Rubin Observatory

PSF Photometry

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Beyond aperture photometry

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- We’ve looked at aperture photometry, where the goal is simply to count up all the photons that we can attribute to a given star.
- This 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 <u>best</u> 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

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

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

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

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

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

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- Which gives us a nice solution for the flux

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

- To say in words what this means:
  - 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!

"Where" to do PSF photometry?

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- We skipped a step: how do we know <u>where</u> to put the PSF model?
- Few steps to that process:
  - 1) Matched filter — Convolve the image with the PSF, finding regions with significant flux
  - 2) Peak finding
  - 3) Centroiding

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- Convolution — heard about this in the earlier talk
- Once we have the detection image, we need to make a list of possible sources to measure. (We don't want to run photometry on every above-background pixel)

- Use a "peak-finding" algorithm; we want to identify pixels that have a greater value than all of their immediate neighbors.

- That "peak" gives us the starting point for photometry

Centroiding

- Peaks give us an integer pixel, but we can measure the position of the source more accurately than that.
- There are several different centroiding algorithms available, usually designed to be robust even when the PSF is poorly known.
- SDSS and Rubin Observatory use successive quartic interpolations.

- An easier algorithm to think about is to compute the mean of the pixel positions in x or y, *weighted by the measured flux*.

PSF Determination

- One more piece of the puzzle: we need to construct the PSF model.
- First we need "PSF Candidates" — sources on the image that have the right size/shape to be stars, with no close neighbors
- There's a bootstrap problem here, we need some rough guess at the PSF size before we know what would be good candidates

PSF Determination

- With PSF candidates in hand, there are a few different algorithms:

  - Model fitting, using Gaussian or a Moffat function (Gaussian core + Lorentizan wings)
  - Fitting to basis functions (e.g. SDSS). Similar to model fitting, but the basis functions are designed to capture the range of variation in the PSF.
  - “Pixel Basis” fitting, where candidates are resampled to a higher-resolution pixel grid, then each pixel is fit separately to capture spatial variation. Used by PSFEx (part of Source Extractor).

PSF Determination for Rubin Observatory

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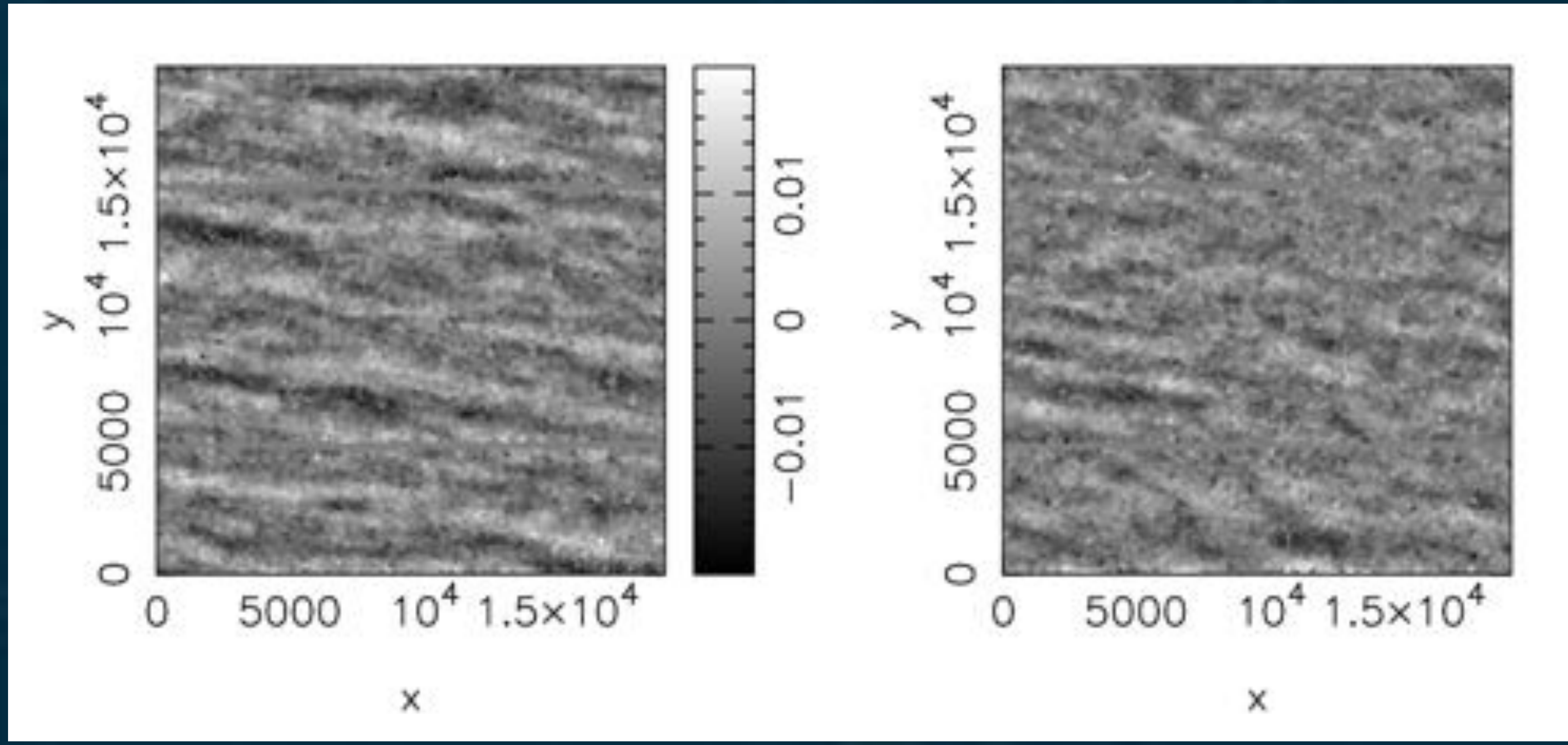
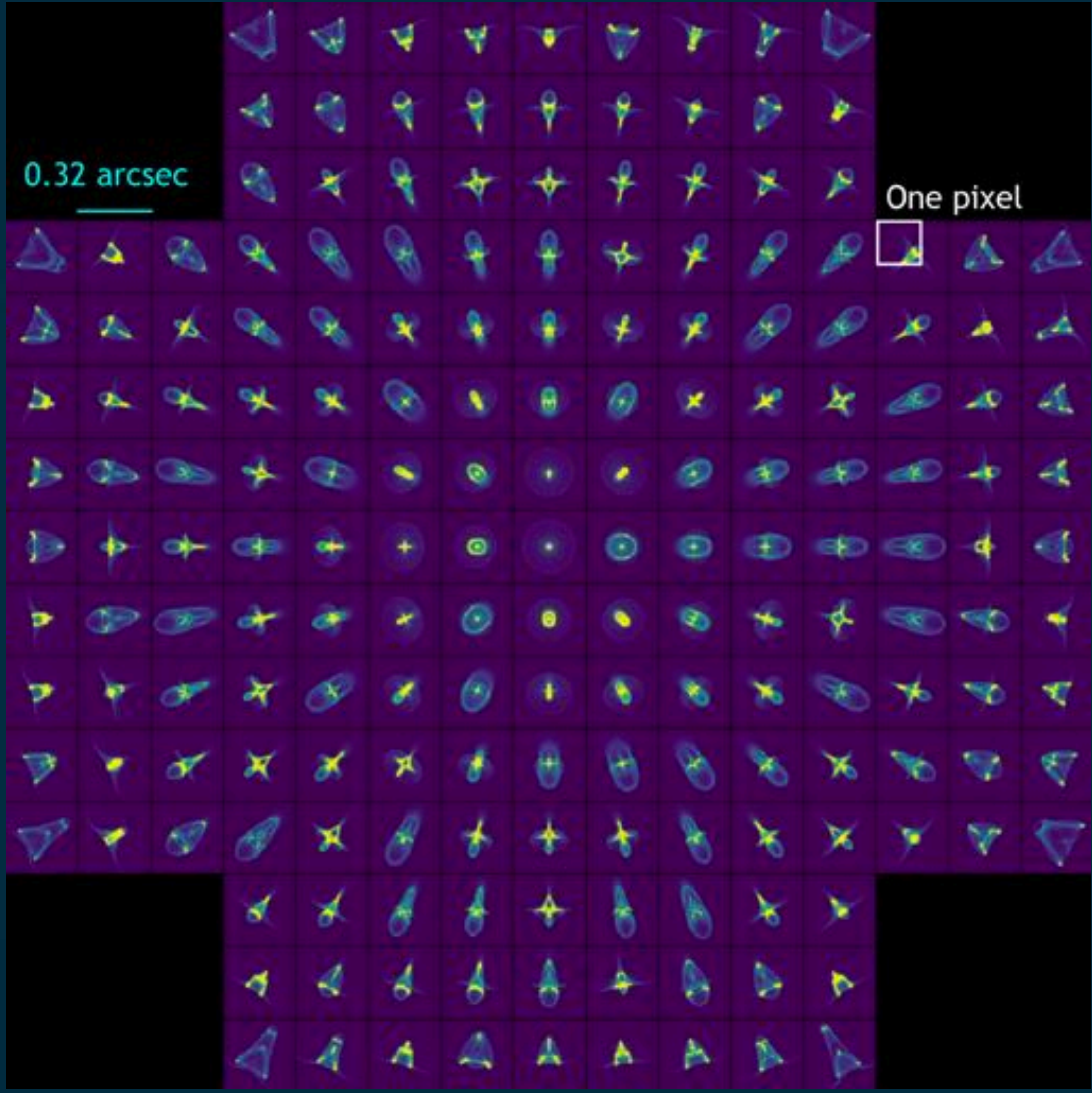
- Goal is to model the optics and the atmosphere *separately*
- Important for galaxy shape measurements, weak lensing.

