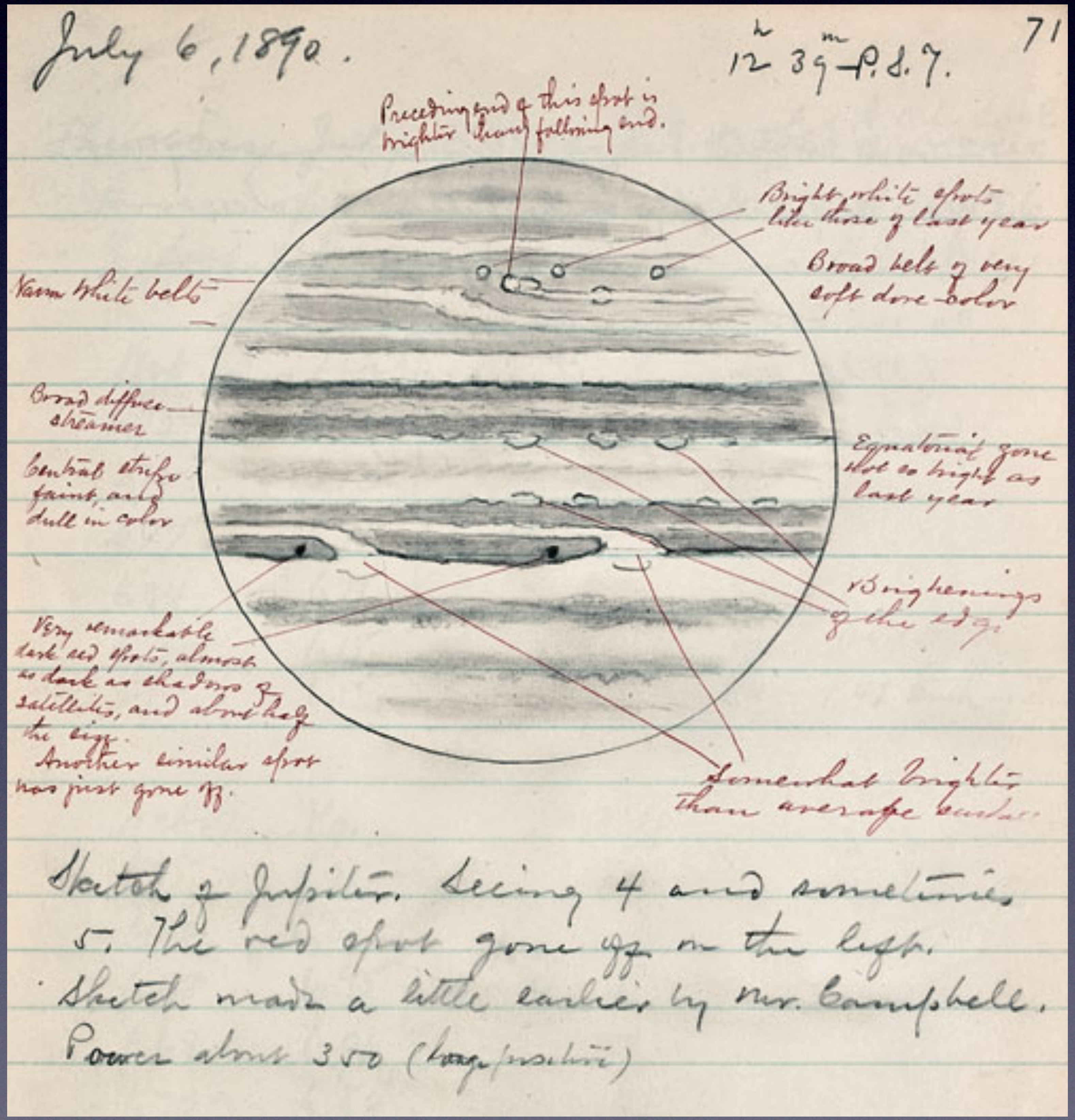
Introduction to CCD Astronomy

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



July 6, 1890.

$12^h 39^m$ P.S.T.

71

Preceding end of this spot is brighter than following end.

Bright white spots like those of last year

Broad belt of very soft dove-color

Warm white belts

Broad diffuse streamer

Central stripe faint, and dull in color

Equatorial zone not so bright as last year

Brightenings of the edges

Very remarkable dark red spots, almost as dark as shadows of satellites, and about half the size. Another similar spot has just gone off.

Somewhat brighter than average border

Sketch of Jupiter. Seeing 4 and sometimes 5. The red spot gone off on the left. Sketch made a little earlier by Mr. Campbell. Power about 350 (long positive)

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

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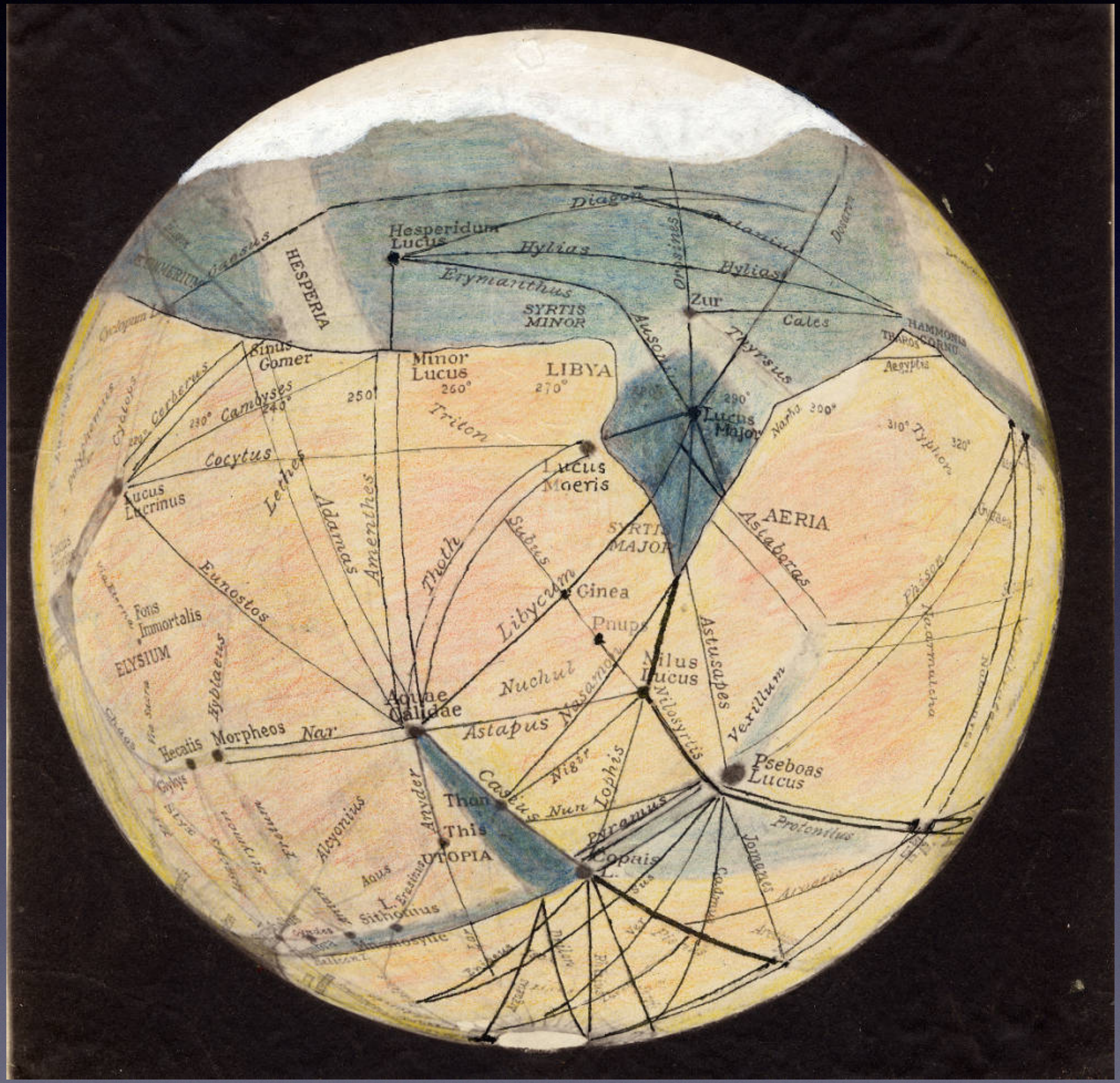
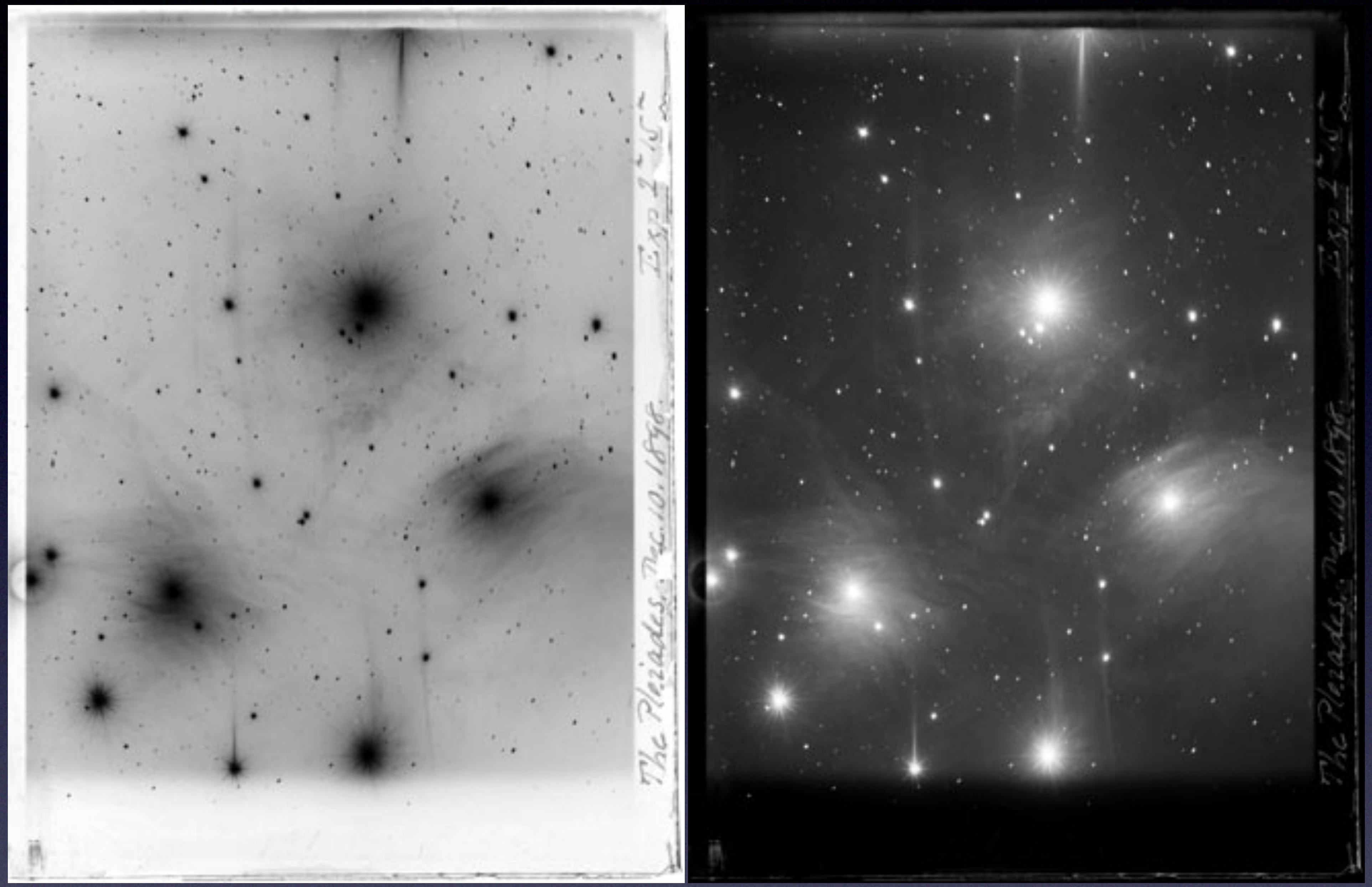
- But still difficult to deal with faint objects, optical illusions

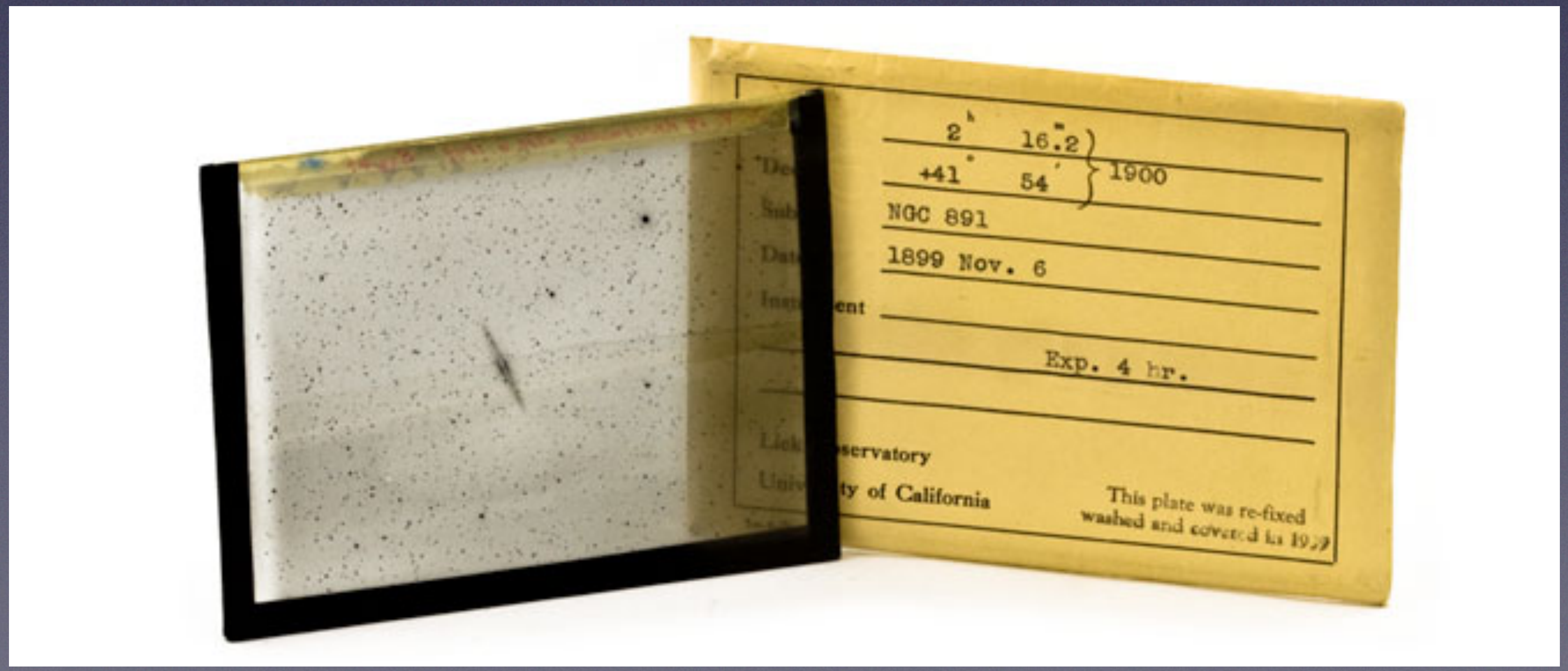


Drawing of 'canals' on Mars by Percival Lowell, 1905 (Credit: Lowell Observatory)

