TP d'observation M1

Telescopic observations with CCD detectors

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v. 9/2/2025

Observatoire de Paris | PSL

Selected references

Howell S. B. (2006) Handbook of CCD astronomy (Cambridge, 2nd edition)
Chromey F.R. (2016) To measure the sky (Cambridge, 2nd edition)
Shepard M. (2017) Introduction to Planetary Photometry (Cambridge)
Léna P. et al (1996) = Observational Astrophysics (Springer)
= Méthodes physiques de l'observation (CNRS-Interéditions, 3rd ed)
Ph. Massey (2019) Observational astronomy: http://www2.lowell.edu/users/massey/Observational.html
Glass I.S. (1999) Handbook of infrared astronomy (Cambridge)
Undergraduate / basics: Gallaway M. (2020) An Introduction to Observational Astrophysics (Springer)
Owocki S. (2022) Fundamentals of Astrophysics (Cambridge)
Martinez P. et Klotz A. (1994) Le guide pratique de l'astronomie CCD (Adagio)

Other docs from Master degree:

https://media4.obspm.fr/portail/
https://ufe.obspm.fr/Ressources-multimedia
https://media4.obspm.fr/ (may require registration)

+ see **M1 lectures** (instrumentation module) + See Meudon library (including online resources)

Docs and tuto applets (from suppliers)

E.g. https://www.hamamatsu.com/sp/sys/en/camera_simulator/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 https://moodle.psl.eu

Images

References of images used here:

http://www.astrosurf.com/cidadao/ [& other sites on astrosurf.com]
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/
https://unison.audio/dithering/
M1/M2 lectures on instrumentation / image formation (M1 by S. Lacour)
Cours Optique et télescopes, found 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

Vade-mecum

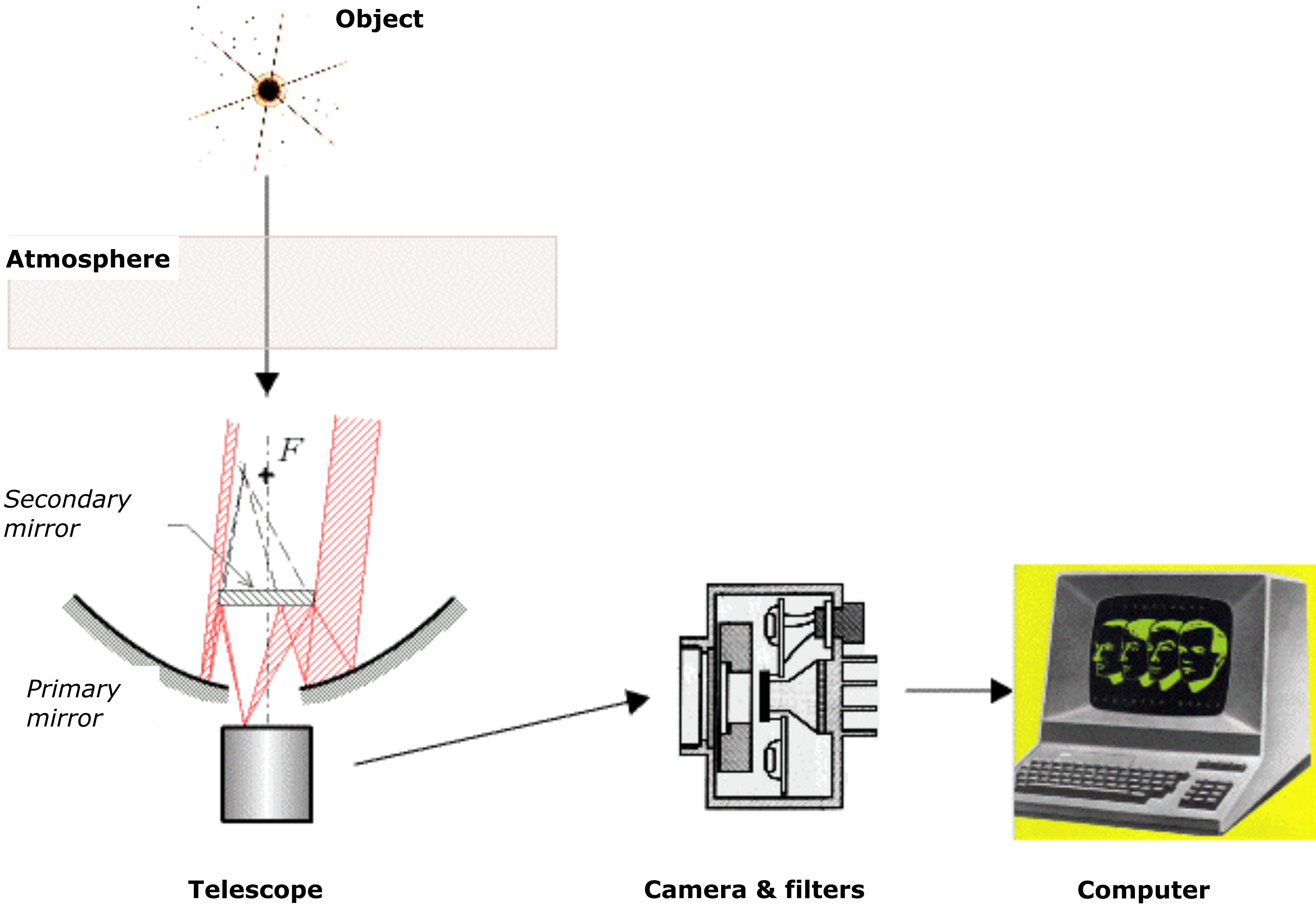
To be optimised during acquisition

- **Observe targets close to the S meridian** (highest elevation / minimum airmass)
- **Binning** (minimises readout noise, if no loss of resolution)
- **Exposure time** (max signal, no saturation)
- **Don't forget to focus! —** Estimate seeing (qualifies turbulence)
- **Maintain observation log** / take notes (events, doubts, questions…)

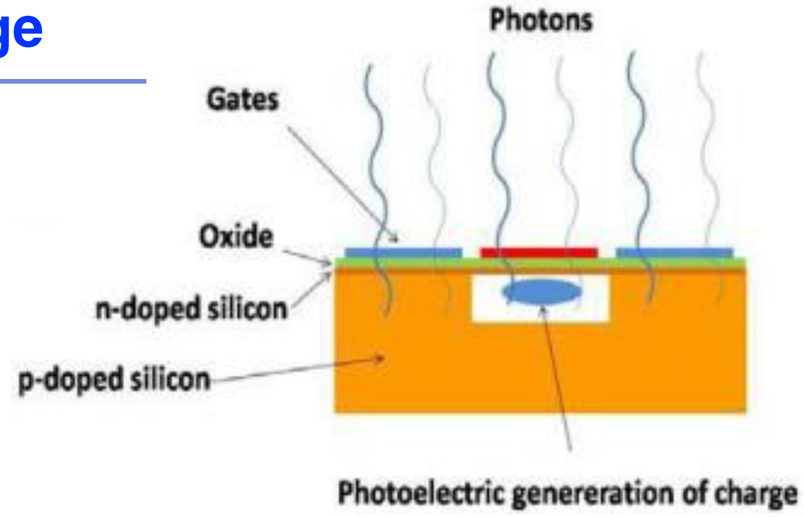
After the fact (by software)

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

Acquisition process in astronomy imaging



Digital detectors in UV-Optical-NIR range



Modern systems

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

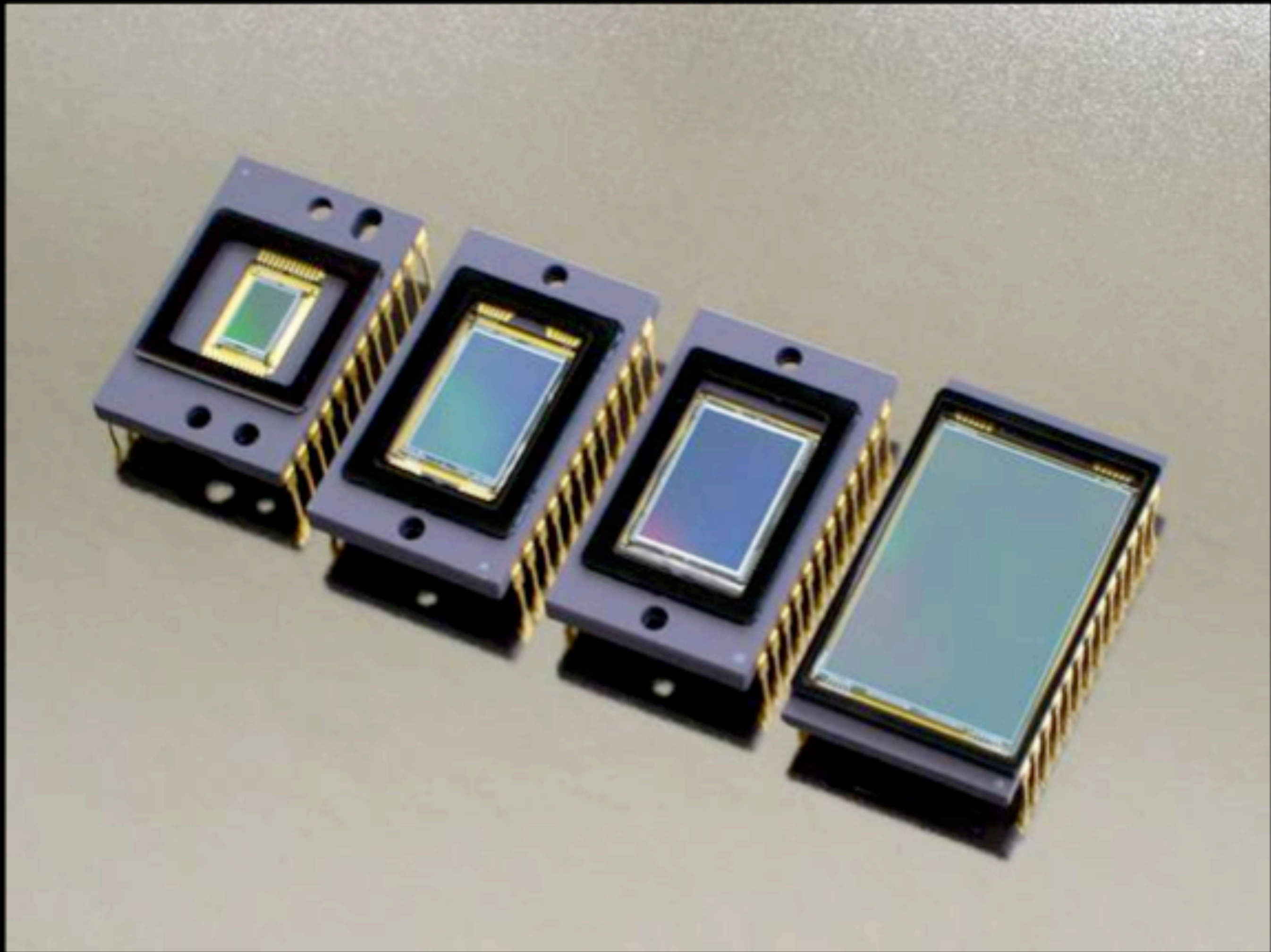
Electric charges accumulate in each photosite, as a function of incident light flux

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

• **Different types of detectors** (with different readout circuits):
⇒ **CCD or CMOS in the optical range**
equivalent systems (HgCdTe, InGaAs, etc) in the IR range

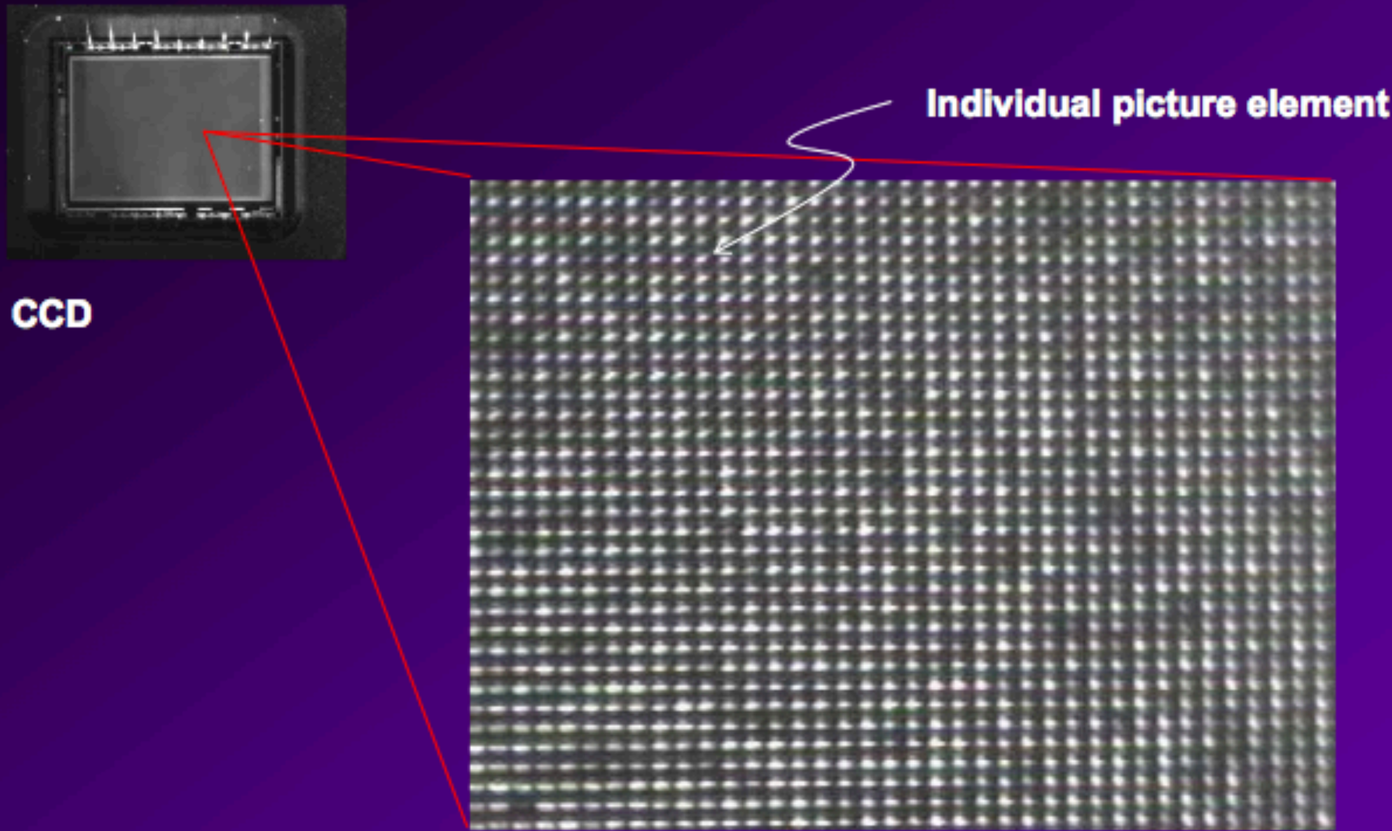
Properties

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



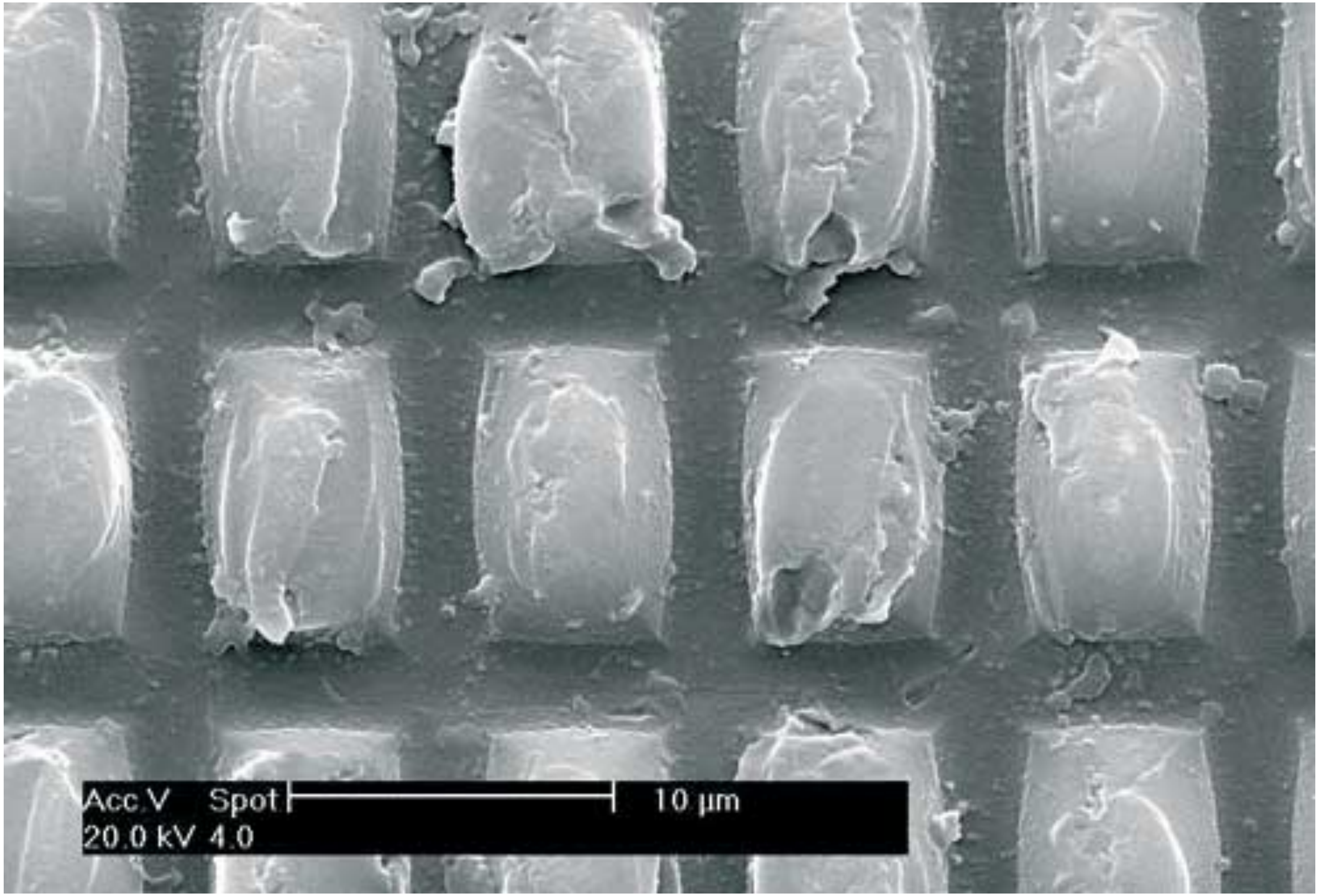
Kodak Full Frame CCDs: KAF-0402ME, KAF-1603ME, KAF-3200ME and KAF-6303E

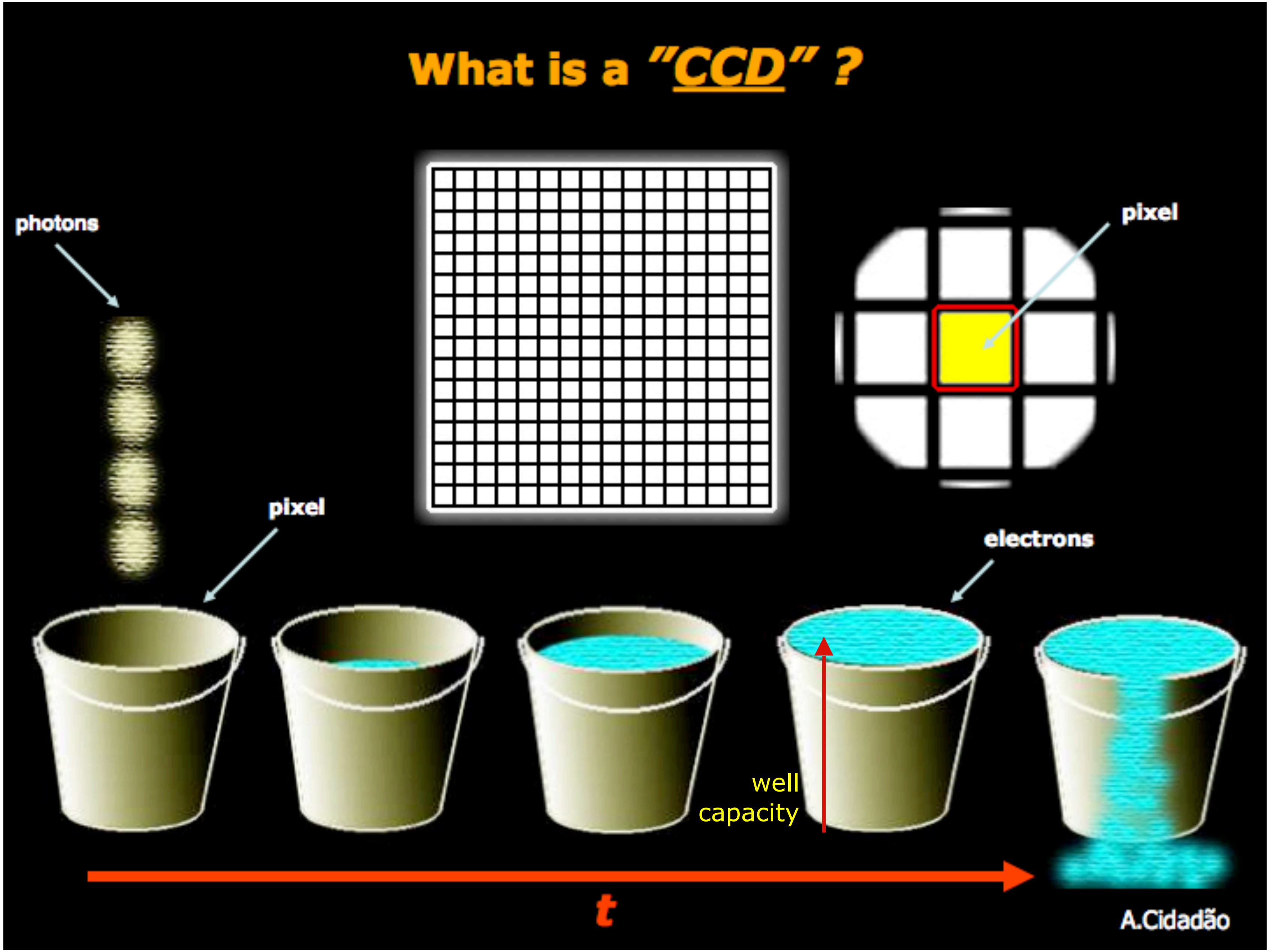
Magnified View of a CCD Array



Close-up of a CCD Imaging Array

Photosites

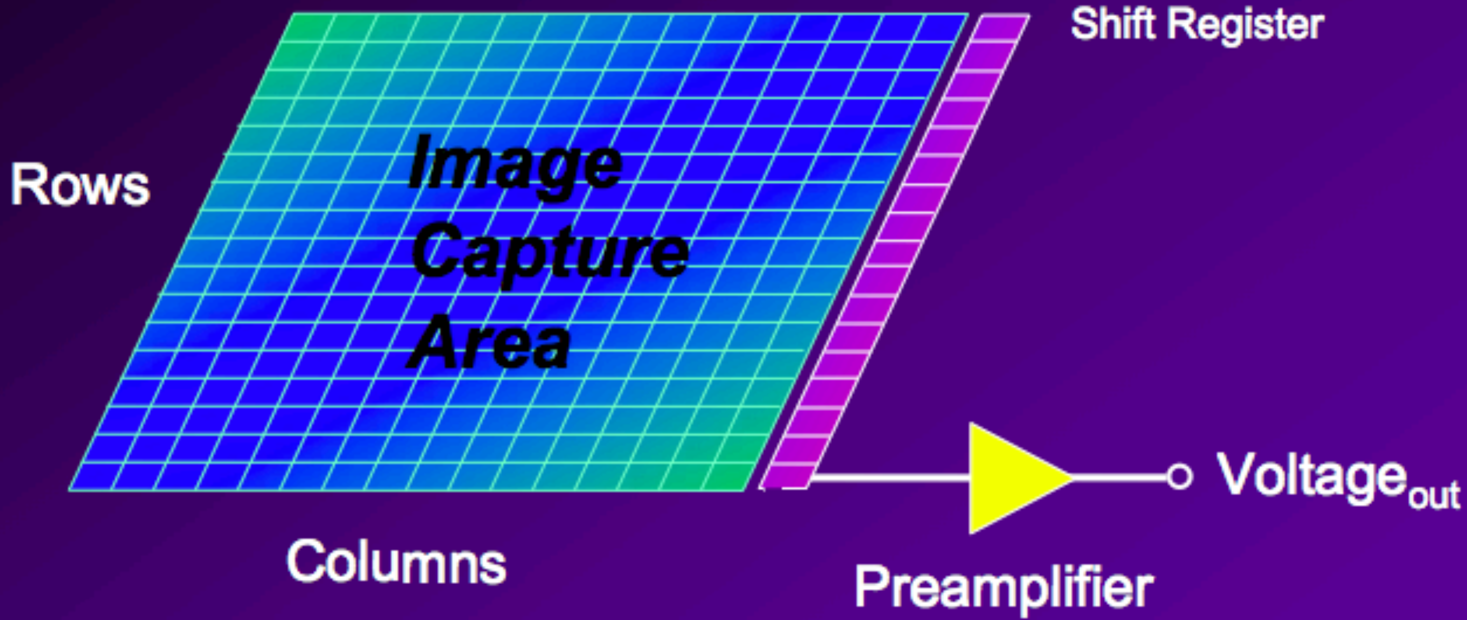




What is a "CCD" ?
photons
pixel
pixel
electrons
well
capacity
t
A.Cidadão

Basic structure of CCD

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



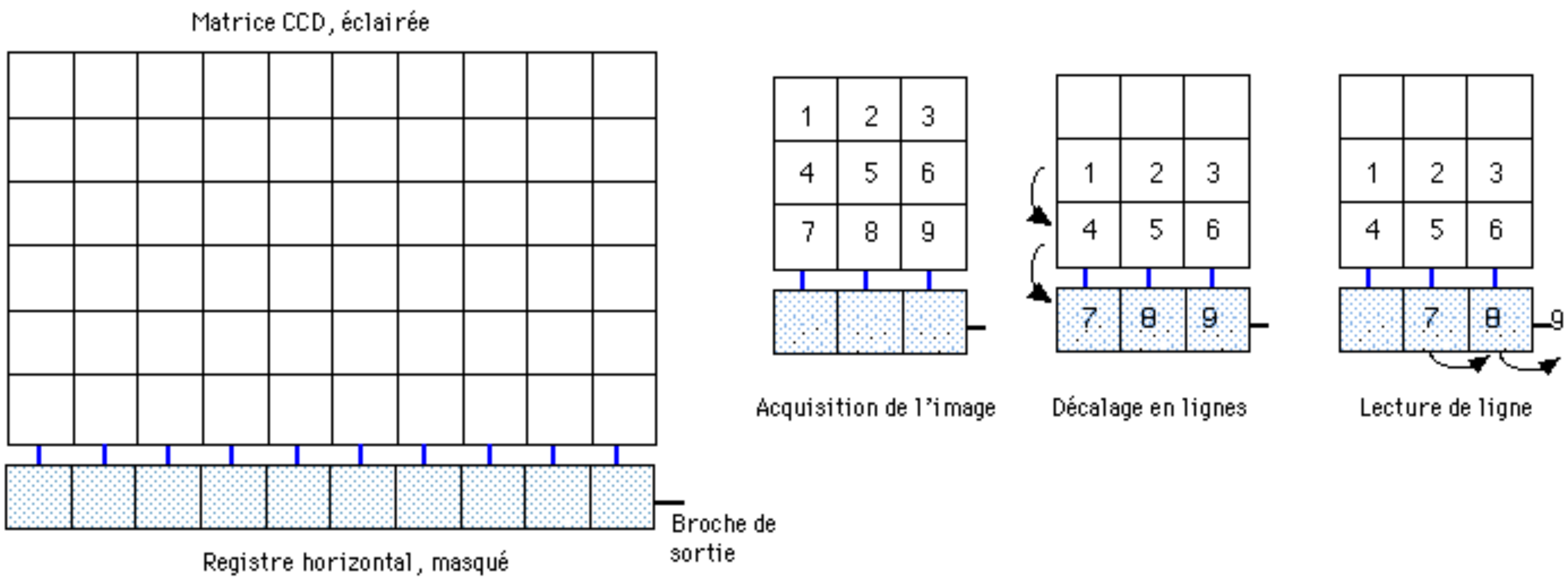
Reading process in CCD

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

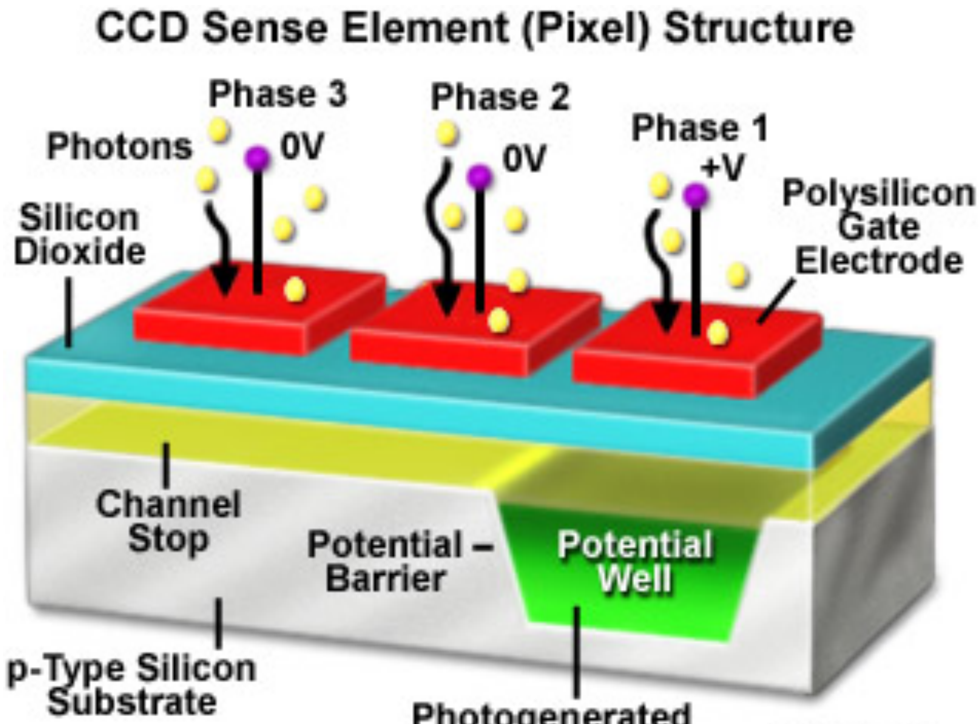
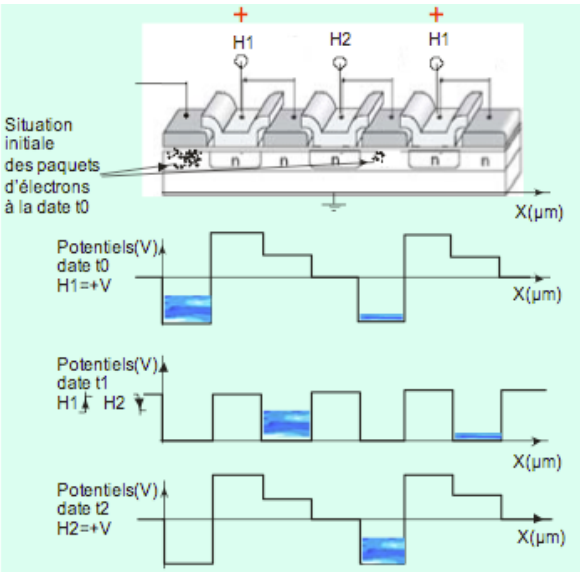


Figure 3

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)



