


Readings for Lecture

From Gallaway "*An Introduction to Observational Astrophysics*":

<u>For next lecture(s):</u> Chapter 13 Spectroscopy

PS#8 is due today

Final Project Details

The final project (PS9) + final exam will be combined into a single Final Project.
This final project will be due at the end of finals period.

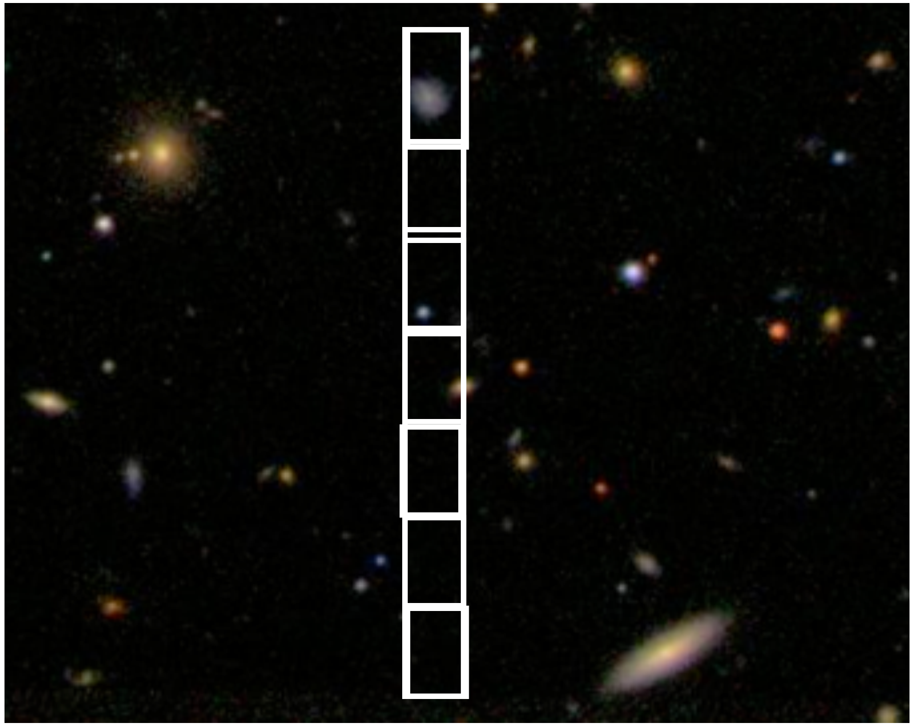
The final project grade will count as either 20% or 30% of your grade.
The midterm exam will count as either 30% or 20% of your grade.

I will take the higher of the two scores to count as 30%

The remaining 50% is from PS#1-8.

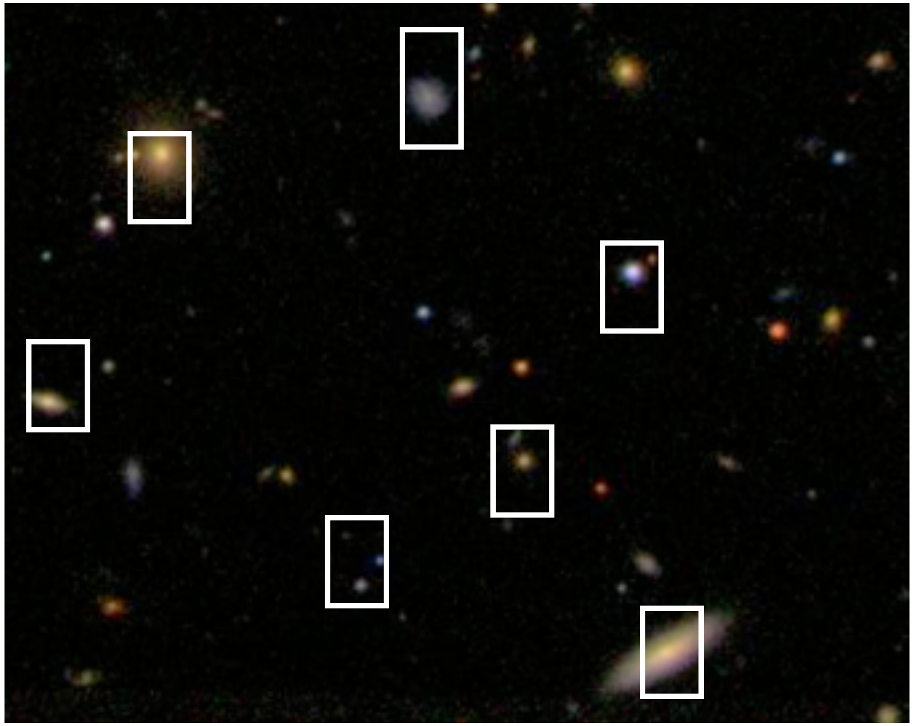
Multi-Slit Spectroscopy

single-slit spectroscopy



=>

multi-slit spectroscopy

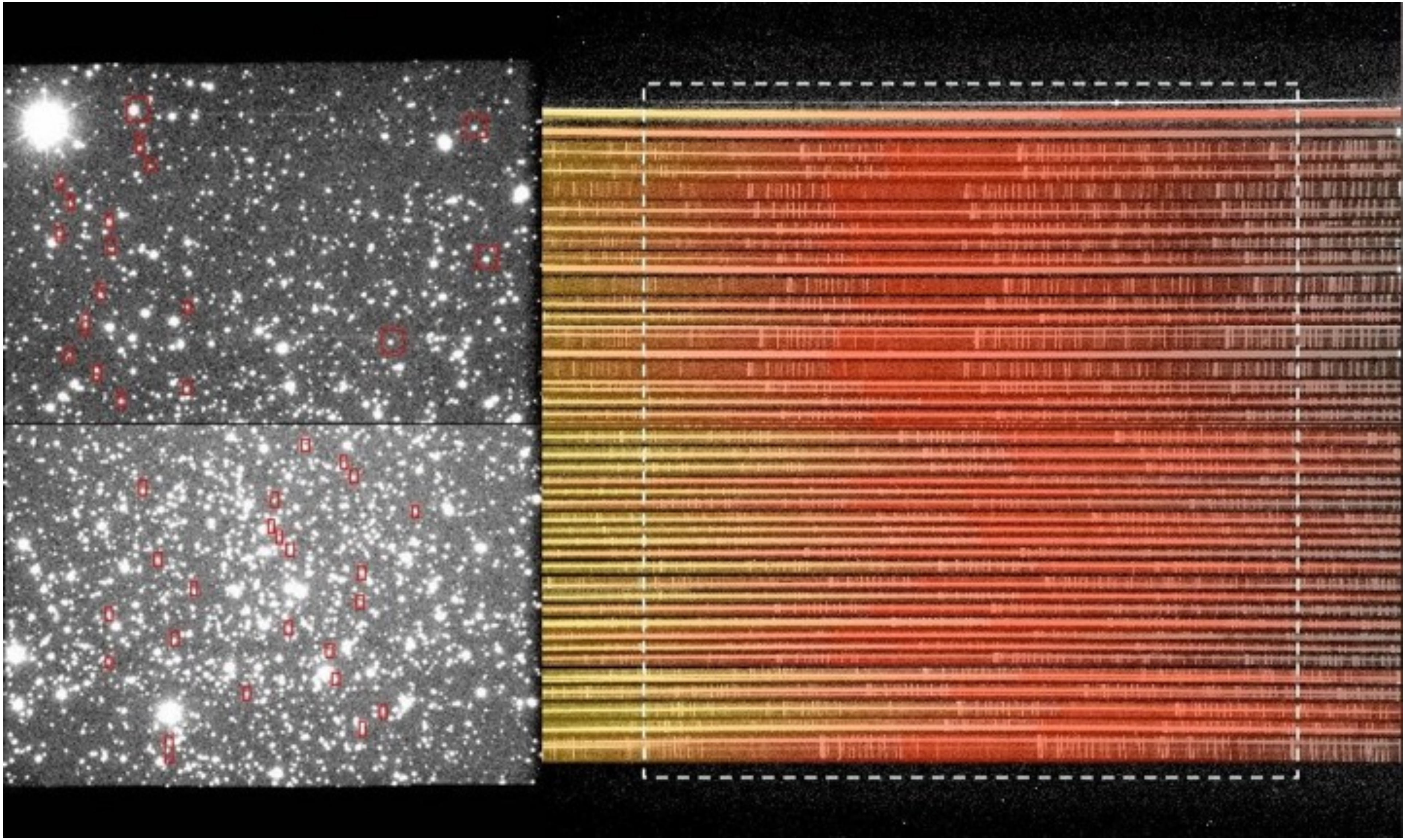


Modes of Spectroscopy

Taking an image of the sky requires 2D detectors (x and y). Spectroscopy of the sky requires 3D (x, y and λ). There are several ways to slicing up this 3D data to fit on our 2D detectors.

- **Slitless Spectroscopy:** Place dispersing element in front of entire image.
  Pro: spectrum of full image.
  Con: overlapping spectra
- **Long-slit spectroscopy:** Place single long-slit, get spectra only of objects falling into slit.
  Pro: Clean spectrum of a single object
  Con: Can observe only one object at a time
- **Multi-slit spectroscopy:** Create a mask or plate with slits at multiple positions.
  Pro: Clean spectra of a multiple objects per exposure
  Con: Need to design/fabricate a mask for each observed field
- **Multi-fiber spectroscopy:** Use many fiber optics to obtain spectra of multiple objects
  Pro: Clean spectra of a multiple objects per exposure, configurable.
  Con: Typically less efficient than slit spectroscopy due to fiber light loss.

MultiSlit Spectroscopy



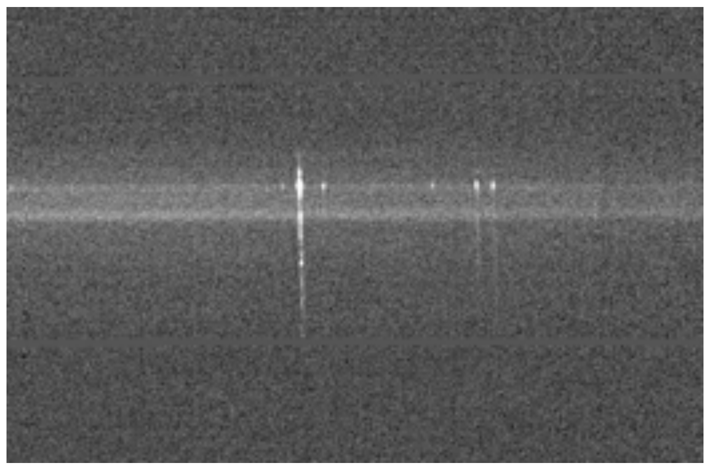
Analyzing Spectra

Observing a spectrum with a detector yields a two-dimensional image (x and λ).

