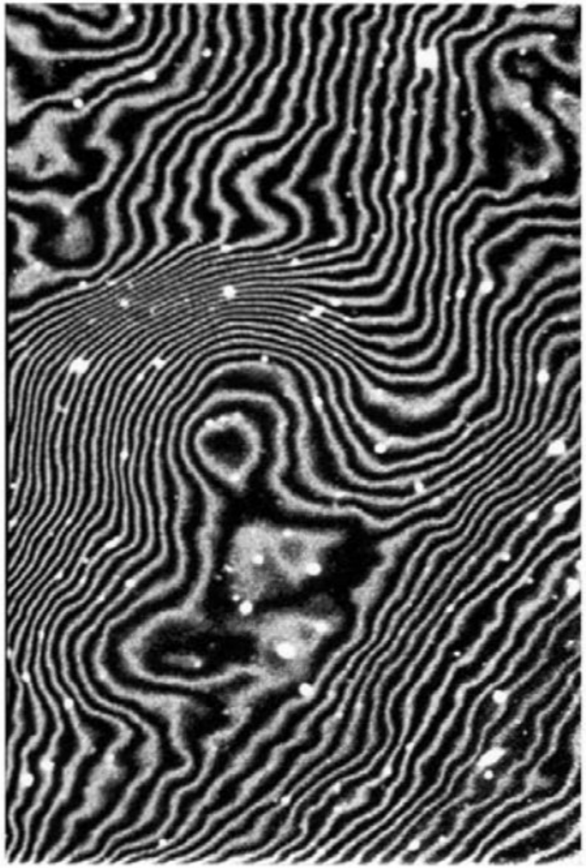
(Day 08)

Detectors and Data

(MegaCam CCD Mosaic, Credit: Canada-France-Hawaii Telescope / 2003)

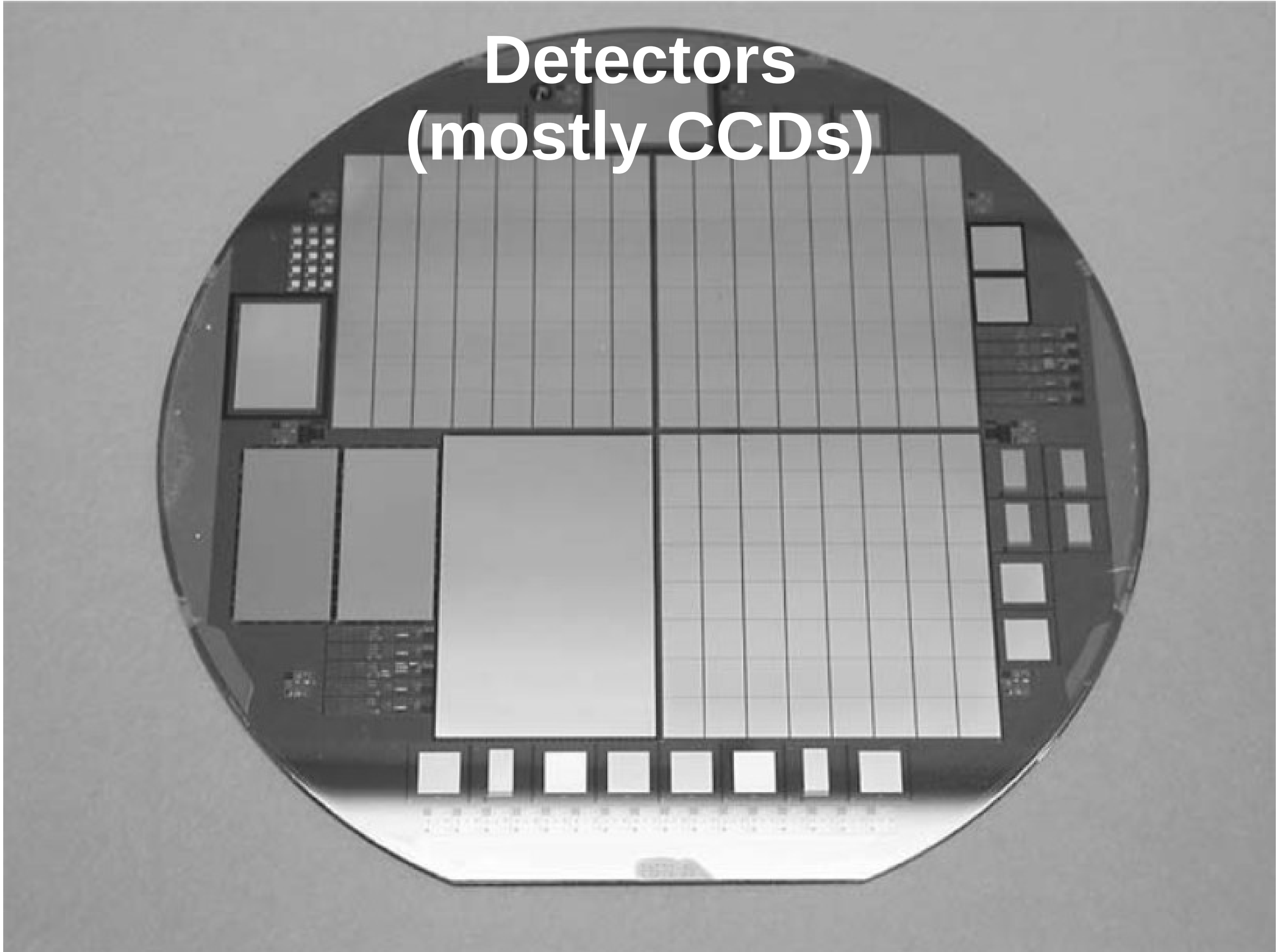
Today



(Severe Fringing Pattern in a CCD image, Credit: McLean 2008)

1. CCDs
2. Signal-to-noise
3. Data processing

Detectors (mostly CCDs)



Types of detectors

- The material interacts with light in a coherent or incoherent way
- Coherent: phase sensitive, response to the electric field strength (far infrared and radio)
- Incoherent: respond to the energy of the photon
  - Photon (quantum) detectors: photons interact with electrons
  - Thermal detectors: photon energy heats up the material (small sensitivity, slow response, broad spectral range)

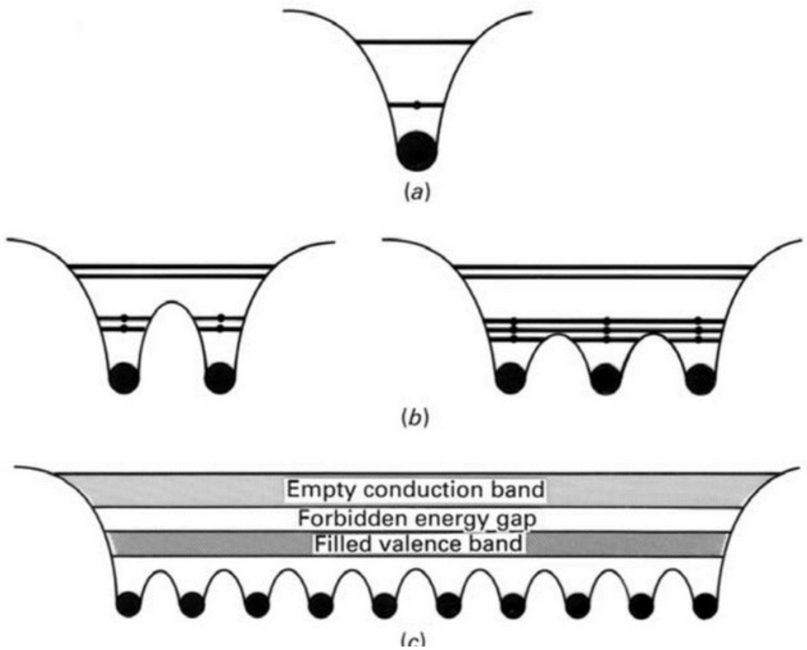
Table 1.1.1. Classification scheme for types of detector.

Sensitive parameter	Detector names	Class
Voltage	Photovoltaic cells	Quantum
	Thermocouples	Thermal
	Pyroelectric detectors	Thermal
Resistance	Blocked impurity band device (BIB)	Quantum
	Bolometer	Thermal
	Photoconductive cell	Quantum
	Phototransistor	Quantum
	Transition edge sensor (TES)	Thermal
Charge	Charge-coupled device (CCD)	Quantum
	Charge injection device (CID)	Quantum
Current	Superconducting tunnel junction (STJ)	Quantum
Electron excitation	Photographic emulsion	Quantum
Electron emission	Photomultiplier	Quantum
	Television	Quantum
	Image intensifier	Quantum
Chemical composition	Eye	Quantum

(Kitchin 2003)

Semiconductors

- When atoms come together to form a crystal, the outer electrons interact to bind the atoms
- The electrons are shared, the levels split
- With many atoms, a band is formed
- **Valence band**: inner filled energy levels
- **Conduction band:** higher energy levels where electrons are free to move under the influence of an electric force field
- **Bandgap**: minimum energy needed to promote electrons between valence and conduction band
- Extrinsic (or doped) semiconductors have impurity atoms to produce intermediate energy levels within the gap



(McLean 2008)

Table 5.2. Forbidden energy gaps for some common semiconductors.

Name	*Symbol*	*T* (K)	E_G (eV)	λ_c (μm)
Gallium nitride	GaN	295	3.45	0.36
Silicon carbide	SiC	295	2.86	0.43
Cadmium sulfide	CdS	295	2.4	0.5
Cadmium selenide	CdSe	295	1.8	0.7
Gallium arsenide	GaAs	295	1.35	0.92
Silicon	Si	295	1.12	1.11
Germanium	Ge	295	0.67	1.85
Lead sulfide	PbS	295	0.42	2.95
Indium antimonide	InSb	295 77	0.18 0.23	6.9 5.4
Mercury cadmium telluride	$Hg_xCd_{1-x}Te$	77	0.1 ($x = 0.8$) 0.5 ($x = 0.554$)	12.4 2.5

See: *http://www.semiconductorsdirect.com*

(McLean 2008)

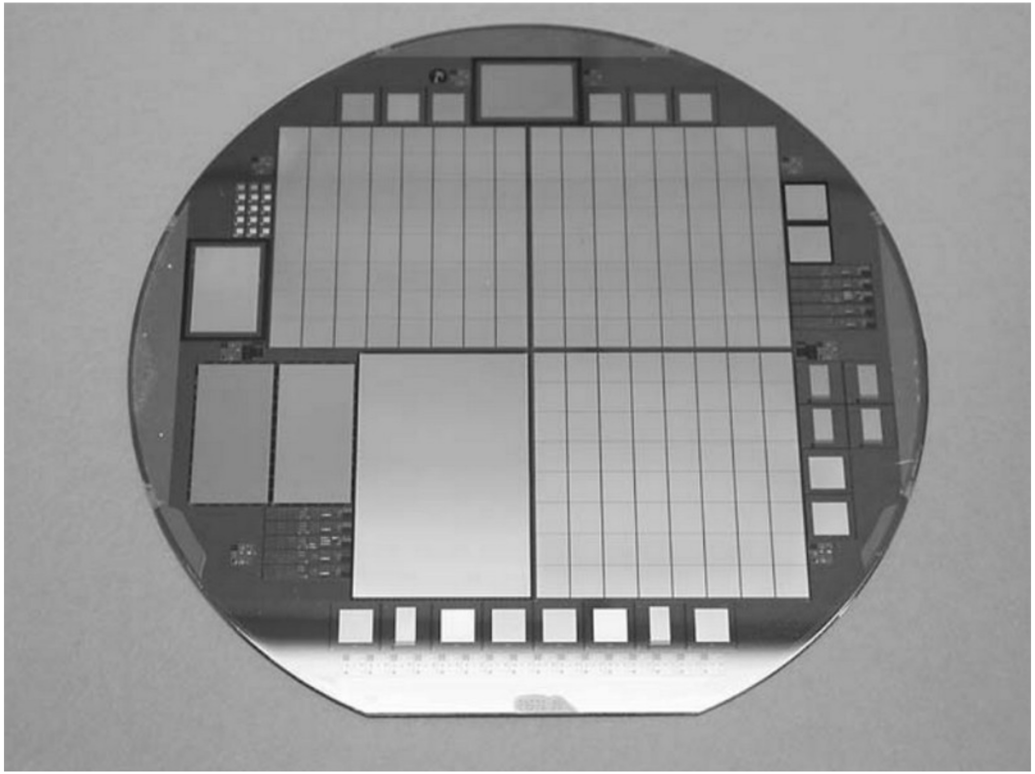
Table 5.3. Extrinsic semiconductors, doping material, and long-wavelength cutoff.

Base	*: Impurity*	λ_c (μm)	*Base*	*: Impurity*	λ_c (μm)
Silicon (Si)	: In	8.0	Germanium (Ge)	: Au	8.27
	: Ga	17.1		: Hg	13.8
	: Bi	17.6		: Cd	20.7
	: Al	18.1		: Cu	30.2
	: As	23.1		: Zn	37.6
	: P	27.6		: Ga	115
	: B	28.2		: B	119.6
	: Sb	28.8		: Sb	129

(McLean 2008)

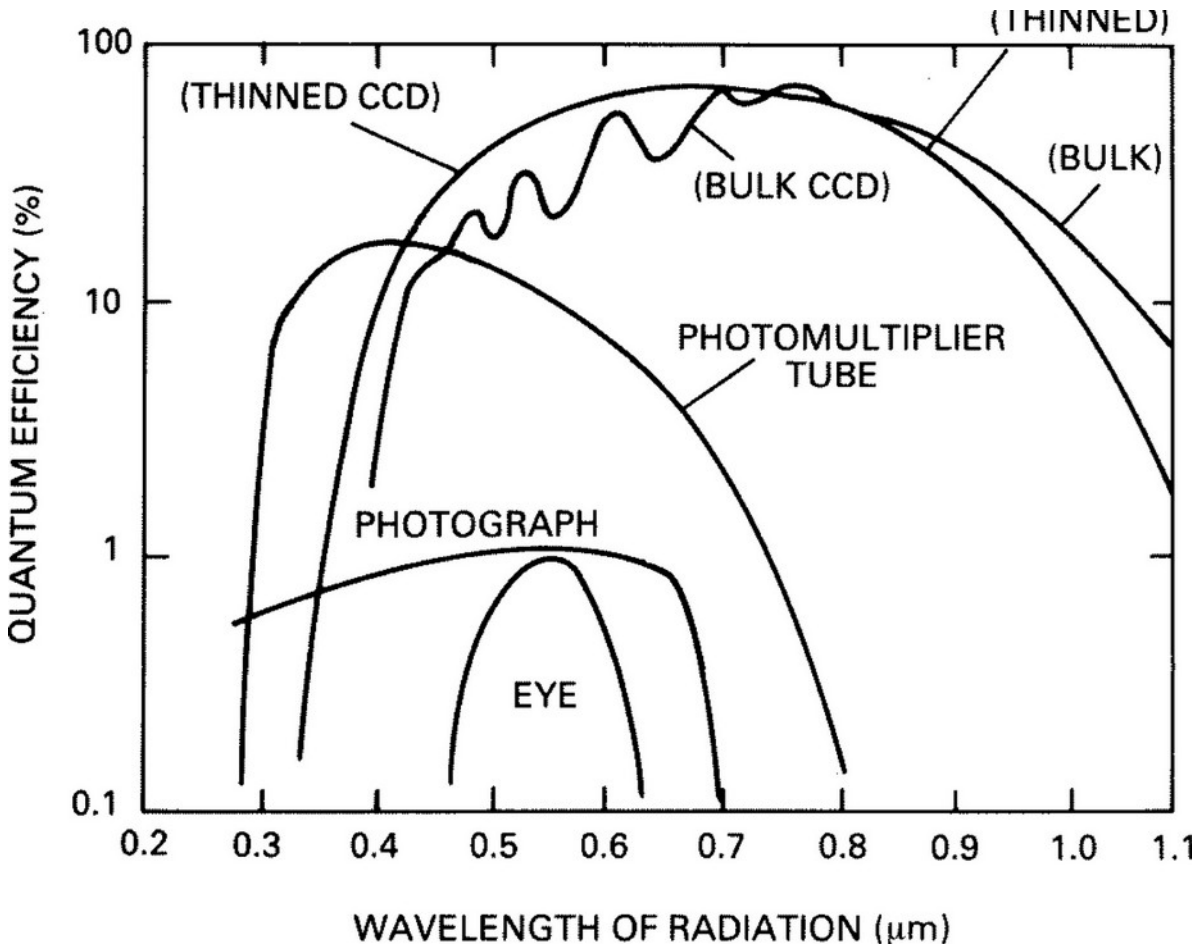
Charge-coupled devices

- Invented by Willard Boyle & George Smith in 1969 (for use as computer memory) at the Bell telephone laboratories
- They were jointly awarded half of the Nobel prize of Physics in 2009 for this discovery
- Dominate optical astronomy since 1980s
  - Linear response
  - Large dynamic range
  - High quantum efficiency
  - Two-dimensional arrays