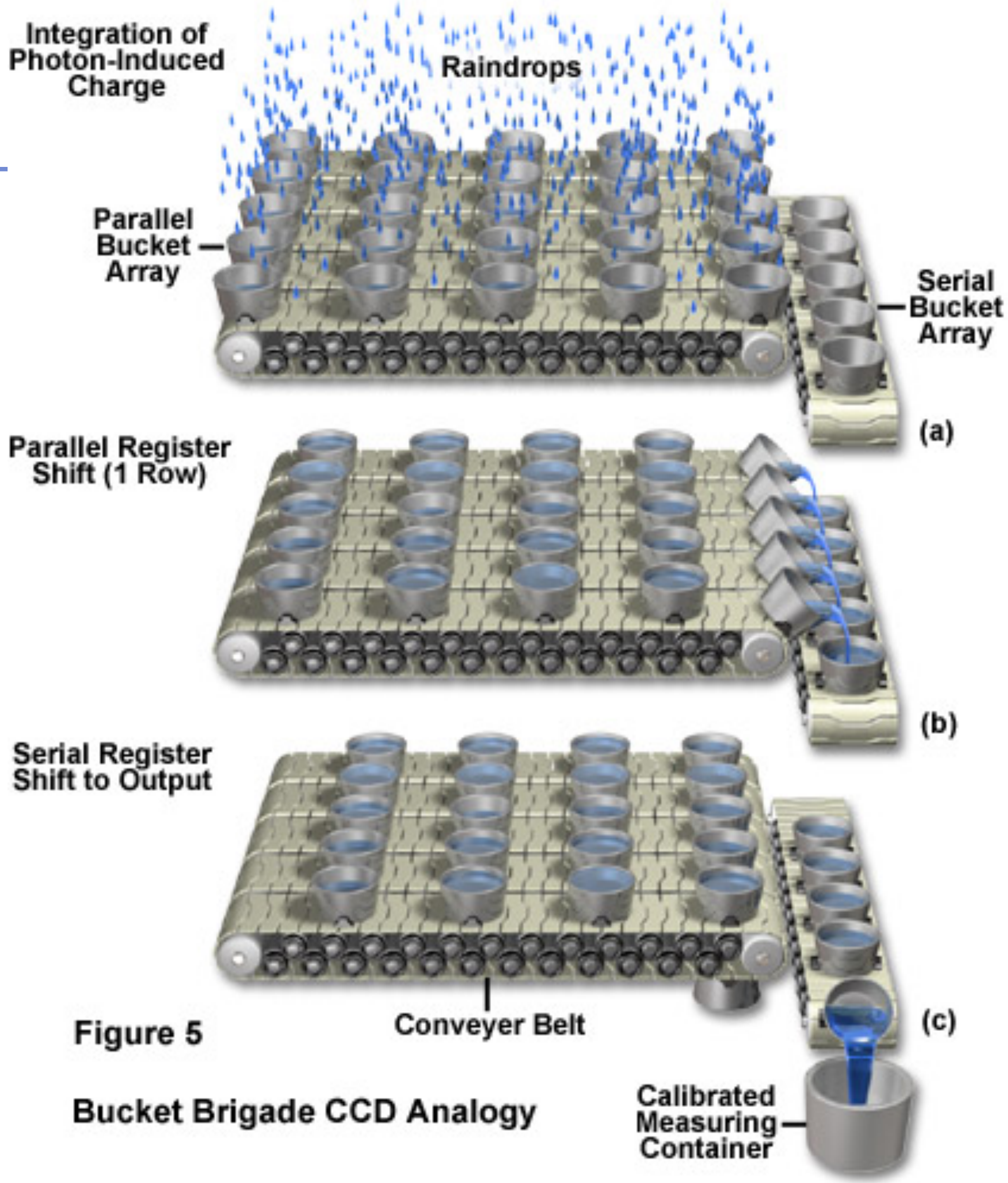


Figure 5

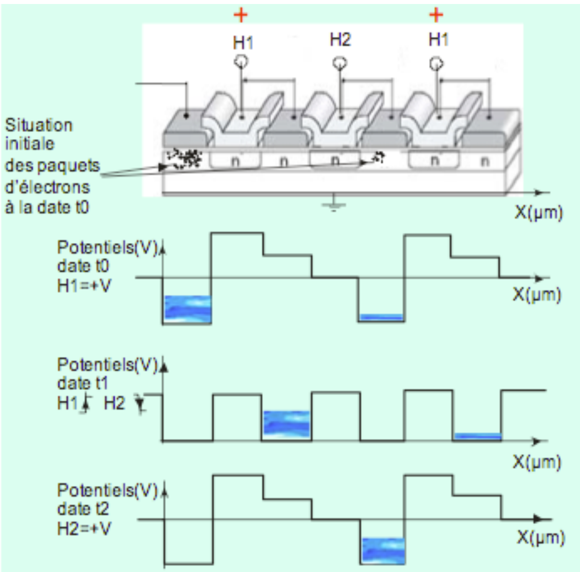
Bucket Brigade CCD Analogy

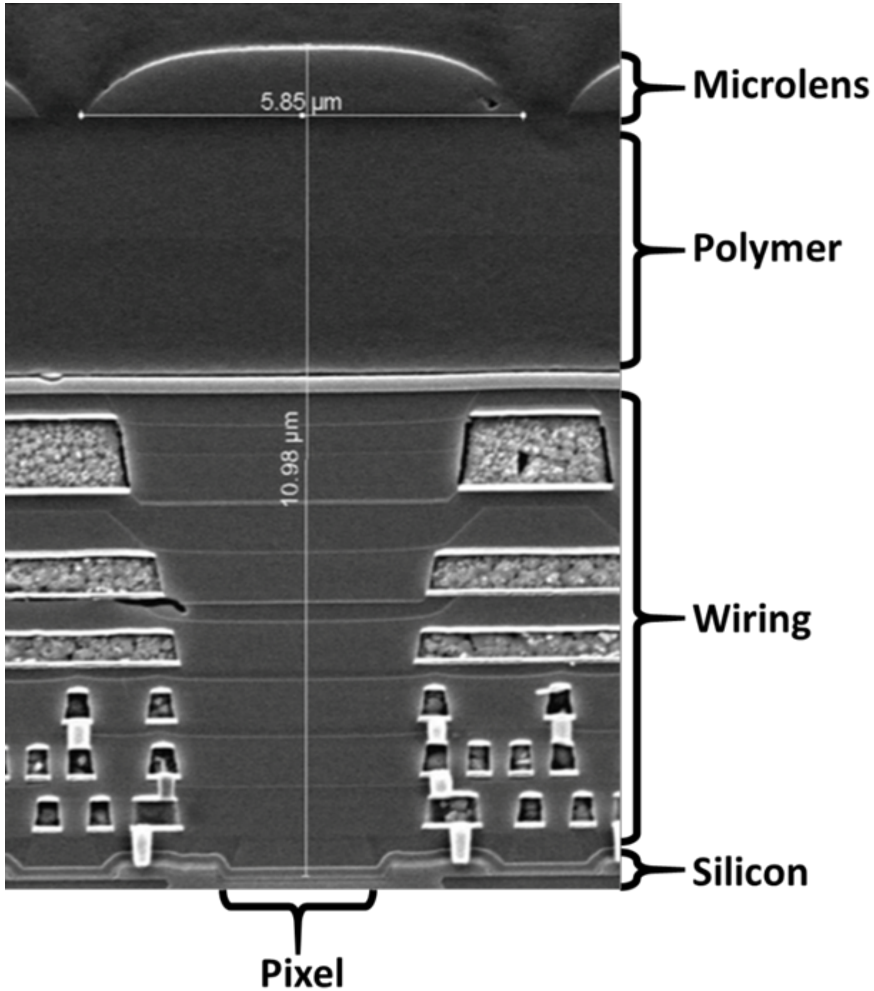
CCD digest

Readout

Charges are shifted by changing the potentials under the rows, in sync

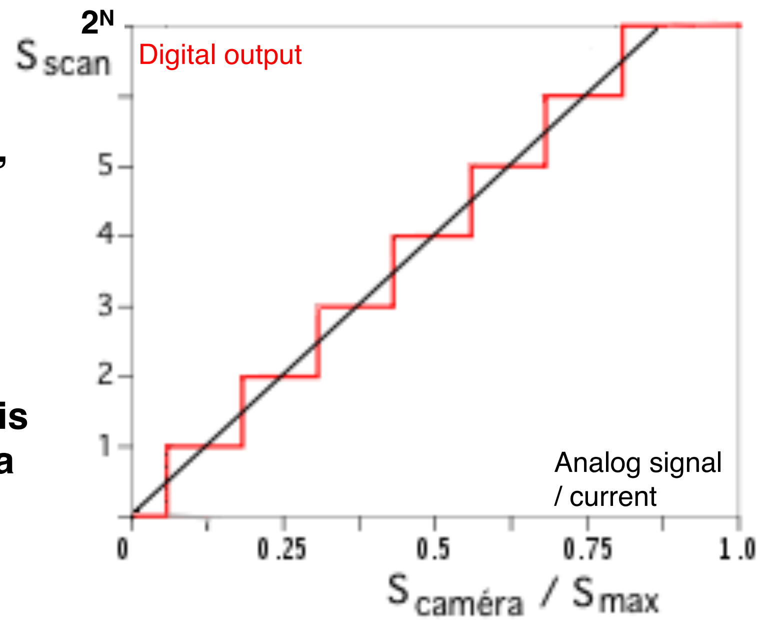
More accurate than CMOS, especially at low fluxes => OK for science measurements





CCD digest

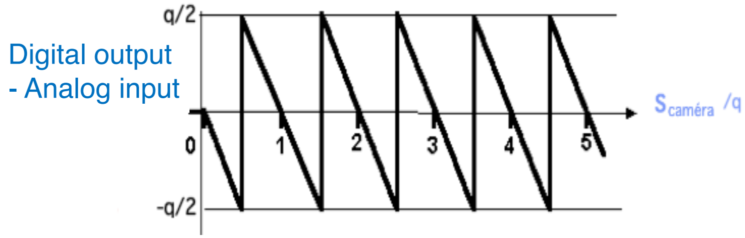
Digitization (French: numérisation!)



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

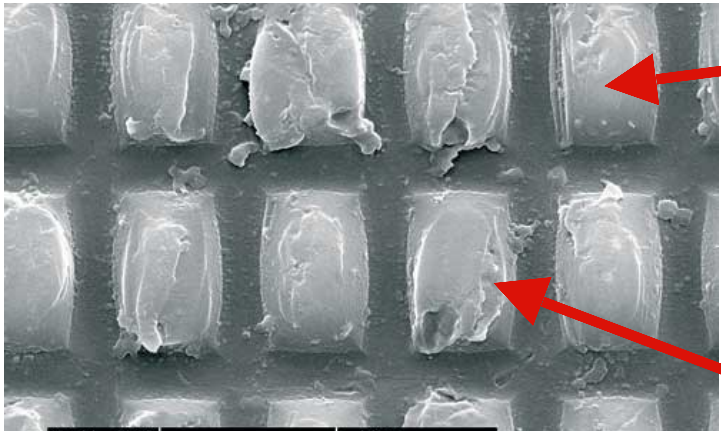
With astronomy cameras, the digitized signal is then transferred to a computer and stored as a file (usually in FITS format)
1 image pixel <=> 1 detector pixel

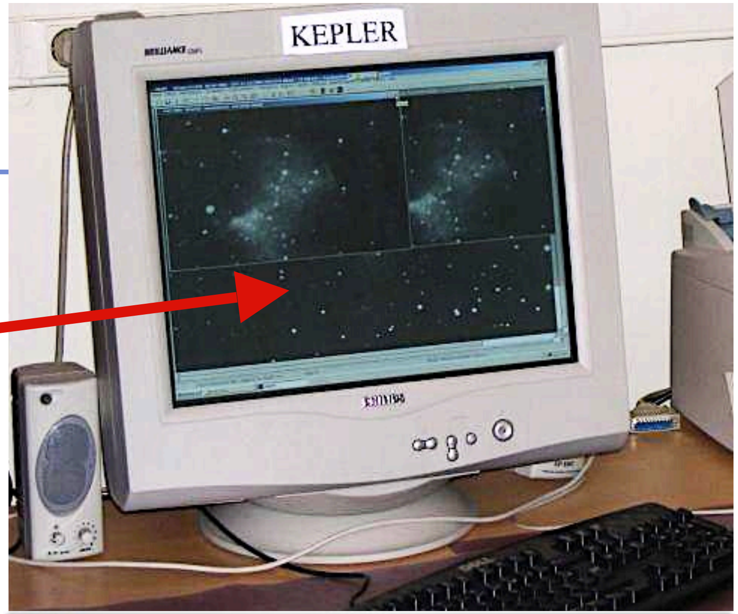
The digitization process results in rounding errors, which can be represented as a noise
(function of number of bits used = N)



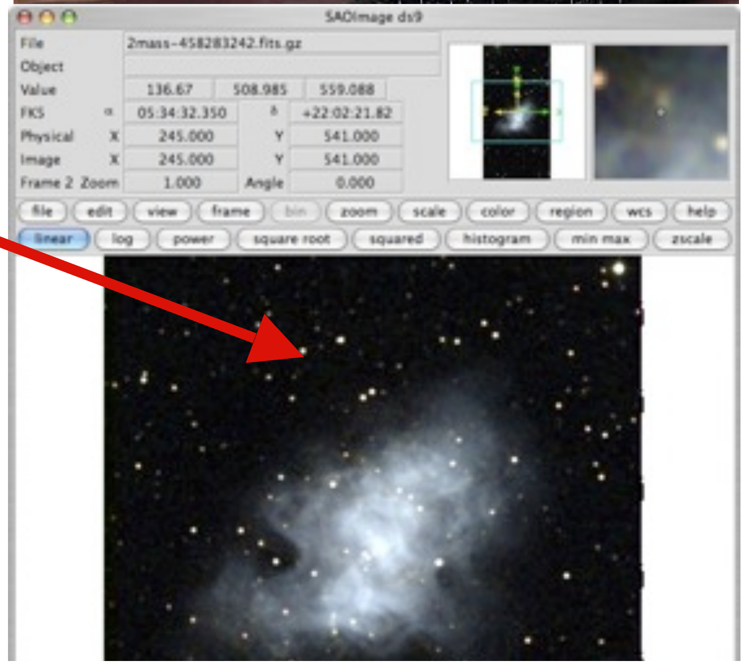
Visualisation of astronomy images

Correspondence between
detector photosite ⇔ screen pixel





In acquisition software
Beware of
- field
- scale
- image quality



In display app
Beware of
- top/bottom inversions

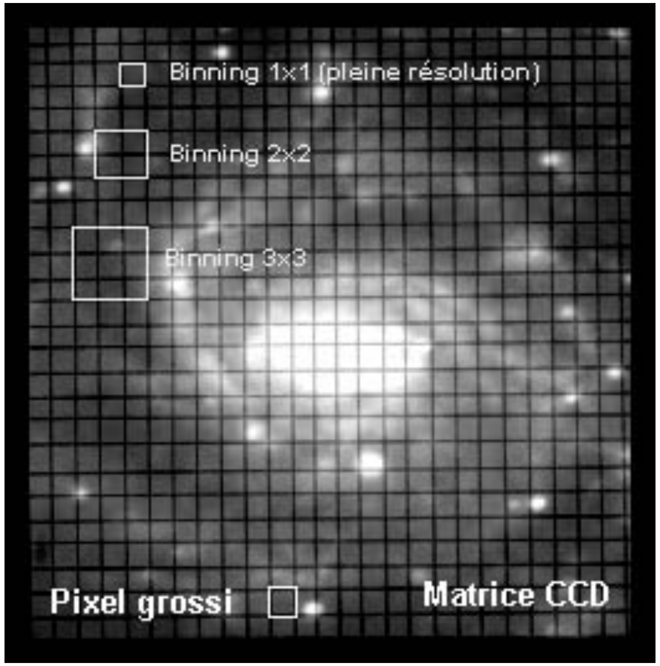
Anything else implies resampling and loss of display quality
(but may be required to see a complete image)

Basic tools to read/display/analyse FITS images:
- ds9/SAOimage
- Aladin
- ATV under IDL
- astropy + matplotlib under python — etc…

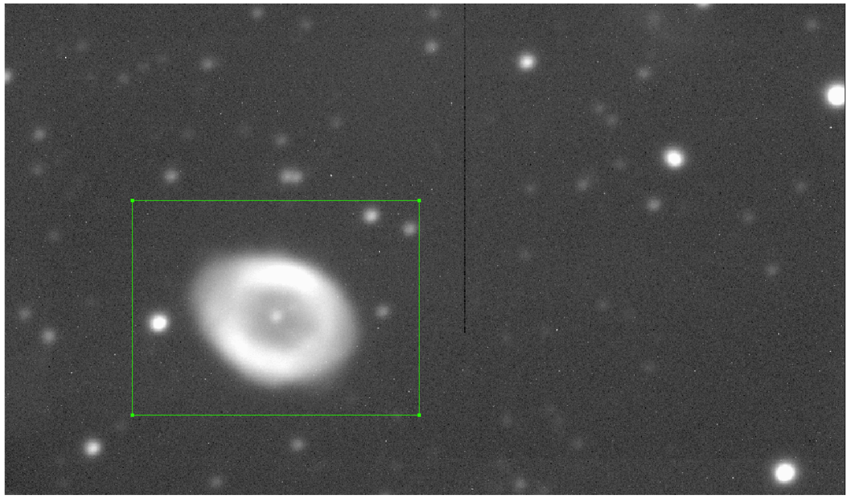
CCD digest

Special readout modes

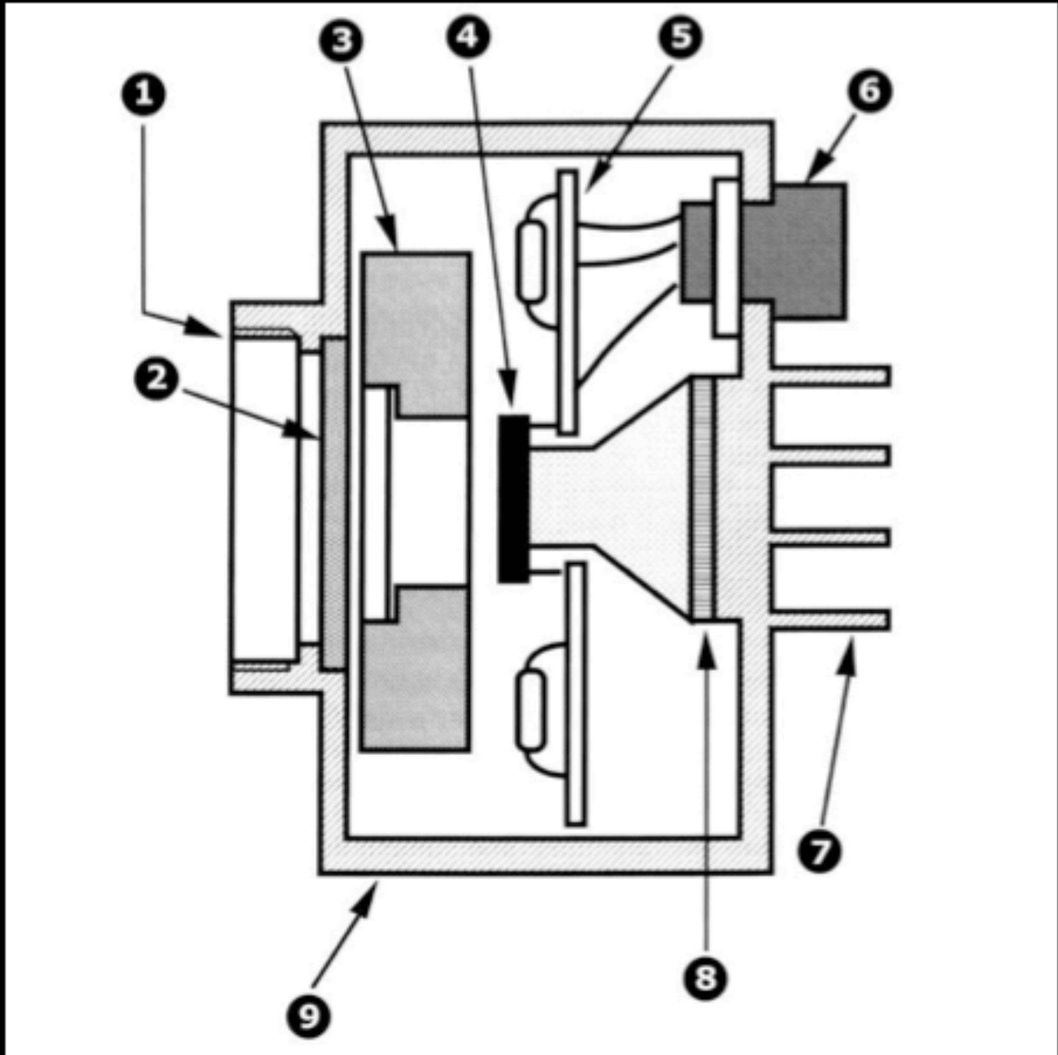
Binning: **several pixels read simultaneously, *before* measurement of output current and digital conversion – intended to lower readout noise, & faster**



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



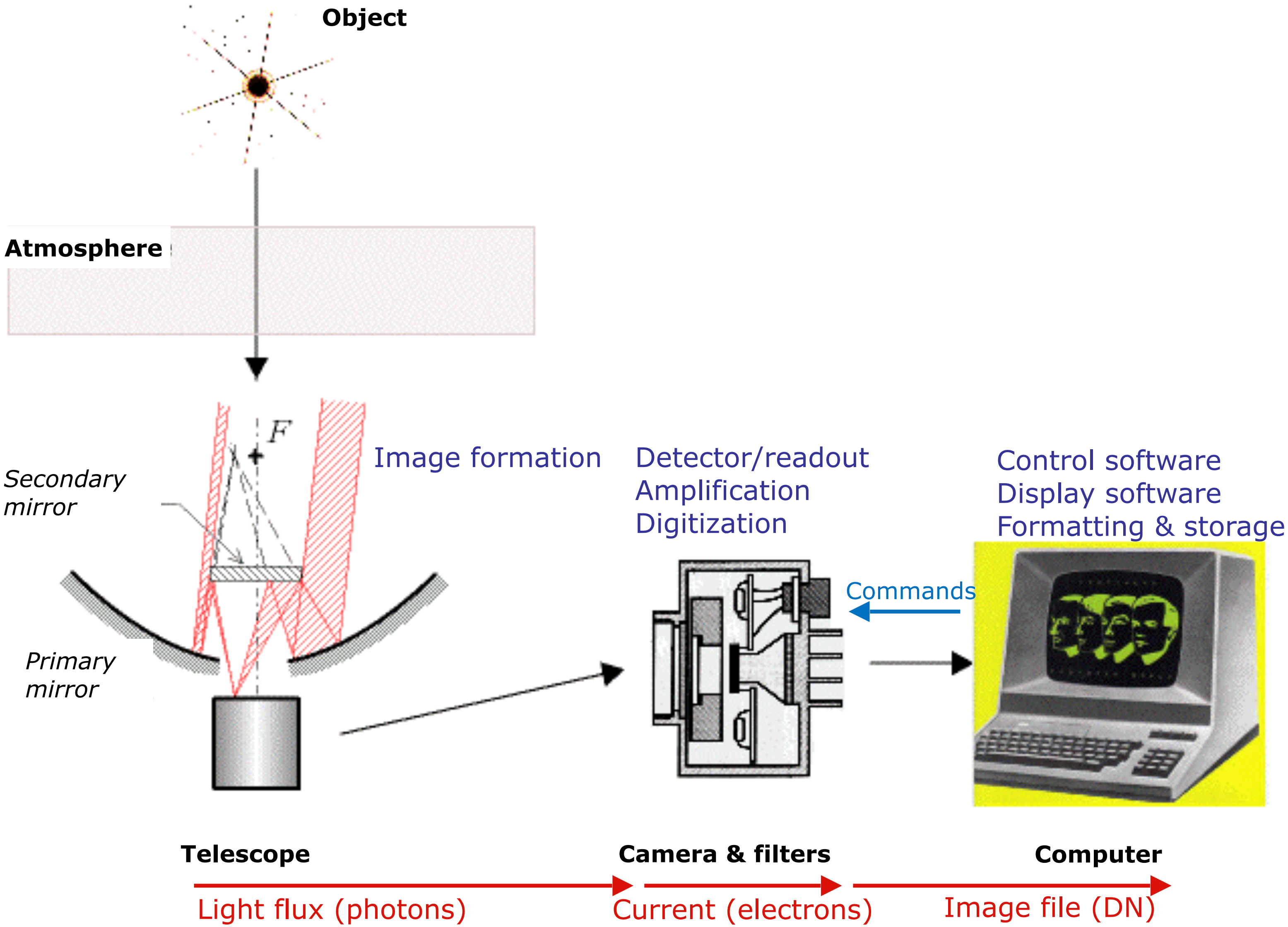
Camera



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
SBIG
ASTRONOMICAL INSTRUMENTS
REMOTE HEAD
POWER
ETHERNET
I2C AUX
USB
SCOPE

Acquisition process in astronomy imaging



Electronic characteristics

Output signal

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

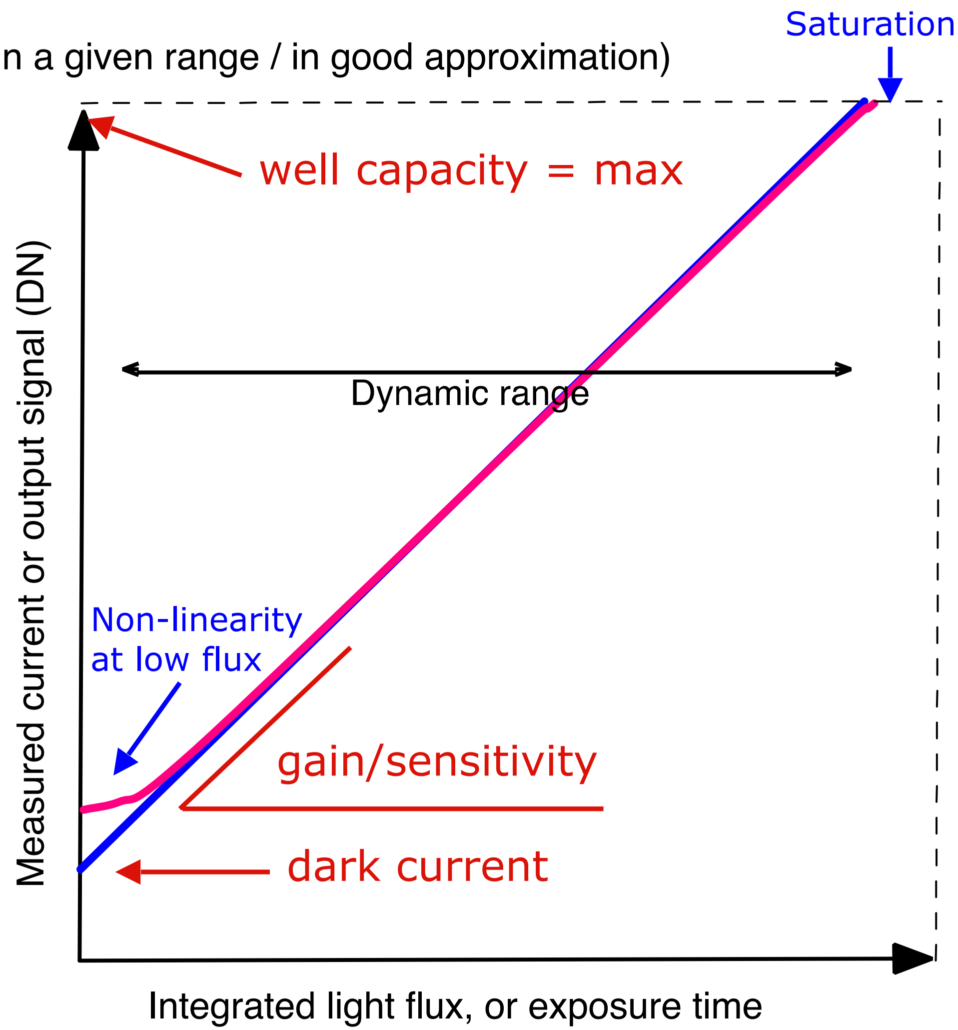
For each pixel:

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

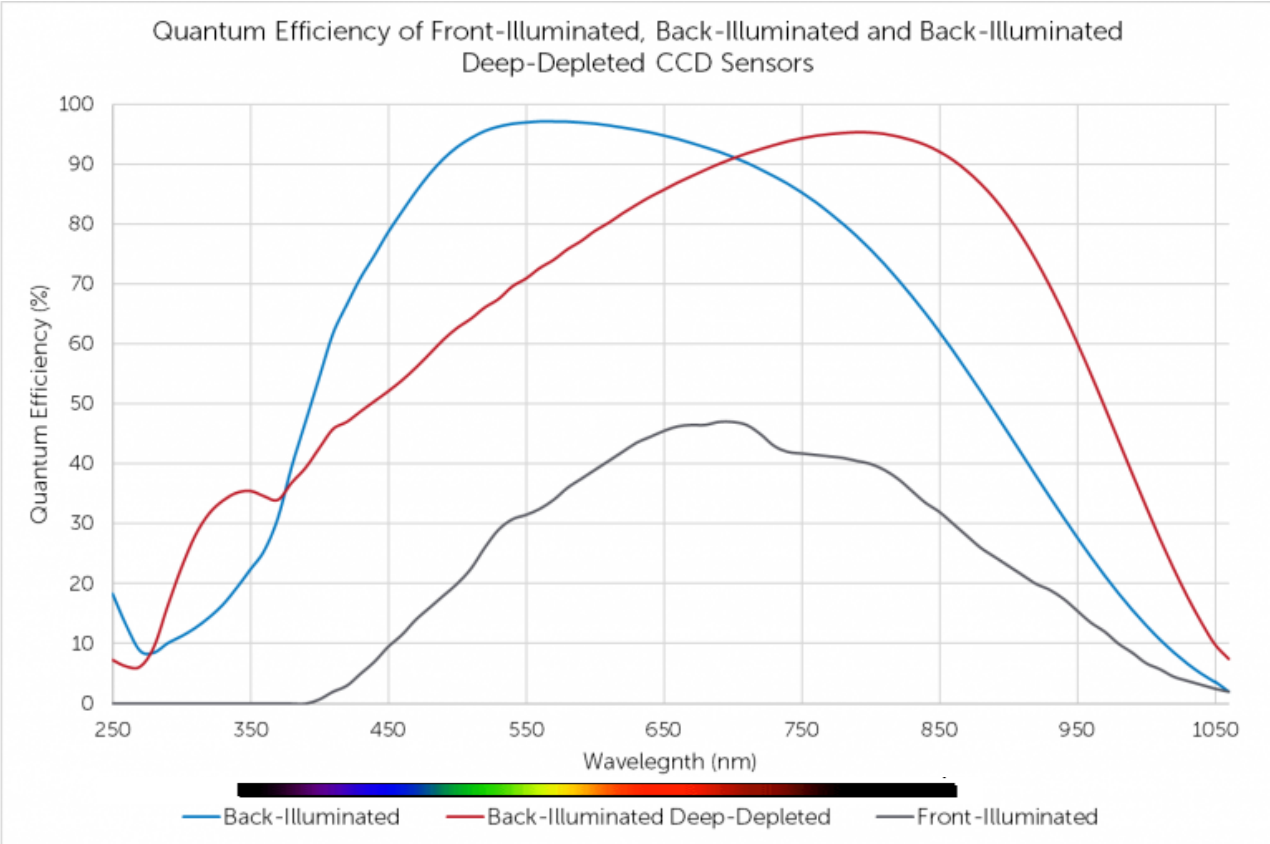
Well capacity / saturation

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

Electronic characteristics

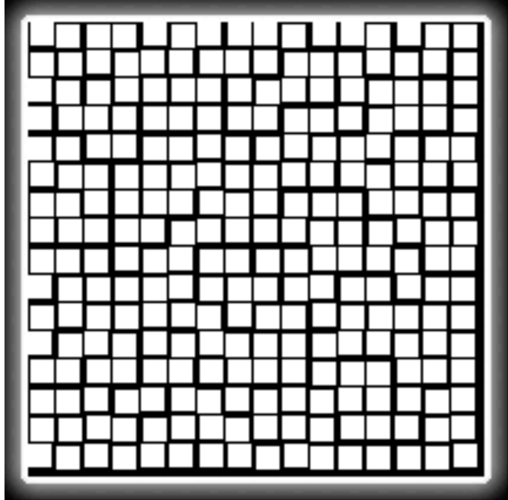
Sensitivity / gain

Equivalent Quantum Efficiency (QE): nb of electrons produced per incident photon
⇒ Function of wavelength ~ 0.4-1.0 μm for standard CCD
Back-illuminated, thinned CCD have expanded spectral range and improved sensitivity



Silicon crystal properties
=> max wvl = 1.1 µm
(gap between valence and conduction bands)

CCD Cameras - *Bias (offset)*



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

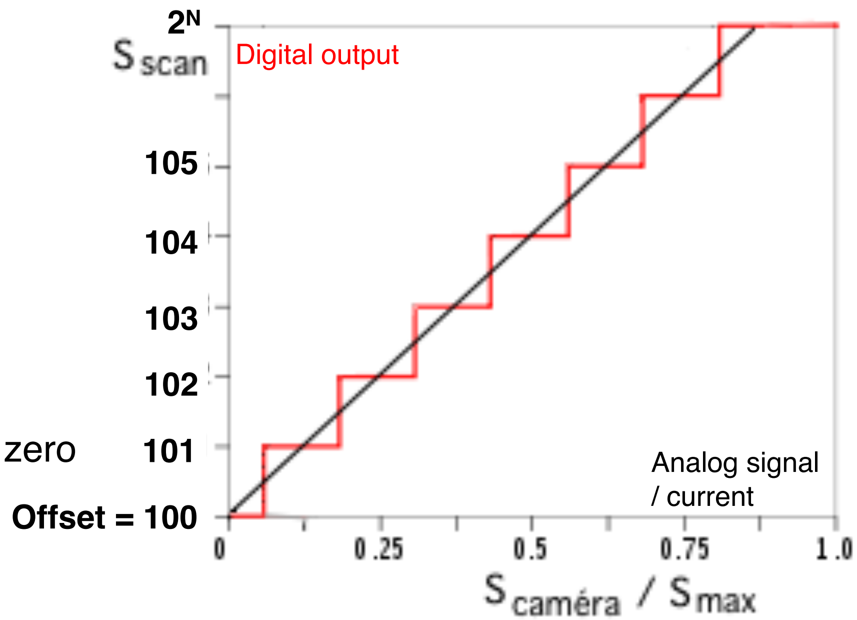
Visible at minimum exposure time

Provides more or less regular patterns, often along column direction

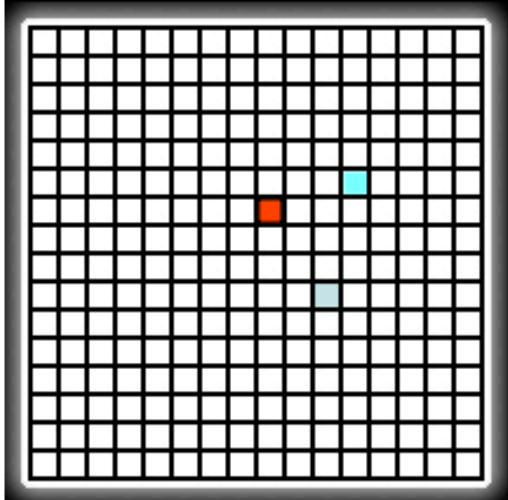
Offset

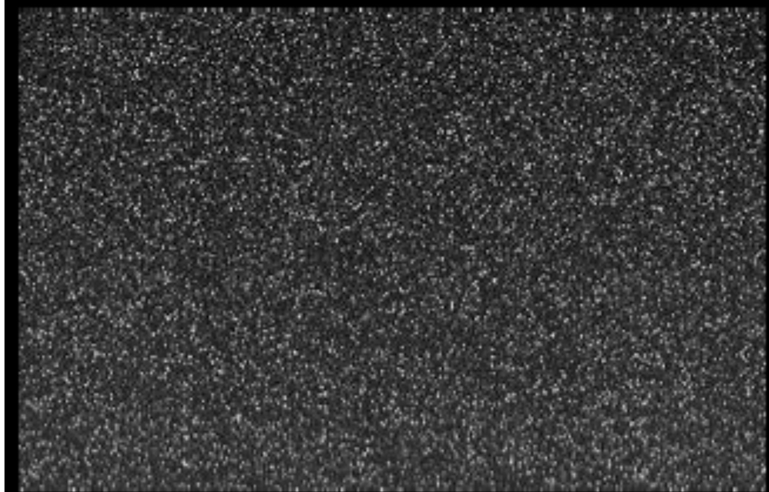
Offset
= base level imposed in the ADC during conversion (does not correspond to any charge / light flux)

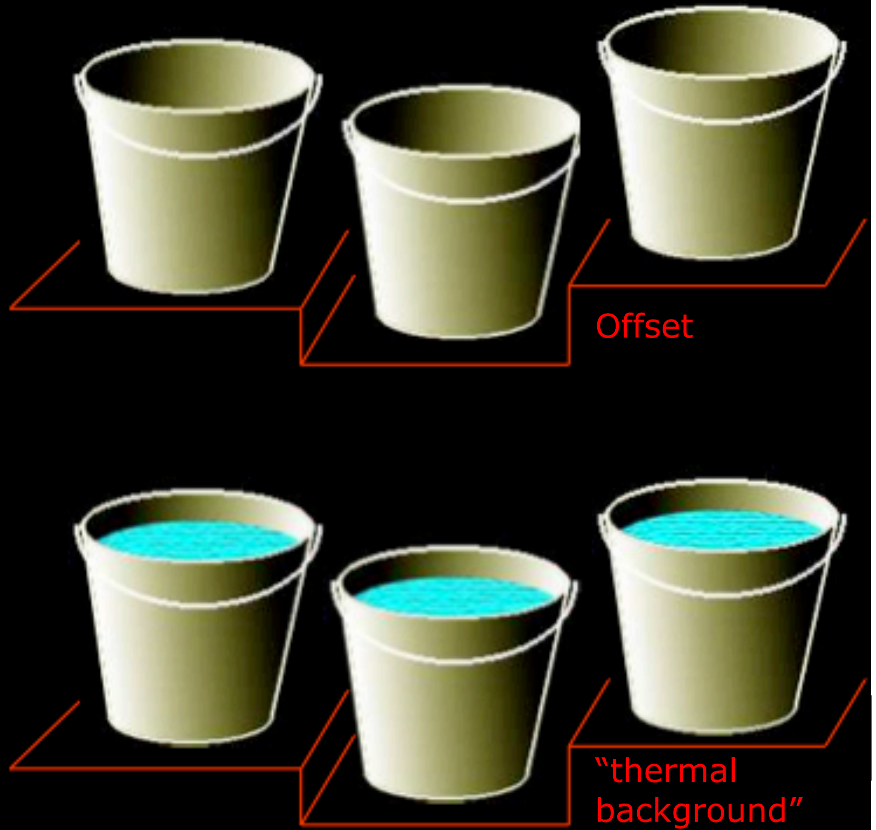
= at least 2 to 3 x noise level, to offset from zero and preserve statistics



CCD Cameras - *Dark current*



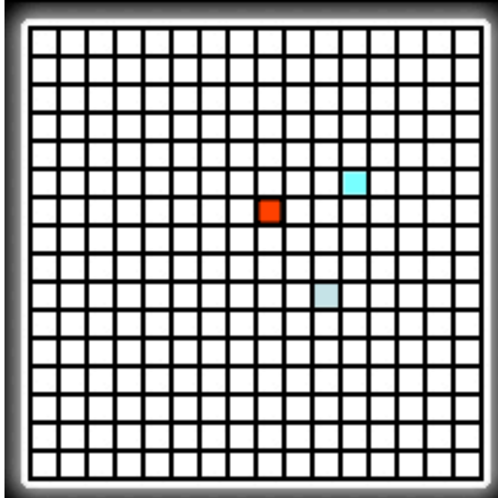


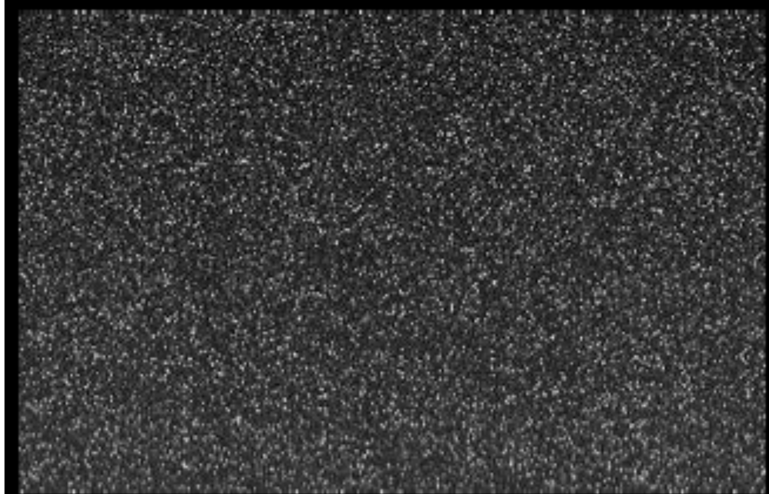


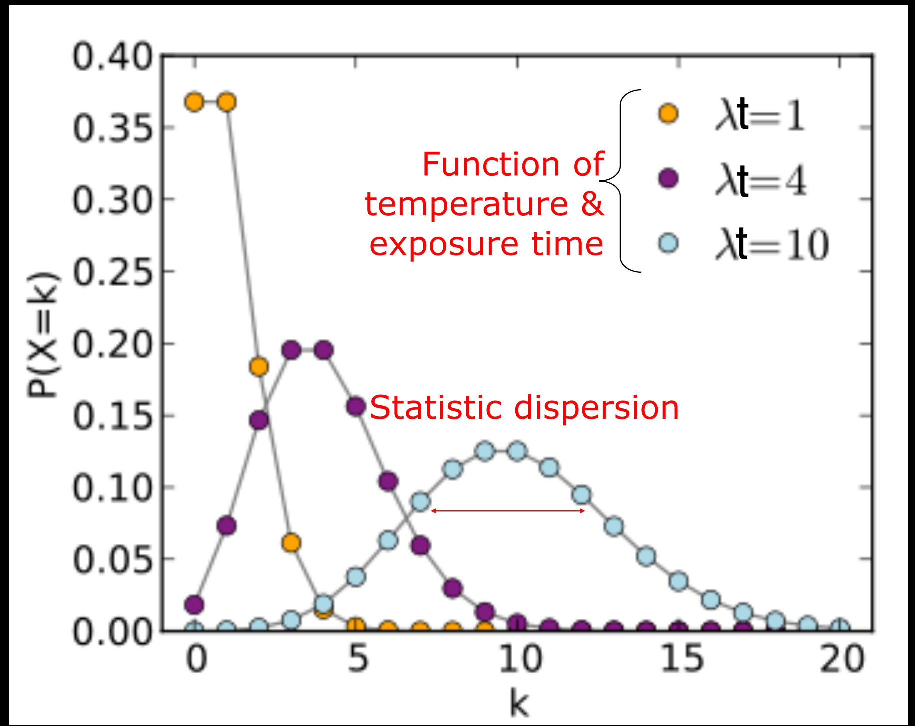
DARK FRAME = BIAS FRAME + THERMAL FRAME

A.Cidadão

CCD Cameras - *Dark current*







Charges are created spontaneously in absence of light
Not necessarily large wrt offset
("thermal" here refers to agitation, not to BB emission!)

