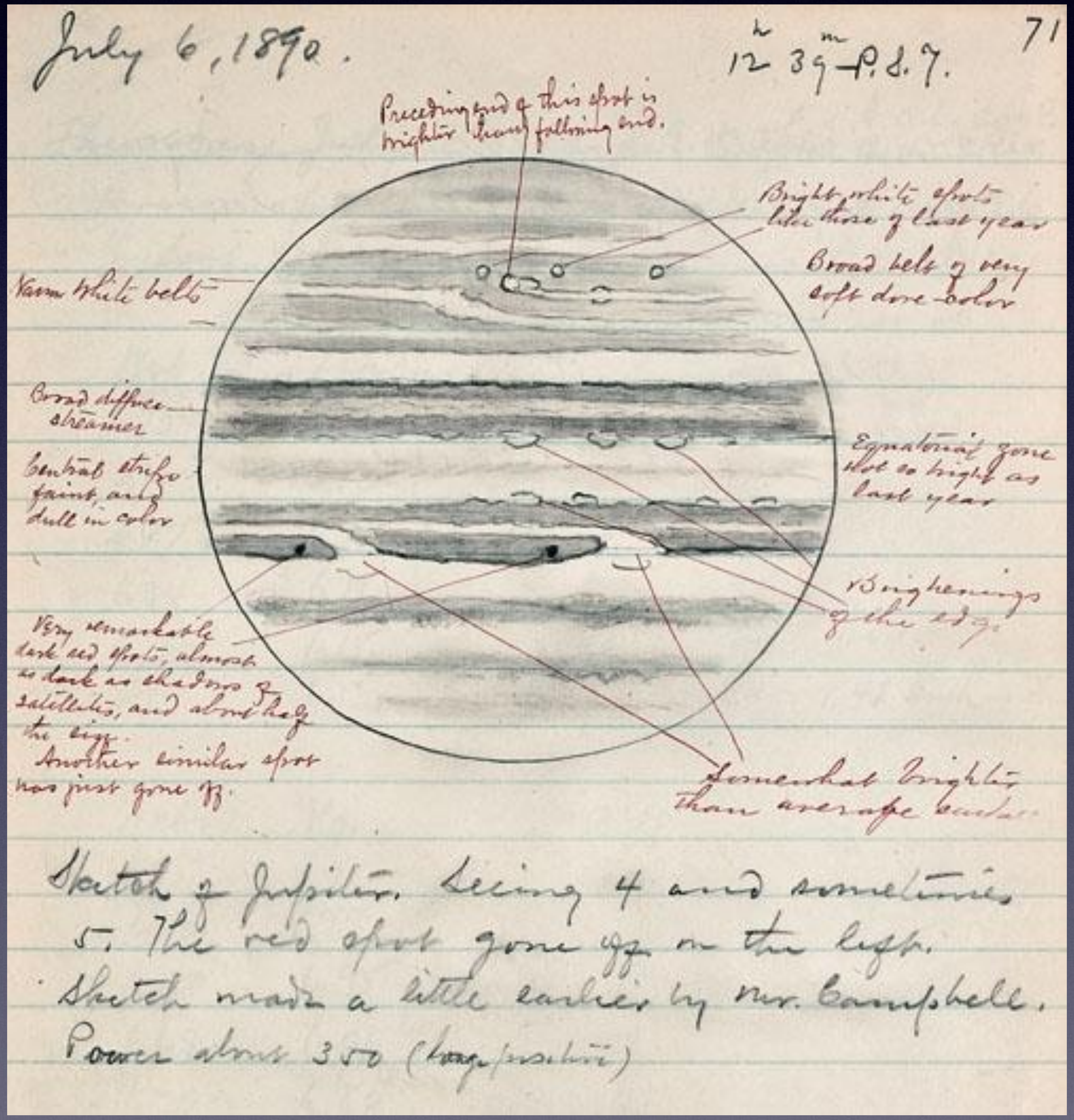
Introduction to CCD Astronomy

Jon Rees
Observational Astronomy Workshop

Astronomy By Eye

- Unaided limiting magnitude ~6
- Telescopes brought step-change
- But no direct record of observations, still limited on faint objects, optical illusions



Drawing of Jupiter by James Keeler, 1890 (Credit: Lick Observatory Historical Collections)

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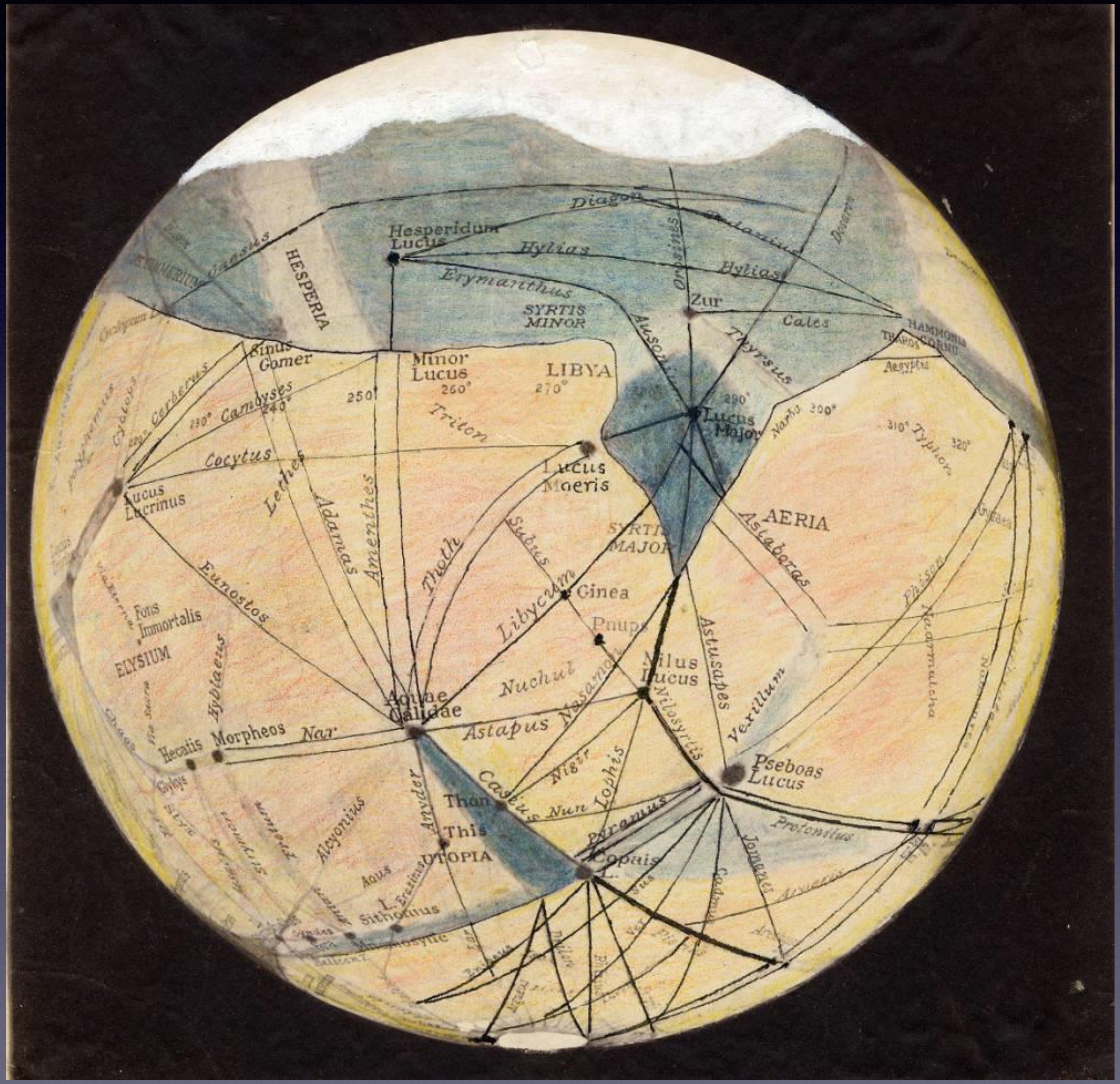


Drawing of ‘canals’ on Mars by Percival Lowell, 1905 (Credit: Lowell Observatory)

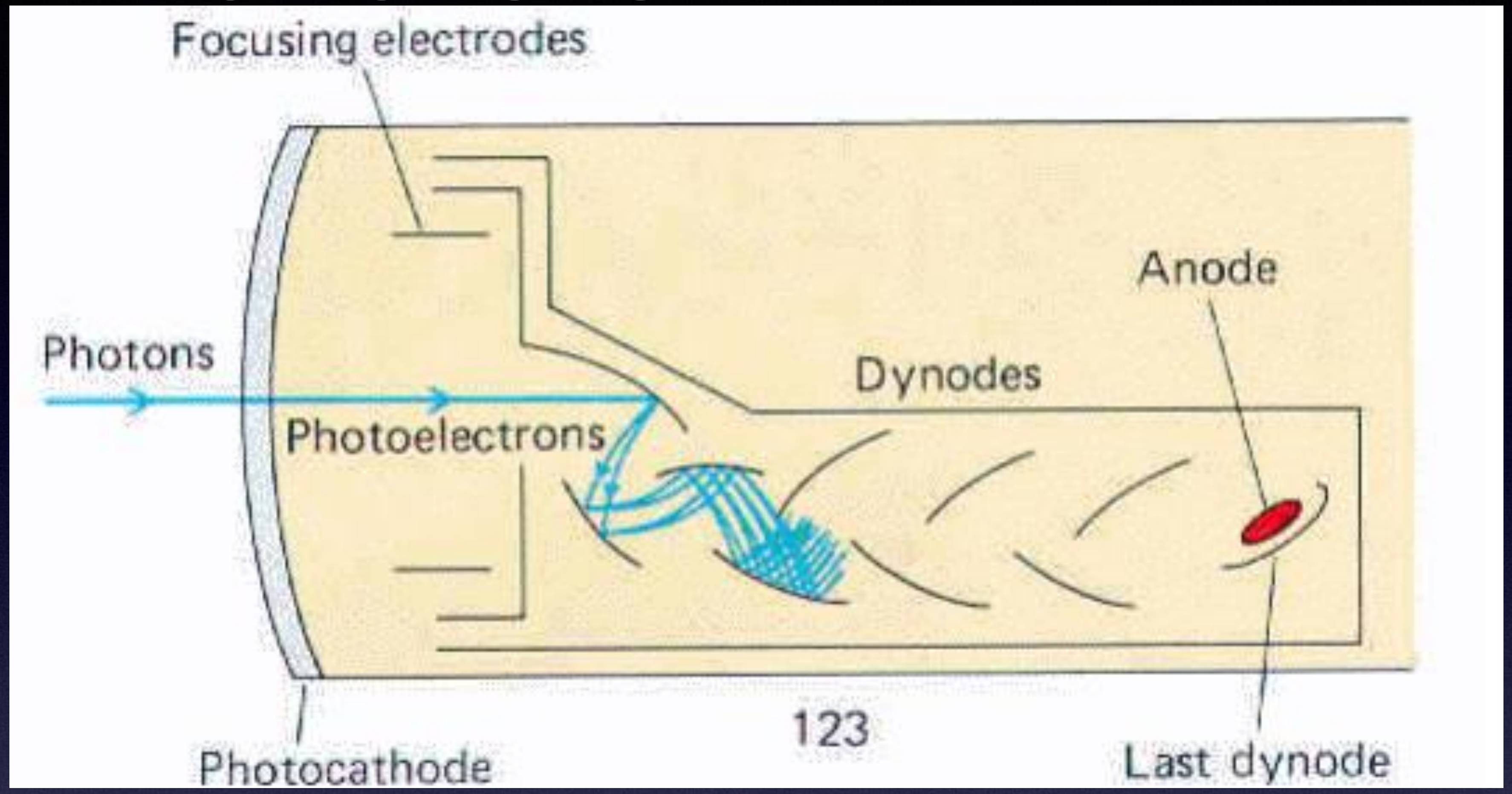
Photographic Plates

- Stable, wide-field observations
- Excellent for large area surveys, e.g. Palomar, Schmidt
- Beyond visual wavelengths
- By exposing for long time - faint objects

Top: Negative (left) and Positive (right) prints of a 135 min exposure of the Pleiades, Dec 1898
Bottom: Photographic plate showing 4 hr exposure of an edge-on galaxy, Nov 1899
(Credit: Lick Observatory Historical Collections)

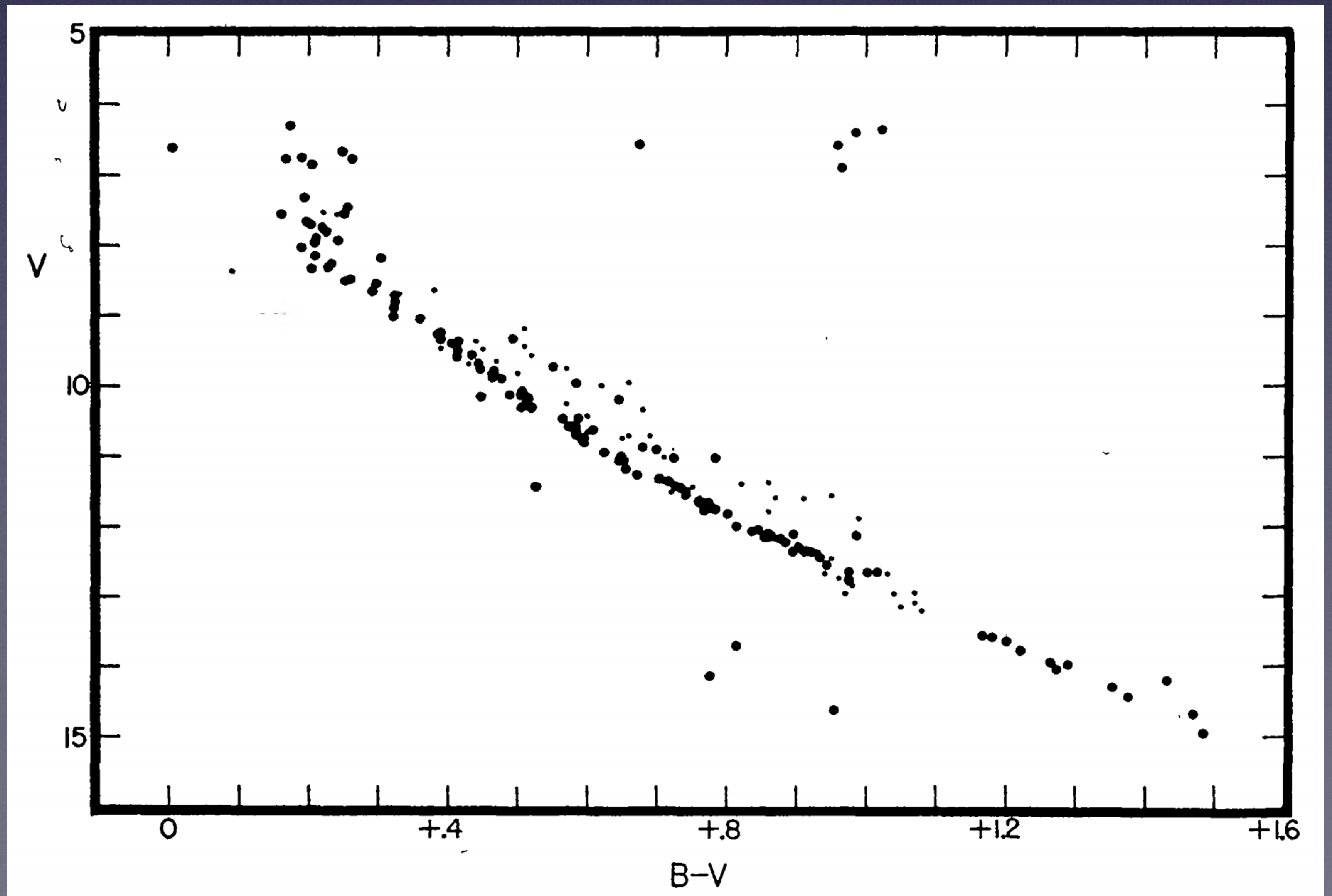
Photomultiplier Tubes

- Photons hit cathode, eject electrons, secondary electrodes amplify the effect
- Converts incident photons to electrical signal
- Linear response - Accurate calibration of photometry
- But only single element



