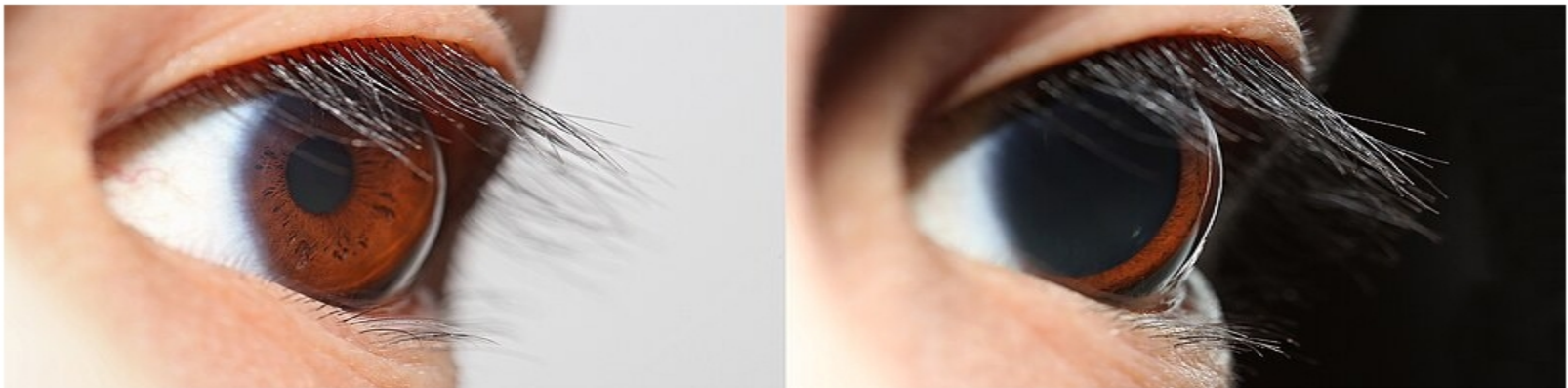




# Imaging / Photometry: basic concepts of observing techniques and calibrations

European Southern Observatory / La Silla summer school, 2024

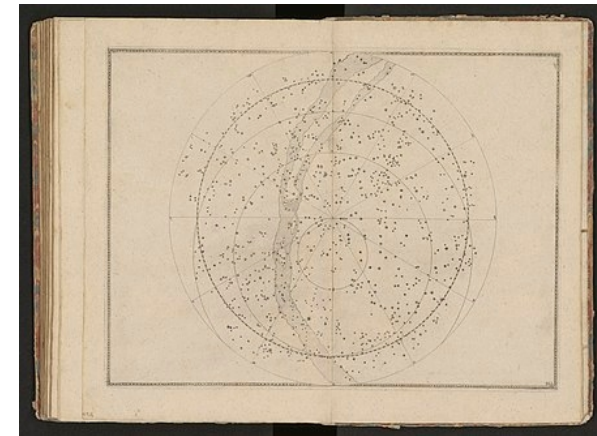
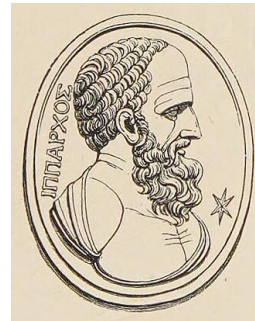
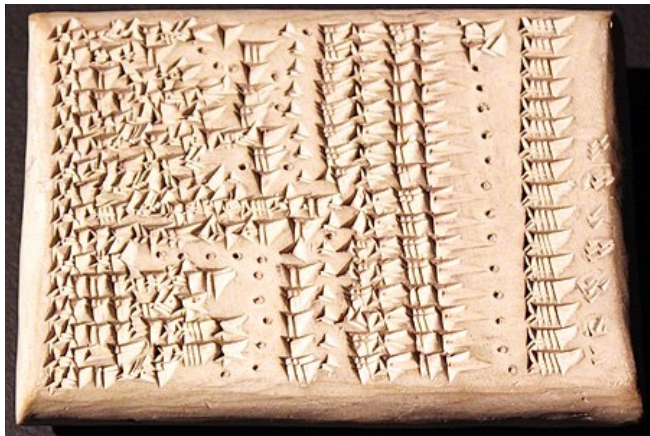
Jonathan Smoker





- What science do you want to do?
- Where do you want to obtain your data?
- Photometric systems
- The CCD equation
- Preparing your observations
- Post-observation data reduction
- Photometry

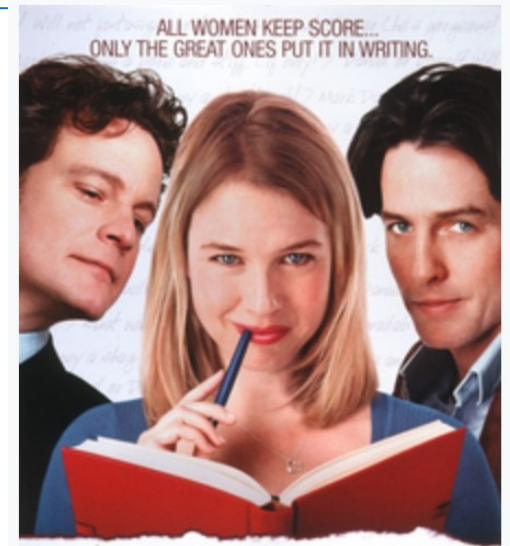
# A long time ago....







# Slightly more recently....







## Imaging / Photometry:

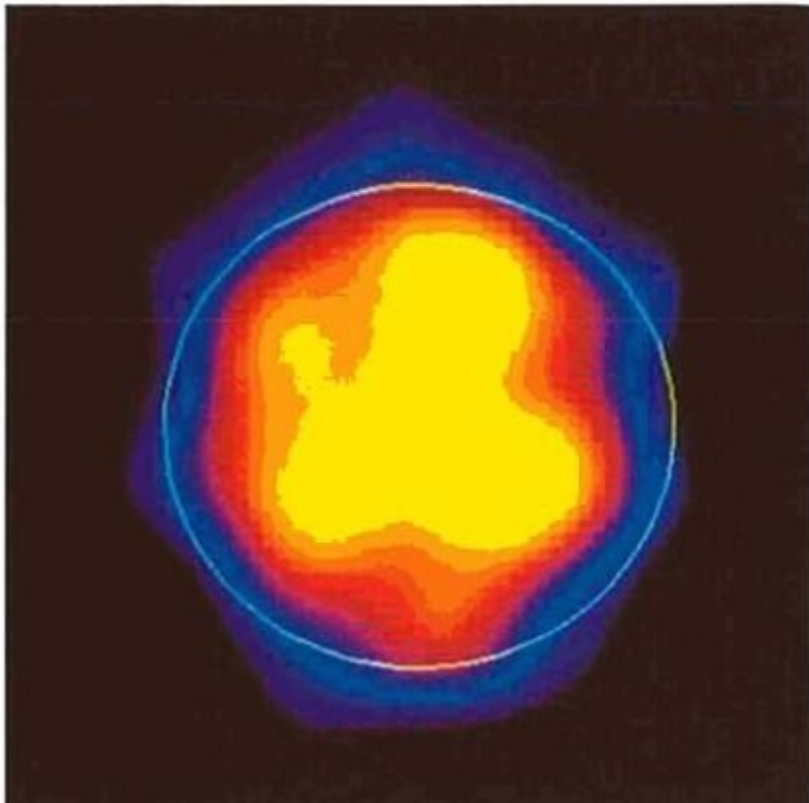
What science do you want to do?



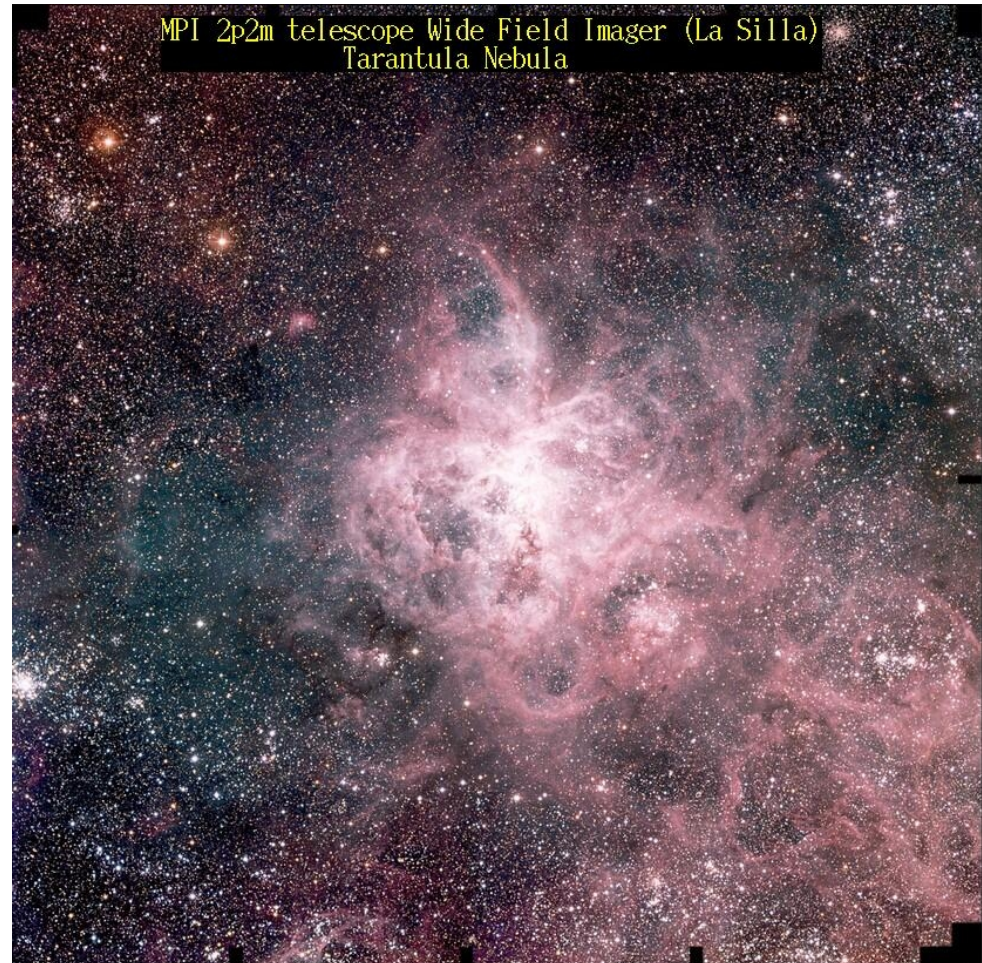
# What science do you want to do ?

## Single object?

NTT Sharp2 image of Titan 0.18" PSF (Beuzit et al. 1994)



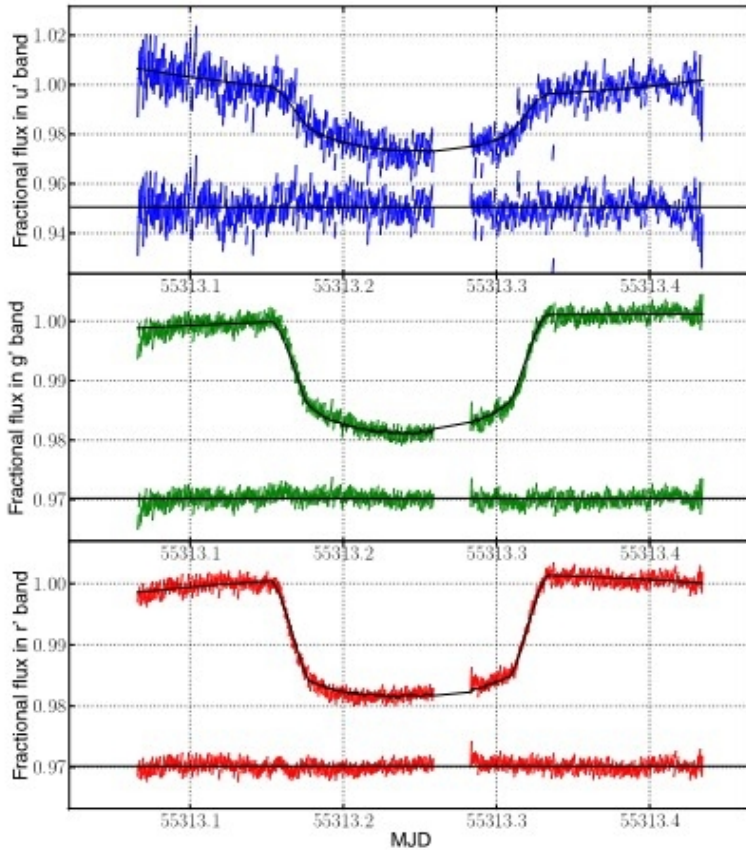
## Wide field?





# What science do you want to do ?

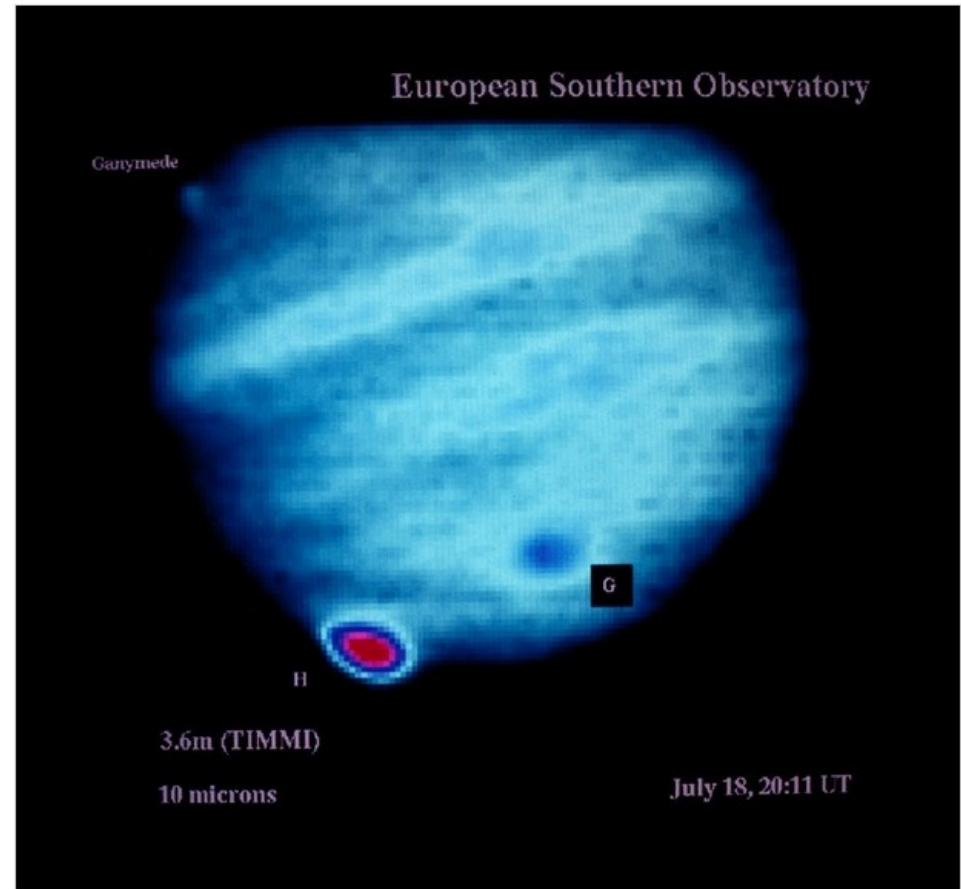
## High time resolution?



, NTT (Bento+ 2013)

## Infrared?

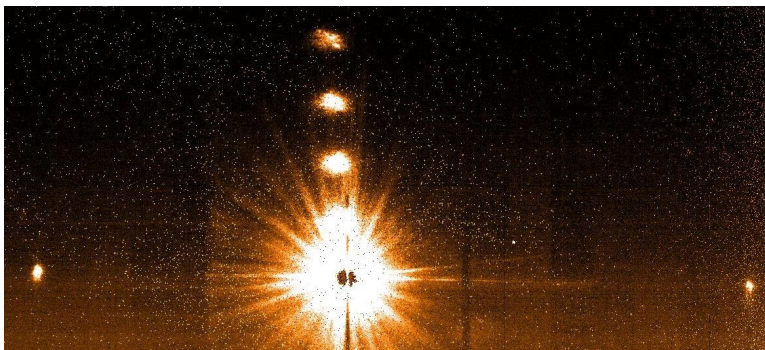
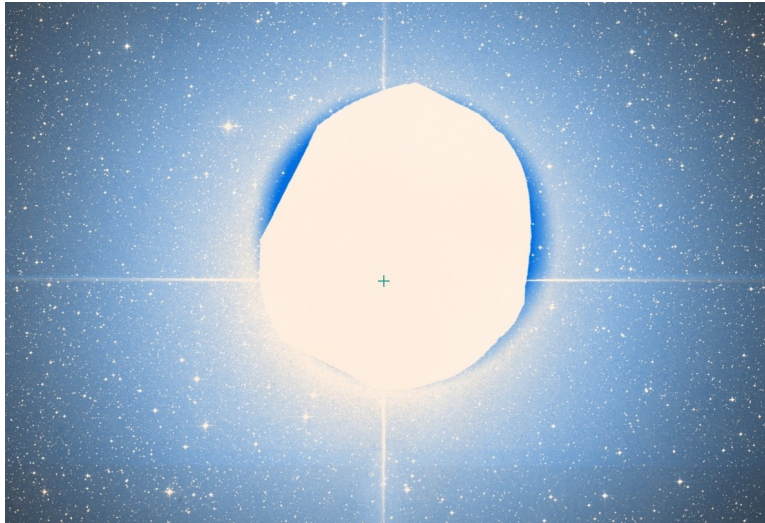
Comet Shoemaker–Levy 9 observations



Observations of comet Shoemaker–Levy 9 impacting Jupiter on July 18, 1994.

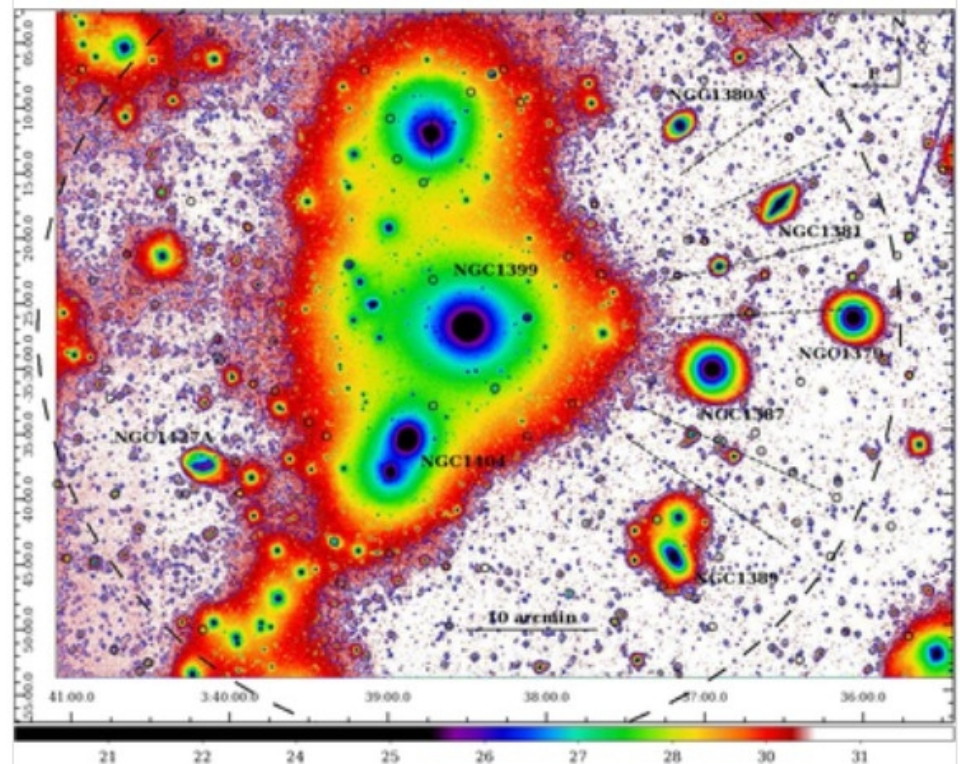
# What science do you want to do ?

Bright objects?



(Sirius: SIMBAD / CRIRES+)

Or faint?



