PHYS 7810: Solar Physics with DKIST

Lecture 8: Spectrographs

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Previous class

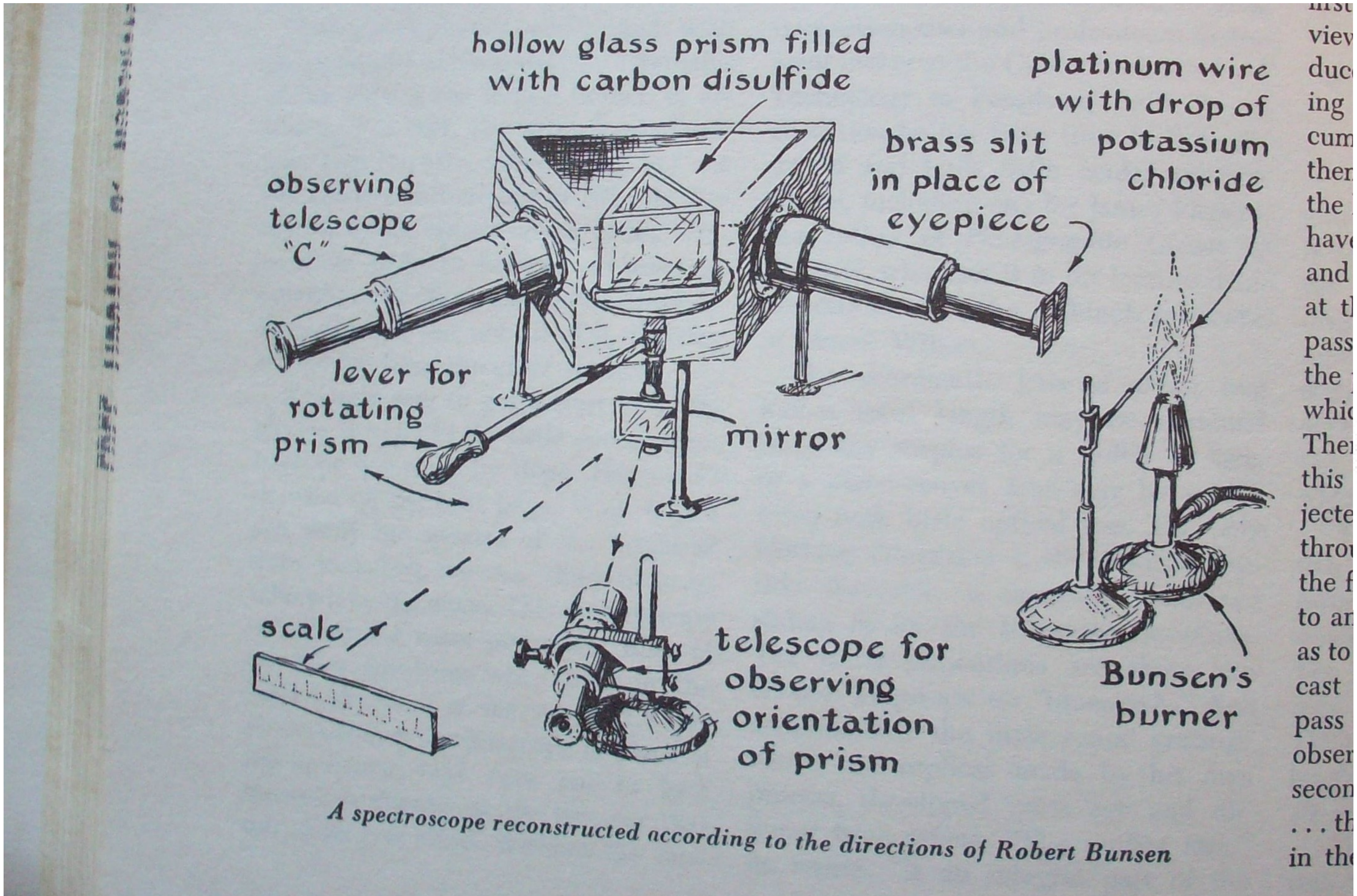
- We discussed theoretical concepts of Fabry-Perot filter
- We sliced the datacube, parallel to **x,y** one wavelength at the time.
- Images are made at one moment of time, but different wavelengths correspond to different times
- Now we will see another way to slice the cube, along **x** or **y**
- Interestingly, this is also a historically first method we used to look at the spectra and is hence called a (slit) spectrograph (spectroscope, spectrometer...)

First solar spectrum ever

Joseph von Fraunhofer (~ 1814)

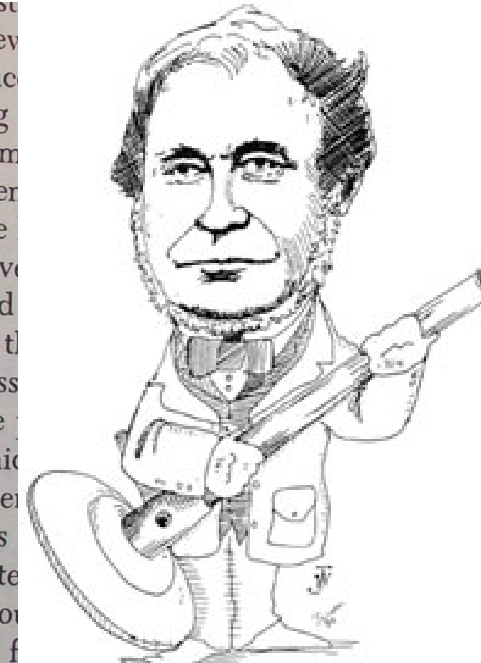
How did he obtain the Plankian distribution at the top?

And the birth of astrophysics



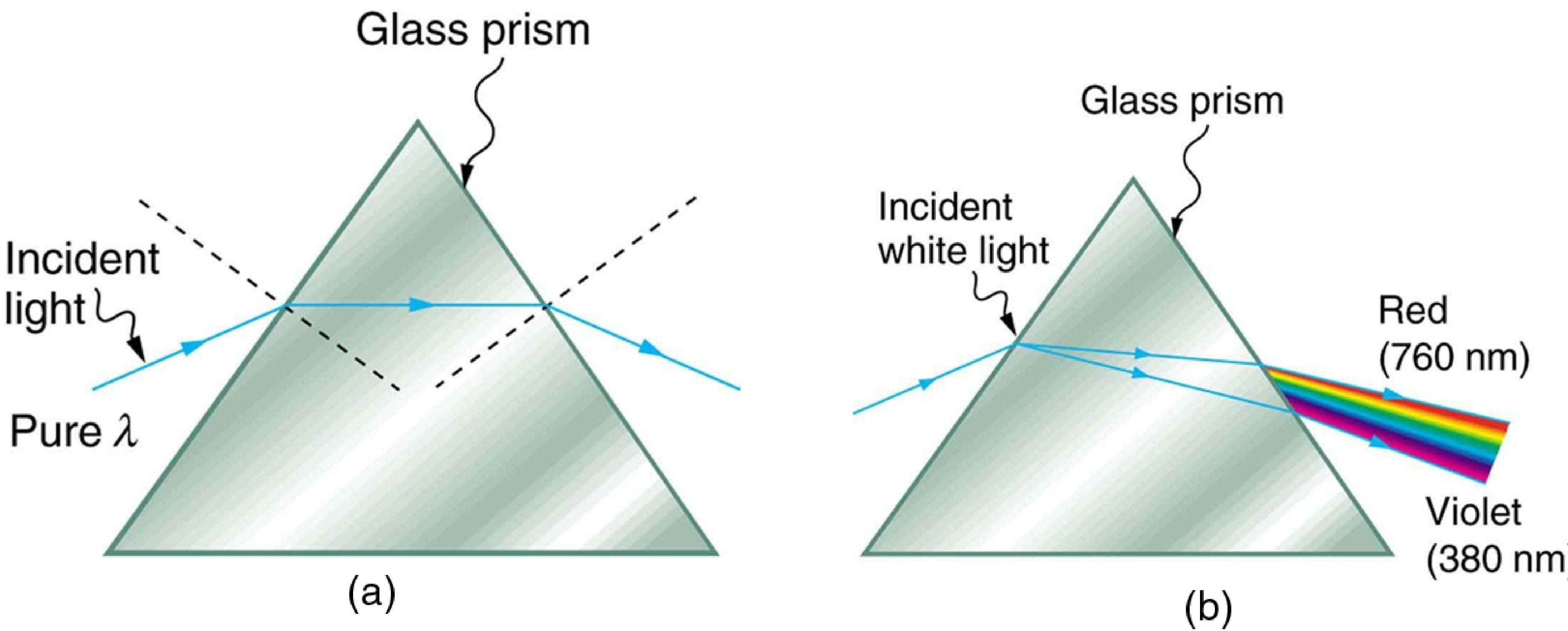
A spectroscope reconstructed according to the directions of Robert Bunsen

Robert Bunsen



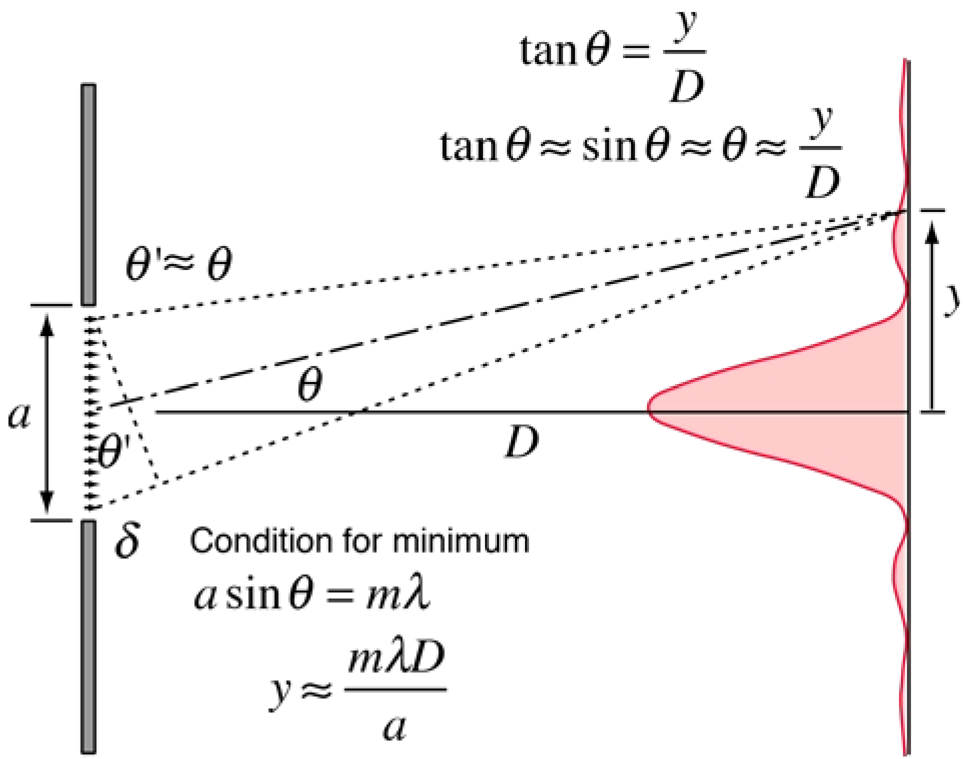
(~ 1860)

In this instrument, we used the prism to analyze the light



The reason for this is that different wavelengths have different indices of refraction. What else can we do to separate the wavelengths?

