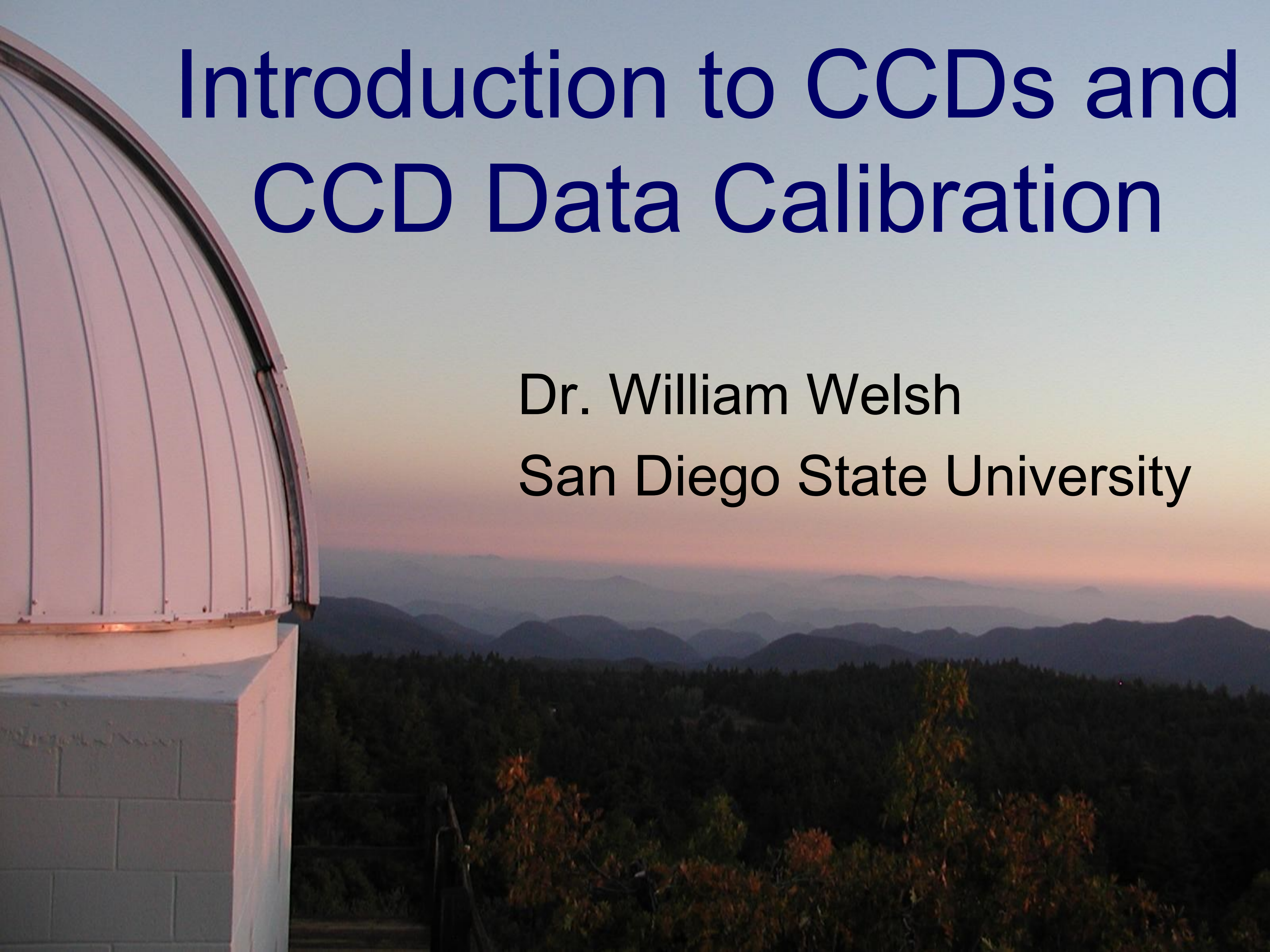
Introduction to CCDs and CCD Data Calibration



Dr. William Welsh

San Diego State University

Fundamental Requirements of Differential Aperture Photometry

1. Light from the *target star* and the *comparison stars* are affected by the atmosphere and telescope in exactly the same way

   ➔ identical extinction and PSF

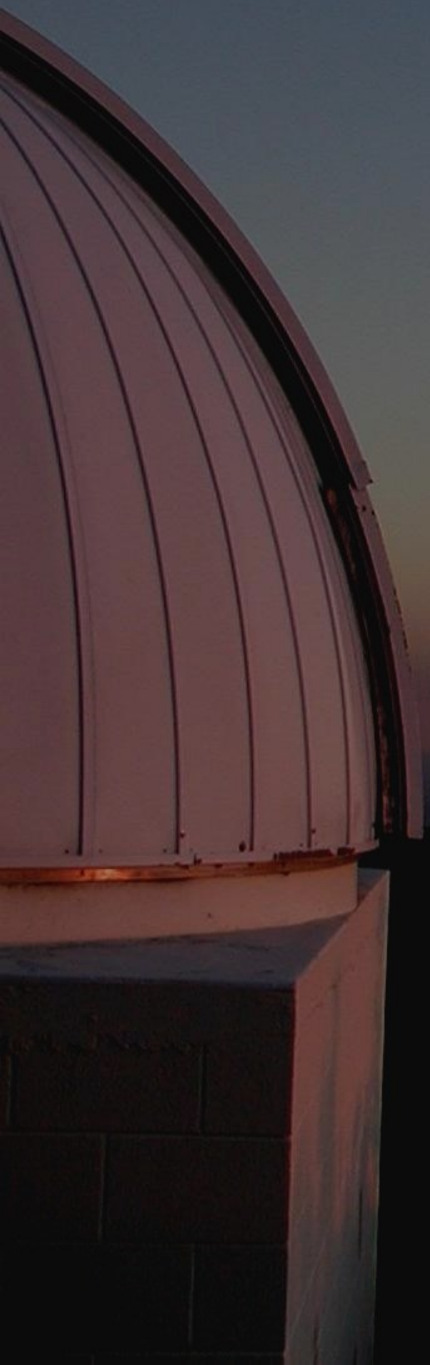
2. Moonlight, twilight, sky emission, light pollution, and *scattered light in the telescope* is exactly the same

   ➔ identical background light

Fundamental Requirements of Differential Aperture Photometry

3. The detector measures the light from all stars in exactly the same way

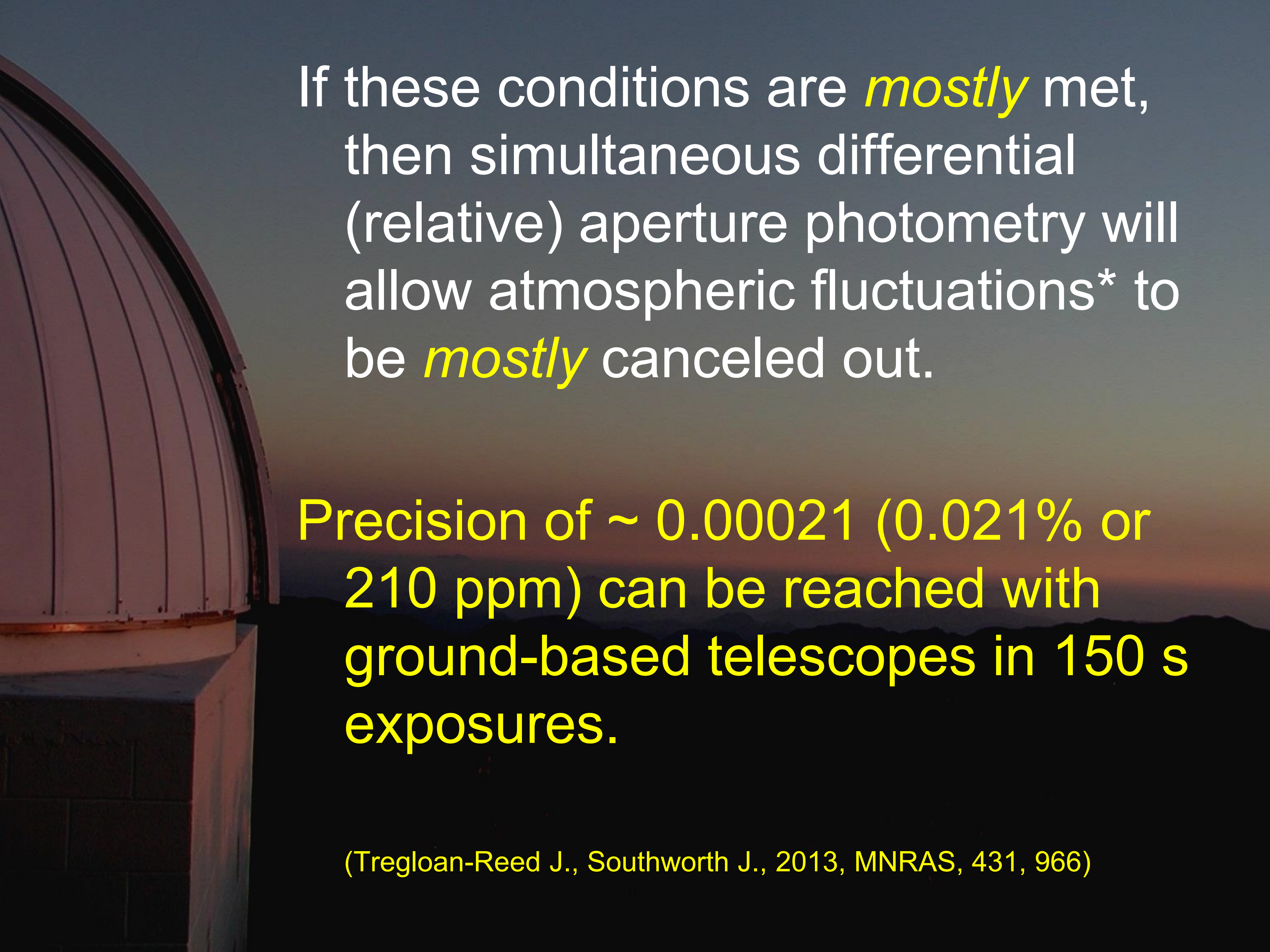
➔ identical pixels (sensitivity and noise)



If these conditions are met, then simultaneous differential (relative) aperture photometry will allow atmospheric fluctuations* to be canceled out.

Relative flux = target star / comp star

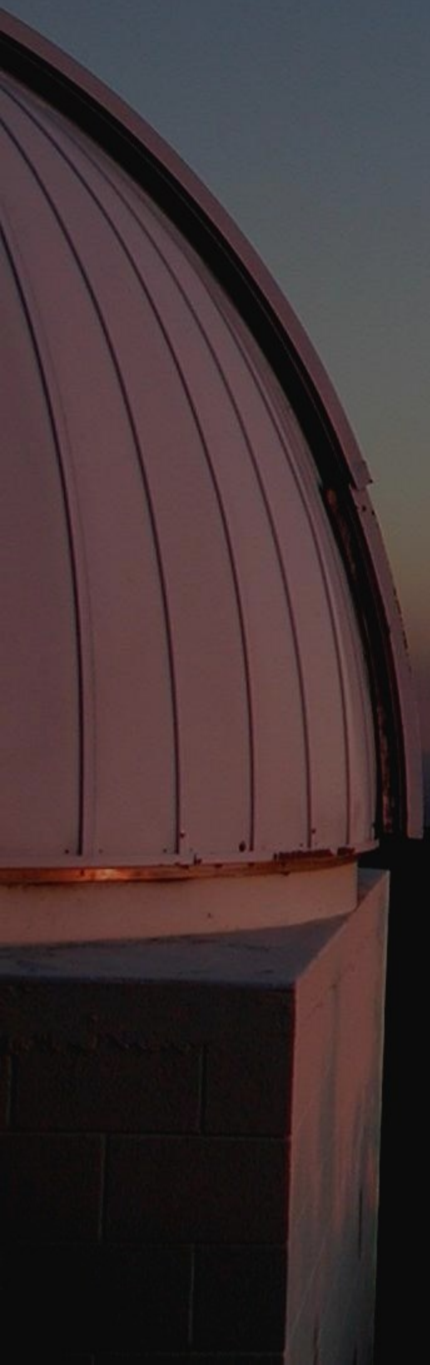
(*) thin clouds, change in transparency, change in sky brightness, change in airmass, etc.

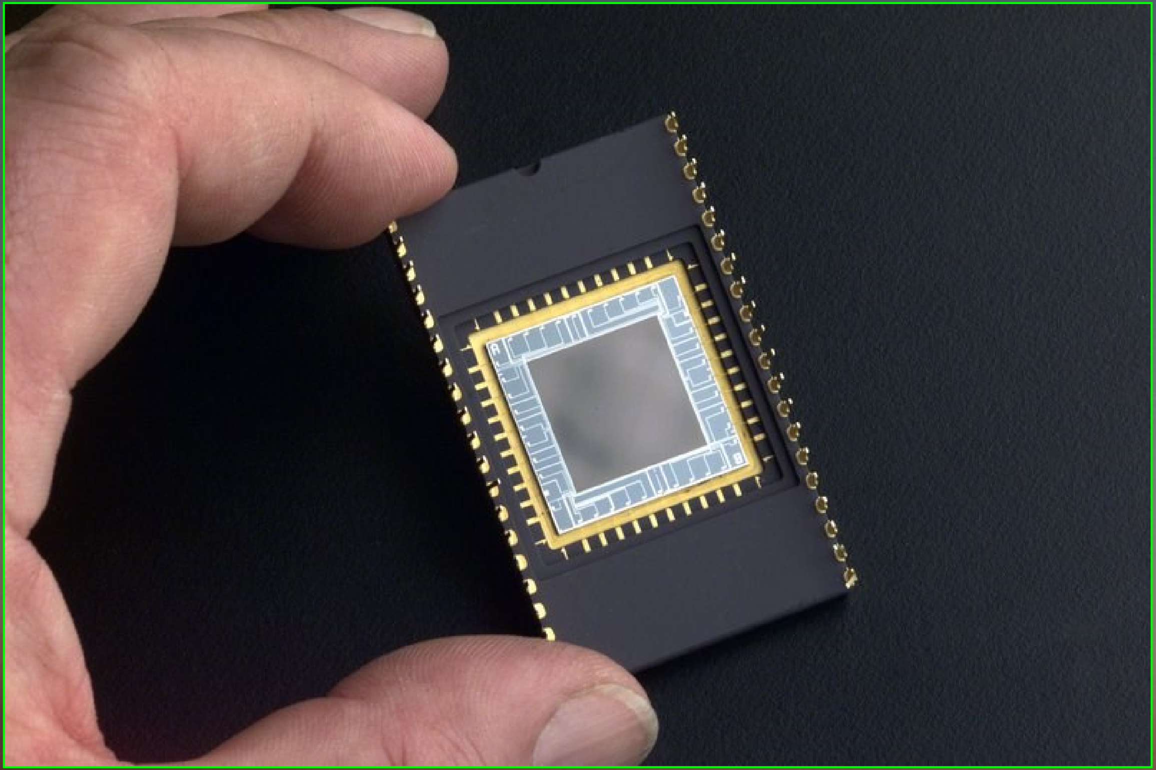


If these conditions are *mostly* met, then simultaneous differential (relative) aperture photometry will allow atmospheric fluctuations* to be *mostly* canceled out.

Precision of ~ 0.00021 (0.021% or 210 ppm) can be reached with ground-based telescopes in 150 s exposures.

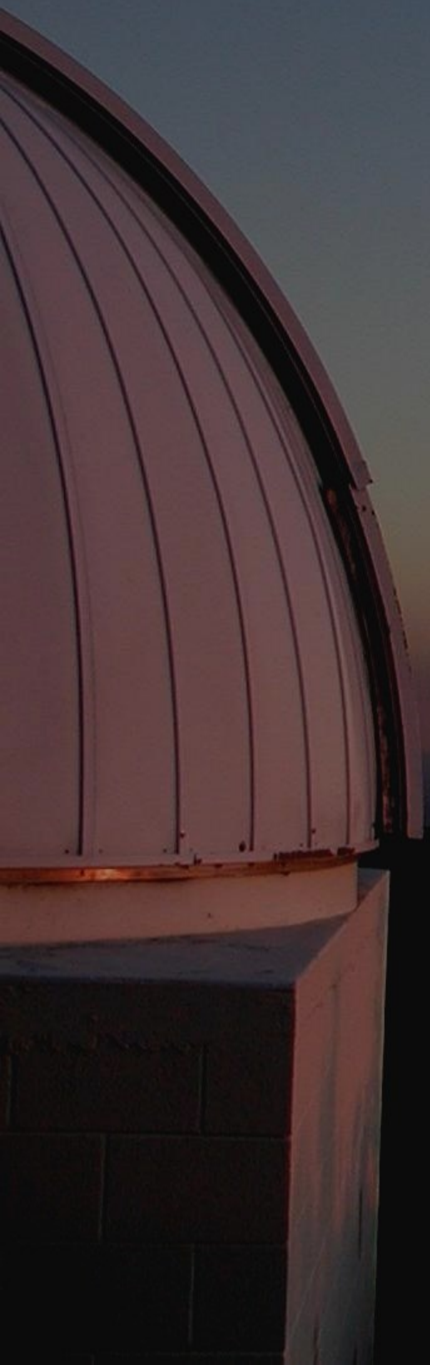
(Tregloan-Reed J., Southworth J., 2013, MNRAS, 431, 966)

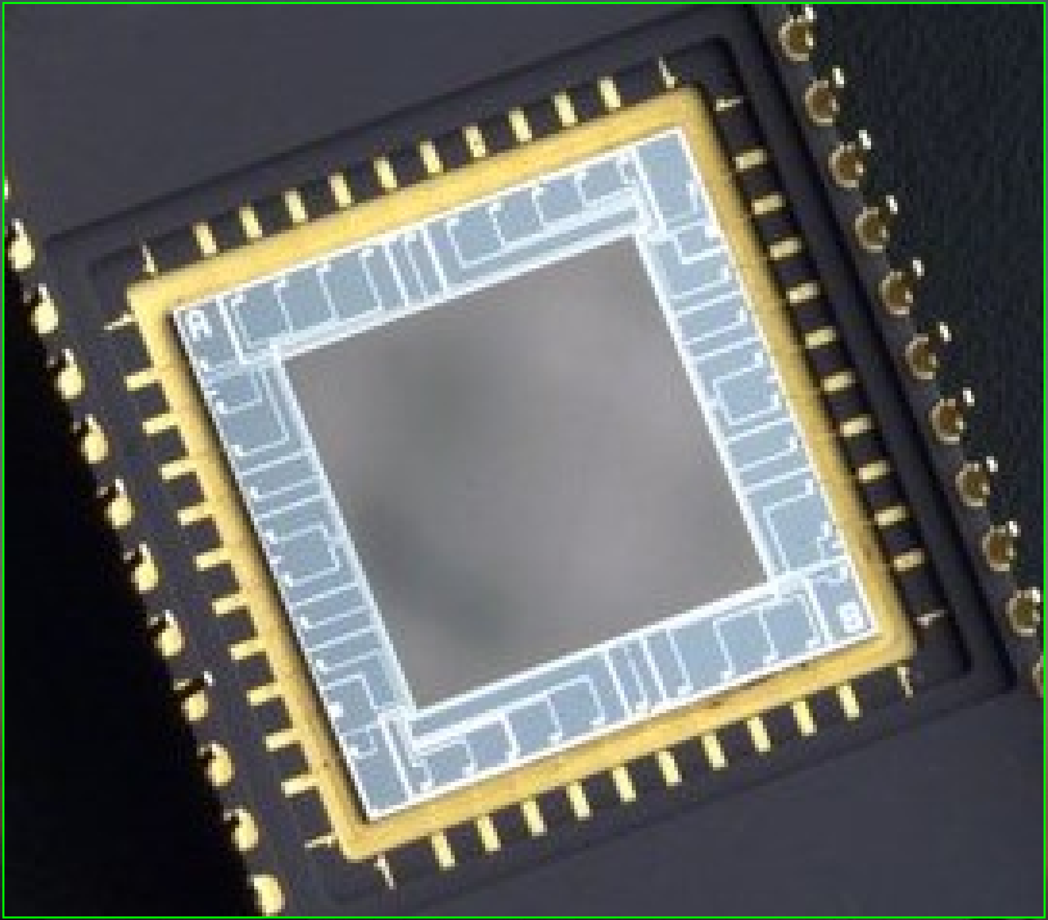




CCD: “charge coupled devices”

integrated circuit silicon chips that can record optical (and X-ray) light





pixel = “picture element”

= independent light detectors

each pixel must be calibrated – no two are the same.

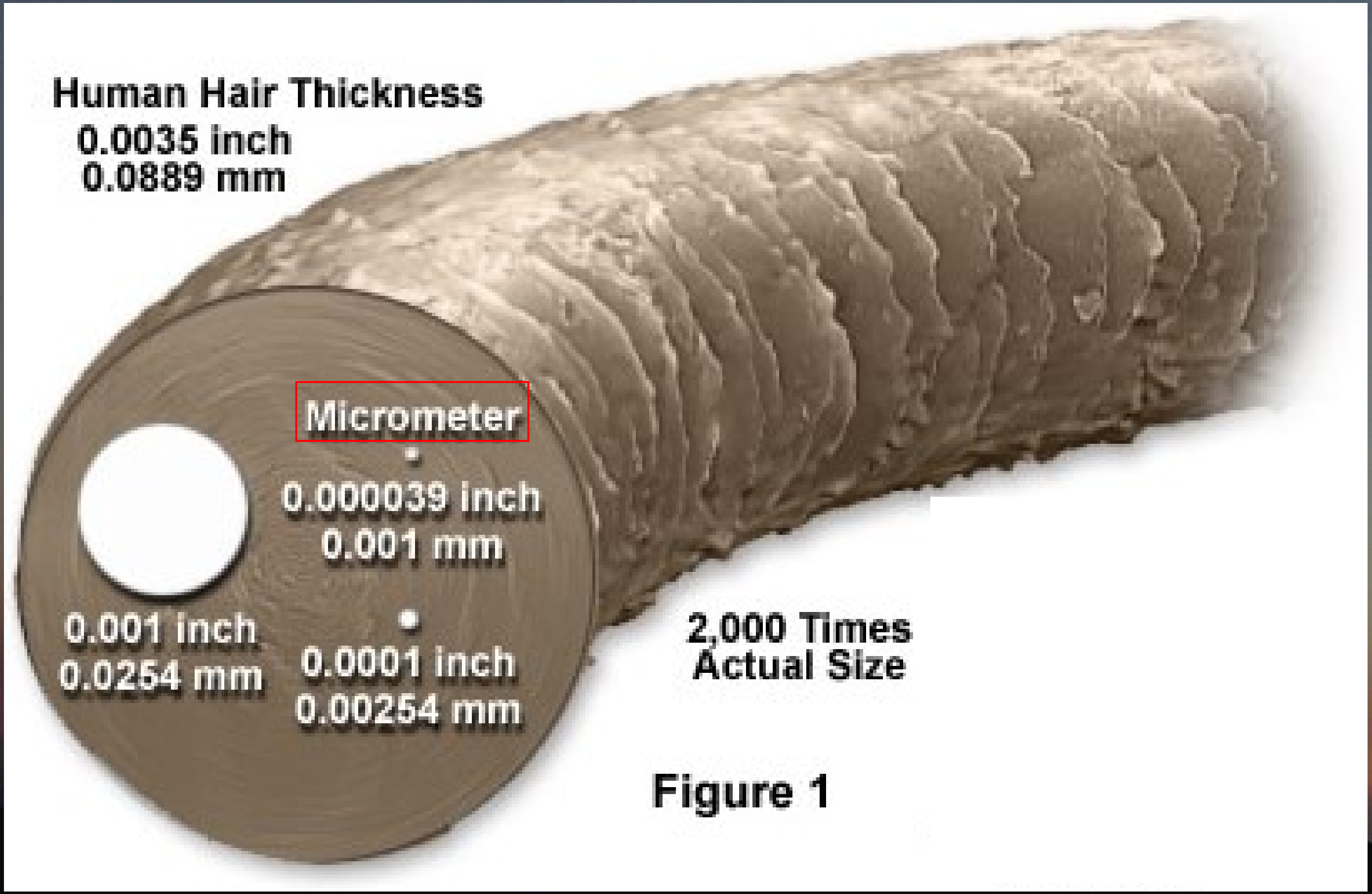
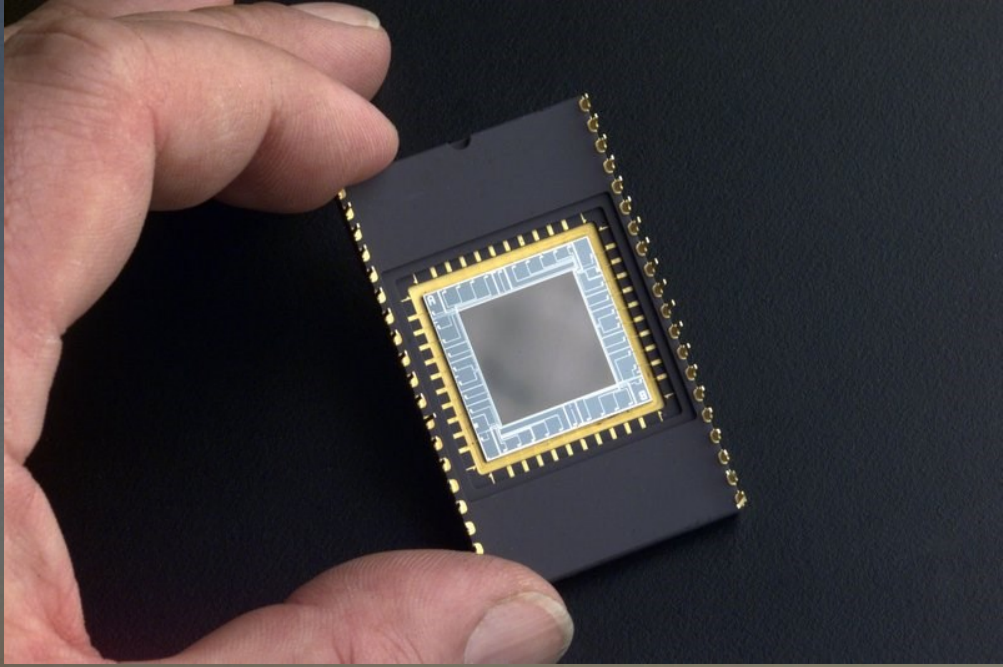


Figure 1

CCD pixels are amazingly small:
typically 5-25 microns wide.



Note: # pixels ≠ resolution!

resolution = ability to see details;

set by physics (diffraction) and optical quality ➔ $\theta = 1.22\,\lambda / D$

e.g. 0.14 arcseconds for a 1-m telescope

– not set by the CCD (unless the CCD is not matched to the camera).

Resolution improves with the diameter of the optics

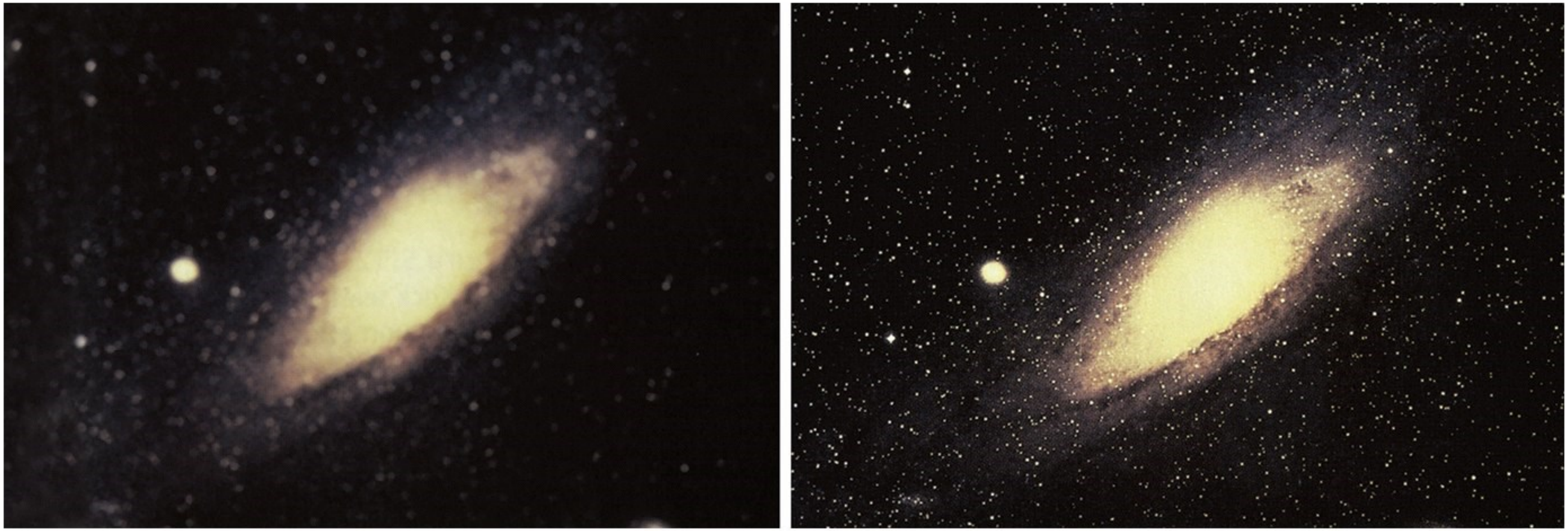
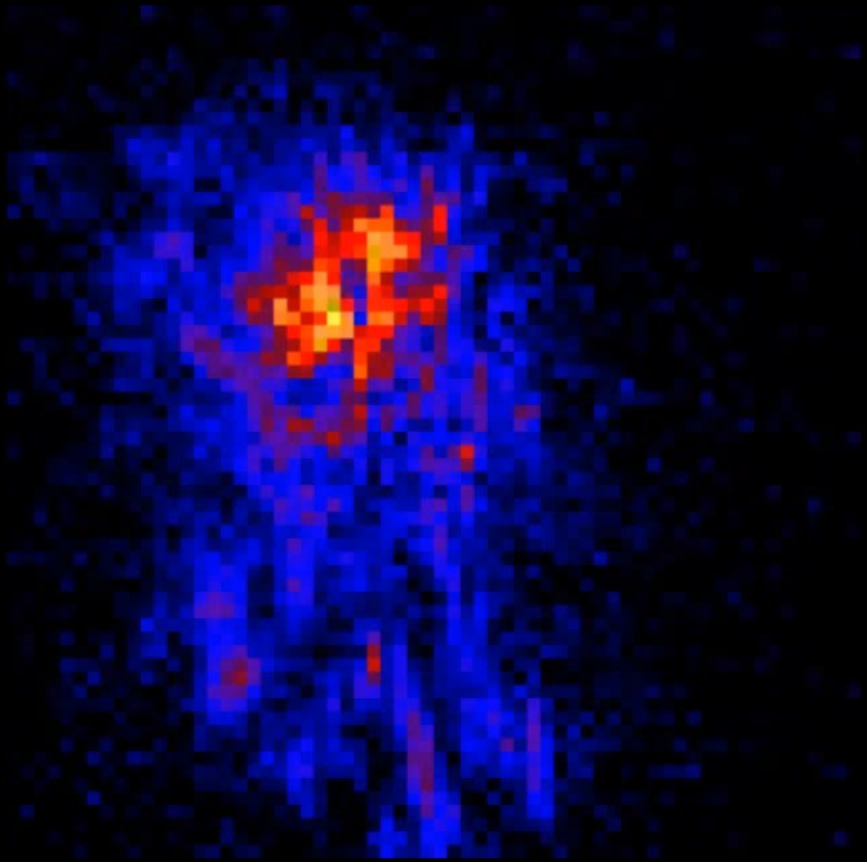


Figure 3-13

Discovering the Universe, Seventh Edition

up to a point...

high-speed video of scintillation (“seeing”)



Why use CCDs?

