Star Formation at Infrared Wavelengths

Infrared imaging and detectors

Jean-Louis Monin

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Introduction

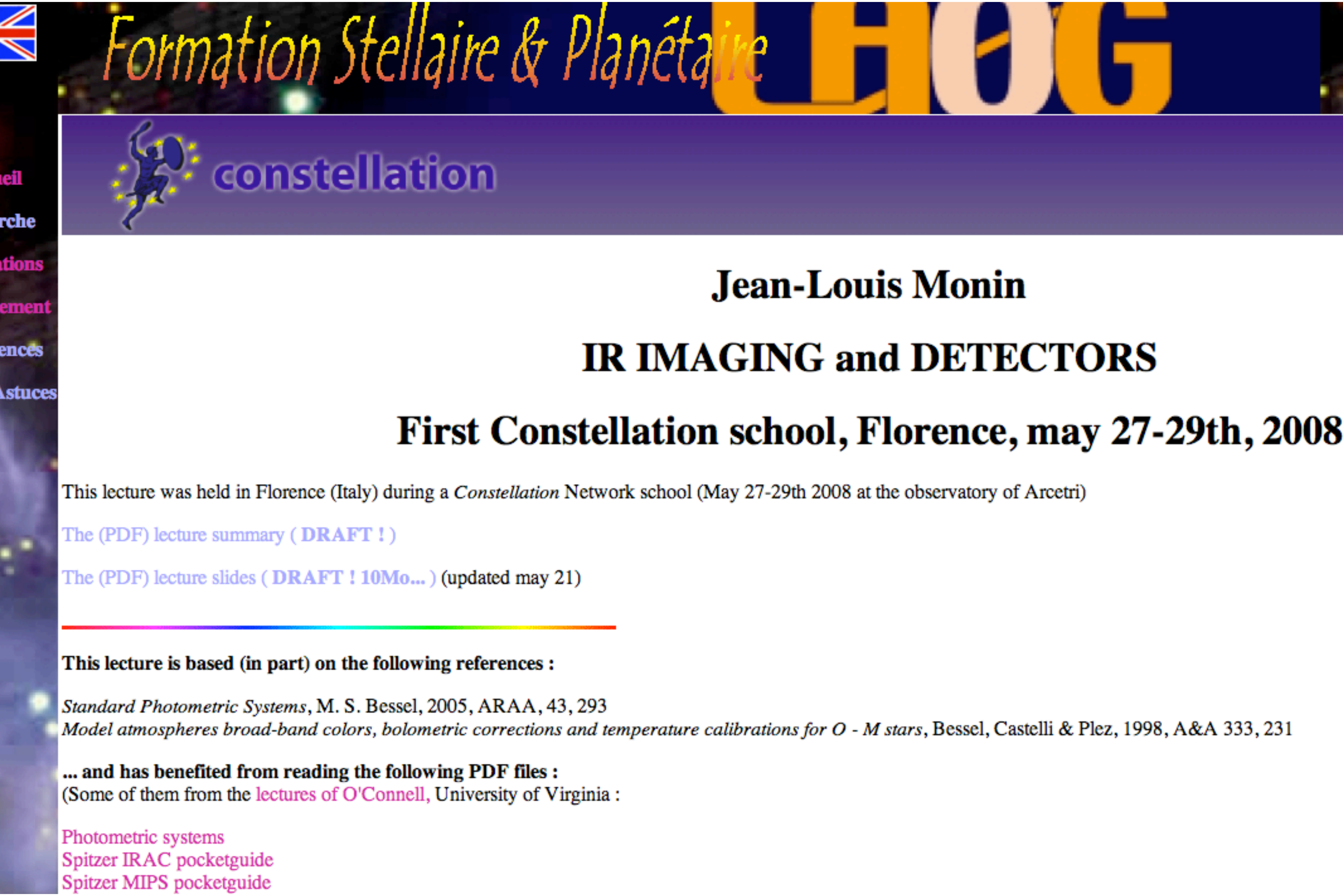
Magnitude systems

Atmospheric windows and imaging filters

The basics of detection

Flat-fielding and Calibration

Photons, electrons, noise and performances



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 λ :

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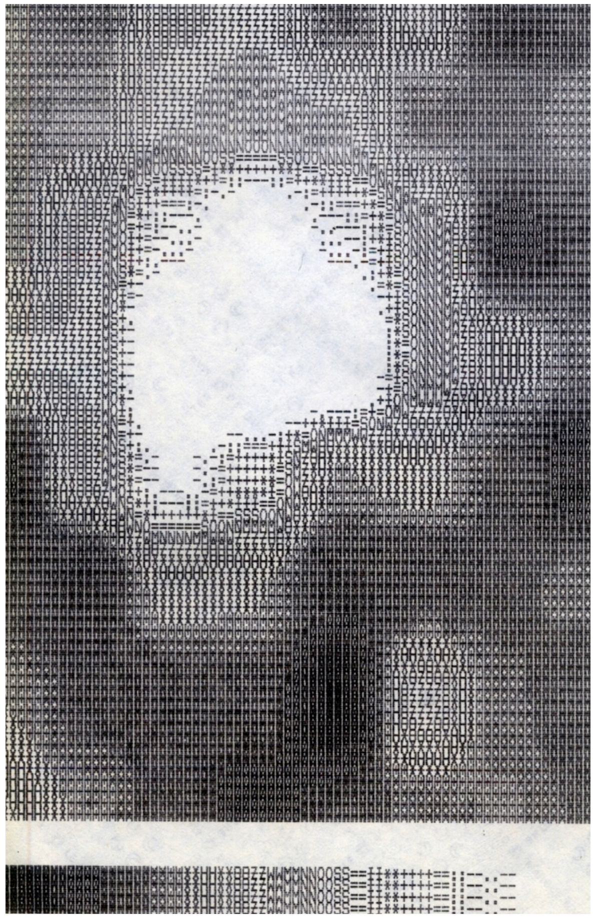

ORION BN
Nebula
(8x8)
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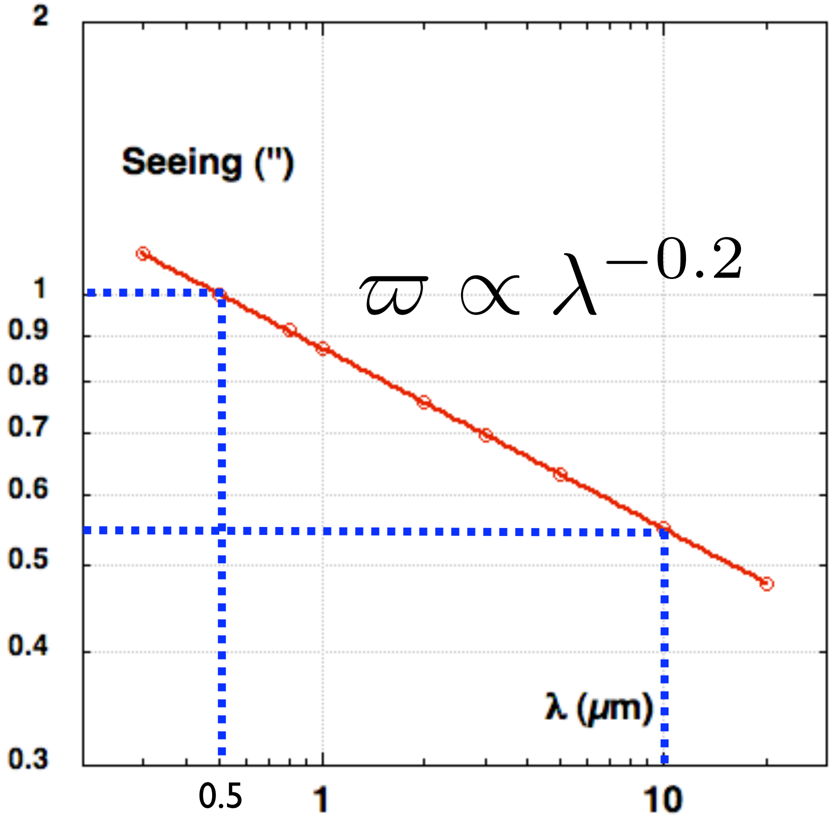

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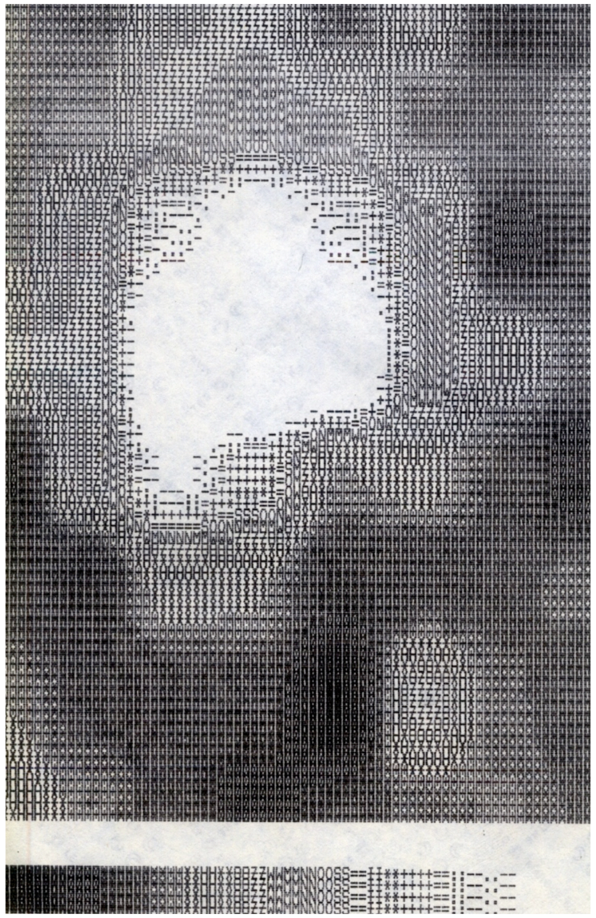

Magnitude systems

(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 λ
(be it for F_λ, flux per unit wavelength or F_ν, flux per unit frequency)

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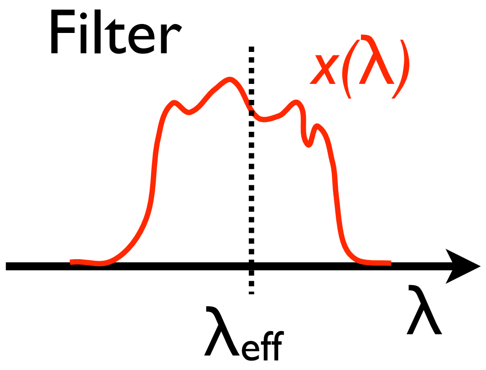
The Vega system



↓

Various reference fluxes F_o

(photon counting detectors)

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

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

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

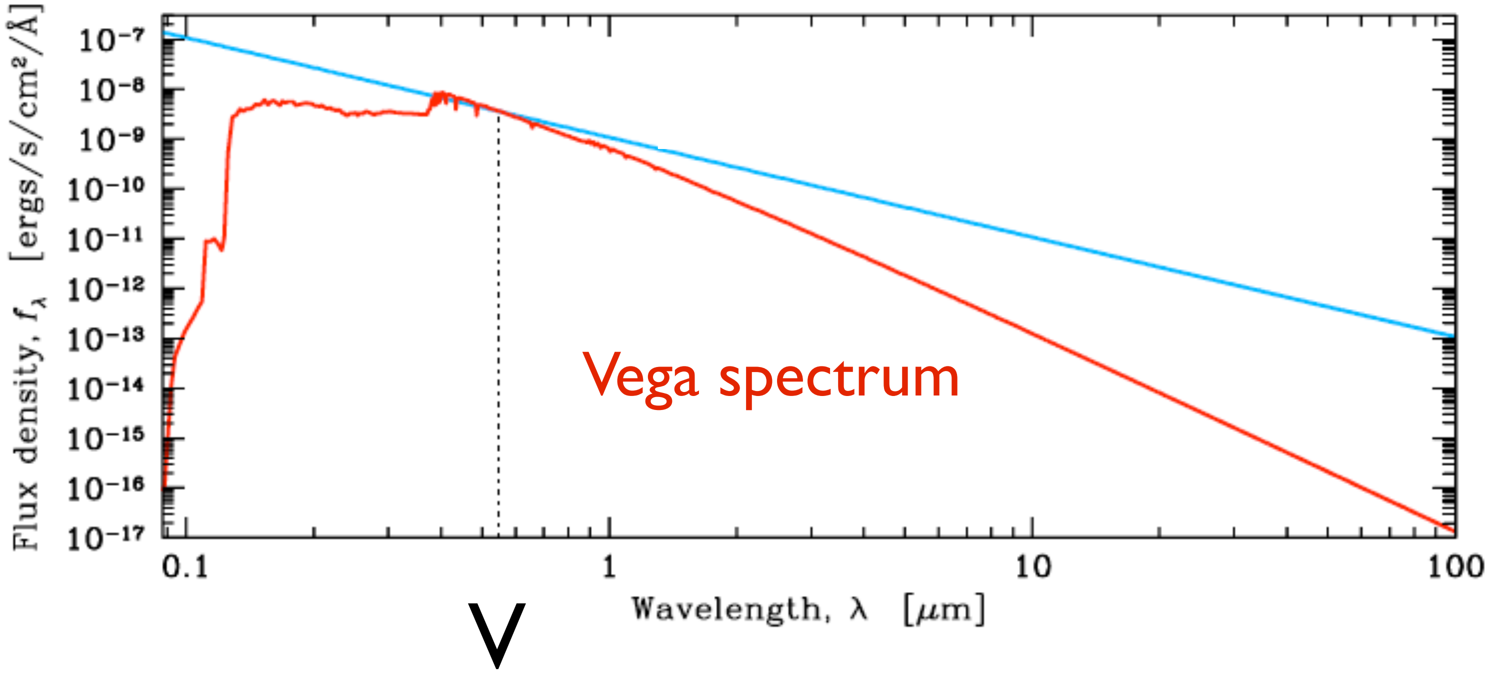
Average flux over the given filter

Reference flux

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

Zero mag fluxes in the Cousins - Glass - Johnson system (erg/cm^2/s/...)

		V	R	I	J	H	K	Kp	L	L*	M	N	Q
(μm)	λ_{eff}	0.545	0.641	0.798	1.22	1.63	2.19	2.12	3.45	3.80	4.80	10	20
× 10^{-20}	f_ν /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
× 10^{-11}	f_λ /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}



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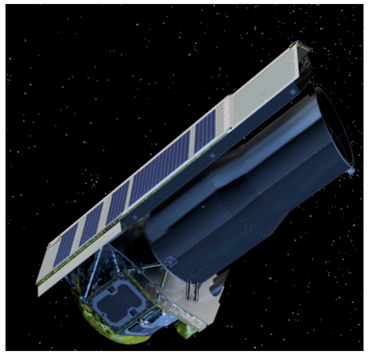
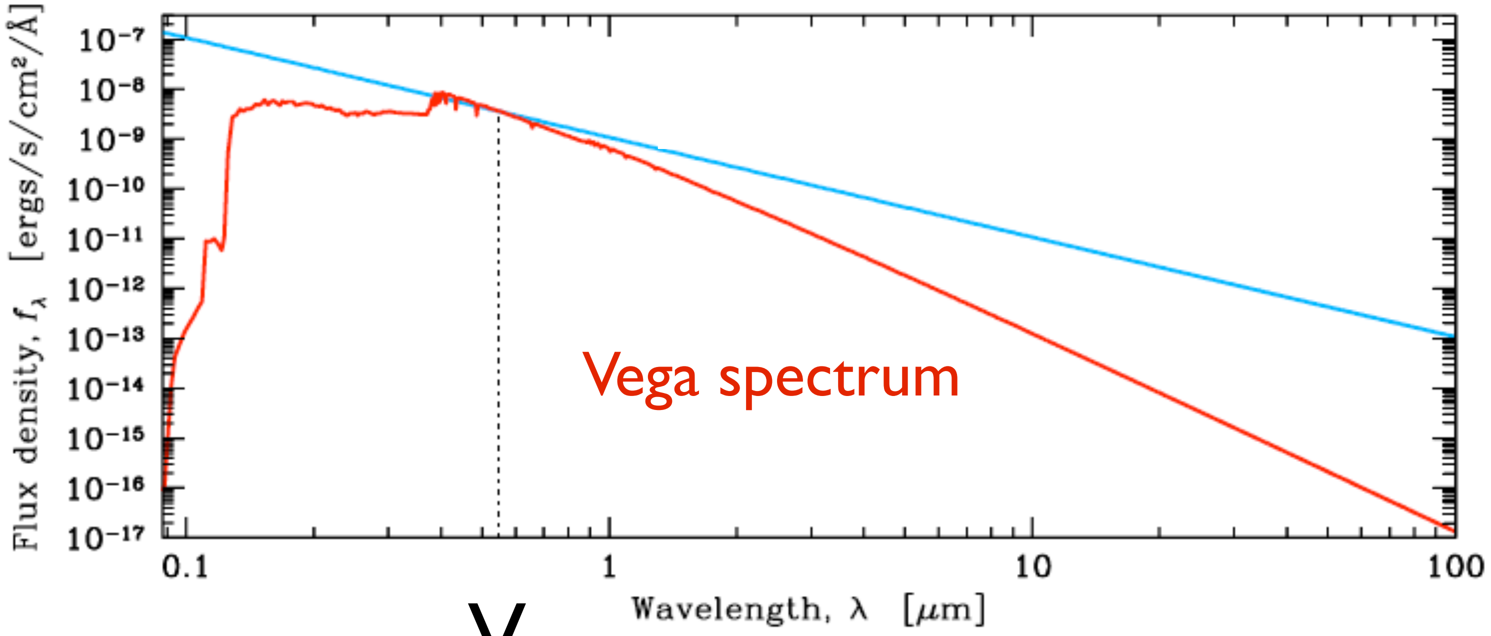




V

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

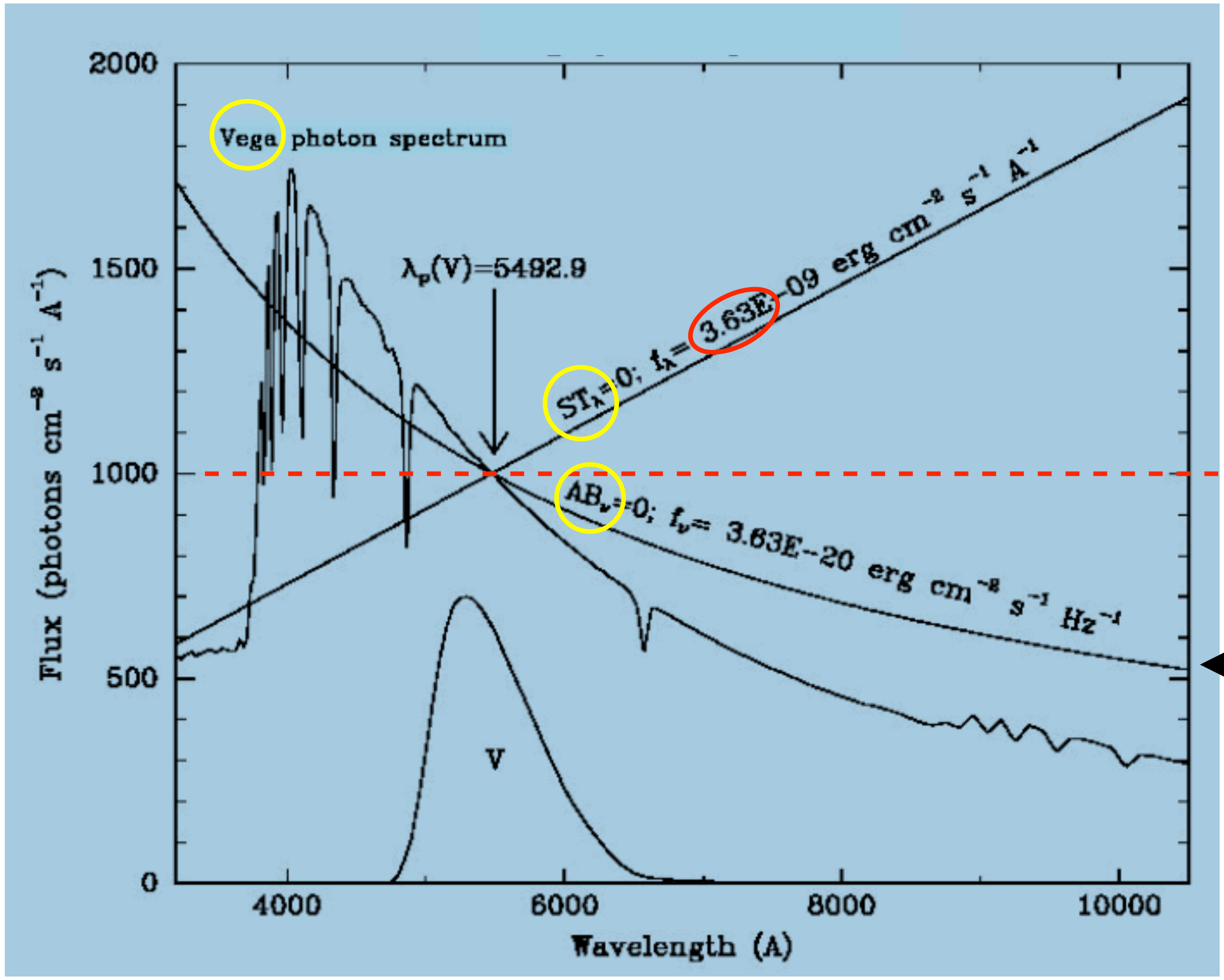
Oke & Gunn, 1983, ApJ, 266, 713

AB : $m_\nu(\lambda) = -2.5 \log F_\nu(\lambda) - 48.6$

ST : $m_\lambda(\lambda) = -2.5 \log F_\lambda(\lambda) - 21.1$

(HST STMAG)

crossing in V



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

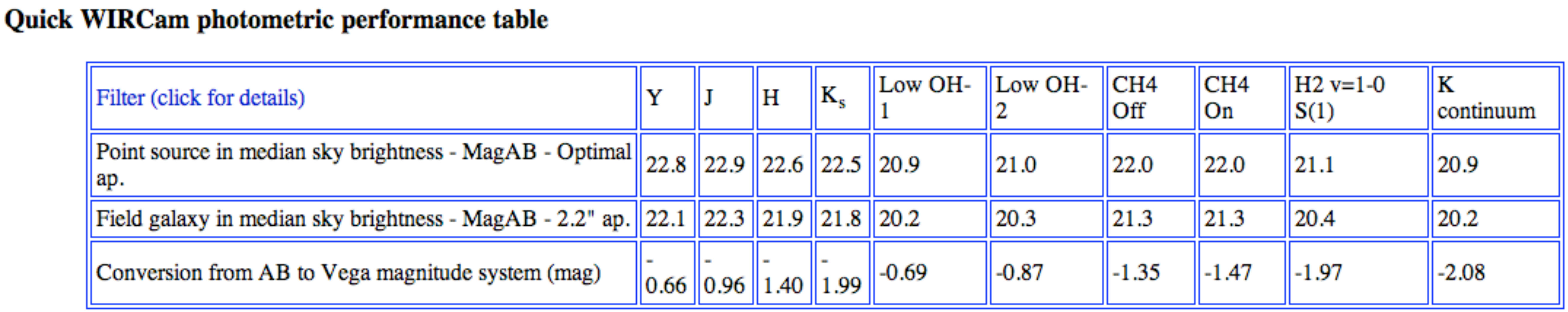
(constant flux F$_\nu$)