CFHT PSF shape residuals (Heymans et al. 2012)



Rubin Obs. Optical PSF model (Meyers)



Recap

- Photometry is often an iterative process.
  - Detection (with a PSF guess)
  - PSF Determination
  - Detection (now with the new PSF)
  - Centroiding
  - PSF Flux measurement

Photometric Calibration

Photometric Calibration

- Let’s start simple.
- Our goal when photometering an image is to report how bright the objects are <u>relative to</u> 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.

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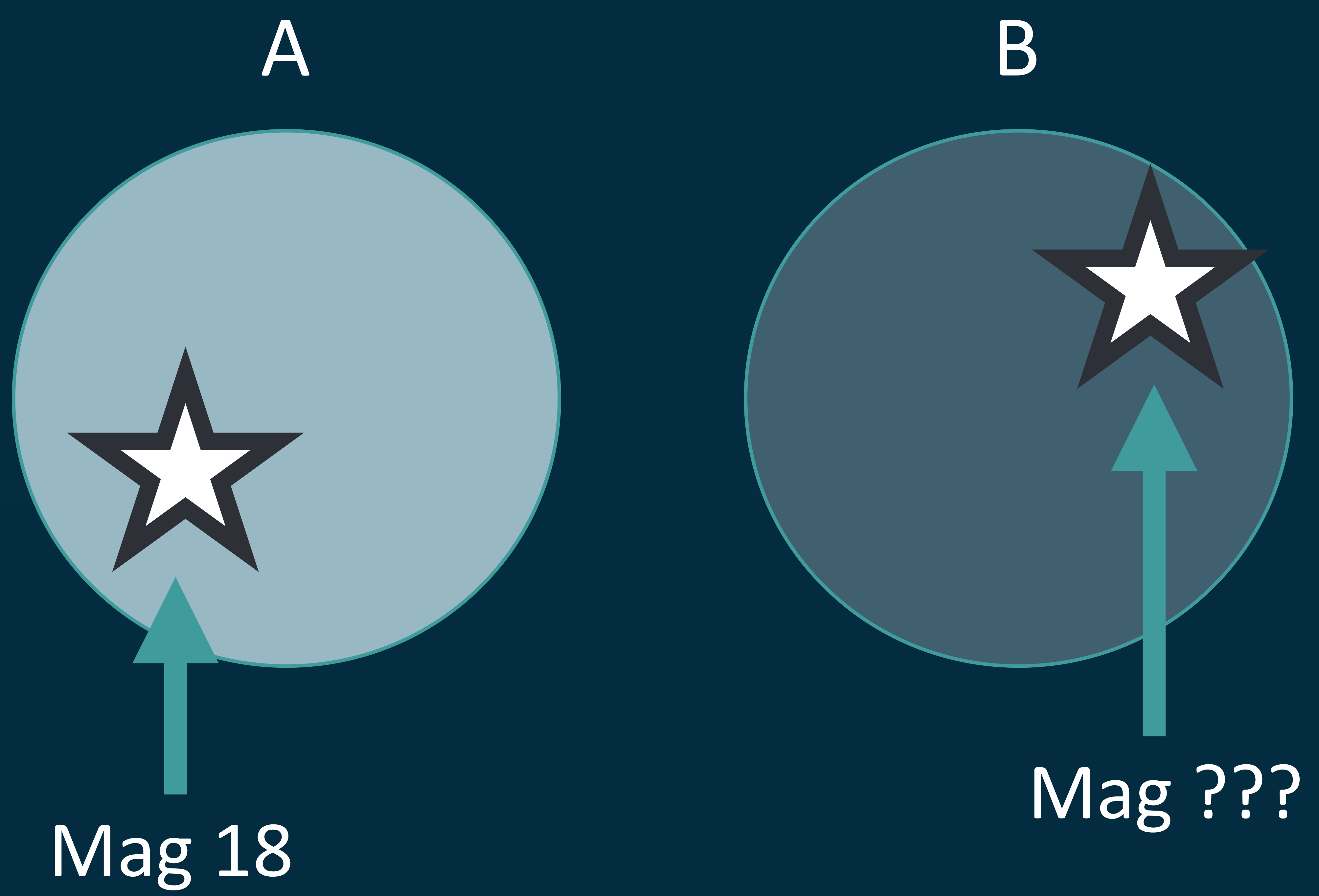
- There are a few important details that this leaves out:
  - Why are Gaia, PS1, or eventually LSST magnitudes good for calibration? How did they calibrate their images?
  - Is the zero point all that matters? What about comparing different surveys?
  - Absolute calibration: what actually defines how bright a magnitude is?

