An introduction to photometry and photometric measurements

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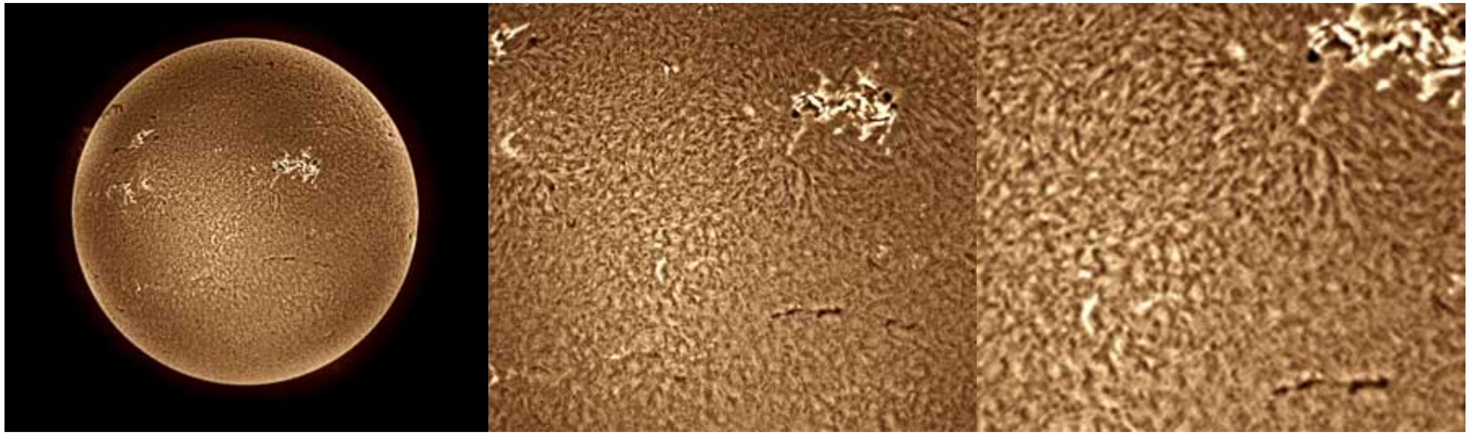
What is photometry?

- Photometry is concerned with obtaining **quantitative physical measurements** of astrophysical objects using electromagnetic radiation.
- The challenge is to relate **instrumental measurements** (like electrons counted in an electronic detector) to physically meaningful quantities like **flux** and **flux density**
- The ability to make quantitative measurements transformed astronomy from a purely descriptive science to one with great explanatory power.

Characterising a source photometrically: the sensible approach



Brightness or **specific intensity** is the same in these three images at different distances. Specific intensity of an object same through a telescope !

* Brightness does not depend on distance, but **flux** does

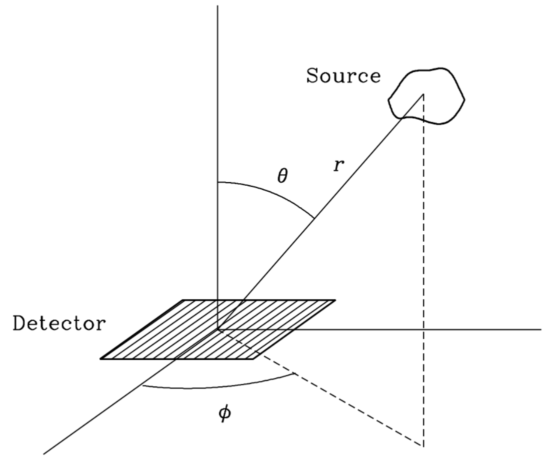
Flux densities

Total source intensity:

$$I = \int_0^\infty I_\nu \, d\nu$$

$$S_\nu \approx \int_{\text{source}} I_\nu(\theta,\phi) d\omega$$

$$\frac{dP}{d\nu \; d\omega} = I_\nu \cos\theta \; \mathrm{dA}$$



Flux densities are appropriate for **compact, unresolved sources**

Specific intensity

Specific intensity is power of radiation per unit area / per unit time / per unit frequency

$$I_\nu \equiv \frac{dP}{\cos\,\theta\;dA\;d\nu\;d\omega}$$

Note that, along a ray, specific intensity is conserved.

Note also that specific intensity is not altered by a telescope!

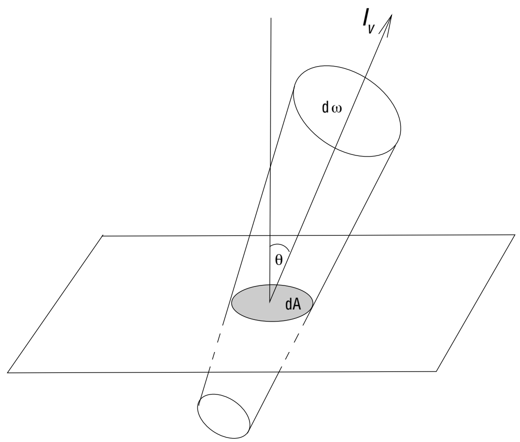


Figure 1: Relationship between radiation intensity, I_v, and energy passing through a surface element of area dA into a solid angle $d\omega$ at an angle of θ to the surface

$$dP = I_\nu \cos\,\theta\;dA\;d\nu\;d\omega$$

$$dE_\nu = I_\nu \cos\theta\, dA\, d\nu\, d\omega\, dt$$

I_ν: radiation intensity

dA: Surface area

dθ: angle with the surface

dω: solid angle

Flux density

The **flux density** the amount of energy per unit area per unit wavelength (note it is

$$1 \text{ Jy} = 10^{-26} \frac{\text{W}}{\text{m}^2 \cdot \text{Hz}} \text{ (SI)} = 10^{-23} \frac{\text{erg}}{\text{s} \cdot \text{cm}^2 \cdot \text{Hz}} \text{ (cgs)}$$ [1]

Janskies of course are too large for astronomy: most source are micro or milli-janskies.

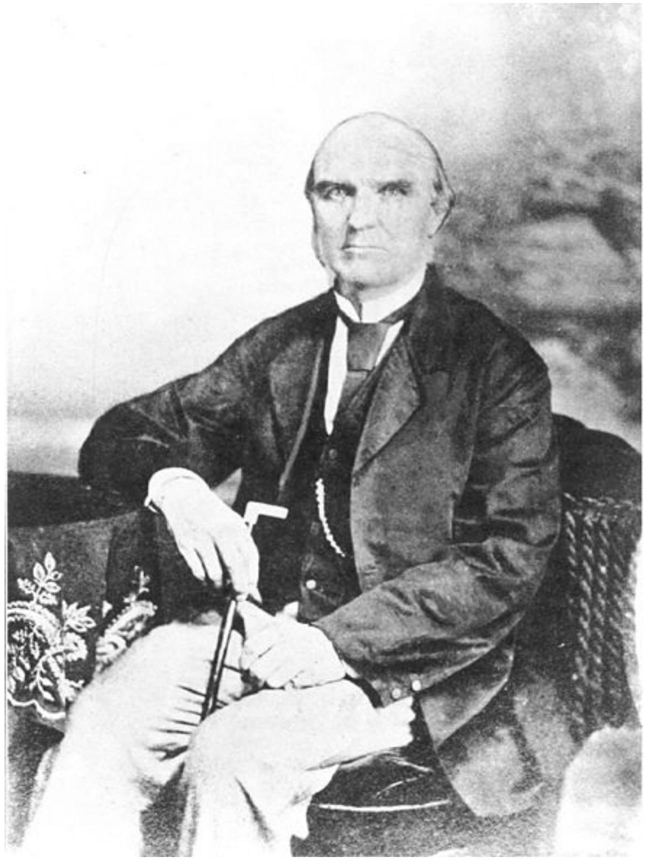
Many astronomical sources are unresolved, and the specific intensity for resolved sources varies over the object, so objects are characterised by their **flux densities**

But, meanwhile in astronomy…

- Hipparchus ranked the brightness of stars, 1 being the brightest and 6 the faintest.
- The human eye has a **logarithmic** response to incident light
- Star in of magnitude 1 is 100 times brighter than magnitude 6

Hipparchus 120BC

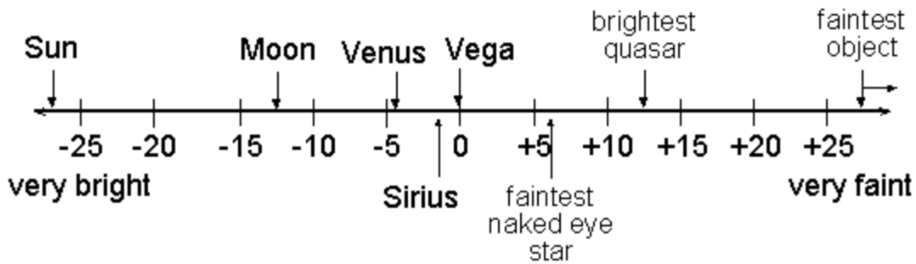
The magnitude scale



Norman Robert Pogson (1829-1891)

This leads to the following definition of "instrumental magnitude" (from N. Pogson): the factor 2.5 was chosen (it's the fifth root of 100) to reproduce Hipparchus' scale, where f_i is the source **flux density**

$$m_i = C - 2.5 \log_{10} f_i$$



Absolute magnitudes

$$m_\lambda - M_\lambda = 5\log_{10} d - 5 + A_\lambda$$

- **Absolute magnitude** is the magnitude a source would have if it was at a standard distance of 10pc