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

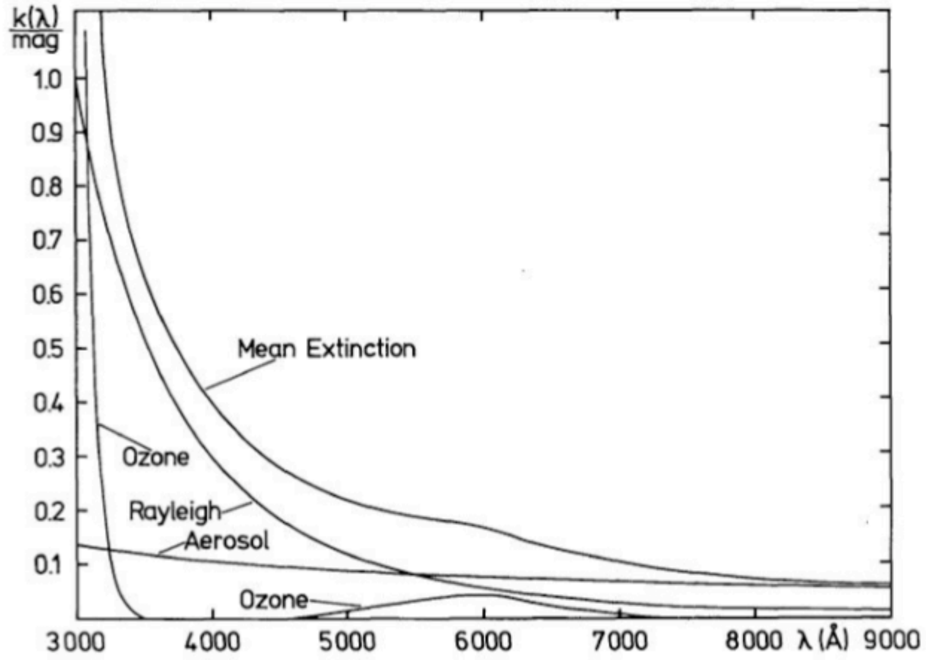
Filter (click for details)	Y	J	H	K_s	Low OH-1	Low OH-2	CH4 Off	CH4 On	H2 v=1-0 S(1)	K continuum
Point source in median sky brightness - MagAB - Optimal ap.	22.8	22.9	22.6	22.5	20.9	21.0	22.0	22.0	21.1	20.9
Field galaxy in median sky brightness - MagAB - 2.2" ap.	22.1	22.3	21.9	21.8	20.2	20.3	21.3	21.3	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

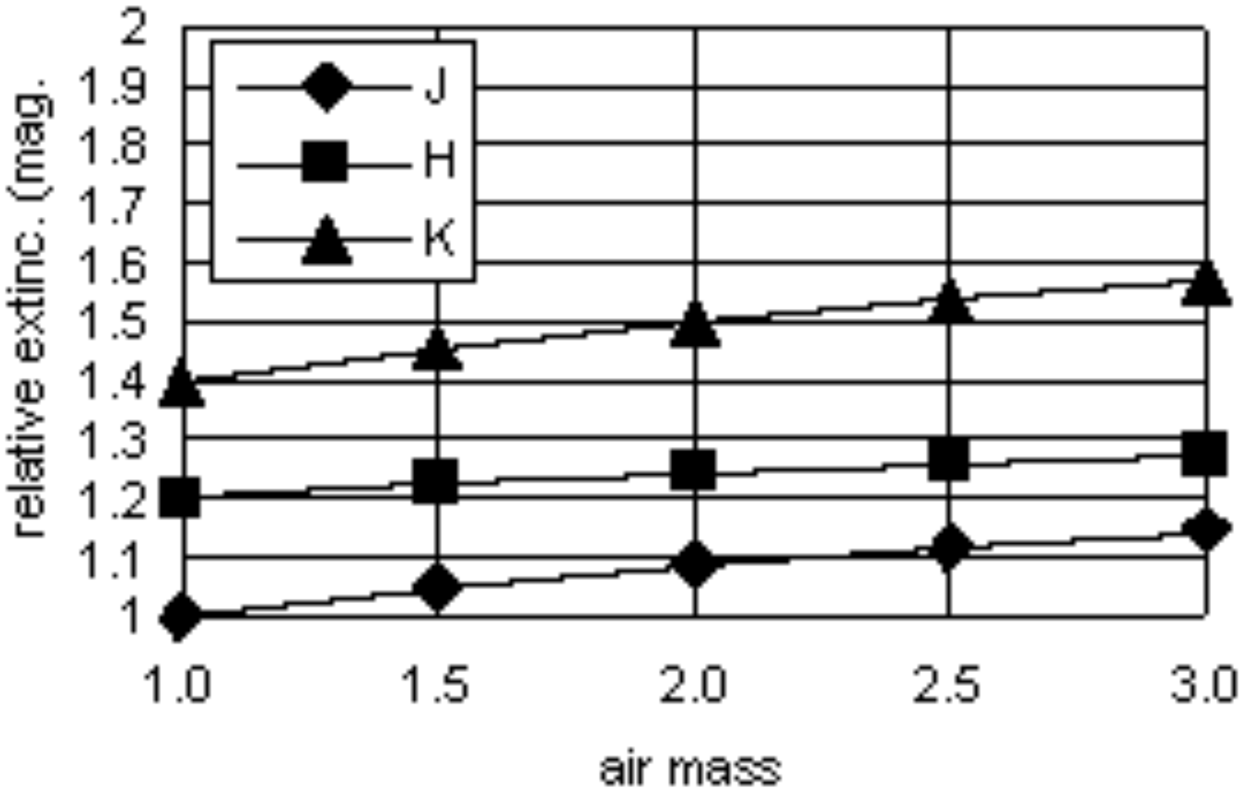
From under to above the atmosphere

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

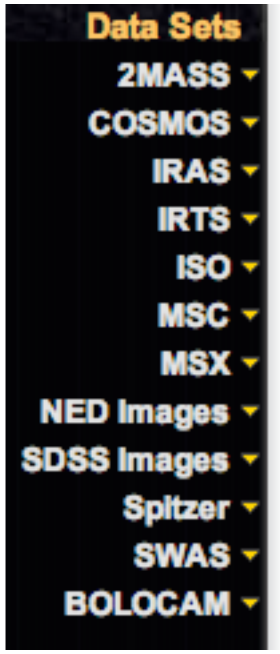
ISO : map selected areas. ISOCam : 2.5 - 5.2 μm & 4-18 μm.

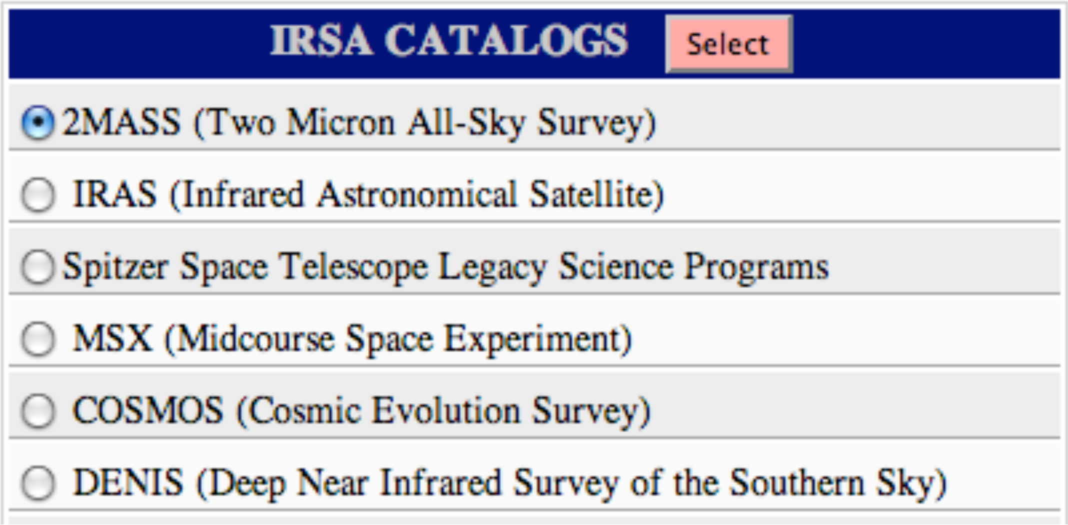
Kessler, 2001, ESA-SP, 460, 53

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/



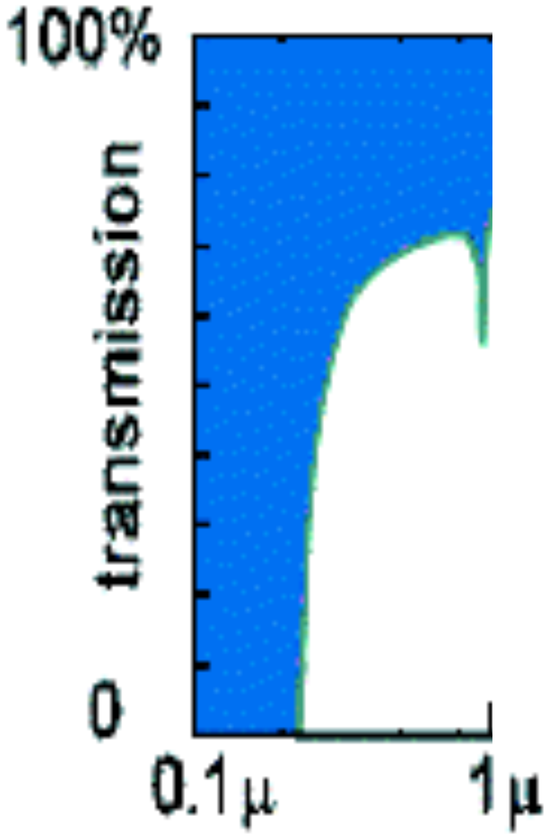


● 2MASS (Two Micron All-Sky Survey)
○ IRAS (Infrared Astronomical Satellite)
○ Spitzer Space Telescope Legacy Science Programs
○ MSX (Midcourse Space Experiment)
○ COSMOS (Cosmic Evolution Survey)
○ DENIS (Deep Near Infrared Survey of the Southern Sky)

Atmospheric windows and imaging filters

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

- the atmosphere is “uniformly” transparent from 0.3μm to 1μm.
- 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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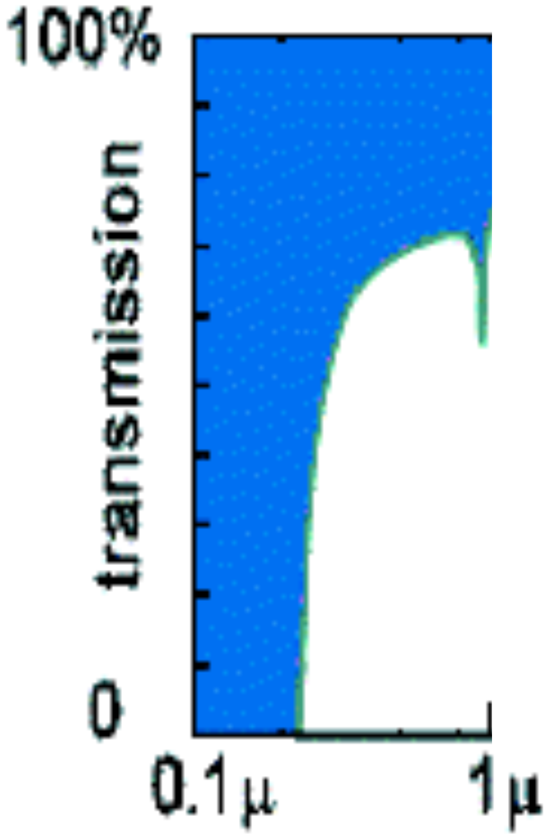

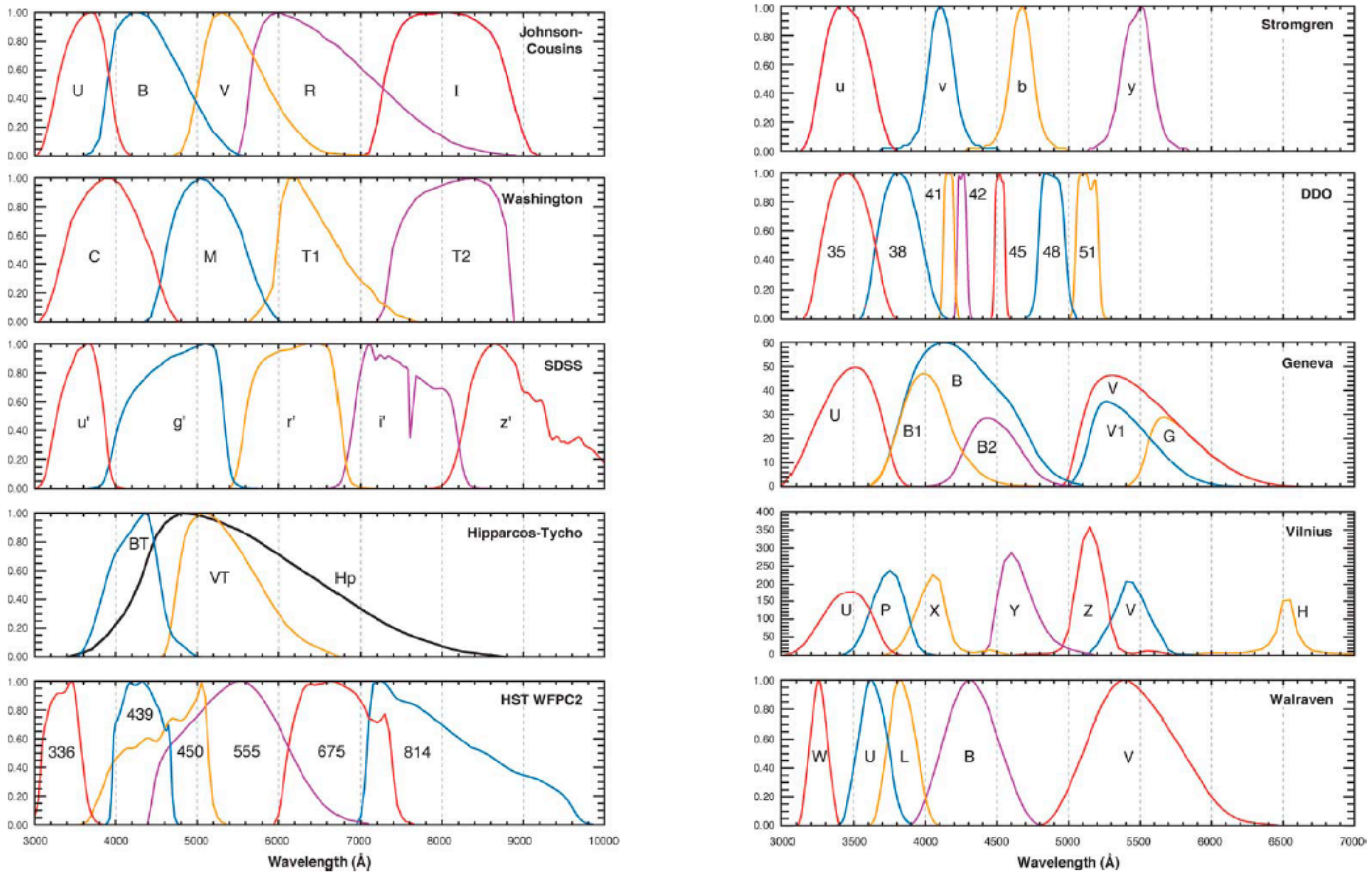

Bessel, 2005

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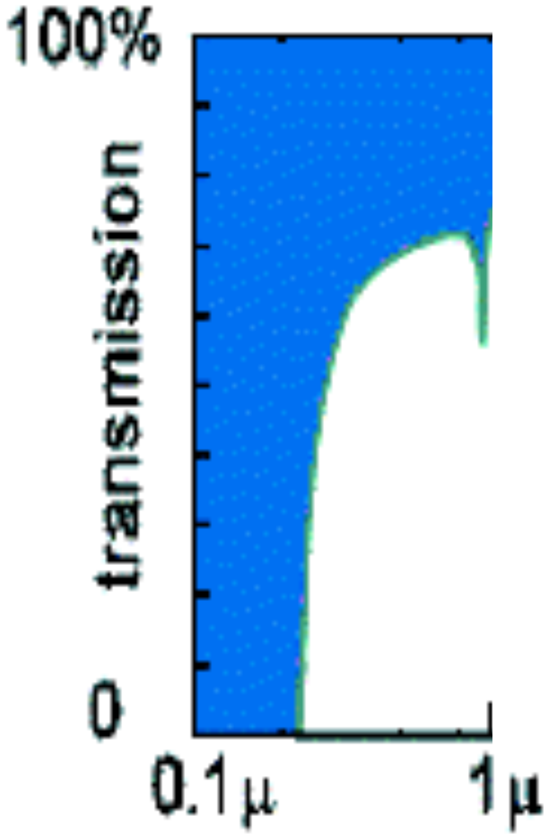

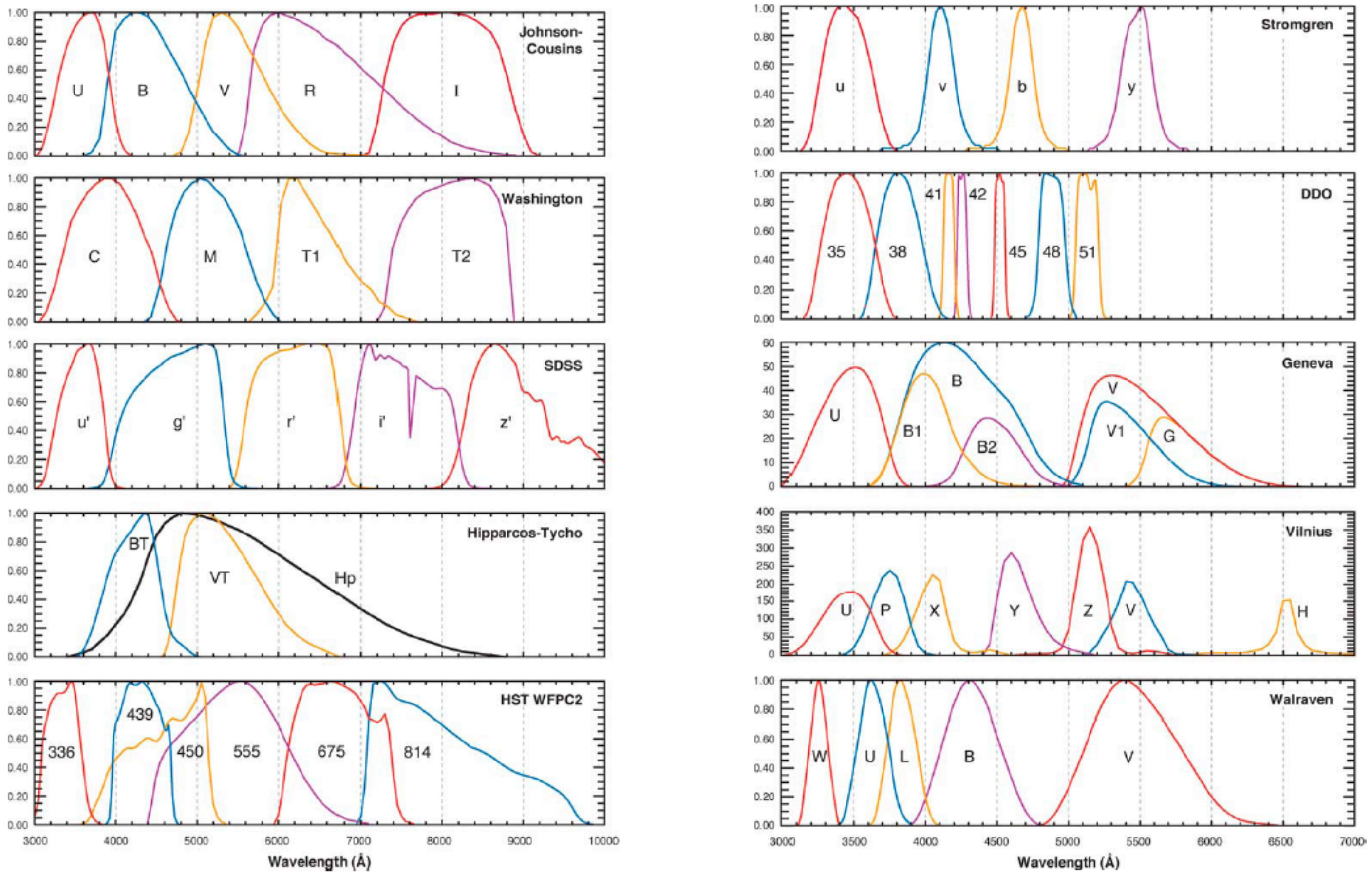

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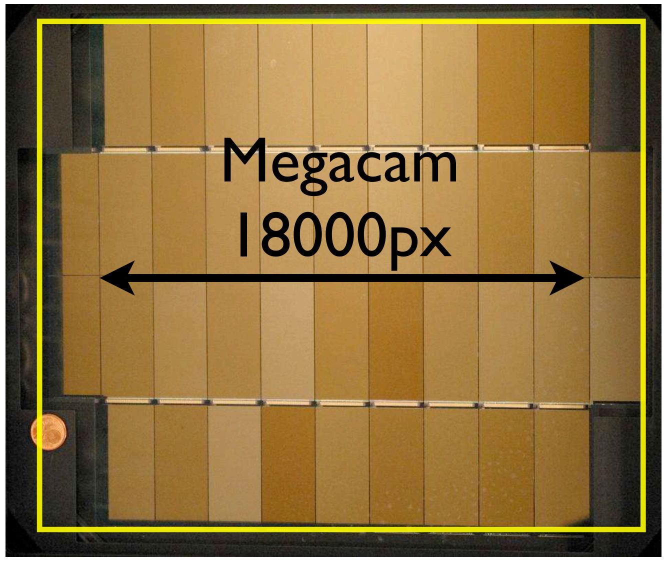
CFHT



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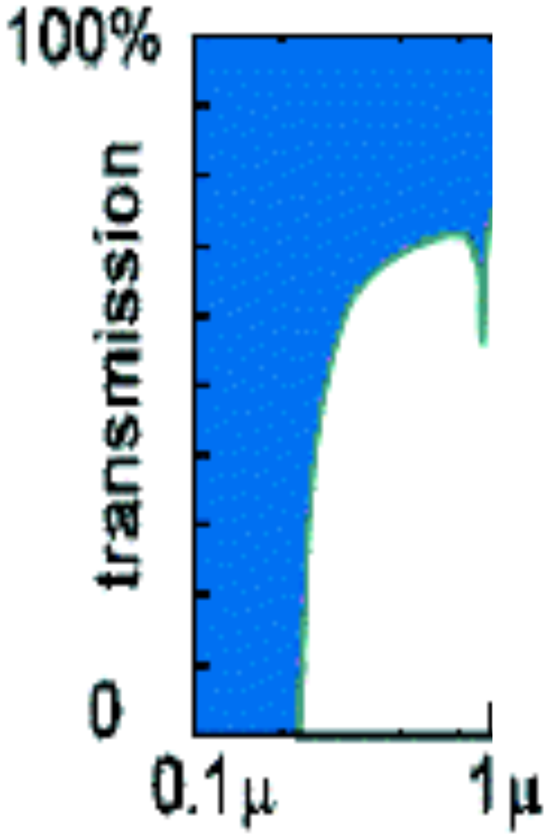

