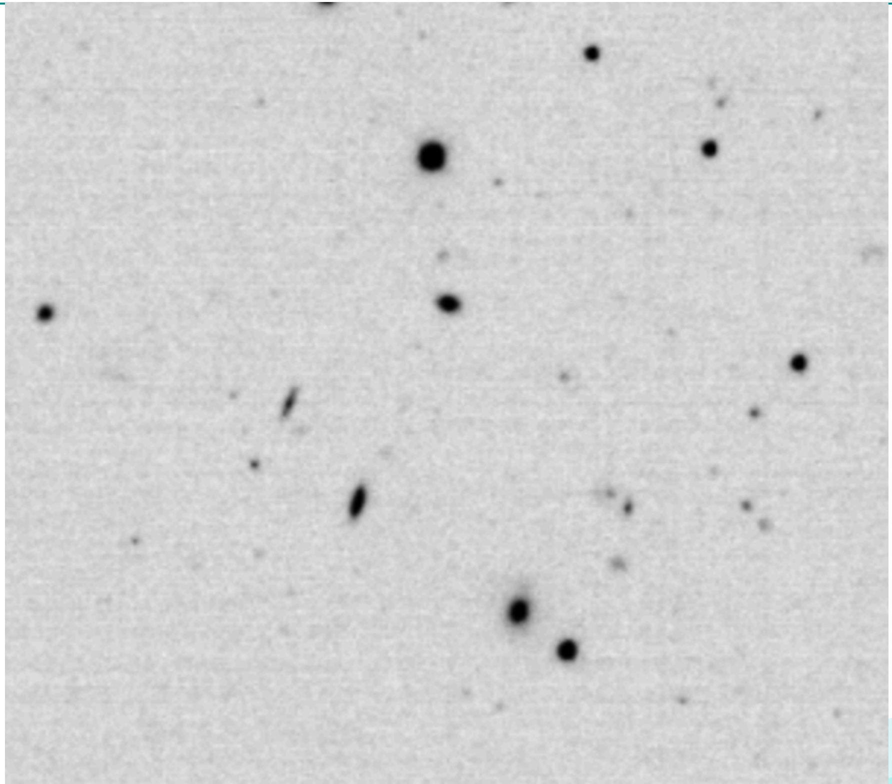
# Source Detection

# Goal of Source Detection

- Intuitively, we want to know where the objects are.



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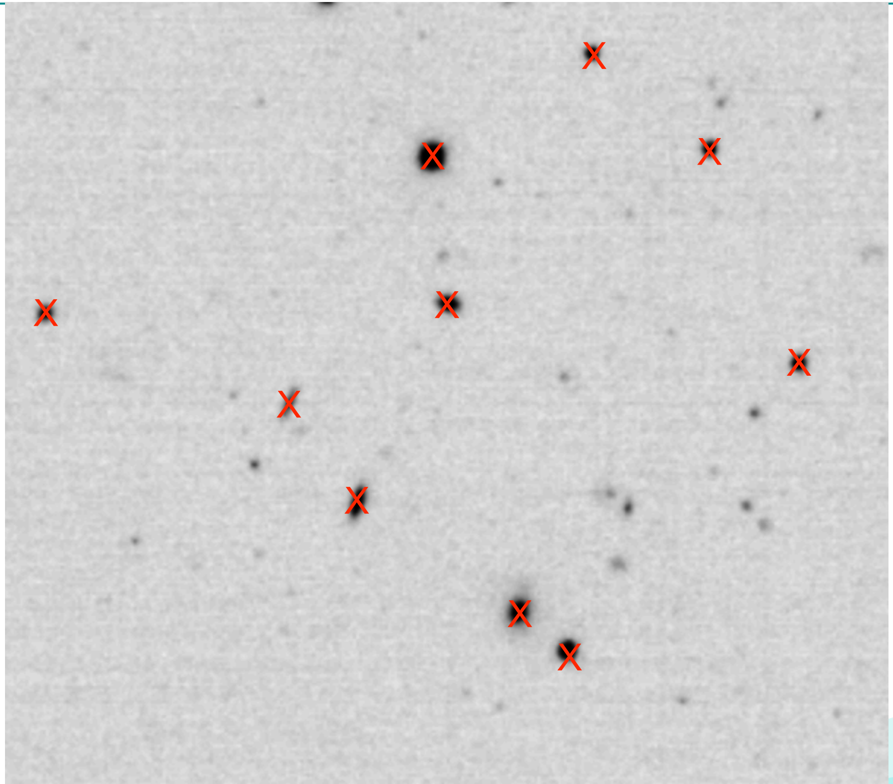
- Many of these are obvious by-eye



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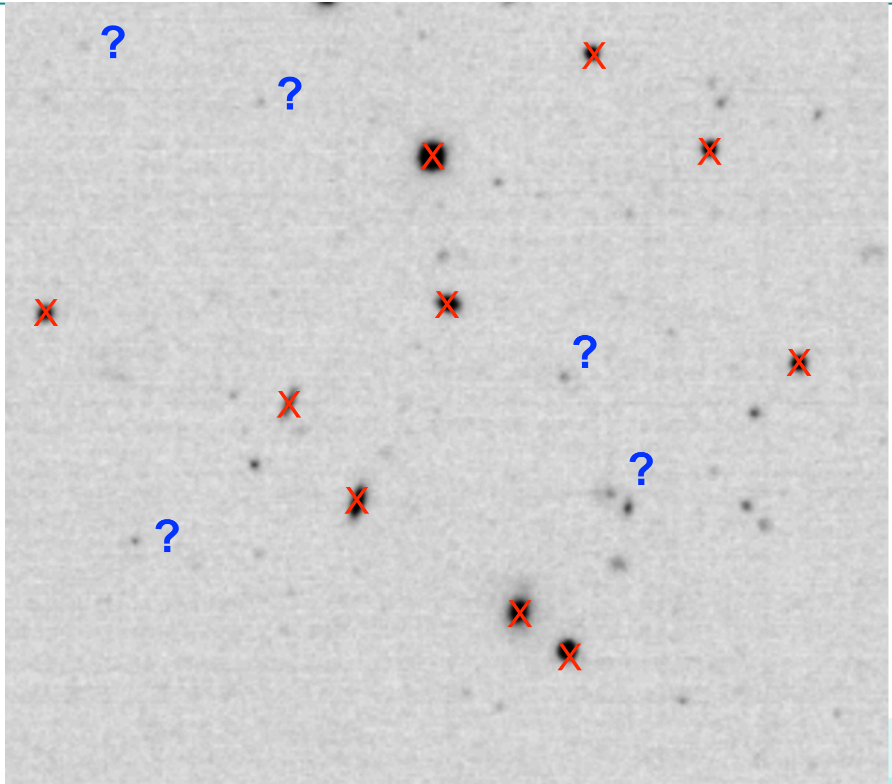
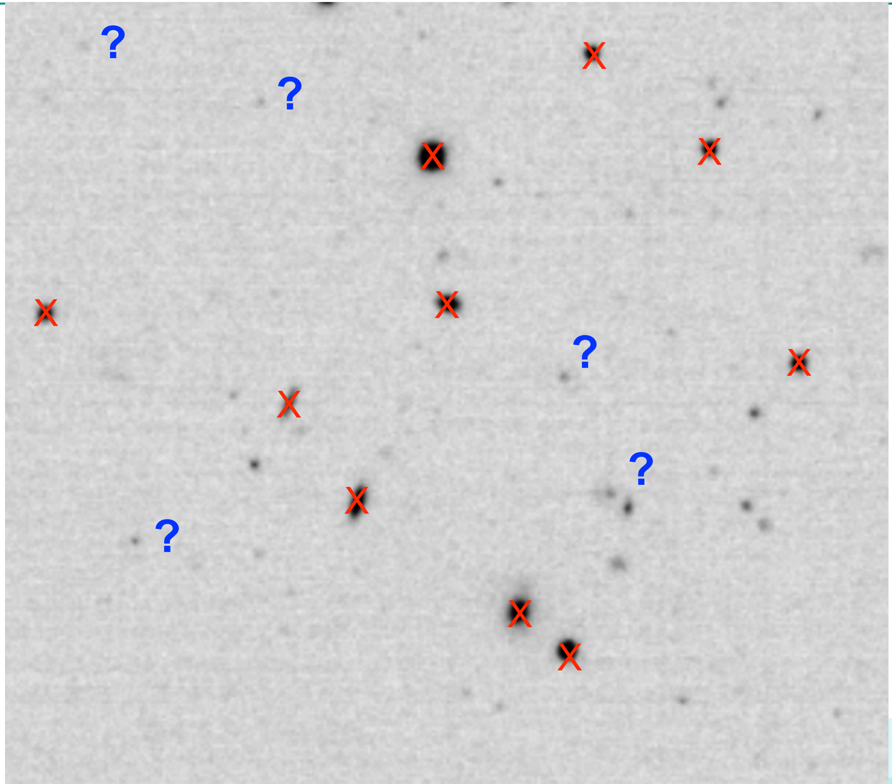
- Intuitively, we want to know where the objects are.
- Many of these are obvious by-eye
- Many of these are not obvious



