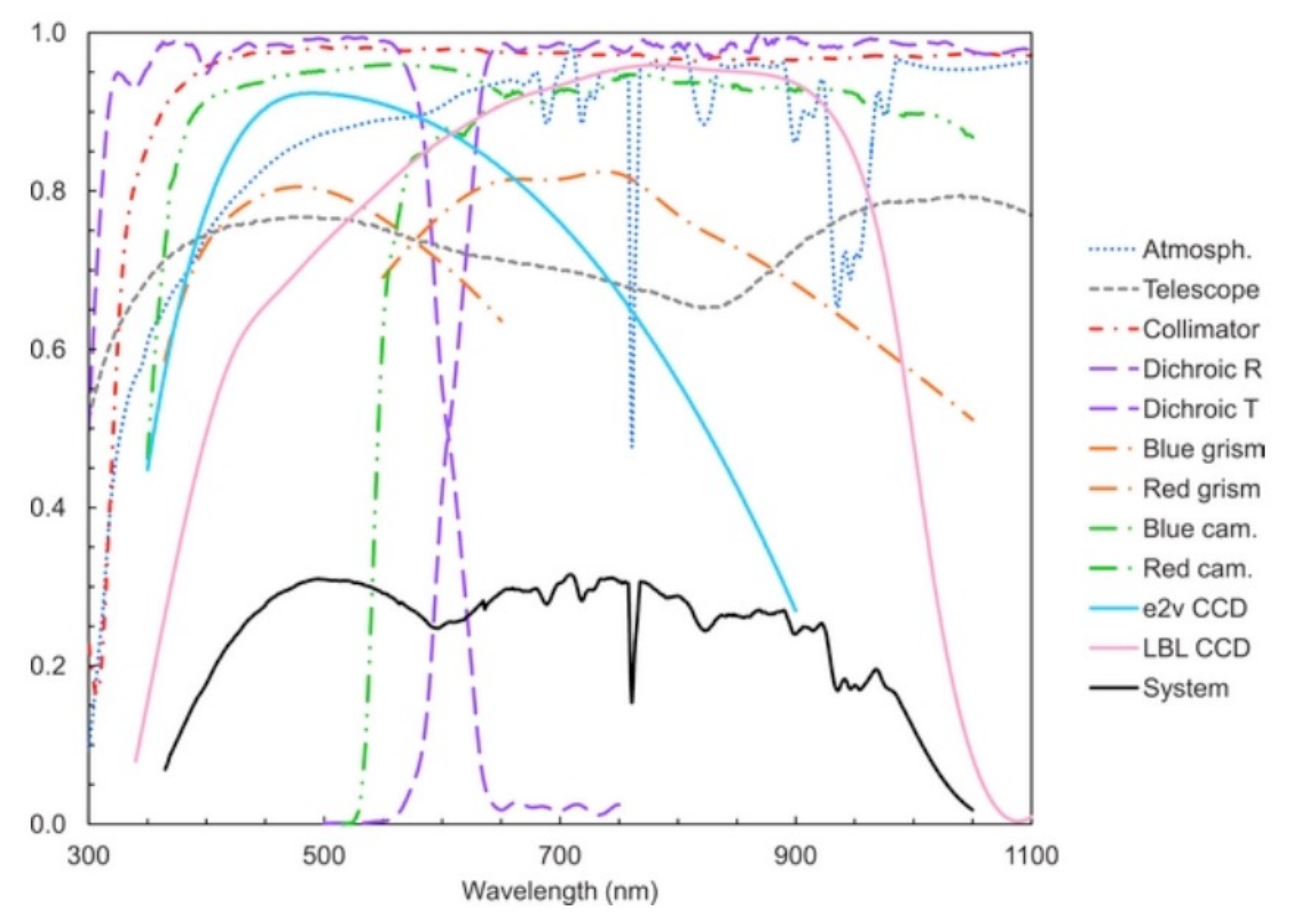


Multi-object spectroscopy: Integral Field Units (IFUs)