Survey Calibration

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

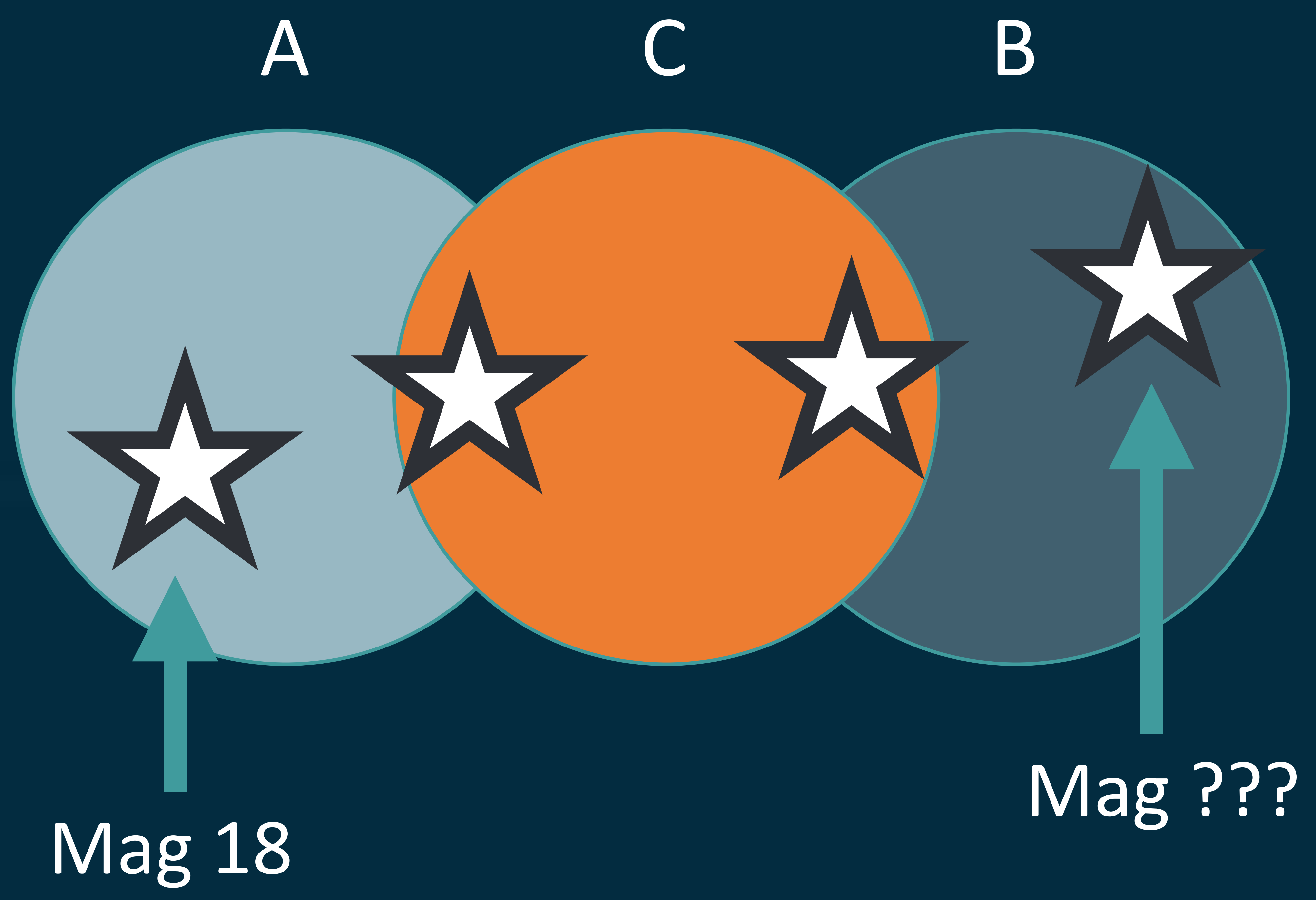
Survey Calibration

- 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.
- Bad news, survey ended, so I'm out of luck.



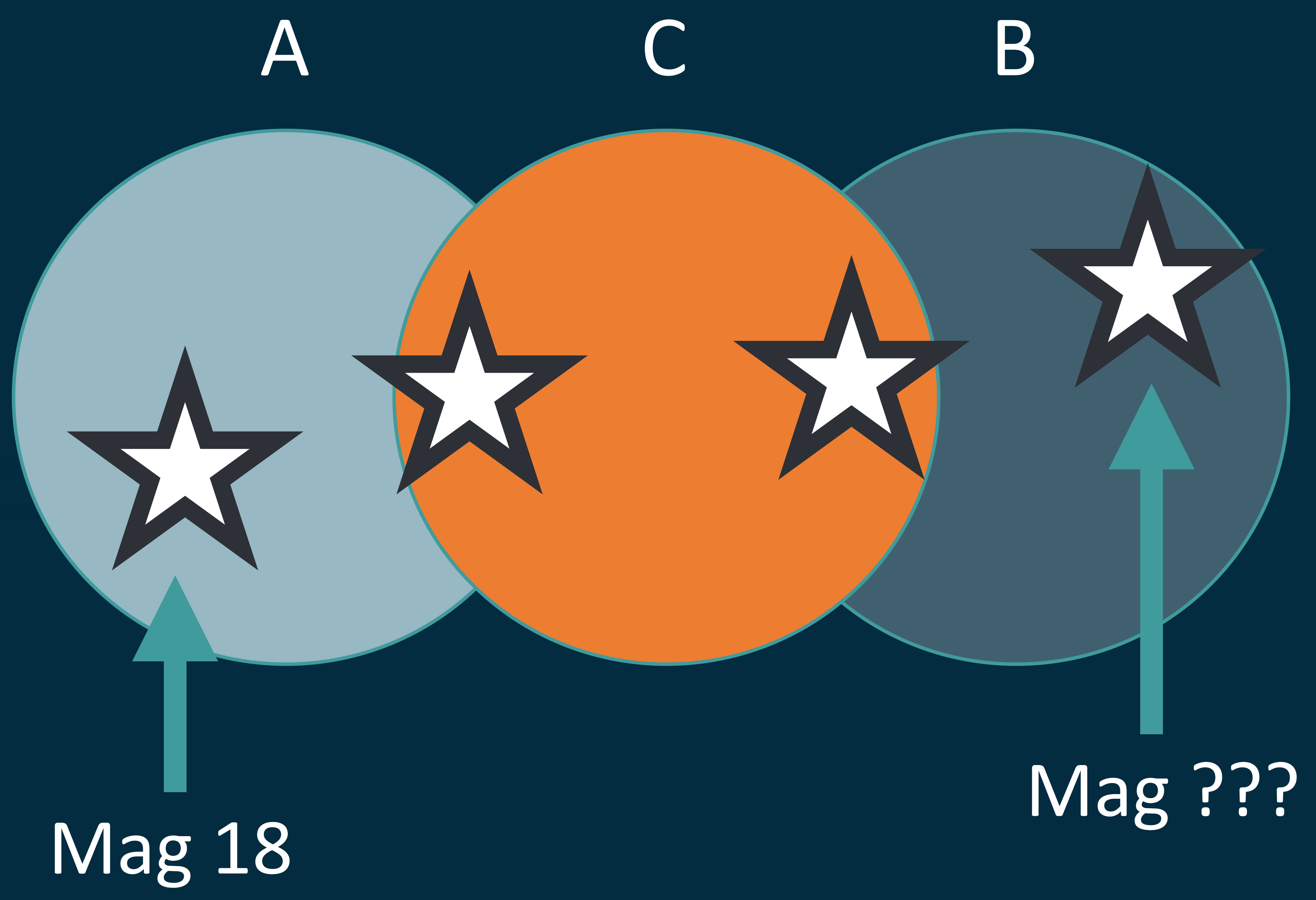
Survey Calibration

- A survey extension is approved!
- 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.

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- 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

Short Break

Color

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- 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>

