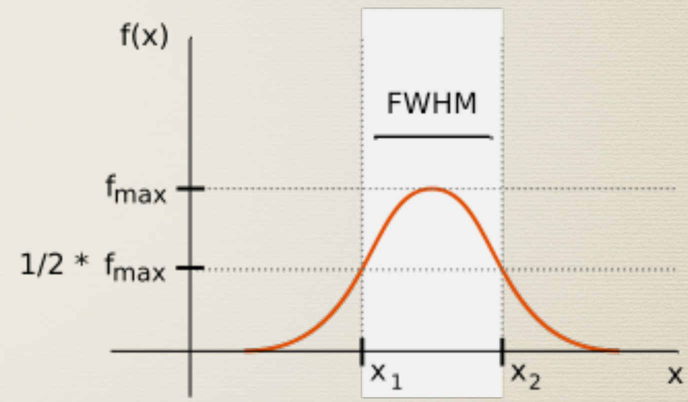
Dealing with images: the Point Spread Function

- The *point spread function* describes what the image of a point source (like a distant star) - i.e. one that is completely unresolved - will look like in the plane of our detector. It may vary across the field, and includes the effects of telescope optics & atmospheric blurring.

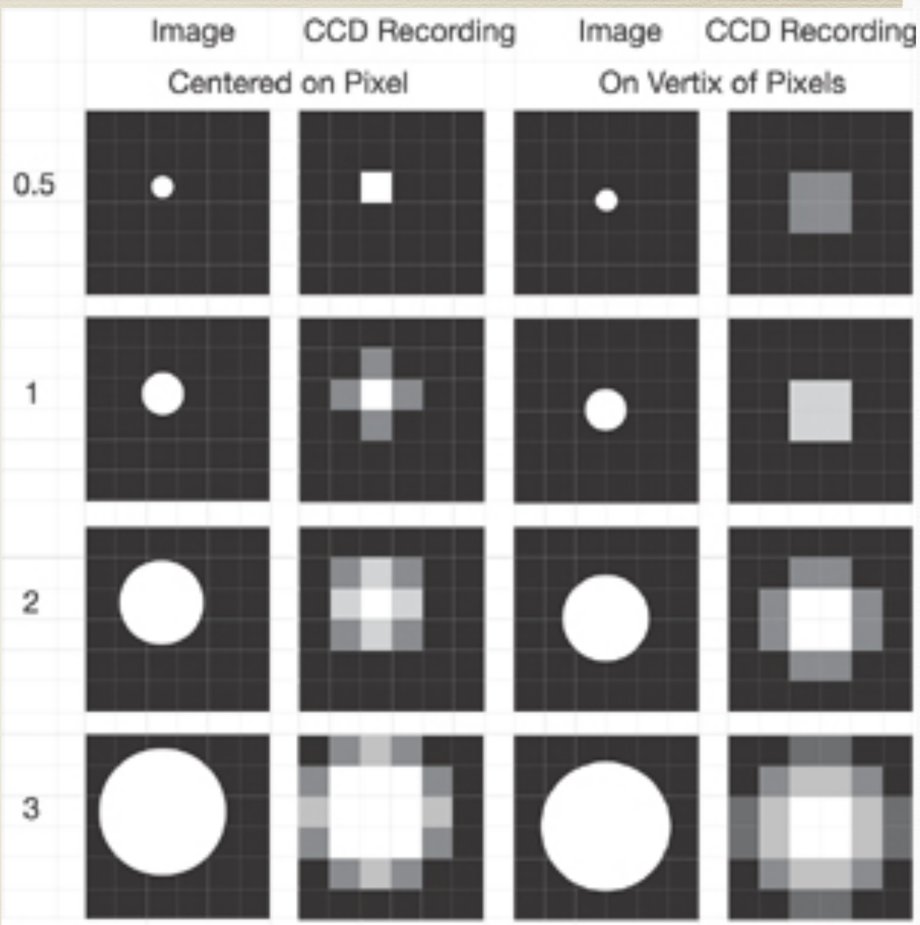
- We generally characterize it by its *full width at half-maximum (FWHM),* which equals 2.35σ for a Gaussian distribution, but it may have spikes, rings, etc. as seen for bright stars.



- However, we measure intensity using a detector with some fixed pixel size. What happens if it is large compared to the FWHM?