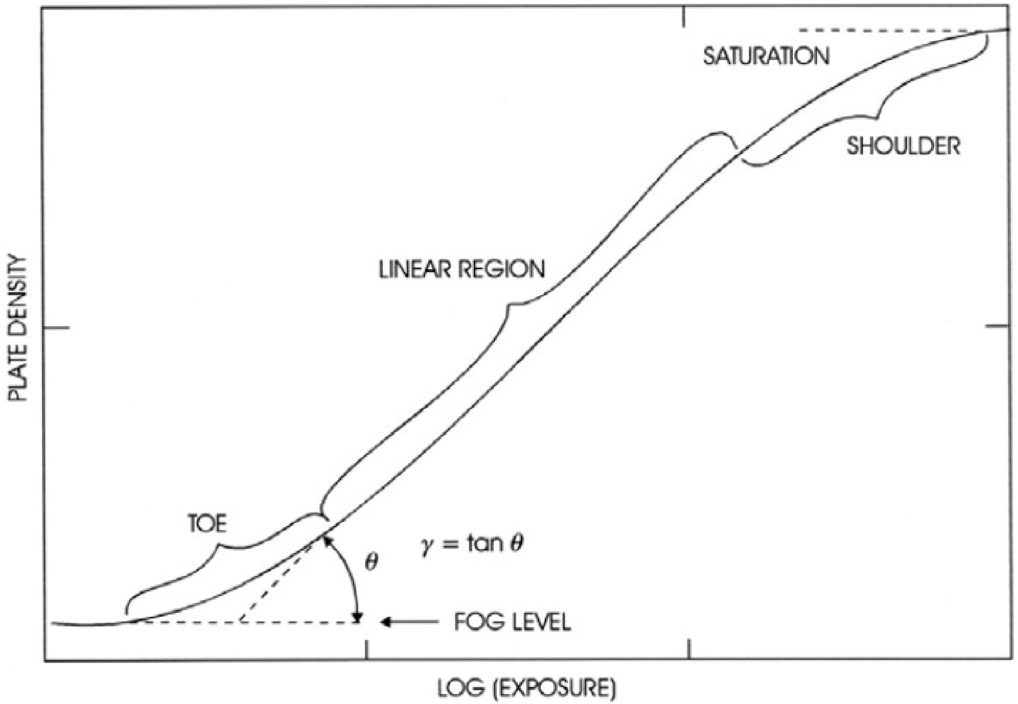


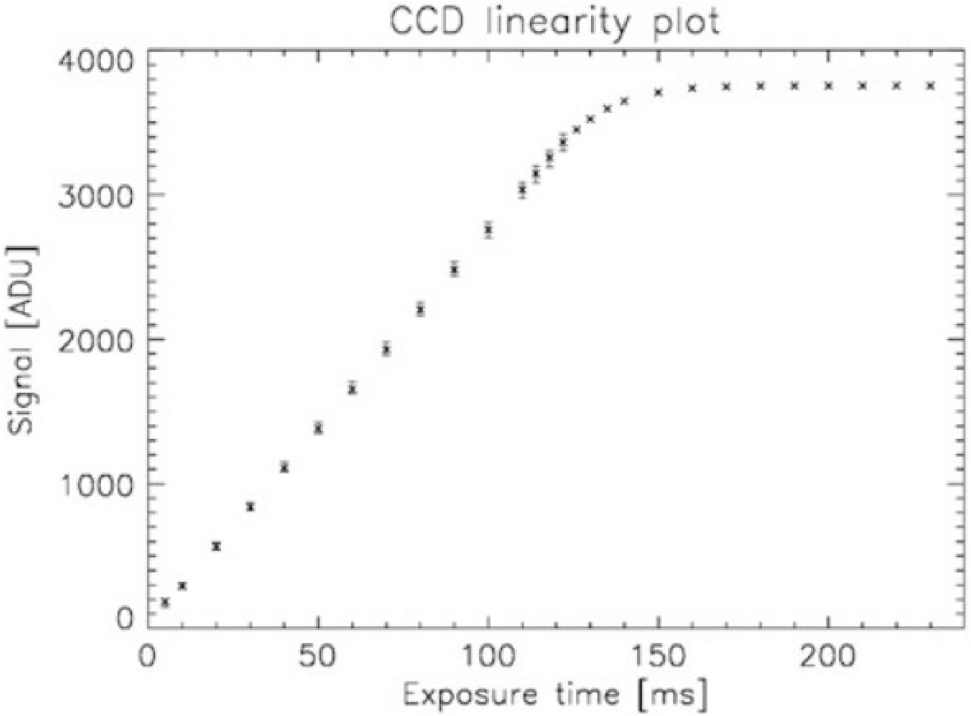
Quantum efficiency

- **Quantum efficiency:** ratio between the number of detected photons and the number of incident photons



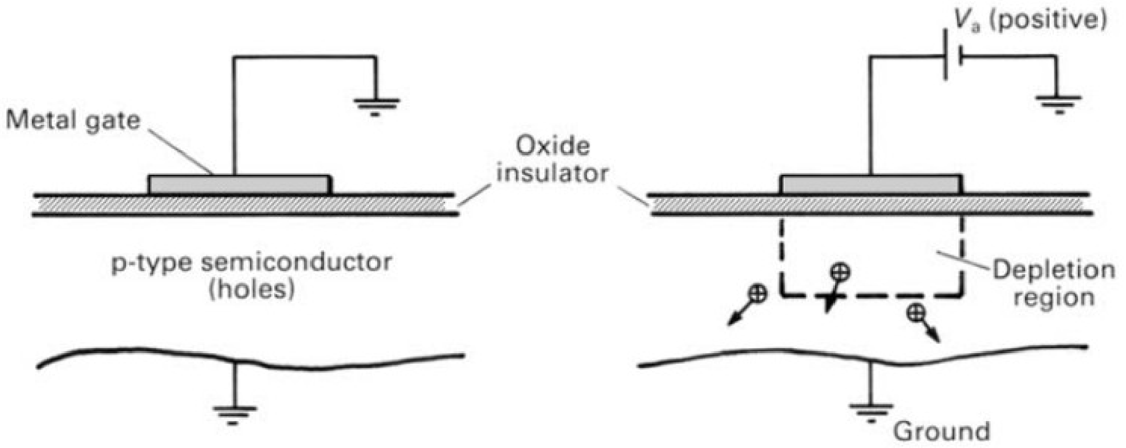
Linearity

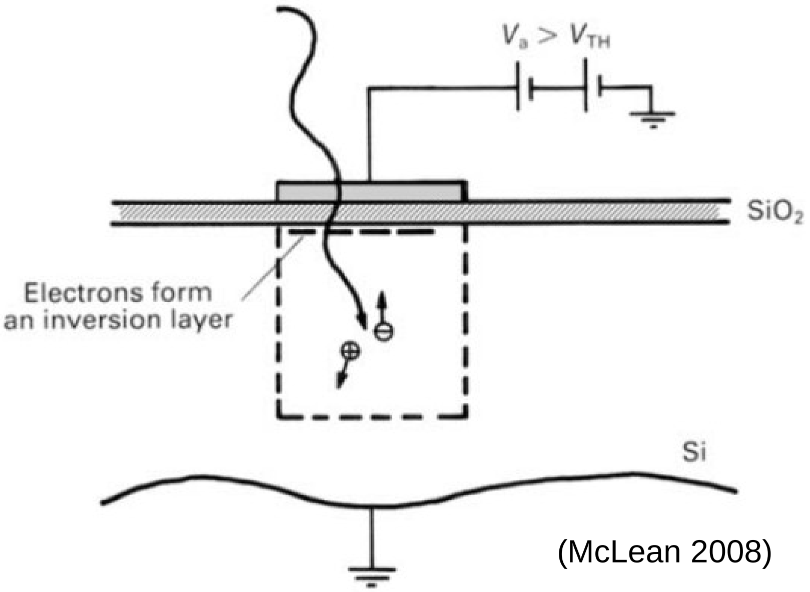

SATURATION
SHOULDER
LINEAR REGION
TOE
$\gamma = \tan\theta$
θ
FOG LEVEL
PLATE DENSITY
LOG (EXPOSURE)


CCD linearity plot
Signal [ADU]
Exposure time [ms]
4000
3000
2000
1000
0
0
50
100
150
200

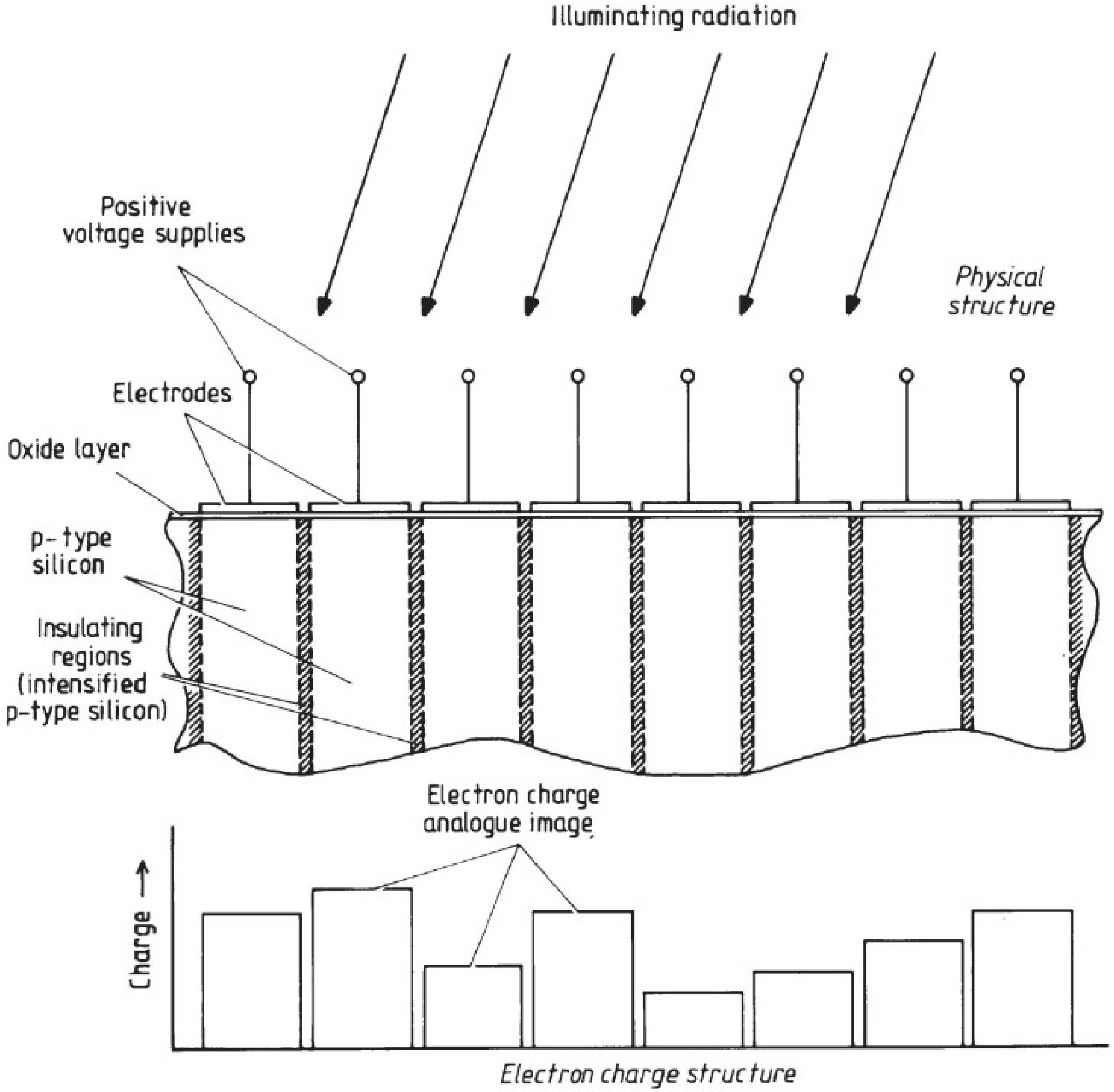
Charge storage

- Semiconductor material (Si) covered with an insulating layer (SiO_2)
- Metal electrode on the top
- Voltage applied to create a depletion region
- Photon crosses the insulating layer, releases electron in the Si
- Electron attracted to the electrode (stop at the insulating layer)
- And so on