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

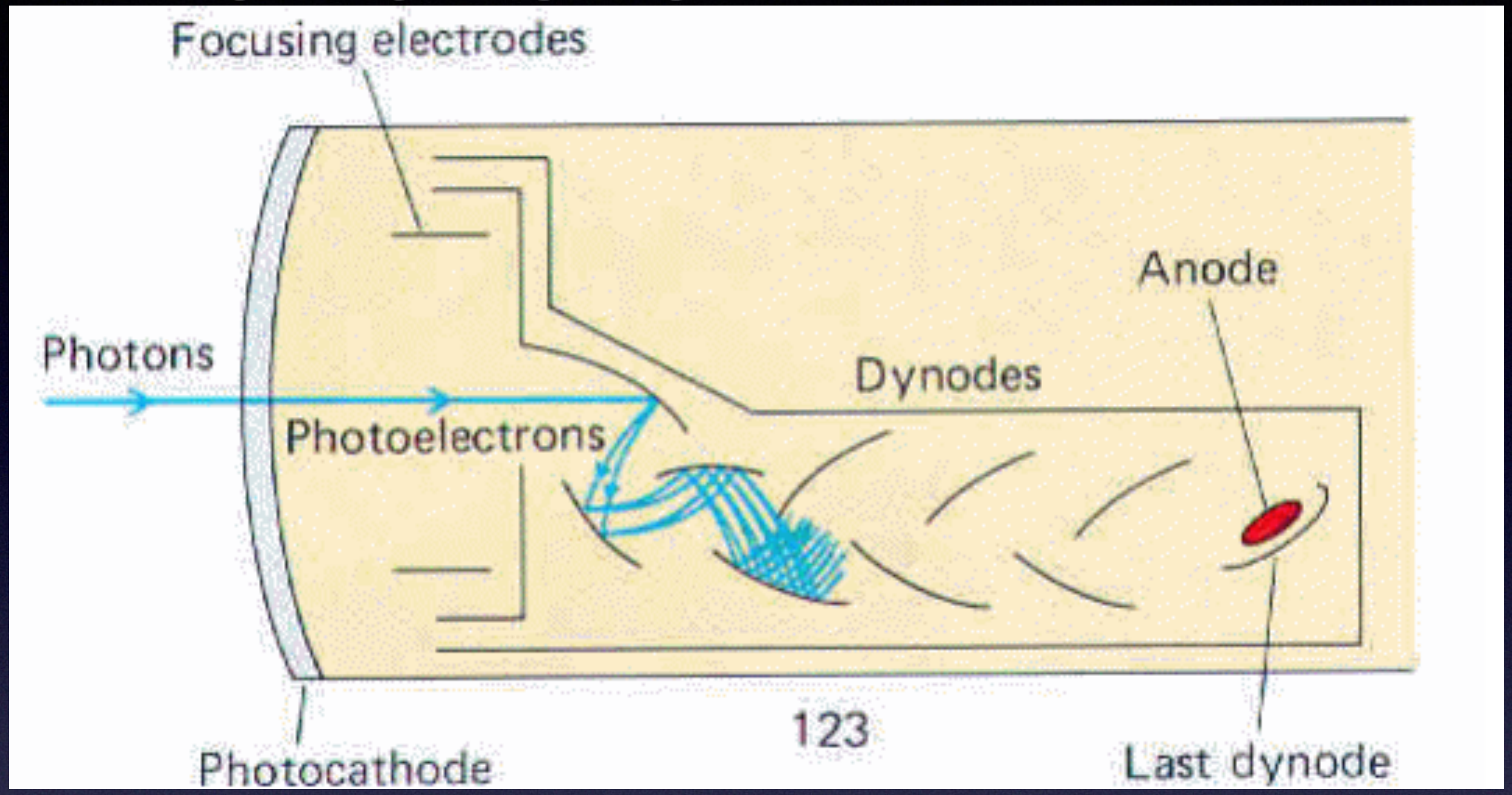




Top: Negative (left) and Positive (right) prints of a 135 min exposure of the Pleiades, Dec 1898
Bottom: Photographic plate showing 4 hr exposure of an edge-on galaxy, Nov 1899
(Credit: Lick Observatory Historical Collections)

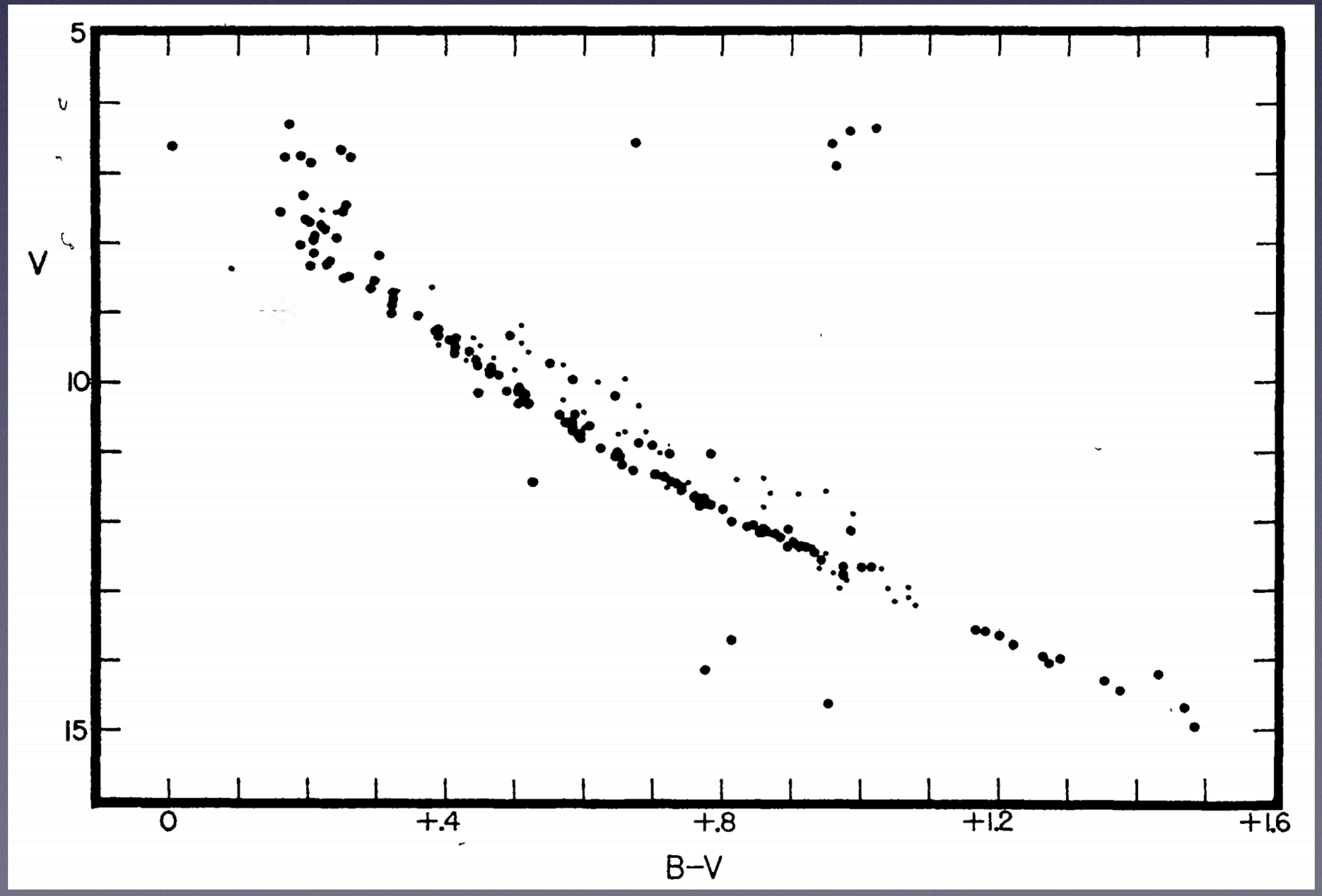
Photomultiplier Tubes

- 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



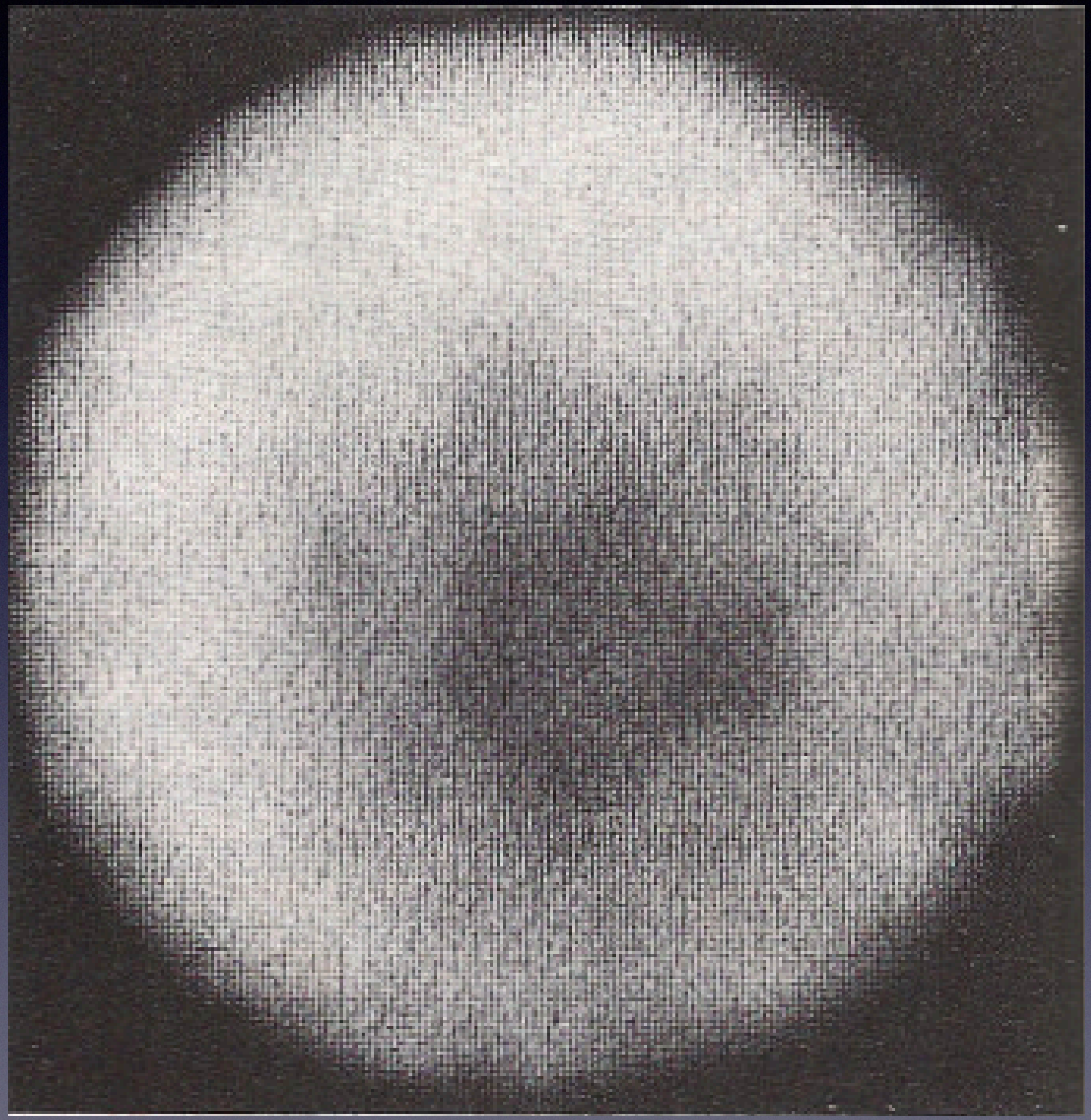
Top: Layout of a Photomultiplier Tube (Credit: R. O'Connell, U.Va)

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



The First CCD Observation

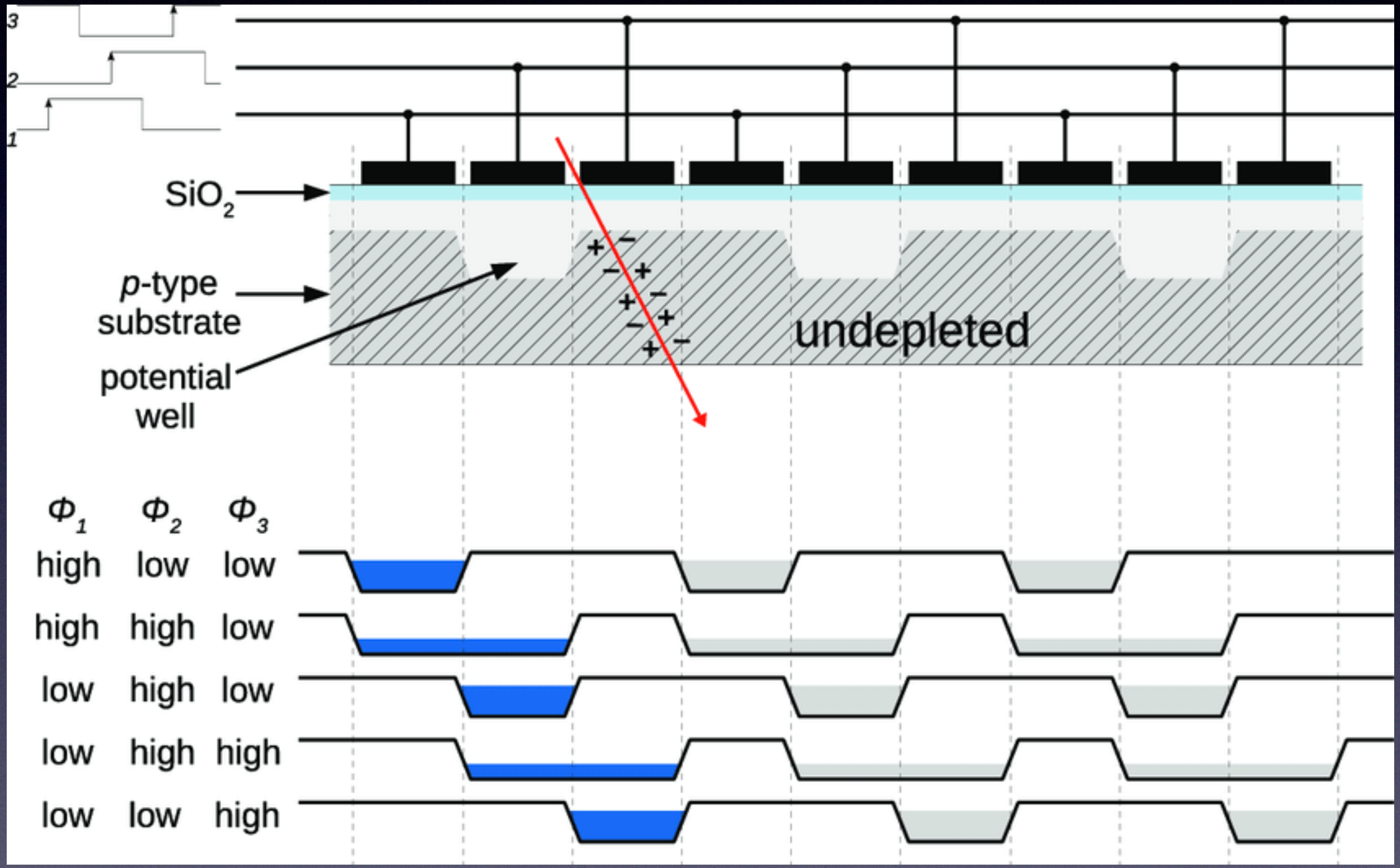
- Created by Bell Labs in 1969.
- First used for Astronomy in 1976 by JPL/UoA



