# TP d’observation M1

# Telescopic observations with CCD detectors

**Stéphane Erard**

v. 14/1/2024

# Some references

**Howell S. B.** (2000) Handbook of CCD astronomy (Cambridge)
**Martinez P. et Klotz A.** (1994) Le guide pratique de l'astronomie CCD (Adagio)
**Chromey, F.R.** (2016) To measure the sky (Cambridge, 2nd edition)

**Léna P.** et al (1996) = Observational Astrophysics (Springer)
= Méthodes physiques de l'observation (CNRS-Interéditions, 3rd ed)
**Gallaway** M. (2020) An Introduction to Observational Astrophysics (Springer)
**Glass I.S.** (1999) Handbook of infrared astronomy (Cambridge)
**Other docs from Master degree**:
https://media4.obspm.fr/portail/
http://ufe.obspm.fr/Ressources-multimedia
http://media4.obspm.fr/ (may require registration)
+ see **M1 lectures** (instrumentation module) + See Meudon library

**Docs and tuto applets** (from suppliers)
E.g. http://www.hamamatsu.com/us/en/technology/innovation/index.html
https://lot-qd.de/en/products/imaging/
https://www.princetoninstruments.com/learn/camera-fundamentals

**Other docs related to the present lecture:**
maybe somewhere under http://moodle.psl.eu

# Images

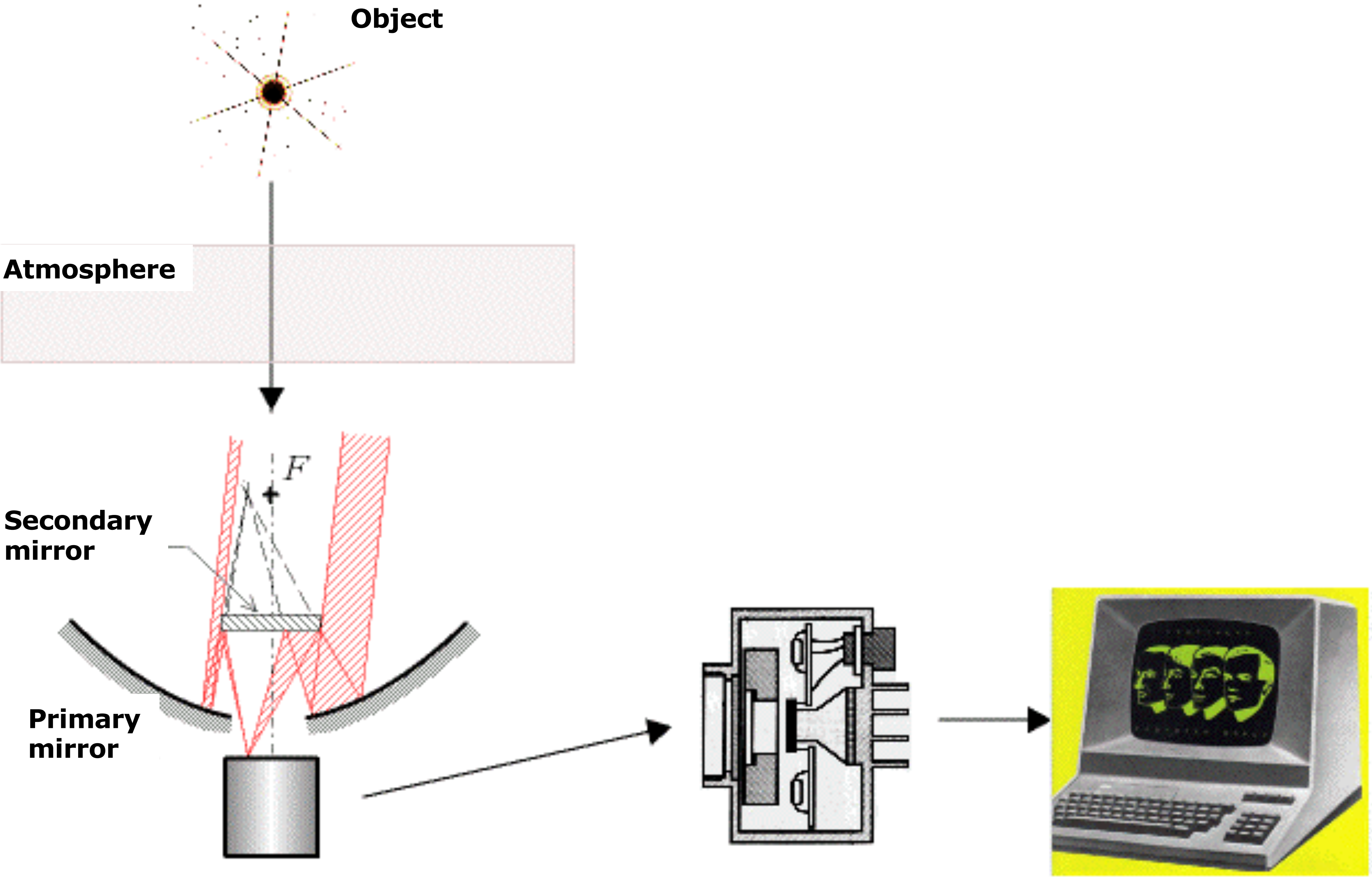
## References of images used here:

http://www.astrosurf.com/cidadao/
+ other sites in astrosurf
https://hantsastro.org.uk/gallery/showcat.php?cat=spectroscopy
http://www.cis.rit.edu/~ejipci/Reports/mcc_DIP_workshop.pdf
http://astrophoto.fr/obstruction_fr.html
http://users.polytech.unice.fr/~leroux/
M1/M2 lectures on instrumentation / image formation (M1 by S. Lacour)
Cours Optique et télescopes, on various web sites (Riaud et al)
LHIRES doc: https://www.shelyak.com/produit/lhires-iii/
Spectro: http://www.astrosurf.com/buil/us/spe2/hresol4.htm

*Optical* :
T1m / Meudon
T80 & T120 / OHP
T1m & TBL / OMP
AMIE / Smart-1, etc…

*Infrared*:
NACO / VLT
SofI / NTT
TBL / OMP
VIRTIS / Rosetta

# Acquisition process in astronomy imaging



**Object**

**Atmosphere**

**Secondary mirror**

**Primary mirror**

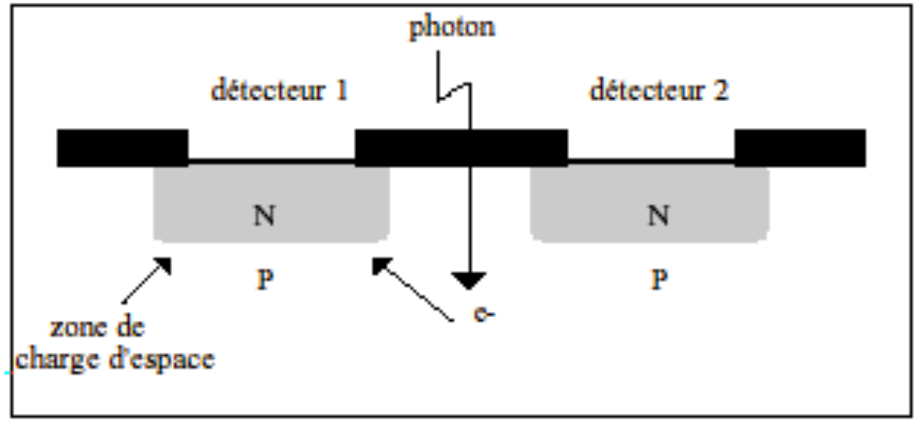
**Telescope**

**Camera & filters**

**Computer**

# Detectors in UV-Optical-NIR range

## Modern systems



- **photosensitive digital detectors**
(semiconductor photodiodes)

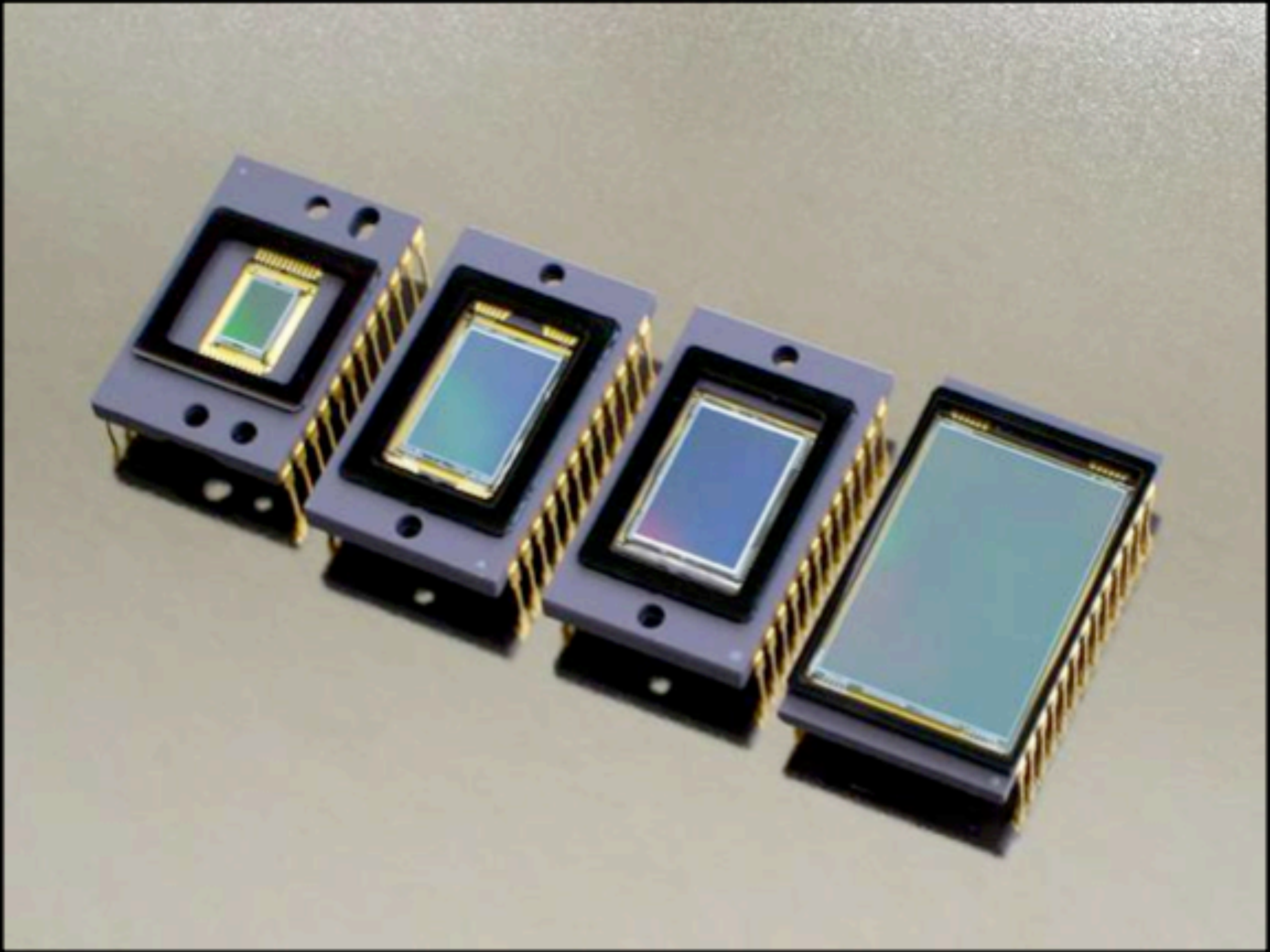
**Electric charges accumulate in each photosite, as a function of incident light flux**

- **Arrays of detectors, with readout and controling electronics**
**Sizes = 256 x 256 to 2048 x 2048** (up to 10000 x 10000 in 2020)

⇒ **CCD or CMOS in the optical range, equivalent systems (HgCdTe) in the IR range**
(with different readout circuits)

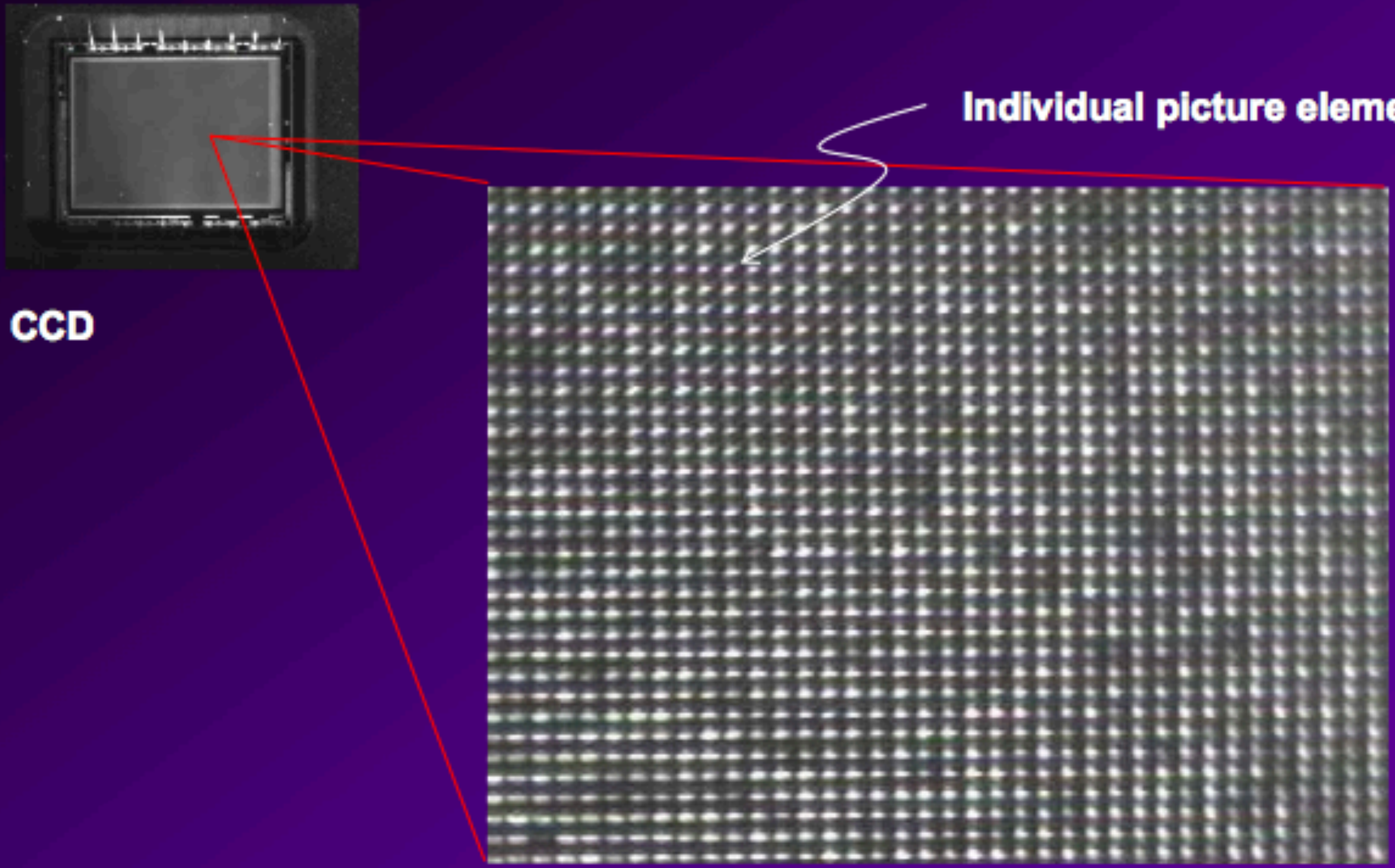
## Properties

- **Efficient** (50-90 % photons detected vs ~5 % for photographic plates)
- **Quick readout** (no chemical processing)
- **Wide spectral range** (UV —> 1 $\mu$m for CCD, 1 —> 6 $\mu$m for IR arrays)
- **Good linearity** (nb of charges $\propto$ nb of incident photons)



**Kodak Full Frame CCDs:** KAF-0402ME, KAF-1603ME, KAF-3200ME and KAF-6303E

# Magnified View of a CCD Array

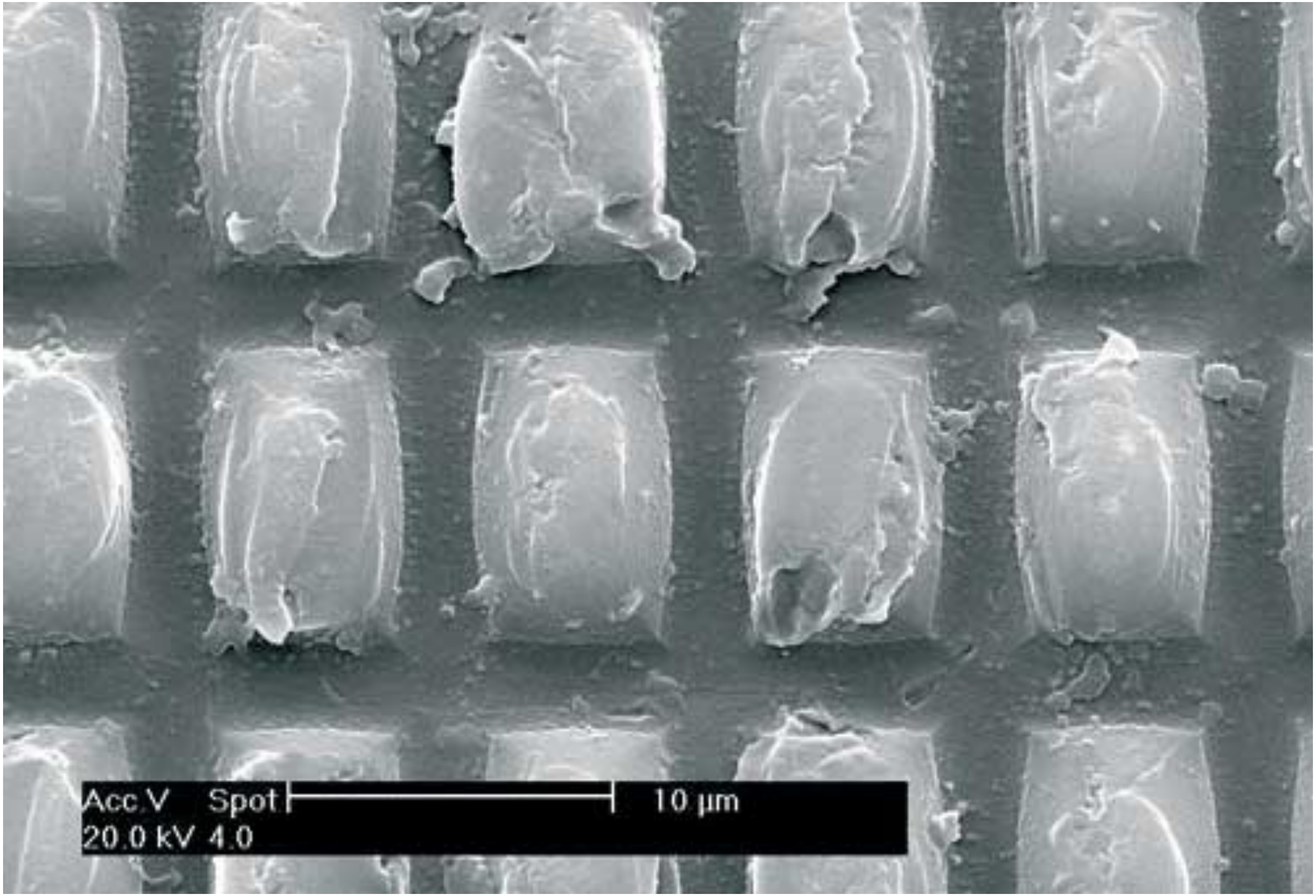


Individual picture element

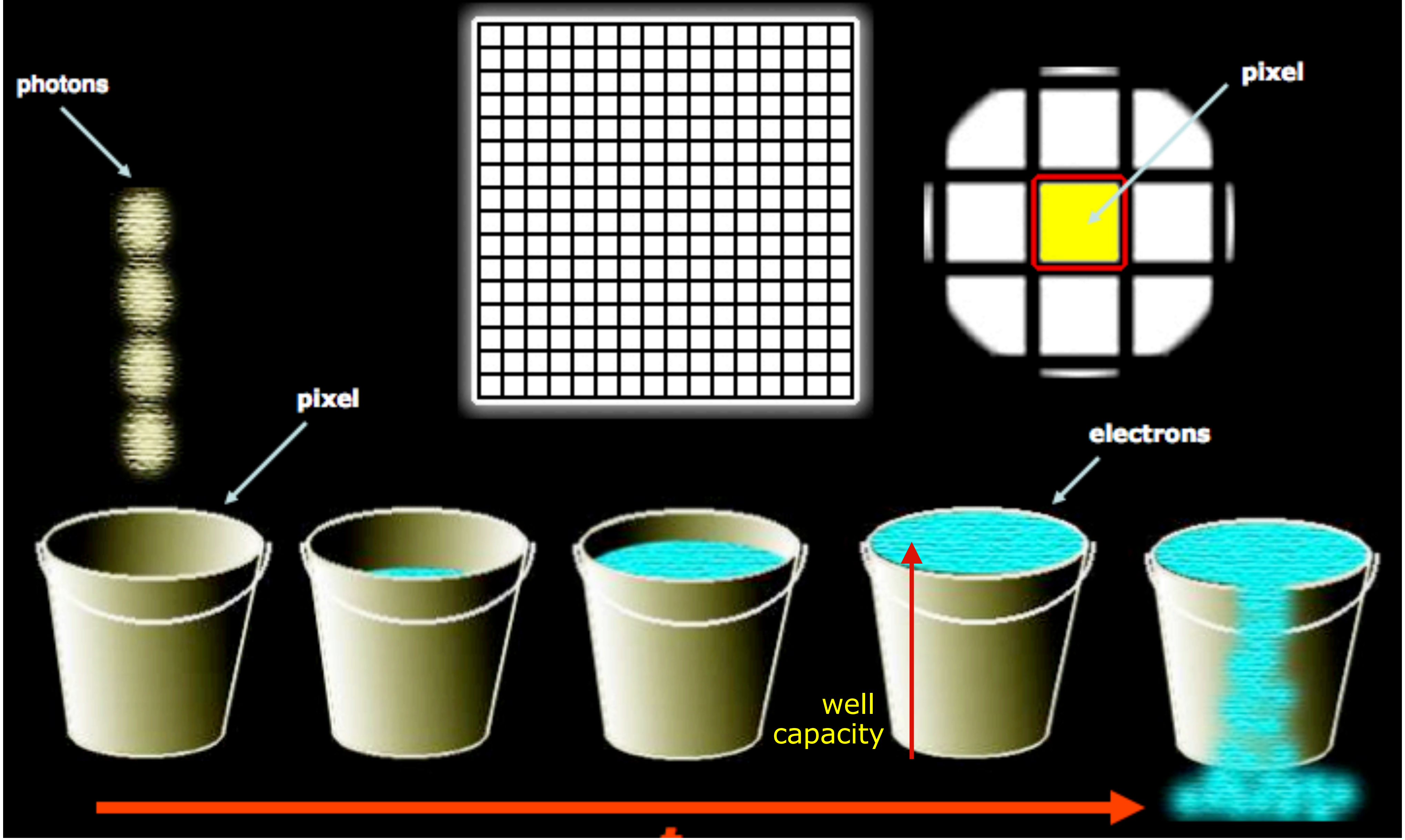
CCD

Close-up of a CCD Imaging Array

# Photosites

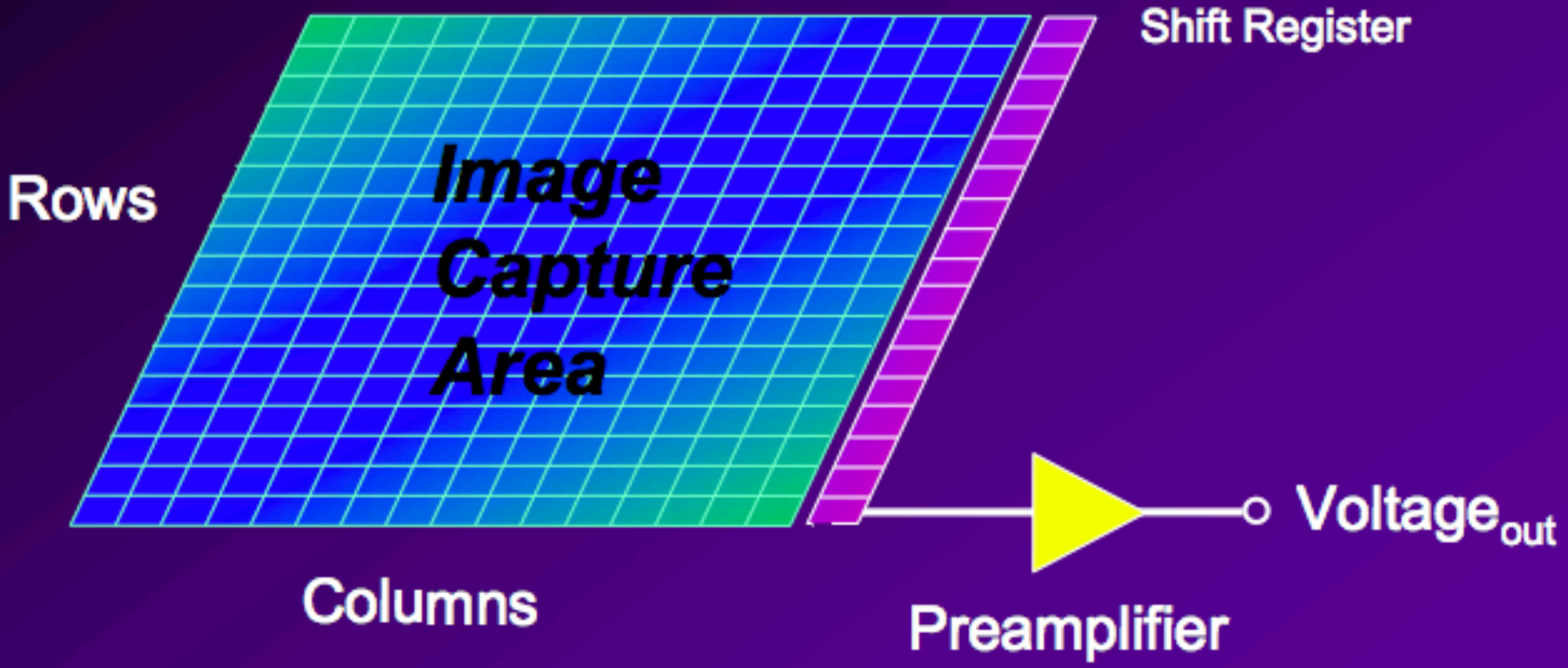


# What is a "CCD" ?



# Basic structure of CCD

Divided into small elements called pixels (*picture elements*).



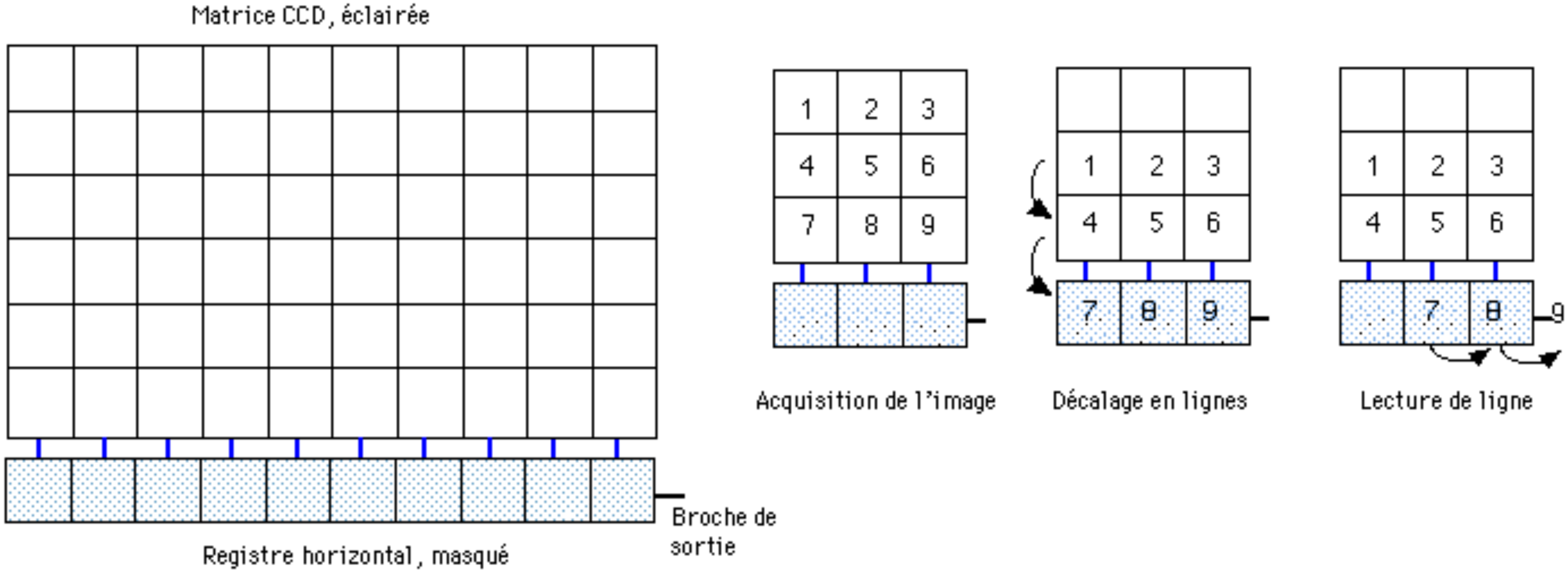
# Reading process in CCD

## Readout

**Control electronics => shift by line/row, then column**
**Tension on output pin is measured**
**Charges are evacuated and the array is reset simultaneously**
**Typical readout time ~ 1 s, which is long**

## Special modes

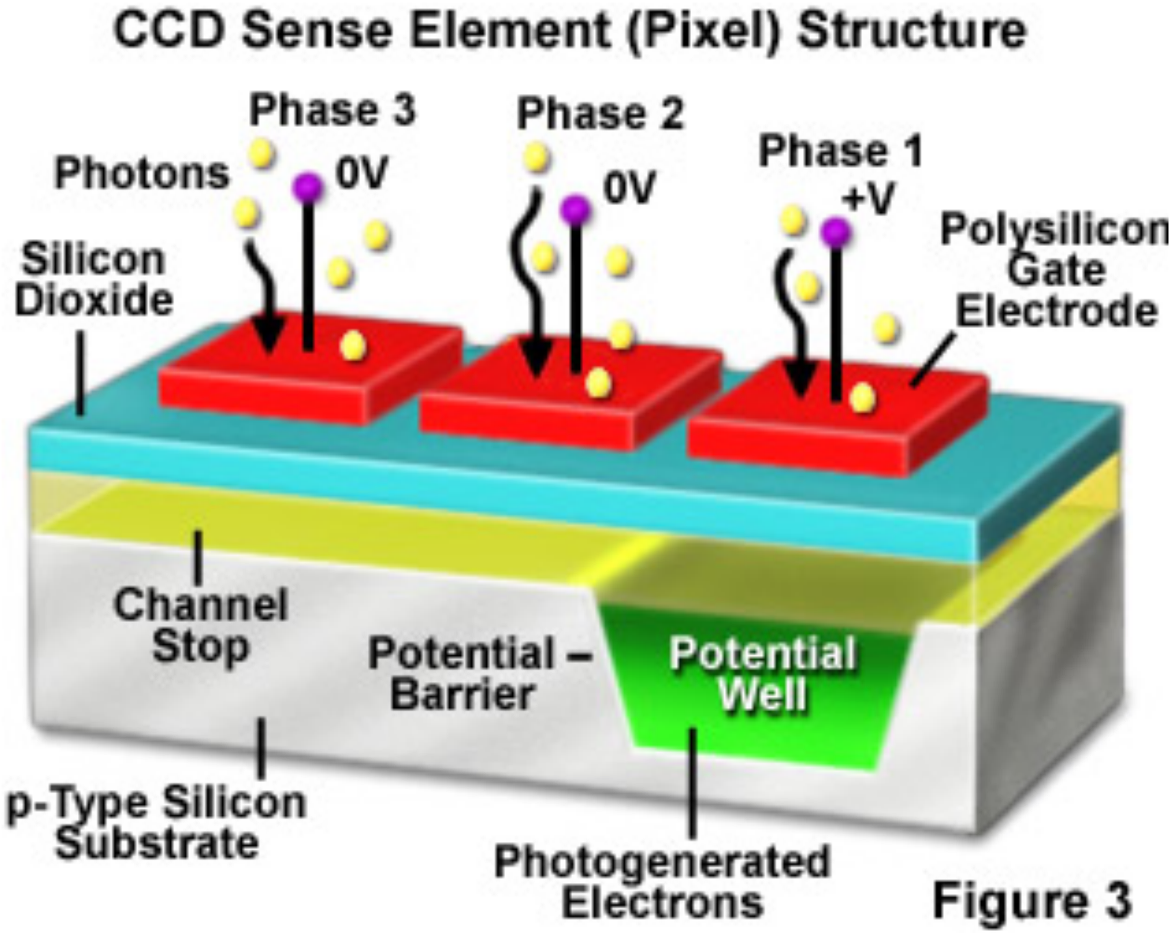
**Windowing (read only a part of the array)**
**Binning (read several pixels simultaneously, before digital conversion)**



# CCD digest

## Detection

**Incident photons generate electrons in the substrate, which are maintained in place during exposure**



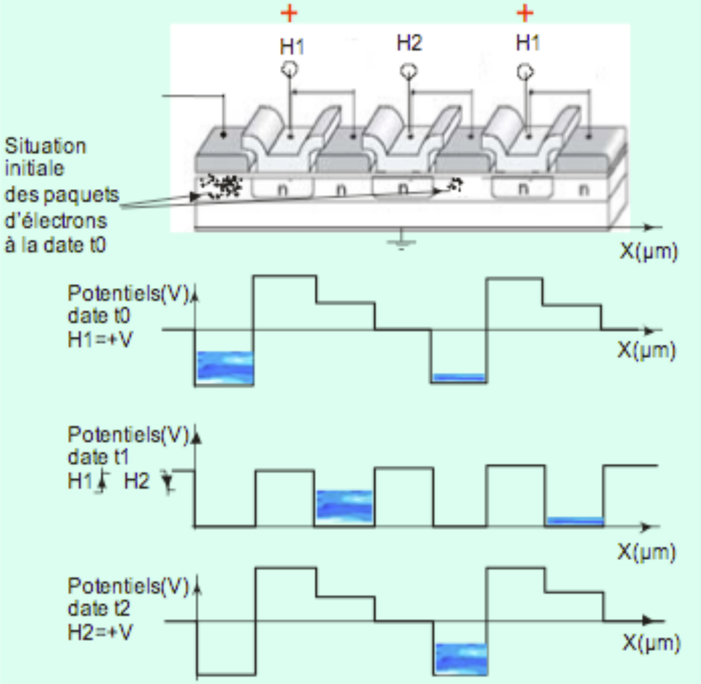
# CCD digest

## Readout

Charges are shifted by changing the potentials under the rows, in sync (=> clocking system)

Rows are shifted, then the output register alone is shifted pixel/pixel

Output current is measured on a pixel basis (analog readout)



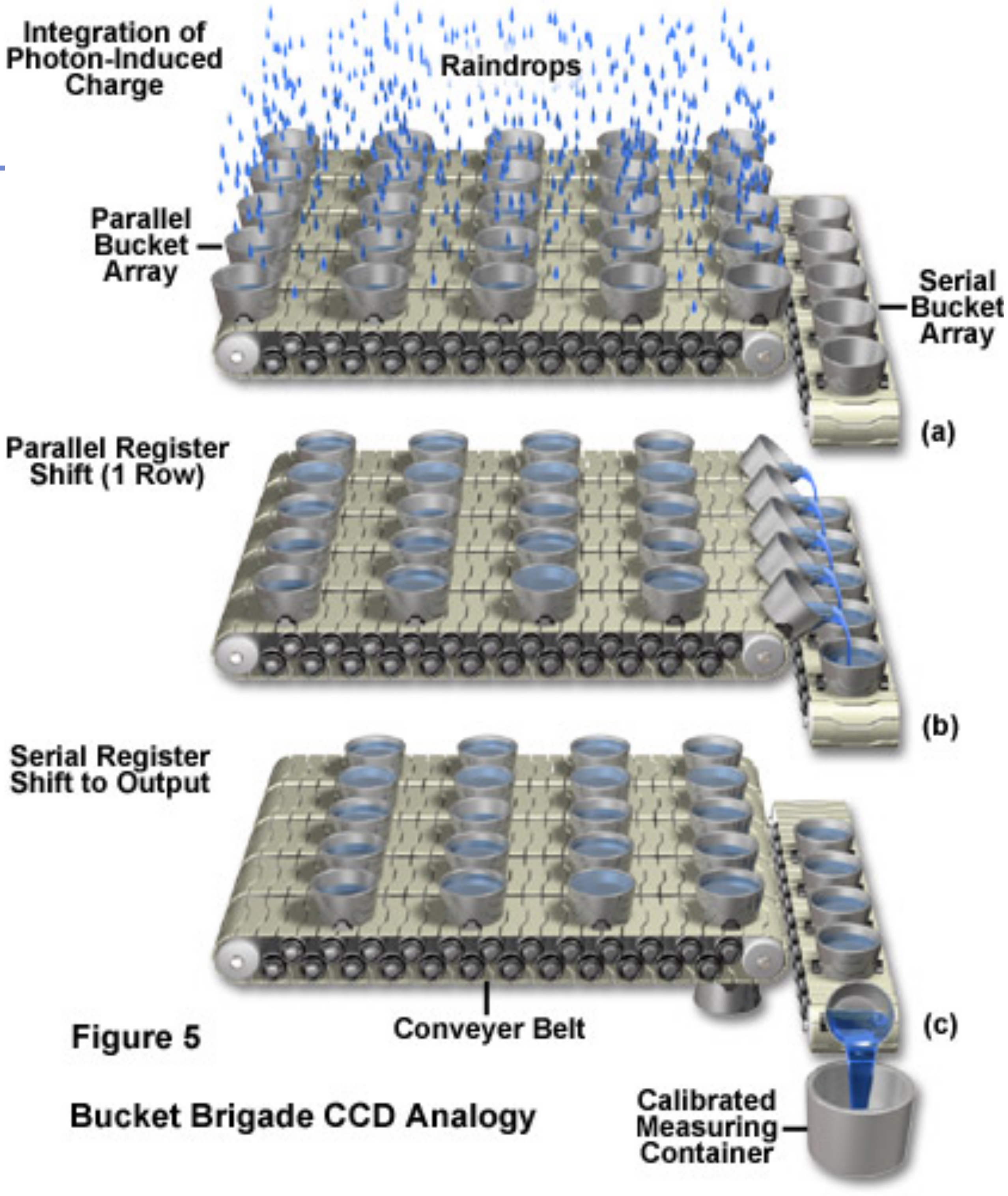
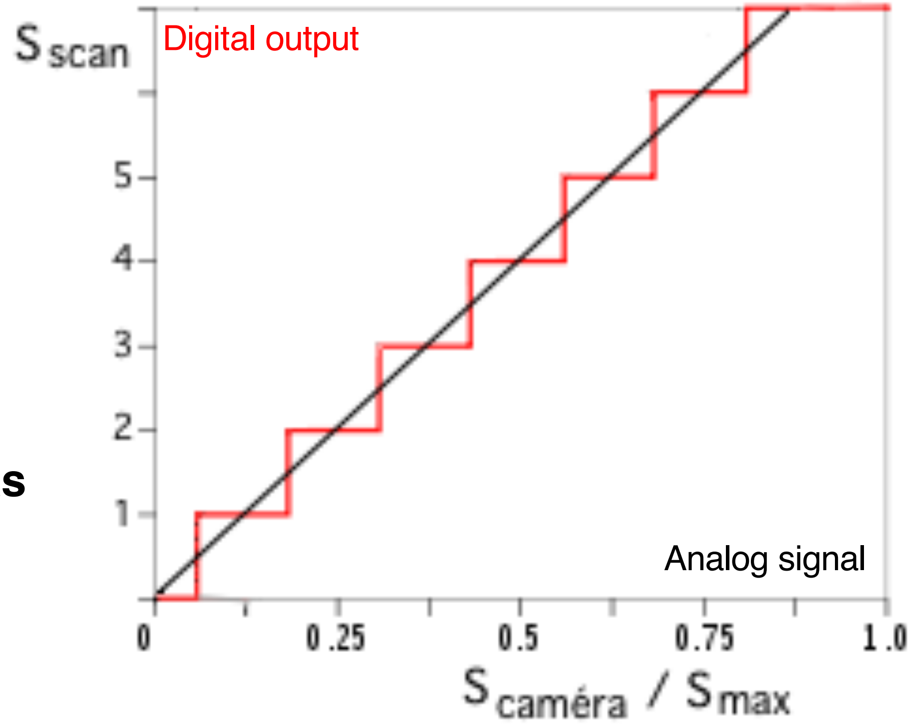


Figure 5

Bucket Brigade CCD Analogy

# CCD digest

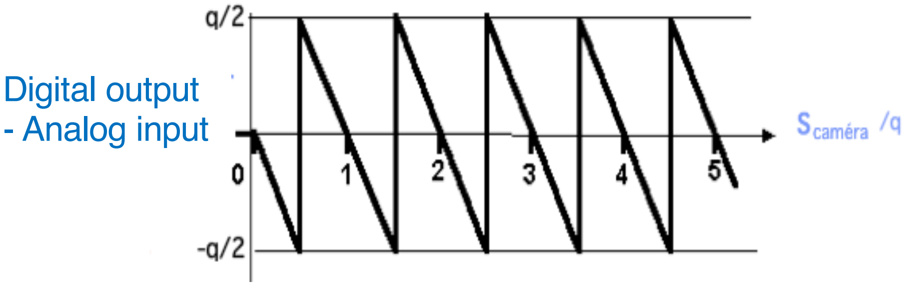
## Digitization (French: numérisation!)