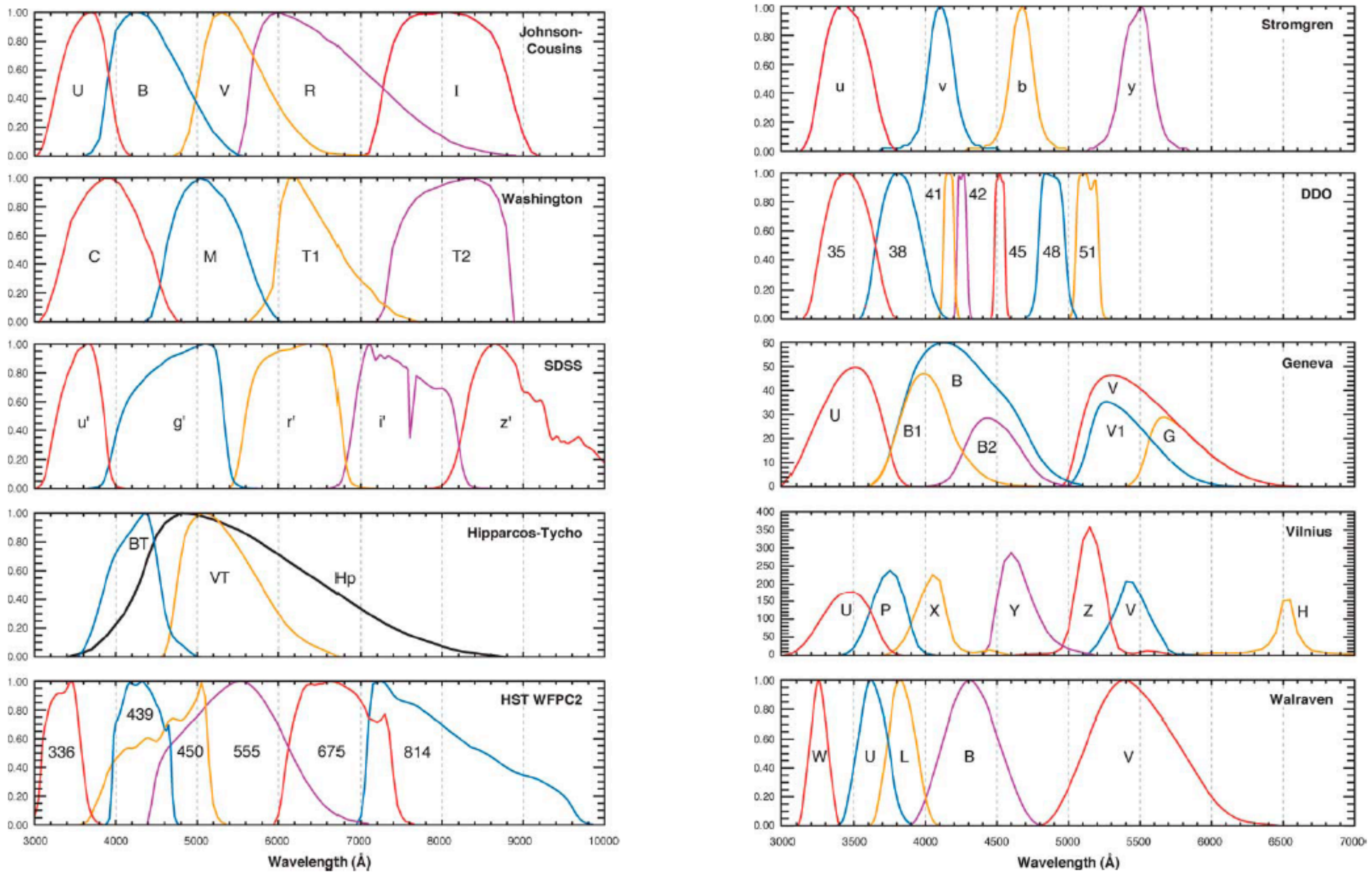

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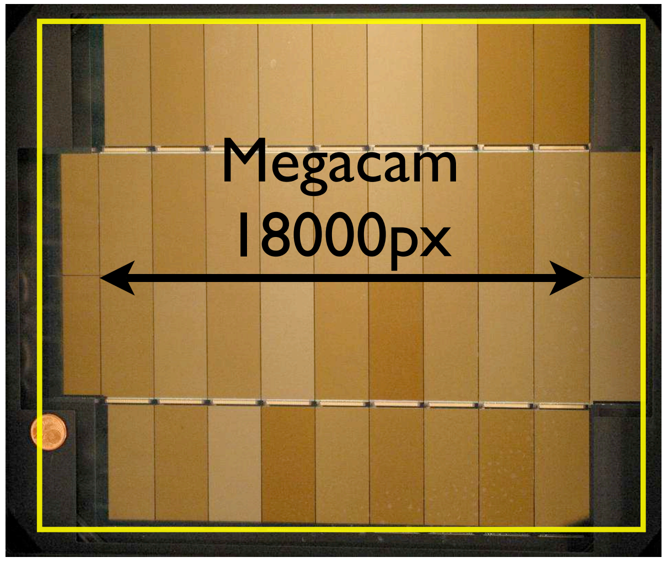
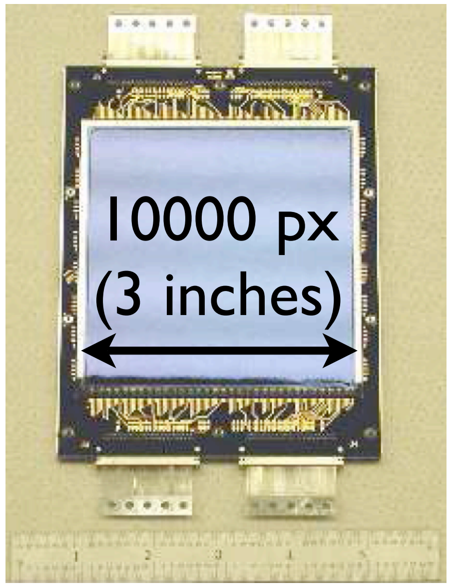
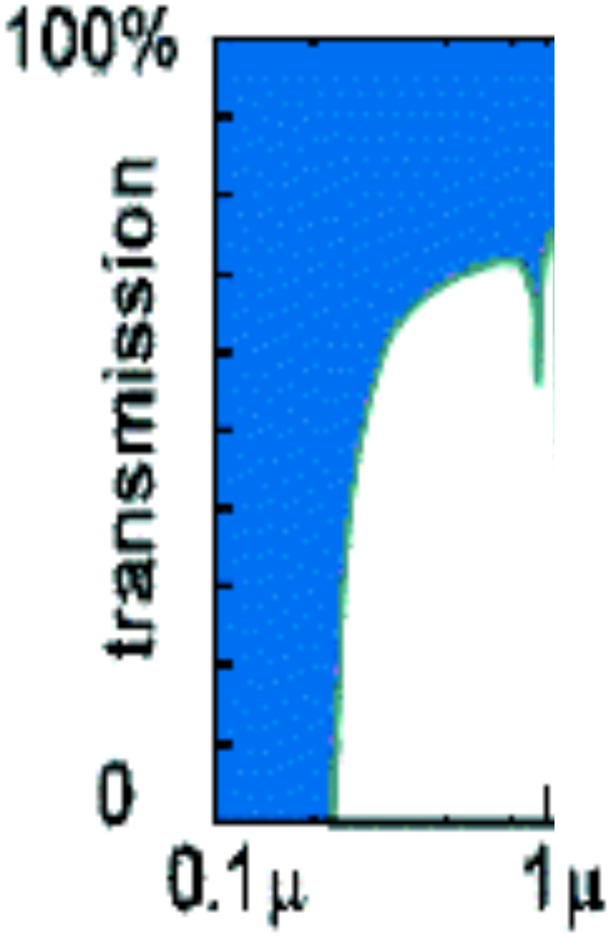




Zacharias et al., 2007, SPIE, 6690

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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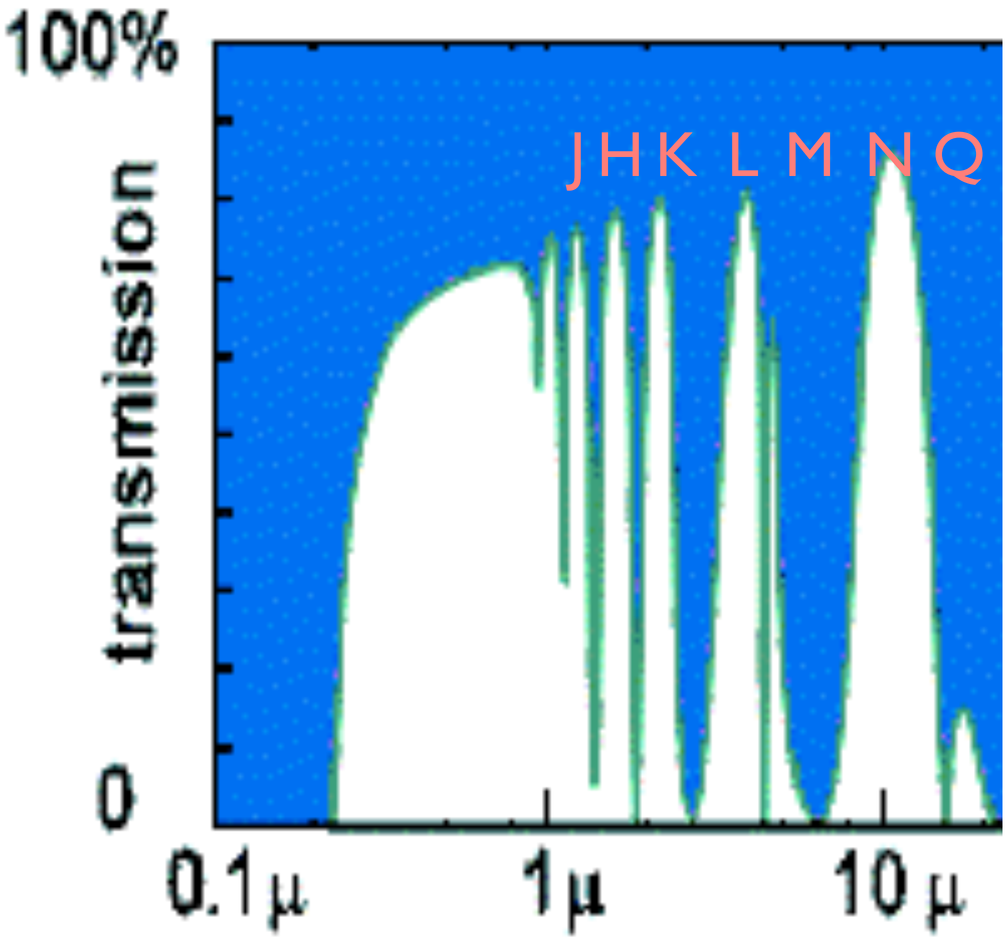

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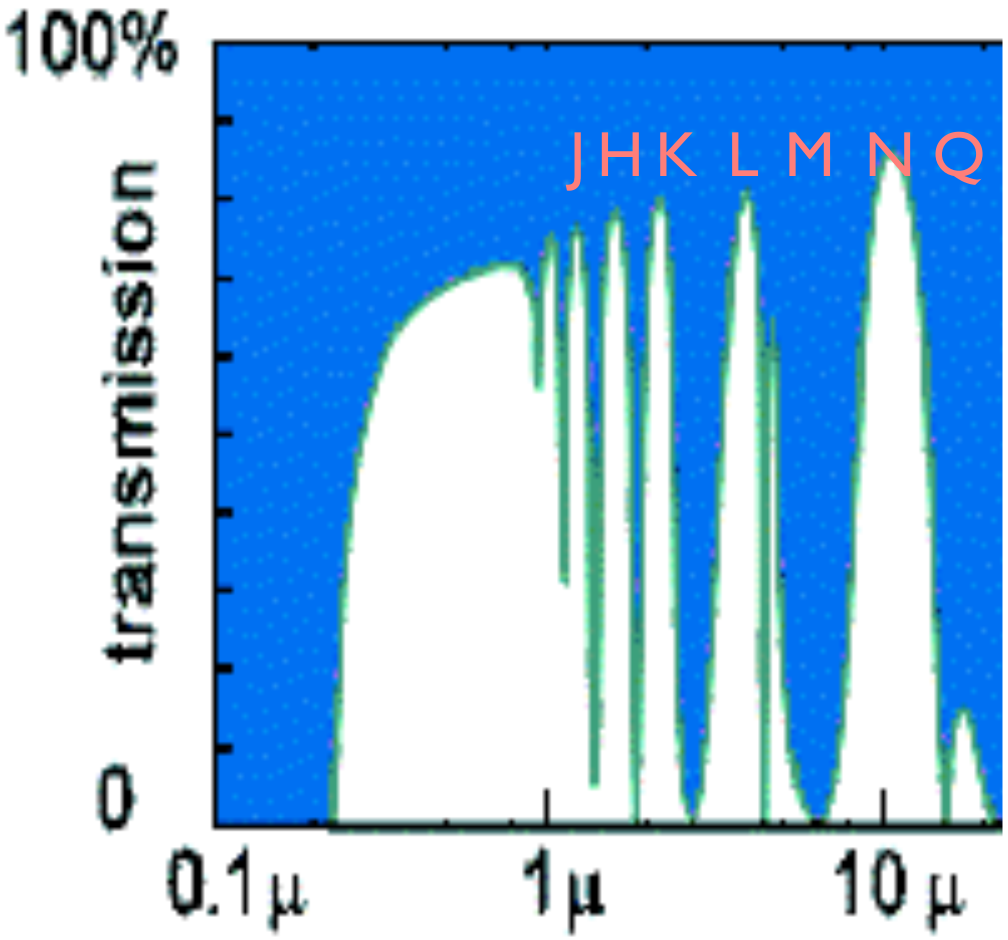
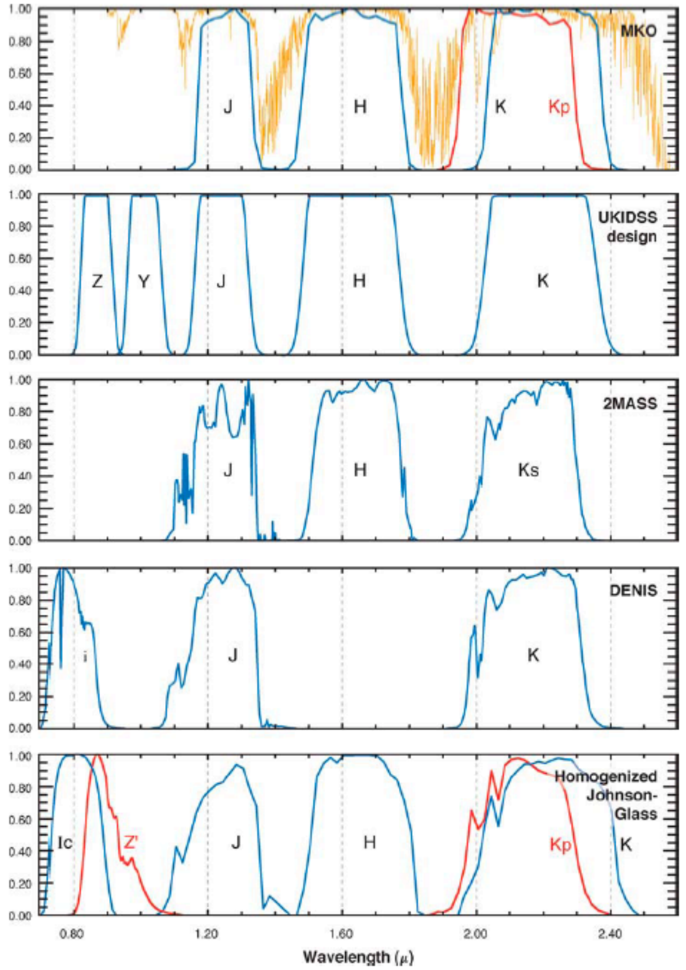
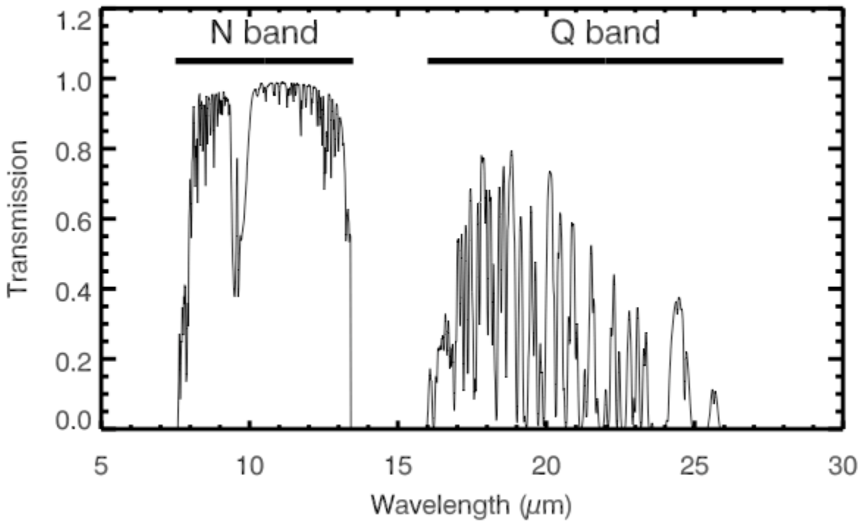




MIR atmosphere transmission at Paranal



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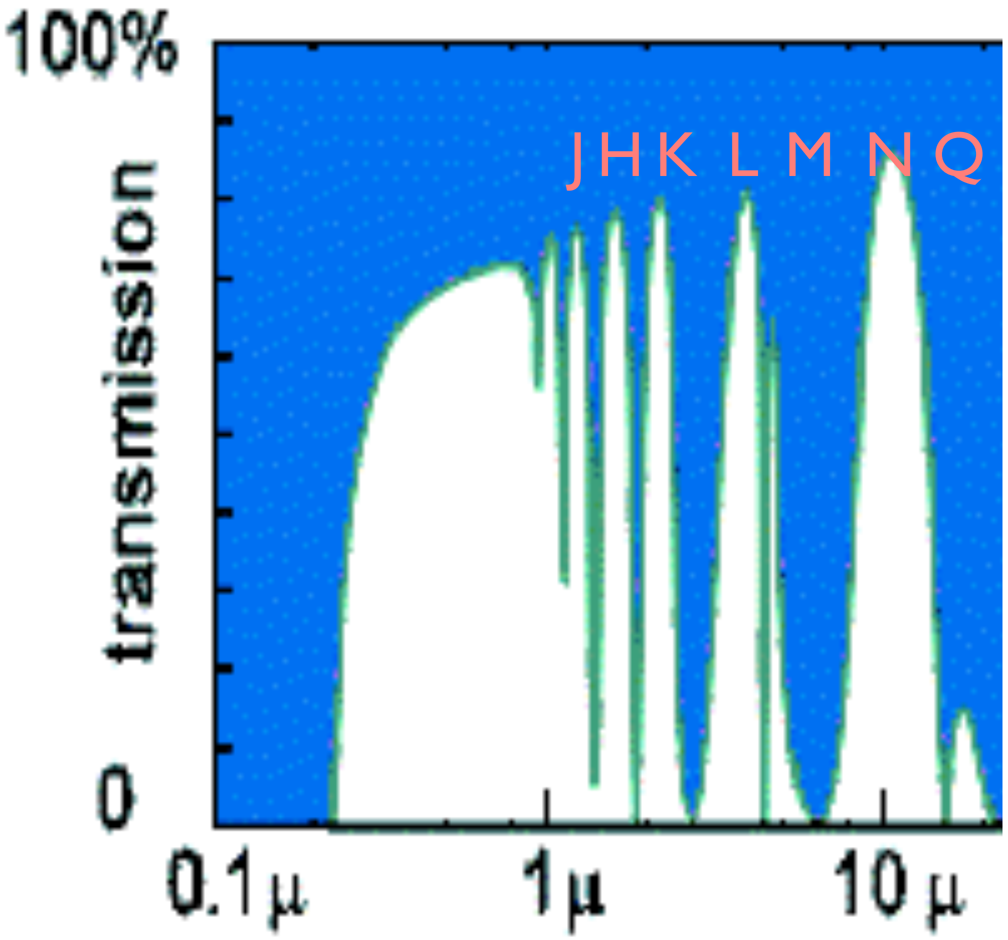
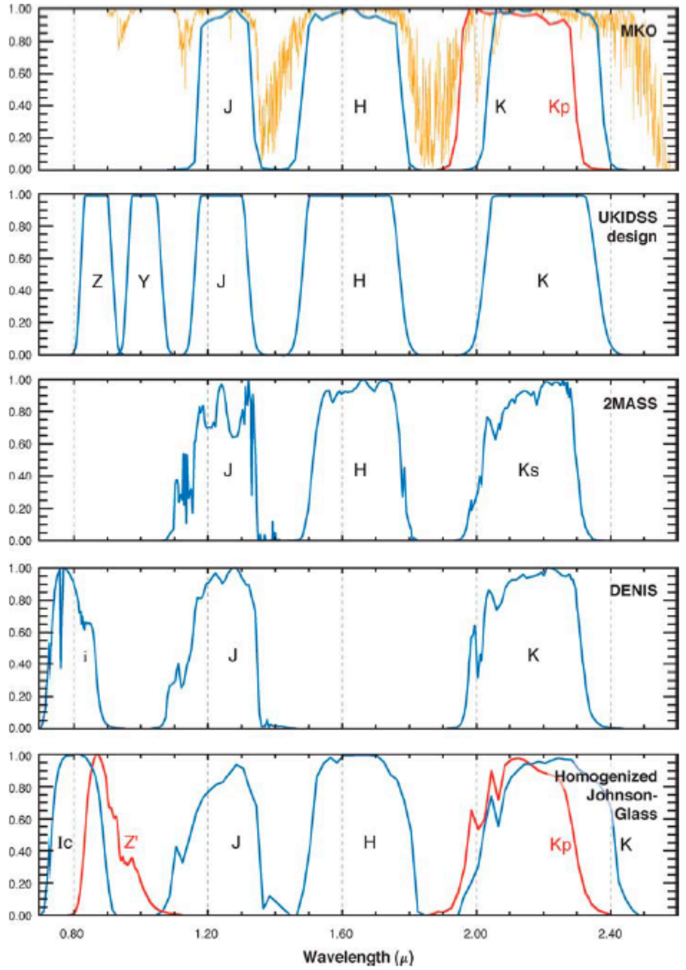
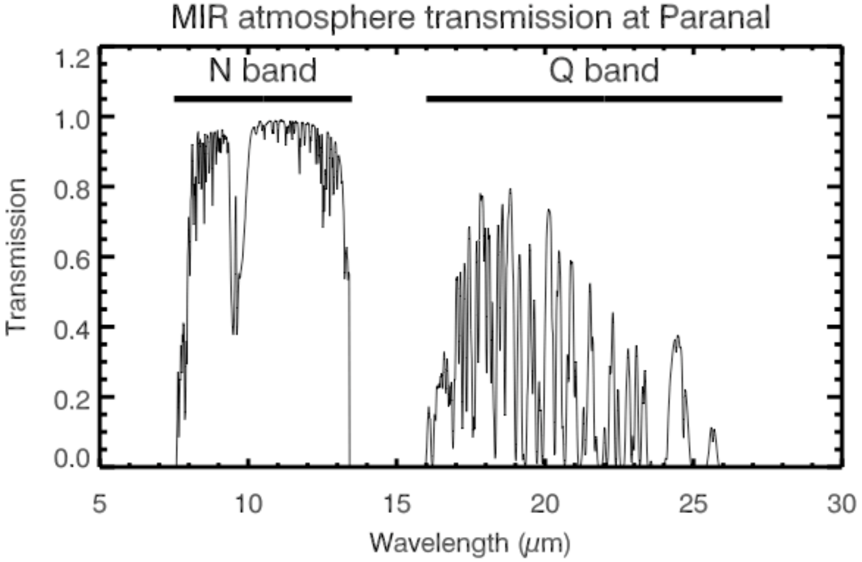
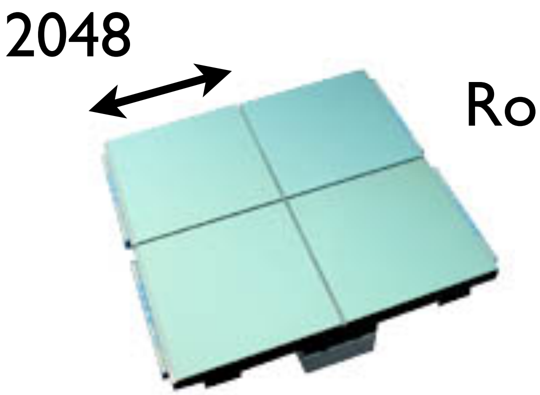








