

ASTR21200

Observational Techniques in Astrophysics

Lecture 3

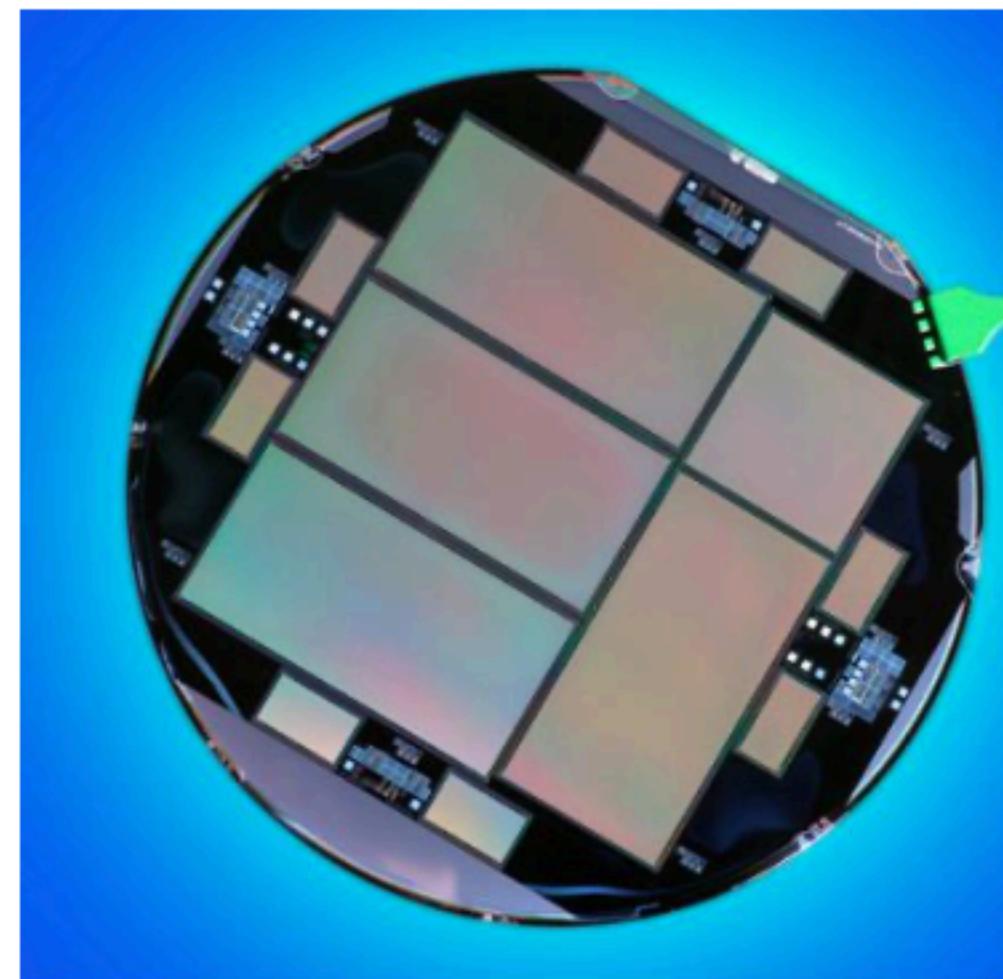
Bradford Benson

Office Hours

- During class:
 - feel free to ask questions before, during, after lecture!
- Slack:
 - feel free to ask questions via direct message or class ASTR21200 Slack channel!
 - (Note: I will invite you all officially tonight to Slack (i.e., based on Q2 in homework))
- Office Hours:
 - Dillon: Monday 4-6pm (ERC 583)
 - Rohan: Wednesday 3-5pm (ERC 583)
 - Brad: Thurs -12-1pm (ERC 589)
 - Will be updated on class wiki homepage:
 - https://github.com/bradfordbenson/ASTR21200_2024/wiki

Charge Coupled Devices (CCDs)

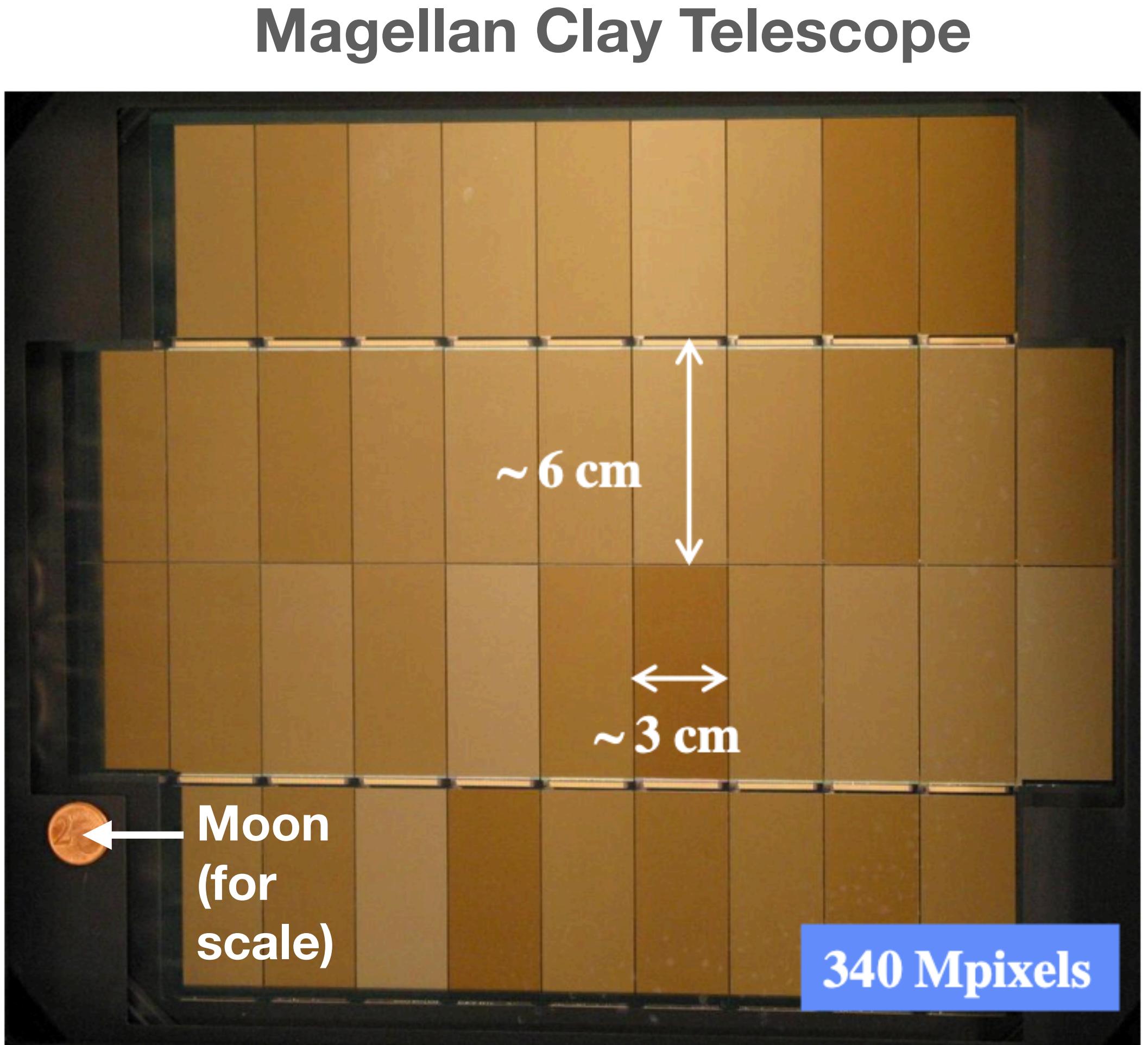
- CCDs are the detector of choice from X-rays to the infrared
- Replaced photographic plates
- Similar to detectors found in all digital cameras



Dark Energy Survey Camera (DECam) – 62 2k x 4k, $(15 \mu\text{m})^2$ -pixel CCDs
NOAO Cerro Tololo Blanco 4-m Telescope (Fall 2012)

Charge Coupled Devices (CCDs)

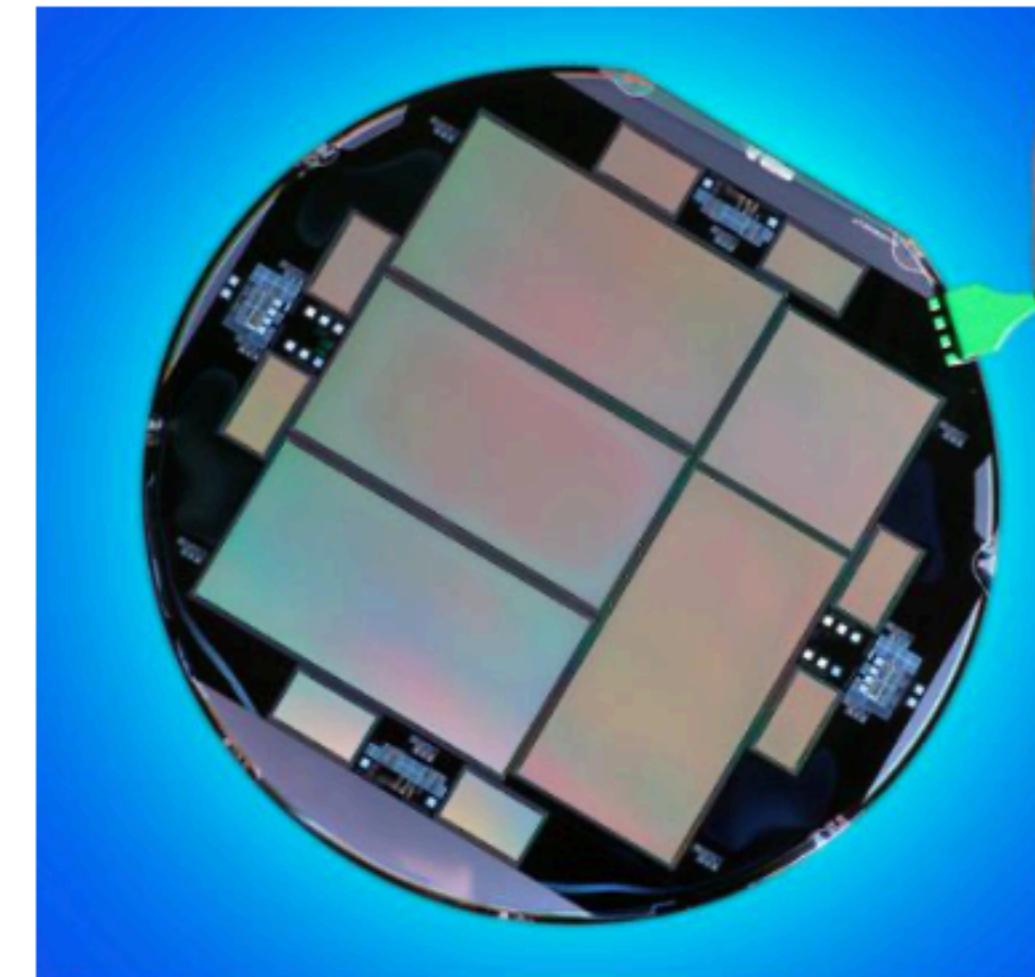
- CCDs are the detector of choice from X-rays to the infrared
- Replaced photographic plates
- Similar to detectors found in all digital cameras



MegaCam – 36 2k x 4k, $(15 \mu\text{m})^2$ -pixel CCDs

CCDs: Advantages

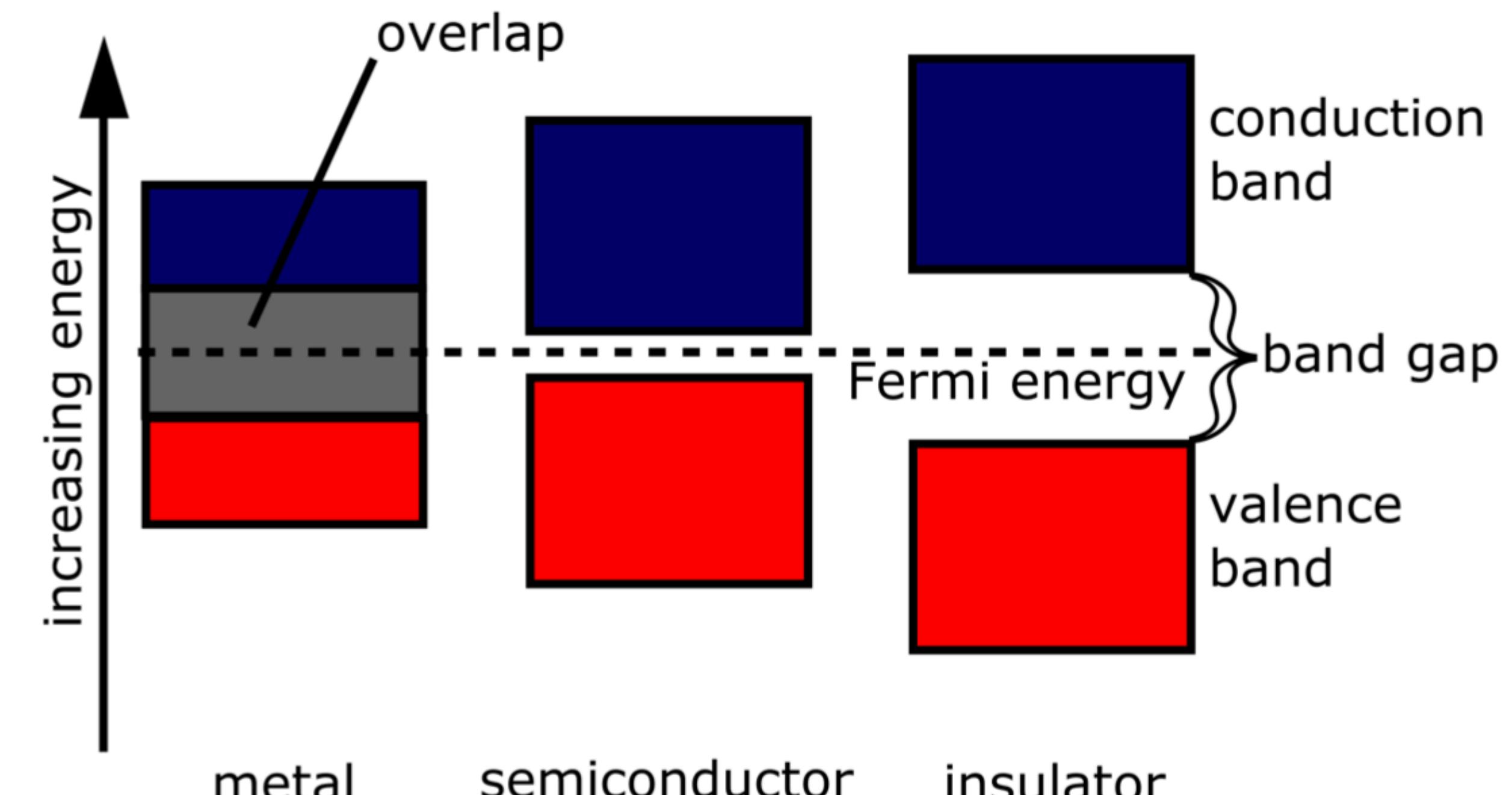
- Nearly linear response
 - $N_{electrons} \sim N_{photons}$
- High sensitivity
- Low noise
 - (especially when cooled)
- Built-in Digitization



Dark Energy Survey Camera (DECam) – 62 2k x 4k, $(15 \mu\text{m})^2$ -pixel CCDs
NOAO Cerro Tololo Blanco 4-m Telescope (Fall 2012)

CCDs Are Semi-Conductors

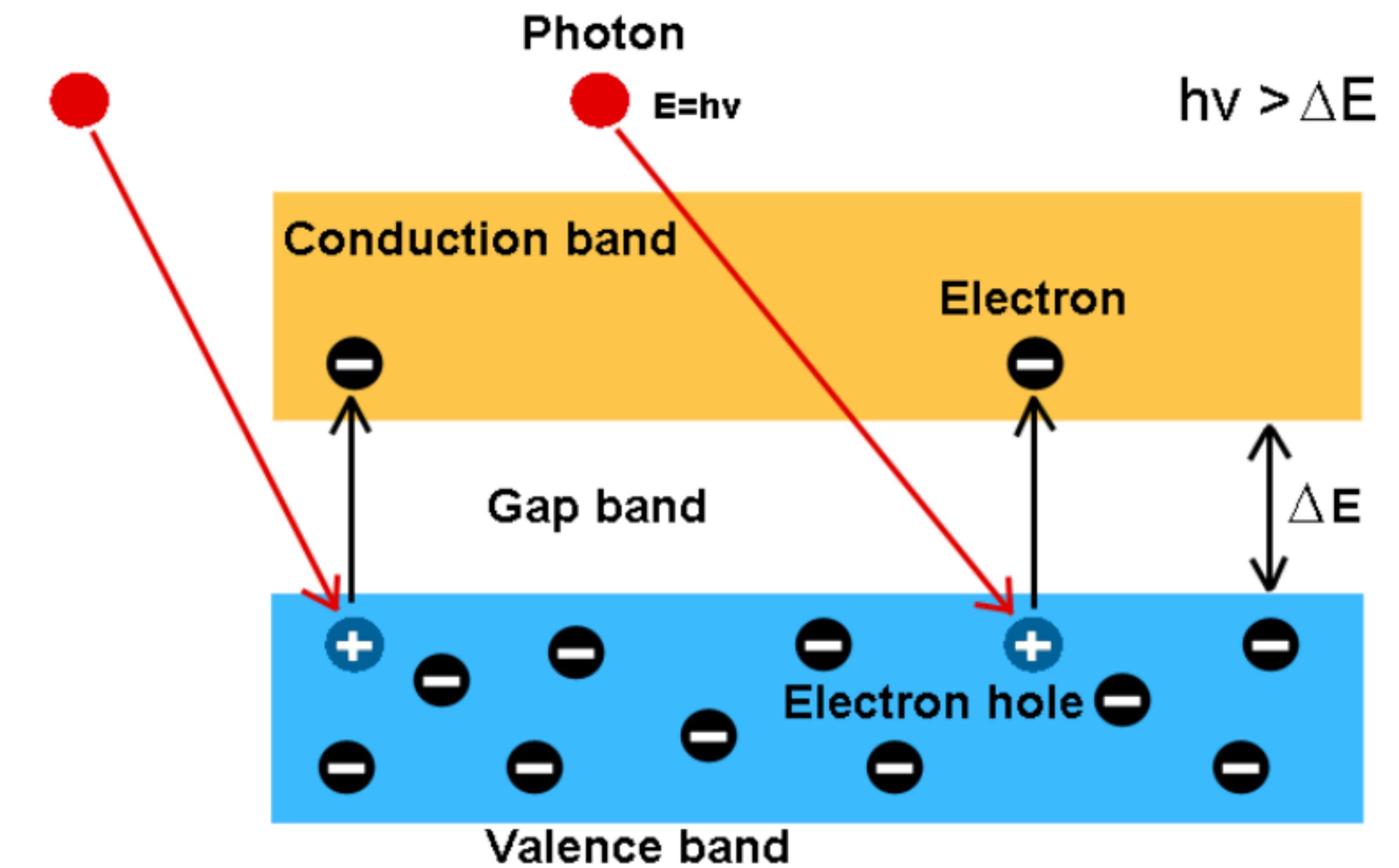
- CCDs are made of semi-conducting silicon wafer
- Key feature: Small energy gap between “valence band” (energy levels of bound electrons) and “conduction band”(energy levels of free electrons)



wikipedia / inductive

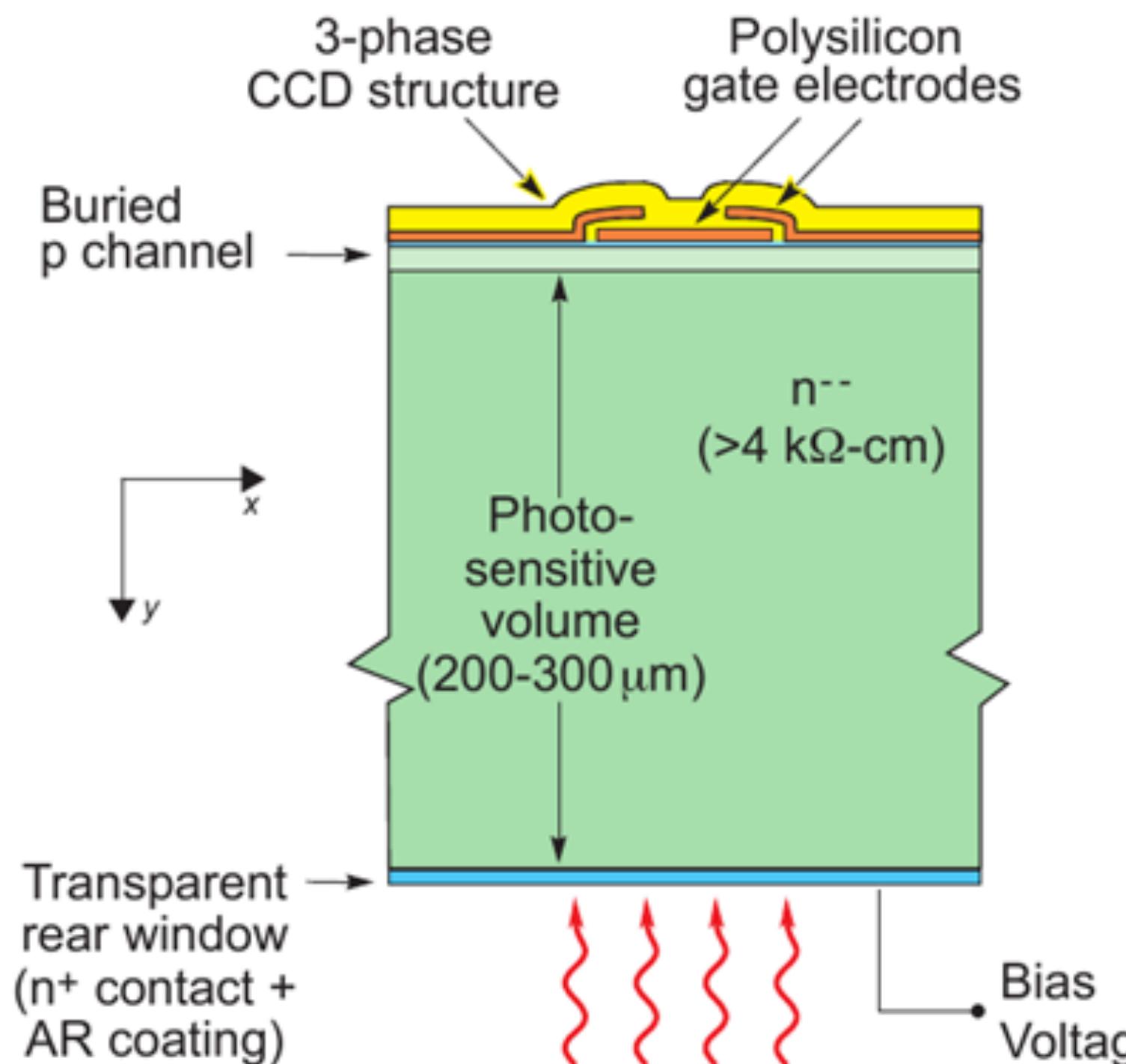
Photoelectric Effect

- Light is quantized in “photons”
- When a photon is absorbed, the energy is transferred to an electron, such that it jumps into the conduction band
- Band gap (ΔE) varies for different materials, e.g.
 - Insulator: $\Delta E > \sim 10$ eV ($< \sim 100$ nm)
 - Semi-conductor: $\Delta E \sim 1$ eV (~ 1 μm)
 - Conductor: $\Delta E < 0$ eV (i.e., mixed)



