CCDs and Photometry

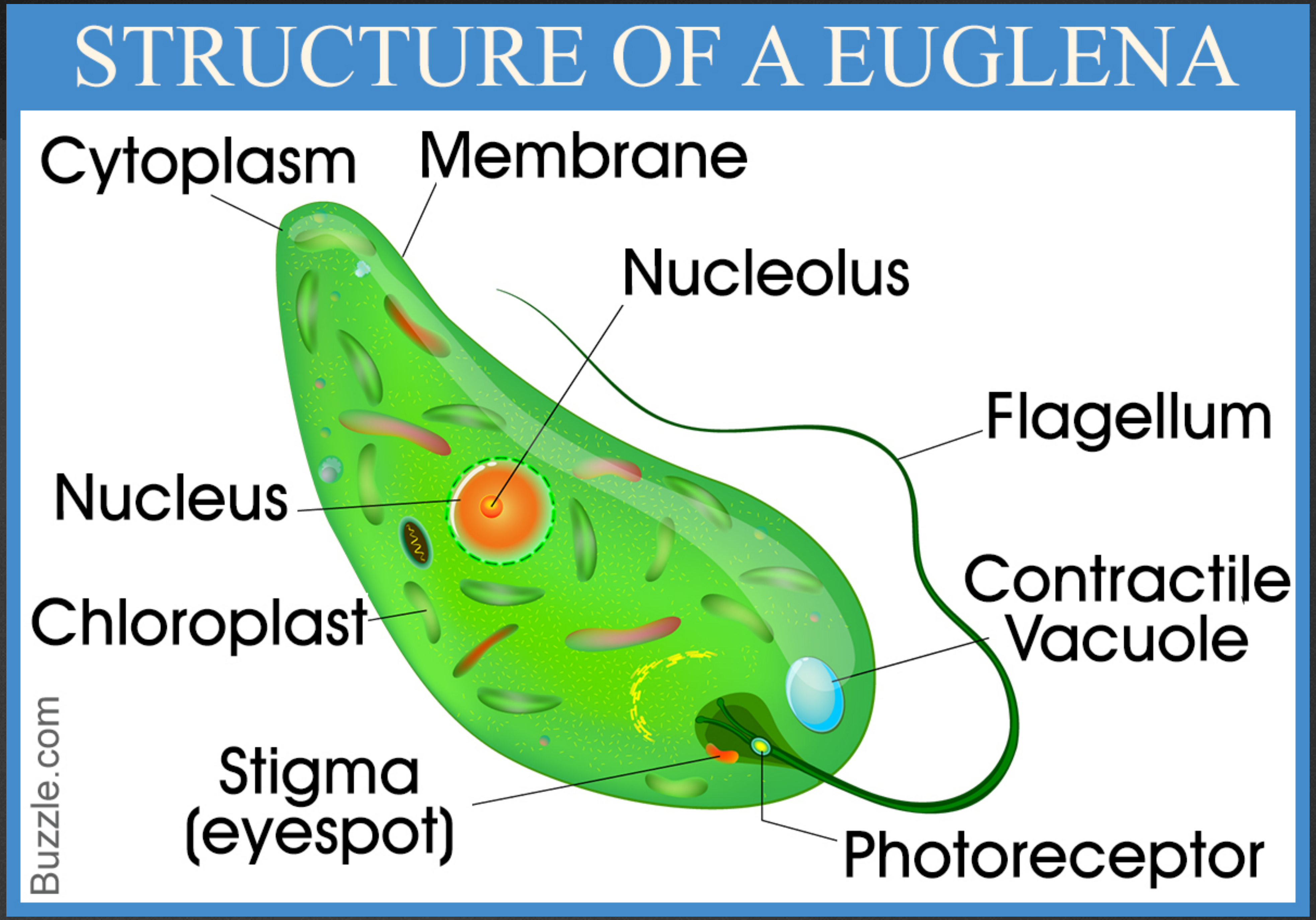
MPAGS 2023

Dr Samuel Gill

Primitive photometers

I - plants

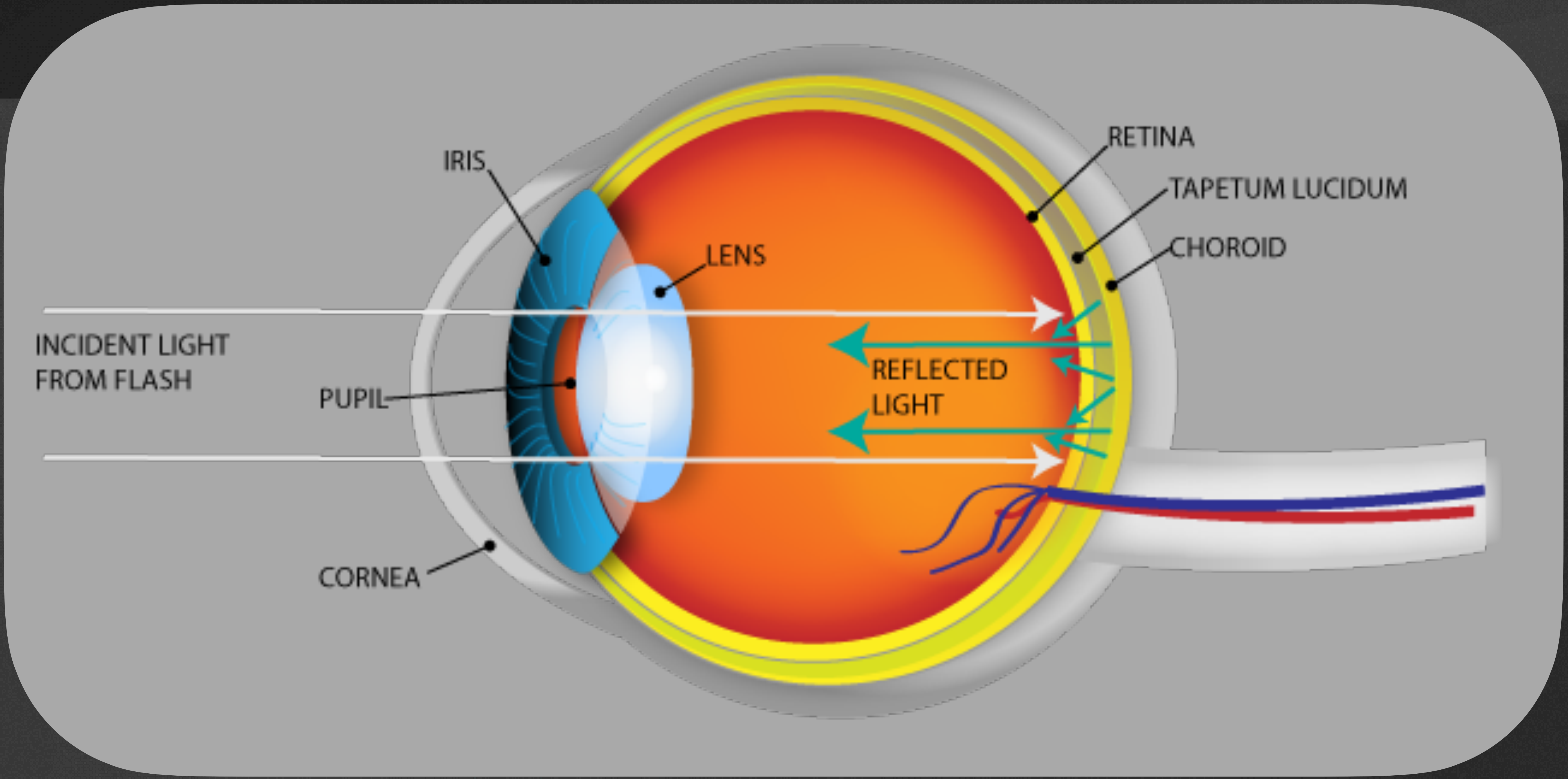
- Photoreceptor proteins can sense light.
- Even found in unicellular organisms allowing them to orient towards light.



Primitive photometers

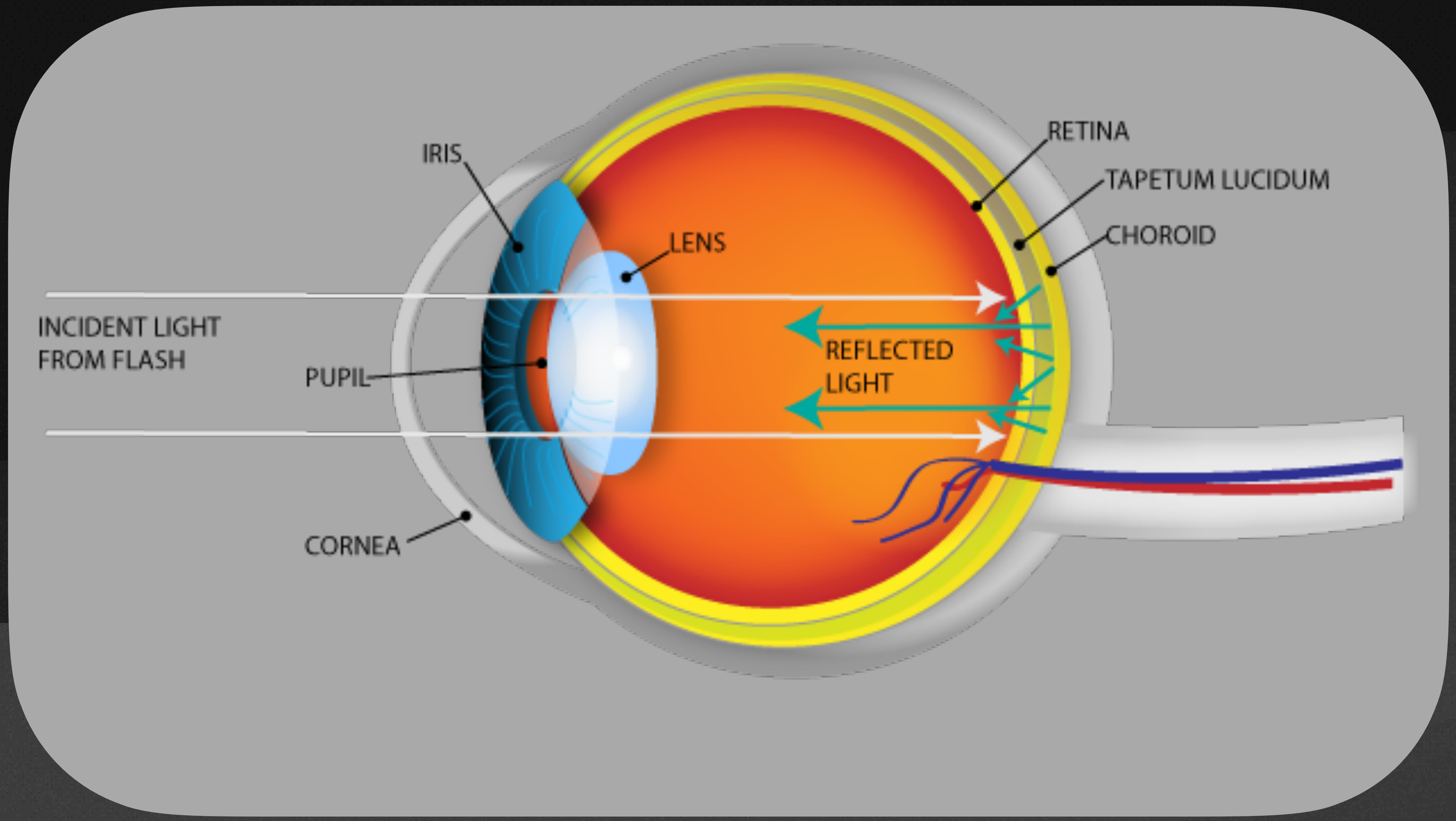
II - animals

- Photoreceptor proteins can sense light.
- Found often in animals, particularly eyes.



Astronomical detectors

I - Human eyes

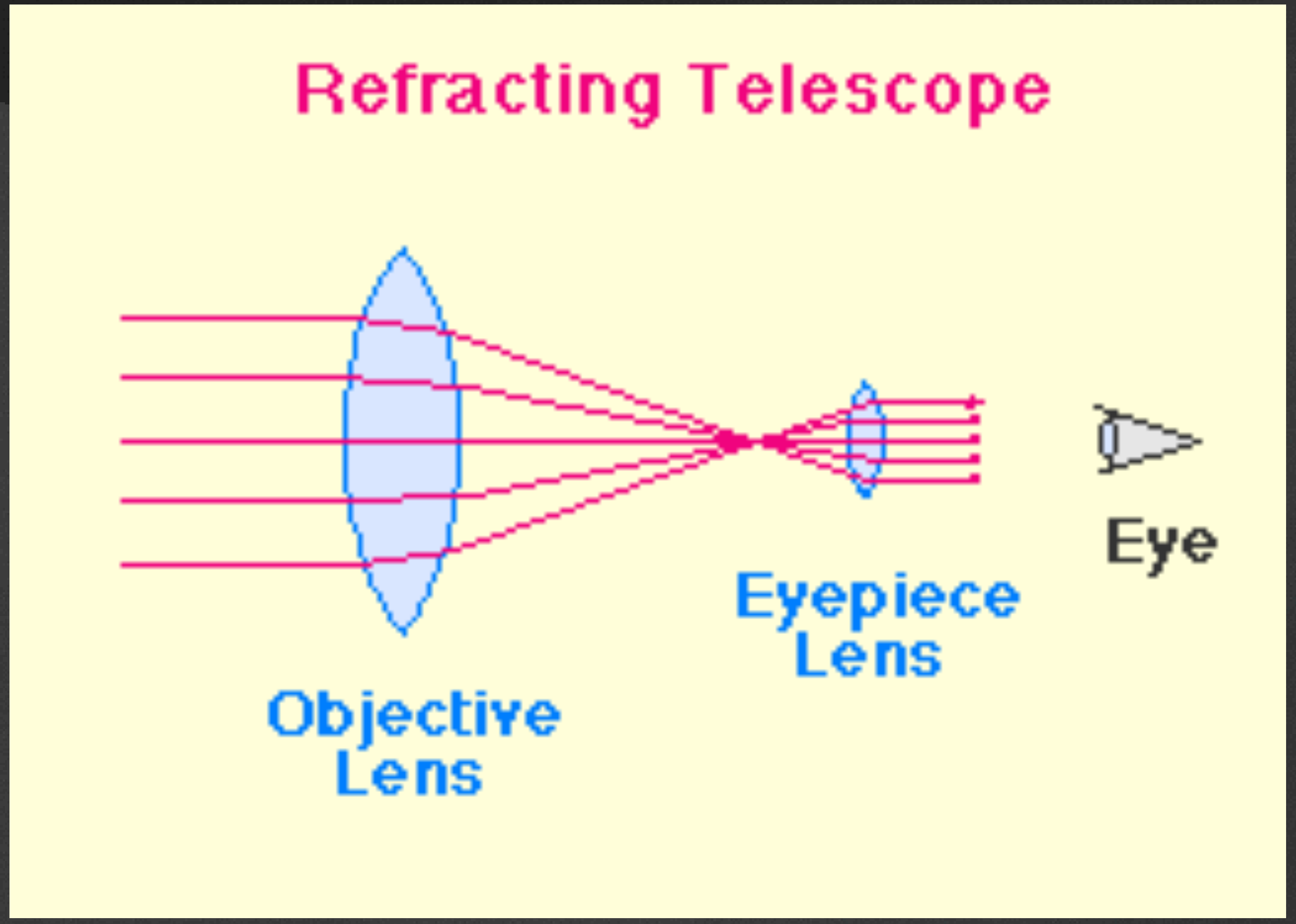


Only perform a qualitative analysis of the stars

Astronomical detectors

II - The first telescope

- 1608: German-Dutch lens maker Hans Lippershey produces a refracting telescope.

