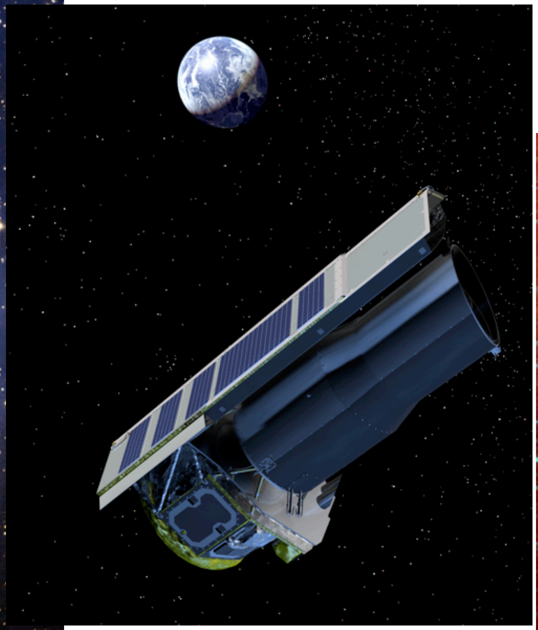
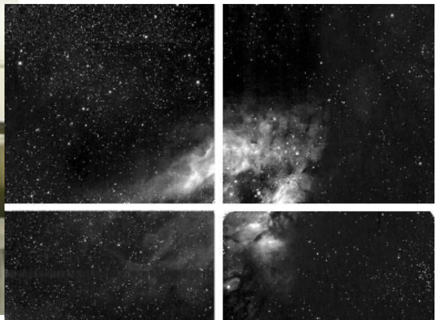
# Star Formation at Infrared Wavelengths

## Infrared imaging and detectors

Jean-Louis Monin

Laboratoire d'AstrOphysique de Grenoble





Introduction

Magnitude systems

Atmospheric windows and imaging filters

The basics of detection

Flat-fielding and Calibration

Photons, electrons, noise and performances

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# Jean-Louis Monin

# IR IMAGING and DETECTORS

# First Constellation school, Florence, may 27-29th, 2008

This lecture was held in Florence (Italy) during a *Constellation* Network school (May 27-29th 2008 at the observatory of Arcetri)

The (PDF) lecture summary ( **DRAFT !** )

The (PDF) lecture slides ( **DRAFT ! 10Mo...** ) (updated may 21)

**This lecture is based (in part) on the following references :**

*Standard Photometric Systems*, M. S. Bessel, 2005, ARAA, 43, 293
*Model atmospheres broad-band colors, bolometric corrections and temperature calibrations for O - M stars*, Bessel, Castelli & Plez, 1998, A&A 333, 231

**... and has benefited from reading the following PDF files :**
(Some of them from the lectures of O'Connell, University of Virginia :

Photometric systems
Spitzer IRAC pocketguide
Spitzer MIPS pocketguide



# Introduction

IR imagery started in the 80s (with 8x8 then 32x32 arrays) and now reaches 4 Mpixels detectors.
It shares a lot of characteristics with Visible imagery but also shows huge differences.
Although imagery gives access to extended sources brightness (astrometry, proper motion, polarimetry, etc.), this lecture concentrates on PSF (point-like) sources measurements.
NB. For ground-based observations,
the image quality (seeing *w*) varies with $\lambda$ :

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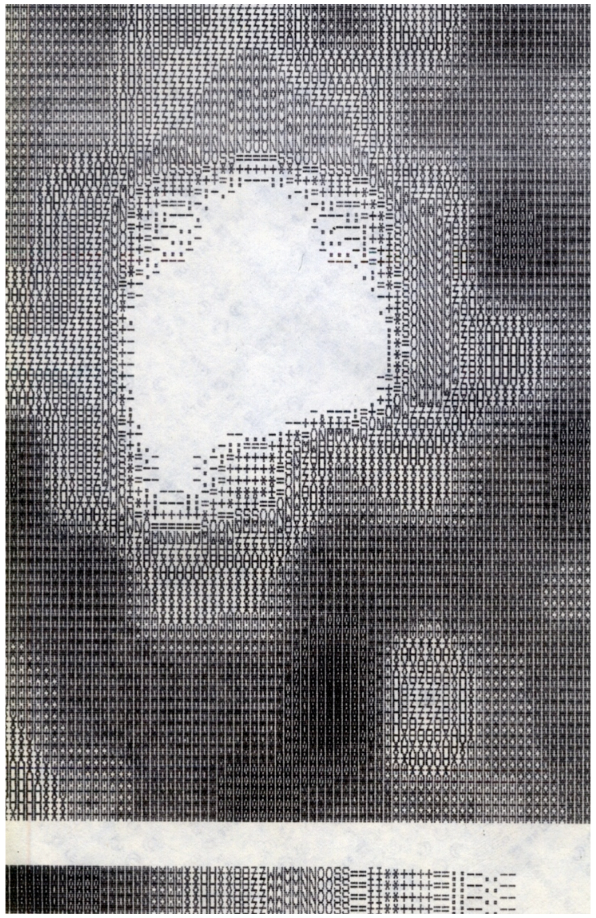
Nebula
(8x8)
TBL 1985





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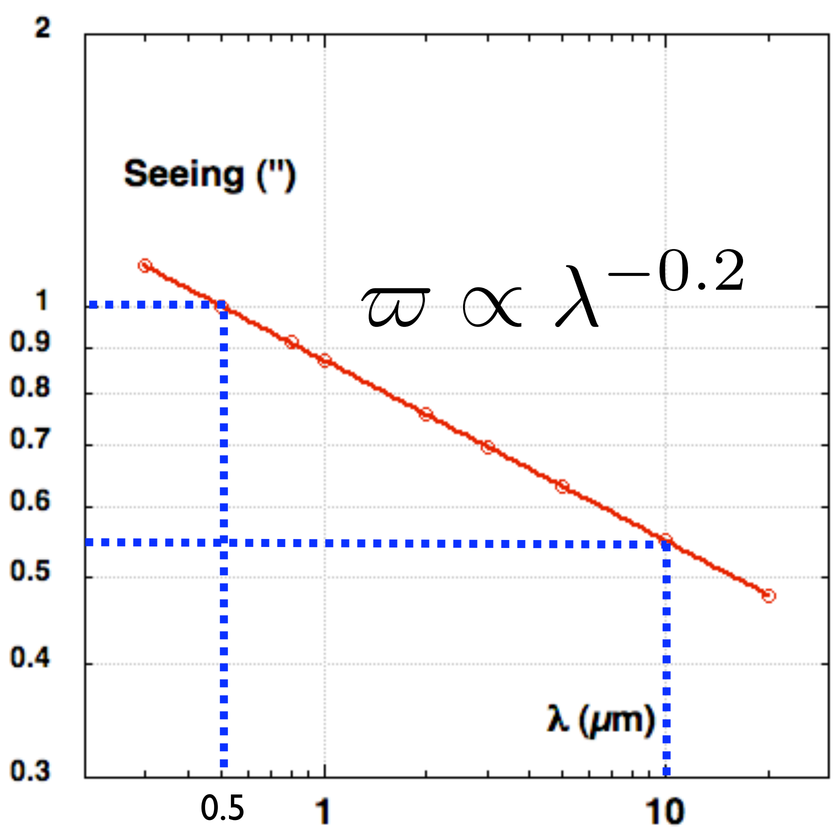


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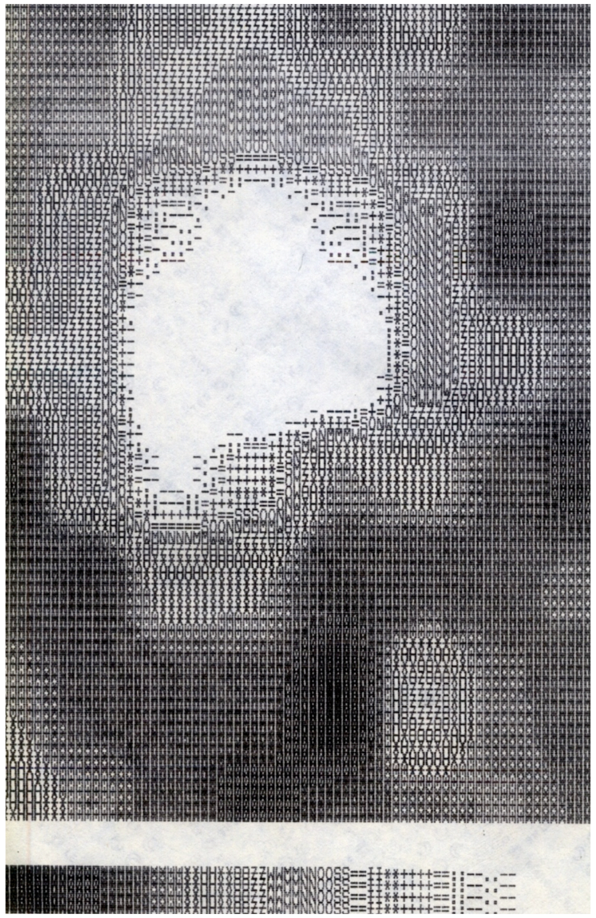

# Magnitude systems
# (above the atmosphere)

# The 2 magnitudes systems : VEGA and AB (ST)

The Vega magnitude system uses the A0 V star Vega as a reference.
By definition, Vega has a magnitude 0 in every band.

The AB system doesn't make any reference to a given object.

NB. All the filter / bands position in a spectrum are labelled by their wavelength $\lambda$
(be it for $F_\lambda$, flux per unit wavelength or $F_\nu$, flux per unit frequency)

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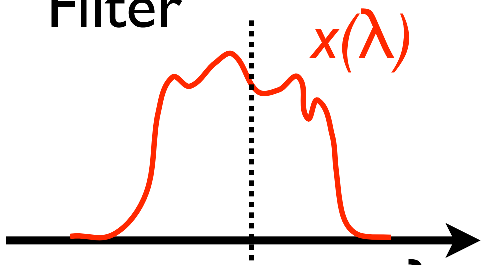
## The Vega system




Various reference fluxes $F_o$

(photon counting detectors)

$$N_\lambda = \frac{\lambda F_\lambda}{hc}$$

$$m_i = -2.5 \log \frac{\int x_i(\lambda)\, \lambda F_\lambda(\lambda)\, d\lambda}{\int x_i(\lambda)\, \lambda F_\lambda^{\mathrm{VEGA}}(\lambda)\, d\lambda}$$

$$m_i = -2.5 \log \frac{< F_\lambda(\lambda) >}{F_\lambda o(i)}$$

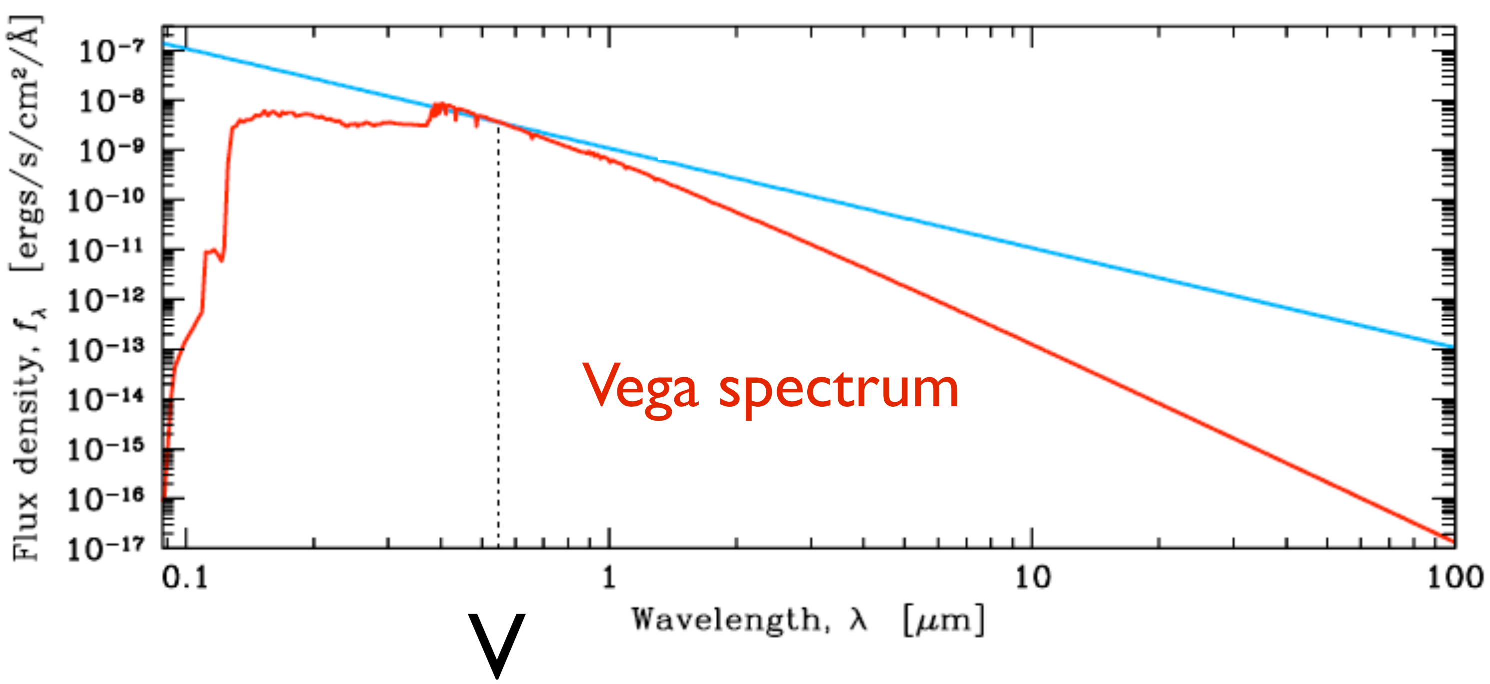
*Average* flux over the given filter

*Reference flux*

# Reference fluxes from the visible to the infrared in the VEGA system

Zero mag fluxes in the Cousins - Glass - Johnson system (erg/cm²/s/...)

| | V | R | I | J | H | K | Kp | L | L* | M | N | Q |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (µm) $\lambda_{eff}$ | 0.545 | 0.641 | 0.798 | 1.22 | 1.63 | 2.19 | 2.12 | 3.45 | 3.80 | 4.80 | 10 | 20 |
| $\times 10^{-20}$ $f_\nu$ /Hz | 3.636 | 3.064 | 2.416 | 1.589 | 1.021 | 0.640 | 0.676 | 0.285 | 0.238 | 0.153 | 0.037 | 0.010 |
| $\times 10^{-11}$ $f_\lambda$ /Å | 363.1 | 217.7 | 112.6 | 31.47 | 11.38 | 3.961 | 4.479 | 0.708 | 0.489 | 0.20 | 0.011 | $7.5\ 10^{-4}$ |



# Reference fluxes from the visible to the infrared in the VEGA system

Zero mag fluxes in the Cousins - Glass - Johnson system (erg/cm²/s/...)

| | | V | R | I | J | H | K | Kp | L | L* | M | N | Q |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (µm) | $\lambda_{eff}$ | 0.545 | 0.641 | 0.798 | 1.22 | 1.63 | 2.19 | 2.12 | 3.45 | 3.80 | 4.80 | 10 | 20 |
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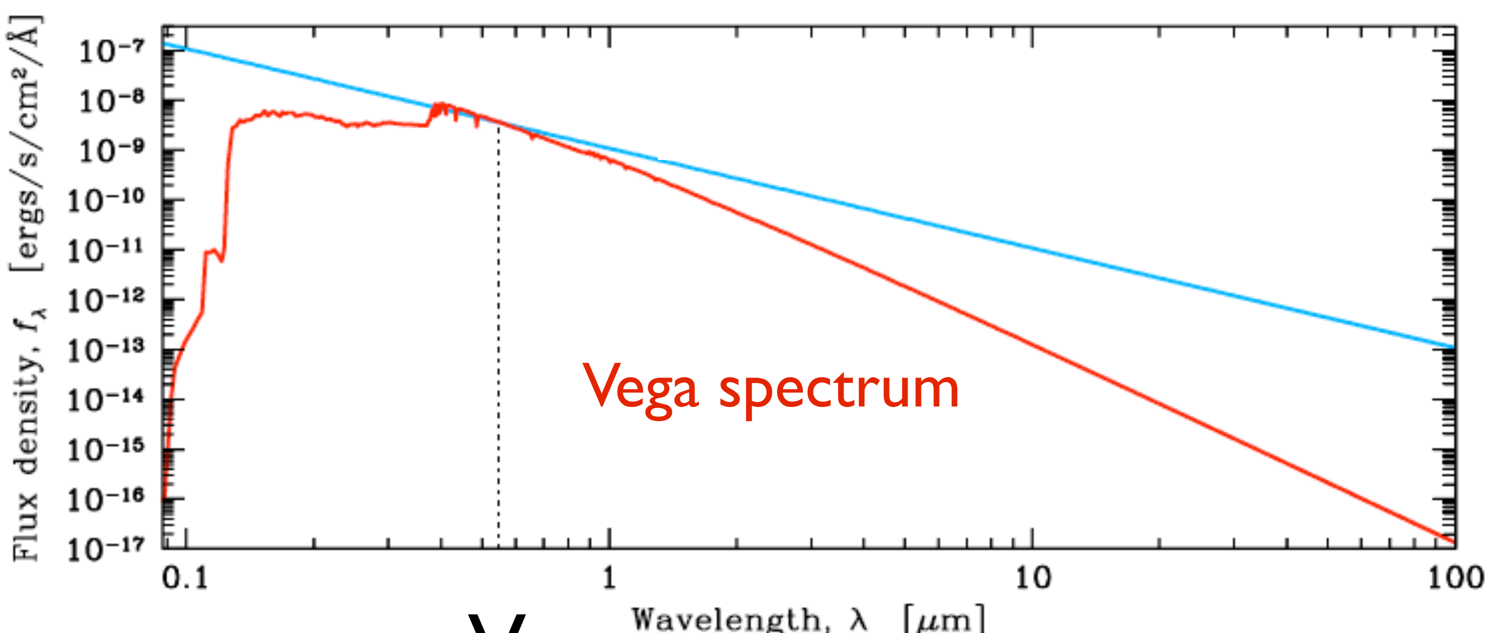
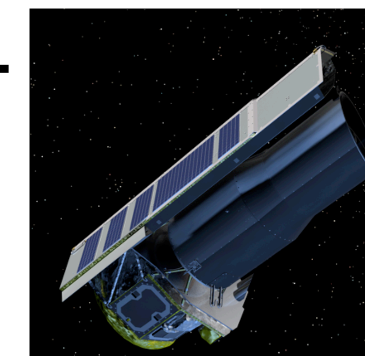



V



| IRAC bands | | |
|---|---|---|
| # | λo (µm) | Fo (Jy) |
| 1 | 3.550 | 280.9 |
| 2 | 4.493 | 179.7 |
| 3 | 5.731 | 115.0 |
| 4 | 7.872 | 64.1 |

(IRAC data handbook)

# The AB (ST) *monochromatic* (spectroscopic) system

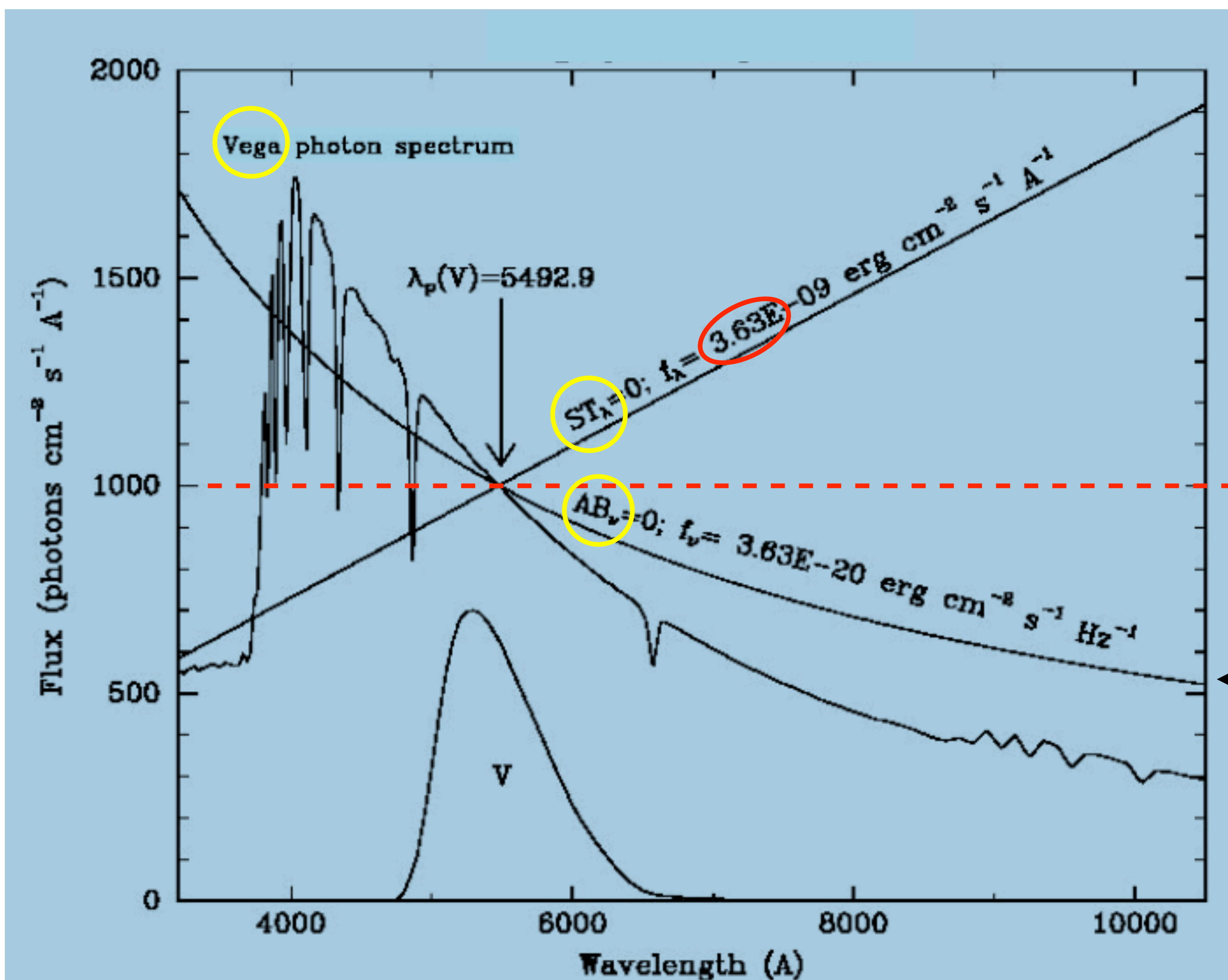
Oke & Gunn, 1983, ApJ, 266, 713

$$\text{AB}: \quad m_\nu(\lambda) = -2.5 \log F_\nu(\lambda) - 48.6$$

$$\text{ST}: \quad m_\lambda(\lambda) = -2.5 \log F_\lambda(\lambda) - 21.1$$

(HST STMAG)

crossing in V




1000 ph/s/cm$^2$/A = 3.63 $10^{-9}$ erg/s/cm$^2$/A

(constant flux $F_\nu$)

Bessel, Castelli & Plez, 1998, A&A 333, 231

# ST and AB magnitudes (integrated) through filters

$$m_{\mathrm{ST}} = -2.5 \log \frac{\int \lambda F_\lambda \, d\lambda}{\int 3.6\, 10^{-9} \, \lambda \, d\lambda} \qquad m_{\mathrm{AB}} = -2.5 \log \frac{\int F_\nu \, d\nu}{\int 3.6\, 10^{-20} \, d\nu}$$

