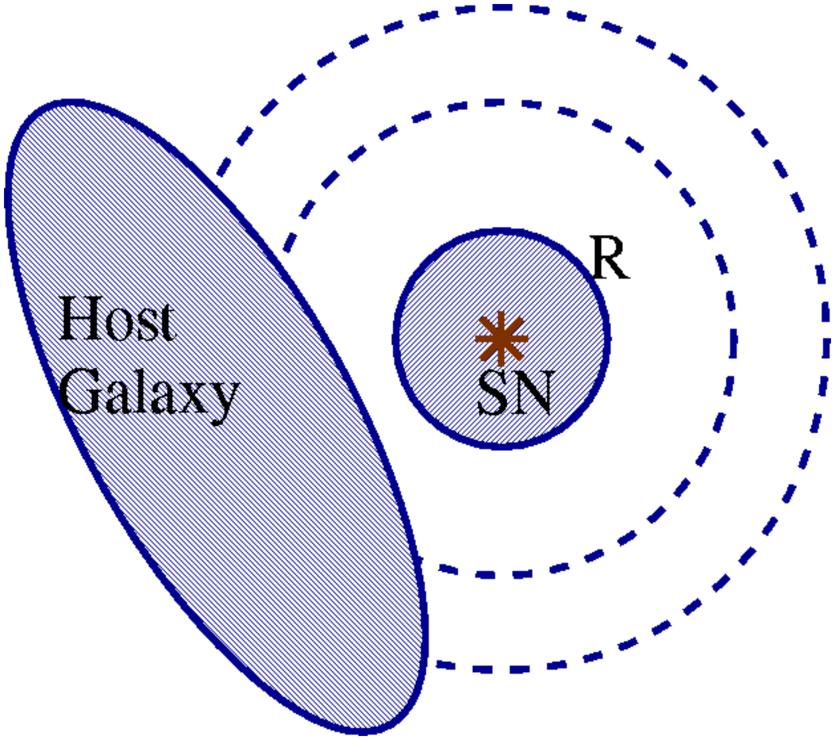
Why do PSF-fitting



The simple aperture photometry has an assumption of *linearly-varying background* in the aperture's vicinity.

- Choice of (optimal) aperture size

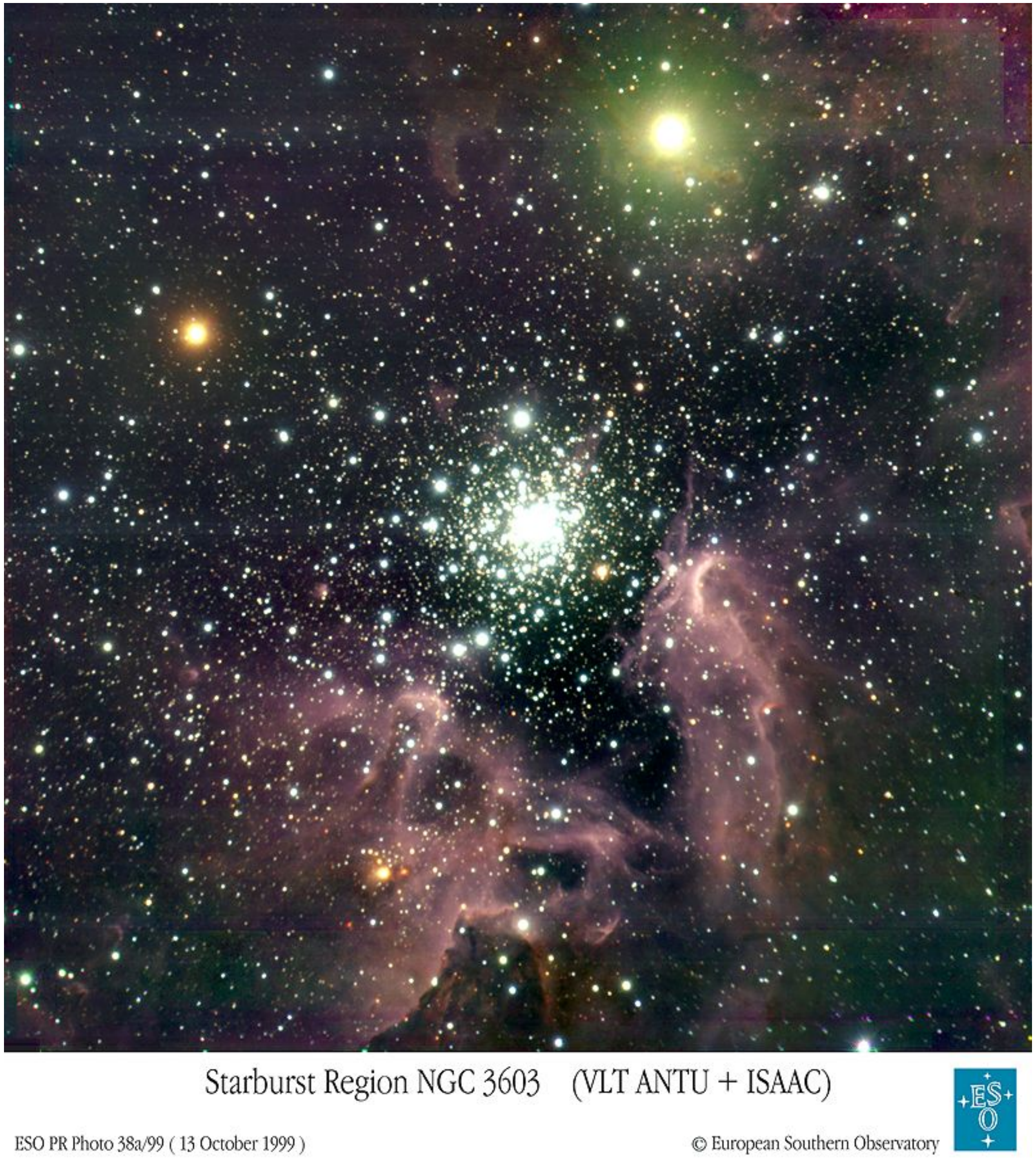
$$S/N = C/\sqrt{\sigma_C^2 + \sigma_{noise}^2} = C/\sqrt{C + \pi * R^2 * RN^2}$$