This process follows a Poisson distribution

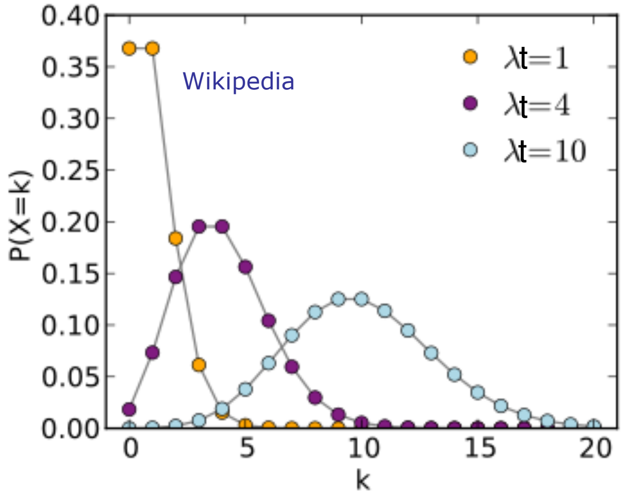
Intermission: the Poisson distribution

Assumptions: - events are random and independent
- event frequency is constant (λ)

Examples: photon emission; creation of thermal charges

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

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

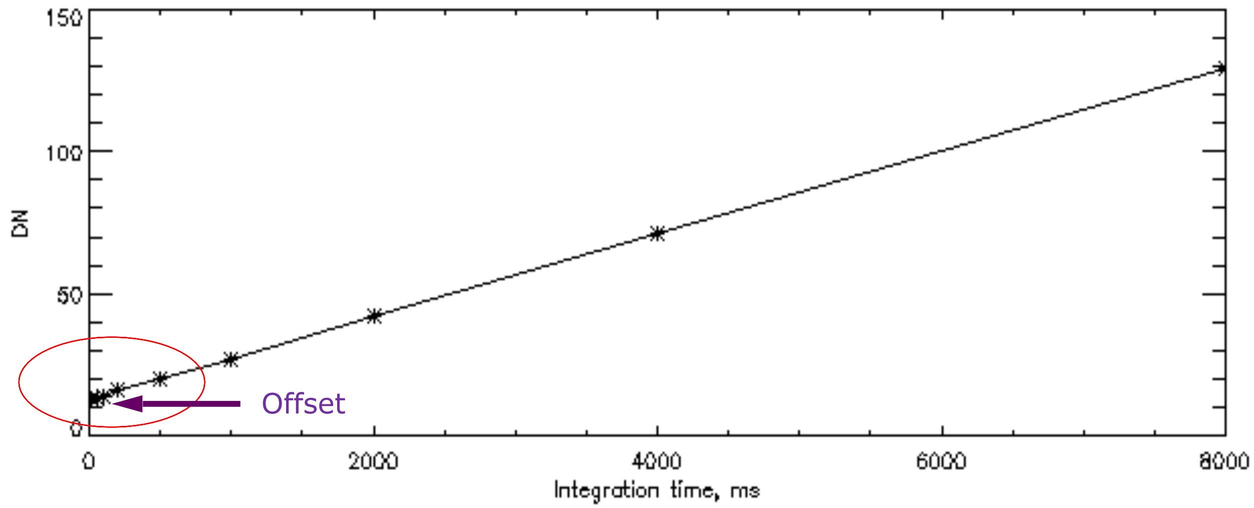


Tends towards a Gaussian distribution
when λt is large (central limit theorem)

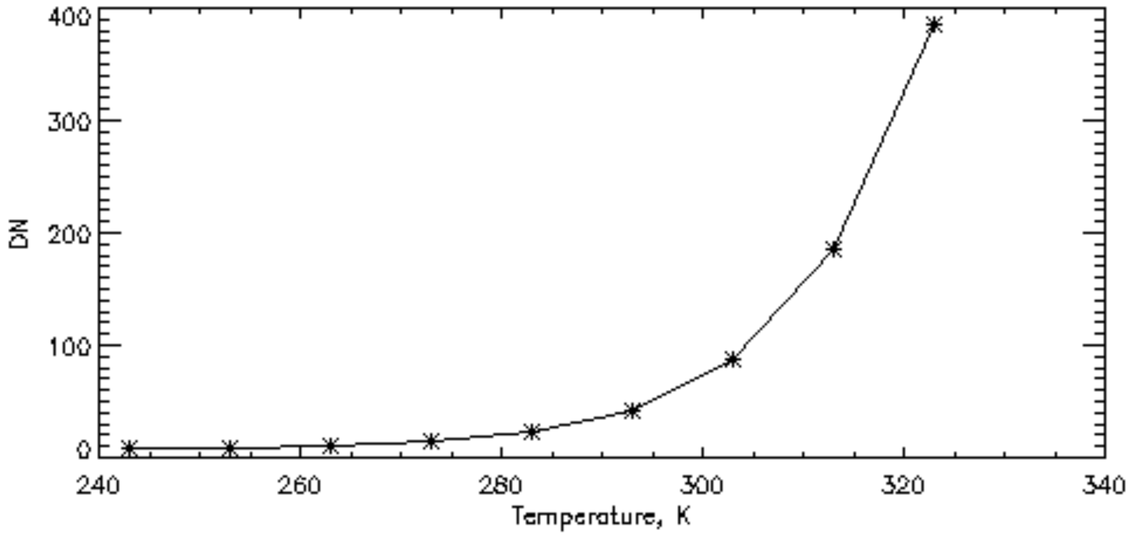
With N = λt:
Mean = N (nb of photons received during t) => Predictable

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*

Darkening with distance to optical axis

Filter transmission × variations of pixel response × "doughnut" patterns

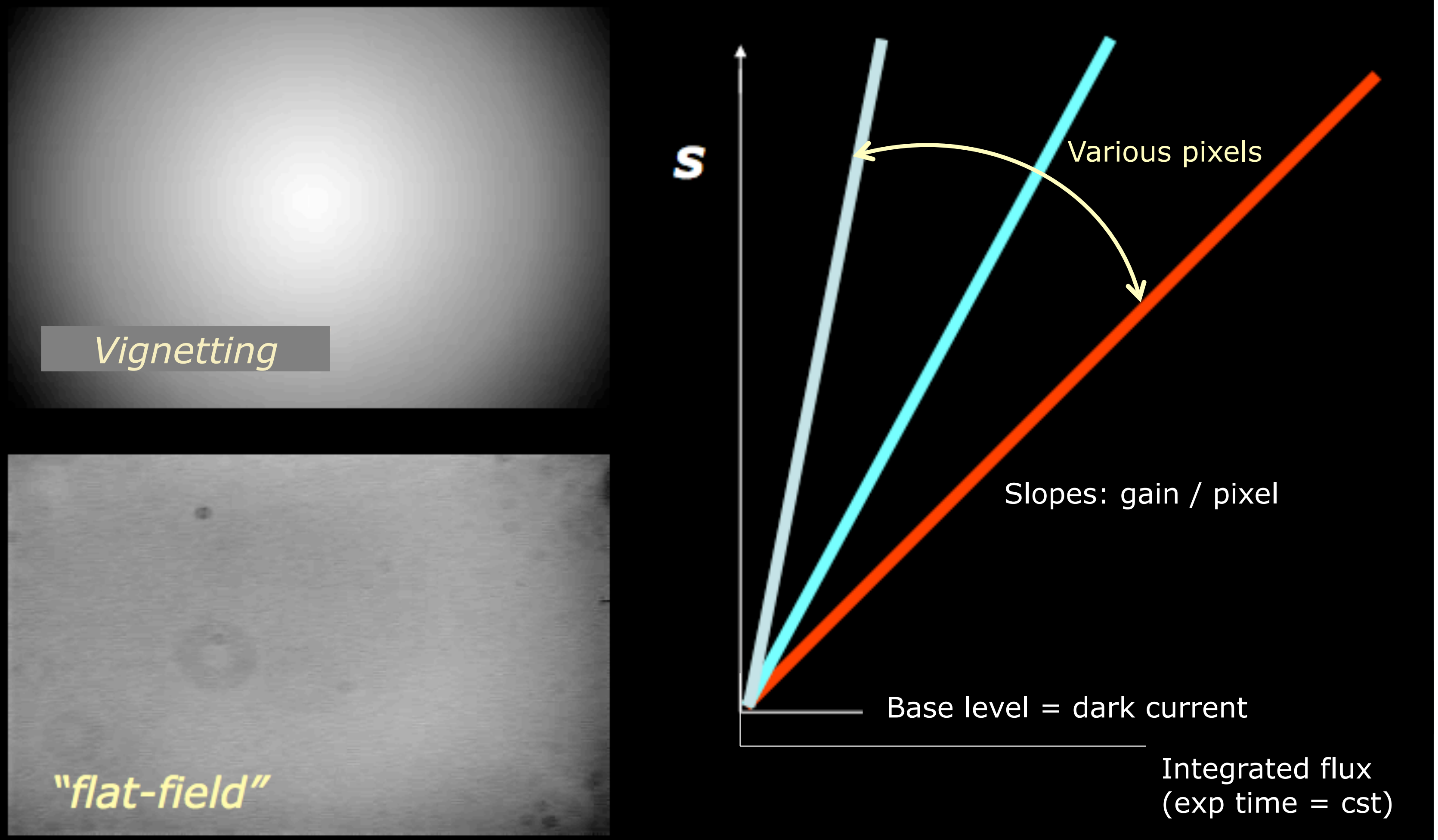
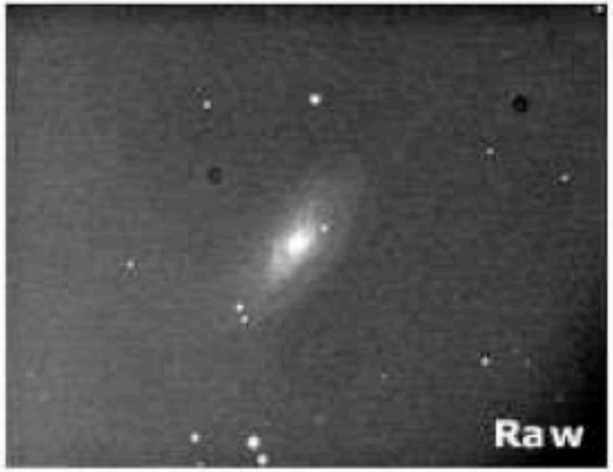


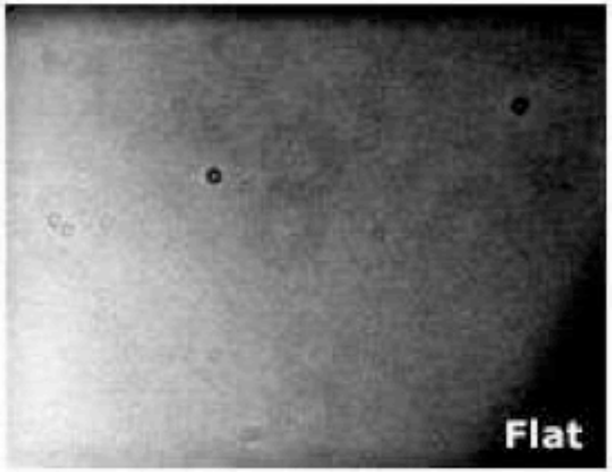
Image calibration / reduction

Exp. time t_{exp}
Filter F



Exposure time t_{exp}

Filter F
Normalised



Calibrated = (Raw - Bias - Thermal frame) / Flat / t_{exp} = (Raw - Dark) / Flat / t_{exp}

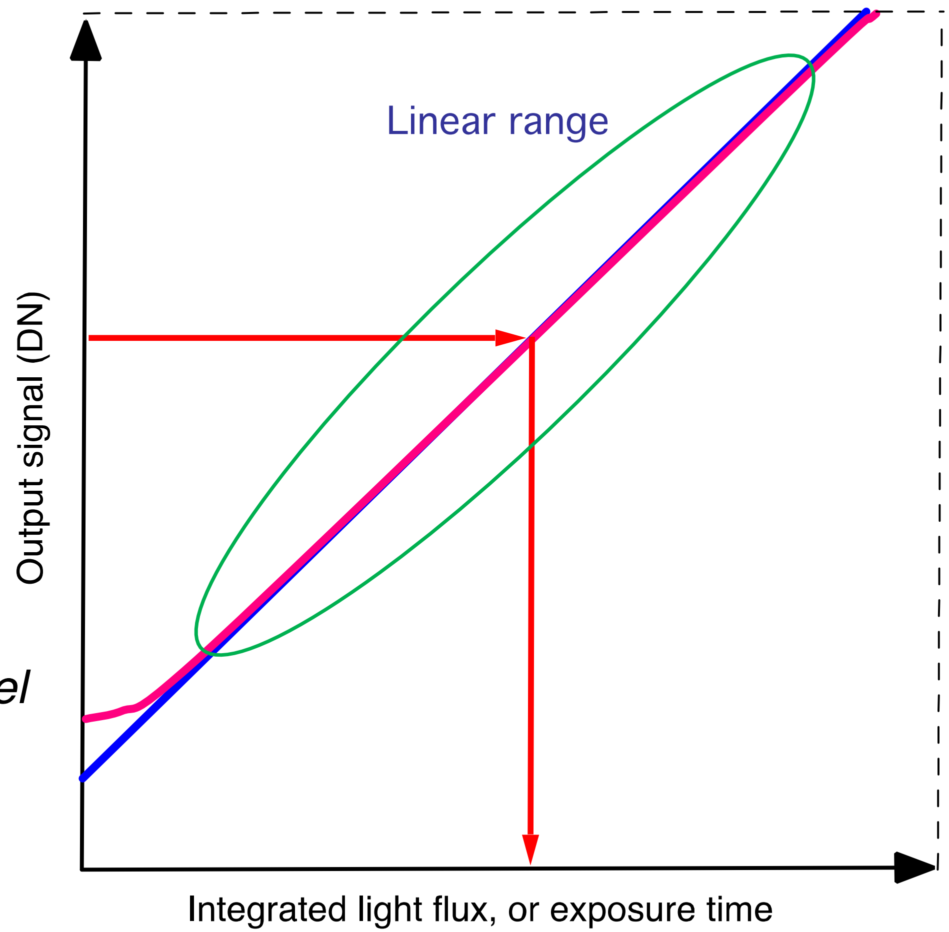
Linear approximation - Only calibrates in a relative sense

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*



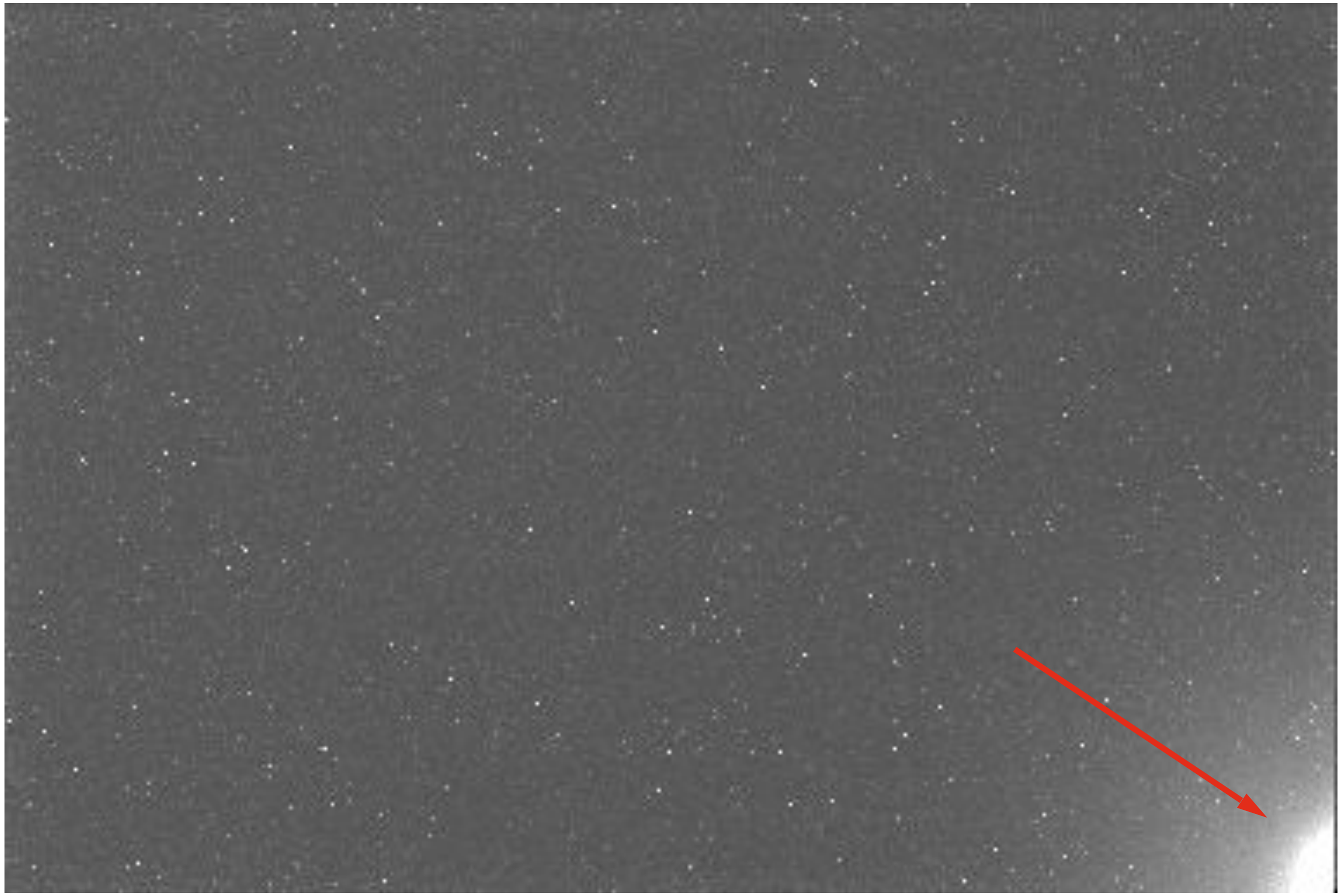
Only calibrates in a relative sense (even if divided by exposure time)

Absolute flux may be derived from comparison with reference sources observed in the same conditions

Electronic artefacts

Electroluminescence

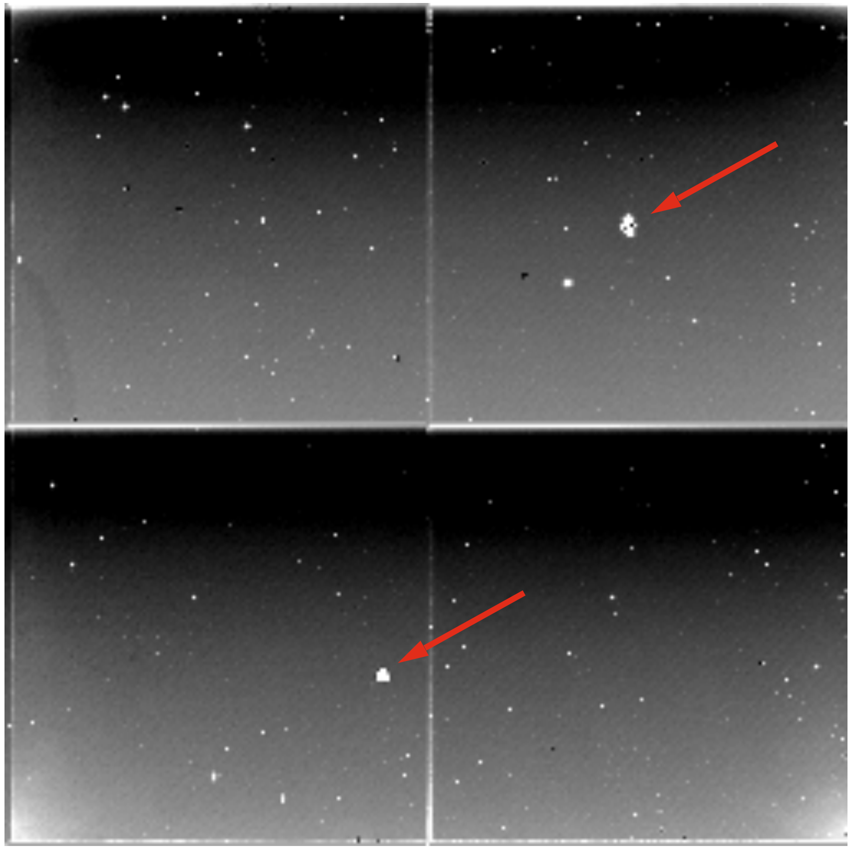
The amp heats a part of the array => dark current increases locally (associated noise also increases)



Electronic artefacts

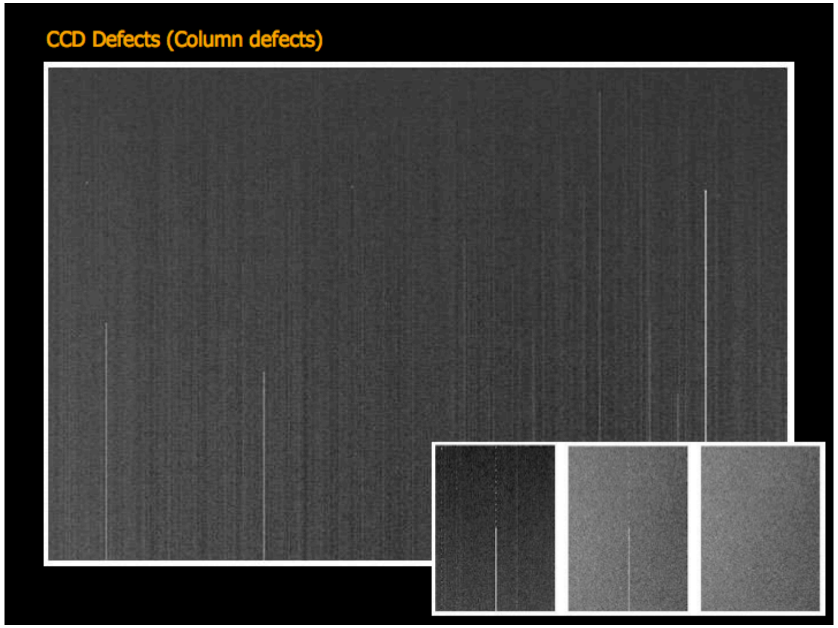
Dead / cold / hot pixels

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

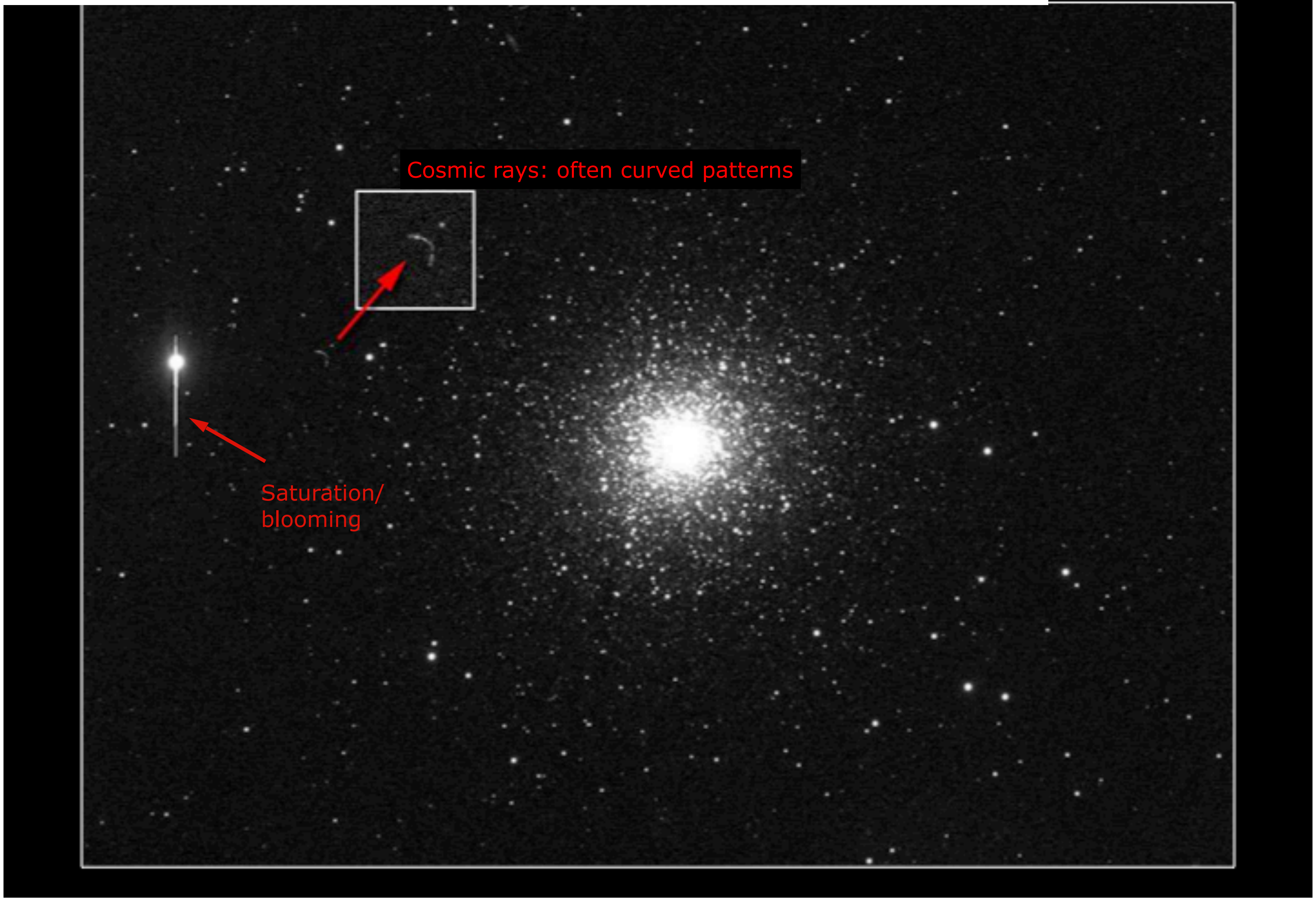


Quadrants: 4 independent readout circuits used in parallel on the same detector

Column defects (related to electrical circuitry)



Electronic artefacts: effects of saturation + cosmic rays



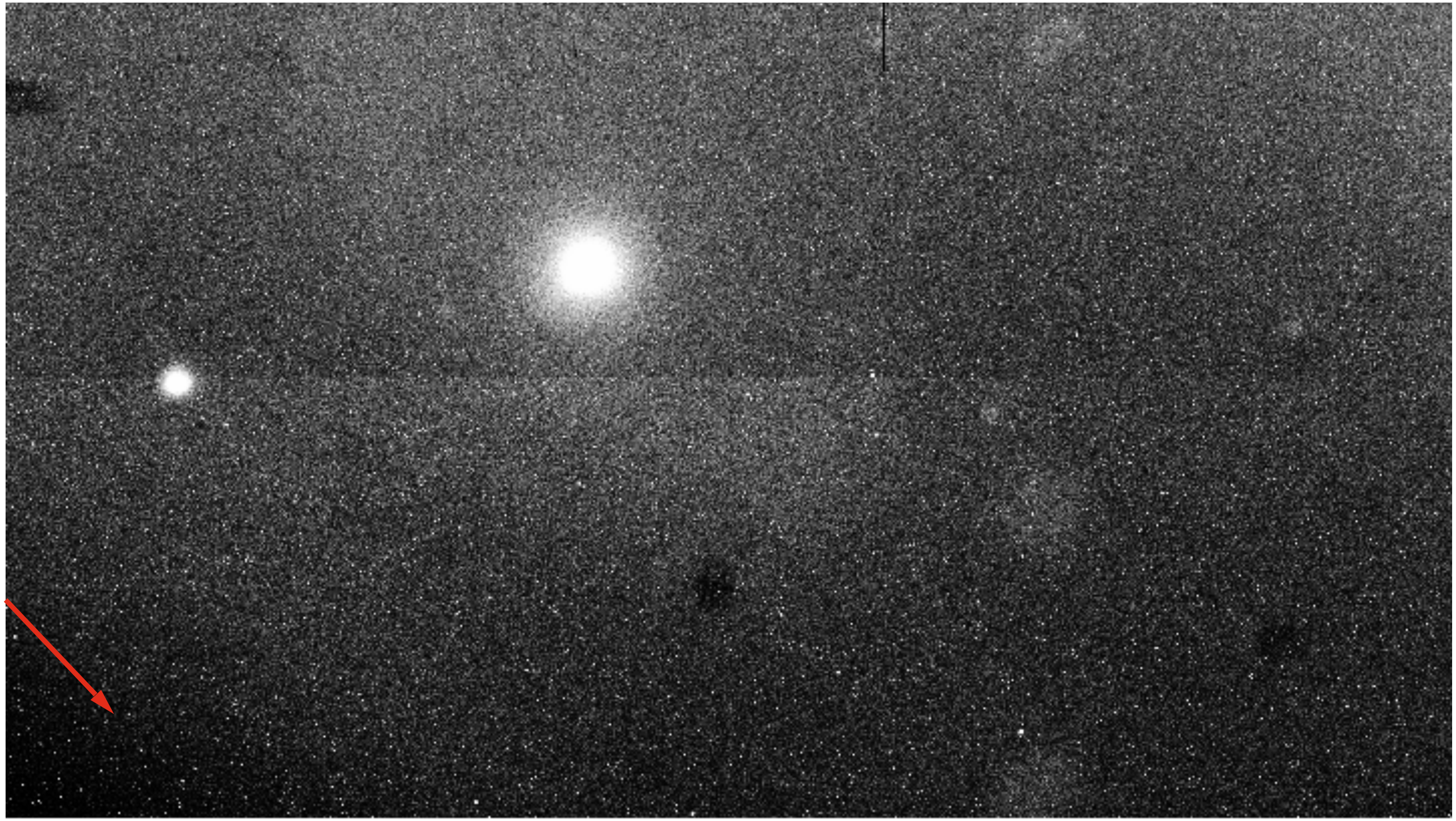
Electronic artefacts: spread of charges

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

Electronic artefacts

Salt and pepper noise, 1/f noise: punctual events / granularity

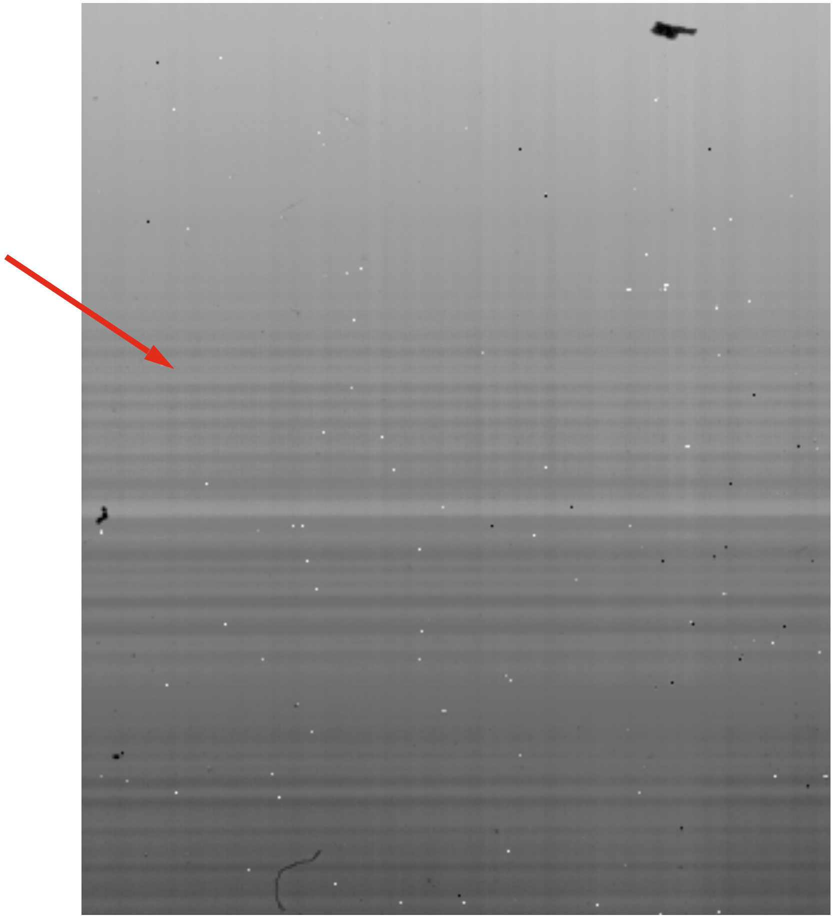
~hots pixels, but nb increases with exposure time. Random pattern, noticeable for t $\gtrsim$ 5 min