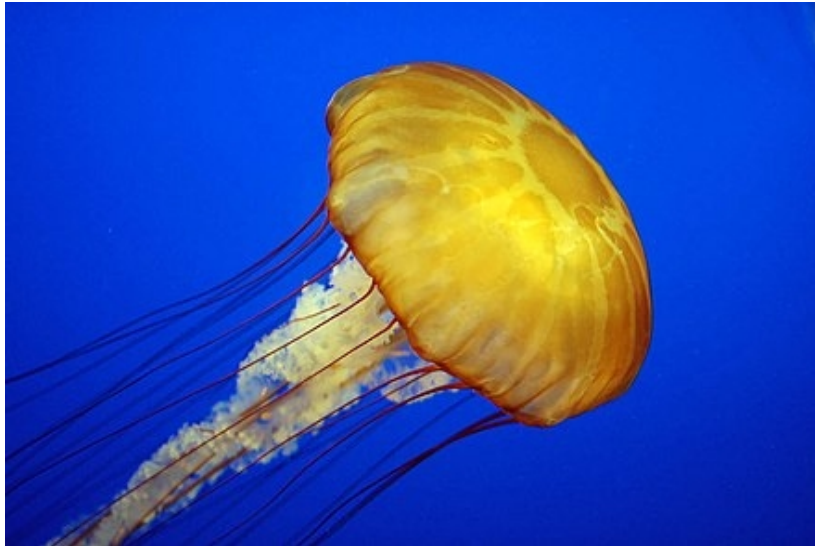
(Iodice+, 2017), Fornax



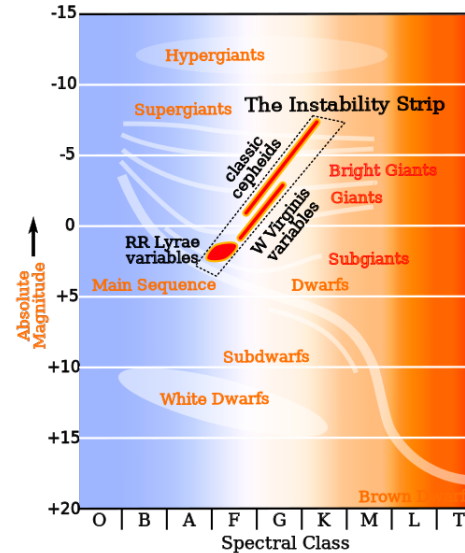


# What science do you want to do ?

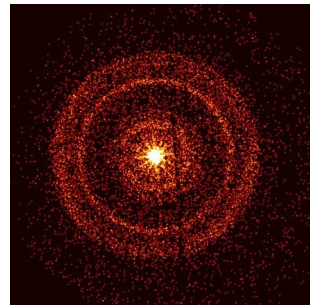
## Fast reaction time needed?



## Or not?



For example gamma ray bursts (below),  
supernovae,  
gravitational wave  
event follow up  
etc.





No instrument can do everything!



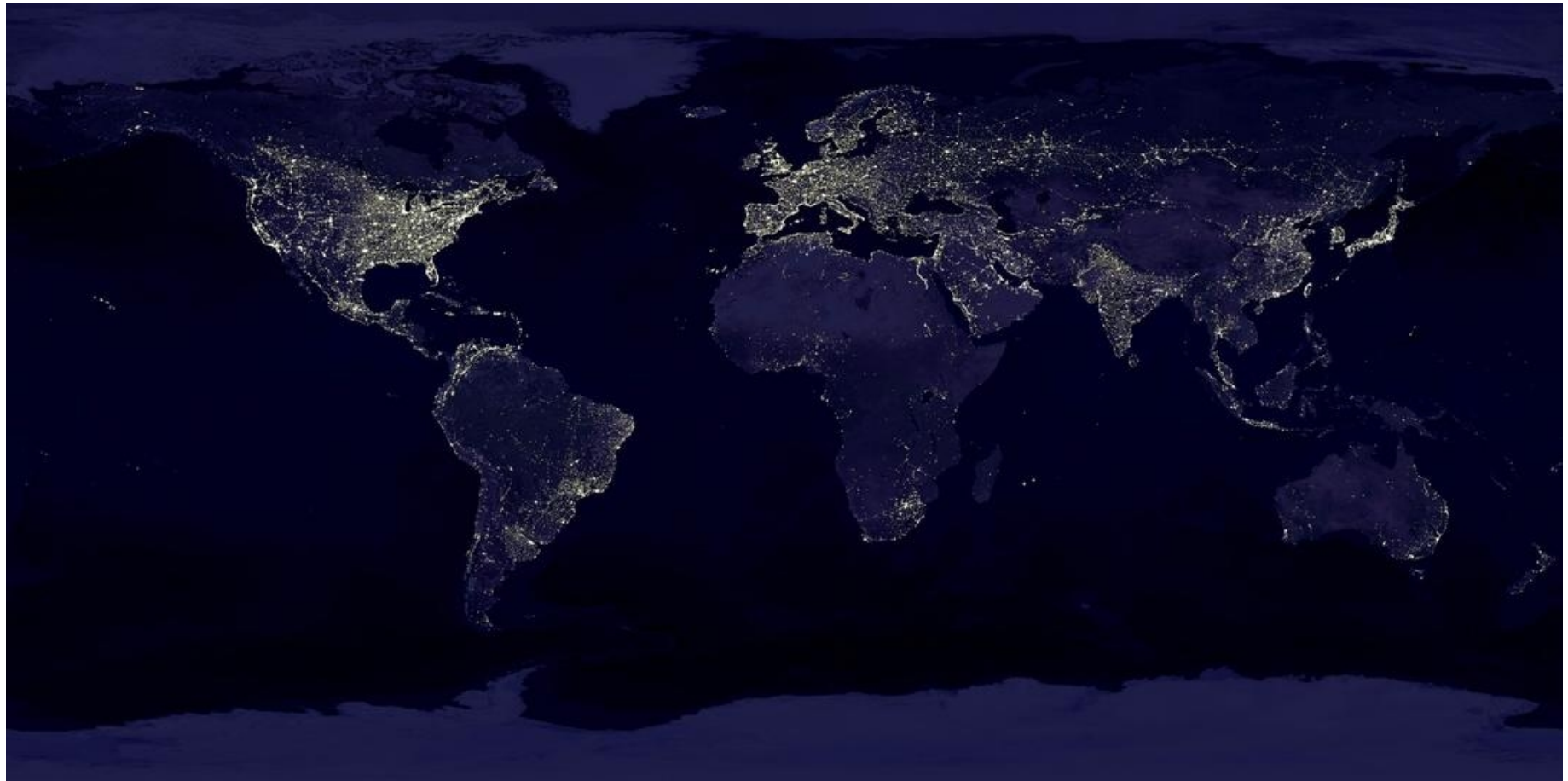




**Imaging / Photometry:  
Where do you want to obtain your data?**



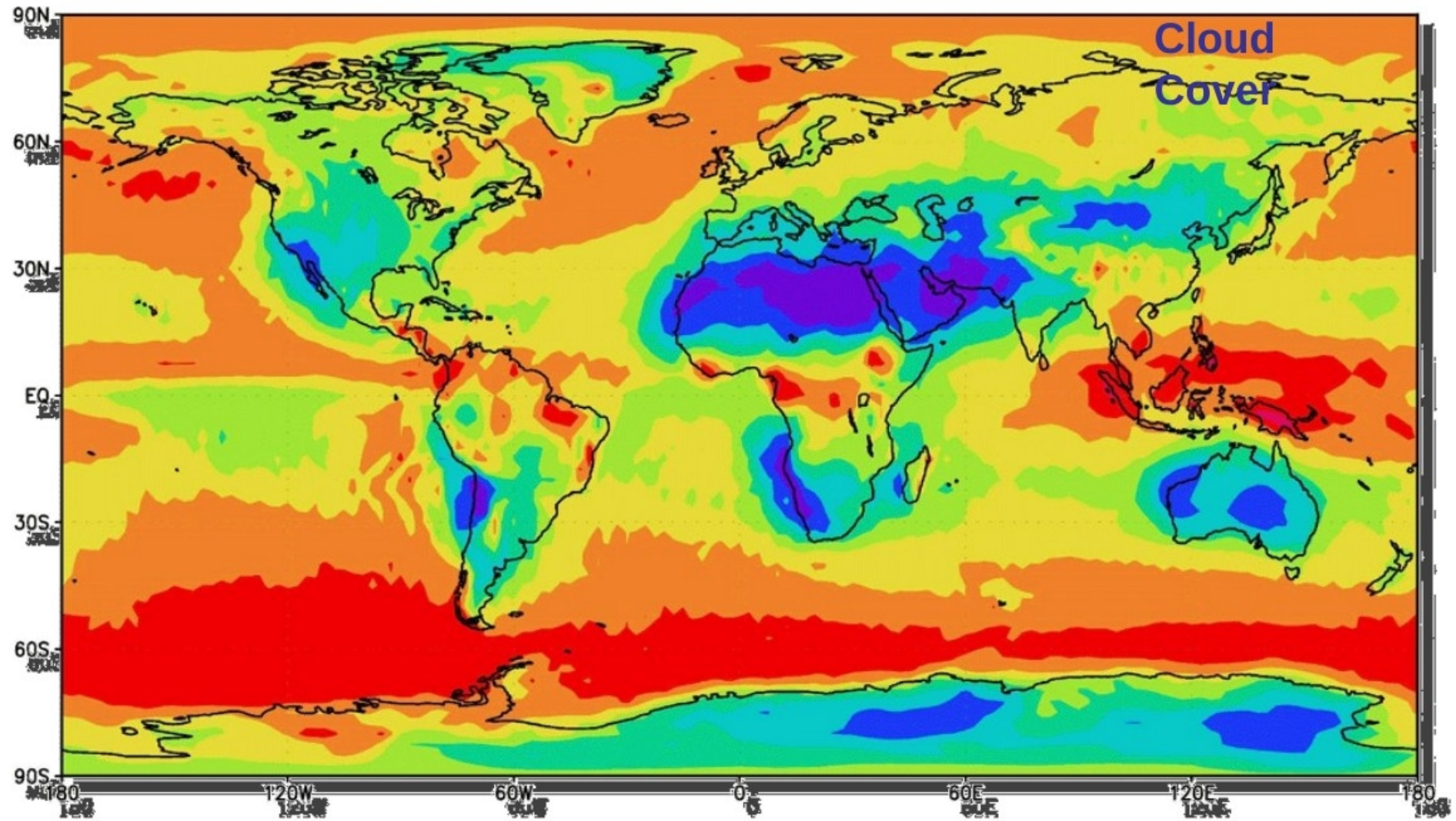
# Somewhere with dark skies







# Somewhere with little or no cloud cover



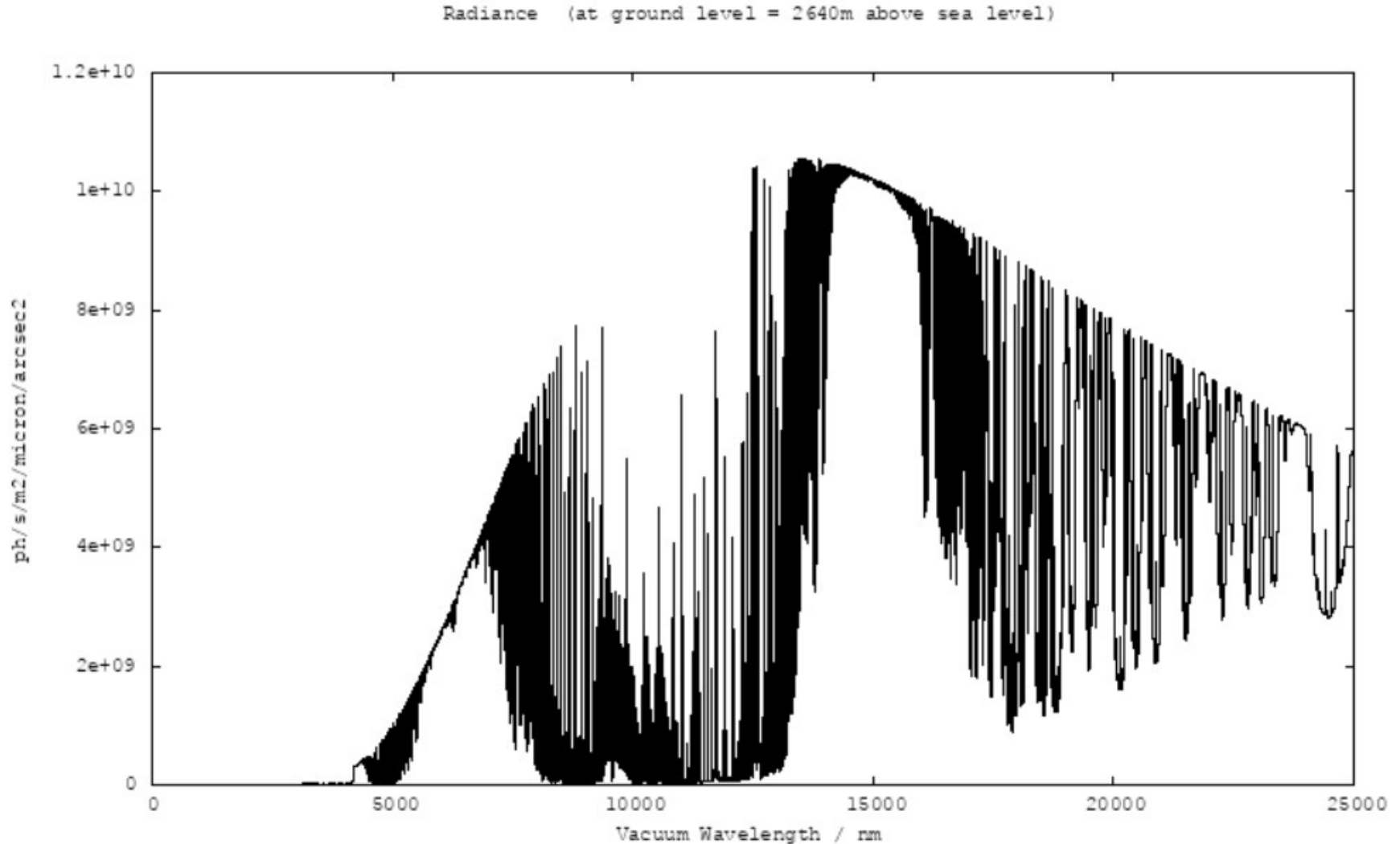
# High and remote mountains!





# Sky counts against wavelength optical to infrared

[www.eso.org/observing/etc/skycalc](http://www.eso.org/observing/etc/skycalc)



What two things stand out from this plot?







# An interlude.... Which is the highest mountain in the world?



*(a) Everest (Nepal; 8848m) (b) Chimborazo (Ecuador; 6263m) (c) Mauna Kea (Hawaii; 4207m) (d) Kilimanjaro Tanzania (5895m).*





## Imaging / Photometry:

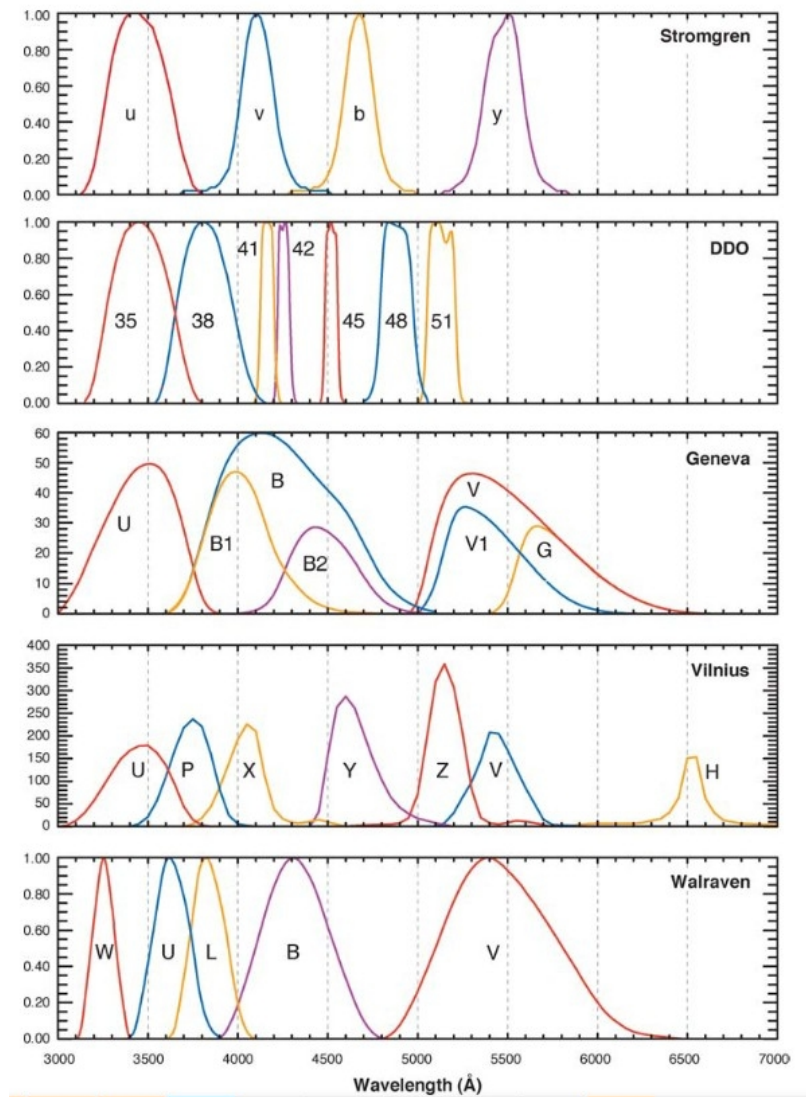
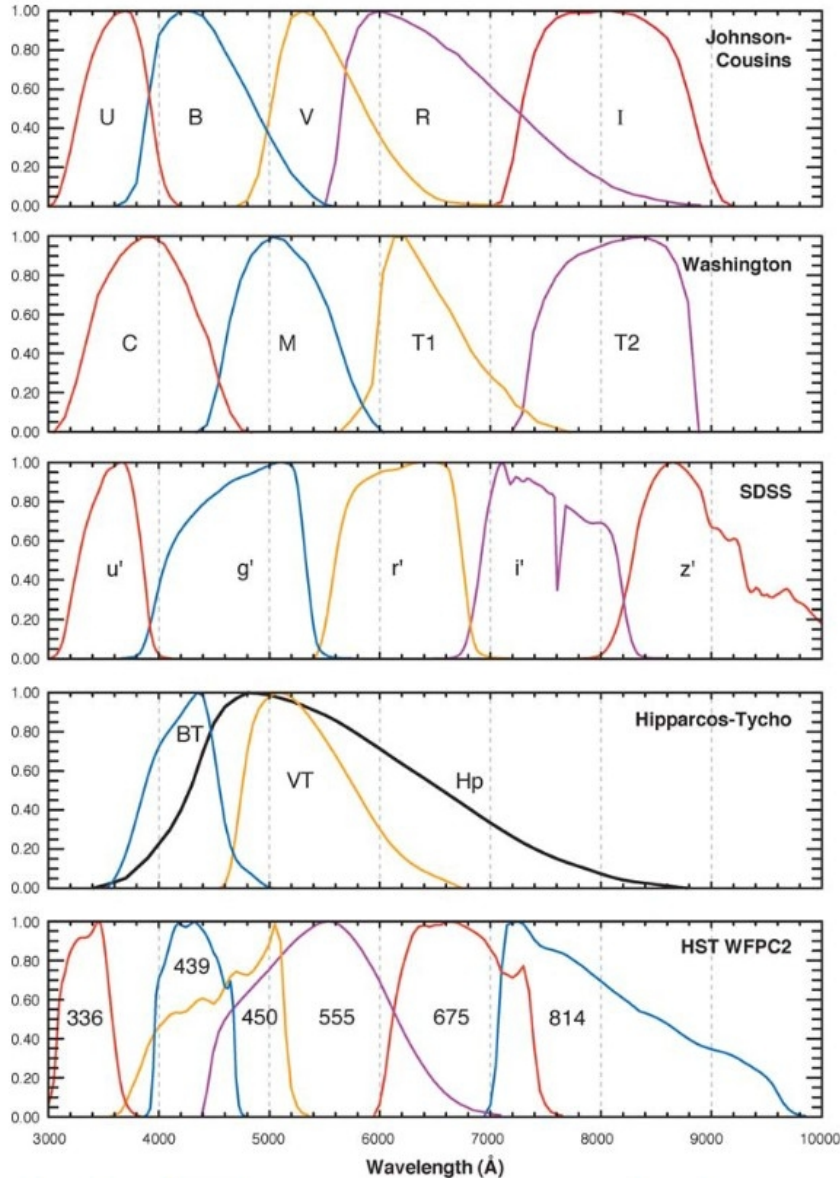
**What wavelength / filter do you want to observe  
and with what filter width?**

**This brings us to photometric systems. These are a defined  
set of passbands (or filters) with a known sensitivity as a  
function of wavelength.**



