# Instruments

Observational Astronomy
Laboratory of Astrophysics

# Instruments & detectors

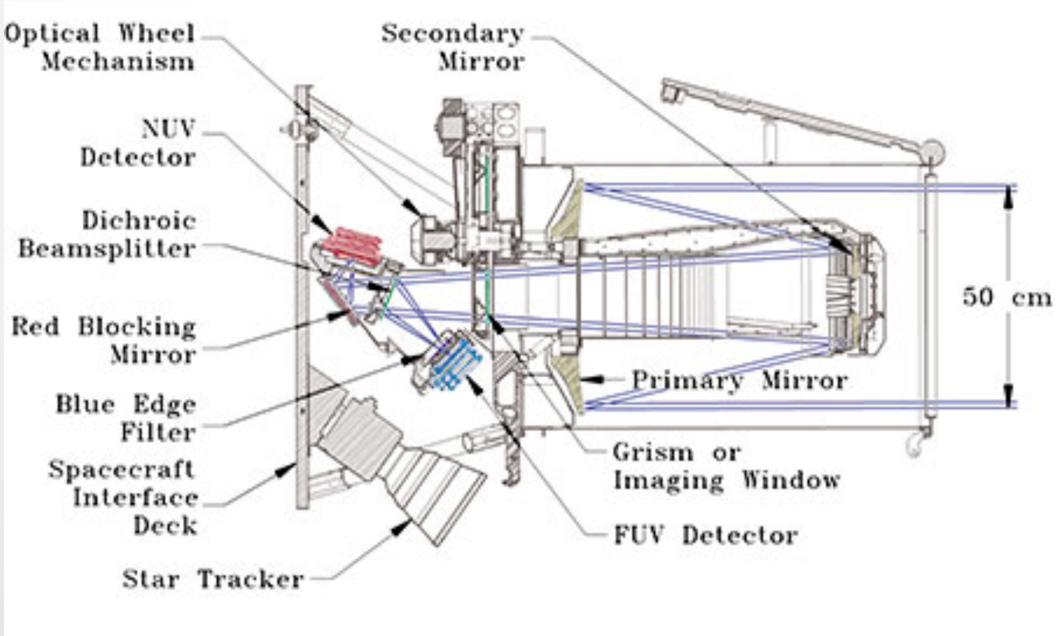
Why do we need instruments?

- detect the light signal
- extract specific information from it
- transform it to other format (e.g. digital)

**Detectors**: human eye, photography, CCD cameras and filters, spectrographs (prisms, gratings), polarimeters, etc.

# Instruments & detectors

A telescope can have many detectors at different foci.



GALEX

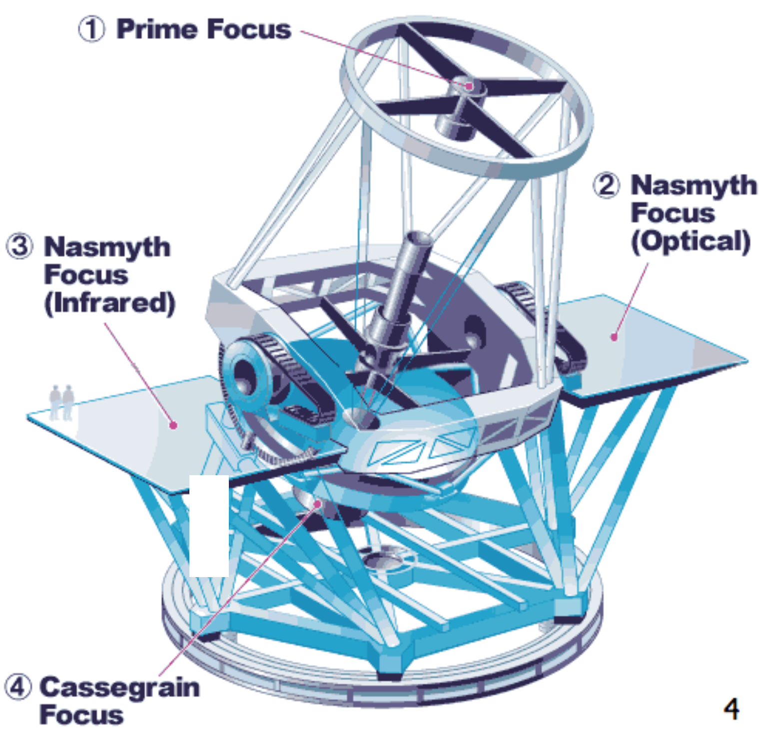


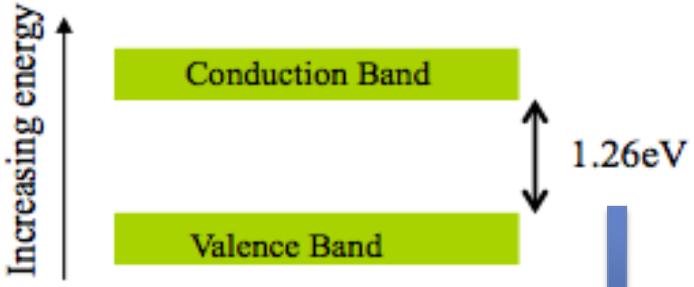
Illustration by Takaetsu Endo, taken from Nikkei Science 1996

# Optical detectors: CCD

**Charged couple devices (CCD)**:

- conversion of photons into electrons
- made of a grid of pixels
- made of semiconductors (silicon)

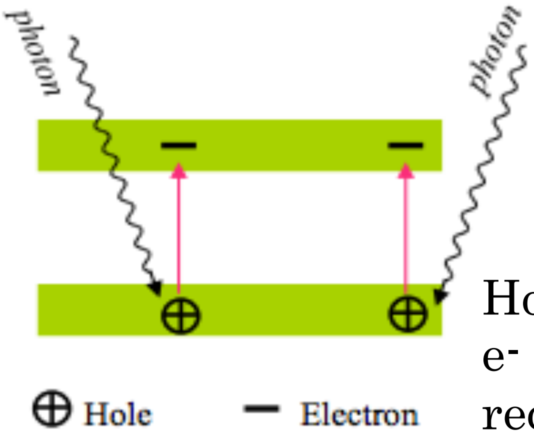
Atoms in a silicon crystal have electrons arranged in discrete energy bands.



