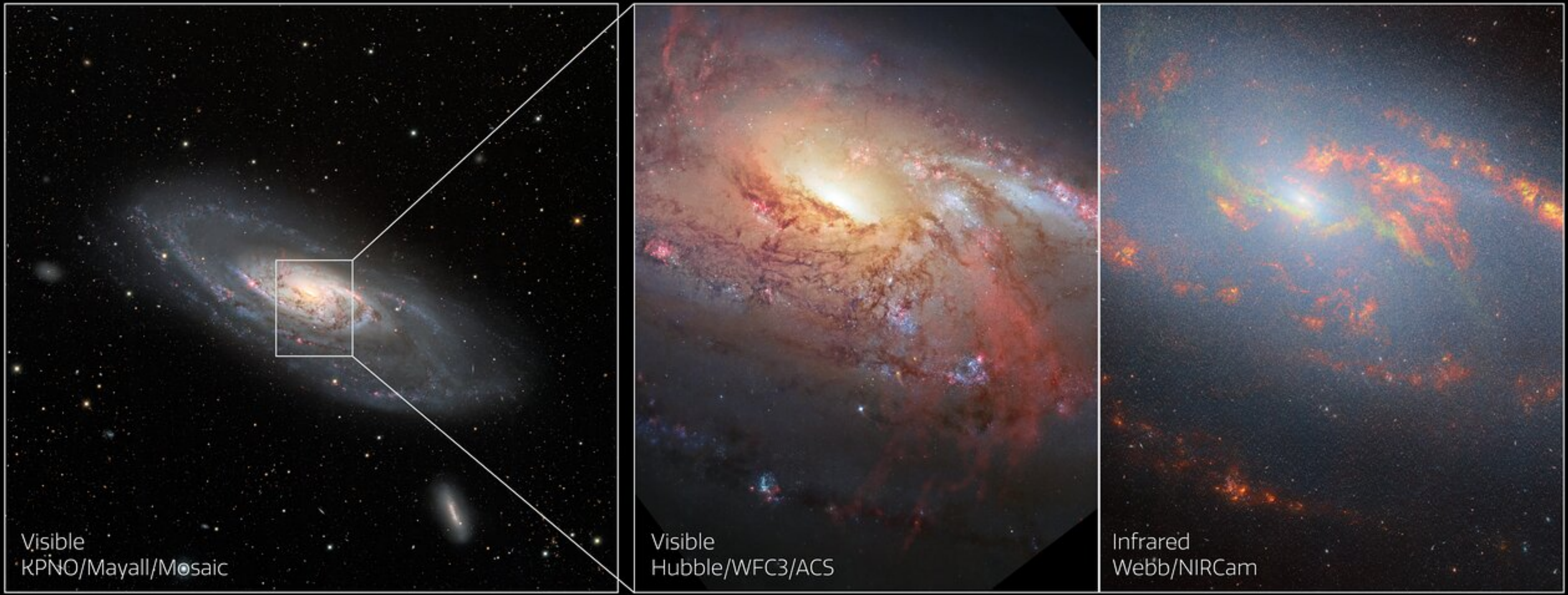
How to measure stars: Methods and Challenges of Photometry



Kayla Owens, University of Chicago

Please interrupt and ask questions at any point

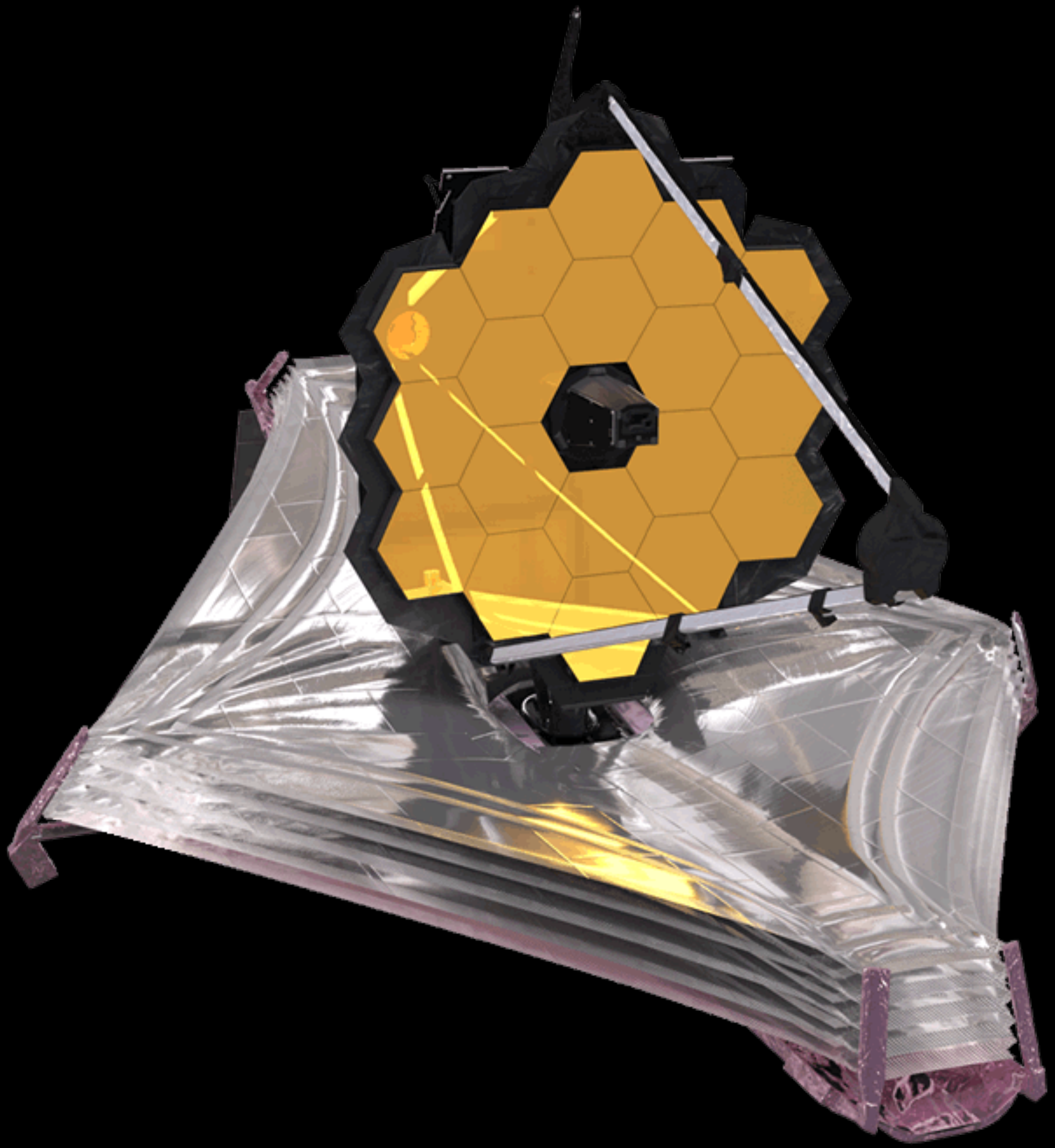



Image credit : NASA

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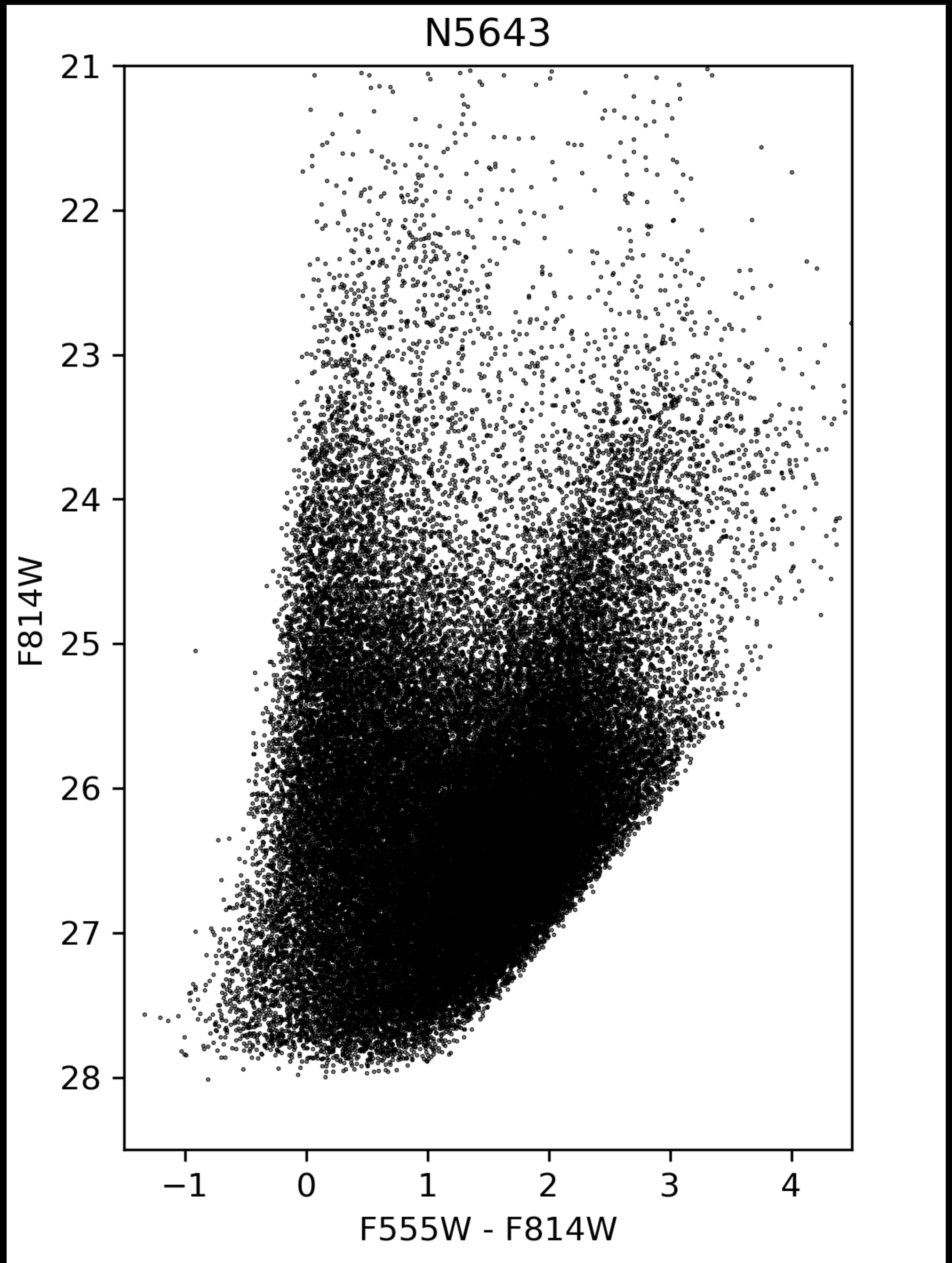
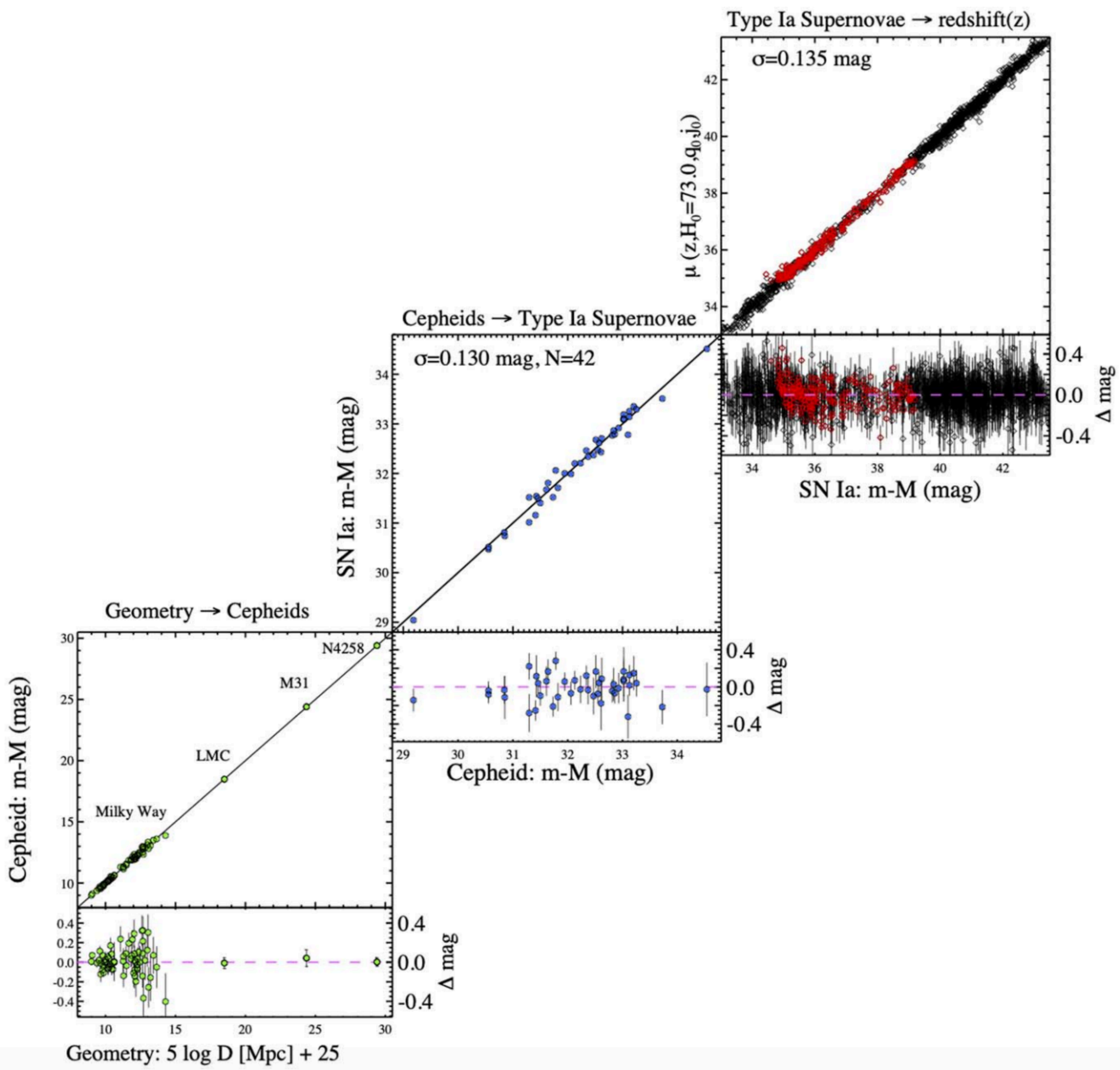
What is photometry?