Image

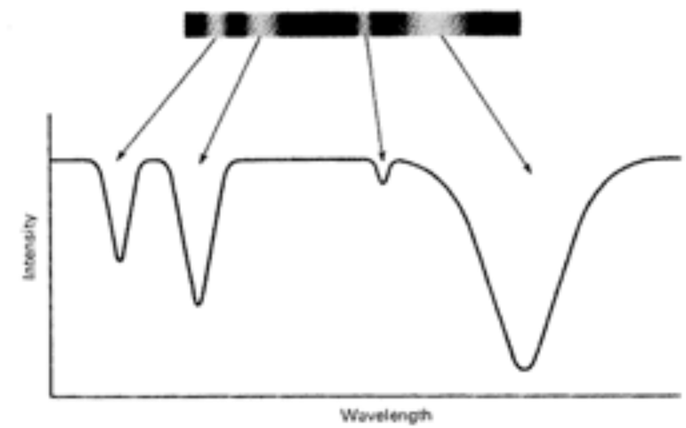
2D Spectrum

spatial ->

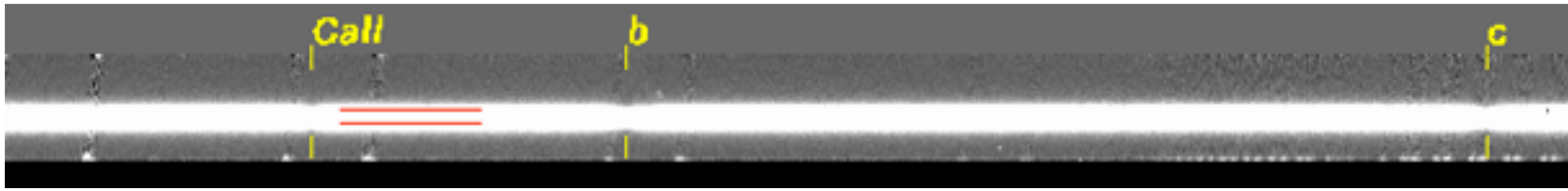


wavelength ->

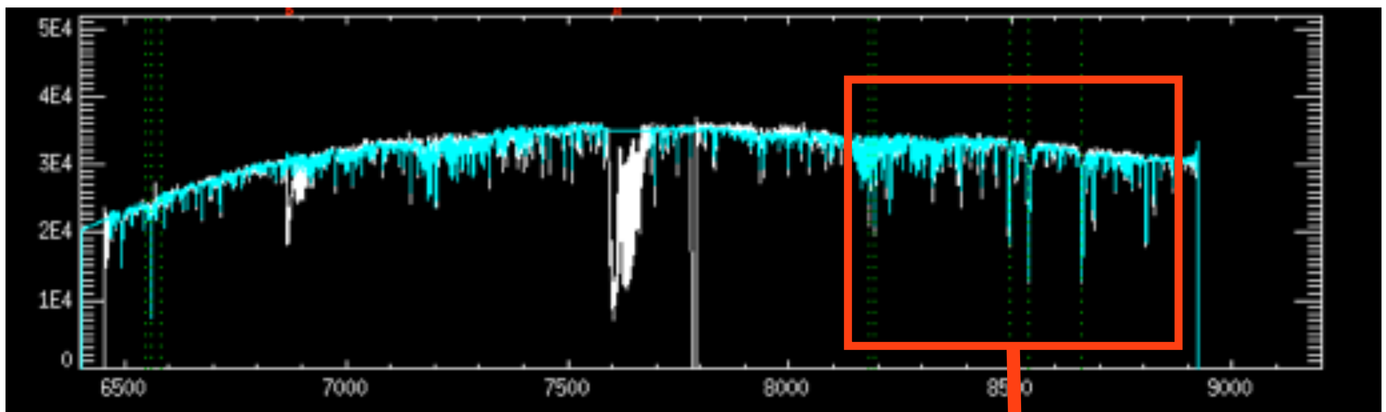
1D Spectrum

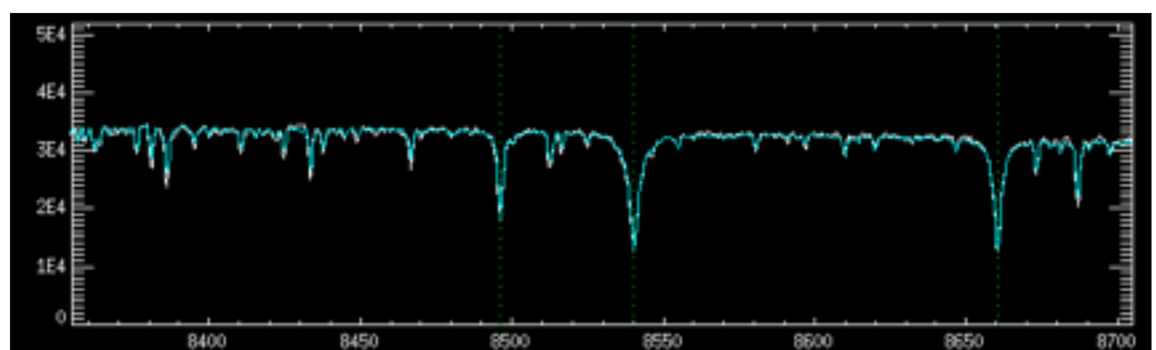


Analyzing Spectra

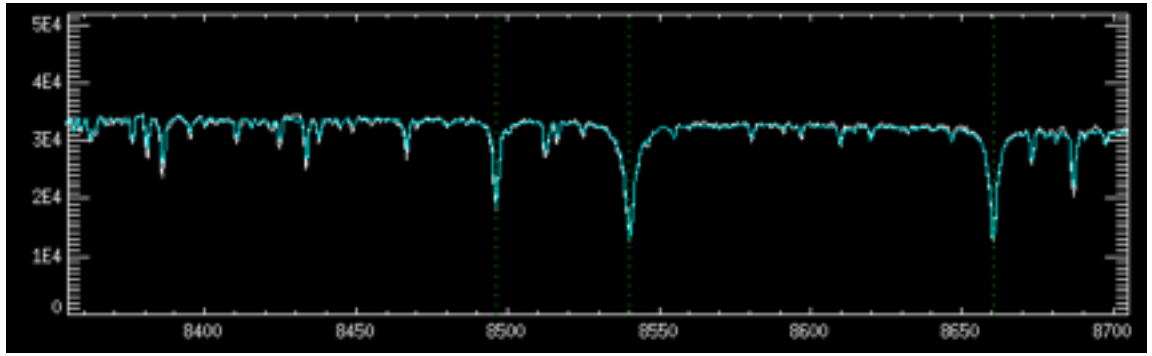


‘Extract the 1D spectrum’

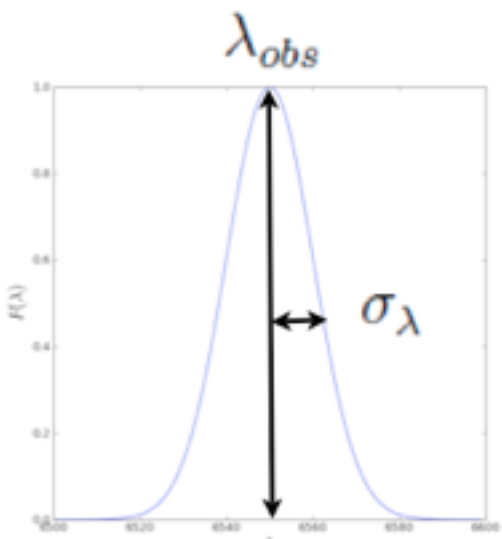




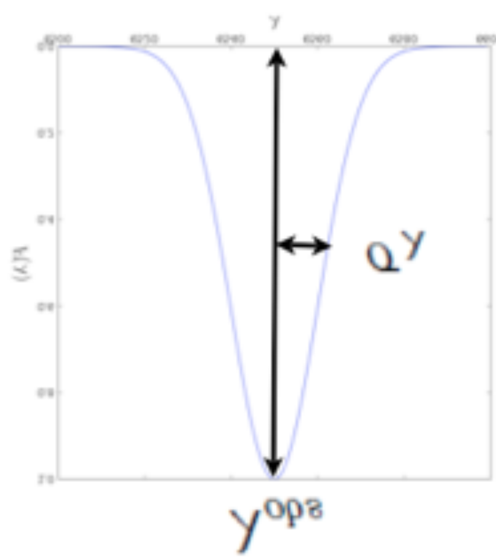
Spectral Lines: Concepts and Terms



Emission Line



Absorption Line



Spectral Lines: Concepts and Terms

The measurable quantities are spectral line center, line width and line area:

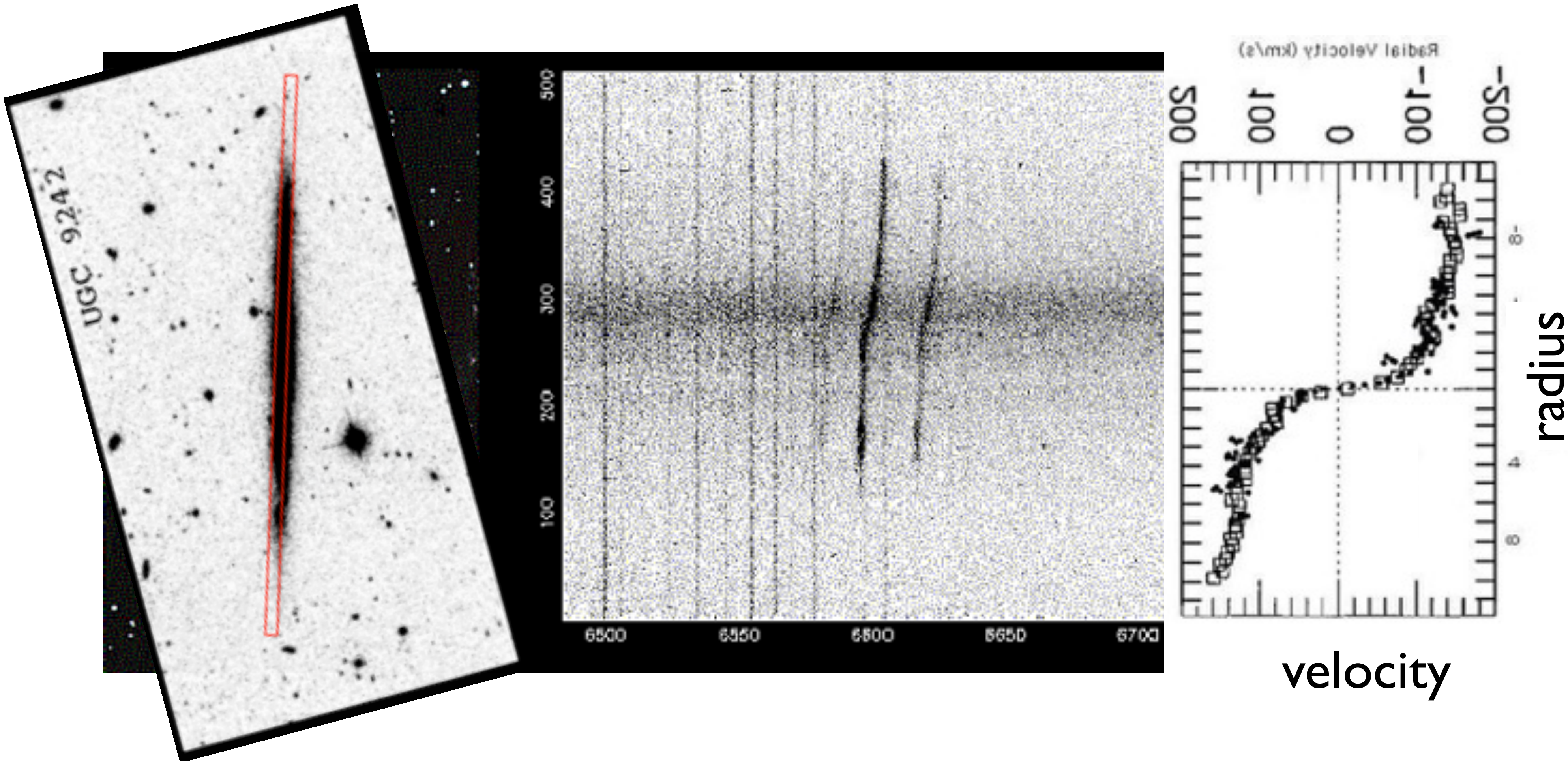
Line Center: Provides an estimate of the object's velocity via Doppler shift

Line Width:

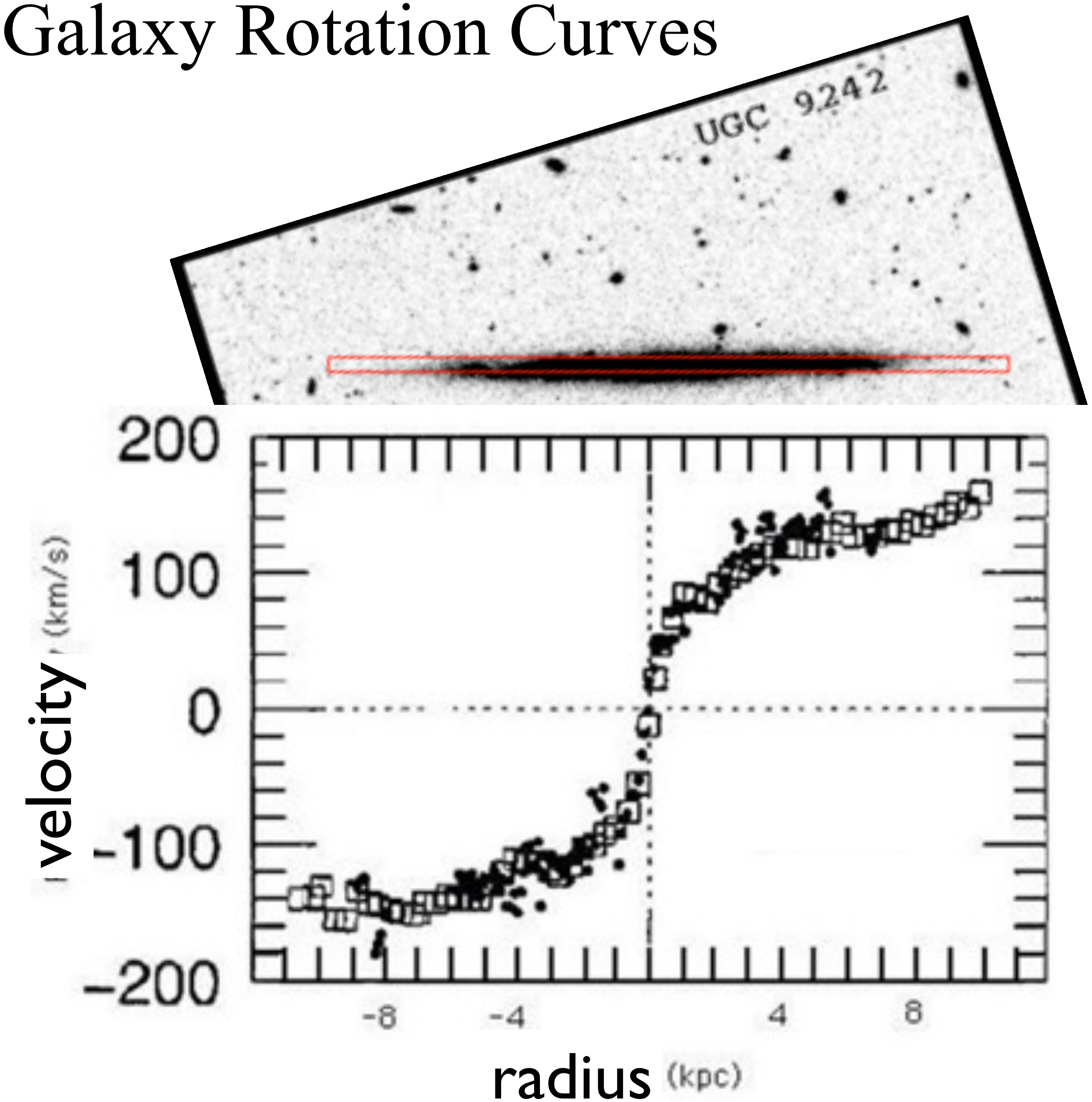
Line Area:

Galaxy Rotation Curves

Can measured internal dynamics of a galaxy.



Galaxy Rotation Curves



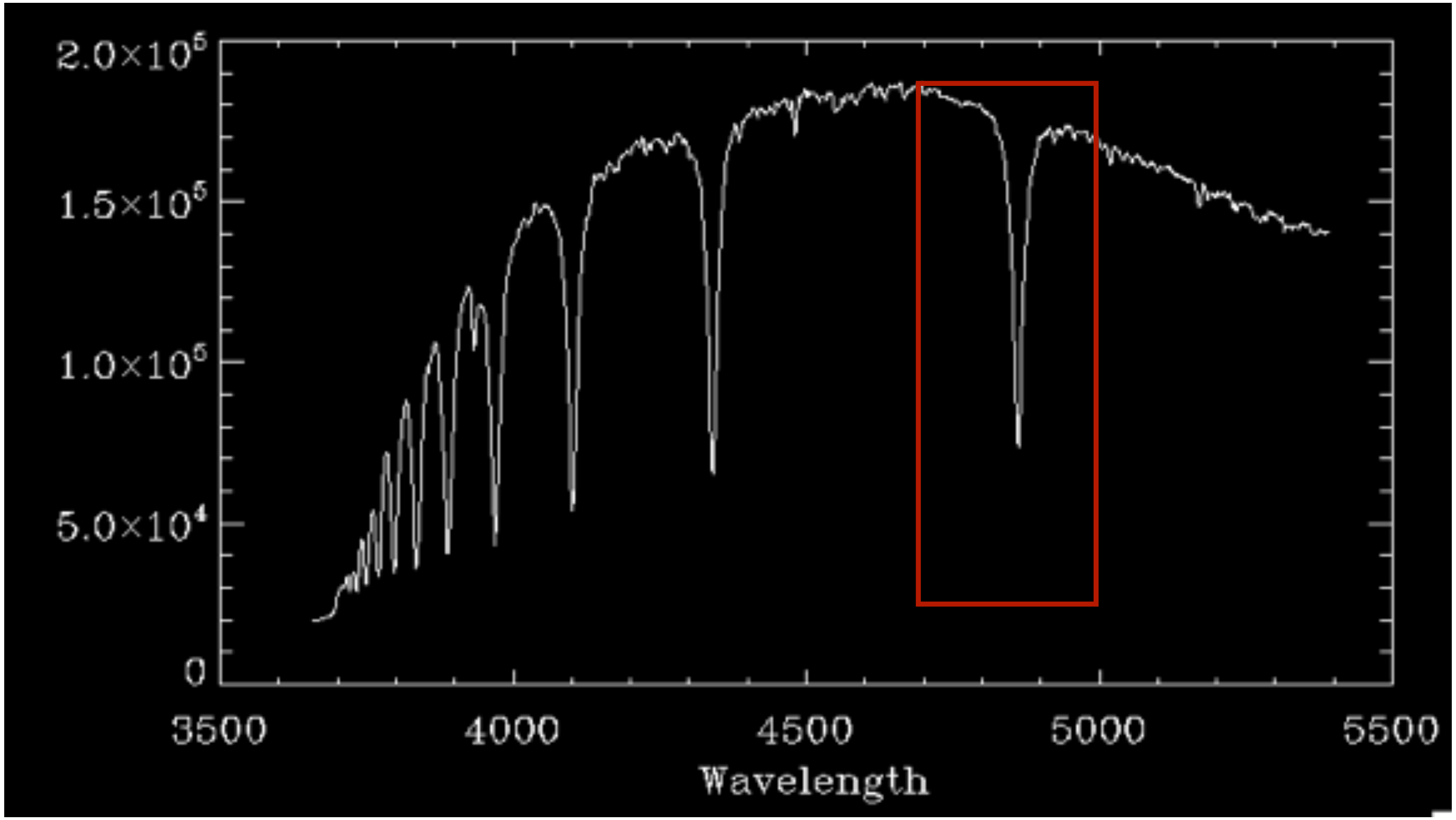
At each radius, we can predict velocity based on luminous matter

Velocity is flat passed radius which encloses 90% of light.

$$M(< R) \approx \frac{v^2 R}{G}$$

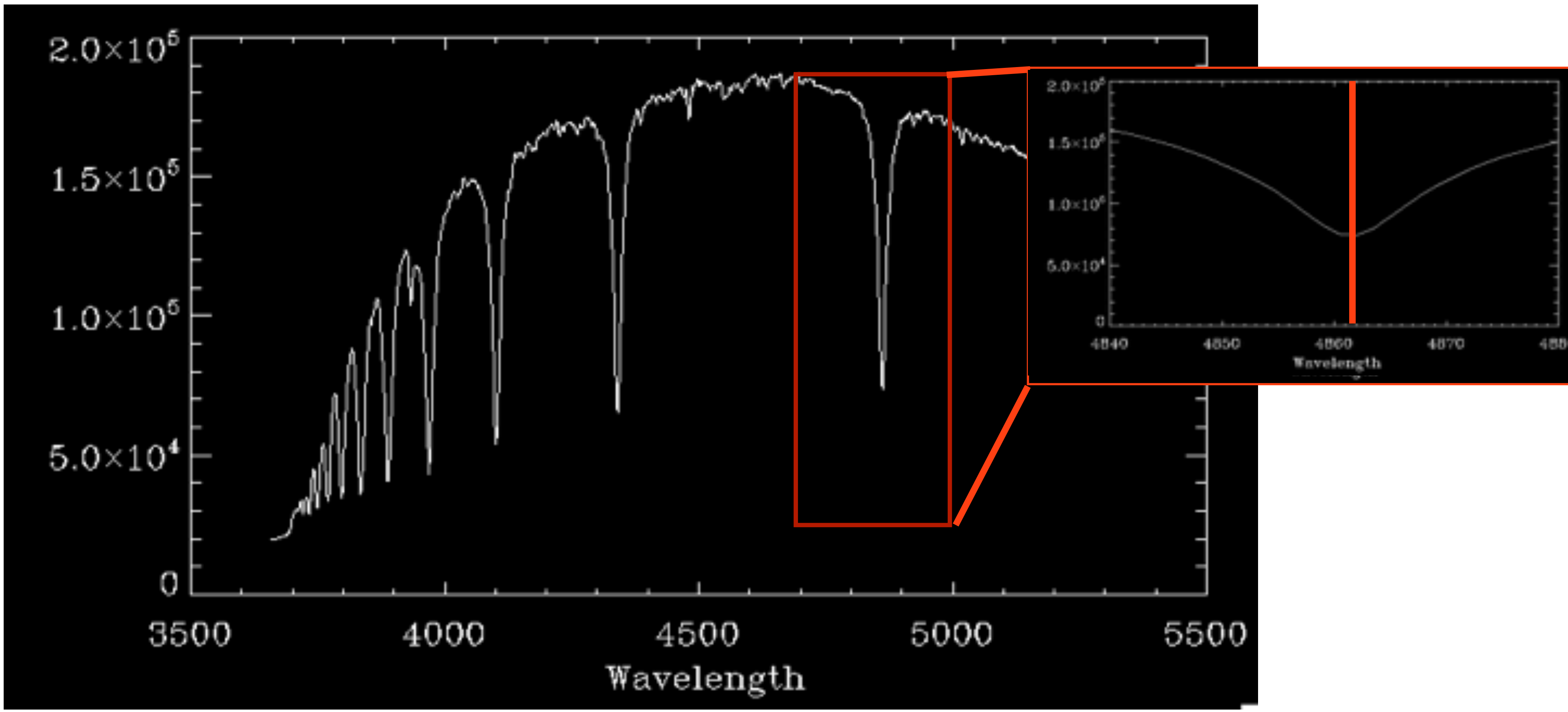
Enclosed mass continues to increase at large radius

Spectral Lines: Measuring Line Centers



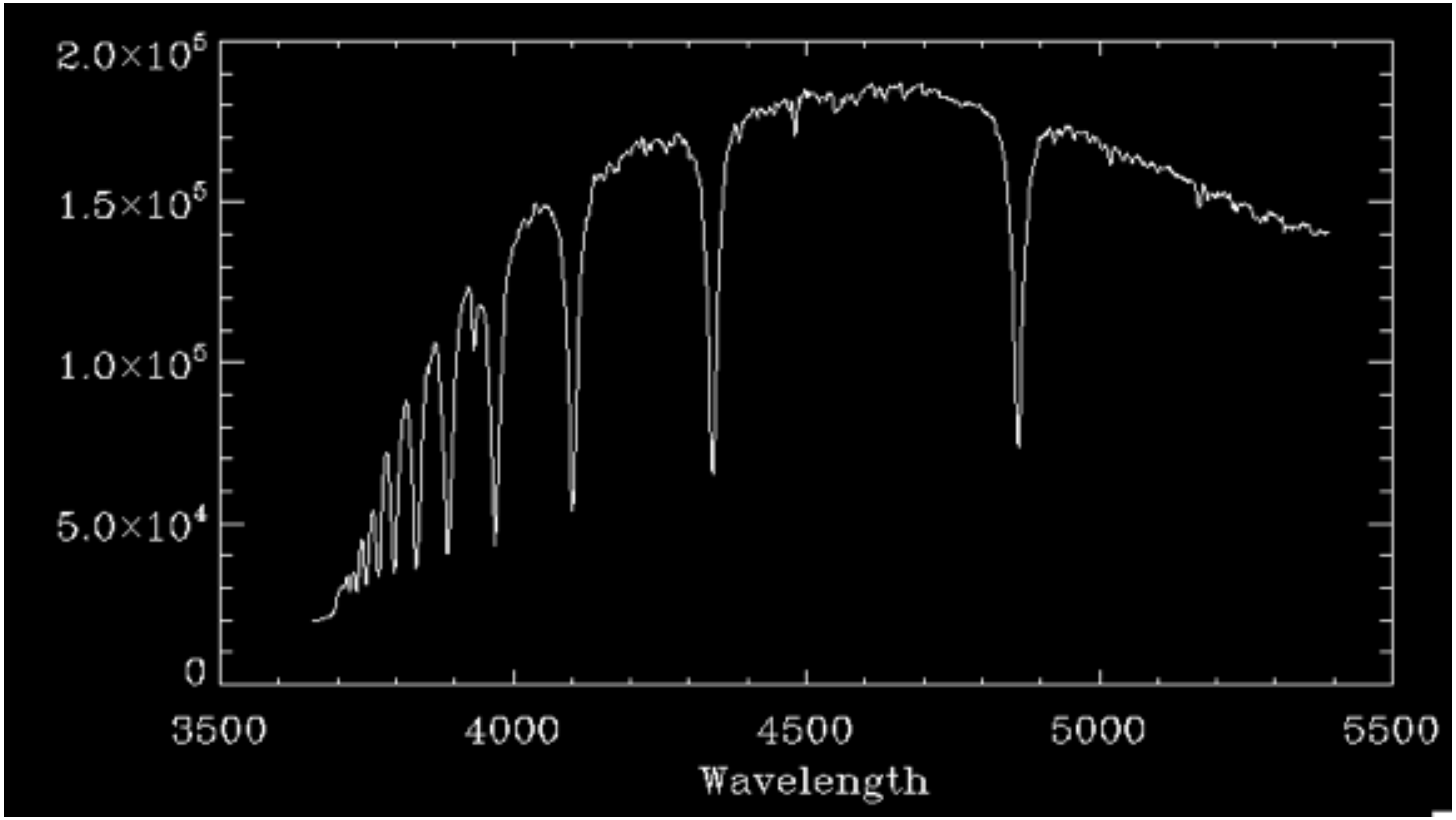
Simplest way to measure redshift/velocity: estimate line centers and compare to rest λ