# An example in the near IR (CFHT WIRCAM) : AB magnitudes

**Quick WIRCam photometric performance table**

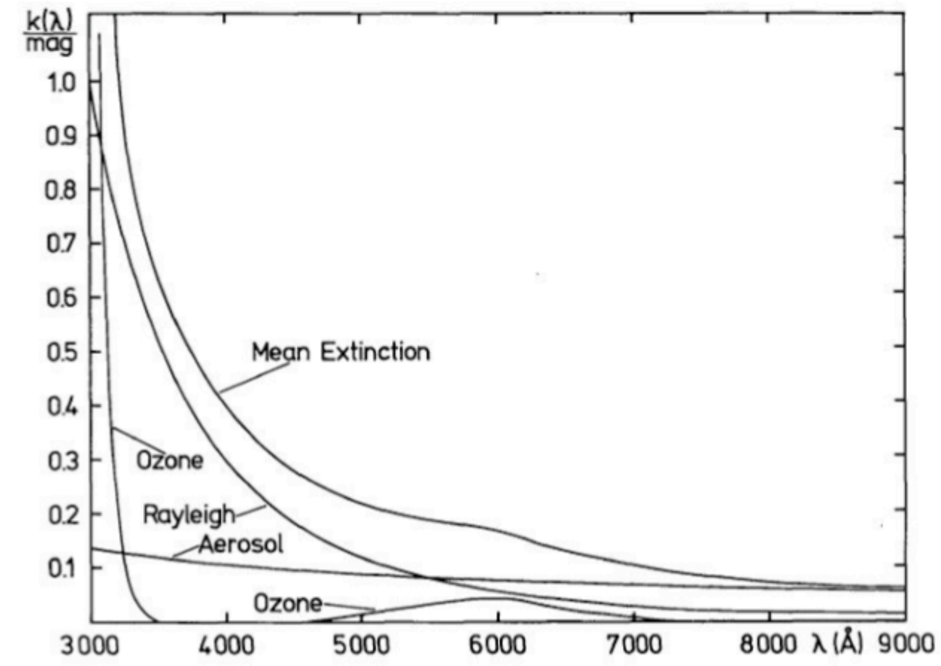
| Filter (click for details) | Y | J | H | $K_s$ | Low OH-1 | Low OH-2 | CH4 Off | CH4 On | H2 v=1-0 S(1) | K continuum |
|---|---|---|---|---|---|---|---|---|---|---|
| Point source in median sky brightness - MagAB - Optimal ap. | 22.8 | 22.9 | 22.6 | 22.5 | 20.9 | 21.0 | 22.0 | 22.0 | 21.1 | 20.9 |
| Field galaxy in median sky brightness - MagAB - 2.2" ap. | 22.1 | 22.3 | 21.9 | 21.8 | 20.2 | 20.3 | 21.3 | 21.3 | 20.4 | 20.2 |
| Conversion from AB to Vega magnitude system (mag) | -0.66 | -0.96 | -1.40 | -1.99 | -0.69 | -0.87 | -1.35 | -1.47 | -1.97 | -2.08 |

(10 sigma detection in a 1 hour exposure under 0.7 arcsecond seeing with 1.5 airmass)

From WIRCAM ETC (DIET) :
http://rpm.cfht.hawaii.edu/~wircam/diet/DIET.rpm
http://www.cfht.hawaii.edu/Instruments/Imaging/WIRCam/dietWIRCam.html#P0

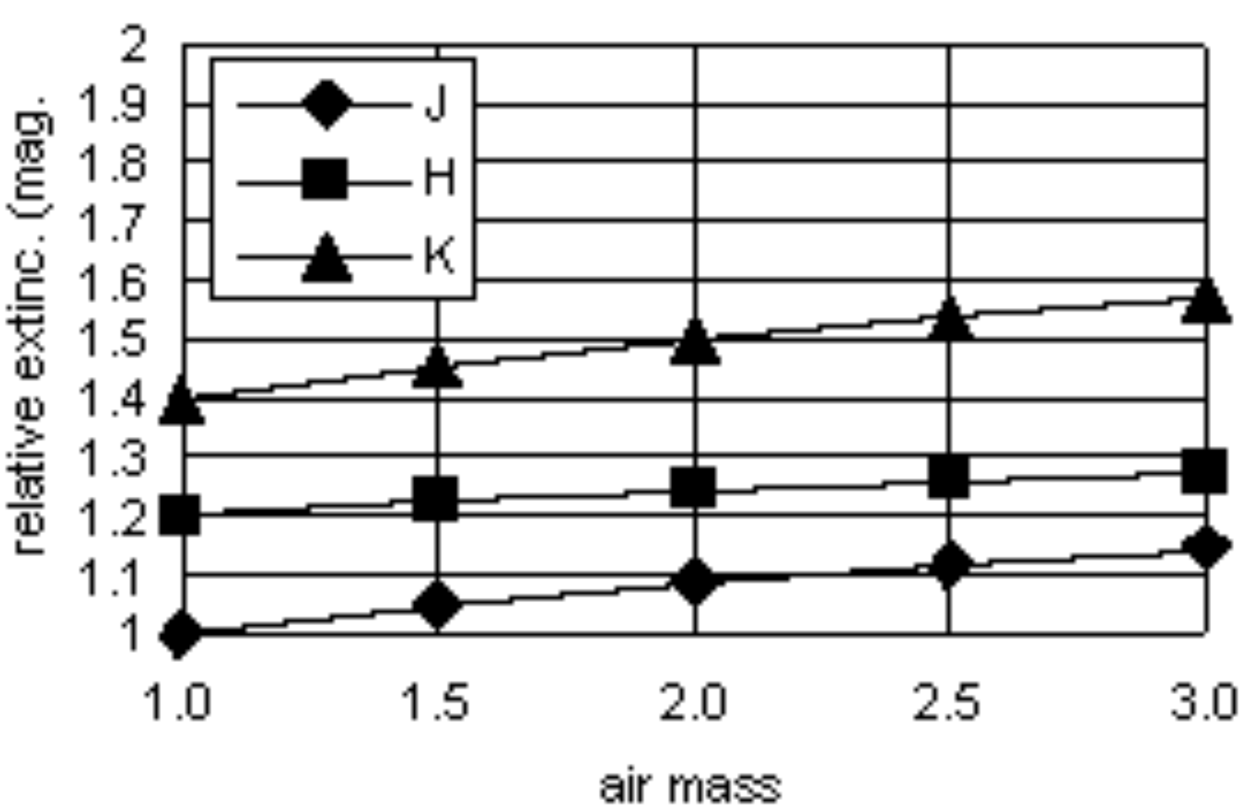
# From under to above the atmosphere

Atmospheric extinction
can be very high in the visible ...




... and much lower in the infrared

From the Redeye manual
(CFHT)
**ΔJ**, or **ΔH**, or **ΔK**
are < 0.1 mag /airmass



# Space based IR imaging

(from Bessel, 2005, ARAA, 43, 293)

IRAS : 12, 25, 60 & 100 μm bands (0.5’ - 12’ resolution)

Cohen et al., 1992, *Spectral irradiance calibration in the infrared. I - Ground-based and IRAS broadband calibrations*, AJ 104, 1650

ISO : map selected areas. ISOCam : 2.5 - 5.2 μm & 4-18 μm.

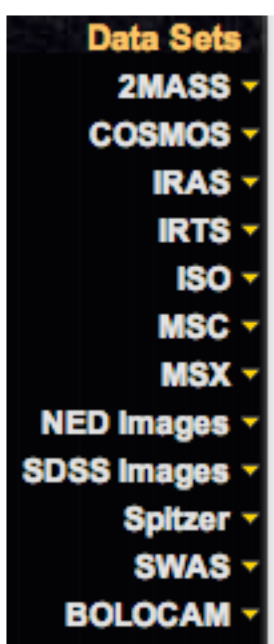
Kessler, 2001, ESA-SP, 460, 53

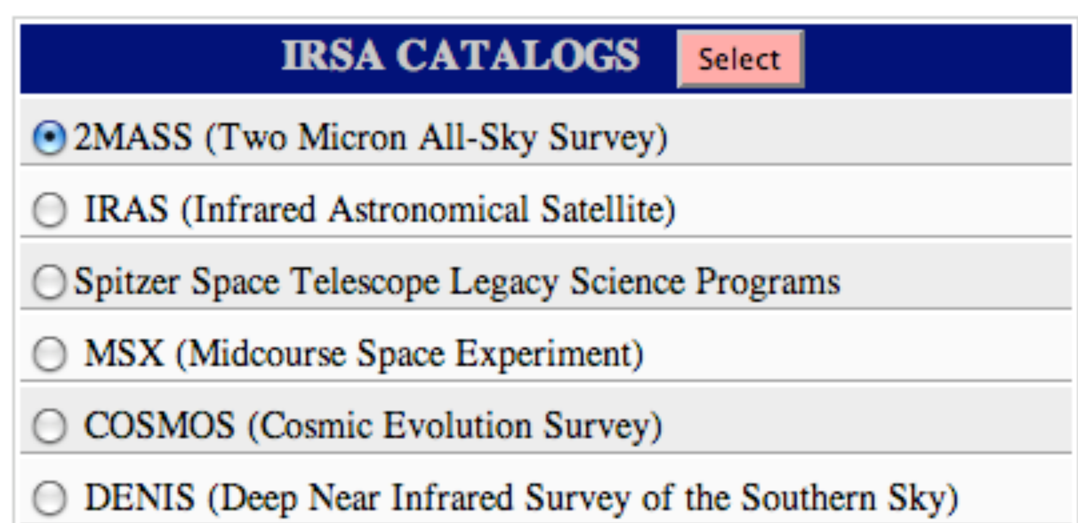
Spizter : IRAC (3.6, 4.5, 5.8 & 8 μm bands)

MIPS (24, 70 & 160 μm bands)

NASA/IPAC Infrared Science Archive (IRSA)

http://irsa.ipac.caltech.edu/applications/Gator/



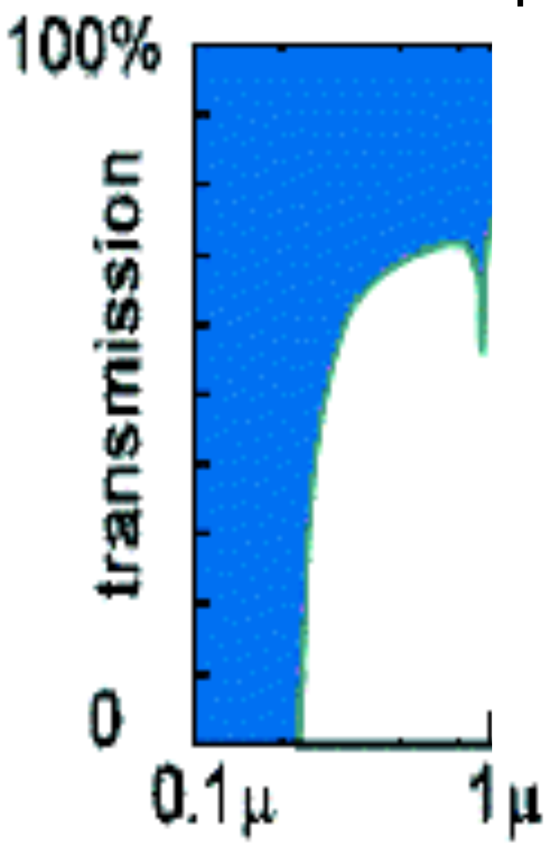


# Atmospheric windows and imaging filters

Laboratoire d'AstroPhysique de Grenoble

**Ground based Imaging in the infrared : where do we start from ?**

- the atmosphere is “uniformly” transparent from 0.3$\mu$m to 1$\mu$m.
- A set of filters has been (freely) designed (U, B, V, R, I, z)
- Large detectors (or bootable) exist
- Use of spatial facilities (HST) more for the UV than for the visible.



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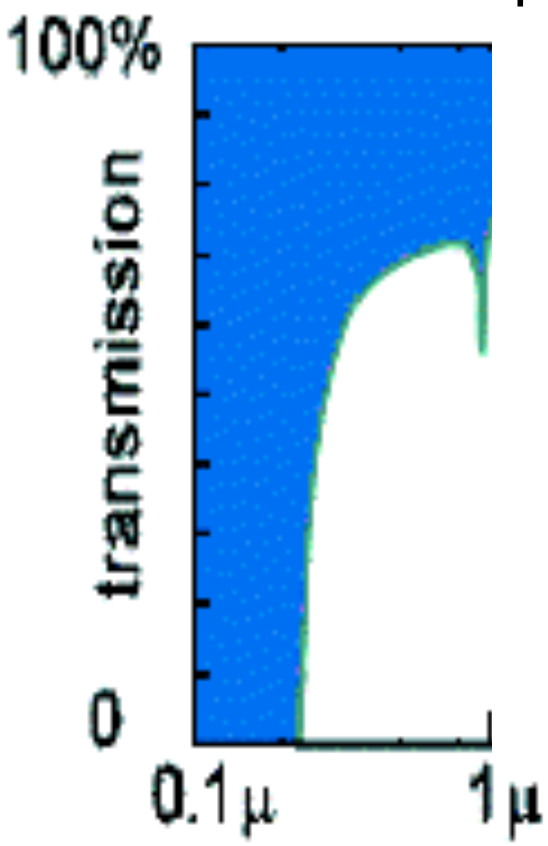


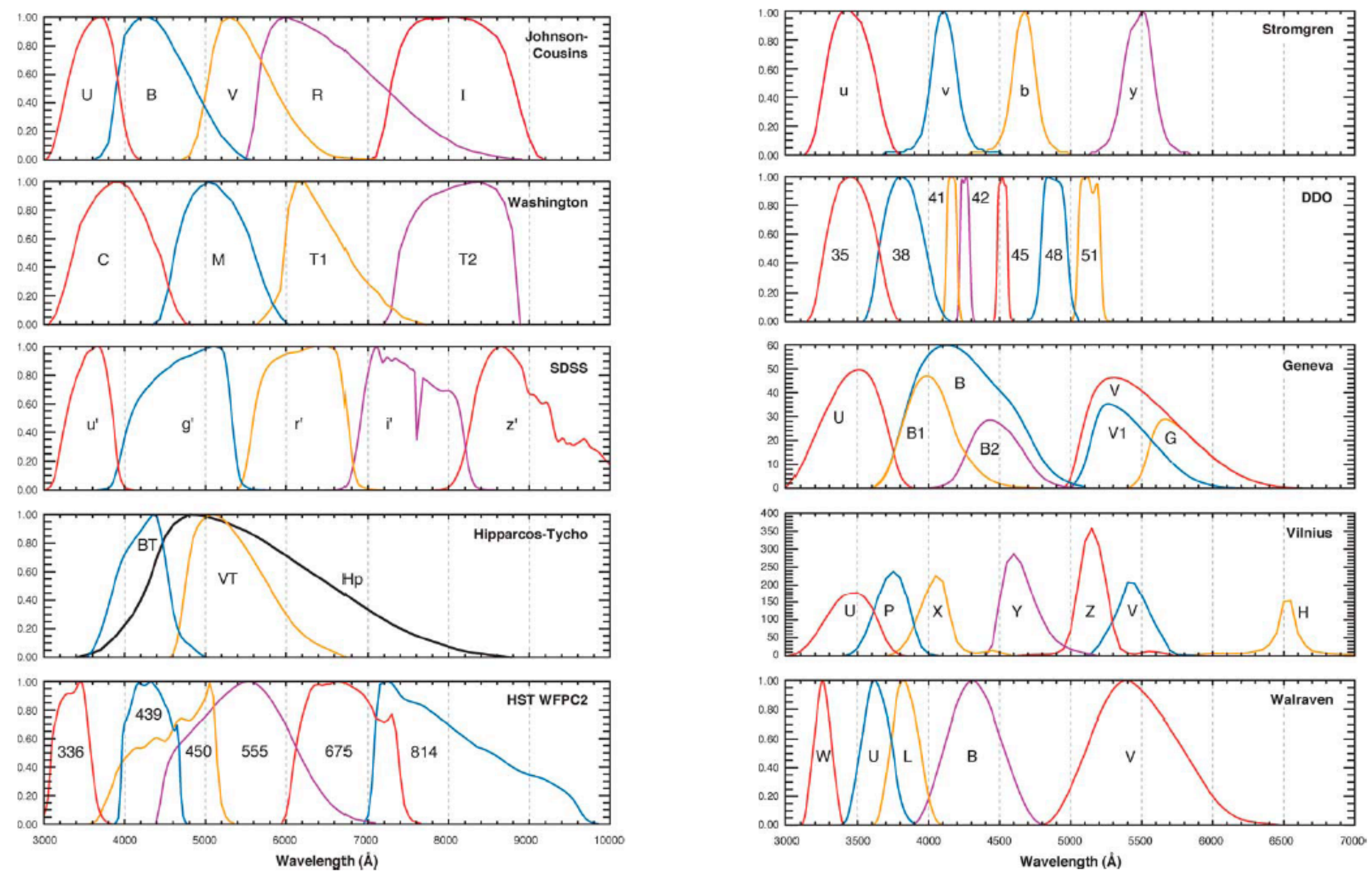


Bessel, 2005

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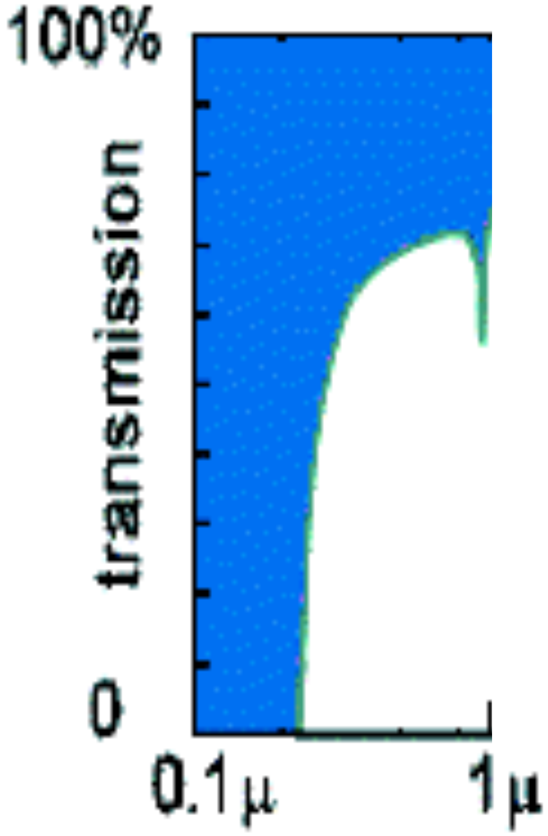
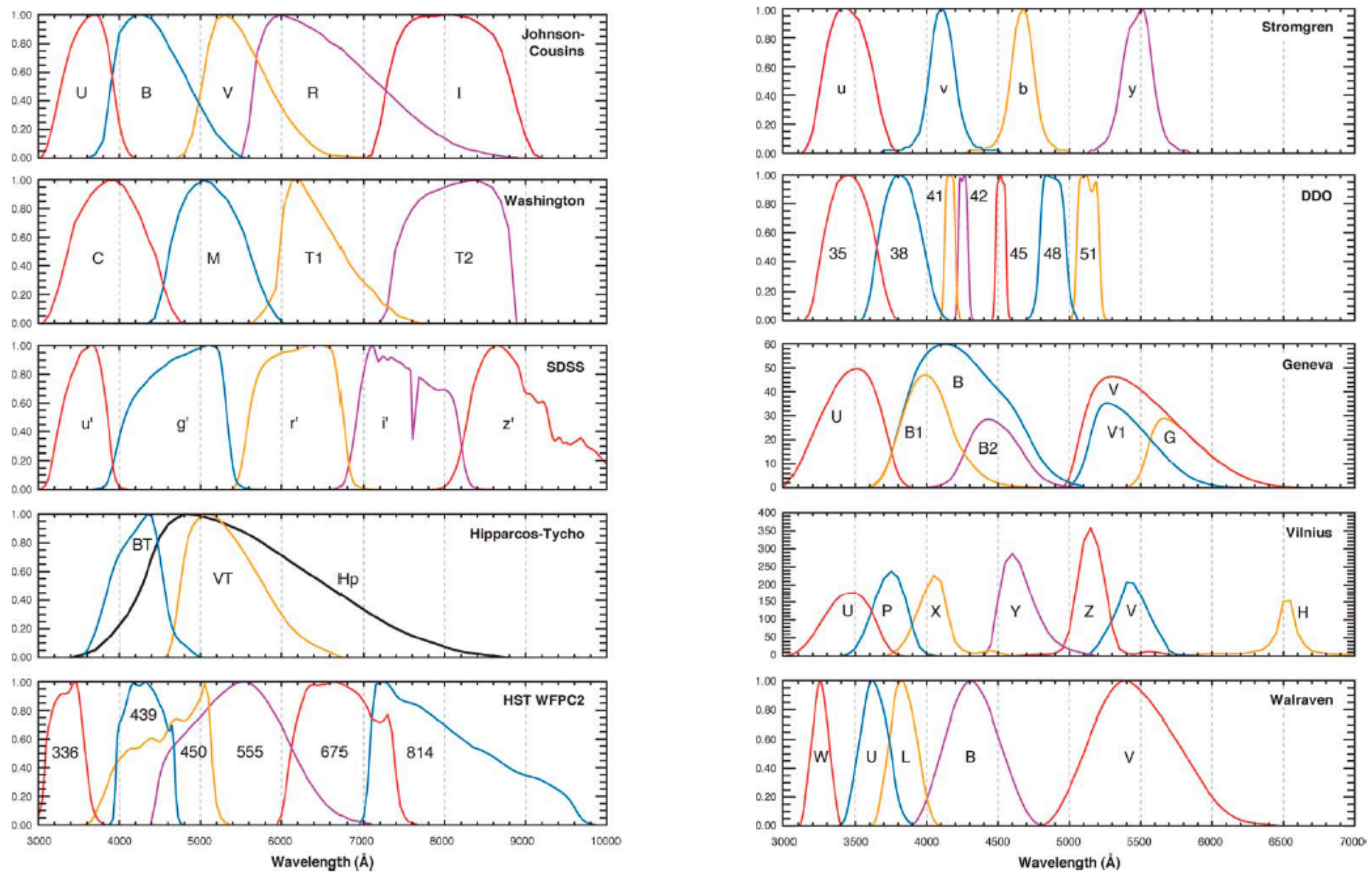
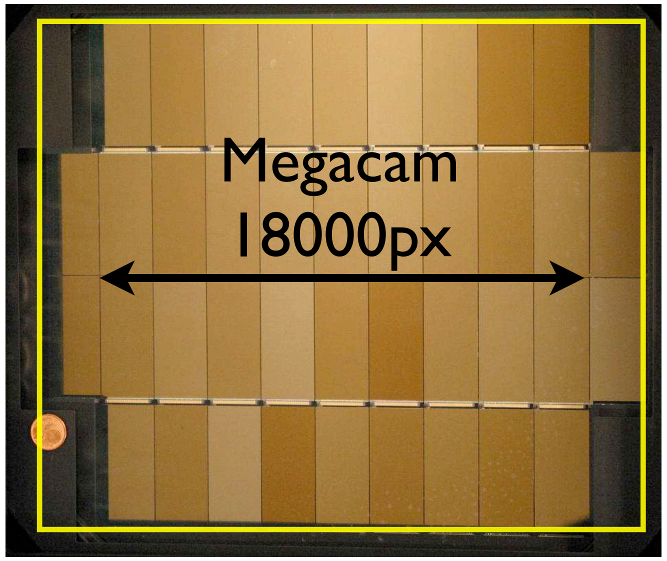



Bessel, 2005

CFHT



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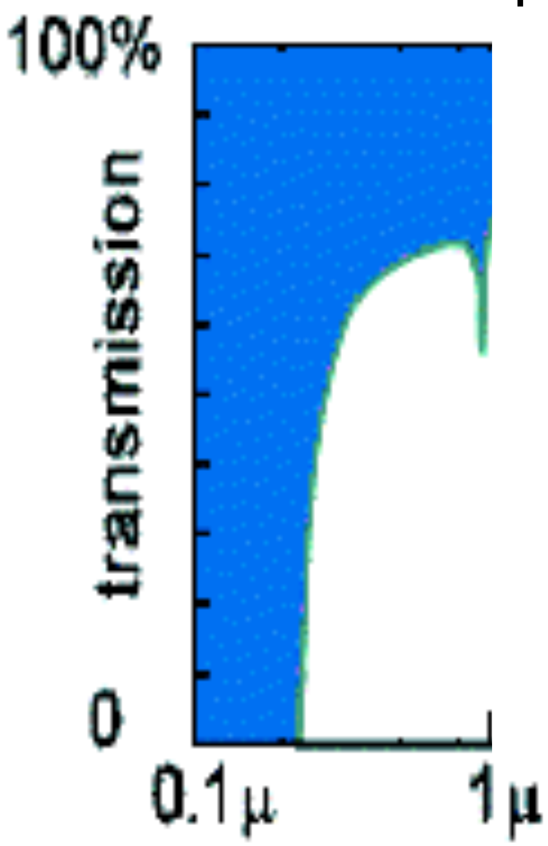


