ASTR21200

Observational Techniques in Astrophysics
Lecture 3

Bradford Benson

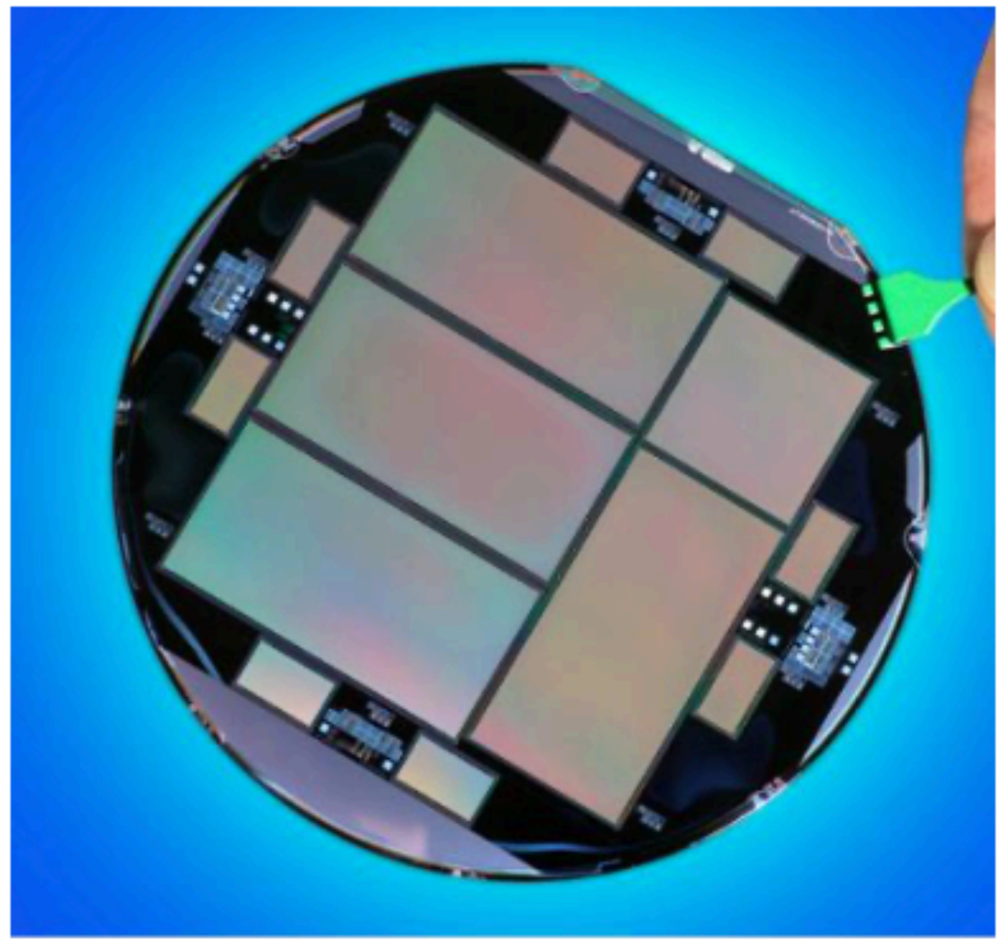
For the Next ~Week

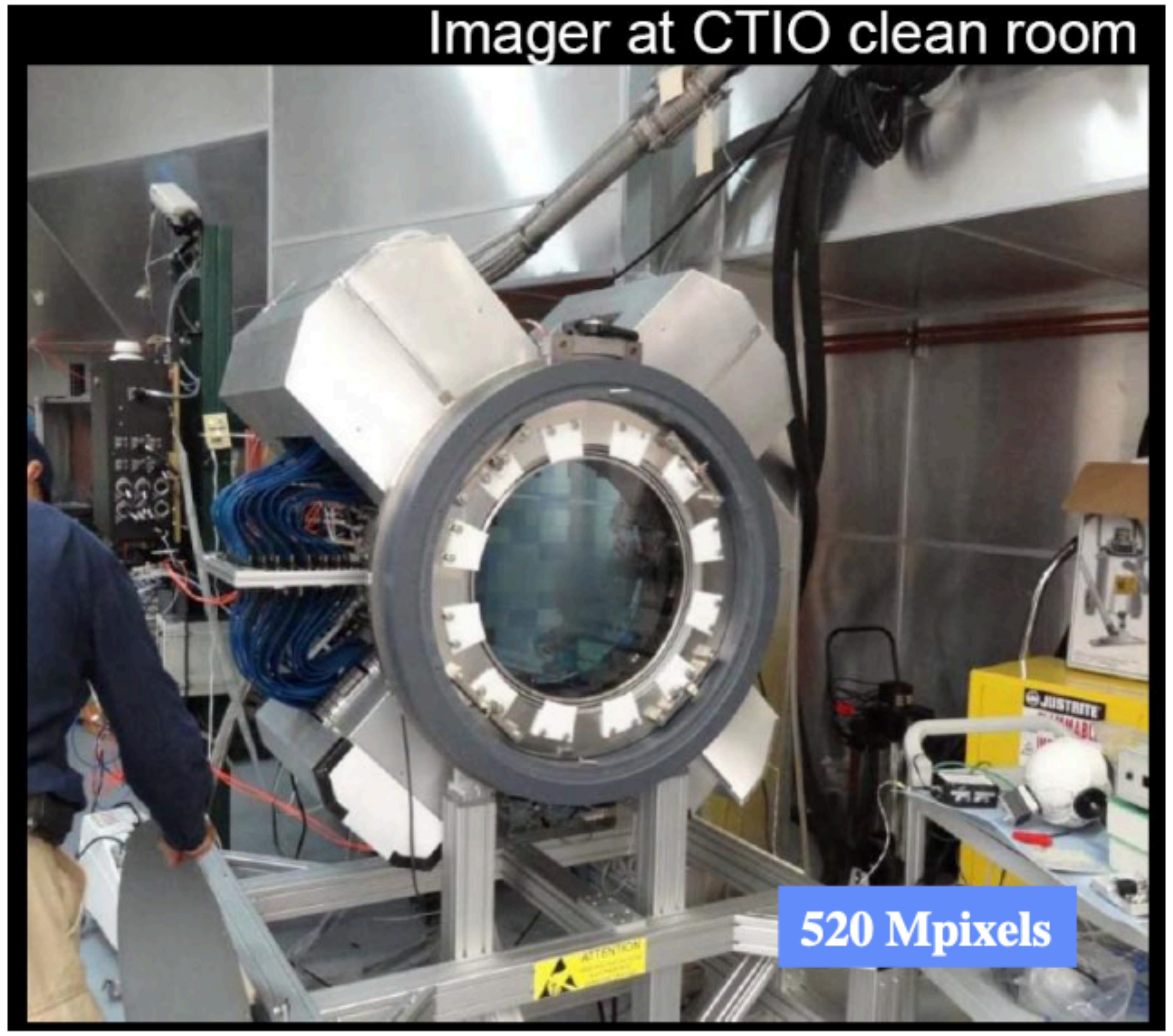
- Homework 2 is due on Tues Apr-8 at 5pm, right before class
    - On class schedule on wiki:
    - Submit on Canvas (with hopefully right link)
- Office hours will start tomorrow!
    - Logan: Friday 3:30-4:30pm (ERC 583)
    - Emory: Monday: 3-4pm (KPTC 320)
    - Brad: Tuesday: 11am-12 (ERC 589)
    - Marc: Tuesday: 3-4pm (ERC 524)
- This Thursday's class:
    - Intro to SEO lecture will be taught by Marc Berthoud
    - After class, Marc will be running through some remote SEO tutorials/demos for those who are interested.

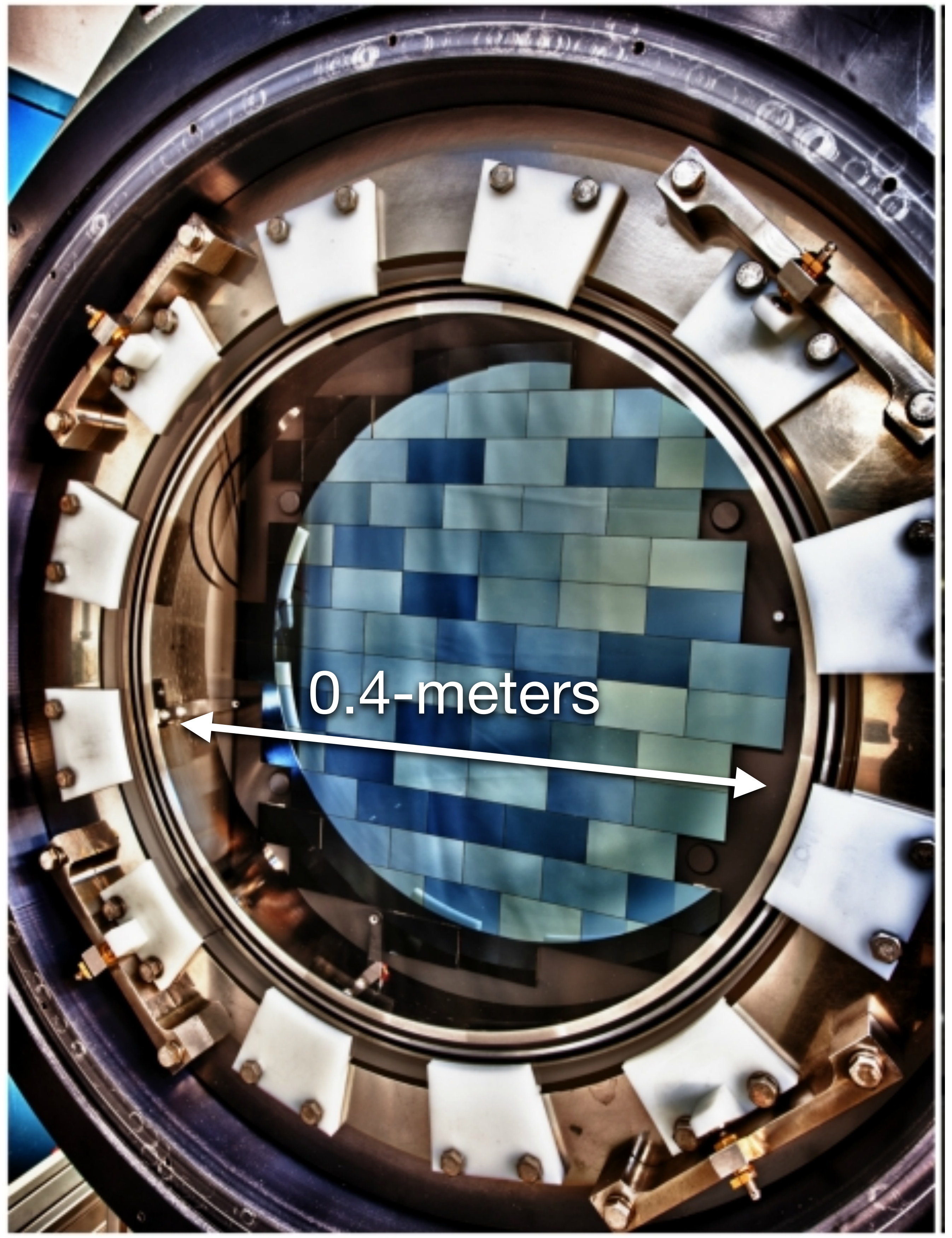
Charge Coupled Devices (CCDs)

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

72 CCD wafers
570 million pixels (Megapixels)







Dark Energy Survey Camera (DECam) – 62 2k x 4k, (15 μm)^2-pixel CCDs
NOAO Cerro Tololo Blanco 4-m Telescope (Fall 2012)

Charge Coupled Devices (CCDs)

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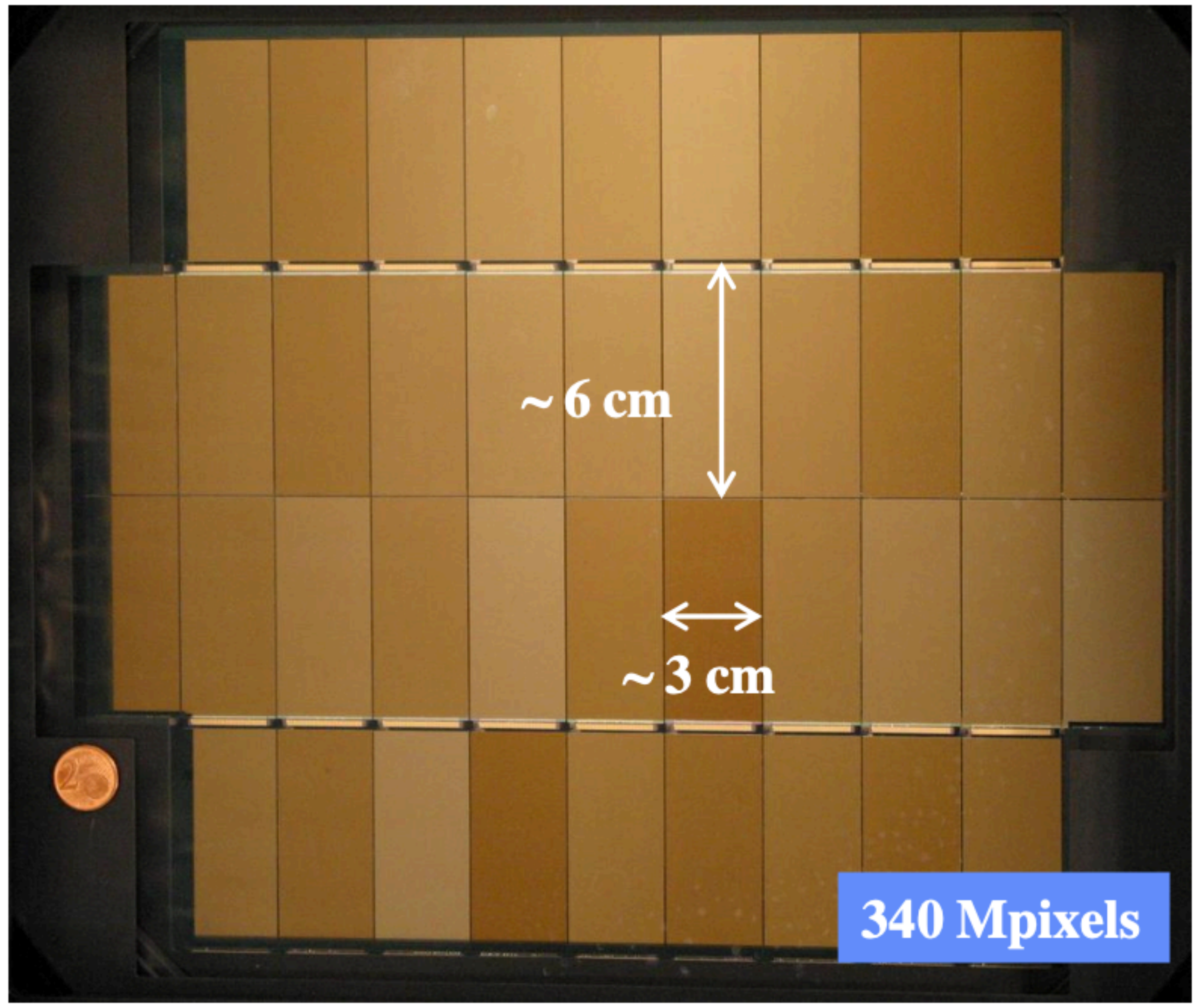
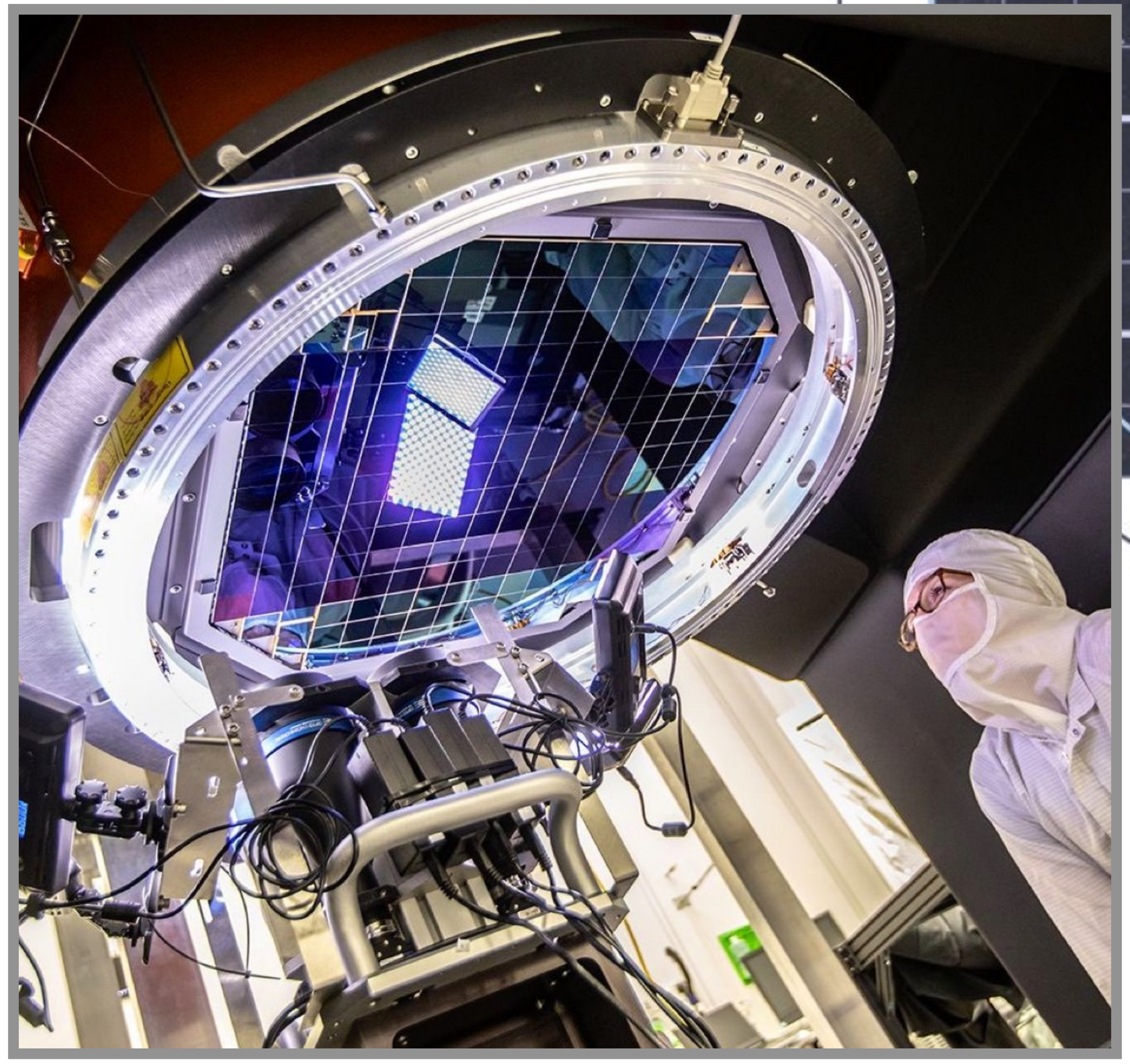
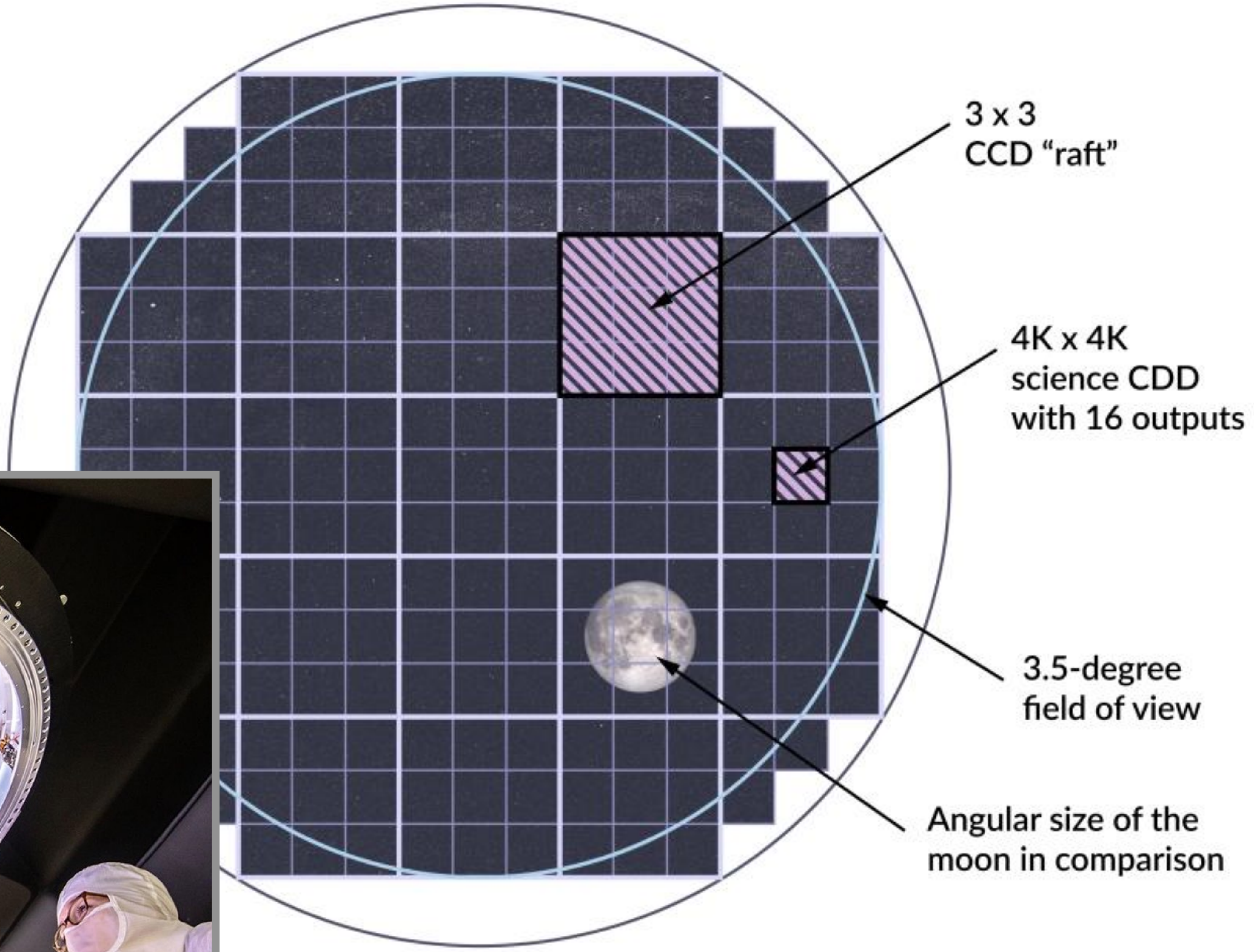
Magellan Clay Telescope



MegaCam – 36 2k x 4k, (15 µm)^2-pixel CCDs

LSST Camera

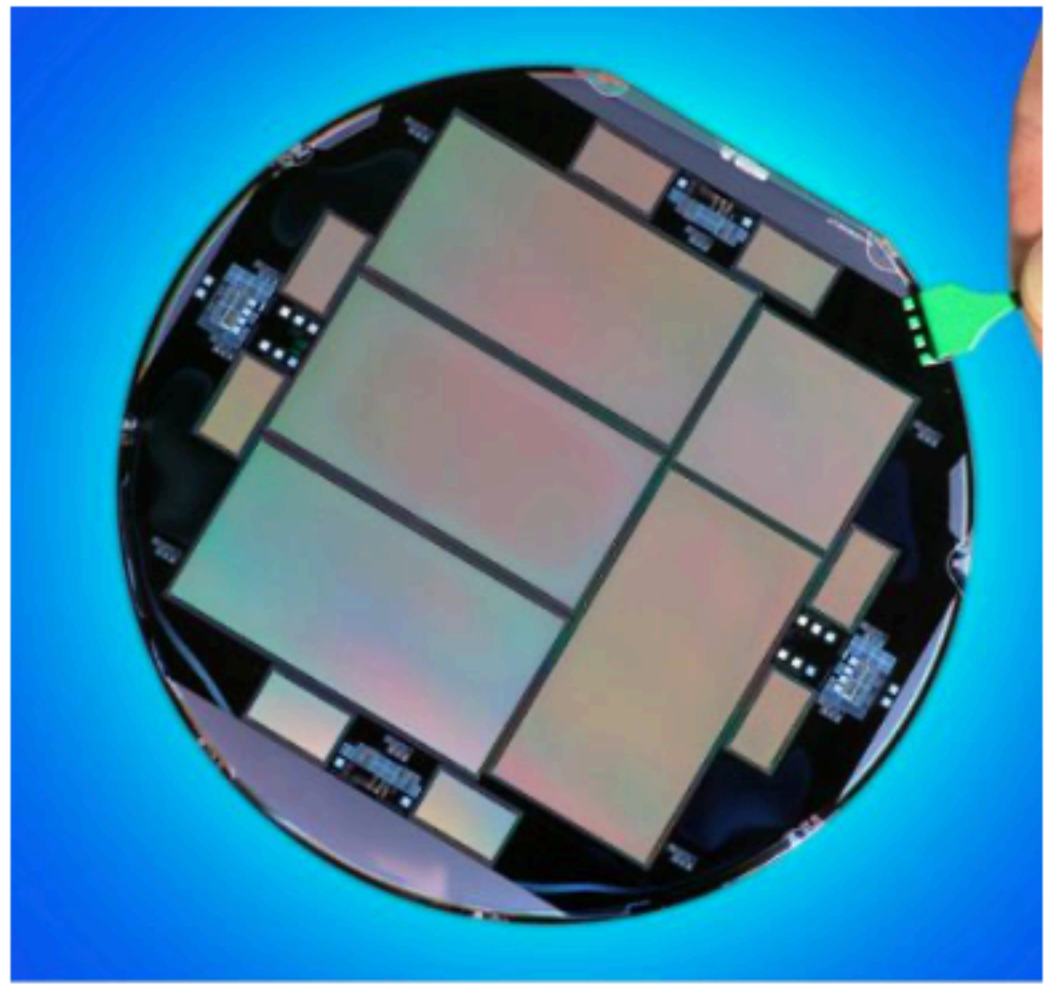


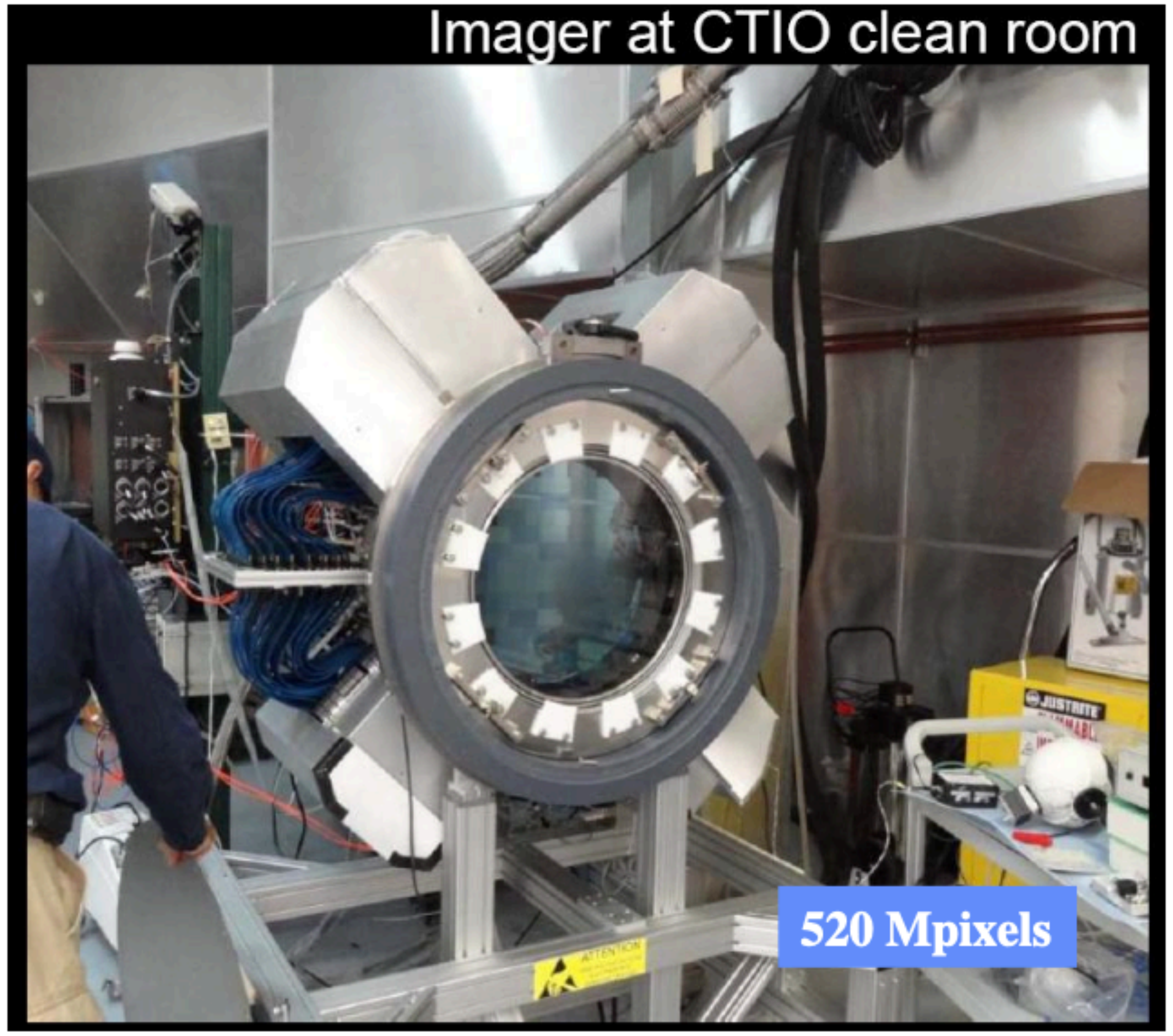


3.2 billion pixels (gigapixels)
10 um x 10 um pixel CCDs

CCDs: Advantages

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

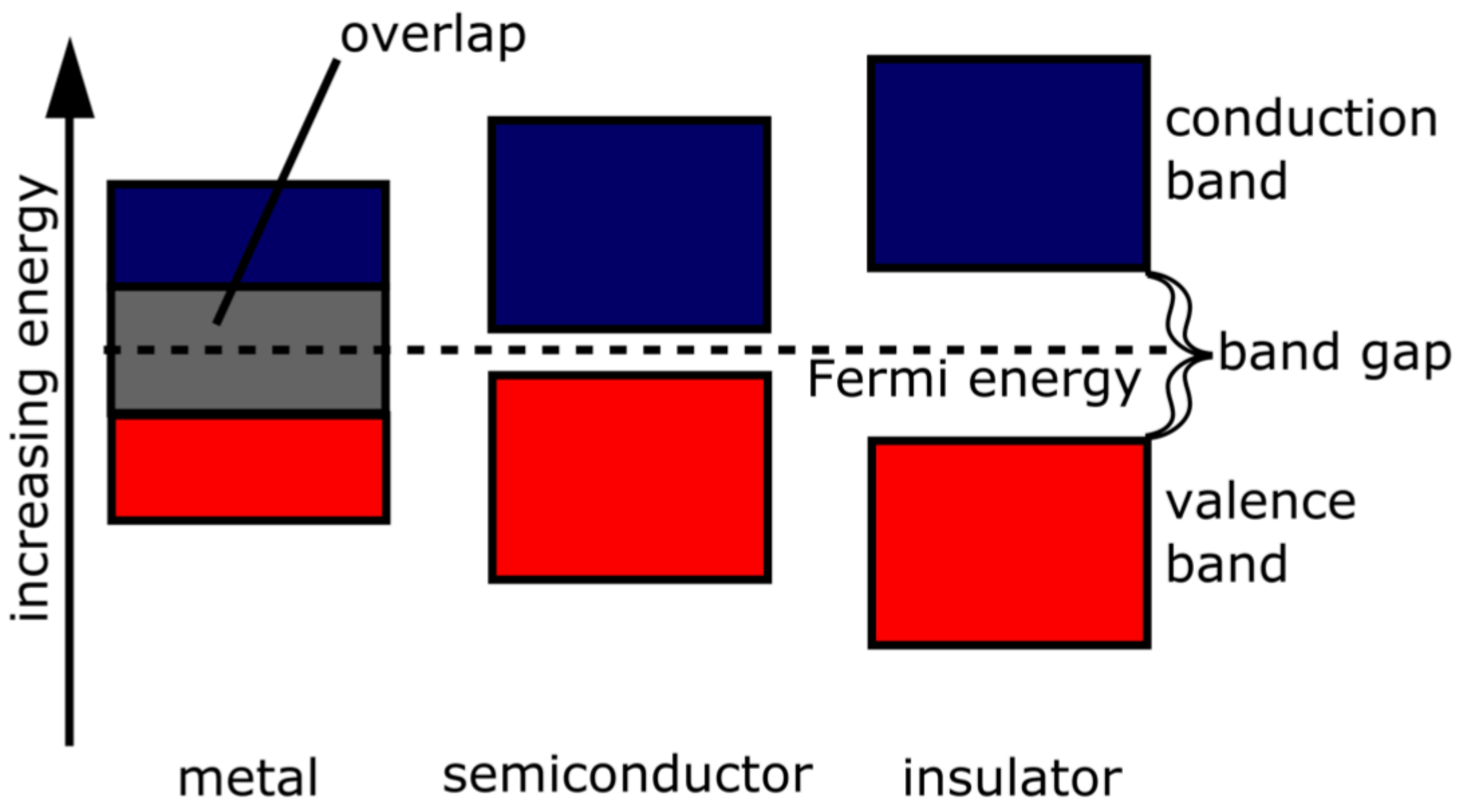




Dark Energy Survey Camera (DECam) – 62 2k x 4k, (15 μm)^2-pixel CCDs
NOAO Cerro Tololo Blanco 4-m Telescope (Fall 2012)

