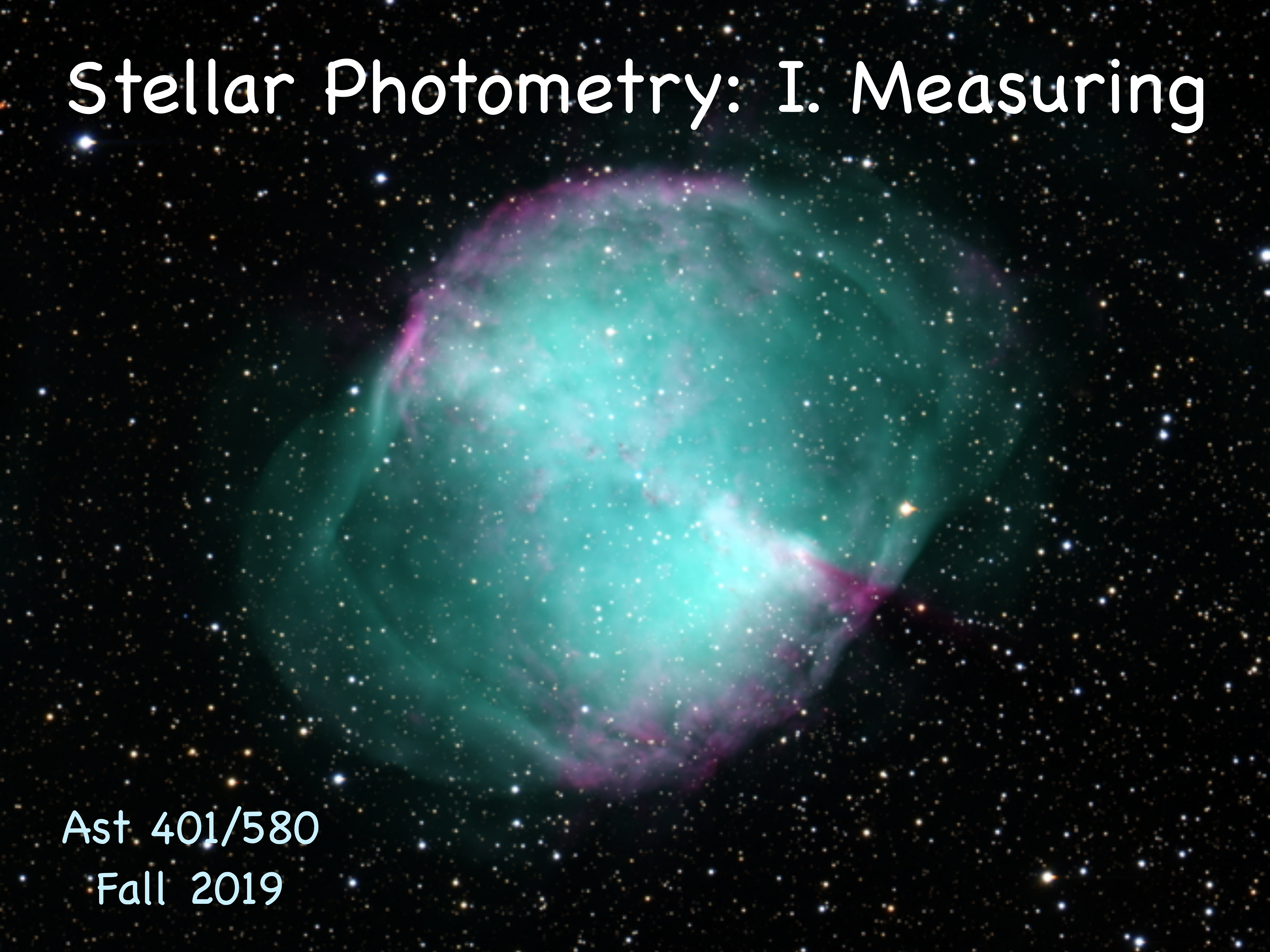
Stellar Photometry: I. Measuring



Ast 401/580

Fall 2019

Photometry

Photometry means measuring how bright something is. Typical goal for photometric precision is 1%, or 0.01 magnitudes.

Basically two types:

Stellar photometry (point sources)

Surface photometry (magnitudes per square arc sec)

Photometry

Stellar photometry:

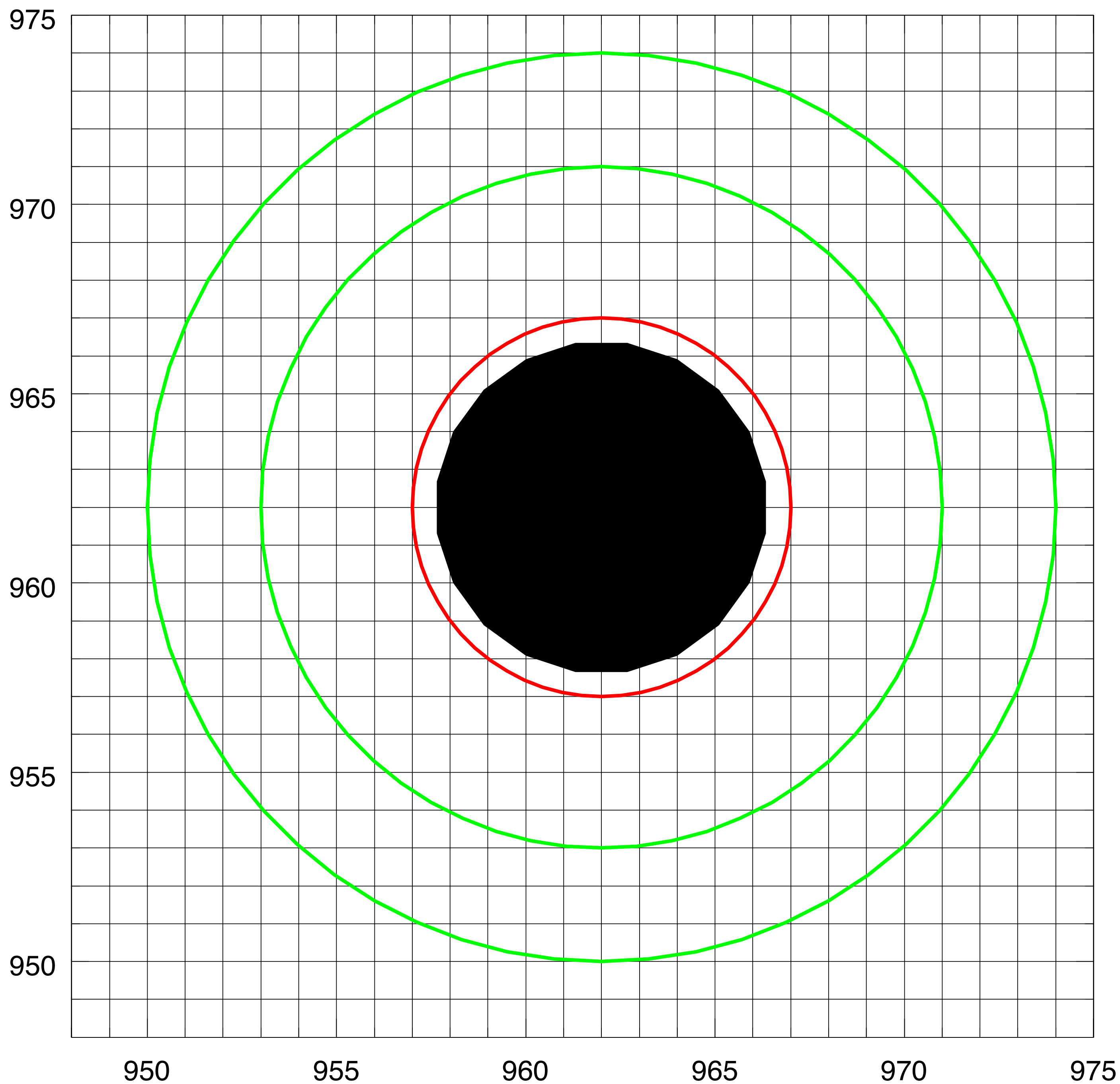
Aperture photometry. Good in sparse fields.

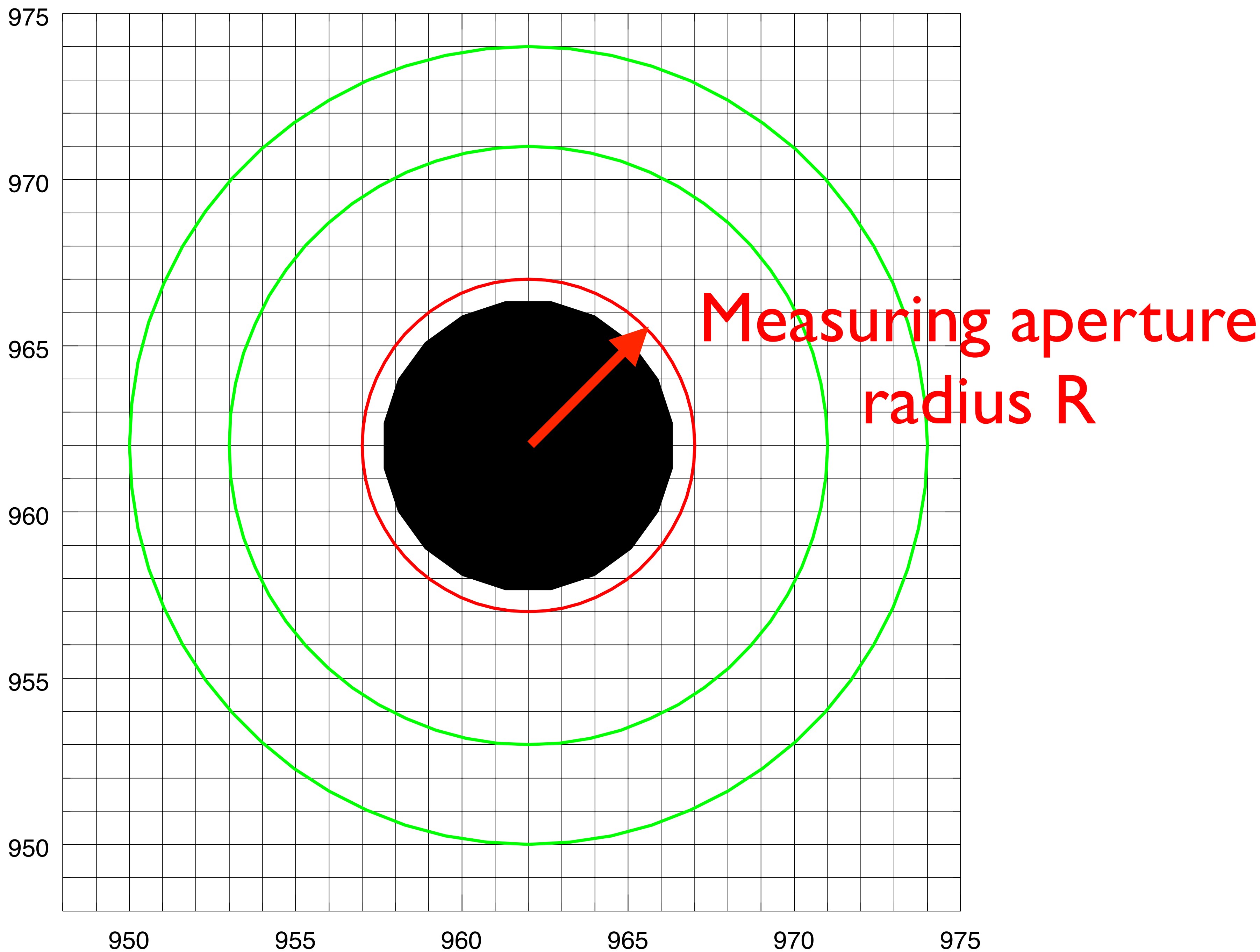
Point-spread-function (PSF) fitting. Needed for crowded fields