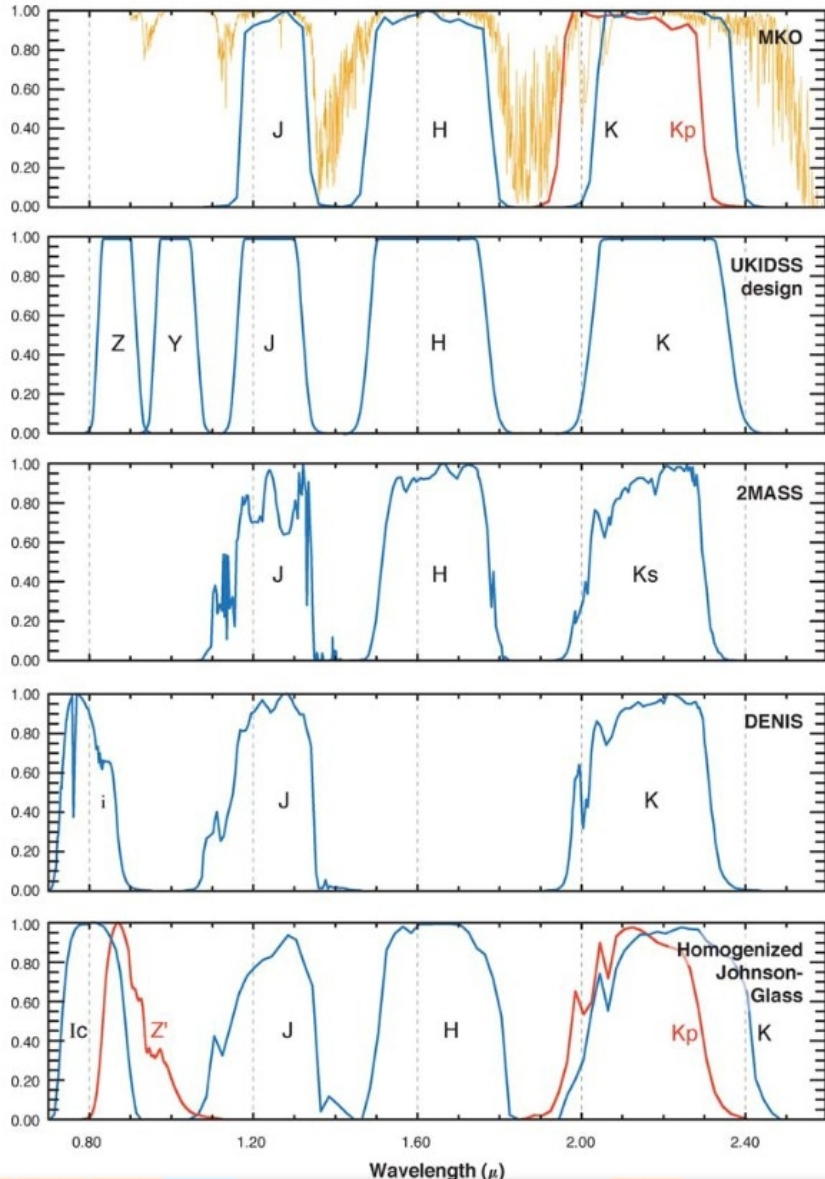
# Photometric systems: optical (from Bessel 2005)

## Can you see any issue with “U” ?





# Photometric systems: near-Infrared (from Bessel 2005)



**L** → 3450 nm

“NIR infrared”

**M** → 4700 nm

**N** → 10500 nm

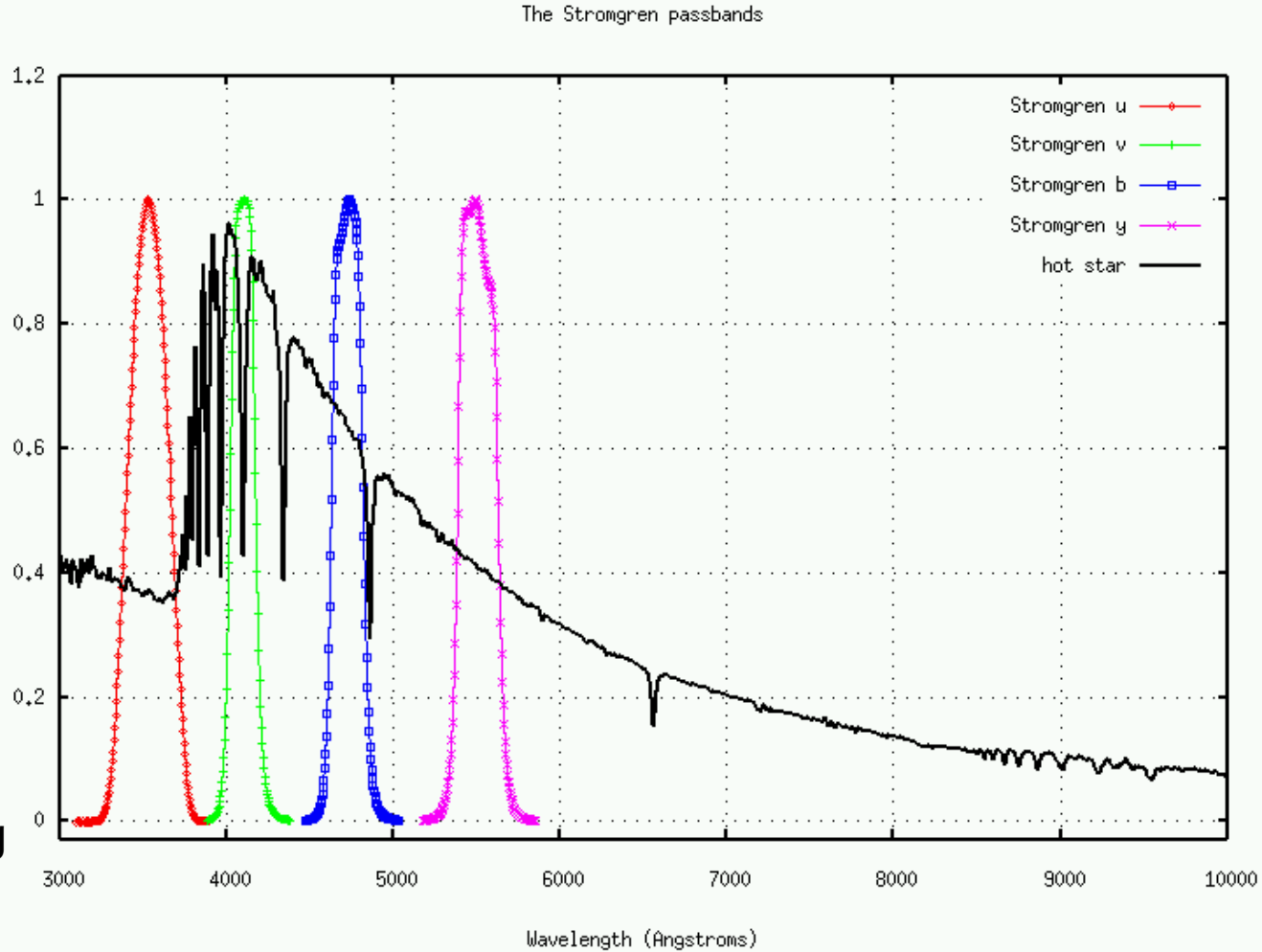
**Q** → 21000 nm

**Bands typically chosen to match atmospheric windows with less telluric absorption.**



# An example of a photometric system: Why were the Stromgren bands chosen to be as they are?

- u avoids the Earths atmospheric UV cutoff
- y measures magnitude ( $y = V$ )
- (b-y) colour gives an Idea of stellar temp hence spectral type
- c1 index that measures the balmer discontinuity
- m1 index to measure line blanketing as v is located where blanketing is strong
- reddening is also estimated



(Michael Richmond: [phys.libretexts.org](http://phys.libretexts.org))



## Imaging / Photometry:

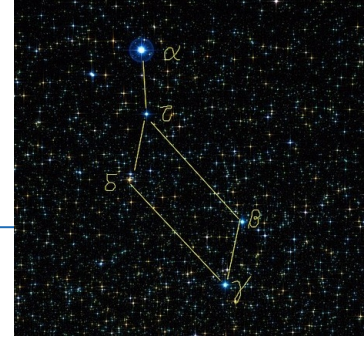
The magnitude scale (or scales...) and “CCD equation”

(CCD = Charged Coupled Detector)





# The magnitude scale (Pogson 1856) and differences between Vega and AB systems



$$m - m_0 = -2.5 * \log (I / I_0) \quad I_1, I_0 \text{ are the extracted counts}$$

An object that has  $m=0$  is 100 times brighter than one at  $m=5$

An object that has  $m=0$  is 100,000,000 times brighter than one at  $m=20$

The “0” subscript refers to a measurement relative to a “standard” star that is used to set the zero point of the system. This was historically chosen to be Vega i.e. in the equation above  $I_0$  is the flux of Vega in a given band.

## Vega magnitudes:

These define:  $U\_Vega = B\_Vega = V\_Vega = R\_Vega = I\_Vega = 0.0$

Unfortunately:

- The spectral energy distribution (SED) of Vega is not actually flat
- If you look at SIMBAD then Vega (alfa Lyr) is a delta Sct Variable

## AB magnitudes:

In this system we define a zero point to be a source with a flat SED.

The zero point in every filter is defined to be 3631 Jy.

# “The CCD equation” to determine S/N ratio

In most cases we want to maximise the S/N ratio in our observations.

To predict the expected S/N, we may use the following equation:

$$\frac{S}{N} = \frac{N_*}{\sqrt{N_* + n_{pix} (N_{sky} + N_{dark} + N_{RON}^2)}}$$

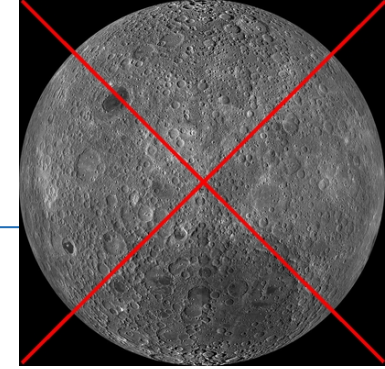
Maximise Numerator!

Minimise Denominator!

How do we maximise the numerator and minimise the denominator?



# How to maximise the S/N ratio for point sources, especially faint targets

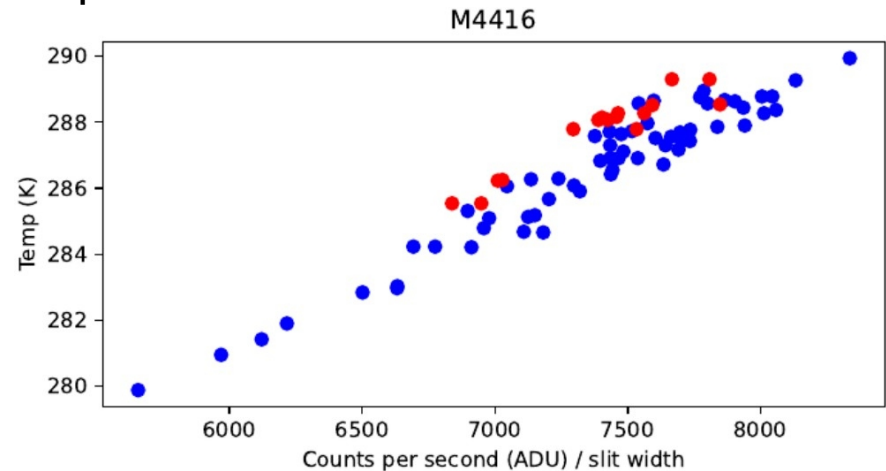


- Have a larger mirror, or integrate for longer.
- Observe as close to the zenith as you can to minimise atmospheric absorption.
- In the optical observe in dark time (little Moon)
- In the mid-infrared observe when the temperature is colder and/or when there is less water vapour in the atmosphere.
- Observe with **better seeing** / image quality (if readout noise an issue), or use adaptive optics. More light on fewer pixels!

**Bright source:**  $S/N = \sqrt{N^*}$

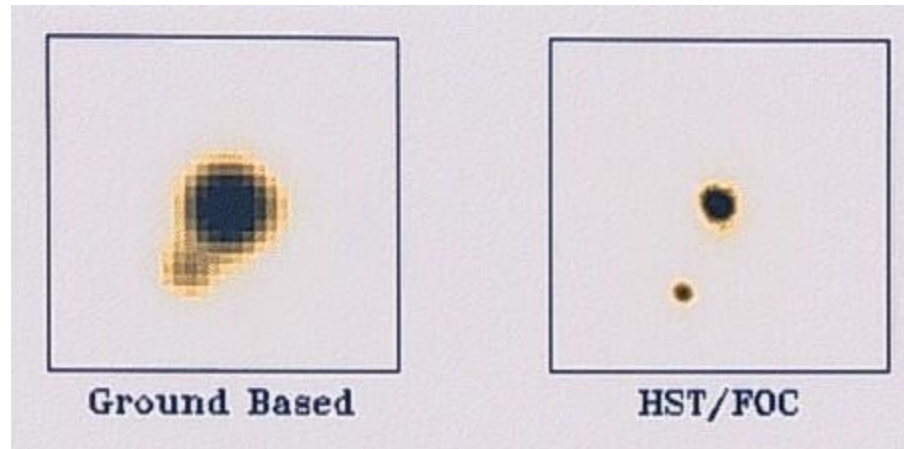
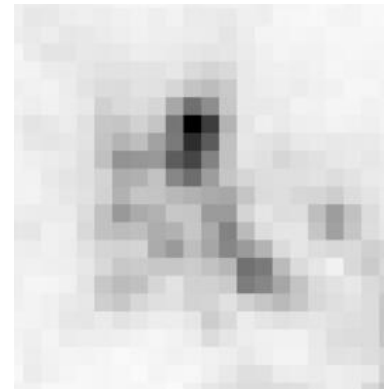
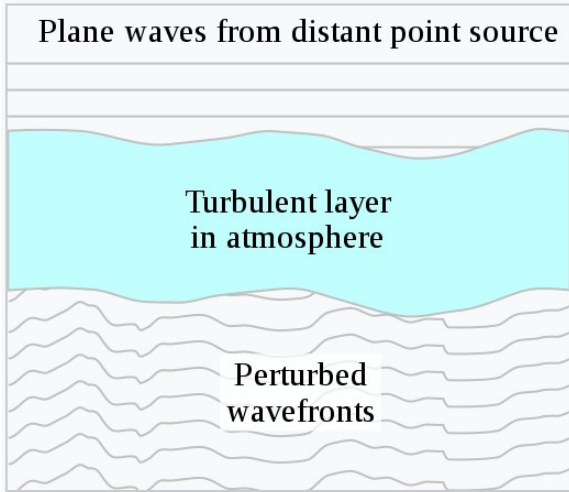
**Sky dominated:**  $S/N$  proportional to  $1/n_{\text{pix}}$  → As  $n_{\text{pix}}$  is proportional to seeing squared then better seeing increases  $S/N$  a lot!

**Readout noise dominated:** If the sky and dark current are low then you need to readout less often (longer integration times) and / or bin the detector if possible



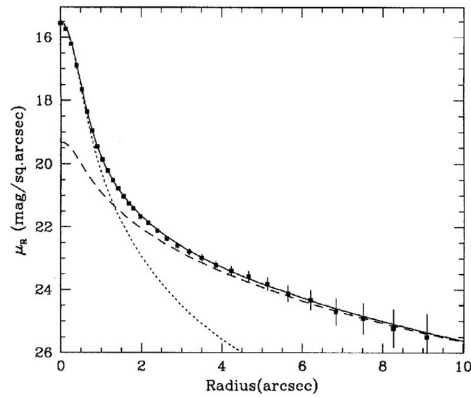


# Effect of the atmosphere on ground based stellar image and comparison between ground based (natural seeing) and space based

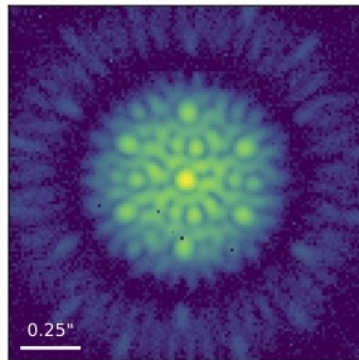


# Effect of the instrument and telescope point spread function on the final image.

NTT  
(Falomo 1996)

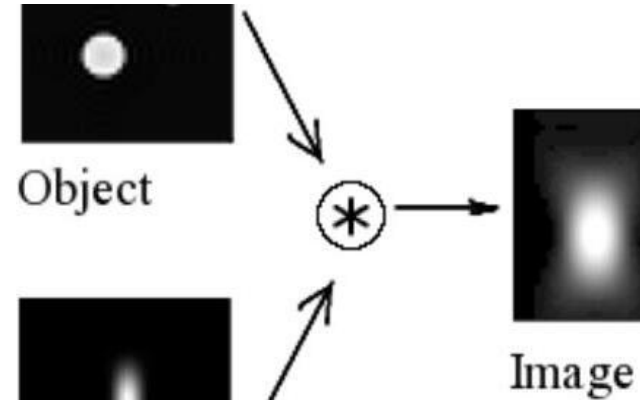
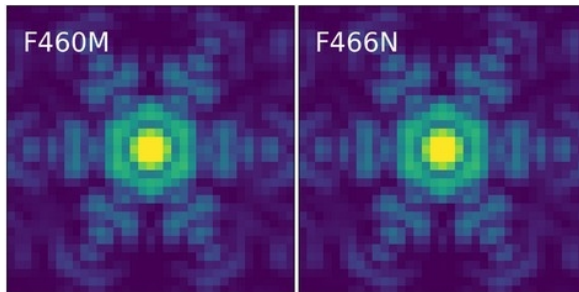