M. Pob

CCD Quantum Efficiency



$$\text{Photon Energy (eV)} = \frac{1.24}{\lambda(\mu\text{m})}$$

- The wavelength cut-off in Silicon due to the band-gap ($\sim 1.1 \text{ eV}$) is about $1 \mu\text{m}$
- The Silicon absorption length is defined as the inverse of the absorption coefficient alpha (α)

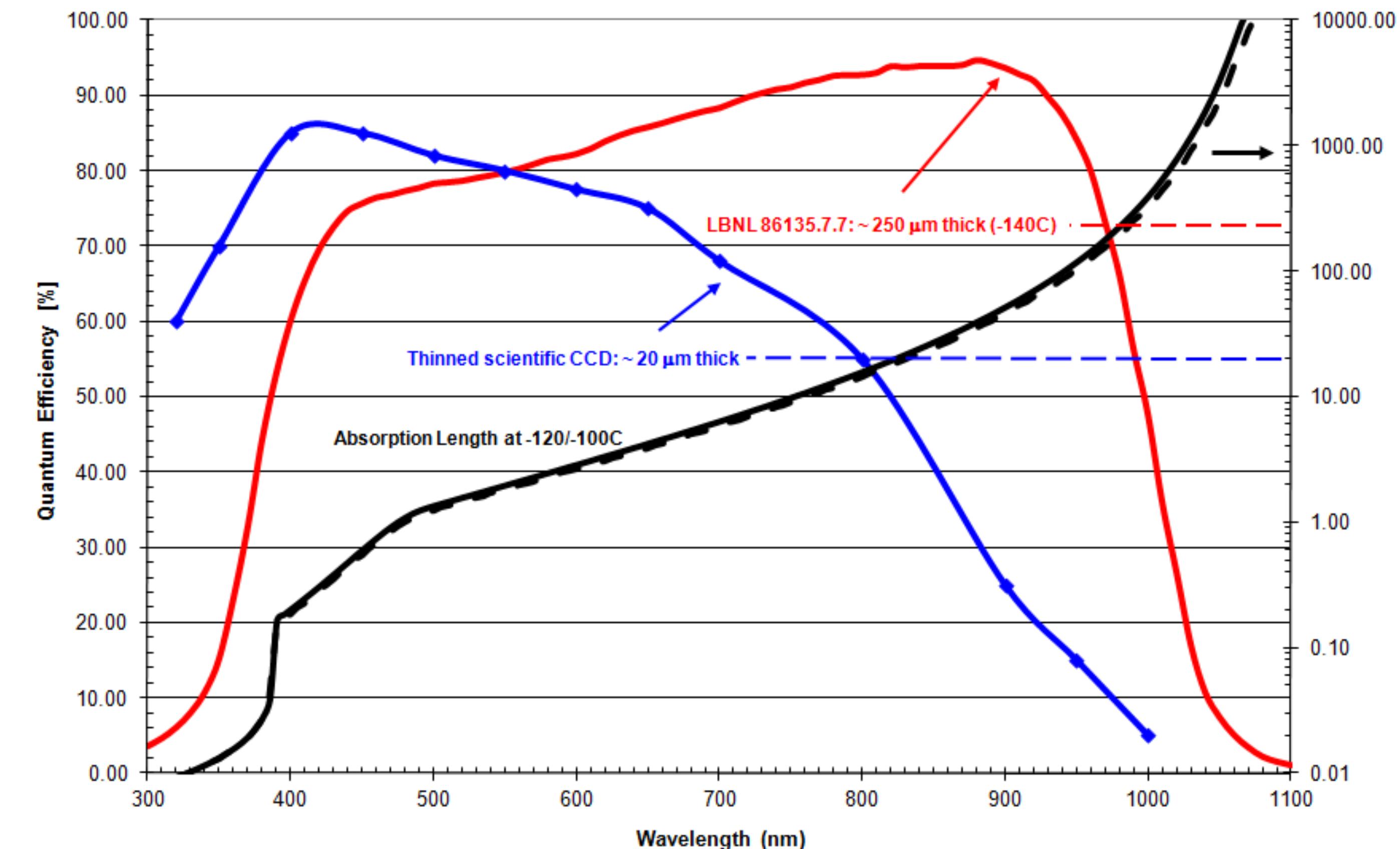
$$I(x) = I_o \exp[-\alpha x]$$

Intensity of incident light

(i.e., thicker
Silicon wafers will
have more
absorption)

CCD Quantum Efficiency

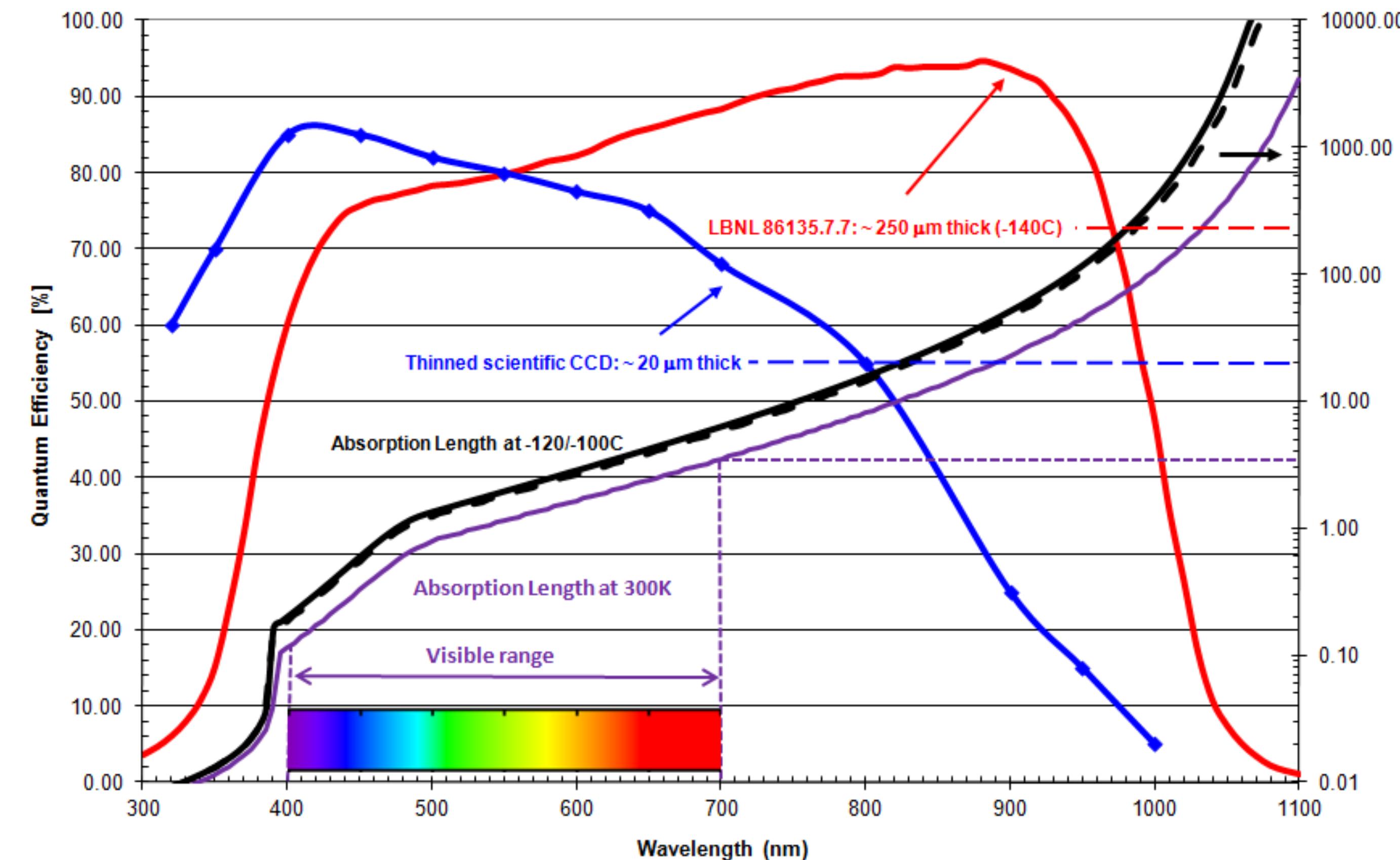
- Defined as the fraction of photons that are absorbed
- Depends on wavelength
- Different materials or technologies lead to Red vs. Blue optimized CCDs



Thicker Silicon
wafers will have
more absorption

CCD Quantum Efficiency

- Defined as the fraction of photons that are absorbed
- Depends on wavelength
- Different materials or technologies lead to Red vs. Blue optimized CCDs

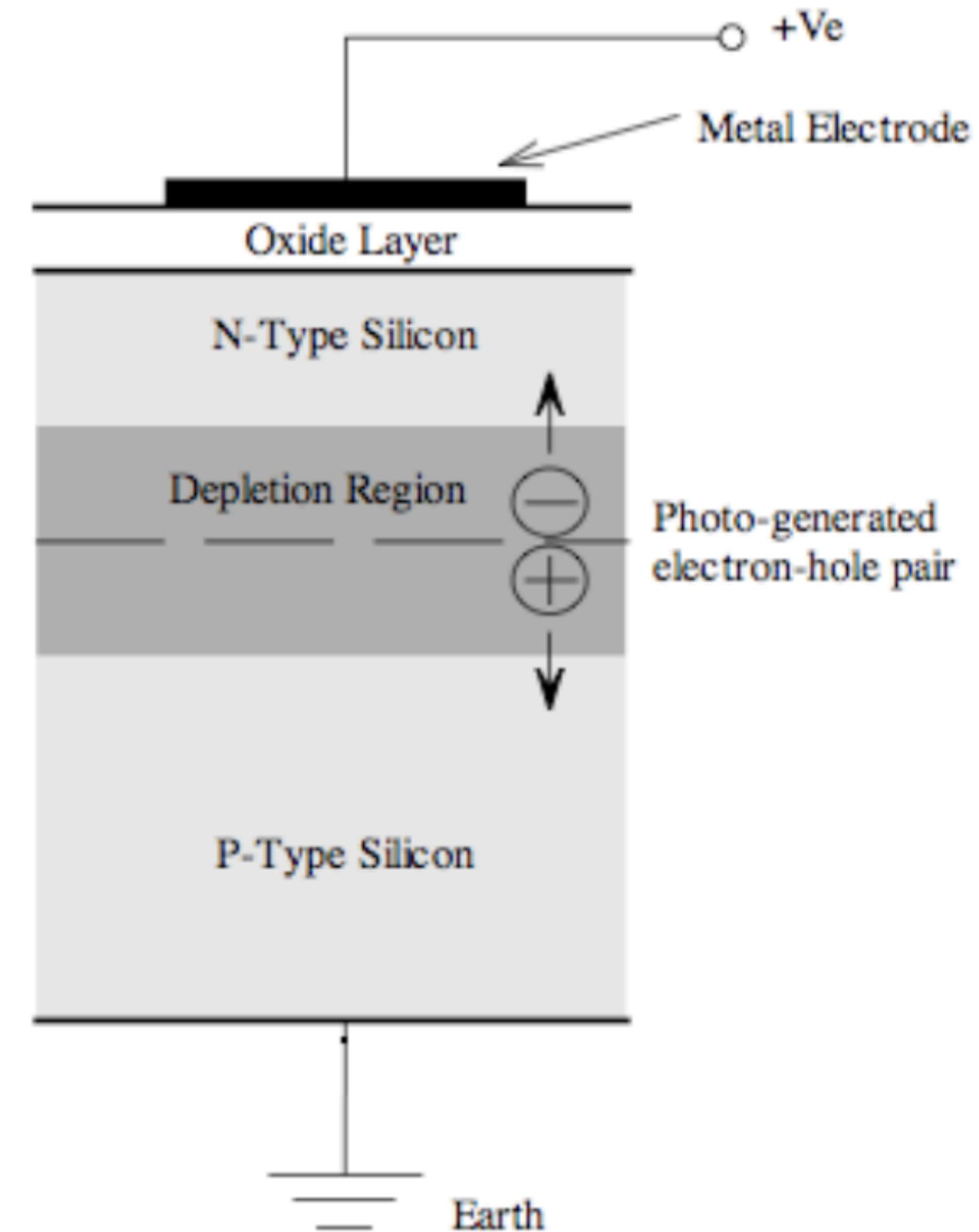


Thicker Silicon wafers will have more absorption

Colder Silicon also increase the absorption length (and improves quantum efficiency)

How do CCDs work? One pixel example

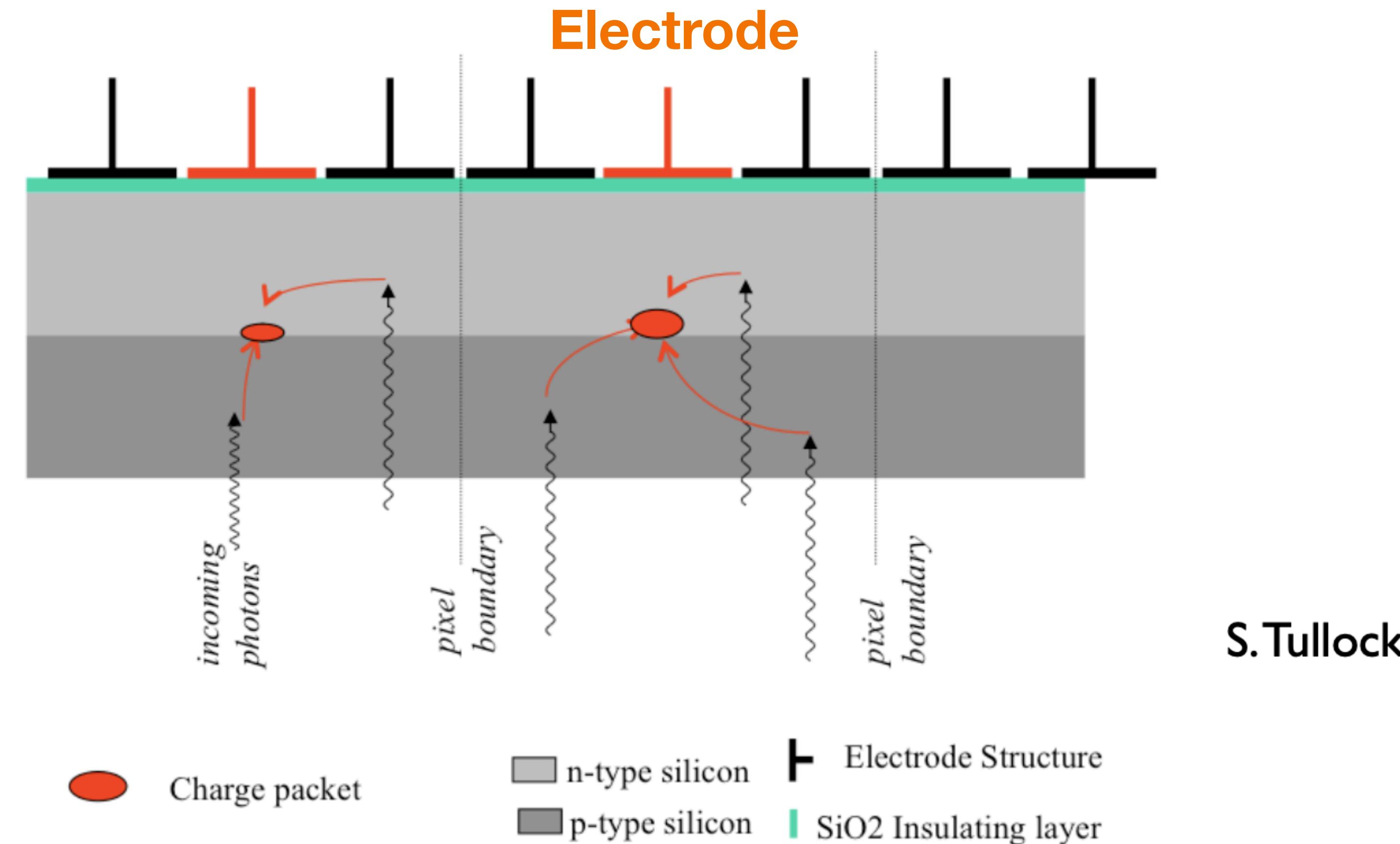
- Apply an electric field across a “doped” Silicon wafer to keep electrons (and holes) separated
- Photons absorbed by the Silicon will knock electrons into conduction band, which then get attracted to voltage applied to electrode connected to surface of the Silicon



Microsoft

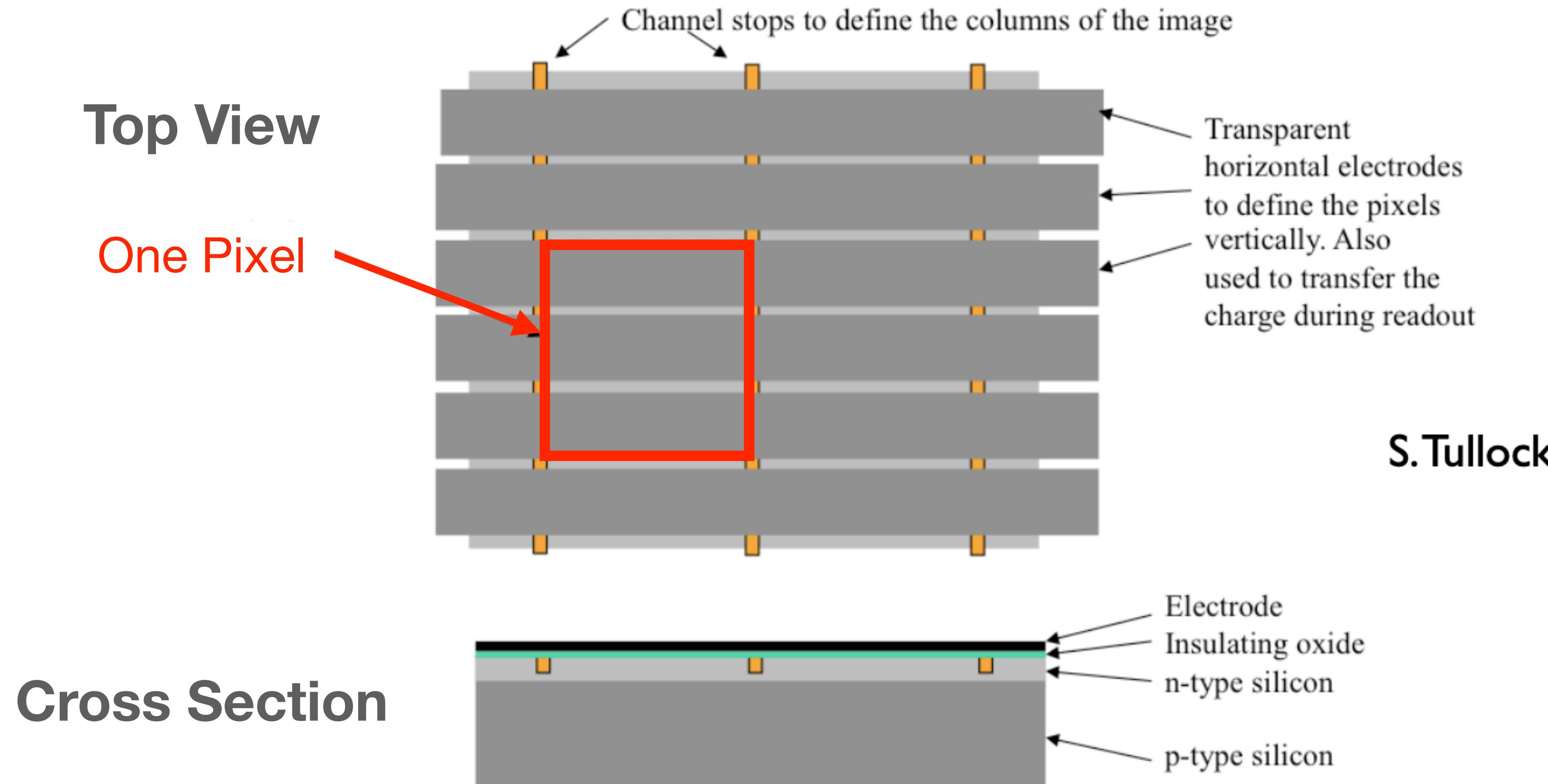
How do CCDs work? Many pixels

- Each CCD wafer will be made from one piece of bulk Silicon
- Pixels are defined by the electric field generated by multiple electrodes applied on one side of the wafer