CCD only sensitive to shorter wavelengths

$\lambda = 1\mu m$

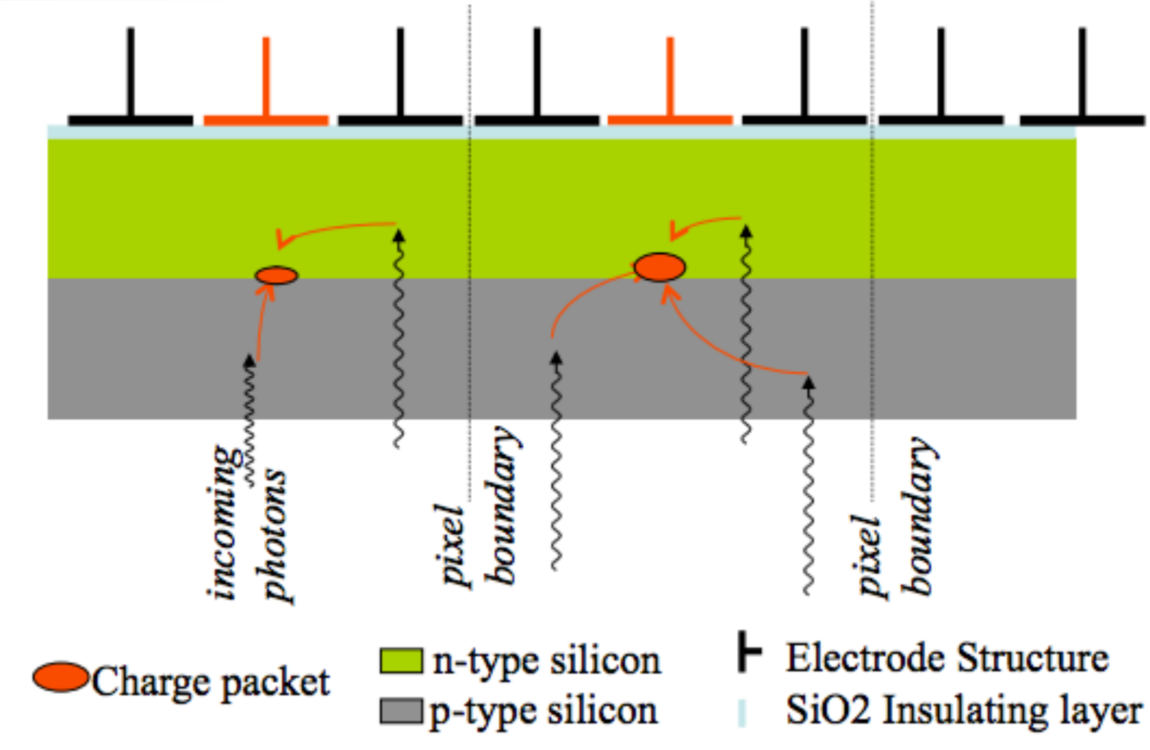
Most e- are in valence band until they absorb a photon (photoelectric effect)