What is photometry?



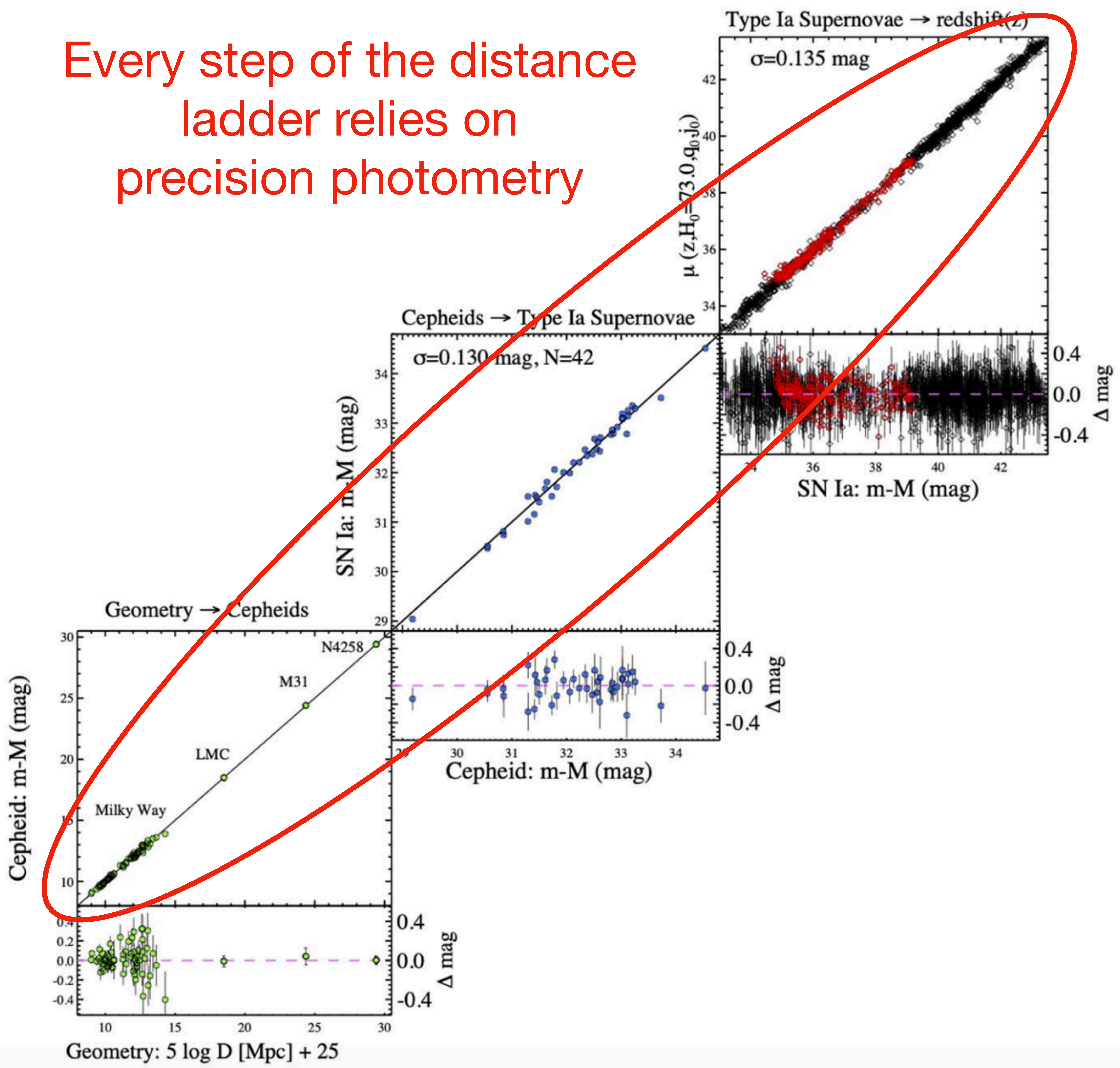
What is photometry?

Measuring the brightness of a source on an image



Riess et al. (2022)

Every step of the distance ladder relies on precision photometry



Riess et al. (2022)

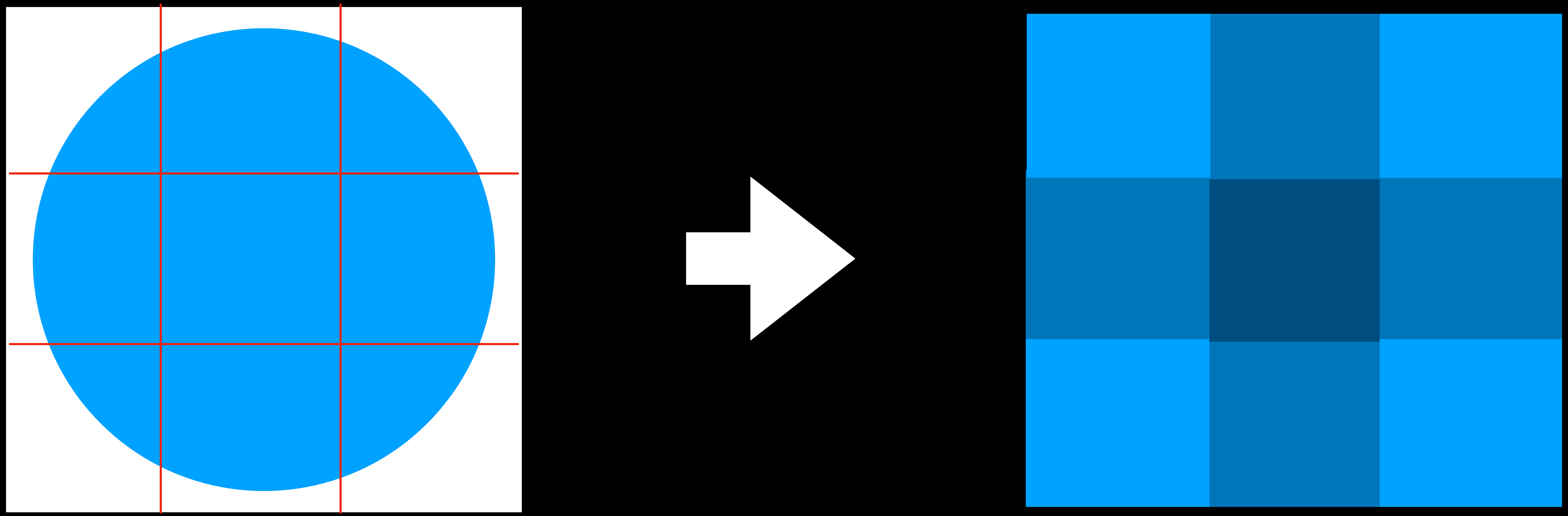
How to take images

- Point a telescope at the sky
- Light is projected onto a detector (a CCD for our wavelengths)
- Photons excite electrons in the detector surface
- Electrons then sit in a pixel well
- Read out : count the electrons in each pixel
- Now you have an image!

Credit: ESA/Hubble & NASA, A. Riess et al.; acknowledgment: Mahdi Zamani

Remember: images are discretized

You can only see detail down to the pixel size



Types of photometry

- **Aperture photometry**
  - Measure counts through a given “aperture” radius

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- **Point-spread function (PSF) photometry**
  - Measure weighted counts based on the shape of a source on an image

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Simple case

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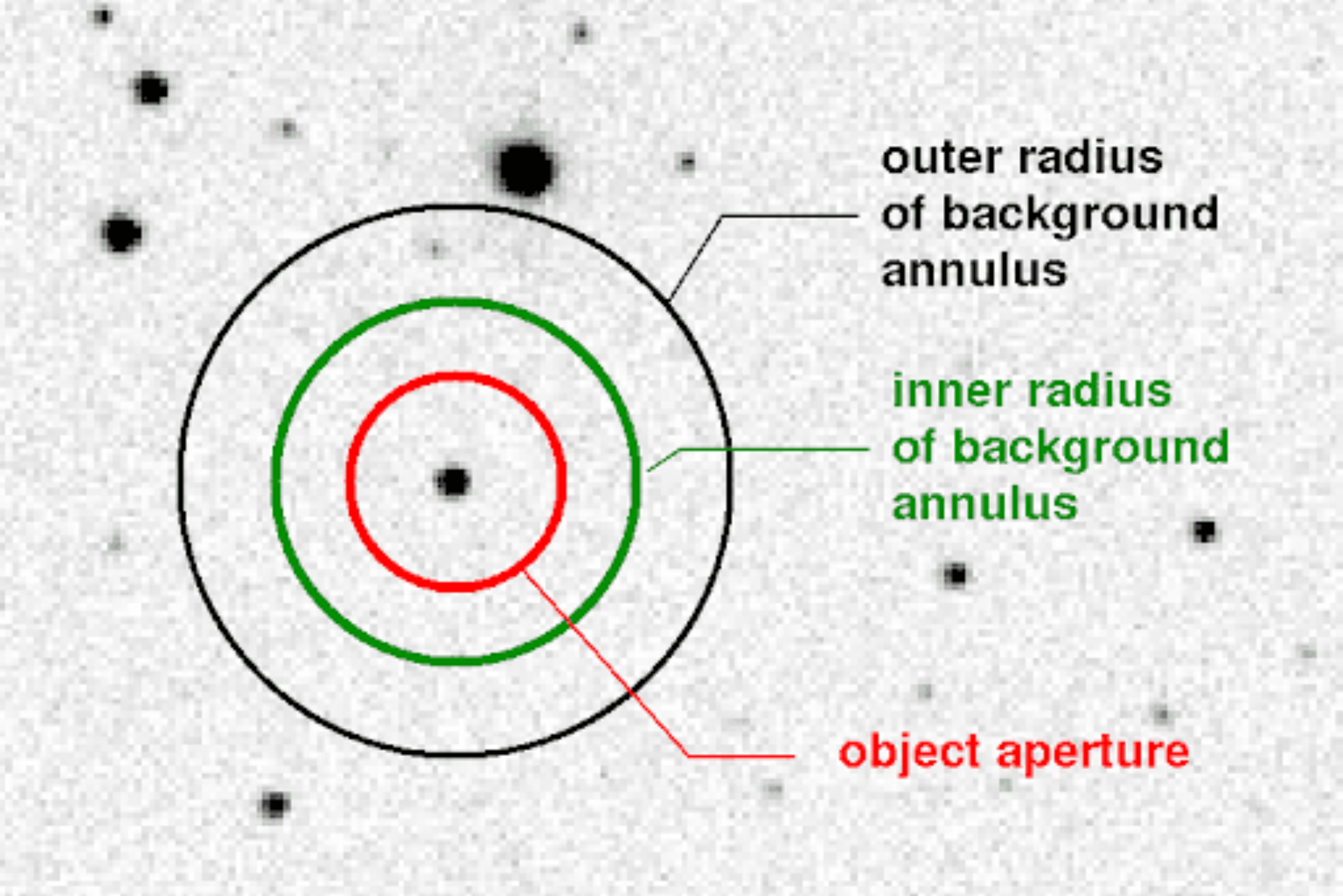
Types of photometry