Aperture photometry

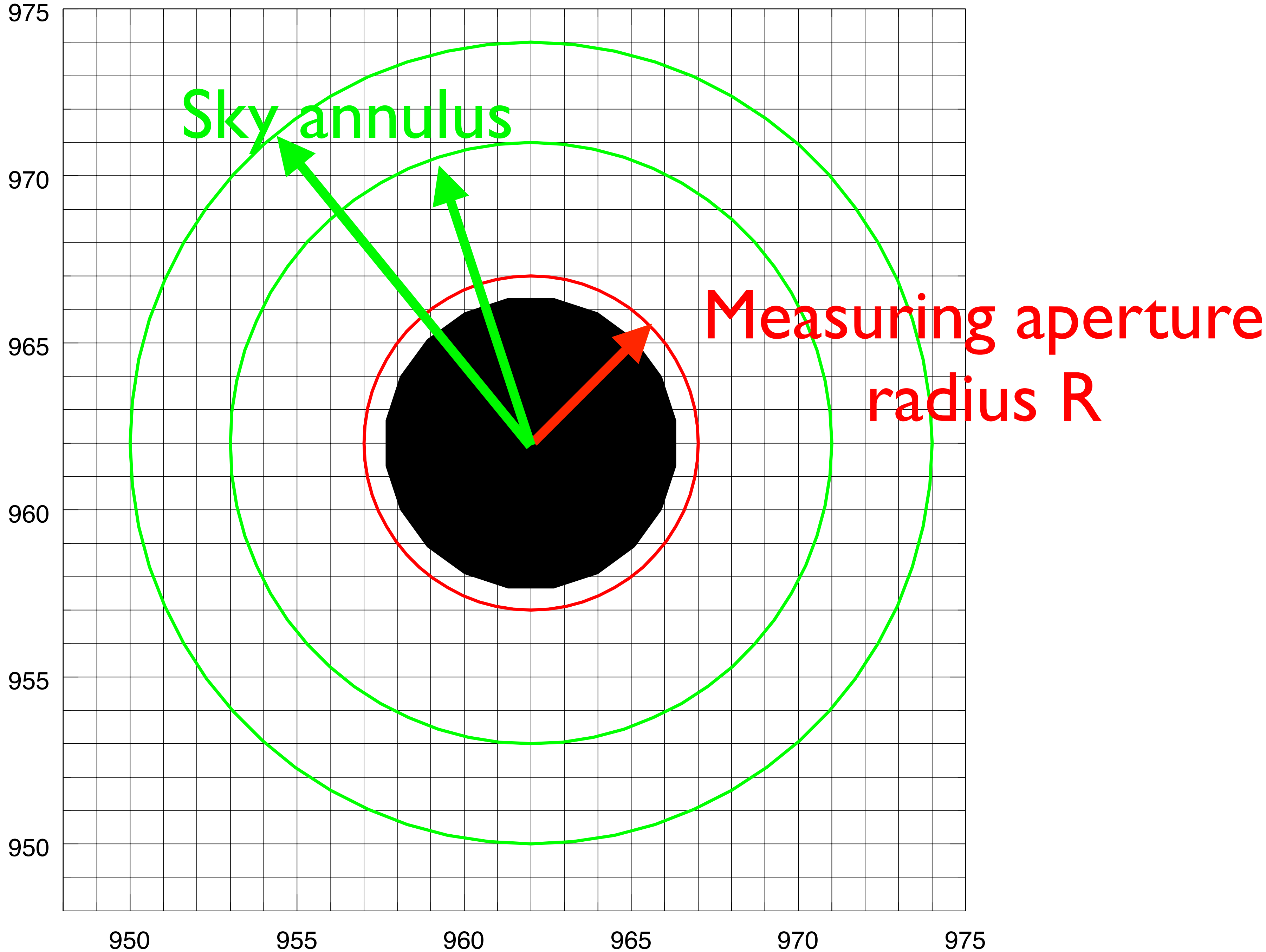
The basic idea is that you add up all the counts within a radius of R (where R ≧ seeing disk), and then subtract sky.

As always, the devil is in the details.


975
970
965
960
955
950
950
955
960
965
970
975



Measuring aperture radius R
975
970
965
960
955
950
950
955
960
965
970
975



Sky annulus
Measuring aperture
radius R
975
970
965
960
955
950
950
955
960
965
970
975

Aperture photometry

1) You add up all of the counts within the measuring aperture. Call this "Sum_all".

2) You use a modal definition to determine the "best" estimate of the sky using an annulus far from the star. Call this "Sky".

3) You subtract Sky x (number of pixels) from Sum_all to get the number of counts above sky. Call this "Sum_above_sky".

4) Instrumental magnitude is = -2.5log(Sum_above_sky/exptime) + C. Usually C is 20 or 25 just to make the numbers look sensible.

Some of the devils…

How large a measuring aperture should you use?
Should you try to get "all of the light"?

At what radius r does a Gaussian drop to zero?

$r = \infty$

Huh?

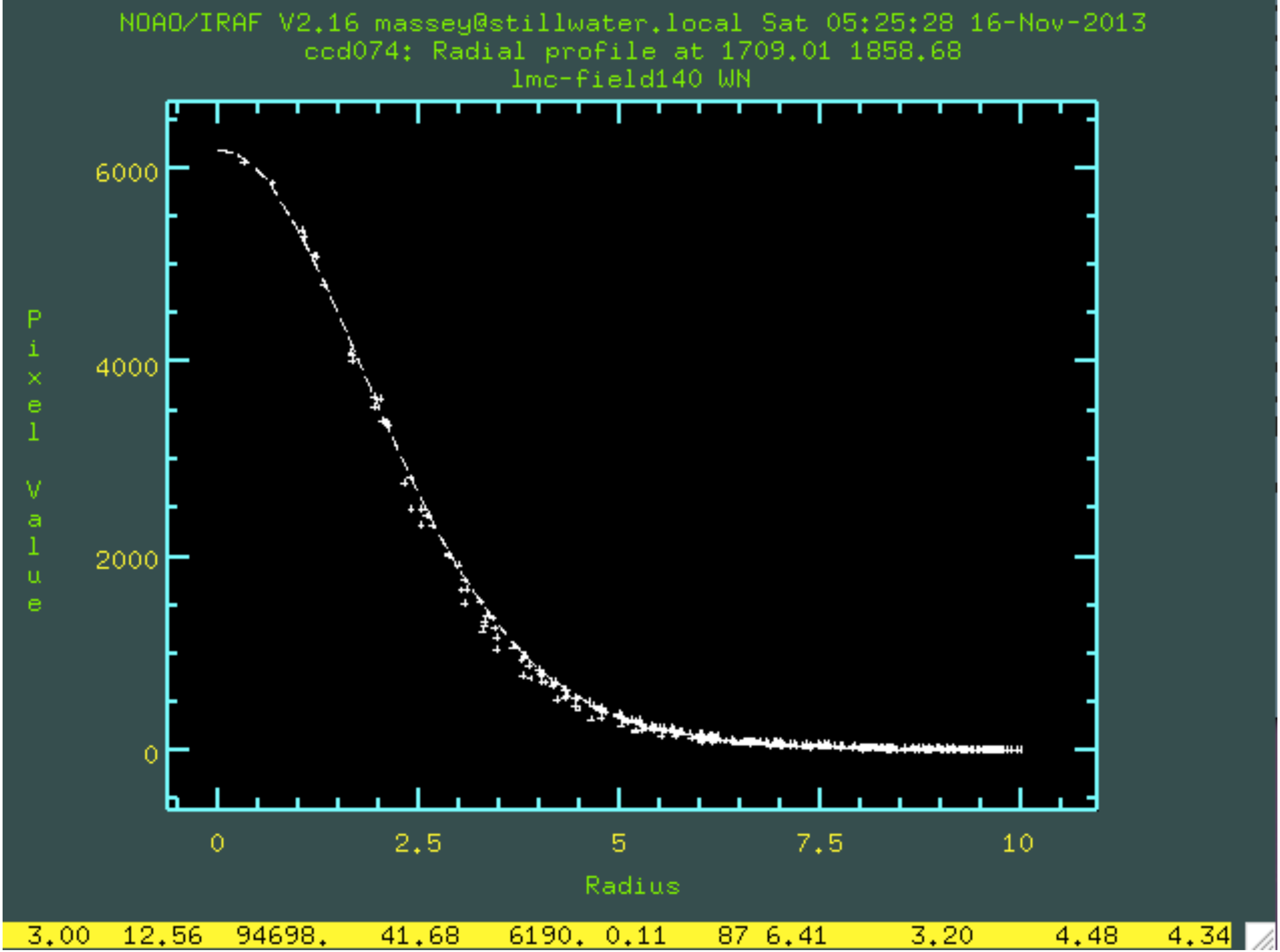
Yes, the light from a star just keeps on going, but getting fainter and fainter until it gets lost in the photon noise from the sky itself.

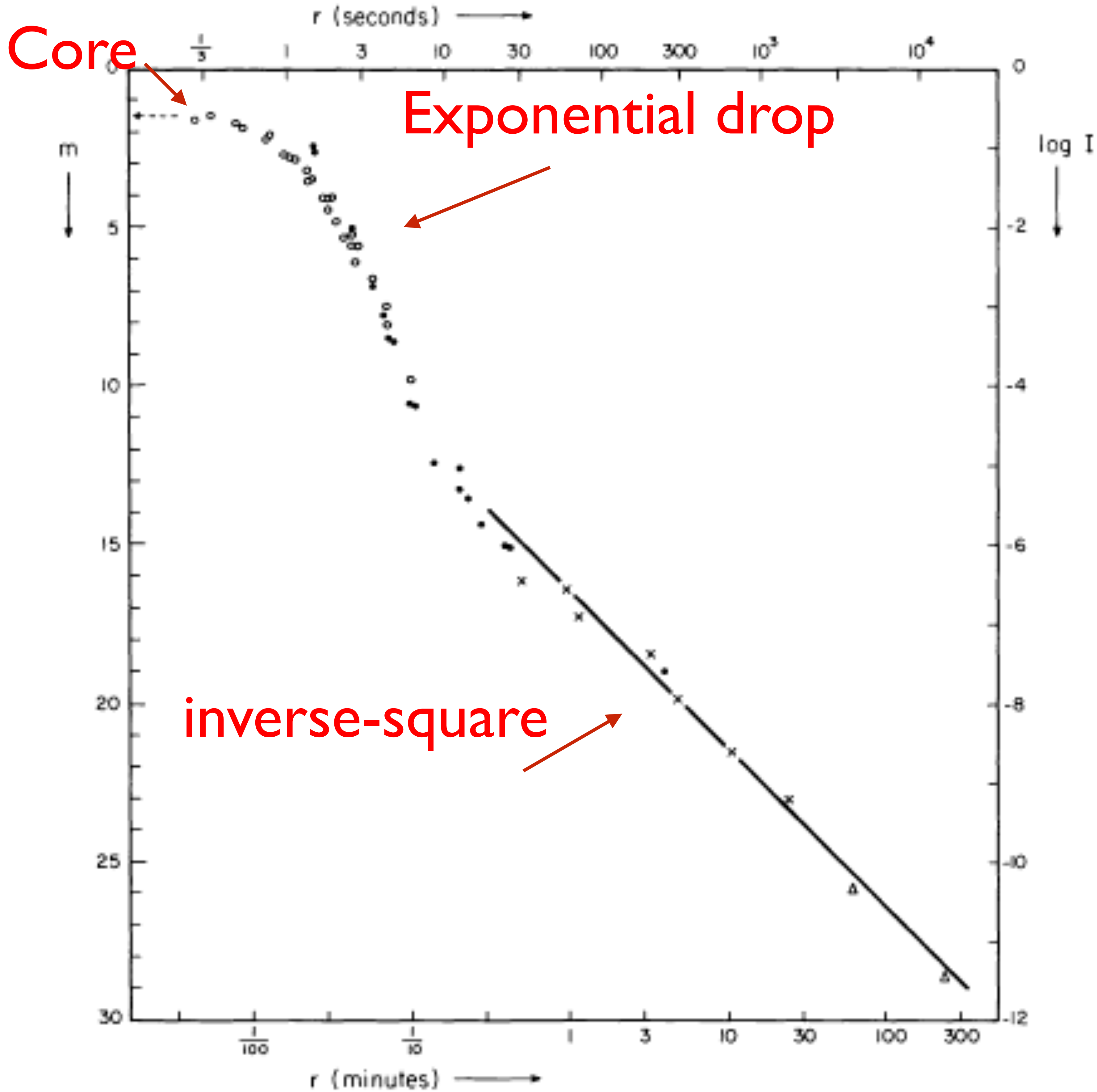
Wow.