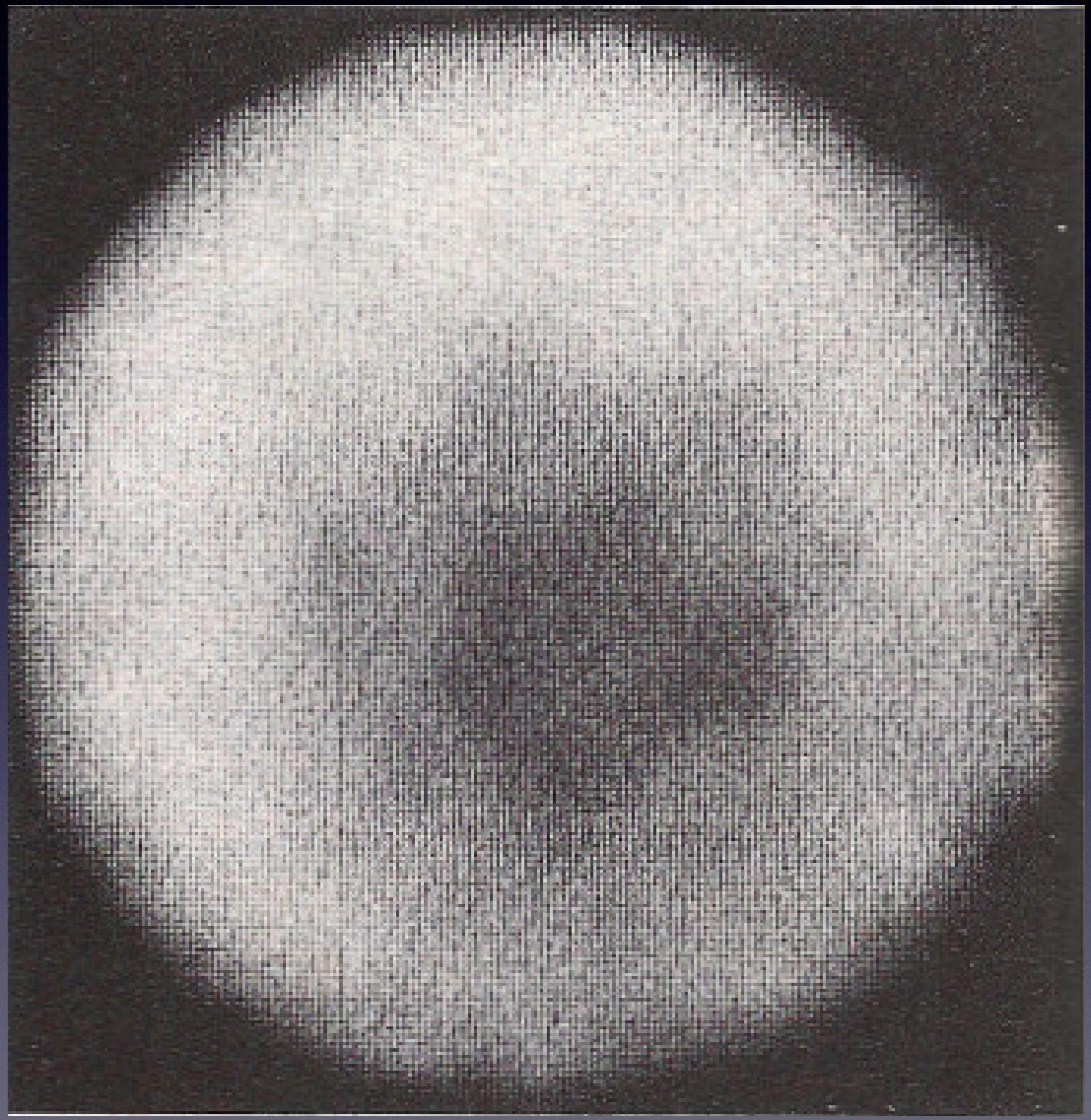
Top: Layout of a Photomultiplier Tube (Credit: R. O'Connell, U.Va)

Bottom: V, B-V CMD of Praesepe (Johnson 1952)



The First CCD Observation

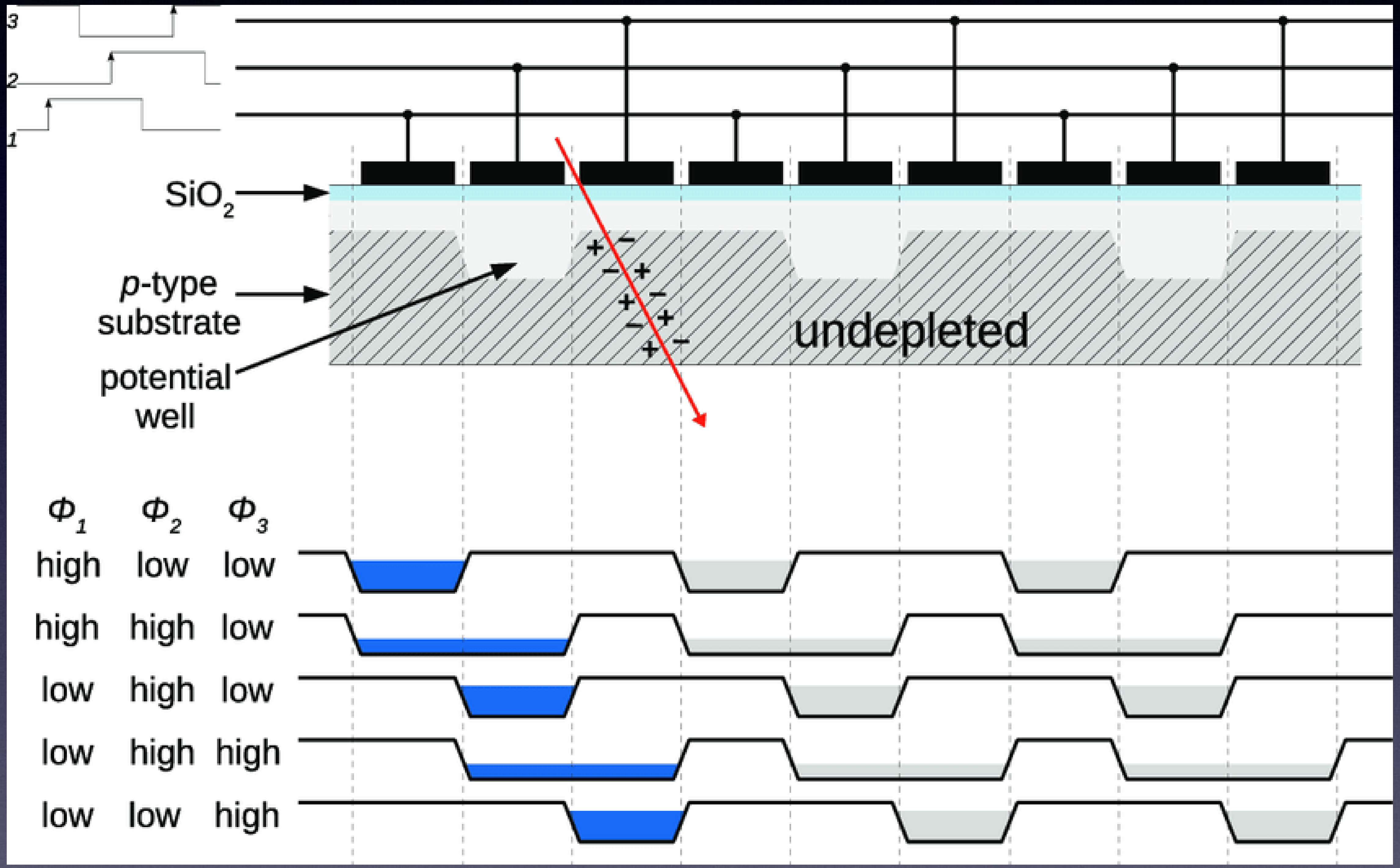
- Created by Bell Labs in 1969.
- First used for Astronomy in 1976 by JPL/UoA



1976 Observation of Uranus from the UoA 61-inch Telescope (Janesick & Blouke, 1987)

CCD Operation

- Doped semiconductor, photons liberate electrons
- Grid of electrodes -> potential wells (pixels)
- Voltages cycled to move charge to read-out amplifiers
- Conversion from analogue voltage to digital counts - ADC
- Gain is set by electronics, e/ADU



Cross section of 3-phase CCD & charge transfer diagram (Dawiec 2011)

File Format (FITS)

- Data stored in ‘FITS’ files
- FITS files start with ascii headers - contain useful information
- Data are stored in arrays after headers
- Many tools exist to read FITS e.g. DS9, IRAF, python routines

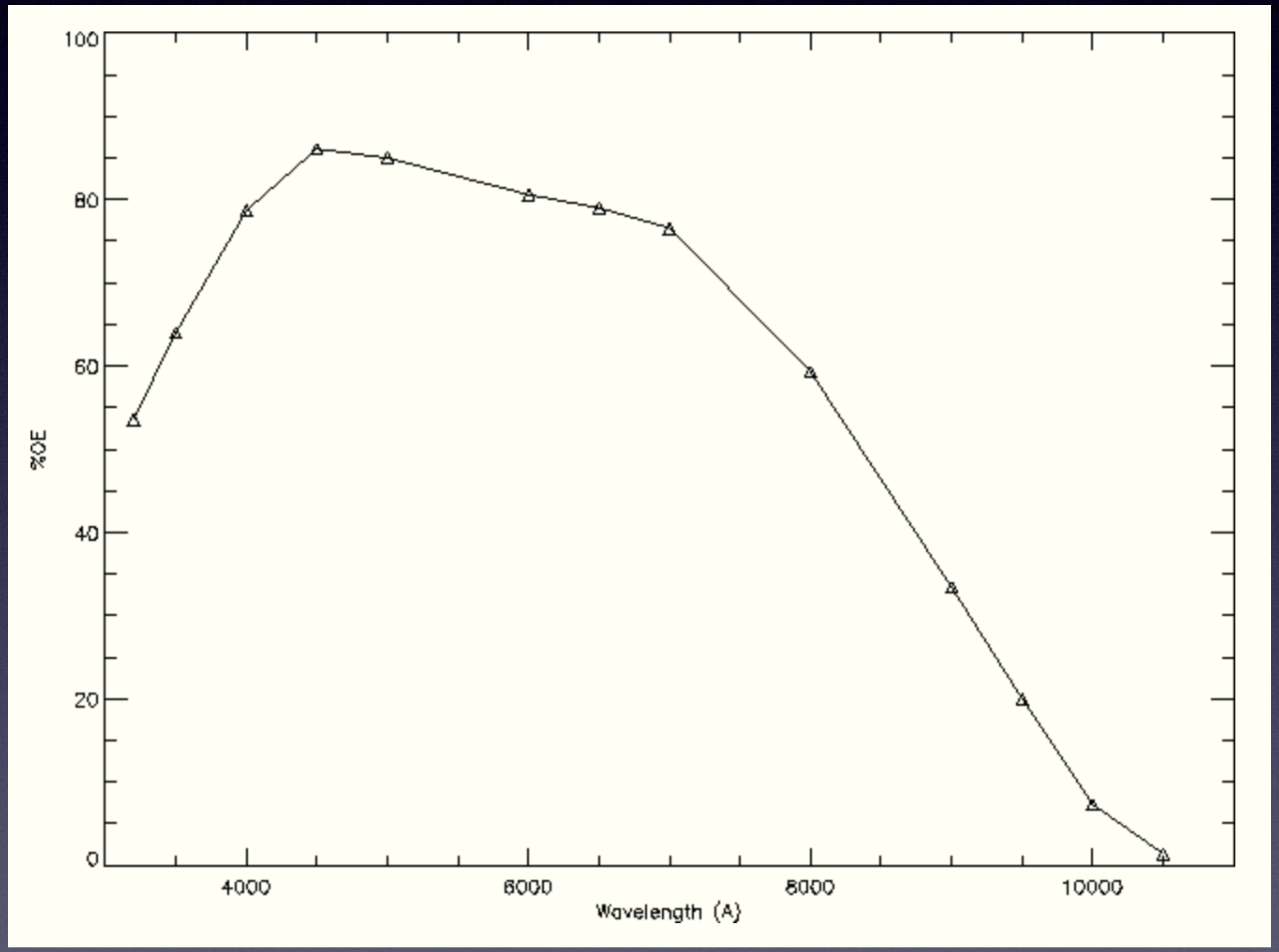
FITS Header for Skyflat

Keyword	Value		Comment
SIMPLE	T		NORMAL FITS IMAGE
BITPIX	16		DATA PRECISION
NAXIS	2		NUMBER OF IMAGE DIMENSIONS
NAXIS1	1056		NUMBER OF COLUMNS
NAXIS2	1024		NUMBER OF ROWS
CRVAL1U	2048		COLUMN ORIGIN
CRVAL2U	2048		ROW ORIGIN
CDELT1U	-2		COLUMN CHANGE PER PIXEL
CDELT2U	-2		ROW CHANGE PER PIXEL
OBSNUM	1041		OBSERVATION NUMBER
IDNUM	2		IMAGE ID
UGEOM	0		UCAM READOUT GEOMETRY
DGEOM	0		DESCRAMBLE GEOMETRY
AMPSROW	1		AMPLIFIERS PER ROW
AMPSCOL	1		AMPLIFIERS PER COLUMN
OBSTYPE	'OBJECT'		IMAGE TYPE
EXPTIME	3		Exp time (not counting shutter error)
BSCALE	1		DATA SCALE FACTOR
BZERO	32768		DATA ZERO POINT
COMMENT			Real Value = FITS*BSCALE+BZERO
PROGRAM	'NEWCAM'		New Lick Camera
VERSION	'nickel_direct'		Data acquisition version
TSEC	1592624447		CLOCK TICK - SECONDS
TUSEC	656880		CLOCK TICK - MICROSECONDS
DATE	'2020-06-20T03:40:47.65'		UT of CCD readout & descramble
DATASEC	'[1:1024,1:1024]'	/ IRAF	NOAO-style data section
COMMENT			End of cards hard-coded in fits_cards
COMMENT			Begin of cards from other times
CSYER2	0.01666669920087		systematic error along direction of WCS axis i
CSYER1	0.01666669920087		systematic error along direction of WCS axis i
CRDER2	5.139999848325E-05		random error along direction of WCS axis i
CRDER1	5.139999848325E-05		random error along direction of WCS axis i
CD2_2	-0.0001027239995892		CTM element i_j from FITS axis j to WCS axis i
CD2_1	3.946270226152E-06		CTM element i_j from FITS axis j to WCS axis i
CD1_2	-3.946270226152E-06		CTM element i_j from FITS axis j to WCS axis i
CD1_1	-0.0001027239995892		CTM element i_j from FITS axis j to WCS axis i

Detector Characteristics

Sensitivity (QE)

- Quantum Efficiency - ability of detector to detect photons
- QE is a function of wavelength
- Detectors can be targeted at different wavelength regimes



Quantum efficiency for Nickel CCD2 (Credit: UCO/Lick)

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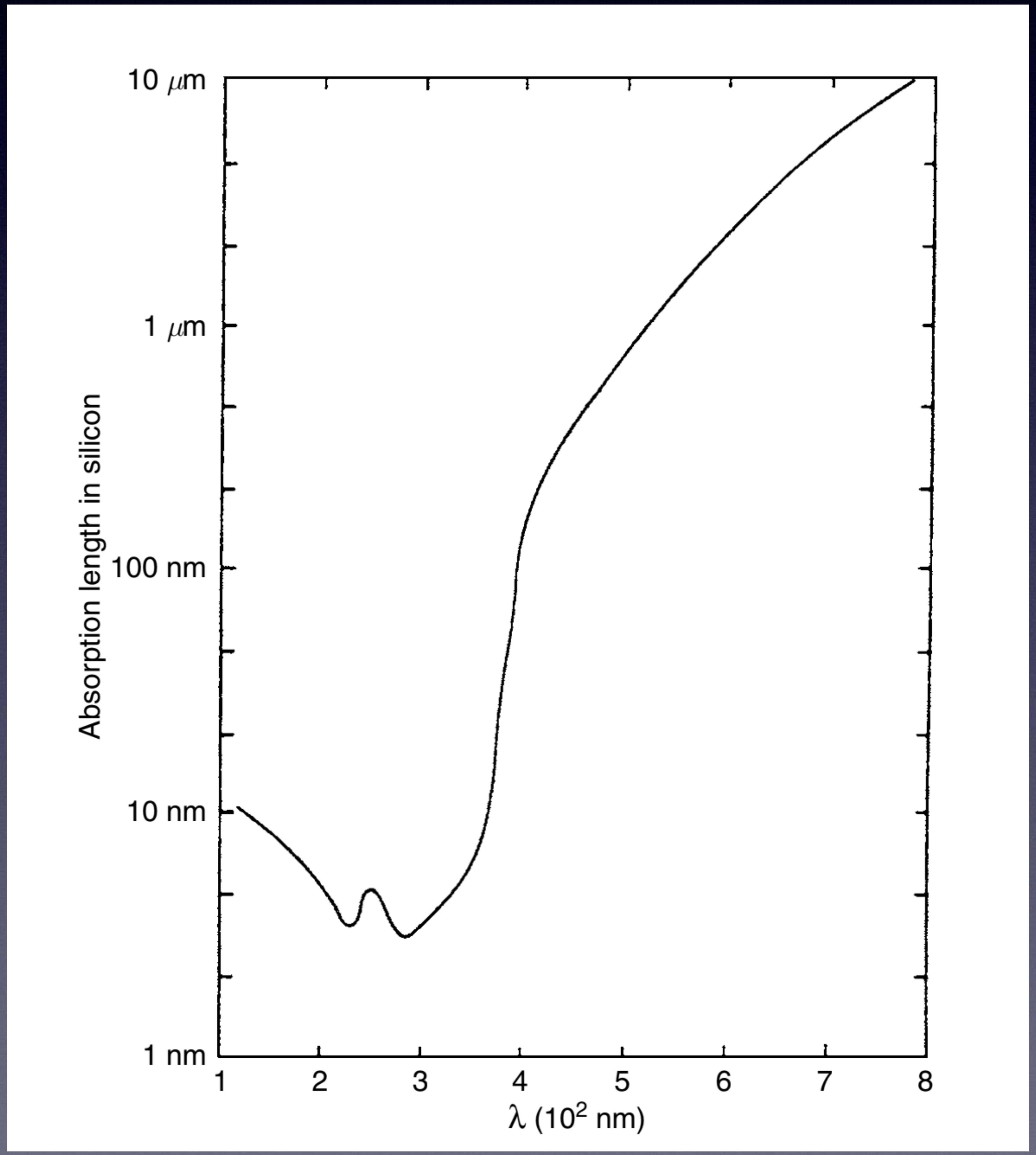