A slit (this not the spectrograph slit)



Single slit diffraction, Fraunhoffer regime

Credits: hyperphysics.phys-astr.gsu.edu

- A coherent wavefront comes from the left.

$$dE(y') = \underbrace{\mathcal{E} \cdot dy'}_{dE_0} \cdot e^{i(kr-\omega t)}$$

$$r = R - y'\sin\theta \approx R - y'\theta$$

$$dE(y') = \mathcal{E} \cdot e^{i(kR-\omega t)} \cdot e^{-iky'\theta}\, dy'$$

$$E = \int_{-\frac{a}{2}}^{\frac{a}{2}} dE(y')\, dy'$$

$$E = \mathcal{E} \cdot e^{i(kR-\omega t)} \cdot \int_{-\frac{a}{2}}^{\frac{a}{2}} e^{-ik\theta y'}\, dy'$$

$$E \propto \frac{\sin\frac{k\theta a}{2}}{\frac{k\theta a}{2}} = \mathrm{sinc}\,\frac{k\theta a}{2}$$

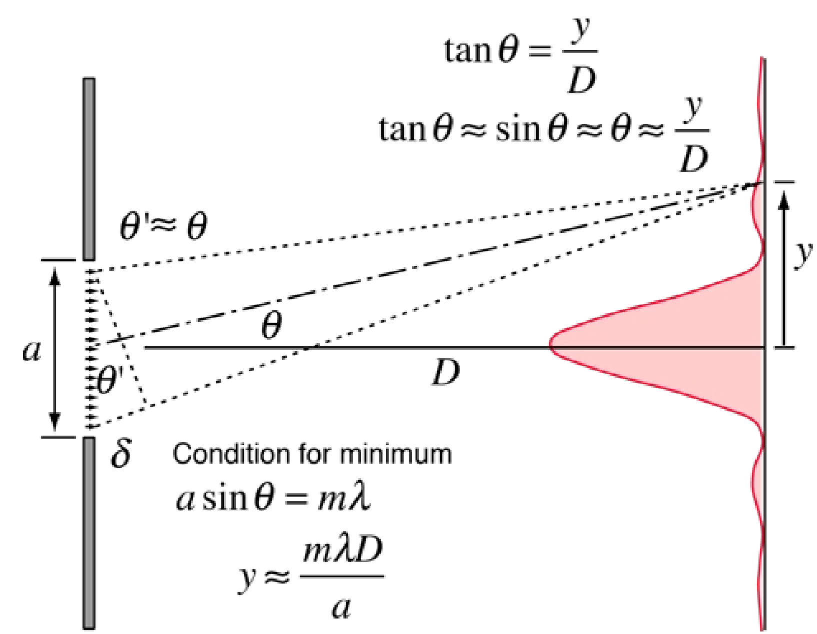
$$I \propto \mathrm{sinc}^2\,\frac{k\theta a}{2}$$

Let's analyze the one slit diffraction a bit more

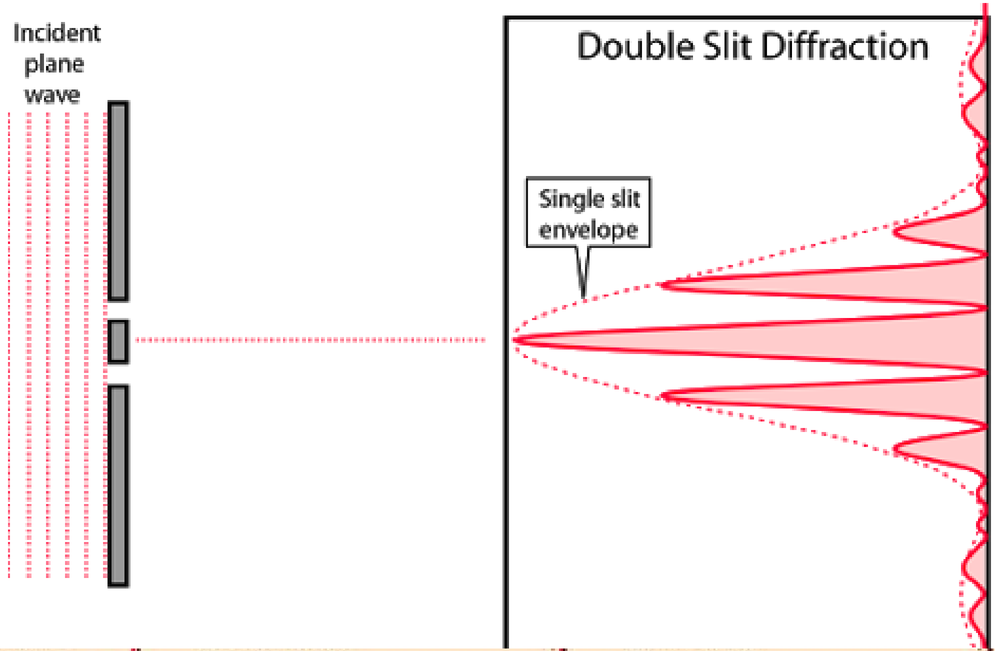
- One big primary maximum, same for all the wavelengths
- Other maxima separated in wavelength, but very weak
- This won't do
- (Although, this is a very good toy model for diffraction on a primary)

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

$$\alpha = \frac{k\theta a}{2} = \frac{\pi \theta a}{\lambda}$$

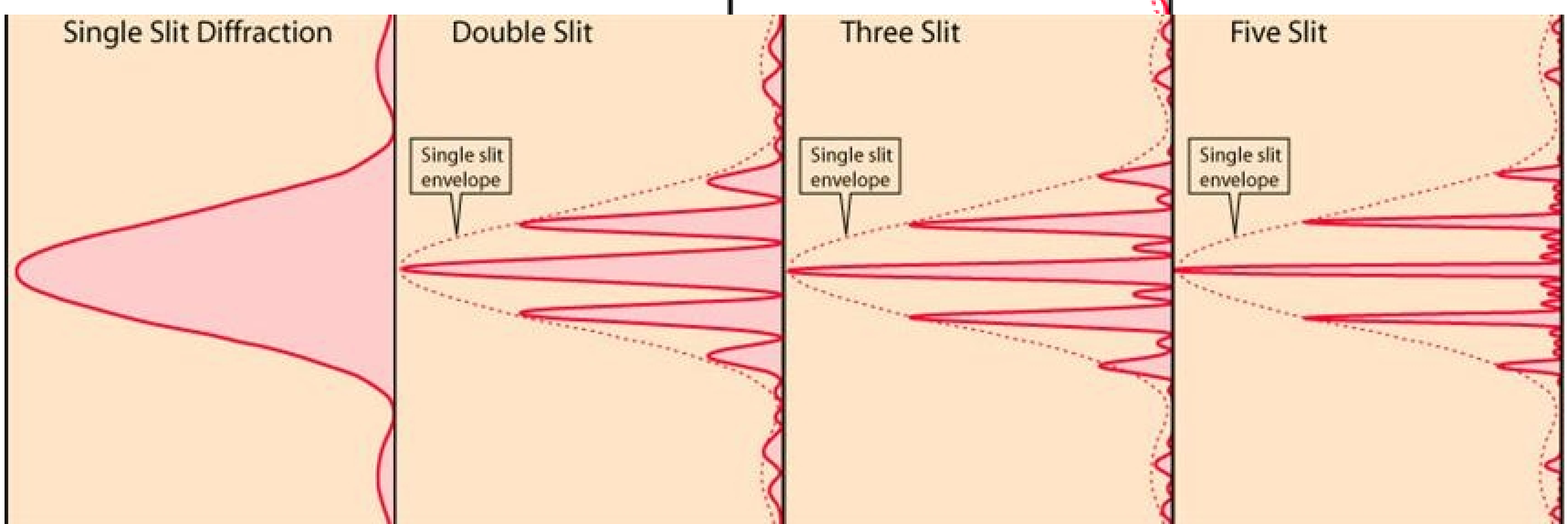


Turns out that multiple slits improve the situation



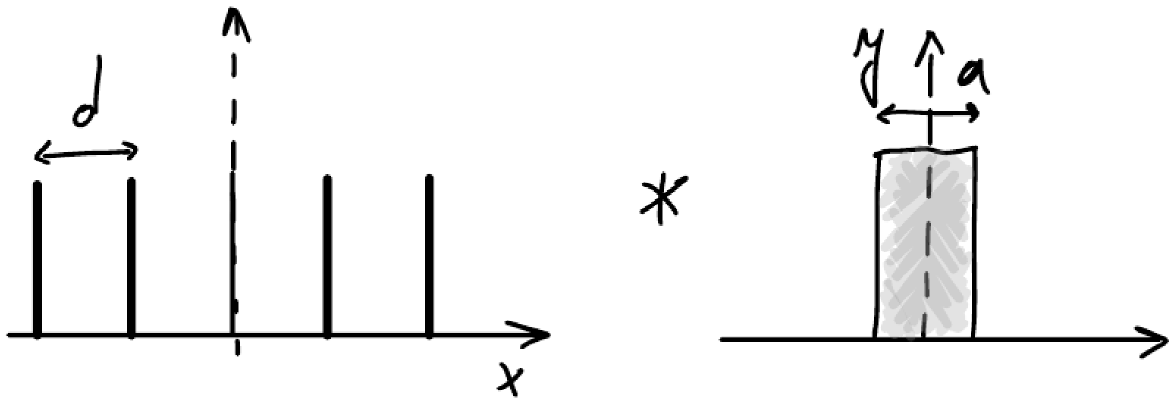
Now the original, one slit diffraction is modulated by 2-slit interference!

We now have more maxima!



How to get the equation for this?