Cosmic.

Aperture size

Stellar profiles are not really Gaussian. There's an inner core that's dominated by seeing and guiding, an exponential drop (dominated by diffraction), and an inverse-square halo (King 1971).


NOAO/IRAF V2.16 massey@stillwater.local Sat 05:25:28 16-Nov-2013
ccd074: Radial profile at 1709.01 1858.68
lmc-field140 WN
Pixel Value
6000
4000
2000
0
0
2.5
5
7.5
10
Radius
3.00 12.56 94698. 41.68 6190. 0.11 87 6.41 3.20 4.48 4.34


Core
Exponential drop
inverse-square
r (seconds)
r (minutes)
m
log I

Aperture size

Stellar profile: the inner part (core) is affected by the seeing and guiding. But the outer two parts are caused by the diffraction of light by dust particles on the mirror (and in the atmosphere).

So how does photometry ever work?

You can never include ALL of the light of a star you're trying to measure. But you can exclude the same fraction as whatever you're using for a reference (such as a standard star). You just need to be sure you're well out on the diffraction part of the profile.

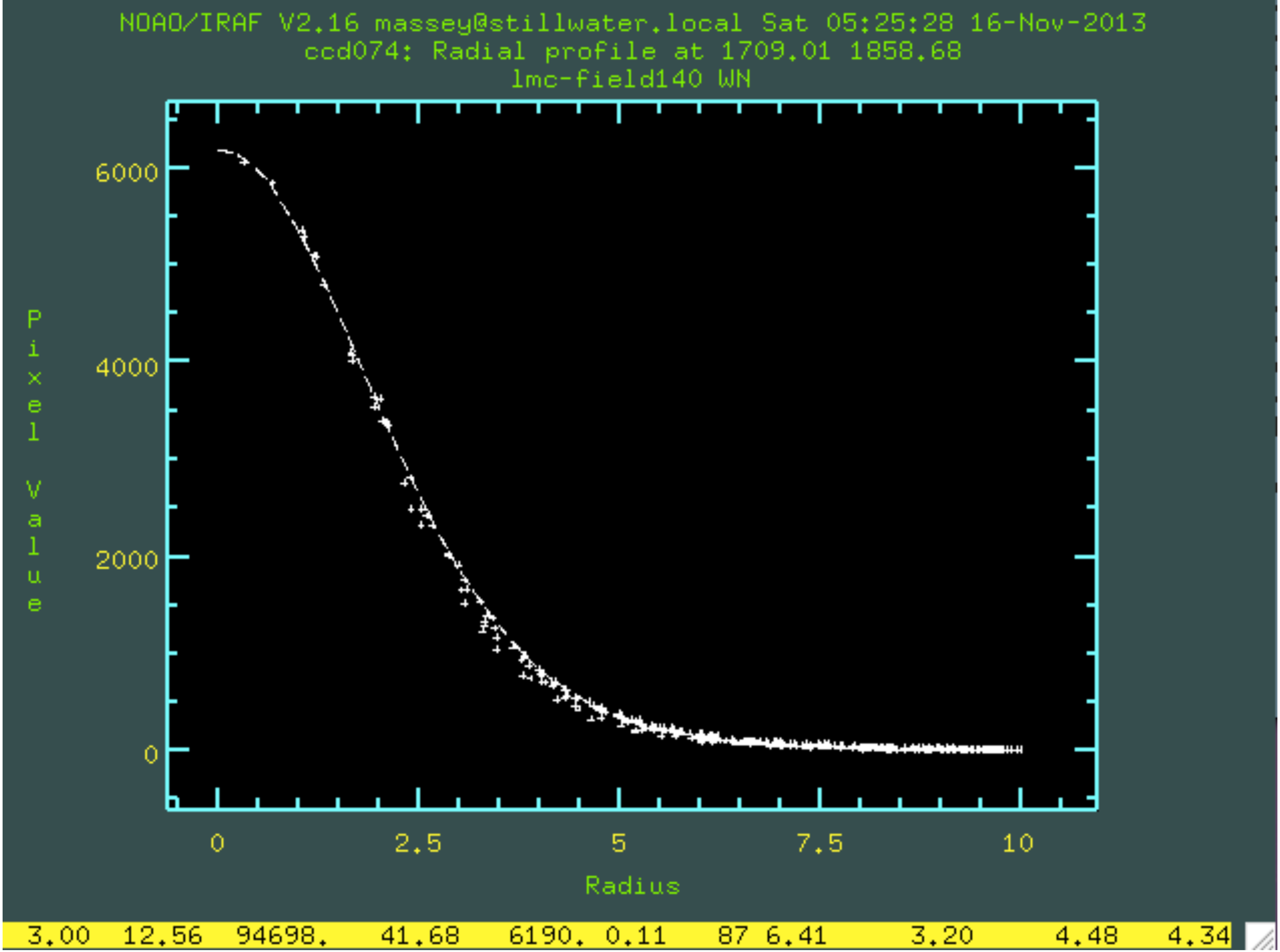
Aperture size

So, what size aperture should you use? What to minimize the errors:

If too small, too little light and errors go up.

If too large, too much sky and the errors go up.

"Optimize" size is with a radius about the same as the FWHM.


NOAO/IRAF V2.16 massey@stillwater.local Sat 05:25:28 16-Nov-2013
ccd074: Radial profile at 1709.01 1858.68
lmc-field140 WN
6000
4000
2000
0
Pixel Value
0
2.5
5
7.5
10
Radius
3.00 12.56 94698. 41.68 6190. 0.11 87 6.41 3.20 4.48 4.34

Aperture size

In this case, one might choose to make R be 5 pixels.

Another devil: the center

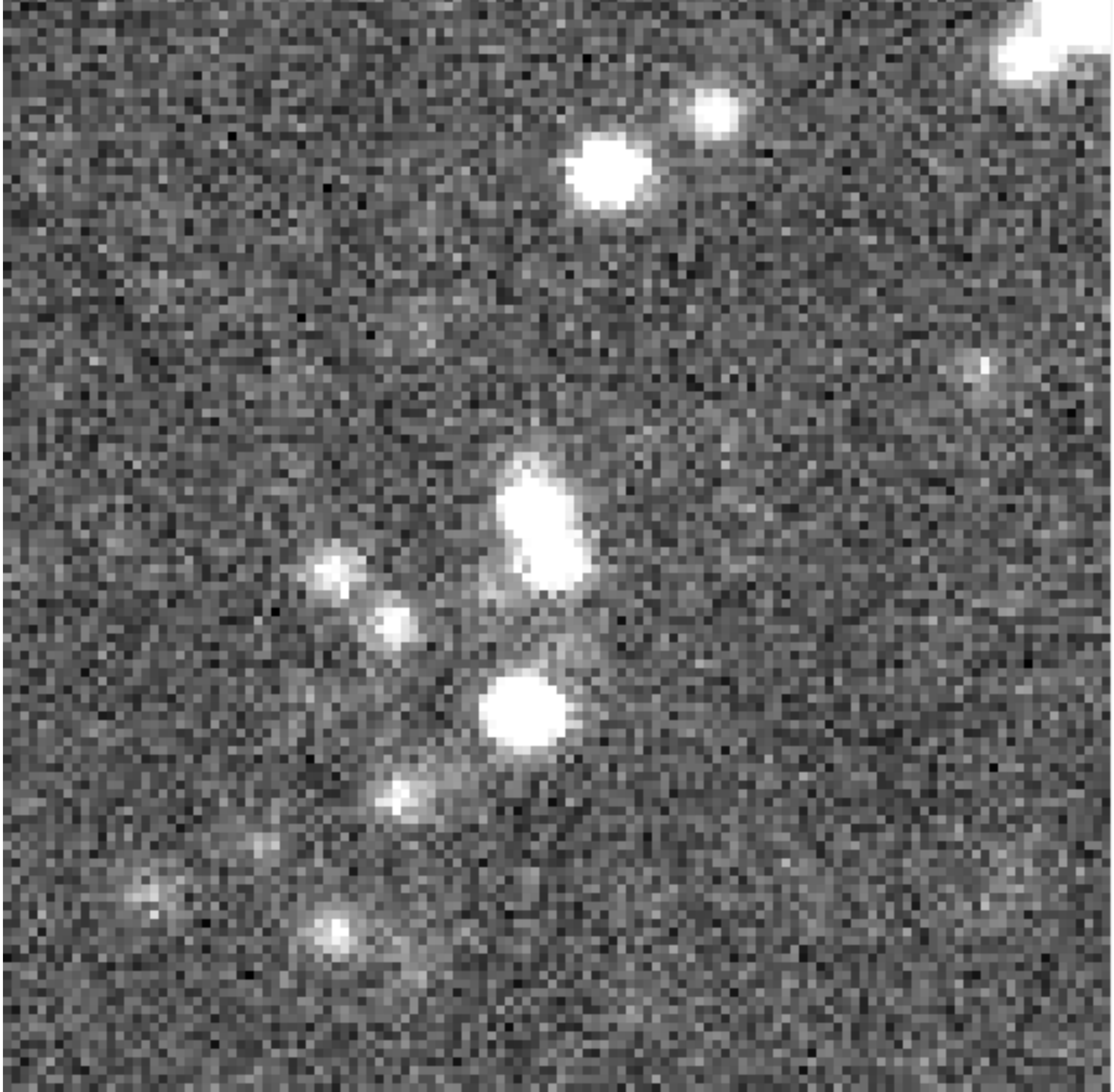
One of the GREAT things about CCD photometry vs the old photoelectric photometry is the issue of centering the aperture on the star digitally rather than trying really, really hard to center the aperture (attached to the telescope) on the star. But, you still need a good center. Easiest thing is to determine a centroid.

centroid_x = Σ(intensity times X)/Σ(intensity)

centroid_y = Σ(intensity times Y)/Σ(intensity)