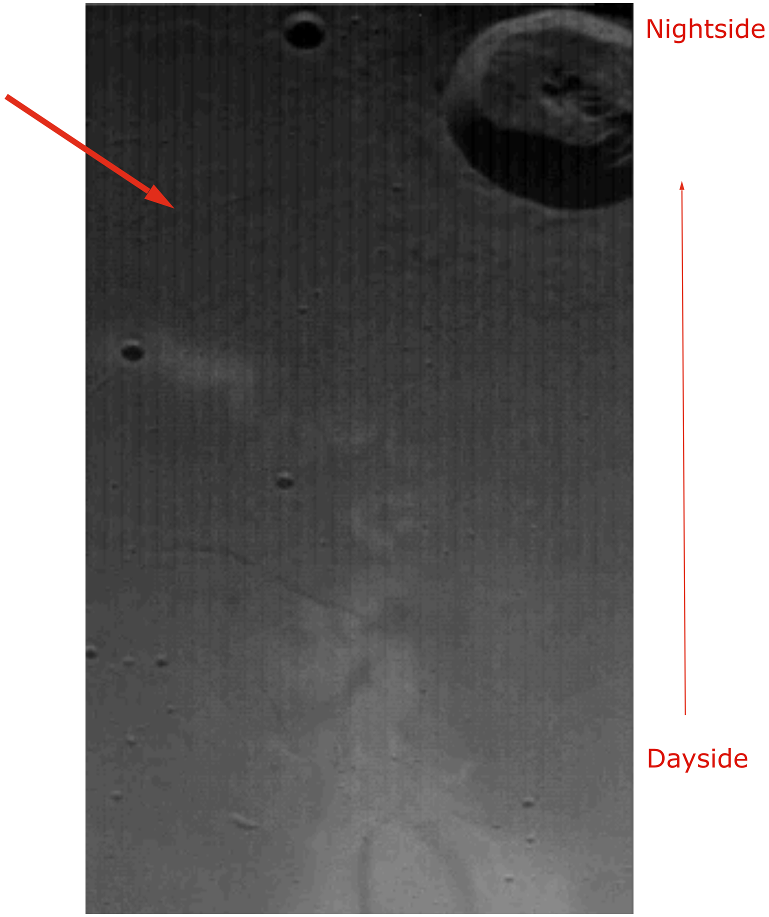


Electronic artefacts

Various frames / patterns in dark current & low level images

Depends on readout circuitry: odd/even interlacing, blocks, quadrants, oblique patterns…
Non-linear behaviour in general (noticeable at low flux)

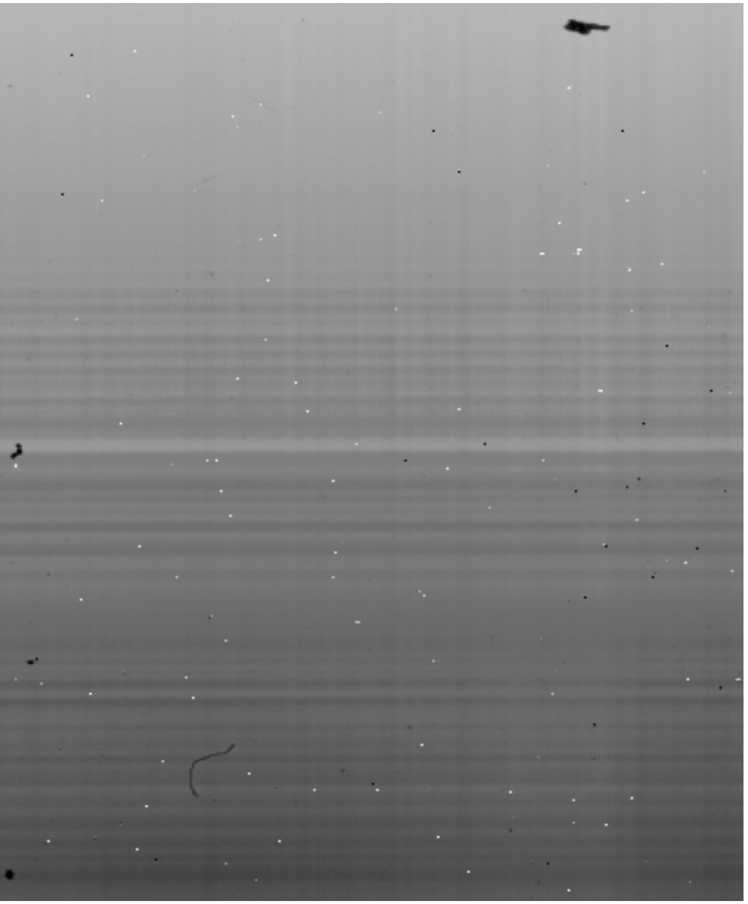


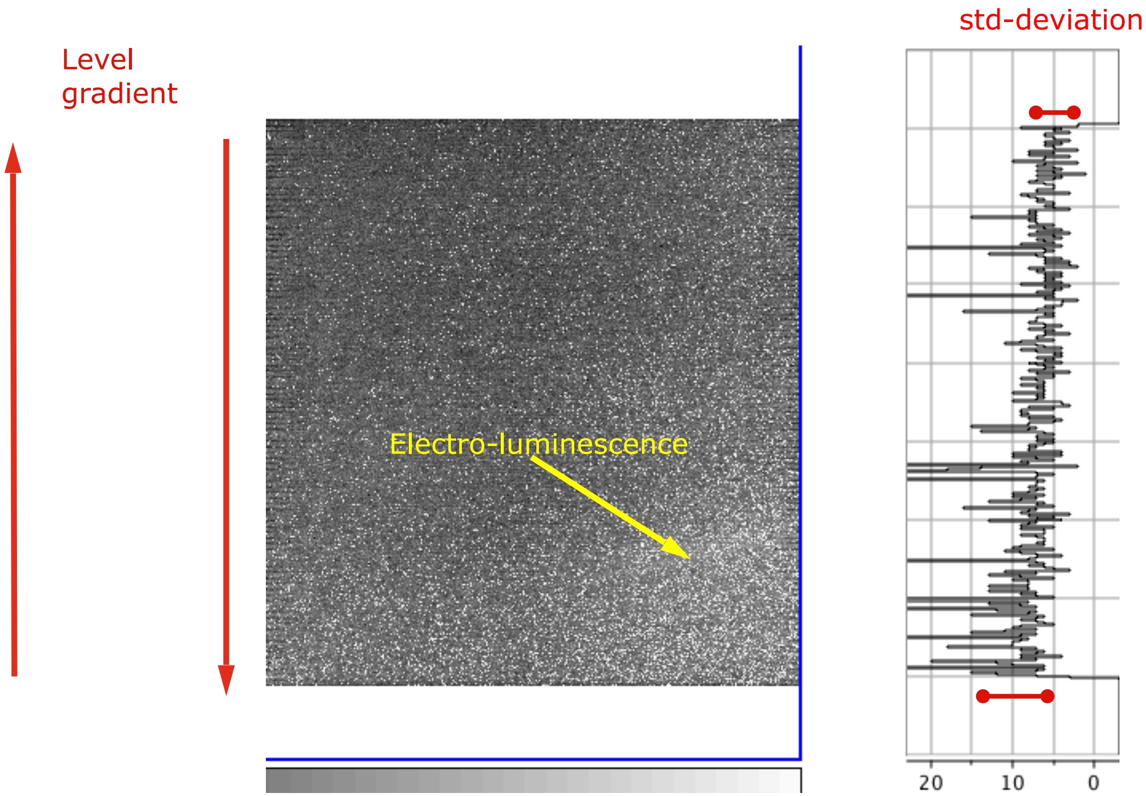


Electronic artefacts

Gradients

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

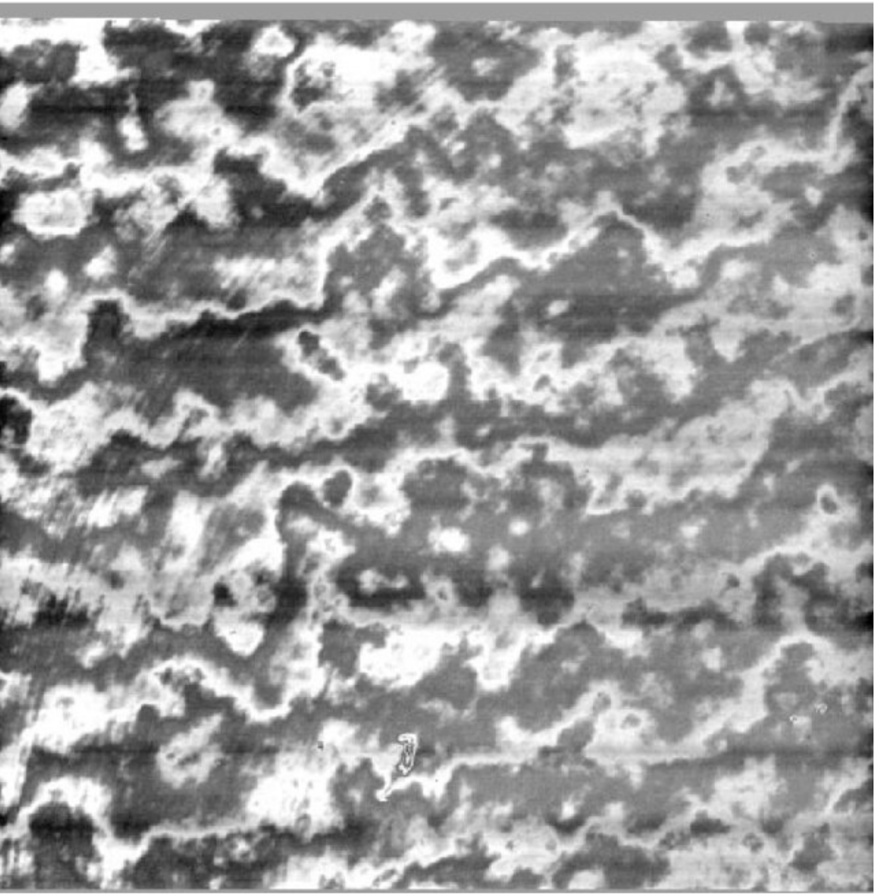




Optical artefacts

Fringes

interferences from two sides of CCD - especially back-illuminated ones
Function of exposure time, temperature and wavelength, additive (can be corrected)



Goudfrooij et al 1998
(flat-field)

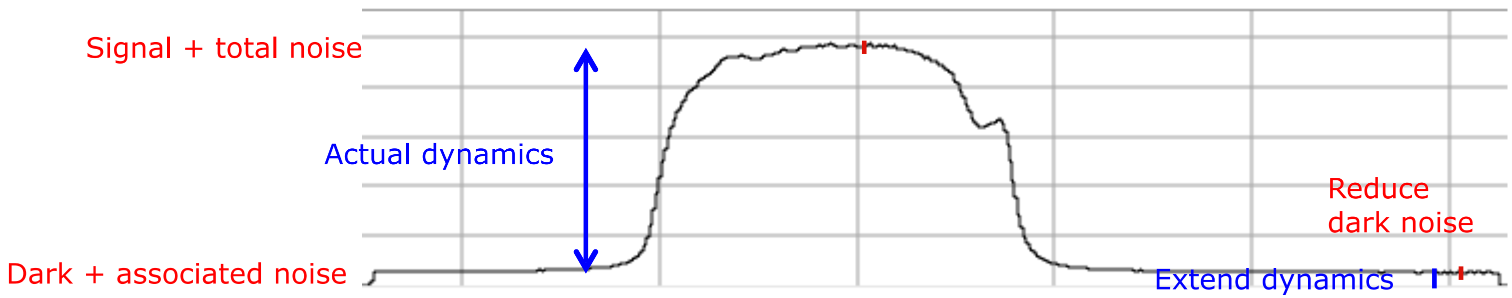
Howell 2012
(stellar field)

Dark current issues

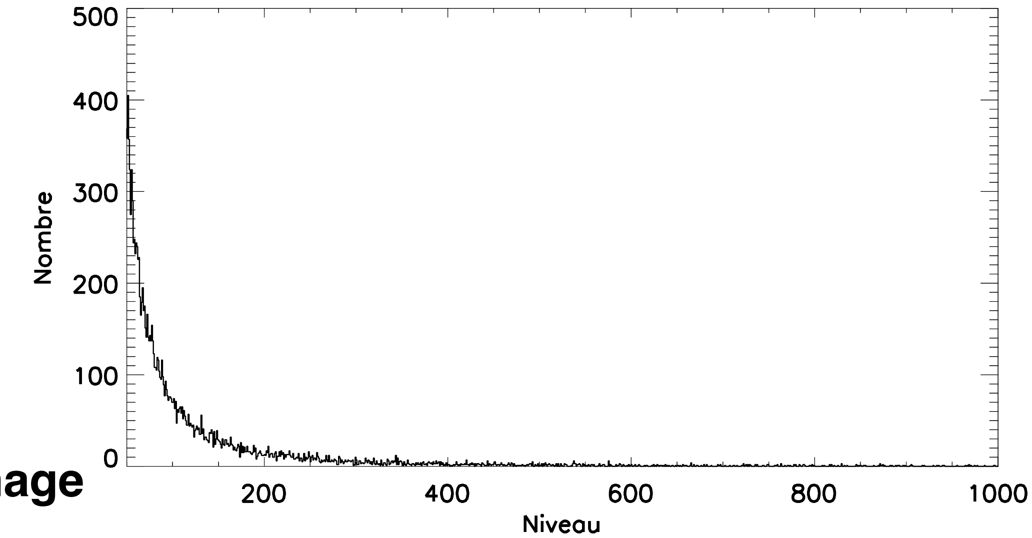
You always want to minimise it, because:
- It restrains dynamics by N (parasite signal, less space for target signal before saturation)
- It is associated with a noise $\sigma = \sqrt{N}$ (remember Poisson!)

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

Special issue in IR range (≳ 4 *μ*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)

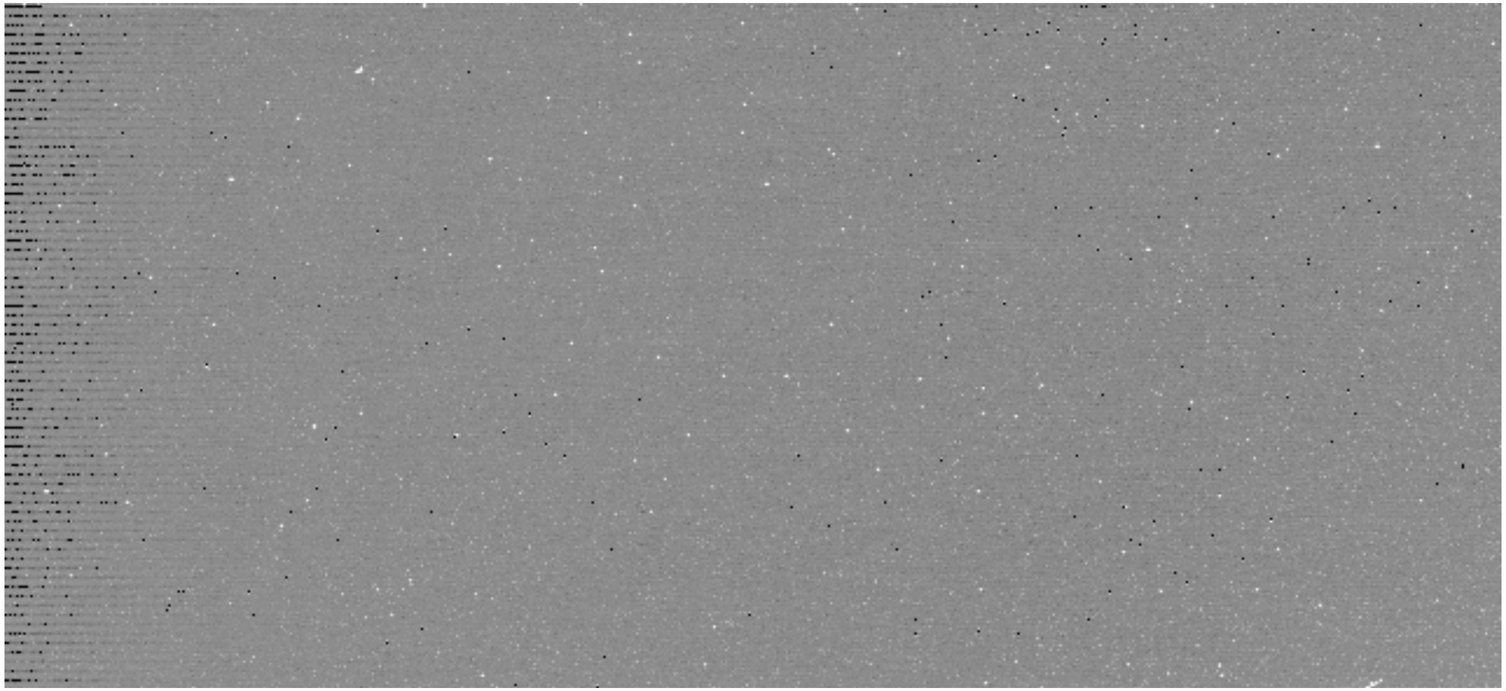


Playtime

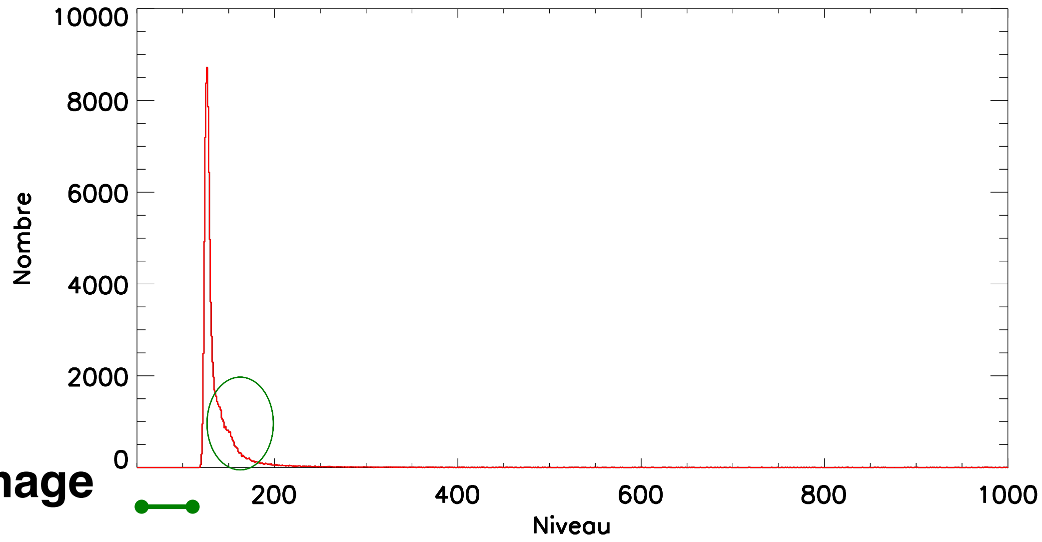


Are histograms helpful?

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

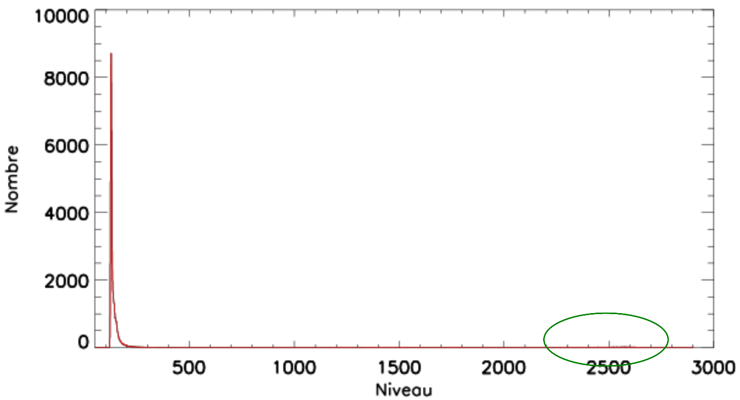


Playtime

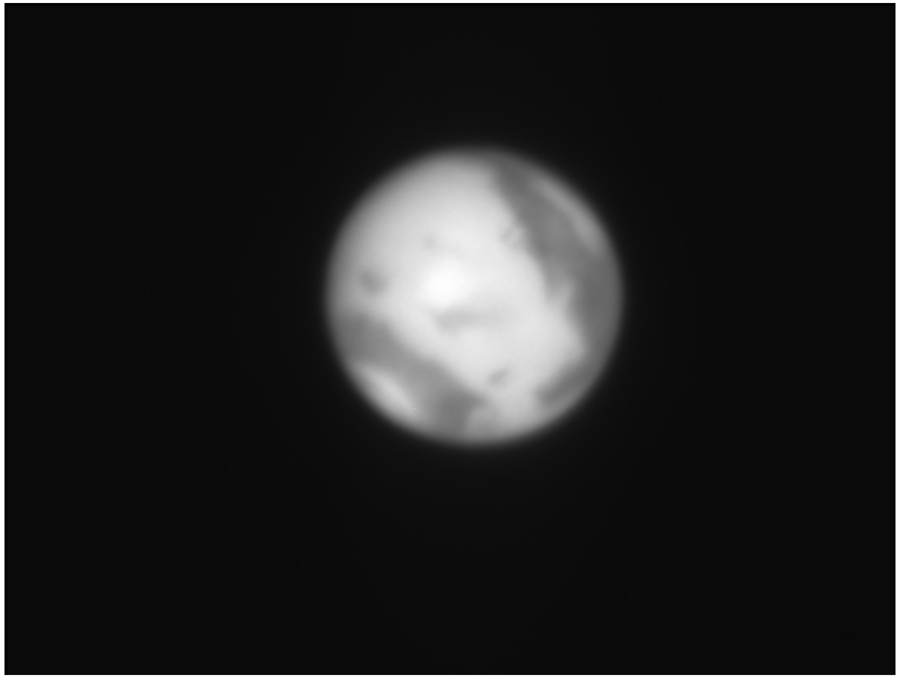


Are histograms helpful?

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



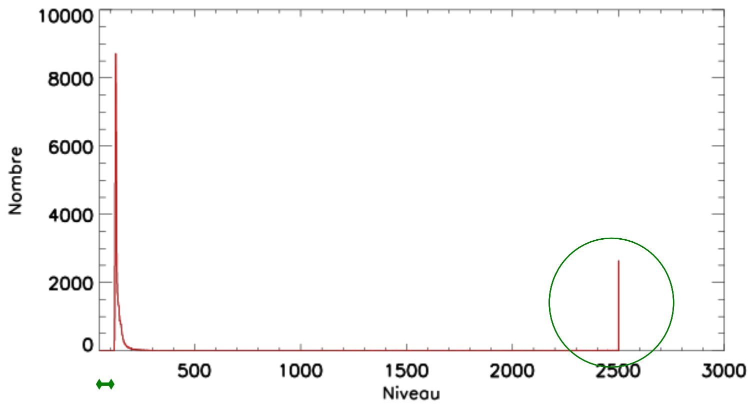
Not easy to distinguish from the dark image
(mostly trailing high values)
=> image structure is always subtle



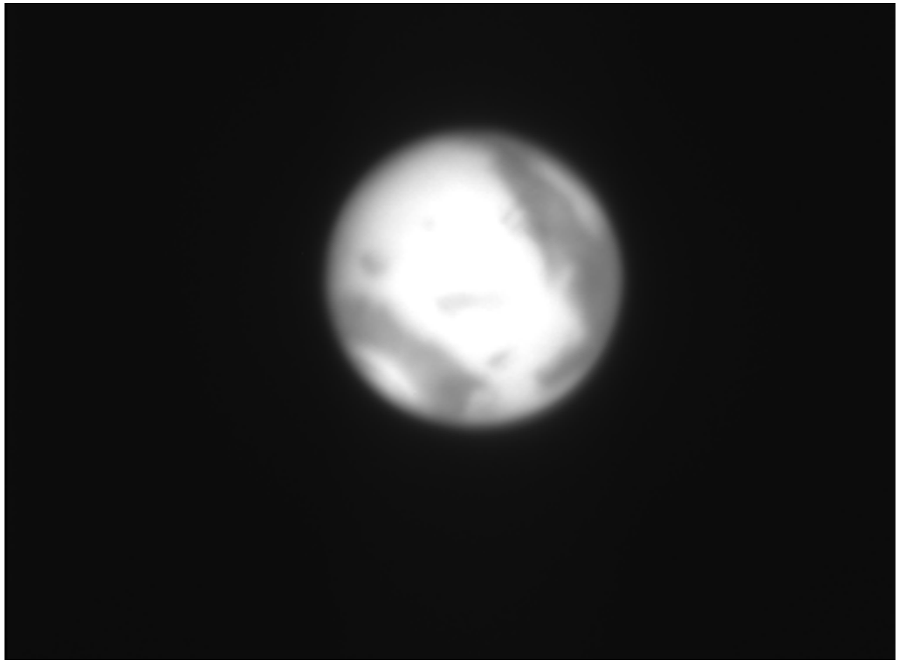
Playtime

Are histograms helpful?

- Same image, saturated



But saturation and offset are readily noticeable



Analyse your images!

Display / profiles

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

=> Adjust contrast, ranges, colour scales

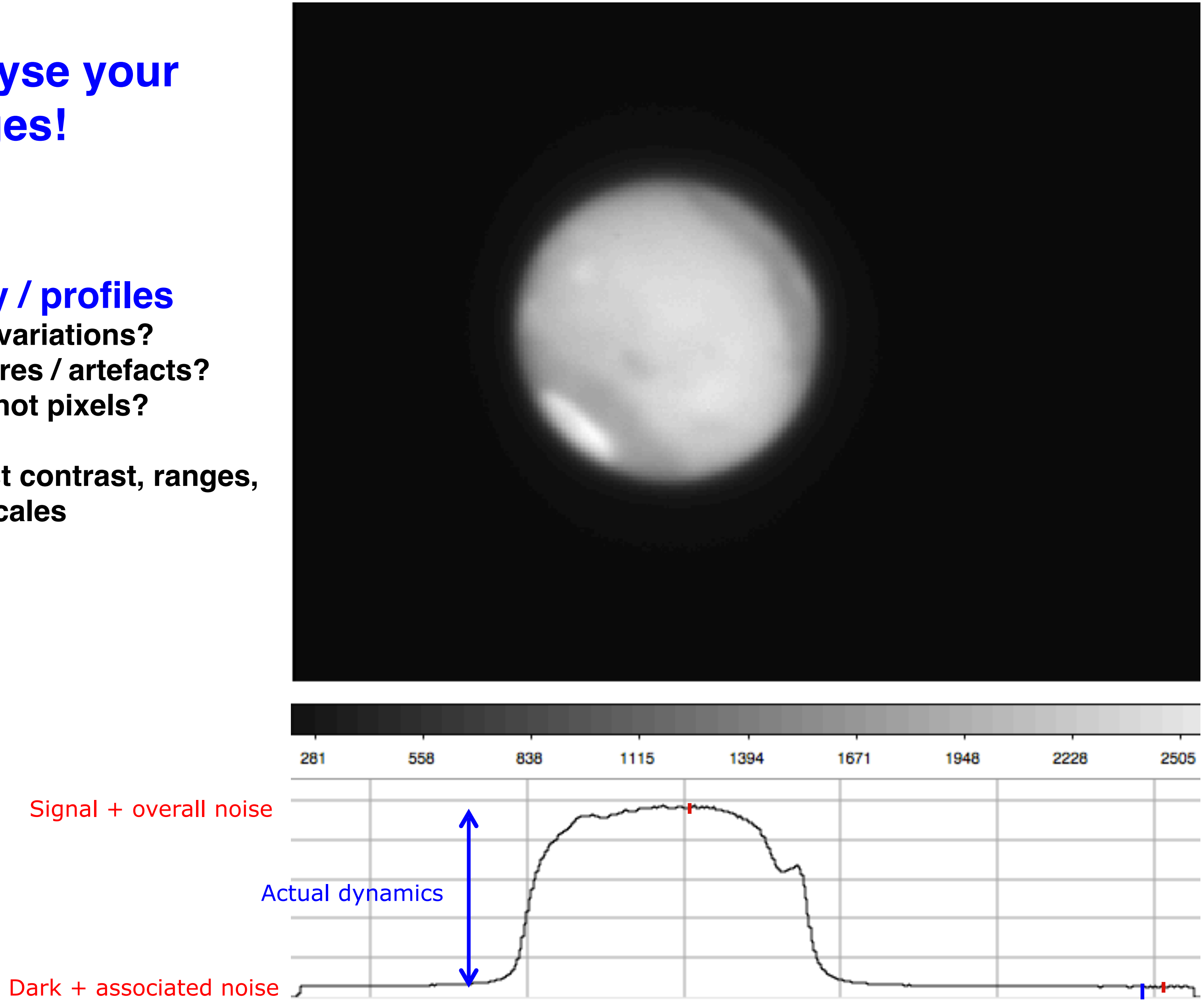


Image displayed in ds9

Filter imaging

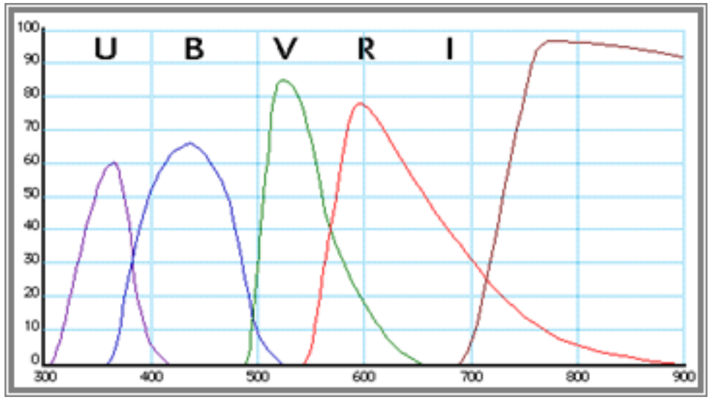
Incident light observed through filters

Main types

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

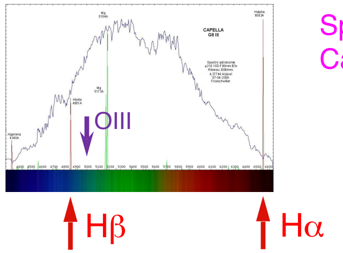
=> Isolate a part of the visible spectrum
initially intended to measure star temperatures

standard colour images = RVB 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

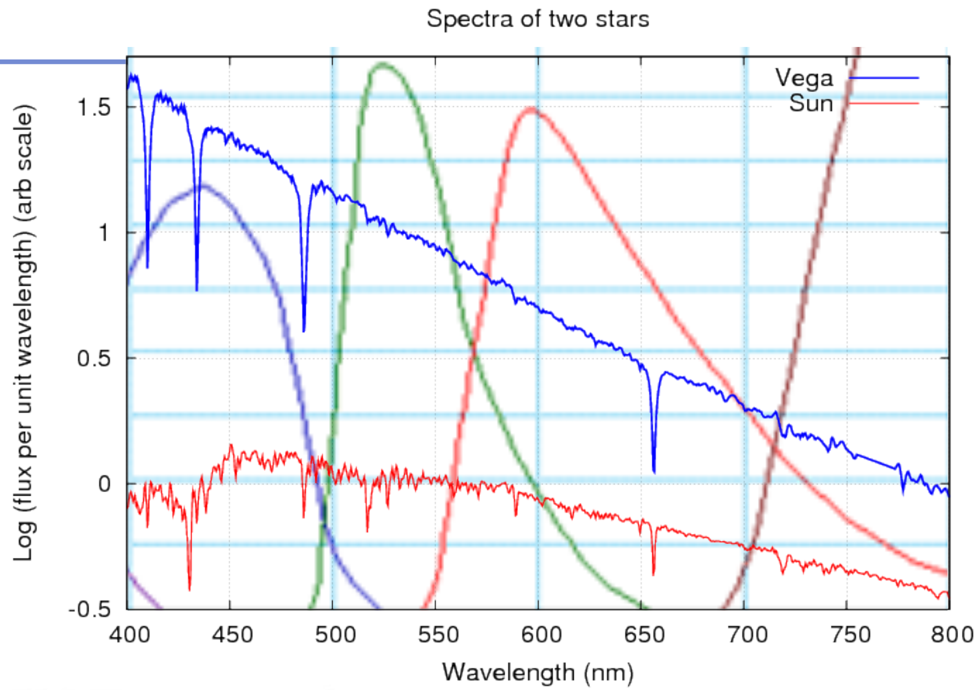
$$I = \int_{\lambda_0}^{\lambda_1} I_{source}\ QE_{CCD}\ T_{filtre}\ d\lambda$$

$\Rightarrow$ **Flux reduction**

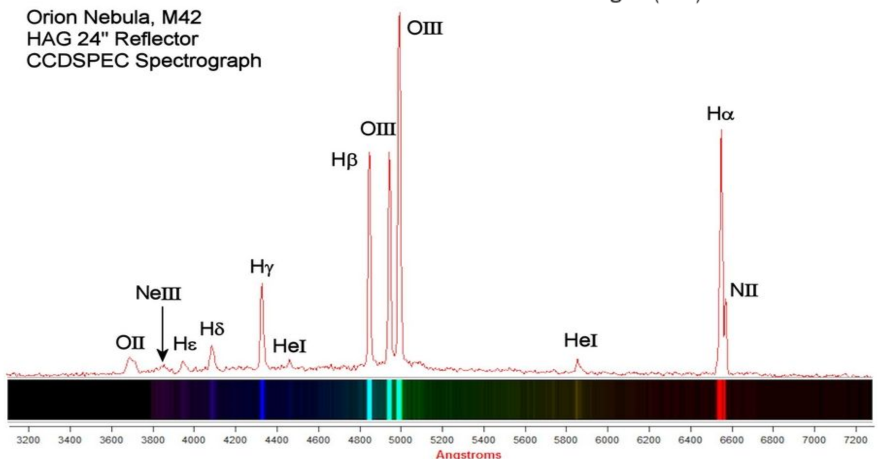
Also includes the detector spectral response (Quantum Efficiency as a function of wavelength)