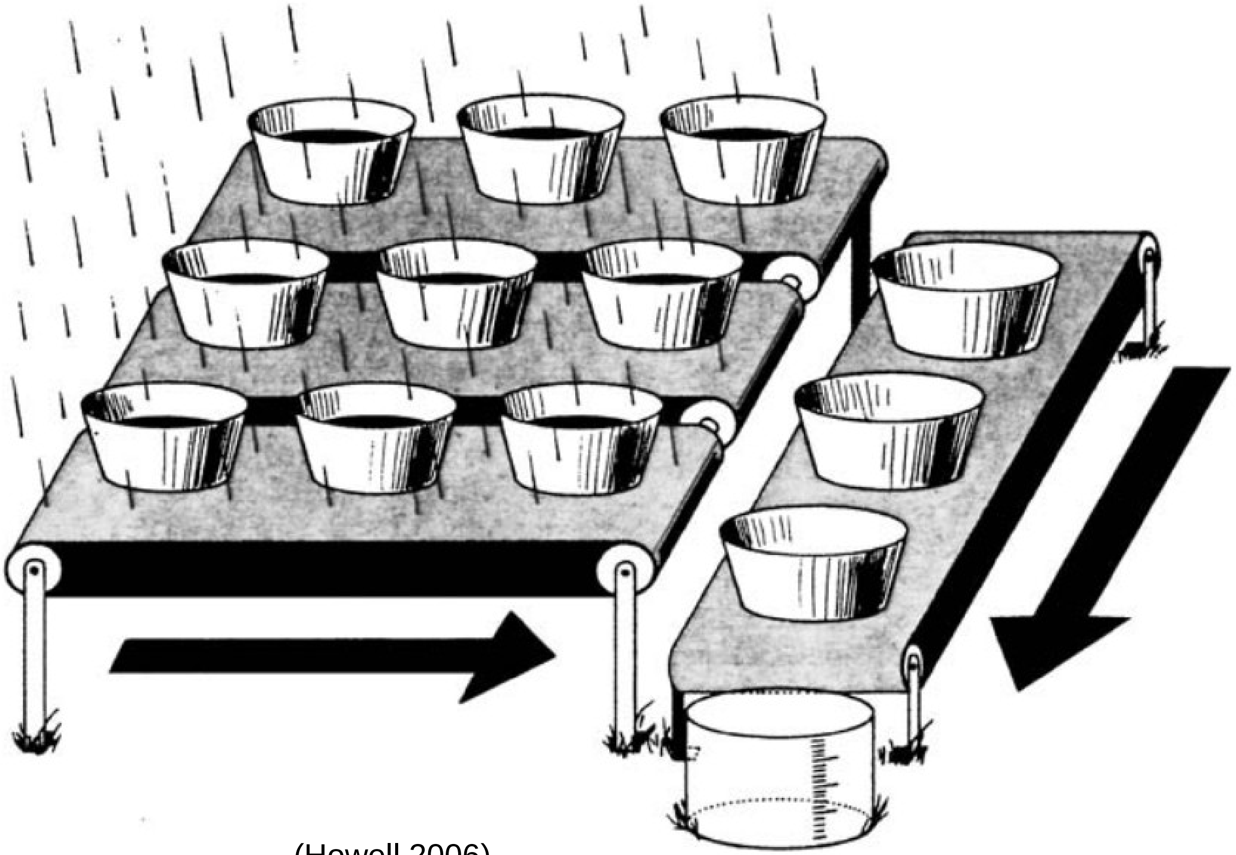
(McLean 2008)



(Kitchin 2003)

Reading out the signal

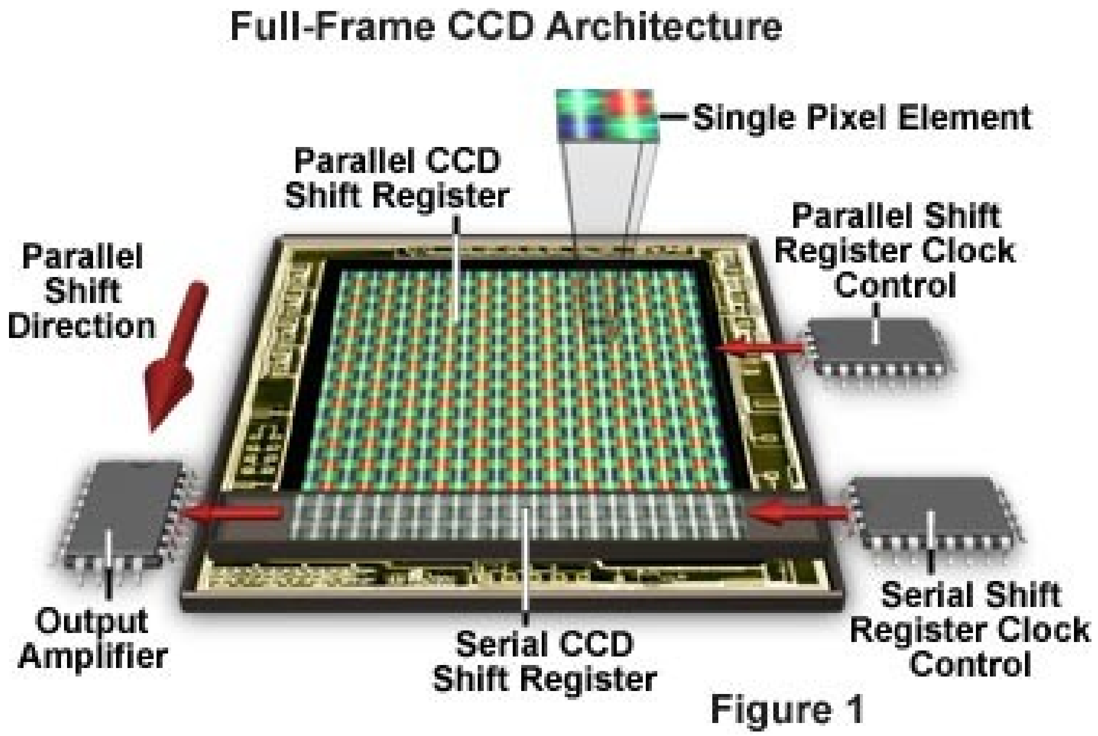
- Rows are moved to a separated region (the output or serial register)
- From where each pixel is sent to the place where the signal is measured (output amplifier)
- Main CCD area: parallel register
- Reading is done pixel by pixel
- Can take 30-60s



(Howell 2006)

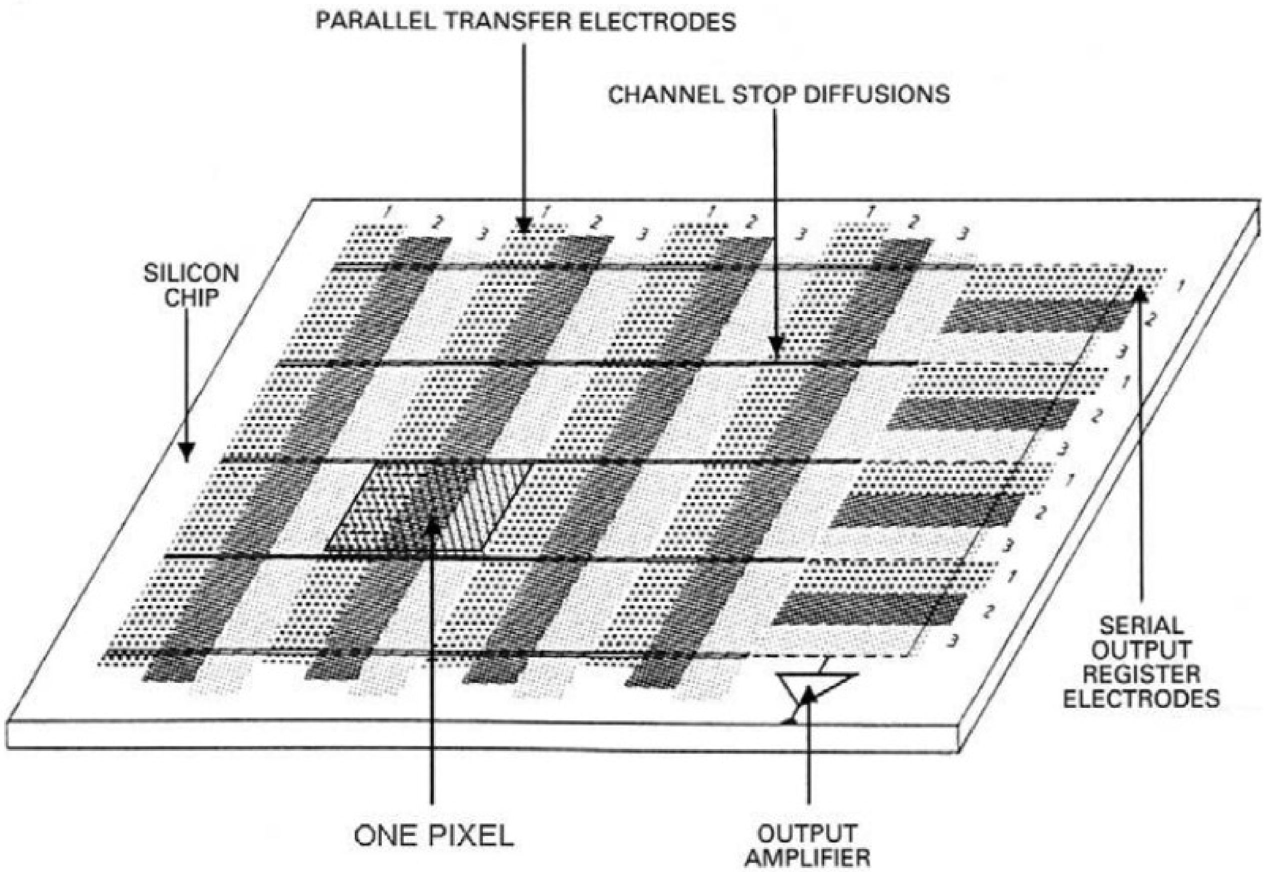
Reading out the signal

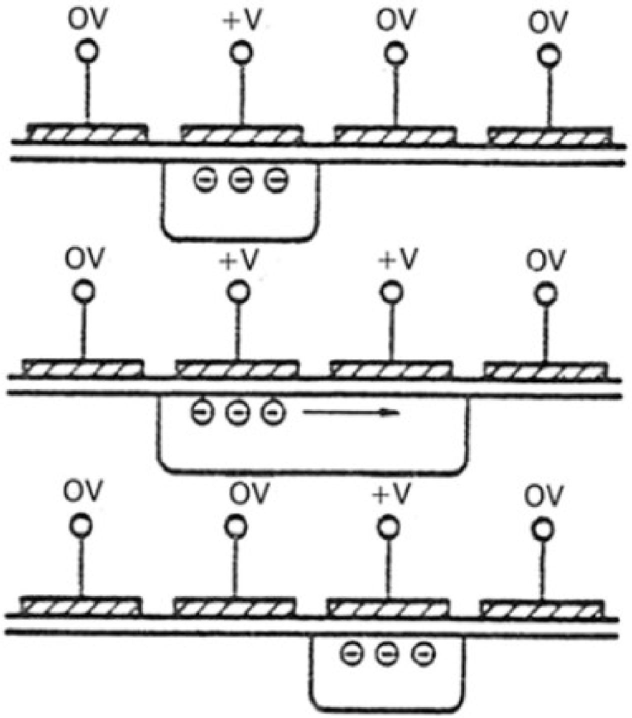
- Rows are moved to a separated region (the output or serial register)
- From where each pixel is sent to the place where the signal is measured (output amplifier)
- Main CCD area: parallel register
- Reading is done pixel by pixel
- Can take 30-60s
- Efficiency > 99.999%
- Some CCDs have more than 1 output register



(Credit: Hamatsu)

Clocking a three-phased CCD

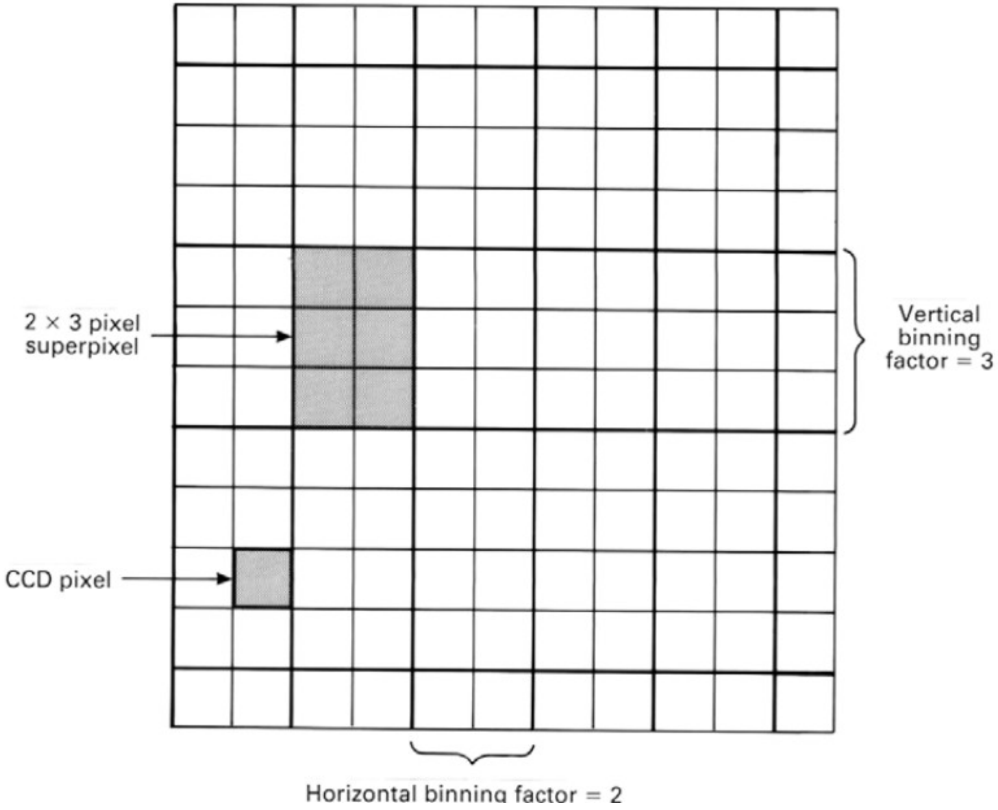




(Howell 2006)

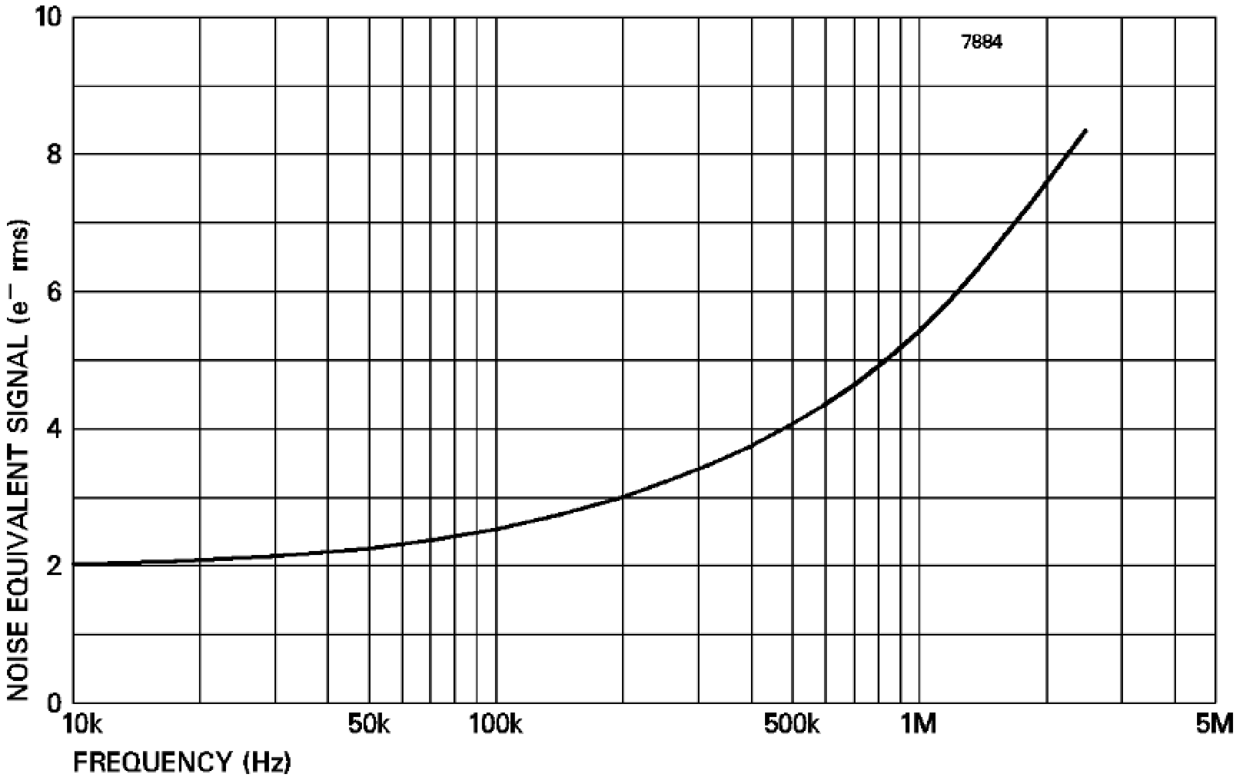
Readout speed, gain and binning

- Some properties might be adjustable:
- **Readout speed:** faster readout increase the readout noise
- **Gain:** conversion between electrons and electronic units (ADU)
  - Bright objects in low gain (more electrons into one ADU)
  - Faint objects in high gain (fewer electrons, signal far from saturation)
  - Digitization noise: conversion is rounded to integer. High gain produce more ADUs, reducing rounding problems
- **On-chip binning:** reduce resolution, increase S/N before adding readout noise