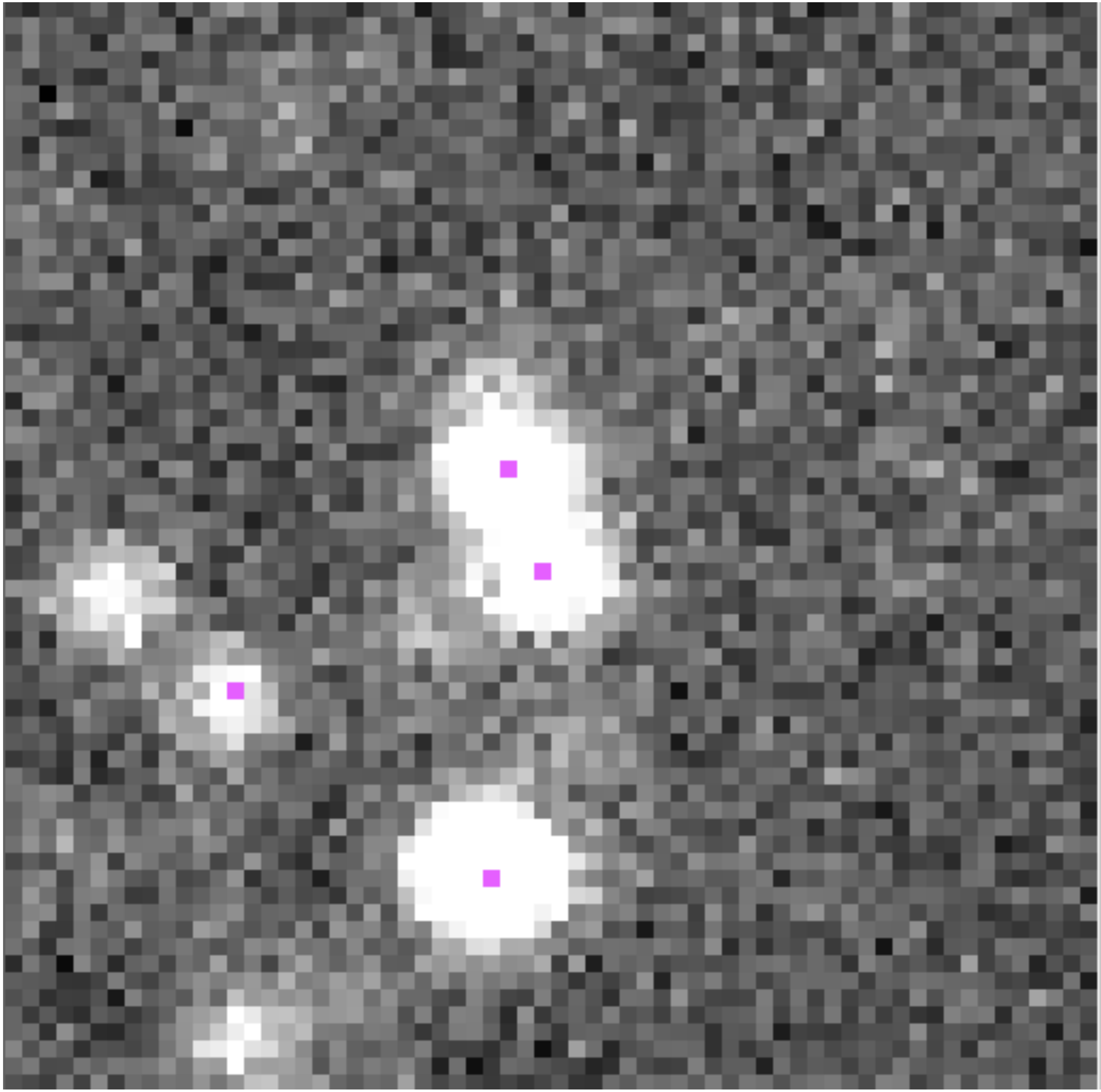
centroids

So, a centroid definition works well unless the object is crowded.



Aperture center

In a crowded field, it's better to identify stars and then NOT centroid. Popular star-finding routines that are good to 1/3rd of a pixel include "daofind" in IRAF, and the linux Source-Extractor (SExtractor).

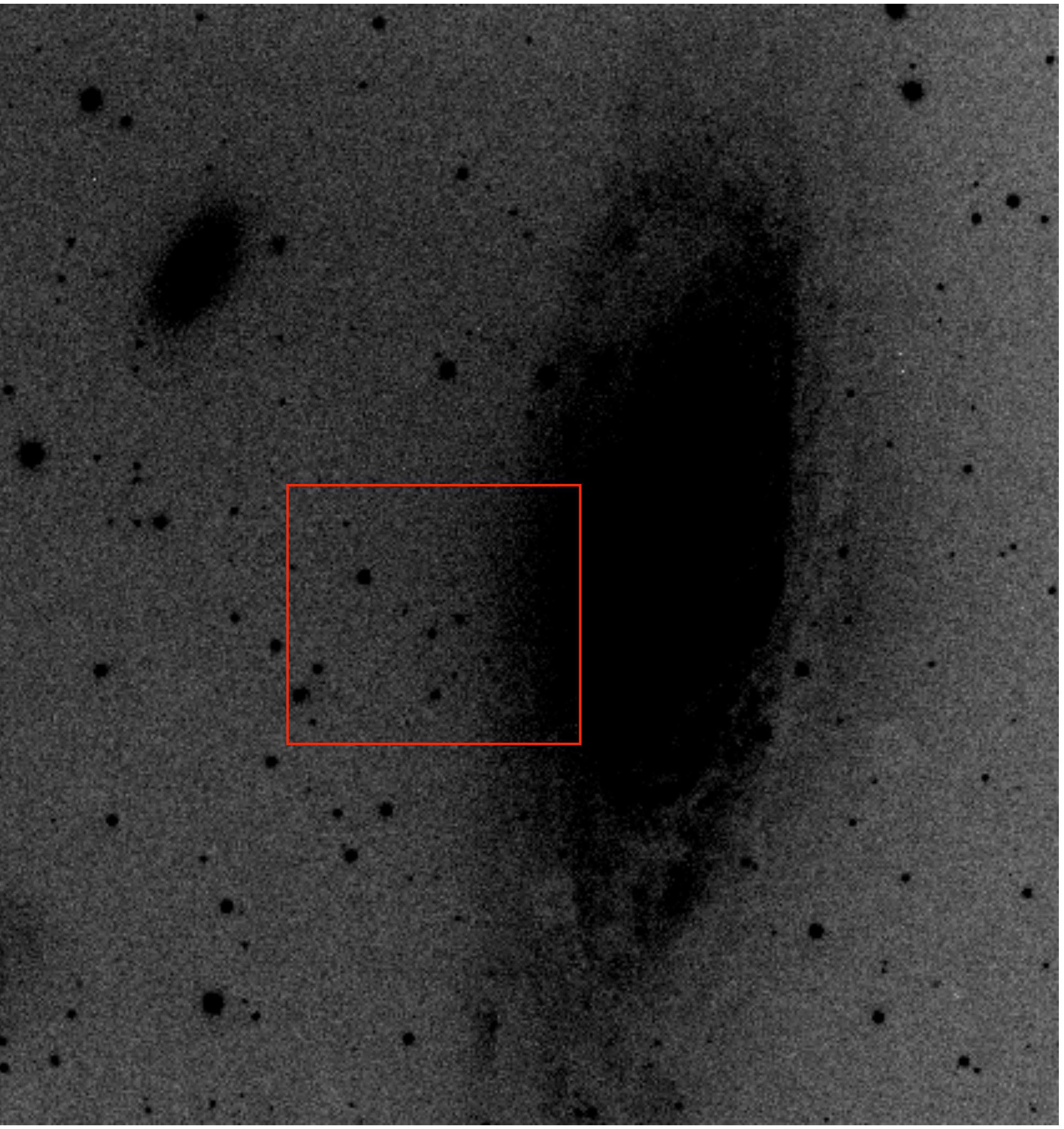


Another devil: the sky

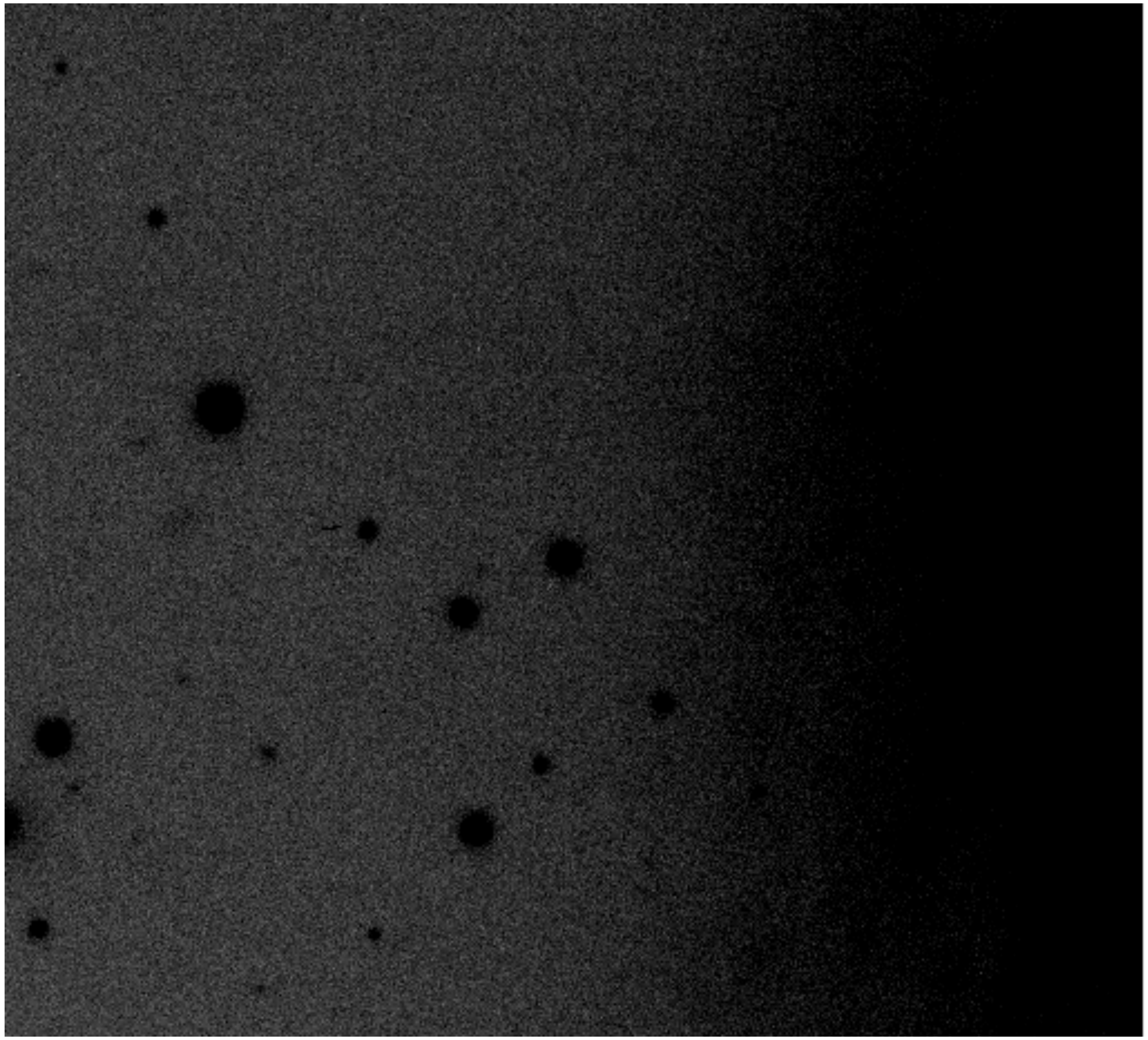
Yet another advantage CCDs have is the ability to determine the sky values locally and simultaneously:

Locally: Very useful when the background is complicated.

