Stellar Photometry: Aperture Sizes and Peak Brightness

Ast 401/580
Fall 2019

Stellar Profiles

What is the “best” aperture size to use for stellar photometry?   The answer depends upon what you’re doing:

1) All-sky photometry (sometimes called “absolute” photometry, but don’t confuse it with absolute magnitudes!) Use a radius that is 3x your worse fwhm, but it keep it the same for everything.

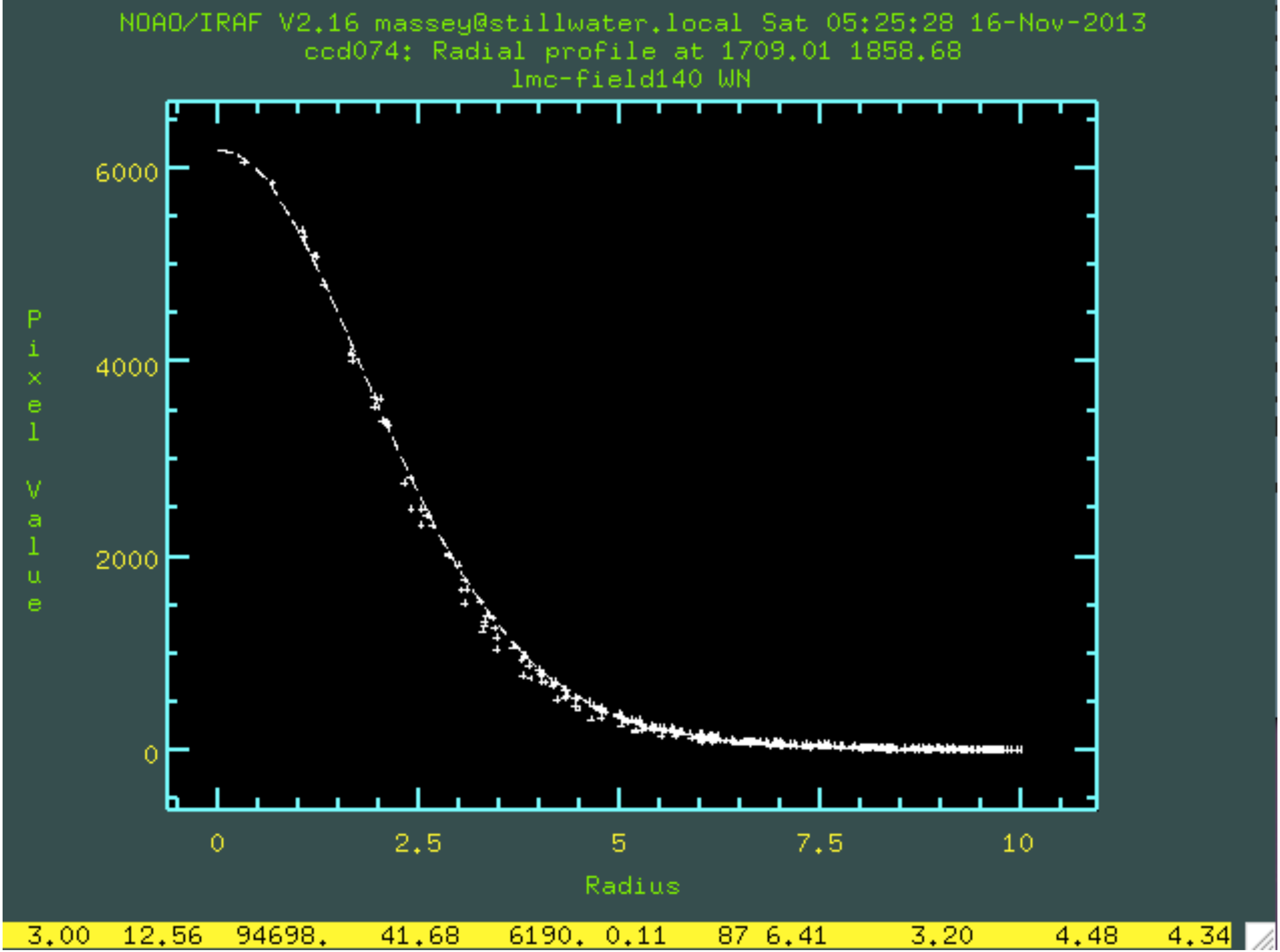
2) Relative photometry: Use a radius that is about the same as your fwhm.