1) high quantum efficiency: QE= ~ 60-90%

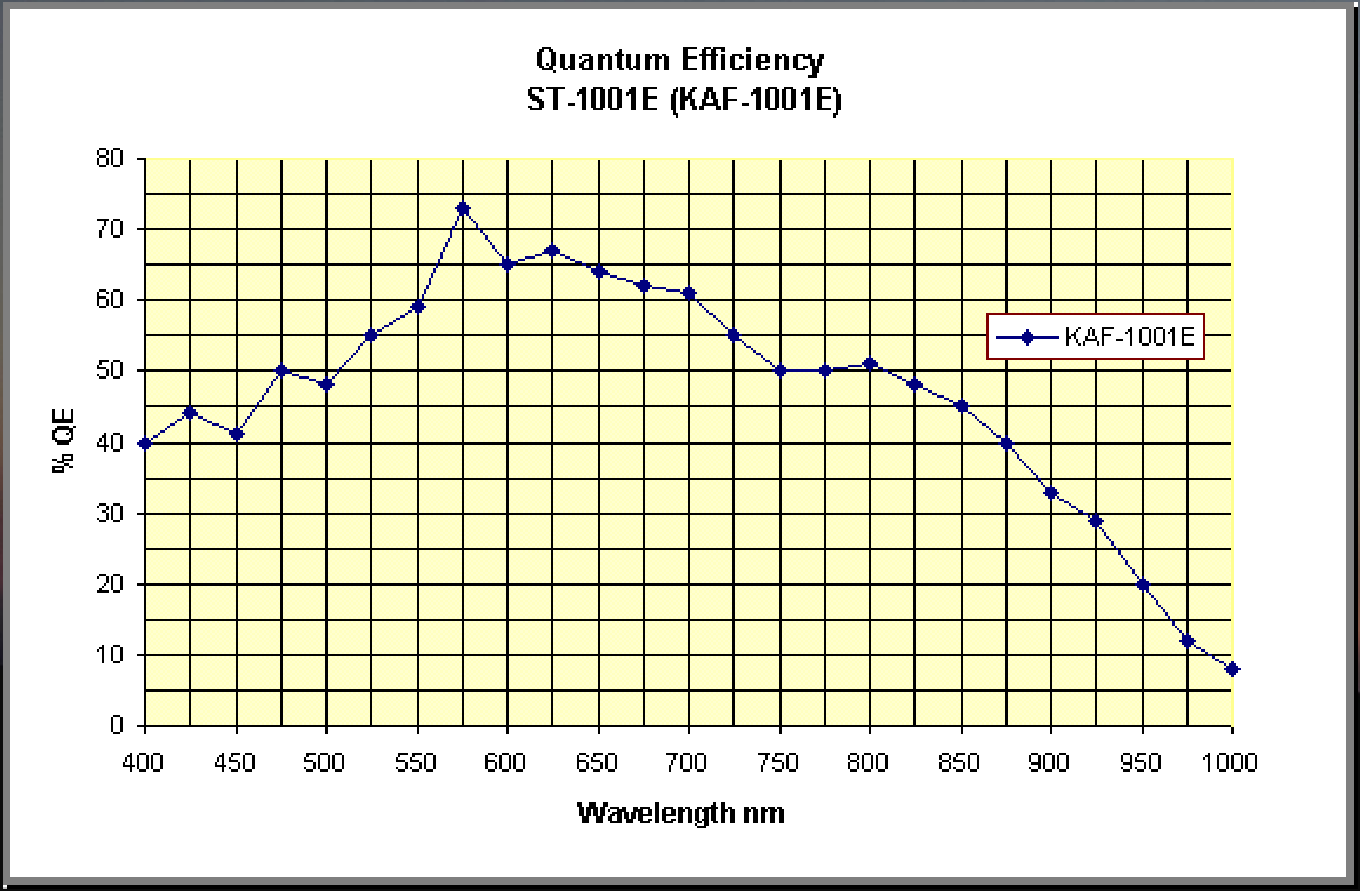
- QE = fraction of input light turned into output e-
- comparison: photographic film ~ 2-3%, 10% at best
  photomultiplier ~ 20%

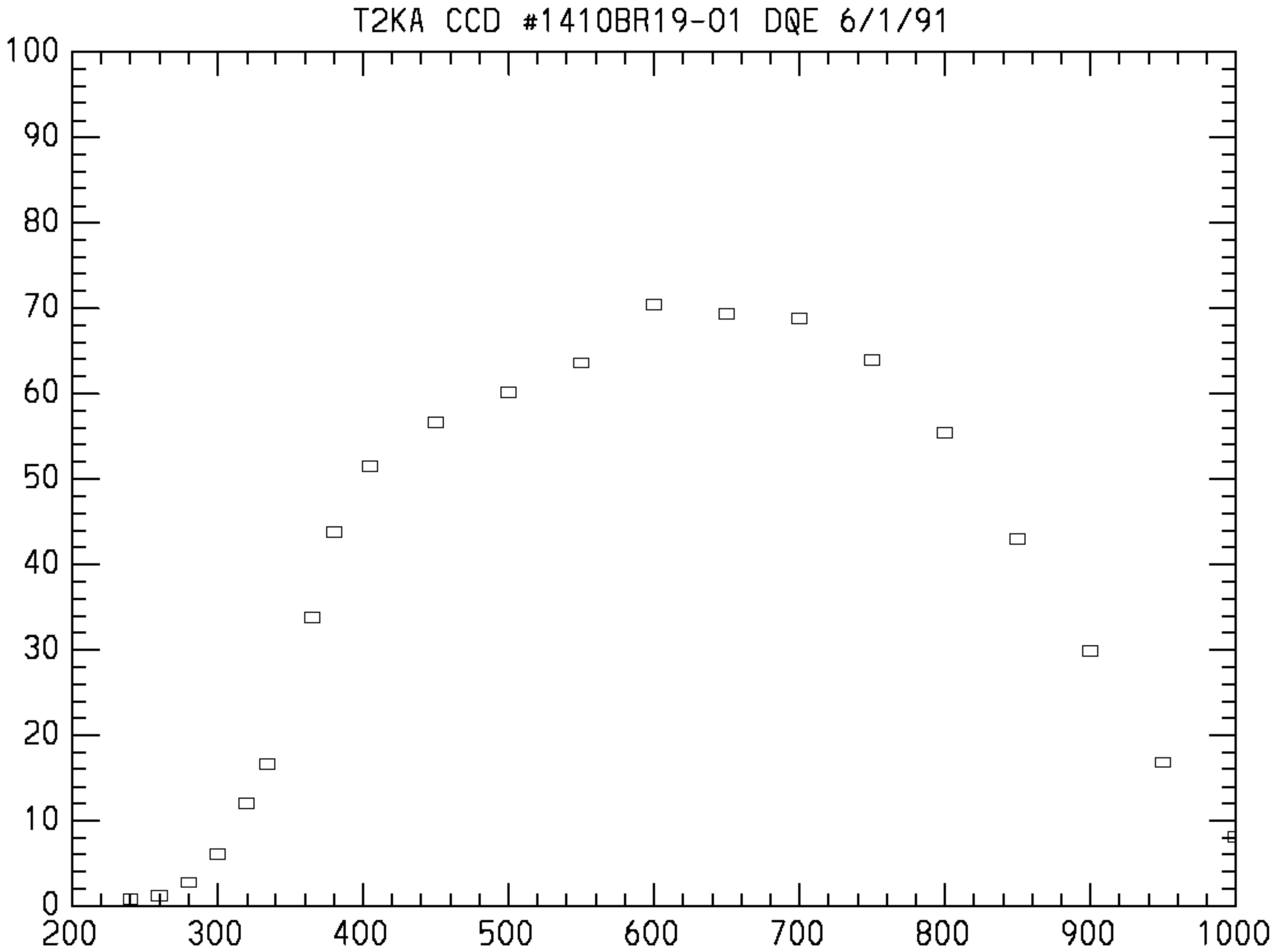
2) linear response:

- output is linearly proportional to input over a large range; For film, this is true only for a small range.

3) CCD is a 2-d imaging detector

- measure target, background (sky), and comparison objects simultaneously


Quantum Efficiency
ST-1001E (KAF-1001E)
% QE
0
10
20
30
40
50
60
70
80
400
450
500
550
600
650
700
750
800
850
900
950
1000
Wavelength nm
KAF-1001E


T2KA CCD #1410BR19-01 DQE 6/1/91
100
90
80
70
60
50
40
30
20
10
0
200
300
400
500
600
700
800
900
1000

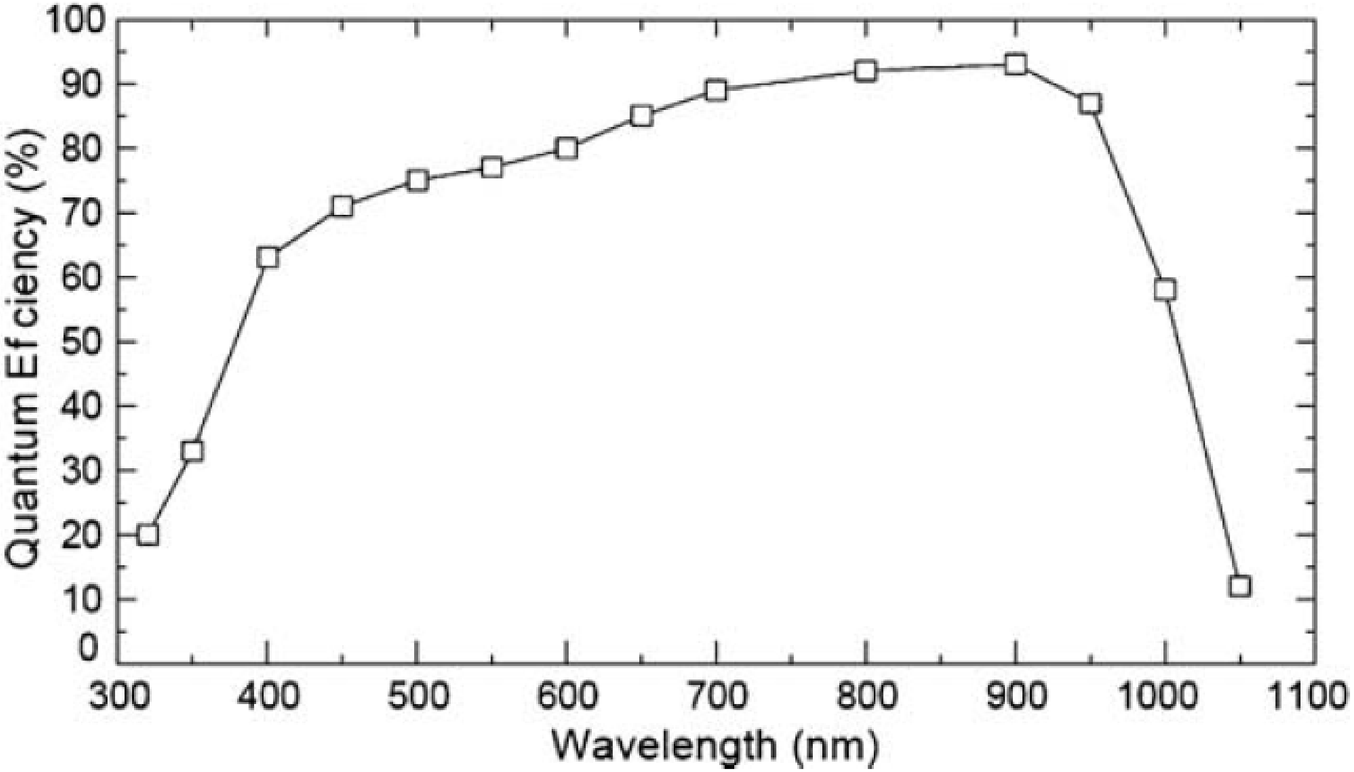


Figure 7. (*top*) Spectral response for different silicon thicknesses; (*bottom*) Lick/LBNL measurements. Courtesy of e2v technologies.

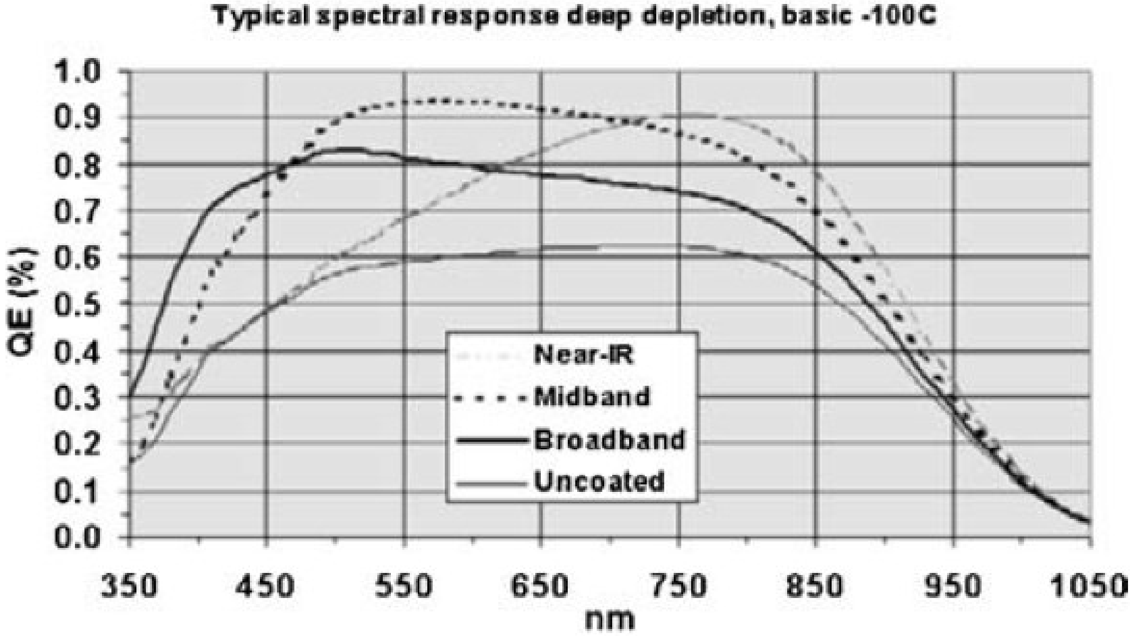
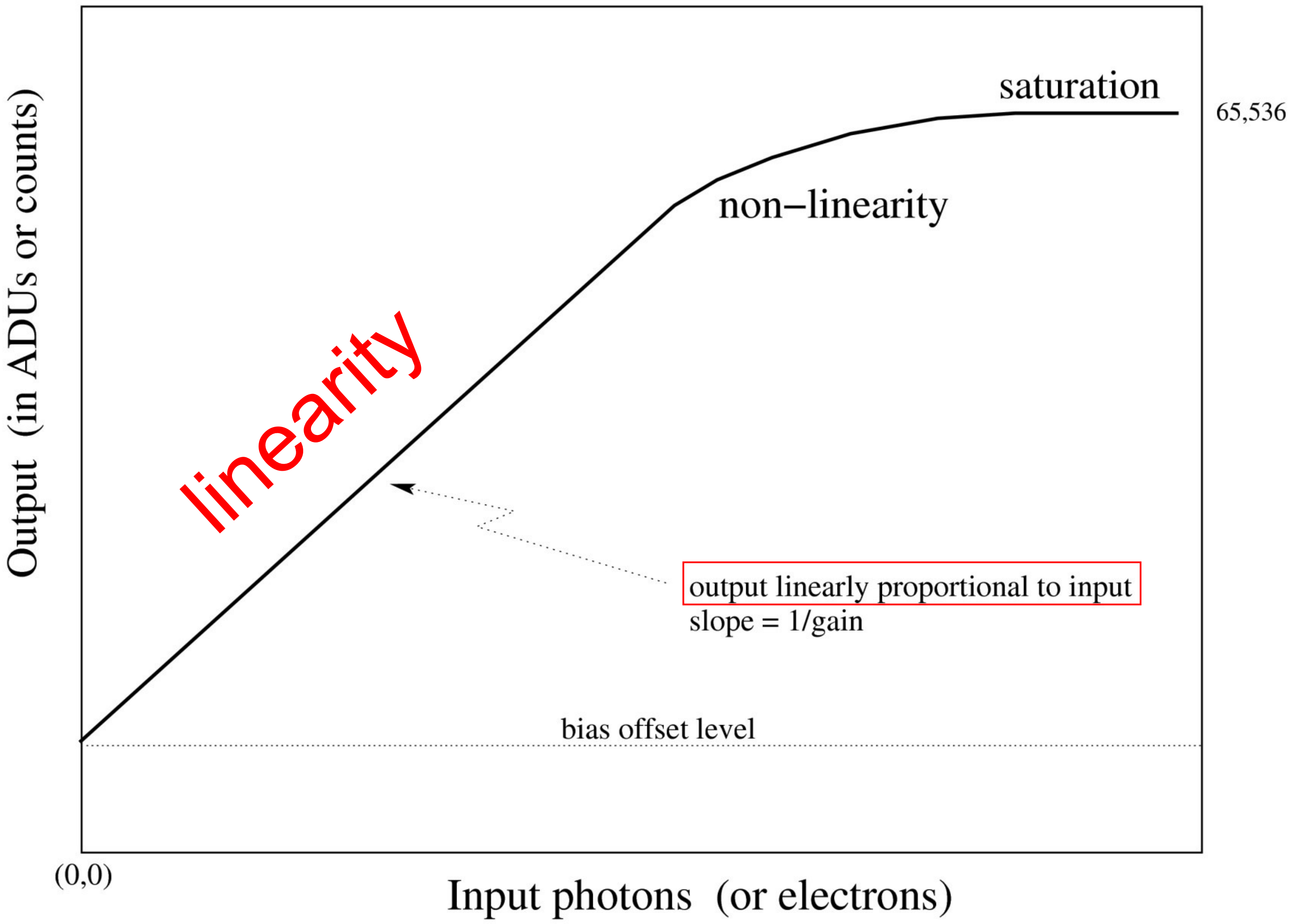
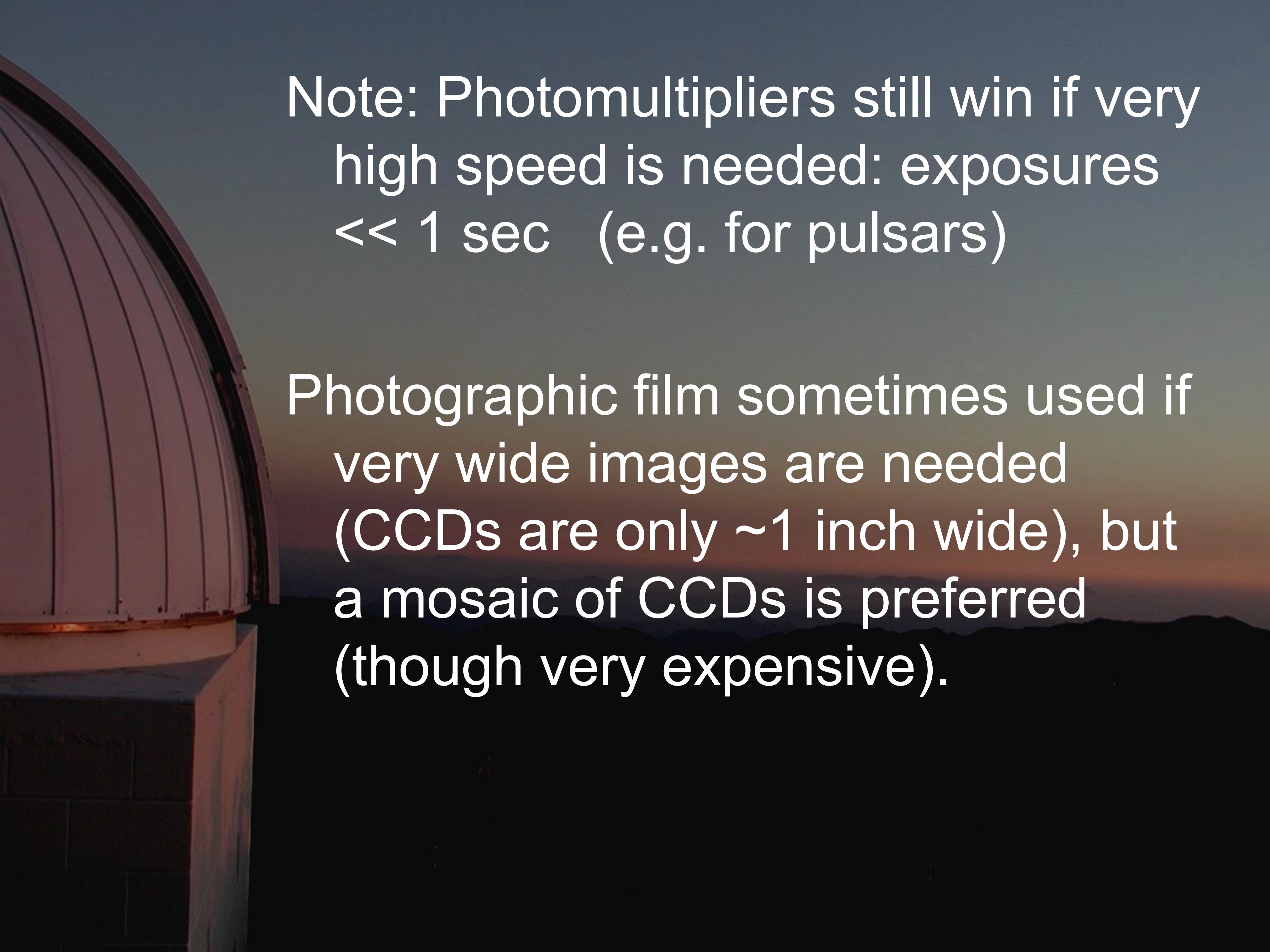


Figure 6. Examples of CCD responses with antireflection coatings optimized for different wavelength regions.

Schematic CCD input/output relationship





Note: Photomultipliers still win if very high speed is needed: exposures << 1 sec (e.g. for pulsars)

Photographic film sometimes used if very wide images are needed (CCDs are only ~1 inch wide), but a mosaic of CCDs is preferred (though very expensive).

Kepler Focal Plane – 42 CCDs

CCD Data Acquisition

1) Photon knocks free an electron in the silicon via the photoelectric effect.

2) CCD electronics transfer e- to an amplifier; charge is measured & digitized, then stored in a file:

photon → e^- → ADU → *.fits* file

“ADU” = analog-digital-unit

or equivalently, a “DN” (data number),

or simply a “count”.

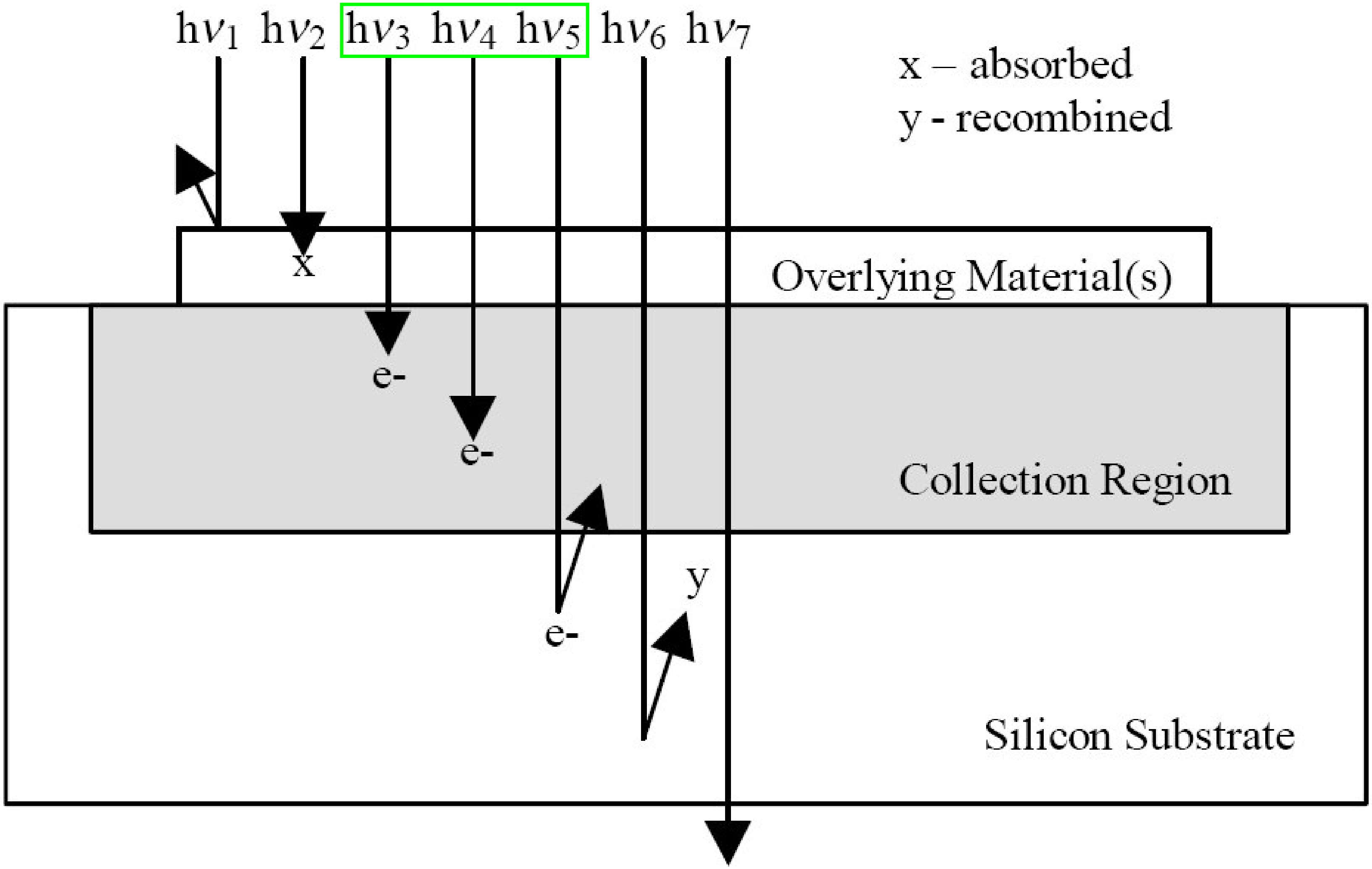


Figure 1: - Photon Interactions with Silicon

To increase the response of the sensor, the backside of the wafer is thinned to very small depths (~10-15µm). With the proper thinning, the CCD is then illuminated from the backside and UV and blue response is increased significantly. Thinning is restricted to FF and FT architectures without VOD structures. The difficulty in thinning the device to such depths leads to lower yields and higher costs. Handling becomes extremely difficult as well.