- Recall that diffraction pattern (in Electric field) is the Fourier transform of the aperture
- Multiple-slit aperture is a convolution of series of delta functions with single slit



$$I \propto \frac{\sin^2(N\delta)}{\sin^2\delta} \qquad\qquad I(\theta) = I_0 \frac{\sin^2\alpha}{\alpha^2}$$

$$\delta = \frac{kd\theta}{2} = \frac{\pi\theta d}{\lambda} \qquad\qquad \alpha = \frac{k\theta a}{2} = \frac{\pi\theta a}{\lambda}$$

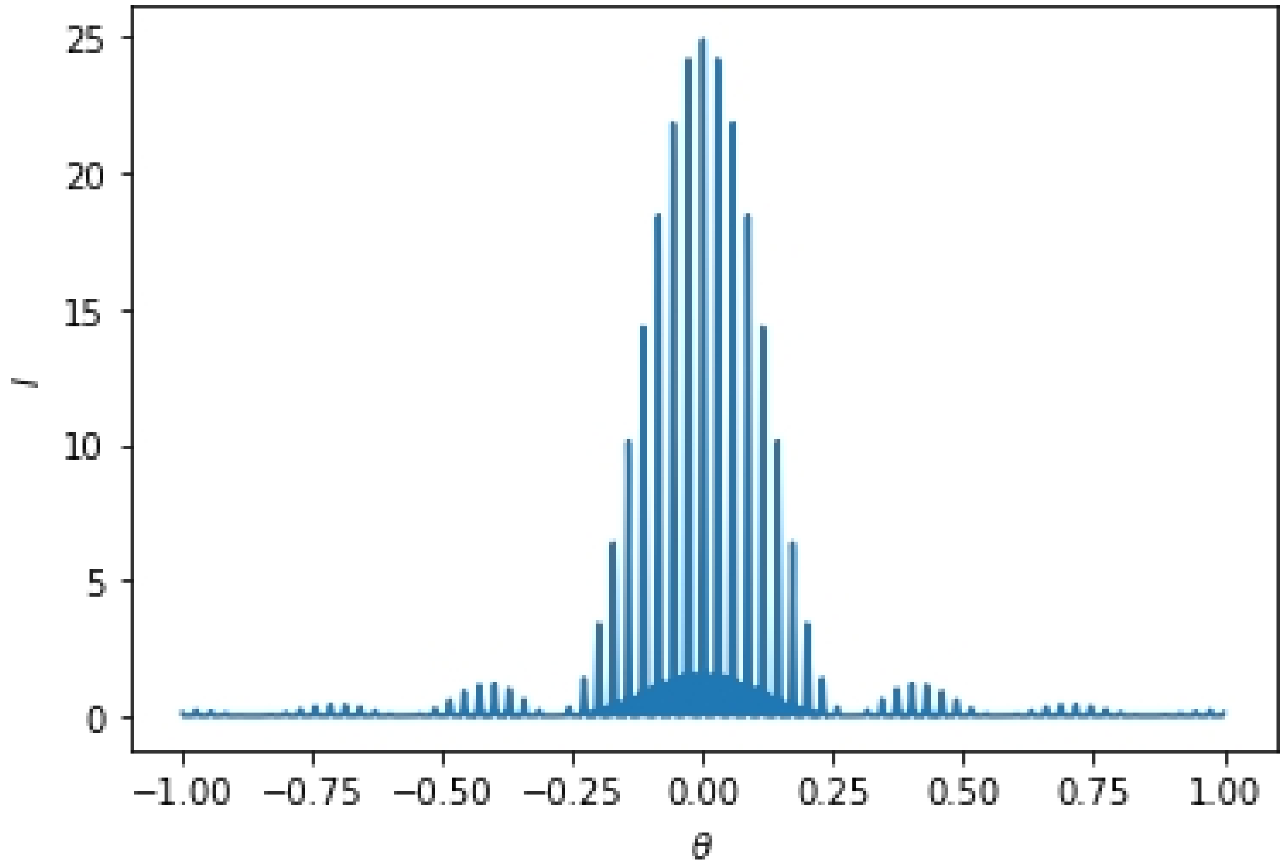
How does it look like?

$$\lambda = 500\,\mathrm{nm}$$

$$a = 0.1\,\mathrm{mm}$$

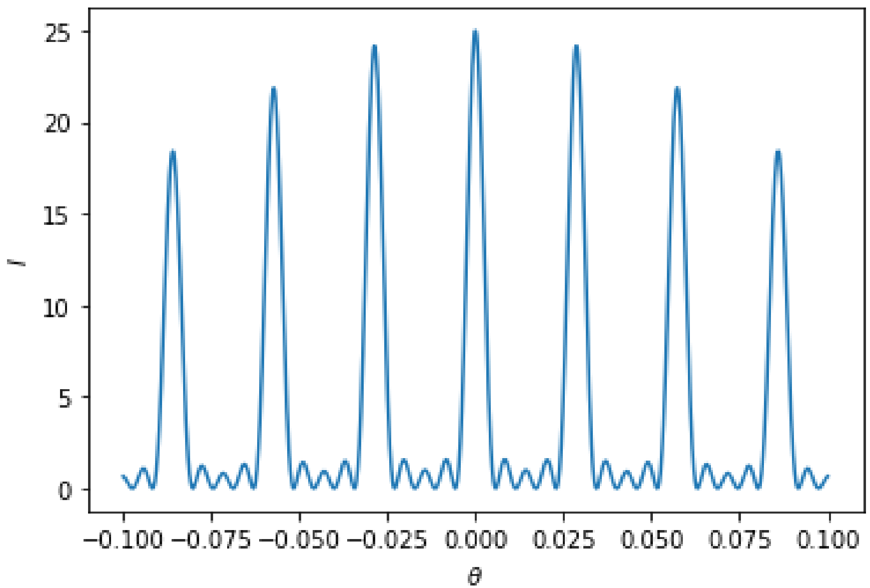
$$d = 1\,\mathrm{mm}$$

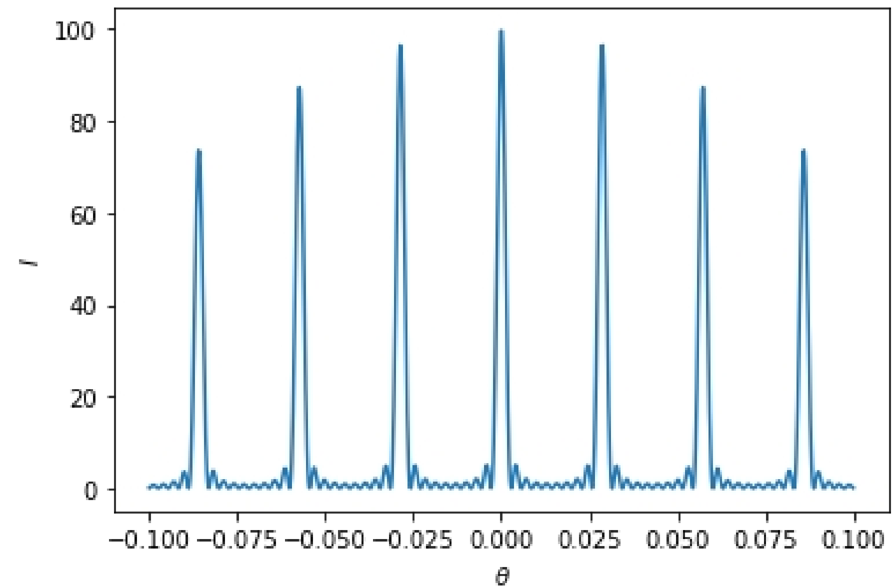
$$N = 5$$



This is the full image, however, here we cannot see a lot of detail, let's focus on the central maximum

This looks a bit more useful, N = 5 vs N = 10

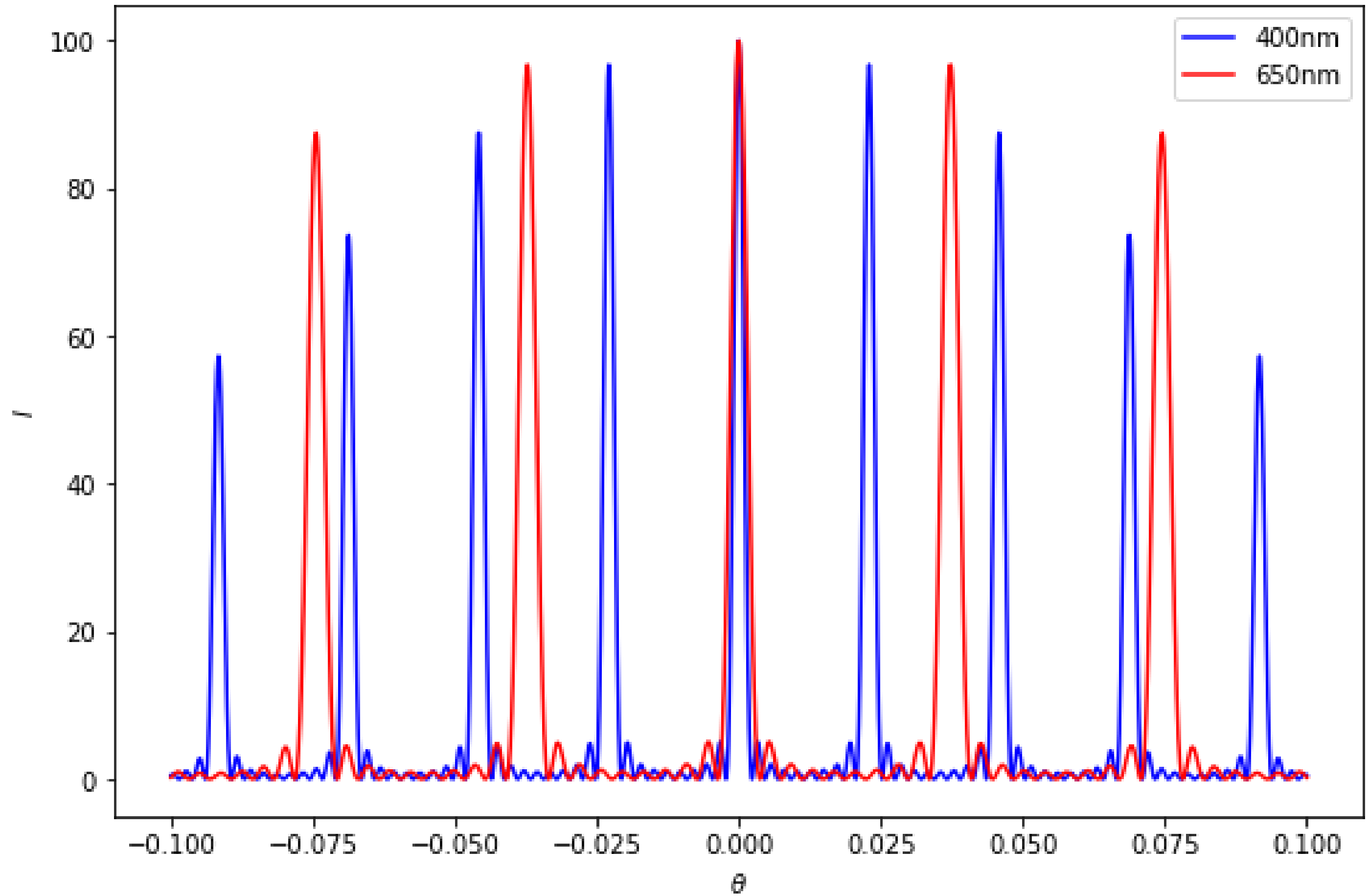




Pay attention to the shape of the maxima and the value of the maximum intensity!