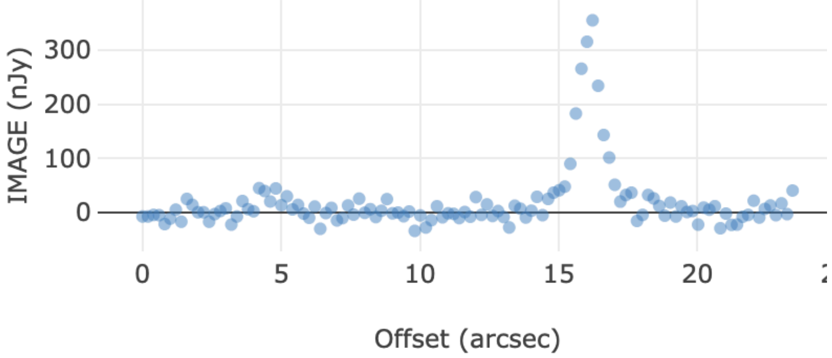
# Goal of Source Detection

- Intuitively, we want to know where the objects are.
- Many of these are obvious by-eye
- Many of these are not obvious

- We need a method that is
  1) Automated
  2) Statistically justified



- Automated:
    - Thresholding of some form — but what sets the threshold?
- Statistically justified — How do we know we're extracting the most information from the image?



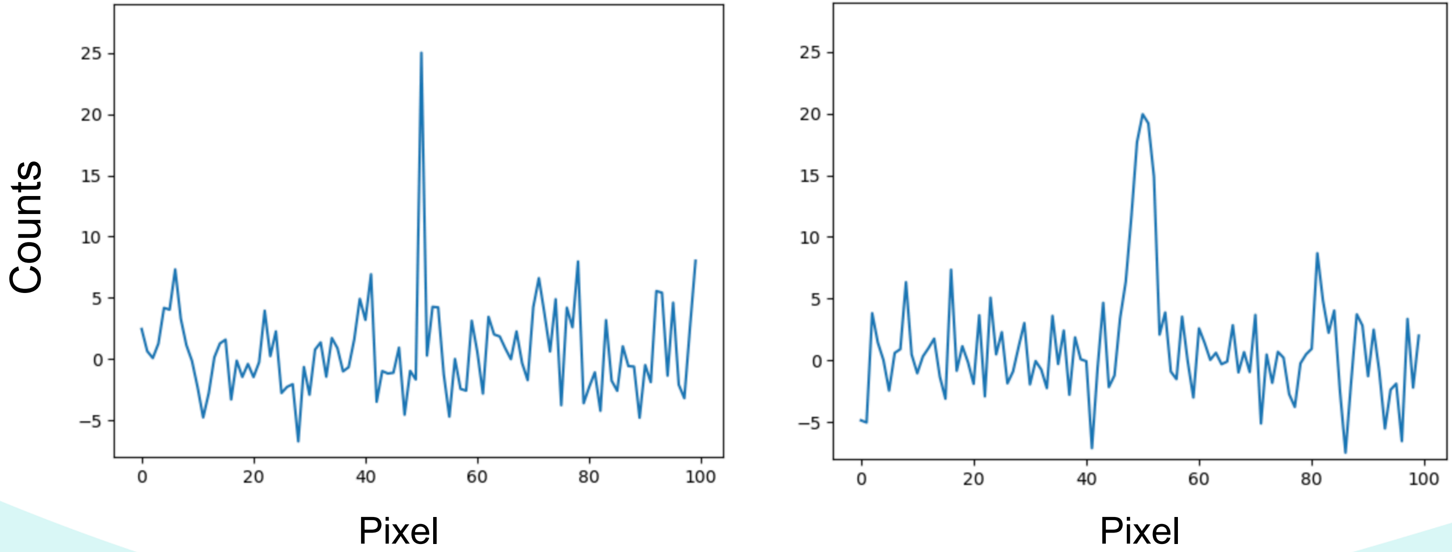
# Where to threshold?

- Conventionally, we say we detect at a “5-sigma” threshold:
  - i.e. given the level of background noise, we think this significance of detection would only appear due to pure noise in 1 out of 3.5 million realizations of that noise.

- 1 in 3.5 million sounds like a rare occurrence, but there are lots of pixels in even a single 4k x 4k sensor — false positives are ubiquitous
- Trade off between not missing a real astrophysical object vs. having to deal with a degree of contamination.

# What to threshold?

- Which of these is more likely to be a star?