(McLean 2008)

Readout noise and clocking frequency

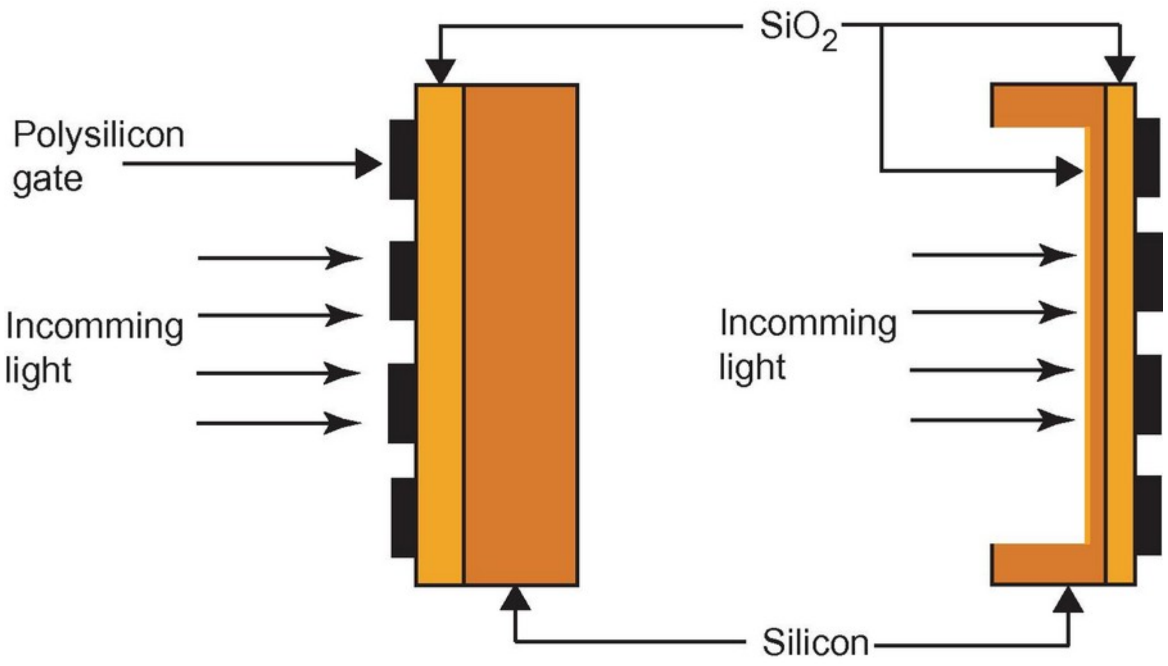


(Credit: e2v; CCD42-90 Scientific CCD Back-illuminated, 2048 x 4612 Pixels)

Thinned, back-illuminated CCDs

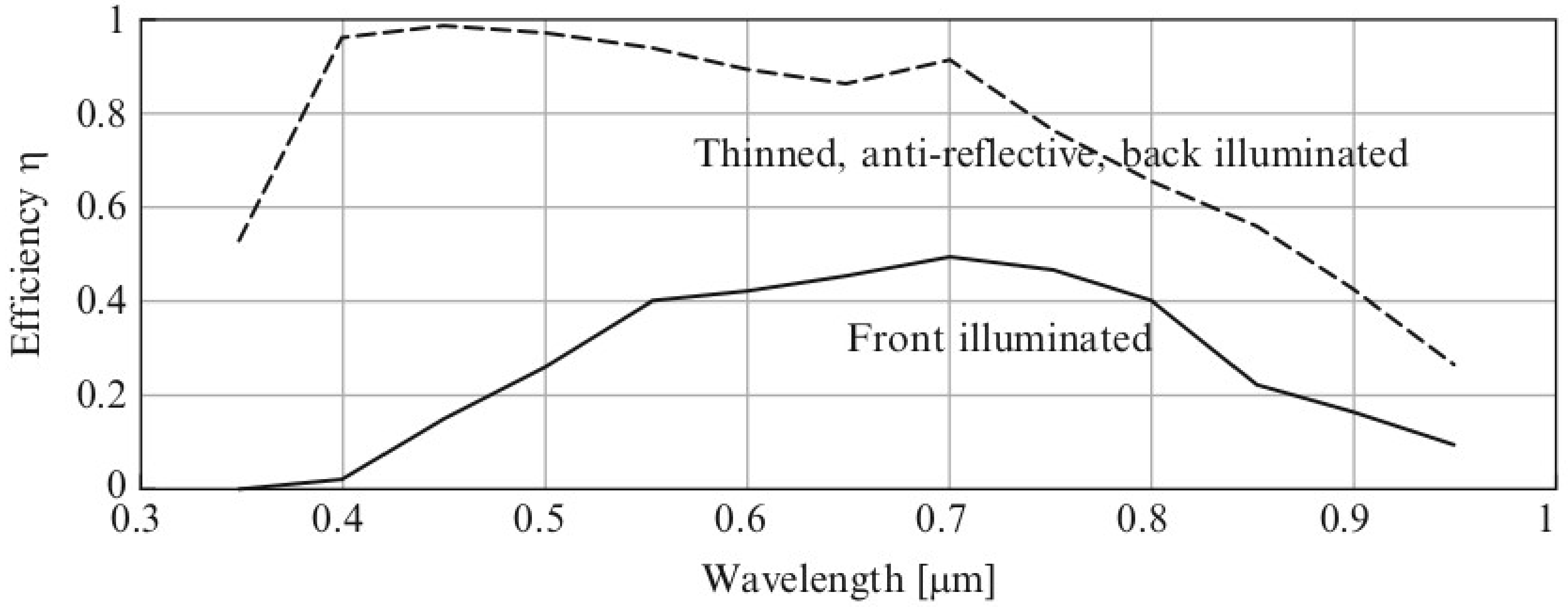
- The electrodes can absorb radiation, particularly in the blue
- **Solution: illuminate from the back!**
- CCDs used to be thick (~300 μm)

  (depletion region ~10 μm)
- Too large region for the electrons to travel
- **Solution: thin the CCD to ~15 μm**
- Great sensitivity in the blue, but fragile and prone to bending
- Also prone to fringing (soon)



(Garnir & Lefèbvre 2005)

Thinned, back-illuminated CCDs

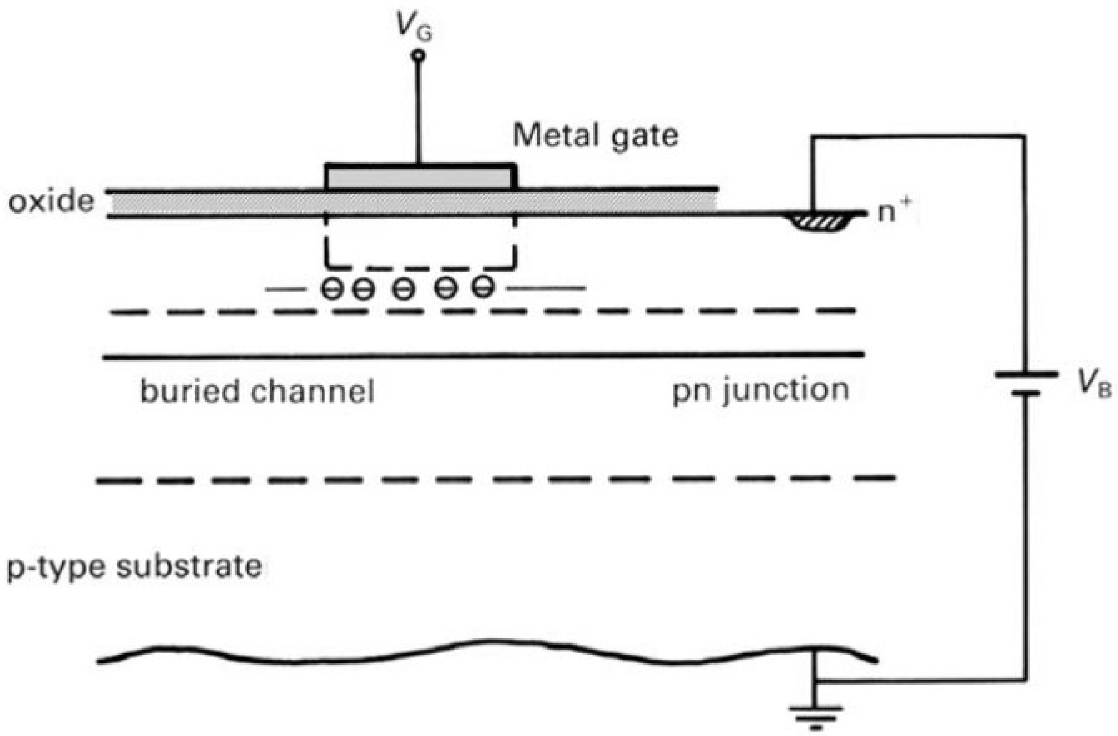


(Lena et al. 2012)

- With a thin layer of antireflection coating on the backside (see Lesser 1994)

Surface channel, Buried channel

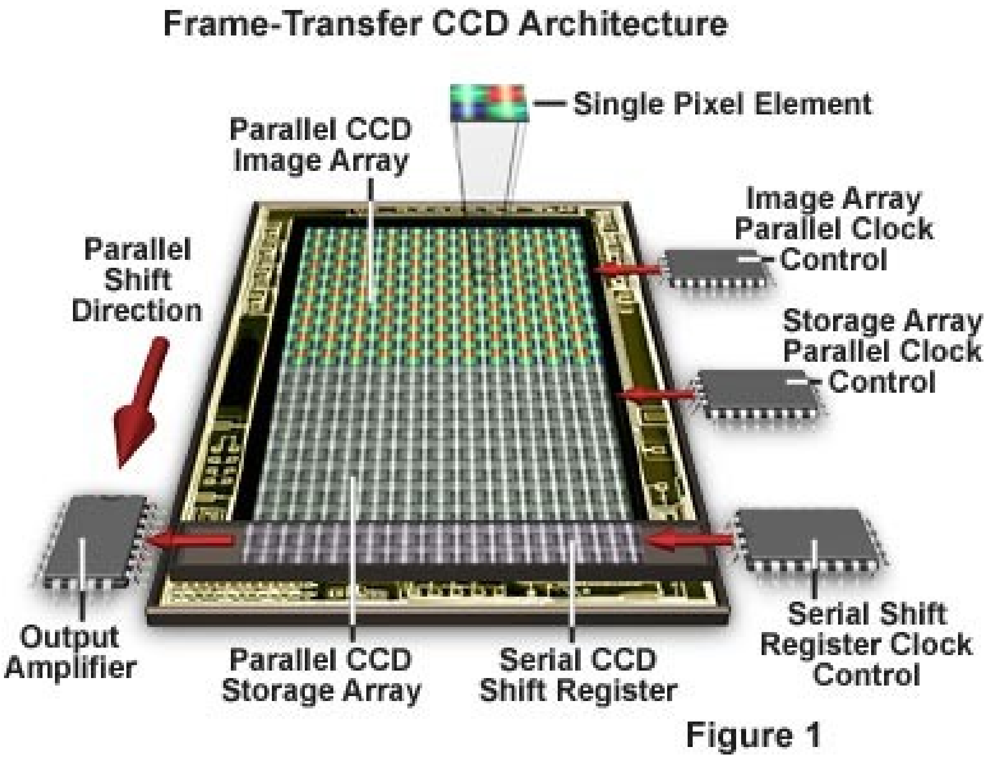
- When electrons are stored and transferred at the surface of the Si layer: **surface channel CCD**
- But the surface layer and edges of electrodes are irregular
- Charges might get trapped
- Add n-type layer on top of a p-type layer (n-type usually Si doped with phosphorus, where P has valence electrons than Si, donating them to the conduction band)
- The material electrons repel the photoelectrons
- The photoelectrons accumulate in a "buried channel"



(McLean 2008)

Frame transfer CCD

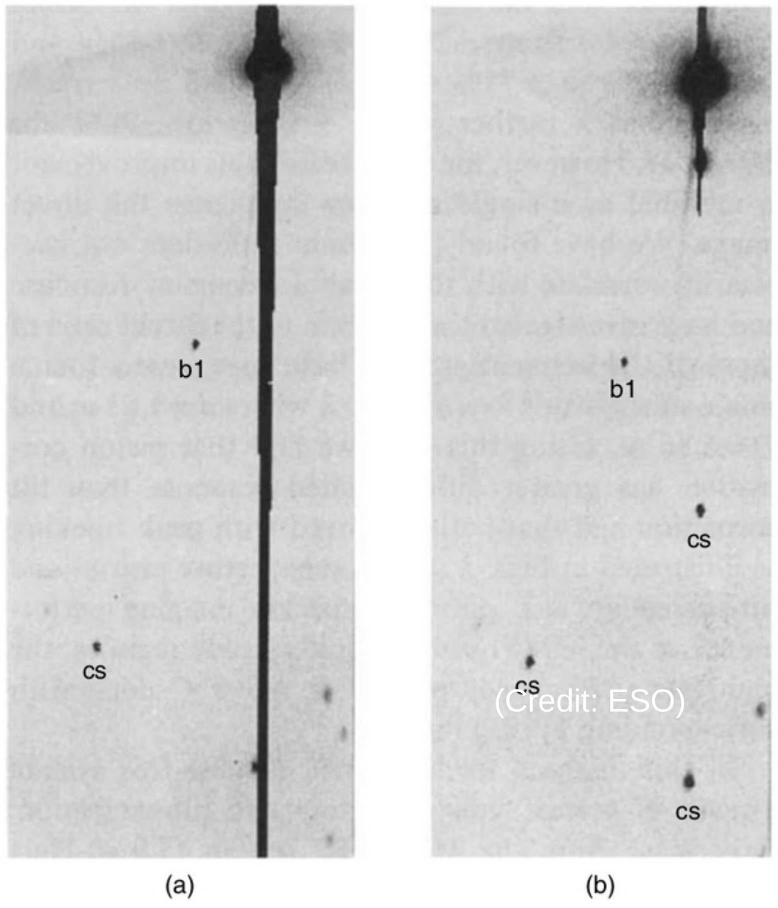
- One type of solution for not loosing exposure time with read out
- Large CCD divided into two equal parts
- One is exposed, the other hidden under a mask
- After exposure, the charges are quickly moved to the hidden area
- The exposed area is quickly ready for a new observation
- The transfer area can then be slowly read-out in the usual way