HIP18714 with SAM-7 Ks



ERIS

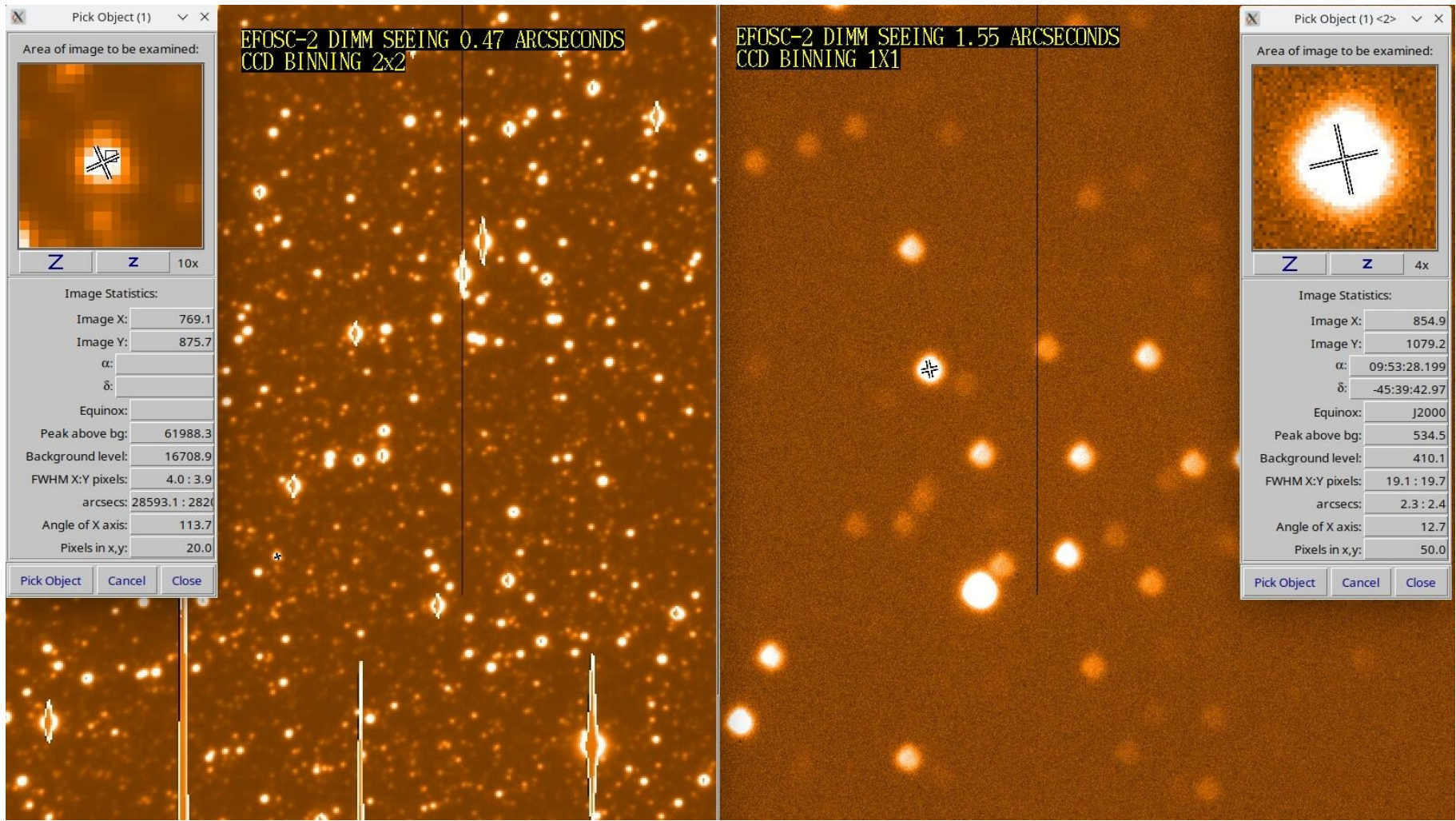
JWST



Instrument and telescope PSF



# “Seeing”: Good (left) and bad (right) image quality EFOSC-2. We are at the mercy of the atmosphere!

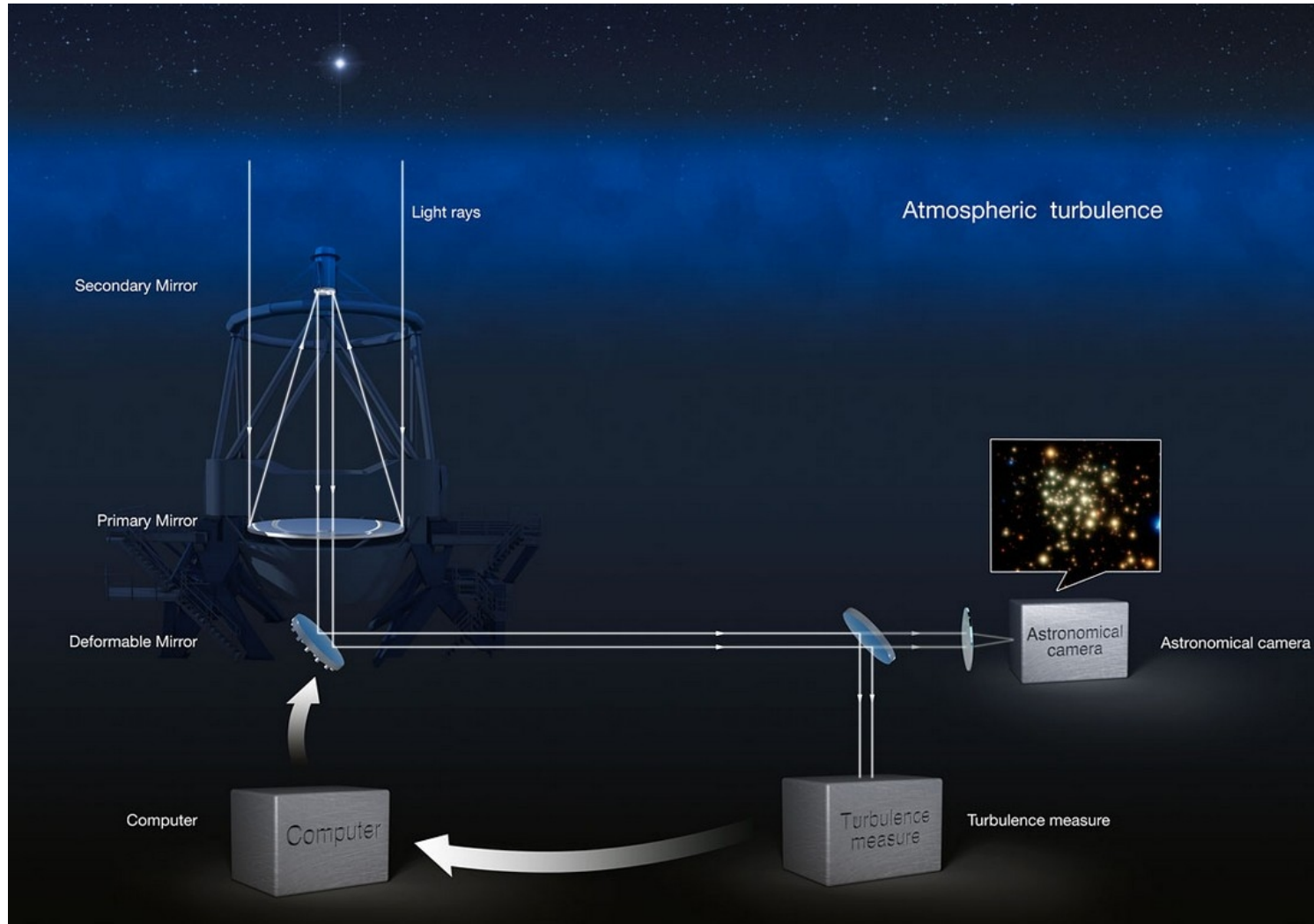
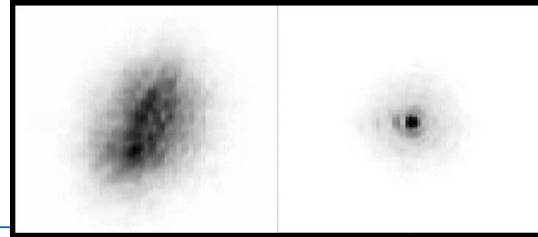


Note “IQ on a large telescope is always better than the seeing due to the finite outer scale of the turbulence” (Martinez 2010).

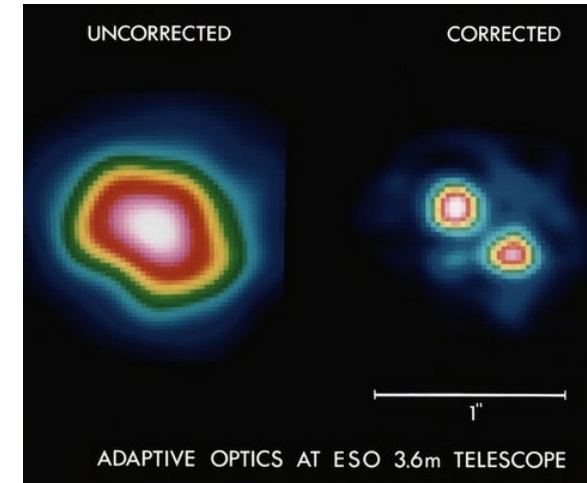
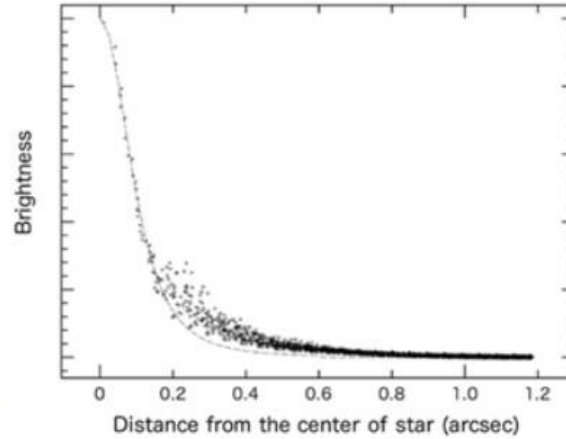
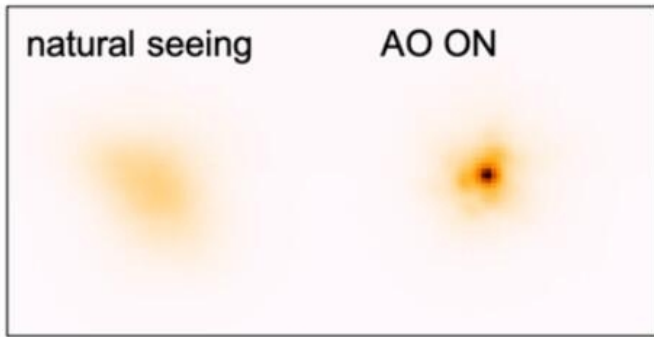




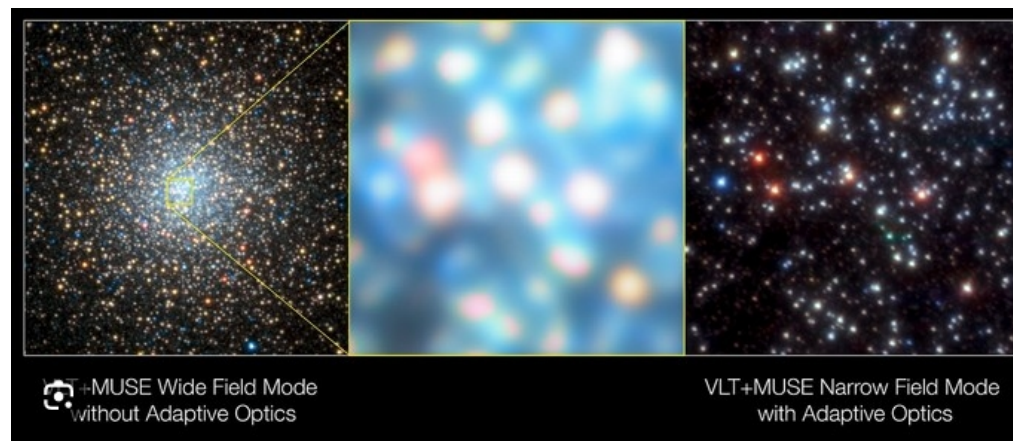
With adaptive optics we can drastically improve the image quality. However, only some instruments have AO.



# Images with and without adaptive optics (top: La Silla 1-m and 3.6-m, bottom: Paranal 8.2-m)

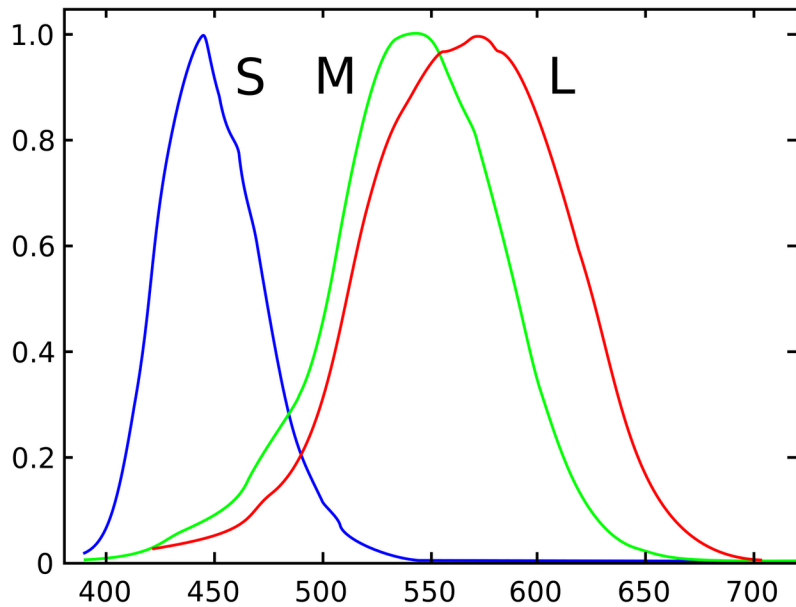
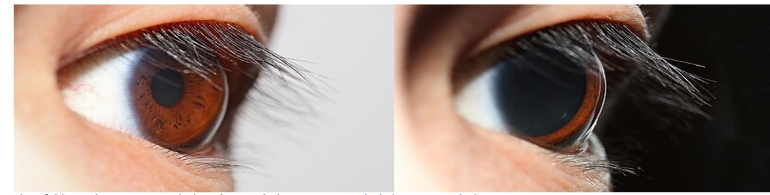


Minezaki et al. (2020) La Silla 1m tel.



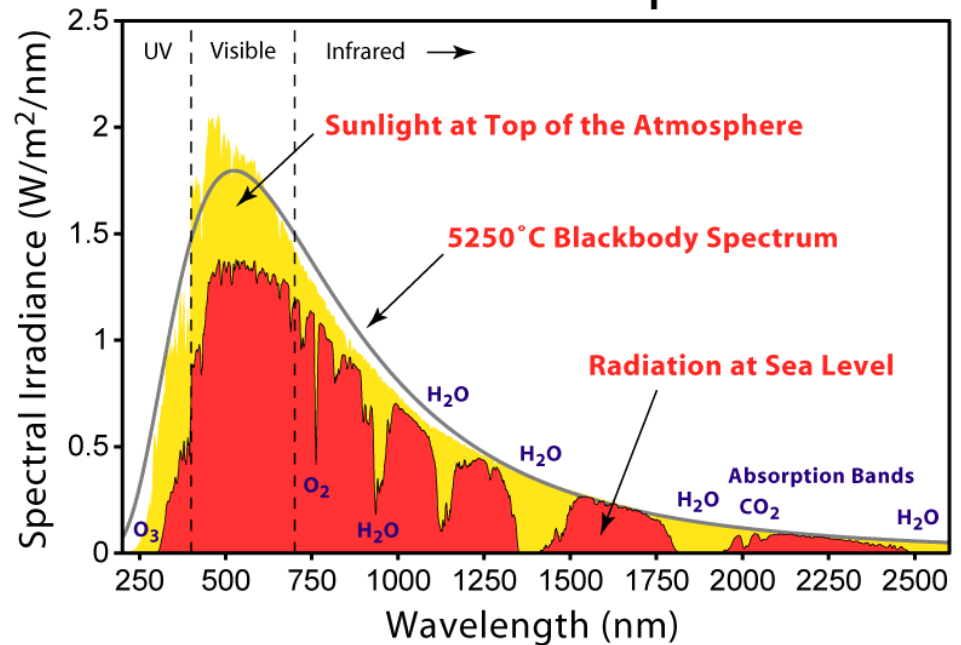


# An interlude - the human eye



(V. Zekowitz)

## Solar Radiation Spectrum








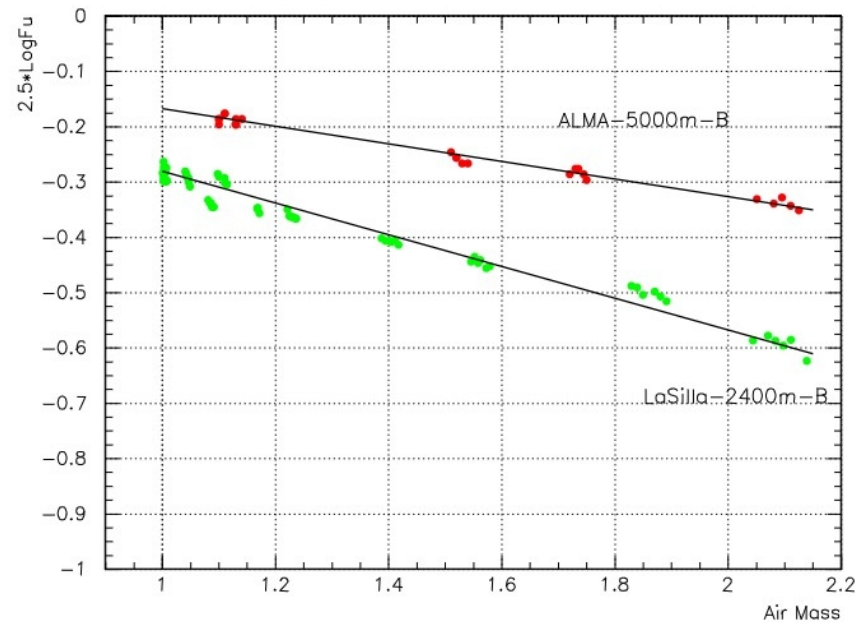
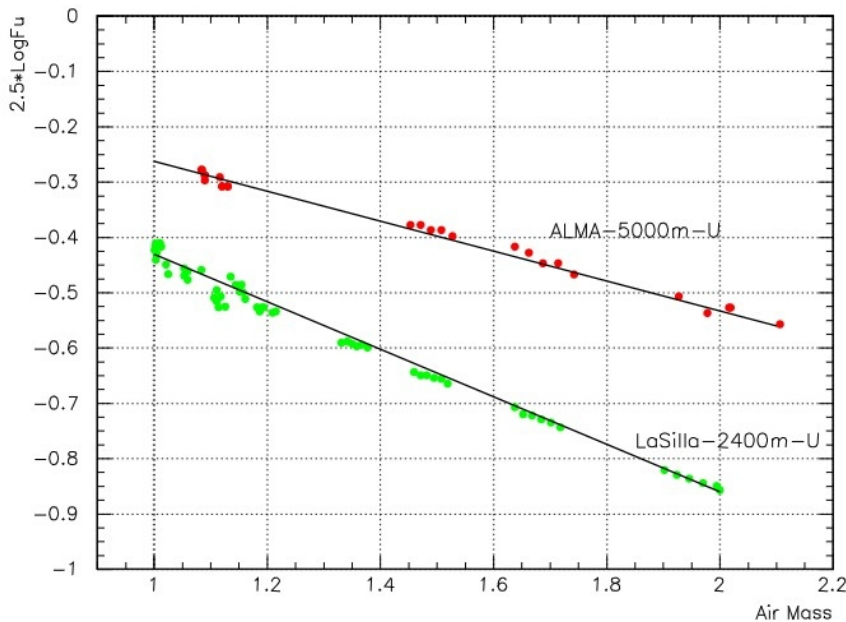
## Imaging / Photometry:

Prior to writing your proposal or to your observing run

- Check your targets are visible (!). Try and observe near to The meridian (Hour Angle = Local Siderial Time – Right Ascension = 0). Why?
- Decide how many standard stars you need to observe and at what airmass. Related to the previous point.
- Decide if you should split your exposures (multiple exposures of the same source e.g. 3x600s instead of 1x1800s). Why? Why not?
- Are chopping and/or nodding needed? Sky frames?
- Estimate the detected counts as a function of exp time, Moon, Moon, sky conditions, airmass & seeing. 

# Often it is best to observe as near to the zenith as possible, especially in the bluer bands.

- Coefficients may change depending on the night. For very accurate photometry you might have to observe a standard star at many different airmasses over the night if observing several targets.
- On La Silla in the U-band, the apparent magnitude difference between observing at the zenith and airmass 2 is about -0.4, corresponding to a difference of 1.44 in flux (or observing time!). Seeing also gets worse.

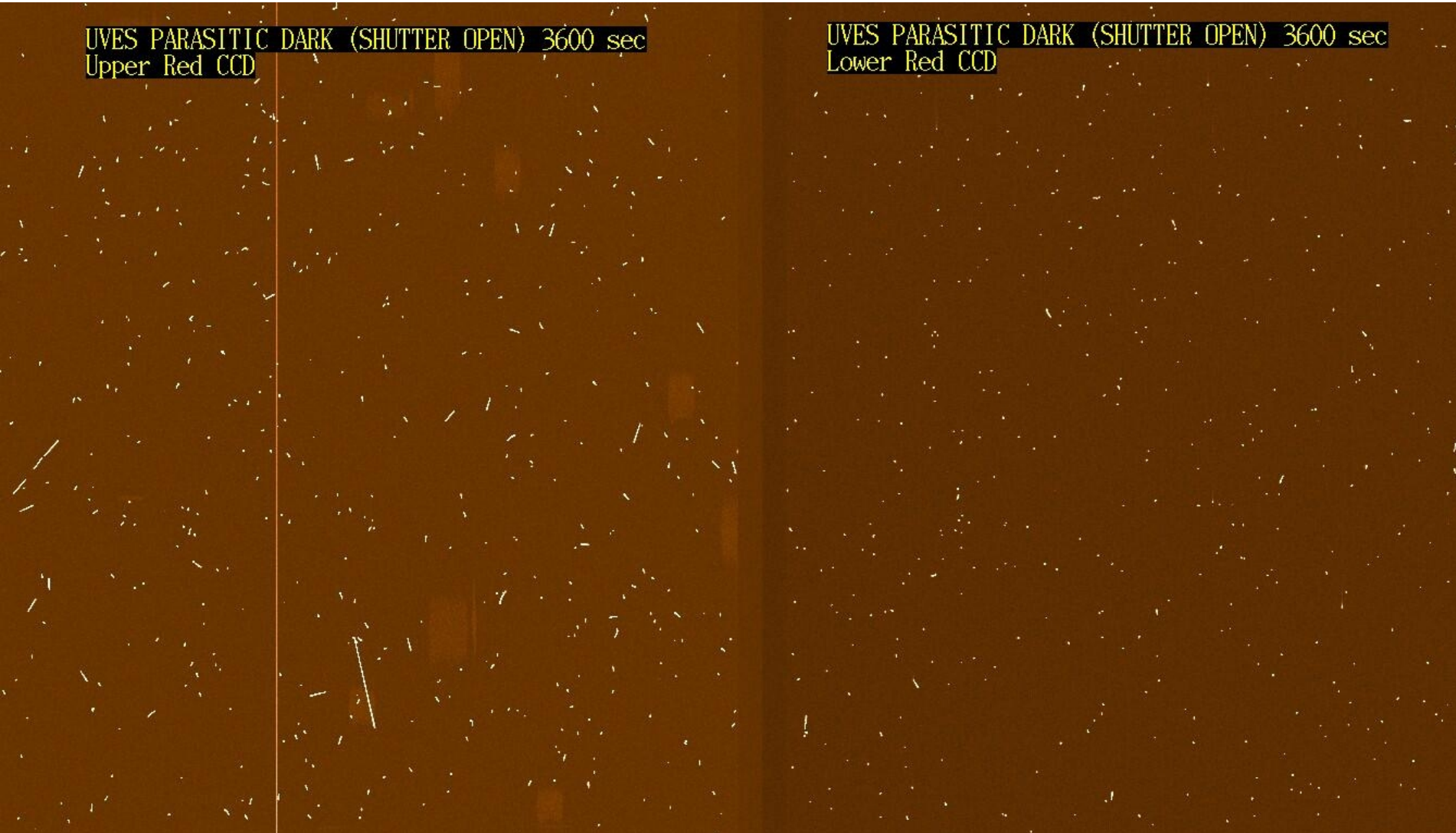


(Giraud et al.)