Especially relevant for low S/N cases.

- If do not know PSF very well – may want to make larger-than optimal. More on this later.
- Varying background can represent a problem. Crowded fields!

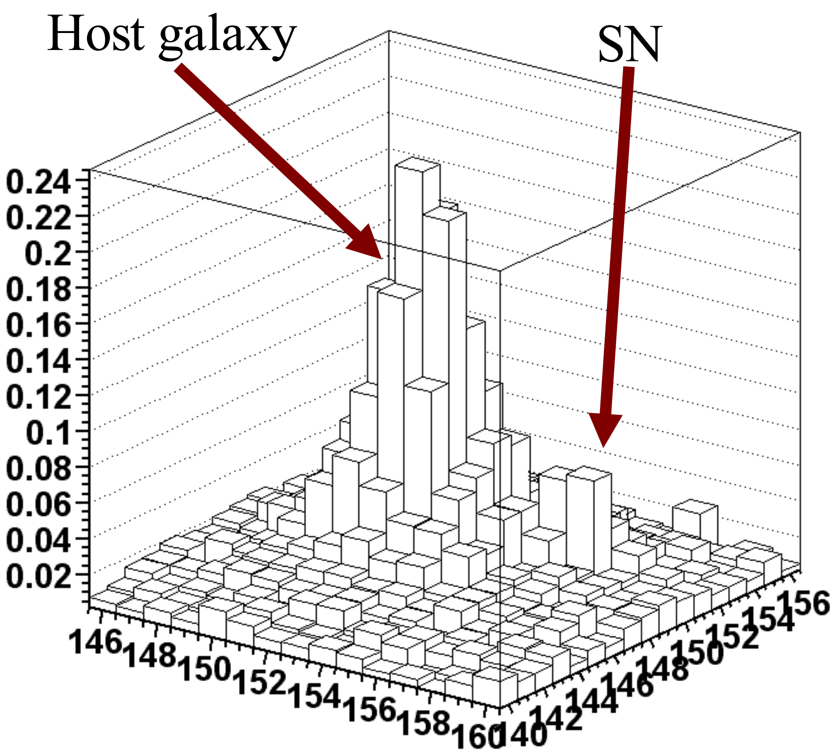
Things to be cautious about:
low S/N,
varying background.

Crowded field example



Even when nominally well separated, bright stars can shadow faint neighbours.

PSF-fitting formalism



What if know PSF well?

Then can use this information to do better in a number of aspects.

Can minimize

$$\chi^2 = \sum (Bkg_i + C * PSF_i - Pix_i)^2 / \sigma_i^2$$

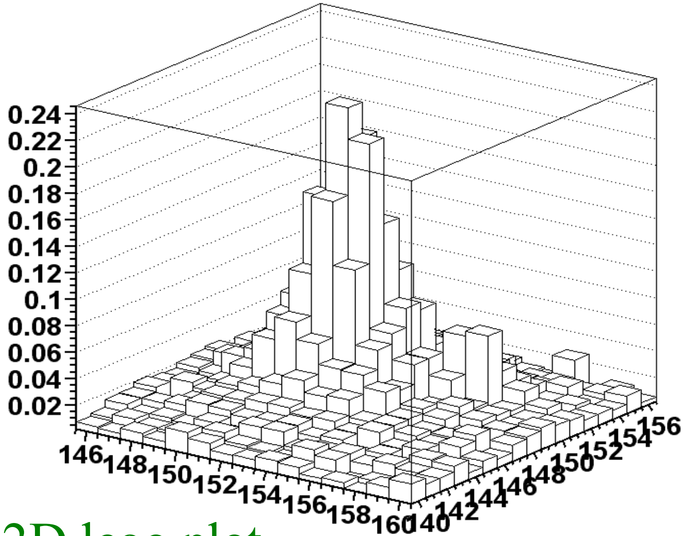
in the star neighbourhood (image patch) to find the SN counts *C*, position and (maybe) the background parameters.