**The ouput current is amplified and measured, then digitized with an Analog-to-Digital Converter (ADC)**
**Usual ramp resolution = 8-16 bits**

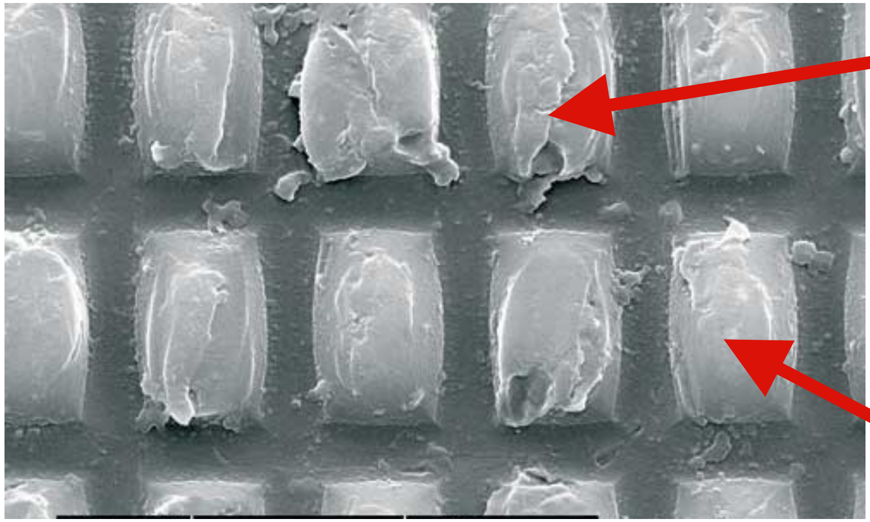
**With astronomy cameras, the digitized signal is then transferred to a computer and stored as a file (usually in FITS format)**
**1 image pixel <=> 1 detector pixel**

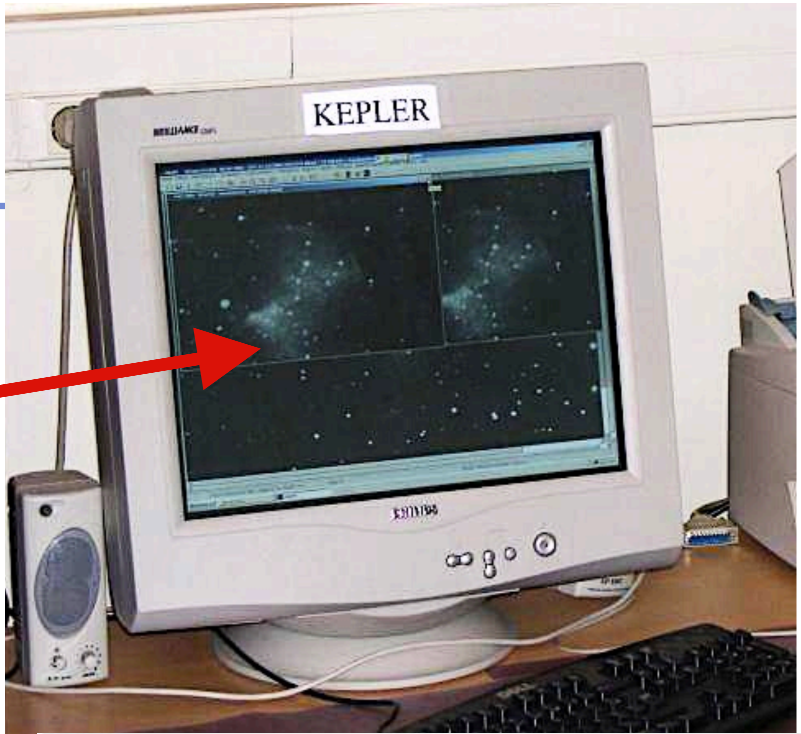
**The digitization process results in rounding errors, which can be represented as a noise**
(function of number of bits used)

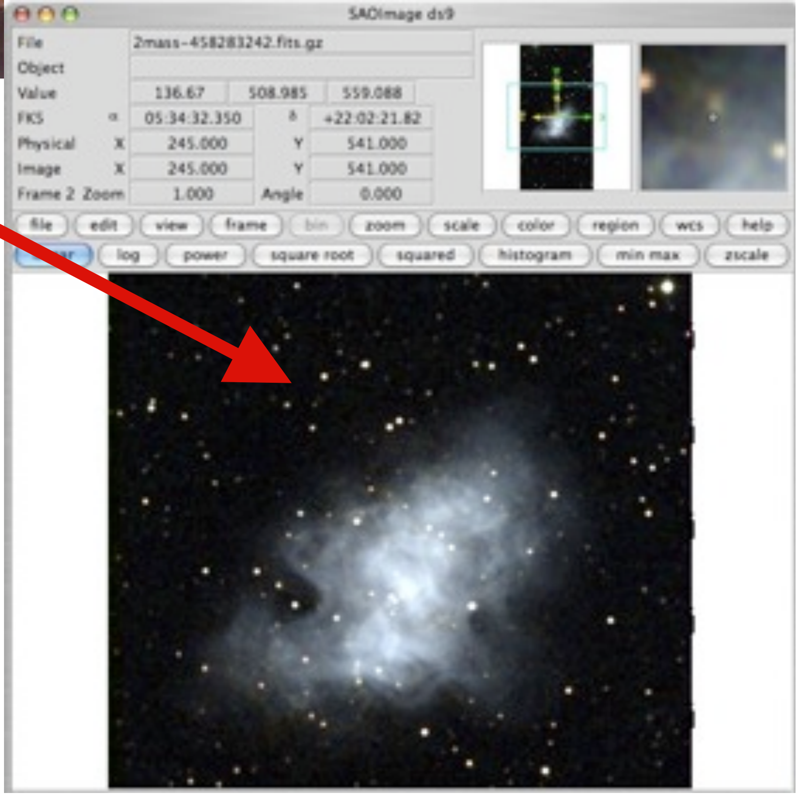


# Visualization of astronomy images

**Correspondence between**
**detector photosite ⇔ screen pixel**







| | | | | |
|---|---|---|---|---|
| File | 2mass-458283242.fits.gz | | | |
| Object | | | | |
| Value | 136.67 | 508.985 | 559.088 | |
| FK5 | α | 05:34:32.350 | δ | +22:02:21.82 |
| Physical | X | 245.000 | Y | 541.000 |
| Image | X | 245.000 | Y | 541.000 |
| Frame 2 Zoom | | 1.000 | Angle | 0.000 |

**Anything else implies resampling and loss of display quality**
(but may be required to see the complete image)

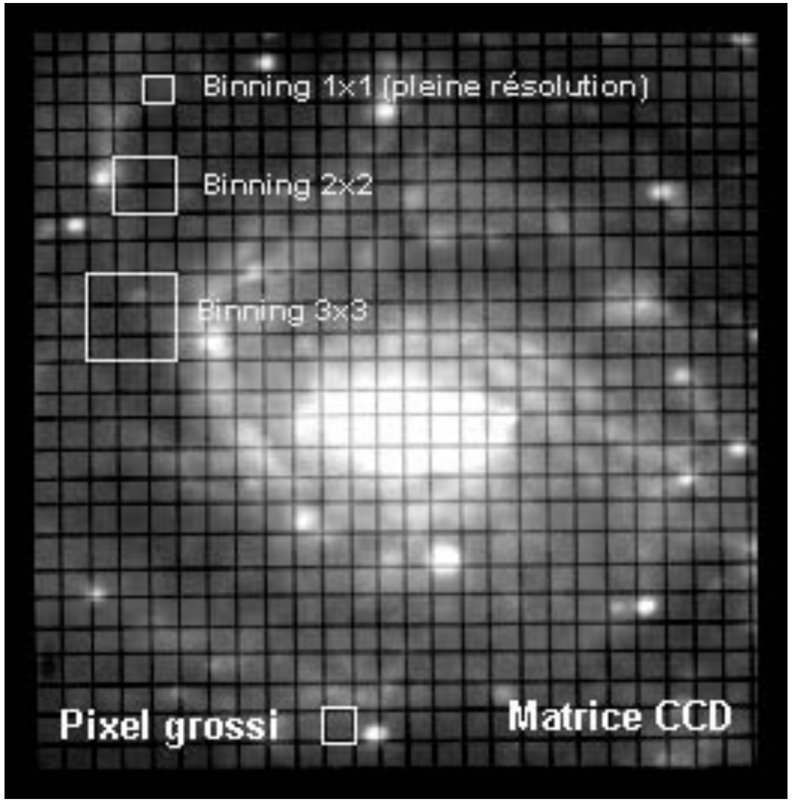
**Basic tools to read/display/analyse FITS images:**

- DS9/SAOimage
- Aladin
- ATV under IDL
- astropy under python — etc…

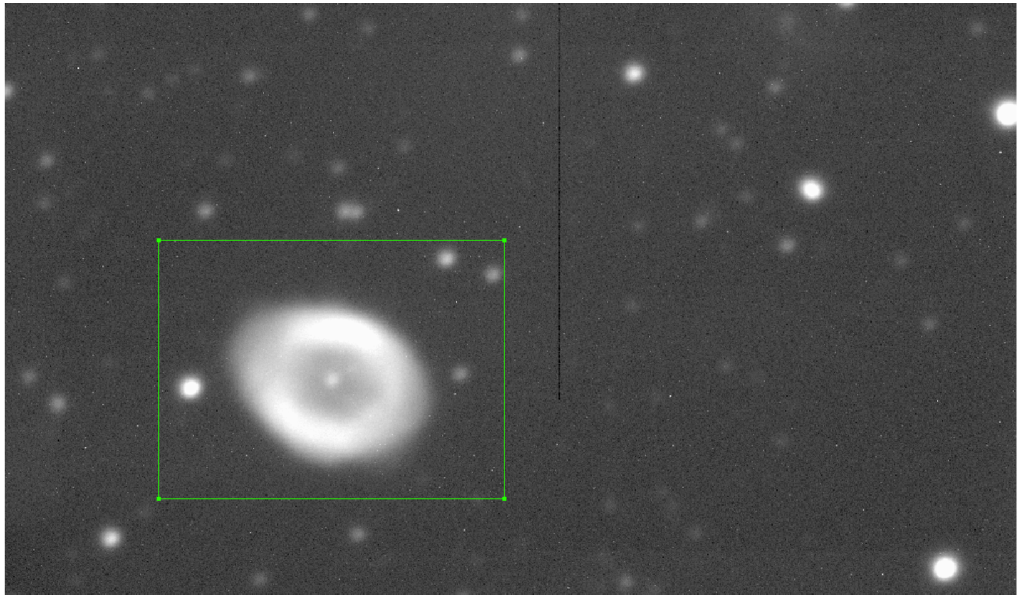
# CCD digest

## Special readout modes

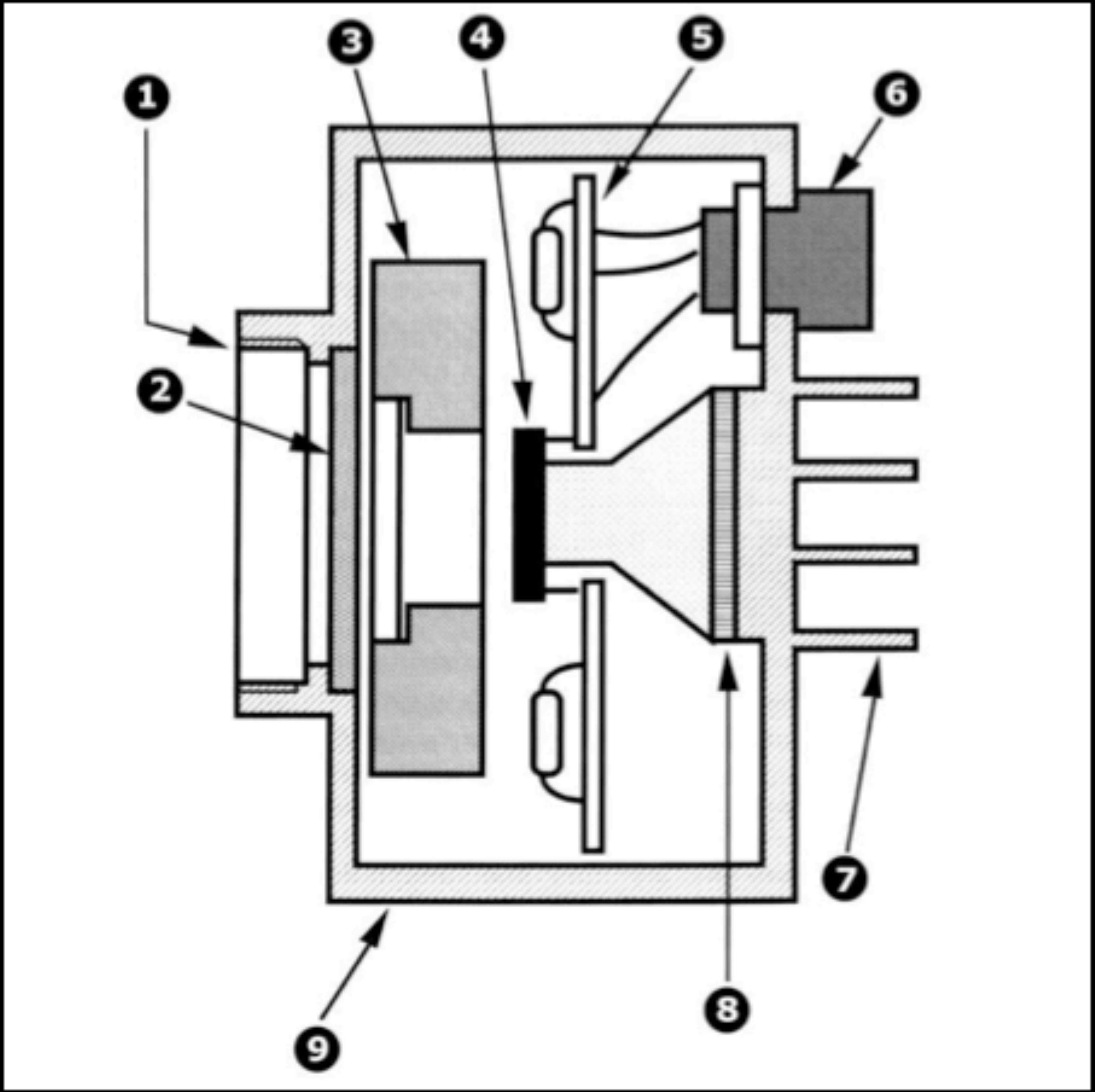
***Binning*: several pixels read simultaneously, *before* measurement of output current and digital conversion – intended to lower readout noise, & faster**



***Windowing*: only the region of interest is read => faster readout and acquisition, e.g. to follow evolving phenomena** (occultations…)



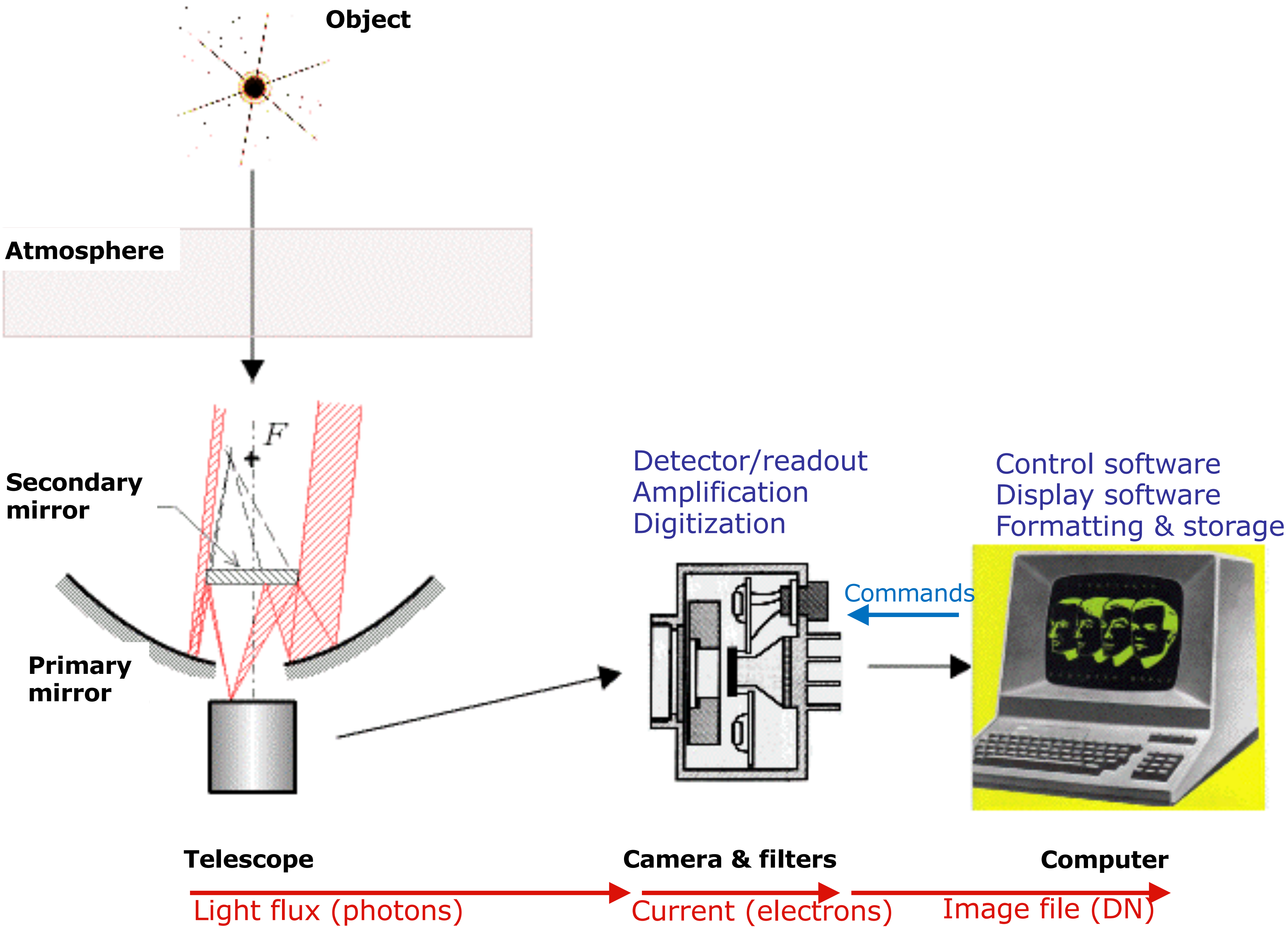
# Camera



**Anatomy of a CCD camera:** 1- Adapter (M42); 2- Optical window; 3- Mechanical shutter; 4- CCD detector; 5- Amplifier; 6- Power connection; 7- Dissipator; 8- Peltier (cooling); 9- Housing.

# SBIG's New STX Series

# Acquisition process in astronomy imaging



**Object**

**Atmosphere**

**Secondary mirror**

**Primary mirror**

Detector/readout
Amplification
Digitization

Control software
Display software
Formatting & storage

Commands

**Telescope**

**Camera & filters**

**Computer**

Light flux (photons)

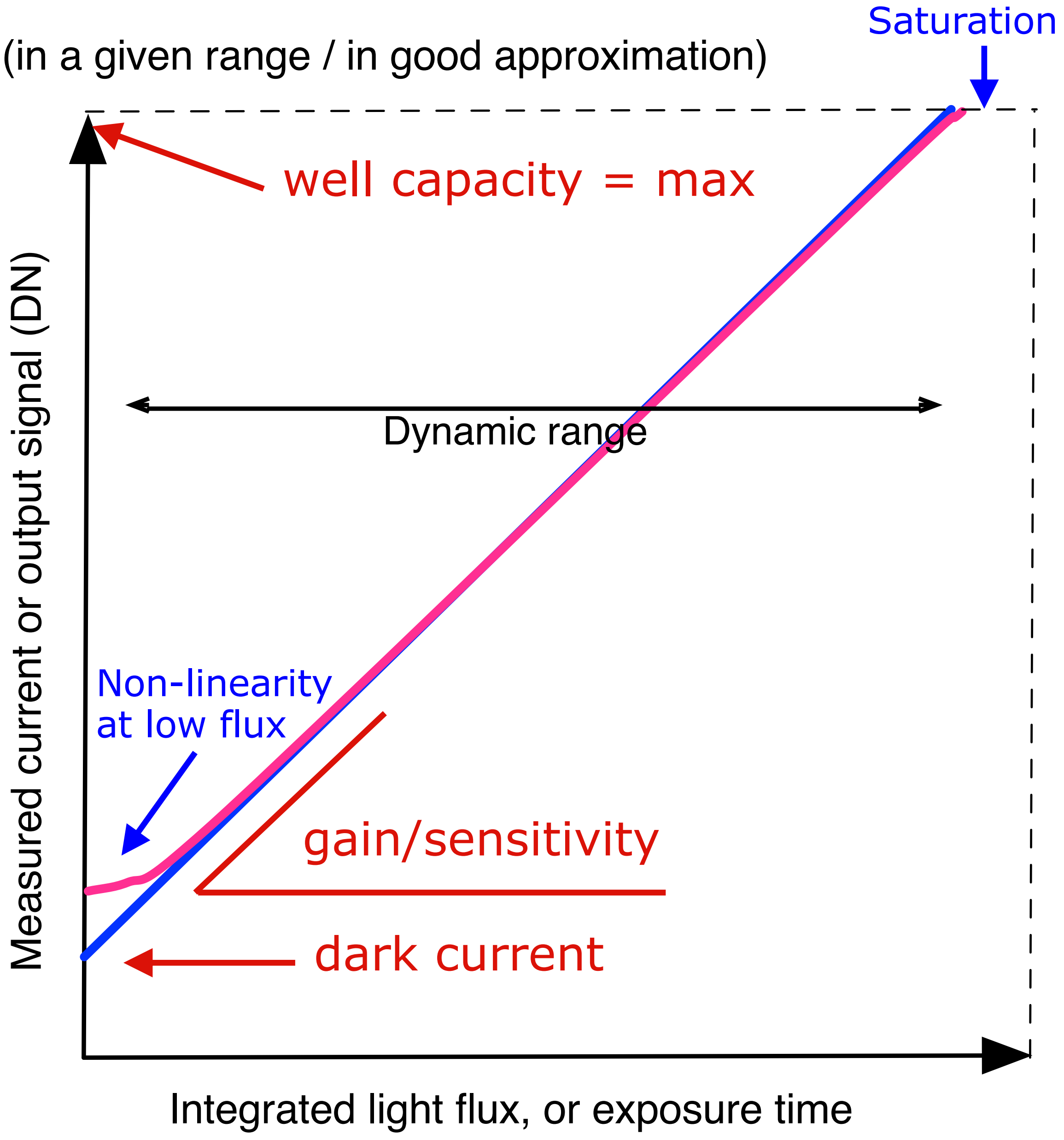
Current (electrons)

Image file (DN)

# Electronic characteristics

## Output signal

**Is proportionnal to incident light flux** (in a given range / in good approximation)



**For each pixel:**

**Signal = flux * gain + dark**

**⇒ gain and dark must be measured together with the raw signal, then applied to the raw signal**

**Gain = sensitivity**

**Allows for quantitative measurements (photometry)**

# Electronic characteristics

## Well capacity / saturation

**Well capacity is finite (~20 000 to 350 000 e$^-$/pixel)**
**=> When full, accumulated charges spill over to neighbouring sites (blooming/smearing)**

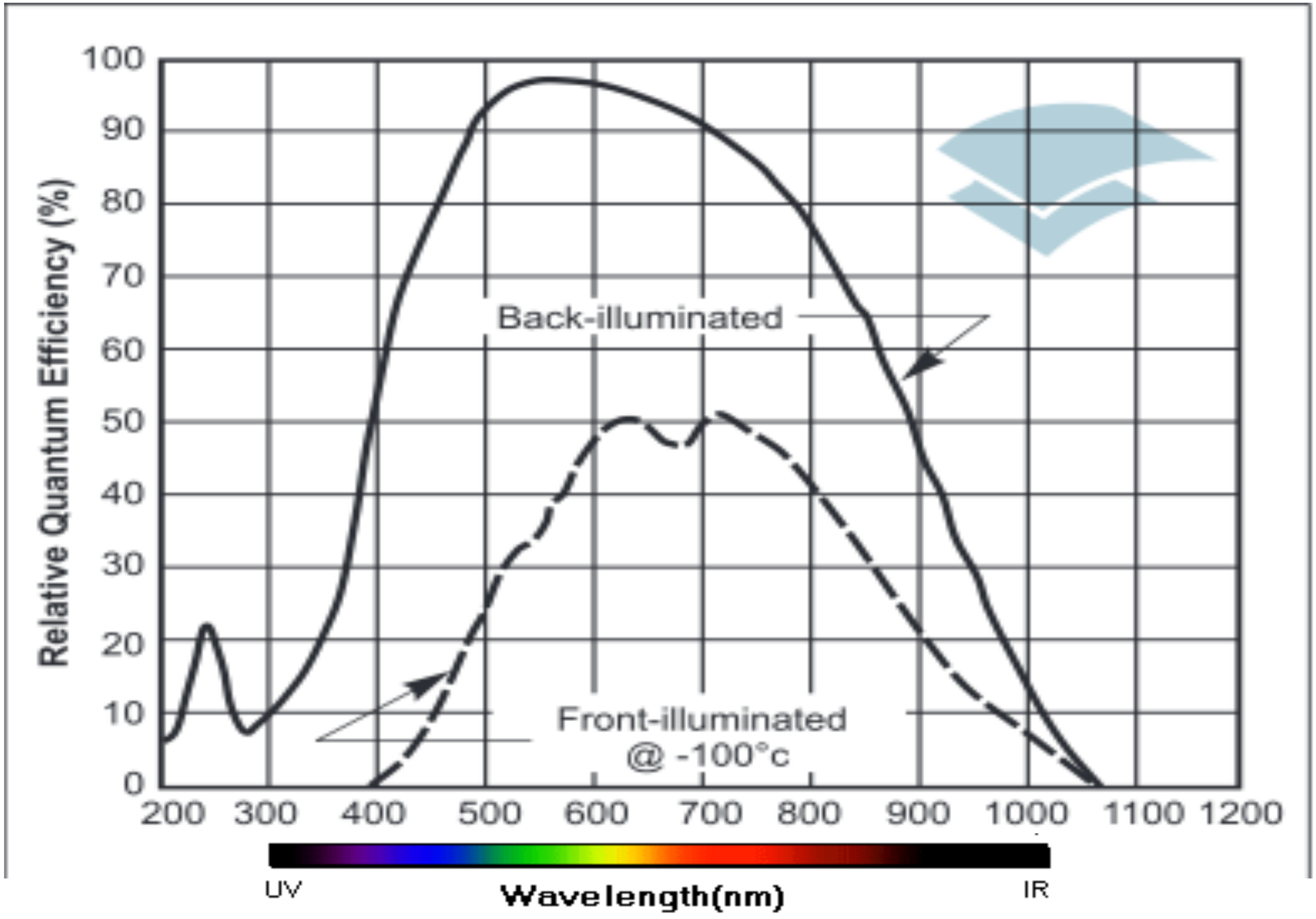
# Electronic characteristics

## Sensitivity / detectivity

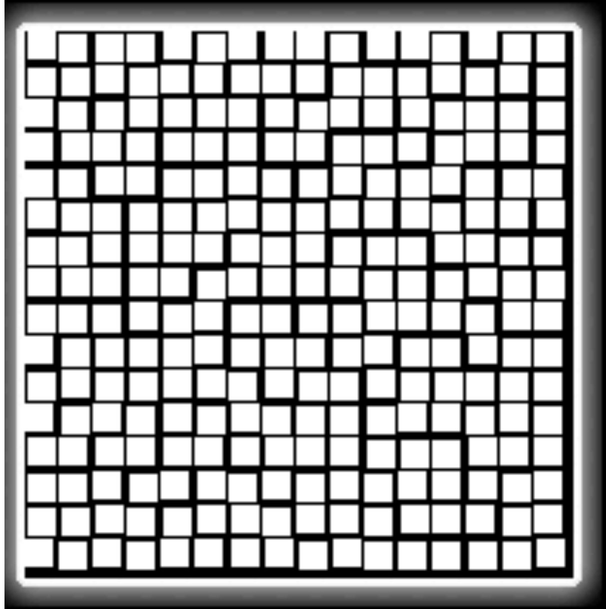
**Equivalent Quantum Efficiency (QE): nb of electrons produced per incident photon**

**⇒ Function of wavelength ~ 0.4-0.95 $\mu$m for standard CCD**

Back-illuminated, thinned CCD have expanded spectral range and sensitivity



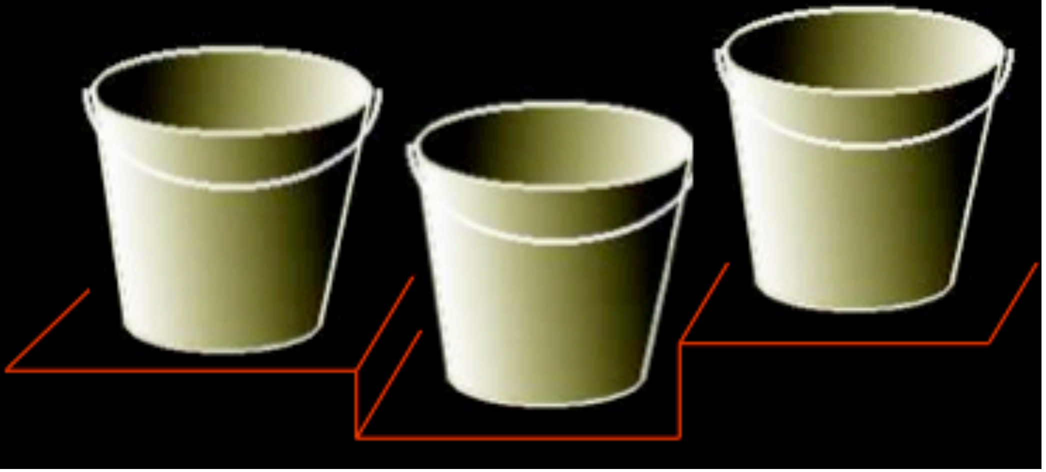
# **CCD Cameras -** *Bias (offset)*



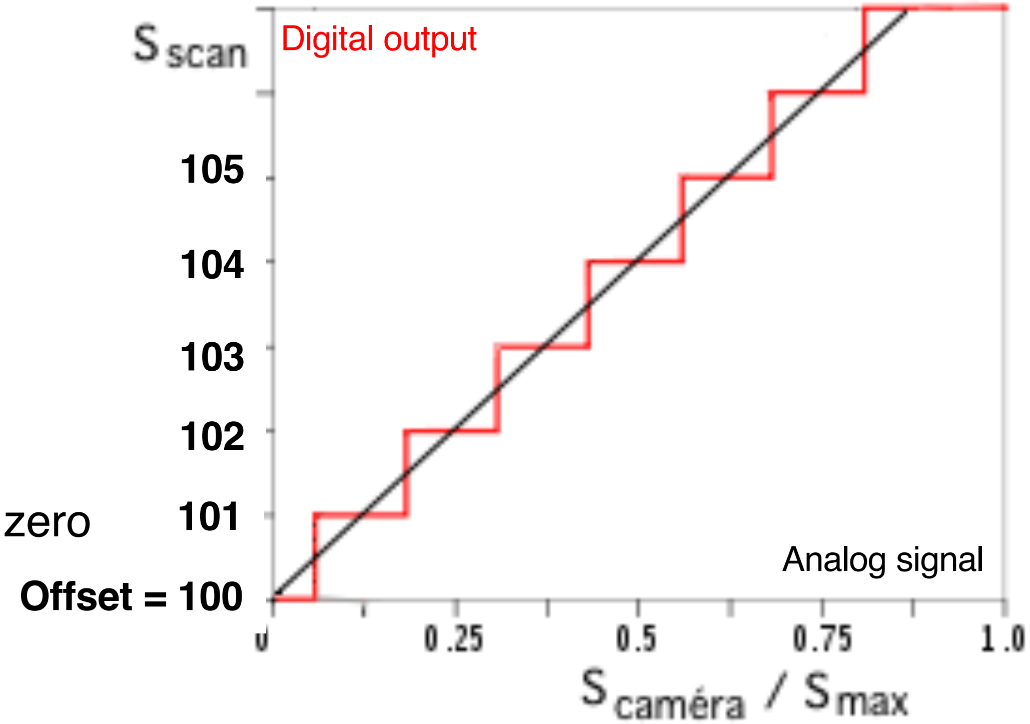
Base level imposed during Analog / Digital conversion: fixed & reproducible (does not correspond to any charge)

Visible at minimum exposure time

Provides more or less regular patterns, often along column direction



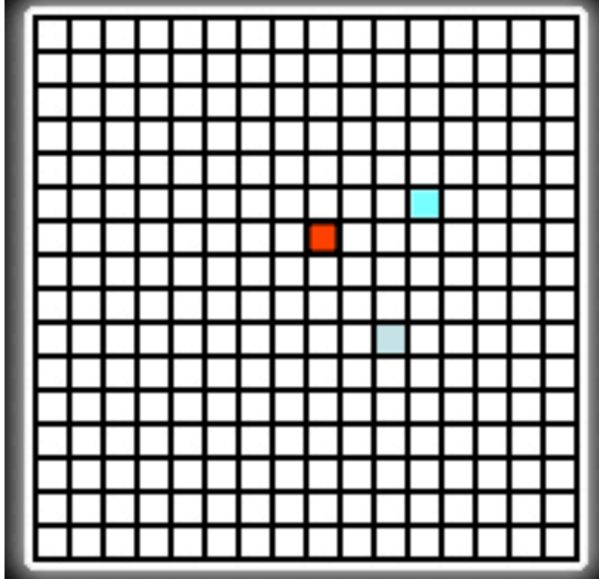
# Offset

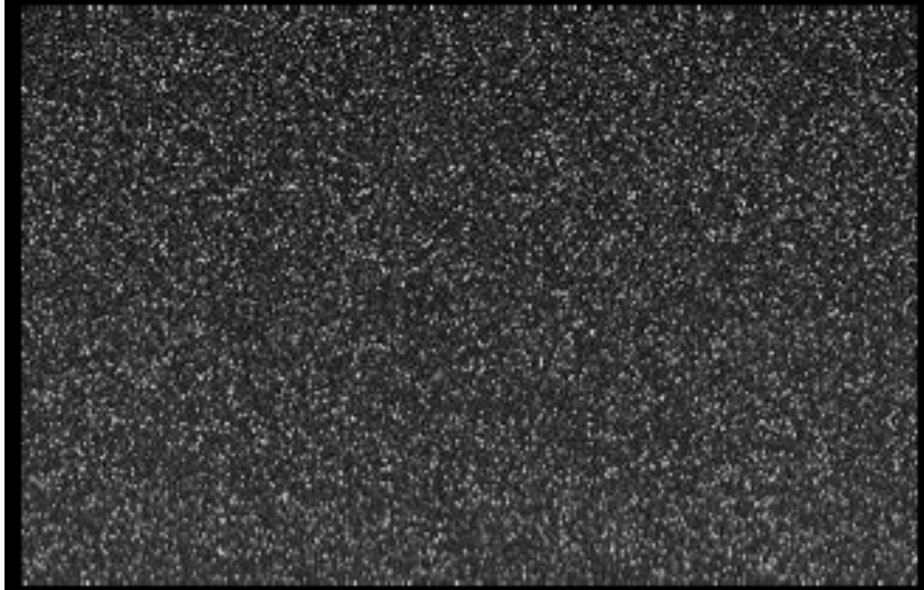


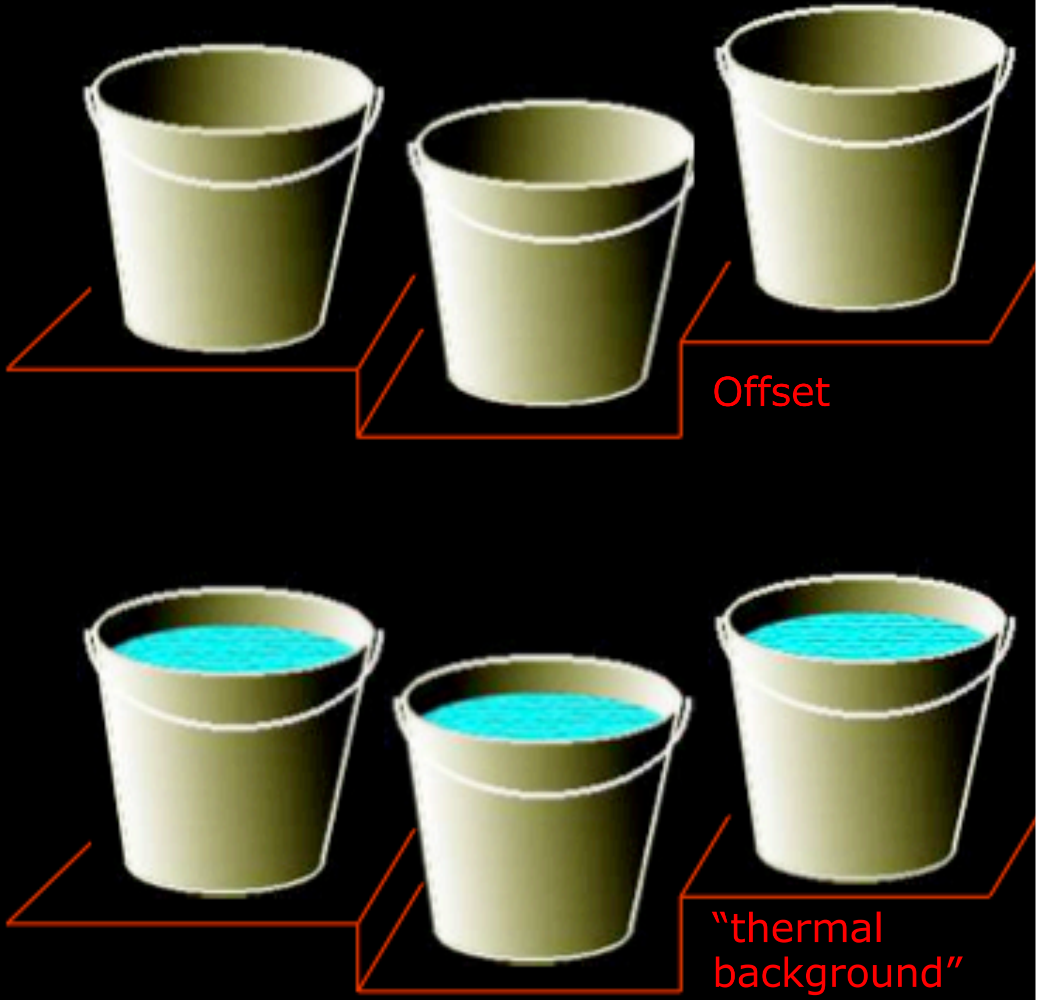
**Offset**
**= base level imposed in the ADC during conversion (does not correspond to any charge / light flux)**

= at least 2 to 3 x noise level, to offset from zero and preserve statistics

# **CCD Cameras** - *Dark current*



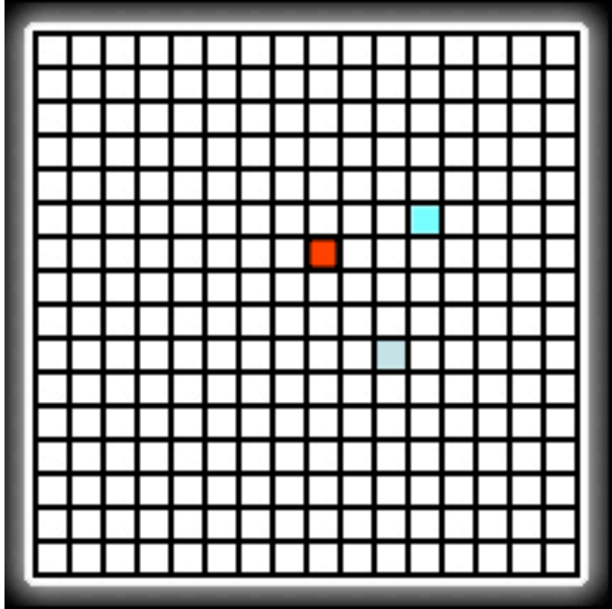


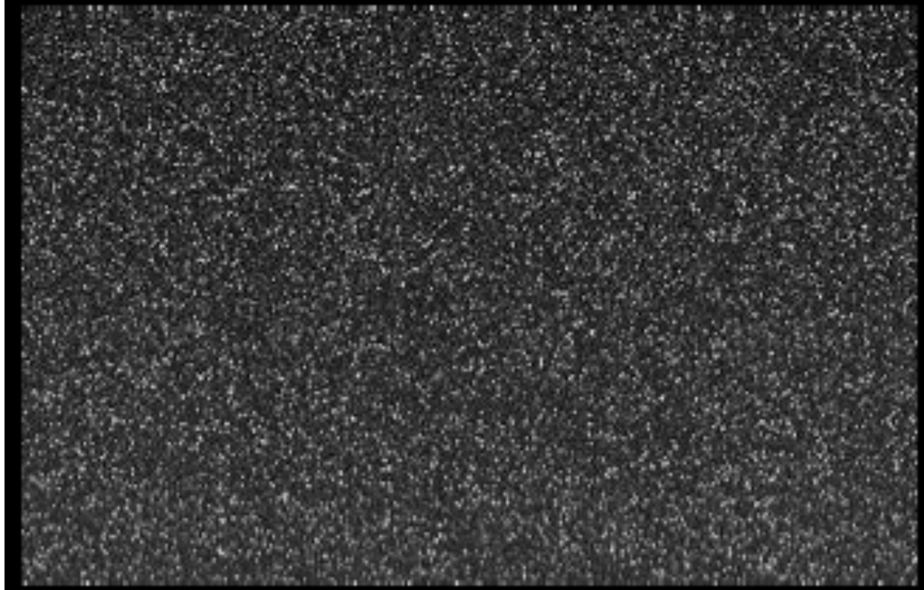


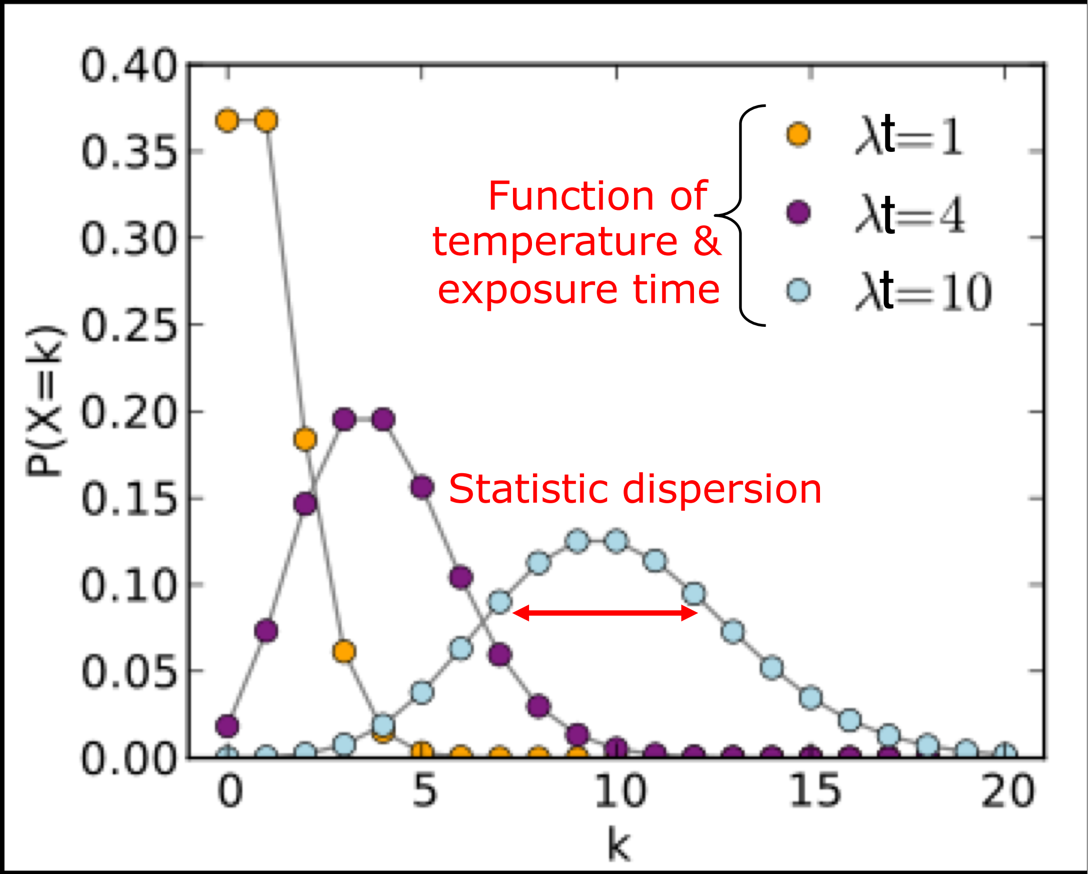
DARK FRAME = BIAS FRAME + THERMAL FRAME

A.Cidadão

# **CCD Cameras** - *Dark current*







Charges are created spontaneously in absence of light
Not necessarily large wrt offset