Simple case

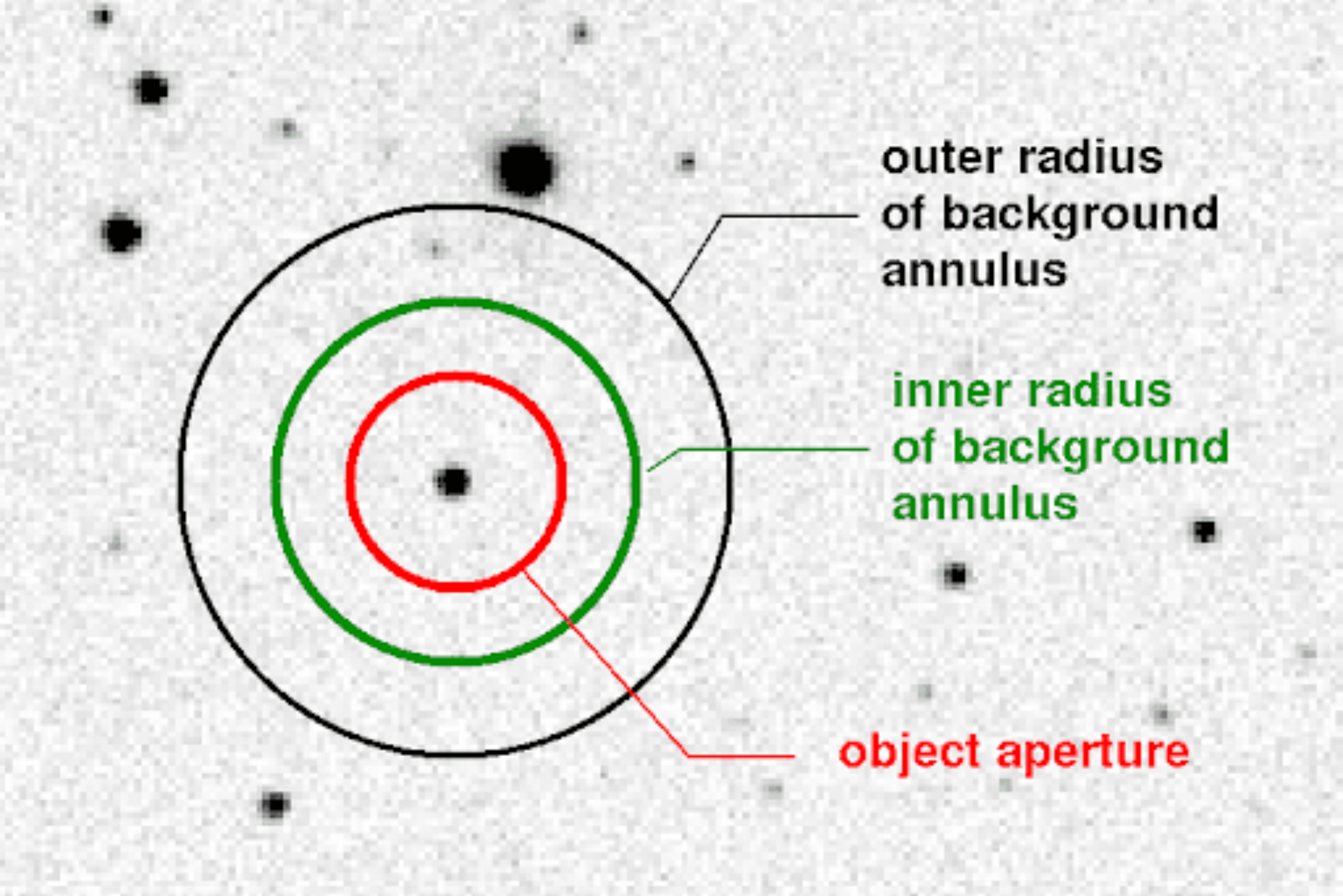
- **Aperture photometry**
  - Measure counts through a given “aperture” radius
- Good for **isolated** stars



Object aperture:

Add up the counts inside of this selection

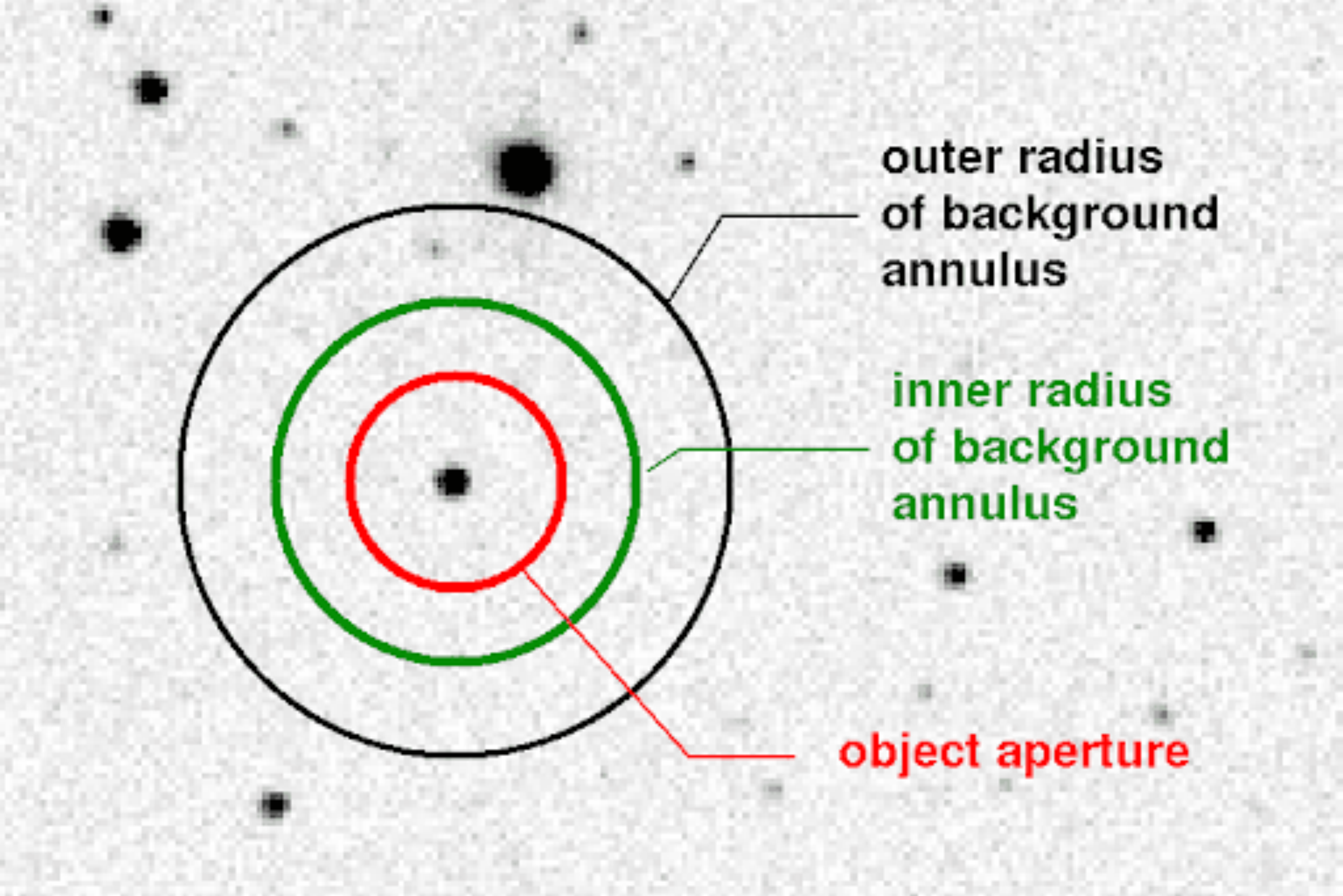
Essentially “how many photons are in this area”



Background annulus:

Used to measure the background flux behind the source

Subtracted from object aperture flux to give only source counts



Source counts:
Aperture - background
(same area)

Calibrated flux:
Divide by reference flux

Types of photometry

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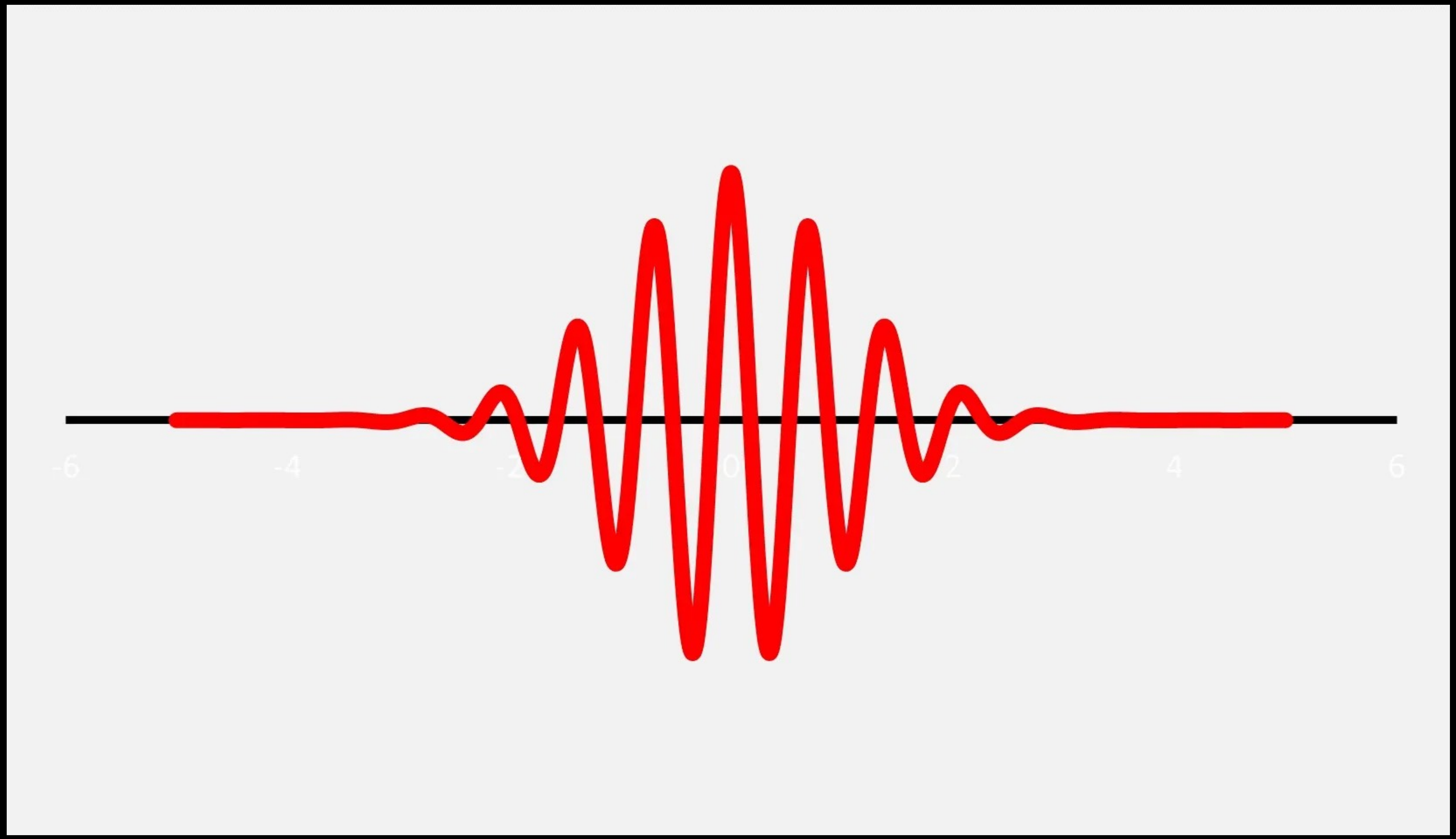
This is what we use for the extragalactic distance scale

Point Spread Function

- How a telescope spreads out the light from a perfect source
- Different for each:
  - Telescope
  - Instrument
  - Wavelength


PSF of JWST/NIRCAM

Light is a wave packet



Point Spread Function

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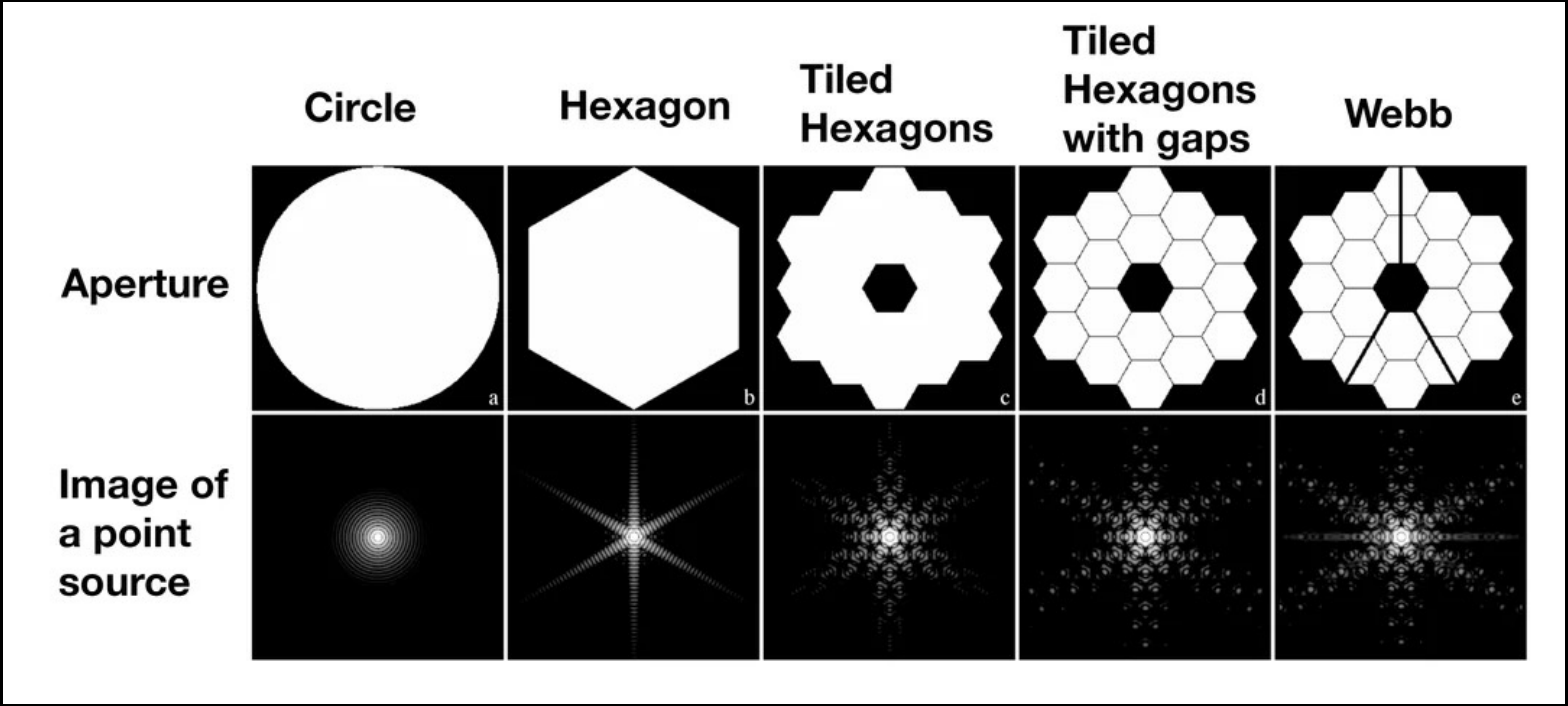
Think of PSFs as a (complicated) interference pattern