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

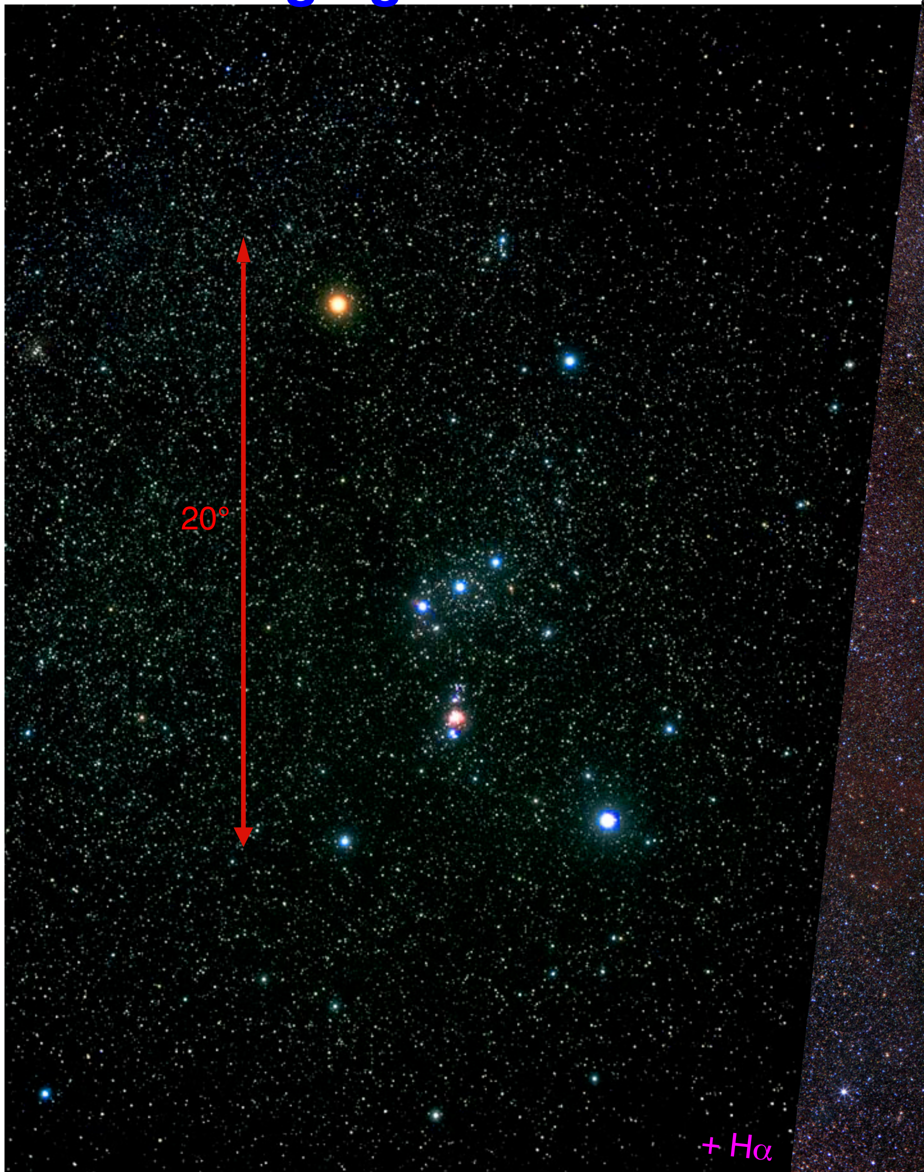
Narrow filters are used e.g. to measure emissions of hot gas



M42 / Orion

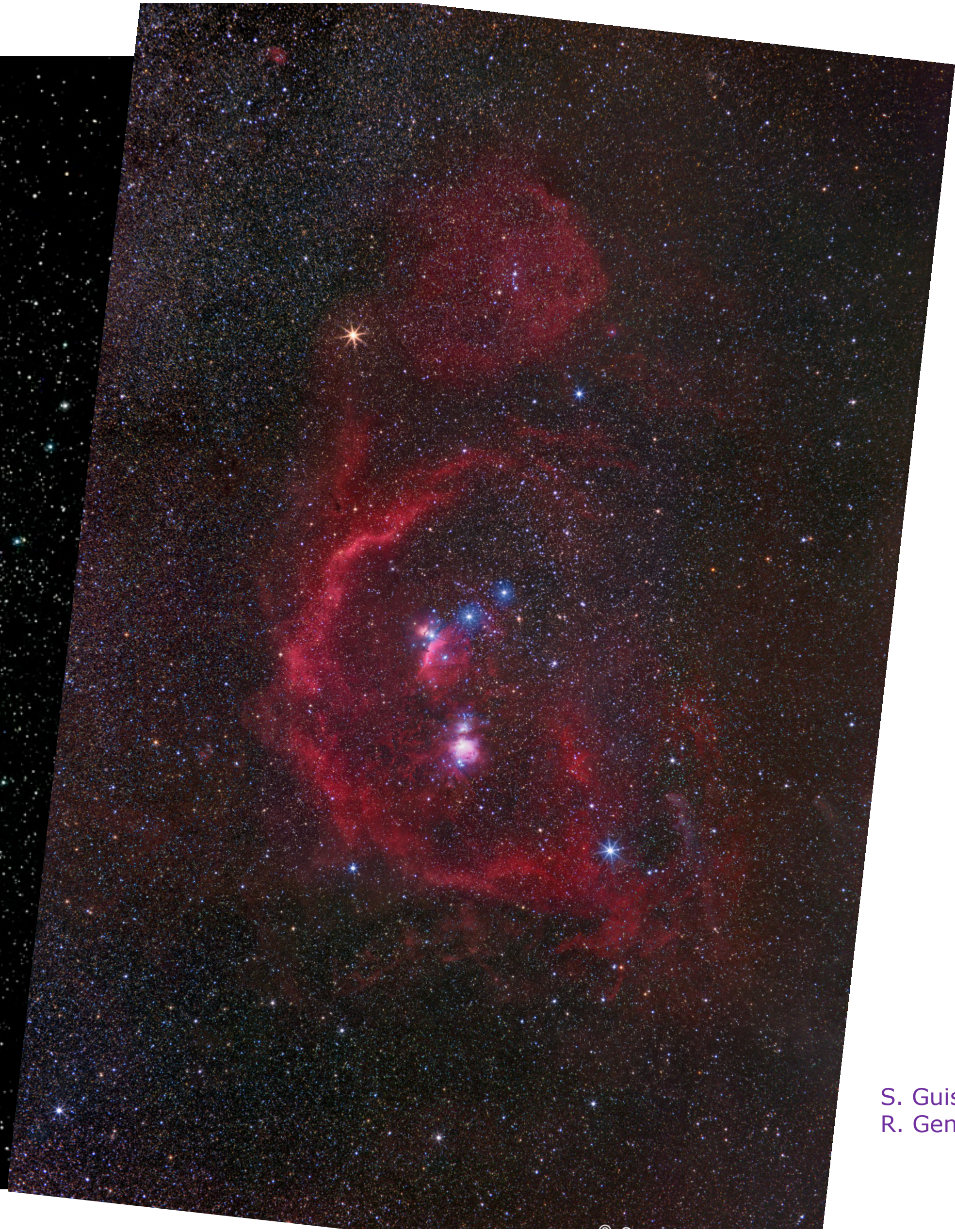


Filter imaging



Akira Fujii

Orion constellation: RVB



S. Guisard &
R. Gendler

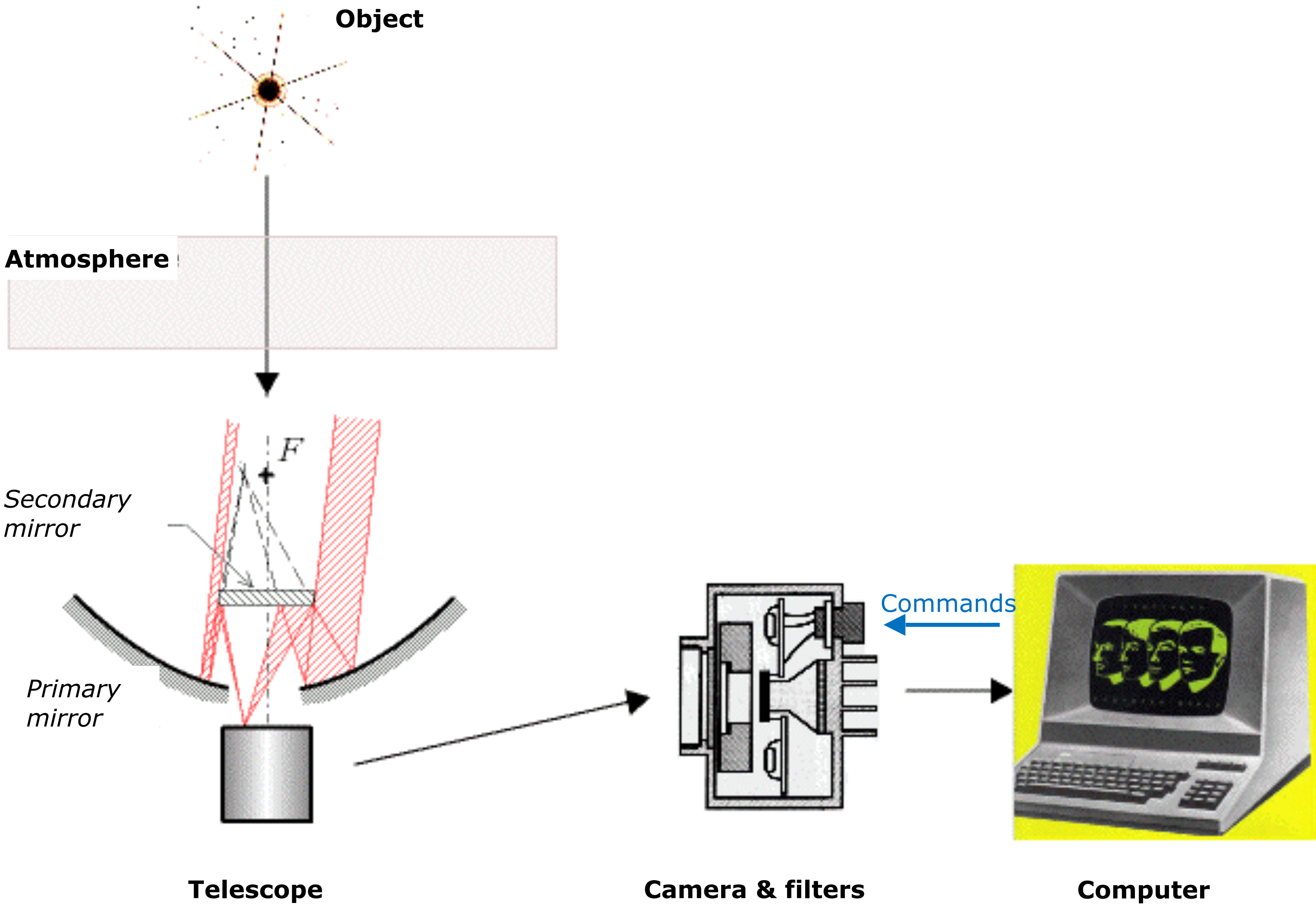
Colour composites: difficulties

(1) Ceres passing M100, T120/OHP
BVr composite, 27/3/2023

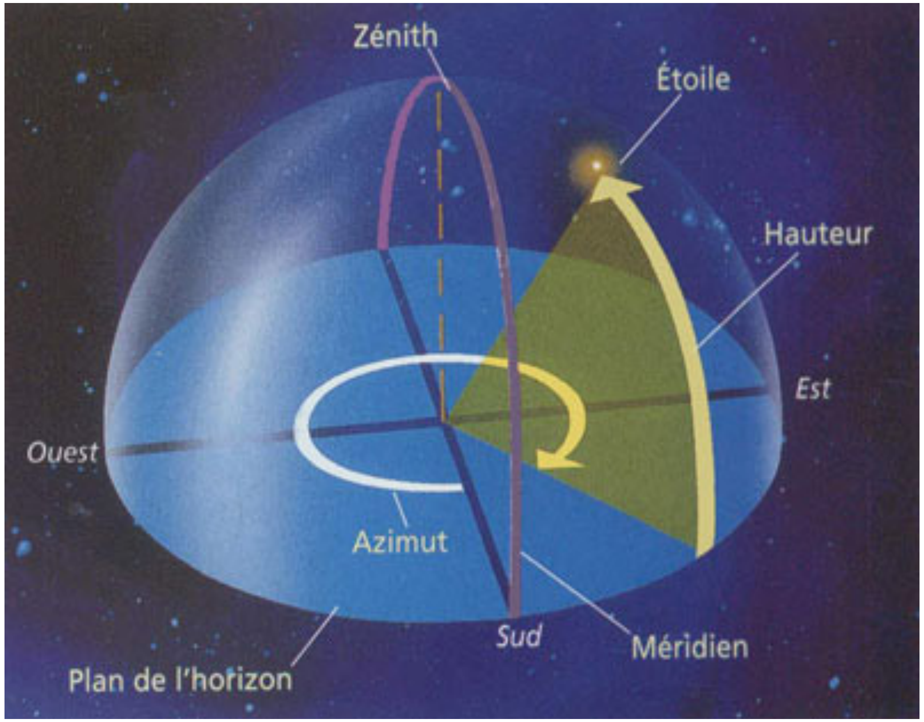
- Difficult to weight filter images correctly (need reference stars)
- Internal deformations
- Different PFS / resolution in each filter
$\Rightarrow$ coloured haloes

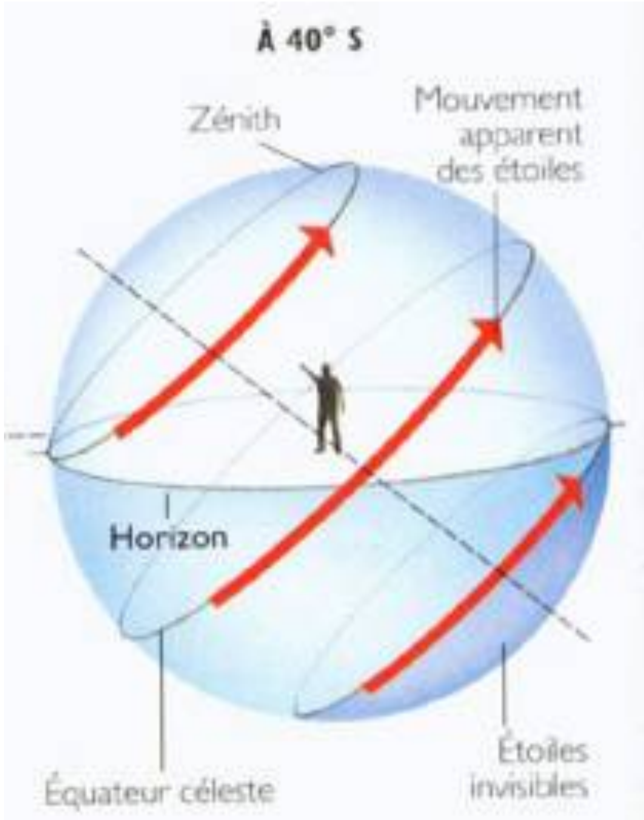
Long
Often frustrating
Colour composites have limited scientific interest anyway ;(

Acquisition process in astronomy imaging



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

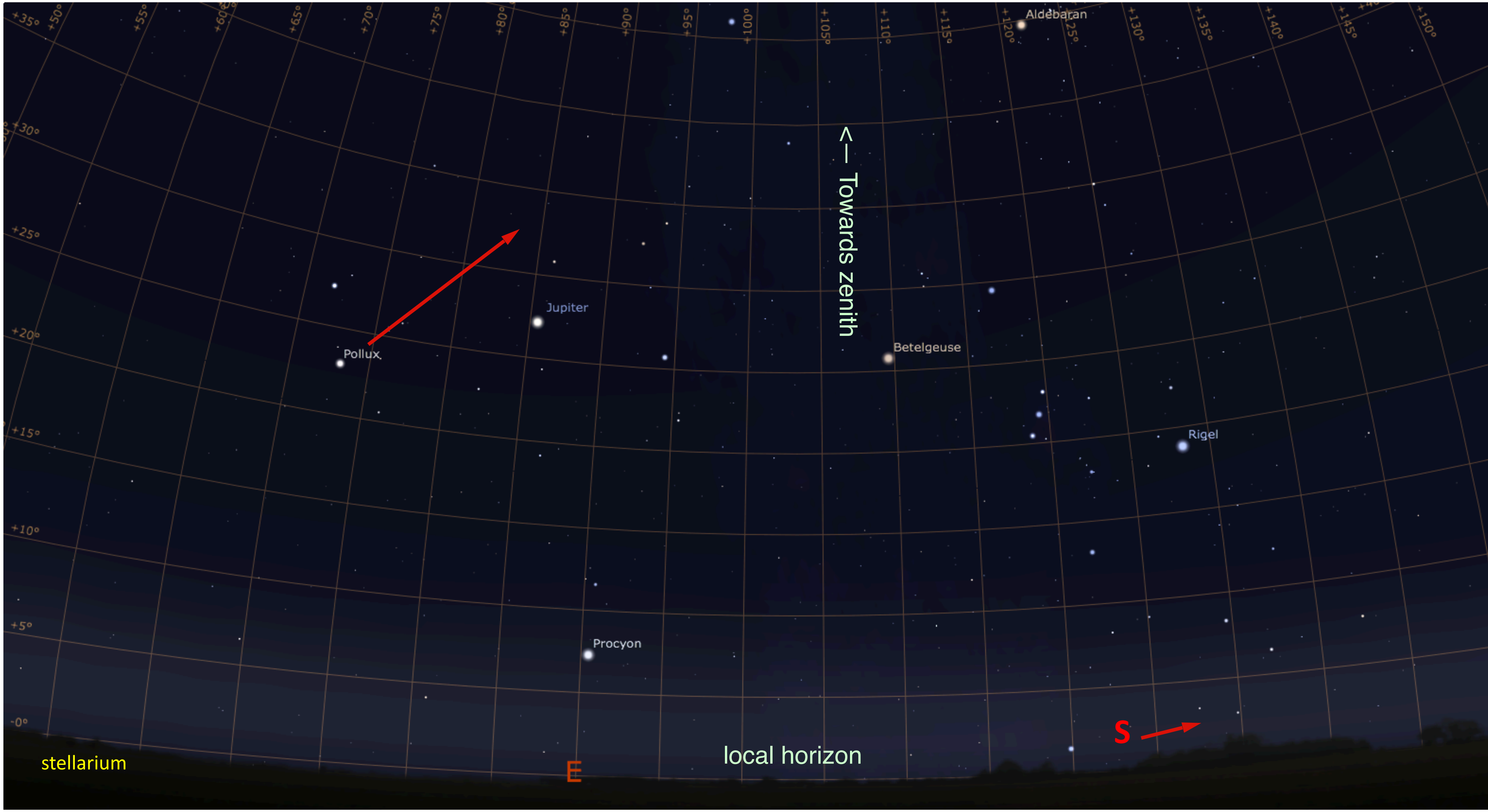
- Stars move around the poles => both coordinates change overnight

- Frame rotates overnight

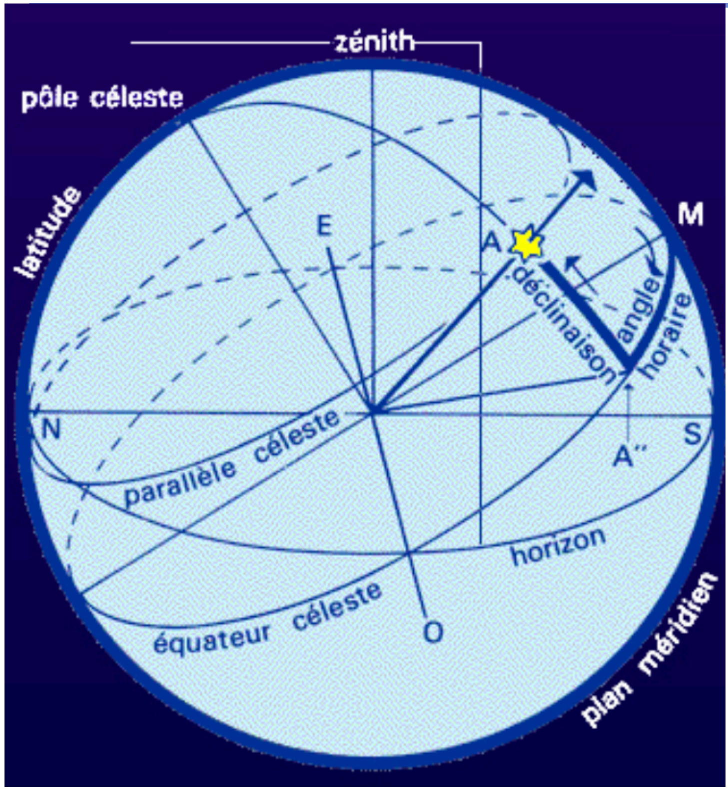
(French = coordonnées azimutales)

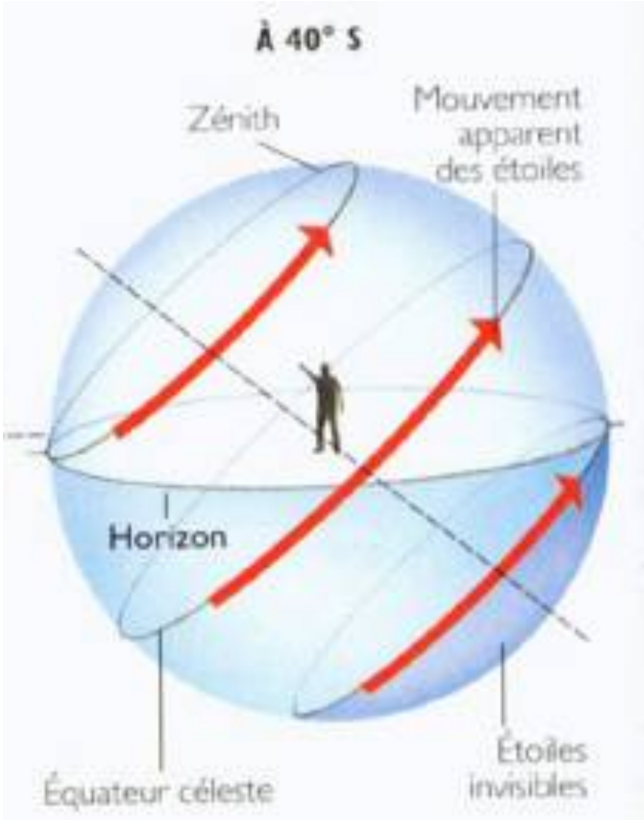
http://www.astrosurf.com/toussaint

Horizontal coordinates



Coordinates for observation: equatorial coordinates (1)





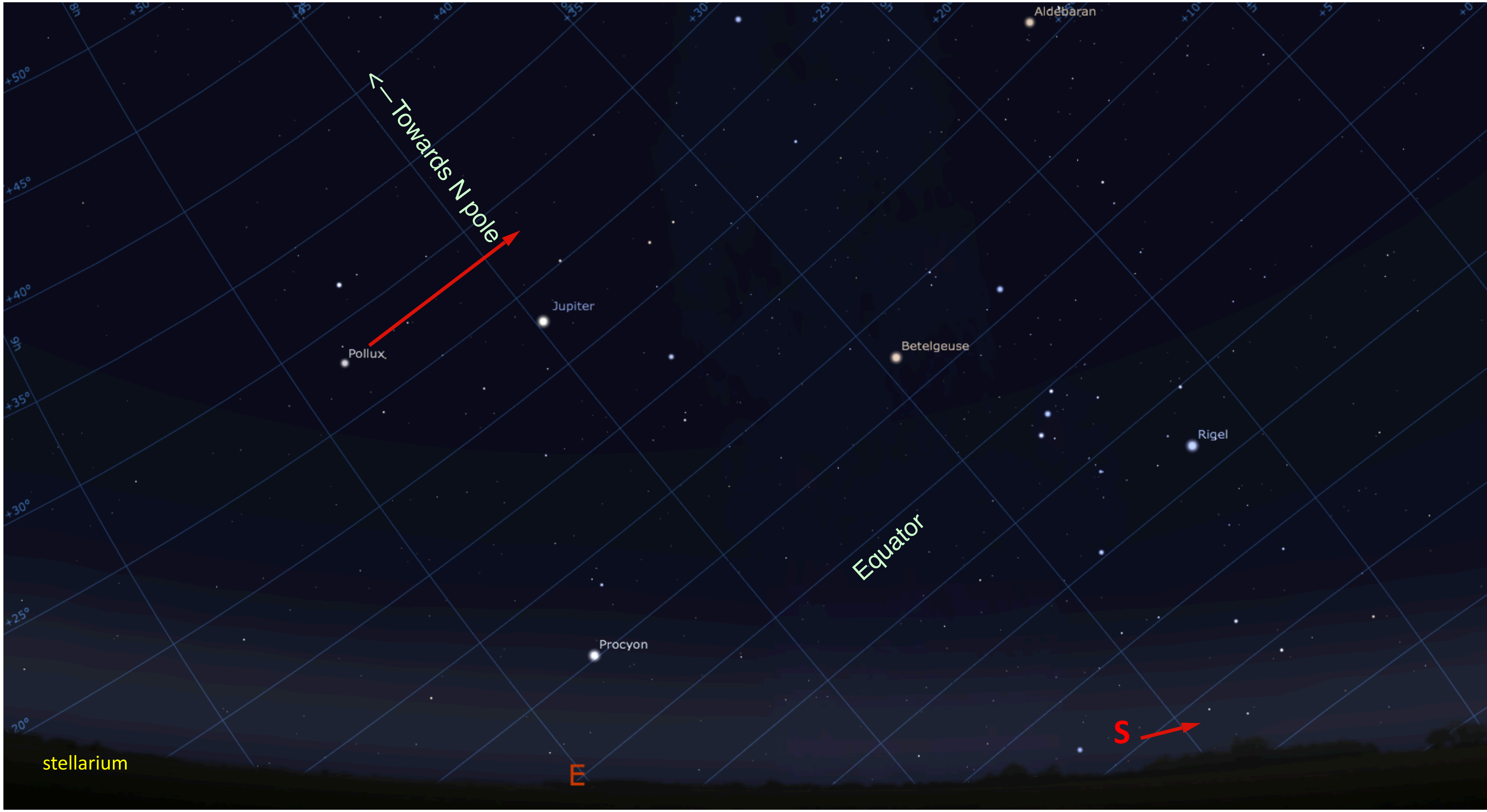
Declination (δ) [wrt Equator] **and hour angle (H)** [wrt meridian]

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

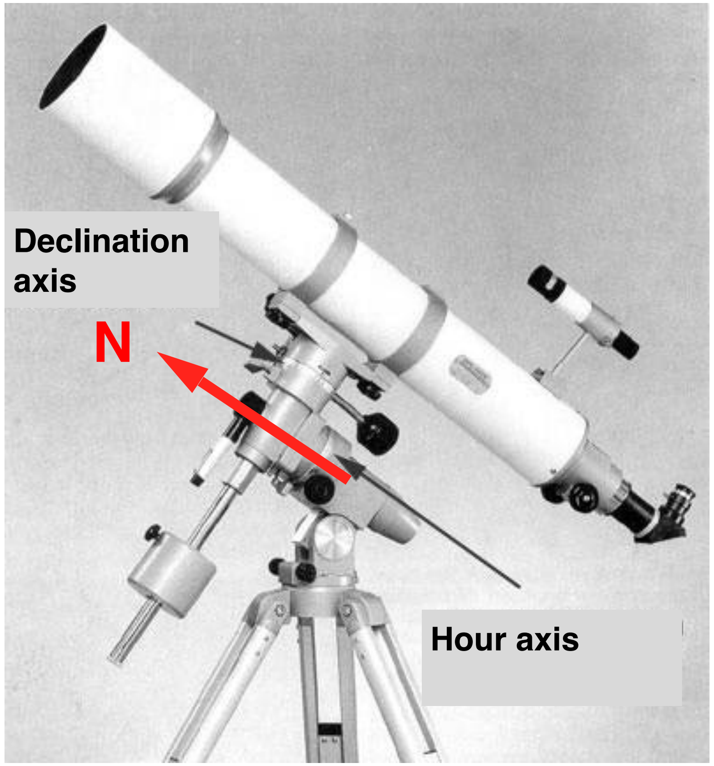
(French = coordonnées horaires – the English name is ambiguous)

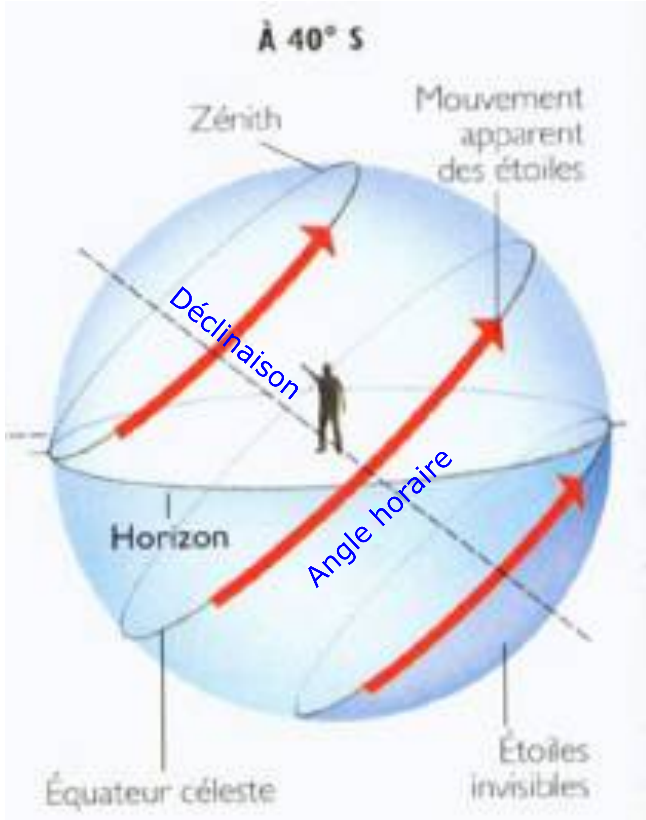
https://www.universalis.fr/encyclopedie/coordonnees-horaires/

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

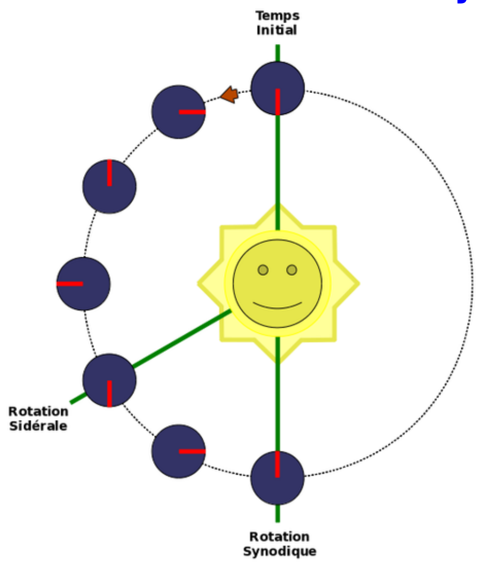
Fun and educational question

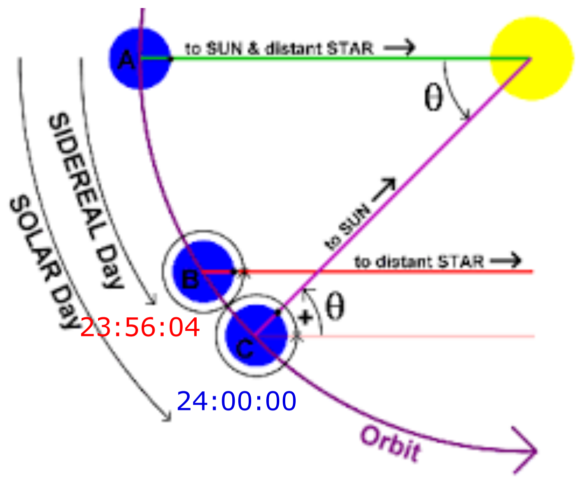
How long does it take for the Earth to revolve around herself?