Looking at two different wavelengths:

- What do you see about the properties and the positions of the maxima here?
- Red maxima are more separated from the center.
- They are also broader.
- Look, third blue maxima occurs “before” the second red one!



Let's derive where these (principal) maxima are (take 5'?)

$$I \propto \mathrm{sinc}^2\alpha \frac{\sin^2(N\delta)}{\sin^2\delta}$$

$$\sin N\delta = 0 \ \wedge \ \sin\delta = 0$$

$$\text{so, } \frac{kd\theta}{2} = m\pi$$

$$\frac{\pi d\theta}{\lambda} = m\pi \Longrightarrow \boxed{\theta_{MAX} = \frac{m\lambda}{d}}$$

$$\frac{\partial\theta}{\partial\lambda} = \frac{m}{d} \longrightarrow \text{DISPERSION}$$

How about the minima?

$$I \propto \text{sinc}^2\alpha \frac{\sin^2(N\delta)}{\sin^2\delta}$$

$$\sin N\delta = 0 \wedge \sin\delta \neq 0!$$

$$\frac{N \pi d \theta}{\lambda} = m' \pi$$

$$\theta_{min} = \frac{m'\lambda}{Nd}$$

(m' AND m ARE DIFFERENT COUNTS)

$$\boxed{W_\theta = \frac{\lambda}{Nd}}$$

Spectral resolution of the diffraction grating

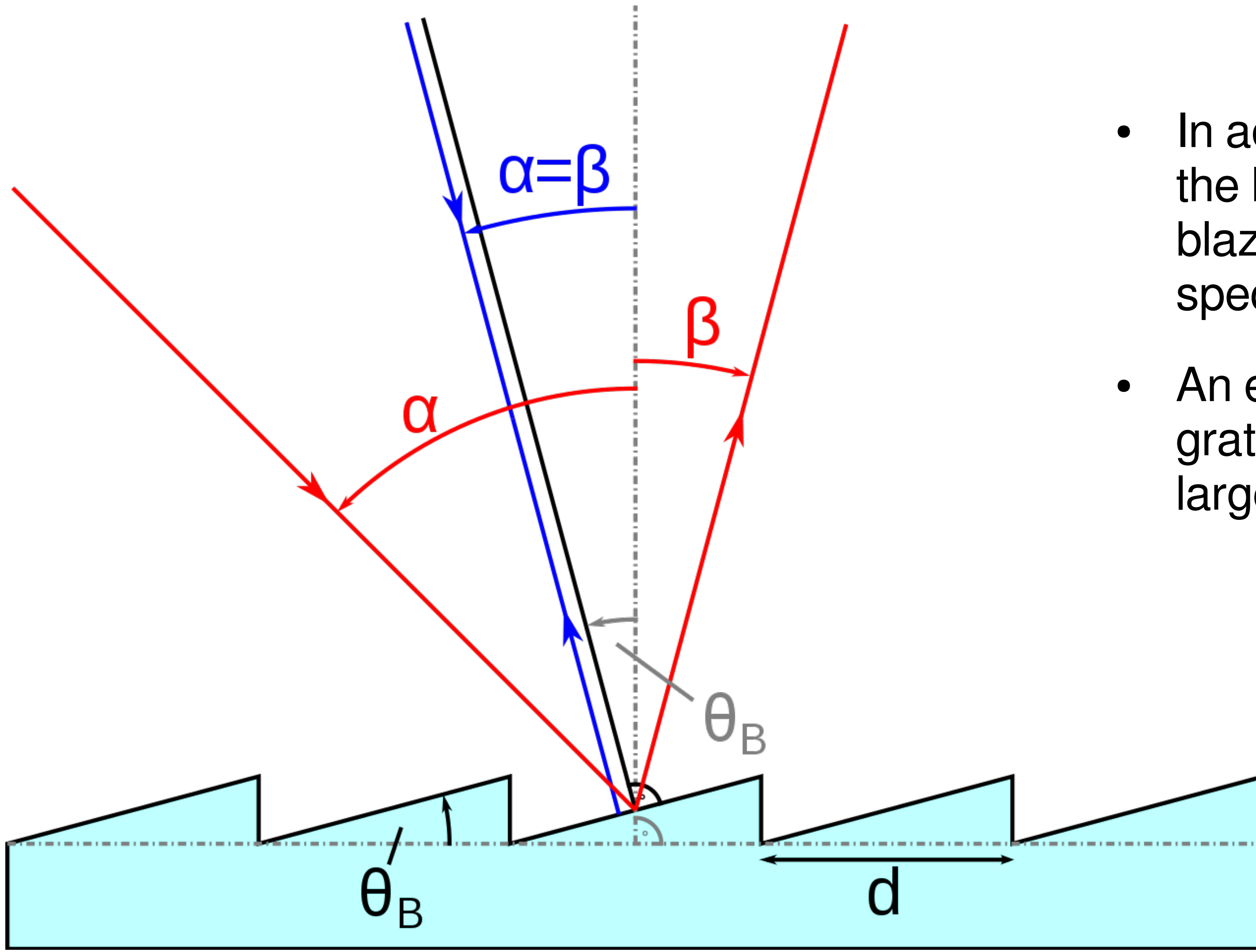
$$\Delta\lambda = W_\lambda = \frac{\partial\theta}{\partial\lambda} W_\theta$$

$$\Delta\lambda = \frac{\lambda}{Nm}$$

$$R = \frac{\lambda}{\Delta\lambda} = mN$$

For higher resolution we go to higher order maxima! We can reach 1E5 or more (VISP should have ~ 2E5)

We can make a reflection grating instead

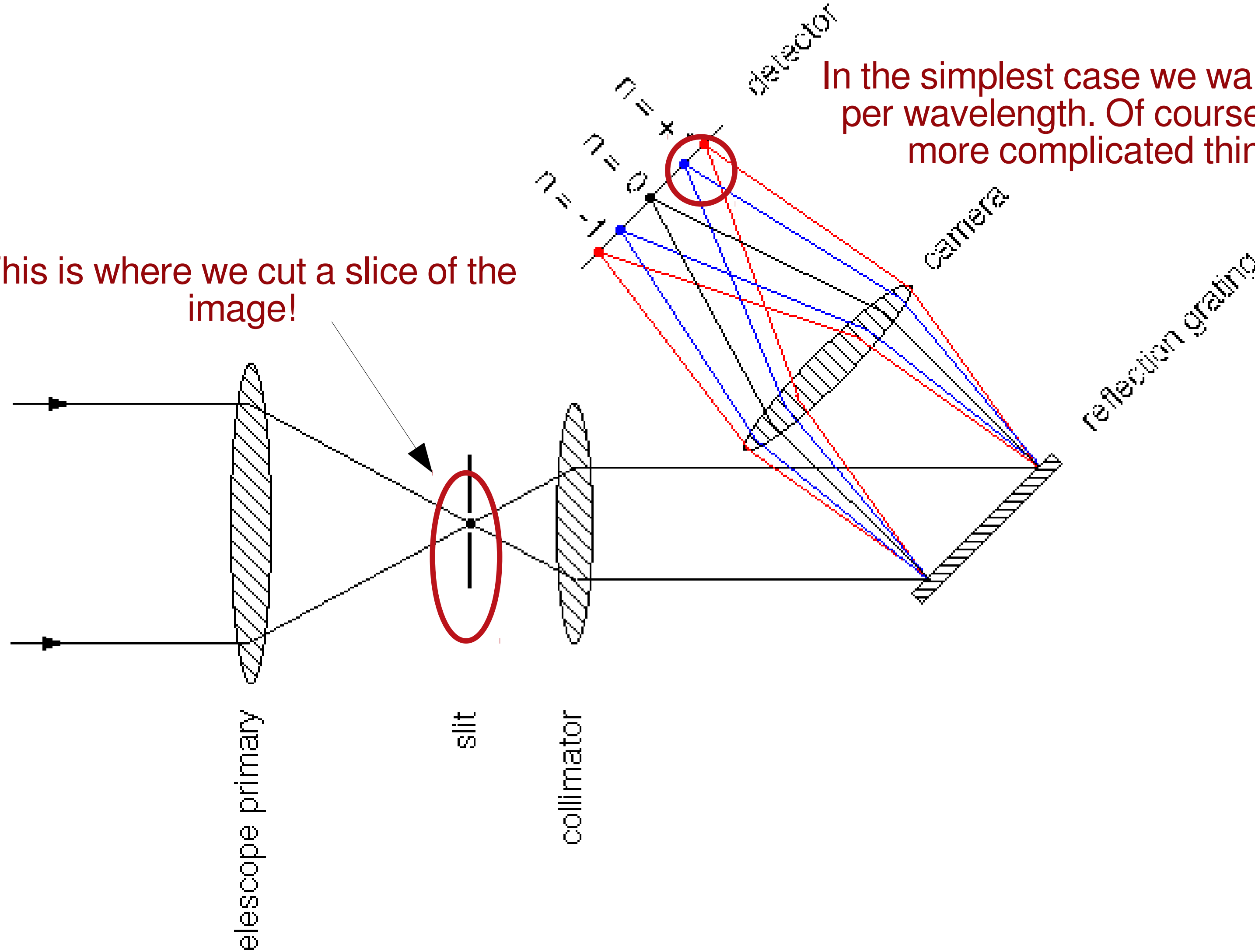


- In addition, we can incline the little mirrors (make a blazed grating) so to amplify specific orders
- An example are Echelle gratings, coarse, but very large blazing angles

Nice, so how does it work with the rest of the telescope?