This process follows a Poisson distribution

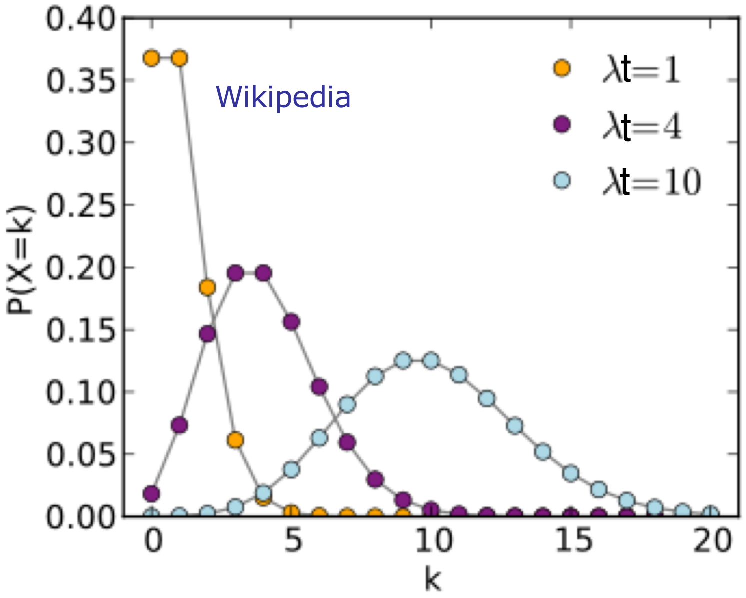
# Intermission: the Poisson distribution

Assumptions: - events are random and independent
- event frequency is constant ($\lambda$)

**Examples: photon emission; creation of thermal charges**

**Probability mass function (to have k events during interval t):**

$$P(k) = e^{-\lambda t}\frac{(\lambda t)^k}{k!}$$

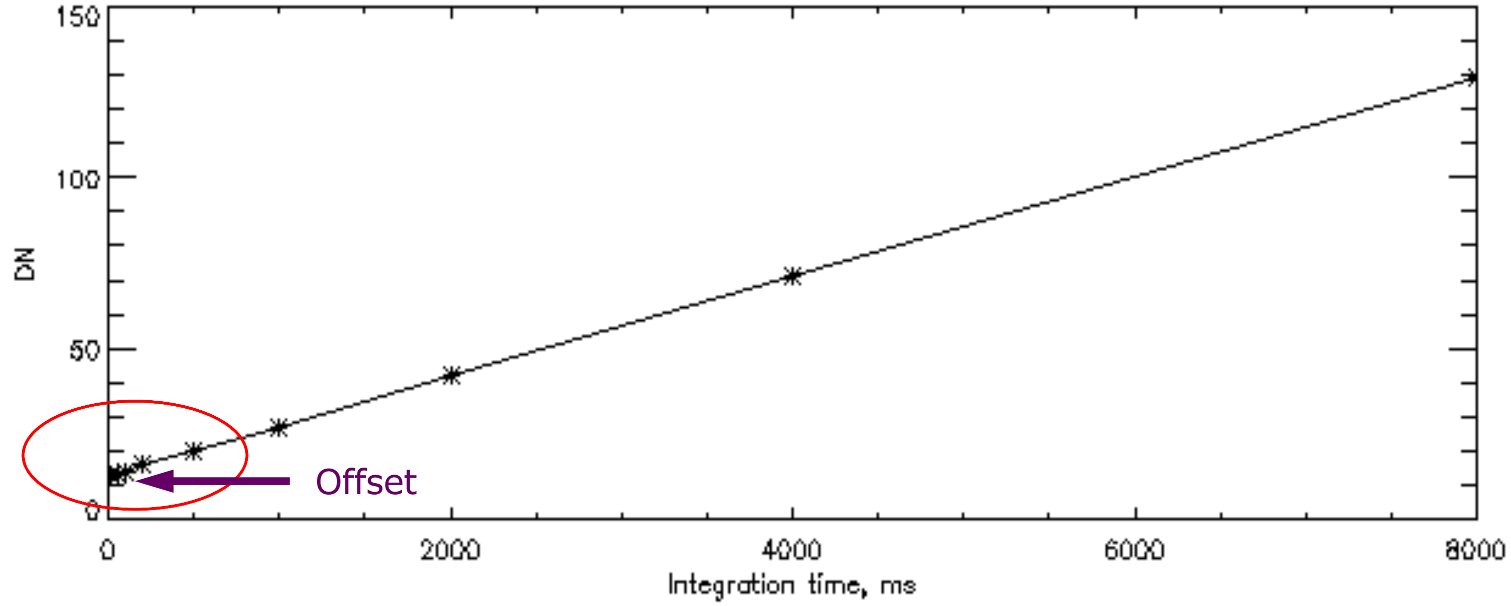


Tends towards a Gaussian distribution
when $\lambda$t is large (central limit theorem)

**With N = $\lambda$t:**
**Mean = N** (nb of photons received during t) => Predictible

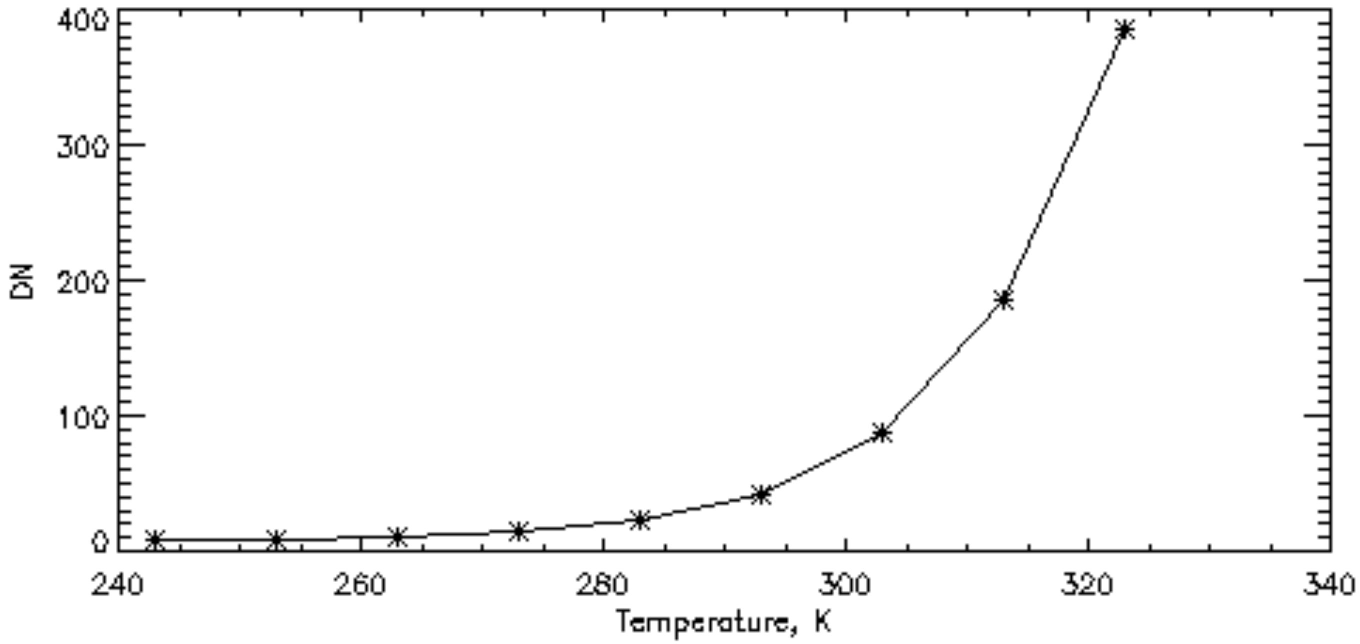
**Standard deviation:** $\sigma = \sqrt{N}$ (mean variation around this value, between successive measurements)
=> Random: *this* is noise

# Darks current: variations



**~ linear with exposure time**

(as long as saturation is not reached)



**Severe with T**

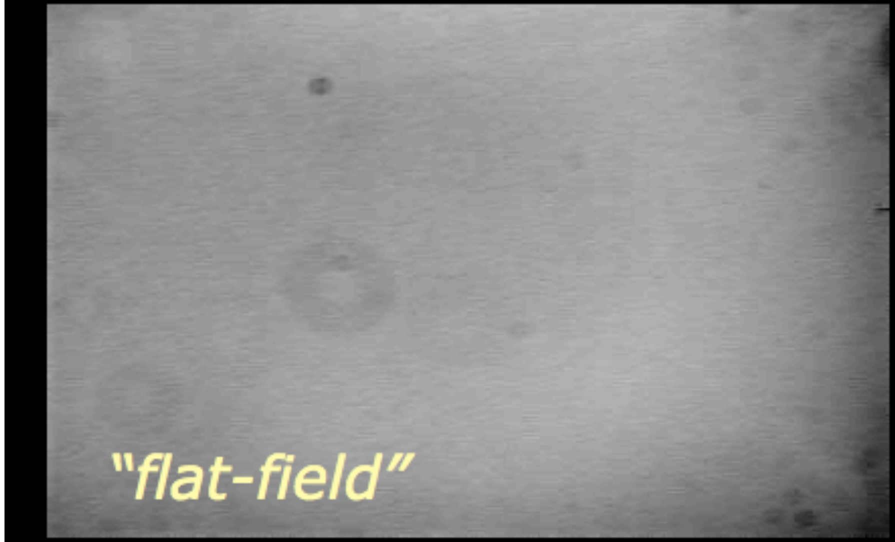
(Boltzmann)

=> Cool down CCD whenever possible

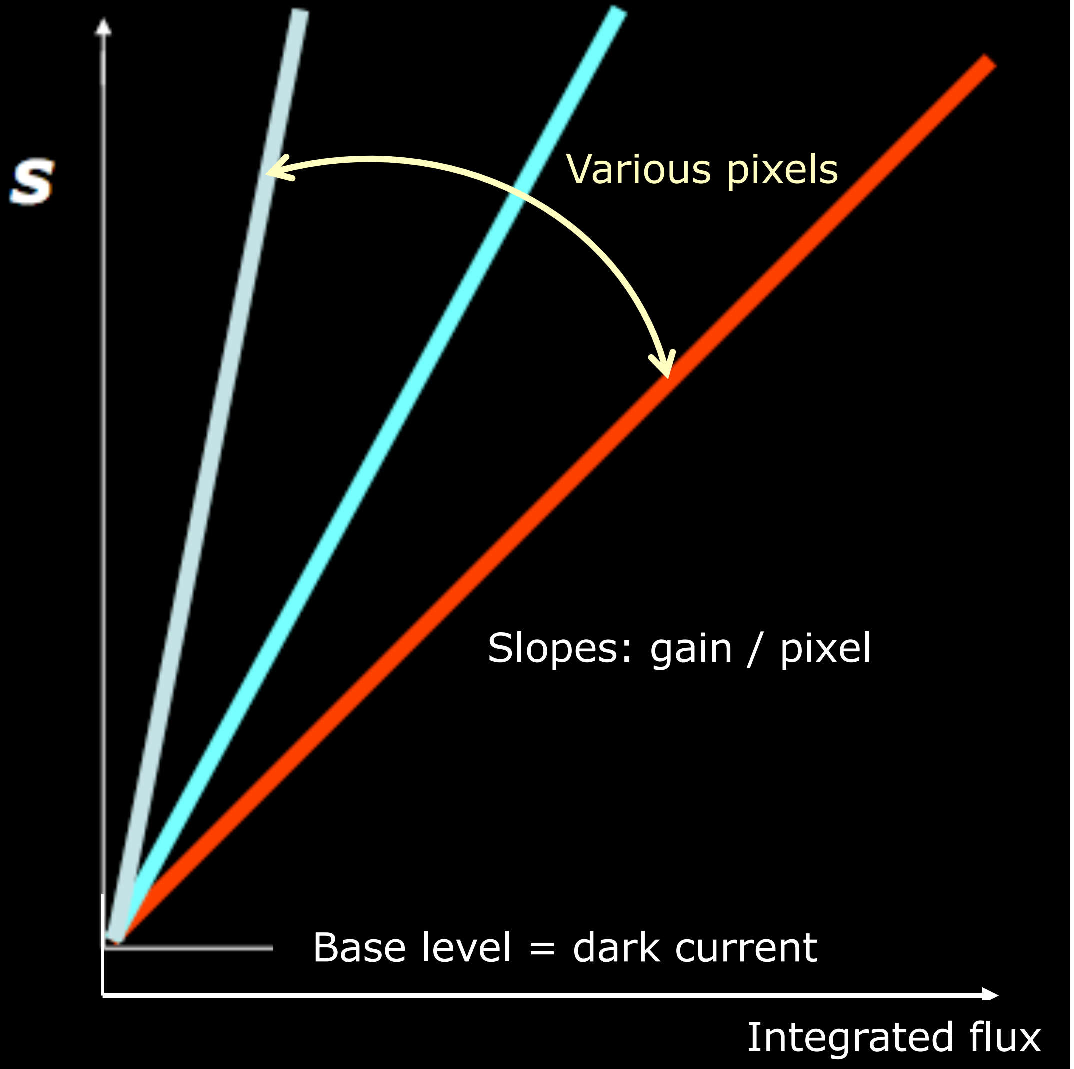
IR detectors: often require very low-T functioning point (90-140K)

# CCD Cameras - *Flat-field*

**Vignetting**



*“flat-field”*



S

Various pixels

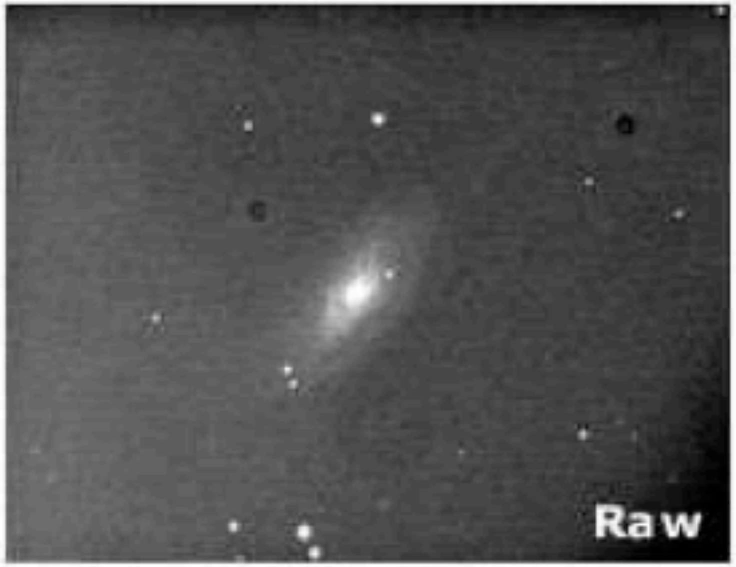
Slopes: gain / pixel

Base level = dark current

Integrated flux

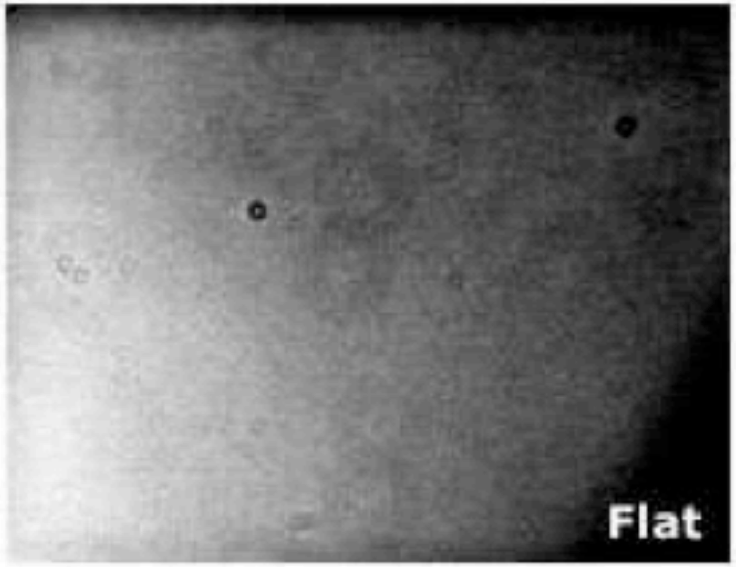
# Image calibration / reduction

Exp. time t
Filter F



Exposure time t

Filter F
Normalised at 1s



(linear approx.)

**Calibrated = (Raw - Bias - Thermal) / Flat = (Raw - Dark) / Flat**

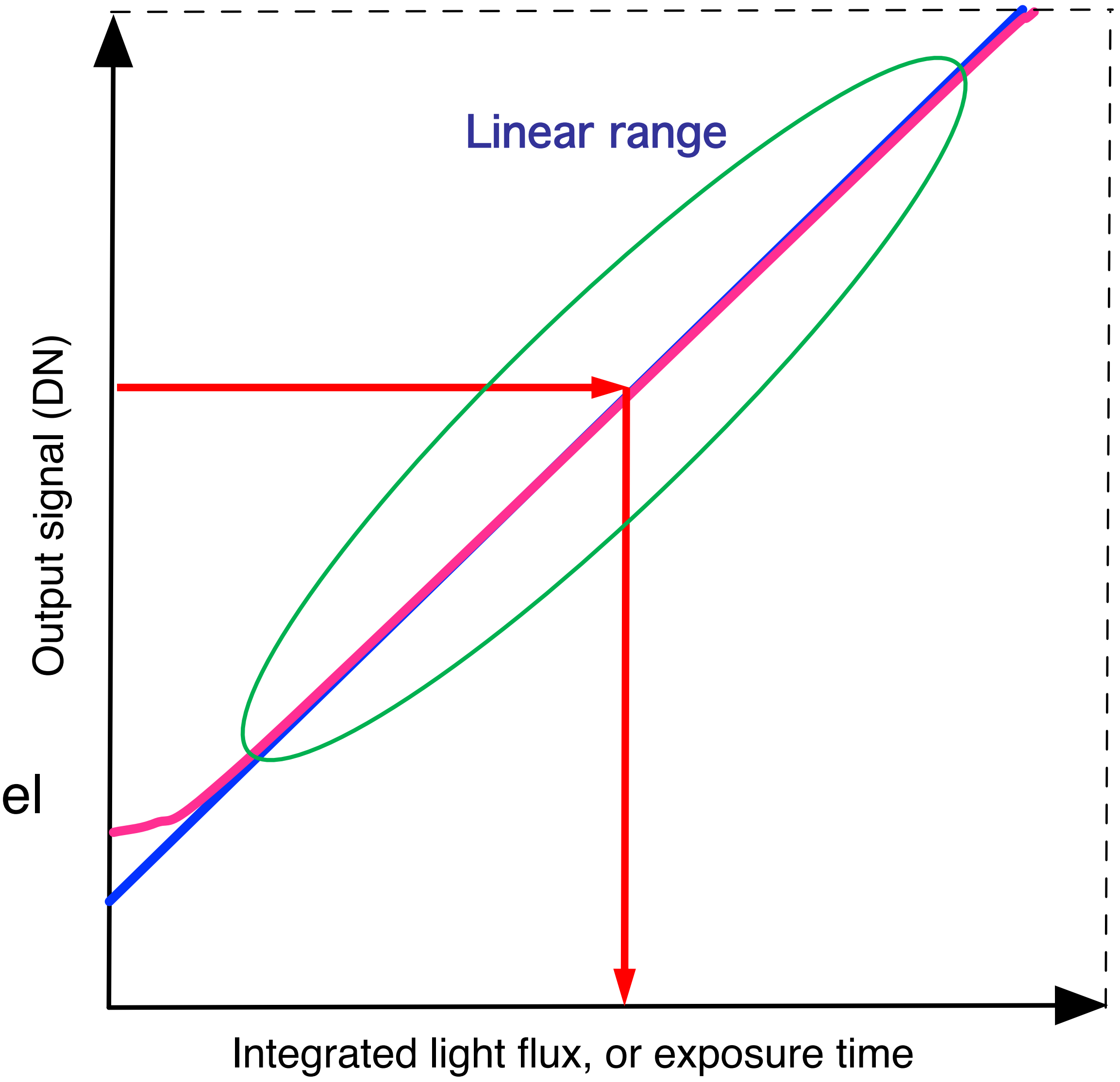
Only calibrates in a relative sense. Absolute flux are derived from comparison with reference sources

# Image calibration / reduction

**Calibrating =**
**recovering the light flux from the output signal**

**You want to use the linear part of the response function**

=> Linear function for each pixel



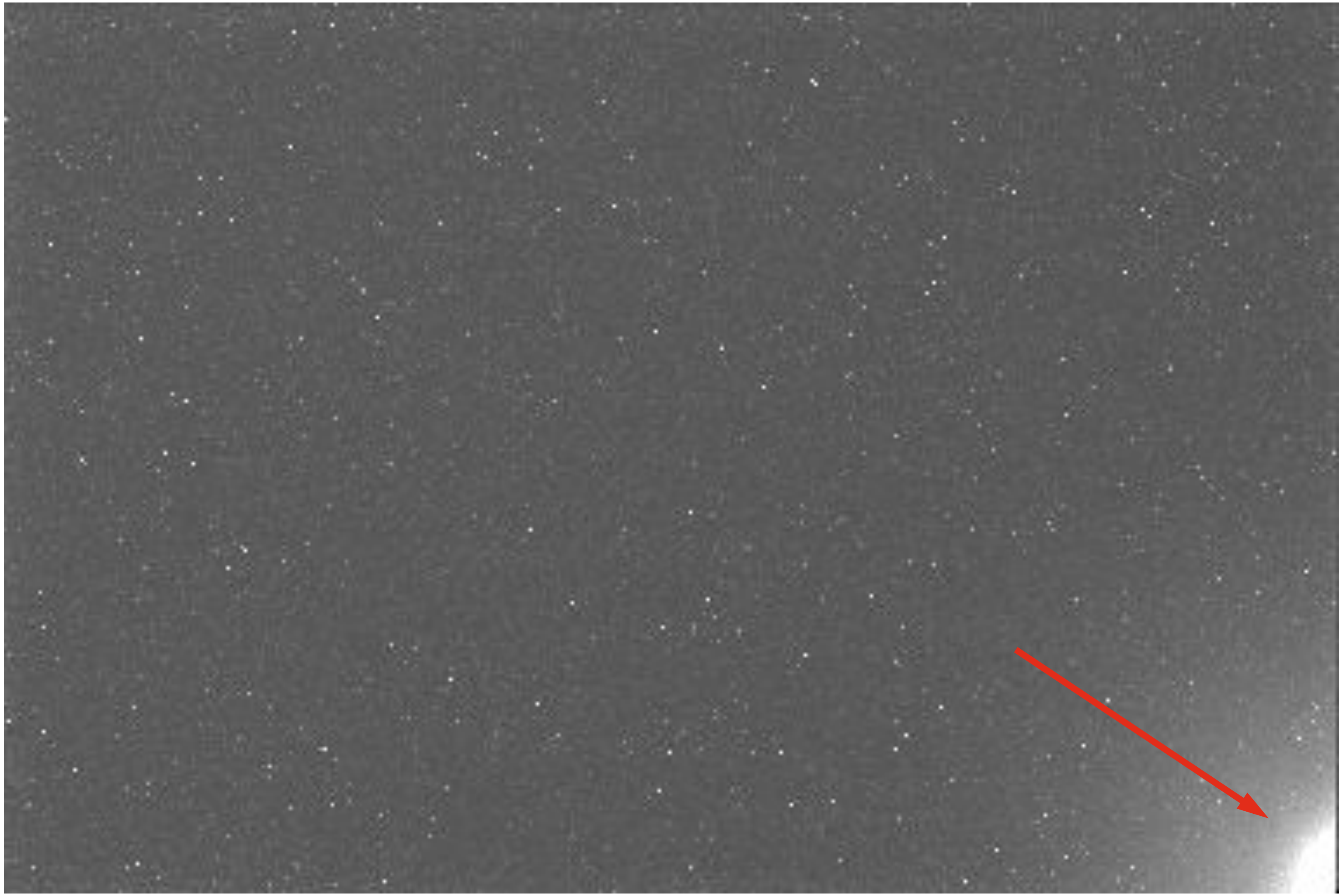
Only calibrates in a relative sense. + need to divide by exposure time

**Absolute flux are derived from comparison with reference sources**

# Electronic artifacts

## Electroluminescence

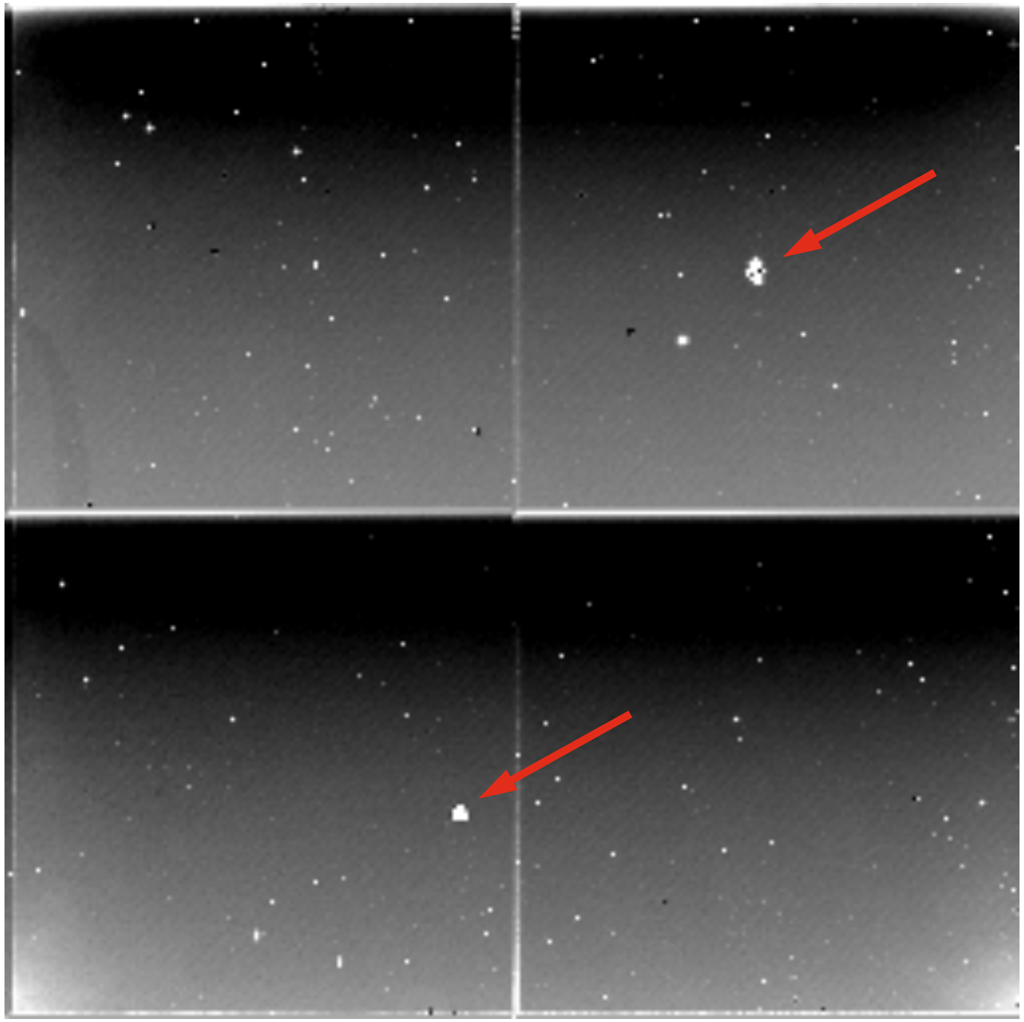
**The amp heats a part of the array => dark current increases locally (together with noise)**



# Electronic artifacts

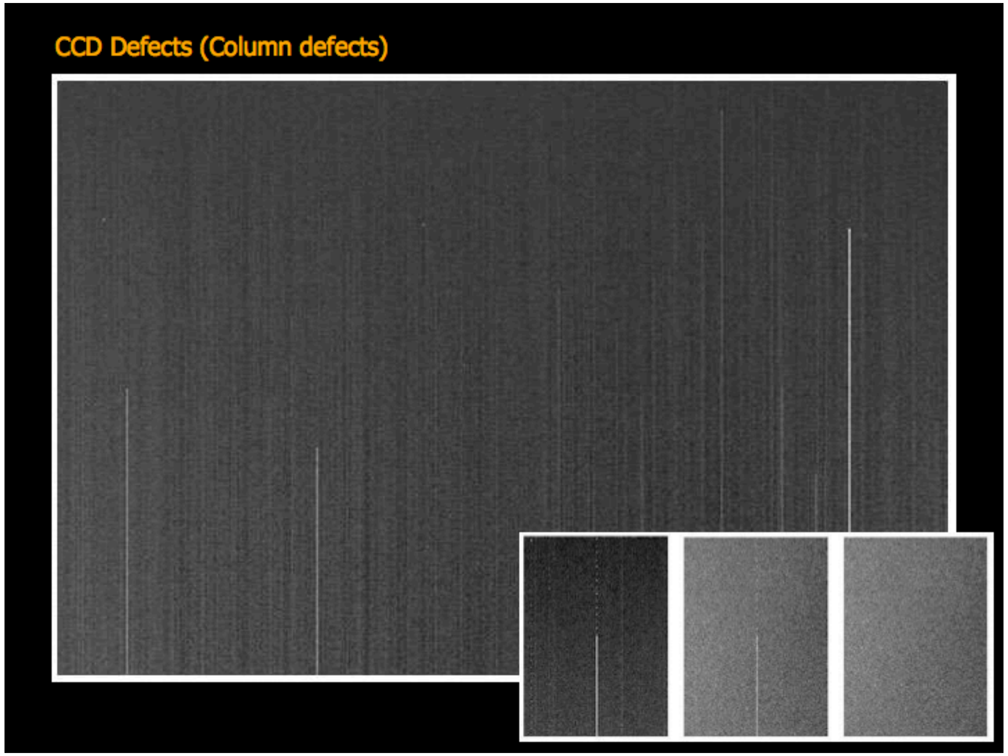
## Dead / cold / hot pixels

**Some pixels have non standard behavior: little or no detection, fast saturation…**
**Often grouped in ”clusters” or regular patterns**

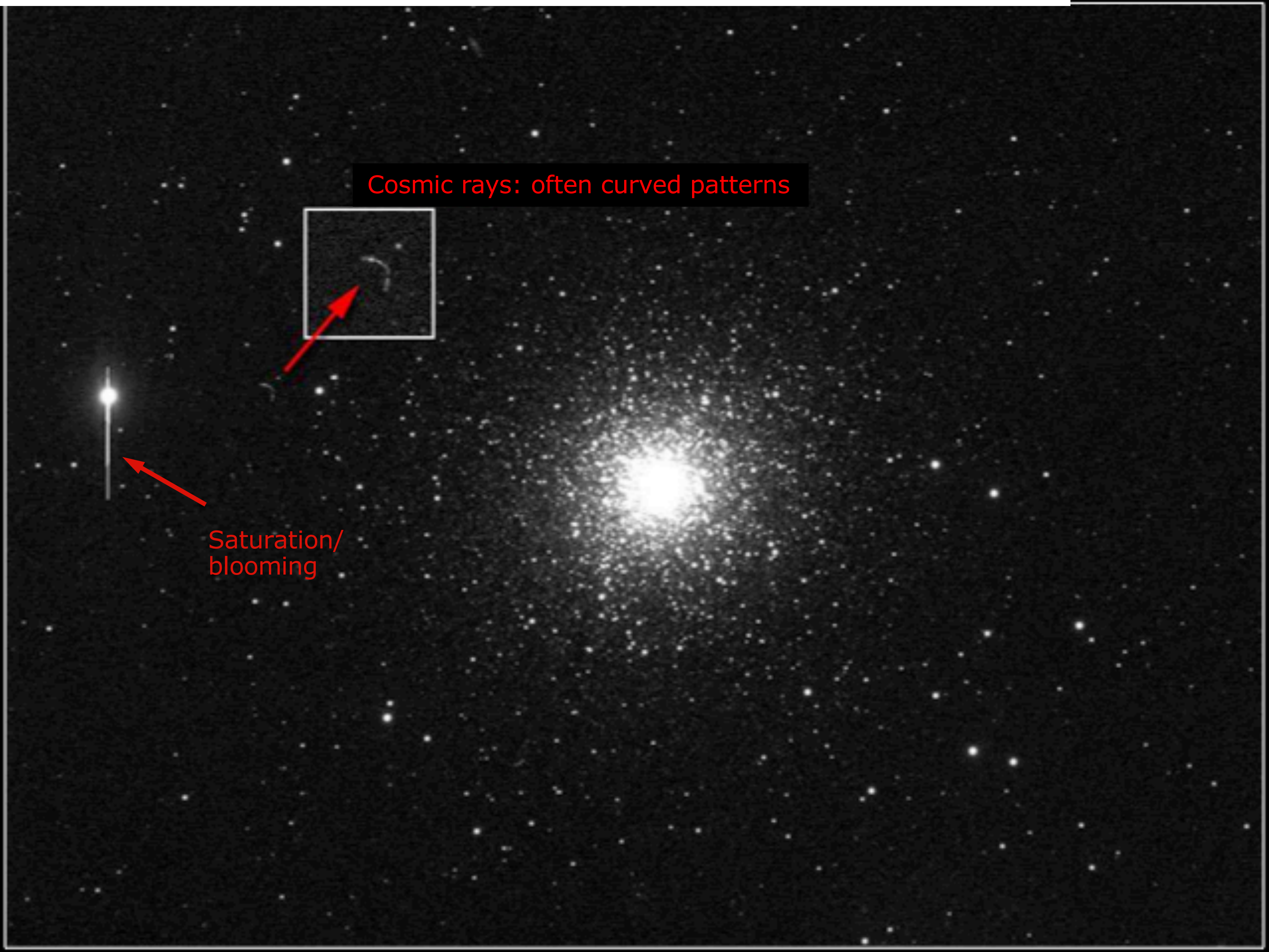


Quadrants: 4 independent readout circuits used in // on the same detector

Column defects (related to electrical circuitry)



# Electronic artifacts: effects of saturation + cosmic rays



Cosmic rays: often curved patterns

Saturation/
blooming

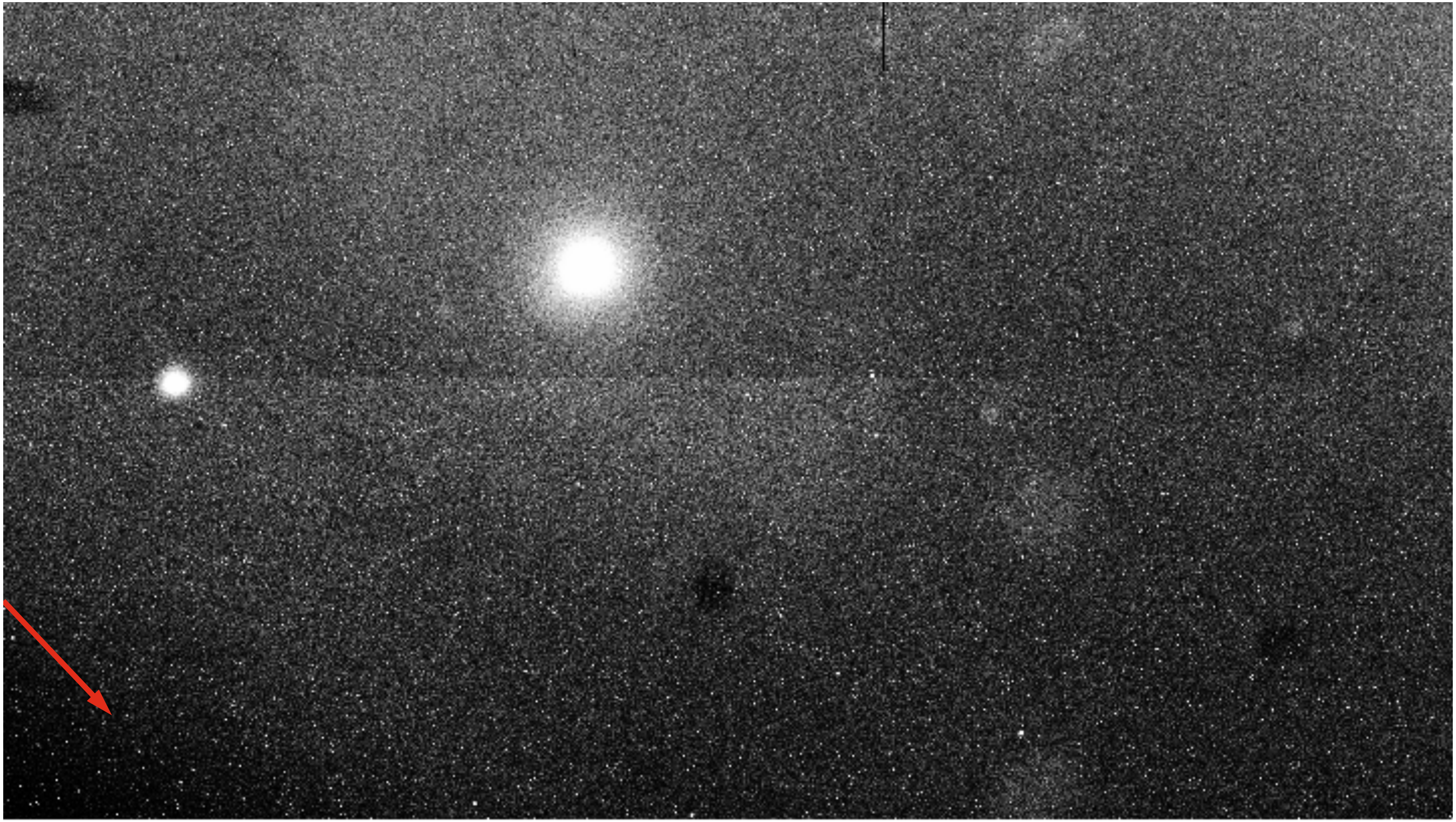
# Electronic artifacts: spread of charges

**Even in absence of saturation, charges may spread along columns during exposure**
**=> reduces contrast and increases noise**