(Credit: Hamatsu)

Saturation and Blooming

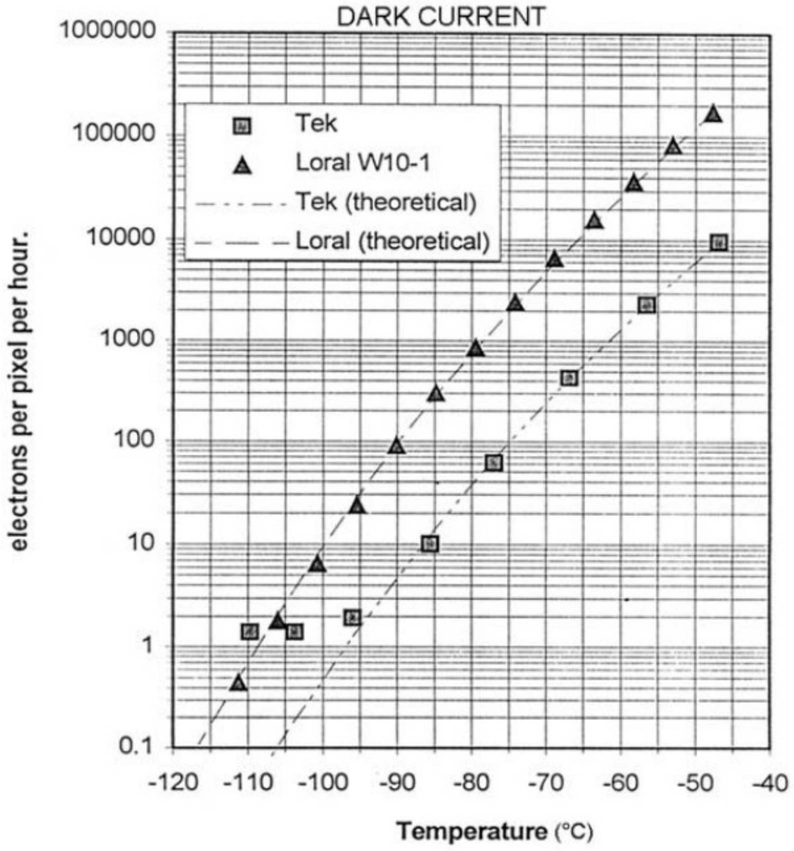
- There is a limit of the charges that a pixel can hold (saturation level)
- Buried channel CCDs saturate earlier than surface channel ones
- But if new photons arrive creating new electrons, the pixel might “bloom” and bleed charges up and down the column
- This can be a problem if there is a bright object in the field you are observing
- Anti-blooming gates can be added to the CCD, so the charges are drained instead of bleeding
- Some pixel area is lost, gaps appear in the spatial coverage, and the pixel well is lower



(Howell 2006)

Dark and operation temperature

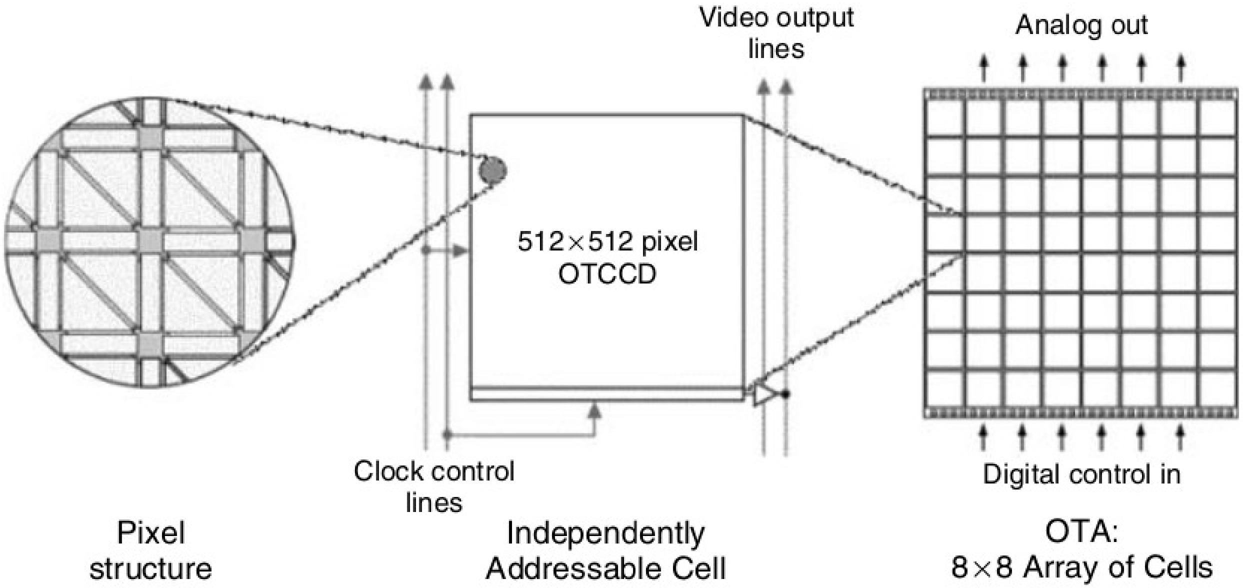
- **Dark current**: just because of the thermal properties, electrons can be promoted to the conduction band, creating spurious signal
- When the observation is readout, dark is just part of the signal (can not be separated)
- At room temperatures, it can reach 100 000 electrons/px/hour (comparable ~150 000 electrons storage capacity)
- Can be reduced by cooling down the CCD
- Using liquid nitrogen (77-220 K)
- For a cooled CCD, typical values of dark can range from <1 to 3-4 electrons/px/hour



(McLean 2008)

Orthogonal Transfer CCDs

- Has the ability to move charges in both directions
- Four electrodes define a pixel
- Two triangular in the centre, and two rectangular
- The rectangular ones act to separate the pixels
- Operation mode is more complex
- Used to help following the centroid of an image, allowing quick readout when it moves in the field



(Howell 2006)

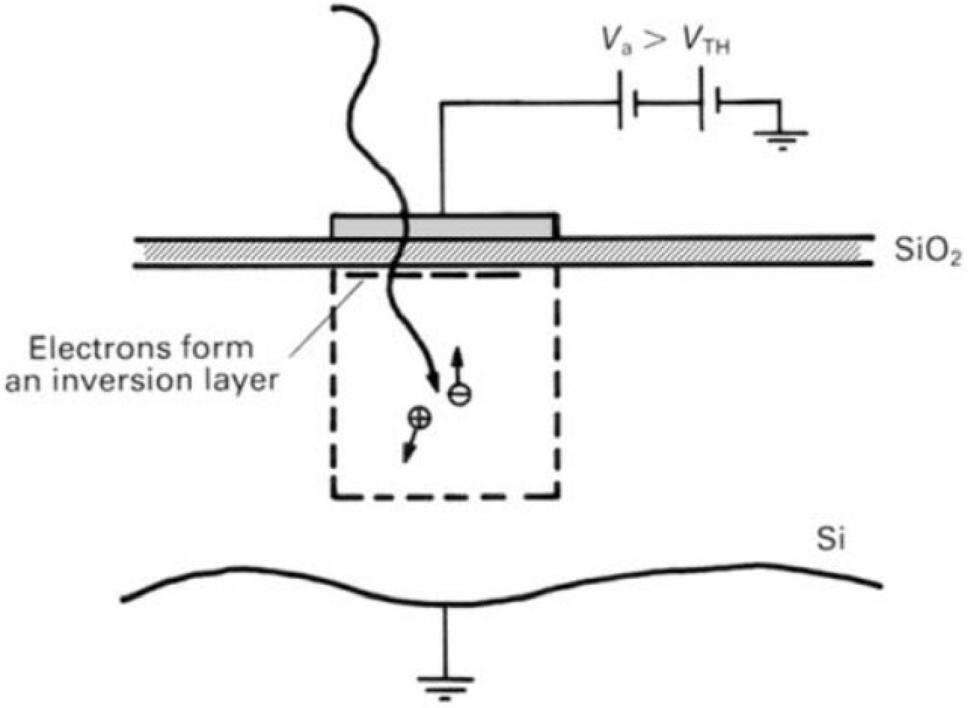
Questions?

(Credit: Shutterstock)

The Signal

- When using a CCD for our observations, we are counting photons
- Signal: The number of photons detected in a given time interval

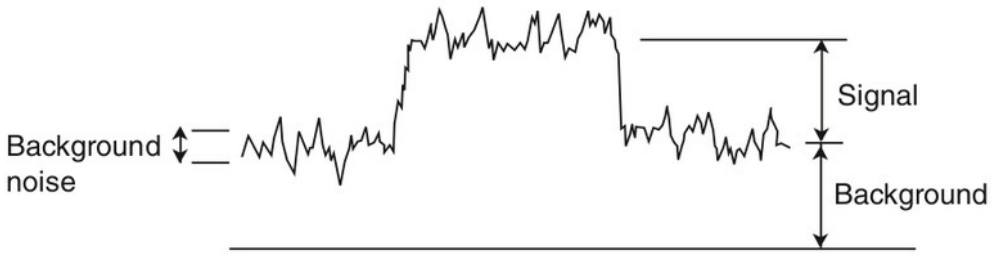
  (Or better, electrons, inside each pixel)
- If the events happen with a constant mean rate,
- And the events in one interval of time are independent from those in another interval of time
- Then the signal (S) is expected to follow a discrete Poisson distribution
- The noise (standard deviation) is N = sqrt(S)



(Credit: McLean 2008)

The Noise

- The “counting noise” is not the only source of noise
- The following noise sources are normally also taken into account:



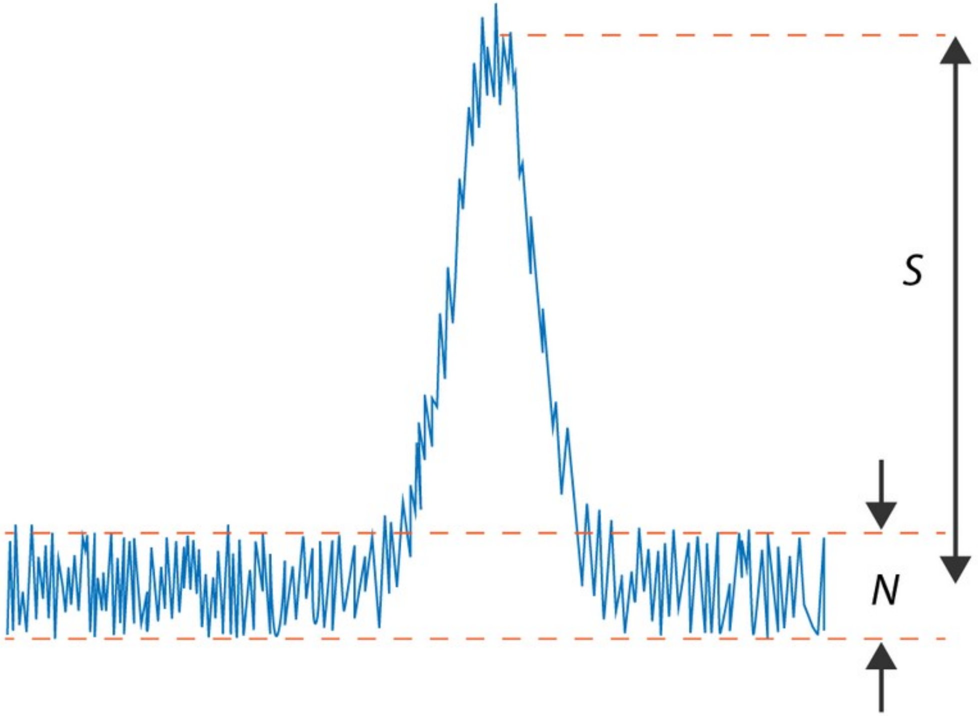
- There is background signal with its own “background noise”

  (the background signal can be corrected)
- There is the read-out noise from the CCD (~2-5 electrons rms)
- The dark current noise
- And other sources, depending on what you are doing

(Credit: Bely 2003)

The Signal to Noise ratio

- Compares the signal to the fluctuation, in units of standard deviation
- **S/N or SNR**
- The S/N is interpreted from a Gaussian point of view
- S/N = 1: 68% chance the signal is real, 1 chance in 3 that it is not real
- S/N = 3: 99.7% of real, 3 in 1000 its not real (3 sigma detection)
- **But are we ever sure the noise is well characterized?**
- S/N = 5: less than 1 in 10^5 chance the signal is not real



If S/N = 5 is so great,
do we ever need higher?

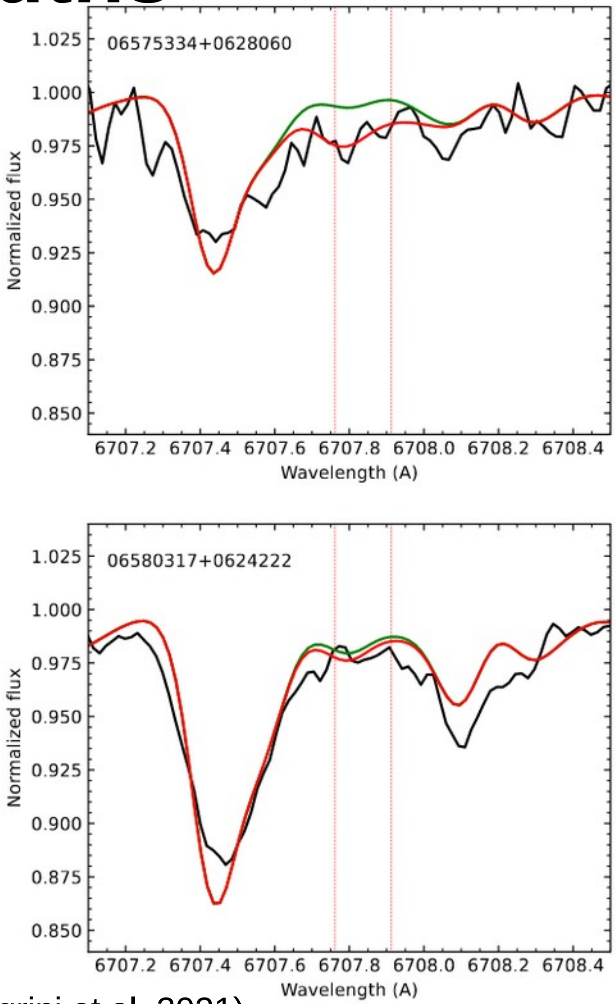
- **Yes!**
- It all comes down to what is it you are trying to measure

S/N and Equivalent Widths

- For example, if measuring the “area” (equivalent width) of an absorption line
- Cayrel (1988) formula gives:

  $\sigma_{EW} \sim 1.6 * \mathrm{sqrt}(FWHM * dw) / SNR$

  (FWHM is the size of the resolution element; dw is the size of the pixel in the detector; SNR is measured at the continuum)
- For R = 50000 at 5000 A, FWHM = 0.1 A. For dw = 0.033 A (sampling of 3 px) and SNR = 100, the error is 1mA.
- So the 5-sigma detection happens for a weak line of ~ 5 mA.