Spectral Lines: Measuring Line Centers



Simplest way to measure redshift/velocity: estimate line centers and compare to rest λ

Spectral Lines: Measuring Line Centers



Simplest way to measure redshift/velocity: estimate line centers and compare to rest λ

More accurate: Chi2- fitting of the spectrum against a template.

Spectral Lines: Chi^2 fitting

Chi^2 fitting of a science spectrum against a template spectrum:

-- Chose a template spectrum which is similar to science spectrum

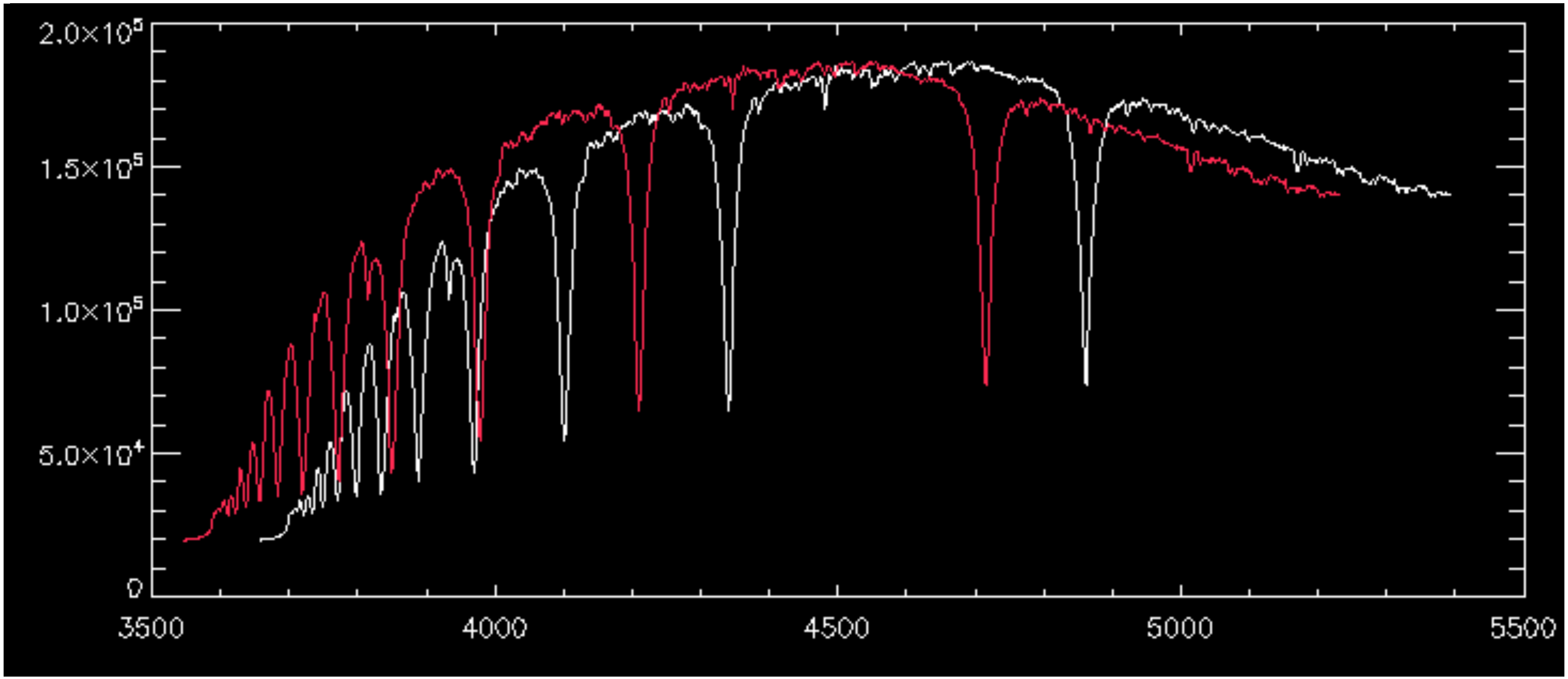
-- Shift template spectrum over a range of velocities

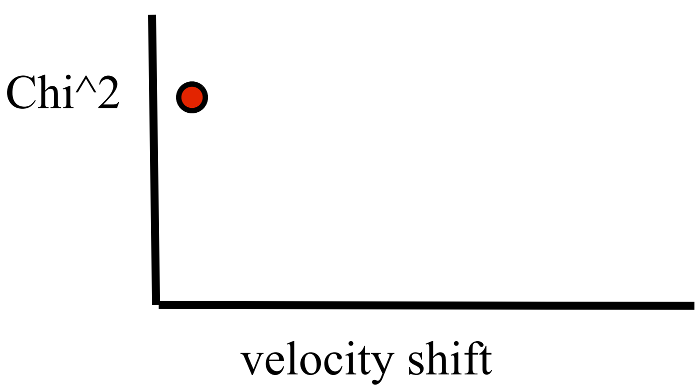
-- At each velocity, calculate difference between template and science.

$$\chi^2 = \sum_{i=0}^{N_{\rm pixel}} \frac{(S_i - T_i)^2}{\mathrm{Err}_i}$$

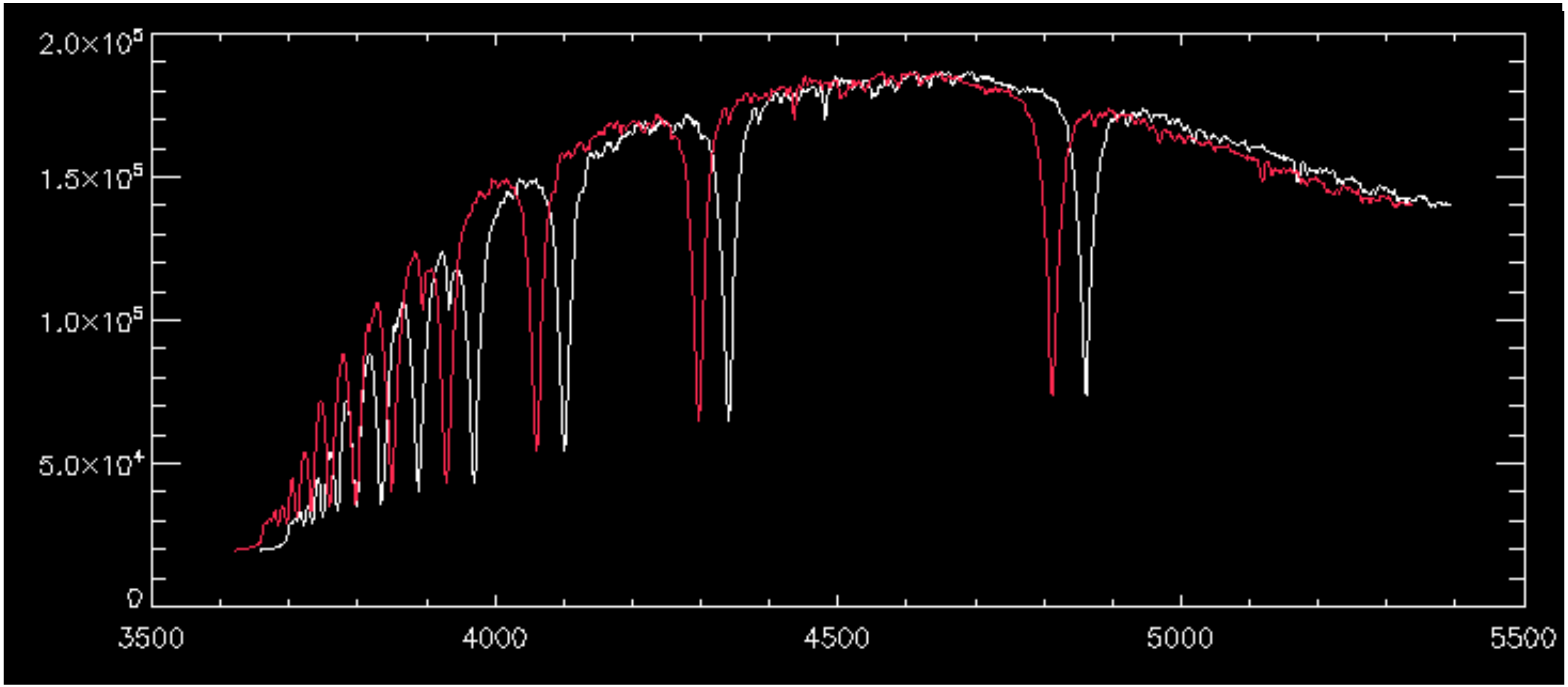
S = science spectrum
T = template spectrum
Err = errors on science