Simultaneously: the sky brightness is constantly changing by small amounts.



Example of variable background



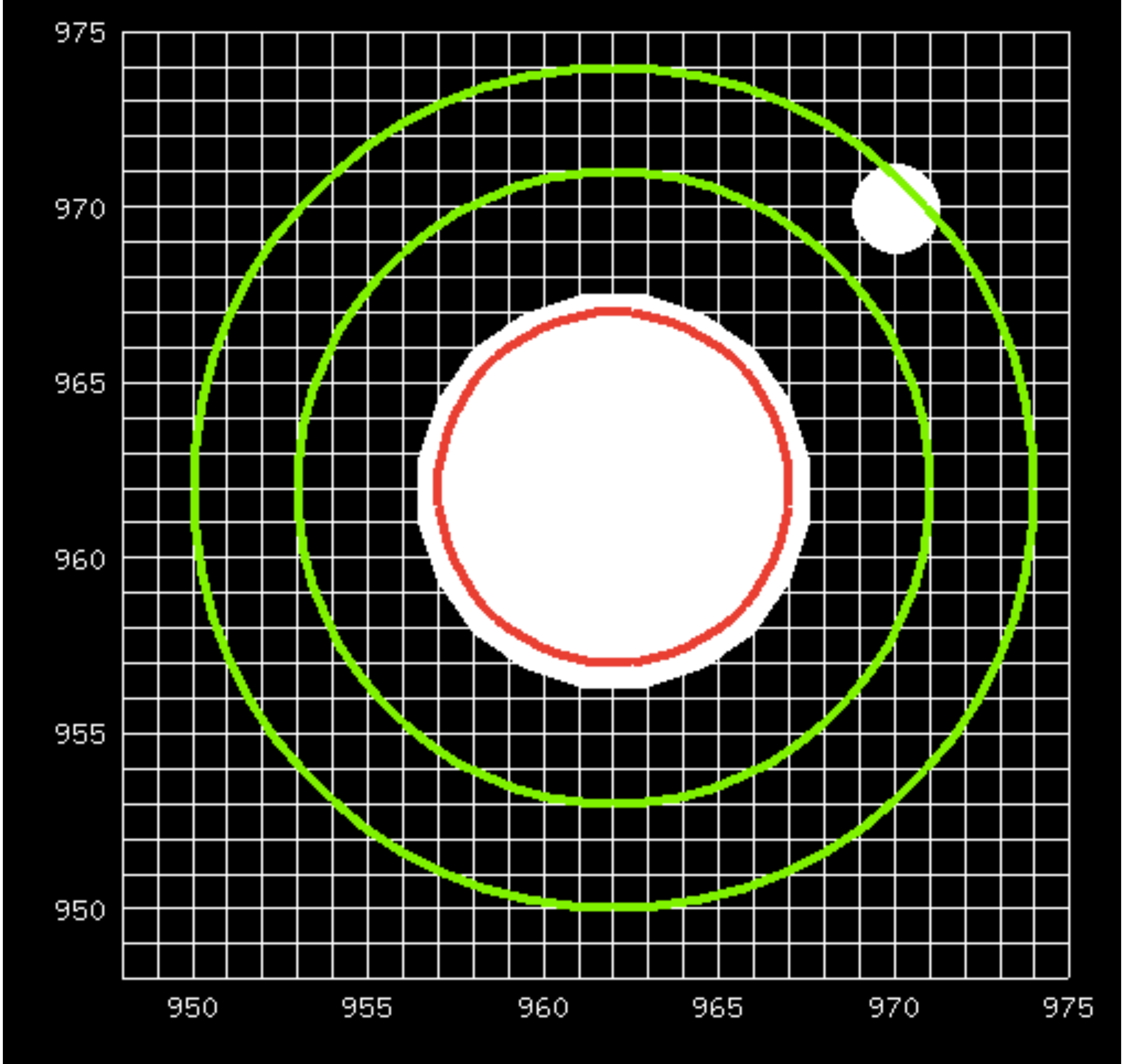
Sky annulus

So, keep the sky annulus close to the star, but not too close. If R=5 pixels, sky annulus of 12–15 is pretty good.

N.B.: LOTS of pixels in that annulus: 3.14 x (15^2-12^2) = 254 pixels

Sky annulus

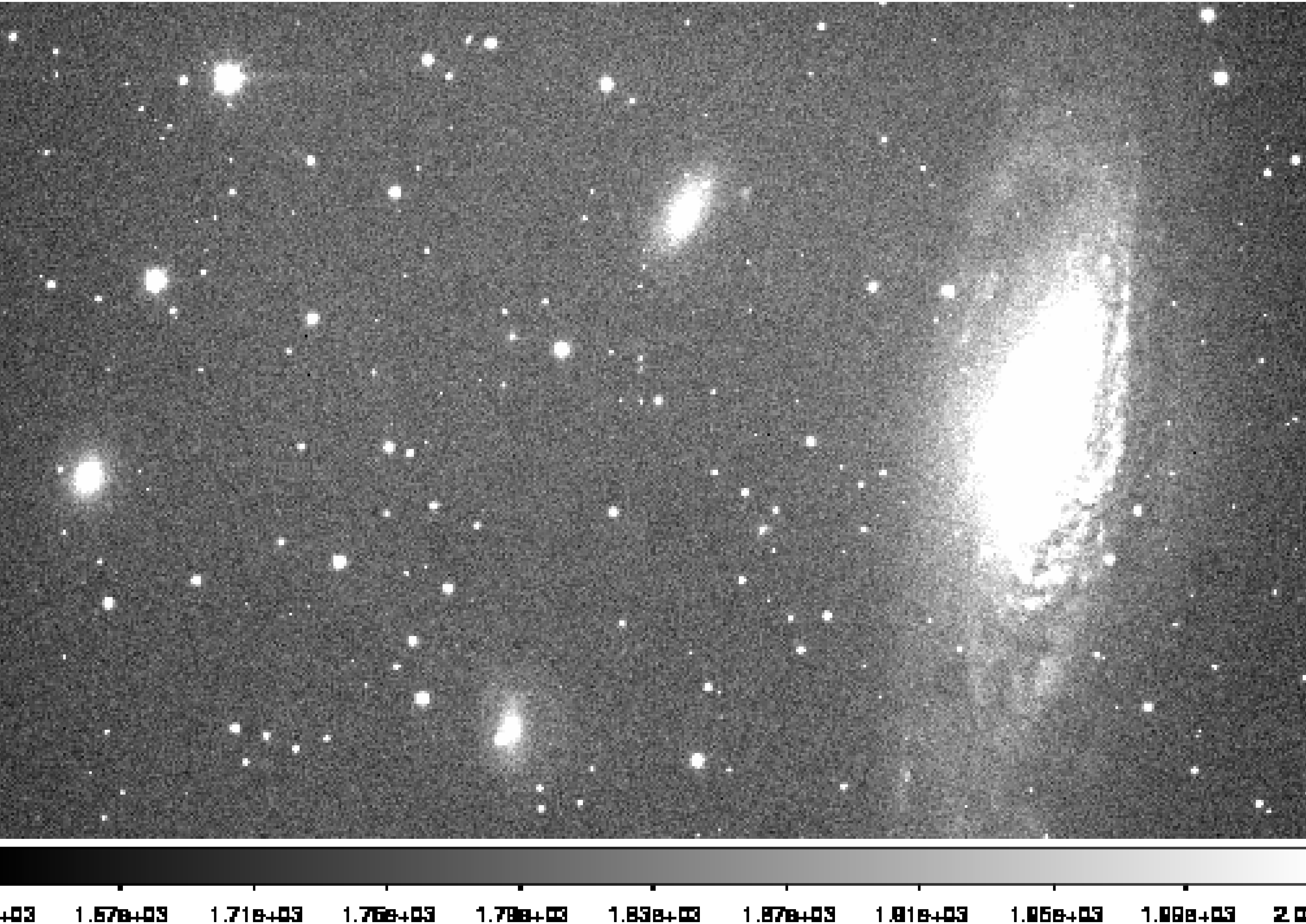
The other issues in the sky annulus is the issue of other stars. Consider the following example:

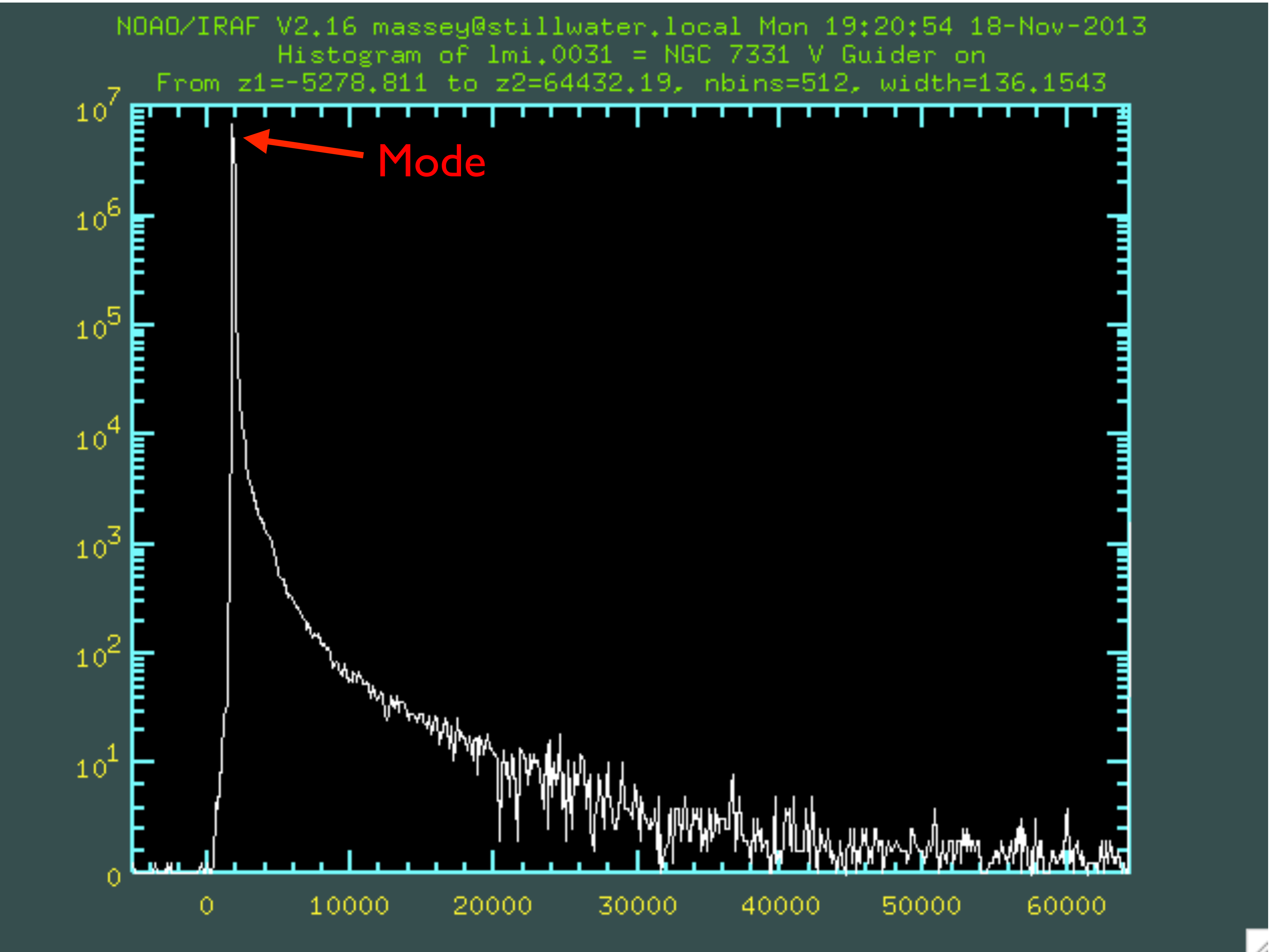


975
970
965
960
955
950
950
955
960
965
970
975

Sky annulus

The result is that the distribution of sky values is not Gaussian.   So, we typically take the mode or median of the sky values.