How do CCDs work? Many pixels

- Insulator strips between columns of pixels (while electrodes define rows)



Reading Out CCDs

- Voltage on electrodes control where charge accumulates in Silicon
- Modulate (or “clocking”) voltages used to move charge across CCD towards end row, where signal can be measured
 - Similar to “rain buckets on conveyer belts”, where 1-raindrop = 1-electron

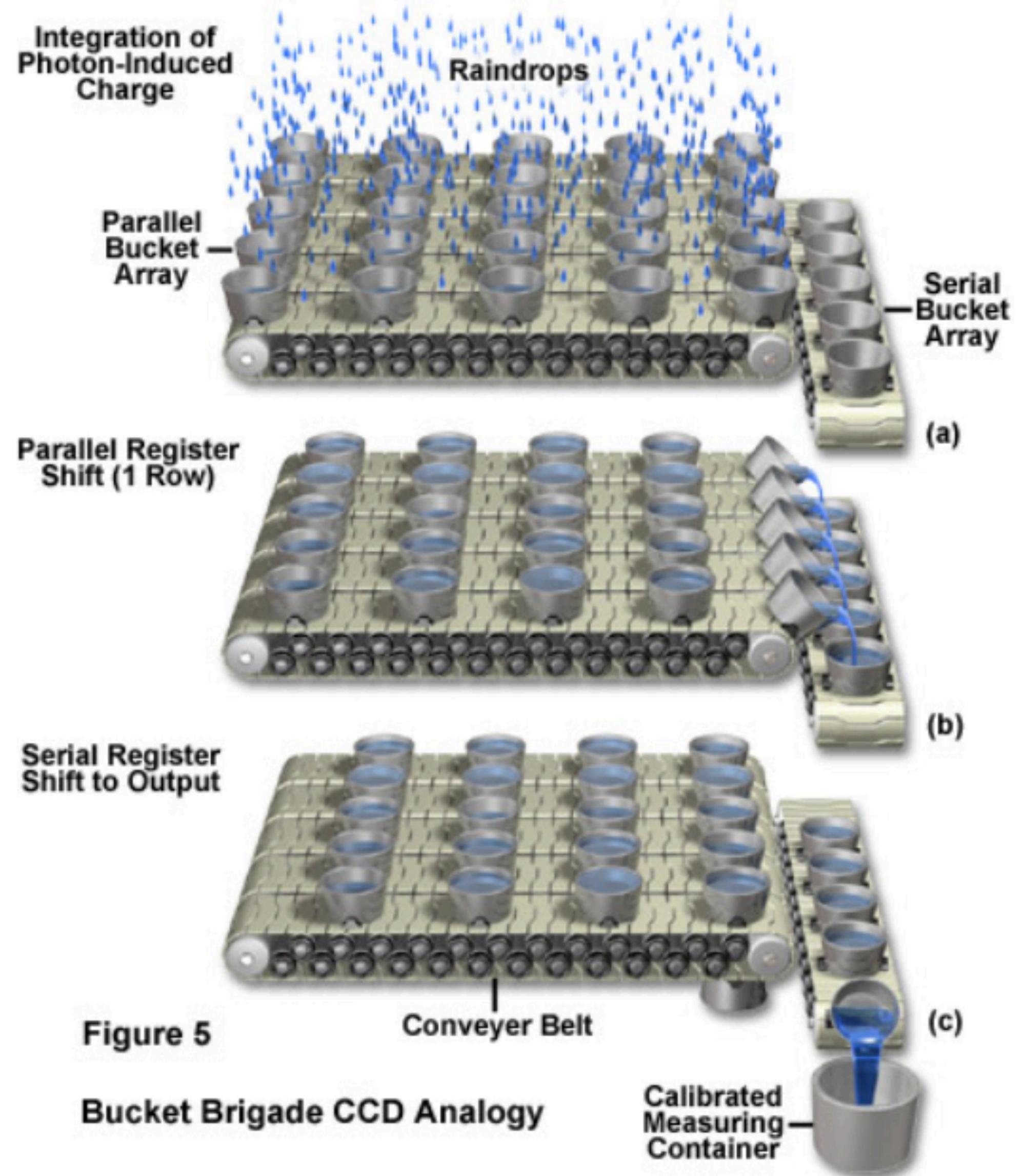
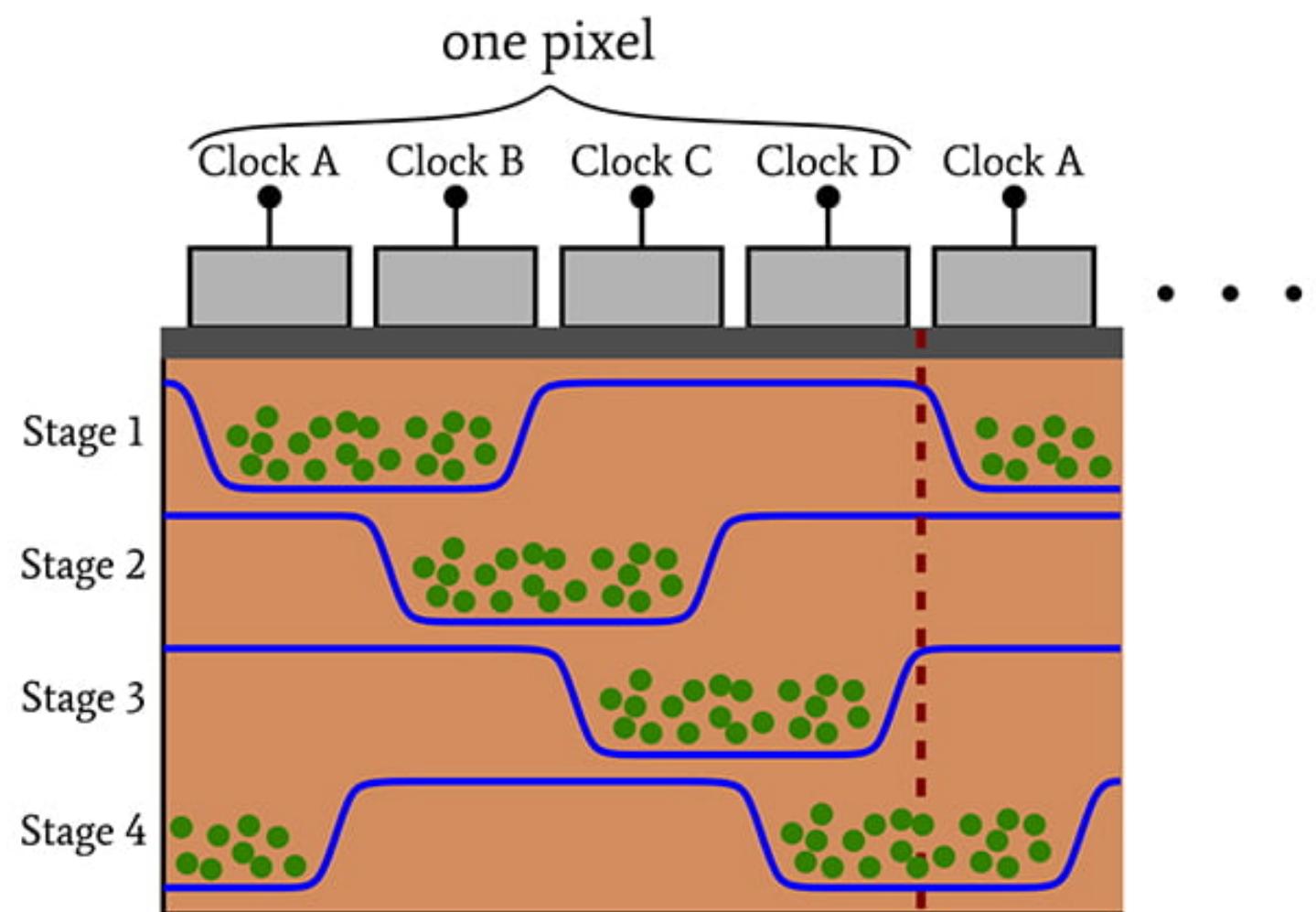


Figure 5

Bucket Brigade CCD Analogy

Cold Spring Harbor Protocols

Assembling the Image

- Charge collection is passed to an amplifier and analog-to-digital converter (ADC)
- Output “counts” as integer value, with 1-photon creating 1-count
- However, in addition, we can also apply an electronic “Gain” via an amplifier, where
 - Gain: $G = (N_{electrons}) / (N_{counts})$

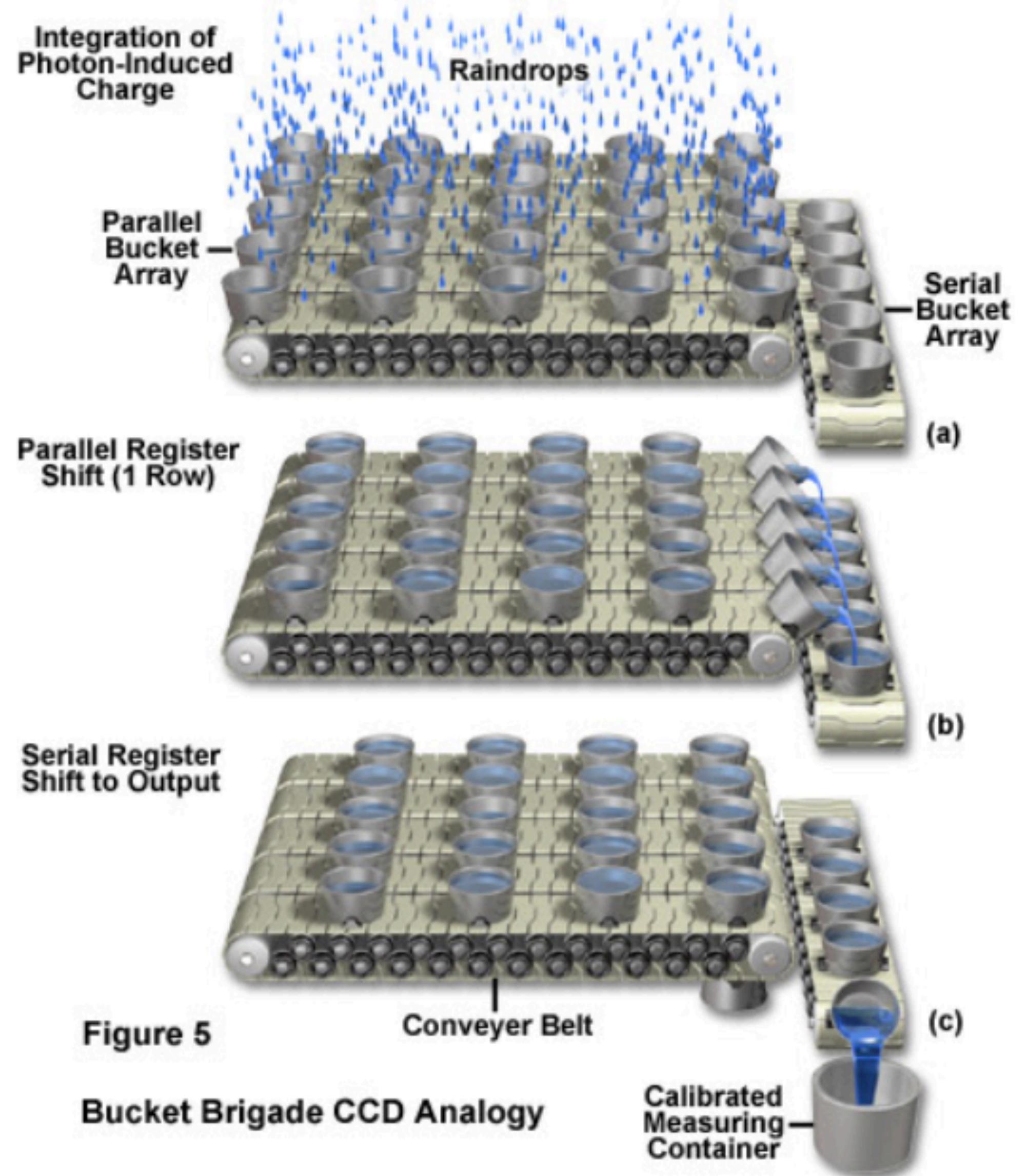


Figure 5

Bucket Brigade CCD Analogy

Cold Spring Harbor Protocols

CCDs vs CMOS detectors

- At Stone Edge, we also use “CMOS” detectors, which are also made from silicon wafers and which detects photons similarly, except:
 - CCDs: Shifting of charge vertically and horizontally to a source follower amplifier that converts charge to voltage
 - CMOS image sensors have an SF amplifier in each pixel eliminating the need for high charge-transfer efficiency

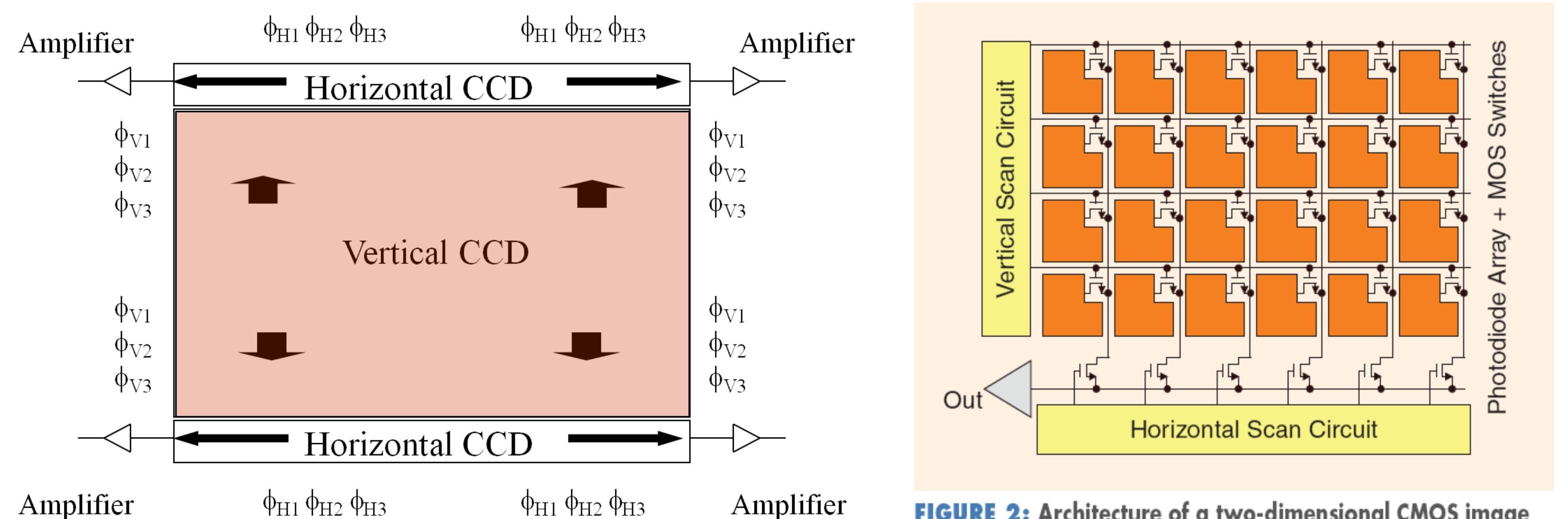


FIGURE 2: Architecture of a two-dimensional CMOS image sensor.

A. Theuwissen, IEEE Solid-State Circuits Magazine, 22, Spring 2010

Scientific CCDs vs Cell-phone CMOS Detectors

Unofficial comparison, scientific CCD versus CMOS image sensor for cell phones (e.g. iPhone 4, TSMC/OmniVision¹)

Parameter	CMOS cell phone	Scientific CCD
# pixels	5 - 8 Megapixels	8 – 16 Megapixels
Pixel size	1.4 – 1.7 μm	10 – 15 μm
Imaging area	15 mm^2 (5M)	3775 mm^2 (16M)
Technology	130 nm CMOS	2.5 μm CCD
Illumination	Back illumination	Back illumination
Optical thickness	$\sim 3 \mu\text{m}$	10 – 250 μm
Peak QE	$\sim 55\%$ (color filter)	$\sim 90 – 95\%$
Operating temp	Up to 50°C	-100°C – -140°C
Dark current	20 – 30 e-/pixel/sec	Few e-/pixel/hr
Read noise	$\sim 2 \text{ e-}$	$\sim 2\text{-}5 \text{ e-}$
Full well	$\sim 4500 \text{ e-}$	$\sim 200,000 \text{ e-}$ (15 μm)

¹Rhodes, 2009 IISW Symp. On Backside Illumination of Solid-State Image Sensors, imagesensors.org and <http://image-sensors-world.blogspot.com/2010/06/iphone-4-bsi-sensor-is-omnivisions.html>

Converting CCD Counts to Flux

Bias Level

- **Bias Level:** An electronically induced offset which ensures that the ADC always gets a positive input
- The bias needs to be **subtracted** so that the counts are proportional to the signal
 - Note: the bias level is not a “counting process”, i.e., it does not go up linearly with longer exposure, and should be known accurately

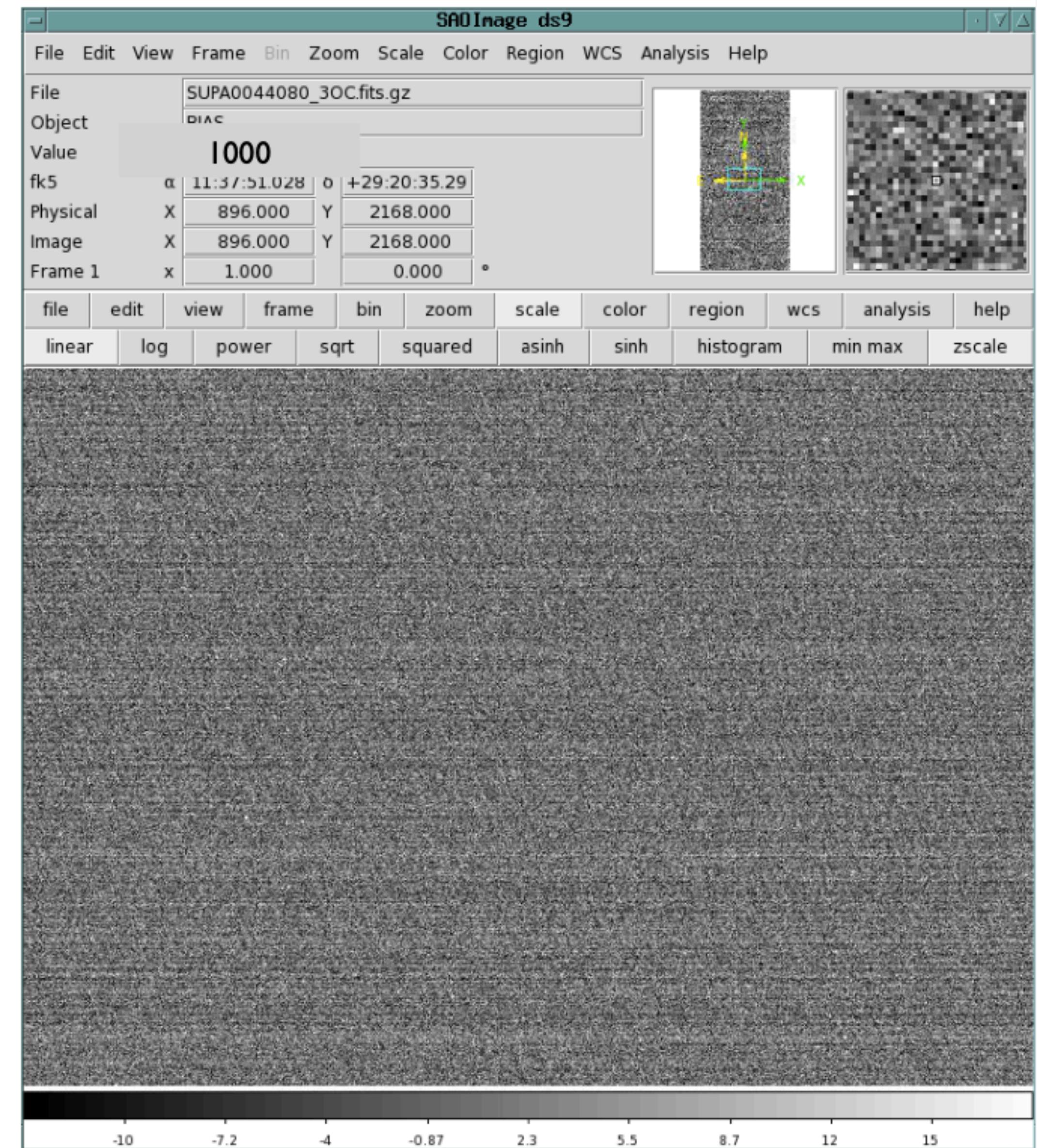
Converting CCD Counts to Flux

Readout Noise

- **Readout Noise:** Noise produced by various electronics during readout, e.g., the amplifiers
- Typically the slower the readout, the lower the readout noise
 - Note: This is a noise term that adds stochastically to the measurement, i.e., you can subtract an estimate of the readout noise, but there will be uncertainty on the noise