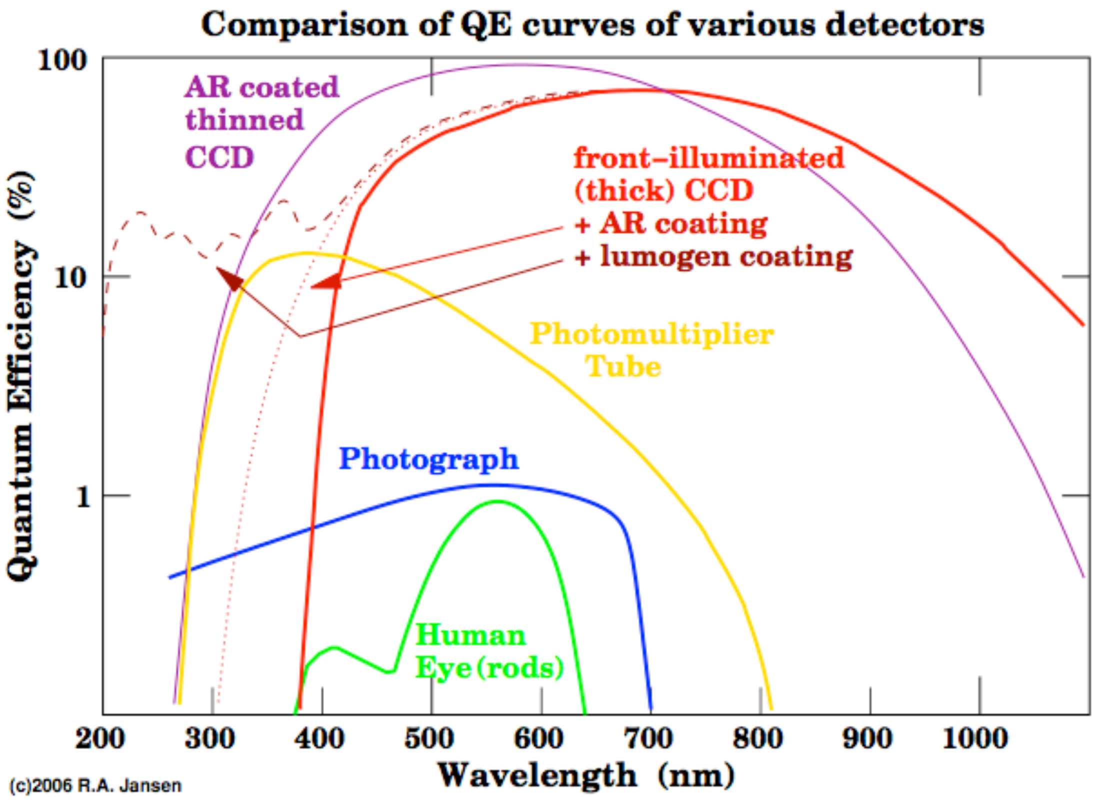
- **Note for cosmological sources, need to use distance modulus and k-correction terms.**
  - Always be careful about “rest frame” and “observed frame” magnitudes, because of redshift

Some particularities:

- Differences in magnitudes correspond to a flux ratio
- Some consequences: small magnitude differences approximately correspond to small flux differences (e.g, delta 5% mag ~ delta 5% flux).
- Magnitudes of objects with negative flux measurements are **undefined** which can be problematic for faint sources. Better to use fluxes in this case!

$$m_i - m_j = -2.5\log_{10}\left(\frac{f_i}{f_j}\right)$$

Standardising magnitudes



- Different detectors have different responses; old "photographic magnitudes" for example were not very practical
- Would like to have information concerning the underlying spectral energy distribution of the objects under investigation
- Would like to be able to compare with measurements made by different groups

Standardising magnitudes: magnitude systems

- VEGA magnitudes
  - Based on the V-band magnitude of Vega. V=0.03 and all colours zero
- AB magnitudes
  - $m_{AB}=2.5\log f_\nu-48.60$ (Still based on Vega)
- griz/Oke/Gunn magnitudes
  - Based on F6 subdwarf, g = 0 magnitude

A magnitude system is not a filter system (you can use a filter in any system)

“Vega” magnitudes

- Vega system tied to the **flux of the star alpha-Lyrae or Vega** (for a given filter) outside the atmosphere, where f_i is the flux density per unit wavelength:

$$m_i - m_{\rm Vega} = 2.5\ \log f_i + 2.5\ \log f_{\rm Vega}$$

- We set the magnitude of vega to be zero (in fact 0.03) *by definition*

$$m \equiv -2.5\ \log f_\lambda + 2.5\ \log f_{\lambda,\rm Vega}$$

- This means also that the *colour* of vega is zero in all bands
- The zero-point of this system **depends on the flux of Vega and is different in different bands.**

Vega magnitudes (II)

- The basic number to remember: **1000 photons in V at the top of the atmosphere.** This is a useful number to remember for the CCD equation!

$$\boldsymbol{\phi^0_\lambda = f^0_\lambda / \mathrm{h}\nu = 1005 \text{ photons cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{\mathring{A}}^{-1}}$$

$$\boldsymbol{m_i = -2.5\,\log_{10} \frac{\int R_i(\lambda)\lambda F_\lambda(\lambda) d\lambda}{\int R_i(\lambda)\lambda F^{\mathrm{VEGA}}_\lambda(\lambda) d\lambda} + 0.03}$$

The AB magnitude system

- In Vega magnitudes, the flux density corresponding to m=0 is **different for each filter:** to get absolute quantities we need to know the spectrum of vega. The spectrum of vega is poorly defined at longer wavelengths.
- It is also difficult to relate vega magnitudes to physical quantities such as energy

AB magnitudes

- Consider f_nu, flux per unit frequency

$$f_\nu \ [\mathrm{ergs\, s^{-1}\, cm^{-2}\, Hz^{-1}}] \ = \ \frac{\lambda^2}{c} \cdot 10^8 \cdot f_\lambda \ \ [\mathrm{ergs\, s^{-1}\, cm^{-2}\, \mathring{A}^{-1}}]$$

$$m \ = \ -2.5 \ \log f_\nu \ - \ (48.585 \pm 0.005)$$

- This constant was chosen to match the flux of vega.

$$m_V^{\mathrm{Vega}} \equiv m_V^{AB} \equiv 0$$

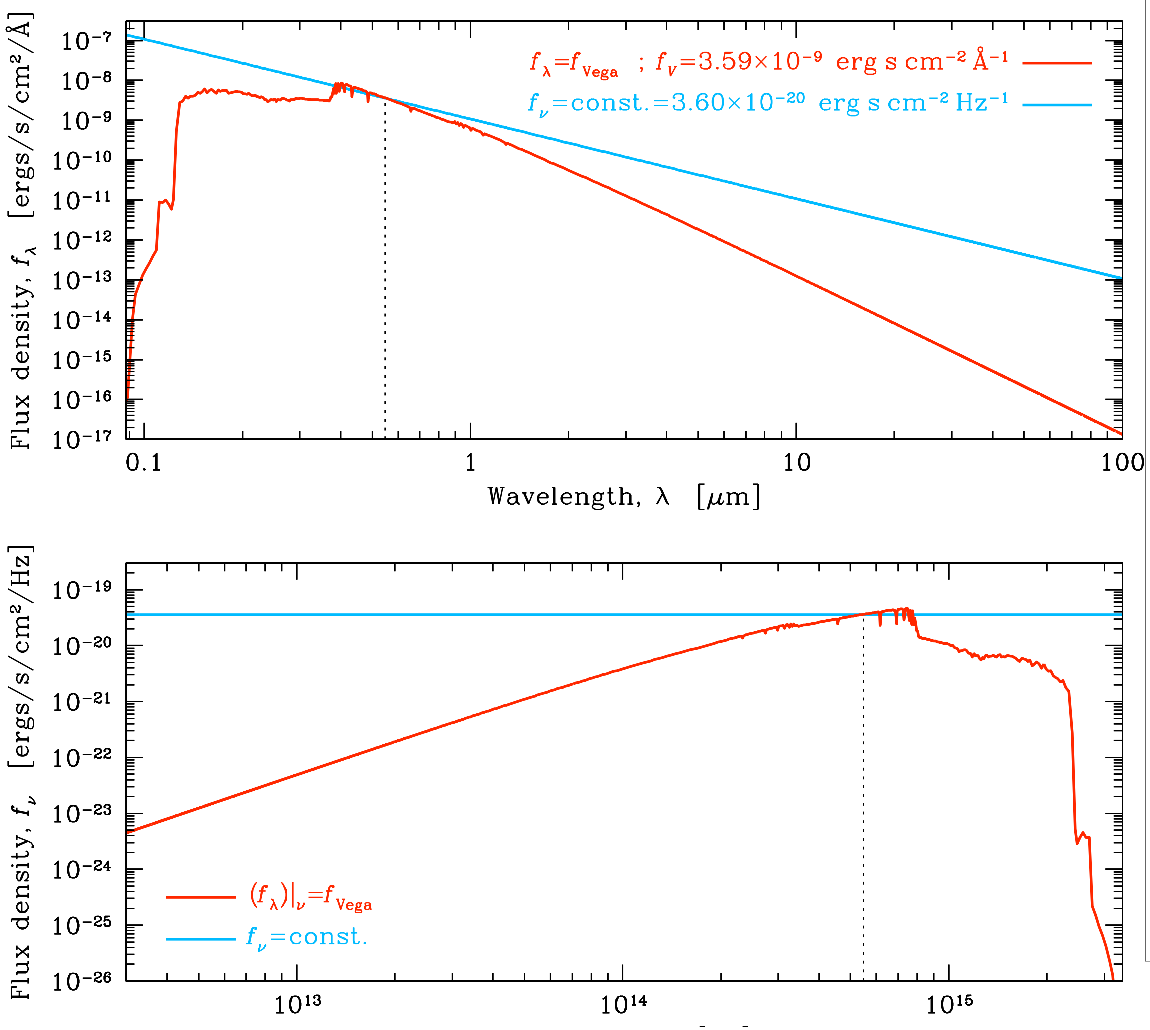
- Advantages: easy to compare with theory, and compare with physical quantites.

- Sometimes known as a "spectrophotometric" system, useful for comparisons over a very wide range in frequencies

AB magnitudes

- One can easily convert between AB magnitudes, janskys and electrons:
- Thus, in AB magnitudes, **mag 0 has a flux of 3720 Jy**
- A source of flux 10^{-3} Jy has a magAB = 2.5*log10(3270/10^{-3})=16.43
- Equally, if your photometric system has a zero-point of 23.75, this corresponds to a flux of 3720 Jy / 2.512^(23.75) = 1.2x10^{-6} and produces one detected electron per second
- An AB mag of 16.43 produces a flux of 2.512^(23.75-16.43)=847 electrons/second

AB and VEGA systems compared



- The difference between AB and VEGA magnitudes becomes very large at redder wavelengths!
- The spectrum of vega is very complicated at IR wavelengths and often model atmospheres are used adding to uncertainties

Absolute calibrations

- We have to figure out how to go from the apparent flux of a star to absolute units of erg/sec/cm^2/Hz!
- Need to compare laboratory light sources with astrophysical sources.
- This absolute calibration was carried out by **observing laboratory light sources across mountain tops** (we don't know how *a priori* what the absolute flux of Vega is)

Absolute calibration

- Vega (α Lyr) / Johnson system
  - Hayes & Latham (1975, ApJ, 197, 593): $f_\nu(\lambda=555.6\text{nm}) = 3500$ Jy
  - Tug, White & Lockwood (1977, A&A, 61, 679): $f_\nu(\lambda= 555.6\text{nm}) = 3570$ Jy
  - Hayes (1985): $f_\nu(\lambda=555.6\text{nm}) = 3590$ Jy, quotes 1.5% accuracy
  - Variance (2.5% full range) gives some indication of *external* errors.