# Electronic artifacts

## 1 / f noise: ponctual events / granulosity

**~hots pixels, but nb increases with exposure time. Random pattern, noticeable for t $\gtrsim$ 5 min**

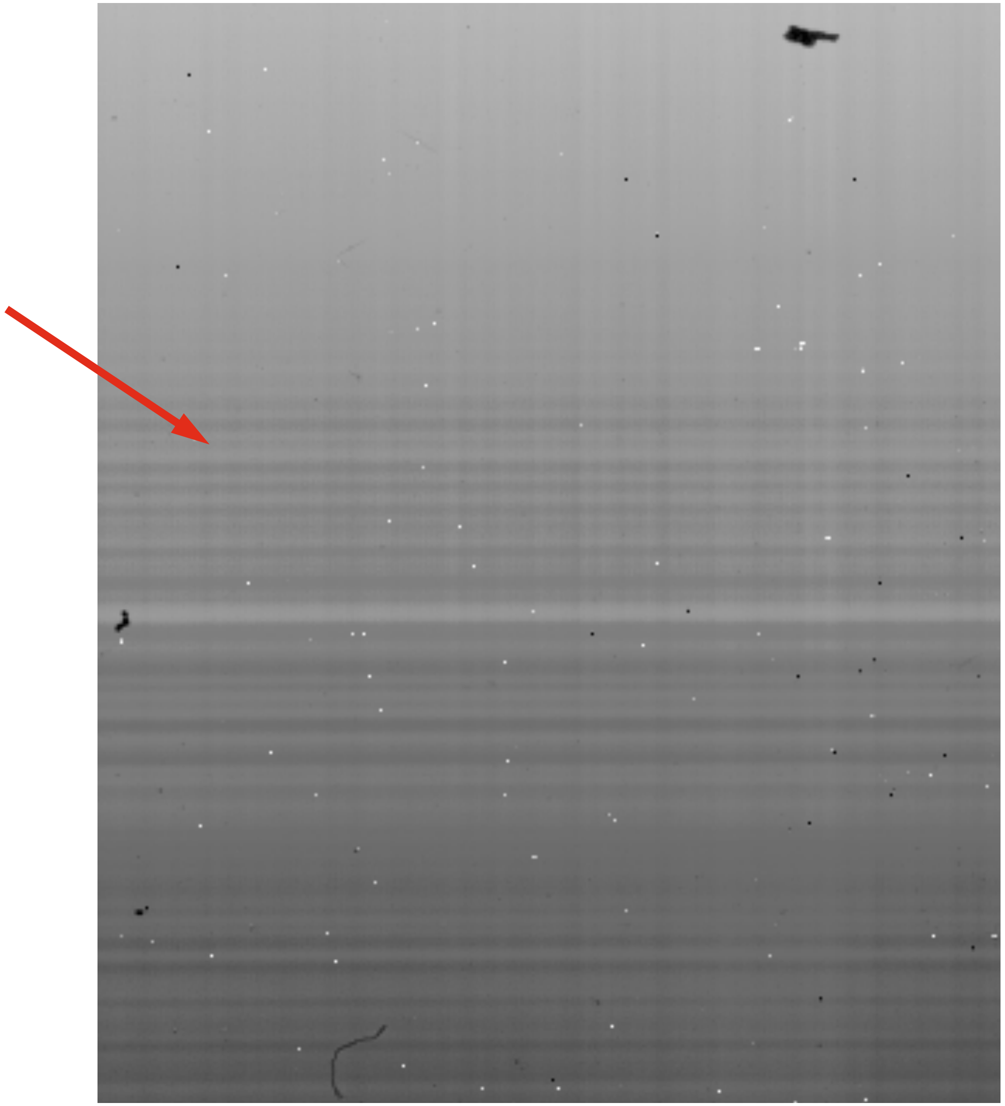


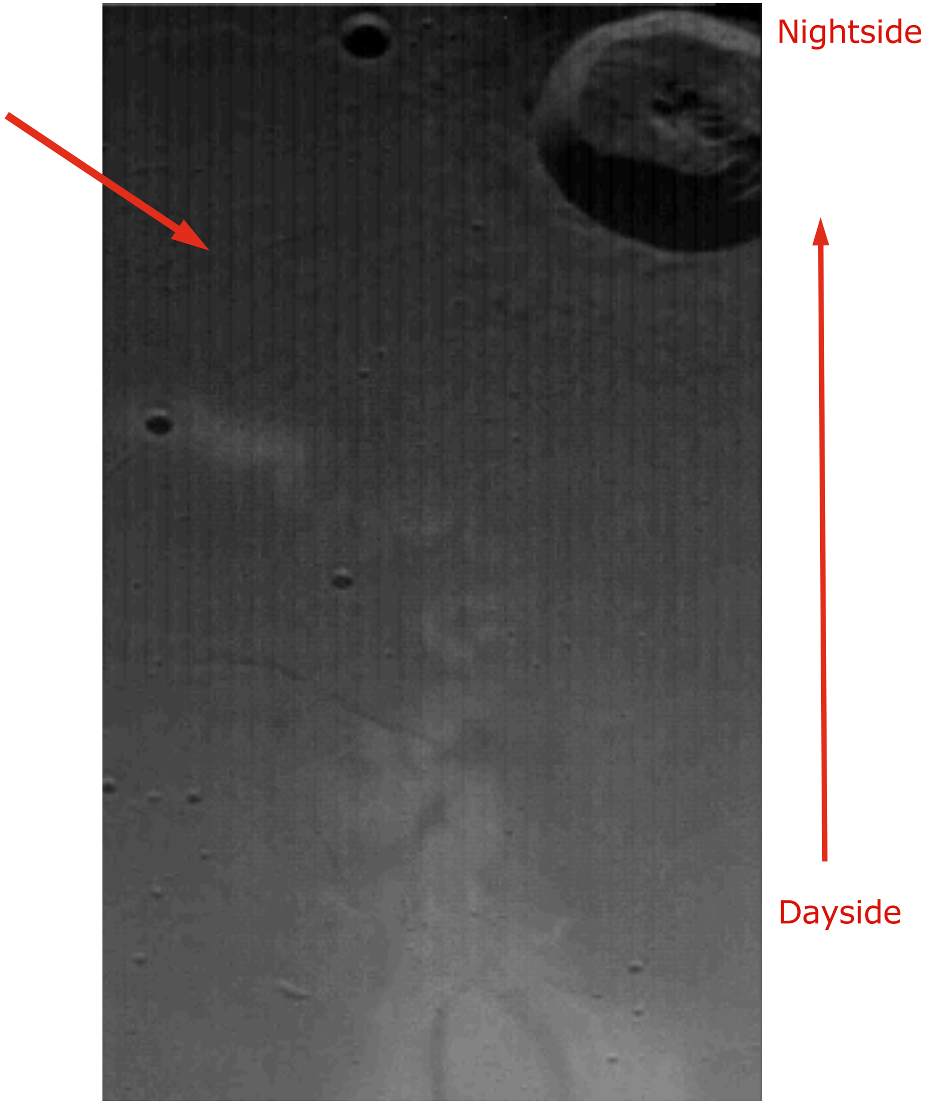
# Electronic artifacts

## Various frames / patterns in dark current & low level images

**Depends on readout circuitry: odd/even interlacing, blocks, quadrants, oblique patterns…**

**Non-linear behavior in general (noticeable at low flux)**

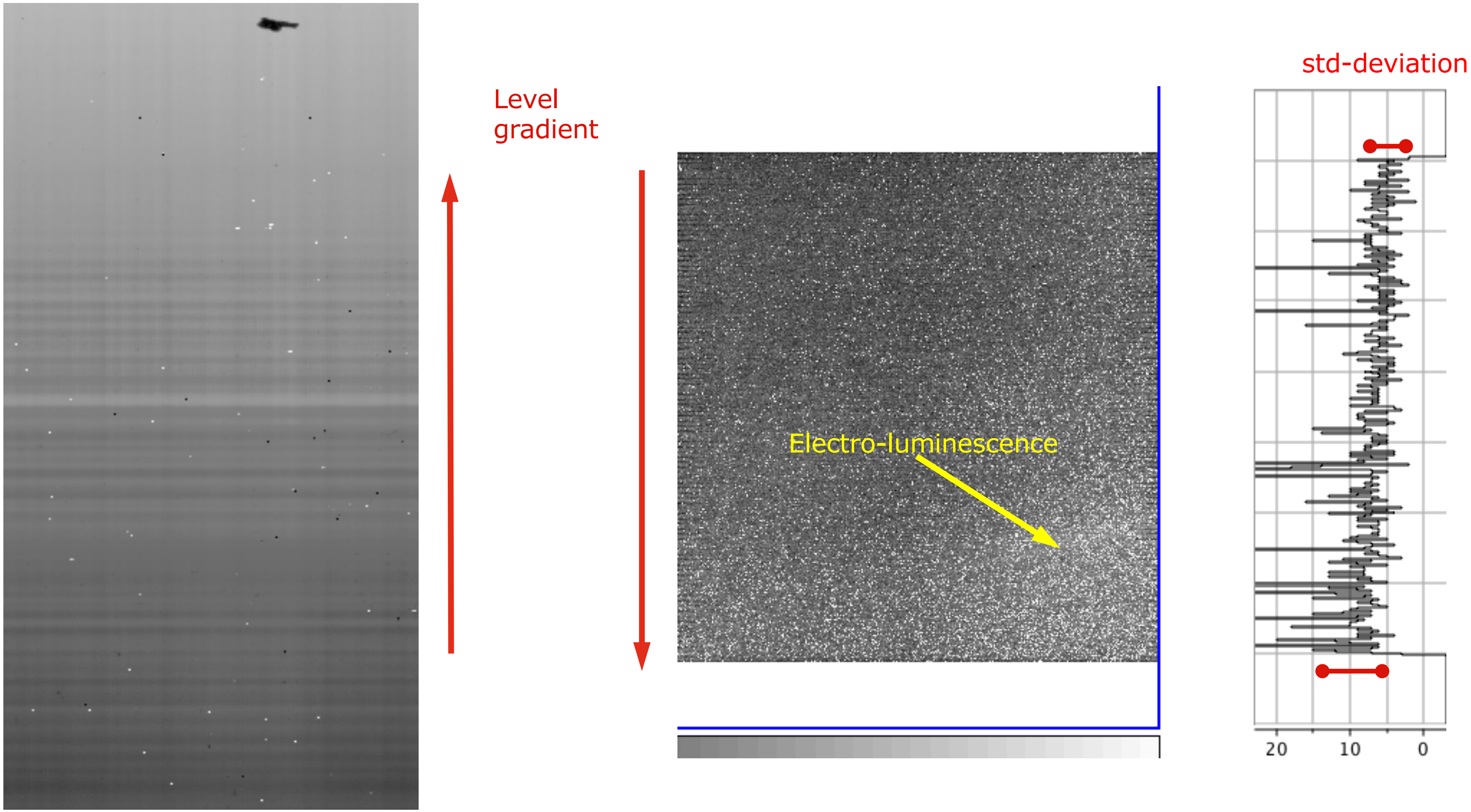




# Electronic artifacts

## Gradients

**Last lines read have higher dark current (and more noise)**
**and are subject to more transfer error** (~$10^{-5}$ : noticeable for large arrays)

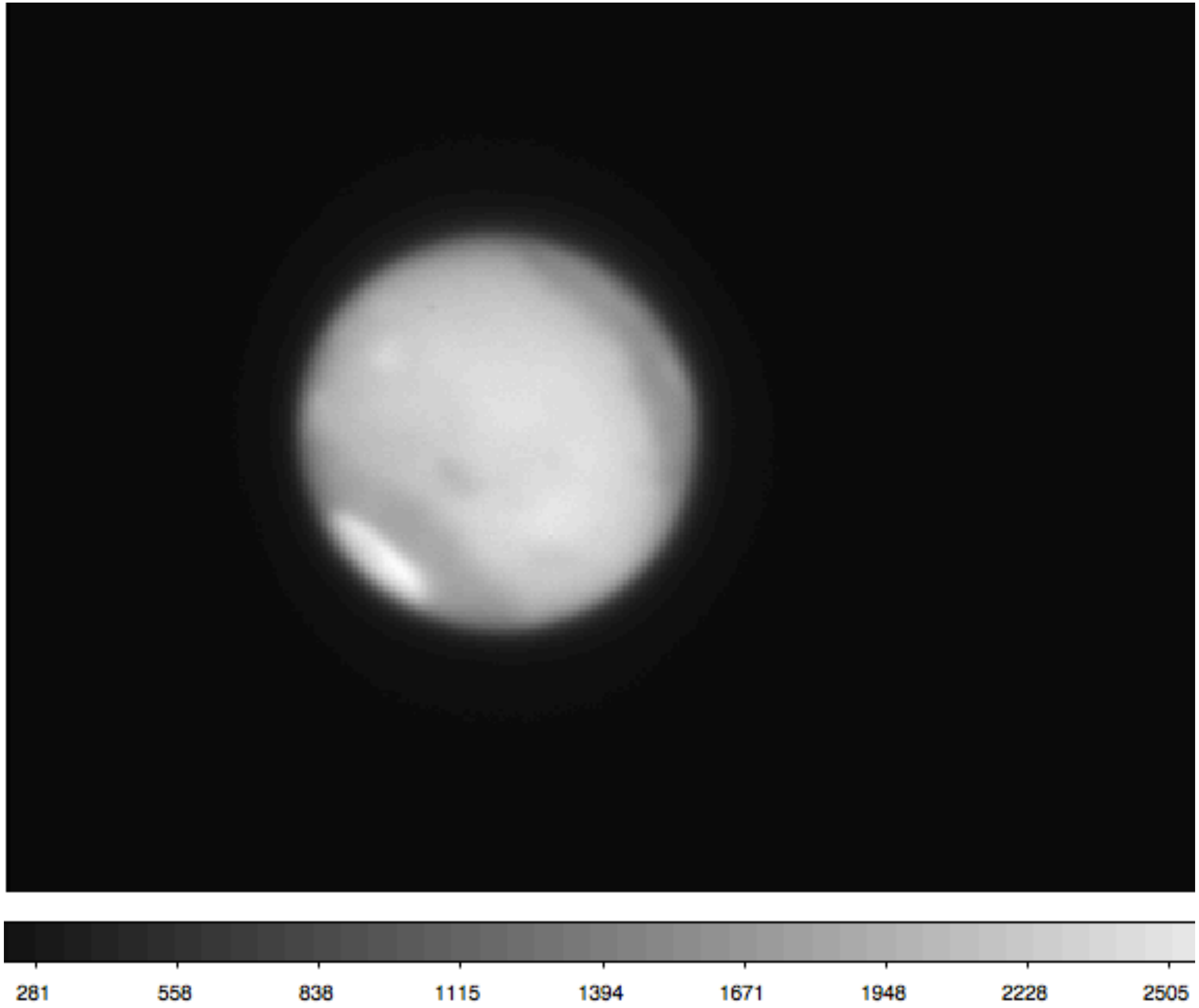


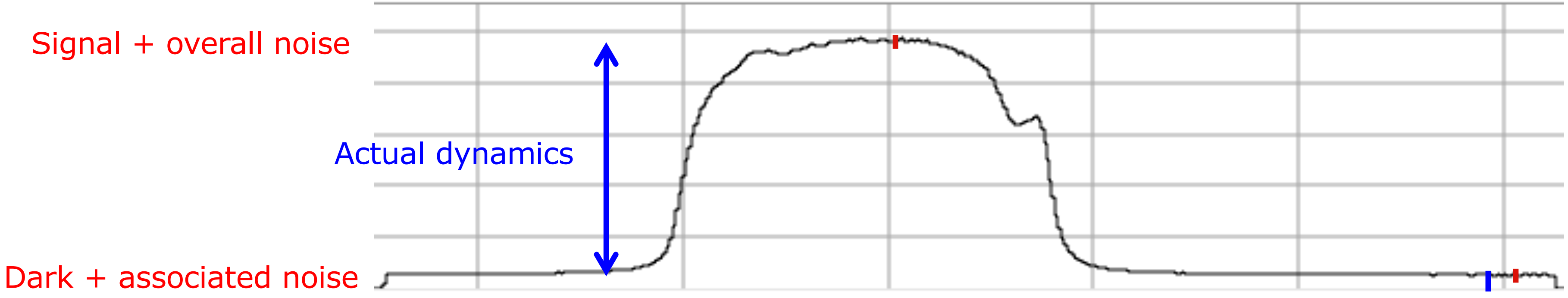
# Analyse your images!

## Display / profiles

- Level / variations?
- Structures / artifacts?
- Dead / hot pixels?

=> Adjust contrast, ranges, colour scales





# Dark current issues

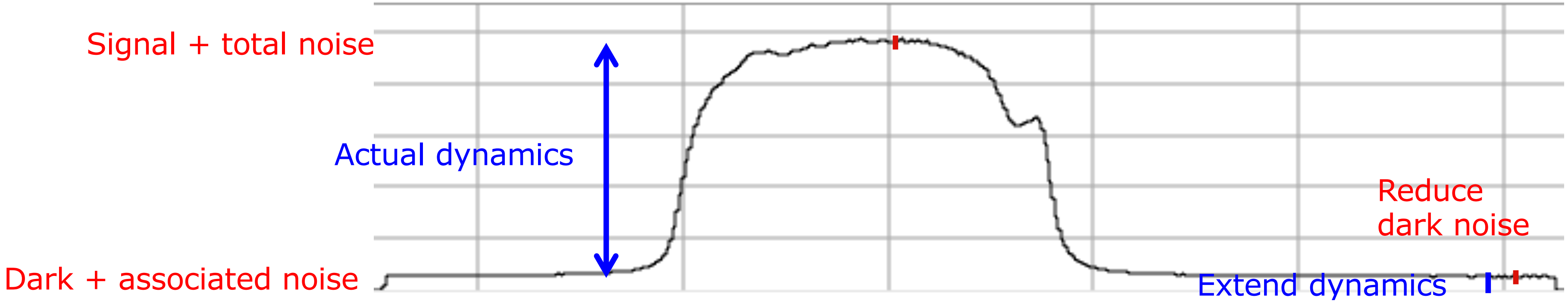
**You always want to minimize it, because:**

- **It restrains dynamics by N** (parasite signal, less space for target signal before saturation)
- **It is associated with a noise** $\sigma = \sqrt{N}$

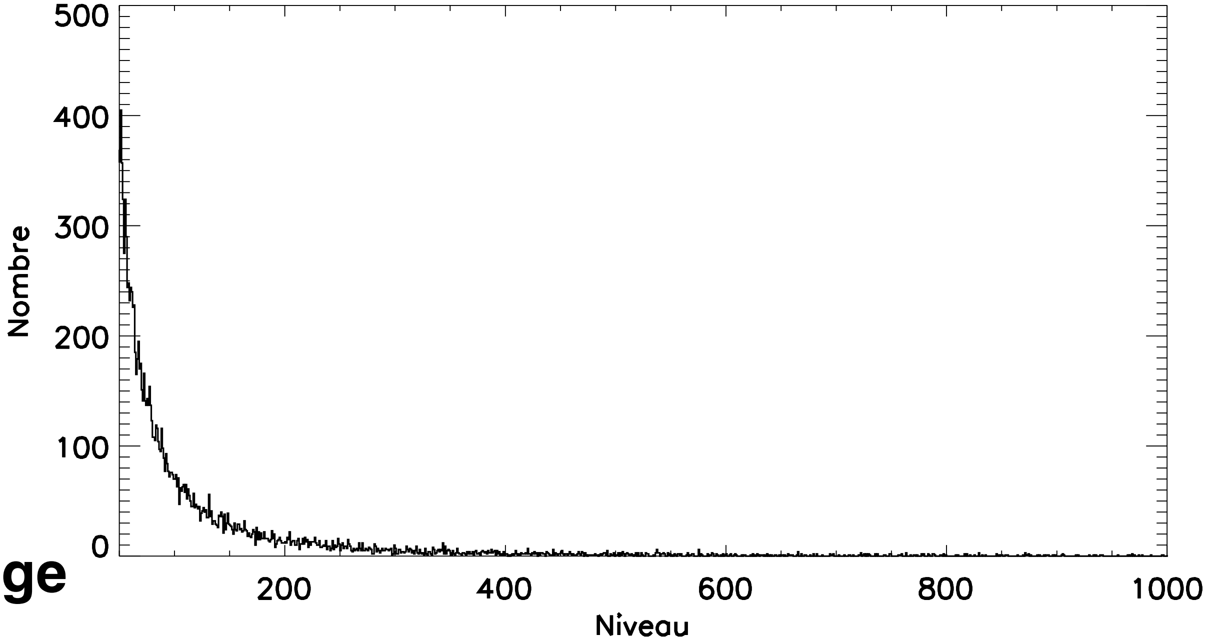
**=> Decrease exposure time?** (but this would also reduce the signal and S/N!)
**=> Decrease temperature** (very efficient)

**Special issue in IR range (≳ 4 $\mu$m) :**

- **Background sky is bright and varies rapidly**
- **Dark current also includes thermal emission from the instrument (thermal charges in CCD + photons *emitted* by the instrument)**

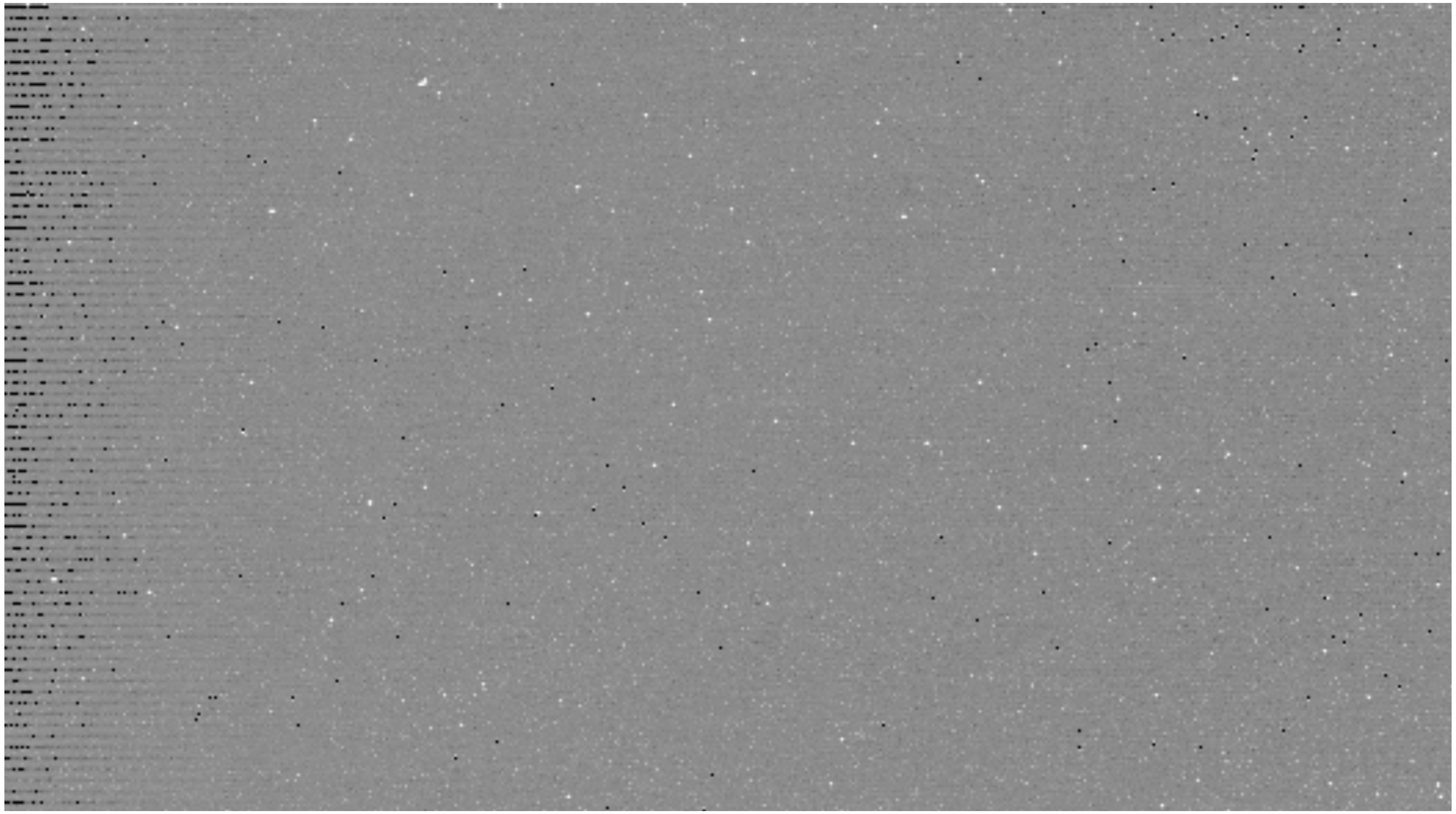


# Playtime

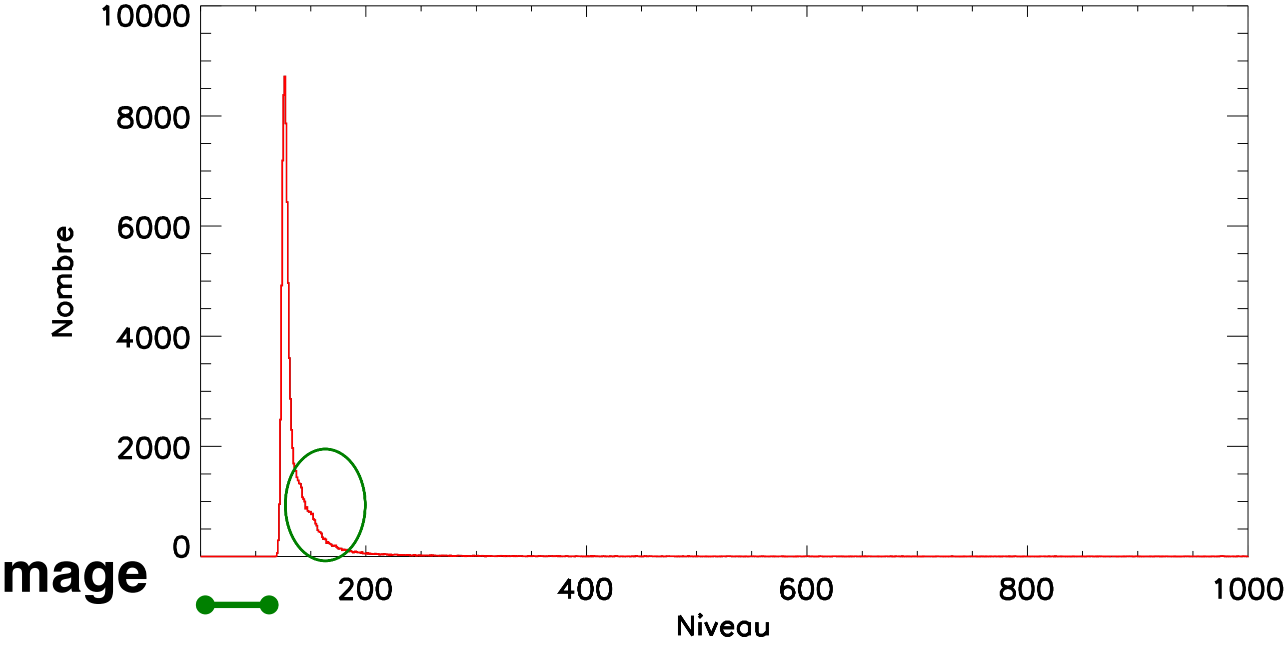


**Are histograms helpful?**

- **Which image?**
- **What does it says about image content?**

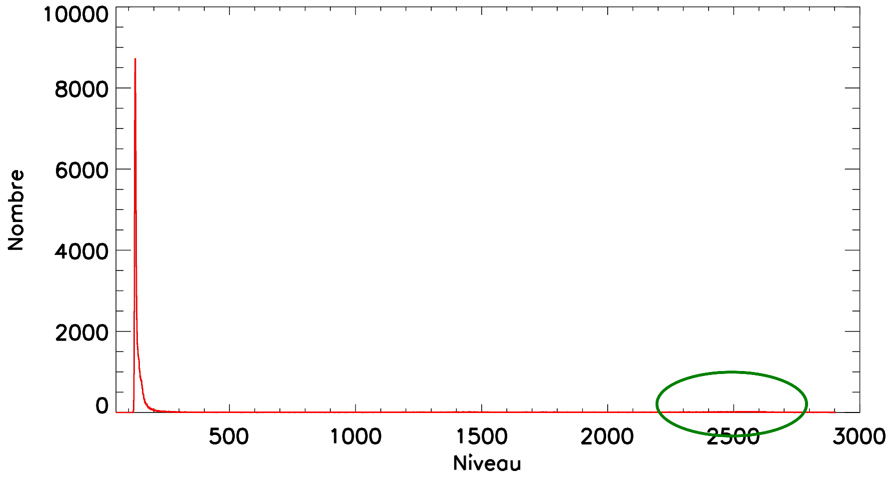


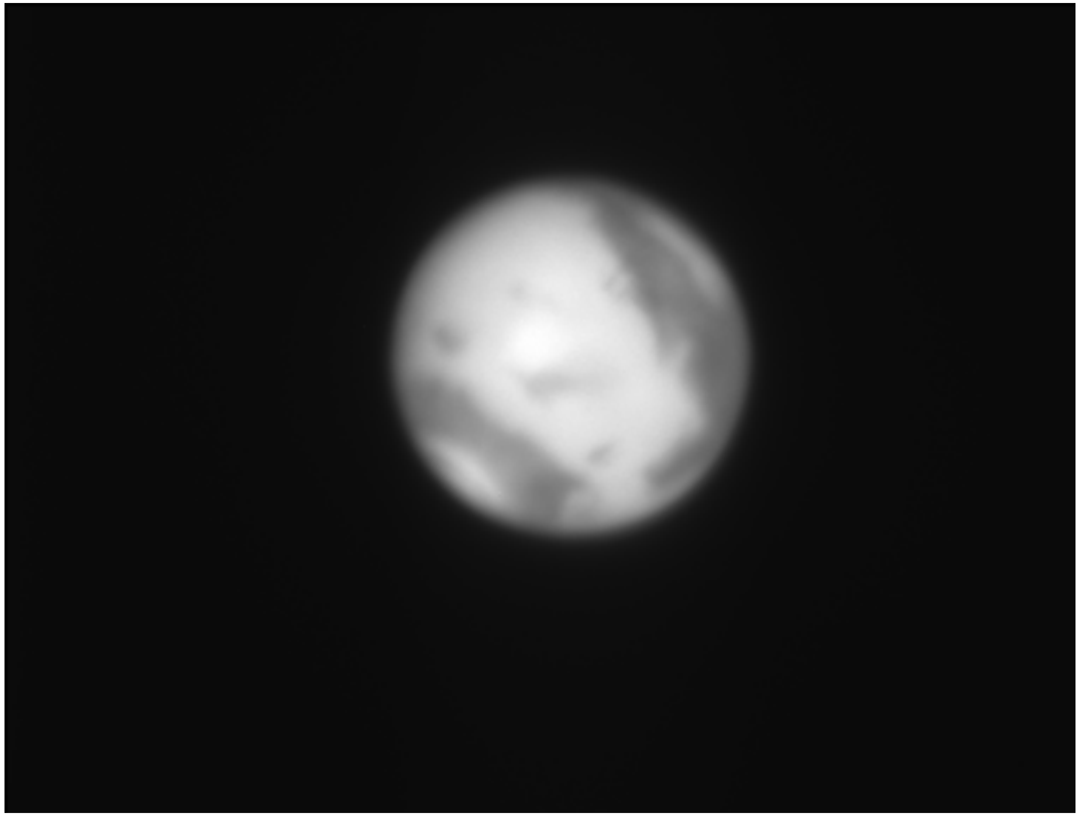
# Playtime



**Are histograms helpful?**

**- Which image?**
**- What does it says about image content?**



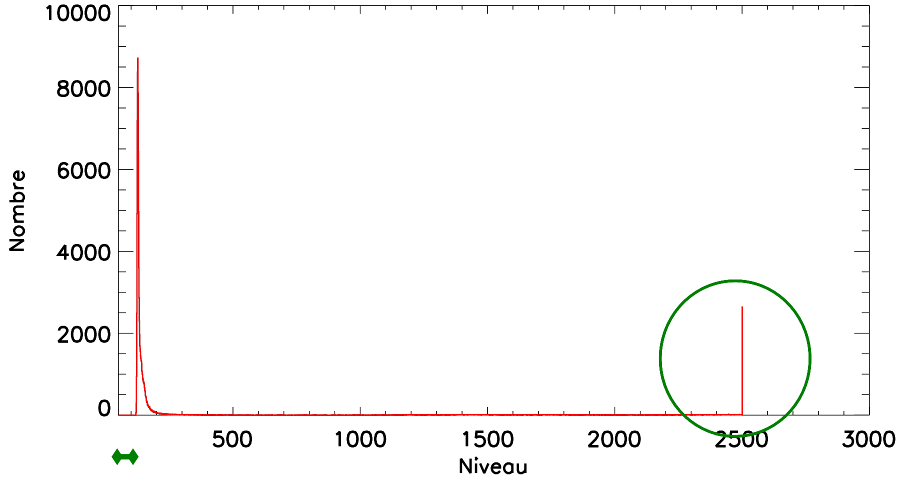


Not easy to distinguish from the dark image (mostly trailing high values)