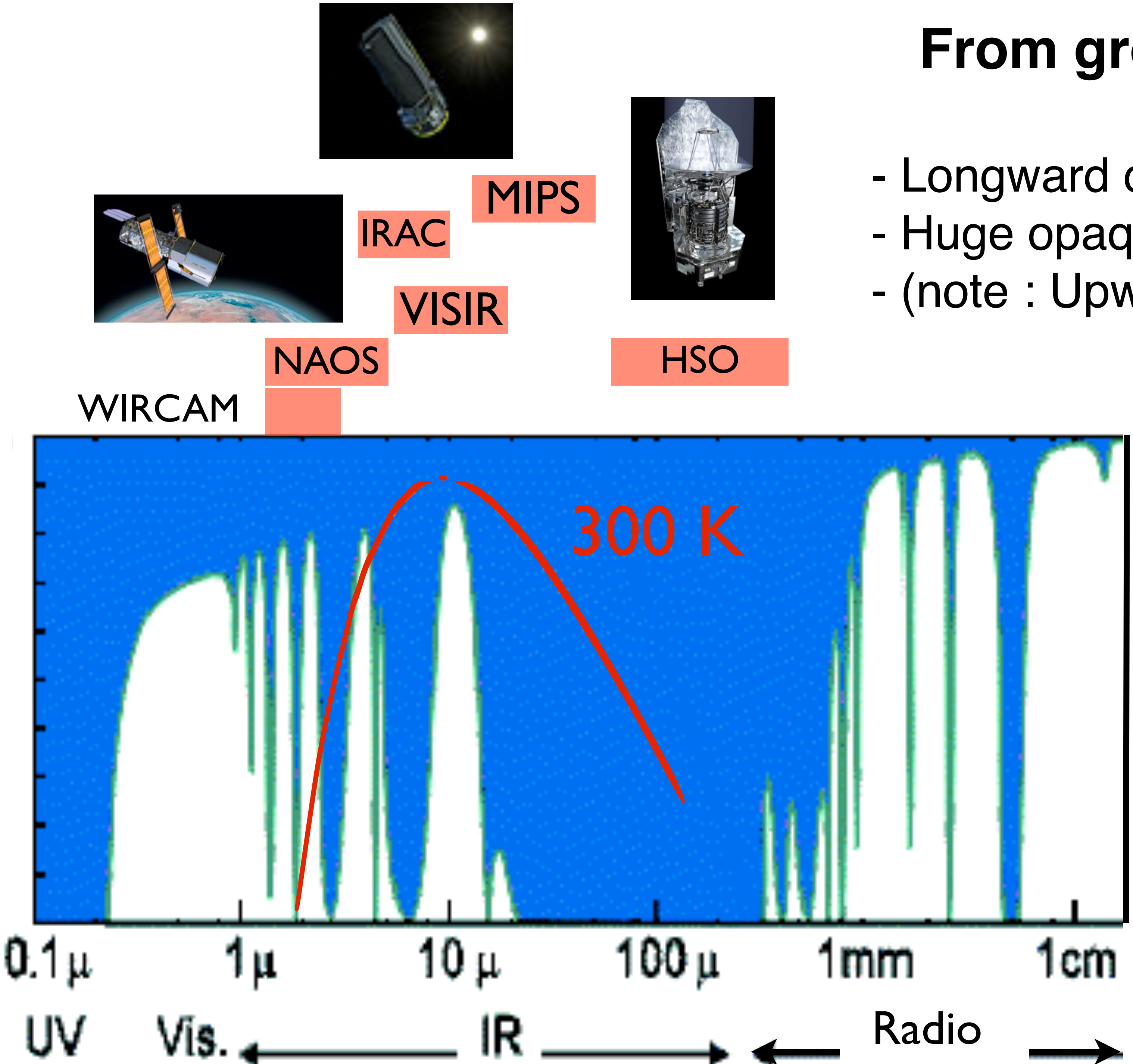
HAWAII-2RG
Rockwell (Teledyne) detector

(JWST)

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

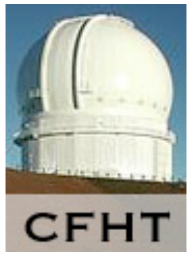
From ground-based to Spatial imaging

- Longward of 2μm : the atmosphere begins to “glow”
- Huge opaque “wall” exist between 20 and 500μm
- (note : Upward 300μm -> *sub-millimeter*)



VLT

IRAM



UKIRT

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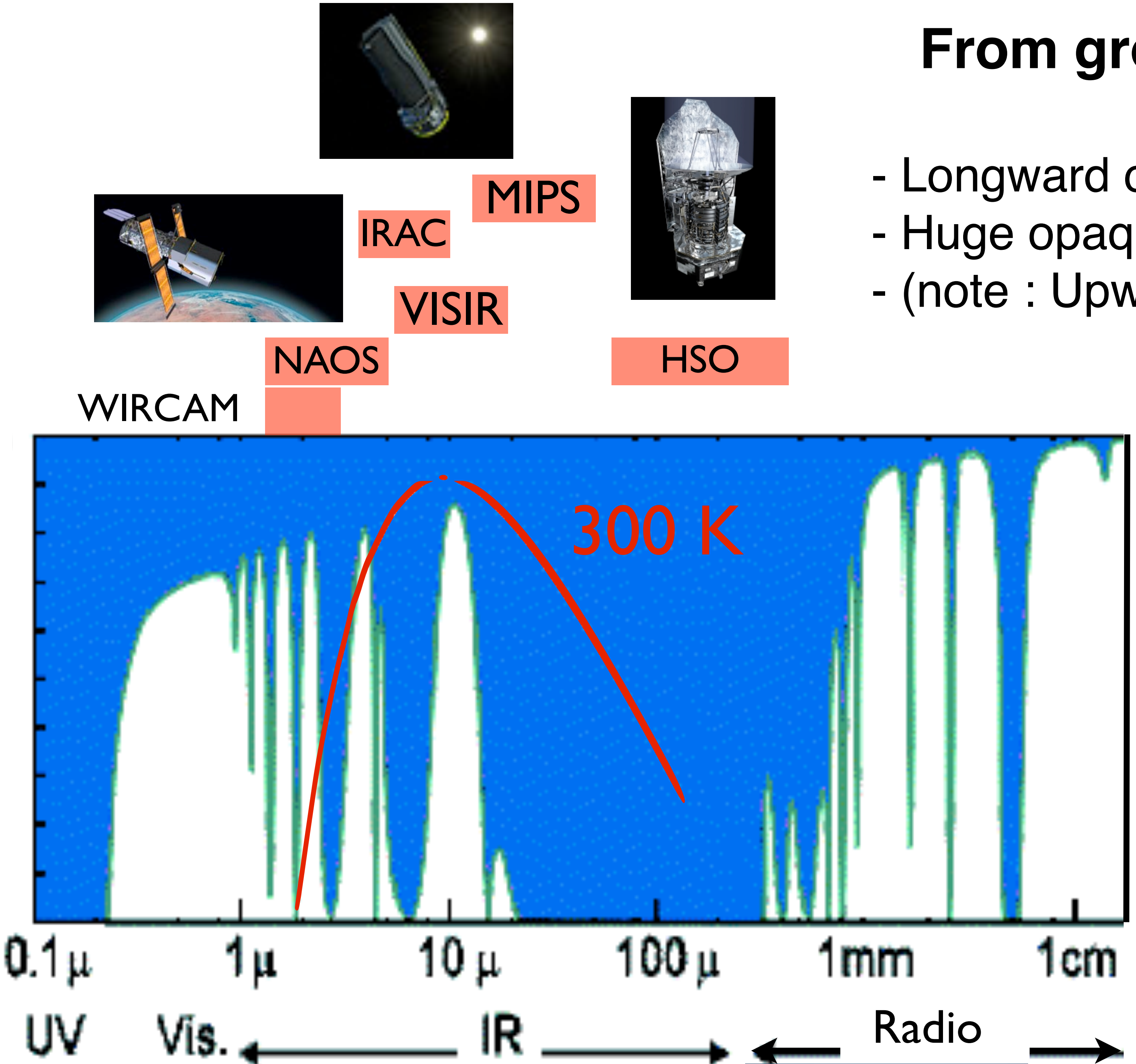

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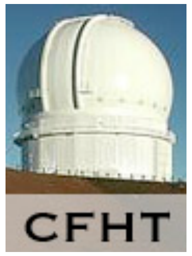

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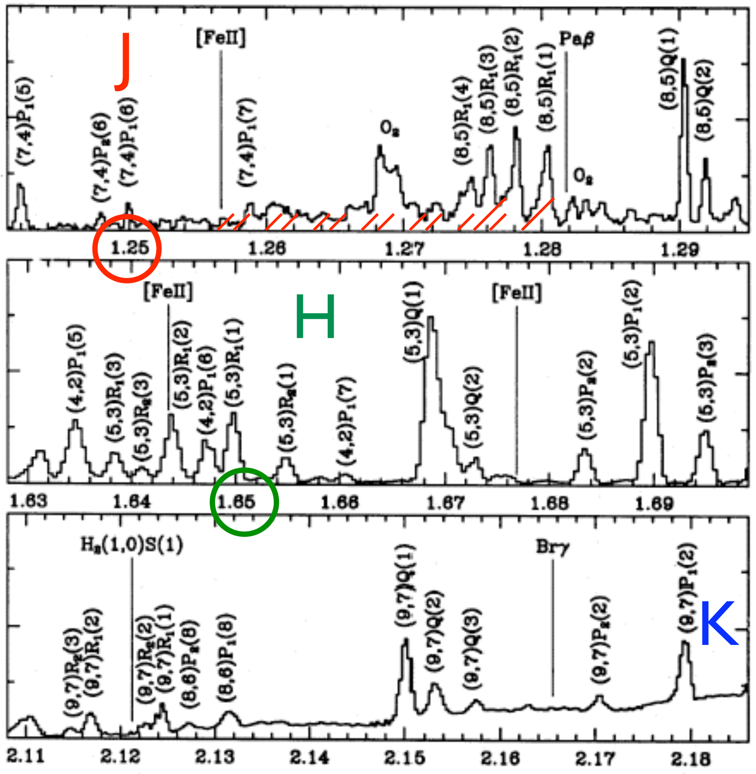
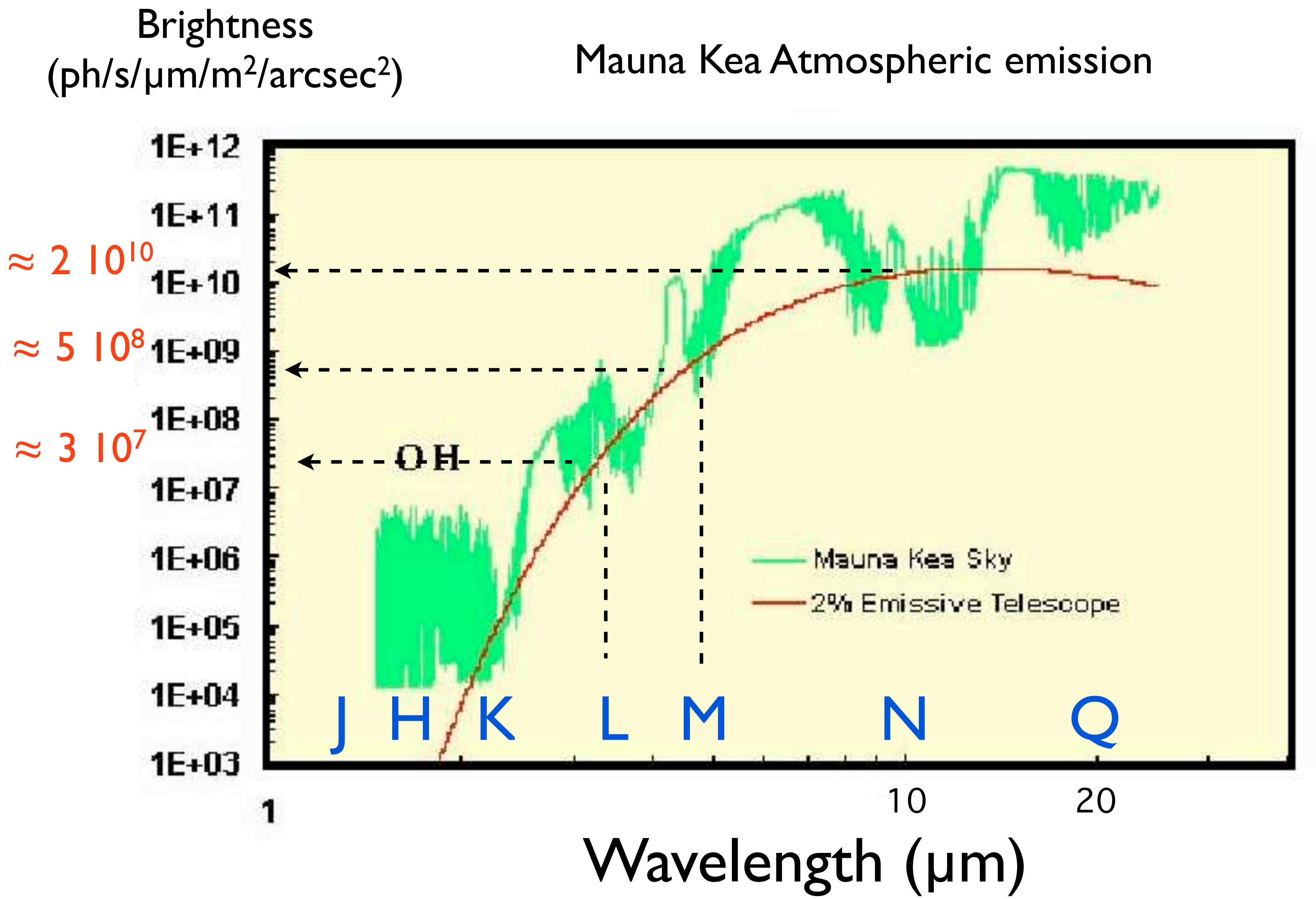


Oliva and Origlia (1992), A&A 254, 466

Looking through the atmosphere : transmission AND emission



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

La Silla

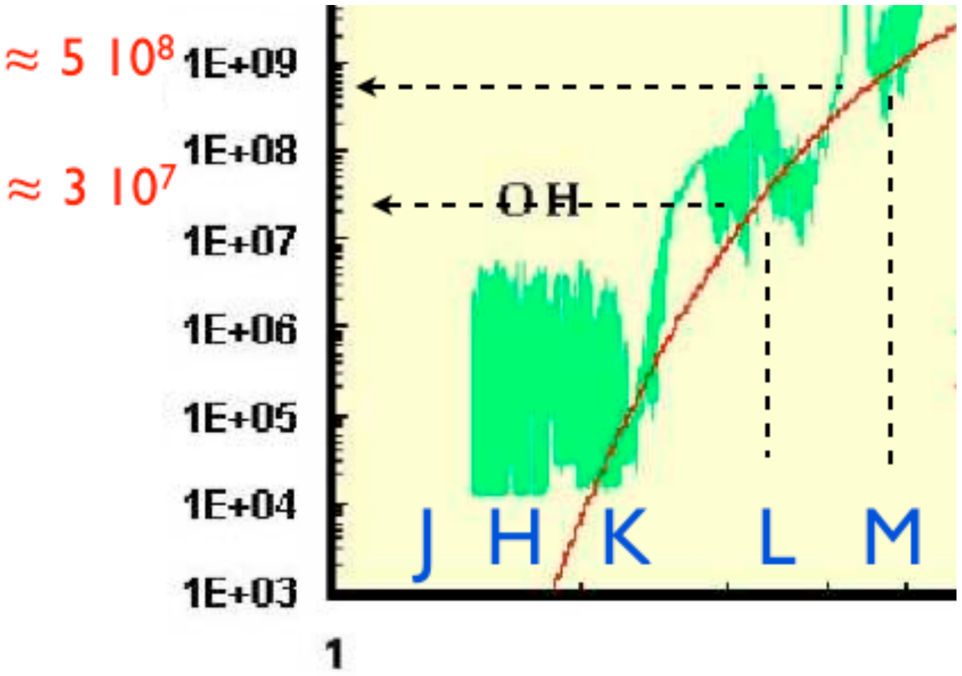
Band	Mag/"2
U	22
B	23
V	22
R	21
I	20
J	15.2
H	13.6
K_S	12.7
K	12.3
L	4.3
M	0.2
N	-6.4
Q	-8.5

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

$$\begin{aligned} m = 0 \rightarrow f_\lambda &= 0.708\,10^{-11}\,\mathrm{erg/s/cm^2/\mathring{A}} = 0.708\,10^{-10}\,W/\mathrm{m^2/\mu m} && (1)\\ m = 0 \rightarrow N_\lambda^o &= 1.2\,10^9\,\mathrm{ph/s/m^2/\mu m} && (2)\\ m = 4.3 \rightarrow N_\lambda^m &= 10^{-4.3/2.5} \times 1.2\,10^9 = 3\,10^7\,\mathrm{ph/s/m^2/\mu m} && (3) \end{aligned}$$

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

$$\begin{aligned} m = 0 \rightarrow f_\lambda &= 0.20\,10^{-11}\,\mathrm{erg/s/cm^2/\mathring{A}} = 0.20\,10^{-10}\,W/\mathrm{m^2/\mu m} && (4)\\ m = 0 \rightarrow N_\lambda^o &= 4.8\,10^8\,\mathrm{ph/s/m^2/\mu m} && (5)\\ m = 0.2 \rightarrow N_\lambda^m &= 10^{-0.2/2.5} \times 4.8\,10^8 = 4\,10^8\,\mathrm{ph/s/m^2/\mu m} && (6) \end{aligned}$$

Comparing source photons with background photons

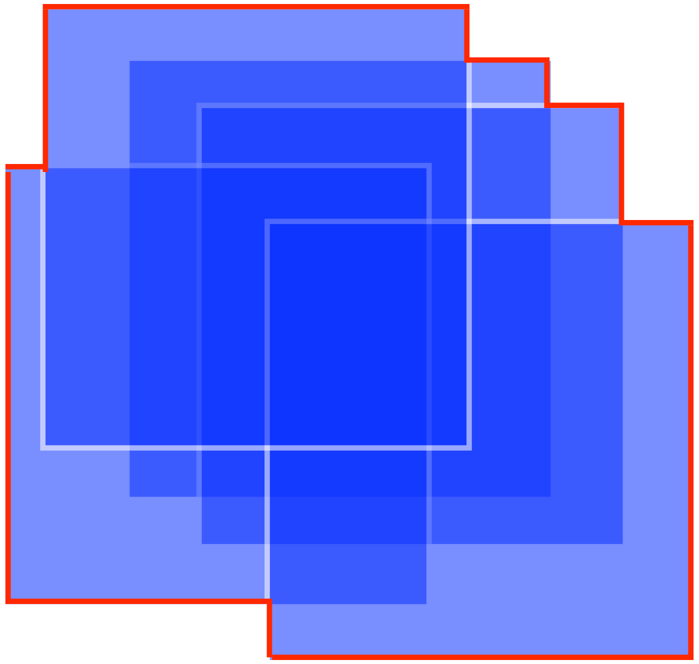
Band	Mag/"^{2}
U	22
B	23
V	22
R	21
I	20
J	15.2
H	13.6
K_S	12.7
K	12.3
L	4.3
M	0.2
N	-6.4
Q	-8.5