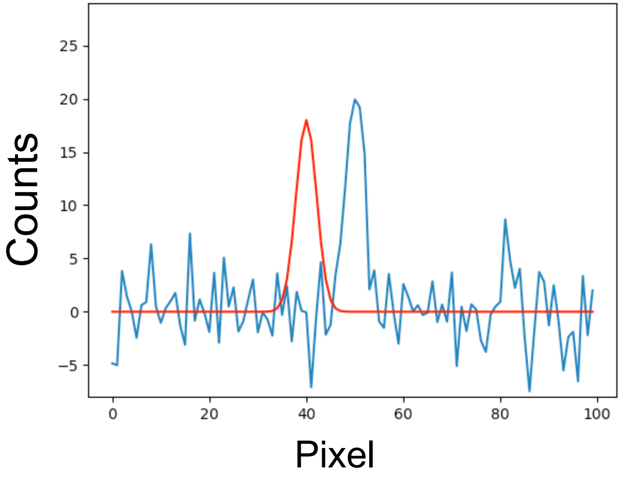
- The signal processing world has this technique they call a “matched filter”, where the desired signal has a known shape but unknown position.

- Trick is to run a correlation (think: convolution) between the model and the input data

# Matched Filter

Red: convolution kernel
Blue: data

Product of kernel
and data: small

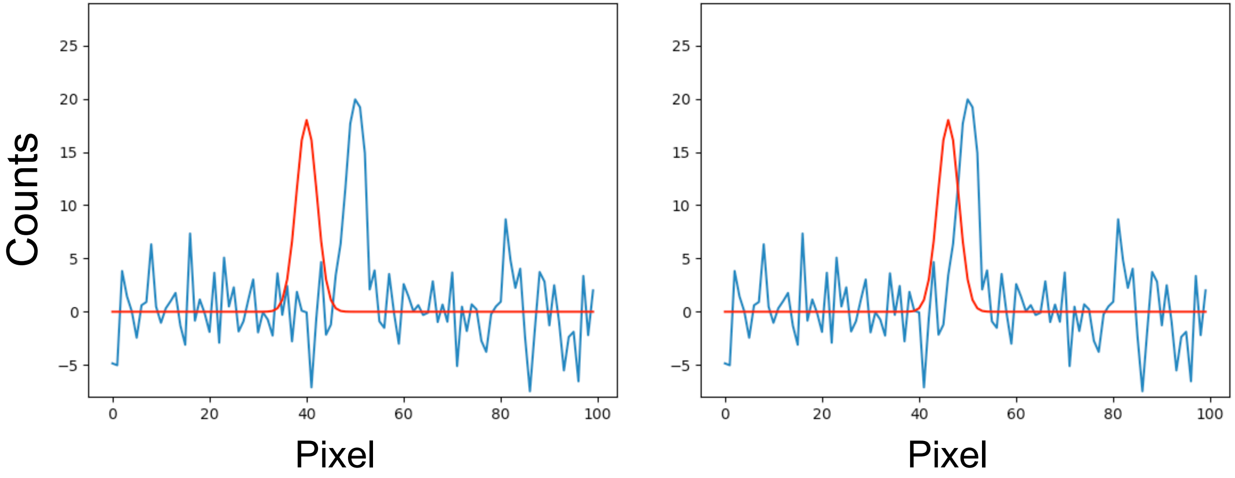


# Matched Filter

Red: convolution kernel
Blue: data

Product of kernel and data: small

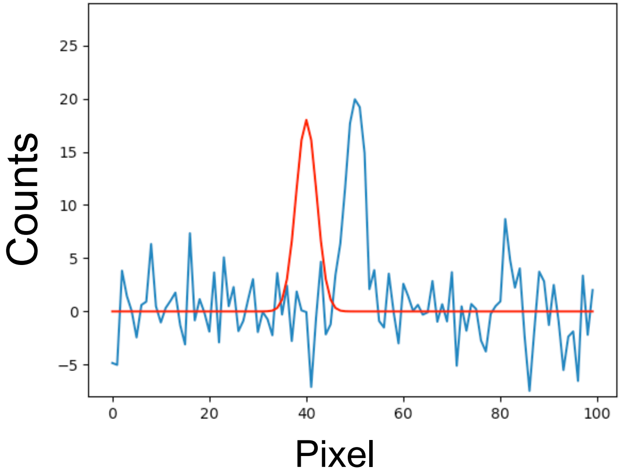
Product of kernel and data: a little bigger!



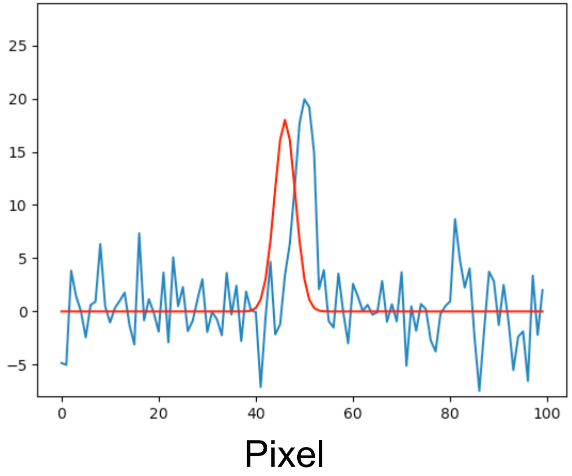
# Matched Filter

Red: convolution kernel
Blue: data

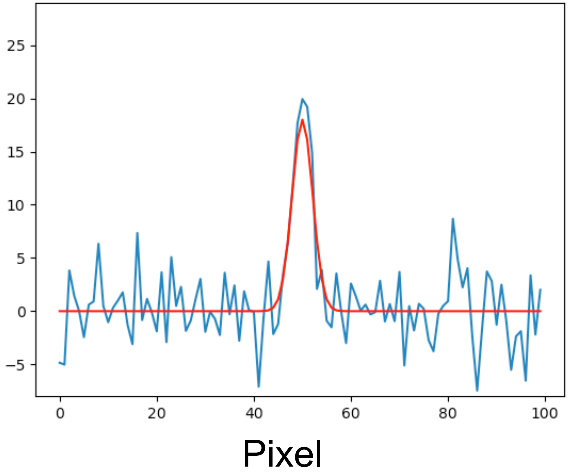
Product of kernel and data: small




Product of kernel and data: a little bigger!




Product of kernel and data: Maximized



- The important point: after convolving with the PSF model, a single pixel >5 sigma **is significant.**

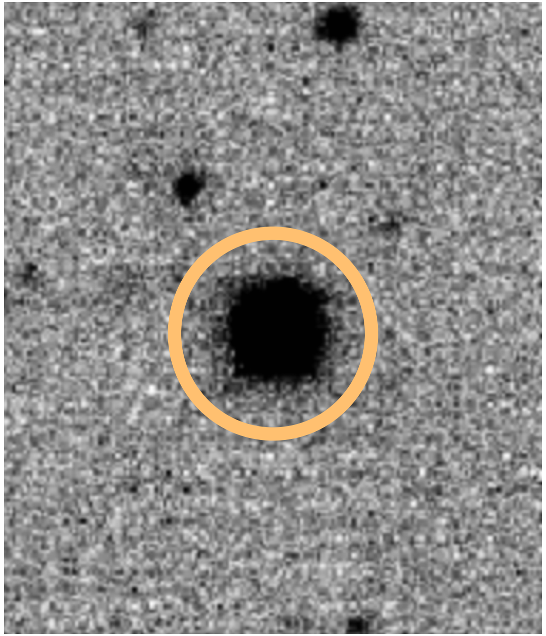
- We typically call these “peaks”, and they’re the starting point for the rest of measurement.