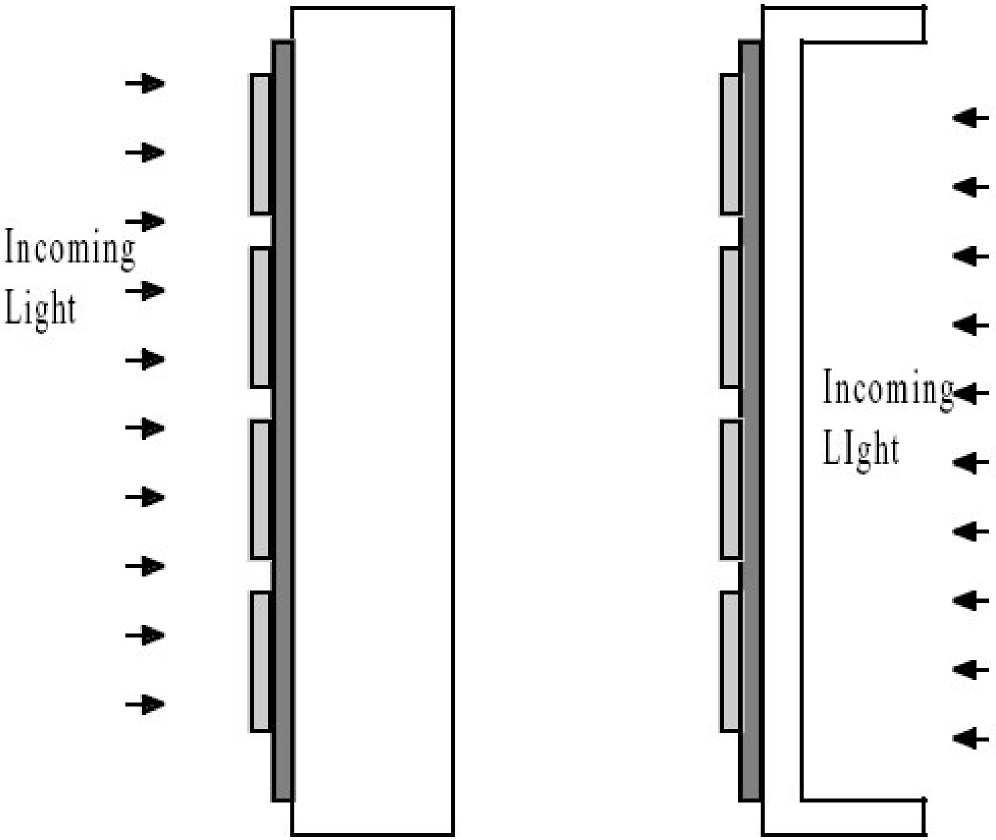


Figure 20: Thick and Thinned CCD

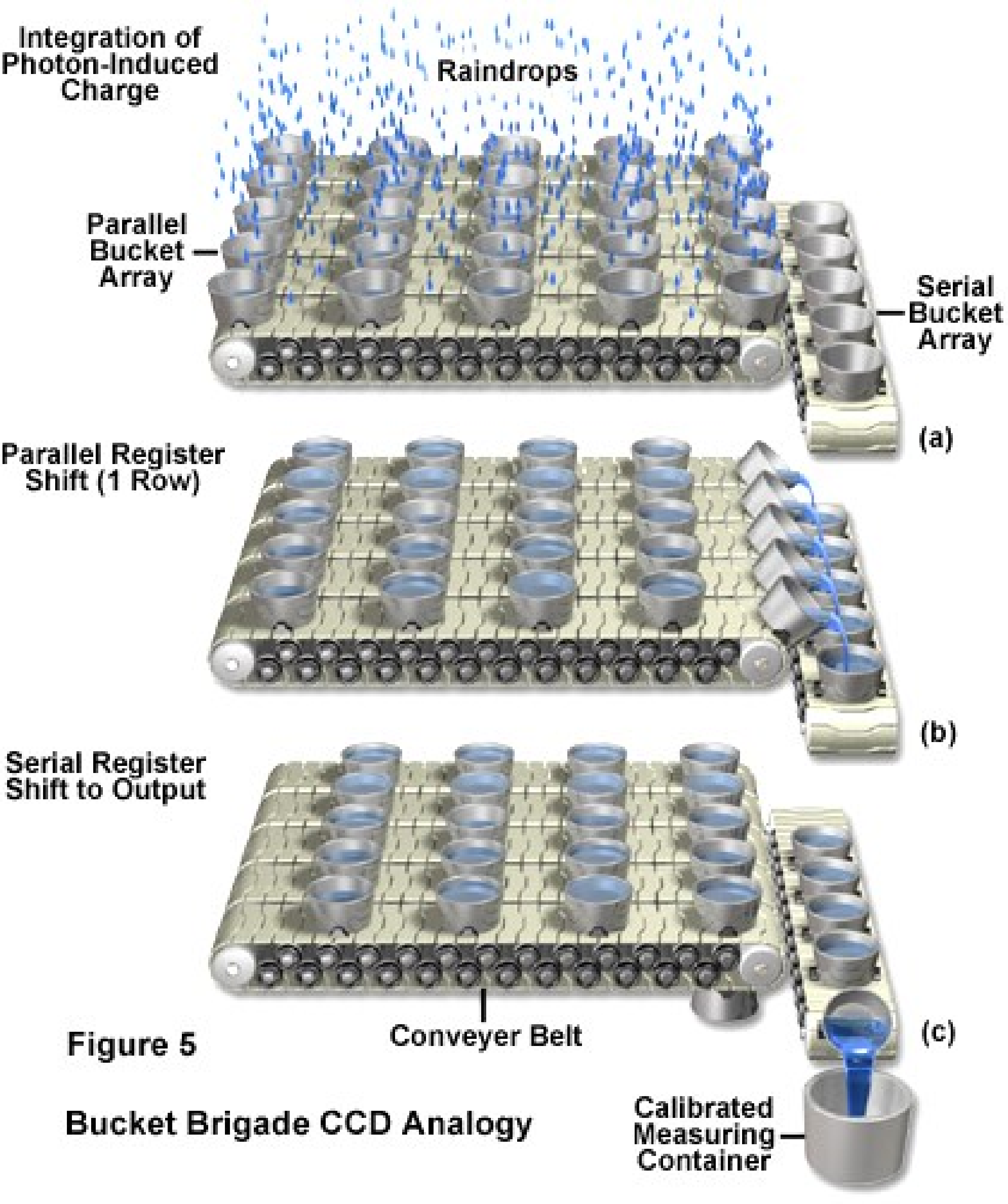
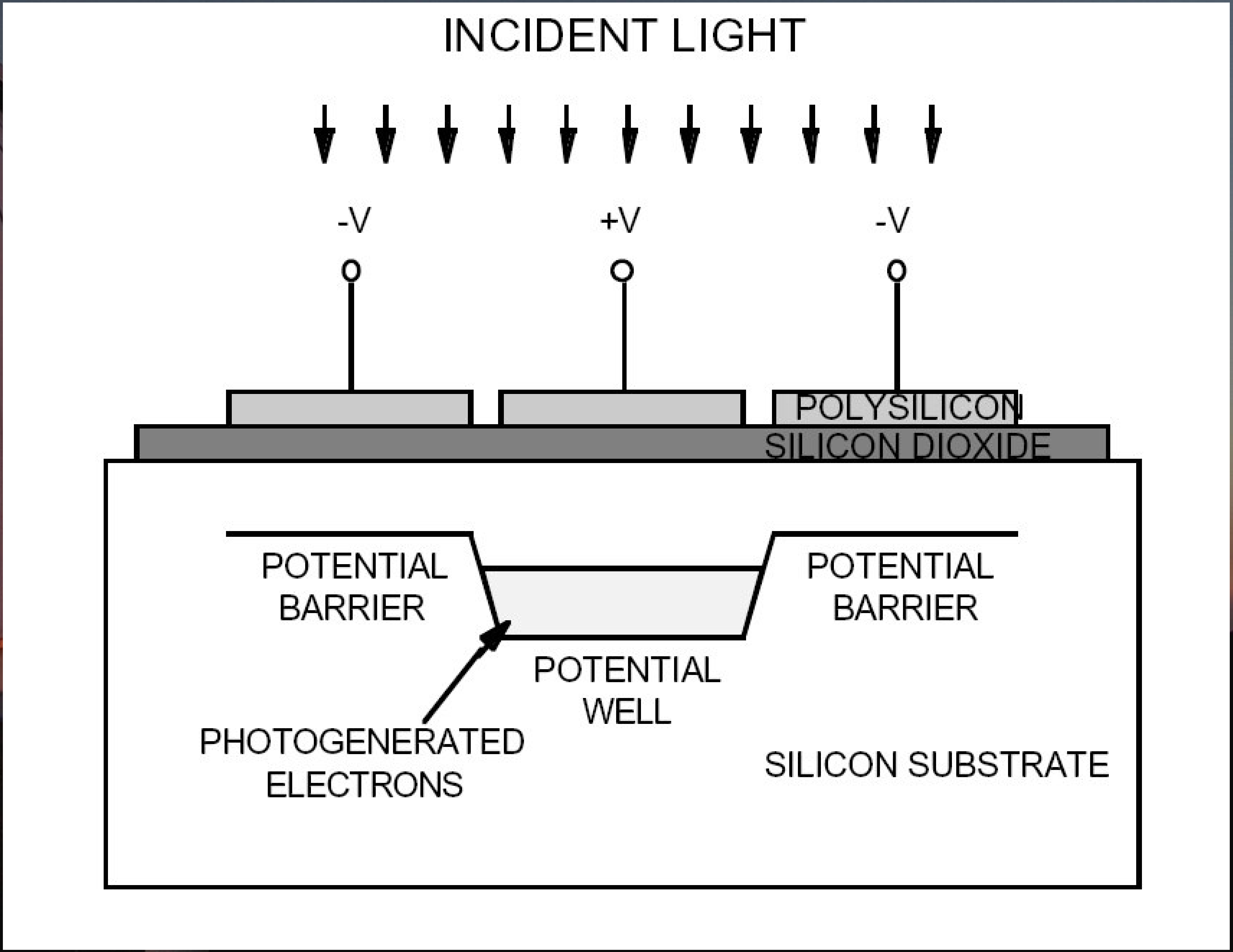


Figure 5

Bucket Brigade CCD Analogy


INCIDENT LIGHT
-V
+V
-V
POLYSILICON
SILICON DIOXIDE
POTENTIAL BARRIER
POTENTIAL BARRIER
POTENTIAL WELL
PHOTOGENERATED ELECTRONS
SILICON SUBSTRATE

Three Phase CCD Clocking Scheme

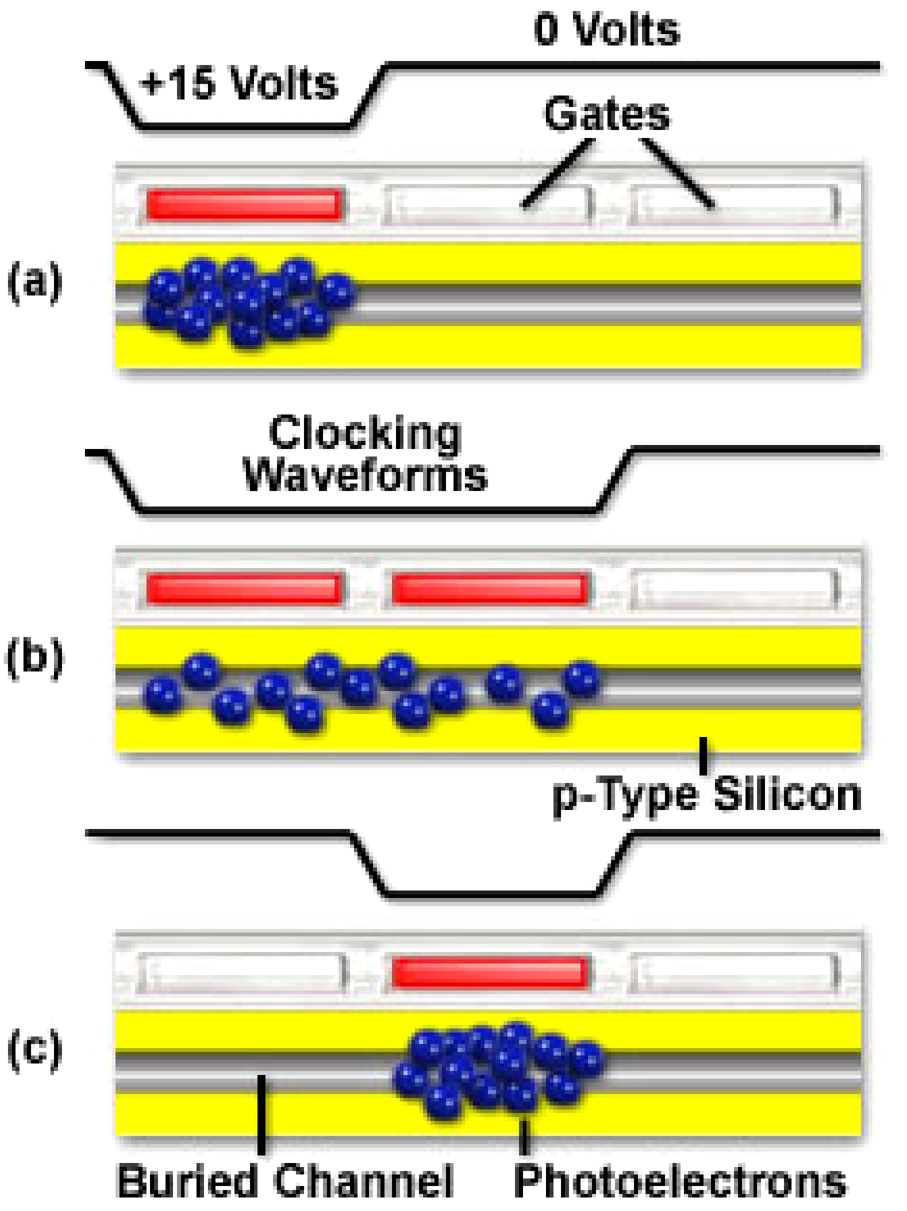


Figure 6

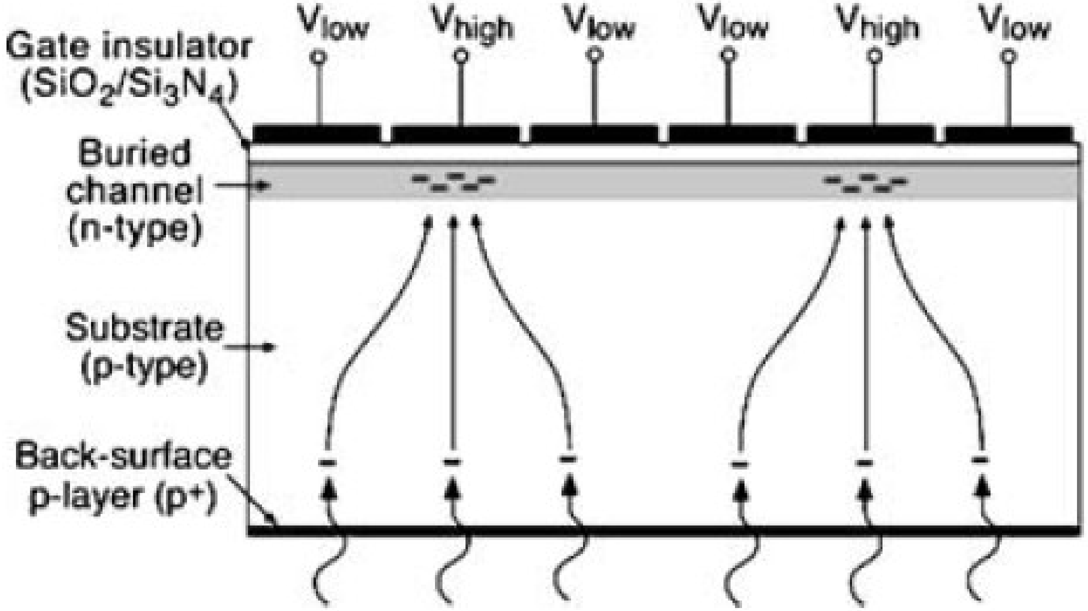


Figure 1. Depiction of the cross section of a three-phase CCD

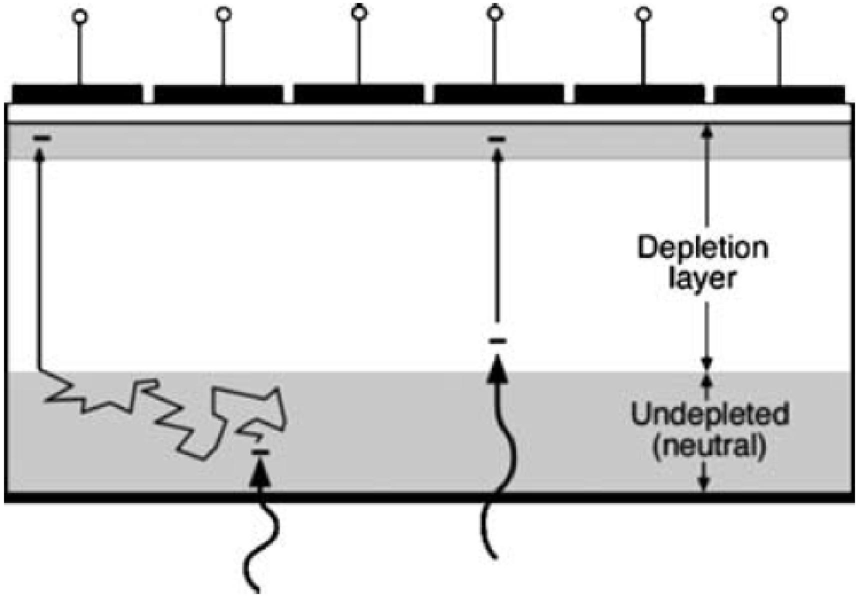


Figure 2. Cross section of a CCD depicting the depletion layer and the neutral undepleted layer at the back surface and its effects on photoelectron charge collection.

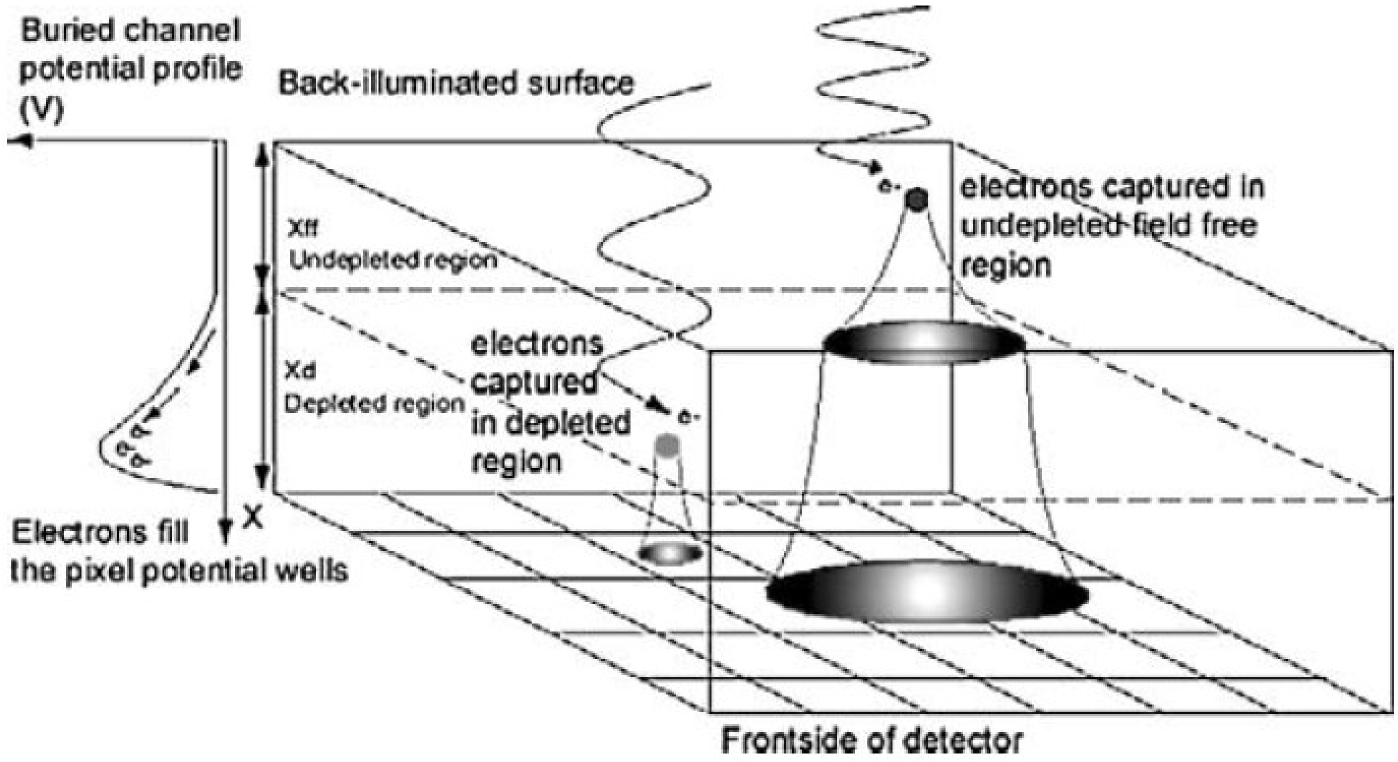
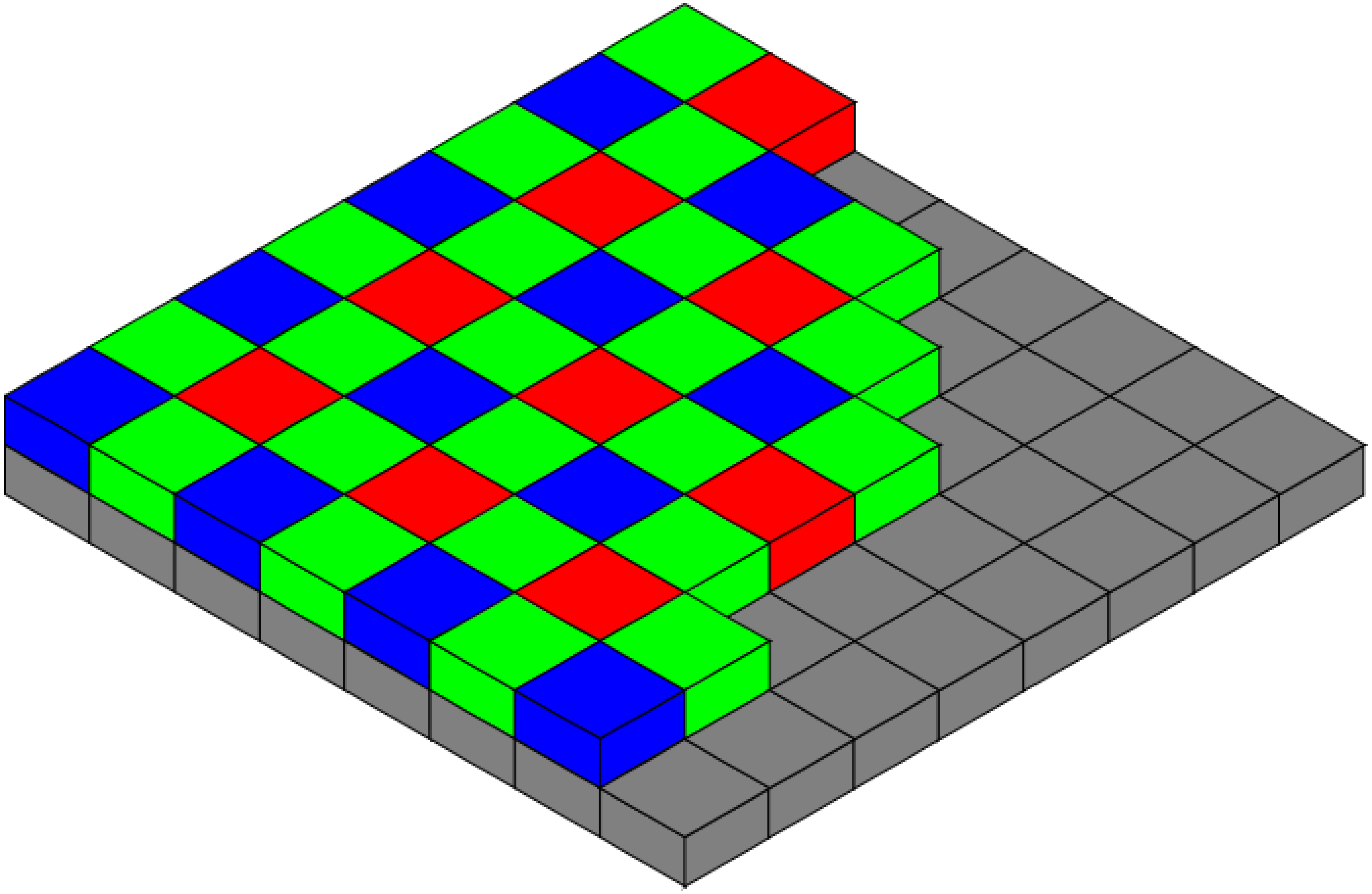
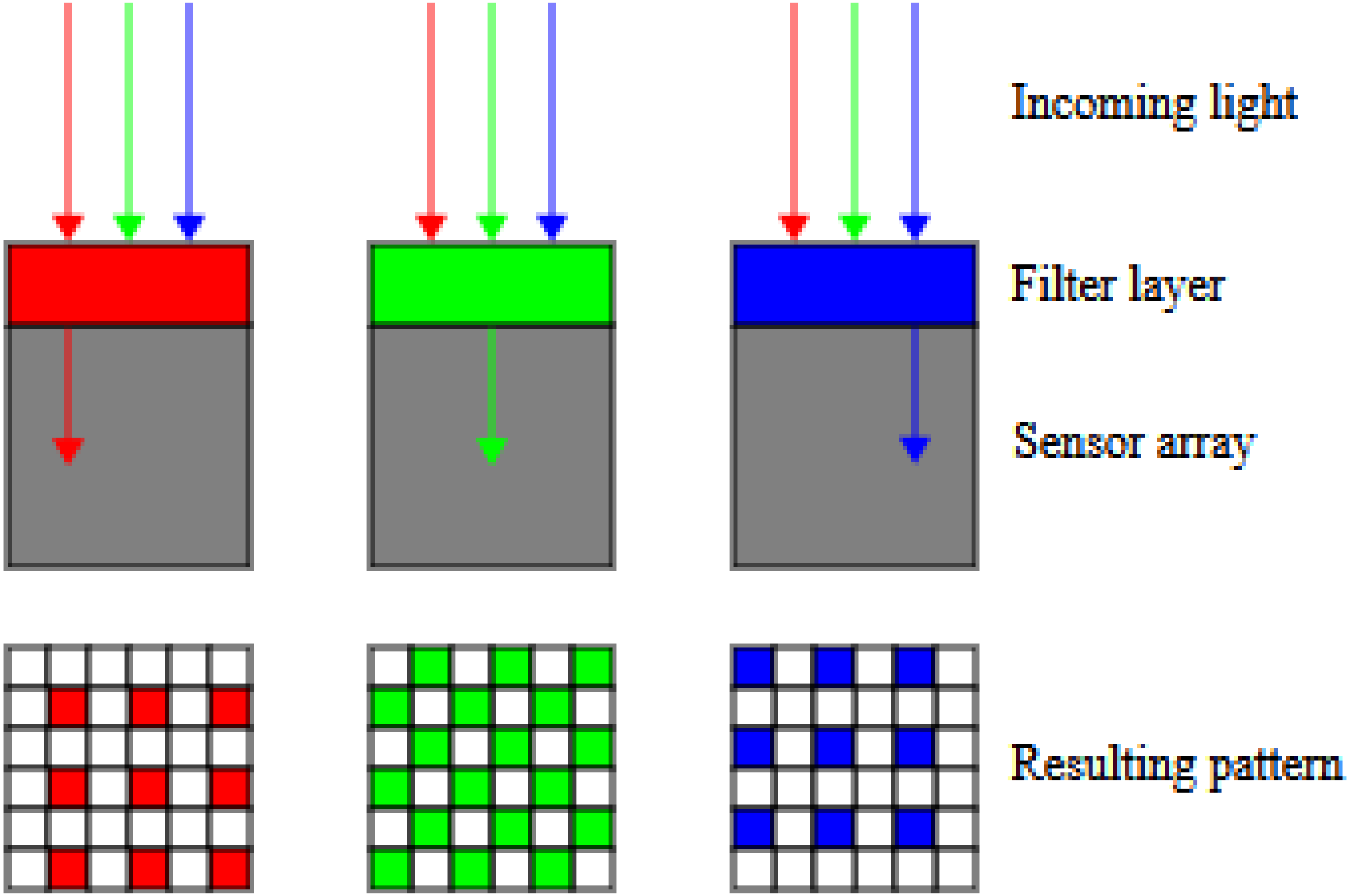


Figure 13. Enlargement of PSF resulting from charge diffusion in the field-free region.

Aside: Color and CCD images



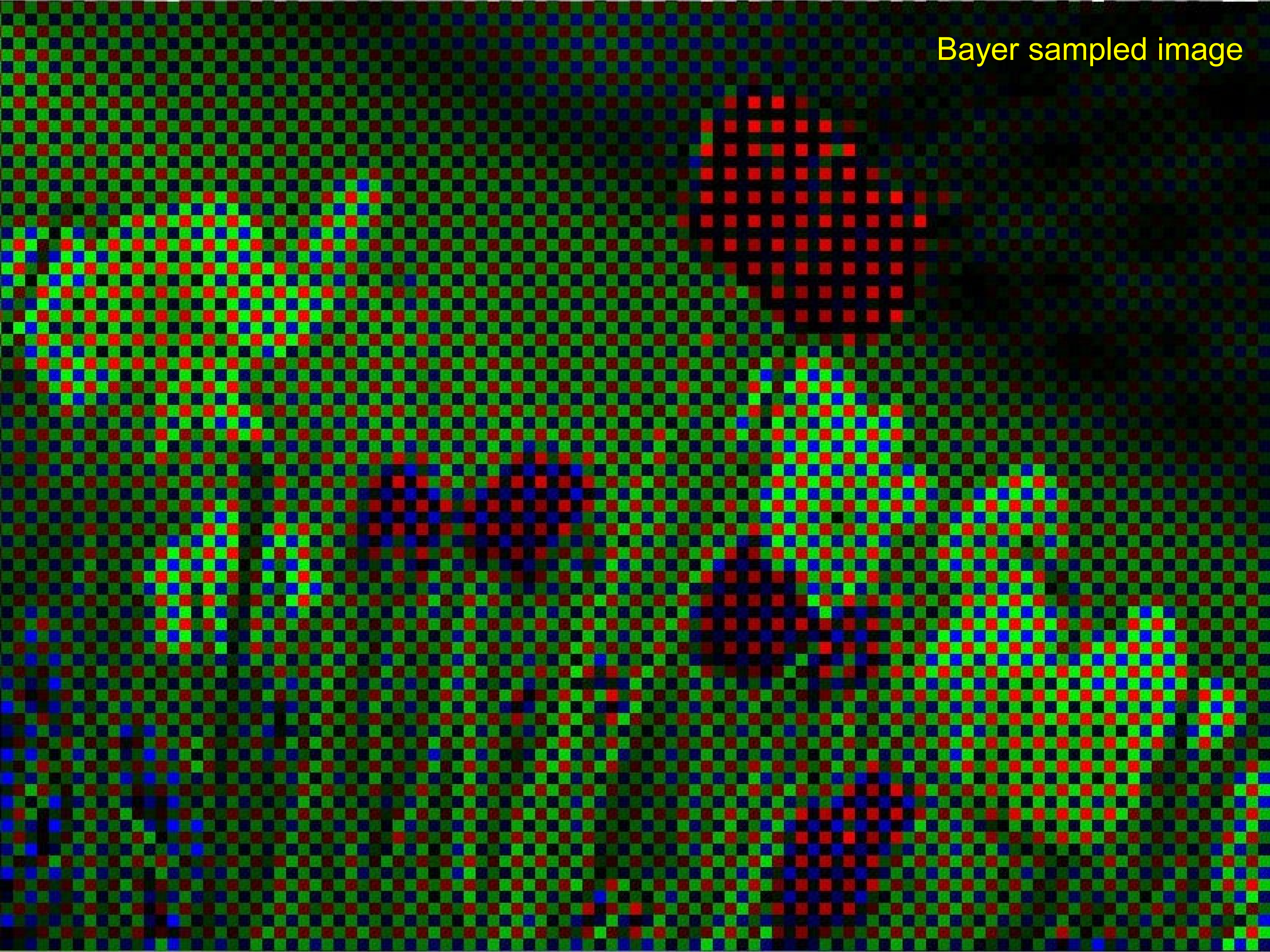
RGB “Bayer” mosaic of a CCD for color images



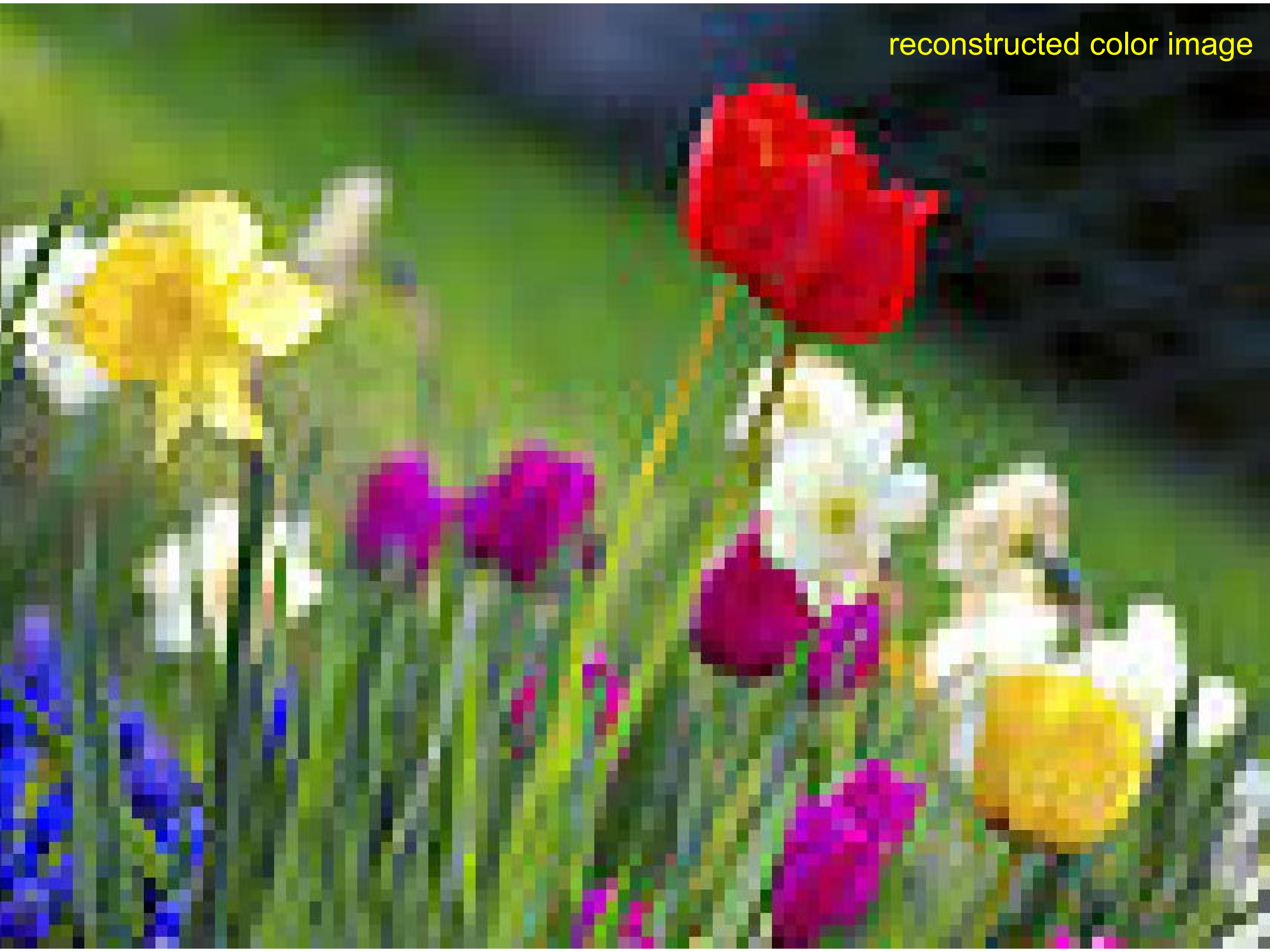
Normal color images are much lower resolution than black and white.