# Why split images? UVES parasitic dark images (shutter open) showing cosmic rays and something else

UVES PARASITIC DARK (SHUTTER OPEN) 3600 sec  
Upper Red CCD

UVES PARASITIC DARK (SHUTTER OPEN) 3600 sec  
Lower Red CCD





# Are sky frames needed? (Optical)



47-Tuc image taken with La Silla 1.0-m Schmidt telescope

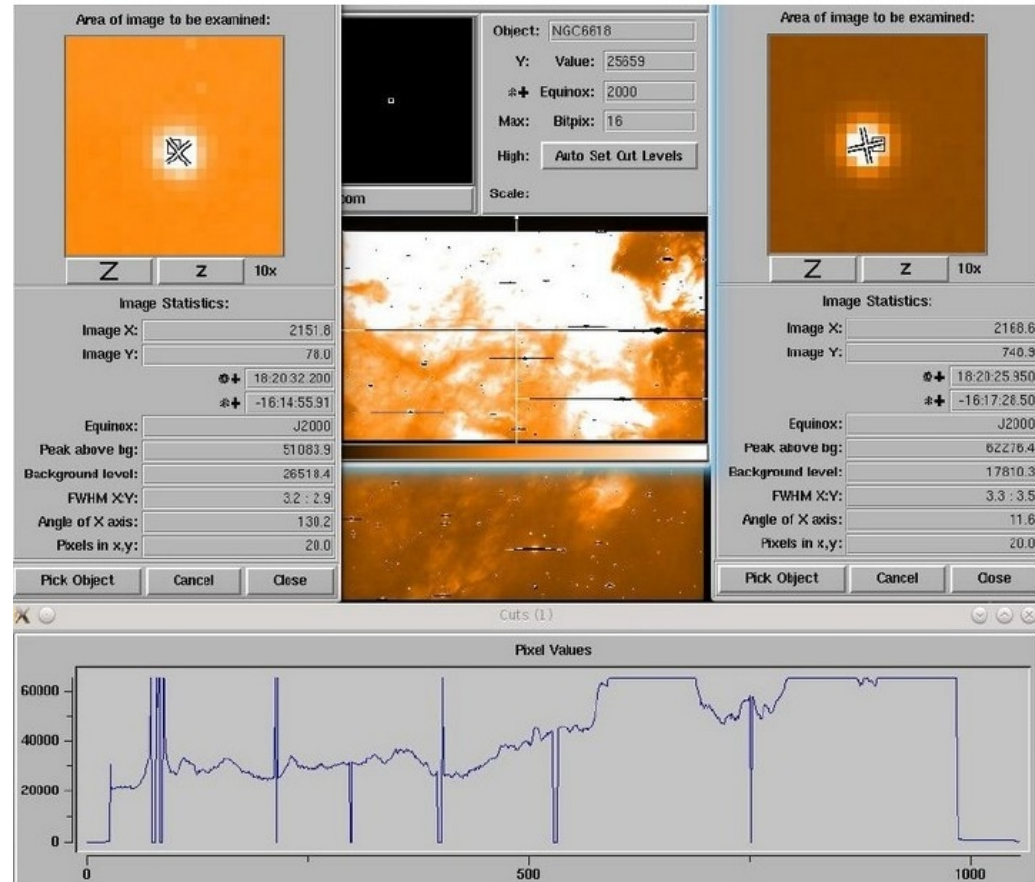
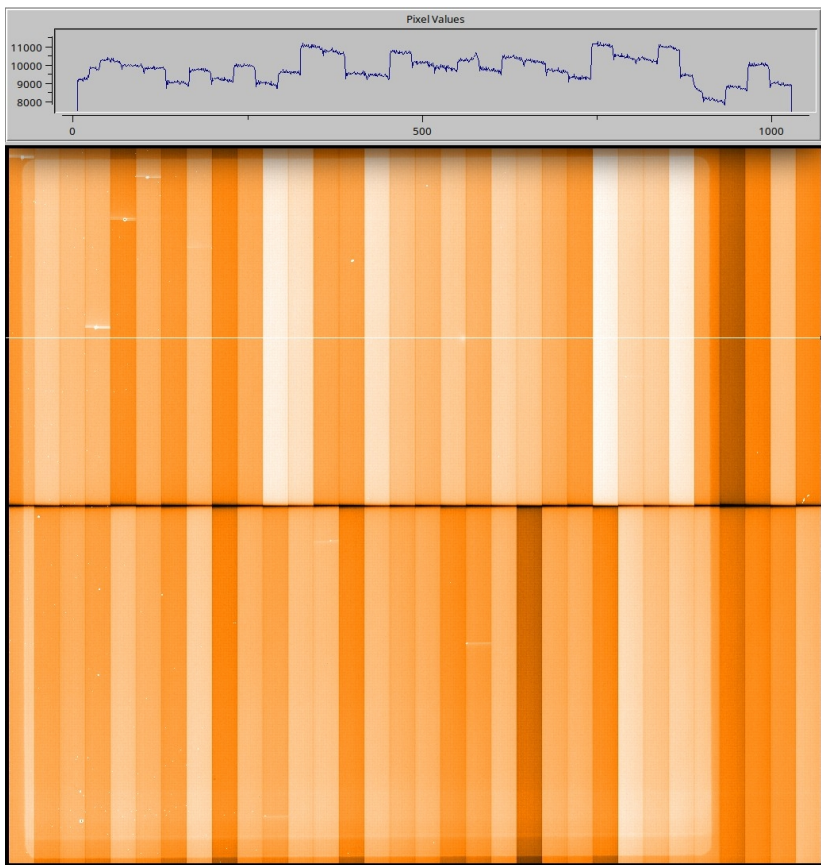


Image of a nebula taken with the FORS2 instrument

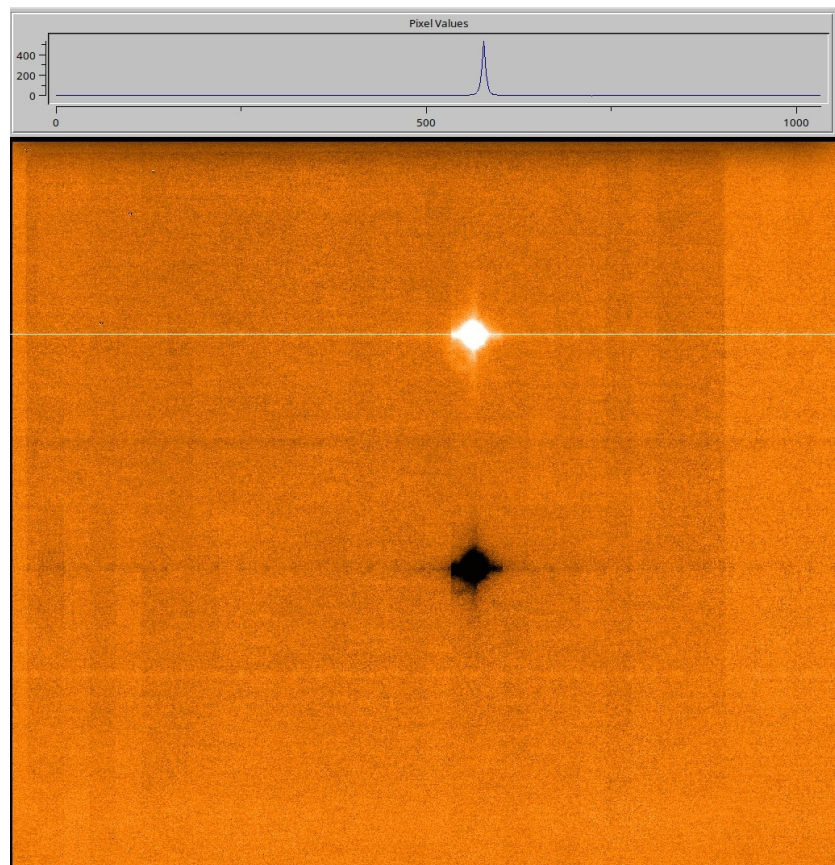




Are sky frames needed? Nearly always in the far infrared (> 5 microns) as the sky level is so high. VISIR image below of mK=2 star with DIT=0.01 seconds!



Individual VISIR M-band image. Star only just visible as sky level is so high.



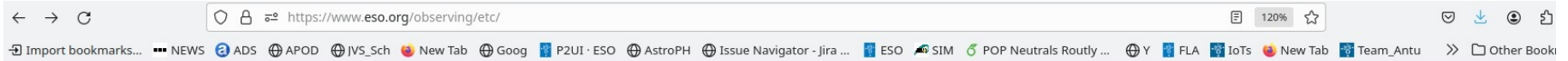
Combined VISIR M-band image with multiple chopping positions subtracted.





# Estimate the expected counts, for example using the ESO exposure time calculators (ETCs):

<https://www.eso.org/observing/etc>



## ESO Exposure Time Calculators



### News and Notes

#### August 31, 2023: P113 phase 1

- HARPS/NIRPS detector parameters updated, including saturation limits. Introduced LSF convolution.

#### August 24, 2023: P113 phase 1

- ERIS-NIX LSS mode supported.
- XSHOOTER: Added a note about NIR stray-light.
- FORS2 imaging: Updated 530-25 +84 filter profile.




#### Bug fixes

[Details here](#)



### Documentation and Tools

- Support: <https://support.eso.org>
- [Frequently Asked Questions](#)
- [Formula Book](#)
- [Database of efficiency profiles](#)
- [Deprecated ETCs](#)
- [SkyCalc Sky Model Calculator](#)
  - with advanced Almanac
  - command-line interface [skycalc\\_cli](#)

 Facility	 Imaging	 Spectroscopy
La Silla	<div data-bbox="836 561 1033 589">EFOSC2</div> <div data-bbox="1058 561 1255 589">SUSI</div> <div data-bbox="836 618 1033 646">WFI</div> <div data-bbox="1058 618 1255 646">SOFI</div>	<div data-bbox="1377 561 1574 589">EFOSC2</div> <div data-bbox="1599 561 1796 589">HARPS/NIRPS</div> <div data-bbox="1377 618 1574 646">FEROS</div> <div data-bbox="1599 618 1796 646">SOFI</div>
Paranal UT1	<div data-bbox="948 675 1145 704">FORS2</div>	<div data-bbox="1377 675 1574 704">FORS2</div> <div data-bbox="1599 675 1796 704">KMOS</div>
Paranal UT2	<div data-bbox="948 753 1145 782">VISIR</div>	<div data-bbox="1377 732 1574 761">UVES</div> <div data-bbox="1599 732 1796 761">UVES-FLAMES</div> <div data-bbox="1377 789 1574 818">GIRAFFE</div> <div data-bbox="1599 789 1796 818">VISIR</div>
Paranal UT3	<div data-bbox="836 861 1033 889">SPHERE-IRDIS</div> <div data-bbox="1058 861 1255 889">SPHERE-ZIMPOL</div>	<div data-bbox="1377 839 1574 868">X-SHOOTER</div> <div data-bbox="1599 839 1796 868">SPHERE-IFS</div> <div data-bbox="1493 889 1690 918">CRIRES</div>
Paranal UT4	<div data-bbox="836 939 1033 968">HAWK-I</div> <div data-bbox="1058 939 1255 968">ERIS</div>	<div data-bbox="1377 939 1574 968">MUSE</div> <div data-bbox="1599 939 1796 968">ERIS</div>
Paranal ICCF		<div data-bbox="1493 996 1690 1025">ESPRESSO</div>
Paranal VLTi	<div data-bbox="884 1053 1081 1082">GRAVITY</div> <div data-bbox="1107 1053 1304 1082">MATISSE</div>	<div data-bbox="1377 1053 1574 1082">VisCalc</div> <div data-bbox="1599 1053 1796 1082">CalVin</div>
Paranal VISTA	<div data-bbox="948 1110 1145 1139">VIRCAM</div>	<div data-bbox="1493 1110 1690 1139">4MOST</div>
Paranal VST	<div data-bbox="948 1160 1145 1189">OmegaCAM</div>	
ELT	<div data-bbox="948 1218 1145 1246">ELT imaging</div>	<div data-bbox="1493 1218 1690 1246">ELT spectroscopy</div>







# Wide field imager ETC

## Target Input Flux Distribution

<input checked="" type="radio"/> Template Spectrum	A0V (Pickles) <input type="text"/>	Redshift z = <input type="text" value="0.00"/>	Target Magnitude and Mag.System: <input type="text" value="V"/> = <input type="text" value="20.00"/> <input checked="" type="radio"/> Vega <input type="radio"/> AB <i>Magnitudes are given per arcsec<sup>2</sup> for extended sources</i>
<input type="radio"/> MARCS Stellar Model	Teff=4000 log(g)=-0.5 [Fe/H]= 0 M= 1 <input type="text"/>		
<input type="radio"/> Upload Spectrum	Select... <input type="text"/>		
<input type="radio"/> Blackbody	Temperature: <input type="text"/> K		
<input type="radio"/> Power Law	Index: <input type="text"/> $F(\lambda) \propto \lambda^{index}$		
<input type="radio"/> Emission Line	Lambda: <input type="text"/> nm Flux: <input type="text"/> $10^{-16}$ ergs/s/cm <sup>2</sup> (per arcsec <sup>2</sup> for extended sources) FWHM: <input type="text"/> nm		

Spatial Distribution:  Point Source  Extended Source

### Sky Conditions

Moon FLI:  Airmass:

Almanac

PWV:  mm *Probability > 95% of realising the PWV  $\leq$  30.0 mm*

Seeing/Image Quality:

Turbulence Category: 

IQ:  arcsec FWHM at the airmass and reference wavelength

### Instrumental Setup

Filter:

Detector mode:  binning:

### Results

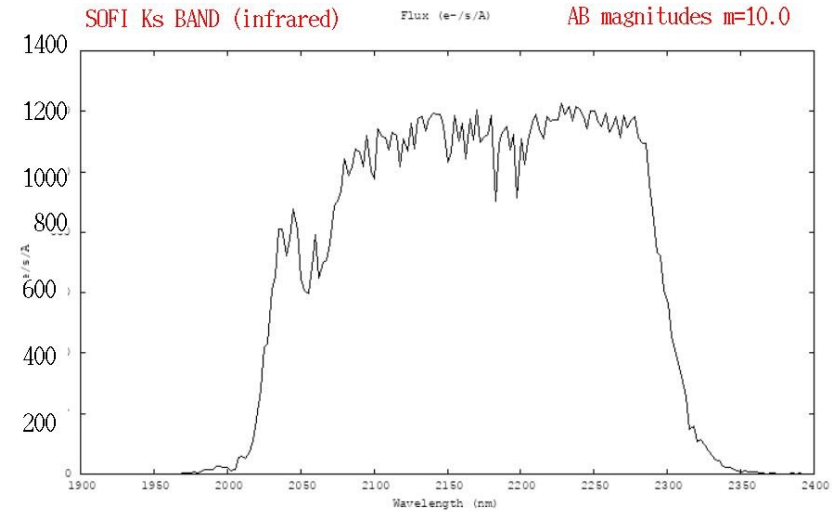
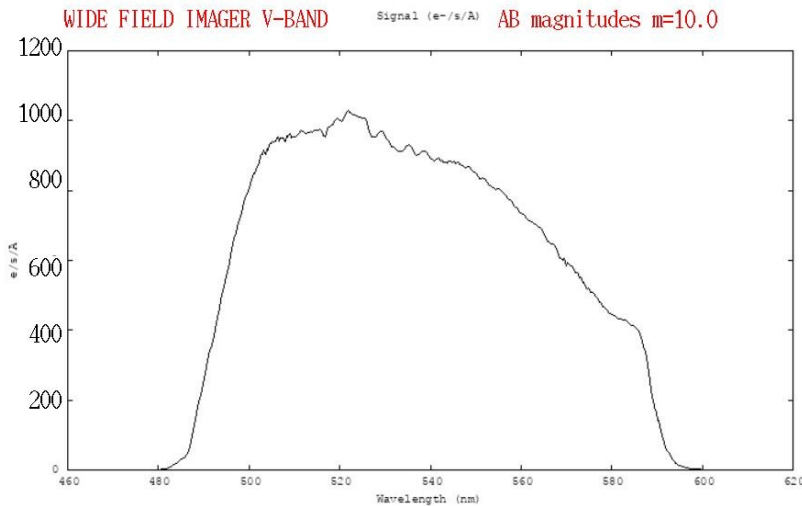
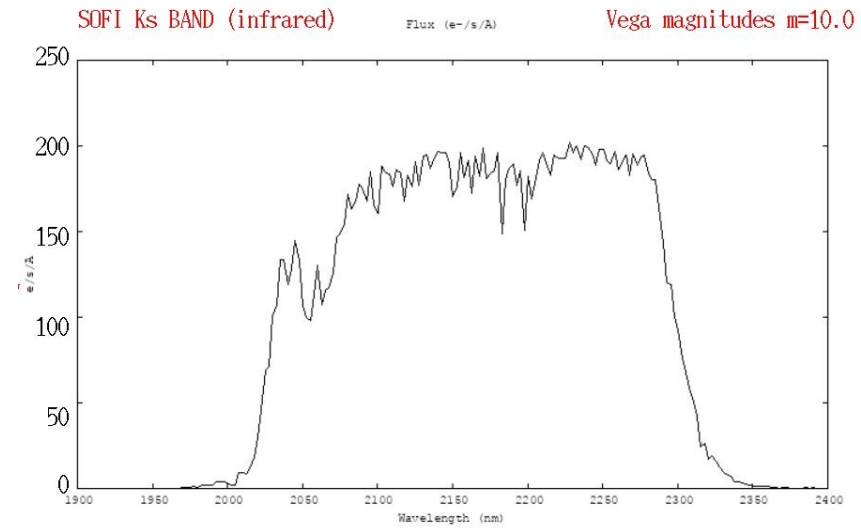
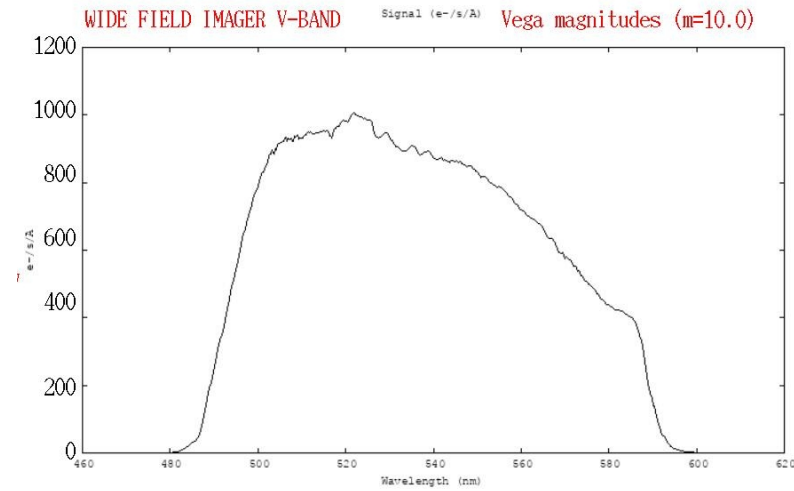
S/N:

Exposure Time:  s

ESOs exposure time calculators basically use the CCD equation plus a sky model.