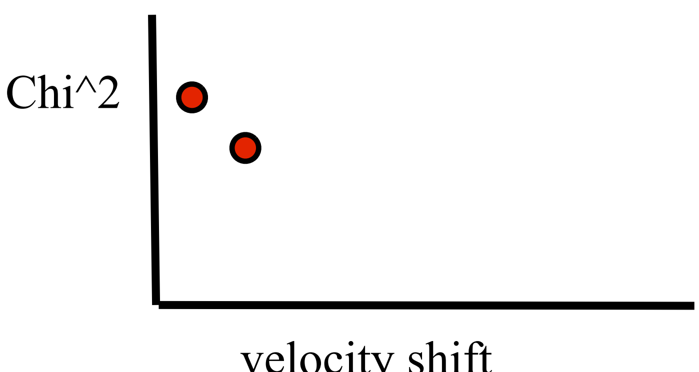
Spectral Lines: Chi^2 fitting



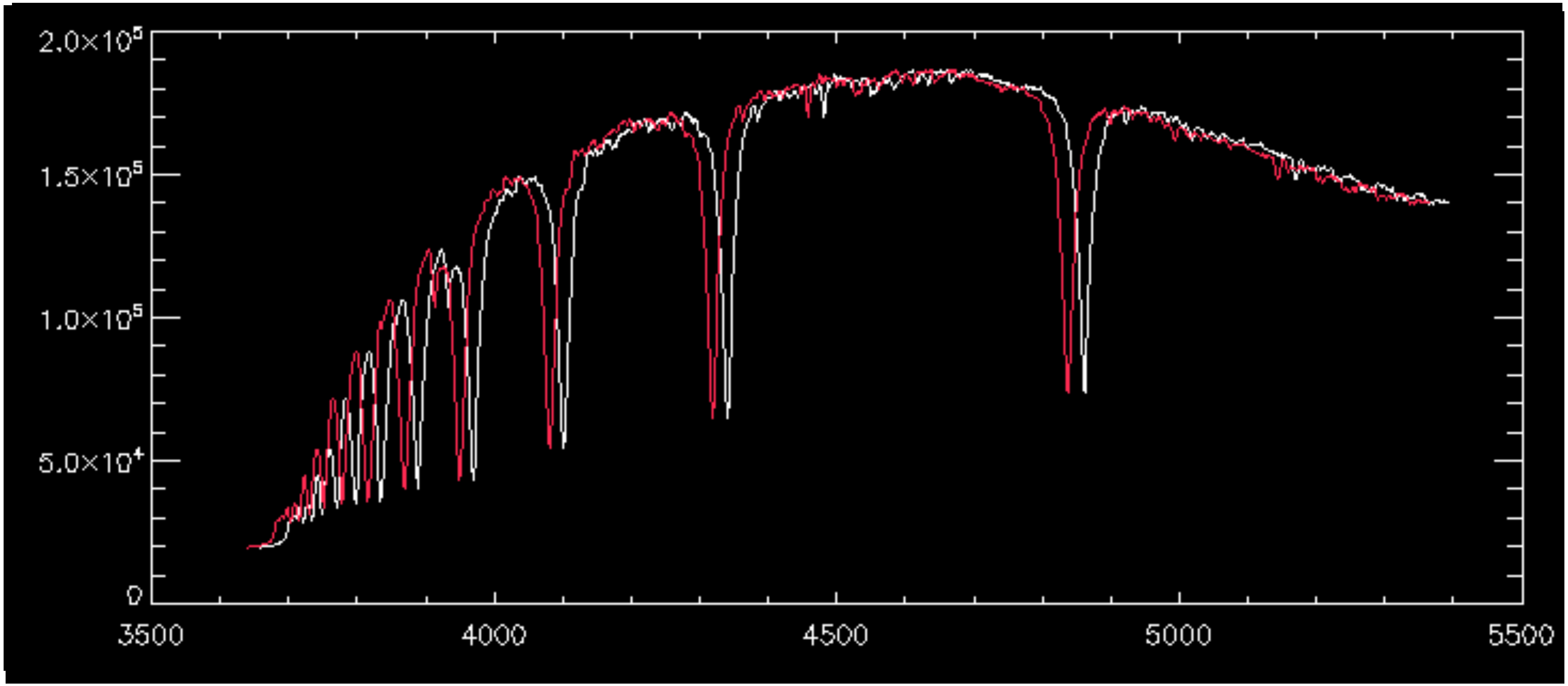


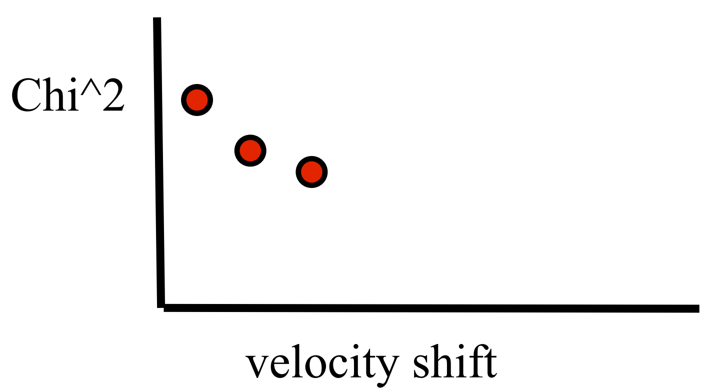
Spectral Lines: Chi^2 fitting



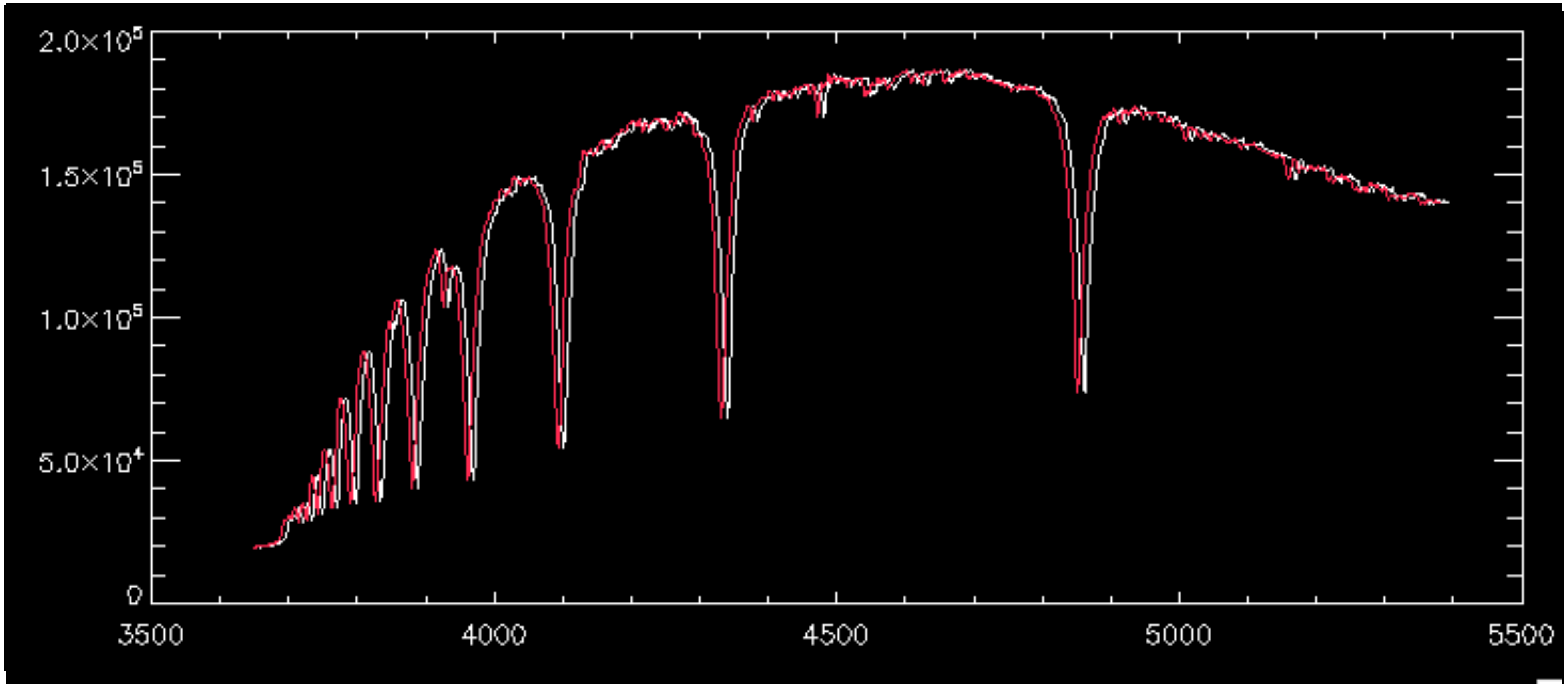


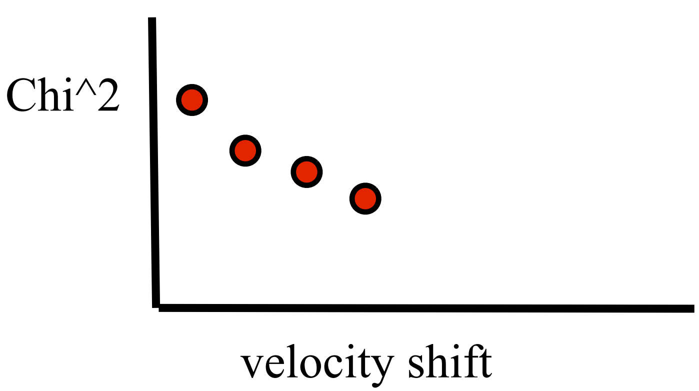
Spectral Lines: Chi^2 fitting



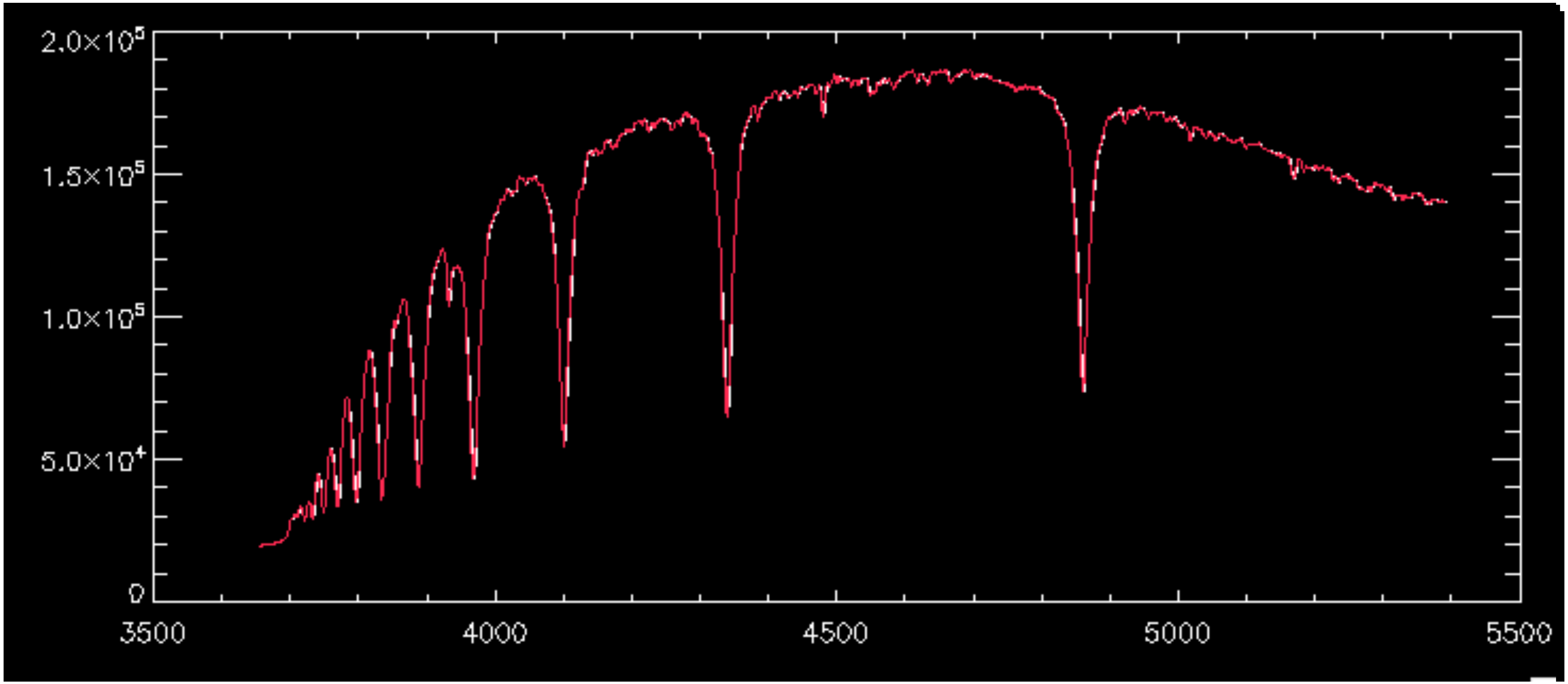


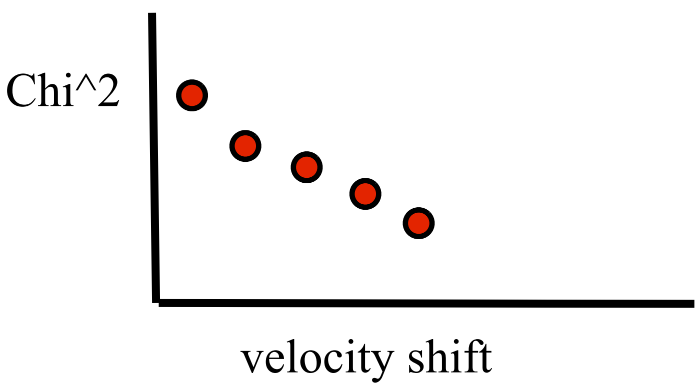
Spectral Lines: Chi^2 fitting



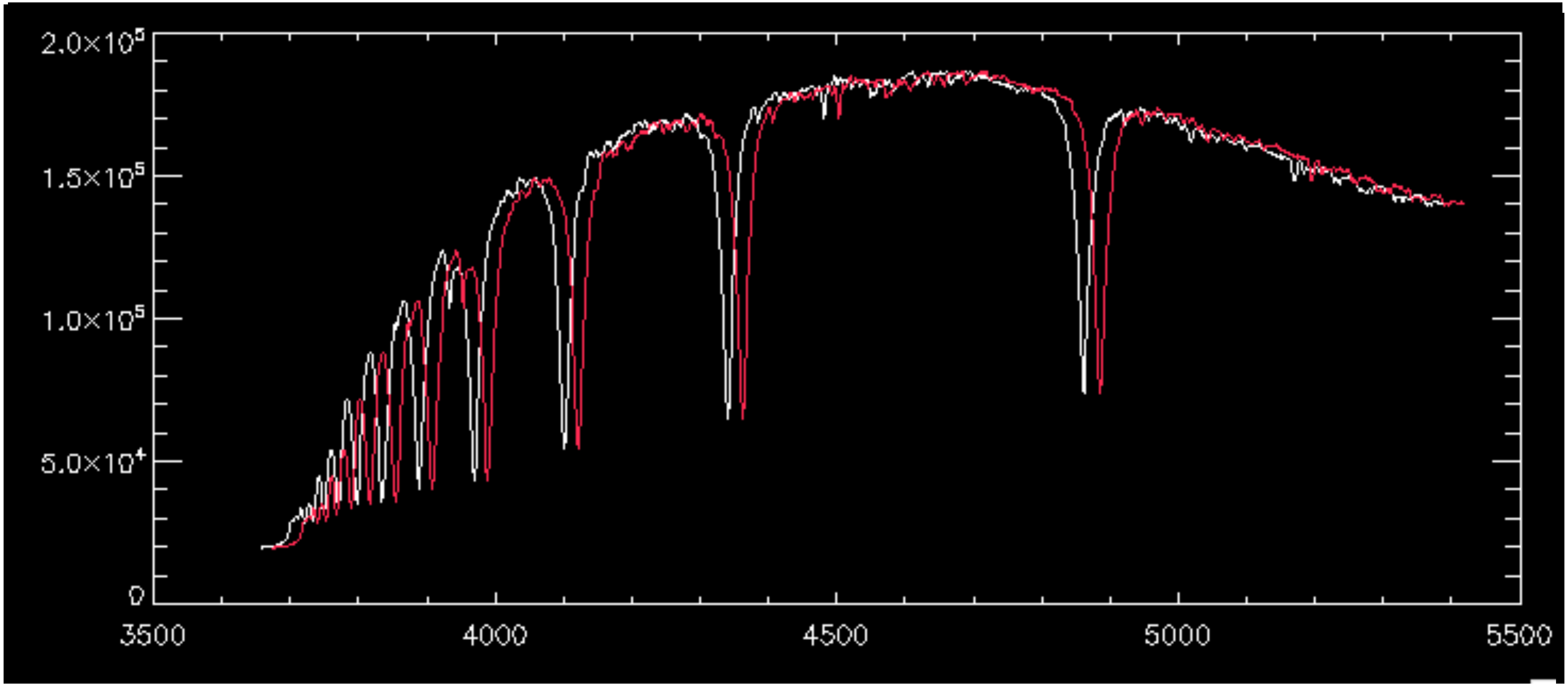


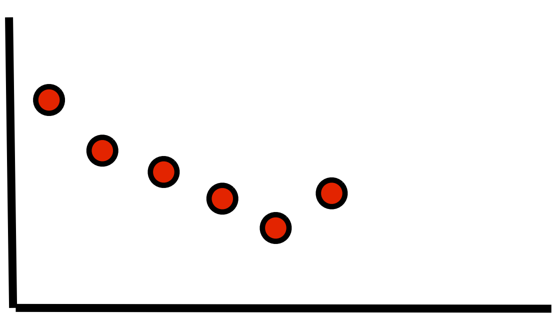
Spectral Lines: Chi^2 fitting





Spectral Lines: Chi^2 fitting





Allows for sub-pixel solutions.

Uses full spectral information (not just one line).

Spectra must be binned logarithmically in wavelength

Spectral Lines: Concepts and Terms

The measurable quantities are spectral line center, line width and line area:

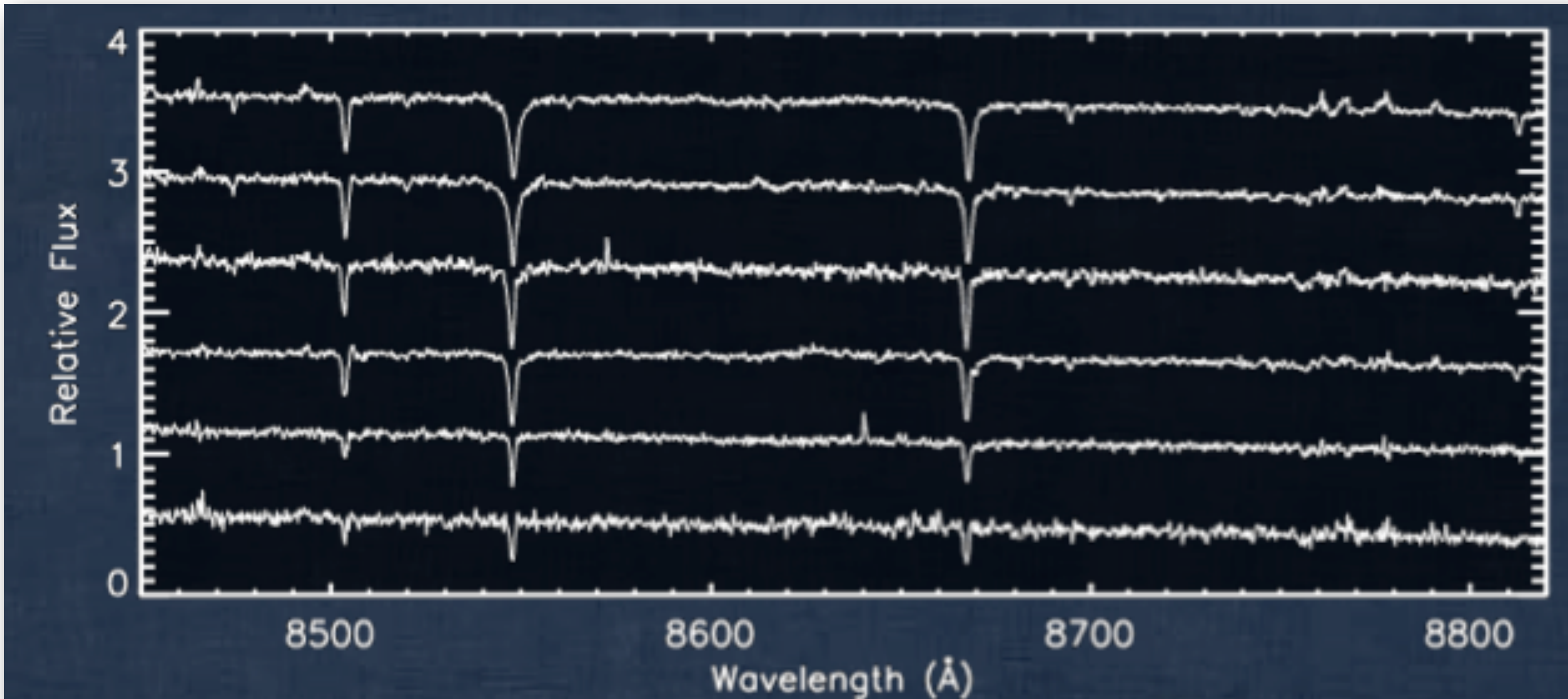
Line Center: Provides an estimate of the object's velocity via Doppler shift

Line Width: Provides an estimate of the object's internal motions

Line Area: Provides an estimate of chemical abundances.

Spectral Lines: Chemical Abundances

Spectra of six stars in a nearby galaxy



metal-rich

metal-poor

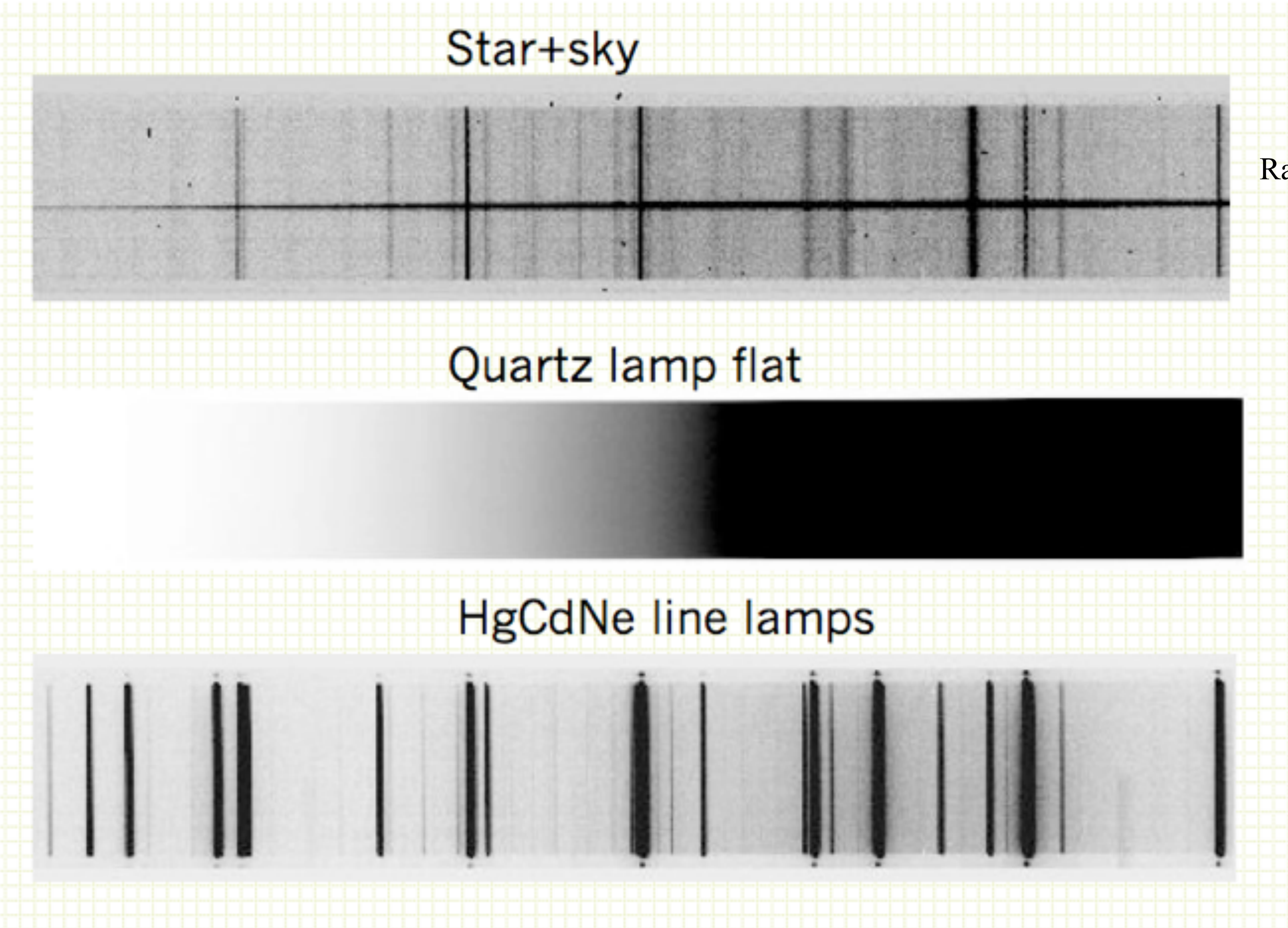
Note that line center and line width are similar.

Line shape is different (e.g., area is larger for stronger lines)

Reducing Spectra

Data reduction of spectroscopic data is similar to that of direct imaging, but requires a few extra steps.

Reducing Spectra



Raw Science spectrum

Spectral Flat Field

Arc lamp

Reducing Spectra

1. **Normal CCD processing**: Bias and dark subtraction

2. **Flat fielding**: ``Flatten'' spectra in both the wavelength and spatial directions.