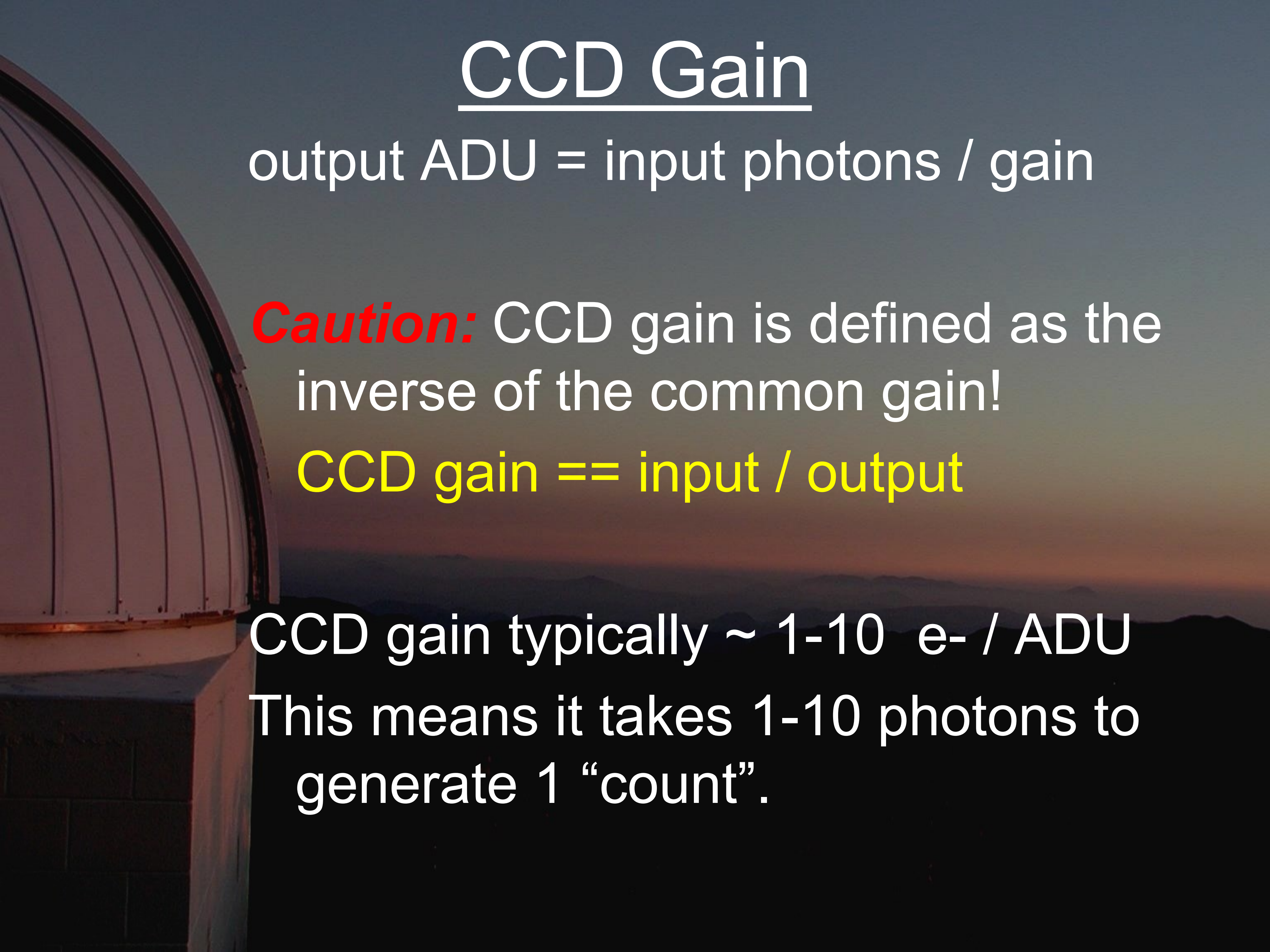
Interpolation is used to fill-in the gaps.


“true” image



Bayer sampled image


reconstructed color image



CCD Gain

output ADU = input photons / gain

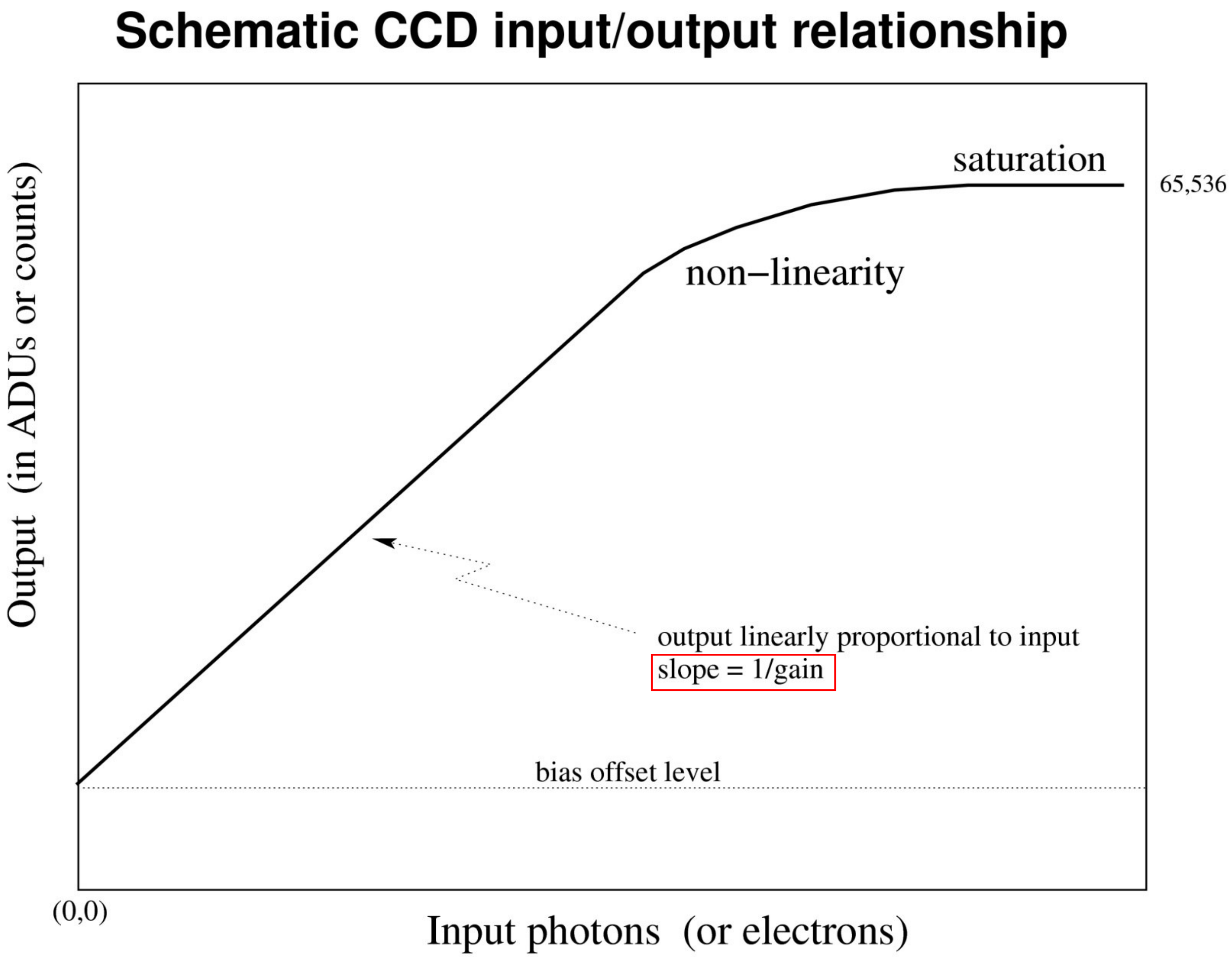
Caution: CCD gain is defined as the inverse of the common gain!

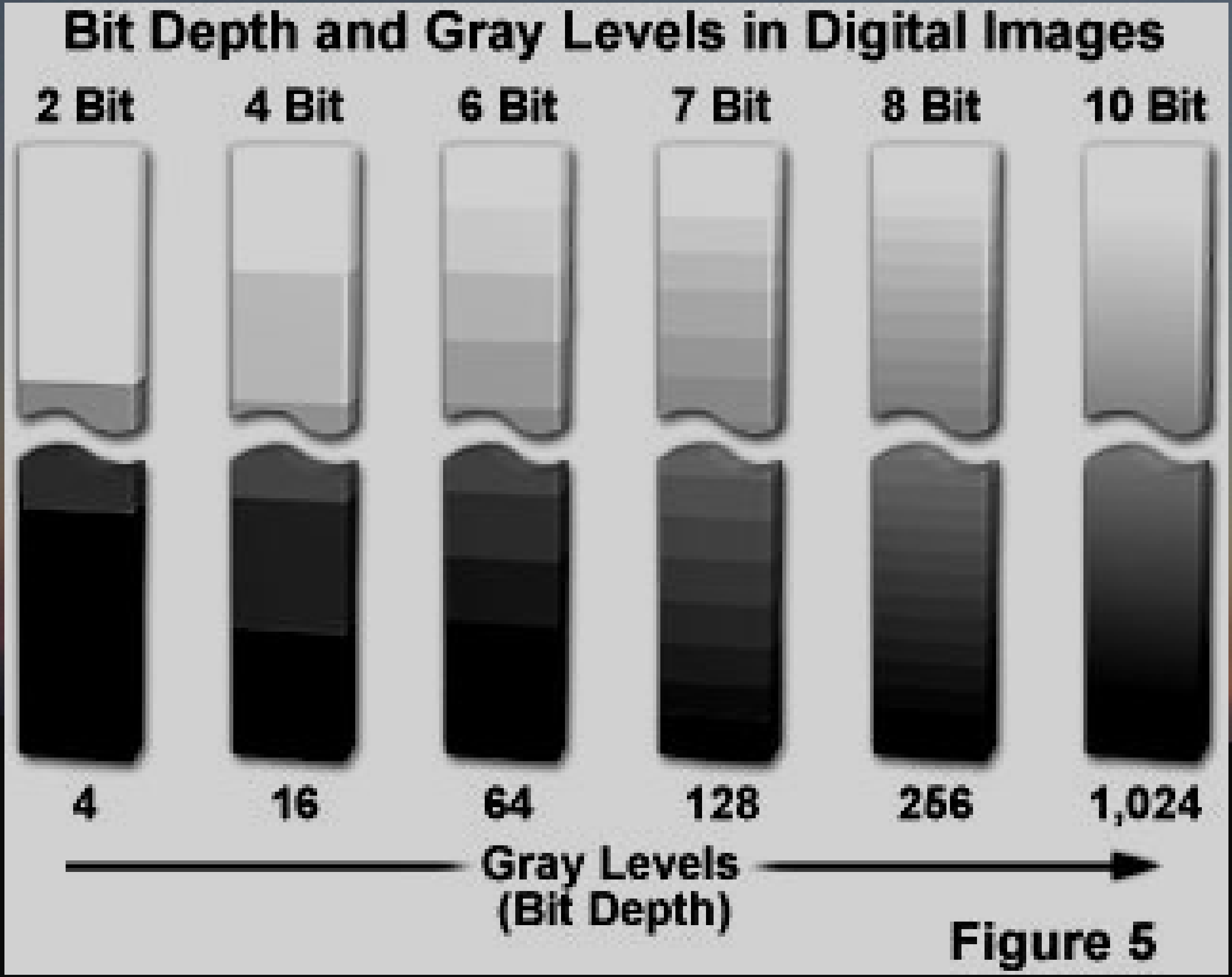
CCD gain == input / output

CCD gain typically ~ 1-10 e- / ADU

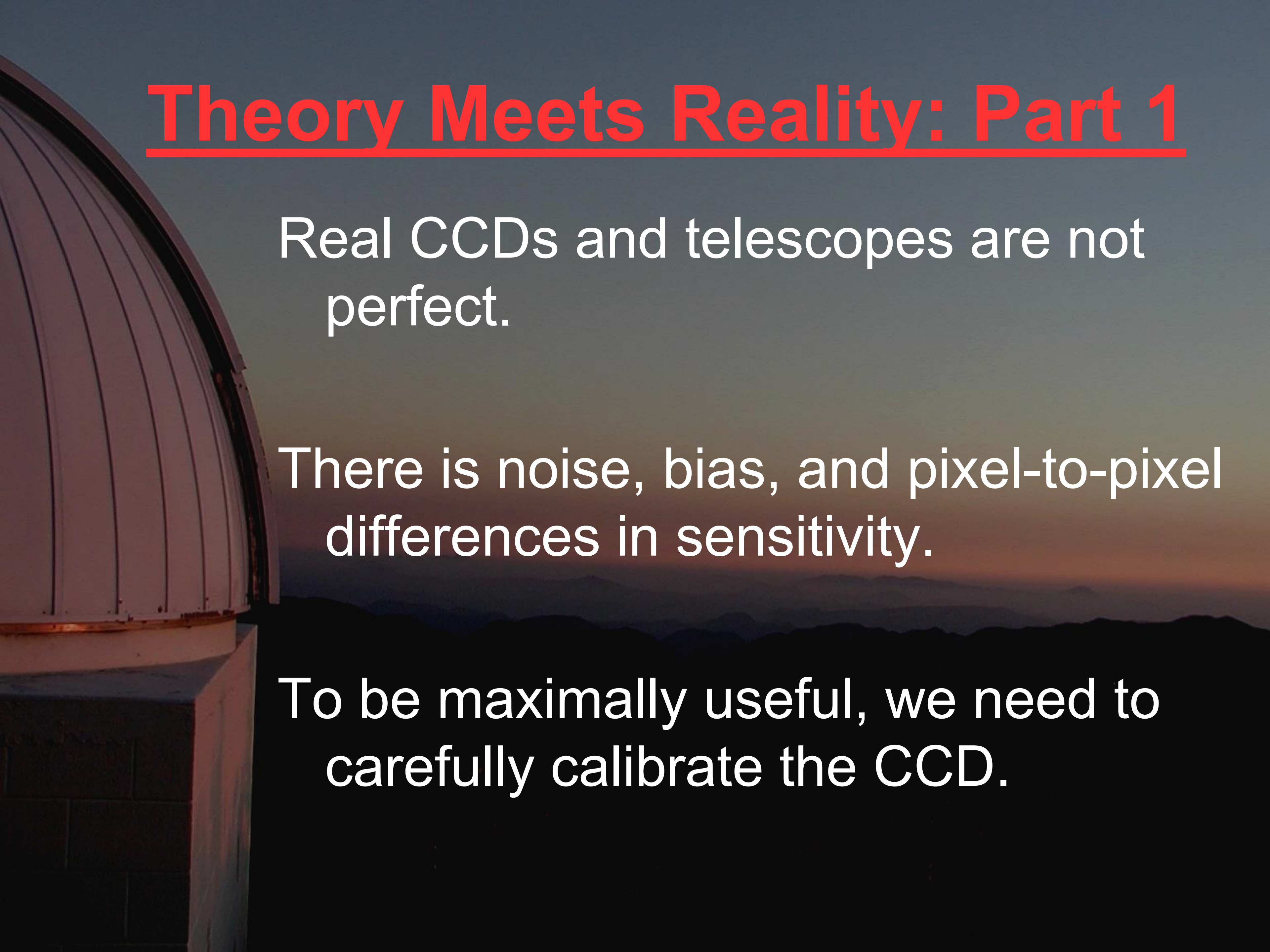
This means it takes 1-10 photons to generate 1 “count”.

CCD Gain


Schematic CCD input/output relationship
saturation
65,536
non–linearity
output linearly proportional to input
slope = 1/gain
bias offset level
Output (in ADUs or counts)
(0,0)
Input photons (or electrons)



16-bit A/D converter allows 2^{16} = 65,536 discrete levels

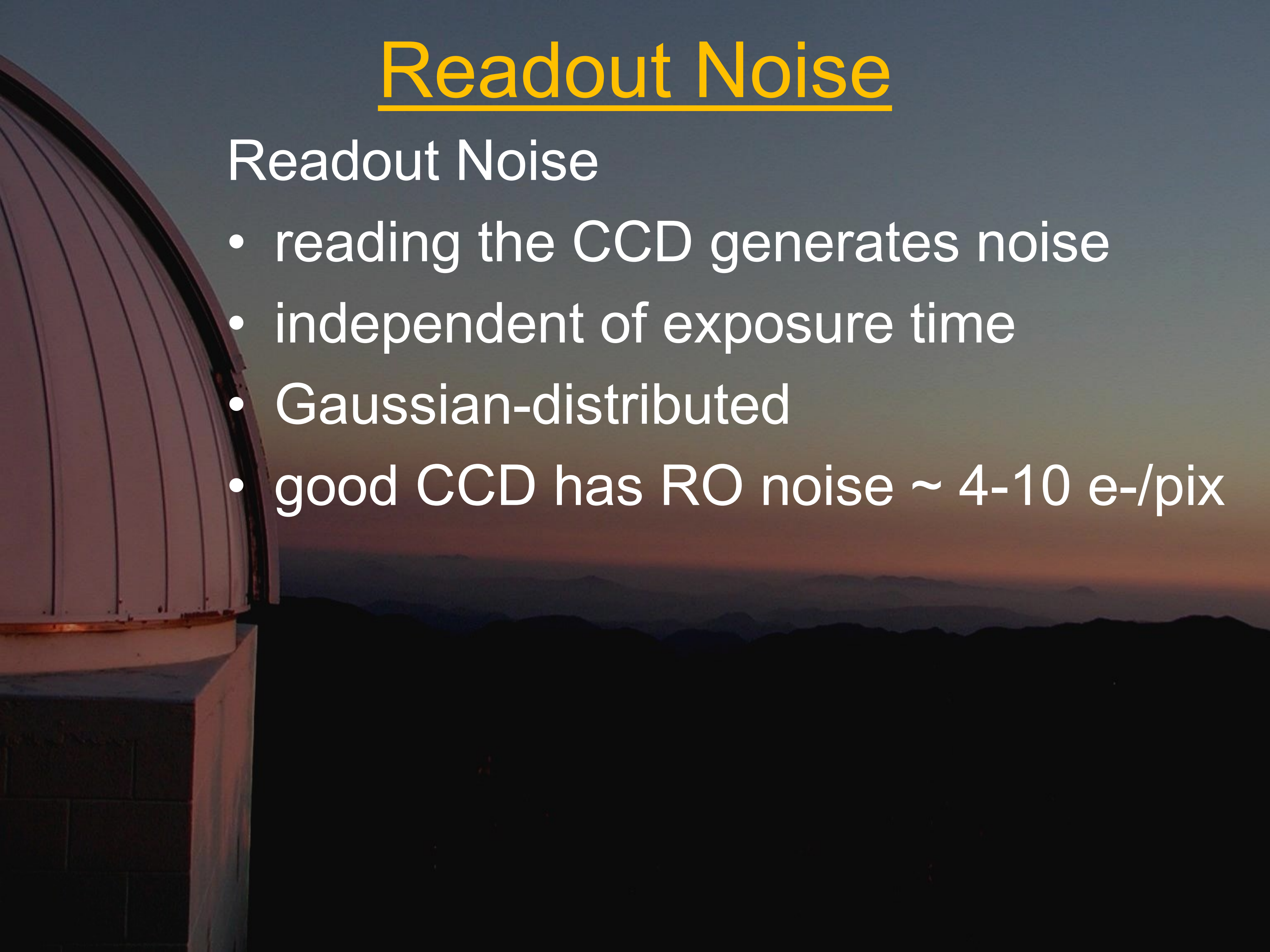


Theory Meets Reality: Part 1

Real CCDs and telescopes are not perfect.

There is noise, bias, and pixel-to-pixel differences in sensitivity.

To be maximally useful, we need to carefully calibrate the CCD.



Readout Noise

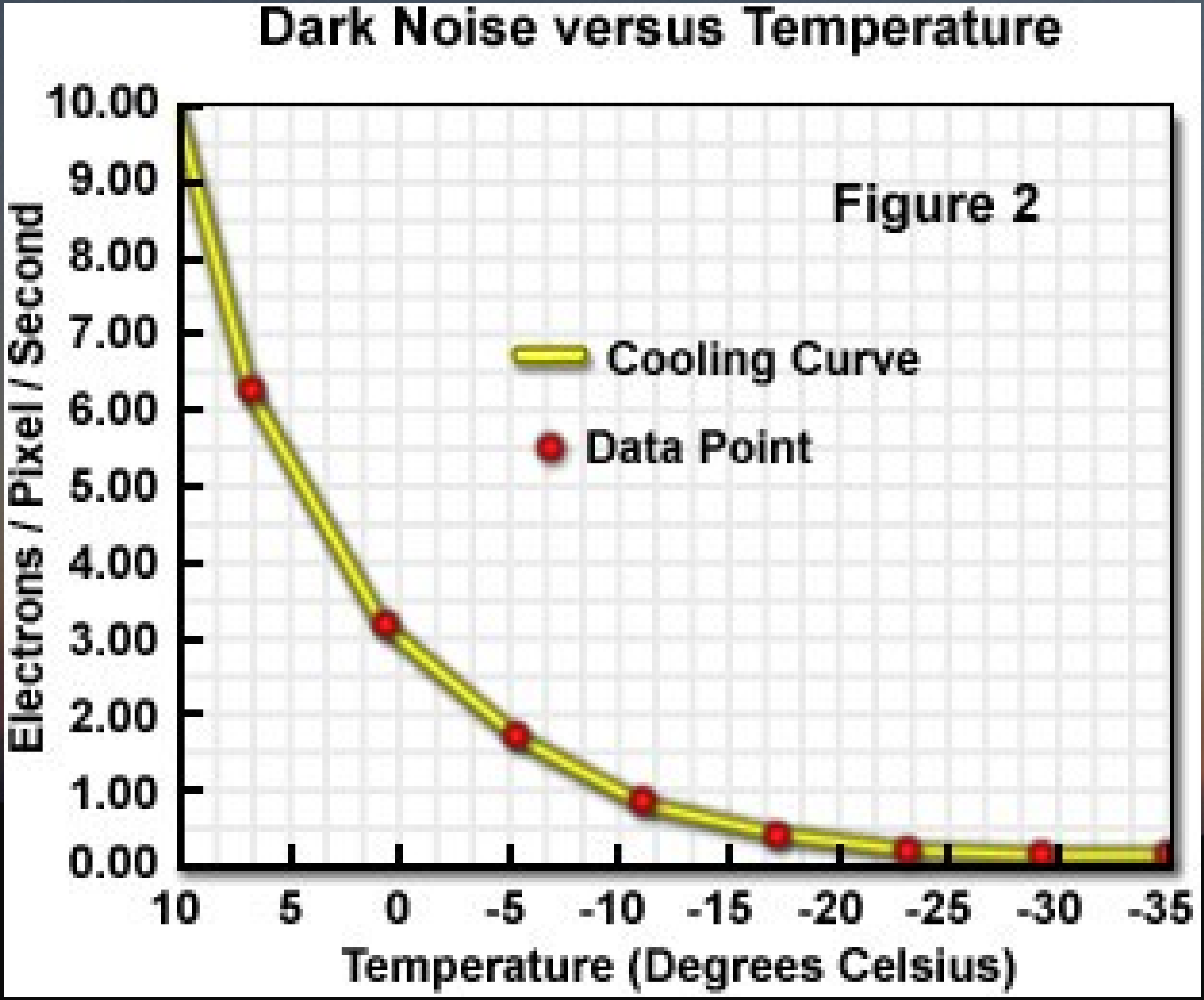
Readout Noise

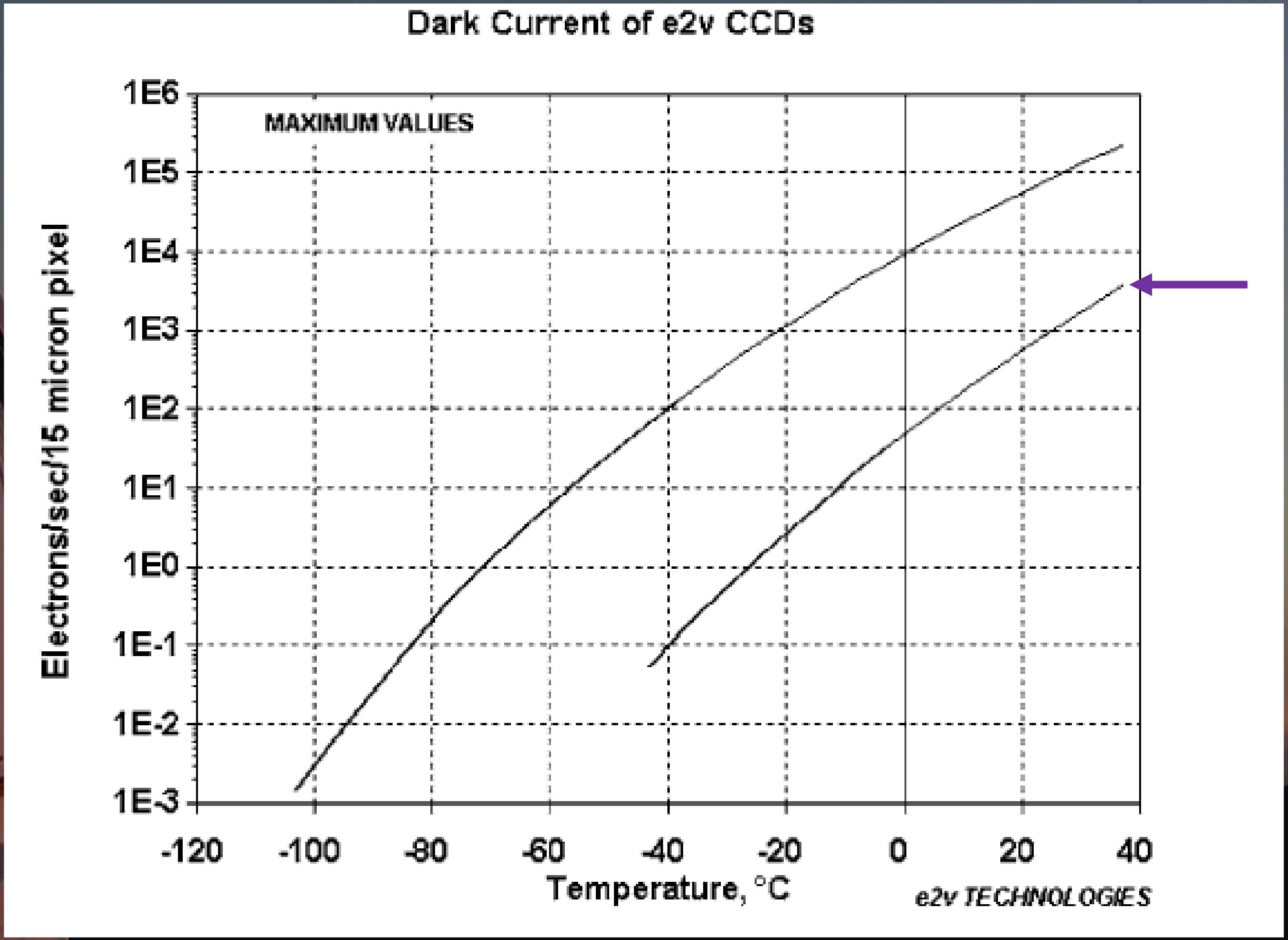
- reading the CCD generates noise
- independent of exposure time
- Gaussian-distributed
- good CCD has RO noise ~ 4-10 e-/pix

Dark Noise

Thermal fluctuations can knock an e- free, and this acts just as if a photon knocked it free.

- Depends on the exposure duration.
- Can be greatly reduced by cooling the CCD.
- Using liquid N_2 can make dark noise negligible: $< \sim 0.02$ e-/s/pix
- Dark current is important if the CCD is not cold, as in amateur CCDs.

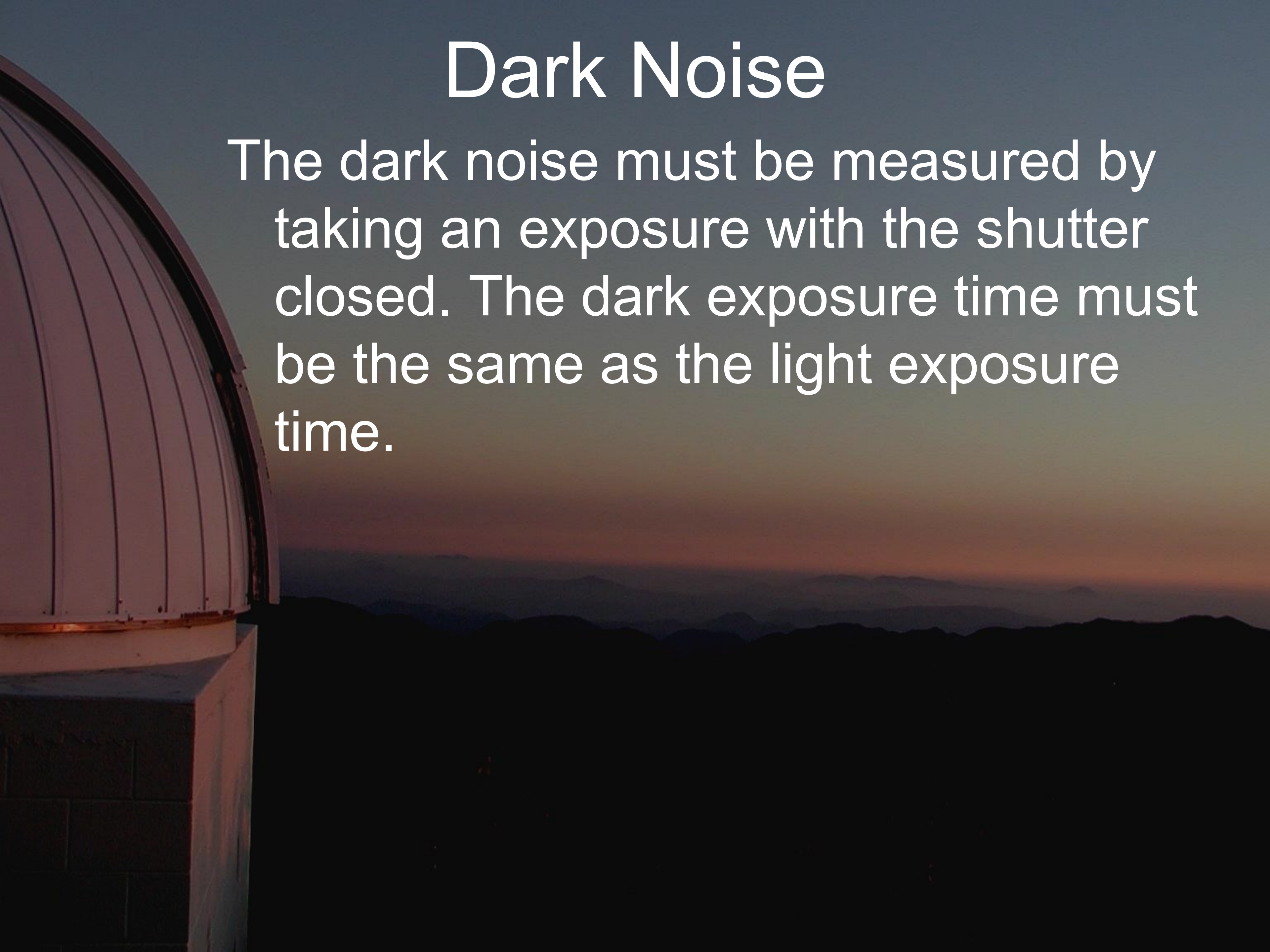

Dark Noise versus Temperature
Figure 2
Cooling Curve
Data Point
Electrons / Pixel / Second
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
10
5
0
-5
-10
-15
-20
-25
-30
-35
Temperature (Degrees Celsius)



Dark Current of e2v CCDs

Dark Noise

The dark noise must be measured by taking an exposure with the shutter closed. The dark exposure time must be the same as the light exposure time.