CCDs Are Semi-Conductors

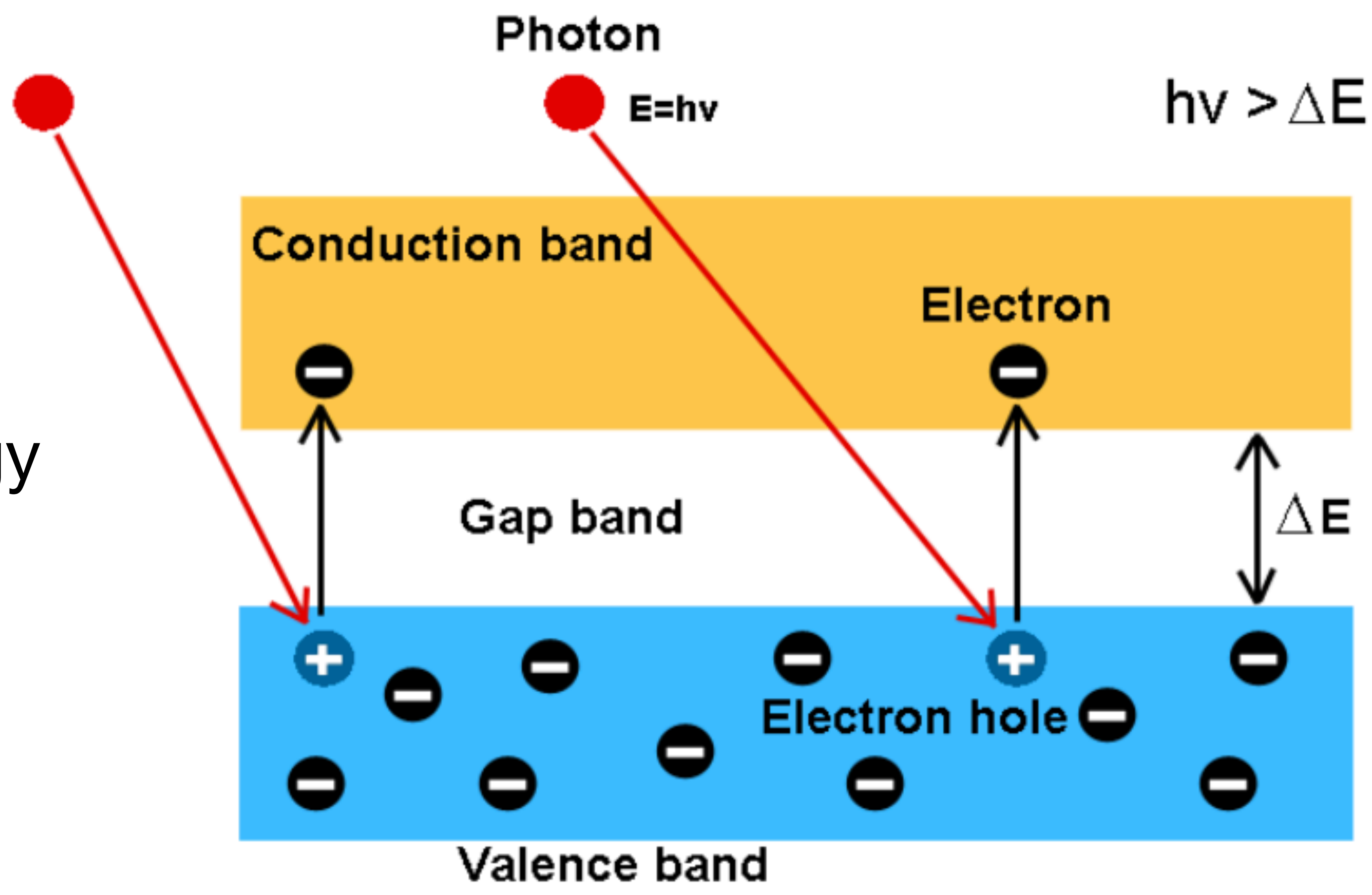
- CCDs are made of semi-conducting silicon wafer
- Key feature: In semi-conductors, there is a small energy gap between:
  - "**valence band**" (energy levels of bound electrons) and
  - "**conduction band**" (energy levels of free electrons)



wikipedia / inductiveload

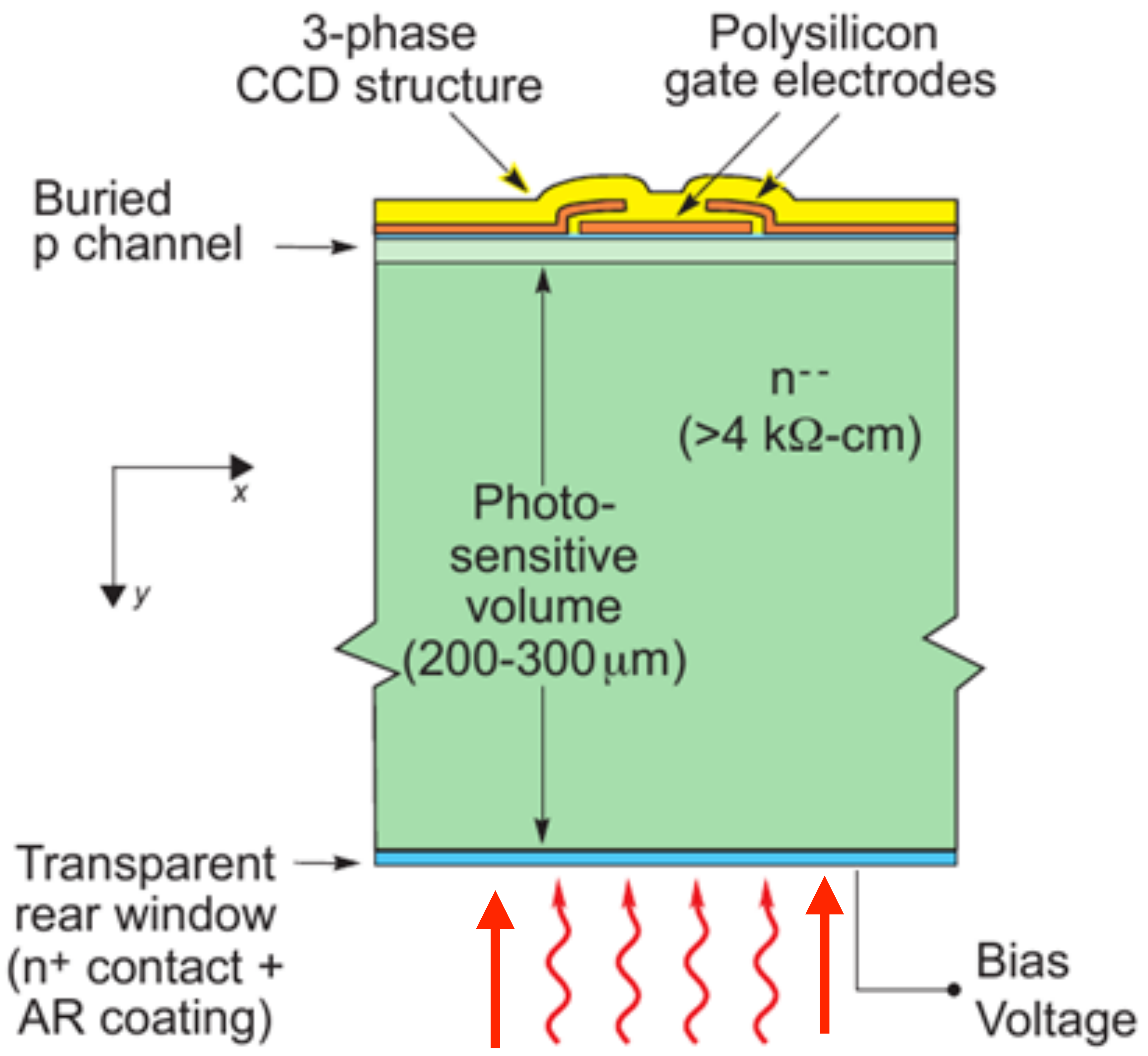
Photoelectric Effect

- Light is quantized in “photons”
    - $E_{photon} = h\,\nu$
    - Photon with 1 eV energy has wavelength of ~1.24 μm
- 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**: ΔE > ~10 eV (< ~100 nm)
    - **Semi-conductor:** ΔE ~1 eV (~1 μm)
    - **Conductor:** ΔE < 0 eV (i.e., mixed)



M. Poblocki

CCD Quantum Efficiency



Photons Incident on Silicon CCD wafer

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

- The wavelength cut-off in Silicon due to the band-gap (~1.1 eV) is about 1 µm
- The Silicon **absorption length** is defined as the inverse of the **absorption coefficient** alpha (α)

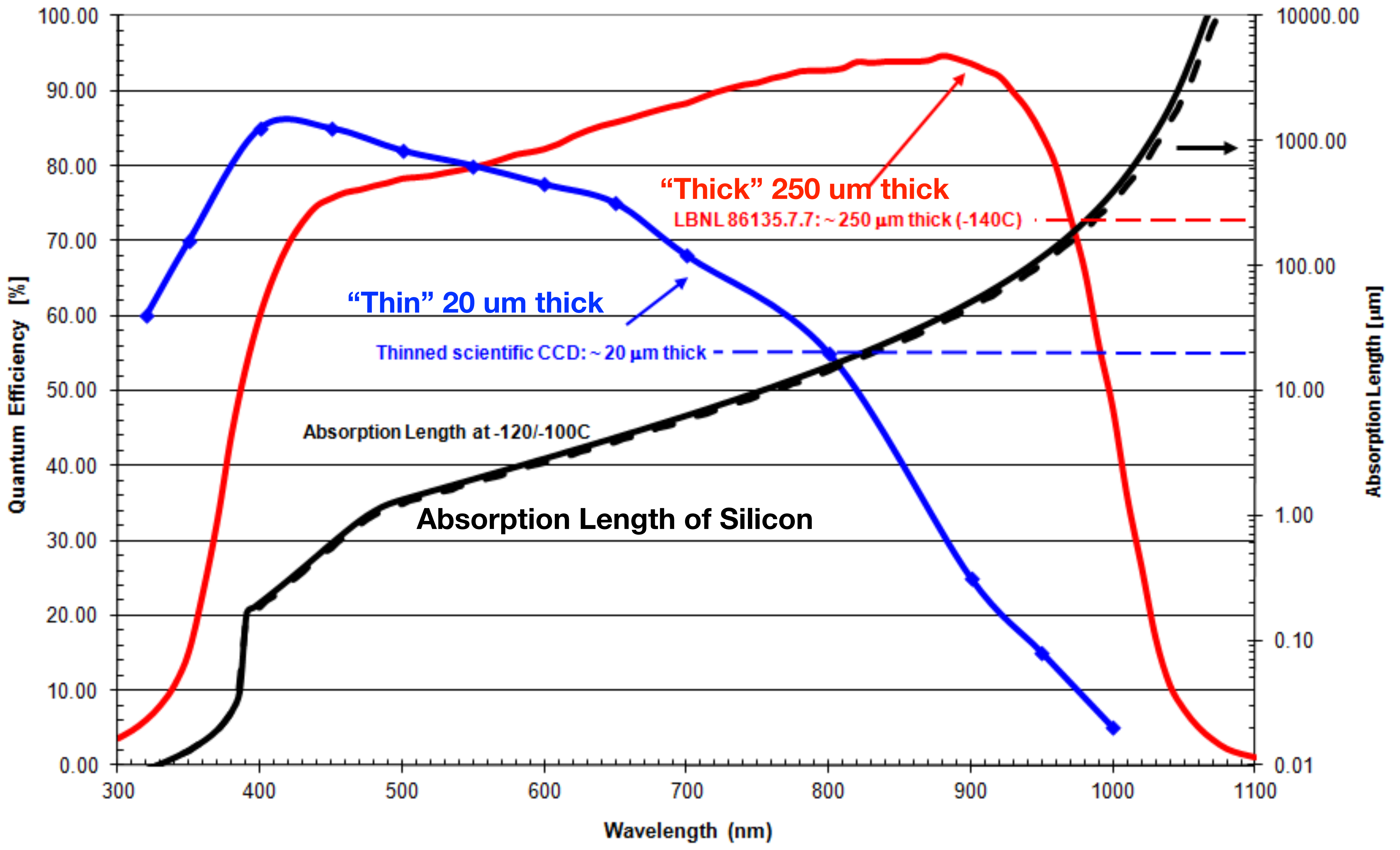
$$I(x) = I_o \exp[-\alpha x]$$

Intensity of incident light

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

CCD Quantum Efficiency

- Quantum efficiency = the fraction of photons that are absorbed
- Depends on wavelength
- Different materials or technologies lead to Red vs. Blue vs. Infrared optimized CCDs



Thicker Silicon wafers will have more absorption

CCD Quantum Efficiency

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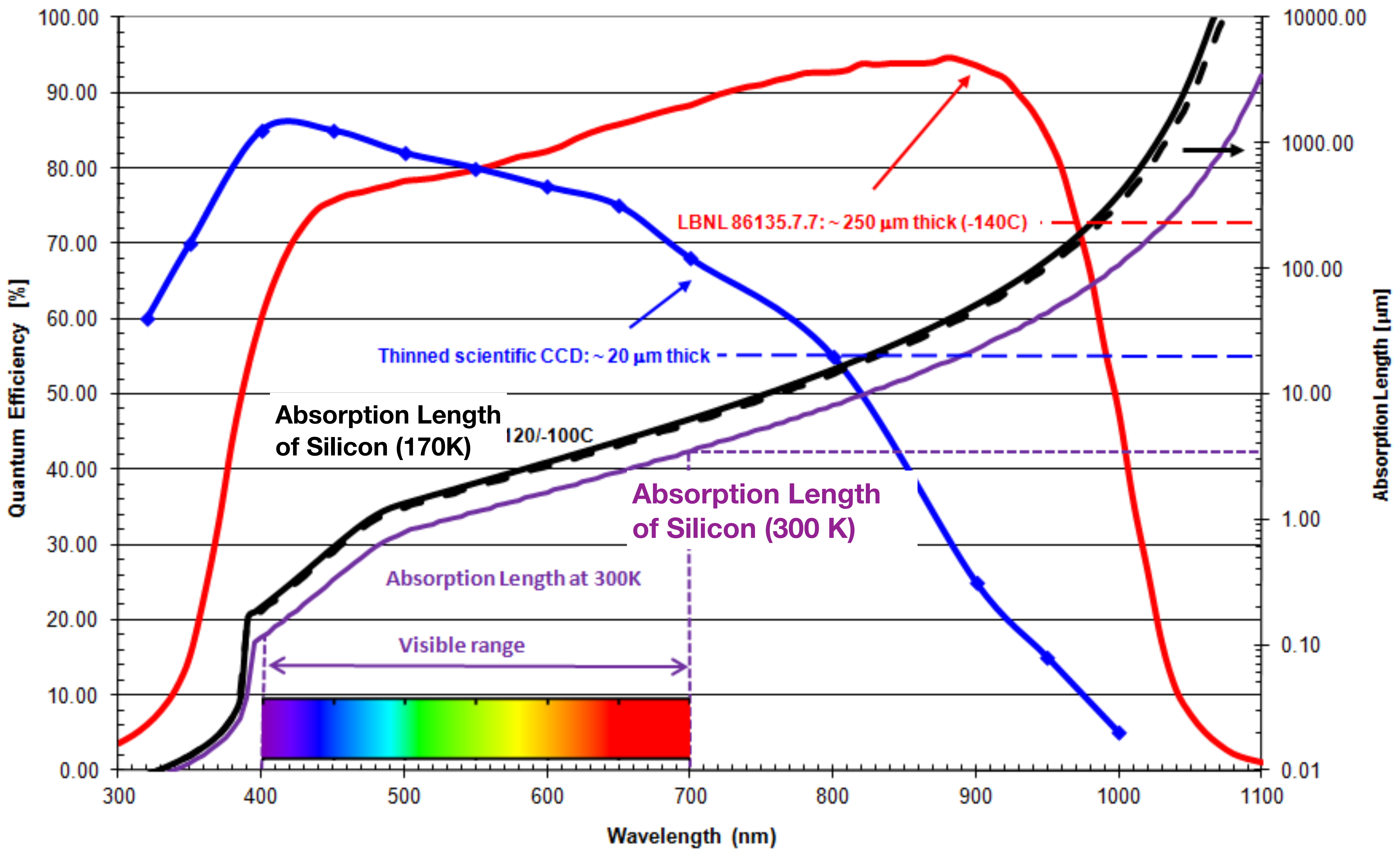
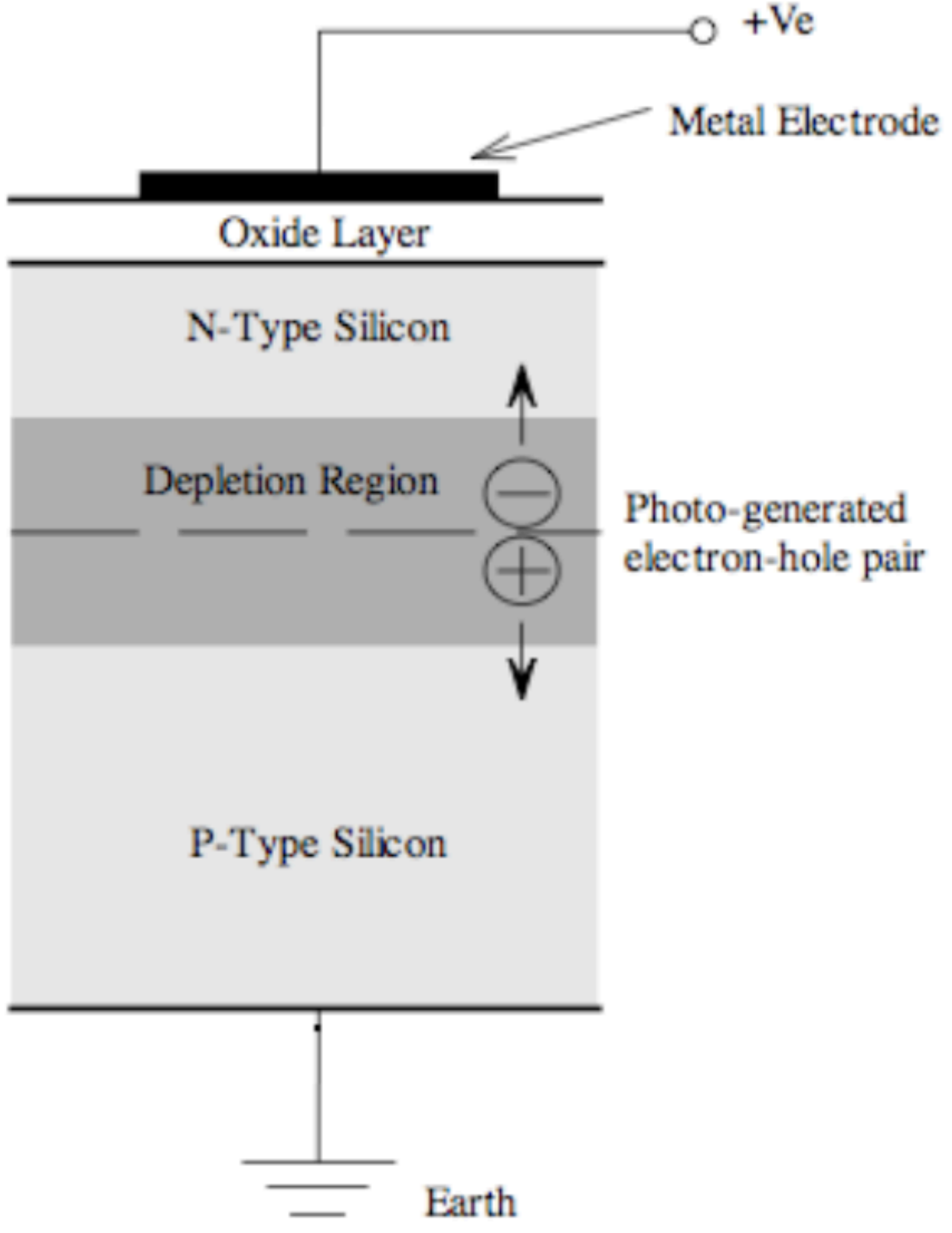


Thicker Silicon wafers will have more absorption

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

How do CCDs work? One pixel example

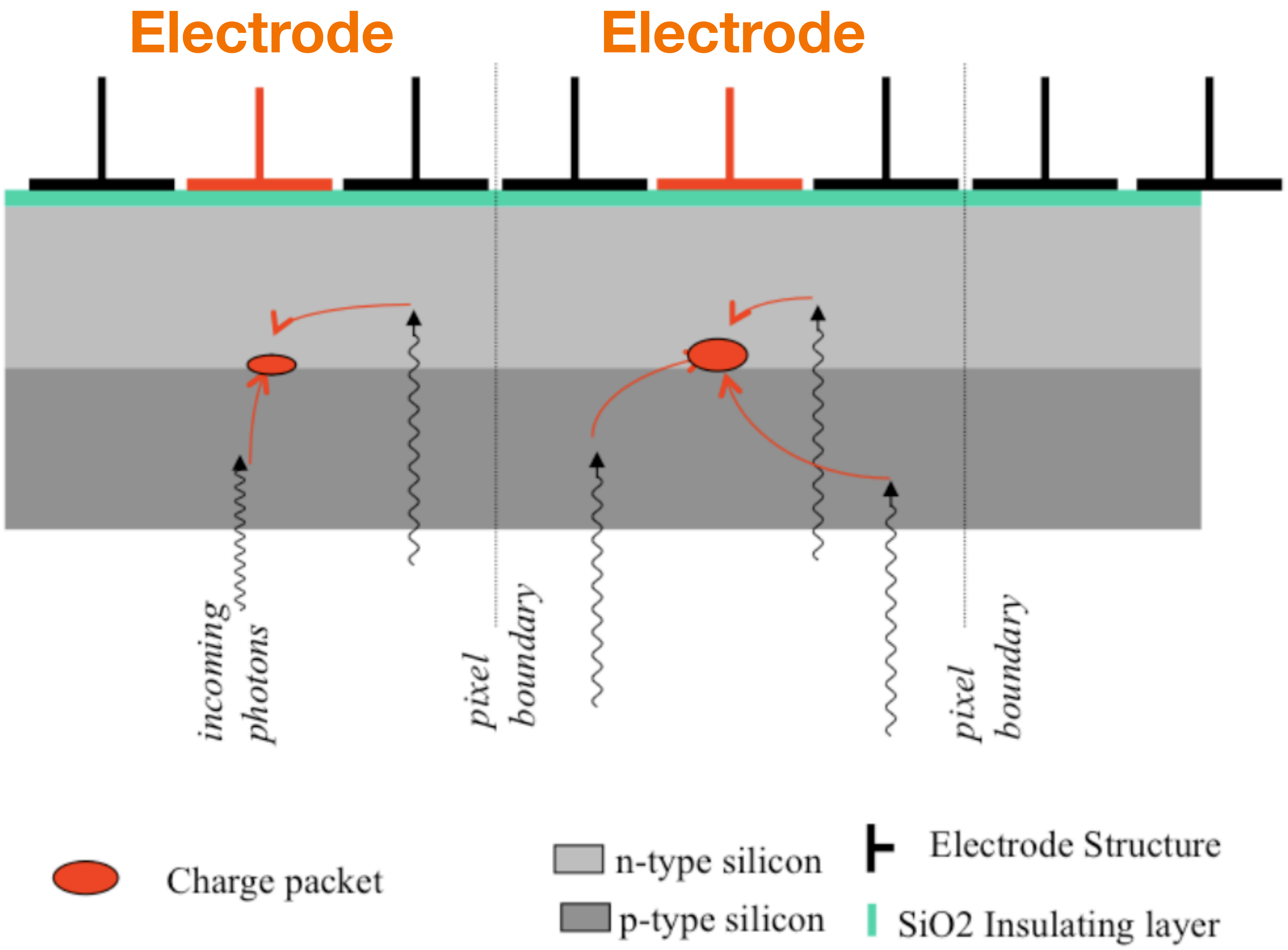
- Apply an electric field across a "doped" Silicon wafer to keep electrons (and holes) separated
    - Photons absorbed by the Silicon will excite electrons into the conduction band
    - Electrons get attracted to voltage applied to electrode connected to surface of the Silicon



Microsoft

How do CCDs work? Many pixels

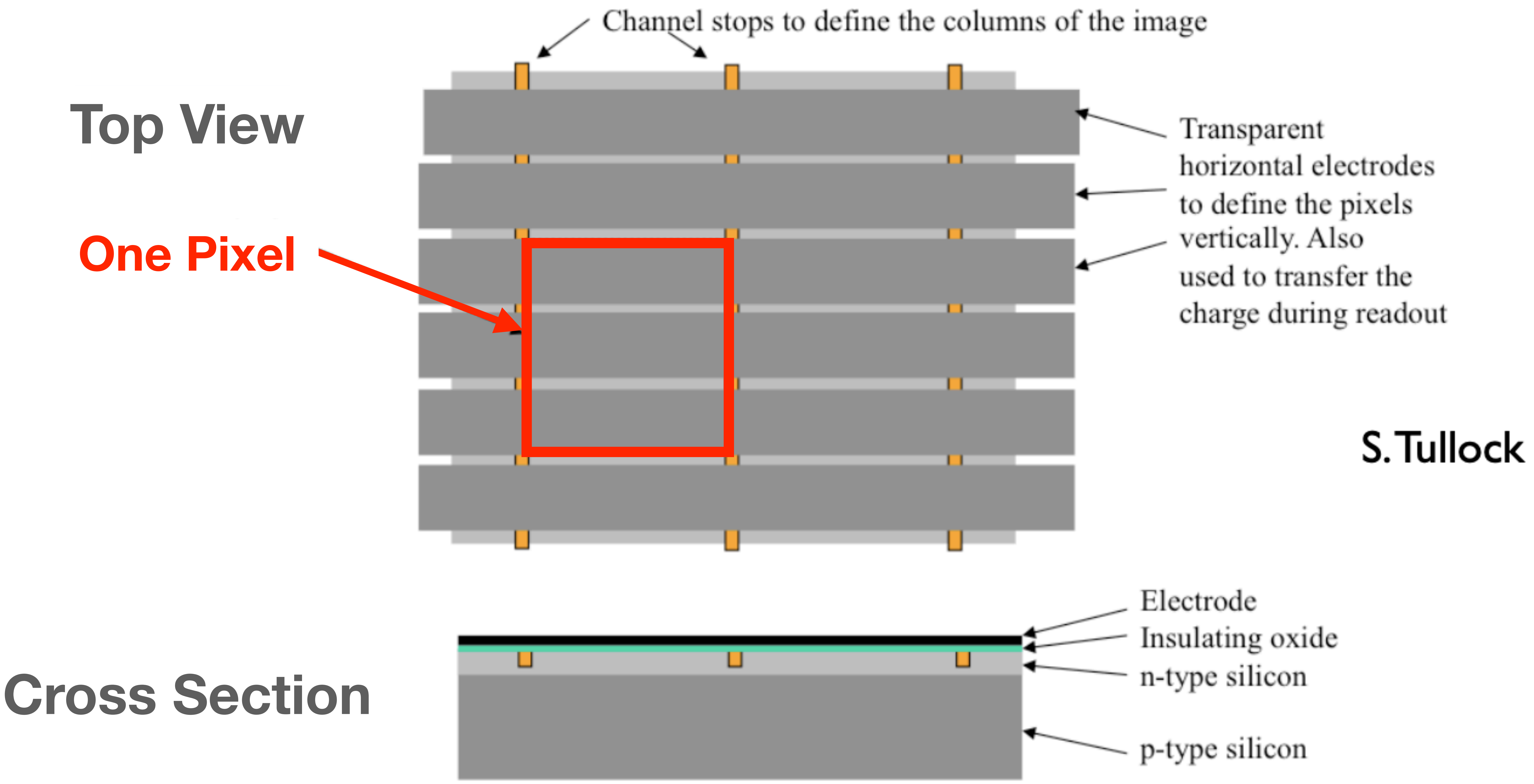
- Each CCD wafer will be made from one piece of bulk Silicon
- Pixels are defined by the electric field generated by multiple electrodes applied on one side of the wafer