Importance of pixel size

- If pixels are large compared to the FWHM, we lose information about where exactly an object was - we cannot reconstruct its position accurately, even with noiseless data. This is key for astrometry (position measurements) & some photometric (brightness measurement) techniques. With well-sampled, high signal-to-noise data, we can determine centroids to ~0.1 pixel or better.

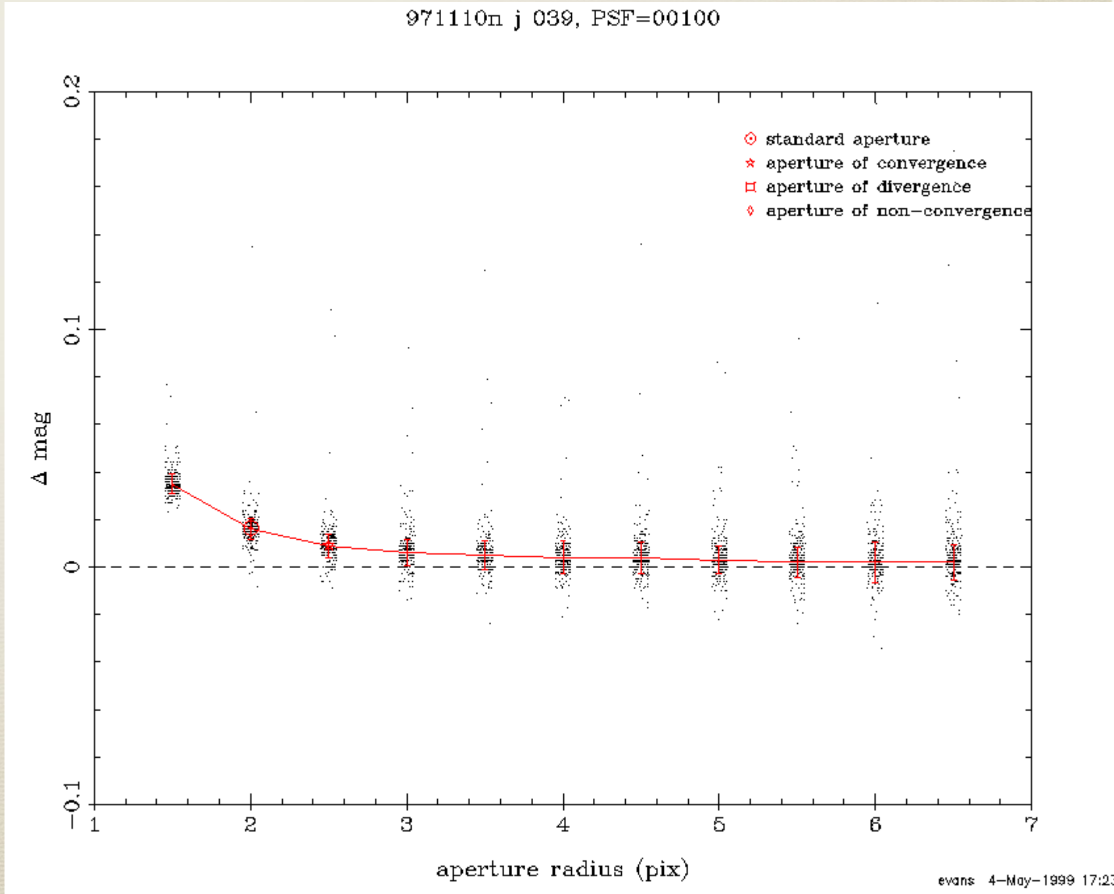


- For 1D signals, sampling at a rate >2x the highest frequency (*Nyquist sampling*) allows perfect reconstruction. In 2D, it's a bit messier, but having at least 2-2.5 pixels per FWHM yields good results.

Aperture photometry

- The Sextractor package performs automated photometry on astronomical images.   It finds sources (stars or galaxies), determines their overall shapes, then measures the total flux (i.e. e-) within either a circular or elliptical region (an 'aperture').

- PSFs often have broad (e.g., Cauchy) wings, so only some fraction of light will fall within a given aperture. *If* we know the light profile of the object and the PSF, we can calculate an 'aperture correction' - a factor to multiply the flux by (or offset magnitudes by) for this.