All sky photometry

Goal is to measure essentially “all” of the light. However, given that the stellar profile goes on forever, you’re never going to get all of the light. Instead, what you need to do is get “most” of the light but do it in a consistent fashion, so that you include the same fraction of the light for all of your data.

Say you have 30 images taken around the sky. You’re measuring one or two stars on each of these, and comparing their brightness to each other. (Some are probably standard stars.)

All this requires is for you to be somewhere out on the diffraction part of the profile.


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

All sky photometry

Inner part of the profile is more-or-less Gaussian. The “size” (full-width-at-half-maximum) is dominated by the seeing and guiding.

The outer part of the profile is dominated by diffraction, and scattering.

If you’re on the diffraction part of the profile, and you keep the SAME size radius for your frames, you’re excluding the same fraction of light (i.e., the same number of magnitudes, say 10% = 0.1 mag).

All sky photometry

You've taken a night's worth of data and you'd like to measure the brightness of your program stars to your standard stars. The best images had a fwhm of 3.0 pixels and the worse images had a fwhm of 4.5 pixels. What measuring radius should you use to relate everything to the standard stars?

a) 3.0 pixels

b) 5.0 pixels

c) 9.0 pixels

d) 15 pixels

All sky photometry

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Relative photometry

Here you are dealing with just photometry from a single image. You measure the brightness of one star (say) relative to the brightness of another star…or maybe relative to the brightness of 100 other stars. Using any size aperture should work, in terms of excluding the same amount of light (fwhm the same everywhere on the image). But you'd like to minimize your errors!

Goldilocks problem

As you use a larger aperture, you include more pixels. Bad because:

a) The amount of read noise goes up.

b) The amount of photon-noise from the sky goes up.

Goldilocks problem

As you use a smallerer and smaller aperture,

a) You are using less and less light from the star

b) More sensitive to partial pixel arithmetic.

c) You become more sensitive to centering issues. (“best” center is probably no better than 1/3rd of a pixel).

Sidebar: adding errors (again!)

With an aperture containing “p” pixels, the total read-noise is going to be:

$$\sigma_{read} = \text{sqrt}(n) \times r$$

where r is the read-noise per pixel [typically 6 to 10 e-]

Why? $\sigma^2 = r^2 + r^2 + r^2 + r^2 + r^2 + r^2 + r^2 + r^2 + \ldots$

$$= n \times r^2$$

$$\sigma_{read} = \text{sqrt}(n) \times r$$

Sidebar: adding errors (again!)

Similarly, the total photon noise from the sky is just going to be:

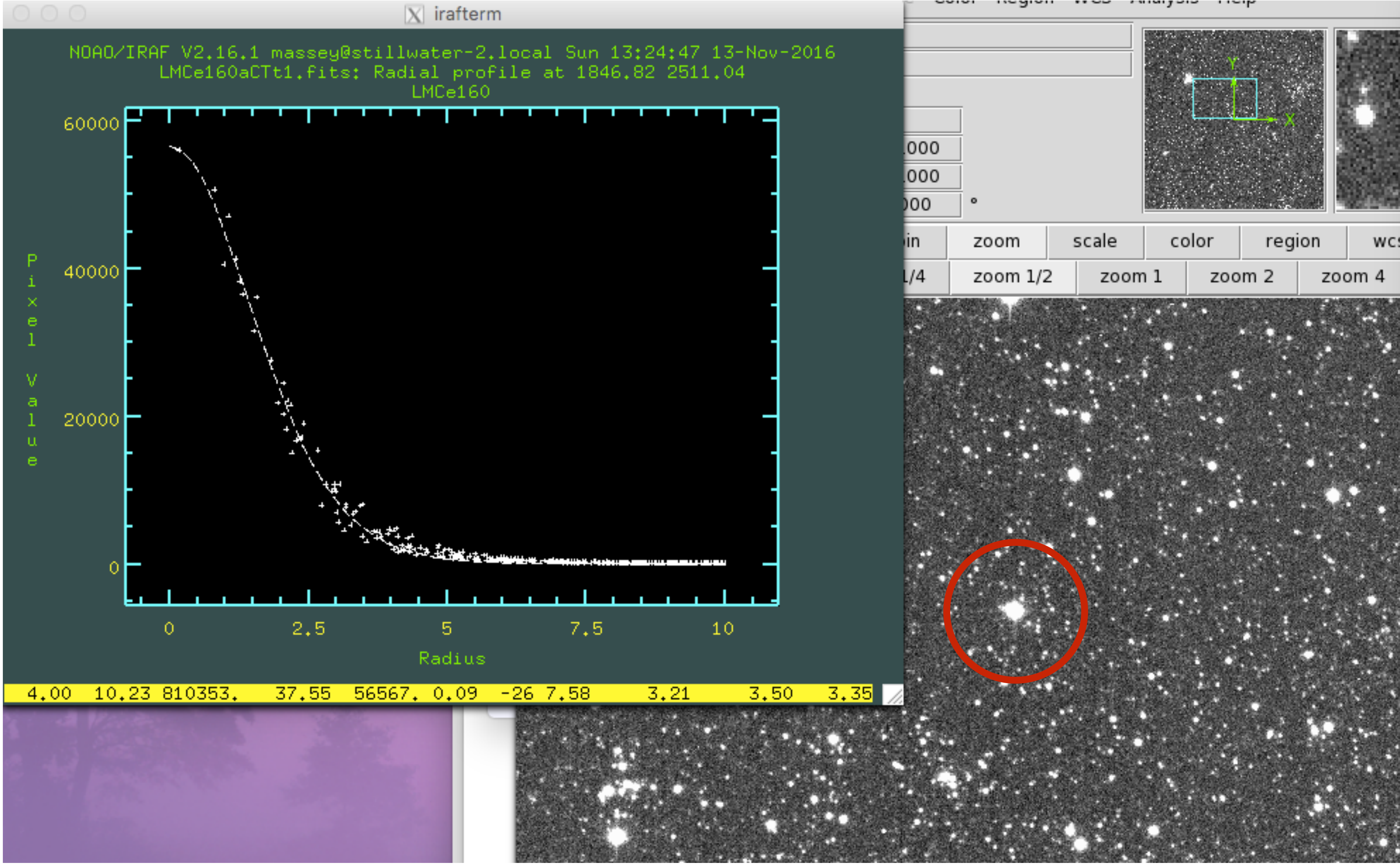
$$\sigma_{sky} = \mathrm{sqrt}(nS)$$

where S is the the average sky value *in electrons per pixel* since the error per pixel will be sqrt(S).

Need to be careful about what is "per pixel" and what isn't.

Goldilocks problem

One way to solve the Goldilocks problem is to perform try measuring a star and seeing where the errors are the smallest. After all, your photometry program is going to be able to calculate these errors for you.