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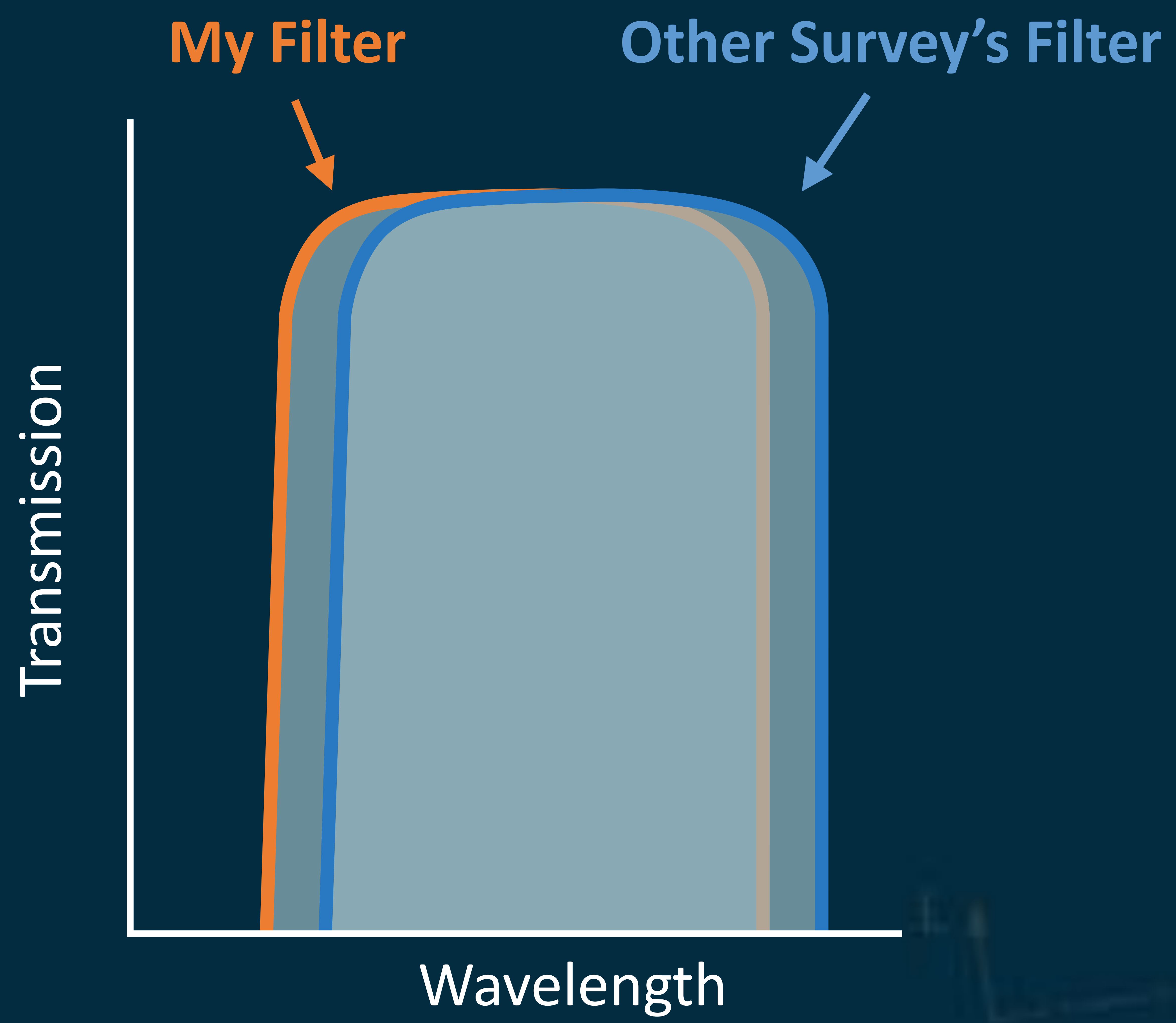
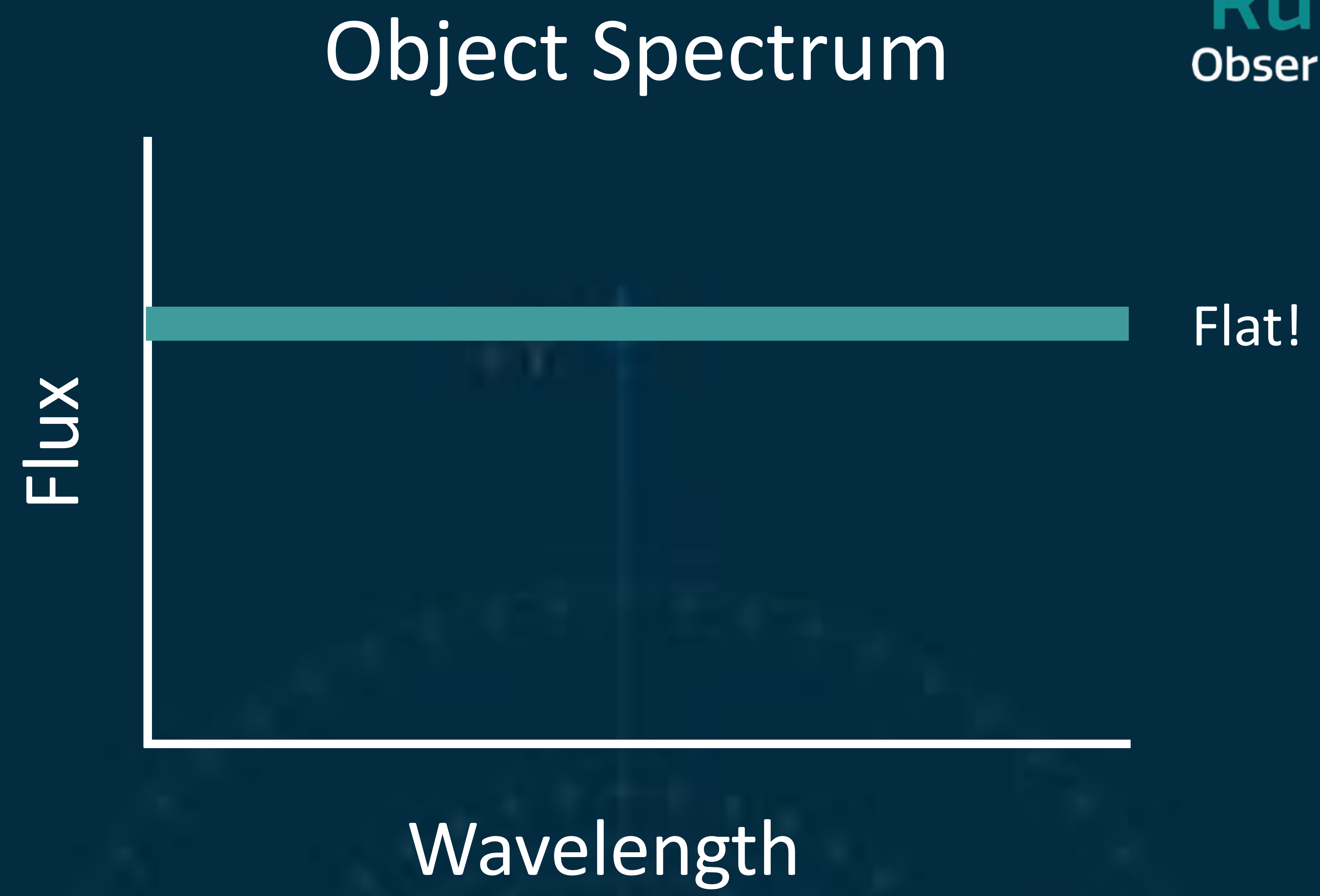
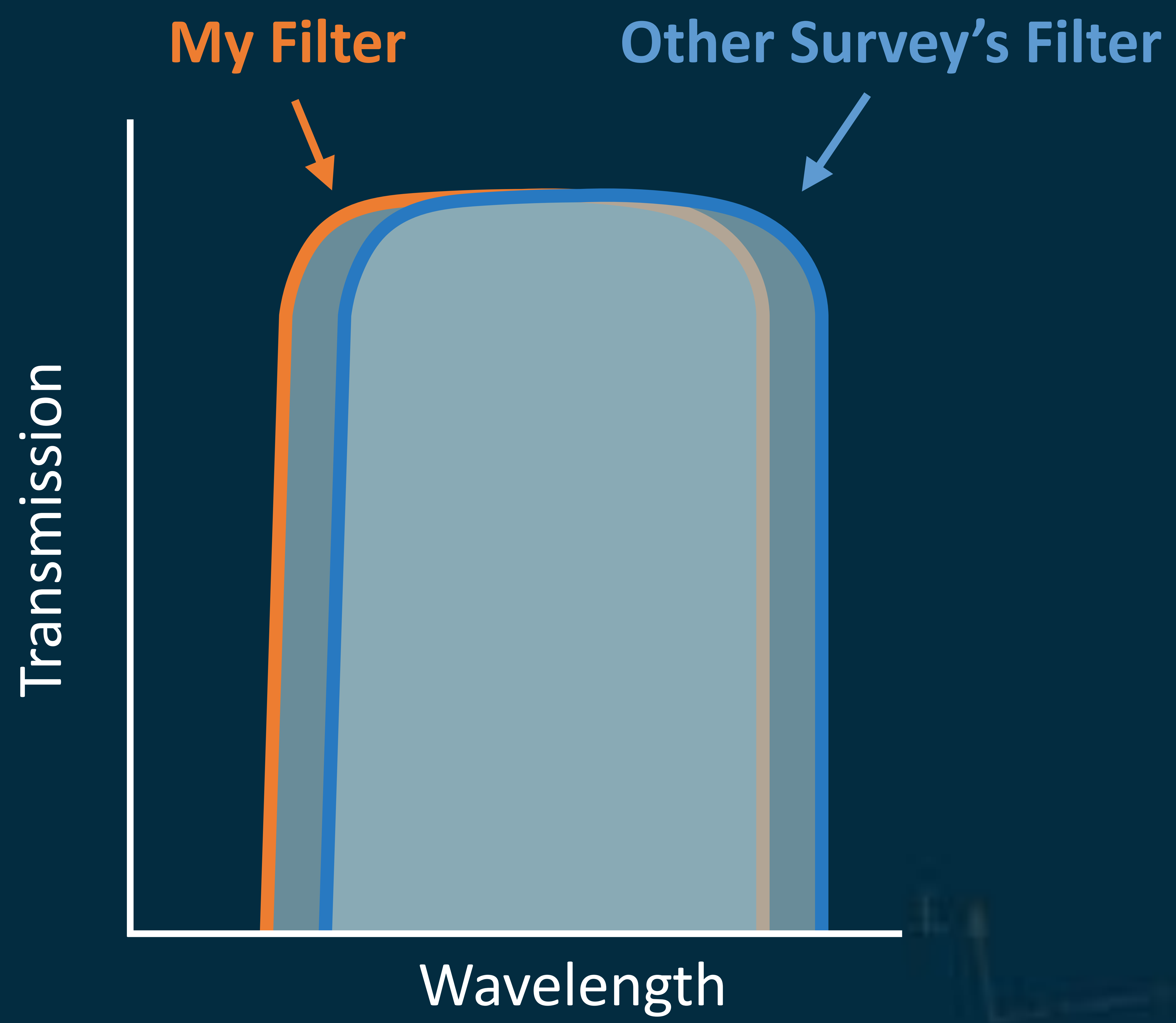