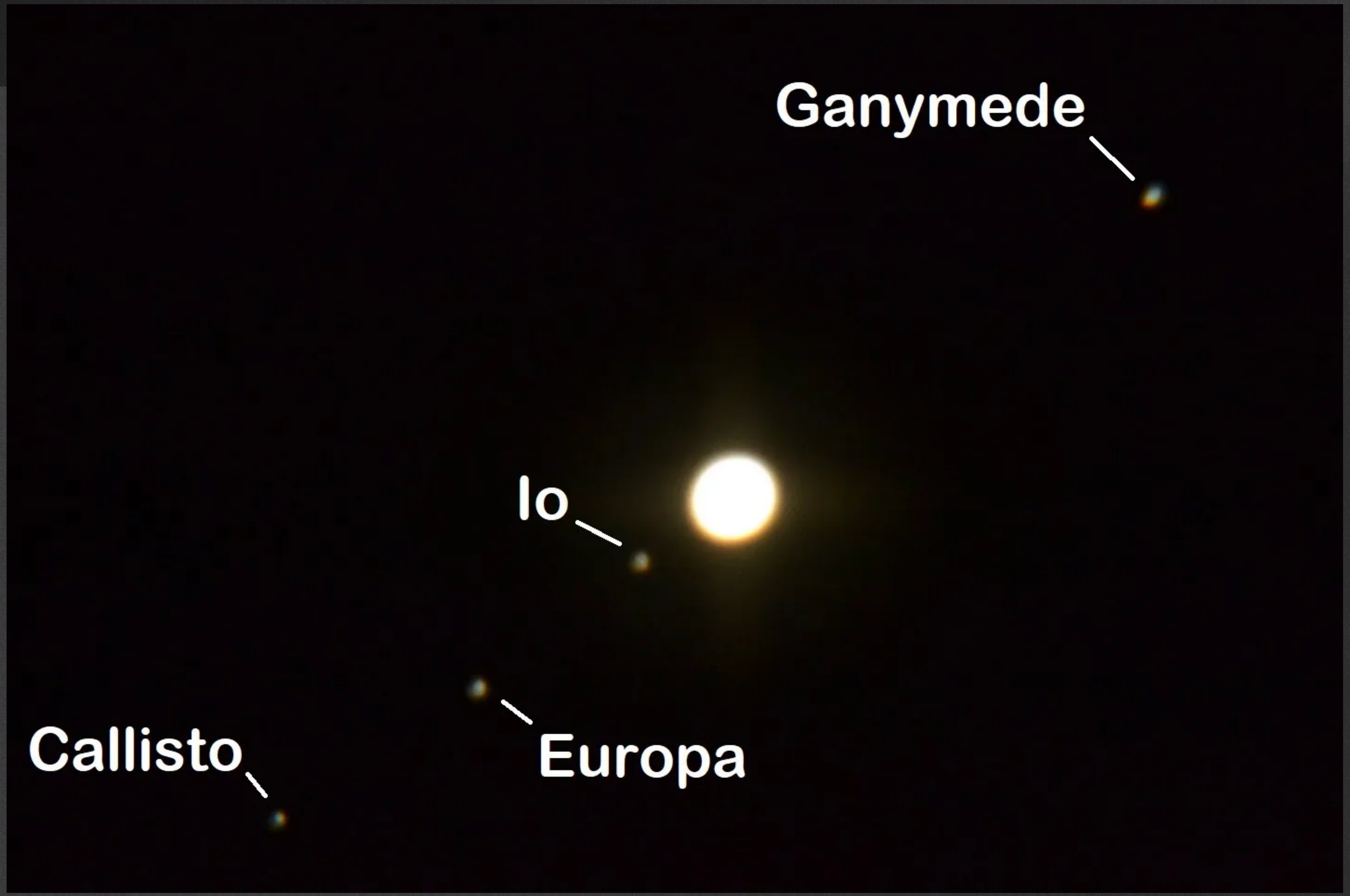


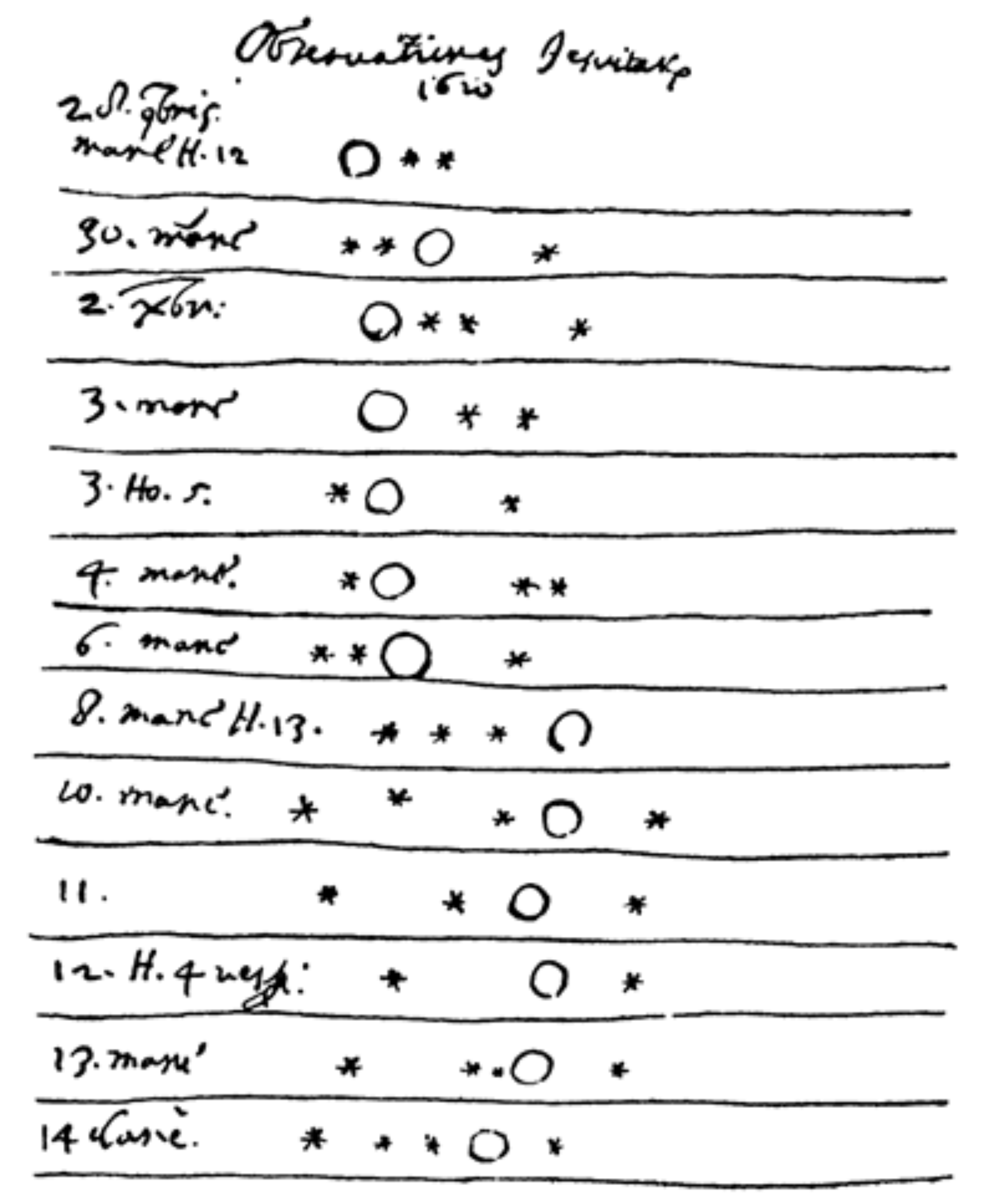
Yerkes 40-inch Telescope

Astronomical detectors

II - The first telescope

- 1610: Italian astronomer Galileo Galilei uses telescope and eye for astronomical imaging.
- Discovered the moons of Jupiter.




Observationes Jesuitarum
1610

2. S. 9bris. mane H. 12 ○ * *

30. mane * * ○ *

2. xbris. ○ * * *

3. mane ○ * *

3. Ho. s. * ○ *

4. mane * ○ * *

6. mane * * ○ *

8. mane H. 13. * * * ○

10. mane * * * ○ *

11. * * ○ *

12. H. 4 vesp. * ○ *

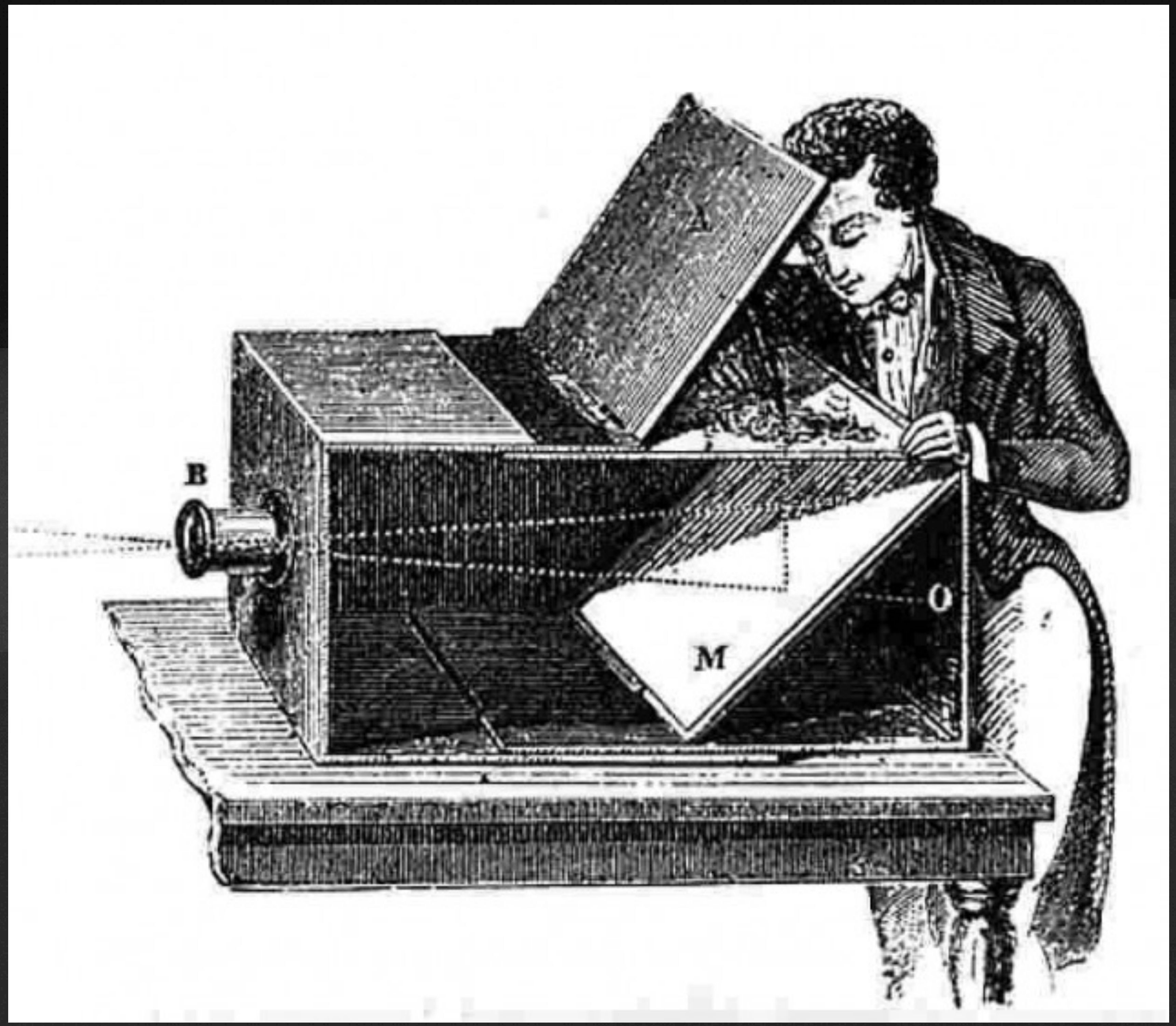
13. mane * * * ○ *

14 Caste. * * * ○ *

Astronomical detectors

III -Photographic plates

- In 1800, Thomas Wedgwood created a black and white negative image with silver nitrate.
- Reported in scholarly journal in 1802 by chemist Humphry Davy.
- Image eventually faded and could not capture a permanent image.



Astronomical detectors

III -Photographic plates

- In 1826/7 Nicéphore Nièpce, succeeded in capturing small camera images on paper treated with silver chloride (another chemical sensitive to light).
- It represented a view from a window at Le Gras (his hometown in Burgundy, France), captured on a pewter plate coated in bitumen diluted in lavender oil. The exposure time was probably several days

Astronomical detectors

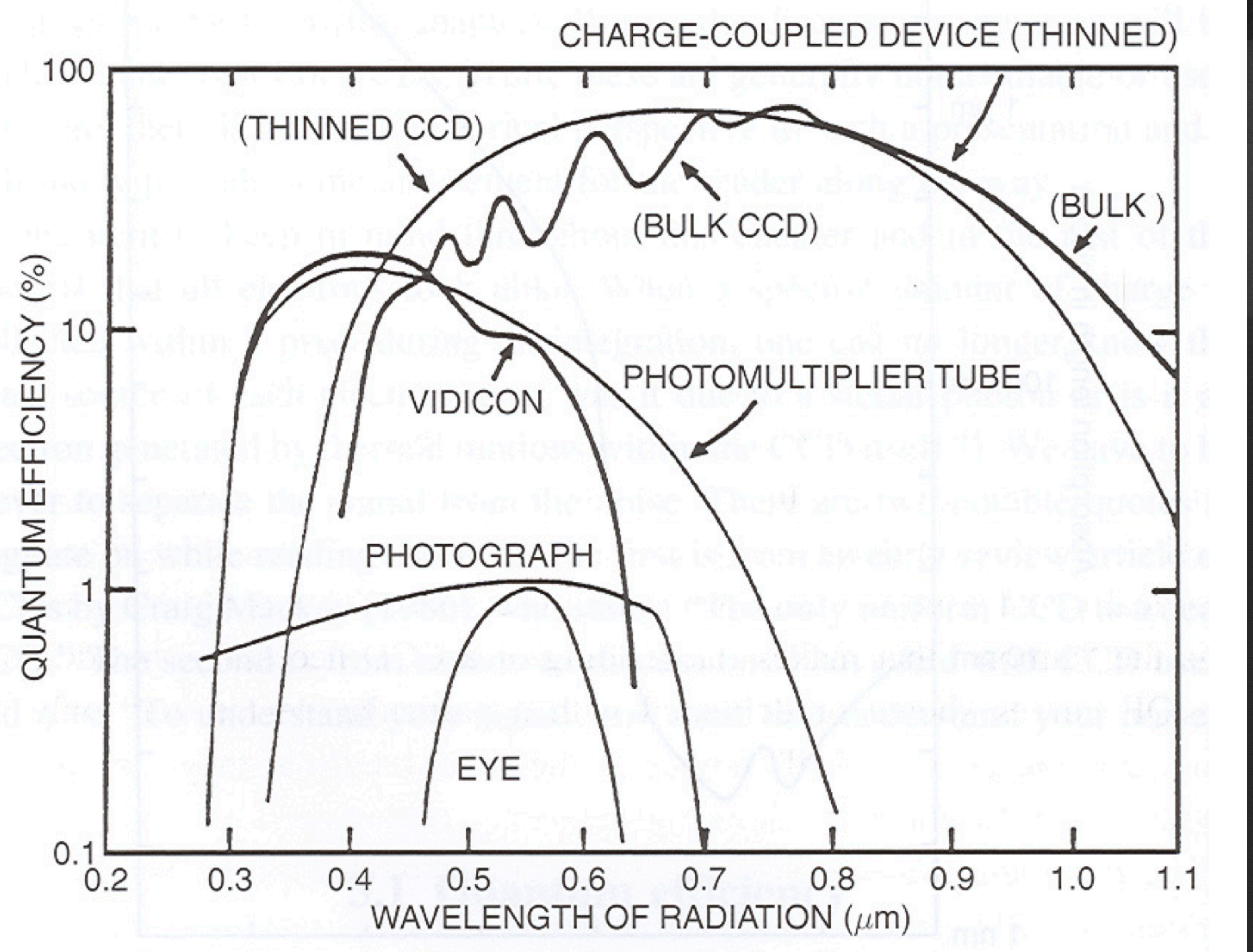
III -Photographic plates

- Astronomers started using photographic plates with telescopes.
- Photographic plates are non-linear, grainy, and difficult to process.
- Quantum efficiency was just a few percent.
- But they allowed for long exposure times. Astronomers began to notice fainter stars. Deep astronomy begins!

Astronomical detectors

III -Photographic plates

$$QE = \frac{\text{detected (stored) photons}}{\text{incoming photons}}$$



Astronomical detectors

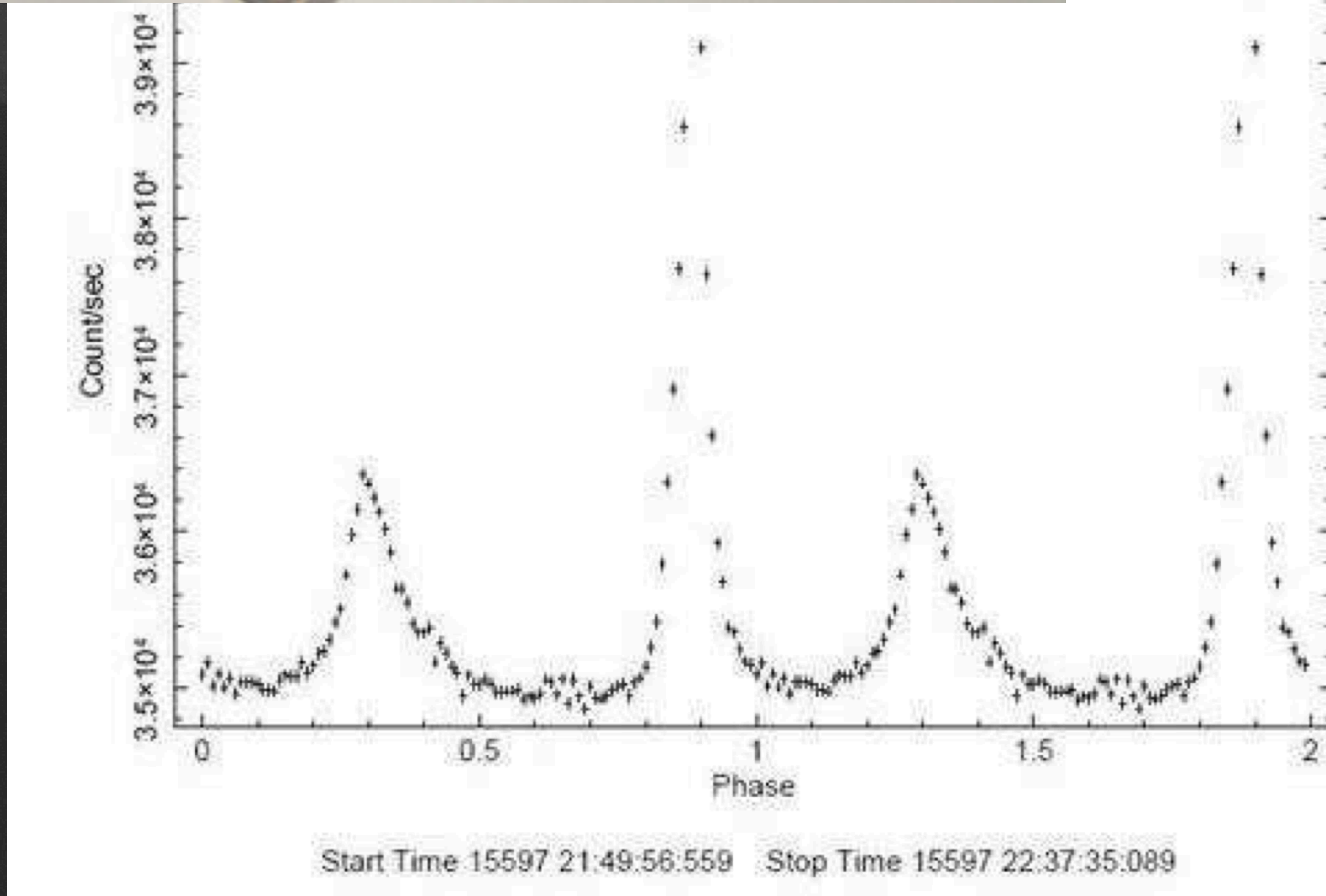
IV -Photomultiplier tubes

- Photomultiplier tubes allow for high Quantum Efficiency, and thus precise photometry.

- No positional information, just counts!

- First photomultiplier tube was made in 1934 by NJ. Harley Iams and Bernard Salzberg in RCA group based in Harrison, NJ.

- Used extensively in astronomy up to the mid 2000’s, when CCDs became viable.