- But the positions are not precise yet — we still need to do centroiding, which we will cover in the next talk.

# PSF Photometry

# Simple photometry: Aperture photometry

After ISR, background subtraction, and source detection, measuring the flux *can* be easy: draw a circle and add up the counts inside the circle.



Pros:

Cons:

# Beyond aperture photometry

Aperture photometry totally works! But we can do better, in two ways:

1. We really should understand the statistical basis for our measurement.
   - Doing so will tell us how to make the best measurement

2. We know that aperture fluxes cannot be optimal
   - Depending on where we set the aperture, we're either throwing away information outside that aperture, or we're including pixels with lots of noisy sky and little signal.

# Maximum Likelihood estimate

- For each pixel, we have a model that we want to compare to the measured value for that pixel in an image, in the presence of noise.
- Going to follow the notation of Portillo, Speagle, Finkbeiner 2020; classic reference is King 1983.

- Our PSF is $p(x, y)$, and our model for a star given a flux $f$ is $f\,p(x, y)$. The PSF must be normalized, $\sum_{x,y} p(x, y) = 1$, and we require the image to be background-subtracted.

# Maximum Likelihood estimate

- Because the noise on each pixel is uncorrelated with the noise on other pixels, the likelihood for the flux measurement is the product of the likelihoods on each individual pixel.
- Let $\hat{f}$ represent the measured flux in pixel $i$, and assuming Gaussian noise

$$\mathscr{L}(x, y, f) = \frac{1}{\sqrt{2\pi\sigma^2}} \prod_i \exp((\hat{f}_i - f p_i(x, y))^2 / (2\sigma^2))$$

- Taking the log likelihood gives us a sum over the model comparisons

$$\ln \mathscr{L}(x, y, f) = -\frac{N}{2}\ln(2\pi\sigma^2) - \frac{1}{2\sigma^2}\sum_i (\hat{f}_i - fp_i(x, y))^2$$

- Find the maximum of the likelihood by setting the partial derivative w.r.t. f to zero, solve for $f_{\mathrm{ML}}$

$$\partial_f \mathscr{L}(x, y, f_{\mathrm{ML}}) = \frac{1}{\sigma^2}\sum_i \hat{f}_i p_i(x, y) - f_{ML} p_i^2(x, y) = 0$$

- Which gives us a nice solution for the flux

$$f_{\mathrm{ML}}(x, y) = \frac{\sum_i \hat{f}_i p_i(x, y)}{\sum_i p_i^2(x, y)}$$

- In words:
  - To measure the flux, we take the product of the PSF model and the image pixels, sum that product, and divide by a normalization.

- PSF photometry can also be thought of as a pixel weighting scheme. To demonstrate, if $p(x, y) = 1/N$, N being the number of pixels in your sum, then:

$$f_{\mathrm{ML}} = \frac{\sum_i \hat{f}_i (1/N)}{\sum_i (1/N^2)} = \frac{\sum_i \hat{f}/N}{N/N^2} = \sum_i \hat{f}_i$$

- That's aperture photometry!

# Putting it together

So our order of operations is:

- ISR
- Background subtraction
- Matched filter and peak finding
- Centroiding — (we skipped this)
- (PSF determination — we're skipping this, sorry!)
- PSF photometry

# Photometric Calibration

# Photometric Calibration

- Let's start simple.
- Our goal when photometering an image is to report how bright the objects are relative to some agreed-on standard.

- Typically today, you're most likely to either Pan-STARRS (PS1) or Gaia stars as your "standards".
- Gaia covers the whole sky; PS1 covers 3/4ths of the sky slightly deeper/ denser, and with grizy filters.

- Ideally, there are “calibration” stars in your image
- You know the magnitude of the calibration stars, and you can measure how many counts they created in your image.

- Simple calibration: $mag = -2.5 \log( counts ) + ZP$
  - With your calibration stars, solve for the “zero point” ZP.

  - For all other stars, compute the magnitude using the measured zeropoint.
- This works because CCDs are very *linear* in their response; makes relative photometry very robust.

There are a few important details that this leaves out:

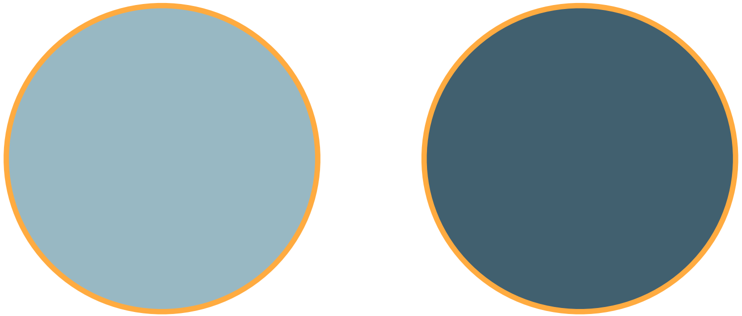
- Why are Gaia, PS1, or eventually LSST magnitudes good for calibration? How did they calibrate their images?

- Is the zero point all that matters? What about comparing different surveys?

- Absolute calibration: what actually defines how bright a magnitude is?

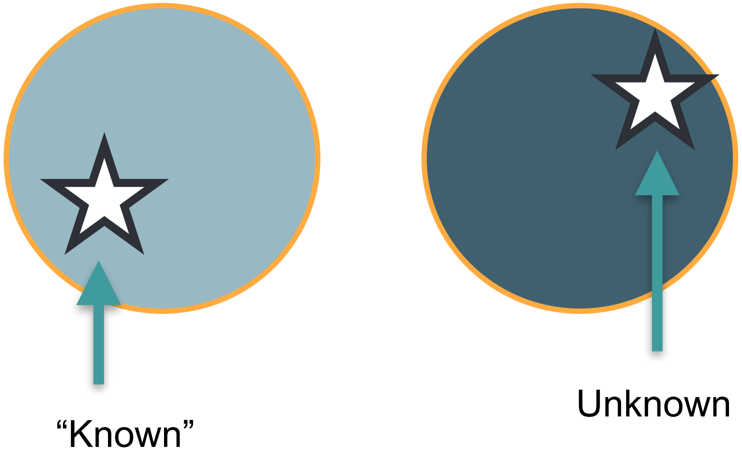
# Survey Calibration

- Let’s say I’m running a big survey.
- I have two fields, A and B.