Aperture photometry

- A key issue is how to define the aperture to use. If only interested in stars, we might use a radius (in arcsec) that will include a large fraction of the flux. We also have to subtract off a background level to get the flux from the object we're interested in.
- Galaxies will appear extended and have varying sizes, so using a fixed aperture size works less well. Common options are:
  - *isophotal magnitudes*: measure the magnitude within some *isophote*, a line of constant surface brightness (flux per area on the sky). 25 mag/arcsec^2 is common; note a dark moonless sky has surface brightness ~22 mag/arcsec^2!
  - *Petrosian magnitudes*: measure the magnitude within an isophote whose level is a fixed fraction of the mean SB within that isophote (SDSS does this). Disadvantage is that determining the right radius/ellipse is noisy.
  - *Kron magnitudes*: measure the magnitude within a region 2.5x larger than the ellipse defined by the first moments of the galaxy flux. Ideally, includes ~95% of the light from a galaxy.

Template-based photometry

- If we know the shape of an object (e.g. the PSF, if we're looking at a star), we can determine its flux better by fitting it with

  *flux = A*template + background* . The value of *A* will tell us how many counts are associated with the object. This will provide the optimum (i.e., lowest error) estimate of the flux from an object.

- If we ignore the background, you can think of this as a weighted mean of the flux, where the pixels with the most counts get the most weight. Furthermore, we can incorporate measurement errors into the fit (as opposed to aperture photometry, where we only use them to propagate errors to get uncertainties in the magnitudes).

- The downside is that getting an accurate flux relies on knowing the template extremely well.

- SDSS uses these techniques for their "PSF" magnitudes (useful for stars) and "model" magnitudes (for galaxies), finding the best fit model galaxy light profile in the latter case.

Photometry packages

- *Sextractor* is used very widely for many-galaxy studies. It can do circular and elliptical aperture photometry, and attempts to 'deblend' close objects to measure the magnitudes of each.

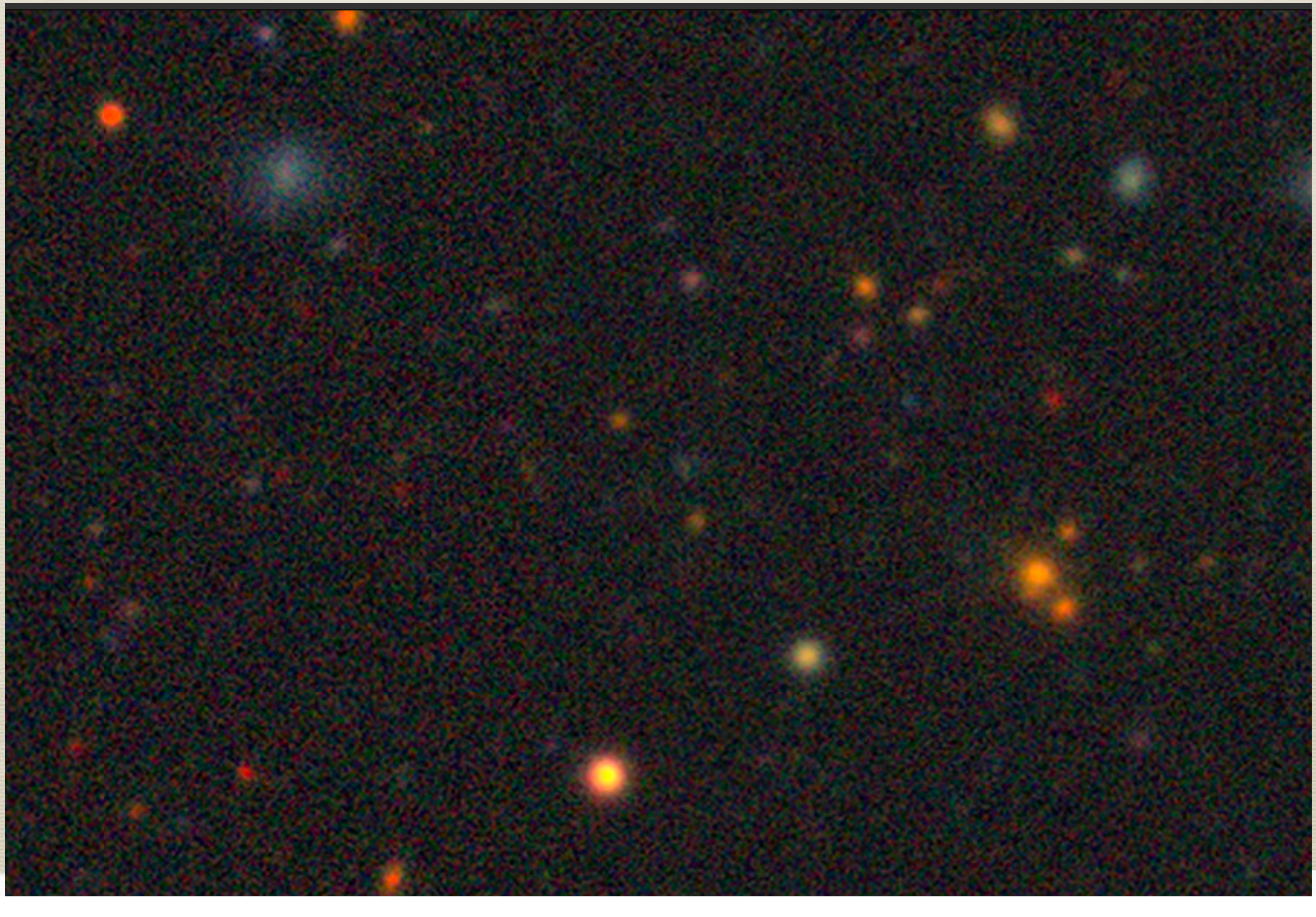
- Deblending is a hard problem; real galaxies have substructure, we don't want to split them into multiple separate objects.