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

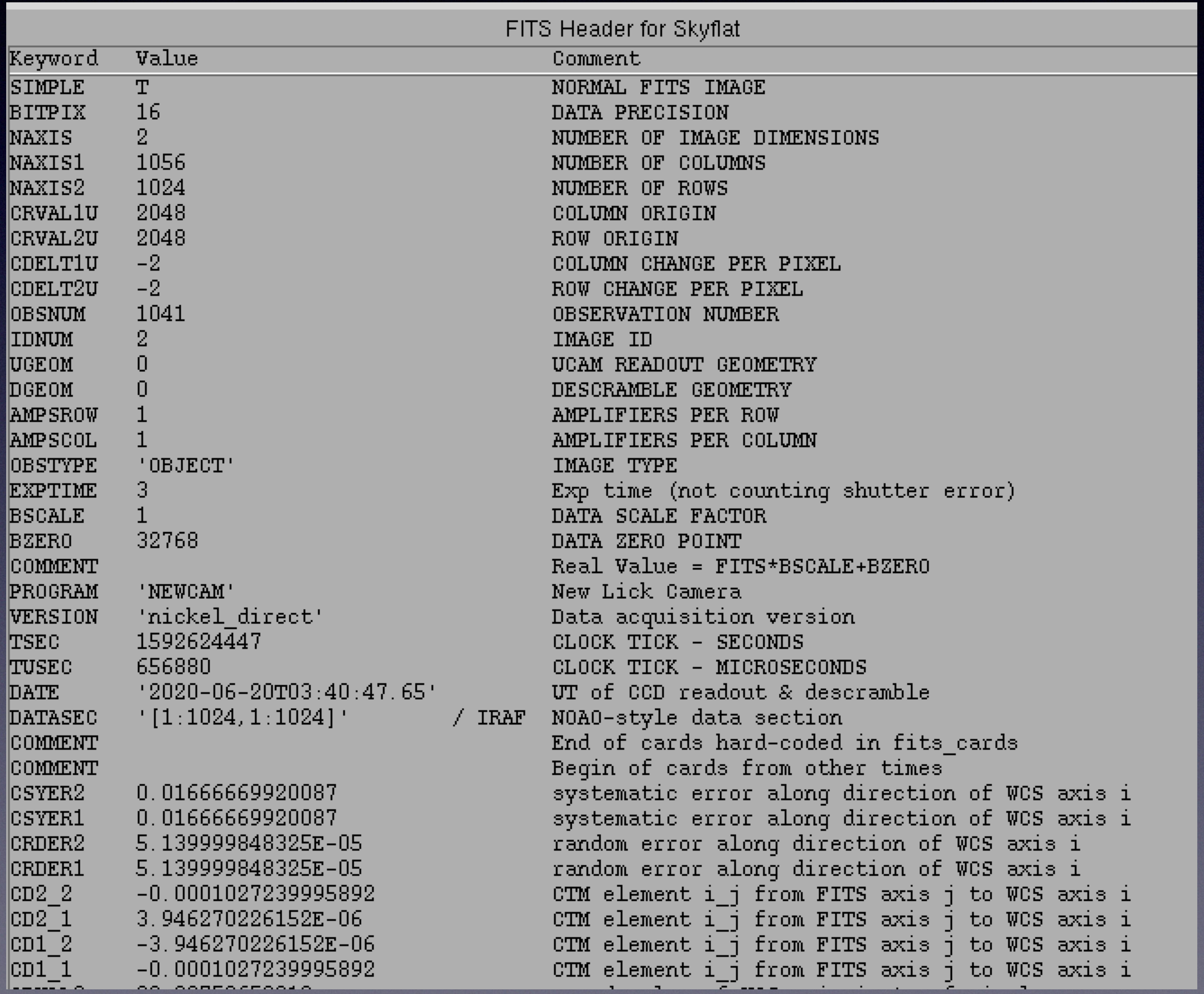


Φ_1	Φ_2	Φ_3
high	low	low
high	high	low
low	high	low
low	high	high
low	low	high

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



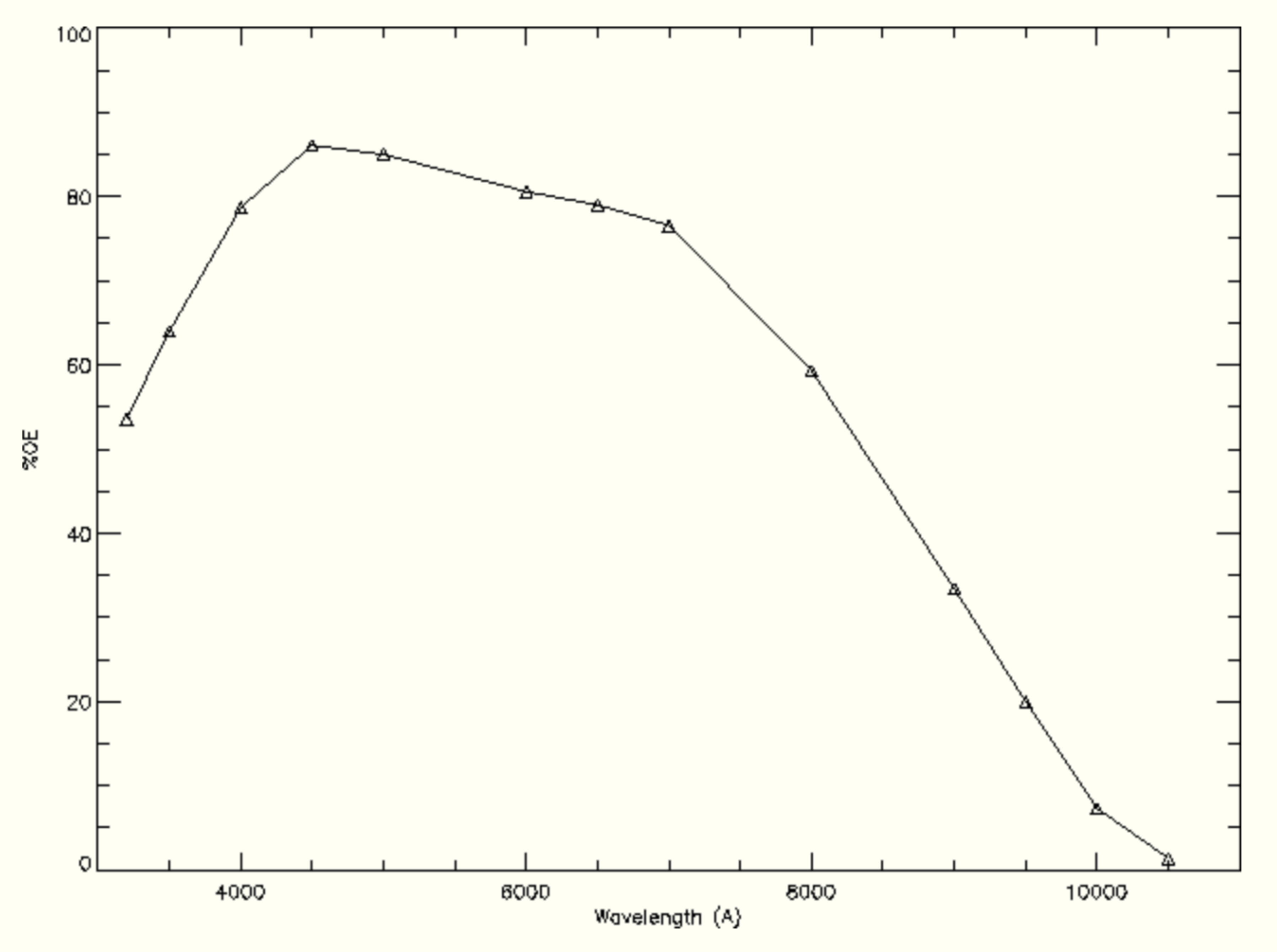
FITS Header for Skyflat

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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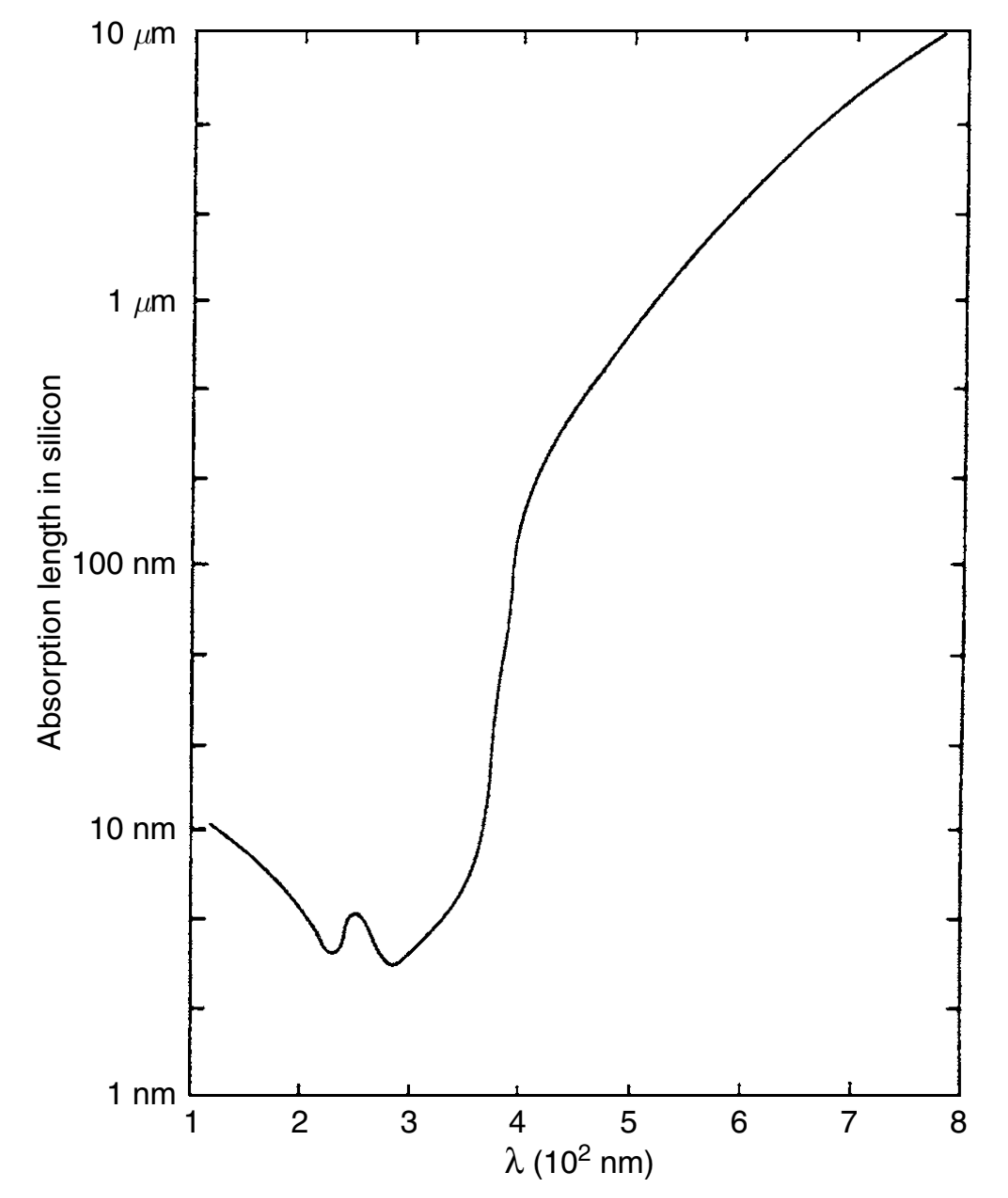

Photon absorption length in silicon (Reicke 1994)

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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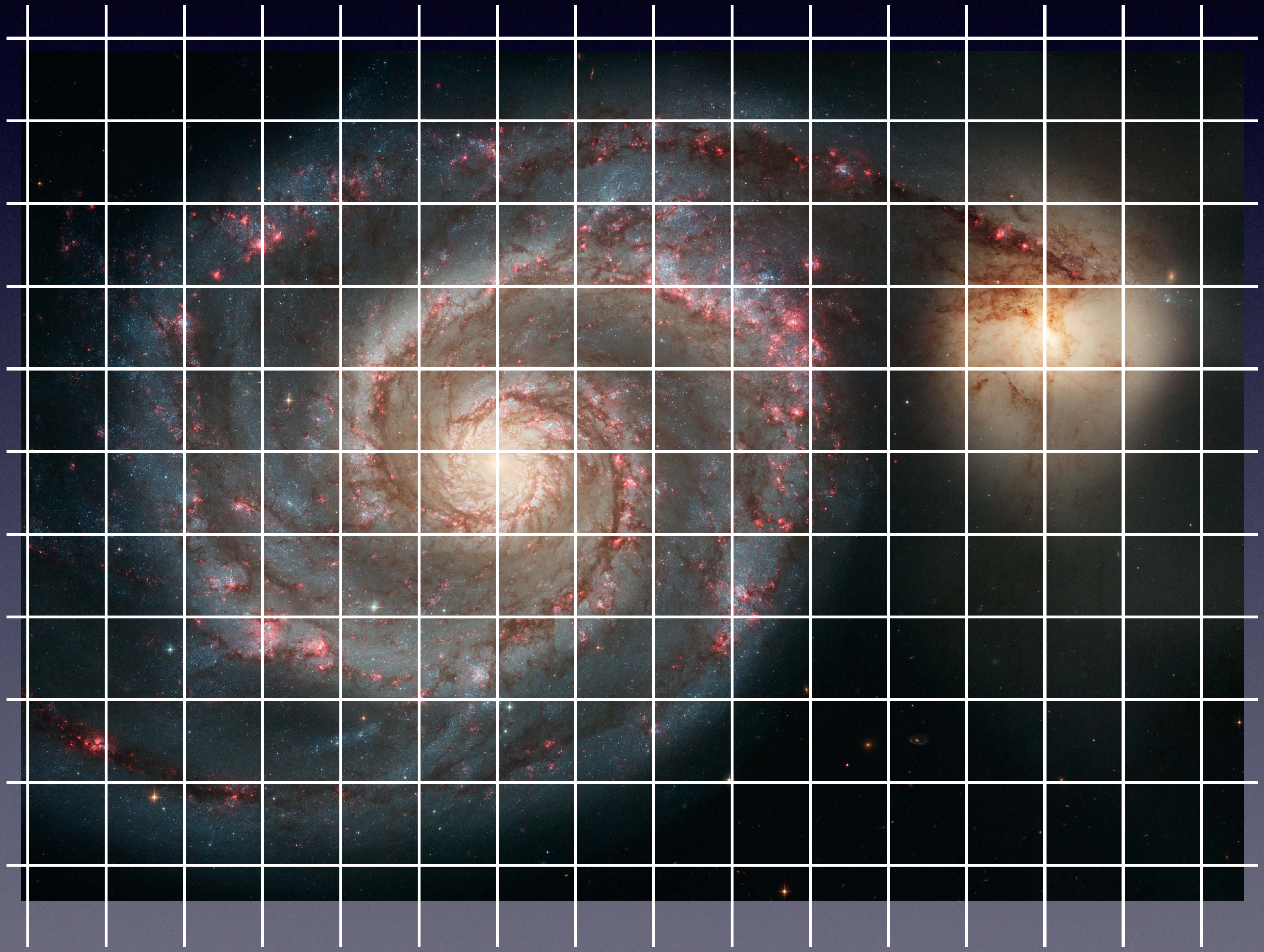
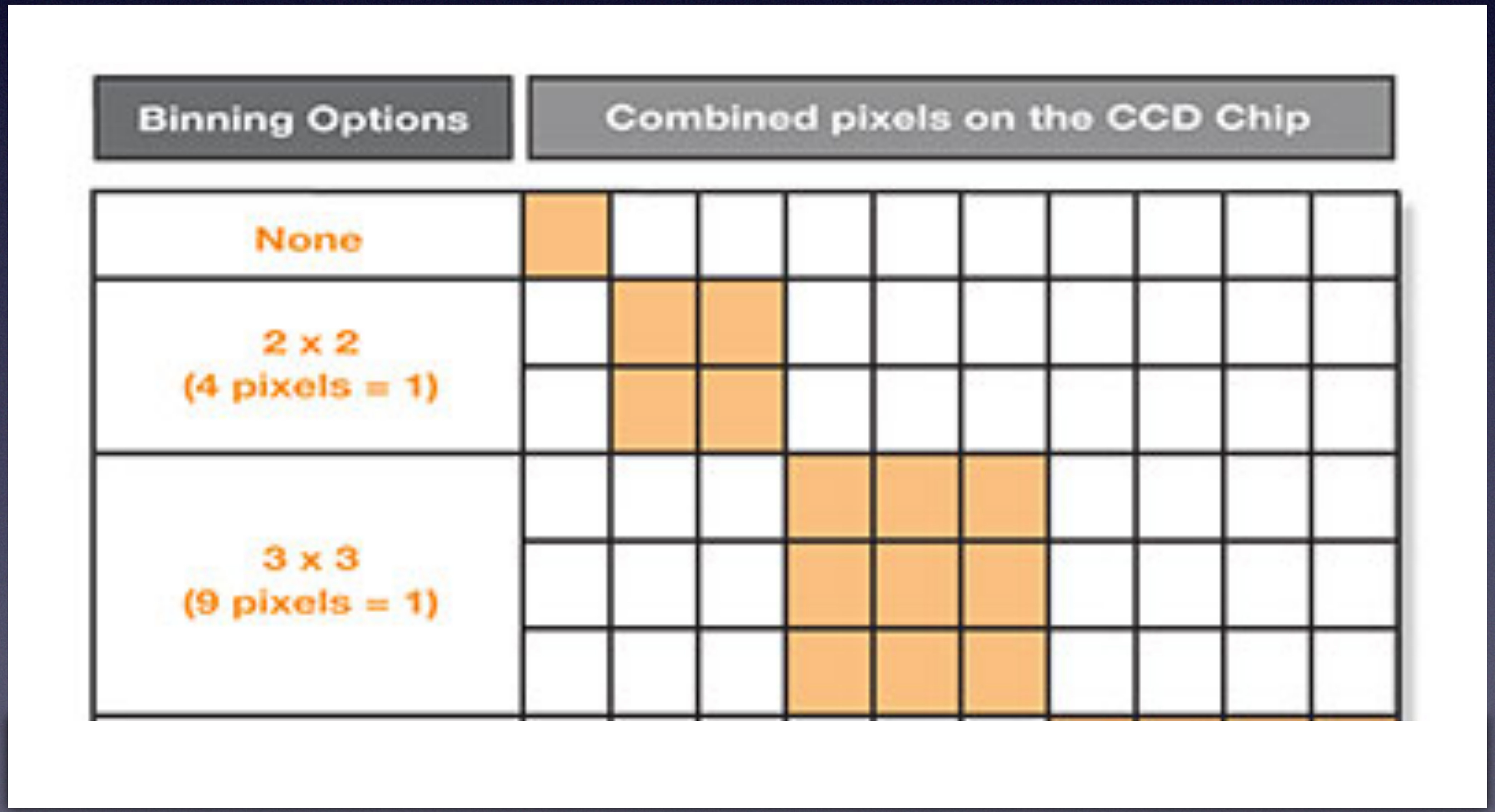