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

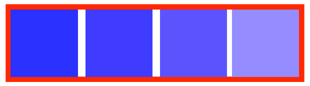


N (odd) frames, α & δ offsets

Median filtering → sky emission

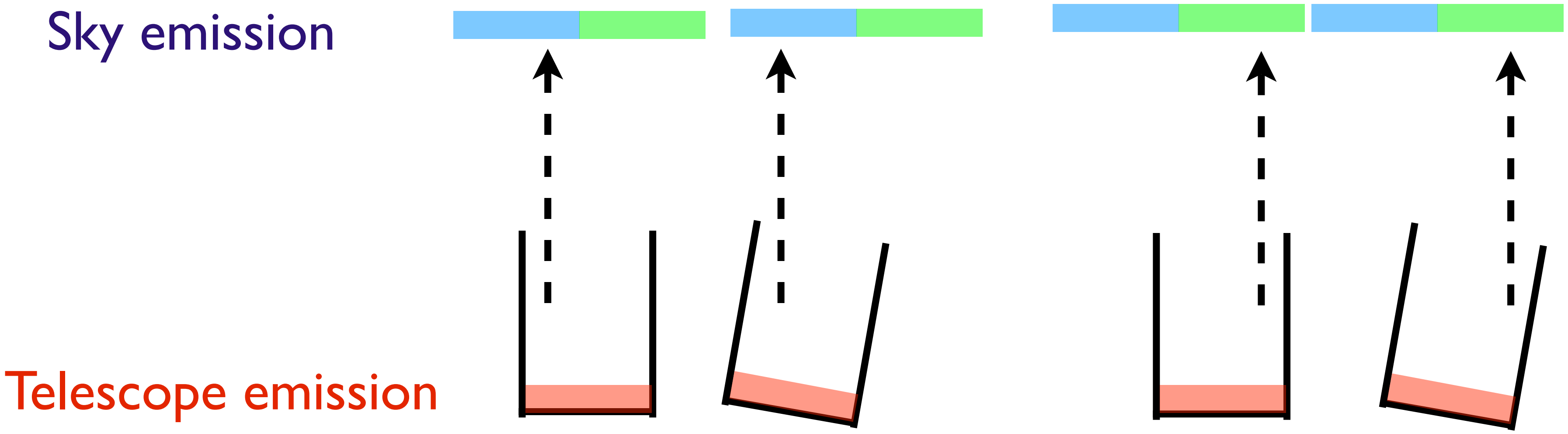
Sky subtraction

! SNR is not uniform across the total field



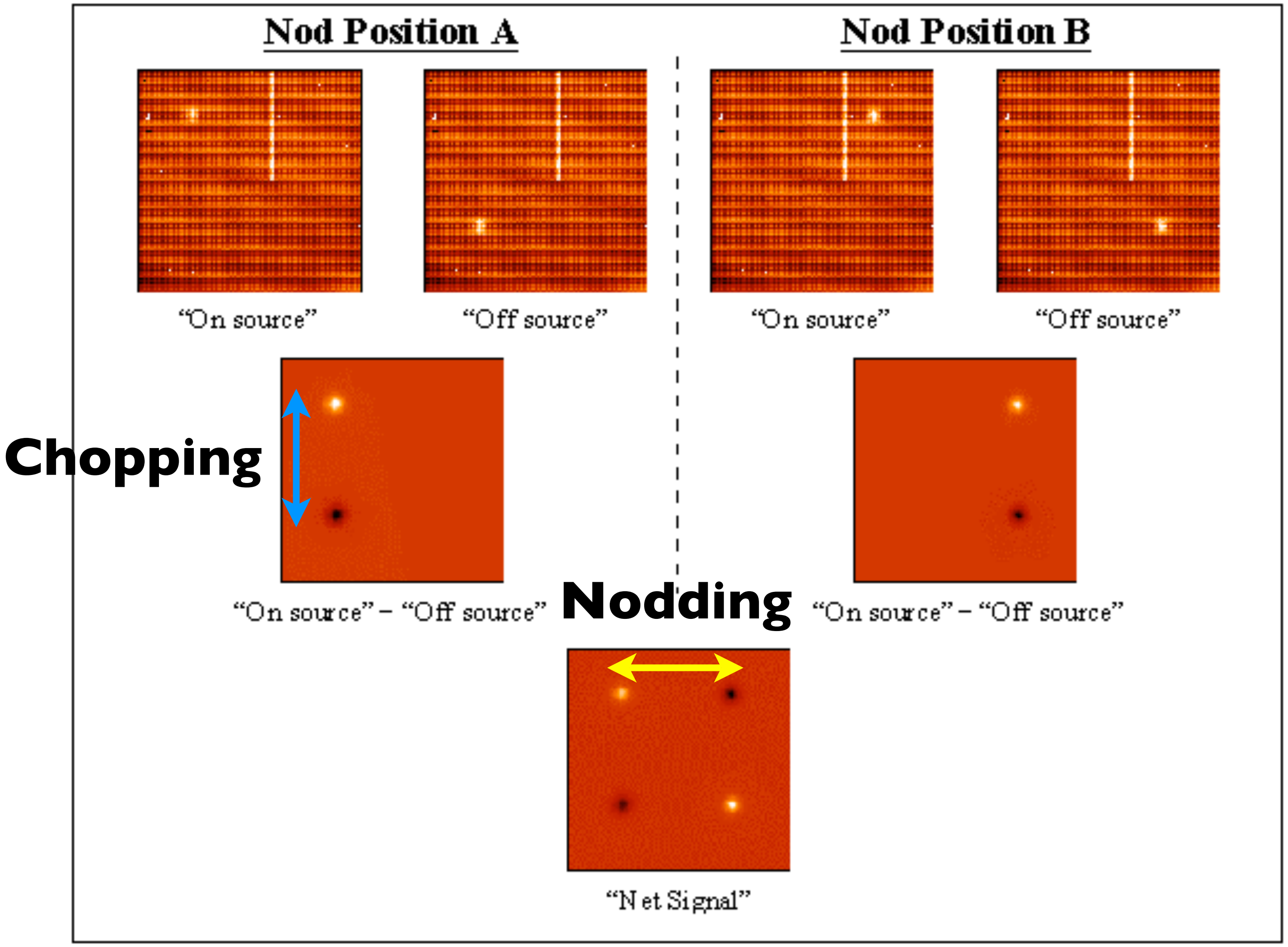
Subtracting sky (and telescope) strong emission II :

Chopping and Nodding on a bright source (star)



Sky emission

Telescope emission

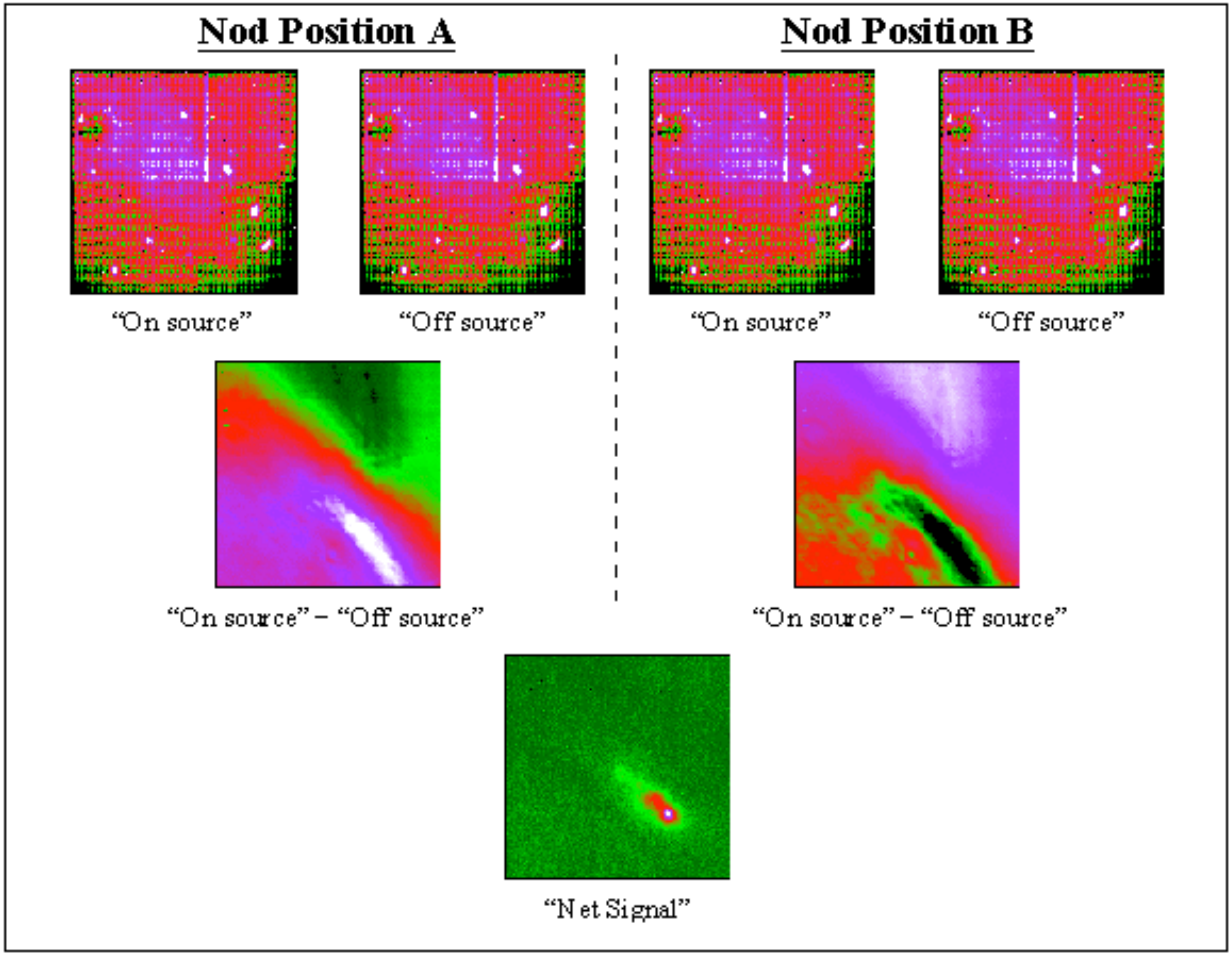


Chopping

Nodding

Subtracting sky (and telescope) strong emission III :

Chopping and Nodding on a faint source (galaxie)



Infrared detectors and imaging Surveys

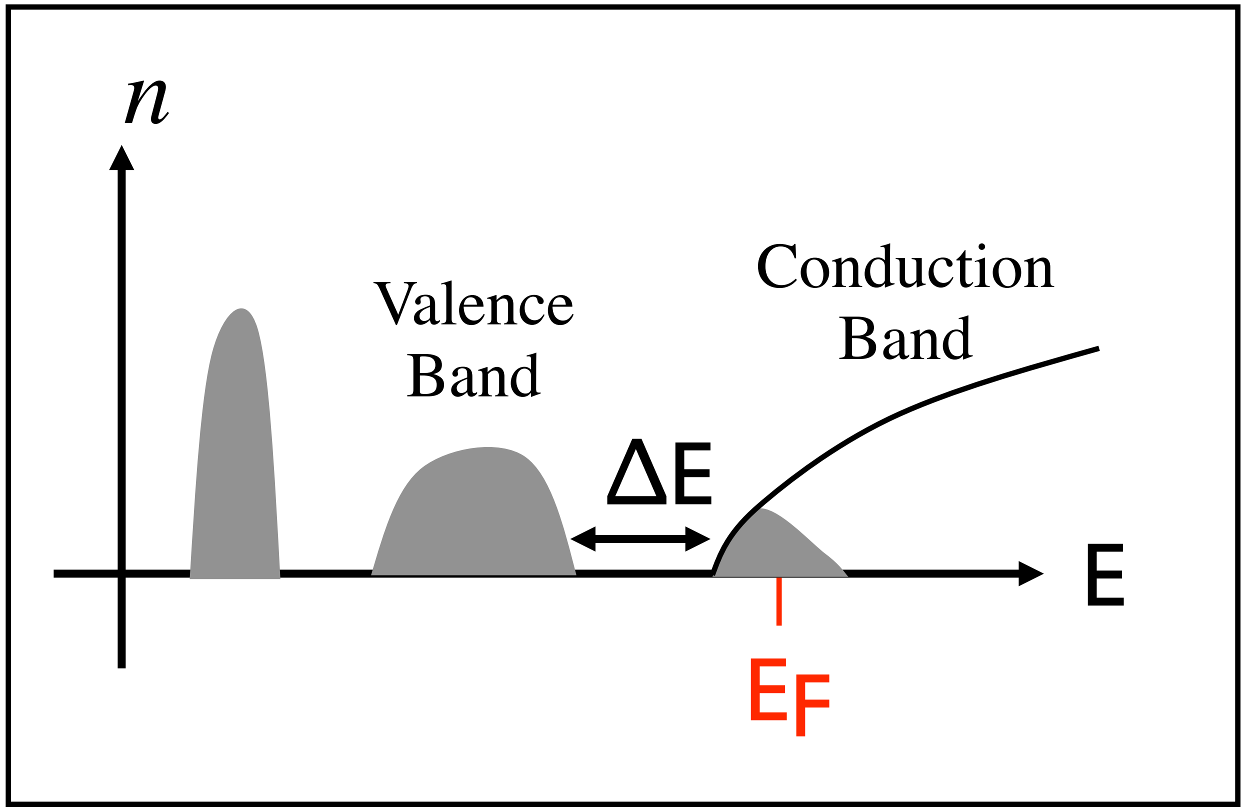
The basics of detection

Interaction of photons with atoms in a cristal

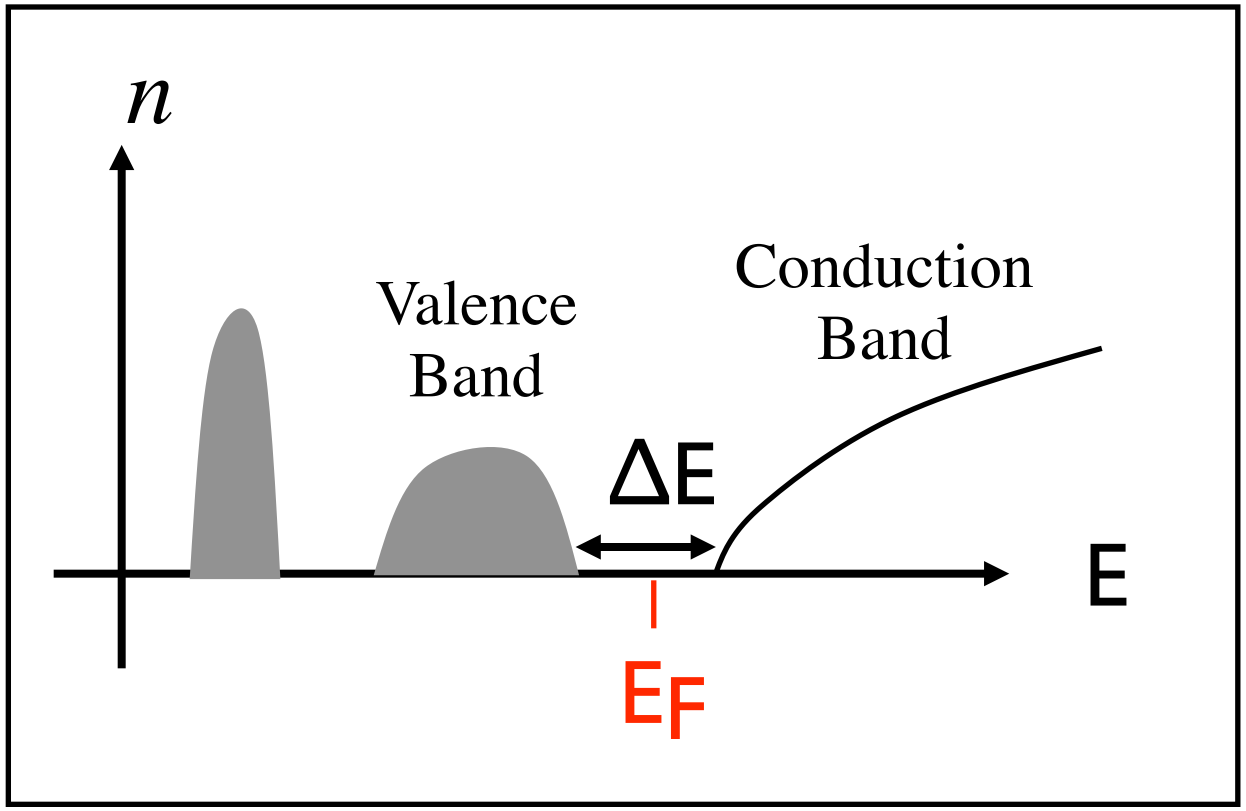
Photoconductive effect in cristals

Cristal :

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



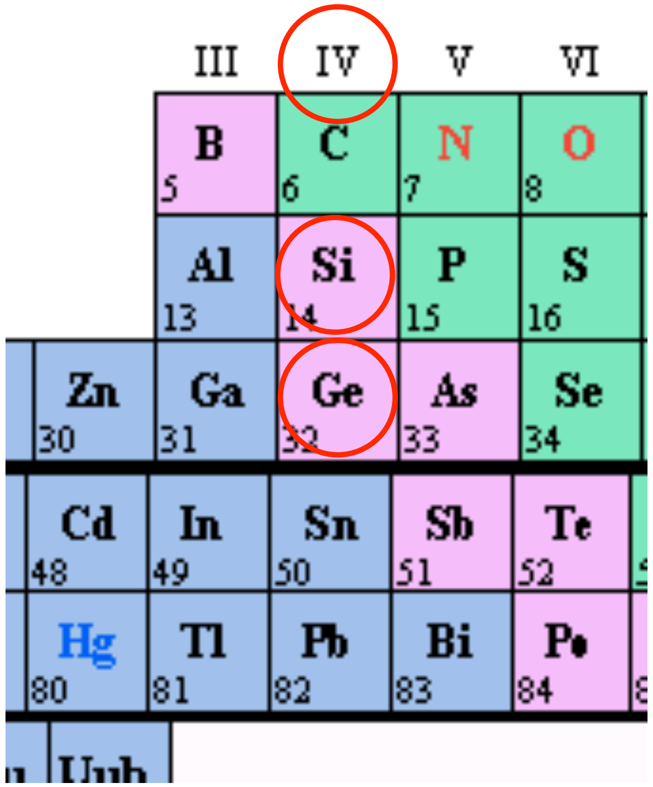
métal : conductor @ 0 K

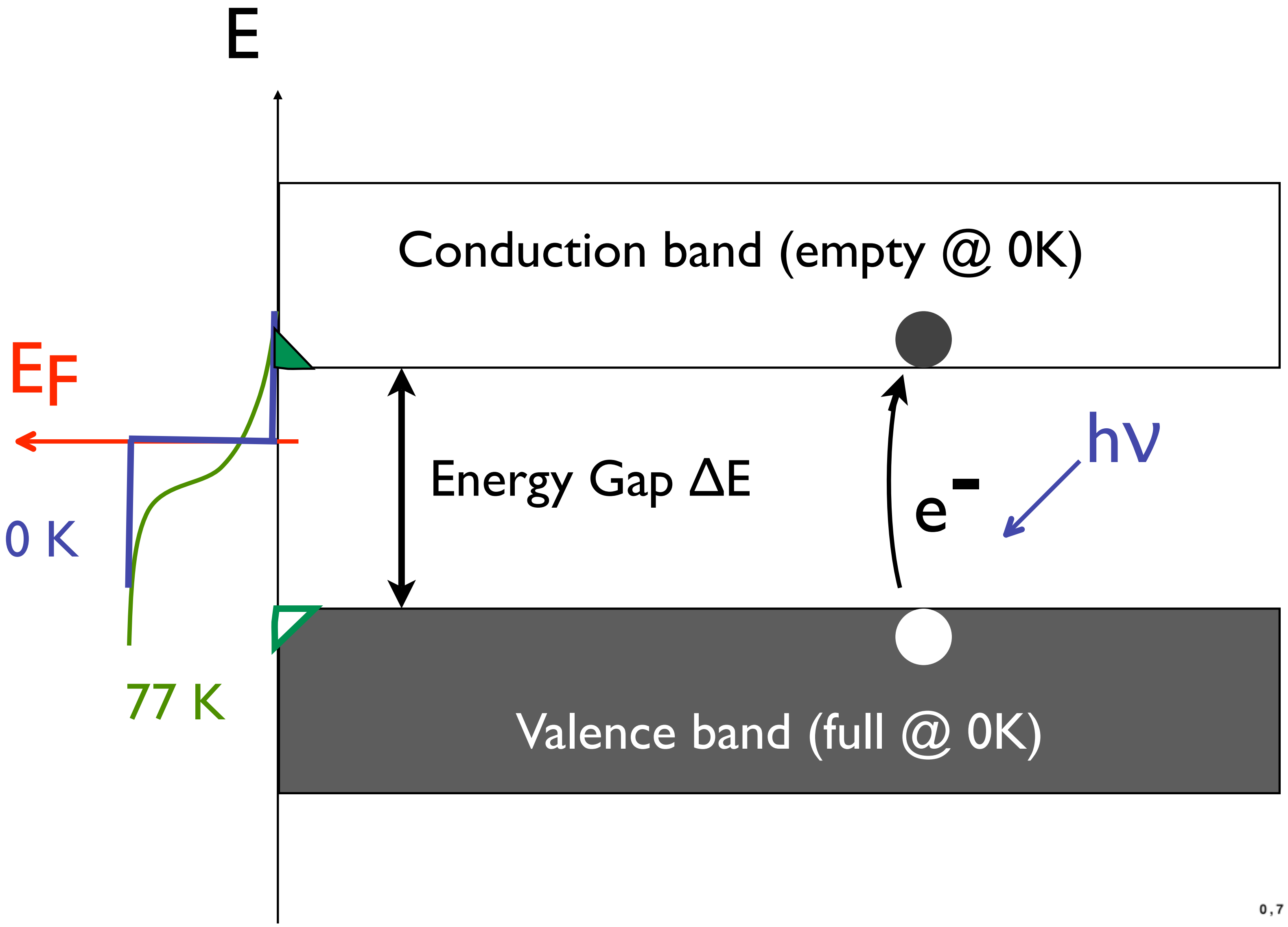


semiconductor : insulator à 0 K

From Visible to Infrared detection

Photoconductive effect in semiconductors





E

Conduction band (empty @ 0K)

E_F

Energy Gap ΔE

e^-

hν

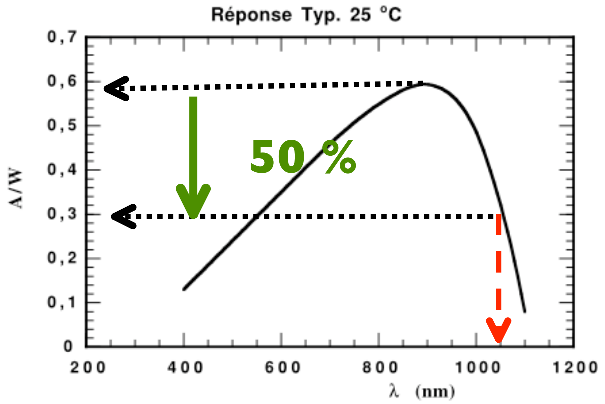
0 K

77 K

Valence band (full @ 0K)

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

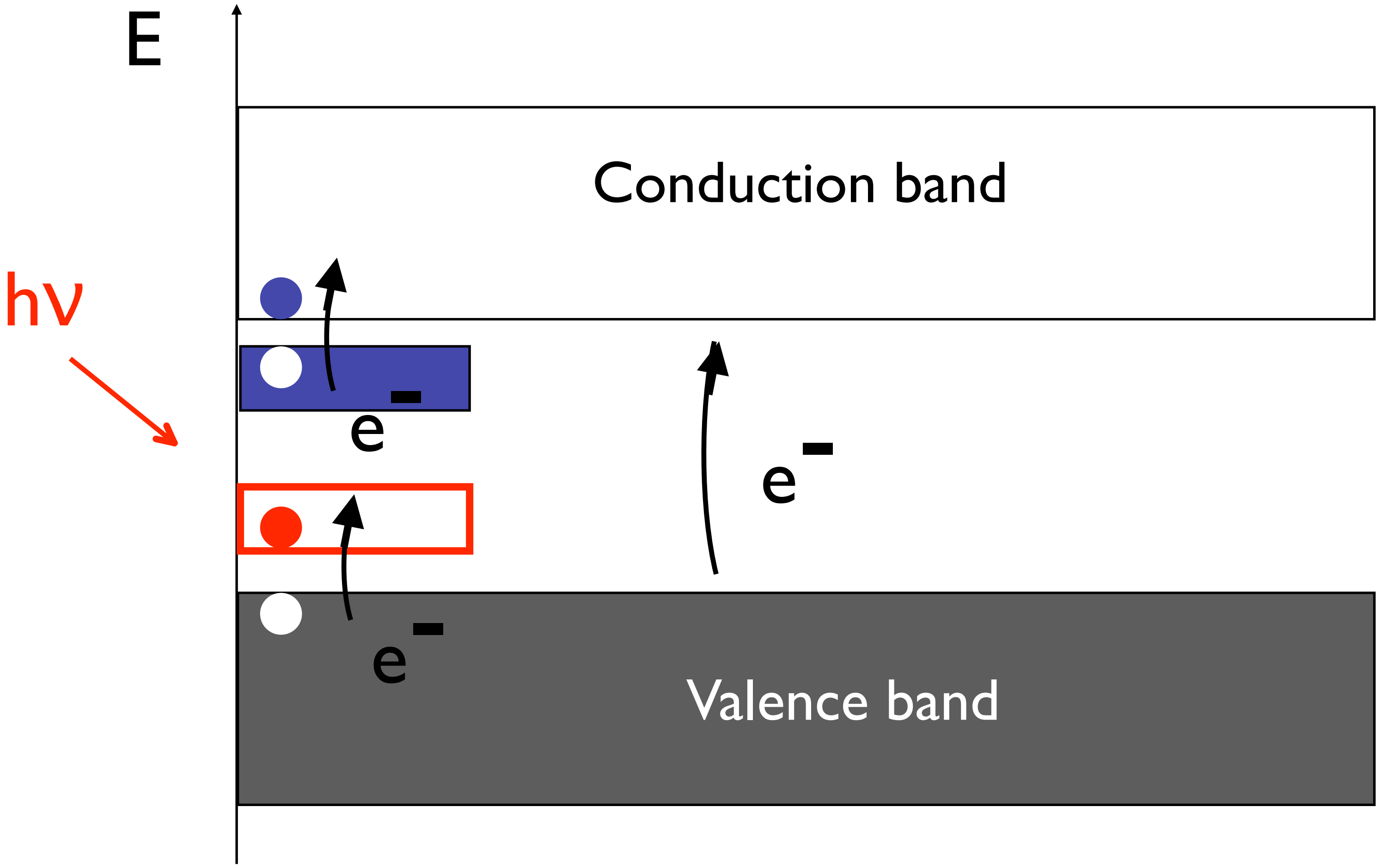
Si : 1.08 eV ⇔ 1.14 µm
Ge : 0.66 eV ⇔ 1.88 µm