(Credit: Magrini et al. 2021)

S/N and magnitudes

3.1 Conversion from S/N to uncertainties on the magnitude scale

Usually errors in astronomy are expressed on the logrithmic magnitude scale. To go from S/N to magnitudes errors consider:

$$
\begin{aligned}
m \pm \sigma(m) &= C_0 - 2.5\log(S \pm N) \\
&= C_0 - 2.5\log[S(1 \pm \tfrac{N}{S})] \\
&= C_0 - 2.5\log(S) - 2.5\log(1 + \tfrac{N}{S}) \\
\sigma(m) &= \pm 2.5\log(1 + \tfrac{1}{S/N})
\end{aligned}
$$

Note, that magnitude errors are often taken to be fractional errors and measurements like $V = 31.9 \pm 0.1$ are claimed to be 10% photometric accuracy. This is close to but not quite correct:

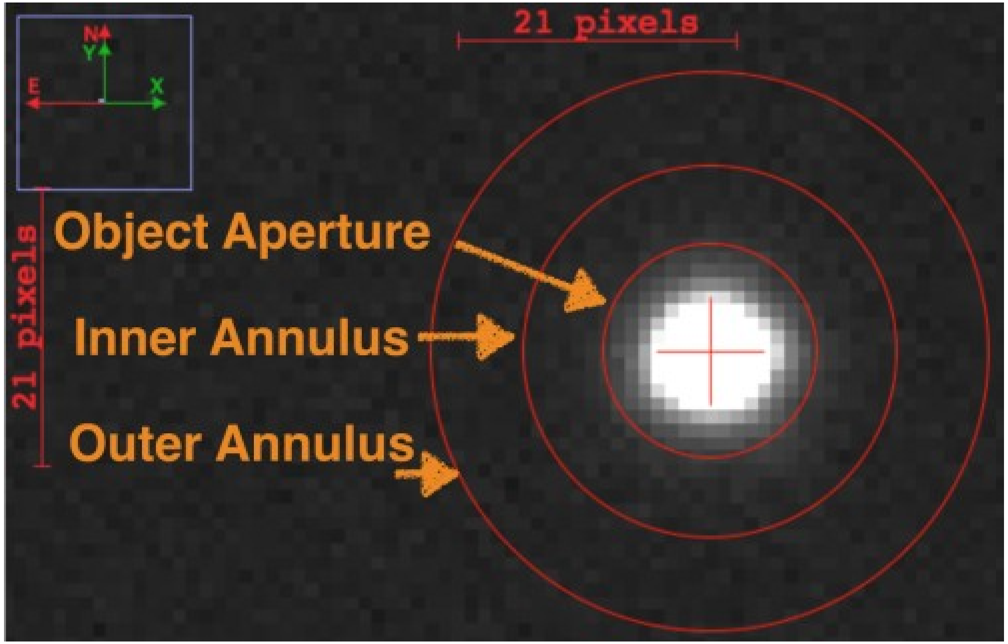
$$
\begin{aligned}
\sigma(m) &= \pm 2.5\log(1 + \tfrac{N}{S}) \\
\sigma(m) &= \pm \tfrac{2.5}{2.3}[\tfrac{N}{S} - \tfrac{1}{2}(\tfrac{N}{S})^2 + \tfrac{1}{3}(\tfrac{N}{S})^3 - ...] \\
\sigma(m) &\approx \pm 1.0875(\tfrac{N}{S})
\end{aligned}
$$

(Credit: Mike Bolte)

The S/N equation

$$\frac{S}{N} = \frac{N_*}{\sqrt{N_* + n_{\text{pix}}(N_S + N_D + N_R^2)}},$$

- N_* = Total number of photo-electrons collected from the source within n_{pix}
- N_S = Total number of photo-electrons collected from the sky (background) per pixel
- N_D = Total number of dark current electrons per pixel
- N_R^2 = Total number of electrons per pixel from the read out (read out noise is usually given as RMS)
- n_{pix} = number of pixels



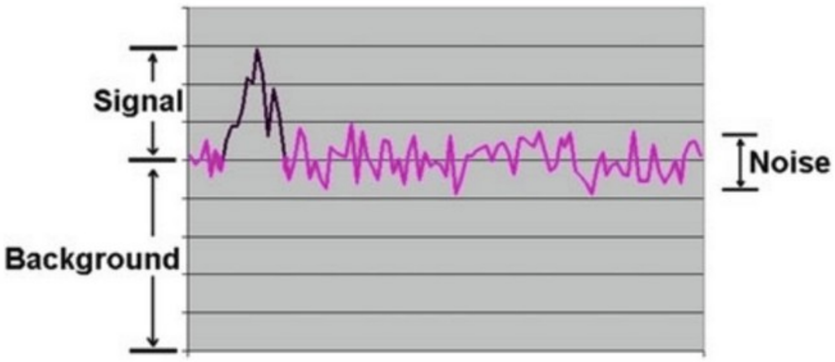
(Credit: Astrobites)

The S/N equation, expanded

- The equation in the previous slide applies for a typical well behaved CCD, for a well sampled not faint source
- More complicated expressions might be needed:

$$\frac{\mathrm{S}}{\mathrm{N}} = \frac{N_*}{\sqrt{N_* + n_{\mathrm{pix}}\left(1 + \frac{n_{\mathrm{pix}}}{n_B}\right)\left(N_S + N_D + N_R^2 + G^2\sigma_f^2\right)}}.$$

- $(1 + n_{pix}/n_B)$ is to take into account errors introduced in the estimation of the background (Merline & Howell 1995)
- n_B = the number of pixels used to estimate the background
- Last term = error introduced by the digitization noise within the A/D converter (Merline & Howell 1995)



(Credit: Eversberg & Vollman 2015)

Limiting cases

$$\frac{\mathrm{S}}{\mathrm{N}} = \frac{N_*}{\sqrt{N_* + n_{\mathrm{pix}}(N_S + N_D + N_R^2)}},$$

- **Bright source**: $N_* >> npix(N_S+N_D+N_R^2)$

$$\frac{\mathrm{S}}{\mathrm{N}} = \frac{N_*}{\sqrt{N_*}} = \sqrt{N_*},$$ or $$S/N \simeq \sqrt{R_* \times t} \propto t^{\frac{1}{2}}$$ (t = exposure time, R_* = photon rate)

- **Background limited**:

$$S/N \simeq \frac{R_* \times t}{\sqrt{n_{\mathrm{pix}} \times R_{\mathrm{sky}} \times t}} \propto t^{\frac{1}{2}}$$

(When the target is weak and background dominates the noise. And only if thermal emission and detector noise have been minimized)

- One needs either a larger telescope, improved image quality (adaptive optics), or avoid strong background (e.g., strong airglow lines)

Limiting cases

- **Detector noise limited**:

$$\mathrm{S/N} = \frac{S\,t}{\sqrt{I_d\, n_{\mathrm{pix}}\, t + R_{\mathrm{n}}^2\, n_{\mathrm{pix}}}}\,.$$

  (S = photon rate from the source; I_d from the dark current, R_n is the read out noise)

- Source and background signals are faint
- Noise of the detector dominates
- Can be the case in high-resolution spectroscopy (for higher resolutions, less photons arrive at a given pixel)
- S/N increases linearly with time, until the signal is large enough that its fluctuations are larger than R_n
- Integration times should be as long as possible

Adding, subtracting, dividing images

- **Two images of S/N = 100 do not make one image of S/N = 200! (S/N' ~ 141)**

- If adding two images (or subtracting, e.g. subtracting a background frame)

➡ $$\sigma_z{}^2 = \sigma_x{}^2 + \sigma_y{}^2 \qquad \text{(Error in a sum or difference)}$$

(so we want the error in the background frame to be as small as possible)

- If dividing two images (e.g., flat field as we will see soon)

➡ $$\left(\frac{\sigma_z}{z}\right)^2 = \left(\frac{\sigma_x}{x}\right)^2 + \left(\frac{\sigma_y}{y}\right)^2 \qquad \text{(Error in a product or quotient)}$$

(so we want the signal in the dividing image to be as high as possible)

Exposure Time Calculator

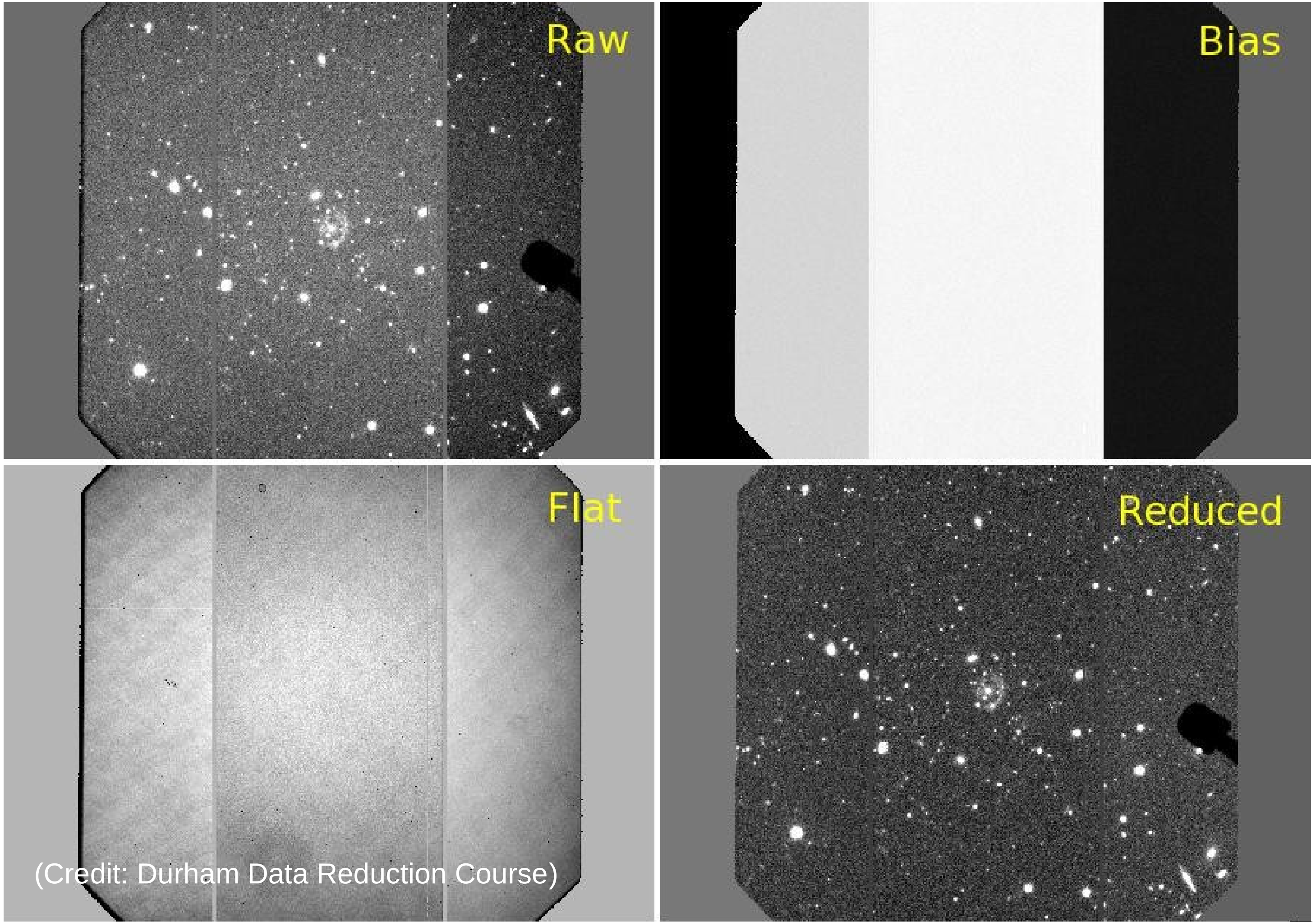
- Each instrument at the VLT has its own exposure time calculator
- This tool will help you to estimate the exposure time you need to reach your desired S/N

- Here a link to the UVES ETC:
- https://www.eso.org/observing/etc/bin/gen/form?INS.NAME=UVES+INS.MODE=spectro

Questions?

(Credit: Shutterstock)

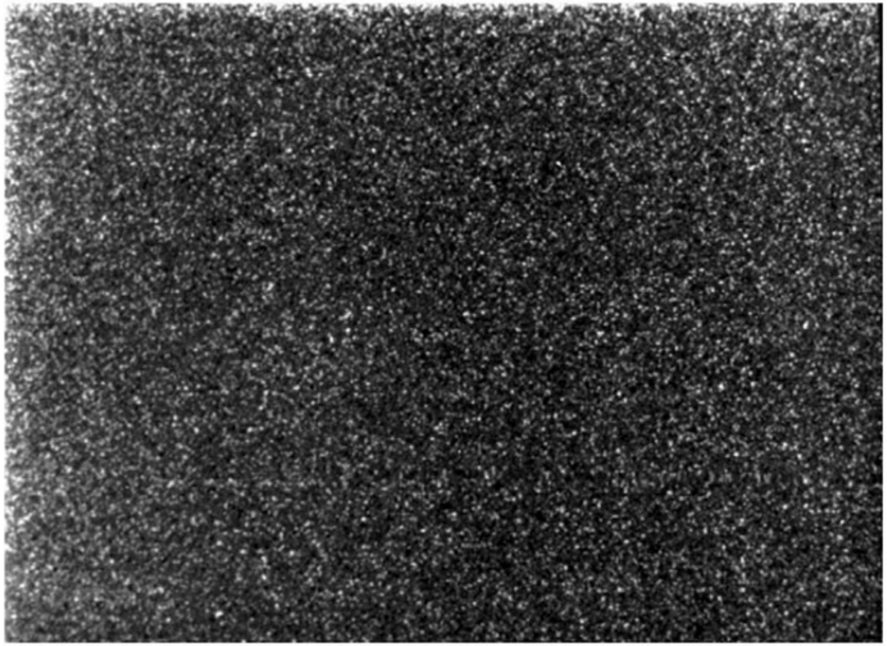
Data reduction



(Credit: Durham Data Reduction Course)

Bias and overscan

- The empty, non-exposed CCD produces a reading for each pixel
- It would be a fluctuation around zero, but storing negative numbers need one bit (decreasing the storage space)
- To avoid that, set up with a positive offset
- **This is the bias level**
- Several bias frames (zero exposure) to reduce the readout noise, and preserve coherent noise and pixel-to-pixel variation
- The mean bias is subtracted from all images
- Or the overscan can be used for a typical “pedestal” level (pseudo-columns generated by the electronics)



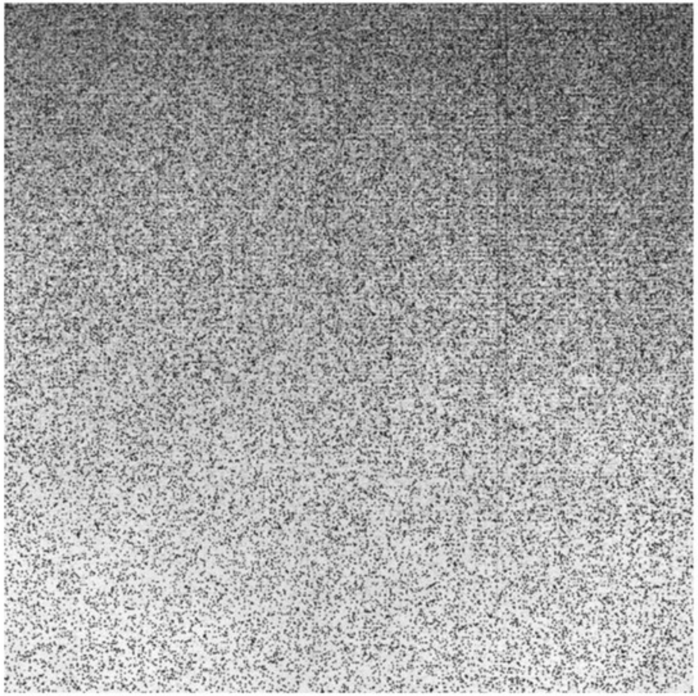
(McLean 2008 – Clean bias showing no structure)