Pixelated image as 2D histogram.

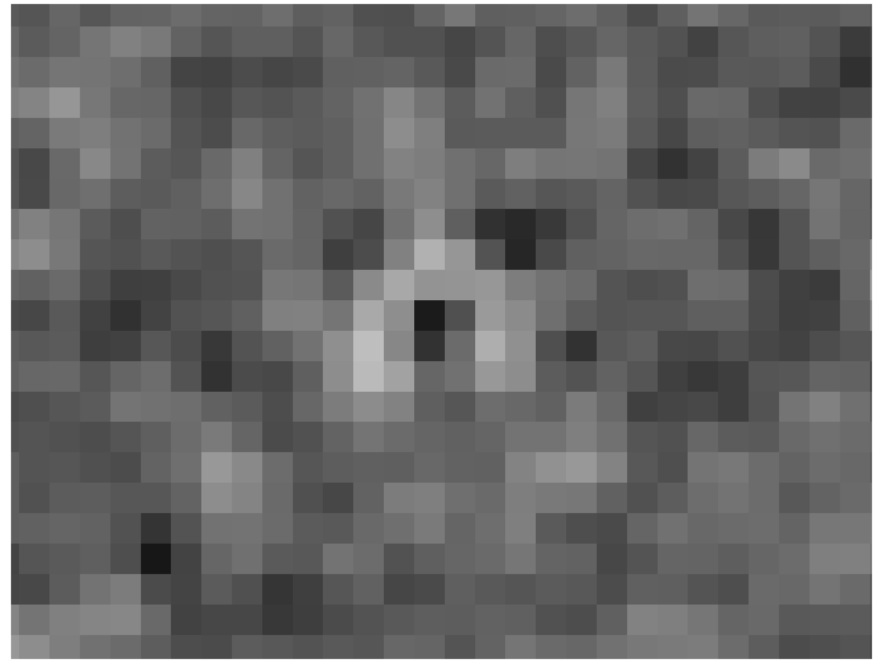
"Just a 2D fit".

Things to be cautious about:
inter-pixel correlations due to diffusion,
intra-pixel efficiency variation (undersampled case).

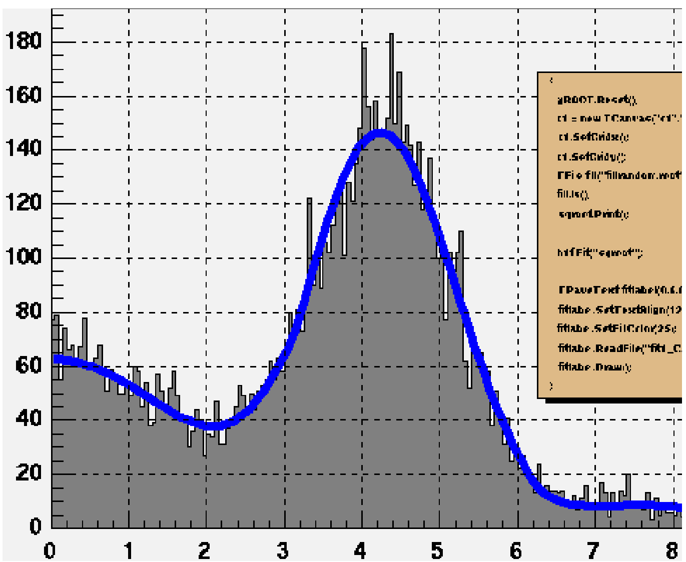
Examining 2D fit results



2D lego plot



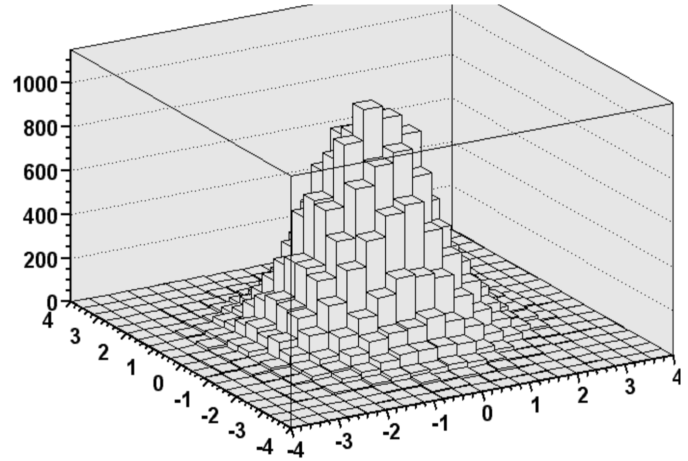
2D fit residuals (doughnut pattern)