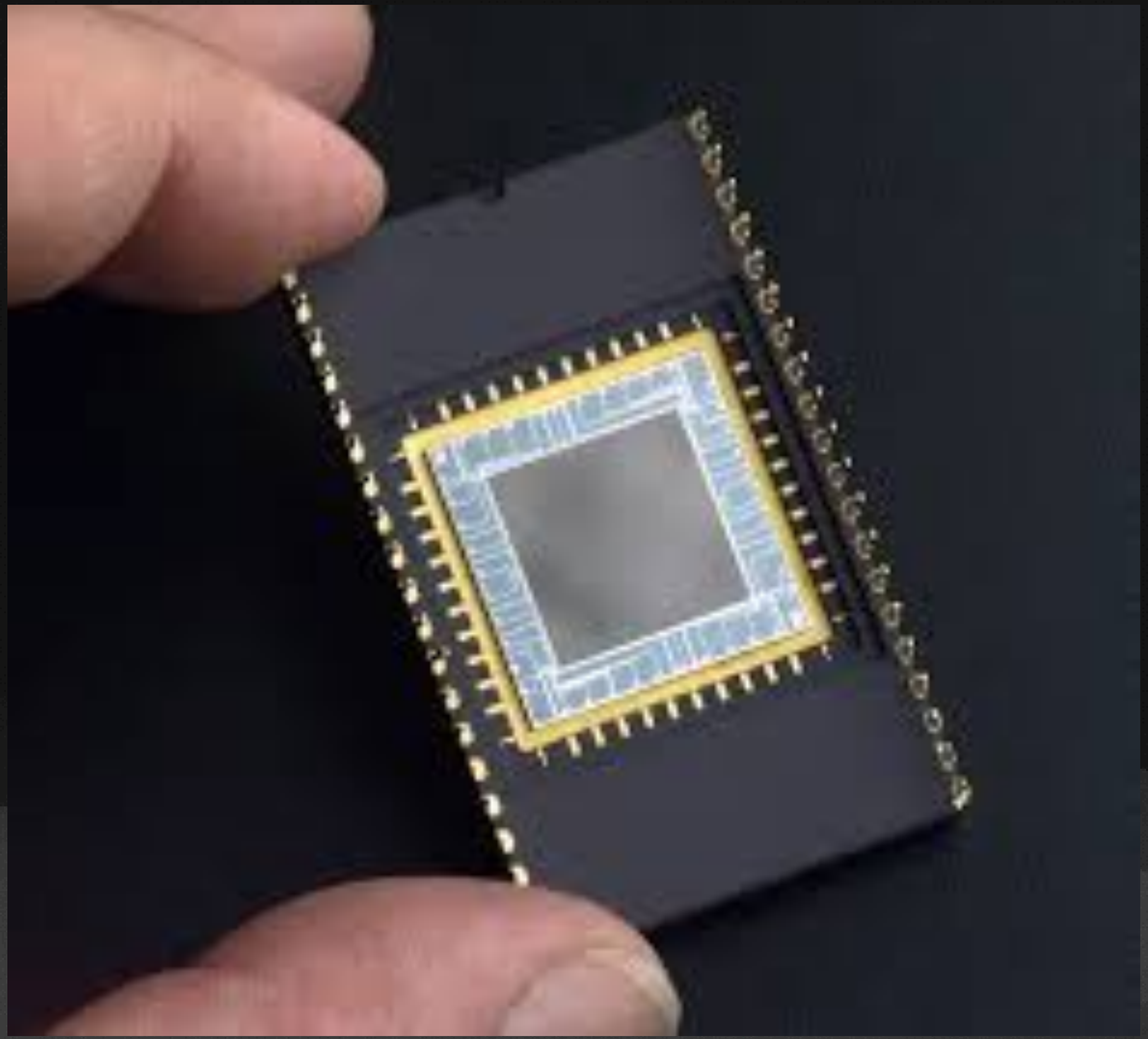


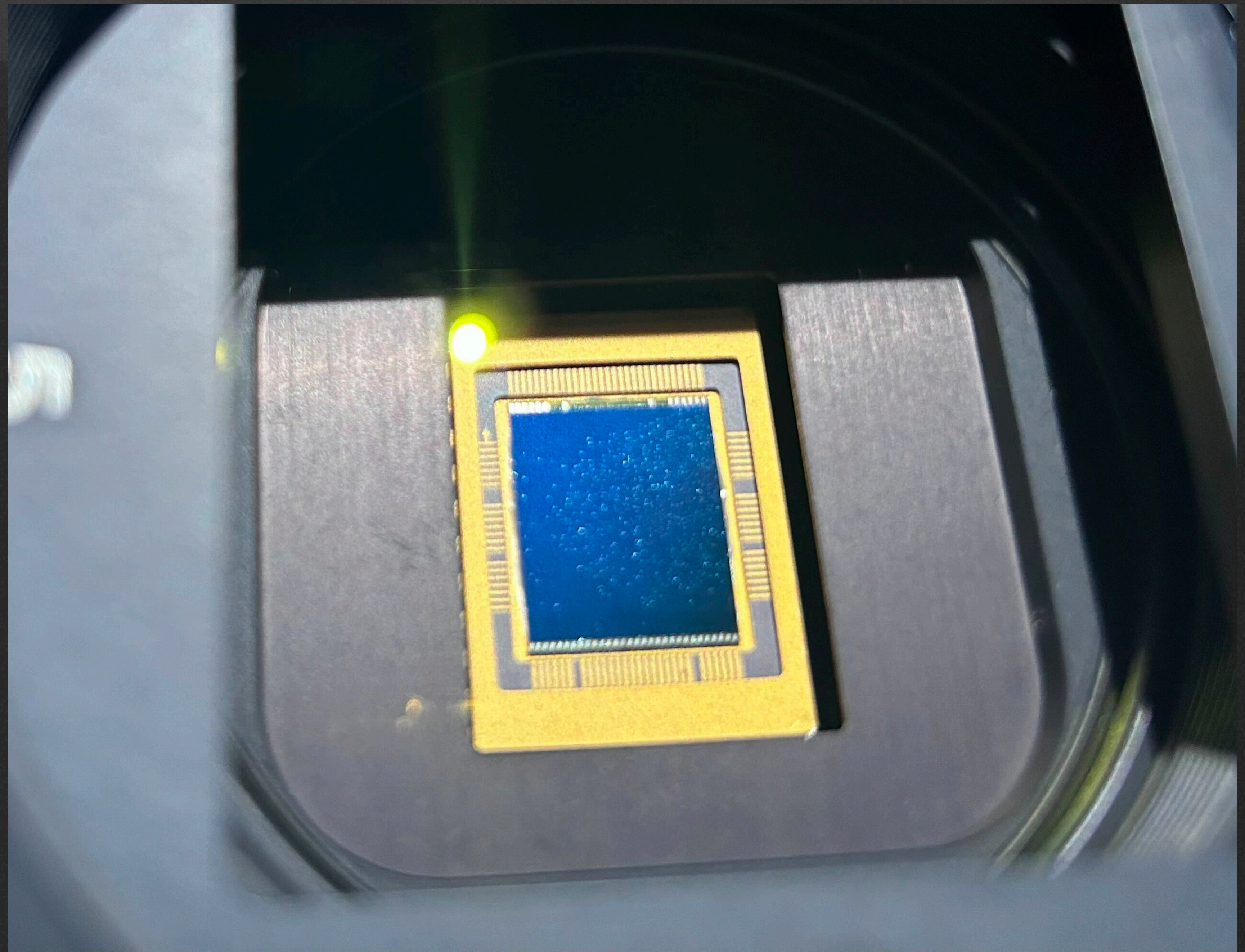
Meddi+2012

Astronomical detectors

V - CCDs

- Charged couple devices
- Silicon wafer with photosensitive sites. Each site corresponds to a pixel in the final image.
- Voltage at each site depends on number of photons that penetrated the silicon surface at that site.

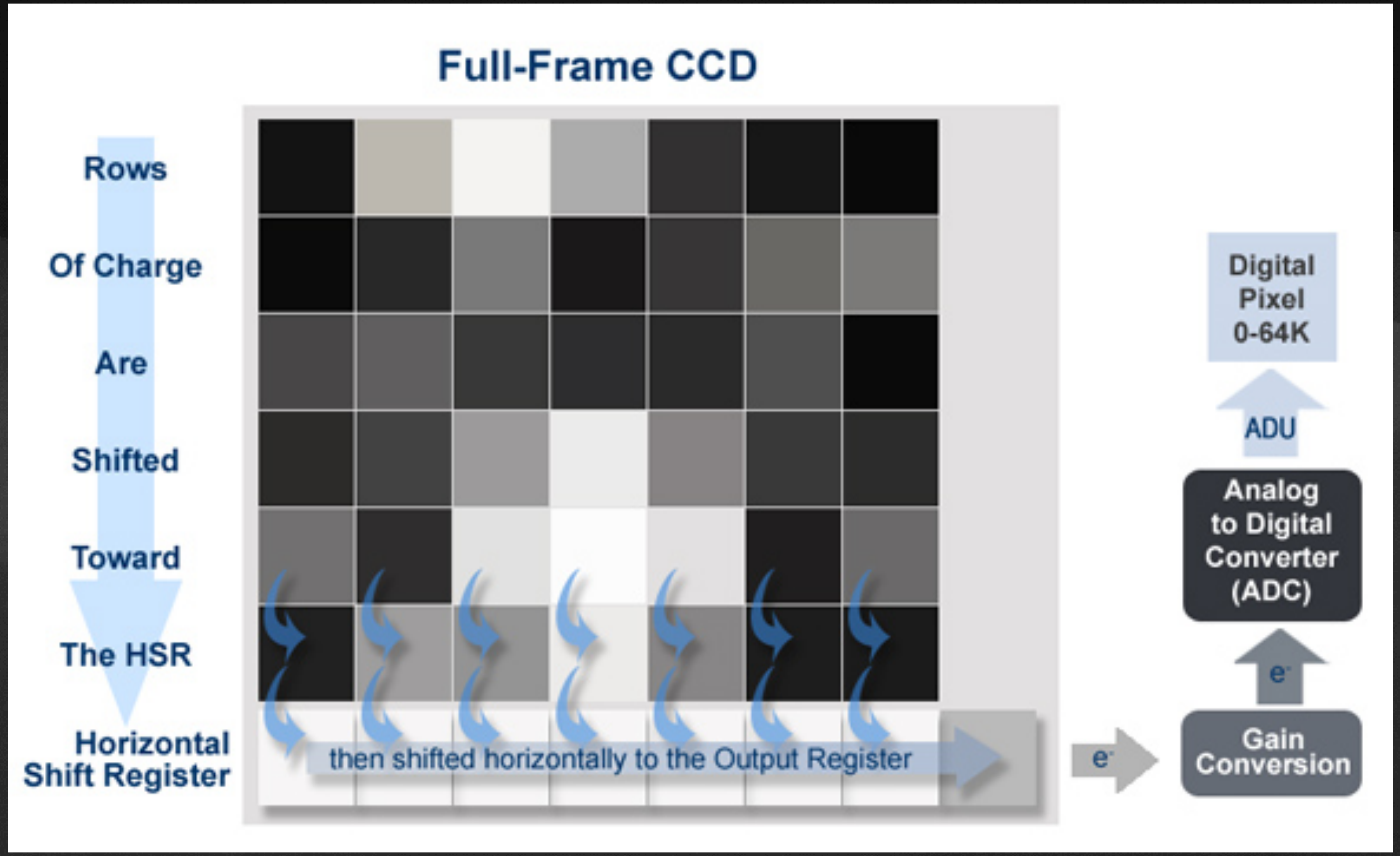




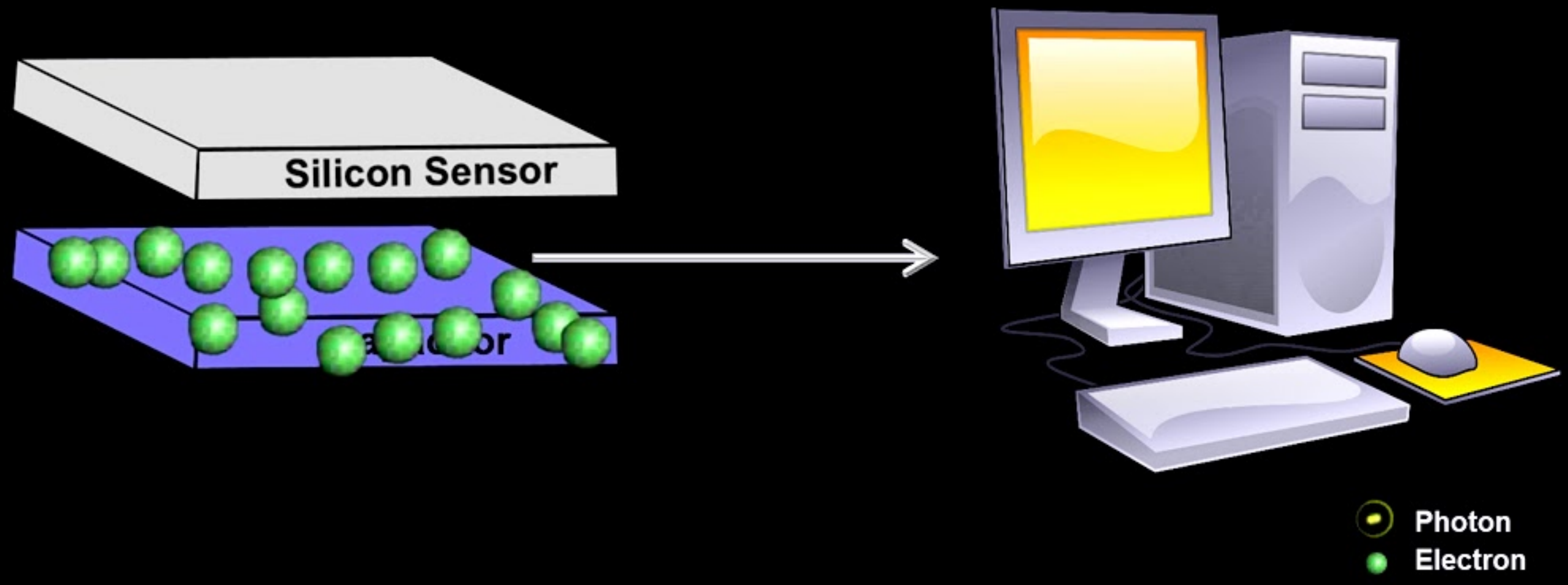
Astronomical detectors

V - CCDs

- Start of an exposure capacitors are positively charged.
- Photons enter silicon and raise e’ from low valence energy band to higher conduction band (i.e. e- liberated from silicon).
- Voltage of each site depends on number of photons that penetrated the silicon surface at that site.
- Electrons are attracted to positive capacitor and discharge it slightly (changing voltage).



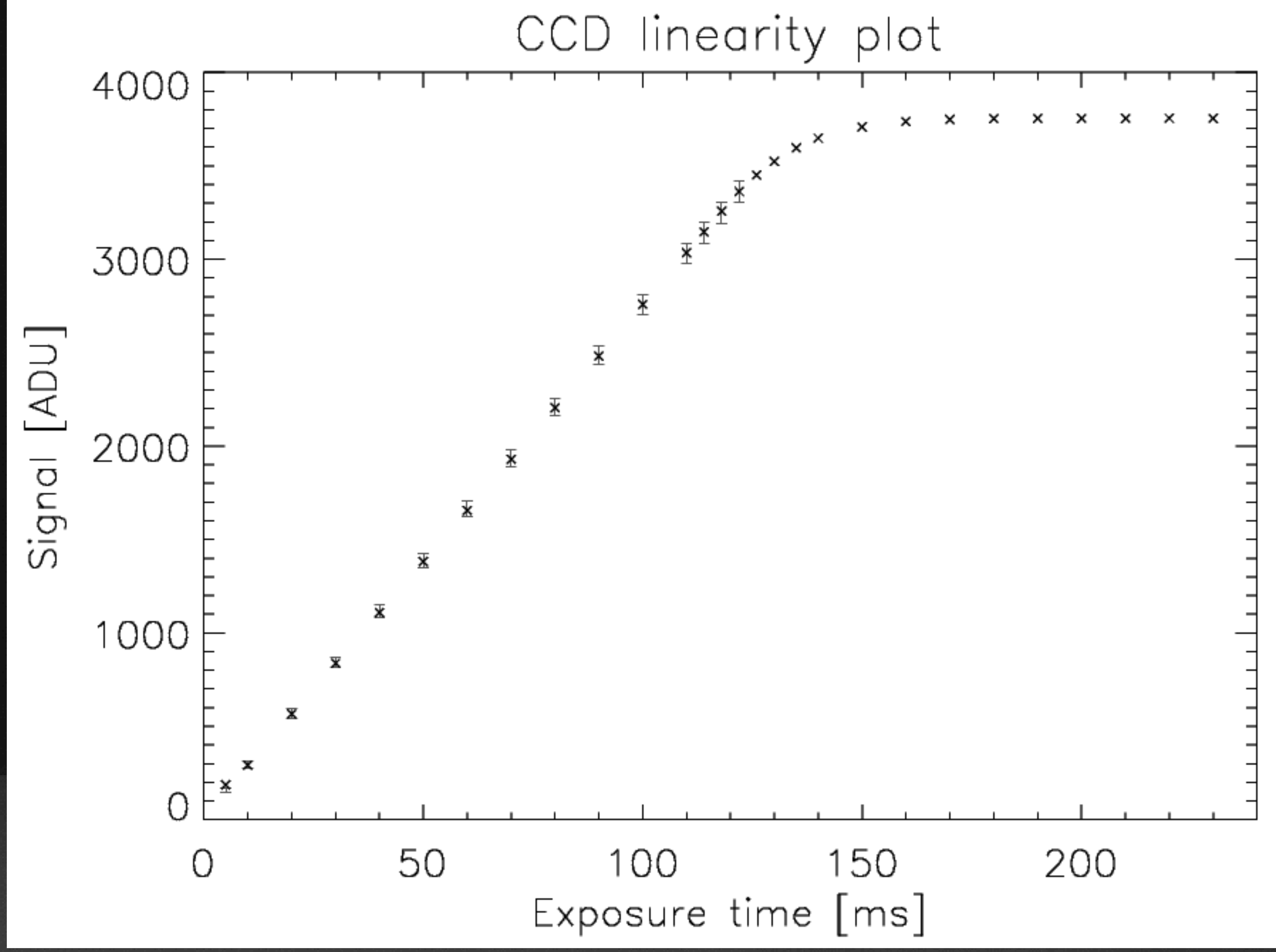
Charge-Coupled Device



Astronomical detectors

V - CCDs

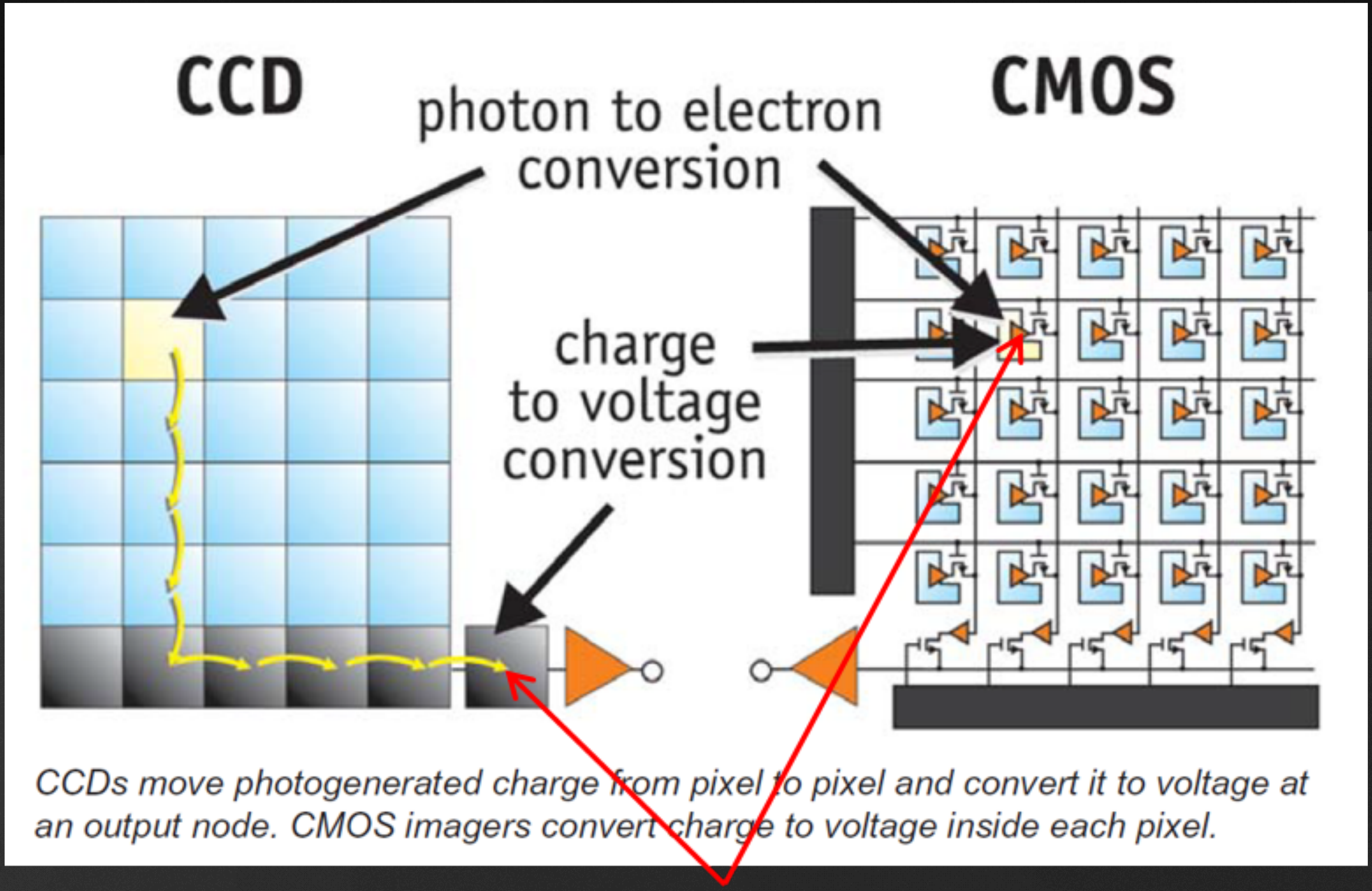
- Only photons > 1.1ev can free electrons (i.e. not for infrared).
- Below 300 microns, silicon becomes reflective.
- CCDs can be near 100% QE.
- CCDs are linear until a site has too many electrons.
- Charge can lead from a photo site (bleeding) if a site is saturated.