Note stars not calibrated in region longward of Balmer limit

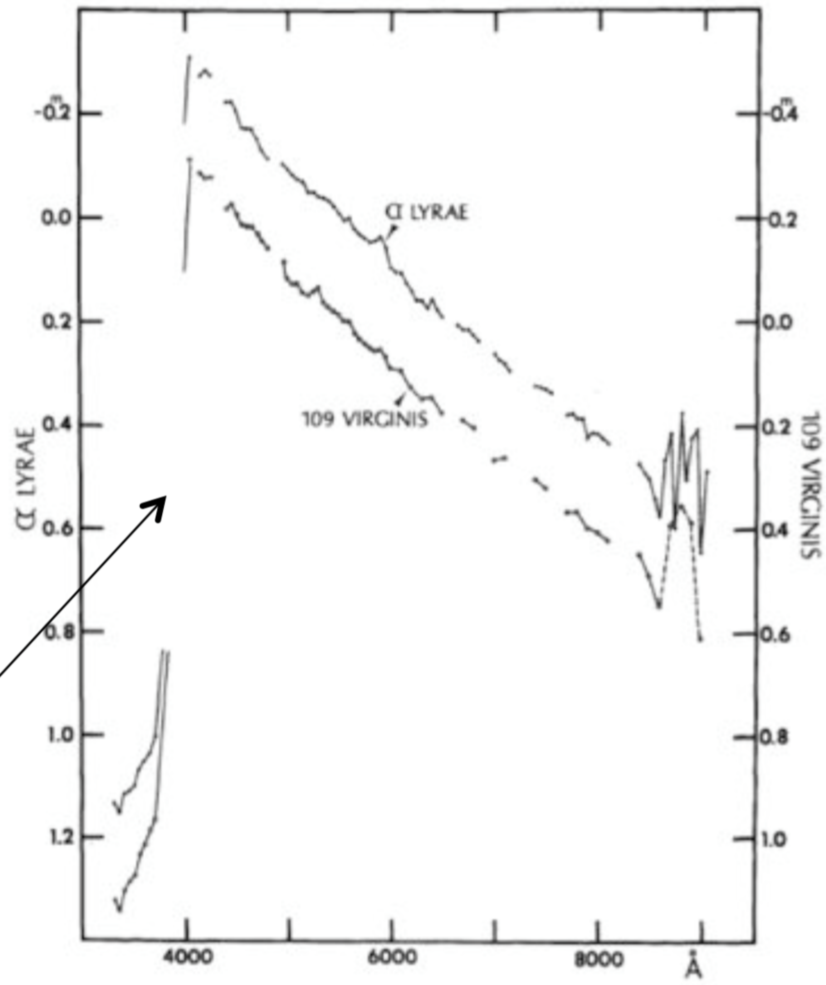
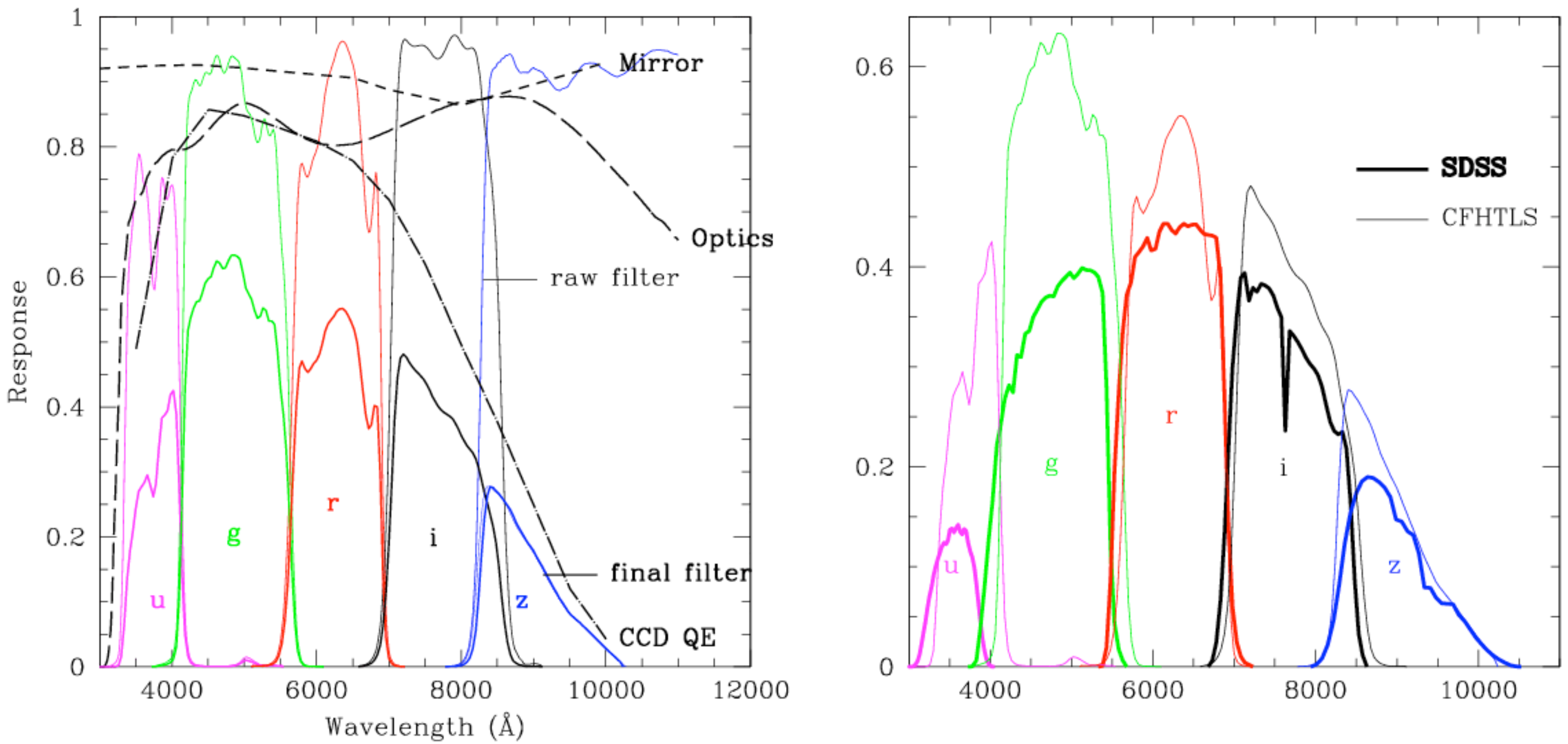


Fig. 2. Final absolute calibration of α Lyr (*upper curve; left ordinate scale*) and 109 Vir (*lower curve, right ordinate scale*) in magnitude units ($M_{1/\lambda}$), normalized to 0.0 mag at 5556 Å

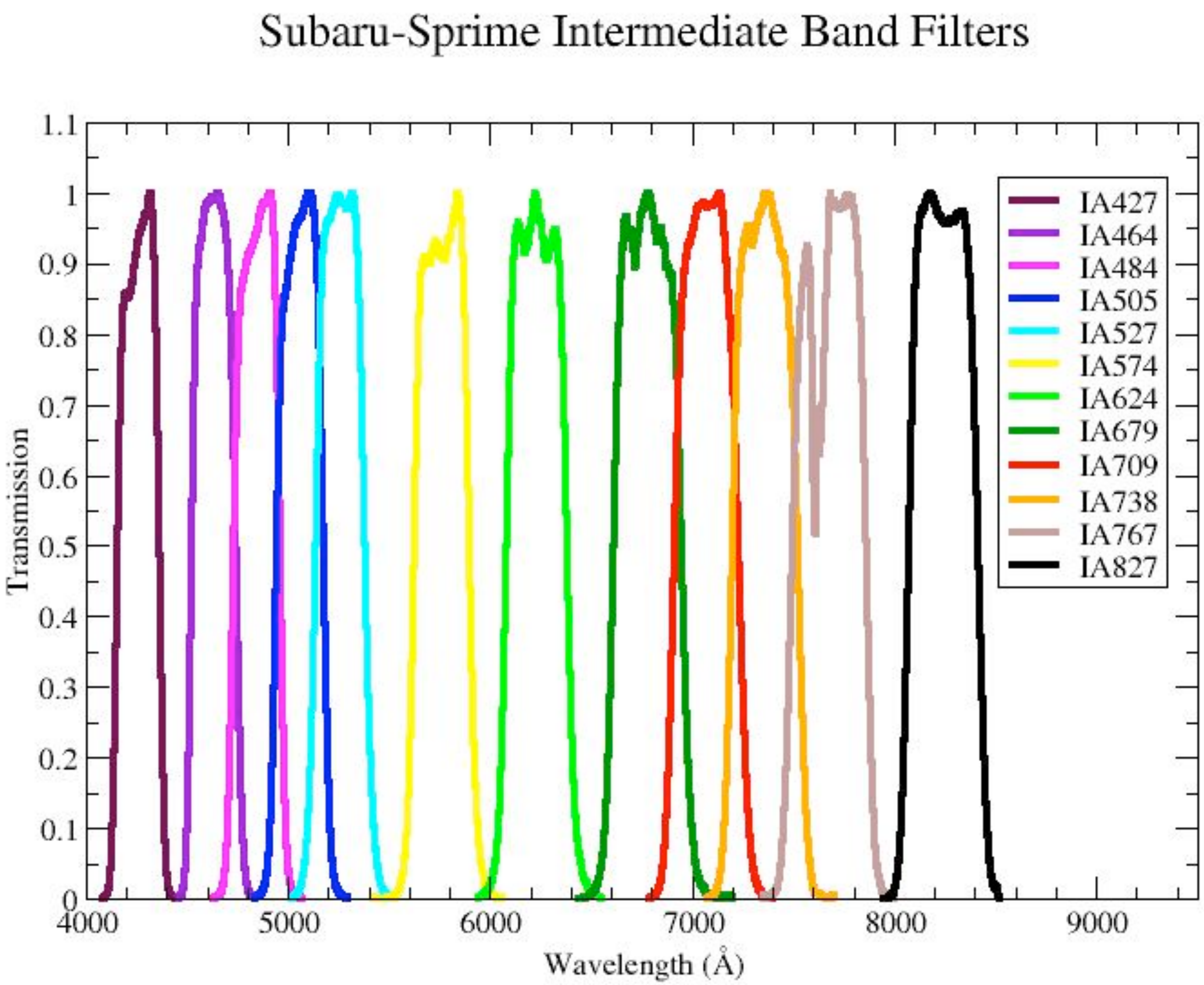
Filter systems

- Note the difference between “response function” and “filter system”
  - The response function includes the effects of atmosphere, detector, instrument
- There are different filters systems created for different astrophysical problems.