Photon absorption length in silicon (Reicke 1994)

Plate Scale/Binning

- Plate scale - relation between detector pixels and physical size on sky
- Holdover from photographic plates
- For CCDs a convenient unit is arcsec/pixel
- 0.18”/pixel for Nickel CCD

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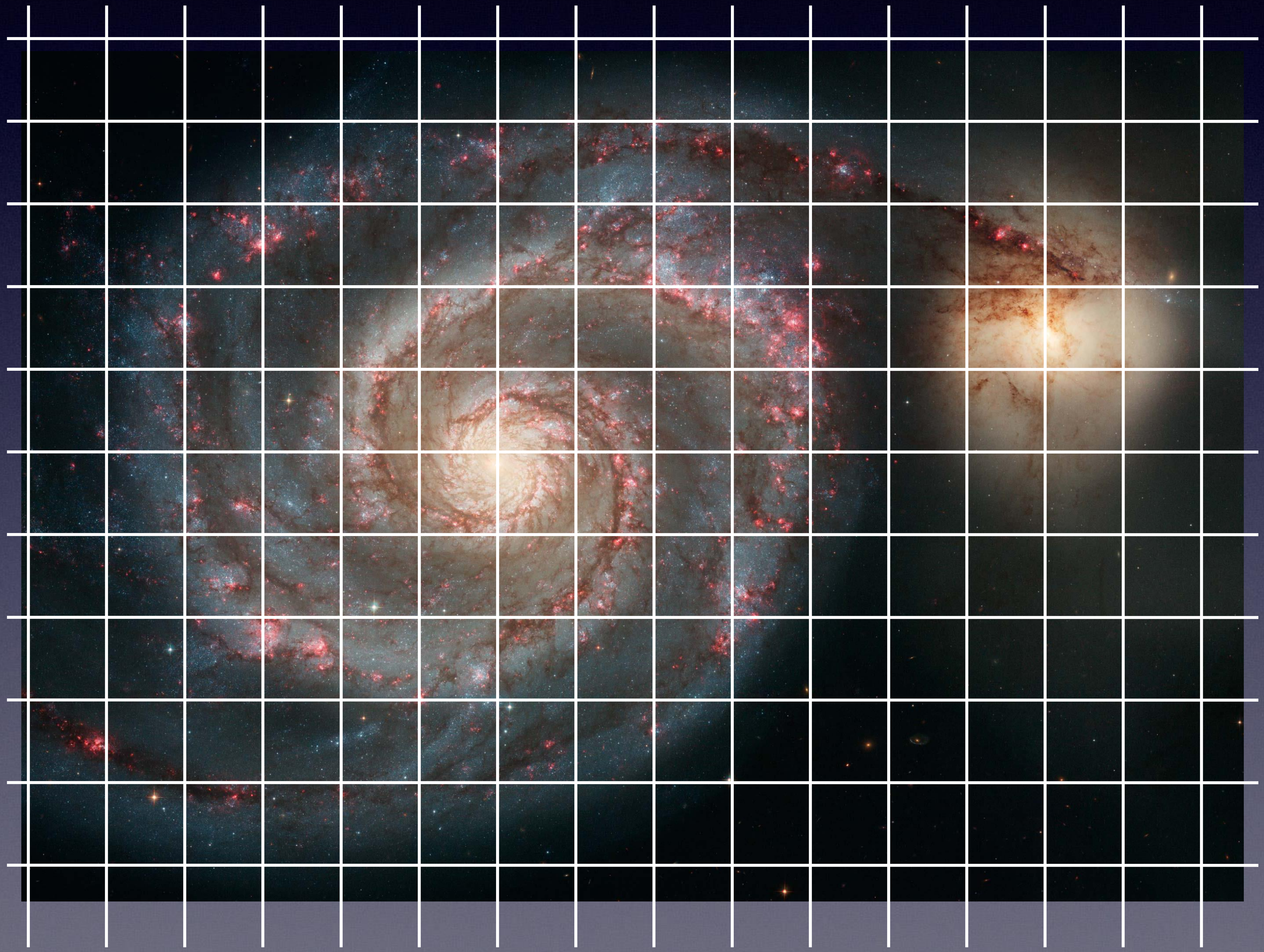
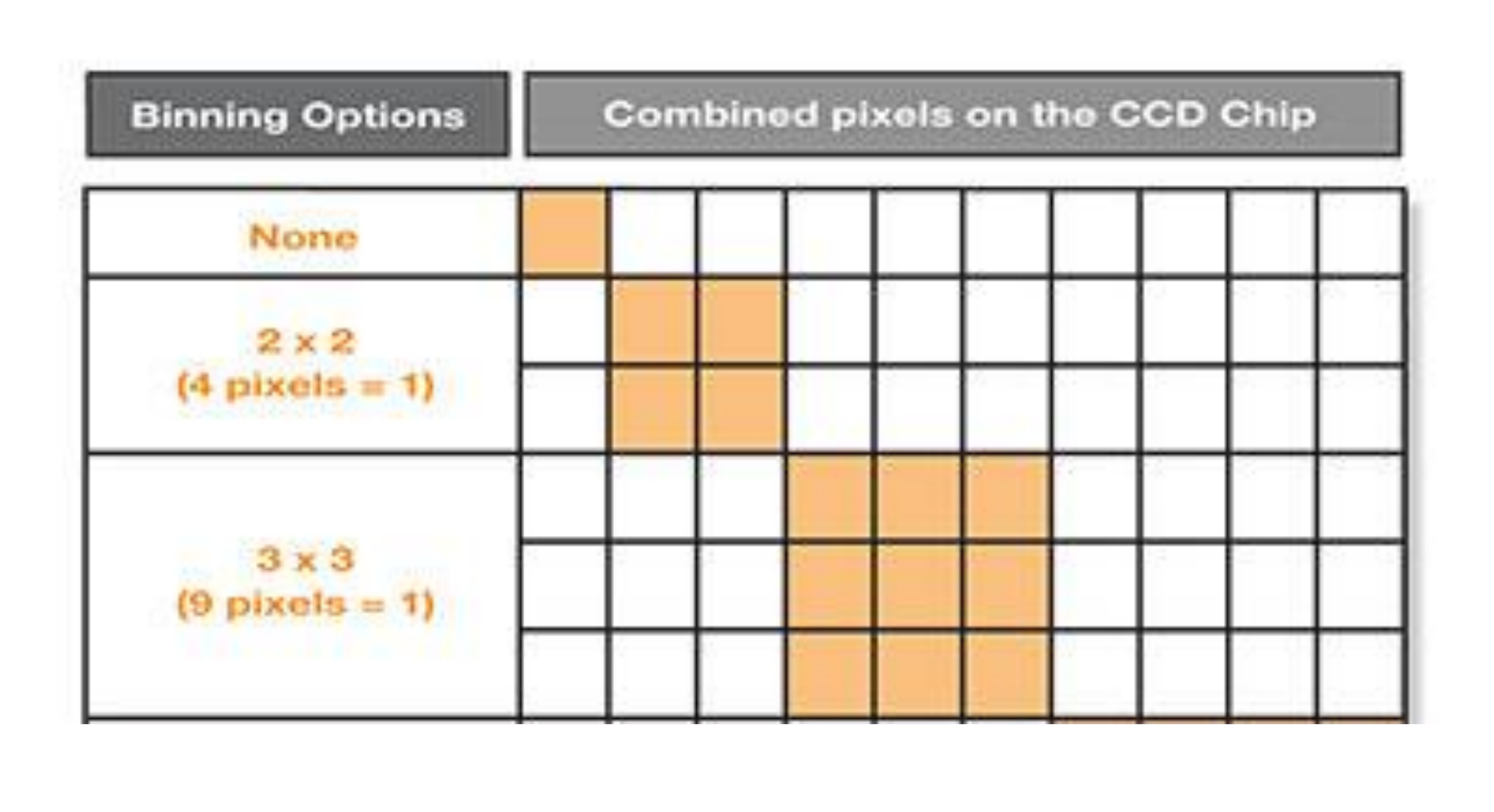


Plate Scale/Binning

- Can ‘bin’ groups of pixels together
- Decreases resolution, but improves readout time and readout noise
- Imaging can bin with fewer downsides (sometimes)
- For spectroscopy, generally no binning



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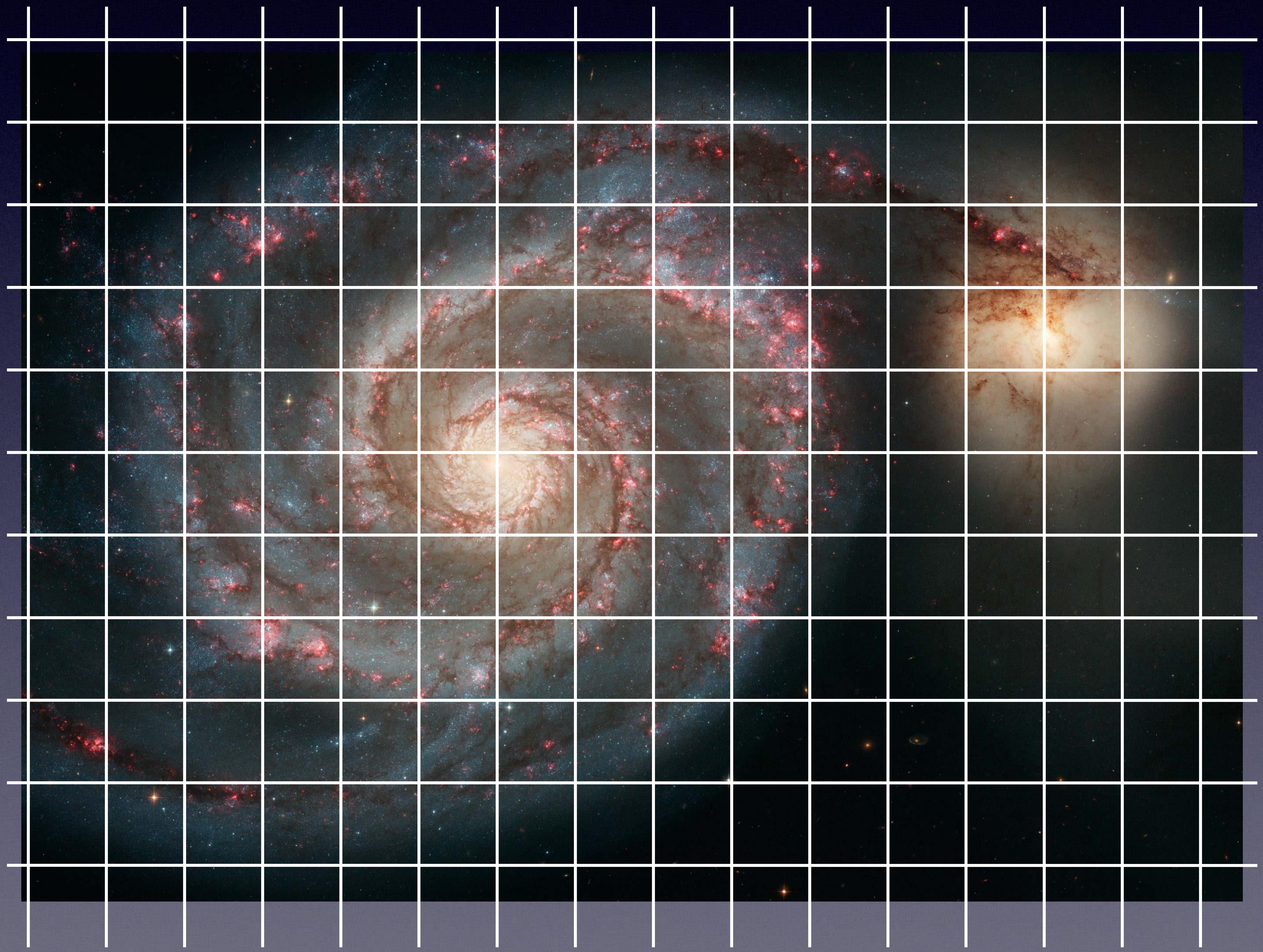

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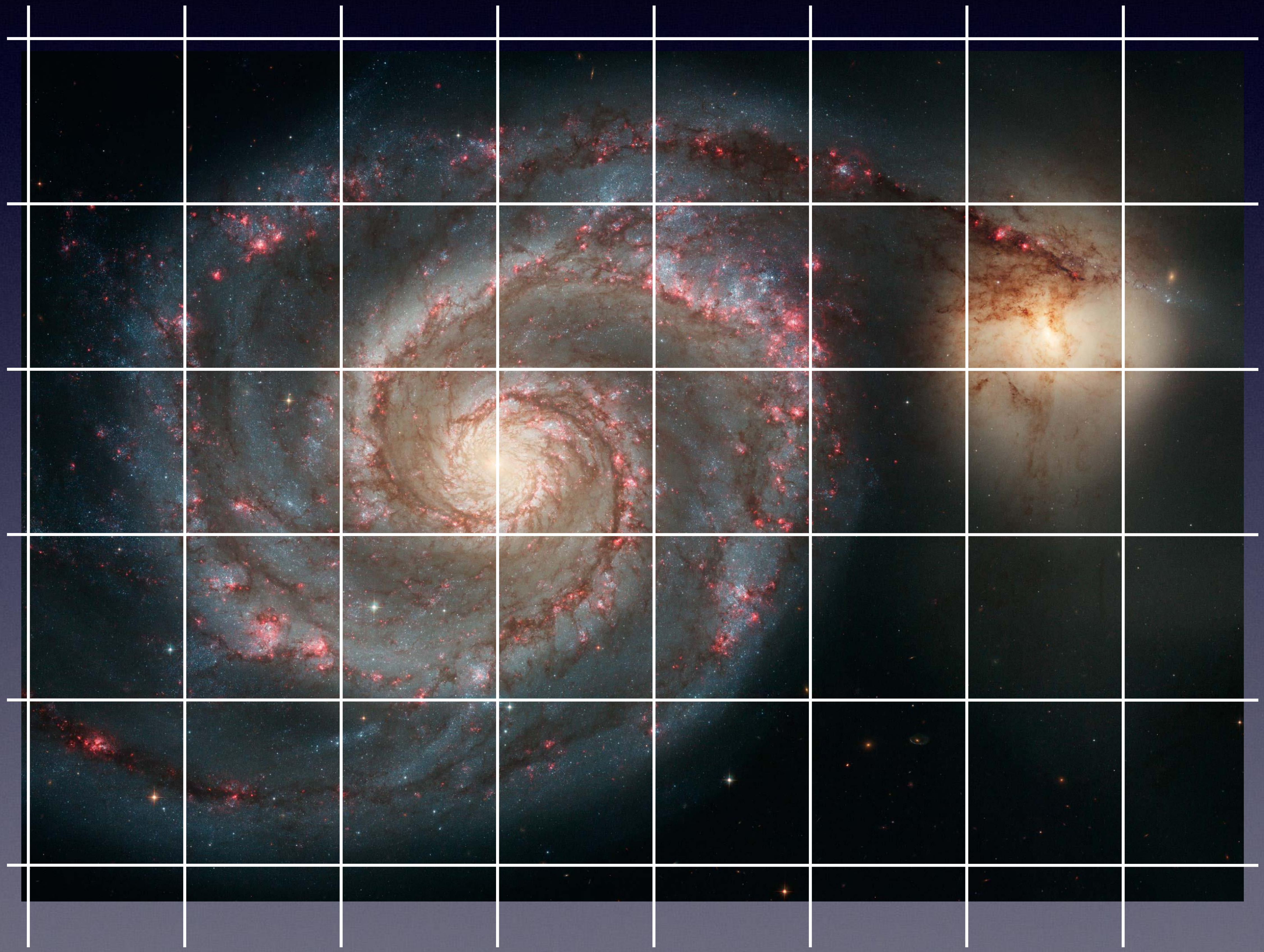

Windowing

- Can window down the detector
- Read out a subset of pixels
- Drastically improve readout time, limit Field of View
- Need to match calibrations to windowed data