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

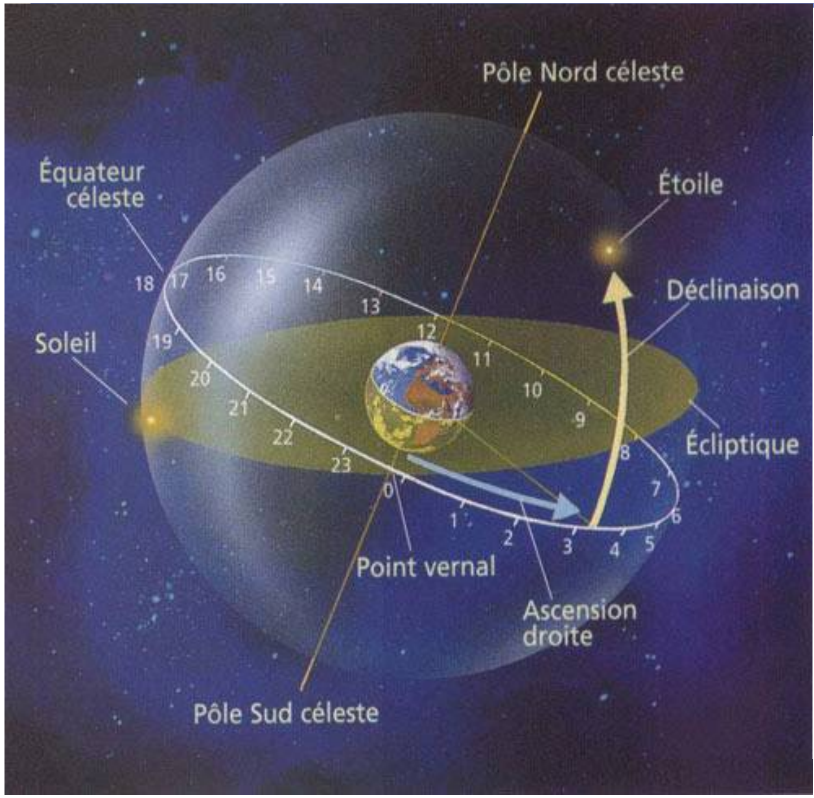
24h = time required for the Sun to return to the same position in the sky
= *mean* solar day (averaged over the year - depends on Earth-Sun distance)

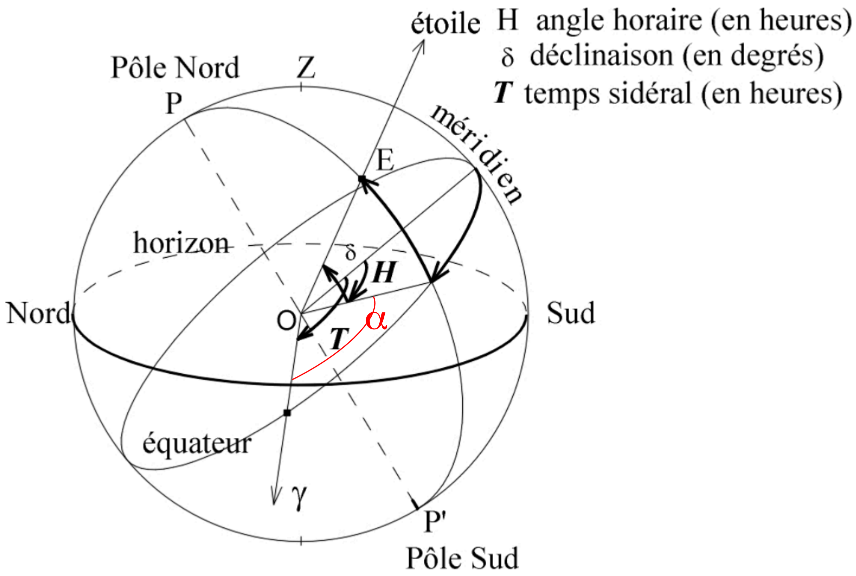
23h 56' 04" = time required for a star to return to the same position in the sky
= sidereal day (period in an ~ inertial frame)





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

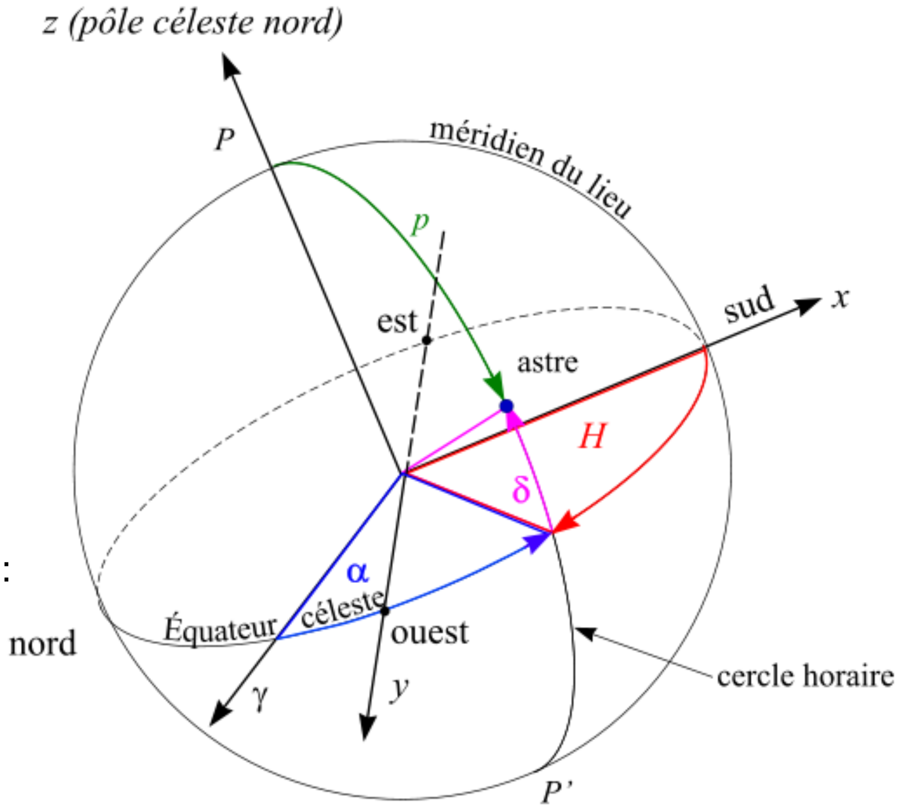
Direction of Sun at N spring / March equinox ♈ (stands for Aries) or γ
= a reference direction in the Equator plane (French: point vernal)

Local sidereal time Θ = hour angle of the vernal point (fct of time and longitude)

Right ascension of an object α (fixed):
Local sidereal time - hour angle

$$\Theta = H + \alpha$$

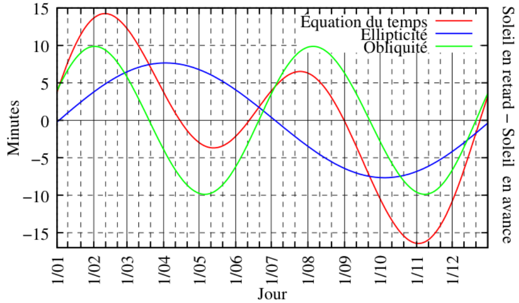
In practice: you know α from a catalogue,
you need H to point the telescope manually:
=> Use a computing applet
(inputs: date, time, location, α)



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 mean solar time over the year



See Equation of time on Wikipedia or anywhere

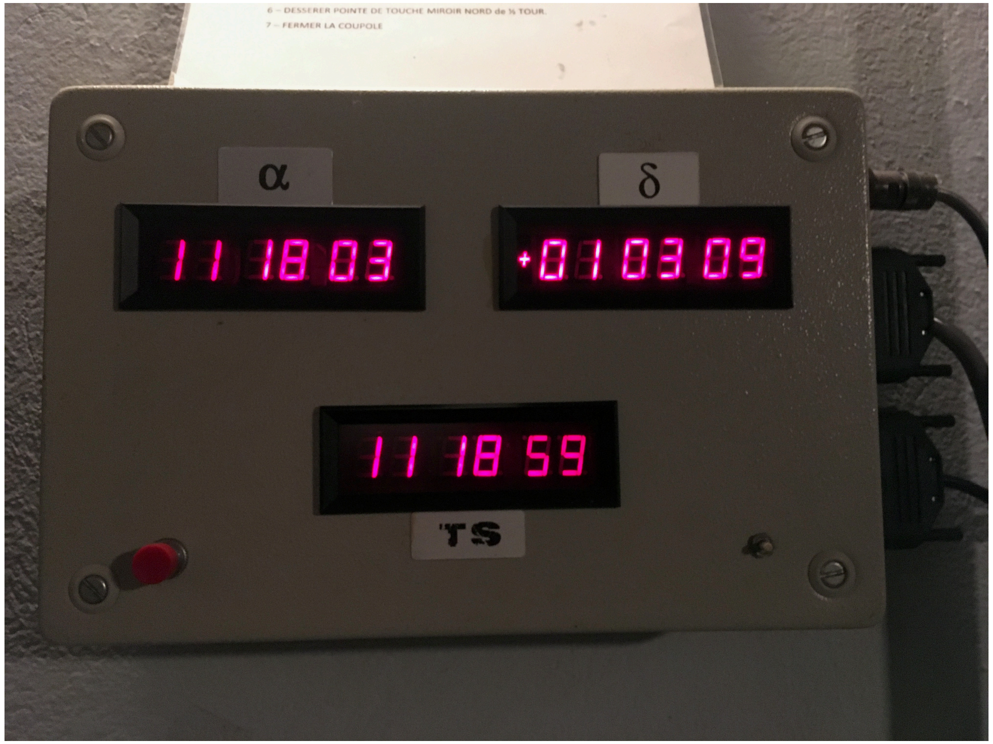
https://media4.obspm.fr/public/ressources_lu/pages_mctc/

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

=> Equatorial coordinates are provided for restrained periods (B1950, J2000) or for the current date

Solar and sidereal times

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



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

Signal and noise — Notations (tentative)

Notation *and even vocabulary* depend on science field and context - be flexible!

***Flux* and *intensity* in particular can refer to very different things**

	(from) Source	(on) Detector	(digital) Instrument output	
"signal" *May be given by unit surface, solid angle, wvl/fq*	Light *flux*, radiant intensity / emitted power / specific intensity ($W/m^2/sr/\mu m$) / radiance = luminance ($W/m^2/sr$) (intrinsic quantity) May be provided on magnitude/ log scale, with various normalisations	Measured power = flux density (W/m^2) / irradiance = brightness = illuminance = radiant flux Depends on observing configuration, distance, field of view, filters, transmission, integration time, etc	Digital Number (DN) = Analog to Digital Unit (ADU) = counts Depends on instrument characteristics and setup Can be calibrated to recover measured power and observed quantity	
Common notations	I, L, ϕ, etc B for a black body	E, F Integrated over spectral range and exposure time	S	
Fluctuations	σ_{source} (std-deviation) S/N, SNR (signal-to-noise ratio)		$\sigma_{tot}^2 = \sigma_{source}^2 + \sigma_{dark}^2 + \sigma_{lecture}^2 + \sigma_{numer}^2$ The *variance* is additive if noise sources are independent	
	see e.g., here: https://en.wikipedia.org/wiki/Radiant_energy https://en.wikipedia.org/wiki/Apparent_magnitude https://en.wikipedia.org/wiki/Photometric_system			

Signal and noise

Every measurement is subject to uncertainty

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

⇒ **S/N increases with**
- longer exposures
- averaging

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

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

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

⇒ **S/N increases with**
- longer exposures
- slower readout mode

- **Digitization noise / roundoff error (constant in DN)**

⇒ **S/N increases with signal**

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 : $S_{tot} = I_{source} \times Flat + Dark$

(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.: they combine in quadratic sum — because they are assumed independent)

Goal: - increase signal / noise ratio
- minimise relative noise

Signal-to-noise ratio = Mean corrected signal / noise std-deviation

The Poisson distribution

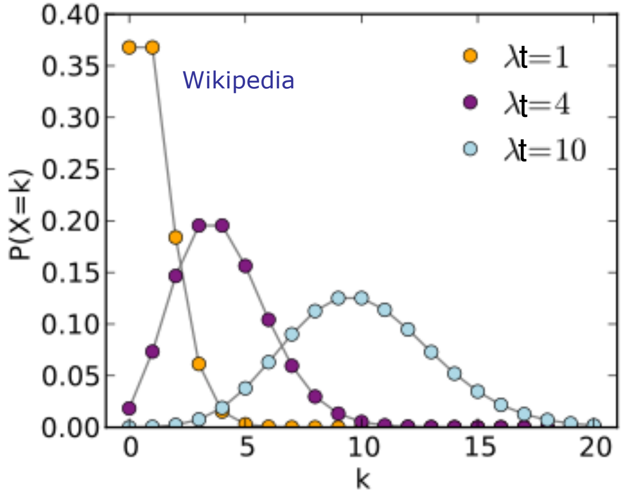
Assumptions: - events are random and independent
- event frequency is constant (λ)

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
https://media4.obspm.fr/public/AAM/pages_proba/poisson.html



Tends towards a Gaussian distribution
when λt is large (central limit theorem)

With N = λt:
Mean = N (nb of photons received during t) => Predictable

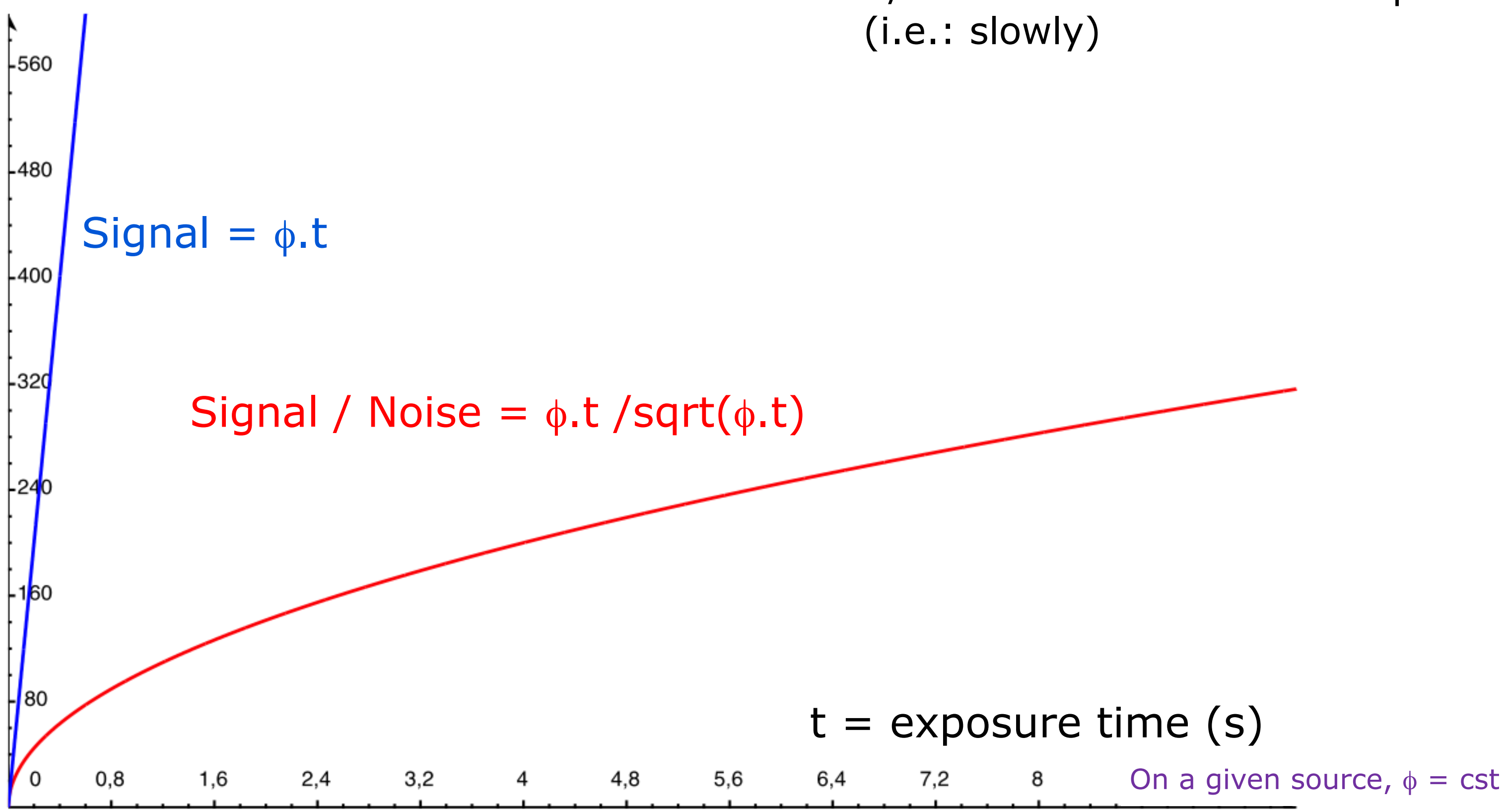
Standard deviation: $\sigma = \sqrt{N}$ (mean variation around this value, between successive measurements)
=> Random: *this* is noise (sometimes referred to as *shot noise*)

The Poisson distribution

Signal to noise ratio
(for a Poisson distribution)

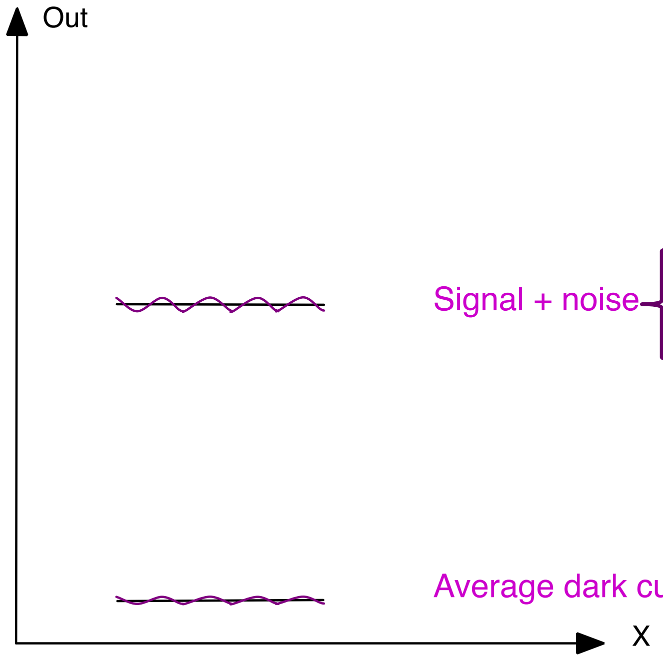
$$\frac{I_{source}}{\sigma_{source}} = \frac{N}{\sqrt{N}} = \sqrt{N} = \sqrt{\phi t}$$

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



Signal and noise

Uniform source



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

↑ Increase exp time

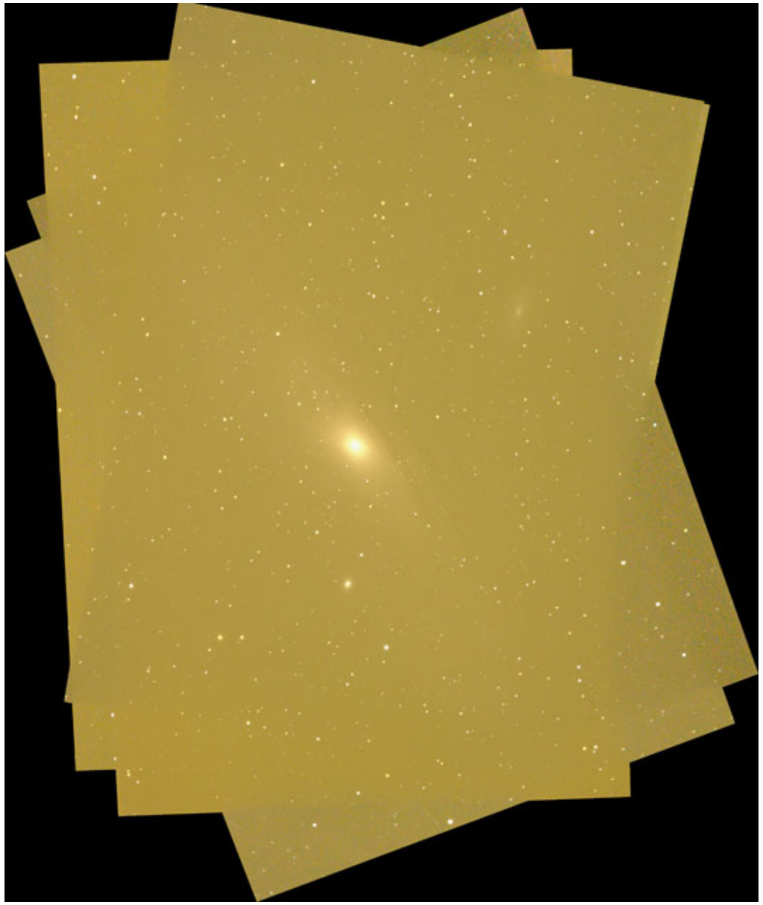
Sum exposures?

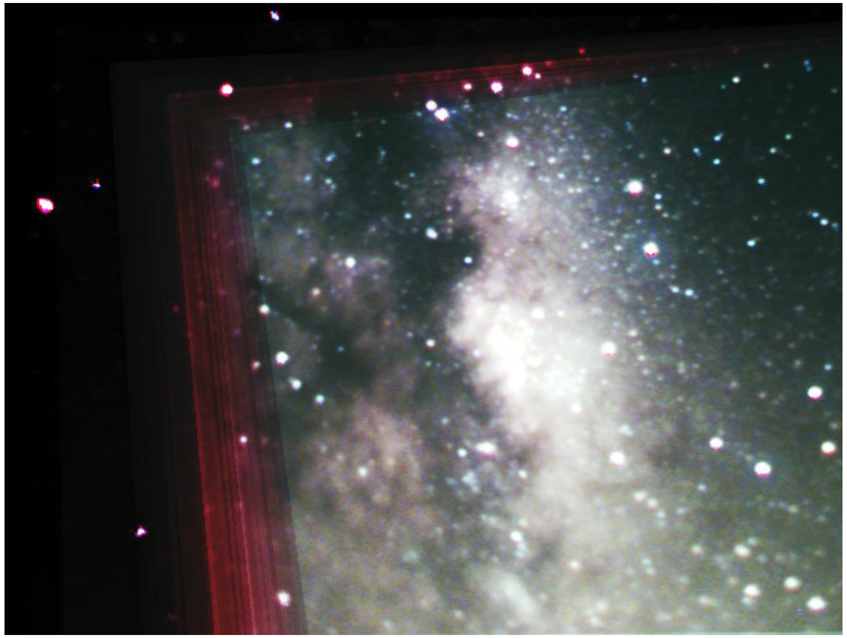
Average dark current + dark noise = (sqrt(dark-offset))

↓ 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
  (may be tricky)

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

n images

S : average signal (over Z)

σ : individual noise

Summing vs readout noise

	Total signal (average)	Readout noise (std-deviation)	Signal-to-noise ratio
1-sec exposure	Signal	σ_{lect}	SNR = Signal / σ_{lect}
Sum of 10 1-sec exposures	10 . Signal	sqrt(10) . σ_{lect}	sqrt(10) . SNR
1 exposure of 10 sec	10 . Signal	σ_{lect}	10 . SNR

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

=> It's always better to use longer exposure when feasible
The same thing applies to binning modes
You normally average several dark frames and flat-field images anyway

Noise reduction techniques

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

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

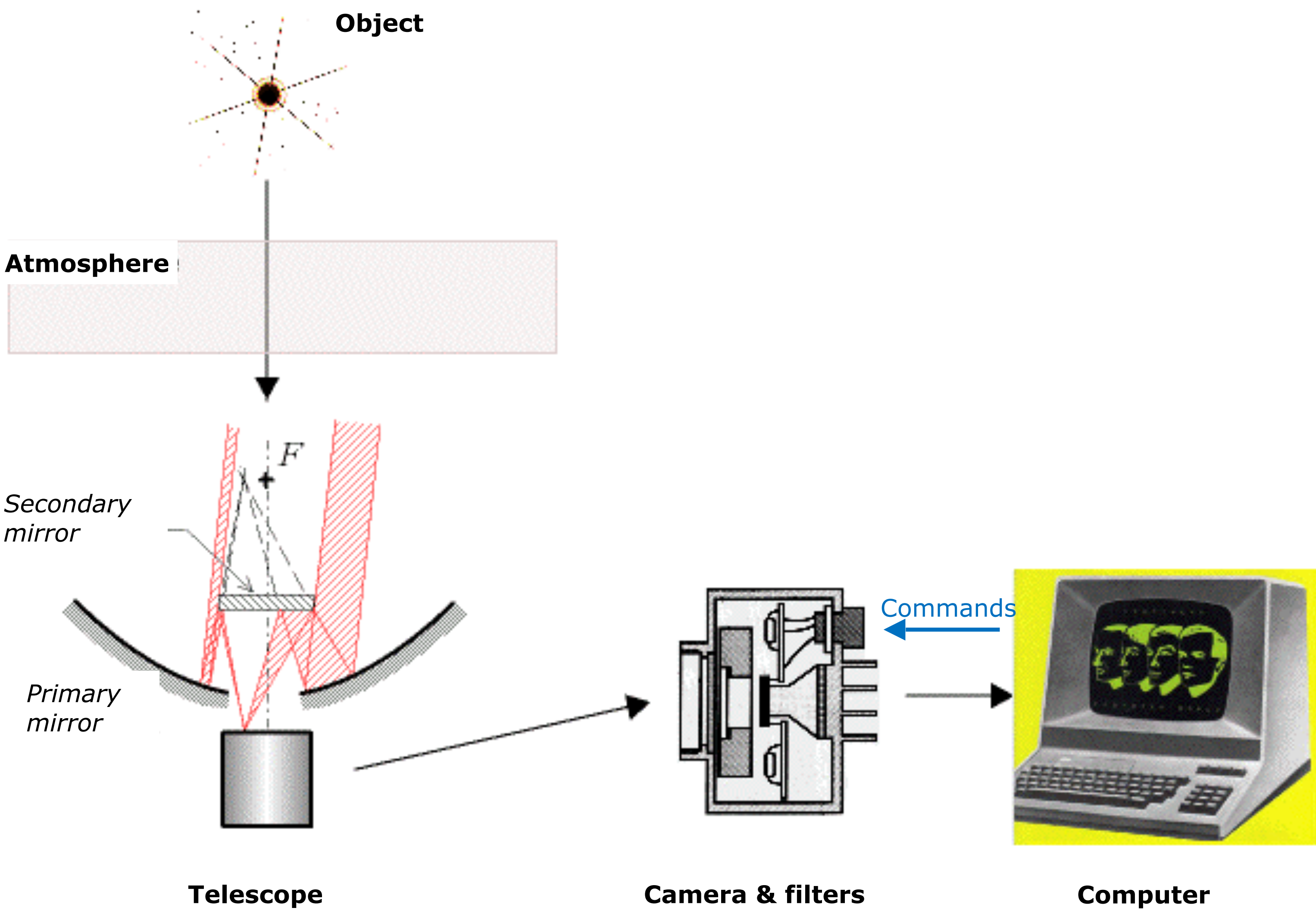
=> Optimise exposure time and binning size during acquisition!

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

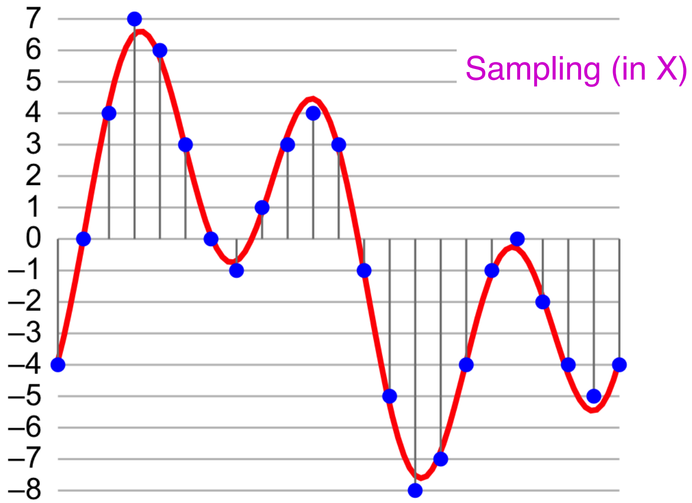
- **Median of successive frames**
  - **- Very efficient to filter outliers** (cosmic rays, parasites…)
  - **- Does not explicitly reduce noise** (but roughly equivalent with 30+ images)

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

Acquisition process in astronomy imaging



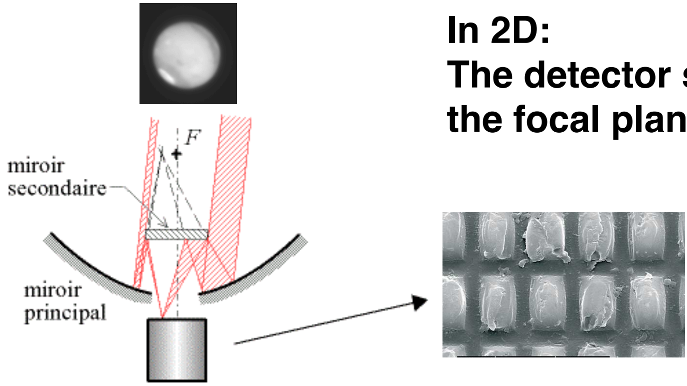
Digitisation (reminder) — sampling effects



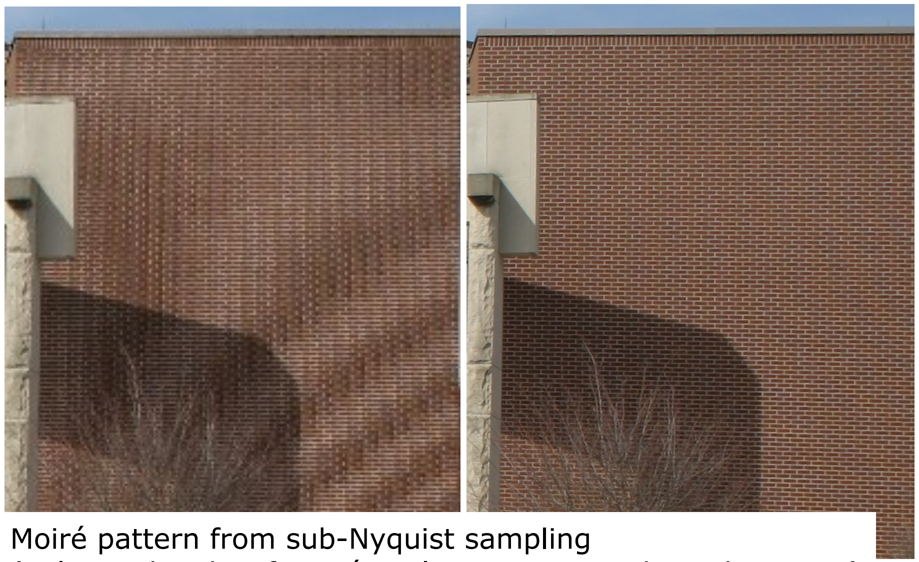
Nyquist-Shannon (sampling) theorem:
Fourier components with
fq > sampling fq / 2 (Nyquist fq) **are lost**
(actually: aliased, folded around sampling fq)

Required
sampling step ≤ size of smallest details / 2

Hear the aliasing!
https://www.audiolabs-erlangen.de/resources/MIR/FMP/C2/C2S2_DigitalSignalSampling.html
See it in movies:
https://en.wikipedia.org/wiki/Wagon-wheel_effect

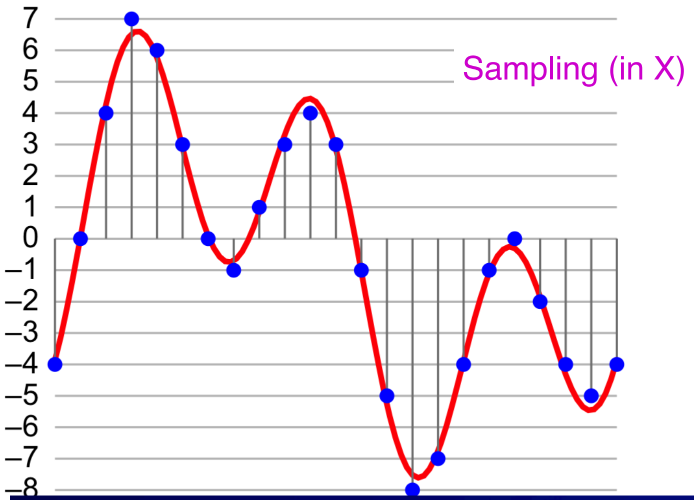


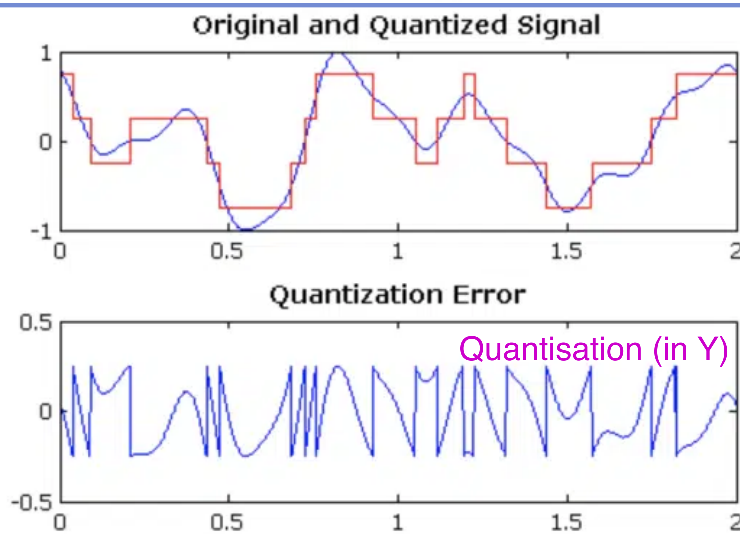
In 2D:
The detector samples the focal plane

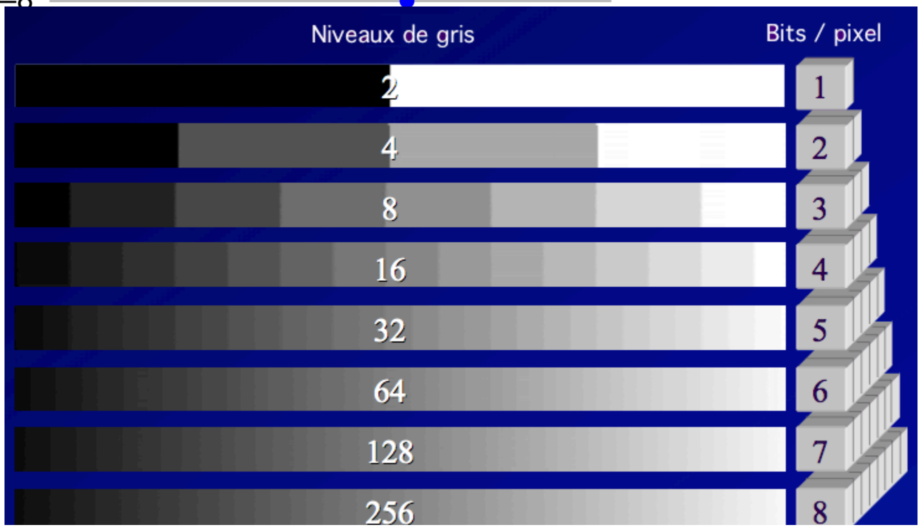


Moiré pattern from sub-Nyquist sampling
(enlarge this doc if Moiré is also present on the right image)

Digitisation (reminder) — Quantisation effects







Continuous values => steps

Nb of grey levels = $2^{bit/px}$ encoded in DN or ADU

(Digital Numbers, or Analog to Digital Units
- French: pas-codeurs)

Quantisation noise = rounding error

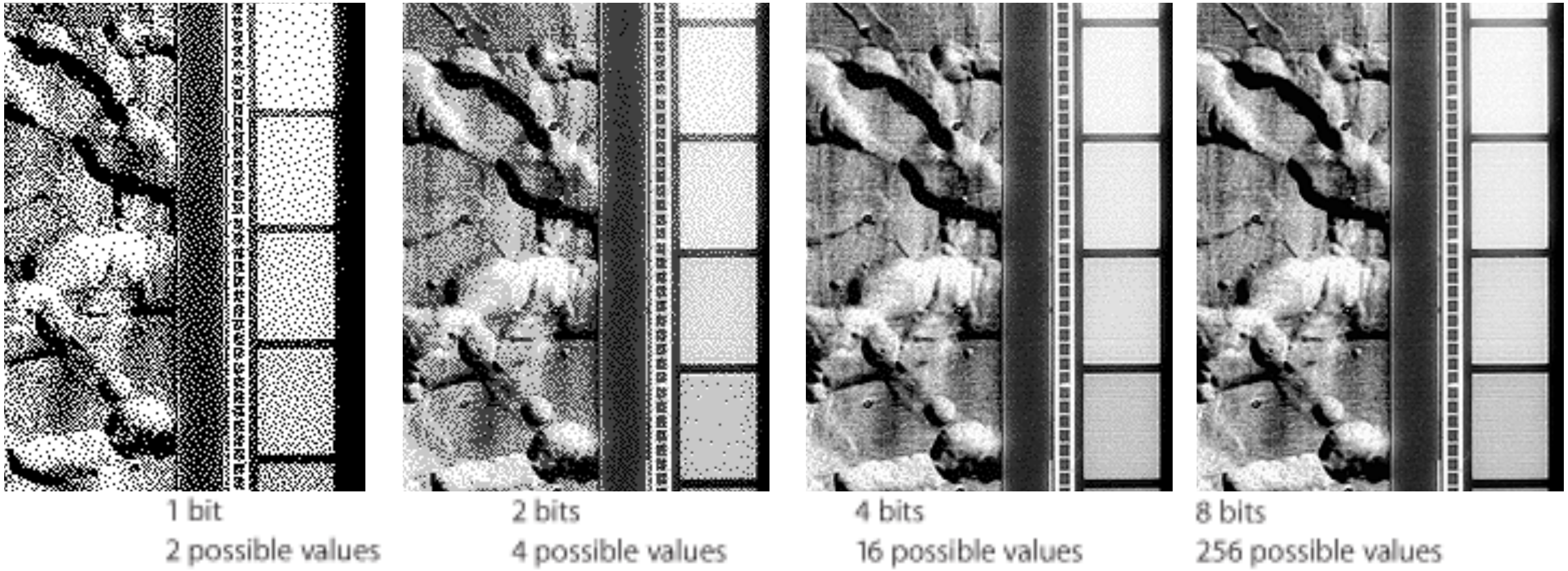
(depends on nb of bits for encoding)

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

Digitisation (reminder)



Mariner 9 / Mars (digitised from analog measurements)

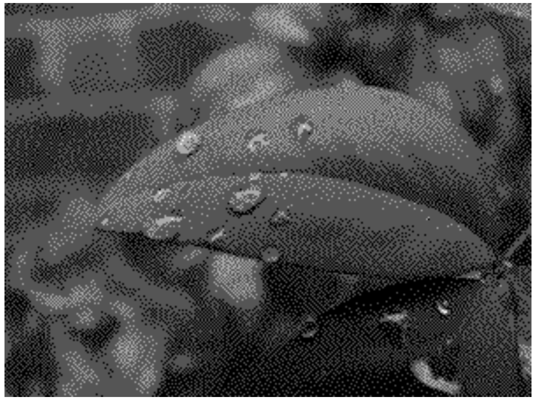
=> Details are lost in visual noise, lesser dynamics affects spatial resolution

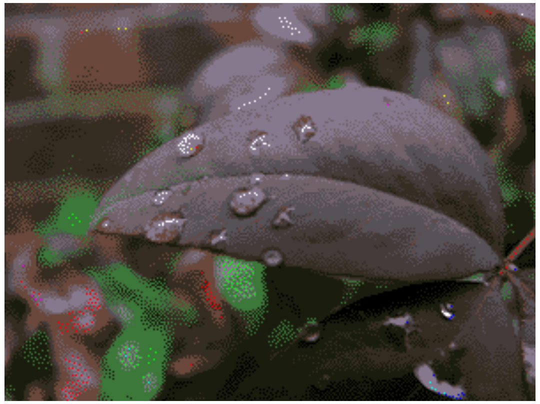
Nb of bits required? Noise encoded on (at least) ~ 1 DN ; N bits => 2^N levels (DN)
=> N such that 2^N > well capacity / readout noise (complete dynamics) - nothing more required