Astronomical detectors

VI - CMOS

- Most commercial digital cameras now use CMOS detectors (Complimentary Metal Oxide Semiconductors).



CCDs move photogenerated charge from pixel to pixel and convert it to voltage at an output node. CMOS imagers convert charge to voltage inside each pixel.

Read-out noise generated

Astronomical detectors

VI - CMOS

- Unlike CCDs, CMOS sensors are not limited to silicon as the detector material. Therefore CMOS can be produced to be sensitive to ultraviolet, visible, or infrared light.

- Very fast readout allows for shutterless operation.

- CMOS detectors are very cheap and use very little power when compared with CCDs.

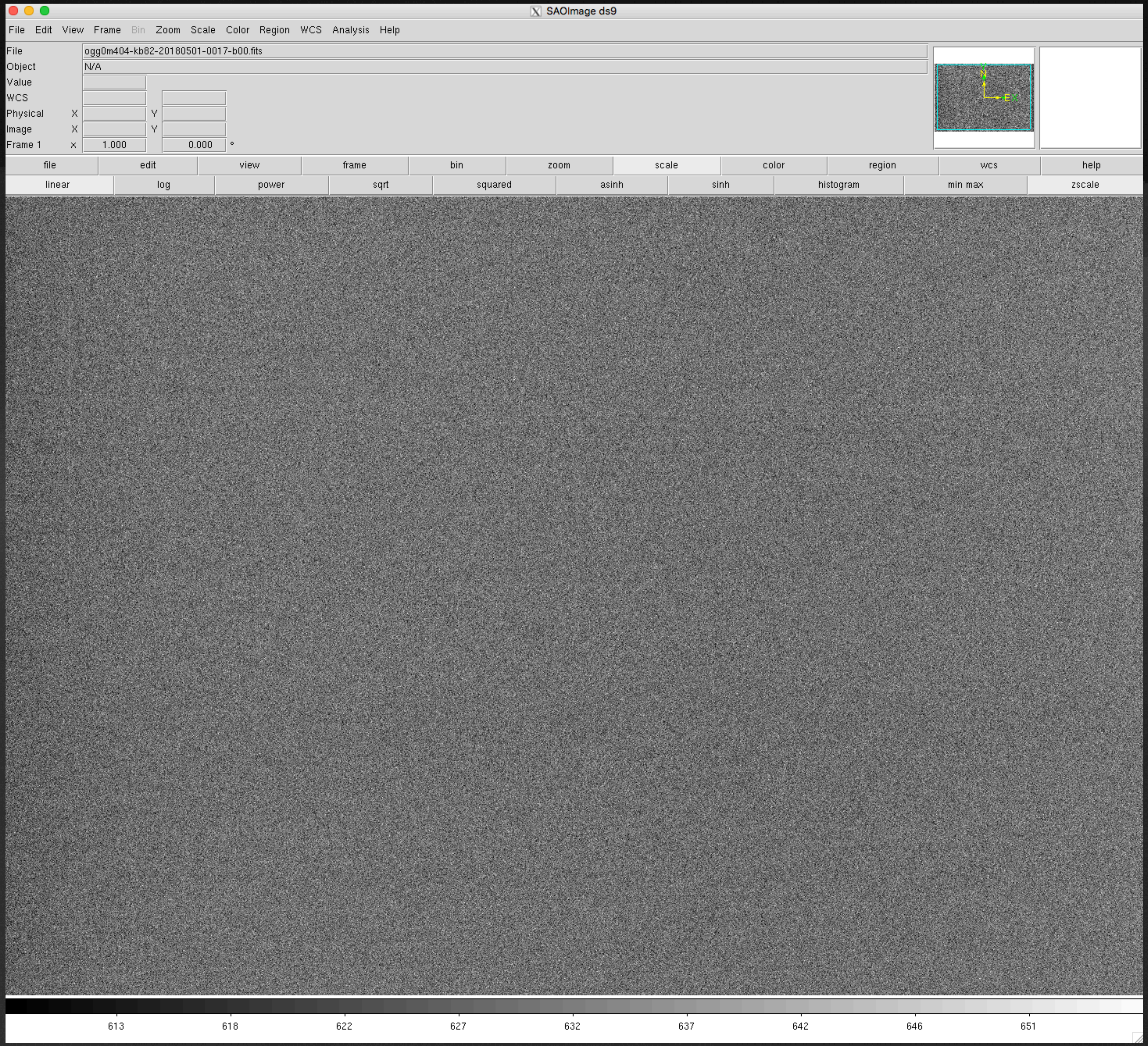
- With CMOS, each pixel has its own charge-to-voltage conversion and each row its own amplifier. So the images have high noise and less uniformity than CCDs.

- Scientific CMOS detectors are starting to appear which rival the quality of CCDs for astro-imaging.

Types of astronomical images

I - Bias image

- 0 second readout.
- Pixels at the “bias” level set by readout electronics.



File ogg0m404-kb82-20180501-0017-b00.fits

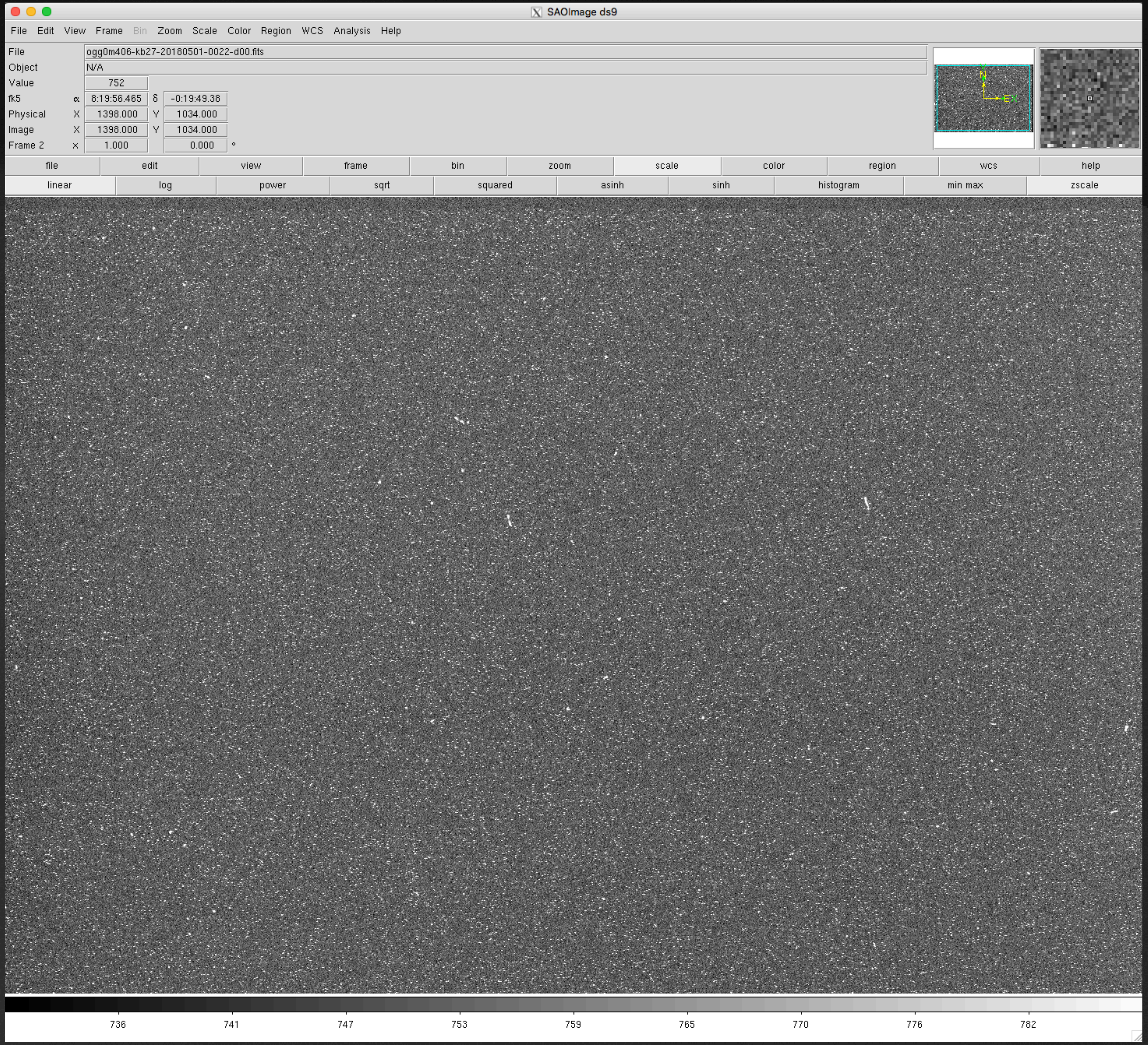
Object N/A

Frame 1 × 1.000 0.000 °

Types of astronomical images

II - Dark image

- Exposure without opening the shutter.
- See “dark current” such as hot pixels, light leaks, dead pixels.

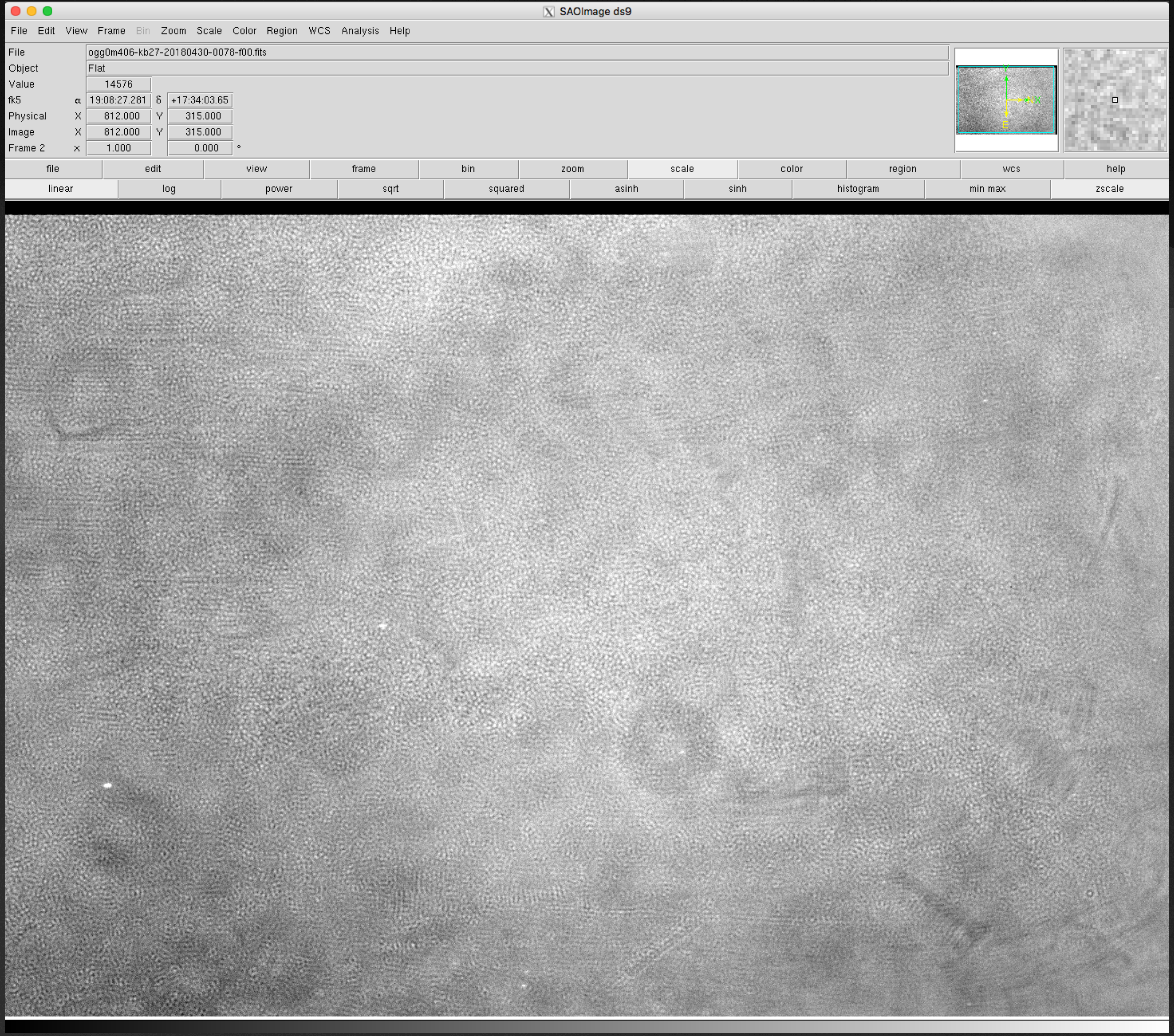


File ogg0m406-kb27-20180501-0022-d00.fits
Object N/A
Value 752
fk5 α 8:19:56.465 δ -0:19:49.38
Physical X 1398.000 Y 1034.000
Image X 1398.000 Y 1034.000
Frame 2 x 1.000 0.000 °

Types of astronomical images

III - Flat field image

- Exposure of twilight sky or a screen.
- See pixels response to universe illumination.
- What’s going on with the optics, CCD window etc.

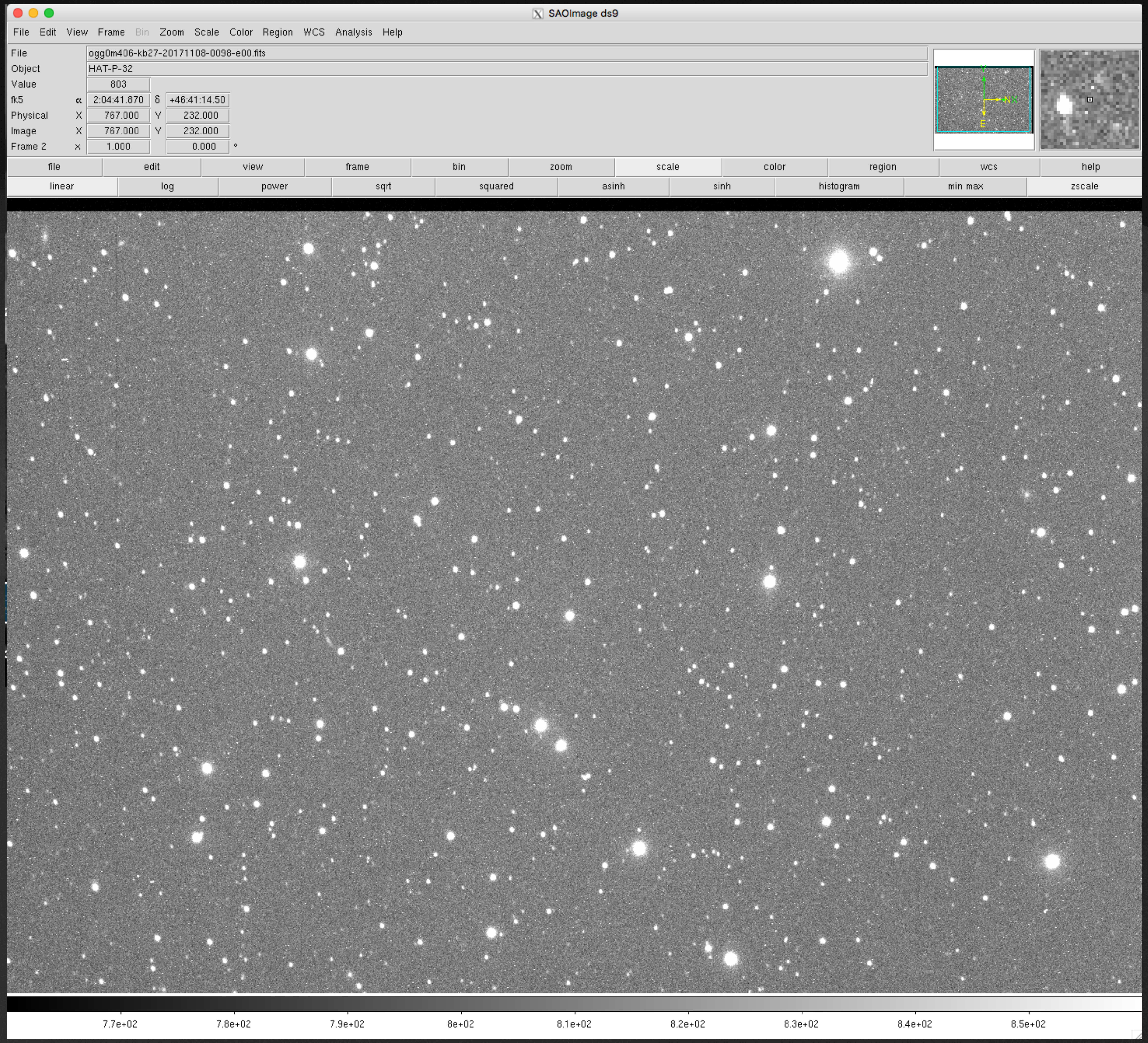


File ogg0m406-kb27-20180430-0078-f00.fits
Object Flat
Value 14576
fk5 α 19:08:27.281 δ +17:34:03.65
Physical X 812.000 Y 315.000
Image X 812.000 Y 315.000
Frame 2 x 1.000 0.000 °

Types of astronomical images

IV- Raw image

- Exposure of sky.
- Not corrected for bias, dark or flat.