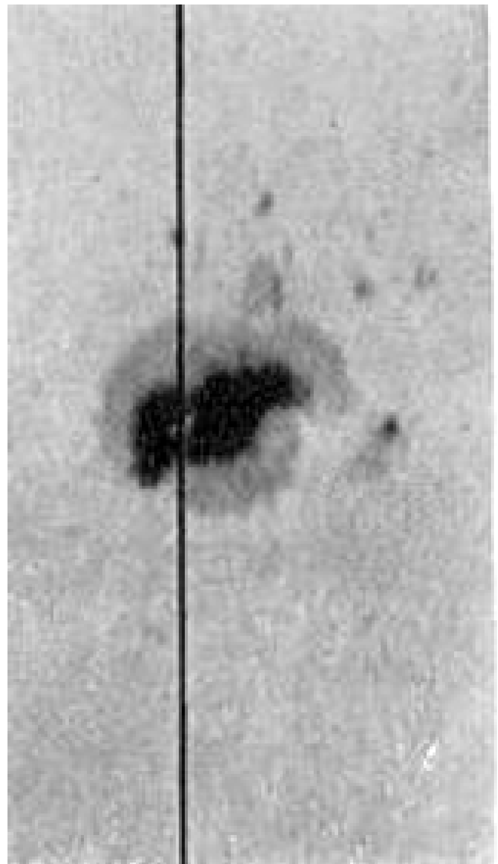
In the simplest case we want one order per wavelength. Of course, there are more complicated thingies :)

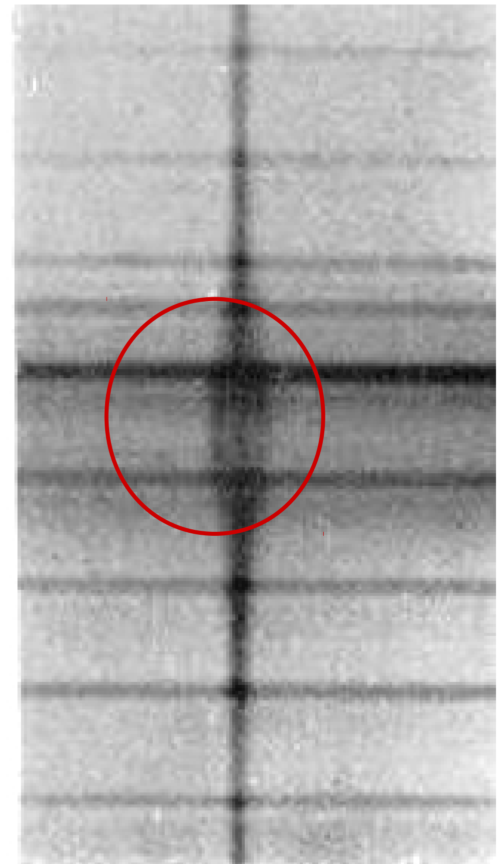
This is where we cut a slice of the image!



So now we understand better what is going on her e

"Slit Jaw" image



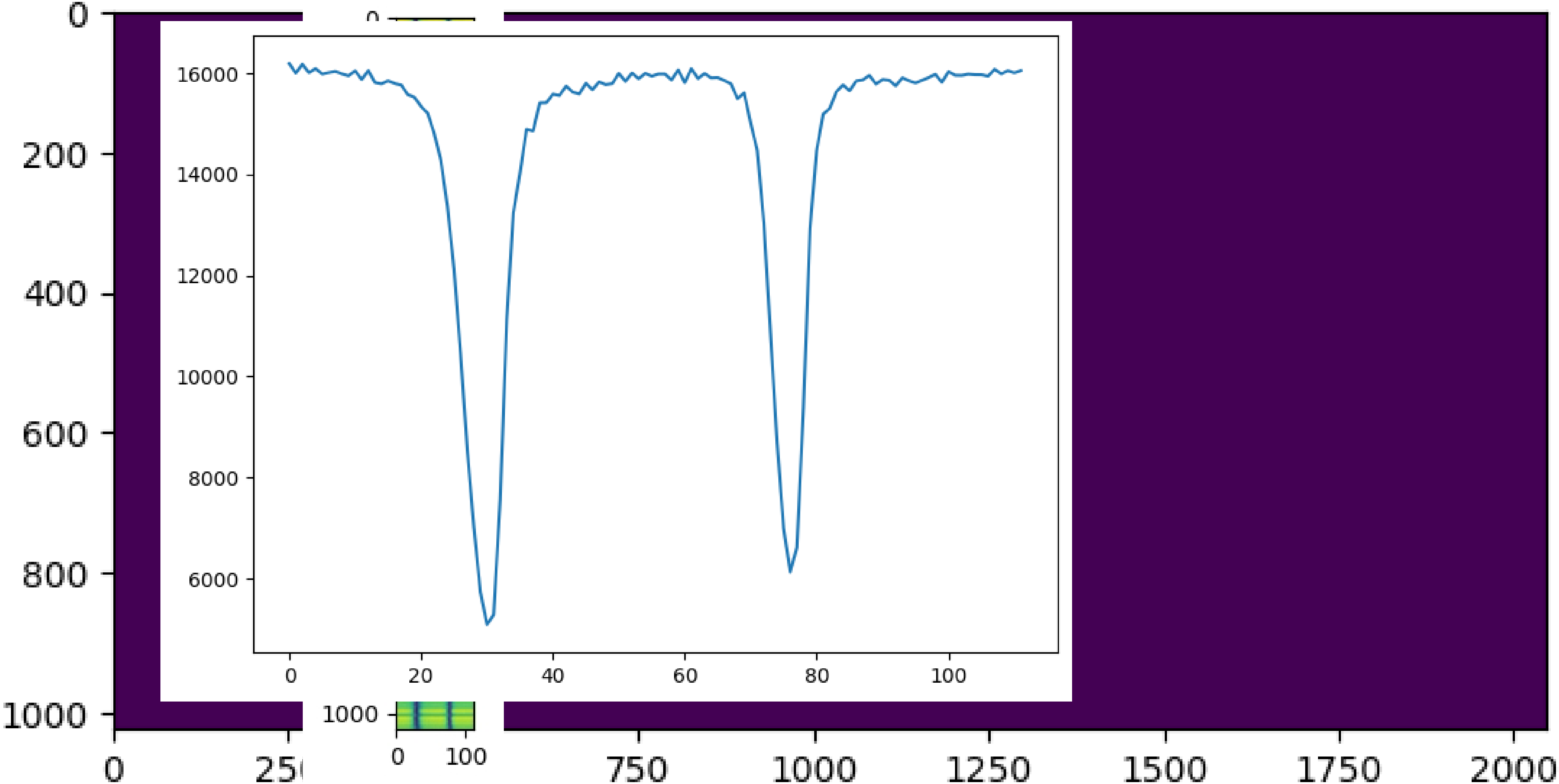


G.E. Hale, F. Ellerman, S.B. Nicholson, and A.H. Joy
(ApJ, 1919)

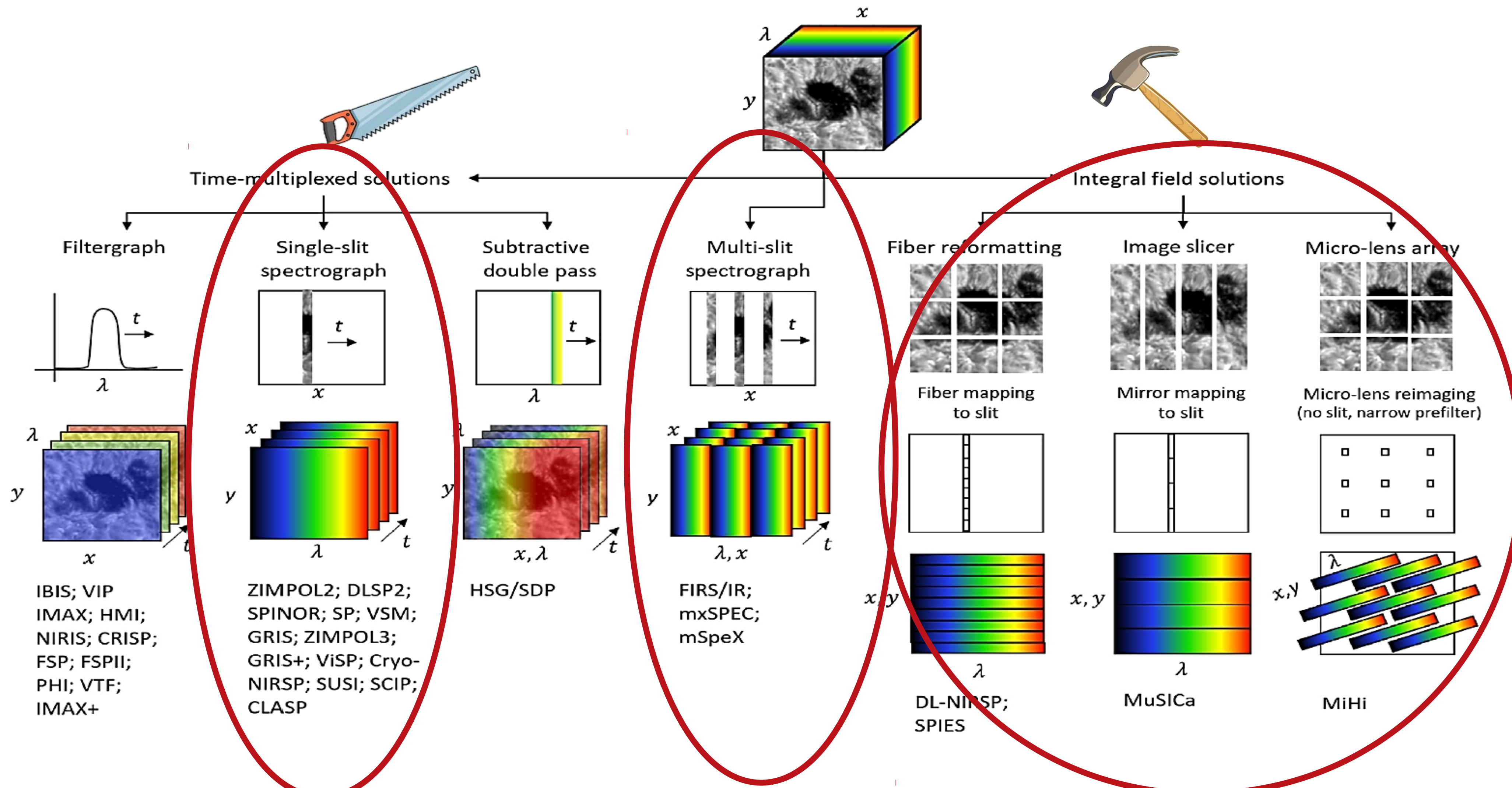
So, we sacrifice one spatial dimension to get wavelength!