Typical broad-band filters and response functions



Intermediate band



Common response functions

- Landolt system: origins in Johnson & Morgan (1951,1953); UBV magnitudes are on the “Johnston” systems, RI magnitudes added later are on the “Cousins” system (1976). Based on average colour of six A0 stars
- SDSS ugriz system: Currently the SDSS has a preliminary magnitude system (u’g’r’i’z’) based on measurements of 140 standard stars. Fluxes of several white dwarfs are measured relative to vega and define the absolute flux calibration
- Work is under way to define new photometric systems not reliant on vega.

Calibrating the systems

- Johnson (1966) described a broad-band photoelectric photometric system based on measurements of A0 stars like vega
- Other work provides an **absolute flux calibration** linked to Vega.
- Practical difficulties: (1) not everyone can (or should) observe Vega -- it's much too bright -- so a network of **secondary standards** of fainter sources have been established.
- The **Landolt system,** based on A0 stars has become the standard magnitude system for many applications.
- Landolt measured stellar magnitudes using **photoelectric photometers** with a 14" (!) aperture; while making measurements with Landolt stars one should use this aperture.

instrumental magnitudes

- In general converting between different magnitude systems is **difficult**: conversion factors depend on the **spectrum** of each object.
- For many applications it's best to leave magnitudes in the **instrumental** system. Model colors can be computed using the filter and telescope response functions. **Colours do not depend on an absolute transformation**.
- In general, for **galaxies** transforming between different photometric systems is difficult because we don't know what the intrinsic spectrum is.

Calibrating data and processing data

Photometric calibrations

- In general, standard stars (usually from the compilations of **Landolt** or **Stetson** should be observed at a variety of zenith distances and colours.
- They should be at approximately the same air-masses at the target field.

$$m_{\mathrm{calib}} = m_{\mathrm{inst}} - A + Z + \kappa X$$

- In this case, A is a constant like the exposure time, Z is the instrumental zero point and kX is the extinction correction.
- This is a simple least-squares fit. But in general a system of equations will have to be solved:

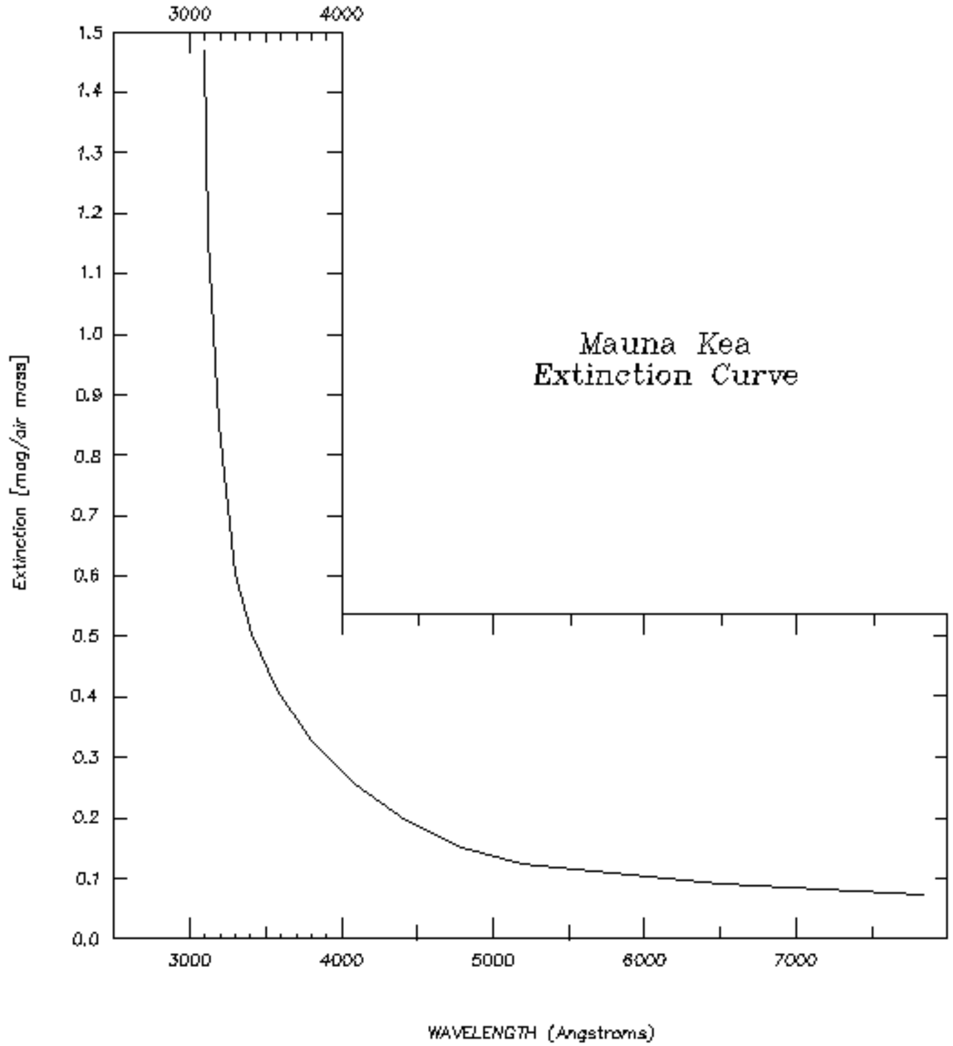
$$\begin{aligned} U &= U_{\mathrm{inst}} - A_u + Z_u + C_u(U-B) + \kappa_u X \\ B &= B_{\mathrm{inst}} - A_b + Z_b + C_b(B-V) + \kappa_b X \\ V &= V_{\mathrm{inst}} - A_v + Z_v + C_v(B-V) + \kappa_v X \end{aligned}$$

Atmospheric extinction and transmission

$$m(\lambda) = m_0(\lambda) + \kappa(\lambda) X(z)$$

$$X(z) = \sec\ z$$

- The extinction coefficients can be determined by observing a set of standard stars at different airmasses throughout the night
- OR you can use a set of precomputed values -- make sure there are no recent volcanic eruptions!
- For extragalactic sources , an additional effect to consider is **Galactic extinction** which can be estimated from IRAS dust maps. (Schlegel et al.)



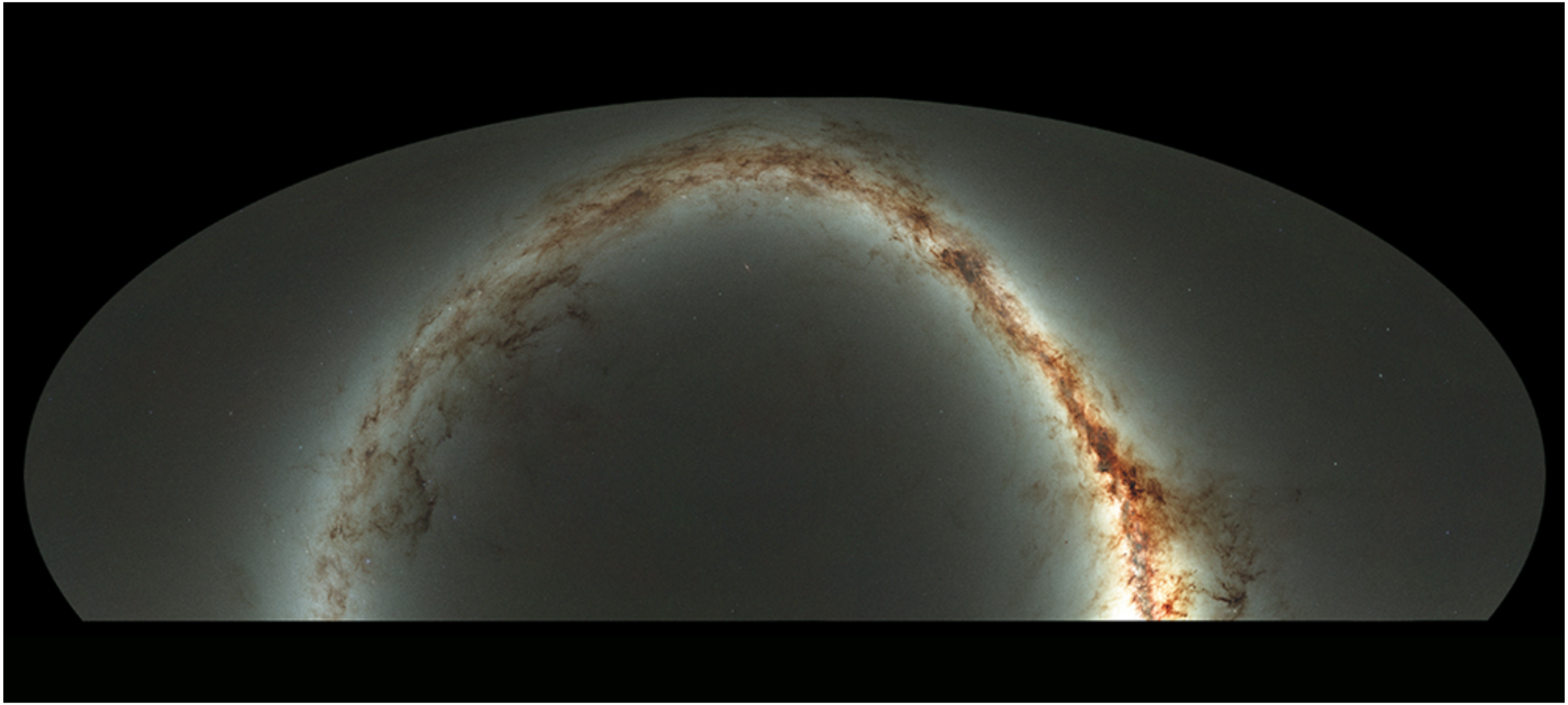
A practical recipe for photometric calibrations

- Observe a set of standard star fields (such as those observed by Landolt) in the filters you wish to calibrate.
- Measure instrumental magnitudes for Landolt's stars in your field and cross-match these stars with Landolt's catalogue.
- If you don't care about colour terms, then a simple least-squares fit will give you the **zero point** (the axis intercept) and (optionally) the extinction coefficient.
- If you do care about colour terms, you will have a system of linear equations to solve.
- Make sure your observations cover a large enough range in airmass

Are there are already photometric calibration stars in your field?