# Survey Calibration

- Let’s say I’m running a big survey.
- I have two fields, A and B.
- A has a calibrated star, magnitude 18
- B doesn’t have any calibration stars, but it has a star I’m interested in.
- If these are my only images, then I’m out of luck.



# Survey Calibration

- But! If I take Exposure C, it will have some stars that overlap Exposure A, and some stars that overlap Exposure B.

- Exposures A and C must “agree” on how bright the stars they share in common are. I.e., I calculate a zero point for C that minimizes the residual of the stars shared with A.
- The same minimization can be done between exposures C and B.

# Survey Calibration

- The exciting part is that we don’t need to solve B and C separately, we can solve the whole survey simultaneously.
- Concept extends to arbitrary numbers of exposures.
- Linear least-squares minimization problem, lots of standard techniques for handling large problems like this.

- What is this accomplishing?

- We know that there are many effects that can change the throughput of the telescope from night to night, exposure to exposure. (Sometimes called a “gray” term, no color dependence)

- E.g., if we observe a field low in the sky (high airmass), more of those photons are scattered/extincted than when we observe the field high in the sky.

- The “traditional” technique was to identify and correct these effects individually, but with survey-scale data we can build and solve a model for multiple photometric effects simultaneously.

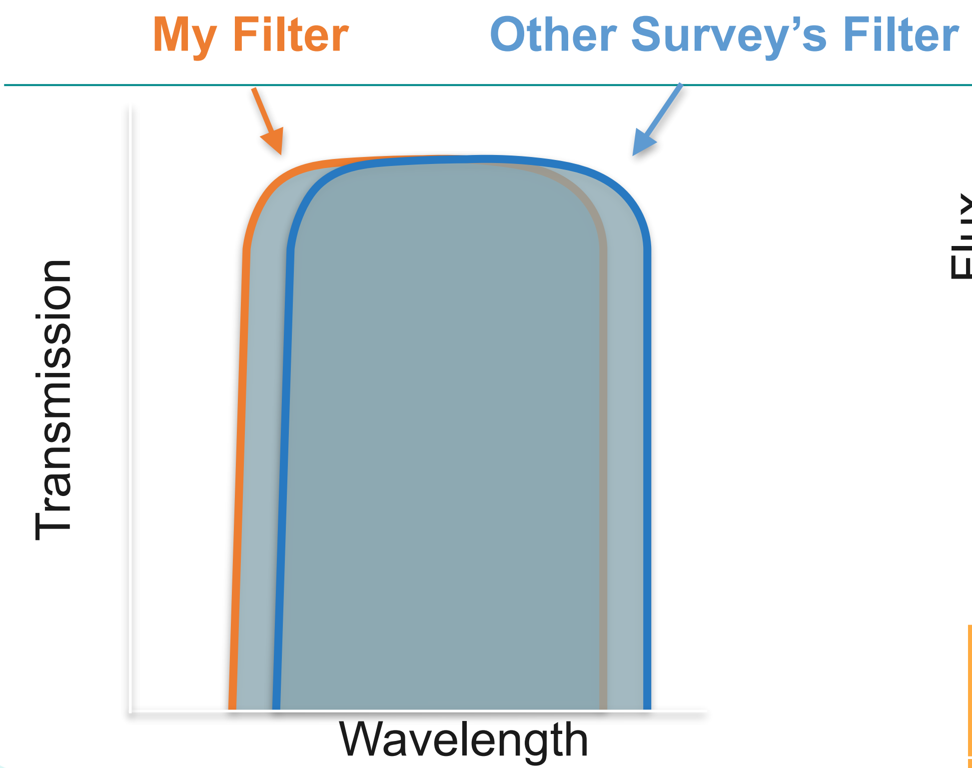
- The result is that we can treat PS1 or Gaia as a consistent photometric system.
- (That doesn’t mean perfect, and we still haven't talked about absolute calibration)

- More info in the respective survey’s papers:
    - SDSS: Padmanabhan et al. 2008, arXiv:astro-ph/0703454
    - Pan-STARRS: Schlafly et al. 2012, arXiv:astro-ph/1201.2208
    - DES: Burke et al. 2018, arXiv:astro-ph/1706.01542

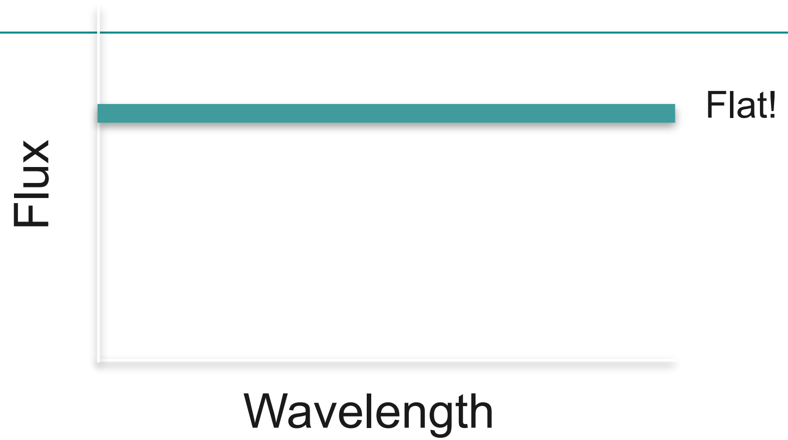
# Color Dependence

- So far we've only dealt with "gray" terms; no spectral dependence at all.

- The modern challenge for surveys like LSST is that there is spectral dependence <u>everywhere</u>