Plate Scale/Binning

- 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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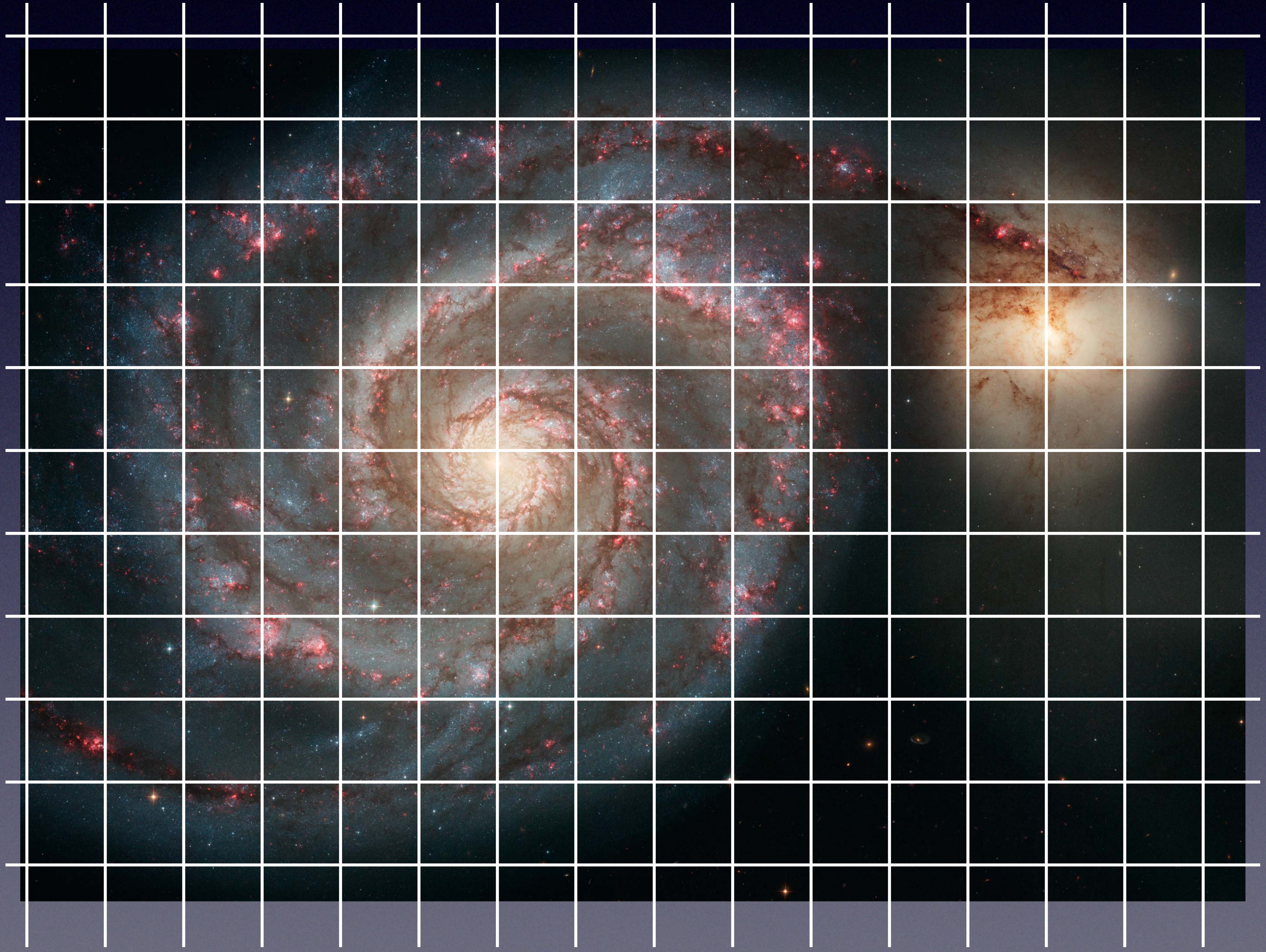

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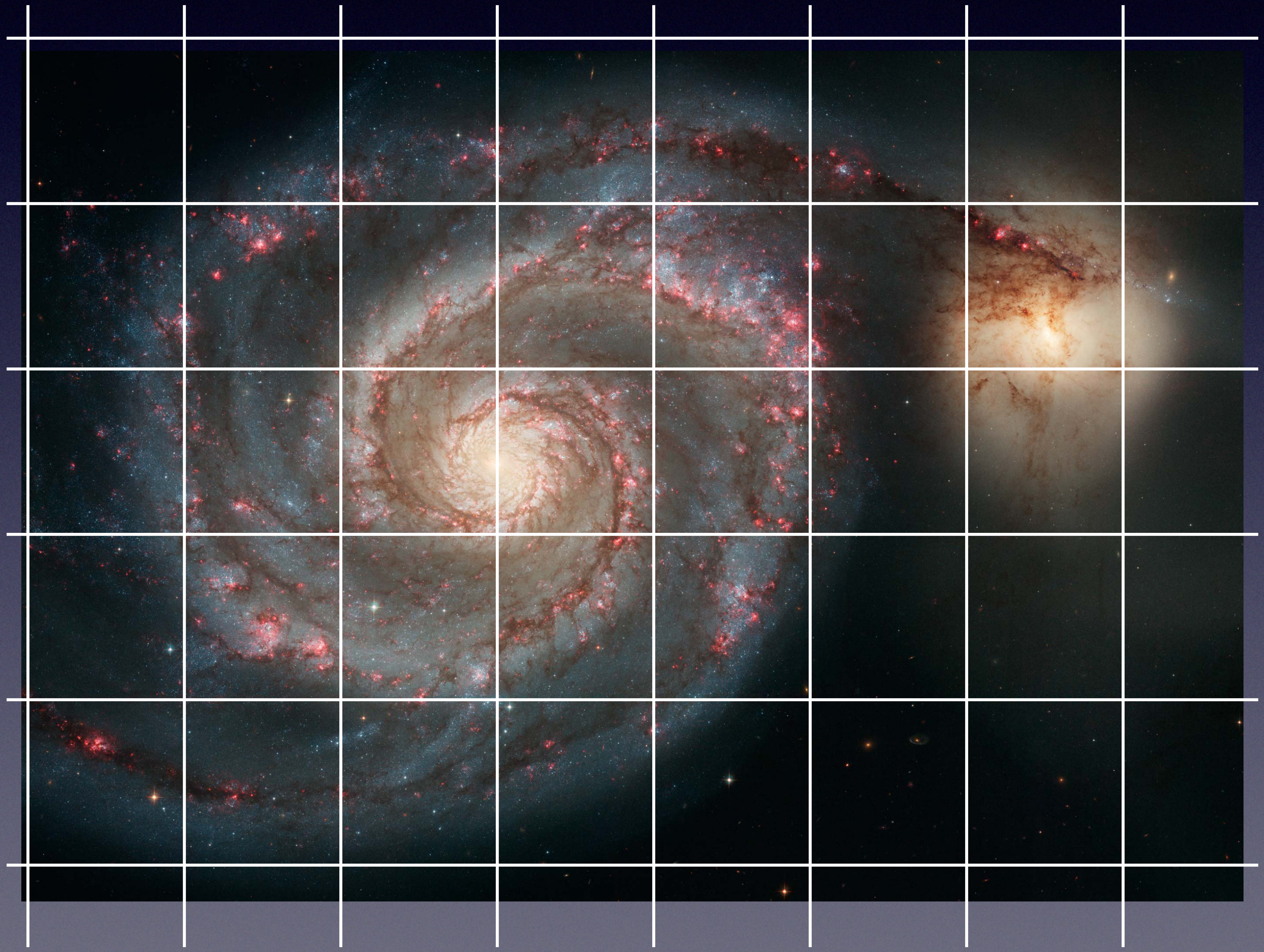

Windowing

- 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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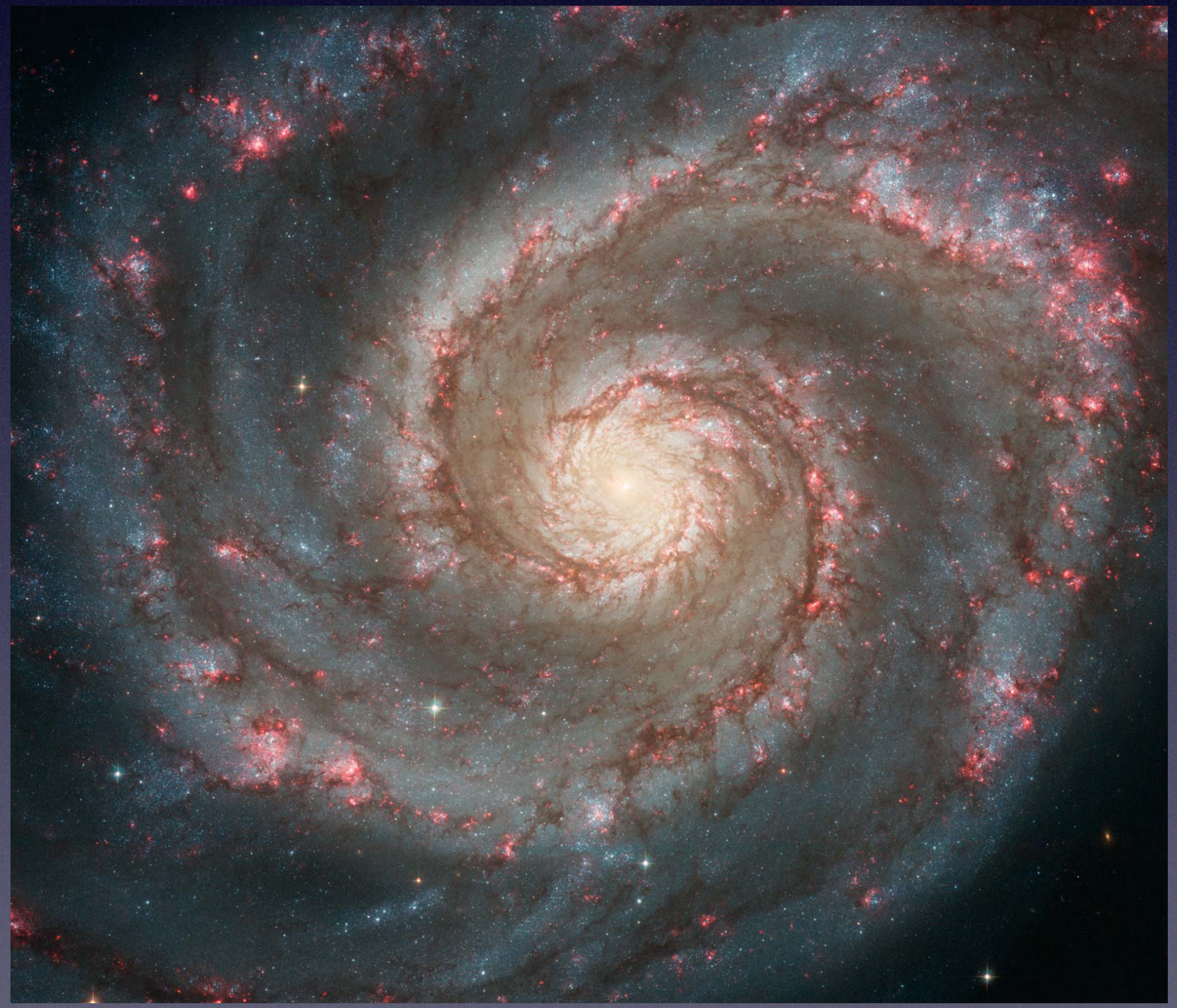
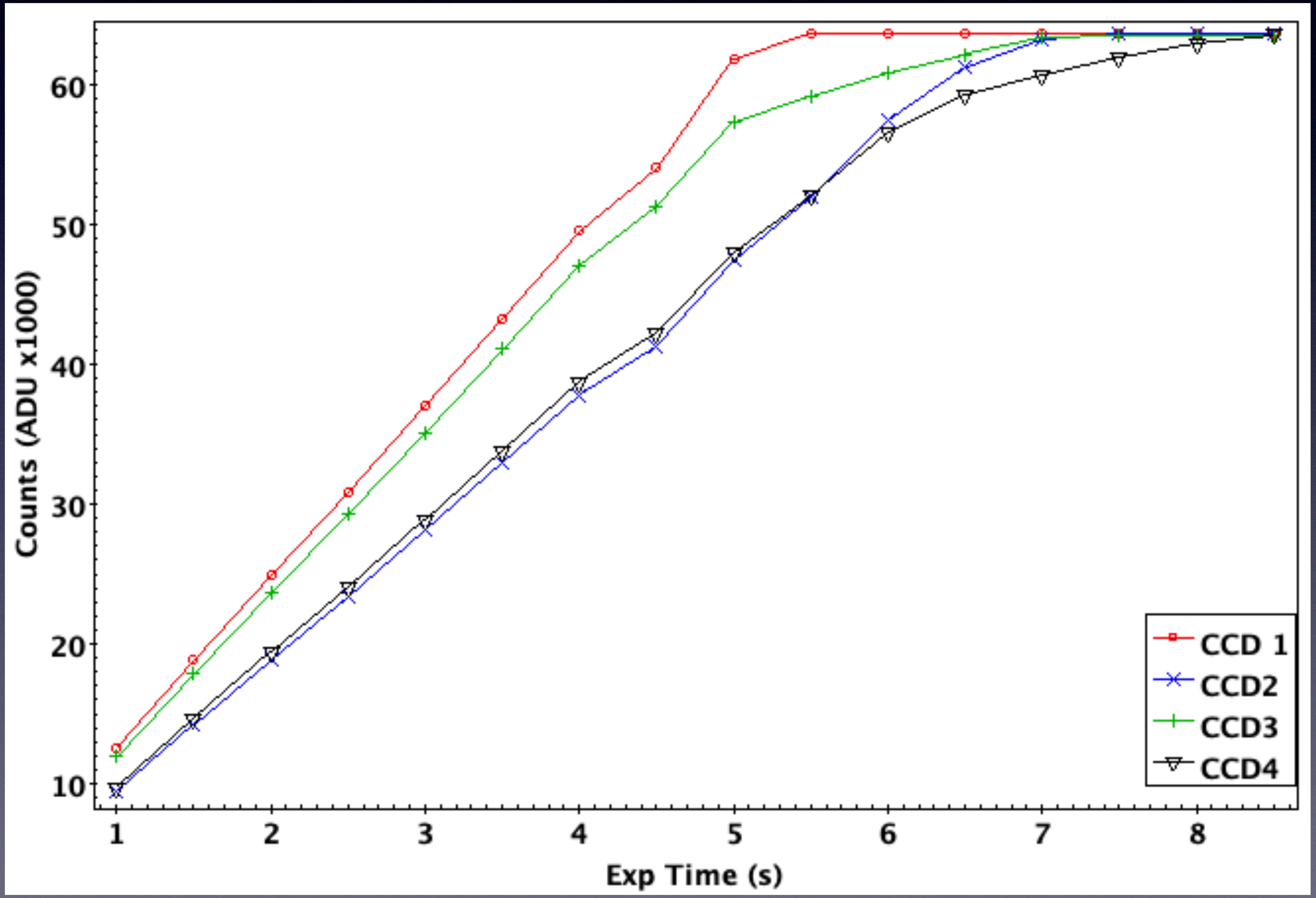