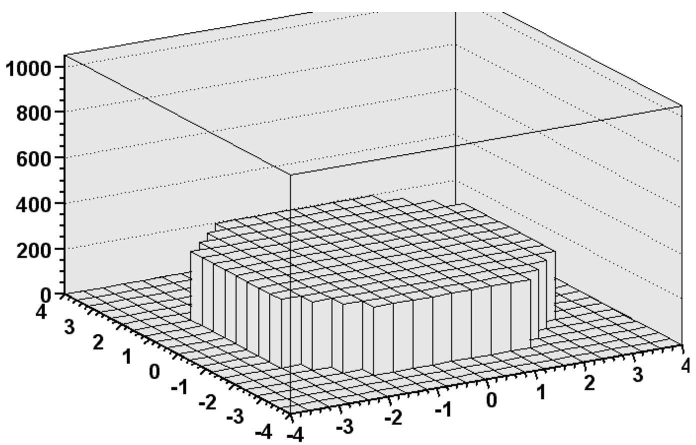
1D fit with function superimposed

Detailed visualization of the 2D data and the fit function comparison is difficult. Resort to examining residuals, to see if the data subtract well.

PSF-fitting advantages



2D Gaussian weight function



Aperture photometry weight function

Can be used in crowded fields – multiple PSF models for multiple overlapping stars.

Can be used in case of SN+galaxy if the galaxy model is known (no subtraction!).

Optimal weighting:
suppose (for simplicity) that Bkg = 0, then

$$C = \frac{\sum Pix_i * PSF_i / \sigma_i^2}{\sum PSF_i * PSF_i / \sigma_i^2}$$

Compare this with the aperture photometry:

$$C = \frac{\sum Pix_i}{\sum PSF_i}$$

AP is psf-fitting with a simplistic shape!

S/N for PSF and aperture photometry

What is the noise level in our procedures? I.e. if we are probing the pure sky, what is the rms of derived counts?

Assume that sky noise is constant $\sigma_i = const$ **then**

$$\sigma(noise) = \sigma_{sky} / \sqrt{\sum PSF_i^2}$$

For the aperture photometry, get

$$\sigma(noise) = \sigma_{sky} * \sqrt{N} / (\sum PSF_i)^2$$

So, the noise ratio (or inverse of the S/N ratio) is

$$\frac{\sigma(aper)}{\sigma(psf)} = \frac{\sqrt{\sum PSF_i^2} * \sqrt{N}}{(\sum PSF_i)^2}$$

For wide aperture, this becomes

$$\frac{\sigma(aper)}{\sigma(psf)} = \sqrt{\sum PSF_i^2} * \sqrt{N} \geq 1$$

PSF shape dependence

For the ground-based telescopes, the PSF shape mostly depends on seeing – variable atmospheric condition.

For a space-based mission, the seeing is non-existent => the following factors are more apparent:

1) color
2) pointing jitter (telemetry info)
3) optical aberrations
4) field dependence

Sampling is crucial for centering, width determination, algorithmic processing, etc.
Undersampled / critically sampled (FWHM 1-2 pix) / oversampled.

Things to be cautious about:
pointing errors (can be easily overlooked),
large-angle scattering (atm. dust, ccd backscattering, etc).

PSF modelling

Can use *analytical* shapes:

1) 2D Gaussian $A * \exp(-r^2/\sigma^2/2)$

2) Lorentz $A/(r^2/\sigma^2+1)$

3) Moffat $A/(r^2/\sigma^2+1)^\beta$

May need sub-pixel integration if not well sampled. Hard to model tails, non-circularity.

***Empirical* modelling off the bright field stars:**

can templetize PSF(x,y) => "any shape"

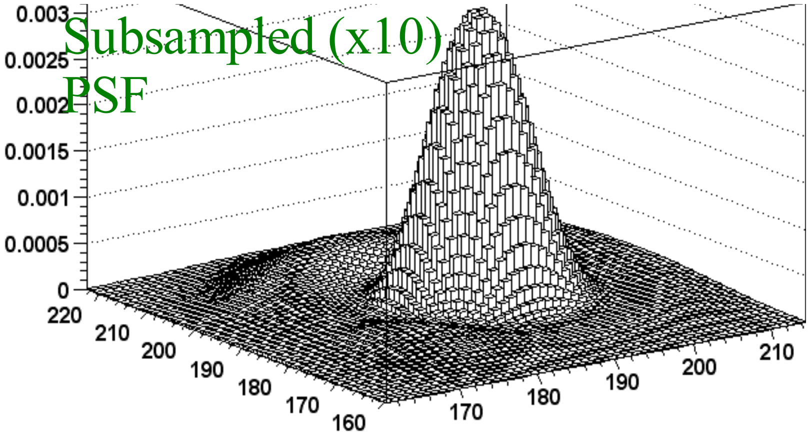
But:

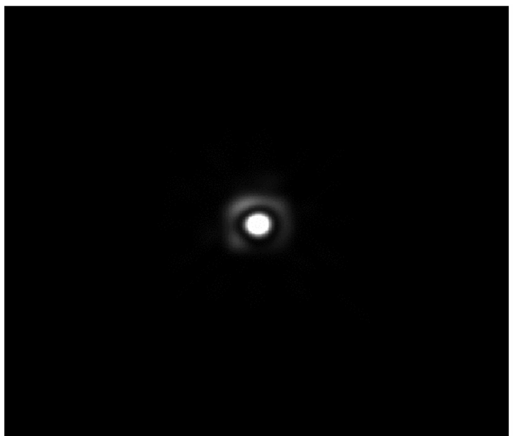
- **noisy,**
- **centering,**
- **interpolation,**
- **may not have enough field stars.**

***Hybrid* approach:**

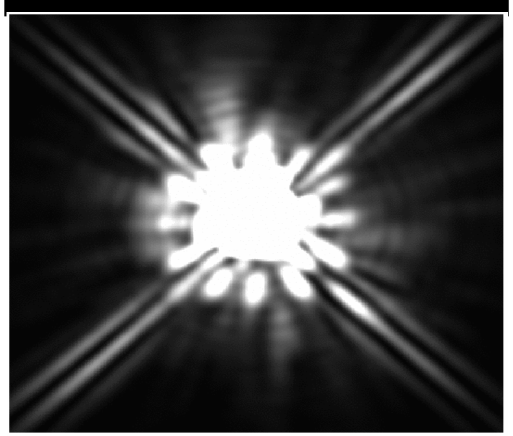
use analytical models for the fast-varying core, then model the (tail) residuals empirically.

PSF modelling (cont.)





log scale 1



log scale 2

Another approach is to model the PSF from the known optical geometry.

TinyTim package for HST instruments gives a sub-sampled PSF template.

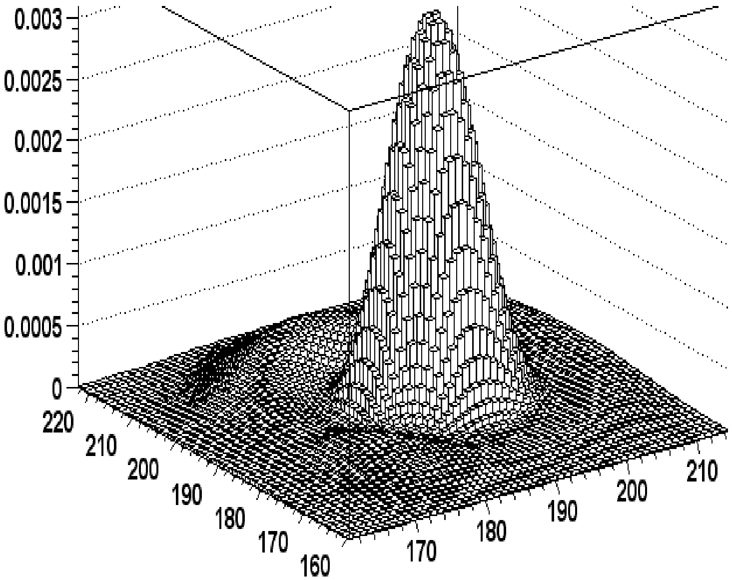
Full geometrical description as an input => can model the diffraction patterns with Airy ring, obscurations, and hard-to-trace features:

1) color dependence,

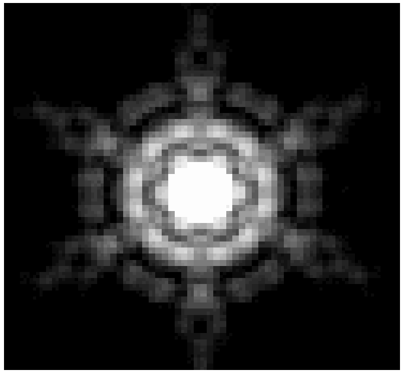
2) field dependence,

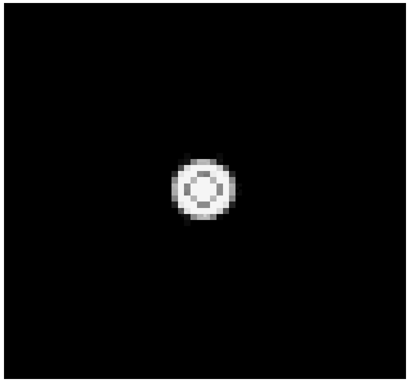
3) focal breathing.

PSF width in Space

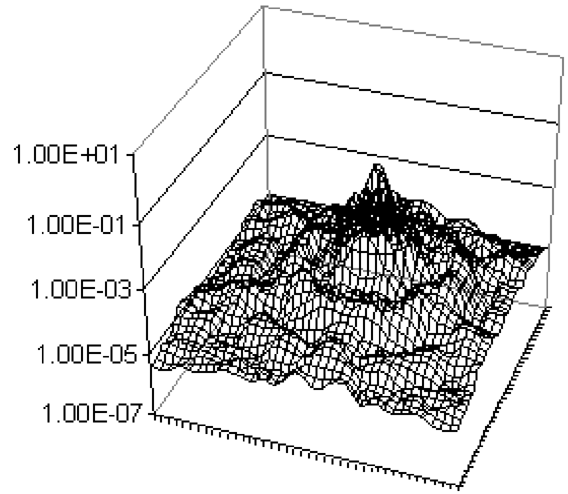


HST (subsampled!)