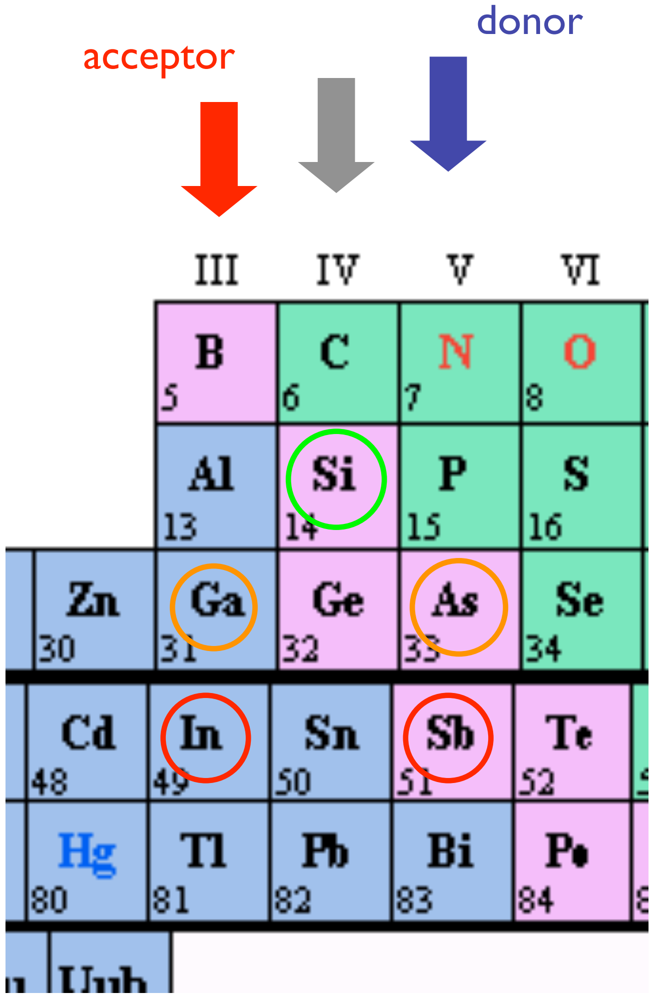


1.05 µm

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



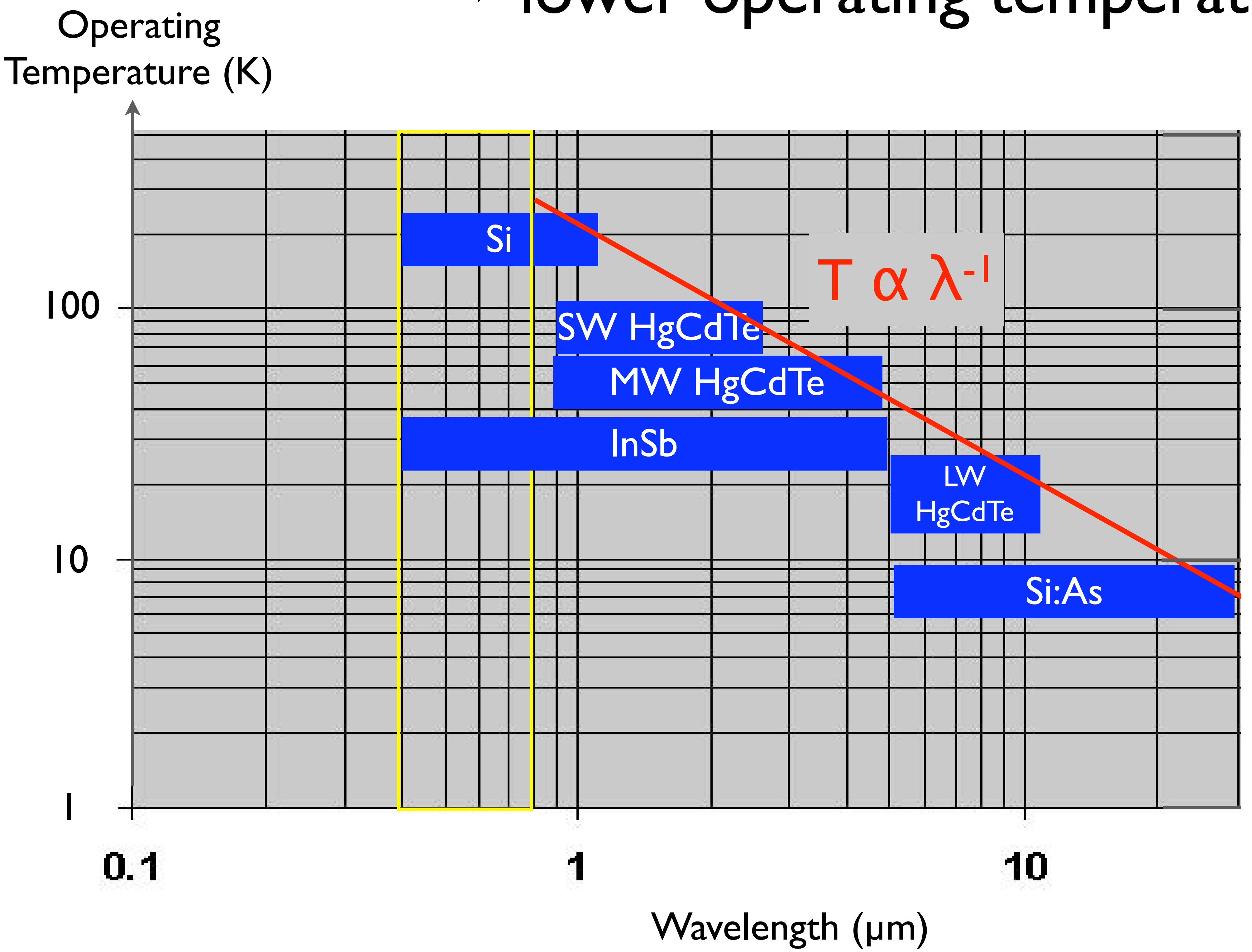


Element(s)	**Cutoff λ (μm)**
Si	1.1
Ge	1.8
Si:In	7.4
Si:Ga	17.8
Si:As	24
Ge:Ga	120
In Sb	5
$Hg_{(1-x)}Cd_{(x)}Te$	λ(x) < 20 μm

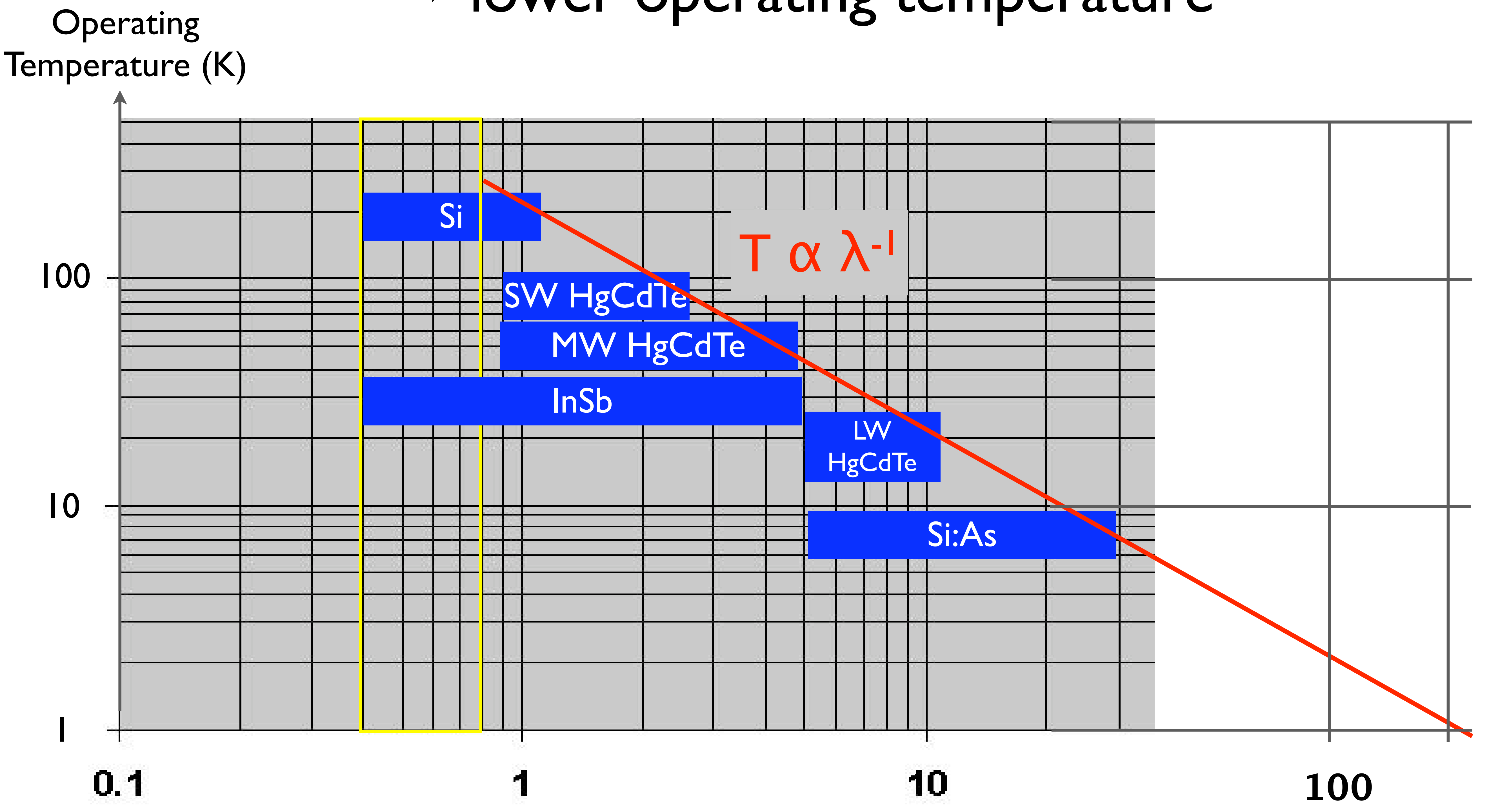
IRAS : 12 - 25 - 60 - 100μm
Si:As *Ge:Ga*

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

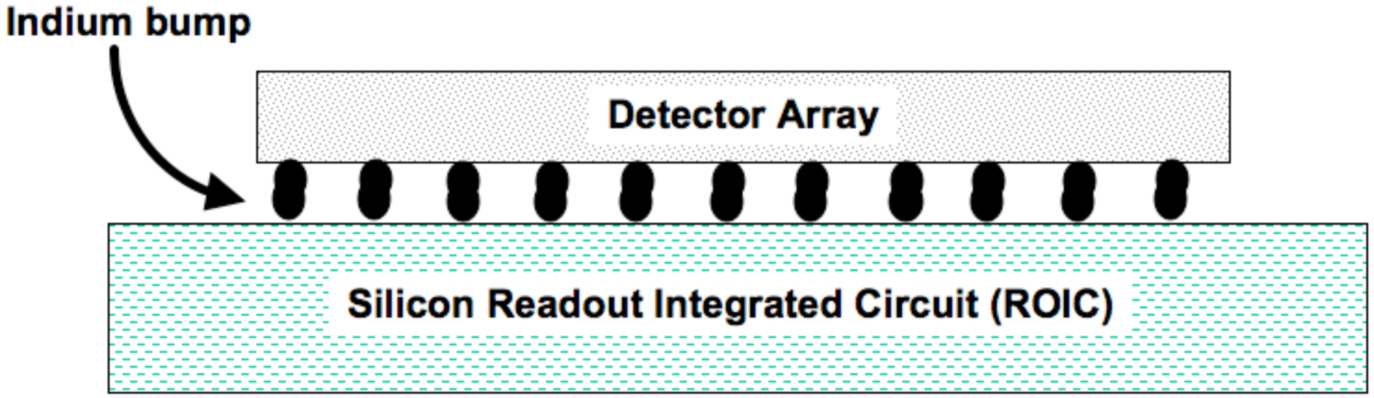


Bolometers > 200 µm
⇒ xx mK

What makes Infrared imagery demanding

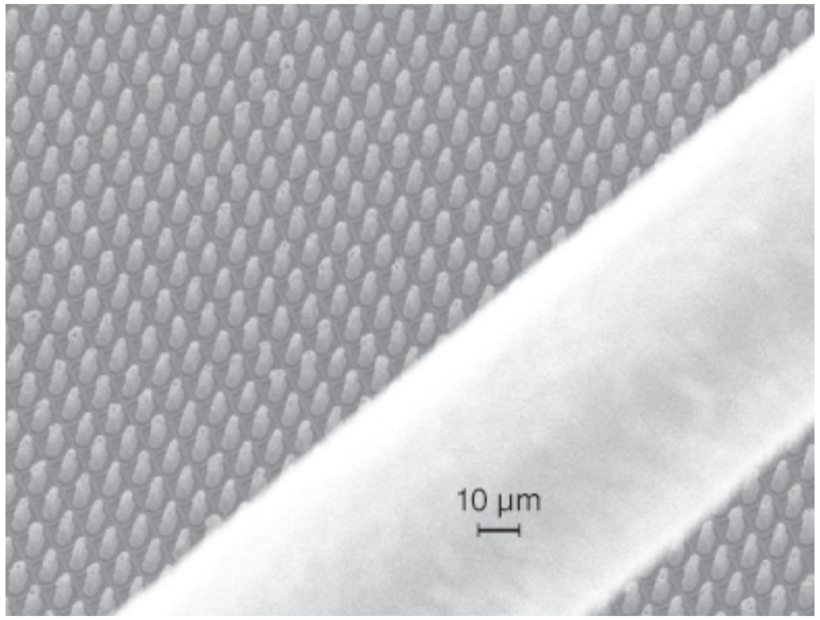
Detection and Readout are built separately and have to be connected together

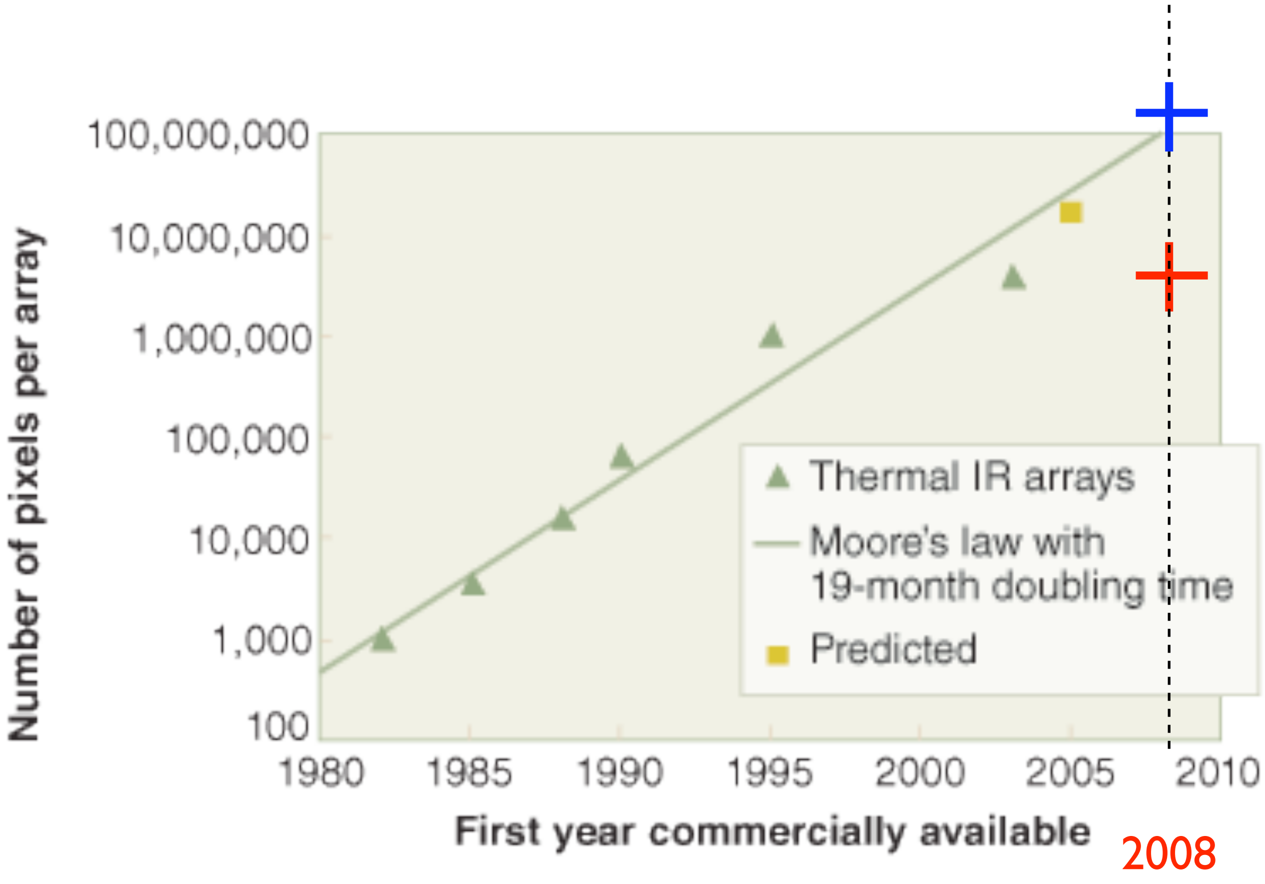
Hybridization between detection & readout