Linearity

- 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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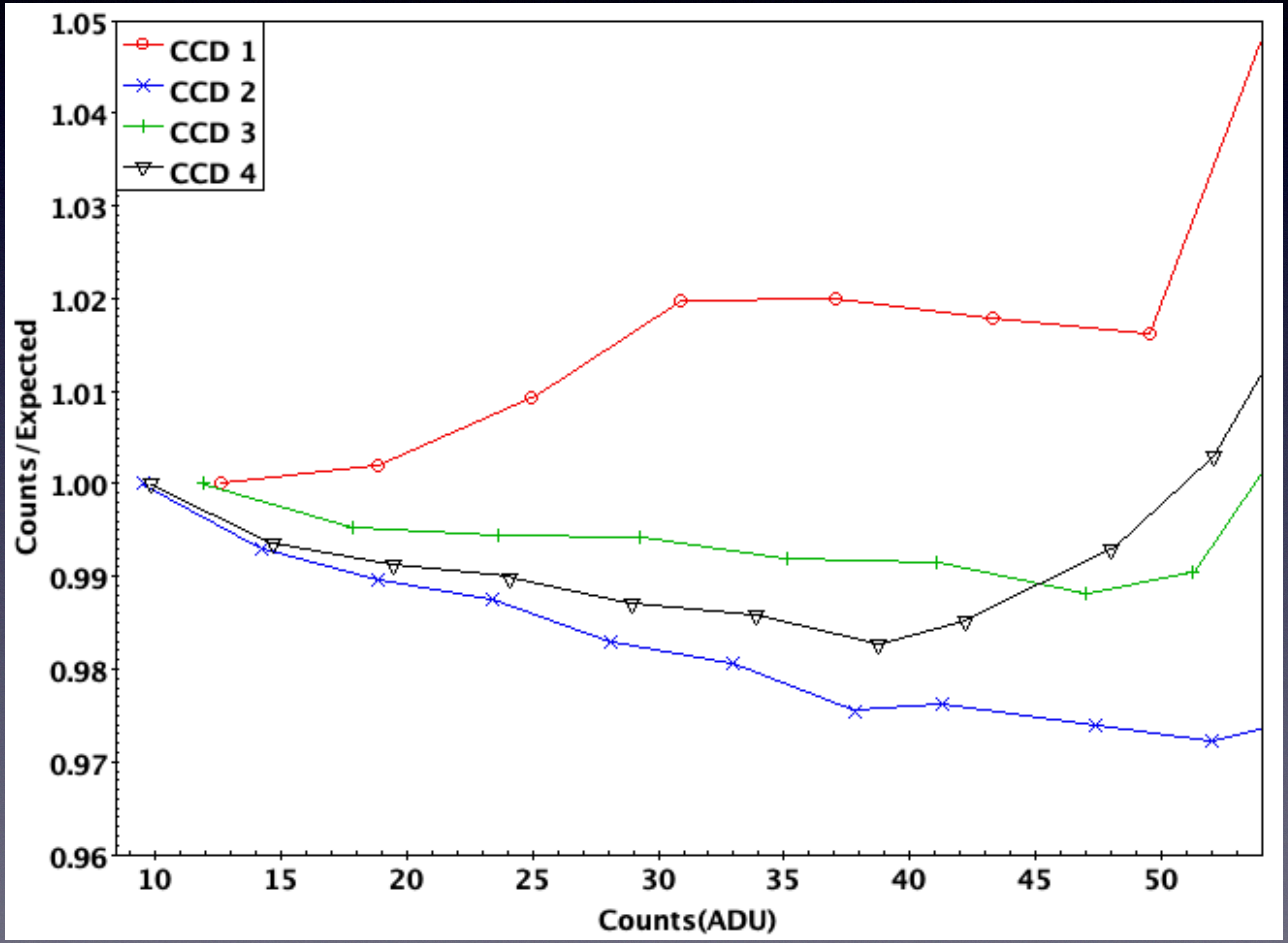
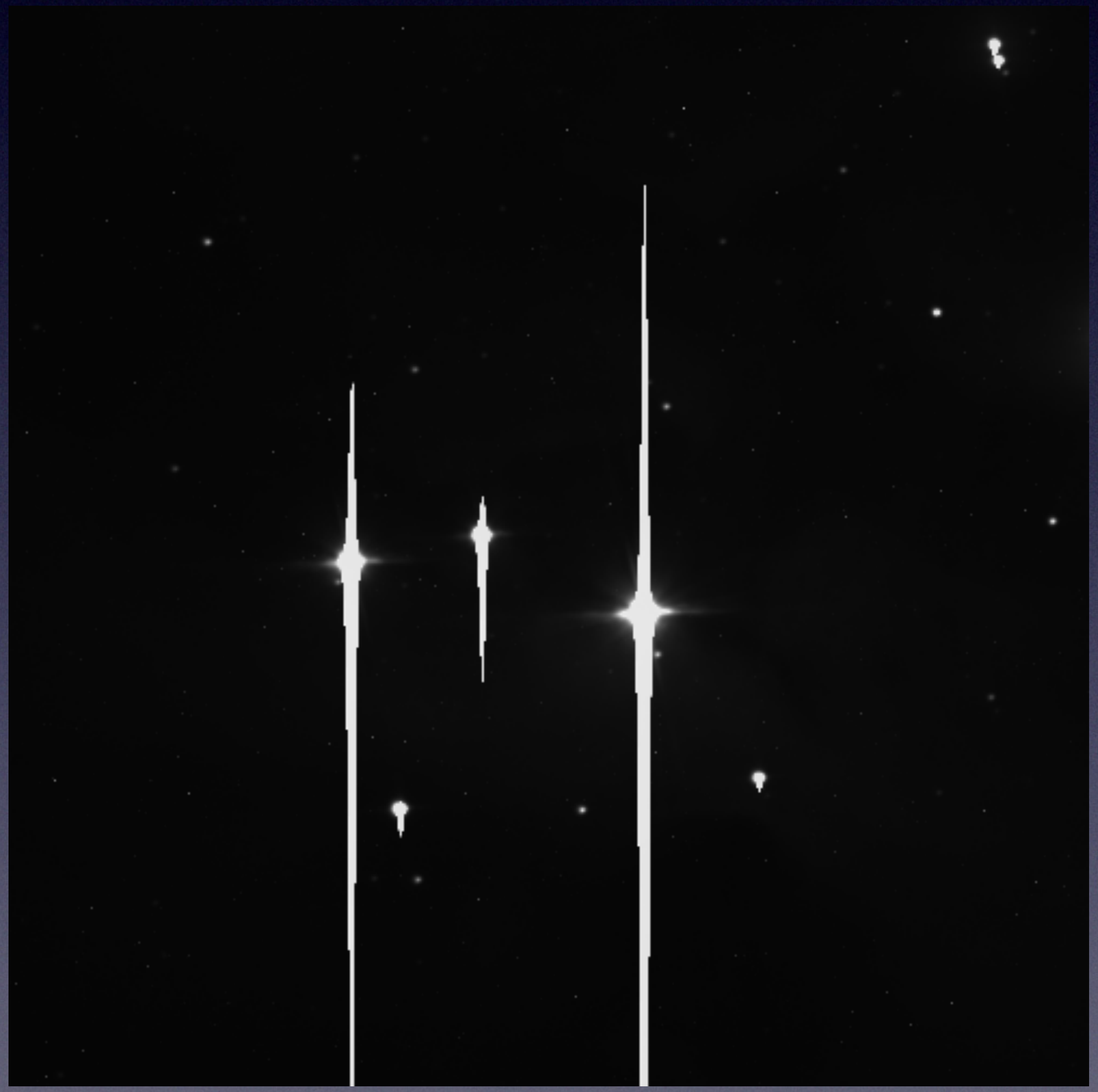


Saturation

- 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

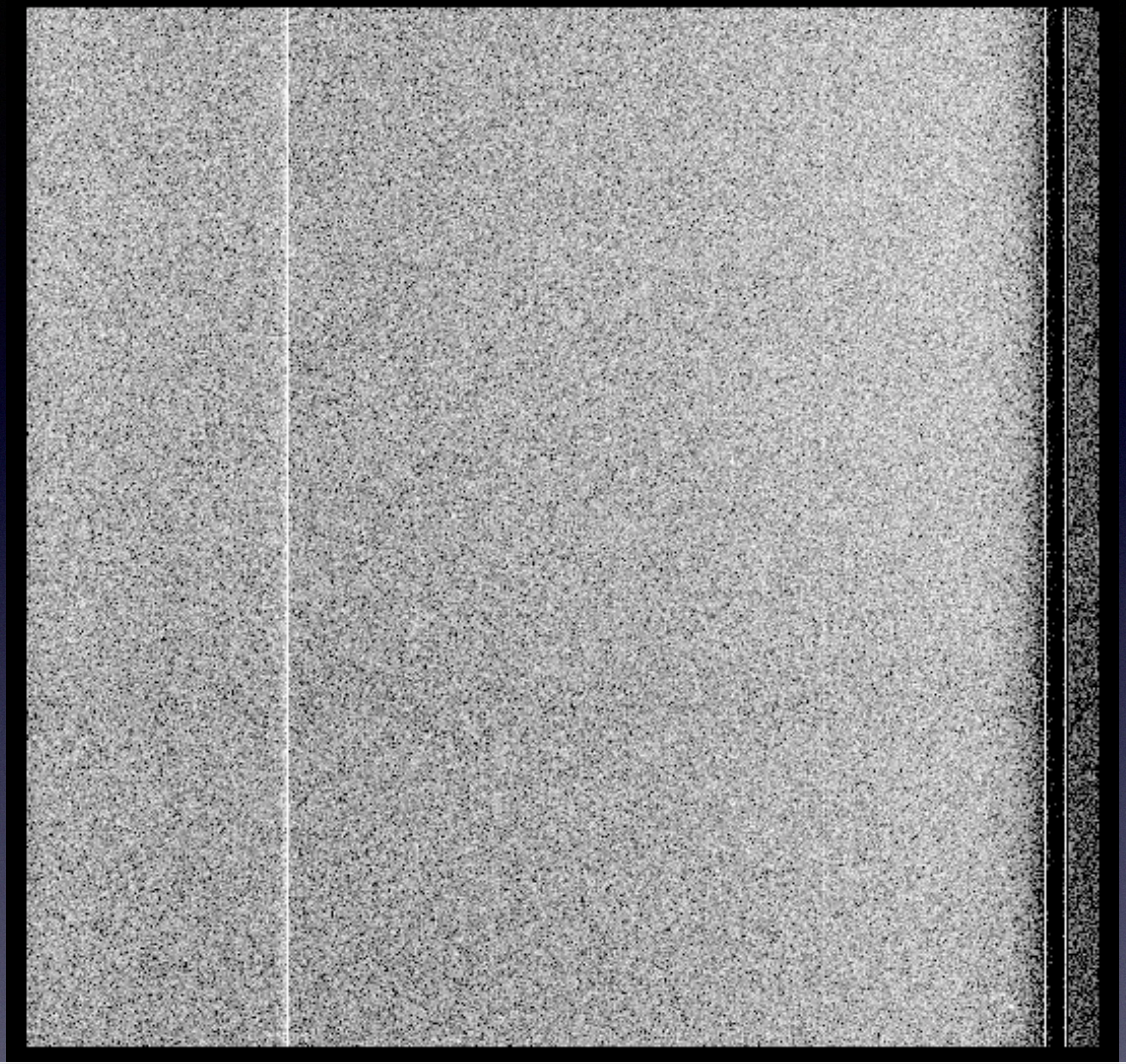
Thermal Noise/Dark Current

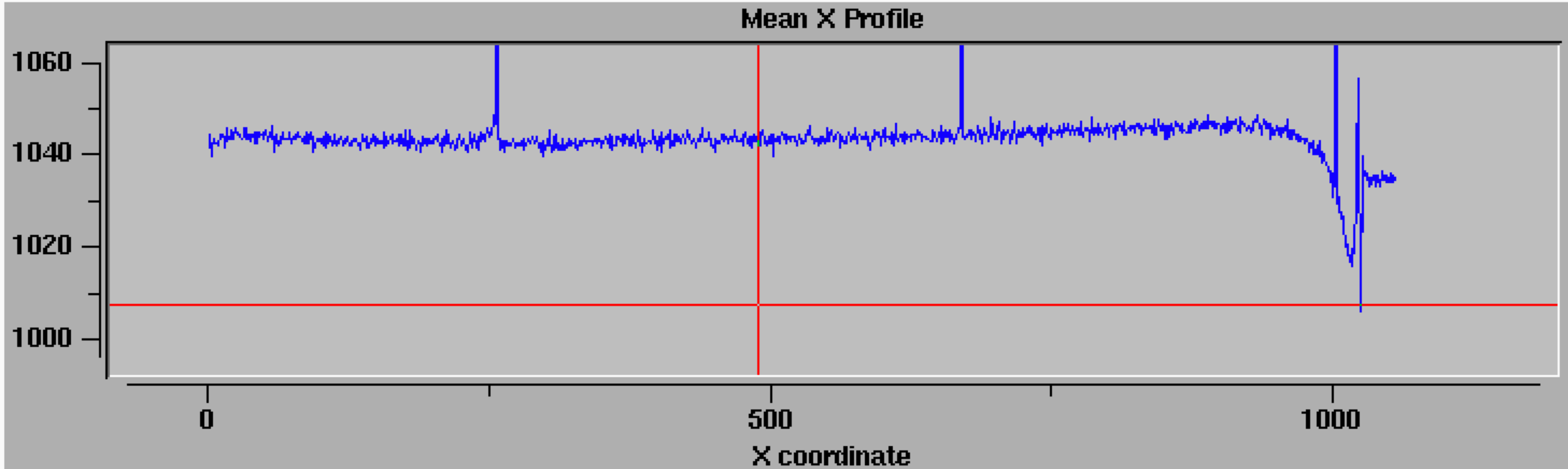
- Thermal energy can liberate electrons
- These are indistinguishable from electrons liberated by photons
- Solution - cool the detector. Generally use liquid nitrogen
- Dark current negligible at these temperatures

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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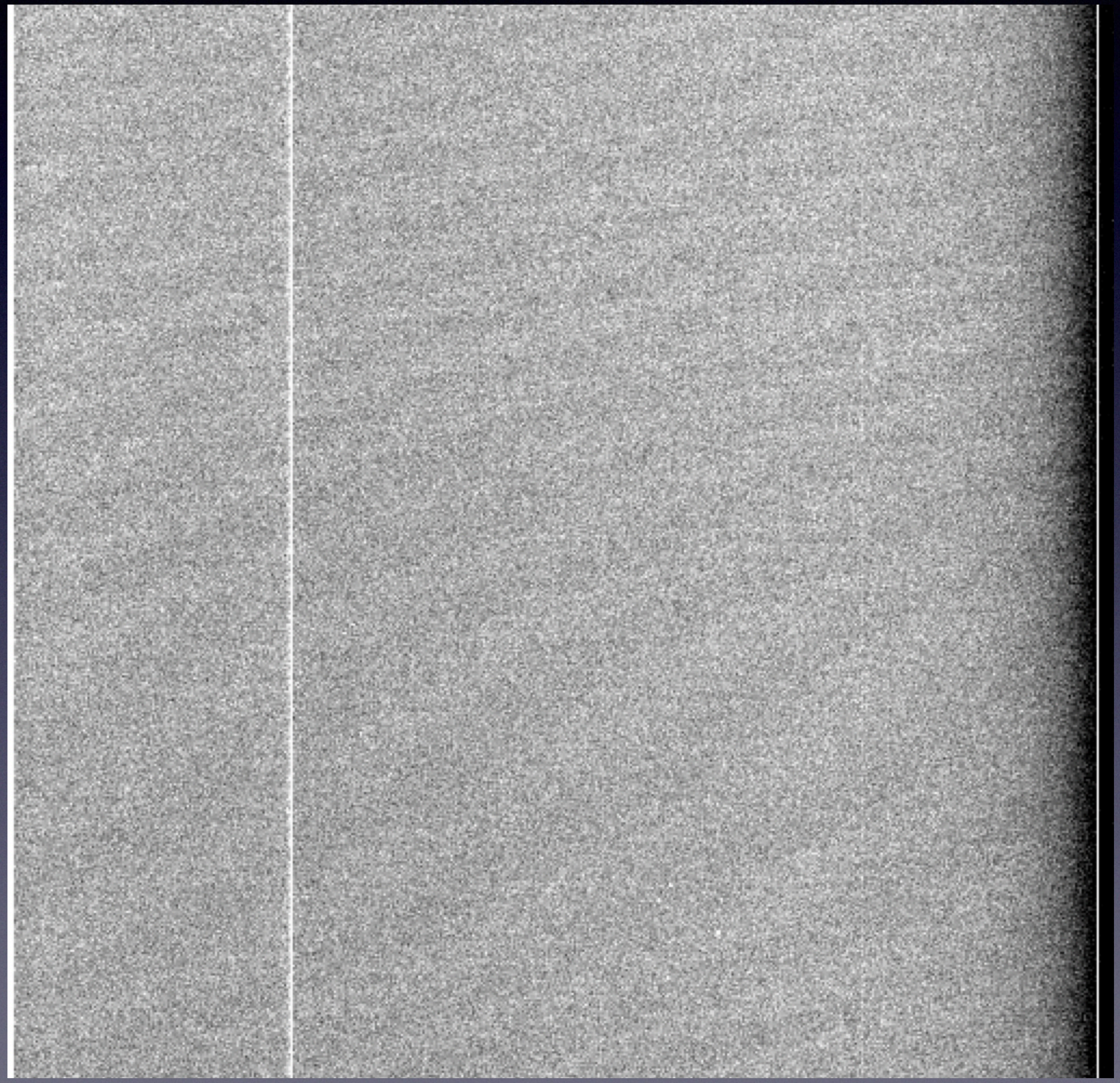
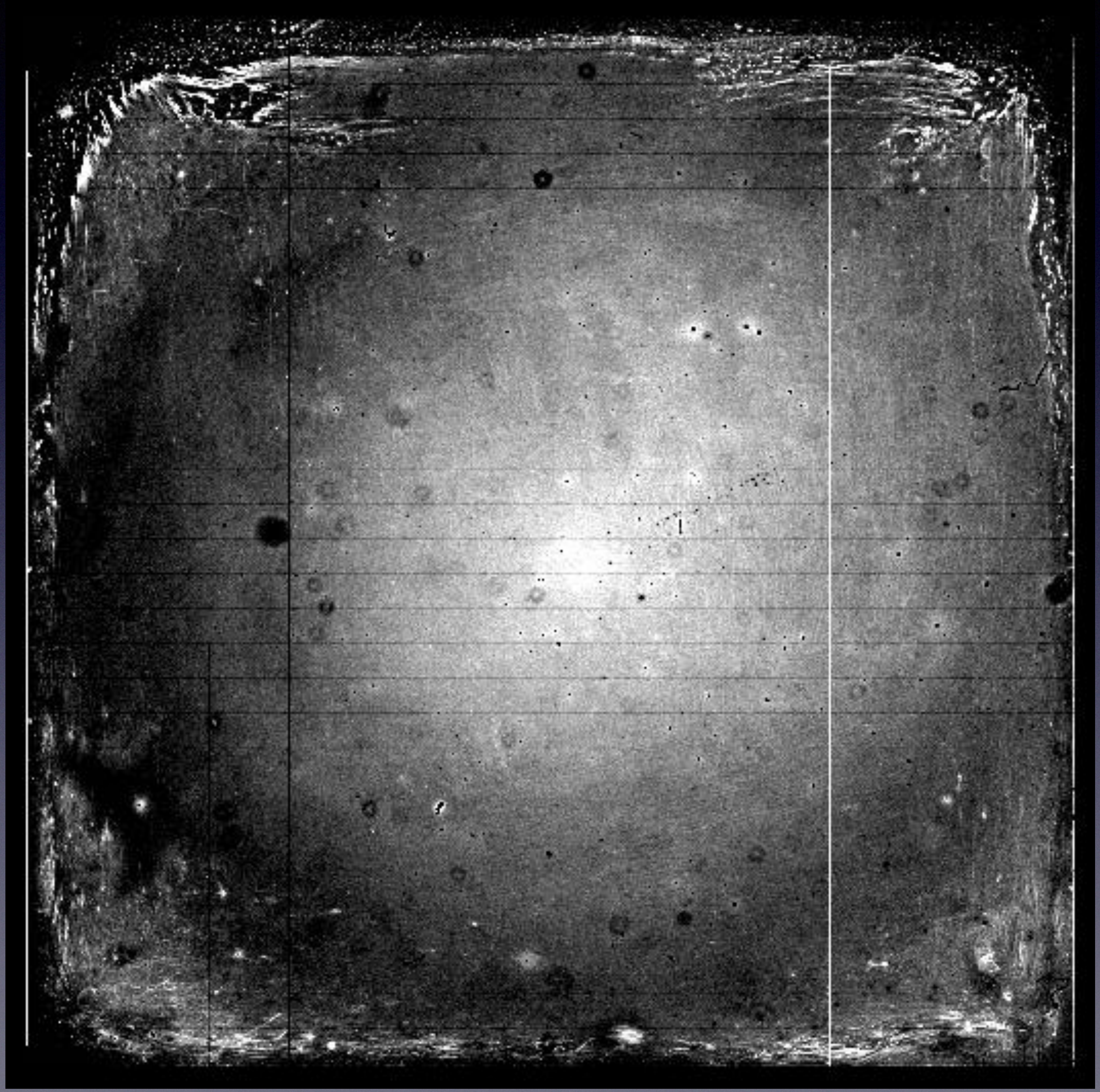