Hole and e- quickly recombine

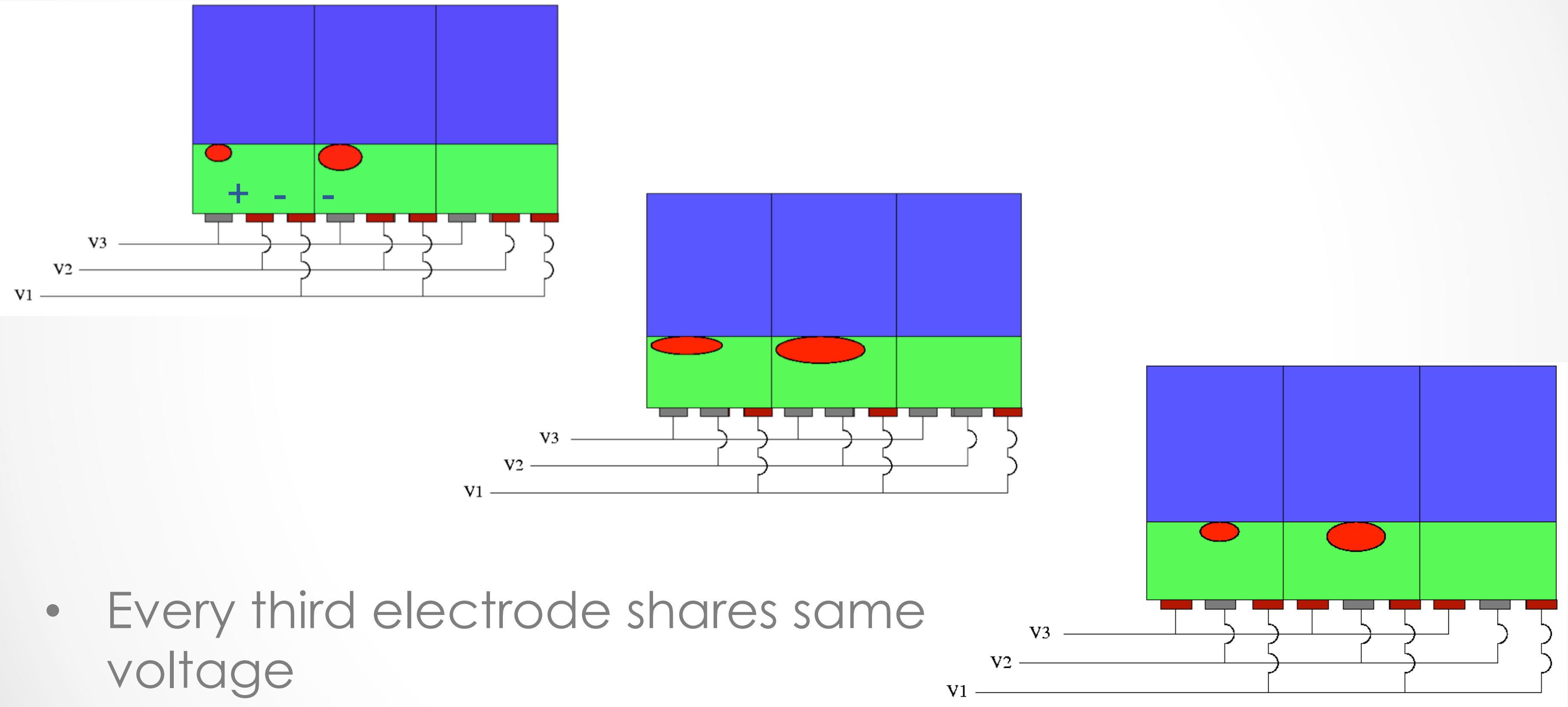
# Optical detectors: CCD

## Charged couple devices (CCD):



- Photons entering CCD create electron-hole pairs
- Electrons are attracted to positive potential creating ¨charge packets¨
- Each packet corresponds to one pixel

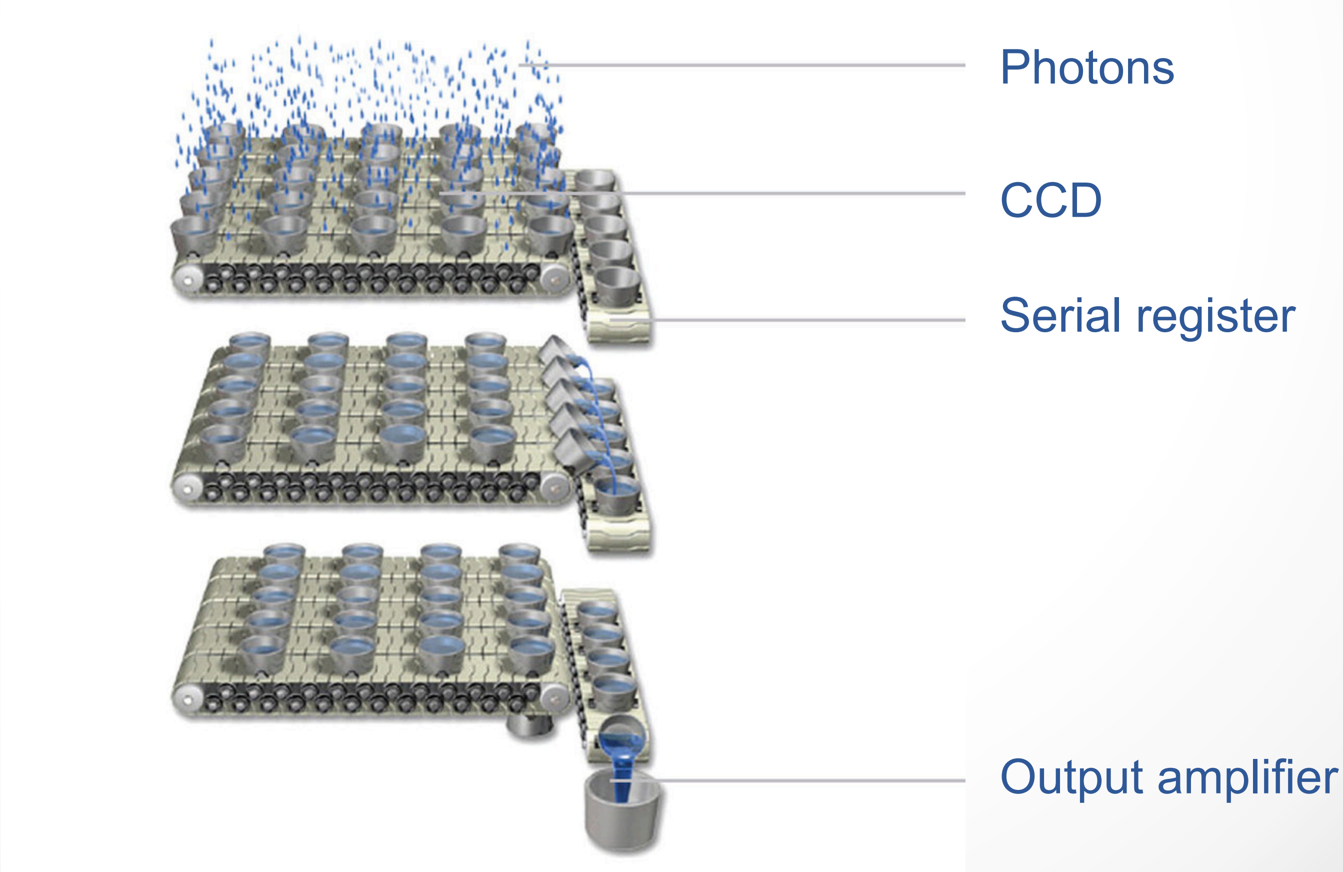
# Optical detectors: CCD



- Every third electrode shares same voltage
- Charge is moved by modulating voltages on electrodes on surface of CCD