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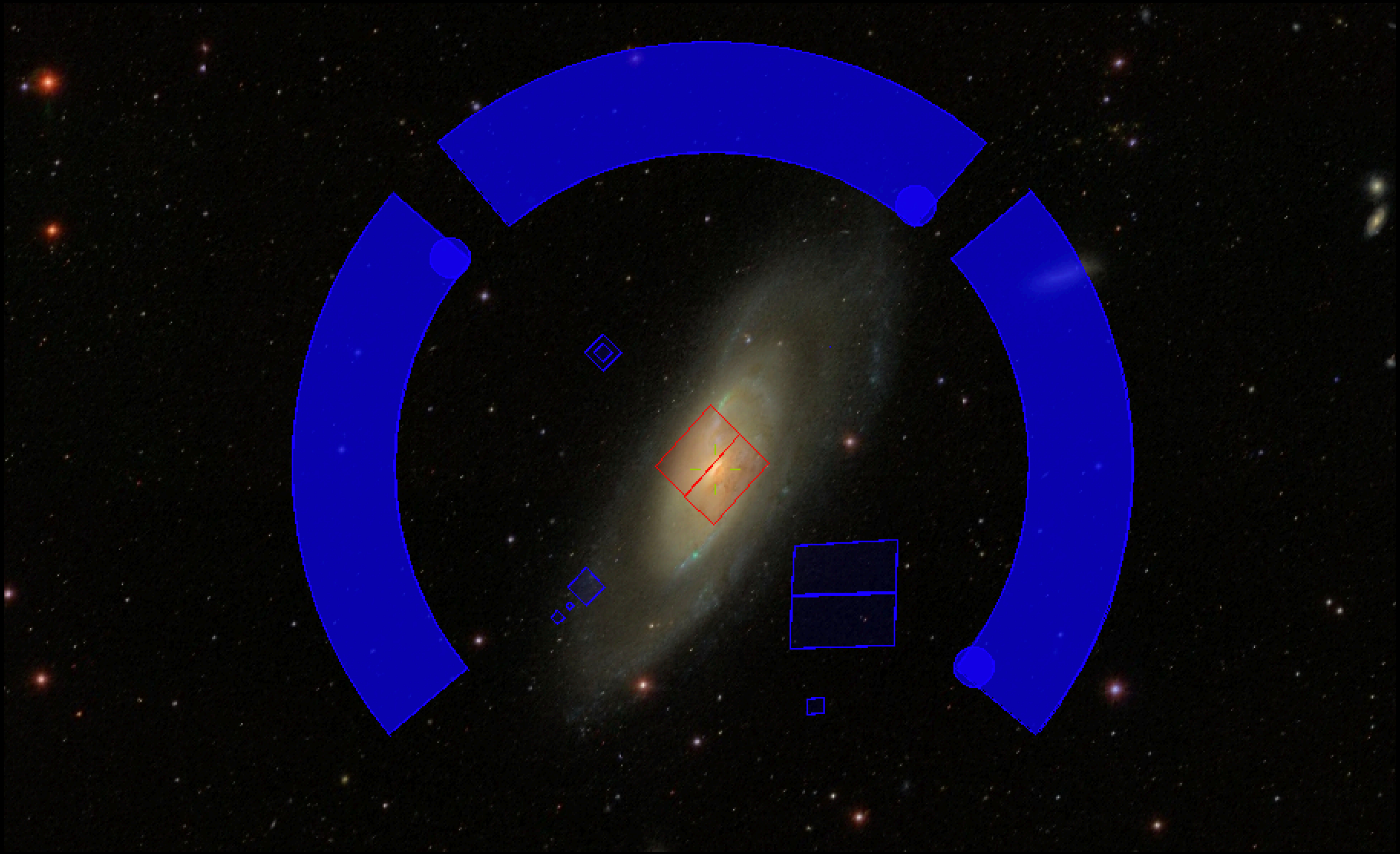

Point Spread Function

- How a telescope spreads out the light from a perfect source
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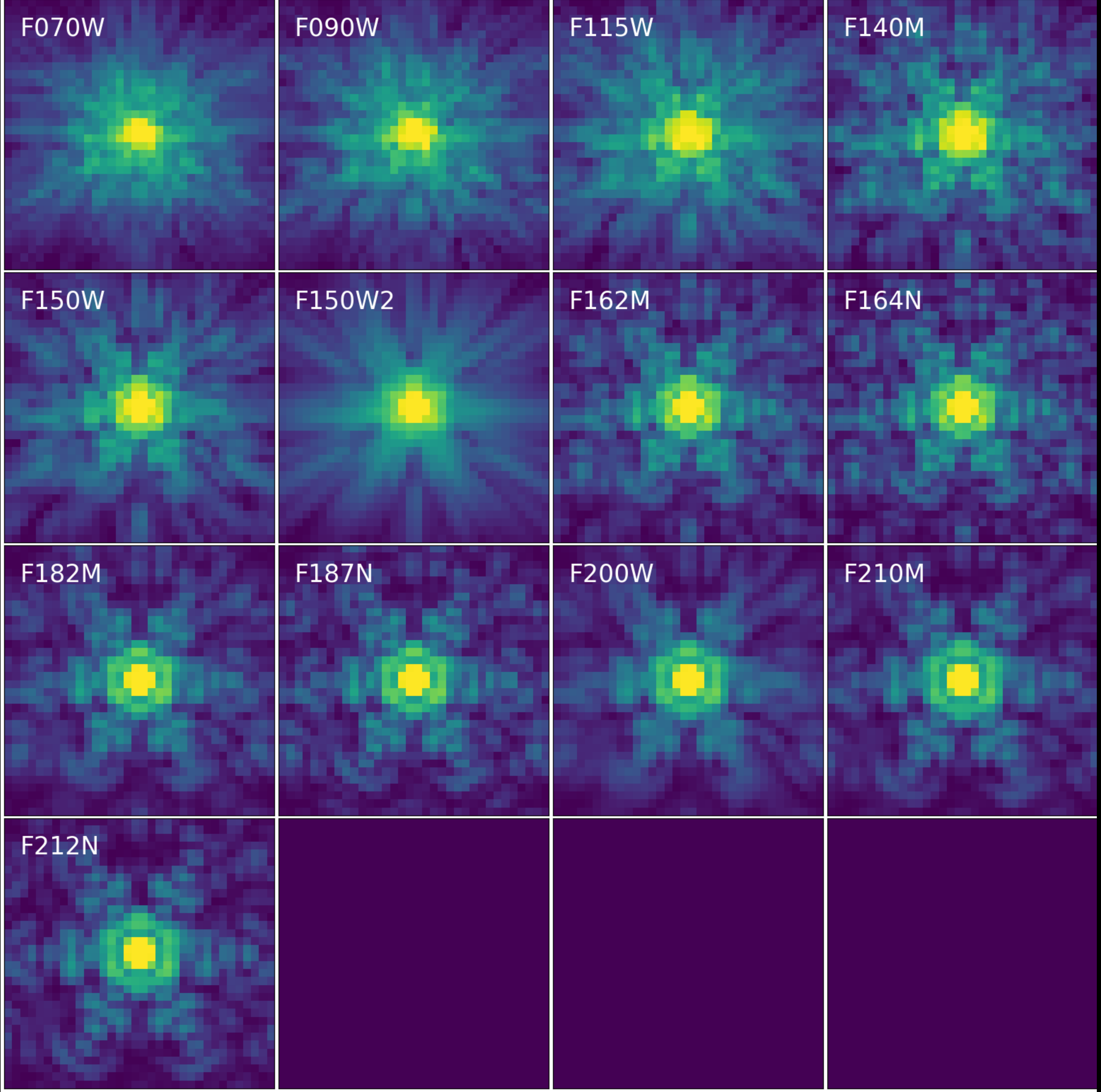
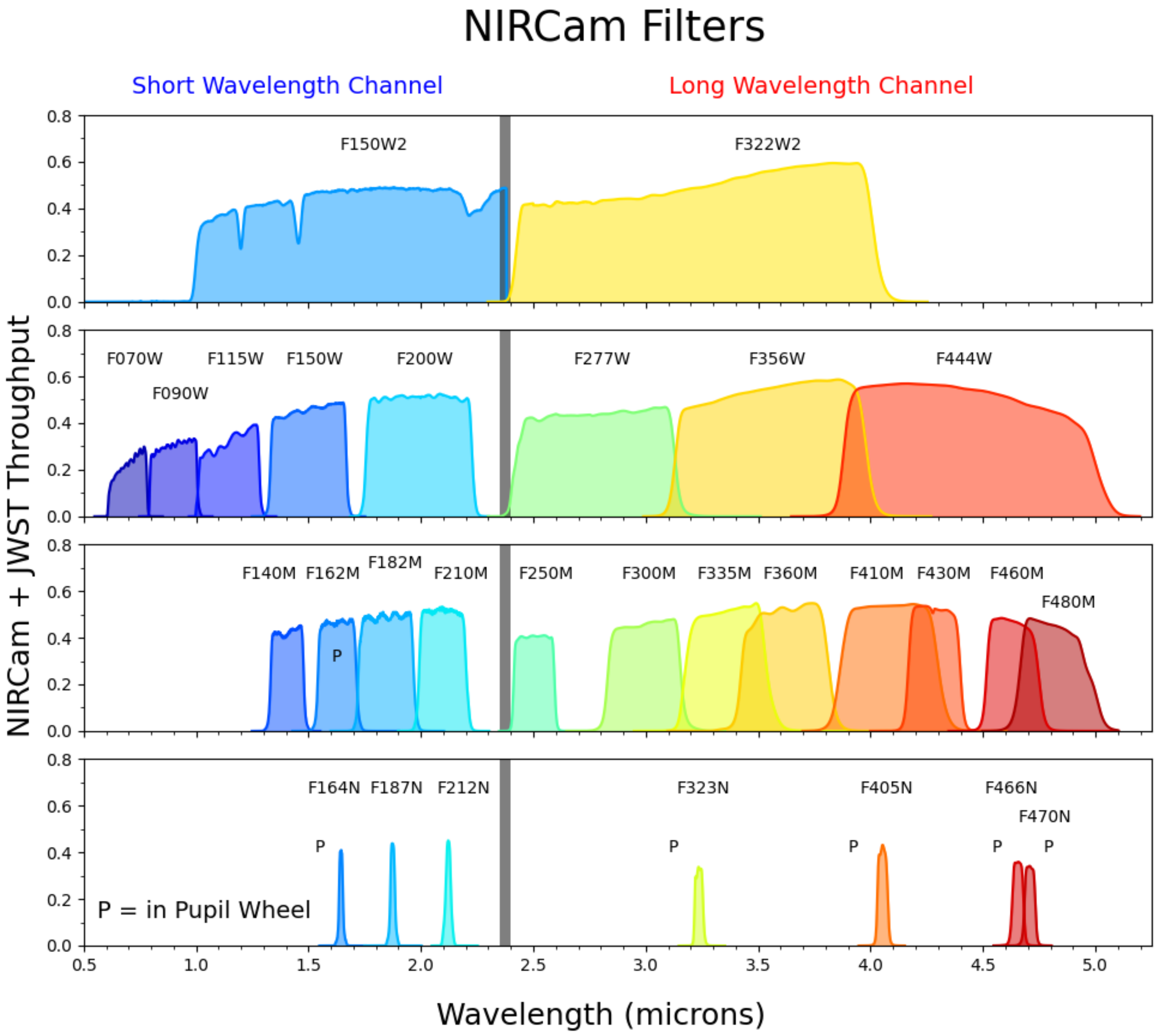