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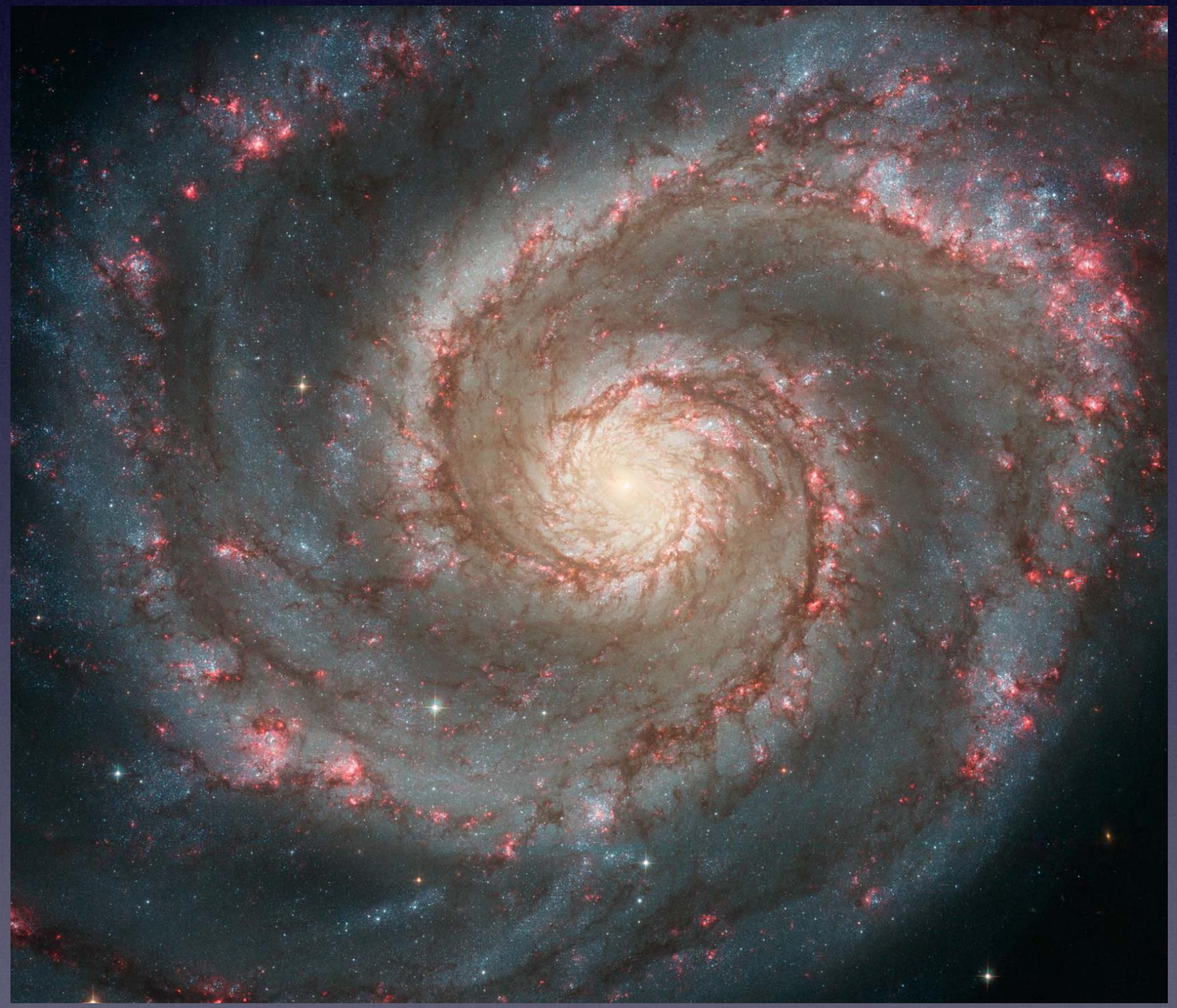
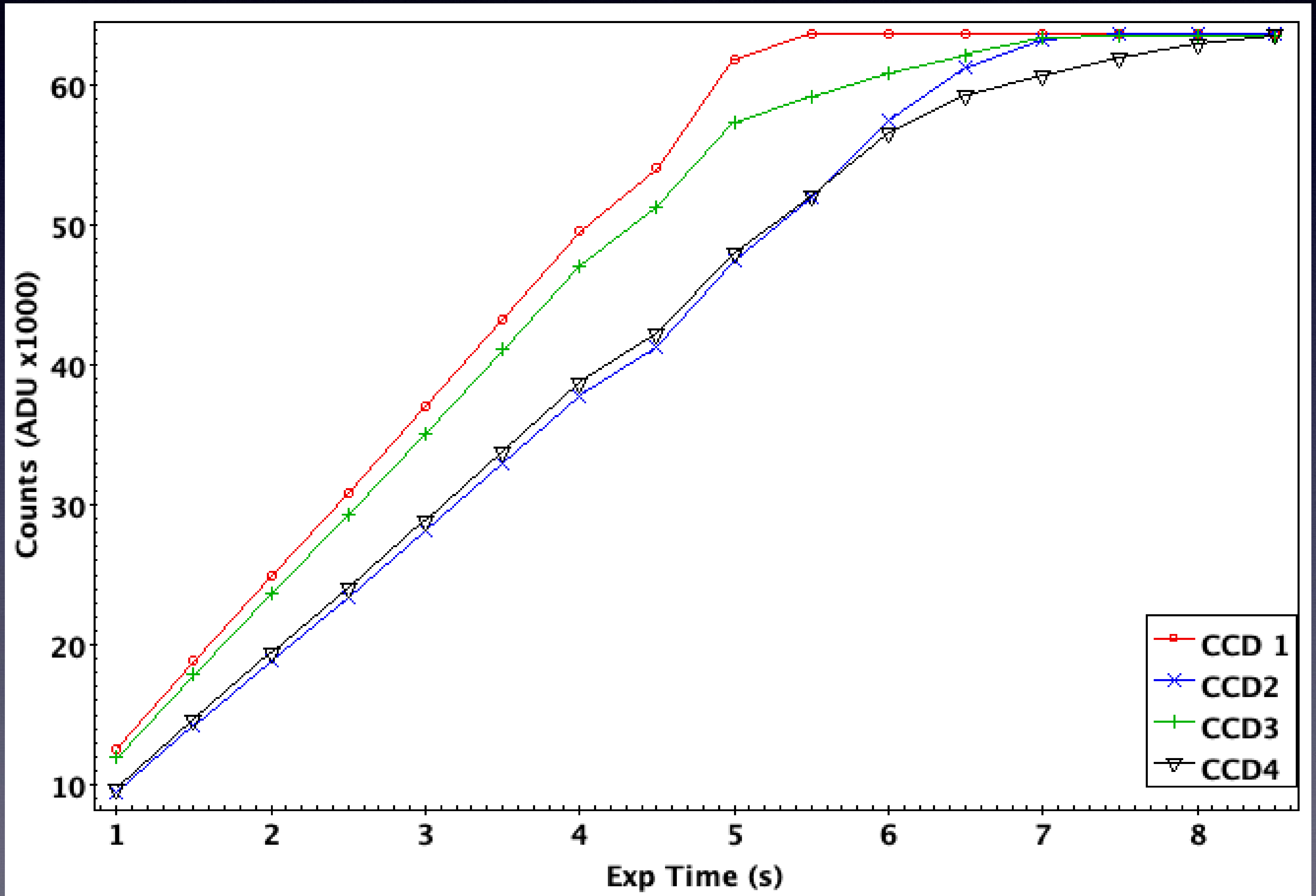


Linearity

- If detector was perfect, double number of photons -> double counts
- Only true up to a certain count limit
- At high counts, detectors may become non-linear



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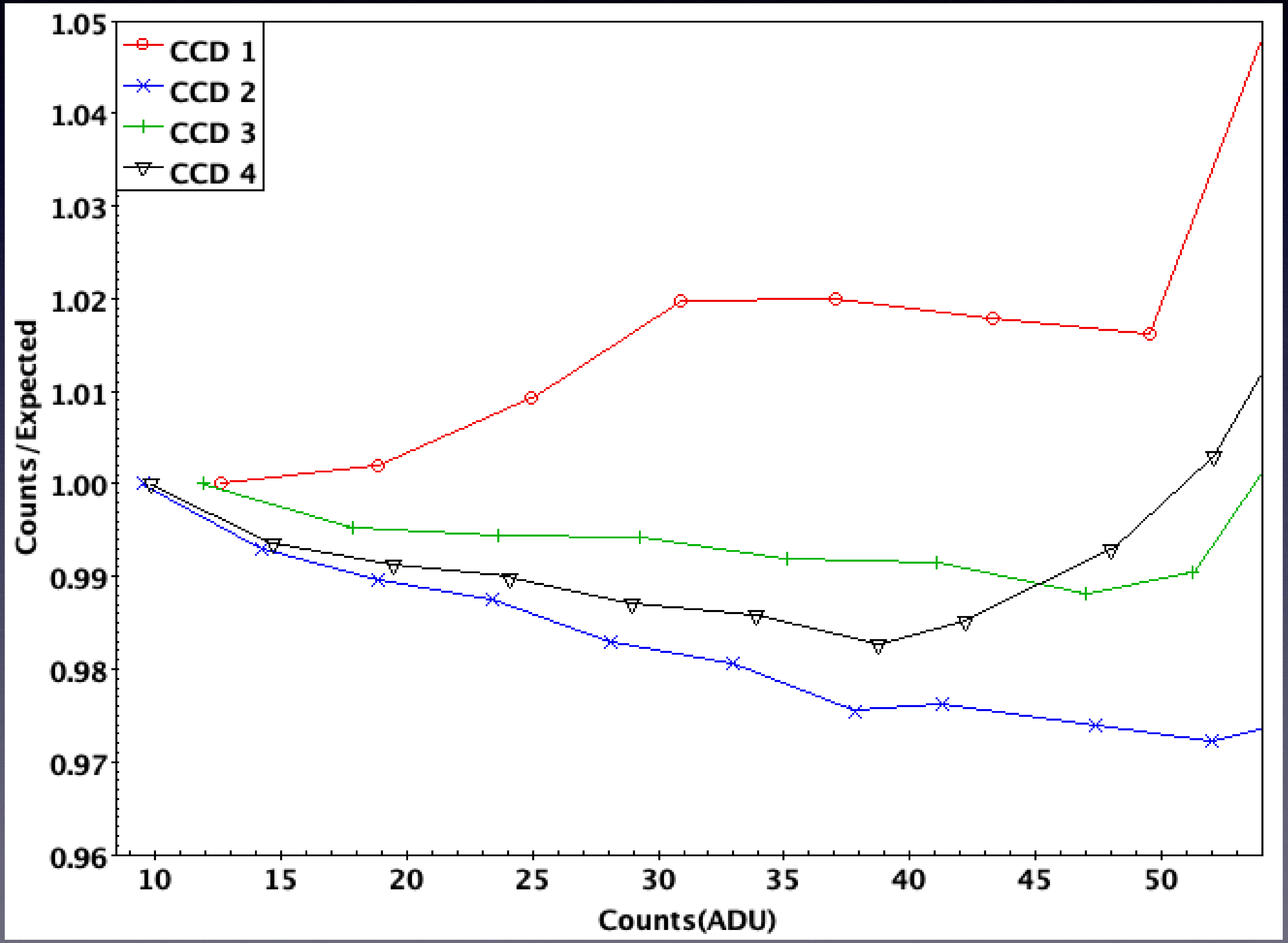
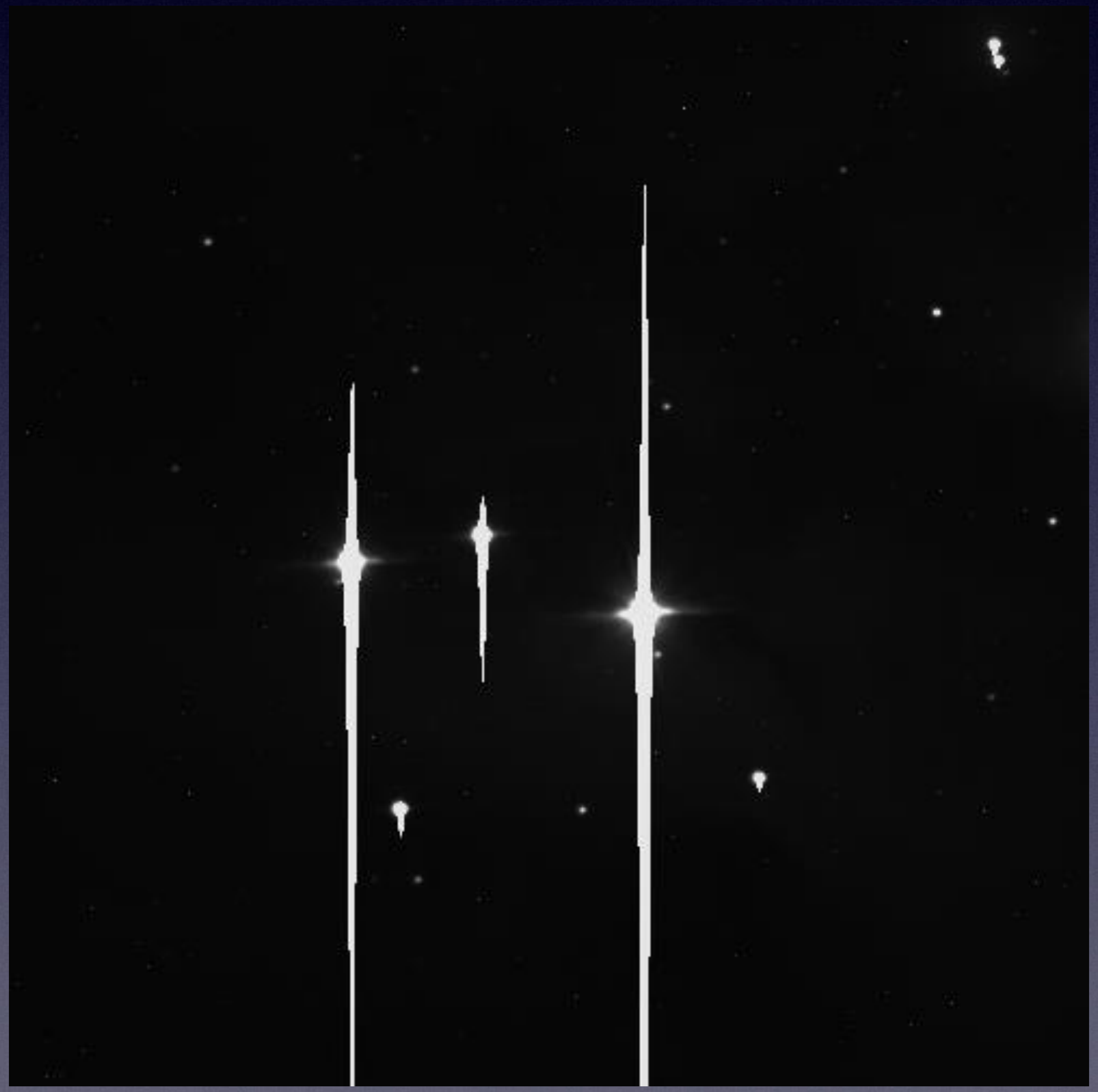


Saturation

- When electrons reach limit of ADC, no more can be counted
- Bright objects can cause electrons to exceed full well depth pixels
- Electrons will start to fill neighbouring pixels causing bleed trails



Electron bleed trails from saturated stars (Credit:ESO)

Read Noise

- Conversion from analog to digital signal introduces noise
- Electronics also introduce spurious electrons throughout readout
- Can often decrease read noise by using slower read out modes