Dithering to get full coverage



Spectroscopic Throughput



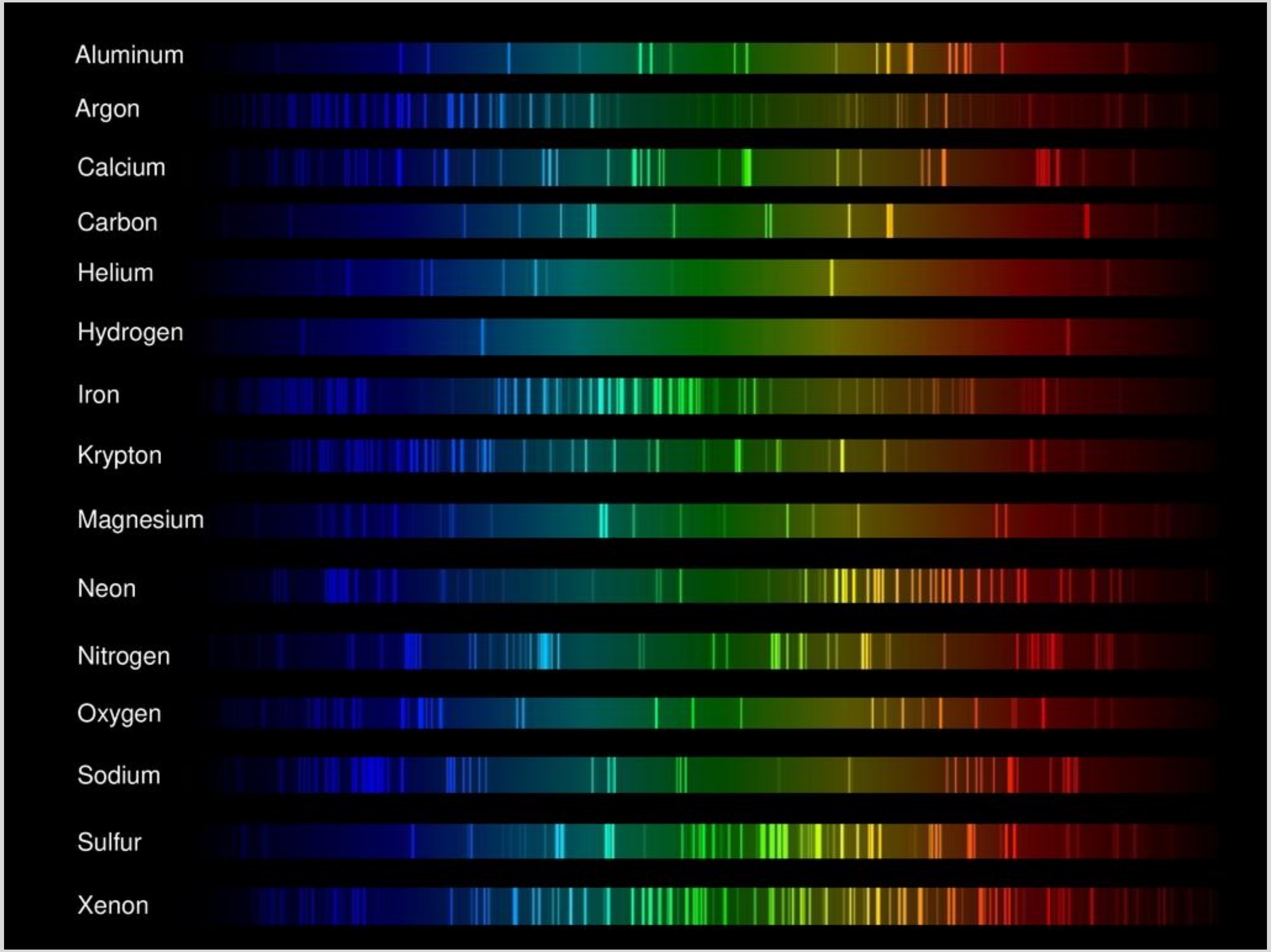
Wavelength Calibration

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