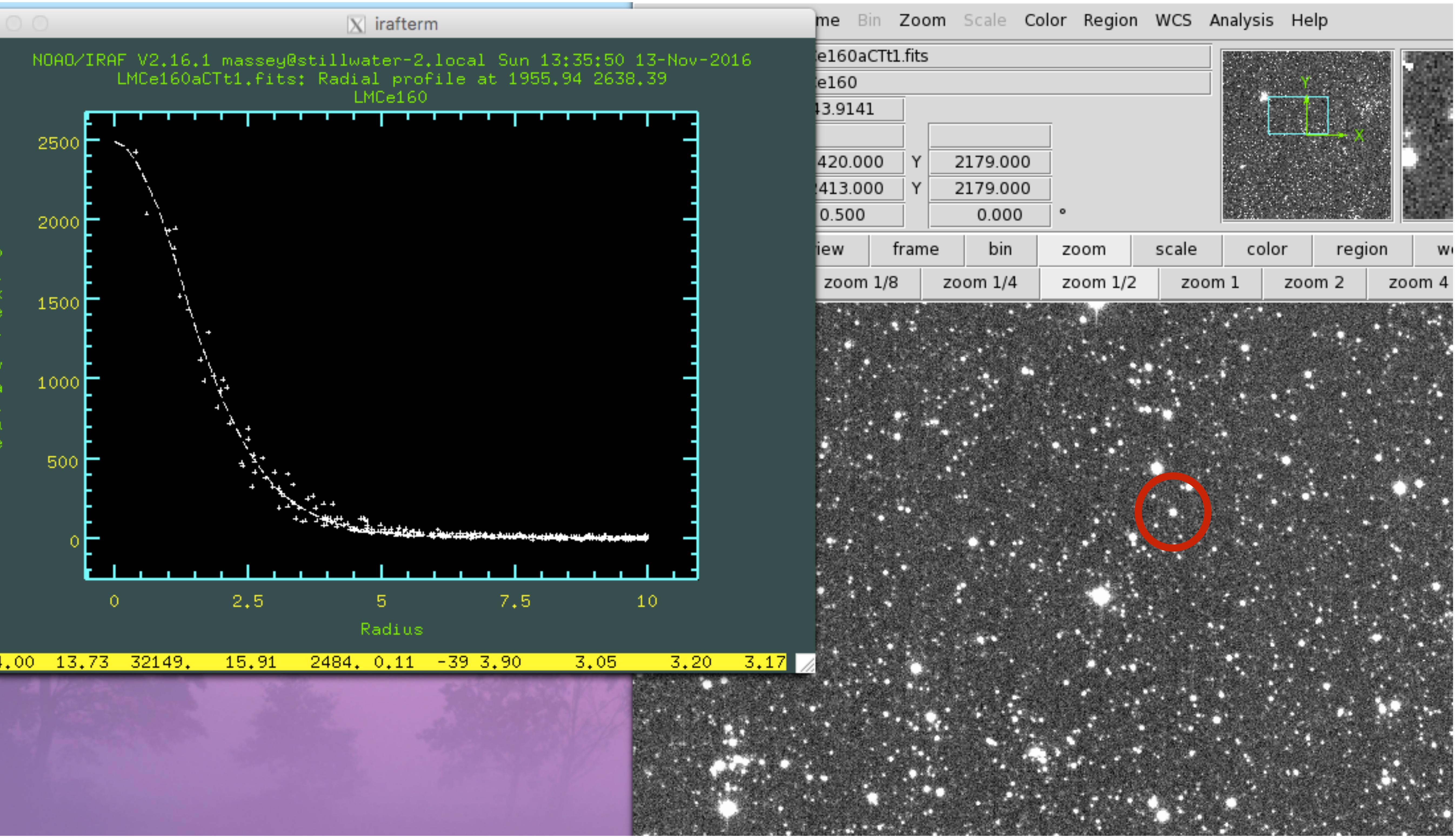
Sky value is about 15 ADU. Gain is 1.0 e/ADU. So we expect read and sky not to matter much.

Goldilocks problem

Very bright star:

radius	mag	magerror
3-pixels	16.655	0.001
10-pixels	16.249	0.001
15-pixels	16.235	0.001

Not much difference in the errors! Big difference inthe amount of light included.