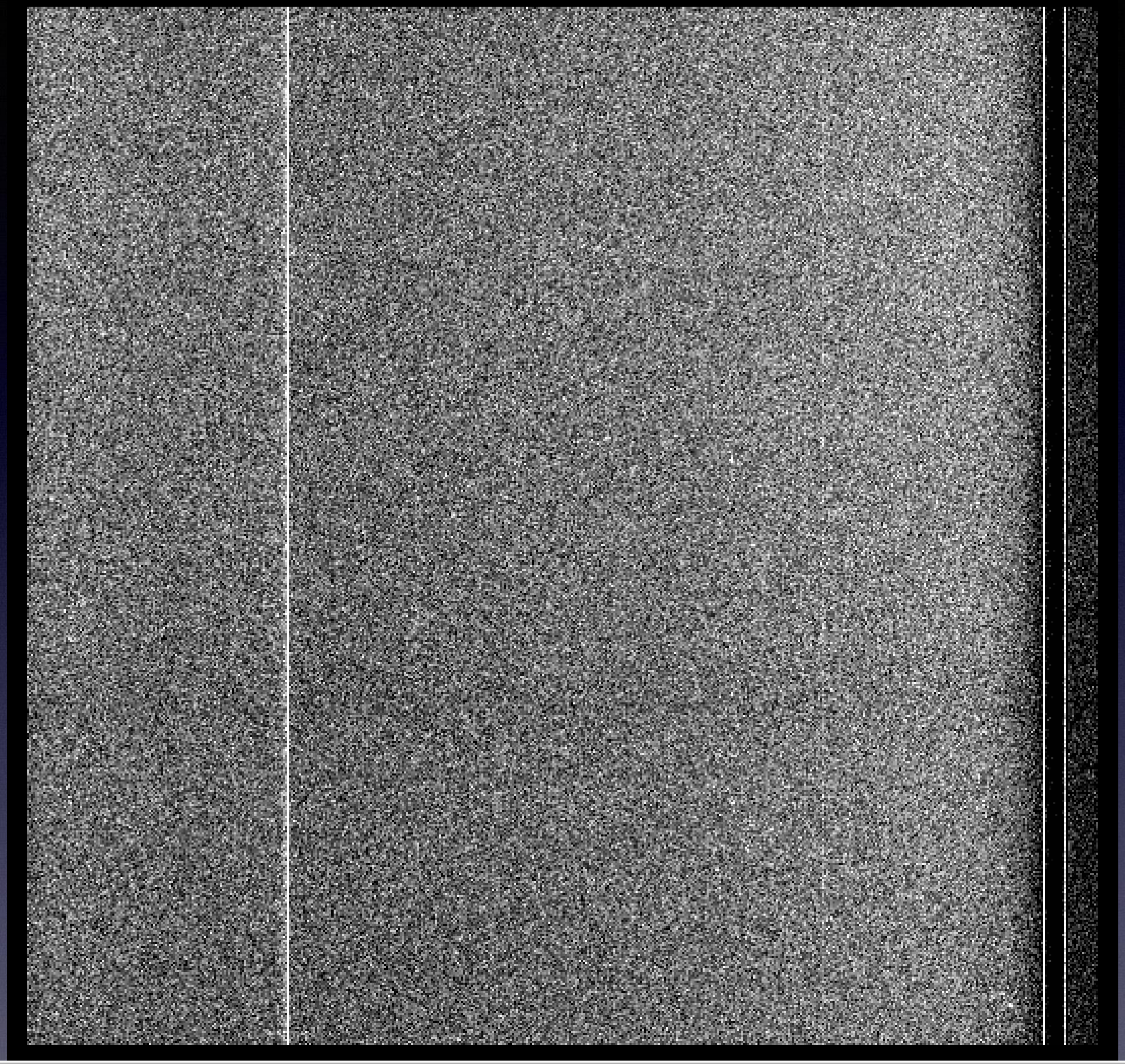
Thermal Noise/Dark Current

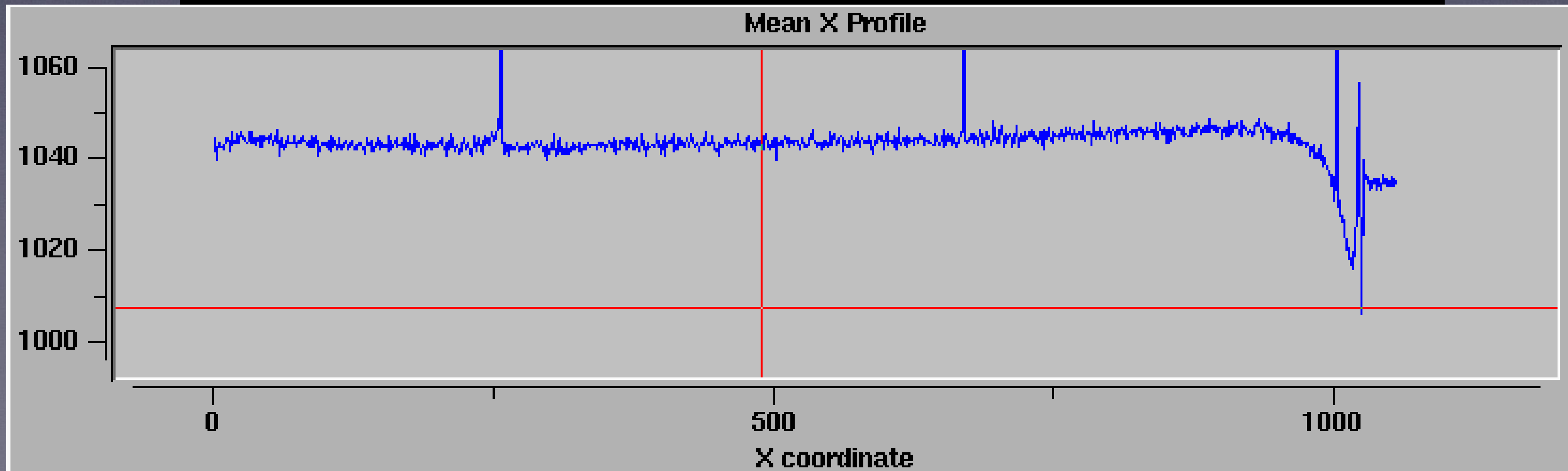
- Thermal energy can liberate electrons
- These are indistinguishable from electrons liberated by photons
- Solution - cool the detector. Generally use liquid nitrogen
- Dark current negligible at these temperatures

Calibration Files

Bias

- Zero second exposure
- But signal isn't zero?
- We apply a constant voltage to the detector
- Positive base signal - prevent negative values
- Overscan vs Bias frame





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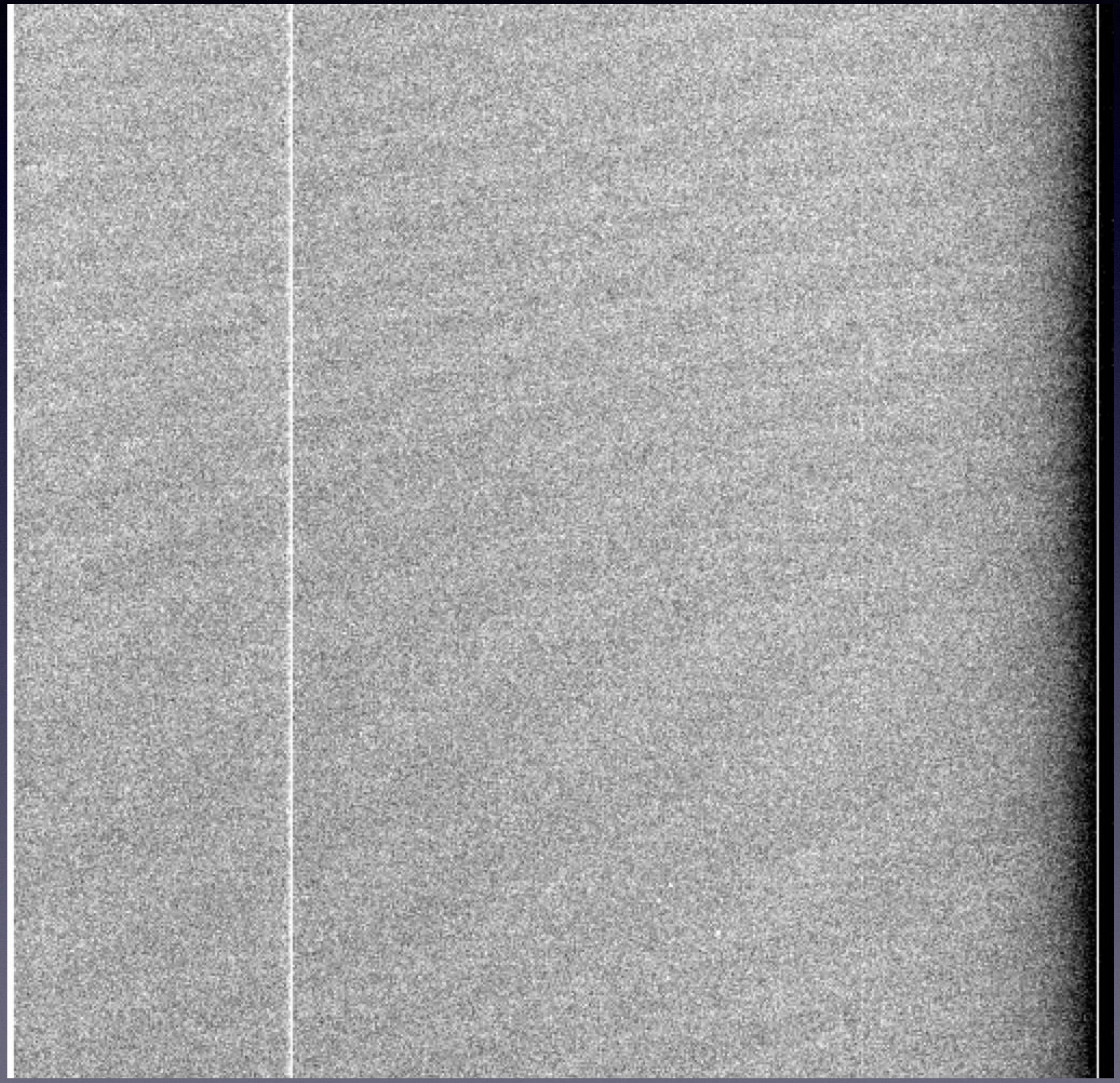
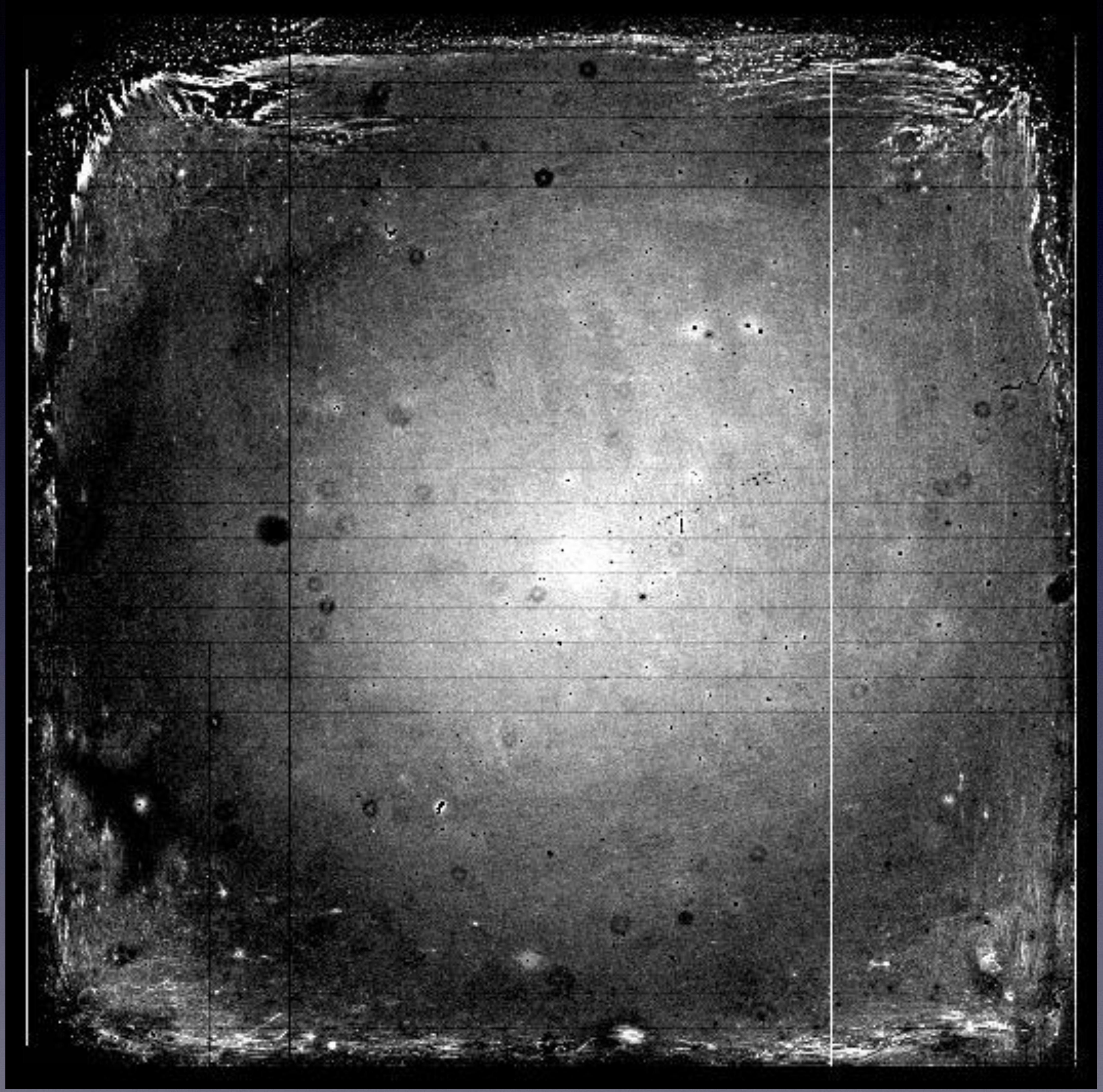


Flat-Field

- Uniform illumination source
- Dome flats (easy) vs twilight sky flats (better)
- Shows non-uniformity of detector, along with e.g. dust, filter imperfections



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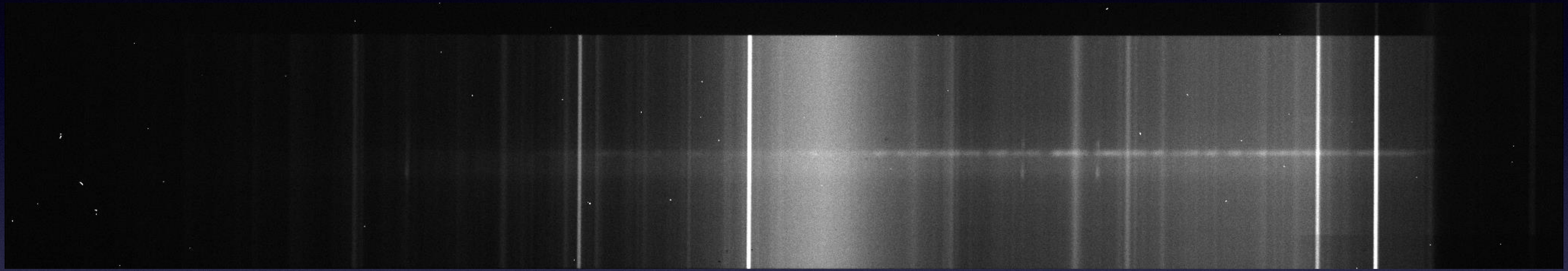
Fringing

- Interference due to photons reflecting within CCD
- Occurs longwards of ~700nm
- Largely due to atmospheric OH - cannot correct with flats
- But largely stable with time - can use library frames to correct