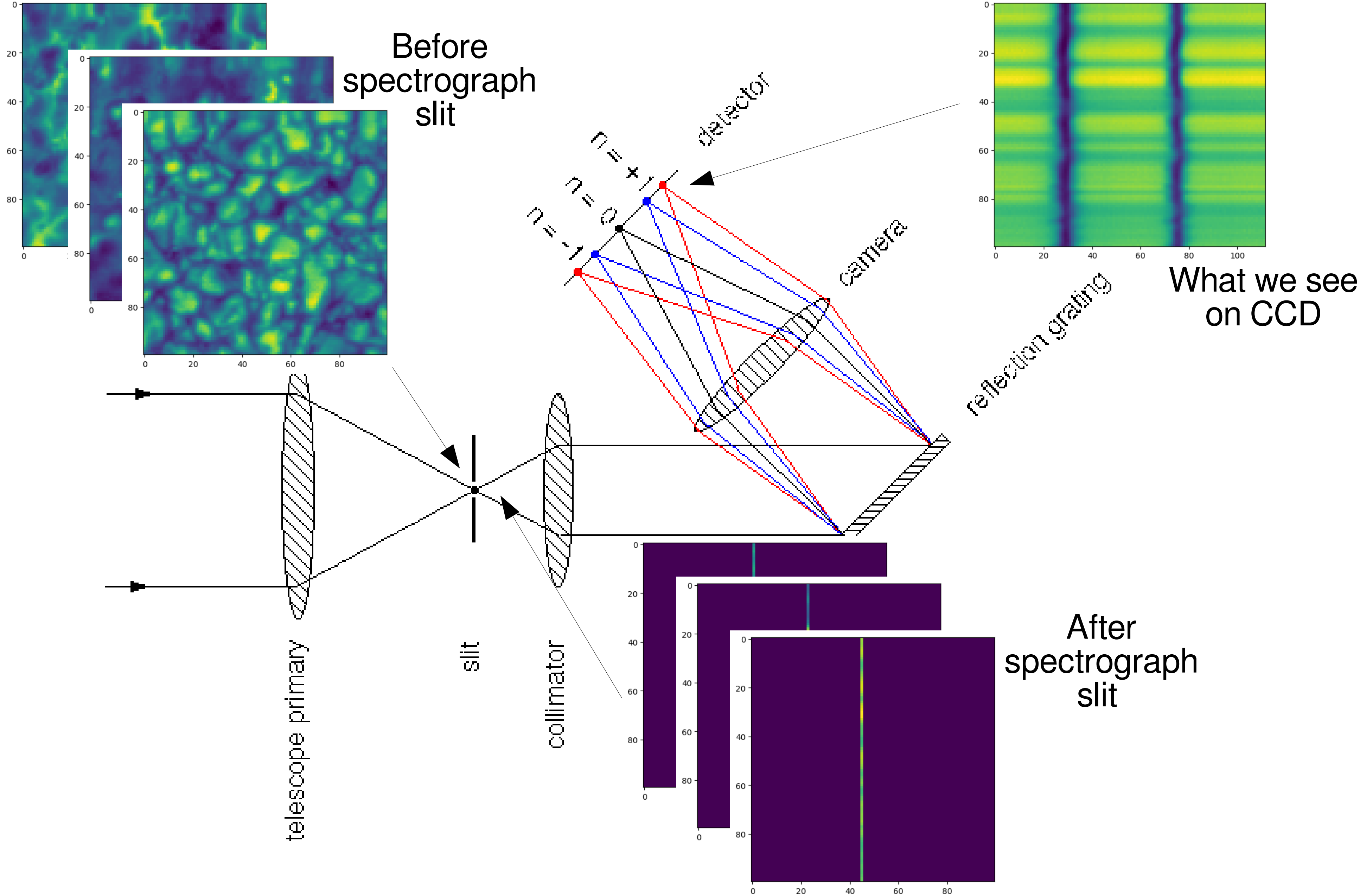
- We will take a slice of the image of the Sun using so called **slit** and disperse it perpendicularly to the slit.
- We record this on a 2D detector
- Ideally, width of the slit should be equal to our optimal spatial sampling (obv wavelength dependent)
- We can then, in principle, move the slit over the image, and sample our datacube **slice per slice**

As in this HINODE cube we saw before



Spectroscopic mapping





Before spectrograph slit
detector
n = +1
n = 0
n = -1
camera
reflection grating
What we see on CCD
telescope primary
slit
collimator
After spectrograph slit

Let’s talk about this famous datacube then

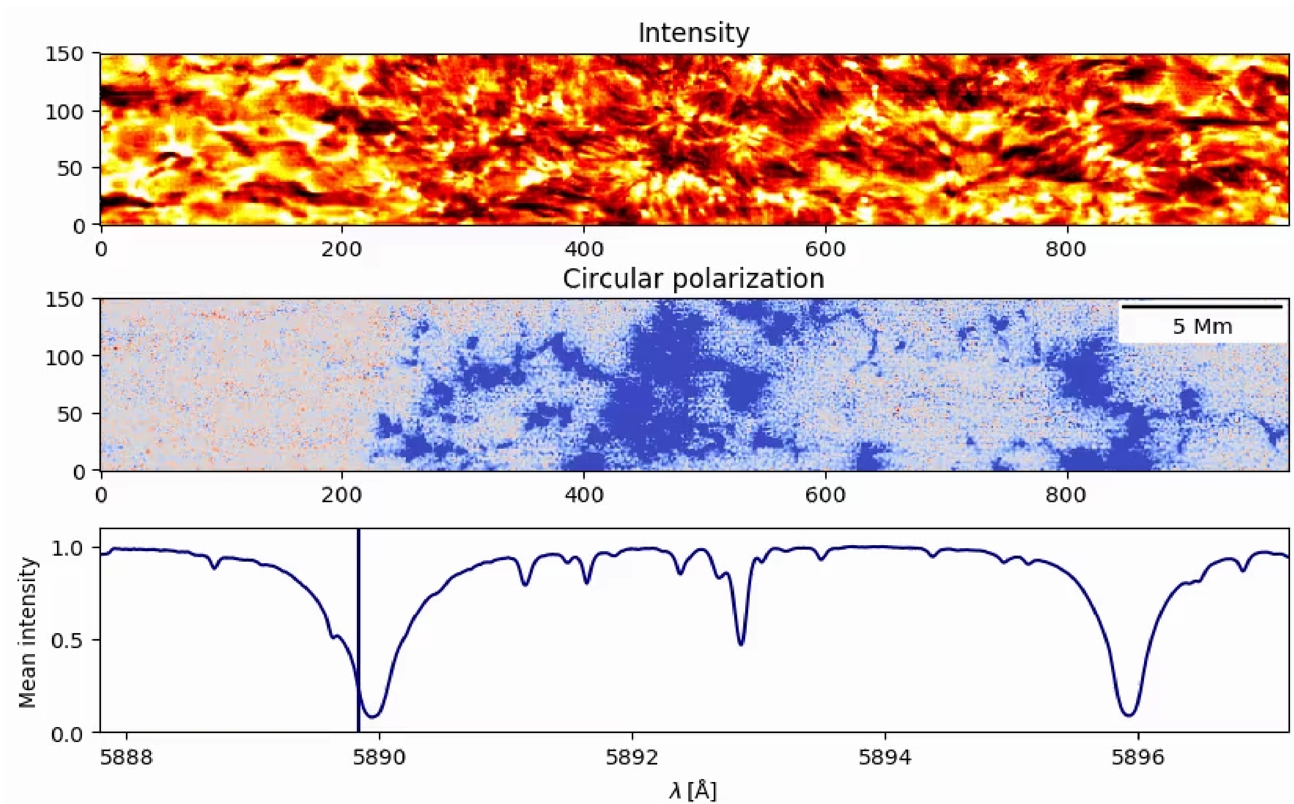
- How many slit positions?
- ~ 2000
- How much to aquire the whole image?
- ~ 3 hours
- How does this compare to typical solar timescale
- Poorly :)

Differences w.r.t. Fabry-Perot

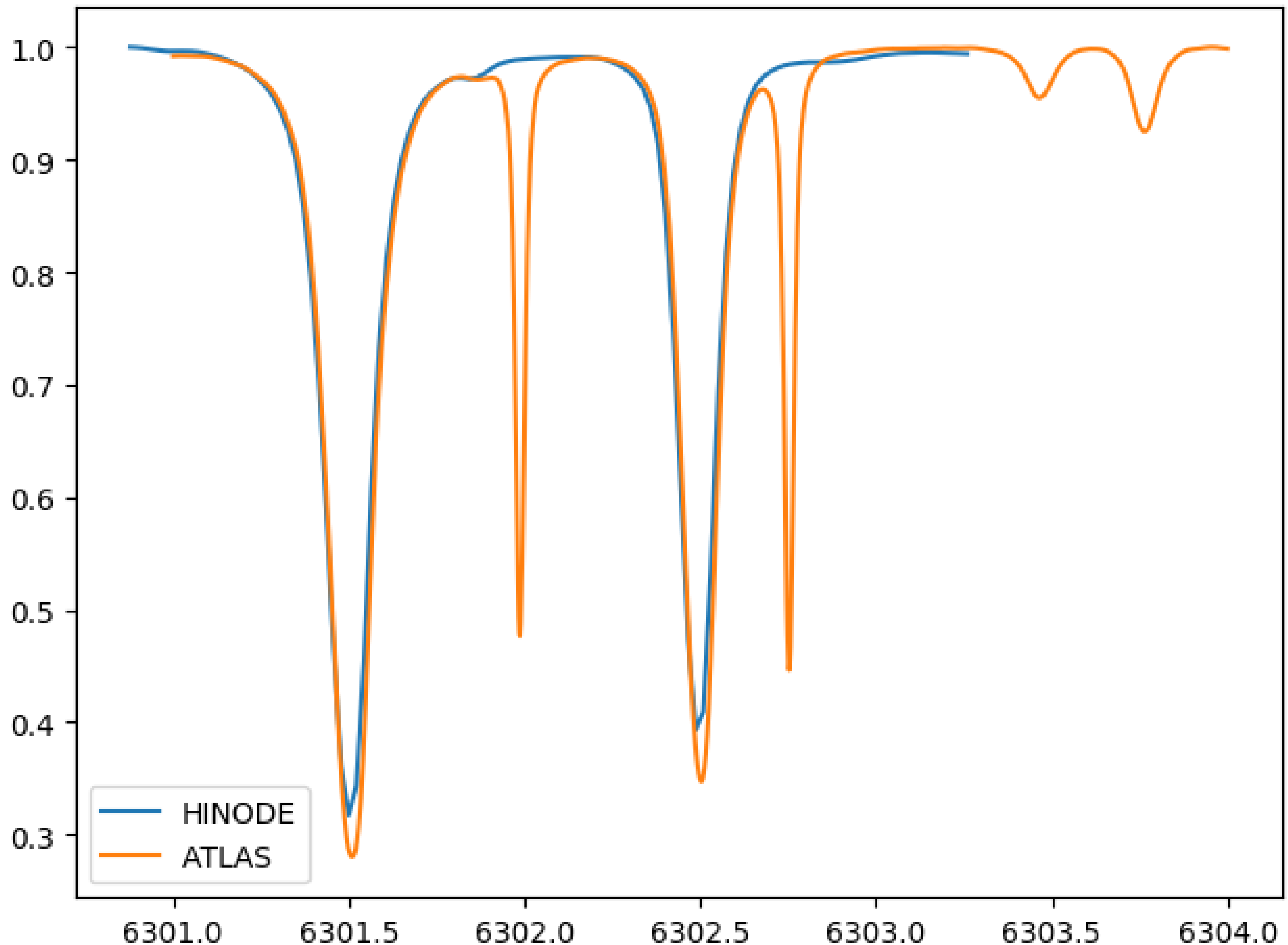
- Slicing over **x or y**, no co-temporal and co-spatial information whatsoever (at least not along the scanning direction)
- We get all the wavelengths at the same time (good if we are looking at some statistical properties, so we don't have to scan)
- Sampling in wavelength almost uniform
- Better-behaved spectral resolution (nicer spectral PSF)
- Worse efficiency (light distributed over multiple maxima)
- Generally used for longer exposures
- No images, can't employ image restoration