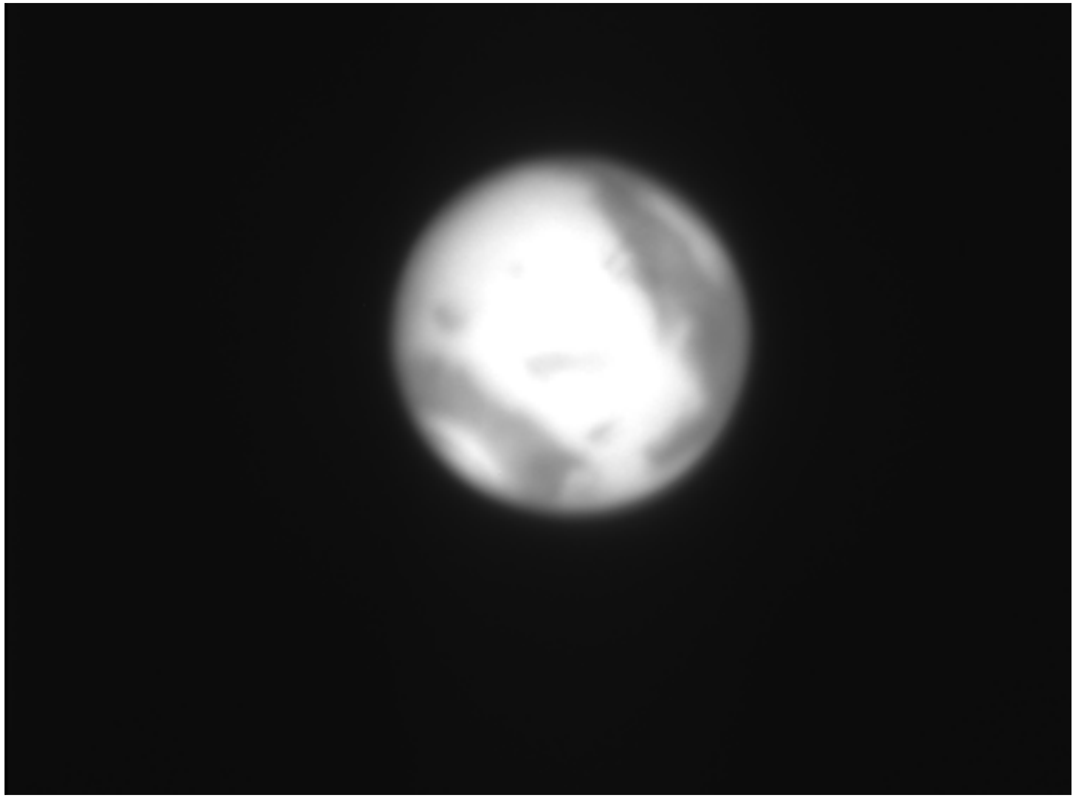
# Playtime

## Are histograms helpful?

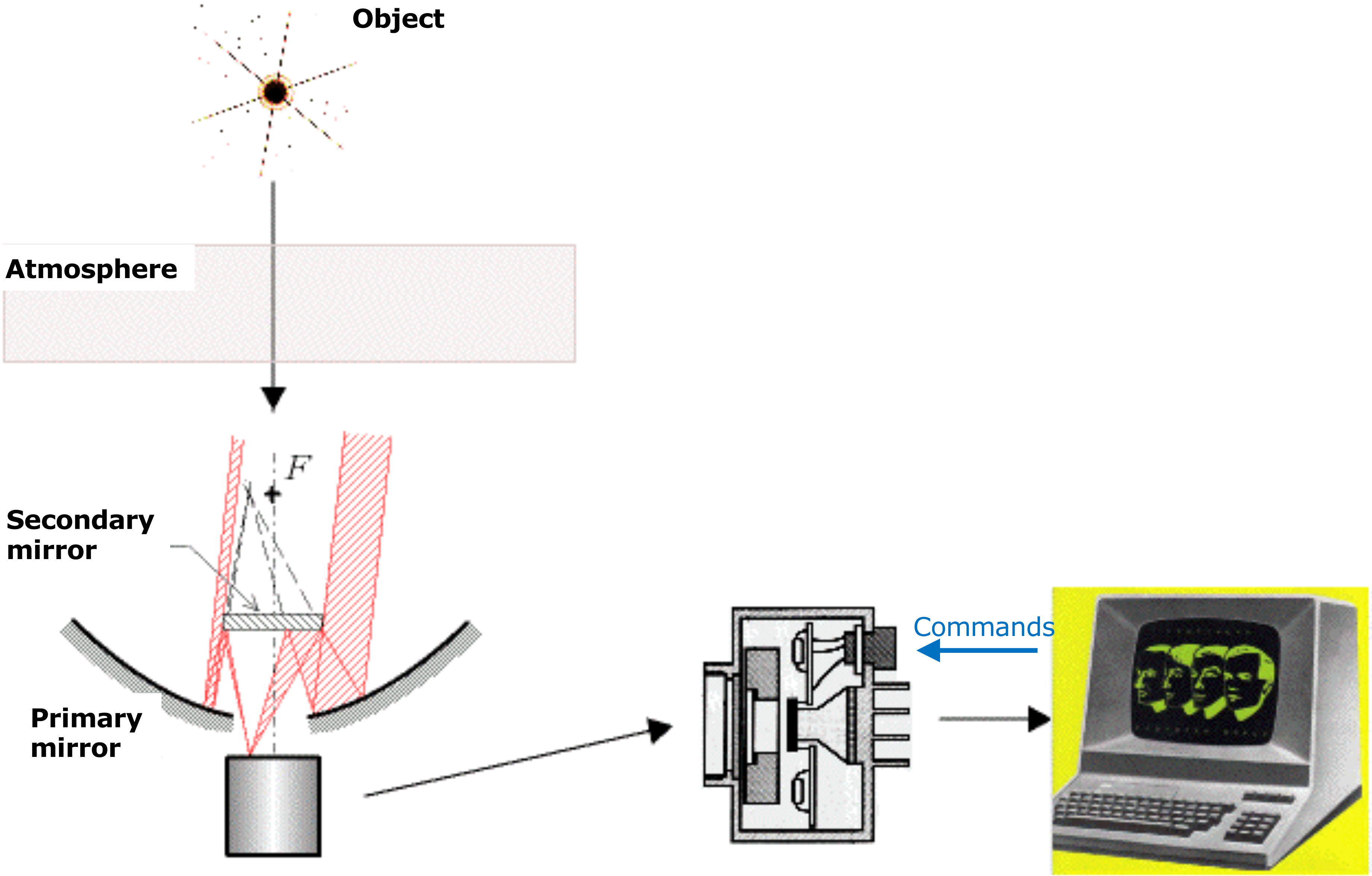
## - Same image, saturated



But saturation and offset are readily noticeable



# Acquisition process in astronomy imaging



**Object**

**Atmosphere**

**Secondary mirror**

**Primary mirror**

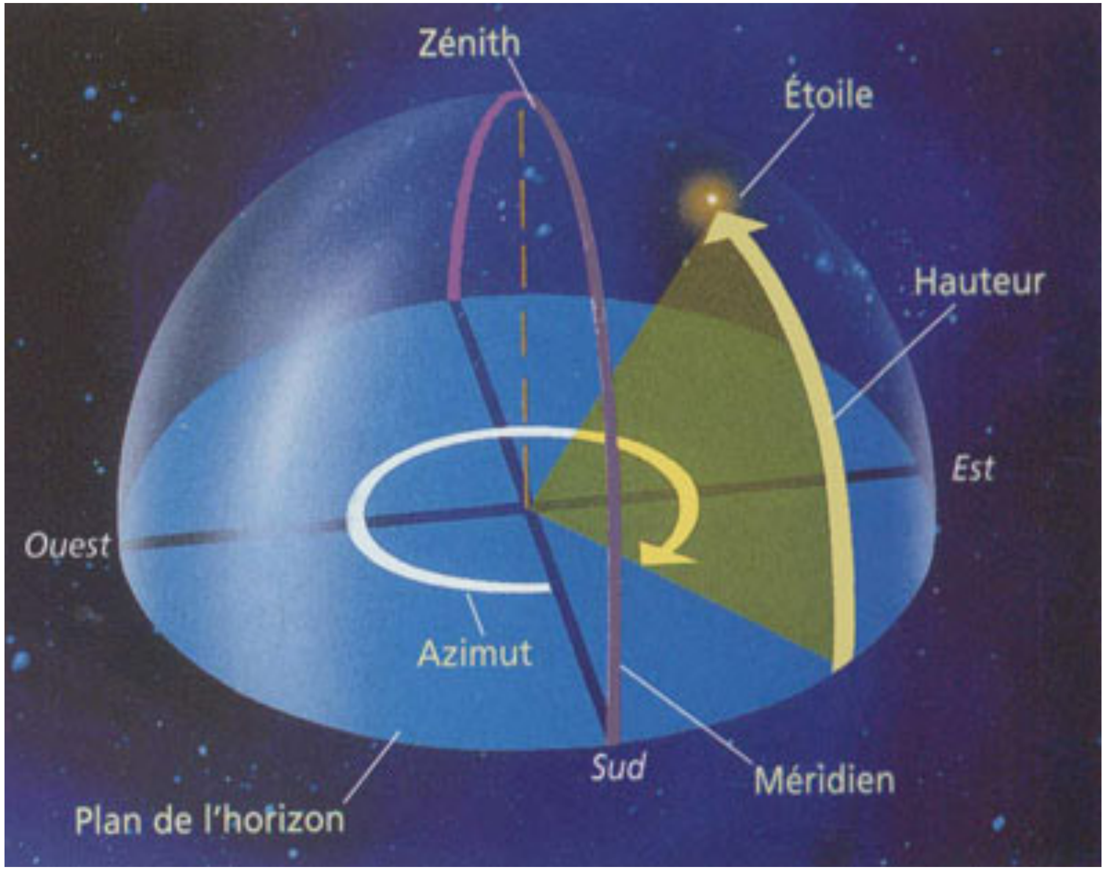
Commands

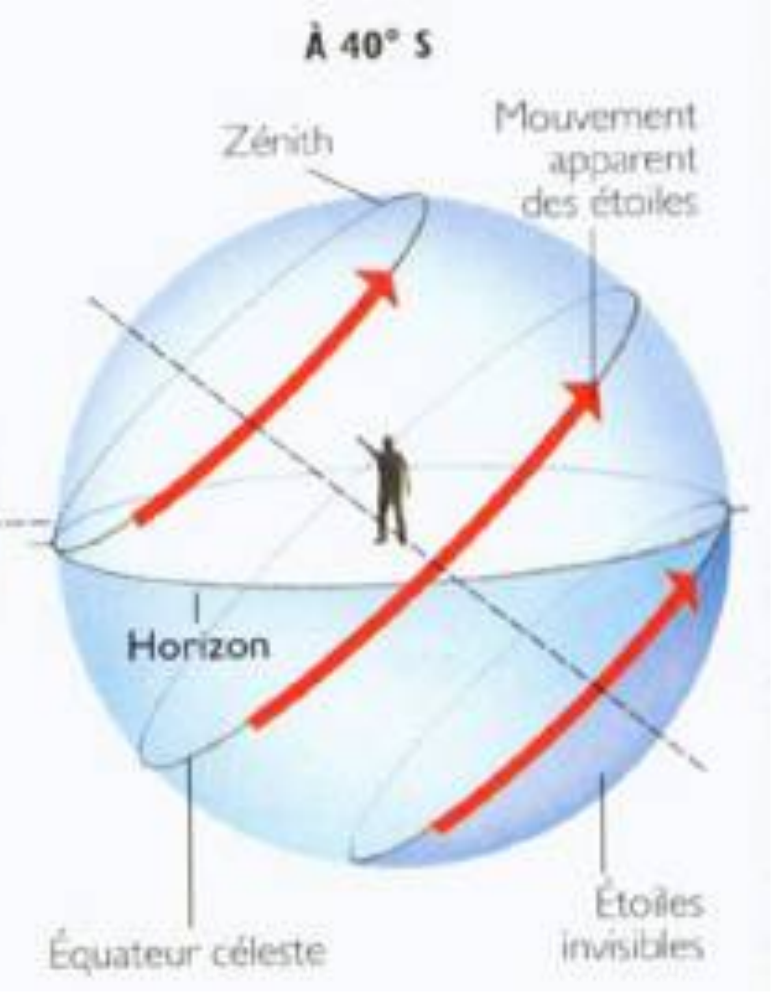
**Telescope**

**Camera & filters**

**Computer**

# Coordinates for observation: horizontal coordinates





**Simple: azimuth (a) and elevation (h)** [wrt horizon]

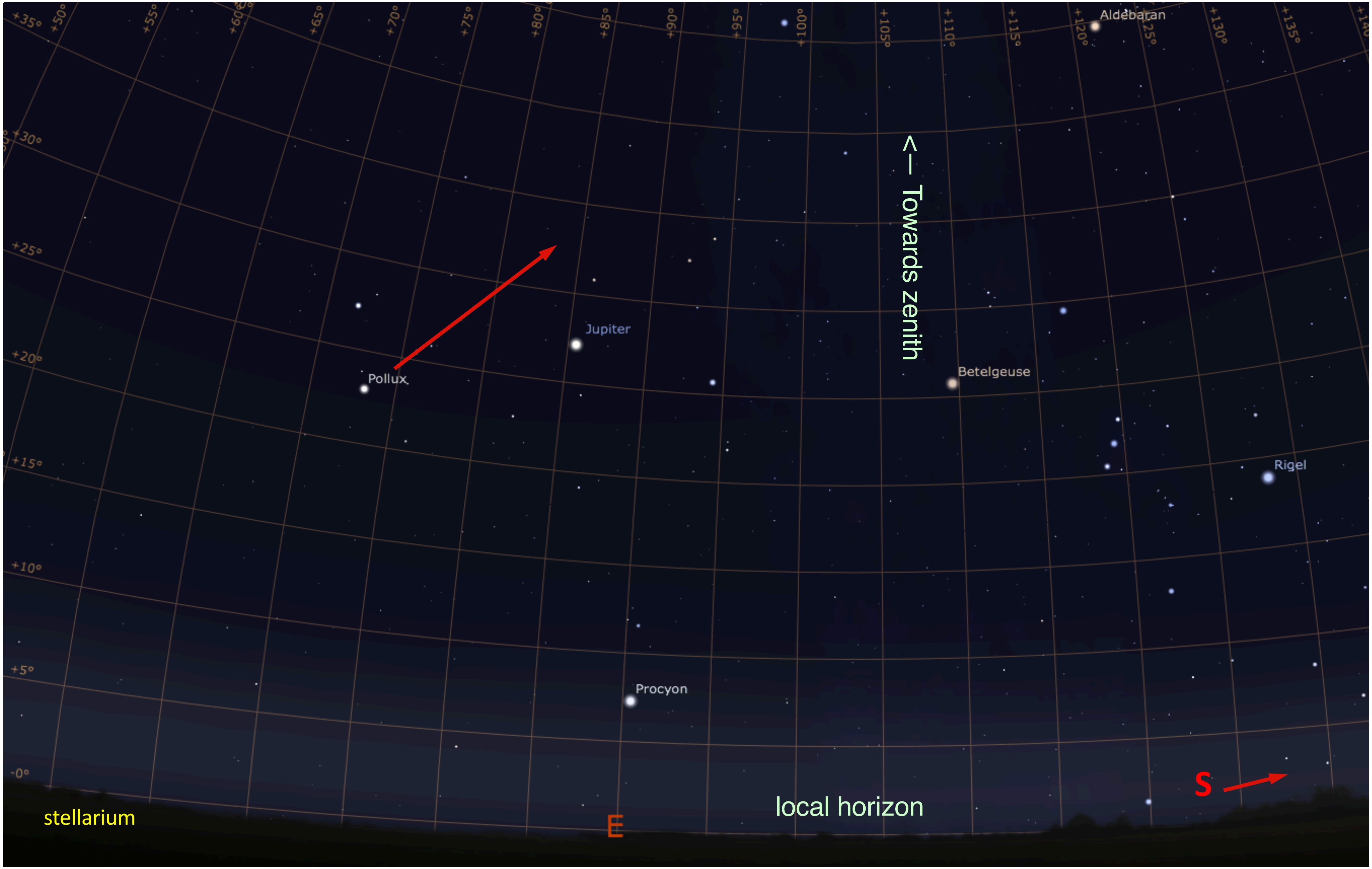
**Problems:**

- **Depend on time and place => not fit to catalog objects with positions**
- **Stars move around the poles => both coordinates change overnight**

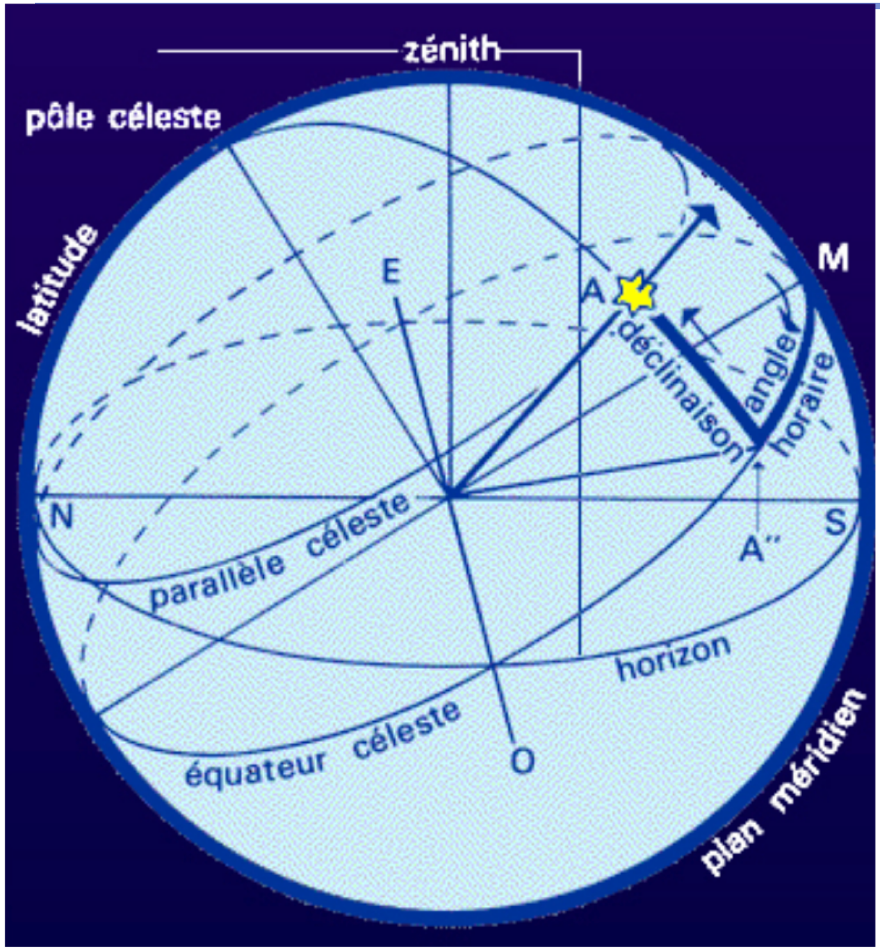
(French = coordonnées azimutales)

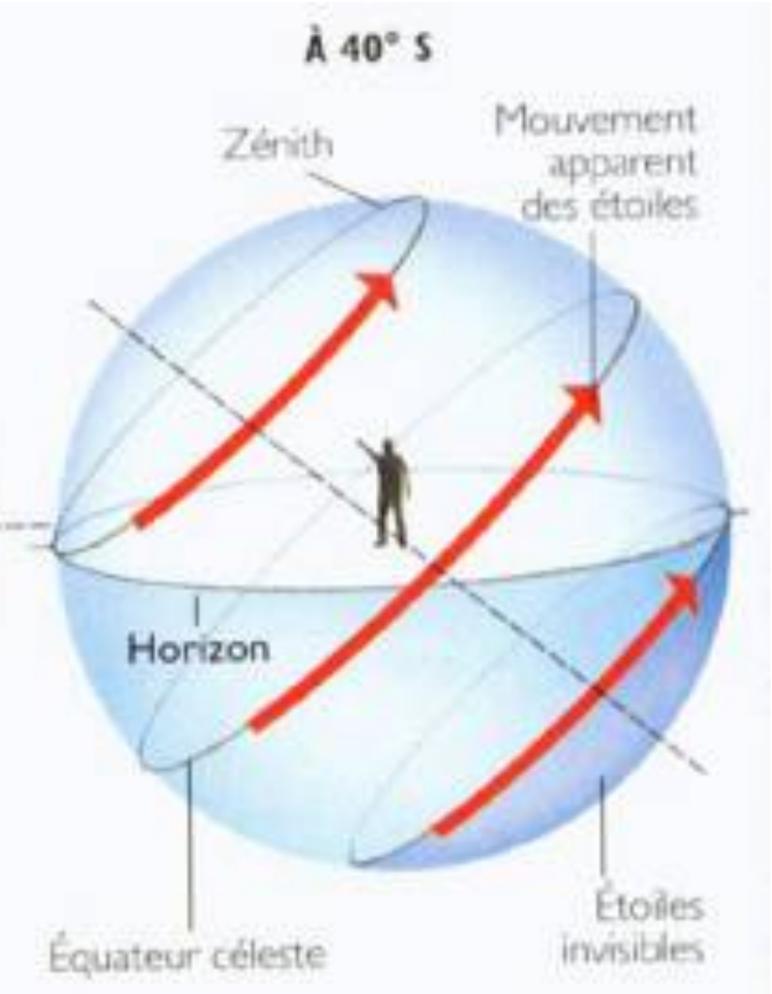
http://www.astrosurf.com/toussaint

# Horizontal coordinates



# Coordinates for observation: equatorial coordinates (1)





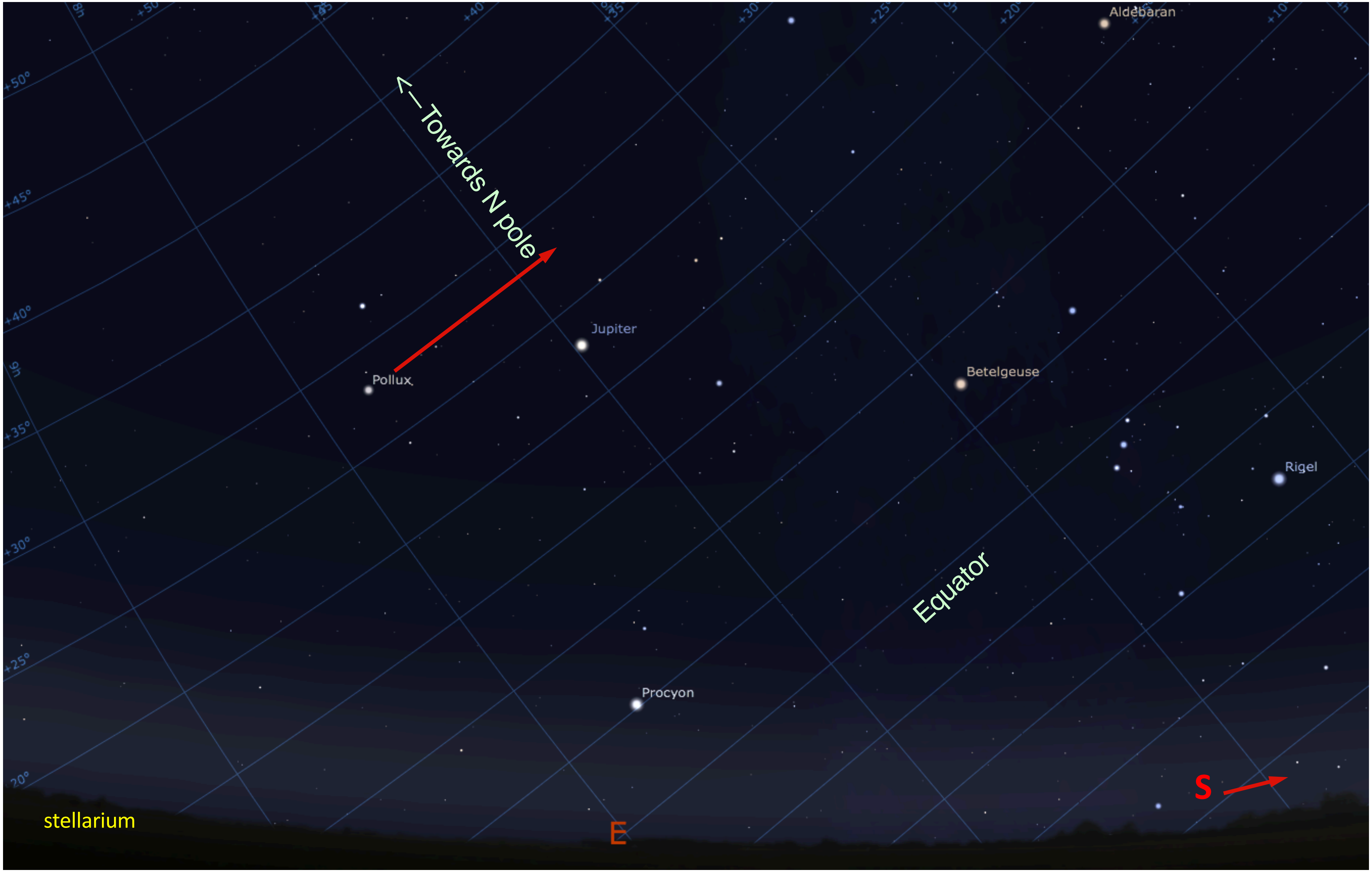
**Declination ($\delta$)** [wrt Equator] **and hour angle (H)** [wrt meridian]

- **Pole distance is constant => only one coordinate changes overnight**
- **H referred to local S direction** (= meridian), practical on the telescope

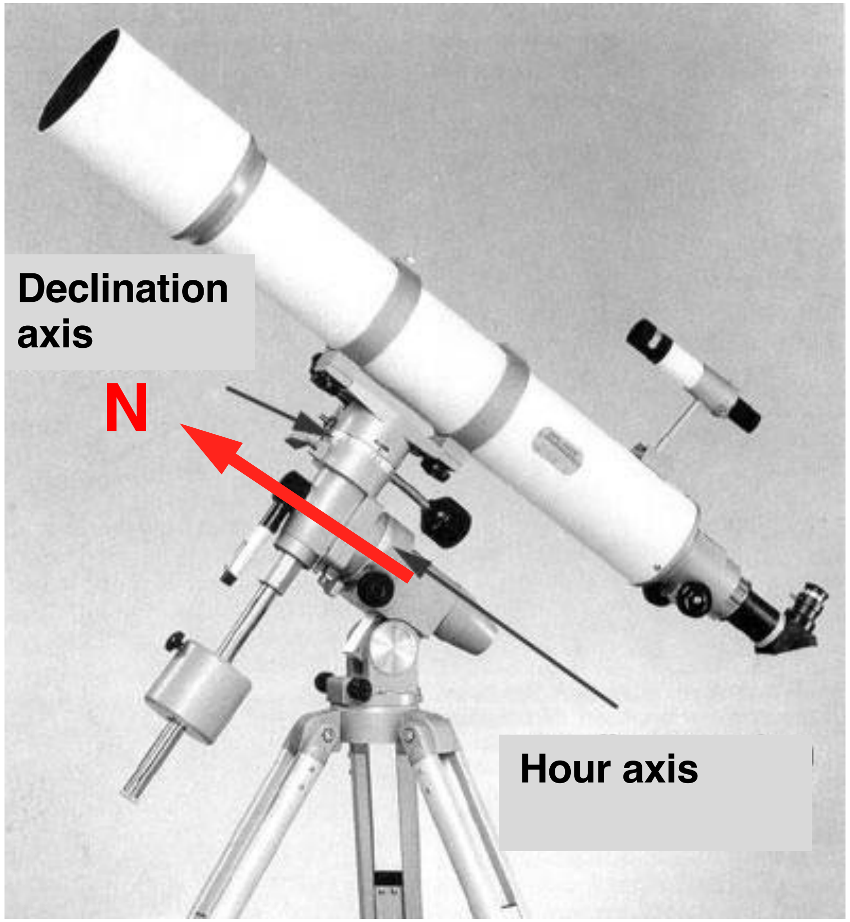
(French = coordonnées horaires – the English word is ambiguous)

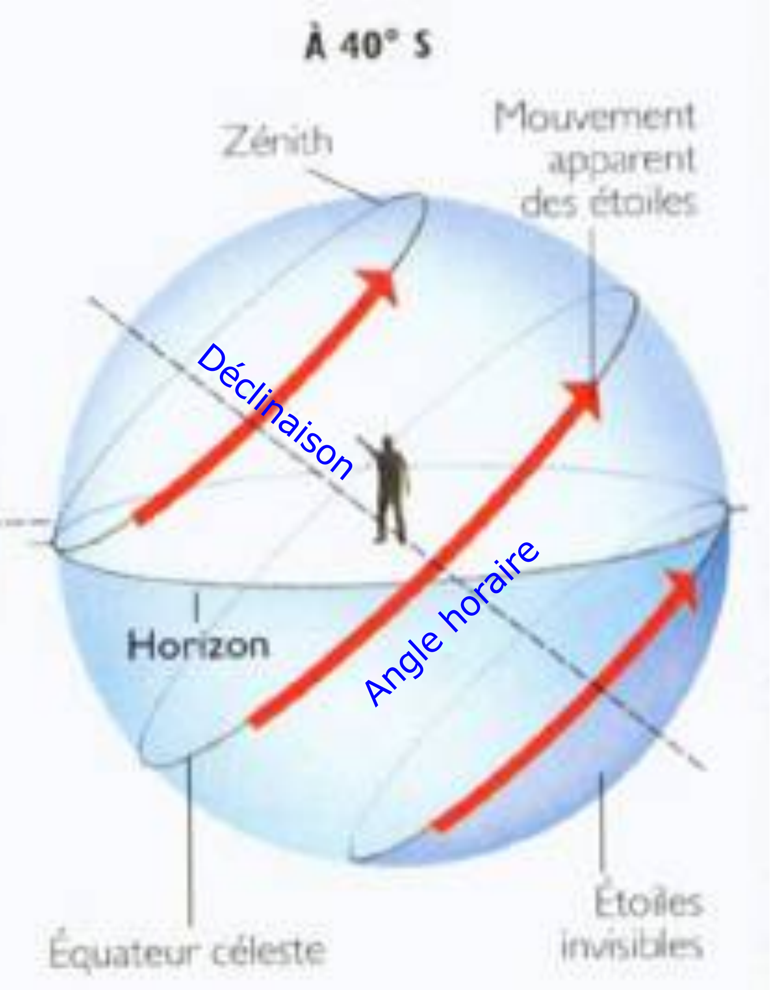
https://www.universalis.fr/encyclopedie/coordonnees-horaires/

# Equatorial coordinates



# Coordinates for observation: Equatorial mount





- **One axis parallel to Earth polar axis**
- **To follow one object overnight: just need to rotate at the same speed,** declination remains constant

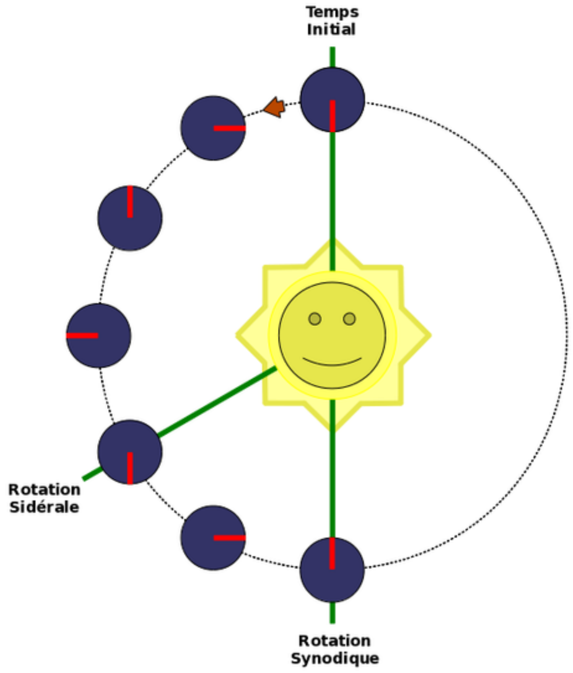
# Fun and educational question

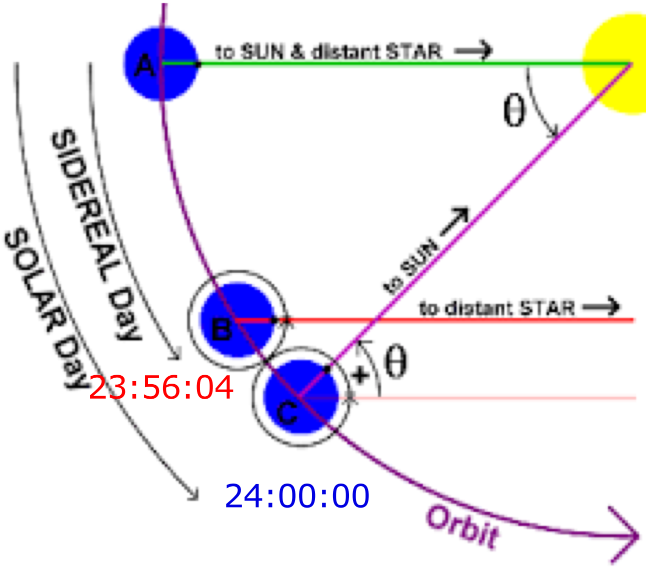
**How long does it take for the Earth to revolve around herself?**

Answer **: depends on ”relative to what”**

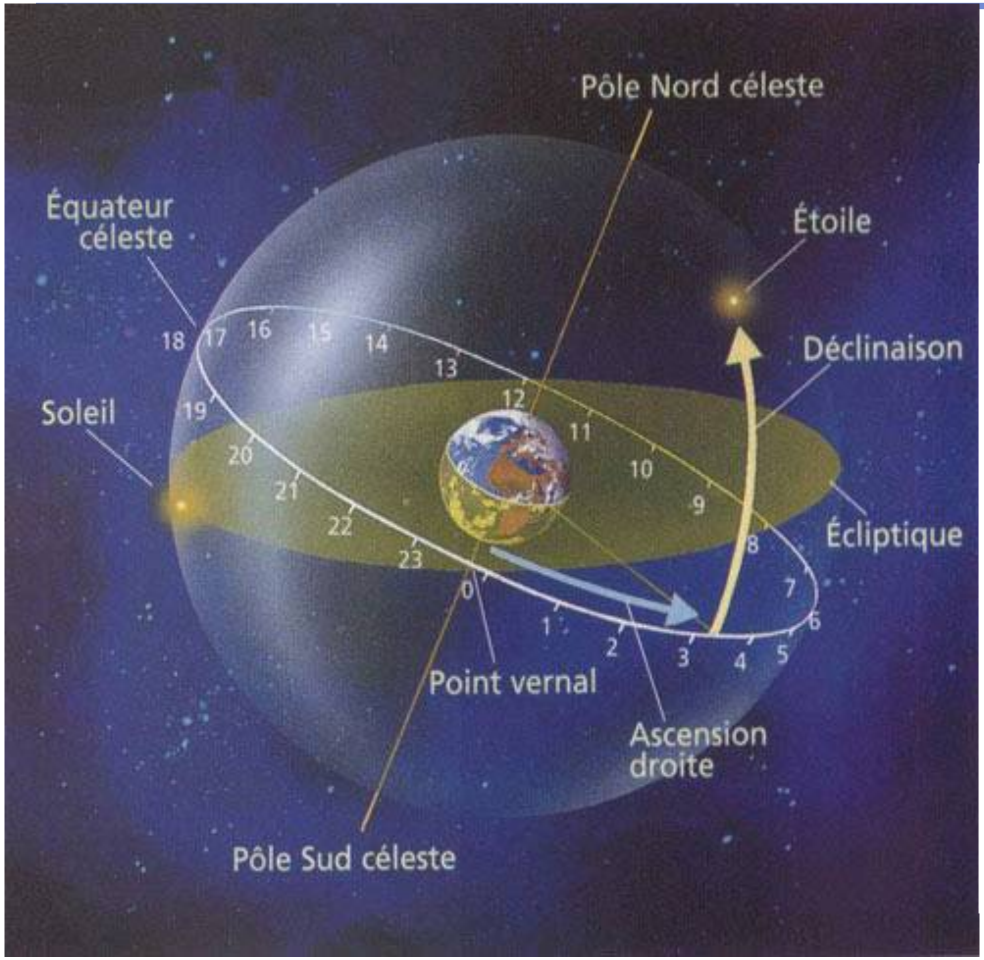
**24h = time required for the Sun to return to the same position in the sky**
**= *mean* solar day** (averaged over the year - depends on Earth-Sun distance)

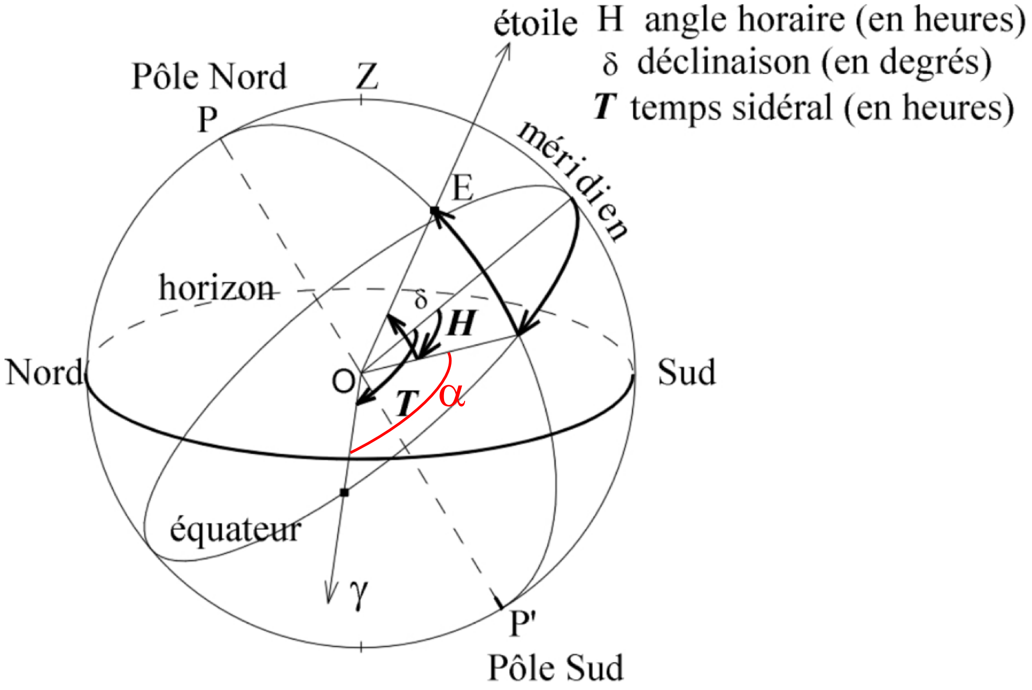
**23h 56’ 04” = time required for a star to return to the same position in the sky**
**= sidereal day** (period in an ~ inertial frame)





# Coordinates for observation: equatorial coordinates (2)





**Declination (δ)** [wrt Equator] **and right ascension (α)** [wrt vernal point]

- **Allows cataloguing of objects** (absolute, on short time scales)
- **2nd fixed coordinate defined by correcting observer's location**
  **(right ascension α -** requires a reference point to be defined on the sky**)**

(French = coordonnées équatoriales)

# Vernal equinox and sidereal time

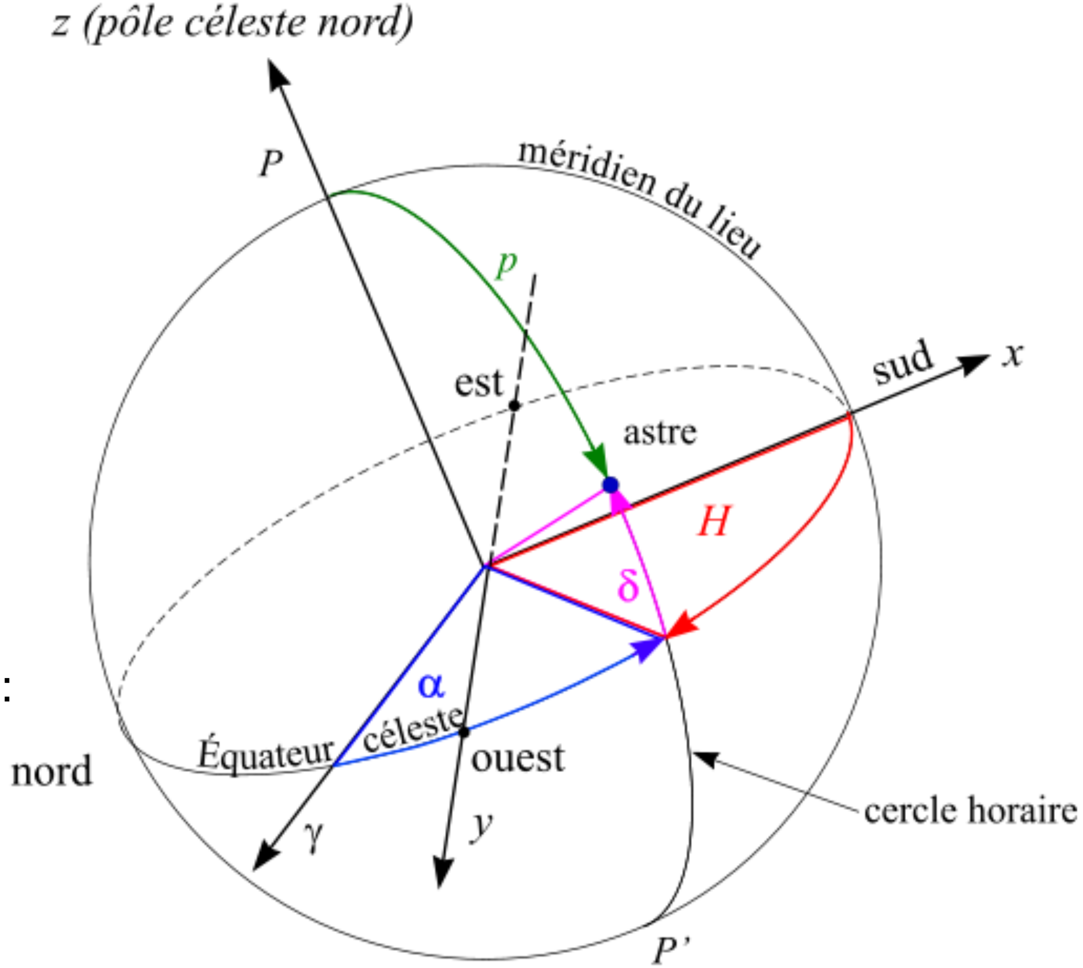
**Direction of Sun at N spring / March equinox ♈** (stands for Aries) or $\gamma$
**= a reference direction in the Equator plane** (French: point vernal)

**Local sidereal time $\Theta$ = hour angle of the vernal point (fct of time and longitude)**

**Right ascension of an object $\alpha$ (fixed):**
**Sidereal time - hour angle**

$$\boxed{\Theta = H + \alpha}$$

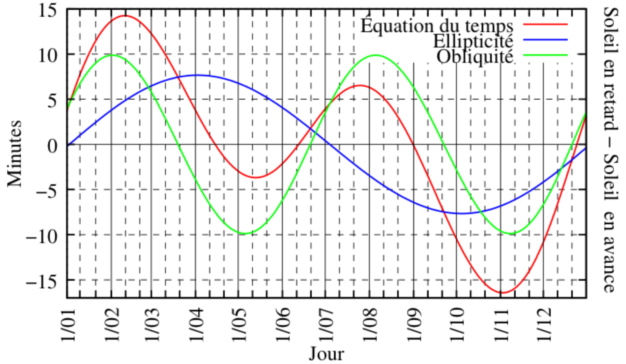
**In practice**: you know $\alpha$ from a catalogue,
you need H to point the telescope manually:
=> Use a computing applet
(inputs: date, time, location, $\alpha$)



# Solar and sidereal times / subtleties

**Local sidereal time Θ = hour angle of vernal point** (fct of time and longitude)
**= right ascension of objects at local meridian** (always)

The **true solar time** depends on the shape of the Earth orbit and axis inclination
**Equation of time** = difference between mean (usual) and true solar times, an oscillating function of solar time over the year



See Equation of time on Wikipedia or anywhere

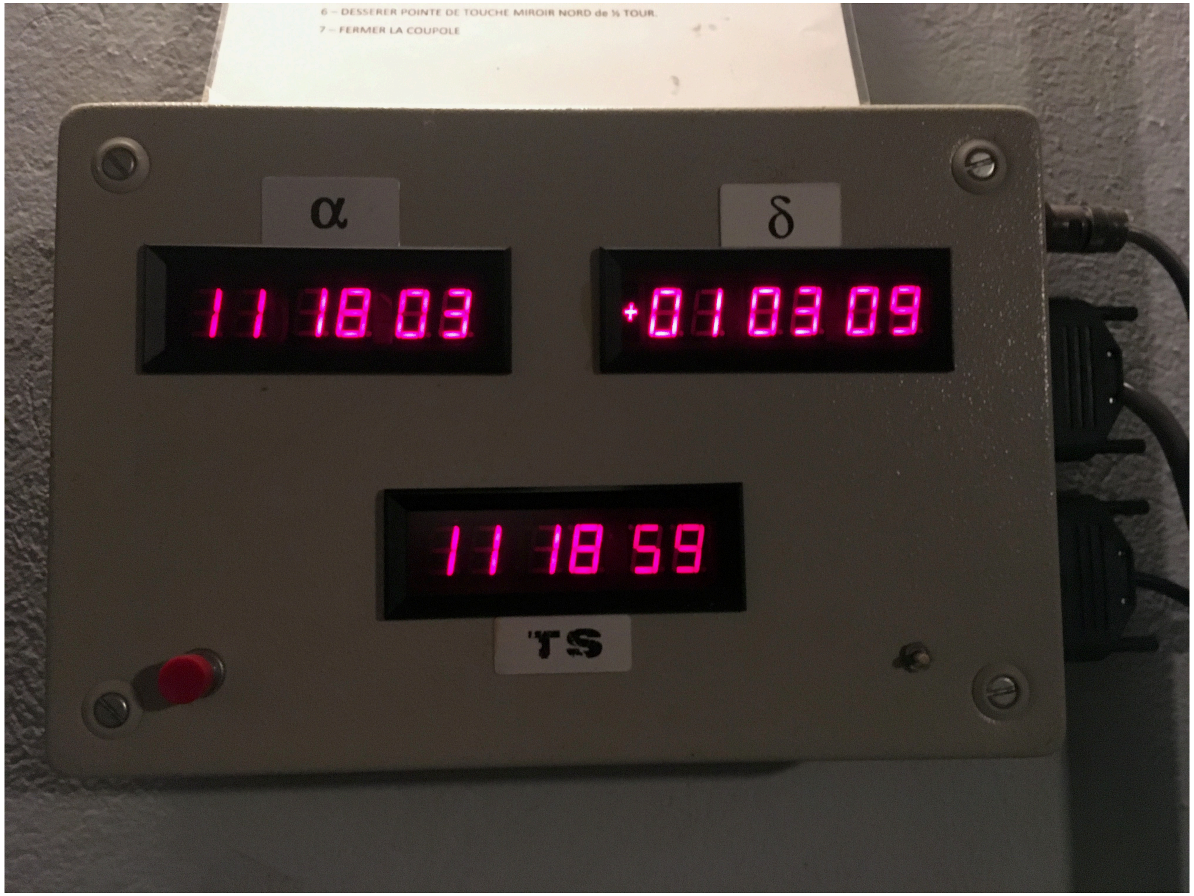
http://media4.obspm.fr/public/AMC

- Additionally: the vernal point drifts with Earth precession (period 26 000 yr, ~ 50''/yr)

=> Equatorial coordinates are provided for restrained periods (J1950, J2000) or current date

# Solar and sidereal times

Typical astronomical clock providing Mean solar time & Sidereal time: the Esclangon clock
(Paris Observatory, bât Perrault)



Pointing display at OHP’s T120 – *figure it out!*
Pointing ~ meridian — α / δ provide the pointing direction
Image time (UTC+2) = 27/3, 00:39
Longitude: 5° 44’ E
(TS = sidereal time)

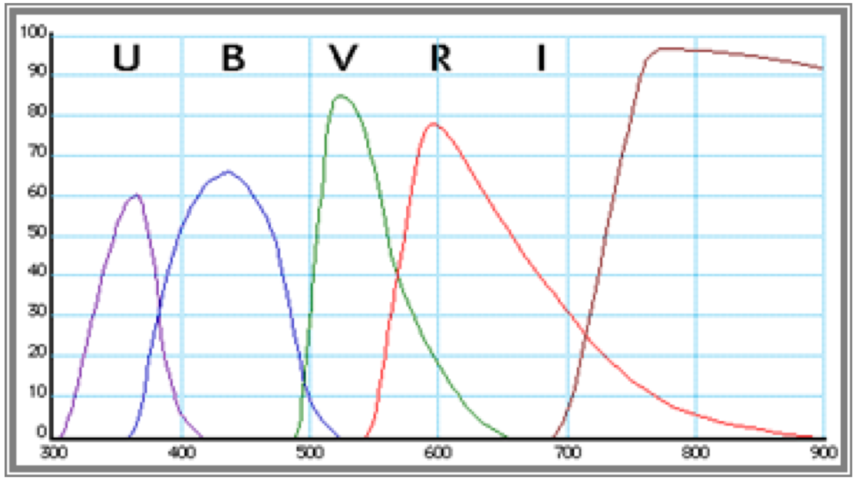
# Filter imaging

## Incident light observed through filters

**Various types**

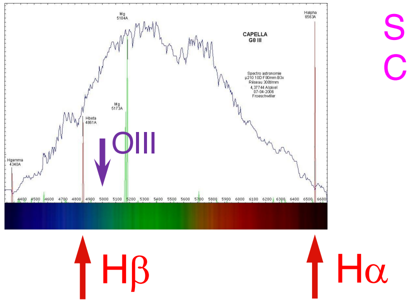
**- Broadband: U, B, V, R, etc**
(as many photometric systems as providers)

**=> Isolate a part of the visible spectrum**
standard colour images = RGB composites



**- Narrow: Hα** (656,3 nm): H, dark red
**OIII** (500,7 nm): $O^{2+}$, turquoise

**=> Isolate atomic transitions**



Spectrum of Capella (G8)