Cosmic Ray Noise

Cosmic rays (particles from solar flares, AGN, supernovae, etc.) and their spallation shower products can ionize the Si atoms in a CCD and create a false signal.

Radiation from the Earth can do this too (e.g. naturally radioactive granite).

Cosmic rays/radiation events are usually very strong and easy to see.

Cosmic rays are usually the limiting factor in the duration of a CCD exposure.

Bias

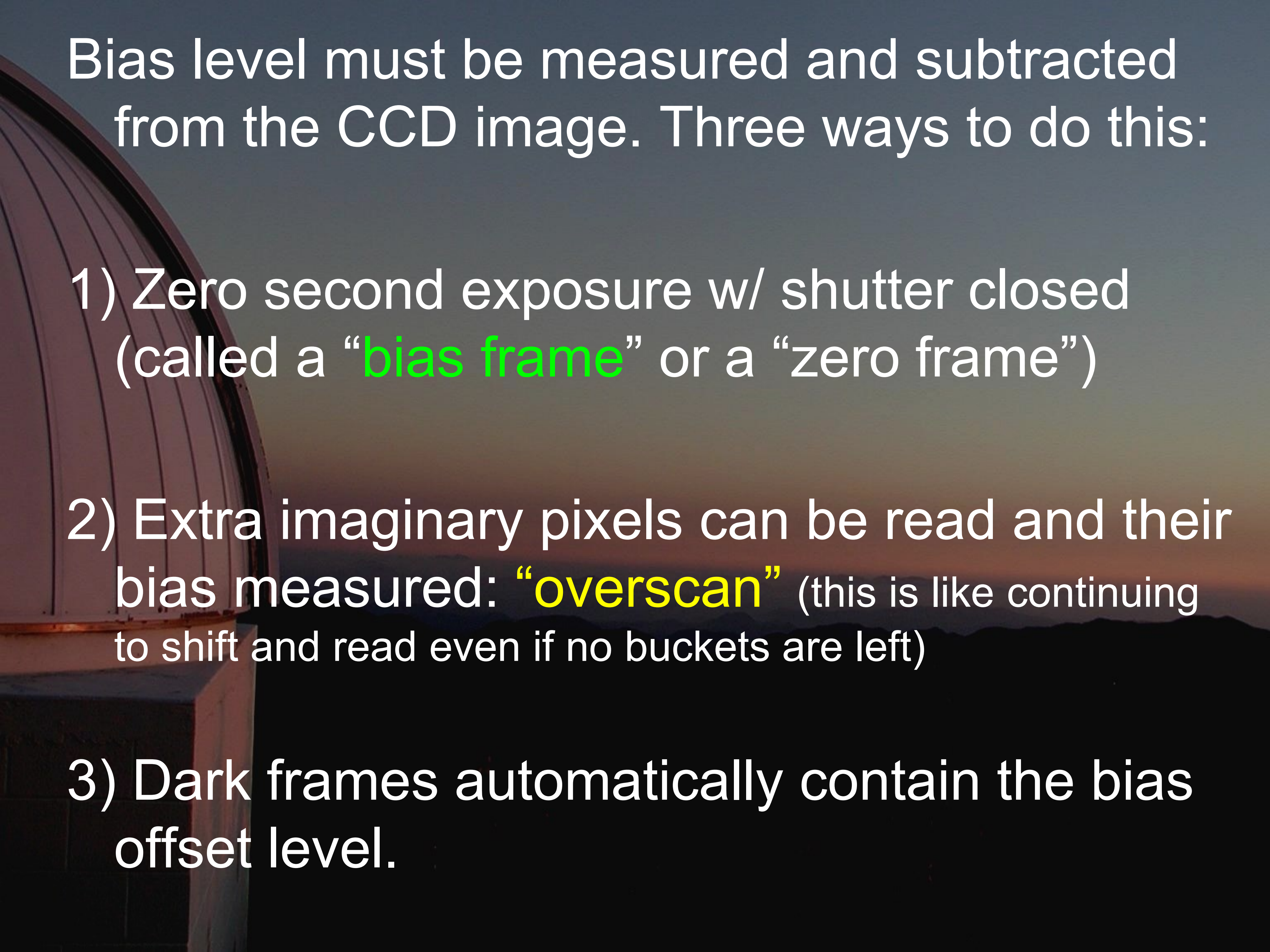
Noise can be positive or negative.

The CCD electronics cannot measure a "negative count" – this could cause a problem.

To prevent any chance of noise causing the output to be negative, an offset is added: the bias level.

Bias is ~ few hundred ADU.

CCD output = (input photons / gain) + bias



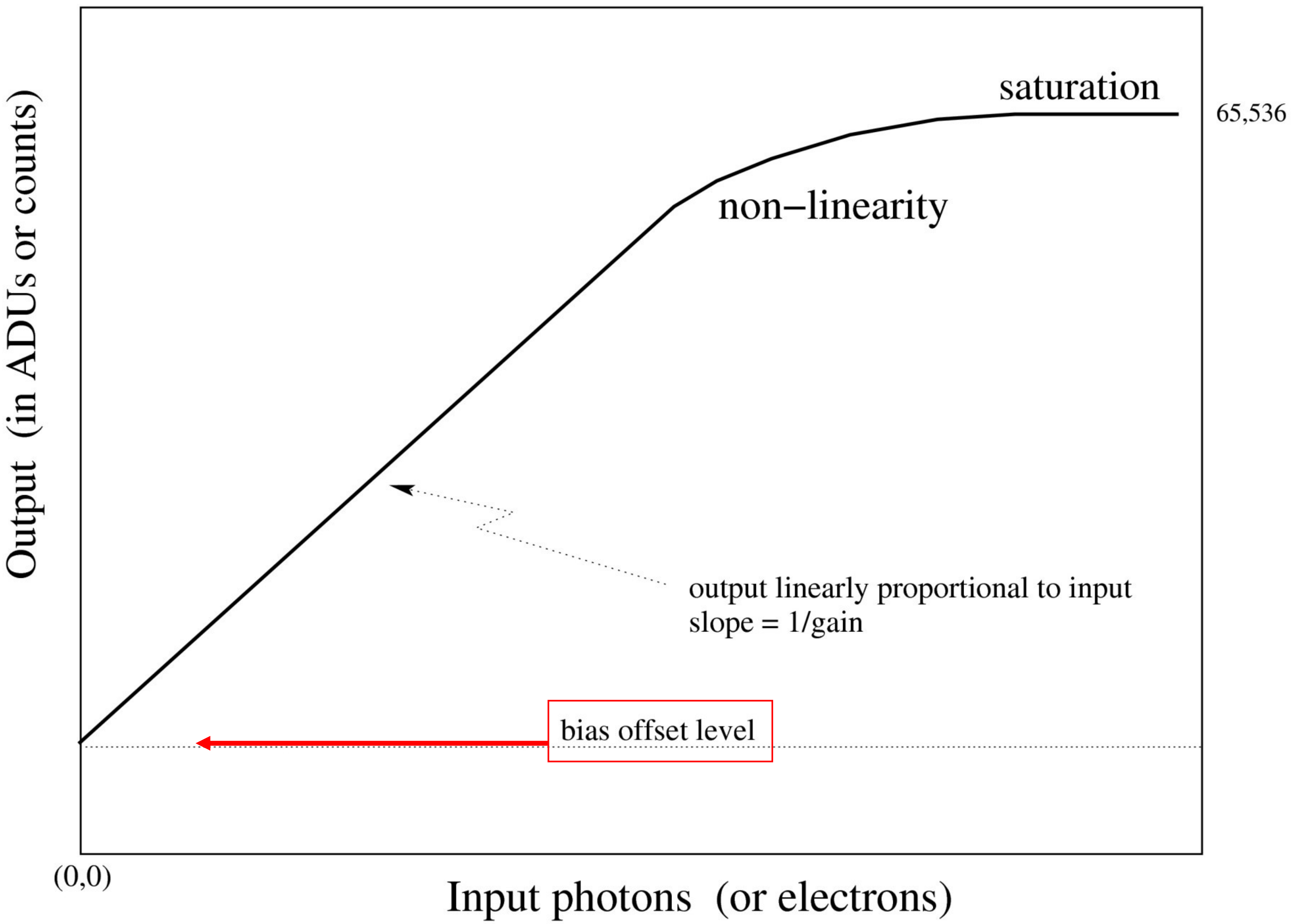
Bias level must be measured and subtracted from the CCD image. Three ways to do this:

1) Zero second exposure w/ shutter closed (called a "bias frame" or a "zero frame")

2) Extra imaginary pixels can be read and their bias measured: "overscan" (this is like continuing to shift and read even if no buckets are left)

3) Dark frames automatically contain the bias offset level.

Schematic CCD input/output relationship



Flat Fields

CCDs have several million nearly independent detectors, and they all must be calibrated to the same sensitivity.

Variations are caused by slight variations in pixel size, thickness, coating, impurities, etc. Differences of a few % are common.

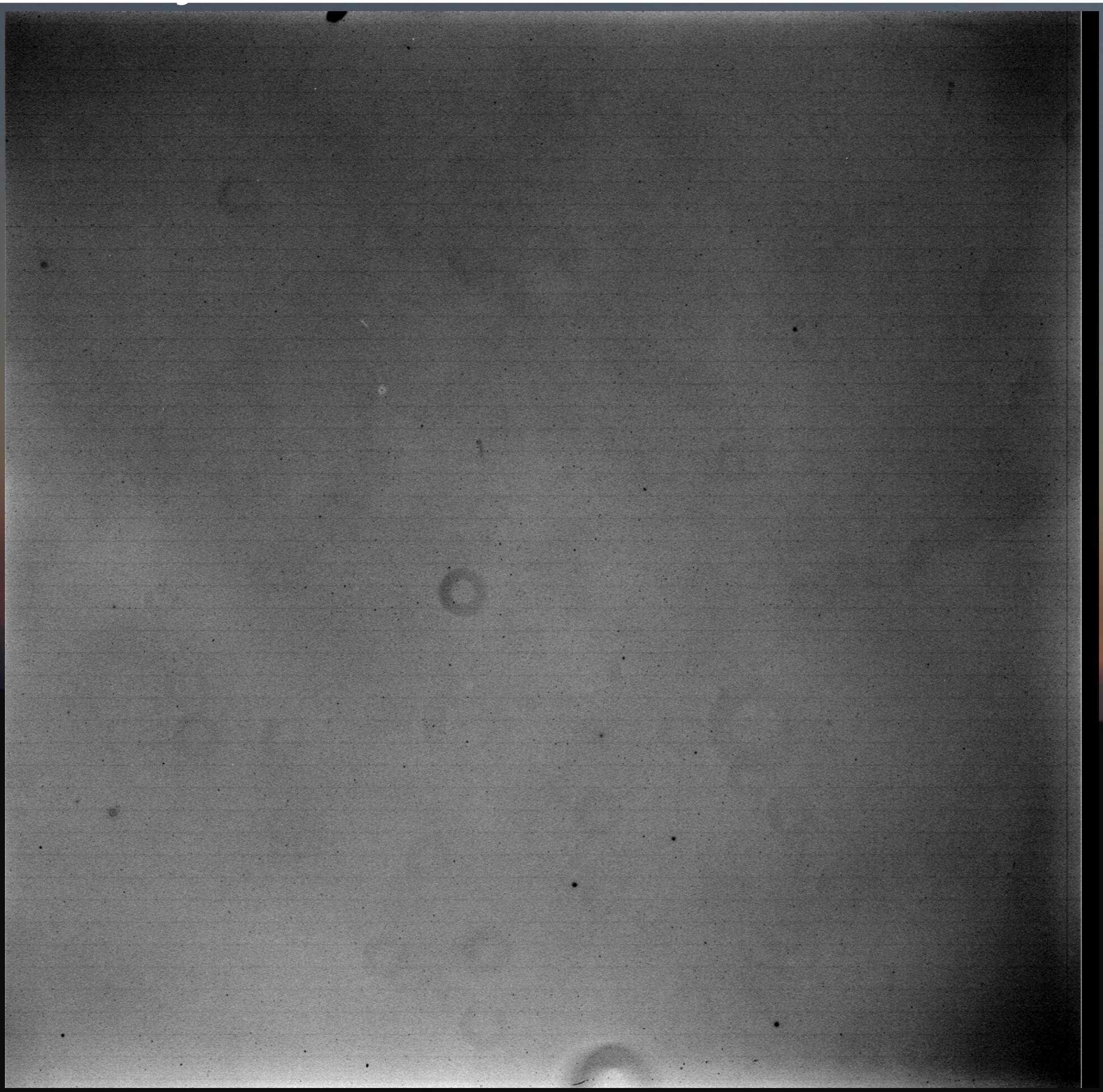
To calibrate these differences, we use flat field images.

Dust and vignetting can also cause light-loss.

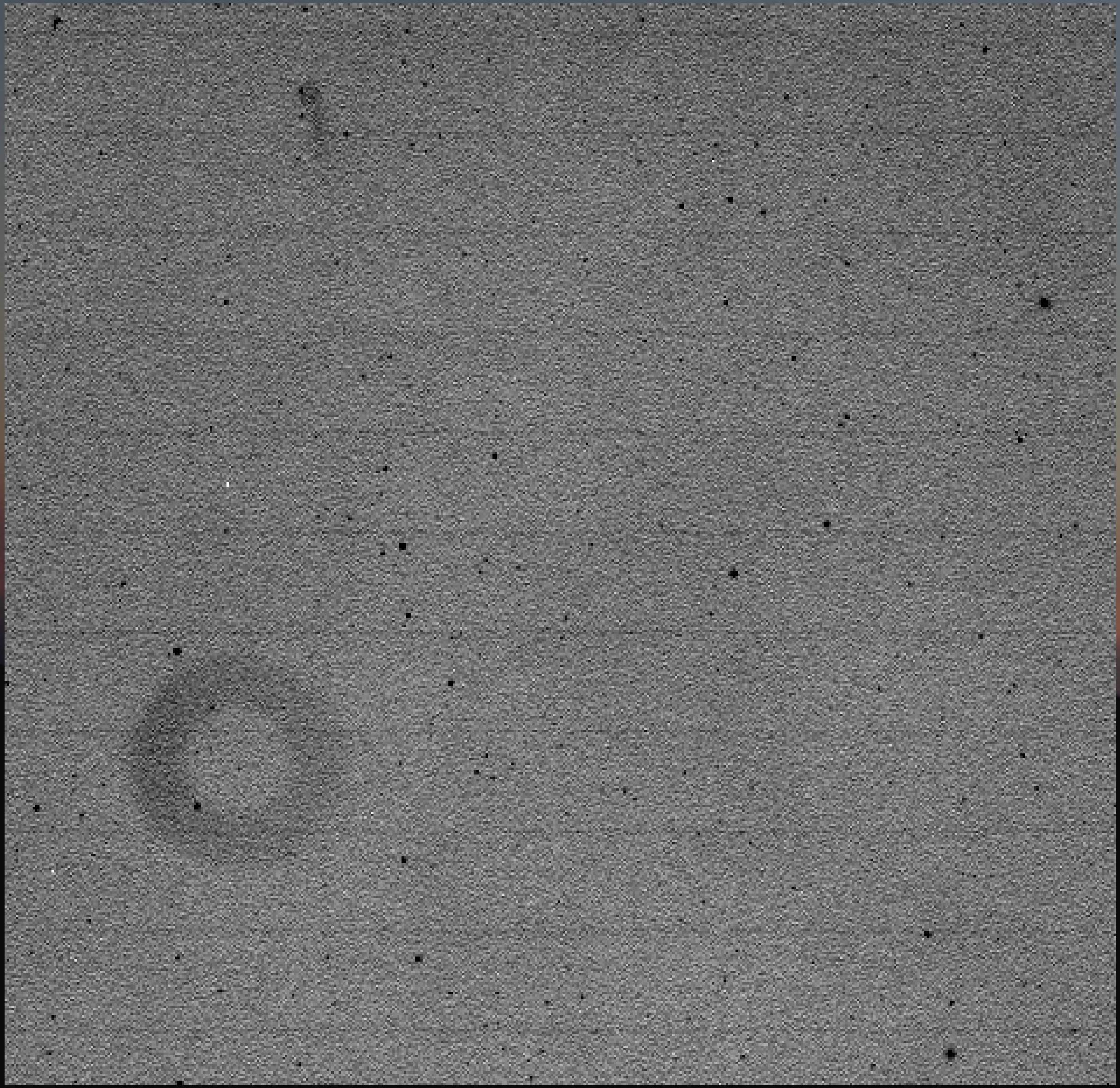
These appear darker in the flat field image.

(Dust on a filter is very out of focus and looks like a donut).

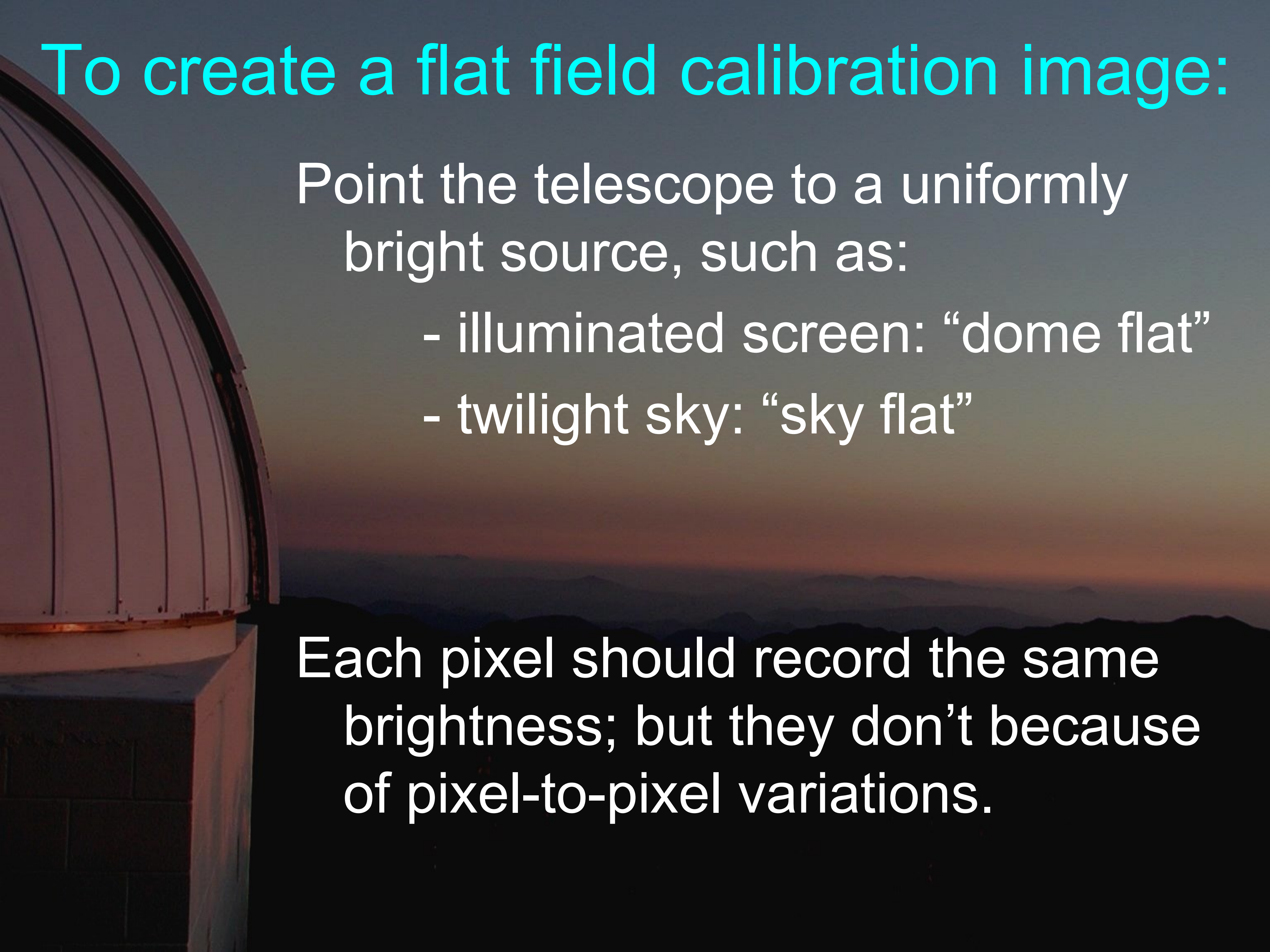
Kitt Peak Mayall 4-m T2KA CCD flat field



Kitt Peak Mayall 4-m T2KA CCD flat field



To create a flat field calibration image:



Point the telescope to a uniformly bright source, such as:

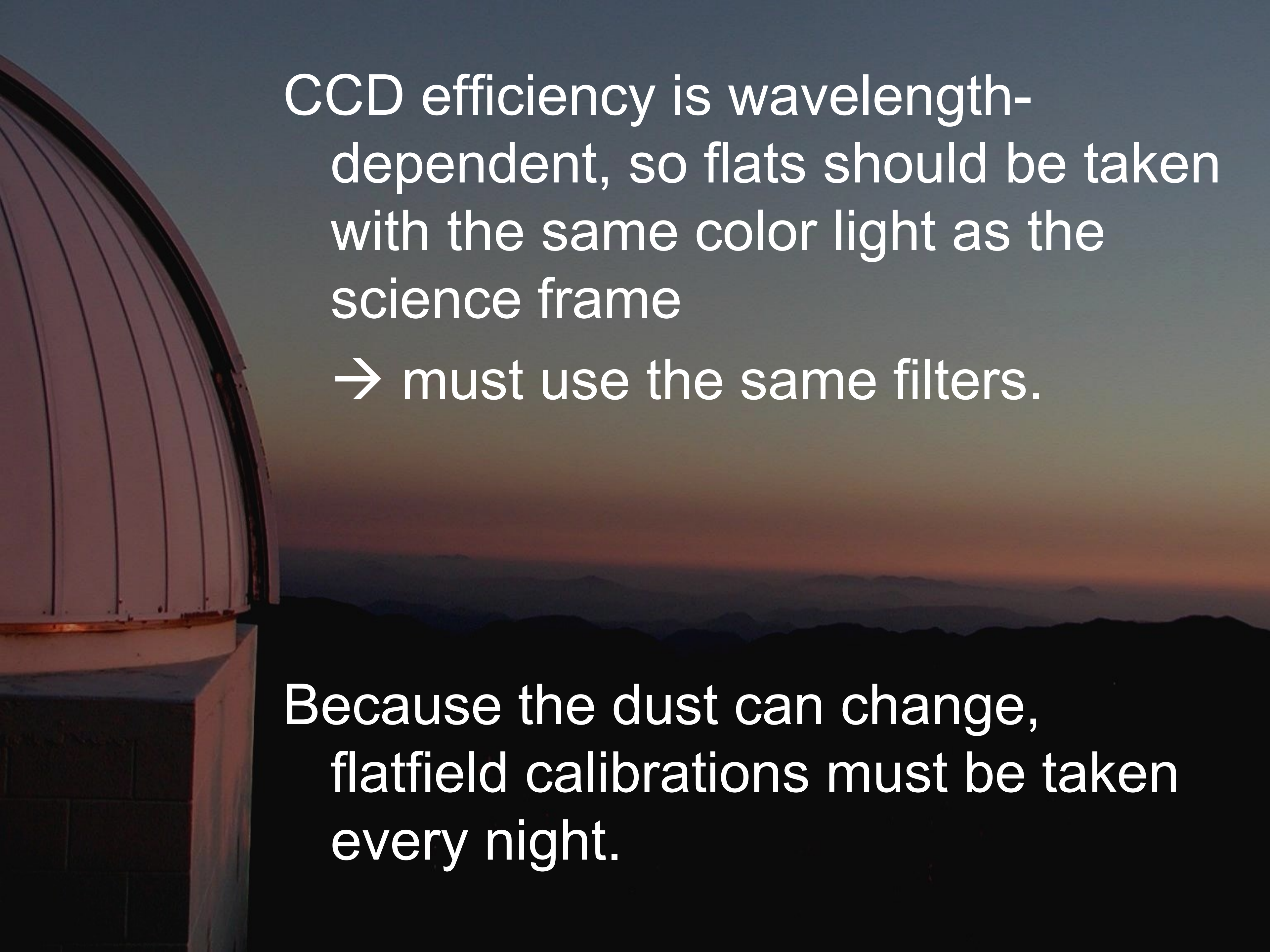
- illuminated screen: “dome flat”
- twilight sky: “sky flat”

Each pixel should record the same brightness; but they don’t because of pixel-to-pixel variations.

To calibrate the CCD science image, you divide by the flat field image.

When you divide by the flat, these defects disappear.

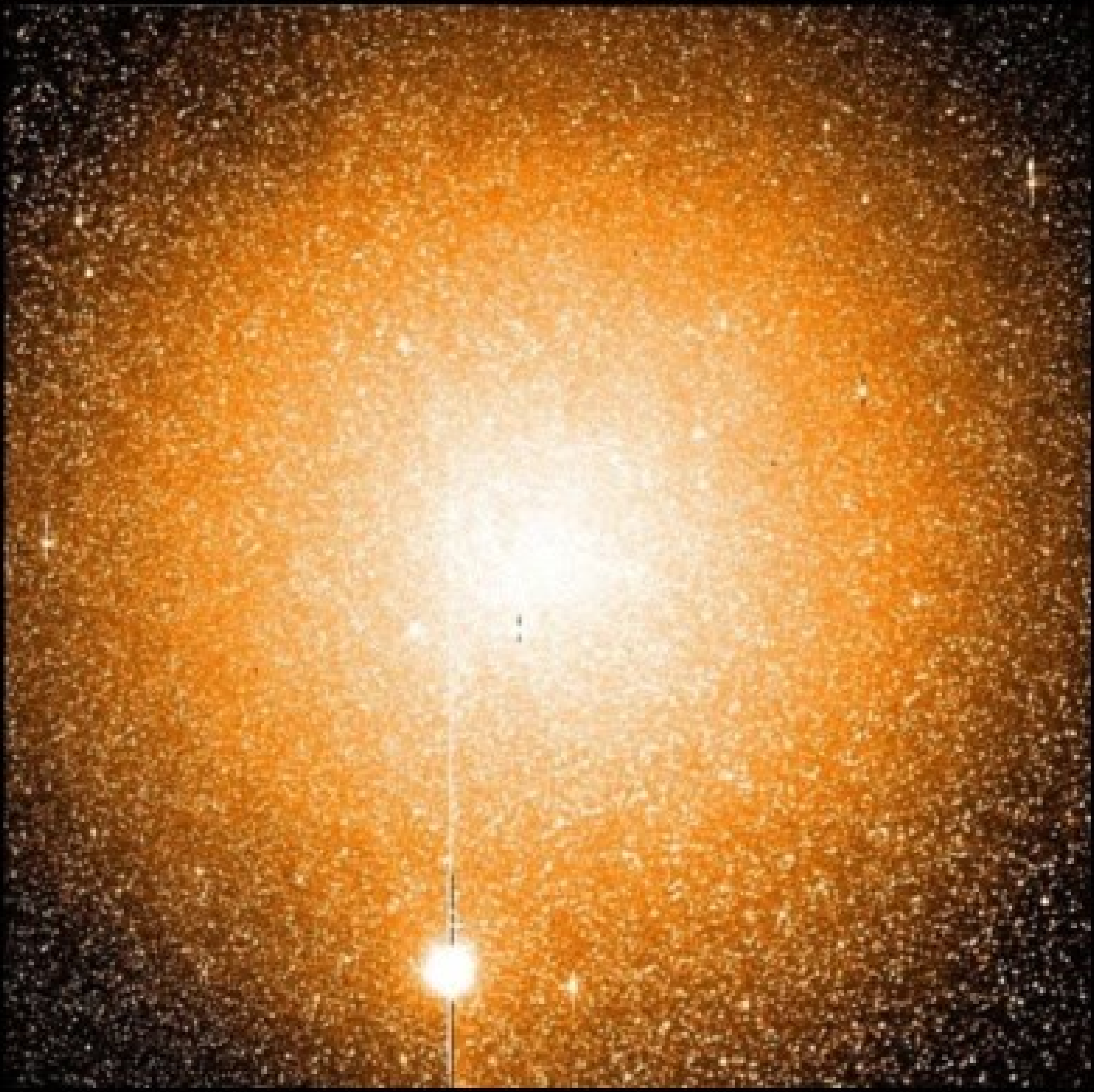
To keep the output proportional to the input, the flat field image is normalized to have a mean = 1.0, so dividing by the flat does not change the fluxes or statistics.



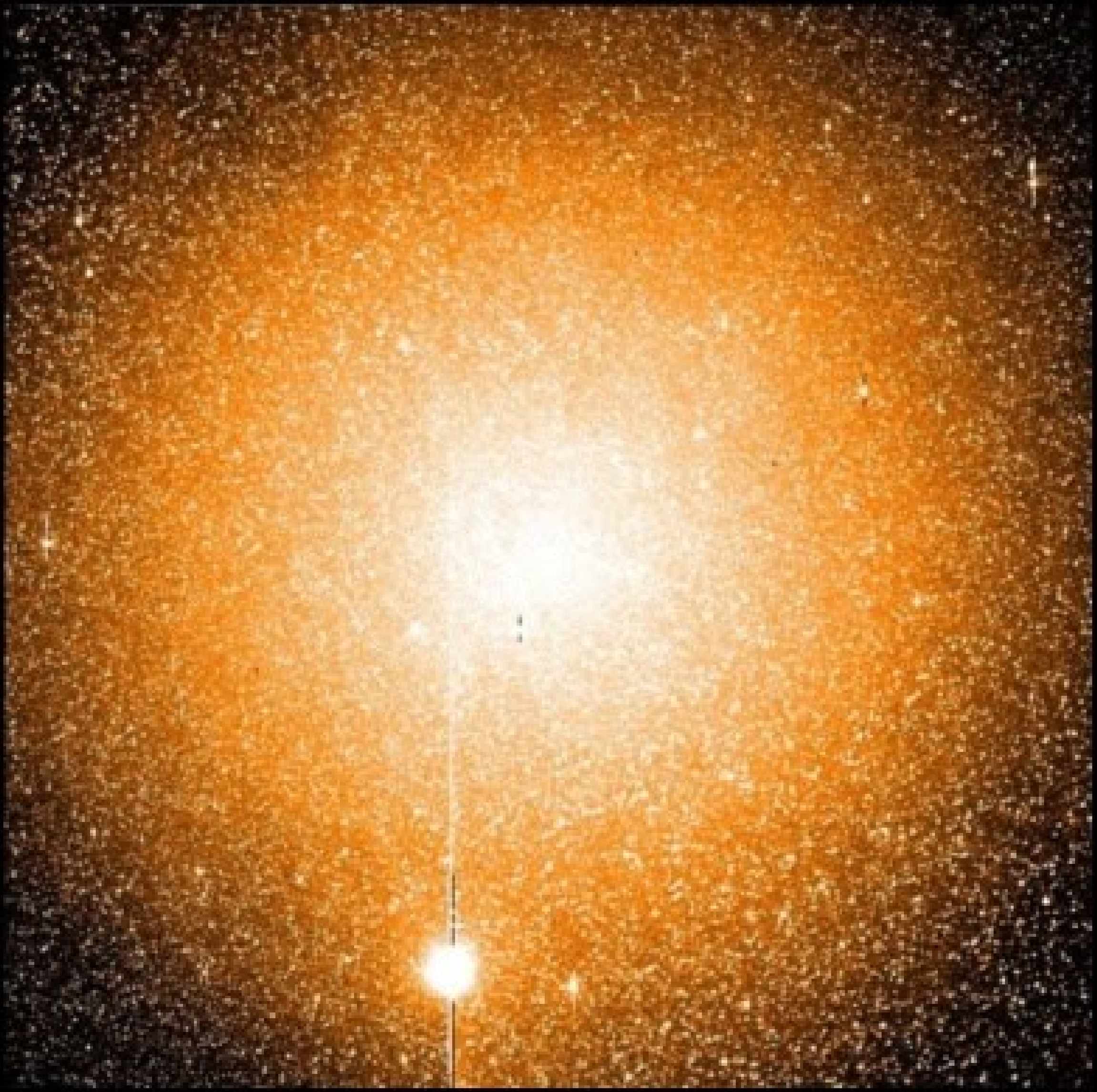
CCD efficiency is wavelength-dependent, so flats should be taken with the same color light as the science frame

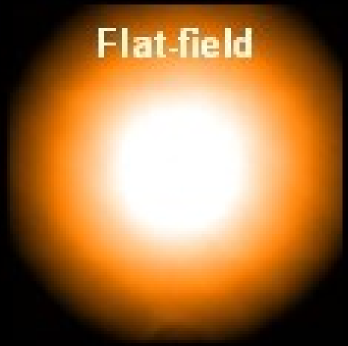
→ must use the same filters.