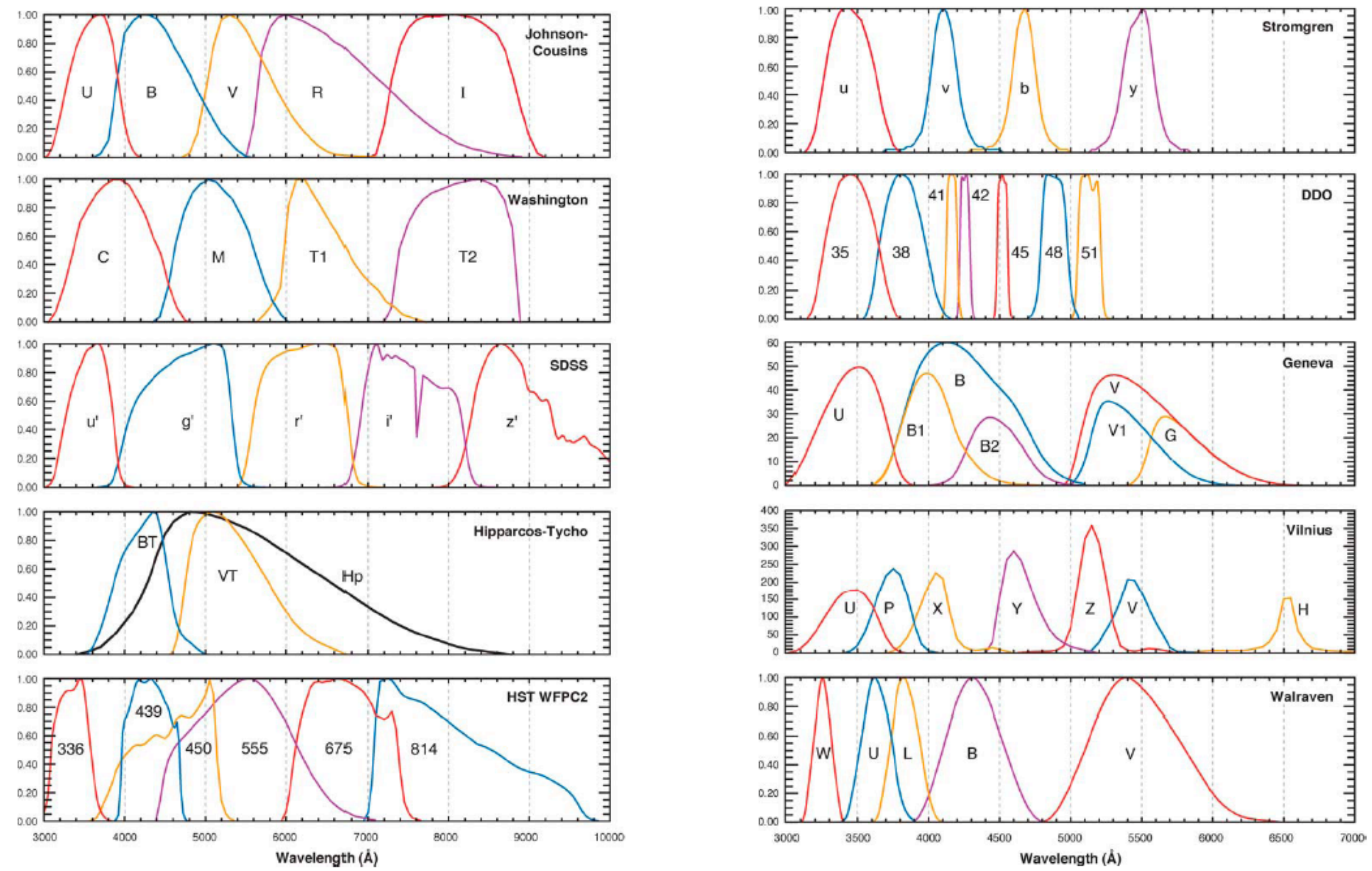


Bessel, 2005

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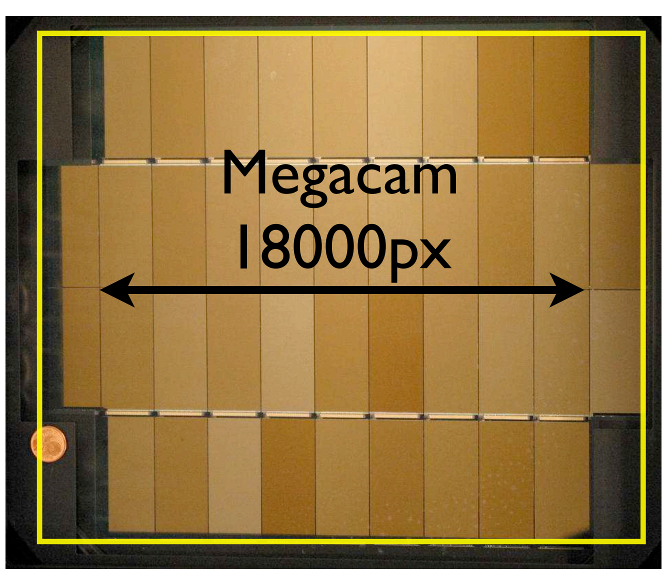
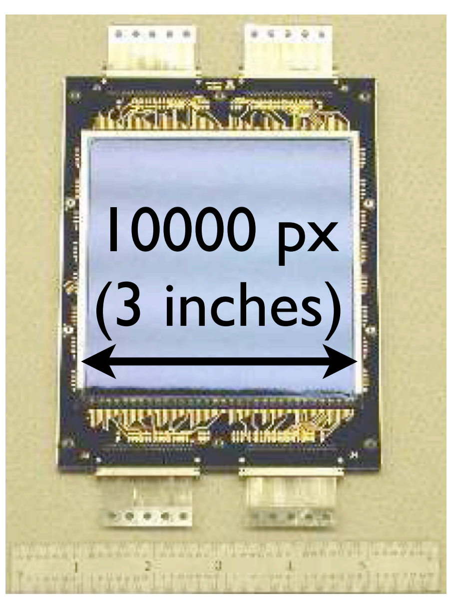
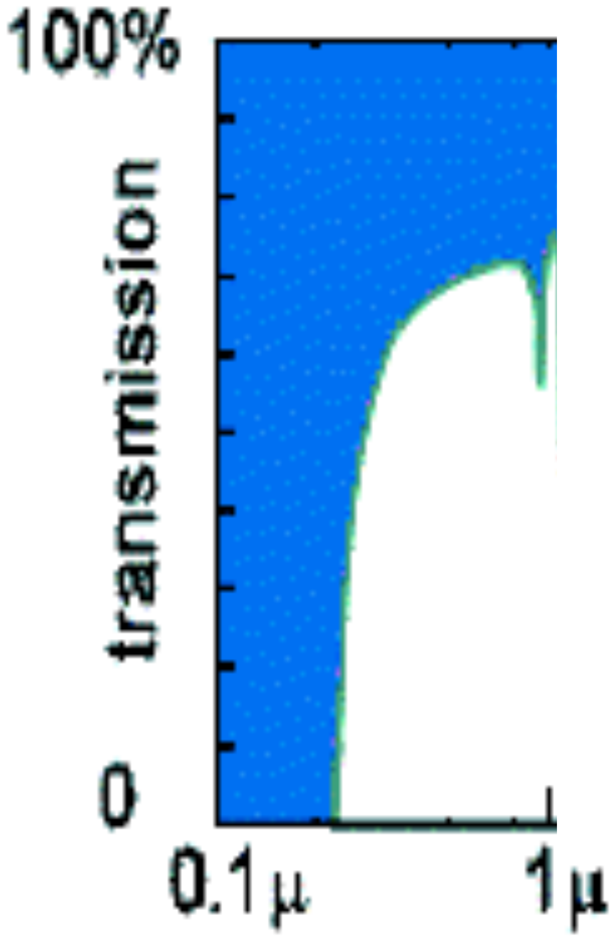



Zacharias et al., 2007, SPIE, 6690

**Ground based Imaging in the infrared : where do we go ?**

- The atmosphere has transparent windows up to 20 microns, with significant opaque gaps.
- One is not free to choose the filters outside of the transparent windows
- Smaller detectors available




(JWST)

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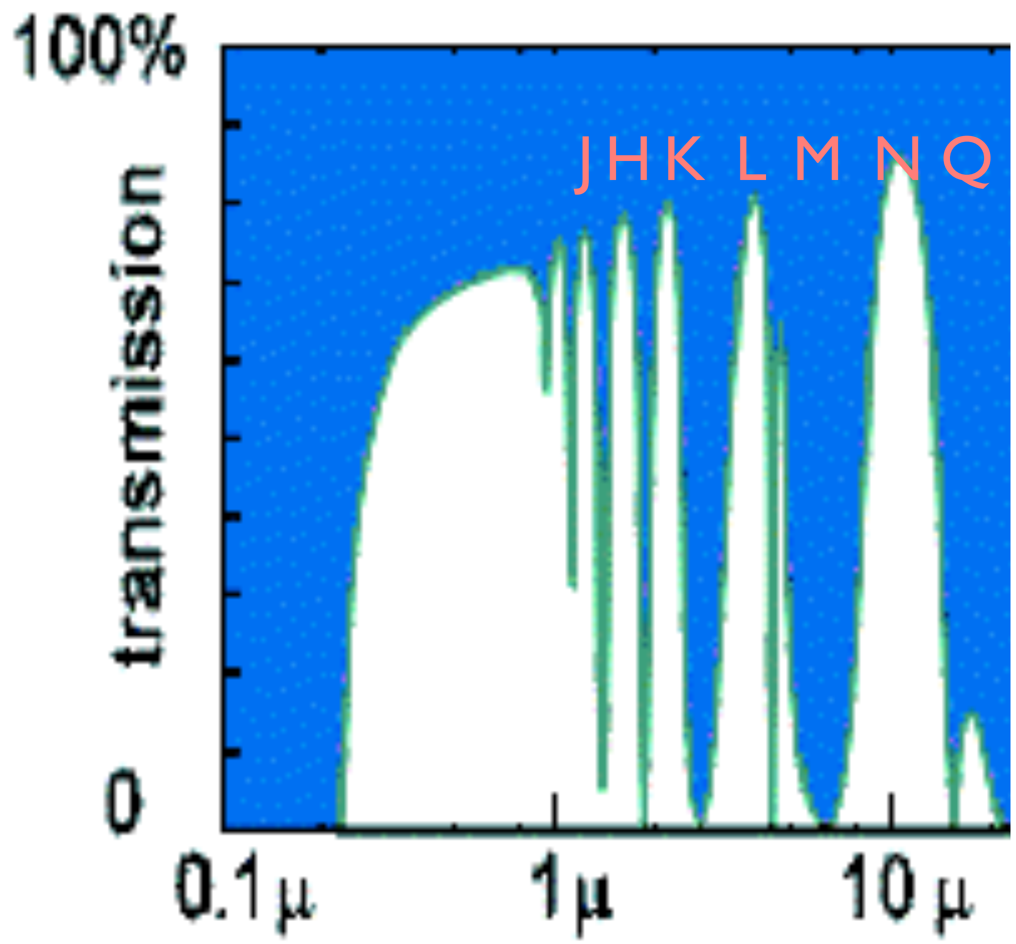


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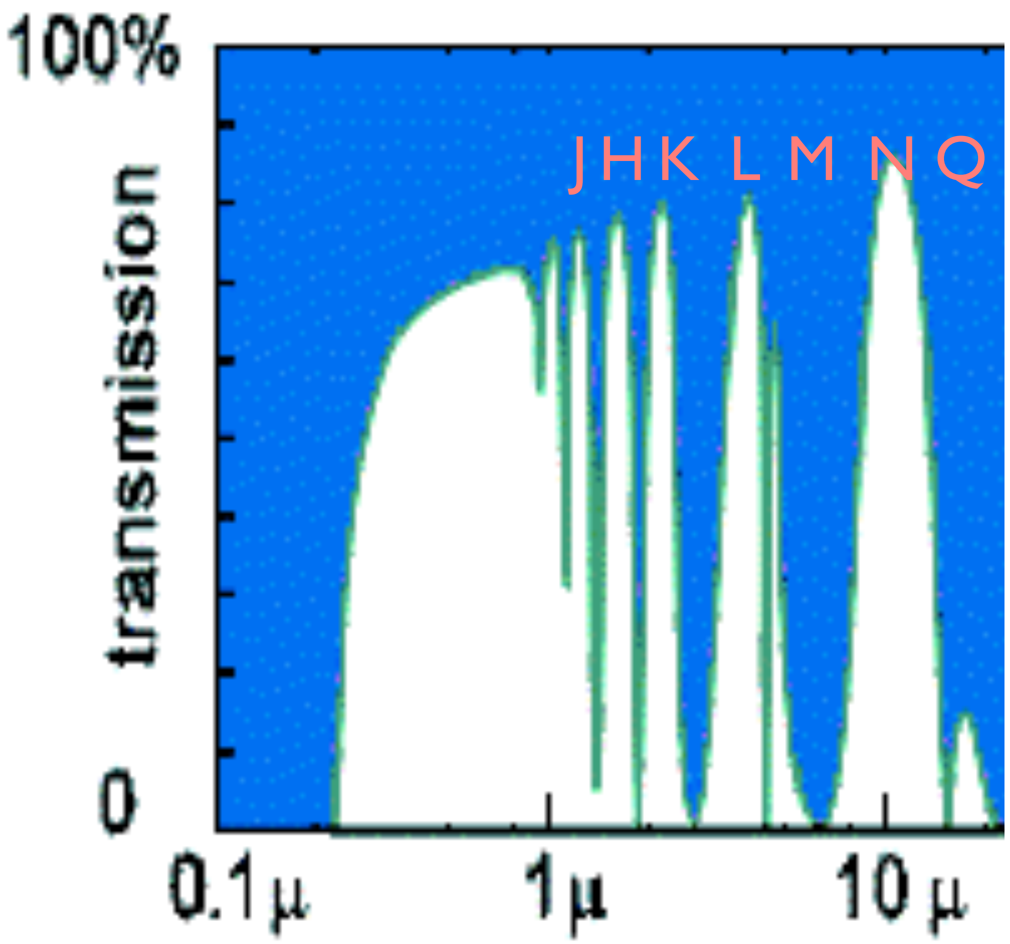


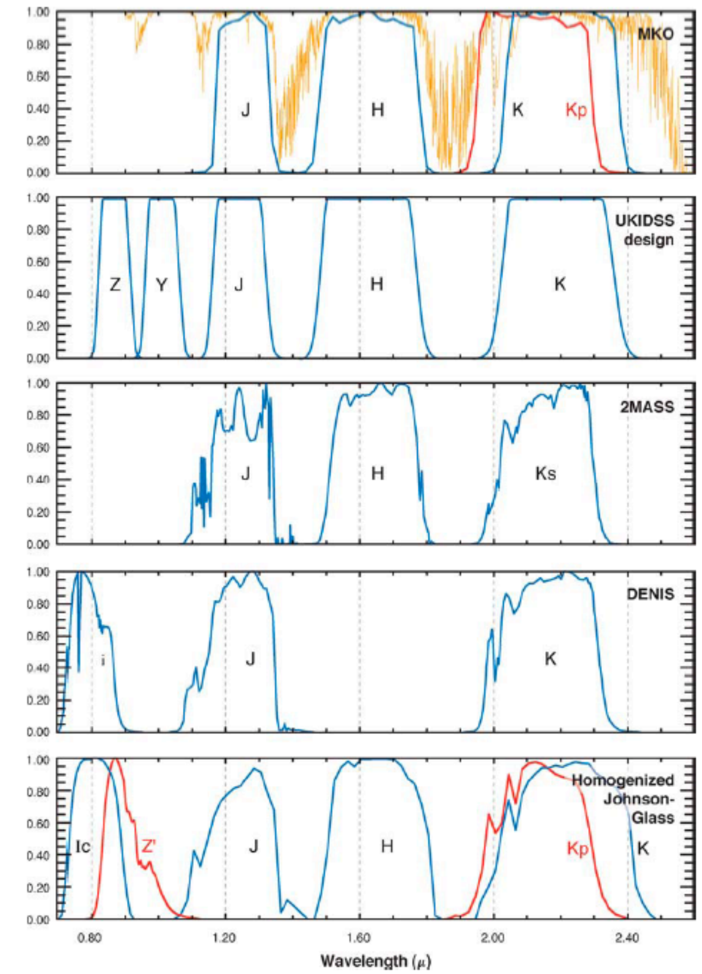


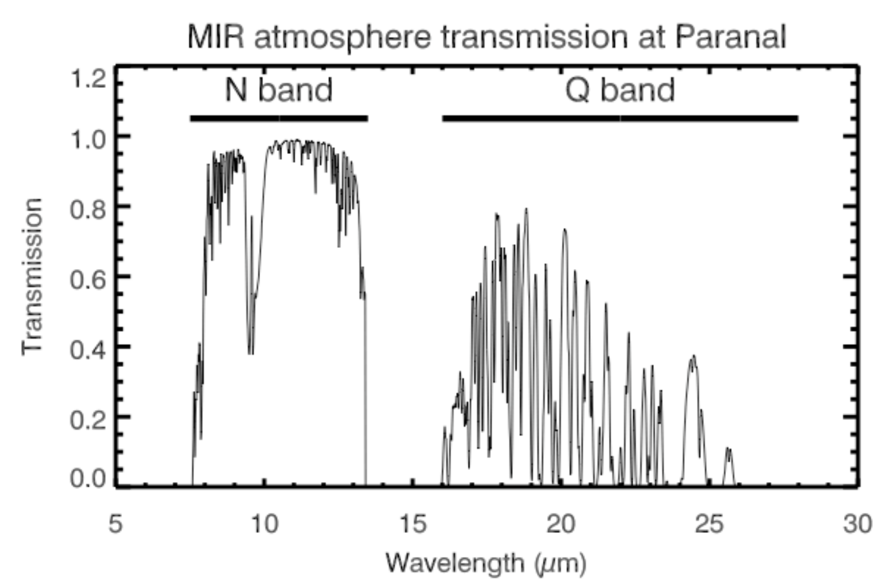


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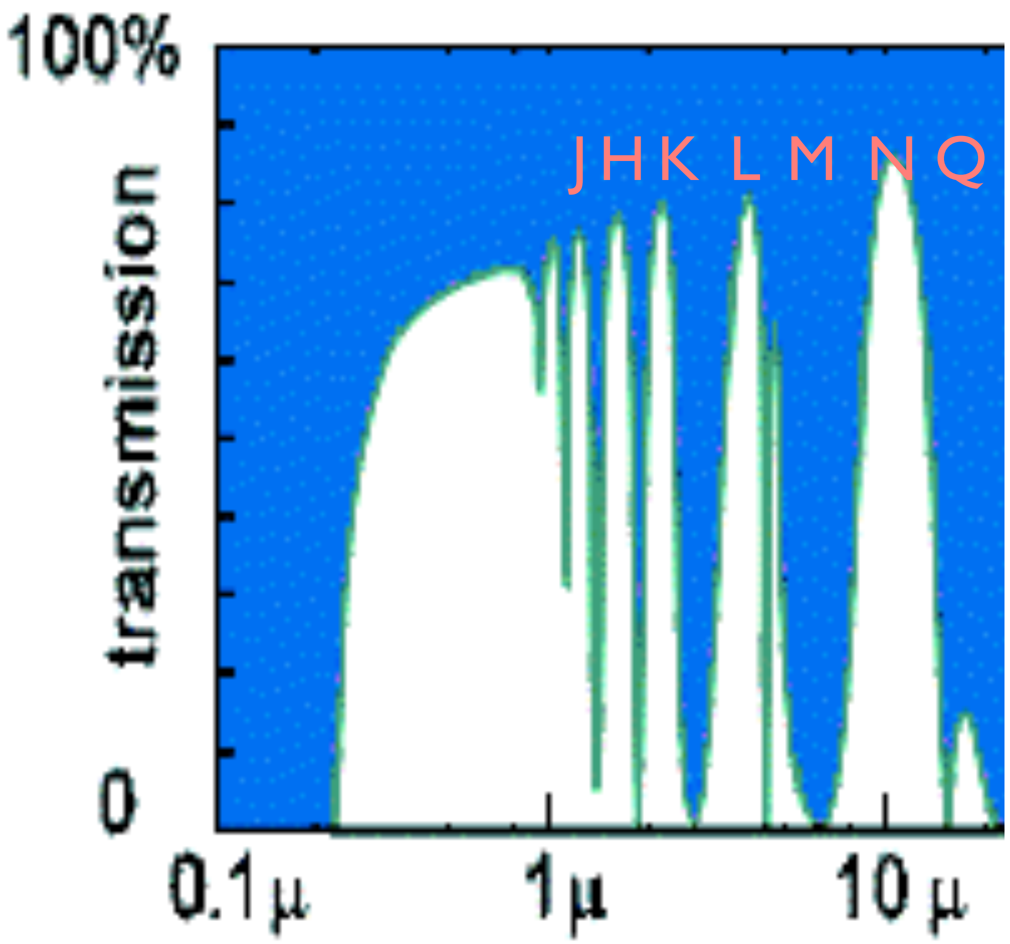
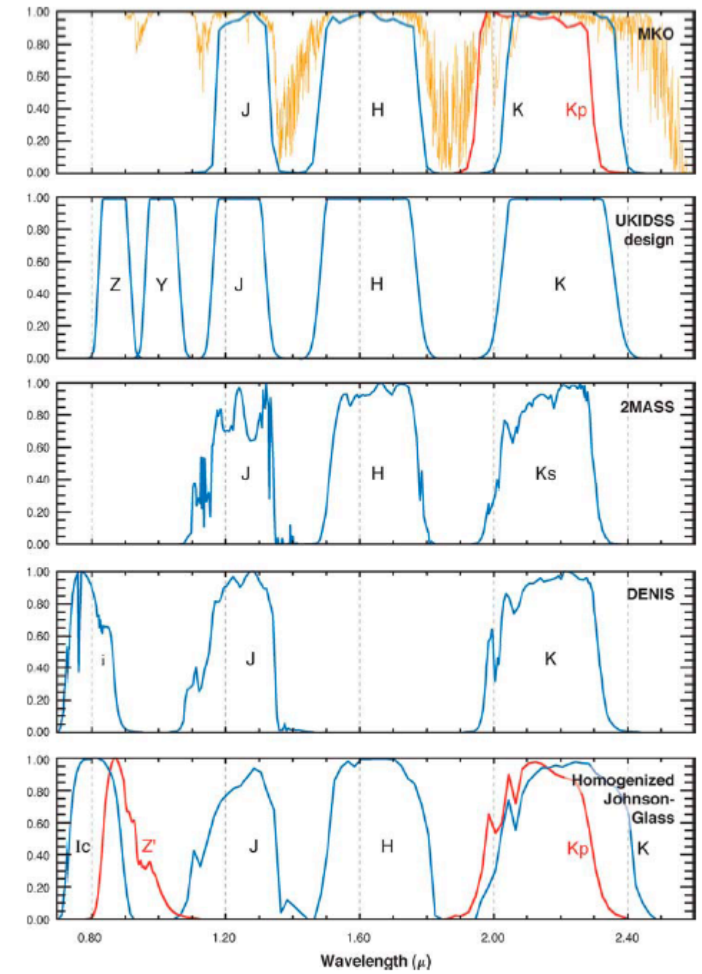
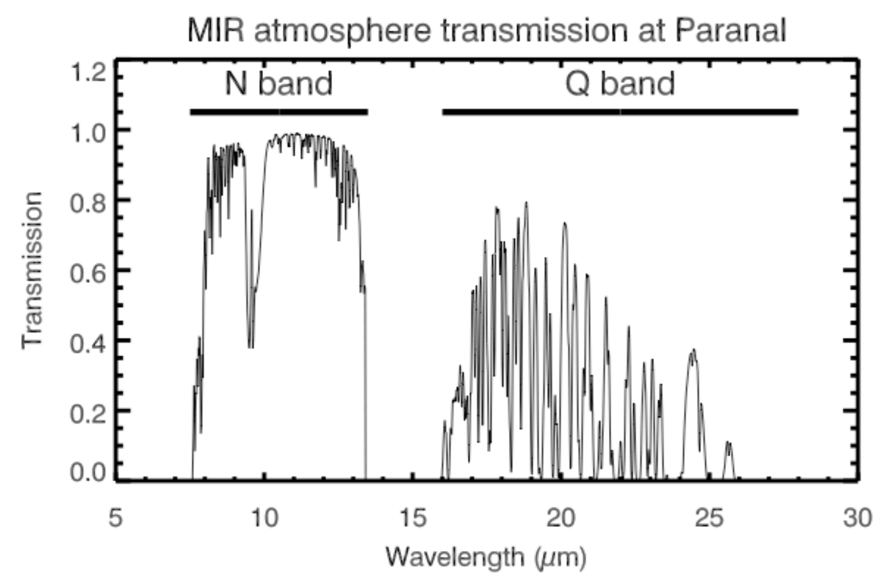
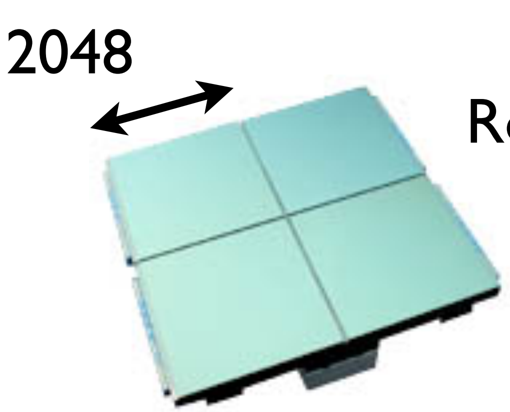