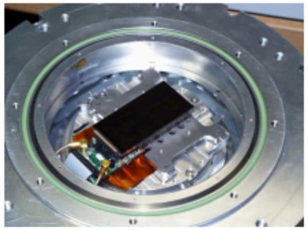
# CCD

## Conveyor belt analogy

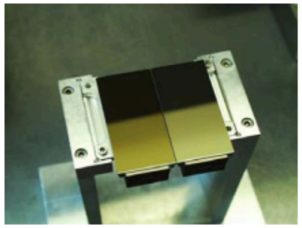


# CCD

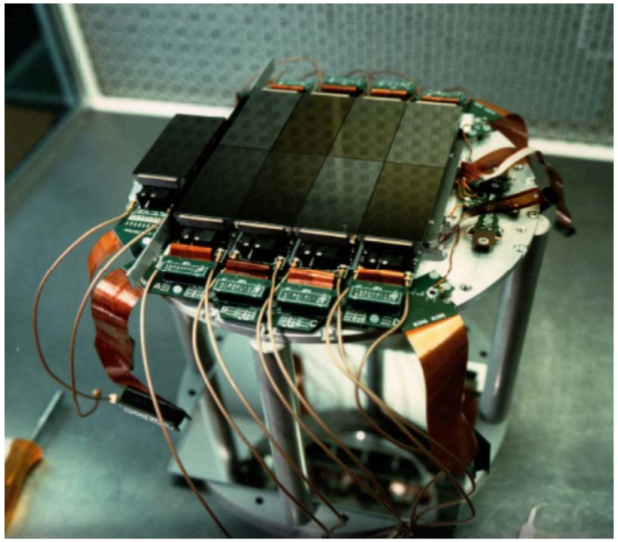
## **CCD**: Examples



Single E2V
2kx4k CCD



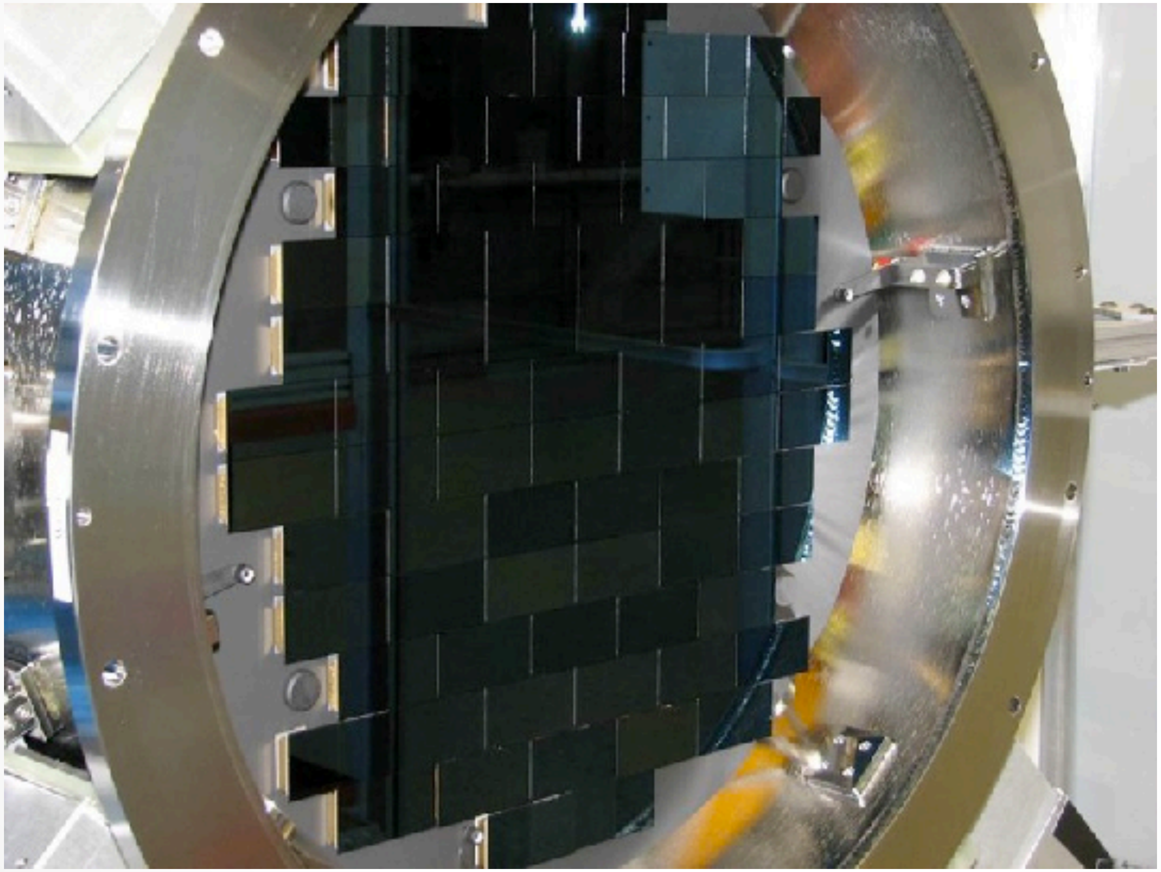
Mosaic of two
E2V 2kx4k CCD



Wide Field Imager
8k x 8k mosaic, 72 million pixels

# CCD

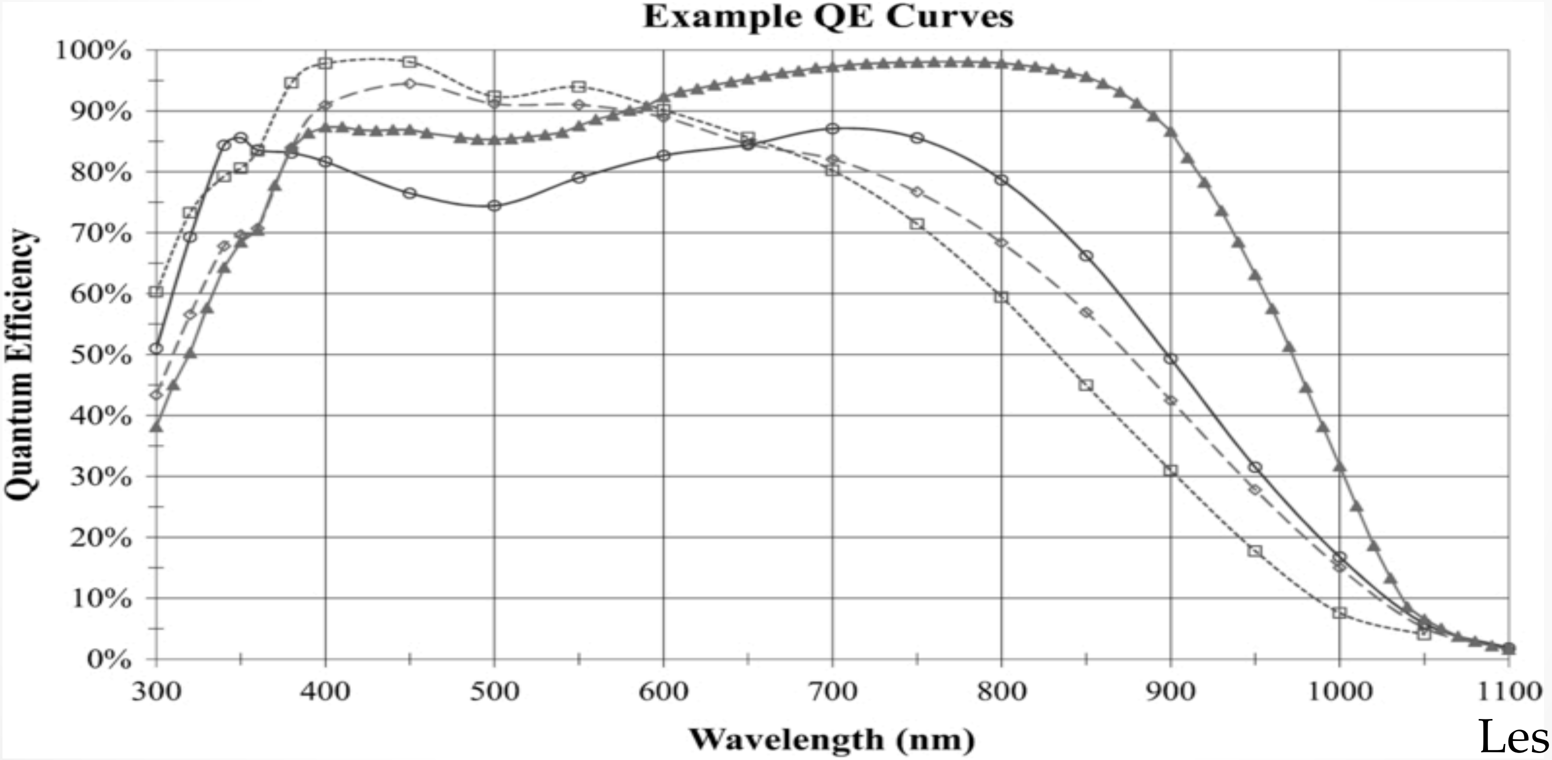
## **CCD**: Examples



DECam
62 CCDs 520 million pixels

# CCD

**Quantum efficiency (QE):** effectiveness to produce electron charge from photons



Lesser (2015)