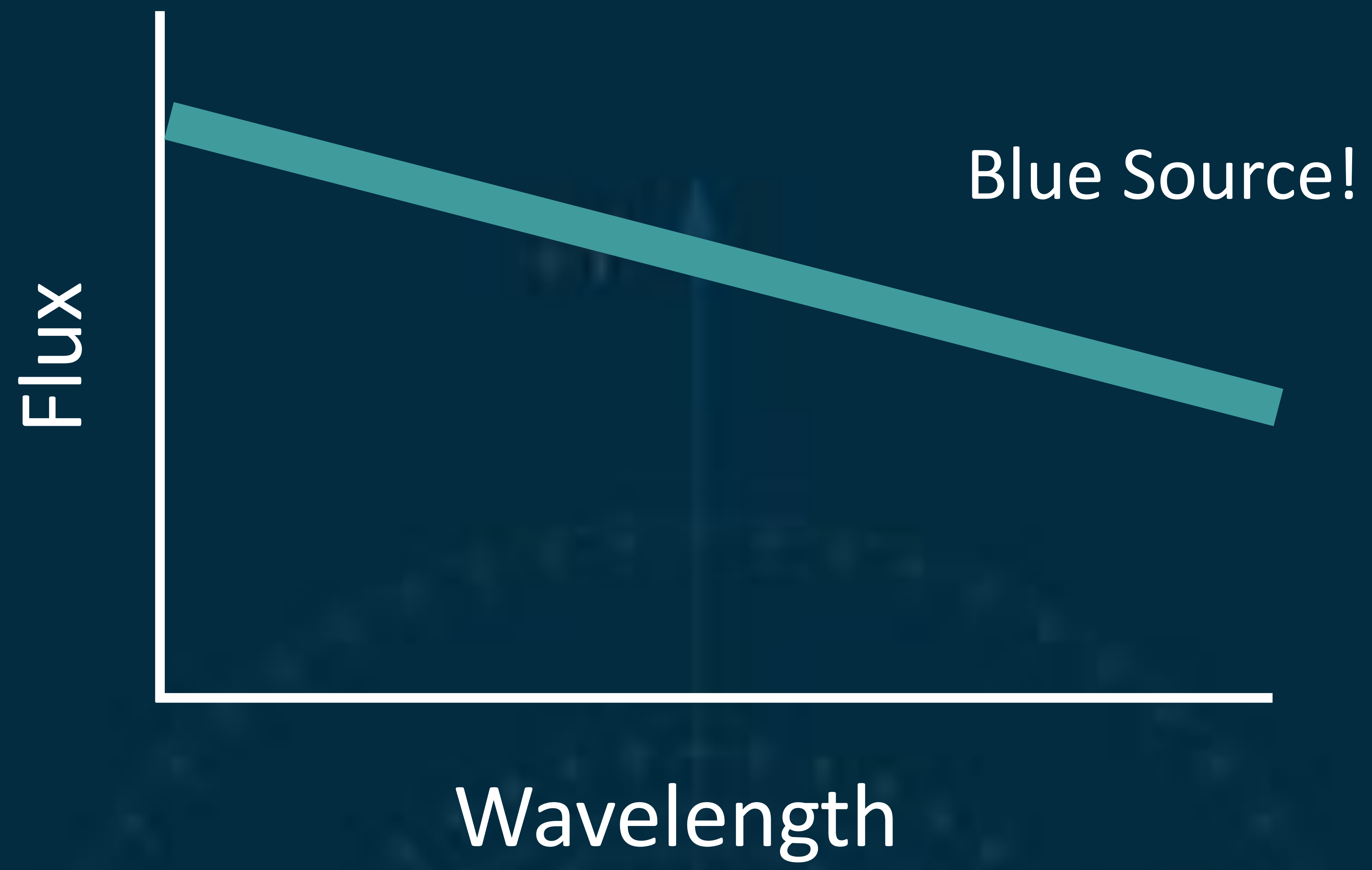


Measured Flux

Other Survey	1.0
My Survey	1.0

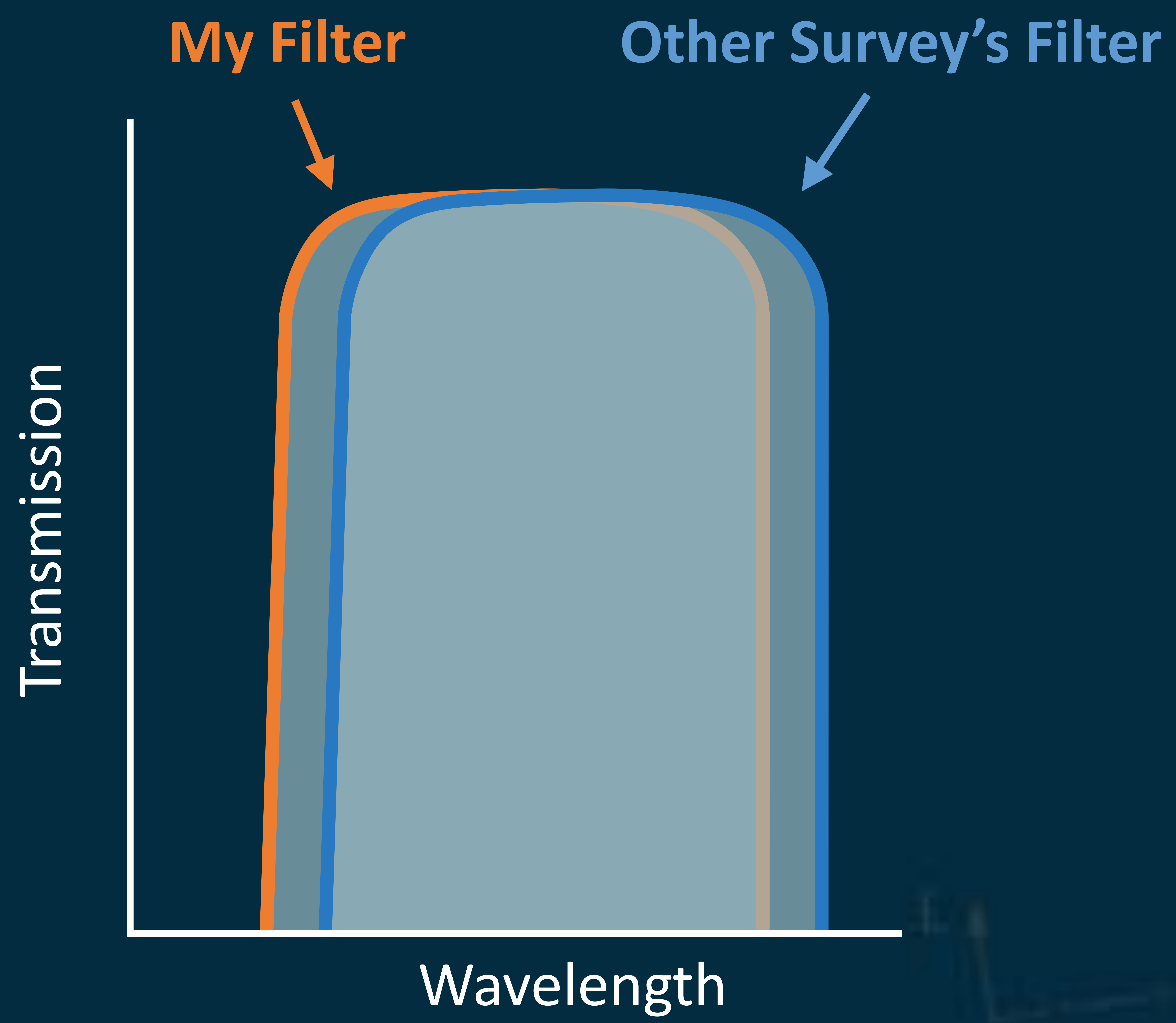


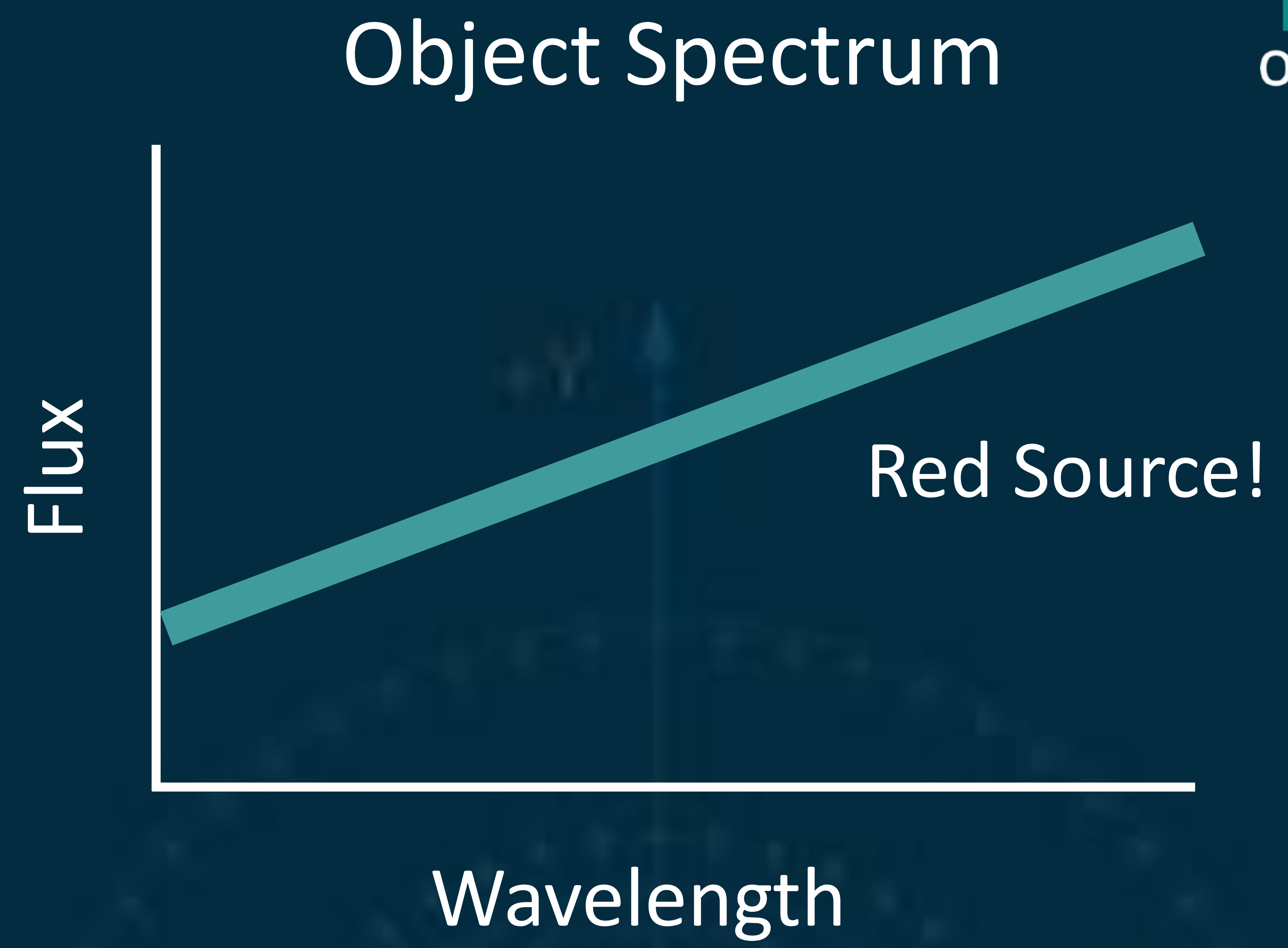
Object Spectrum



Measured Flux

Other Survey	**1.0**
My Survey	**1.1**





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" that I've added, but it's a systematic effect that could affect science.

- Traditional solution is to adopt a "color term", so that my measurement becomes something like:
  - mag = -2.5 log(counts) + ZP + C(g-r)
  - where C is a constant, and (g-r) is the color of the star that I'm measuring. (picking g and r as arbitrary example filters)

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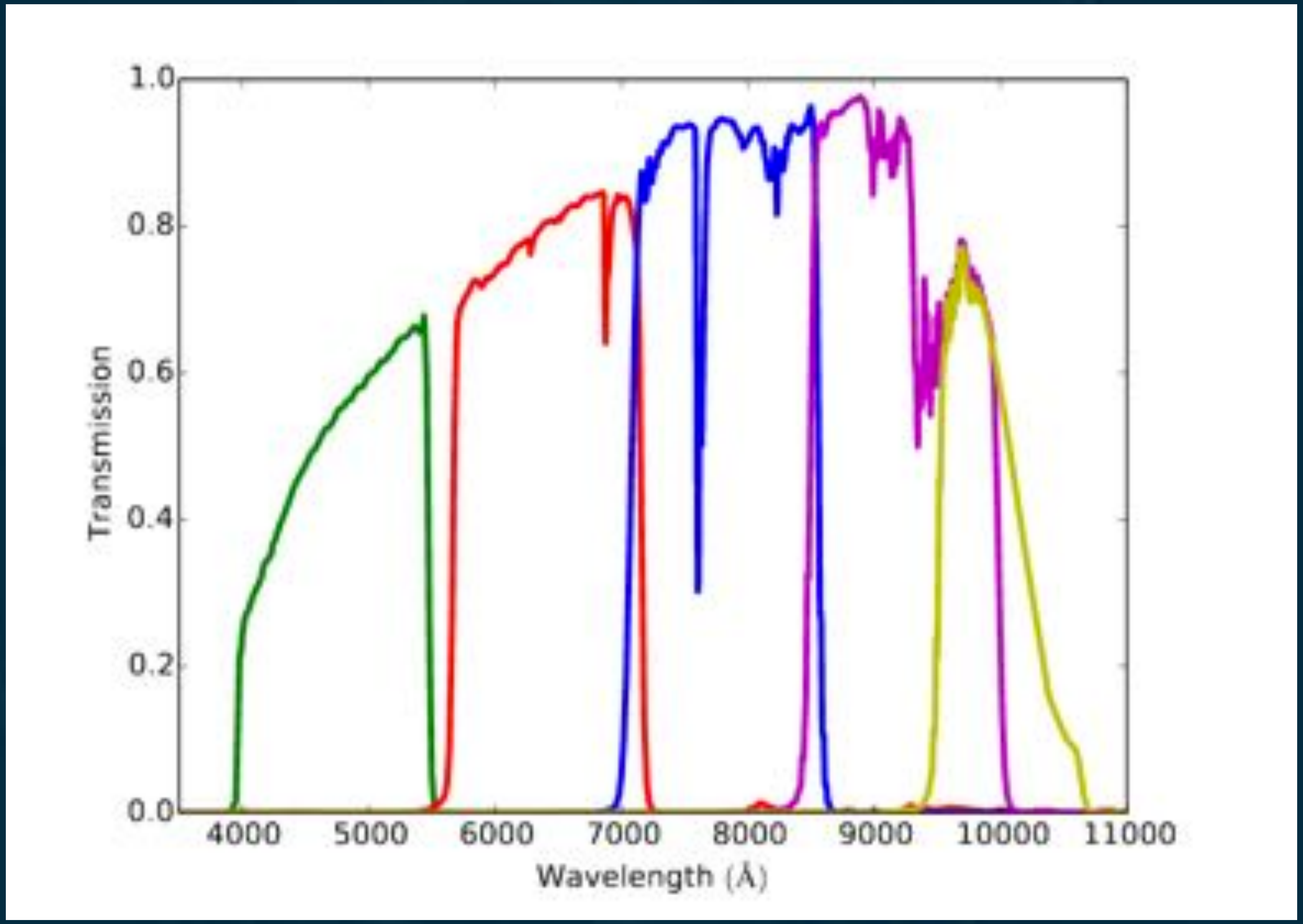
- Color terms might be sufficient if we're just correcting fixed filter edge differences. But reality is more complicated:

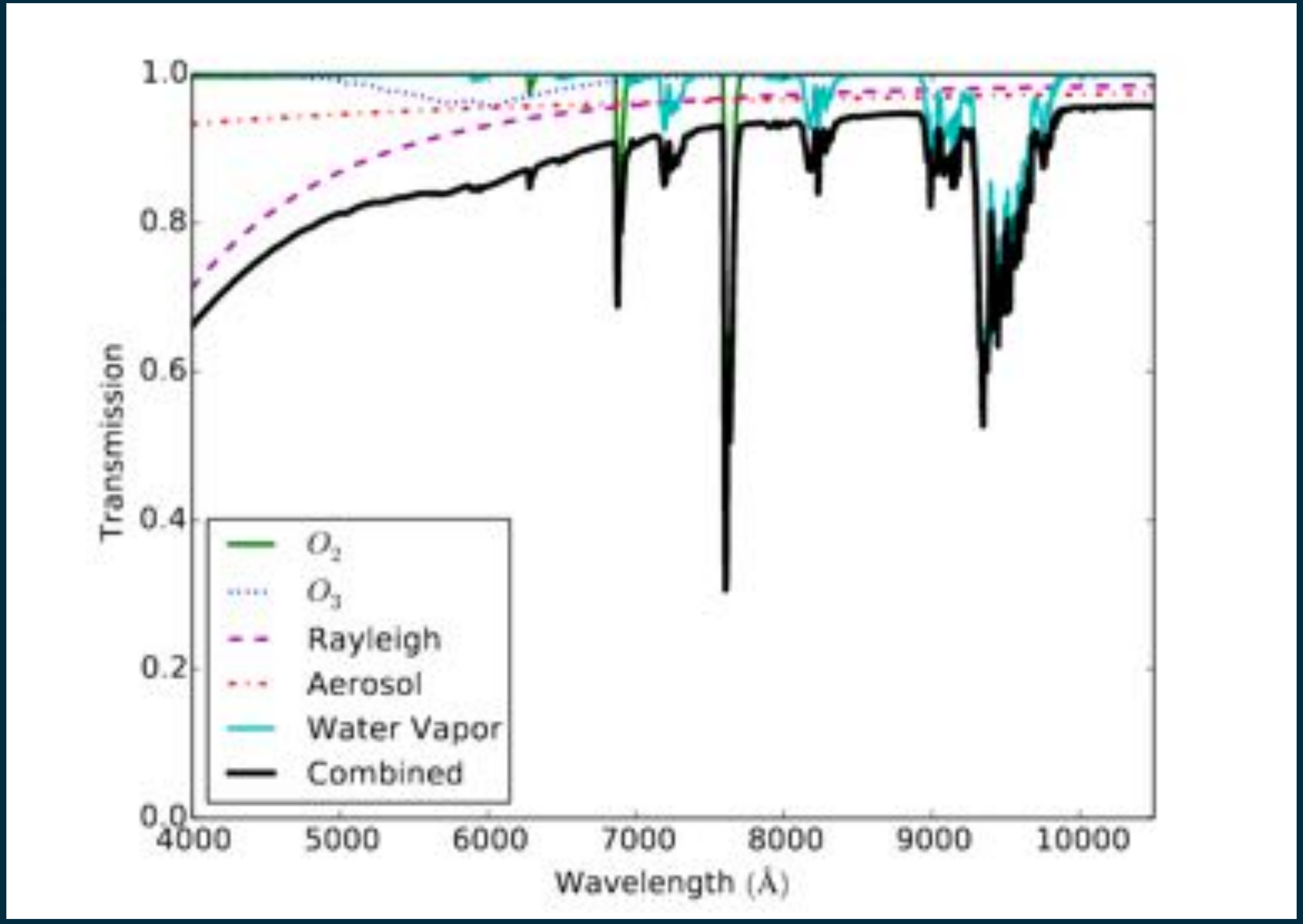
- "Total" passband throughput, including the atmosphere, changes over time.
  - => Even within a survey, with fixed hardware, chromatic variation is present between exposures.

• Individual atmospheric components vary within a night

DES Passbands, including atmosphere

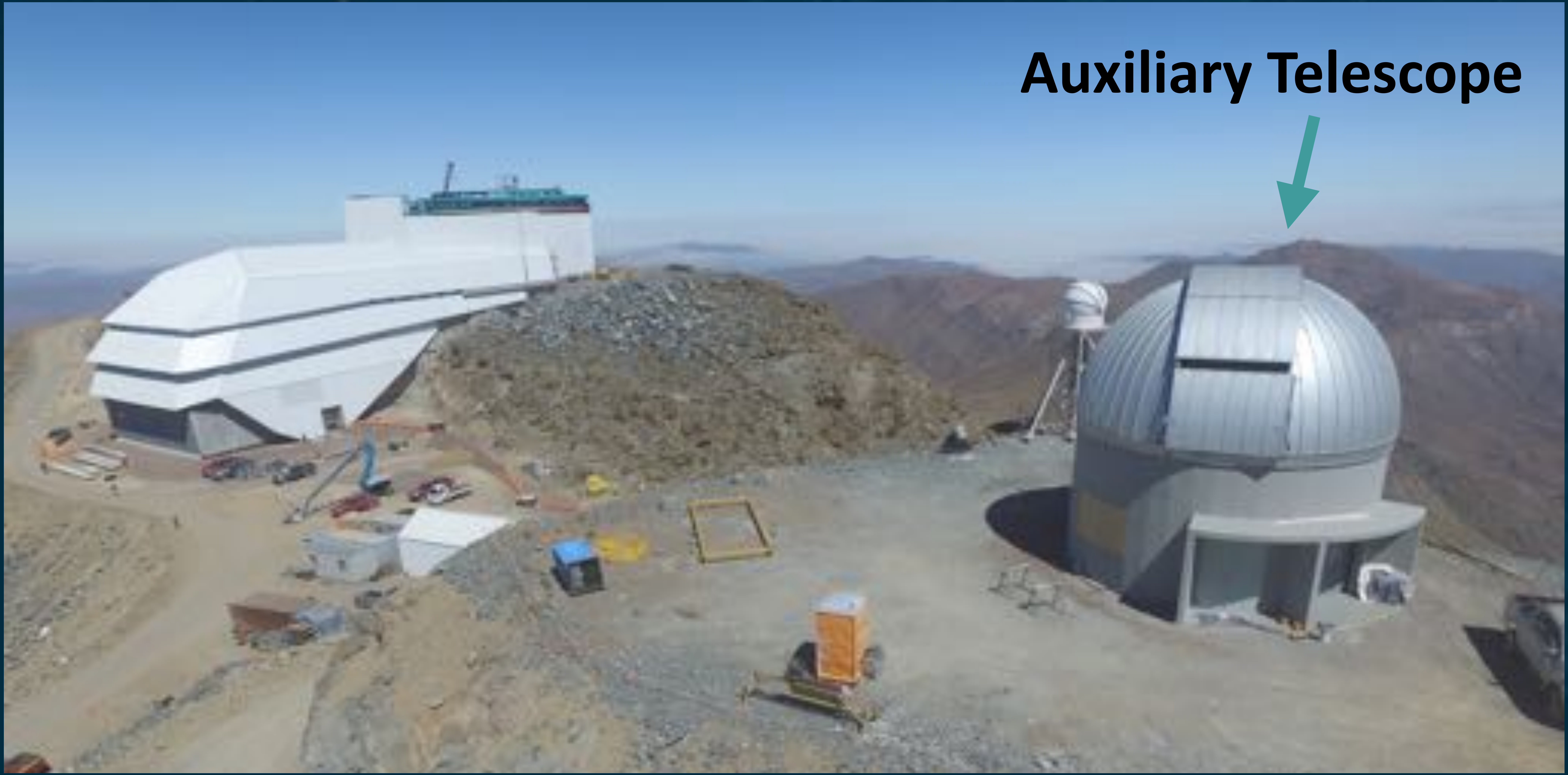


Model Atmosphere



From Burke et al. 2017

Rubin Observatory plans



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.