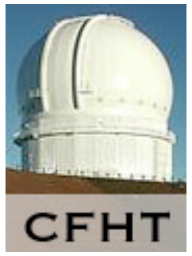
IR sensitive material

Silicon CCD or CMOS readout

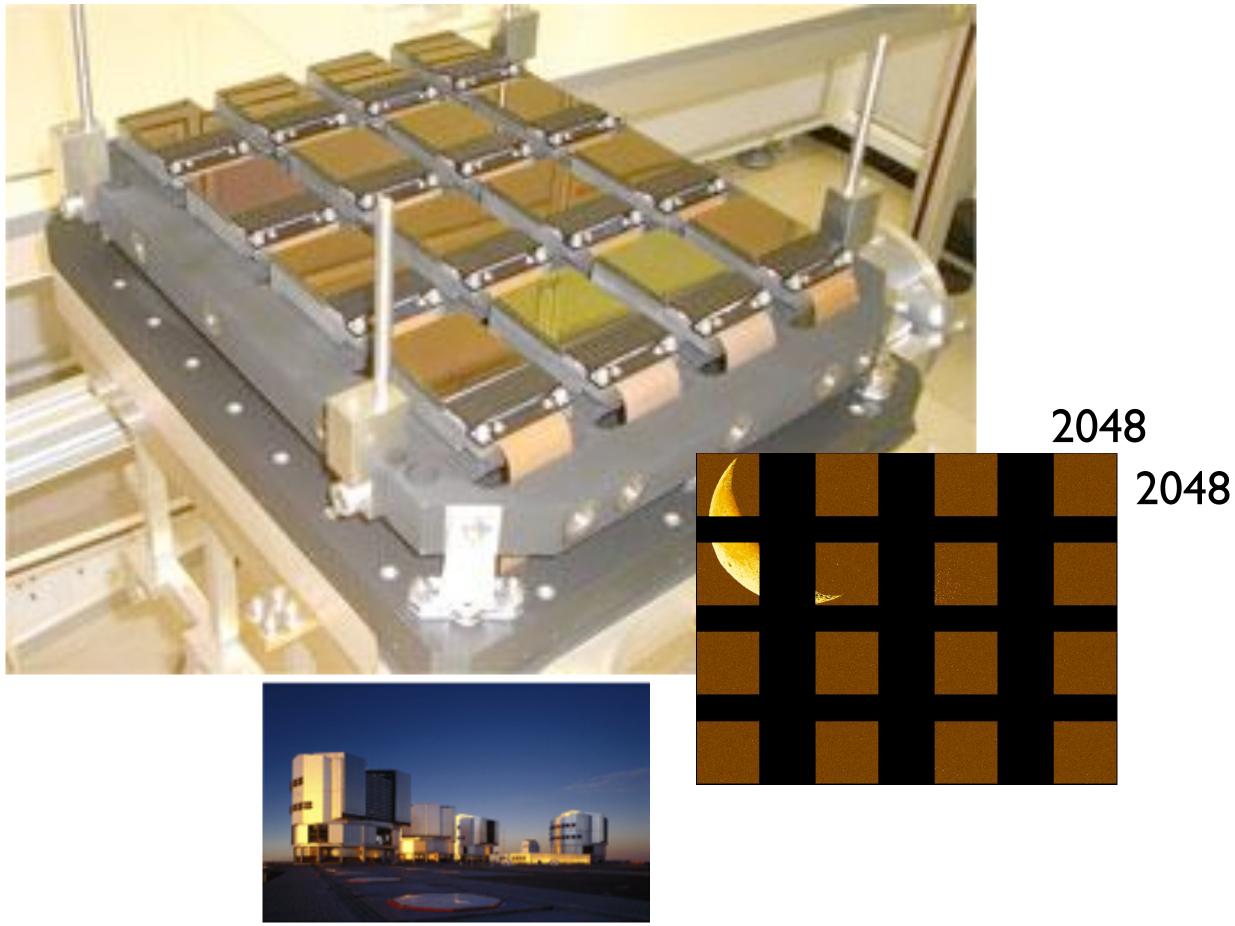


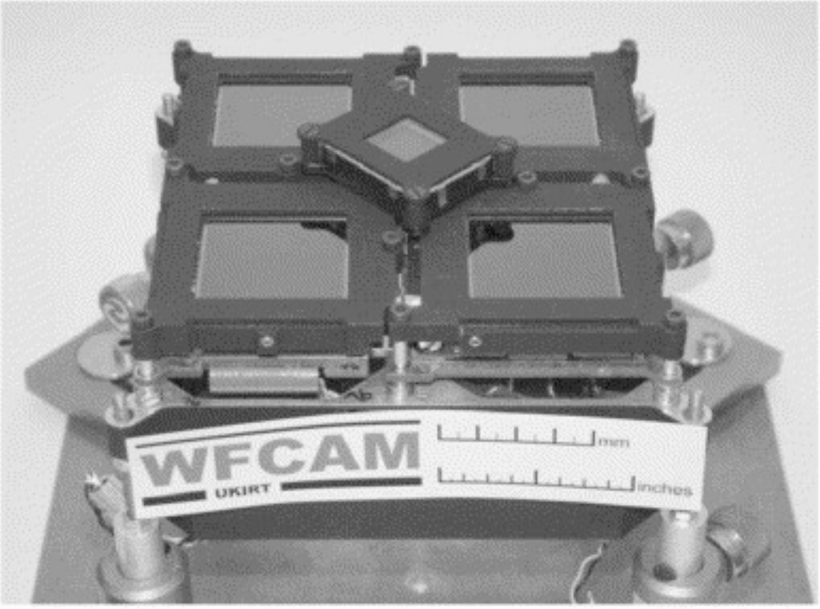


From small to large (multi-detector) IR arrays



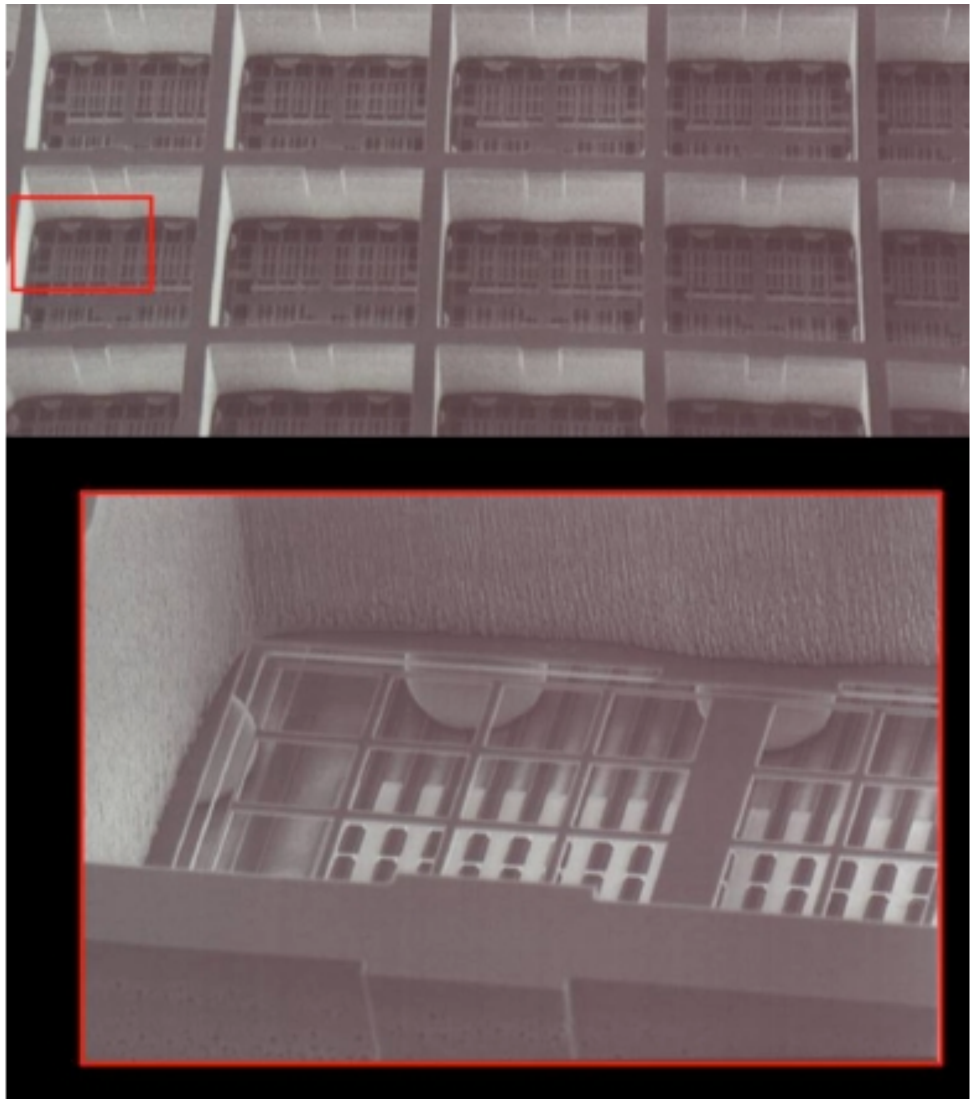
ESO VISTA array



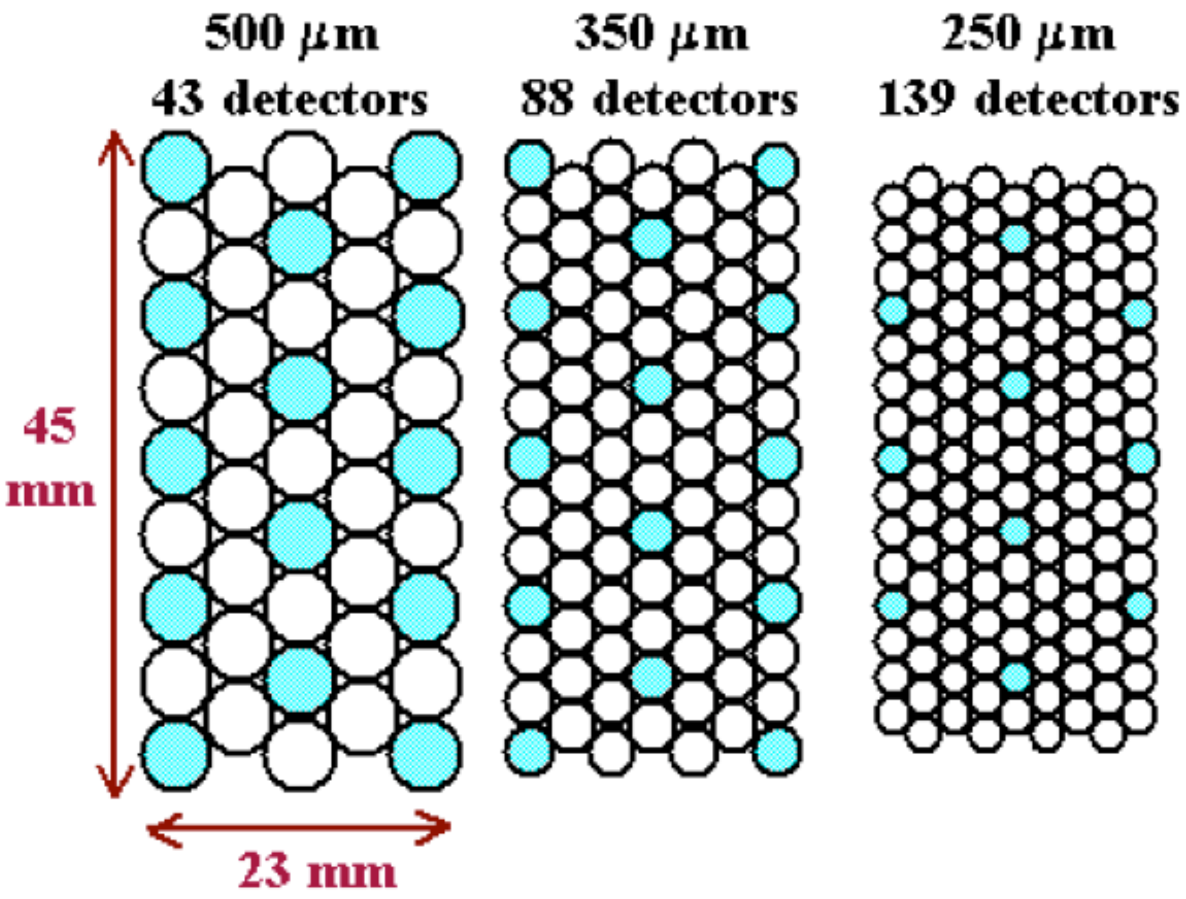


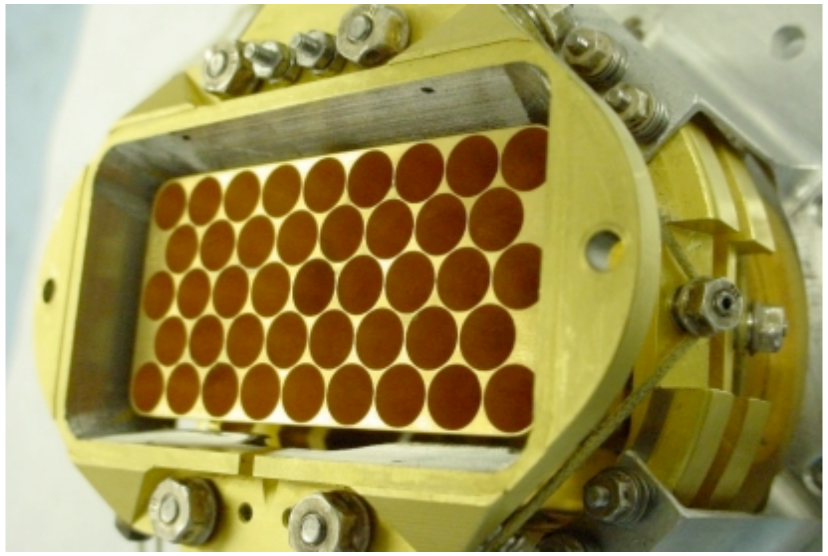
Longer wavelength (space borne) detector are more a collection of bolometers than actual arrays

PACS



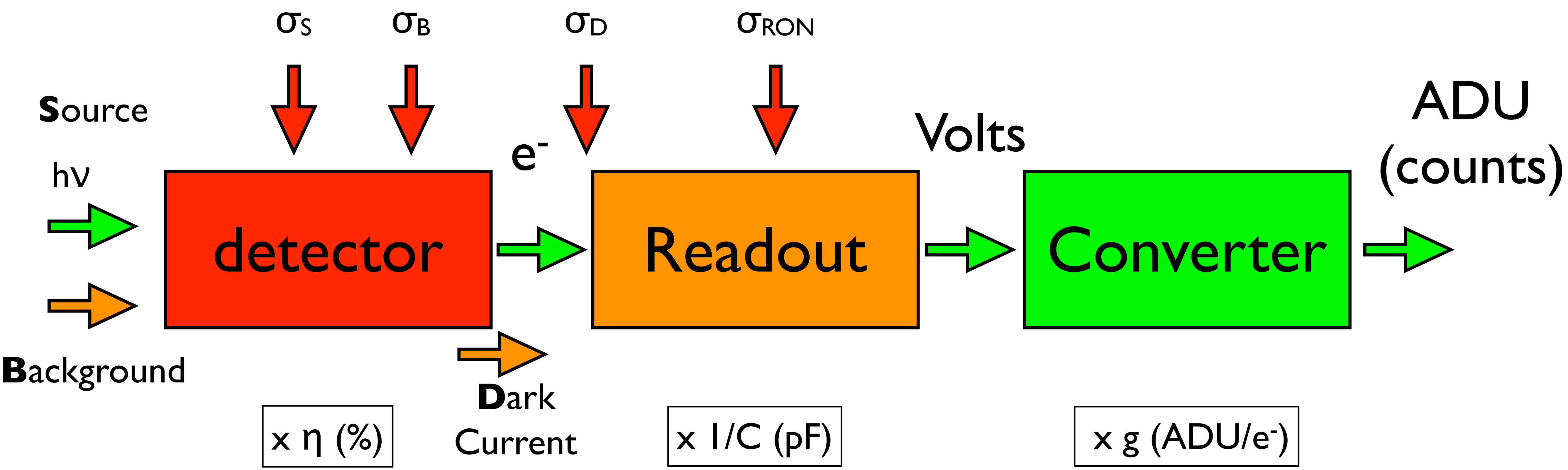
SPIRE





Photons, electrons, noise and performances

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



σ_S σ_B σ_D σ_{RON}

Source

hν

Background

detector

x η (%)

e⁻

Dark Current

Readout

x 1/C (pF)

Volts

Converter

x g (ADU/e⁻)

ADU (counts)

photons and electrons are quanta

→ Poisson ('shot') Noise

Gaussian, white, independant noises :

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

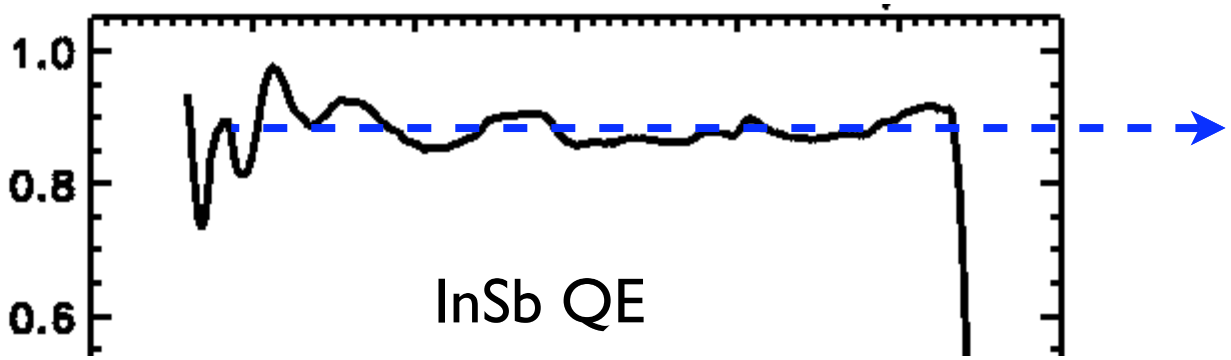
My first SNR computation :
how quantum efficiency (mildly) affects the Signal to Noise Ratio

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

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)
Dark 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 : σ_{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)

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

(unless B measured with a very high precision)

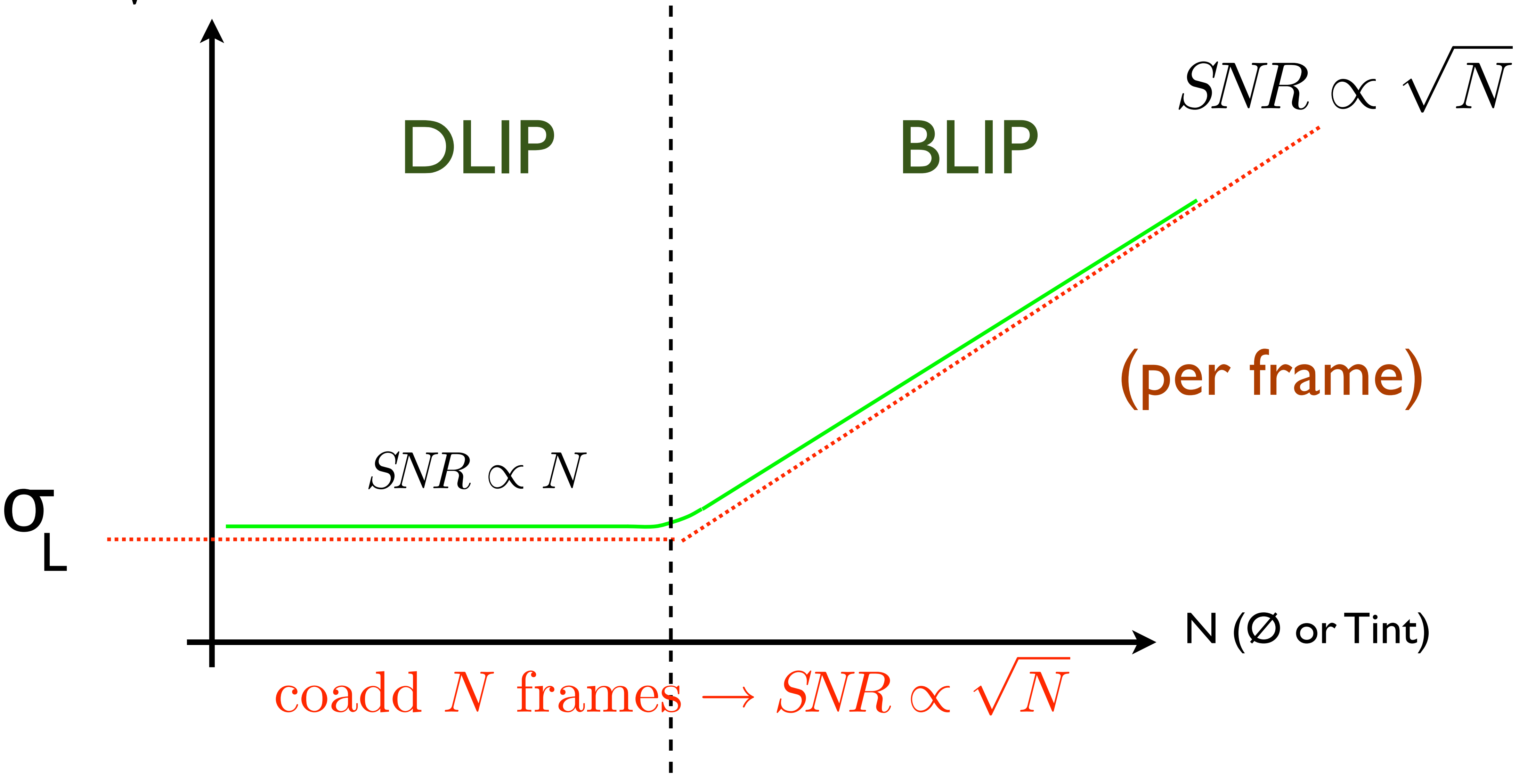
photon and readout noise(s) : which one dominates ?

Fixed readout noise : σ_L

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

(VIS) (IR)

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



(per frame)

coadd N frames $\rightarrow SNR \propto \sqrt{N}$

Tint the longer, the better

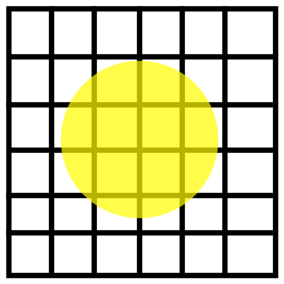
don't care too much about Tint

(beware of cosmic rays)

(if observation efficiency is good, take many frames)

From peak pixel to PSF (N pixels)

pixel signal : Random Variable (x, σ)



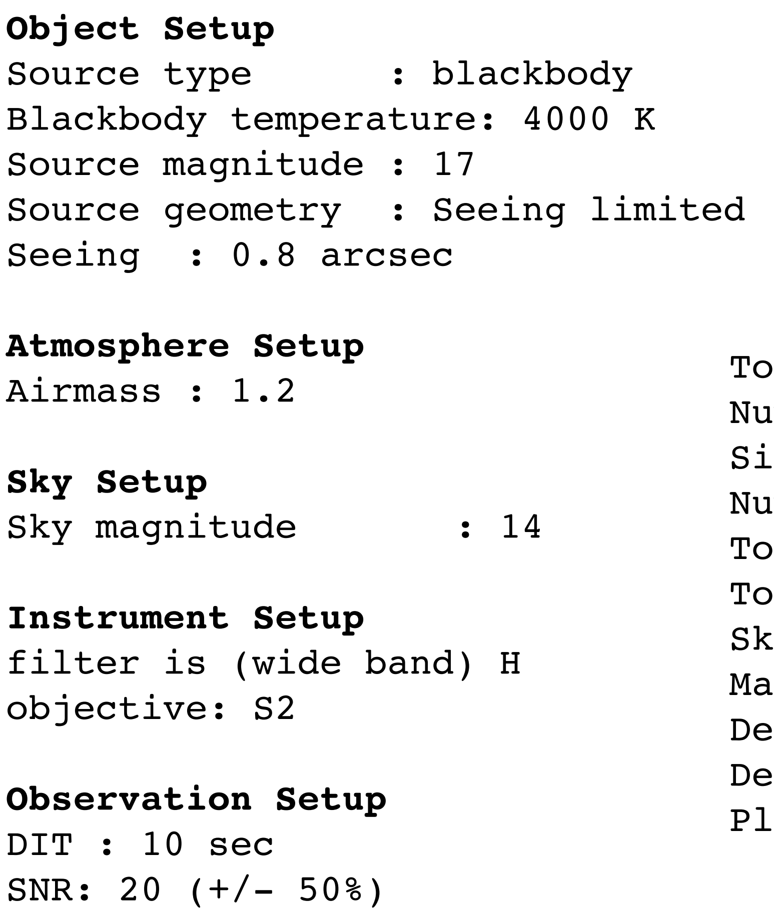
$$SNR_{\text{peak}} = \frac{x}{\sigma}$$

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

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

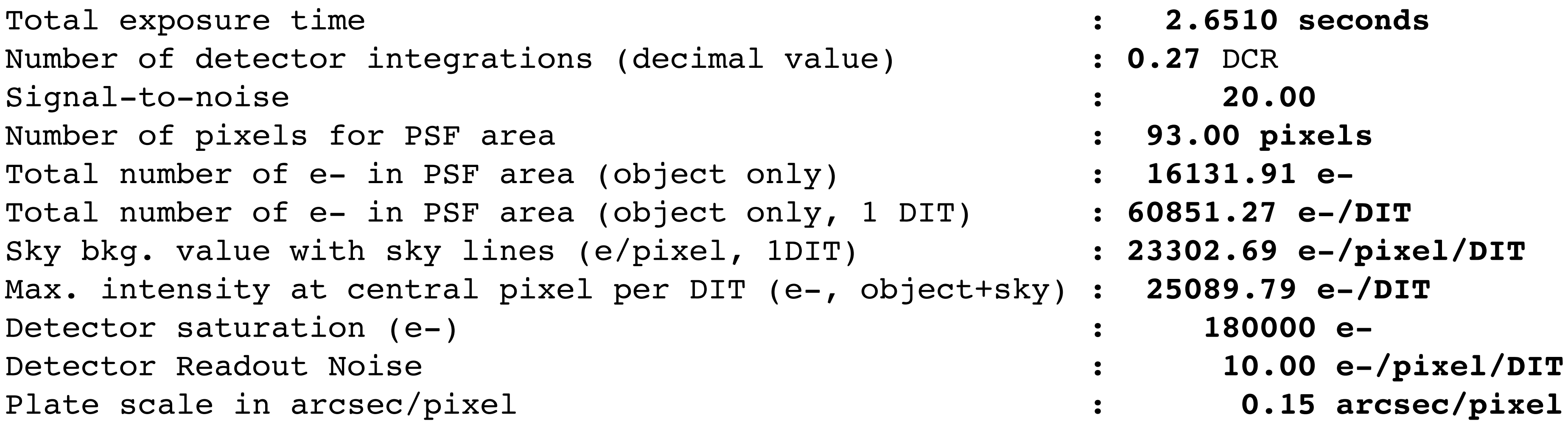
ISAAC SW (ESO) Exposure time simulator (ETC)

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

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

Peak pixel

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

From magnitudes to e/pixel

Sky emission in H band : $m_H = 14/\mathrm{arcsec}^2$
$\Omega_{\mathrm{px}} = 0.15^2 = 2.25\,10^{-2}$