+03
1.67e+03
1.71e+03
1.75e+03
1.79e+03
1.83e+03
1.87e+03
1.91e+03
1.95e+03
1.99e+03



NOAO/IRAF V2.16 massey@stillwater.local Mon 19:20:54 18-Nov-2013
Histogram of lmi.0031 = NGC 7331 V Guider on
From z1=-5278.811 to z2=64432.19, nbins=512, width=136.1543
Mode
10^7
10^6
10^5
10^4
10^3
10^2
10^1
0
0
10000
20000
30000
40000
50000
60000

Aperture photometry

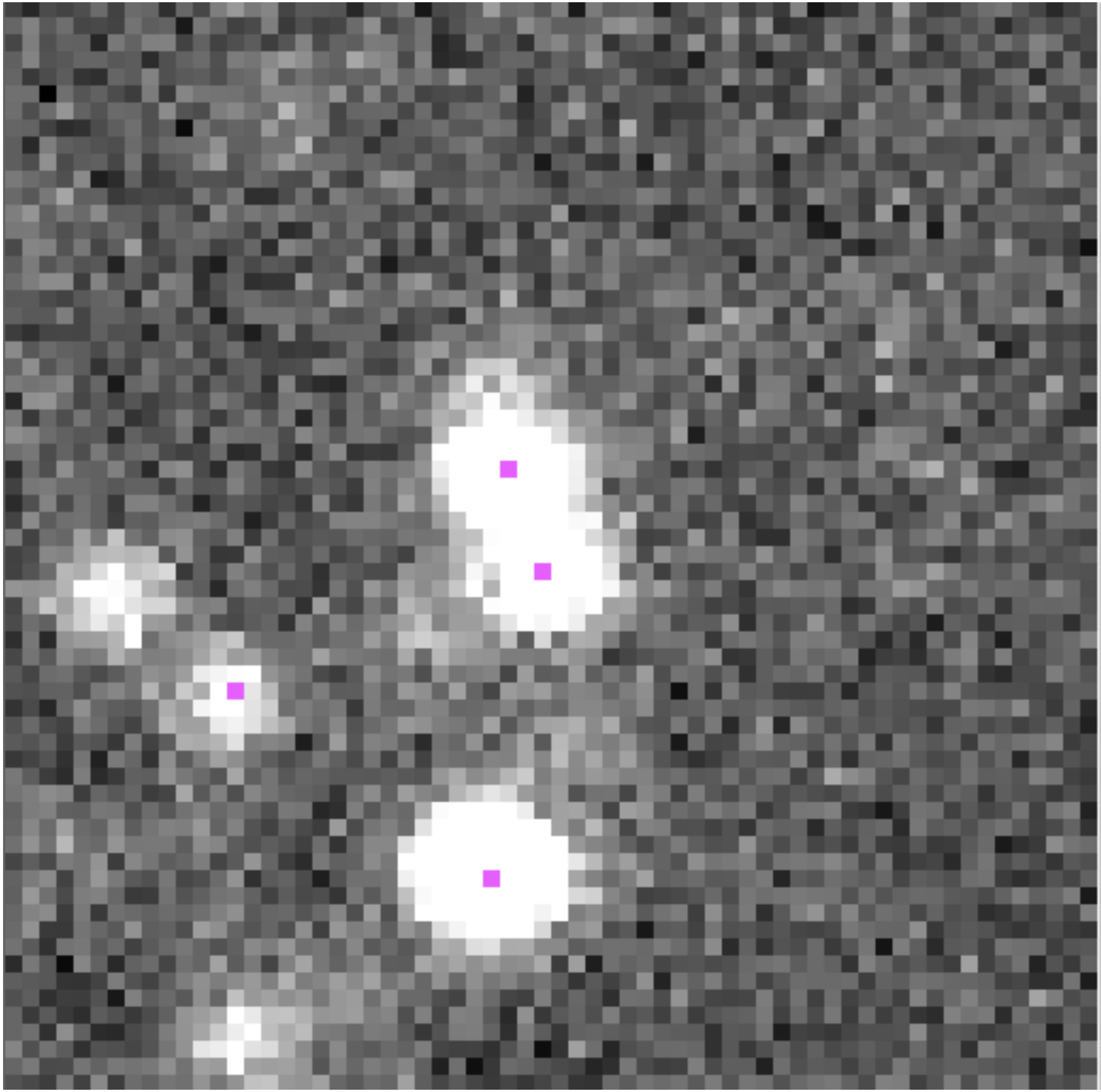
Summary:

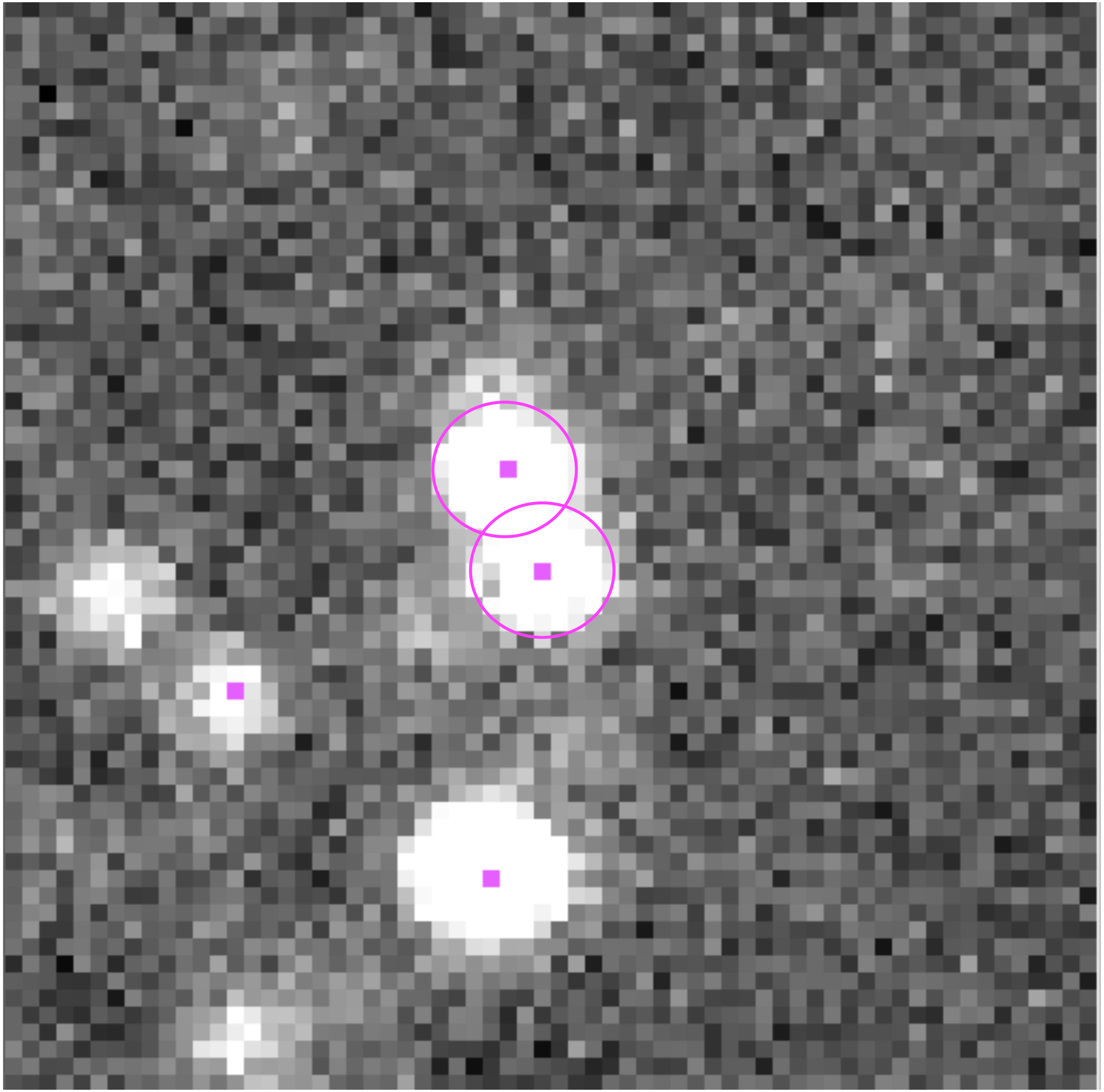
Define center of star by centroid (if uncrowded) or adopt. Needs to be accurate to 1/10th of measuring radius.

Define measuring aperture. Want to minimize errors. To minimize error, radius should be similar to the fwhm.

Define sky annulus and algorithm (mode or median are good choice).