Bias Images

- An image with 0-sec exposure time
- **Single bias frame:** Pixel values scatter around the bias level, with the width of this distribution equal to the readout noise
- **Master bias frame** (median of many bias frames): In the master, readout noise is averaged out, such that remaining structure is due to electronics



Dark Current

- Thermal noise can lead to extra charge accumulation, where electrons are (randomly) thermal excited into the conduction band
- Proportional to exposure time
- Cooling the CCDs significantly reduces dark current
- Professional astronomical CCDs cooled to order -100 Celsius

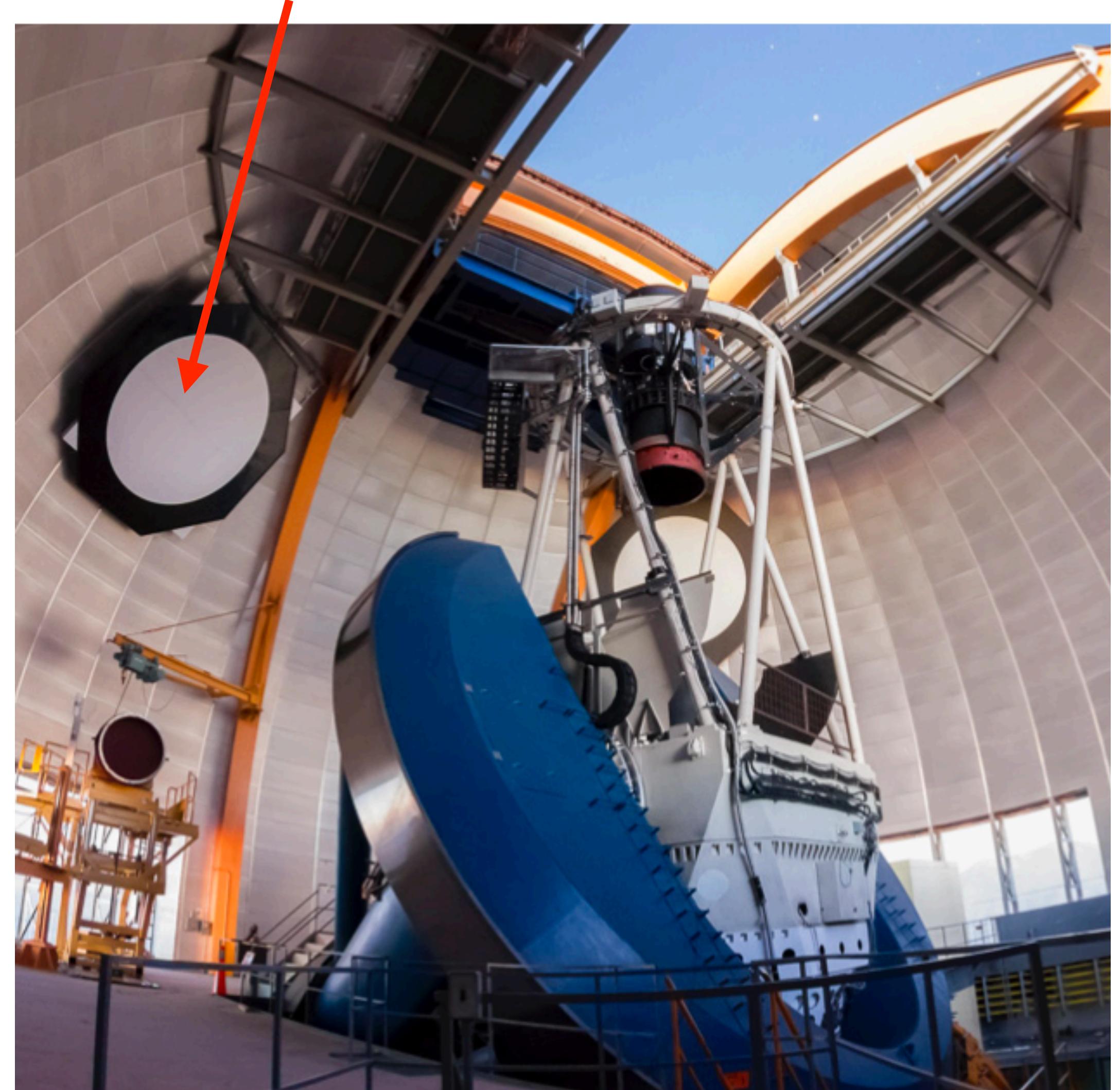
Dark Frames

- **Dark Frame:** Image taken with a closed shutter
- Similar to bias frames, needs to be subtracted
 - For SEO, (I think) dark frames only need to be subtracted (i.e., because dark current is much larger than bias current).
 - Dark frames should be taken with a similar temperature and exposure length to the observations that you are taking

Flat-Field

- The pixels in a CCD do not have uniform sensitivity
- Due to variations in the Silicon, electric field, pixel size, optics, vignetting, etc.
 - $N_{electrons} = A_{ij} N_{photons}$
- A_{ij} will be different for each pixel (i,j)
- Need to correct for differences for meaningful measurements via a “Flat-Field”

Screen in dome at DES/
CTIO for “flat-fielding”



Flat-Field

- **Flat-field:** Take an image of a spatially uniform source of light (e.g., most commonly a white screen in the dome, the twilight sky) to measure the response across the CCD
- Input signal ($N_{photons}$) is the same for each pixel, so variations in N_{counts} are due to different pixel sensitivities

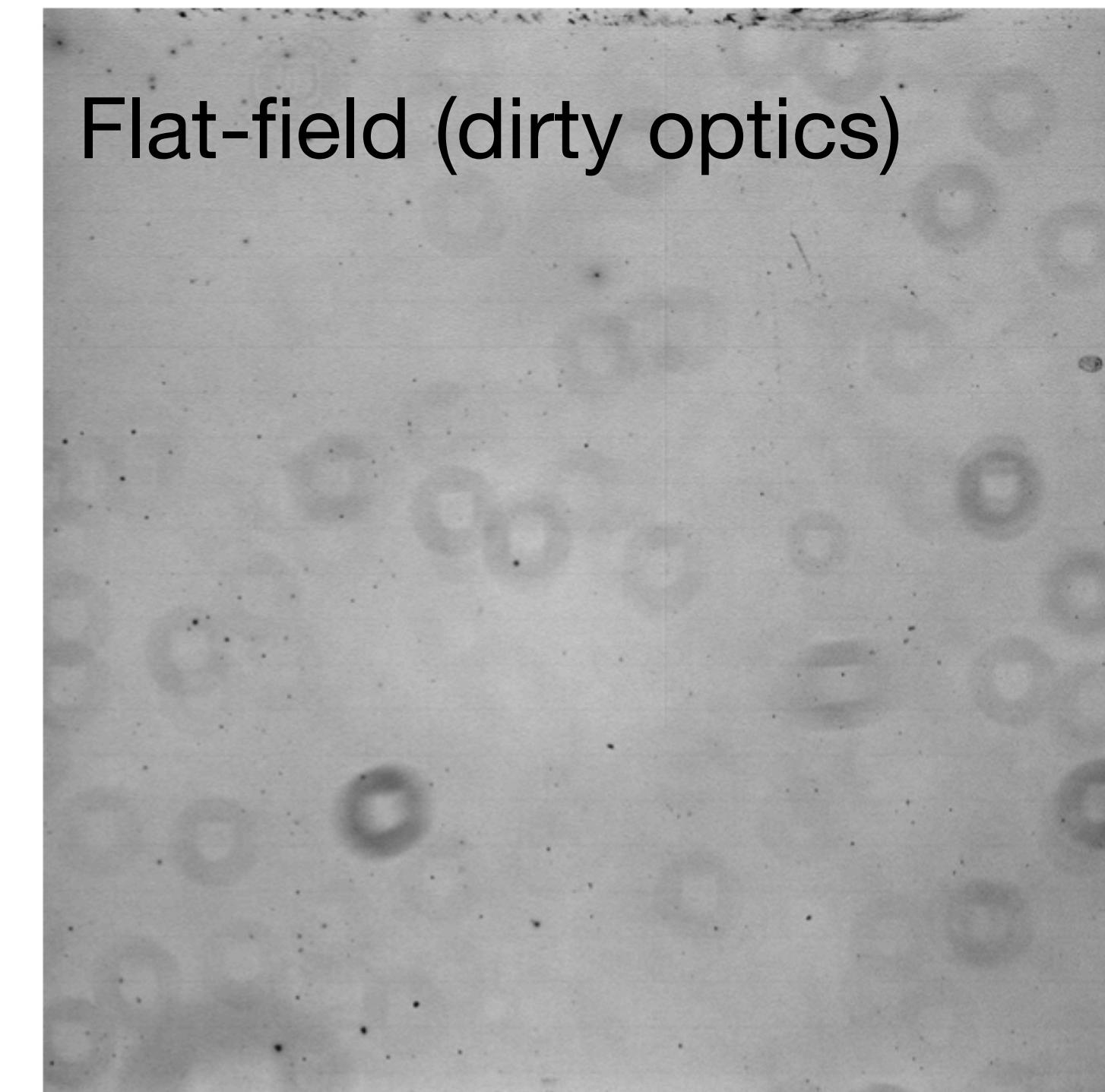
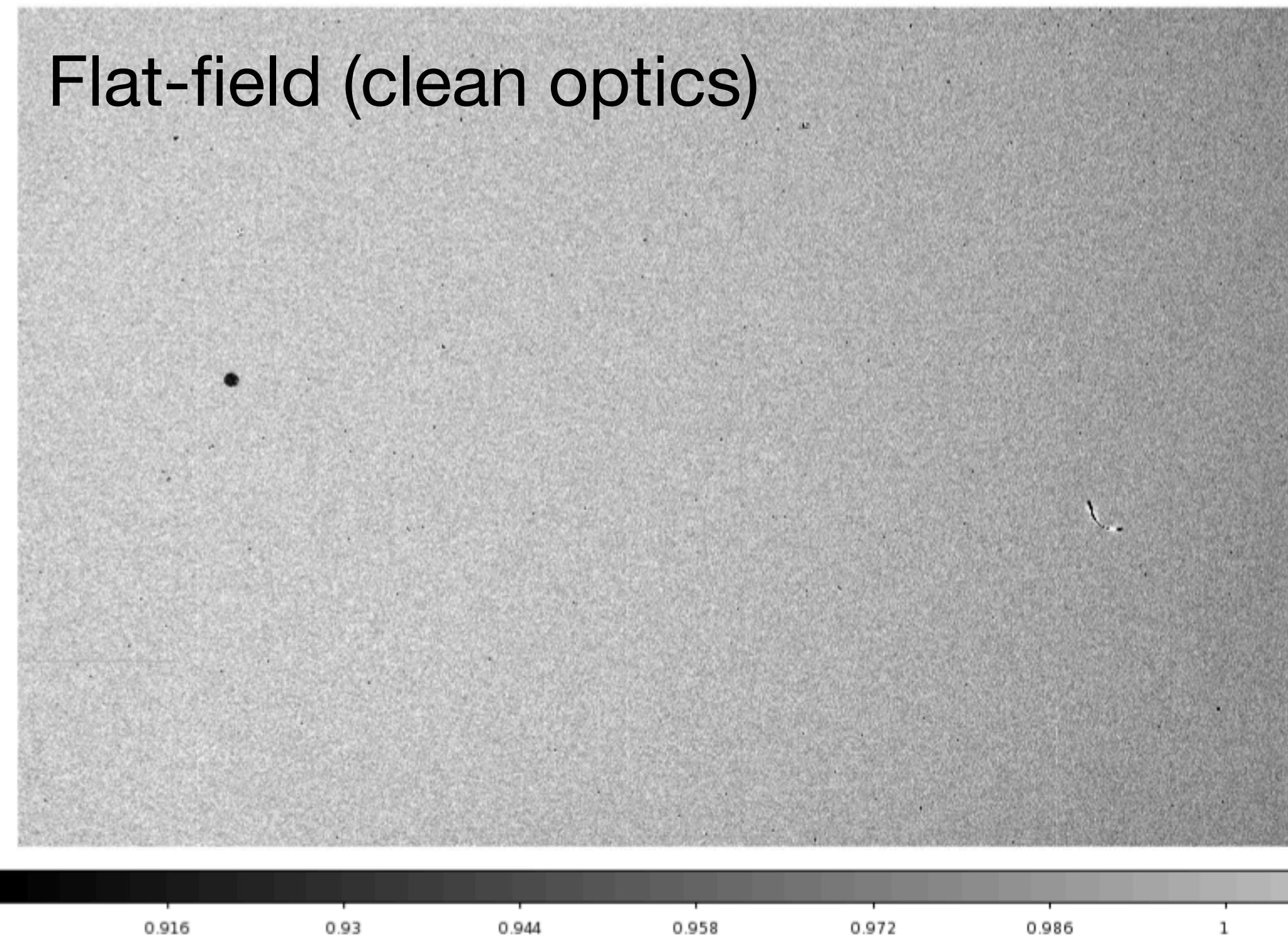


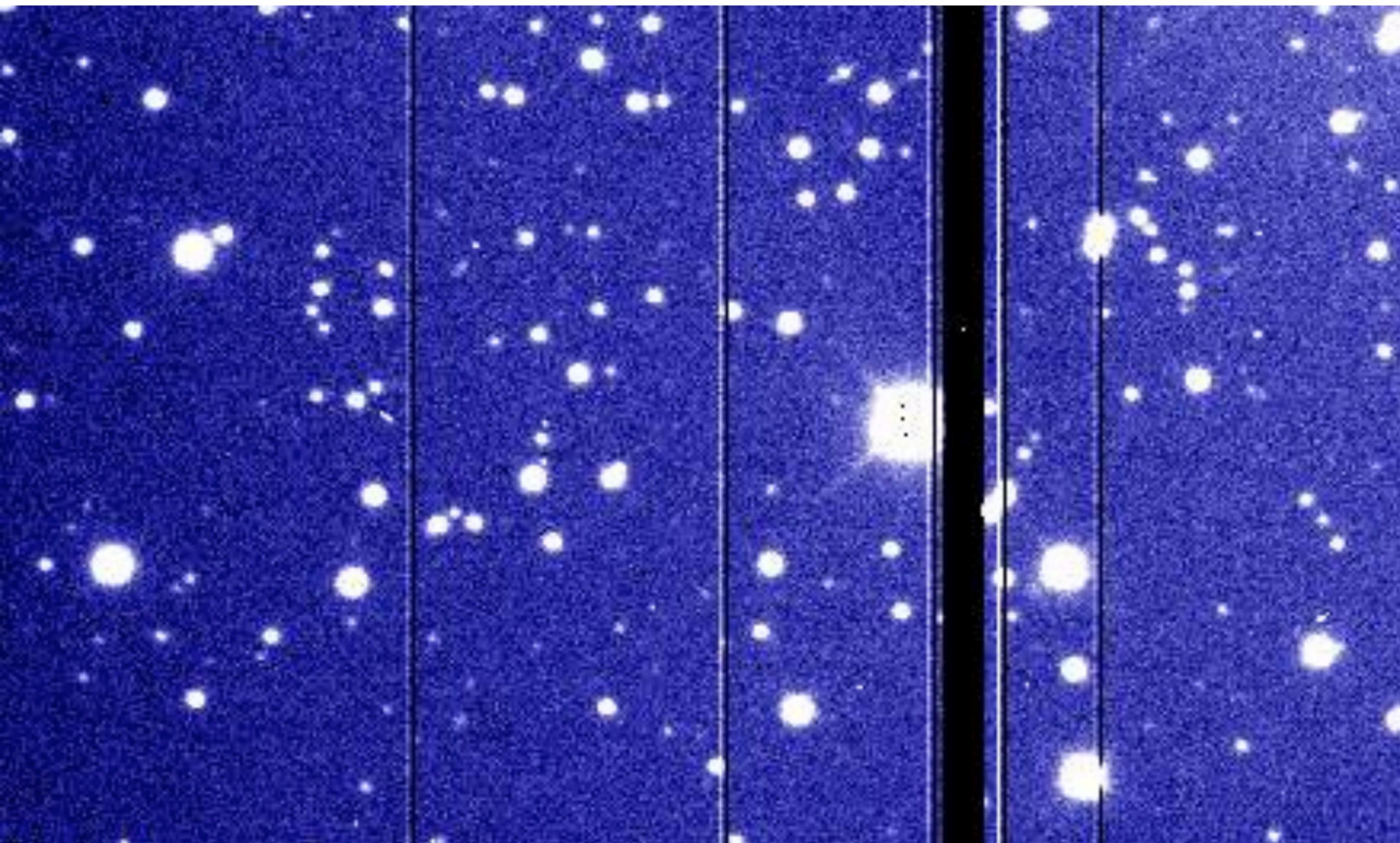
Fig. 6.— Flat field indicates the effects of dust.