Astronomical CCDs have QE~90-100%

# CCD

**Quantum efficiency (QE):** effectiveness to produce electron charge from photons

**ADU**: Analog to digital units. Each pixel has some counts of ADU.

**Gain:** amplification of initial number of pixel photoelectrons into final ADU counts:
gain = # of electrons/ #counts [$e^-$/ADU]

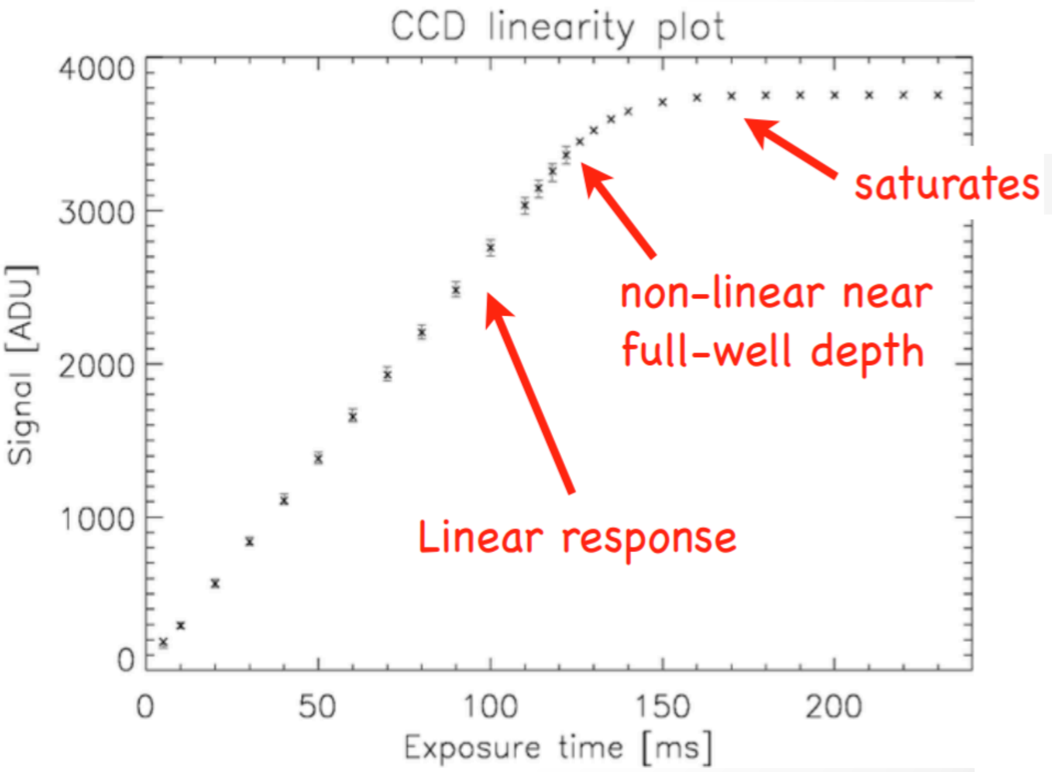
This is chosen so that maximum ADU matches the Full well depth (maximum charge a pixel can hold).