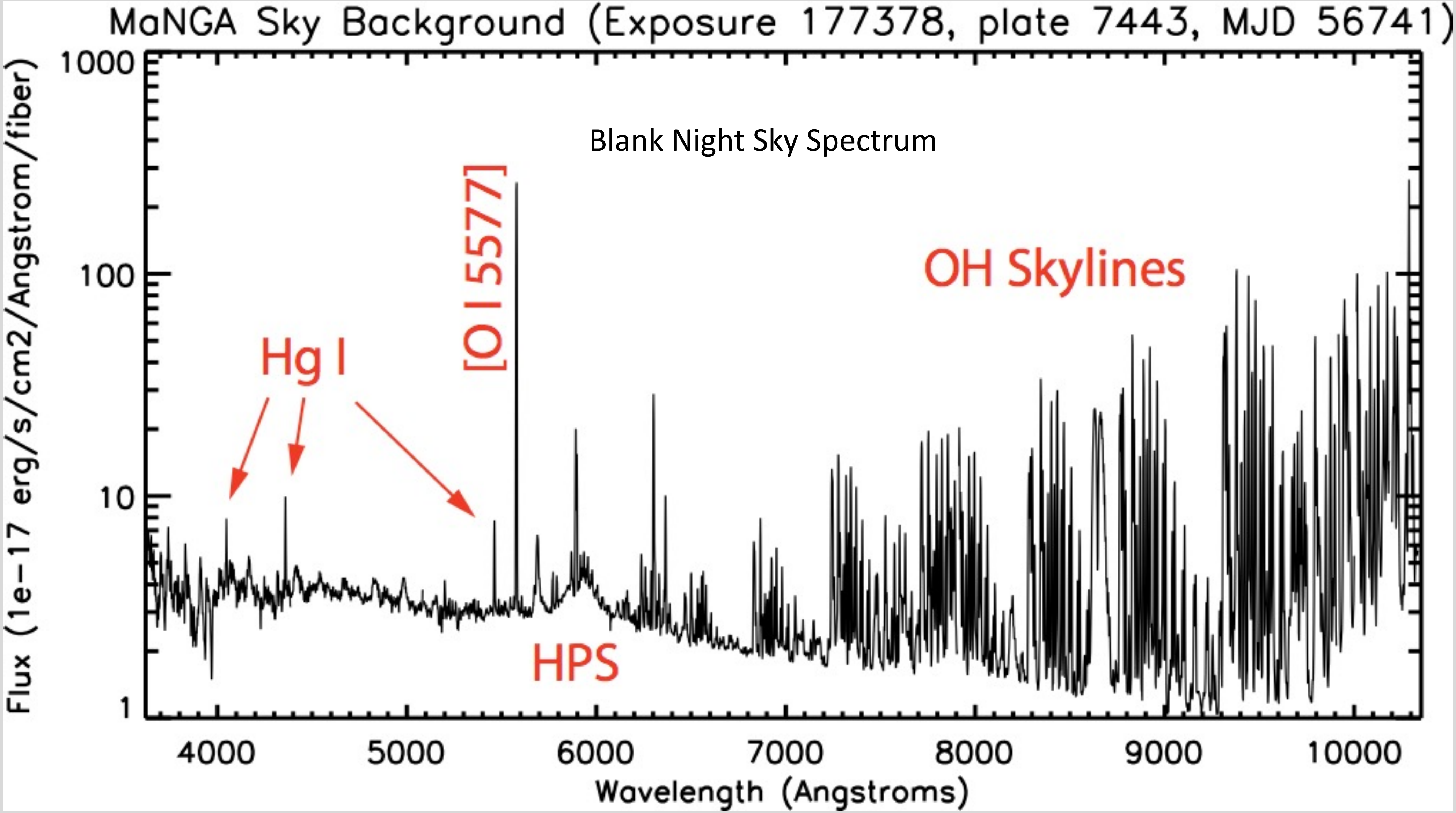
Measure the X position of the lines, fit a high order polynomial function given the known wavelengths:

$$\lambda = f(X)$$

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



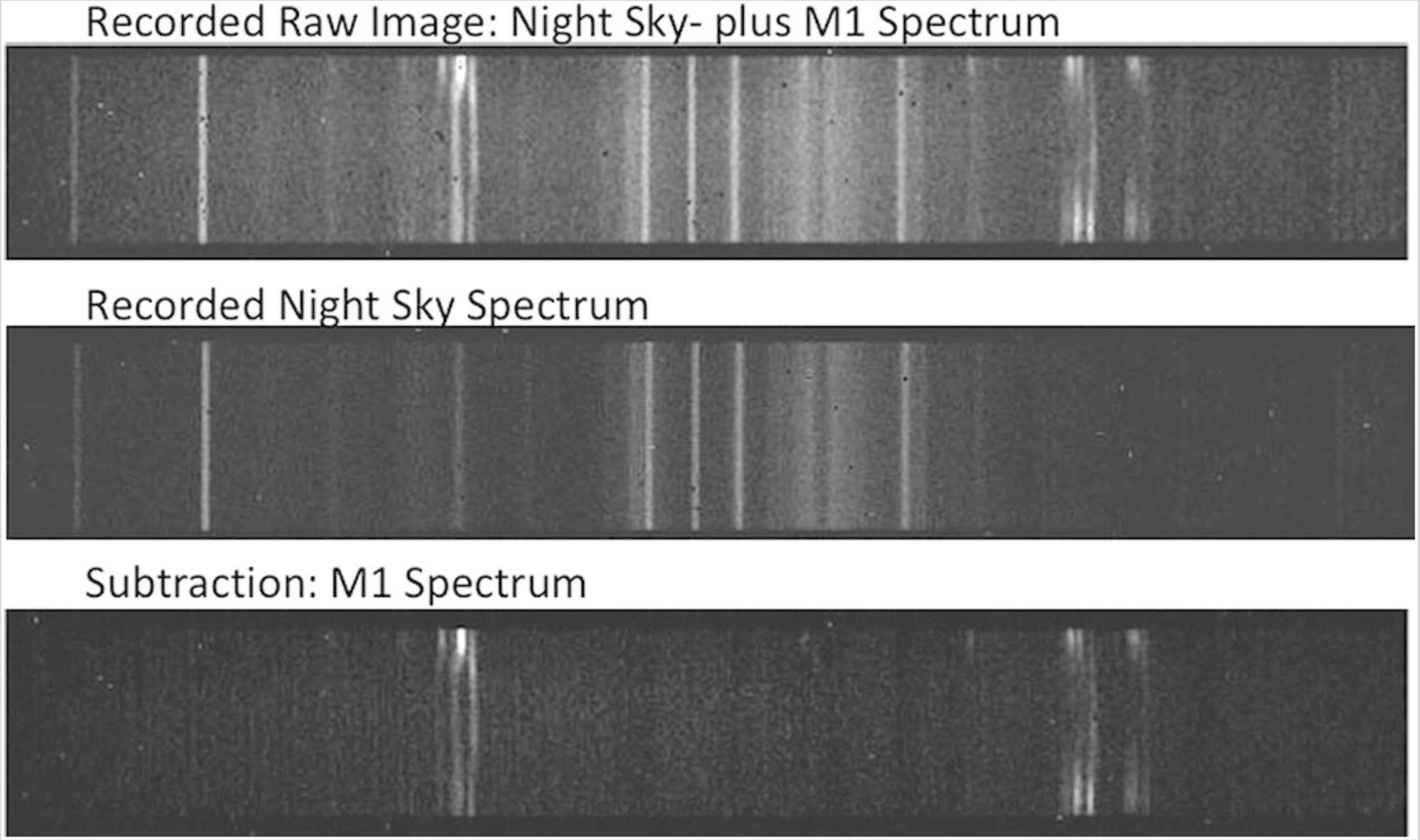
Spectroscopic Sky Subtraction



Spectroscopic Sky Subtraction

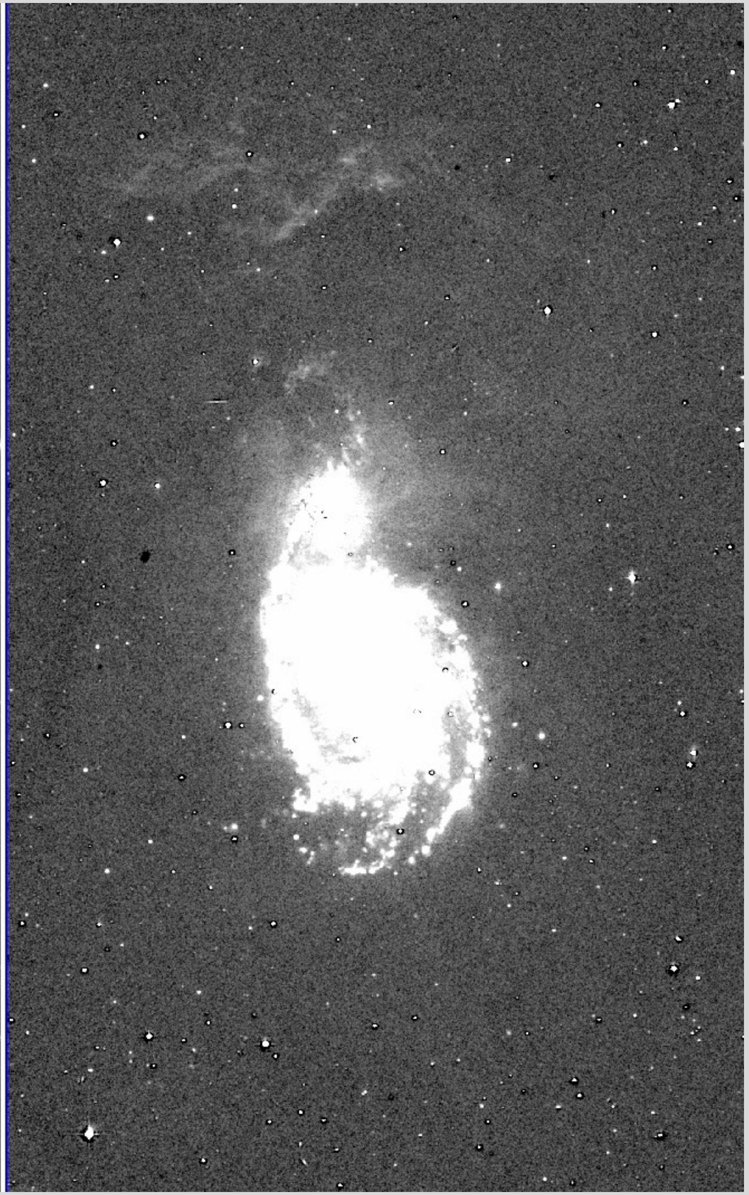
Take blank sky spectra and subtract:

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



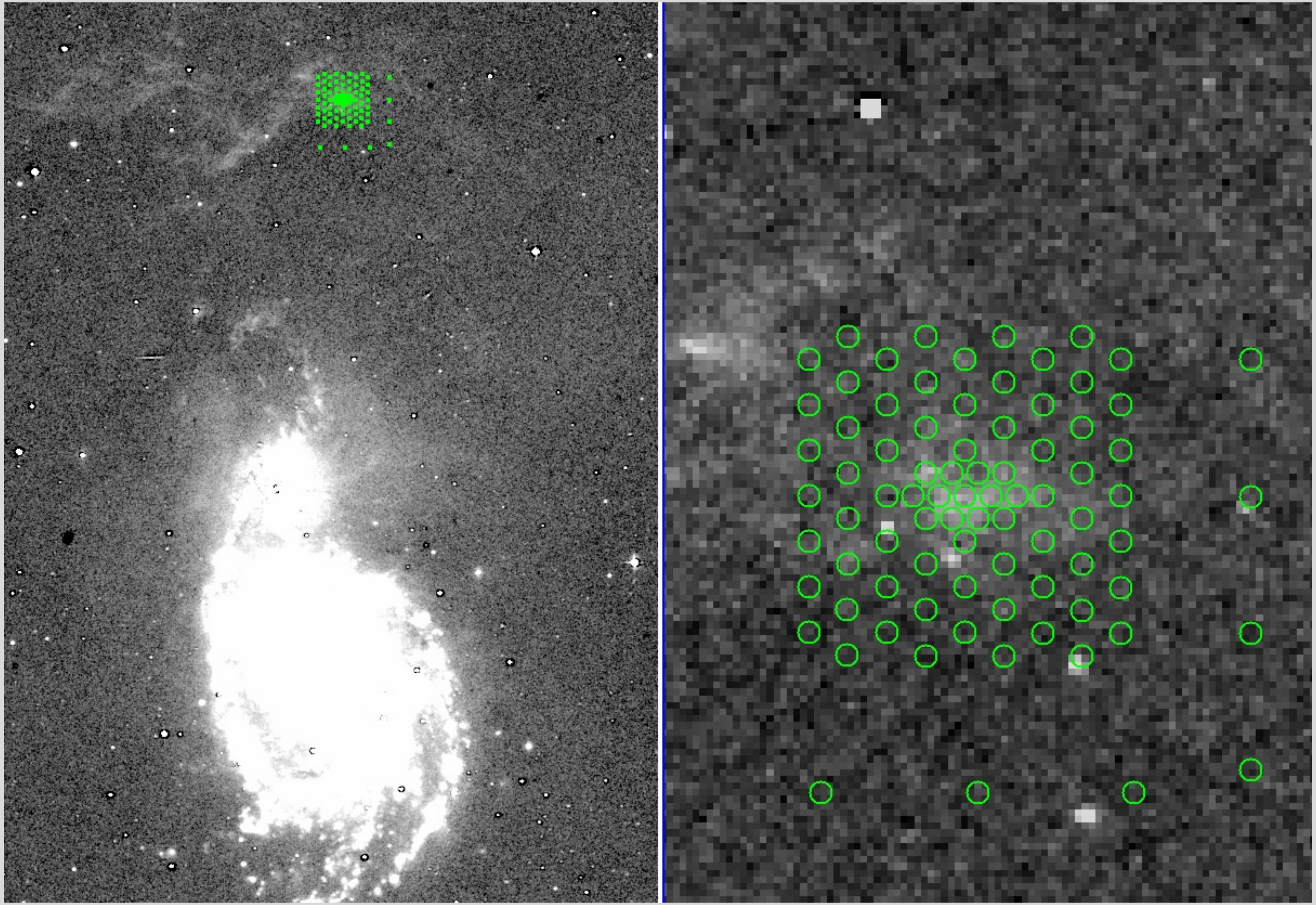
Spectroscopic Sky Subtraction

M51 (B)