irafterm
NOAO/IRAF V2.16.1 massey@stillwater-2.local Sun 13:35:50 13-Nov-2016
LMCe160aCTt1.fits: Radial profile at 1955.94 2638.39
LMCe160
2500
2000
1500
1000
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0
0
2.5
5
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10
Radius
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me Bin Zoom Scale Color Region WCS Analysis Help
e160aCTt1.fits
e160
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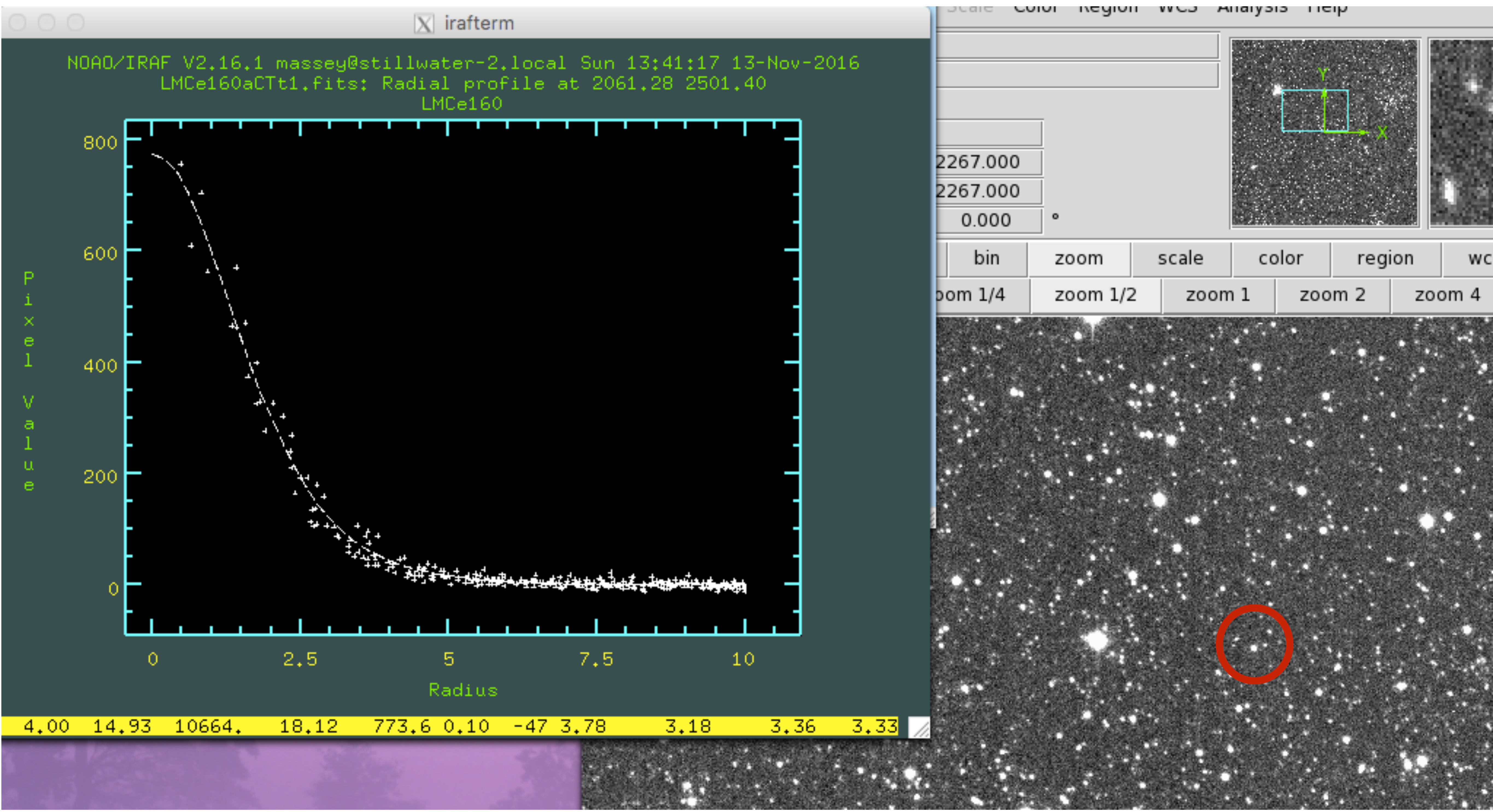
iew frame bin zoom scale color region
zoom 1/8 zoom 1/4 zoom 1/2 zoom 1 zoom 2 zoom 4

Goldilocks problem

medium bright star:

radius	mag	magerror
3-pixels	20.107	0.007
10-pixels	19.758	0.006
15-pixels	19.741	0.008

So, we would want something > 3 and <15.


irafterm
NOAO/IRAF V2.16.1 massey@stillwater-2.local Sun 13:41:17 13-Nov-2016
LMCe160aCTt1.fits: Radial profile at 2061.28 2501.40
LMCe160
Pixel Value
800
600
400
200
0
0
2.5
5
7.5
10
Radius
4.00 14.93 10664. 18.12 773.6 0.10 -47 3.78 3.18 3.36 3.33
2267.000
2267.000
0.000
bin
zoom
scale
color
region
zoom 1/2
zoom 1
zoom 2
zoom 4

Goldilocks problem

faint star:

radius	mag	magerror
3-pixels	21.364	0.012
10-pixels	20.987	0.014
15-pixels	20.948	0.019