Flat-Field

- 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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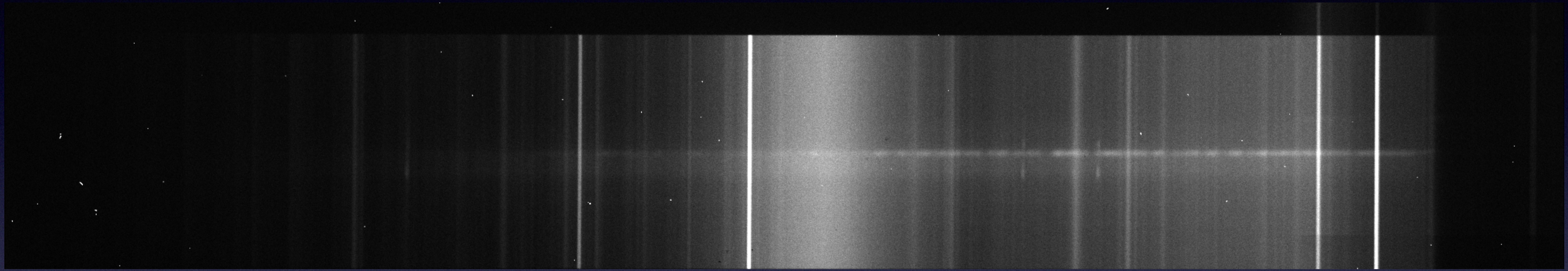
Fringing

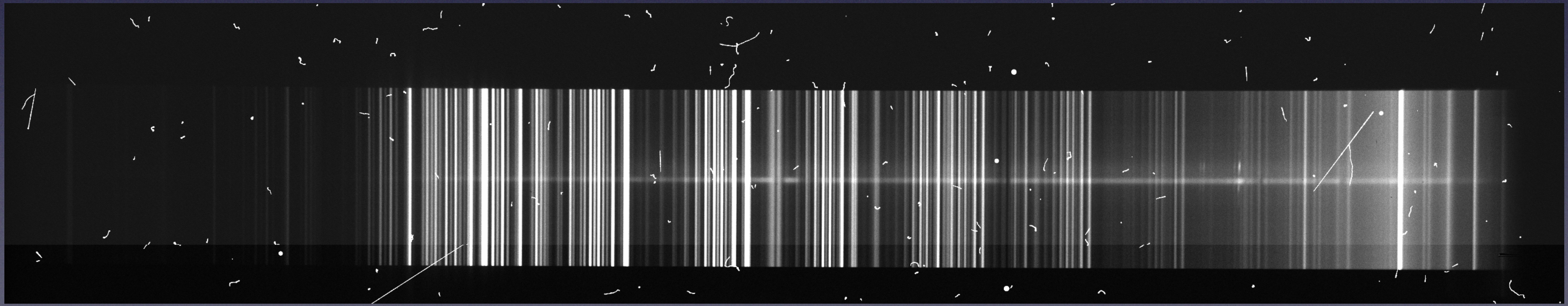
- Interference due to photons reflecting within CCD
- Occurs longwards of ~700nm
- Largely due to atmospheric OH - cannot correct with flats
- But largely stable with time - can use library frames to correct

Example Z-band fringe frame for INT-WFC

Cosmic Rays

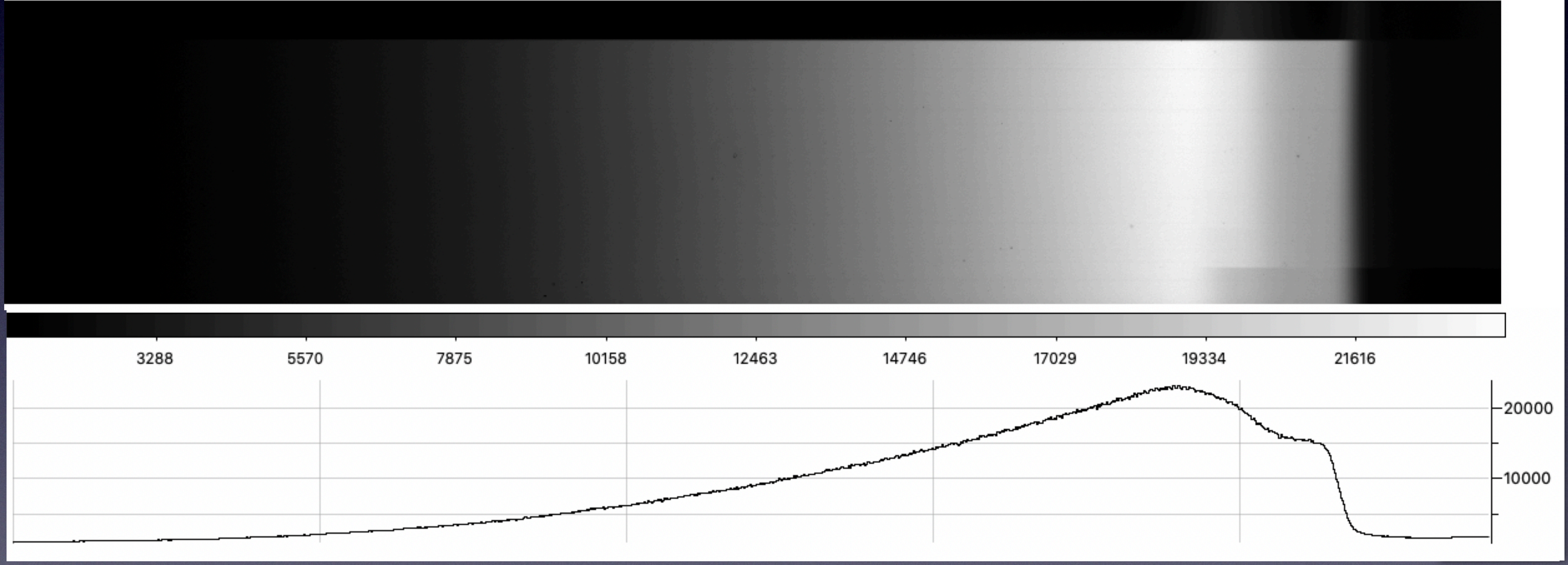
- Blue - Relatively few events
- Red - Thicker chip, many cosmic ray events



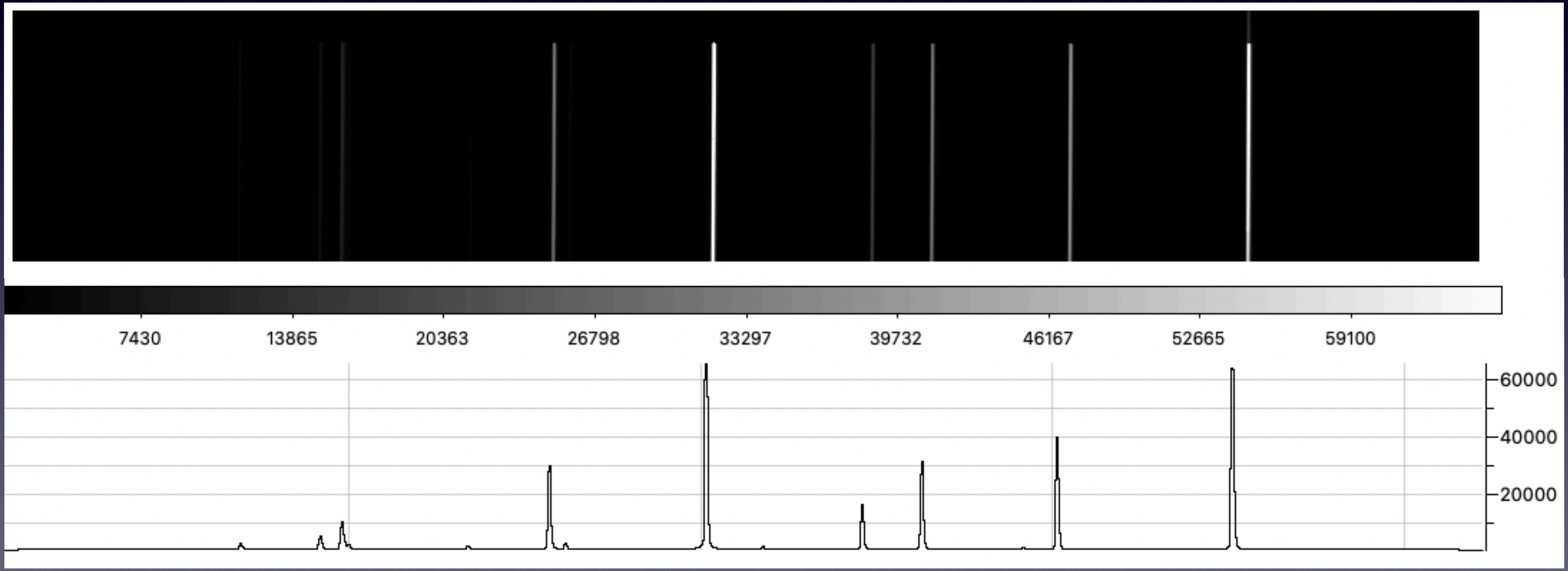


Spectroscopy

- 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

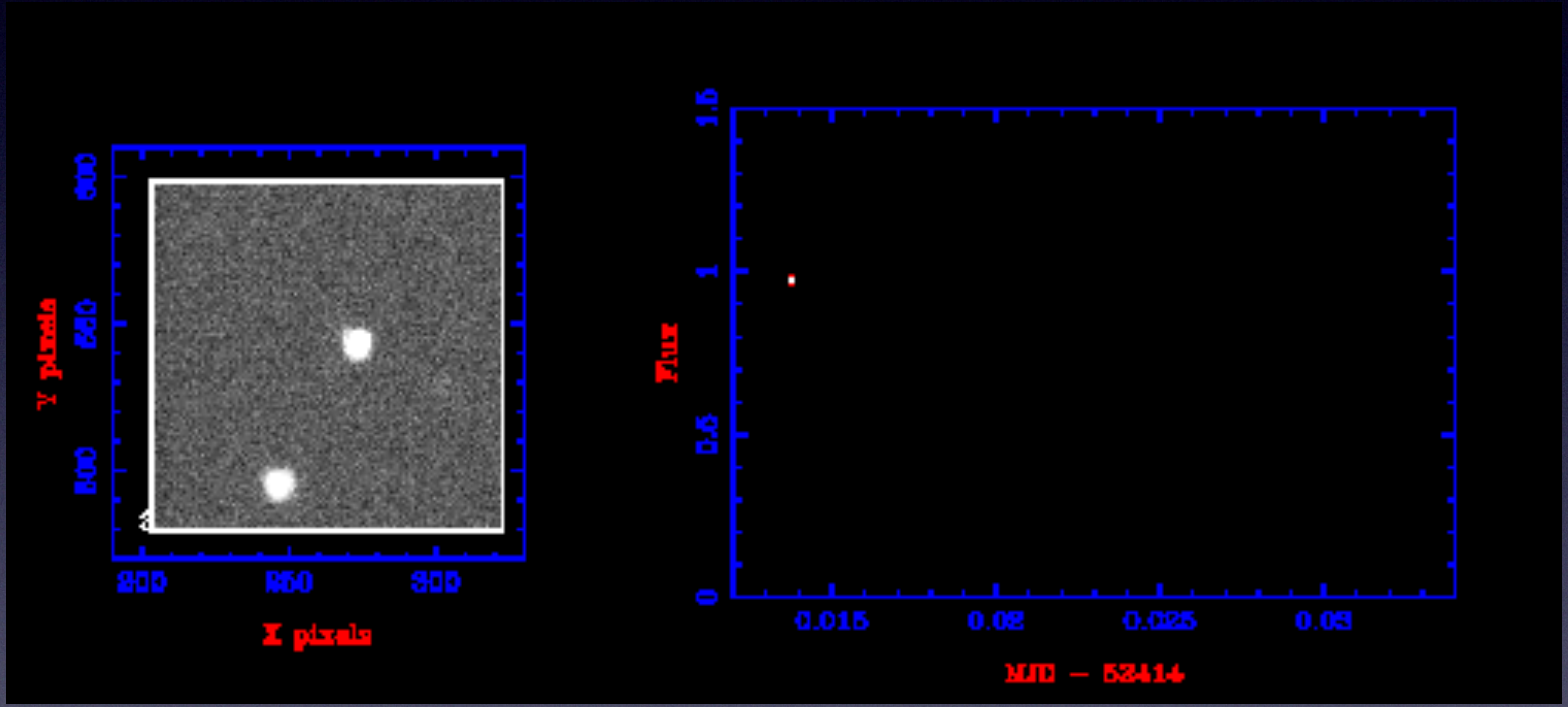
- CCDs are great!
- CCDs are not perfect
- Beware of non-linearity/saturation
- Remember calibration files