3. **Wavelength calibration:** Use arc lamps with known lines. Identify lines, determine line centers and fit function to centers vs. wavelength.

4. **Flux calibration**: Correction for throughput as a function of wavelength. Not always required.

5. **Sky subtraction**: Subtract emission lines from the sky.

6. **Object reduction**: Extracting object spectrum (``tracing'' the object) to create 1D spectrum

Reducing Spectra - Flat Fields

In the spirit of flat fielding direct images, spectral flats need to be flat in the spatial AND wavelength directions. In practice, use a white screen illuminated by a flat-field lamp, usually a hot quartz lamp with a strong continuum.

wavelength ->

Flat Field Step 1: Co-add flat fields to remove cosmic rays

Flat Field Step 2: Normalize flat field to unity

Flat Field Step 3: Divide/multiply into science frames

Reducing Spectra

1. **Normal CCD processing**: Bias and dark subtraction

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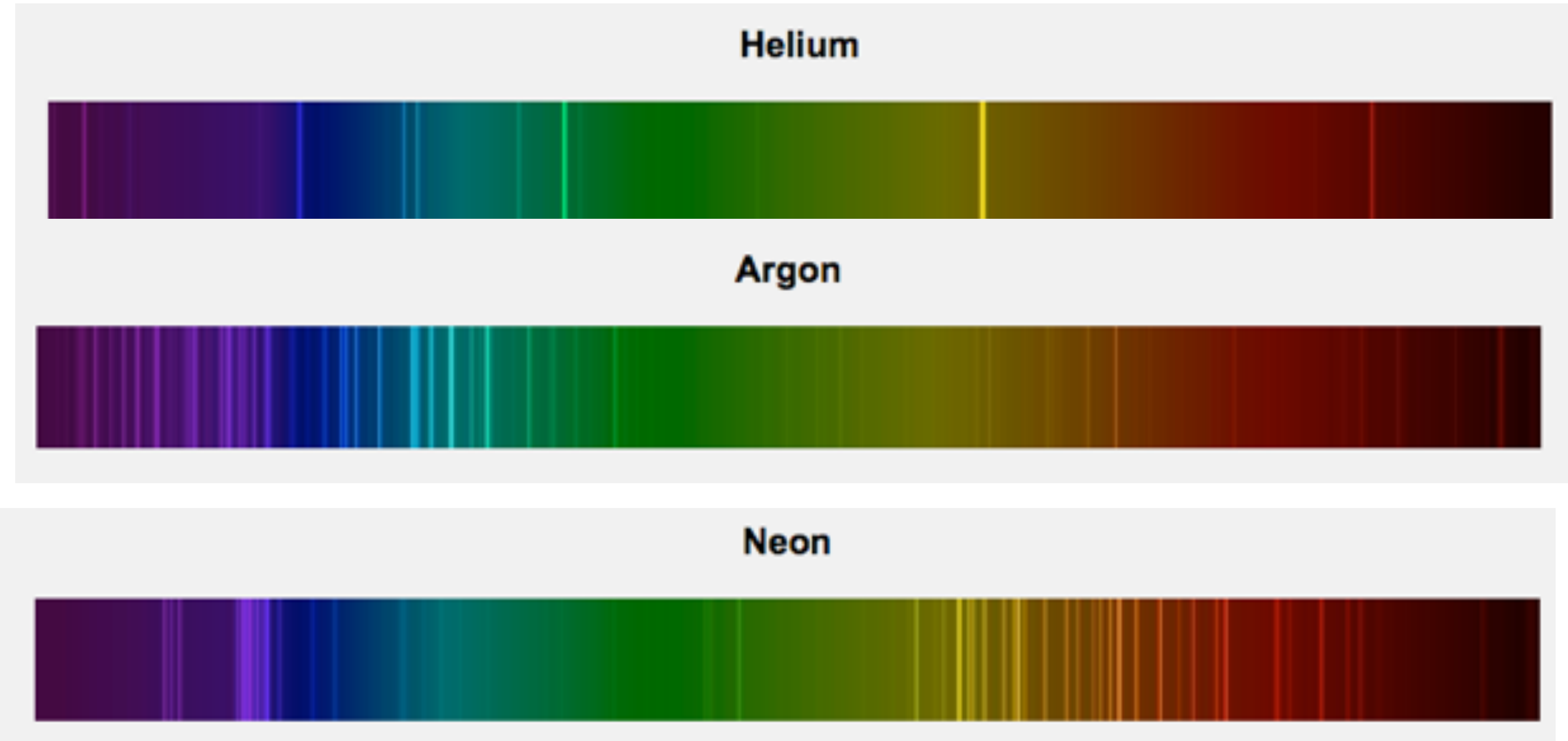
Reducing Spectra - Wavelength Calibration

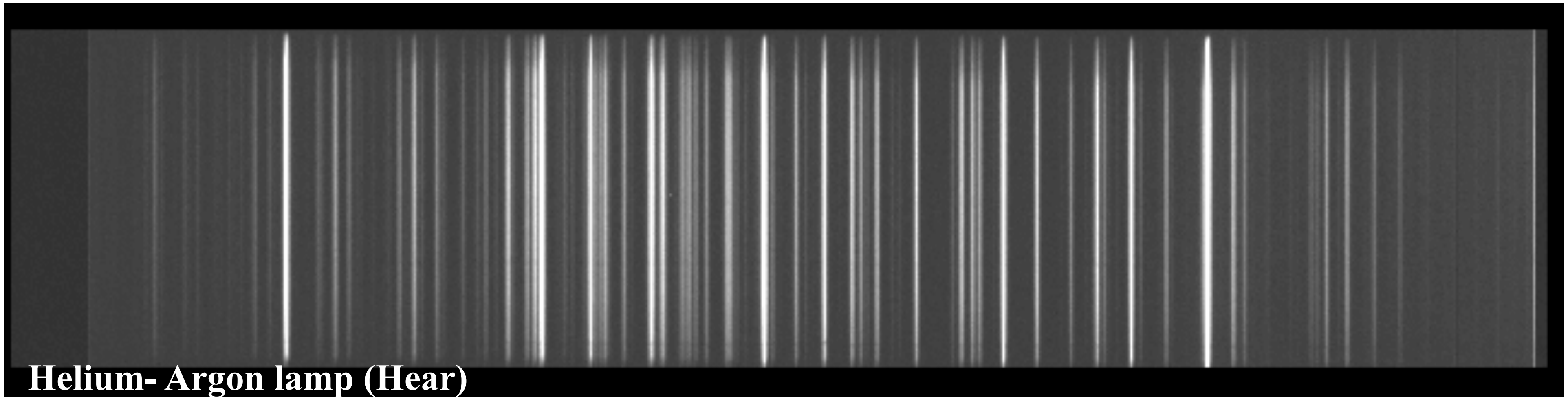
In order to determine the mapping between pixels and wavelength, we take images of a known emission line source, the same type of source as the gas-emission tubes.



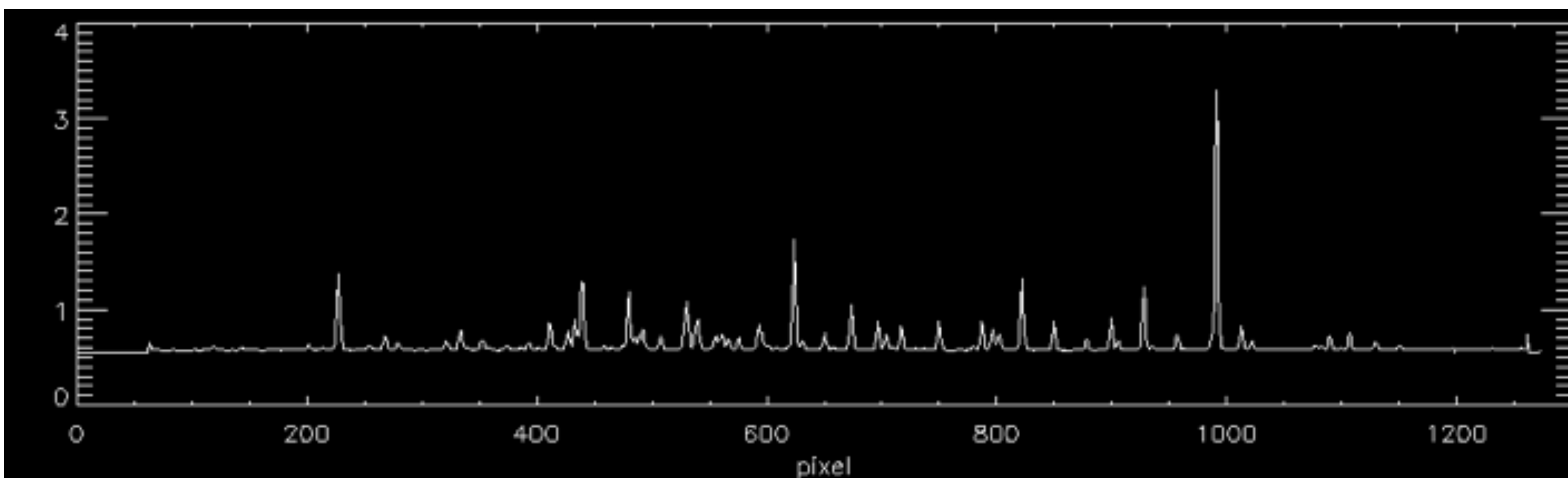
For the final project data, the calibration used Helium and Argon tubes, in part because the data are in the blue.

Reducing Spectra - Wavelength Calibration

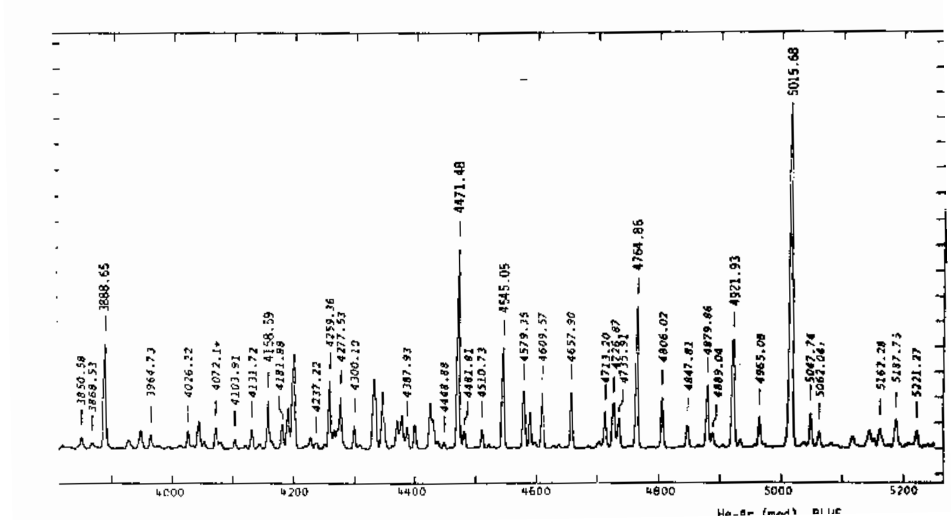
The goal is to produce a function $\lambda = f(x,y)$ which gives λ for any pixel position on the CCD.