Well, in principle we can

- TRIPPEL spectrograph at SST, spectral resolution ~ 100000
- Co-temporal context images, that allow the spectra to be restored (van Noort, 2017)
- Scanning is fast, almost continuous, noise is somewhat large

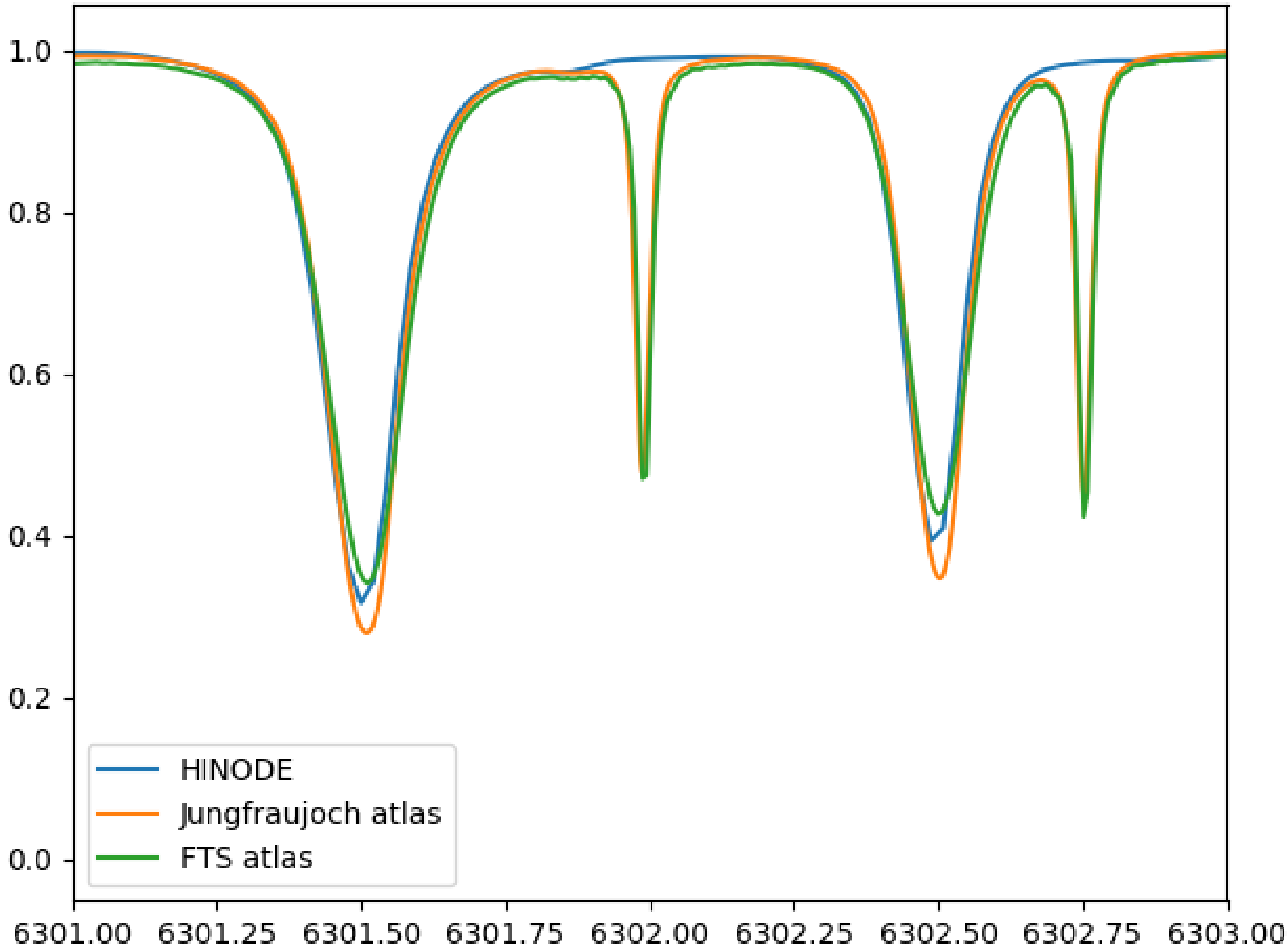


Effects of spectral resolution



I was unhappy with this

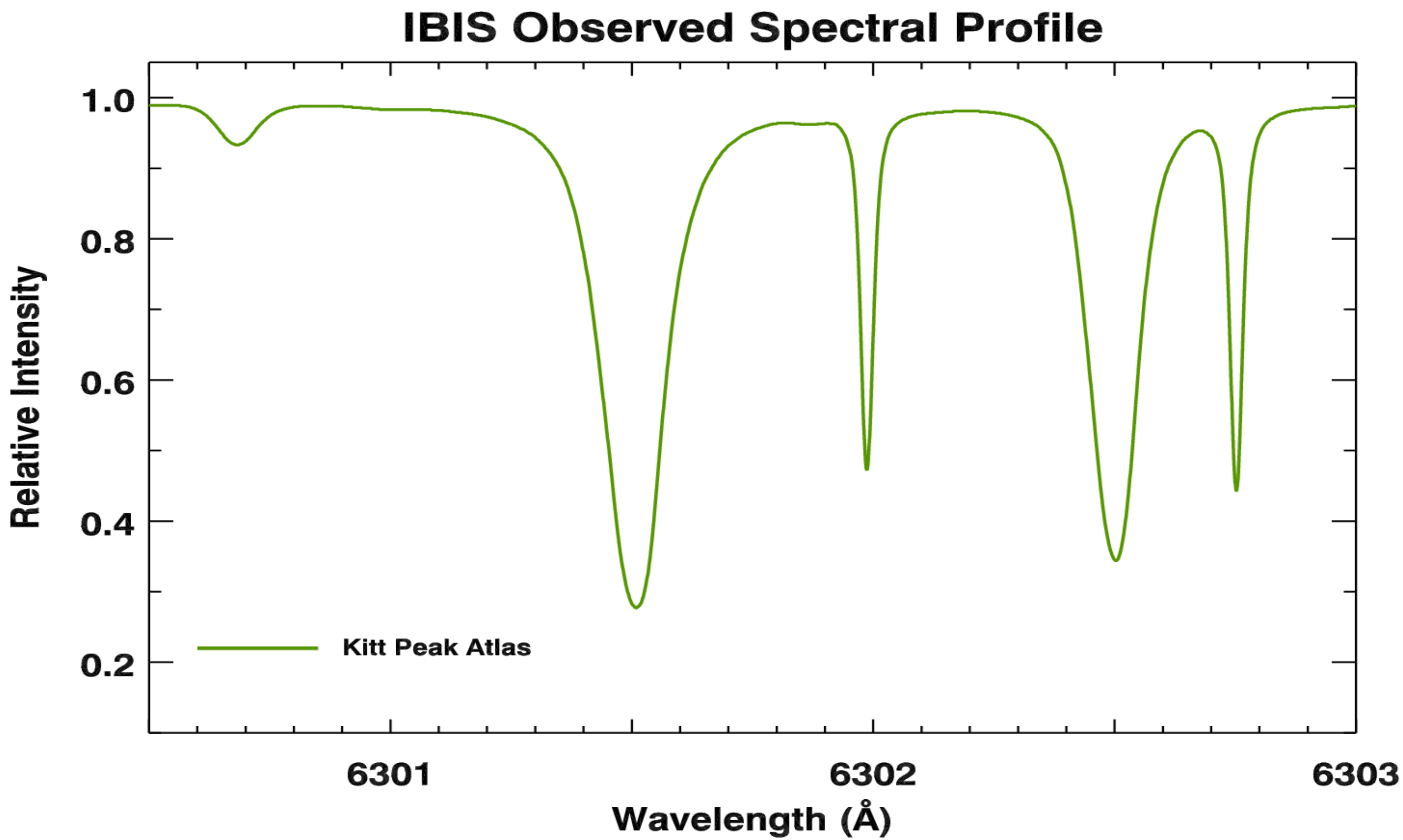
- Lines looked very similar (broadening was not visible)
- There was some scattered light that was important for you to see, but I wanted to emphasize instrumental broadening
- I looked up online, HINODE SOT/SP has 200 000 resolution (it is actually downsampled)
- Sadly, it is not always easy to find references. A little bird once told me that Jungfraujoch is around 400 000, not so much, eh
- Ok, let’s look at another atlas. I went and downloaded Brault & Neckel atlas from 1987….