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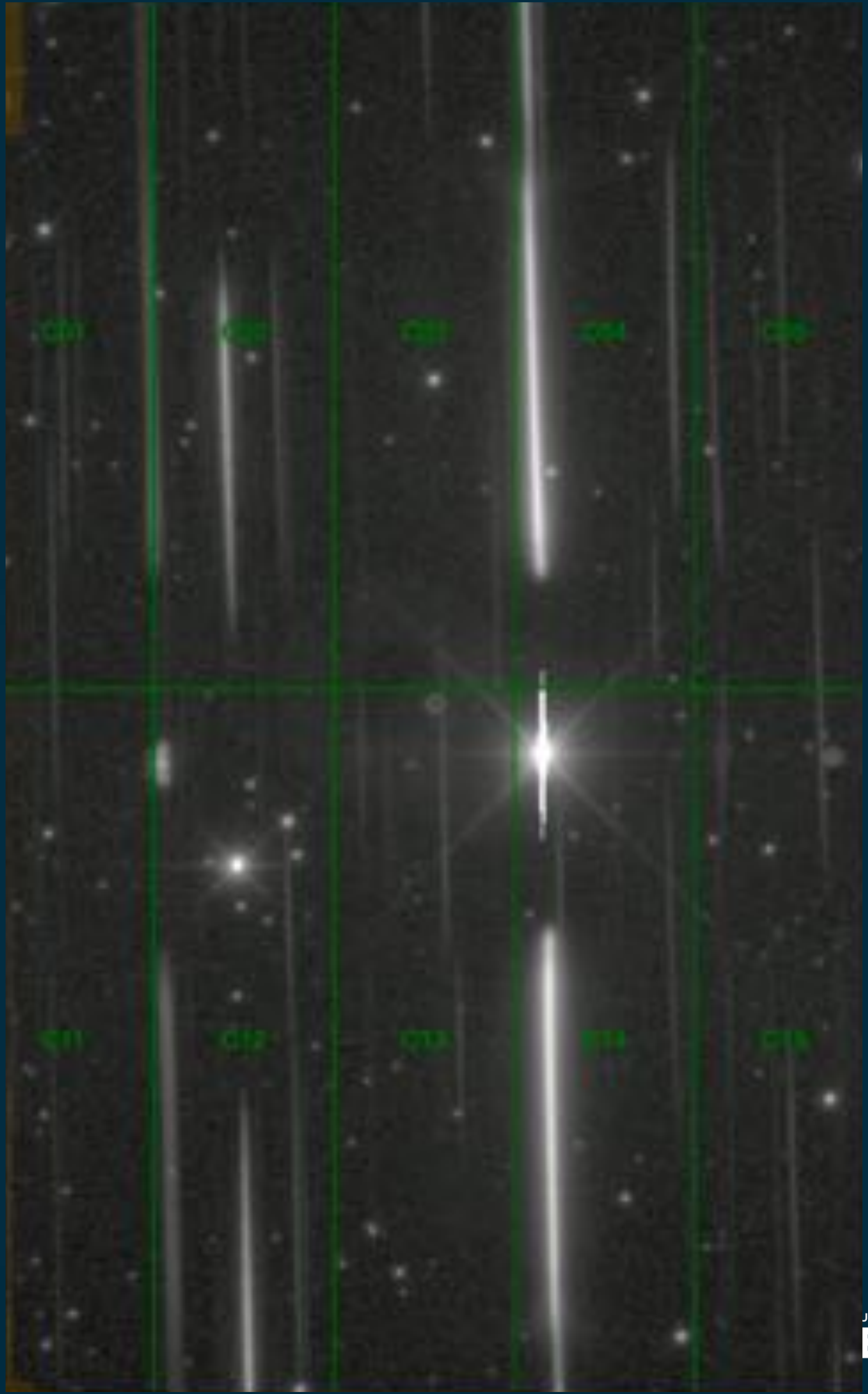
- Fit atmospheric models to these spectra, tells us what the “effective” passbands are for the main survey as a function of time, for each night of observing.



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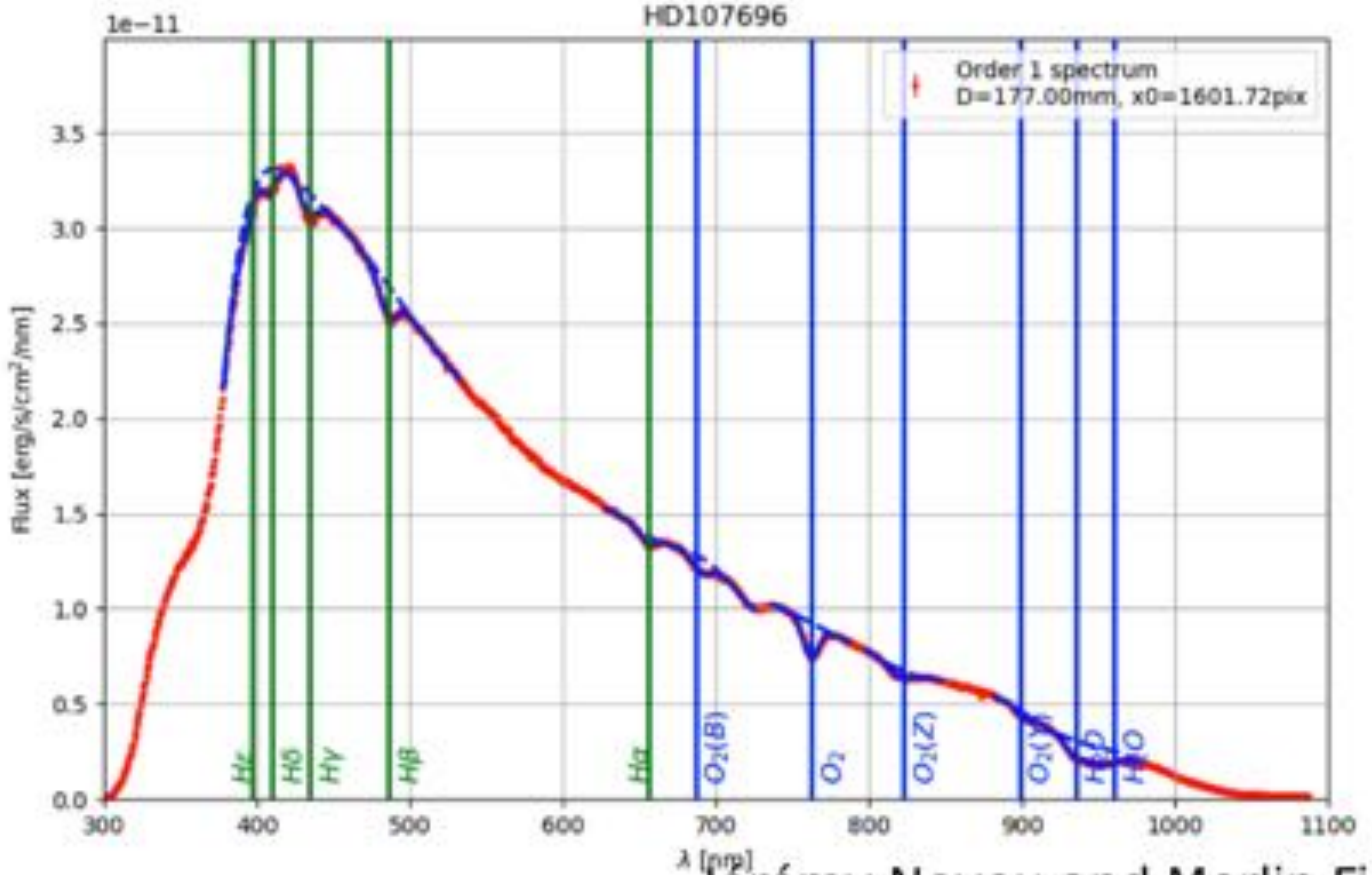

Jérémy Neveu and Merlin Fisher-Levine

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.