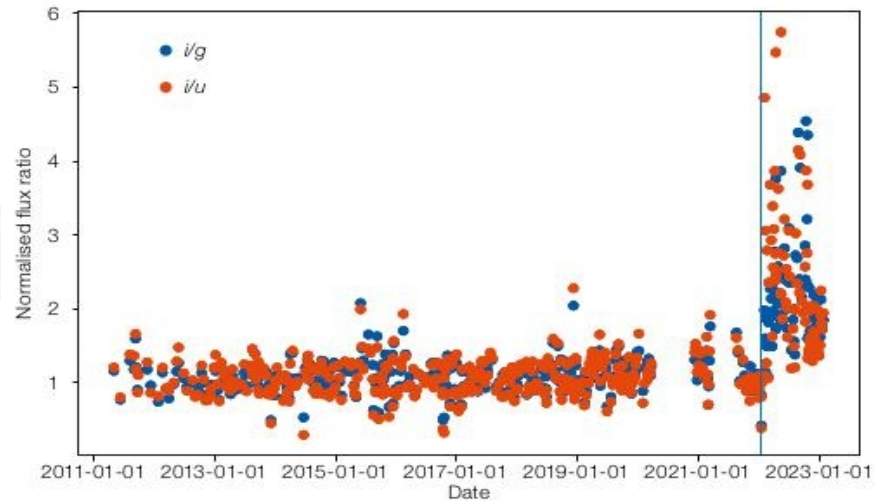
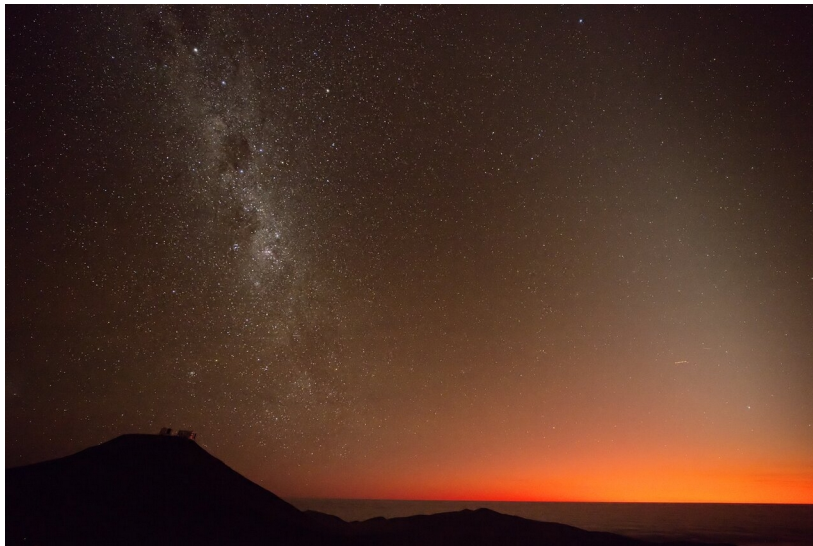
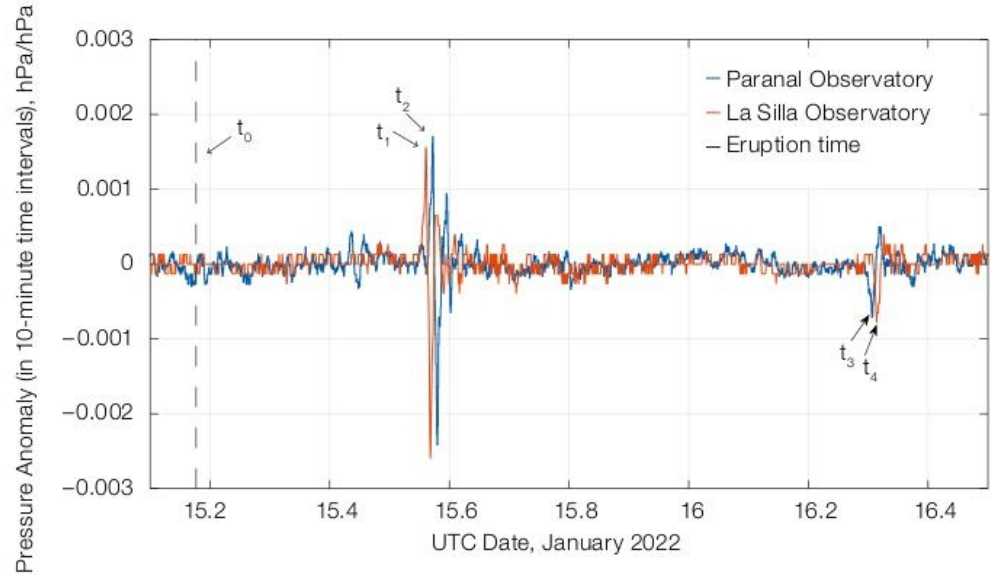
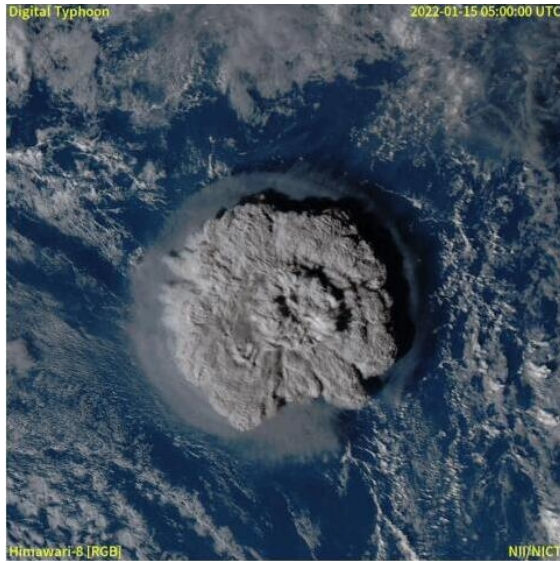


# Expected counts in the optical (left) and infrared (right) using Vega magnitudes (top) and AB mags (bottom)



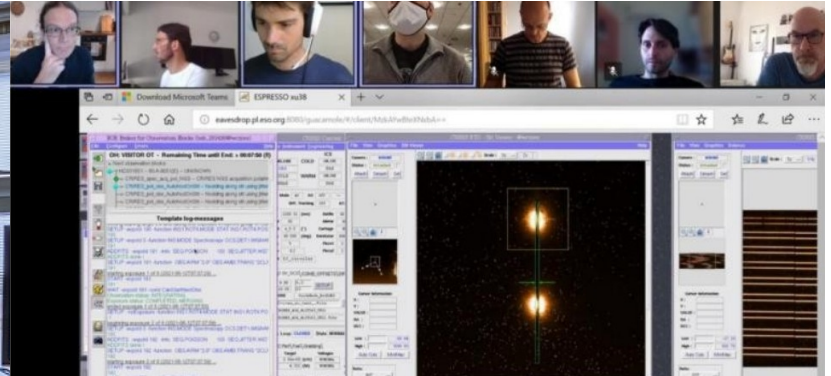


# An interlude: Effects of the Hunga-Tonga Volcanic eruption on observations at La Silla and Paranal





# You take your observations....



..or remotely...



Either in person....

Then back home to finish reducing your data!

Depending on the detector used, calibration of imaging observations uses some or all of the following steps:

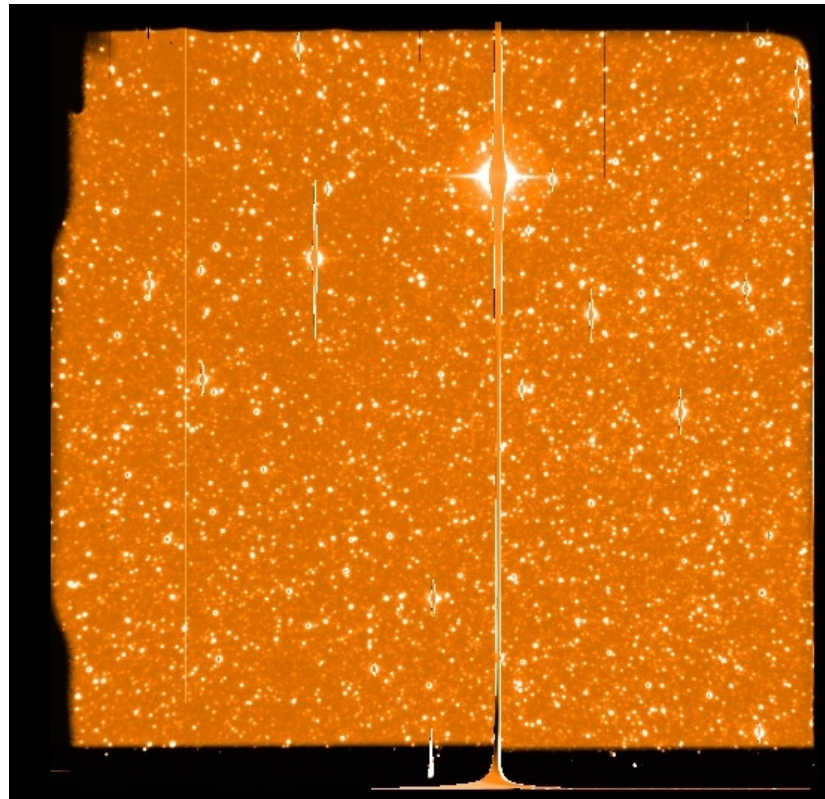
- Look at your images (both calibration and science)!
- Bias and dark subtraction
- Non linearity correction
- Flatfielding
- Fringe removal
- Subtraction of sky image (especially in the infrared)
- Correction of persistence
- Cosmic ray removal
- Illumination correction
- Correction for airmass



# There is a **lot** of information available in FITS headers (200+ lines in this case for EFOSC)

FITS headers often have information such as ambient conditions, instrument state, airmass etc etc etc.

These headers are often read by data reduction pipelines.



dfits EFOSC.2007-07-02T05:33:34.709.fits | fitsort ra dec tel.ambi.temp exptime ins.filt1.name tel.ambi.fwhm.start

FILE	RA	DEC	TEL.AMBI.TEMP	EXPTIME	INS.FILT1.NAME	FWHM.START
EFOSC.2007-07-02T05:33:34.709.fits	262.157304	-29.15728	15.90	300.0005	R#642	0.48







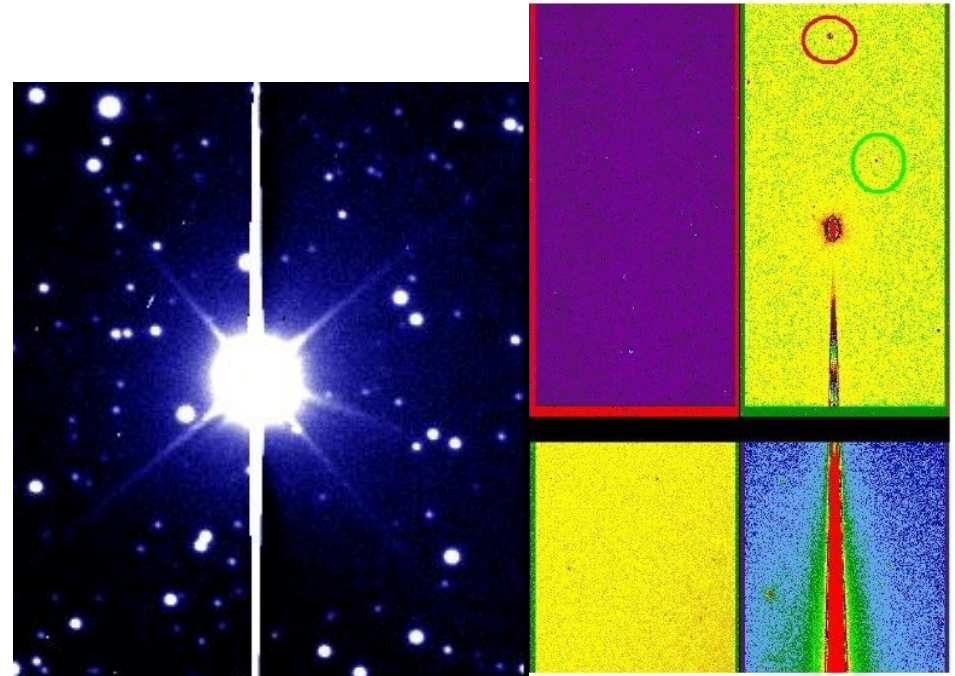
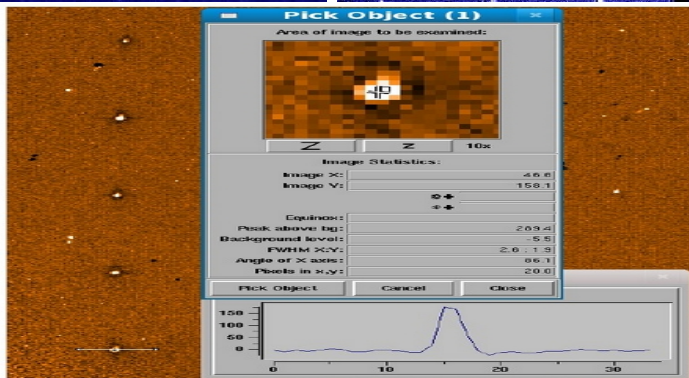
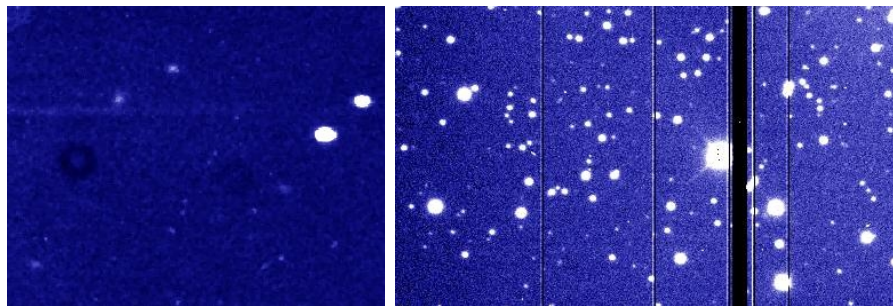
# First, visually inspect your data and calibrations

See: [https://www.eso.org/~ohainaut/ccd/CCD\\_artifacts.html](https://www.eso.org/~ohainaut/ccd/CCD_artifacts.html)

If you are using a data reduction pipeline, rubbish in → rubbish out

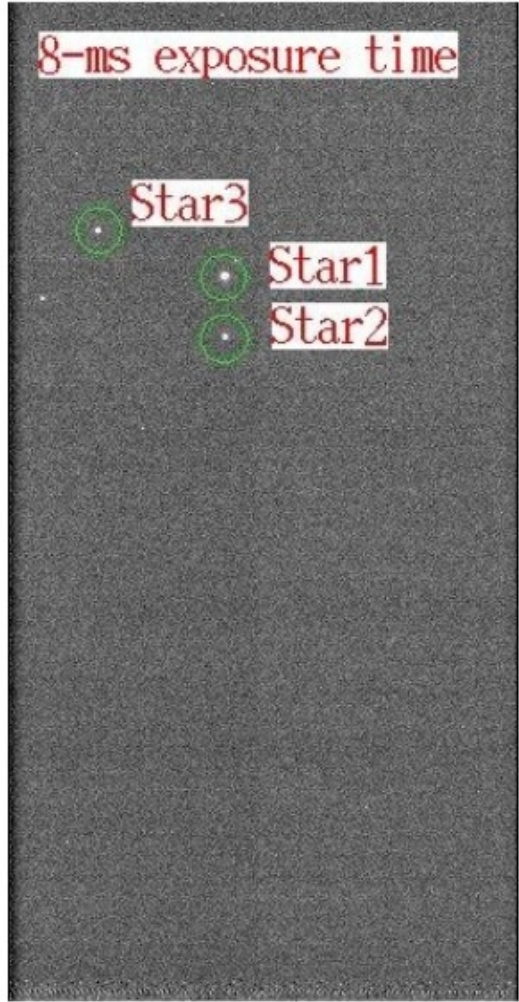
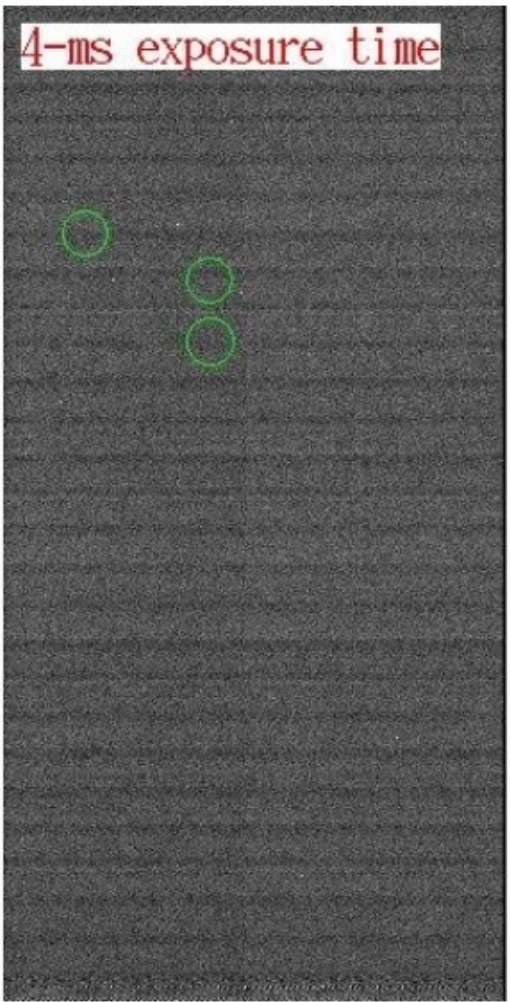
Things to check:

- Vignetting (dome not tracking with telescope, wrong component in light path)
- Features caused by condensation on the dewar entrance window. Bad columns.
- Stray light (nearby bright planet when you observed)
- Saturation trails & diffraction spikes, satellite trails or lasers
- Persistence due to previous observations of bright objects. Dust on filters etc etc etc





# Visually check data: Instrument and camera shutters have a non-infinite speed! (OmegaCAM)



The general point is if you are taking data close to the performance limit of an instrument you have to be on the lookout for unforeseen effects.



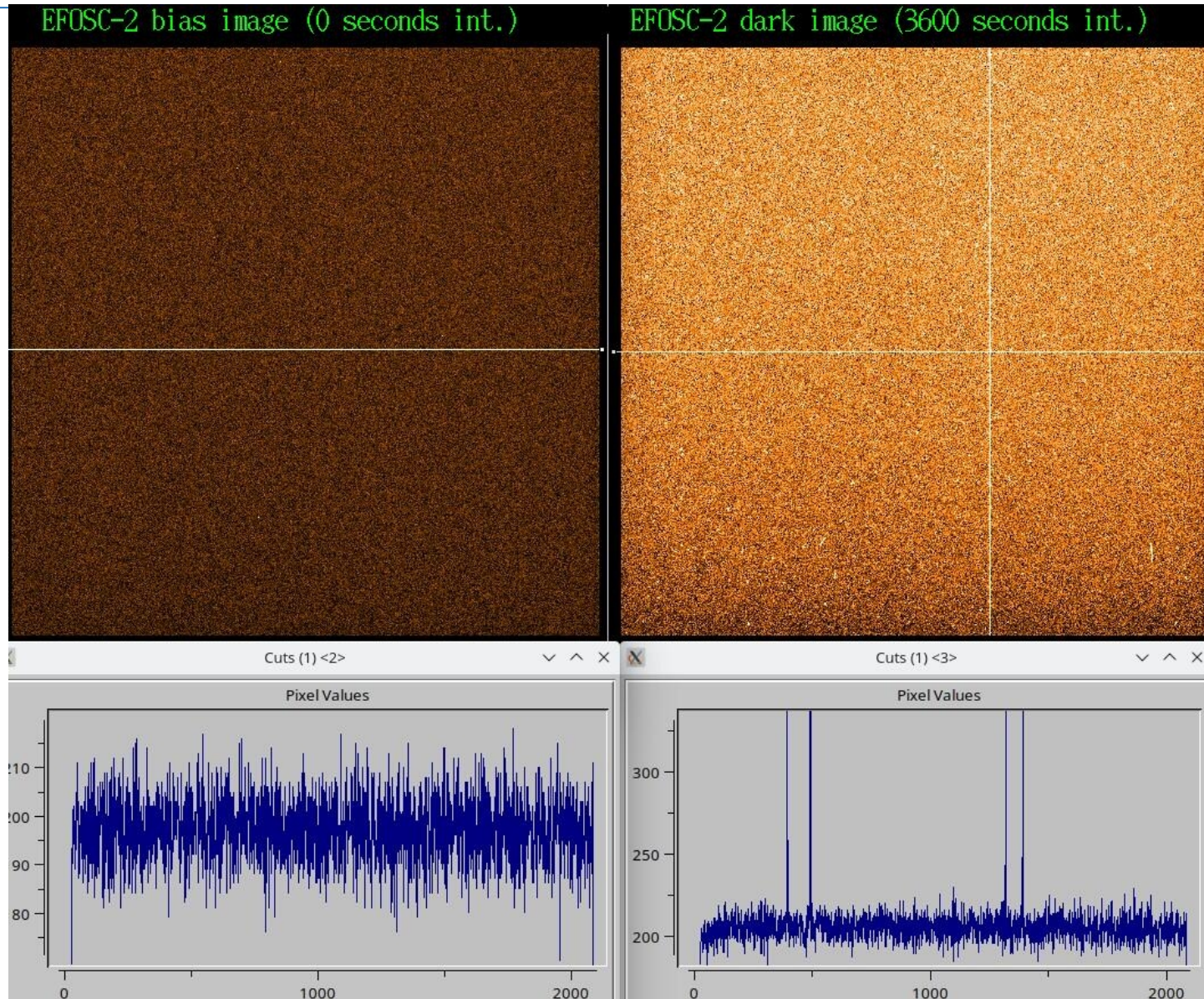


# Bias and dark removal: EFOSC-2 bias and darks

Left image:  
EFOSC-2 bias  
frame (exposure  
time 0-s) with  
horizontal cut of  
counts.

Right image:  
EFOSC-2 dark  
frame (3600-s  
integration time)  
with horizontal  
cut of counts.