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

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

`ISAAC ETC : 23302.69`

From magnitudes to e/pixel

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

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

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

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

ISAAC ETC : 23302.69

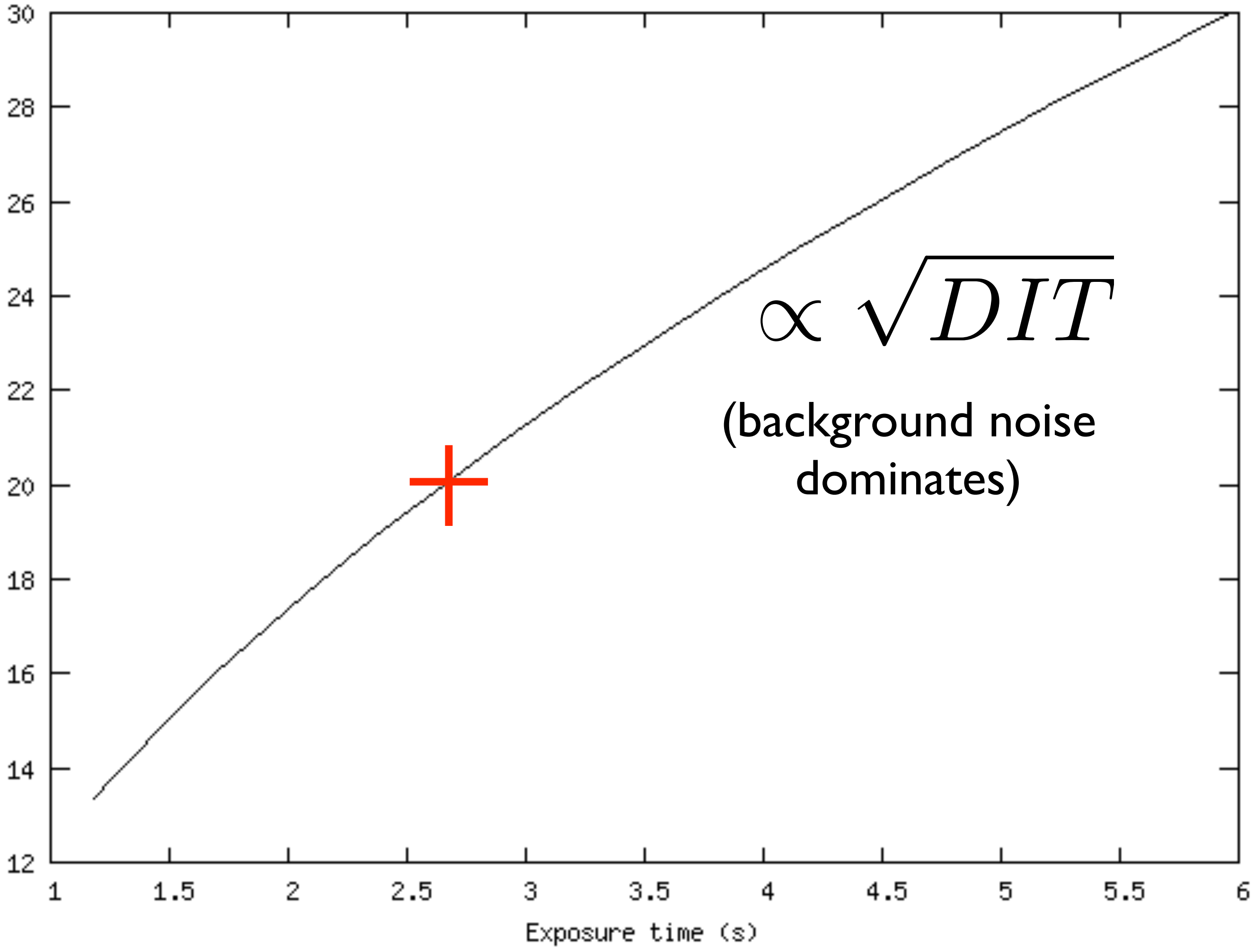
Source magnitude *m*

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

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

SNR variations with DIT and / or seeing

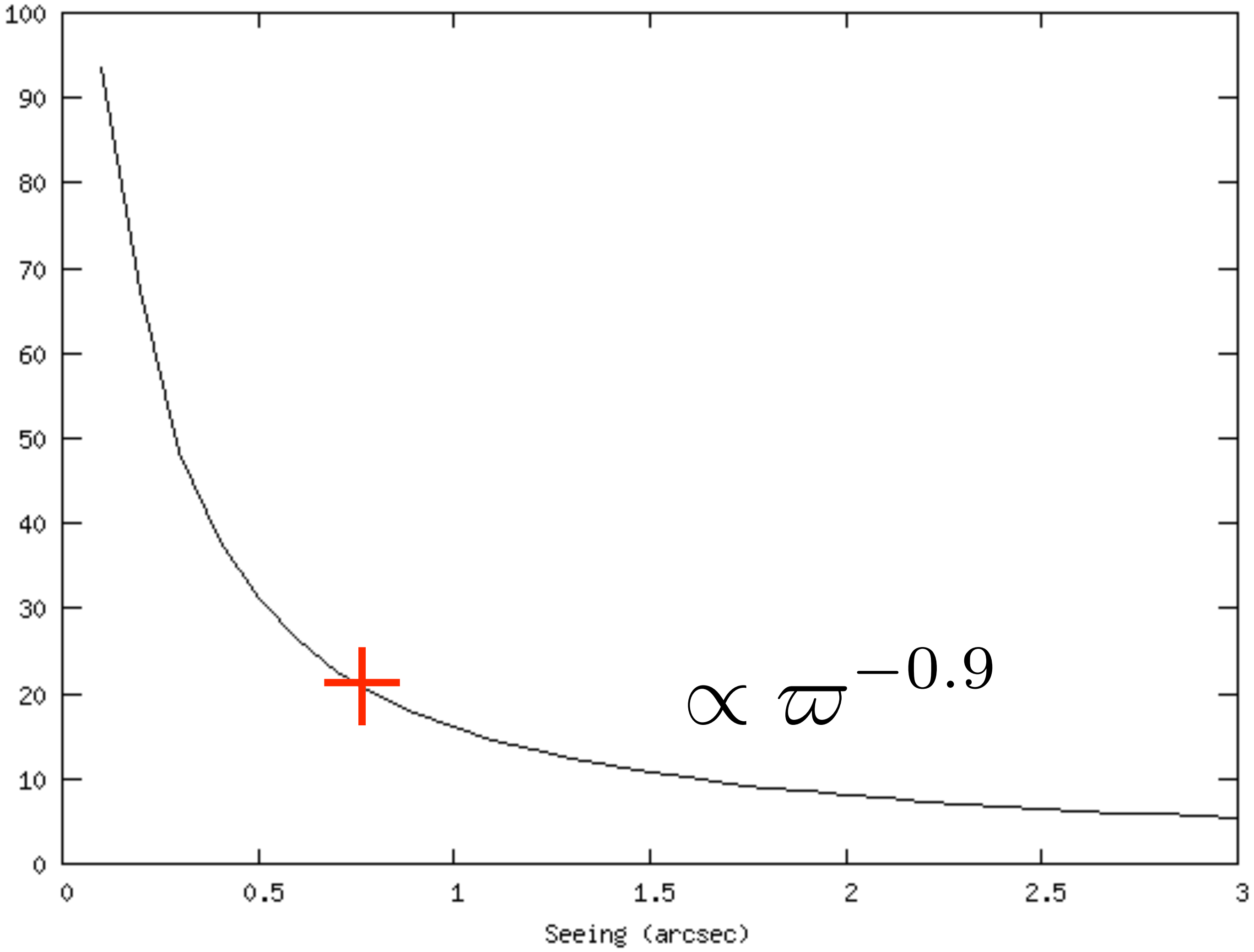
(PSF) SNR vs. exp. time



$\propto \sqrt{DIT}$

(background noise dominates)

(PSF) SNR vs. seeing



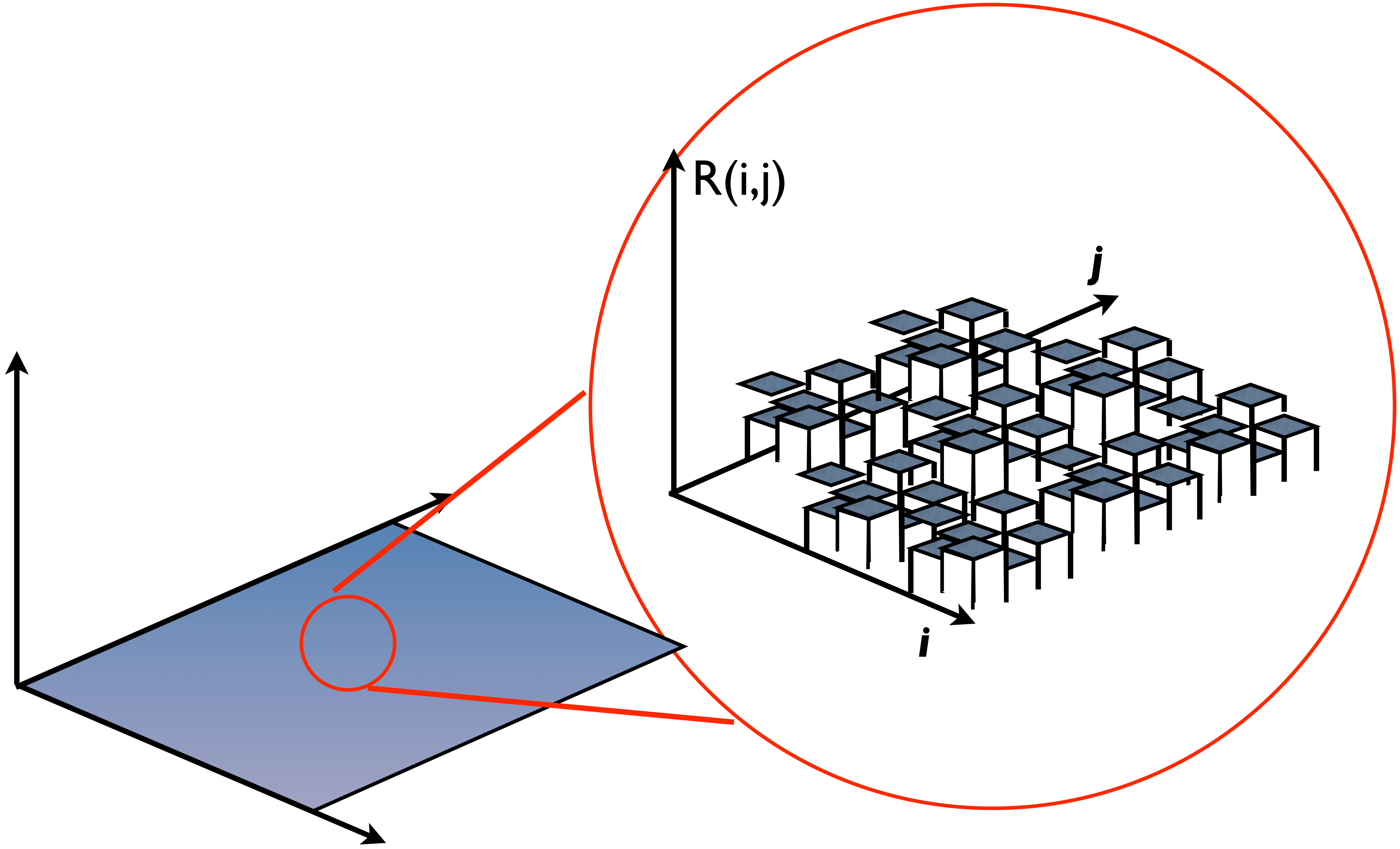
$\propto \varpi^{-0.9}$

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

Flat-fielding and Calibration

Flat-fielding

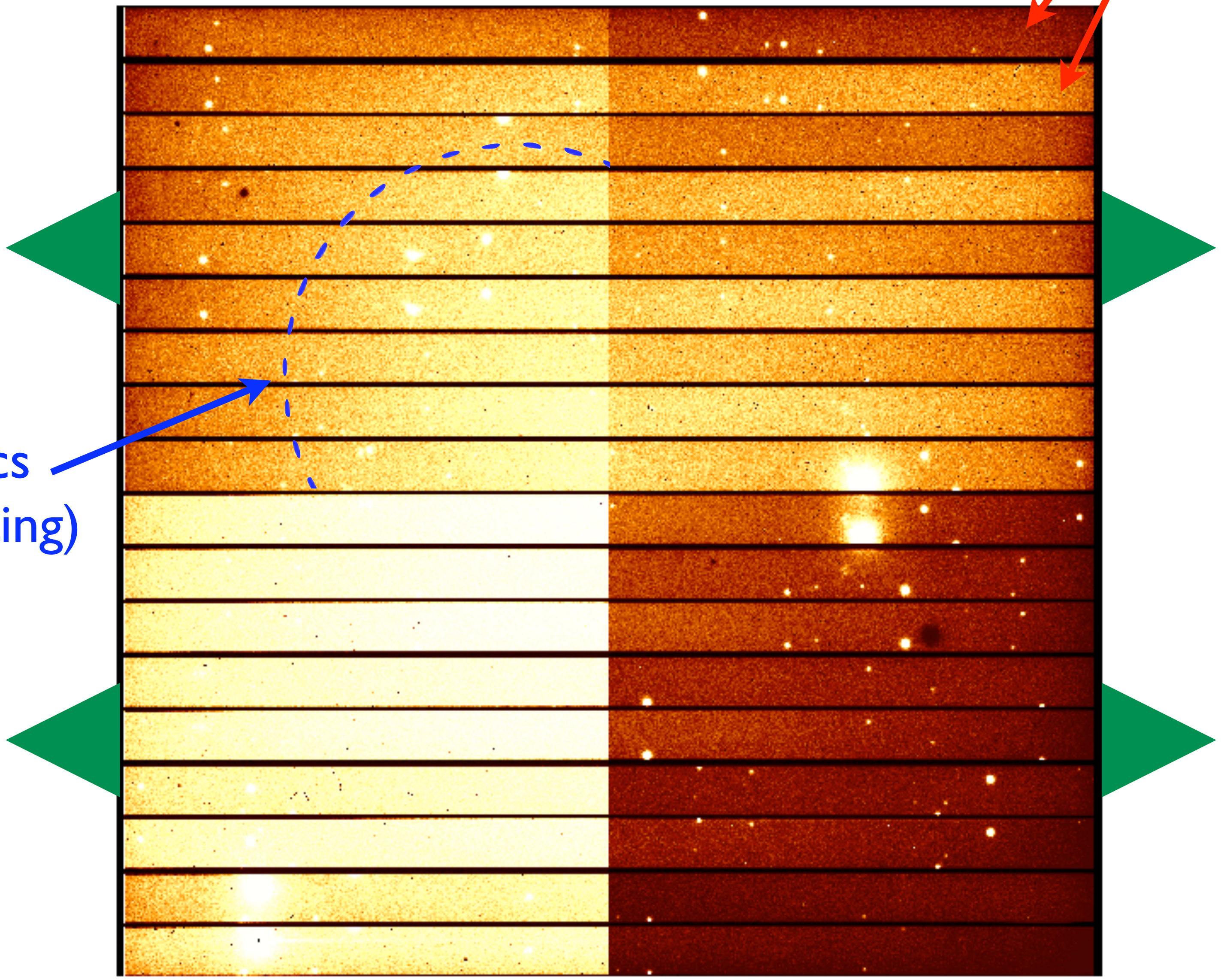
HF : pixel to pixel response



Flat-fielding

LF : Optics
(and electronics)

4 quadrants readout
(4 gains)



Polarimeter

gain 1

gain 4

Optics
(vignetting)

gain 2

gain 3

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 $I(i,j) = Y(i,j)/X(i,j) = S(i,j)/U \propto S(i,j) \ \forall \ i,j$

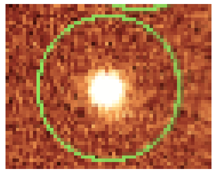
Photometry

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

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

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

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



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

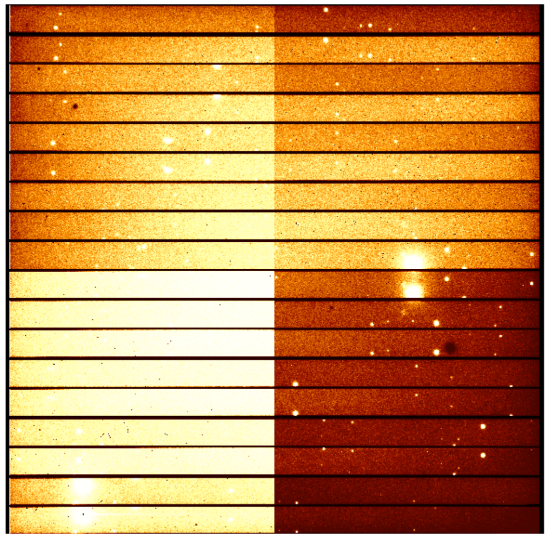
Standard stars : same Airmass, Spectral type, Magnitude

IR imagery : FITS format

FITS Header :

```
SIMPLE  =                T        / Standard FITS format (NOST-100.0)
BITPIX  =               16        / # of bits storing pix values
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
HIERARCH ESO DET OUT1 RON    =        6.07 / Readout noise per output (e-)
```

→ N_{ADU} (max) = 2^{16} = 65536



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

→ $N_{e-} = 3.26\, N_{ADU}$

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
```

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

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
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Number of pixels for PSF area                         :     224.00 pixels
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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
```
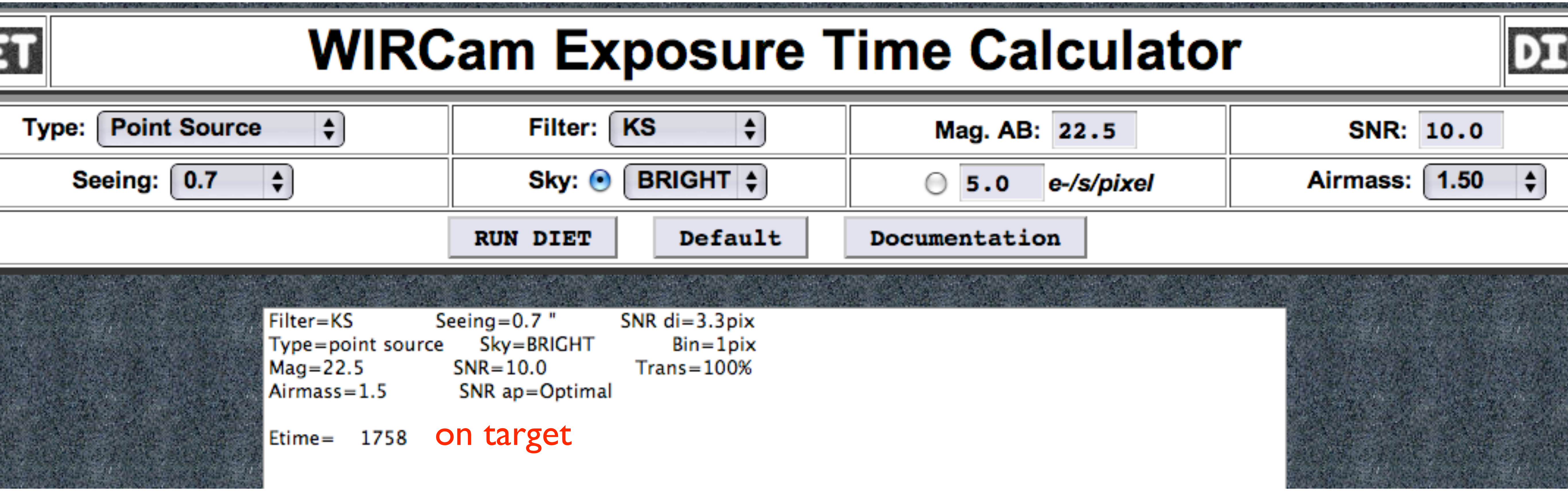

$$
\begin{aligned}
N_{\mathrm{px}} &= 224 \\
S &= 698 \\
\text{readout} & \quad 224 \times 50^2 \\
\text{signal} & \quad 698 \\
\text{background (twice)} & \quad 224 \times 149454 \\
SNR_{\mathrm{DIT}} &= \frac{698}{\sqrt{224 \times 50^2 + 698 + 2 \times 224 \times 149454}} = 0.085 \\
0.085 \rightarrow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

Use of various ETC.

WIRCAM (CFHT)



WIRCam Exposure Time Calculator

Type: Point Source

Filter: KS

Mag. AB: 22.5

SNR: 10.0

Seeing: 0.7

Sky: ● BRIGHT

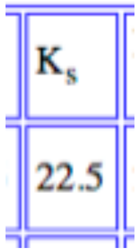
○ 5.0 e-/s/pixel

Airmass: 1.50

```
Filter=KS            Seeing=0.7 "          SNR di=3.3pix
Type=point source       Sky=BRIGHT             Bin=1pix
Mag=22.5               SNR=10.0            Trans=100%
Airmass=1.5            SNR ap=Optimal

Etime=    1758
```

on target

→ 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)

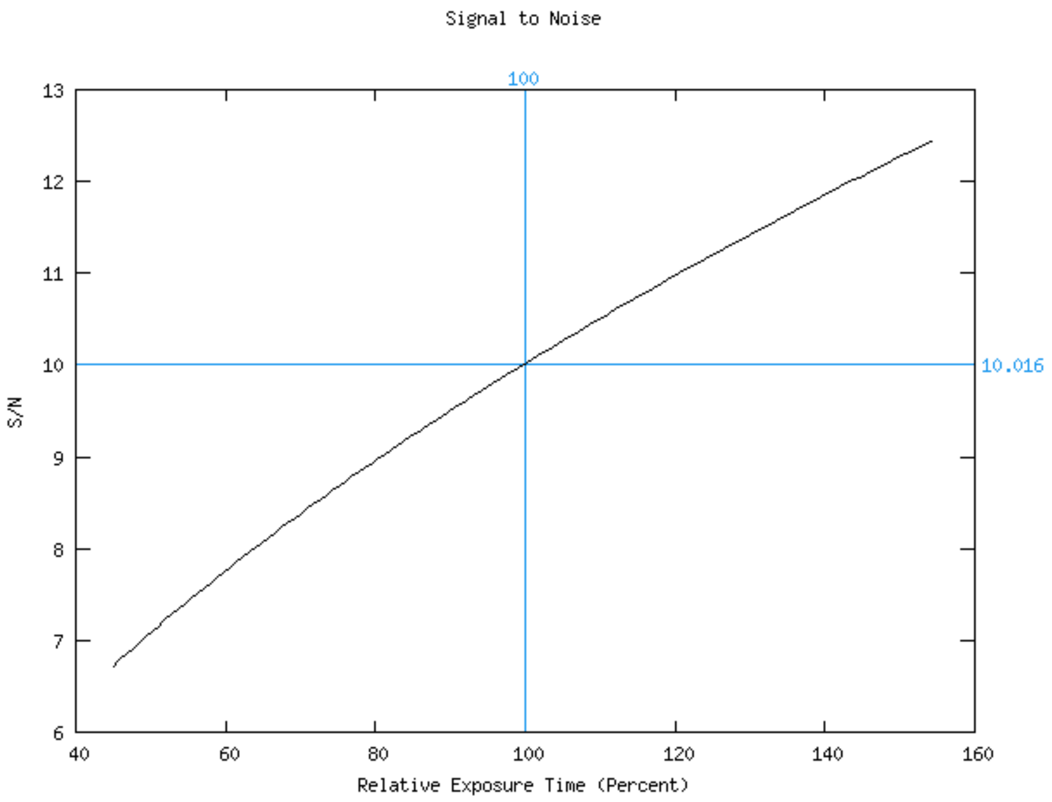
Use of various ETC.

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(deg^2)	BE (m^2 deg^2)	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)