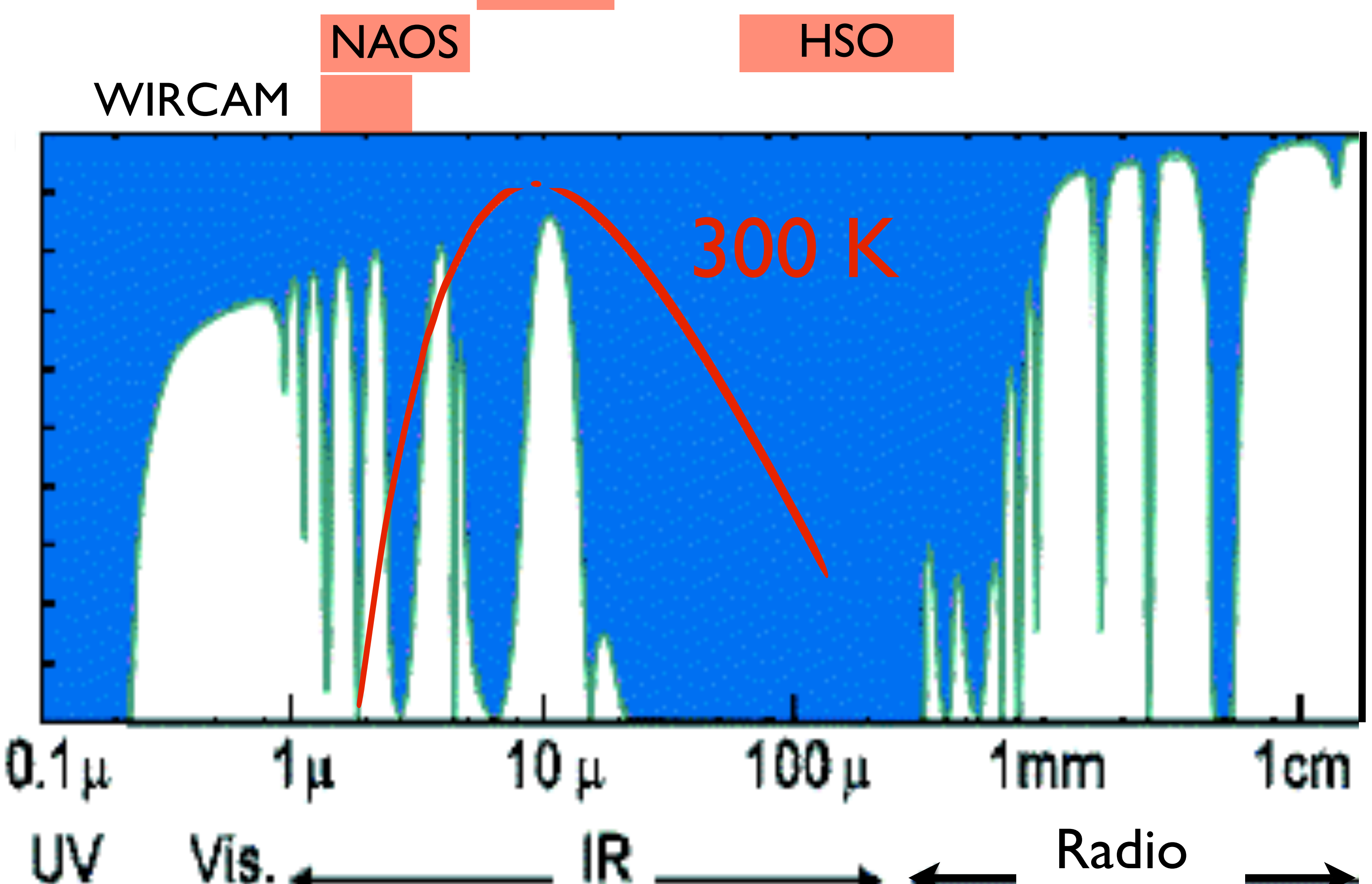

HAWAII-2RG
Rockwell (Teledyne) detector

(JWST)

http://www.teledyne-si.com/infrared_visible_fpas/index.html

# From ground-based to Spatial imaging

- Longward of 2$\mu$m : the atmosphere begins to "glow"
- Huge opaque "wall" exist between 20 and 500$\mu$m
- (note : Upward 300$\mu$m -> *sub-millimeter*)




VLT

IRAM


UKIRT

K

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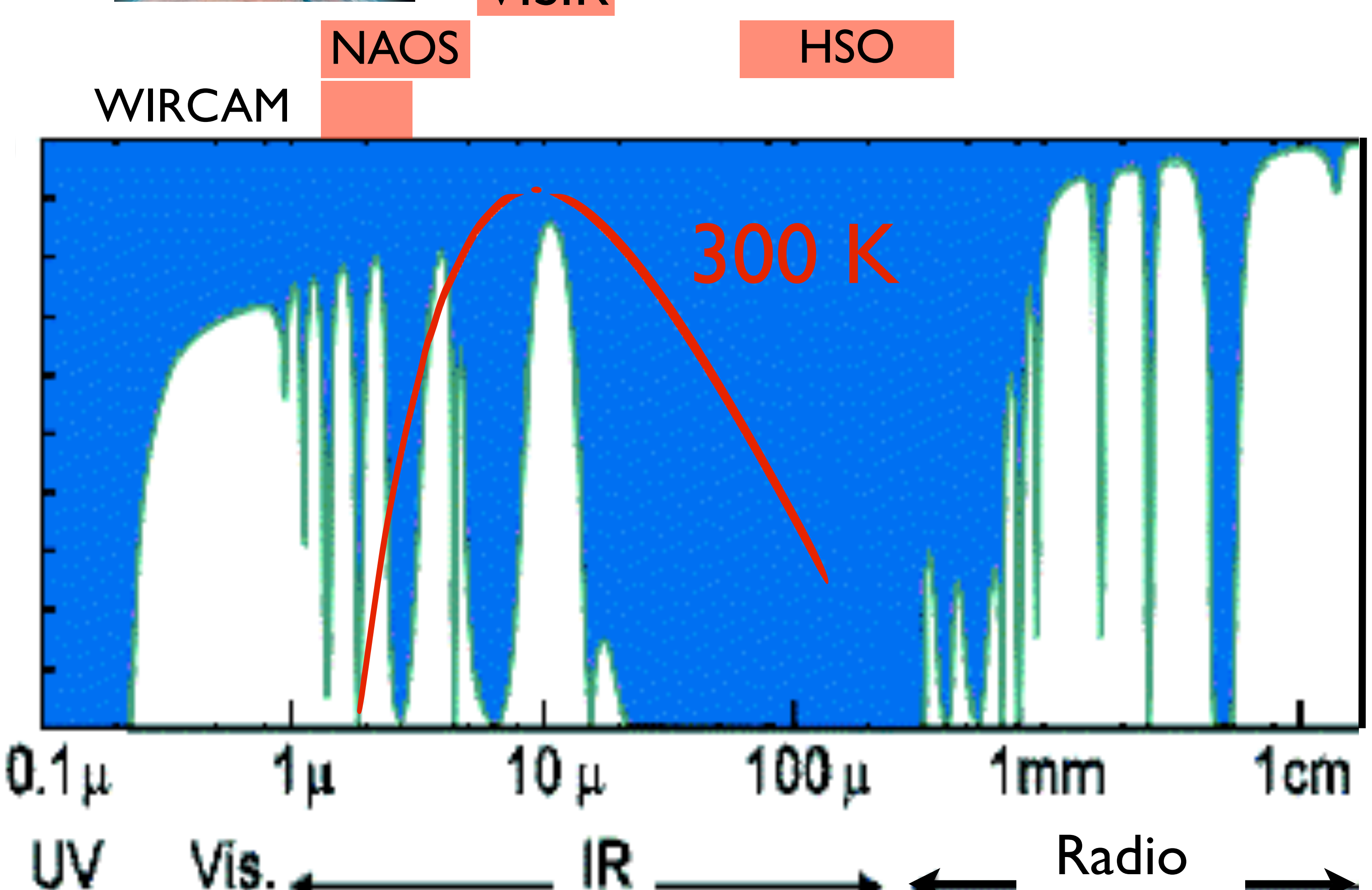


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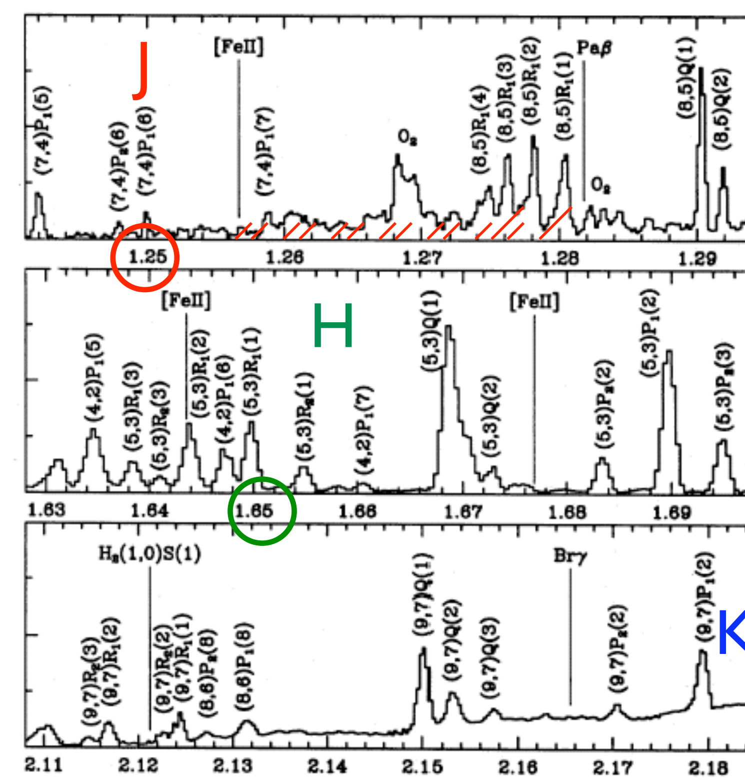
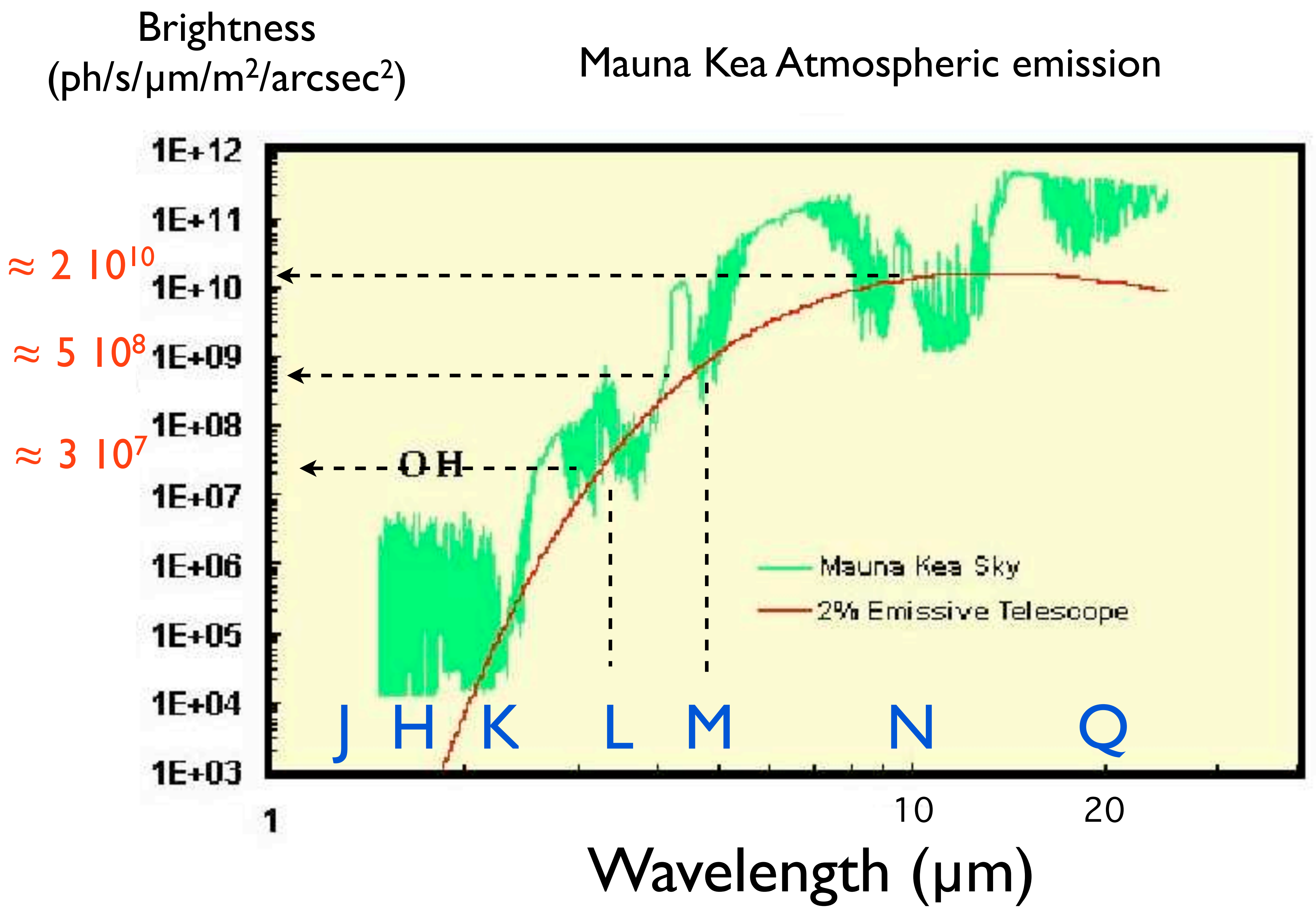



Oliva and Origlia (1992), A&A 254, 466

# Looking through the atmosphere : transmission AND emission

Mauna Kea Atmospheric emission




(cf. Roche, 2003, ASR 34, 583)

## La Silla

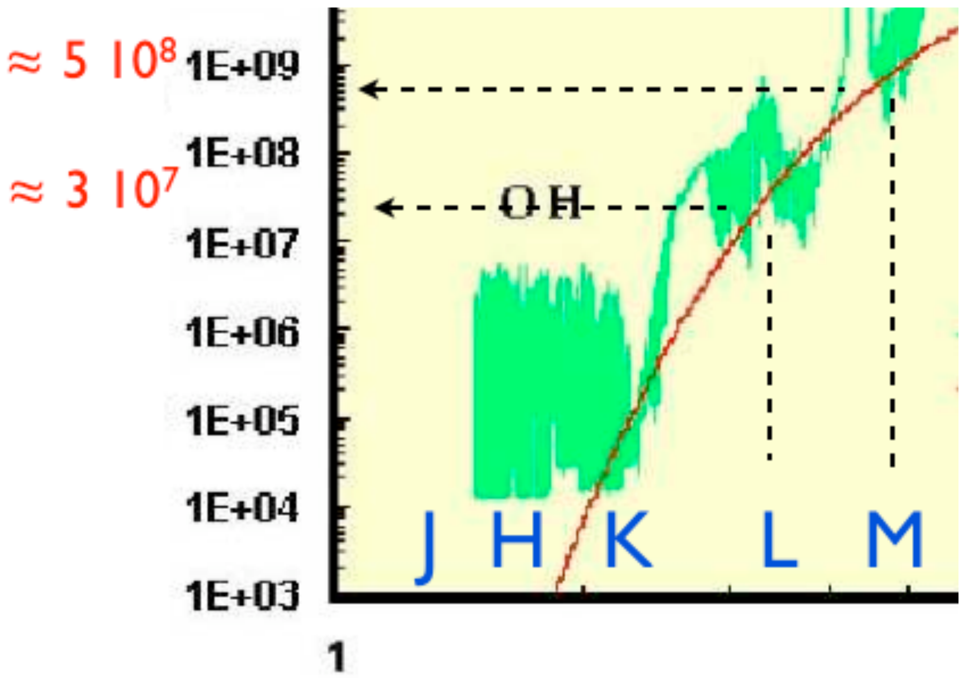
| Band | Mag/"2 |
|---|---|
| U | 22 |
| B | 23 |
| V | 22 |
| R | 21 |
| I | 20 |
| J | 15.2 |
| H | 13.6 |
| $K_S$ | 12.7 |
| K | 12.3 |
| L | 4.3 |
| M | 0.2 |
| N | -6.4 |
| Q | -8.5 |

(Vega mag)

$$I(\tau) = I_o e^{-\tau_{atm}} + B(1 - e^{-\tau_{atm}})$$

# Background photons from sky magnitude/arcsec$^2$ : La Silla vs. Mauna Kea

| | |
|---|---|
| L | 4.3 |
| M | 0.2 |




**L band** ; $\lambda = 3.5\,\mu\text{m}$ ; $h\nu = hc/\lambda = 5.7\,10^{-20}$ J
La Silla brightness : 4.3 mag/arcsec$^2$.
From Bessel et al., 1998 :

$$m = 0 \rightarrow f_\lambda = 0.708\,10^{-11}\,\text{erg/s/cm}^2/\AA = 0.708\,10^{-10}\,W/\text{m}^2/\mu\text{m} \quad (1)$$

$$m = 0 \rightarrow N^o_\lambda = 1.2\,10^9\,\text{ph/s/m}^2/\mu\text{m} \quad (2)$$

$$m = 4.3 \rightarrow N^m_\lambda = 10^{-4.3/2.5} \times 1.2\,10^9 = 3\,10^7\,\text{ph/s/m}^2/\mu\text{m} \quad (3)$$

**M band** ; $\lambda = 4.8\,\mu\text{m}$ ; $h\nu = hc/\lambda = 4.1\,10^{-20}$ J
La Silla brightness : 4.3 mag/arcsec$^2$.
From Bessel et al., 1998 :

$$m = 0 \rightarrow f_\lambda = 0.20\,10^{-11}\,\text{erg/s/cm}^2/\AA = 0.20\,10^{-10}\,W/\text{m}^2/\mu\text{m} \quad (4)$$

$$m = 0 \rightarrow N^o_\lambda = 4.8\,10^8\,\text{ph/s/m}^2/\mu\text{m} \quad (5)$$

$$m = 0.2 \rightarrow N^m_\lambda = 10^{-0.2/2.5} \times 4.8\,10^8 = 4\,10^8\,\text{ph/s/m}^2/\mu\text{m} \quad (6)$$

# Comparing source photons with background photons

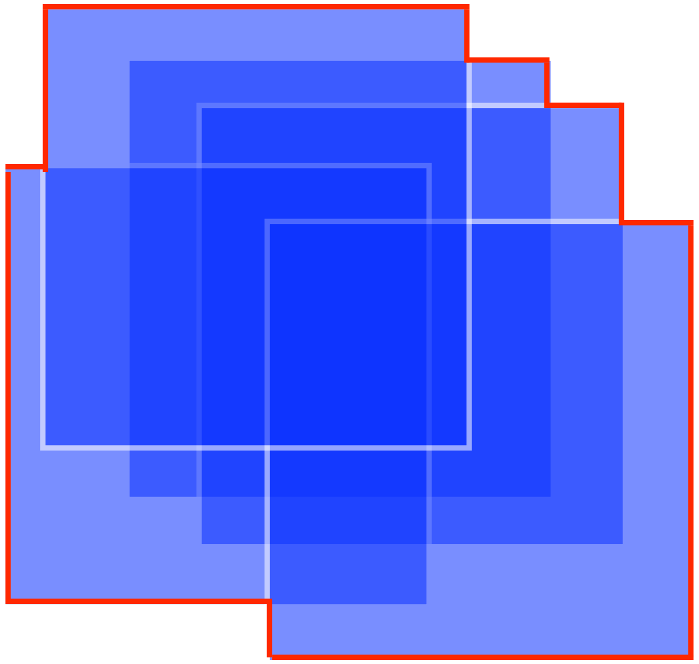
| Band | Mag/"2 |
|---|---|
| U | 22 |
| B | 23 |
| V | 22 |
| R | 21 |
| I | 20 |
| J | 15.2 |
| H | 13.6 |
| $K_S$ | 12.7 |
| K | 12.3 |
| L | 4.3 |
| M | 0.2 |
| N | -6.4 |
| Q | -8.5 |

This table gives the needed magnitude of a source with a PSF ≈ 1 $arcsec^2$ to provide the same number of photons than the sky background.

This yields a very strong constraint on the observing procedure when sources are faint : Jitter, Chopping & Nodding

# Subtracting (weak) sky emission I :

## Jitter

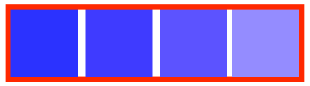


N (odd) frames, α & δ offsets

Median filtering → sky emission

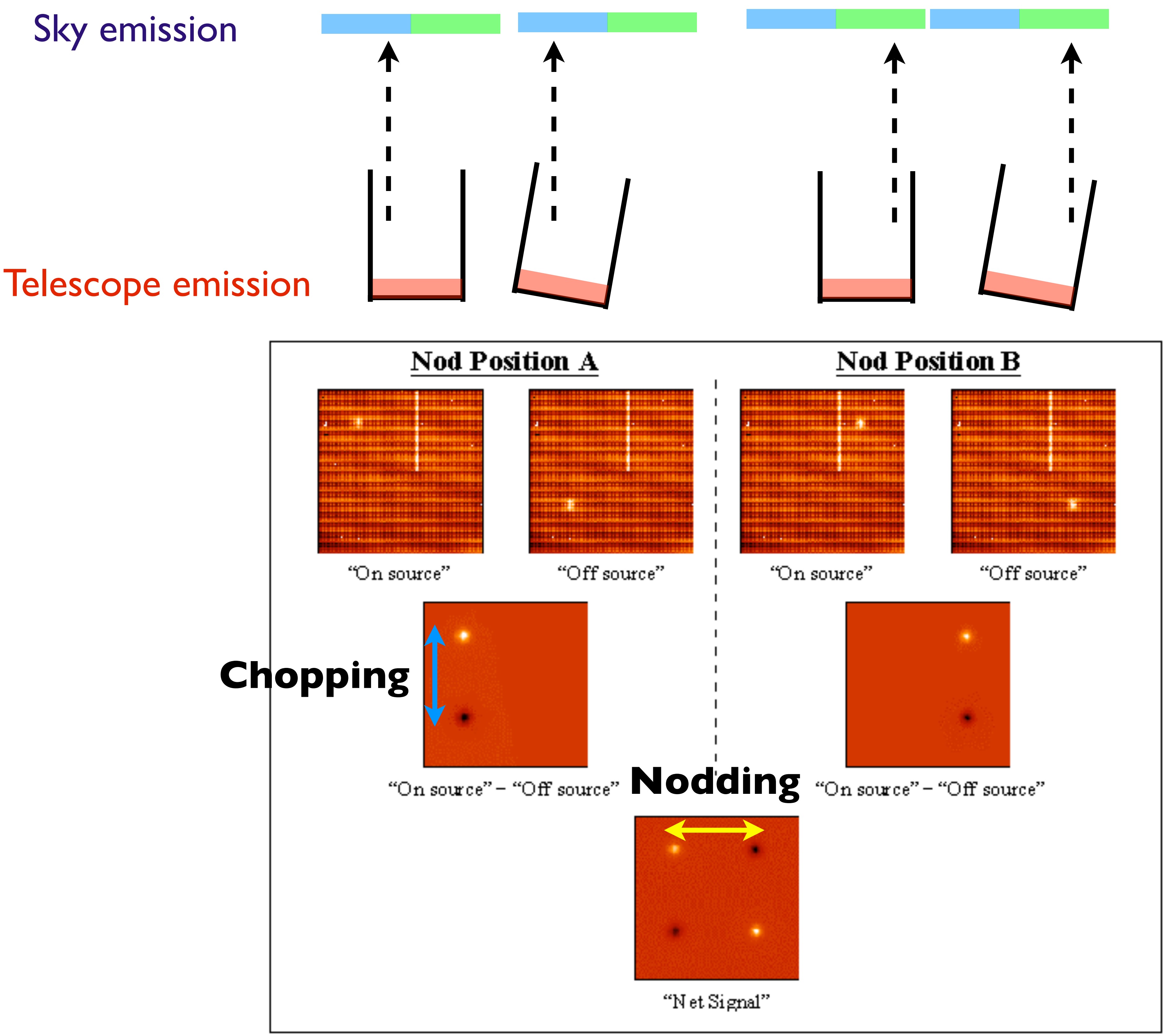
Sky subtraction

! SNR is not uniform across the total field



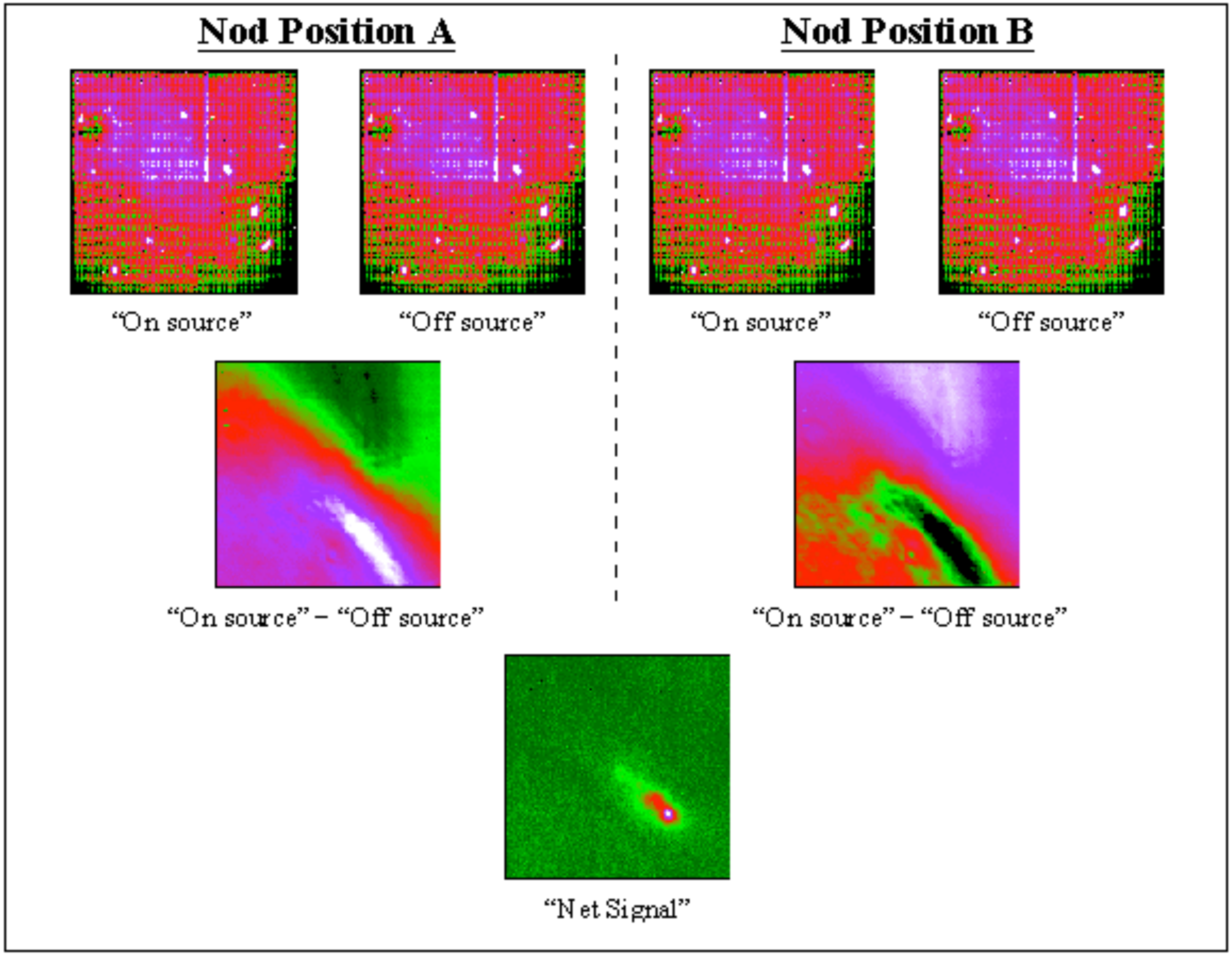
# Subtracting sky (and telescope) strong emission II :