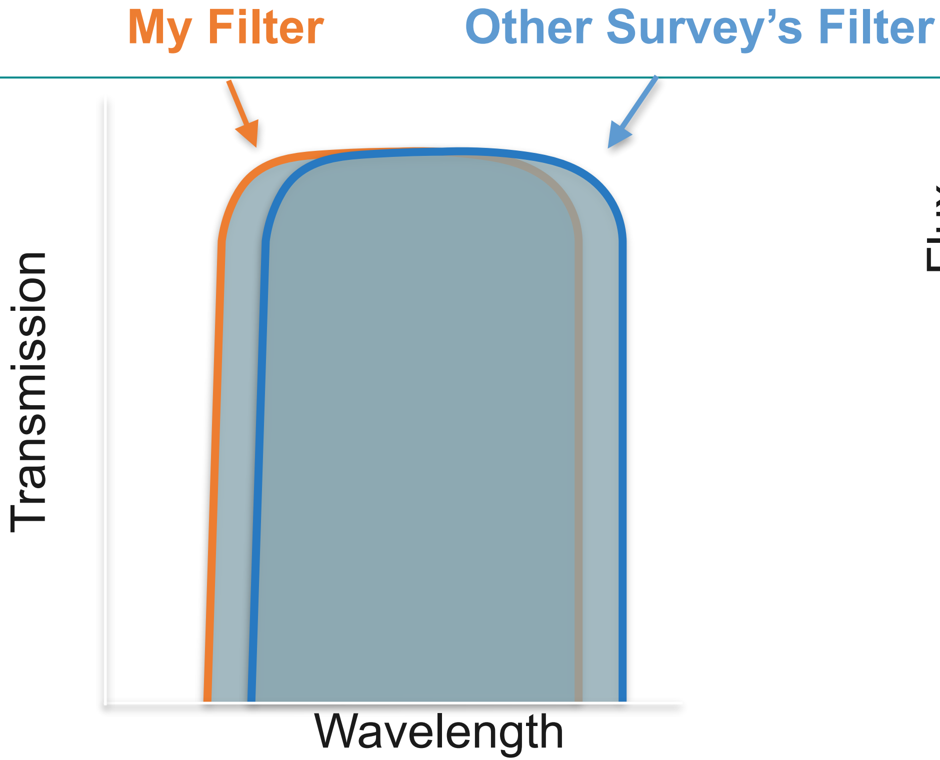



## Object Spectrum




**Measured Flux**

| | |
|---|---|
| **Other Survey** | **1.0** |
| **My Survey** | **1.0** |

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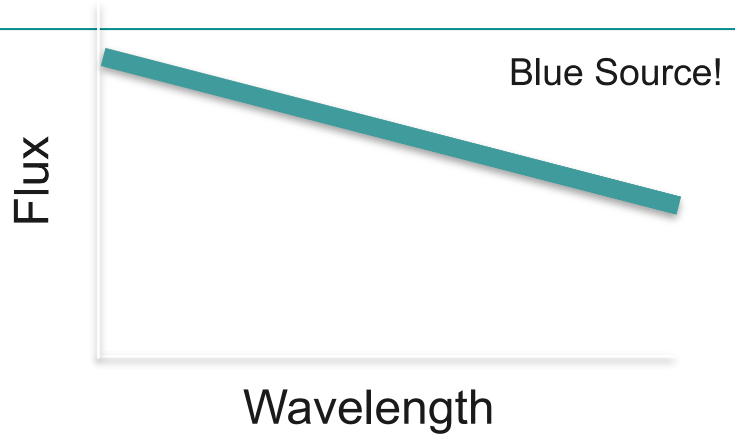
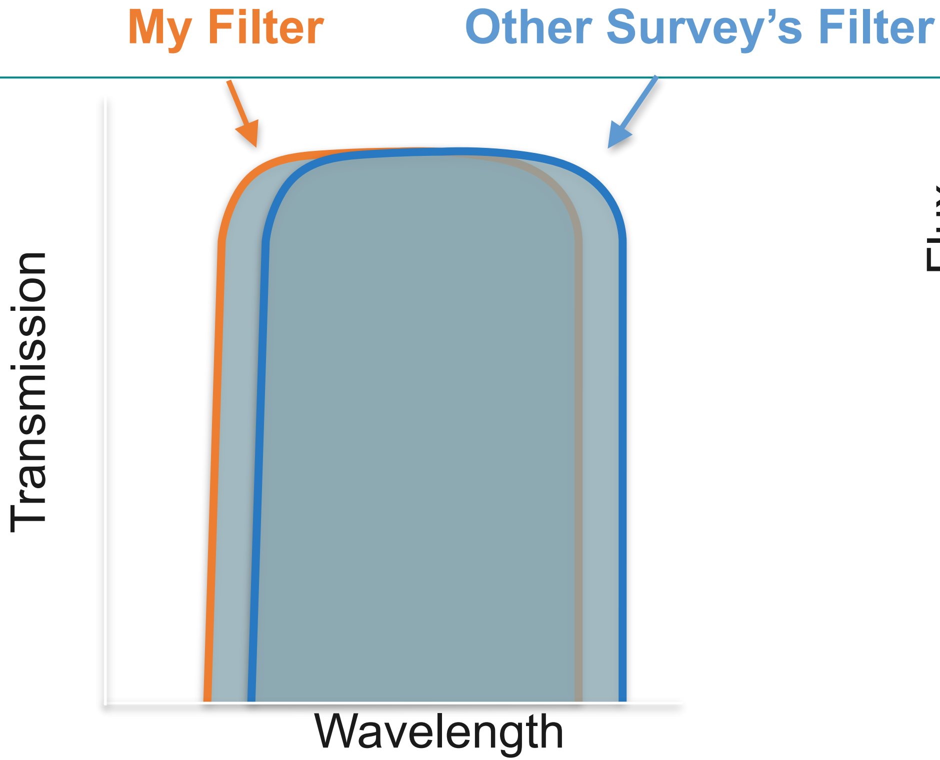
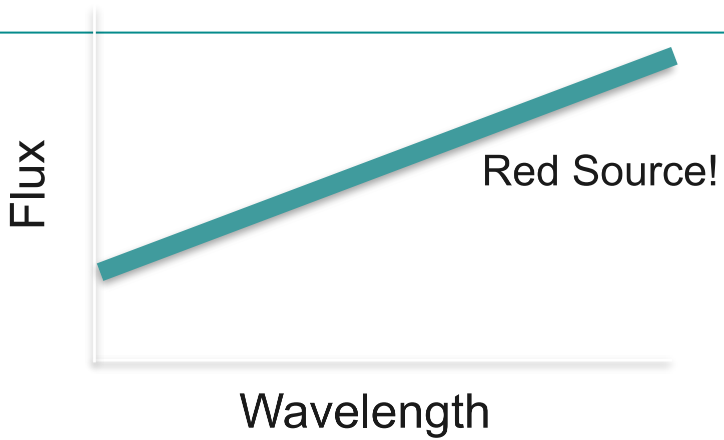



**Measured Flux**

| | |
|---|---|
| **Other Survey** | **1.0** |
| **My Survey** | **1.1** |




## Object Spectrum




## Measured Flux

| | |
|---|---|
| **Other Survey** | **1.0** |
| **My Survey** | **0.9** |

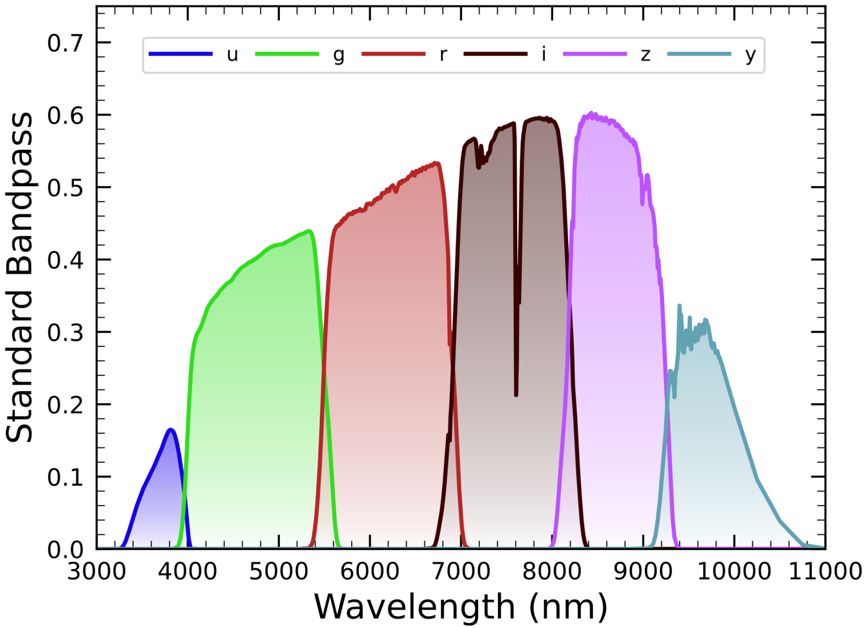
# Color terms

- Every image will have both blue and red sources present, so there's no adjustment to the zero point that will correct for both.
- Optimistically this might be "just noise", but it's a systematic effect that could affect science.