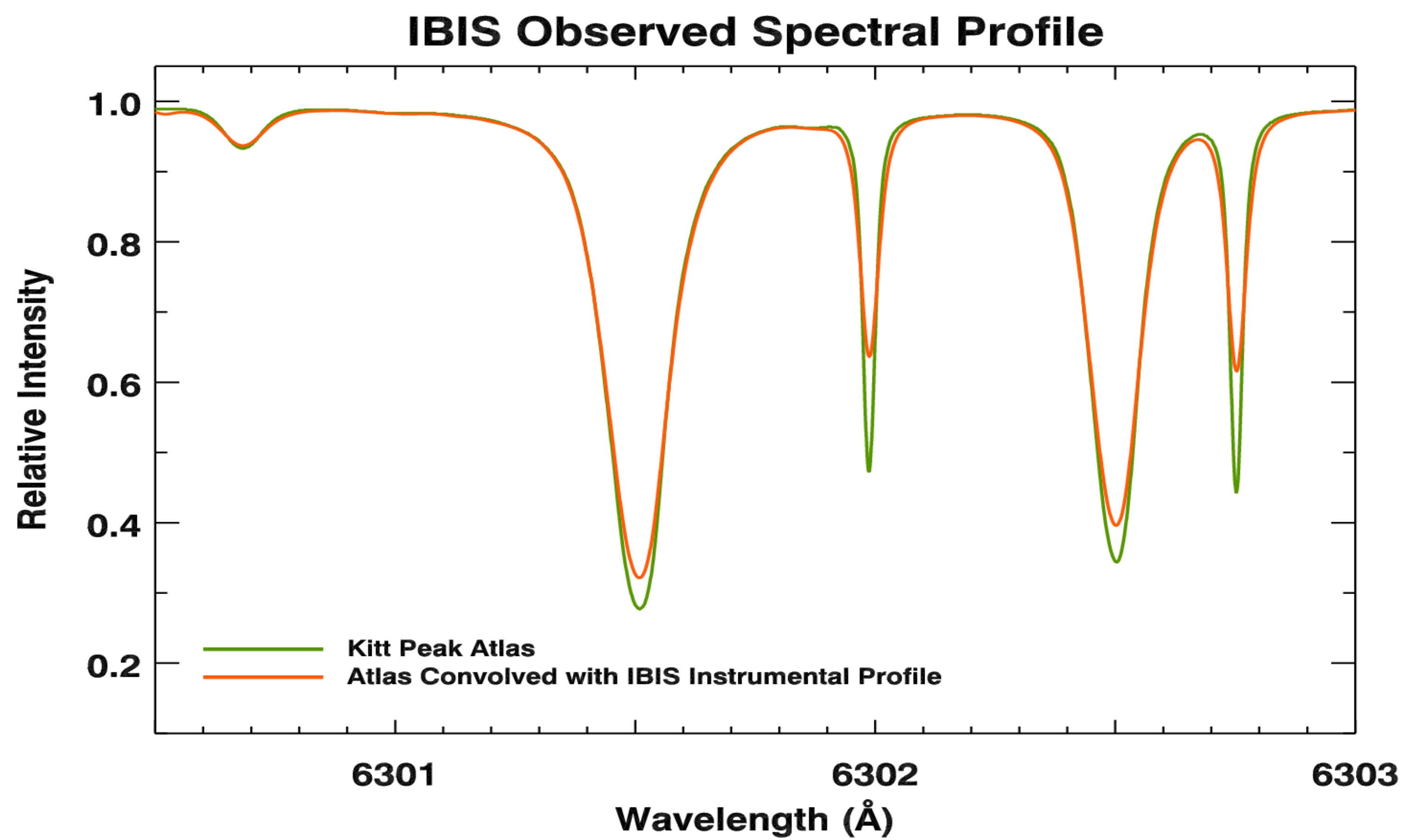


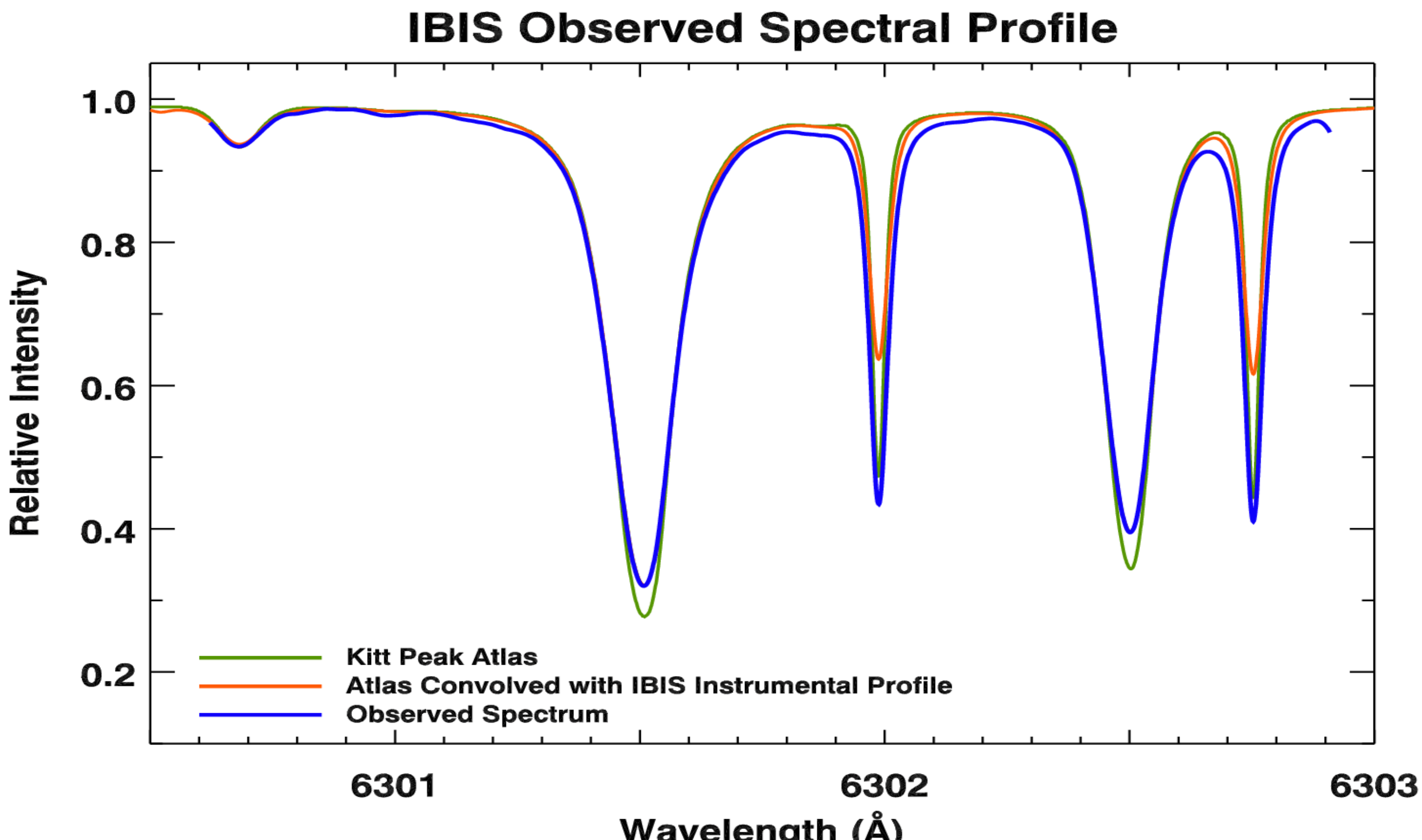
Wow this atlas is different, why?

That's right, one corresponds to disk center, the other one to the whole Sun.

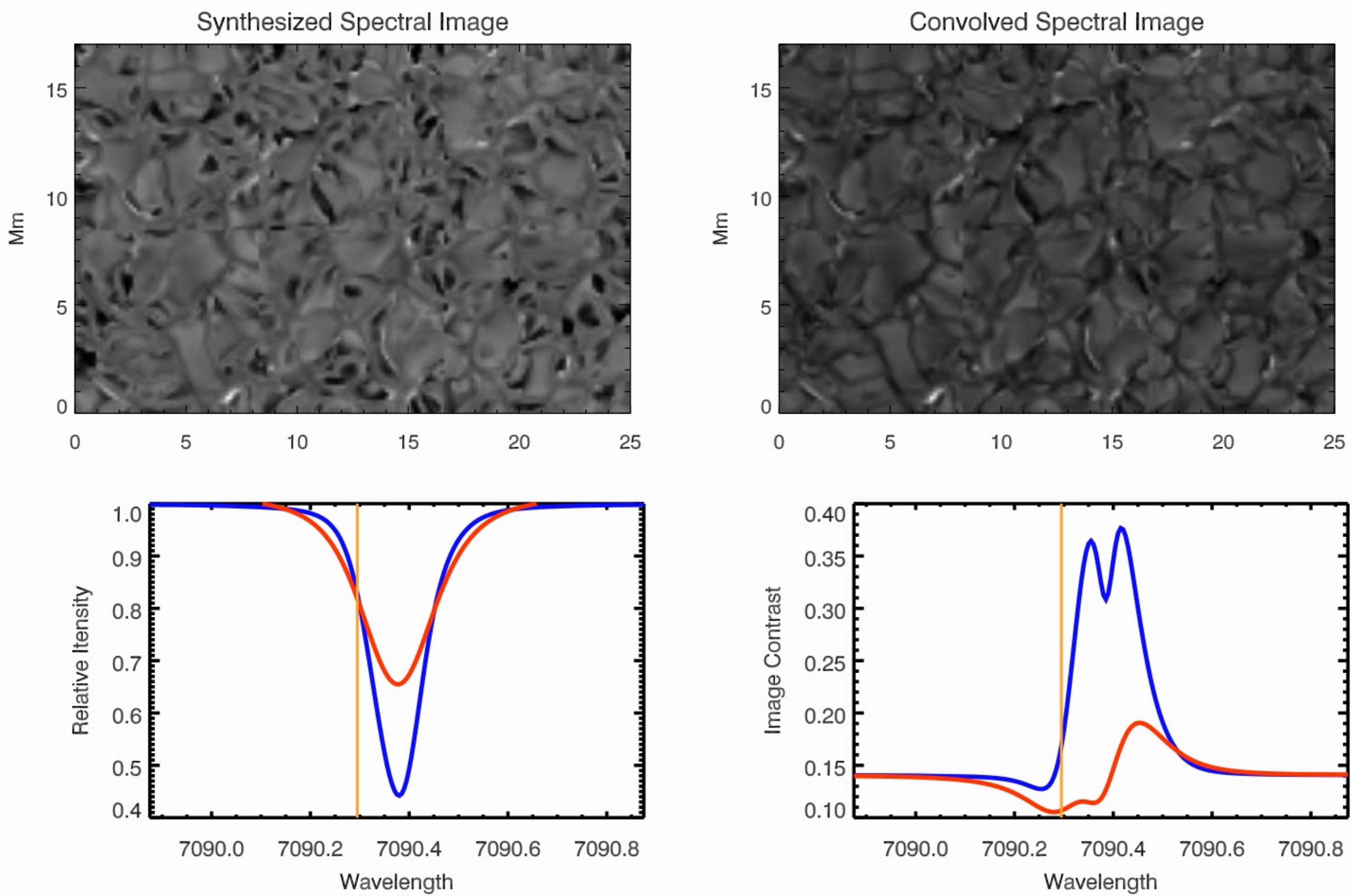
Ok, then let's go to Kevin
(next few slides courtesy of Kevin Reardon)




IBIS Observed Spectral Profile
1.0
0.8
0.6
0.4
0.2
Relative Intensity
6301
6302
6303
Wavelength (Å)
Kitt Peak Atlas
Atlas Convolved with IBIS Instrumental Profile



IBIS Observed Spectral Profile
Relative Intensity
1.0
0.8
0.6
0.4
0.2
6301
6302
6303
Wavelength (Å)
Kitt Peak Atlas
Atlas Convolved with IBIS Instrumental Profile
Observed Spectrum


Synthesized Spectral Image
Convolved Spectral Image
Mm
0
5
10
15
20
25
Relative Itensity
Image Contrast
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.40
0.35
0.30
0.25
0.20
0.15
0.10
7090.0
7090.2
7090.4
7090.6
7090.8
Wavelength

Summary

- Spectrographs and Fabry-Perot filters allow us to sample our observations in wavelength
- We always need to sacrifice something to get the wavelength information
- Can we not, somehow, get everything?
- Yes we can, there are so called IFU, that provide both simultaneously
- Still, even in this case you are sacrificing something, in this case, field of view (camera simply has a finite size, we can’t beat that)
- Webpage will have some useful links so you can play with spectra and reproduce what you saw here