Dark frames

- CCD is not exposed, but integration time is equal to that of the science image

  (not always the dark is linear)

- For collecting the dark current signal
- For many modern CCDs, dark is very low and usually ignored
- Dark images also contain the bias (so one can consider skipping bias correction)
- Averaging together multiple dark frames is the best to reduce noise (but not always practical)
- Dark current is more significant for infrared arrays

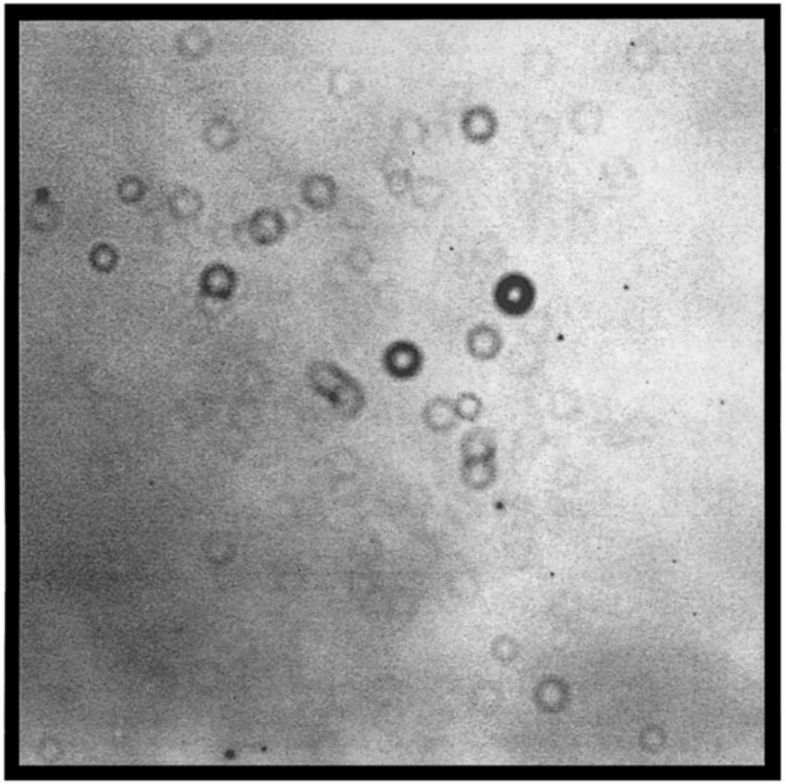


(Howell 2006 – Dark frame showing non uniform level)

Flat fielding

- Pixel-to-pixel variations in quantum efficiency exist (to a few percent)
- If not corrected, it leaves additional noise on the images
- Flat field frame is a frame with very high S/N obtained uniformly illuminating the CCD
- Also help to correct non-uniform illumination of the detector itself
- Frames are needed for each filter, wavelength region, or instrumental setup used for science
- Several frames should be averaged together to reduce noise

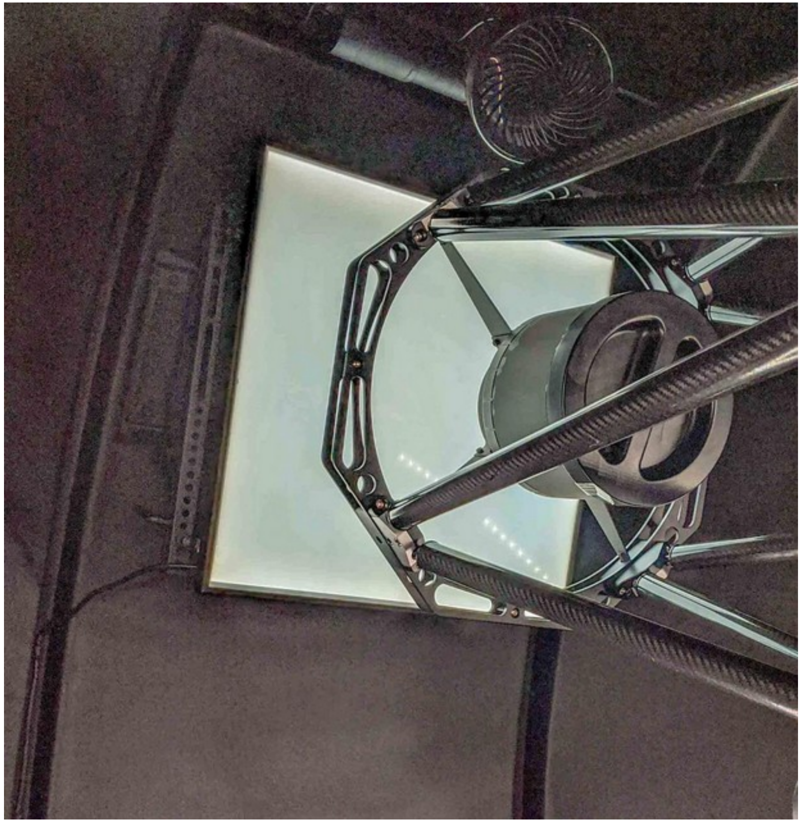
$$\text{Final Reduced Object Frame} = \frac{\text{Raw Object Frame} - \text{Bias Frame}}{\text{Flat Field Frame}}$$



(Howell 2006 – Flat field frame with dust affecting the illumination)

Flat field variations

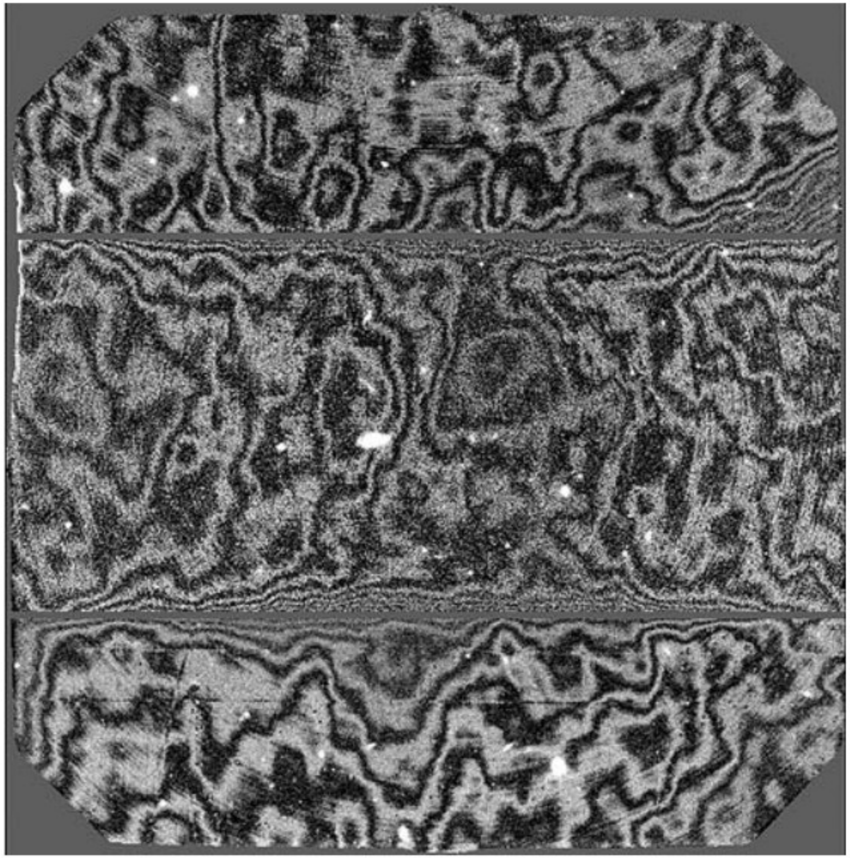
- Flat-fielding: tricky and hardly ever done perfectly
- Ideally, uniform illumination of every pixel with a source of same spectral response of the object
- **Dome flat:** illuminate a screen inside the dome
- **Twilight flat:** image dawn or dusk sky
- **Sky flat:** image a dark night area
- **Lamp (projector) flat:** a high intensity lamp illuminates the slit (for spectroscopy)
- Concerns: 1) Uniform illumination to 0.1% is hard; 2) Pixel-to-pixel variations are λ dependent (twilight and lamps have their own spectral distribution); 3) Sky flats can take a long time to integrate (and we'd like several)



(Credit: Terry White)

Fringes

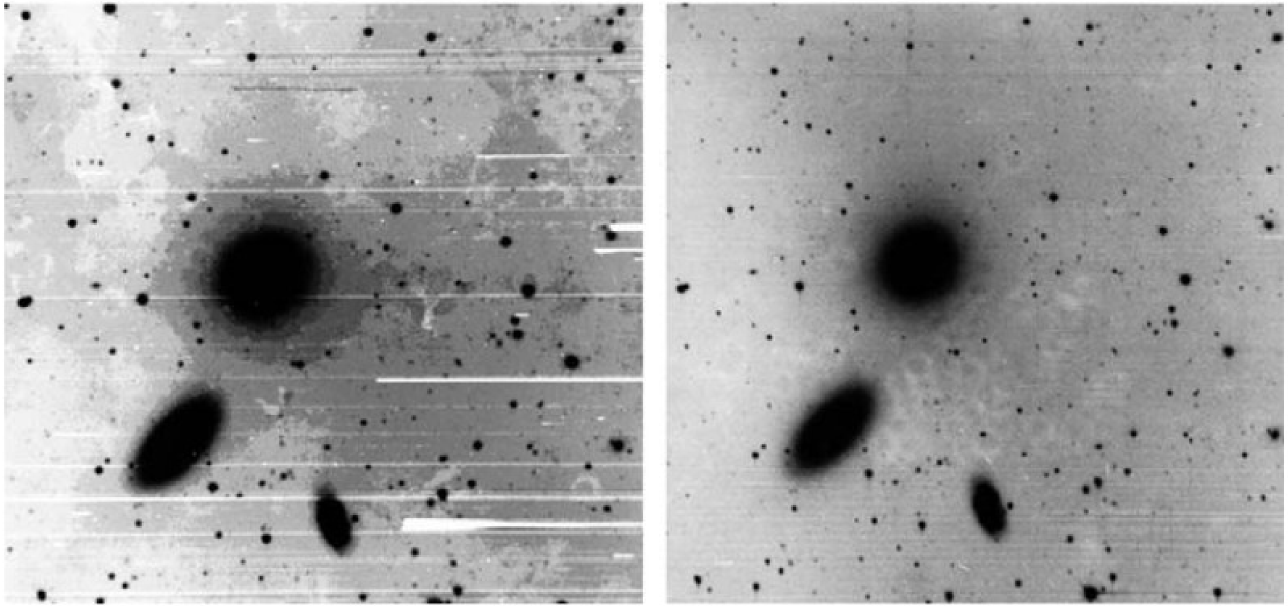
- Fringes caused by interference of light reflected within the CCD
- May occur: in the red part of the optical spectrum; when using narrow-band filters; observing strong narrow emission lines
- And it might be quite variable
- Fringing from nigh sky emission lines will not appear in dome or twilight flats
- Sky fringe frame can help (but is time consuming)
- Neon lamp, with emission lines, flat fields (see Howell 2012)
- New CCDs with anti-reflection coating have reduced the problem



(Howell 2006; GMOS, z' filter, @8800 A)

Bad pixels

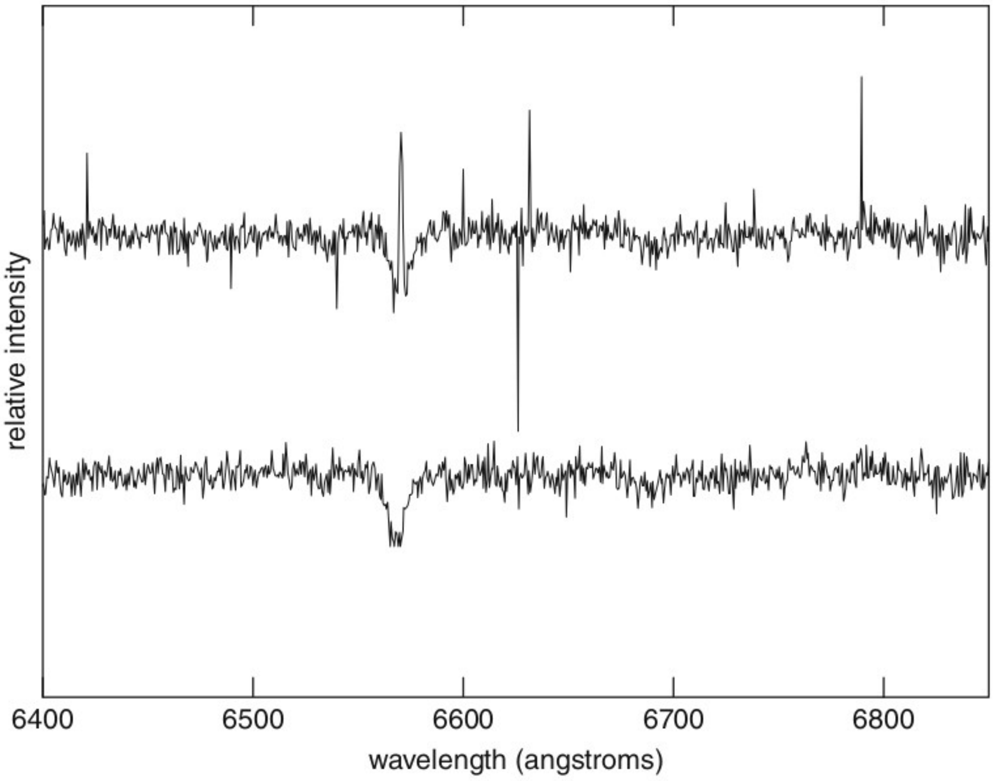
- Older CCDs could be prone to several cosmetic defects
- Dead pixels, hot pixels, blocked columns
- Bad pixel map used for interpolation
- Dithering during observations to filter out the problems during reduction



(McLean 2008)