## Chopping and Nodding on a bright source (star)



# Subtracting sky (and telescope) strong emission III :

## Chopping and Nodding on a faint source (galaxie)



# Infrared detectors and imaging Surveys

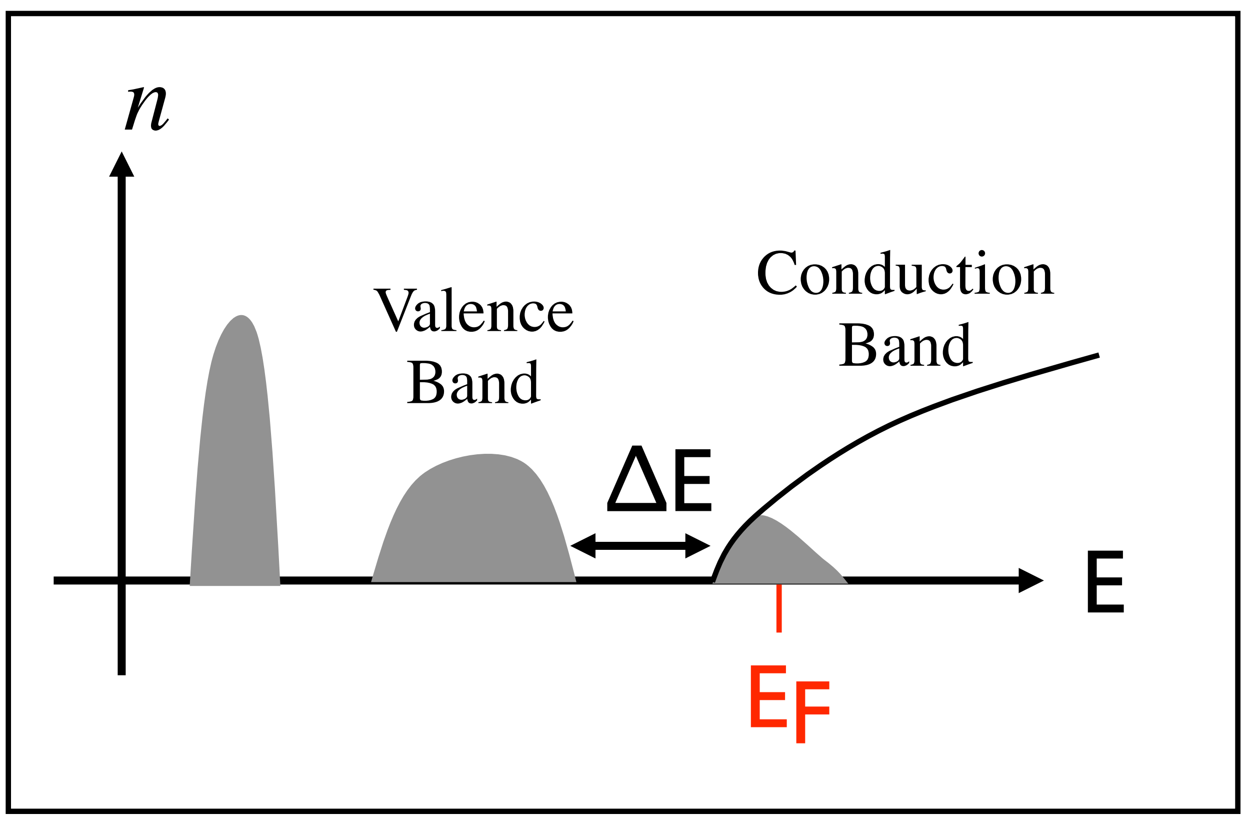
## The basics of detection

Interaction of photons with atoms in a cristal

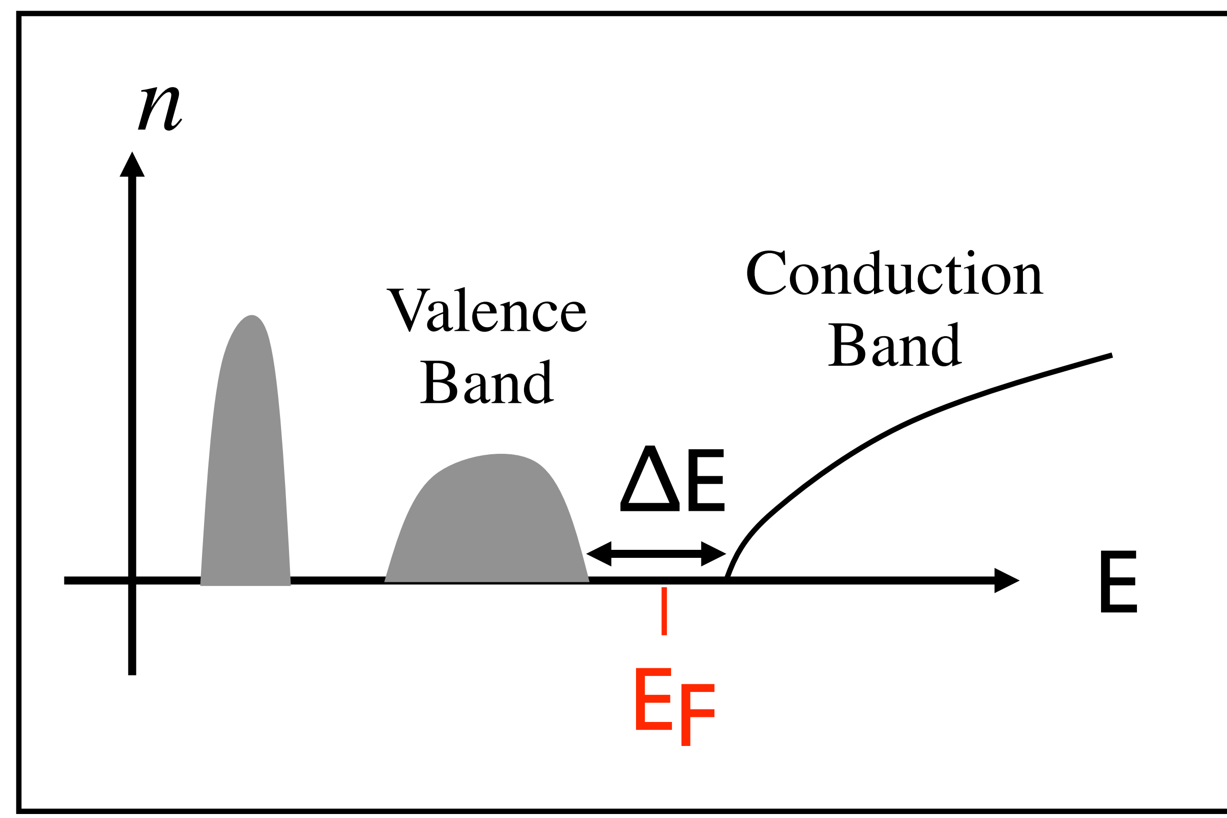
# Photoconductive effect in cristals

Cristal :

• atoms in a periodic network
• Energy levels → Energy bands
• distinction between metals / semi-conductors



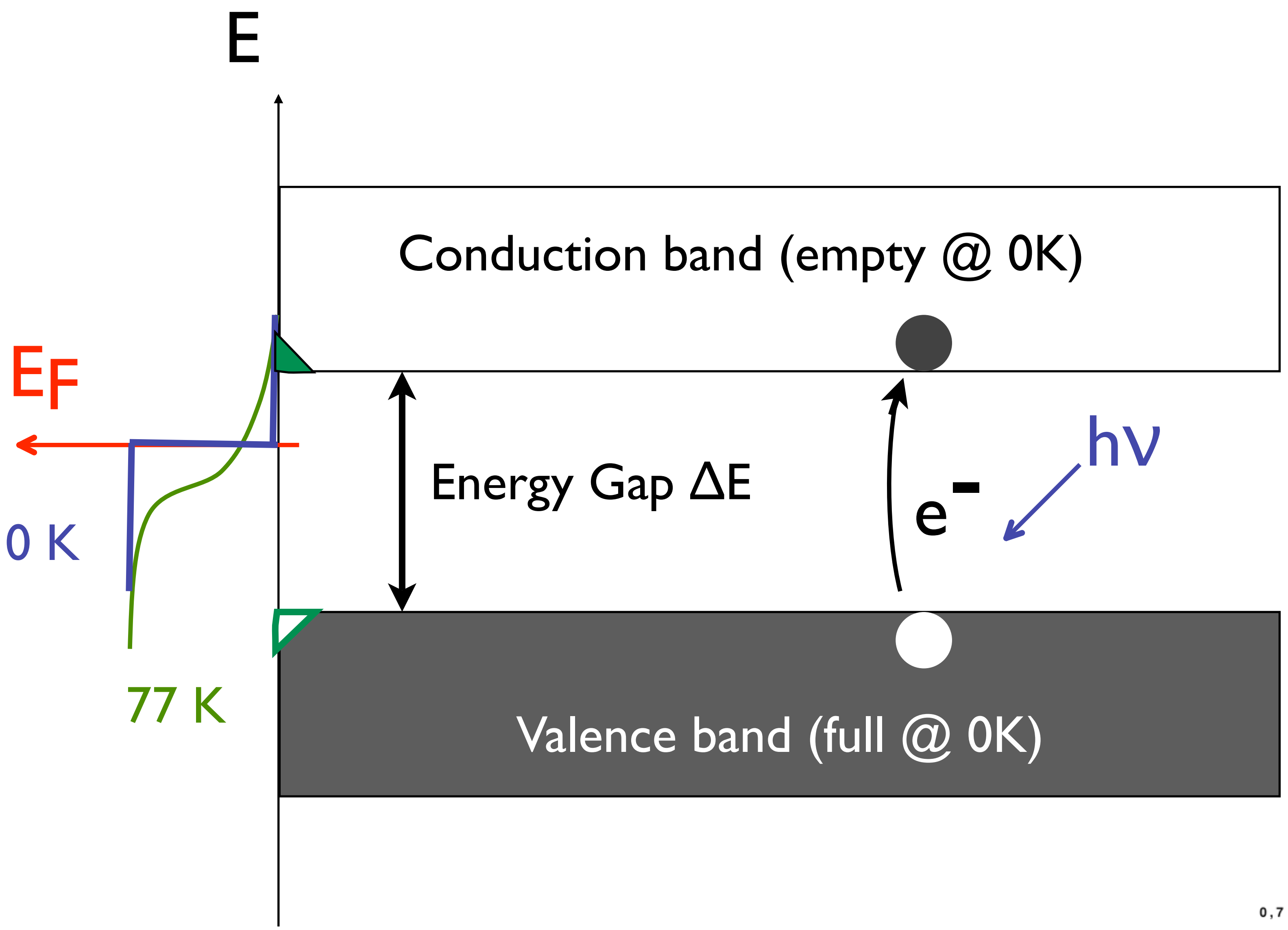

métal : conductor @ 0 K

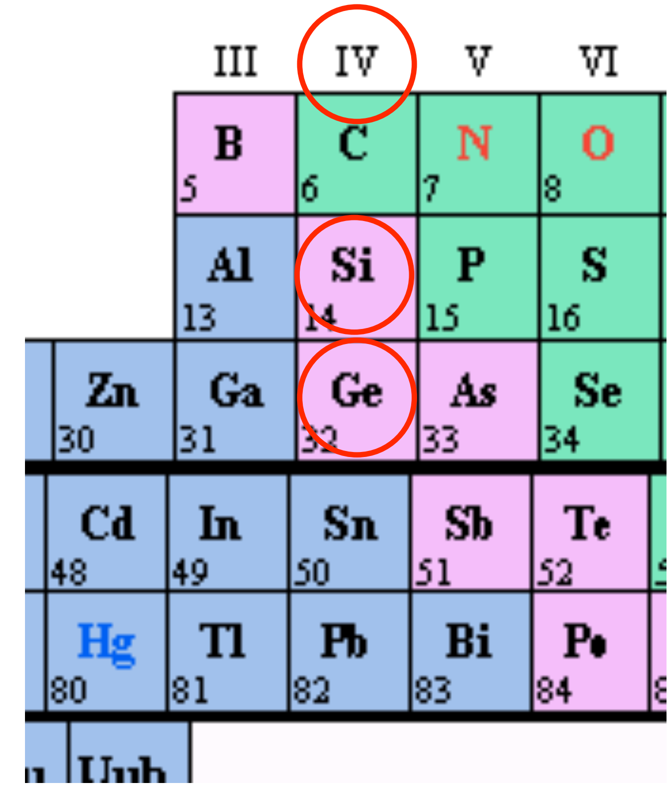



semiconductor : insulator à 0 K

# From Visible to Infrared detection

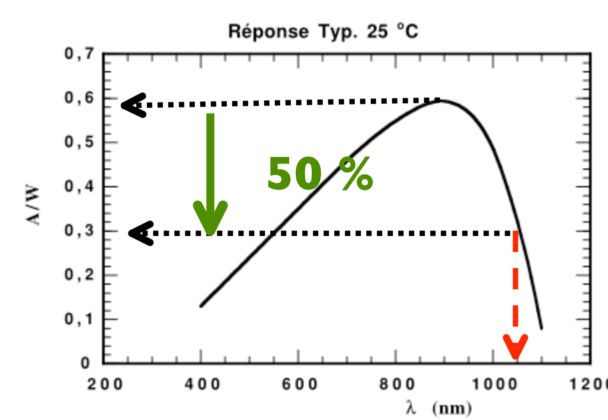
## Photoconductive effect in semiconductors




$$\Delta E = h\nu = \frac{hc}{\lambda}$$

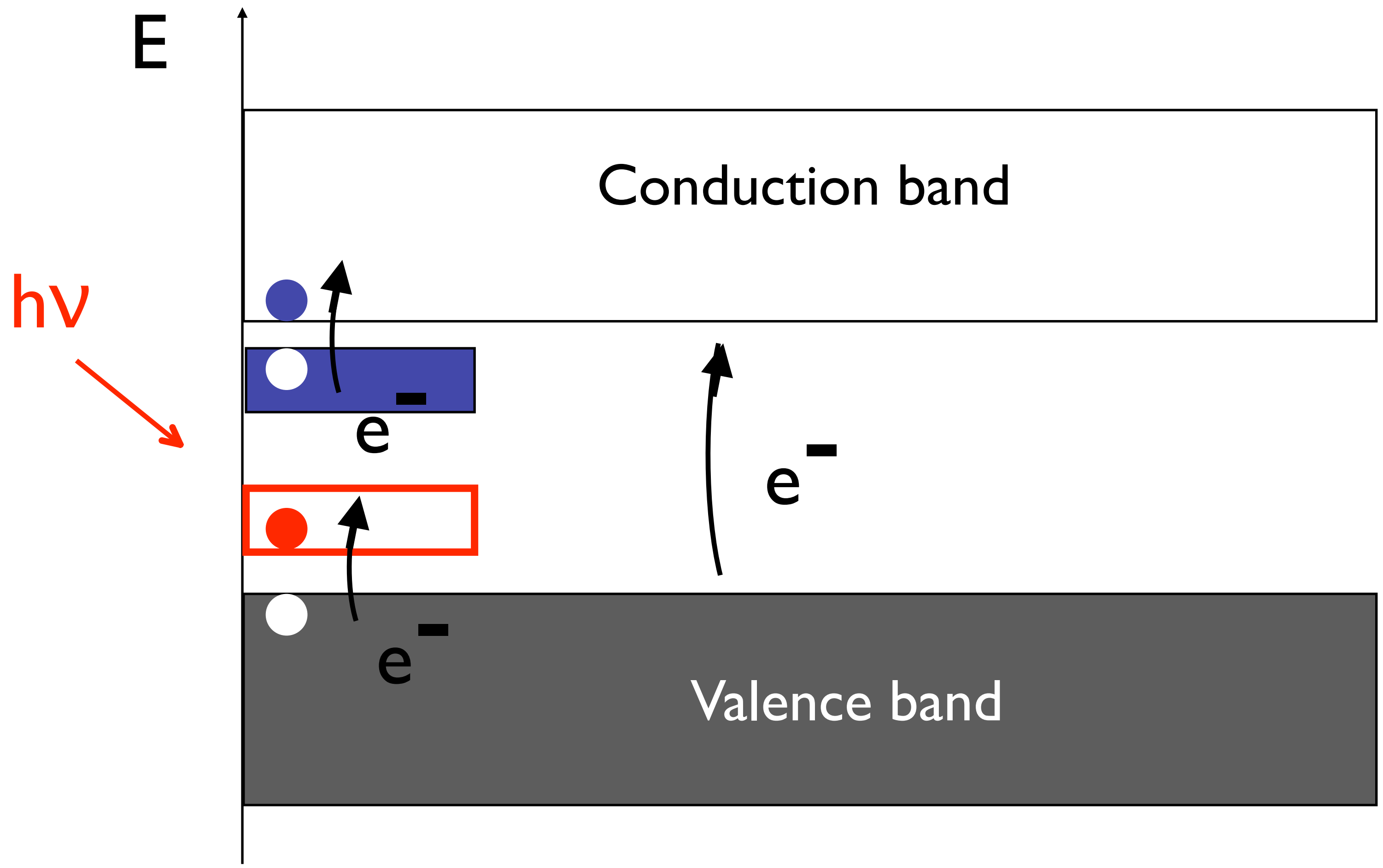
**Si : 1.08 eV ⇔ 1.14 µm**
**Ge : 0.66 eV ⇔ 1.88 µm**

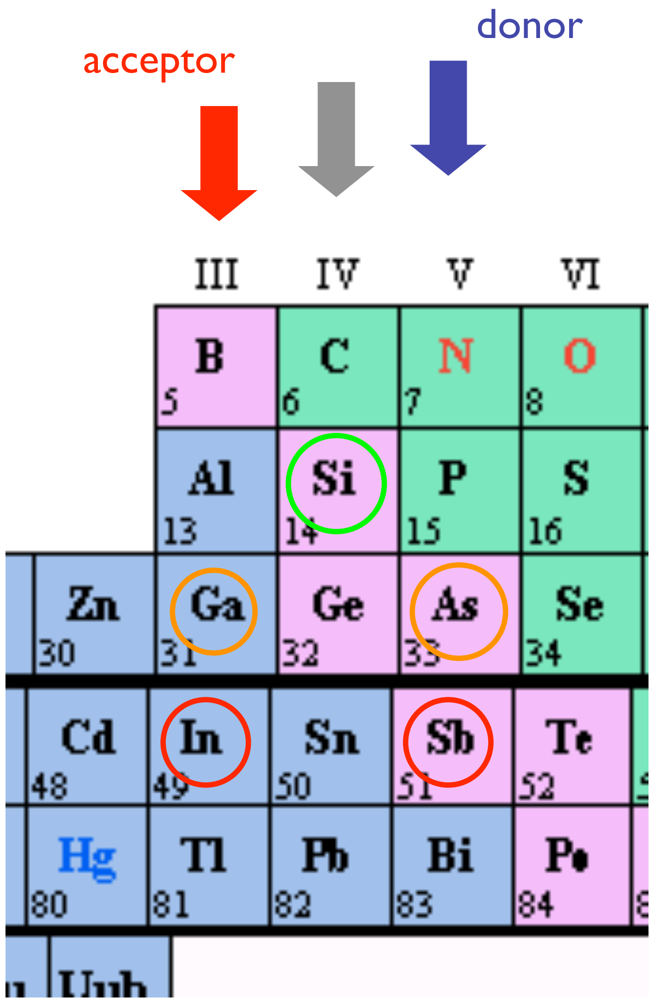



1.05 µm

Advantage : the detecting and the readout circuits are the same (made of Silicon)

# As always : dope to increase performances ... with wavelengths
# Add energy levels to give weaker photons a leg up



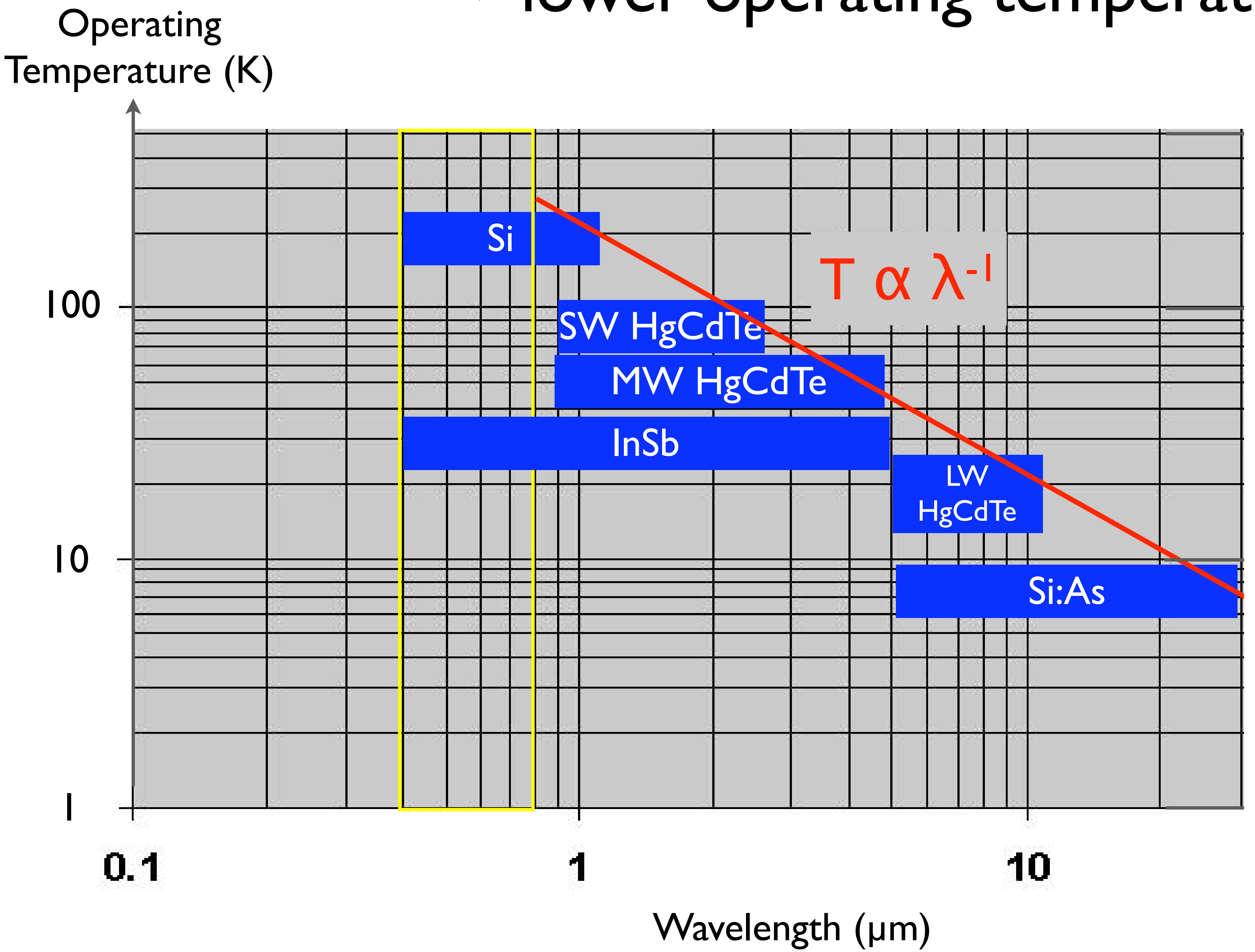




| Element(s) | Cutoff λ (μm) |
|---|---|
| Si | 1.1 |
| Ge | 1.8 |
| Si:In | 7.4 |
| Si:Ga | 17.8 |
| Si:As | 24 |
| Ge:Ga | 120 |
| In Sb | 5 |
| $Hg_{(1-x)}Cd_{(x)}Te$ | $\lambda(x) < 20$ μm |