Because the dust can change, flatfield calibrations must be taken every night.



Raw image =>

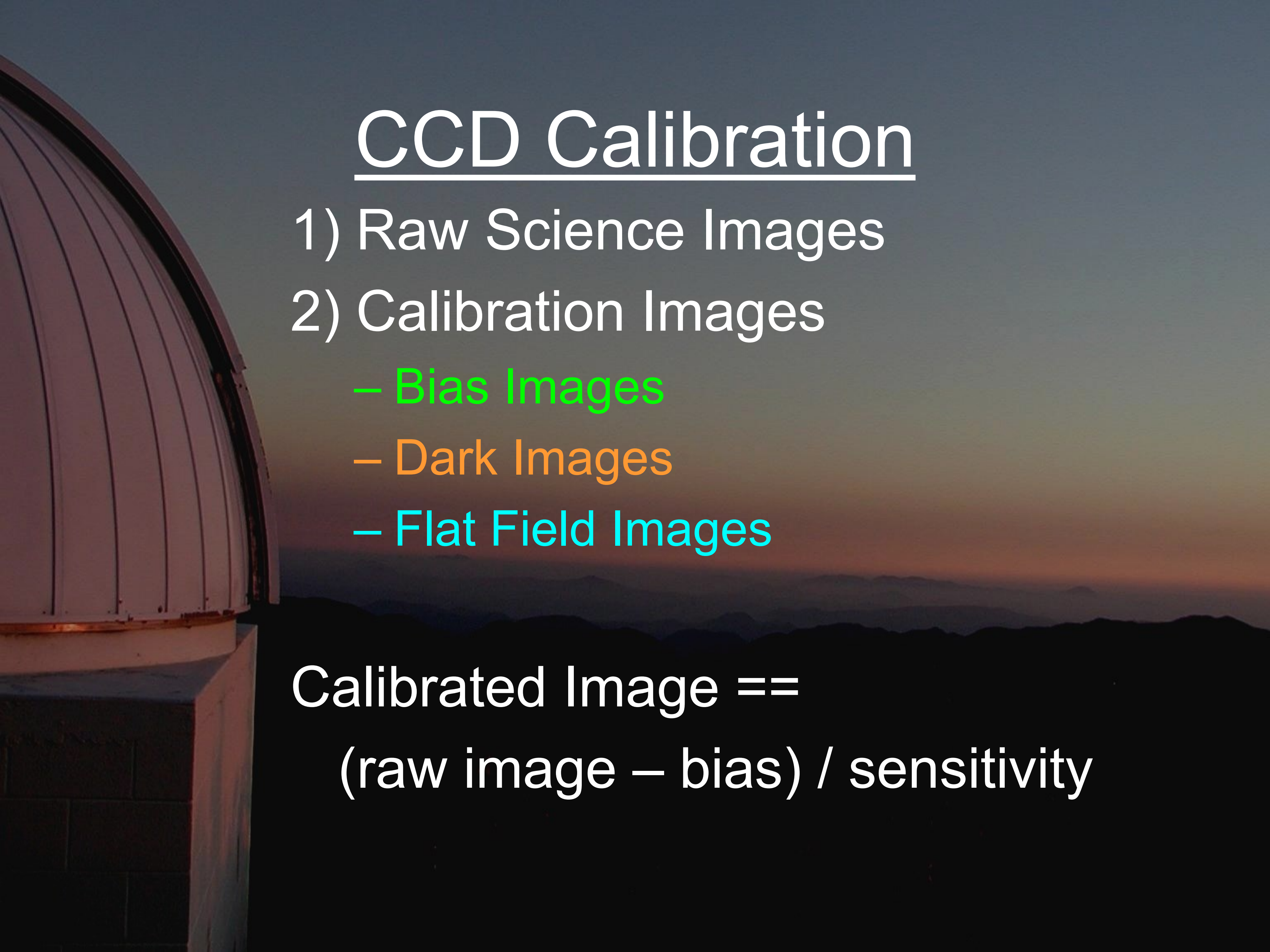




Raw image => **Corrections**

www.superWASP.org

=> Final image



CCD Calibration

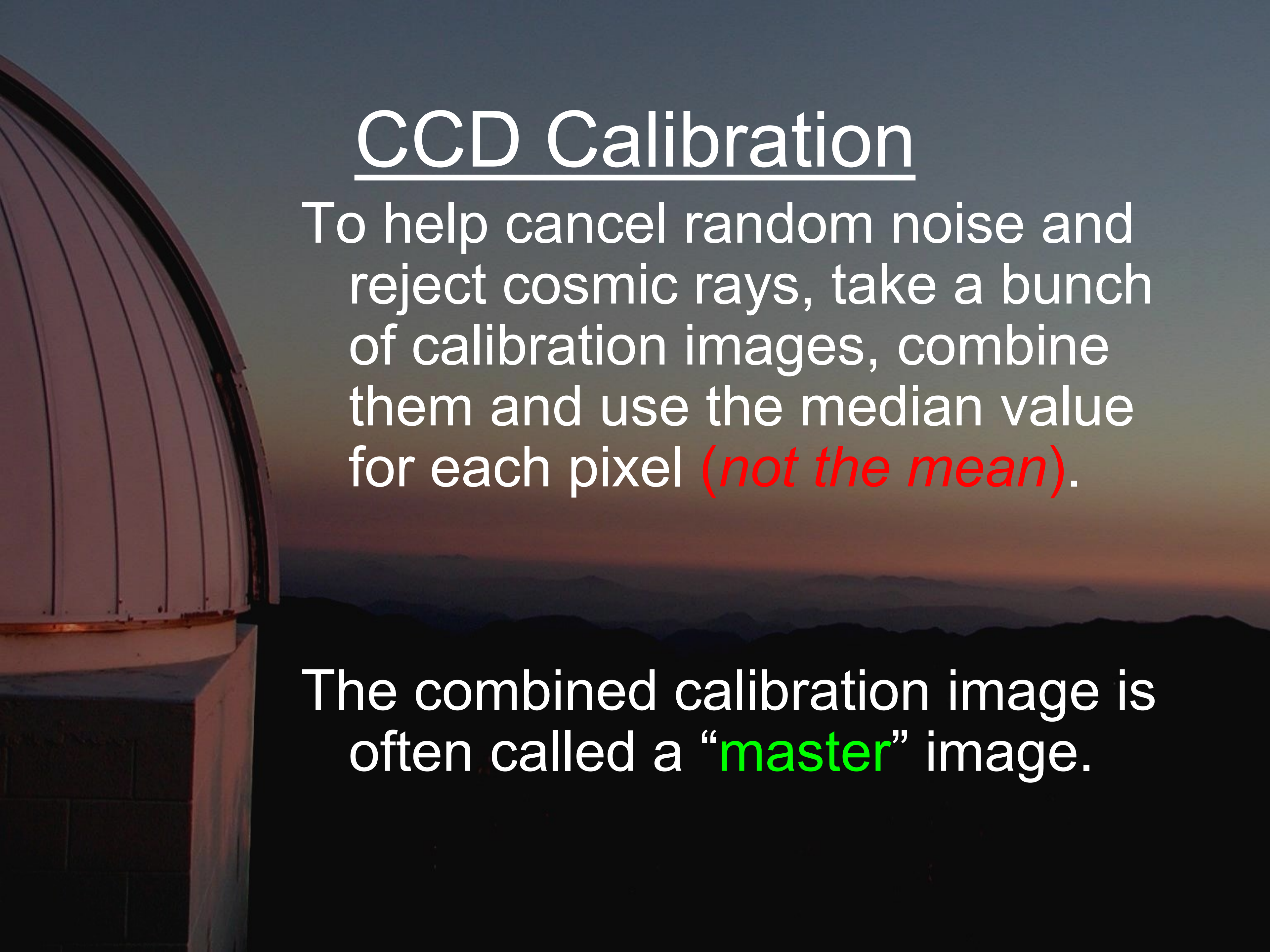
1) Raw Science Images

2) Calibration Images

  - Bias Images
  - Dark Images
  - Flat Field Images

Calibrated Image ==

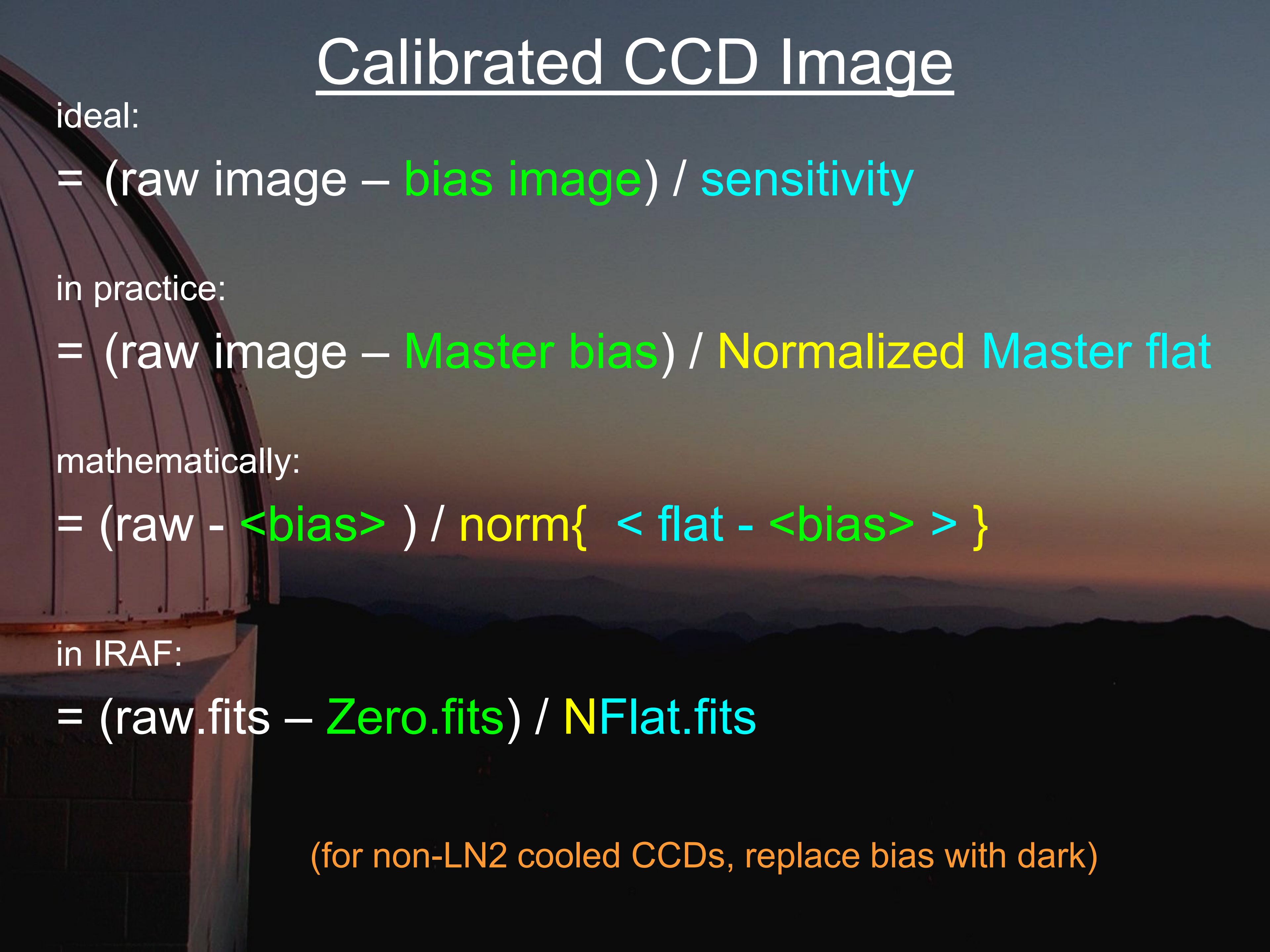
(raw image – bias) / sensitivity



CCD Calibration

To help cancel random noise and reject cosmic rays, take a bunch of calibration images, combine them and use the median value for each pixel (*not the mean*).

The combined calibration image is often called a "master" image.



Calibrated CCD Image

ideal:

= (raw image – bias image) / sensitivity

in practice:

= (raw image – Master bias) / Normalized Master flat

mathematically:

= (raw - <bias>) / norm{ < flat - <bias> > }

in IRAF:

= (raw.fits – Zero.fits) / NFlat.fits

(for non-LN2 cooled CCDs, replace bias with dark)

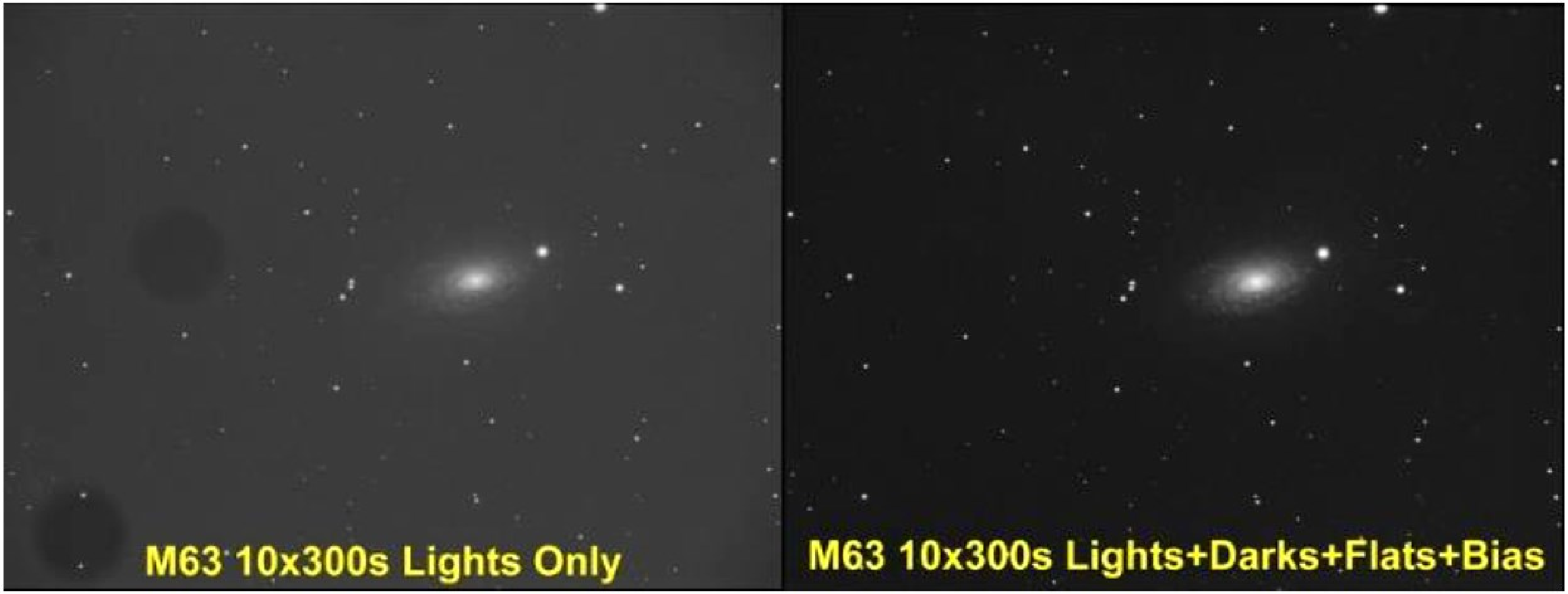


Figure 27. The galaxy Messier 63 with no corrections (left) and with the full Dark, Bias and Flat correction (right). Lights (Skys): 10x300s; Darks: 3x300s; Flats: 20x1.5s; Bias: 13x0.001s (Credit Jason Melquist)

Defocusing??!

(i) Flat field corrections are never perfect

(ii) Intra-pixel sensitivity variations cannot be corrected.

So there will always be some pixel-to-pixel variations. How can we mitigate this?

(a) Keep the guiding close to perfect: keep the center of light from wandering more than a small fraction of a pixel. This is how Kepler achieves such high precision.

Defocusing??!

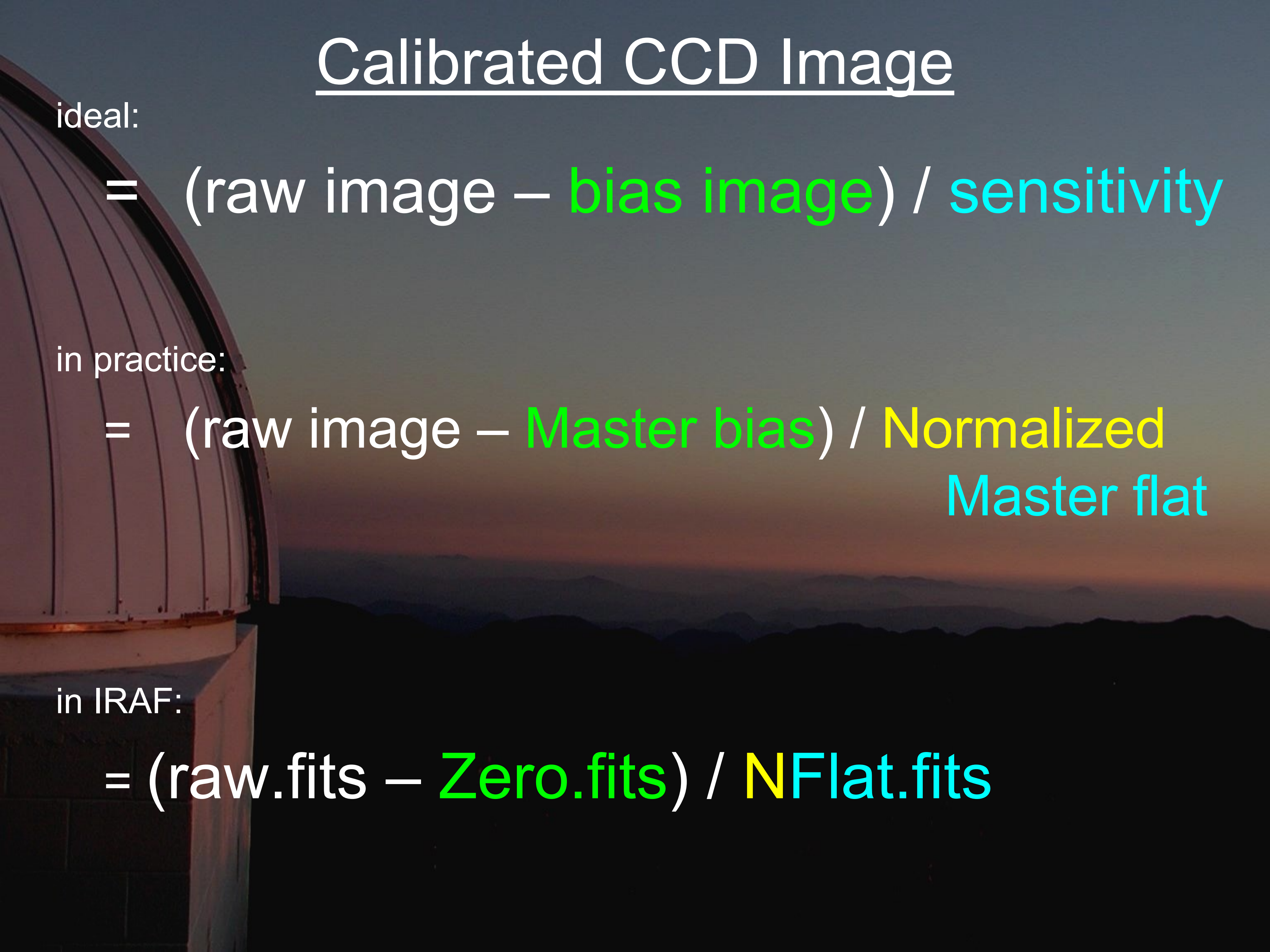
(i) Flat field corrections are never perfect

(ii) Intra-pixel sensitivity variations cannot be corrected.

(b) Spread the light out over many, many pixels. The more pixels used, the less any one particular pixel matters. You average out any pixel-to-pixel sensitivity variations.

This works well for bright, isolated stars.

Bad idea for faint stars or crowded fields.



Calibrated CCD Image

ideal:

= (raw image – bias image) / sensitivity

in practice:

= (raw image – Master bias) / Normalized Master flat

in IRAF:

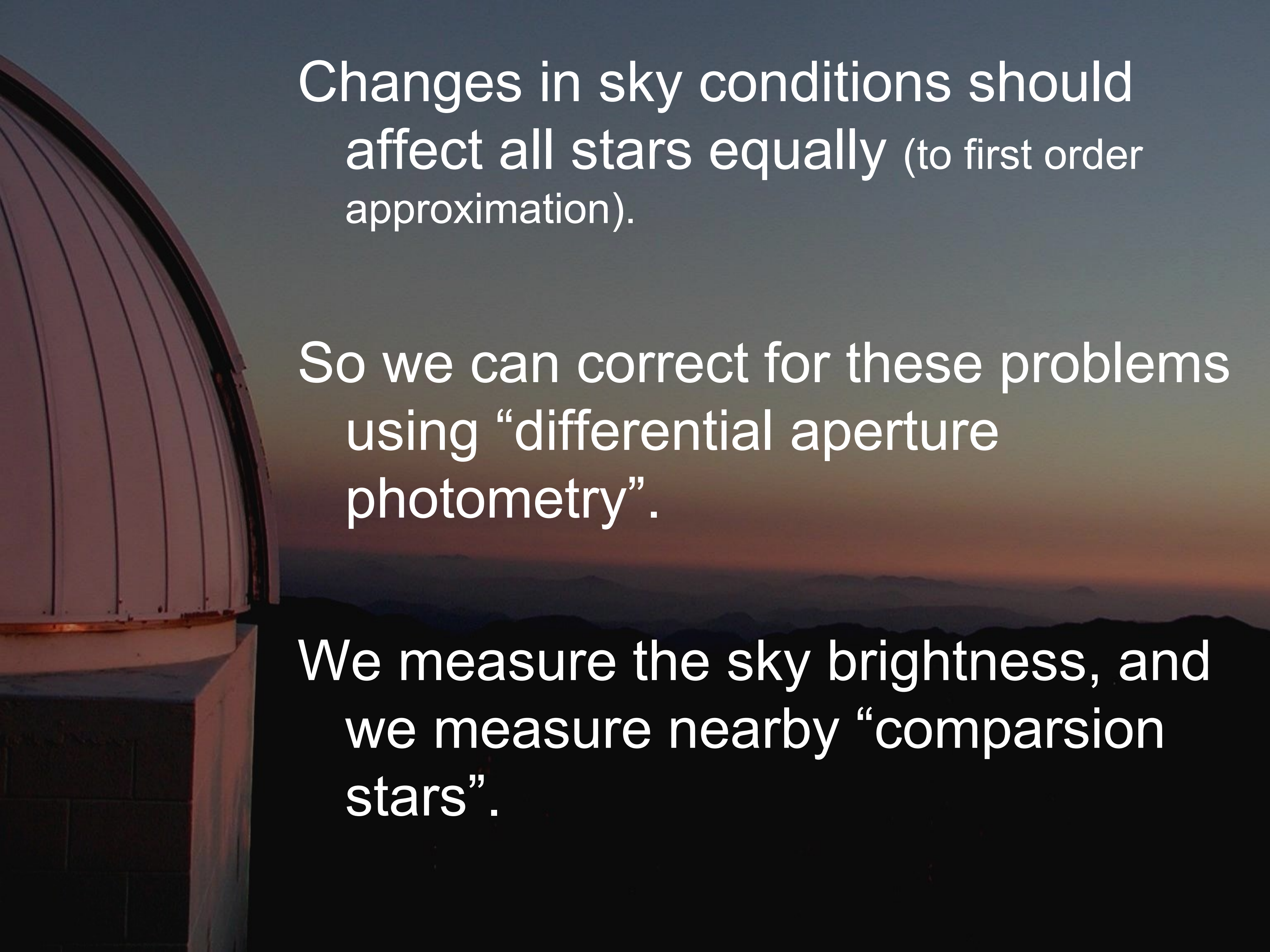
= (raw.fits – Zero.fits) / NFlat.fits

Theory Meets Reality: Part 2

The sky is not perfectly transparent, e.g., clouds, dust, turbulent air (causing “twinking”), water vapor, etc.

The sky is not perfectly dark, e.g., Moon, twilight, light pollution.

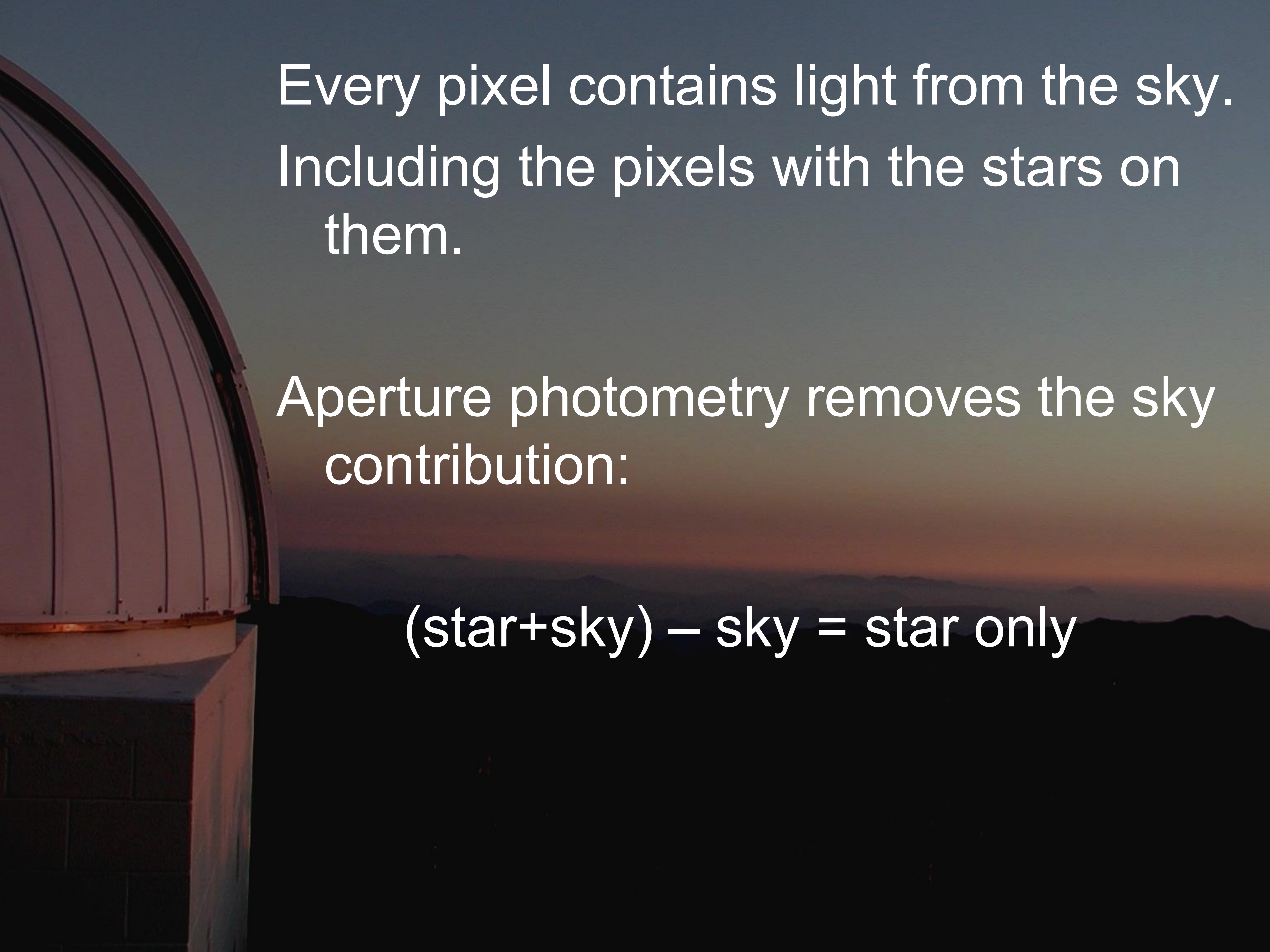
Nor are these constant – they change throughout a night.



Changes in sky conditions should affect all stars equally (to first order approximation).

So we can correct for these problems using “differential aperture photometry”.

We measure the sky brightness, and we measure nearby “comparsion stars”.