Spitzer



1st diffraction minimum is at $R = 1.22\,\lambda / d$ =>
PSF is wider at longer λ and smaller mirror diameter.

Aperture Correction

Aperture photometry is not free of PSF-related knowledge.

If correct to infinity:
1) do AP on a star => C_{raw}
2) do AP on the normalized PSF to account for the tails => ε
3) get the full flux $C_{\infty} = C_{raw} / \varepsilon$

The uncertainty on the PSF correction is small if ε **is close to 1.**

Another way to do the large-angle correction is to forget about them. Calibrate the flux within fixed radius to standards. HST WFPC2 used R = 0.5 “. Relevant if there may be a large-angle scatter. (This “fixed” radius may vary with seeing.)

"Standard" PSF-fitting packages

Things to be cautious about:
a standard package is a just piece of software, which somebody wrote, and somebody else uses. Domains of applicability vary!

Differences:
- PSF shape,
- background,
- bad pixels.

All for stars photometry.

None accounts for custom errors.

ROMAFOT (Buonanno 1983) – developed at Rome Observatory, originally for photographic plates. Gaussian or Moffat PSF.

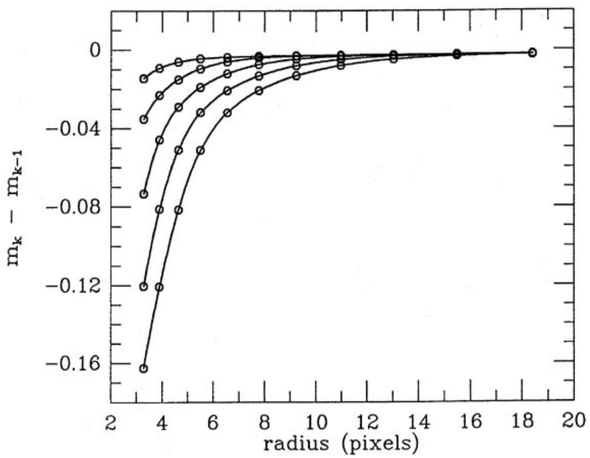
STARMAN (Penny 1995) – a stand-alone program from UK. Hybrid Lorentz-Gaussian-empirical profile. Can deal with very crowded and very undersampled images, as well as field-variable PSF.

DAOPHOT (Stetson 1987) – probably the most famous package, included in IRAF. Uses a hybrid approach to PSF building (Gaussian/Moffat/Lorentz). Has bad pixel thresholds.

DoPHOT (Schechter 1993) – written with automated processing in mind. Analytical or empirical PSF. Capability to detect CRs and saturated pixels.

HSTPHOT (Dolphin 2000) – written for HST WFPC2. Features TinyTim PSF library with per-image adjustments, bad pixel masks, CTE corrections.

Typical steps (with DAOPHOT)



A family of growth curves at different seeings.

Typical steps with PSF photometry in a crowded field include:

1) find all stars above a threshold

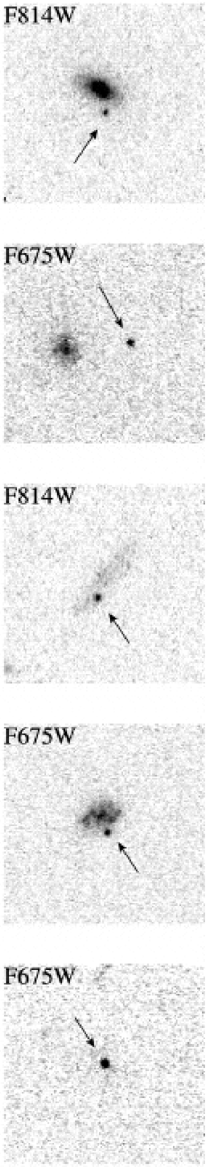
2) run aperture photometry on all stars

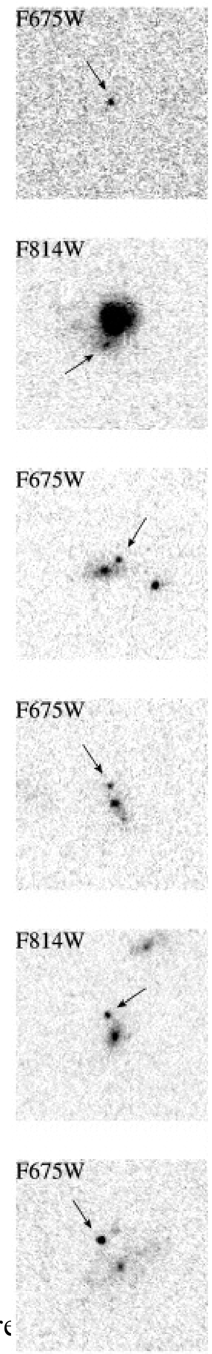
3) choose a set of bright "good" stars (*growth* curves)

4) build a hybrid psf from the sample in step (3)

5) PSF fit with position from the centroid and the background from the aperture photometry, i.e. just amplitude.