- For detailed galaxy modeling (e.g. separating exponential light profiles (like spirals) from $r^{1/4}$ light profiles (like ellipticals) , *GALFIT* and *GIM2D* are standard. *GALFIT* can do simultaneous modeling of overlapping galaxies; the GALAPAGOS package automates this.

- For stellar photometry in dense fields (like globular clusters or other galaxies), *DAOPHOT/ALLFRAME*, *DoPHOT*, and *HSTPHOT* are standard.
  - These all perform template photometry with a known PSF, and iteratively subtract off the stars found so they can detect still fainter ones.

The Legacy Surveys: *Tractor* processing

- Legacy survey data you may use for projects is processed with *Tractor*, which does galaxy modeling and photometry at the same time.
- To see data, models and residuals go to https://www.legacysurvey.org/viewer



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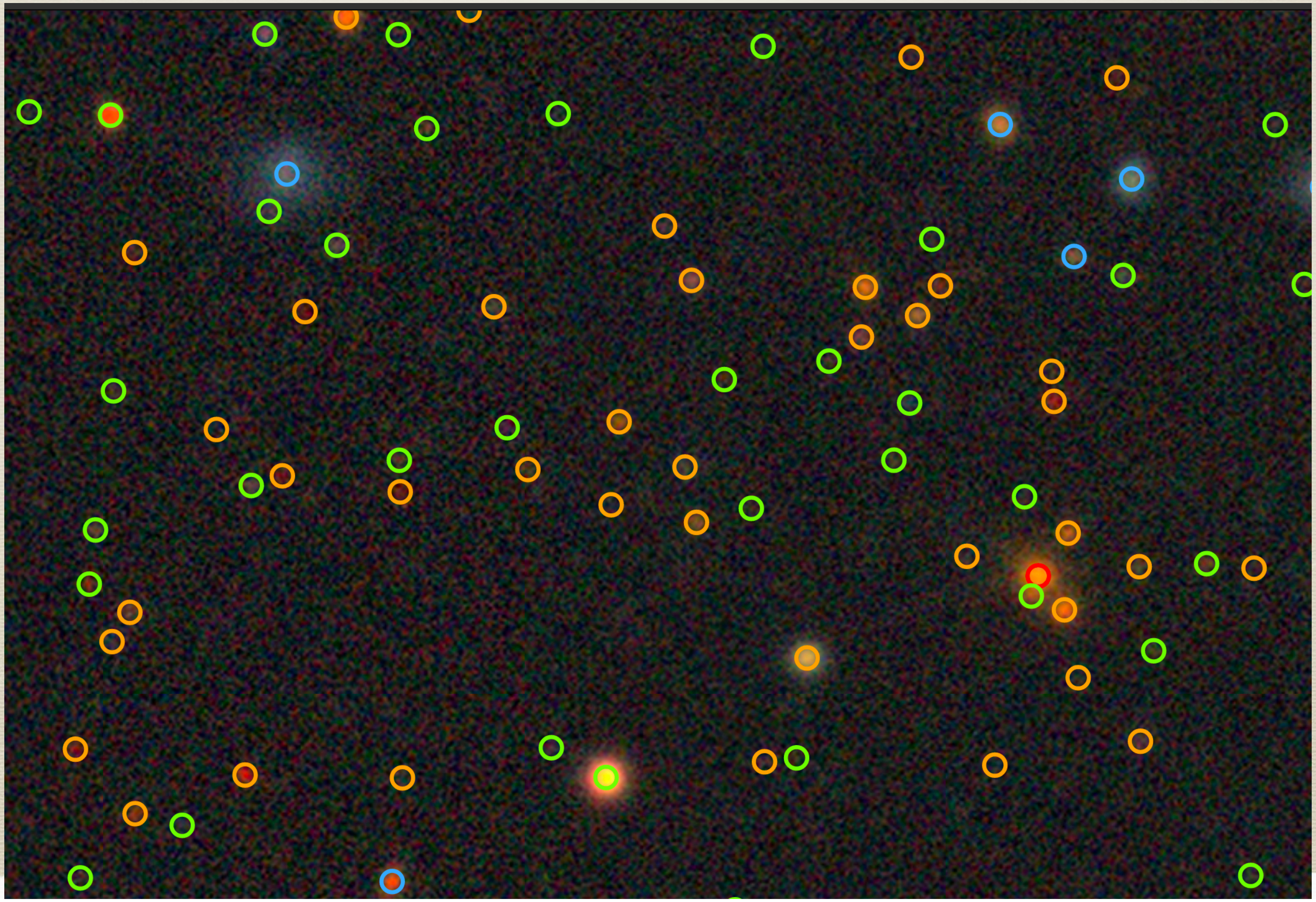
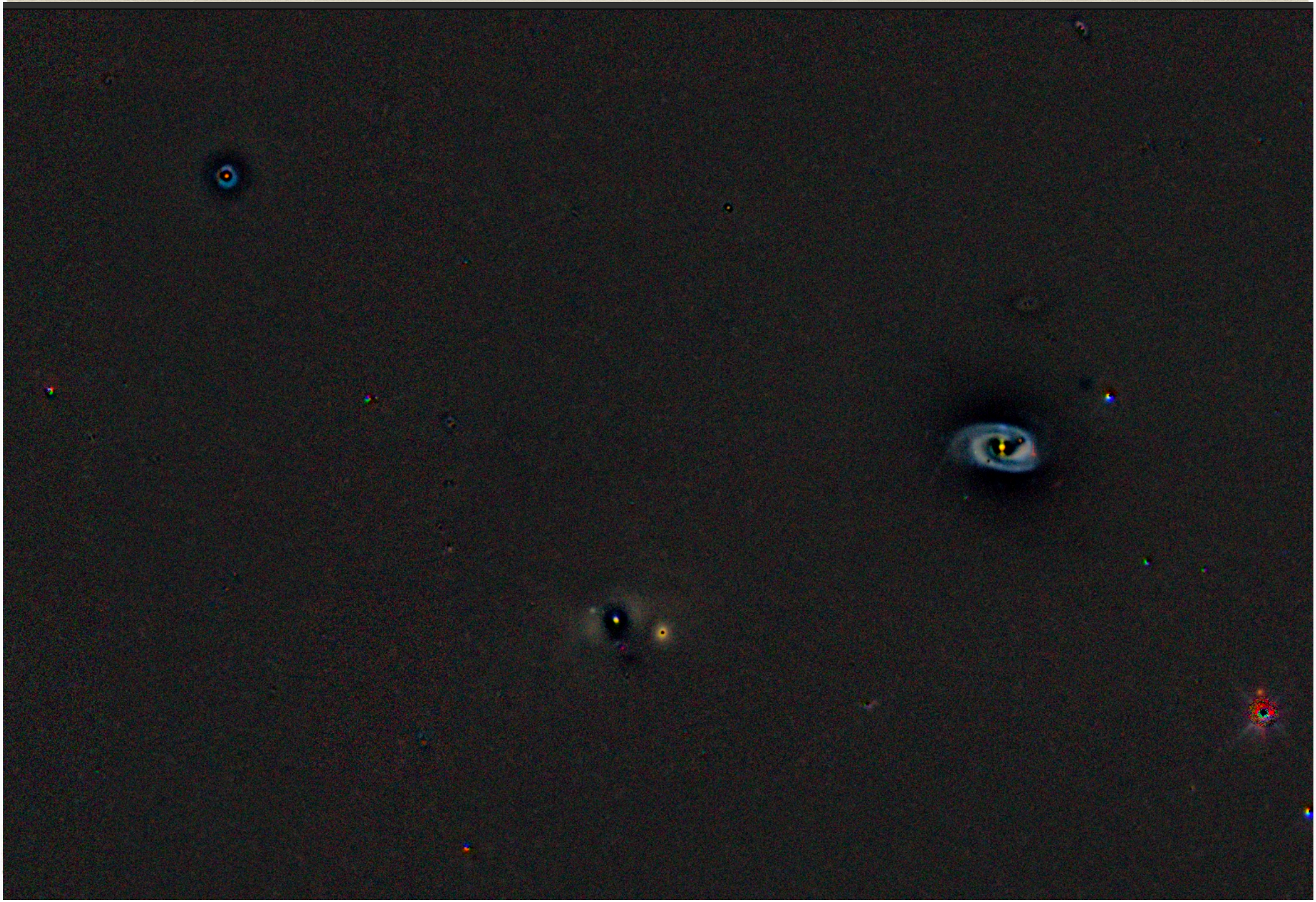