F070W
F090W
F115W
F140M
F150W
F150W2
F162M
F164N
F182M
F187N
F200W
F210M
F212N



NIRCam Filters
Short Wavelength Channel
Long Wavelength Channel
NIRCam + JWST Throughput
Wavelength (microns)
0.0
0.2
0.4
0.6
0.8
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
F150W2
F322W2
F070W
F090W
F115W
F150W
F200W
F277W
F356W
F444W
F140M
F162M
F182M
F210M
F250M
F300M
F335M
F360M
F410M
F430M
F460M
F480M
P
F164N
F187N
F212N
F323N
F405N
F466N
F470N
P = in Pupil Wheel

PSF photometry

The basic process

- Prepare your images
- Measure or adopt a PSF
- Detect sources on the image
- Fit the brightness of those sources using the PSF
- Subtract detected sources
- Second (or more) passes for detection
- Apply aperture corrections and photometric zero point

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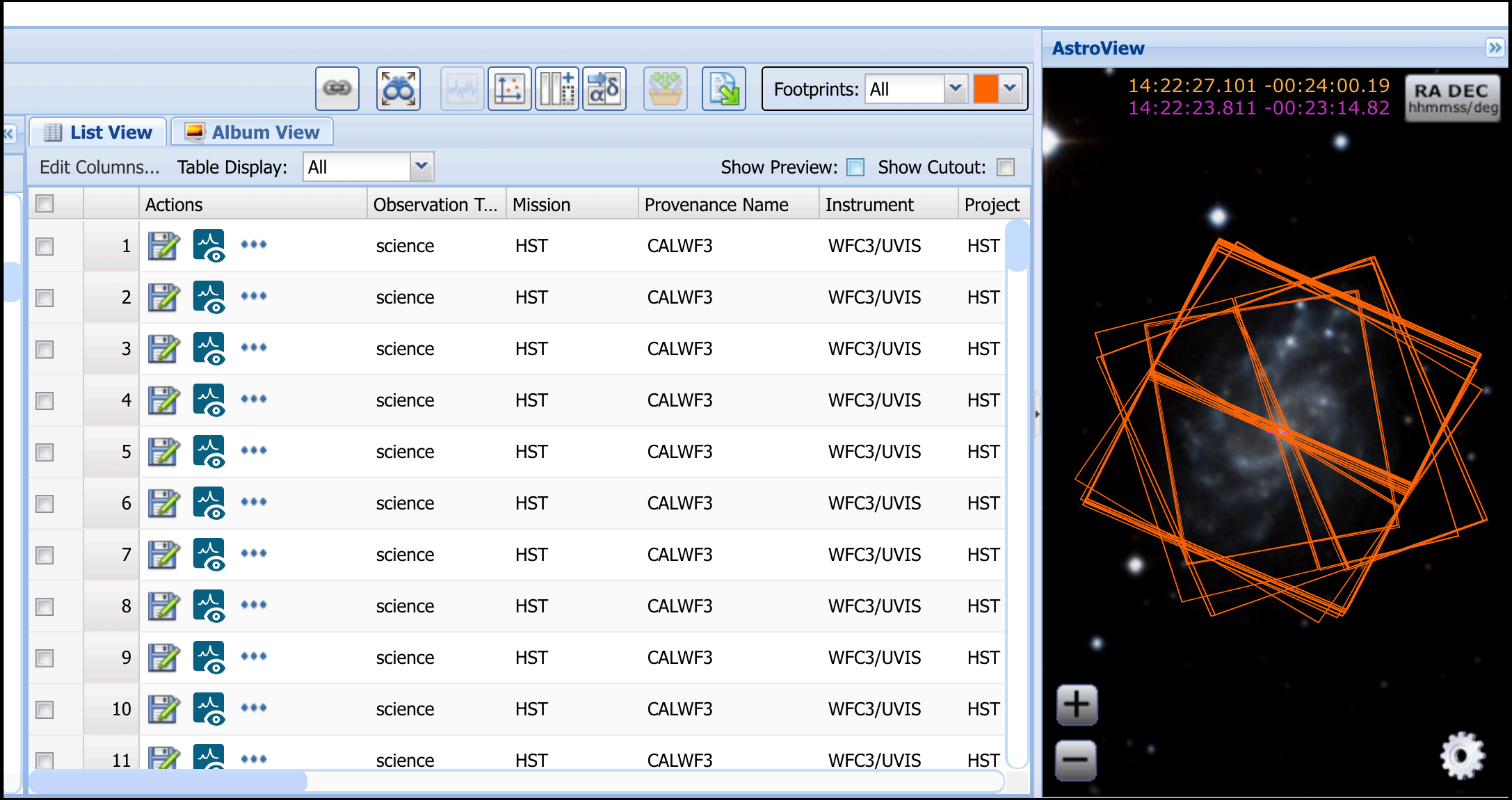
Astronomical images

- .fits format
- Image in either electron “counts” or converted to convenient energy units
- Header: contains information about the image, including position
- World Coordinate System (WCS) -> assign each pixel a location on the sky

What we get from the telescope



What we get from the telescope

Multiple images

Frequently over multiple visits

What we get from the telescope

Image Alignment

- Detect sources on each image
- Eliminate cosmic rays
- Calculate geometric transformation to match images

- Subpixel alignment: less than 0.1 pixels, or 0.006”

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This is my least favorite step in the the entire process of photometry

Image drizzling

- Package provided by Space Telescope Science Institute (STScI)

Image drizzling

- Three things drizzling does:
- 1. Produces a “stacked” image with higher SNR and better resolution
- 2. Eliminates cosmic rays
- 3. Applies geometric and pixel area corrections

Smaller drops -> Finer resolution

Bigger drops -> Better SNR

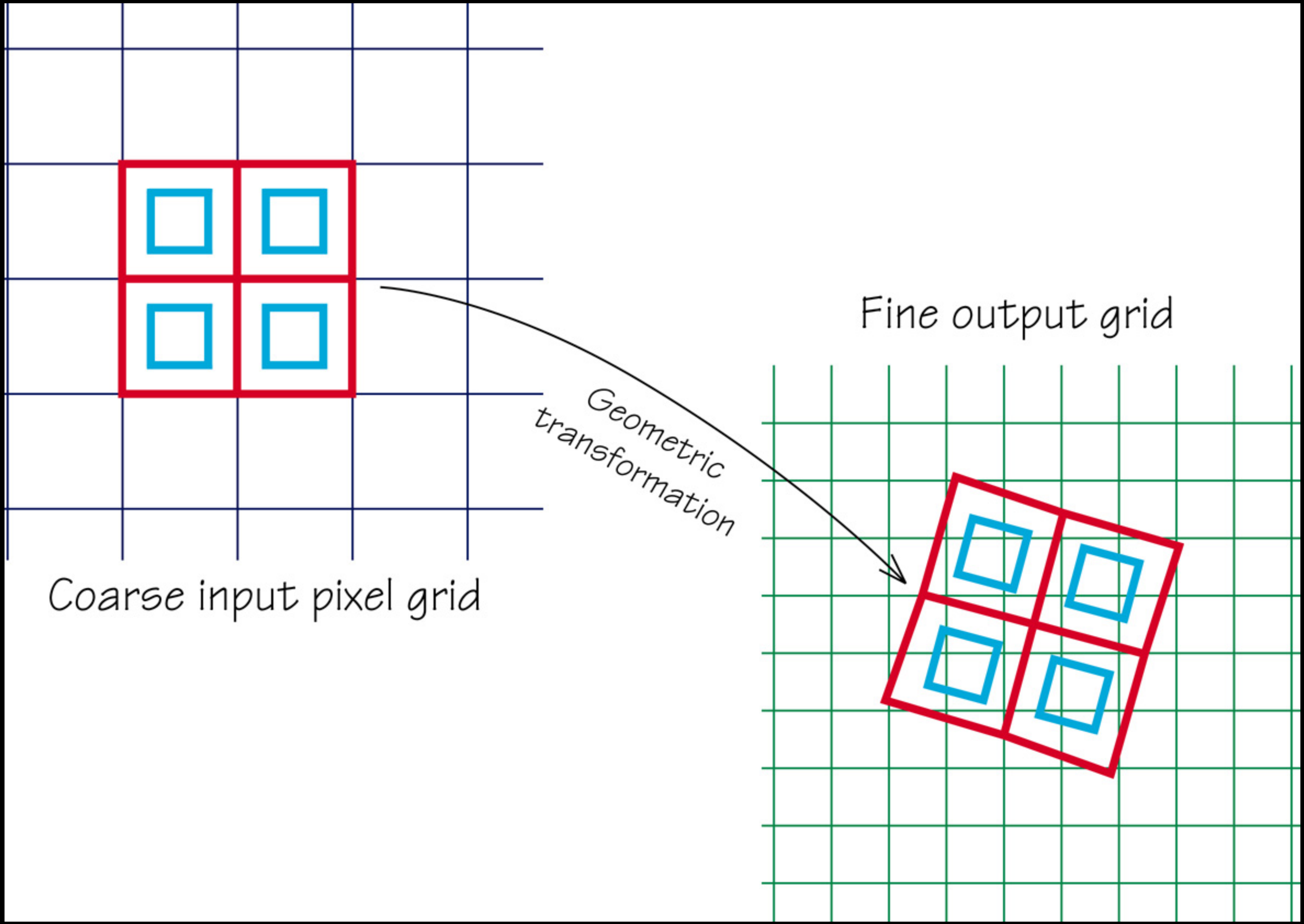
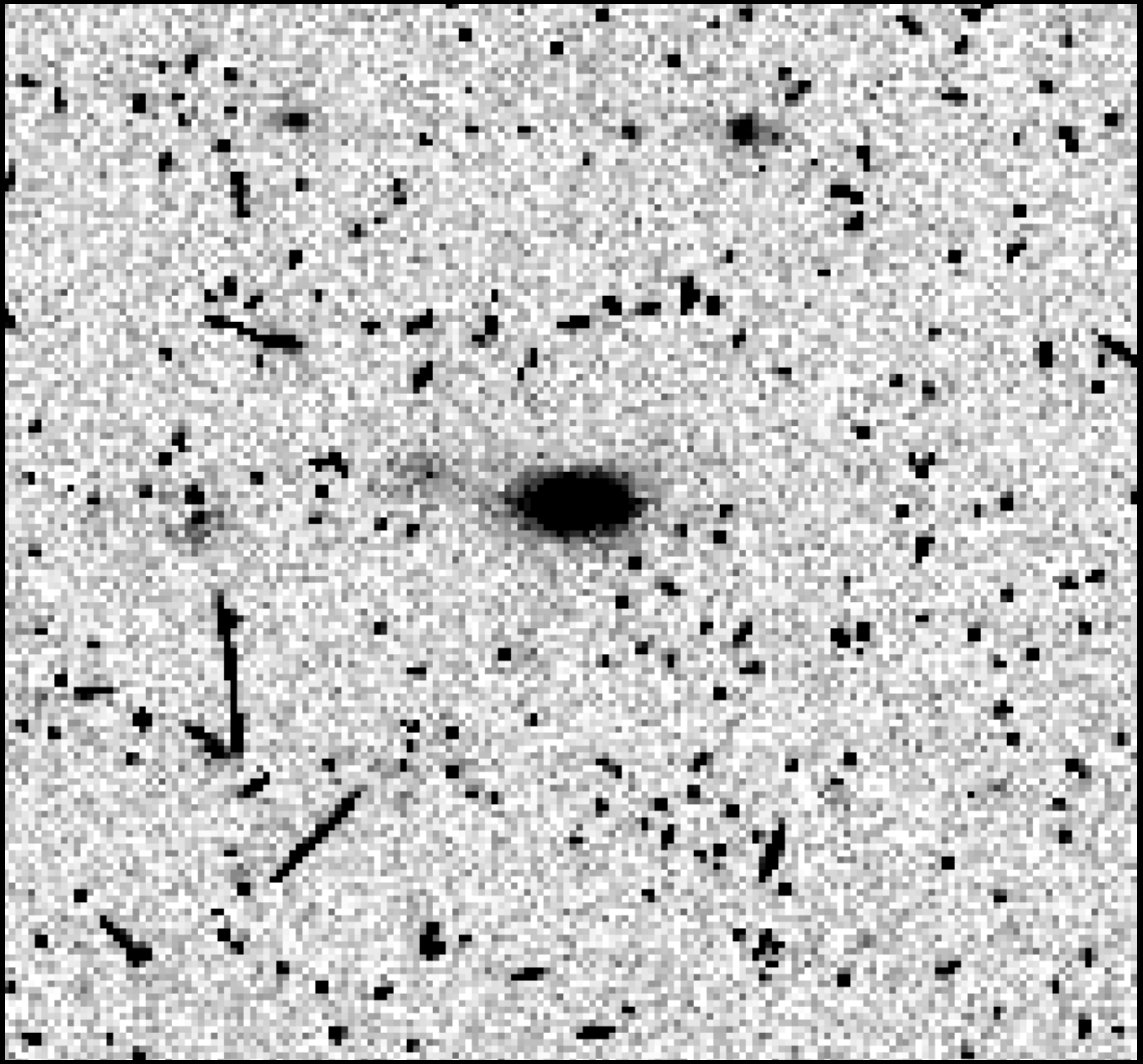
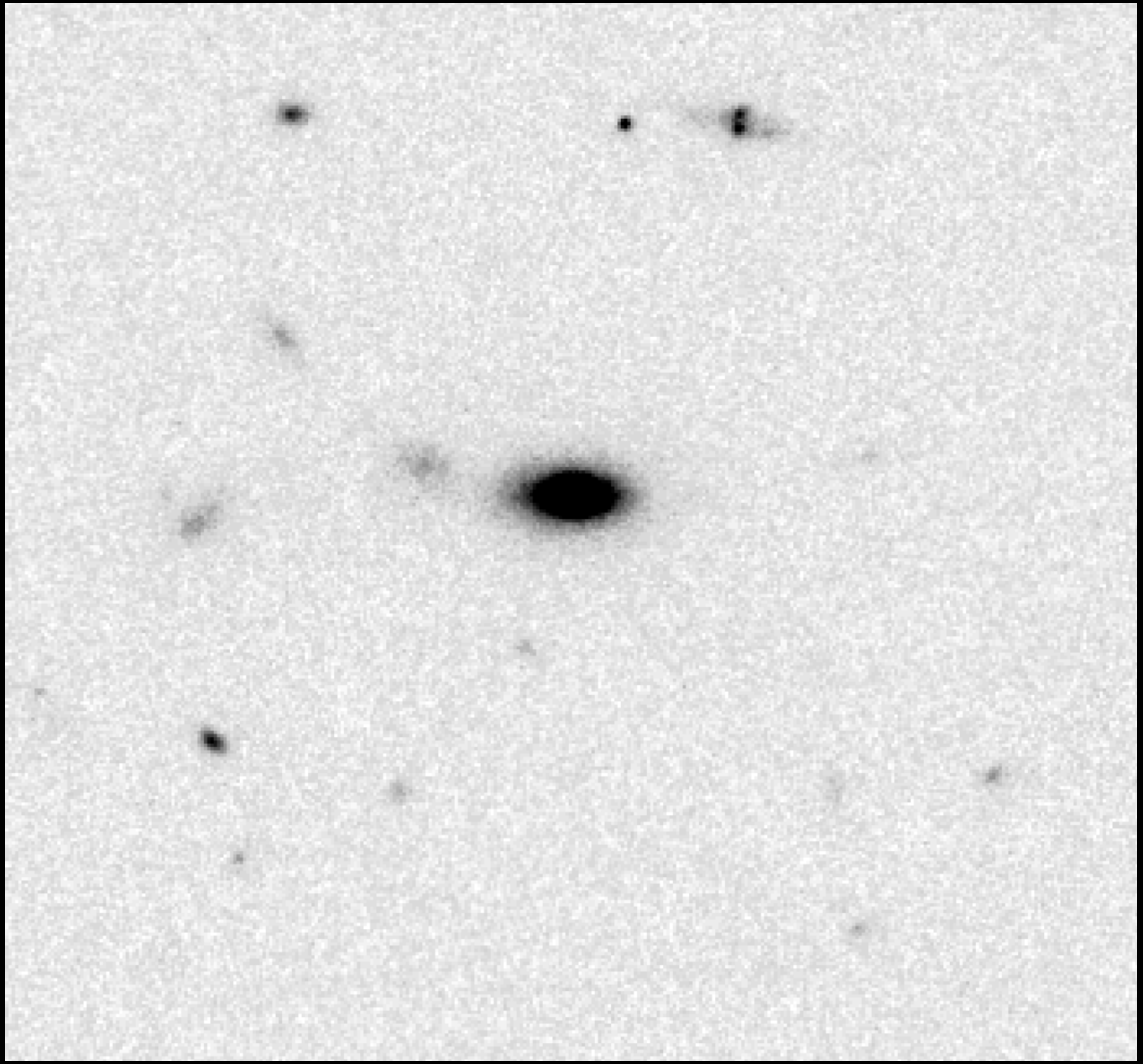