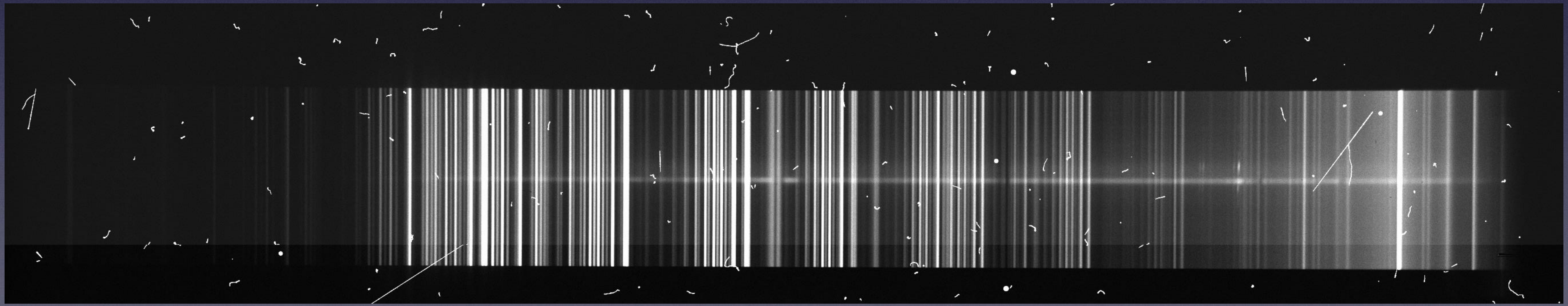
Example Z-band fringe frame for INT-WFC

Cosmic Rays

- Blue - Relatively few events

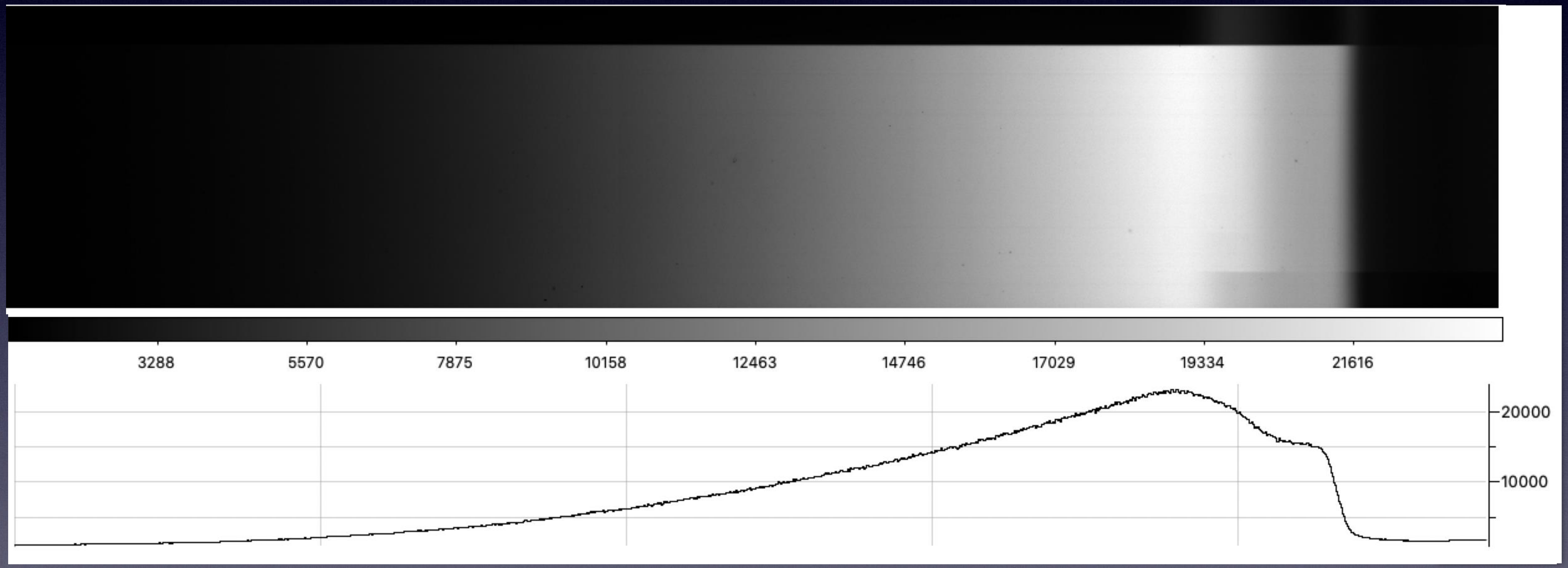


- Red - Thicker chip, many cosmic ray events

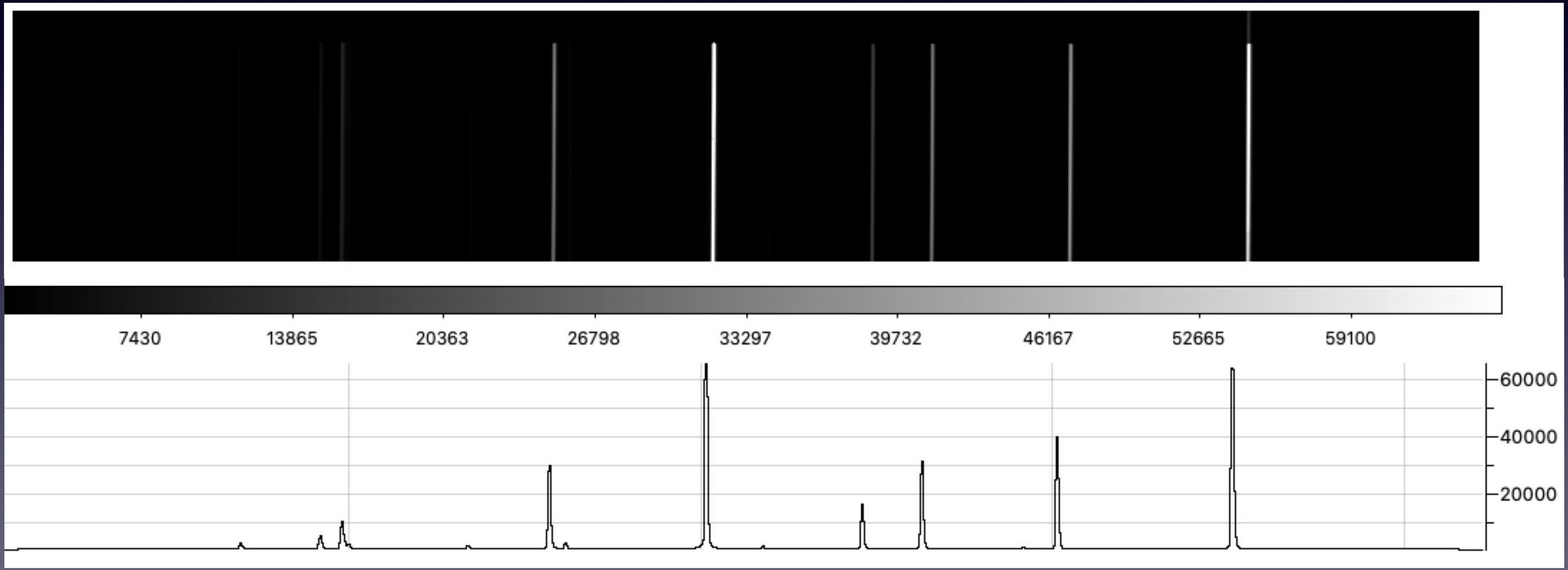


Spectroscopy

- Same ideas apply to spectroscopy
- Bias/Flat fields
- Also arc lamps - wavelength calibration



Arcs


7430
13865
20363
26798
33297
39732
46167
52665
59100
60000
40000
20000

Conclusions

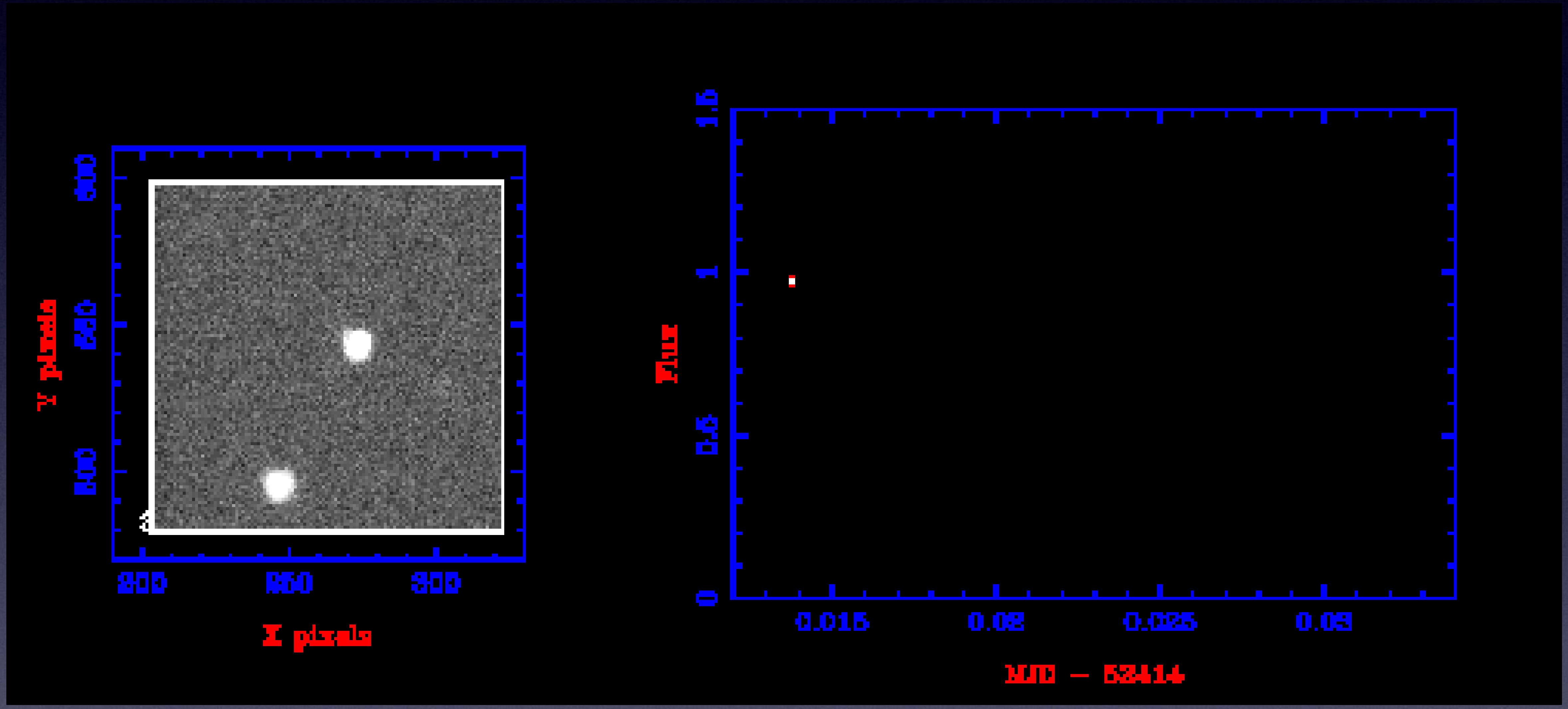
- CCDs are great!
- CCDs are not perfect
- Beware of non-linearity/saturation
- Remember calibration files

Conclusions

- Calibration Files:
  - Bias (Bias Voltage)
  - Flat Field (Non-uniform response)
  - Arcs (Wavelength Calibration)
  - Fringe Frame, Standard Star

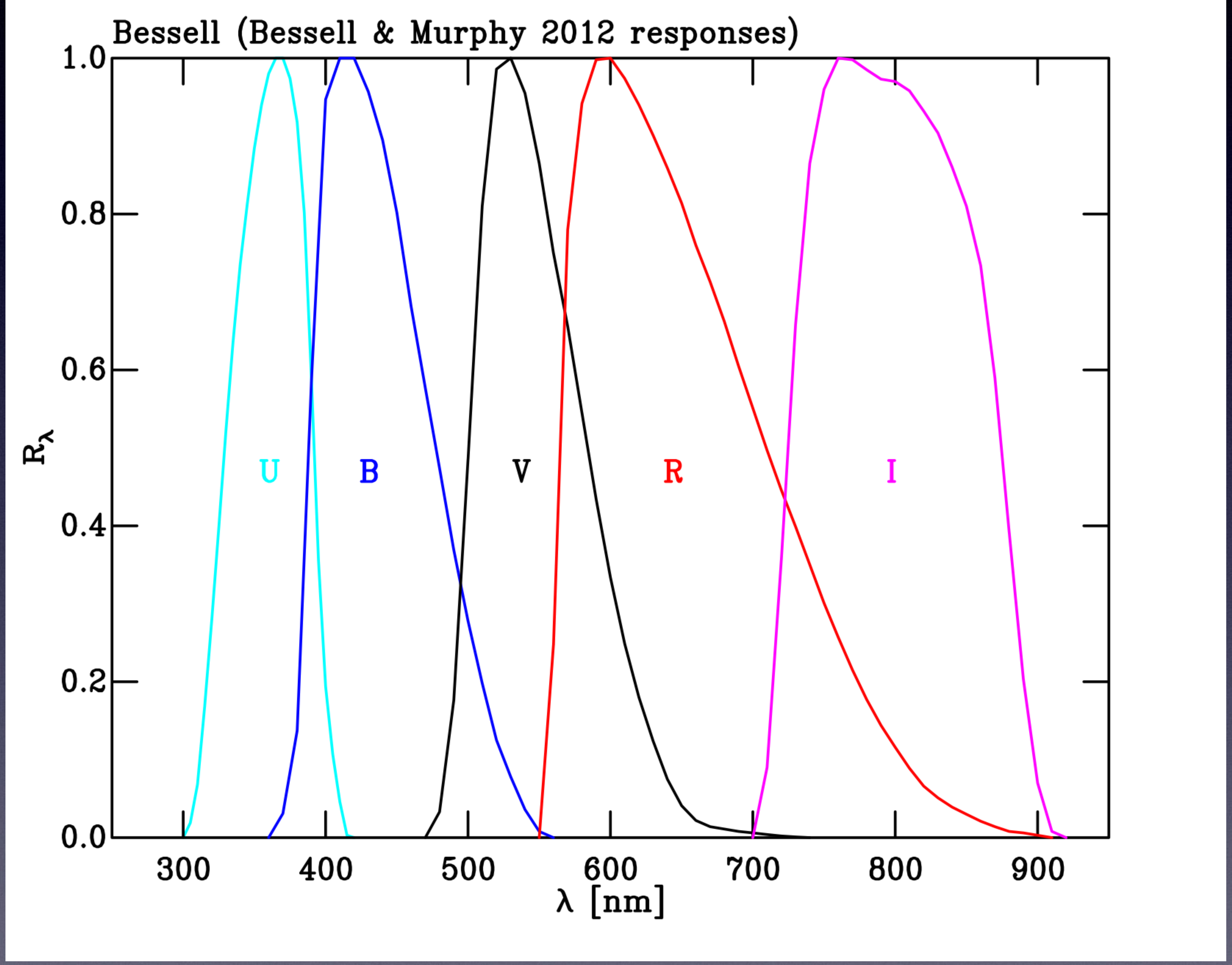
Extras: Photometry

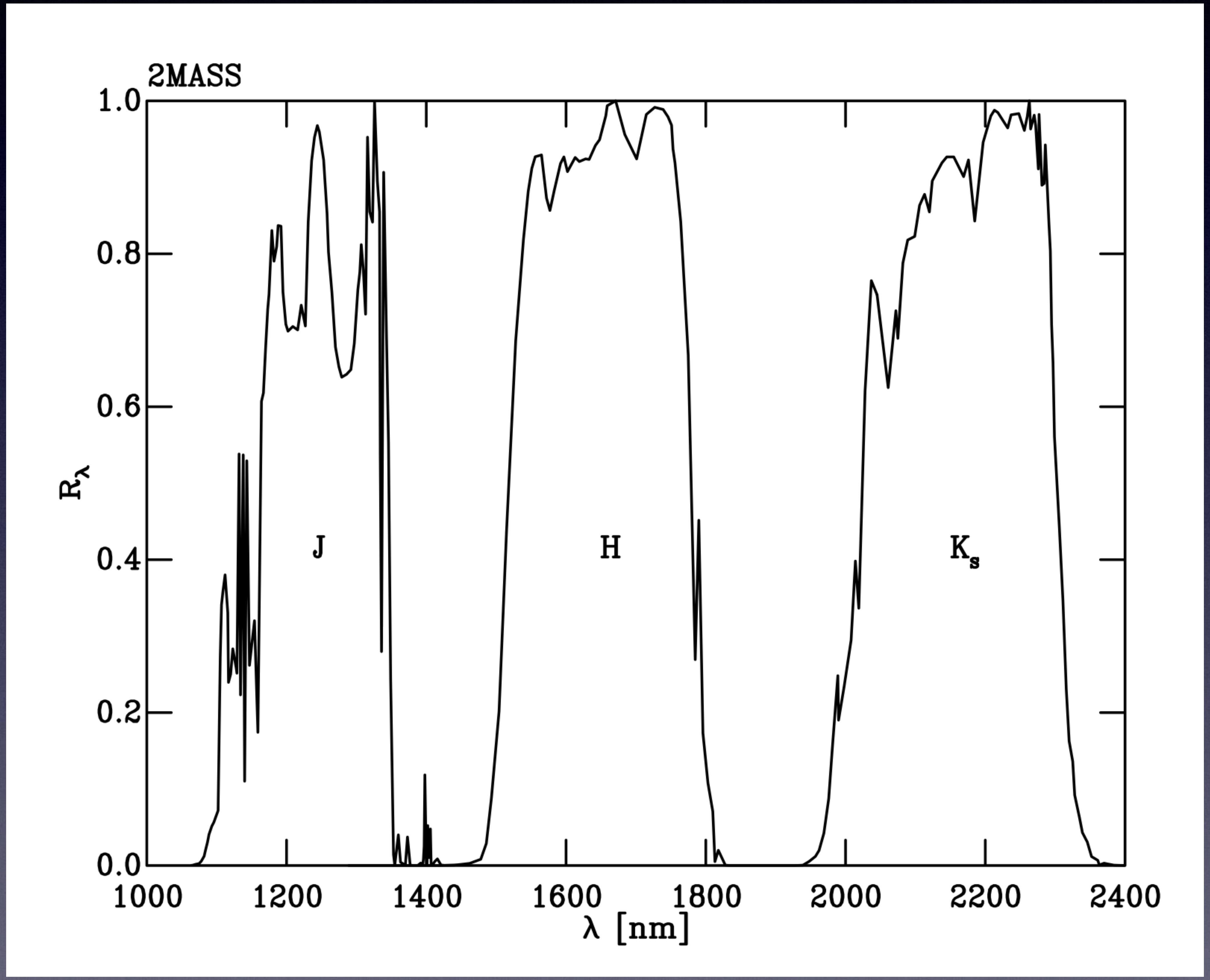
- We have photons - now what?
- Brightness or flux of star - easy to measure
- Variation with time - lightcurves
- Using filters can get you colour information



Credit: S. Littlefair (Sheffield University)