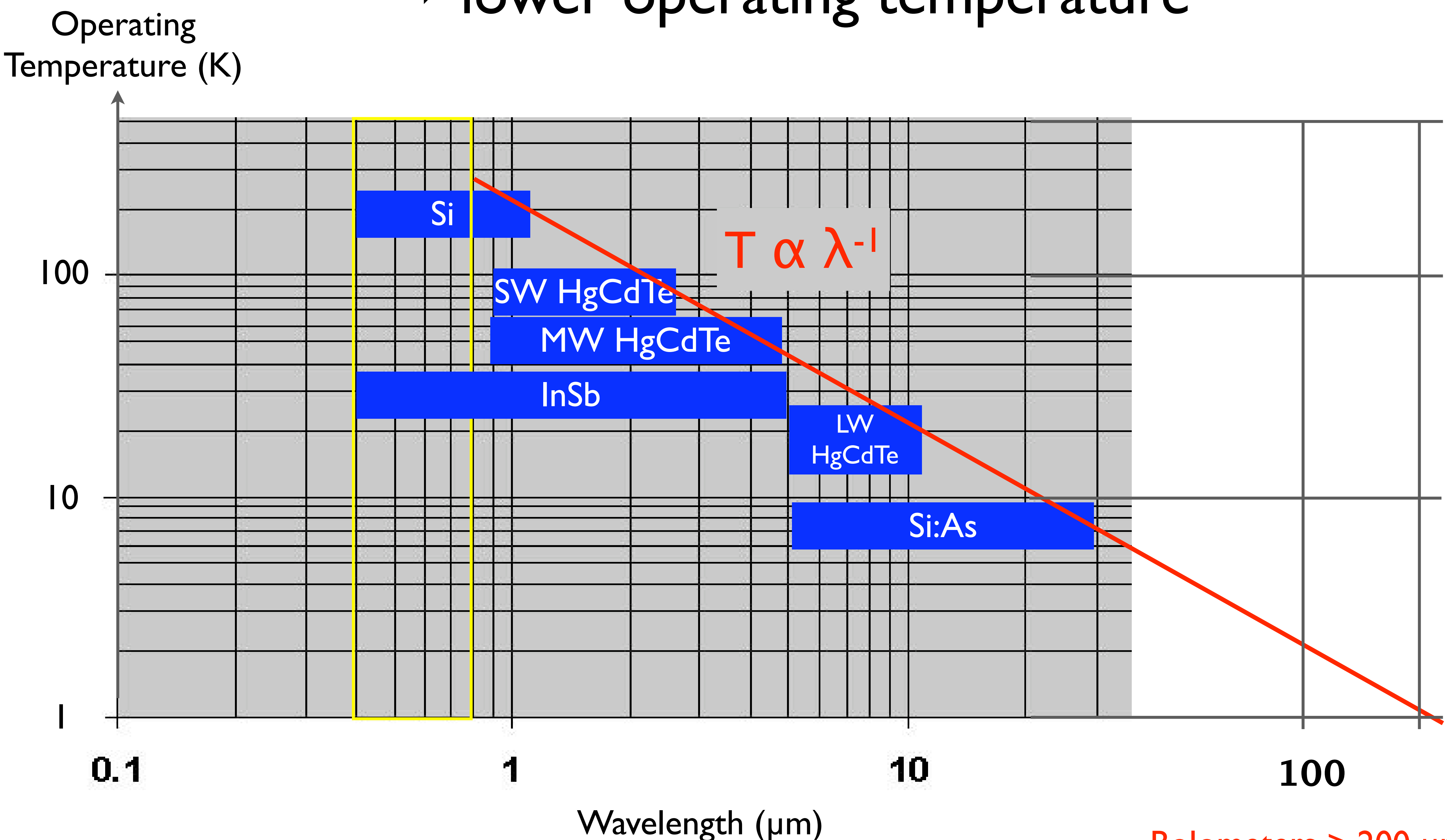
**IRAS : 12 - 25 - 60 - 100μm**
***Si:As*** ***Ge:Ga***

**Spitzer : 3.6 - 5.8 *μm* ... 24 - 70 *μm***
**InSb** **Si:As** **Ge:Ga**

# Higher cutoff-wavelength → lower operating temperature



# Higher cutoff-wavelength → lower operating temperature

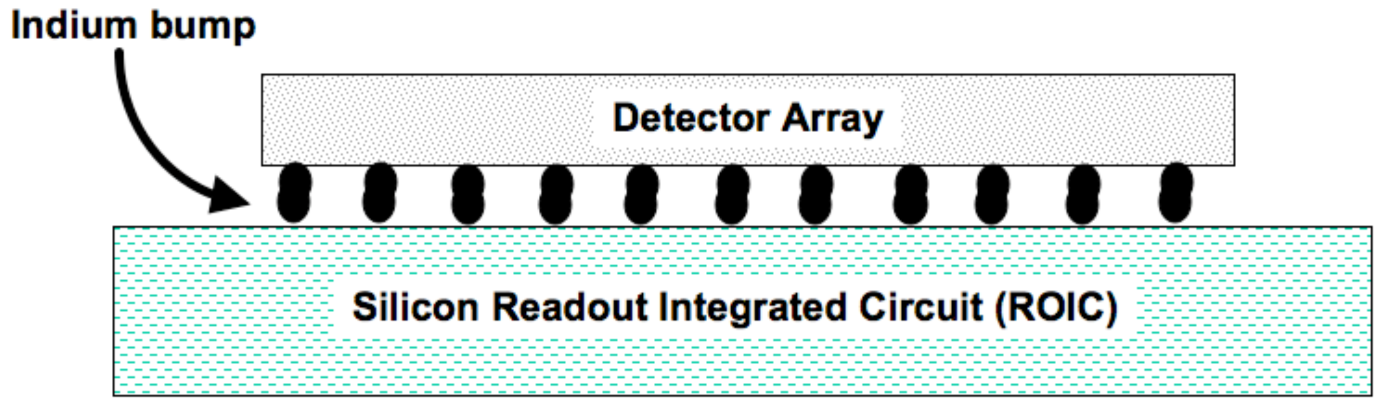



Bolometers > 200 μm
⇒ xx mK

# What makes Infrared imagery demanding

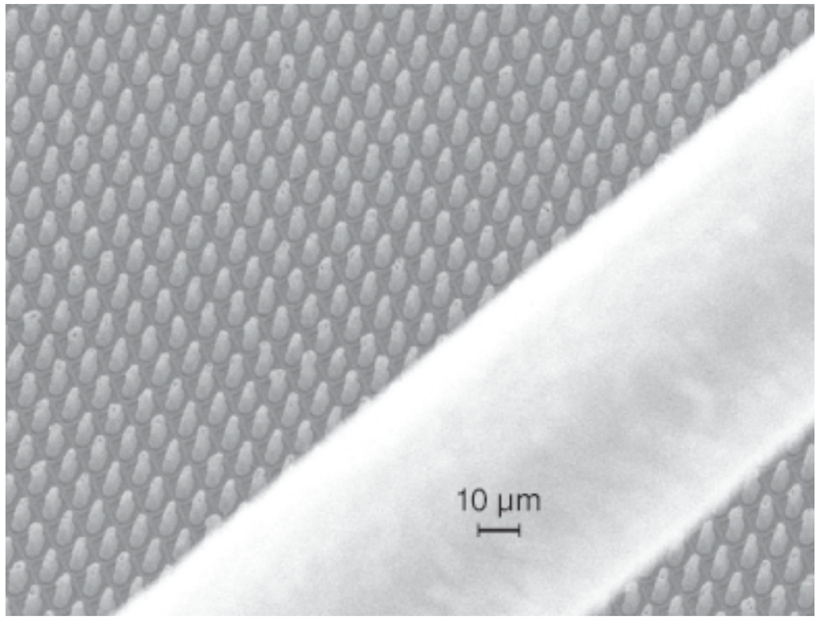
Detection and Readout are built separately and have to be connected together

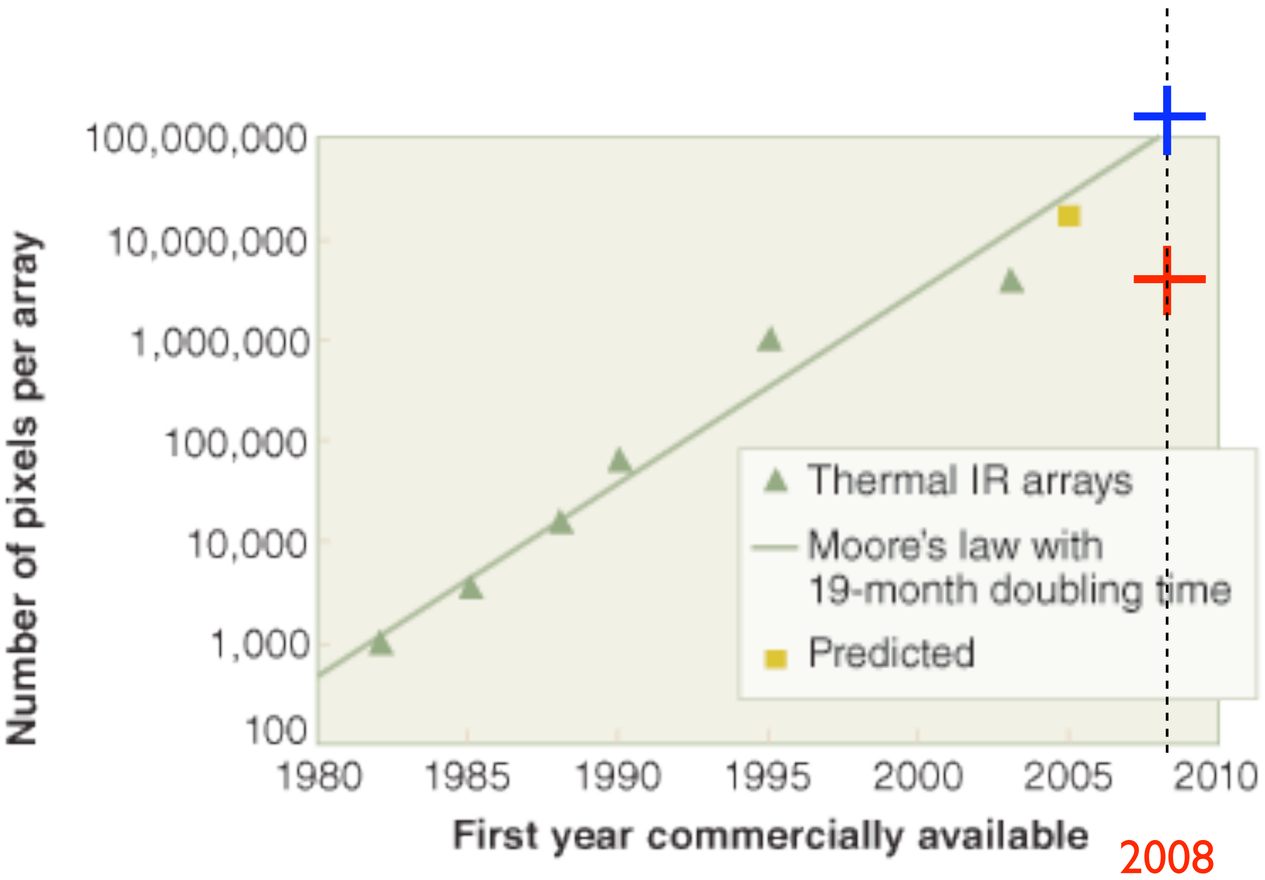
Hybridization between detection & readout




IR sensitive material

Silicon CCD or CMOS readout

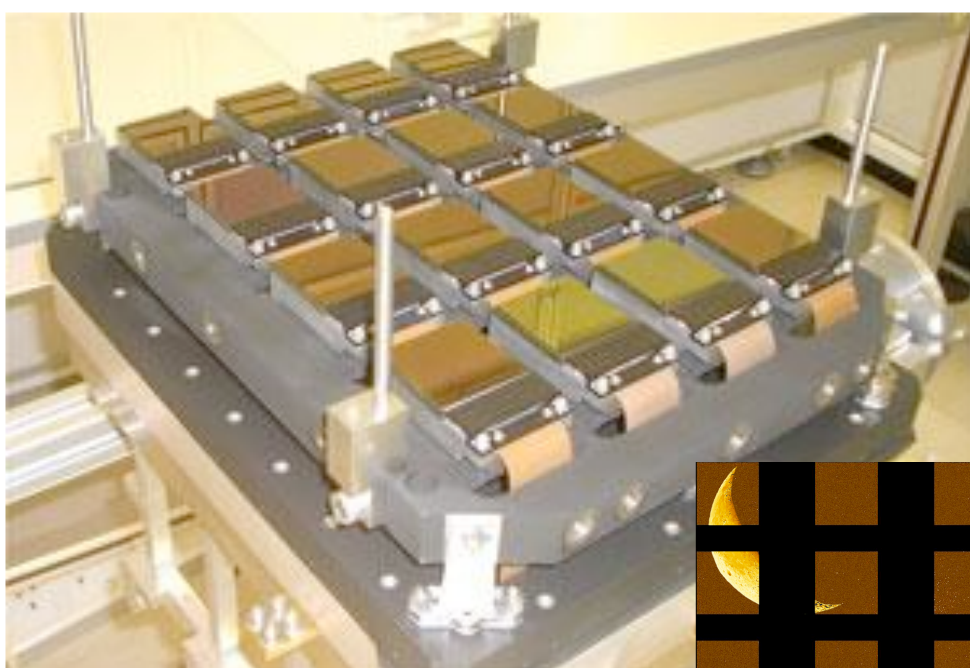


# From small to large (multi-detector) IR arrays

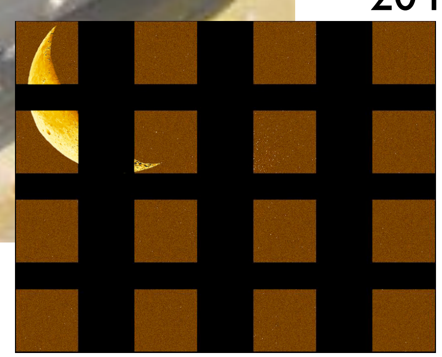


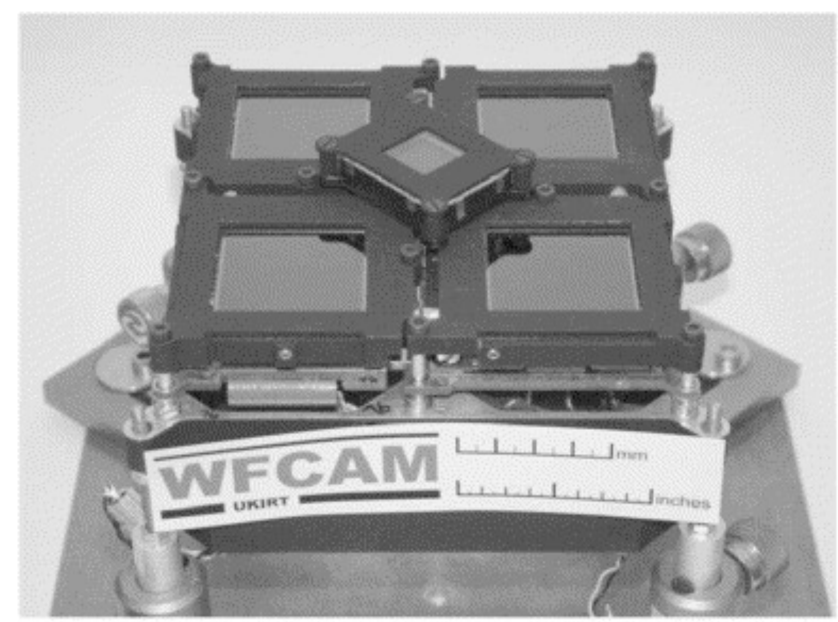
ESO VISTA array



2048

2048

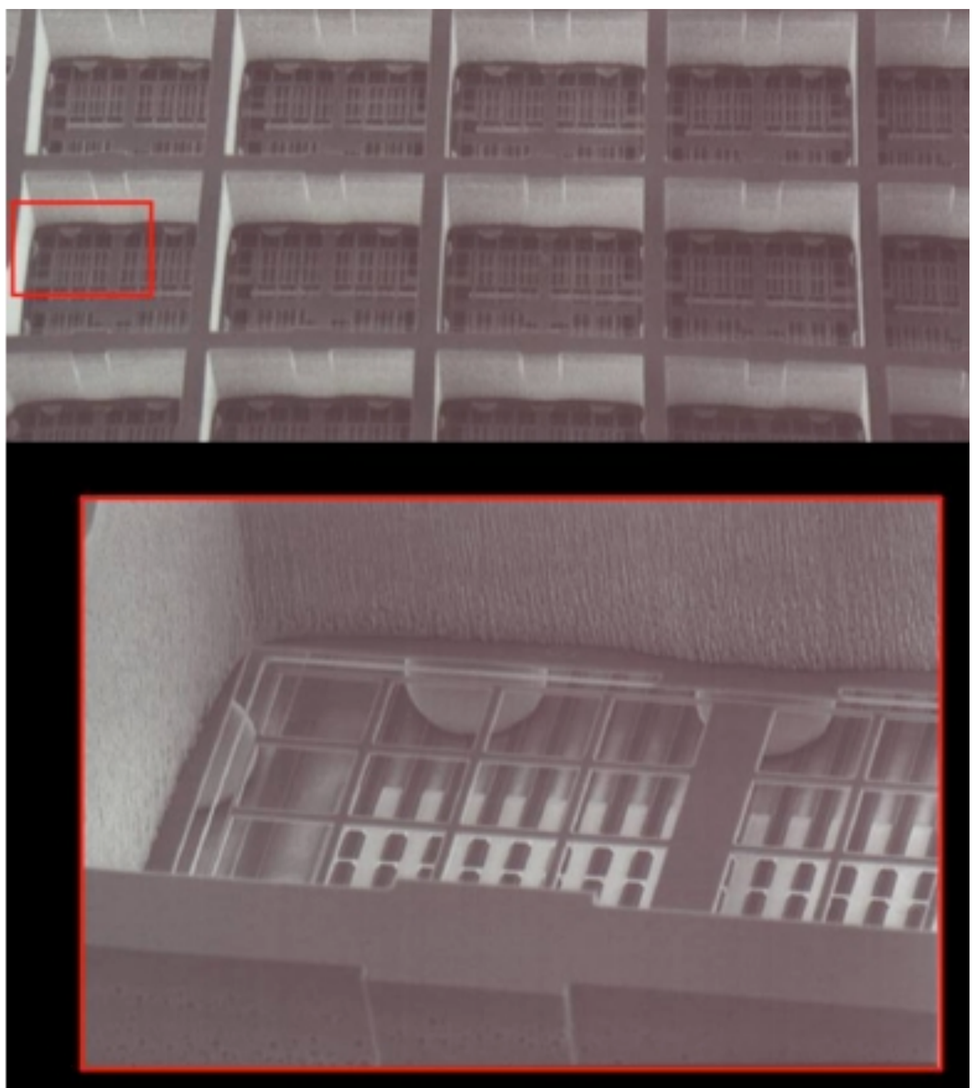




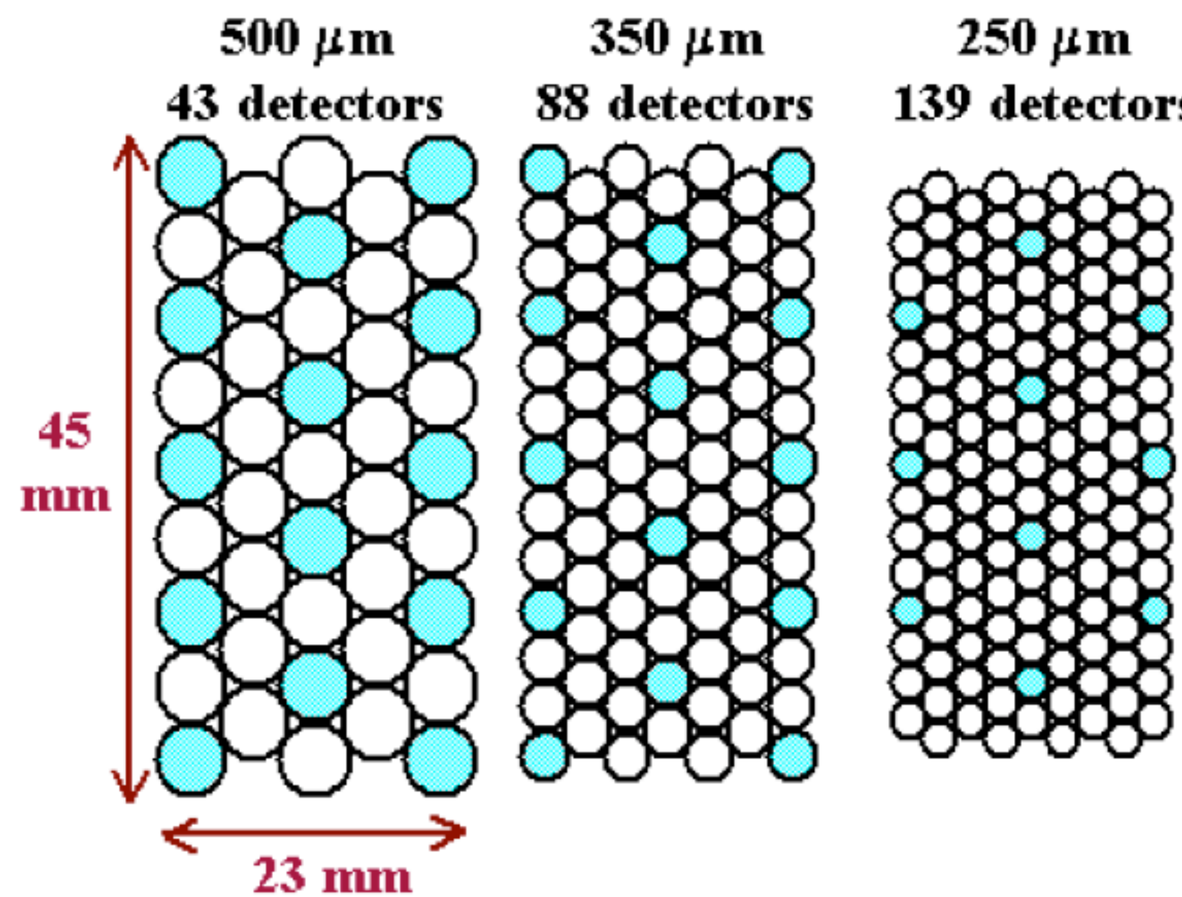


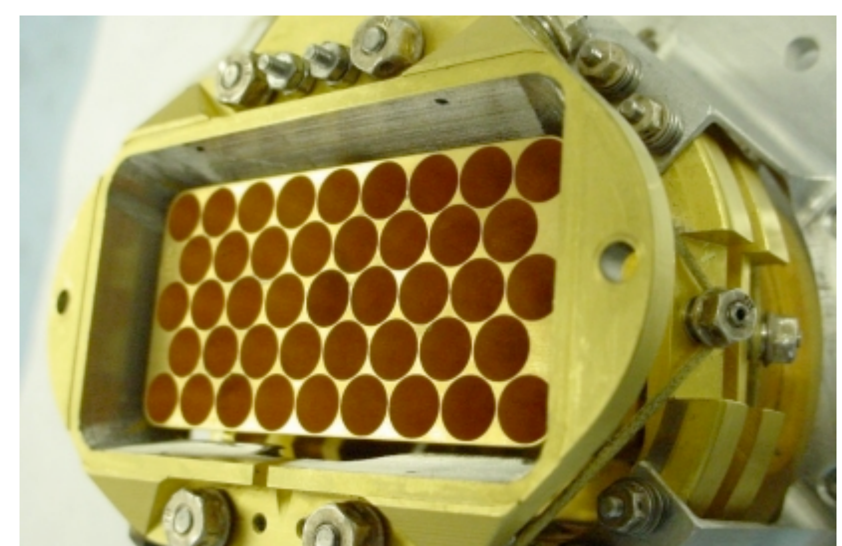
# Longer wavelength (space borne) detector are more a collection of bolometers than actual arrays