Flat-Field

- **Flat-field** is a multiplicative correction
 - In practice, will take a series of flat-field image (correcting each with appropriate dark frame), and from a master flat-field averaged over many to reduce noise
- Bias/Dark field is a additive / subtractive correction
- Such that applying both should look something like:
 - **Final Image = $(\text{Raw Image} - (\text{Bias+Dark Frame})) / (\text{Flat Field} - (\text{Bias+Dark Frame}))$**

CCD Artifacts: Dead or Hot Pixels

- **Dead pixels:** No (or little) response
- **Hot pixels:** Very high noise
- In either case, signal is not recoverable, pixels need to be ignored in analyses

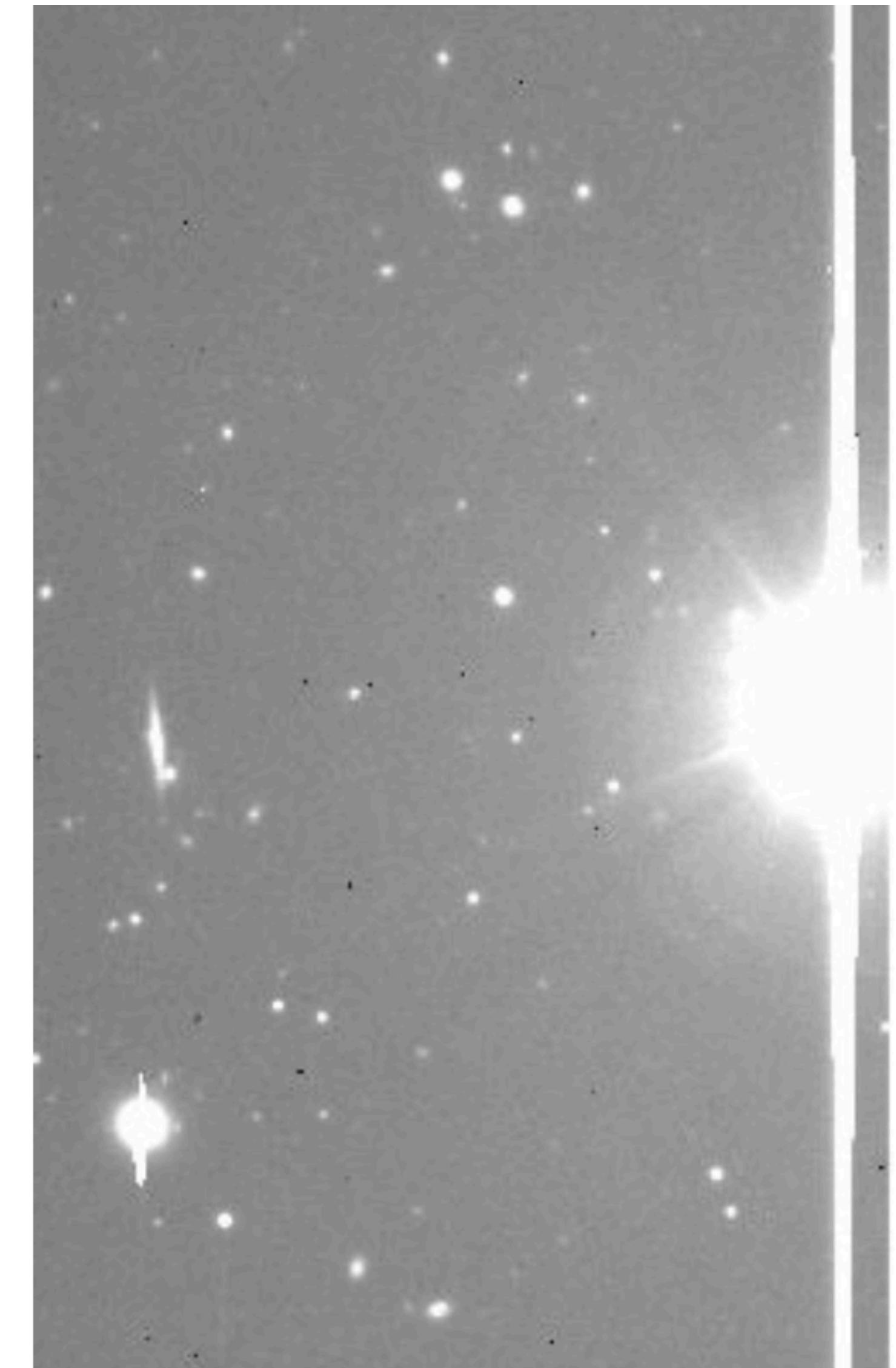
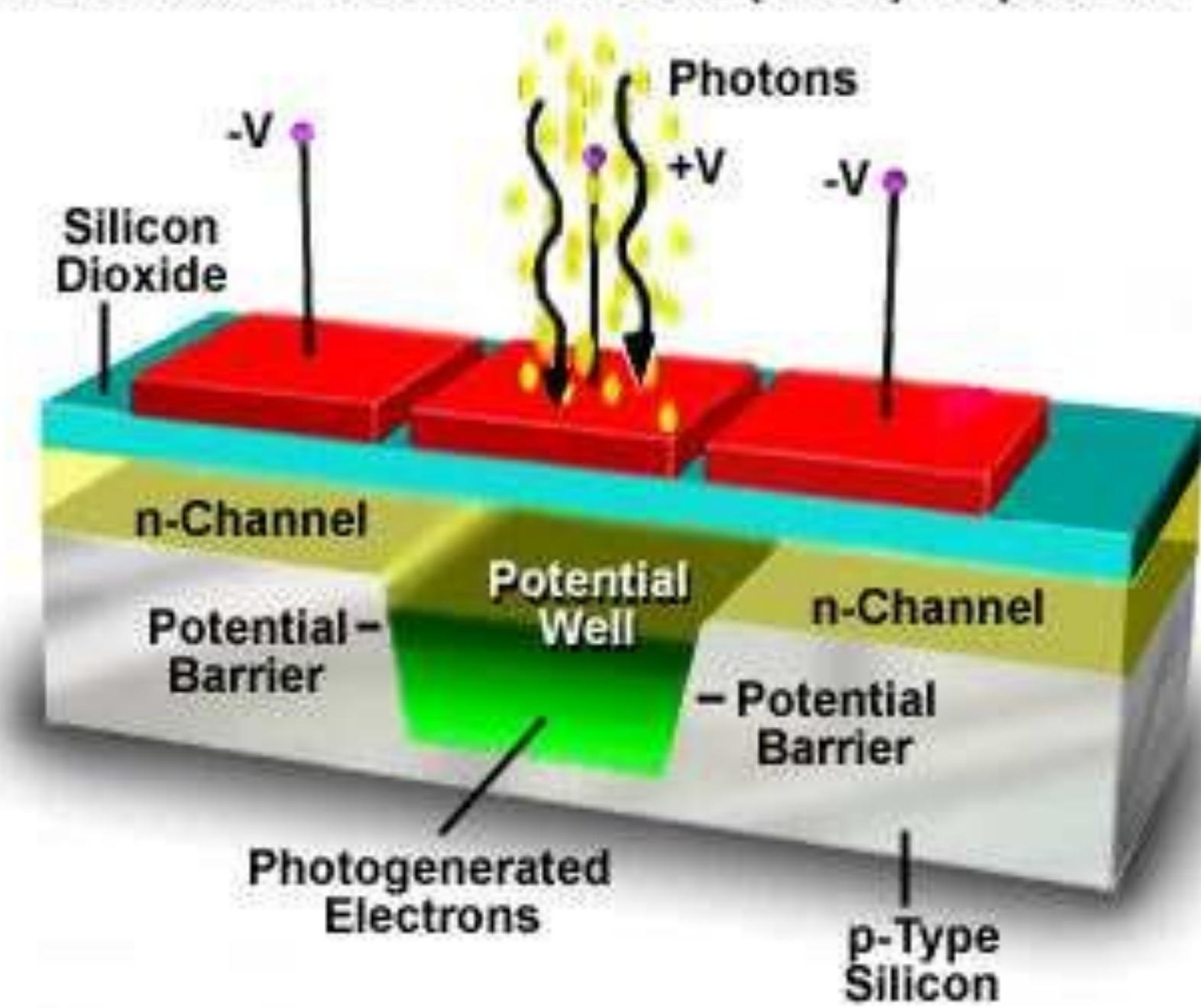


ESO

CCD Artifacts: Saturation

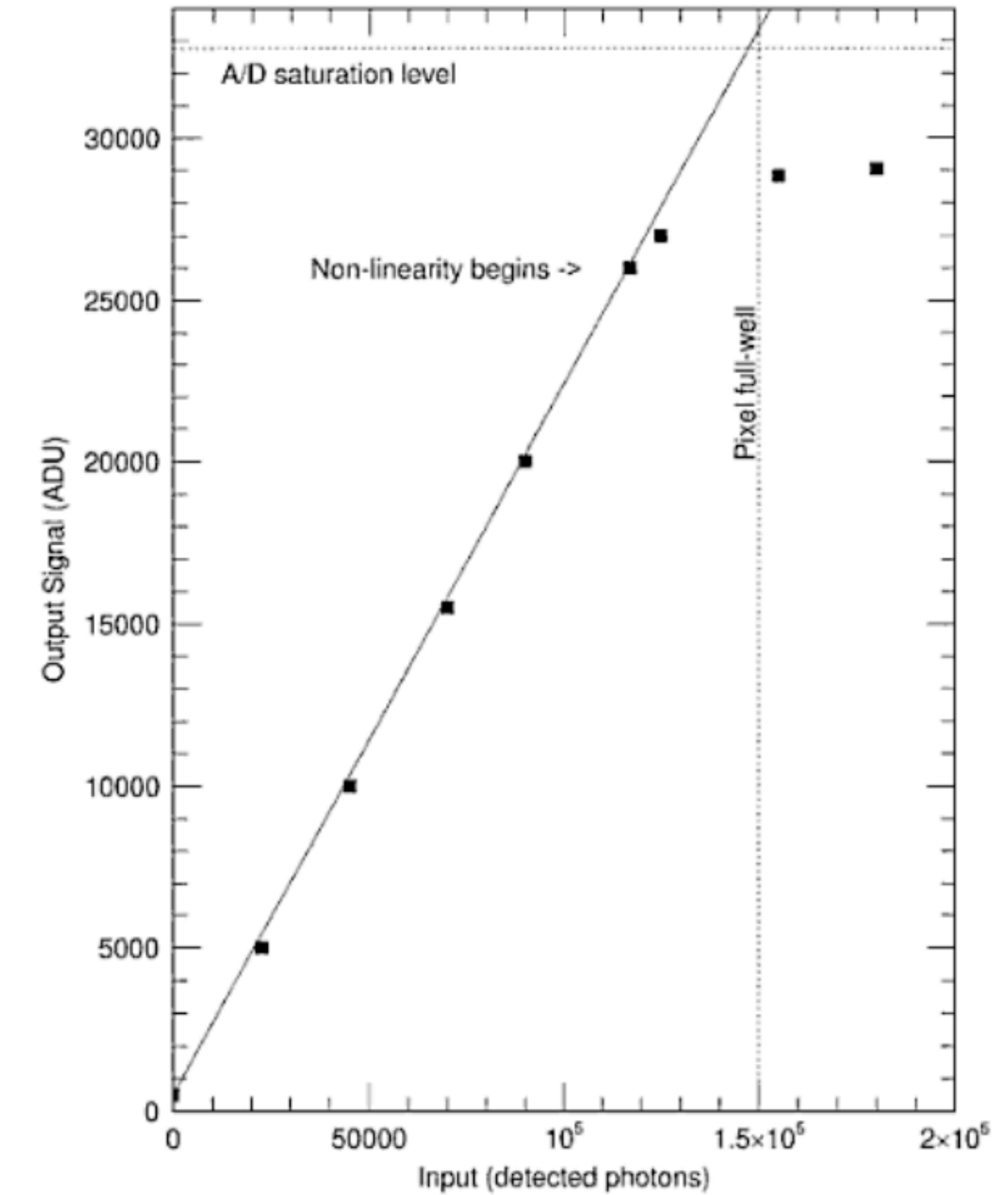
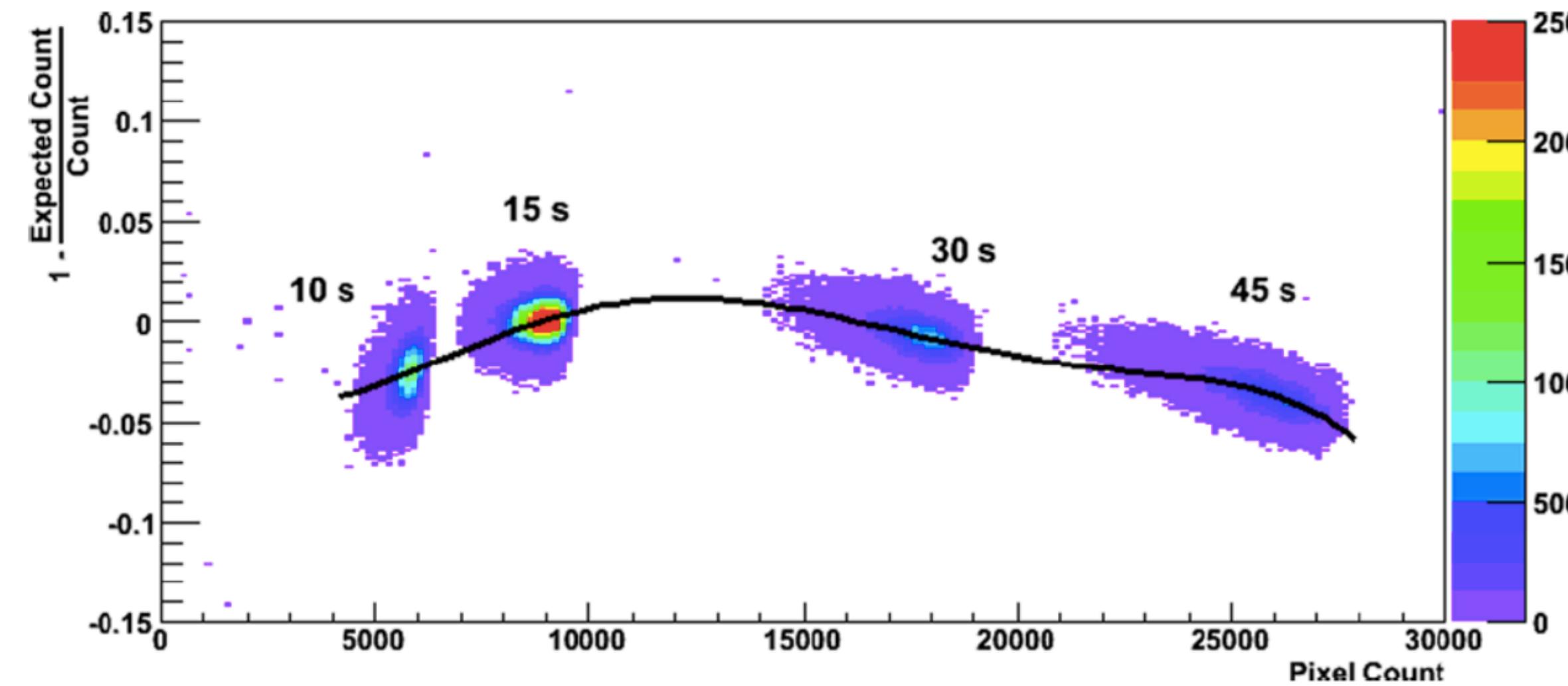
- **Saturation:** Bright object's signal fills pixels
electron “well” capacity, electrons spill over into
neighboring pixels.
 - Typical “well” in scientific CCD can hold ~100,000 electrons
 - (If you see this, likely a good idea to reduce your exposure
time, e.g., from 120-sec to 10-sec)

Metal Oxide Semiconductor (MOS) Capacitor



CCD Artifacts: Non-Linearity

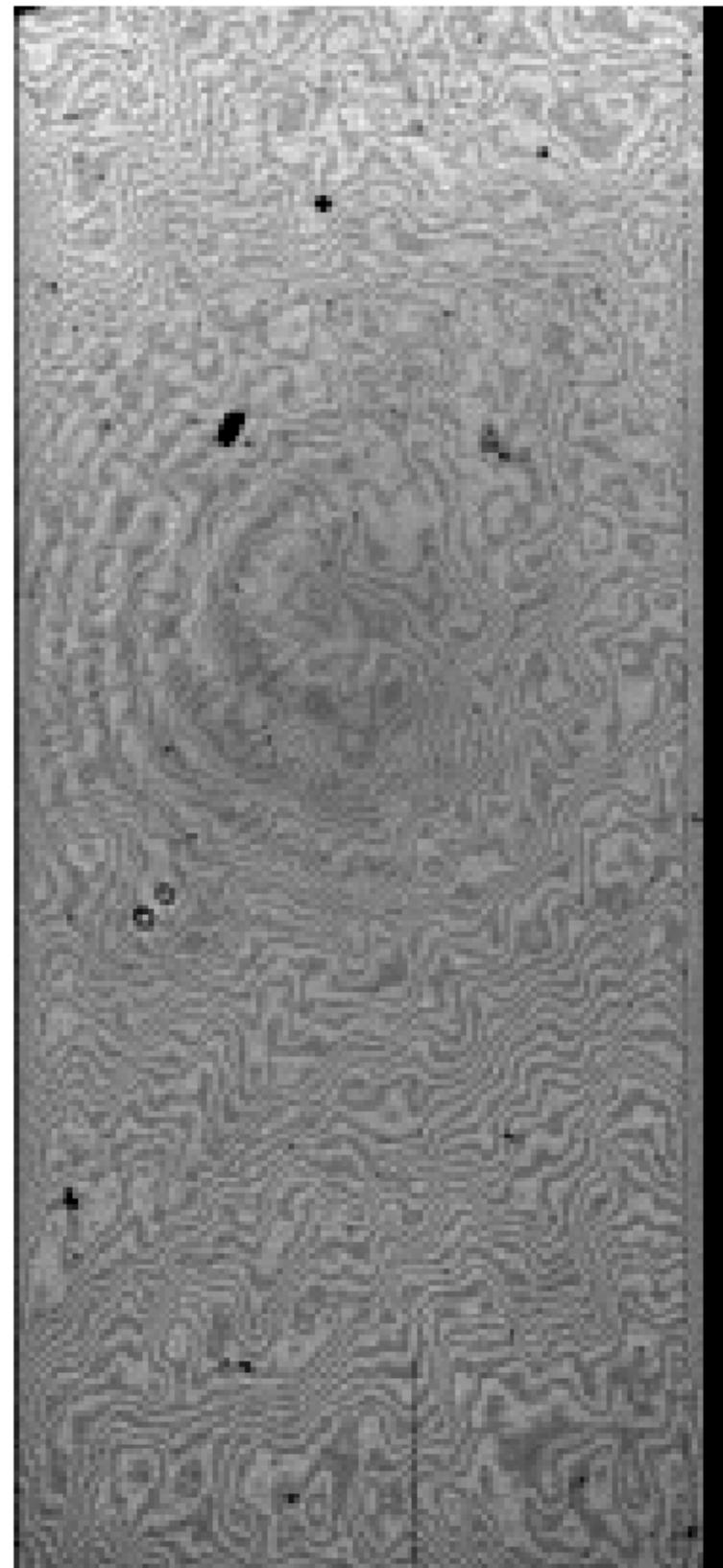
- **Non-linearity:** Even before saturation, response will typically become non-linear.
 - e.g., can be measured from dome-flats with different exposure



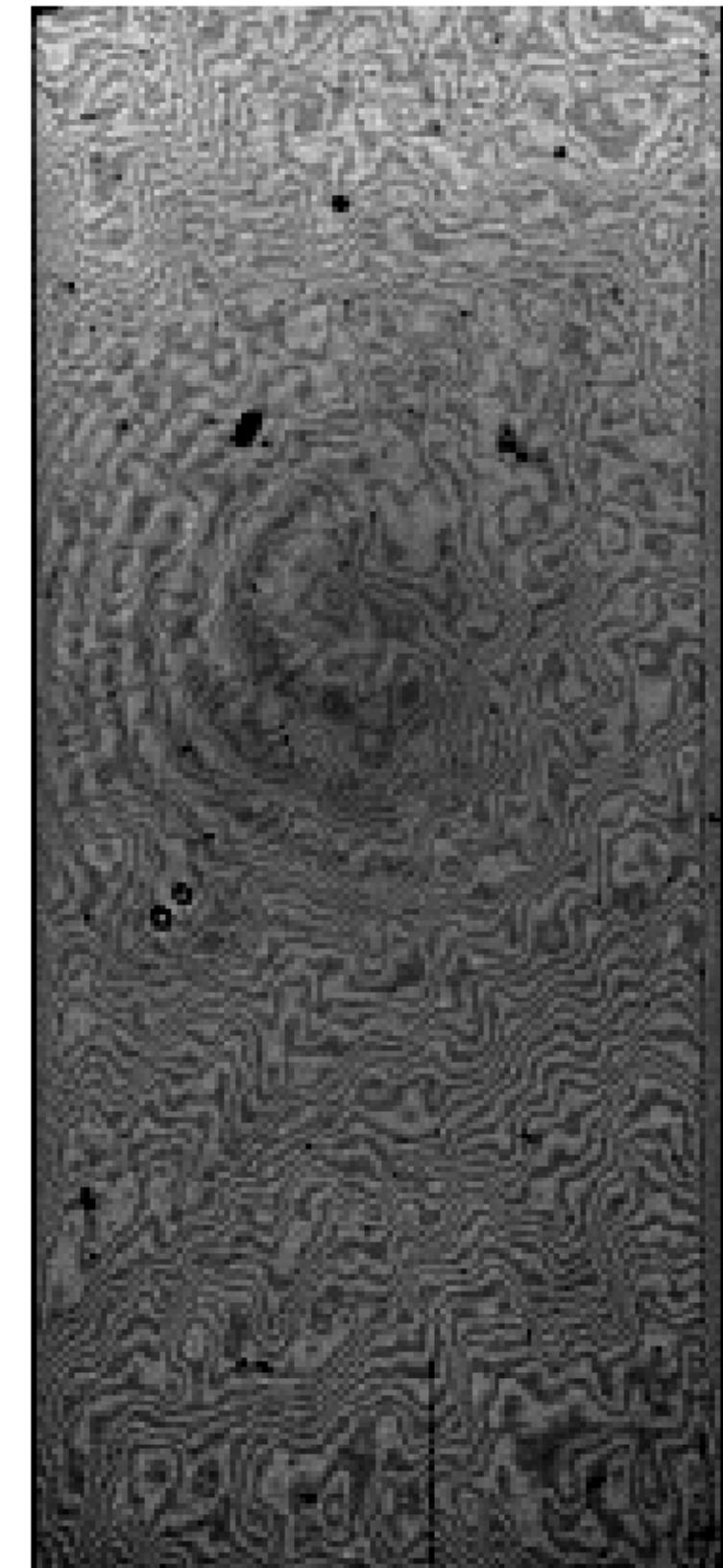
CCD Artifacts: “Fringing”

- CCDs can have “**fringing**” from coherent interference of the light incident on the Silicon
 - Due to reflections off of air/wafer boundary, which causes either constructive or destructive interference of the light
 - More likely to be noticeable as wafer thickness gets closer to observing wavelength
 - Necessarily depends on the wavelength (so will change across the band)