Image source : https://www.stsci.edu/~fruchter/dither/drizzle.html

Two options for photometry

- Drizzled photometry (work directly on the stacked image)
- Individual image photometry (often necessary for variable stars)

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PSF options

Model PSF	Model PSF with on-image adjustments	Empirical PSF
Provided by telescope team	Measure real stars on image and make small adjustments to model	Build a PSF model on image from the stars

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Model PSF	Model PSF with on-image adjustments	Empirical PSF
Provided by telescope team	Measure real stars on image and make small adjustments to model	Build a PSF model on image from the stars
Easy, but sometimes inaccurate	**A good balance**	**Ideal, but sometimes impossible**

PSF photometry

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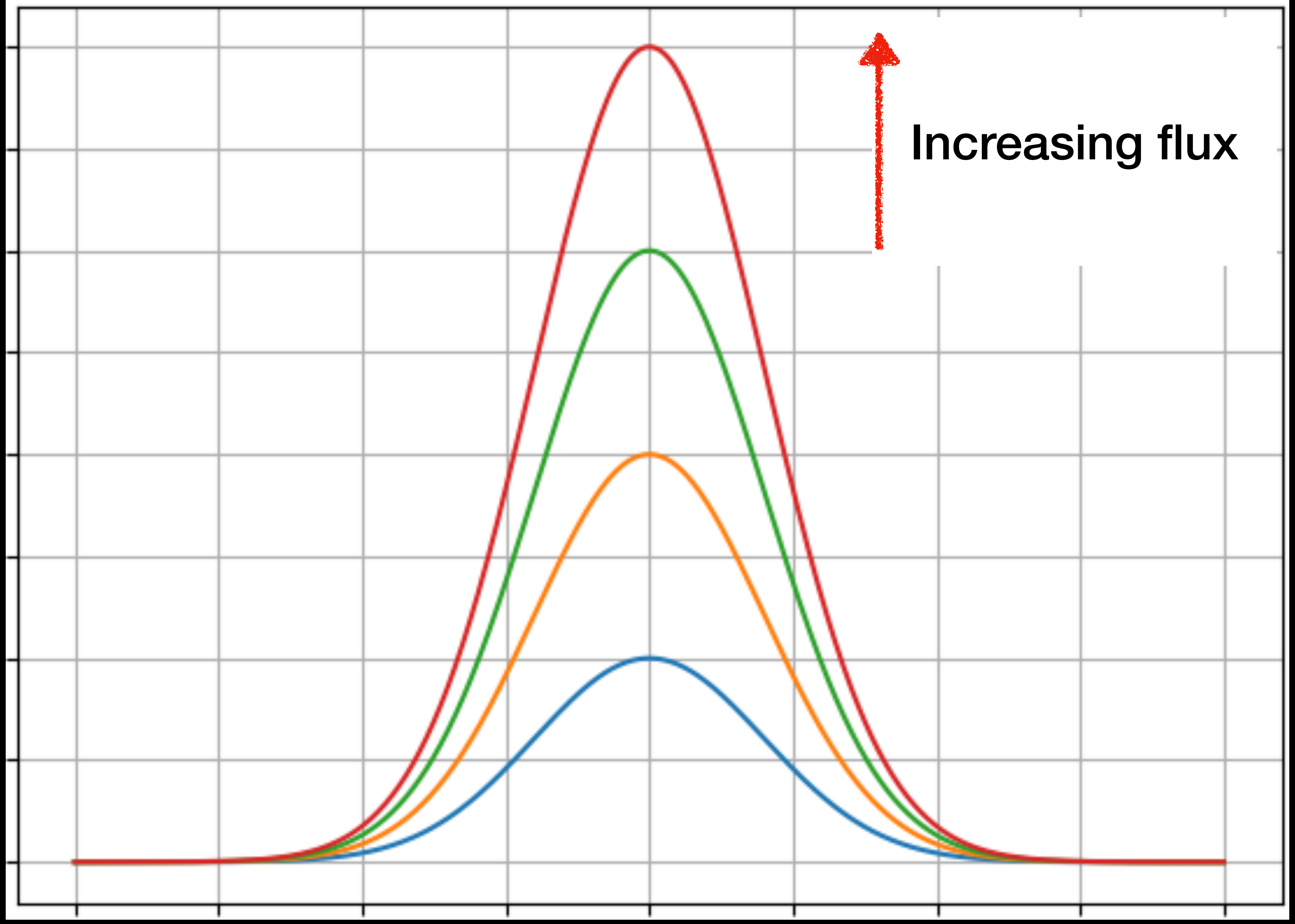
Fitting a PSF

Two properties to adjust

- How bright is the star?



Fitting a PSF

Two properties to adjust

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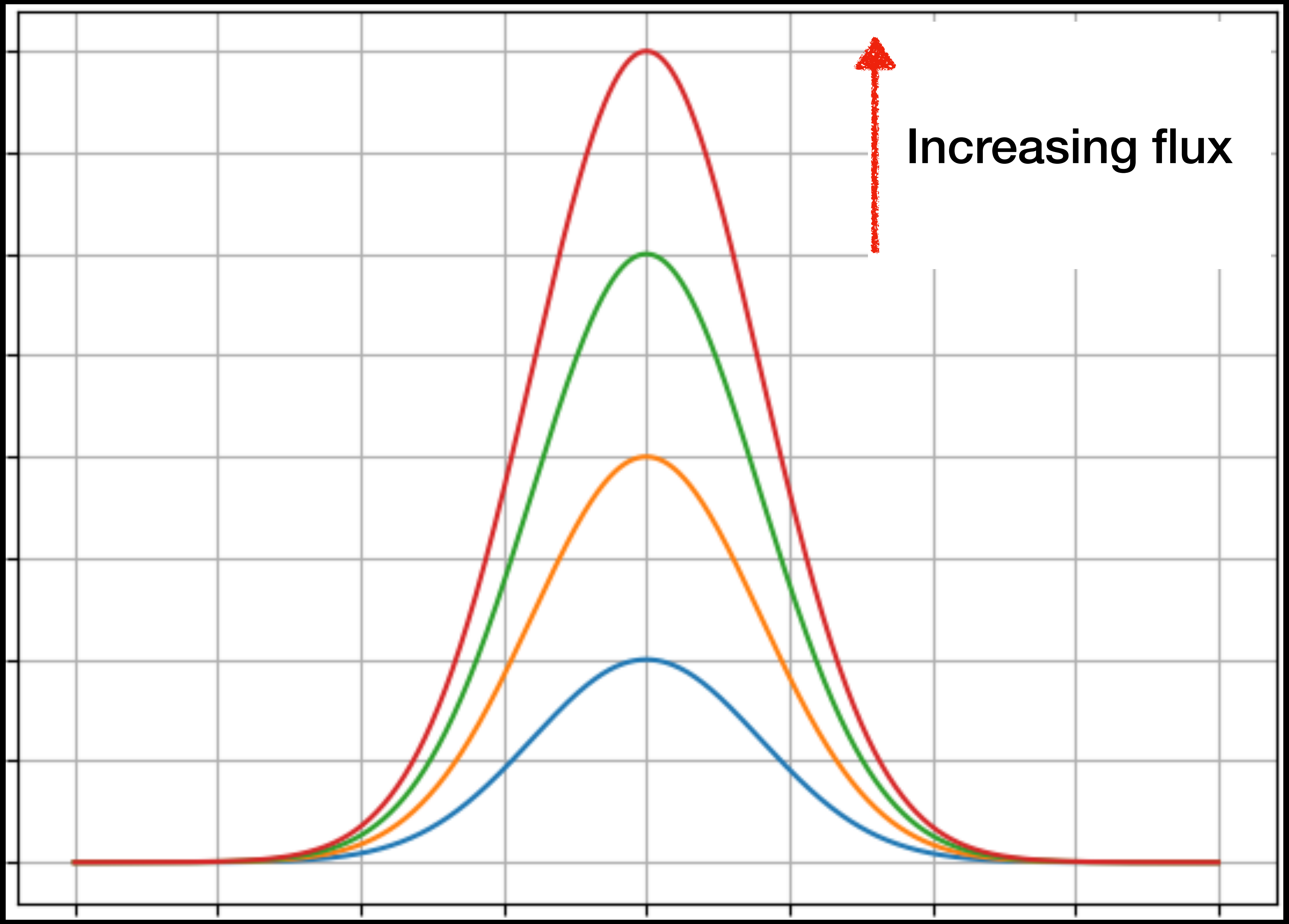
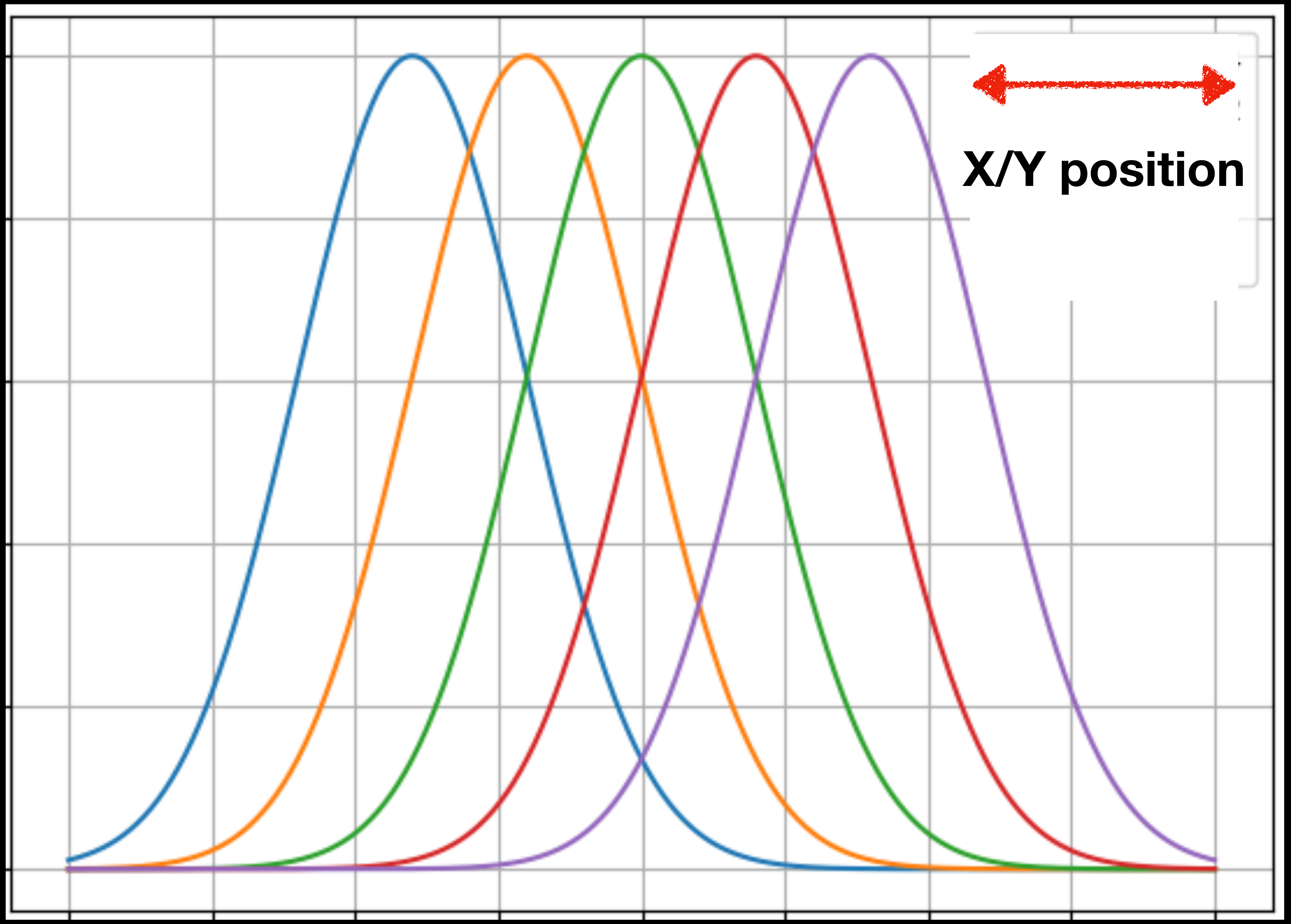