S.Tullock

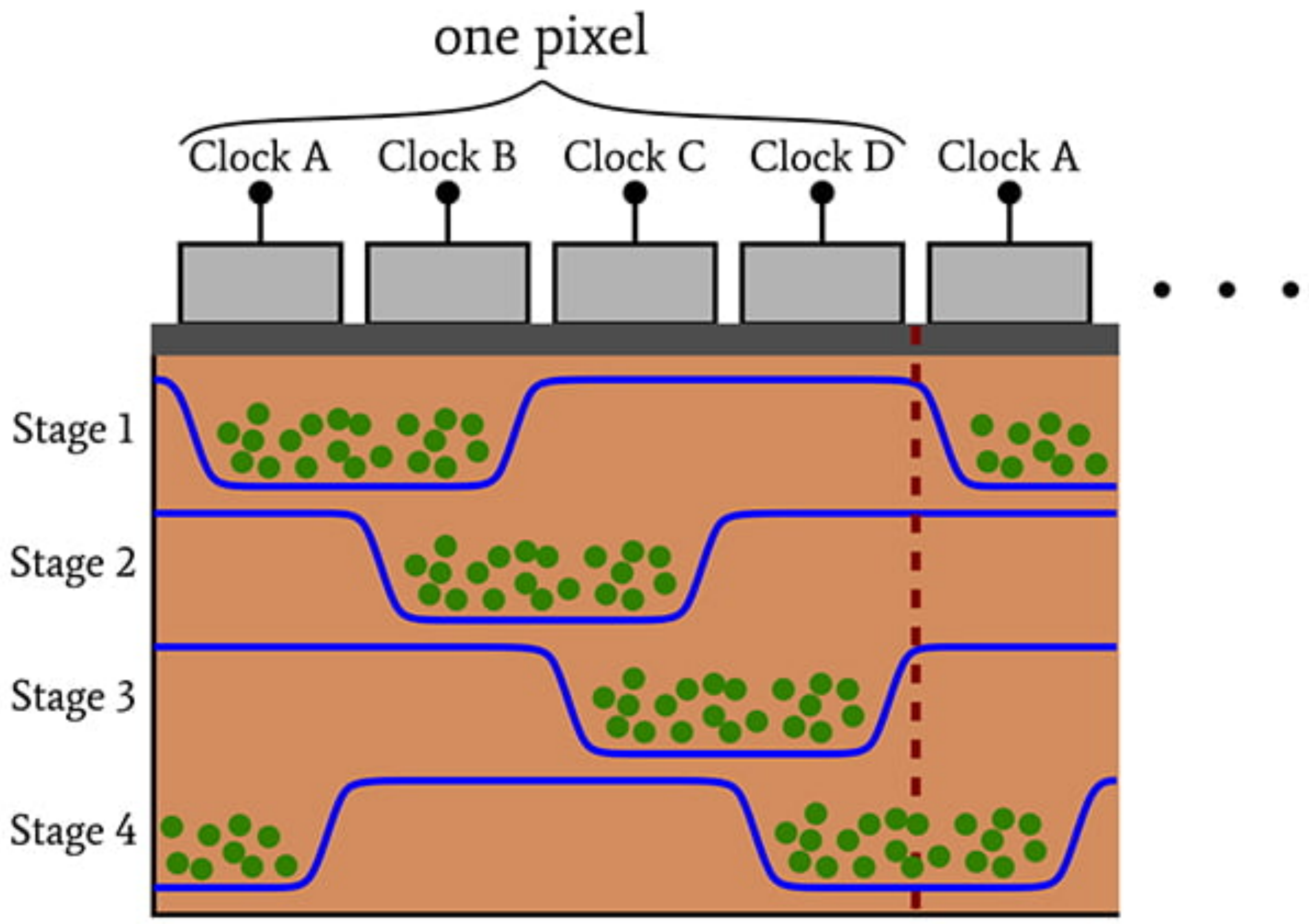
How do CCDs work? Many pixels

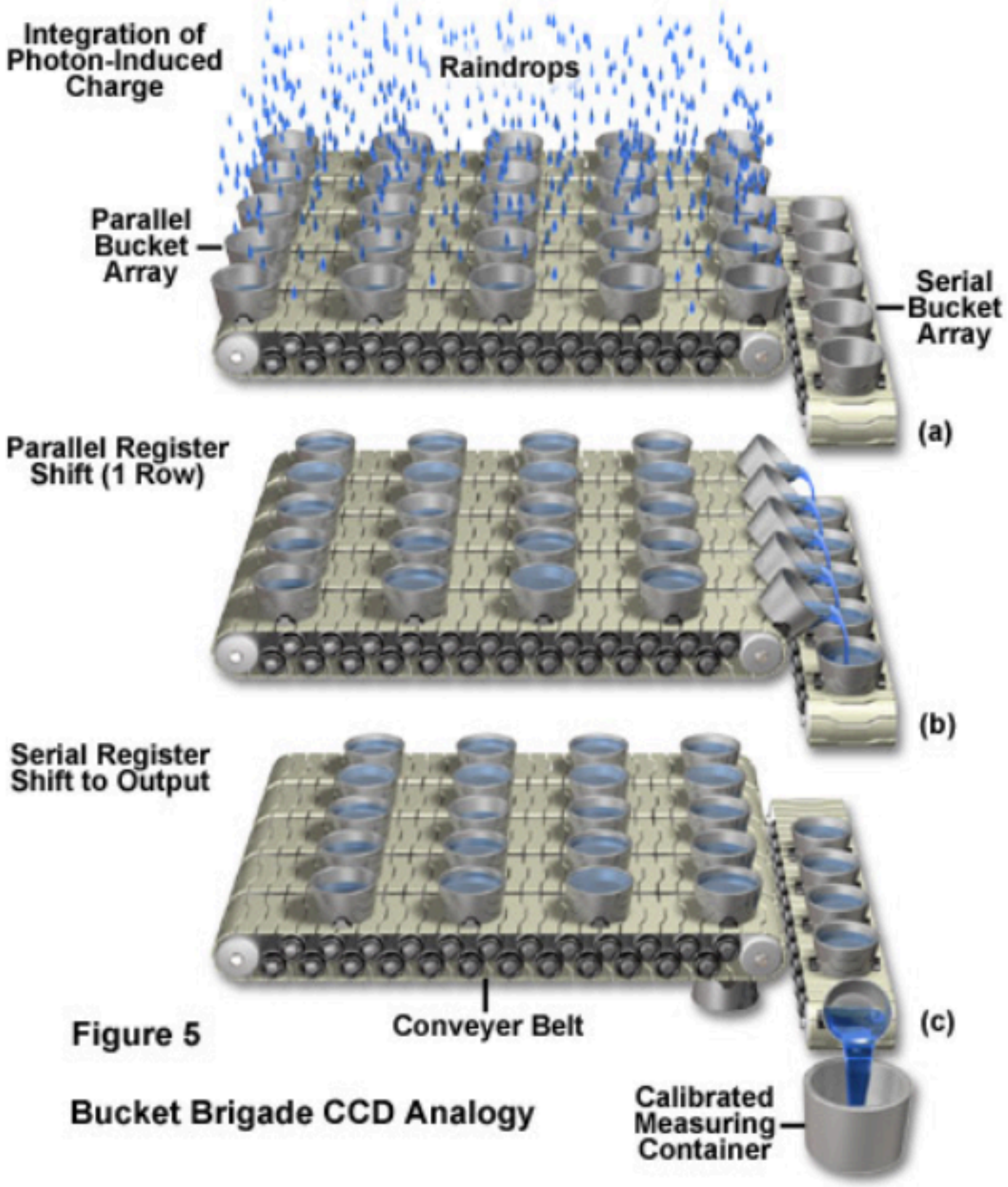
- Insulator strips between columns of pixels (while electrodes define rows)



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

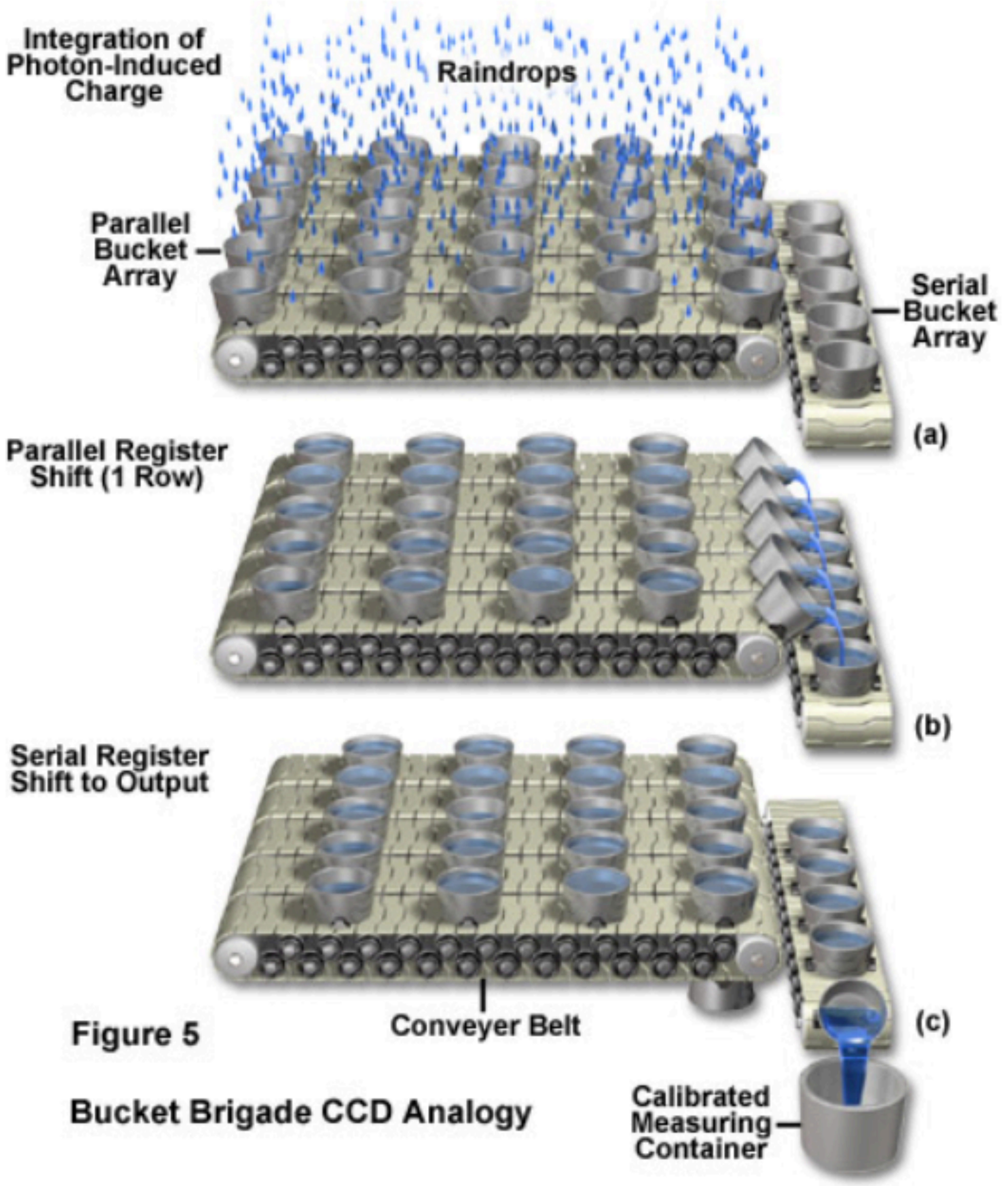




Cold Spring Harbor Protocols

Assembling the Image

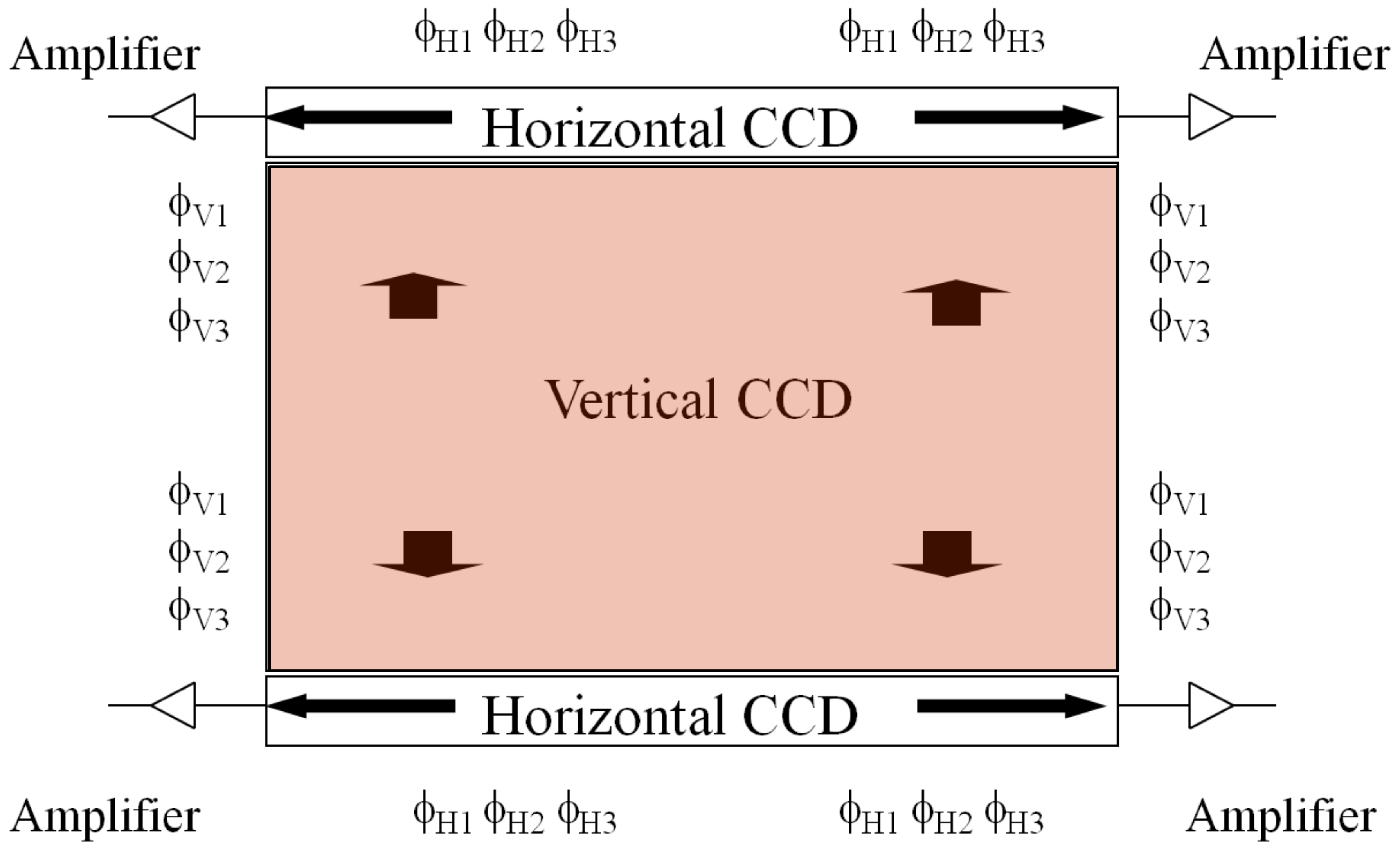
- Charge collection is passed to an amplifier and analog-to-digital converter (ADC)
- Output “counts” as integer value, with 1-photon creating 1-count
- However, in addition, we can also apply an electronic “Gain” via an amplifier, where
    - Gain: $G = (N_{electrons}) / (N_{counts})$



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



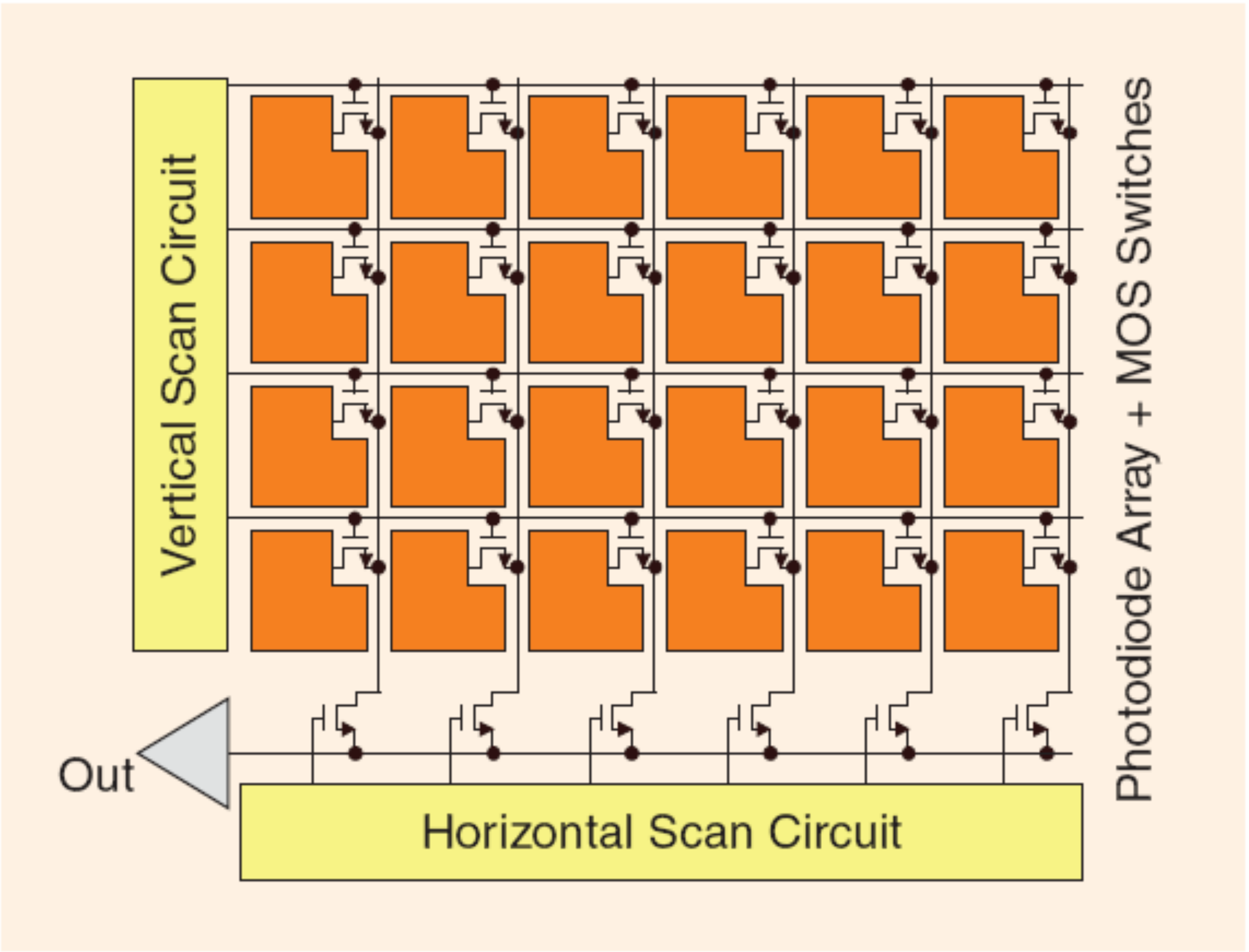


FIGURE 2: Architecture of a two-dimensional CMOS image sensor.

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/OmniVision[1])

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	~ 3 μm	10 – 250 μm
Peak QE	~ 55% (color filter)	~ 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	~ 2 e-	~ 2-5 e-
Full well	~ 4500 e-	~ 200,000 e- (15 μm)

[1]Rhodes, 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 analog to digital converter (**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

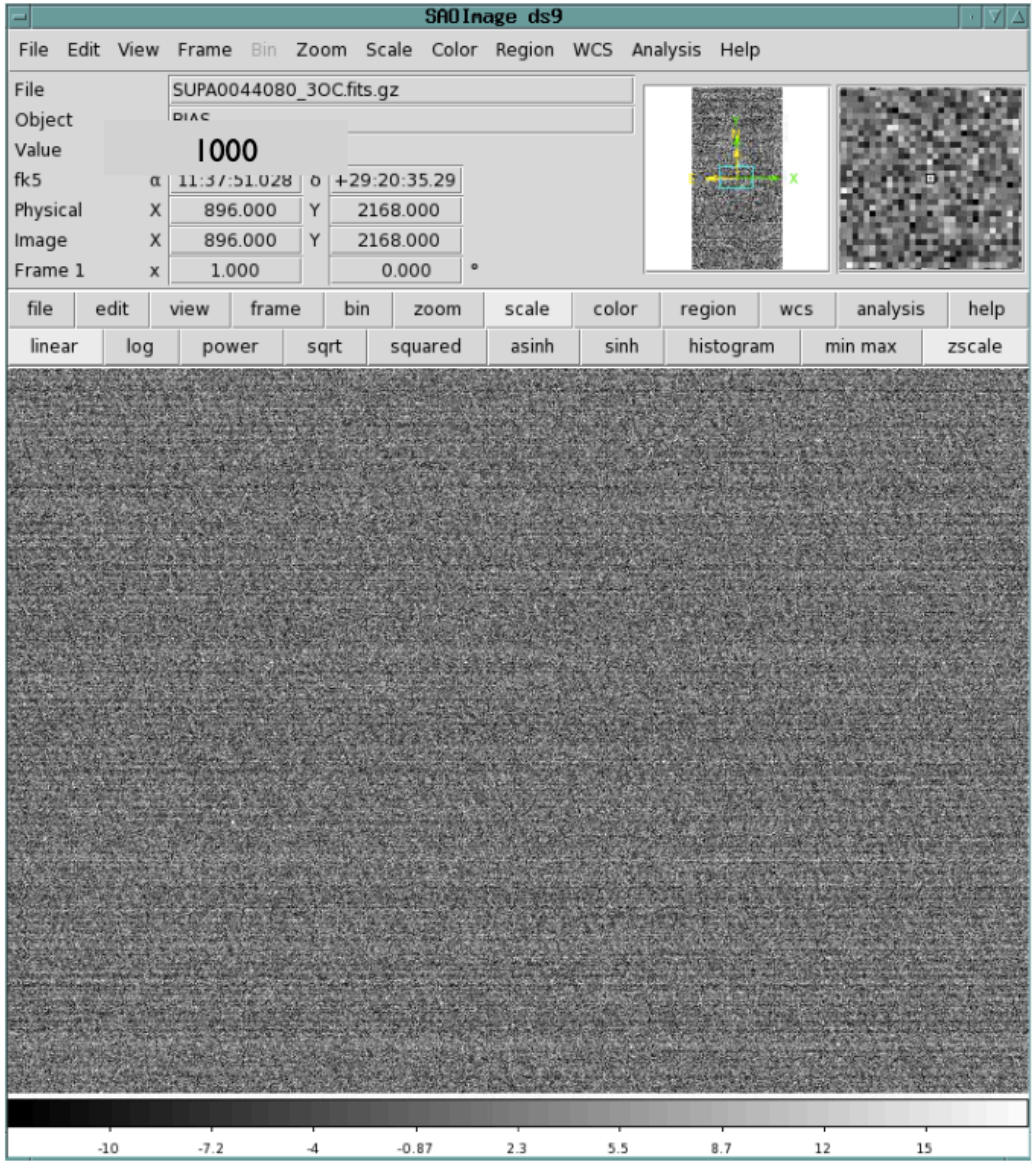
Converting CCD Counts to Flux

Readout Noise

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

1) 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 (170 Kelvin)

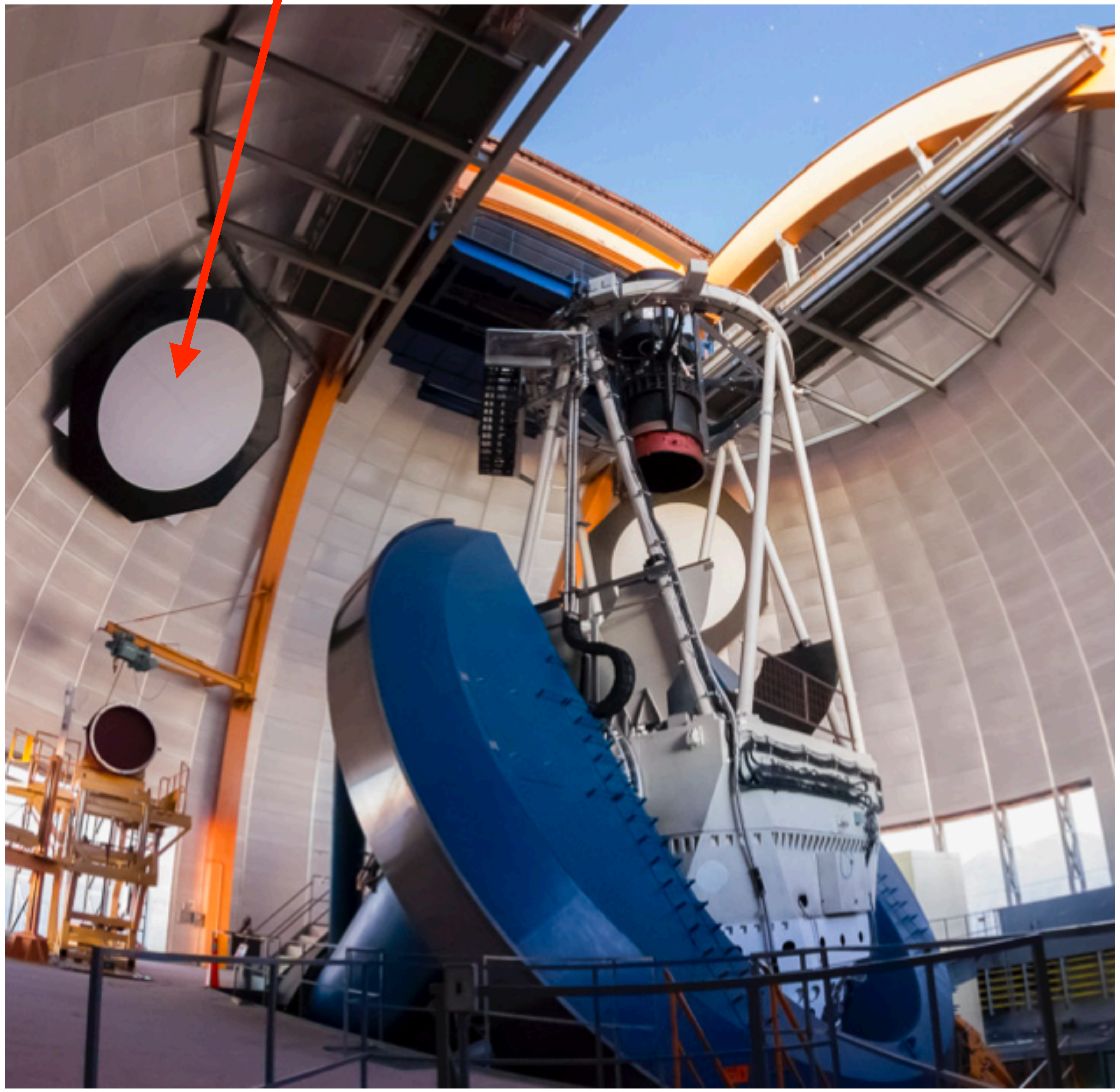
2) Dark Frames

- **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

3) Flat-Field

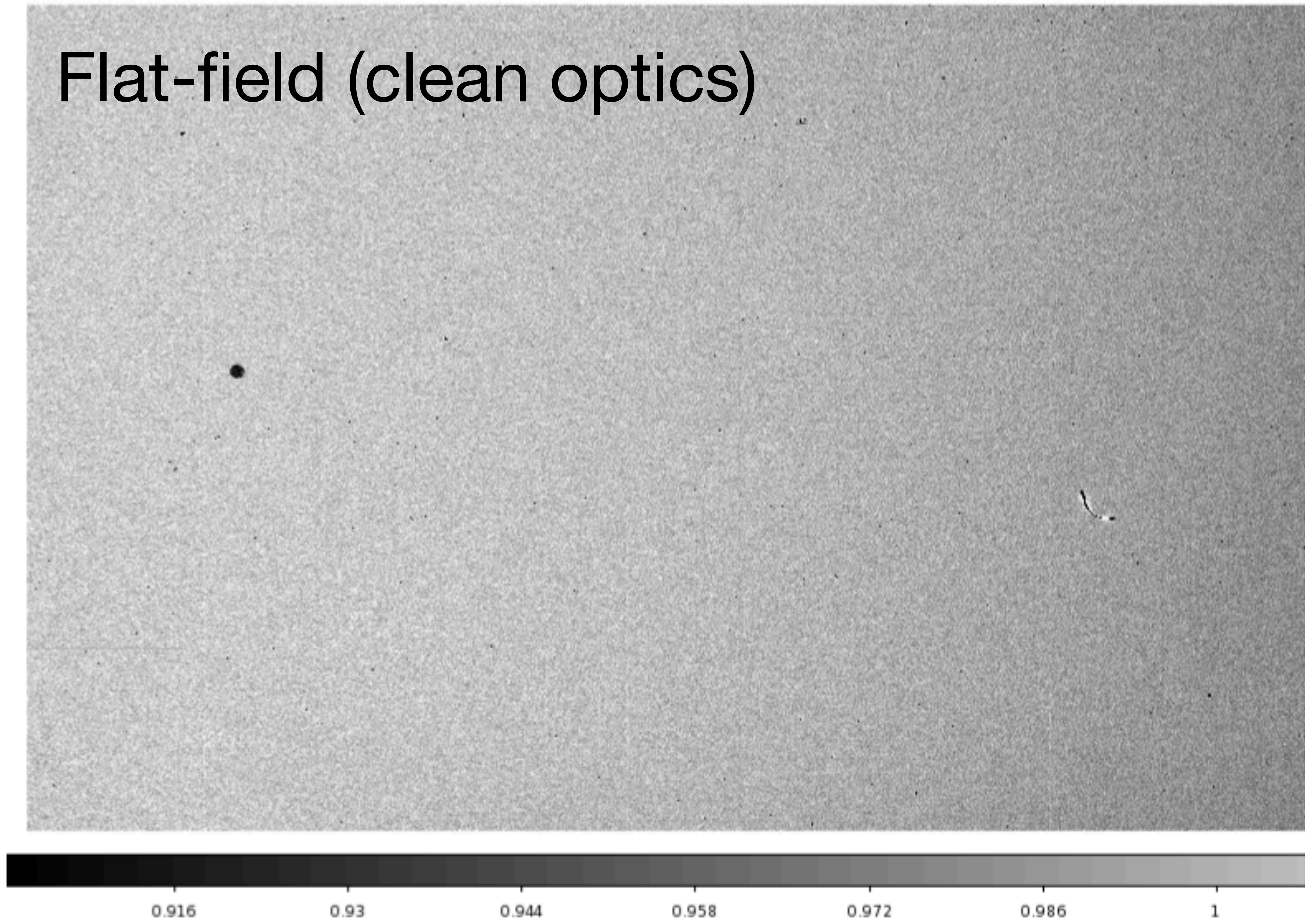
- The pixels in a CCD do not have uniform sensitivity
- Due to variations in the Silicon, electric field, pixel size, optics, vignetting, etc.
    - $N_{electrons} = A(x,y)\, N_{photons}$
    - Where A(x,y) is a “gain” factor that accounts for these variations across your focal plane / detector array
- Need to correct for differences for meaningful measurements via a “**Flat-Field**”