Fringing due to multiply-reflected light (uniform illumination, 10–20 μm thick CCD)



$$\lambda = 800 \text{ nm}$$



$$900 \text{ nm}$$

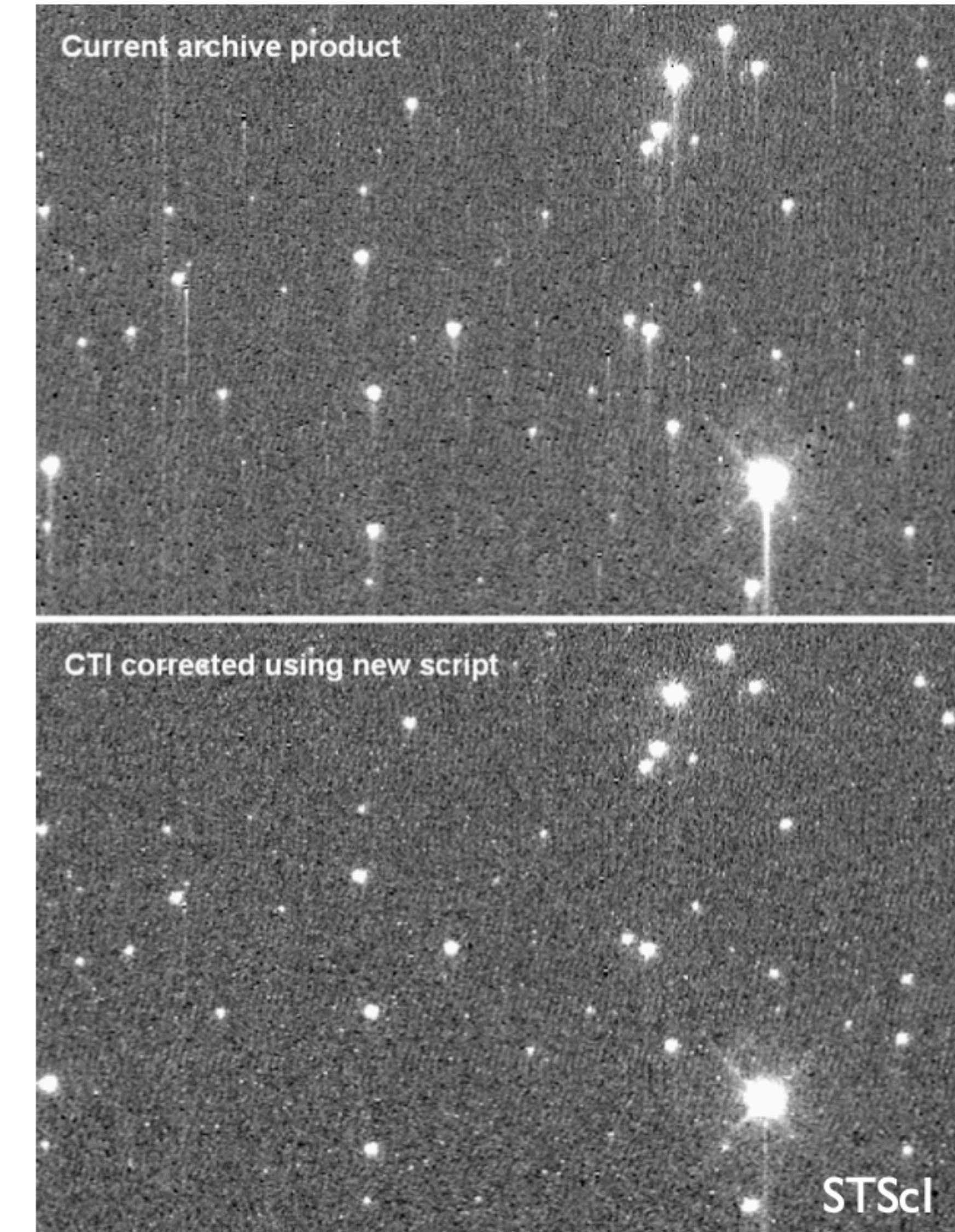


$$1 \mu\text{m}$$

Measurements courtesy of R. Stover, M. Wei of Lick Observatory

CCD Artifacts: Charge Transfer Efficiency

- **Charge Transfer Inefficiency (CTI):** Not all electrons are transferred from one pixel to the next during readout
- Charge Transfer Efficiency (CTE): Fraction of photons that are transferred.
- CTI is a significant issue with Hubble Space Telescope (HST) due to radiation damage



FITS Files

What format do you get the images in?

- FITS: Flexible Image Transport System
- Open standard for astronomical images
- Two parts:
 - **Image:** Binary format, integer or float
 - **ASCII header** with information about image.
- Can have multiple extensions (images)

FITS Files: Headers

Mandatory Structure:

Table 5.1: Mandatory keywords for primary header.

- 1 `SIMPLE`
- 2 `BITPIX`
- 3 `NAXIS`
- 4 `NAXISn, n = 1, ..., NAXIS`

(other keywords)

last `END`

Conforms to standard:
T(true) / F(false)

Bits per pixel:
16: integer
32: float

Number of axes:
2d image: `NAXIS=2`

Image dimensions

End of header

FITS Files: Example Header

X,Y size
of image



Observatory
information
(e.g., Lat/Long
of Stone Edge)



What RA/Dec did
You observe?



```
M31_g-band_30s_bin2_2021-10-26_seo_berthoud_RAW.fits

SIMPLE = T / file does conform to FITS standard
BITPIX = 16 / number of bits per data pixel
NAXIS = 2 / number of data axes
NAXIS1 = 2056 / length of data axis 1
NAXIS2 = 2048 / length of data axis 2
BZERO = 32768 / offset data range to that of unsigned short
BSCALE = 1 / default scaling factor
DEWTEM1 = -0.1 / dewar temperature (C)
DETECTOR= 'gsense4040'
GAIN = 0.86 / e-/ADU
DARKTIME= 45 / time since last read (seconds)
XBIN = 2
YBIN = 2
PIXSIZE1= 9 / pixel size for axis 1 (microns)
PIXSIZE2= 9 / pixel size for axis 2 (microns)
OBSERVAT= 'StoneEdge'
TELESCOP= '0.5meter'
OBSLONG = -122.504 / east longitude in degrees
OBSLAT = 38.2887 / latitude in degrees
ELEVATIO= 60 / elevation in meters
TELSCALE= 51.6 / arc-seconds/mm
ROTATOR = 179.8 / degrees
OBSERVER= 'sirius '
RA = '00:42:47.63'
DEC = '41:16:48.28'
EQUINOX = 2000
OVER = F
```

FITS Files: Example Header

Airmass →

AIRMASS =	1.06 / secant z
DOMEAZ =	88.3 / degrees
TRAKHA =	15.041 / arc-sec/second
TRAKDEC =	0 / arc-sec/second
TELFOCUS=	3967 / mm
AMBIENT =	11.9 / Lower truss North (C)
PRIMARY =	13.4 / Primary mirror cell (C)
SECONDAR=	11.6 / Outside ring (C)
CLOUD =	-0.97 / cloud coverage (0-1)
FILTER = 'g-band'	
SLIT = 'open'	
MIRROR = 'open'	
CRPIX1 =	1028
CRPIX2 =	1024
CTYPE1 = 'RA---TAN'	
CTYPE2 = 'DEC--TAN'	
CRVAL1 =	10.698458
CRVAL2 =	41.280078
WCSDIM =	2
CD1_1 =	-0.0002579484
CD1_2 =	9.004135E-07
CD2_2 =	-0.0002579484
CD2_1 =	-9.004135E-07
EXPTIME =	30 / exposure time (seconds)
SHUTTER = 'open'	/ camera shutter
TIMESYS = 'UTC approximate'	
DATE-OBS= '2021-10-26T04:57:30'	
UT = '04:57:30'	/ shutter opening time
MJD-OBS = 59513.20659722	/ MJD of observation start
MJDHDR = 59513.20697979	/ MJD of header creation
LSTHDR = '23:06:39'	/ LST of header creation
IMAGETYP= 'OBJECT'	
END	

Exposure time →

UTC and MJD during observations →

FITS Files: Specifying Coordinates

The astrometric information in FITS images (also referred to as the WCS) is stored in the header using a standard set of keywords. The reference location is defined by the following keywords:

- CRVAL1: defines the right (α) ascension of the reference pixel
- CRVAL2: defines the declination (δ) of the reference pixel
- CRPIX1: the x location of the reference pixel
- CRPIX2: the y location of the reference pixel

The plate scale and rotation of the image is contained in the CD MATRIX (CD?_? keywords).

- CD1_1 is the partial of first axis coordinate w.r.t. x
- CD1_2 is the partial of first axis coordinate w.r.t. y
- CD2_1 is the partial of second axis coordinate w.r.t. x
- CD2_2 is the partial of second axis coordinate w.r.t. y

$$\begin{pmatrix} CD1_1 & CD1_2 \\ CD2_1 & CD2_2 \end{pmatrix} = scale * \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix}$$

FITS Files: Specifying Coordinates

$$\begin{pmatrix} CD1_1 & CD1_2 \\ CD2_1 & CD2_2 \end{pmatrix} = scale * \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix}$$

Thus, to go from image coordinates (x,y) to sky coordinates (α, δ) :

$$\begin{pmatrix} \alpha - CRVAL1 \\ \delta - CRVAL2 \end{pmatrix} = \begin{pmatrix} CD1_1 & CD1_2 \\ CD2_1 & CD2_2 \end{pmatrix} \begin{pmatrix} x - CRPIX1 \\ y - CRPIX2 \end{pmatrix}$$

FITS Files: Specifying Coordinates

WCS coordinates nominally specified in the header, populated during initial data reduction step for the fits file.

However, you might find that this could be improved, via a program like *astrometry.net* (see wiki under Computing Resources)

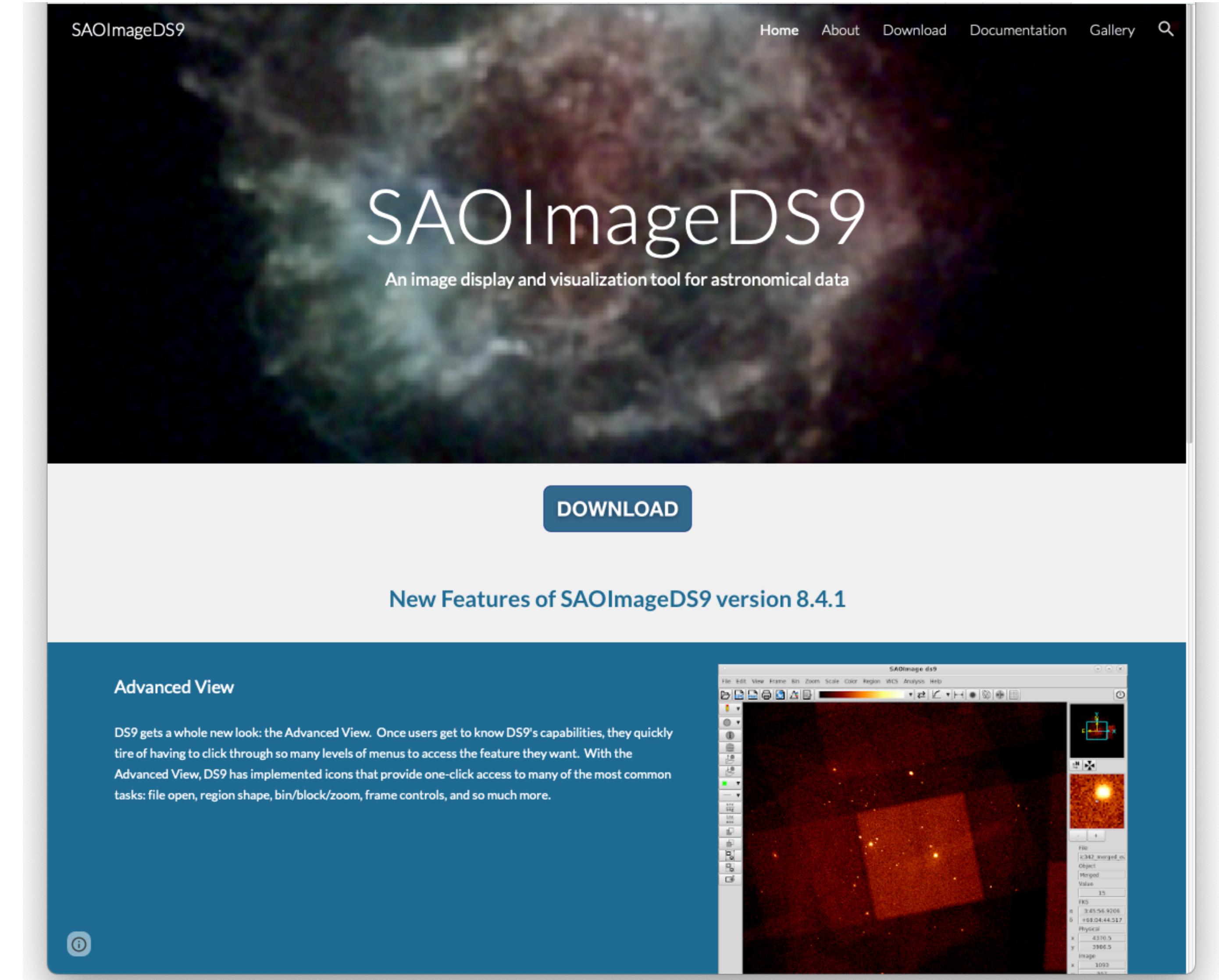
```
CRPIX1 = 1028
CRPIX2 = 1024
CTYPE1 = 'RA---TAN'
CTYPE2 = 'DEC--TAN'
CRVAL1 = 10.698458
CRVAL2 = 41.280078
WCSDIM = 2
CD1_1 = -0.0002579484
CD1_2 = 9.004135E-07
CD2_2 = -0.0002579484
CD2_1 = -9.004135E-07
EXPTIME = 30 / /
```

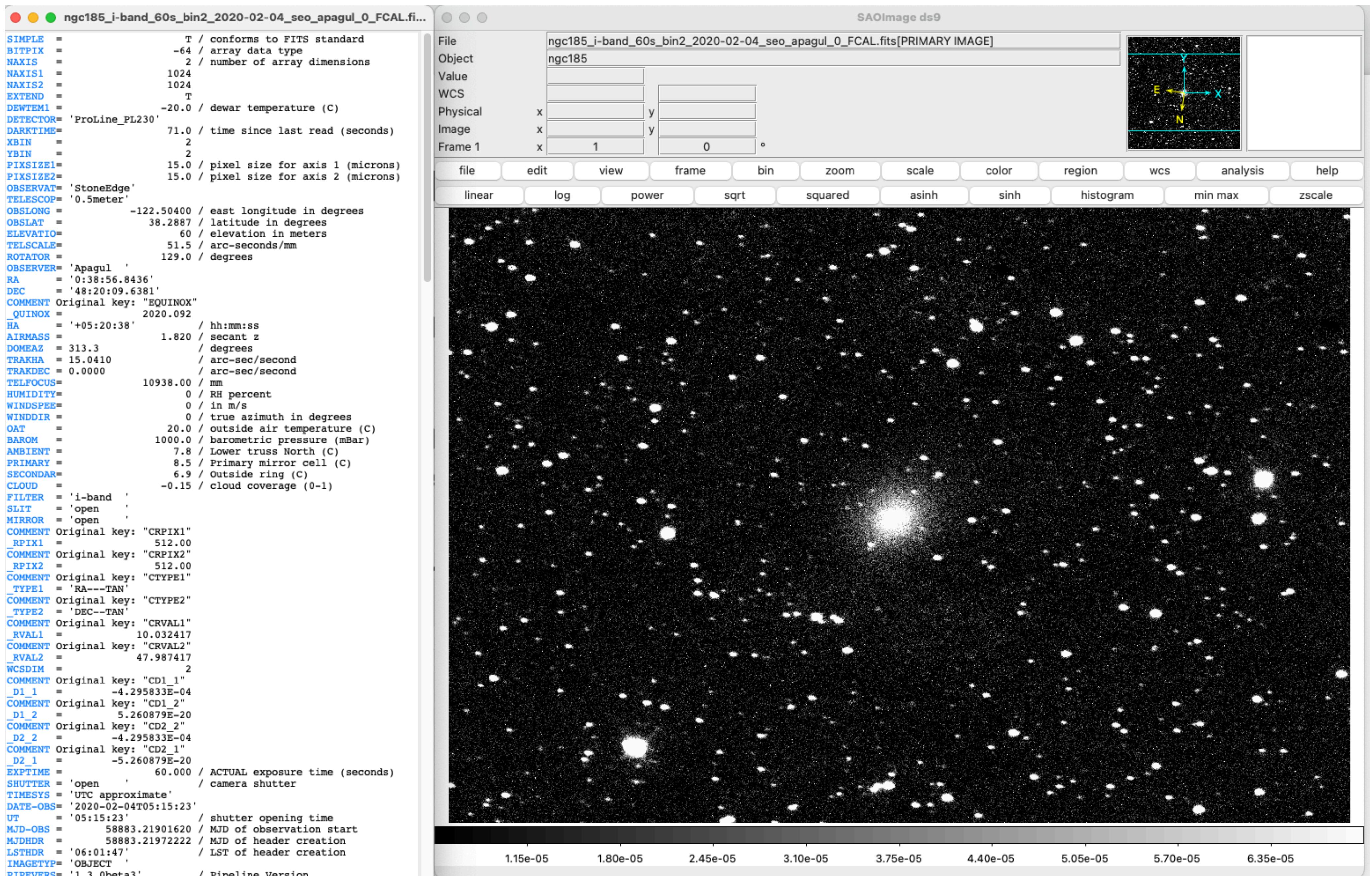
Thus, to go from image coordinates (x,y) to sky coordinates (α, δ) :

$$\begin{pmatrix} \alpha - \text{CRVAL1} \\ \delta - \text{CRVAL2} \end{pmatrix} = \begin{pmatrix} \text{CD1_1} & \text{CD1_2} \\ \text{CD2_1} & \text{CD2_2} \end{pmatrix} \begin{pmatrix} x - \text{CRPIX1} \\ y - \text{CRPIX2} \end{pmatrix}$$

Viewing FITS Images

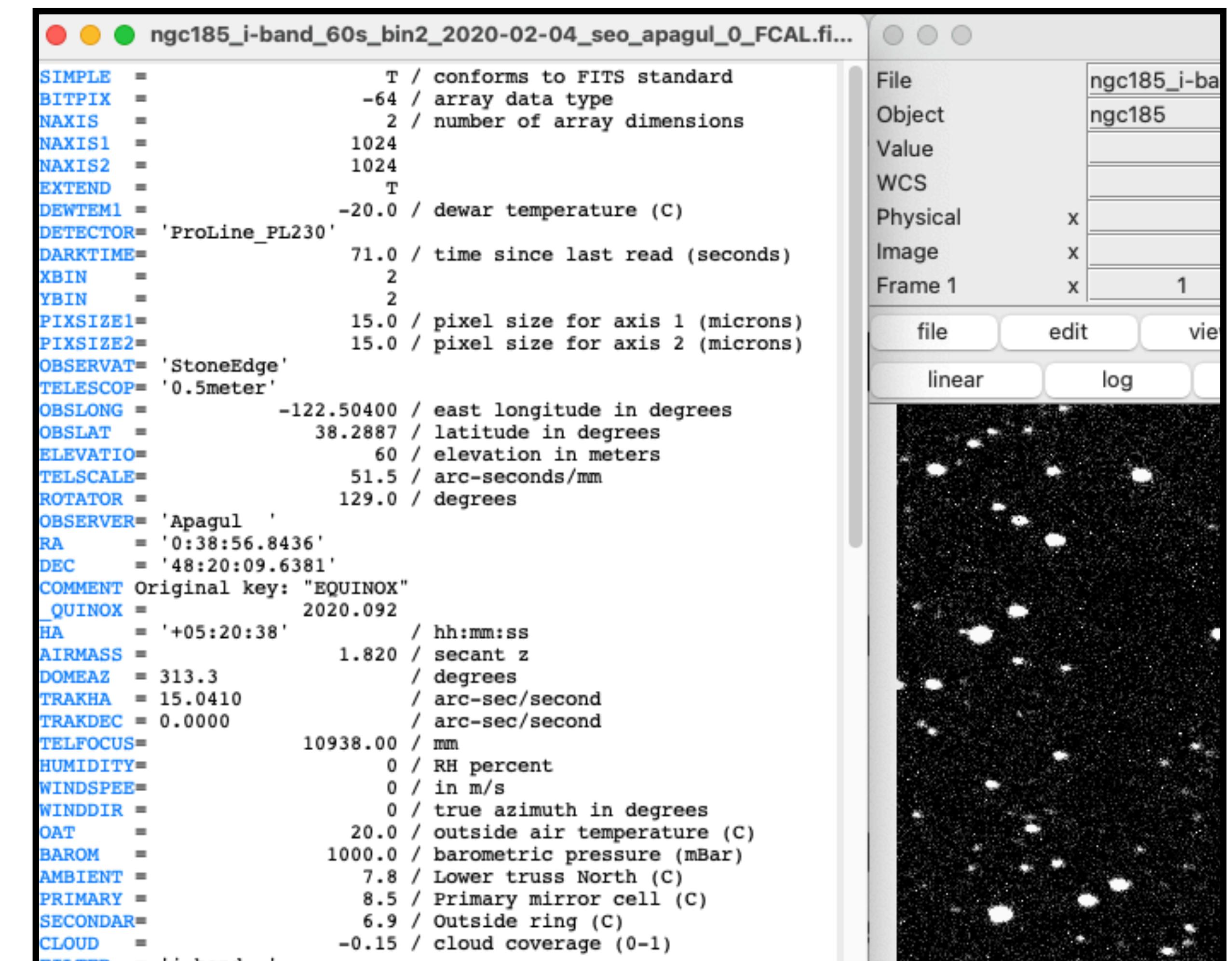
- Easiest done with specialize software
- Most common is **ds9**
 - <https://sites.google.com/cfa.harvard.edu/saoimageds9>
 - Also common to read fits files using most programming languages (e.g., python), and use standard astro packages for analyses (e.g., astropy)





Viewing FITS Headers

- Ds9: In File -> Header
- Python (see tutorial on wiki)
 - R, C, IDL, .. all have
- Command-line tools in Unix,
e.g., fits, fitsort.