The Legacy Surveys: Processed image

The Legacy Surveys: *Tractor* model of the image

The Legacy Surveys: Processed image

The Legacy Surveys: Residuals



Calibrating photometry

- Once you've measured the number of electrons/sec registered for some object, we want to turn that into a magnitude: $m = 2.5 \log_{10} (f_0/f)$, where f_0 is some standard reference flux and f is the measured flux. The hard part is figuring out f_0...

- Alternatively, we can frame this as $m = ZP - 2.5 \log_{10} (f \text{ in e-/s})$; ZP is called the 'zero point' for our data.

- The general strategy is to observe objects we know the magnitudes for with our instrument on the same night we're taking data; then adjust ZP until the magnitudes for those objects match what we expect (from some catalog).

Calibrating photometry

- One problem is that the calibration stars in the catalog were generally observed with different filters than we are using.

- Further, we are observing at different angles from the zenith (straight up) during the night

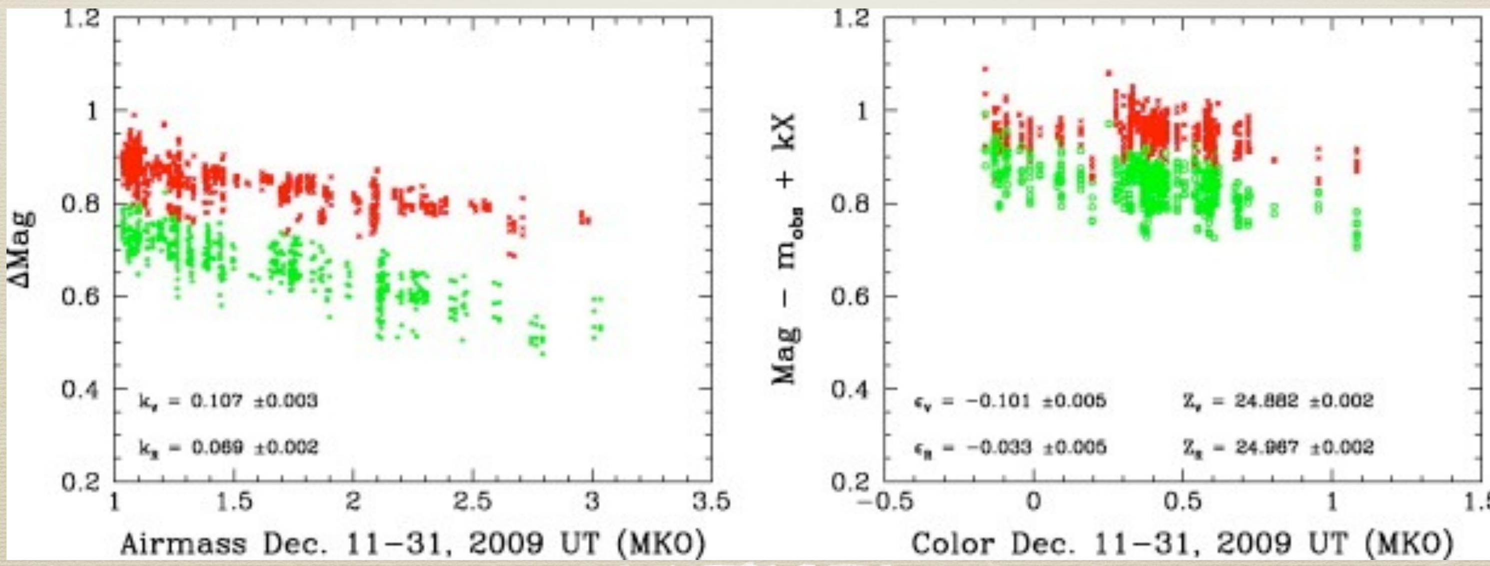
  - For a plane-parallel atmosphere, the amount of atmosphere we look through goes as X=sec(z), where z is the angle from zenith and X is called the *airmass*. The effects of atmospheric absorption should scale with airmass.