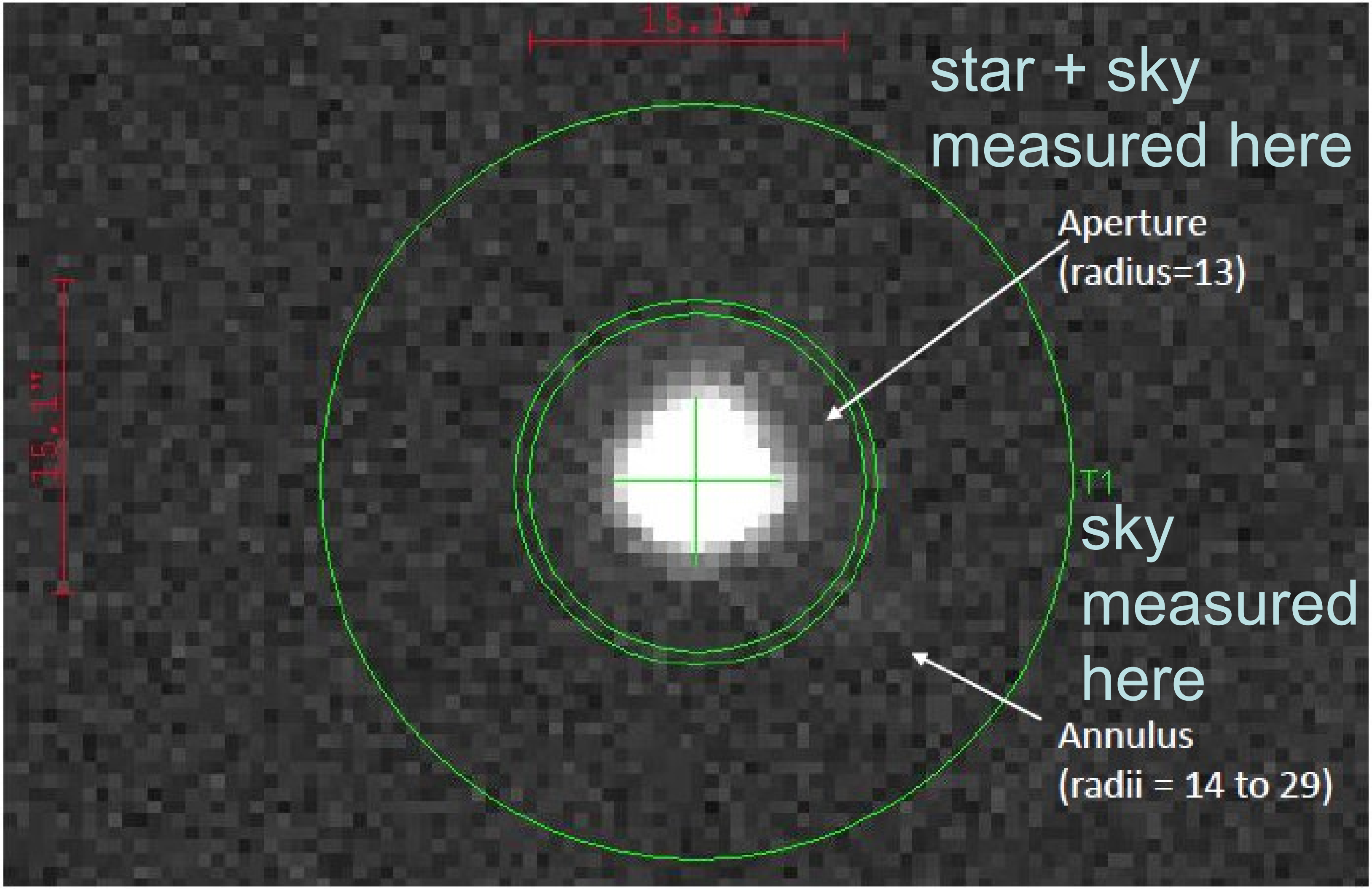


Every pixel contains light from the sky.

Including the pixels with the stars on them.

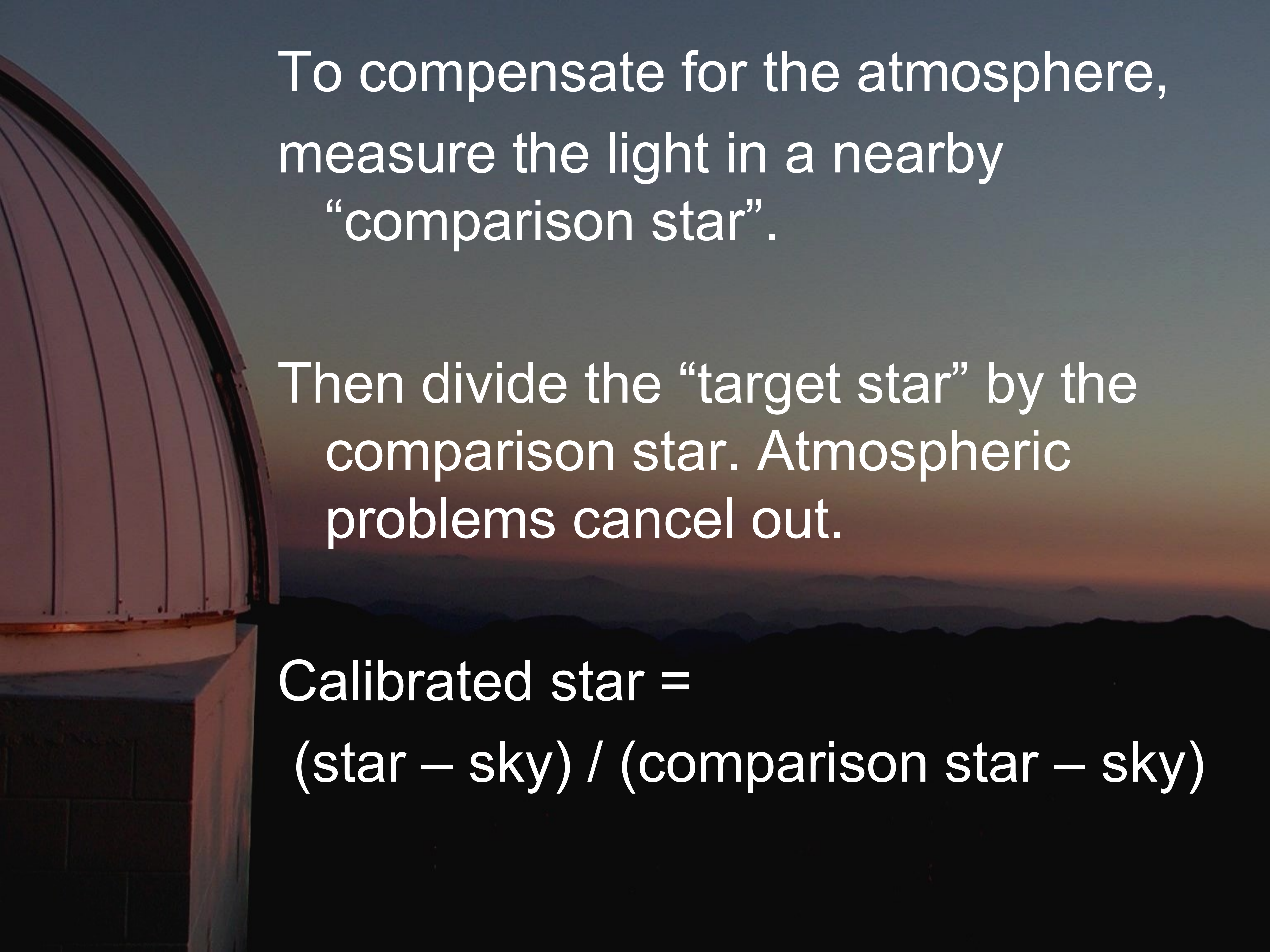
Aperture photometry removes the sky contribution:

(star+sky) – sky = star only



star + sky measured here

sky measured here



To compensate for the atmosphere, measure the light in a nearby "comparison star".

Then divide the "target star" by the comparison star. Atmospheric problems cancel out.

Calibrated star =
(star – sky) / (comparison star – sky)

To get the best results, average together several comparison stars.

Then divide the “target star” by the average comparison star.

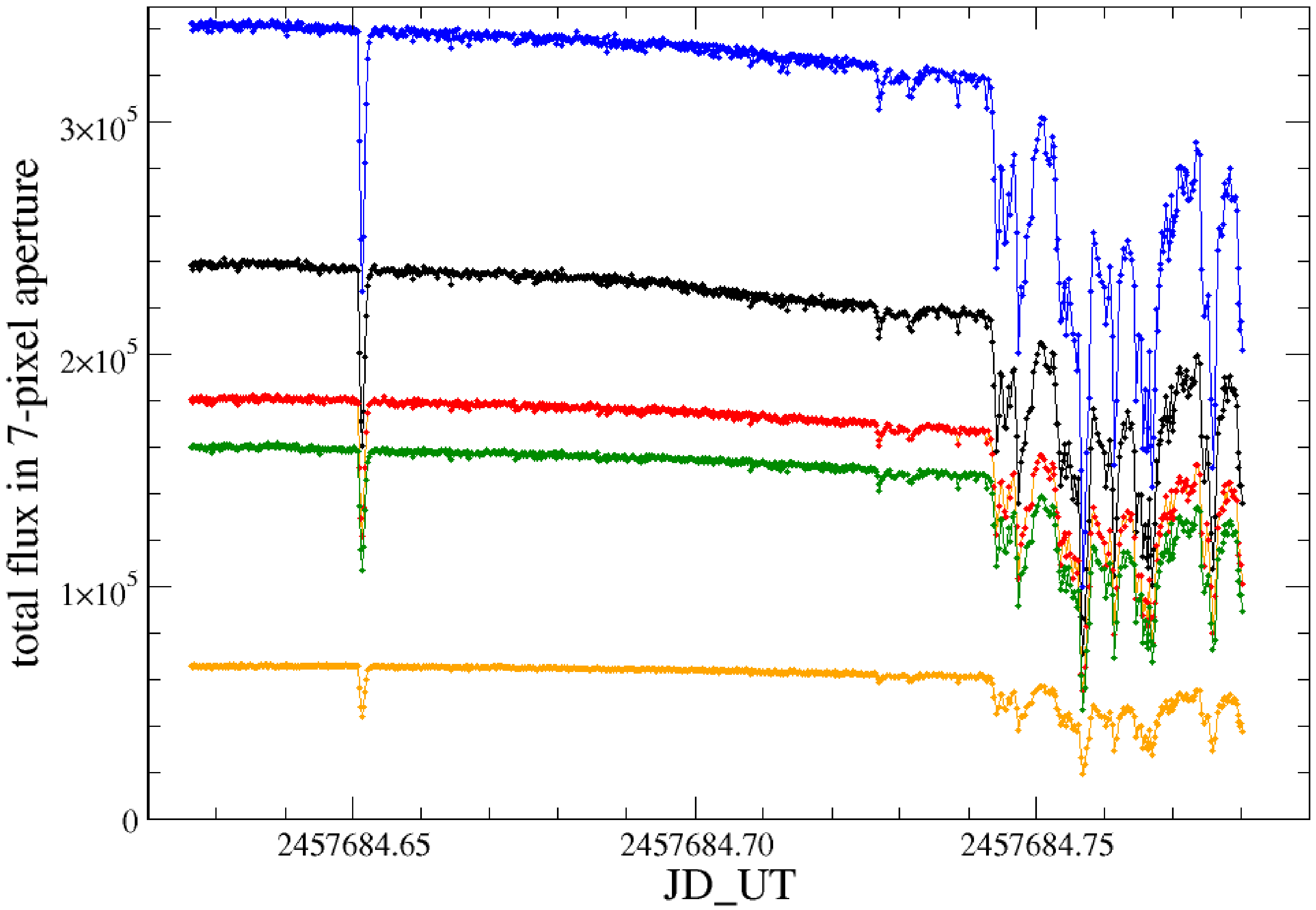
Thus:

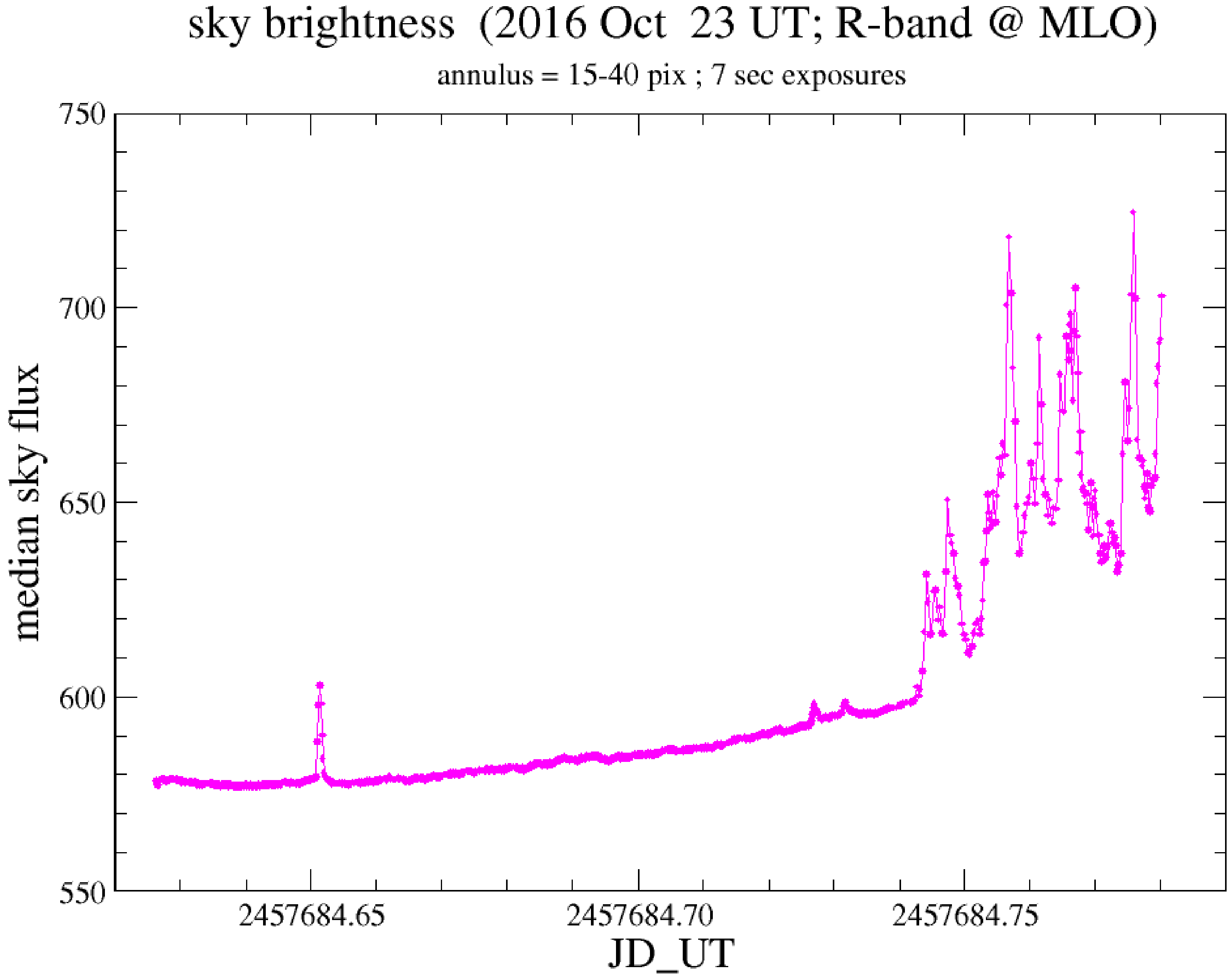
Calibrated target star =

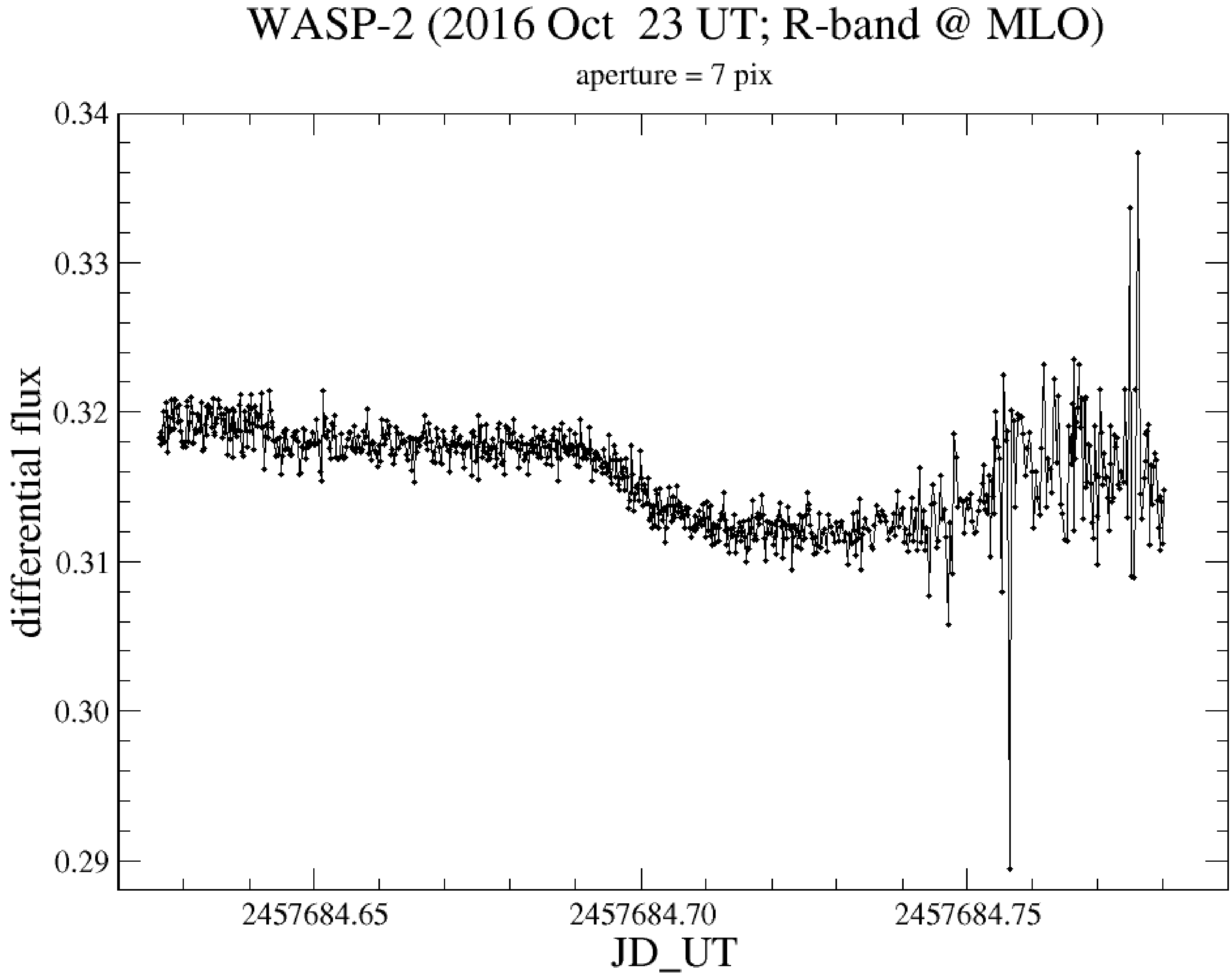
(target star – sky) / <comparison star>

WASP-2 light curves (2016 Oct 21 UT) R-band

"raw" light curves of target star [redacted] and comparision stars




sky brightness (2016 Oct 23 UT; R-band @ MLO)
annulus = 15-40 pix ; 7 sec exposures
median sky flux
750
700
650
600
550
2457684.65
2457684.70
2457684.75
JD_UT

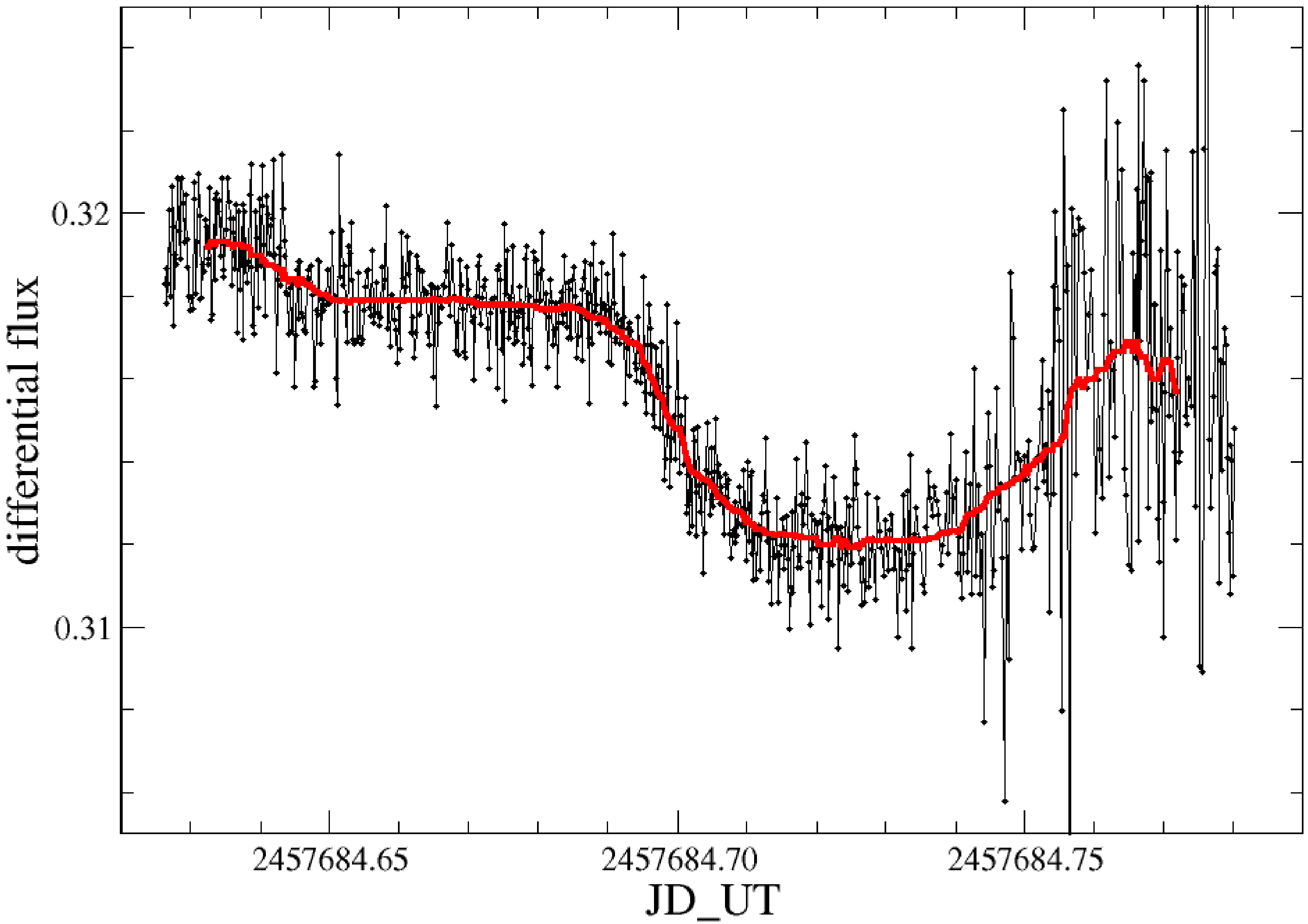


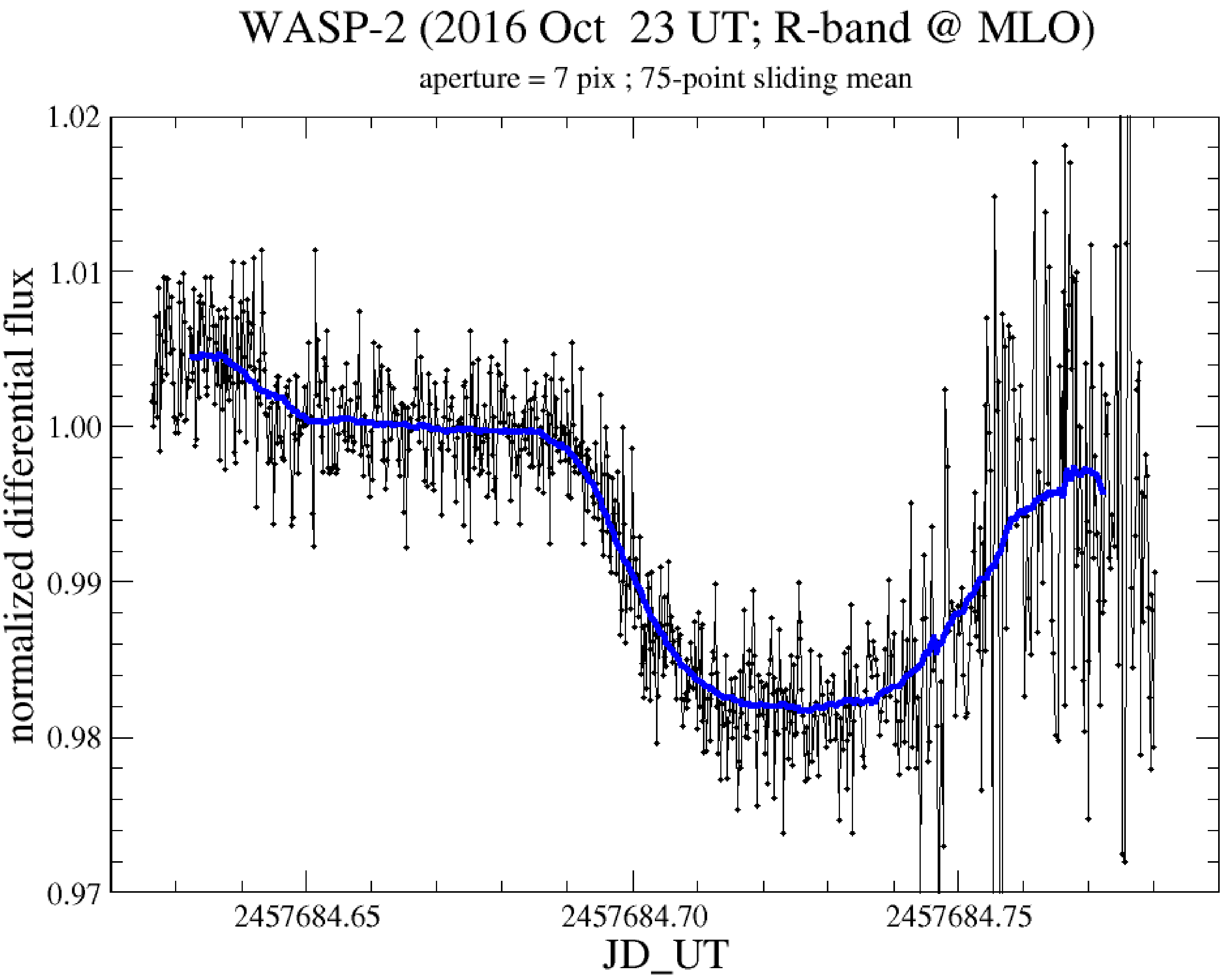
WASP-2 (2016 Oct 23 UT; R-band @ MLO)

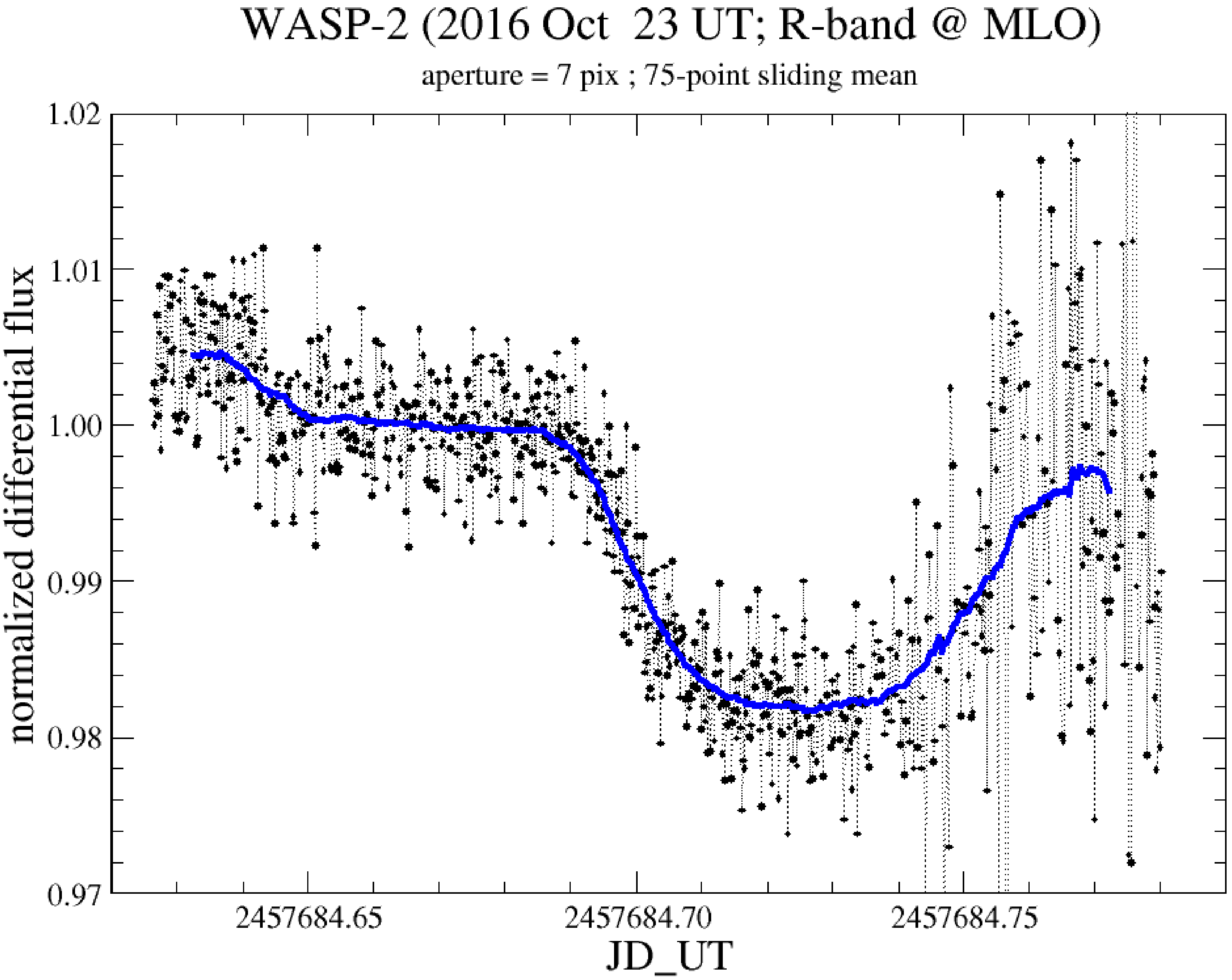
aperture = 7 pix

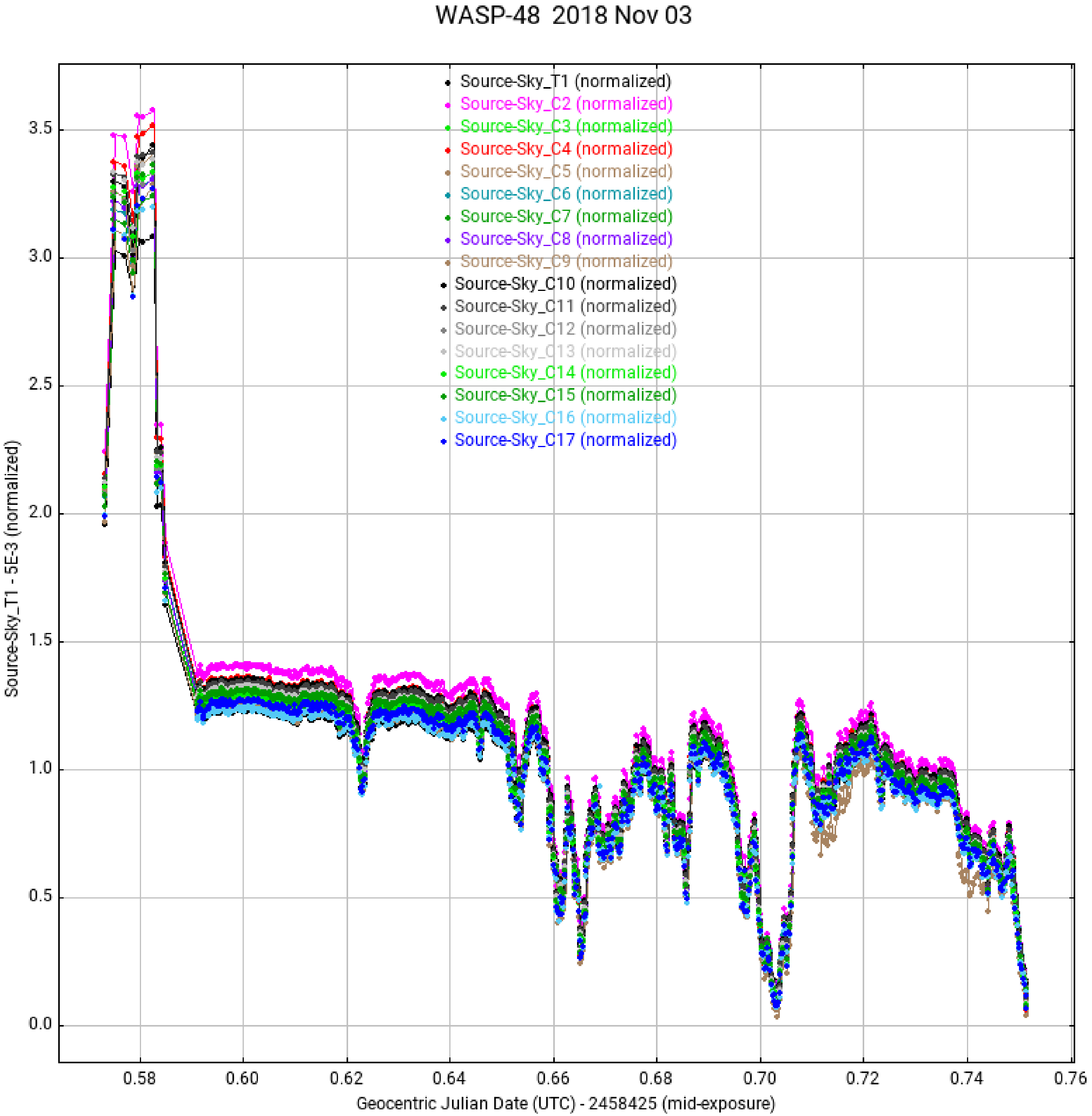
WASP-2 (2016 Oct 23 UT; R-band @ MLO)