Viewing FITS Headers

- Ds9: In File -> Header
- **Python (see tutorial on wiki)**
 - R, C, IDL, .. all have
- Command-line tools in Unix,
e.g., fits, fitsort.

The screenshot shows a GitHub repository page for 'bradfordbenson / ASTR21200_2023'. The repository is public and has 2 watches, 0 forks, and 0 stars. The 'Code' tab is selected, showing the file 'ASTR21200_2023 / Tutorials / FITS images in python.ipynb'. The notebook title is 'FITS images in python; image statistics and plots'. It describes reading a FITS image into a numpy array, plotting a histogram of measured count values, and determining basic statistics. The code in the first cell imports numpy, matplotlib, astropy.io.fits, and scipy.stats, and opens a FITS file named '00000026.BIAS.FIT'.

```
### for array operations
import numpy as np

### for plotting
import matplotlib
matplotlib.use('TkAgg')
import matplotlib.pyplot as plt
%matplotlib inline

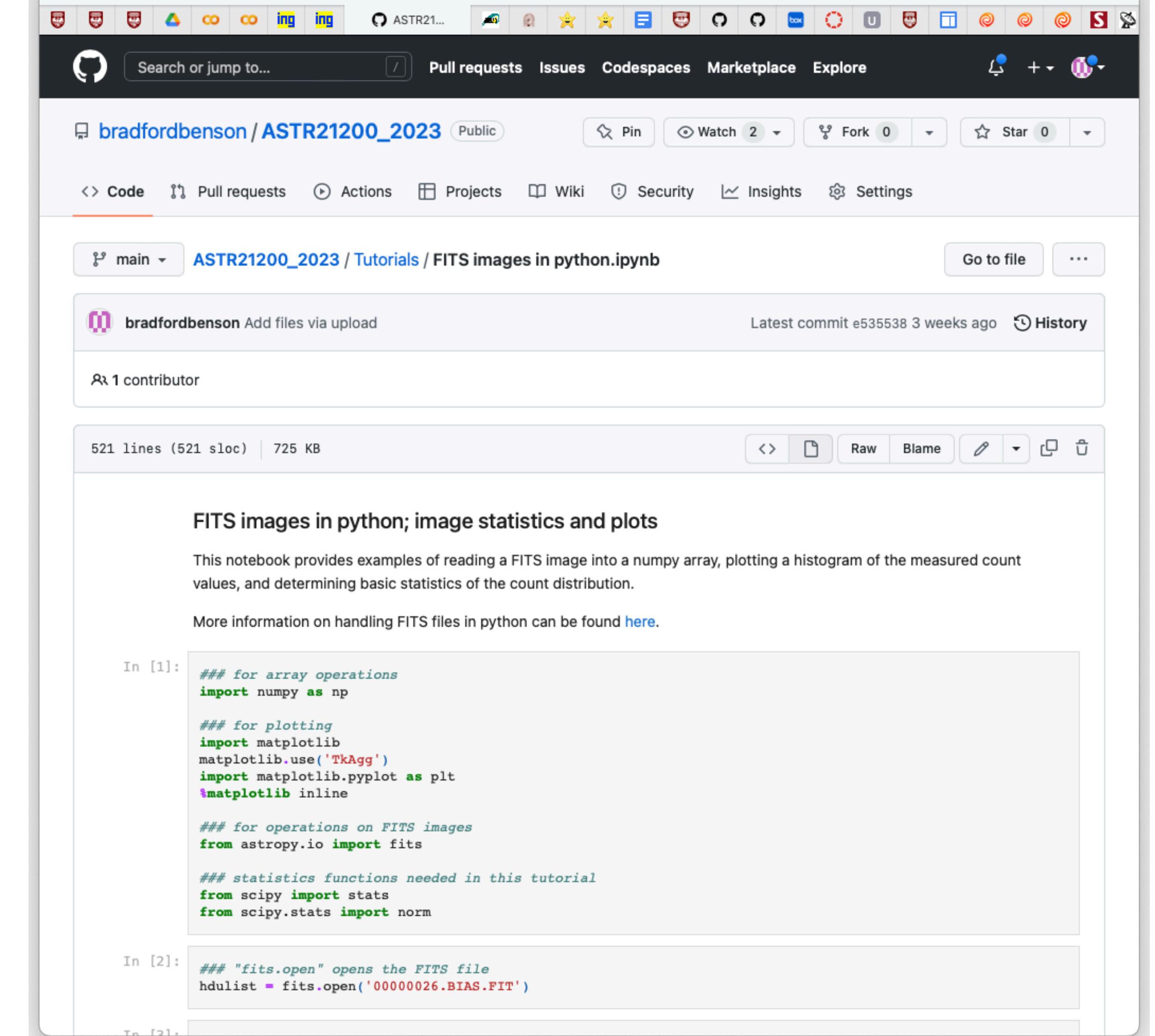
### for operations on FITS images
from astropy.io import fits

### statistics functions needed in this tutorial
from scipy import stats
from scipy.stats import norm

### "fits.open" opens the FITS file
hdulist = fits.open('00000026.BIAS.FIT')
```

FITS Image Manipulation (Math)

- **Python (see tutorial on wiki)**
 - Reading in FITS file, numpy, plotting, histograms, etc.
- R: FITSio package
- Matlab: Fitsread, etc.
- C: cfitsio library
- IDL: readfits.pro



The screenshot shows a GitHub repository page for `bradfordbenson / ASTR21200_2023`. The repository has 2 watches, 0 forks, and 0 stars. The main branch is `main`, and the notebook `ASTR21200_2023 / Tutorials / FITS images in python.ipynb` is selected. The notebook title is `FITS images in python; image statistics and plots`. It describes examples of reading a FITS image into a numpy array, plotting a histogram of the measured count values, and determining basic statistics of the count distribution. A note says more information on handling FITS files in python can be found [here](#). The code in the notebook includes imports for numpy, matplotlib, astropy.io.fits, scipy.stats, and norm, along with specific operations like `matplotlib.use('TkAgg')` and `*matplotlib inline`.

```
In [1]:  
### for array operations  
import numpy as np  
  
### for plotting  
import matplotlib  
matplotlib.use('TkAgg')  
import matplotlib.pyplot as plt  
%matplotlib inline  
  
### for operations on FITS images  
from astropy.io import fits  
  
### statistics functions needed in this tutorial  
from scipy import stats  
from scipy.stats import norm  
  
In [2]:  
### "fits.open" opens the FITS file  
hdulist = fits.open('00000026.BIAS.FIT')
```

Python Tutorials

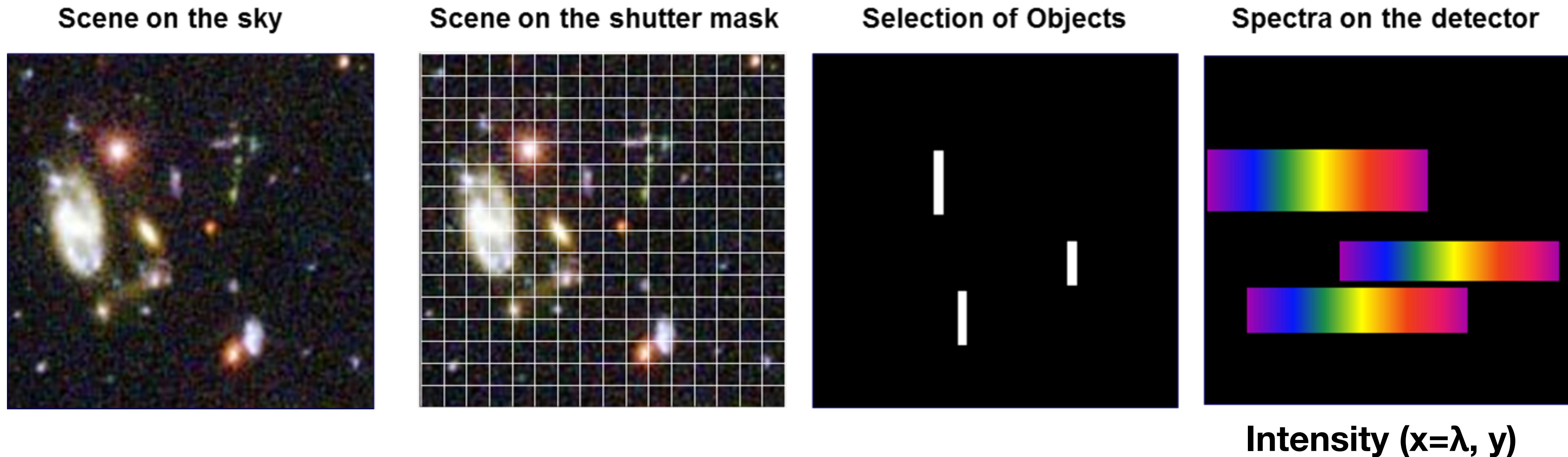
- Tutorials are in Jupyter Notebook format
- On your laptop:
 - If you installed python through “anaconda” on your labor, jupyter is included
 - If python is not on your laptop, try google collab
 - See more discussion / instructions on the wiki under Python, Jupyter in the sidebar, or the Tutorials

The image shows a GitHub repository interface with three main sections highlighted:

- Schedule Spring 2024:** A table showing weekly topics, lectures, homework/lab assignments, and tutorials. The "Tutorial" column contains links to Jupyter notebooks. A red circle highlights the "Tutorial" column.
- Jupyter:** A page describing Jupyter notebooks and their benefits. It includes a link to the Anaconda documentation for installation.
- Python:** A page providing an introduction to Python, details about its execution mode (shell vs. script), and a list of computing resources. Two specific items in the "Computing Resources" sidebar are circled in red: "Jupyter" and "Python".

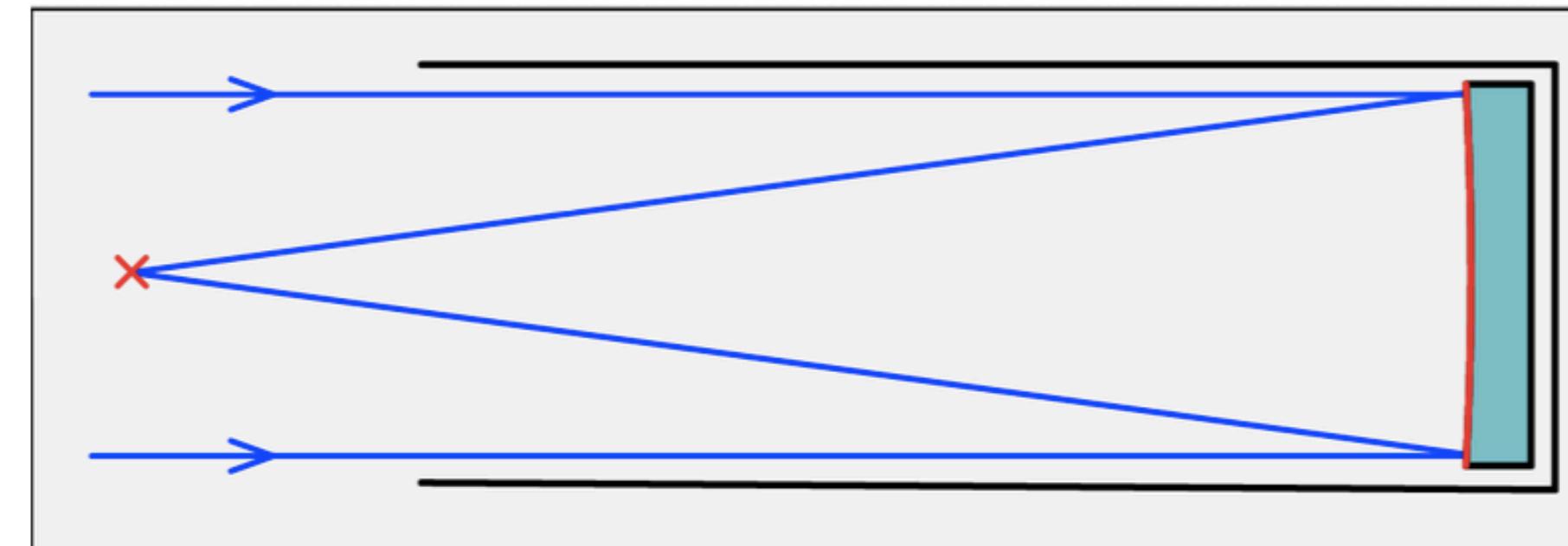
Slits and Spectroscopy

- Introduce a “slit” mask at the focal plane (in front of camera) that only accepts light from objects that you want to measure spectra for
 - For multi-slit spectroscopy requires a round of pre-imaging, so that you can physically make a mask appropriate for your field

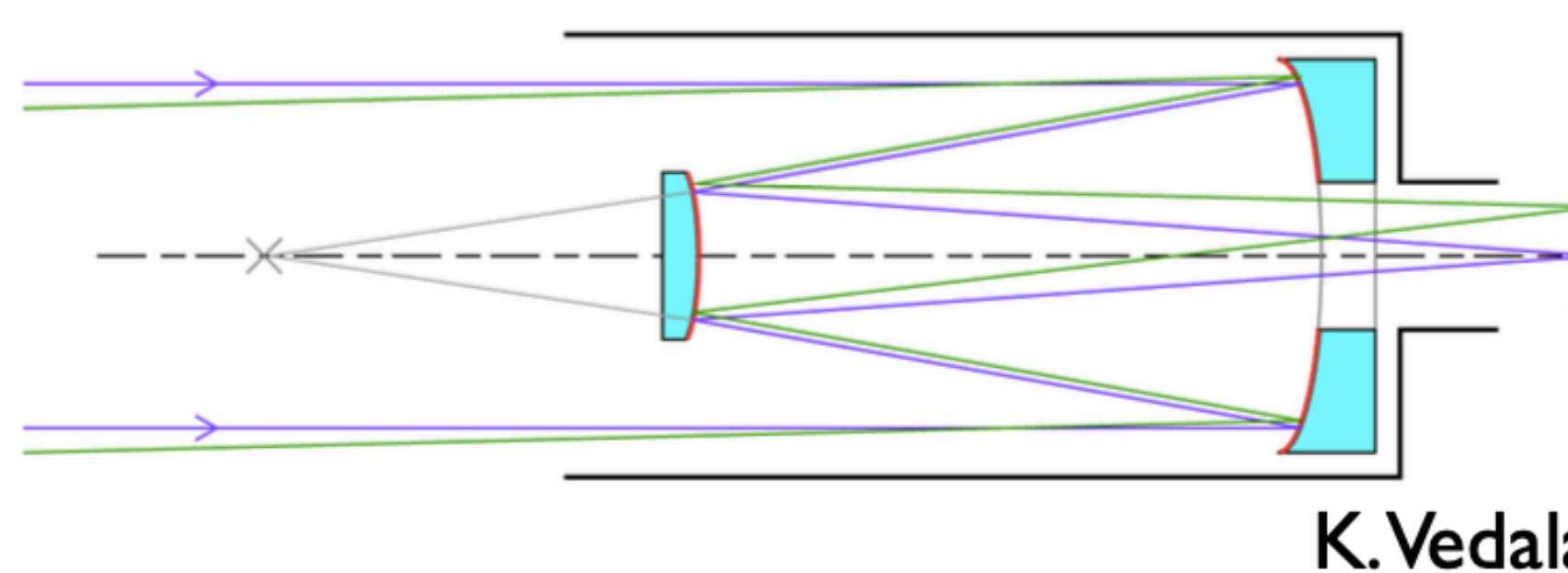


Telescope Foci

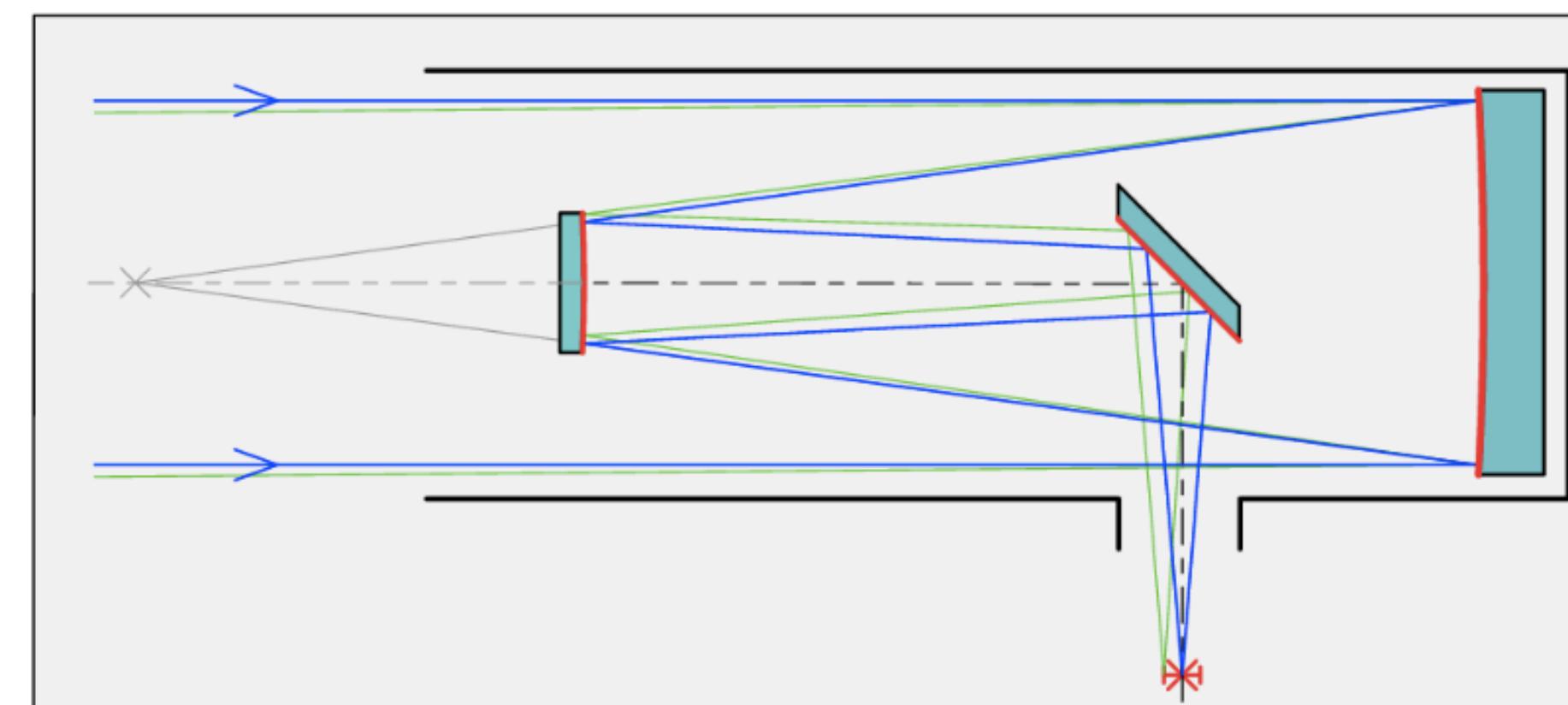
- prime focus: focus of primary mirror



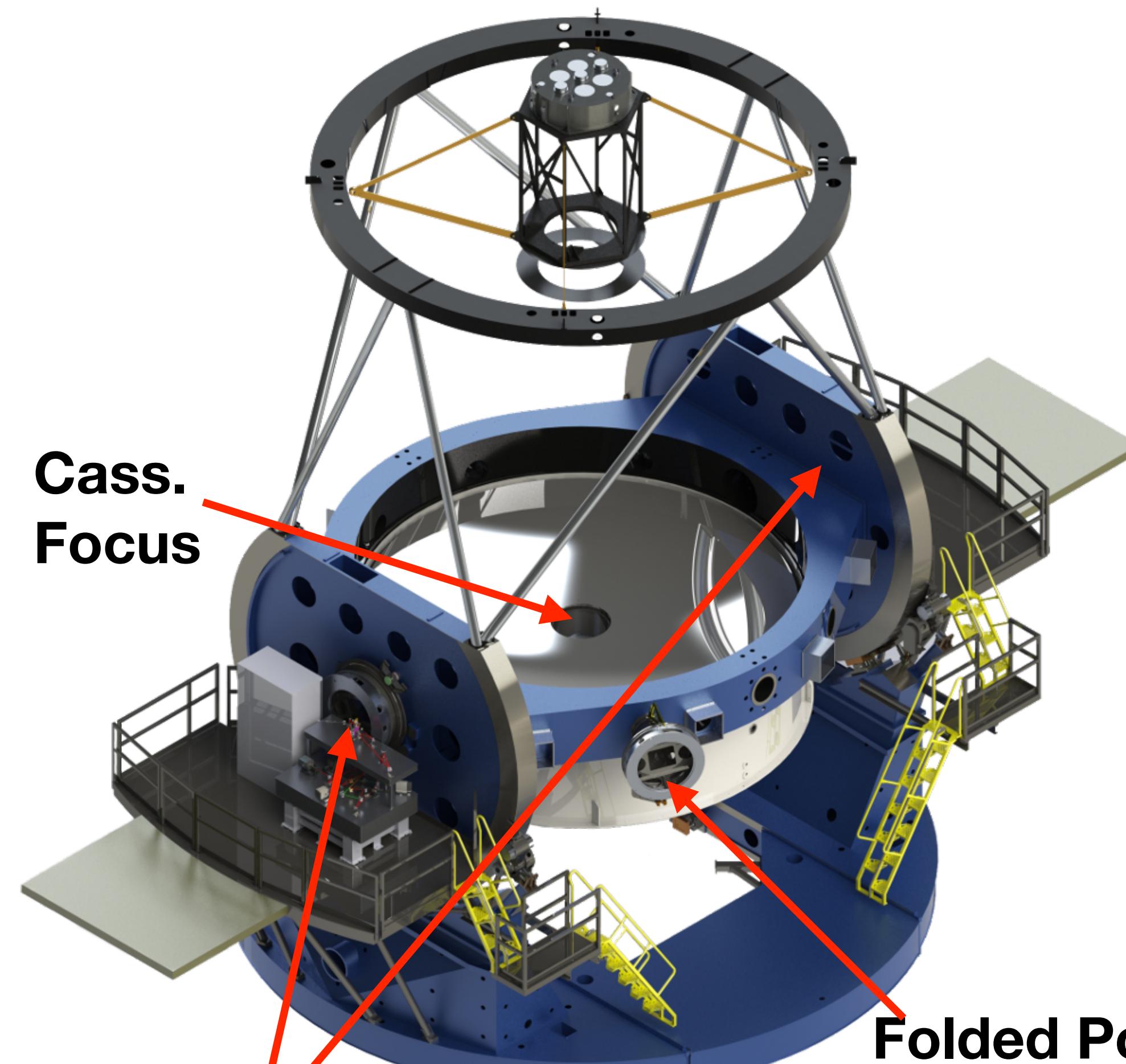
- Cassegrain focus: secondary mirror in front of prime focus; secondary focus behind primary mirror