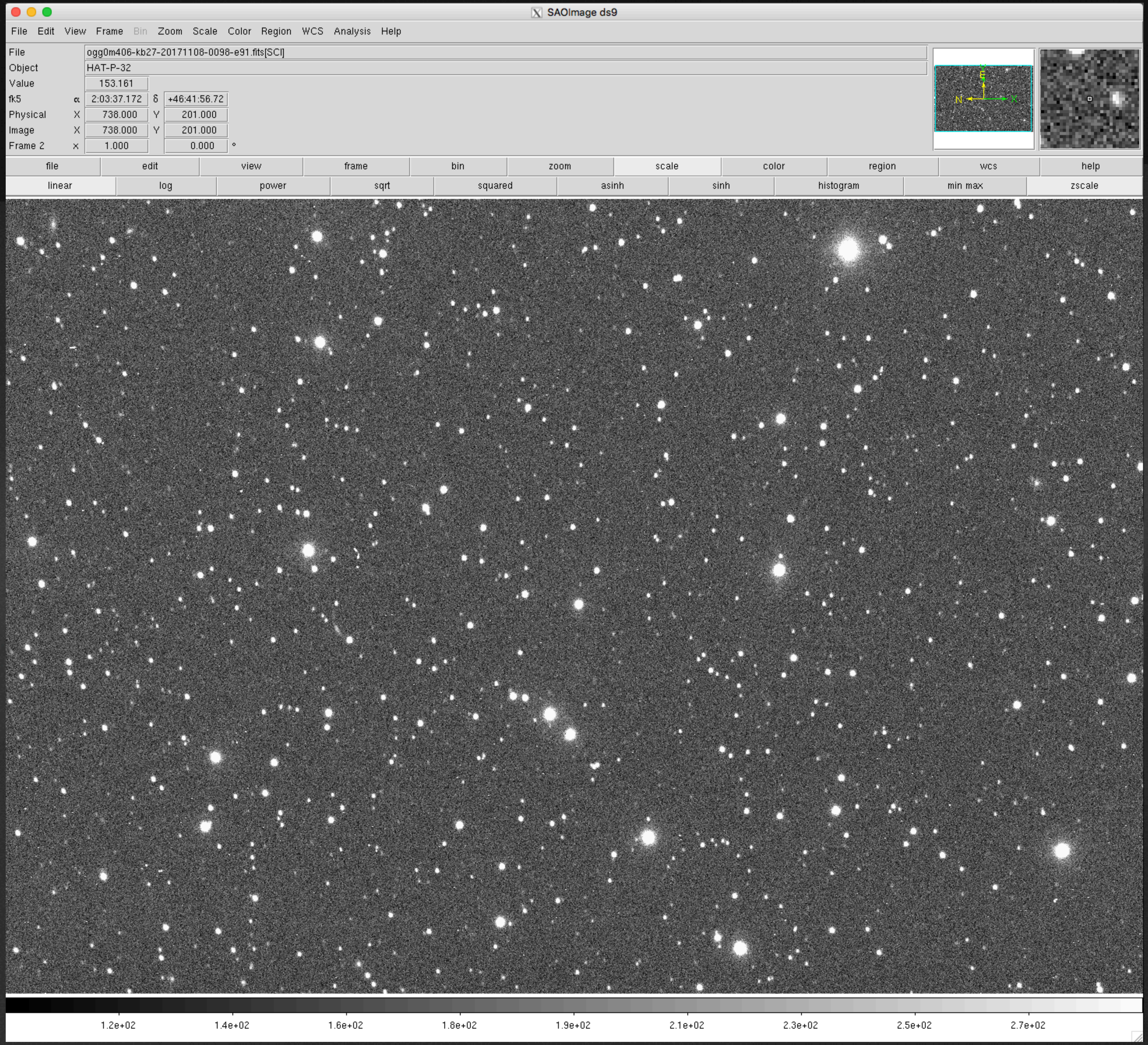


File ogg0m406-kb27-20171108-0098-e00.fits
Object HAT-P-32
Value 803
fk5 α 2:04:41.870 δ +46:41:14.50
Physical X 767.000 Y 232.000
Image X 767.000 Y 232.000
Frame 2 x 1.000 0.000 °

Types of astronomical images

V- Reduced image

- Exposure of sky.
- Corrected for bias, dark or flat.



File ogg0m406-kb27-20171108-0098-e91.fits[SCI]
Object HAT-P-32
Value 153.161
fk5 α 2:03:37.172 δ +46:41:56.72
Physical X 738.000 Y 201.000
Image X 738.000 Y 201.000
Frame 2 × 1.000 0.000 °

Photometry

I - Reducing astronomical images

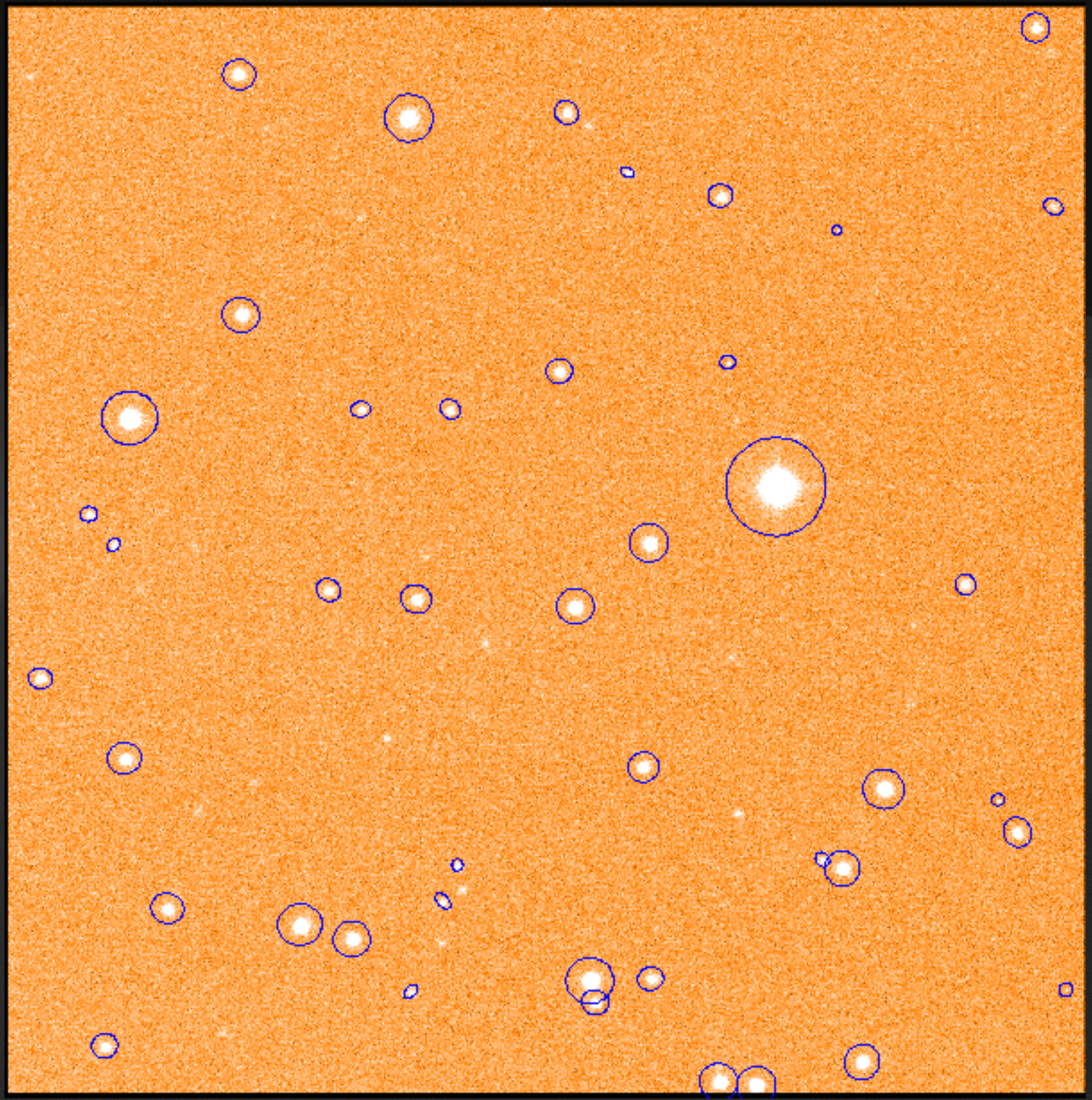
$$\text{science}_{reduced} = \frac{\text{science}_{raw} - \text{master bias} - \text{dark current}_{scaled}}{\text{master flat}_{reduced,\ normalized}}$$

- Create a master bias frame for the night.
- Create a master dark current image by removing the bias from several dark frames and combining those bias-subtracted frames
- Scale the dark current image to match the raw image exposure time.
- Create a master flat by calibrating several flat images using the master bias and dark, normalising the images and combining those to make a master image.

Photometry

II - Source identification

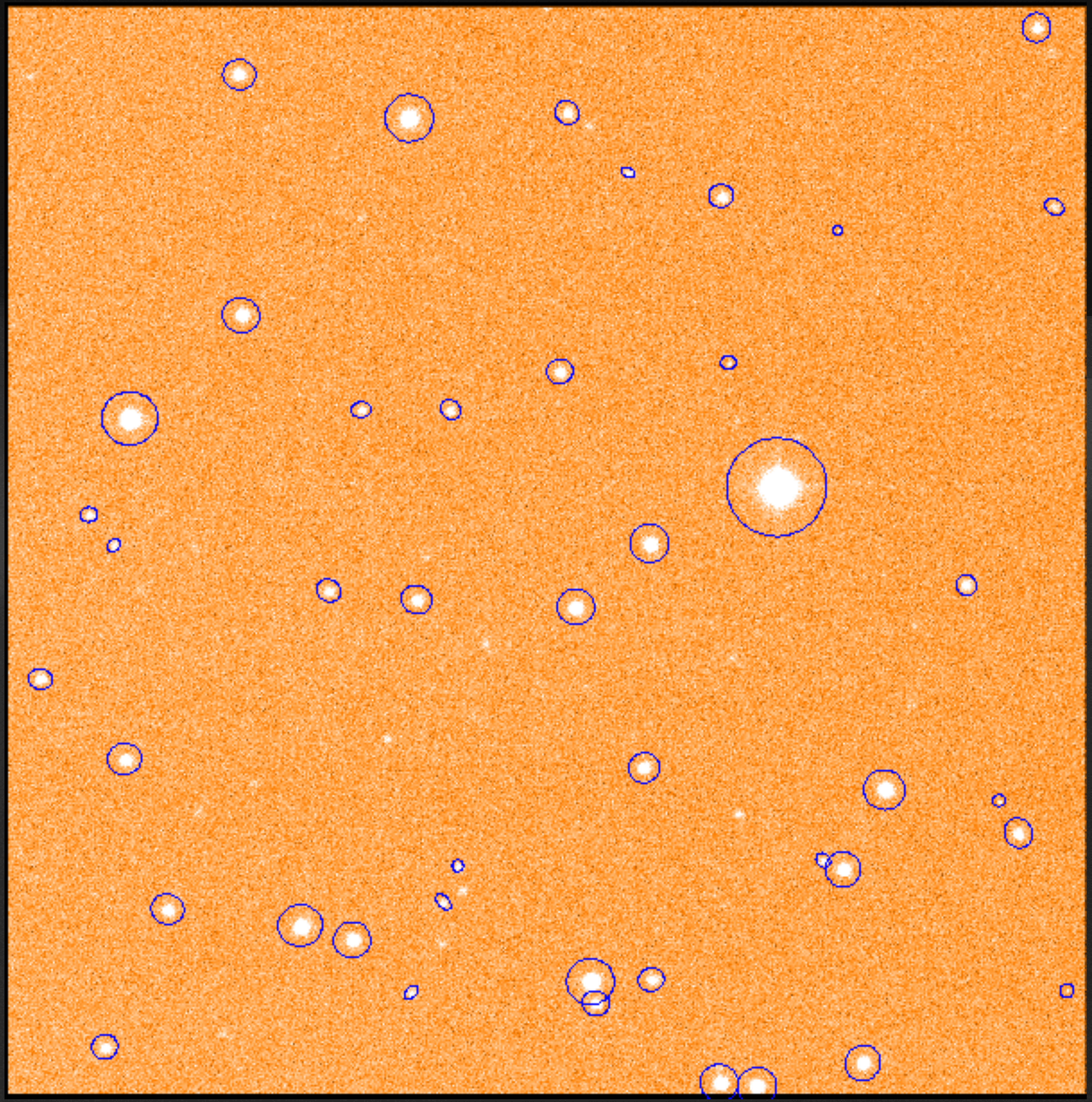
- How do you identify stars in an image?
- One way could be to search for areas where local density maxima exceeds some threshold.
- Very quick, efficient routines available (e.g. DAOStar finder, SEP).



Photometry

III - WCS solutions

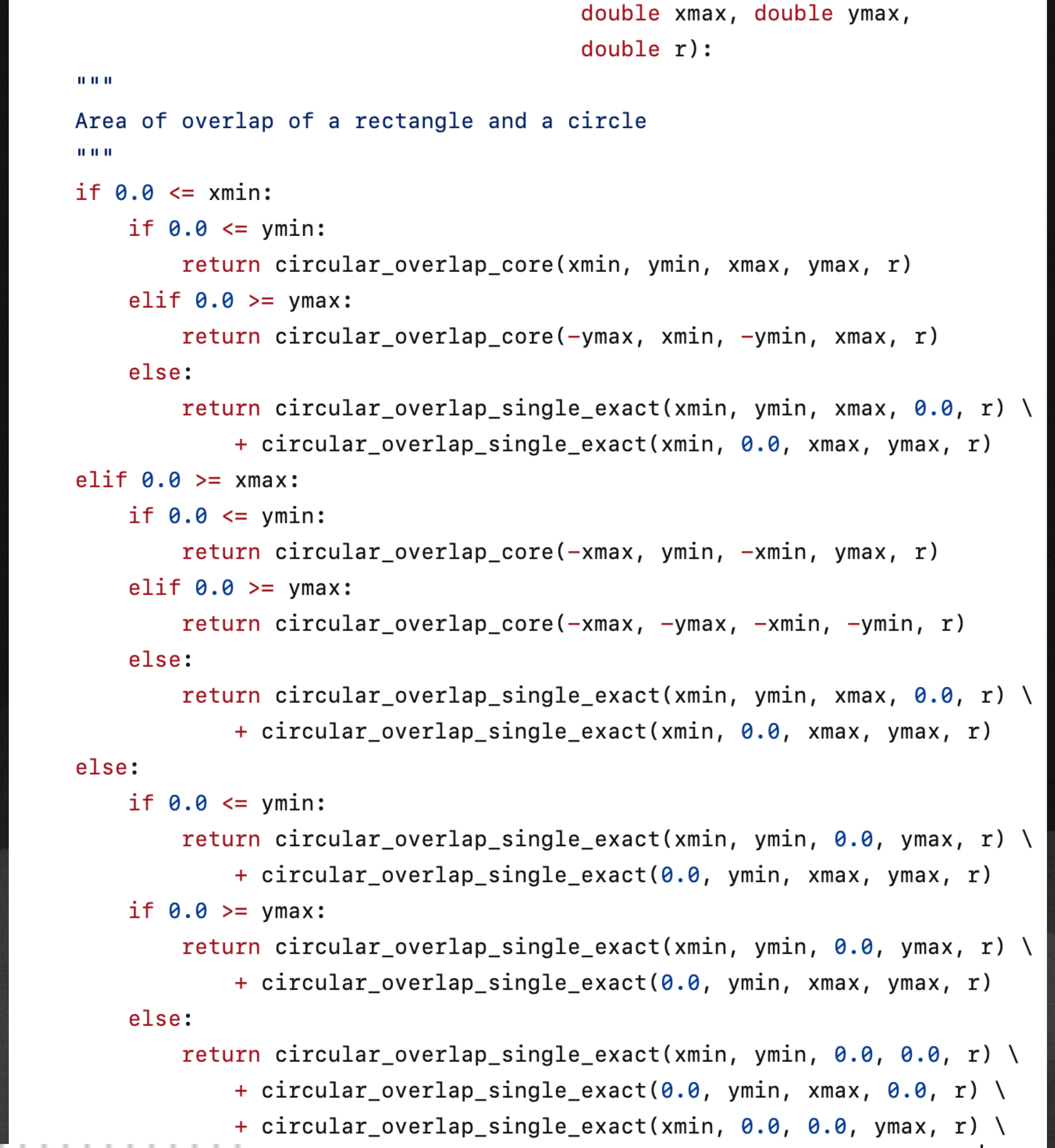
- WCS = World coordinate systems
- A way to convert each pixel of an image to RA and Dec.
- Way to identify and cross-match sources with catalogues.
- astrometry.net is very good for this, along with astropy.wcs
- Recommend ready astropy WCS documentation



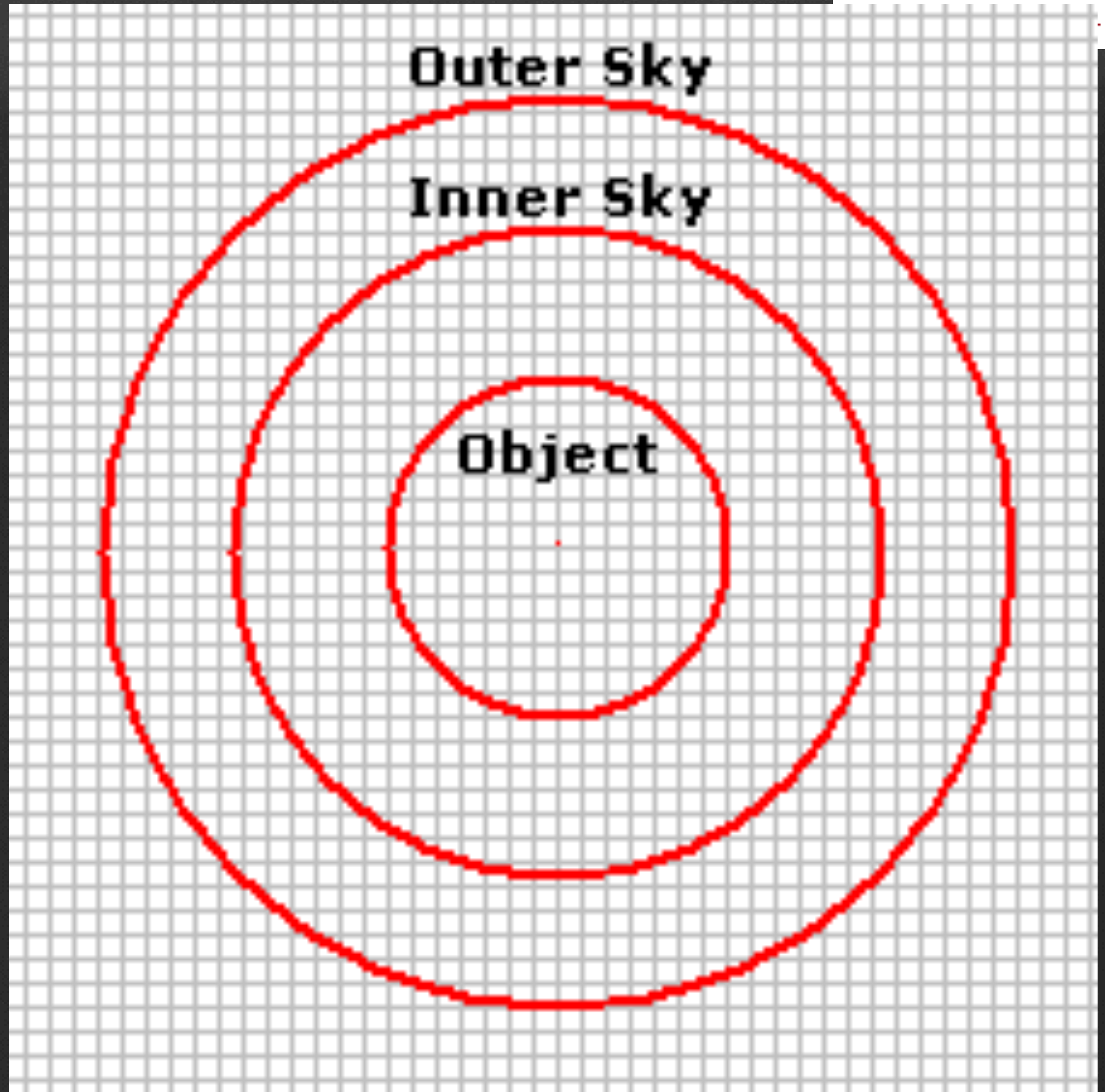
Photometry

IV - Counting ADU

- Simplest photometry is just to count the ADU in the pixels within an aperture and subtract off the sky counts.
- Called aperture photometry.
- How to do it? All pixels in aperture? How to handle partial pixels?
- What shape aperture?