Same wavelength scale

# Filter imaging

**Measured flux equals Source x Filter**

$$I = \int_{\lambda_0}^{\lambda_1} I_{source}\; T_{filtre}\; d\lambda$$

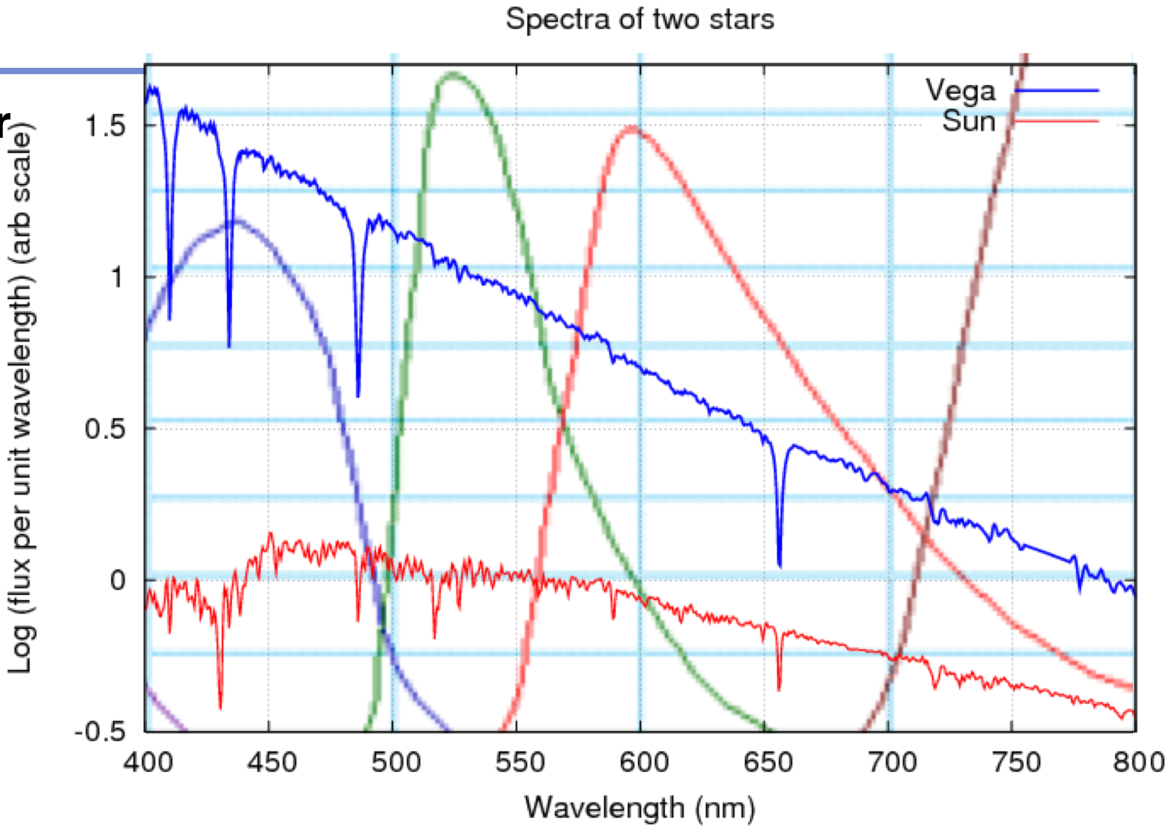
$\Rightarrow$ **Flux reduction**

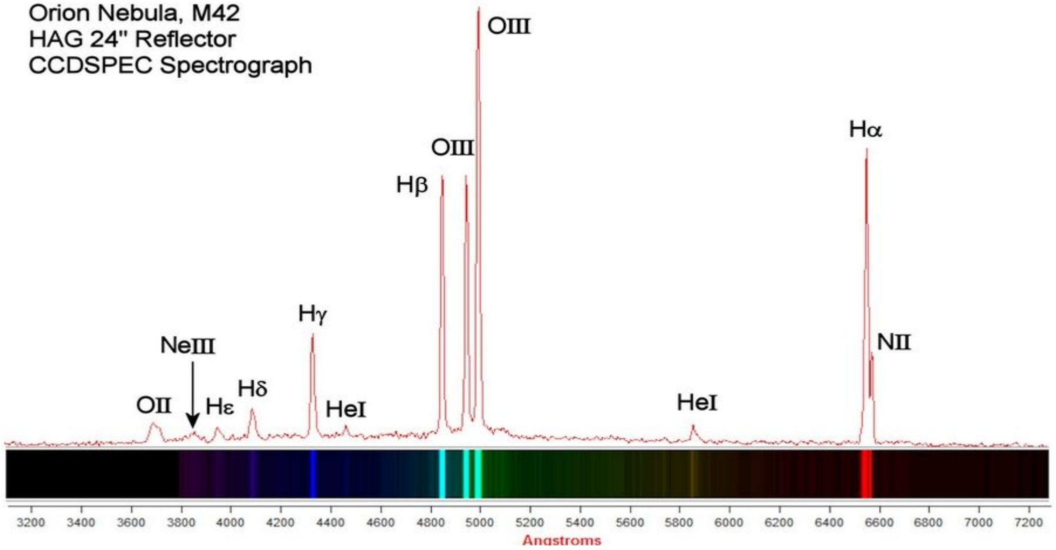
Also needs to multiply this by detector spectral response (a function of wavelength)

**=> Exposure time to be adjusted depending on both filter and source**

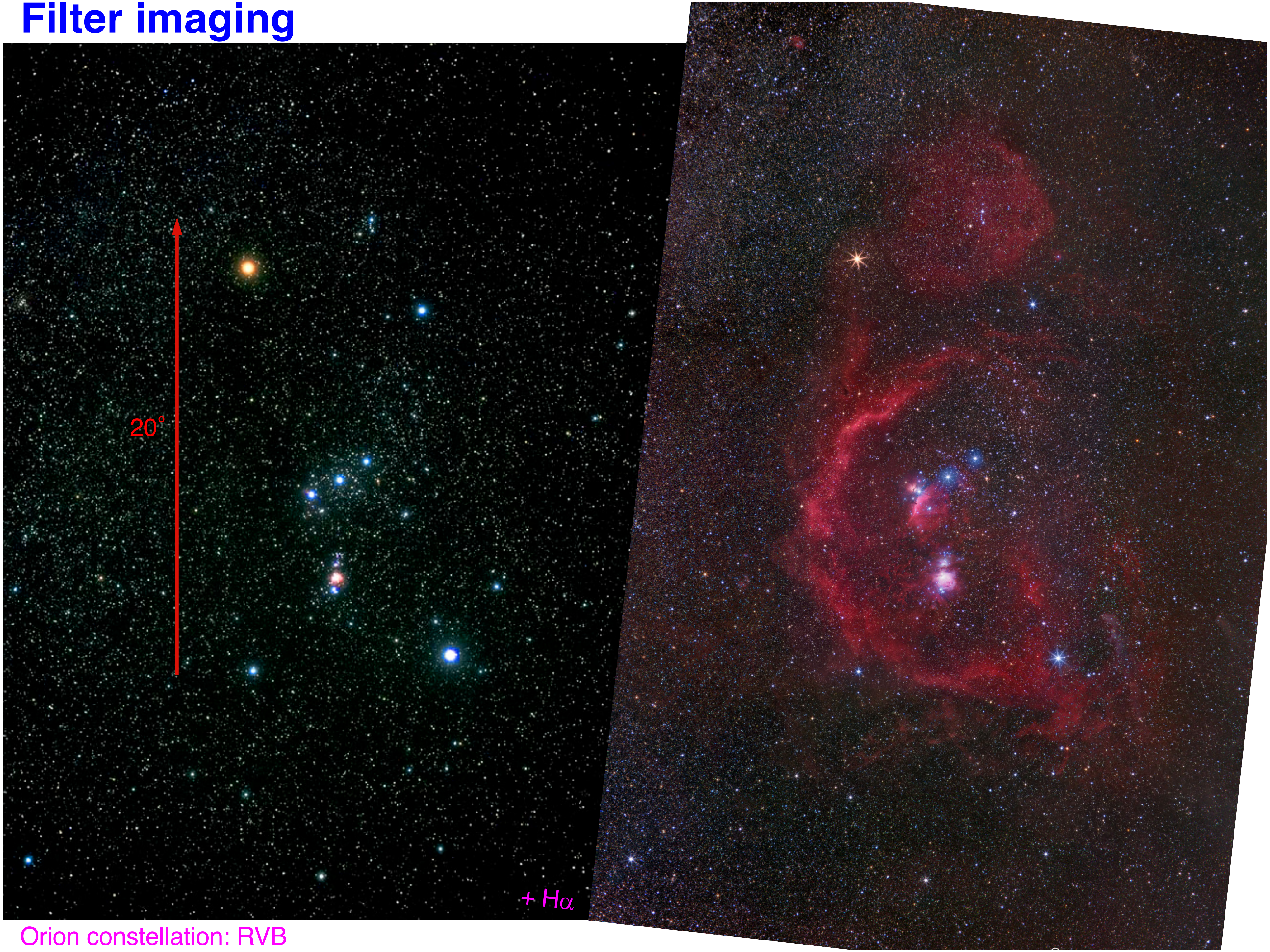
**Narrow filters are used e.g. to measure emissions of hot gas**

M42 / Orion





# Filter imaging



Orion constellation: RVB

# Filter imaging: difficulties

Ceres in front of M100, T120/OHP
BVr composite, 27/3/2023

- Balance is difficult to get right
(need reference stars)
- Internal deformations
- Different PFS /resolution in each filter

⇒ colored haloes

Often frustrating
RGB composites have limited scientific interest ;(

# Signal and noise

## Every measurement is subject to uncertainty

- **Readout noise (~10 to 100 $e^-$ / pixel)**
  - **- Charge transfer efficiency**
  - **- Accuracy of analog amplification**
  - **- Usually dominates**

⇒ S/N increases with longer exposures

- **Thermal (Johnson) noise**
  - **- Uncertainty on accumulated thermal charges**
  - **- Poisson distribution =>** $\sigma_{therm} = \sqrt{N_{therm}}$

⇒ S/N increases with
- longer exposures
- lower temperatures

- **Photon noise**
  - **- Intrinsic variability of source**
  - **- Poisson distribution =>** $\sigma_{source} = \sqrt{N_{source}}$

⇒ S/N increases with
- longer exposures
- averaging

**Various noises combine in quadratic sum**
(because they are assumed independent)

**Signal-to-noise ratio = Average corrected signal / Overall noise**

# Signal and noise

**Measured signal :** $S_{tot} = S_{source} \times Flat + Dark$

**(Overall noise)²:** $\sigma^2_{tot} = \sigma^2_{source} + \sigma^2_{dark} + \sigma^2_{lecture} + \sigma^2_{numer}$

**Total noise = Root mean square of various noises**
(i.e.: combine in quadratic sum — because they are assumed independent)

Goal: - increase signal / noise ratio
- minimize *relative* noise

**Signal-to-noise ratio = Mean corrected signal / Overall noise**

# The Poisson distribution

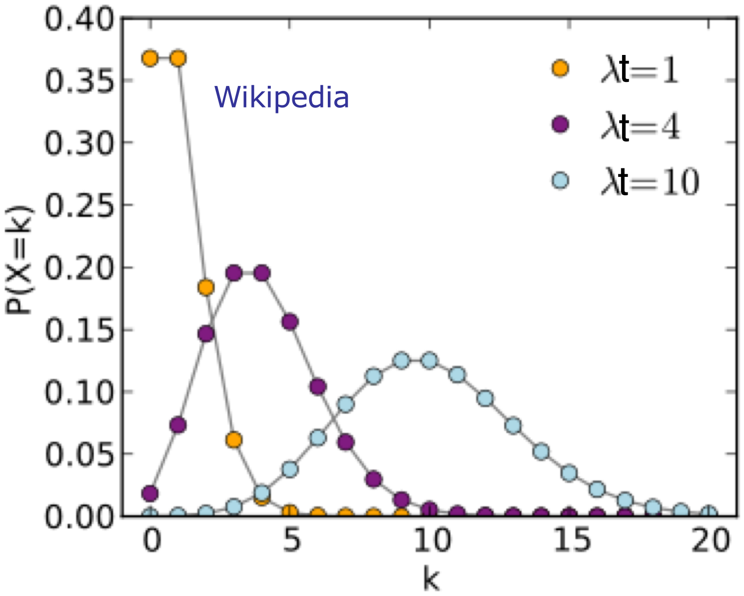
Assumptions: - events are random and independent
- event frequency is constant ($\lambda$)

**Examples: photon emission; creation of thermal charges**

**Probability mass function (to have k event during interval t):**

$$P(k) = e^{-\lambda t}\frac{(\lambda t)^k}{k!}$$

Demonstration: see MPA site
http://media4.obspm.fr/public/AAM/pages_proba/poisson.html



Tends towards a Gaussian distribution when $\lambda$t is large (central limit theorem)

**With N = $\lambda$t:**
**Mean = N** (nb of photons received during t) => Predictible

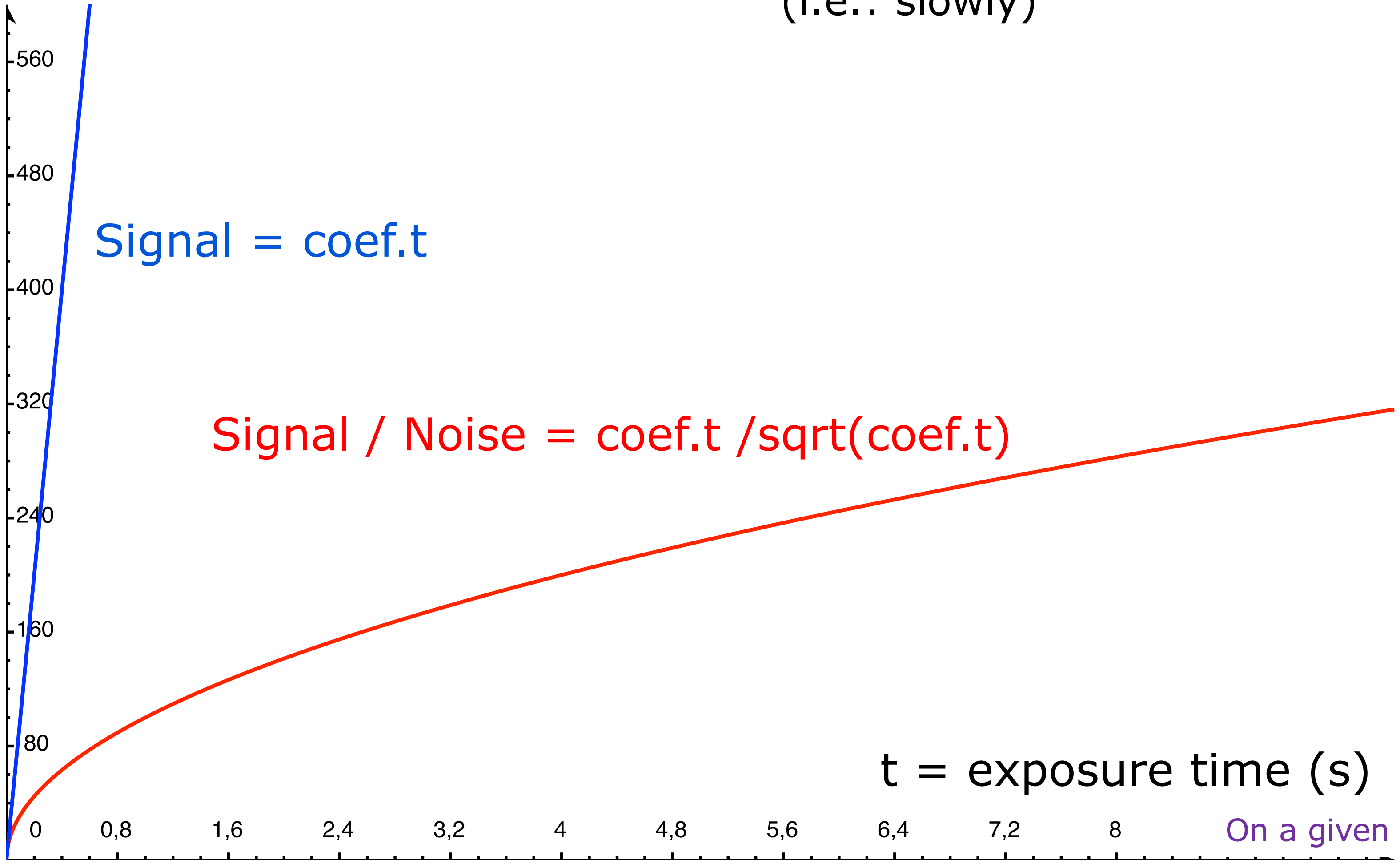
**Standard deviation:** $\sigma = \sqrt{N}$ (mean variation around this value, between successive measurements)
=> Random: *this* is noise

# The Poisson distribution

Signal to noise ratio = $\frac{S_{source}}{\sigma_{source}}$ = N / sqrt(N) = sqrt(N) = sqrt(ϕ.t)

(for Poisson distribution)

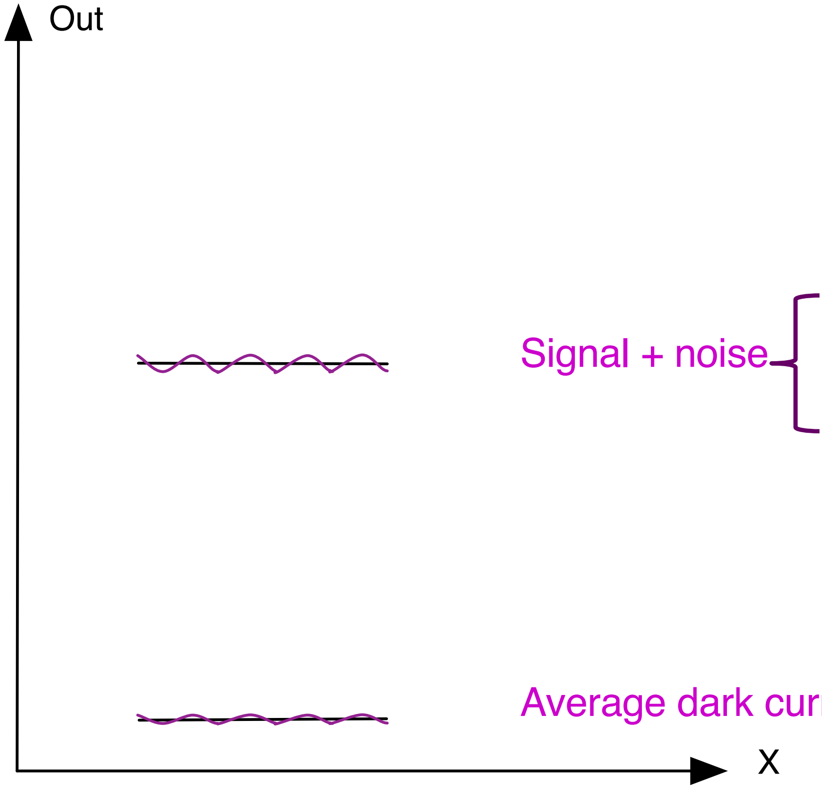
S/N ratio increases as the square root of t (i.e.: slowly)



On a given source, ϕ = cst

# Signal and noise

Uniform source



Signal + noise
- Photon noise ( sqrt(source signal) )
- Readout noise (constant)
- Digitization noise (low)

↑ Increase exp time

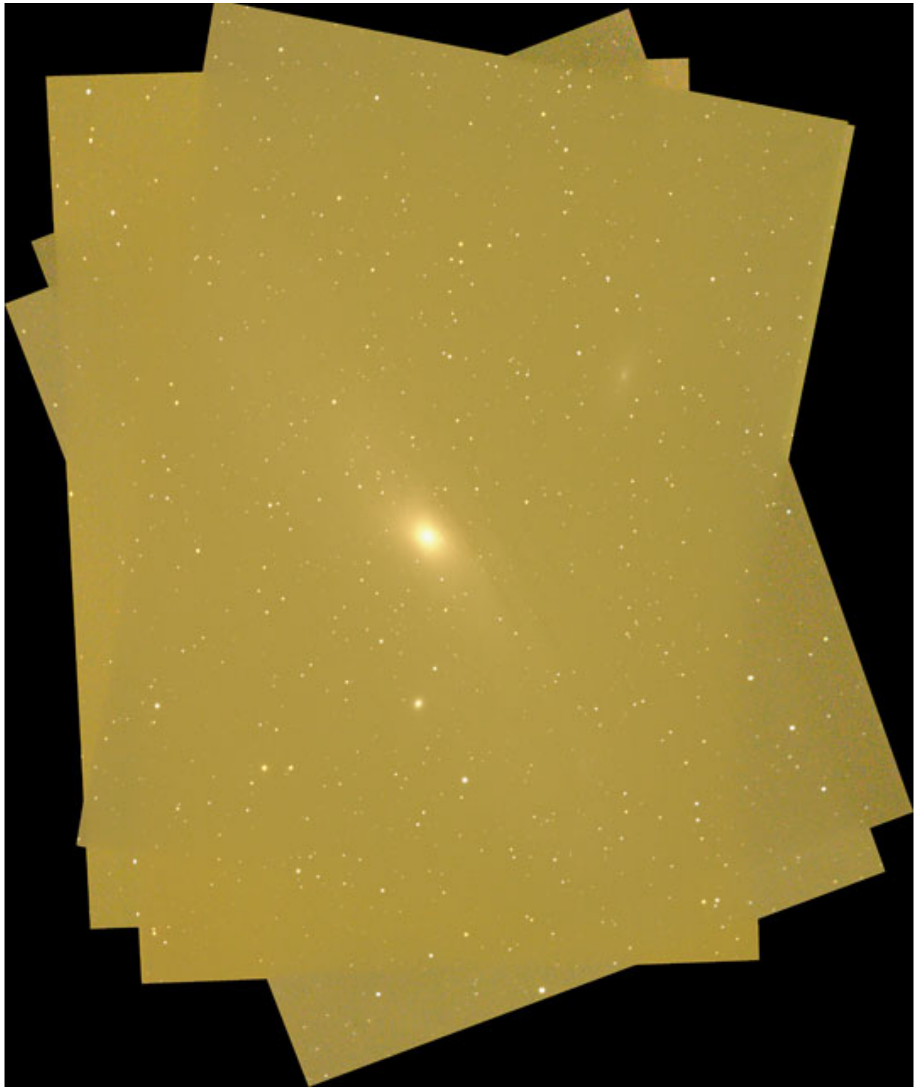
***Sum exposures?***

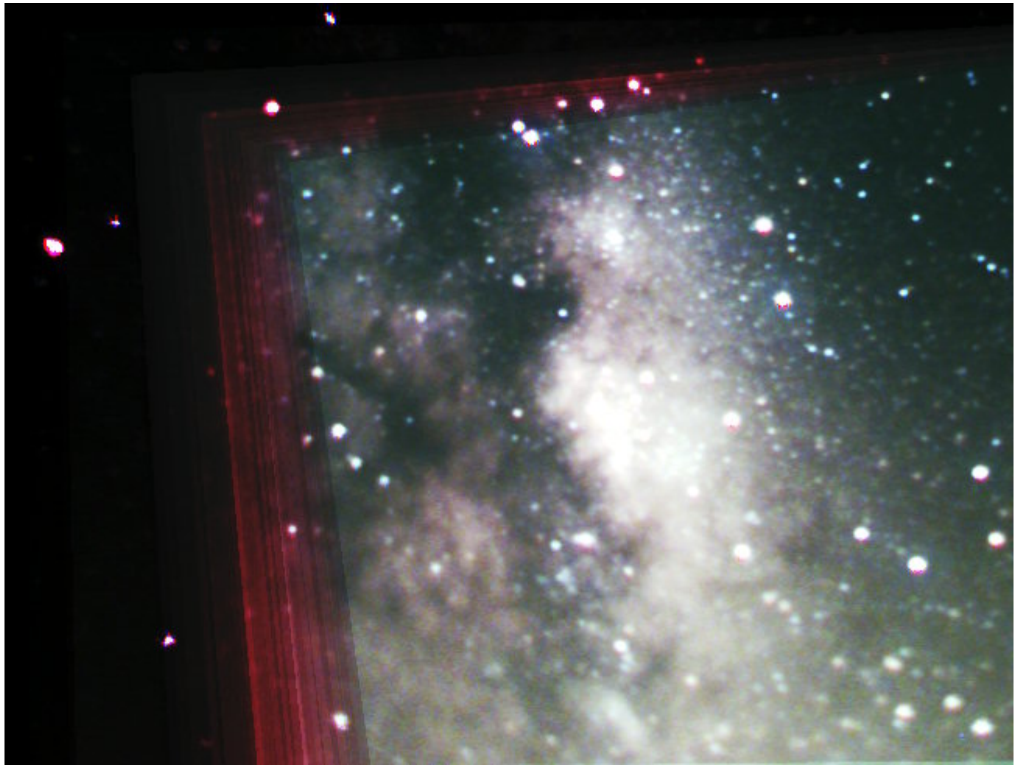
Average dark current + dark noise = ( sqrt(dark-offset) )

↓ Cool down

# Reducing noise by summing

- Successive exposures => image stacks centred / aligned on object





# Reducing noise by summing

- **Images must correspond in X/Y plane**
  **=> centring, rotation, scaling**

- **Summing, average or median over Z**
  (i.e., pixel by pixel)

**n images**

**S : average signal (over Z)**

**$\sigma$ : individual noise**

# Summing vs readout noise

| | Total signal (average) | Readout noise (std-deviation) | Signal-to-noise ratio |
|---|---|---|---|
| 1-sec exposure | Signal | $\sigma_{lect}$ | R = Signal / $\sigma_{lect}$ |
| Sum of 10 1-sec exposures | 10 . Signal | sqrt(10) . $\sigma_{lect}$ | sqrt(10) . R |
| 1 exposure of 10 sec | 10 . Signal | $\sigma_{lect}$ | 10 . R |

Signal-to-noise ratio when readout noise is
the main source of uncertainty (usual case)

=> Always better to use longer exposure when feasible
Same thing applies to binning modes

# Noise reduction techniques

- **Summing successive frames**
  - **Signals add linearly (n x S)**
  - **Readout noises add quadratically (sqrt(n) x B)**
  - **Signal to noise ratio increases slowly – always OK for dark frames or flat-fields**

- **Longer Exposure**
  - **Signals add (n x S)**
  - **Readout noise is unchanged (B)**
  - **Signal to noise ratio increases rapidly if and only if readout noise dominates!**
  - **Signal to noise ratio increases slowly whenever photon noise dominates**

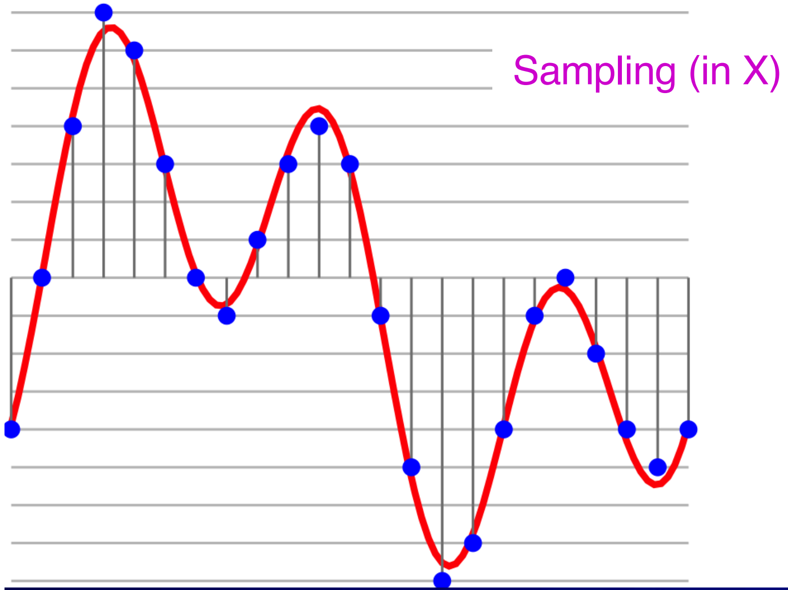
**=> Optimize exposure time and binning size during acquisition!**

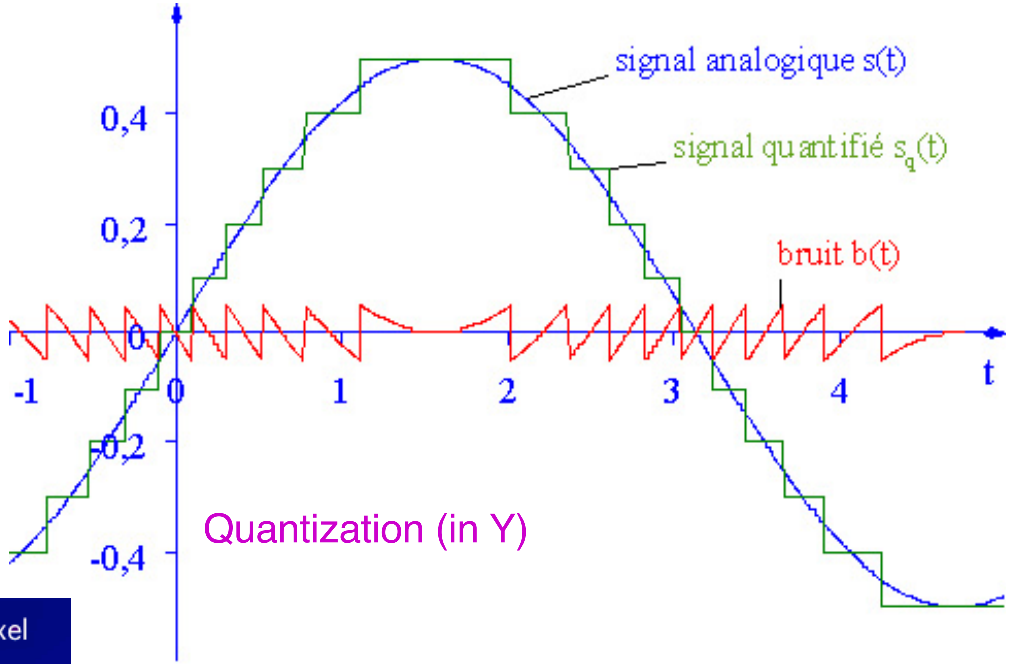
- **Binning**
  - **Efficient only if done at readout time** (reduces relative readout noise)
  - **Less efficient if done after acquisition** (by software)

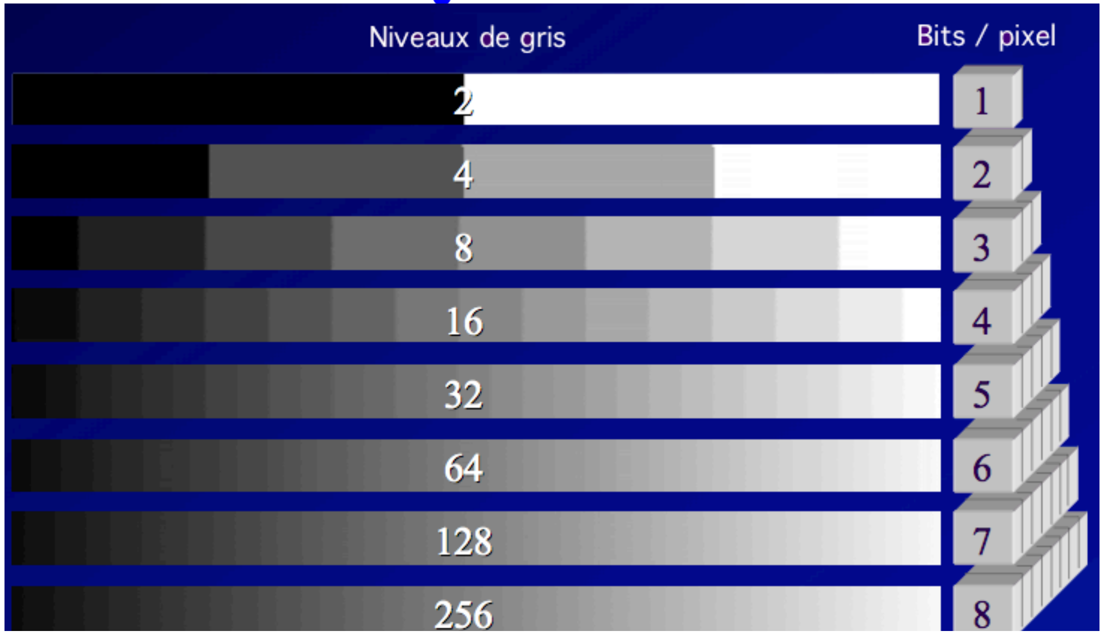
- **Median of successive frames**
  - **Very efficient to filter outliers** (cosmic rays, parasites…)
  - **Does not actually reduce noise** (but roughly equivalent with 30+ images)

- **Sigma-clipping**
  - **Iterative average & rejection of outliers: eliminates peaks and increases S/N ratio**

# Digitization (reminder)







**Nb of gray levels = $2^{bit/px}$**
**Level encoded in DN or ADU**
(Digital Numbers, or Analog to Digital Units - French: pas-codeurs)

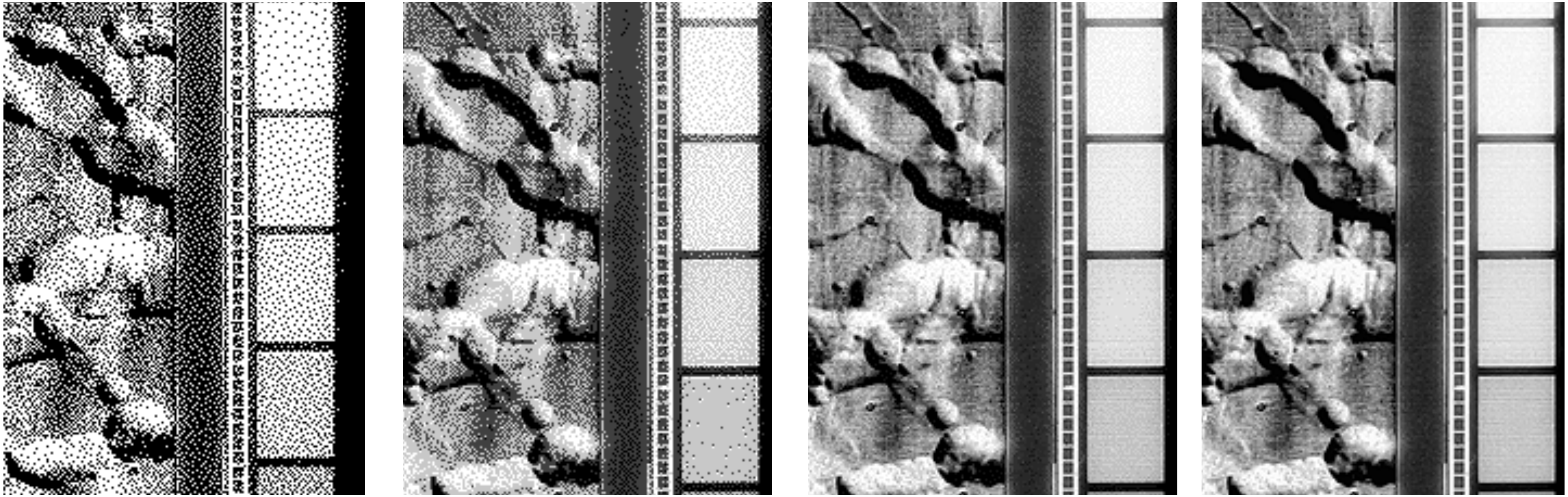
**Quantization noise = rounding error**
(depends on nb of bits for encoding)

Have fun! Show that

$$\sigma_{numer} = 1/\sqrt{12} \quad \text{(in DN)}$$

Hear the noise! https://www.audiolabs-erlangen.de/resources/MIR/FMP/C2/C2S2_DigitalSignalQuantization.html

# Digitization (reminder)



1 bit
2 possible values

2 bits
4 possible values

4 bits
16 possible values

8 bits
256 possible values

Mariner 9 / Mars (digitized from analog measurements)

=> Details are lost in visual noise, lesser dynamics affects spatial resolution

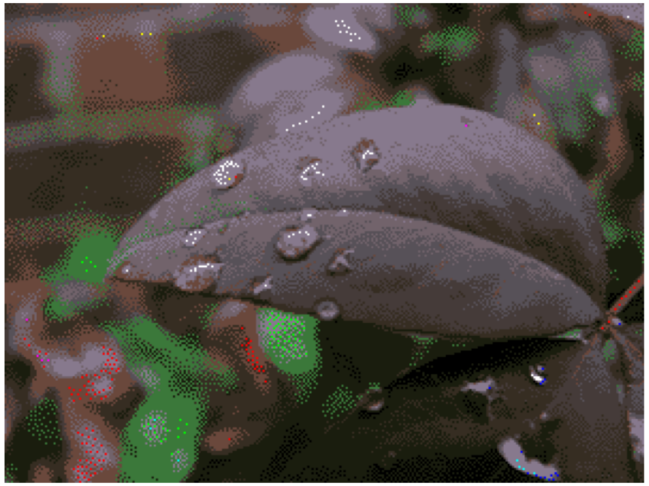
**CCD used in astronomy typically encode on 12-16 bits**
Warning: claimed depth is not always reached (<= irregular ramps)

Nb of bits required? N bits => $2^N$ levels (DN)
Complete possible dynamics encoded on $2^N$ ; noise encoded on (at least) ~ 1 DN

# Digitization (reminder)

Same thing in colours

2 bits



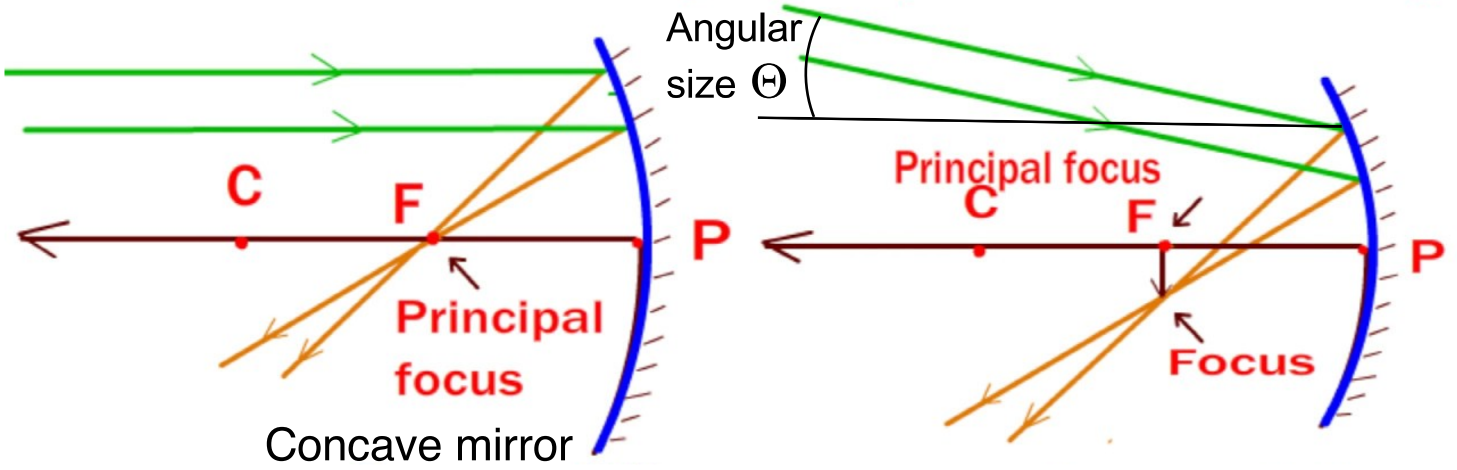
4 bits

8 bits

(Nb of bits in each colour plane)

=> Colours disappear
Details are lost in visual noise, lesser dynamics affects spatial resolution

# Basic optics (reminder)

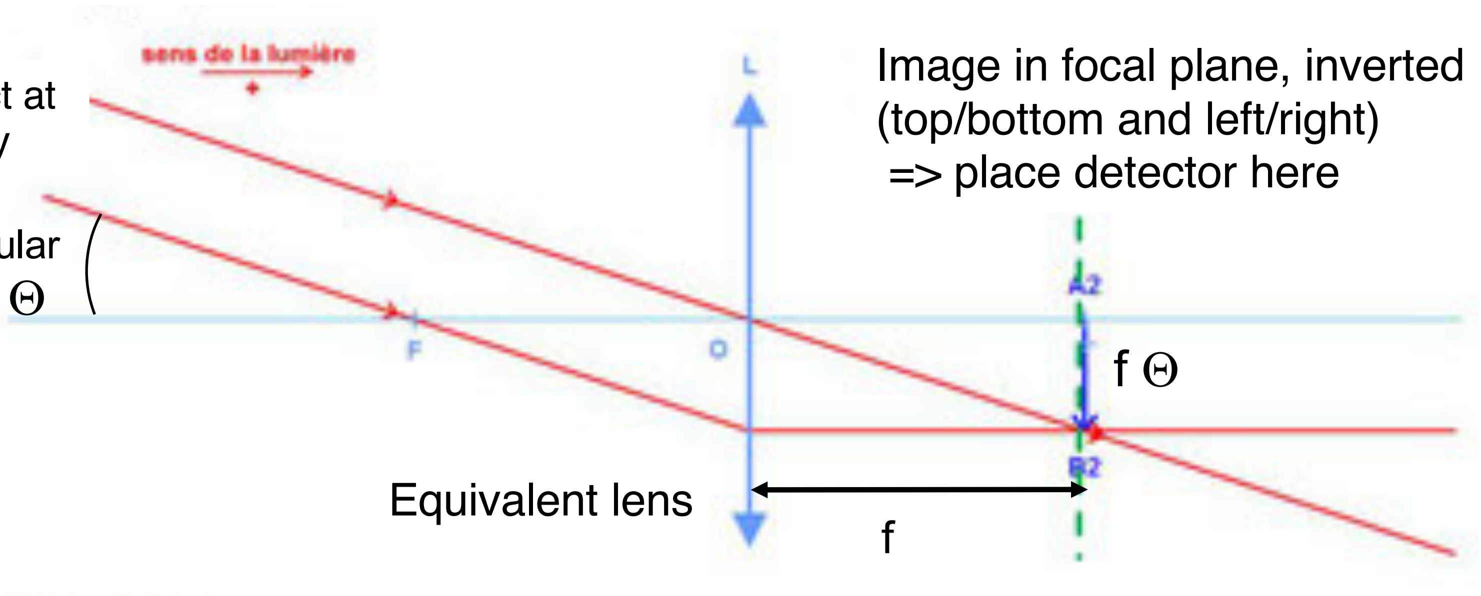


Object at infinity, along optical axis (field center)