Conclusions

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

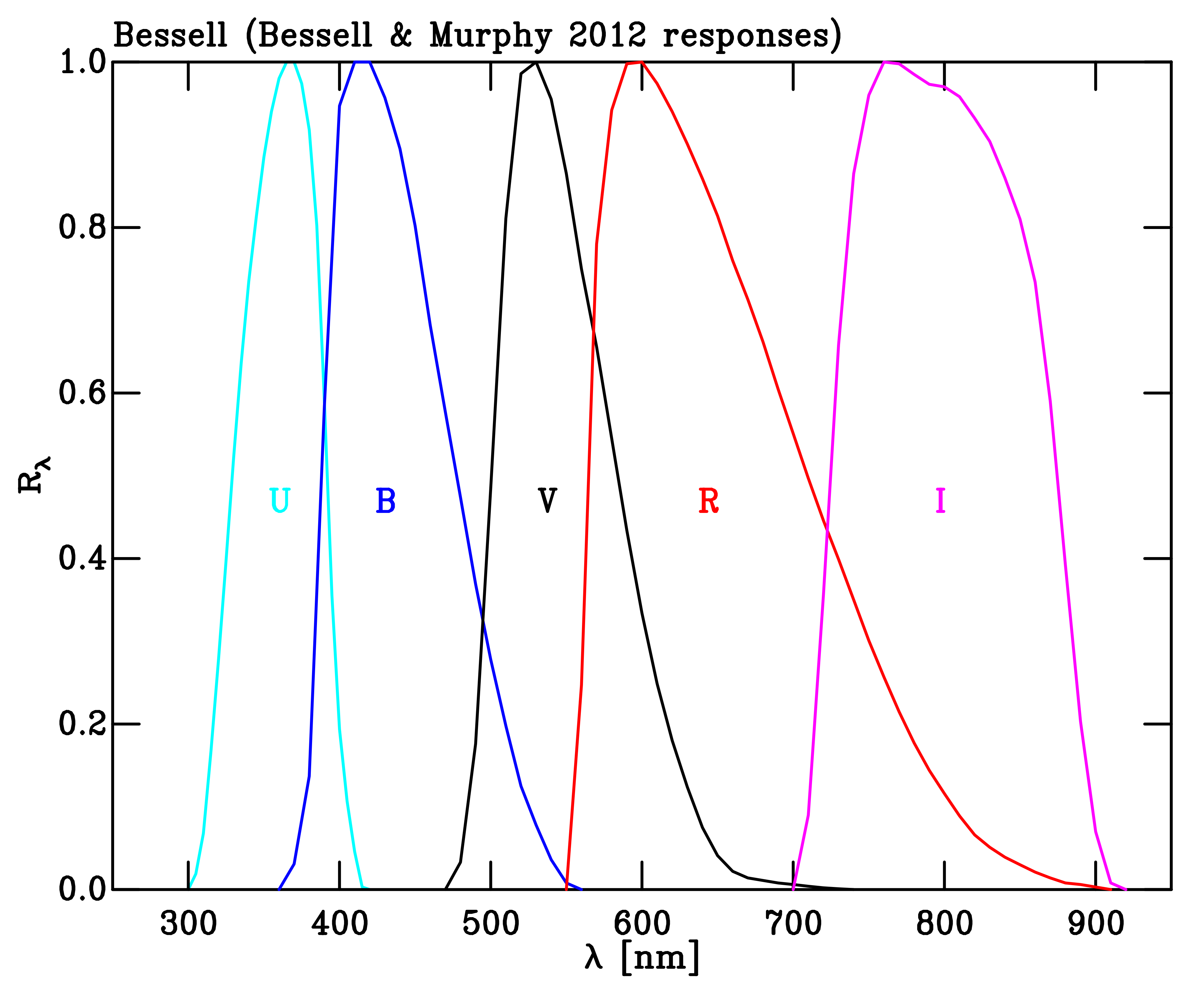
Extras: Photometry

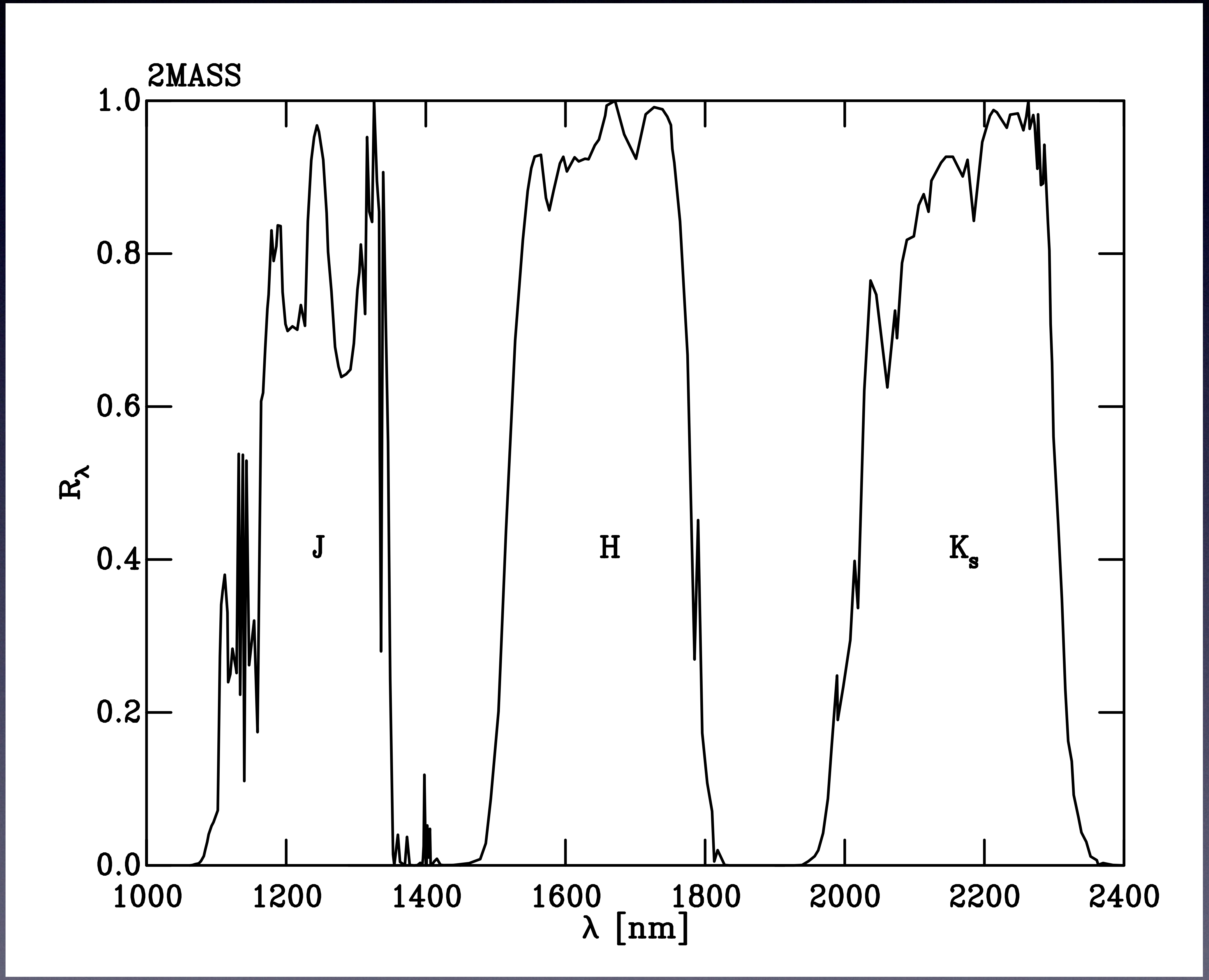
- We have photons - now what?
- Brightness or flux of star - easy to measure
- Variation with time - lightcurves
- Using filters can get you colour information



Credit: S. Littlefair (Sheffield University)

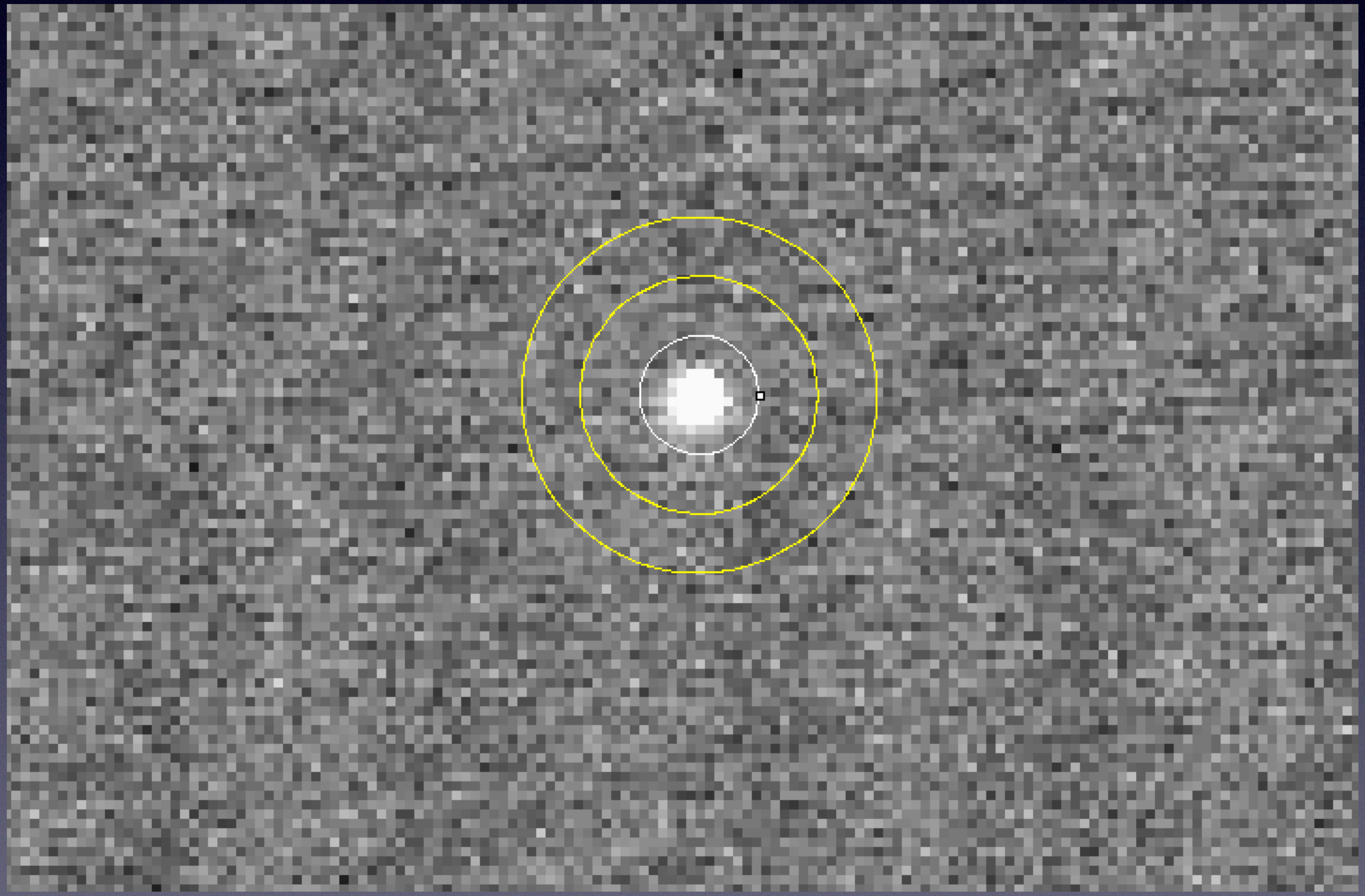
Photometry: Filter Systems





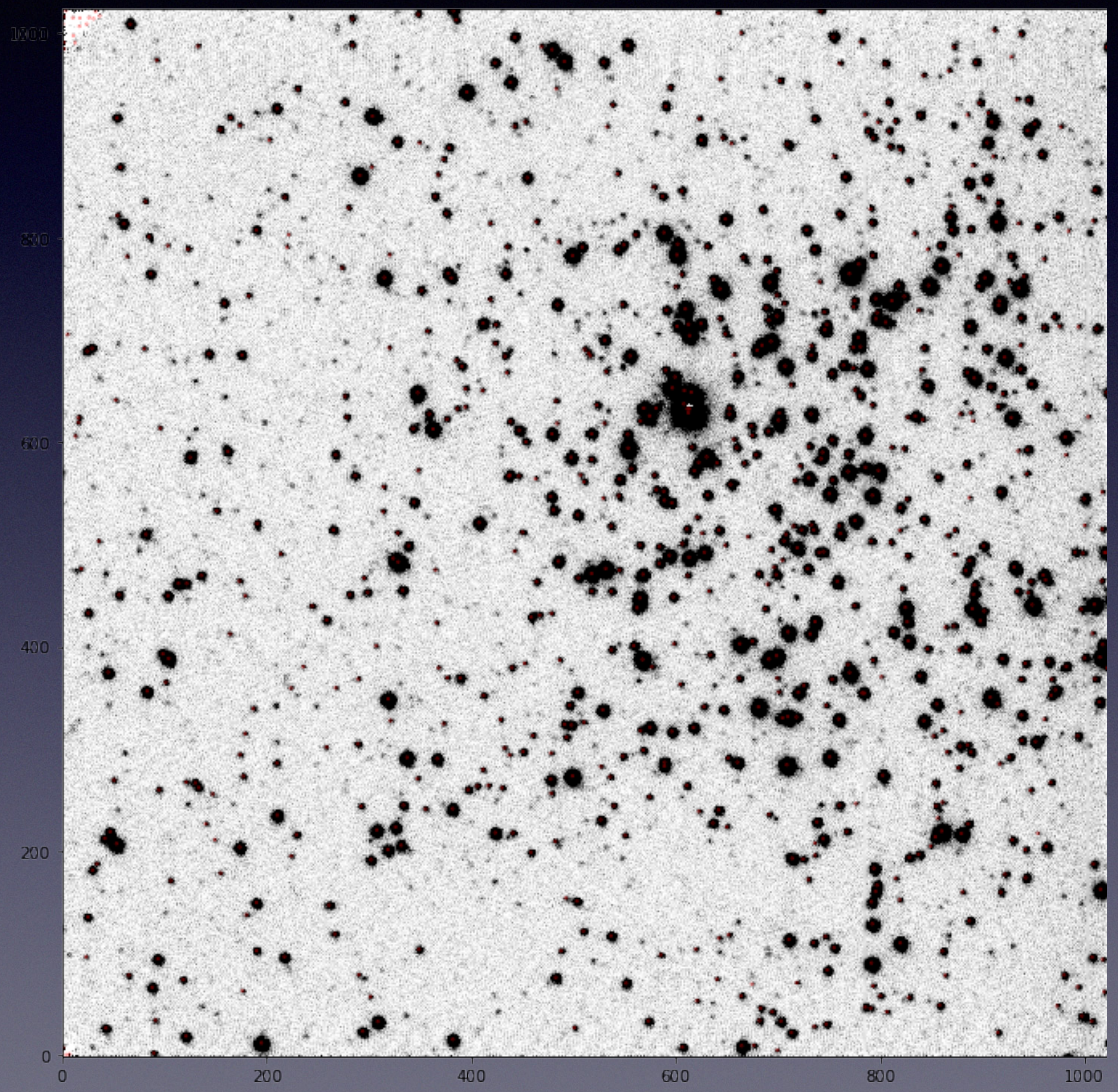
Photometry: Aperture Photometry

- 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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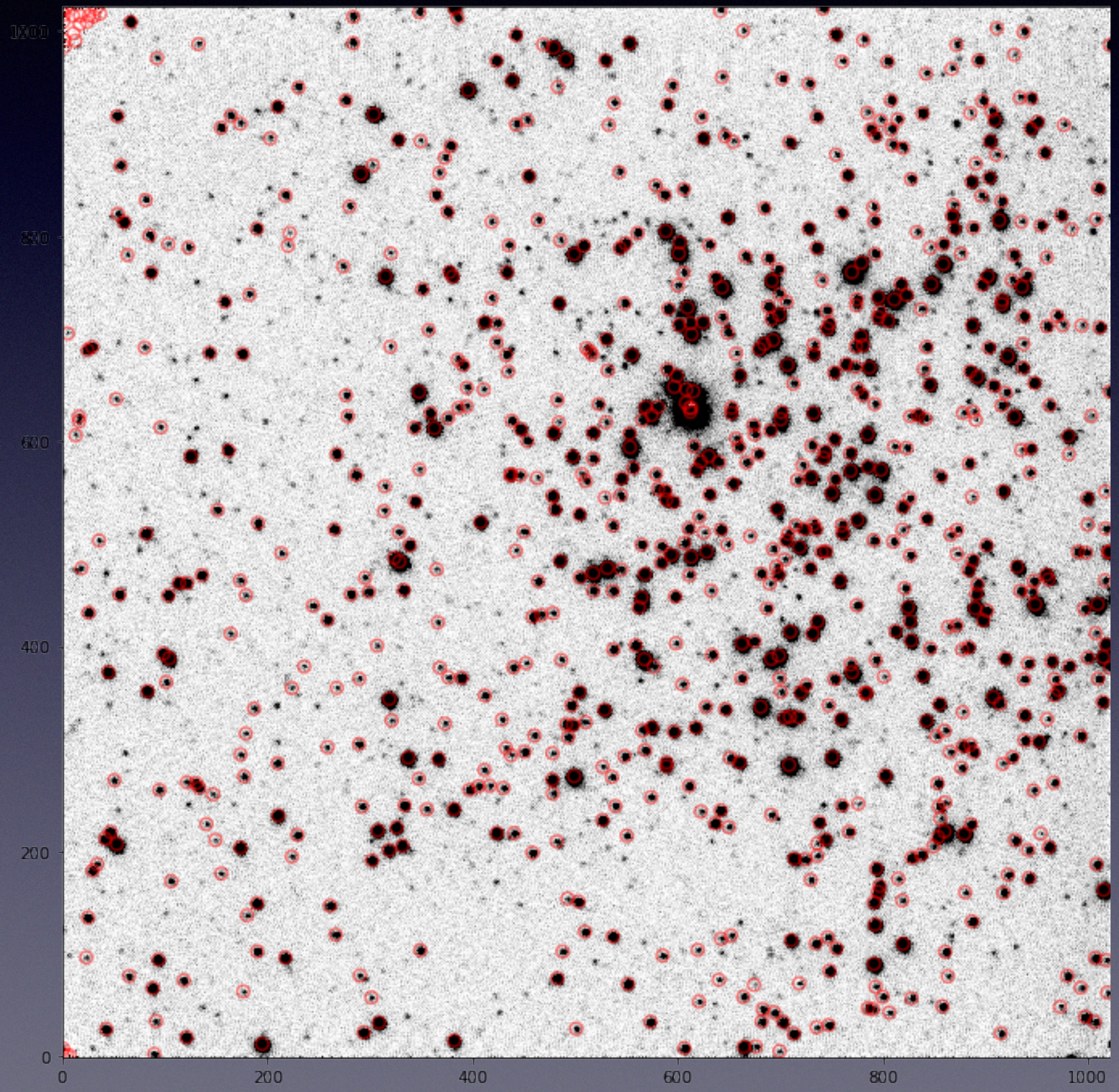


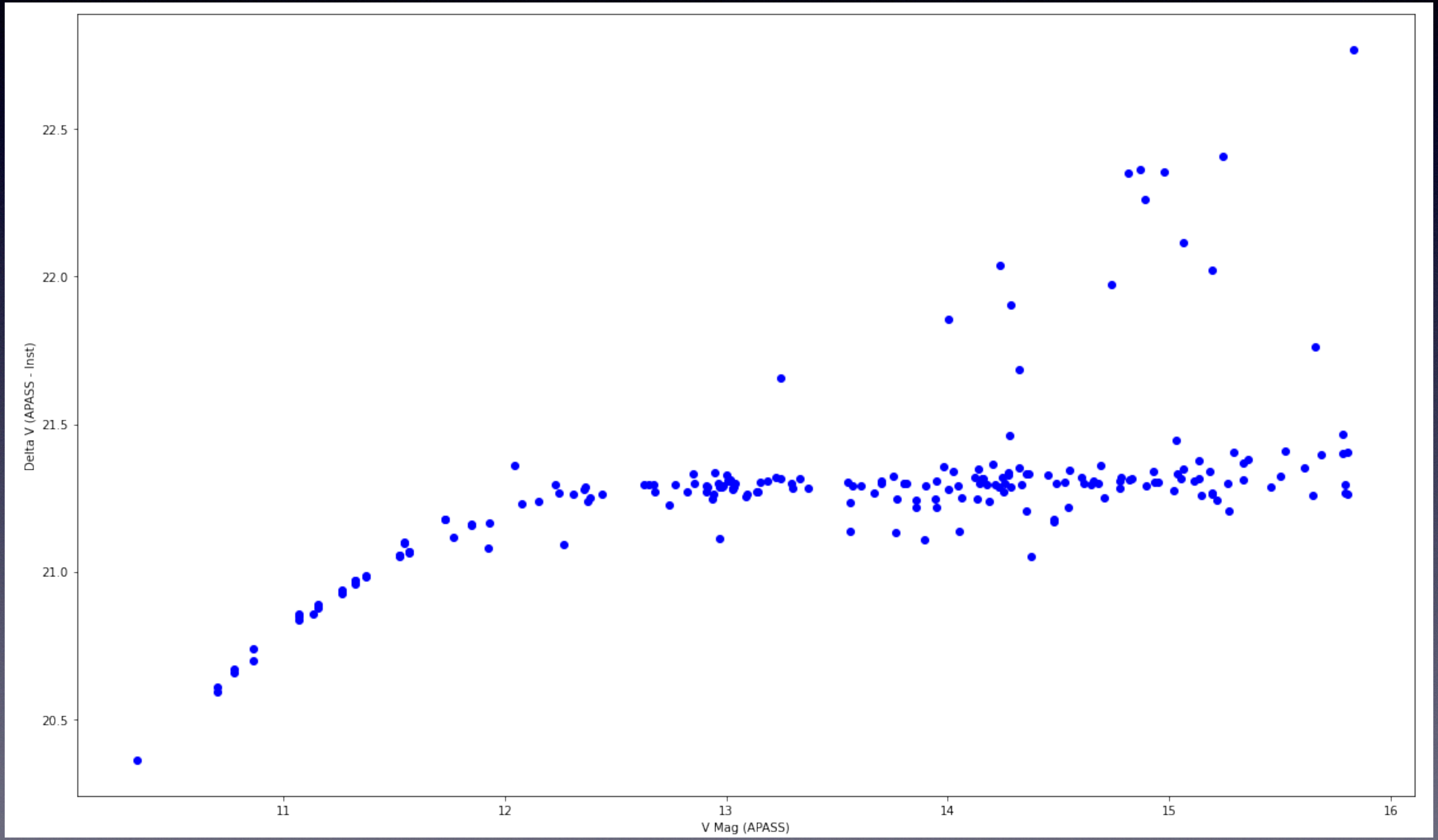
Photometry: Calibration

- We now have instrumental mag

- How do we relate back to other systems?