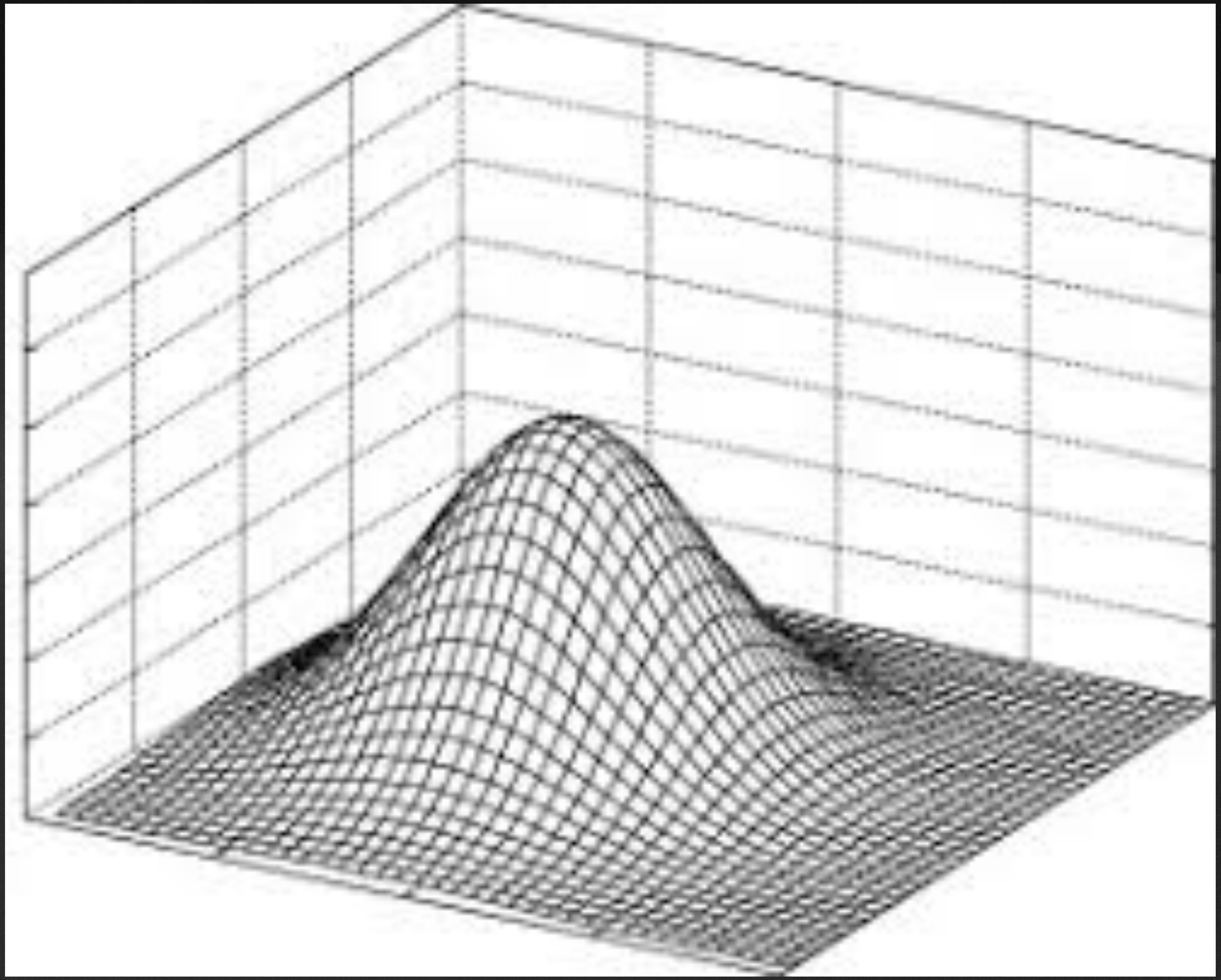
```
                                      double xmax, double ymax,
                                      double r):
"""
Area of overlap of a rectangle and a circle
"""
if 0.0 <= xmin:
    if 0.0 <= ymin:
        return circular_overlap_core(xmin, ymin, xmax, ymax, r)
    elif 0.0 >= ymax:
        return circular_overlap_core(-ymax, xmin, -ymin, xmax, r)
    else:
        return circular_overlap_single_exact(xmin, ymin, xmax, 0.0, r) \
            + circular_overlap_single_exact(xmin, 0.0, xmax, ymax, r)
elif 0.0 >= xmax:
    if 0.0 <= ymin:
        return circular_overlap_core(-xmax, ymin, -xmin, ymax, r)
    elif 0.0 >= ymax:
        return circular_overlap_core(-xmax, -ymax, -xmin, -ymin, r)
    else:
        return circular_overlap_single_exact(xmin, ymin, xmax, 0.0, r) \
            + circular_overlap_single_exact(xmin, 0.0, xmax, ymax, r)
else:
    if 0.0 <= ymin:
        return circular_overlap_single_exact(xmin, ymin, 0.0, ymax, r) \
            + circular_overlap_single_exact(0.0, ymin, xmax, ymax, r)
    if 0.0 >= ymax:
        return circular_overlap_single_exact(xmin, ymin, 0.0, ymax, r) \
            + circular_overlap_single_exact(0.0, ymin, xmax, ymax, r)
    else:
        return circular_overlap_single_exact(xmin, ymin, 0.0, 0.0, r) \
            + circular_overlap_single_exact(0.0, ymin, xmax, 0.0, r) \
            + circular_overlap_single_exact(xmin, 0.0, 0.0, ymax, r) \
            + circular_overlap_single_exact(0.0, 0.0, xmax, ymax, r)
```



Photometry

IV - PSF photometry

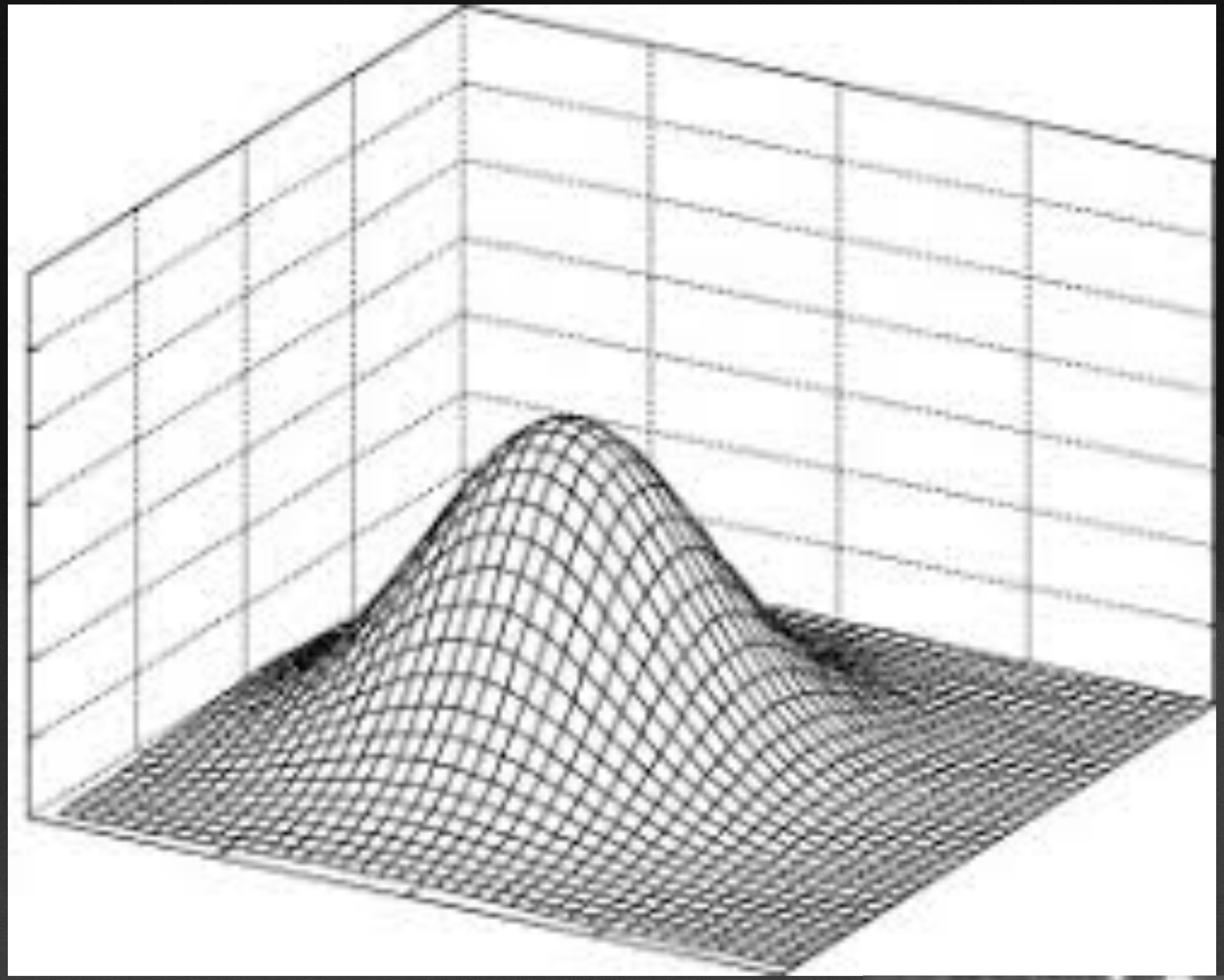
- The “Shape of the star on the CCD contains information.
- Called the point-spread function (PSF).
- Can be fit and photometry derived.



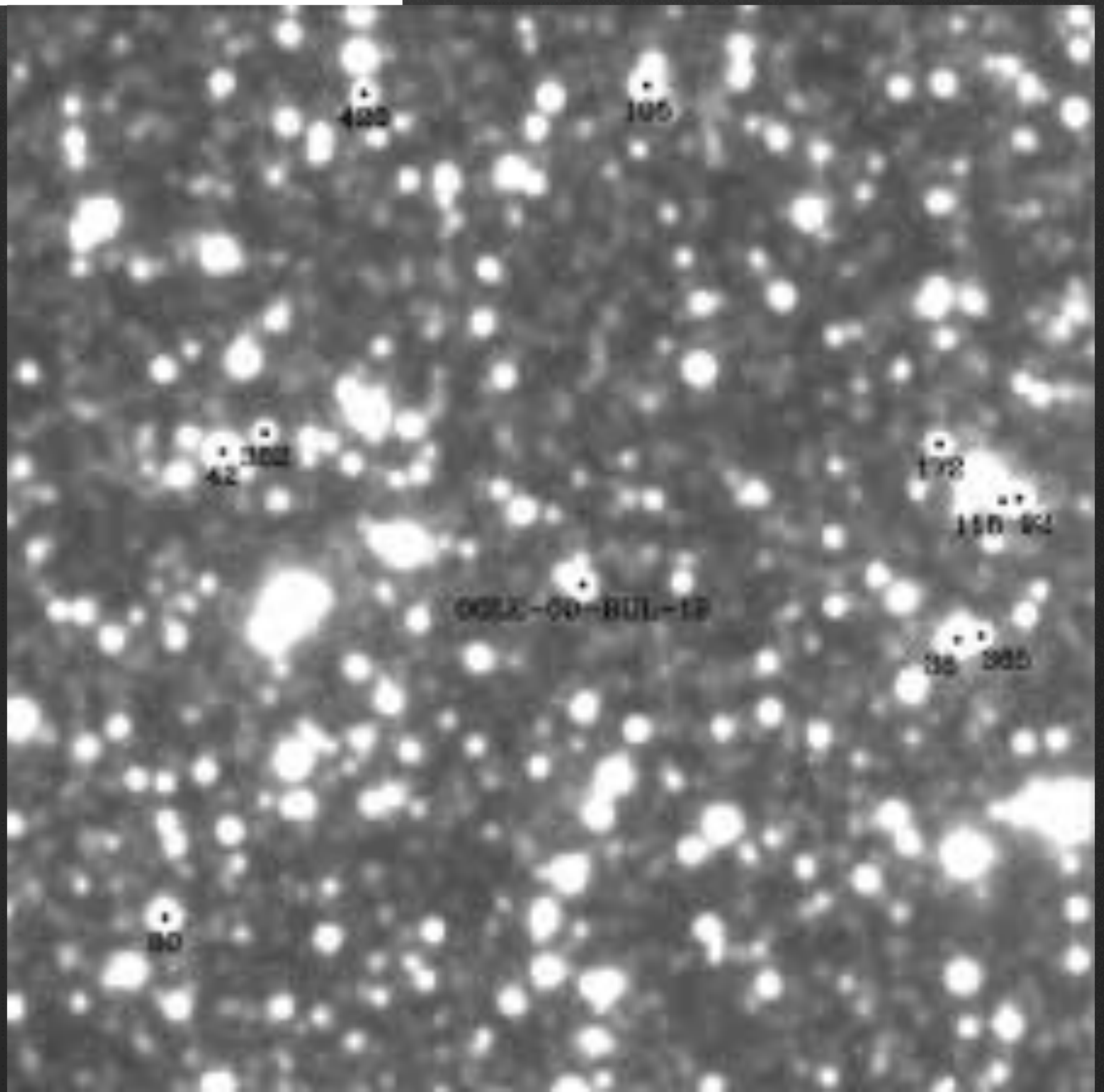
Photometry

V - Difference imaging

- For crowded fields, photometry might not work.
- Make a master template for the field.
- For each image, deconvolve template to resolution of the ondicual image.
- Subtract deconvoled master image.
- Constant light sources do not appear, only variations!



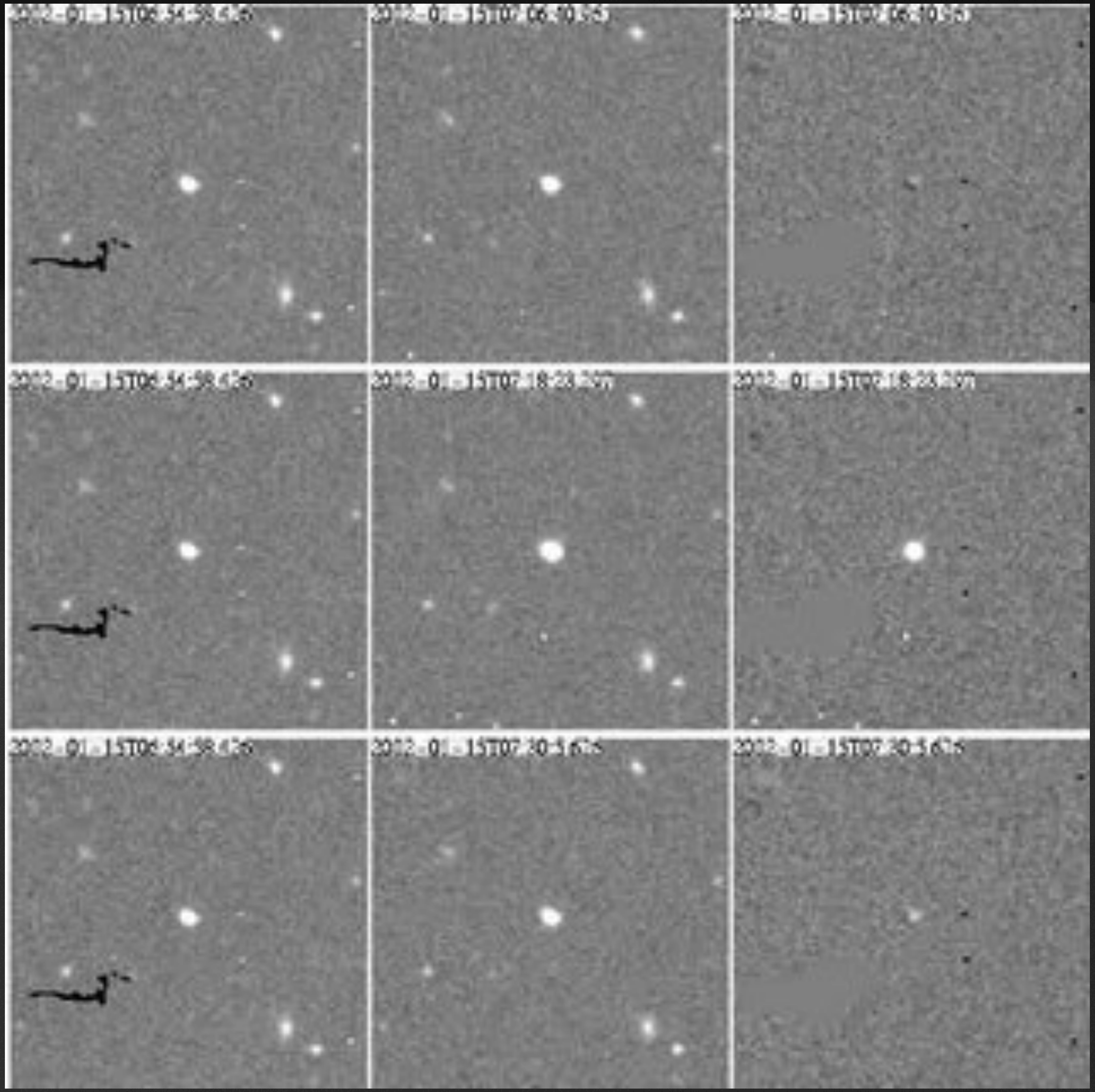
Good for microlensing, supernovae work or moving objects!



Photometry

V - Difference imaging

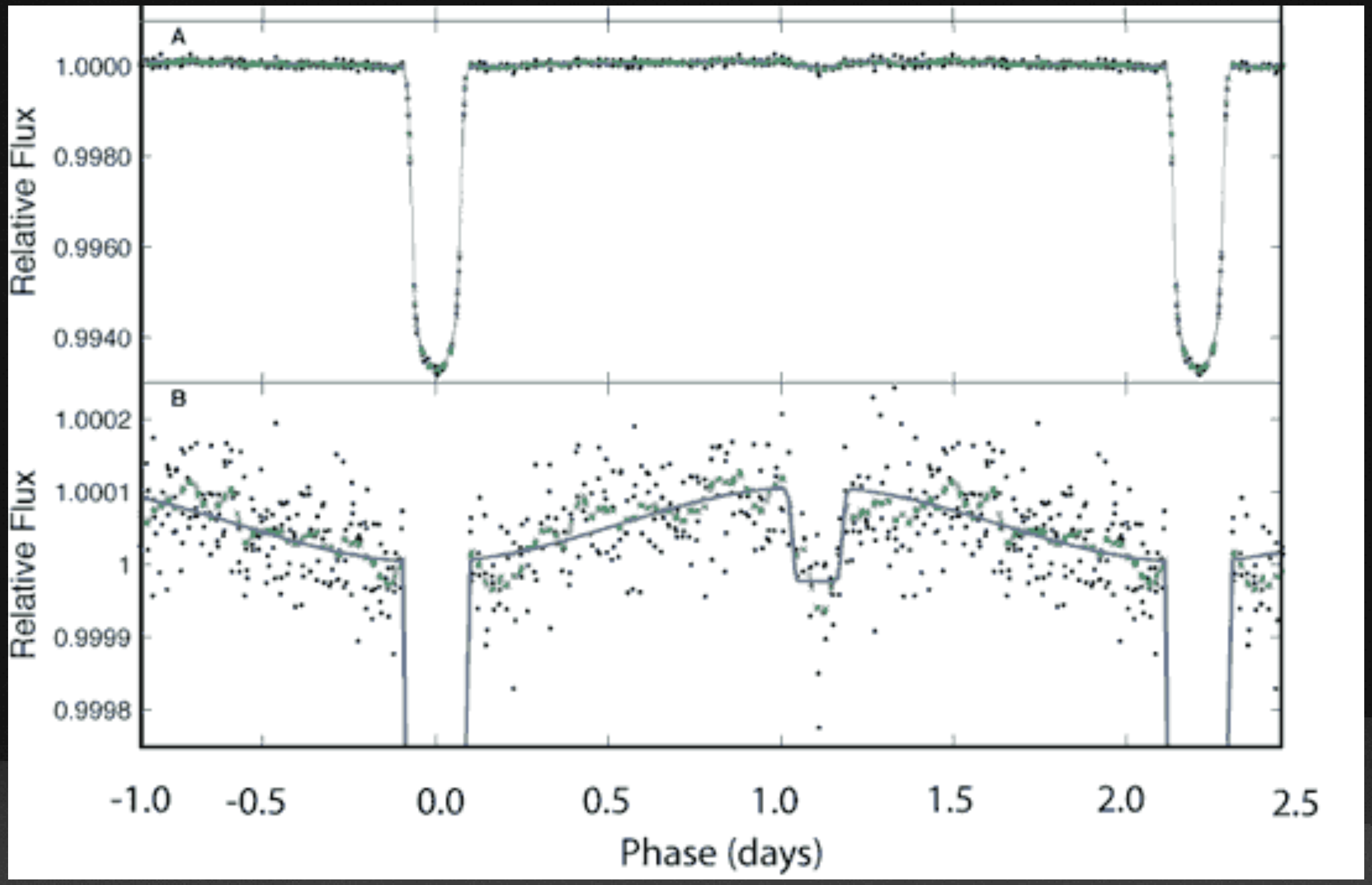
Good for microlensing, supernovae work or moving objects!