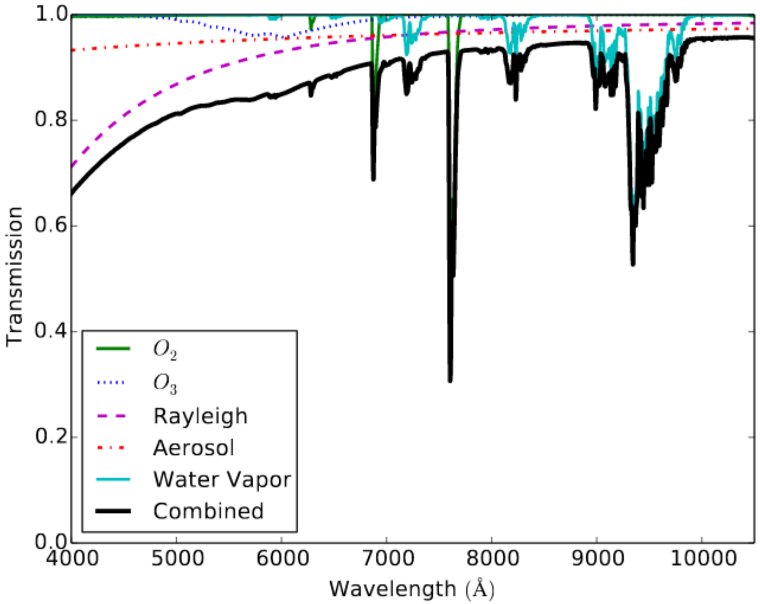
- Even worse, "total" bandpass throughput, including the atmosphere, changes over time.
  - => Even within a survey, with fixed hardware, chromatic variation is present between exposures.

# Individual atmospheric components vary within a night

## ComCam bands, including atmosphere




## Model Atmosphere



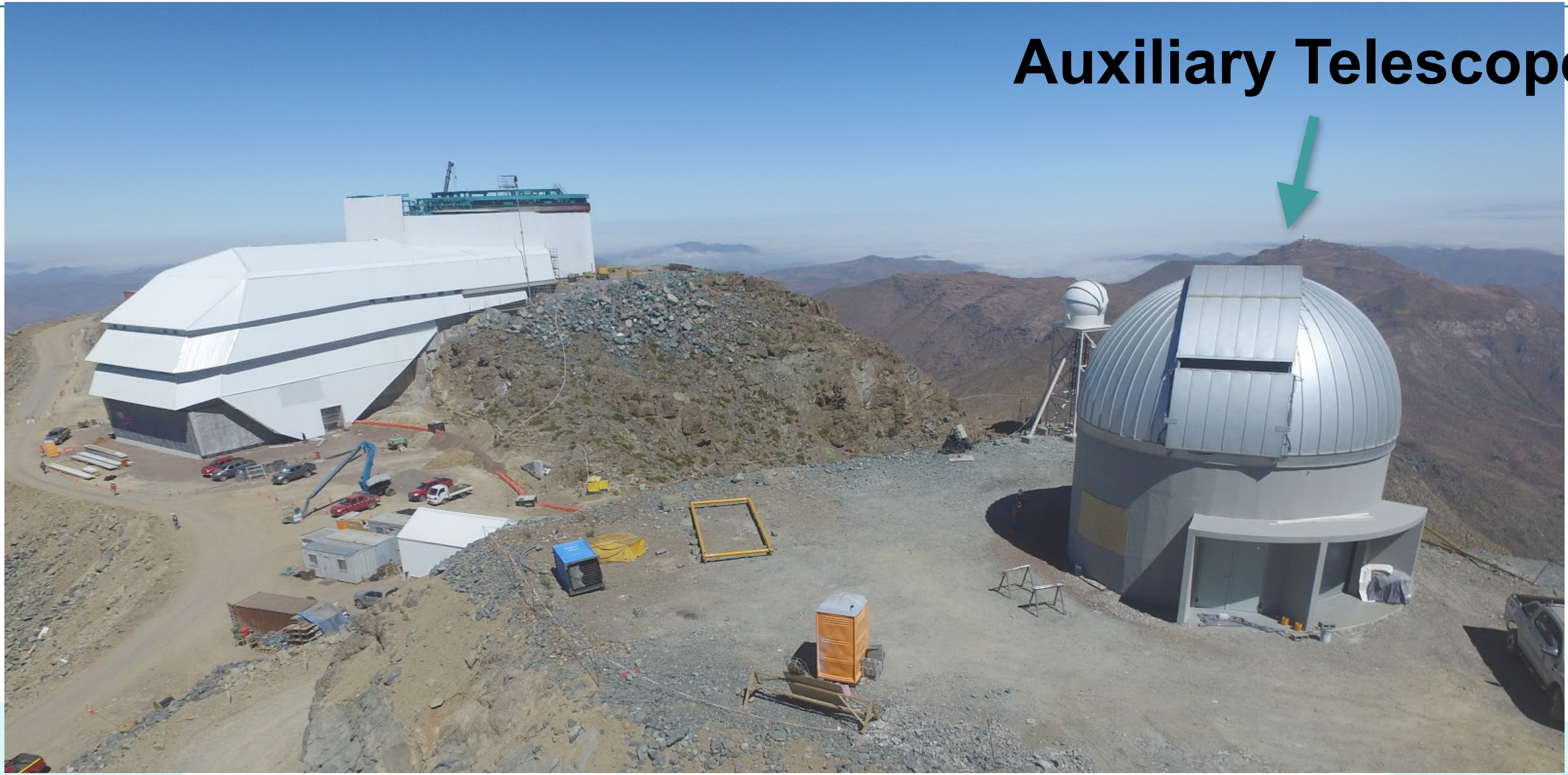

From Burke et al. 2017

# Summarizing Photometric Calibration

- Large surveys “self-calibrate” to create their own internally-consistent magnitude system
- System is tied to an external “absolute” calibration for physical flux, using a small set of calibrators.
- Measured magnitudes are dependent on the exact bandpass used for measurement.
- Bandpasses change from survey to survey, from night to night within a survey, and even within a night.
- Accurate bandpass calibration is at the forefront of improving photometric accuracy.