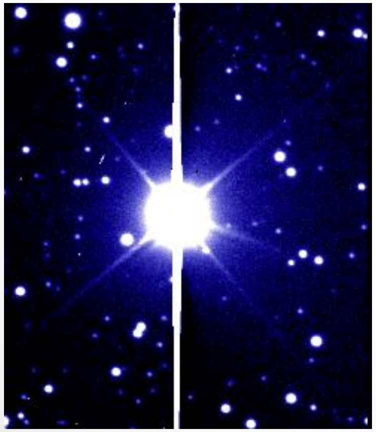
# CCD linearity

**Linearity** of response: amount of photons is linearly proportional to signal over large range

**Saturation**: max. number of electrons in potential well of pixel is reached

➔ non-linear response





# Sources of noise

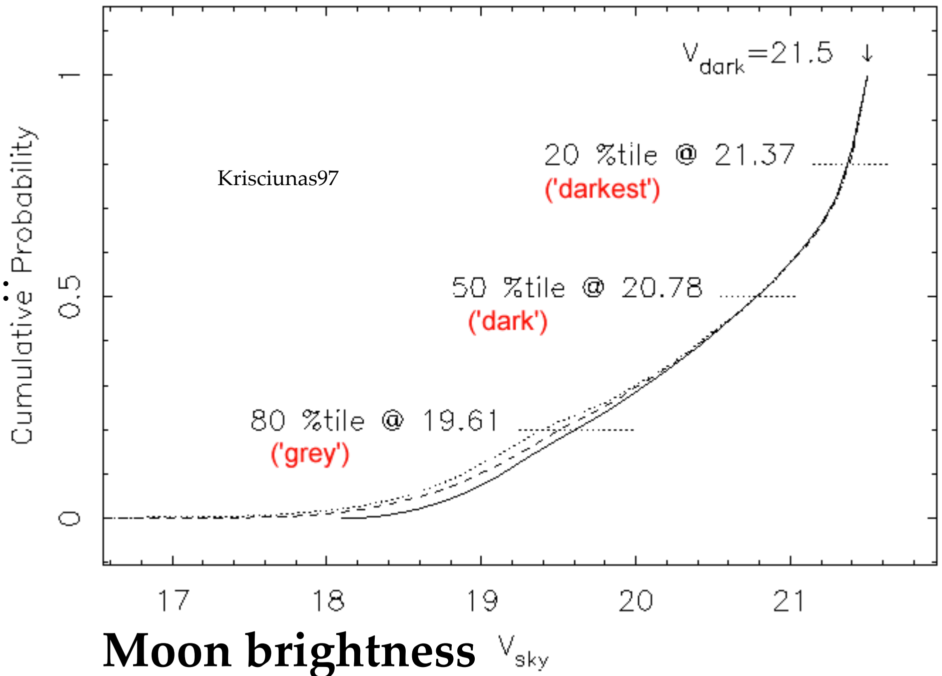
- **Shot noise or Poisson noise**: statistical fluctuations of discrete particles of charge/light. At high $N_{*}$, target counts [$e^{-}$/s/pix]:

$$\sigma_{*} \approx \sqrt{N_{*} \times Q_{E} \times t}$$

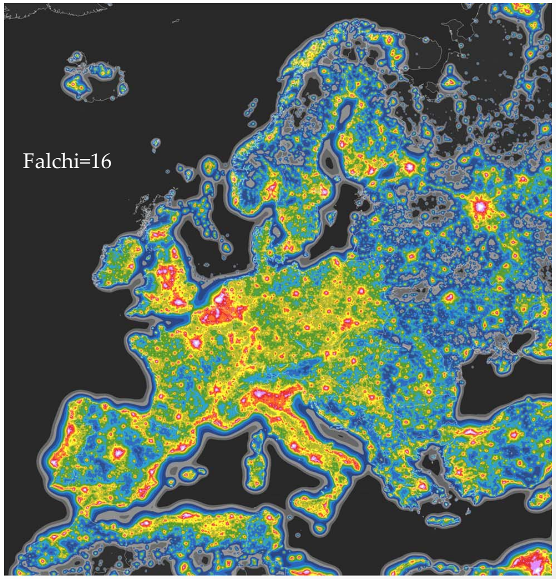
# Sources of noise

- **Shot noise or Poisson noise**: statistical fluctuations of discrete particles of charge/light. At high $N_*$, target counts [e⁻/s/pix]: $\sigma_* \approx \sqrt{N_* \times Q_E \times t}$
- **Sky or background noise**: Poisson noise from the sky, with the count rate $S$ [e⁻/s/pix] (depends for example on moon phase or light pollution): $\sqrt{S \times Q_E \times t}$