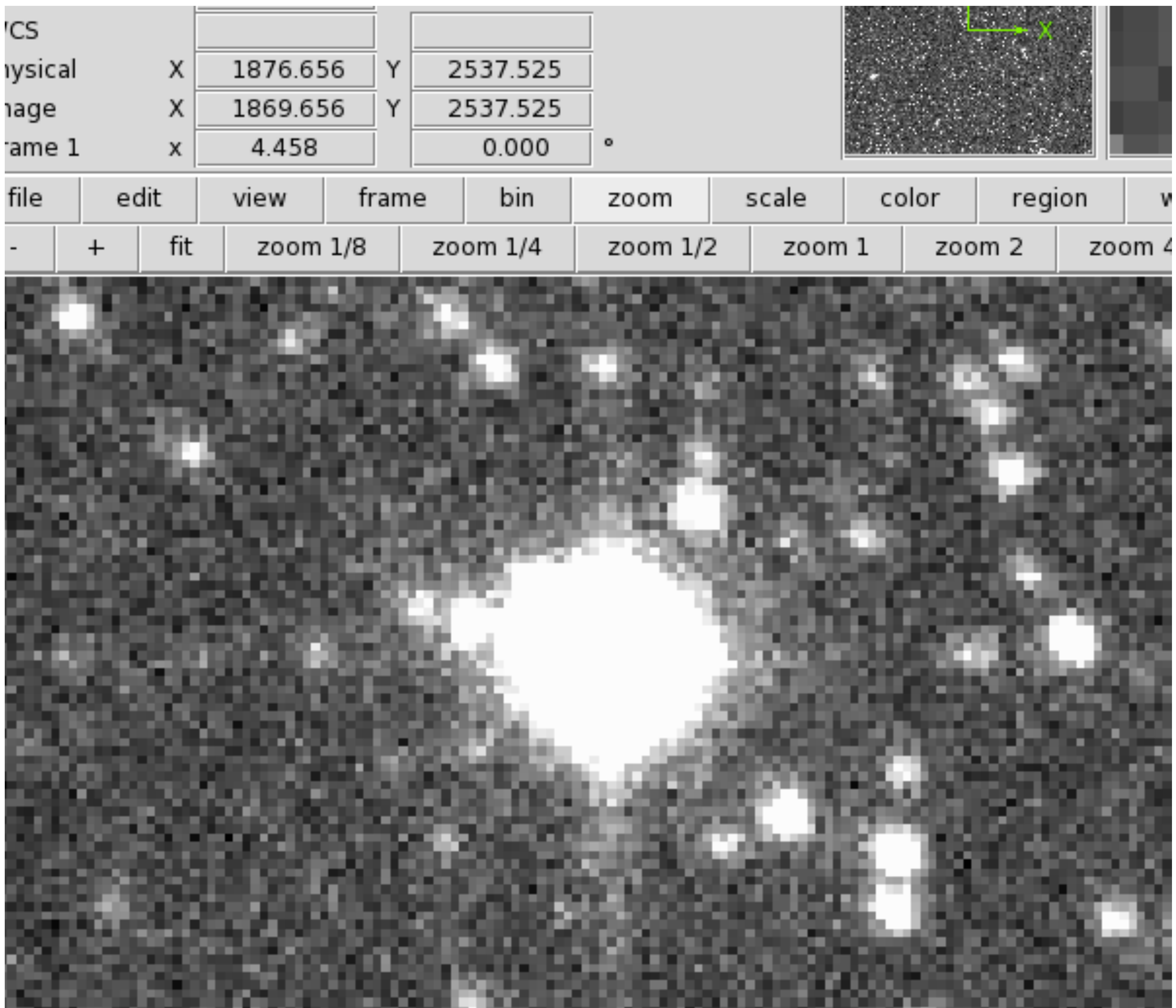
So, we would want something < 10. How much less?

Goldilocks problem

rad	mag	merr
2.5	21.972	0.016
3	21.433	0.013
4	21.181	0.011
5	21.075	0.011
6	21.029	0.011
7	21.009	0.012
8	20.999	0.012
9	20.983	0.013

Goldilocks problem

So for a moderately faint star (still not “faint”) my claim that you want a measuring radius a bit larger than the fwhm was valid. For the brighter stars you would have lower errors with larger radii. But why might you not want to go that route?



'CS
iysical
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Y
2537.525
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zoom 1/8
zoom 1/4
zoom 1/2
zoom 1
zoom 2

We could do the math..

$$I(r) = A \exp(-r^2/2\sigma^2)$$

where $A = 1/(2\pi\sigma^2)$ is a normalization factor so that the integral is 1 going all the way to infinity.

That denotes the intensity at a given radius for the inner part of the star profile. What we want is the integral from 0 to R. Tricky, but could do this in matlab. Note that the σ describing the width of the Gaussian is related to the more commonly used "fwhm" (full-width at half-maximum) as fwhm= 2 sqrt (2 ln 2) σ = 2.35 σ.

Relationship between peak intensity and integral

If F is the total number of counts in your star, then this is related to the peak intensity I roughly as

F/fwhm^2.

Doing this correctly, I = F/1.13 * fwhm^2 (thanks to Larry Wasserman).