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



3) 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



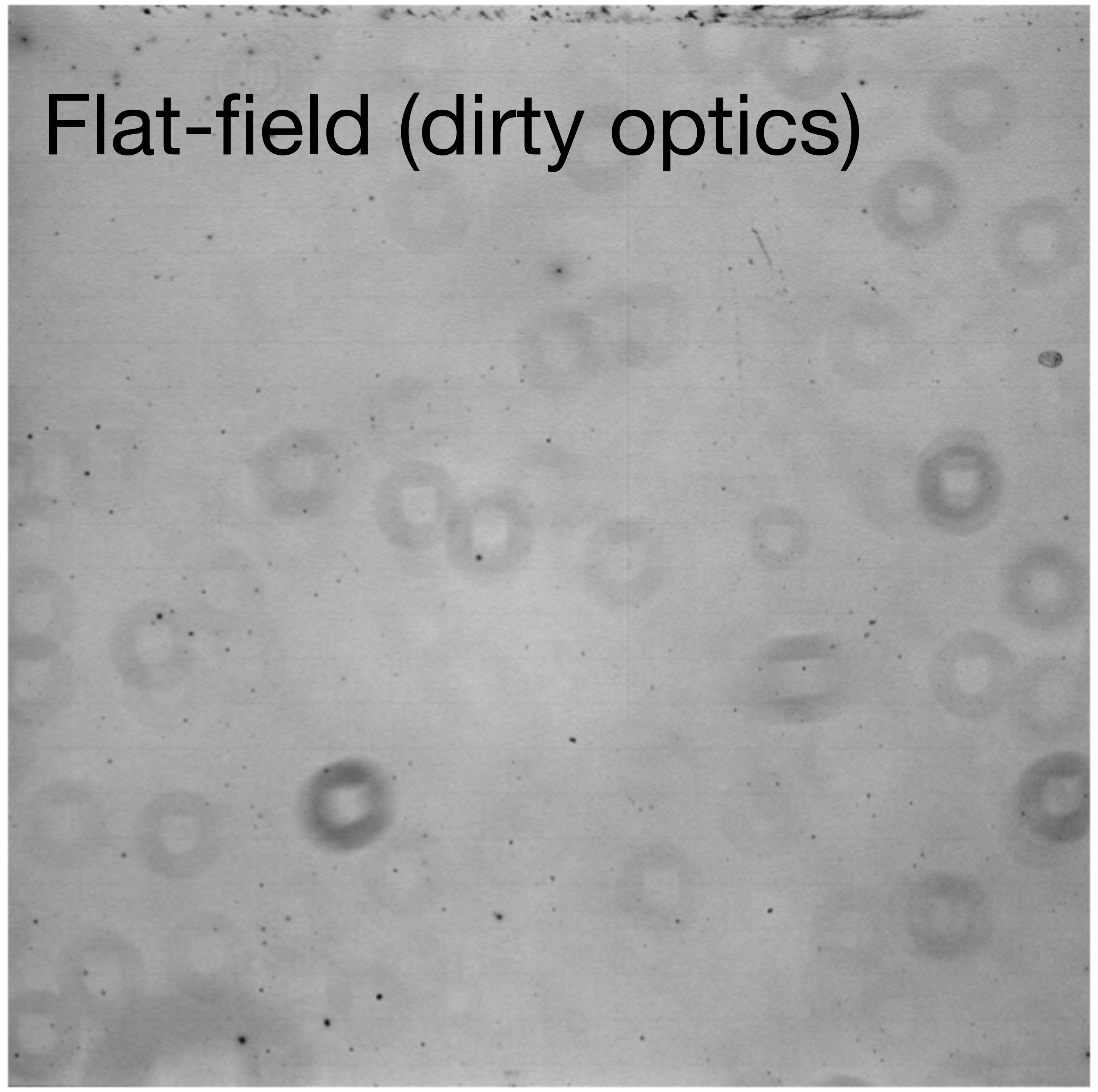


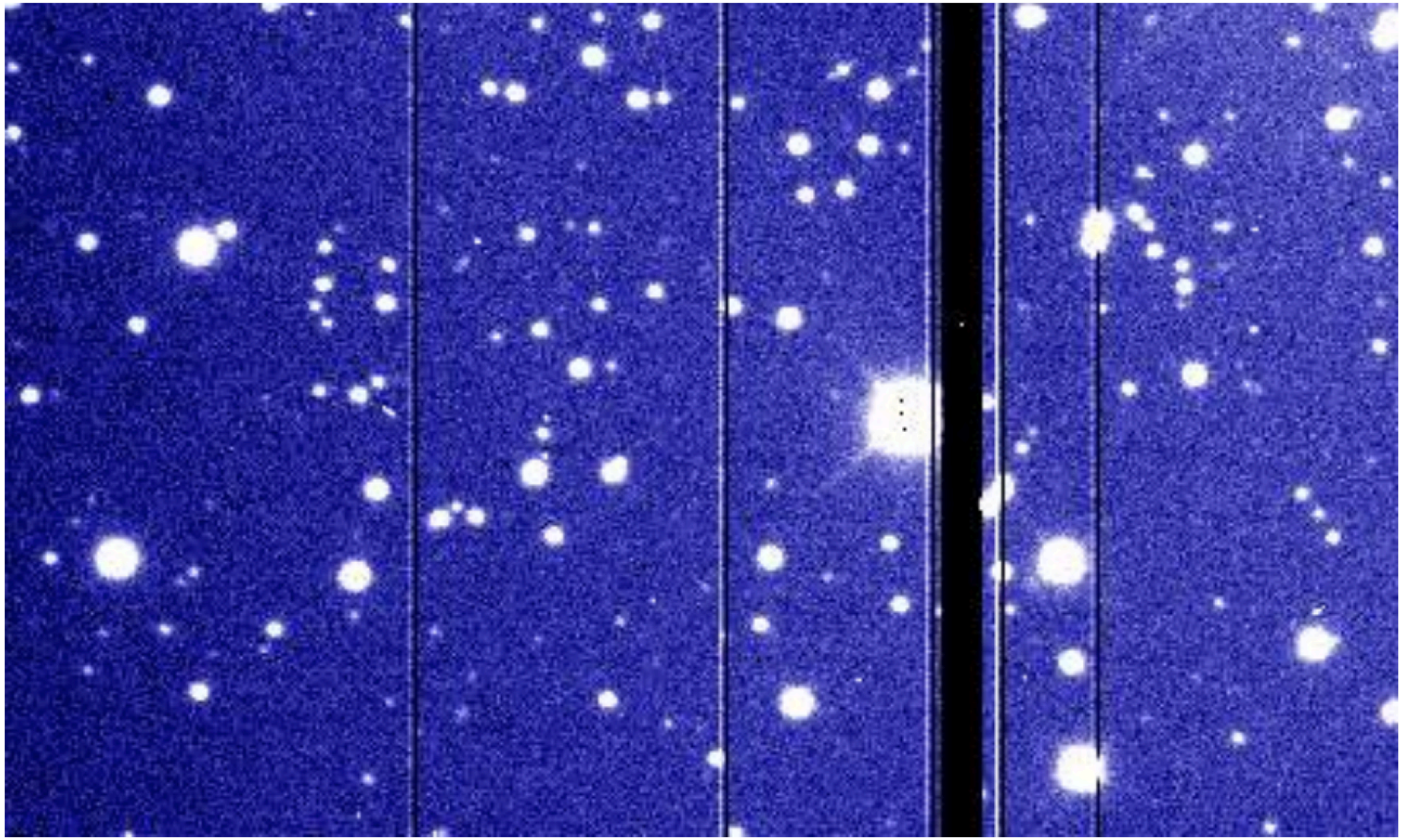
Fig. 6.— Flat field indicates the effects of dust.

3) 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 and Dark frames are an additive / subtractive correction
- So to correct your “raw image” for these various Bias, Dark, and flat-field effects, your correction should roughly be::
    - **Final Image = [Raw Image - (Bias+Dark Frame)] / [Flat Field - (Bias+Dark Frame)]**

CCD Artifacts: Dead or Hot Pixels

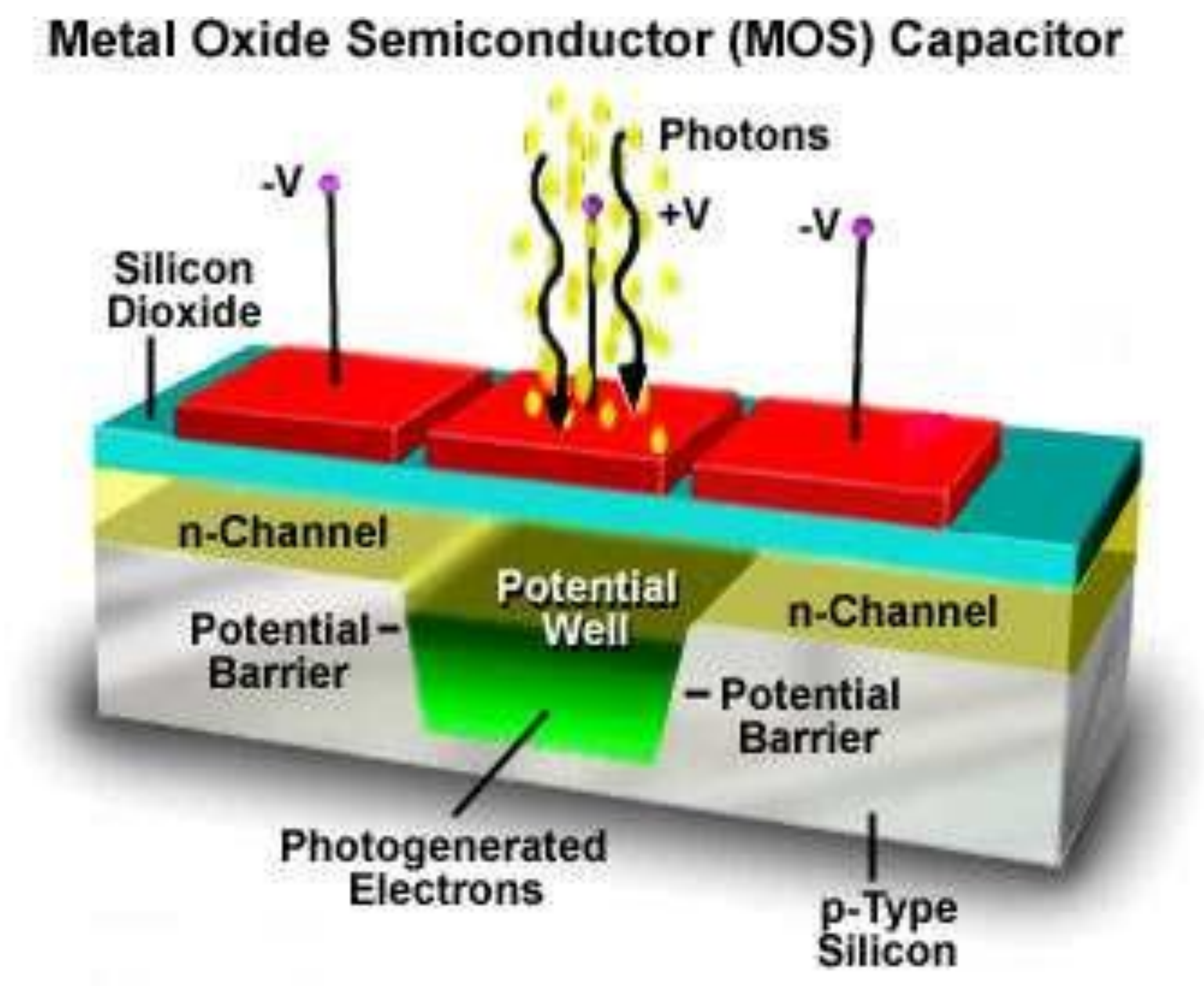
- **Dead pixels:** No (or little) response
- **Hot pixels:** Very high noise
- In either case, signal is not recoverable, pixels need to be ignored in analyses

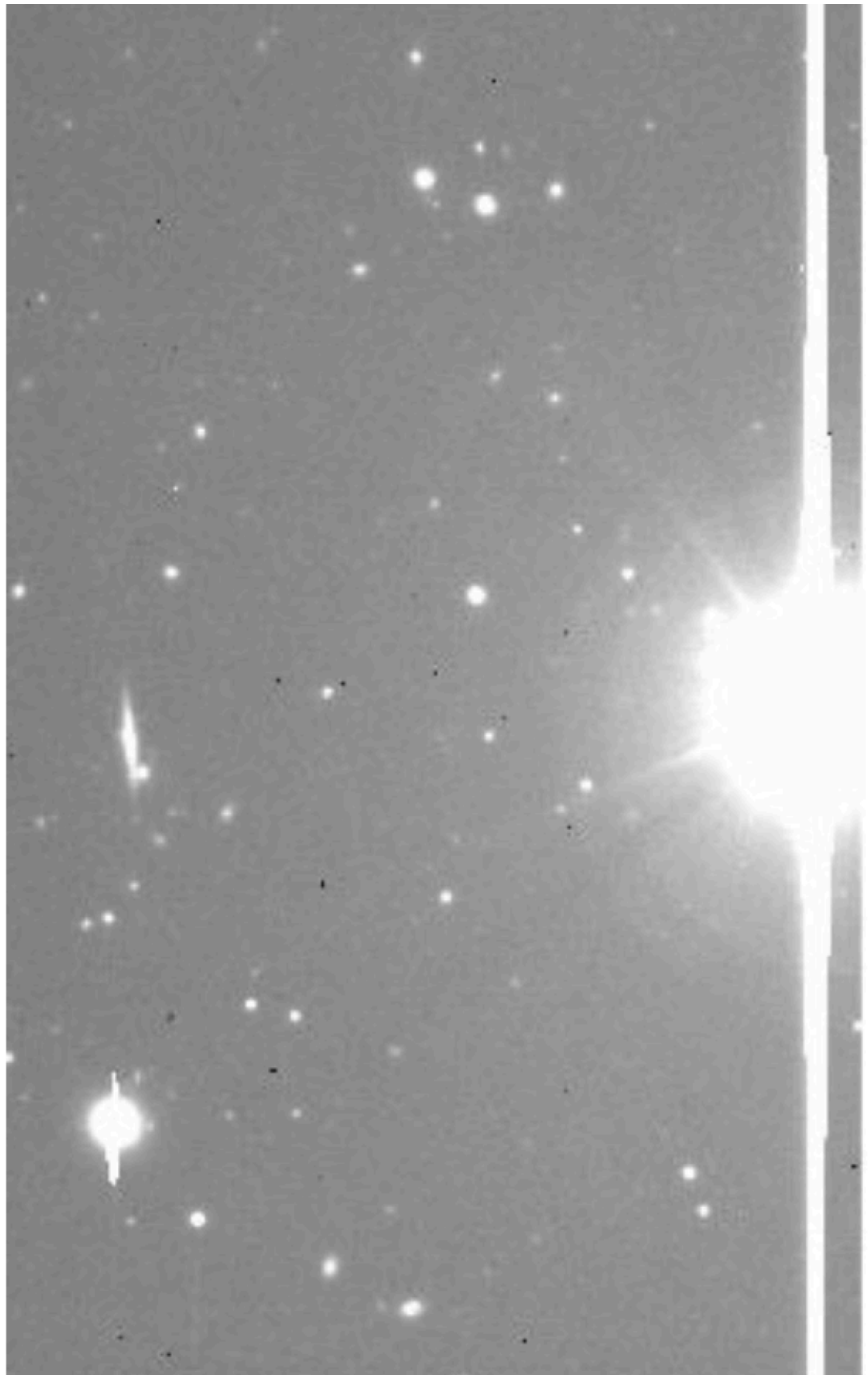


ESO

CCD Artifacts: Saturation

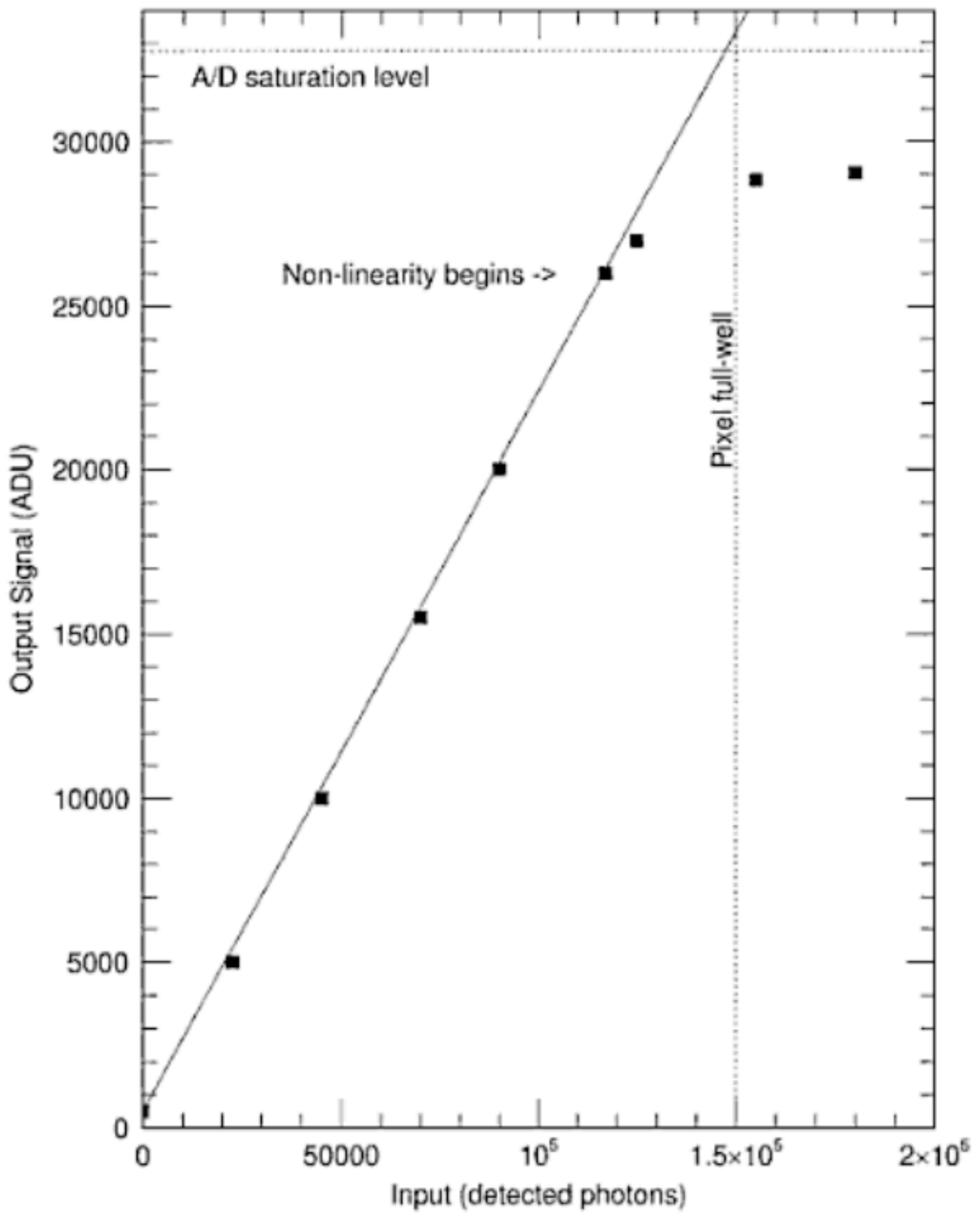
- **Saturation:** Bright object's signal fills pixels electron "well" capacity, electrons spill over into neighboring pixels.
  - Typical "well" in scientific CCD can hold ~100,000 electrons
  - (If you see this, likely a good idea to reduce your exposure time, e.g., from 120-sec to 10-sec)





CCD Artifacts: Non-Linearity

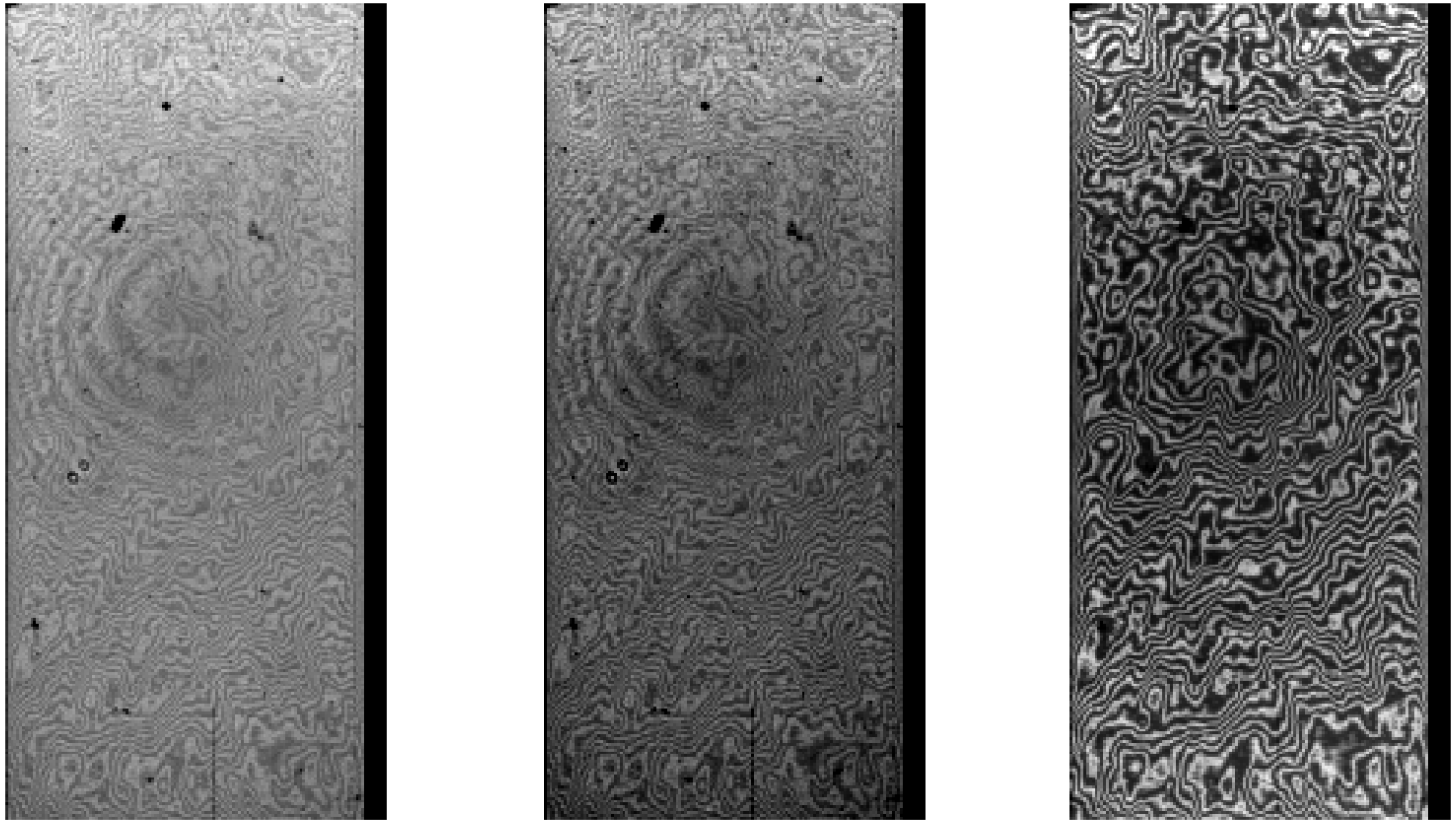
- **Non-linearity:** Even before situation, response will typically become non-linear.
    - This can be measured from dome-flats with different exposure lengths



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)

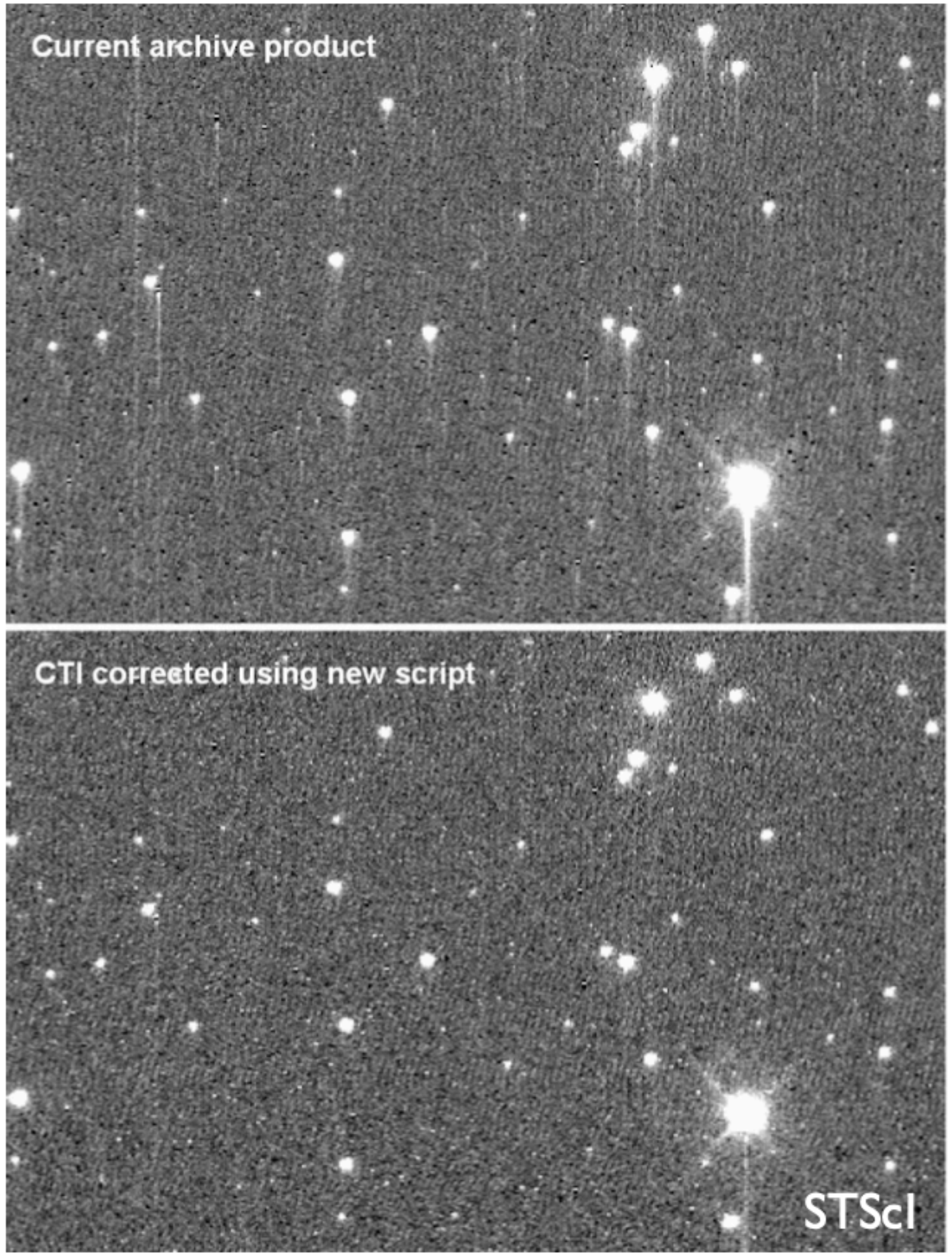


λ = 800 nm 900 nm 1 μm

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(rue) / F(alse)

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

Filter (g,r,i,z)

Exposure time

UTC and MJD during observations

```
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
```

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)*:

$$\begin{pmatrix} \alpha - \mathrm{CRVAL1} \\ \delta - \mathrm{CRVAL2} \end{pmatrix} = \begin{pmatrix} \mathrm{CD1\_1} & \mathrm{CD1\_2} \\ \mathrm{CD2\_1} & \mathrm{CD2\_2} \end{pmatrix} \begin{pmatrix} x - \mathrm{CRPIX1} \\ y - \mathrm{CRPIX2} \end{pmatrix}$$

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)