- **2MASS near-infrared JHK catalogue** covers the entire sky an can be used to carry out very reliable photometric calibrations. Many NIR telescopes now rely on this survey to carry out their calibrations. 2MASS can provided a calibration of ~0.03 mags (absolute)
- **SDSS digital sky survey** can provide precise optical calibrations (providing of course you can convert between SDSS magnitudes and your instrumental system)

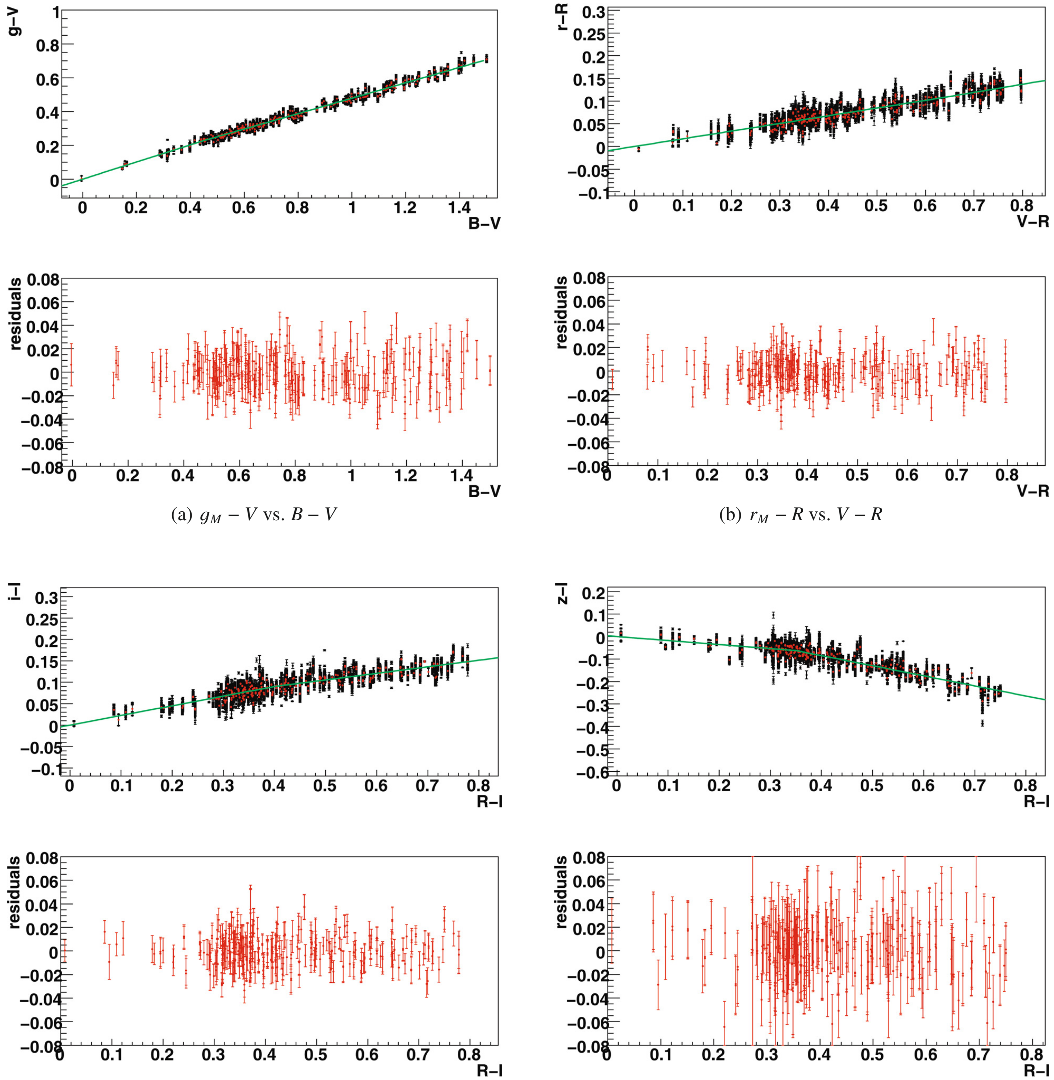
..and PS1



An example: Calibrating megacam

- Studies of distant supernovae require a very precise absolute flux calibration, better than 1% over the full MEGACAM field of view: very challenging
- Photometric redshifts also require very precise and homogenous photometric calibration
- Regnault et al. calculate in detail the transformation between CFHT instrumental magnitudes and Landolt standard star magnitudes

Transforming to Landolt



(a) $g_M - V$ vs. $B - V$

(b) $r_M - R$ vs. $V - R$

Regnault et al. (2009)

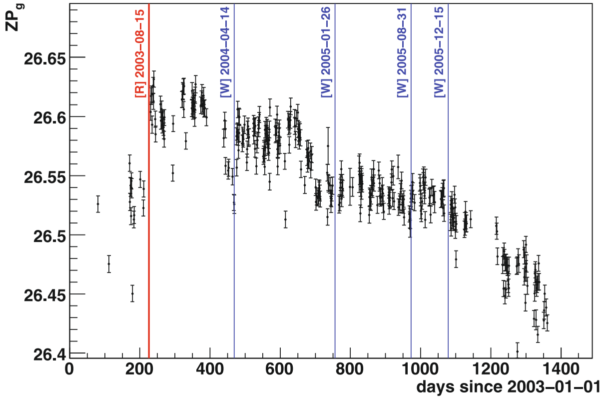
airmass term   Colour term

$$\begin{aligned}
\hat{g}_{\mathrm{ADU}|\boldsymbol{x}_0} &= V - k_g(X-1) + C(B-V;\alpha_g,\beta_g) + ZP_g \\
\hat{r}_{\mathrm{ADU}|\boldsymbol{x}_0} &= R - k_r(X-1) + C(V-R;\alpha_r,\beta_r) + ZP_r \\
\hat{\imath}_{\mathrm{ADU}|\boldsymbol{x}_0} &= I - k_i(X-1) + C(R-I;\alpha_i,\beta_i) + ZP_i \\
\hat{z}_{\mathrm{ADU}|\boldsymbol{x}_0} &= I - k_z(X-1) + C(R-I;\alpha_z,\beta_z) + ZP_z.
\end{aligned}$$

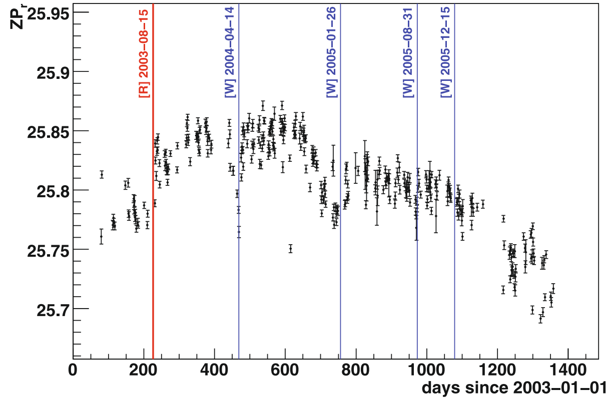
$$F_{|\boldsymbol{x}} = 10^{-0.4\,(m_{|\boldsymbol{x}} - m_{\mathrm{ref}})} \times \int S_{\mathrm{ref}}(\lambda) T(\lambda;\boldsymbol{x}) \mathrm{d}\lambda$$

- A spectrophotometric standard which has been observed in landolt is used for the absolute flux calibration