Angular size Θ

Concave mirror

Shreem Ganesh, modified



Object at infinity

Angular size Θ

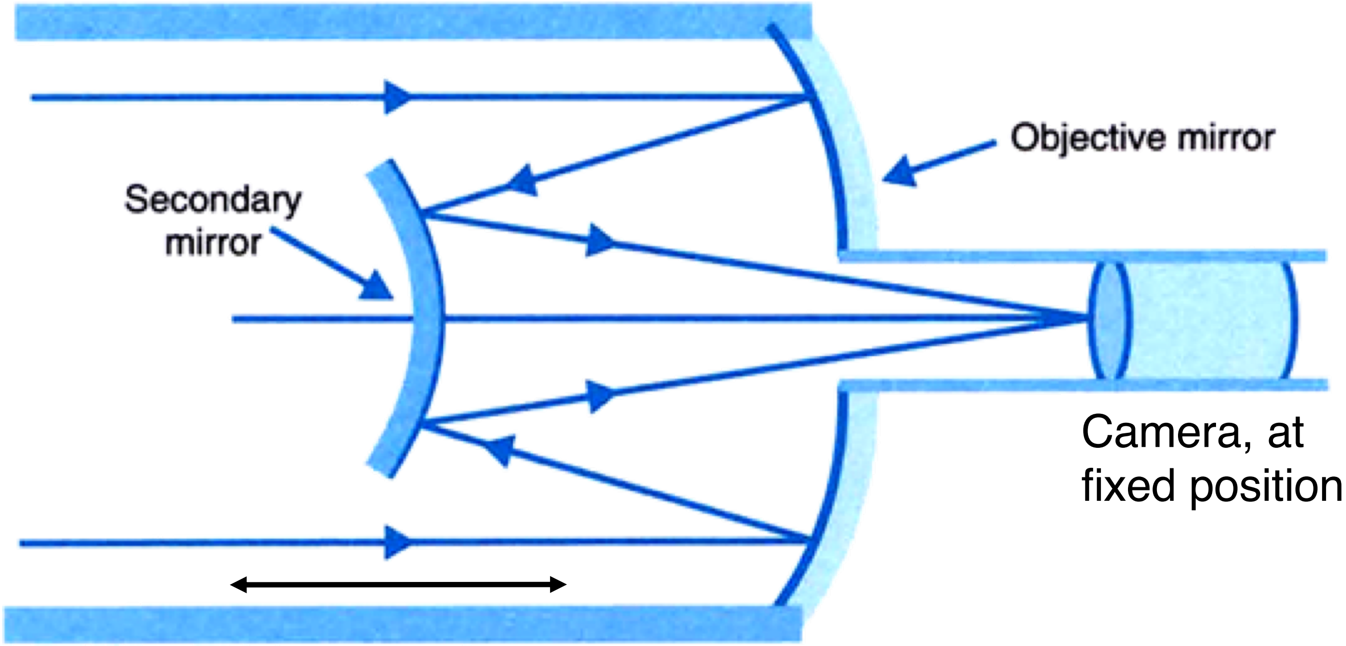
Image in focal plane, inverted (top/bottom and left/right)
=> place detector here

f Θ

Equivalent lens

f

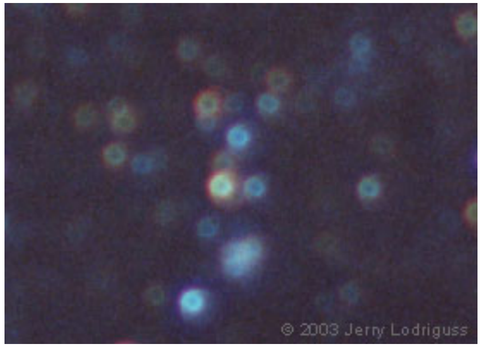
# Basic optics (reminder)

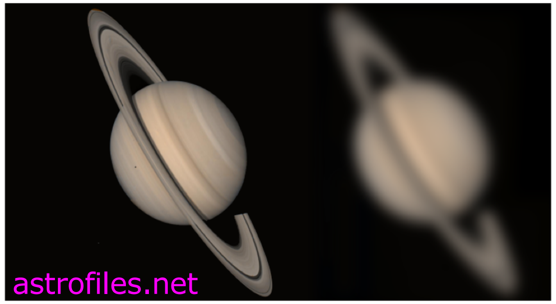


Camera, at fixed position

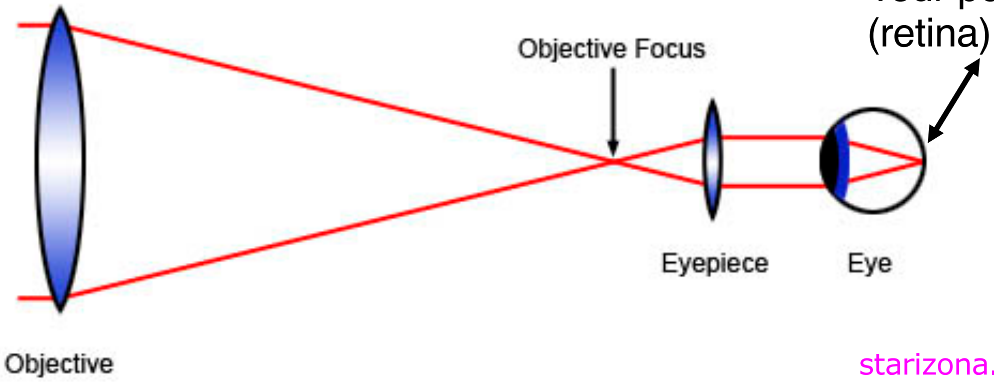
Secondary mirror shifted to move focal plane onto detector

Don’t forget to focus!





astrofiles.net



Your personal detector (retina) comes with a lens

starizona.com

Visual observations:

eyepiece needed to provide parallel rays to eye’s inner lens

# Image formation (reminder)

## See your optics / instrumentation lectures

**A lens = a machine to make Fourier transforms**

**What is there in the light path?**

**Source at infinity (direct space)**

Stands for: convolution

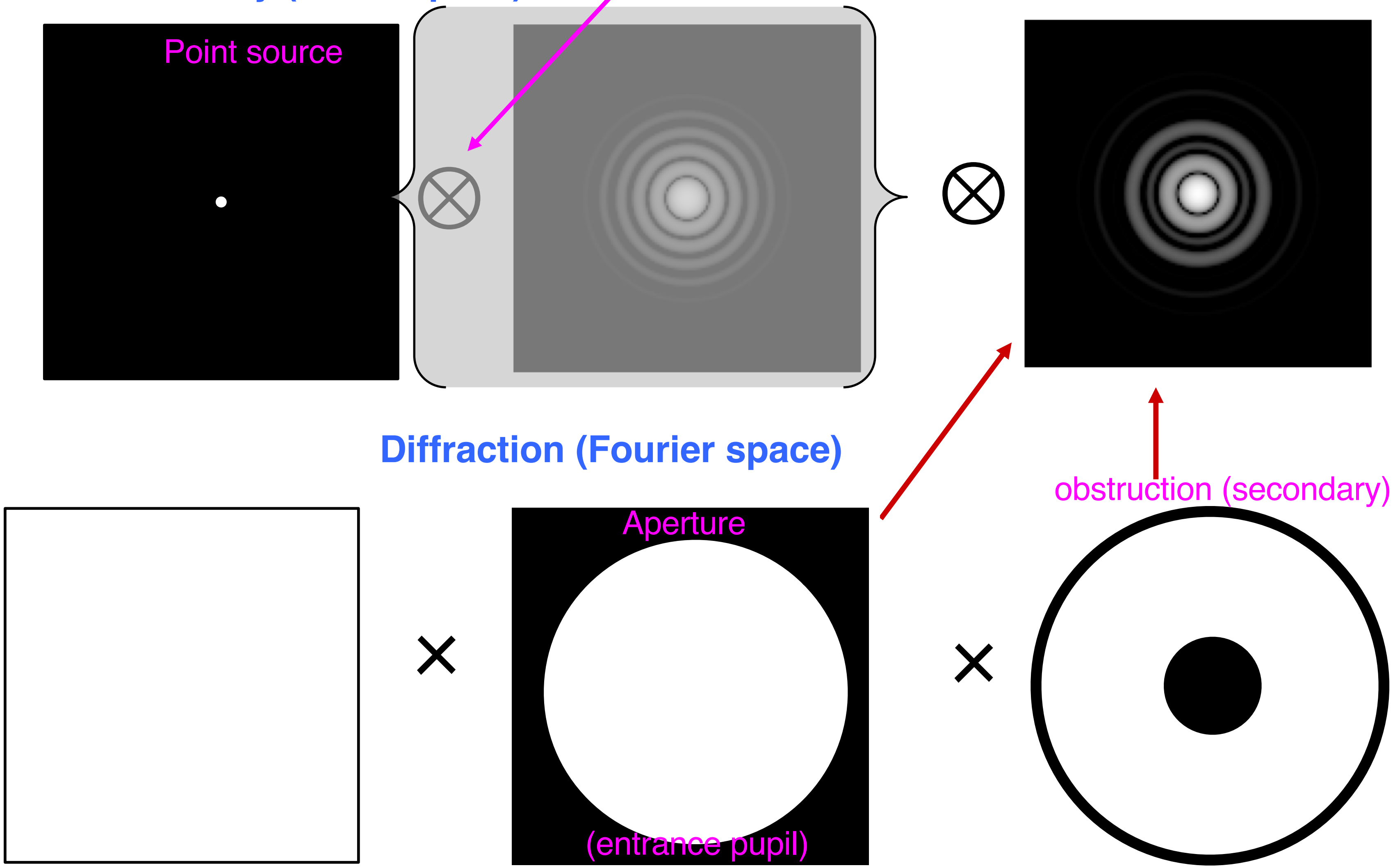


Image plane

Point source ⊗ ⊗

**Diffraction (Fourier space)**

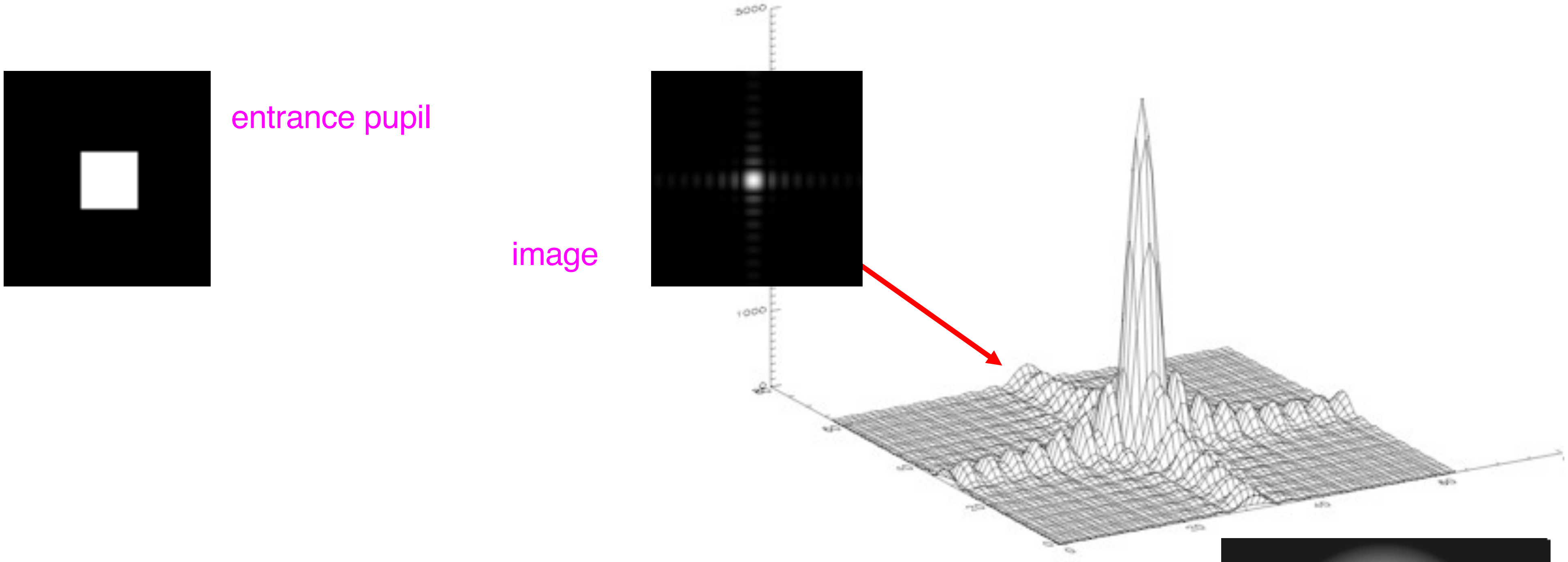
Fourier plane

× Aperture (entrance pupil) × obstruction (secondary)

# Image formation (reminder)

## See your optics / instrumentation lectures

- In the best possible conditions, the image of a point is an extended pattern
  - Entrance pupil illuminated by a distant source => Image intensity = (FT of pupil)$^2$
  - Rectangular pupil, spectrometer slit => Intensity in sinc$^2$ (French: sinus cardinal)



- Circular pupil => same with circular symmetry:
  **Airy function** (involves Bessel functions of the 1st kind)

⇒ **The image of a point by a perfect optic with a circular pupil is a series of concentric, decreasing rings**

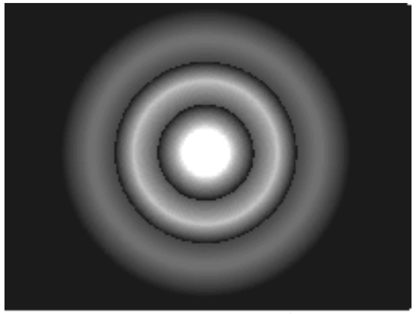
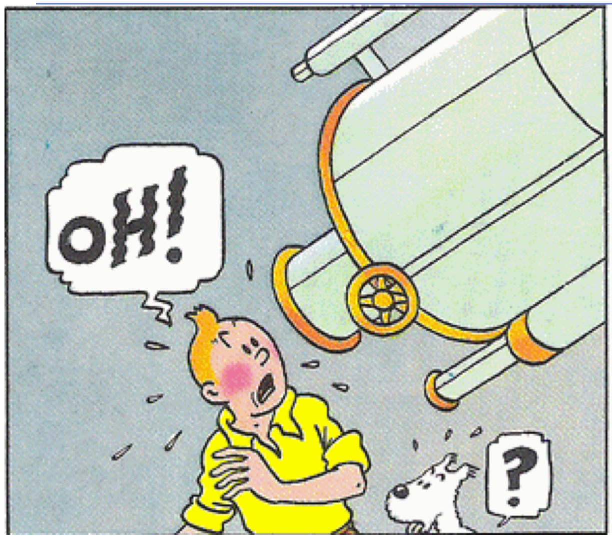
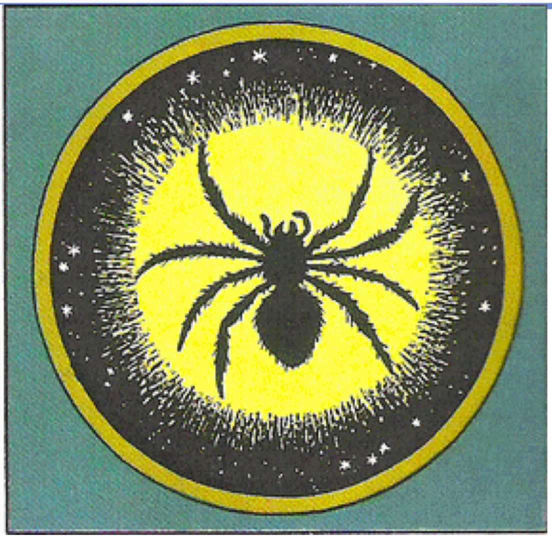
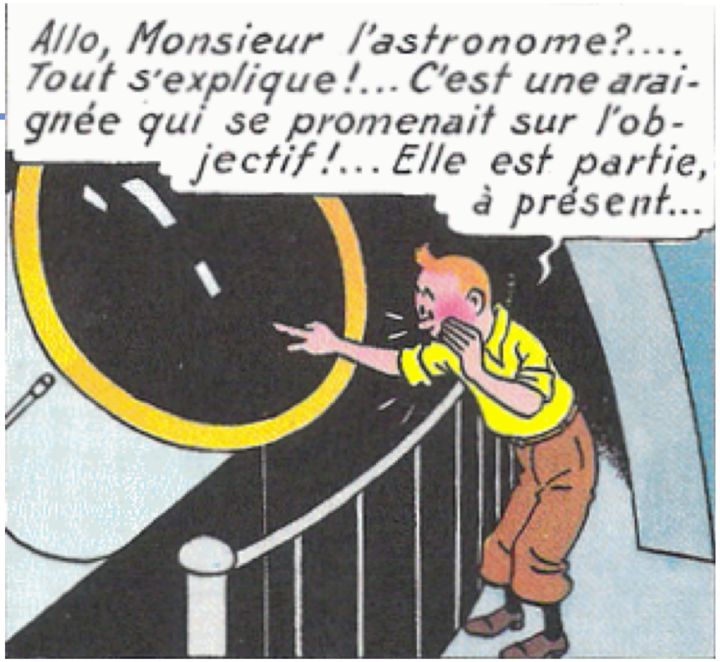


Figure1 : Image d'une étoile

# The non-Fourierist spider

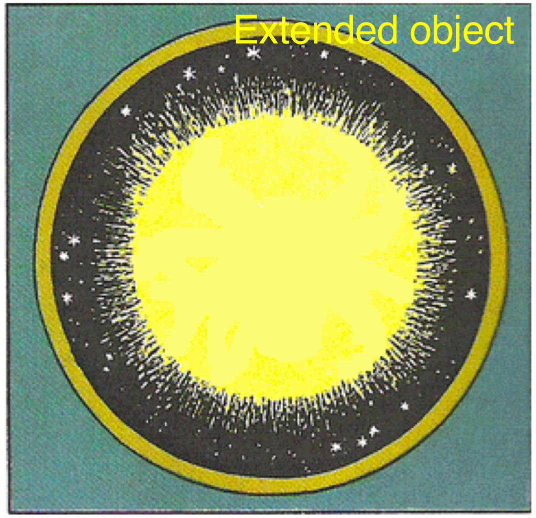






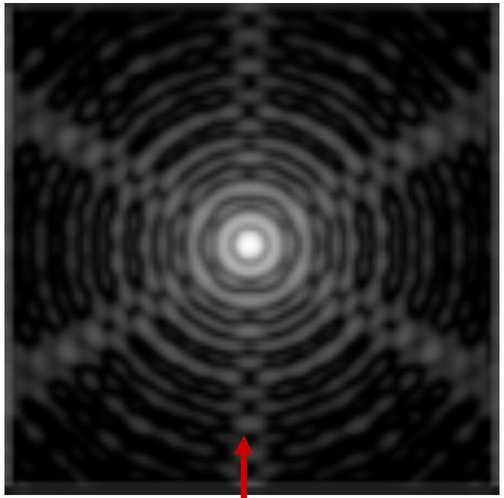
?

# Tintin and the non-Fourierist spider

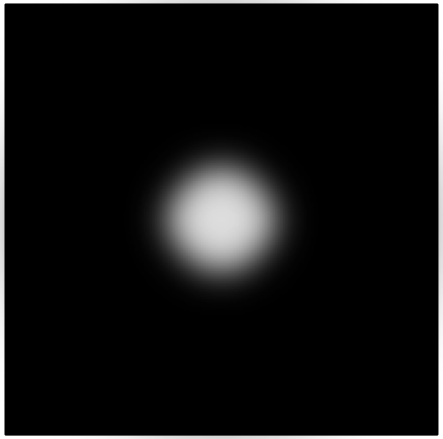


$\otimes$

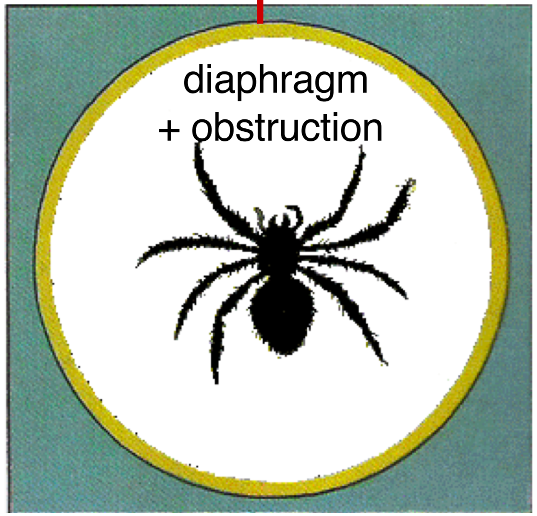
Source at infinity (direct space)



Diffraction (Fourier space)



×

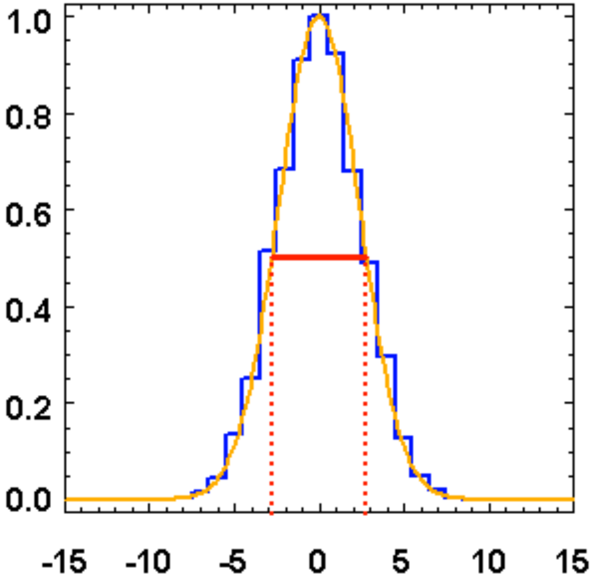


# Image formation (reminder)

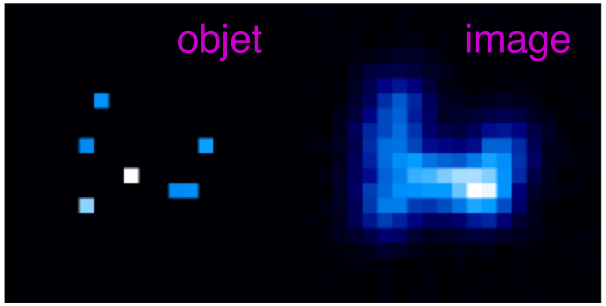
**Pratically:**
**Impulse response in intensity = Point-Spread Function (PSF)**
– French: Fonction d'étalement de point
**~ Gaussian profile** (FT of pupil spread by atmospheric turbulence)

**Image = object ⊗ PSF**

convolution



Broader PSF => blurred image



**If PSF is compact with circular symmetry, characterized by Full-Width at Half-Maximum (FWHM)**

Not necessarilly uniform in the field of view
Secondary lobes may be present

**Modulation Transfer Function (MTF) ~ FT of PSF, normalized**

**Finite pupil => MTF with bounded support <=> filters high spatial frequencies**
The larger the pupil/mirror, the more details you get (as long as there is no other diaphragm)
=> We're losing details because of the limited field of view
**(pupil = low-pass filter for spatial frequencies)**

# Dependences of PSF?

- **Telescope** (diametre D) :

**Angular resolution ~ 1,22 $\lambda$ / D** (distance of first zero of Airy pattern
= half-width of central peak, in radians)
Improves at shorter wavelengths and with larger mirror

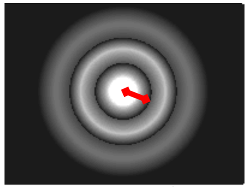


Figure1 : Image d'une étoile

- **Atmosphere :**

**Turbulence reduces angular resolution**
Turbulence cells => ~ 50 cm telescope (= Fried parametre)
Improves at longer wavelengths (IR), short exposures, and in zenithal direction

**Seeing:**
Estimate of resolution at time of observations
2” is very good, 0.5” is exceptional (= diffraction limit with D ~ 1m)

**How can we improve this?**
- remove atmosphere (orbital telescope)
- limit/correct turbulence (short exposures, speckle interferometry, Adaptive Optics)

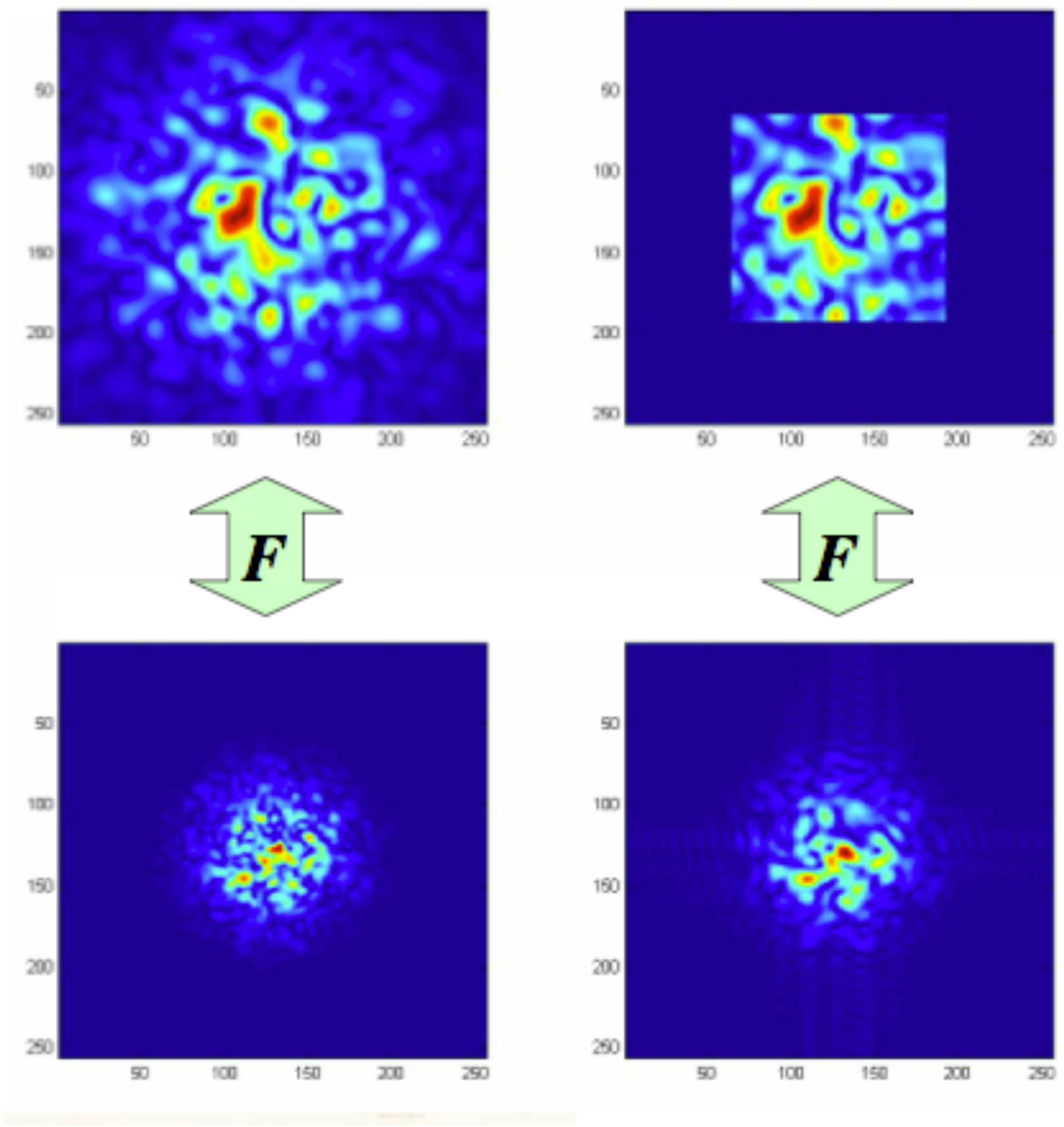
# Dependences of PSF? Field width

Wider aperture $u$

$u \cdot \mathrm{rect}$ Diaphragmed aperture

Fourier plane

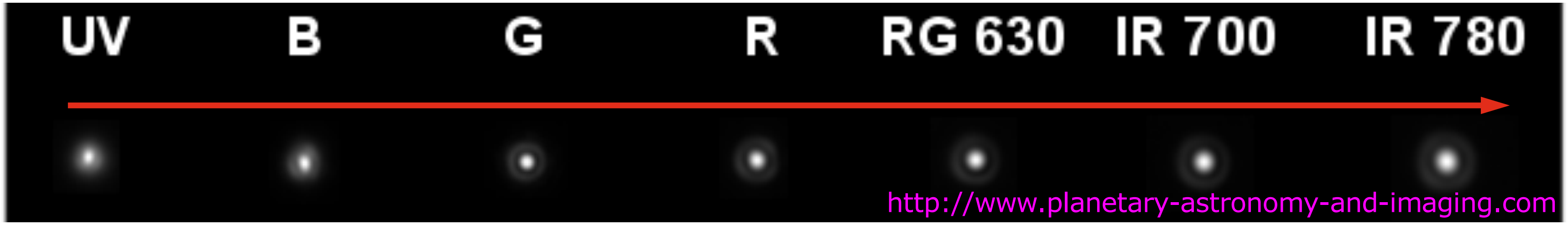
Image plane



- **Reduced resolution**
- **"Ringing"**
  **(<= secondary lobes of sync function)**

P. Riaud et al

# Dependences of PSF? Optics and wavelength

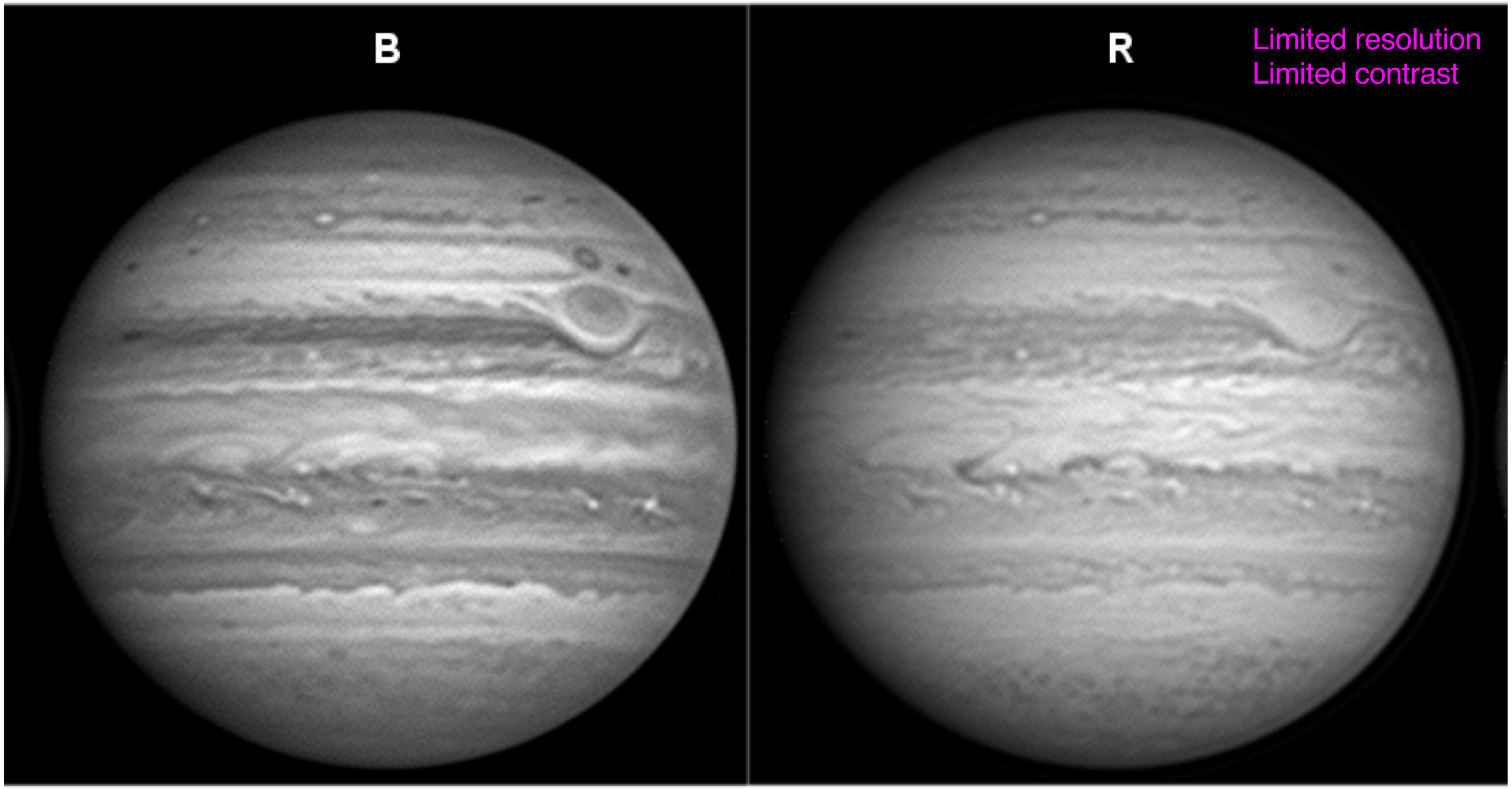


wider
PSF

http://www.planetary-astronomy-and-imaging.com

**Variation with wavelength: influence of optics**
(conditions of a very stable atmosphere [quite rare] and a small telescope)

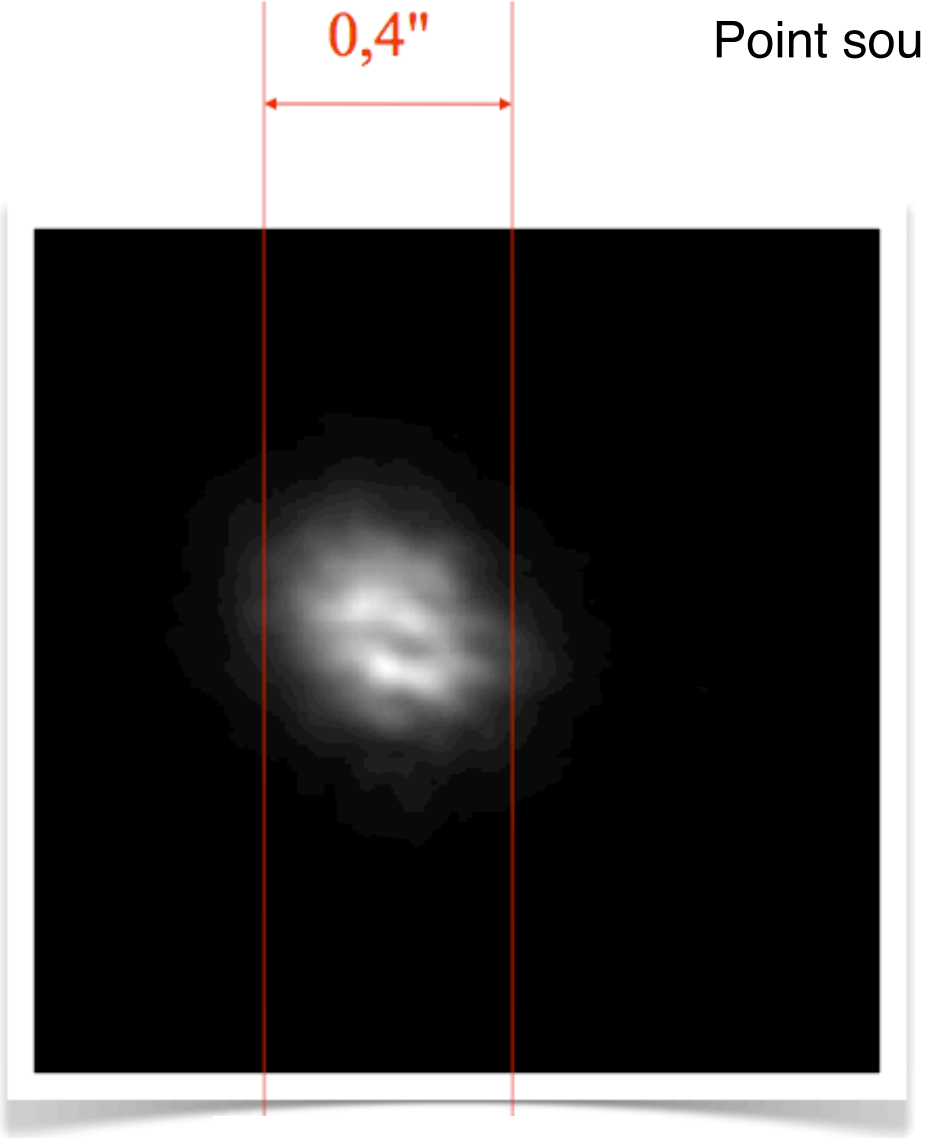
D = 0,25 m



Limited resolution
Limited contrast

# Dependences of PSF? Turbulence

Point source



Best atmospheric
image from VLT

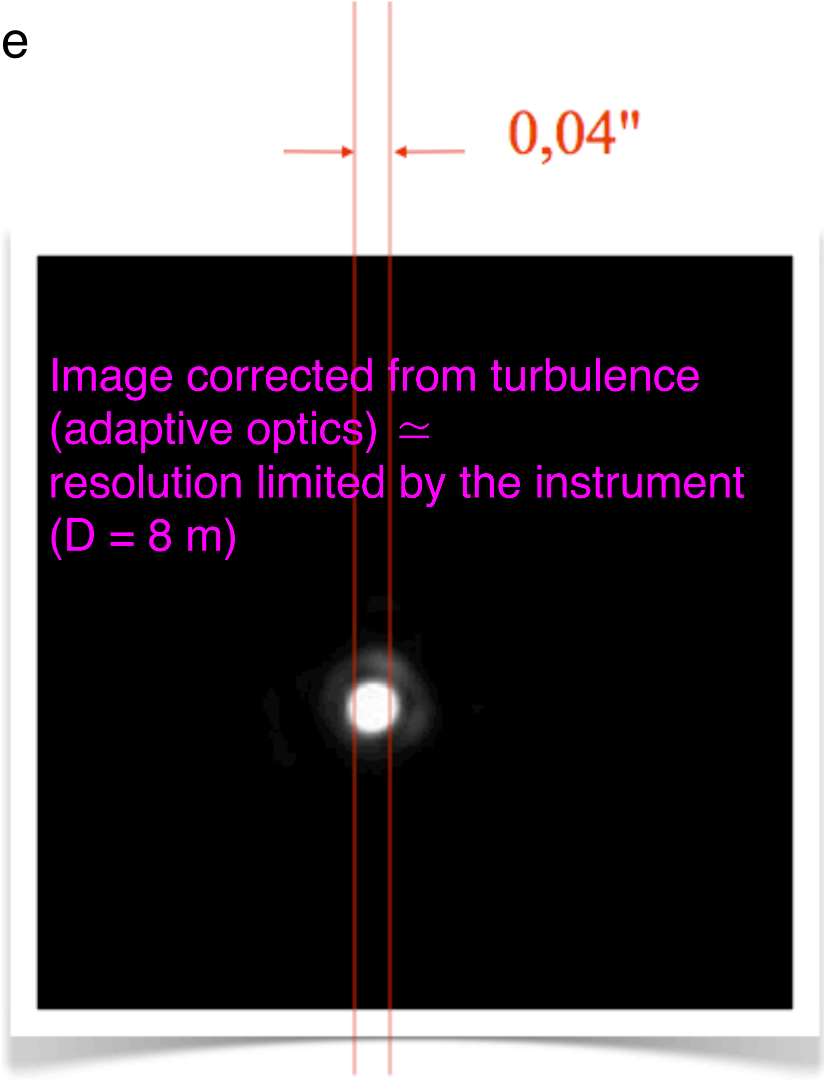


Image corrected from turbulence
(adaptive optics) $\simeq$
resolution limited by the instrument
(D = 8 m)

VLT+NAOS image at 2.2 $\mu$m

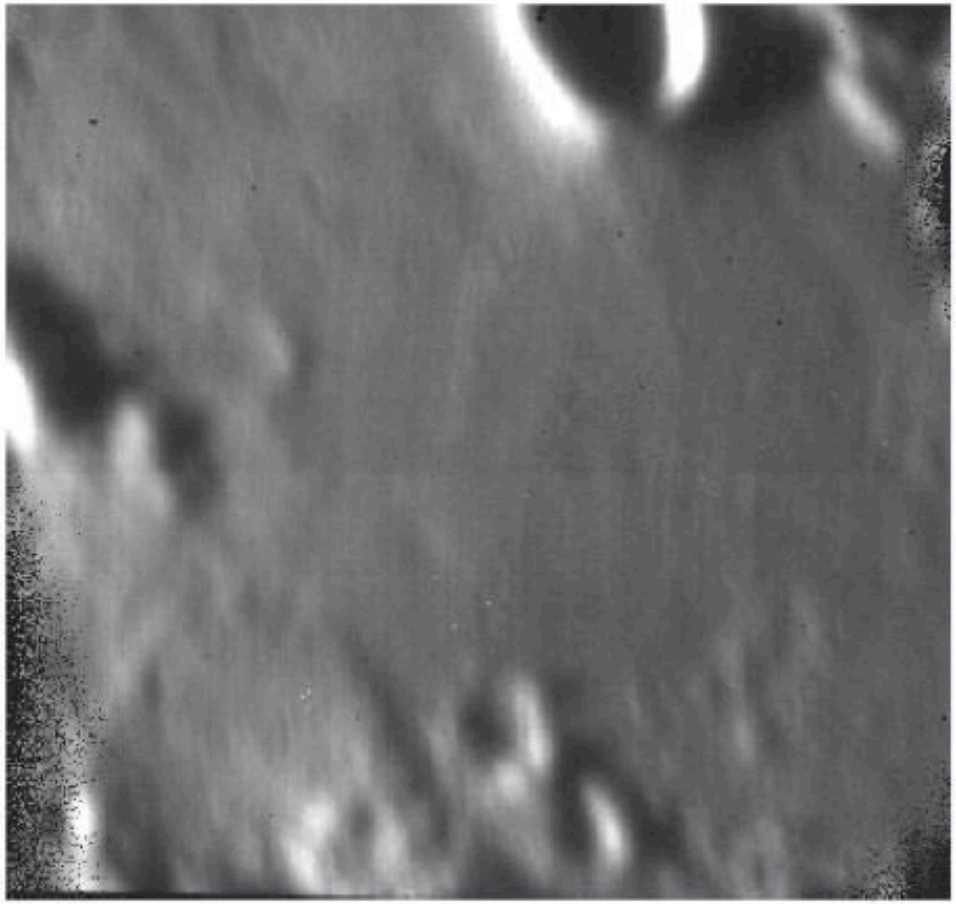
$1,22 \times 2.2\ \mu m / 8\ m \sim 0,31.10^{-6}\ rad \sim 0,07''$