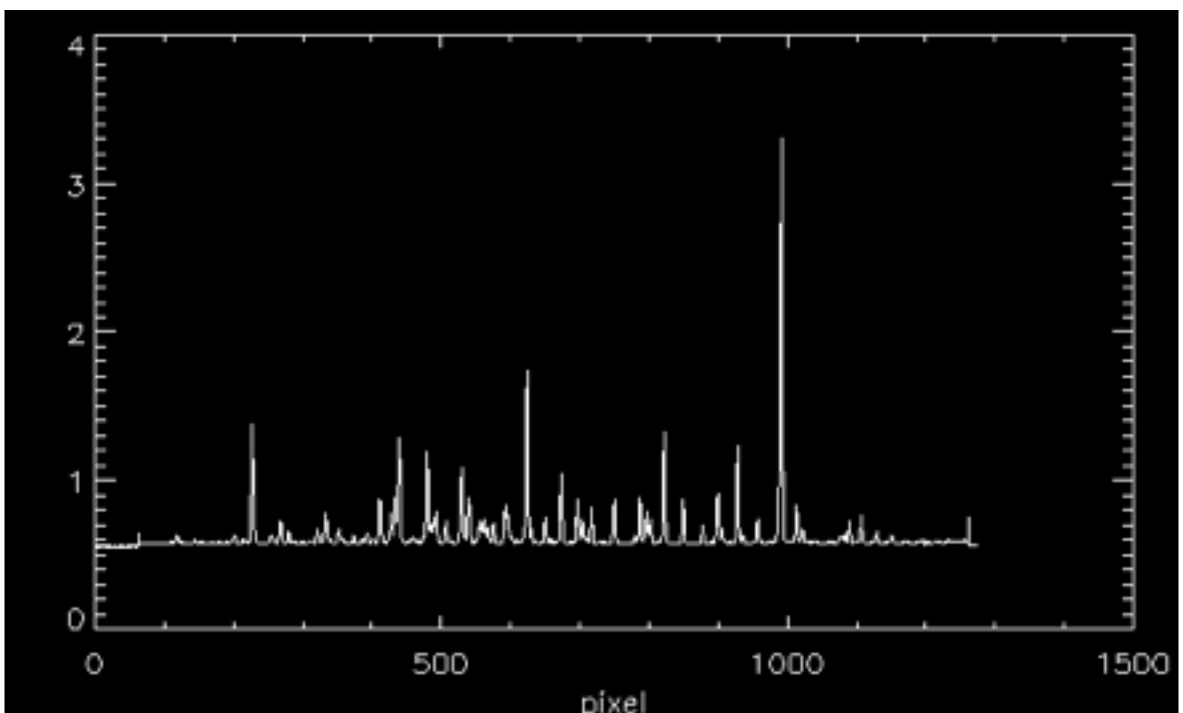


Need a script to collapse 2D to 1D spectrum

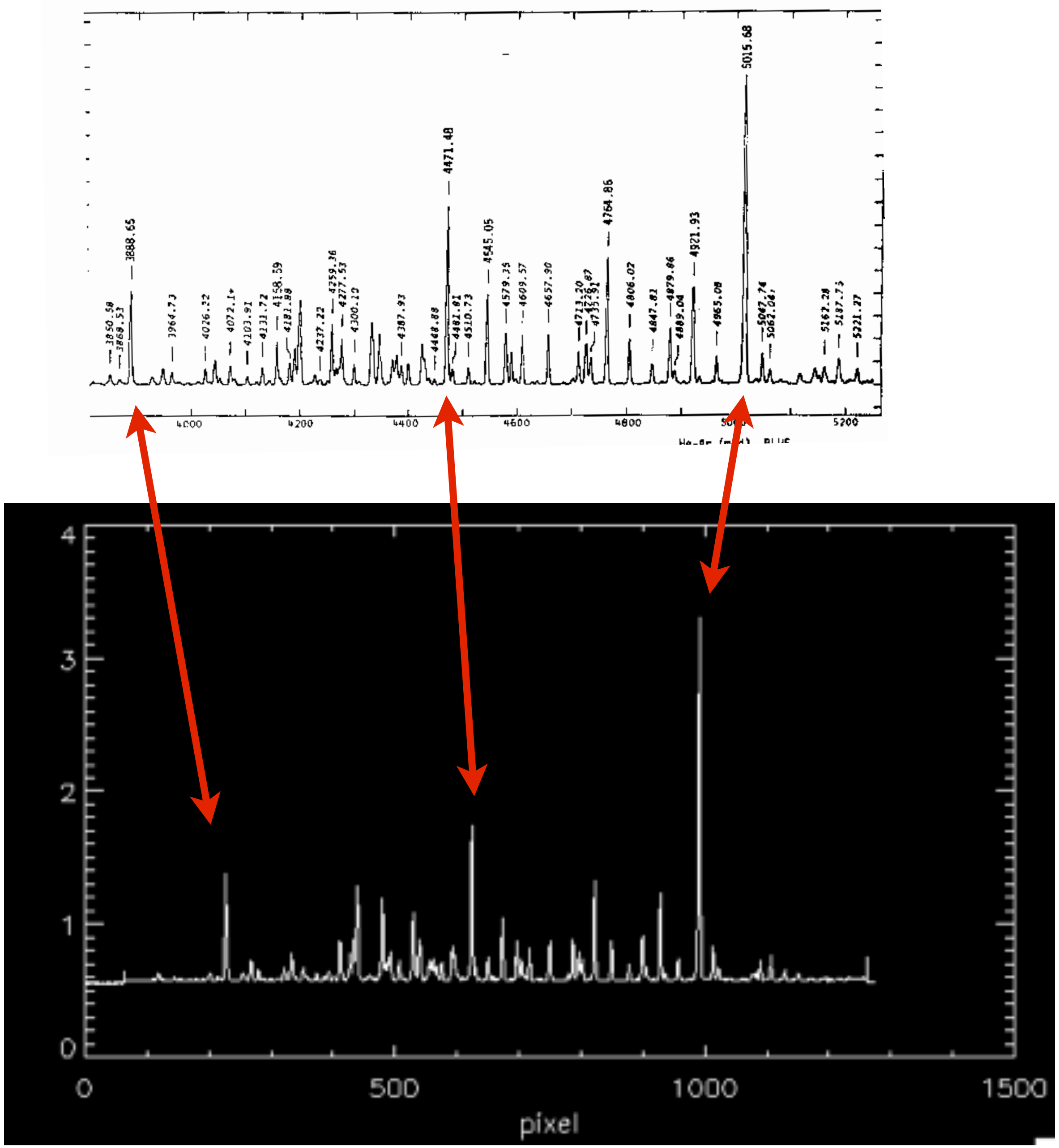


Reducing Spectra - Wavelength Calibration



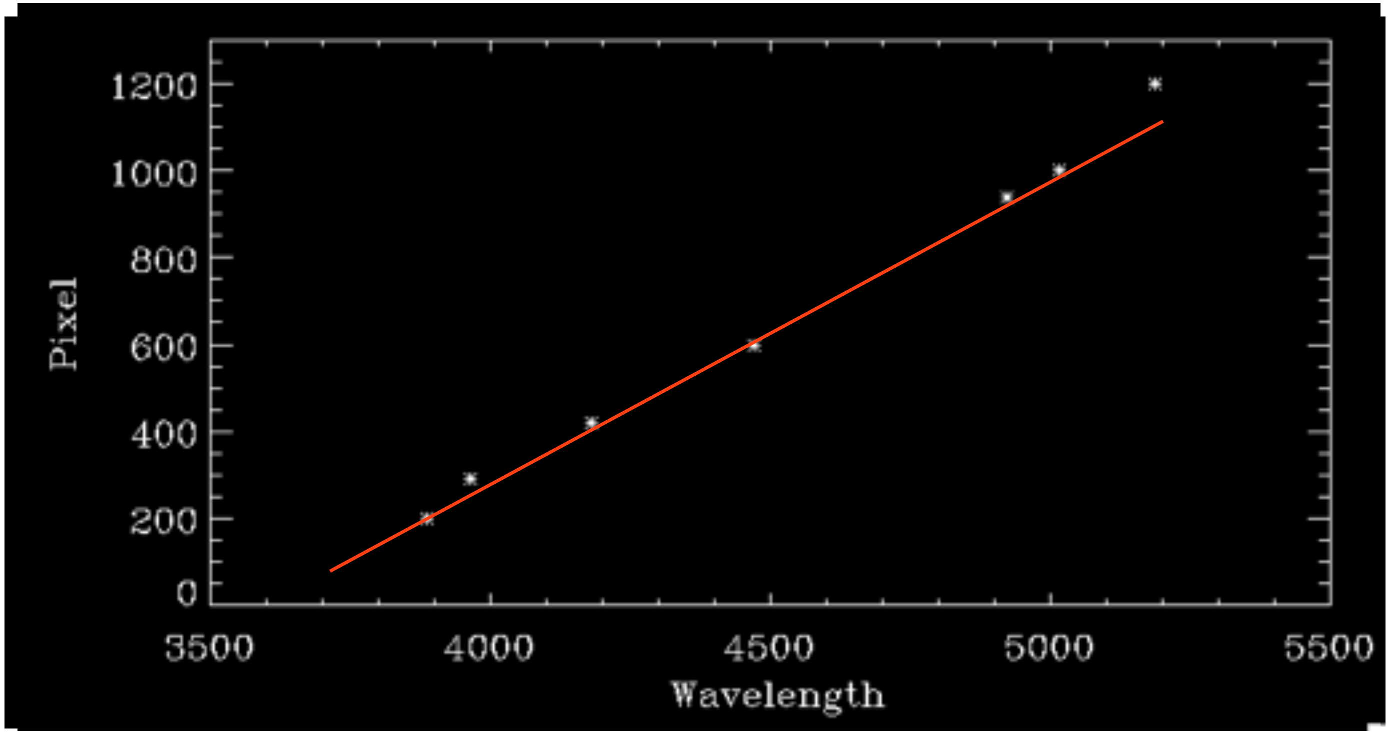


Reducing Spectra - Wavelength Calibration



Pixel	λ
1000	5015.68
600	4471.48
200	3888.65

Reducing Spectra - Wavelength Calibration



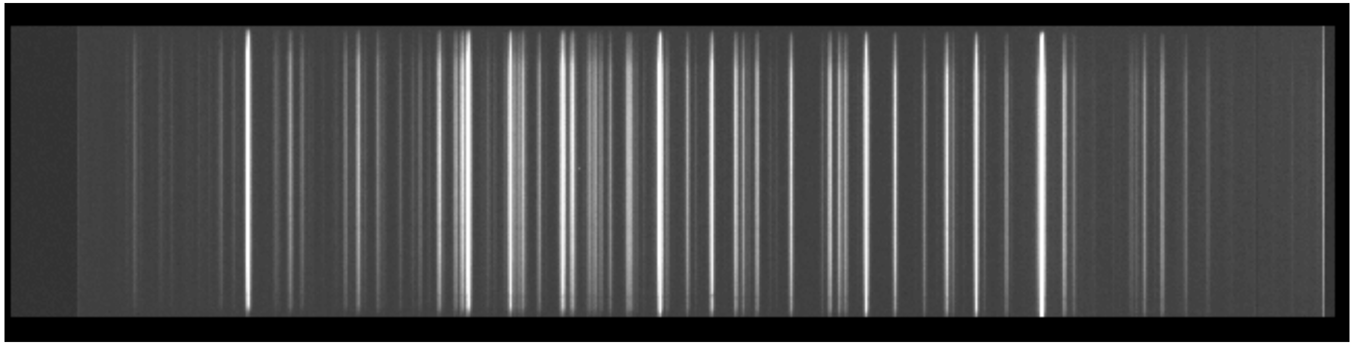
Pixel	λ
1000	5015.68
600	4471.48
200	3888.65

Wavelength Step 1: Identify arc lines using arc line list provided (minimum of 10 lines).

Wavelength Step 2: Fit function to these points (start linear, increase to a polynomial order 3-4)

Reducing Spectra - Wavelength Calibration

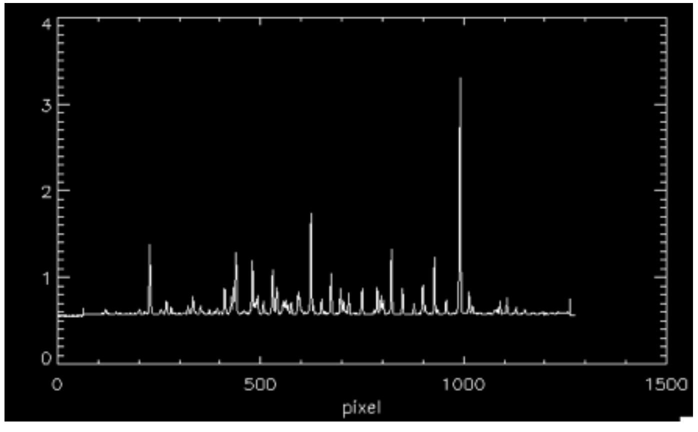
The goal is to produce a function $\lambda = f(x,y)$ which gives λ for any pixel position on the CCD.



For BH project, you can assume that wavelength is a function of x only (not y).

$$\lambda = m*x + b \qquad \text{or} \qquad \lambda = m*x^2 + n*x + b$$

Wavelength Optional Steps:



-- Rather than estimate line centers by eye, determine line center by fitting a Gaussian to each peak

-- Iterate the fit above, removing lines which deviate from overall fit.