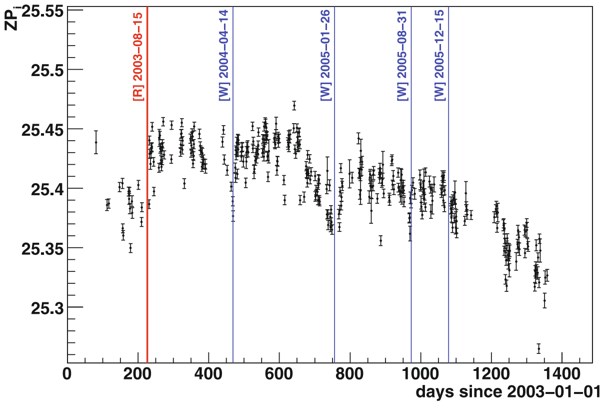
Zero-point evolution



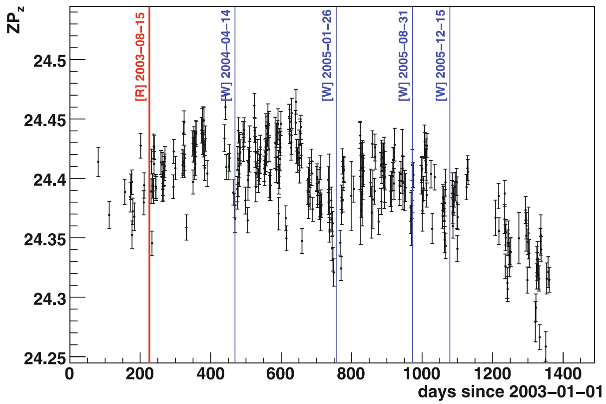
(a) g_M



(b) r_M



(c) i_M

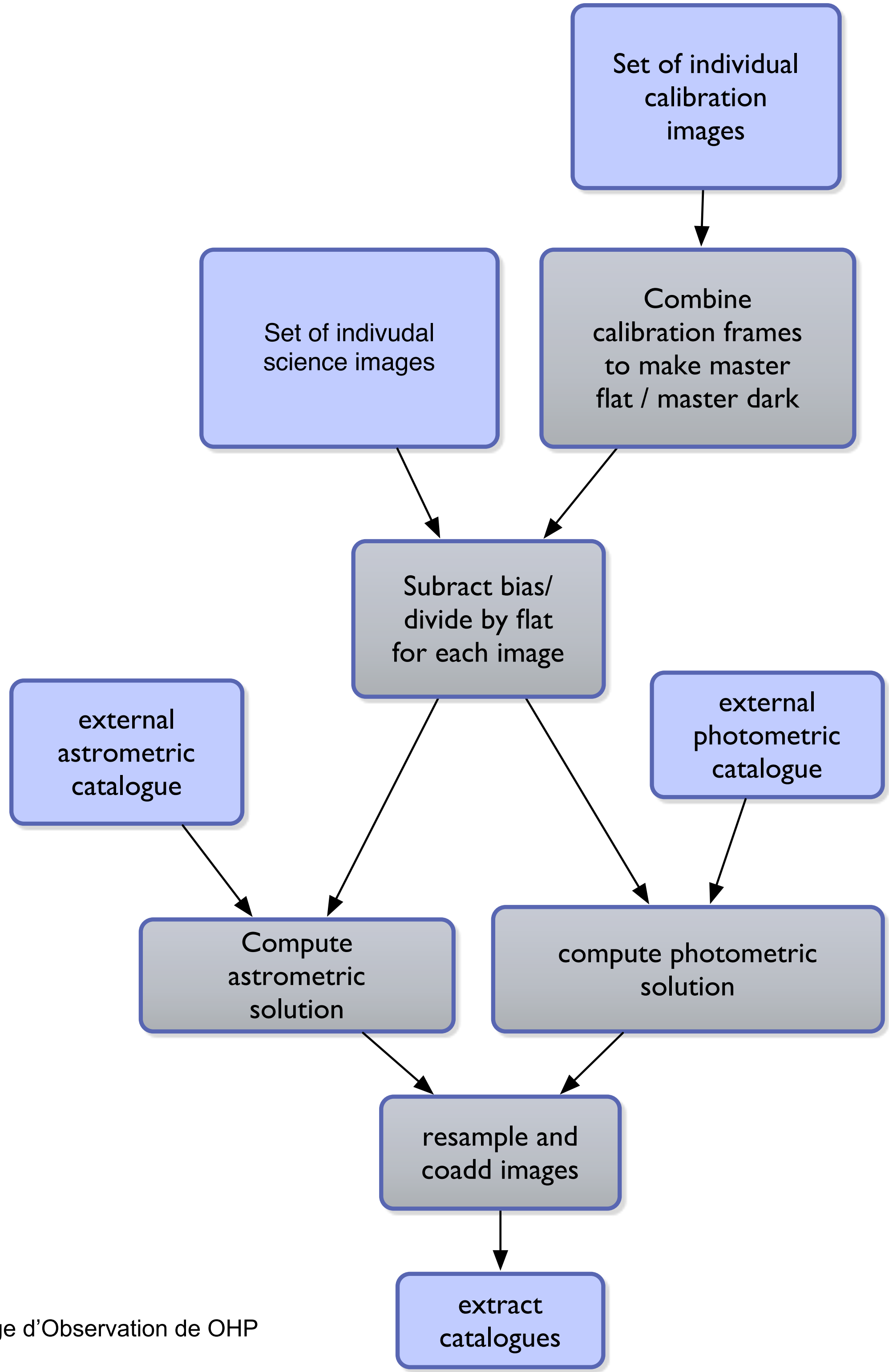


(d) z_M

- Zero point of telescopes can evolve due to dust build-up inside the telescope or mirror changes
- VISTA also provides a similar example with mirror coating degrading progressively with time...

Regnault et al. (2009)

Data reductions



- IRAF task such as **imcombine**, **imarith** can be used for the pre-reductions
- **swarp, scamp,** can be use used for the calibration
- **sextractor, phot, daophot:** are good ways to make phtometric measurements

CCD equation I

- Read noise follows a Gaussian or normal distribution
- Shot noise follows a Poissonian distribution (counting statistics)

$$P_n = \frac{m^n e^{-m}}{n!}$$

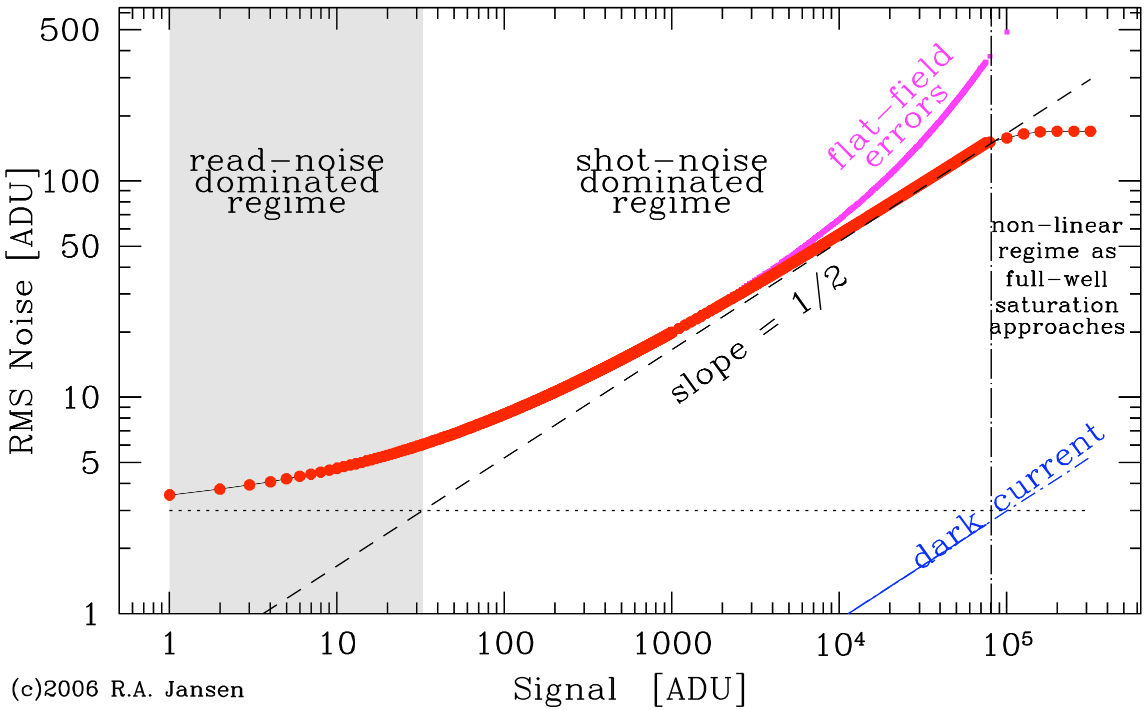
$$\sigma = \sqrt{m}$$

$$N = \sqrt{S_\star + S_S + t \cdot dc + \mathcal{R}^2}$$

- N: Total counts per pixel, electrons
- $S_\star$: Astronomical Source
- S_S: Sky background
- $t \cdot dc$: Dark current
- $\mathcal{R}^2$: Read noise

CCD equation II

$$\frac{S}{N} = \frac{S_\star}{\sqrt{S_\star + n_{\rm pix} \cdot \left(1 + \frac{n_{\rm pix}}{n_{\rm sky}}\right) \cdot \left(S_S + t \cdot dc + \mathcal{R}^2 + \mathcal{G}^2 \sigma_f^2\right)}}$$



Photometric errors

- Most photometric software like `sextractor` provide an estimate of the error for a given photometric aperture
- Bright sources like stars are dominated by **photon counting noise**; faint source like galaxies are dominated by **background noise**
- However in "real" data which may have been resampled the noise background could be under-estimated and for faint objects, magnitude errors will be **incorrect**.
- Often need to do **simulations** to get the right answer or find the "fudge factor"

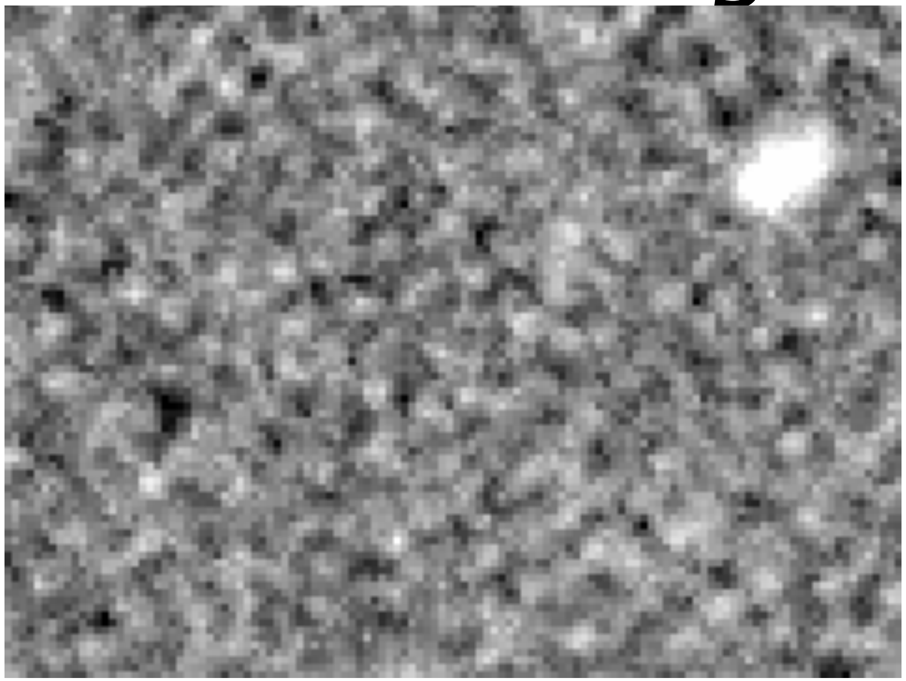
$$\Delta m = 1.0857 \frac{\sqrt{A\sigma^2 + \frac{F}{g}}}{F}$$

Background noise^2 x area (pixels)

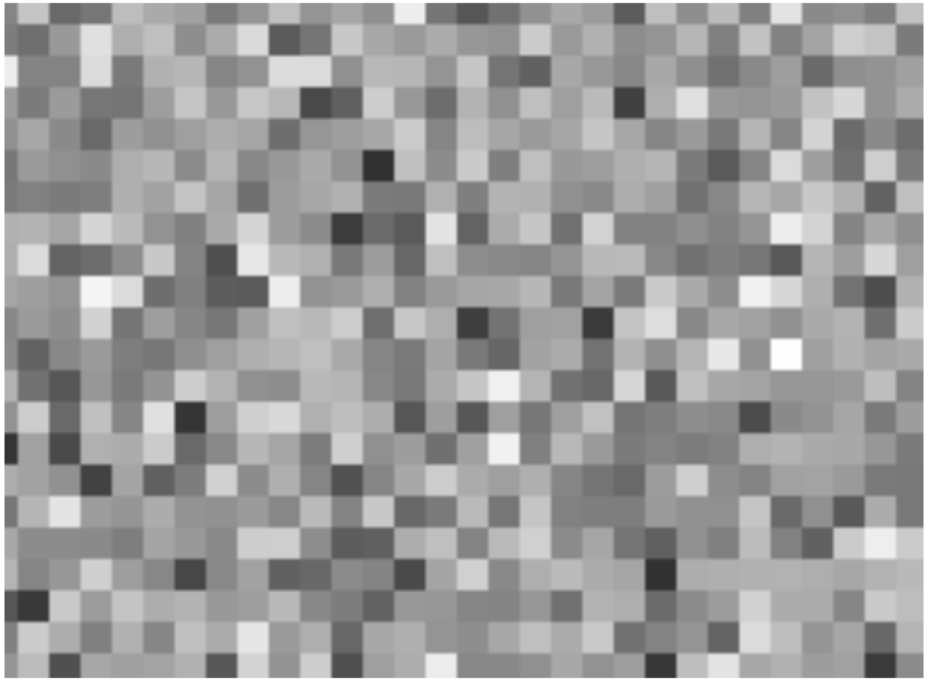
Object flux/gain

- This does not take into account **systematic errors** which could be caused by bad photometric calibration

Sometimes the sky noise isn't gaussian..