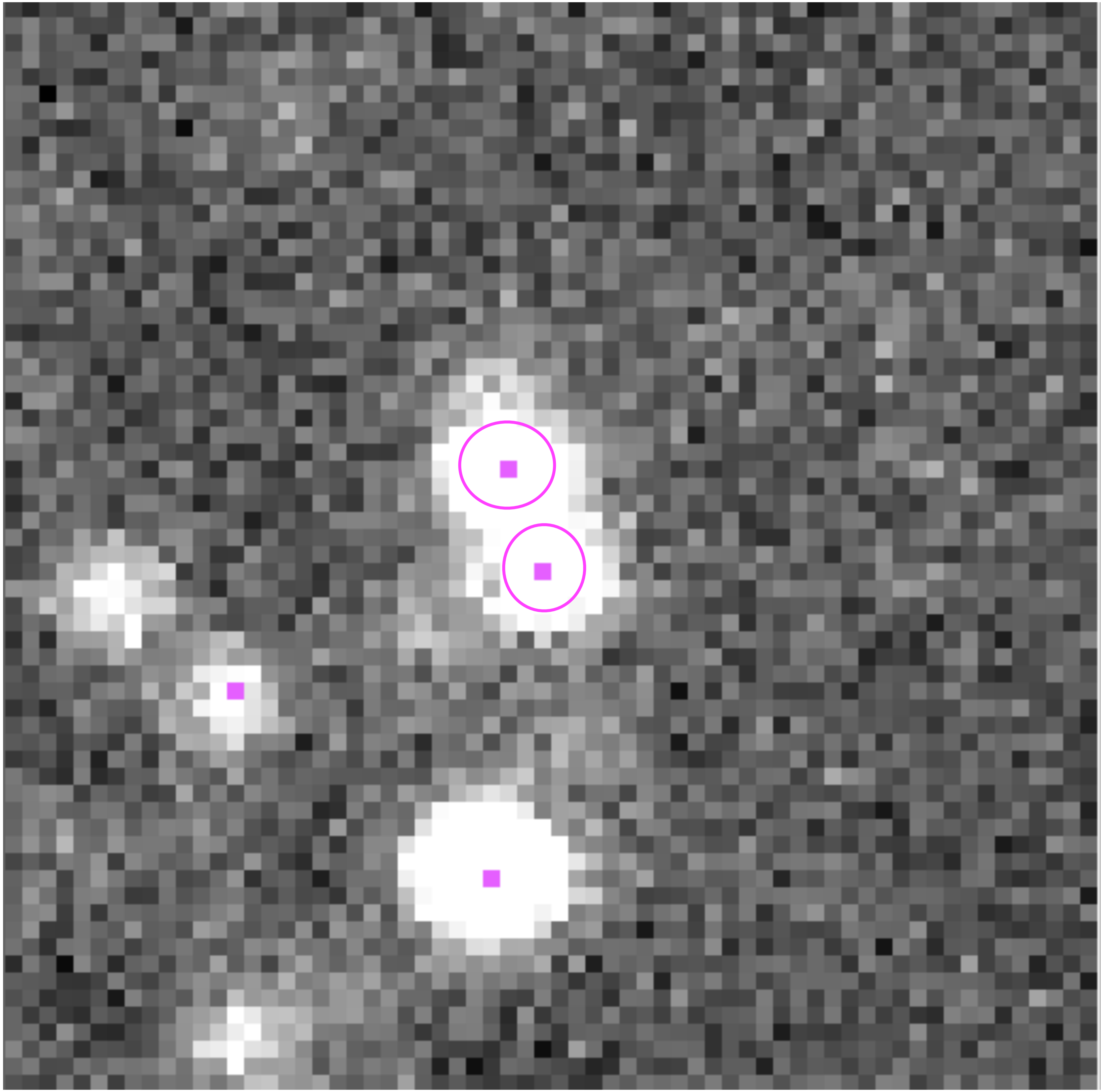
Aperture photometry not always a good choice





Crowded field photometry

Could use smaller apertures....



Crowded field photometry

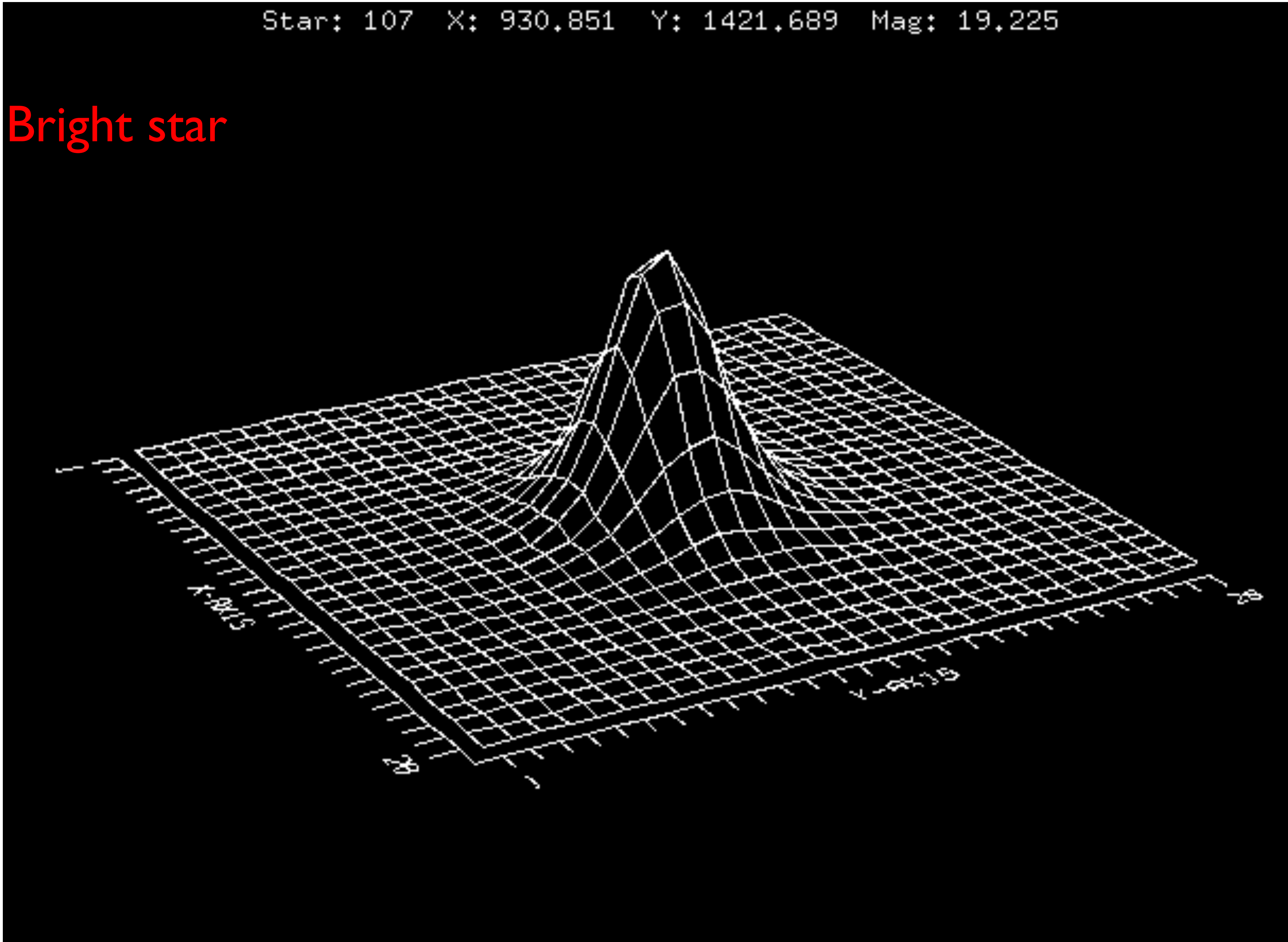
That helps some but the light of one star is still contaminating the light of the other star.

Crowded field photometry

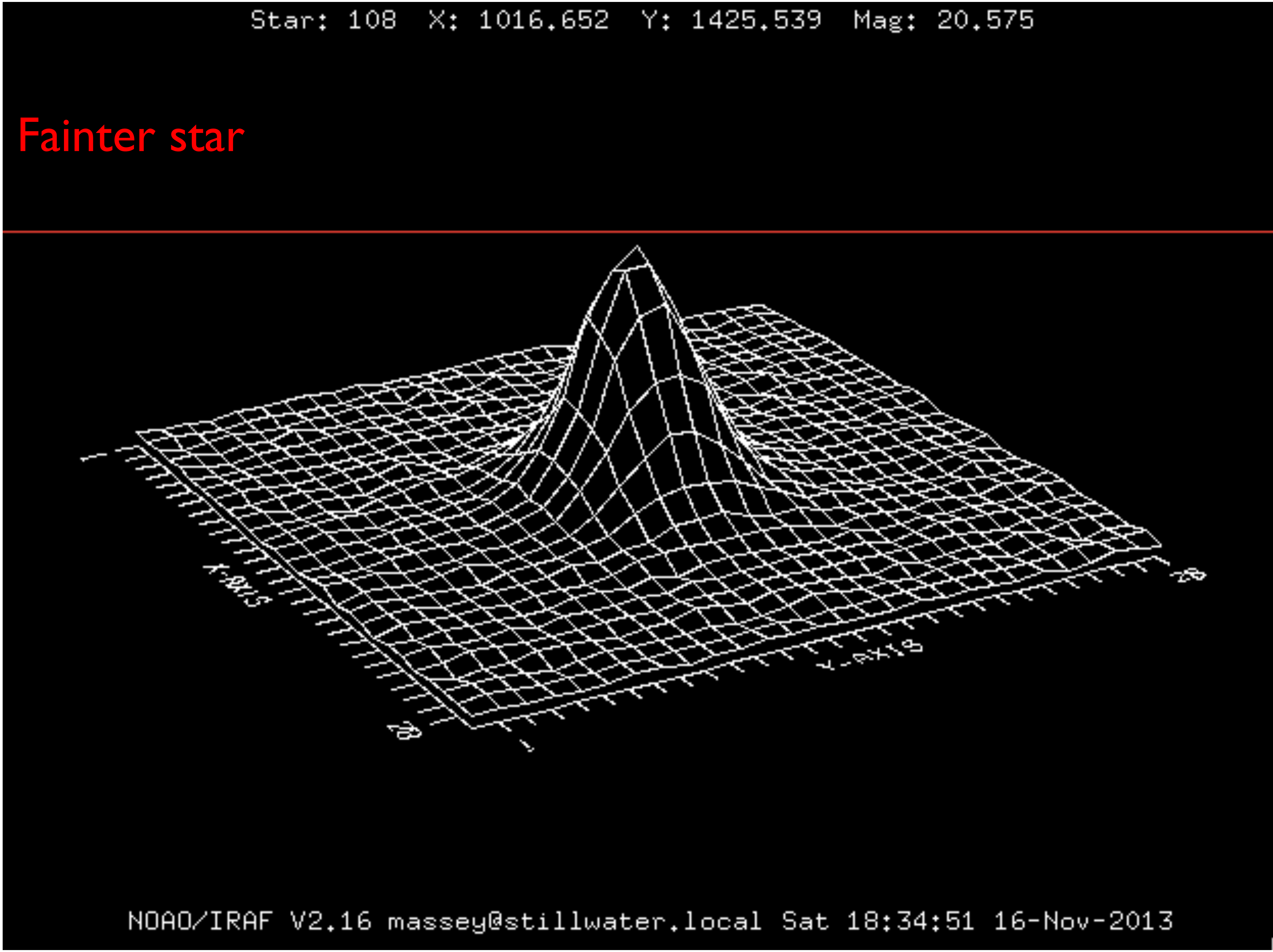
An alternative to aperture photometry: point-spread-function fitting.