(There is a star grouping with simultaneous fit in the crowded field.)





Supernova specifics and extensions

Why invent something new? Because it is necessary...

Typically there is a host galaxy near SN => a fast-varying background in the vicinity of the signal.

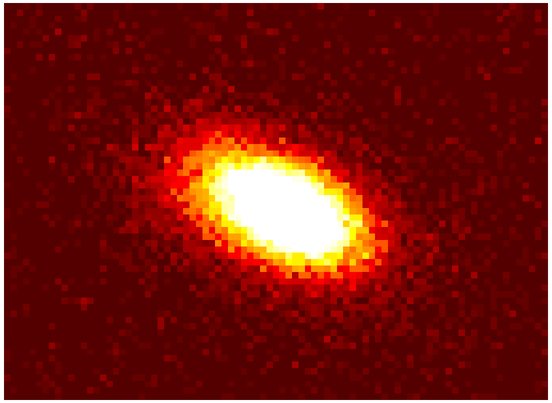
Usually the packages assume slowly varying background. Can use them if align and subtract the final reference, with *statistical penalty for subtraction*.

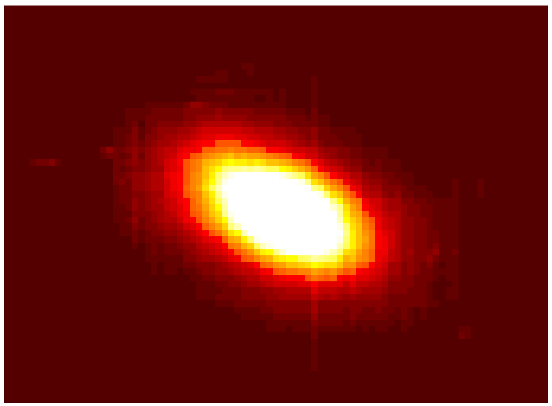
Extensions:

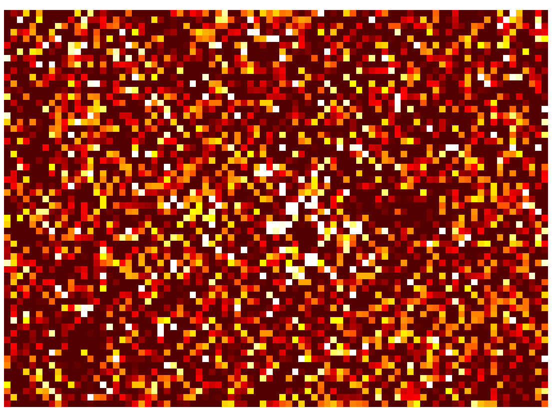
<u>a) PSF + polynomial bkg. behaviour (Rob's paper)</u>

One step ahead of the usual assumptions. *Partially separated SN and galaxy*. Valid in particular redshift range and PSF width. *Do not need final references*.

Thumbnail images from Rob's paper







Supernova specifics and extensions (cont.)

Extensions (cont):

b) <u>PSF + galaxy model (Nicolas Regnault's thesis)</u>

Used when SN-galaxy distance is less and low-order polynomials do not model the background well. *Need final references.*

Fit image slices (rows) by the following function:

$$\phi(x)=\phi_0/(1+\alpha*|x-x_0|^{\beta})$$

Then use spline interpolation for the function values in a column.

This is an intermediate solution between pure 2D spline (noisy) and low-pass filter (blurs galaxy profile).

An example with galaxy, its model and residuals.

Supernova specifics and extensions (cont.)