- Nasmyth focus: pick-up mirror, can be placed through mount axis



Magellan Instruments:



Cass.
Focus

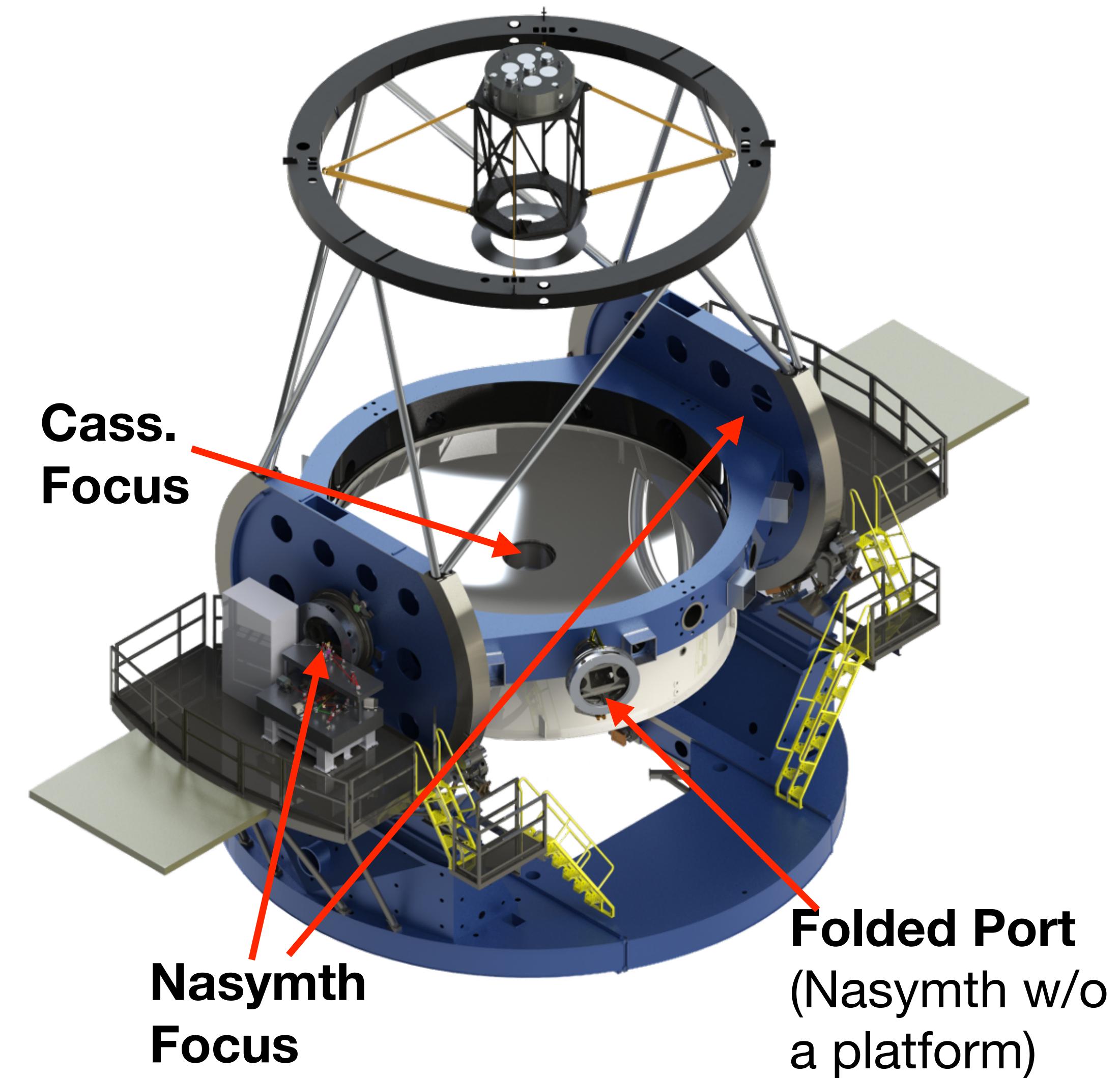
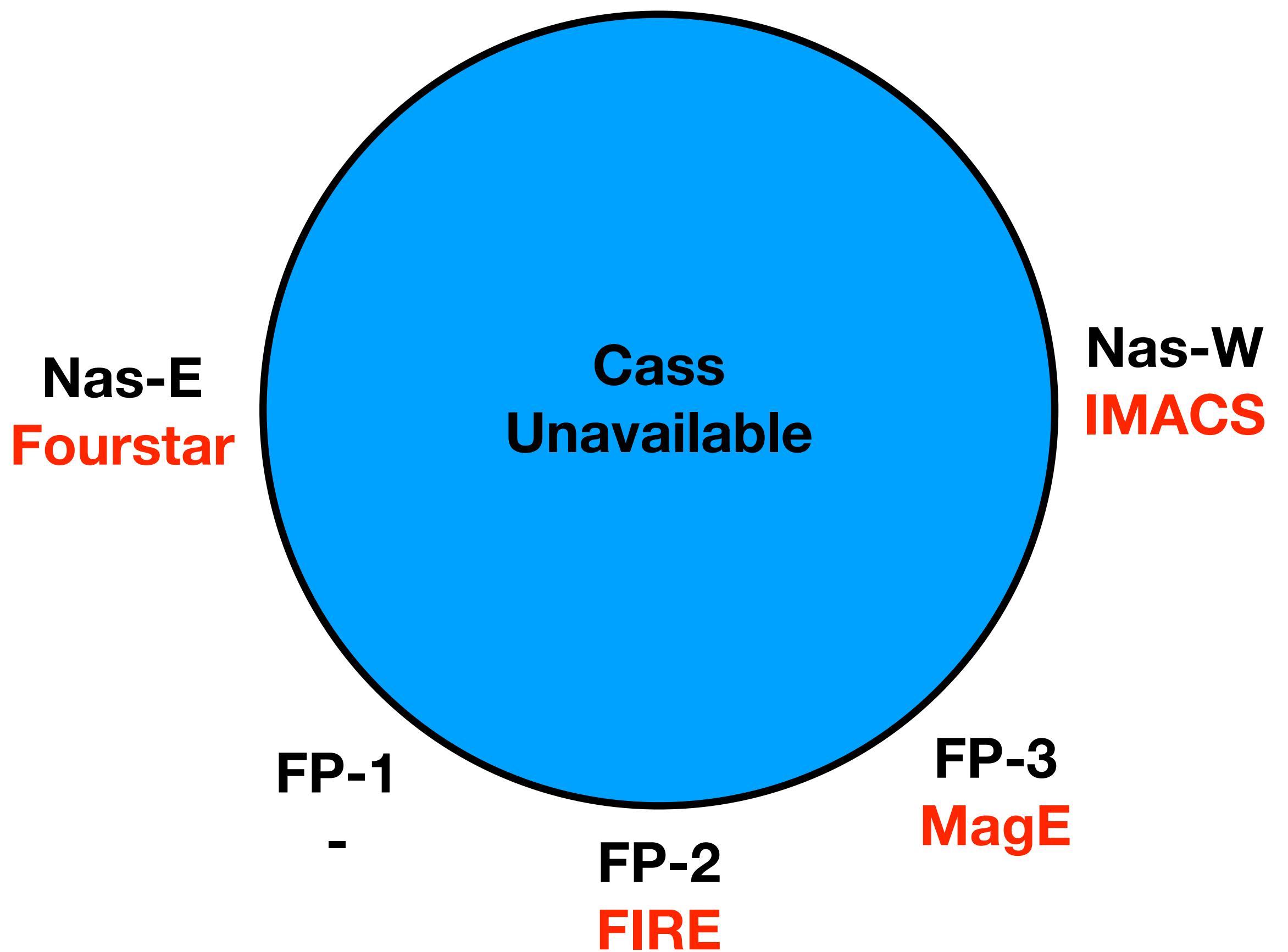
Nasymth
Focus

Folded Port
(Nasymth w/o
a platform)

Magellan Instruments: Baade Telescope

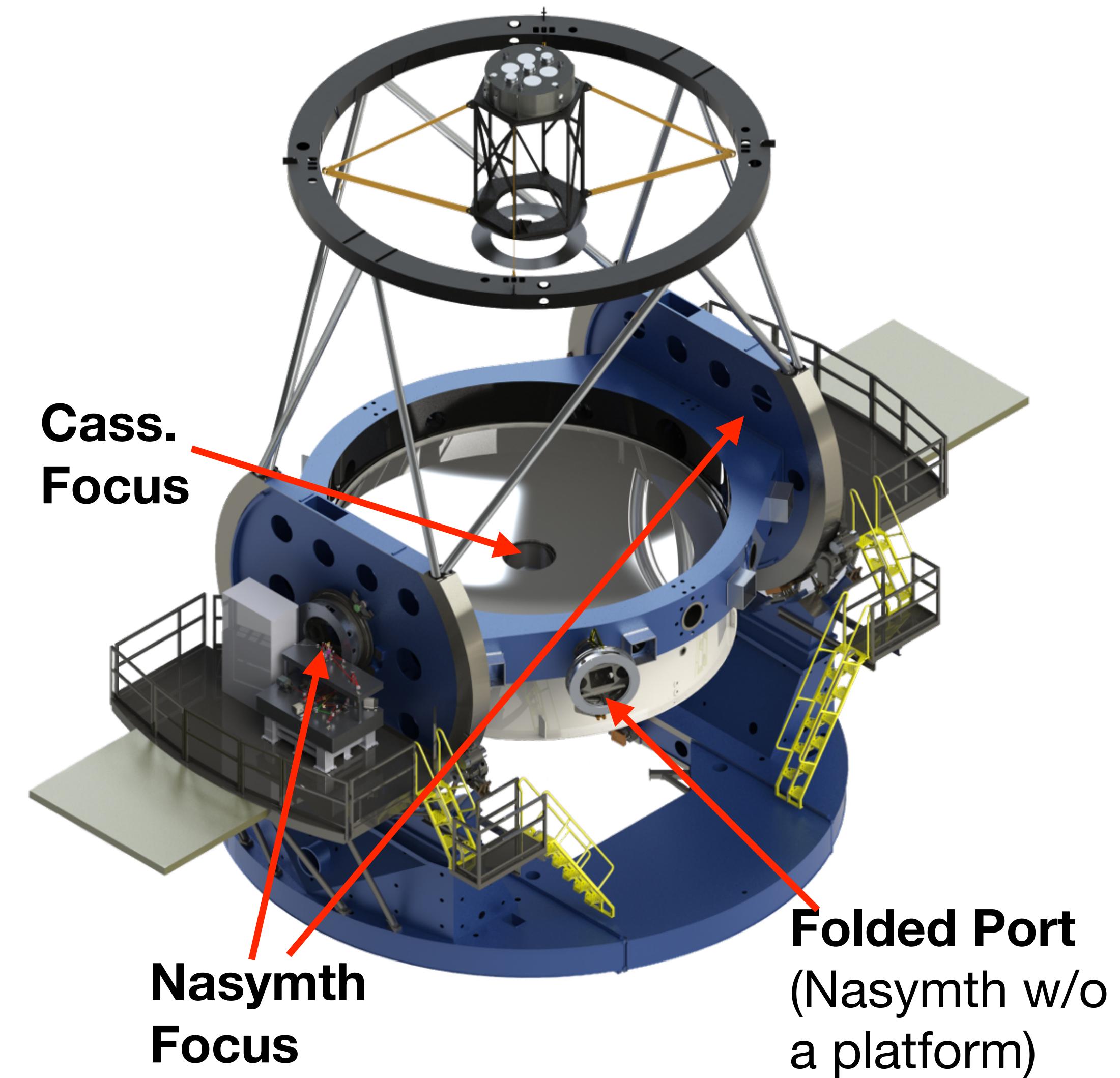
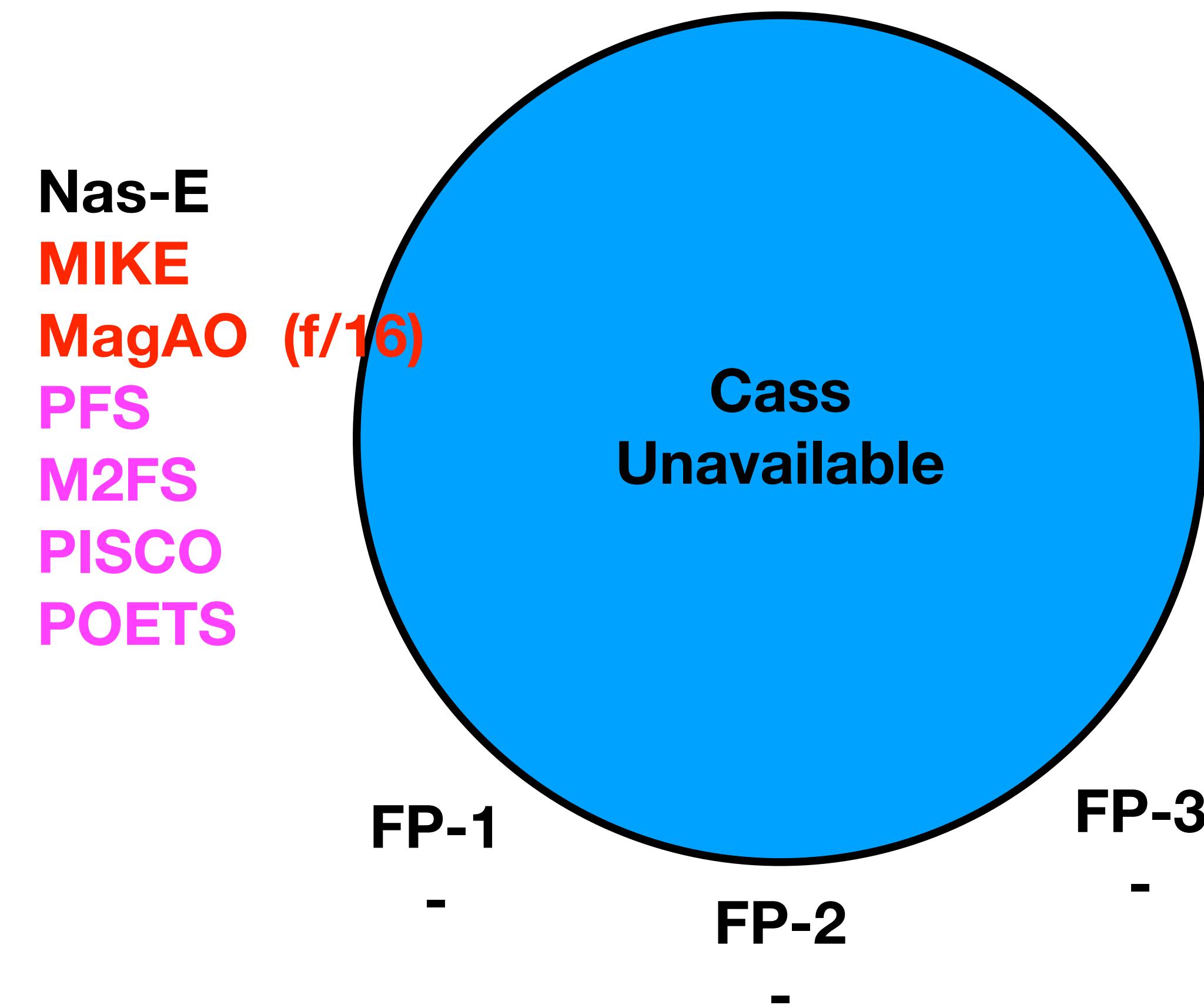
Facility Instruments in **Red**

PI Instruments in **Purple**



Magellan Instruments: Clay Telescope

Facility Instruments in **Red**
PI Instruments in **Purple**





- f/5 -

- **IMACS**: Extremely versatile wide-field (15-27 arcmin) imaging multi-object spectrograph.
- **FIRE**: Infrared echelle providing R~6,000 cross-dispersed spectra covering the entire near-IR.
- **FourStar**: a wide-field 11'x11' JHK imager using 4 Rockwell Hawaii II RG arrays
- **MagE**: an R~6,000 optical echelle spectrograph

- **Megacam**: 36 CCD mosaic camera FOV 25'x25'

- f/16 AO -

- **VisAO**: Adaptive Optics visible camera
- **CLIO2**: 1-5 micron near-IR imager, coronagraph, and spectrograph

- f/11 -

- **MIKE**: a high-throughput dual channel echelle spectrograph.
- **LDSS3**: imaging multi-object spectrograph

- f/11 PI -

- **PFS**: a high precision RV spectrograph.
- **M2FS**: a low/medium/high resolution fiber-fed multi-object spectrograph.
- **PISCO**: a simultaneous multi-band imager.
- **POETS**: a portable high speed imager.

Baade

2017 Instrument Suite

Clay

Magellan Instruments

- See: <https://www.lco.cl/magellan-instruments/>

Instrument suite:

Telescope	Instrument	Type	Wavelength	Wavelength range	FOV (arcmin)	R (for spectrographs)	Pixelscale, arcsec/pix
6.5-m Magellan Baade	IMACS	imager / multislit spectrograph	optical	365-1000 nm	14' or 24-27'	500 .. 20000	0.11 or 0.2
	FOURSTAR	imager	infrared	1000 - 2510 nm	10.8 x 10.8'	-	0.16
	FIRE	spectrograph	infrared	820 - 2510 nm	7" slit	500 .. 6000	0.18
	MAGE	spectrograph	optical	310 .. 1100 nm	10" slit	4000 .. 8000	0.3
6.5-m Magellan Clay	LDSS3	imager / multislit spectrograph	optical	360 .. 1100 nm	8.3' (diameter)	850 .. 1900	0.189
	MIKE	spectrograph	optical	320 .. 1000 nm	5" slit	22000 .. 83000	
	PFS	spectrograph	optical	388..668 nm	3.7" slit	38000 .. 127000	
	M2FS	double-arm fiber spectrograph	optical	370 .. 1050 nm	30'	1500 .. 34000	
	MEGACAM	imager	optical	350 .. 900 nm	25'	-	0.08
	VISAO	imager / Adaptive optics	optical	600 .. 1000 nm	8"x8"	-	0.008
	CLIO	imager / Adaptive optics	infrared	1000 .. 5300 nm	16" x 8" 28" x 14"	-	0.016 0.027

For Next Week

- Homework 1 is due on Tues Mar-26 at 5pm, right before class
 - On [class schedule on wiki](#):
 - Submit on [Canvas](#) (with hopefully right link)
- Office hours will start next week!
 - Dillon: Monday 4-6pm (ERC 583)
 - Rohan: Wednesday 3-5pm (ERC 583)
 - Brad: Thurs -12-1pm (ERC 589)
- Next Thursday's class:
 - Intro to SEO lecture co-taught by Amanda Pagul and Marc Berthoud
 - After class (TBC), Marc will be running through some remote SEO tutorials/ demos for those who are interested.

For Next ~1-Week

- Homework 2 is due on Tues Apr-2 at 5pm, right before class
 - On [class schedule on wiki](#):
 - Submit on [Canvas](#)
- Office started this week!
 - Dillon: Monday 4-6pm (ERC 583)
 - Rohan: Wednesday 3-5pm (ERC 583)
 - Brad: Thurs -12-1pm (ERC 589)
- This Thursday's class:
 - Intro to SEO lecture co-taught by Amanda Pagul and Marc Berthoud
- Next week Tuesday:
 - Labs start!