Sky background and cosmic rays

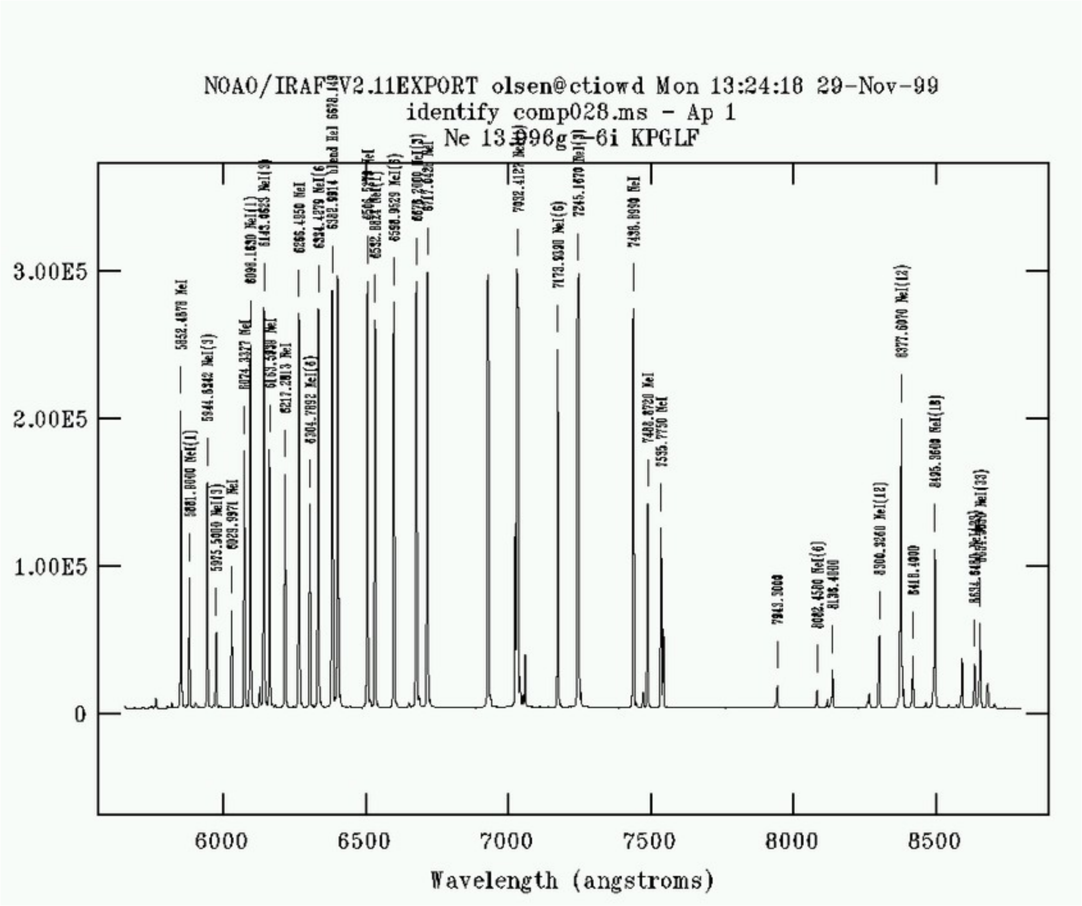
- For photometry, you can estimate the sky background in the image and remove from the object
- For spectroscopy, the long slit also takes a sky background spectrum
- Fibers can also be allocated to the sky
- Cosmic-rays can hit the CCD and leave behind huge numbers of electrons
- Its recommended to take at least three images to be able to identify cosmic ray hits
- There are cleaning algorithms that make a very good job of removing hits



(Massey & Hanson 2013)

Additional calibrations

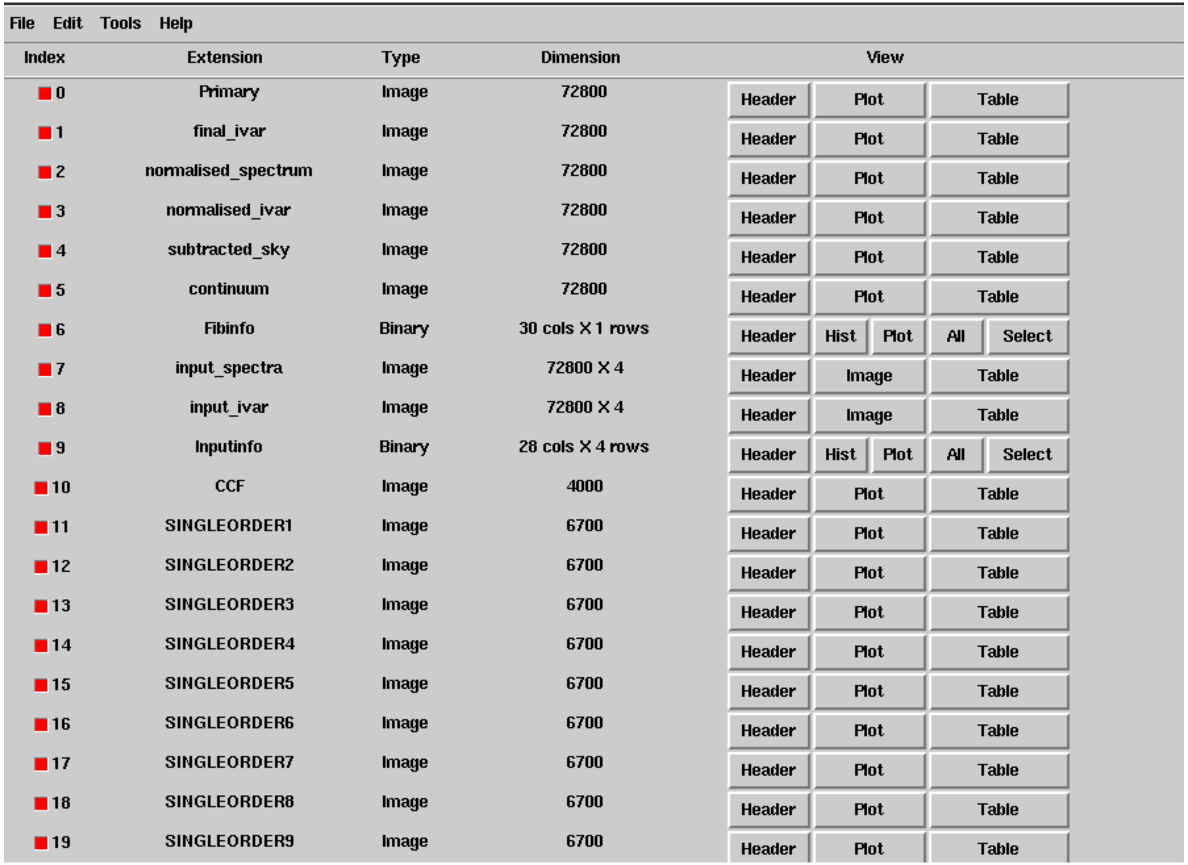
- For spectroscopy:
  - wavelength calibration (e.g. ThAr lamps);
  - radial velocity standards;
  - radial velocity calibration lamps;
  - telluric standards;
  - flux standards
- For photometry:
  - flux standards
- **Always check the instrument manual to know about the calibration needs and possibilities**



(Credit: ESO)

Data formats

- FITS (Flexile Image Transport System)
- FITS is the widely used (old and ackward) standard
- Can be made of several extensions, each with a header and data
- Data can be binary tables or images
- Several limitations on sizes and rules for format (see Pence et al. 2010)
- Alternatives: "HDF" (hierarchical data format)



File Edit Tools Help

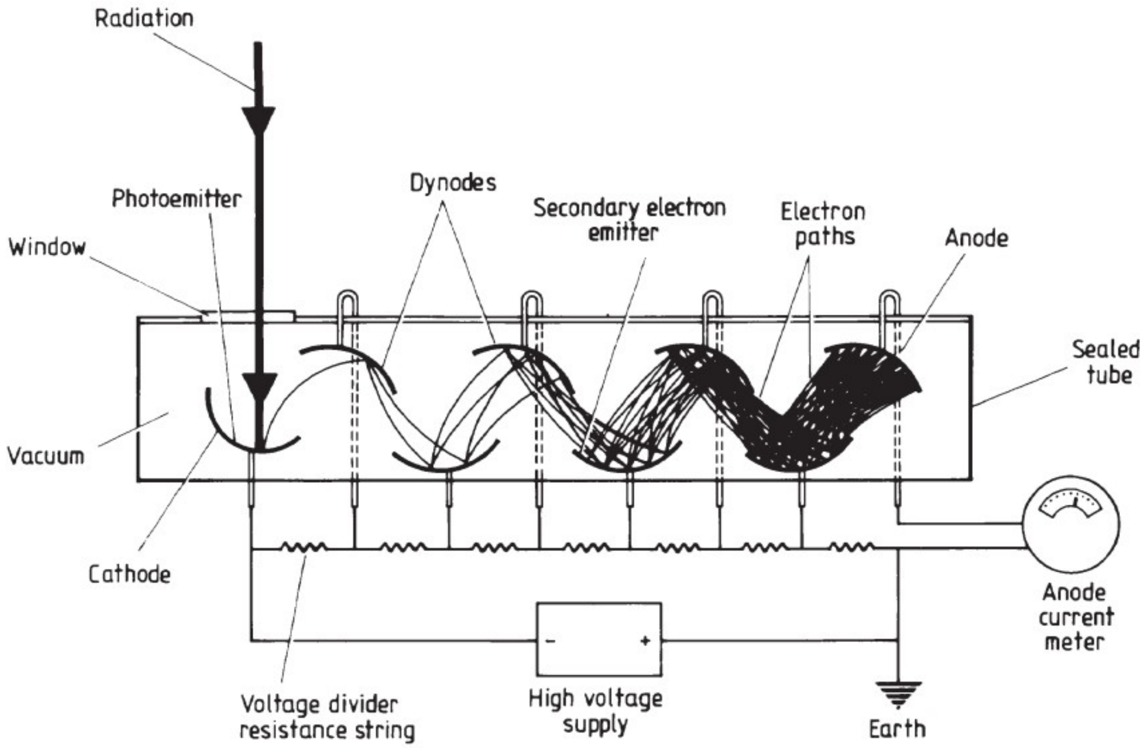
Index	Extension	Type	Dimension	View				
0	Primary	Image	72800	Header	Plot		Table	
1	final_ivar	Image	72800	Header	Plot		Table	
2	normalised_spectrum	Image	72800	Header	Plot		Table	
3	normalised_ivar	Image	72800	Header	Plot		Table	
4	subtracted_sky	Image	72800	Header	Plot		Table	
5	continuum	Image	72800	Header	Plot		Table	
6	Fibinfo	Binary	30 cols X 1 rows	Header	Hist	Plot	All	Select
7	input_spectra	Image	72800 X 4	Header	Image		Table	
8	input_ivar	Image	72800 X 4	Header	Image		Table	
9	Inputinfo	Binary	28 cols X 4 rows	Header	Hist	Plot	All	Select
10	CCF	Image	4000	Header	Plot		Table	
11	SINGLEORDER1	Image	6700	Header	Plot		Table	
12	SINGLEORDER2	Image	6700	Header	Plot		Table	
13	SINGLEORDER3	Image	6700	Header	Plot		Table	
14	SINGLEORDER4	Image	6700	Header	Plot		Table	
15	SINGLEORDER5	Image	6700	Header	Plot		Table	
16	SINGLEORDER6	Image	6700	Header	Plot		Table	
17	SINGLEORDER7	Image	6700	Header	Plot		Table	
18	SINGLEORDER8	Image	6700	Header	Plot		Table	
19	SINGLEORDER9	Image	6700	Header	Plot		Table	

Questions?

(Credit: Shutterstock)

Photomultipliers

- Once widely used for photometry; still used in neutrino and cosmic-ray detectors (Cherenkov light)
- One aperture (one pixel)
- Each photon detected as a burst
- Photon releases one electron in the cathode; accelerated in the electric field
- The it strikes a secondary emitter where secondary electrons are emitted
- Final pulse may contain 10^6 electrons for each photon



(Kitchin 2003)

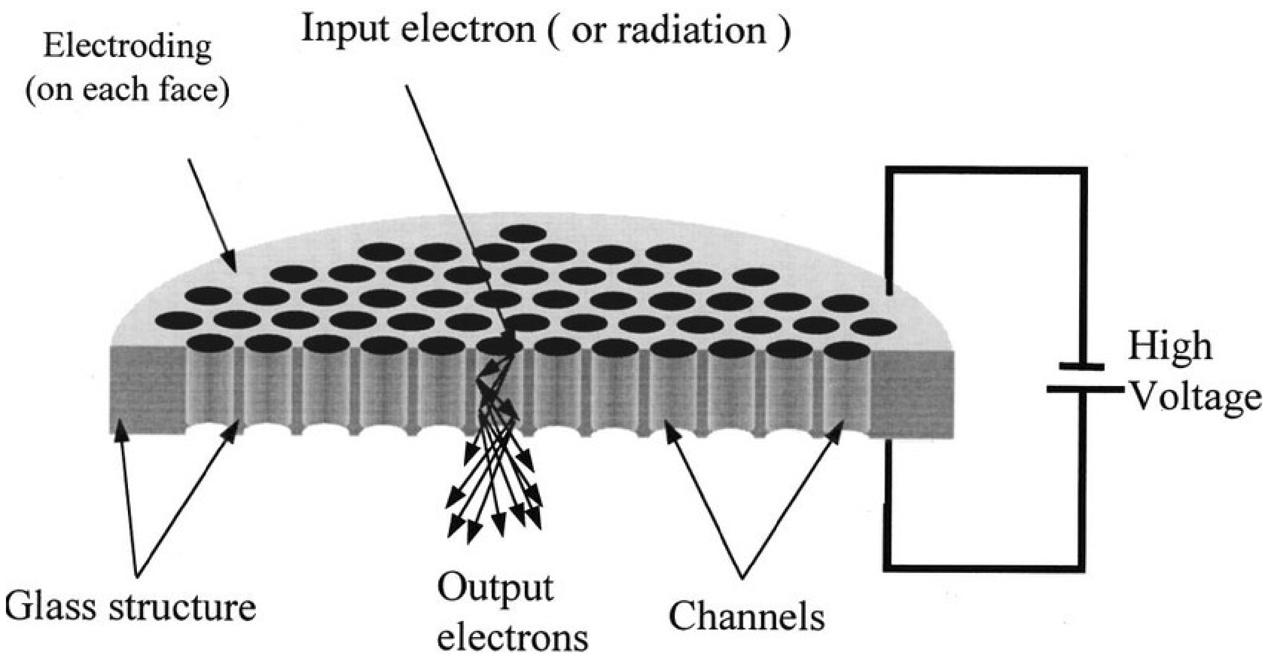
Table 1.1.3. Photoelectron emitting substances.

Substance	Long wavelength cut-off point (nm)
Sodium chloride (NaCl)	150
Potassium bromide (KBr)	155
Rubidium iodide (RbI)	185
Cuprous chloride (CuCl)	190
Caesium iodide (CsI)	200
Copper/beryllium (Cu/Be)	200
Copper iodide (CuI)	210
Rubidium telluride ($RbTe_2$)	300
Caesium telluride (Cs_2Te)	350
Caesium antimonide ($Cs_{2.9}Sb$)	600–700
Bi-alkali ((K_2Cs)Sb)	670
Tri-alkali ((Cs) Na_2KSb)	850
Gallium arsenide (GaAs (Cs))	1000
Silver/oxygen/caesium (Ag/Cs_2O)	1000–1100
Secondary electron emitting substances	
Beryllium oxide (BeO (Cs))	
Caesium antimonide (Cs_3Sb)	
Gallium phosphide (GaP (Cs))	
Magnesium oxide (MgO (Cs))	
Potassium chloride (KCl)	
Silver/magnesium (Ag/Mg)	

(Kitchin 2003)

Micro channel plate

- Multi-Anode Micro-channel Arrays (MAMAs)
- Thin glass plate with tiny holes (~10 μm)
- Top has a negative potential and is coated with a photoelectron emitter substance
- The electrons are accelerated downwards
- Collisions with the walls release further electrons, multiplying the signal
- The burst can then be detected by another method



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