Calibrating photometry

- So we observe calibration stars through the night, at different airmasses, and fit using all the stars for:

$m_{from\ catalog} = ZP - 2.5\ \log_{10}\ (f \text{ in e-/s}) - A^*X + K^*(m_1\text{-}m_2)\ [+ K_2^*\ (m_1\text{-}m_2)^2 \ldots]$

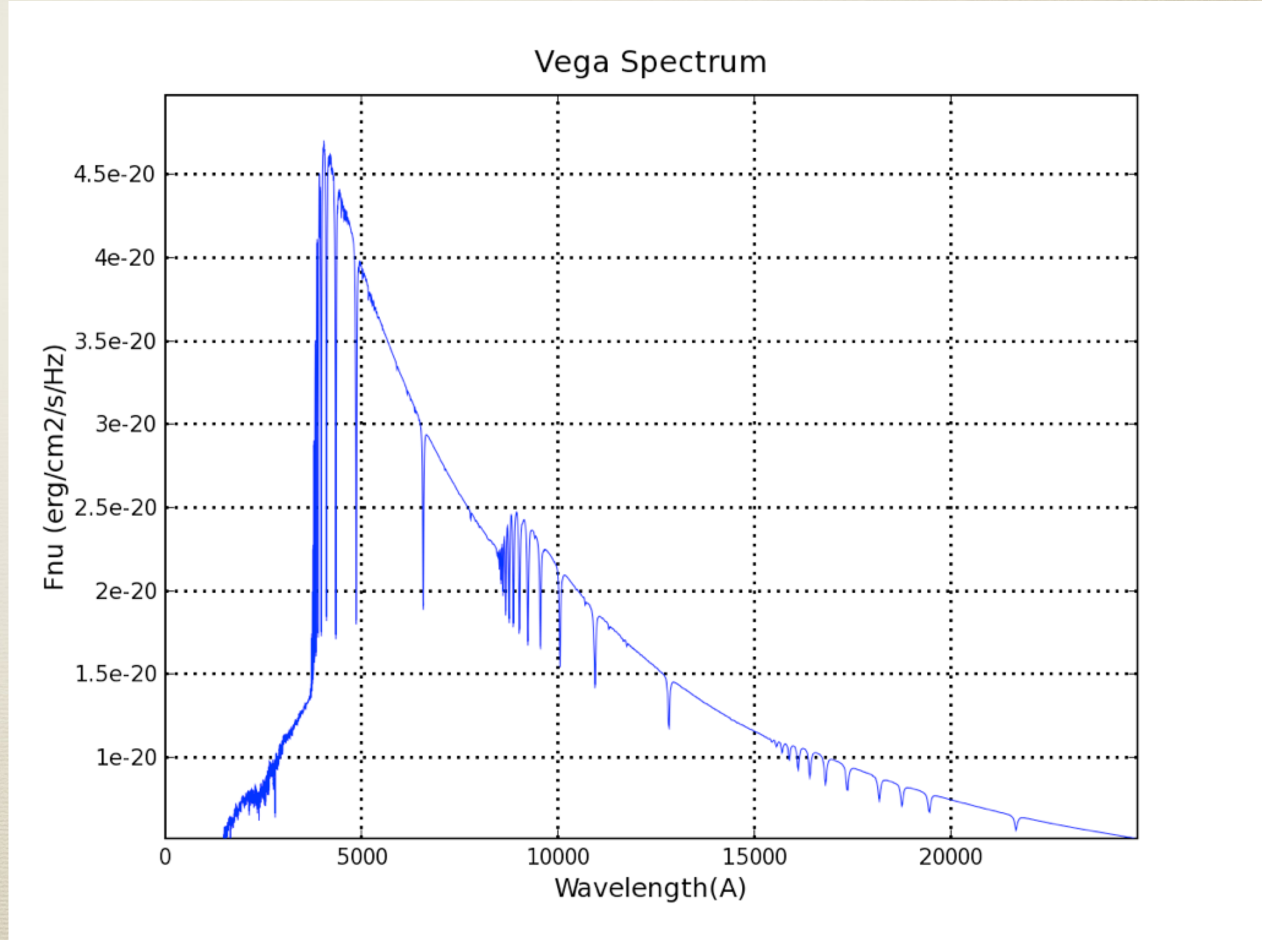
- Here A is called an *extinction coefficient*, and K is a *color term*. Here m_1 and m_2 are the magnitudes we observe for the star in question through two different filters; the color terms allow us to correct for the fact that our throughput curves may have different shape than those used for the calibrating datasets.