Point-spread-function (PSF)

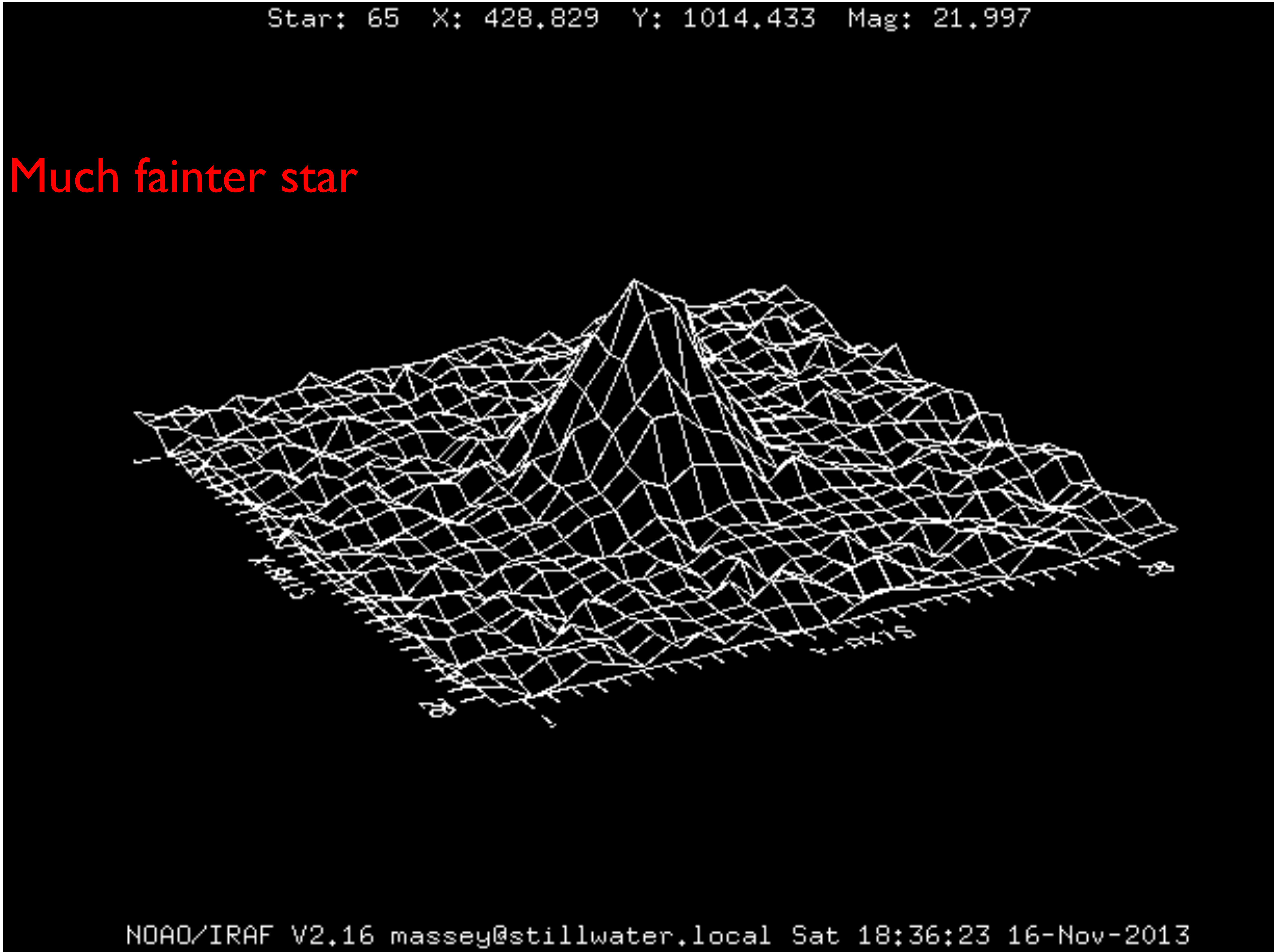
The premise of PSF fitting is that the shapes of stars are the same across the entire frame, and regardless of brightness. In other words, bright stars are not actually “bigger” than faint stars. The shape is


Star: 107 X: 930.851 Y: 1421.689 Mag: 19.225
Bright star

Fainter star



Much fainter star



PSF-fitting

The shape stays the same! But it gets noiser!

PSF-fitting

First, find the stars using some mechanism, like "daofind".

2) Do aperture photometry so that you know the sky value and the approximate intensity relative to the stars you'll use to define the PSF.

3) Define a good clean PSF from bright isolated stars on the frame.

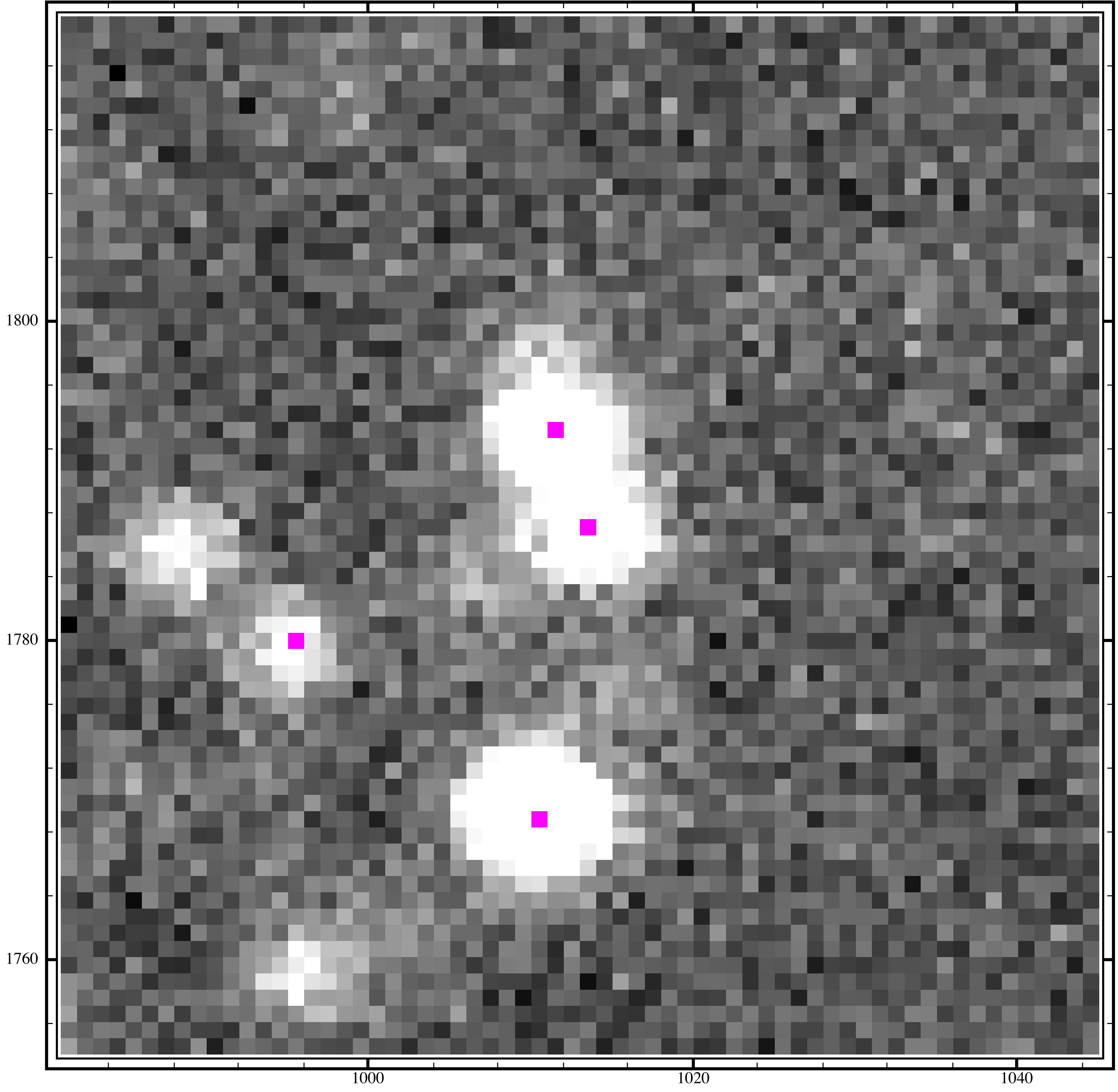
PSF-fitting

4) Now you can fit all of the stars on the frame simultaneously. There are three parameters:

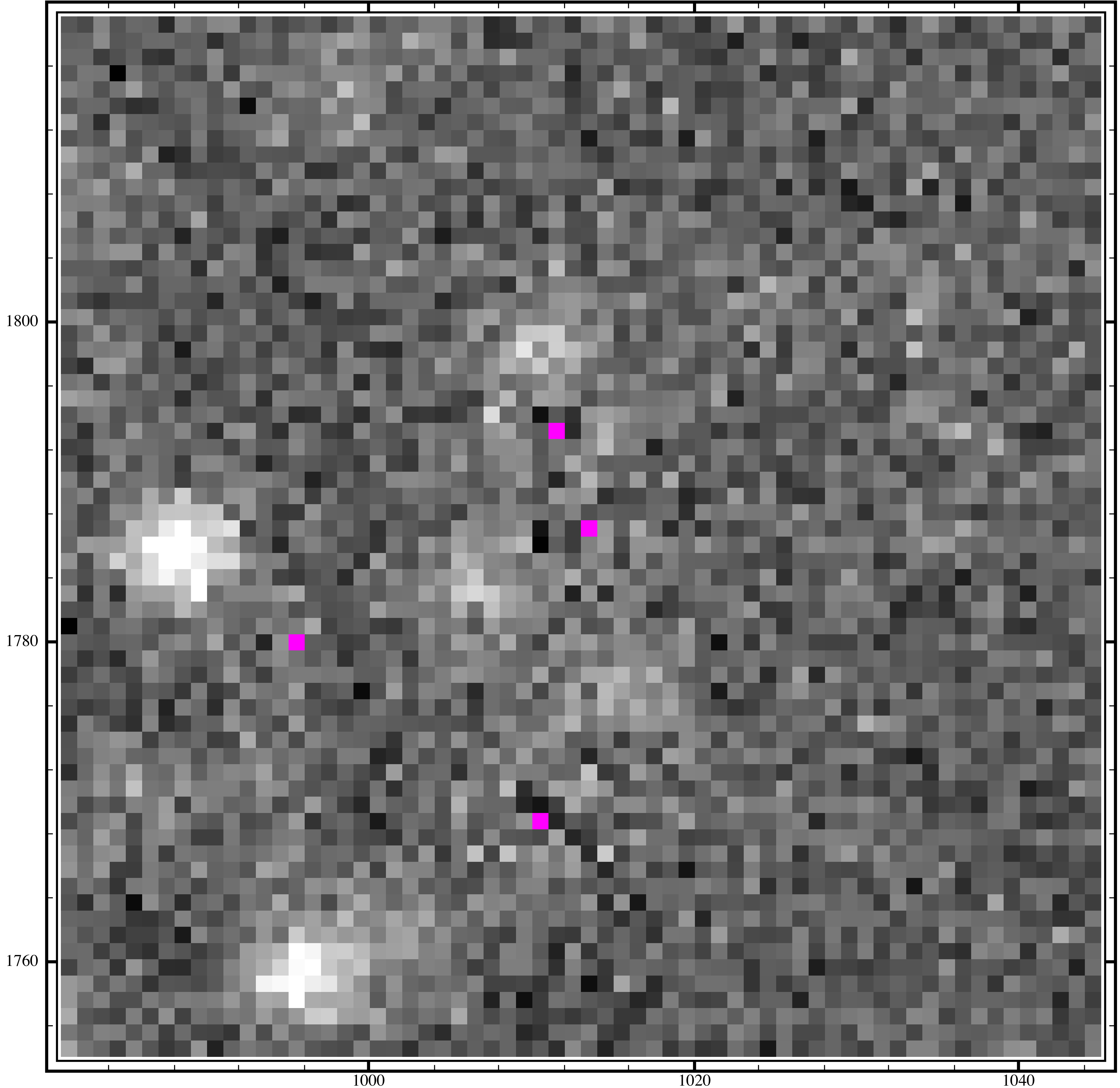
x, y, and Intensity, where the Intensity is the scaling factor between the sample PSF and the star.

PSF-fitting

5) You can subtract the fitting PSFs from the frame to see how well you did. Also it lets you find additional stars that were hidden under the other stars.



1800
1780
1760
1000
1020
1040


1800
1780
1760
1000
1020
1040

Summary

Instrumental magnitude:

-2.5 log (counts_above_sky/exptime)+C

signal-to-noise S/N:

(Sum_above_sky) x gain / total noise

where total noise= sqrt((Sum_all x gain)+Npixel x readnoise^2)

Uncertainity in magnitudes = 1.08 x (1/(S/N))