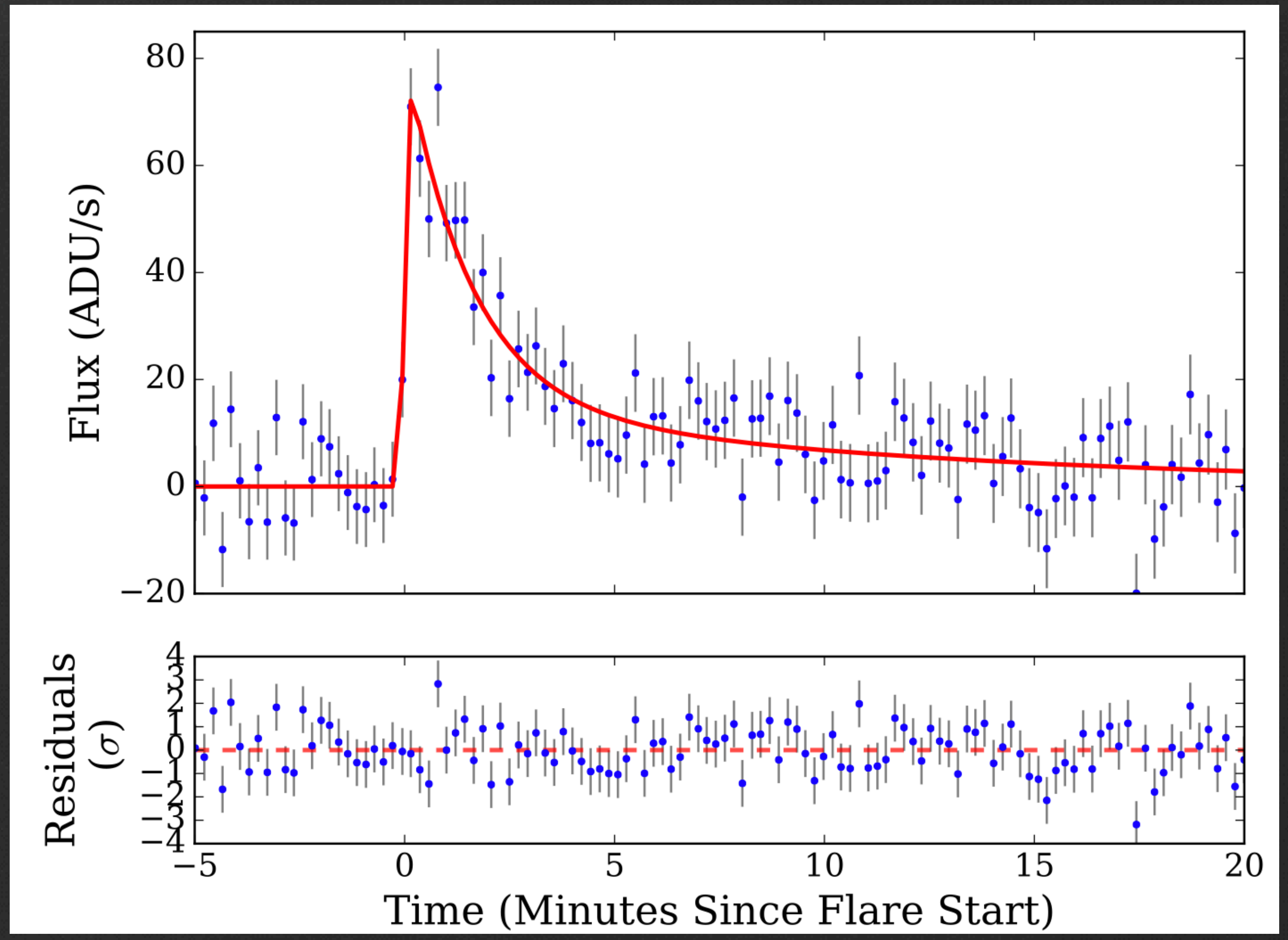
Photometry

VI - Time-series photometry

- If we count flux from a star for each image in a sequence, we can see how the light from star varies.
- Exoplanet, eclipsing binaries, stellar variability, gravitational interactions, flares etc.



HAT-P-7b secondary eclipse using Kepler (from Borucki et al., 2010). Signal is just 113ppm at 11.3 sigma

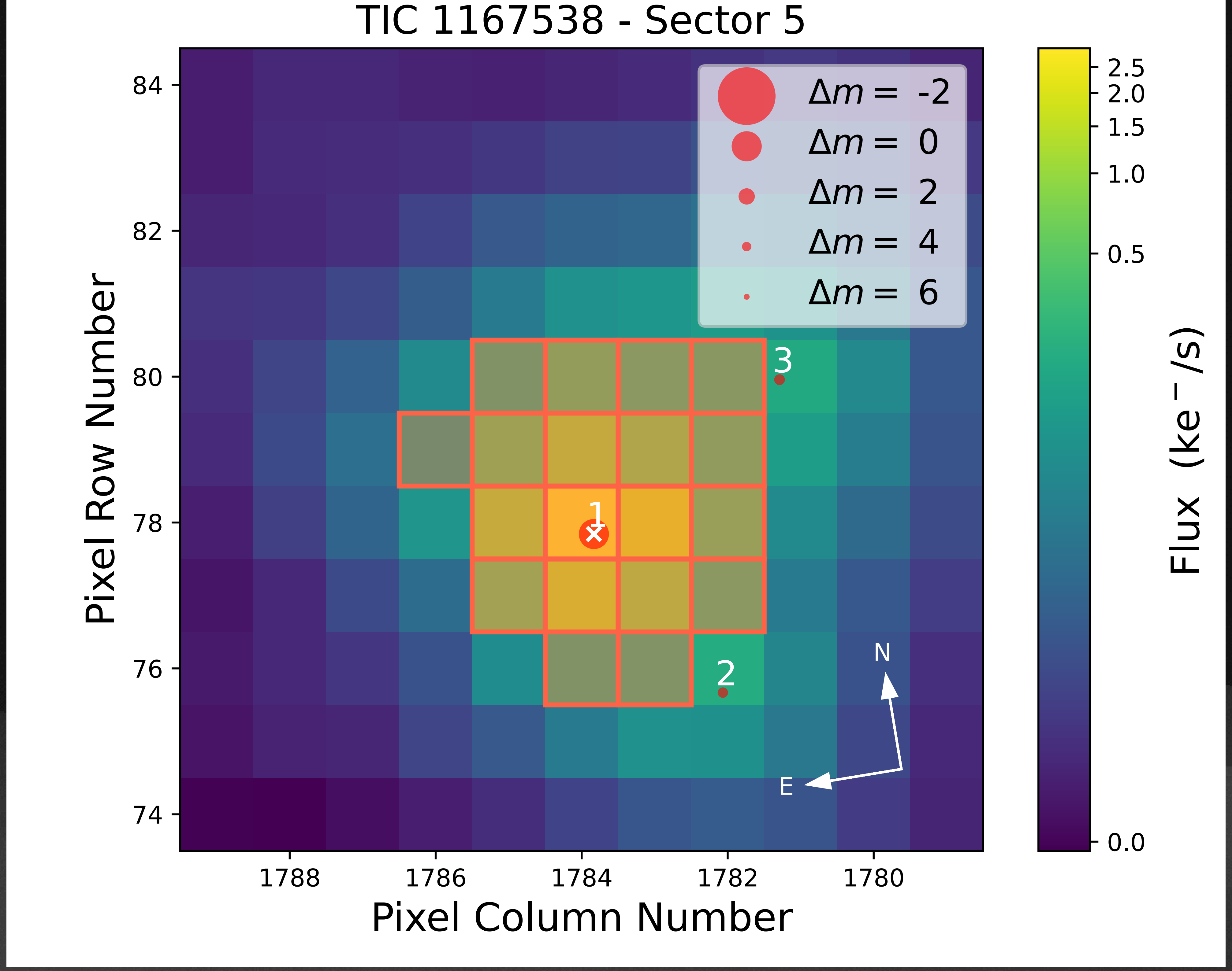


Flare from an L2.5 flare with NGTS (Jackman+2019)

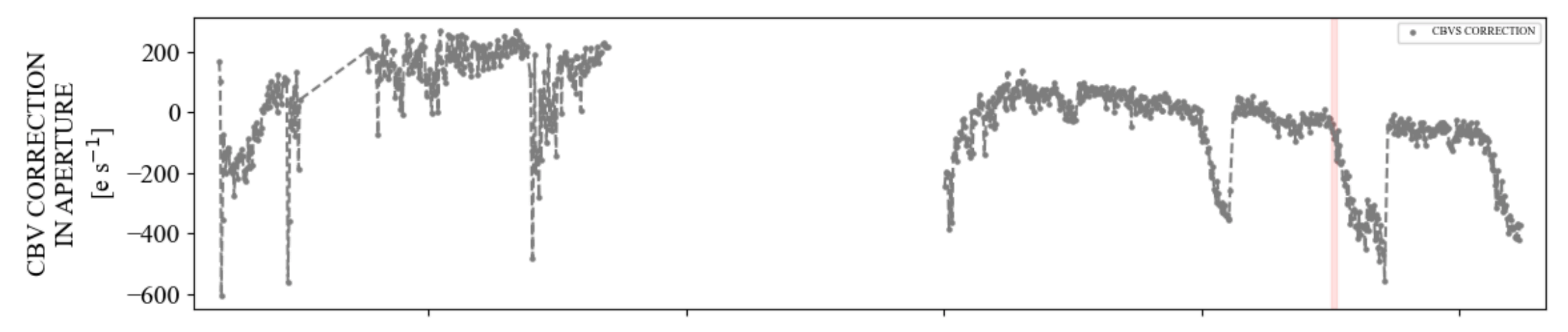
Photometry

VI - Time-series photometry in space

- Simple in space (e.g. TESS, Kepler, PLATO).
- No atmosphere to deal with, only spacecraft systematics.
- Sometimes, these are non-trivial to deal with!



TPF of TOI-2447 (Gill+2023)

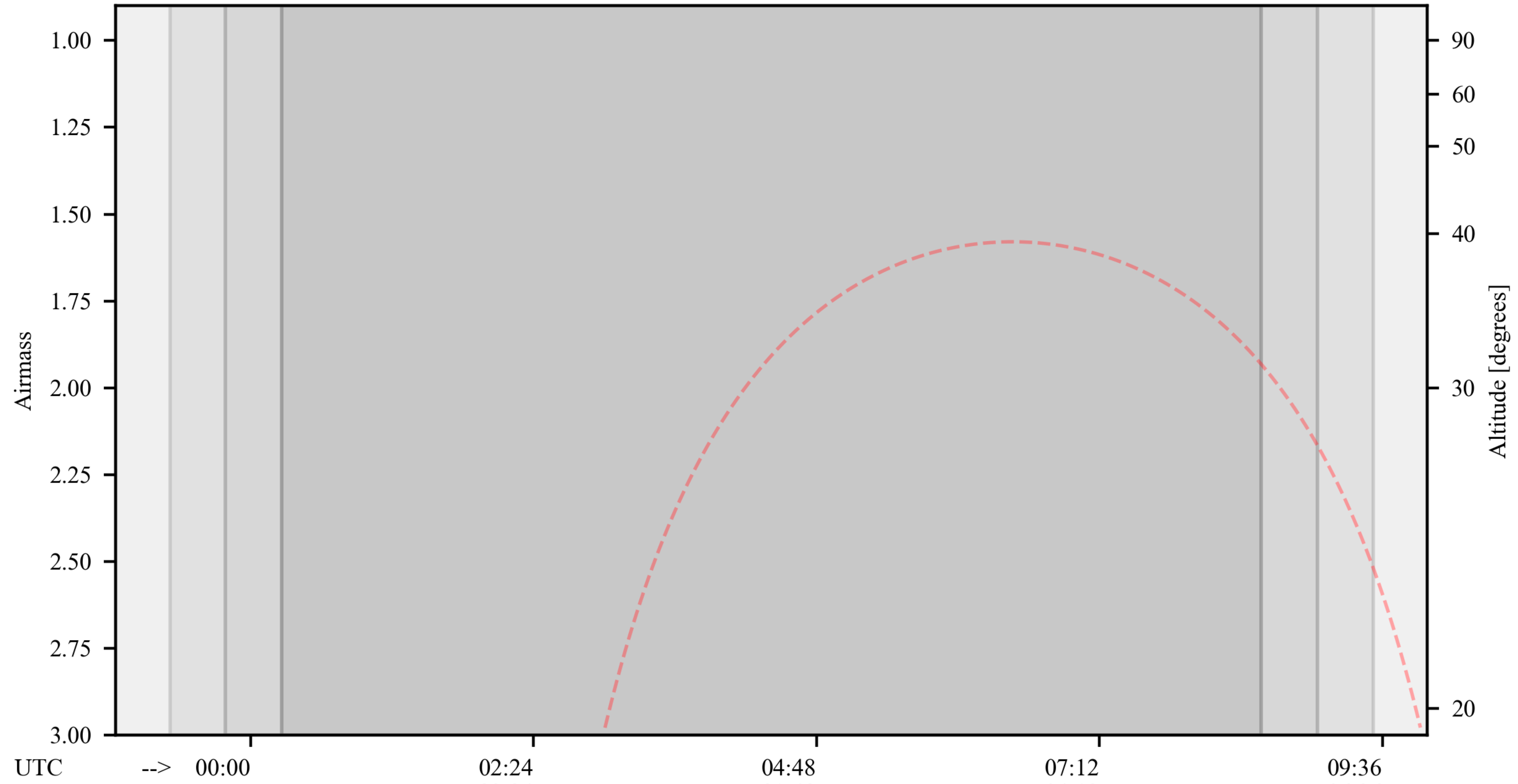


Systematics of TIC-64070648
in TESS sector 4

Photometry

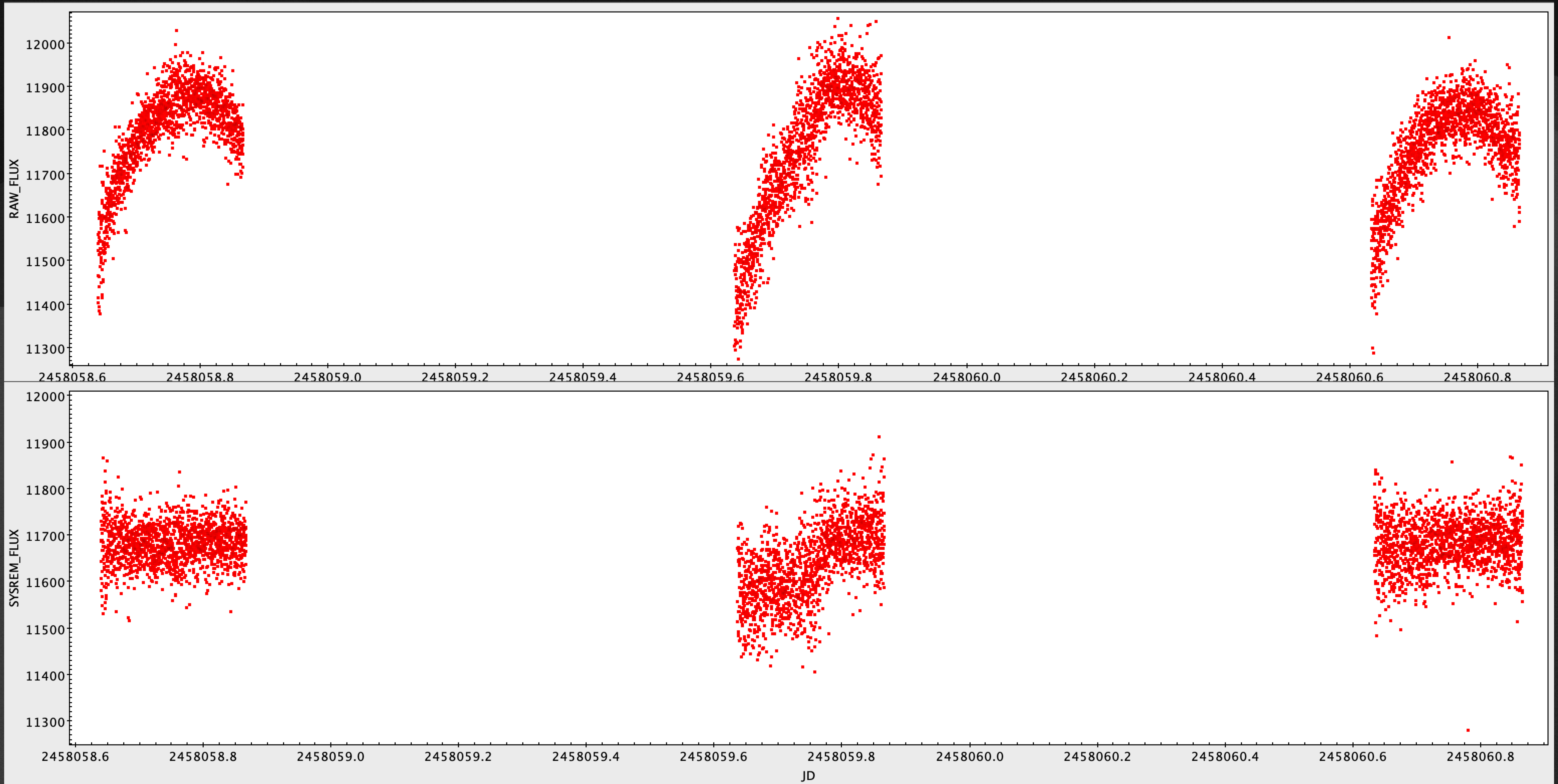
VI - Time-series photometry from the ground

- Much harder as have to deal with atmosphere.
- Observe stars through different amounts of air masses (1 at zenith, ~3 for 20 deg elevation).
- Different amount of flux is scattered and thus strong airmass trends in raw flux.