Dark sky: 22mag/ arcsec^2



**Moon brightness**



**Light pollution**

Lisbon ~10 x dark sky

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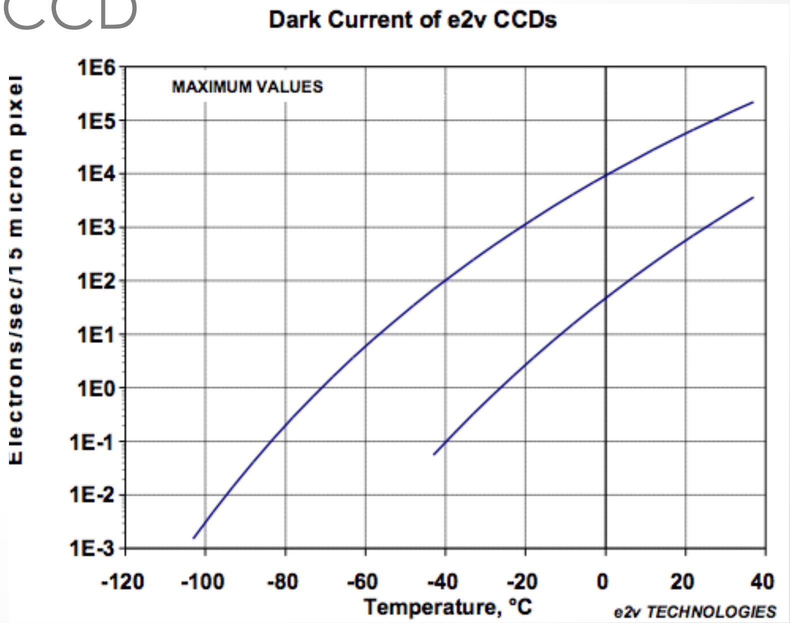
- **Sky or background noise**: noise from the sky, with the count rate $S$ [$e^{-}$/s/pix] (depends for example on moon phase or light pollution):

$$\sqrt{S \times Q_{E} \times t}$$

- **Dark current:** thermal fluctuations: some electrons jump potential well of CCD

- depends on temperature
- is proportional to time.
- With $I_D$ [e/s/pix] as the dark current:

$$\sqrt{I_{D} \times t}$$



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$$\text{total noise}=\sqrt{\sigma_*^2 + \sigma_{sky}^2 + \sigma_{dark}^2 + RON^2}$$

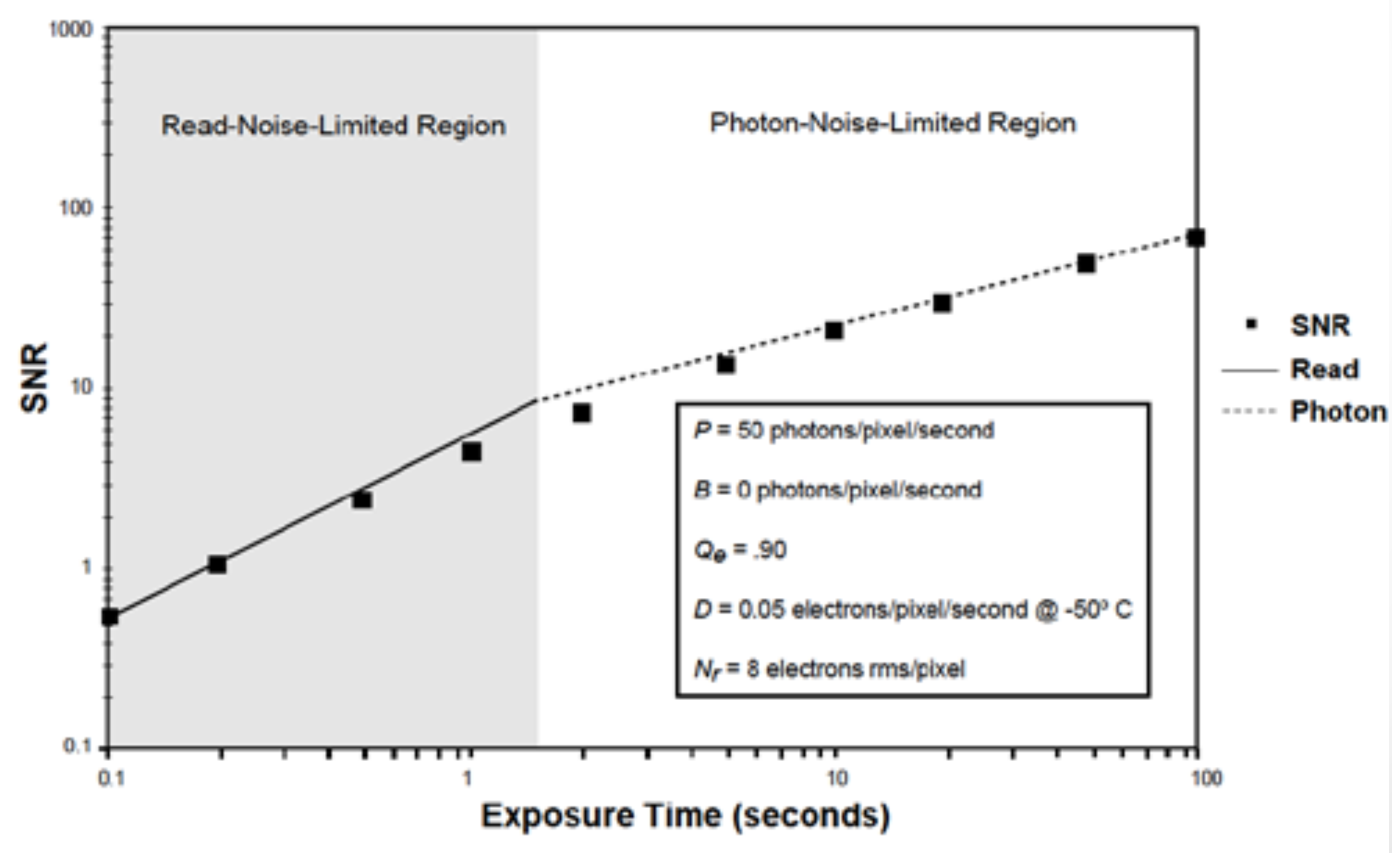
# Signal-to-noise

$$SNR = \frac{\overbrace{N_* Q_E t}^{\text{signal}}}{\sqrt{\left(\underbrace{N_*}_{\text{shot}} + \underbrace{S}_{\text{sky}}\right) Q_E t + \underbrace{I_D t}_{\text{dark}} + \underbrace{N_R^2}_{\text{readout}}}}$$