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

Digitisation (reminder)

Same thing in colours



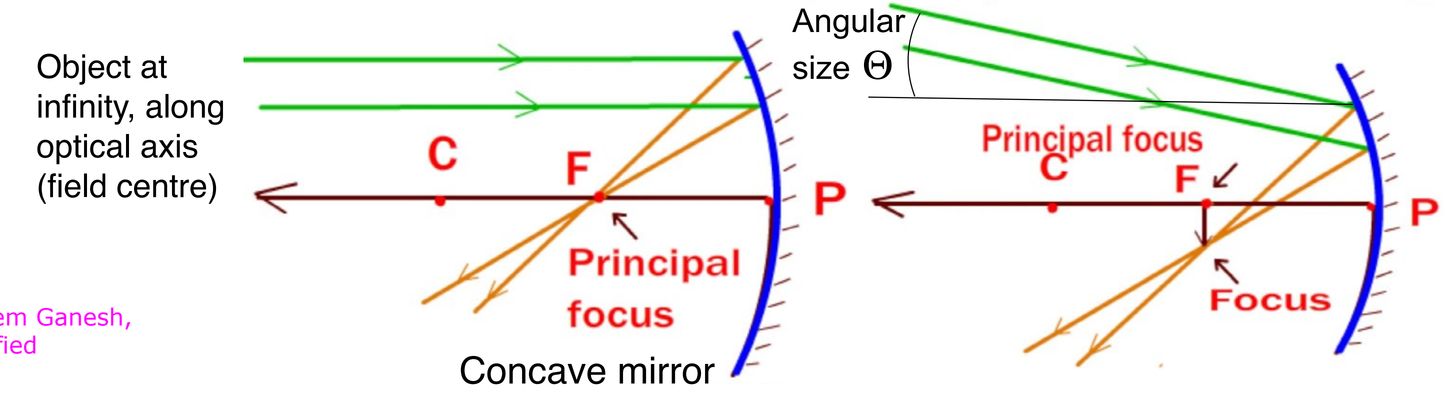


2 bits 4 bits 8 bits

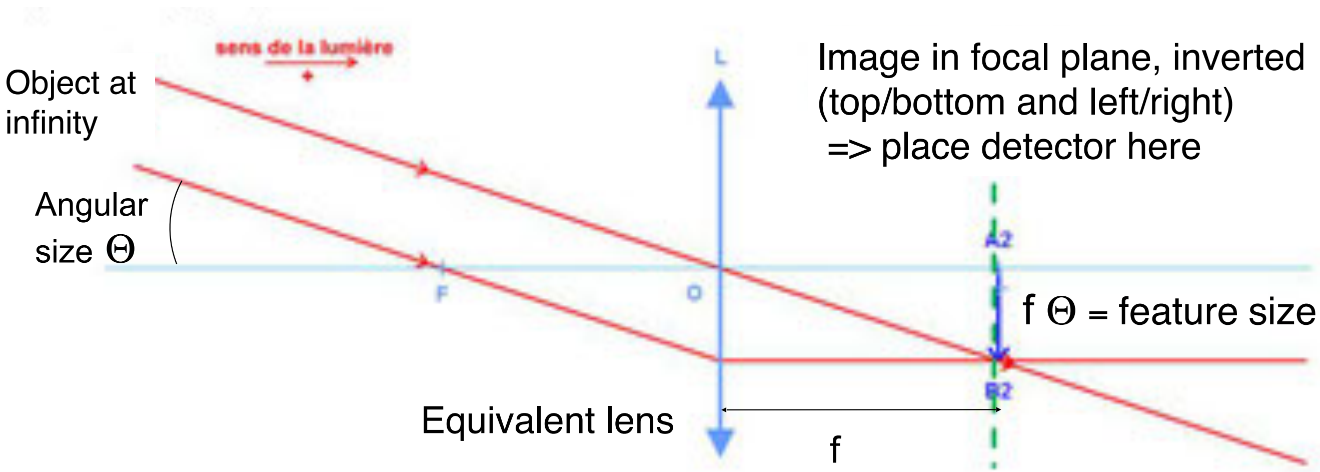
(Nb of bits in each colour plane)

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

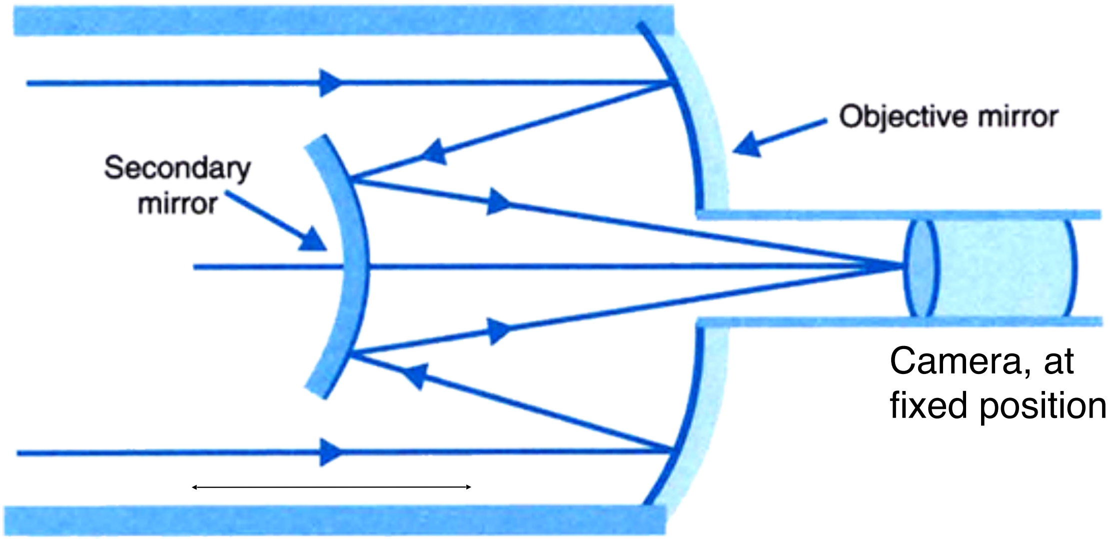
Geometric optics (reminder)



Shreem Ganesh, modified



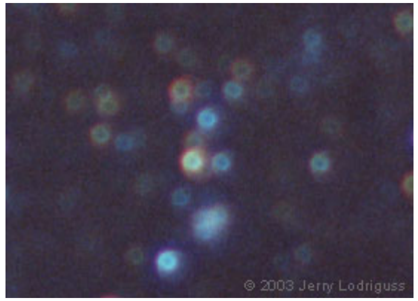
Geometric optics (reminder)

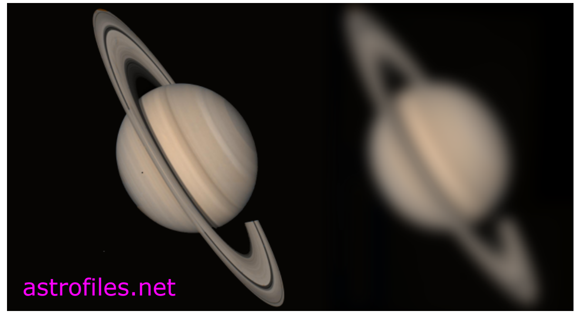


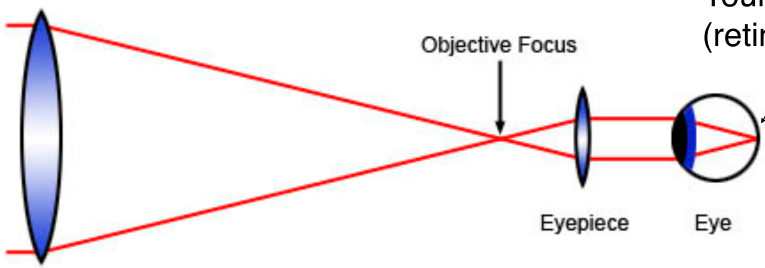
Camera, at fixed position

Secondary mirror is shifted to move focal plane onto detector

Don’t forget to focus!







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?

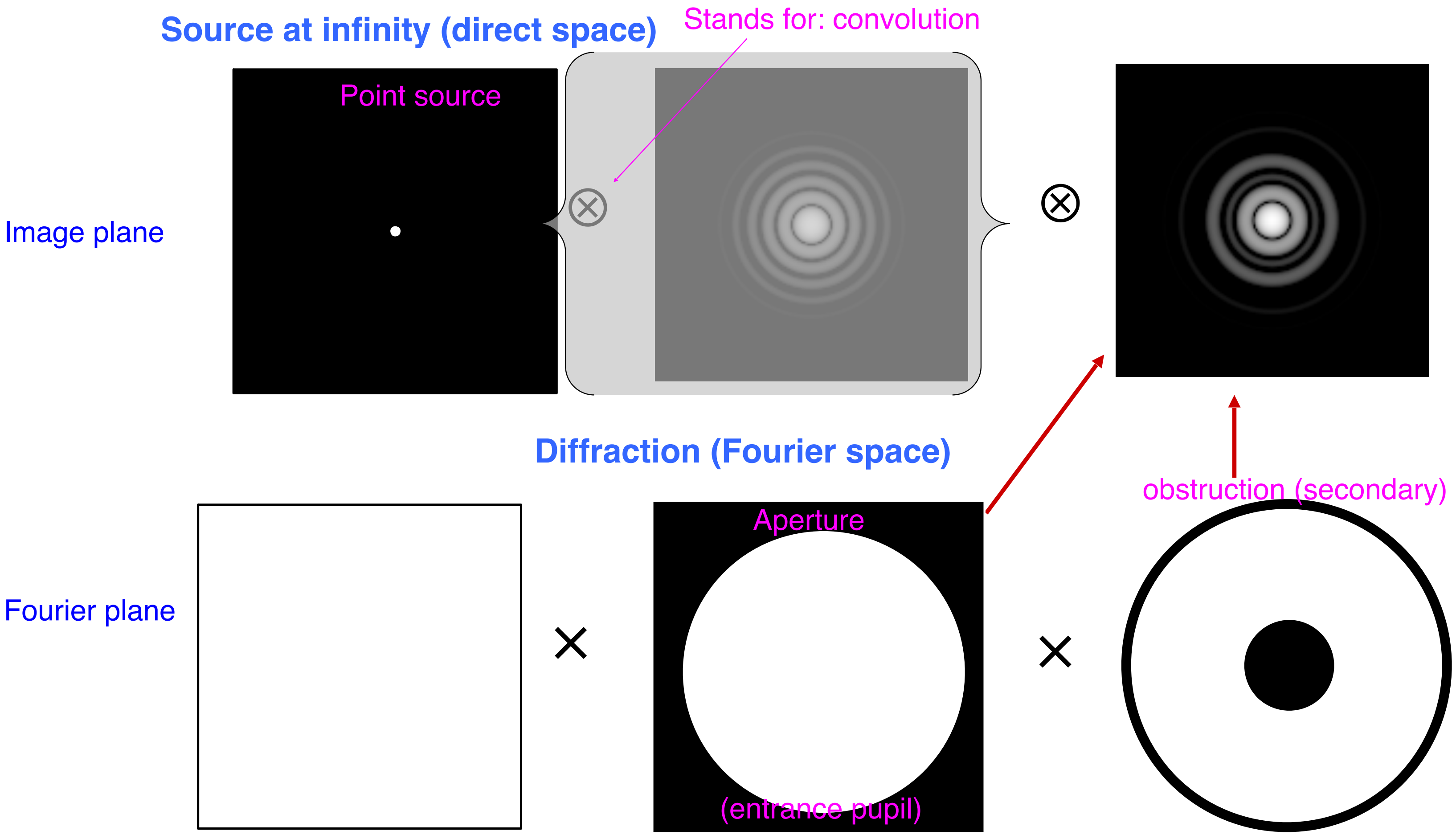
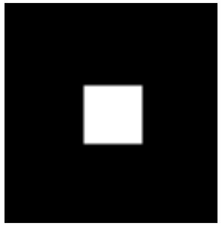


Image formation (reminder)

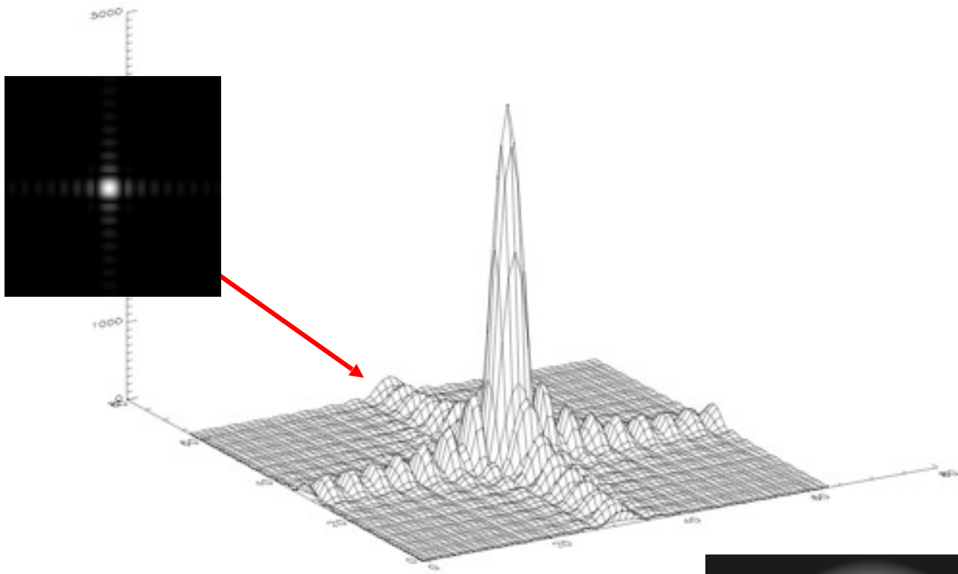
See your optics / instrumentation lectures

- **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)**



entrance pupil

image



- **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

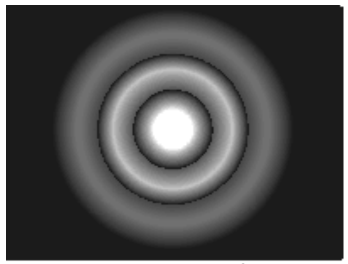
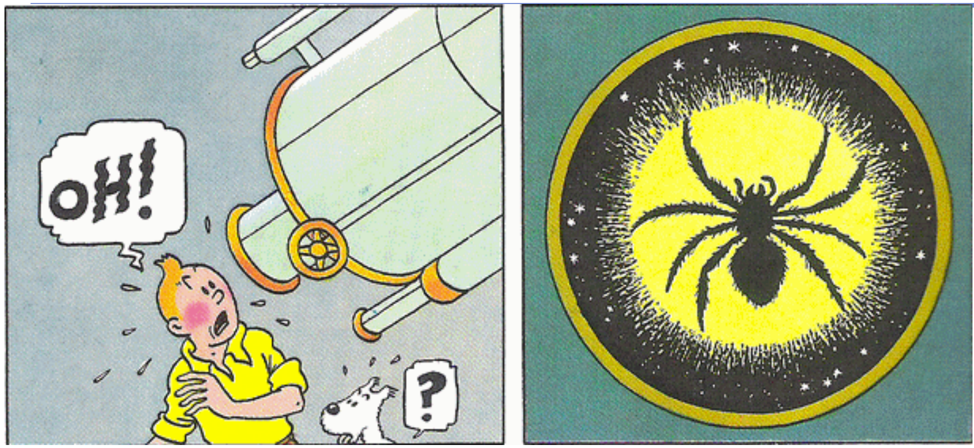


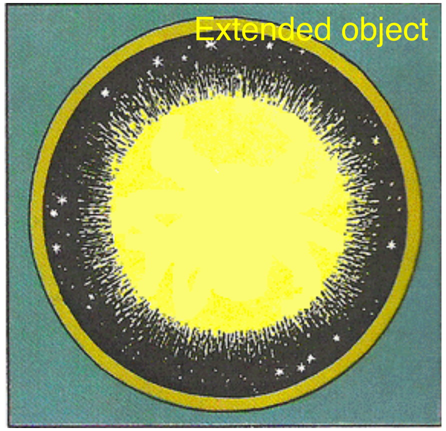
Figure1 : Image d'une étoile

The non-Fourierist spider

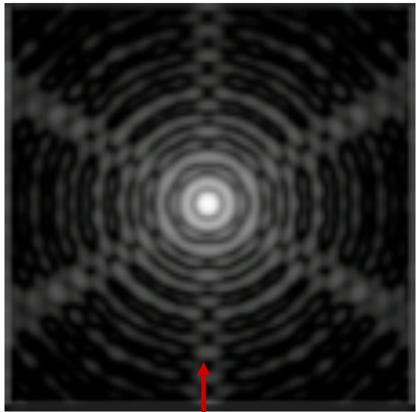


?

Tintin and the non-Fourierist spider

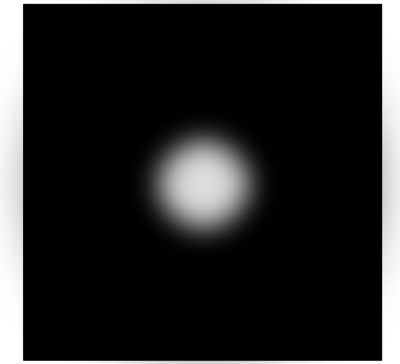


$\otimes$



Source at infinity (direct space)

Diffraction (Fourier space)



$\times$

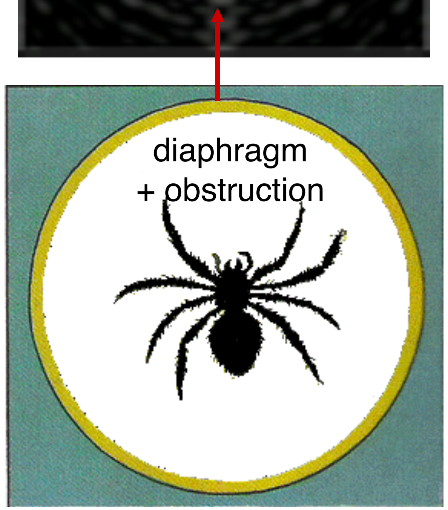
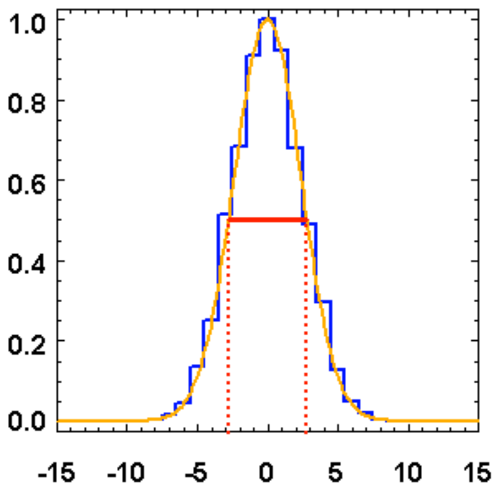


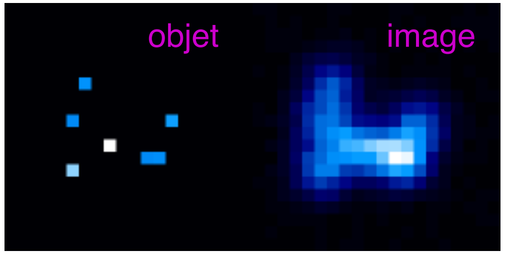
Image formation (reminder)

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

Image = object ⊗ PSF
convolution



Broader PSF => blurred image



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

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

Modulation Transfer Function (MTF) ~ FT of PSF, normalised

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 λ / D (distance of first zero of Airy pattern
= width of central peak, in radians)
Improves at shorter wavelengths and with larger mirror

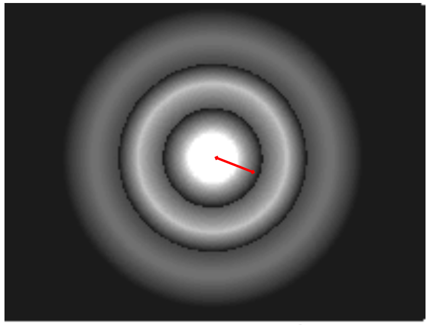


Figure1 : Image d'une étoile

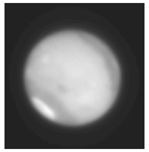
• **Atmosphere :**

Turbulence reduces angular resolution
Turbulence cells, blurring the image => ~ 50 cm telescope (= Fried parameter)
Improves at longer wavelengths (IR), short exposures, and in zenith direction

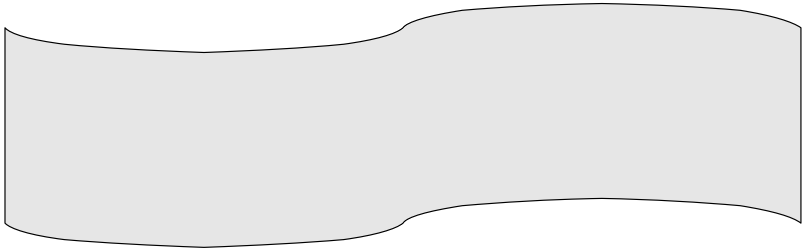
Seeing:
Estimate of resolution at time of observations
2” is very good, 0.5” is exceptional (= diffraction limit with D ~ 1m)

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

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

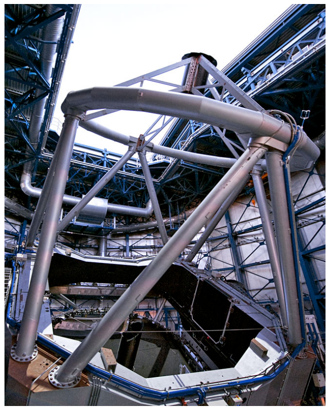


Object



Atmosphere

Seeing = 0.4″ (very good)



8 m VLT, no AO
diffraction limit = 0.02″

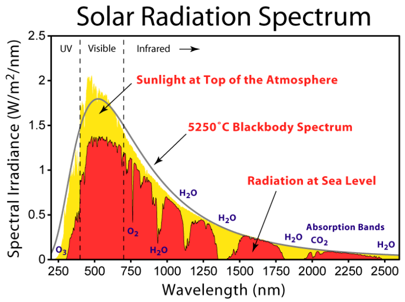
30 cm tel
diffraction limit = 0.4″

Both provide the same angular resolution ~ 0.4″
(but much better luminosity at VLT)

Camera: samples the focal plane with step= pixel size
Px size/focal must *always* sample the PSF > Nyquist frequency
— but not more => bin when seeing is not optimal

Effects of the atmosphere

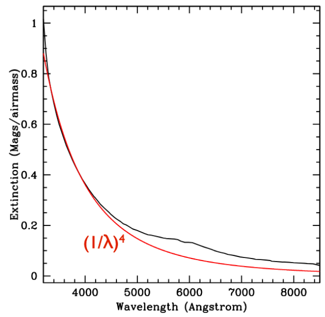
• **Turbulence / seeing**
Limitation in angular resolution (see below)



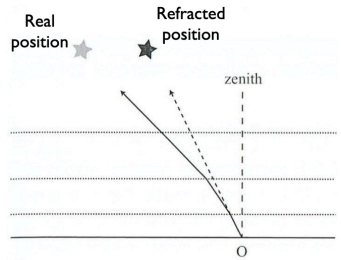
Wikipedia

• **Absorption / transmission**
Depends on wavelengths (bands), variable with time

Ph. Massey:
http://www2.lowell.edu/users/massey/7_Atmosphere.pdf



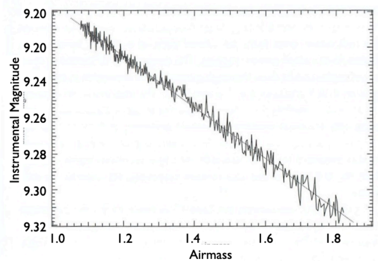
• **Scattering / extinction**
Depends on wavelengths, low frequency => spectral slope
May scintillate / twinkle => another source of noise

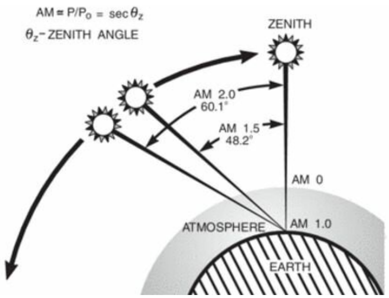


• **Refraction / dispersion**
Changes apparent direction of source, depends on wavelength
=> effect on spectra

H. Al-Taani
doi: 10.21625/archive.v3i1.441

• **Effects depends on atmospheric path length = airmass**
X = 1 / cos(zenith angle)
=> Observe as high as possible - typically at S meridian
=> Measure and correct extinction (Bouguer law)





Dependences of PSF? Field width

Wider aperture u

$u \cdot \mathrm{rect}$ Narrow (diaphragmed) aperture

Fourier plane

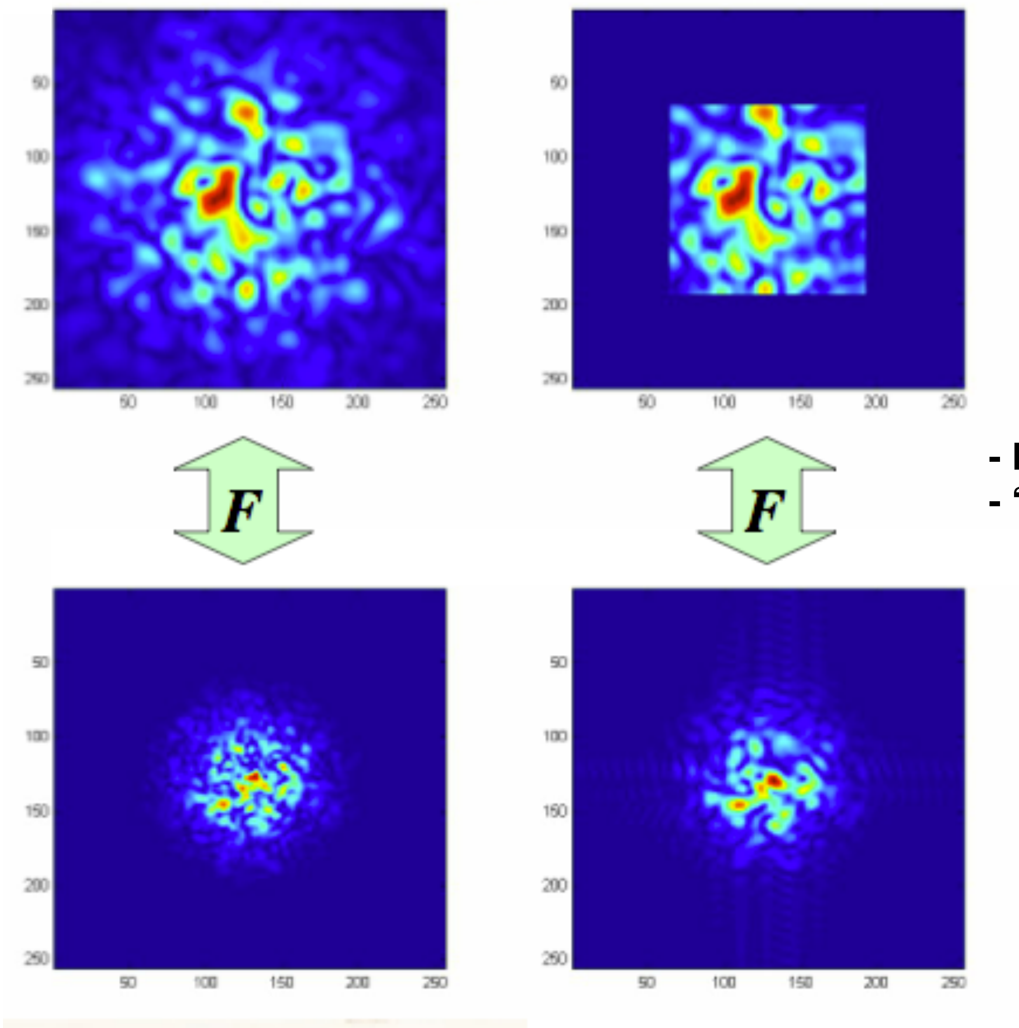
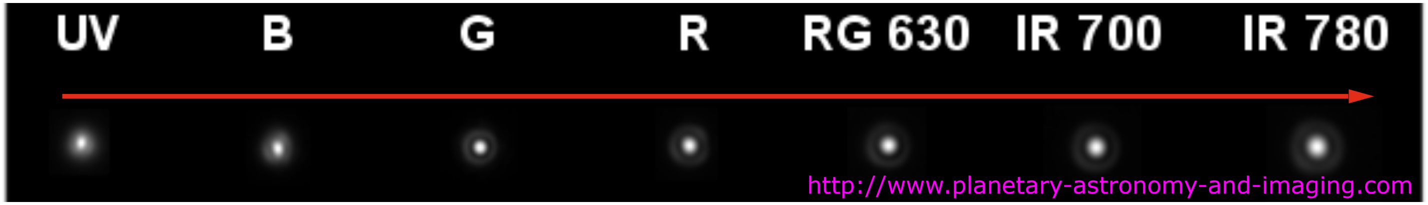


Image plane

- Reduced resolution
- “Ringing” (<= secondary lobes of sync function)

P. Riaud et al

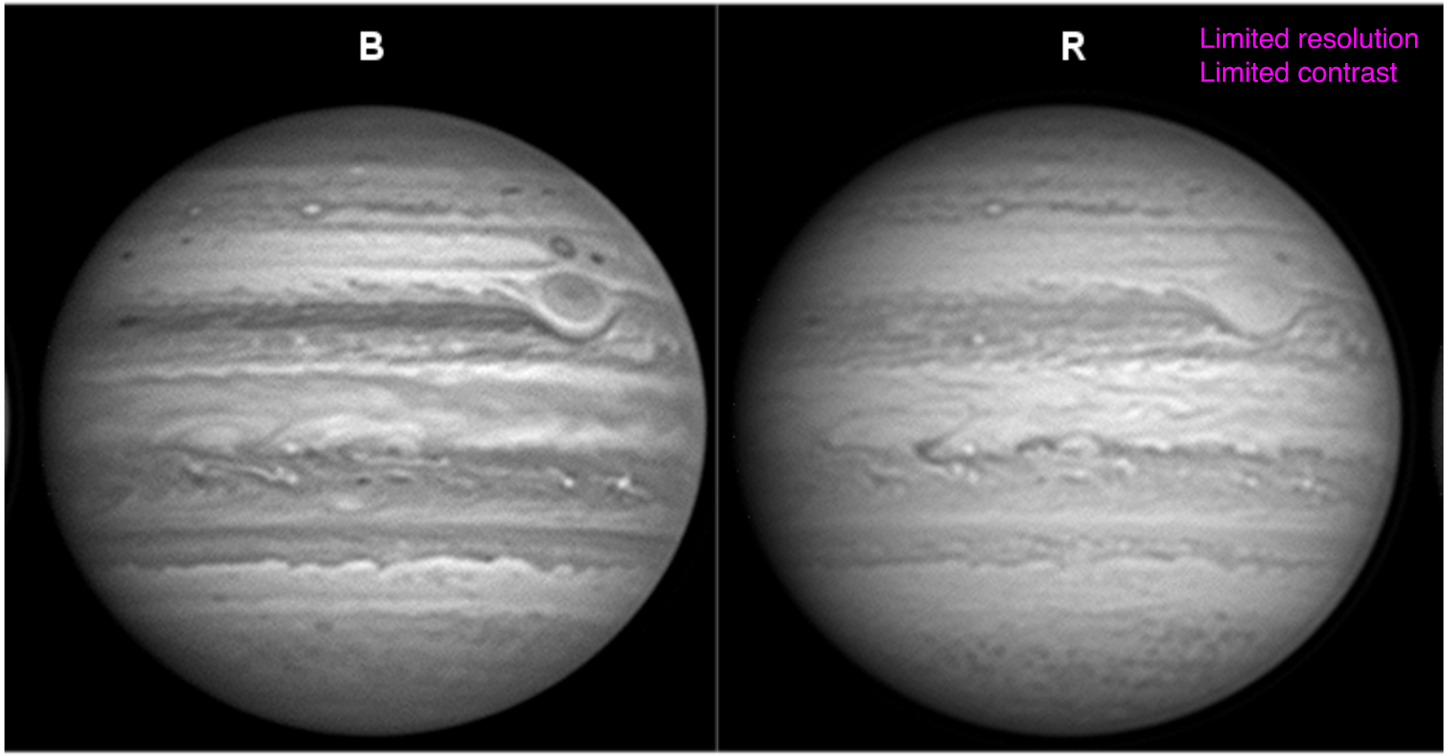
Dependences of PSF? Optics and wavelength



wider PSF

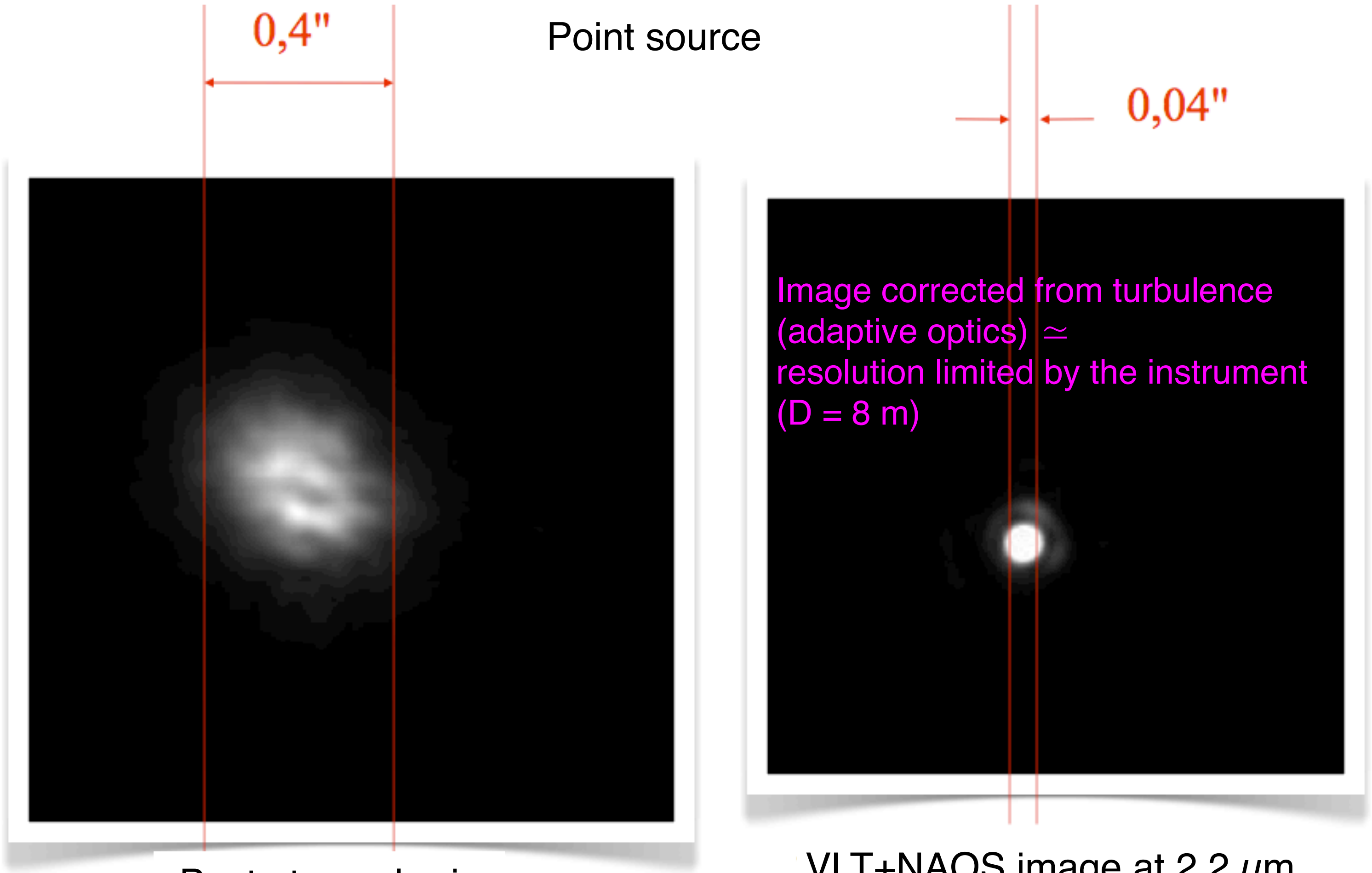
Variation with wavelength: influence of optics
(conditions of a very stable atmosphere [quite rare] and a small telescope)