aperture = 7 pix ; 75-point sliding median

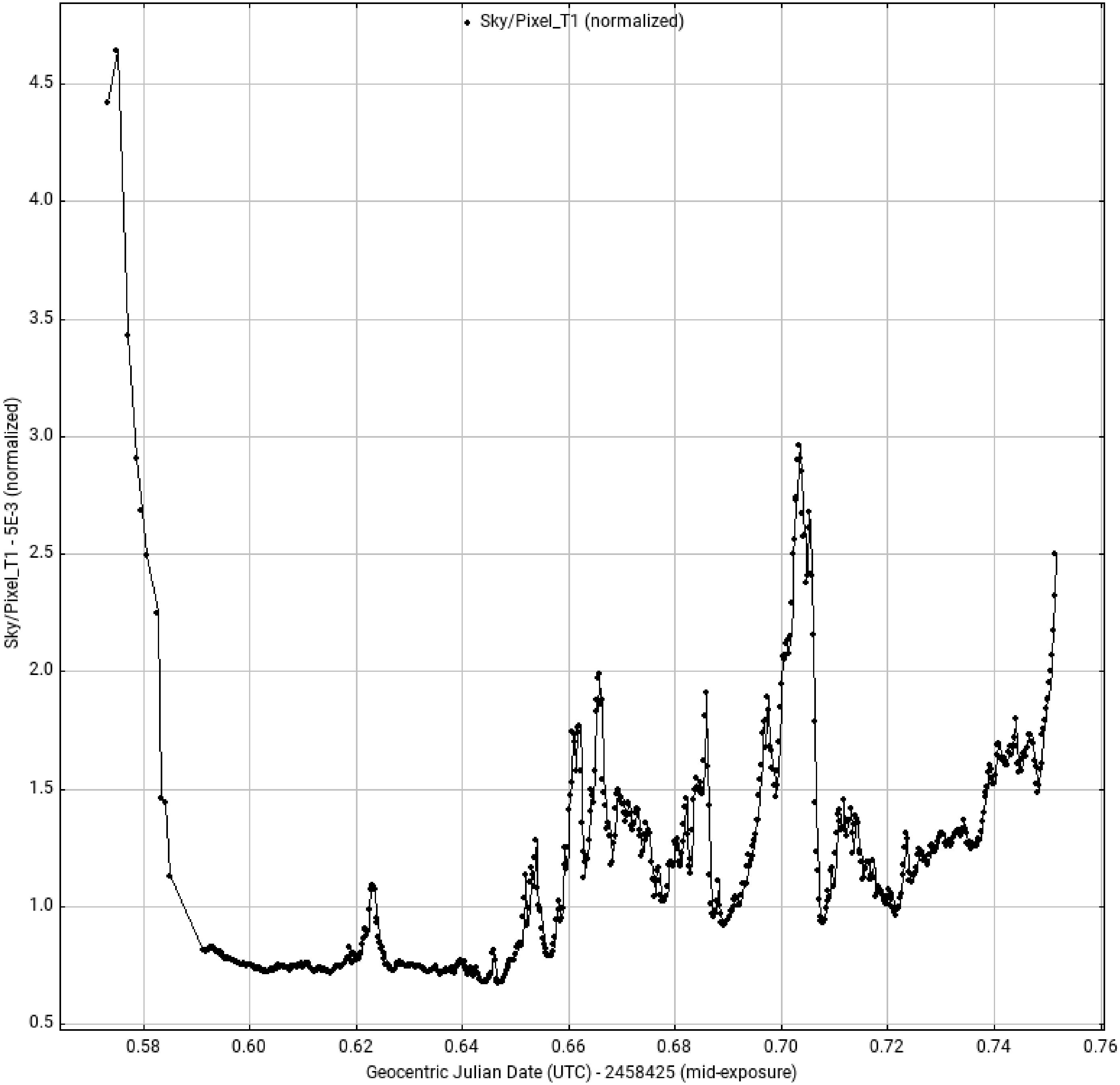


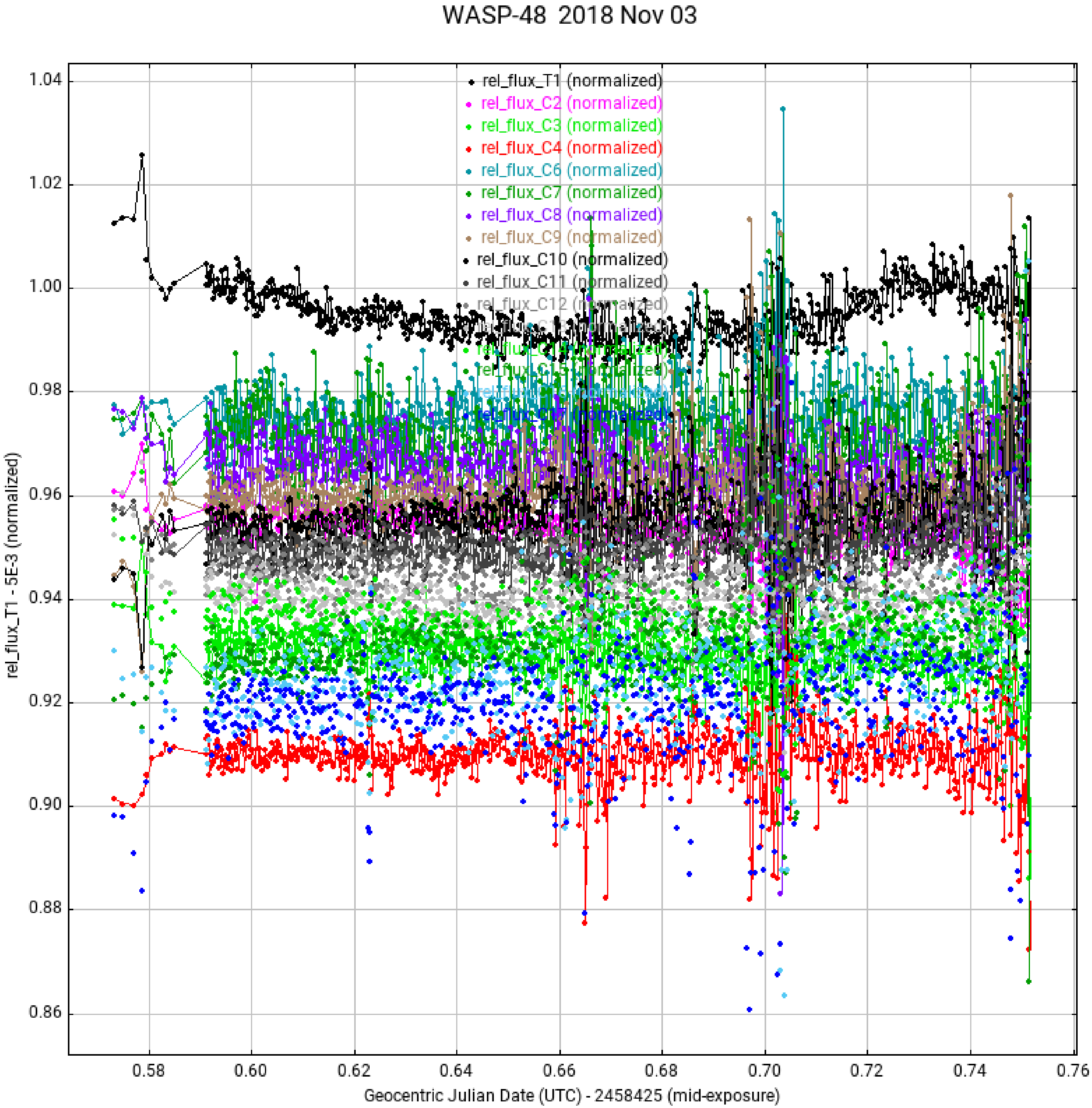

WASP-2 (2016 Oct 23 UT; R-band @ MLO)
aperture = 7 pix ; 75-point sliding mean
normalized differential flux
1.02
1.01
1.00
0.99
0.98
0.97
2457684.65
2457684.70
2457684.75
JD_UT

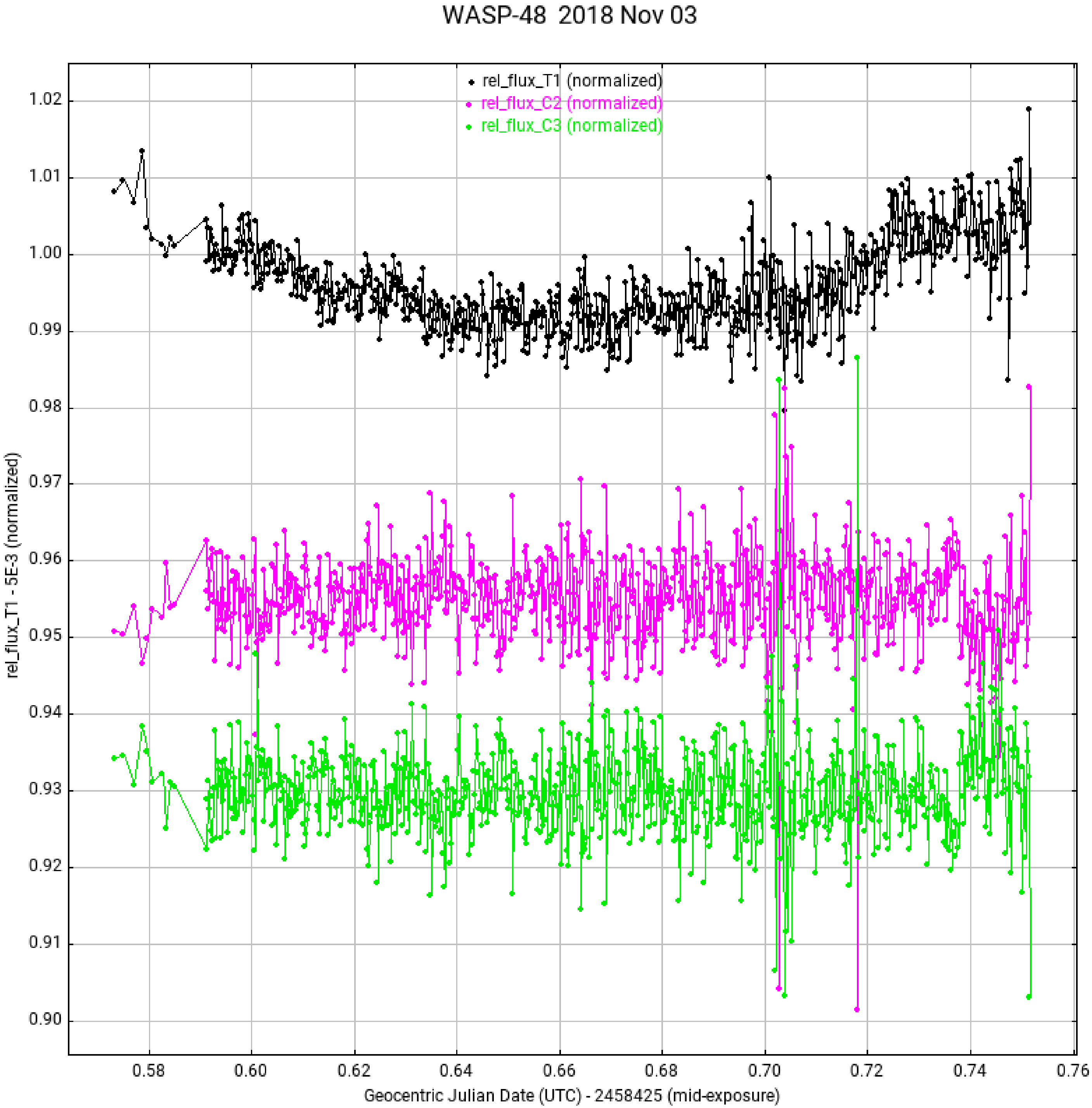

WASP-2 (2016 Oct 23 UT; R-band @ MLO)
aperture = 7 pix ; 75-point sliding mean
normalized differential flux
1.02
1.01
1.00
0.99
0.98
0.97
2457684.65
2457684.70
2457684.75
JD_UT


WASP-48 2018 Nov 03
Source-Sky_T1 (normalized)
Source-Sky_C2 (normalized)
Source-Sky_C3 (normalized)
Source-Sky_C4 (normalized)
Source-Sky_C5 (normalized)
Source-Sky_C6 (normalized)
Source-Sky_C7 (normalized)
Source-Sky_C8 (normalized)
Source-Sky_C9 (normalized)
Source-Sky_C10 (normalized)
Source-Sky_C11 (normalized)
Source-Sky_C12 (normalized)
Source-Sky_C13 (normalized)
Source-Sky_C14 (normalized)
Source-Sky_C15 (normalized)
Source-Sky_C16 (normalized)
Source-Sky_C17 (normalized)
Source-Sky_T1 - 5E-3 (normalized)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.58
0.60
0.62
0.64
0.66
0.68
0.70
0.72
0.74
0.76
Geocentric Julian Date (UTC) - 2458425 (mid-exposure)

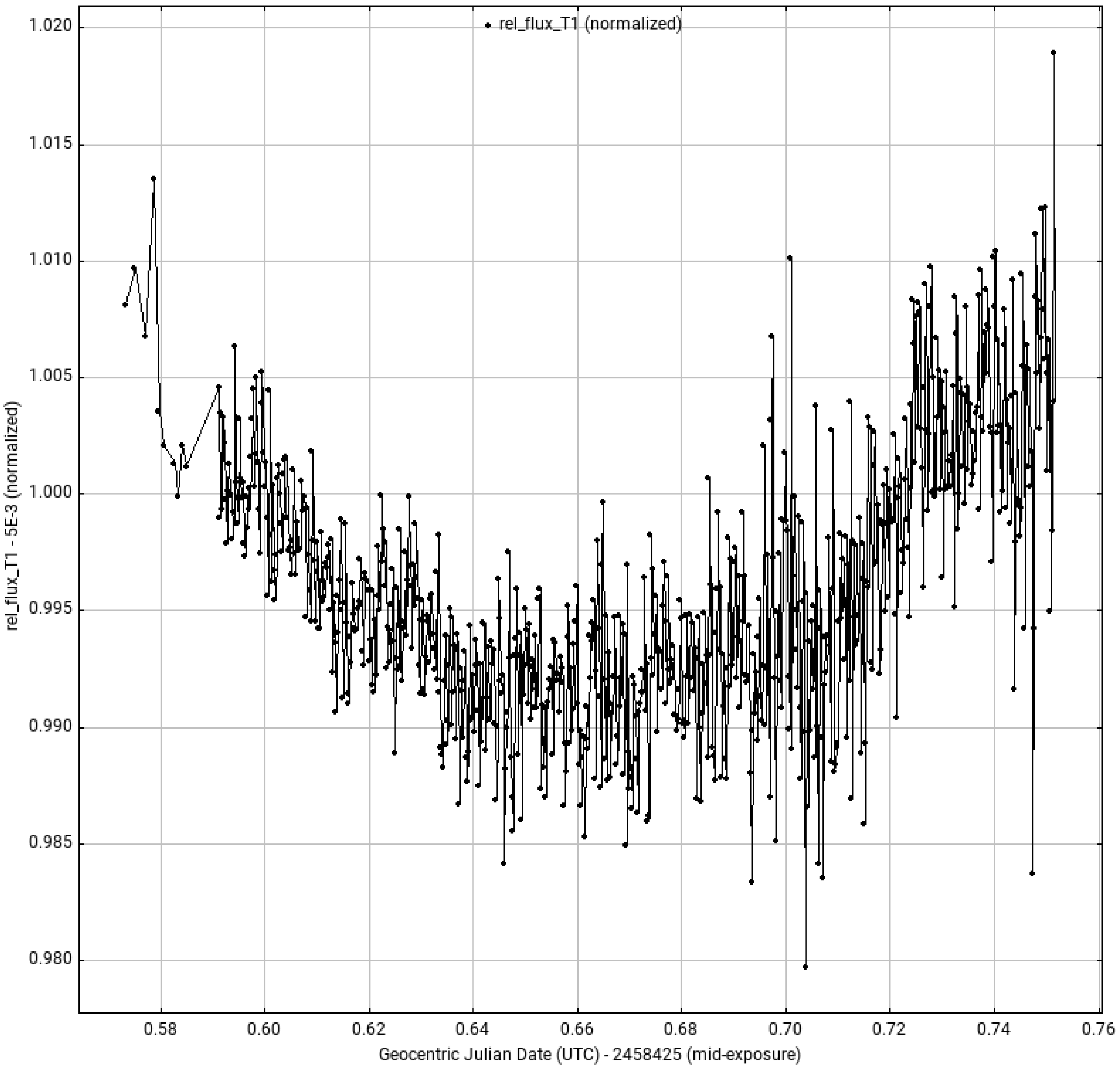
WASP-48 2018 Nov 03

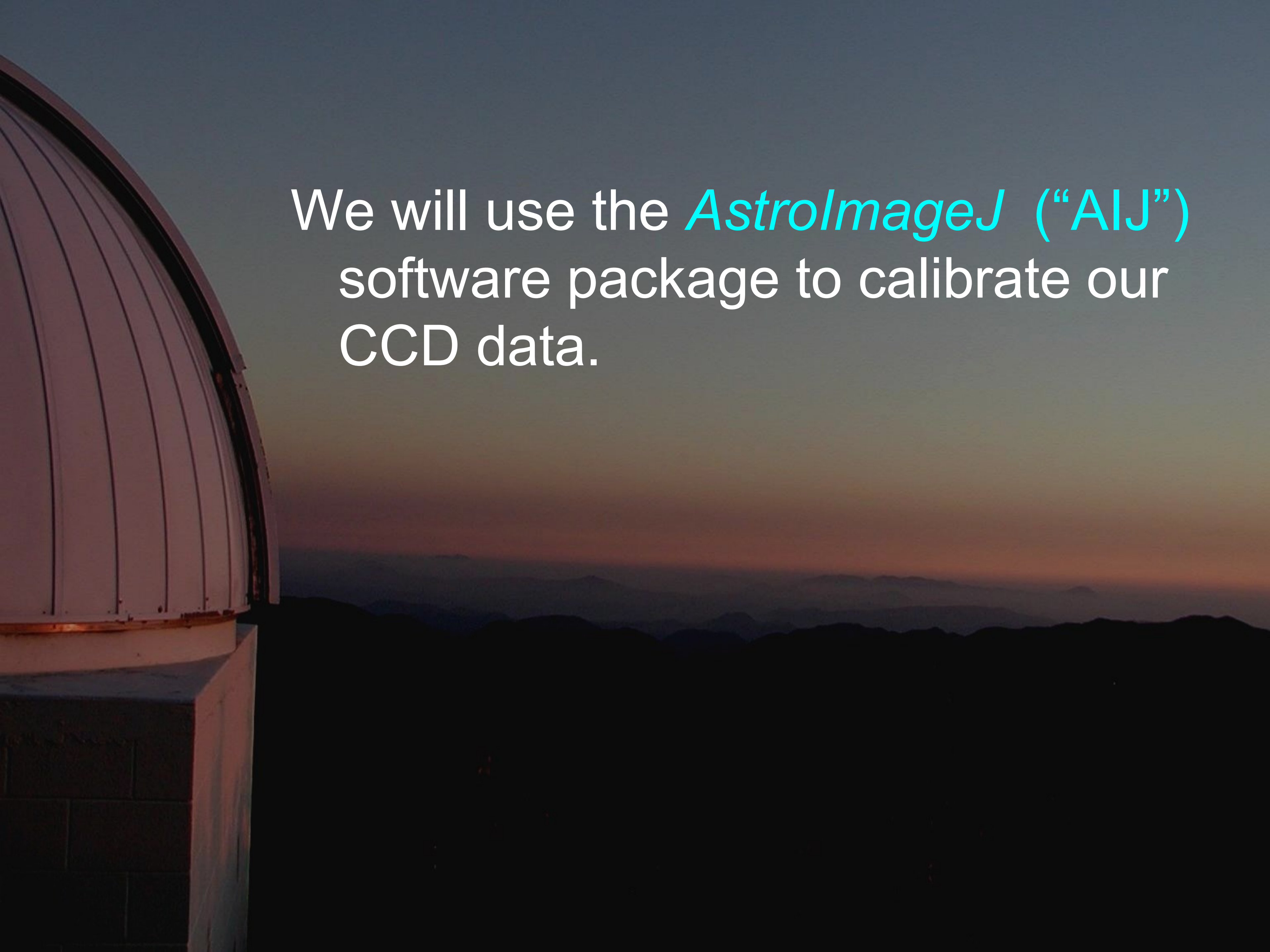



WASP-48 2018 Nov 03
rel_flux_T1 (normalized)
rel_flux_C2 (normalized)
rel_flux_C3 (normalized)
rel_flux_C4 (normalized)
rel_flux_C6 (normalized)
rel_flux_C7 (normalized)
rel_flux_C8 (normalized)
rel_flux_C9 (normalized)
rel_flux_C10 (normalized)
rel_flux_C11 (normalized)
rel_flux_C12 (normalized)
rel_flux_C17 (normalized)
rel_flux_T1 - 5E-3 (normalized)
1.04
1.02
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0.86
0.58
0.60
0.62
0.64
0.66
0.68
0.70
0.72
0.74
0.76
Geocentric Julian Date (UTC) - 2458425 (mid-exposure)


WASP-48 2018 Nov 03
rel_flux_T1 (normalized)
rel_flux_C2 (normalized)
rel_flux_C3 (normalized)
1.02
1.01
1.00
0.99
0.98
0.97
0.96
0.95
0.94
0.93
0.92
0.91
0.90
rel_flux_T1 - 5E-3 (normalized)
0.58
0.60
0.62
0.64
0.66
0.68
0.70
0.72
0.74
0.76
Geocentric Julian Date (UTC) - 2458425 (mid-exposure)

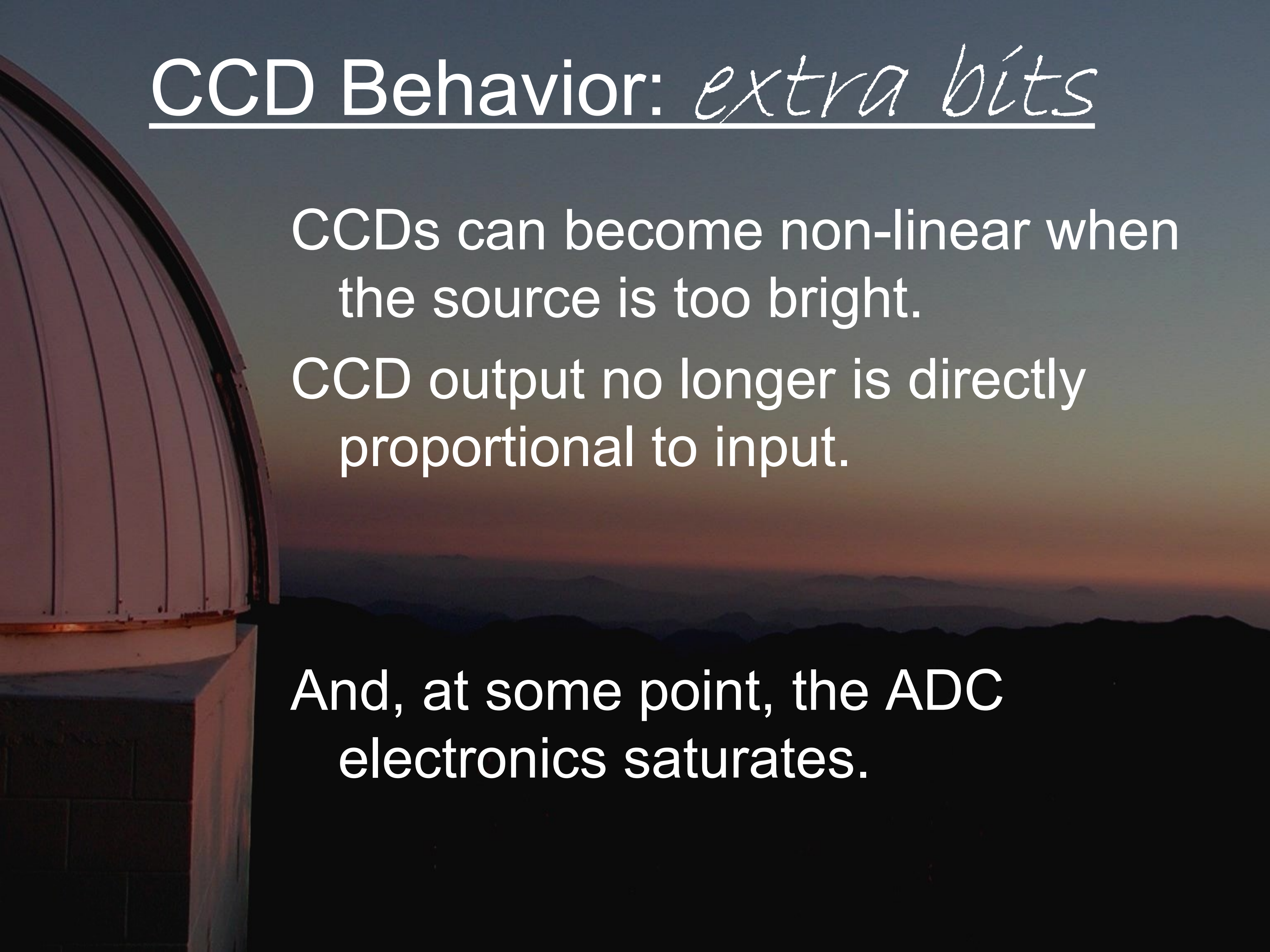
WASP-48 2018 Nov 03





We will use the *AstroImageJ* (“AIJ”) software package to calibrate our CCD data.

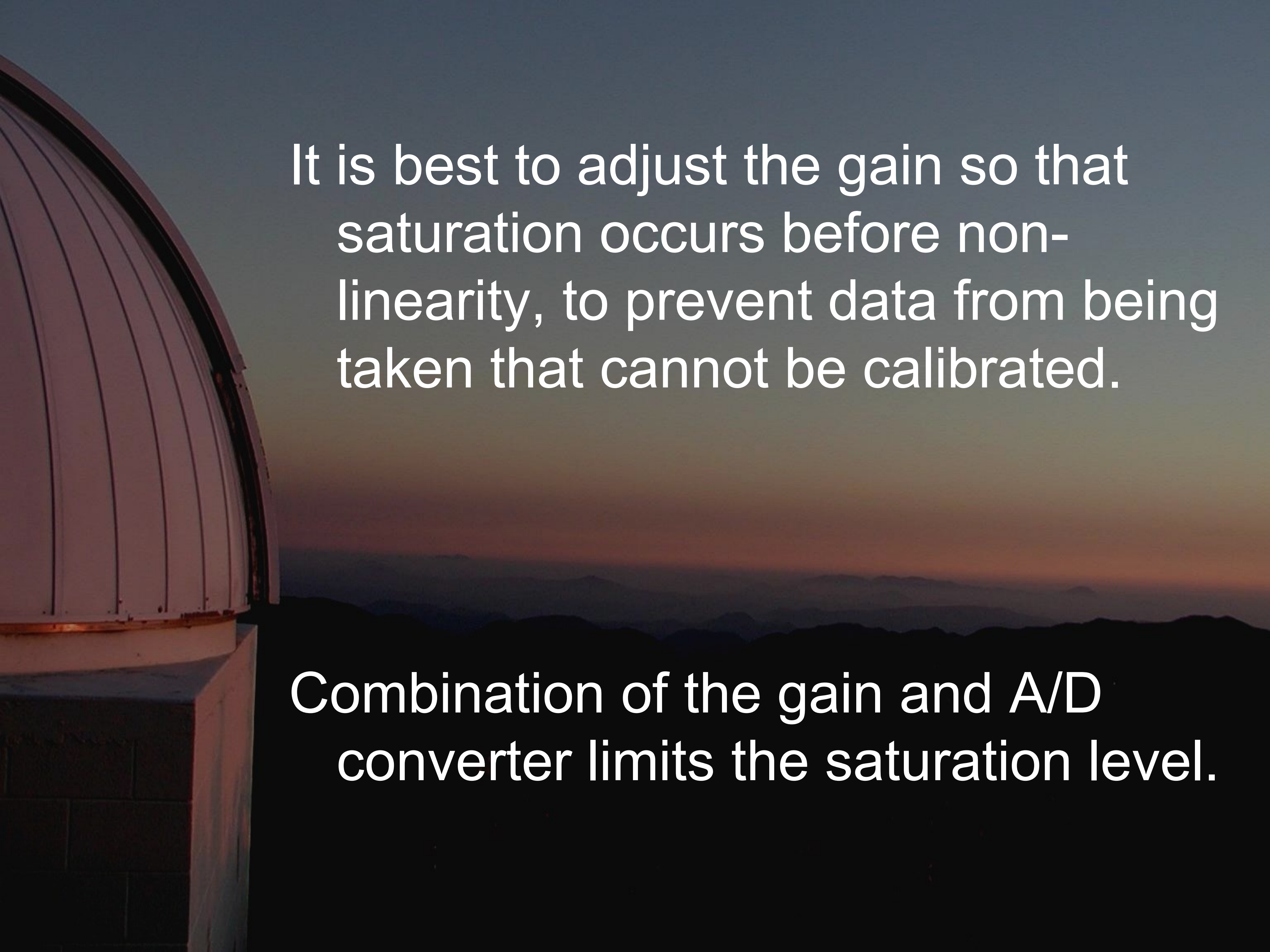
CCD Behavior: *extra bits*



CCDs can become non-linear when the source is too bright.

CCD output no longer is directly proportional to input.

And, at some point, the ADC electronics saturates.



It is best to adjust the gain so that saturation occurs before non-linearity, to prevent data from being taken that cannot be calibrated.

Combination of the gain and A/D converter limits the saturation level.

Illustrative CCD input/output response curve