Correlated noise in oversampled deep J-band exposure (WFCAM)



Normal "white" noise

Incompleteness and reliability

What it is

- On a given astronomical image to a given flux limit can define the concepts of **incompleteness** and **reliability**
- **Incompleteness**: does the catalogue contain all sources to a given flux limit?
- **Reliability:** are all the sources real sources (i.e., not false detections)?
- Obviously it is best to science with catalogues which are **complete** and **reliable** preferably many sigmas from the detection limit.

How to estimate it

- **Reliability**: where do the sources lie in a flux-radius size plane?
- **Reliability:** in a "negative" image at the same flux limit how many sources are there?
- **Completeness:** How do the number density of objects compare with deeper surveys?
- **Completeness** can also be estimated by numerical simulations

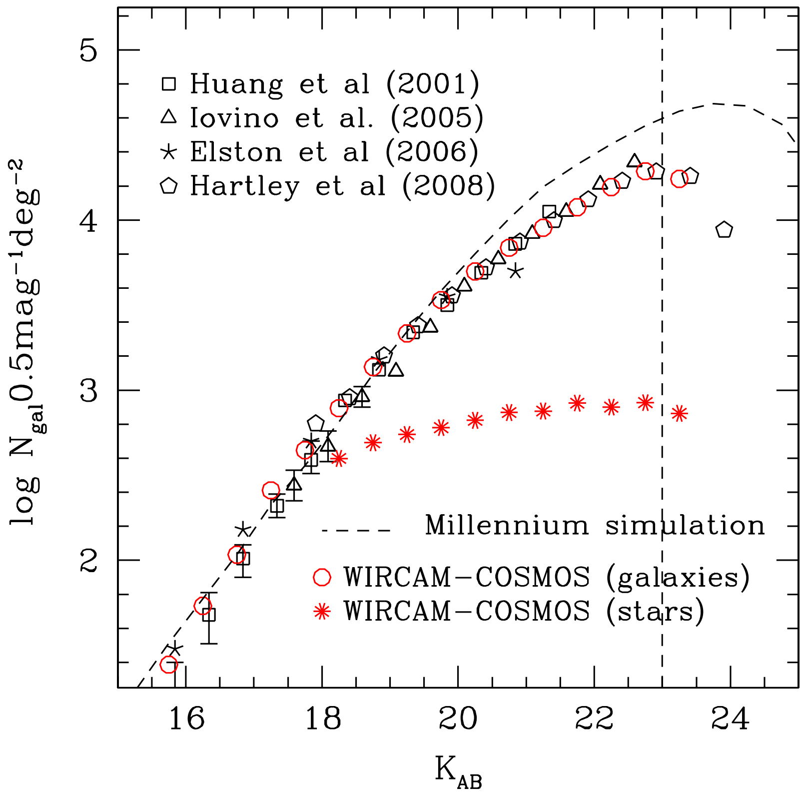
Detection limits

- **The signal to noise ratio** is simply 1/(magnitude error)
- **The detection limit** indicates to what magnitude limit an image can be scientifically exploitable.

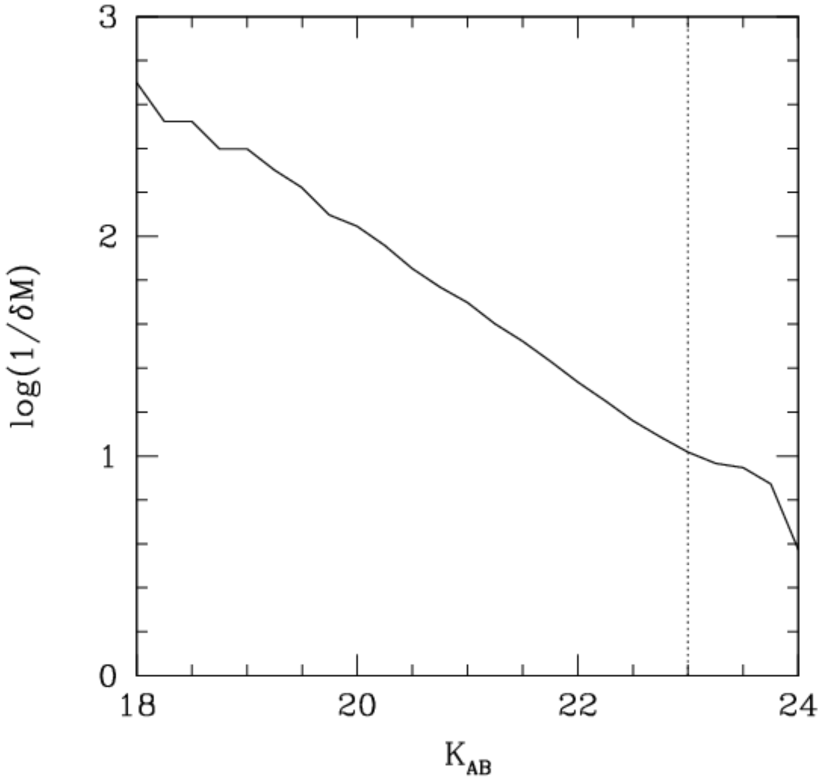
- **Magnitude errors** rise rapidly as one approaches the detection limit
- Can make a simple estimate the detection limit from the sky noise

Number counts and s/n

Number of objects vs magnitude



signal-to-noise vs magnitude



Detection limits and sky noise

$$\text{detection limit} = -2.5\log(\text{SN} \times \sigma\sqrt{\text{N}}) + \text{ZP}$$

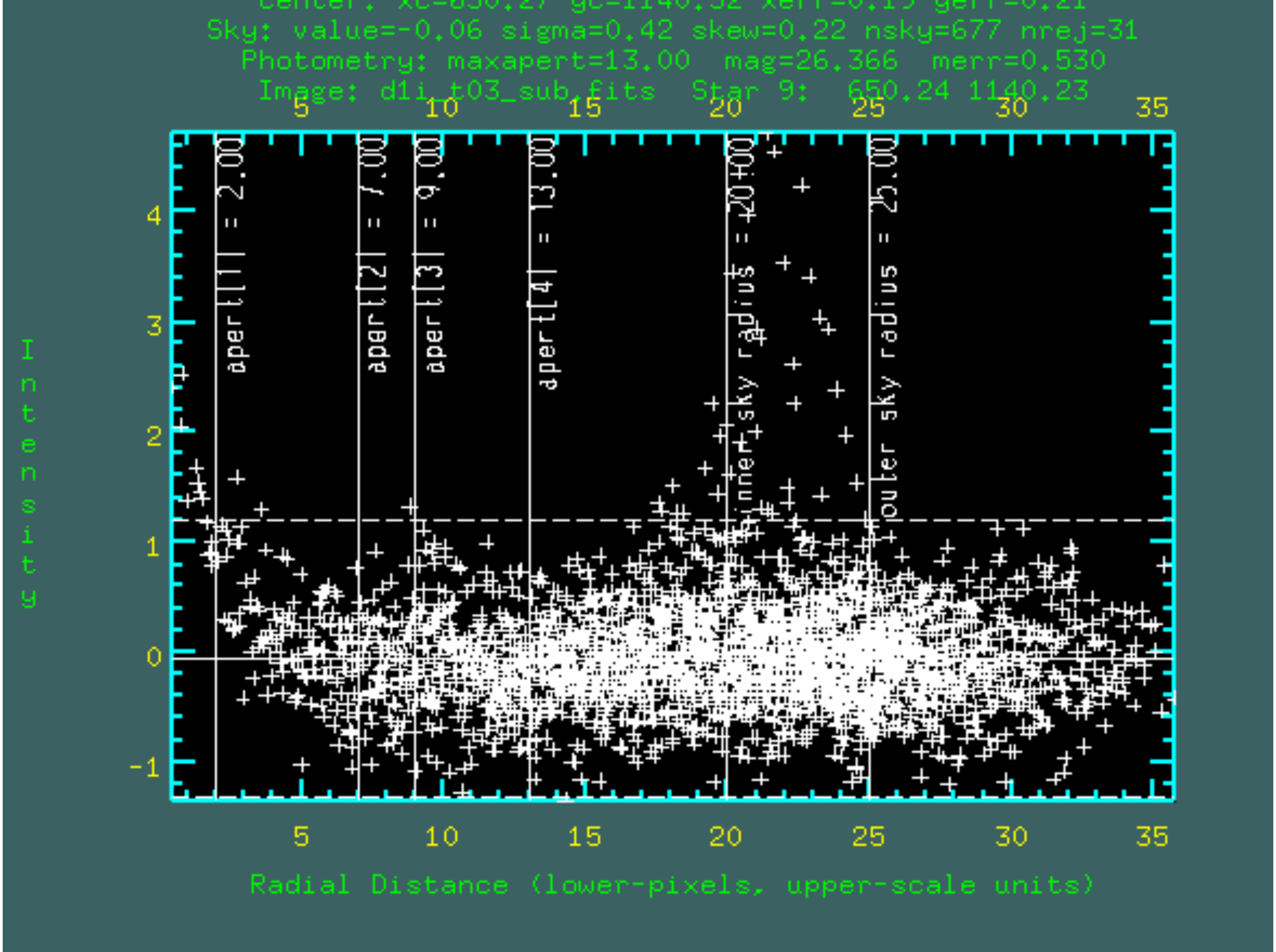
- **N** given by the number of pixels in the (normally) circular aperture
- **sigma** is the noise per pixel in the image
- ZP conversion between ADU and magnitudes