D = 0,25 m



Dependences of PSF? Turbulence

Point source



Best atmospheric image from VLT

VLT+NAOS image at 2.2 μm

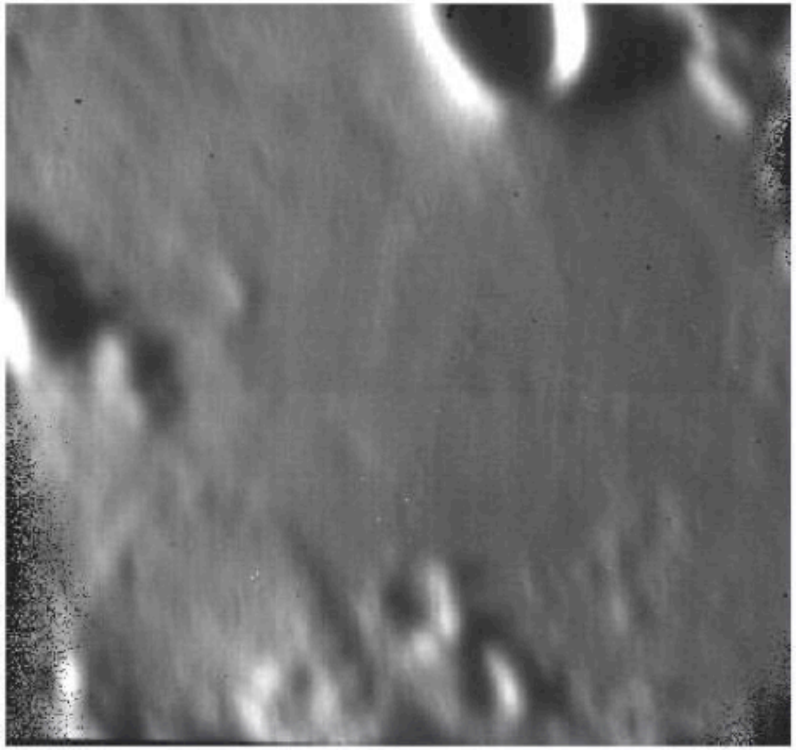
1,22 x 2.2 μm / 8 m ~ 0,31.10^{-6} rad ~ 0,07"

S. Lacour

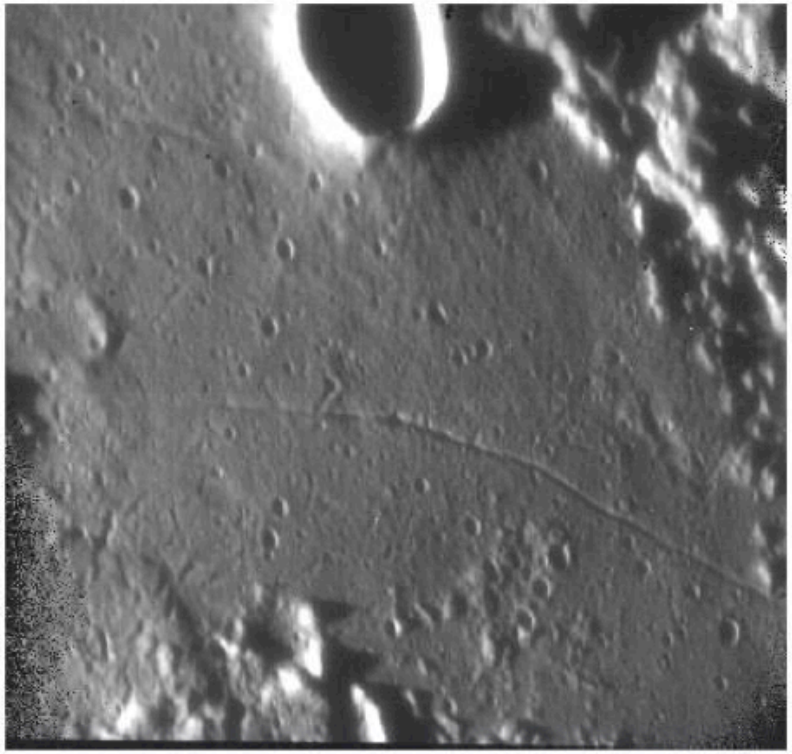
Angular resolution

Continuous field

Atmospheric image, object ⊗ turbulence



AO corrected image, object ⊗ instrument



~60 km ~30 arcsec

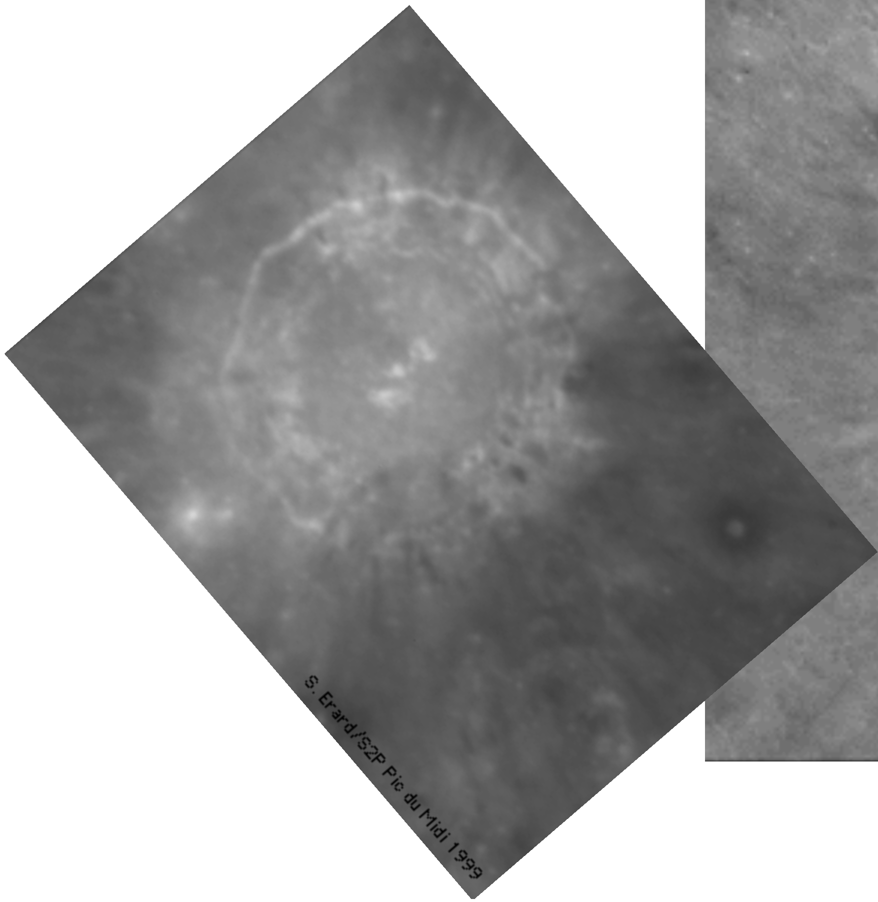
NACO / VLT

S. Lacour

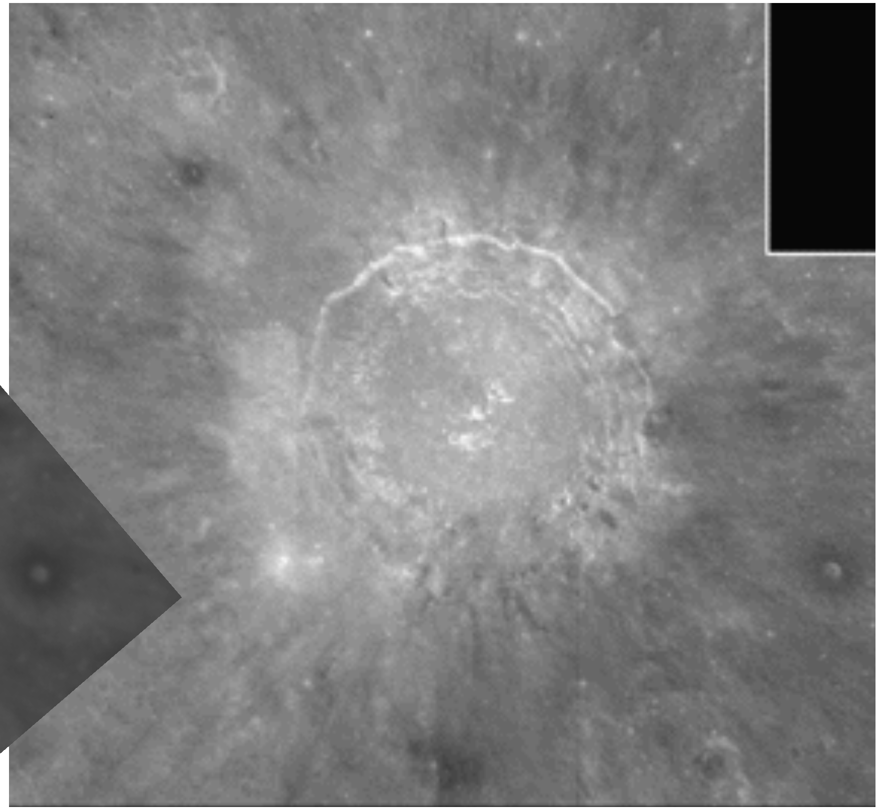
Angular resolution

Continuous field

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



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

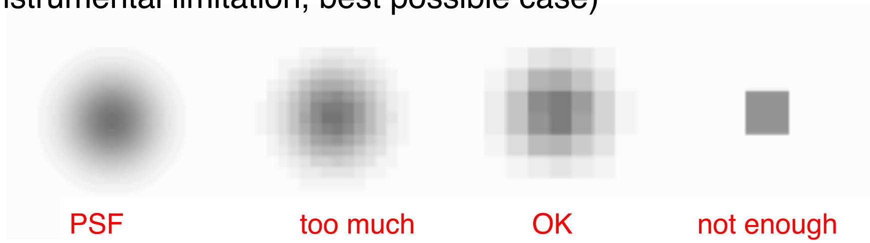


Sampling of the image plane (reminder)

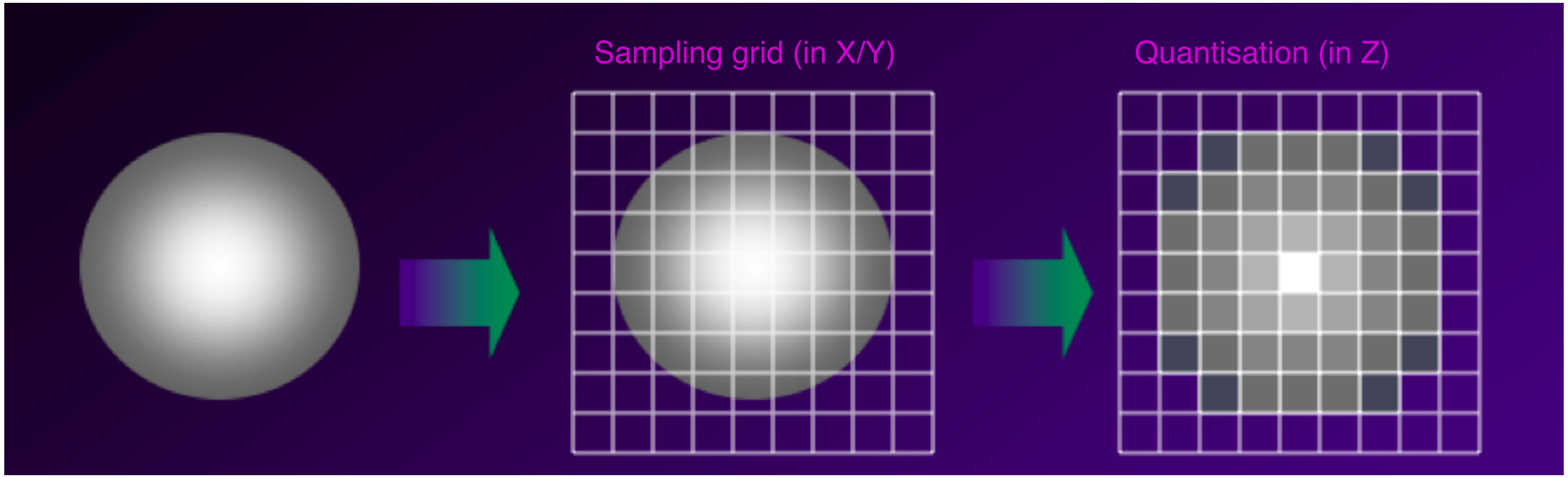
- **Smallest resolved object = Θ_{min} (PSF size)**
- **Size of Θ_{min} in focal plane = f x Θ_{min}**
- **Shannon theorem: 2 measurement points / resolved element** (ie: inside PSF)

⇒ **size of detector pixels = 0,61 f λ / D** (for instrumental limitation, best possible case)

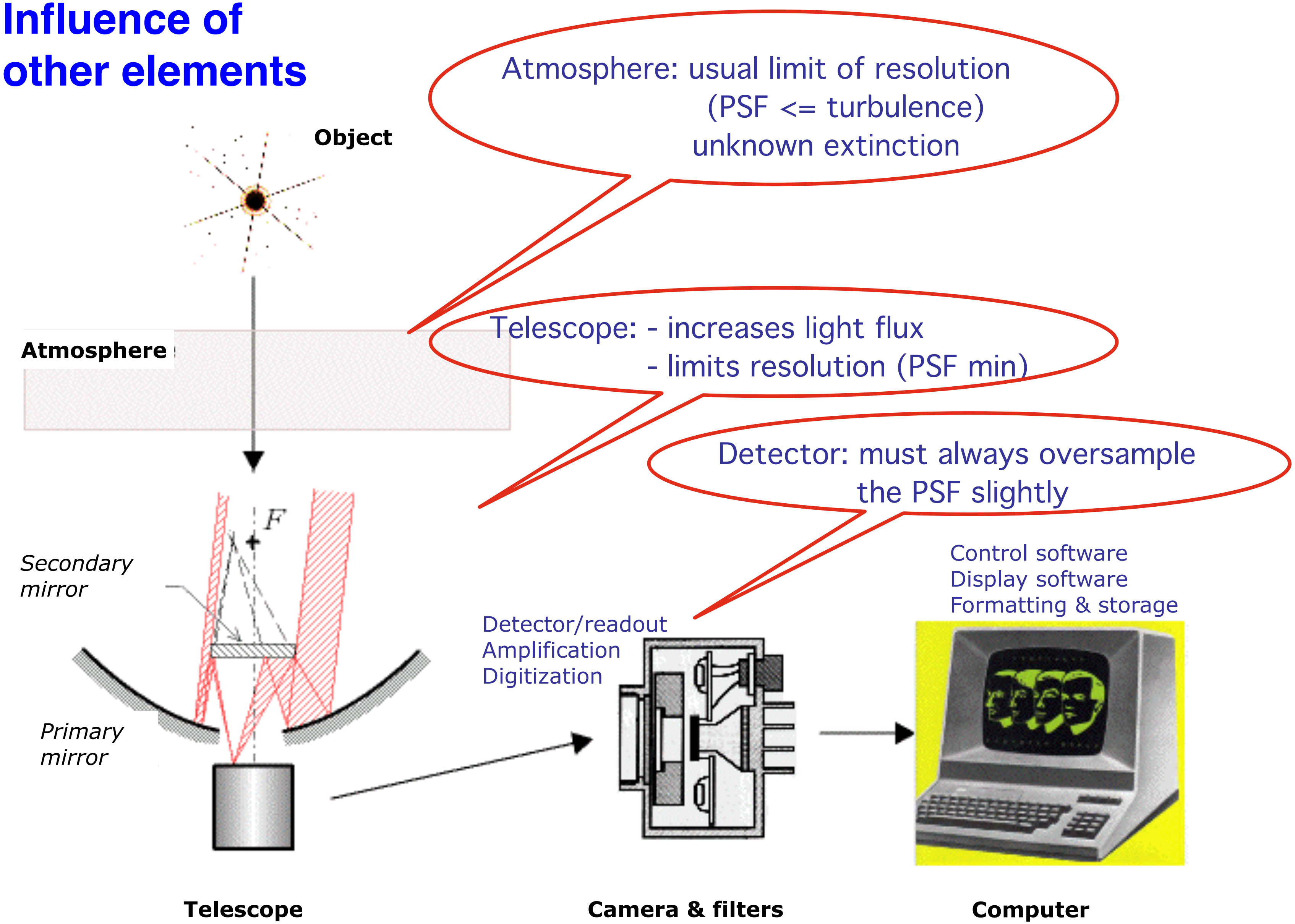
Resolution ≠ pixel size!
Resolution is driven by PSF size,
not by pixel size
which is always smaller



In non-optimal cases, binning is always preferred!



Influence of other elements



Vade-mecum

To be optimised during acquisition

- **Observe targets when close to the S meridian** (highest elevation / minimum airmass)
- **Binning** (minimises readout noise, if no loss of resolution)
- **Exposure time** (max signal, no saturation)
- **Don't forget to focus! —** Estimate seeing (qualifies turbulence)
- **Maintain observation log** / take notes (events, doubts, questions…)

After the fact (by software)

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

Other things you can do with a telescope

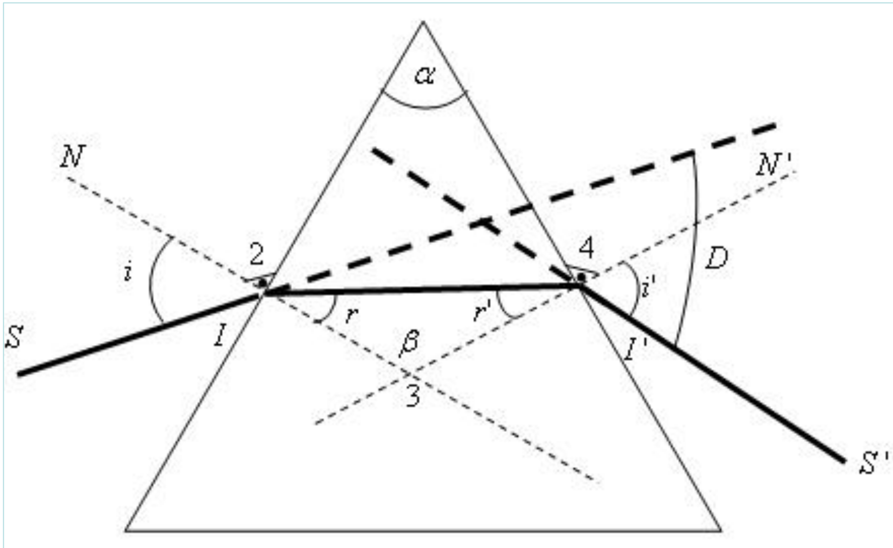
Spectroscopy

- 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

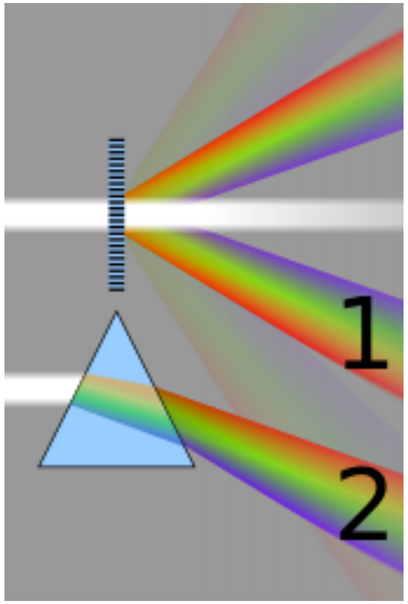
Refraction in different directions
= > dispersion of light

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

wikipedia

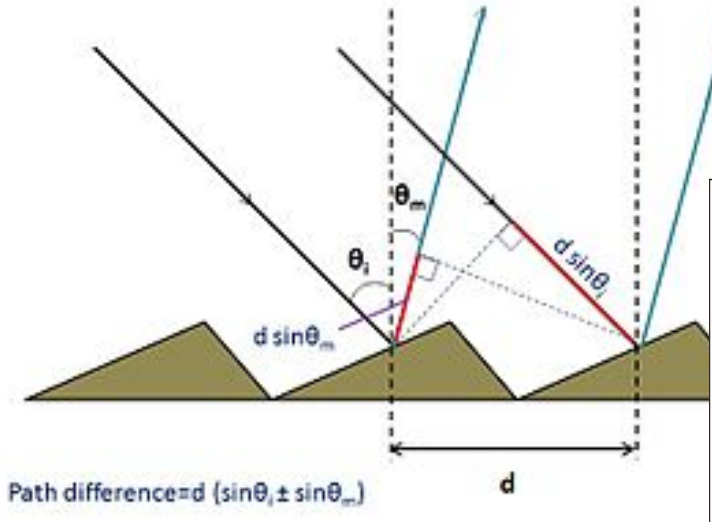
Spectroscopy (reminder)

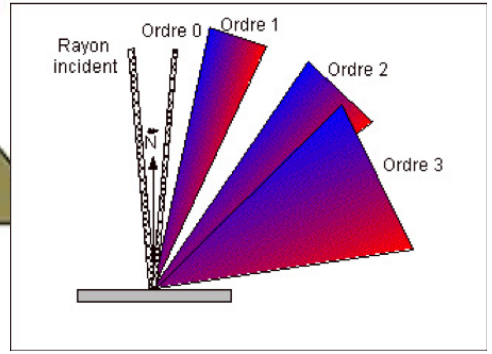
Transmissive diffraction grating



wikipedia

Reflective diffraction grating





Constructives interferences in given directions θ_m for a given λ

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

d = grating line distance

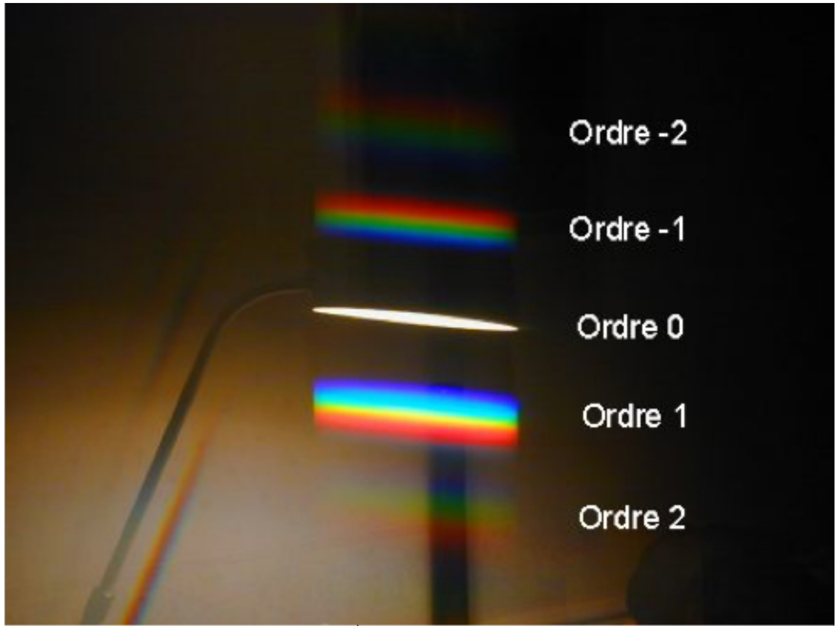
m = integer number => several spectra (successive grating orders)

Order 0 is not diffracted, but reflected

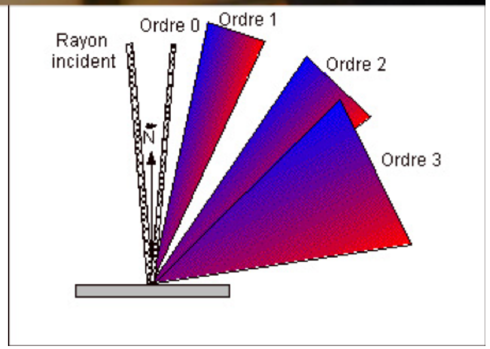
Spectroscopy

Diffraction grating

Monochromatic source (laser)



White light



Images C. Buil

Spectroscopy

Spectrometre

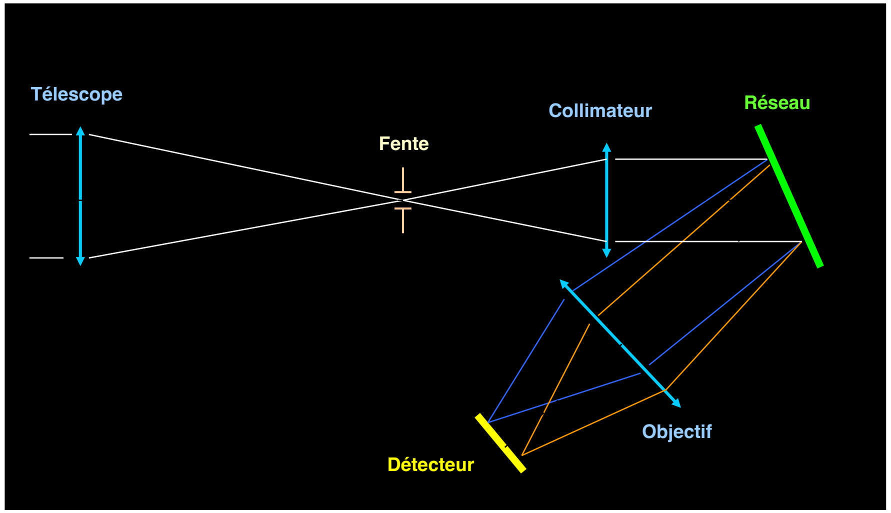
• Light from target is diffracted along a spectral direction
⇒Light beam is blocked in this direction to isolate objects
⇒Entry slit in orthogonal direction
⇒On the CCD: one spectral dimension, the other spatial

• Grating to be illuminated by a collimated beam
⇒Extra lens behind the telescope (collimator)

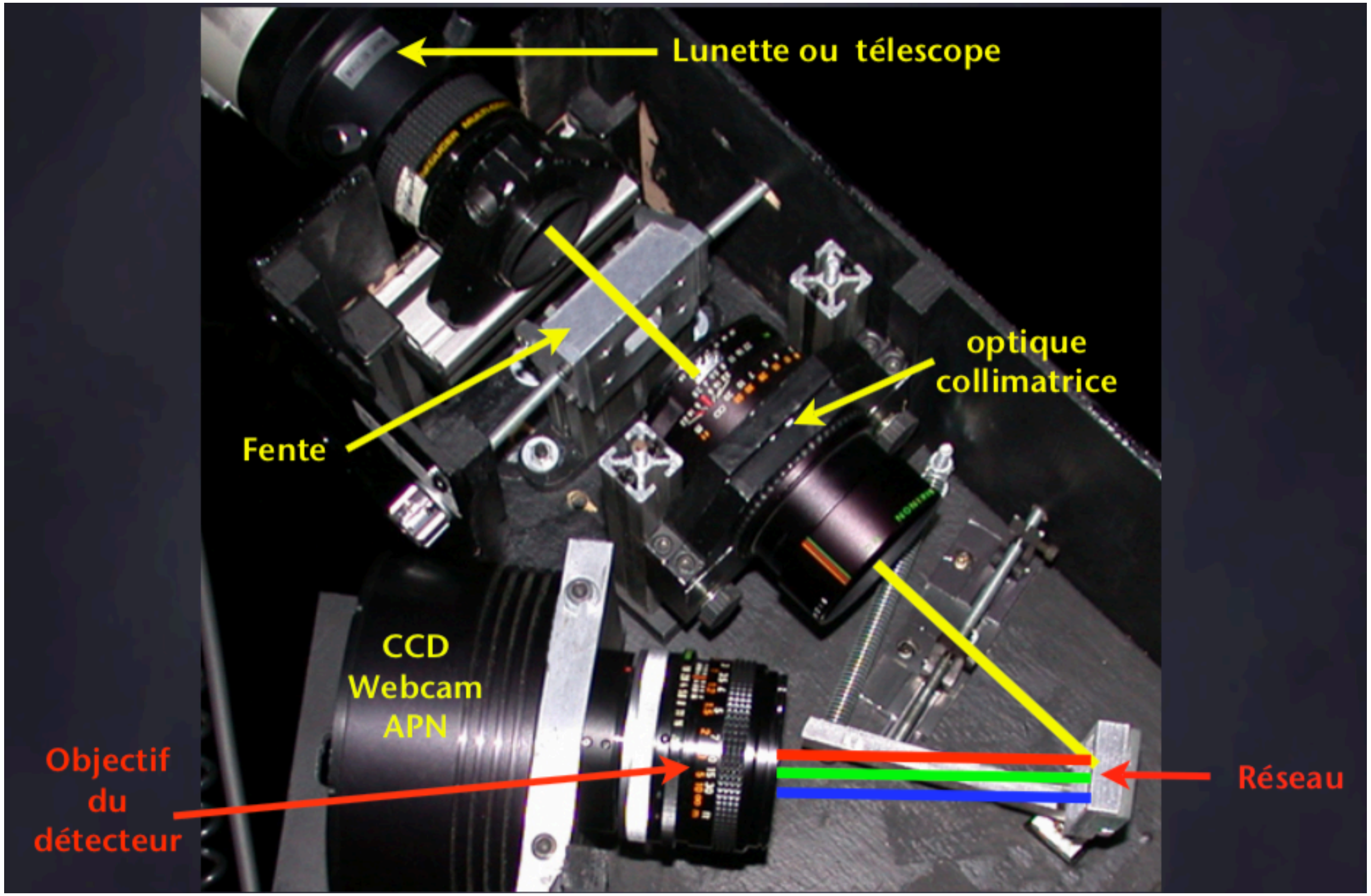
• Need to form an image after the grating
⇒Extra lens behind the grating (objective)

• 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

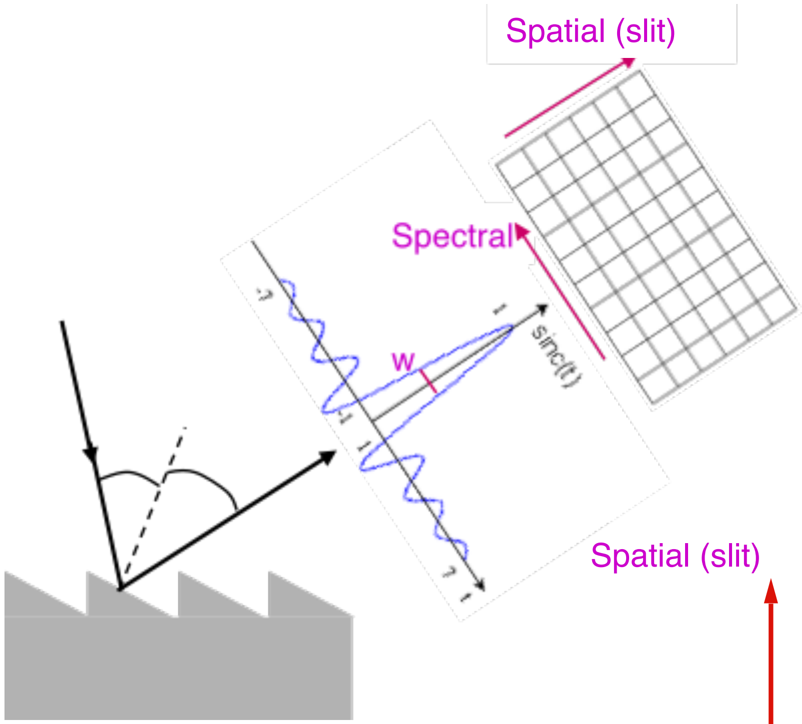
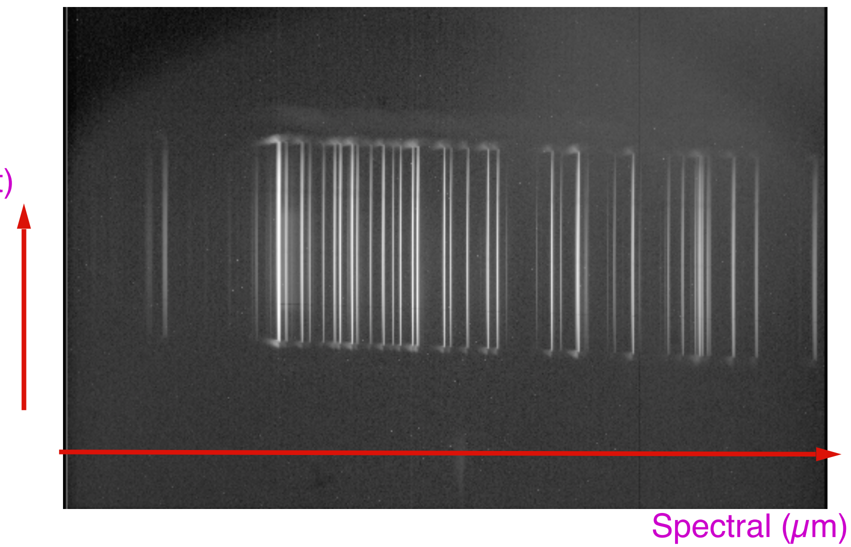
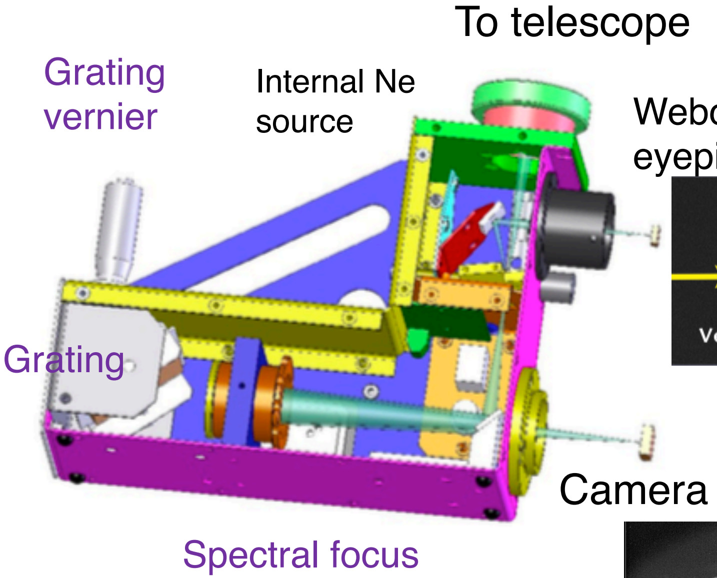


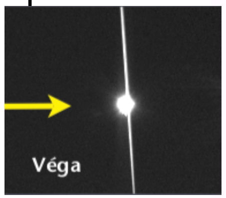
Image of the slit at various wavelengths

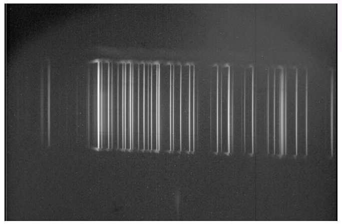
• Slit must be aligned on CCD array
• Spectral axis must be calibrated
⇒Reference sources with known spectral lines: Ne



LHIRES







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

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