Normally you  
average or  
median many  
bias or dark  
frames before  
subtracting from  
science / calibs

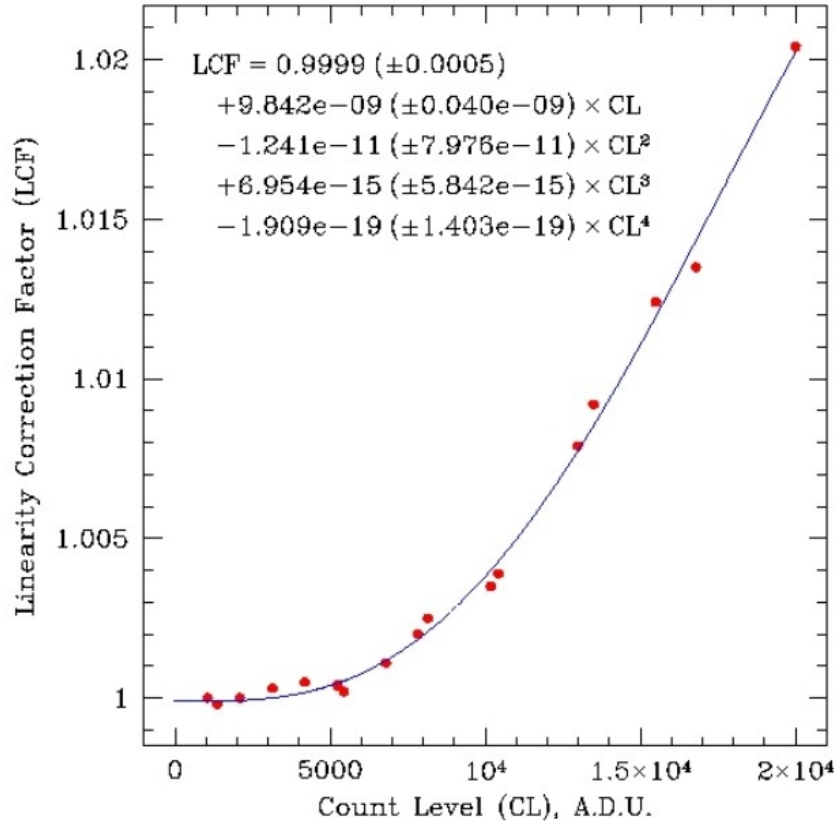






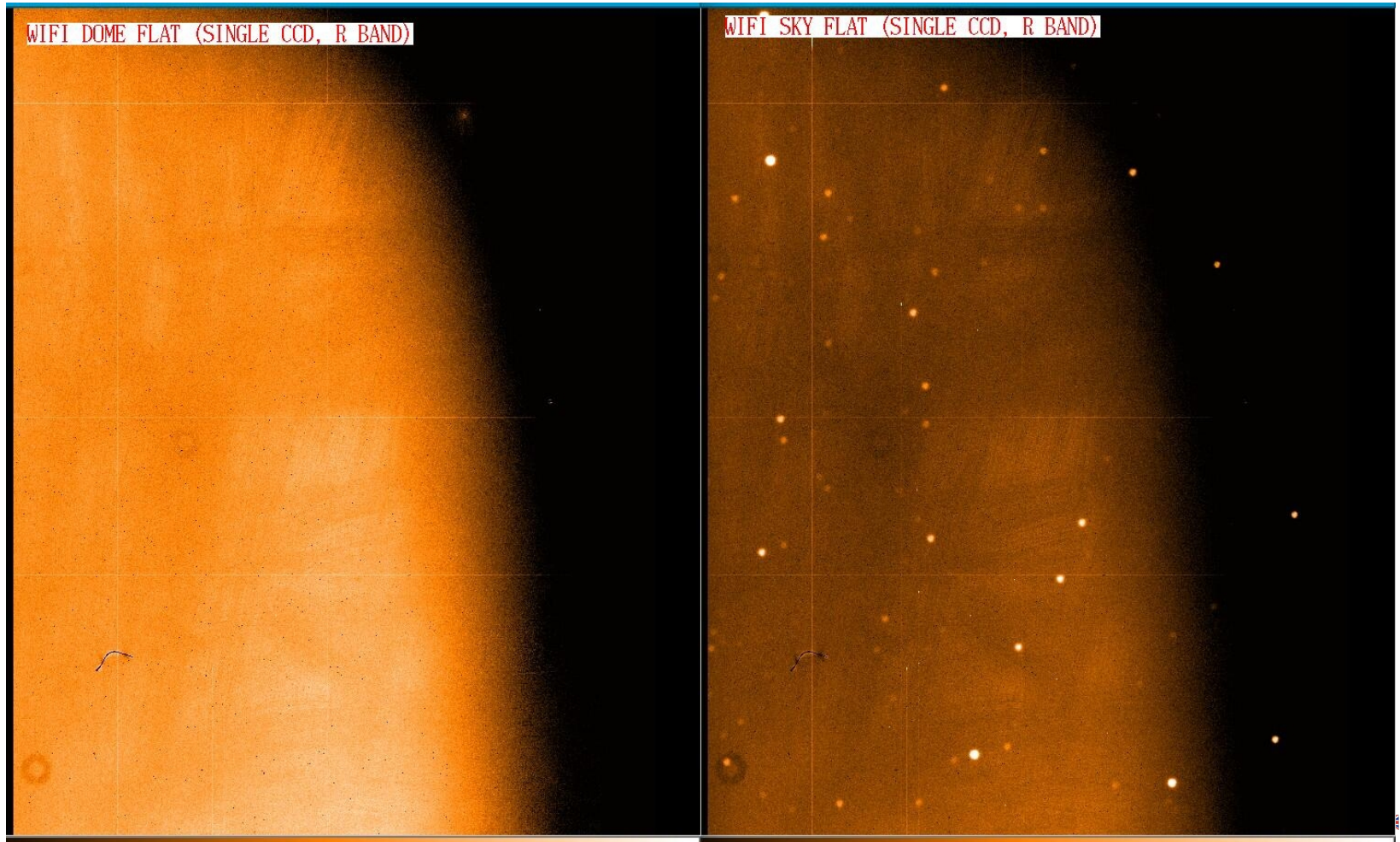
# Detector responses are not linear – SOFI non linearity curve. You may need to correct for this.

As you get closer and closer to the saturation limit of the detector, the same number of input photons produce fewer output electrons. This effect has to be corrected, ideally on a pixel-to-pixel basis. Often there will be a static calibration file to do this as part of a pipeline release.



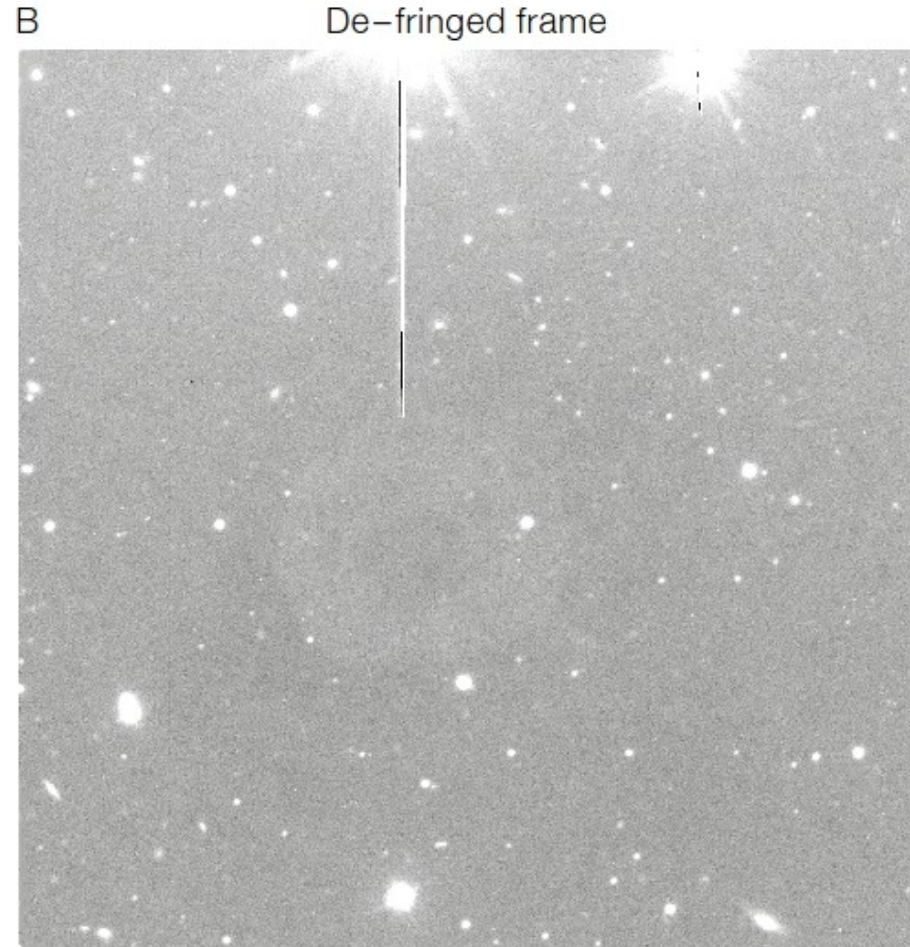
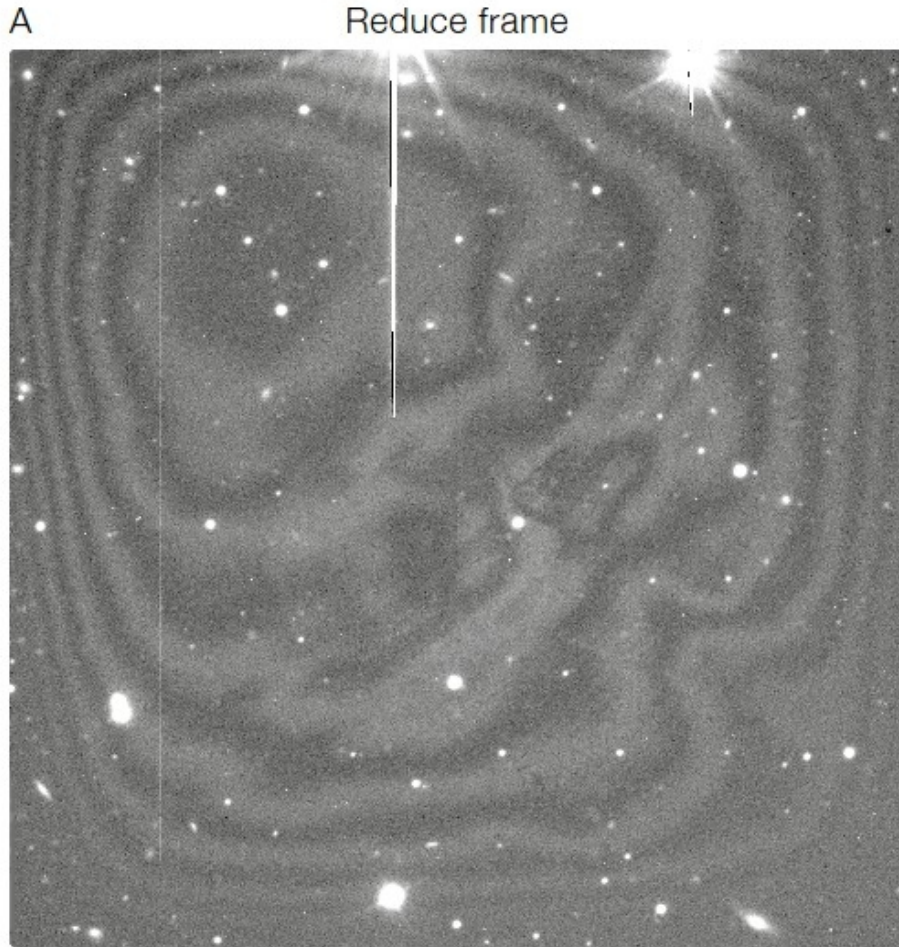
# Flatfielding: WIFI dome and sky flatfield images

- Median filter jittered sky flats to get rid of stellar features
- Divide data by normalised flats to reduce pixel-to-pixel variations
- Both dome and sky flats have their advantages and disadvantages





# Fringes: Effects of fringing on EFOSC-2 images (La Silla) and their removal

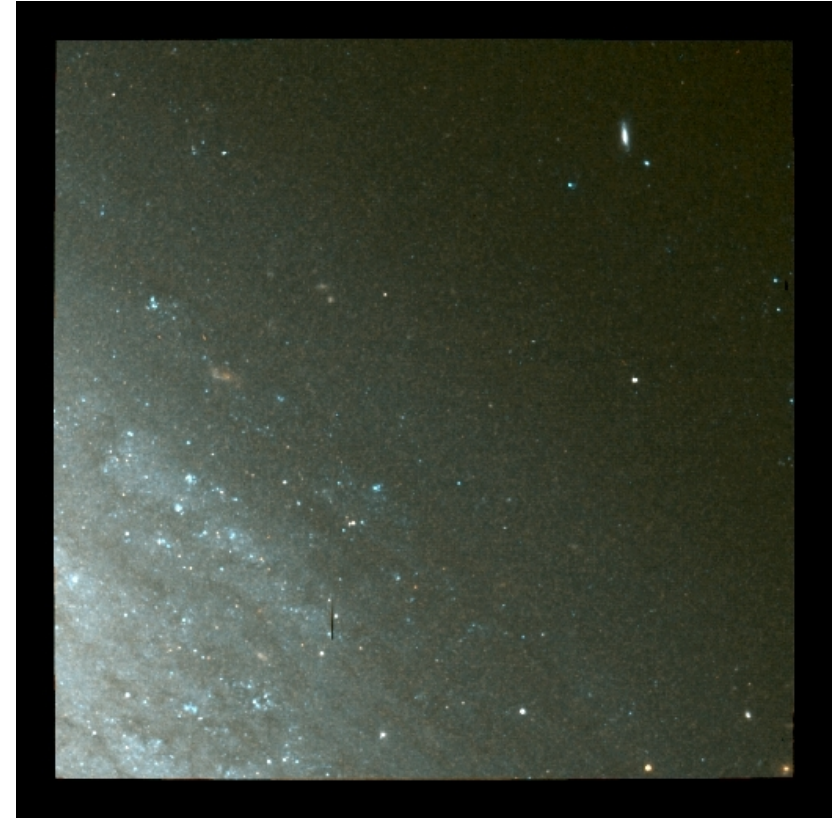


EFOSC-2 image (left) and de-fringed frame (Snodgrass & Carry 2013)



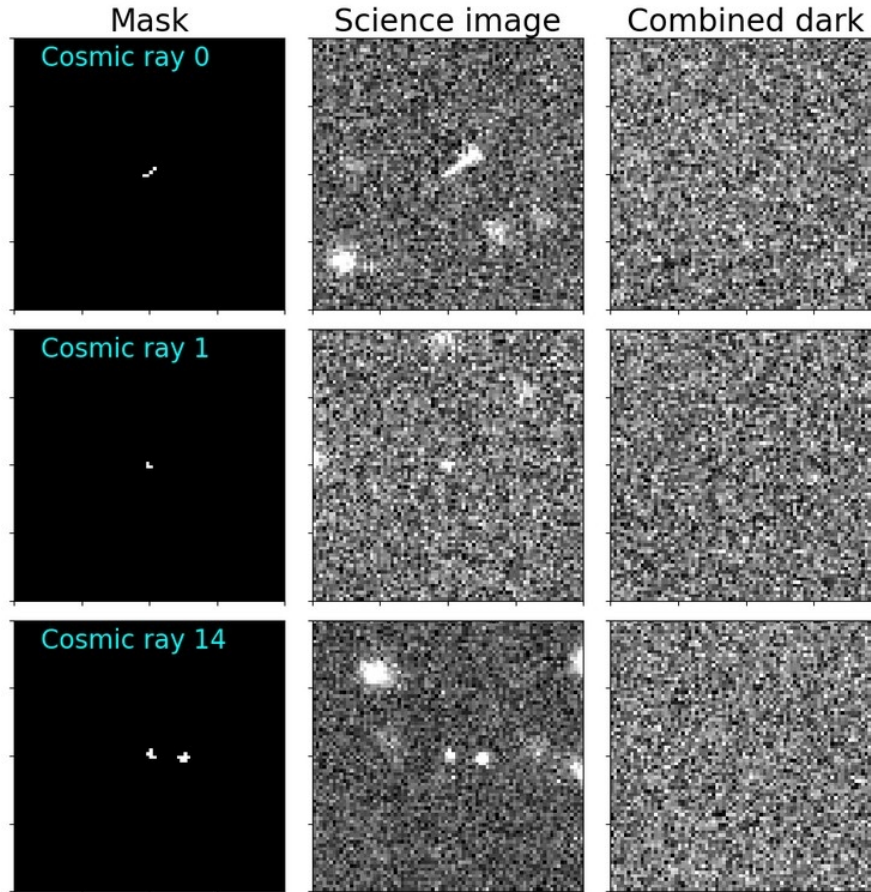


# Cosmic rays: removal by taking the median of several images. Needs two or more images.



(Michael Richmond <http://spiff.rit.edu/classes/phys445/lectures/median/median.html> )

# Cosmic rays: detection by sigma clipping. Then mask the affected region or interpolate using nearby pixels.



(AstroPy LACosmic:

<https://www.astropy.org/ccd-reduction-and-photometry-guide/v/dev/notebooks/08-03-Cosmic-ray-removal.html>)

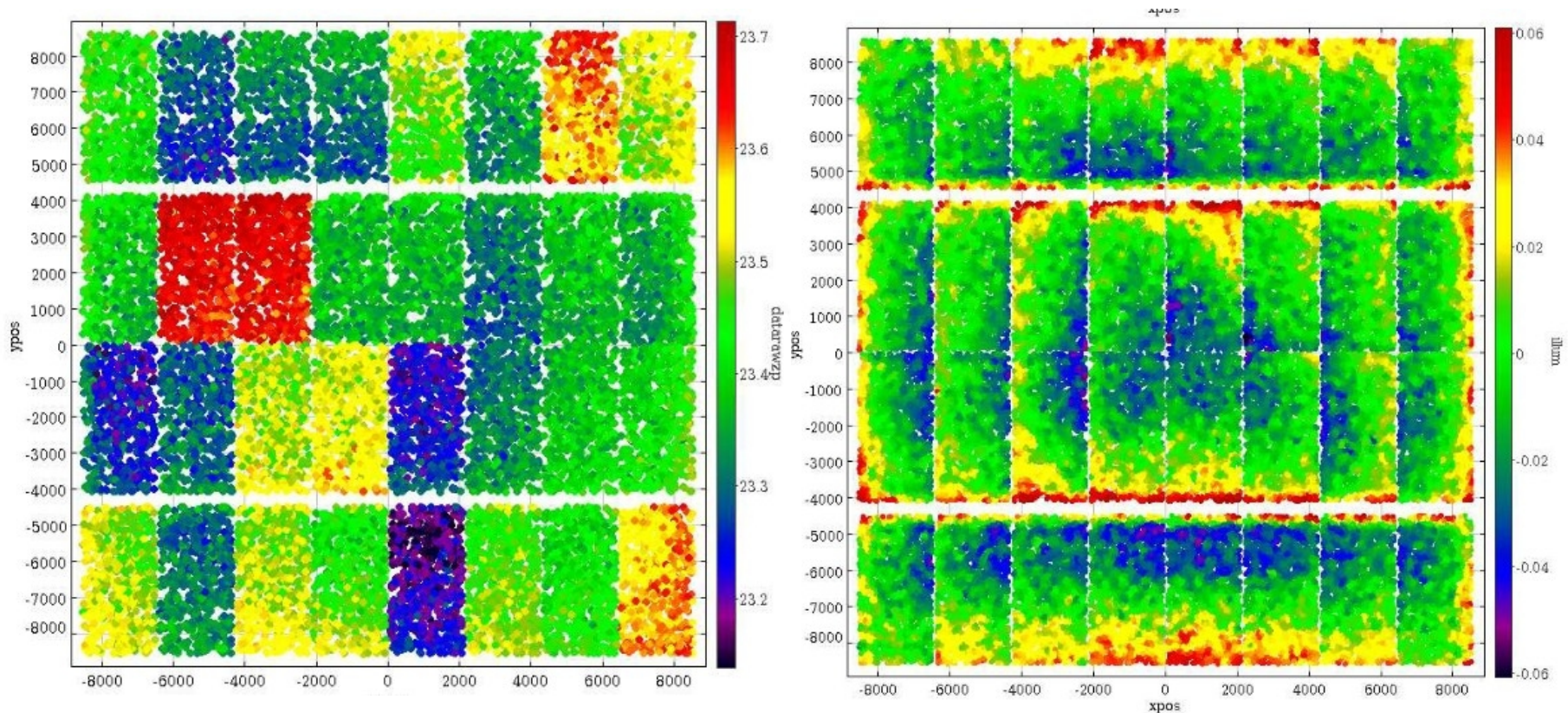




# Illumination correction – not all parts of the focal plane have the same response!



The illumination correction map is derived from observations of the same star (or stars) with a jitter pattern covering the entire array and measuring the stellar magnitude at each position.