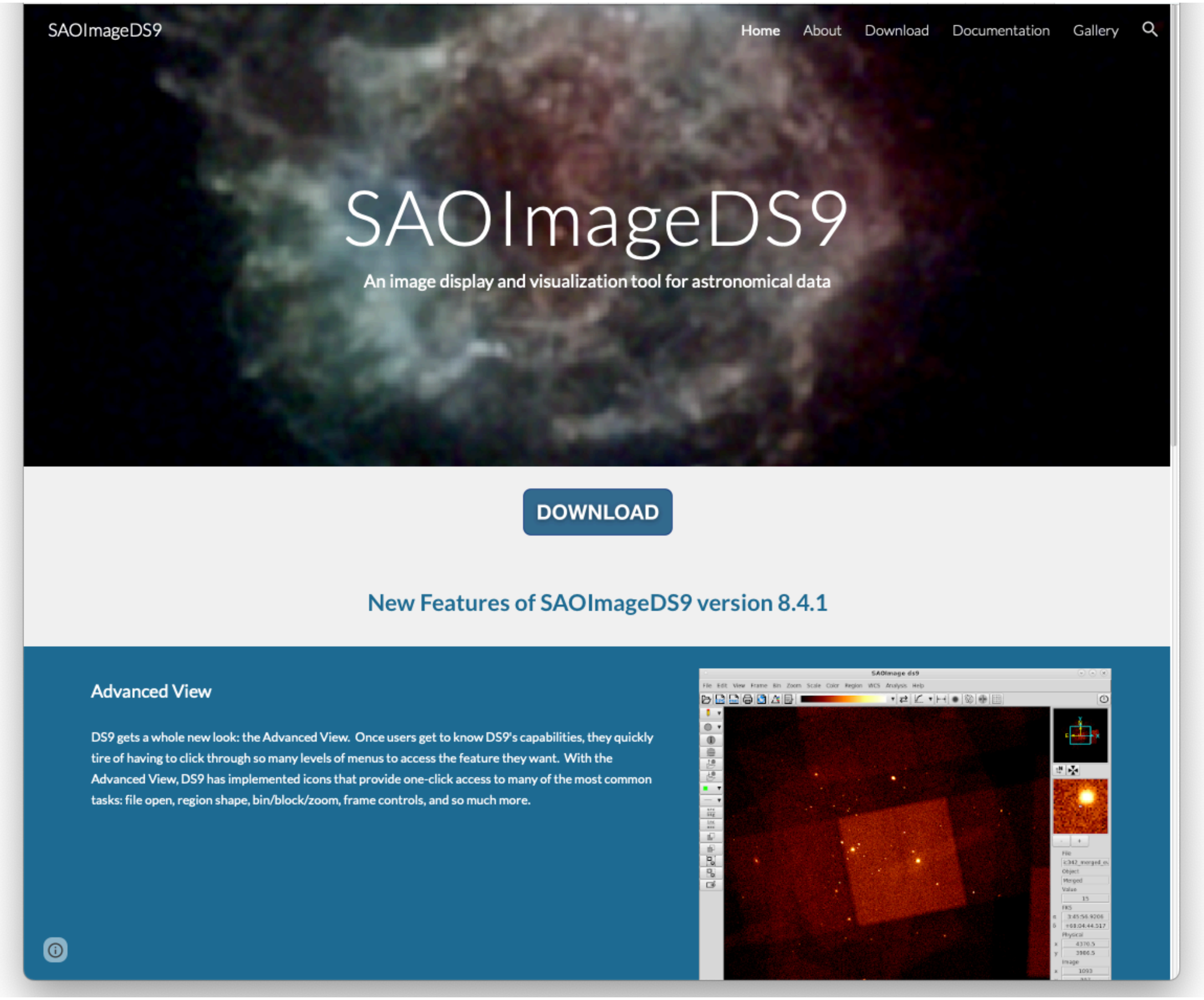
```
CRPIX1  =                 1028
CRPIX2  =                 1024
CTYPE1  = 'RA---TAN'
CTYPE2  = 'DEC--TAN'
CRVAL1  =            10.698458
CRVAL2  =            41.280078
WCSDIM  =                    2
CD1_1   =        -0.0002579484
CD1_2   =         9.004135E-07
CD2_2   =        -0.0002579484
CD2_1 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

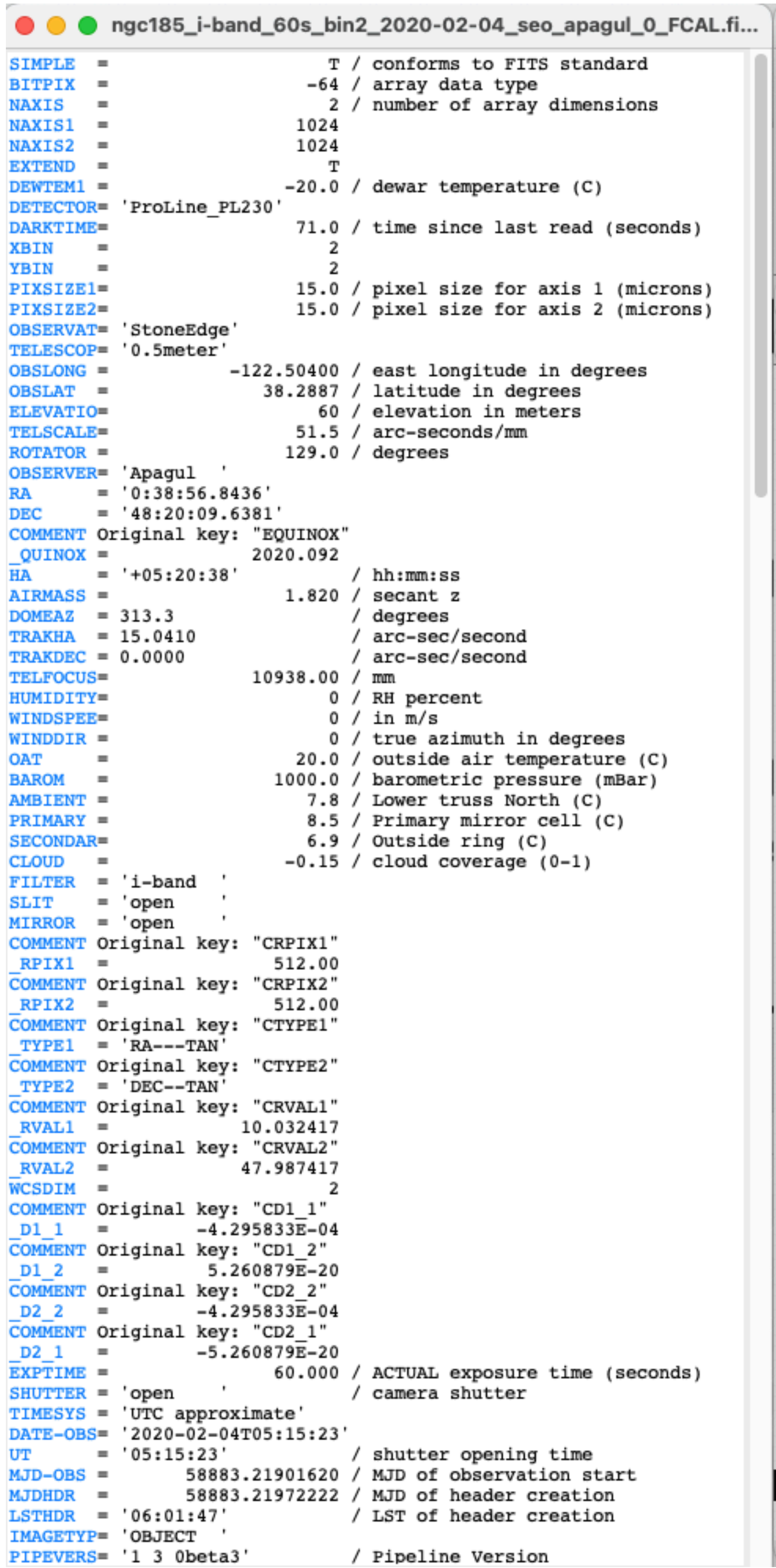
Thus, to go from image coordinates *(x,y)* to sky coordinates *(α,δ)*:

$$\begin{pmatrix} \alpha - \mathrm{CRVAL1} \\ \delta - \mathrm{CRVAL2} \end{pmatrix} = \begin{pmatrix} \mathrm{CD1\_1} & \mathrm{CD1\_2} \\ \mathrm{CD2\_1} & \mathrm{CD2\_2} \end{pmatrix} \begin{pmatrix} x - \mathrm{CRPIX1} \\ y - \mathrm{CRPIX2} \end{pmatrix}$$

Viewing FITS Images

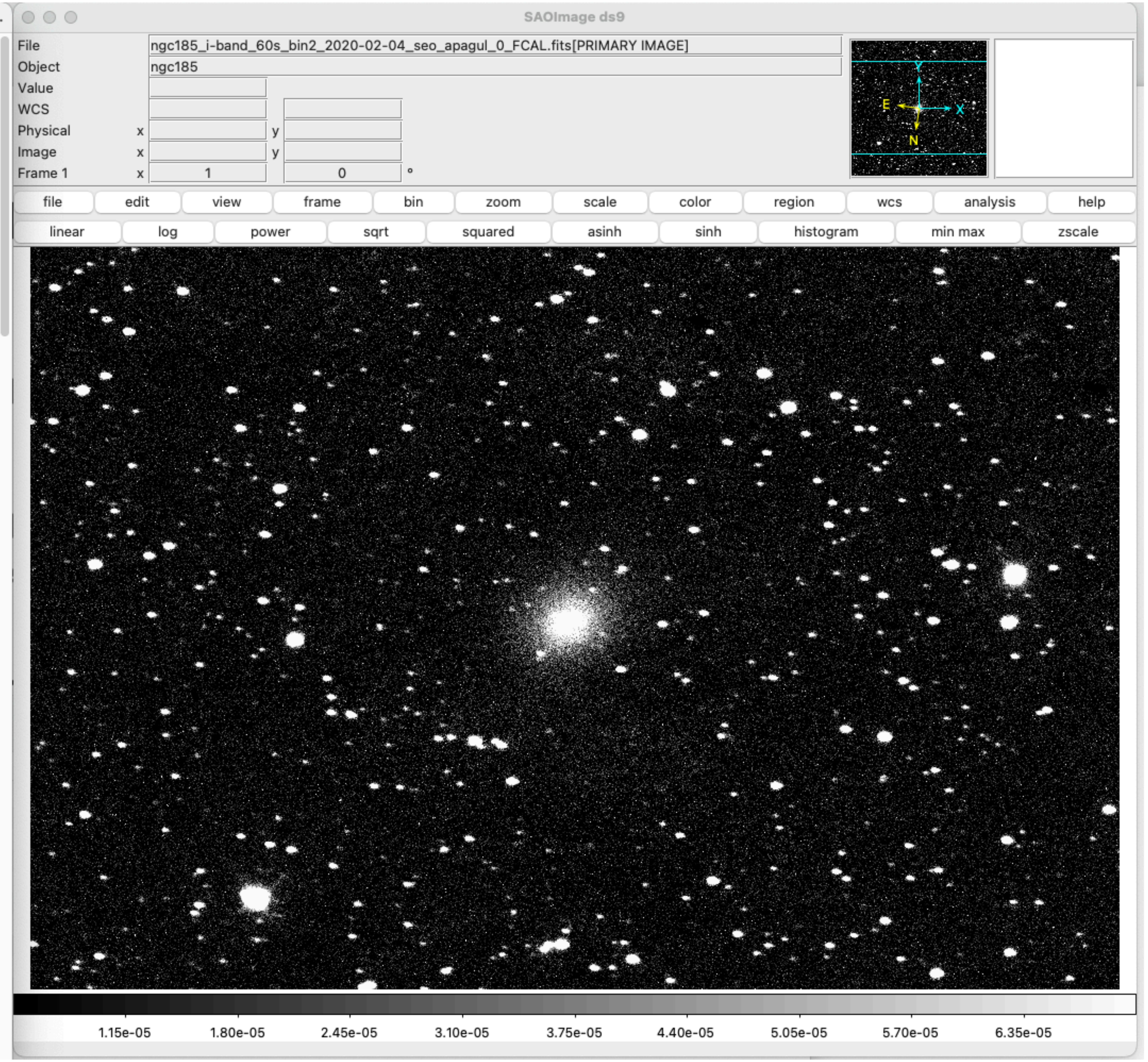
- Easiest done with specialize software
- Most common is **ds9**
    - https://sites.google.com/cfa.harvard.edu/saoimageds9
    - Also common to read fits files using most programming languages (e.g., python), and use standard astro packages for analyses (e.g., astropy)





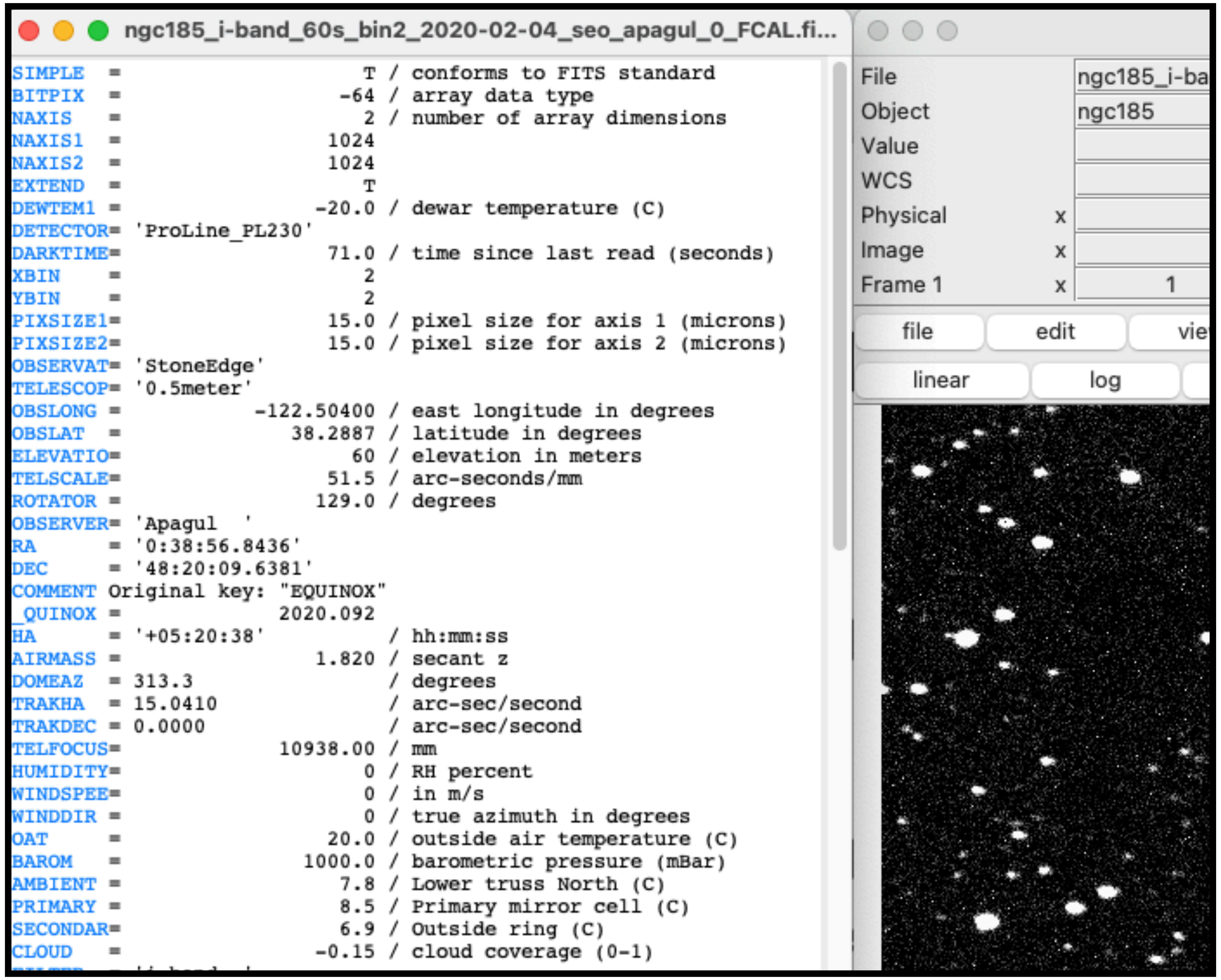
ngc185_i-band_60s_bin2_2020-02-04_seo_apagul_0_FCAL.fi...