Photometry

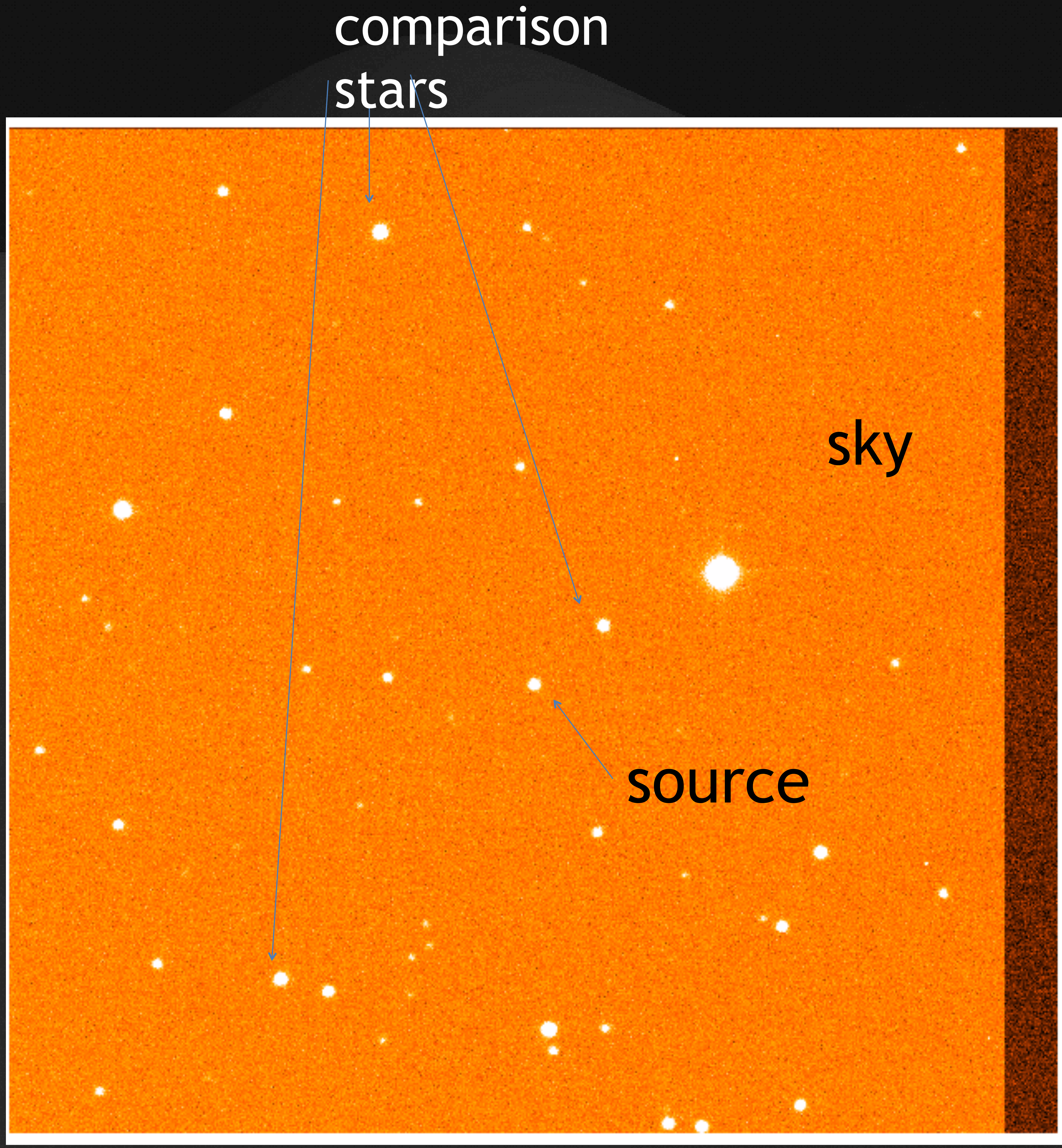
VI - Time-series photometry from the ground



Photometry

VI - Time-series photometry from the ground

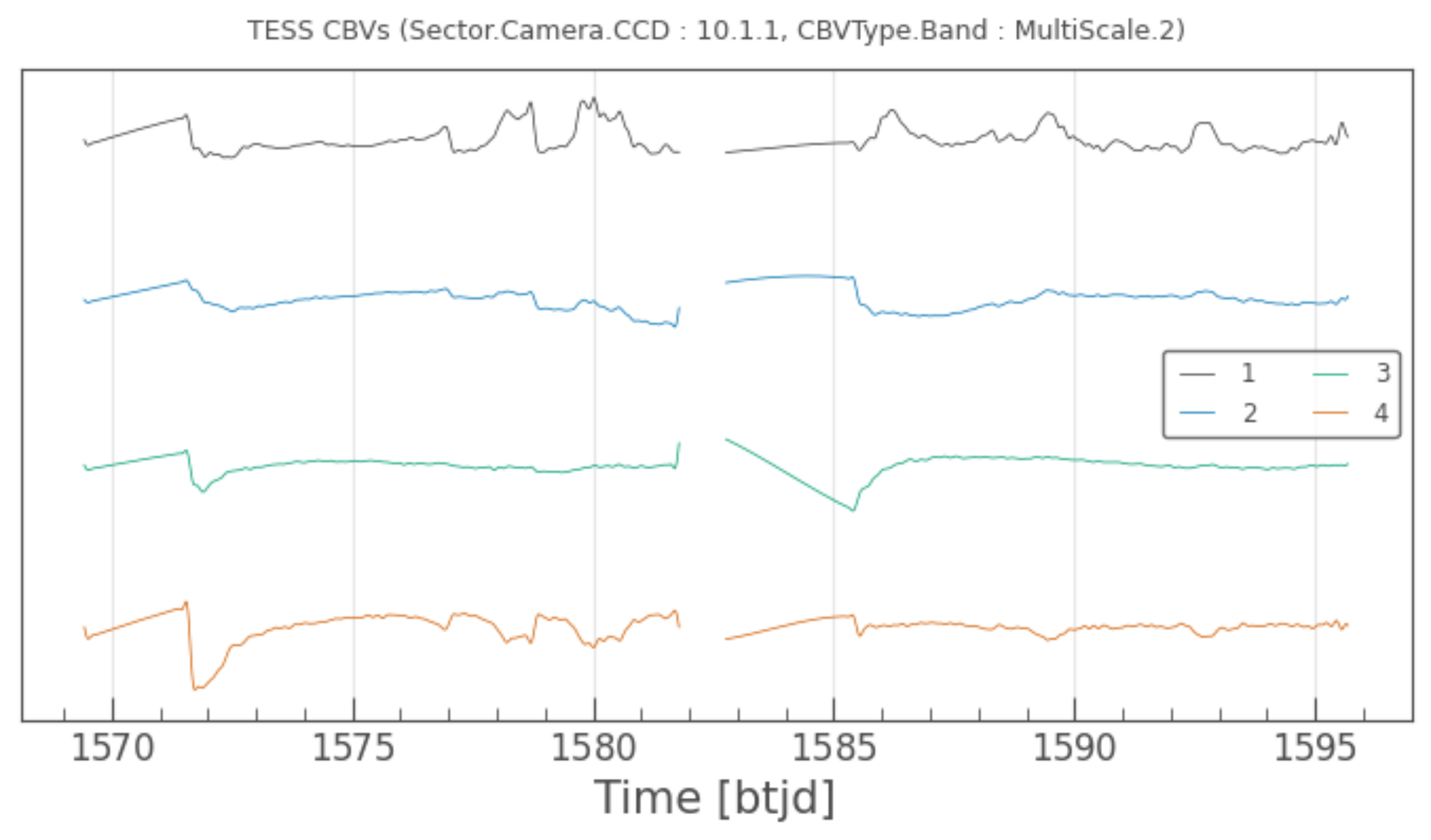
- One way to remove trend is through comparison stars.
- Detrended flux is source flux divided by comparison star flux
- No sky background estimated (although it may help).
- Requires careful selection of stars with similar brightness, colour and spectral type.
- Red-noise may still persist.



Photometry

VI - Time-series photometry from the ground

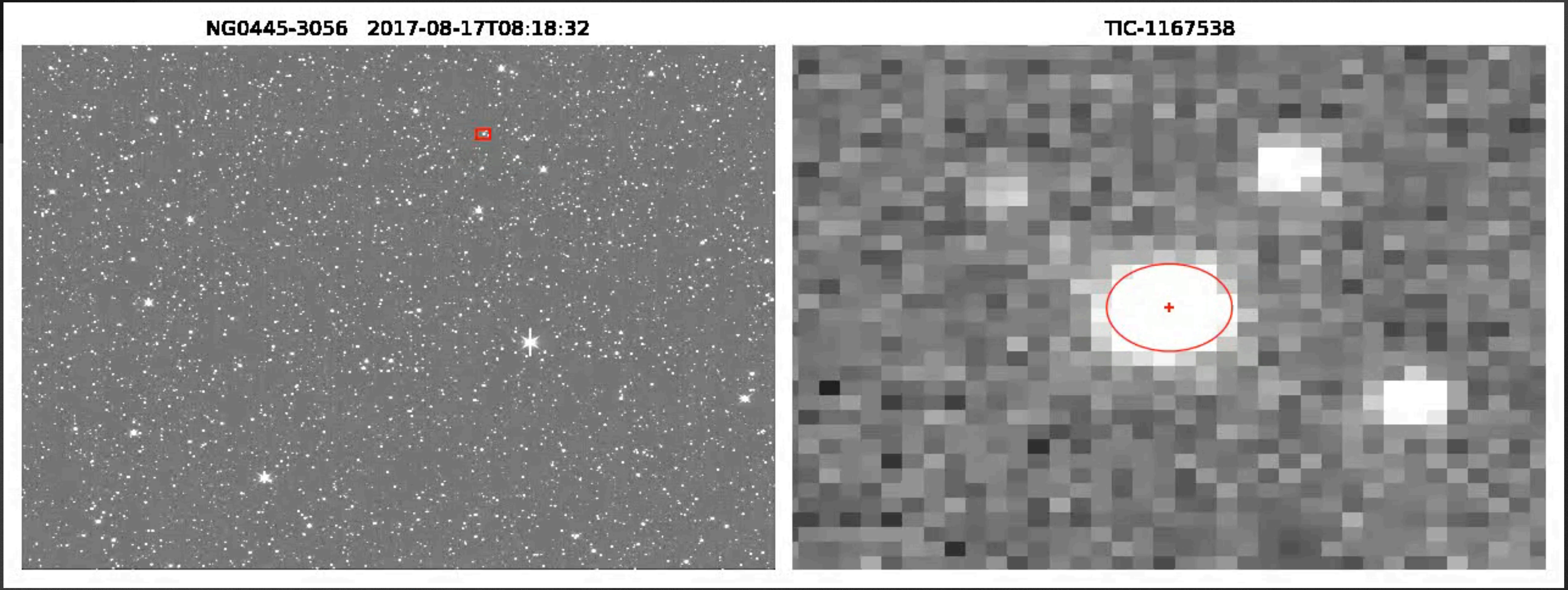
- Another way is to take the lightcurves for all stars in the fields.
- Determine common trends (often refered to as basis vectors).
- These represent the components of trends in all lightcurves, and can be fitted to each to detrend them. (System, PCA)
- Struggles for variable stars, have to infer components from nearby stars.
- Use in ground based (e.g. NGTS, WASP) and space based (e.g. TESS, Kepler) photometry.



Photometry

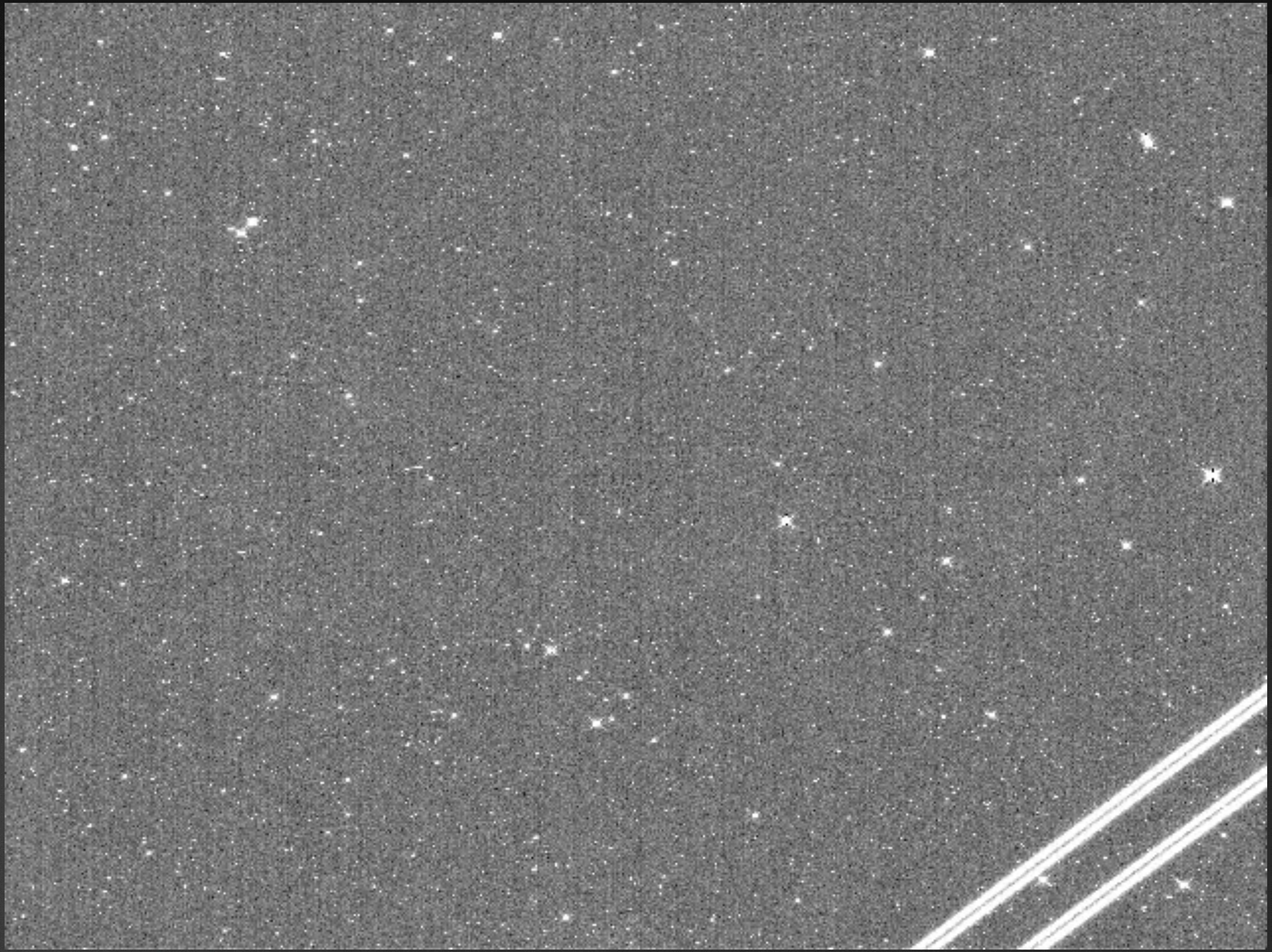
VI - Time-series photometry from the ground

- There may be other trends too, like pixel position, point-speed function, difference in sky background.



Photometry

VI - Time-series photometry from the ground



Photometry

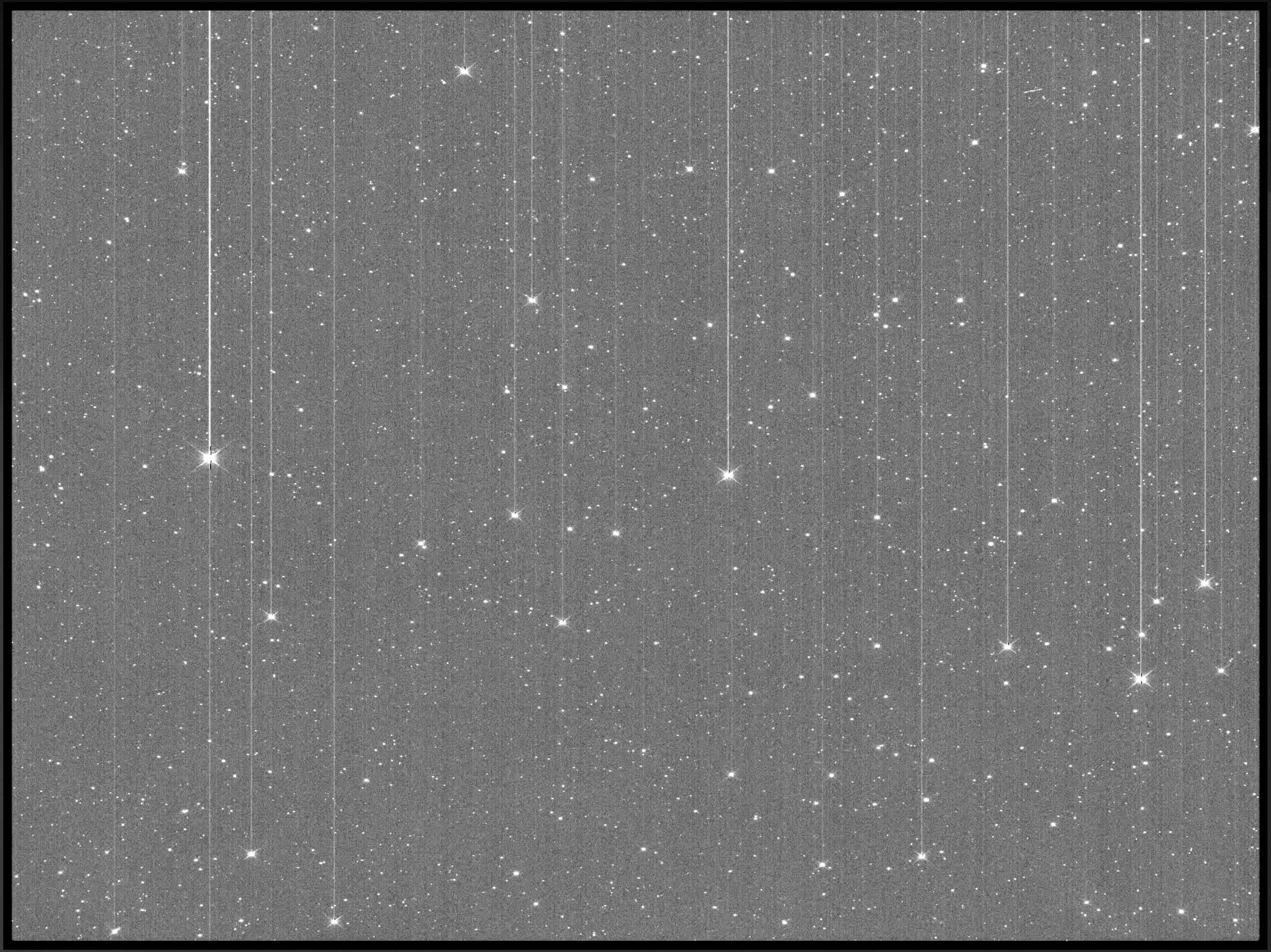
VI - Time-series photometry from the ground

Photometry

VI - Time-series photometry from the ground

Photometry

VI - Time-series photometry from the ground



Photometry

VI - Time-series photometry from the ground

Assignment

- You have observed a transit of a target with the Next Generation Transit Survey.
- You will now perform aperture photometry to extract a light curve.
- All data is given online.
- I have written a Jupyter notebook to help you, work through it slowly and produce:
  - A plot of time VS raw flux
  - A plot of time VS detrended flux
  - A comment on what you can see.

You will need python, and anaconda

Thanks for listening

Any questions?