- Where is the star in pixel space



PSF photometry

The basic process

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- Subtract detected sources
- Second (or more) passes for detection
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PSF photometry

The basic process

- Prepare your images
- Measure or adopt a PSF
- Detect sources on the image (starting here)
- Fit the brightness of those sources using the PSF
- Subtract detected sources
- Second (or more) passes for detection (do it again!)
- Apply aperture corrections and photometric zero point

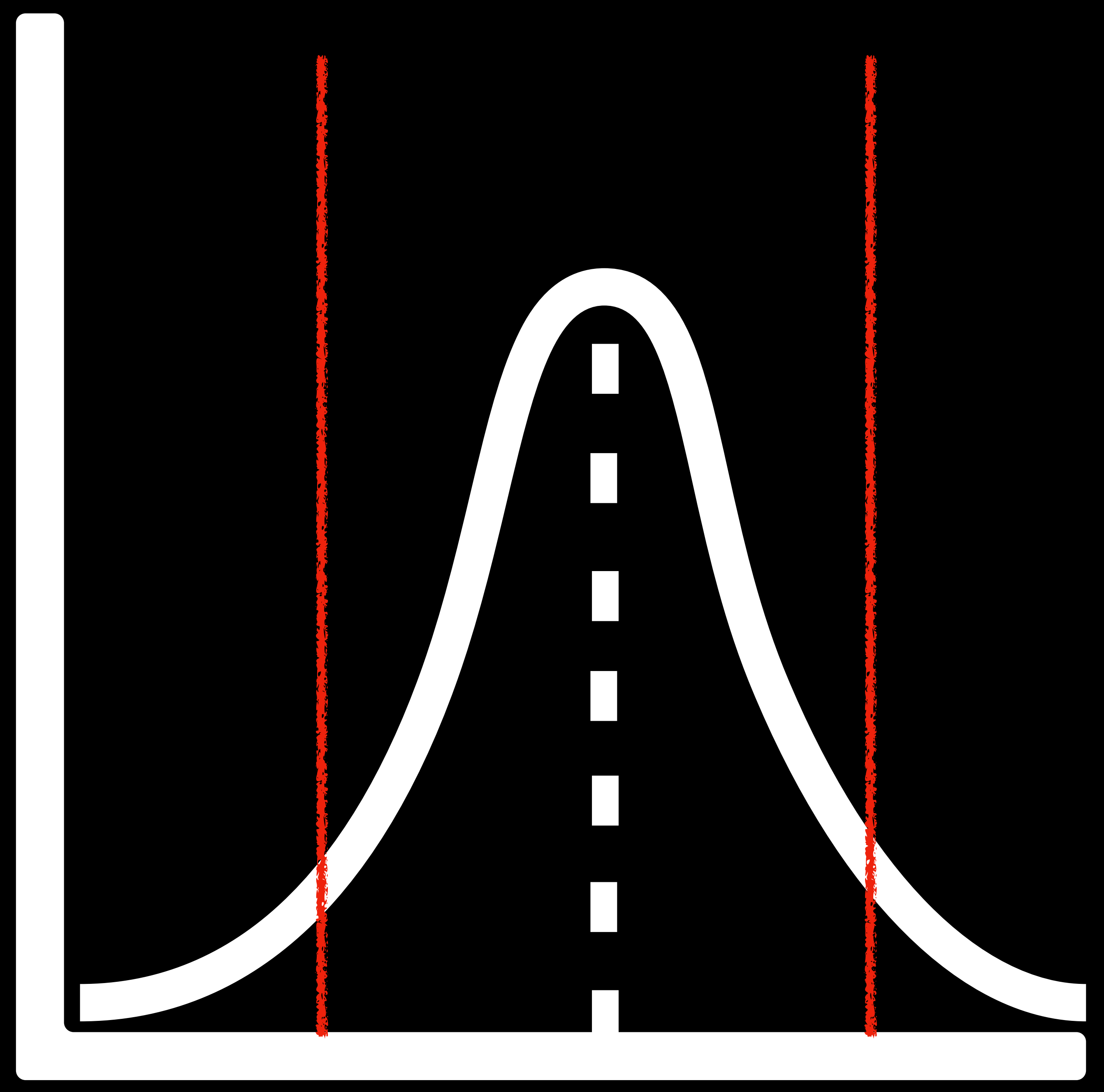
PSF photometry

The basic process

- Prepare your images
- Measure or adopt a PSF
- Detect sources on the image
- Fit the brightness of those sources using the PSF
- Subtract detected sources
- Second (or more) passes for detection
- Apply aperture corrections and photometric zero point

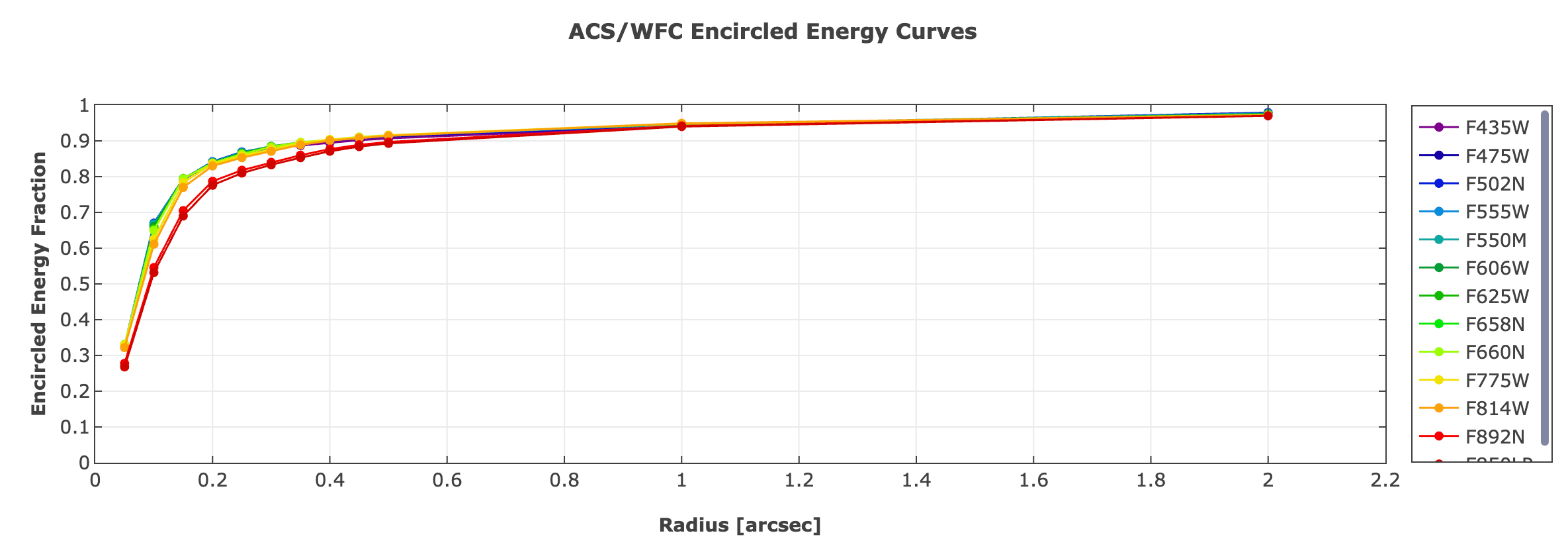
Aperture corrections (first order)

- PSFs extend to infinity!
- We only measure out to 70-80% of the flux in PSF photometry, 90% in aperture photometry
- Need to add the “missing” flux



Aperture corrections (second order)

- Measure bright and isolated stars on the image
- Construct a “growth curve” -> magnitude of star in consecutive apertures



Source: STScI

Aperture corrections (second order)

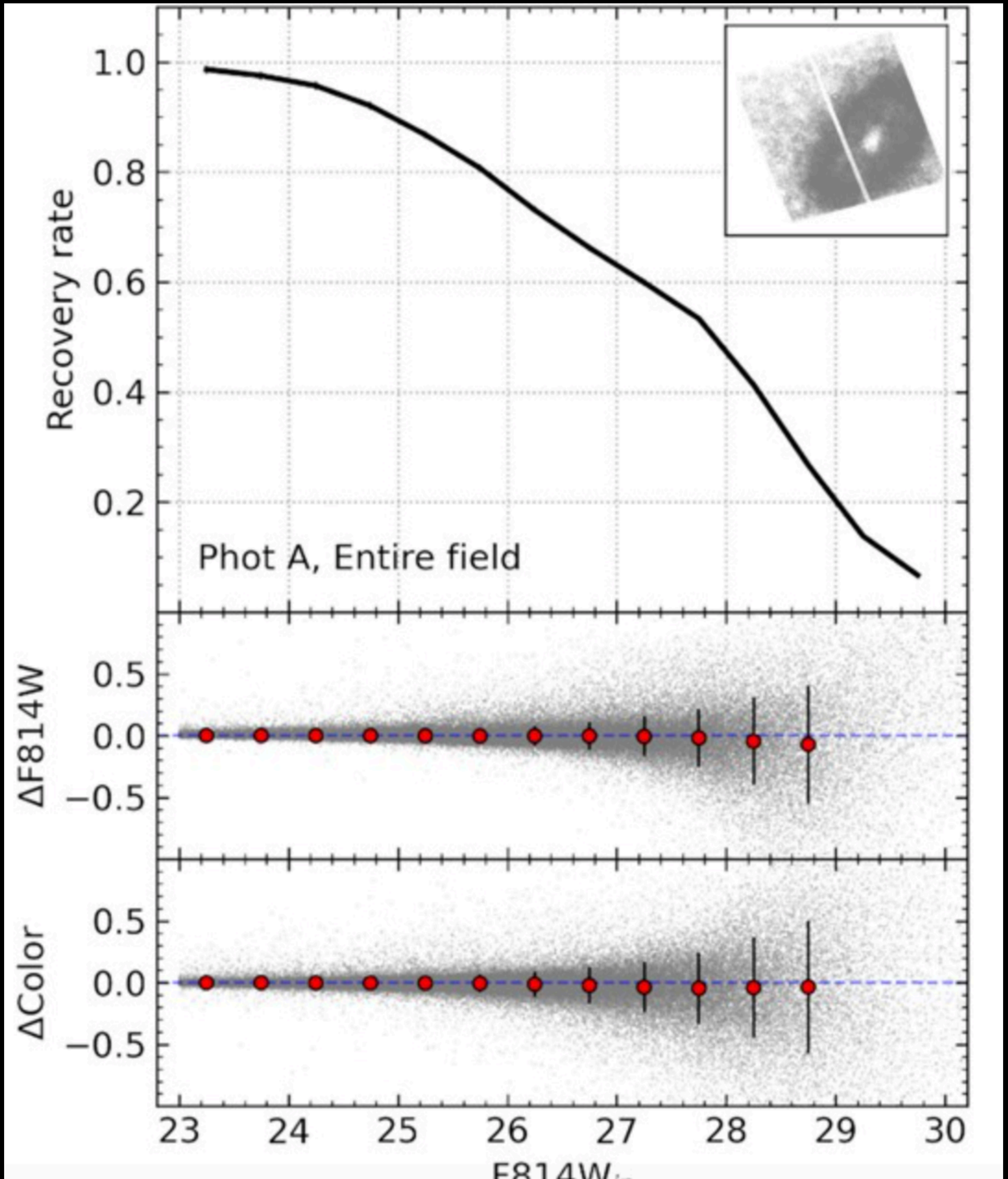
- Measure bright and isolated stars on the image
- Construct a “growth curve” -> magnitude of star in consecutive apertures
- Difference between PSF magnitude and aperture magnitude is the aperture correction

Artificial star corrections

- Place “fake sources” on an image
- Remeasure them through the exact same process as the real stars

What can artificial stars tell you?