```
SIMPLE  =                    T / conforms to FITS standard
BITPIX  =                  -64 / array data type
NAXIS   =                    2 / number of array dimensions
NAXIS1  =                 1024
NAXIS2  =                 1024
EXTEND  =                    T
DEWTEM1 =                -20.0 / dewar temperature (C)
DETECTOR= 'ProLine_PL230'
DARKTIME=                 71.0 / time since last read (seconds)
XBIN    =                    2
YBIN    =                    2
PIXSIZE1=                 15.0 / pixel size for axis 1 (microns)
PIXSIZE2=                 15.0 / pixel size for axis 2 (microns)
OBSERVAT= 'StoneEdge'
TELESCOP= '0.5meter'
OBSLONG =           -122.50400 / east longitude in degrees
OBSLAT  =              38.2887 / latitude in degrees
ELEVATIO=                   60 / elevation in meters
TELSCALE=                 51.5 / arc-seconds/mm
ROTATOR =                129.0 / degrees
OBSERVER= 'Apagul  '
RA      = '0:38:56.8436'
DEC     = '48:20:09.6381'
COMMENT Original key: "EQUINOX"
_QUINOX =             2020.092
HA      = '+05:20:38'          / hh:mm:ss
AIRMASS =                1.820 / secant z
DOMEAZ  = 313.3                / degrees
TRAKHA  = 15.0410              / arc-sec/second
TRAKDEC = 0.0000               / arc-sec/second
TELFOCUS=             10938.00 / mm
HUMIDITY=                    0 / RH percent
WINDSPEE=                    0 / in m/s
WINDDIR =                    0 / true azimuth in degrees
OAT     =                 20.0 / outside air temperature (C)
BAROM   =               1000.0 / barometric pressure (mBar)
AMBIENT =                  7.8 / Lower truss North (C)
PRIMARY =                  8.5 / Primary mirror cell (C)
SECONDAR=                  6.9 / Outside ring (C)
CLOUD   =                -0.15 / cloud coverage (0-1)
FILTER  = 'i-band  '
SLIT    = 'open    '
MIRROR  = 'open    '
COMMENT Original key: "CRPIX1"
_RPIX1  =               512.00
COMMENT Original key: "CRPIX2"
_RPIX2  =               512.00
COMMENT Original key: "CTYPE1"
_TYPE1  = 'RA---TAN'
COMMENT Original key: "CTYPE2"
_TYPE2  = 'DEC--TAN'
COMMENT Original key: "CRVAL1"
_RVAL1  =            10.032417
COMMENT Original key: "CRVAL2"
_RVAL2  =            47.987417
WCSDIM  =                    2
COMMENT Original key: "CD1_1"
_D1_1   =        -4.295833E-04
COMMENT Original key: "CD1_2"
_D1_2   =         5.260879E-20
COMMENT Original key: "CD2_2"
_D2_2   =        -4.295833E-04
COMMENT Original key: "CD2_1"
_D2_1   =        -5.260879E-20
EXPTIME =               60.000 / ACTUAL exposure time (seconds)
SHUTTER = 'open    '           / camera shutter
TIMESYS = 'UTC approximate'
DATE-OBS= '2020-02-04T05:15:23'
UT      = '05:15:23'           / shutter opening time
MJD-OBS =       58883.21901620 / MJD of observation start
MJDHDR  =       58883.21972222 / MJD of header creation
LSTHDR  = '06:01:47'           / LST of header creation
IMAGETYP= 'OBJECT  '
PIPEVERS= '1 3 0beta3'         / Pipeline Version
```



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

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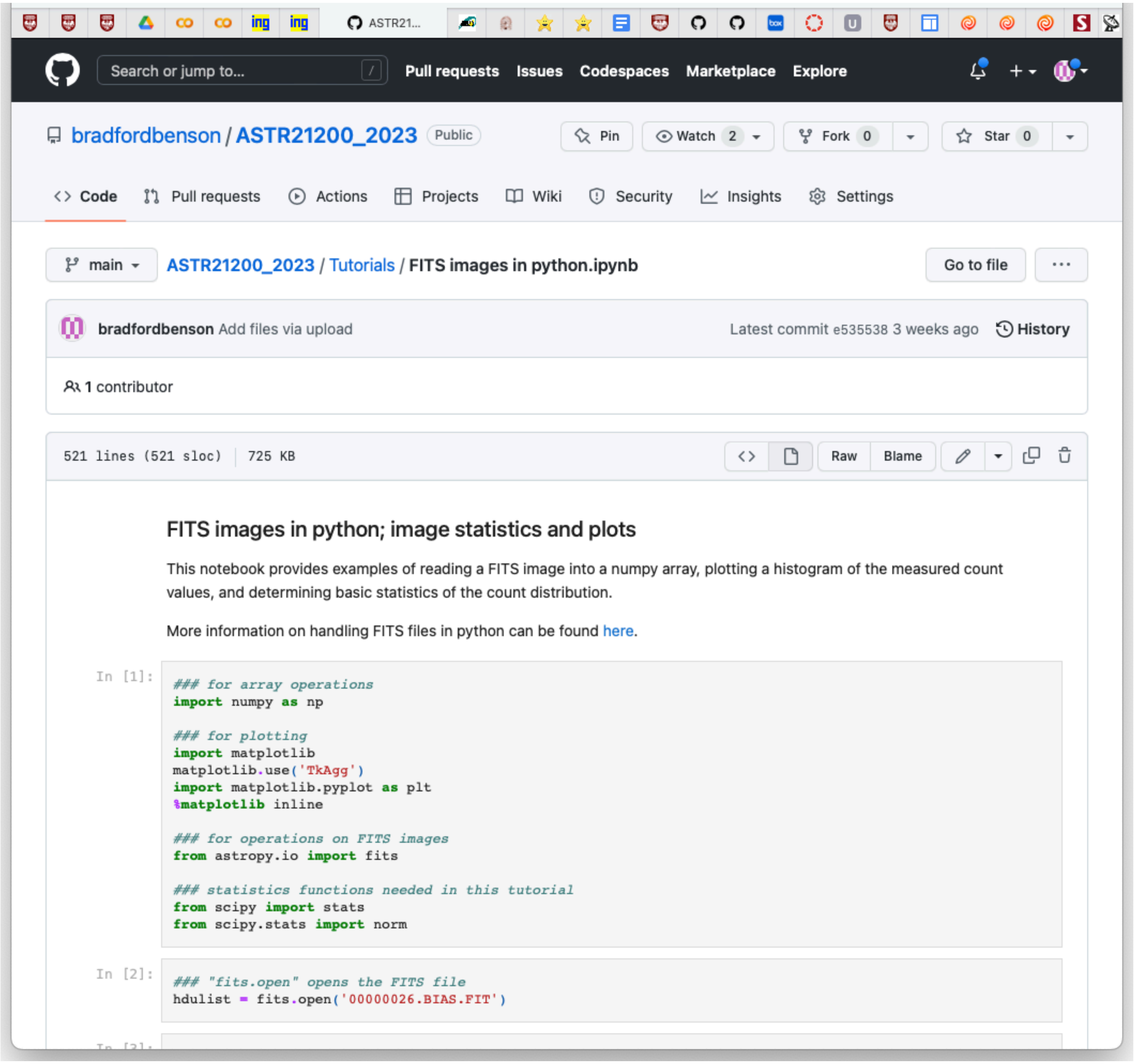
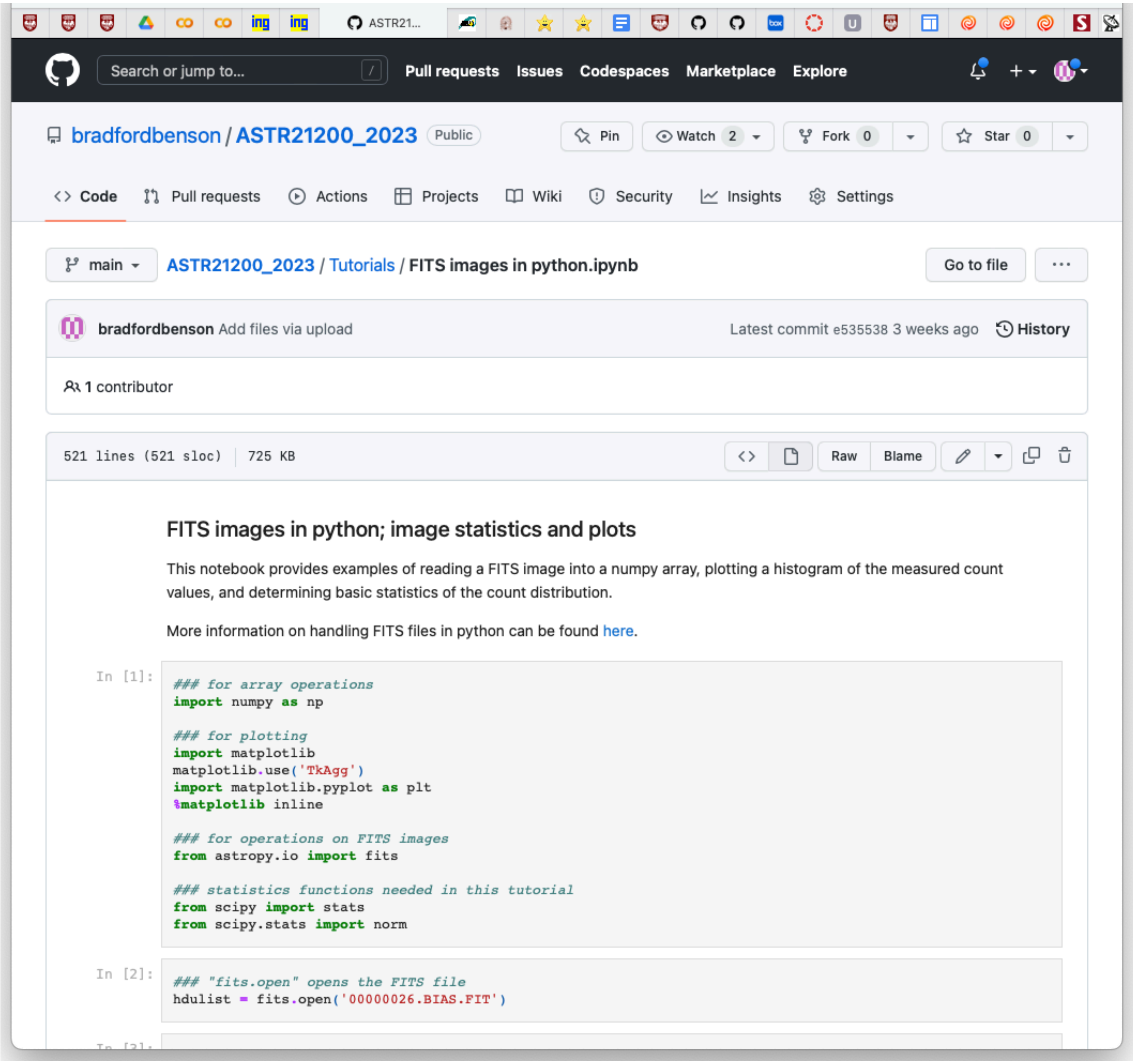


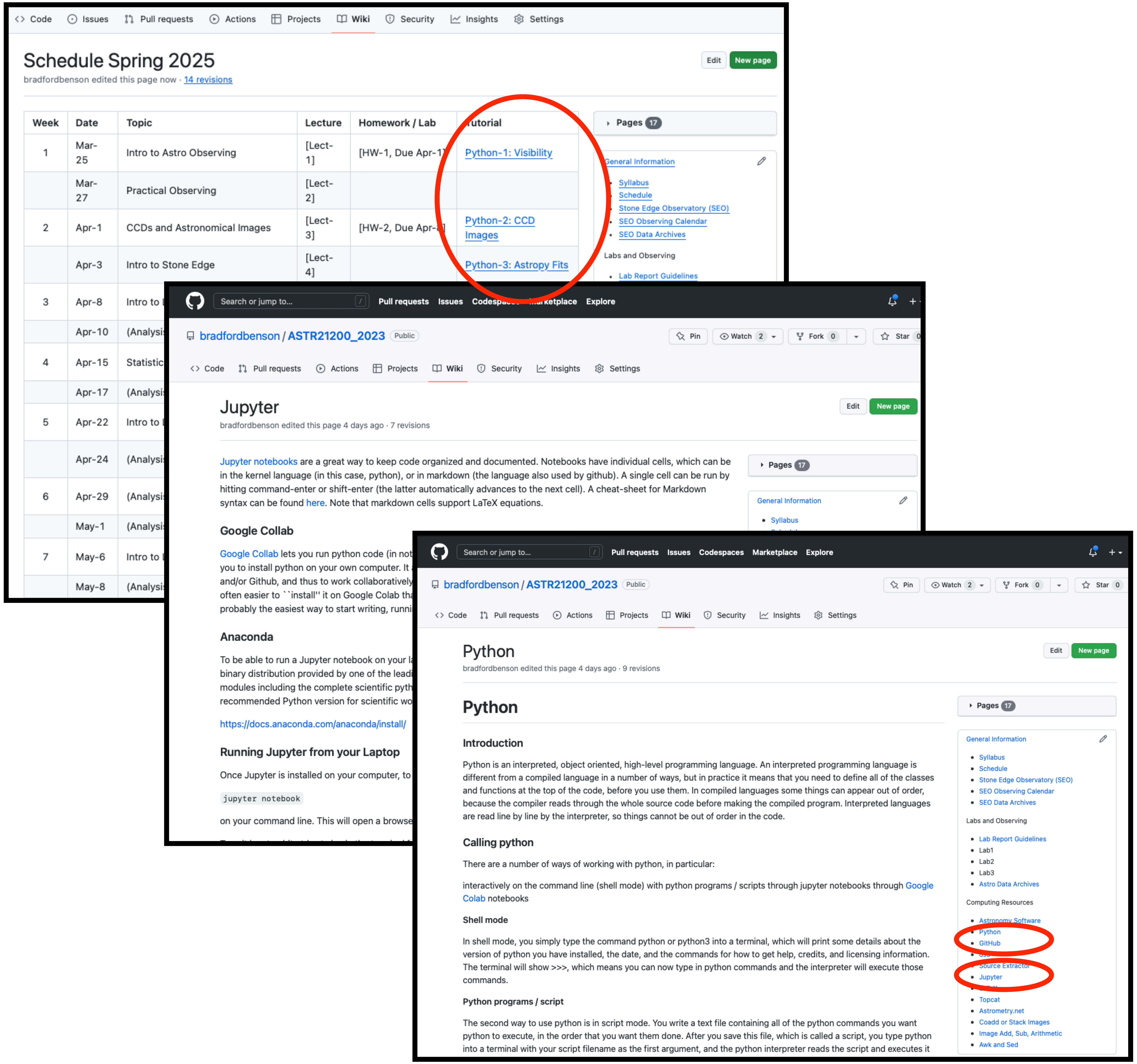
FITS Image Manipulation (Math)

- ***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



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



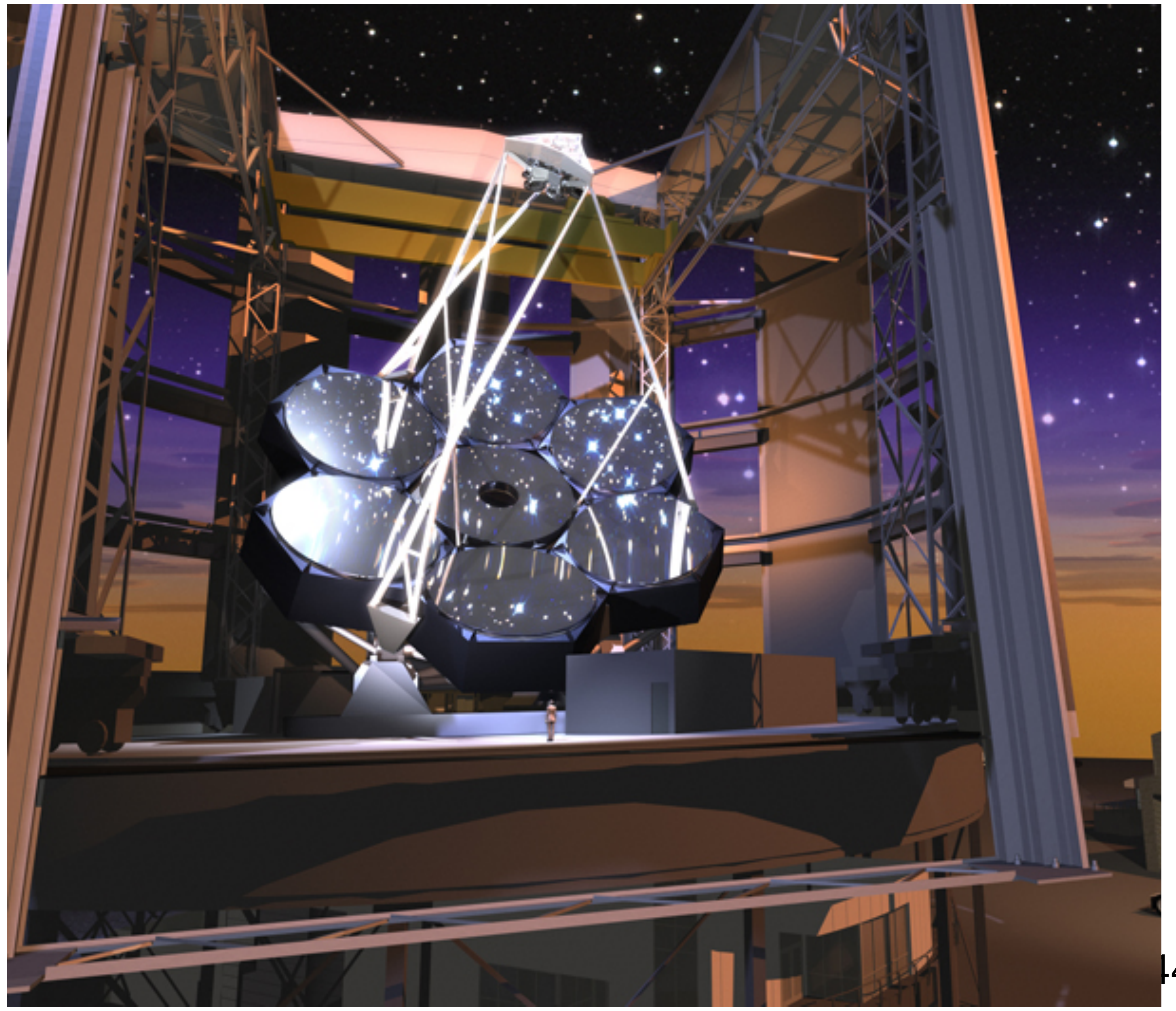
Putting it all Together: Telescopes and Different Cameras

- Astronomy is always trying to detect fainter objects
- So need to gather as much light as possible
- The diameter (aperture) of the mirror is one of the main characteristics of a telescope that determines its sensitivity (remember: Flux ~ dA)