# Backup

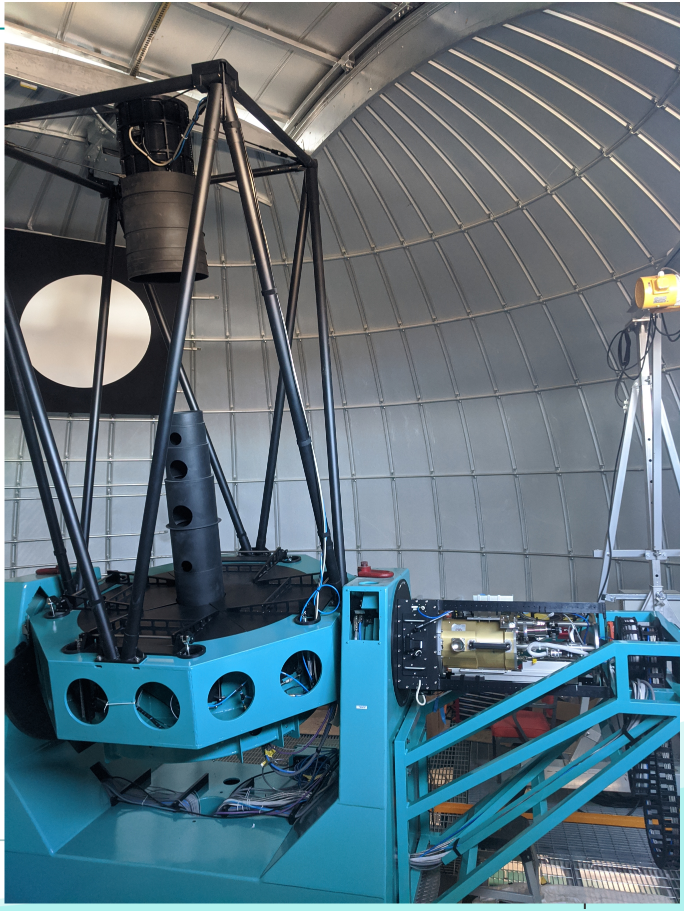
## Auxiliary Telescope



# Auxiliary Telescope

- AuxTel continuously takes spectra of standard stars, with broad wavelength coverage

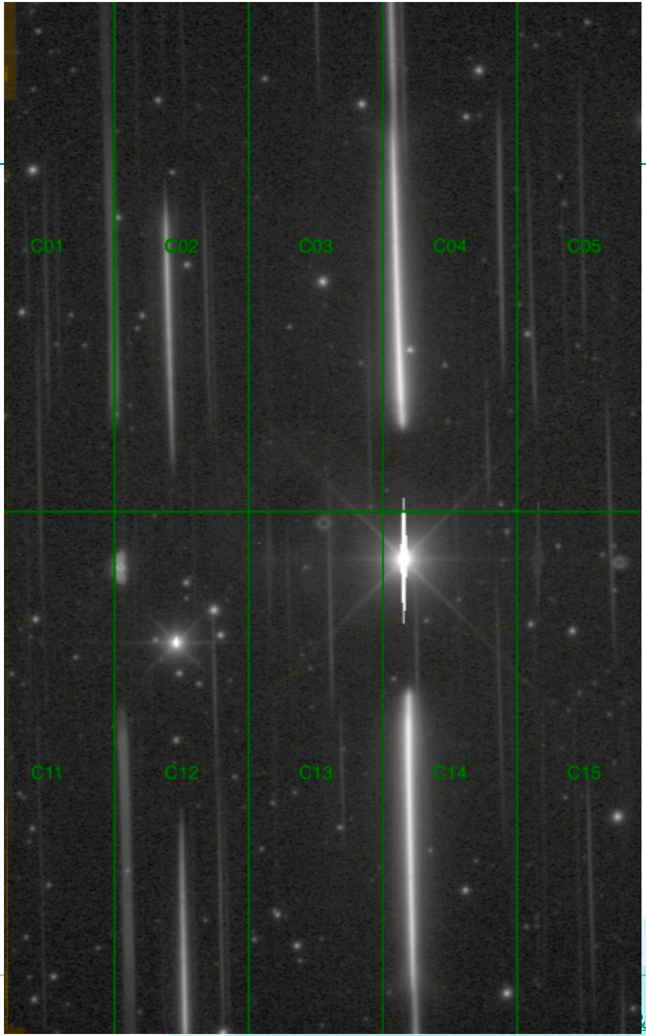
- Fit atmospheric models to these spectra, tells us what the “effective” passbands are for the main survey.

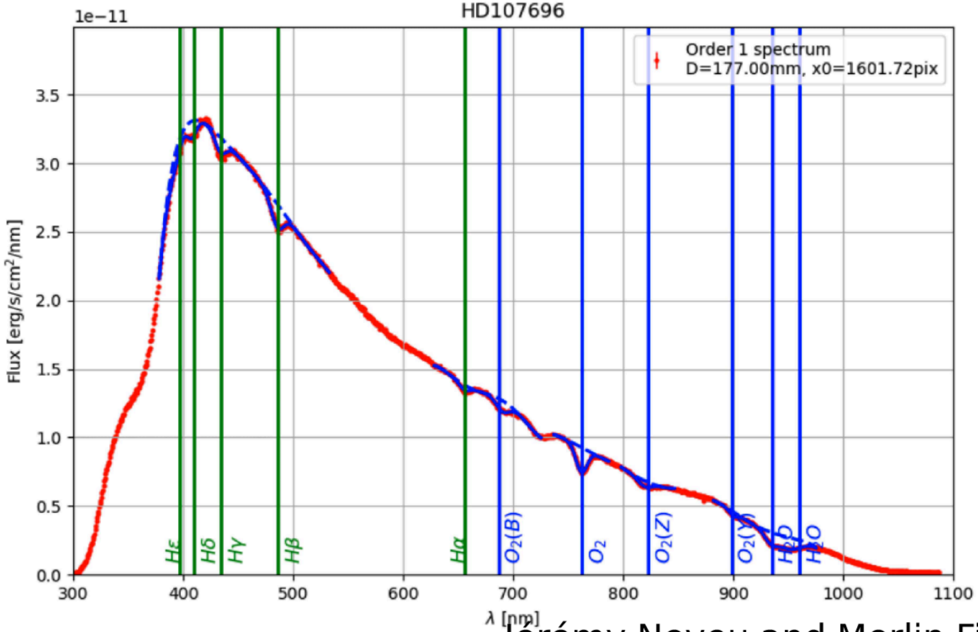


# Auxiliary Telescope

- AuxTel continuously takes spectra of standard stars, with broad wavelength coverage

- Fit atmospheric models to these spectra, tells us what the “effective” passbands are for the main survey as a function of time, for each night of observing.






Jérémy Neveu and Merlin Fisher-Levine