**Note that N*,S and QE are a function of wavelength!!**

# Signal-to-noise

$$SNR = \frac{N_* Q_E t}{\sqrt{(N_* + S) Q_E t + I_D t + N_R^2}}$$



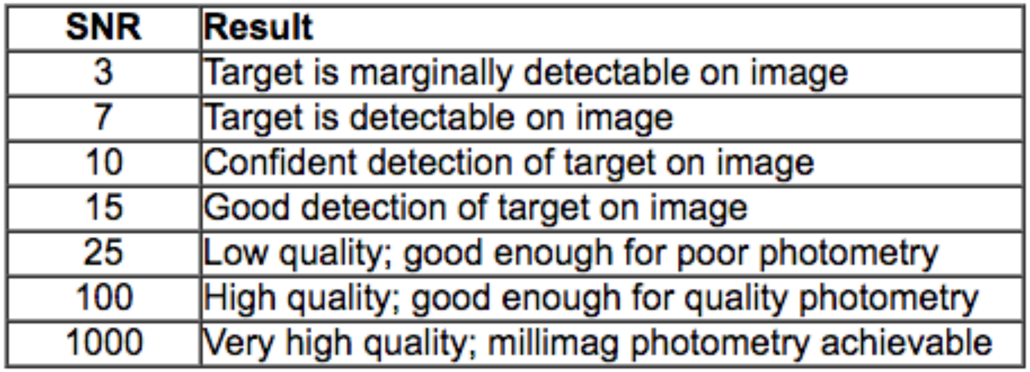
# Exposure time calculators

Given your telescope and detector specifications, and a given target you want to observe, what is the integration time to achieve a certain signal?

- Given a magnitude $m_*$ of an object (and a reference star $m_{ref}$ and $N_{ref}$):

$$N_* = N_{ref} \times 10^{-\left(m_* - m_{ref}\right)/2.5}$$

- Solve the *SNR* equation for exposure time *t*



| SNR | Result |
|---|---|
| 3 | Target is marginally detectable on image |
| 7 | Target is detectable on image |
| 10 | Confident detection of target on image |
| 15 | Good detection of target on image |
| 25 | Low quality; good enough for poor photometry |
| 100 | High quality; good enough for quality photometry |
| 1000 | Very high quality; millimag photometry achievable |

Hands-on!

# FORS2-VLT

**VLT Telescope characteristics:**

- Ritchey-Chretien telescope
- Aperture diameter: 8m
- Secondary diameter: 1m
- Focal length: 120m
- Alt-az mount

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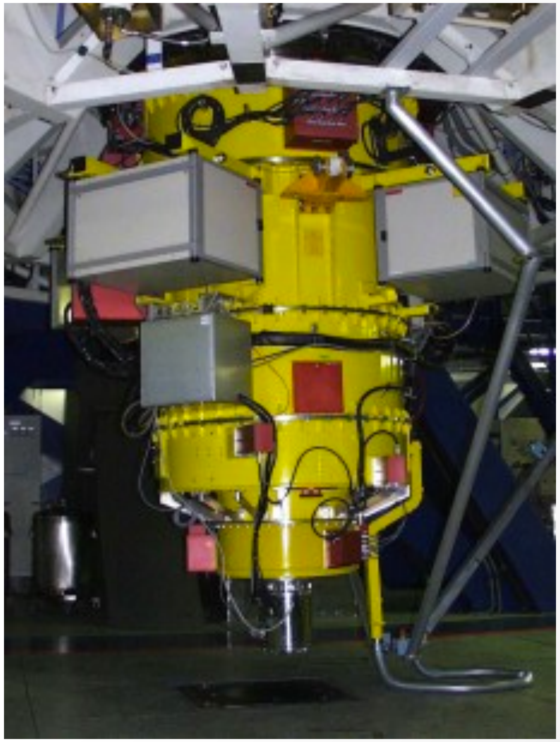
**FORS2 Instrument characteristics:**

❑ Observing modes: imaging, spectroscopy, polarimetry
❑ Size: two CCDS of 2000 x 4000 pixel
❑ Pixel size: 15 x 15 $\mu$m
❑ Field of view: 6.8’ x 6.8’
❑ Focal length: 1233mm



Hands-on!

# FORS2-VLT

1) **How long do we need to expose at VLT with the imaging mode of FORS2 to obtain S/N = 10,50,100 for:**

- SU Cyg (V=7mag) - variable, VW Hya (V=12mag) – eclipsing binary, ULAS J1342+0928 (U=20.3mag) - quasar
- Dumbbell M27 (V=7.5, A=8’.0x5’.6) – planetary nebula, Andromeda - M31 (V=17, A=3.167°x1°) - galaxy, Orion nebula, NGC-2362, NGC-7098

Use of exposure time calculator:

https://www.eso.org/observing/etc/

Hands-on!

# FORS2-VLT

2) **How would the images look like in the field of view of FORS2 for same objects:**

- SU Cyg (V=7mag) - variable, VW Hya (V=12mag) – eclipsing binary, ULAS J1342+0928 (U=20.3mag) - quasar
- Dumbbell M27 (V=7.5, A=8'.0x5'.6) – planetary nebula, Andromeda - M31 (V=17, A=3.167°x1°) - galaxy, Orion nebula, NGC-2362, NGC-7098

Use of field-of-view:

https://observability.date/