## PACS



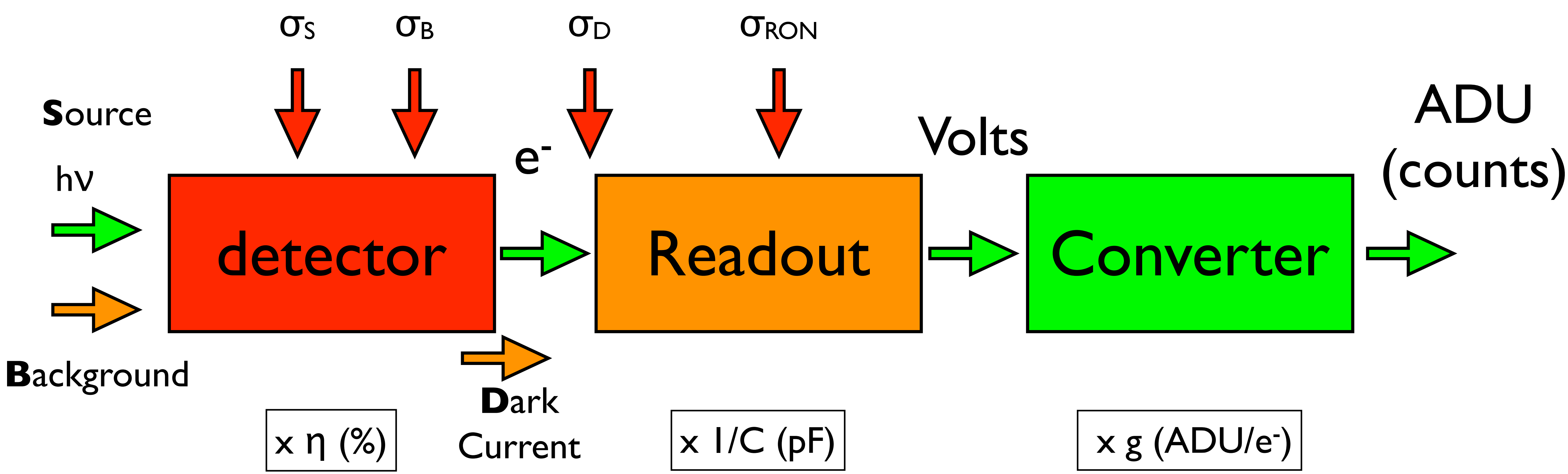
## SPIRE



# Photons, electrons, noise and performances

# Imaging detector : what's inside ?
# (pixel / pixel view)




photons and electrons are quanta

→ Poisson ('shot') Noise

Gaussian, white, independant noises :

$$\sigma^2 = \sigma_1^2 + \sigma_2^2 + \sigma_1^3 + \ldots$$

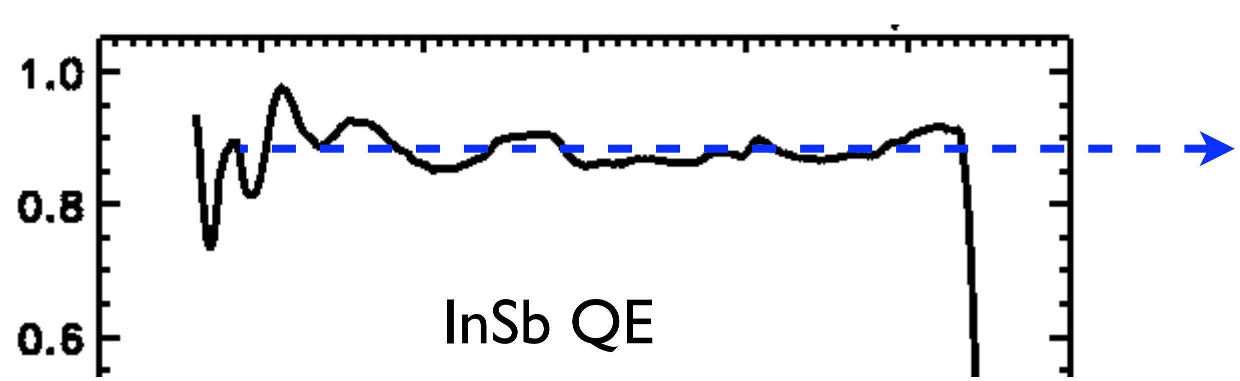
# My first SNR computation :
# how quantum efficiency (mildly) affects the Signal to Noise Ratio

photons : $\sigma_{\mathrm{ph}} = \sqrt{N_{\mathrm{ph}}}$ ; $SNR(\mathrm{ph}) = \sqrt{N_{\mathrm{ph}}}$

$$N_{\mathrm{e}} = \eta N_{\mathrm{ph}}$$

electrons : $\sigma_{\mathrm{e}} = \sqrt{N_{\mathrm{e}}}$ ; $SNR(\mathrm{e}) = \sqrt{N_{\mathrm{e}}} = \sqrt{\eta}\ \sqrt{N_{\mathrm{ph}}}$

$$\boxed{SNR(\mathrm{e}) = \sqrt{\eta}\ SNR(\mathrm{ph}) \lesssim SNR(\mathrm{ph})}$$




$\sqrt{0.88} \approx 0.94$

# Global Signal to noise ratio per frame

Good and bad signals :

magnitude == Flux (W/m2/Hz) → photon flux → electron flux (**S**ource and **B**ackground)

**D**ark current → electron flux

x Integration time : $N_S$, $N_B$, $N_D$

Varying and fixed noise :

statistical noise : $\sigma_X = \sqrt{N_X}$

readout noise : $\sigma_{RON}$

$$SNR = \frac{N_S}{\sqrt{N_S + N_B + N_D + \sigma^2_{\mathrm{RON}}}}$$

n frames → $SNR \times \sqrt{n}$

# Global Signal to noise ratio per frame

Good and bad signals :

magnitude == Flux (W/m2/Hz) → photon flux → electron flux (**S**ource and **B**ackground)
**D**ark current → electron flux
x Integration time : $N_S$, $N_B$, $N_D$

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readout noise : $\sigma_{RON}$

$$SNR = \frac{N_S}{\sqrt{N_S + N_B + N_D + \sigma^2_{\mathrm{RON}}}}$$

n frames → $SNR \times \sqrt{n}$

But $N_S$ is obtained by
$N_S=(N_S+N_B)-N_B$
(subtract the background)

$$SNR = \frac{N_S}{\sqrt{N_S + 2(N_B + N_D + \sigma^2_{\mathrm{RON}})}}$$

(unless B measured with a very high precision)

# Global Signal to noise ratio per frame

Good and bad signals :

magnitude == Flux (W/m2/Hz) → photon flux → electron flux (**S**ource and **B**ackground)

**D**ark current → electron flux

x Integration time : $N_S, N_B, N_D$

Varying and fixed noise :

statistical noise : $\sigma_X = \sqrt{N_X}$

readout noise : $\sigma_{RON}$

$$SNR = \frac{N_S}{\sqrt{N_S + N_B + N_D + \sigma^2_{\mathrm{RON}}}}$$

n frames → $SNR \times \sqrt{n}$

But $N_S$ is obtained by

$N_S=(N_S+N_B)-N_B$

(subtract the background)

$$SNR = \frac{N_S}{\sqrt{N_S + 2(N_B + N_D + \sigma^2_{\mathrm{RON}})}}$$

(unless B measured with a very high precision)

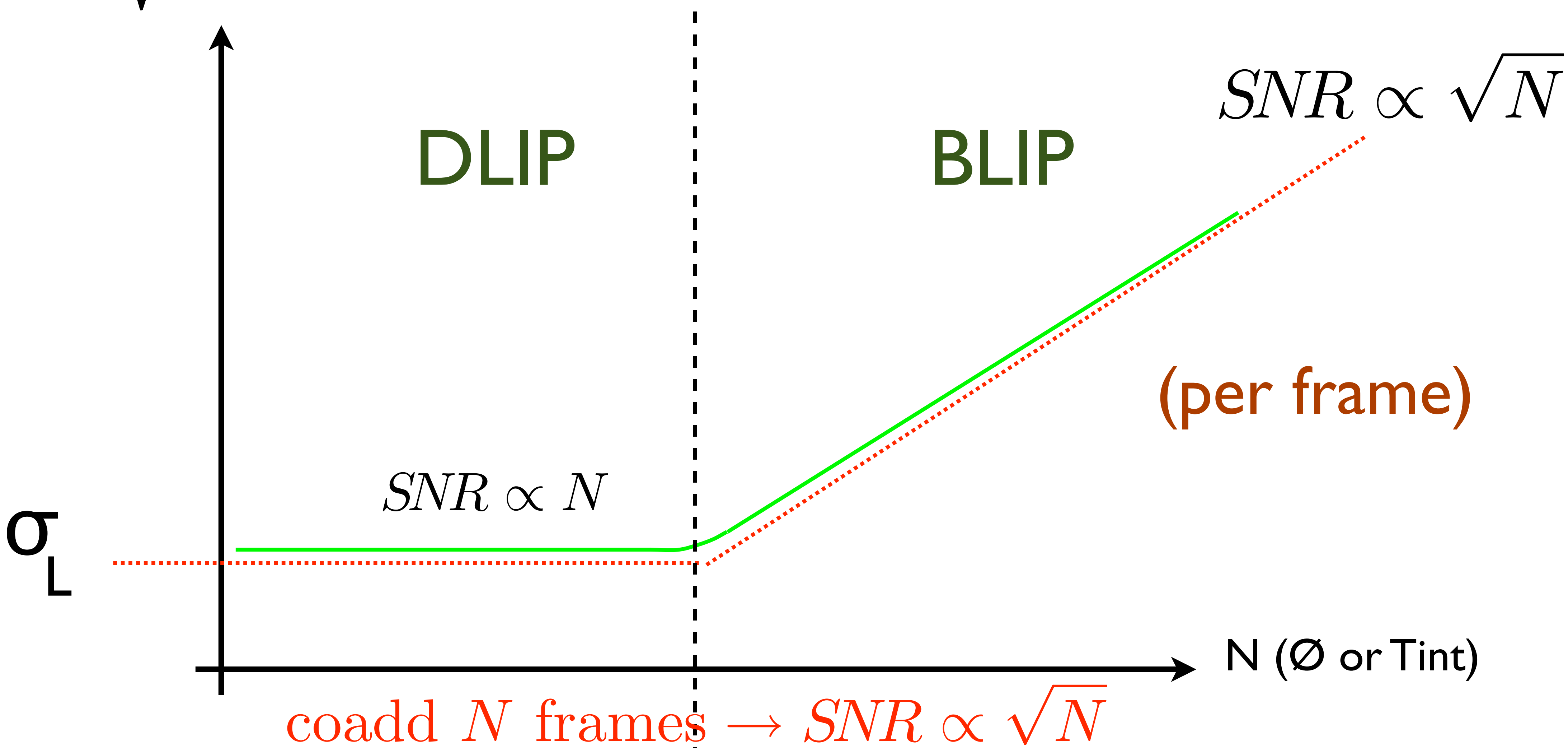
# photon and readout noise(s) : which one dominates ?

Fixed readout noise : $\sigma_L$

Variable photon noise : $\sigma_{\rm ph} = \sqrt{N}$ (N = $N_S$+$N_B$+$N_D$)

(VIS) (IR)

$$\sigma_T = \sqrt{\sigma_L^2 + N^2}$$




Tint the longer, the better

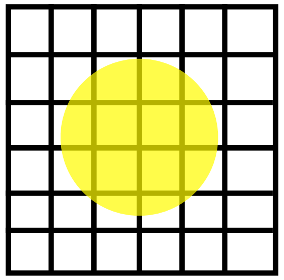
(beware of cosmic rays)

don't care too much about Tint

(if observation efficiency is good, take many frames)

# From peak pixel to PSF (N pixels)

pixel signal : Random Variable $(x, \sigma)$



$$SNR_{\text{peak}} = \frac{x}{\sigma}$$

PSF $X = \Sigma\, x_i \approx N x$ $\sigma'^2 = \Sigma\, \sigma^2 \approx N \sigma \rightarrow \sigma' = \sqrt{N}\, \sigma$

$$SNR_{\text{PSF}} = \frac{X}{\sigma'} = \frac{N\, x}{\sqrt{N}\, \sigma} \approx \sqrt{N}\, SNR_{\text{peak}}$$

# ISAAC SW (ESO) Exposure time simulator (ETC)

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

**Object Setup**
Source type : blackbody
Blackbody temperature: 4000 K
Source magnitude : 17
Source geometry : Seeing limited
Seeing : 0.8 arcsec

**Atmosphere Setup**
Airmass : 1.2

**Sky Setup**
Sky magnitude : 14

**Instrument Setup**
filter is (wide band) H
objective: S2

**Observation Setup**
DIT : 10 sec
SNR: 20 (+/- 50%)

one frame < DIT

| | |
|---|---|
| Total exposure time | : **2.6510 seconds** |
| Number of detector integrations (decimal value) | : **0.27** DCR |
| Signal-to-noise | : **20.00** |
| Number of pixels for PSF area | : **93.00 pixels** |
| Total number of e- in PSF area (object only) | : **16131.91 e-** |
| Total number of e- in PSF area (object only, 1 DIT) | : **60851.27 e-/DIT** |
| Sky bkg. value with sky lines (e/pixel, 1DIT) | : **23302.69 e-/pixel/DIT** |
| Max. intensity at central pixel per DIT (e-, object+sky) | : **25089.79 e-/DIT** |
| Detector saturation (e-) | : **180000 e-** |
| Detector Readout Noise | : **10.00 e-/pixel/DIT** |
| Plate scale in arcsec/pixel | : **0.15 arcsec/pixel** |

(no dark current : 1e/s ?)

## PSF

$$
\begin{aligned}
N_{\rm px} &= 93 \quad [\approx \pi \left(\frac{2\times 0.8}{0.15}\right)^2] \\
S &= 16132 \\
\sigma^2 &= 10^2 + 23302 \times 93 \times \frac{2.65}{10} + 16132 = 774^2 \\
SNR &= \frac{16131}{774} = 20.83
\end{aligned}
$$

## Peak pixel

$$
\begin{aligned}
N_{\rm px} &= 1 \quad (!) \\
S &= (25090 - 23302) \times \frac{2.65}{10} = 474 \\
\sigma^2 &= 10^2 + 23302 \times \frac{2.65}{10} + 474 = 82^2 \\
SNR &= \frac{474}{82} = 5.77
\end{aligned}
$$

# From magnitudes to e/pixel

Sky emission in H band : $m_H = 14/\text{arcsec}^2$

$\Omega_{\text{px}} = 0.15^2 = 2.25\,10^{-2}$

← Sky emission is a brightness (Jy/sr == mag/arcsec$^2$)

$$
\begin{aligned}
F &= F_o(H)\,10^{-\frac{m_H}{2.5}} \times \Omega_{\text{px}} \\
N &= \frac{F}{h\nu_H} \times S \times \Delta\nu(H) \times DIT \\
&= \frac{1000\,10^{-26}\,10^{-\frac{14}{2.5}} \times 2.25\,10^{-2}}{11.4\,10^{-20}} \times 50 \times 42\,10^{12} \times 10 \\
&\approx 10000 \text{ e/px}
\end{aligned}
$$

**ISAAC ETC : 23302.69**

# From magnitudes to e/pixel

Sky emission in H band : $m_H = 14/\text{arcsec}^2$

$\Omega_{\text{px}} = 0.15^2 = 2.25\,10^{-2}$

← Sky emission is a brightness (Jy/sr == mag/arcsec$^2$)

$$
\begin{aligned}
F &= F_o(H)\,10^{-\frac{m_H}{2.5}} \times \Omega_{\text{px}} \\
N &= \frac{F}{h\nu_H} \times S \times \Delta\nu(H) \times DIT \\
&= \frac{1000\,10^{-26}\,10^{-\frac{14}{2.5}} \times 2.25\,10^{-2}}{11.4\,10^{-20}} \times 50 \times 42\,10^{12} \times 10 \\
&\approx 10000 \ \texttt{e/px}
\end{aligned}
$$

**ISAAC ETC : 23302.69**

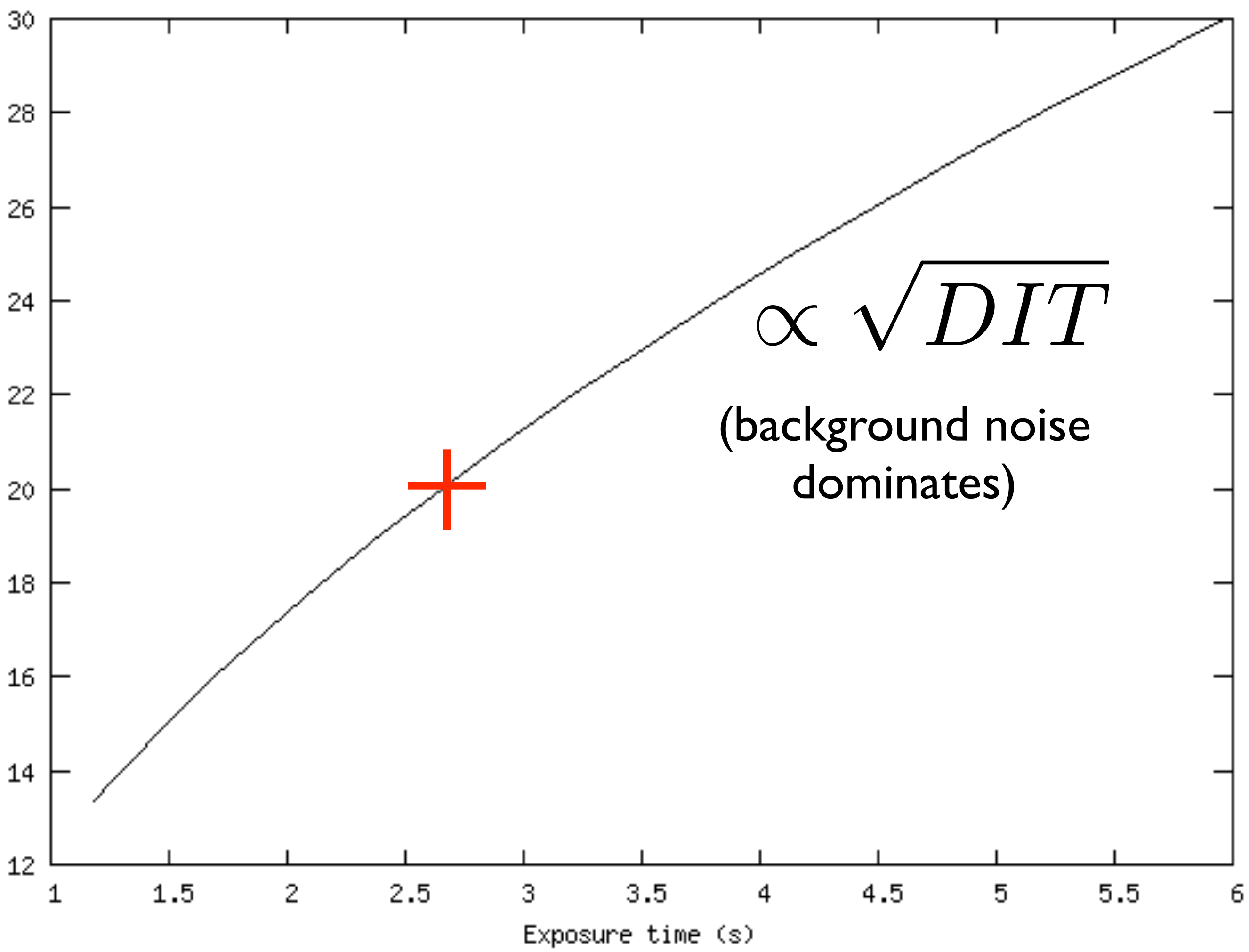
Source magnitude $m$

← Source emission is a flux spread over a PSF covering $N_{px}$ pixels (Jy == mag)

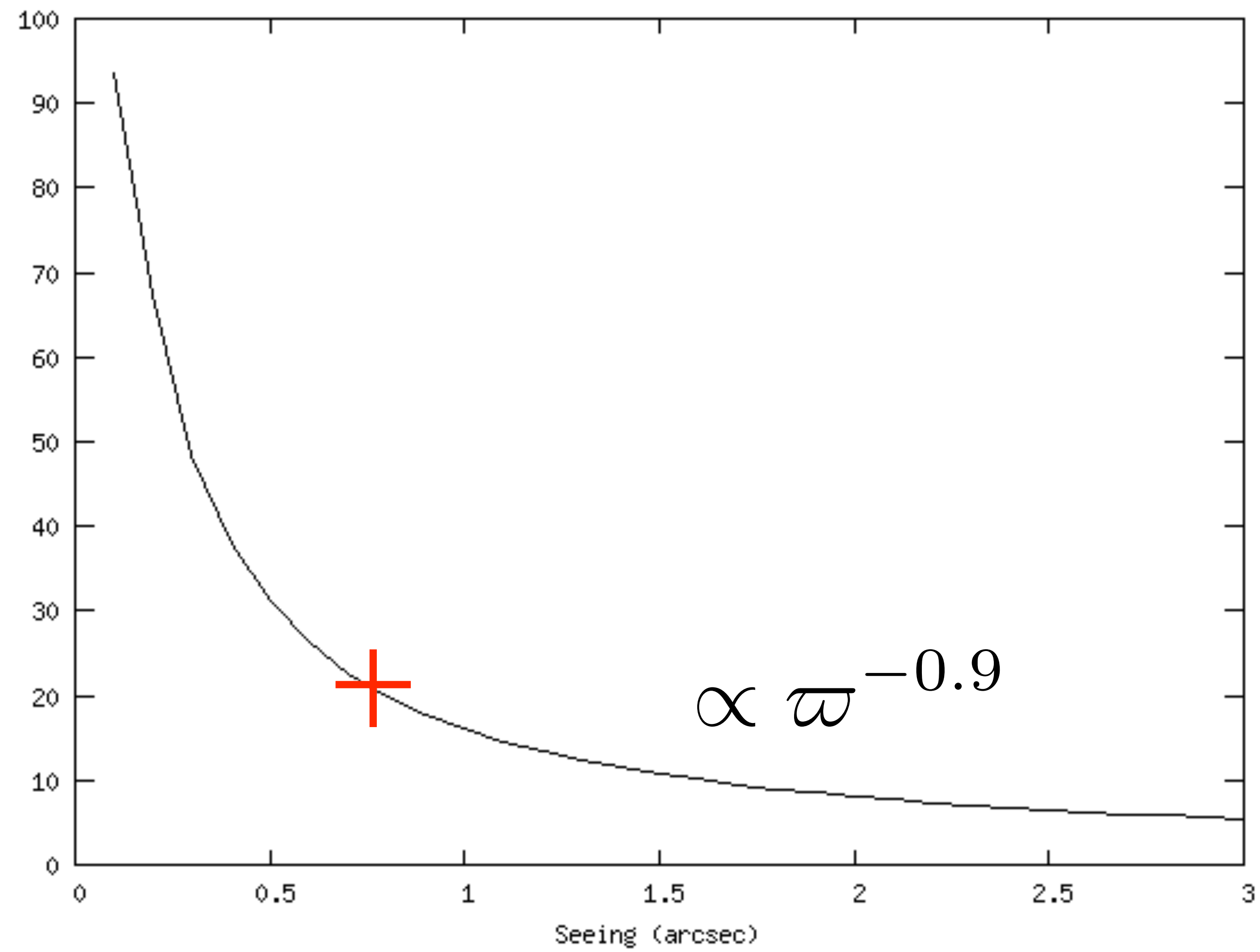
$$SNR = \frac{\frac{F_o}{h\nu}\,10^{-\frac{m}{2.5}}.S.\Delta\nu.DIT}{N_{\text{px}}.RON^2 + N_{\text{px}}.DC + \frac{F_o}{h\nu}.S.\Delta\nu.DIT\left(10^{-\frac{m}{2.5}} + N_{\text{px}}\,0^{-\frac{m_B}{2.5}}\right)}$$