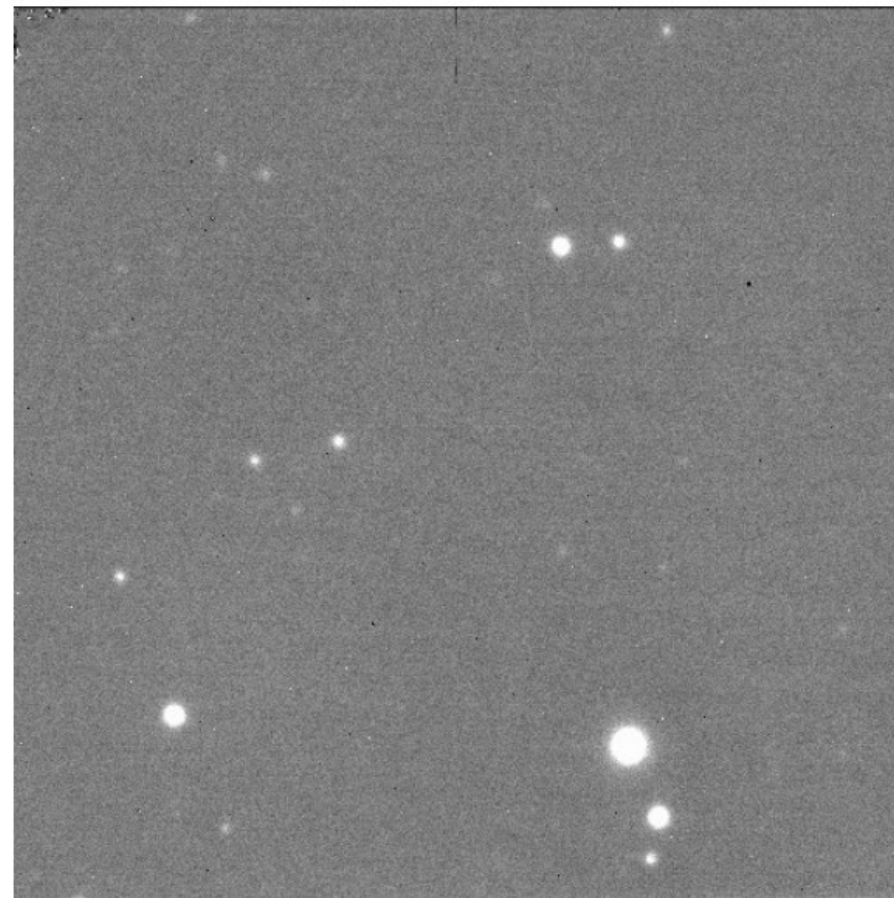
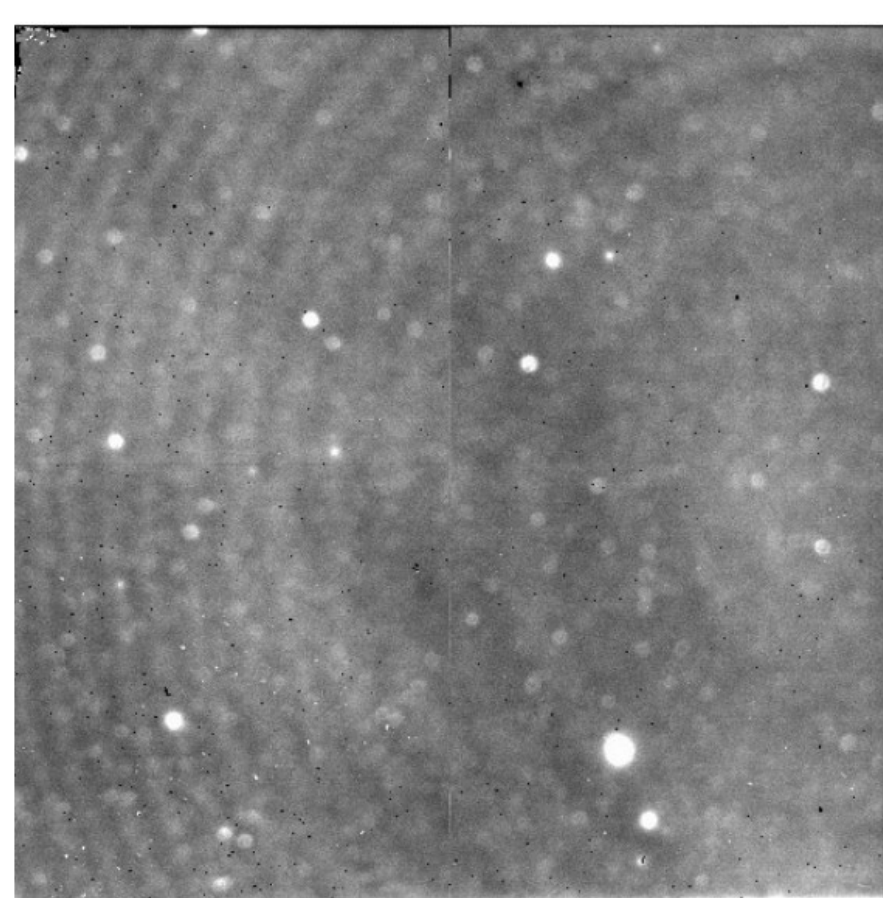


(OmegaCAM instrument consortium)





# OK, we have reduced our data! Infrared image before and after data reduction



# An interlude: Anything strange here?



(Boris Haeussler)

# An interlude: Anything strange here as well?



(Boris Haeussler)



- **Photometry**
- **Narrow band imaging**
- **Differential photometry**

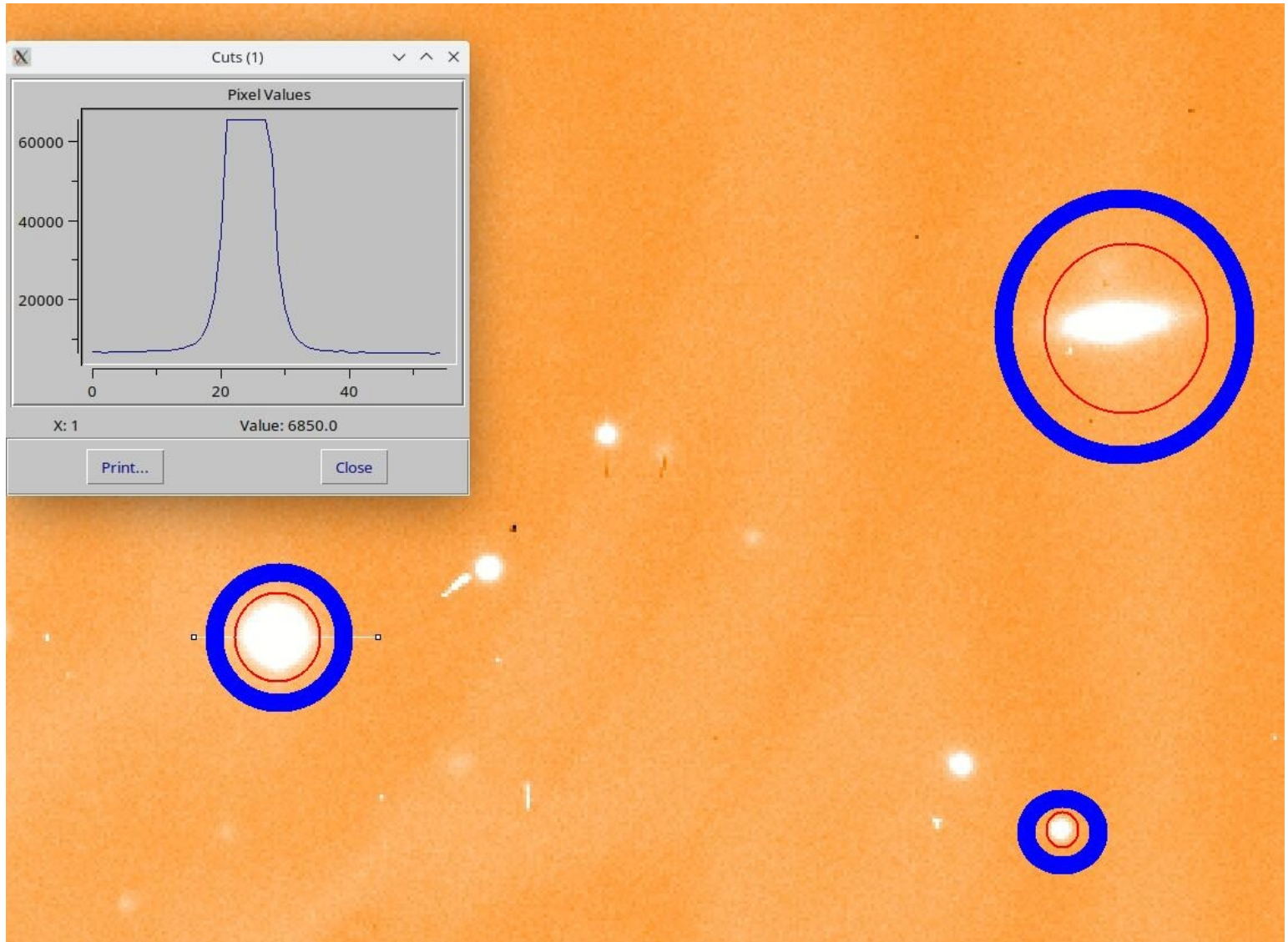


Aperture photometry (EFOSC-2 data) – we find the stars, sum the light within a defined radius per star and subtract the sky level per pixel derived in another aperture from the total object count (per pixel).  
Quick and simple!

Only one of the three objects is really applicable for circular aperture photometry.

Why?

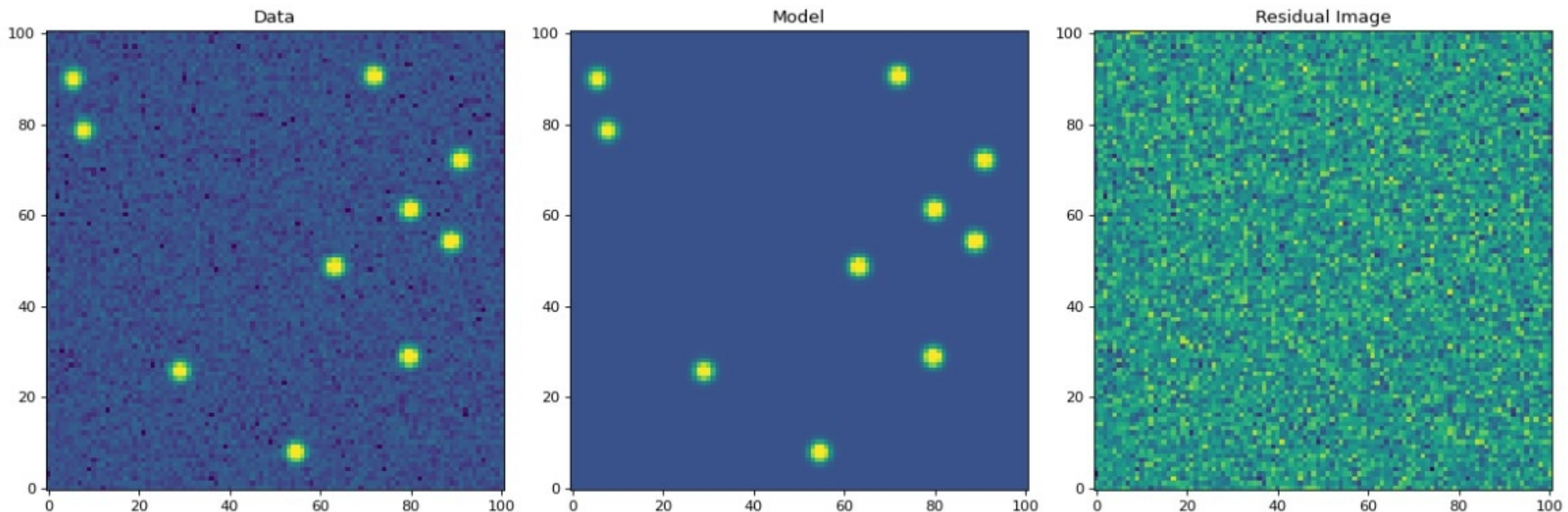
What other limitations does this technique have?





# Point spread fitting photometry

- Often more accurate than aperture photometry in crowded fields. As in aperture photometry we first search for objects such as stars and galaxies.
- We use isolated stars to create the point spread function. This can be an analytical function, or use the data, or a combination of the two. It may change depending on the position on the image plane and almost certainly changes from exposure to exposure for ground based images (why?).
- A scaled version of the PSF is then subtracted at each stellar position and the magnitude estimated.



<https://photutils.readthedocs.io/en/stable/psf.html>

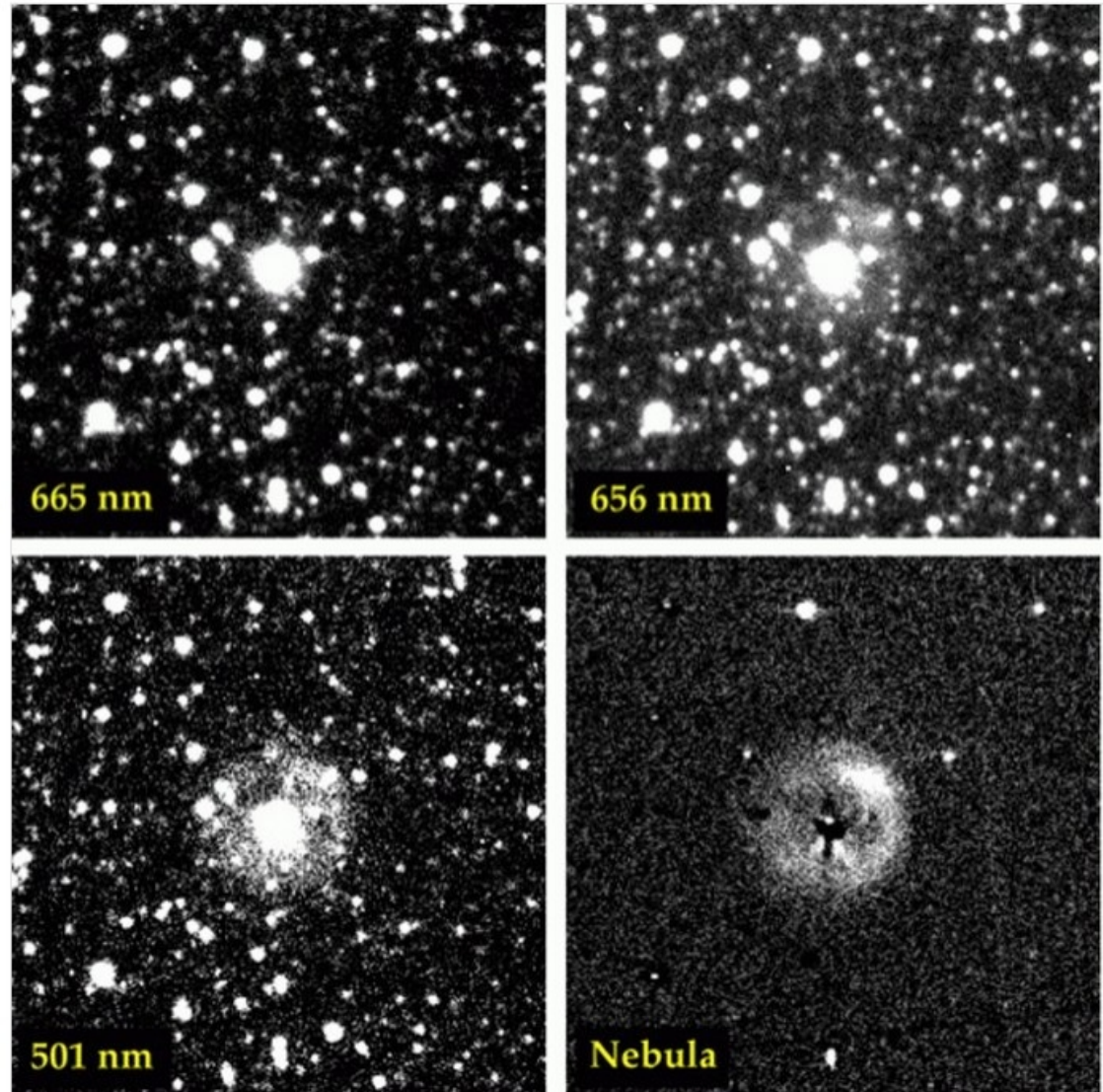


# Narrow band photometry

Narrow band filters can be used to study a particular line, in this case [OIII] (bottom left) and H alpha (top right with bottom right showing continuum subtracted image).

Advantage of using a narrow band filter is that you can see structure otherwise washed out in the broad band image.

What are the disadvantages? (at least two...)



(La Silla Danish 1.5m)

# Other examples of narrow band photometry



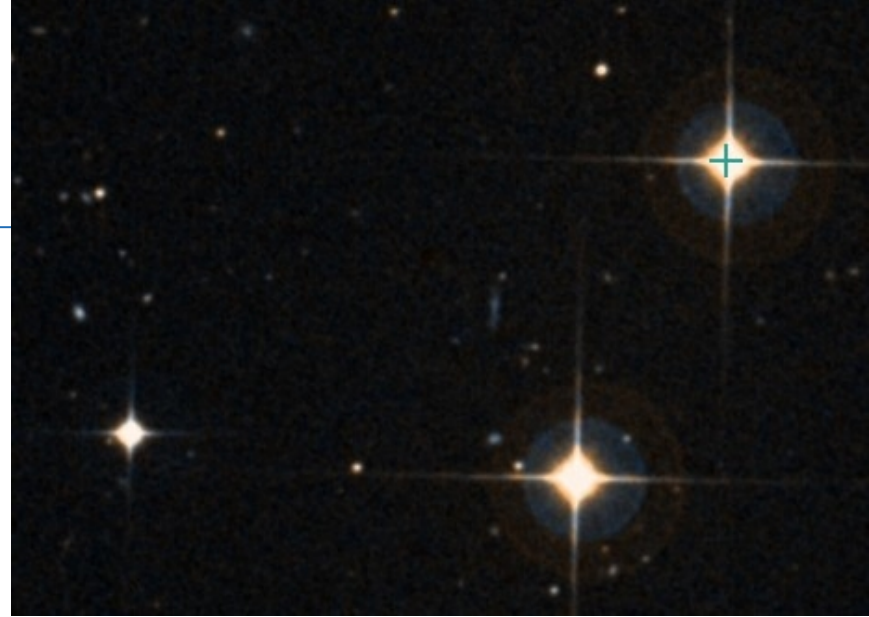
(GOODS south field, H-alpha and Lyman alpha combination)



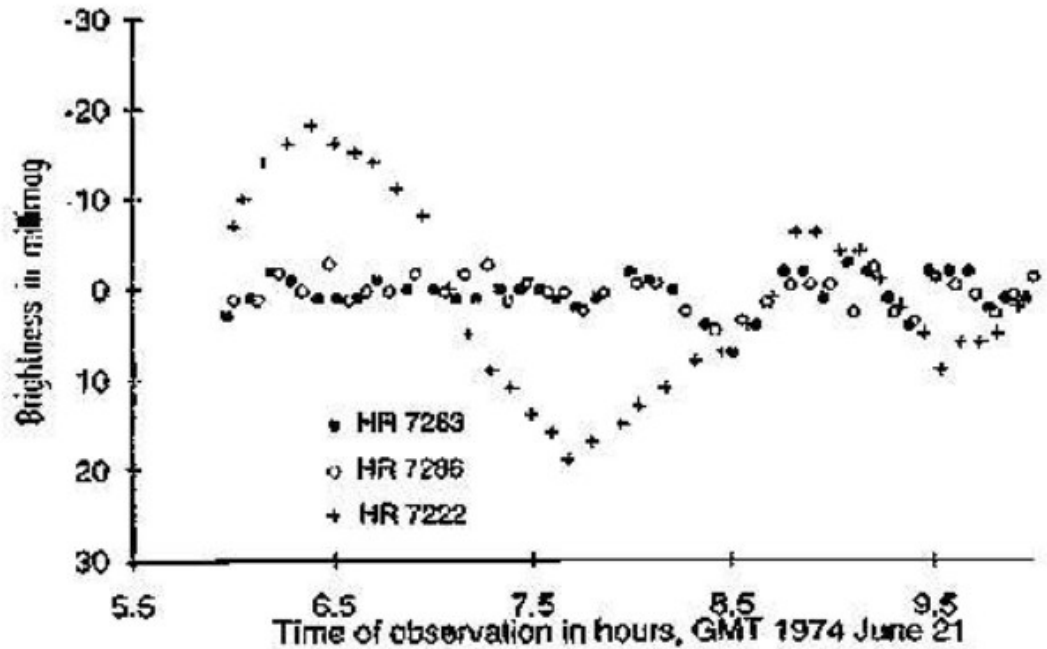
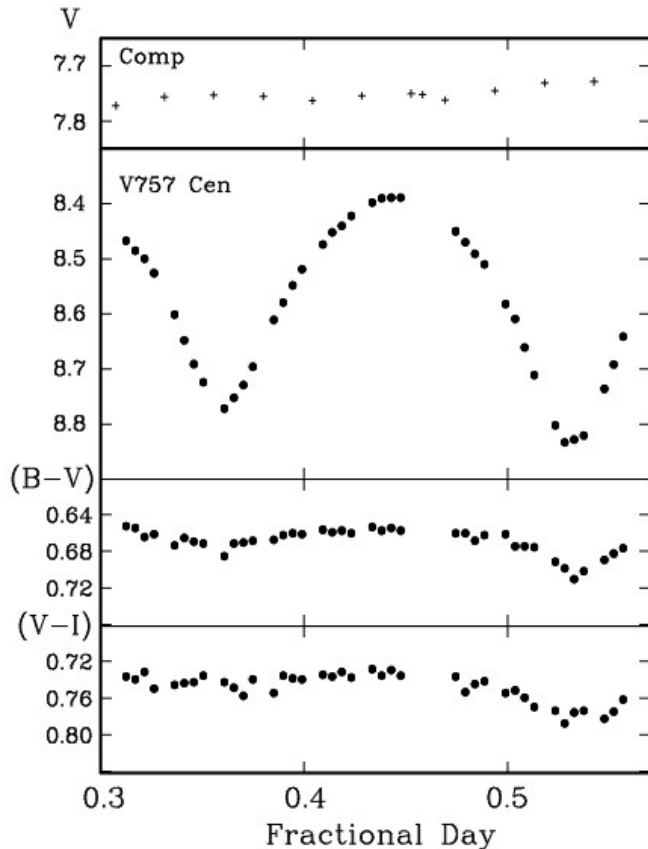




# Differential photometry



- Observe multiple stars simultaneously, the target and one or more comparison stars.
- Changes in the Earth's atmosphere (for example due to thin cirrus) affect all stars, hence can be calibrated out.



(Kilkenny 1974)







# The End! Thanks for attending :)





# Acknowledgements

- Images are from ESOs website [www.eso.org](http://www.eso.org) or wikipedia if not otherwise noted.
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