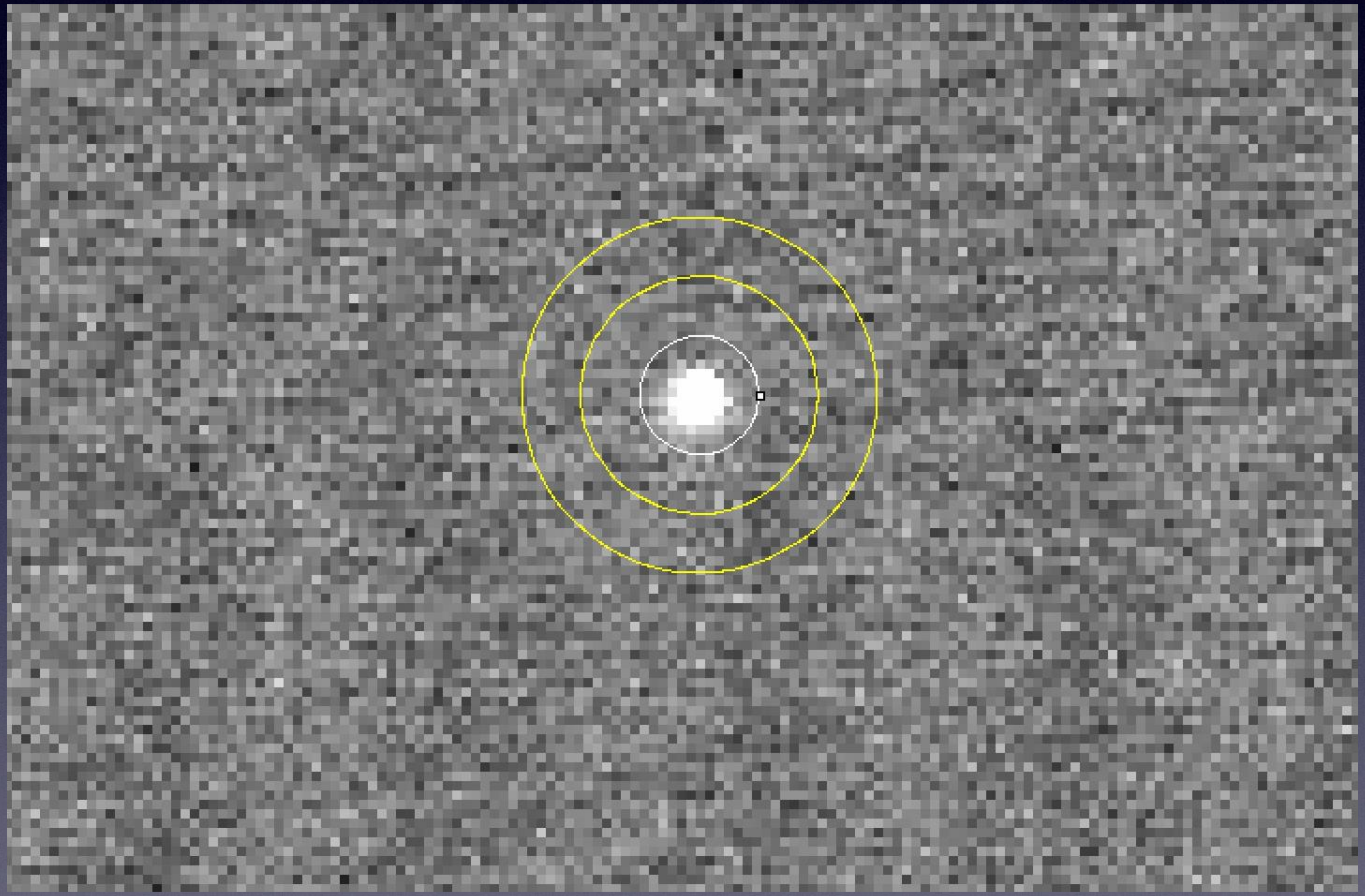
Photometry: Filter Systems





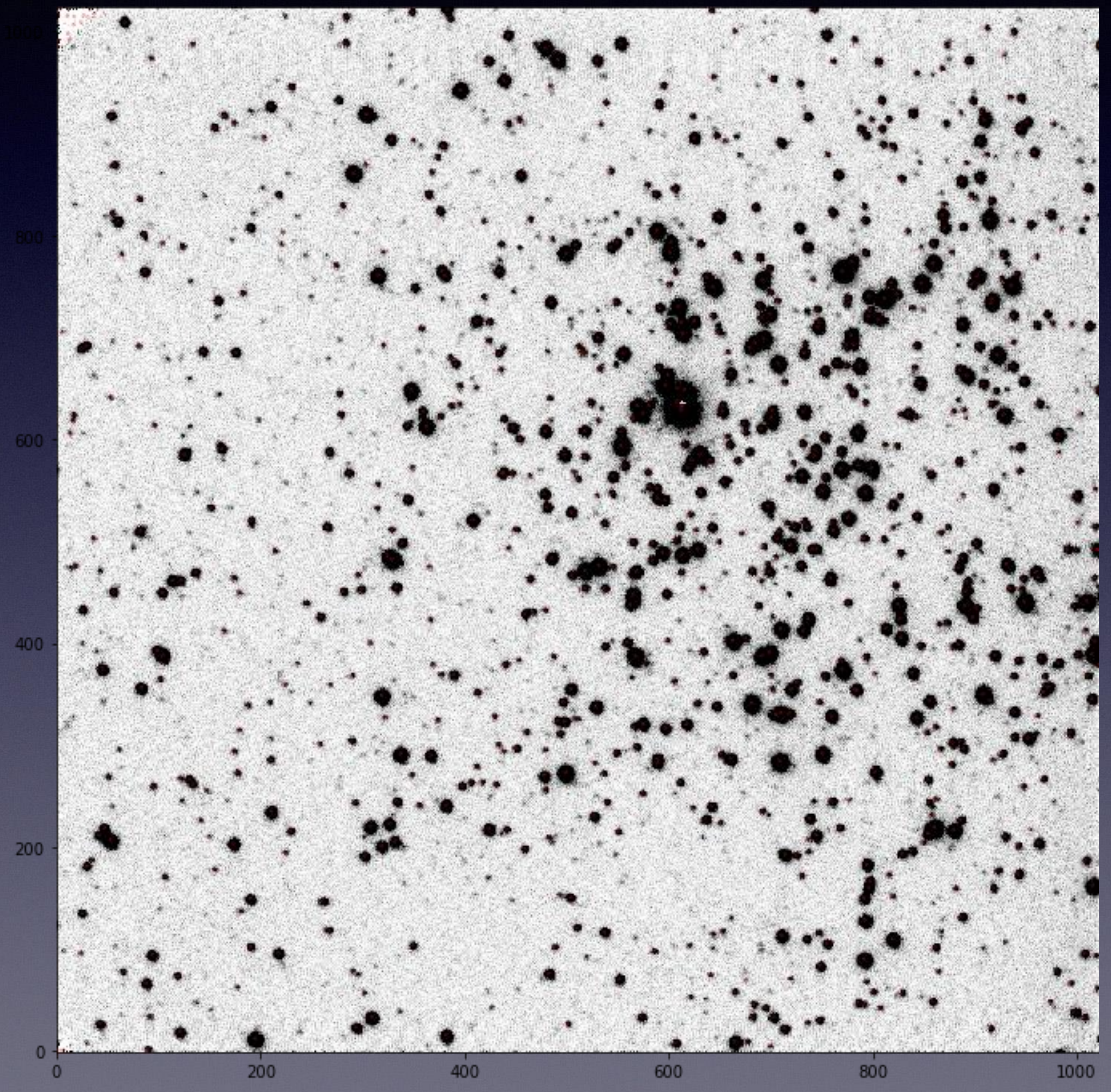
Photometry: Aperture Photometry

- Aperture photometry is most common
- Sum up pixels in an aperture centered on the star
- But what about sky brightness?
- Use annulus near star devoid of other sources
- Subtract average (median) sky from target star



Photometry: Centroiding/Sky

- But what if we have a lot of stars?
- Automate identifying stars
- Measure sky background, look for things a few sigma above background level
- Fit stellar profile with a gaussian to determine center



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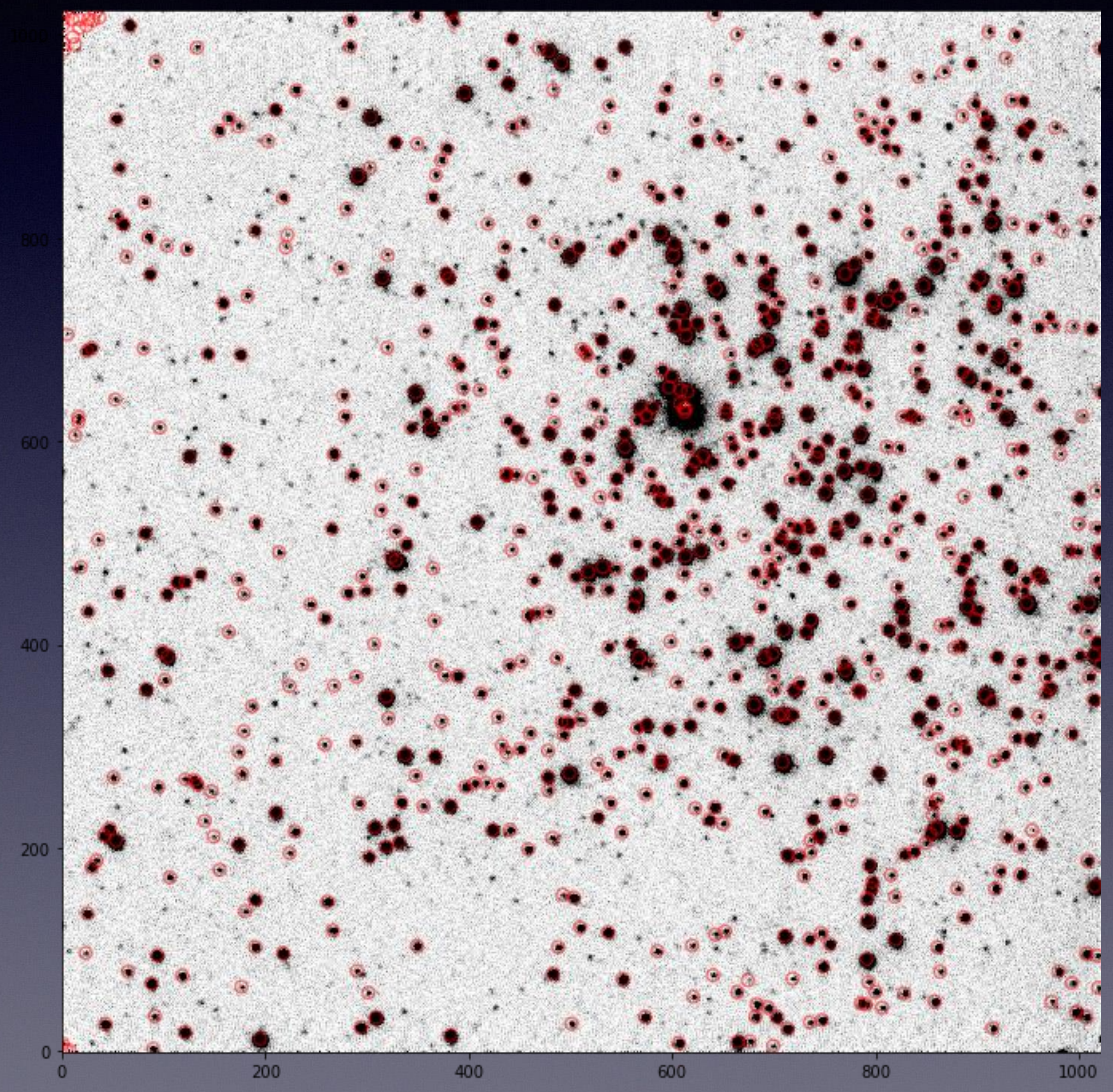
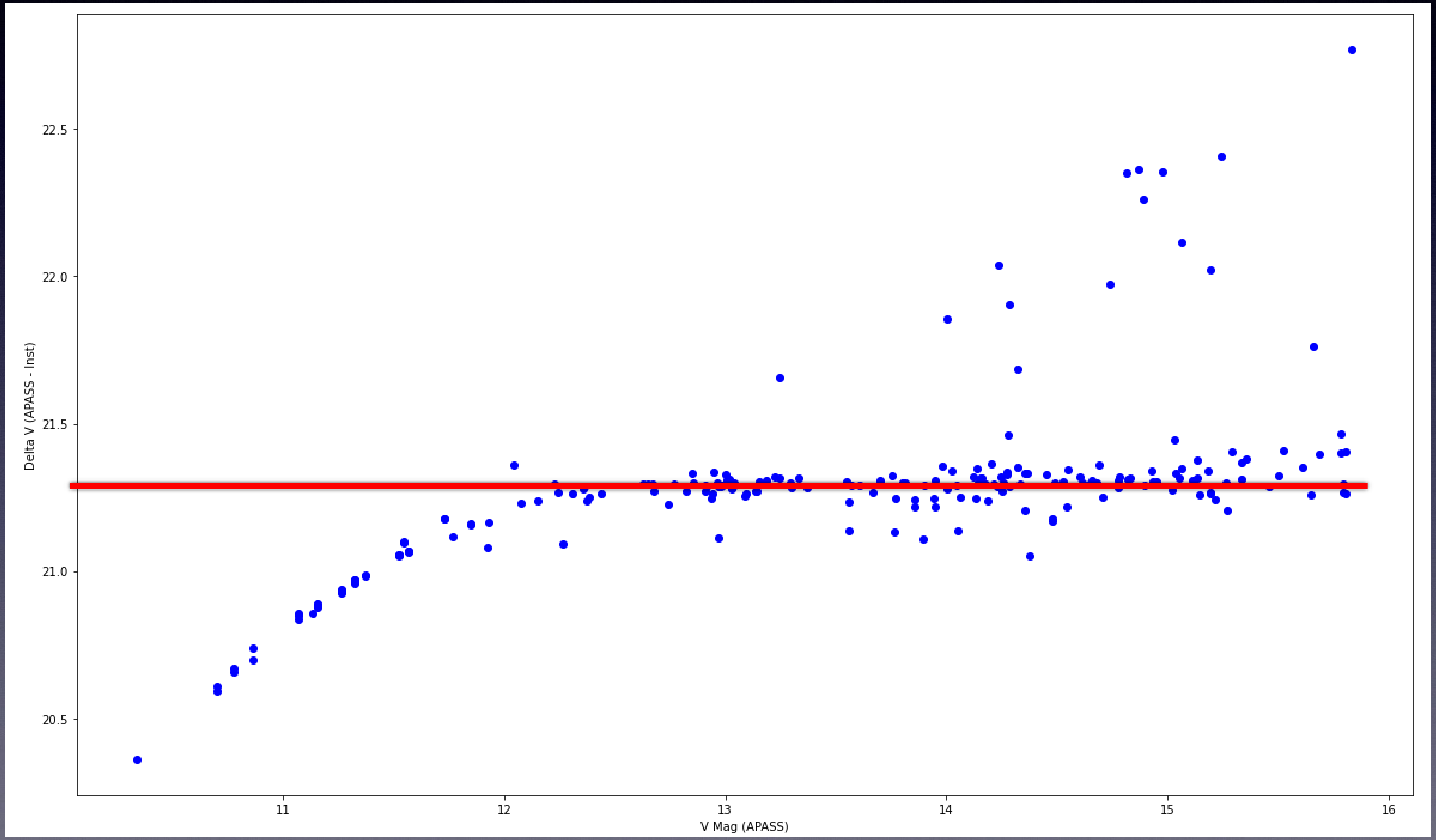


Photometry: Calibration

- We now have instrumental mag
- How do we relate back to other systems?
- Typically - standard stars
- These days, wide-field surveys can provide an alternate method