# SNR variations with DIT and / or seeing

(PSF) SNR vs. exp. time




(PSF) SNR vs. seeing

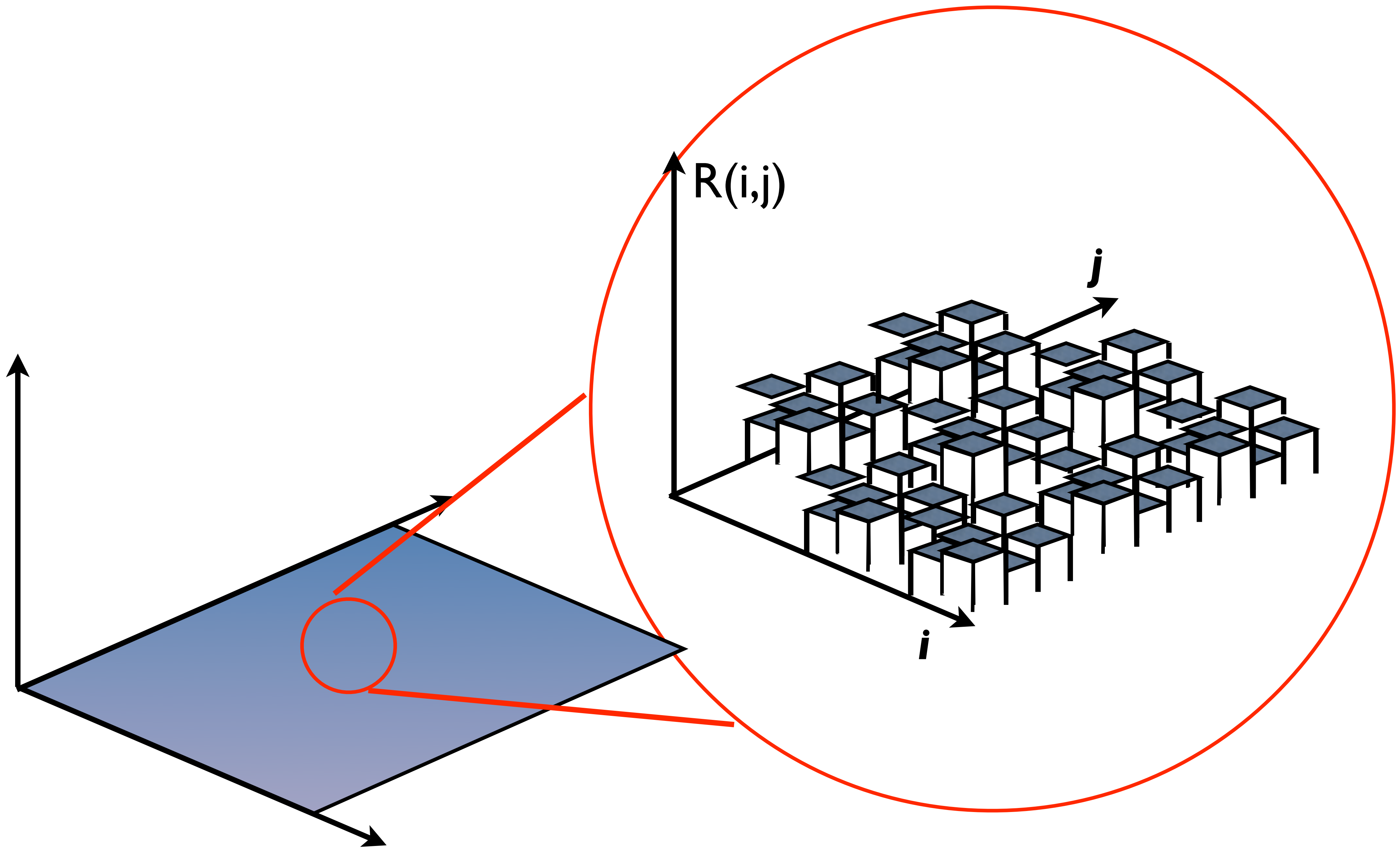



(peak SNR $\propto \varpi^{-2}$)

# Flat-fielding and Calibration

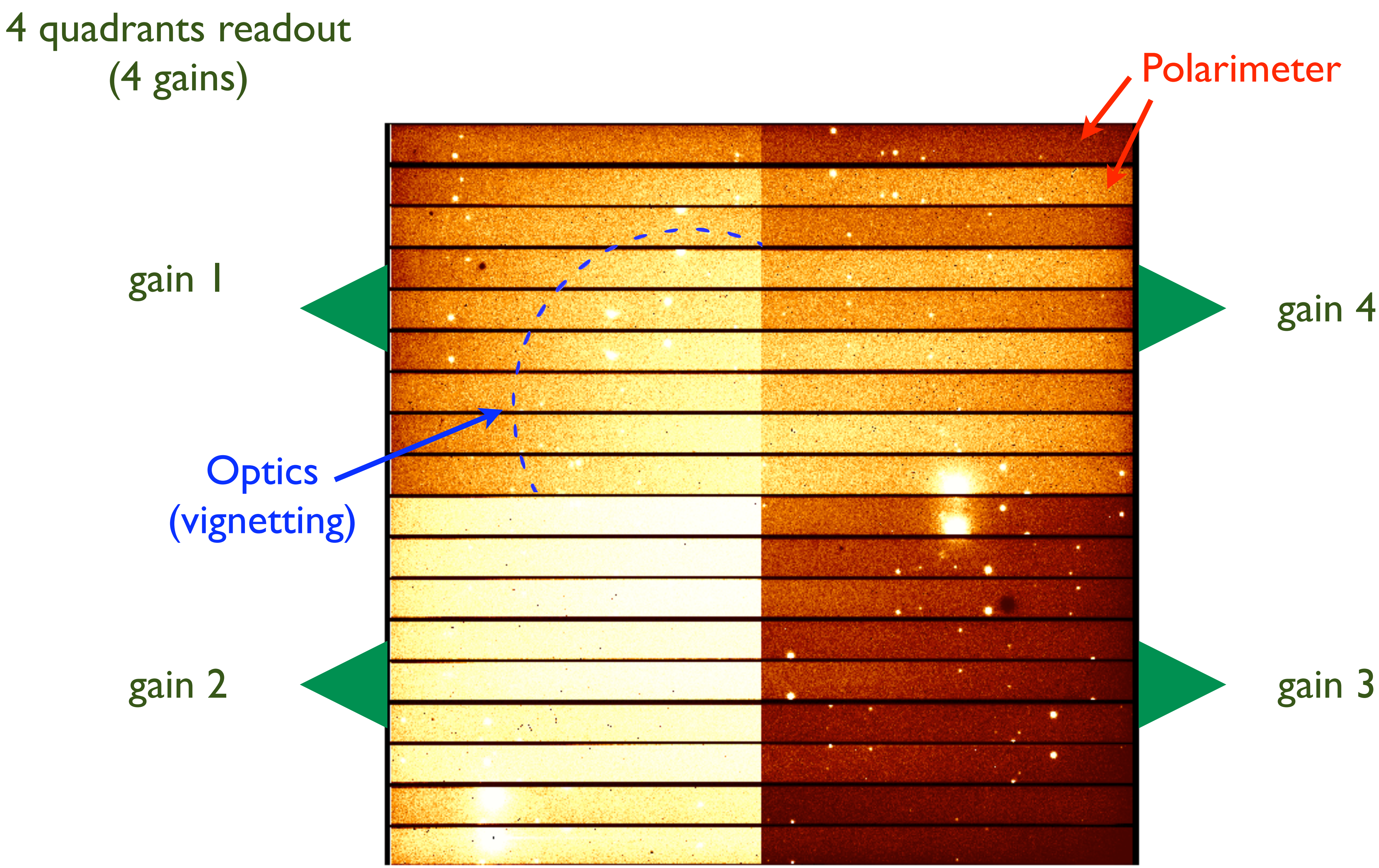
# Flat-fielding

## HF : pixel to pixel response



# Flat-fielding

## LF : Optics (and electronics)



# Photometric Calibrations

O'Connell lectures :

http://www.astro.virginia.edu/class/oconnell/astr511/lectureindex.html

## Flat field :

- (unknown) Pixel' response distribution — R(i,j)
- Uniform Source [sky @ dawn, screen, etc.] — U

1) Measure flat-field — X(i,j) = U . R(i,j)
2) Observe complex source : S(i,j) → Y(i,j) = R(i,j) . S(i,j)
3) FF calibration — I(i,j) = Y(i,j)/X(i,j) = S(i,j)/U α S(i,j) ∀ i,j

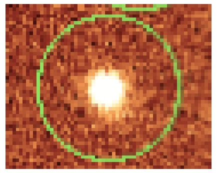
## Photometry

- Pointlike Source : FLUX (one or more pixels) == Jy/pixel
- Extended Source : BRIGHTNESS (ADU/pixel) == Jy/arcsec$^2$

$$\frac{\text{ADU}}{\text{pixel}} = \frac{\text{ADU}}{\text{Jy}} \times \frac{\text{Jy}}{\text{arcsec}^2} \times \frac{\text{arcsec}^2}{\text{pixel}}$$

*measure* — *calibration* — *(unit)* — *optics : pixel scale*

$$\sum X_{ij} = X_{(ADU)}$$



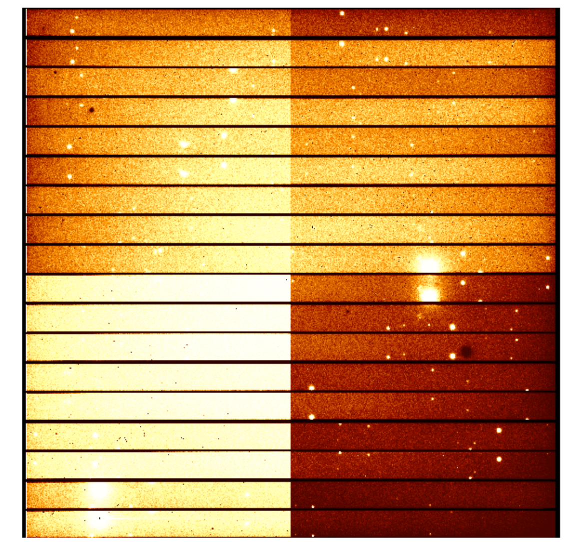
$$\int s\,d\Omega = S_{(Jy,magnitude)}$$

Standard stars : same Airmass, Spectral type, Magnitude

# IR imagery : FITS format

## FITS Header :

SIMPLE = T / Standard FITS format (NOST-100.0)
BITPIX = 16 / # of bits storing pix values → $N_{ADU}$ (max) = $2^{16}$ = 65536
NAXIS = 2 / # of axes in data array
NAXIS1 = 2080 / # pixels/axis
NAXIS2 = 2048 / # pixels/axis
ORIGIN = 'ESO ' / European Southern Observatory
(...)
DATE-OBS= '2001-12-10T03:49:03.978' / Date of observation
EXPTIME = 180.0025 / Total integration time
(...)
INSTRUME= 'FORS1 ' / Instrument used
TELESCOP= 'ESO-VLT-U3' / ESO Telescope Name
RA = 64.710280 / 04:18:50.4 RA (J2000) pointing
DEC = 28.18850 / 28:11:18.6 DEC (J2000) pointing
(...)
ST = '04:23:12.811' / ST at start
AIRMASS = 1.65200 / Averaged air mass
IMAGETYP= 'OBJECT ' / Observation type
FILTER1 = 'I_BESS ' / Filter 1 name
(...)
HIERARCH ESO **DET** OUTPUTS = 4 / # of outputs
(...)
HIERARCH ESO **DET** OUT4 CONAD = 3.26 / Conversion from ADUs to electrons → $N_{e-} = 3.26\ N_{ADU}$
HIERARCH ESO **DET** OUT1 RON = 6.07 / Readout noise per output (e-)



$$SNR(ADU) \neq SNR(e)$$

HIERARCH ESO : **OBS**, **TPL**, **DPR**, **TEL**, **ADA**, **INS**, **DET**

# Use of various ETC. ISAAC LW (ESO)

```
Source type        : blackbody
Blackbody temperature: 4000
Source magnitude : 15
Source geometry  : Seeing limited
Seeing                  : 0.6 arcsec
```

**Atmosphere Setup** Airmass : 1.2
**Sky Setup** Sky magnitude : 3.9
**Instrument Setup** wide band L
objective: L3
**Observation Setup**
DIT : 0.11 sec
SNR: 20 (+/- 50%)

Chopping mode : S = (S+B) - B

| | | |
|---|---|---|
| Total exposure time | : | **6086.9336 seconds** |
| Number of detector integrations (decimal value) | : | **55335.76** (**chopping**) UCR |
| Signal-to-noise | : | **20.00** |
| Number of pixels for PSF area | : | **224.00 pixels** |
| Total number of e- in PSF area (object only) | : | **38657869.53 e-** |
| Total number of e- in PSF area (object only, 1 DIT) | : | **698.61 e-/DIT** |
| Sky bkg. value with sky lines (e/pixel, 1DIT) | : | **149454.92 e-/pixel/DIT** |
| Max. intensity at central pixel per DIT (e-, object+sky) | : | **149463.54 e-/DIT** |
| Detector saturation (e-) | : | **289000 e-** |
| Detector Readout Noise | : | **50.00 e-/pixel/DIT** |
| Plate scale in arcsec/pixel | : | **0.07 arcsec/pixel** |

$$
\begin{aligned}
N_{\rm px} &= 224 \\
S &= 698 \\
\text{readout} & \quad 224 \times 50^2 \\
\text{signal} & \quad 698 \\
\text{background (twice)} & \quad 224 \times 149454 \\
SNR_{\rm DIT} &= \frac{698}{\sqrt{224 \times 50^2 + 698 + 2 \times 224 \times 149454}} = 0.085 \\
0.085 \rightarrow 20 : \times 235 & \rightarrow 235^2 = 55431 \text{ frames}
\end{aligned}
$$

# Use of various ETC. ISAAC LW (ESO)

```
Source type         : blackbody
Blackbody temperature: 4000
Source magnitude : 15
Source geometry  : Seeing limited
Seeing                  : 0.6 arcsec
Atmosphere Setup Airmass       : 1.2
Sky Setup Sky magnitude        : 3.9
Instrument Setup   wide band      L
objective: L3
Observation Setup
DIT : 0.11 sec
SNR: 20 (+/- 50%)
```

Chopping mode : S = (S+B) - B

```
Total exposure time                                 :    6086.9336 seconds
Number of detector integrations (decimal value)     :    55335.76 (chopping) UCR
Signal-to-noise                                     :       20.00
Number of pixels for PSF area                       :      224.00 pixels
Total number of e- in PSF area (object only)        : 38657869.53 e-
Total number of e- in PSF area (object only, 1 DIT) :      698.61 e-/DIT
Sky bkg. value with sky lines (e/pixel, 1DIT)       :   149454.92 e-/pixel/DIT
Max. intensity at central pixel per DIT (e-, object+sky) : 149463.54 e-/DIT

Detector saturation (e-)                            :      289000 e-
Detector Readout Noise                              :       50.00 e-/pixel/DIT
Plate scale in arcsec/pixel                         :        0.07 arcsec/pixel
```

$$N_{\mathrm{px}} = 224$$

$$S = 698$$

$$\text{readout} \quad 224 \times 50^2$$

$$\text{signal} \quad 698$$

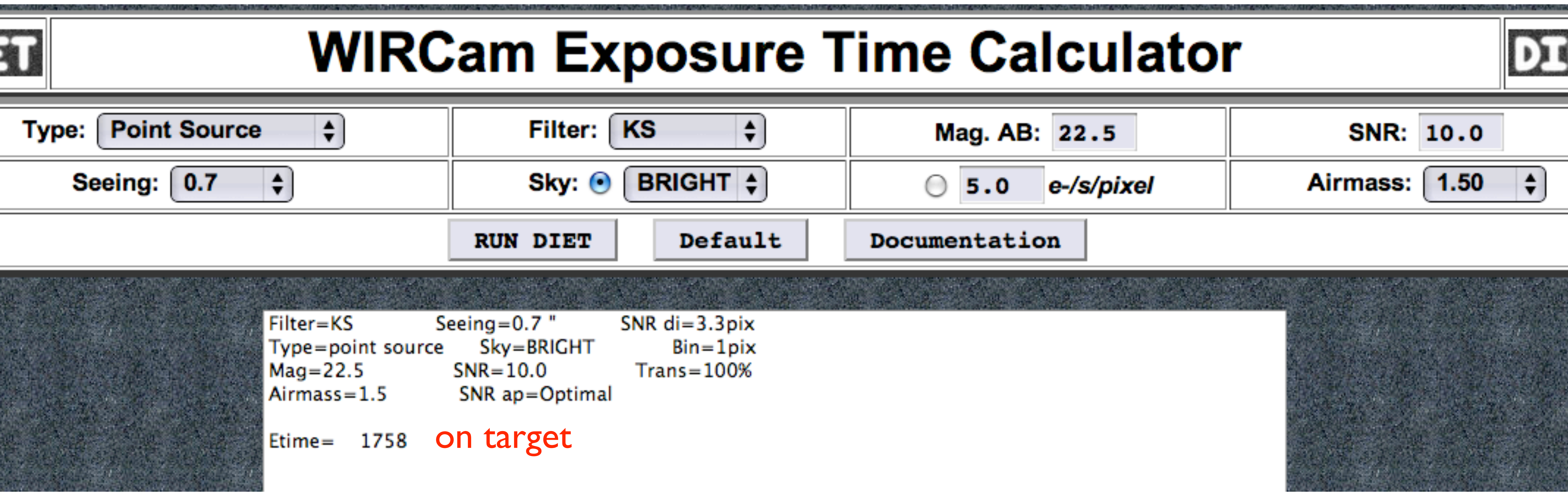
$$\text{background (twice)} \quad 224 \times 149454$$

$$SNR_{\mathrm{DIT}} = \frac{698}{\sqrt{224 \times 50^2 + 698 + 2 \times 224 \times 149454}} = 0.085$$

$$0.085 \rightarrow 20 : \times 235 \rightarrow 235^2 = \boxed{55431} \text{ frames}$$

# Use of various ETC.

## WIRCAM (CFHT)




→ x 2 (= 1hour) to measure and subtract the background emission

| |
|---|
| $K_s$ |
| 22.5 |

(10 sigma detection in a 1 hour exposure under 0.7 arcsecond seeing with 1.5 airmass)

# Use of various ETC.

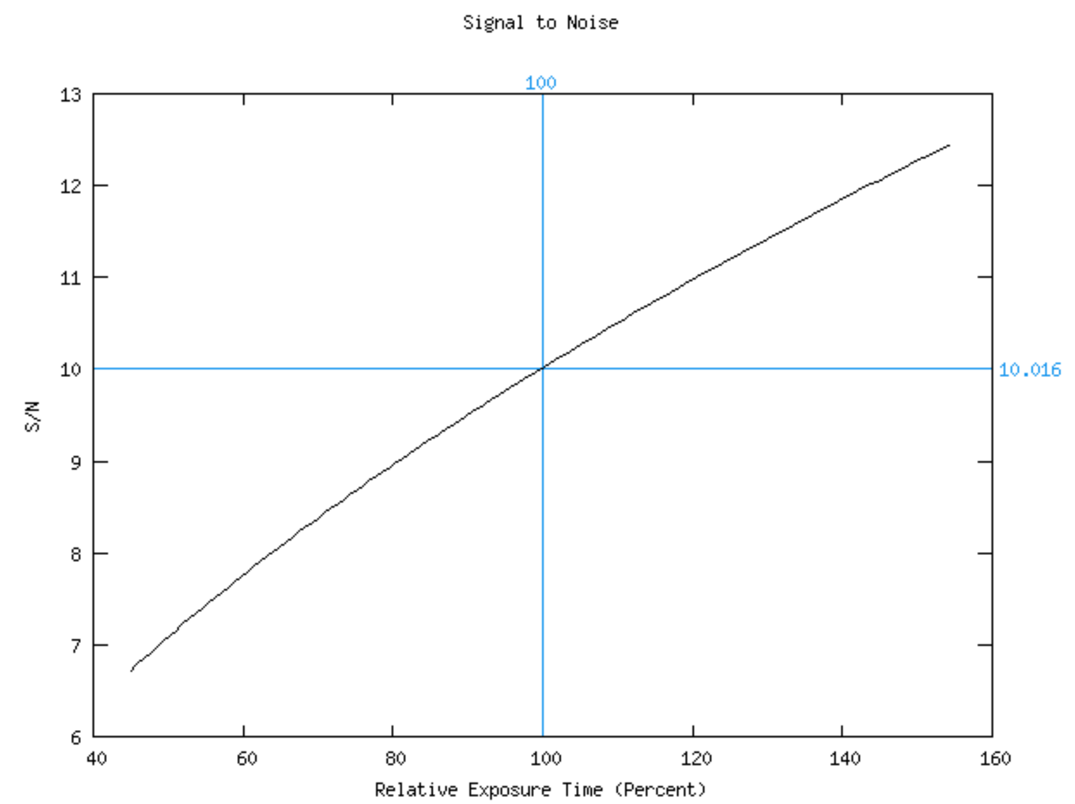
## VISIR (ESO)

```
Target Setup
Target source flux distribution type    : blackbody
Parameters                              : T=3000.0 K
Target source flux scaled to            : 1000.0 mJy at 17750.0 nm
Target source magnitude                 : Q = 2.14
Target source geometry                  : Point source
Atmosphere Setup
Seeing                                  : 0.80 arcsecs
Airmass                                 : 1.15
Instrument Setup
Filter                                  : Q1
Detector read-out mode                  : large_cap
Detector parameters                     : RON  = 15.60 e-/pixel/DIT
                                          Dark = 7000.00 e-/pixel/s

Observation Setup
User requested:  Exposure Time for a given S/N
```

(visible)

10 µm
0.44 arcsec




```
Pixel scale                                                       :      75.000 mas/pixel
Signal-to-noise ratio                                             :      10.016
Detector Integration Time for one exposure                    DIT :       0.0400 s
Number of detector integrations (rounded up)                 NDIT :     226
Total exposure time  (without overheads)             INT=NDIT*DIT :       9.040 s
Max. intensity at central pixel per DIT (object+sky)              :  6.92599e+06 e-/DIT
Detector linearity/flat-fielding limit                            :  1.30000e+07     e-
Detector saturation limit                                         :  1.80000e+07     e-
Radius of S/N reference area                                      :       0.438 arcsec
Number of pixels in S/N reference area                            :     107      pixels
Total number of e- in S/N reference area (object only)            :  3.54189e+07 e-
Total number of e- in S/N reference area per DIT (object only)    :      156721 e-/DIT
Total sky background signal per DIT                               :  6.92198e+06 e-/pixel/DIT
```

= 4 x seeing surface @ 10µm

# A collection of available IR arrays

| Telescope | Country | Tel. Diam. | Detector | "/pixel | FOV(deg²) | BE (m² deg²) | date |
|---|---|---|---|---|---|---|---|
| VISTA | UK | 4 m | 8k x 8k | 0.30" | 0.25 | 3.14 | |
| UKIRT +WFCAM | UK | 3.8 m | 4k x 4k | 0.40" | 0.20 | 2.27 | 2003-Q1 |
| CFHT + WIRCAM | FR-Can-US | 3.6 m | 4k x 4k | | 0.11 | | |
| INT + CIRSI | UK | 2.5 m | 2k x 2k | 0.45" | 0.062 | 0.31 | 1999 |
| VLT +NIRMOS | ESO | 8.2 m | 4k x 4k | 0.21" | 0.054 | 2.71 | 2002-Q1 |
| 2MASS | US | 1.3 m (2 of) | (3 x) 256 x 256 | 2.0" | 0.02 | 0.080 | 1998 |
| NTT-SOFI | ESO | 3.5 m | 1k x 1k | 0.292 | 0.0069 | 0.066 | 1998 |
| WHT + INGRID | UK+NL | 4.2 m | 1k x 1k | 0.25 | 0.0051 | 0.070 | 2000 |
| VLT-ISAAC | ESO | 8.2 m | 1k x 1k | 0.147 | 0.00175 | 0.088 | operational mid-1999 |
| Gemini-NIRI f/6 | US-UK-Can | 8 m | 1k x 1k | 0.116 | 0.0011 | 0.055 | 2000-Q4 |
| UKIRT+UFTI | UK | 3.8 m | 1k x 1k | 0.05 | 0.00020 | 0.0023 | 1999 |
| VLT+NAOS | ESO | 8.2 m | 1kx1k | ≈ | ≈ | ≈ | |

(JL Beuzit)