Magnitude systems

- See: http://www.astro.utoronto.ca/~patton/astro/mags.html
- Over history, different standard sets of zero points have been used. These define a magnitude system. Some important ones are:
- Vega: defines the star Vega to have zero magnitude in all filters.

- Johnson/Kron-Cousins (Landolt): defines Vega to have magnitude 0.03 in all filters



Magnitude systems

- AB: $m(AB) = -2.5 \log(f) - 48.60$, where f is flux in units of erg sec^{-1} cm^{-2} Hz^{-1}. This is gradually becoming standard, but has the disadvantage of it being extremely difficult to determine your true flux to high accuracy. AB colors are zero for an object with constant flux per unit frequency interval.

- SDSS: SDSS was intended to be on an AB magnitude system. However, the zero points between SDSS and AB remain uncertain to a few percent.

Conversion from AB magnitudes to Johnson magnitudes:

The following formulae convert between the AB magnitude systems and those based on Alpha Lyra:

V	=	V(AB) + 0.044	(+/- 0.004)
B	=	B(AB) + 0.163	(+/- 0.004)
Bj	=	Bj(AB) + 0.139	(+/- INDEF)
R	=	R(AB) - 0.055	(+/- INDEF)
I	=	I(AB) - 0.309	(+/- INDEF)
g	=	g(AB) + 0.013	(+/- 0.002)
r	=	r(AB) + 0.226	(+/- 0.003)
i	=	i(AB) + 0.296	(+/- 0.005)
u'	=	u'(AB) + 0.0	
g'	=	g'(AB) + 0.0	
r'	=	r'(AB) + 0.0	
i'	=	i'(AB) + 0.0	
z'	=	z'(AB) + 0.0	
Rc	=	Rc(AB) - 0.117	(+/- 0.006)
Ic	=	Ic(AB) - 0.342	(+/- 0.008)

Source: Frei & Gunn 1995

Google: Astronomical Magnitude Systems

Signal-to-noise calculation

- We often talk about how good a measurement is in terms of its signal-to-noise ratio: i.e., measurement/sigma(measurement)
- For photometry, we generally hope to achieve an S/N=5 or 10 measurement at some specified flux or magnitude. We then design our observations to reach that depth. Let's take:

N_{obj} = electrons from object = $f_{obj}\, t$

σ_{read} = read-out noise

N_{sky} = electrons from background = $f_{sky}\, n_{pixels}\, t$

- So signal $S = N_{obj}$; noise (assuming Poisson statistics) will be $N=(N_{obj}+ N_{sky}+n_{pixels}\, \sigma_{read}^2)^{1/2}$.
- Important regimes:
  - *Photon-limited*: $N_{obj} >>$ other errors. Then S/N $\propto t^{1/2}$
  - *Readout-limited*: $n_{pixels}\, \sigma_{read}^2 >>$ other errors. Then S/N $\propto t$
  - *Sky-limited*: $N_{sky} >>$ other errors. Then S/N $\propto t^{1/2}$