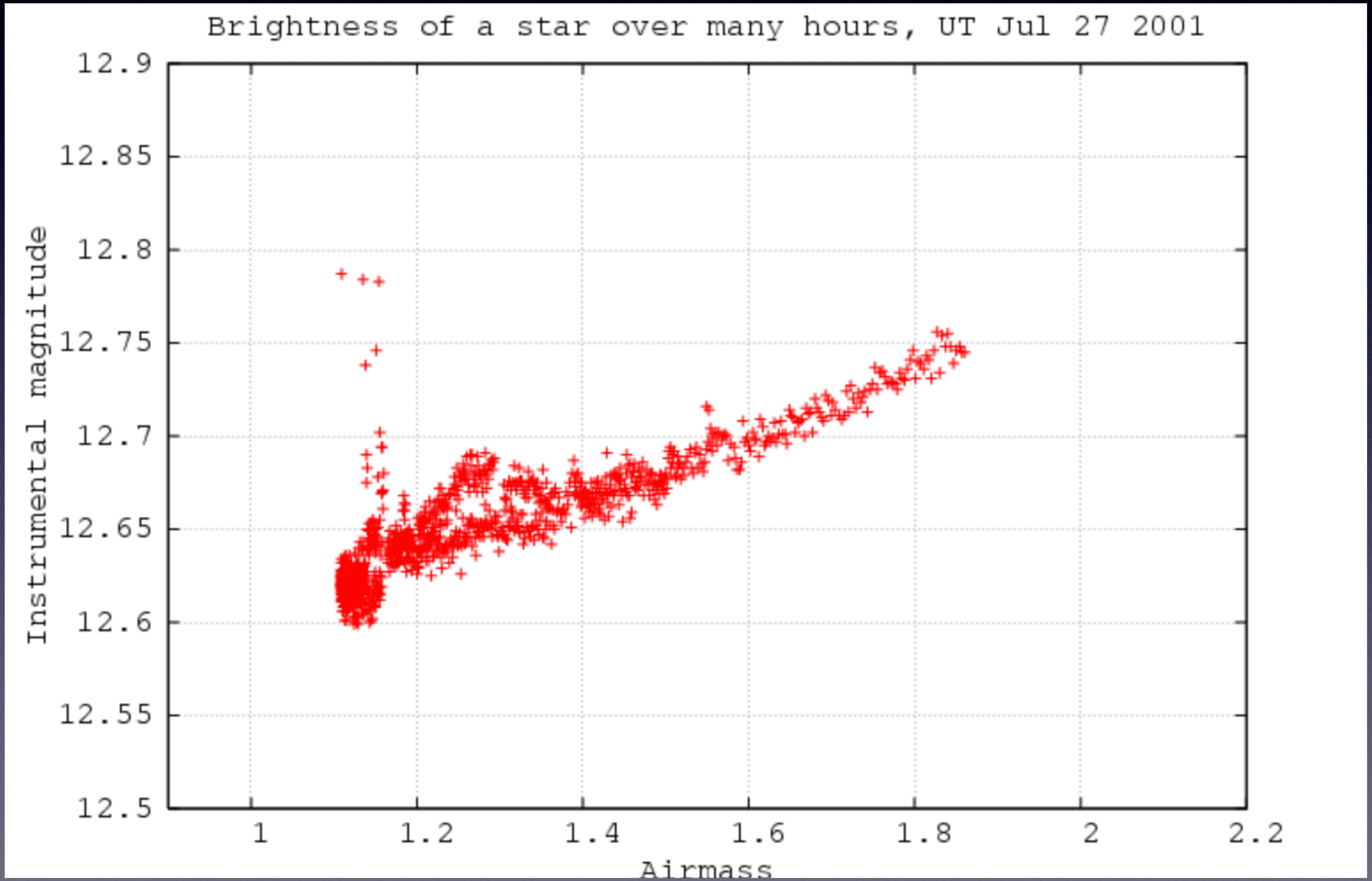
- Typically - standard stars

- These days, wide-field surveys can provide an alternate method

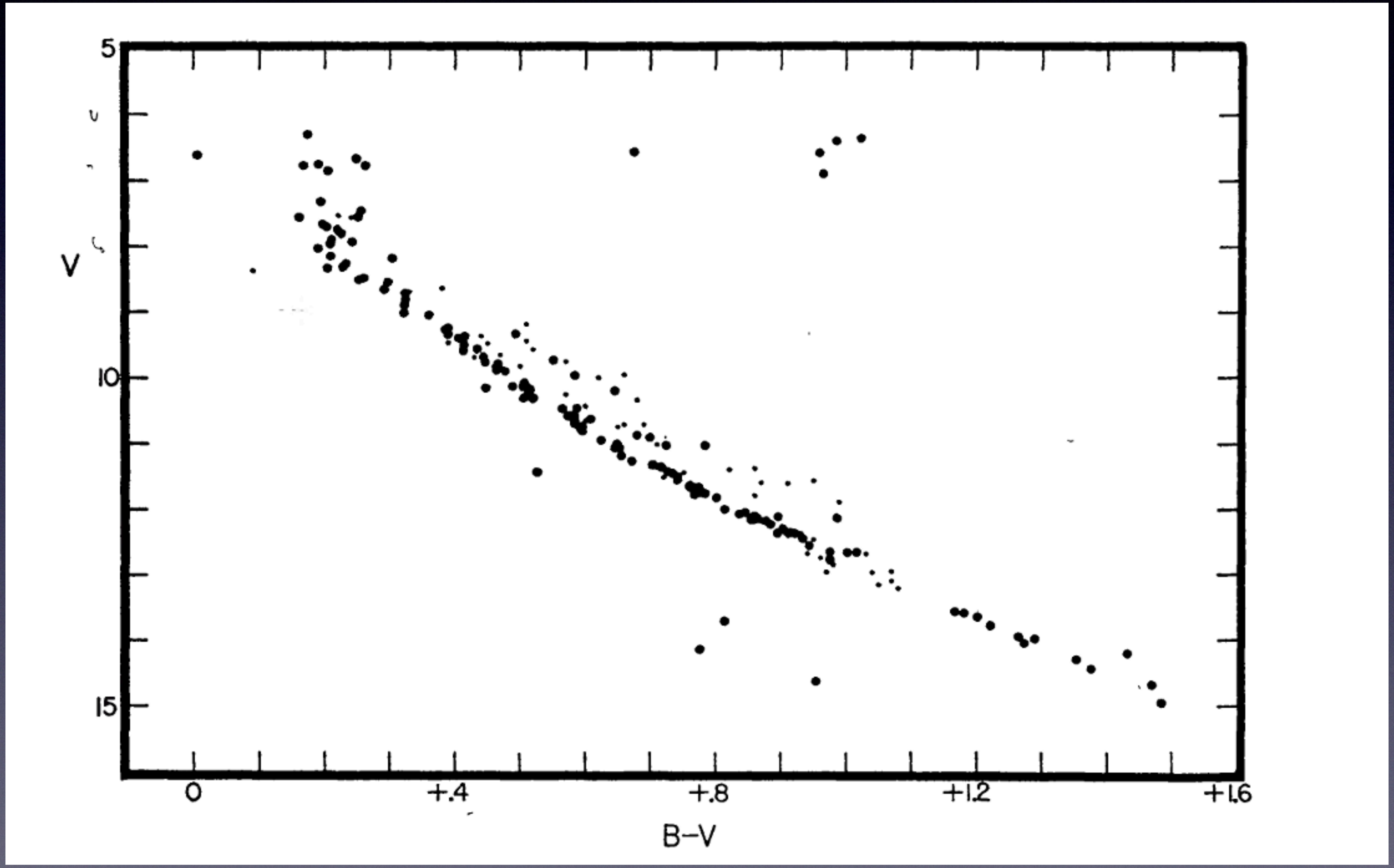


Photometry: Calibration

- 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

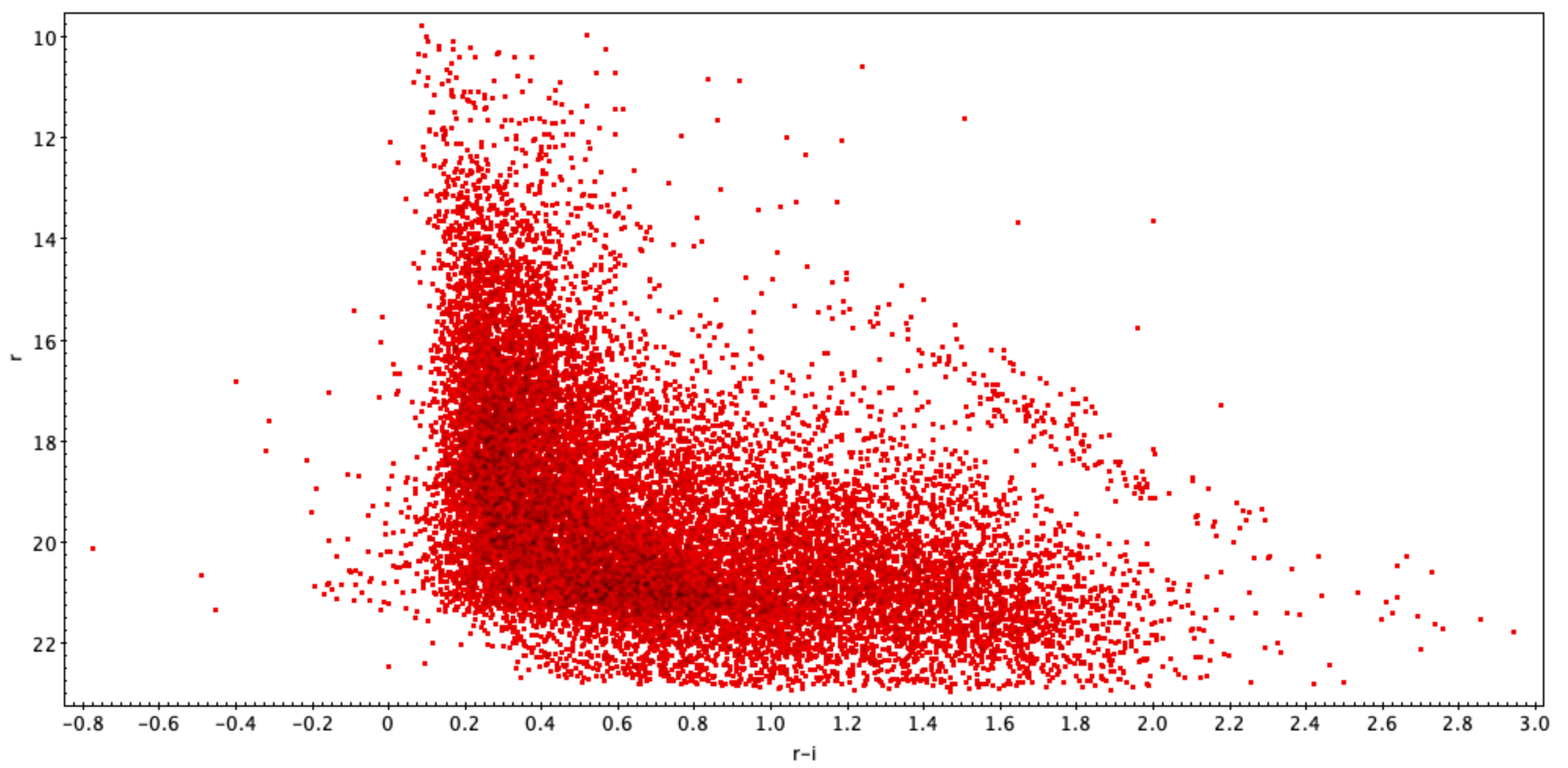


Photometry: CMDs



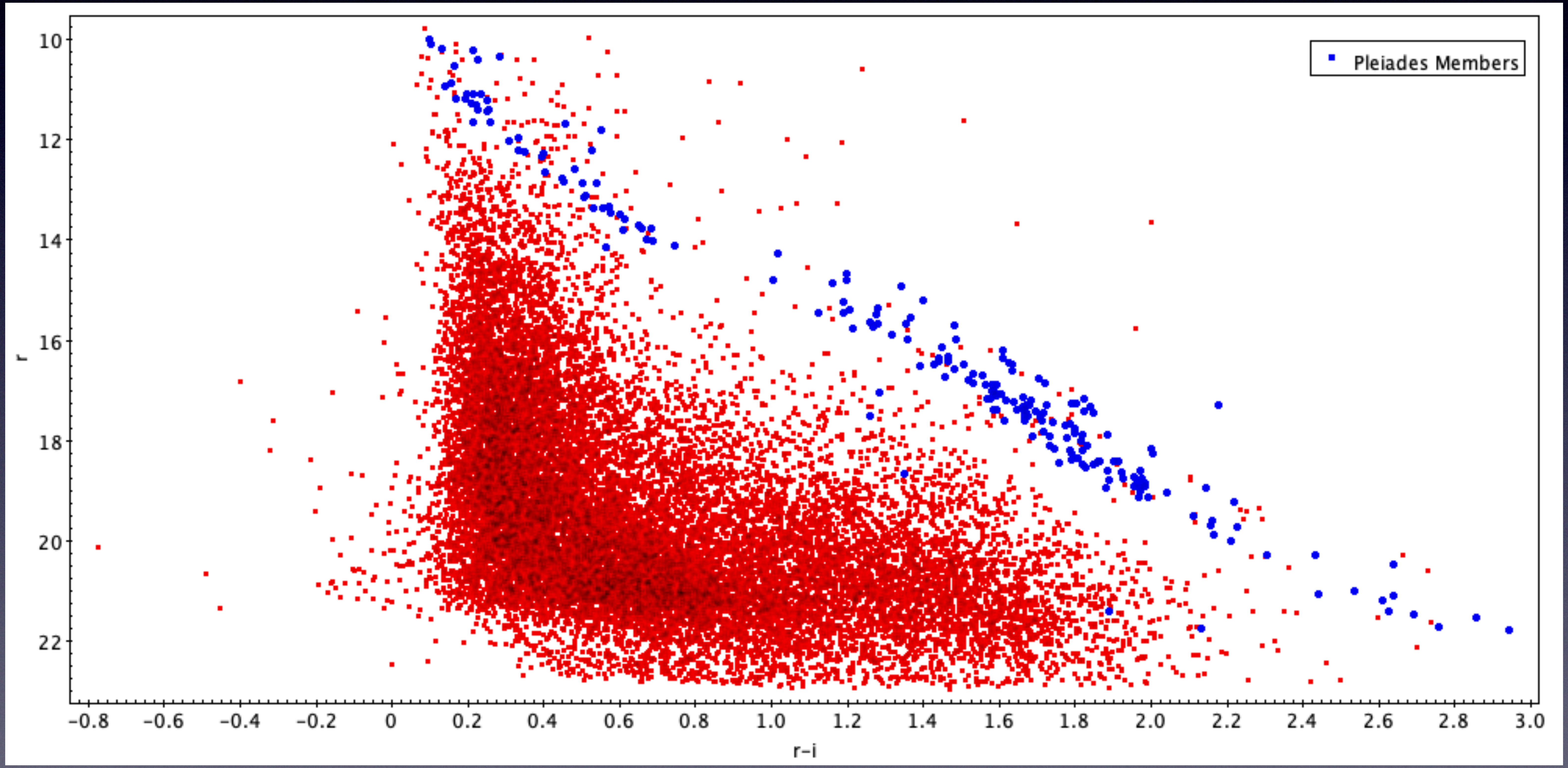
V, B-V CMD of Praesepe (Johnson 1952)

Photometry: CMDs



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

Photometry: CMDs



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