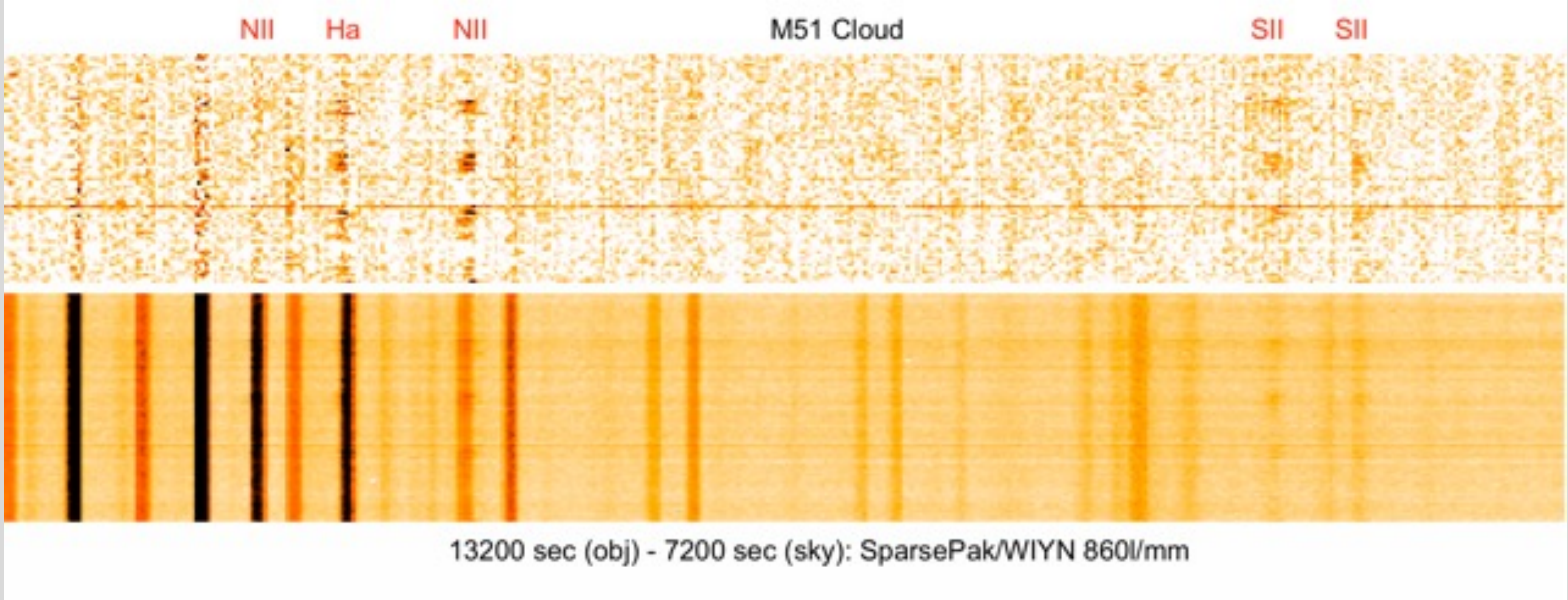
M51 (Hα)

Spectroscopic Sky Subtraction



WIYN/Sparsepak pointing

Spectroscopic Sky Subtraction



Spectroscopic Sky Subtraction