Magellan Telescopes: 6.5-meter

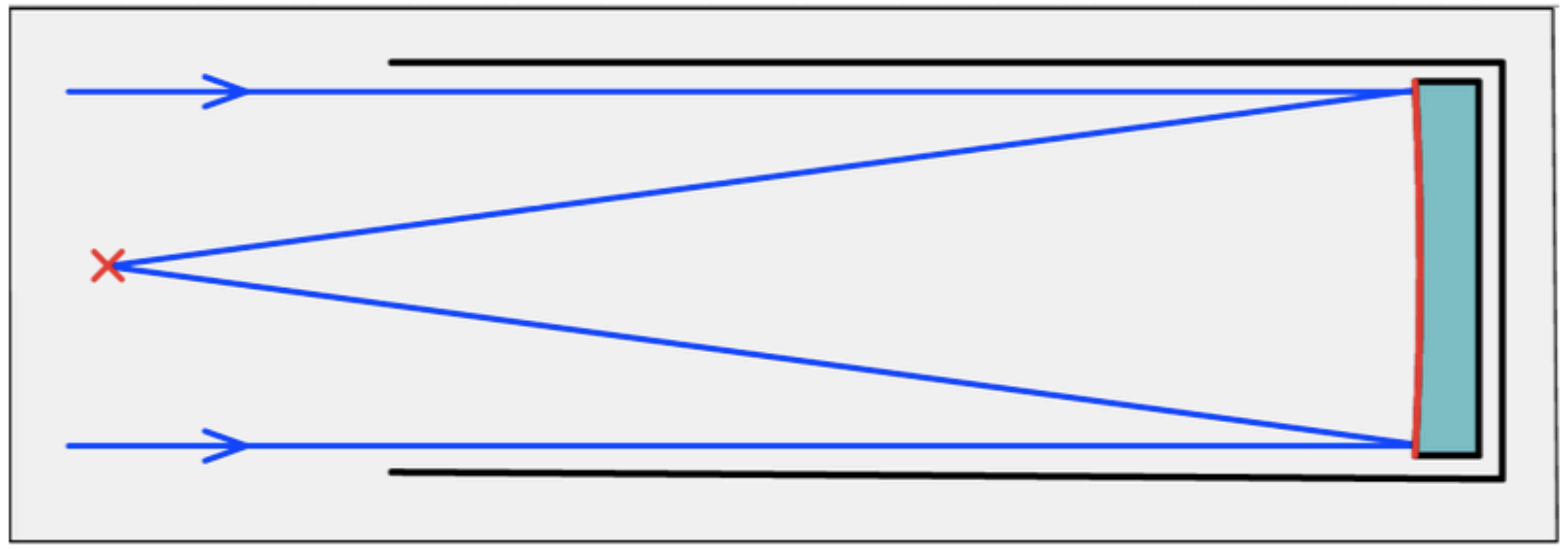
Keck Telescopes: 10-meter

Next-Generation 30-m telescopes (~2030s)
(Including the "Giant Magellan Telescope)

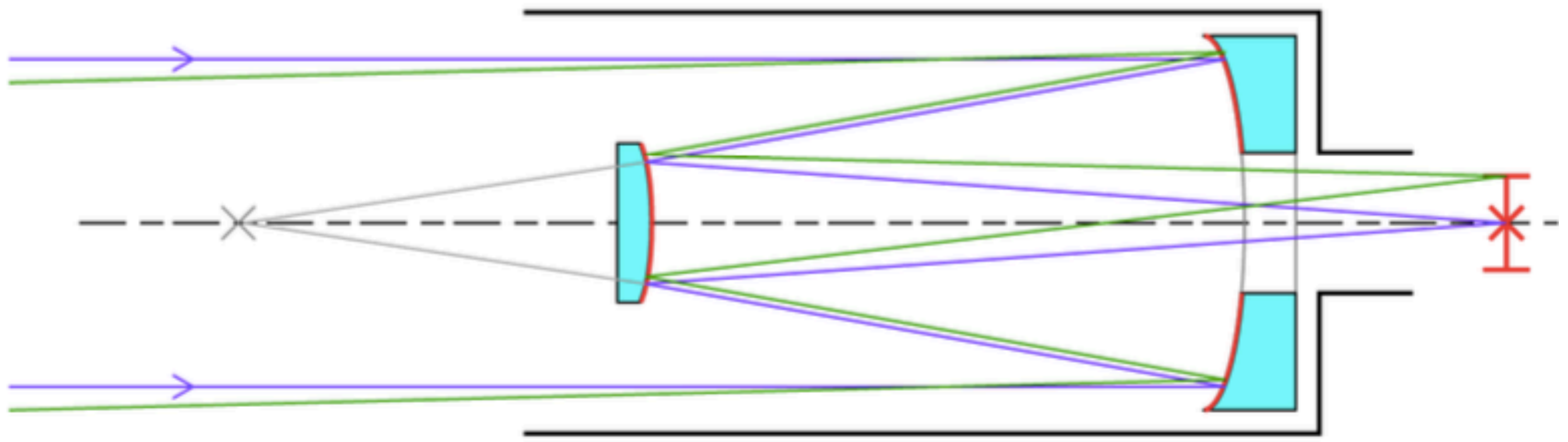


Telescope Foci

- prime focus: focus of primary mirror

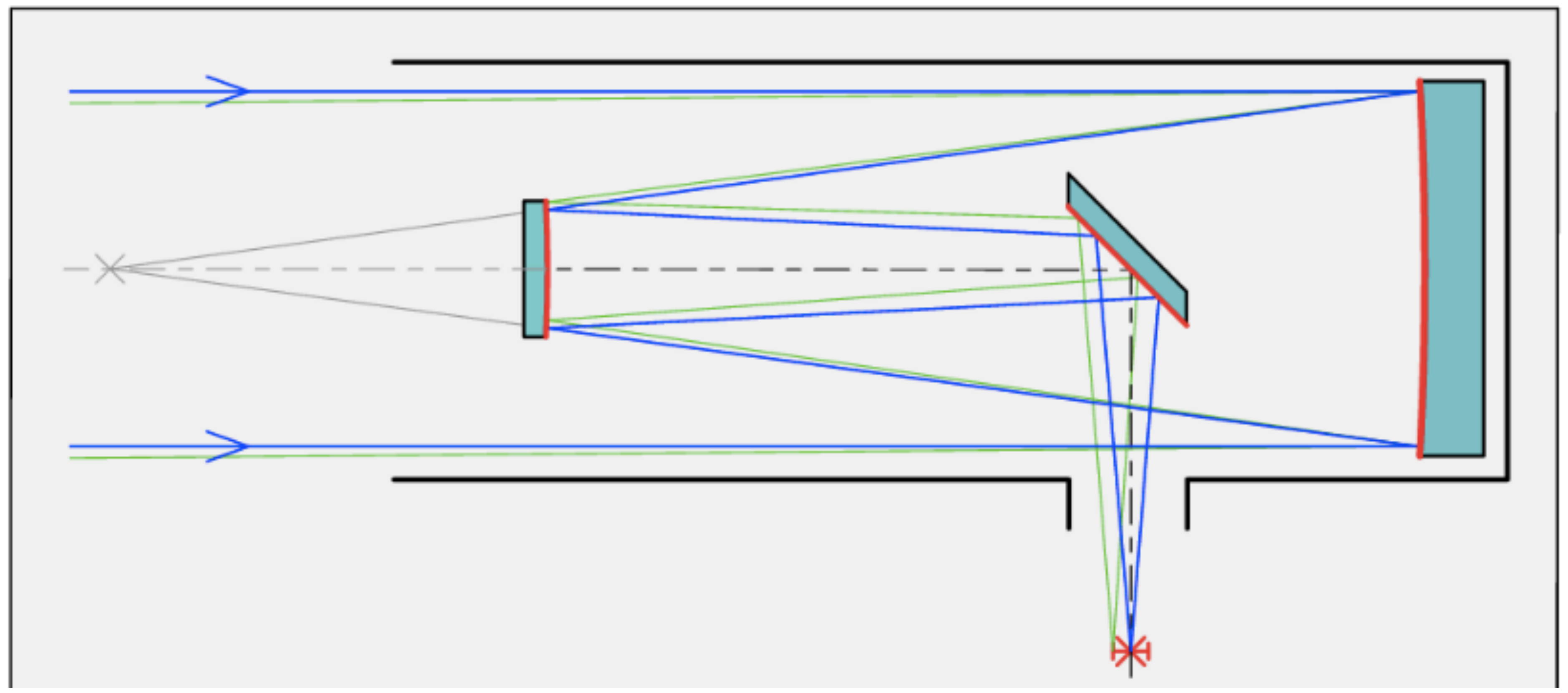


- Cassegrain focus: secondary mirror in front of prime focus; secondary focus behind primary mirror



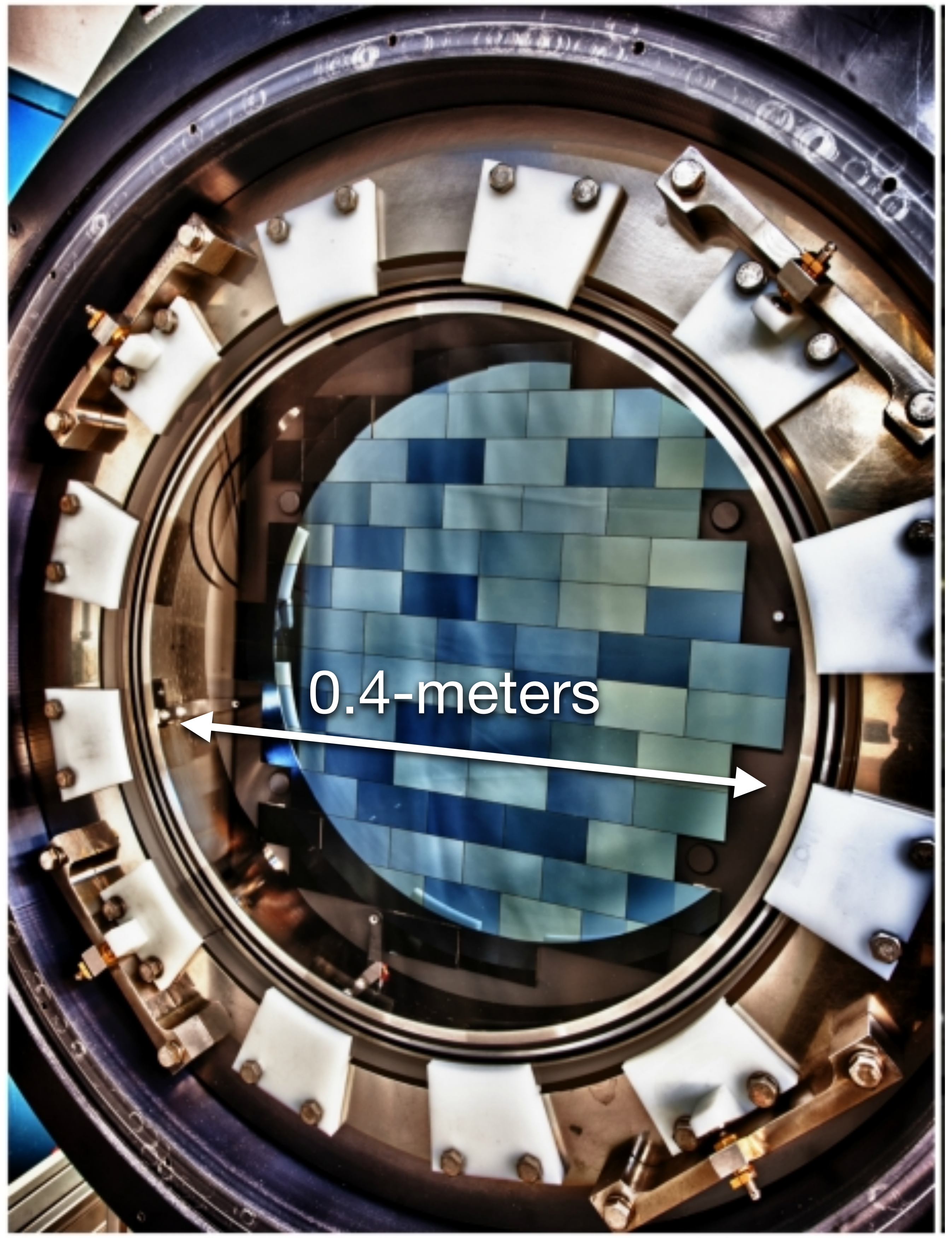
K. Vedala

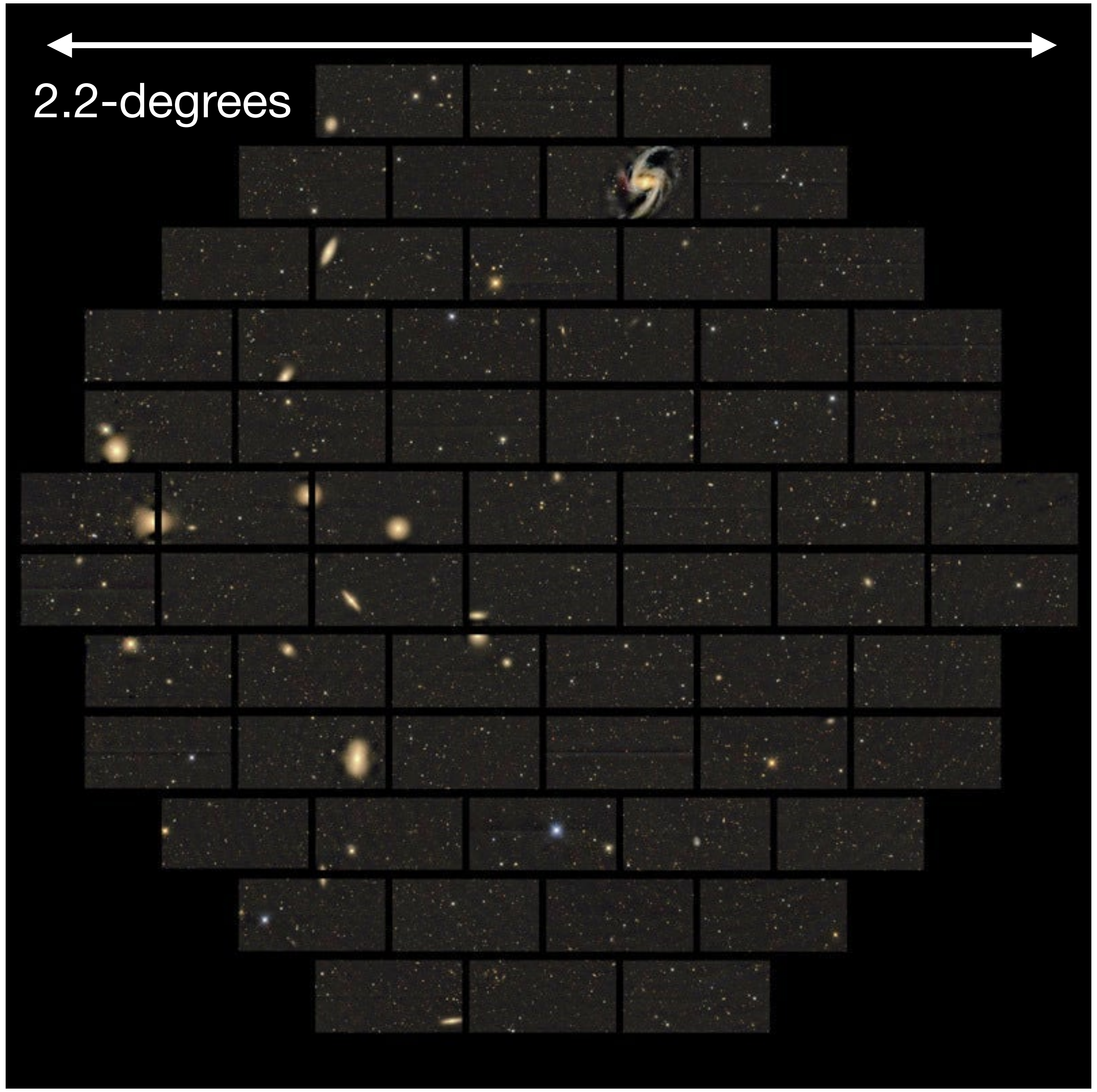
- Nasmyth focus: pick-up mirror, can be placed through mount axis

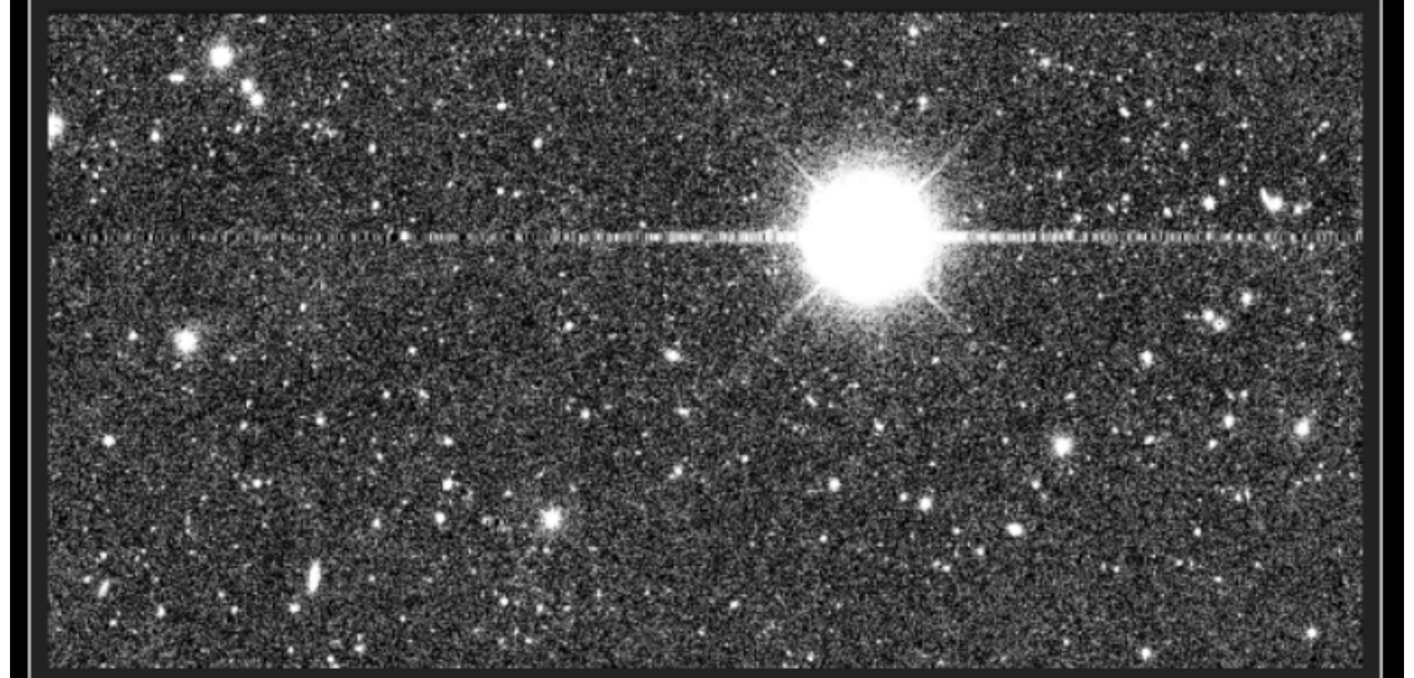


An example: Dark Energy Survey (DES)

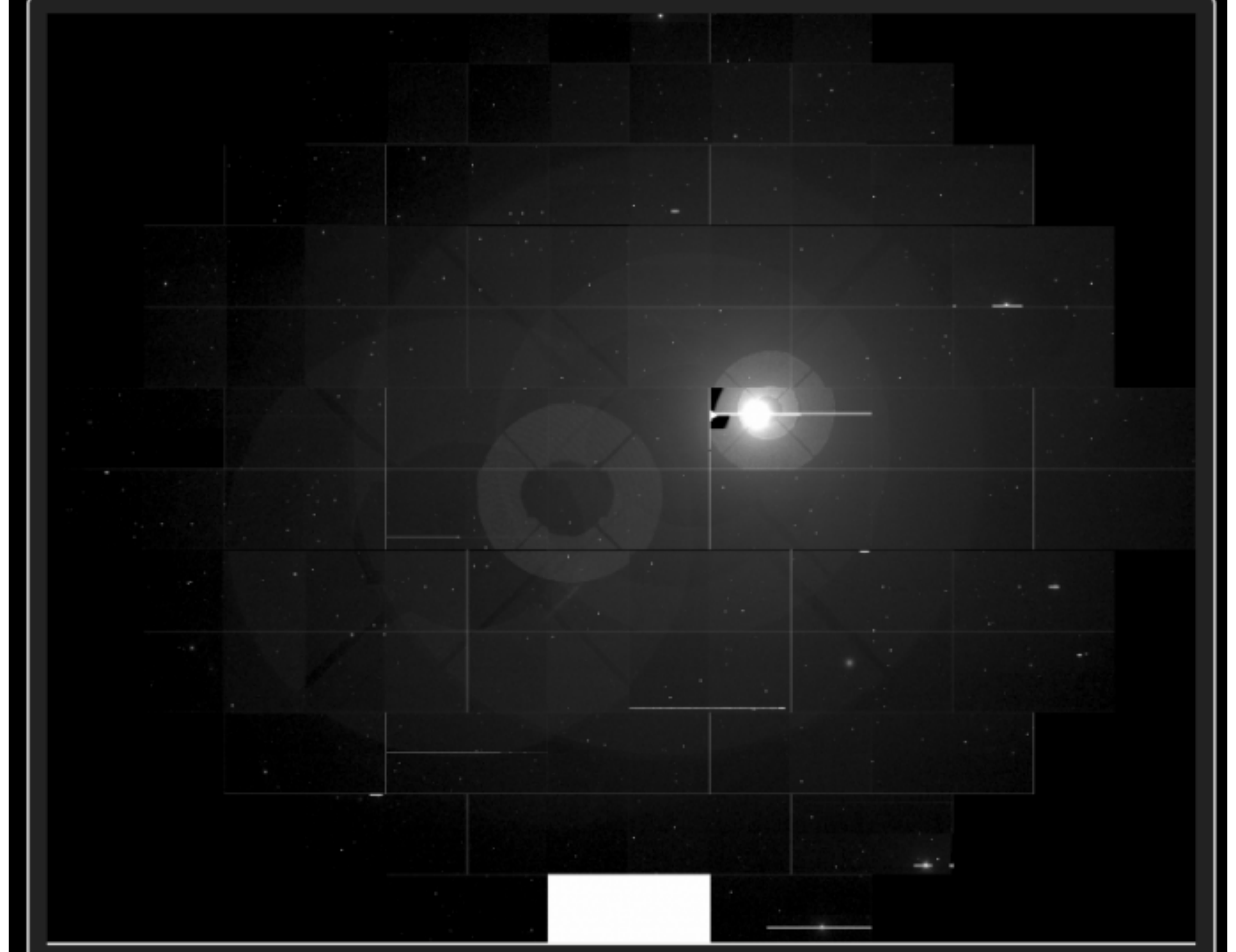
72 CCD wafers
570 million pixels (Megapixels)







A bright star “spills over” into the row of nearby pixels.



Achernar, aka Alpha Eri, the 10th brightest star in the sky, reflects off the structures that hold up DECam – right onto our image.

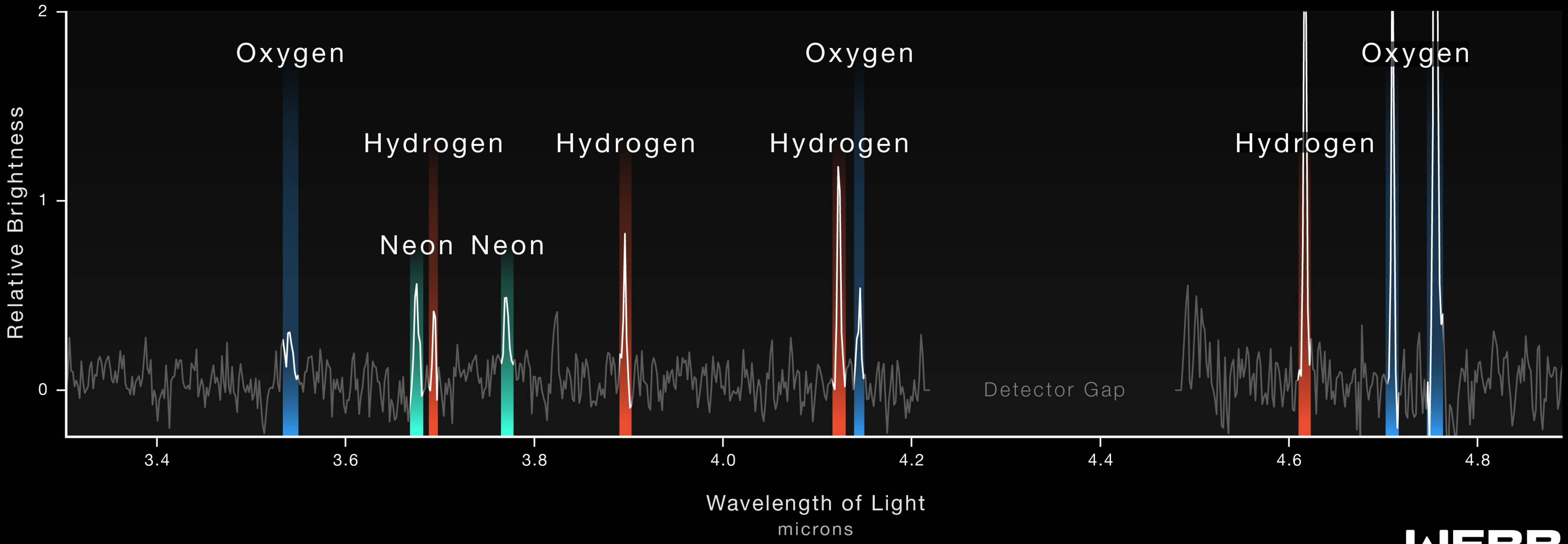
https://www.darkenergysurvey.org/darchive/journey-photon-camera-catalog/

DISTANT GALAXY BEHIND SMACS 0723

WEBB SPECTRUM SHOWCASES GALAXY'S COMPOSITION

NIRCam Imaging

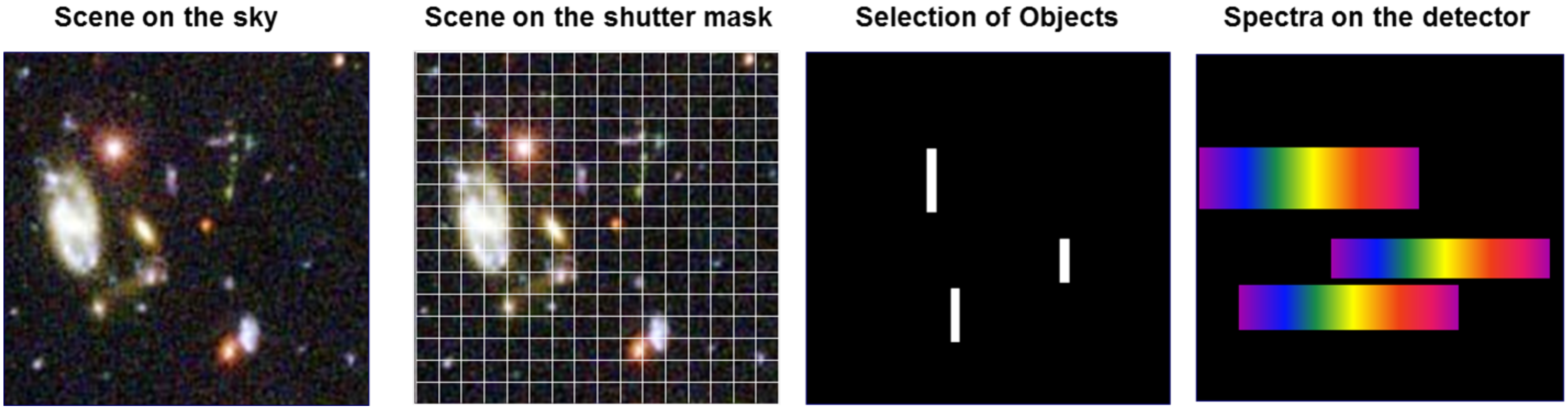
NIRSpec Microshutter Array Spectroscopy



WEBB SPACE TELESCOPE

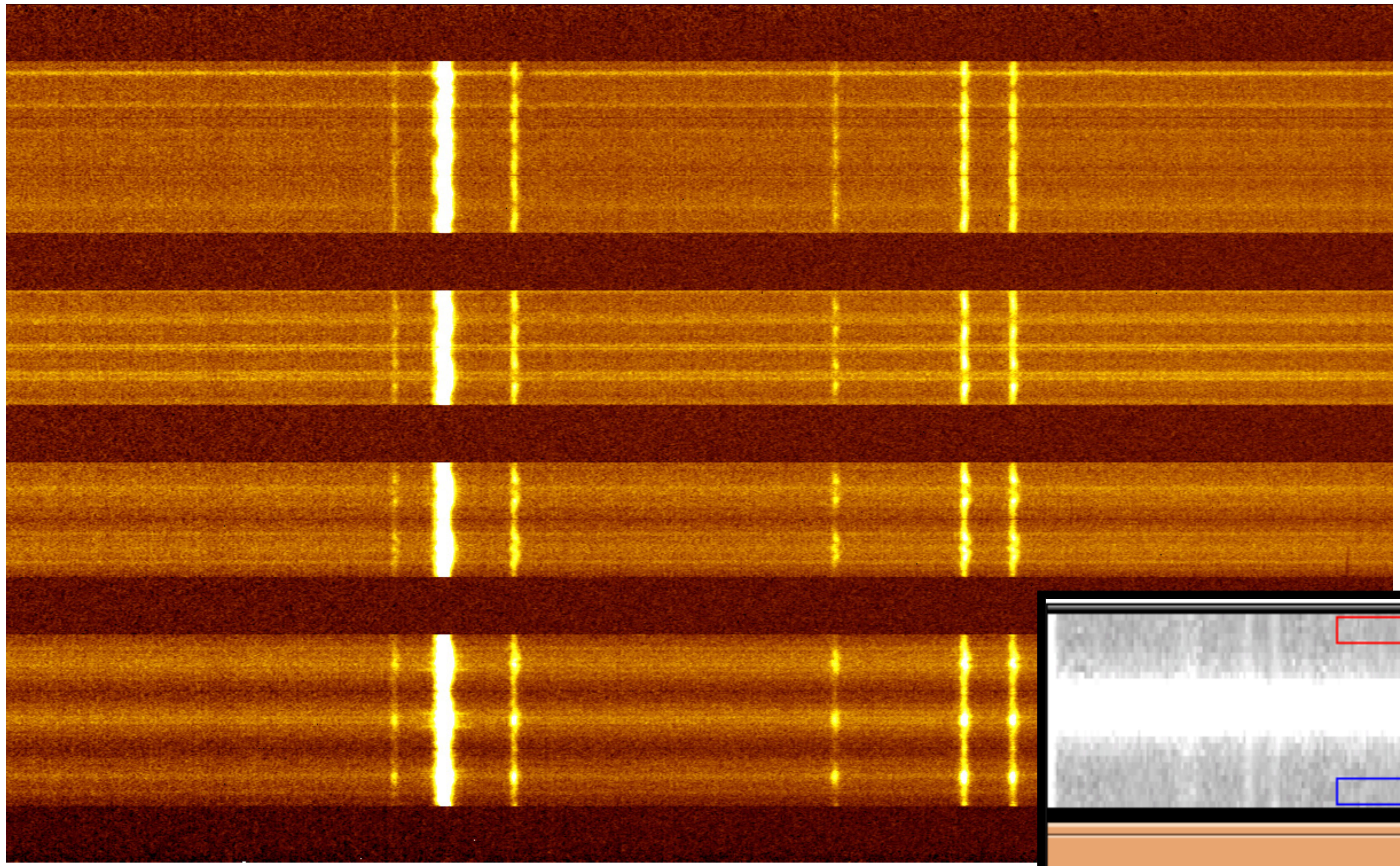
Slits and Spectroscopy

- 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



Intensity (x=λ, y)

Example Spectra on a CCD



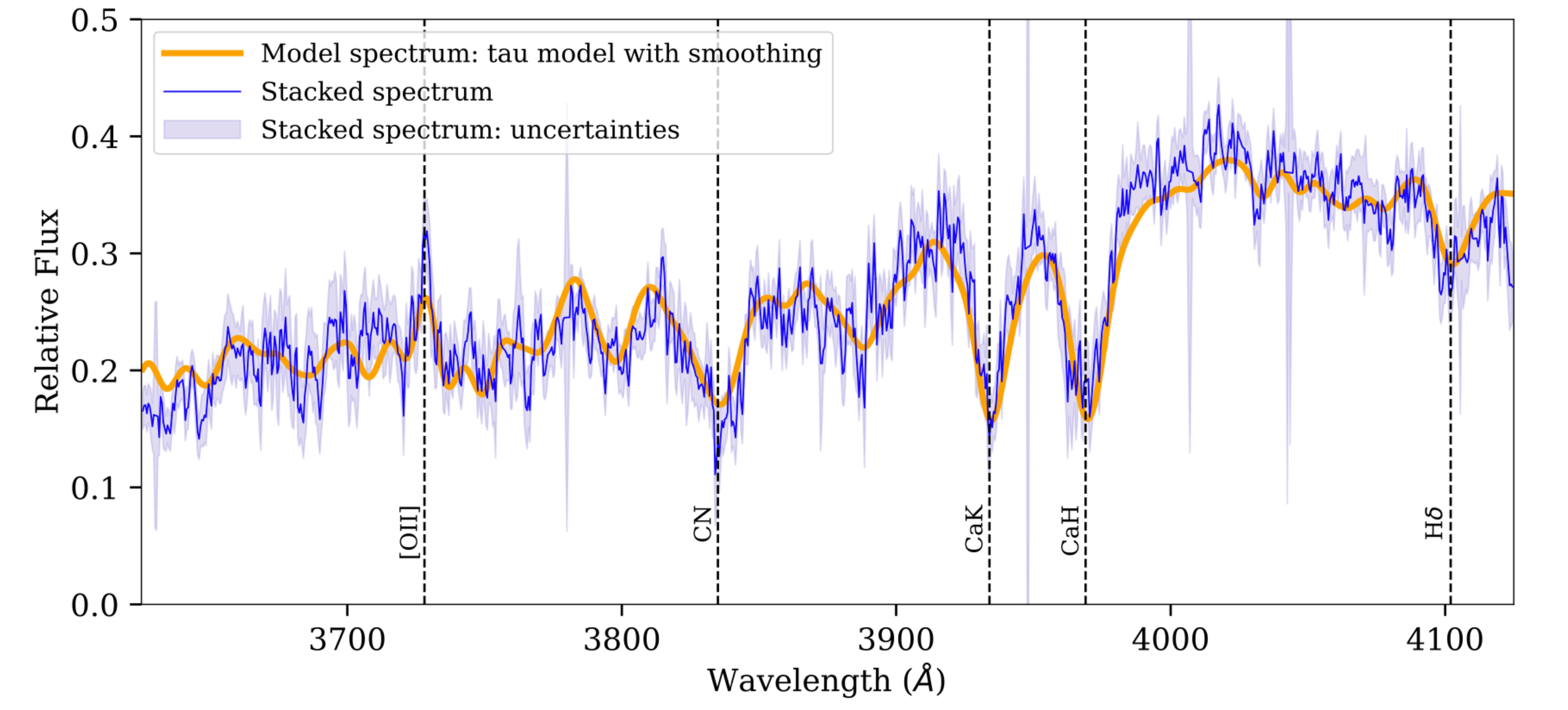


Figure 10. Stacked spectrum analysis for the 28 passive galaxies across 5 clusters reported in this paper. The light blue band corresponds to 68% confidence interval based on a linear combination of statistical and systematic uncertainties in the stack. Orange spectrum corresponds to an exponential tau model of star formation that is 1.7 Gyr old, at a metallicity log (Z/Z⊙) = +0.33 (see Section 5.5 for a more detailed description). Dotted lines correspond to rest frame [OII], CN, Ca II H&K, and Hδ features.

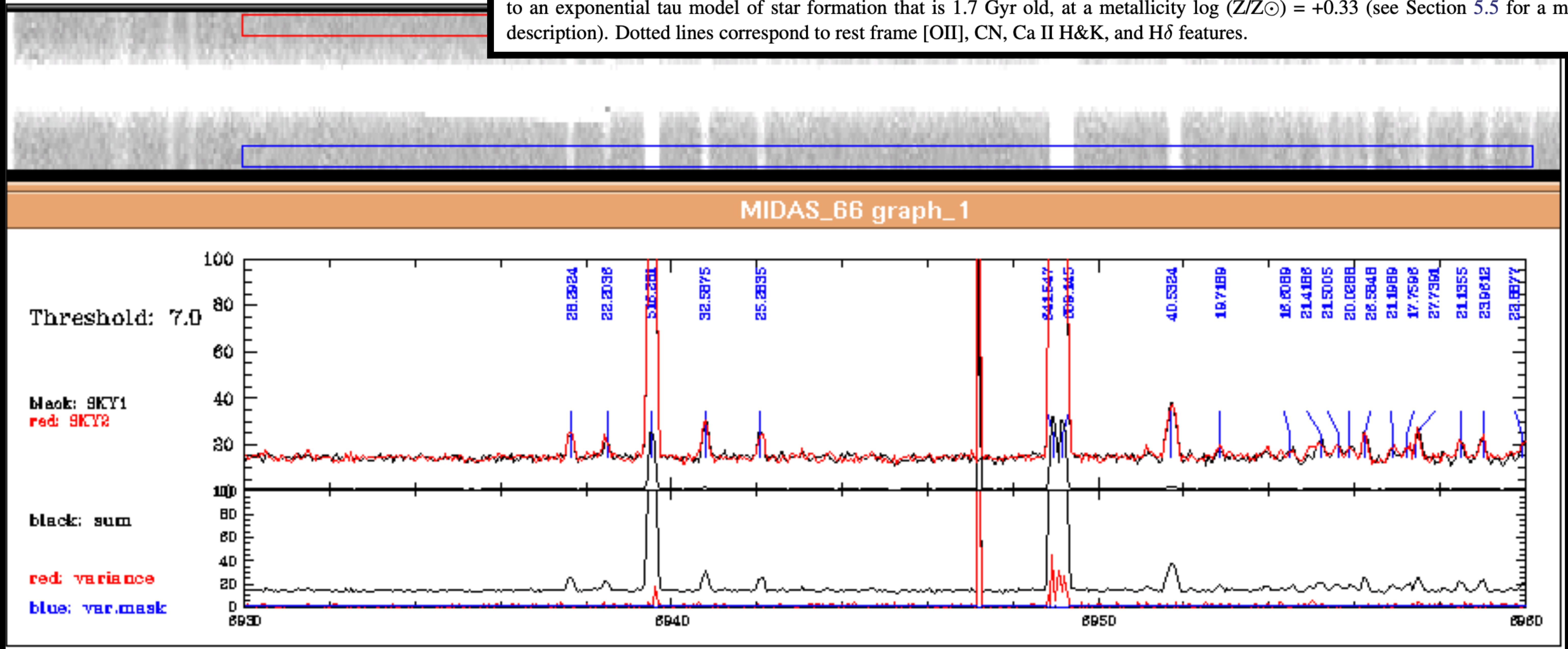
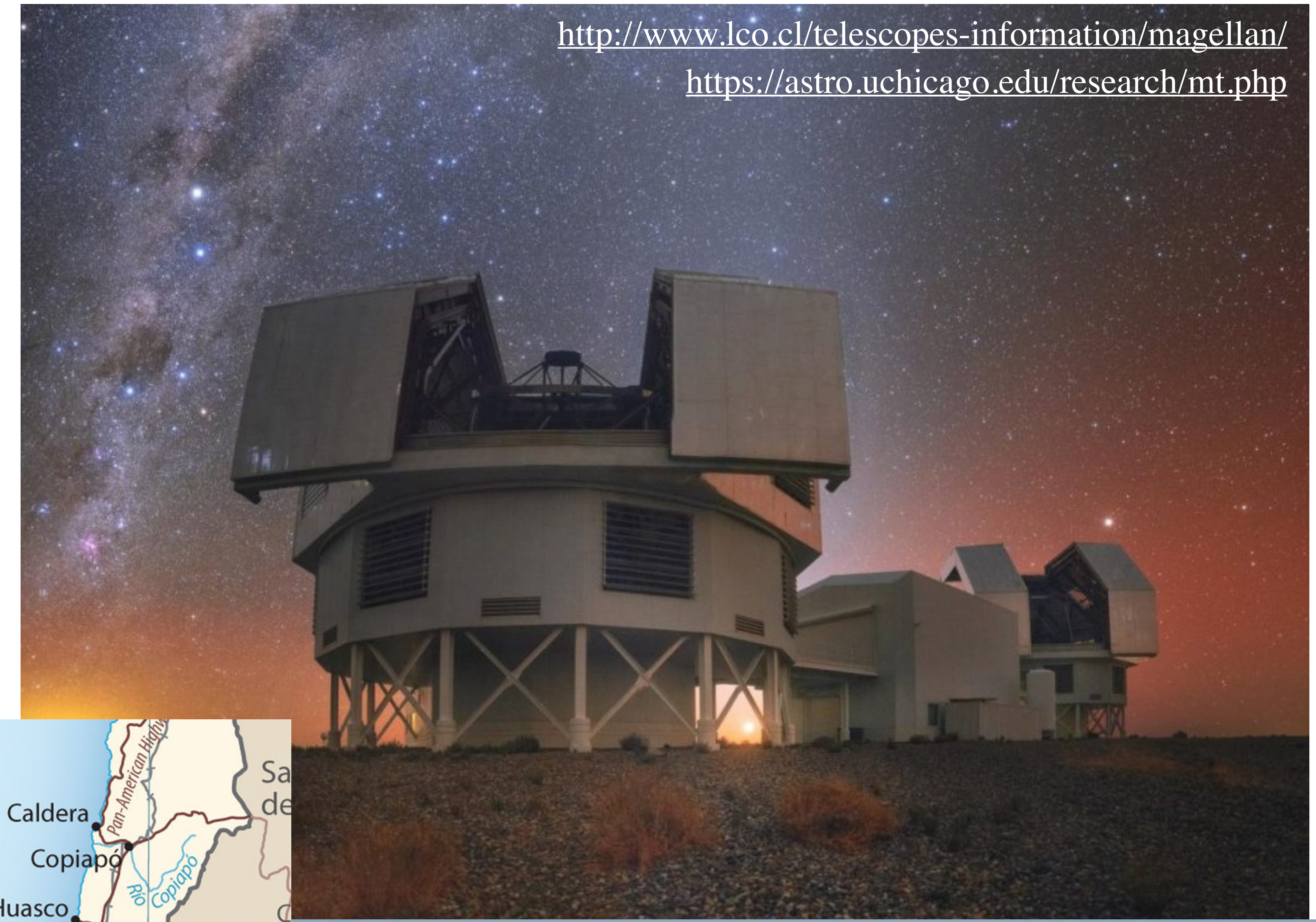


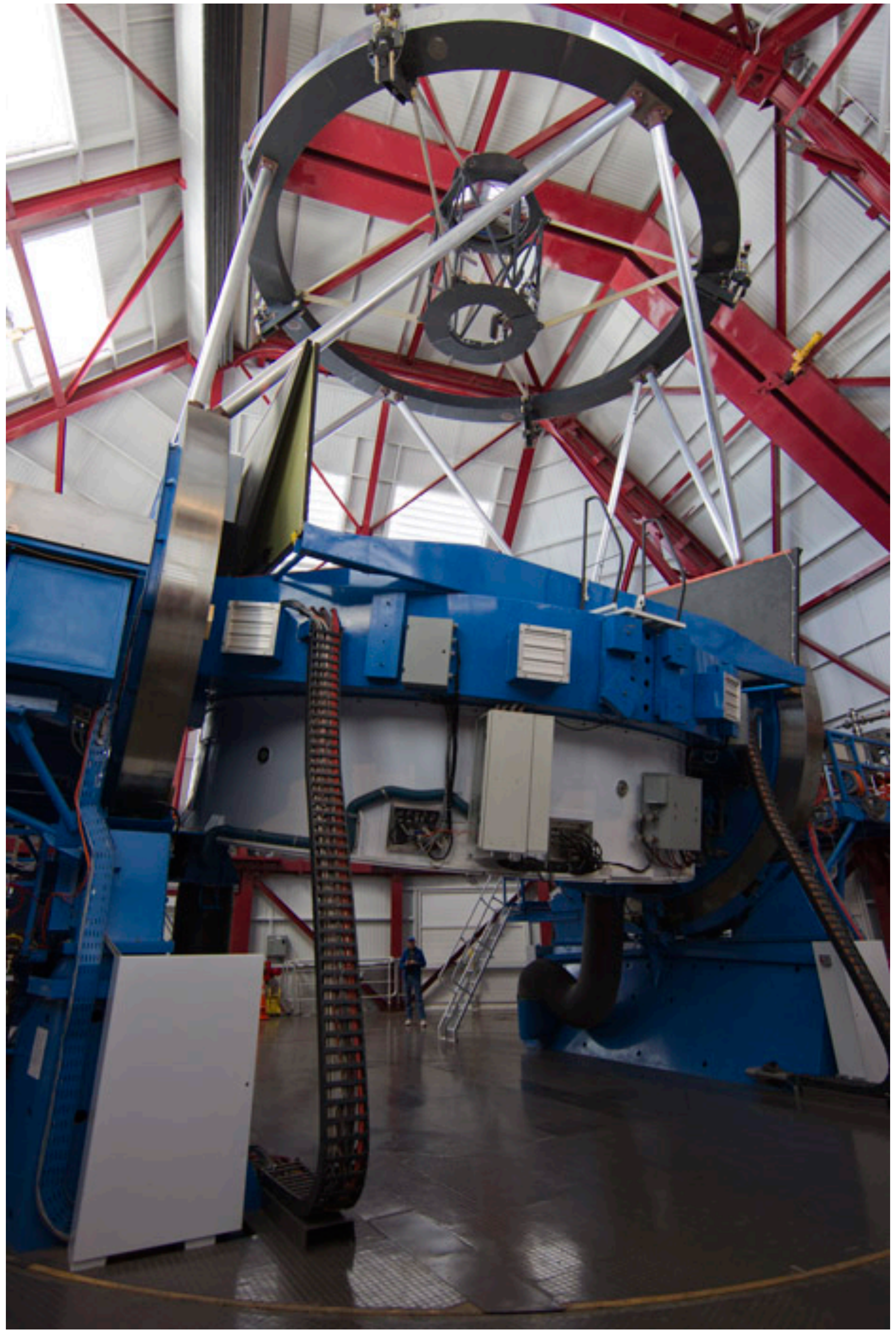
Fig. 1: Extraction and line identification. The upper display shows the pipeline-delivered 2D spectrum with slit coordinate in vertical direction. Blue and red frames mark the lower and upper sky windows. Bright and faint sky emission lines are readily visible. The lower graph has been used to identify emission lines. The black and red lines mark the *extracted* SKY windows. There is also a SKY plot at reduced intensity (factor 10) to show the brightest line profiles. The lowermost graph has the combined signal (SKY1+SKY2) and the difference spectrum (abs[SKY1-SKY2]). The difference (error) plot has been used to discriminate the extremely bright feature at 6947 (being due to a residual cosmic).

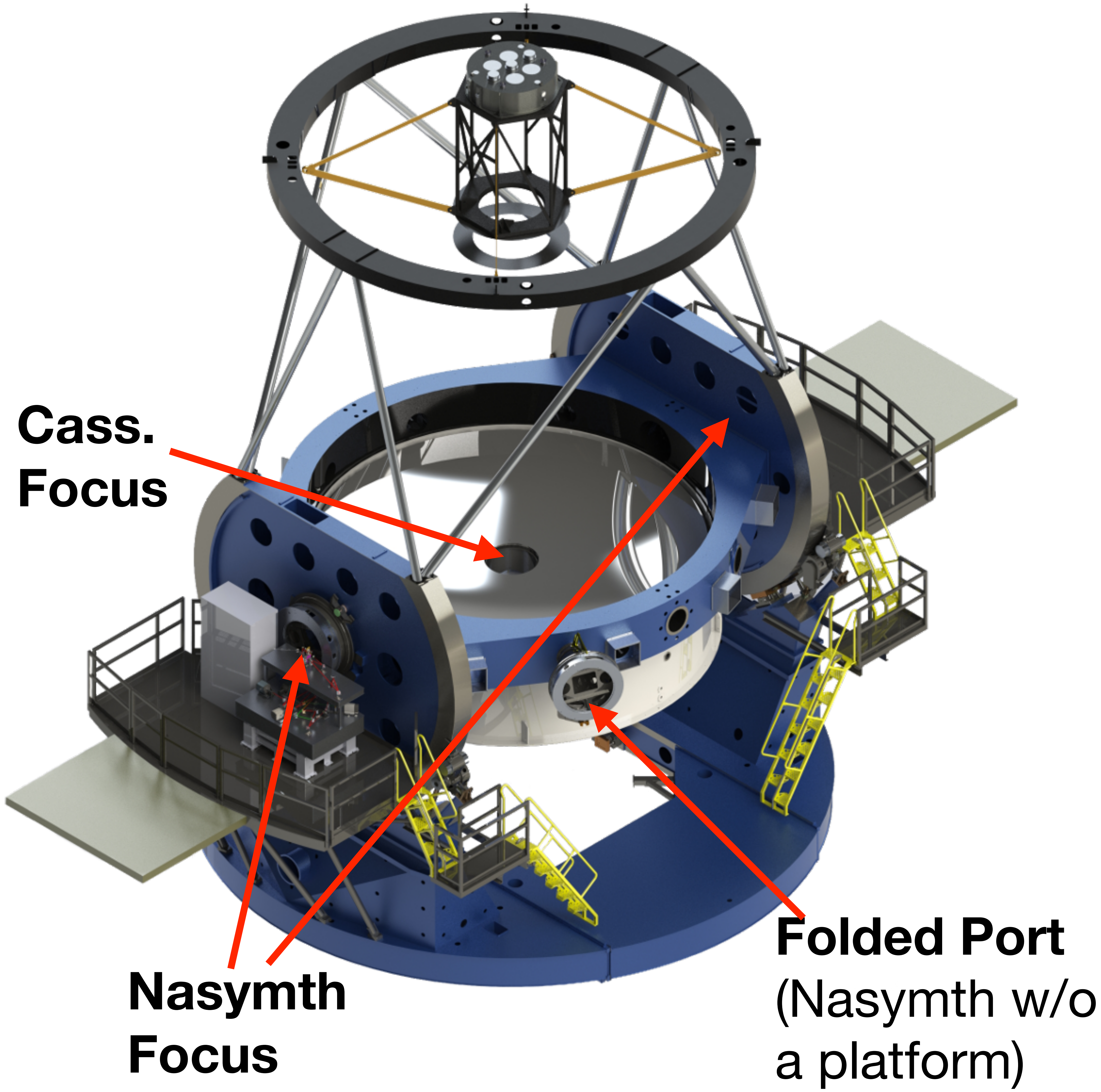
Telescopes: The Magellan Telescopes

- Magellan: Two 6.5-m telescopes (Baade, Clay)
- At <u>Las Campanas Observatory (LCO)</u> in Chile
  - 2500-m / 8500-ft
- U. Chicago has ~28-nights / year total on both telescope
  - Observing Semesters; UC proposals due in April and October each year
- LCO also future site of <u>Giant Magellan Telescope (GMT)</u>



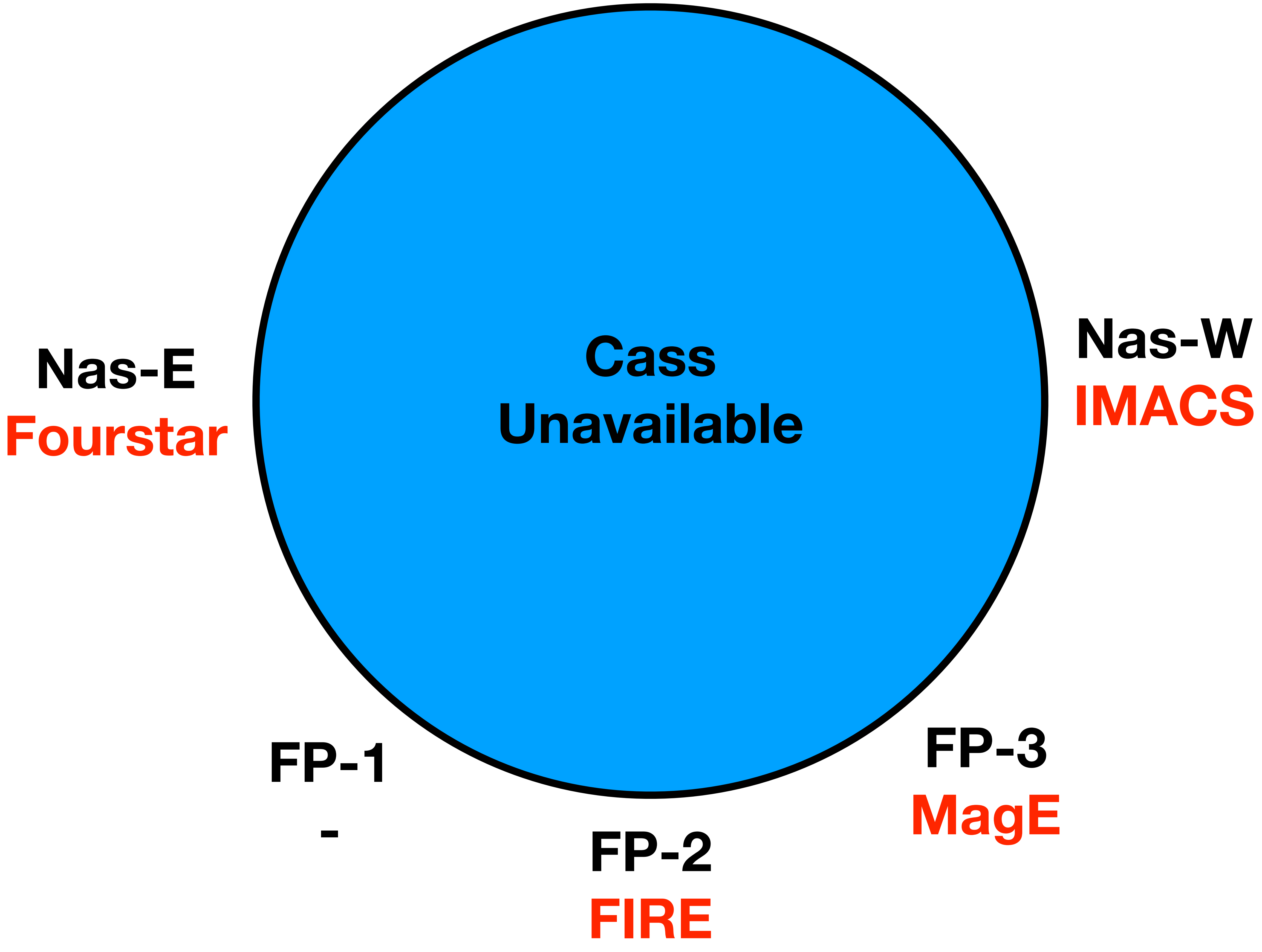
Magellan Instruments:

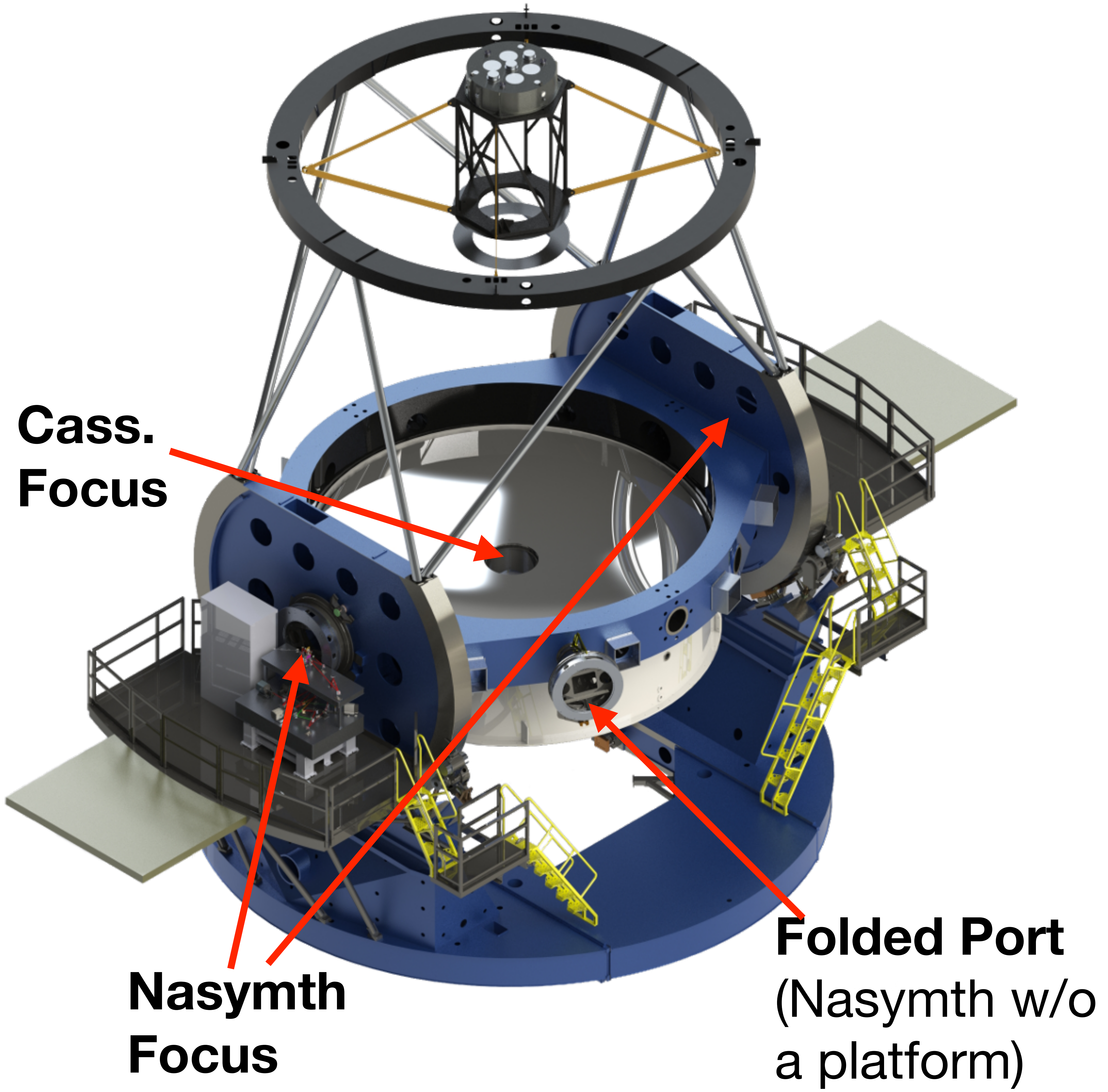




Magellan Instruments: Baade Telescope

Facility Instruments in Red
PI Instruments in Purple





Magellan Instruments: Clay Telescope

Facility Instruments in Red
PI Instruments in Purple

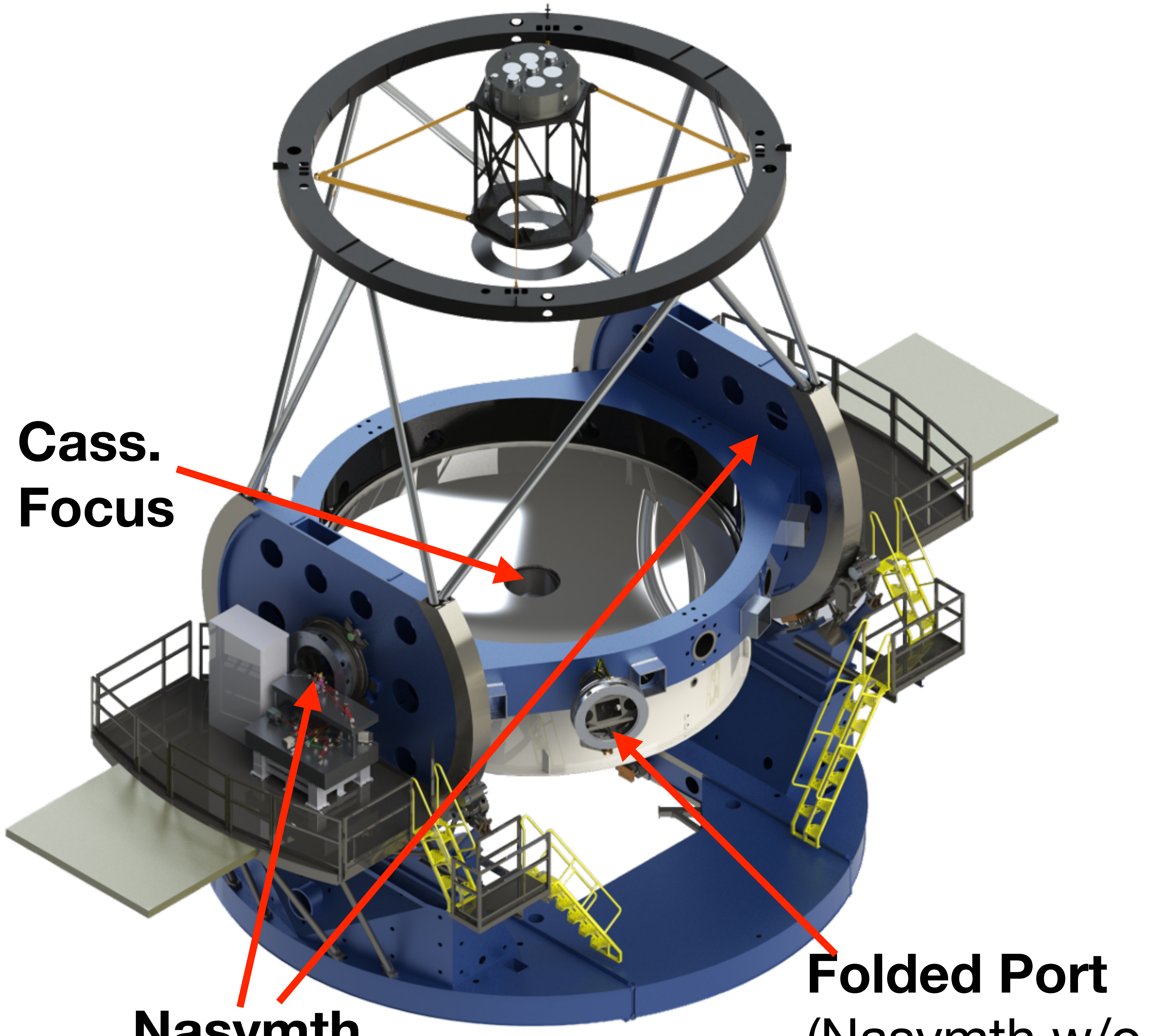
Nas-E
MIKE
MagAO (f/16)
PFS
M2FS
PISCO
POETS

Cass
Unavailable