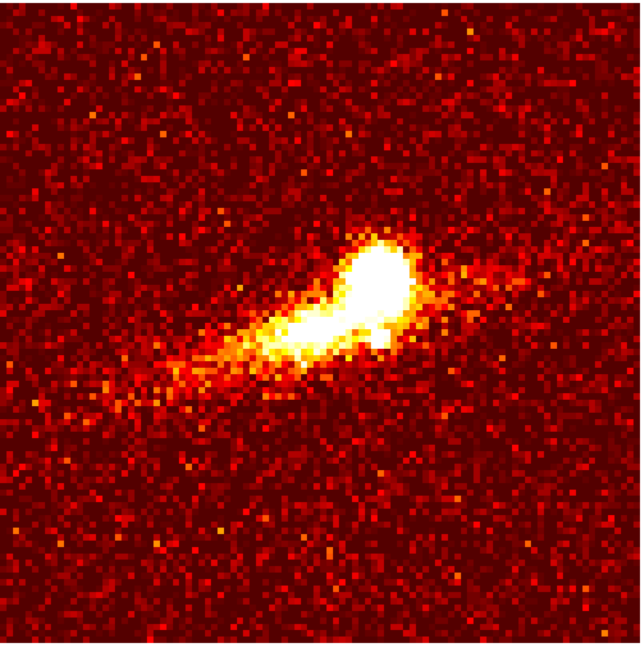
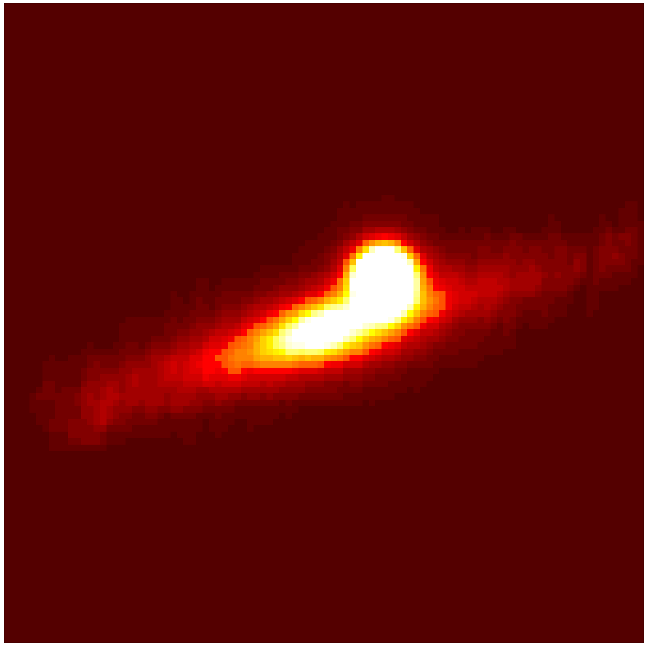
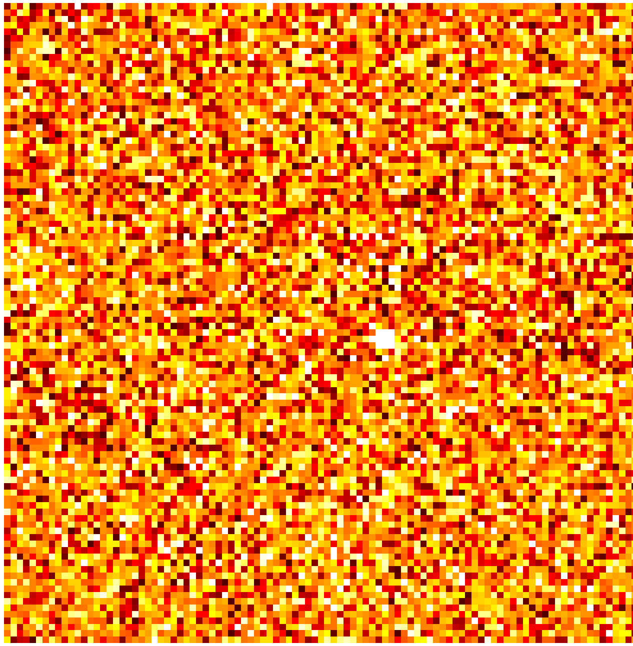


Image with SN and host galaxy



Fit function (galaxy model + PSF)



Residuals

Then each SN image is fit with 2 templates: PSF function and galaxy function. There is a problem with matching different seeings. In this case it was solved by distorting the galaxy profile:

$$Gal(x, y) = H * Gal_0(\alpha * x + \beta * y + \gamma * x * y)$$

Supernova specifics and extensions (cont.)

Extensions (cont):

c) <u>PSF fit to all lightcurve images with pixel-by-pixel background model (Sebastian Fabbro)</u>

Fairly general background consideration. *Need final references*. Field-adaptive PSF and background.

Simultaneous fit for all lightcurve images. TOADS.

-- Best seeing image is chosen as a grid/model reference => D_{0ij} . All other images are aligned and resampled to its grid. Assumed noiseless. *The pixelized shape* of the galaxy on this image is *the galaxy model*.

-- PSFs and convolution kernels K_l are determined off the field stars.

-- Simultaneous fit for SN flux, position and galaxy model for images 0...n :

$$I_{0ij} = s_0 P_0(x_i - x_s, y_j - y_s) + G(x_i, y_j) + B_0$$
$$I_{1ij} = s_1 [K_1 \otimes P_1(x_i - x_s, y_j - y_s)] + [K_1 \otimes G(x_i, y_j)] + B_1$$
$$I_{nij} = s_n [K_n \otimes P_n(x_i - x_s, y_j - y_s)] + [K_n \otimes G(x_i, y_j)] + B_n$$

Minimize $\chi^2 = \sum_l \sum_{i,j} W_{l,i,j} [D_{l,i,j} - I_{l,i,j}]^2$

Iterative weight adjustment to account for variances of image bkg, PSF, kernel, and model.

Further reading

P. Stetson "The Techniques of Least Squares and Stellar Photometry with CCDs"
(insights of the DAOPHOT author)

N. Regnault thesis
(Good general introduction in SN+galaxy photometry; in French)

S. Fabbro "simfit" writeup
(Concise description of the method)