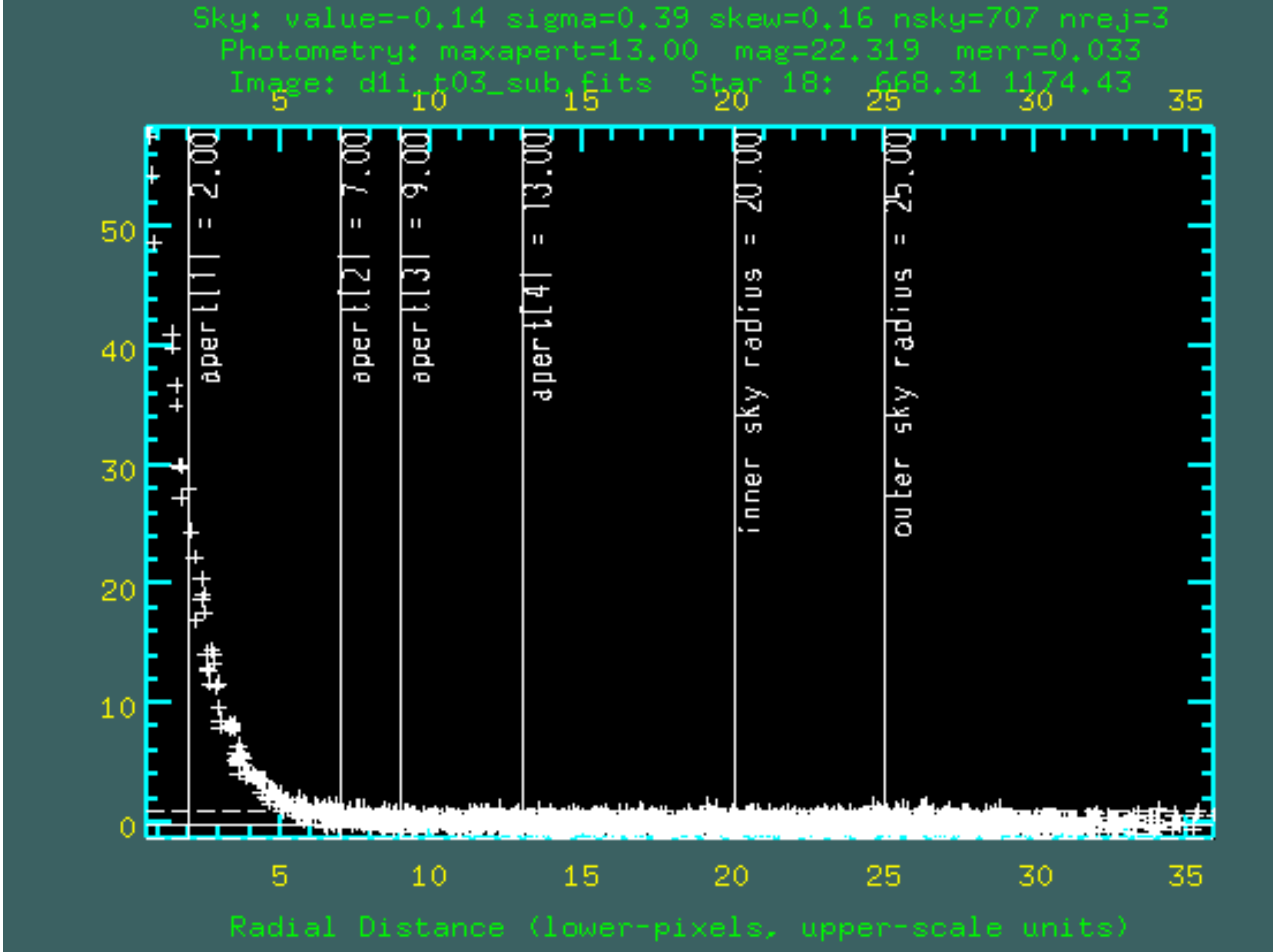
Aperture magnitudes

- In **aperture photometry** one simply measures the total flux inside a (normally circular) aperture and subtracts the sky flux. Programs like PHOT in IRAF can do this for you.
- If the size of the aperture is **too small**, flux is lost
- However, if the aperture is **too large**, too much sky is included (measurement becomes noisy).

Aperture magnitudes

- In a **curve of growth** analysis, the flux in a series of apertures is measured. In this way a correction to **total magnitude** can be estimated for the smallest apertures (which are the least contaminated by crowding, but miss the largest amount of flux).
- Note that aperture magnitudes can be sensitive to point-spread-function (PSF) variations.


Sky: value=-0.06 sigma=0.42 skew=0.22 nsky=677 nrej=31
Photometry: maxapert=13.00 mag=26.366 merr=0.530
Image: d1i_t03_sub.fits Star 9: 650.24 1140.23
apert[1] = 2.00
apert[2] = 7.00
apert[3] = 9.00
apert[4] = 13.00
inner sky radius = 20.00
outer sky radius = 25.00
Intensity
Radial Distance (lower-pixels, upper-scale units)



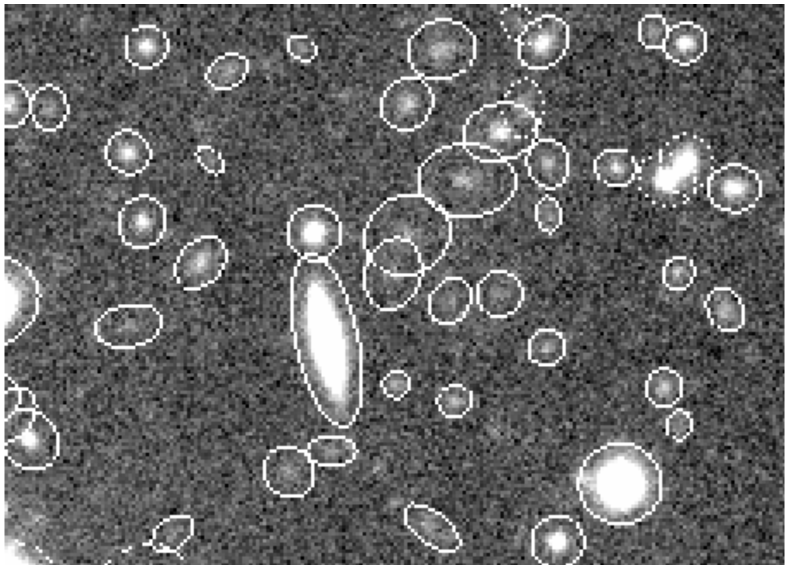
Sky: value=-0.14 sigma=0.39 skew=0.16 nsky=707 nrej=3
Photometry: maxapert=13.00 mag=22.319 merr=0.033
Image: d1i_t03_sub.fits Star 18: 668.31 1174.43
apert[1] = 2.00
apert[2] = 7.00
apert[3] = 9.00
apert[4] = 13.00
inner sky radius = 20.00
outer sky radius = 25.00
0
10
20
30
40
50
5
10
15
20
25
30
35
Radial Distance (lower-pixels, upper-scale units)

Faint source photometry

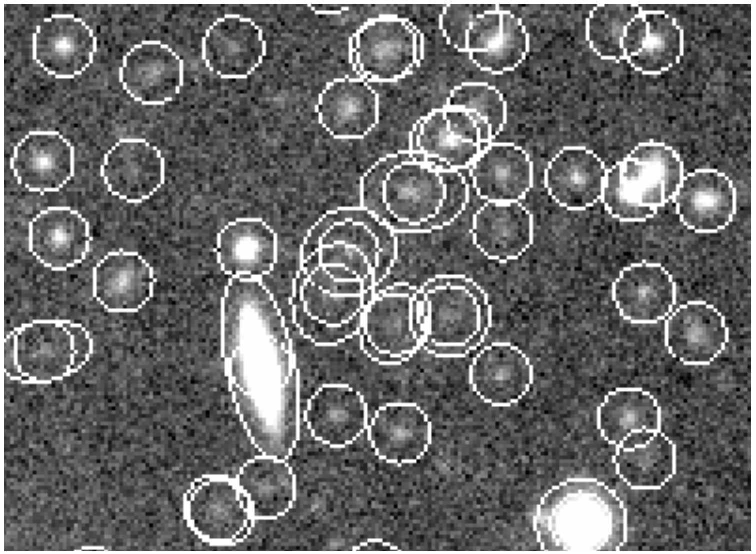
- In **variable-aperture photometry** a photometric aperture is chosen and then the flux is summed up out to this radius.
- Kron (1980) magnitudes use the first image moment to determine the radius of the elliptical or circular aperture for flux integration.
- Sextractor integrates the galaxy profile out $2.5*r_1$; Simulations show that this recovers around 95% of the galaxies flux.
- There can objects with unusual profiles where the amount of flux lost is much greater.
- In **crowded fields** Kron magnitudes are perturbed by the presence of nearby sources. In these cases it's almost better use **PSF-fitting photometry** (at least for stars)

Optimal settings for deep imaging data

- Effect of activating the `PHOT_AUTOAPERS` which sets the minimum Kron radius in deep Megacam images.



PHOT_AUTOAPERS 0,0



PHOT_AUTOAPERS 16,16

- For very faint objects it can be difficult to measure accurately the size of the Kron radius

Point–spread fitting photometry

- For crowded fields (like globular clusters) **blending** can become important. Kron magnitudes are corrupted.
- **Iterative** point-spread fitting programs like DAOPHOT and DAOFIND are very good for crowded stellar fields (for example, globular clusters)
- Obviously PSF-fitting photometry can only work for stellar fields! Current generation psf-fitting software also assumes the object PSF is constant over the field of view.

Photometry of faint sources with SExtractor

- Sextractor provides many kinds of magnitudes.
  - MAG_APER measures a fixed aperture magnitudes in a user-specified diameter
  - MAG_ISO are **isophotal magnitudes** - integrations carried out to a fixed isophotal limit above the sky background
  - MAG_AUTO are **Kron magnitudes -** integrations carried out to a fixed radius defined by the second moment
  - MAG_PETRO are Petrosian magnitudes - integrations carried out to some multiple of the Petrosian radius r_P.

$$\eta = \frac{I(r_\mathrm{P})}{2\pi \int_0^{r_\mathrm{P}} I(r) r dr / (\pi r_\mathrm{P}^2)} .$$

What magnitudes to use

- Best magnitudes to use depends on the astrophysical application: nearby, bright galaxies; distant unresolved point-like objects; crowded stellar fields; deep galaxy fields.

Making multi-band catalogues

- In many astrophysical applications we are interested in measuring not only the magnitude of objects but also their **colour** - the difference in magnitude between two bands.
- An easy way to do this is to use the ‘dual image mode’ in sextractor, where one image is used as a **detection image** and another image is used as a **measurement image**. In this way object lists are matched as the same detection image is used in all bands.

Making multi-band catalogues

- Another way is simply to cross-correlate the two catalogues, but you may not be sure you are measuring the **same aperture on the same galaxy**
- The choice of the **detection image** is important and once again depends on the type of astrophysical application. Generally however we want to choose the reddest possible bandpass.
- The "**chisquared" image** is a useful way to make multiple band images

Swarp and scamp

- SCAMP is software which does astrometric calibration (x,y to RA->DEC)
- SWARP is software which does resampling

Quality control

- **At the telescope:**
  - Is it the right source / field?
  - Is the source saturated (look at a radial profile)?
  - Are we read-noise limited (are there enough counts in the sky and in the source)?
- **At home:**
  - Does applying the calibration frames reduce the amount of noise per pixel in the image?
  - Does the noise scale correctly with the number of exposures?