FP-1
-

FP-2
-

FP-3
-



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

- f/5 -

- ***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

Clay

2017 Instrument Suite

Magellan Instruments

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

Instrument suite:

R=Spectral Resolution
$R = \lambda / \Delta\lambda$

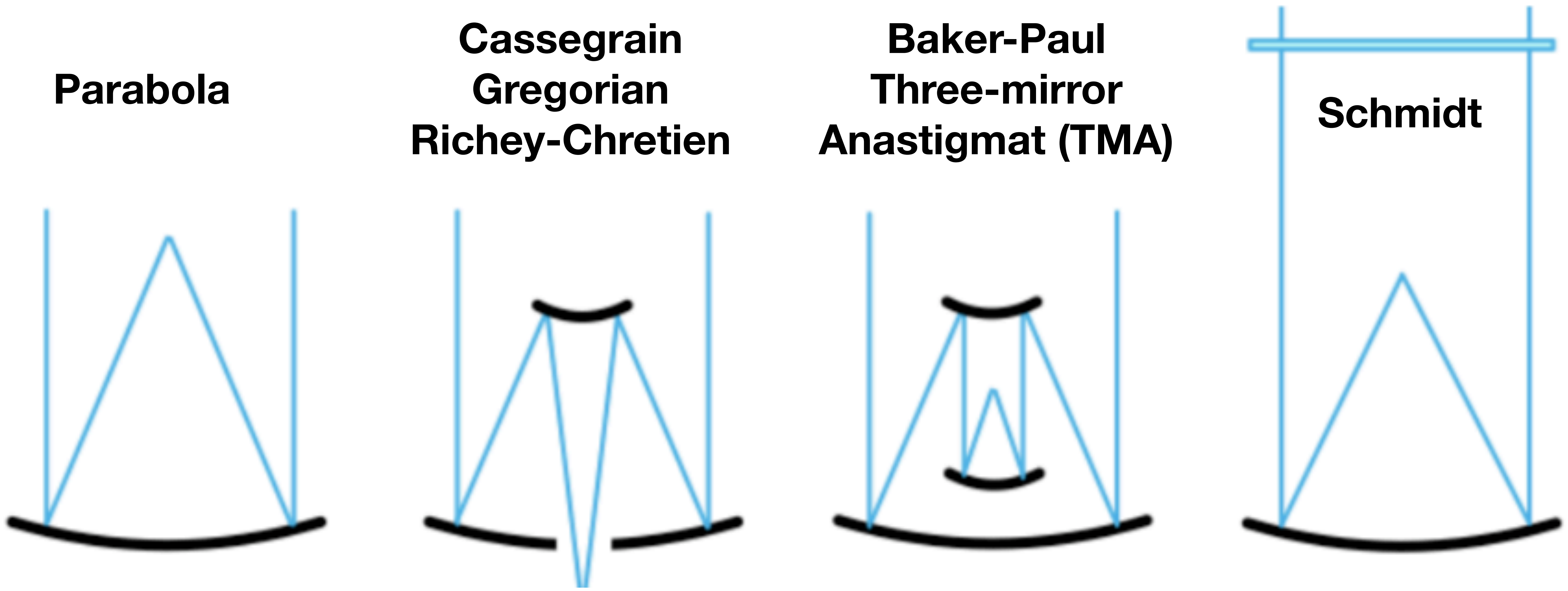
Telescope	Instrument	Type	Wavelength	Wavelength range	FOV (arcmin)	R (for spectrographs)	Pixelscale, arsec/pix
6.5-m Magellan Baade	IMACS	imager / multislit spectrograph	optical	365-1000 nm	14' or 24-27'	500 .. 20000	0.11 or 0.2
	FOURSTAR	imager	infrared	1000 - 2510 nm	10.8 x 10.8'	-	0.16
	FIRE	spectrograph	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 the Next ~Week

- Homework 2 is due on Tues Apr-8 at 5pm, right before class
    - On class schedule on wiki:
    - Submit on Canvas (with hopefully right link)
- Office hours will start tomorrow!
    - Logan: Friday 3:30-4:30pm (ERC 583)
    - Emory: Monday: 3-4pm (KPTC 320)
    - Brad: Tuesday: 11am-12 (ERC 589)
    - Marc: Tuesday: 3-4pm (ERC 524)
- This Thursday's class:
    - Intro to SEO lecture will be taught by Marc Berthoud
    - After class, Marc will be running through some remote SEO tutorials/demos for those who are interested.

Extras

Correcting Aberrations



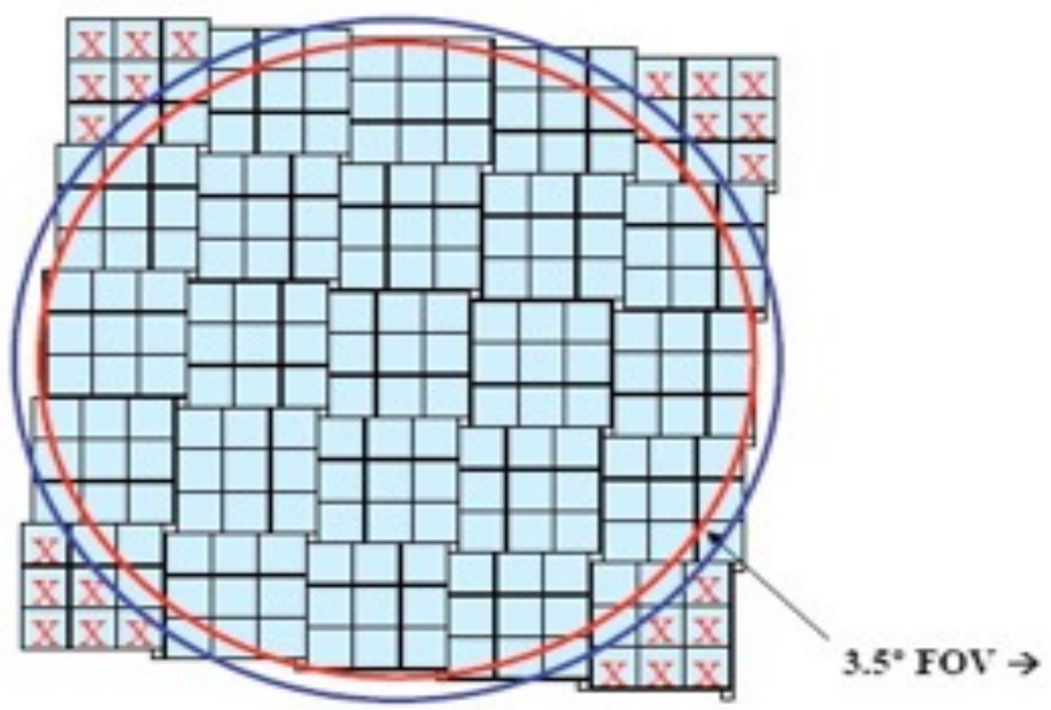
- Generally possible to correct for one aberration per optical surface
- **Parabolic** mirror: corrects spherical aberration
- **Cassegrain** or **Gregorian** (2-mirror) corrects for only spherical aberation
- **Richey-Chretien** (2-mirror) corrects spherical aberration and coma by using a hyperbolic primary (in place of parbolic primary in Cassegrain ssystem)
  - Most modern telescopes are RC, e.g., Hubble, Keck, VLT
- **Baker-Paul / TMA** (3-mirror) corrects for spherical aberration, coma, and astigmatism
  - Gives wider field-of-fiew, e.g., LSST, JWST, WFIRST, SP-TMA
- **Schmidt** telescope (spherical mirror+thin lens/corrector plate)
  - Efficient way to achieve large field-of-view with only one reflector (e.g., Kepler)

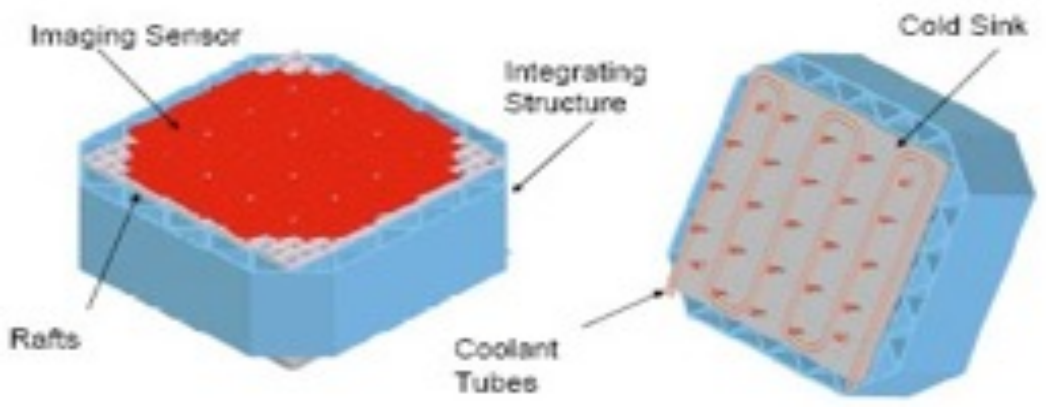
Large Synoptic Survey Telescope

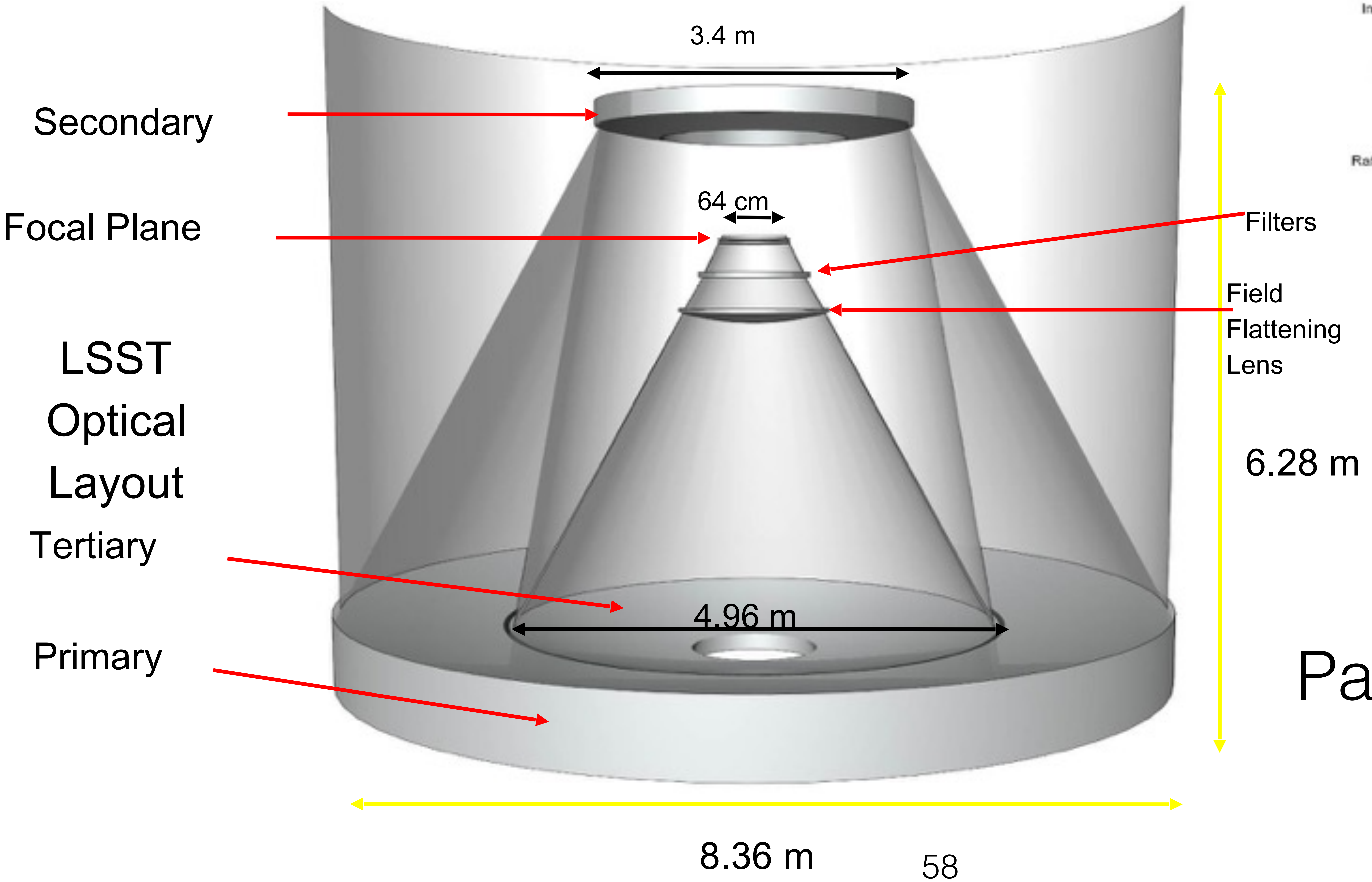
3.5° field of view for all-sky survey

Primary and Tertiary mirrors to be made at Arizona *on the same substrate*

200 4k x 4k detectors

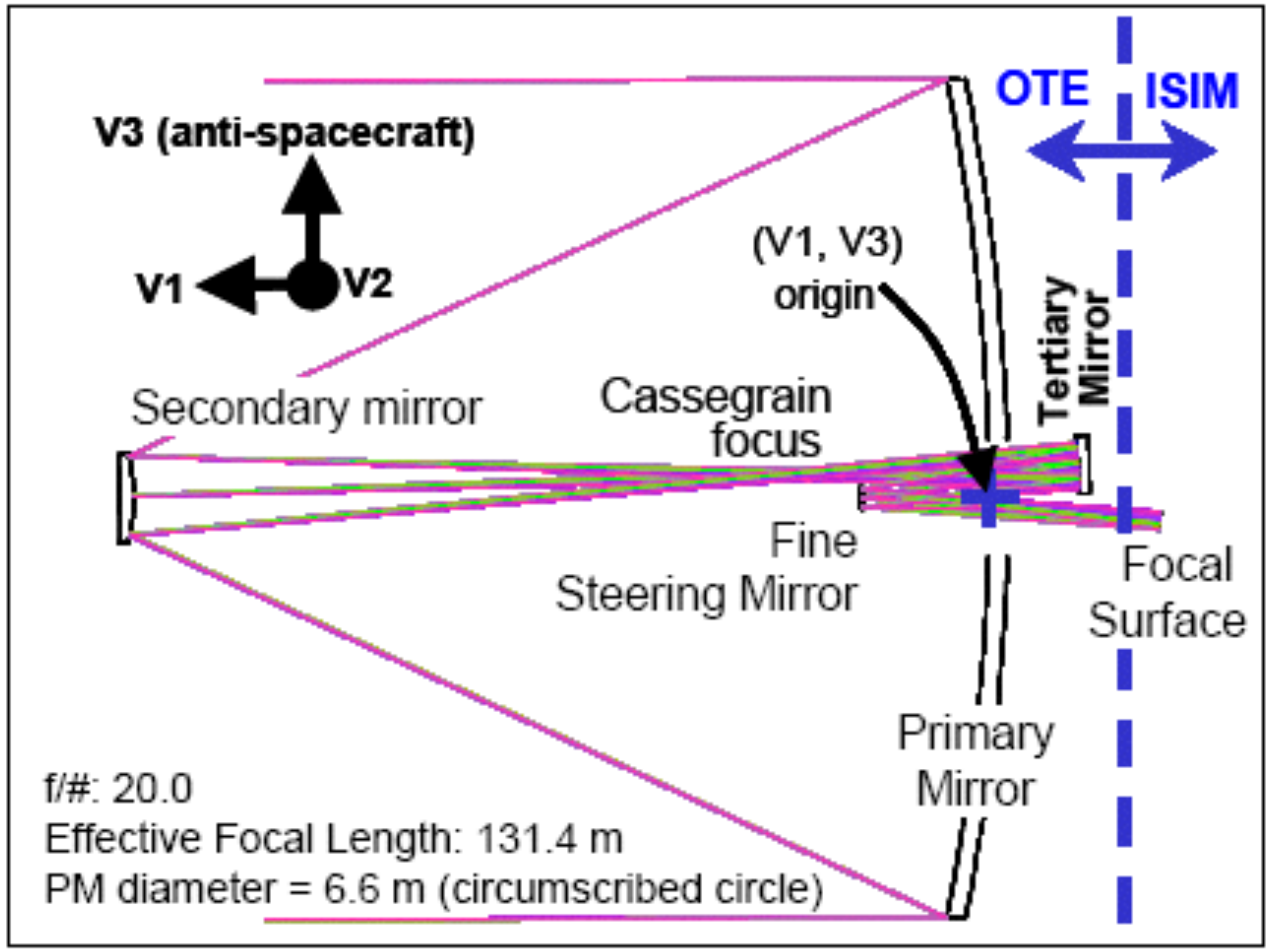


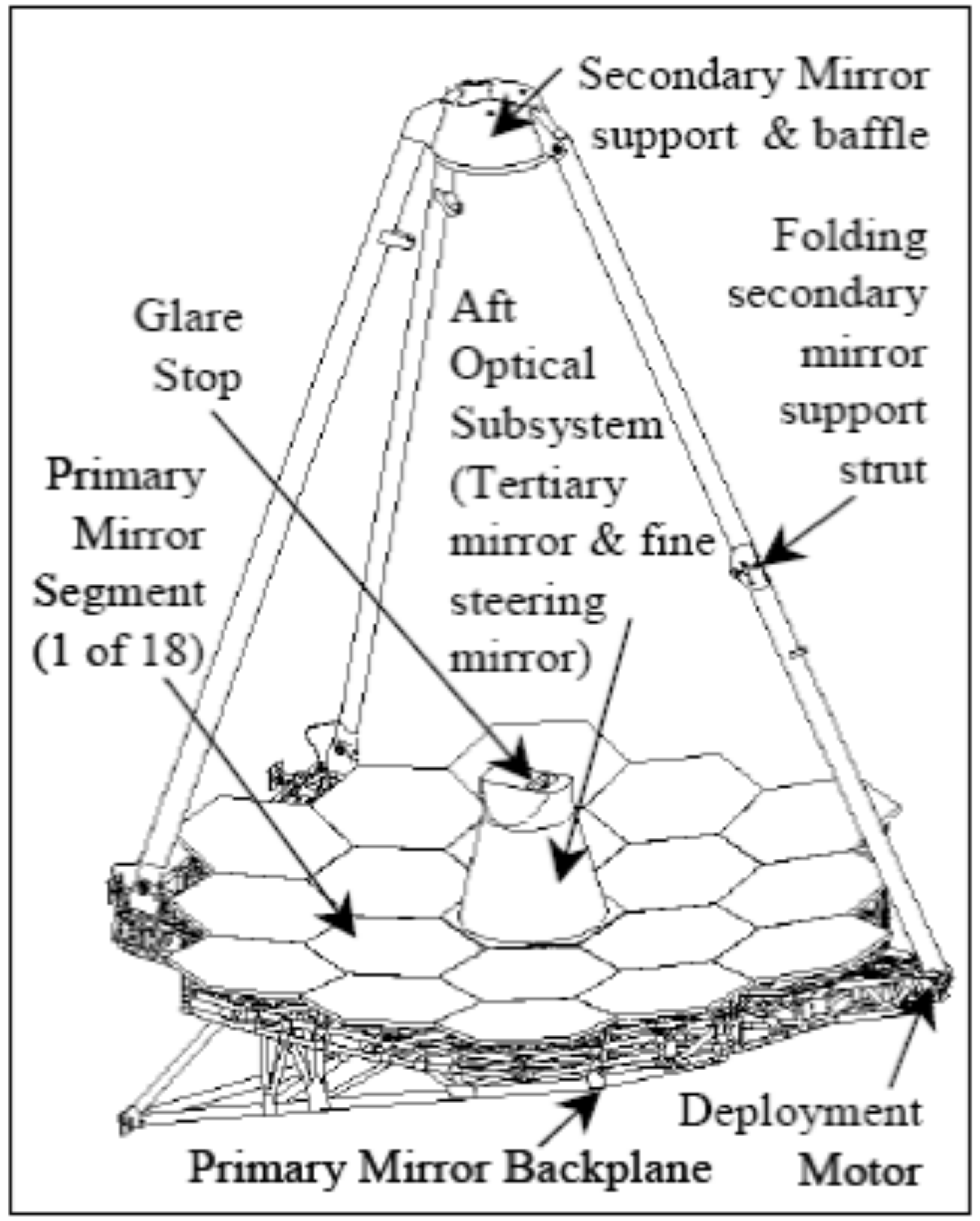


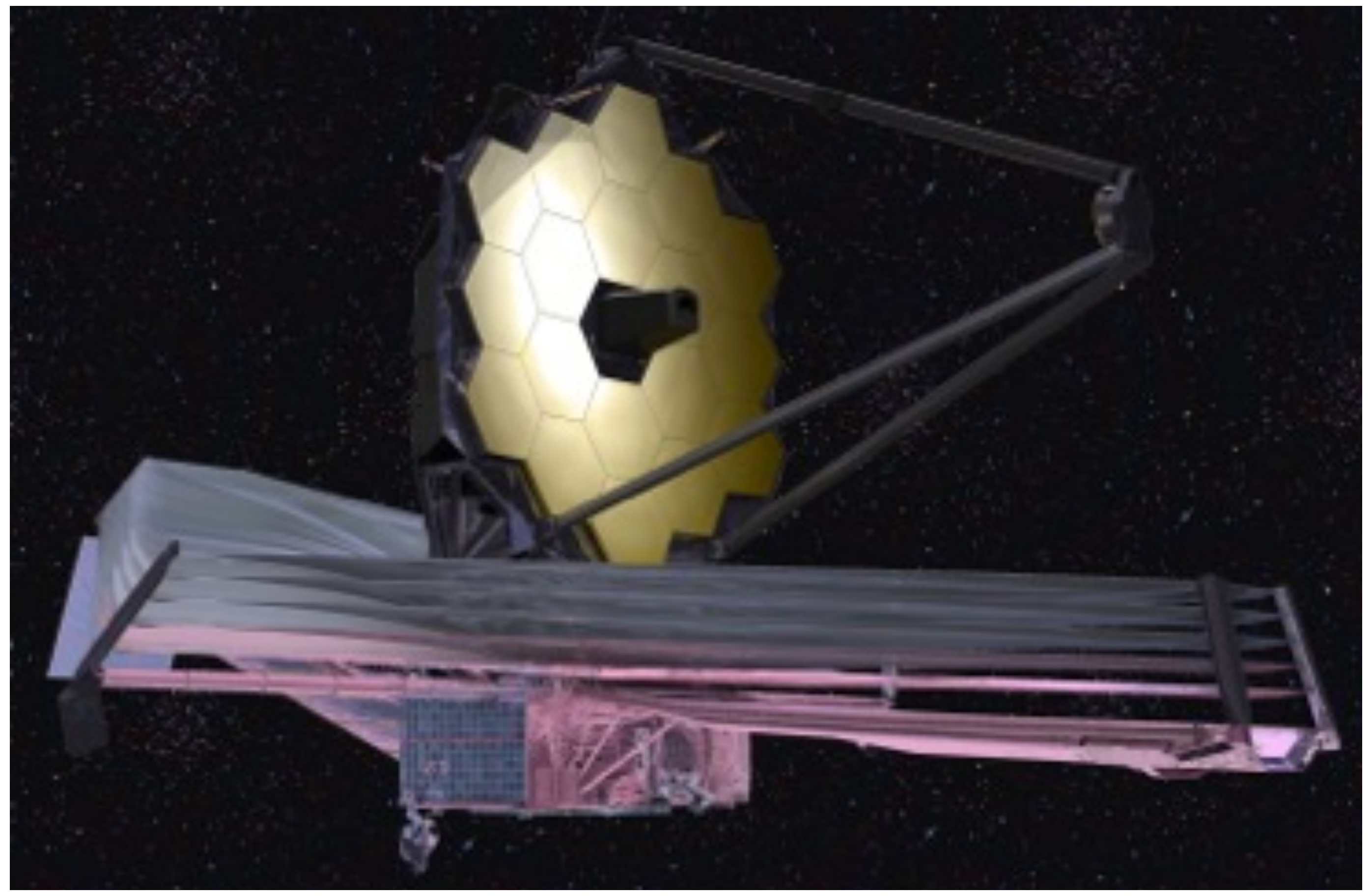


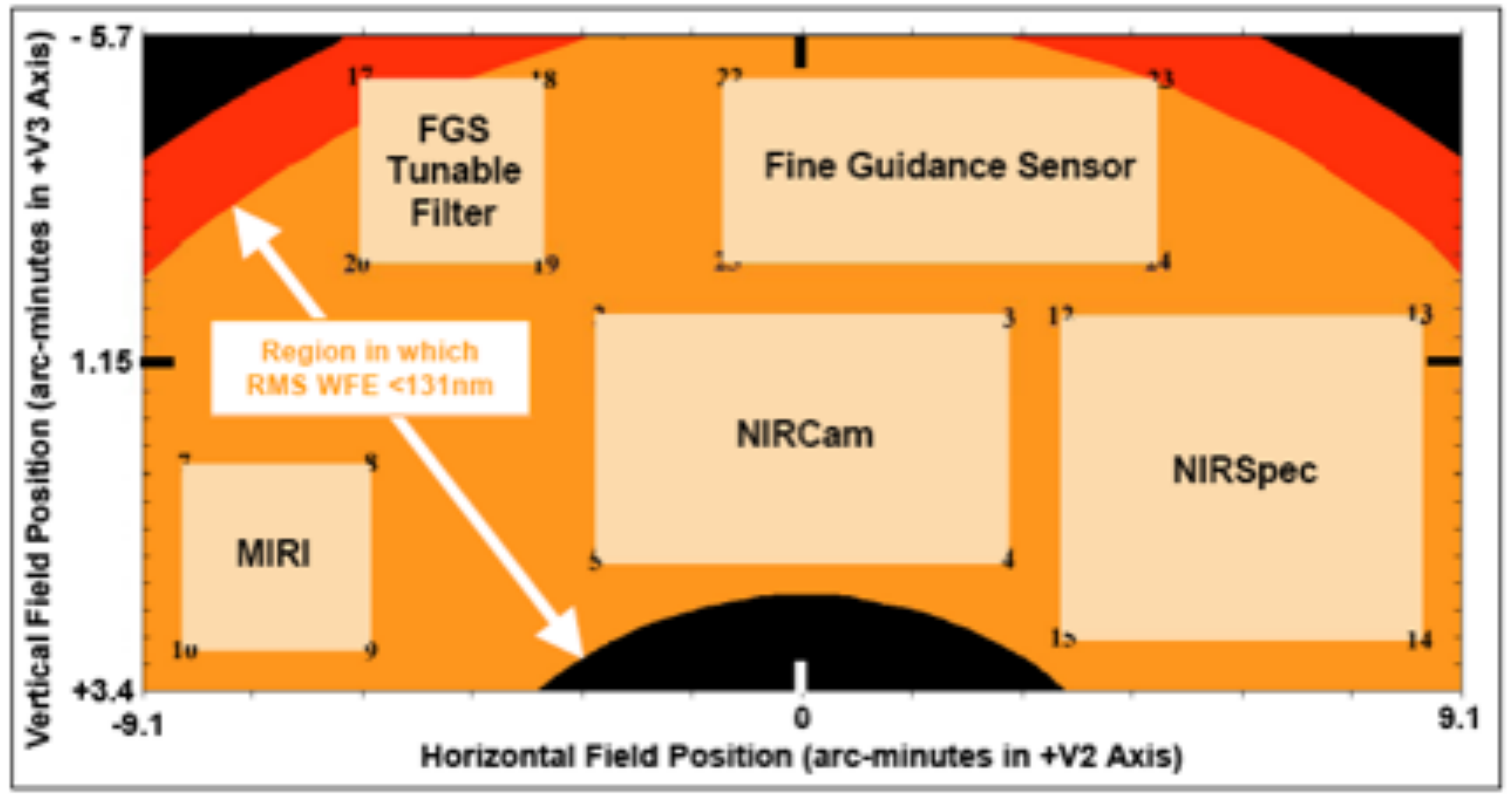
Paul-Baker Design

JWST: Three Mirror Anastigmat (TMA)









Telescopes: Putting it all together

- Physical Size:
  - Keep f/# small (<~2) to keep telescope size small; for 6-10 m class telescope want f# < ~2 to keep overall telescope of reasonable size
  - Small f/# (<~2) also keeps focal plane reasonable size to fit in a cryostat. For example, CD/TMA for SO/CMB-S4 has a ~2-m diameter focal plane with ~5-mm pixels (i.e., with pixel-size >1.2 (f/#) λ)
- Surface quality:
  - Keep RMS surface accuracy of mirrors < λ/40 to minimize loss in the main beam
    - Ruze formula: Loss = $1 - \exp[-(4\pi\sigma_{rms} / \lambda)^2]$, with σ_{rms} = RMS surface variation
    - e.g., for λ=1-mm and σ_{rms} = λ/40 = 25-um -> 10% loss
- Mechanical Support:
  - Deflection of circular plate ~ $(\text{diameter})^4 / (\text{thickness})^2 = D^4 / t^2$
  - So need $t \sim D^2$ to keep deformation constant i.e., going from D=1-m to 10-m, requires a 100x stiffer support!
- Thermal Gradients
  - Keep thermal gradients across the mirror low, e.g., a 5-K gradient would lead to a 20-um deflection, either during observations or during machining