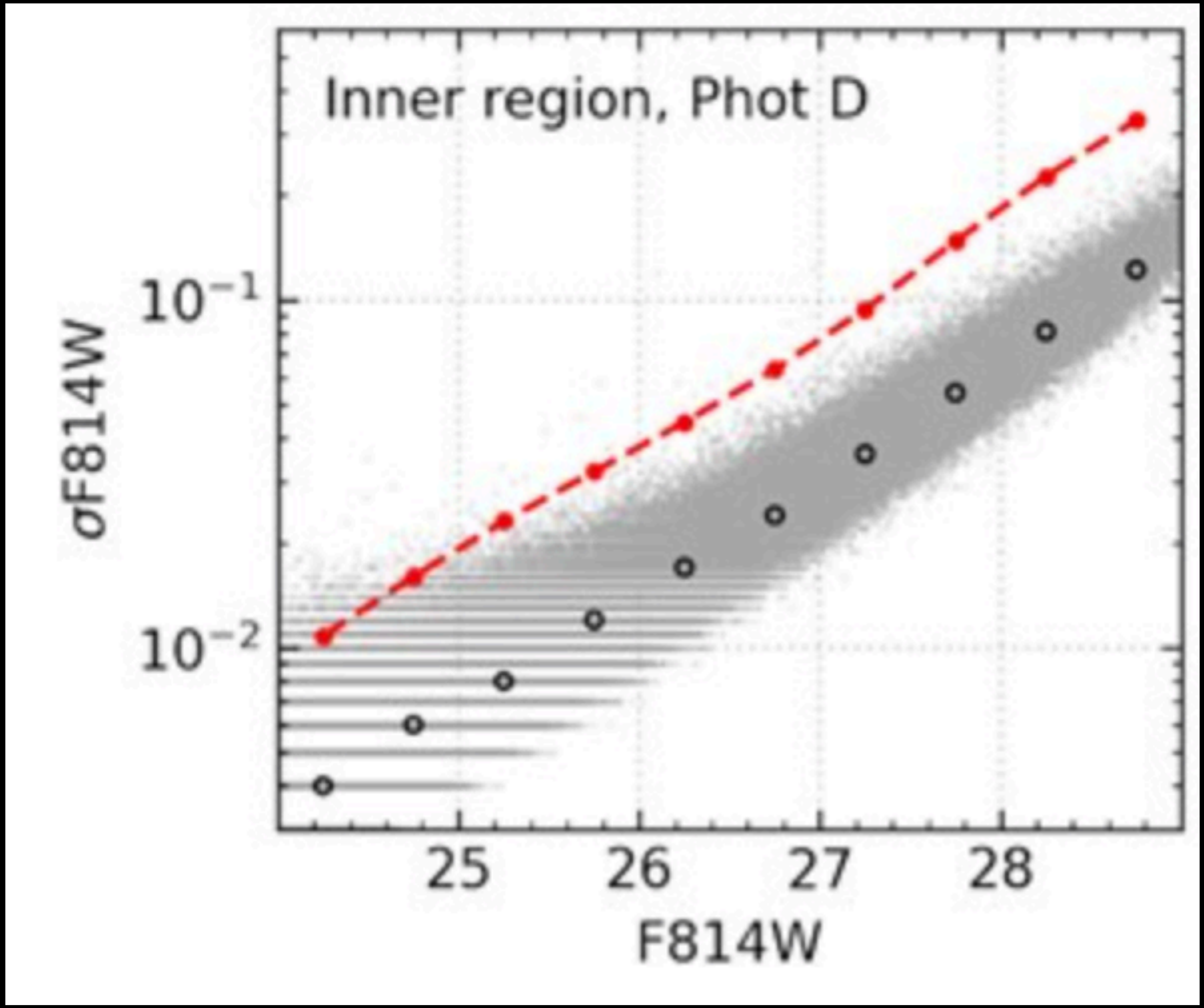
- Recovery rate:
- What fraction of stars of a given brightness do you detect?



Jang et al. 2023

What can artificial stars tell you?

- Actual error bars
- Photometry softwares underestimate errors



Jang et al. 2023

What can artificial stars tell you?

- Crowding / blending bias (not usually large for TRGB)
- Important for Cepheids

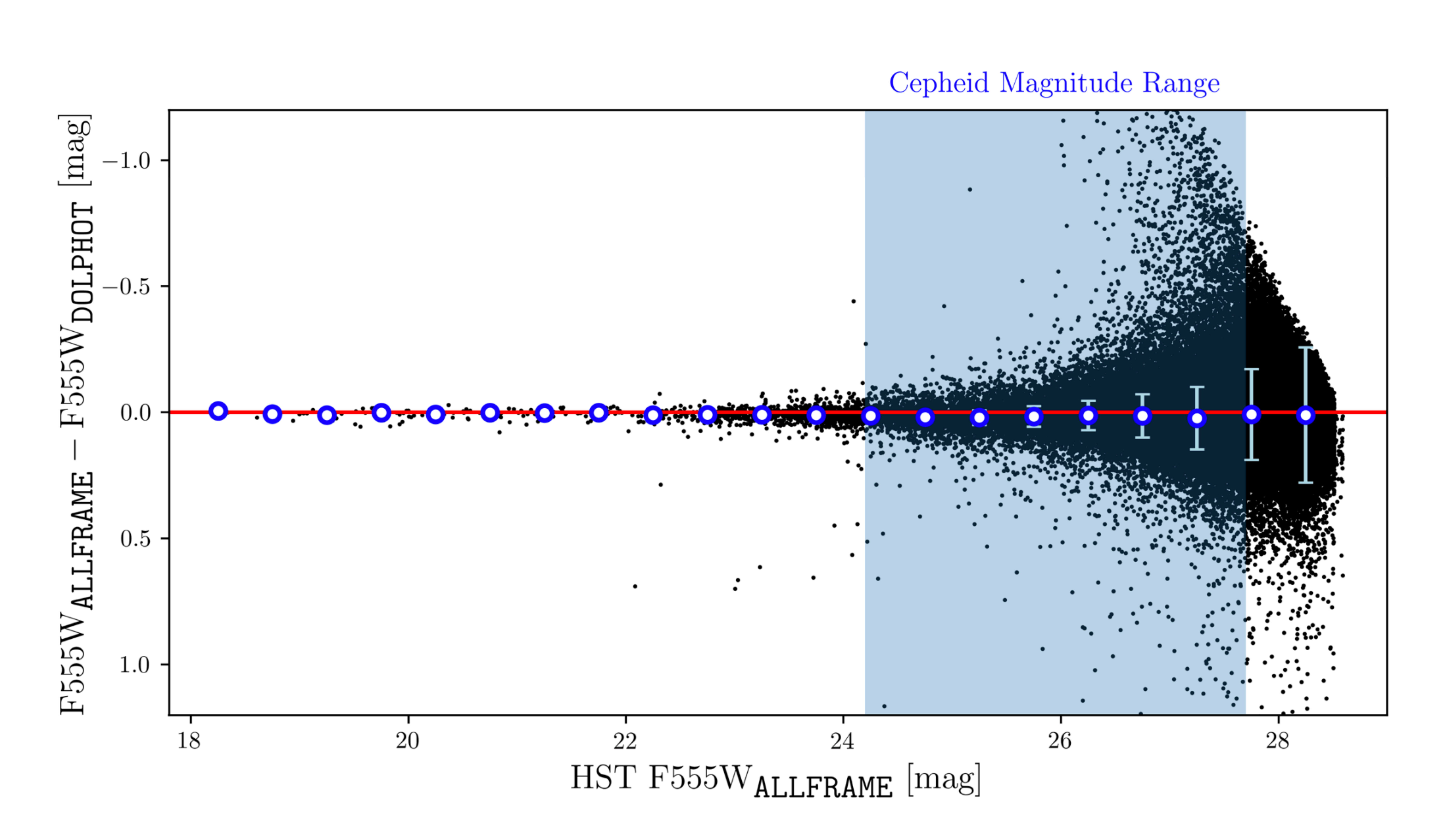
What can artificial stars tell you?

- Crowding / blending bias (not usually large for TRGB)
- Important for Cepheids
- Incorrect sky measurement
- Additionally, when the PSF of two stars become too close together, you can’t distinguish them

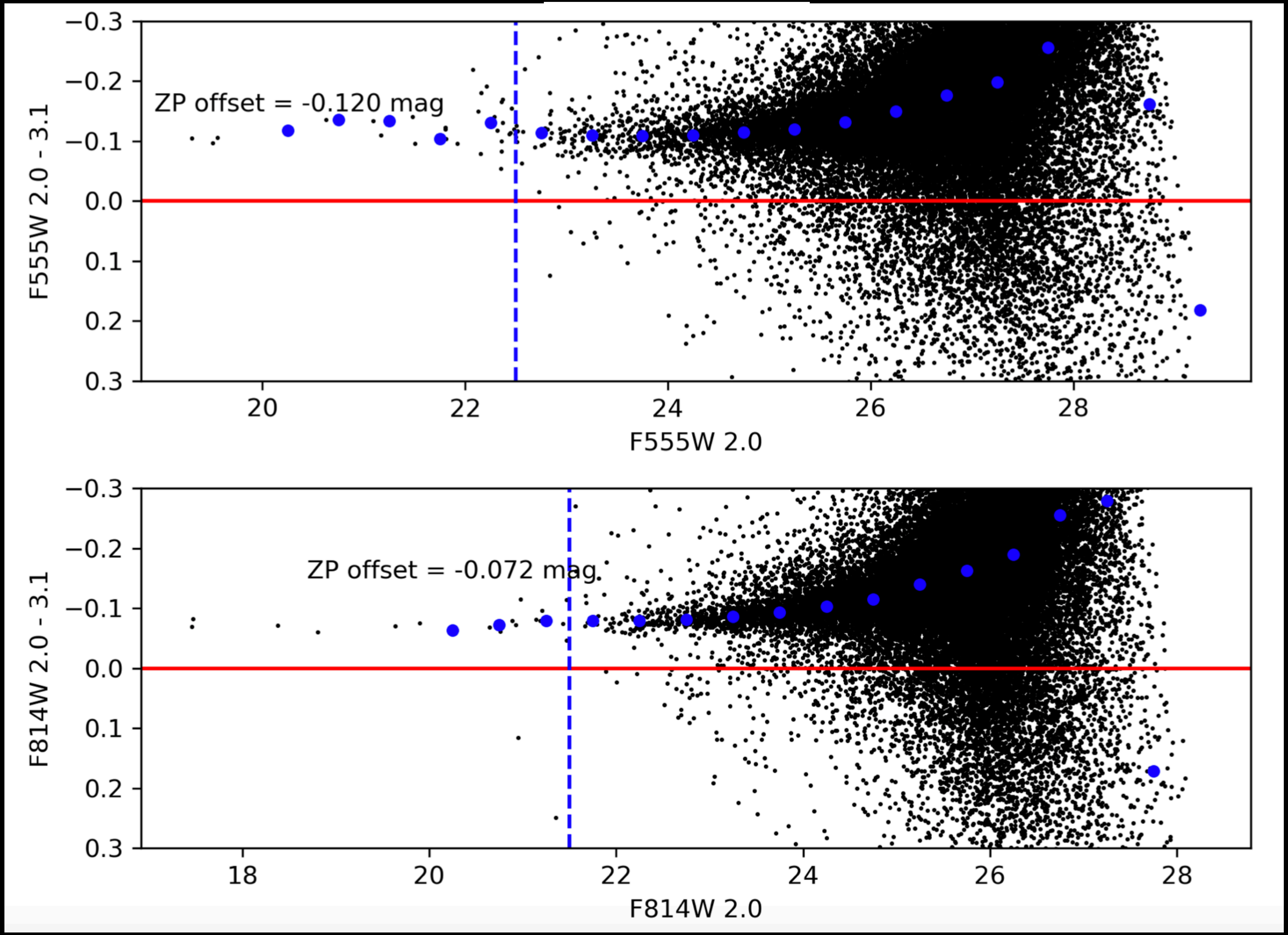
Credit: ESA/Hubble & NASA, A. Riess et al.; acknowledgment: Mahdi Zamani

How stable is photometry?

Sometimes, very!



Sometimes, not so much …



(This is an extreme case)