S. Lacour

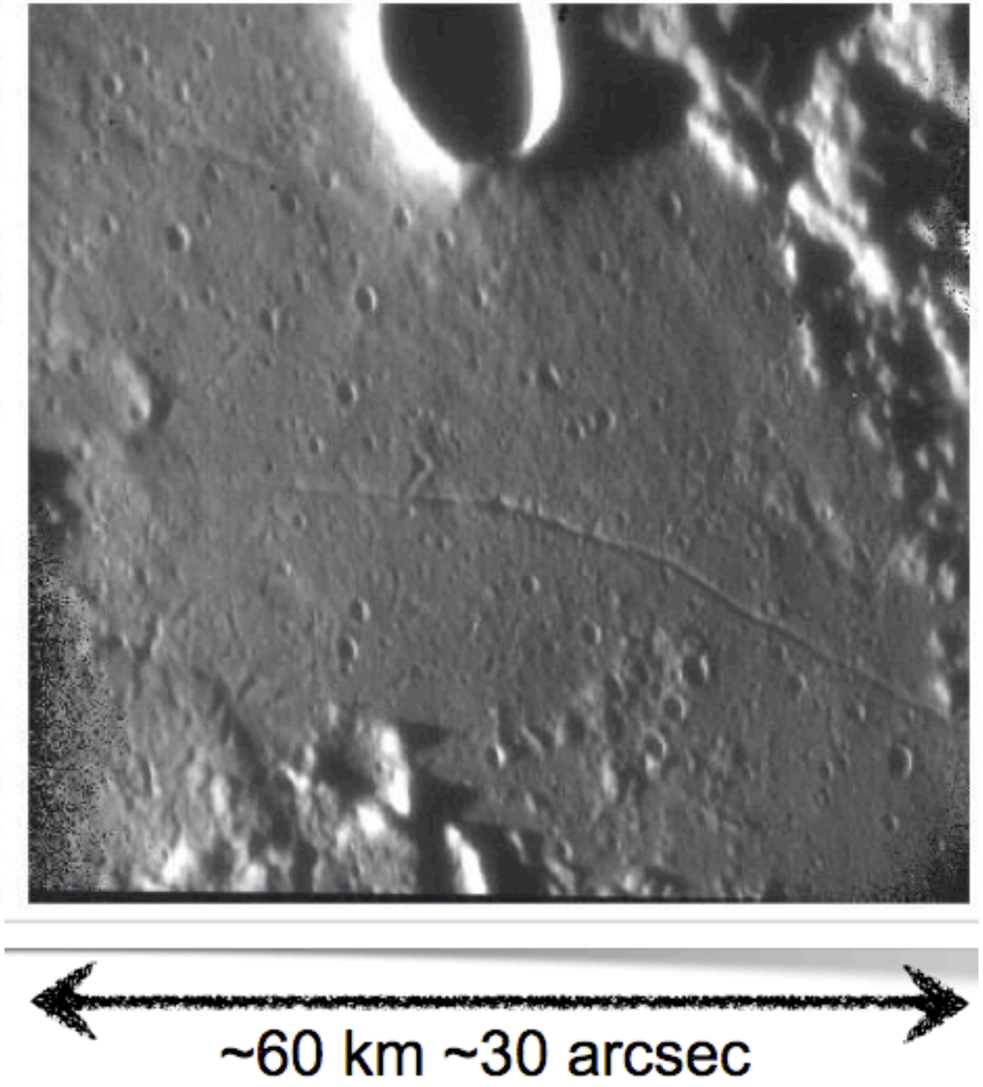
# Angular resolution

Continuous field

Atmospheric image, object ⊗ turbulence



AO corrected image, object ⊗ instrument



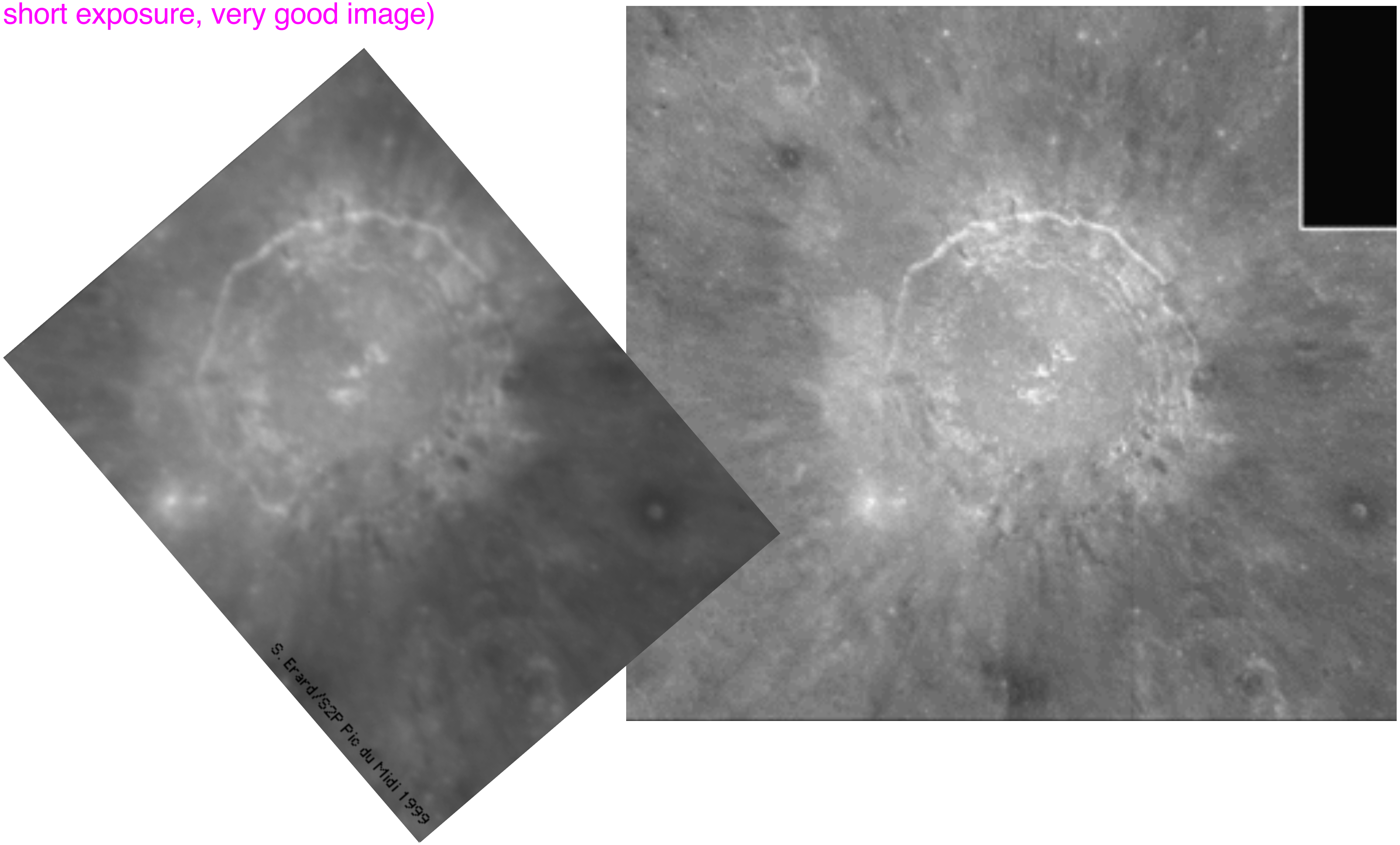
NACO / VLT

# Angular resolution

Continuous field

T1m / OMP (altitude 3000 m,
short exposure, very good image)

HST (no turbulence, D = 2,4m)



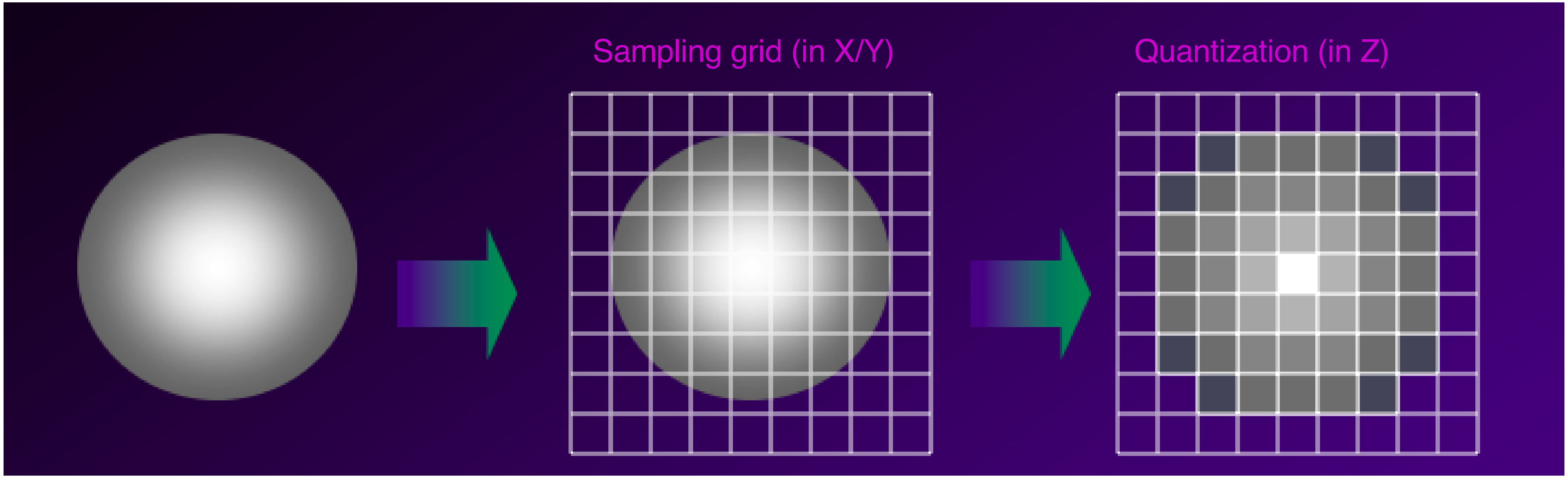
# Sampling of the image plane (reminder)

- **Smallest resolved object = $\Theta_{min}$ (PSF size)**
- **Size of $\Theta_{min}$ in focal plane = f x $\Theta_{min}$**
- **Shannon theorem: 2 measurement points / resolved element** (ie: inside PSF)

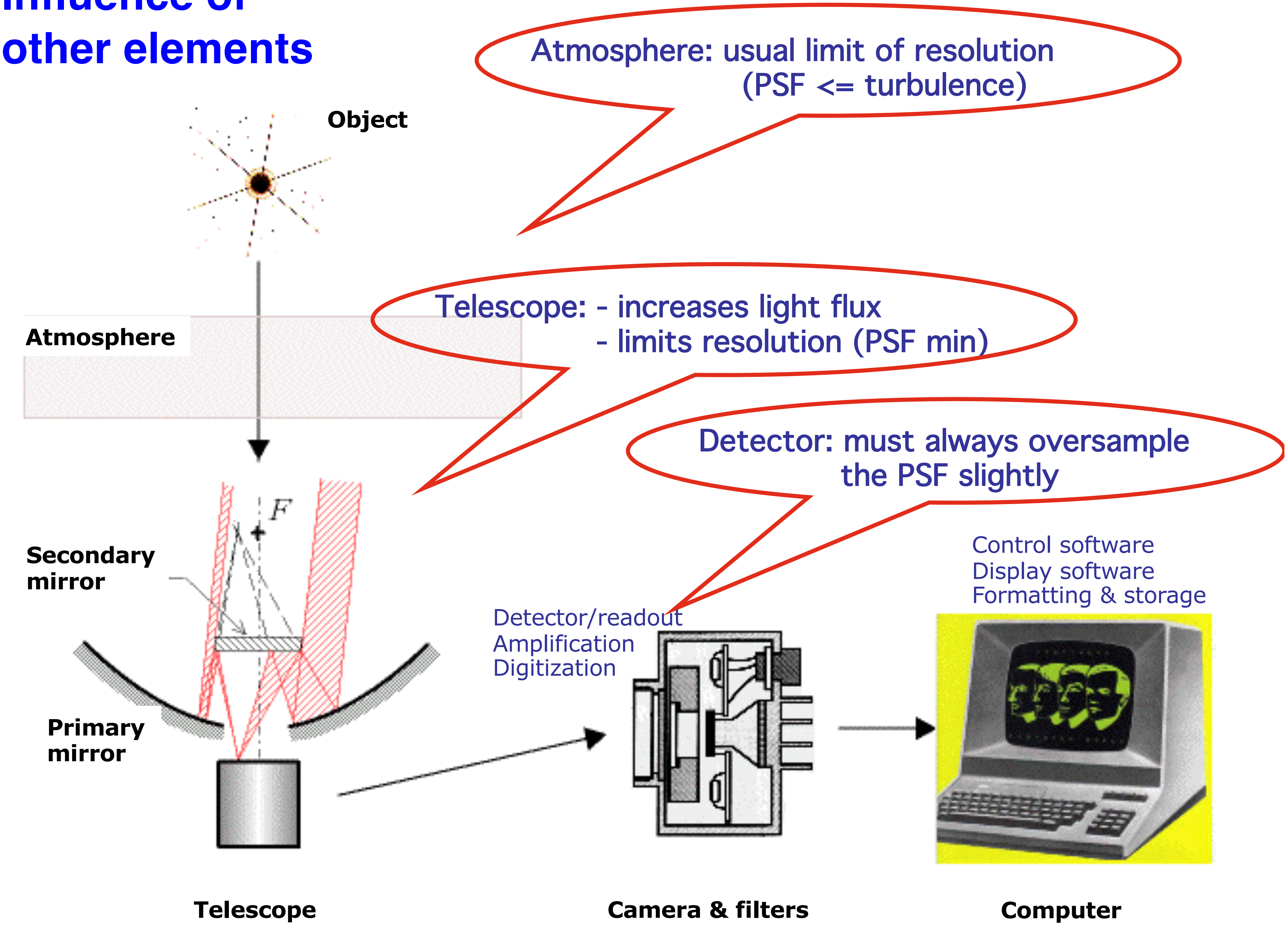
$\Rightarrow$ **size of detector pixels = 0,61 f $\lambda$ / D** (for instrumental limitation, best possible case)

**Resolution ≠ pixel size!**
**Resolution is driven by PSF size,**
**not by pixel size**
**which is always smaller**

**In non-optimal cases, binning is always preferred!**



# Influence of other elements



Atmosphere: usual limit of resolution
(PSF <= turbulence)

Telescope: - increases light flux
- limits resolution (PSF min)

Detector: must always oversample
the PSF slightly

Detector/readout
Amplification
Digitization

Control software
Display software
Formatting & storage

# Vade-mecum

## To be optimized during acquisition

- **Estimate seeing** (qualifies turbulence)
- **Binning** (minimizes readout noise, if no loss of resolution)
- **Exposure time** (max signal, no saturation)
- **Don’t forget to focus!**
- **Maintain observation log** / take notes (events, doubts, questions…)

## After the fact (by software)

- **Stacks + summing / median <= center on object**
- **Calibration**
- **Further processing**

# Other things you can do with a telescope

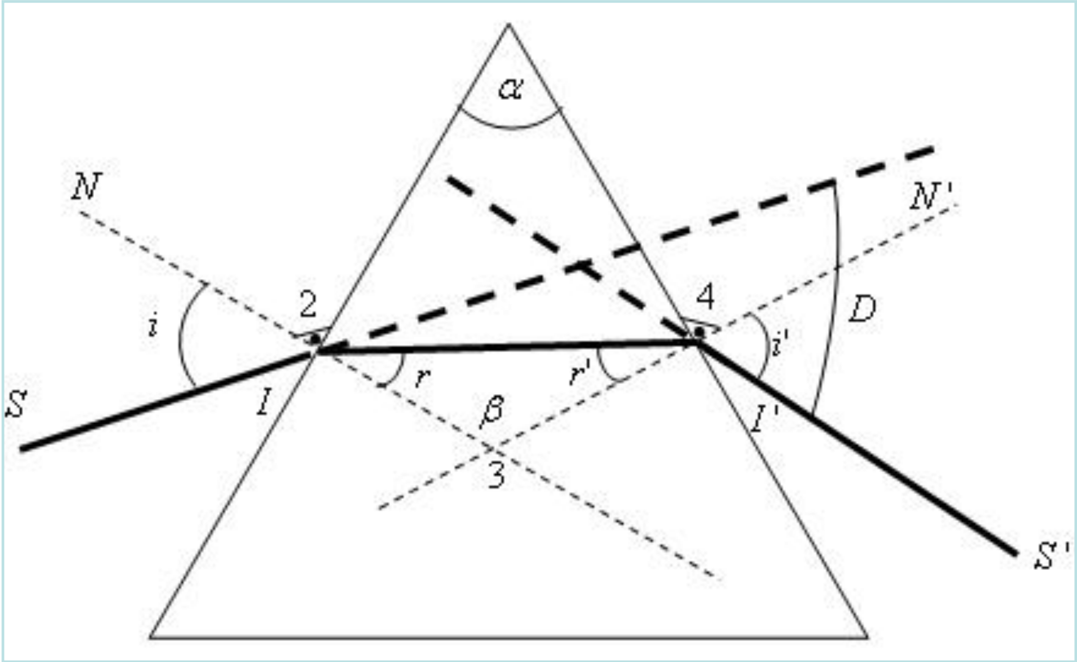
## Spectroscopy

- Disperse light in wavelength

⇒ Estimate objects temperature
⇒ Study of composition (emission or absorption lines)
⇒ With high resolution: pressure, temperatures… (line profiles)

# Spectroscopy (reminder)

## Prism



Index n, function of wavelength

Refraction in different directions
=> dispersion of light

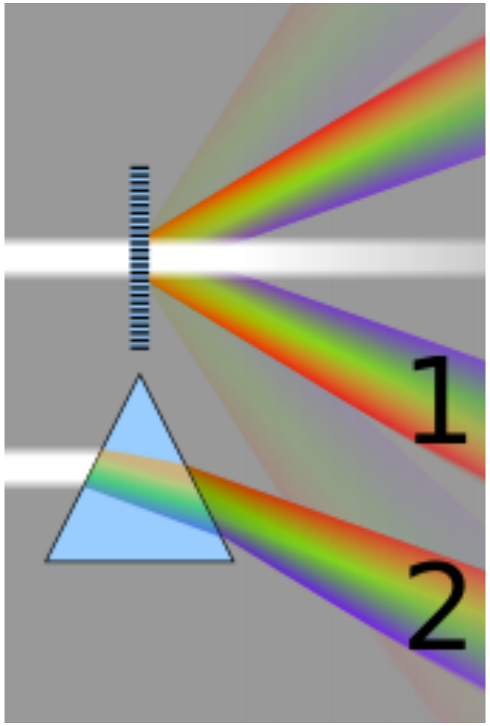
http://physique.coursgratuits.net/optique-geometrique/prisme.php

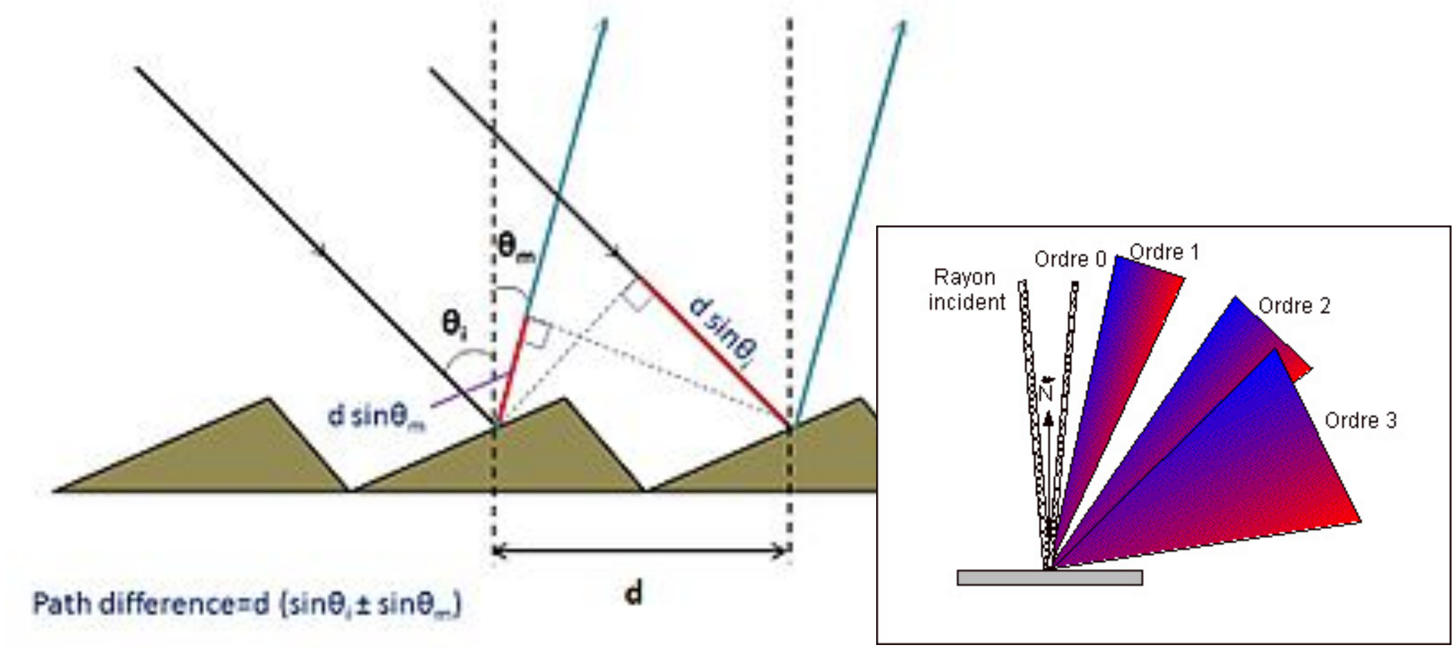
wikipedia

# Spectroscopy (reminder)

## Transmissive diffraction grating

## Reflective diffraction grating





Constructives interferences in given directions $\theta_m$ for a given $\lambda$

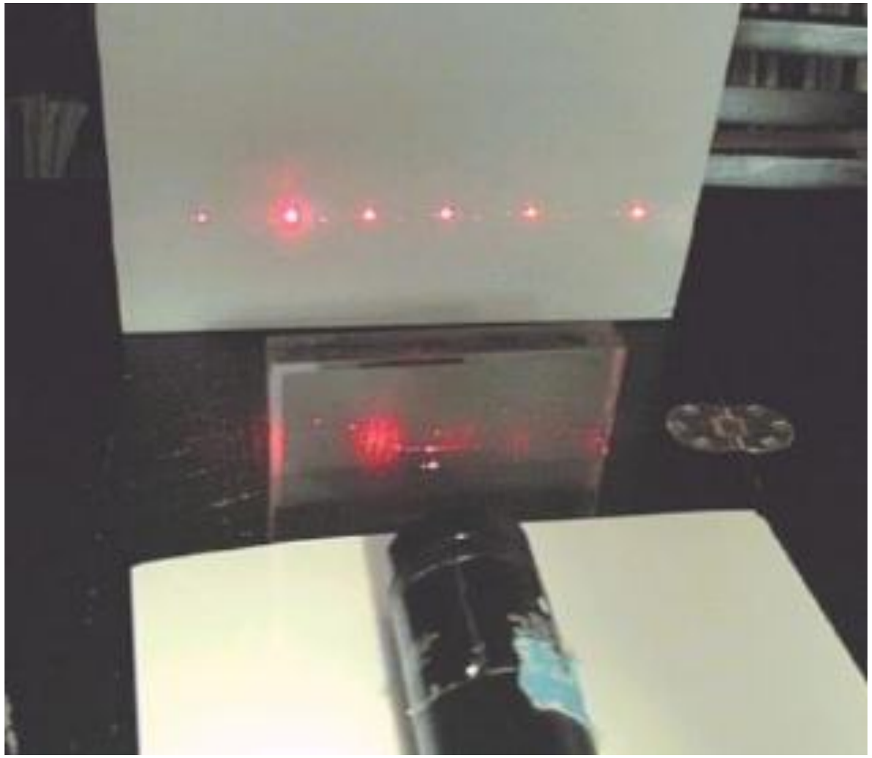
$\Rightarrow$ Max luminosity at $$n_1 \sin\theta_m = n_1 \sin\theta_i - m\frac{\lambda}{d}$$

d = grating line distance
m = integer number => several spectra (successive grating orders)
Order 0 is not diffracted, but reflected

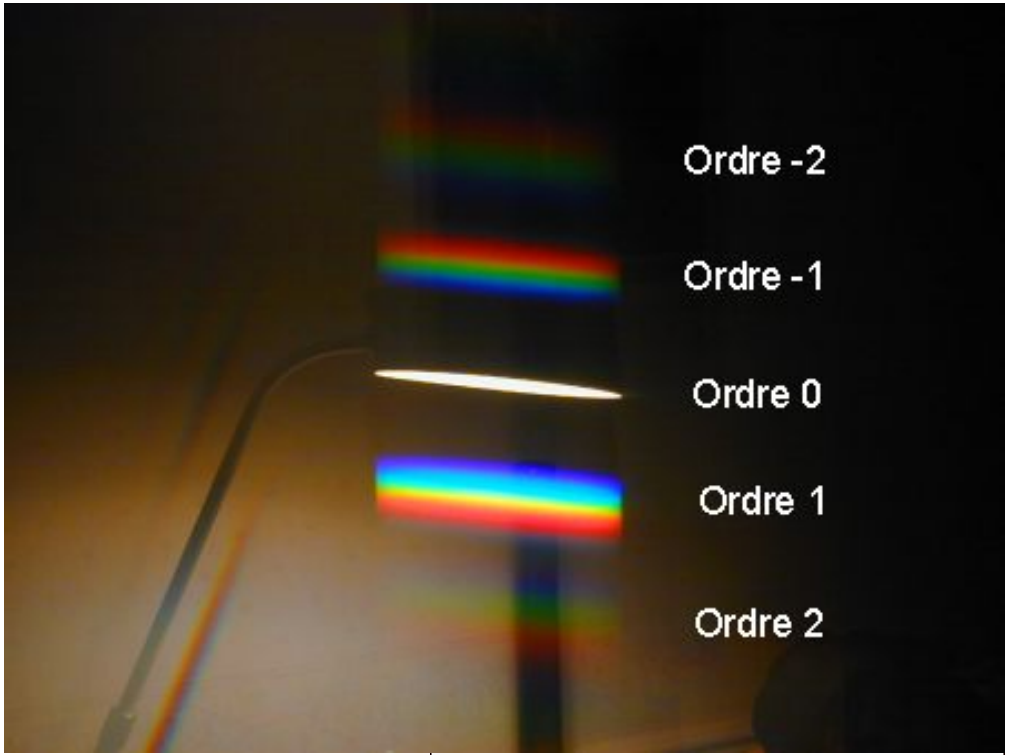
wikipedia

# Spectroscopy

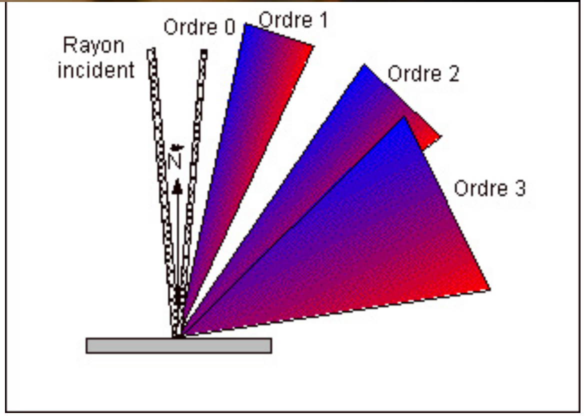
## Diffraction grating



Monochromatic source (laser)



White light



Images C. Buil

# Spectroscopy

## Spectrometre

- Light from target is diffracted along a spectral direction

⇒ Light beam is blocked in this direction to isolate objects
⇒ Entry slit in orthogonal direction
⇒ On the CCD: one spectral dimension, the other spatial

- Grating to be illuminated by a collimated beam

⇒ Extra lens behind the telescope (collimator)

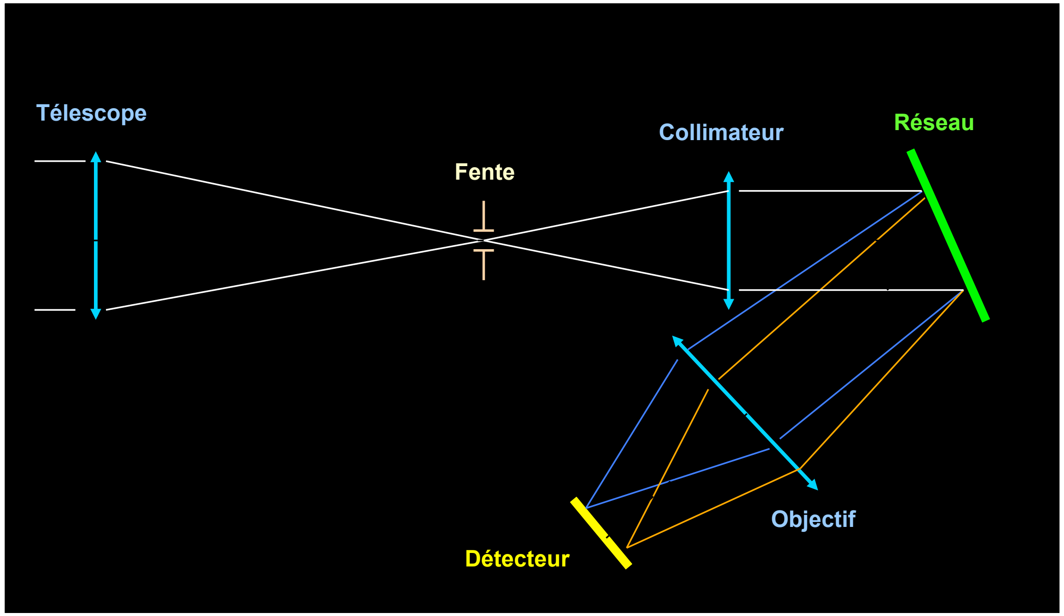
- Need to form an image after the grating

⇒ Extra lens behind the grating (objective)

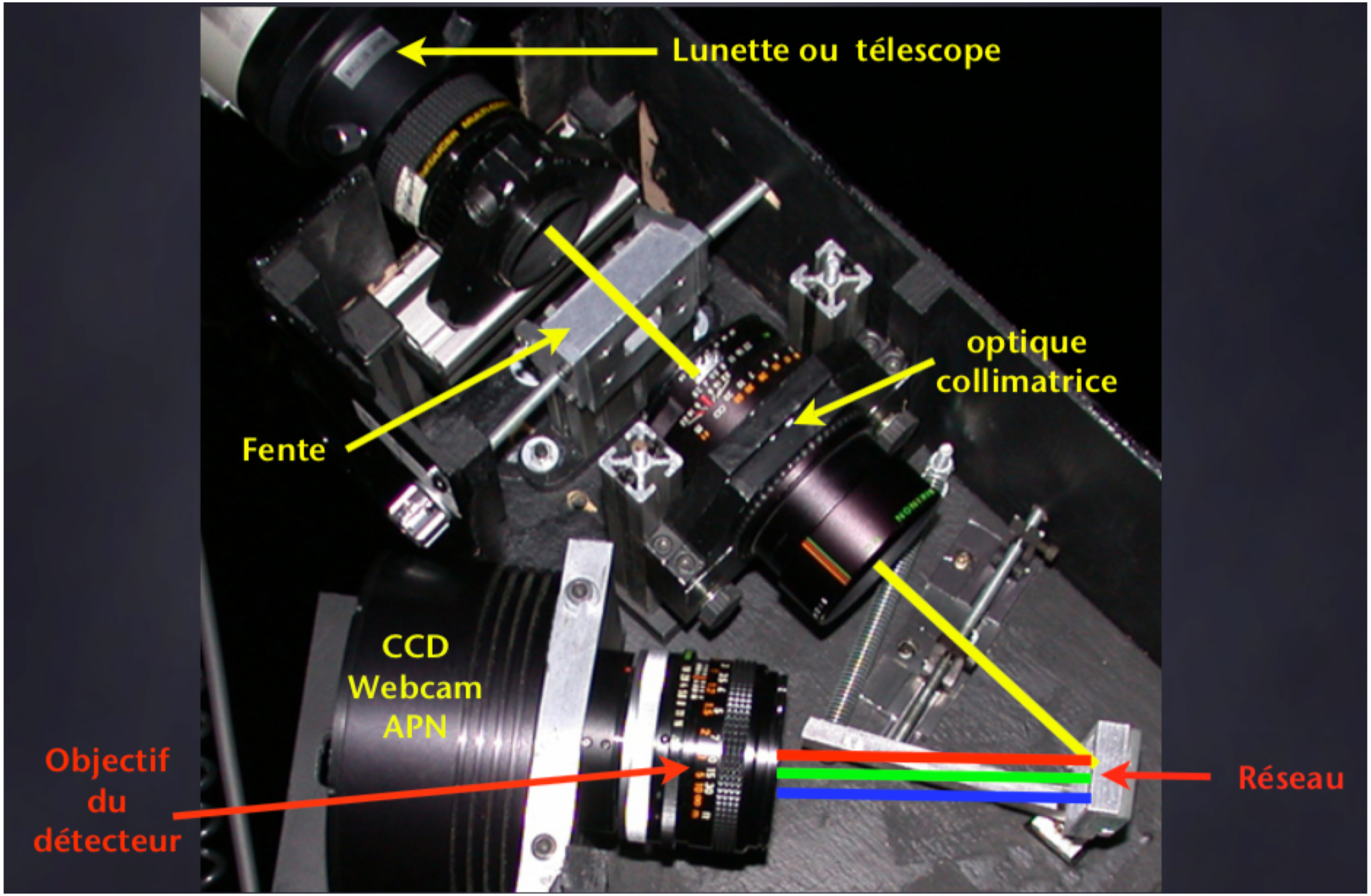
- If high dispersion:

⇒ Rotate the grating to scan the complete spectral range

Littrow mount:
A setup using 2 coinciding lenses (collimator = objective)



# Spectroscopy



https://www.shelyak-instruments.com
20061111_Olivier-Garde-Spectro.pdf

# Spectroscopy

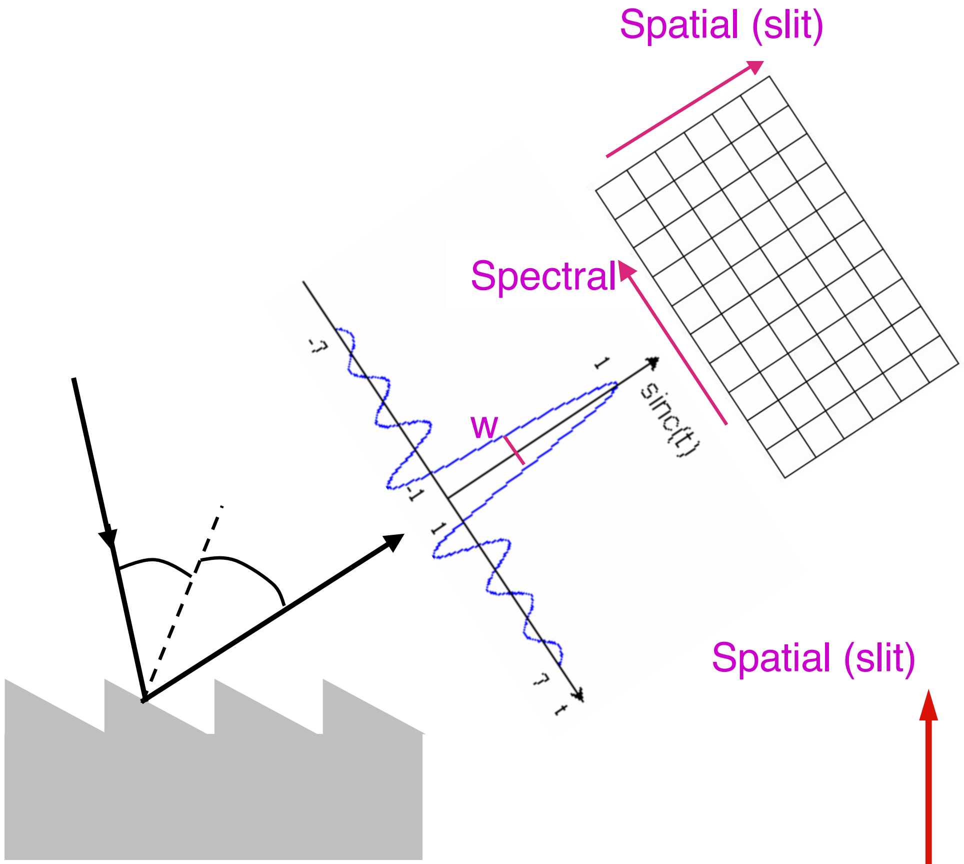
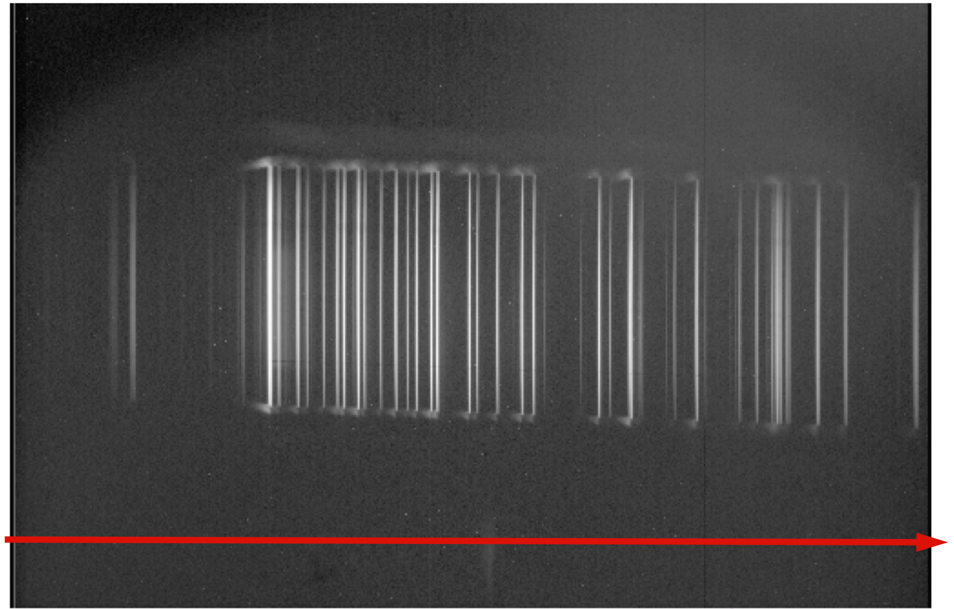


Image of the slit at various wavelengths

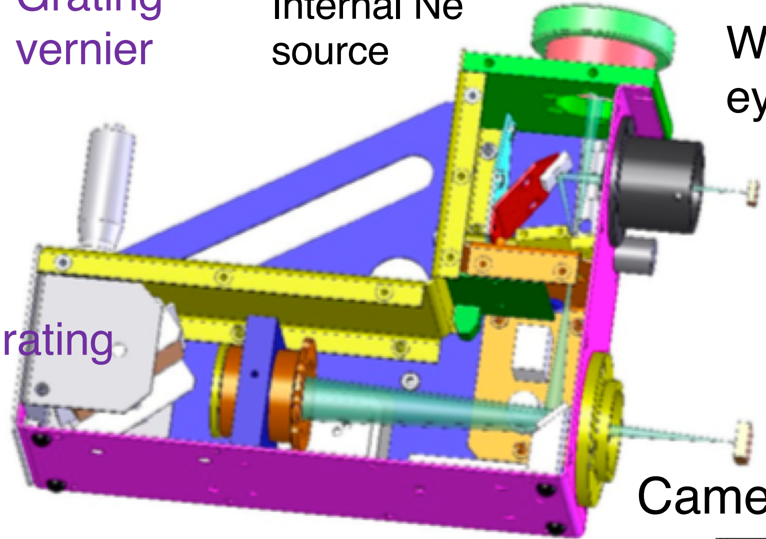
- Slit must be aligned on CCD array
- Spectral axis must be calibrated

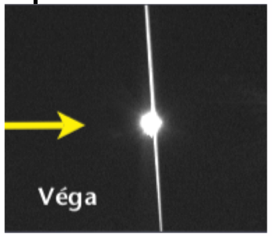
⇒ Reference sources with known spectral lines: Ne

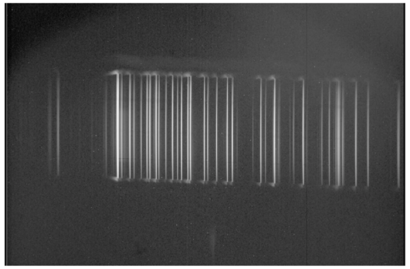


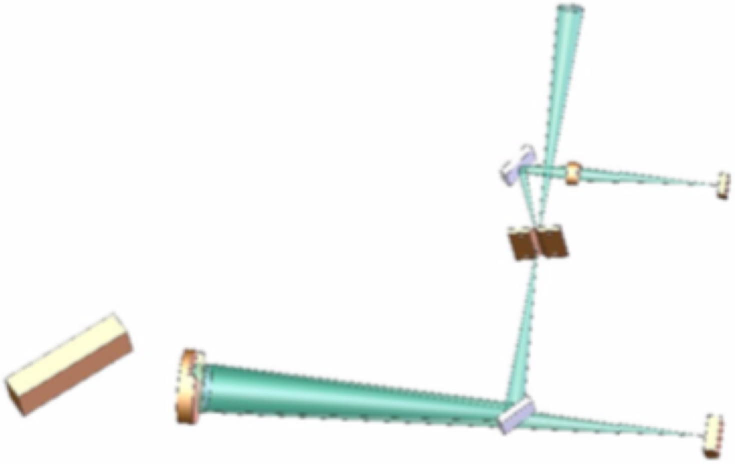
# Spectroscopy

## LHIRES









Littrow mount:
A setup using 2 coinciding lenses
(collimator = objective)

# Spectroscopy

## LHIRES

**Settings:**

- Install eyepiece instead of camera, focus
- Identify/note 3 fixed vernier positions to observe 3 overlapping parts of spectrum (red, green, blue) — use the internal source and ambient light
- Calibrate X-axis with internal source (Neon) on these 3 vernier positions:
  - Install and align camera (slit image must be // to Y-axis)
  - Focus (camera in lens focal plane => narrow lines; different from eyepiece)
  - Expose images for the 3 vernier positions

- At the telescope:
- With eyepiece or webcam:
  - Acquire target on slit and focus (slit in telescope focal plane, with webcam)
  - Toggle input mirror when done
- With camera:
  - Expose images for the 3 vernier positions