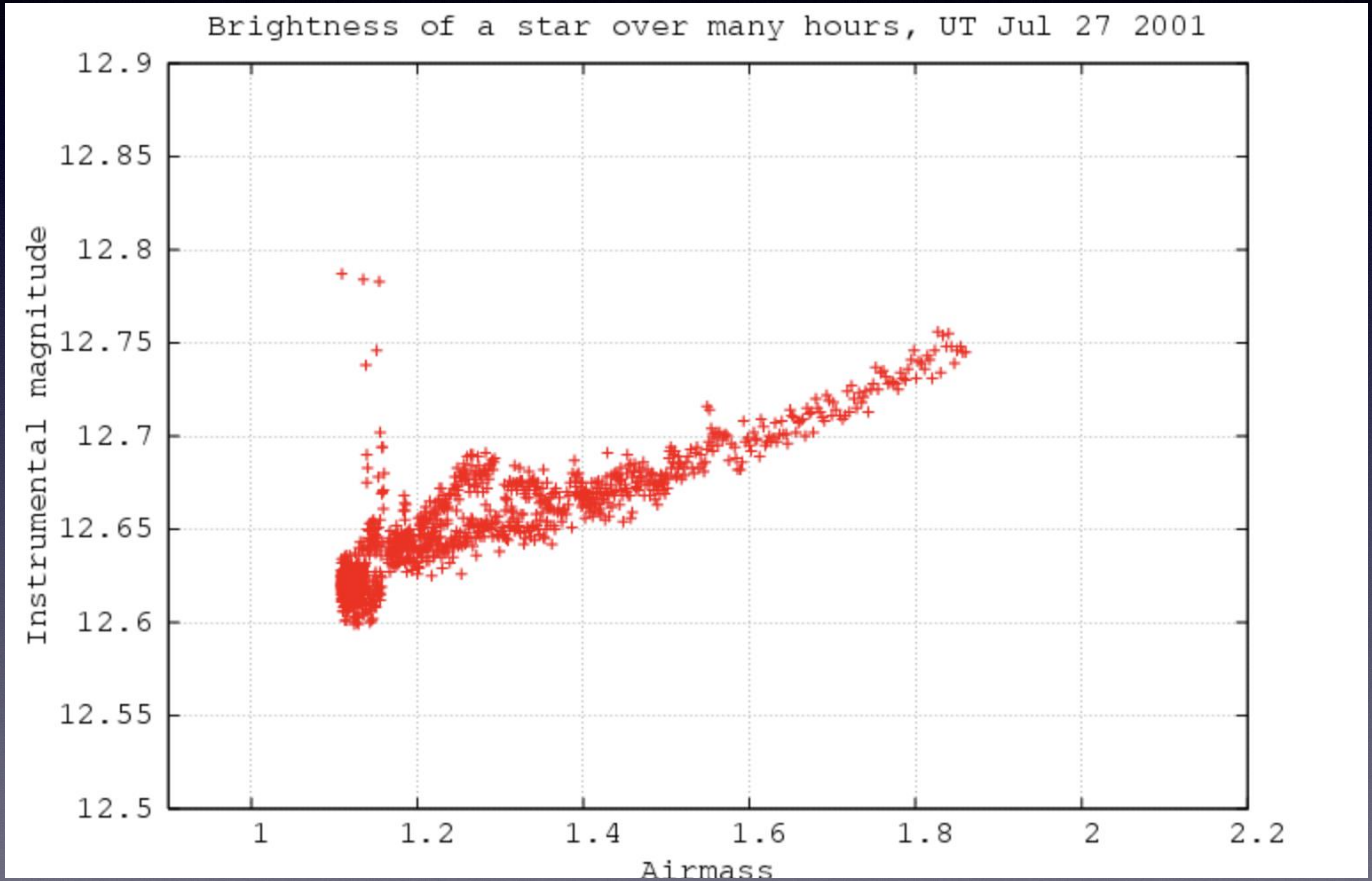


Photometry: Calibration

- Star brightness will vary as a function of airmass

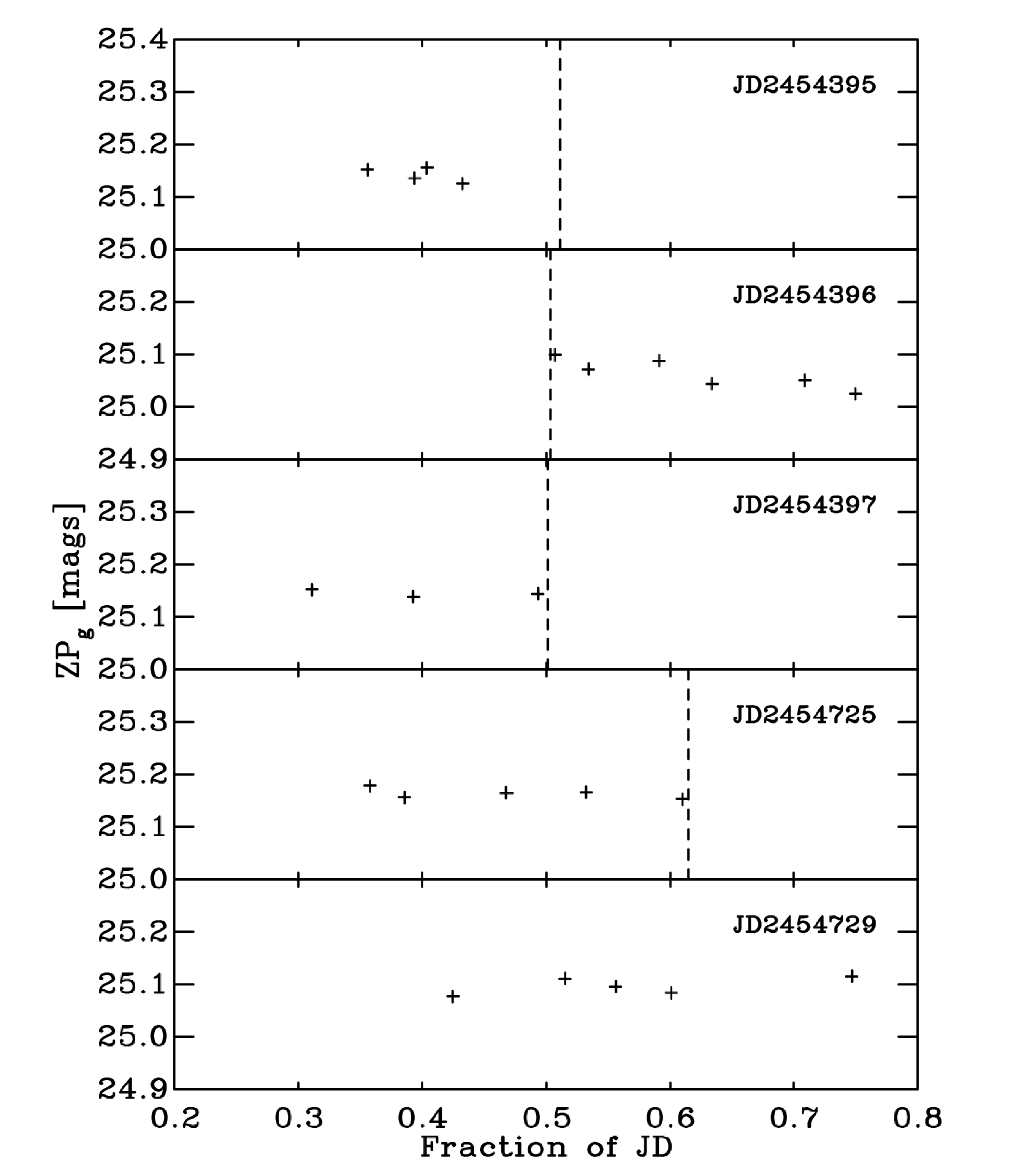
- If using standard stars, will typically need to observe them over a range of airmass

- Determine correction as a function of airmass



Photometry: Calibration

- Star brightness will vary as a function of airmass
- If using standard stars, will typically need to observe them over a range of airmass
- Determine correction as a function of airmass
- Also need to worry about temporal variations – photometric conditions?



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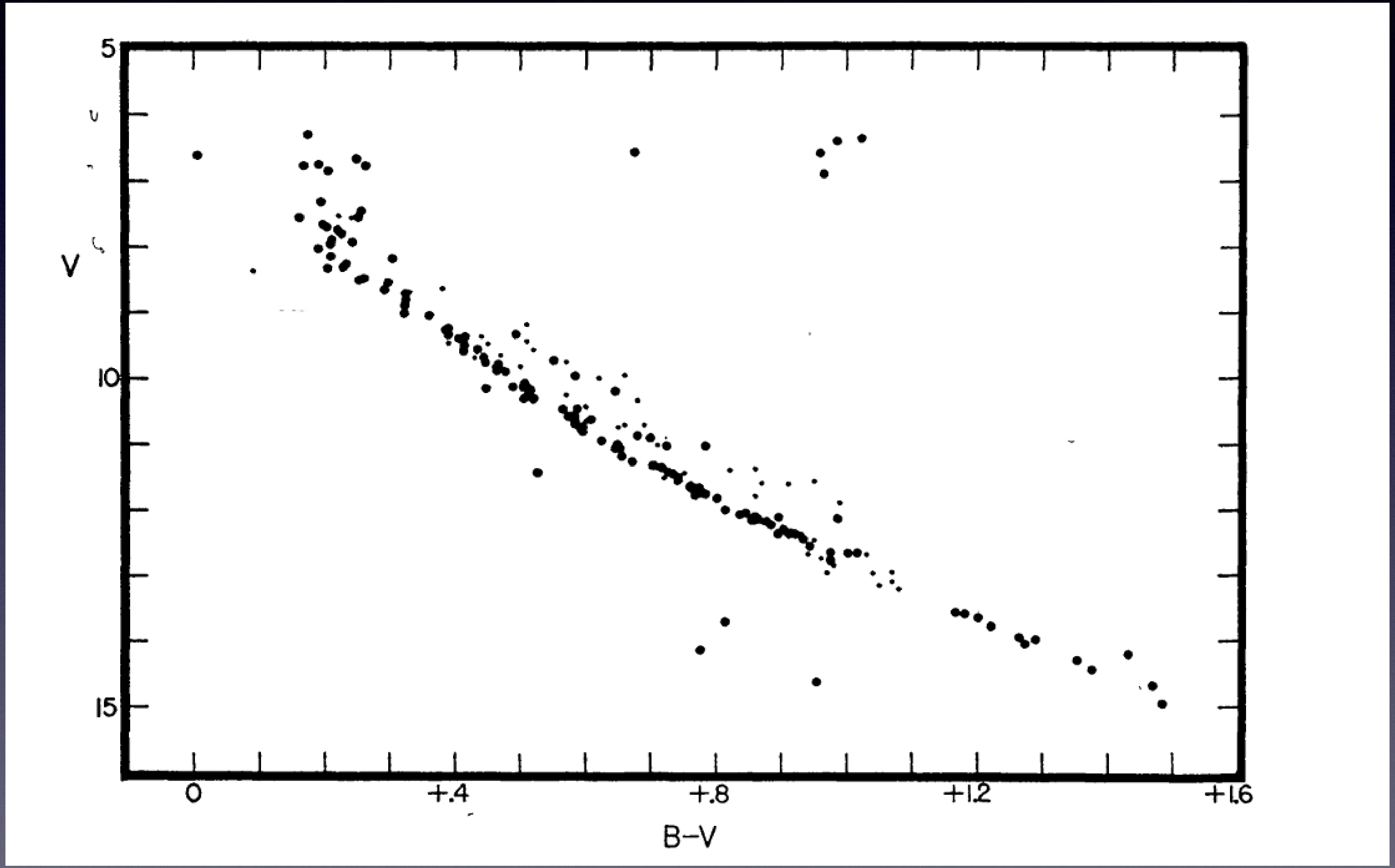

V, B-V CMD of Praesepe (Johnson 1952)

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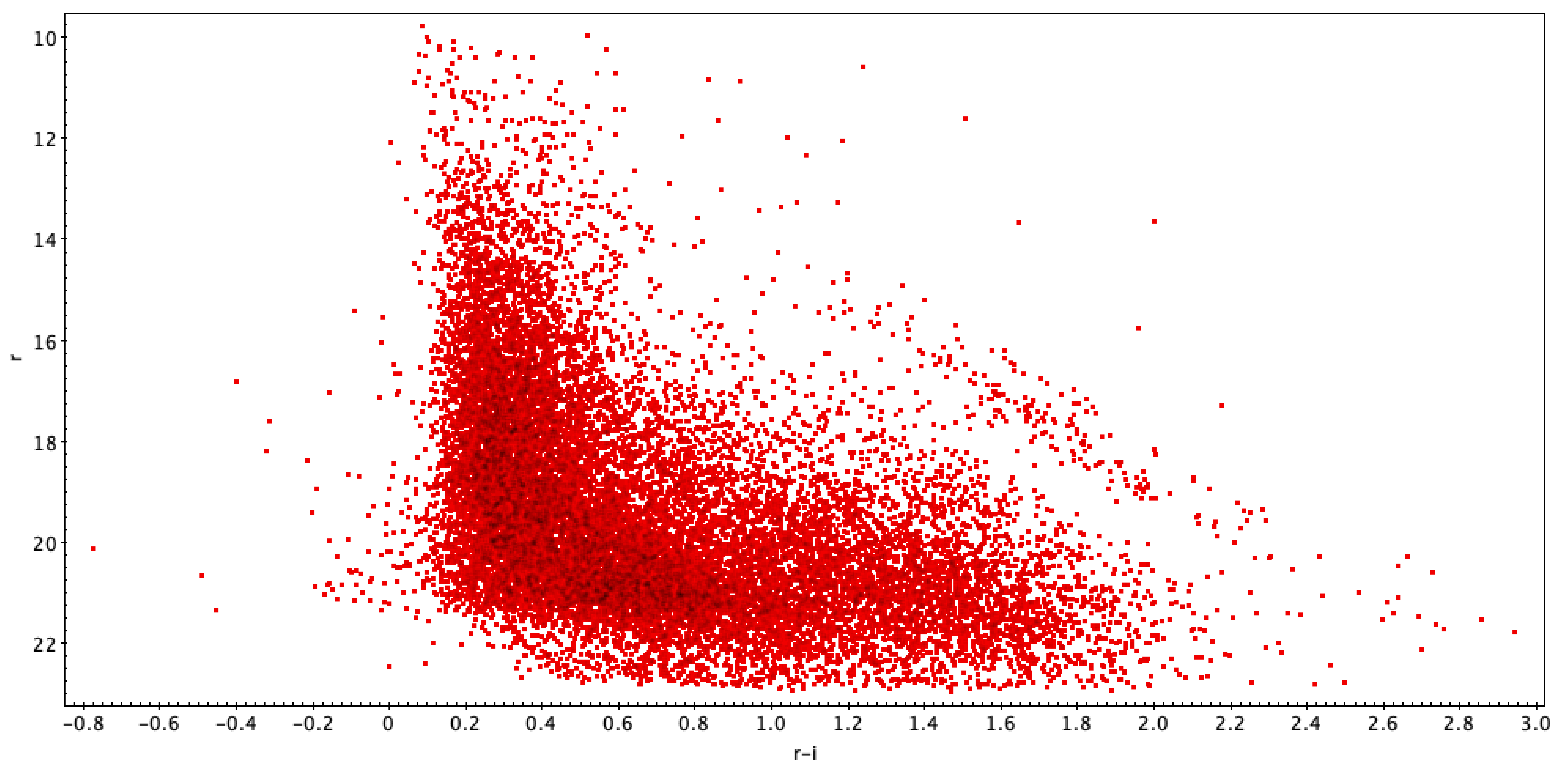
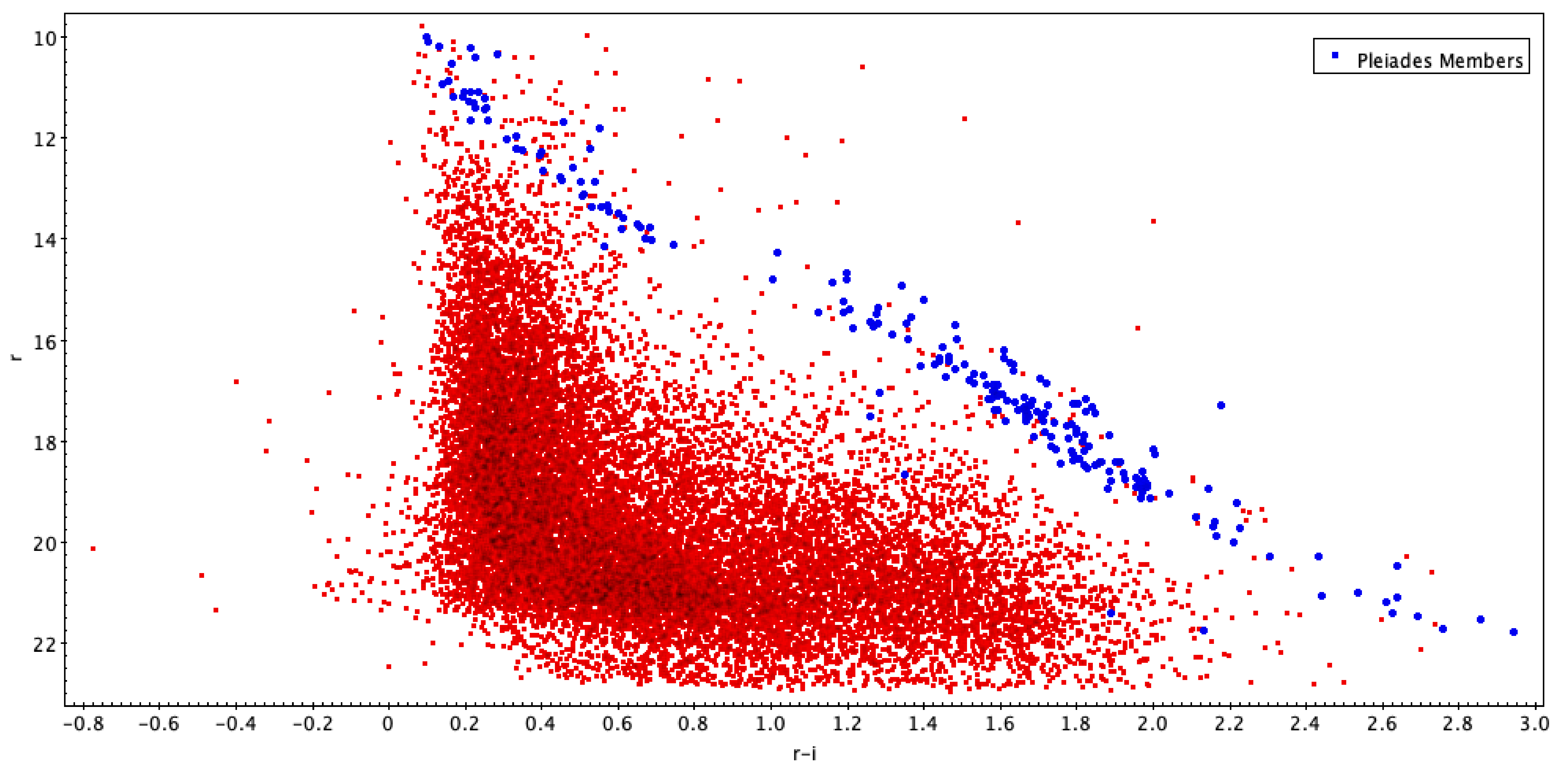


r, r-i CMD of Pleiades (Rees 2016)

Photometry: CMDs



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